Flavour Physics and CP Violation

Marcel Merk

Bormio pre-conference Lecture, 20-1-2019.

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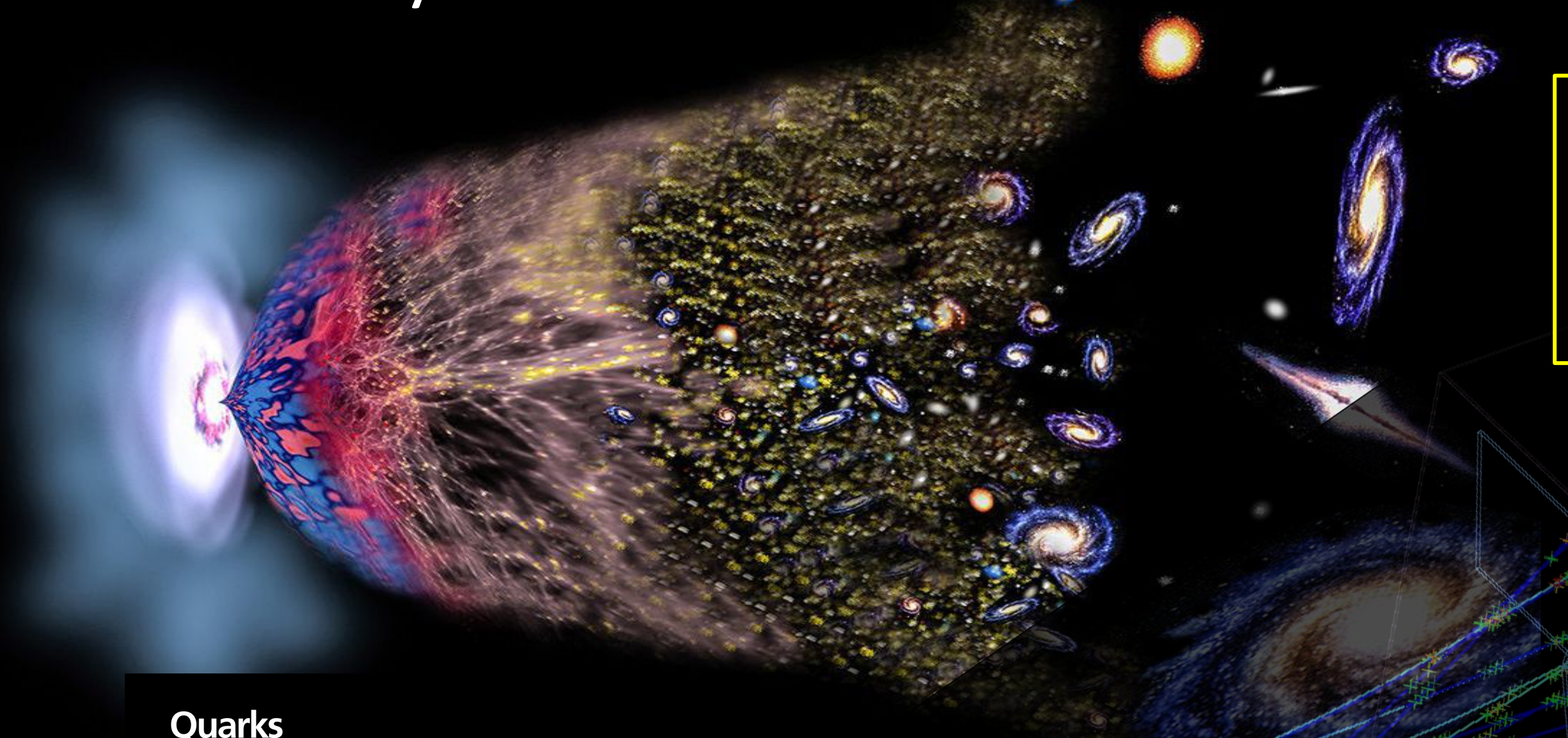
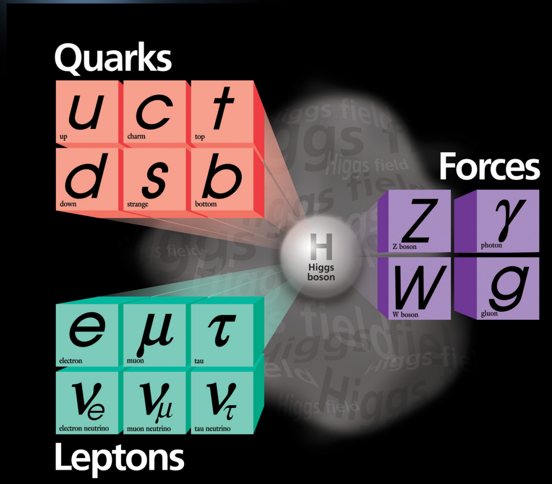
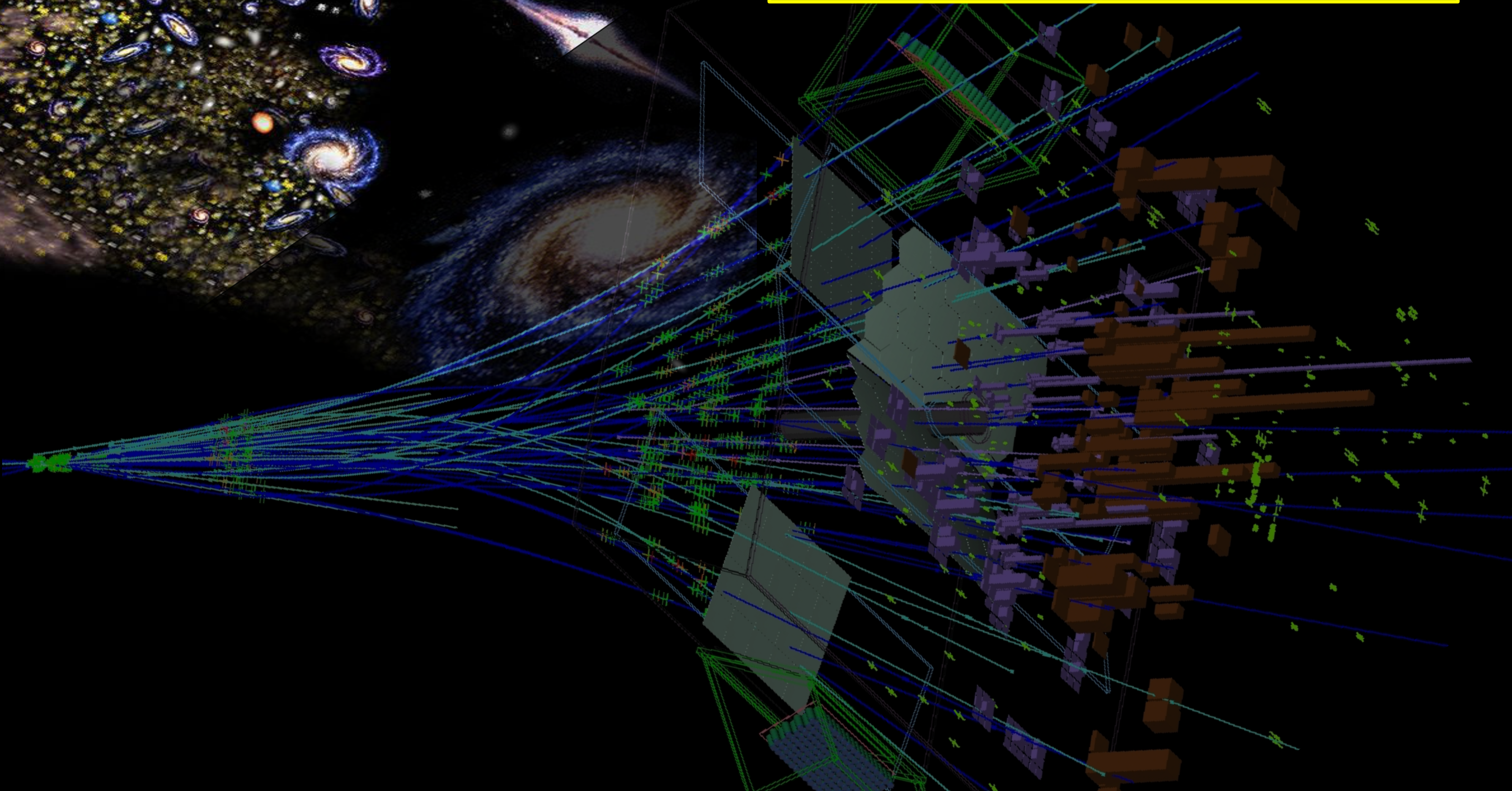
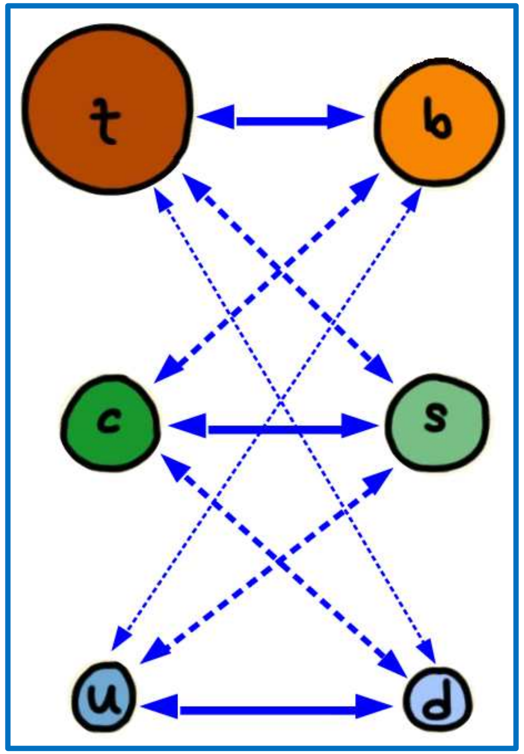


Flavour Puzzles:
- Why no antimatter particles?
- Why three generations?
- Why these particle masses?





The Antimatter Mystery


t
b
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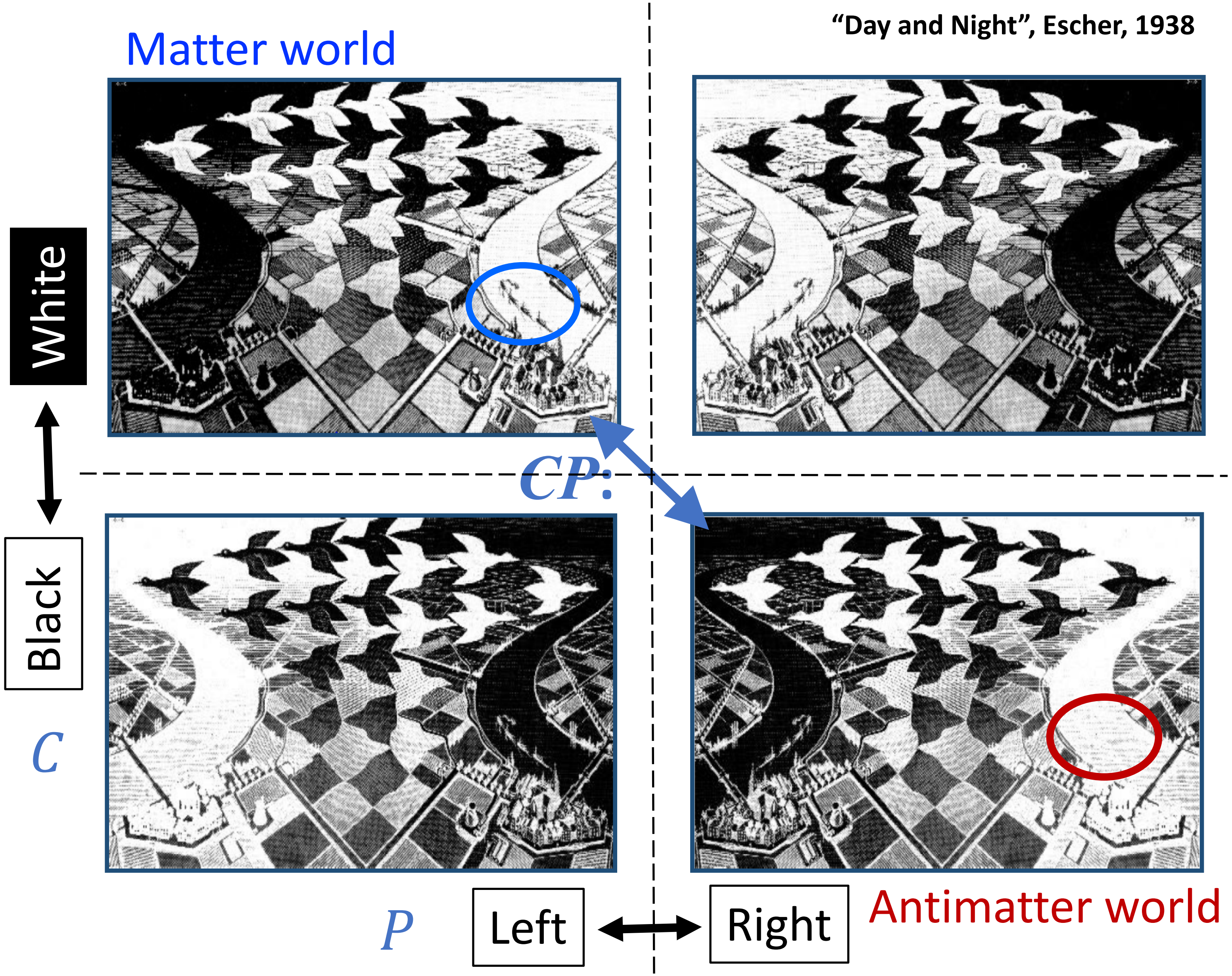
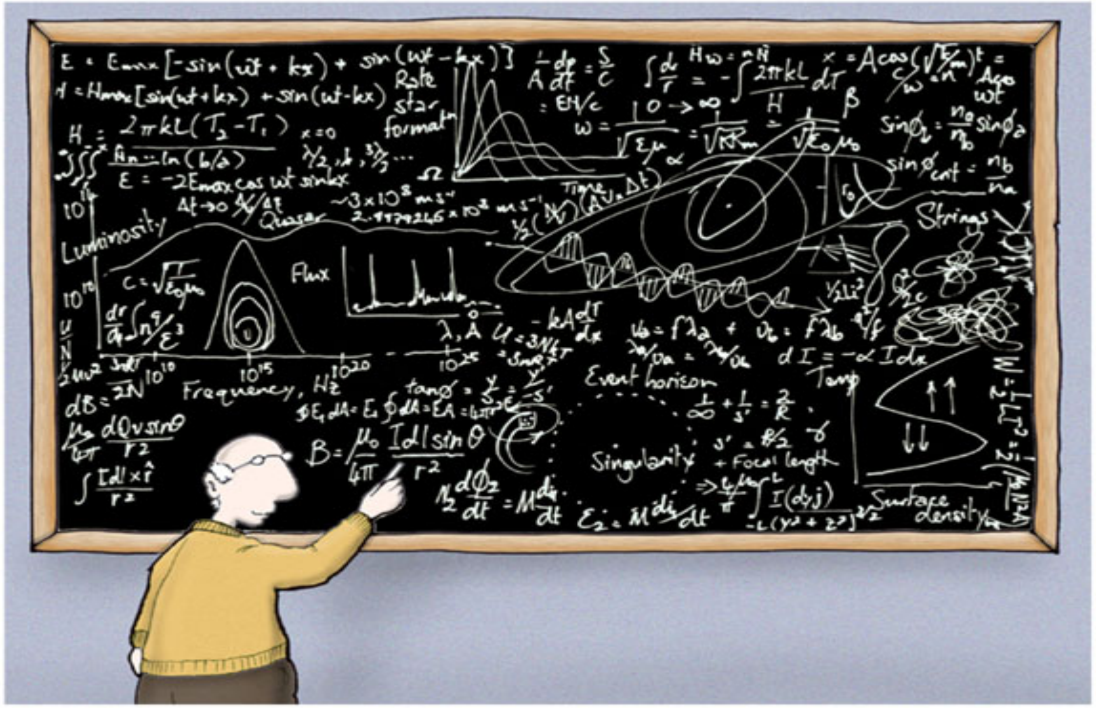

"Day and Night", Escher, 1938
Matter world
White
Black
C
CP:
P
Left
Right
Antimatter world

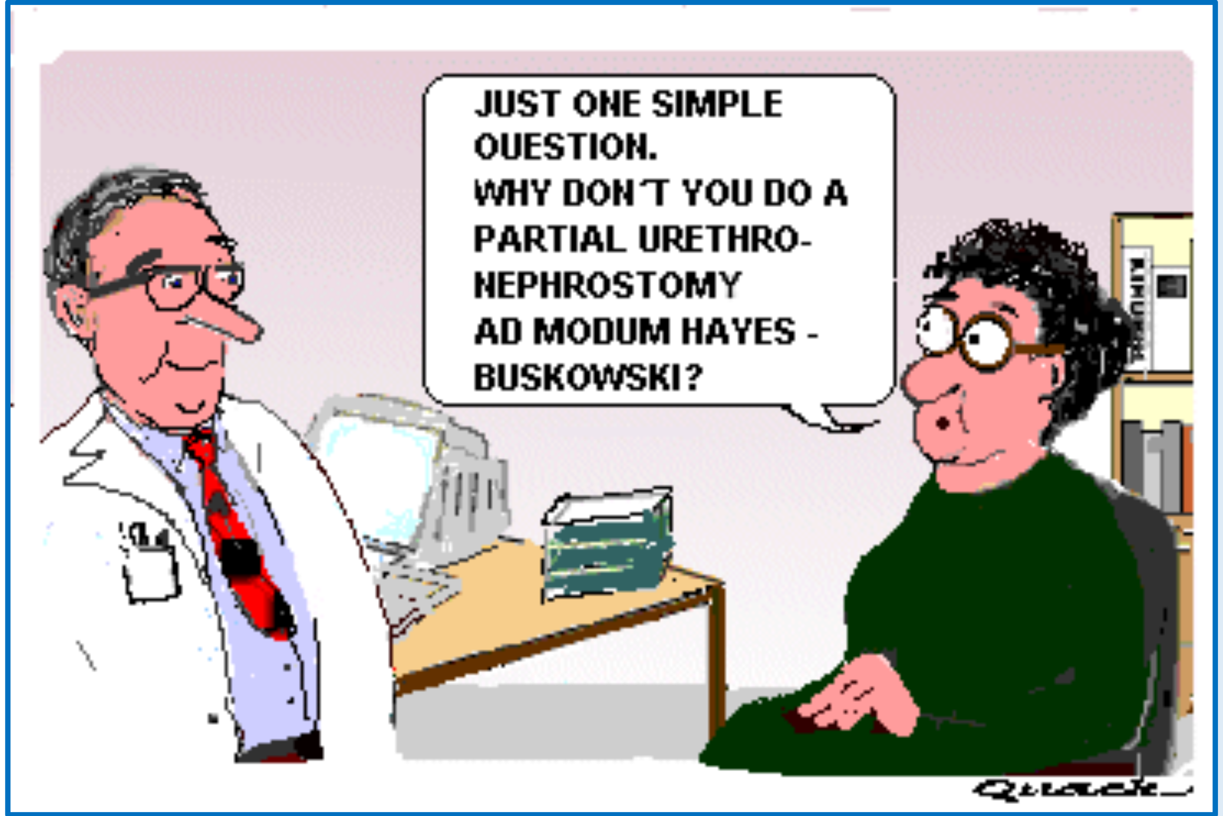
Contents:



Luminosity
Flux
Frequency
Event horizon
Singularity
Strings
Surface density

Contents:

Don't be afraid to ask questions…

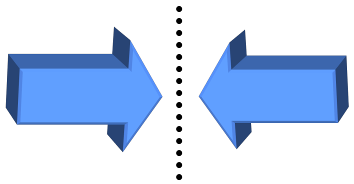


Contents:

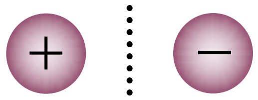
Check the mirror
Objects in the rear view mirror
may appear closer than they are

C, P, T Symmetries

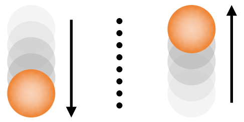
- [Parity, P:](#) *unobservable: (absolute handedness)*
  - Reflects a system through the origin.
    Converts right-handed to left-handed.
    - $\vec{x} \rightarrow -\vec{x}$, $\vec{p} \rightarrow -\vec{p}$ (vectors) but $\vec{L} = \vec{x} \times \vec{p}$ (axial vectors)



- Charge Conjugation, C: *unobservable: (absolute charge)*
  - Turns internal charges to opposite sign.
    - $e^+ \rightarrow e^-$, $K^- \rightarrow K^+$



- Time Reversal, T: *unobservable: (direction of time)*
  - Changes direction of motion of particles
    - $t \rightarrow -t$



- CPT Theorem:
  - All interactions are invariant under combined C, P and T operation
  - A particle ***is*** an antiparticle travelling backward in time
  - Implies e.g. particle and anti-particle have equal masses and lifetimes

Classical Mirror Worlds → Invariant!

- Parity: $\vec{x} \to -\vec{x}$
  - Mass m — $P\,m = m$: scalar
  - Force $\vec{F}$ $(\vec{F} = d\vec{p}/dt)$ — $P\,\vec{F} = P\,d\vec{p}/dt = -\,d\vec{p}/dt = -\vec{F}$: vector
  - Acceleration $\vec{a}$ $(\vec{a} = d^2\vec{x}/dt^2)$ — $P\,\vec{a} = -\,d^2x/dt^2 = -\vec{a}$: vector
  - Angular momentum $\vec{L}, \vec{S}, \vec{J}$ $(\vec{L} = \vec{x}\times\vec{p})$ — $P\;\vec{L} = -\vec{x} \times -\vec{p} = \vec{L}$: axial vector

- Parity: Newton's law is *invariant* under P-operation (i.e. the same in the mirror world):

$$\vec{F} = m\,\vec{a} \xrightarrow{P} -\vec{F} = -m\vec{a} \quad \Leftrightarrow \quad \vec{F} = m\,\vec{a}$$

- Charge: Lorentz Force in the C-mirror world is *invariant*:

$$\vec{F} = q\left[\vec{E} + \vec{v}\times\vec{B}\right] \xrightarrow{C} \vec{F} = -q\left[-\vec{E} + \vec{v}\times-\vec{B}\right]$$

- Time: laws of physics are also *invariant* unchanged under T-reversal, since:

$$\vec{F} = m\,\vec{a} = m\,\frac{d^2\vec{x}}{dt^2} \xrightarrow{T} \vec{F} = m\,\frac{d^2\vec{x}}{d(-t)^2} \quad \Leftrightarrow \quad \vec{F} = m\,\vec{a}$$

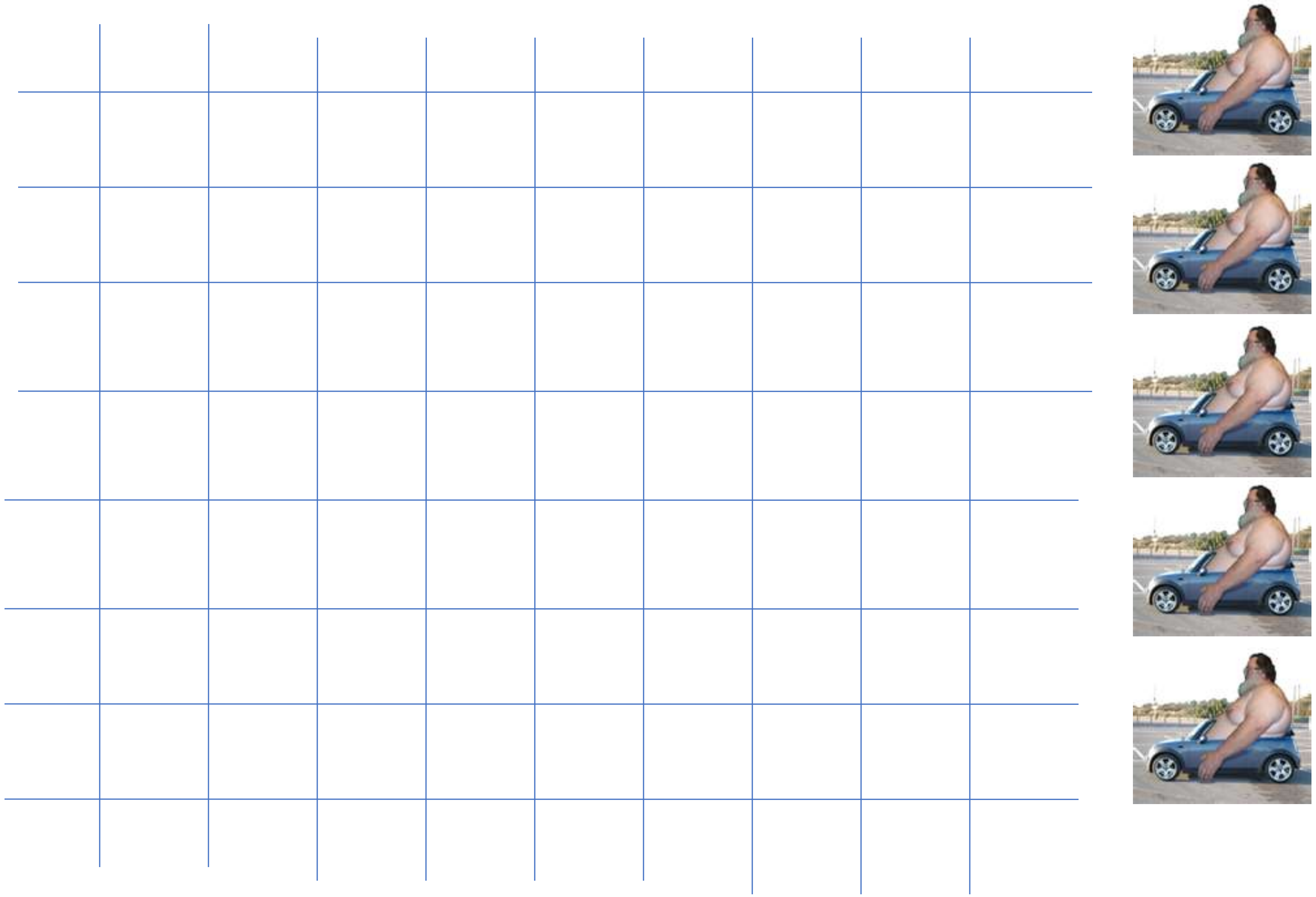
  - QM: Consider Schrodinger's equation $(t \to -t)$: $\quad ih\dfrac{\partial\psi}{\partial t} = -\dfrac{\vec{\nabla}^2\psi}{2m}$

  Complex conjugation is required to stay invariant: $\quad \psi \xrightarrow{T} \psi^*$

C-, P-, T- Symmetry

- Classical Theory is invariant under C, P, T operations; i.e. they conserve C, P, T symmetry
  - Newton mechanics, Maxwell electrodynamics.
- Suppose we watch some physical event. Can we determine unambiguously whether:
  - We are watching the event where all ***charges are reversed*** or not?
  - We are watching the event ***in a mirror*** or not?
    - Macroscopic biological asymmetries are considered *accidents of evolution* rather than fundamental asymmetry in the laws of physics.
  - We are watching the event in a ***film running backwards*** or not?
    - The arrow of time is due to thermodynamics: i.e. the realization of a macroscopic final state is *statistically more probable* than the initial state

Macroscopic time reversal (T.D. Lee)



- At each crossing: 50% - 50% choice to go left or right
- After many decisions: reverse the velocity of the final state and return
- Do we end up with the initial state?

Macroscopic time reversal (T.D. Lee)

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- After many decisions: reverse the velocity of the final state and return
- Do we end up with the initial state?

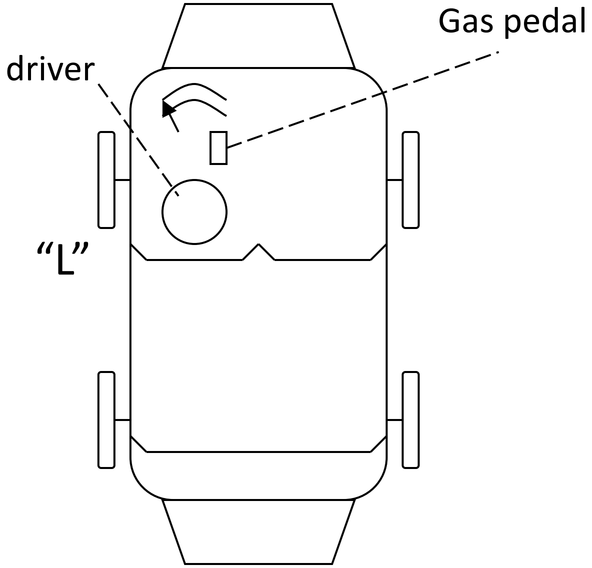
Macroscopic time reversal

This is why we don't teach our children about entropy until much later...

Parity Violation

Before 1956 physicists were **convinced** that the laws of nature were left-right symmetric. Strange?

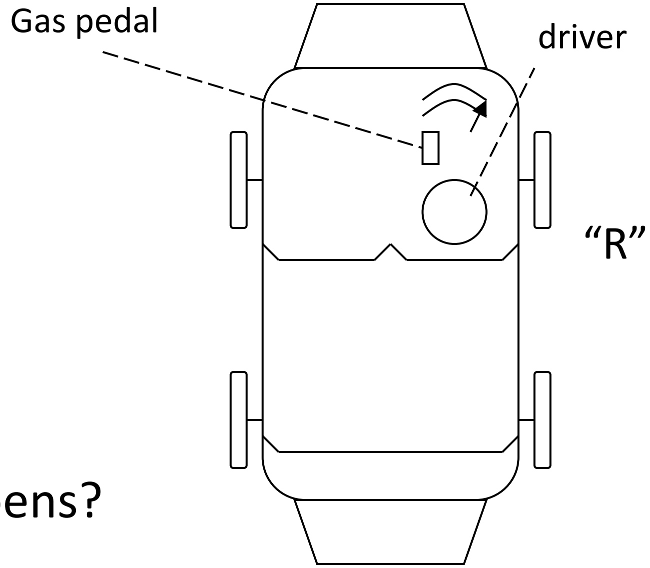
A "gedanken" experiment: consider two perfectly mirror symmetric cars:



"L" and "R" are fully symmetric,
Each nut, bolt, molecule etc.
However the engine is a black box

Person "L" gets in, starts, ….. 60 km/h

Person "R" gets in, starts, ….. What happens?



What happens in case the ignition mechanism uses, say, Co^{60} β decay?

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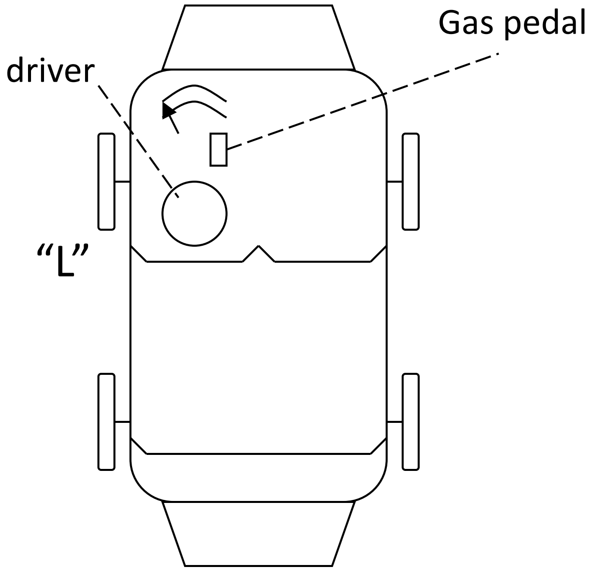
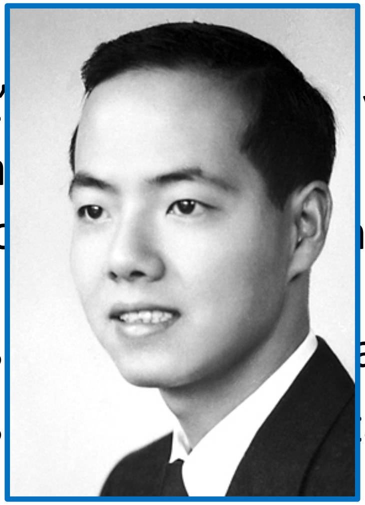


T.D. Lee

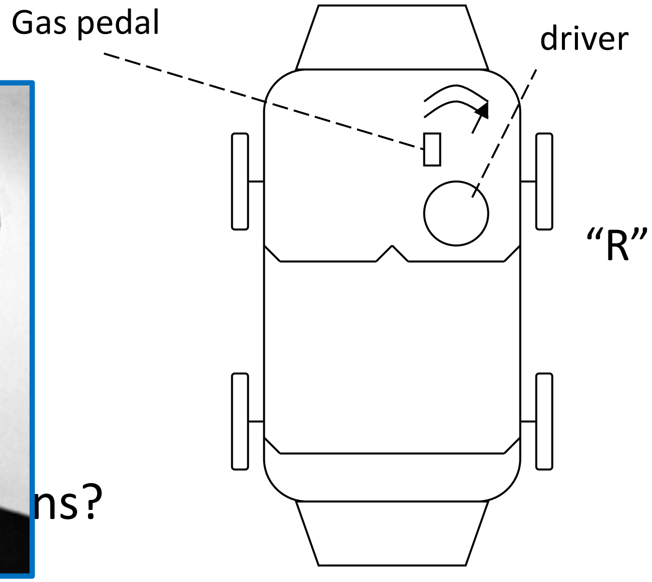


C.N. Yang

“L” … y syn
Ea … ecul
Ho … e is a

Pers … arts,

Pers … arts, … ns?

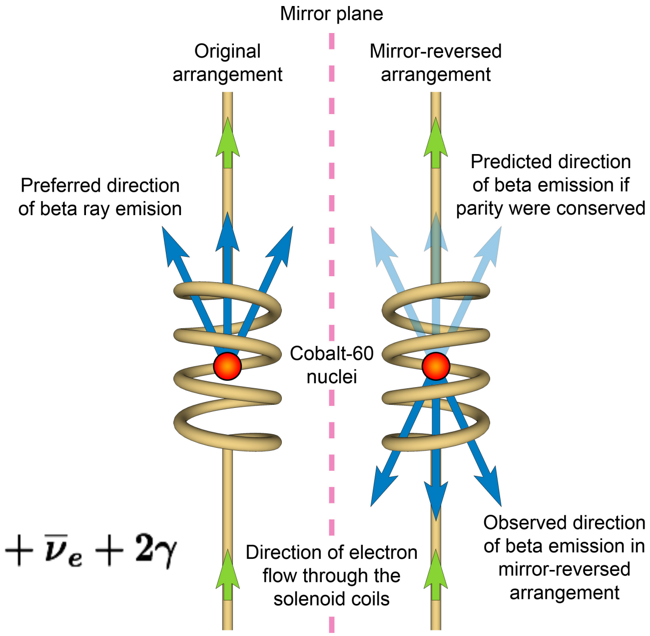


What happens in case the ignition mechanism uses, say, Co^{60} β decay?

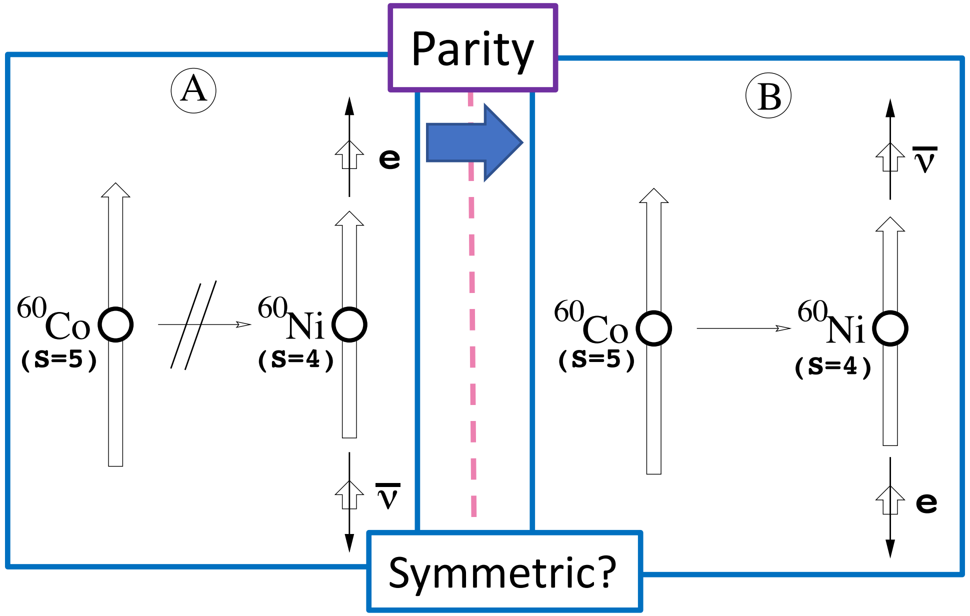
Discovery of Parity Violation

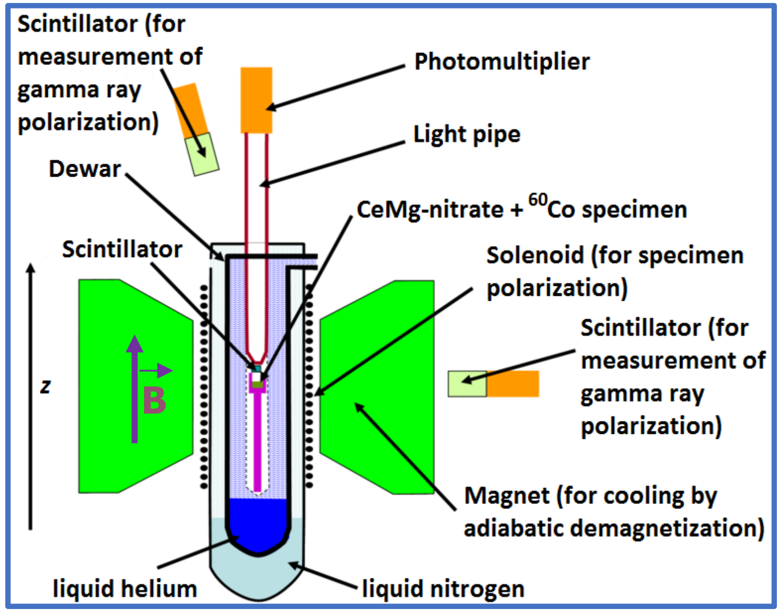
Spin is pseudoscalar, P: $\vec{S} \to \vec{S}$

$$^{60}_{27}\mathrm{Co} \to ^{60}_{28}\mathrm{Ni} = e^- + \bar{\nu}_e + 2\gamma$$



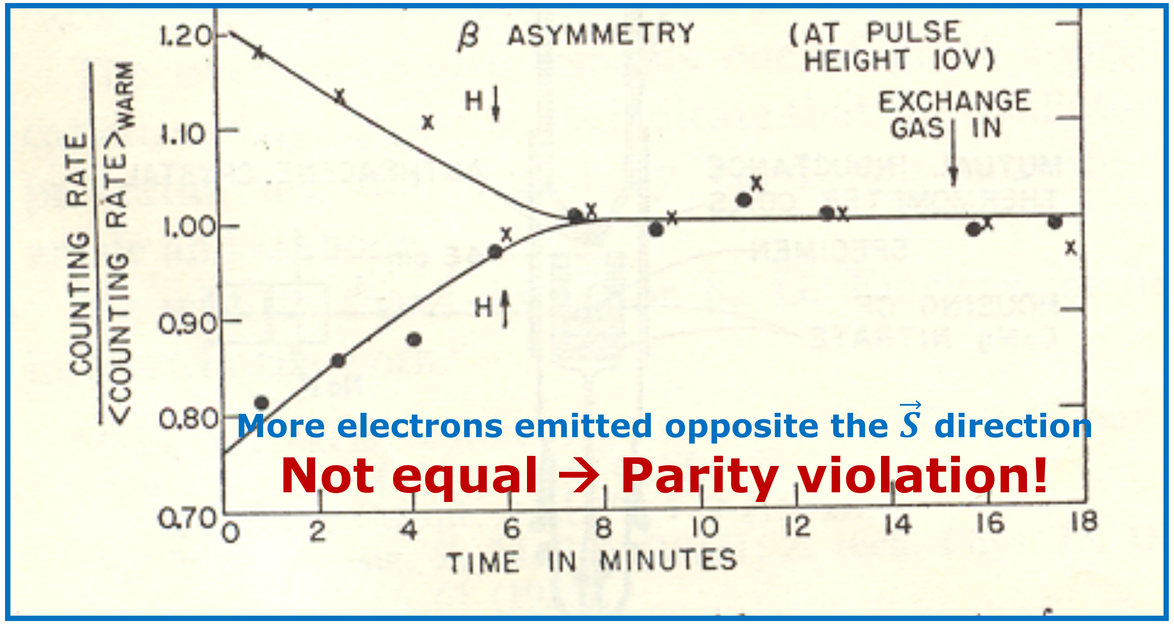
B-field





Is physics is parity invariant?

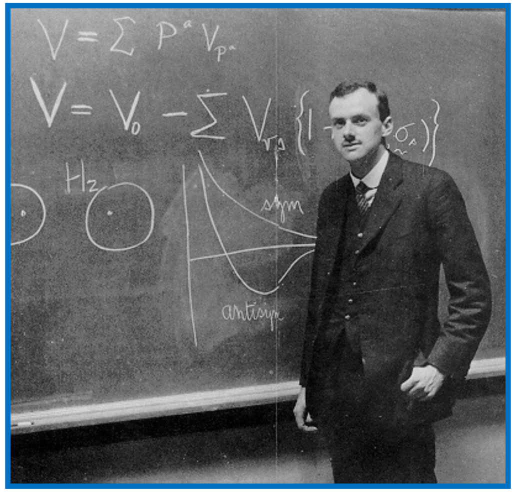
Only if electron decay rate is symmetric wrt spin direction!



More electrons emitted opposite the $\vec{S}$ direction

Not equal → Parity violation!

CP operation



- In Dirac theory particles are represented as spinors

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$

+1/2, -1/2 helicity solutions for the particle

+1/2, -1/2 helicity solutions for the antiparticle

Antimatter!

- Implementation of P and C operators in Dirac theory:

$$P: \quad \psi \rightarrow \psi' = \gamma^0 \psi(-\vec{x}, t)$$

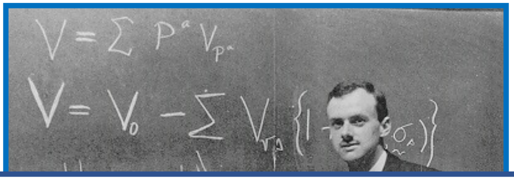
$$\begin{pmatrix} [(i\gamma^0\partial_0 - i\gamma^i\partial_{x_i}) - m]\psi(\vec{x}, t) = 0 \\ \gamma^0[(i\gamma^0\partial_0 + i\gamma^i\partial_{x_i}) - m]\psi'(-\vec{x}, t) = 0 \end{pmatrix}$$

$$C: \quad \psi \rightarrow \psi' = i\gamma^2\psi^*(\vec{x}, t)$$

$$\begin{pmatrix} \text{Elect. } \psi: & [\gamma^\mu(i\partial_\mu + eA_\mu) - m]\psi = 0 \\ \text{Posit. } \psi': & [\gamma^\mu(i\partial_\mu - eA_\mu) - m]\psi' = 0 \end{pmatrix}$$

- QED (Dirac theory) is symmetric under CP conjugation. Reversing electric charges keeps electrodynamics invariant.

CP operation



- In Dirac theory particles are represented as spinors

$$\gamma^0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}, \quad \gamma^1 = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix}, \quad \gamma^2 = \begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{pmatrix}, \quad \gamma^3 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

- Implementation of P and C operators in Dirac theory:

$$P: \quad \psi \to \psi' = \gamma^0 \psi(-\vec{x}, t)$$

$$\left(\begin{array}{l} \left[\left(i\gamma^0\partial_0 - i\gamma^i\partial_{x_i}\right) - m\right]\psi(-\bar{x}, t) = 0 \\ \gamma^0\left[\left(i\gamma^0\partial_0 + i\gamma^i\partial_{x_i}\right) - m\right]\psi'(-\bar{x}, t) = 0 \end{array} \right)$$

$$C: \quad \psi \to \psi' = i\gamma^2\psi^*(\vec{x}, t)$$

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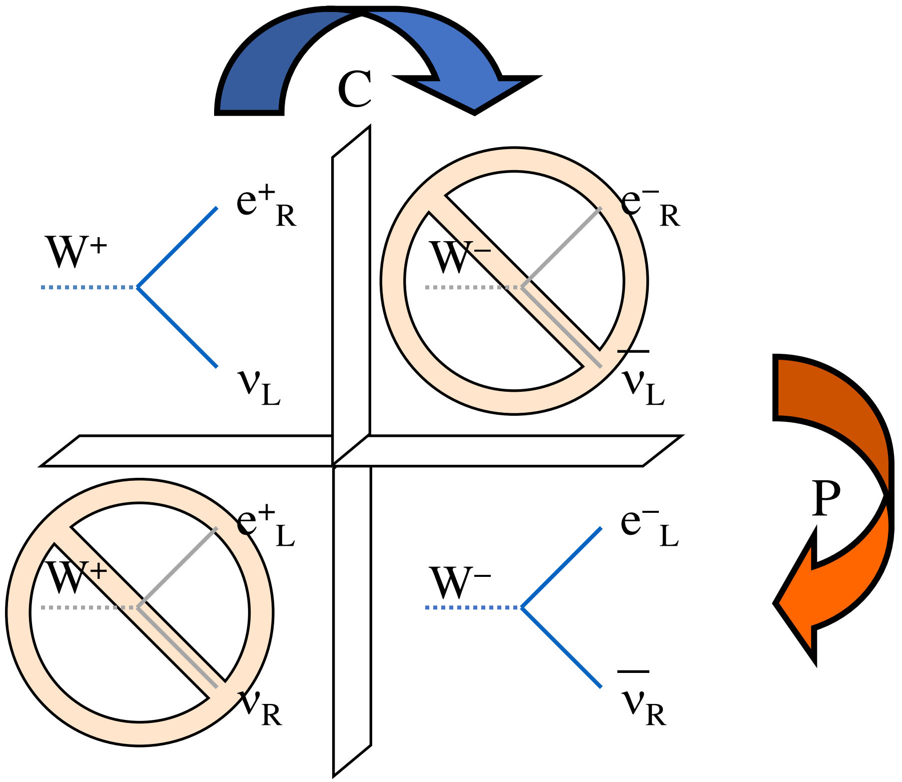
Weak Force breaks C and P, is CP really OK?

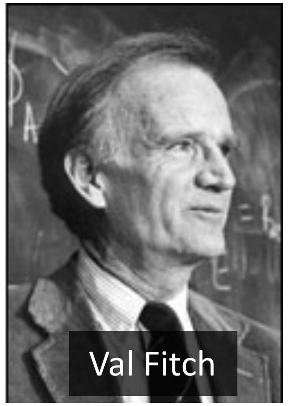


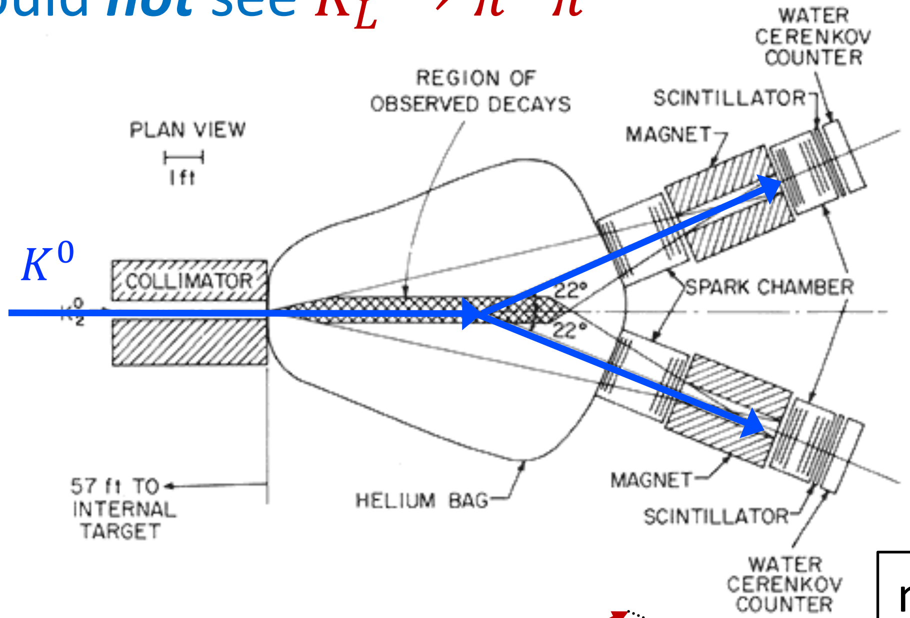
- Weak interaction breaks ***C*** and ***P*** symmetry maximally!
  - Nature is left-handed for matter and right-handed for antimatter.
- Despite *maximal* violation of ***C*** and ***P***, combined ***CP*** seemed *conserved*…
- But in 1964, Christenson, Cronin, Fitch and Turlay observed ***CP*** *violation* in decays of neutral kaons!

Discovery of CP-Violation

- Create a pure K_L beam ("wait" for K_S to decay)
- If CP is conserved, should ***not*** see $K_L \to \pi^+\pi^-$

K_S: Short-lived is CP even:
$K_1^0 \to \pi^+\pi^-$ (fast)
K_L: Long-lived is CP odd:
$K_2^0 \to \pi^+\pi^-\pi^0$ (slow)

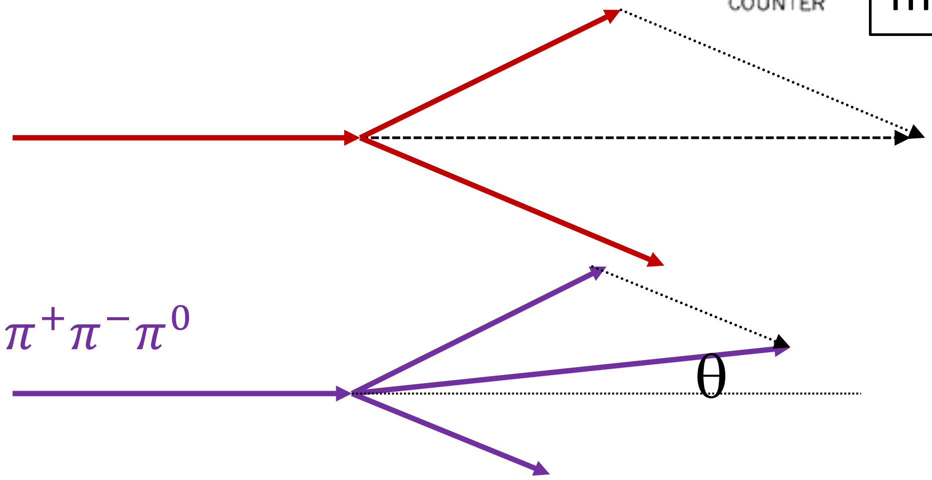


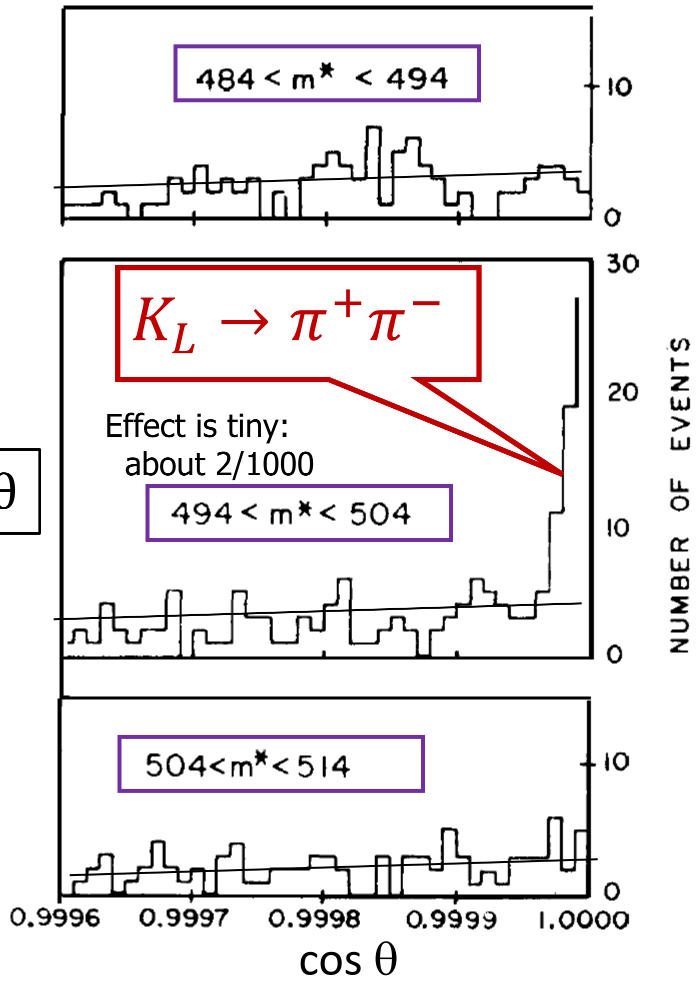


mass, θ

Signal: $K_L \to \pi^+\pi^-$

Background: $K_L \to \pi^+\pi^-\pi^0$





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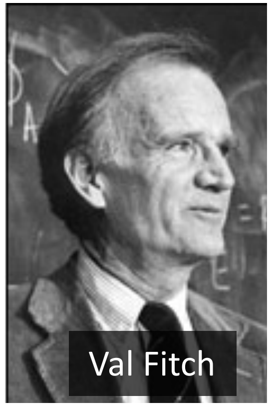
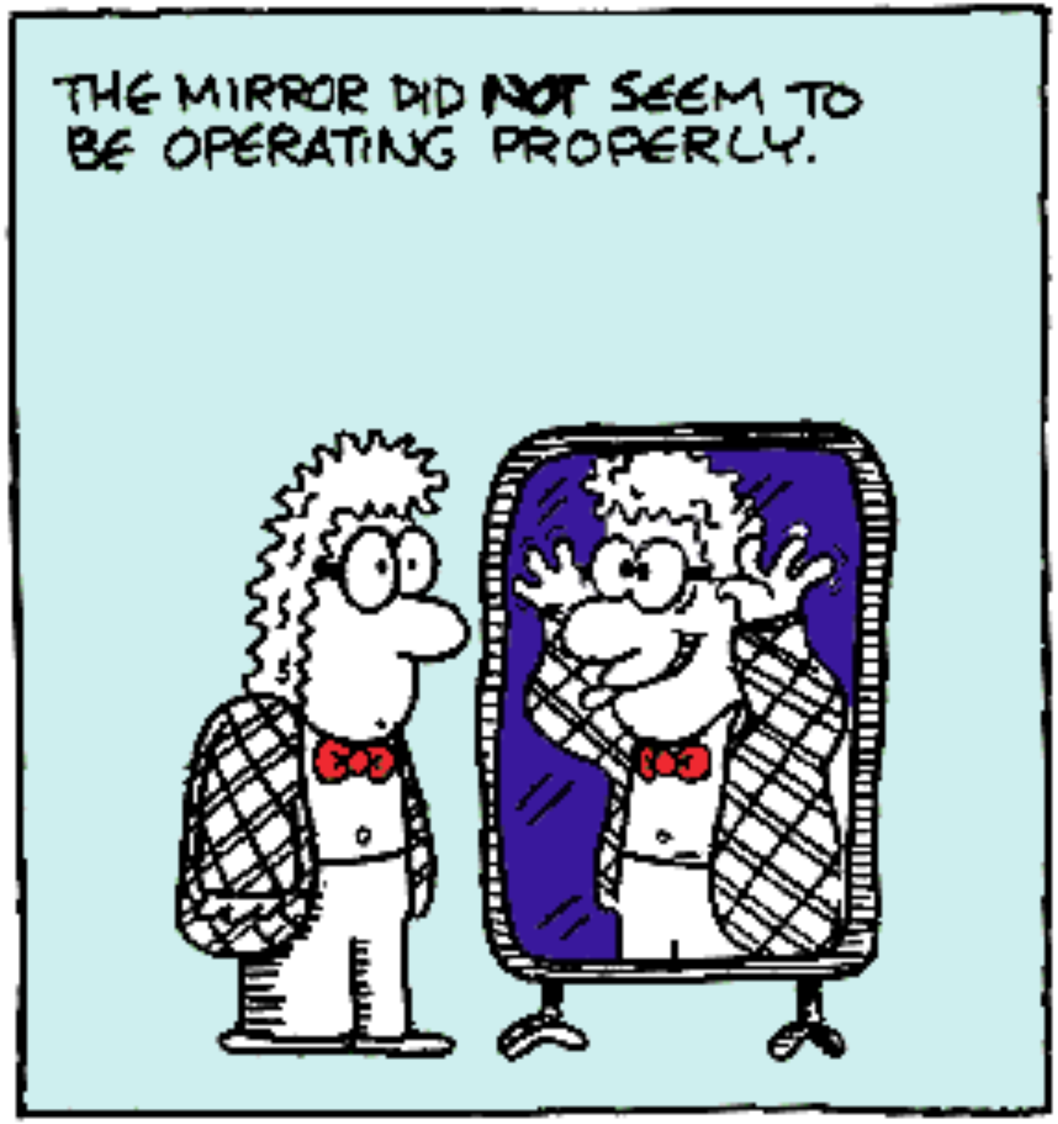
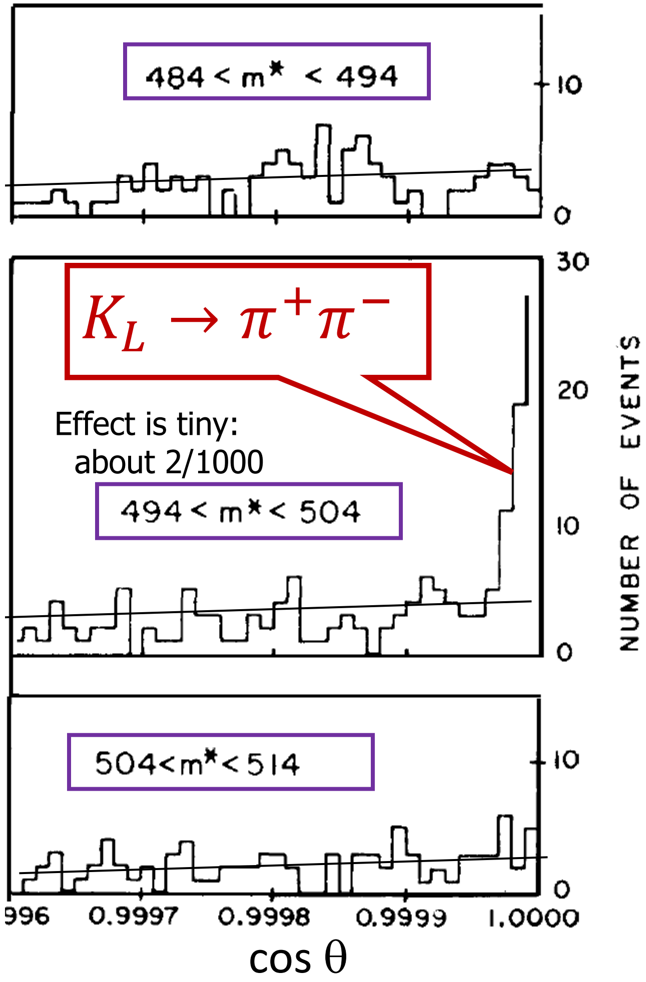




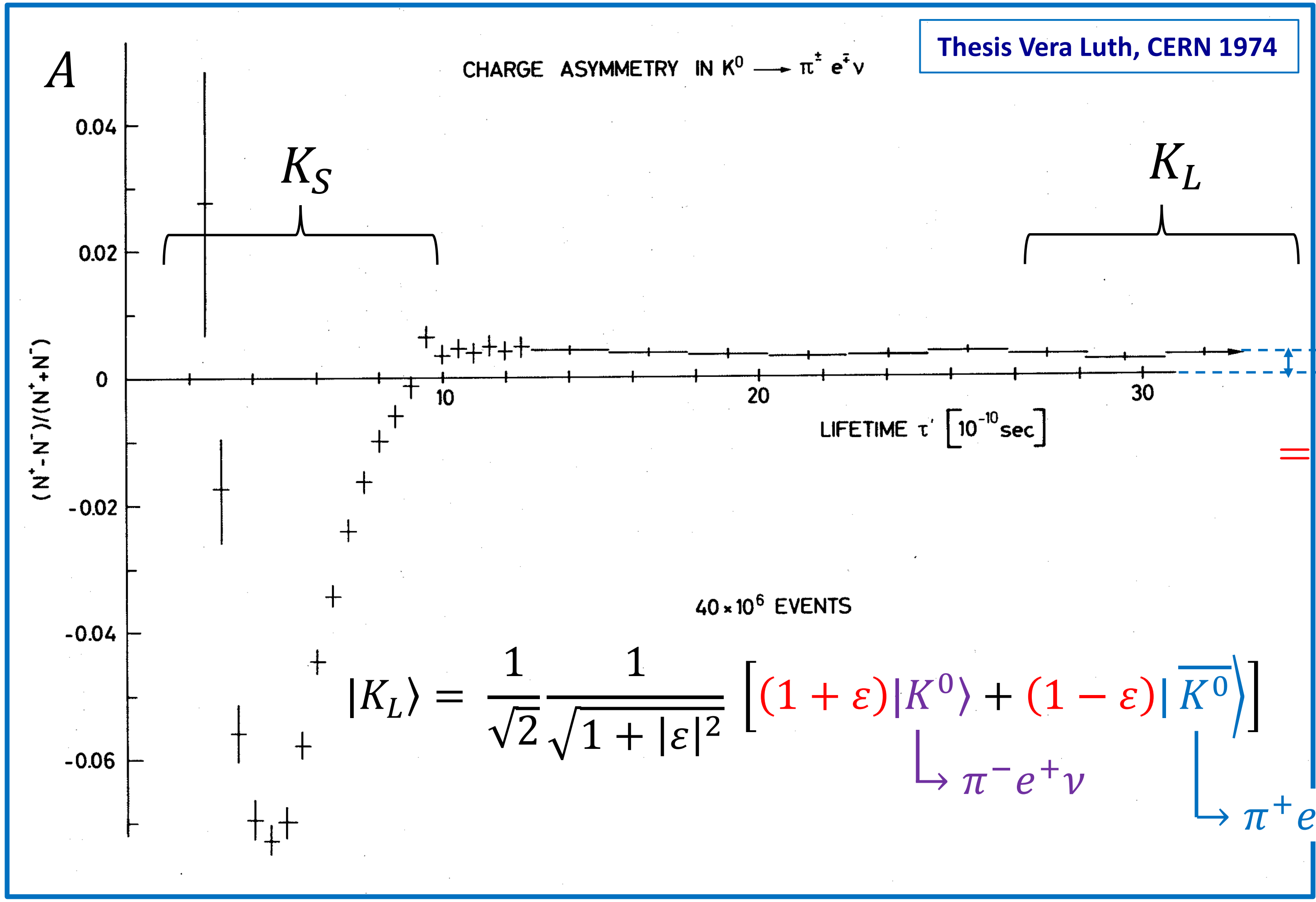


Signal: $K_1^0 \to \pi$

Background: K

Alternative: Charge Asymmetry in K^0 decays

Measure $A = \frac{N^+ - N^-}{N^+ + N^-}$ with $N^+ = K^0 \rightarrow \pi^- e^+ \nu$, $N^- = \overline{K^0} \rightarrow \pi^+ e^- \bar{\nu}$ vs the K^0 decay time

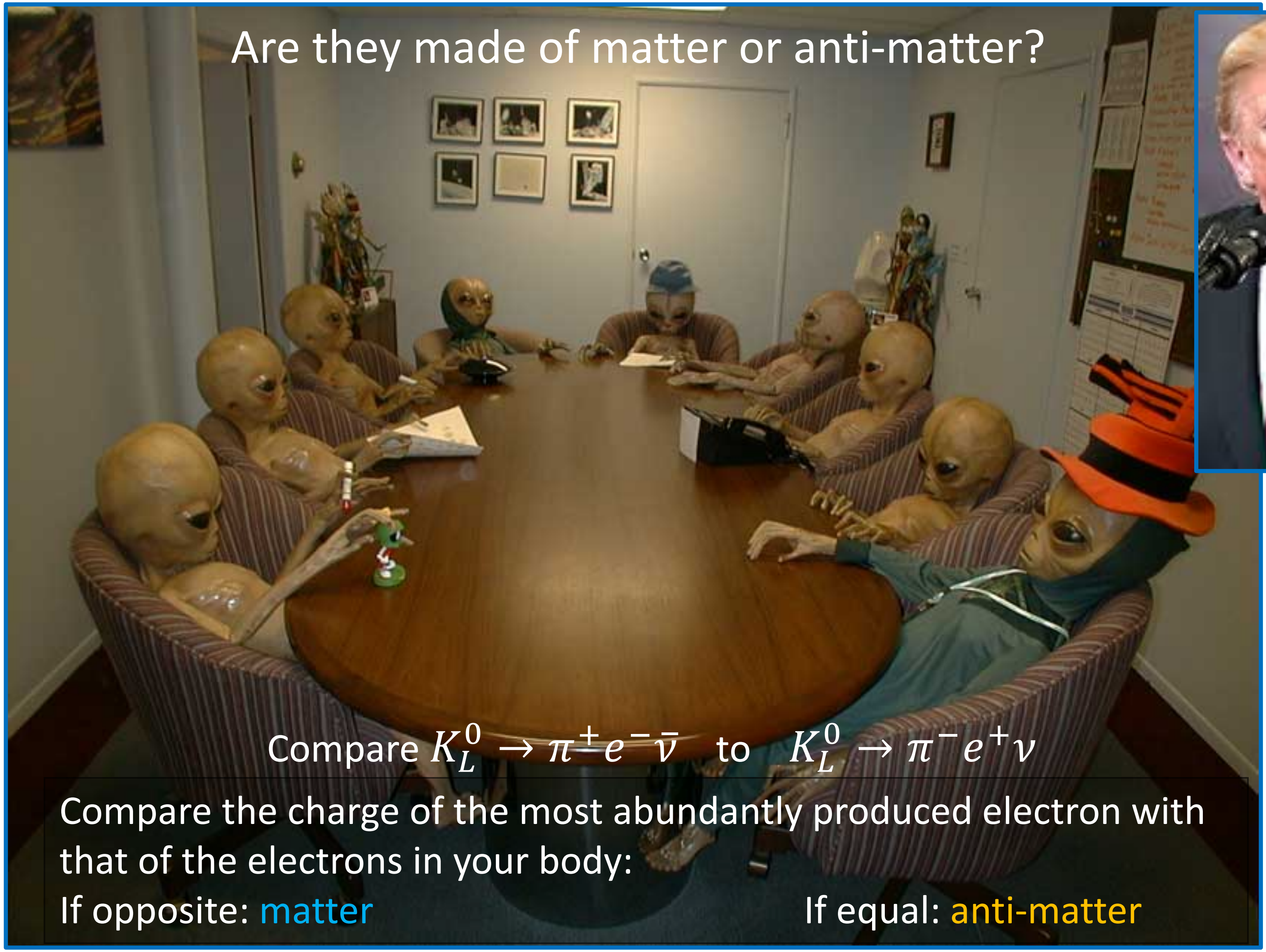


$$|K_L\rangle = \frac{1}{\sqrt{2}} \frac{1}{\sqrt{1 + |\varepsilon|^2}} \left[\underbrace{(1+\varepsilon)|K^0\rangle}_{\pi^- e^+ \nu} + \underbrace{(1-\varepsilon)|\overline{K^0}\rangle}_{\pi^+ e^- \bar{\nu}} \right]$$

$$\boxed{4\Re(\varepsilon)} = \left| \frac{(1+\varepsilon)}{(1-\varepsilon)} \right|^2$$

CP violation in meson mixing.

Contact with Aliens !



Are they made of matter or anti-matter?

Compare $K_L^0 \to \pi^+ e^- \bar{\nu}$ to $K_L^0 \to \pi^- e^+ \nu$

Compare the charge of the most abundantly produced electron with that of the electrons in your body:

If opposite: matter

If equal: anti-matter

CPT Violation...

CPT symmetry implies that an antiparticle is ***identical*** to a particle travelling backwards in time.

Contents:

Check the mirror
Objects in the rear view mirror
may appear closer than they are

Contents:

Forceful Spices
Leptons
Collect all 6!
Weak
Gravity
Strong
E-M
REALITY STEW
QUARKS

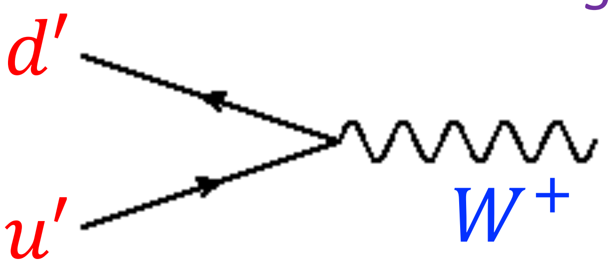
Weak interaction in three Flavour Generations

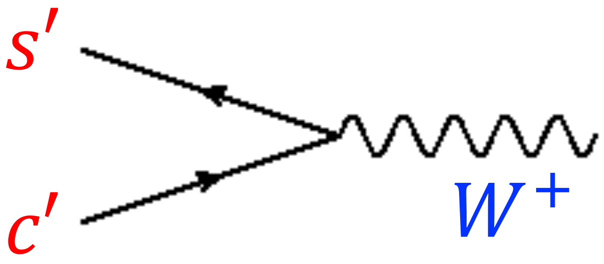
- Weak Interaction is 100% parity violating.
  - Wolfgang Pauli: *“I cannot believe God is a weak left-hander.”*

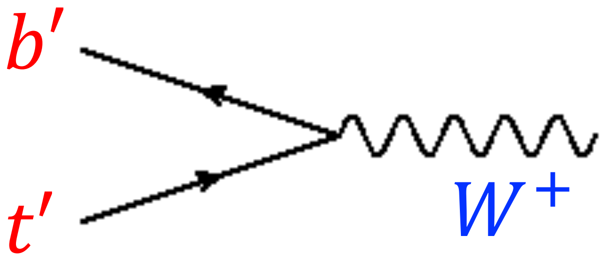
- Implement an $SU(2)_L$ symmetry for *massless* particles:

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \, \gamma_\mu \, W^\mu \, d'_L \qquad \text{x3 !}$$

- Flavour universality: *identical interactions* in three generations.
  - In fact: *how to distinguish a massless d' quark from s' quark?*







- There is *no CP violation* in these massless interactions
  - What happens when particles acquire mass?

Spontaneous Symmetry Breaking → Origin of Mass

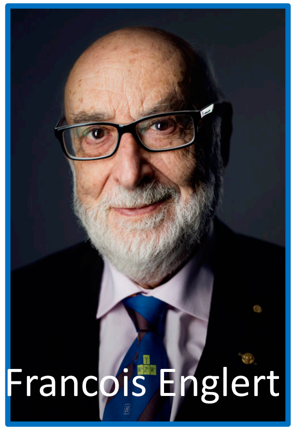
- Yukawa couplings to massless particles:

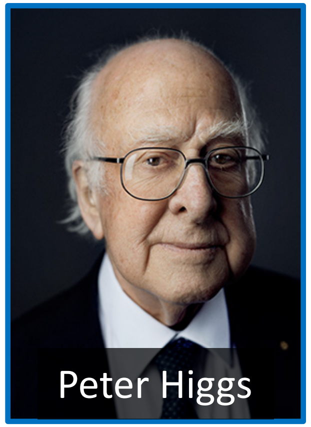
$$\mathcal{L}_Y = Y^d_{ij}\ (\overline{u}'_i, \overline{d}'_i)_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} d'_{jR} + Y^u_{ij}\ (\overline{u}'_i, \overline{d}'_i)_L \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} u'_{jR}$$

- Yukawa interaction is *not* flavour universal!

→*Unknown origin of Yukawa matrix acting on generations "i" and "j"*

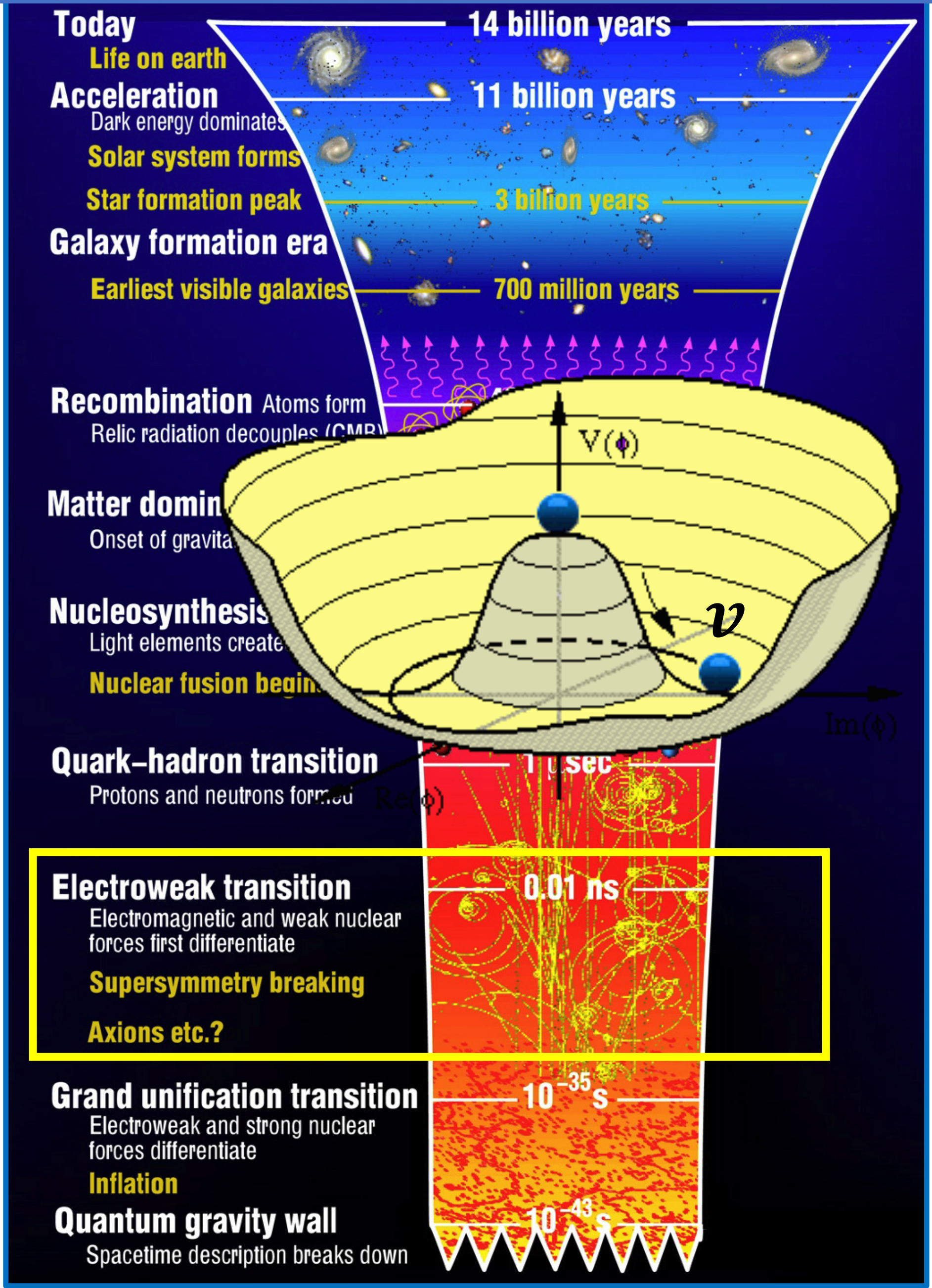
- SSB: B-E-H Mechanism:





$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

➔ Massive W- and Z- bosons



Spontaneous Symmetry Breaking → Origin of Mass

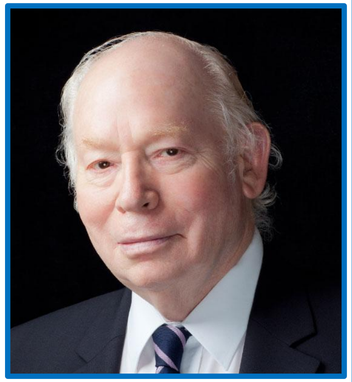
- Yukawa couplings to massless particles (Weinberg):

$$\mathcal{L}_Y = Y^d_{ij}\ (\bar{u}'_i, \bar{d}'_i)_L \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} d'_{jR} + Y^u_{ij}\ (\bar{u}'_i, \bar{d}'_i)_L \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} u'_{jR}$$

- Yukawa interaction is *not* flavour universal!

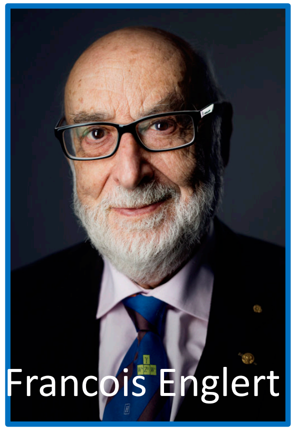
→ *Unknown origin of Yukawa matrix acting on generations "i" and "j"*

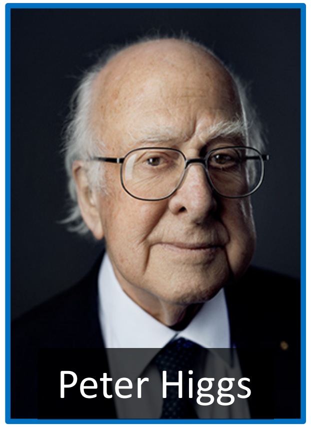
→ Massive fermions



- SSB: B-E-H Mechanism:

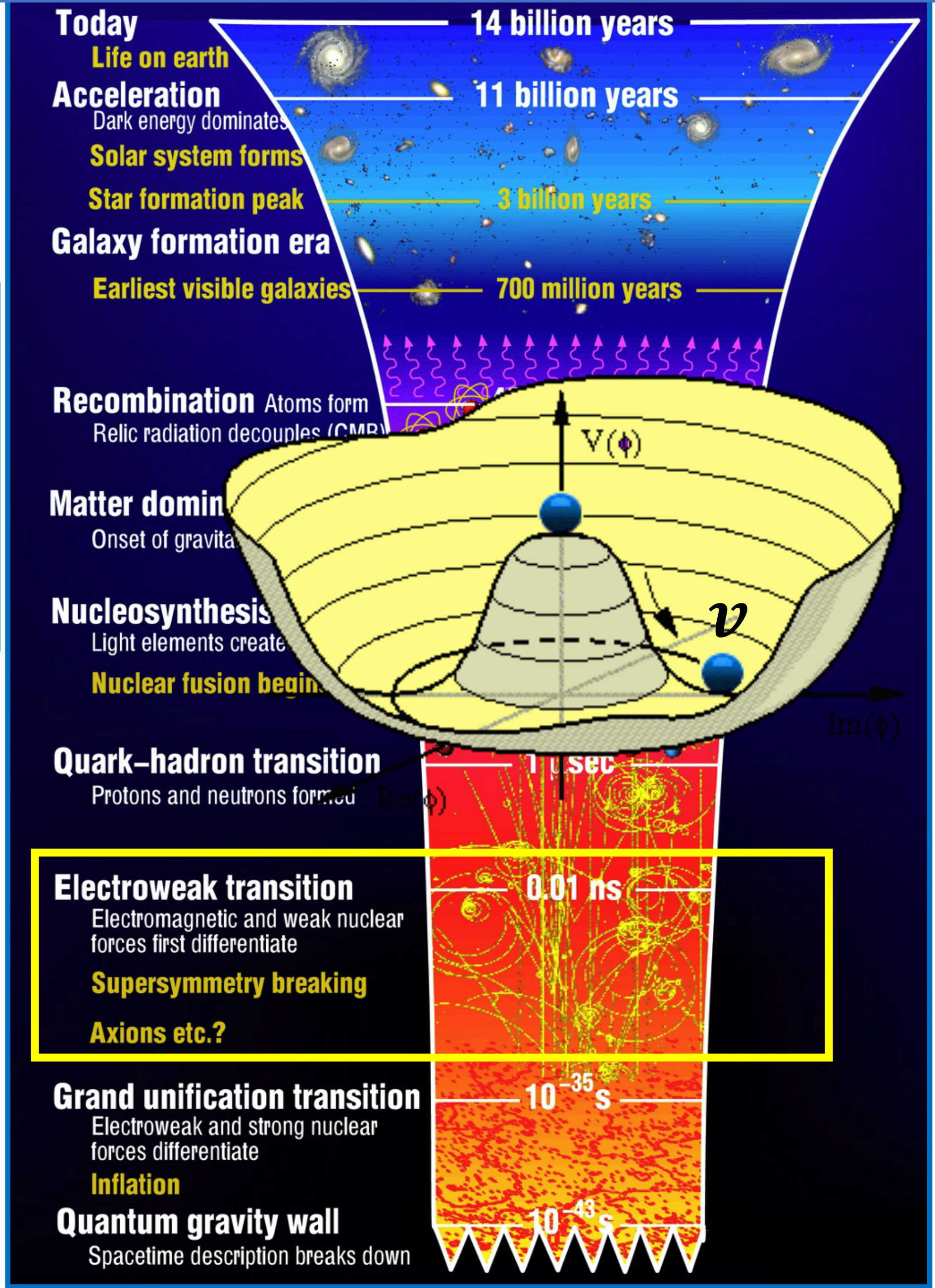

Robert Brout


Francois Englert


Peter Higgs

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

→ Massive W- and Z- bosons



Spontaneous Symmetry Breaking → Origin of Mass

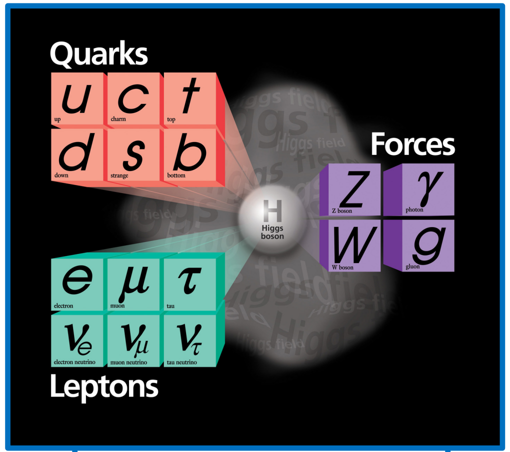
- Yukawa couplings to massless particles:

$$\mathcal{L}_Y = Y^d_{ij}\ (\overline{u'_i}, \overline{d'_i})_L \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} d'_{jR} + Y^u_{ij}\ (\overline{u'_i}, \overline{d'_i})_L \begin{pmatrix} v/\sqrt{2} \\ 0 \end{pmatrix} u'_{jR}$$

- Diagonalize Y_{ij} :

  $u_i = (V^u)_{ij}\, u'_j$ and $d_i = (V^d)_{ij}\, d'_j$

  → mass and flavour eigenstates

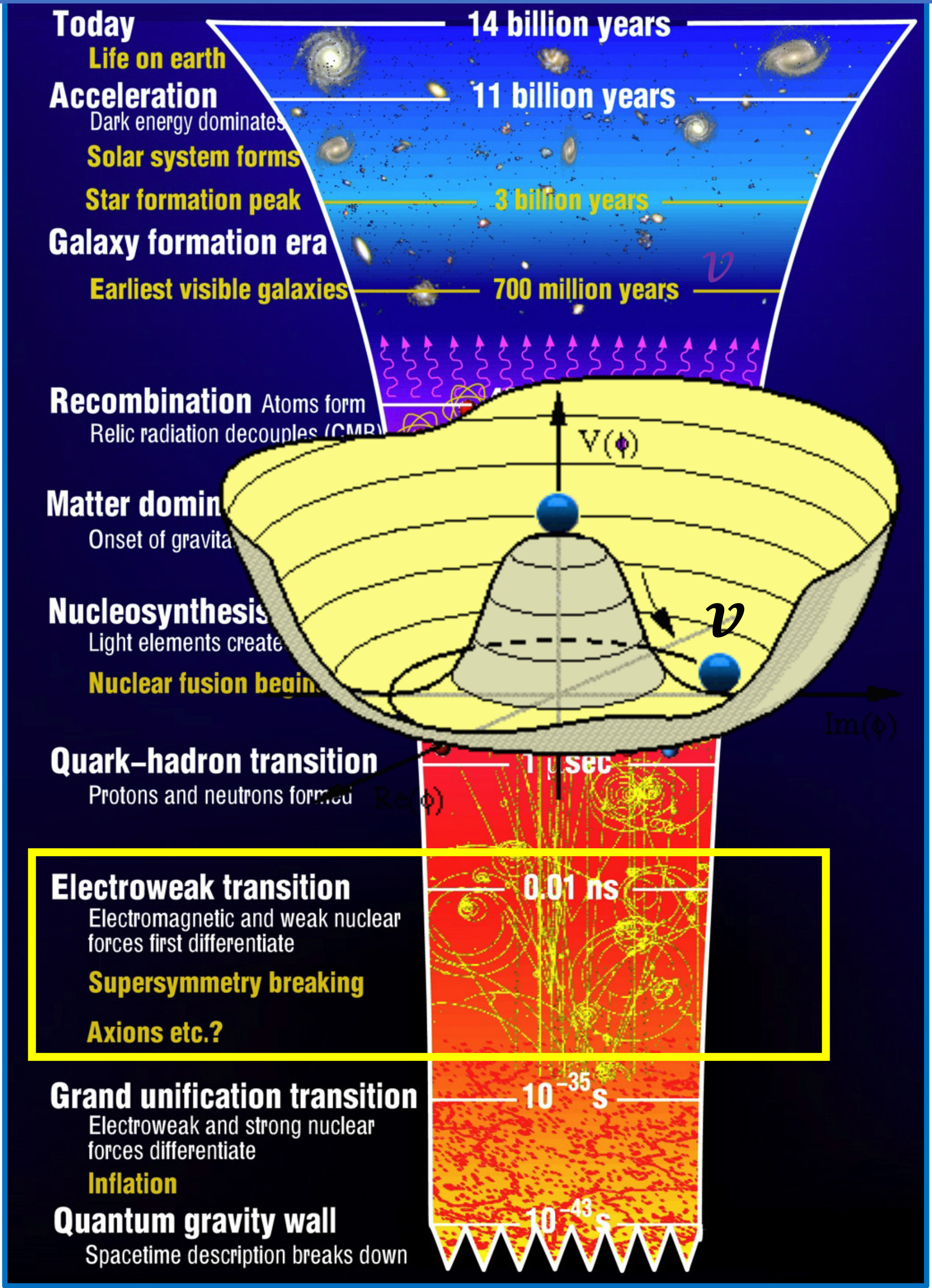


Physical particles

- Mass terms: $M_{ij} = Y_{ij}\, v/\sqrt{2}$

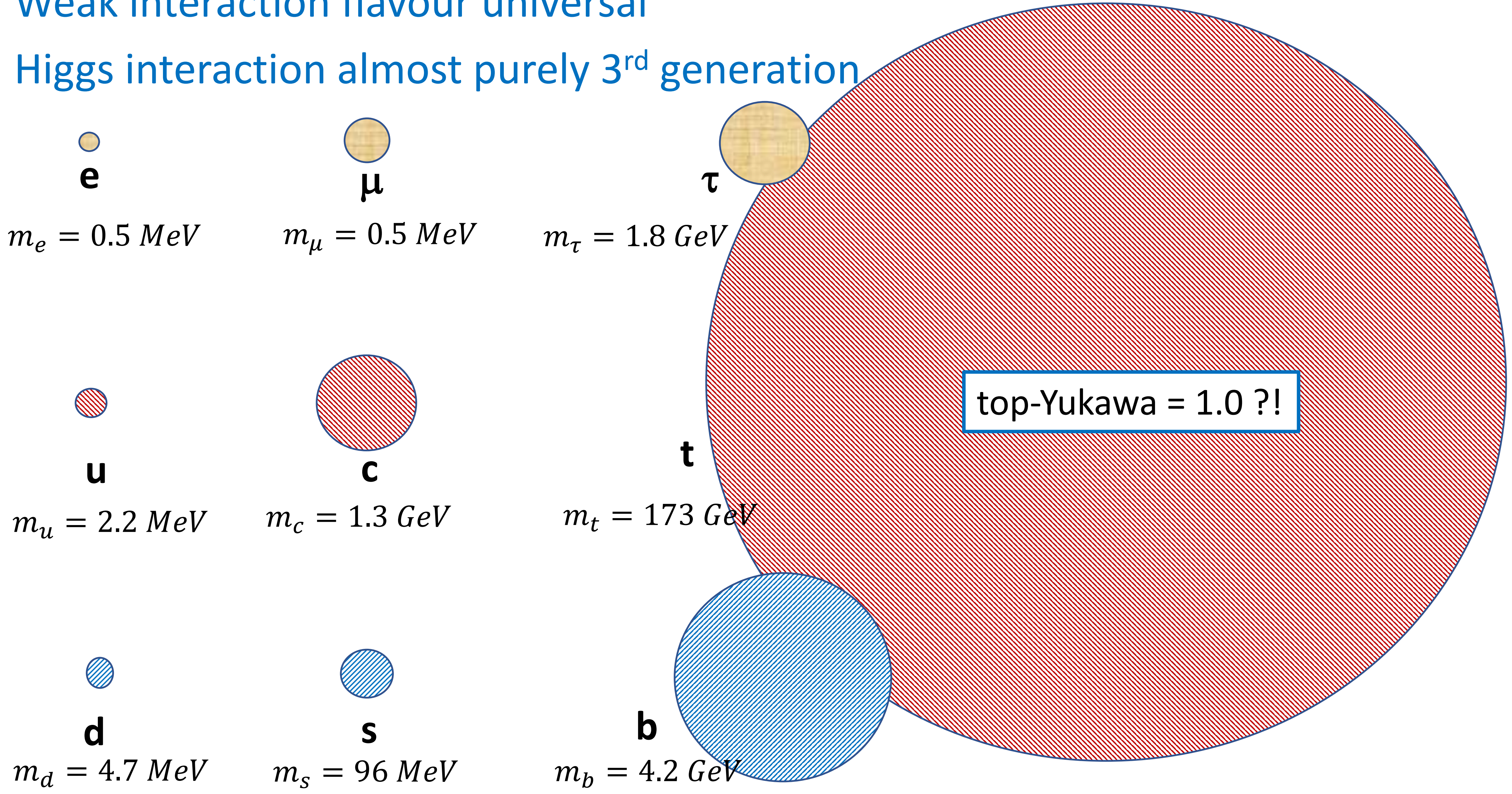
$$\mathcal{L}_Y \to \mathcal{L}_H = m_d\, d_L\, d_R + m_u\, u_L\, u_R$$

- Top quark mass: $m_{top} = 1.0\, v/\sqrt{2}$
  - *To first order Higgs couples only to top with coupling strength 1.0 !*
    - *Very* flavour non-universal



Flavour Puzzle: particle masses? Origin Yukawa couplings?

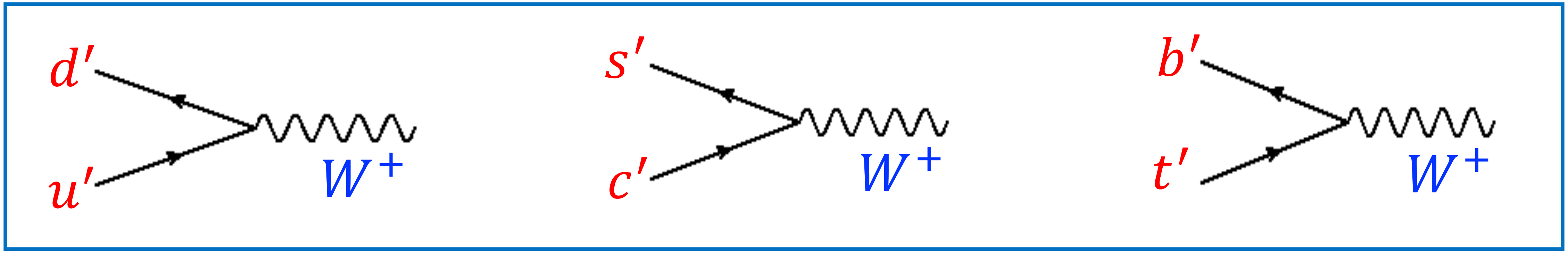
- Weak interaction flavour universal
- Higgs interaction almost purely 3rd generation



The Weak Interaction → Flavour Mixing

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L$$

- *No CP violation*



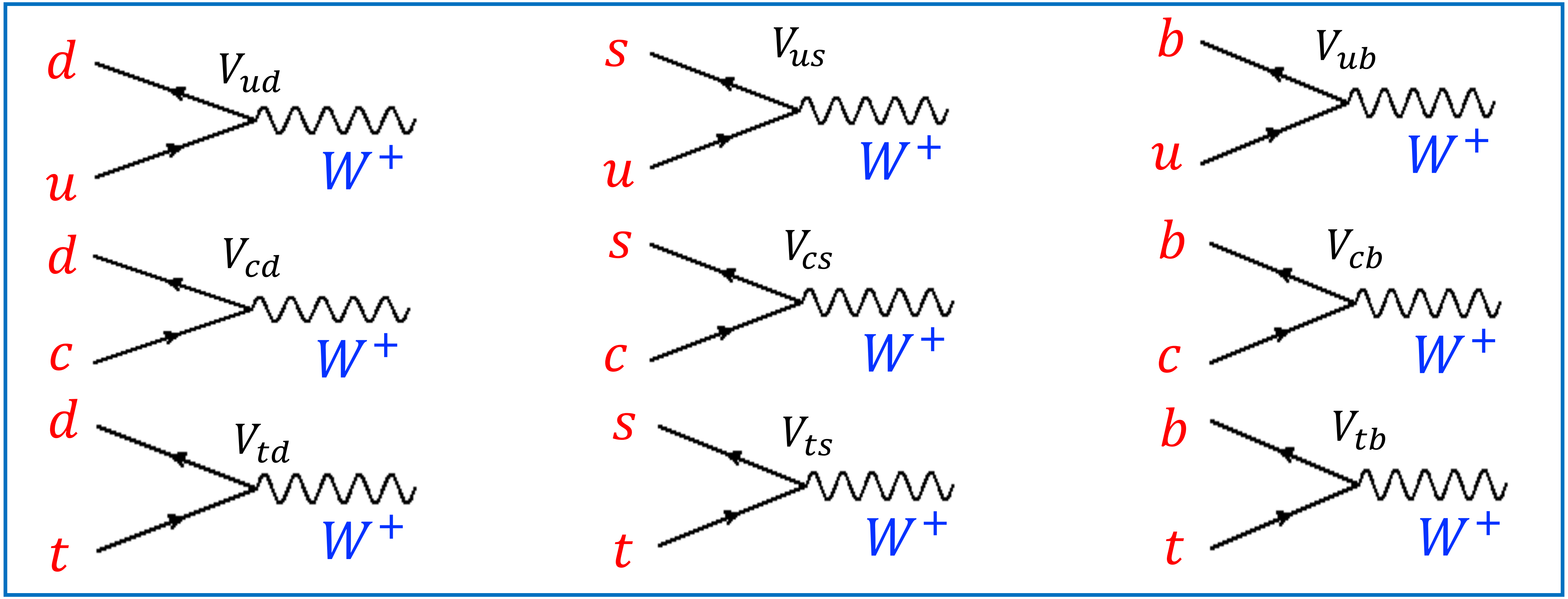
Redefine: $u'_i = (V^u)_{ij} u_i$ and: $d'_i = \left(V^d\right)^\dagger_{ij} d_i$, such that: $V_{CKM} = \left(V^u V^{d\dagger}\right)_{ij}$ …

(Interaction basis) (Mass basis)

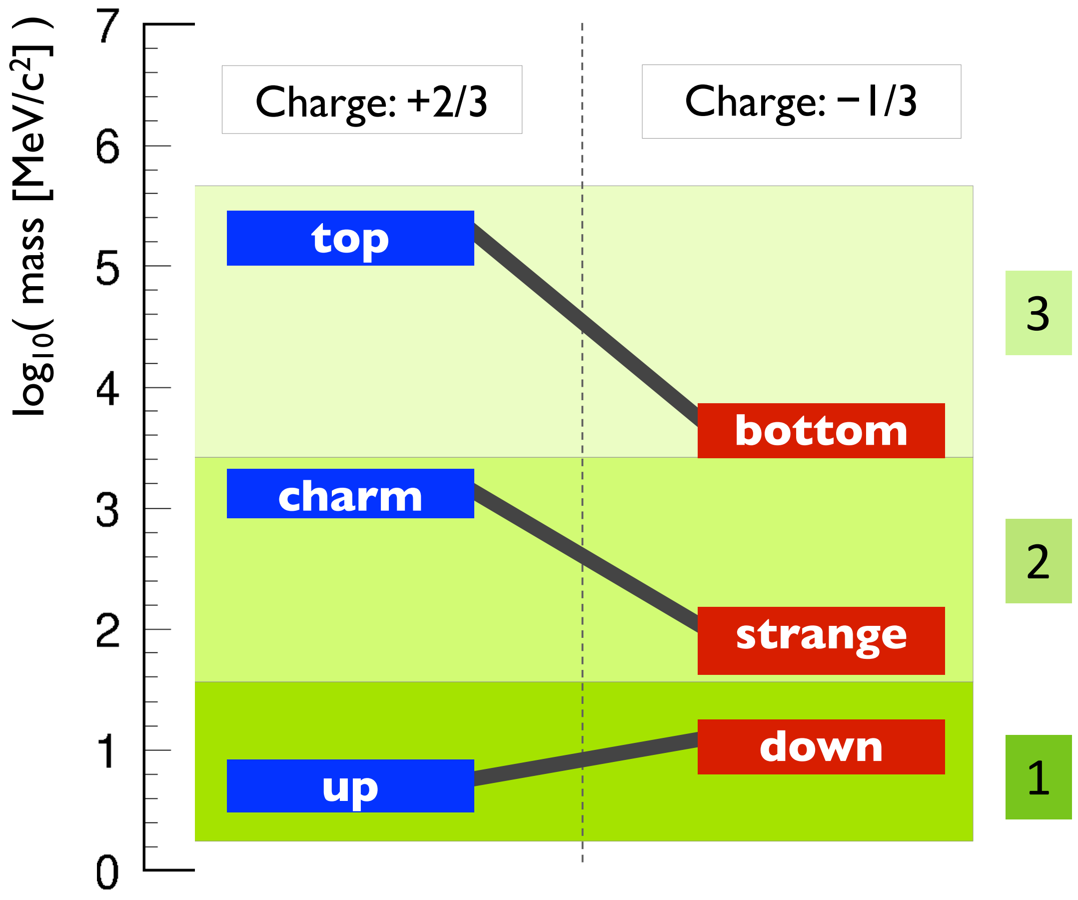
$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L \longrightarrow \mathcal{L}_W = \frac{g}{\sqrt{2}} V_{CKM} u_L \gamma_\mu W^\mu d_L$$

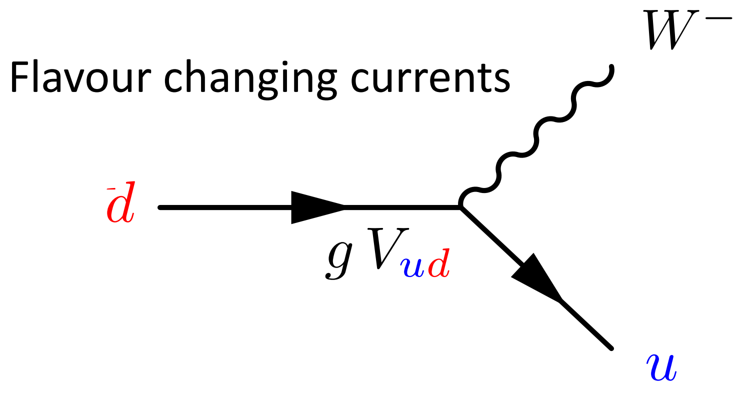
Redefine: $u'_i = (V^u)_{ij} u_i$ and: $d'_i = \left(V^d\right)^\dagger_{ij} d_i$, such that: $V_{CKM} = \left(V^u V^{d\dagger}\right)_{ij}$ …

Generation structure of weak interaction, *now includes CP violation.*



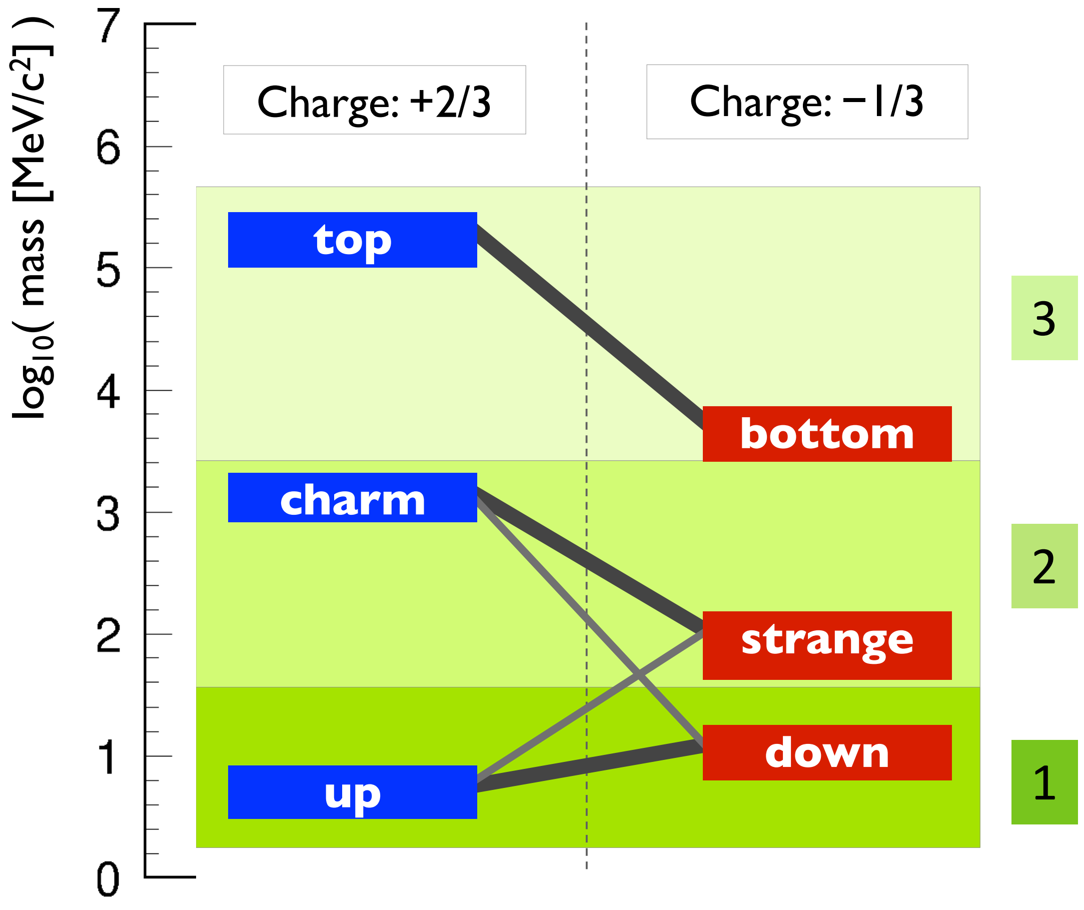
Flavour Changing Quark Interactions



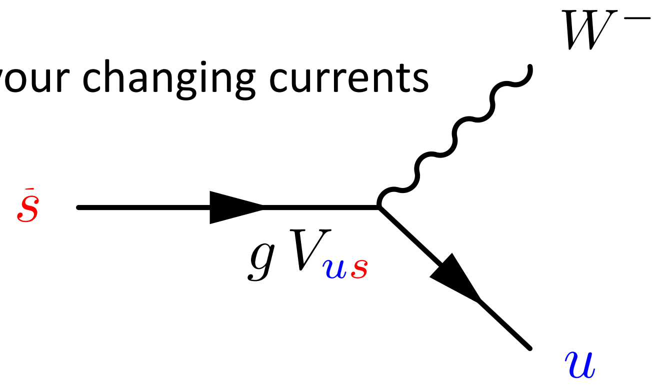


$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & & \\ & V_{cs} & \\ & & V_{tb} \end{pmatrix}$$

Flavour Changing Quark Interactions

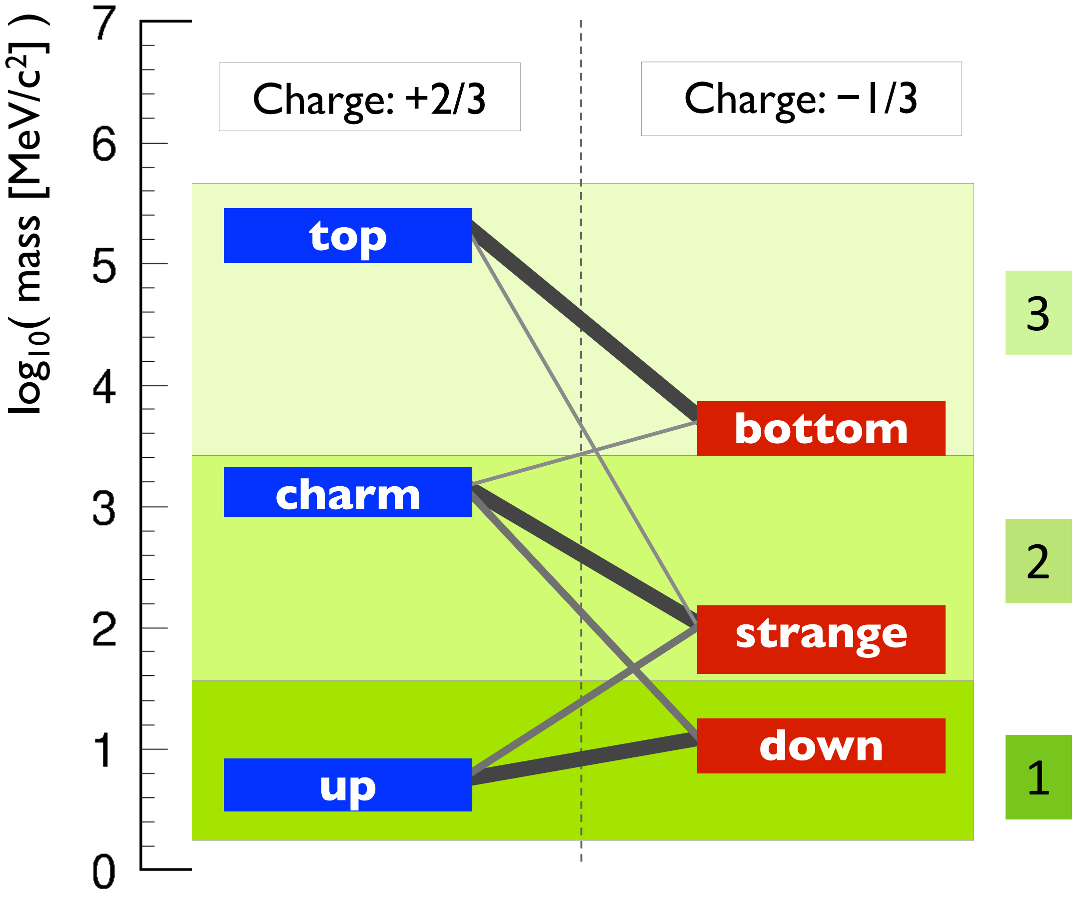


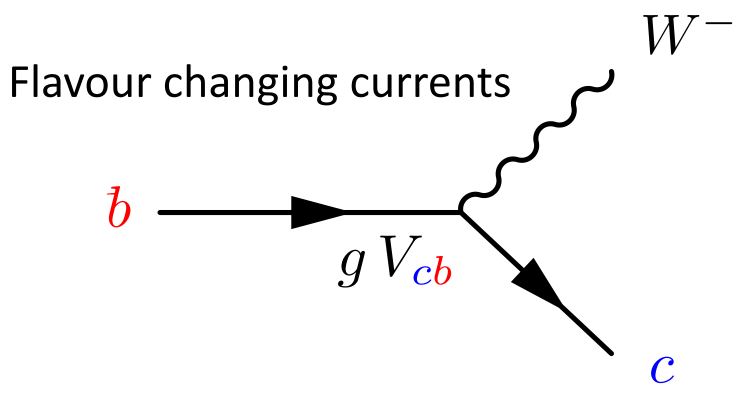
Flavour changing currents



$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & \\ V_{cd} & V_{cs} & \\ & & V_{tb} \end{pmatrix}$$

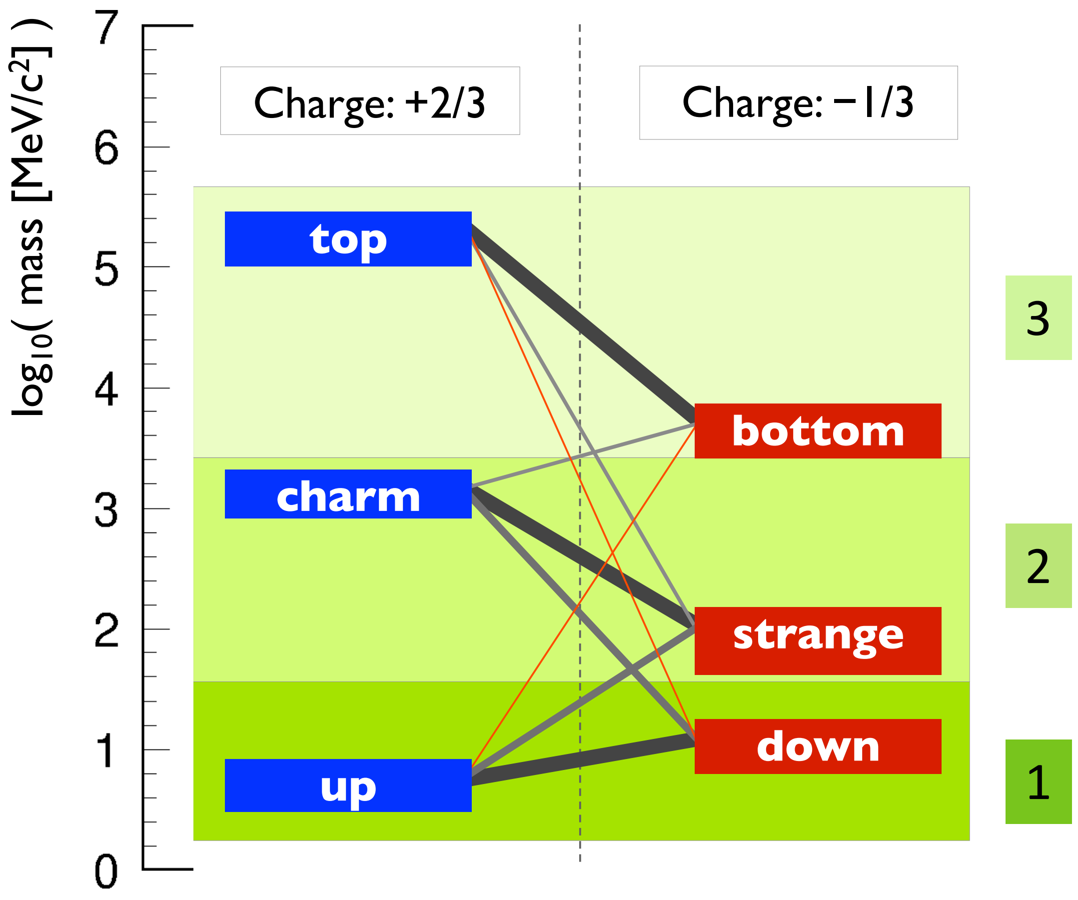
Flavour Changing Quark Interactions



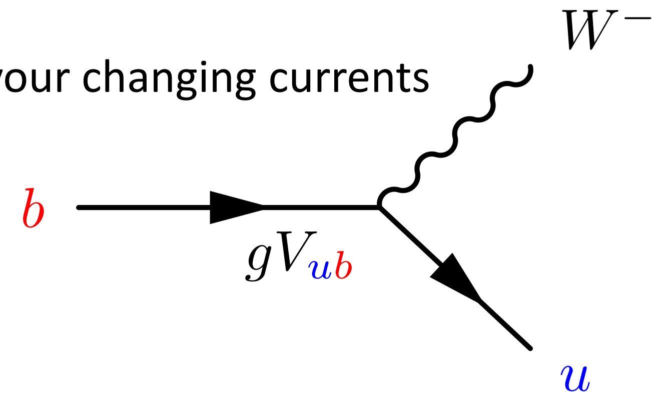


$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & \\ V_{cd} & V_{cs} & V_{cb} \\ & V_{ts} & V_{tb} \end{pmatrix}$$

Flavour Changing Quark Interactions

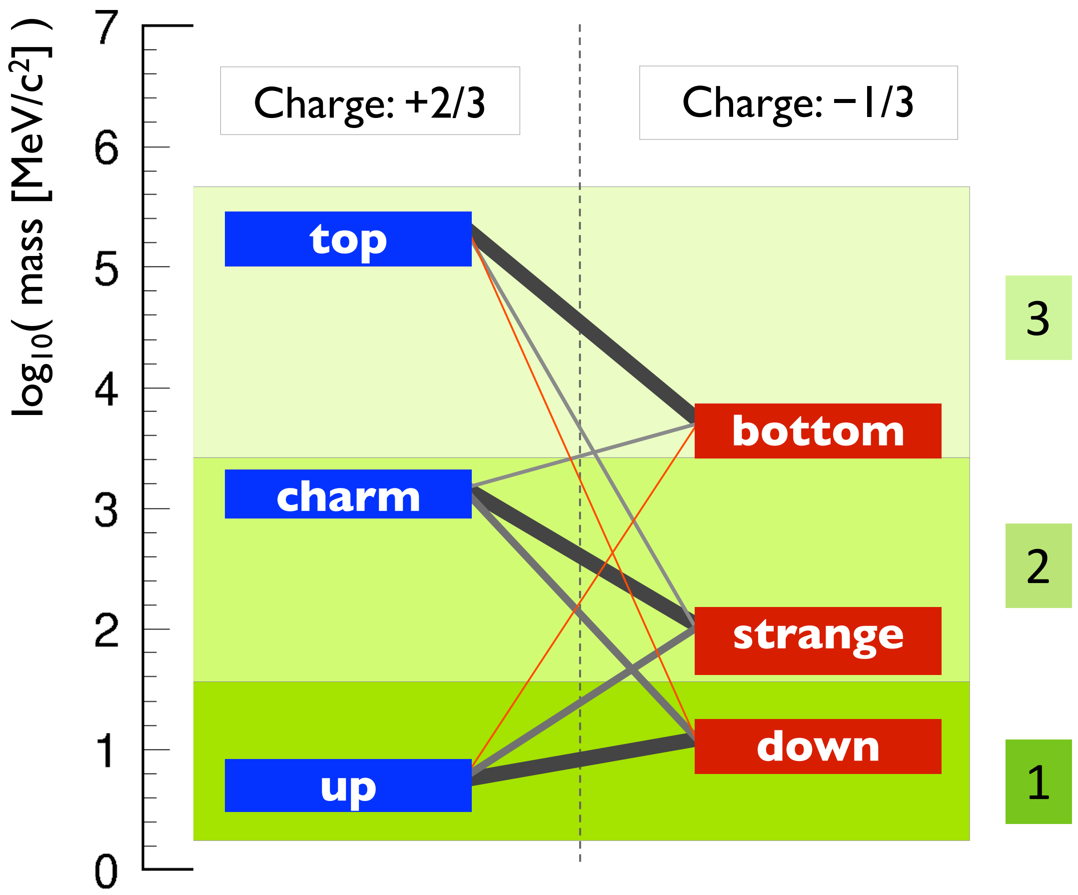


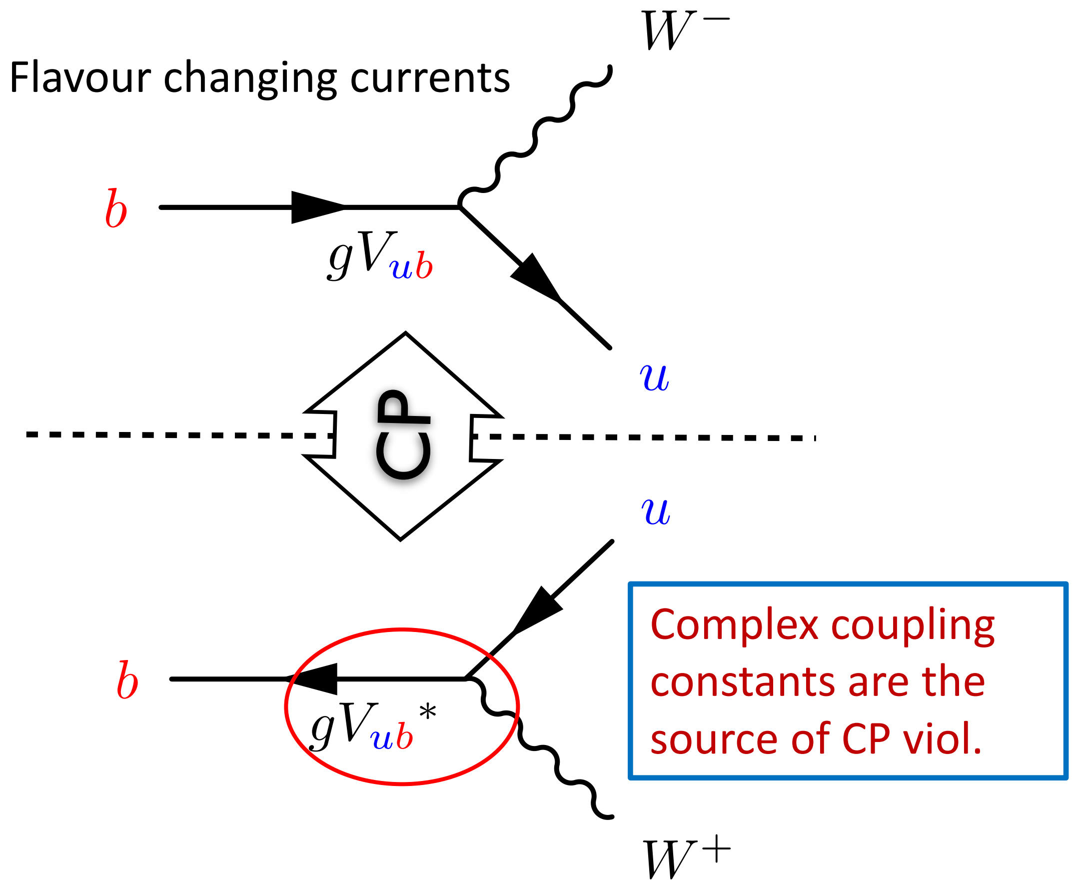
Flavour changing currents



$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Flavour Changing Quark Interactions – CP Violation





- Particles and antiparticles have complex conjugated coupling constants

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

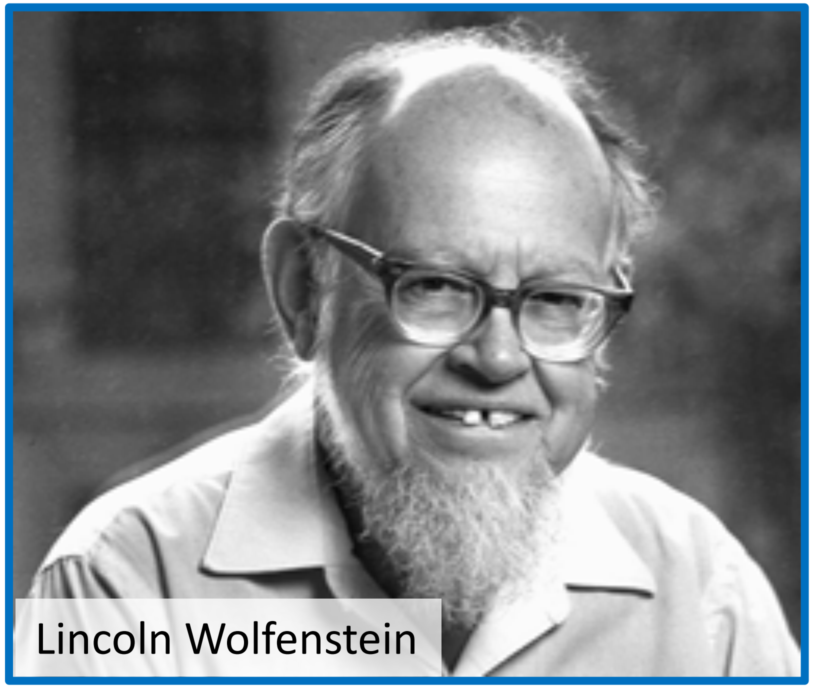
The CKM matrix V_{CKM} - 3 Generations

$$V_{CKM}: \quad \begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} \boxed{V_{ud}} & V_{us} & V_{ub} \\ V_{cd} & \boxed{V_{cs}} & V_{cb} \\ V_{td} & V_{ts} & \boxed{V_{tb}} \end{pmatrix} \end{array}$$

- Wolfenstein parametrization: $V_{CKM} =$

$$\begin{pmatrix} 1 - {}^{1}/_{2}\,\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - {}^{1}/_{2}\,\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

➔ 1 CP violating phase



Lincoln Wolfenstein

The CKM matrix V_{CKM} - 3 vs 2 Generations

$$V_{CKM}: \begin{array}{c|ccc} & d & s & b \\ \hline u & & & \\ c & & \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} & \\ t & & & \end{array}$$

- Wolfenstein parametrization: V_{CKM} =

$$\begin{pmatrix} 1 - {}^1\!/_2\,\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - {}^1\!/_2\,\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

→ 1 CP violating phase

$$V_{CKM}: \begin{array}{c|cc} & d & s \\ \hline u & \multicolumn{2}{c}{\multirow{2}{*}{$\begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix}$}} \\ c & & \end{array}$$

V_{CKM} =

$$\begin{pmatrix} 1 - {}^1\!/_2\,\lambda^2 & \lambda \\ -\lambda & 1 - {}^1\!/_2\,\lambda^2 \end{pmatrix}$$

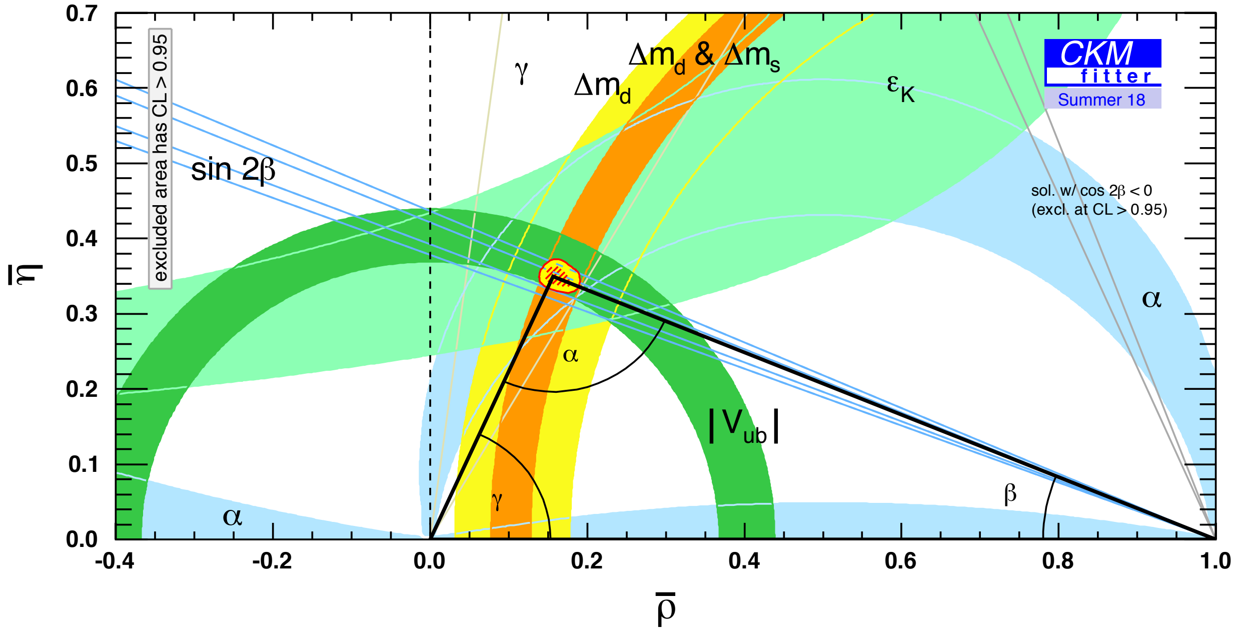
→ No CP violation

- *3 generations is the minimal particle content to generate CP violation* (In Standard Model).

The CKM matrix V_{CKM} - 3 Generations

$$V_{CKM}: \quad \begin{array}{c|ccc} & d & s & b \\ \hline u & & & \\ c & & \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} & \\ t & & & \end{array}$$

Unitarity: $V_{CKM}V_{CKM}^{\dagger} = 1$



- Wolfenstein parametrization: V_{CKM} =

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

CP violation:
➔ Surface $\neq 0$
➔ Non-zero CP-phases.

Contents:

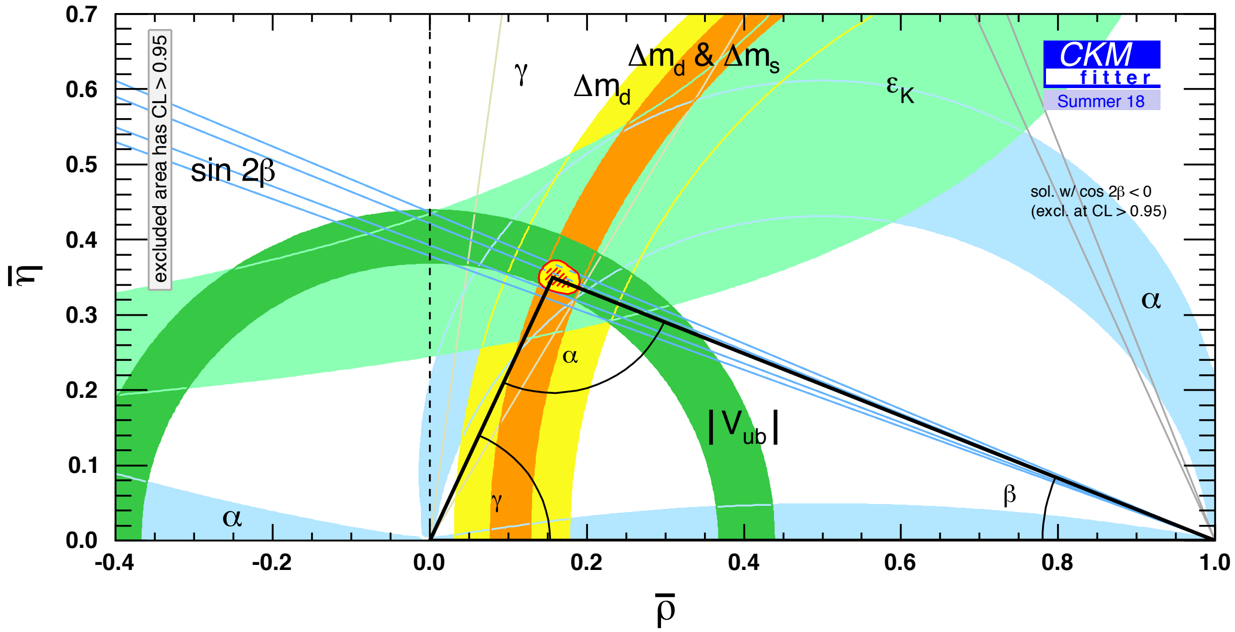
Leptons
Collect all 6!
Forceful Spices
Weak
Gravity
Strong
E-M
REALITY STEW
QUARKS

Contents:

Trying to describe the size of the Big Bang

How large is CP violation?

- Large CP violation requires *large mixing* and *large phases* in the CKM matrix.
  - Surface of unitarity triangle
  - Jarlskog invariant: $J = 3 \times 10^{-5}$



- CP violation also requires three generations with non-zero quark masses
  - In fact, ***different*** masses are required:
    - $m_u \neq m_c \quad ; \quad m_c \neq m_t \quad ; \quad m_t \neq m_u$
    - $m_d \neq m_s \quad ; \quad m_s \neq m_b \quad ; \quad m_b \neq m_d$

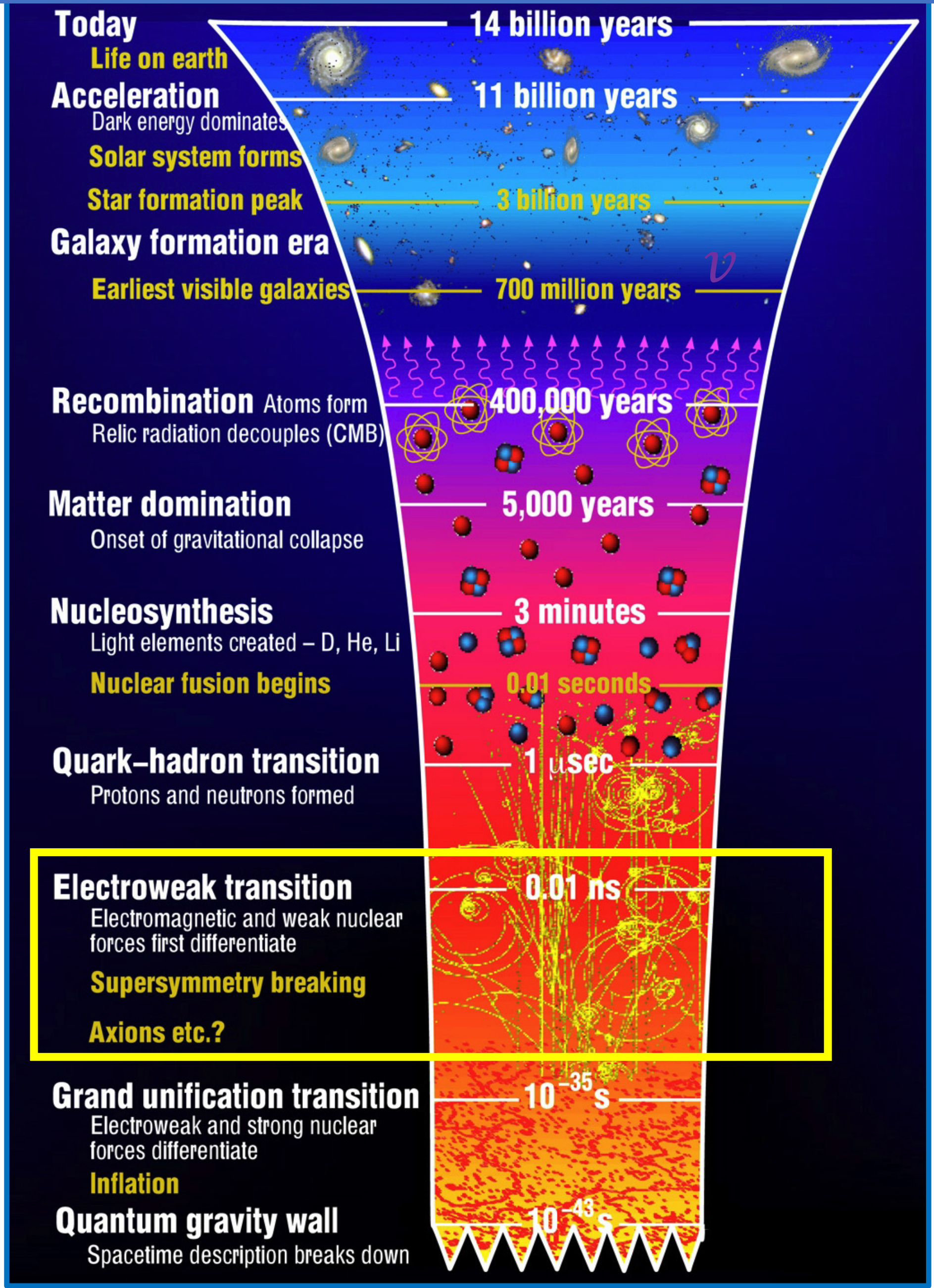
- Jarlskog criterion (1987) for amount of CP violation:
  - $\det[M_u M_u^\dagger, M_d M_d^\dagger] = 2\, i\, J\, (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2) \times (m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)$

$$\boxed{M_{ij} = Y_{ij}\, v/\sqrt{2}}$$

SU(2)

- W interaction flavour universal

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L$$



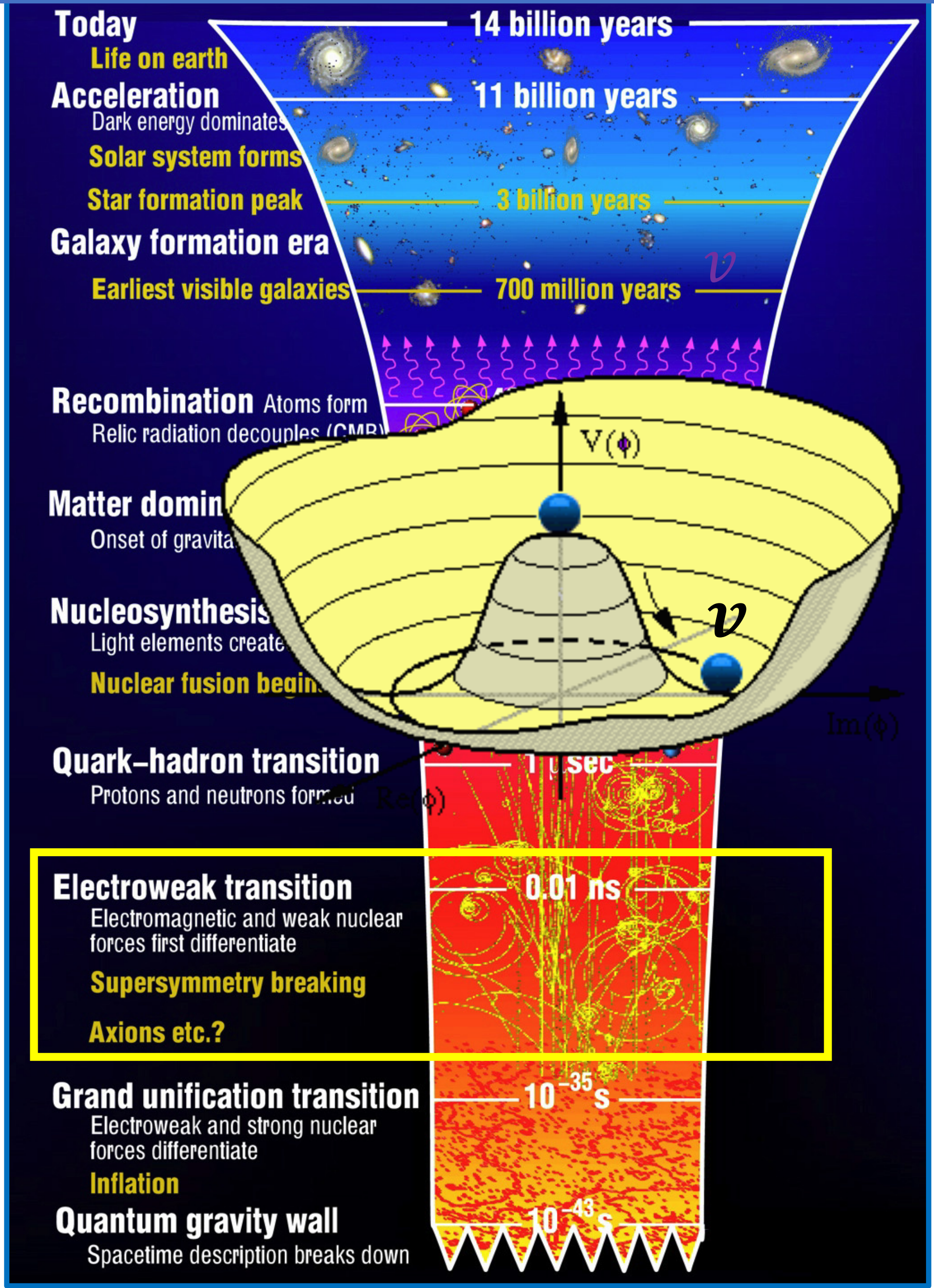
SU(2) → Higgs vev

- W interaction flavour universal

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \gamma_\mu W^\mu d'_L$$

- Higgs interaction *not* flavour universal

$$\mathcal{L}_H = Y^d_{ij} \left(\overline{u'_i}, \overline{d'_i}\right)_L \begin{pmatrix} 0 \\ v \end{pmatrix} d'_{jR} + Y^u_{ij} \left(\overline{u'_i}, \overline{d'_i}\right)_L \begin{pmatrix} v \\ 0 \end{pmatrix} u'_{jR}$$



SU(2) → Higgs vev → Origin of Mass

- W interaction flavour universal

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \, \gamma_\mu \, W^\mu \, d'_L$$

- Higgs interaction *not* flavour universal

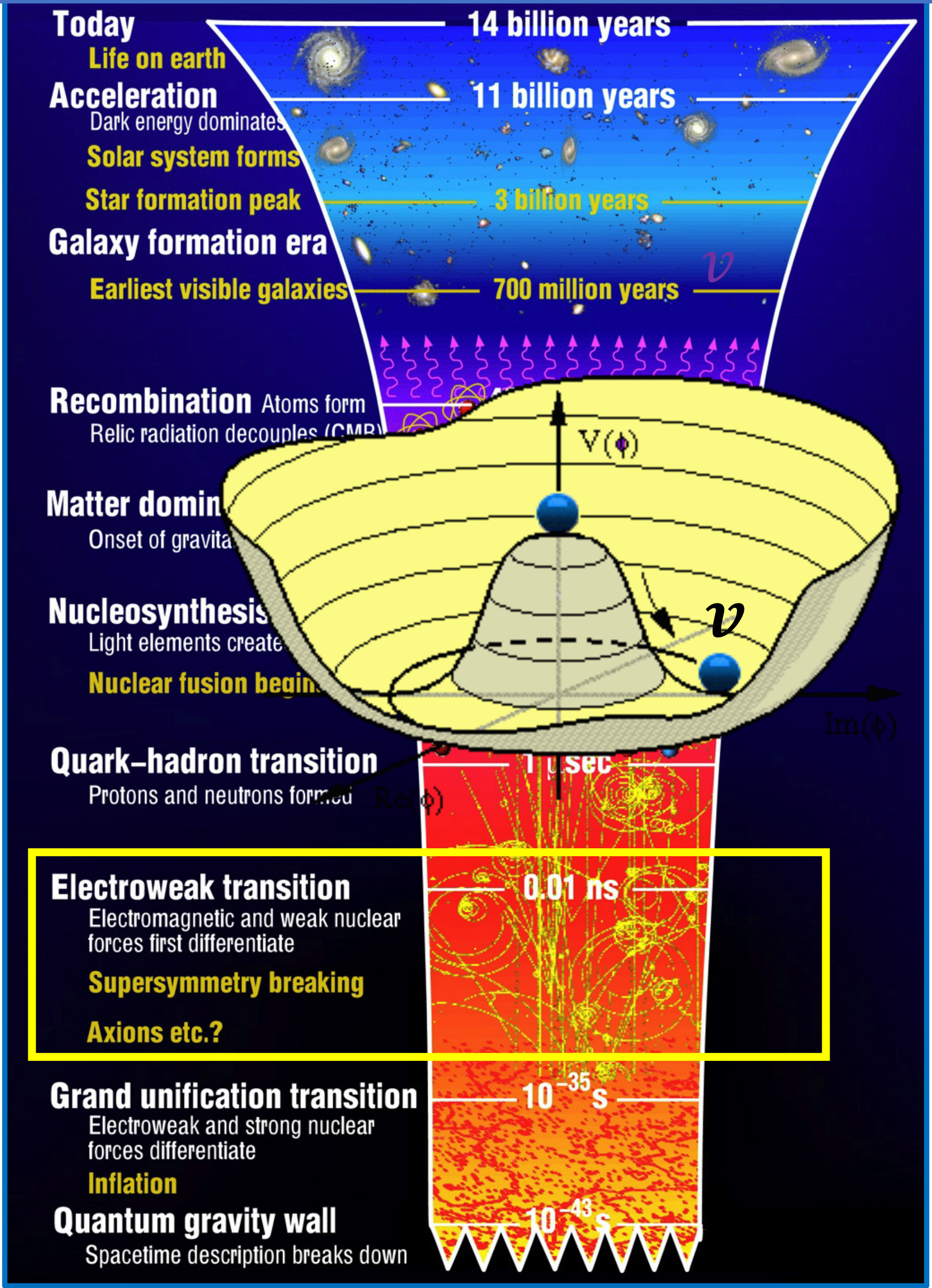
$$\mathcal{L}_H = Y^d_{ij} \left(\overline{u'_i}, \overline{d'_i}\right)_L \begin{pmatrix} 0 \\ v \end{pmatrix} d'_{jR} + Y^u_{ij} \left(\overline{u'_i}, \overline{d'_i}\right)_L \begin{pmatrix} v \\ 0 \end{pmatrix} u'_{jR}$$

- Mass vs Interaction states:

$$u_i = (V^u)_{ij} \, u'_j \qquad\qquad d_i = \left(V^d\right)_{ij} \, d'_j$$

- Amount of CP violation:

$$\det\left[M_u M_u^\dagger , M_d M_d^\dagger\right] = 2\, i\, J\, (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2) \times \left(m_b^2 - m_s^2\right)\left(m_s^2 - m_d^2\right)\left(m_d^2 - m_b^2\right)$$



SU(2) → Higgs vev → Origin of Mass → Origin of CP violation?

- W interaction flavour universal

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} u'_L \, \gamma_\mu \, W^\mu \, d'_L$$

- Higgs interaction *not* flavour universal

$$\mathcal{L}_H = Y^d_{ij} \left(\overline{u'_i}, \overline{d'_i}\right)_L \binom{0}{v} d'_{jR} + Y^u_{ij} \left(\overline{u'_i}, \overline{d'_i}\right)_L \binom{v}{0} u'_{jR}$$

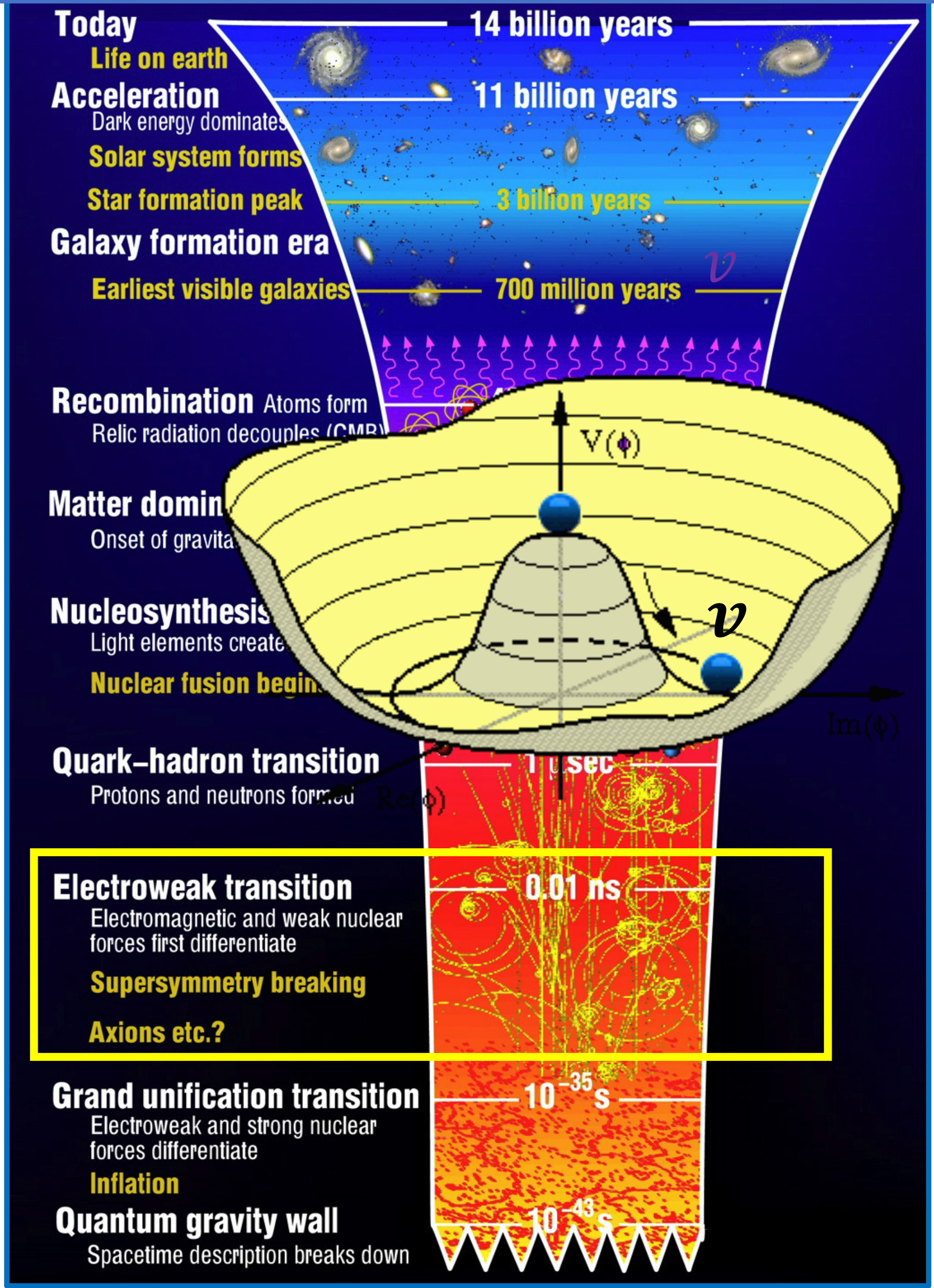
- Mass vs Interaction states:

$$u_i = (V^u)_{ij} \, u'_j \qquad\qquad d_i = \left(V^d\right)_{ij} d'_j$$

- Amount of CP violation:

$$\det\left[M_u M_u^\dagger, M_d M_d^\dagger\right] = 2\, i\, J\, (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2) \times \left(m_b^2 - m_s^2\right)\left(m_s^2 - m_d^2\right)\left(m_d^2 - m_b^2\right)$$

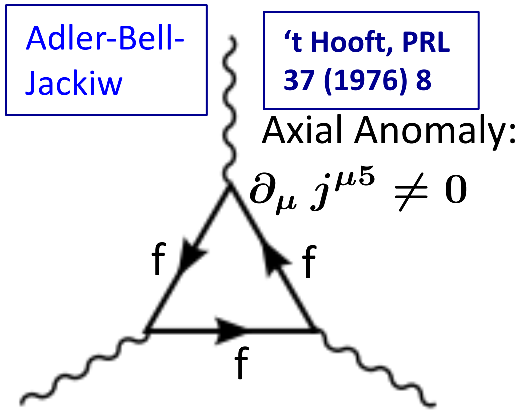
- *Does the Standard Model include CP violation* ***before*** *symmetry breaking?*
  - *Is CP violation perhaps an emergent phenomenon?*



The Baryogenesis Puzzle – Electroweak Baryogenesis?

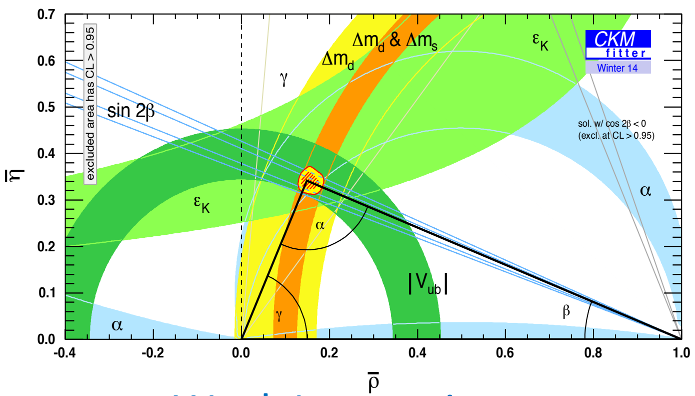
- Sacharov Conditions
  - ✓All present in S.M.

✔ Baryon Number Violation



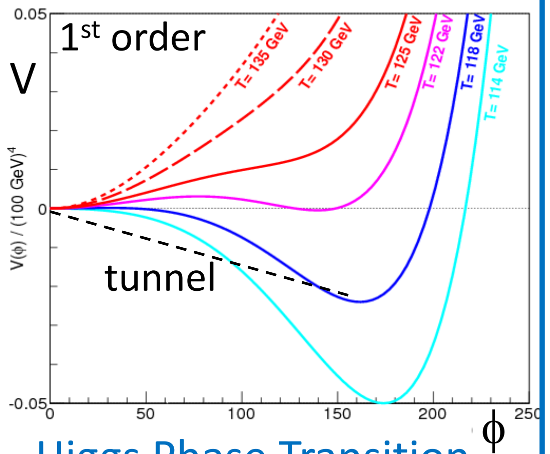
Quantum anomaly

✔ C and CP Violation



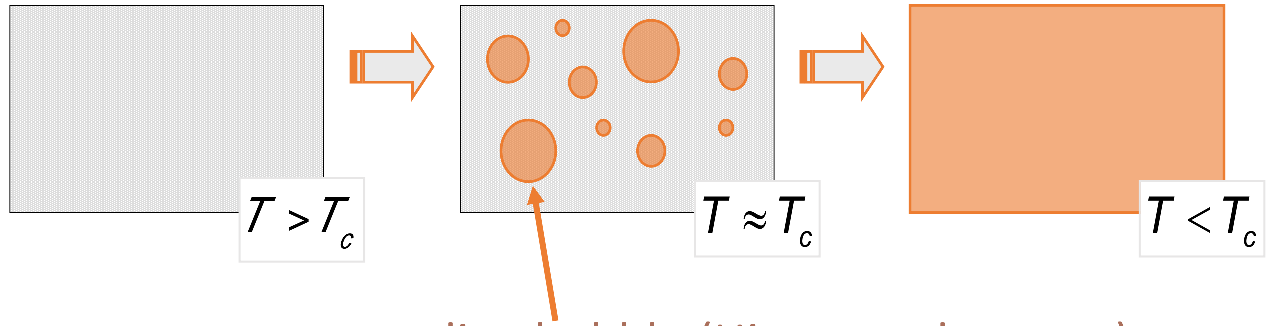
Weak Interaction

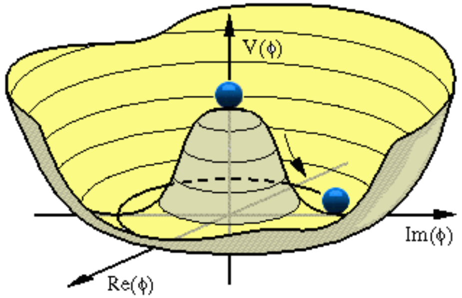
✔ Thermal non-equilibrium



Higgs Phase Transition

- Baryogenesis from Higgs symmetry breaking?





The Baryogenesis Puzzle – Electroweak Baryogenesis?

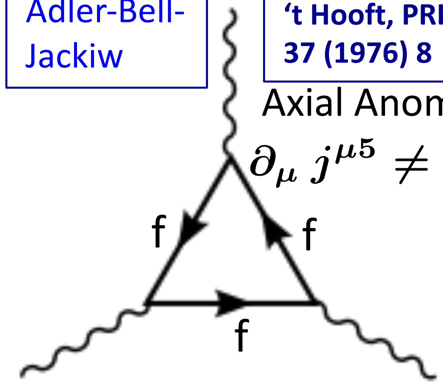
- Sacharov Conditions
  - ✓All present in S.M.
  - ✖Not Enough?

✔ Baryon Number Violation

Adler-Bell-Jackiw

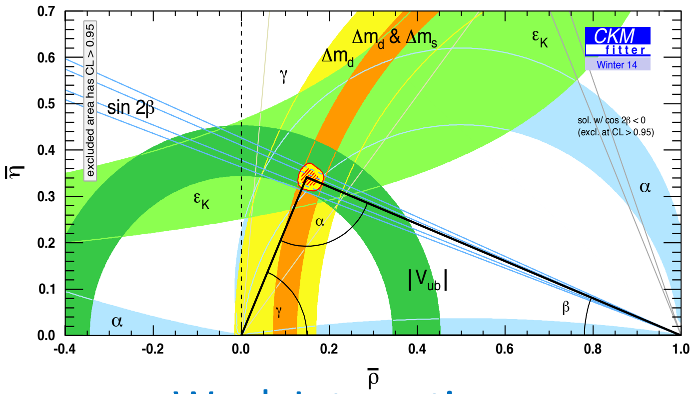
't Hooft, PRL 37 (1976) 8

Axial Anomaly: $\partial_\mu j^{\mu 5} \neq 0$



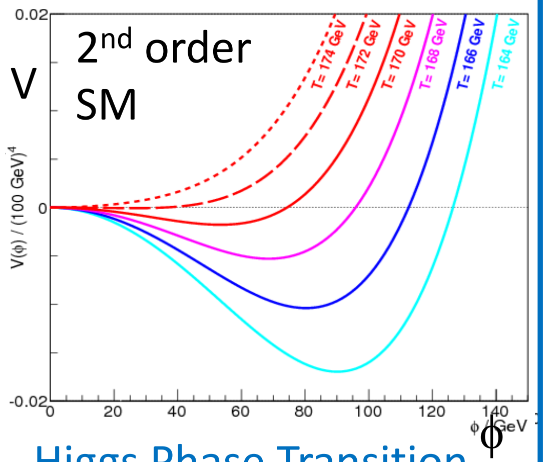
Quantum anomaly

✖ C and CP Violation



Weak Interaction

✖ Thermal non-equilibrium

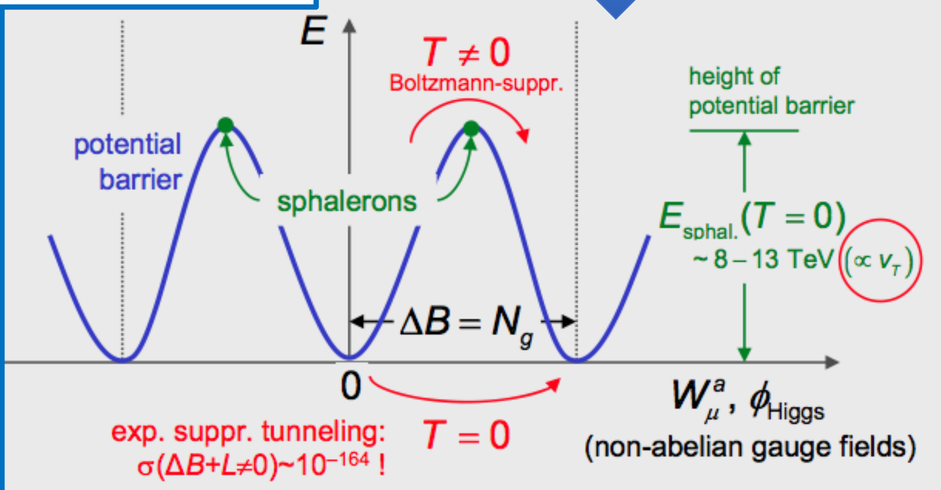


Higgs Phase Transition

✖ 1st order?

- SM: $M_H <$ ~70 GeV
- THDM: M_H ~ 125 OK

✔ Sphalerons

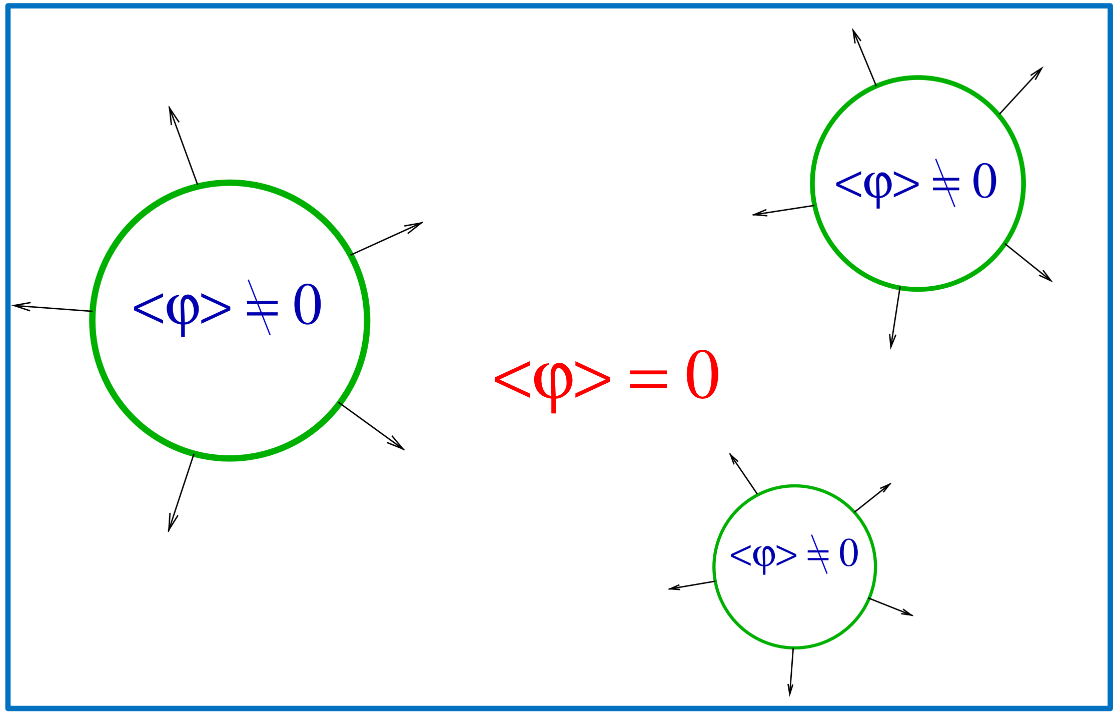


✖ CPV from CKM

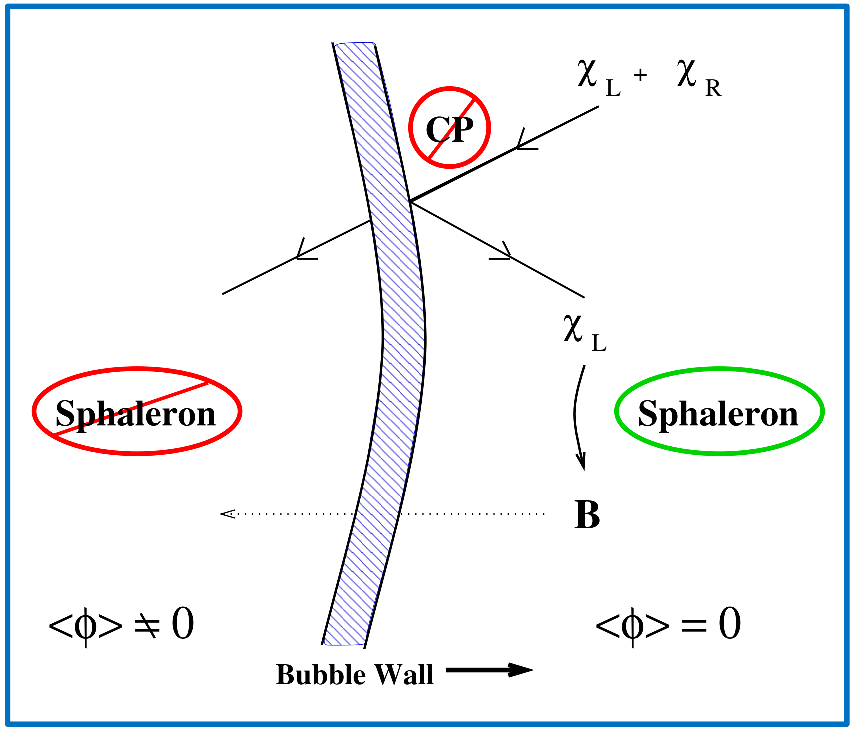
- BAU: $\frac{\Delta n_B}{n_\gamma} \approx 10^{-10}$
- $A_{CP} = J_{inv} \times (m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_u^2 - m_t^2) \times (m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_d^2 - m_b^2)$
  - From CKM: $A_{CP}/T_c^{12} \approx 10^{-20}$ → Too small
  - Used $T_c \sim 100$ GeV

The Baryogenesis Puzzle – Electroweak Baryogenesis?

Expanding bubbles of broken phase
In a medium of symmetric phase



Baryon production in
front of bubble wall



➔ *Was the phase transition in the early universe of 1st order?*

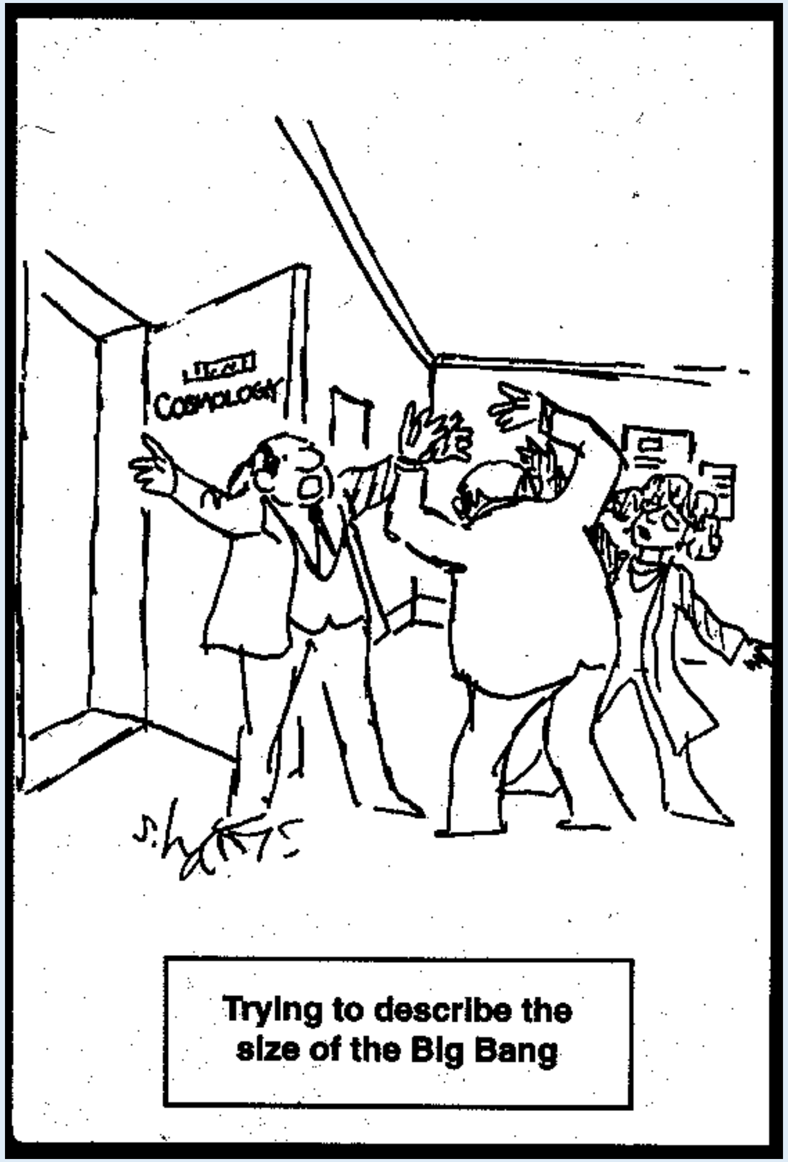
➔ *Higgs potential?*

➔ *If new physics is abundant in thermal plasma of early universe:*

➔ *Likely to be of TeV energy scale.*

Alternative Explanation…

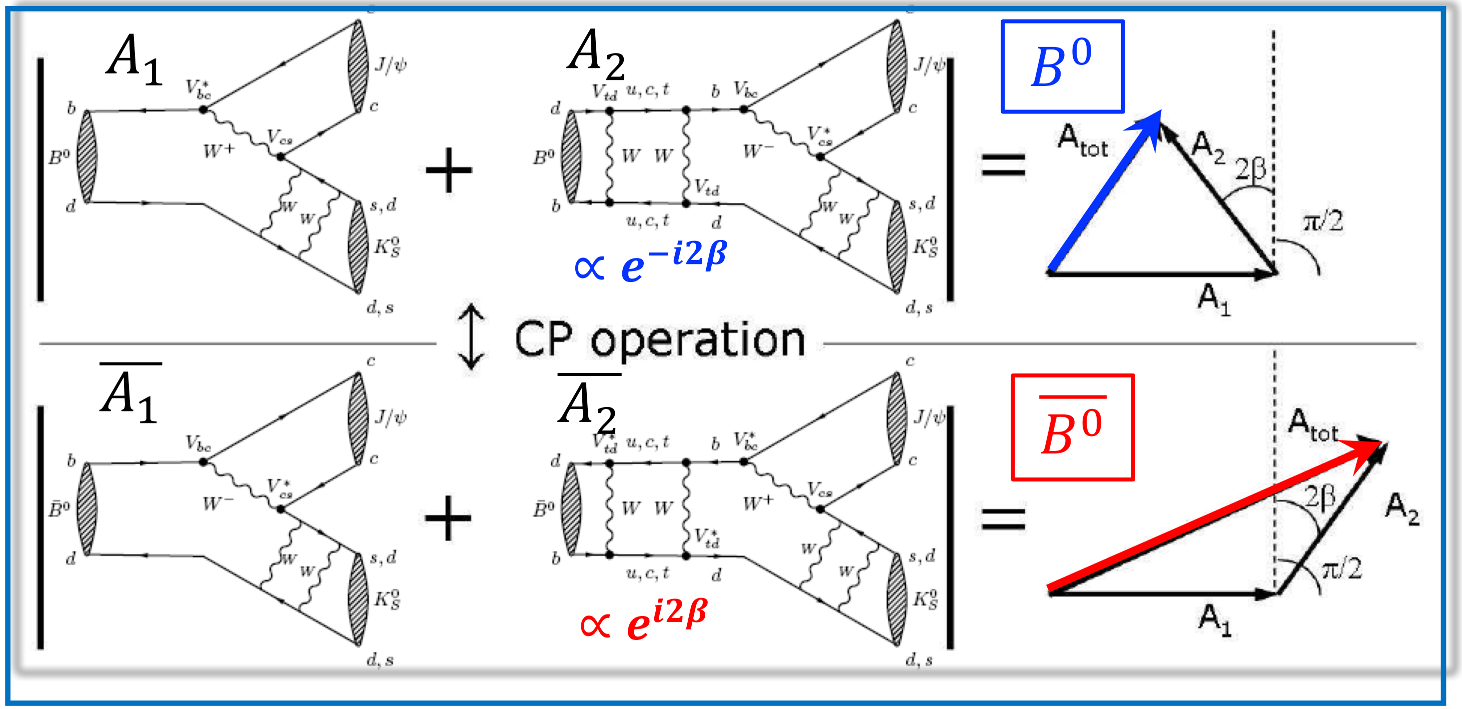
Contents:

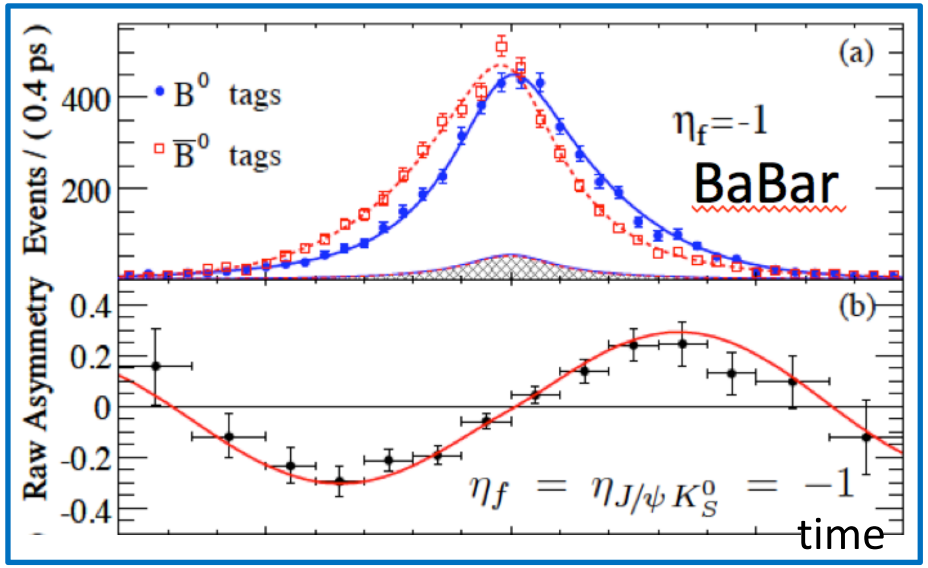


Contents:

CP violation: a quantum interference experiment

- Quantum process with two amplitudes A_1 and A_2:
  - Eg.: $A_1 = B^0 \rightarrow J/\psi\, K_s$ and $A_2 = B^0 \rightarrow \overline{B^0} \rightarrow J/\psi\, K_s$



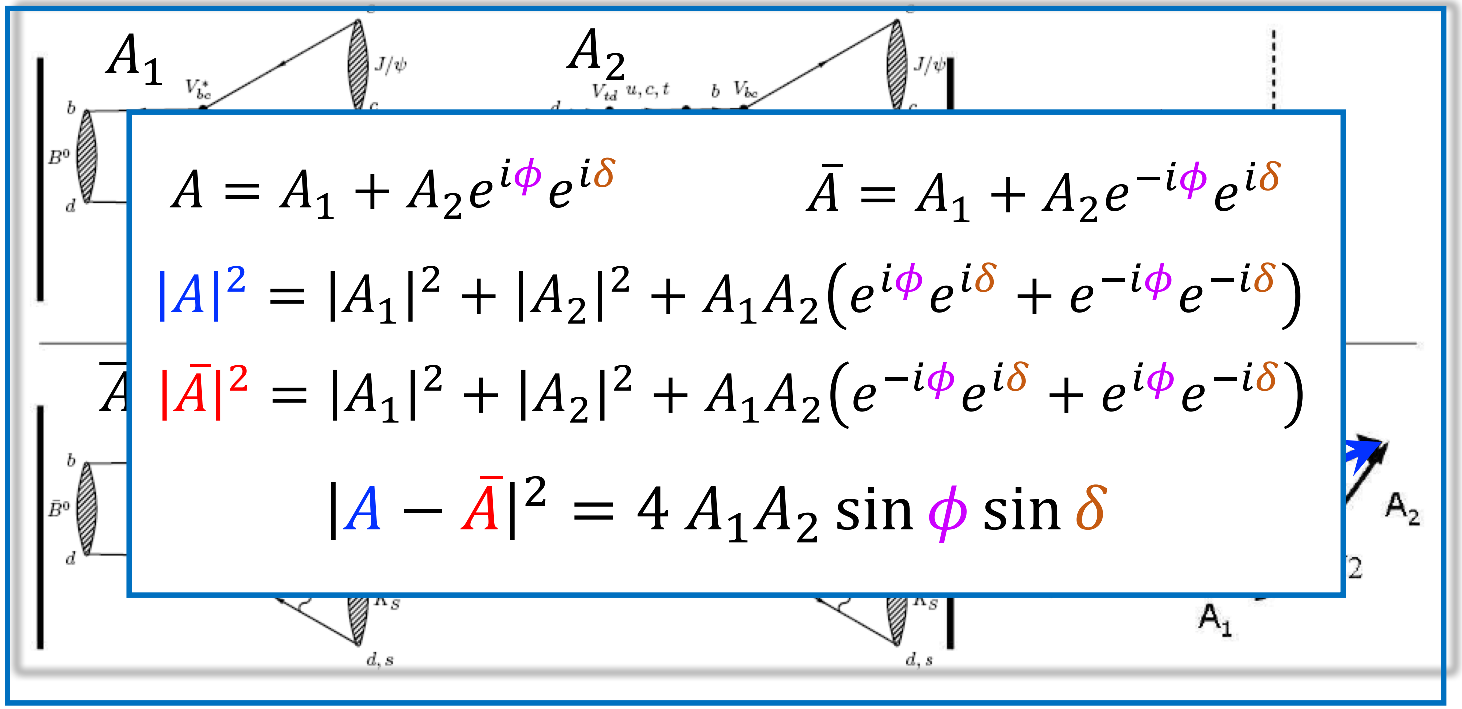


$|A_1| = |\overline{A_1}|$, $|A_2| = |\overline{A_2}|$,

but $|A_1 + A_2| \neq |\overline{A_1 + A_2}|$

CP violation: a quantum interference experiment

- Quantum process with two amplitudes A_1 and A_2:
  - Eg.: $A_1 = B^0 \to J/\psi\, K_s$ and $A_2 = B^0 \to \overline{B^0} \to J/\psi\, K_s$

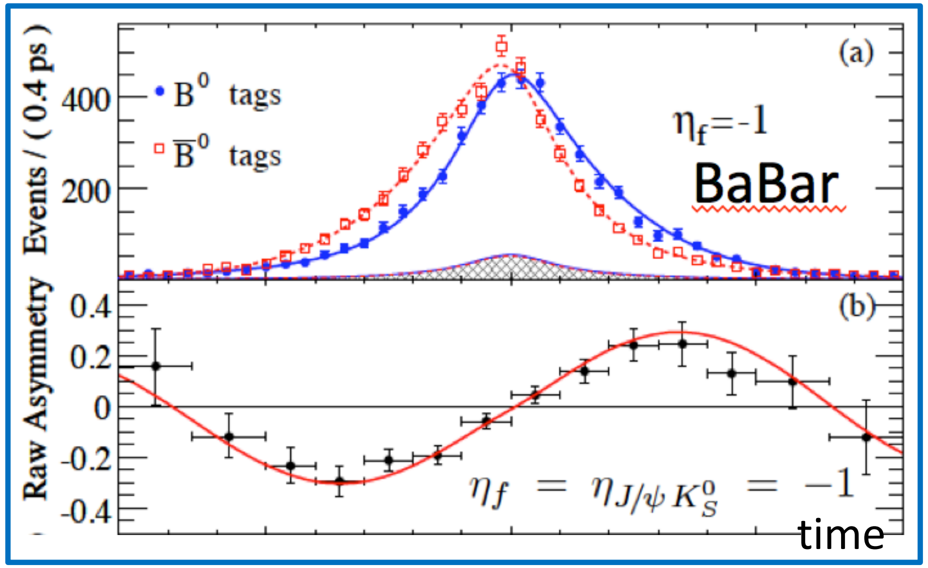


$$A = A_1 + A_2 e^{i\phi} e^{i\delta} \qquad \bar{A} = A_1 + A_2 e^{-i\phi} e^{i\delta}$$

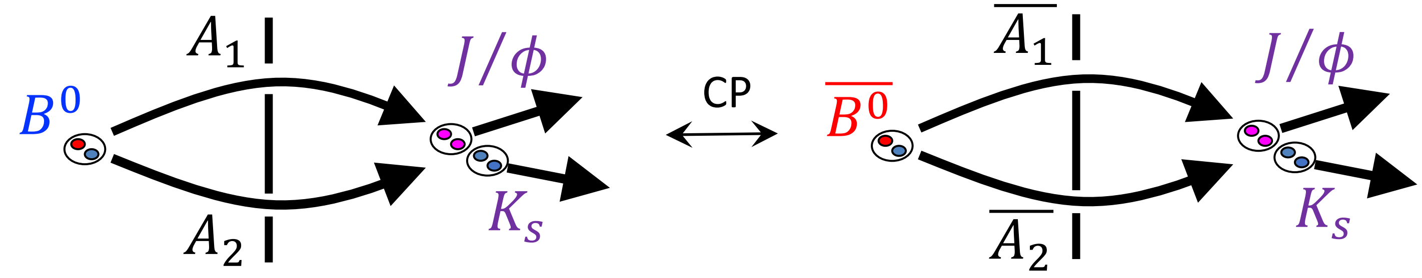
$$|A|^2 = |A_1|^2 + |A_2|^2 + A_1 A_2 \left(e^{i\phi} e^{i\delta} + e^{-i\phi} e^{-i\delta}\right)$$

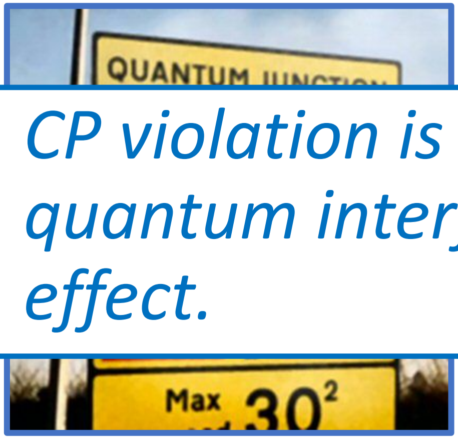
$$|\bar{A}|^2 = |A_1|^2 + |A_2|^2 + A_1 A_2 \left(e^{-i\phi} e^{i\delta} + e^{i\phi} e^{-i\delta}\right)$$

$$|A - \bar{A}|^2 = 4\, A_1 A_2 \sin\phi \sin\delta$$



$|A_1| = |\overline{A_1}|$, $|A_2| = |\overline{A_2}|$,
but $|A_1 + A_2| \neq |\overline{A_1 + A_2}|$

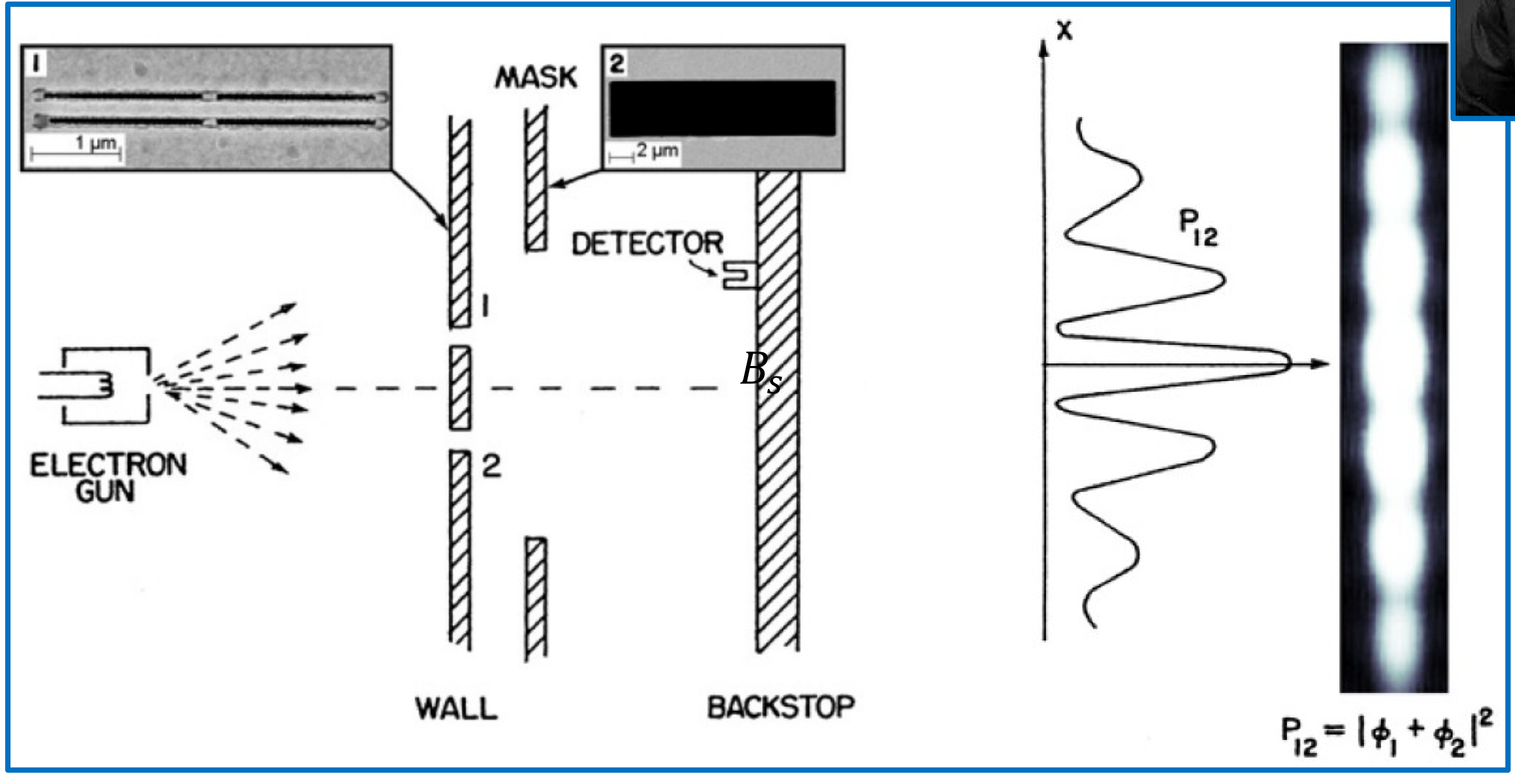


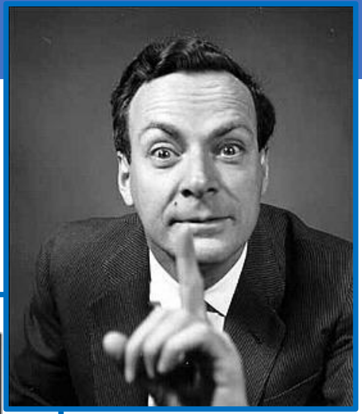


- *CP violation is a pure quantum interference effect.*

Intermezzo: CP violation and Interference

- Feynman: “In the end all quantum phenomena are manifestations of the double slit experiment.”





- *Assuming CPT, symmetry, CP violation implies a quantum arrow of time*
  - *Quantum interference ←→ arrow of time?*

Three types of observable CP violation

a) *"indirect"* CP Violation: 1964 (CCFT)

- Prob$(K^0 \to \overline{K^0}) \neq$ Prob $(\overline{K^0} \to K^0)$

  $|\varepsilon|$ = (2.228 ± 0.011) x 10^{-3} (PDG)
- Also called: ***CPV in mixing***

Interfere *dispersive* and *absorptive*:

$$K^0 \xrightarrow{M_{12}} \overline{K^0}, \qquad K^0 \xrightarrow{-\frac{i}{2}\Gamma_{12}} \overline{K^0}$$

b) *"direct"* CP violation: 1999 (NA48 & KTeV):

- Decay rates $\Gamma(K^0 \to \pi^+\pi^-) \neq \Gamma(\overline{K^0} \to \pi^+\pi^-)$

  Re(ε'/ε) = (1.65 ± 0.26) x 10^{-3} (PDG)
- Also called: ***CPV in decay***

Interfere *Isospin amplitudes*:

$$A = a_{0(K\to\pi\pi)} + a_{2(K\to\pi\pi)}$$

c) "mixing induced" CP violation: 2001 (Belle & Babar):

- Also: ***CPV in interference of mixing and decay***

  sin 2β = 0.682 ± 0.019 (PDG)

Interfere *direct* and *mixed*:

$$B \to J/\psi\, K_S, \qquad B \to \bar{B} \to J/\psi\, K_S$$

Three types of observable CP violation

a) *"indirect"* CP Violation: 1964 (CCFT)

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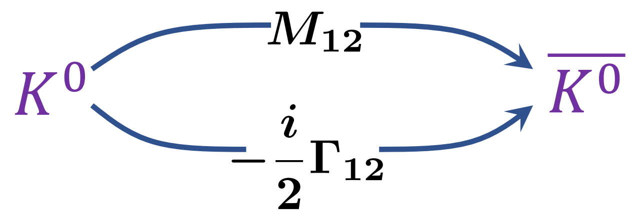
Interfere *dispersive* and *absorptive*:



b) "direct" CP violation: 1999 (NA48 & KTeV):

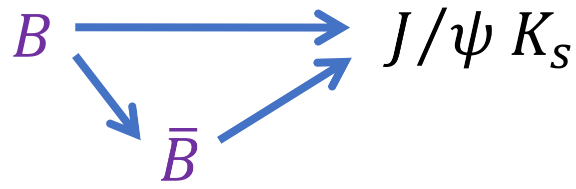
All CP violation processes result from quantum interference including three generations of fermions.

c) "mixing induced" CP violation: 2001 (Belle & Babar):

- Also: ***CPV in interference of mixing and decay***

  sin 2β = 0.682 ± 0.019 (PDG)

Interfere *direct* and *mixed*:



Grappa analogy: Three types of Flavour Violation…

1. “In Mixing”

2. “Direct”

3. “Mixing induced”

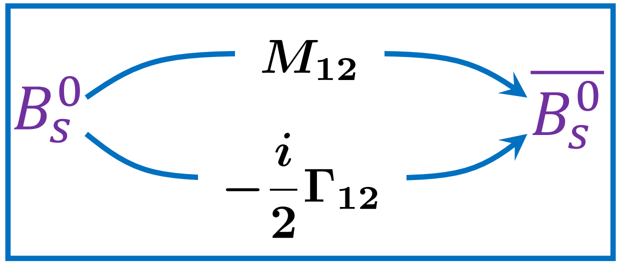
(interference of 1. and 2.)

→ Interference experiments lead to interesting effects!

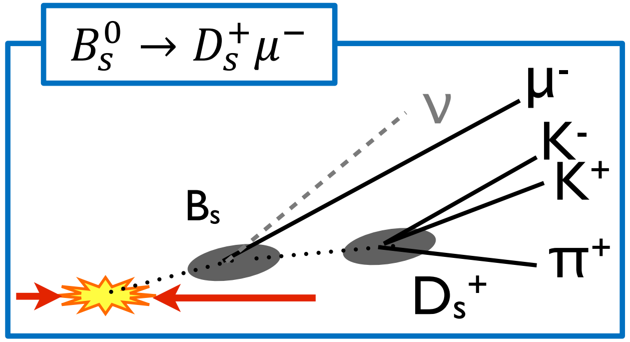
(Constructive or destructive??)

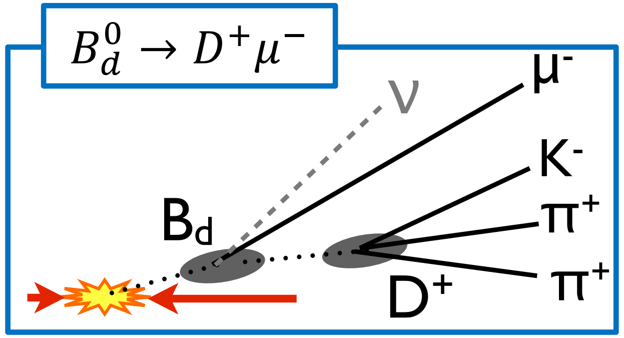
Type-1: CP violation *in mixing*: $a_{SL}(B_d)$ en $a_{SL}(B_s)$

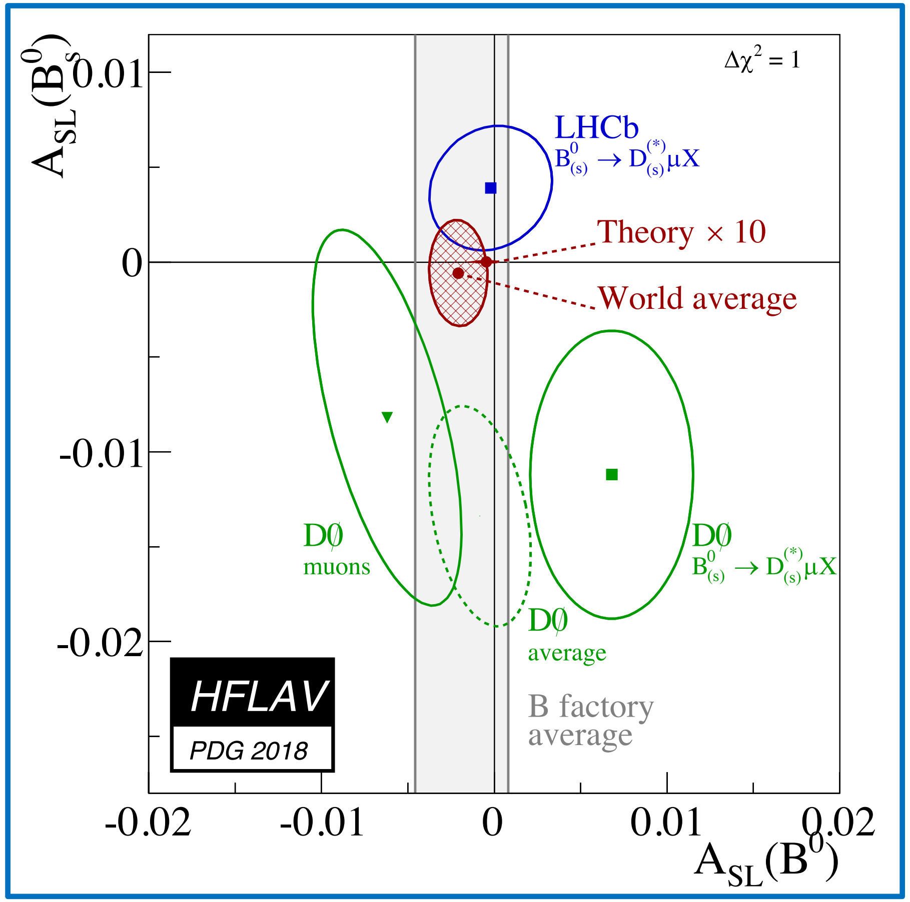
- Interfere *dispersive* and *absorptive* amplitudes ("indirect"):



$$\mathcal{A}_{meas} = \frac{\Gamma_{(B_s^0 \to D_s^- \mu^+)} - \Gamma_{(B_s^0 \to D_s^+ \mu^-)}}{\Gamma_{(B_s^0 \to D_s^- \mu^+)} + \Gamma_{(B_s^0 \to D_s^+ \mu^-)}} = \frac{1}{2}\, a_{SL}(B_s^0)$$







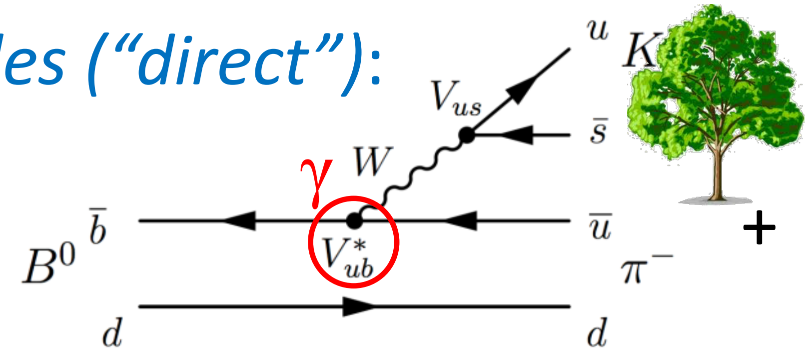
CP violation in mixing *does not happen* in B_d^0 and B_s^0 mesons:

- $B \to \bar{B}$ goes at same rate as $\bar{B} \to B$
- Contrary to ϵ in kaons.

Type-2: CP violation in *decay*: $B_d^0 \to K\pi$ and $B_s^0 \to K\pi$

- Interfere *two decay amplitudes (“direct”)*:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$



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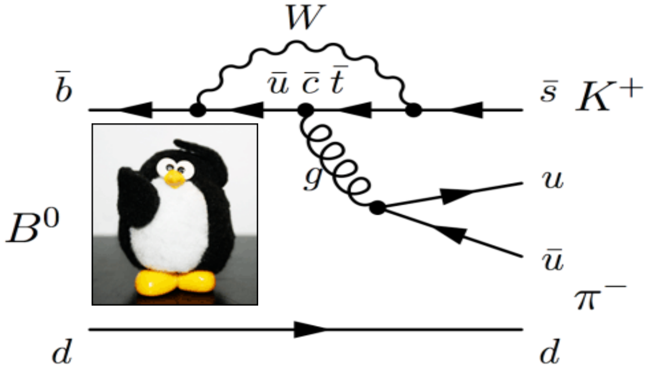
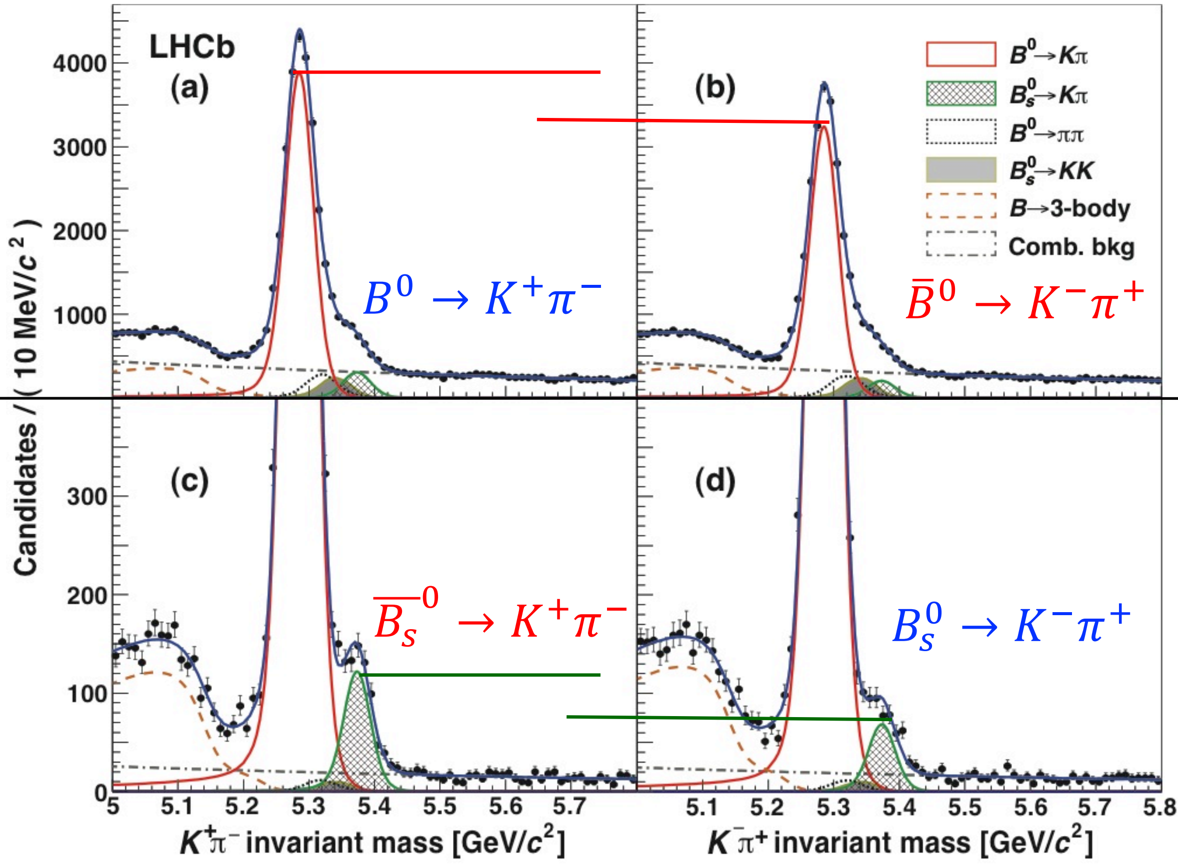


$B_d^0 \to K\pi$

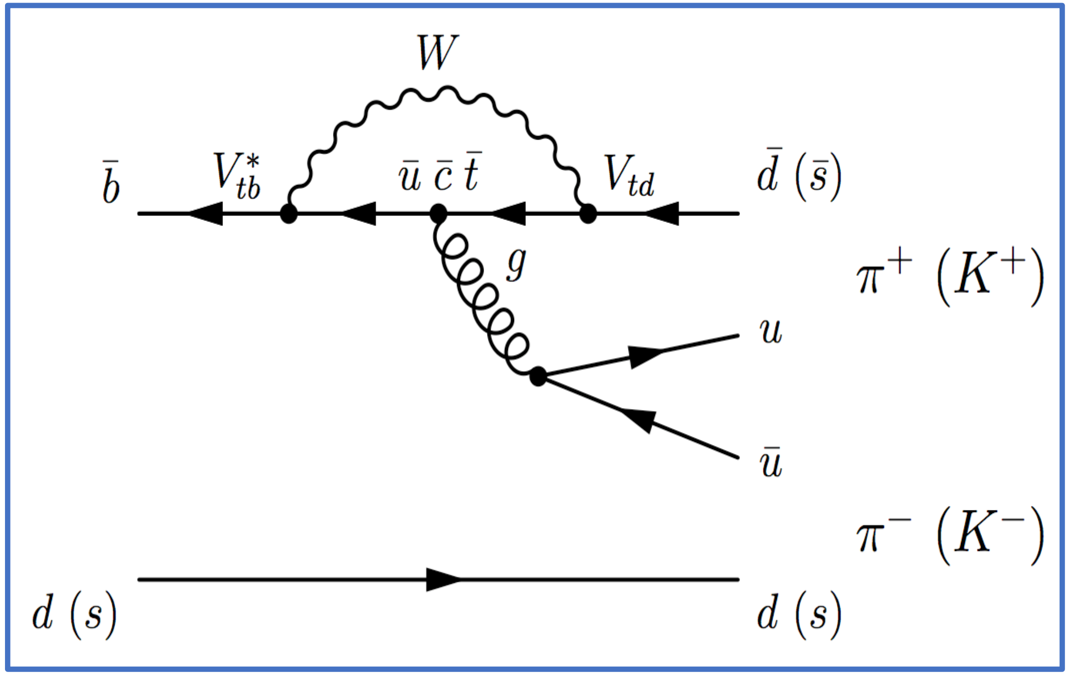
$B_s^0 \to K\pi$

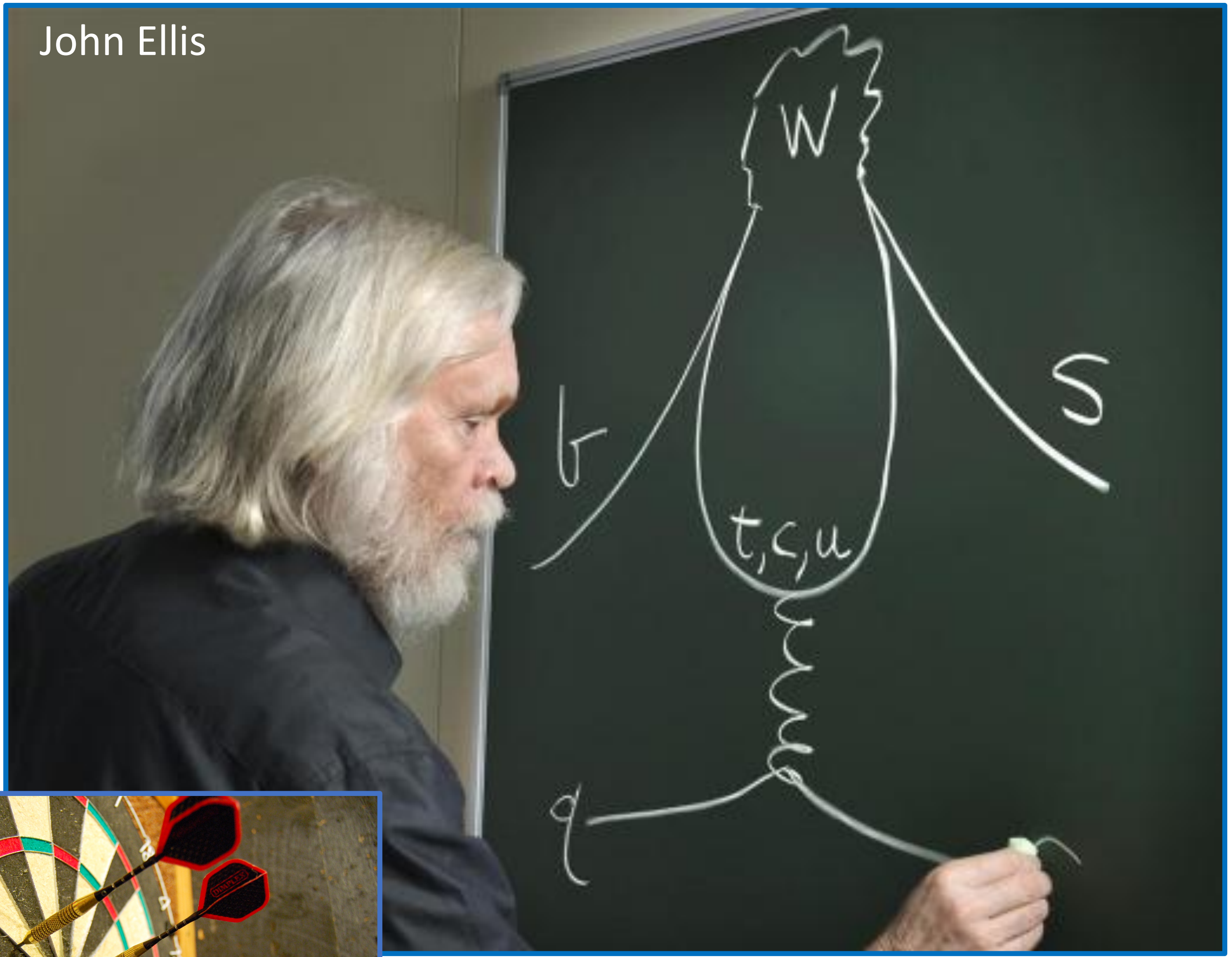
First observation of CP violation in B_s decays

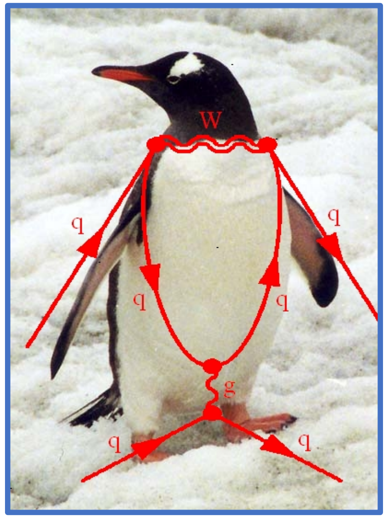


- Quarks from three generations involved
- Large interference
- Large CP violation!
  - Contrary to ϵ' in the kaon system

A story on darts and penguins



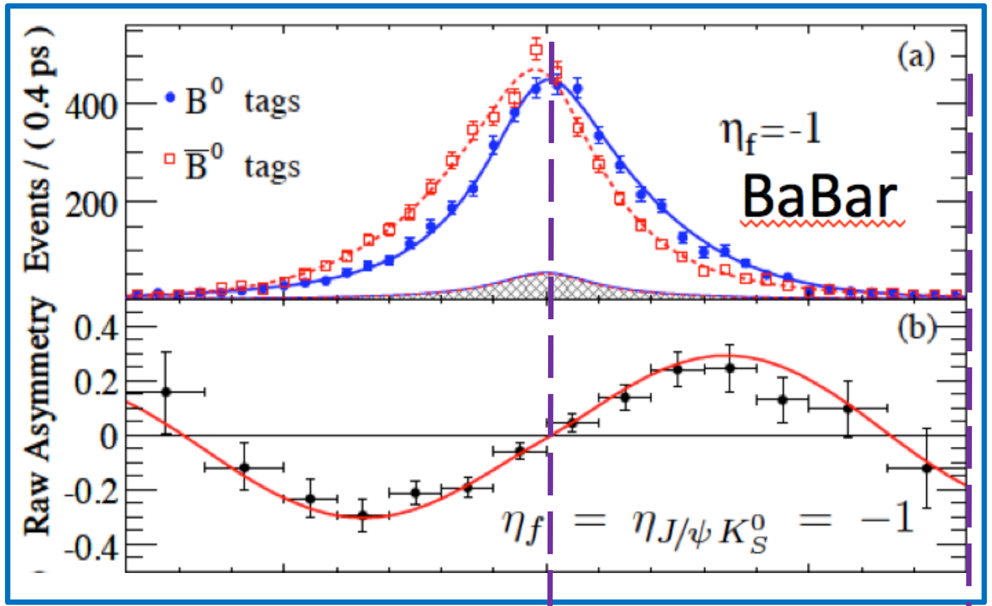




Type-3: CP violation in *interference of mixing and decay*

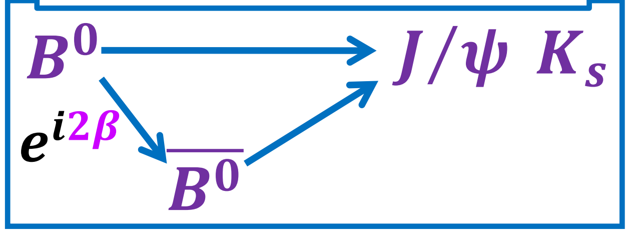
- Interfere *direct* with *mixed* decay ("mixing induced"):

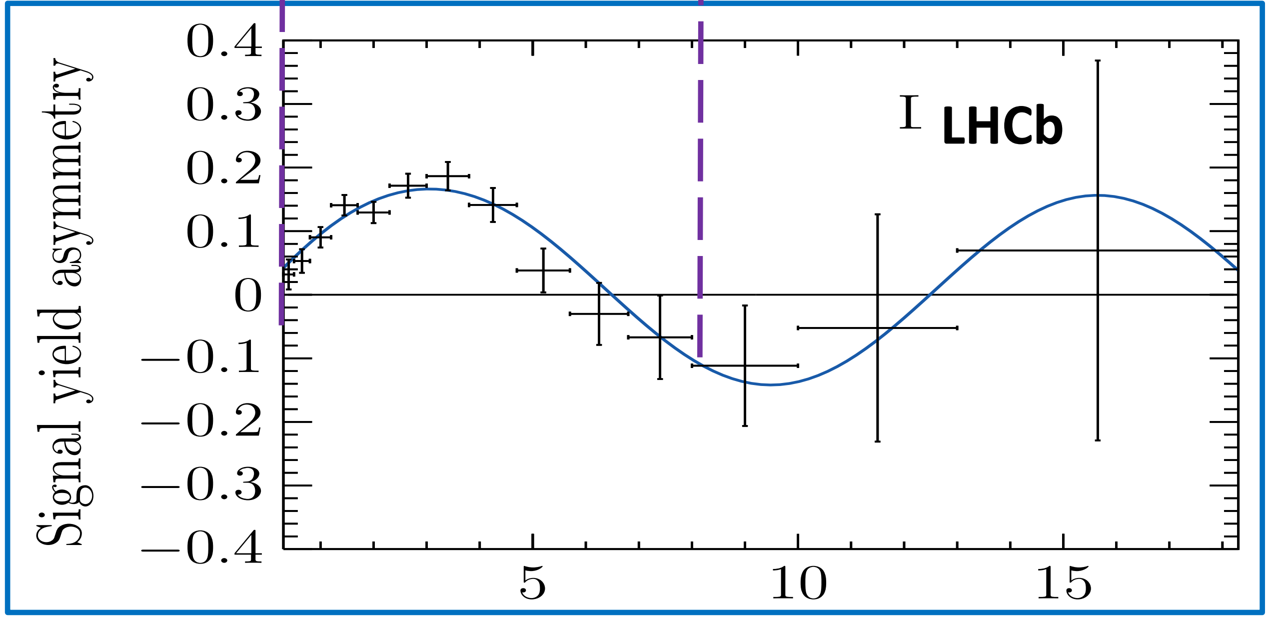
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)}$$



Decay-time dependent CP violation

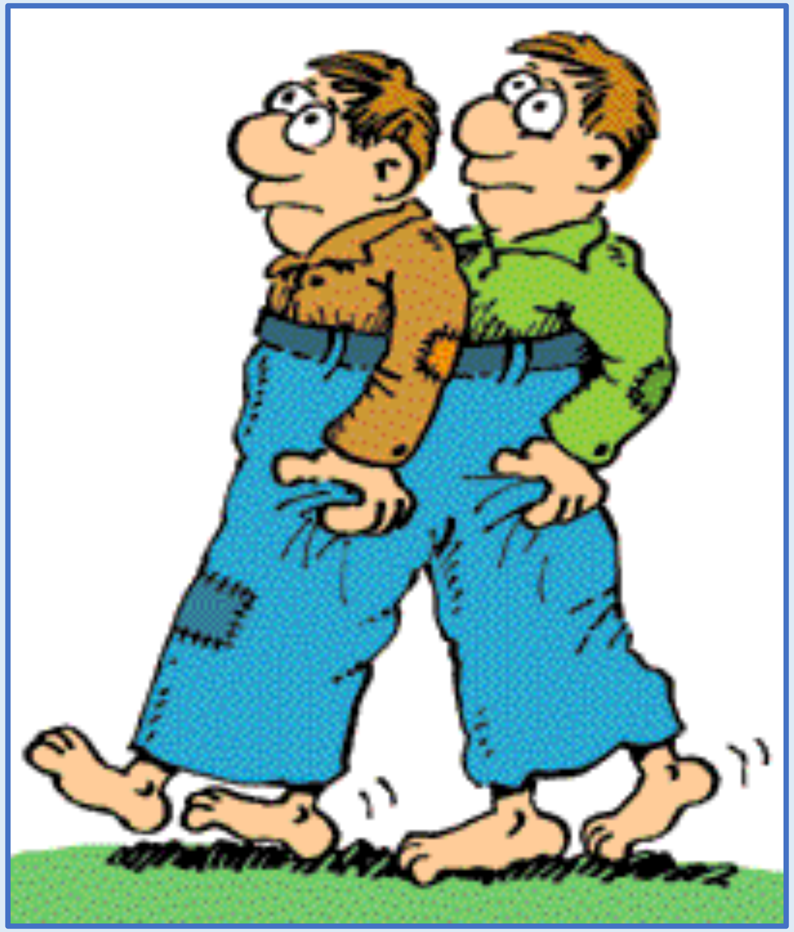
Interfere *direct* and *mixed*



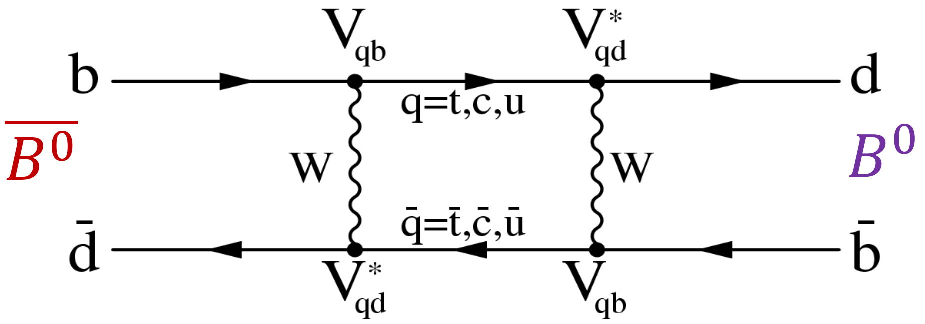


$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

Contents:



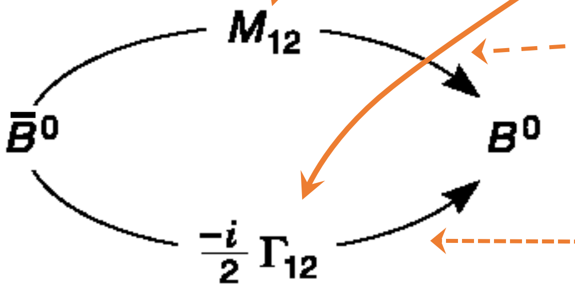
- Quantum mechanics with $\overline{B^0}$ and B^0 states: *“What is a particle?”*
  - Particle – antiparticle transitions $\overline{B^0} \leftrightarrow B^0$ mesons happen spontaneously.



- Time evolution of B^0 and $\overline{B^0}$ described by an effective Hamiltonian

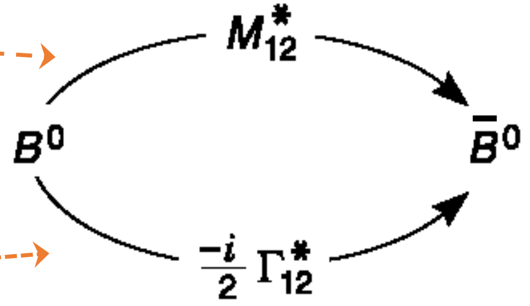
$$i\frac{\partial}{\partial t}\psi = H\psi \qquad \rightarrow \qquad \psi(t) = a(t)|B^0\rangle + b(t)|\overline{B^0}\rangle \quad \equiv \quad \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

$$H = \underbrace{\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix}}_{\textit{Hermitean Mass-matrix}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}}_{\textit{Hermitean Decay-matrix}}$$



M_{12} describes $B^0 \leftrightarrow \overline{B^0}$ via *off-shell* states, e.g. the weak box diagram (“dispersive”)

Γ_{12} describes $B^0 \leftrightarrow f \leftrightarrow \overline{B^0}$ via *on-shell* states, e.g. $f = \pi^+\pi^-$ (“absorptive”)



Solving the Schrödinger Equation

$$i\frac{\partial}{\partial t}\psi(t) = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}\psi(t)$$

Eigenvectors:

$$|B_H(t)\rangle = |B_H\rangle e^{-i\omega_+ t}$$

$$|B_L(t)\rangle = |B_L\rangle e^{-i\omega_- t}$$

B_H , B_L : Mass eigenstates

$$|B_H\rangle = p|B^0\rangle + q|\overline{B^0}\rangle$$

$$|B_L\rangle = p|B^0\rangle - q|\overline{B^0}\rangle$$

B^0 , $\overline{B^0}$: Flavour eigenstates

From the eigenvalue calculation:

$$q/p = -\sqrt{\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)\Big/\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)}$$

Solution: (α and β are initial conditions):

$$\Rightarrow \quad \psi(t) = \alpha|B_H(t)\rangle + \beta|B_L(t)\rangle$$

$$\omega_\pm = m_\pm - \frac{i}{2}\Gamma_\pm \quad \begin{cases} m_\pm = M \pm \frac{1}{2}\Delta m & \text{Masses} \\ \Gamma_\pm = \Gamma \pm \frac{1}{2}\Delta\Gamma & \text{Lifetimes} \end{cases}$$

Δm and $\Delta\Gamma$ follow from the $\overbrace{\text{the}}^{\text{weak}}$ Hamiltonian:

$$\Delta m = 2\,\Re\sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)}$$

$$\Delta\Gamma = 4\,\Im\sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)}$$

Examples

B^0 : $\Delta\Gamma \approx 0$, $|q/p| = 1$

B_s^0 : $\Delta\Gamma/\Delta m \ll 0$, $|q/p| = 1$

K^0 : $\Delta\Gamma/\Delta m \simeq 1$, $|q/p| - 1 \simeq 10^{-3}$

B^0 Oscillation Amplitudes

For an initially produced B^0 or a $\overline{B^0}$ it then follows:

using:

$$|B^0\rangle = \frac{1}{2p}(|B_H\rangle + |B_L\rangle)$$

$$|\overline{B^0}\rangle = \frac{1}{2q}(|B_H\rangle - |B_L\rangle)$$

$|\psi(t)\rangle$:

$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \frac{q}{p}g_-(t)|\overline{B^0}\rangle$$

$$|\overline{B^0}(t)\rangle = g_+(t)|\overline{B^0}\rangle + \frac{p}{q}g_-(t)|B^0\rangle$$

with $$g_{\pm(t)} = \frac{e^{-i\omega_+ t} \pm e^{-i\omega_- t}}{2}$$

For B^0, expect:
$\Delta\Gamma \sim 0$,
$|q/p| = 1$

$$g_{\pm(t)} = e^{-imt}e^{-\Gamma t/2}\left[\frac{e^{-\frac{1}{2}i\,\Delta mt} \pm e^{+\frac{1}{2}i\,\Delta mt}}{2}\right]$$

$$g_+(t) = e^{-imt}e^{-\Gamma t/2}\cos\frac{\Delta mt}{2}$$

$$g_-(t) = e^{-imt}e^{-\Gamma t/2}\, i\,\sin\frac{\Delta mt}{2}$$

B^0 Oscillations

$B^0 \xrightarrow{g_+(t)} B^0 \rightarrow l^- \bar{\nu}_l X^+$

$B^0 \xrightarrow{\frac{q}{p} g_-(t)} \overline{B^0} \rightarrow l^+ \nu_l X^-$

$\overline{B^0} \xrightarrow{\frac{p}{q} g_-(t)} B^0 \rightarrow l^- \bar{\nu}_l X^+$

$\overline{B^0} \xrightarrow{g_+(t)} \overline{B^0} \rightarrow l^+ \nu_l X^-$

Calculate:

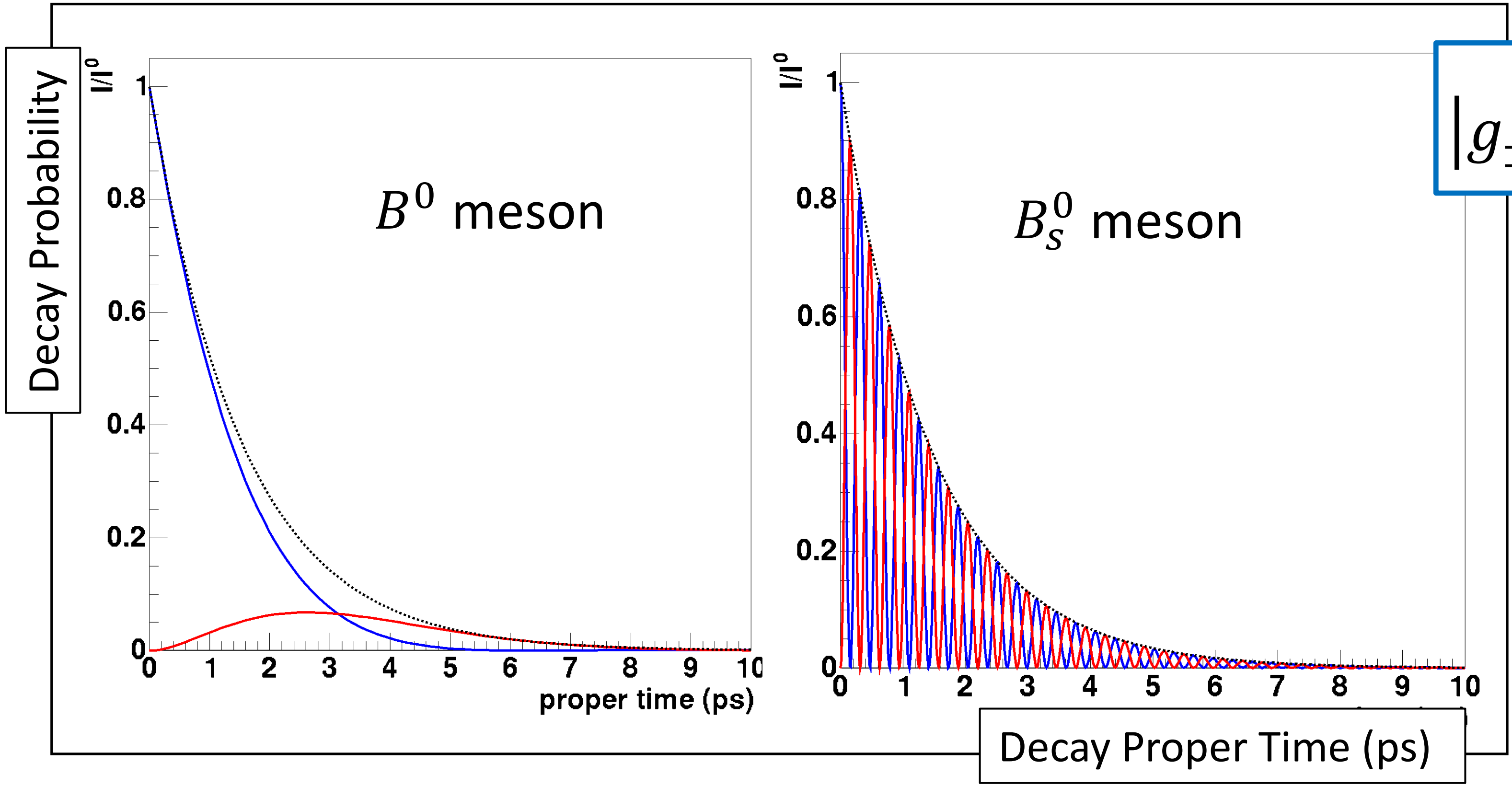
$|\langle B(t)|B^0\rangle|^2$

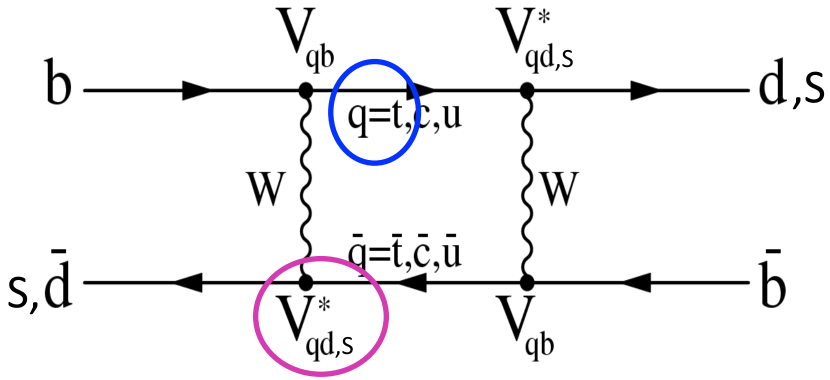
$|\langle \bar{B}(t)|B^0\rangle|^2$

For B^0, expect:
$\Delta\Gamma \sim 0\,,\quad |q/p| = 1$

$$|g_\pm(t)|^2 = \frac{e^{-\Gamma t}}{2}\,[1 \pm \cos(\Delta m \cdot t)]$$

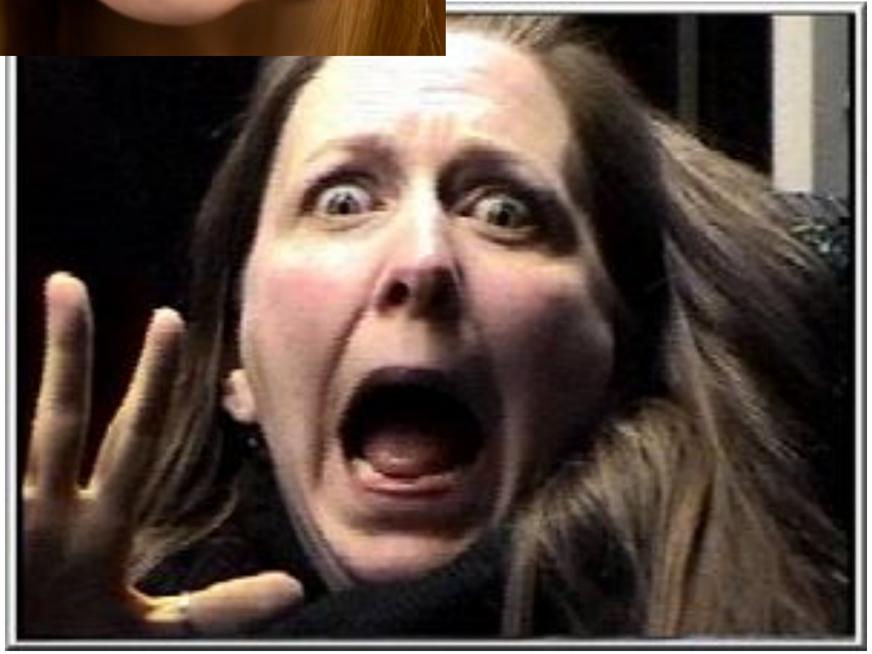
Flavour Oscillations!

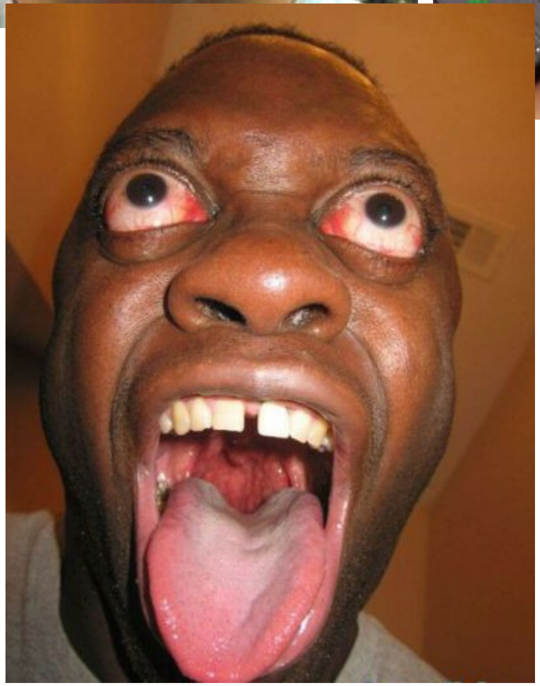




So far, so good…?

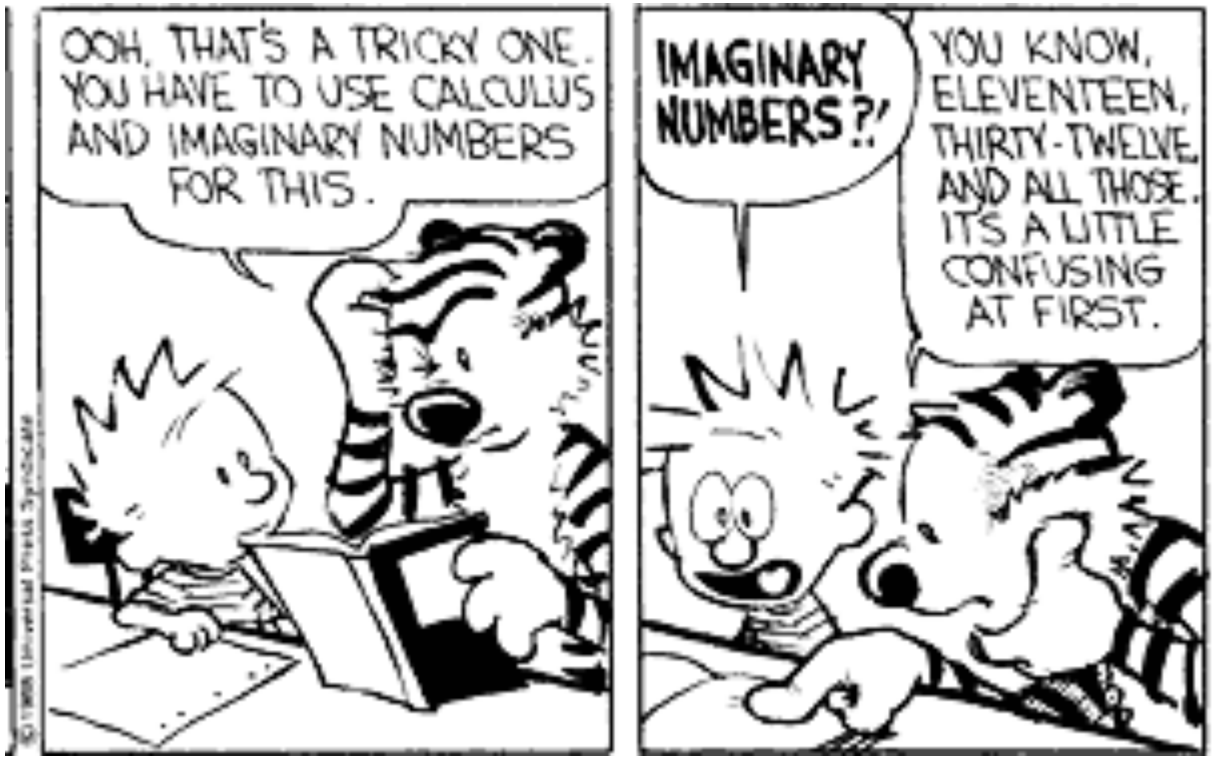
Hope not...





Observing CP Violation

- It's all about imaginary numbers…



B Decays to common final states: CP eigenstates

$$\begin{tikzcd}
 & B^0 \arrow[d] \\
B^0 \arrow[ur, bend left, "g_+(t)"] \arrow[dr, bend right, "\frac{q}{p} g_-(t)"'] & J/\psi\ K_s \\
 & \overline{B^0} \arrow[u]
\end{tikzcd}$$

$B^0 \to J/\psi\, K_s$

+

$B^0 \to \overline{B^0} \to J/\psi\, K_s$

$\longleftarrow$ CP $\longrightarrow$

$\overline{B^0} \to J/\psi\, K_s$

+

$\overline{B^0} \to B^0 \to J/\psi\, K_s$

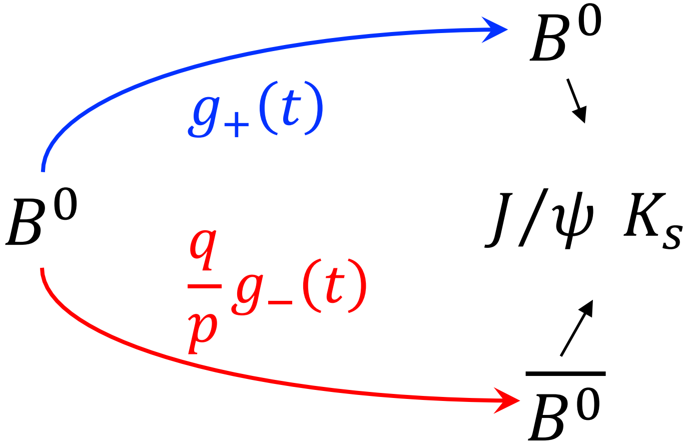
$$\begin{tikzcd}
 & B^0 \arrow[d] \\
\overline{B^0} \arrow[ur, bend left, "\frac{p}{q} g_-(t)"] \arrow[dr, bend right, "g_+(t)"'] & J/\psi\ K_s \\
 & \overline{B^0} \arrow[u]
\end{tikzcd}$$

Instead of:

$$\begin{tikzcd}
 & B^0 \arrow[d] \\
B^0 \arrow[ur, bend left, "g_+(t)"] \arrow[dr, bend right, "\frac{q}{p} g_-(t)"'] & l^- \bar{\nu}_l\, X^+ \\
 & l^+ \nu_l\, X^- \\
 & \overline{B^0} \arrow[u]
\end{tikzcd}$$

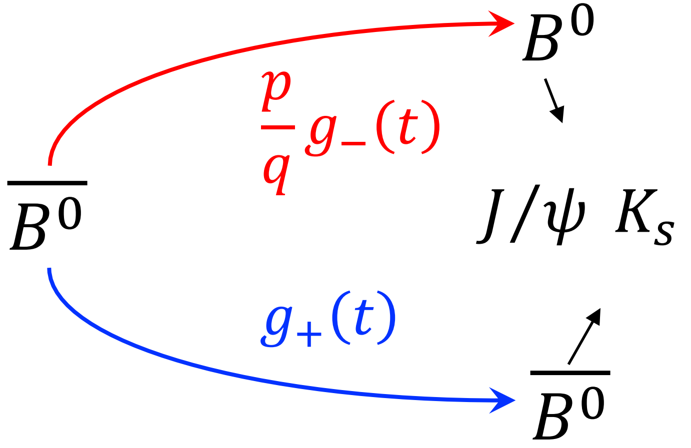
$$\begin{tikzcd}
 & B^0 \arrow[d] \\
\overline{B^0} \arrow[ur, bend left, "\frac{p}{q} g_-(t)"] \arrow[dr, bend right, "g_+(t)"'] & l^- \bar{\nu}_l\, X^+ \\
 & l^+ \nu_l\, X^- \\
 & \overline{B^0} \arrow[u]
\end{tikzcd}$$

B Decays to common final states: CP eigenstates



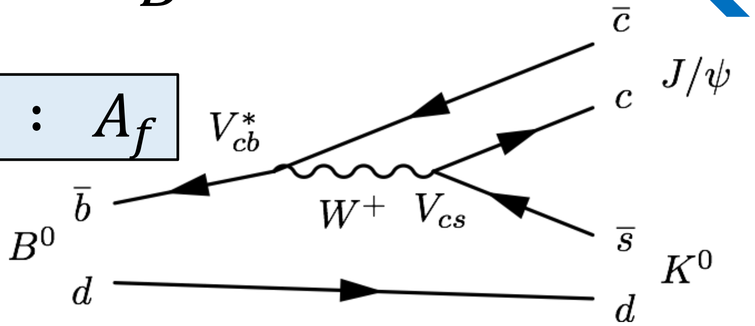
$B^0 \to J/\psi\, K_s$
+
$B^0 \to \overline{B^0} \to J/\psi\, K_s$

$\overline{B^0} \to J/\psi\, K_s$
+
$\overline{B^0} \to B^0 \to J/\psi\, K_s$



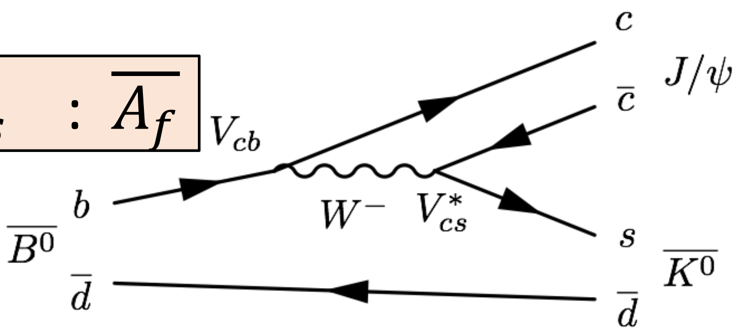
CP

$B^0 \to J/\psi\, K_s \ :\ A_f$



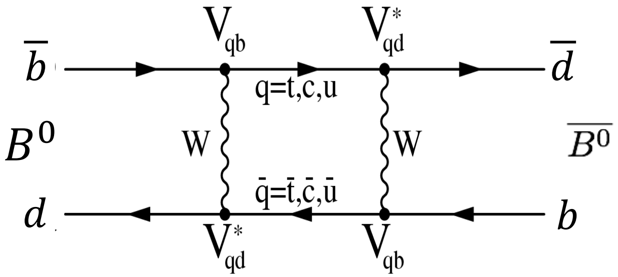
+

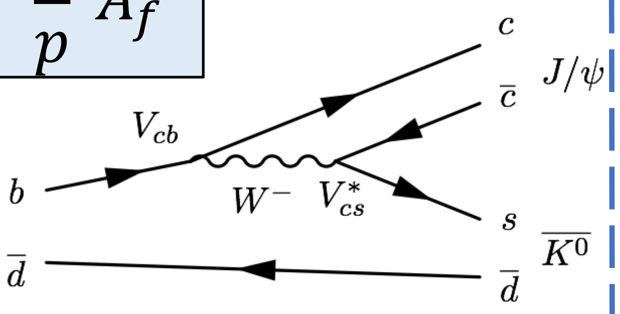
$\overline{B^0} \to J/\psi\, K_s \ :\ \overline{A_f}$



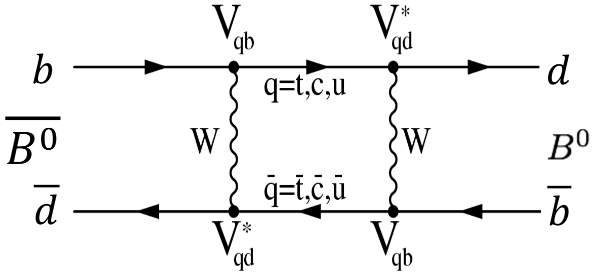
+

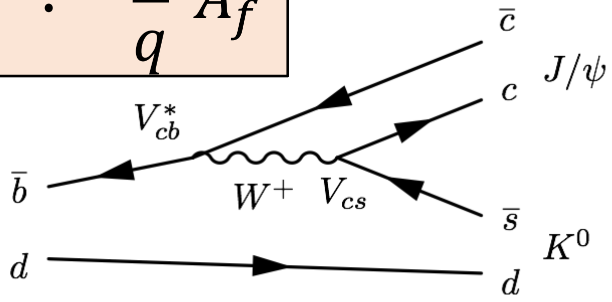
$B^0 \to \overline{B^0} \to J/\psi\, K_s \ :\ \frac{q}{p}\,\overline{A_f}$





$\overline{B^0} \to B^0 \to J/\psi\, K_s \ :\ \frac{p}{q}\,A_f$



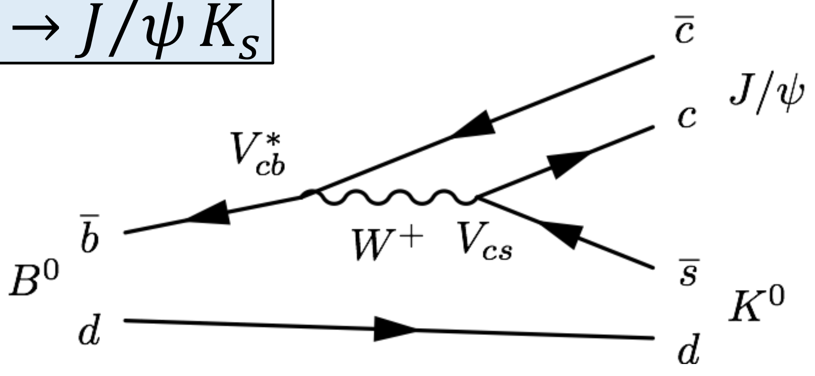


B Decays to common final states: CP eigenstates

$B^0 \rightarrow J/\psi\, K_s$

$$A_f \equiv \langle f | B^0 \rangle$$

$$\lambda \equiv \frac{q}{p}\frac{\overline{A_f}}{A_f}$$

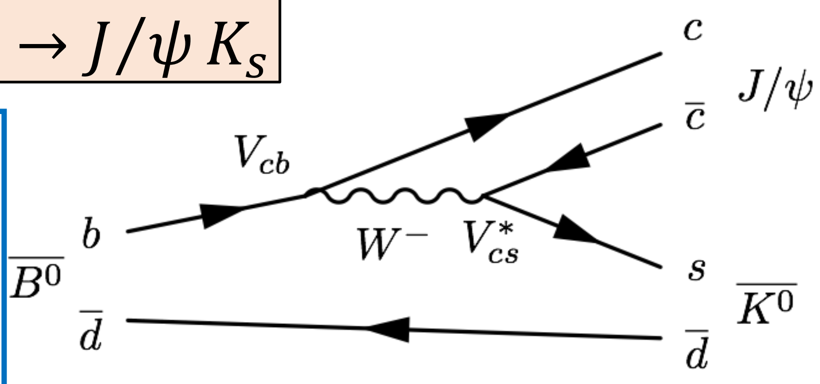


$\bar{\lambda} = 1/\lambda$

$\overline{B^0} \rightarrow J/\psi\, K_s$

$$\overline{A_f} \equiv \langle f | \overline{B^0} \rangle$$

$$\bar{\lambda} \equiv \frac{p}{q}\frac{A_f}{\overline{A_f}}$$



- Calculate the decay rate of a B-meson into a final state f: $\Gamma_{(B(t)\rightarrow f)} = |\langle f | B^0(t) \rangle|^2$
- From solving Schrodinger's equation we already had:

$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \frac{q}{p}g_-(t)\left|\overline{B^0}\right\rangle$$

$$\left|\overline{B^0}(t)\right\rangle = g_+(t)\left|\overline{B^0}\right\rangle + \frac{p}{q}g_-(t)|B^0\rangle$$

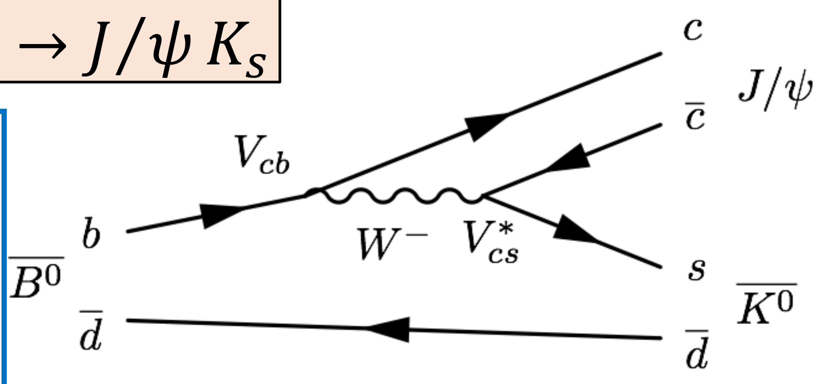
$$g_\pm(t) = \frac{e^{-i\omega_+ t} \pm e^{-i\omega_- t}}{2}$$

with: $\omega_\pm = m_\pm - \frac{i}{2}\Gamma_\pm$, $m_\pm = M \pm \frac{1}{2}\Delta m$, $\Gamma_\pm = \Gamma \pm \frac{1}{2}\Delta\Gamma$

$A_f \equiv \langle f|$

$\lambda \equiv \frac{q}{p} \frac{\overline{A}}{A}$

$\overline{0} \to J/\psi\, K_s$

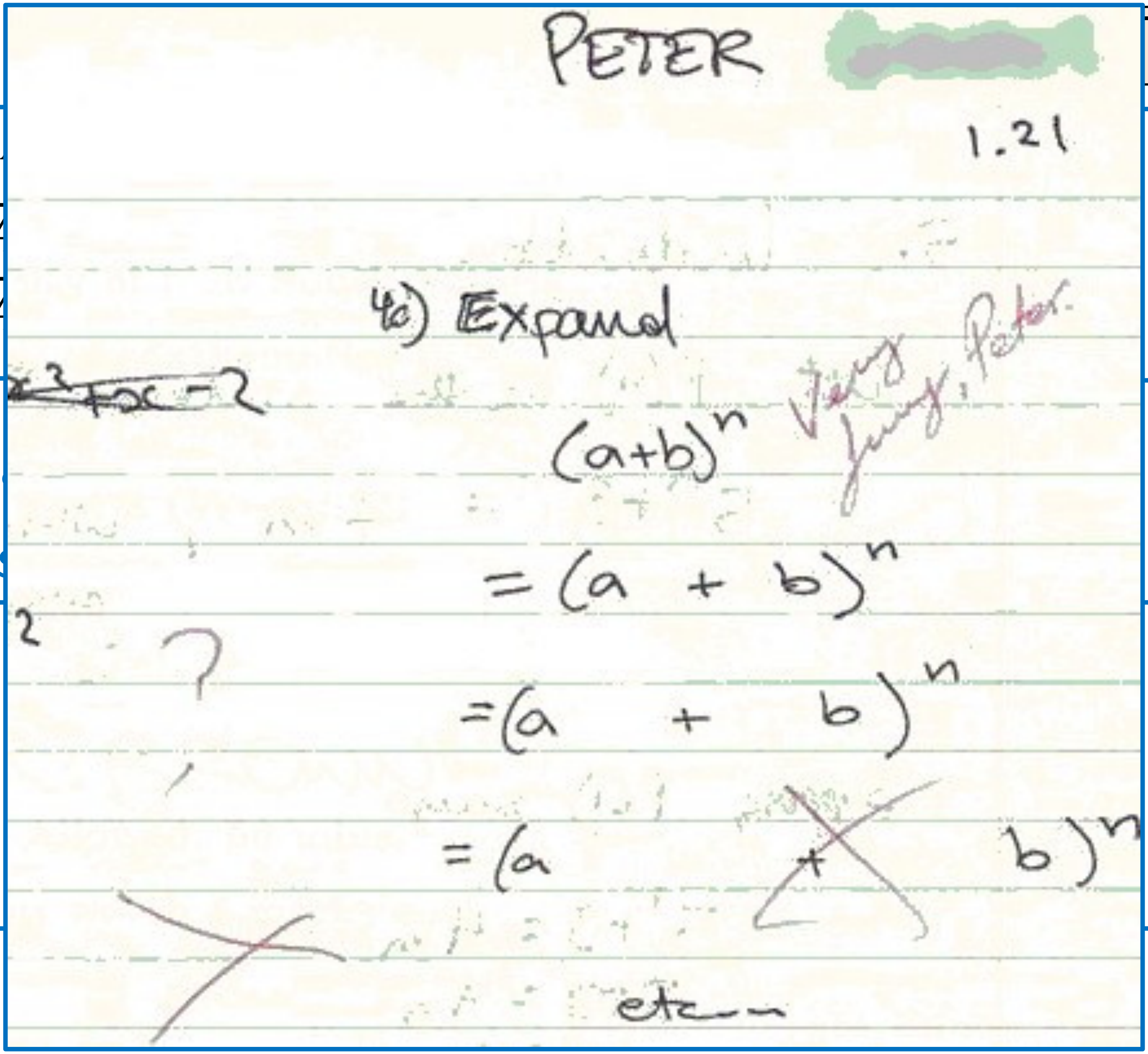


- Calcul … f: $\Gamma_{(B(t)\to f)} = |\langle f|B^0(t)\rangle|^2$
- From s

just expand by taking the square…

$$= \frac{e^{-i\omega_+ t} \pm e^{-i\omega_- t}}{2}$$

$\Delta m\ ,\ \ \Gamma_\pm = \Gamma \pm \frac{1}{2}\Delta\Gamma$



Master formula for neutral B decays

- Just by (tediously) writing it out…

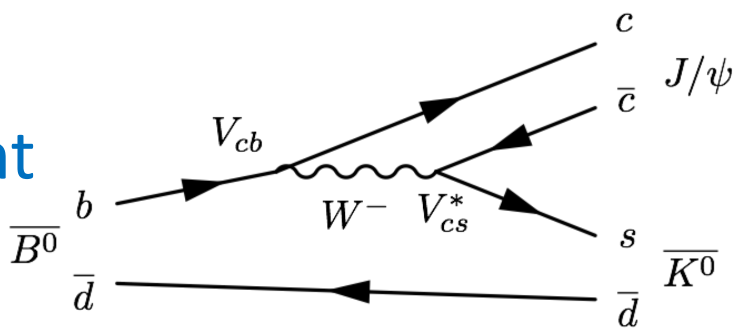
$$\Gamma_{(B\to f)}(t) = |A_f|^2 \left(1+|\lambda_f|^2\right)\frac{e^{-\Gamma t}}{2} \cdot \left(\cosh\frac{\Delta\Gamma t}{2} + D_f \sinh\frac{\Delta\Gamma t}{2} + C_f \cos\Delta m t - S_f \sin\Delta m\, t\right)$$

$$\Gamma_{(\overline{B}\to f)}(t) = |A_f|^2 \left|\frac{q}{p}\right|^2 \left(1+|\lambda_f|^2\right)\frac{e^{-\Gamma t}}{2} \cdot \left(\cosh\frac{\Delta\Gamma t}{2} + D_f \sinh\frac{\Delta\Gamma t}{2} - C_f \cos\Delta m t + S_f \sin\Delta m\, t\right)$$

with: $D_f = \frac{2\Re\lambda_f}{1+|\lambda_f|^2}$, $C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$, $S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2}$

- Coefficients D_f, C_f and S_f are measured by experiment

➔ Measurement of CKM parameters via: $\lambda_f \equiv \frac{p}{q}\frac{\overline{A}_f}{A_f}$



How does it give CP violation?

$t = 0$	t	Amplitude

$$g_\pm(t) = \frac{e^{-i\omega_1} \pm e^{-i\omega_2 t}}{2}$$

$$\begin{tikzcd}
& \overline{B}^0 \arrow[d, "\overline{A}_{f_{CP}}"] \\
B^0 \arrow[ur, bend left, "\frac{q}{p} g_-(t)"] \arrow[dr, bend right, "g_+(t)"'] & f_{CP} \\
& B^0 \arrow[u, "A_{f_{CP}}"']
\end{tikzcd}$$

$$A_{f_{CP}}\left(g_+(t) + \lambda g_-(t)\right)$$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}$$

$$g_+(t) = \frac{e^{-i(m-\Delta m/2)t}\, e^{-\Gamma t/2} + e^{-i(m+\Delta m/2)t}\, e^{-\Gamma t/2}}{2}$$

$$= e^{-imt}\, e^{-\Gamma t/2} \cos\frac{\Delta m t}{2}$$

CP

$$g_-(t) = \frac{e^{-i(m-\Delta m/2)t}\, e^{-\Gamma t/2} - e^{-i(m+\Delta m/2)t}\, e^{-\Gamma t/2}}{2}$$

$$= e^{-imt}\, e^{-\Gamma t/2}\, \boldsymbol{i} \sin\frac{\Delta m t}{2}$$

$$\begin{tikzcd}
& B^0 \arrow[d, "A_{f_{CP}}"] \\
\overline{B}^0 \arrow[ur, bend left, "\frac{p}{q} g_-(t)"] \arrow[dr, bend right, "g_+(t)"'] & f_{CP} \\
& \overline{B}^0 \arrow[u, "\overline{A}_{f_{CP}}"']
\end{tikzcd}$$

$$\overline{A}_{f_{CP}}\left(g_+(t) + \frac{1}{\lambda} g_-(t)\right)$$

$$\bar{\lambda}_{f_{CP}} = \frac{p}{q}\frac{A_{f_{CP}}}{\overline{A}_{f_{CP}}} = \frac{1}{\lambda_{f_{CP}}}$$

For neutral B mesons, g_- has a 90° (= i) phase difference wrt. g_+

Interfering Amplitudes

$t = 0$		t	Amplitude
B^0	$\rightarrow$	f_{CP}	$A_{f_{CP}}\left(g_+(t) + \lambda g_-(t)\right)$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\overline{A}_{f_{CP}}\left(g_+(t) + \frac{1}{\lambda} g_-(t)\right)$

$$g_+ = e^{-imt}\, e^{-\Gamma t/2} \cos\frac{\Delta m t}{2}$$

$$g_- = e^{-imt}\, e^{-\Gamma t/2}\, \boldsymbol{i} \sin\frac{\Delta m t}{2}$$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}} \qquad \text{(CKM)}$$

Interfering Amplitudes

$t = 0$		t	Amplitude
B^0	$\rightarrow$	f_{CP}	$A_{f_{CP}}(a_1 + a_2\, e^{-i\phi_w}\, e^{i\pi/2})$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\bar{A}_{f_{CP}}(a_1 + a_2\, e^{+i\phi_w}\, e^{i\pi/2})$

$$g_+ = e^{-imt}\, e^{-\Gamma t/2} \cos\frac{\Delta m t}{2}$$

$$g_- = e^{-imt}\, e^{-\Gamma t/2}\, \boldsymbol{i} \sin\frac{\Delta m t}{2}$$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}} \qquad \text{(CKM)}$$

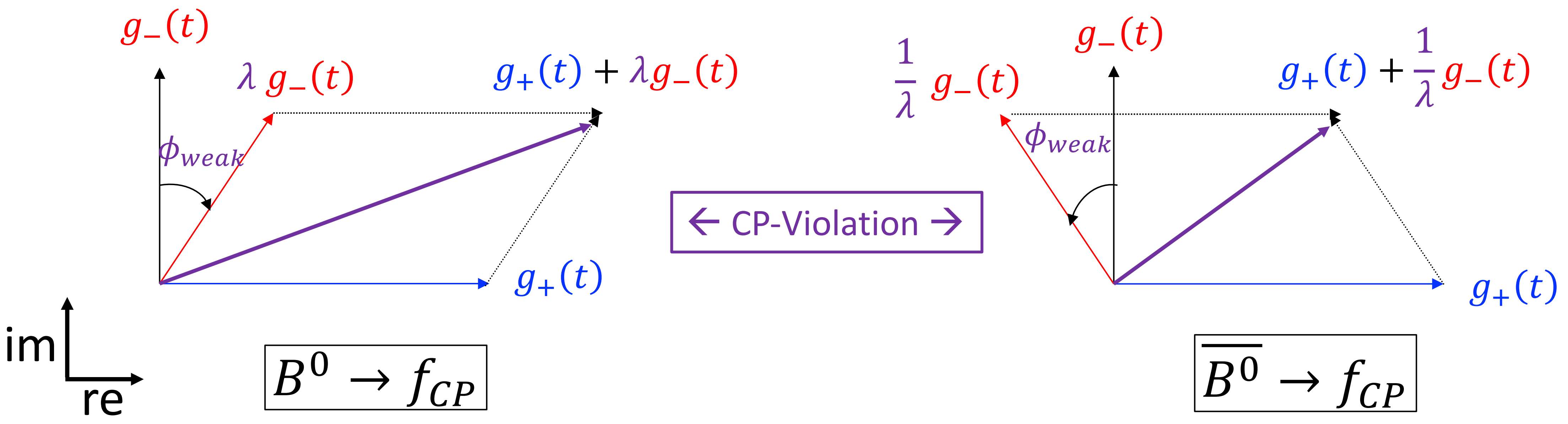
Interfering Amplitudes: CP violation!

$t=0$		t	Amplitude
B^0	$\rightarrow$	f_{CP}	$A_{f_{CP}}\left(g_+(t)+\lambda g_-(t)\right)$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\overline{A}_{f_{CP}}\left(g_+(t)+\frac{1}{\lambda}g_-(t)\right)$

$$g_+ = e^{-imt}\, e^{-\Gamma t/2}\, \cos\frac{\Delta mt}{2}$$

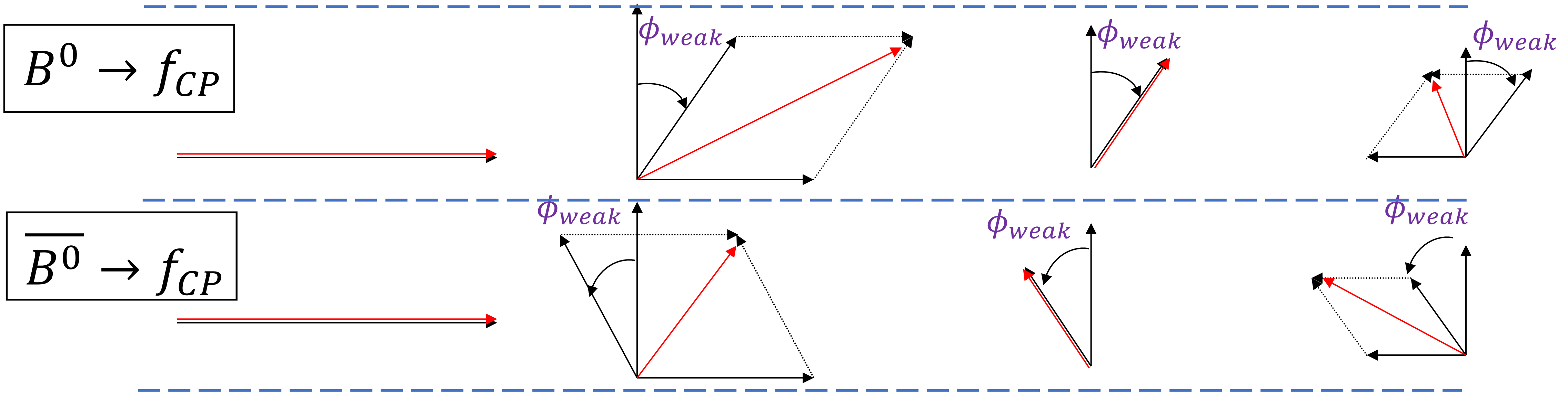
$$g_- = e^{-imt}\, e^{-\Gamma t/2}\, i\, \sin\frac{\Delta mt}{2}$$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}} \quad \text{(CKM)}$$



Interfering Amplitudes: time dependent CP violation!

$t = 0$		t	Amplitude
B^0	$\rightarrow$	f_{CP}	$A_{f_{CP}}\, e^{-imt} e^{-i\Gamma t/2}\left(\cos\frac{\Delta mt}{2} + i\,\lambda\,\sin\frac{\Delta mt}{2}\right)$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\bar{A}_{f_{CP}}\, e^{-imt} e^{-i\Gamma t/2}\left(\cos\frac{\Delta mt}{2} + i\,\frac{1}{\lambda}\,\sin\frac{\Delta mt}{2}\right)$



$\Delta mt/2 = 0$ | $\Delta mt/2 = \pi/4$ | $\Delta mt/2 = \pi/2$ | $\Delta mt/2 = 3\pi/4$

No CPV

CPV!

➔ Decay-Time Dependent CP Asymmetry!

From Amplitude to Decay rate

$t = 0$		t	Amplitude
B^0	$\rightarrow$	f_{CP}	$A_{f_{CP}}\, e^{-imt} e^{-i\Gamma t/2} \left(\cos\frac{\Delta mt}{2} + i\,\lambda\, \sin\frac{\Delta mt}{2} \right)$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\overline{A}_{f_{CP}}\, e^{-imt} e^{-i\Gamma t/2} \left(\cos\frac{\Delta mt}{2} + i\,\frac{1}{\lambda}\, \sin\frac{\Delta mt}{2} \right)$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

- Decay rate is the ***square*** of the amplitude (work it out):

$$B^0 \rightarrow f_{CP} \quad : \qquad \left| \cos\frac{\Delta mt}{2} + i\,\lambda \sin\frac{\Delta mt}{2} \right|^2 \propto 1 + \frac{\left(1-|\lambda|^2\right)}{\left(1+|\lambda|^2\right)} \cos \Delta mt - \frac{(2\Im\lambda)}{\left(1+|\lambda|^2\right)} \sin \Delta mt$$

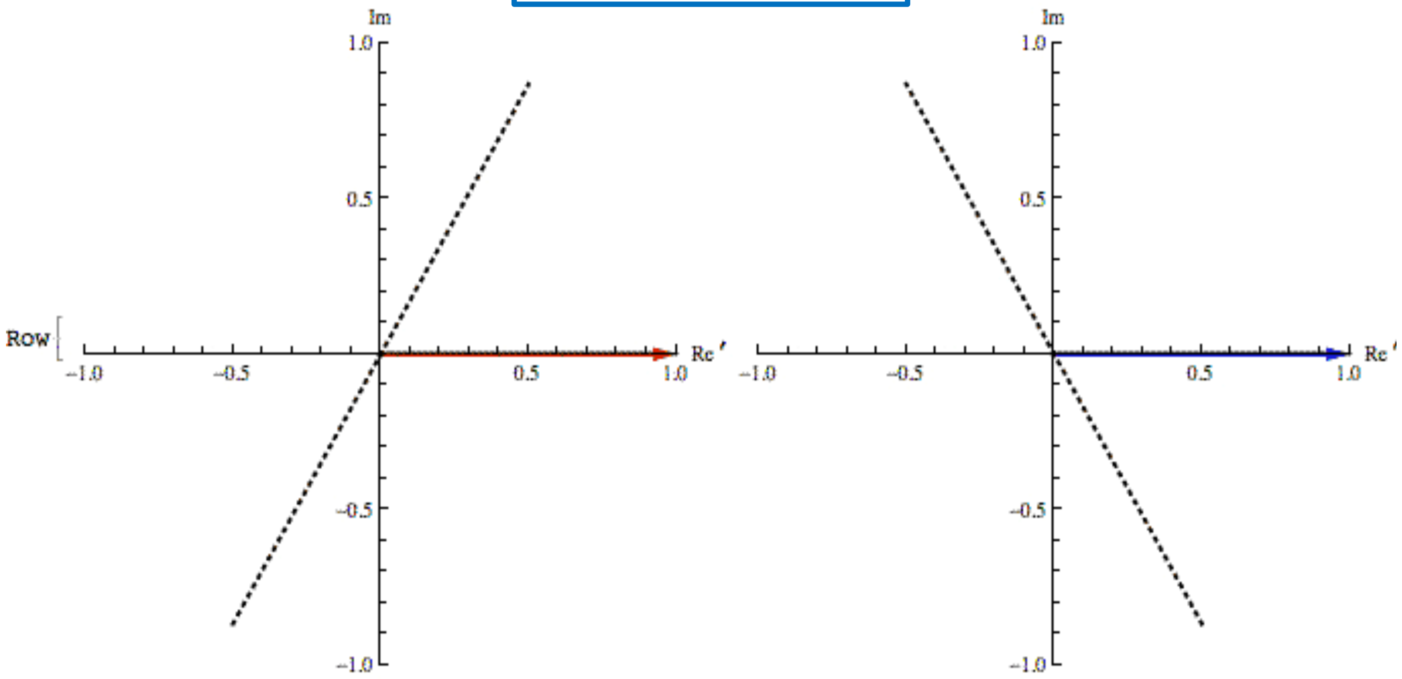
$$\overline{B^0} \rightarrow f_{CP} \quad : \qquad \left| \cos\frac{\Delta mt}{2} + i\,\frac{1}{\lambda} \sin\frac{\Delta mt}{2} \right|^2 \propto 1 - \frac{\left(1-|\lambda|^2\right)}{\left(1+|\lambda|^2\right)} \cos \Delta mt + \frac{(2\Im\lambda)}{\left(1+|\lambda|^2\right)} \sin \Delta mt$$

Time Dependent CP violation

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

$t = 0$		t	Amplitude
B^0	$\rightarrow$	f_{CP}	$A_{f_{CP}}\, e^{-imt} e^{-i\Gamma t/2}\left(\cos\frac{\Delta mt}{2} + i\, e^{-i\phi_{weak}}\, \sin\frac{\Delta mt}{2}\right)$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\bar{A}_{f_{CP}}\, e^{-imt} e^{-i\Gamma t/2}\left(\cos\frac{\Delta mt}{2} + i\, e^{+i\phi_{weak}}\, \sin\frac{\Delta mt}{2}\right)$

Decay Amplitudes

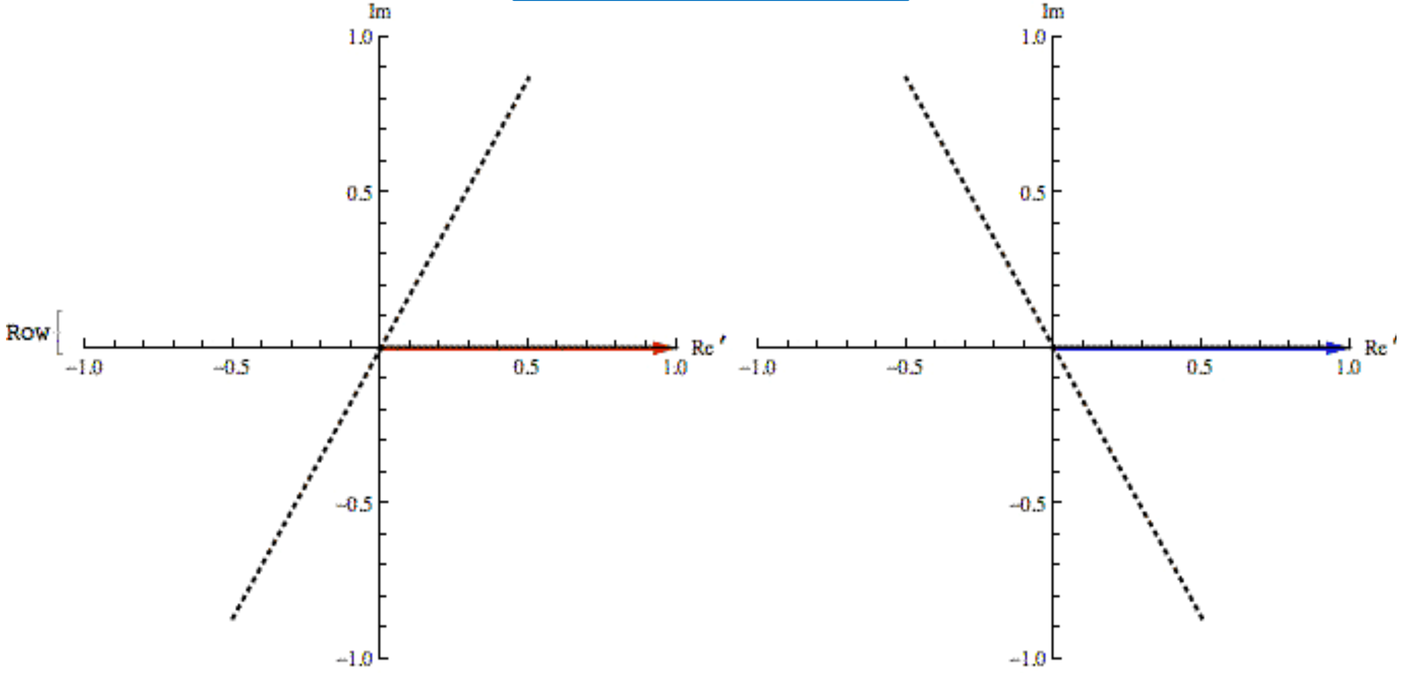


Time Dependent CP violation

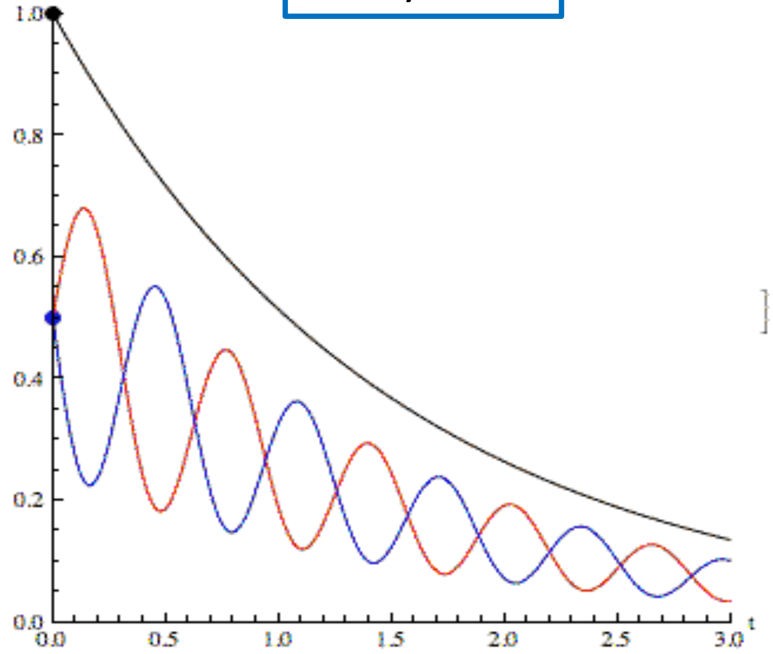
$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

$t=0$		t	Decay Rate
B^0	$\rightarrow$	f_{CP}	$\propto\; e^{-\Gamma t}\,[1 + \sin\phi_{weak}\sin\Delta m t]$
$\overline{B^0}$	$\rightarrow$	f_{CP}	$\propto\; e^{-\Gamma t}\,[1 - \sin\phi_{weak}\sin\Delta m t]$

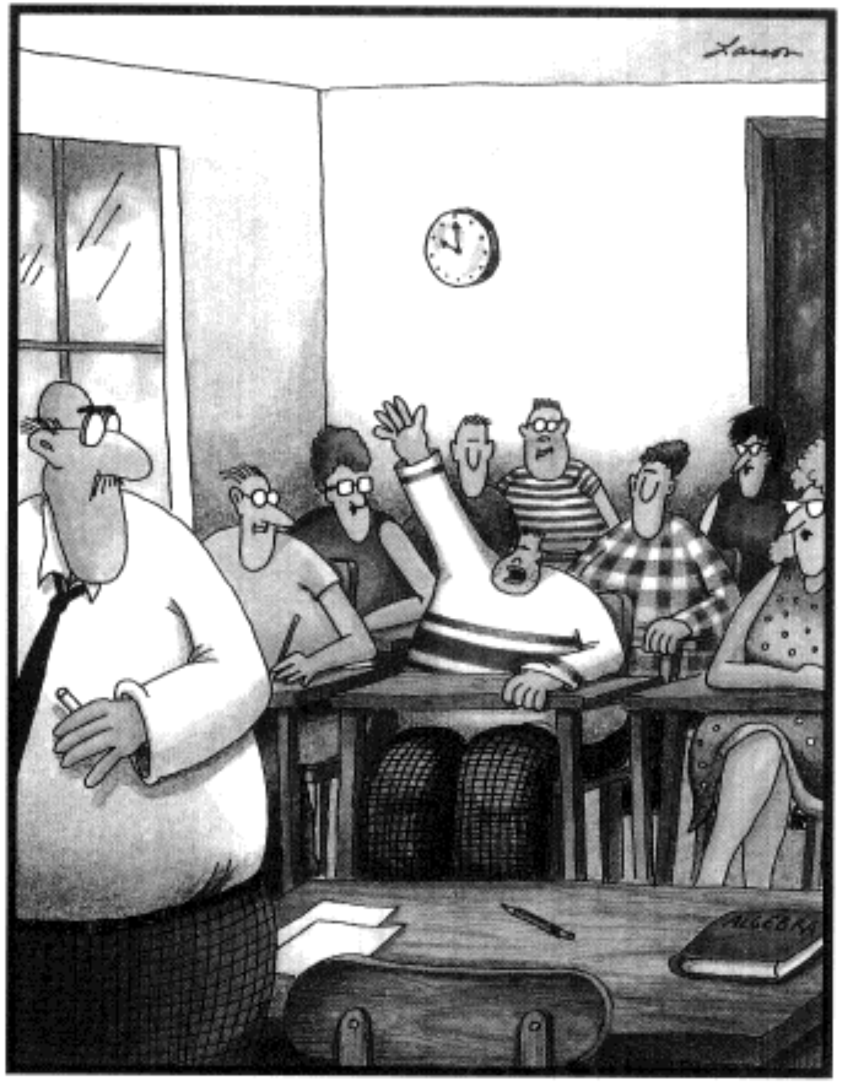
Decay Amplitudes



Decay Rates



Where were we?



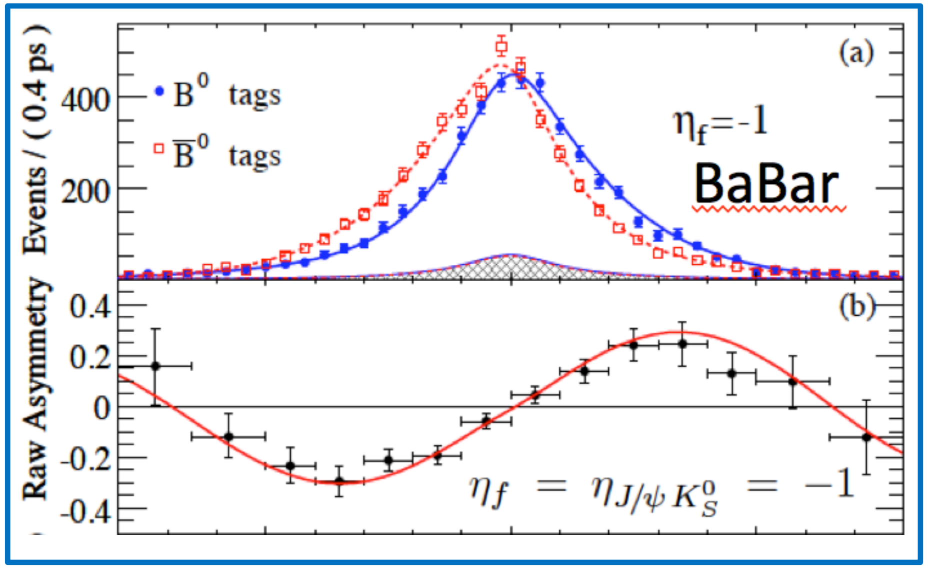
"Mr. Osborne, may I be excused?
My brain is full."

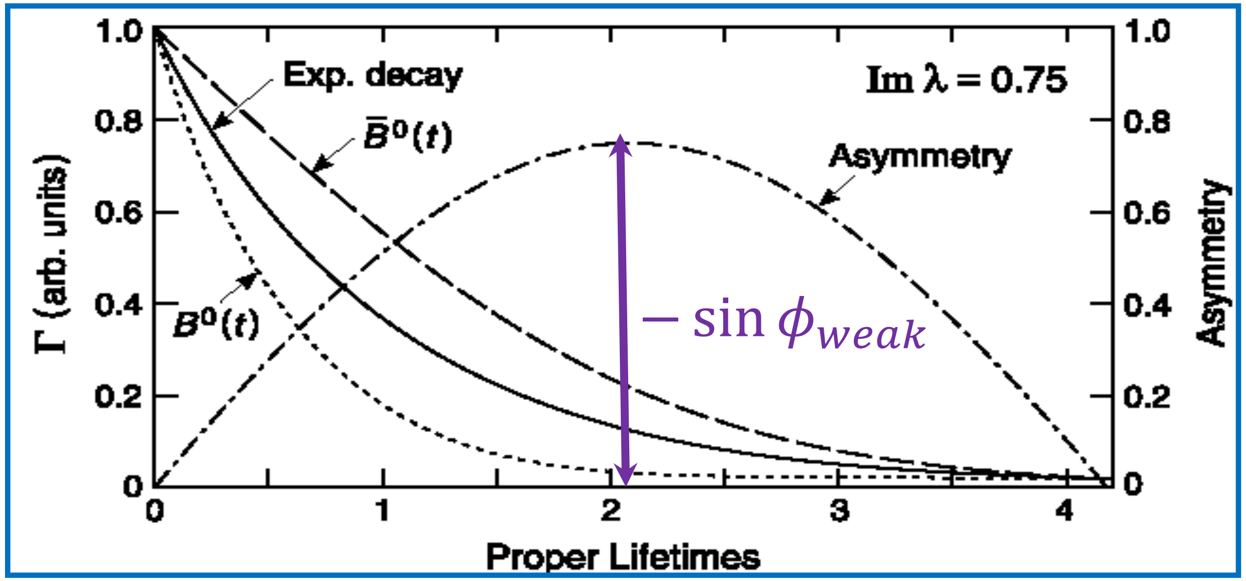
Time Dependent CP Asymmetry

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

$t = 0$	t	Decay Rate
B^0	$\rightarrow f_{CP}$	$\propto e^{-\Gamma t}\ [1 + \sin\phi_{weak}\sin\Delta m t]$
$\overline{B^0}$	$\rightarrow f_{CP}$	$\propto e^{-\Gamma t}\ [1 - \sin\phi_{weak}\sin\Delta m t]$

$$\mathcal{A}_{CP} = \frac{\Gamma\left(\overline{B^0} \to f_{CP}\right) - \Gamma(B^0 \to f_{CP})}{\Gamma\left(\overline{B^0} \to f_{CP}\right) + \Gamma(B^0 \to f_{CP})} = -\sin\phi_{weak}\ \sin\Delta m t$$



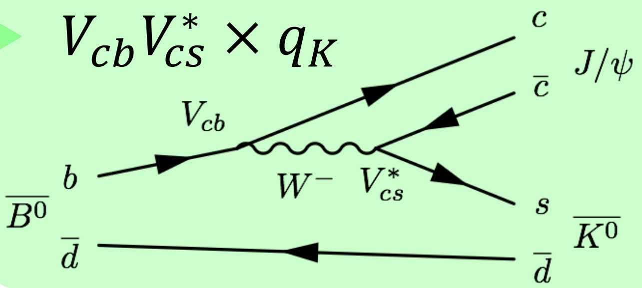


$\lambda_{J/\psi K_S}$ for "Golden" mode: $B^0 \rightarrow J/\psi K_S$

$$\lambda_{f_{CP}} = \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{weak}}$$

$$\lambda_{J/\psi K_S} \equiv -\frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

$V_{cb}V_{cs}^* \times q_K$

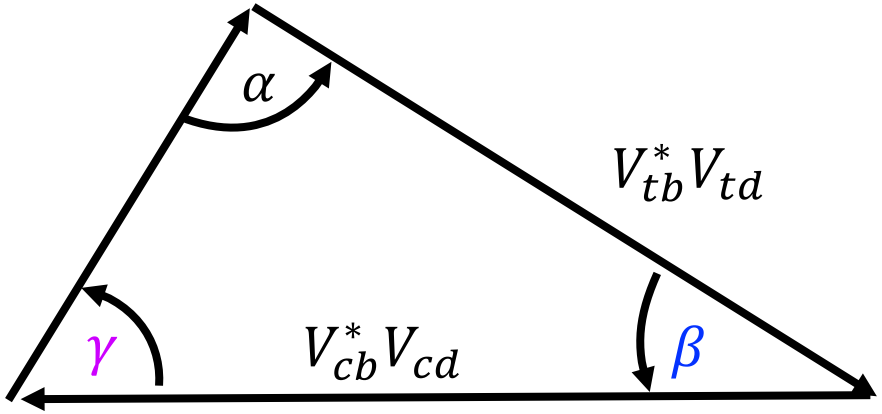


$\overline{K^0} \times \langle K_s | \overline{K^0} \rangle$

$$\phi_{weak} = 2\beta$$

$$\lambda_{J/\psi K_S} = -\frac{V_{tb}^* V_{td}}{V_{tb}V_{td}^*}\frac{V_{cb}V_{cd}^*}{V_{cb}^* V_{cd}} = -e^{-2i\beta}$$

$$\mathrm{V_{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$



- Similarly with this method of time dependent CP violation:

$B^0 \rightarrow J/\psi K_S \rightarrow 2\beta$; $B^0 \rightarrow \pi^+\pi^- \rightarrow 2\beta + 2\gamma$

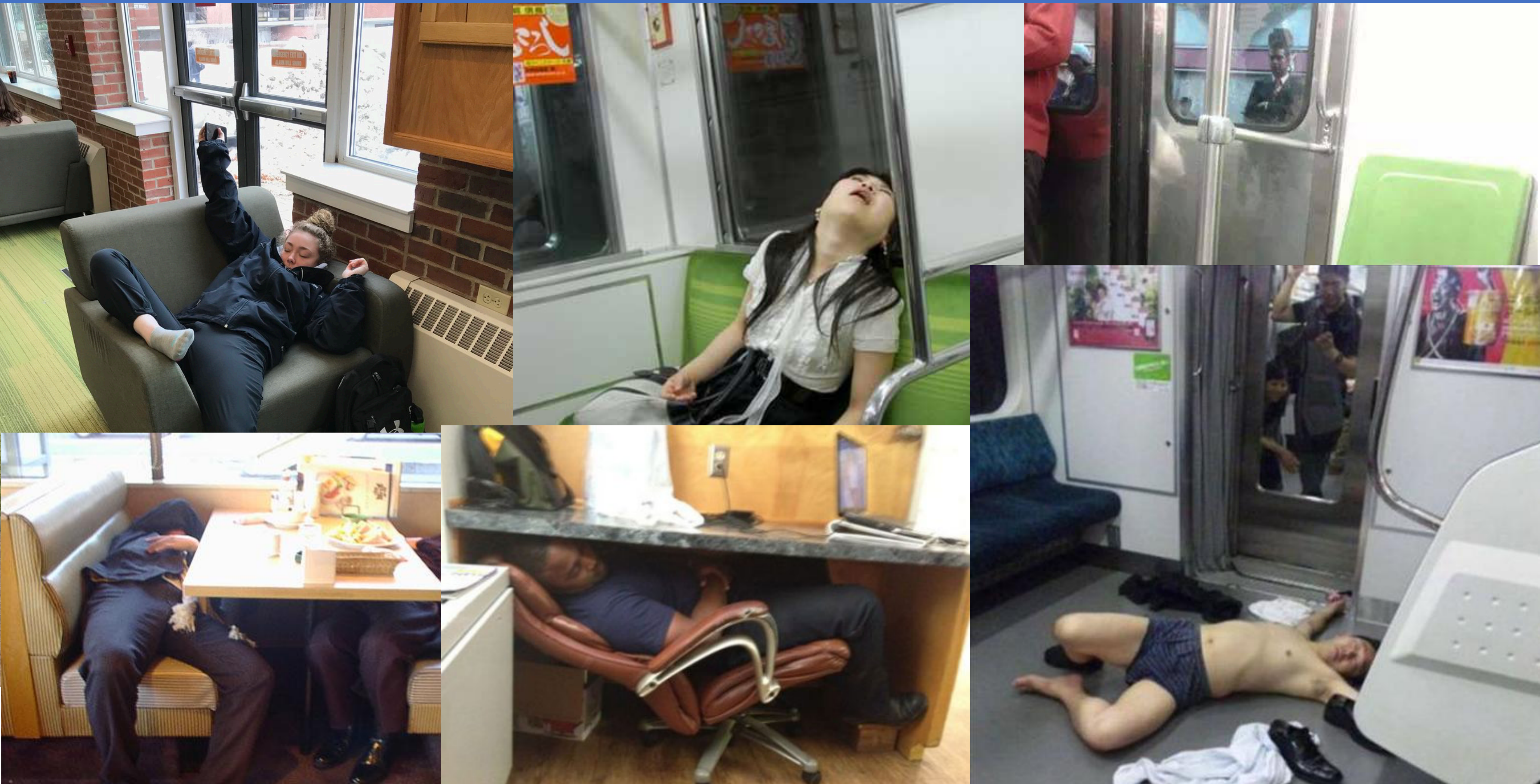
$B_s \rightarrow J/\psi\,\phi \rightarrow 2\beta_s$; $B_s^0 \rightarrow K^+K^- \rightarrow 2\beta_s + 2\gamma$; $B_s^0 \rightarrow D_s^{\mp}K^{\pm} \rightarrow 2\beta + \gamma$

➔ B_s physics is mainly done at the LHC …

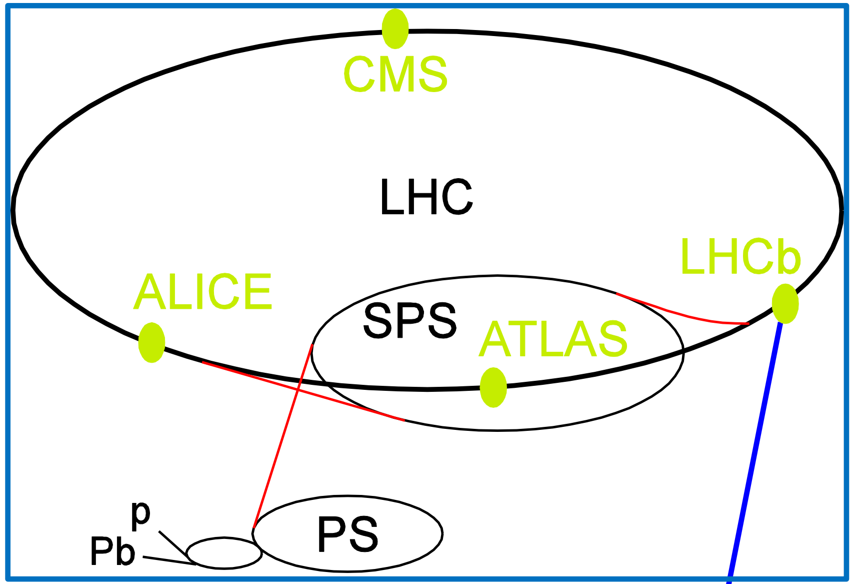
How are you doing?

How are you doing?

How are you doing?



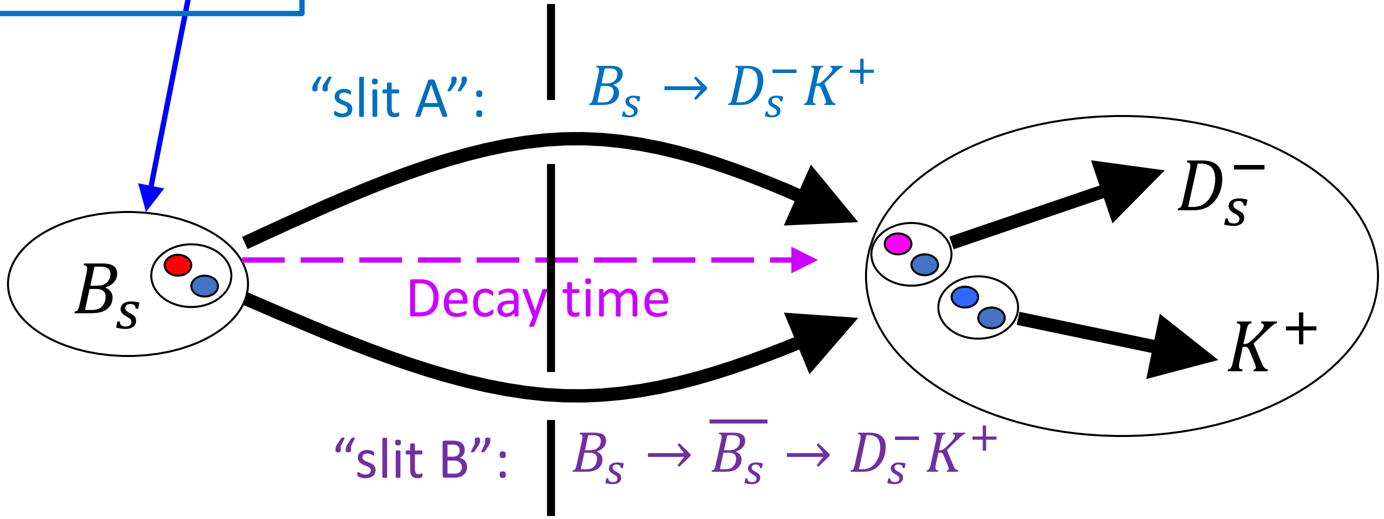
$B_s \to D_s K$: Quantum Interference Experiment @ LHCb



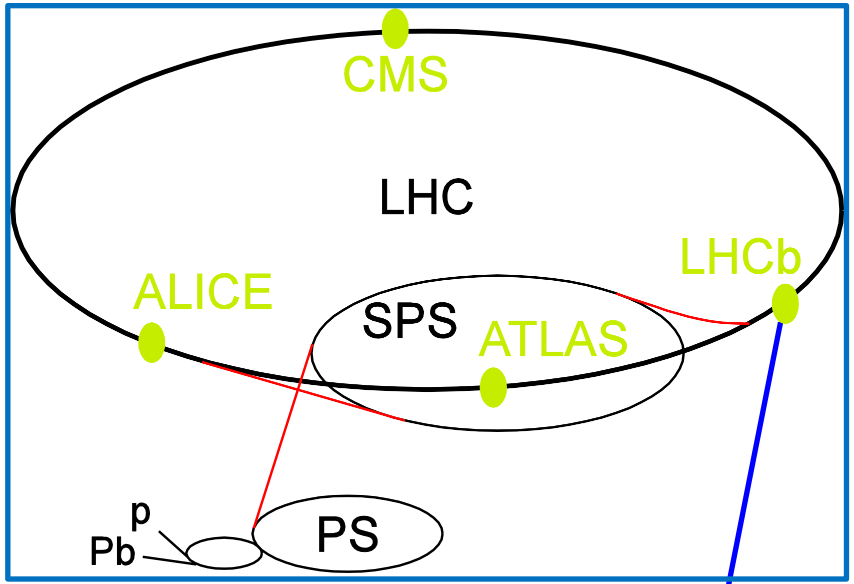
Measure:

$$B_s \to \left(\overline{B_s} \to\right) D_s^- K^+$$

$$\overline{B_s} \to (B_s \to) D_s^- K^+$$



$B_s \to D_s K$: Quantum Interference Experiment @ LHCb

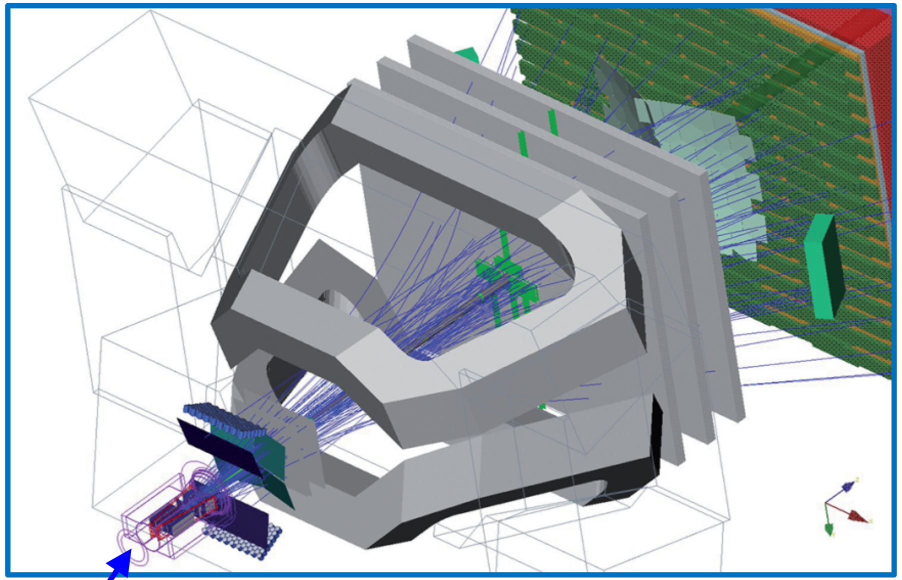


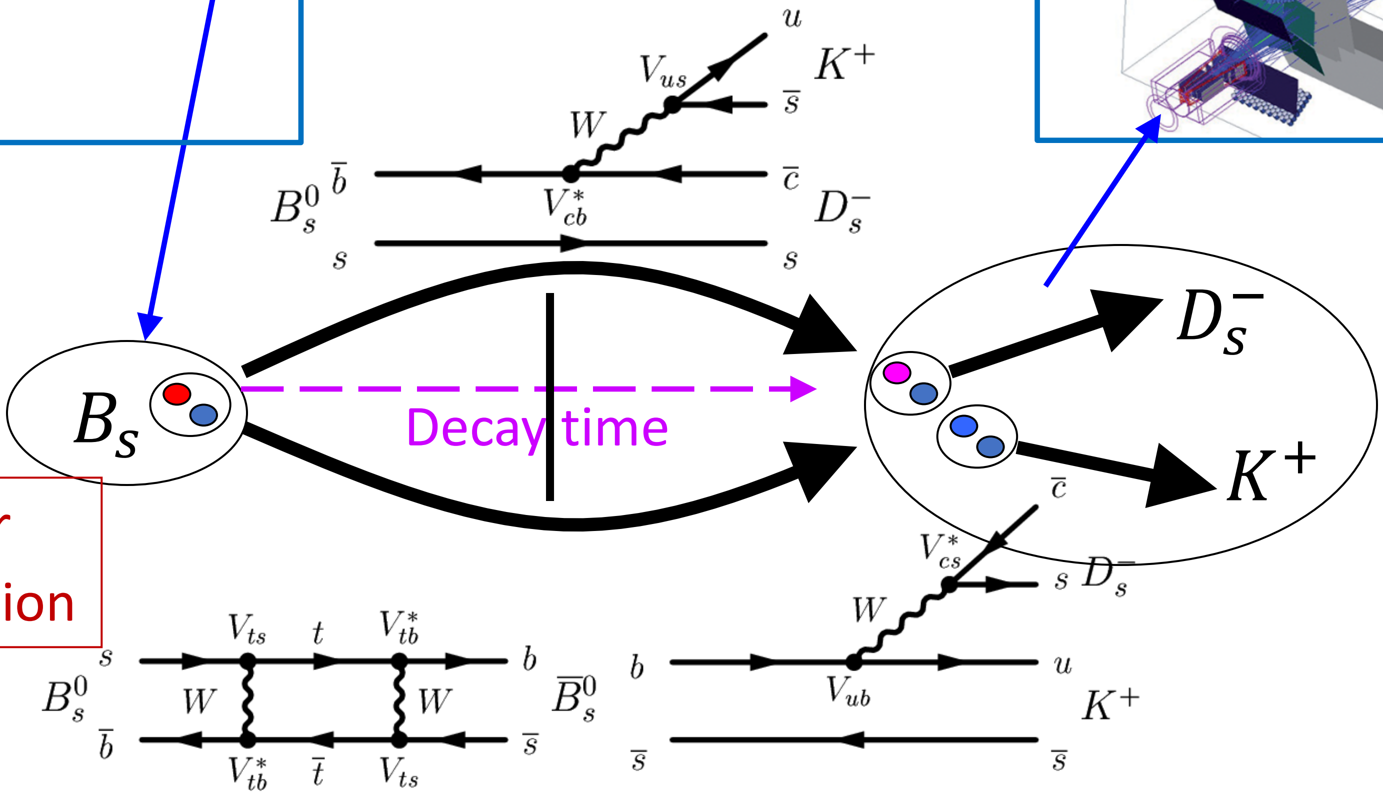
Measure:

$B_s \to (\overline{B_s} \to)\ D_s^- K^+$

$\overline{B_s} \to (B_s \to)\ D_s^- K^+$

Repeat for $D_s^+ K^-$

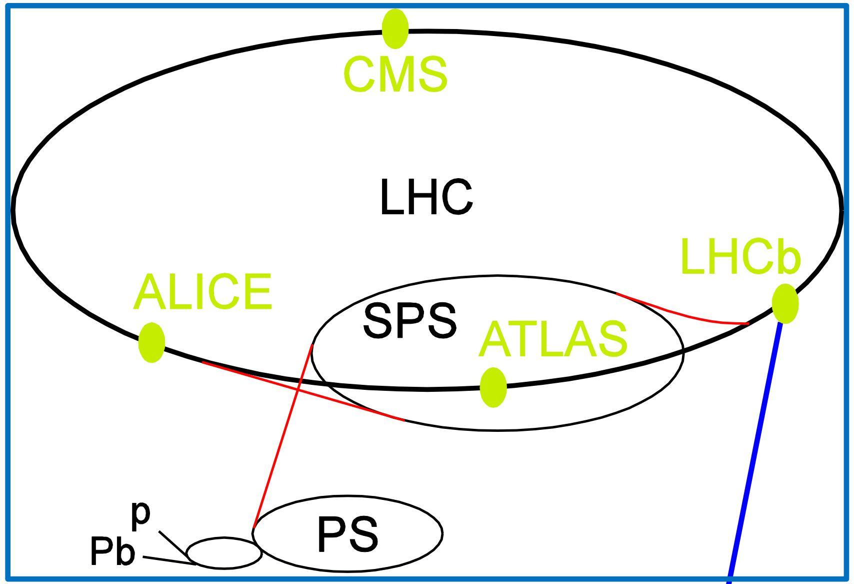




2) Measure decay rate as function of decay-time

1) Determine whether B_s or $\overline{B_s}$ at production

$B_s \to D_s K$: Quantum Interference Experiment @ LHCb

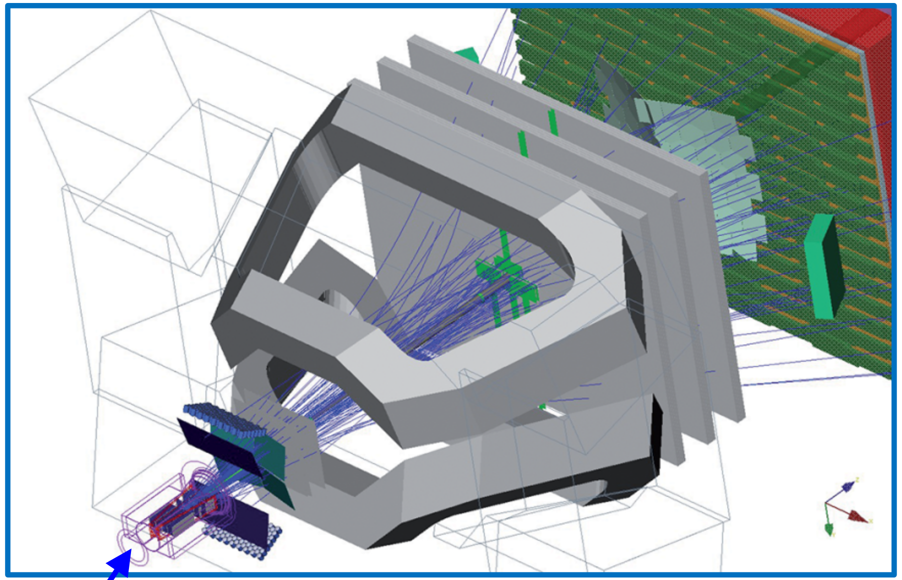


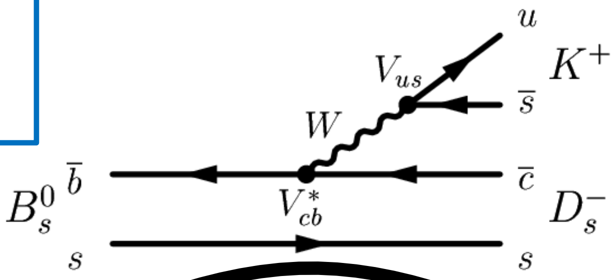
Measure:

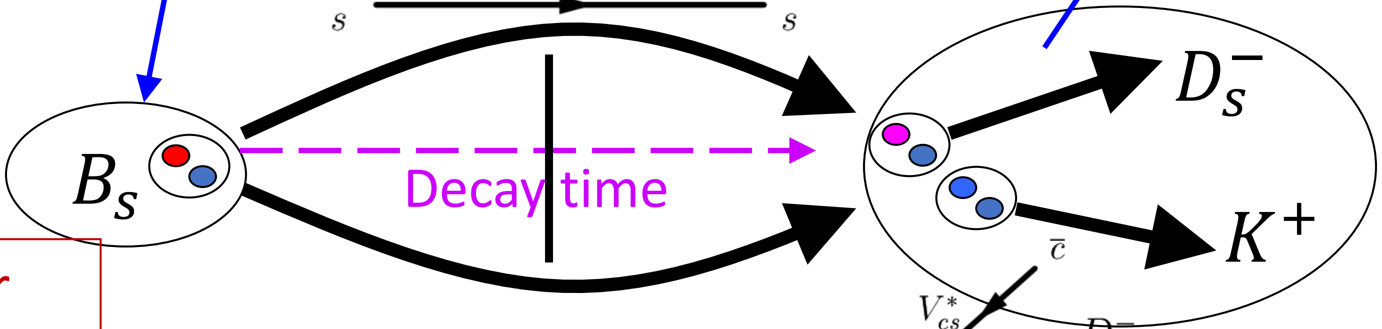
$B_s \to (\overline{B_s} \to)\ D_s^- K^+$

$\overline{B_s} \to (B_s \to)\ D_s^- K^+$

Repeat for $D_s^+ K^-$

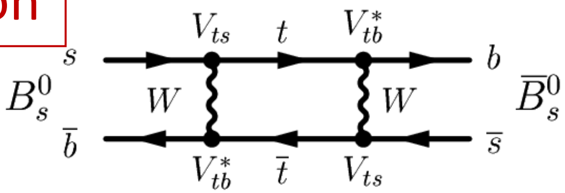


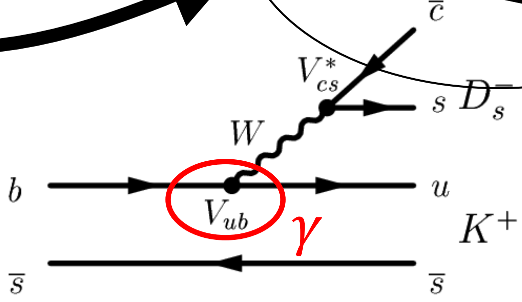




2) Measure decay rate as function of decay-time

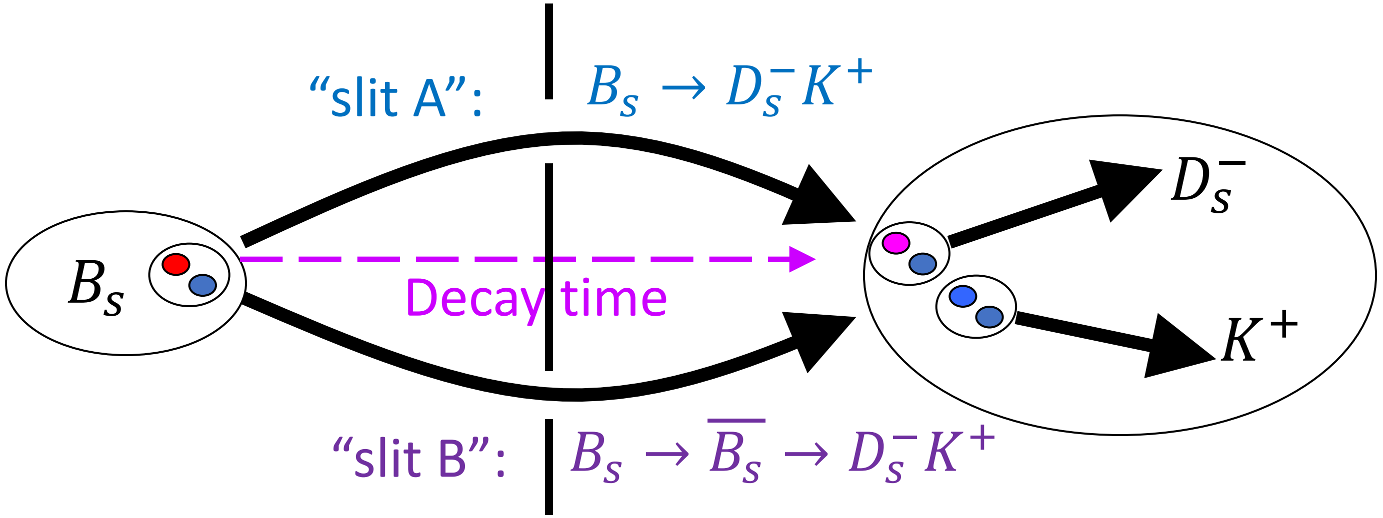
1) Determine whether B_s or $\overline{B_s}$ at production

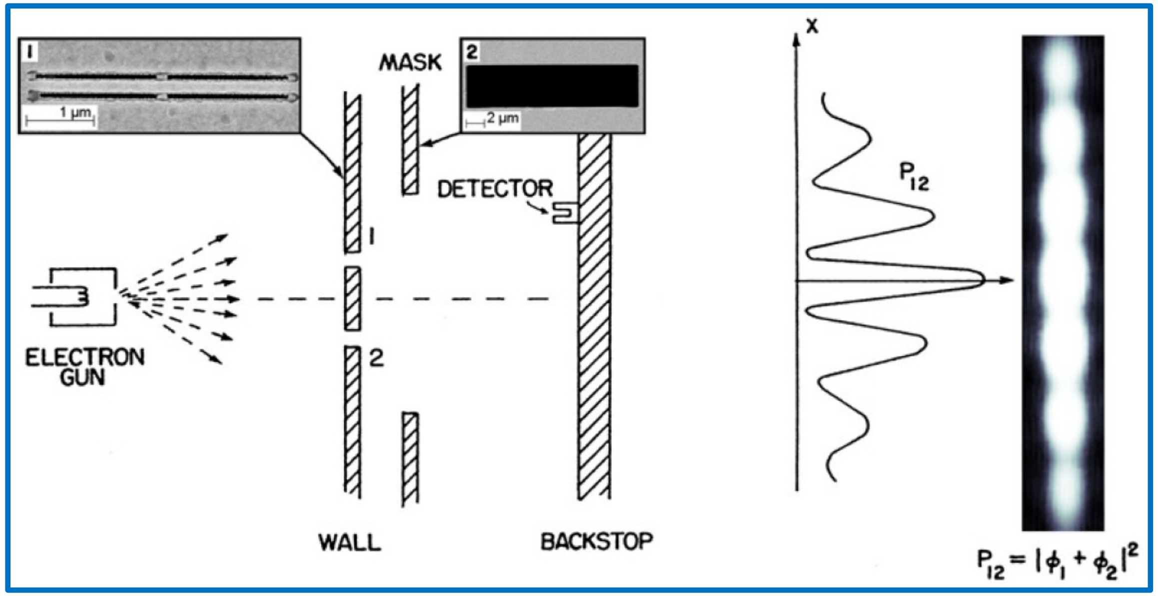




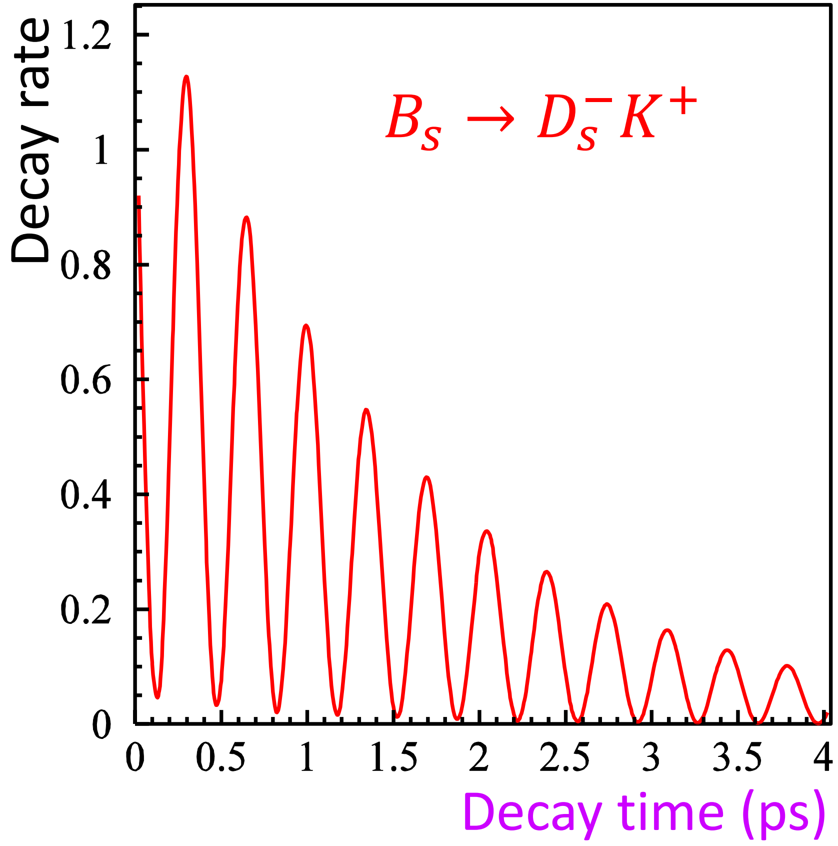
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

$B_s \to D_s K$: Quantum Interference Experiment @ LHCb

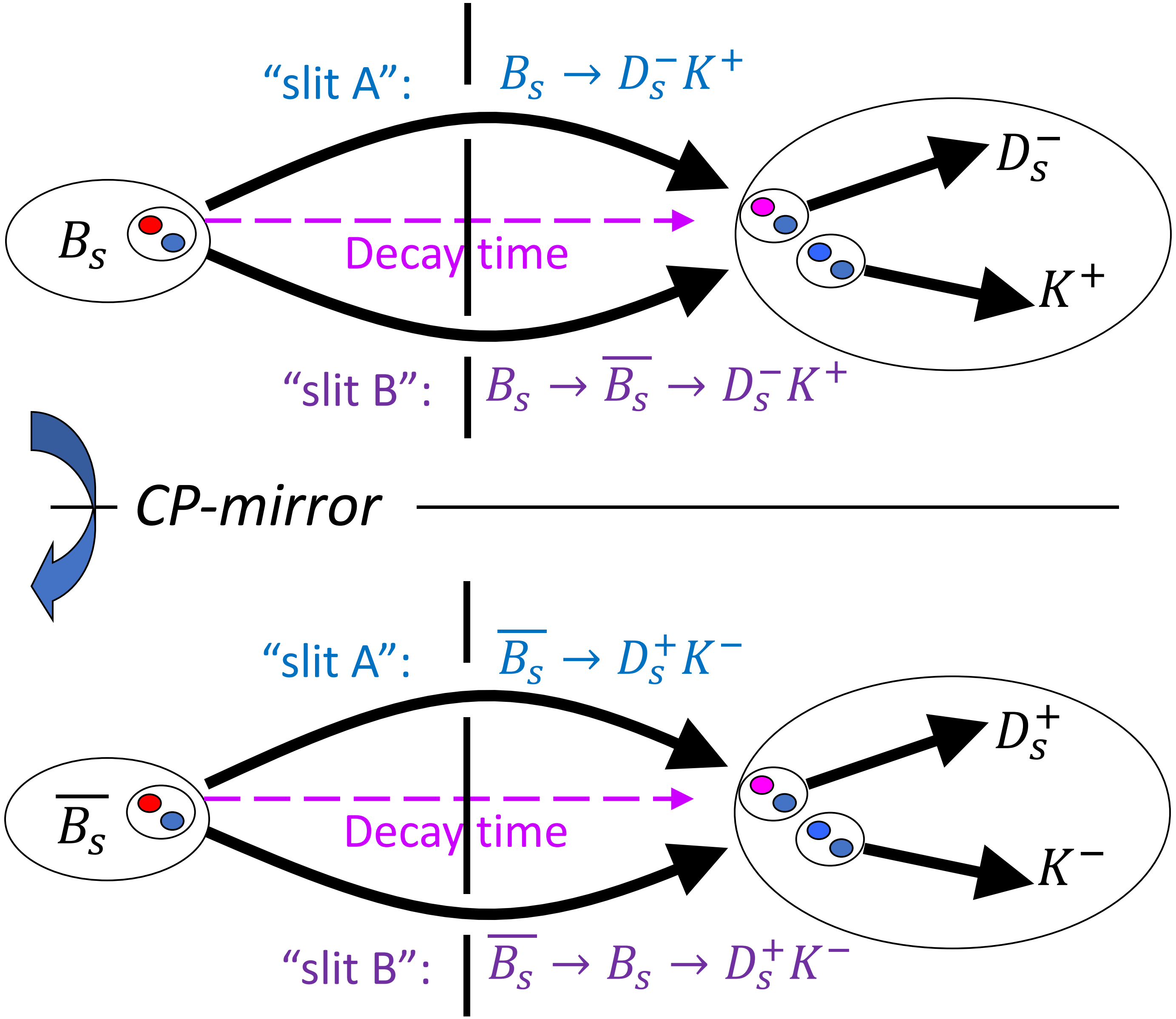




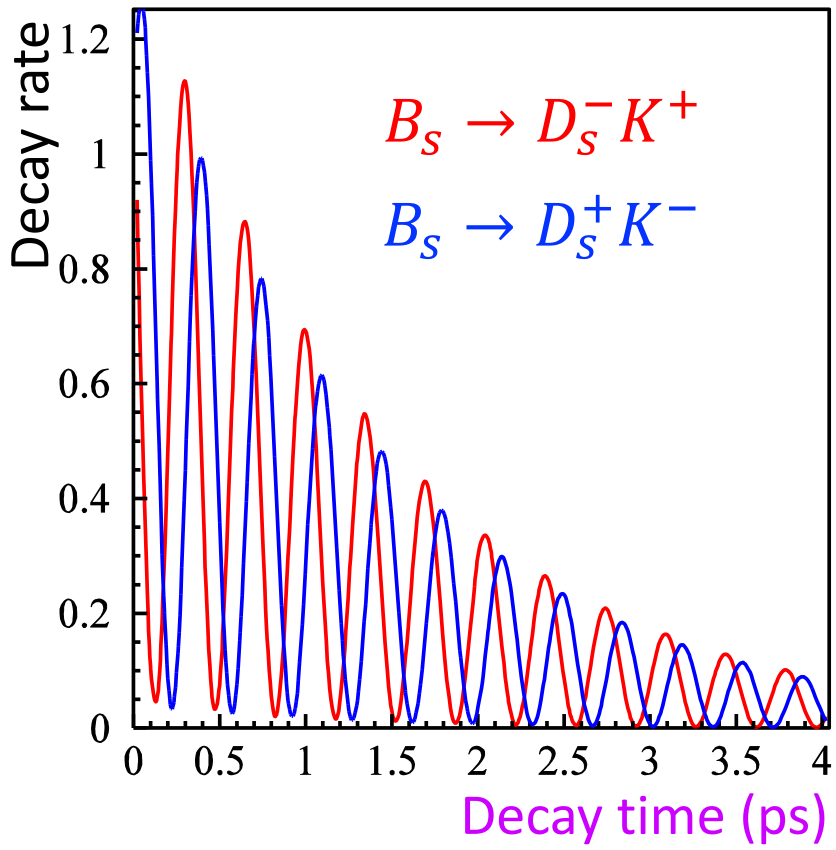
An interference pattern:



$B_s \to D_s K$: Quantum Interference Experiment @ LHCb

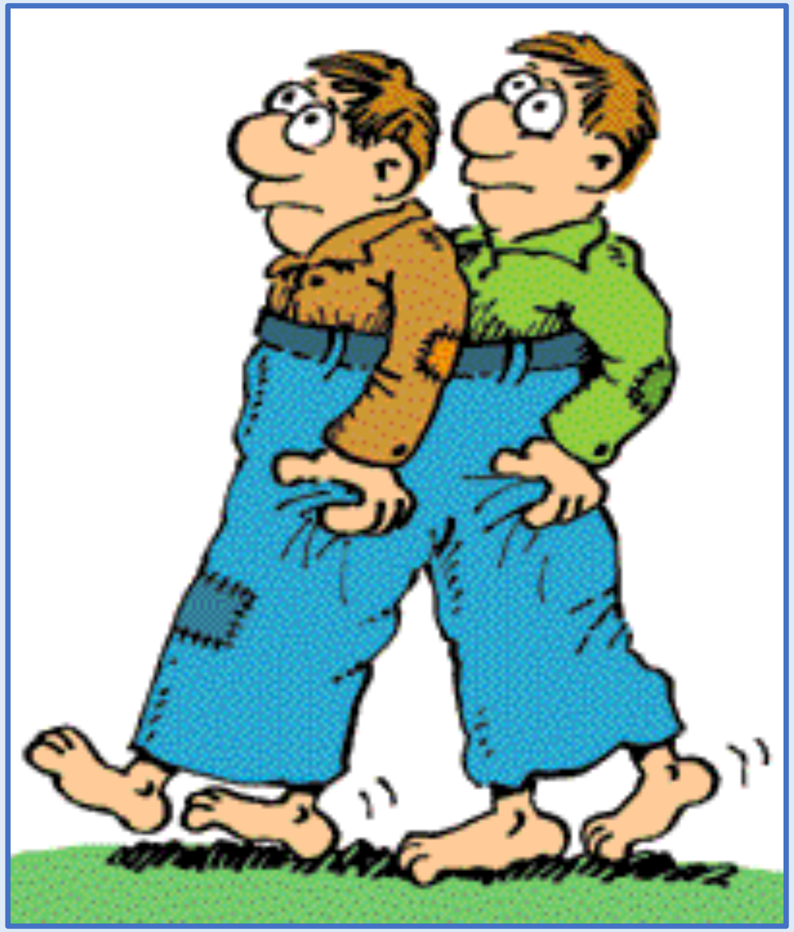


An interference pattern:



Time dependent CP violation!

Contents:



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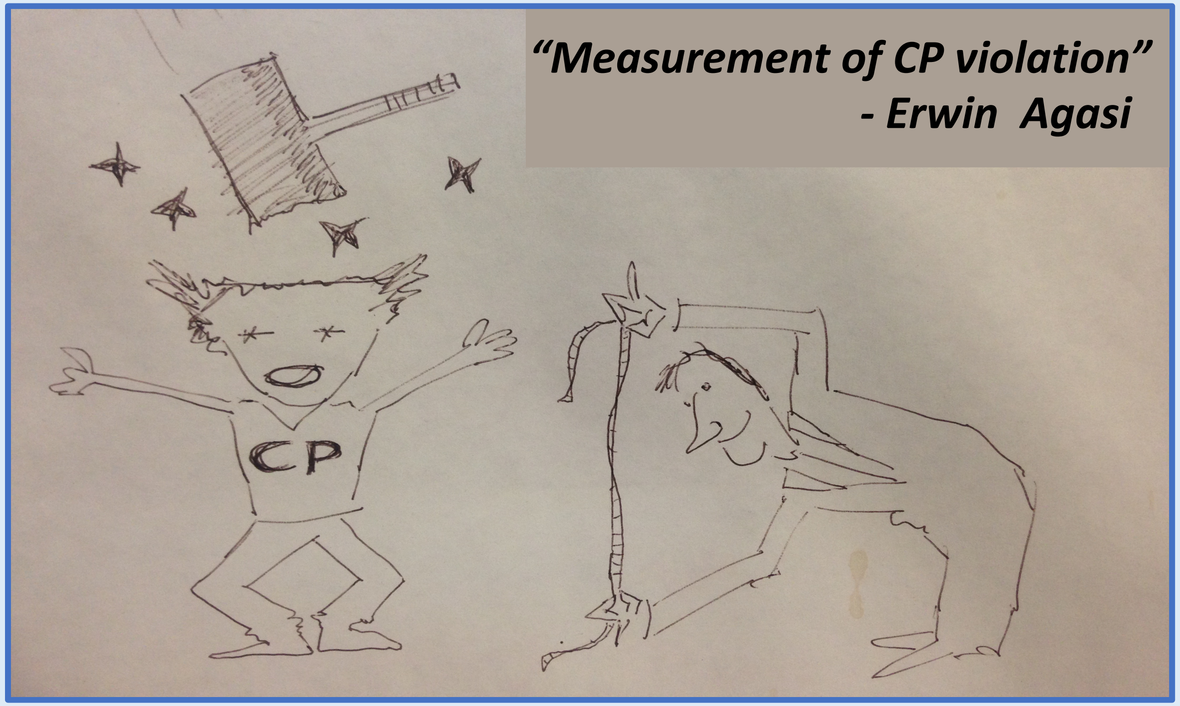
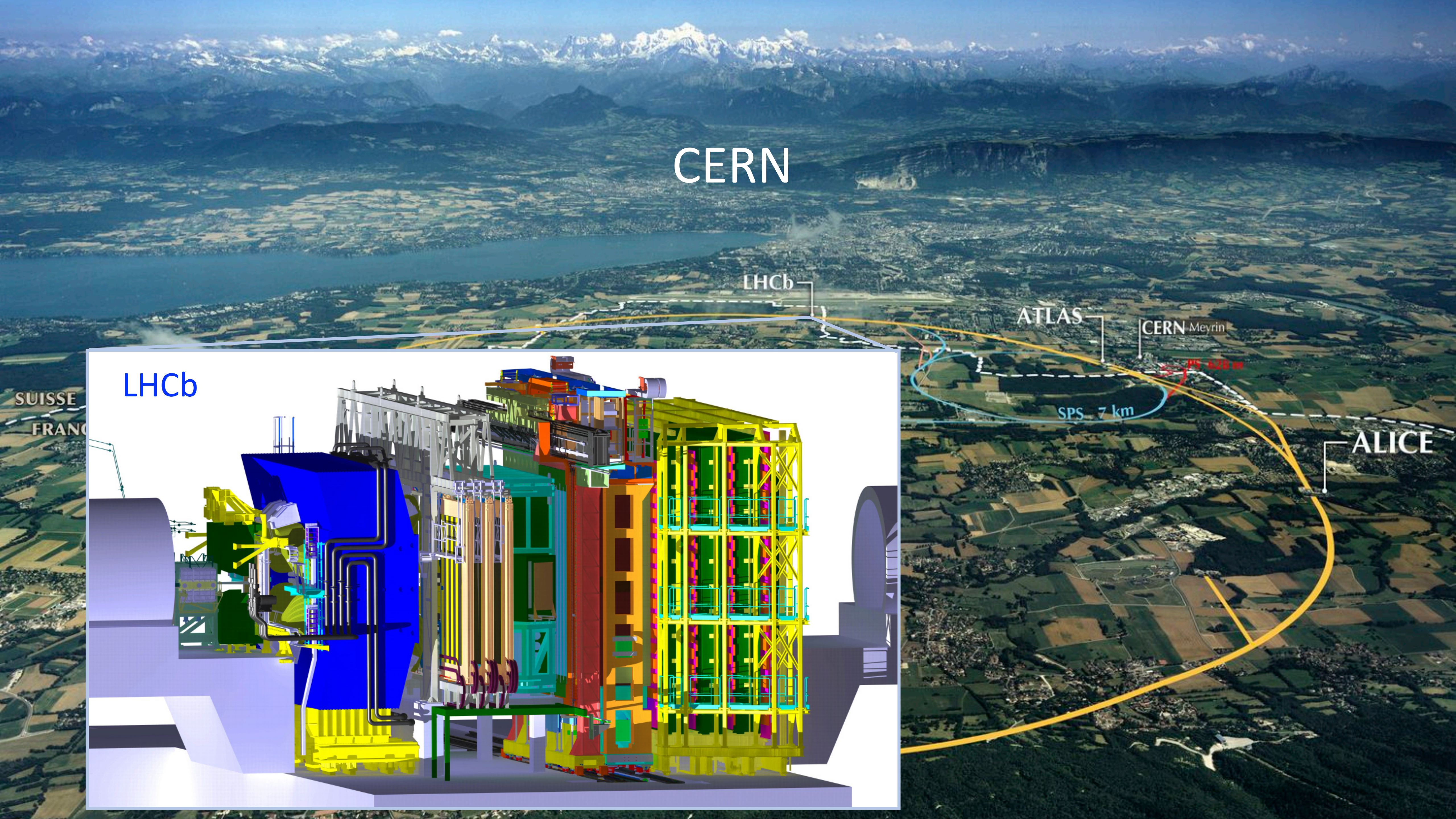
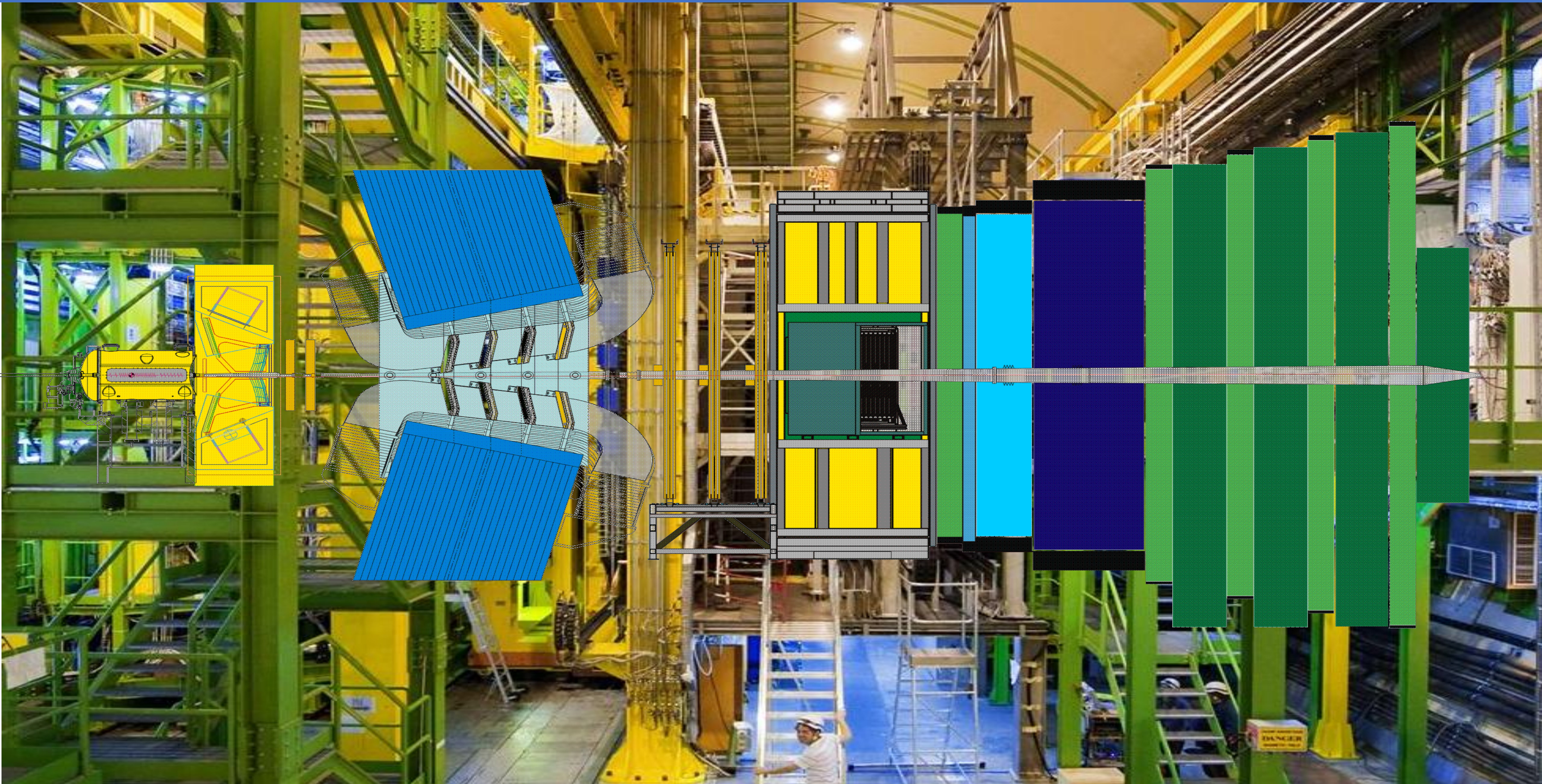


"Measurement of CP violation"
- Erwin Agasi

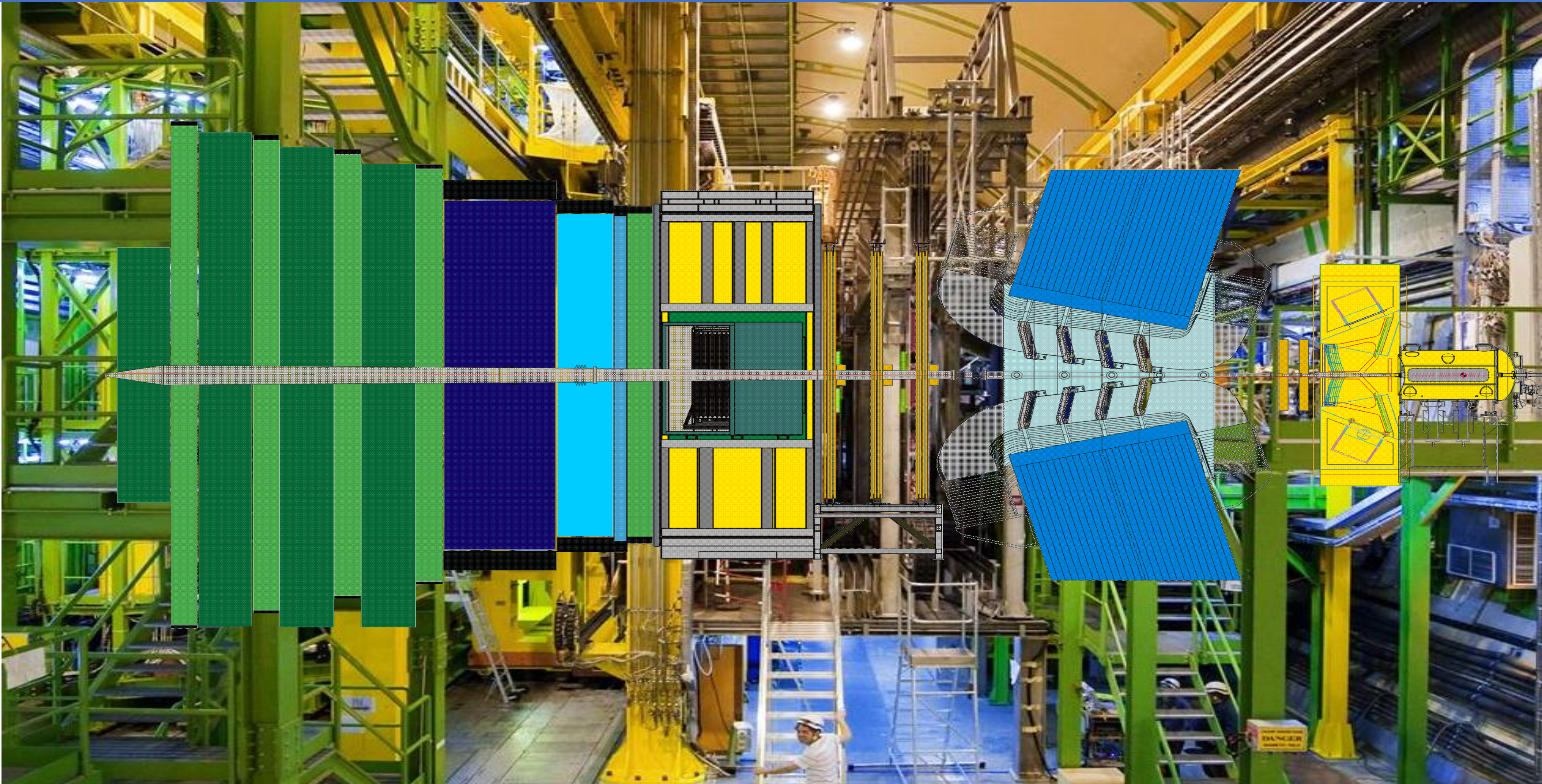


CERN
LHCb
ATLAS
CERN Meyrin
SPS 7 km
ALICE
SUISSE
LHCb

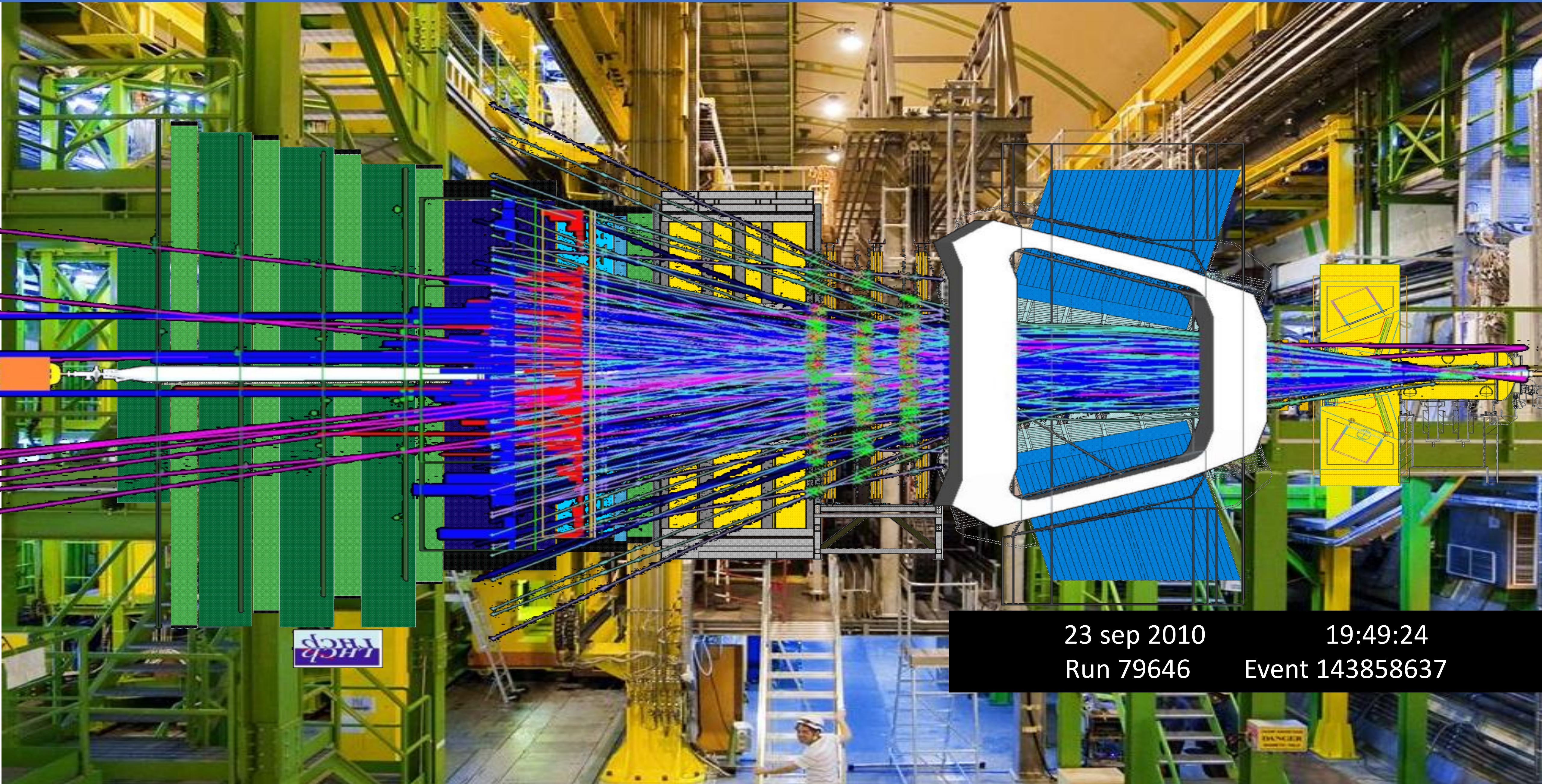
The LHCb Detector? dƆHꞀ



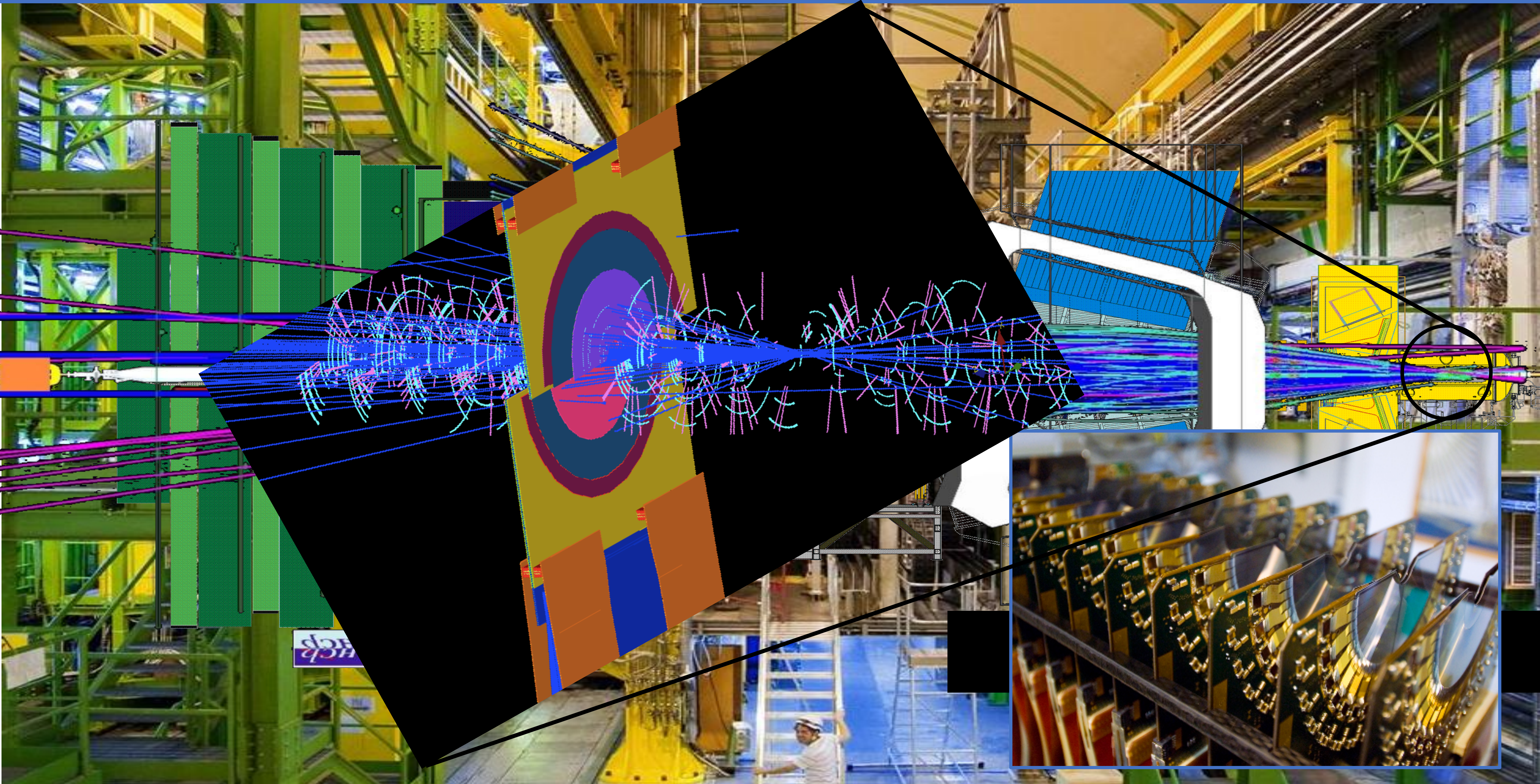
The LHCb Detector!



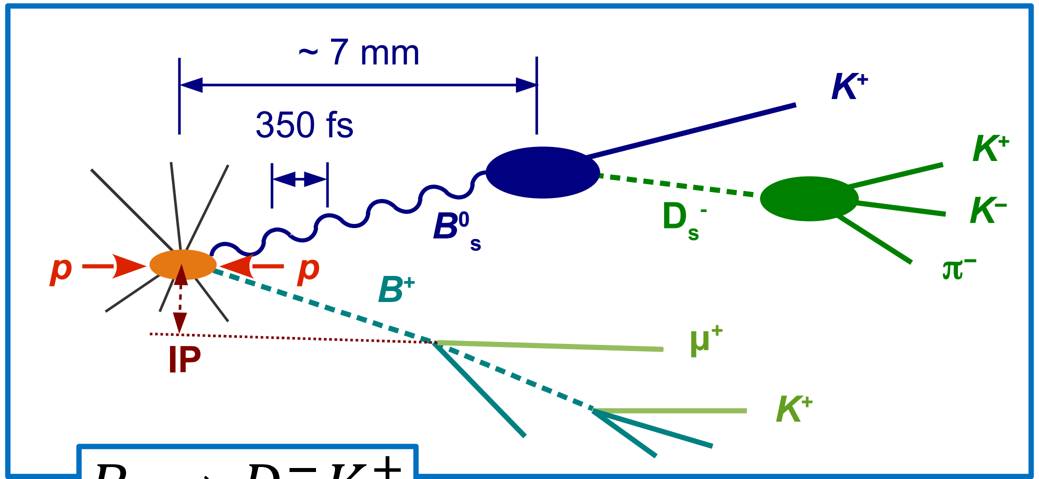
The LHCb Detector



Meaure time dependent B and $\overline{B}$ decay rates



B_s Physics at LHCb



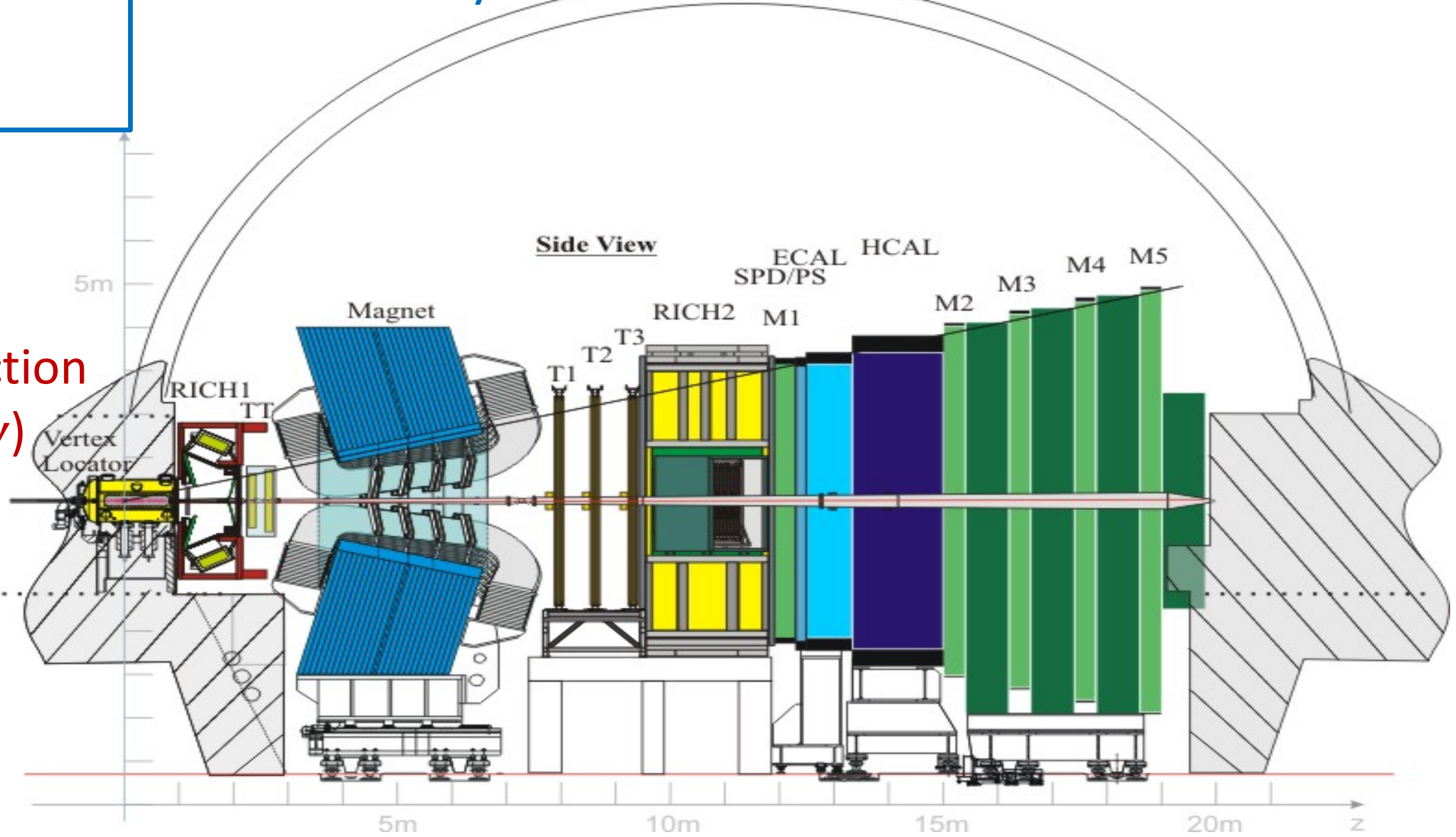
$B_s \to D_s^- K^+$

Physics Requirements:

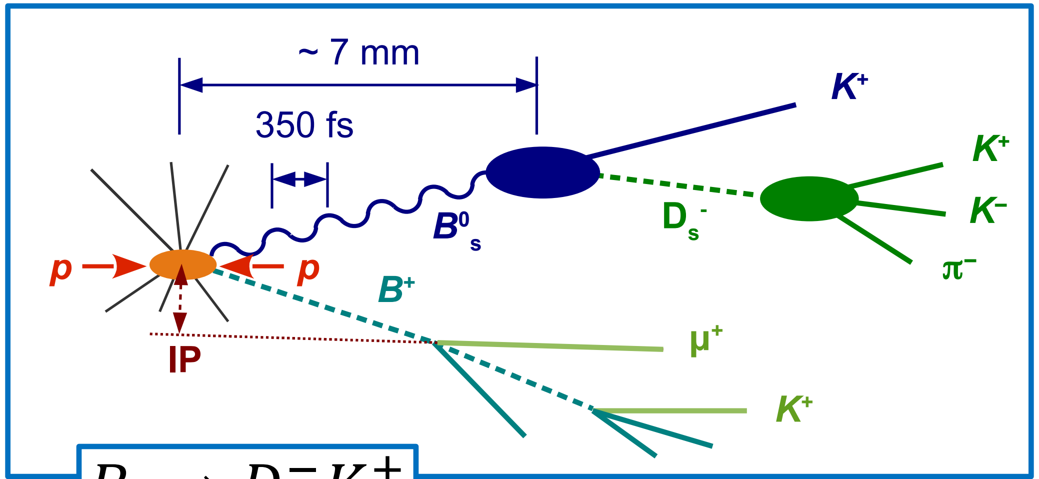
- Signal selection and background suppression
- Flavour tagging: B or $\overline{B}$ at production
- Decay time measurement

Detector Requirements:

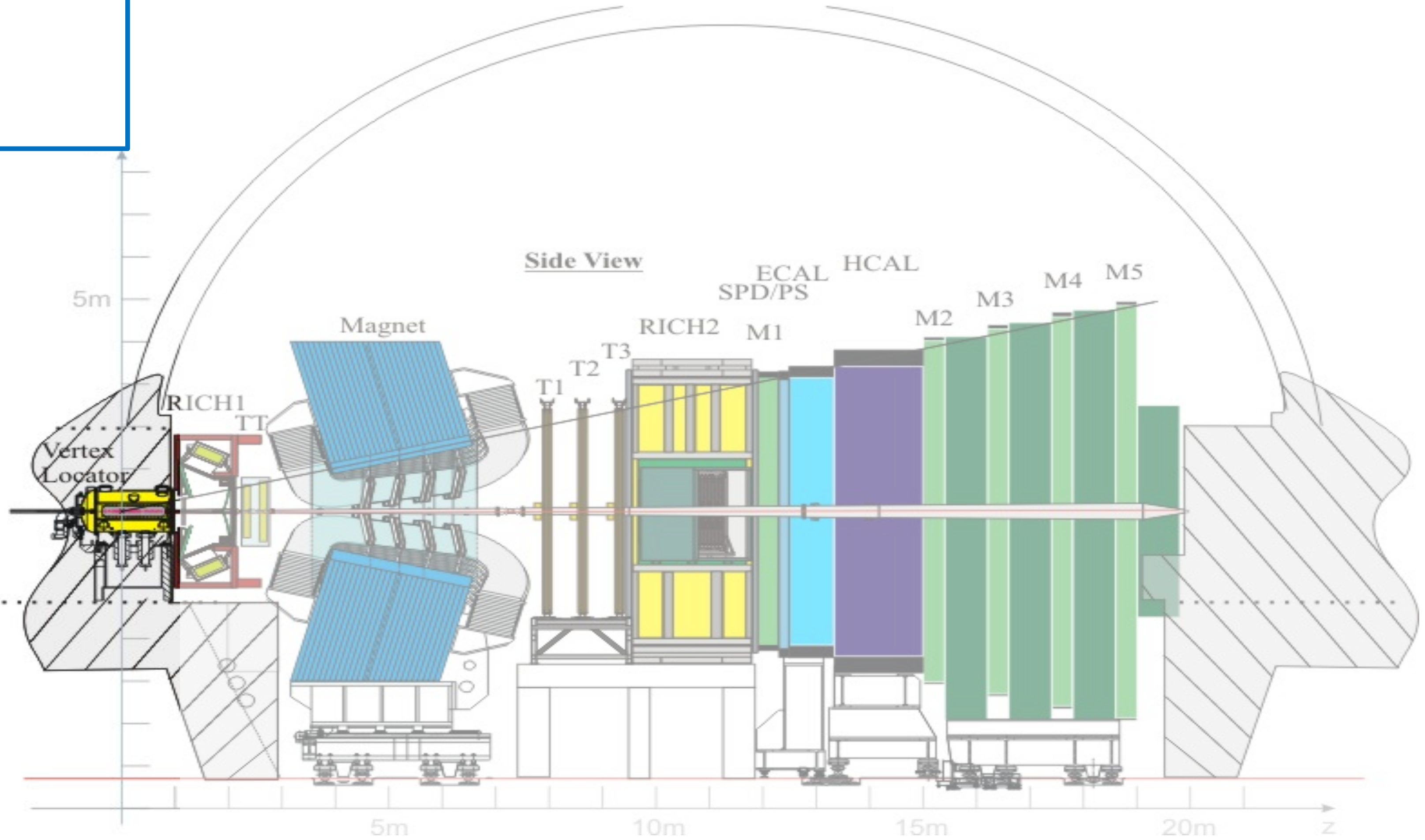
- Vertex reconstruction
- Momentum and mass reconstruction
- Particle identification (π, K, μ, e, γ)
- Trigger (Online reconstruction)



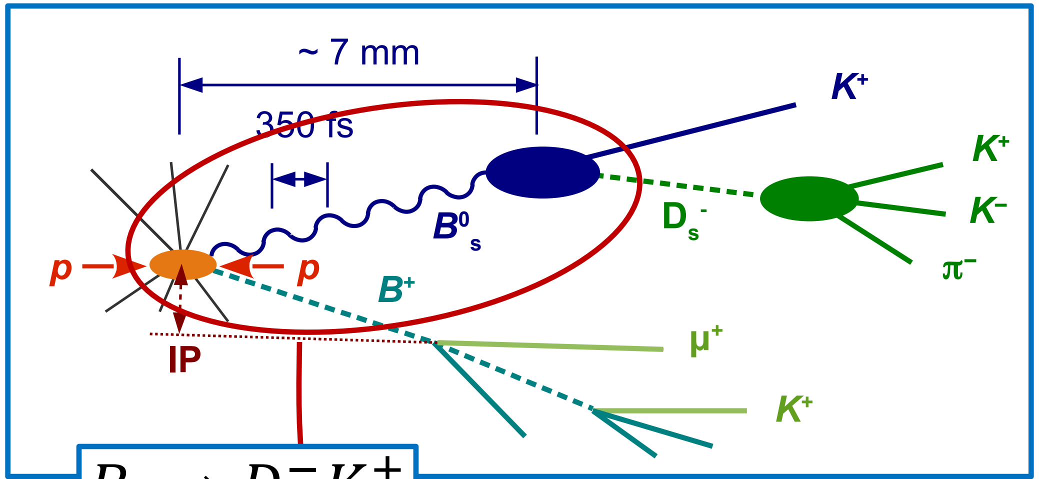
B_s Physics at LHCb - Vertex reconstruction



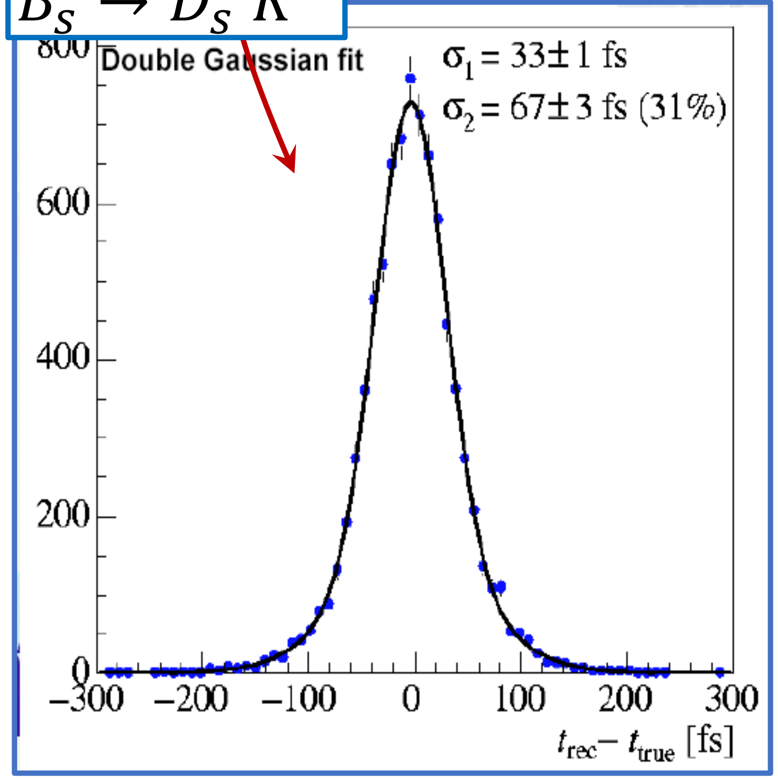
$B_s \to D_s^- K^+$

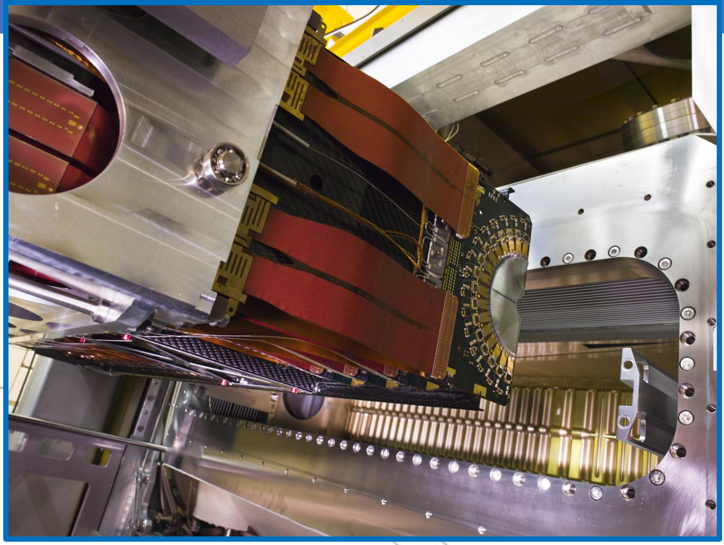


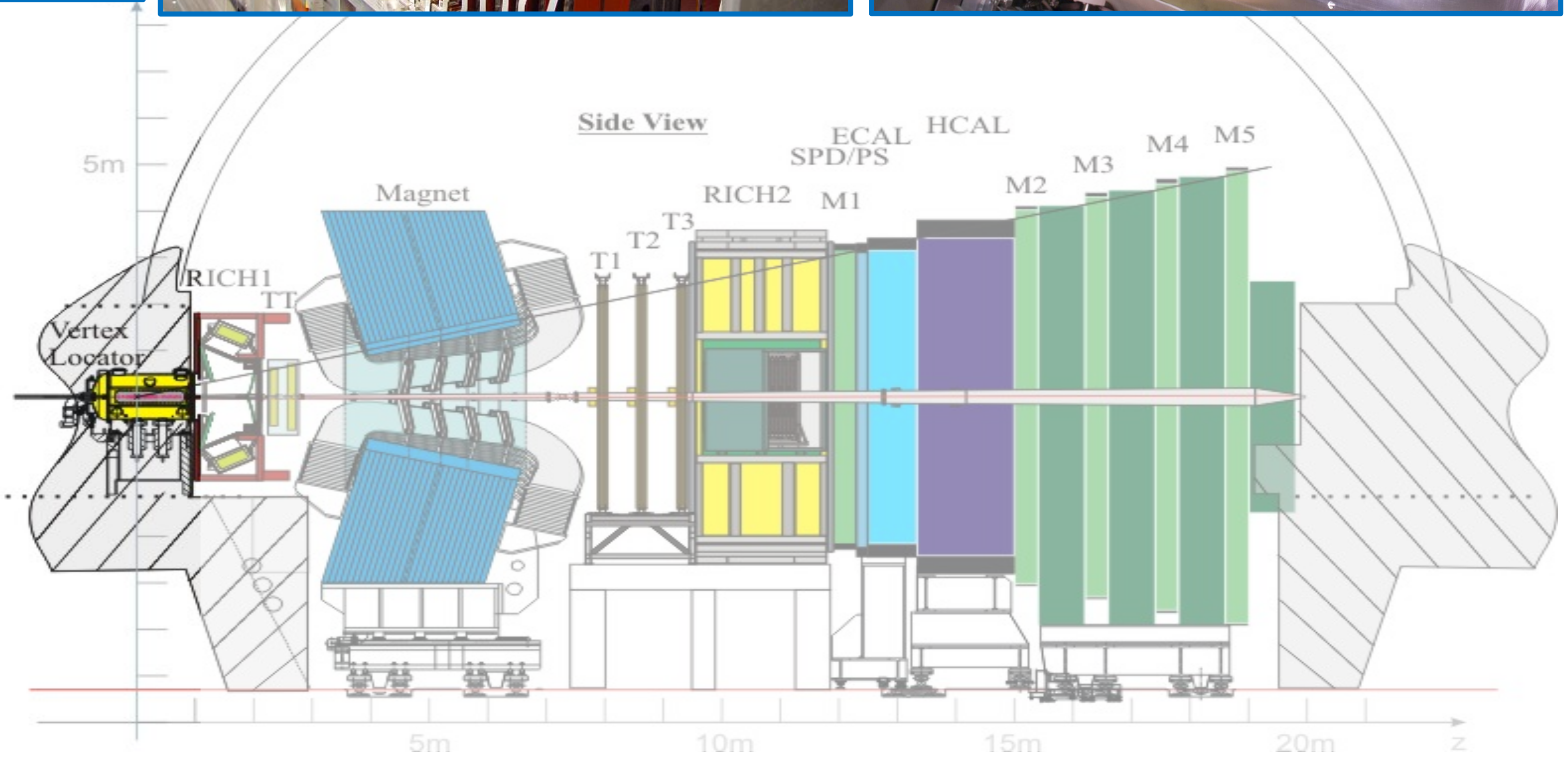
B_s Physics at LHCb - Vertex reconstruction



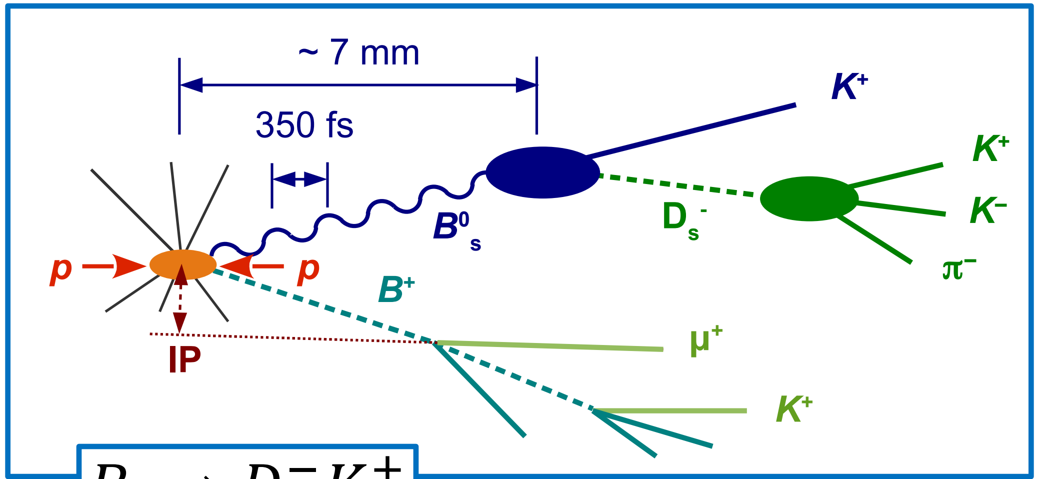
$B_s \to D_s^- K^+$



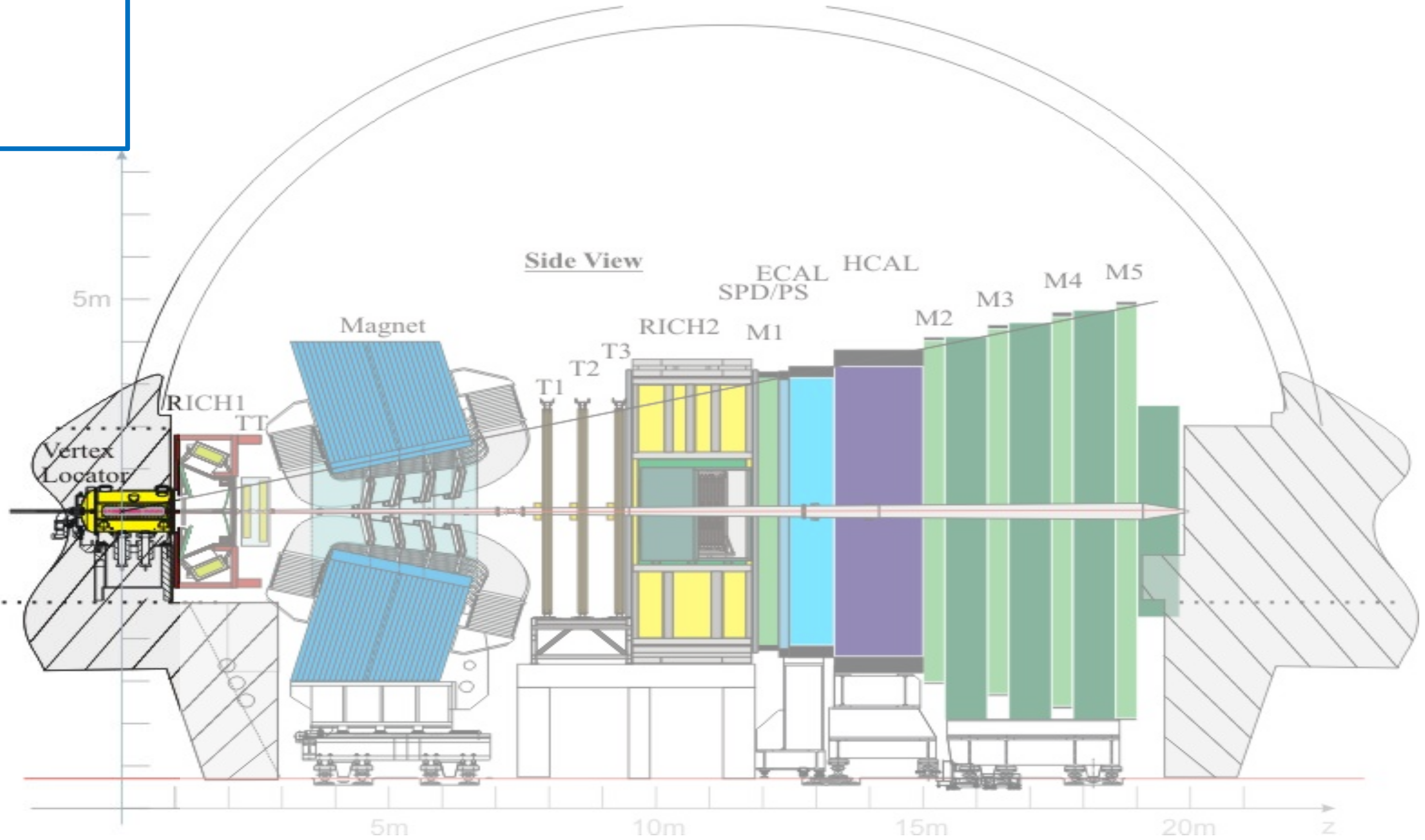




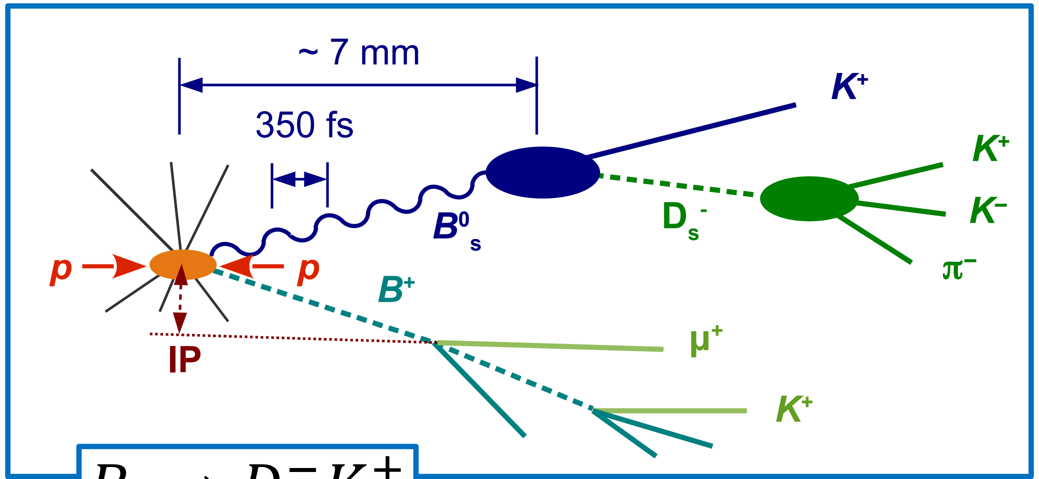
B_s Physics at LHCb



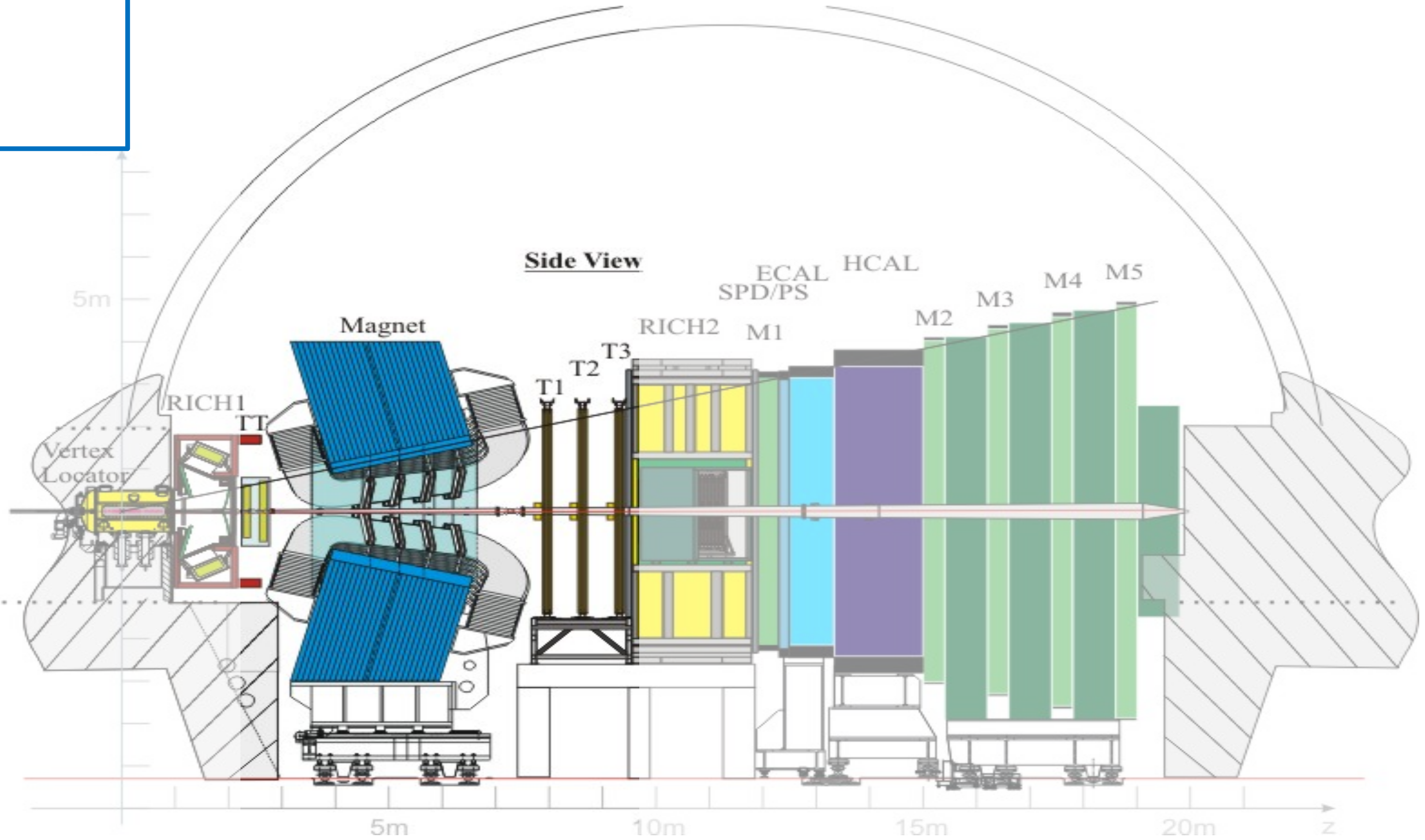
$B_s \to D_s^- K^+$



B_s Physics at LHCb – momentum and mass determination



$B_s \rightarrow D_s^- K^+$



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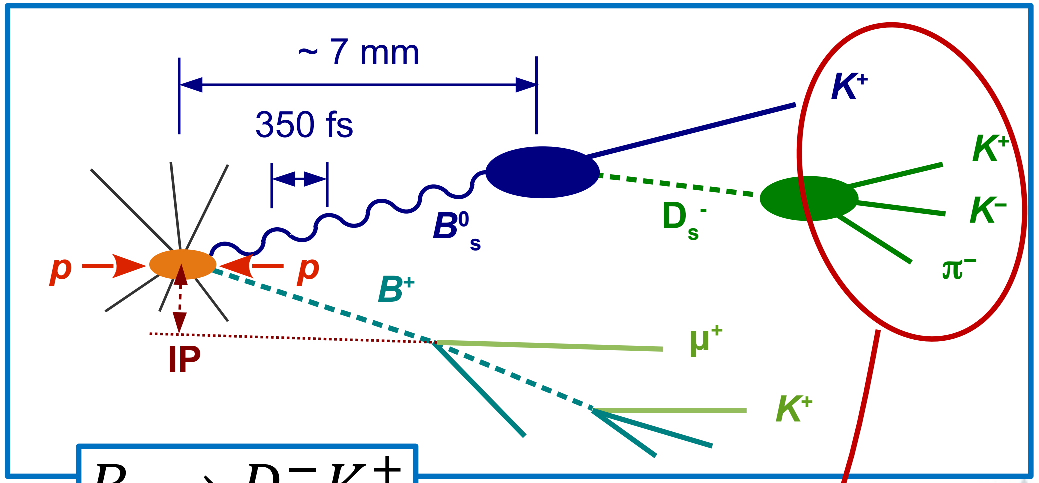
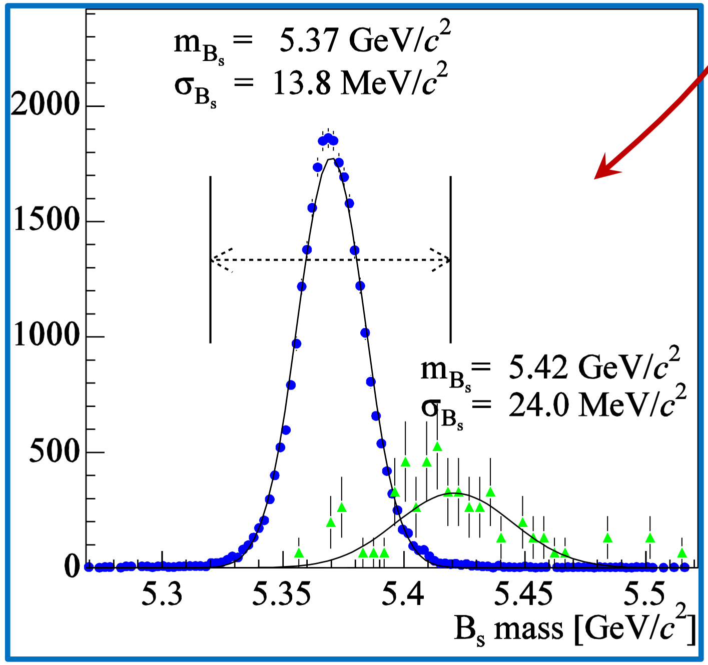
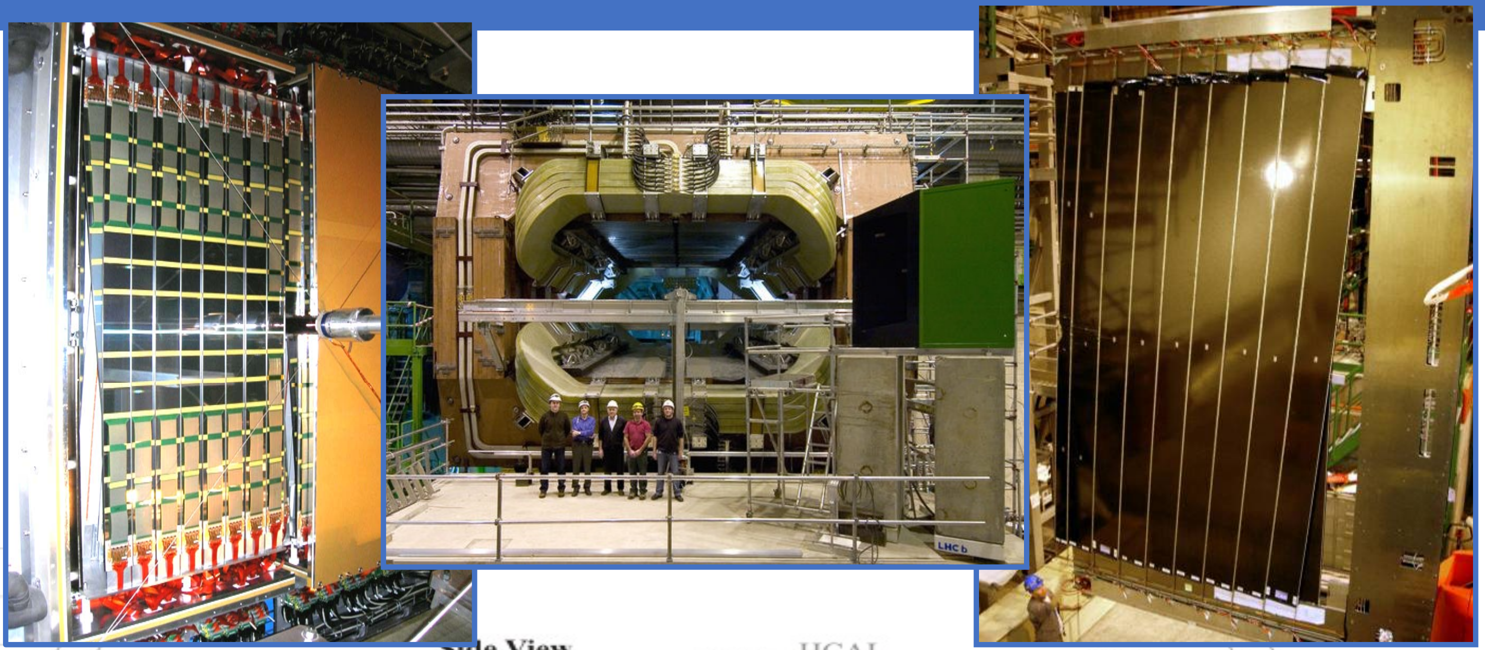
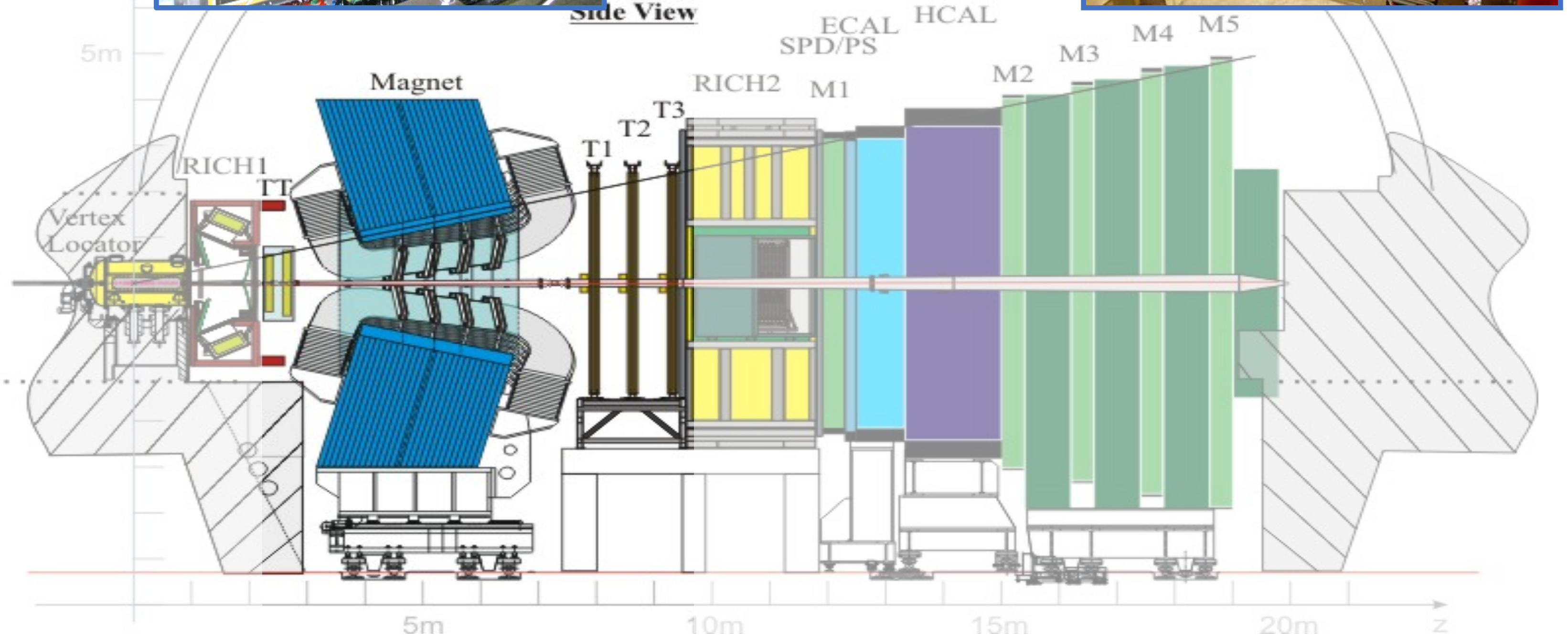


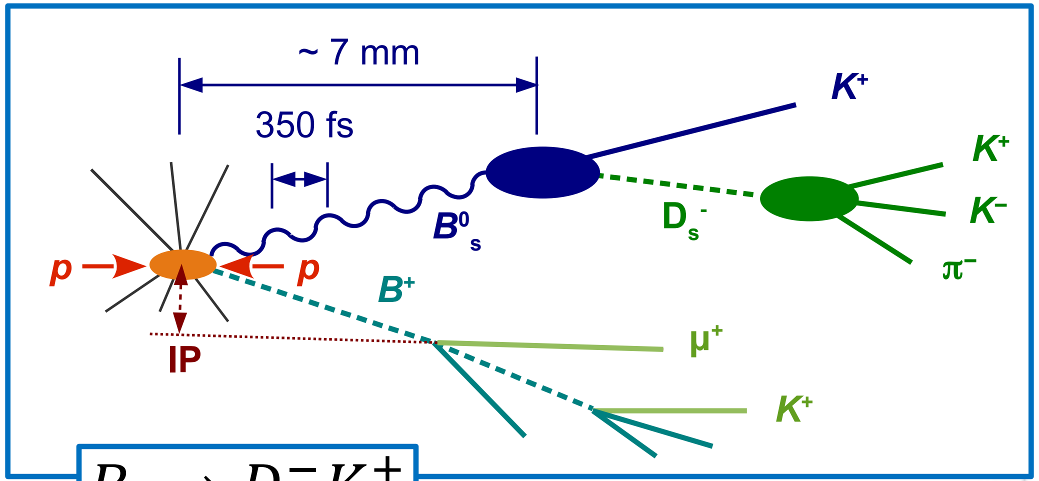
$B_s \to D_s^- K^+$



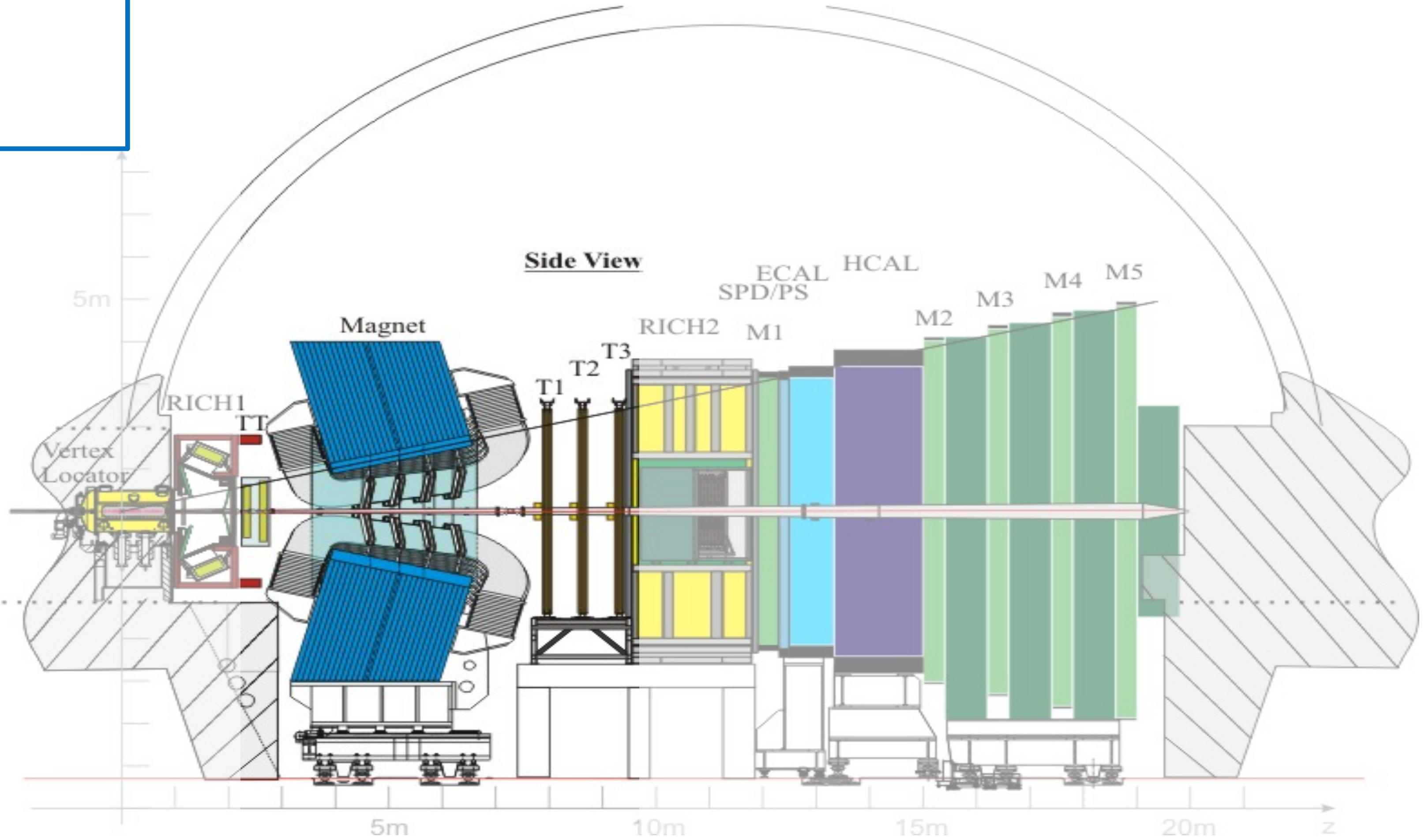




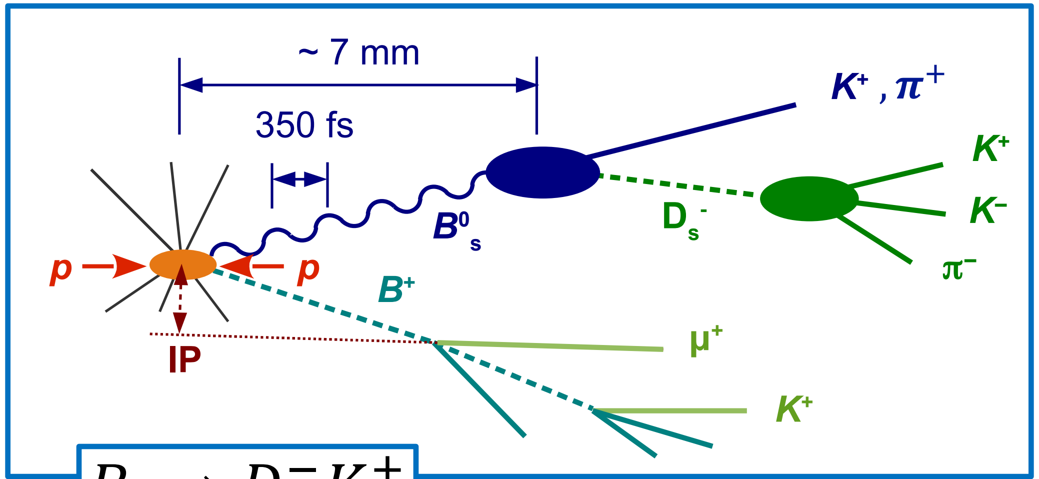
B_s Physics at LHCb



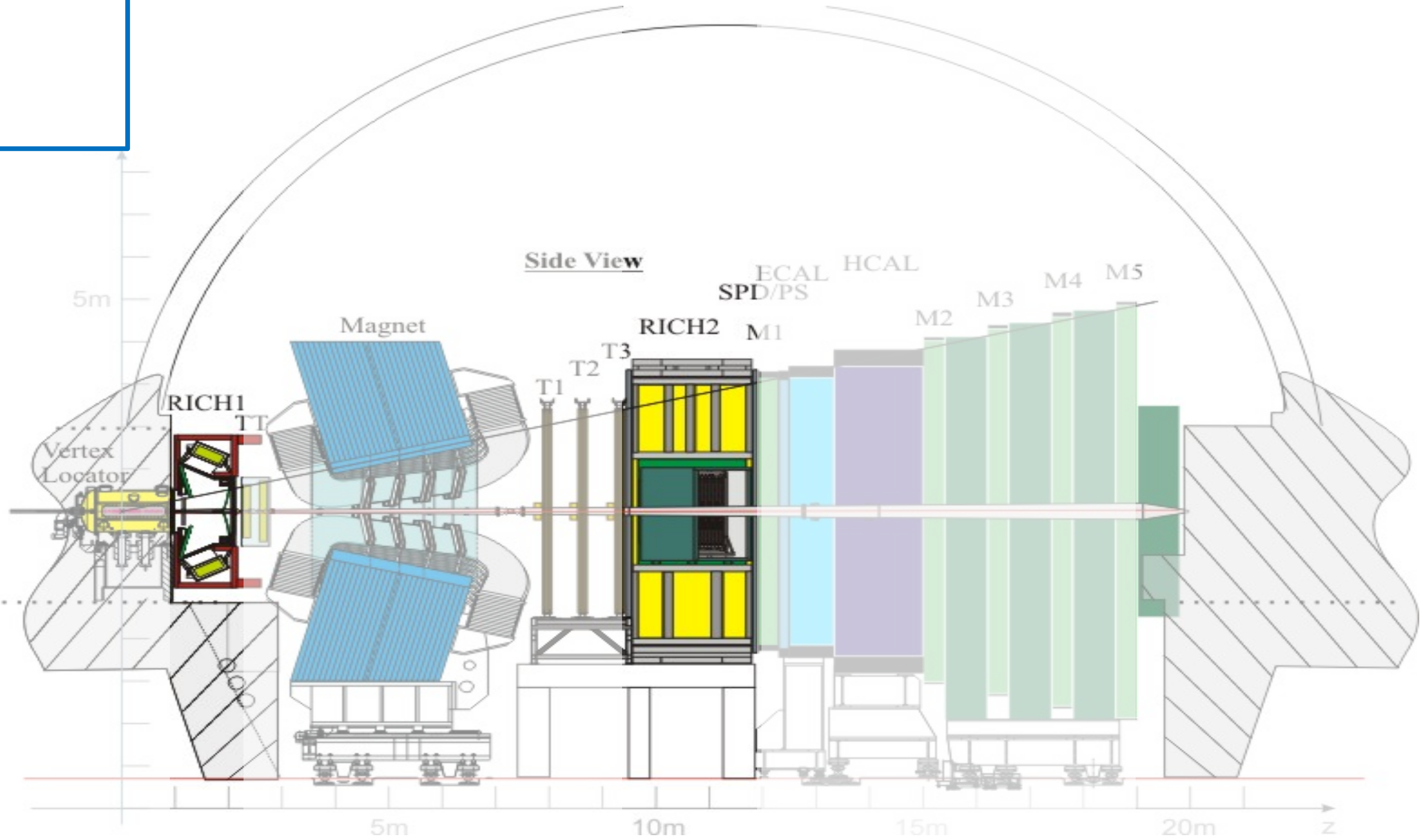
$B_s \to D_s^- K^+$



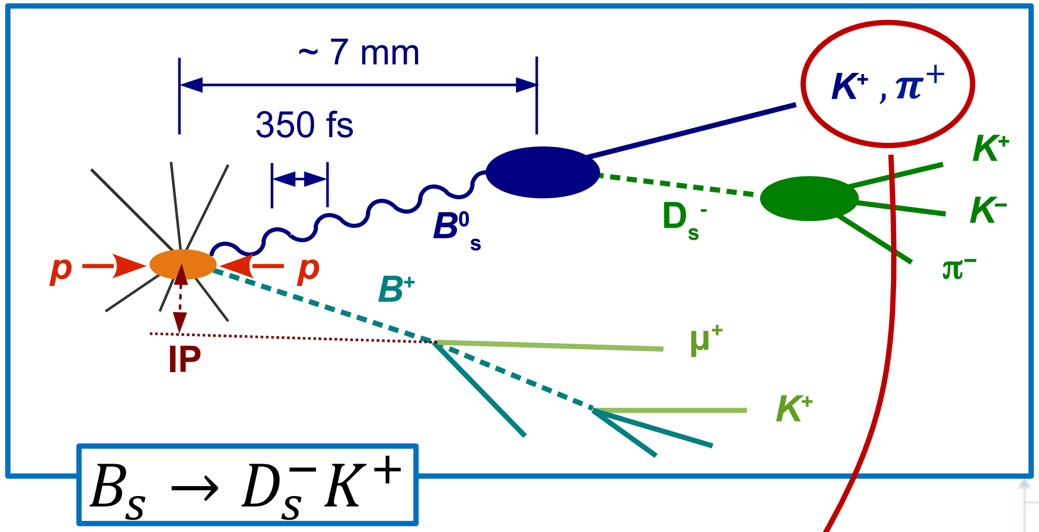
B_s Physics at LHCb – Particle Identification with RICH

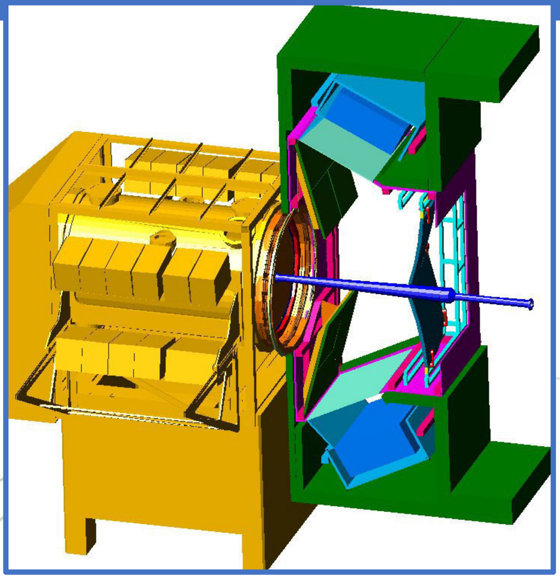


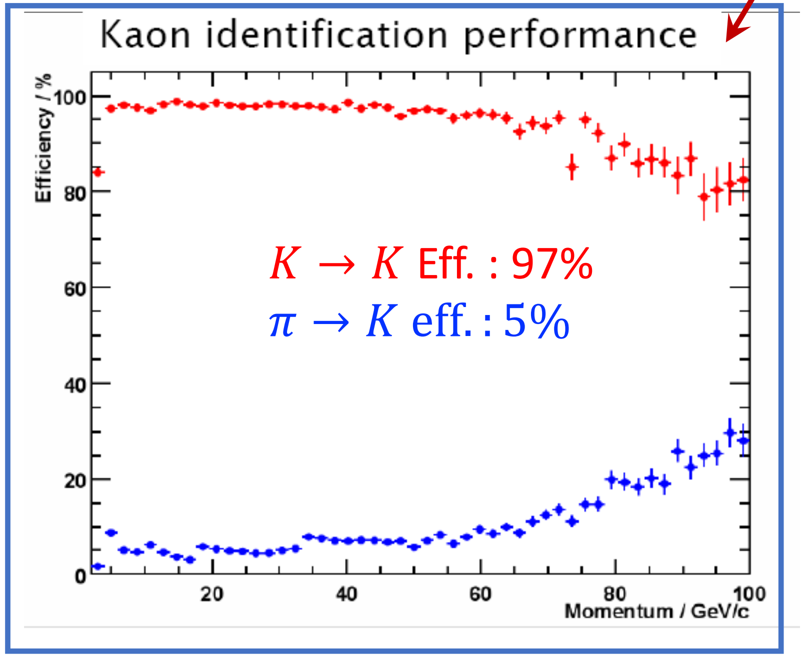
$B_s \rightarrow D_s^- K^+$

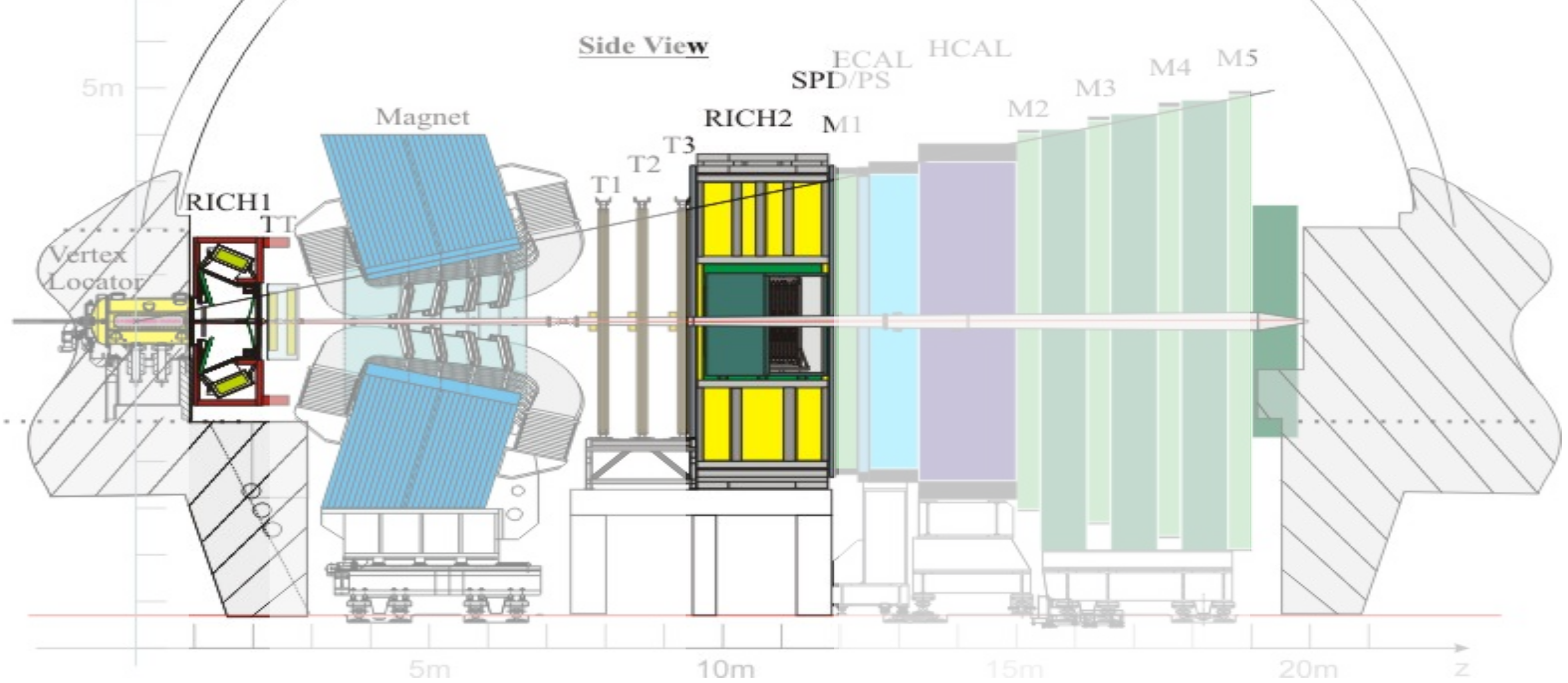


B_s Physics at LHCb – Particle Identification with RICH

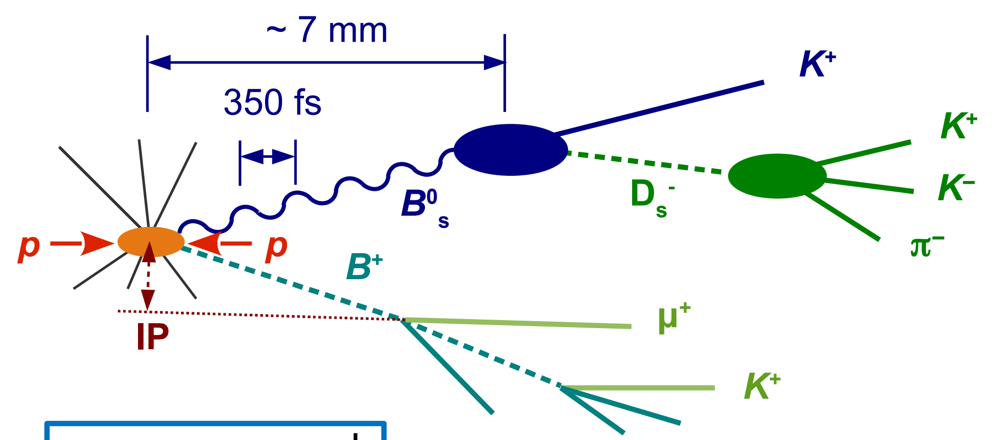




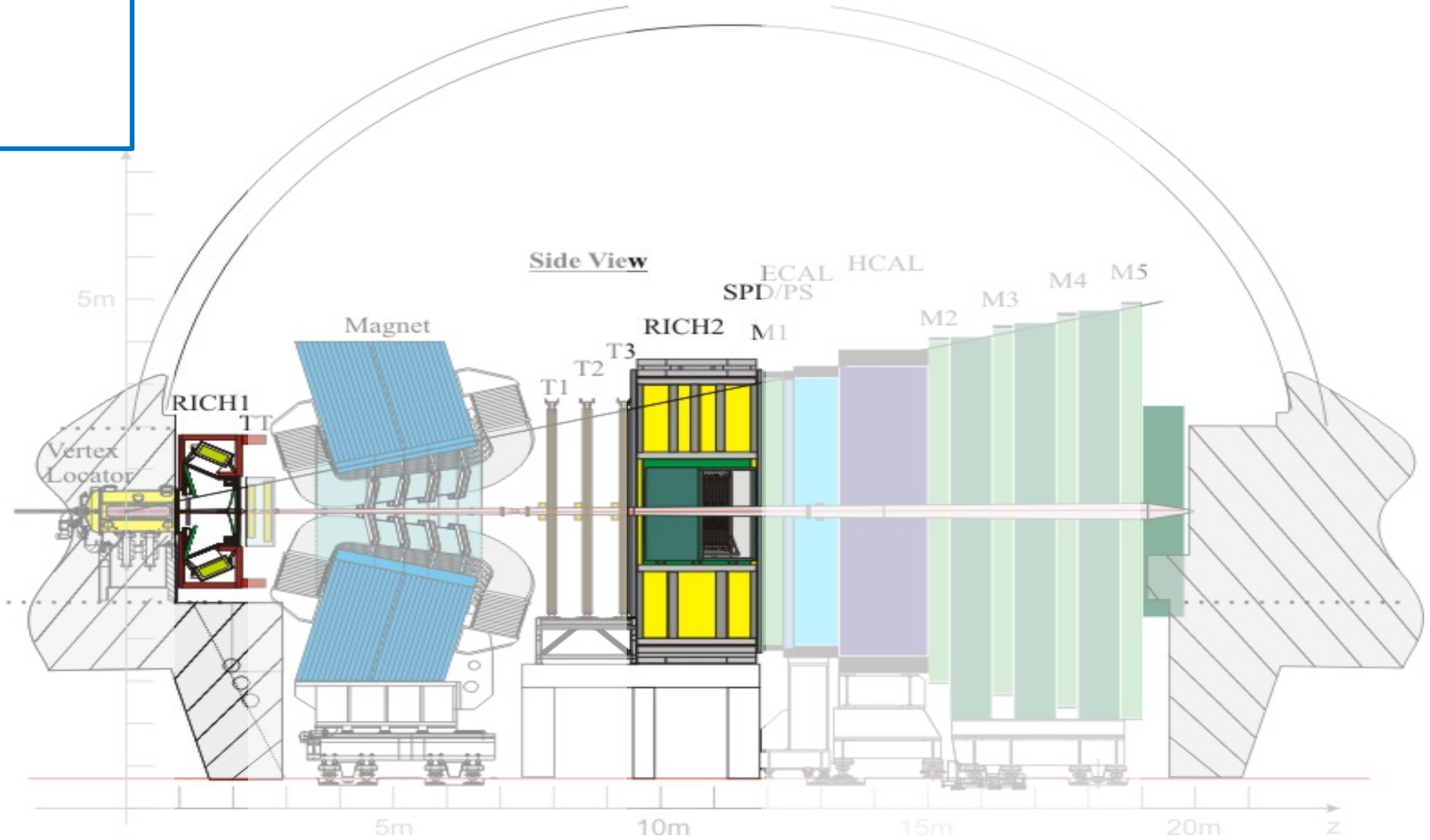




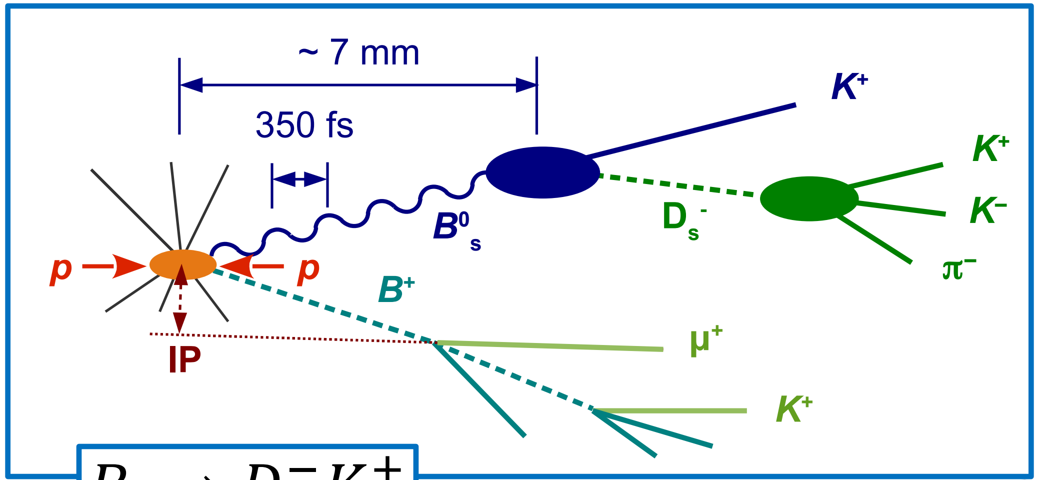
B_s Physics at LHCb



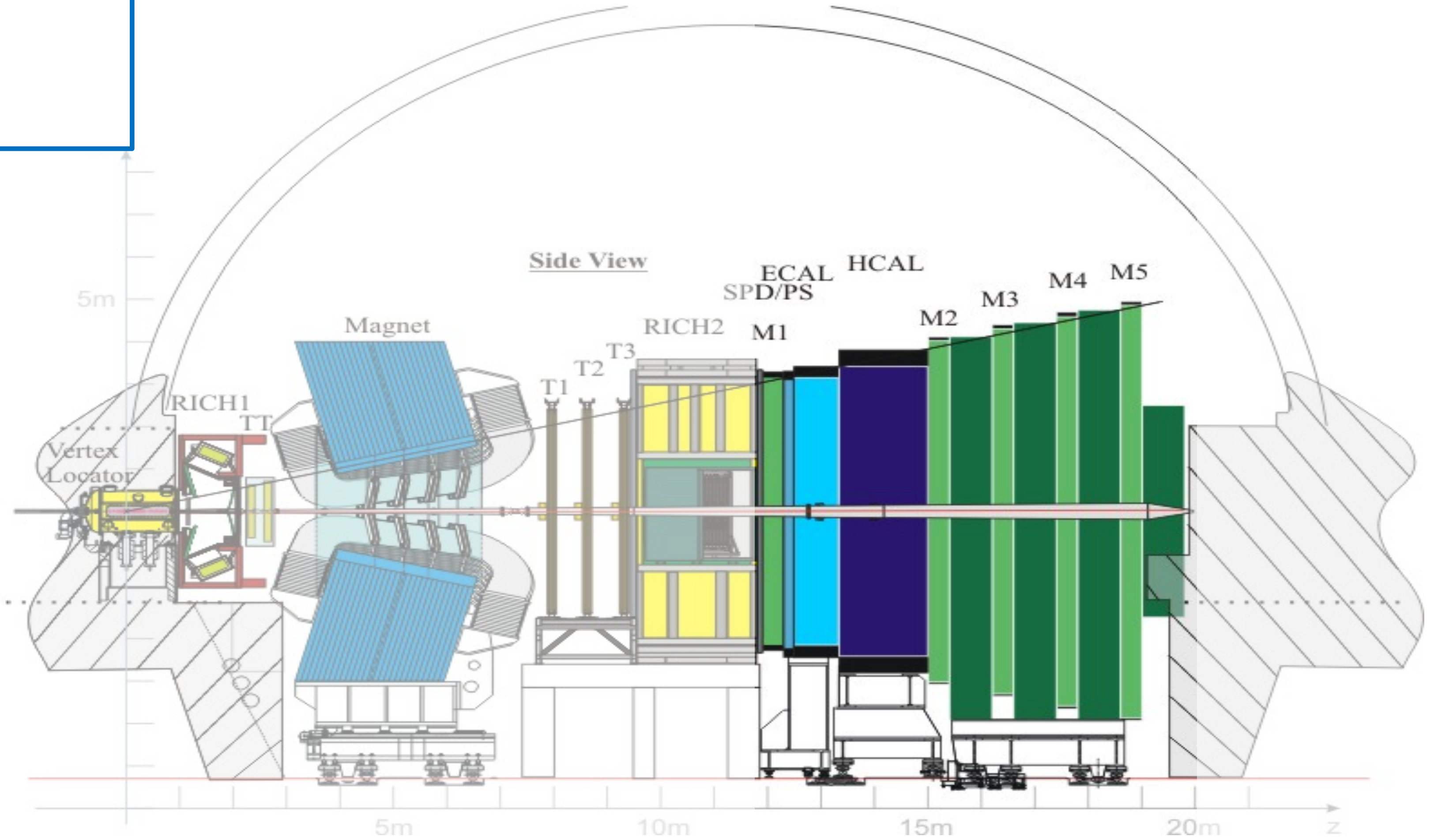
$B_s \to D_s^- K^+$



B_s Physics at LHCb – Trigger/Tag with Calorimeters and Muon



$B_s \to D_s^- K^+$



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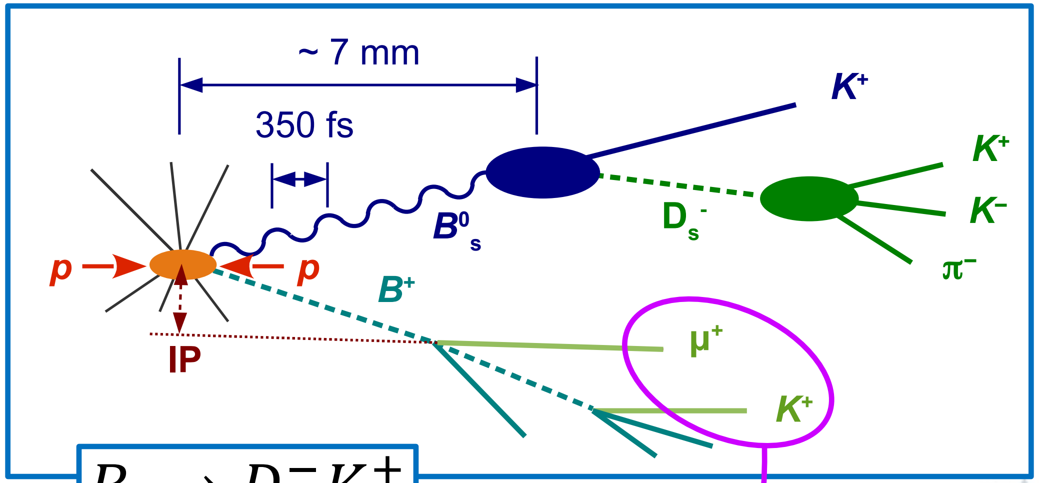
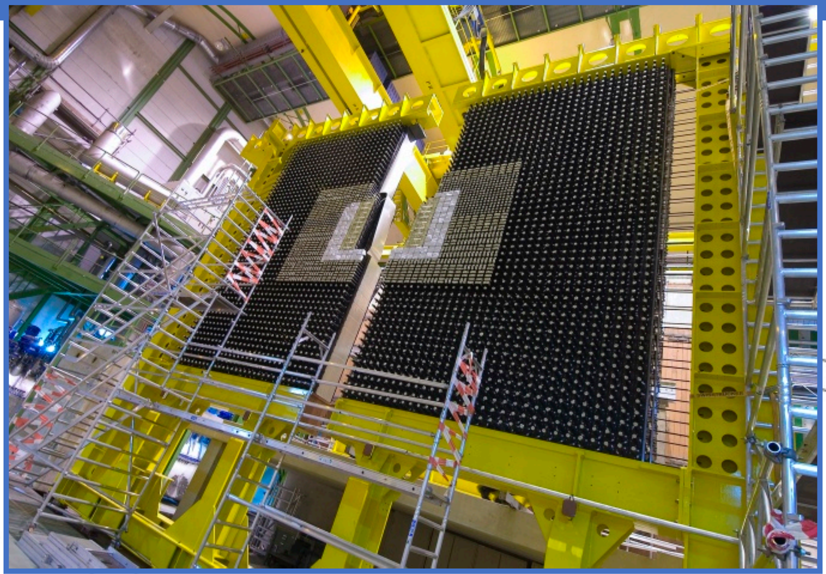
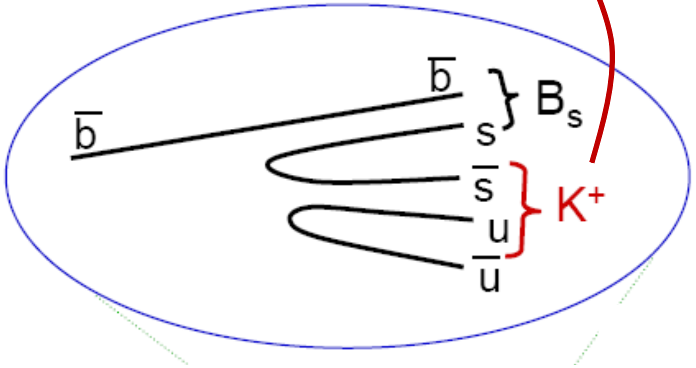


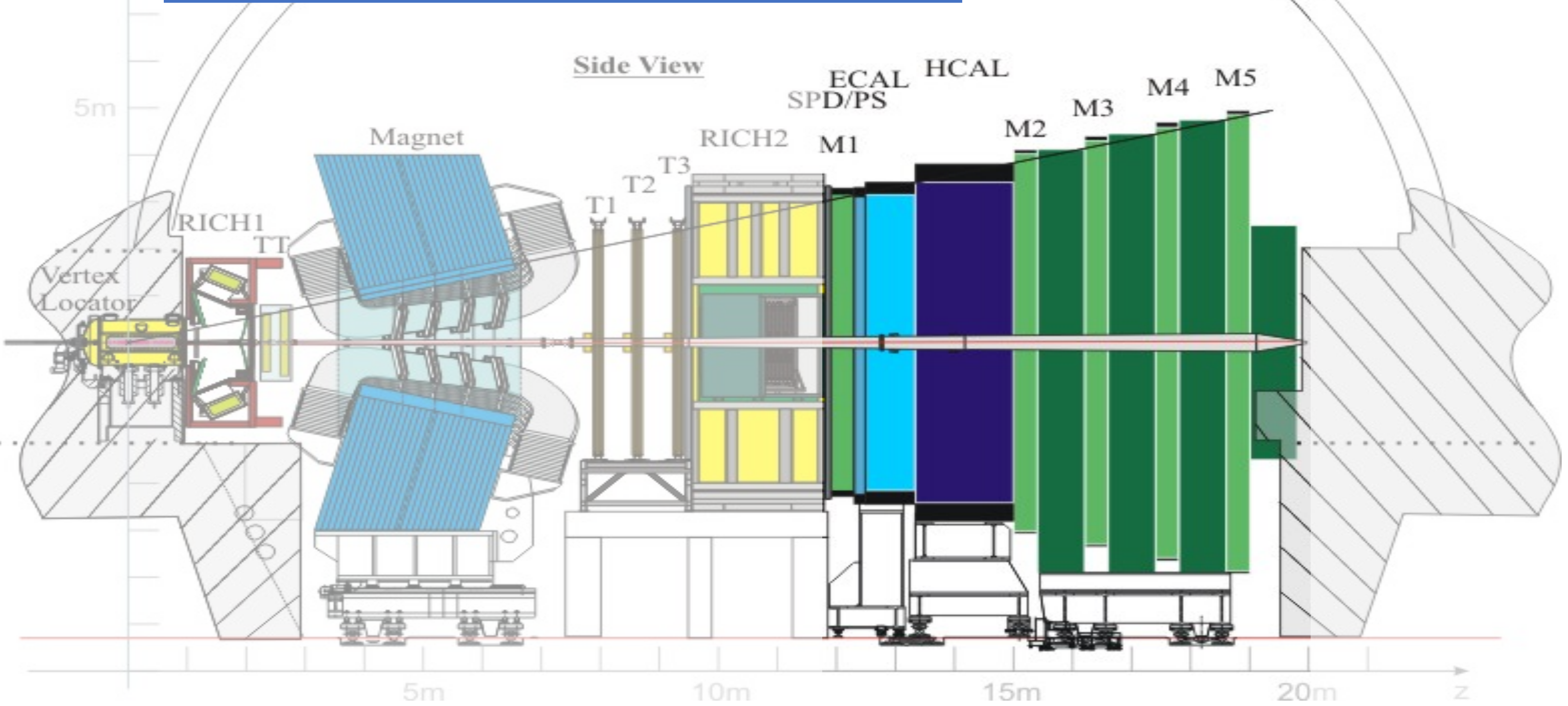
$B_s \rightarrow D_s^- K^+$



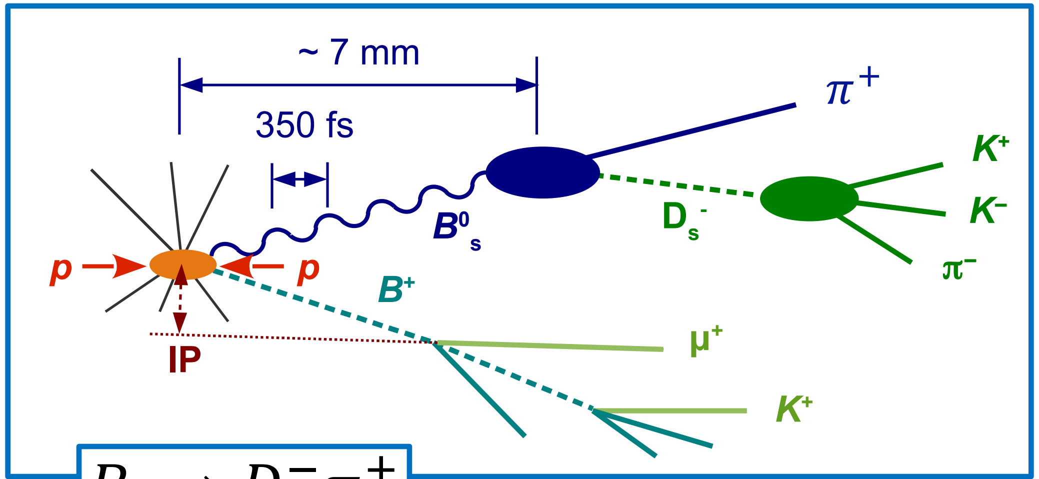
Identification of γ, e , μ:

- Triggering
- Flavour tagging:
  - Opposite or same side



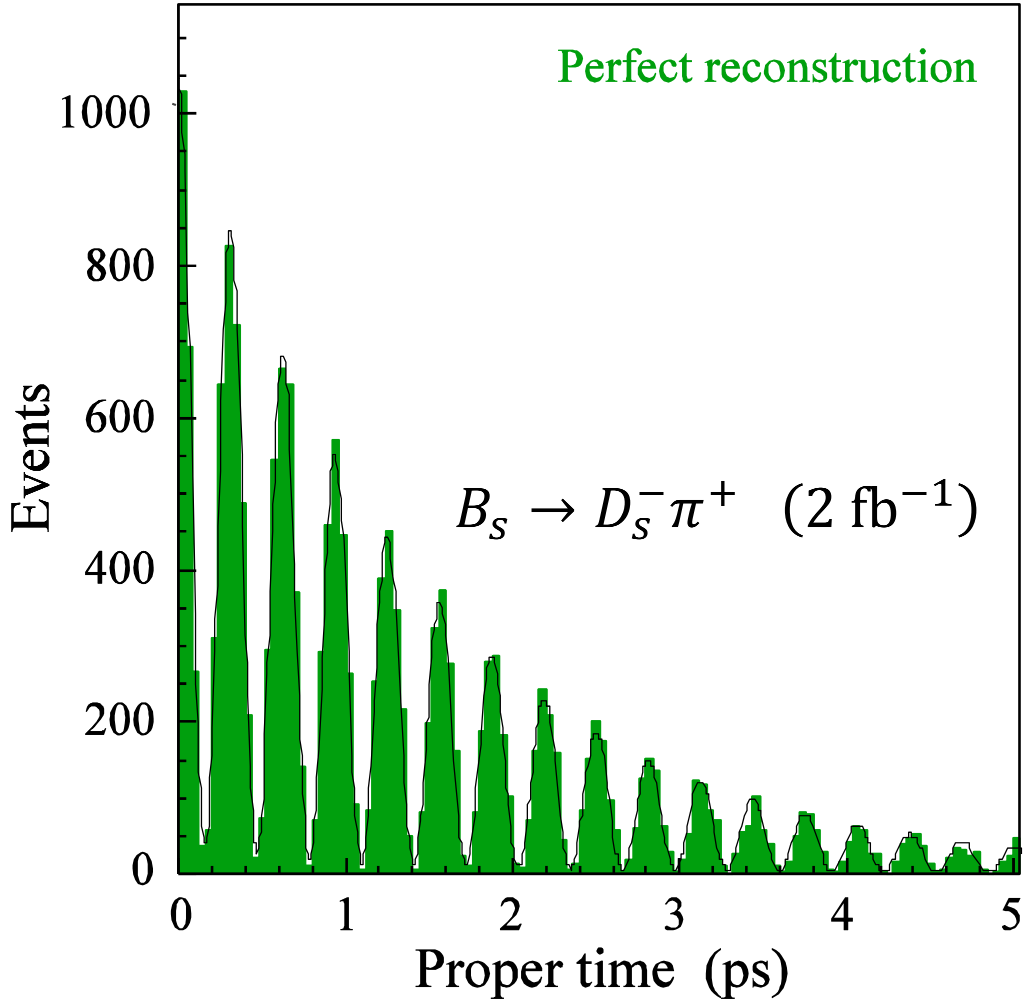


Measuring B_s - $\overline{B_s}$ Oscillations (Self tagging $B_s \to D_s\pi$)



$B_s \to D_s^- \pi^+$

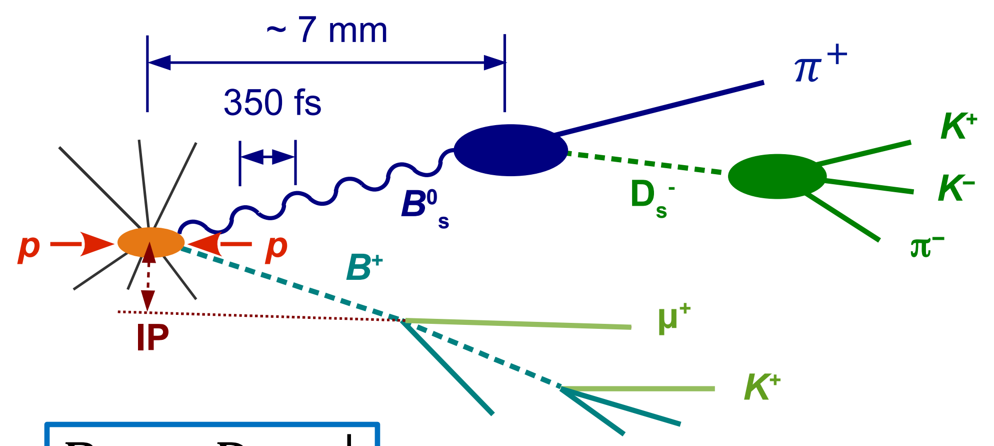
Proper-time dependent decay rate:



Experimental Situation:

Ideal measurement (no dilutions)

Measuring B_s - $\overline{B_s}$ Oscillations



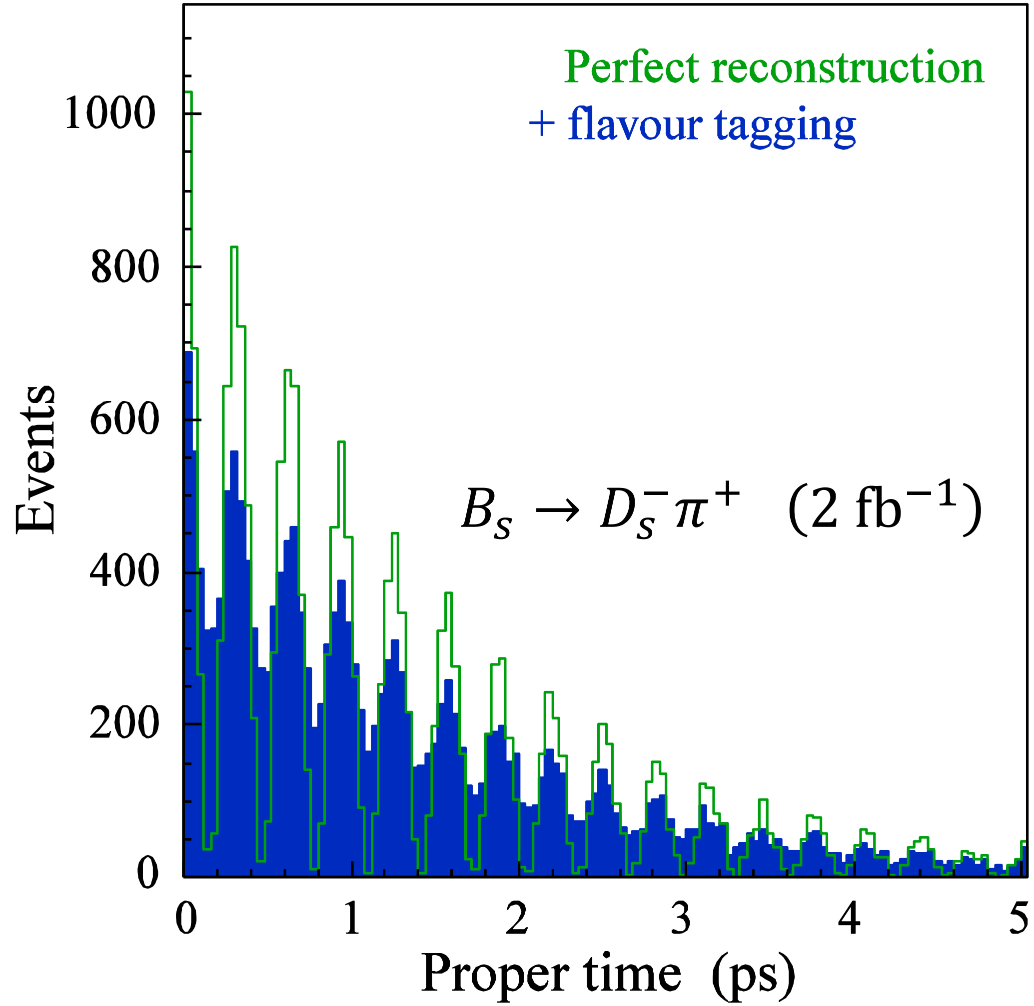
$B_s \to D_s^- \pi^+$

Experimental Situation:

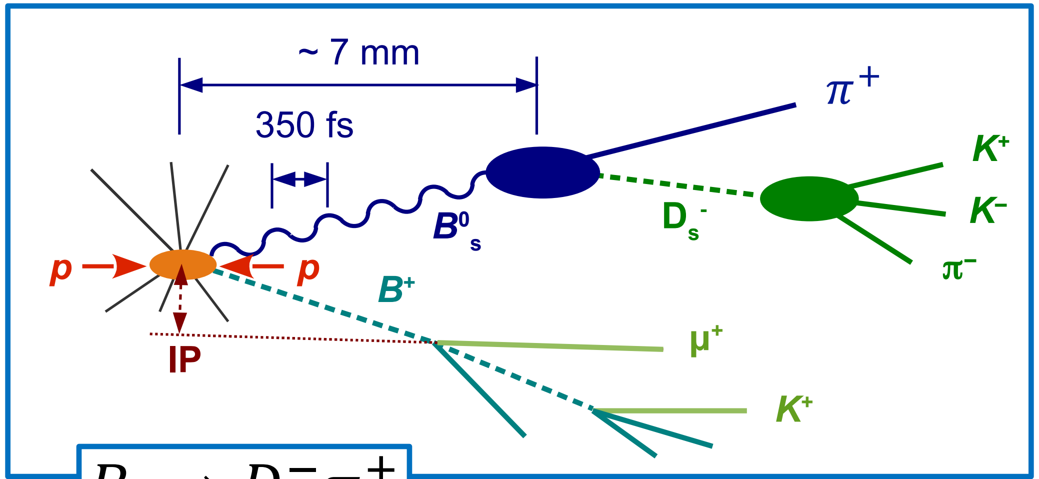
Ideal measurement (no dilutions)

+ Realistic flavour tagging dilution

Proper-time dependent decay rate:



Measuring B_s - $\overline{B_s}$ Oscillations



$B_s \to D_s^- \pi^+$

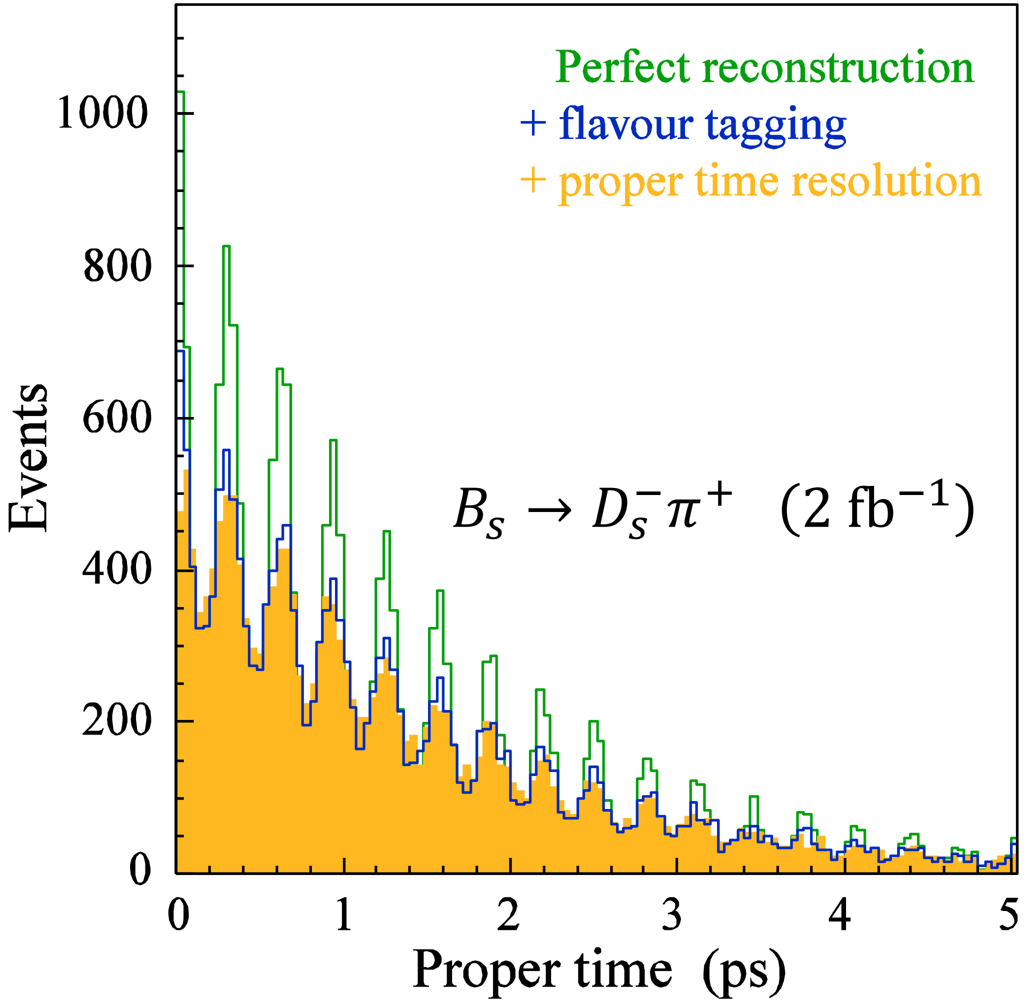
Experimental Situation:

Ideal measurement (no dilutions)

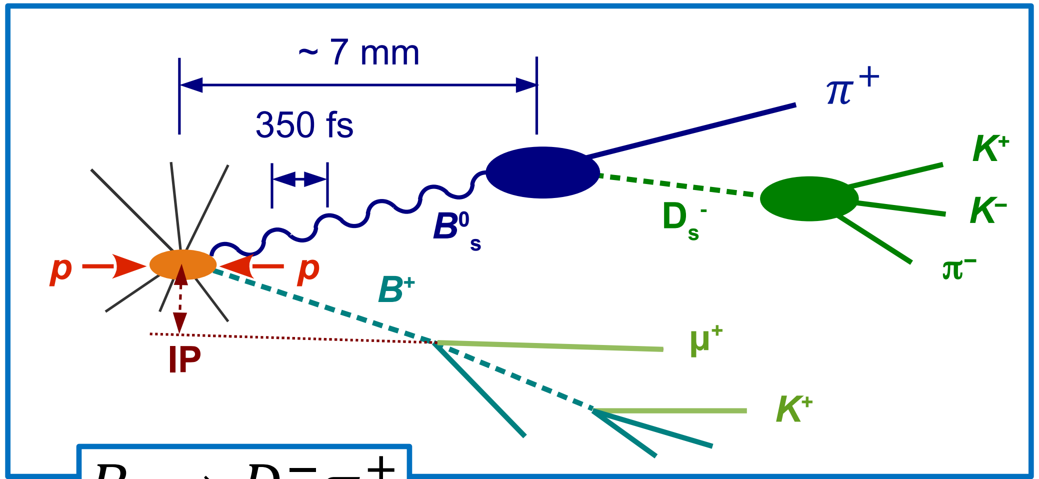
+ Realistic flavour tagging dilution

+ Realistic decay time resolution

Proper-time dependent decay rate:



Measuring B_s - $\overline{B_s}$ Oscillations



$B_s \to D_s^- \pi^+$

__Experimental Situation:__

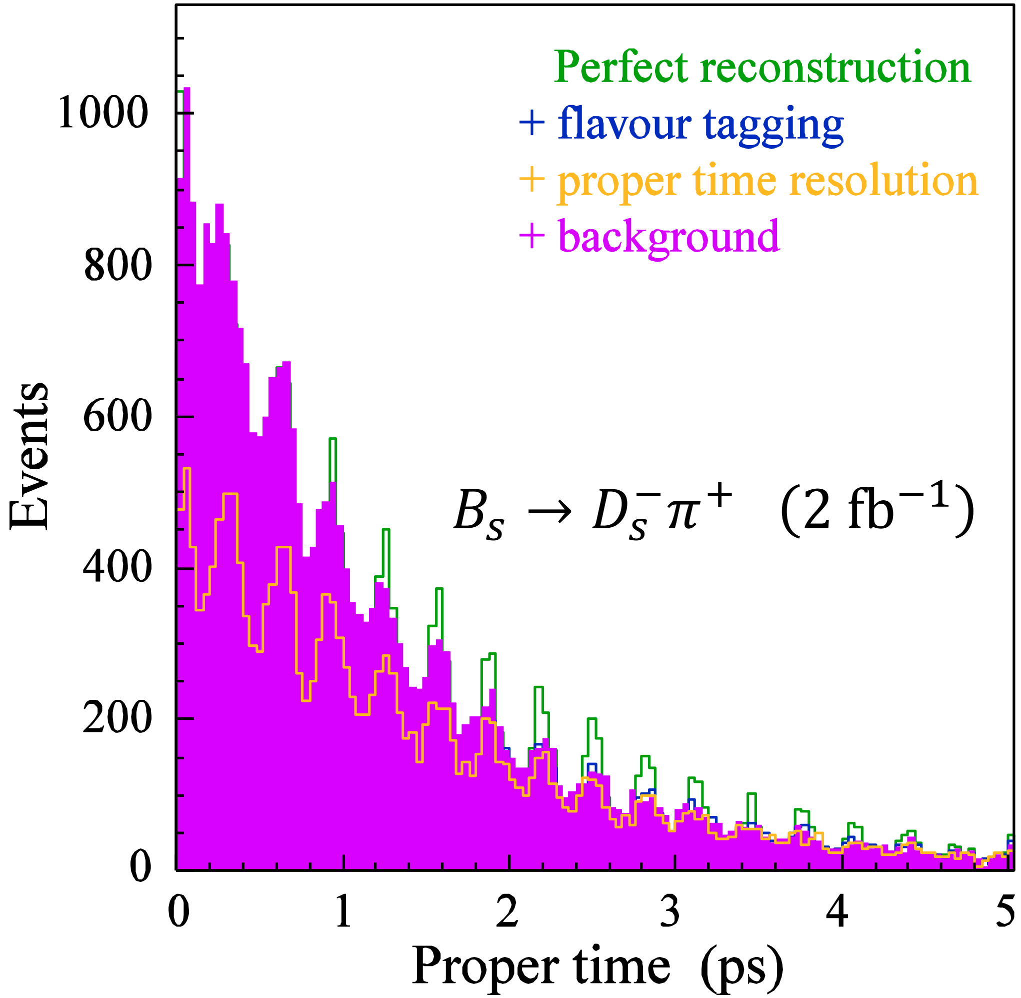
Ideal measurement (no dilutions)

+ Realistic flavour tagging dilution

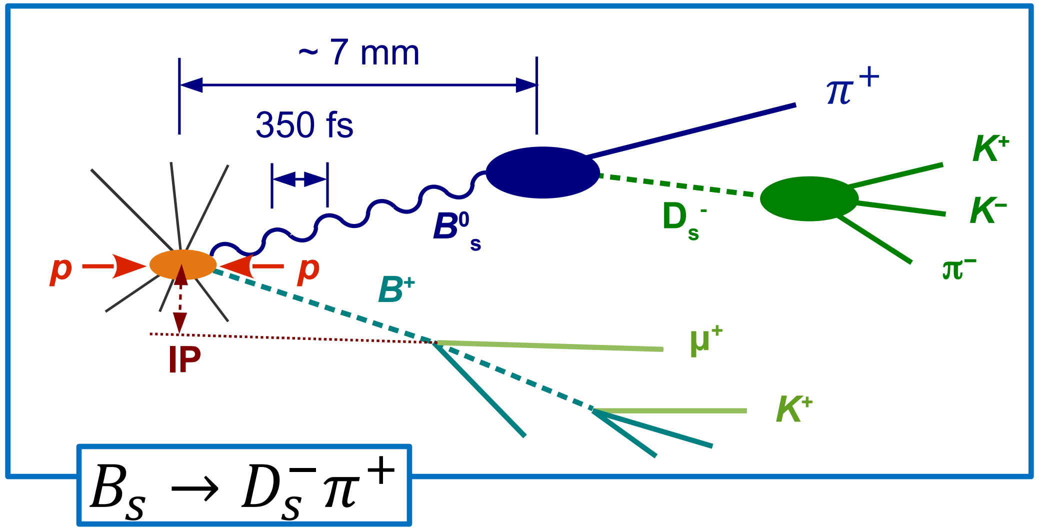
+ Realistic decay time resolution

+ Background events

Proper-time dependent decay rate:



Measuring B_s - $\overline{B_s}$ Oscillations



__Experimental Situation:__

Ideal measurement (no dilutions)

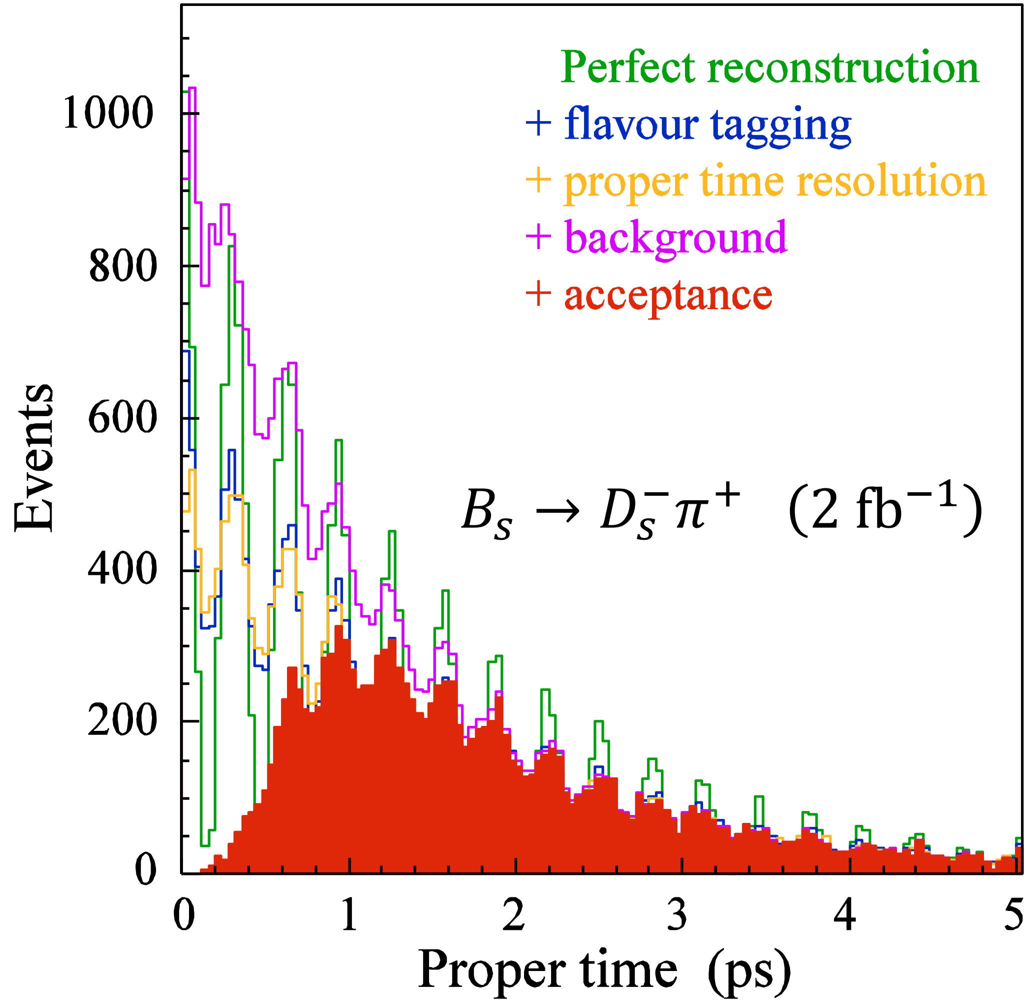
+ Realistic flavour tagging dilution

+ Realistic decay time resolution

+ Background events

+ Trigger and selection acceptance

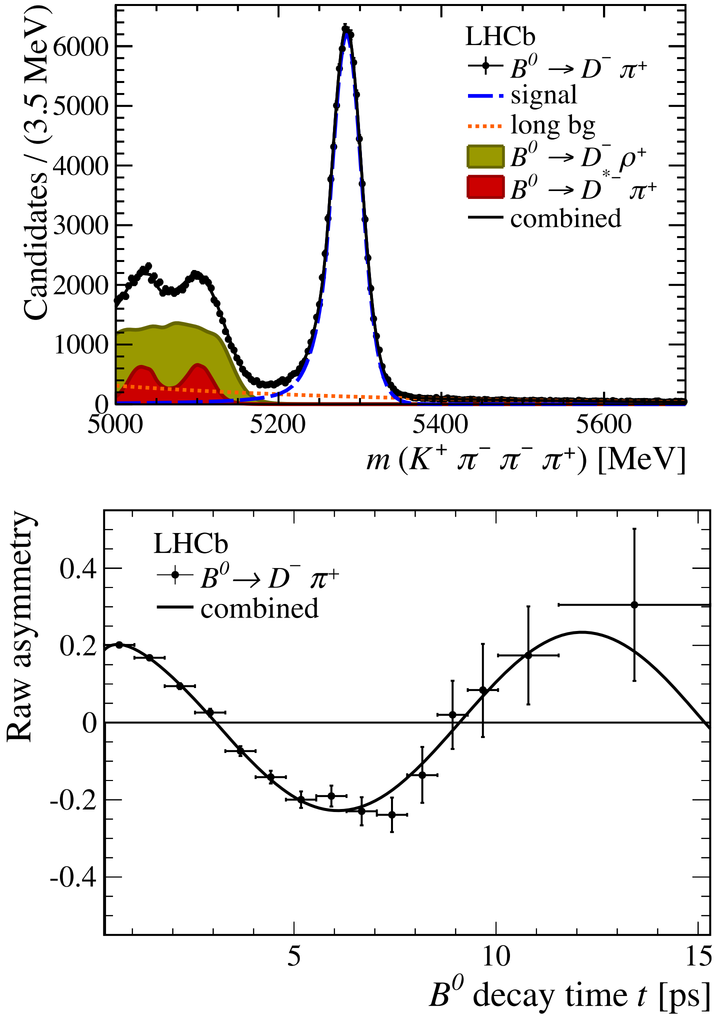
Proper-time dependent decay rate:



Meson mixing in LHCb: does is actually work?

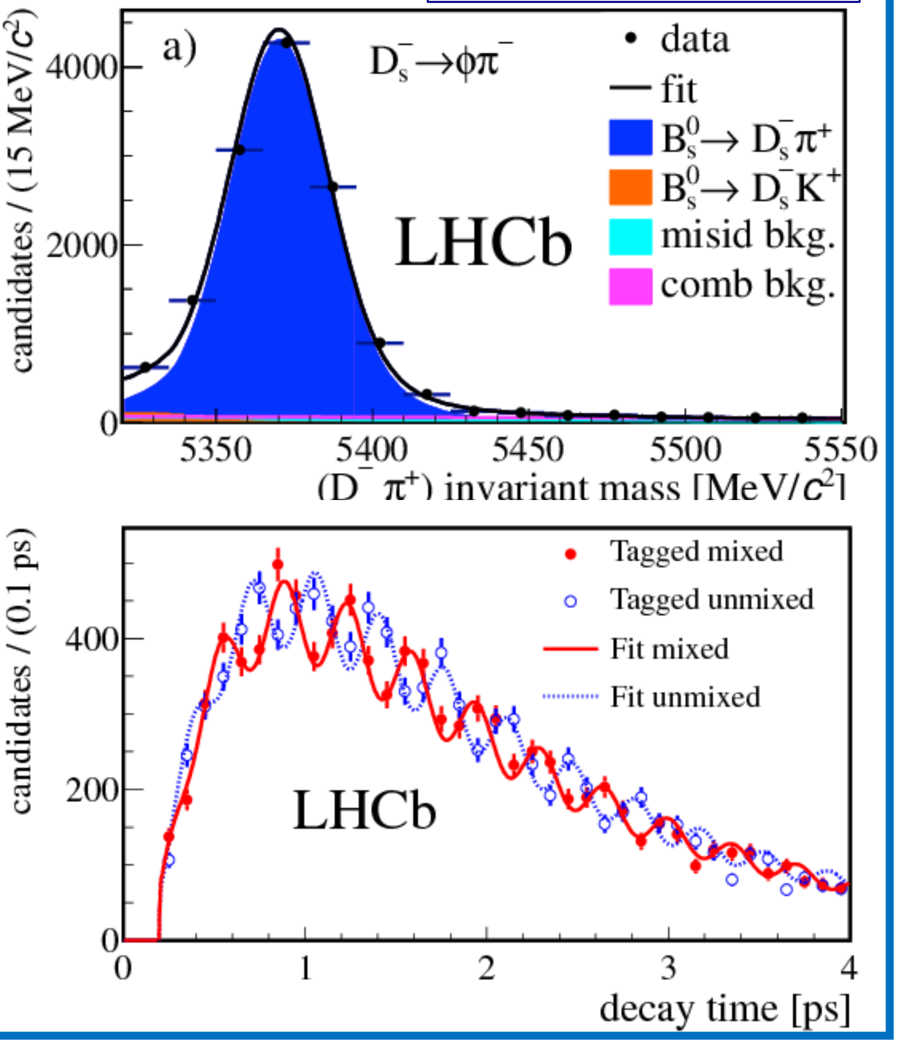
$B^0 - \overline{B^0}$ mixing

$B^0 \to D^- \pi^+$ **Phys.Lett.B719 (2013) 318**



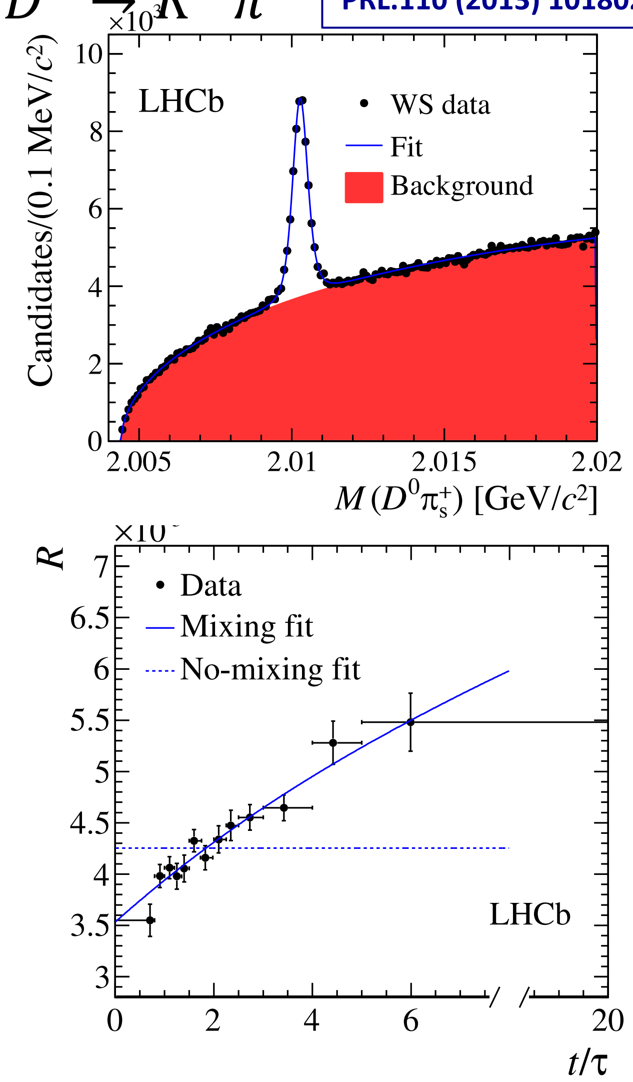
$B_s^0 - \overline{B_s^0}$ mixing

$B_s^0 \to D_s^- \pi^+$ **New.J.Phys.15 (2013) 053021**



$D^0 \to \overline{D^0}$ mixing

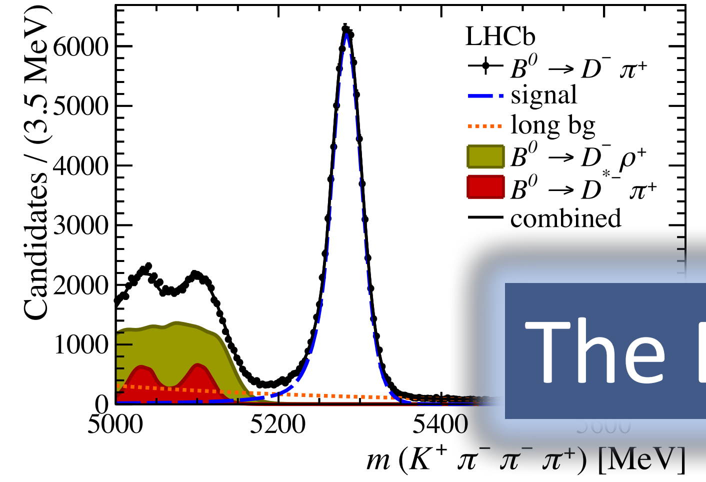
$D^0 \to K^+ \pi^-$ **PRL.110 (2013) 101802**

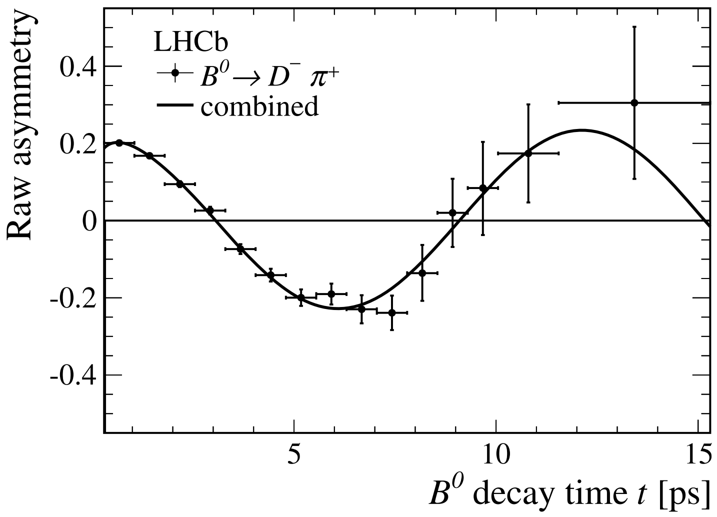


Meson mixing in LHCb: does is actually work?

$B^0 - \overline{B^0}$ mixing

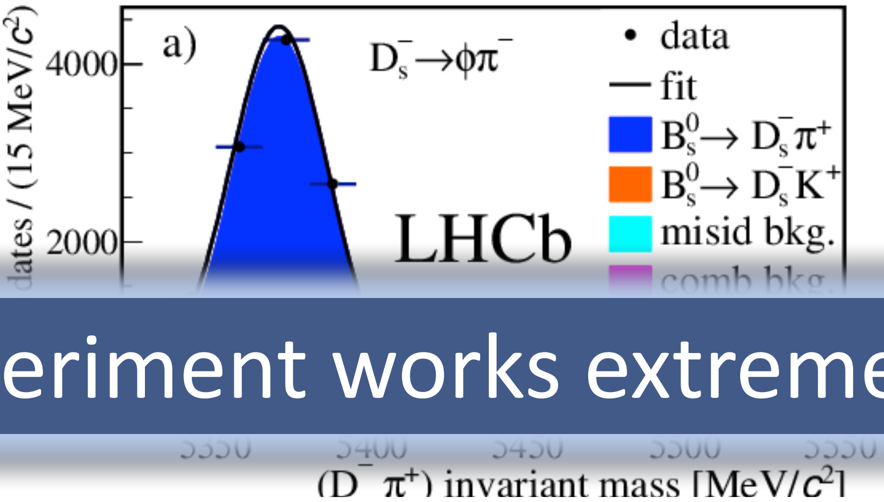
$B^0 \rightarrow D^- \pi^+$ **Phys.Lett.B719 (2013) 318**

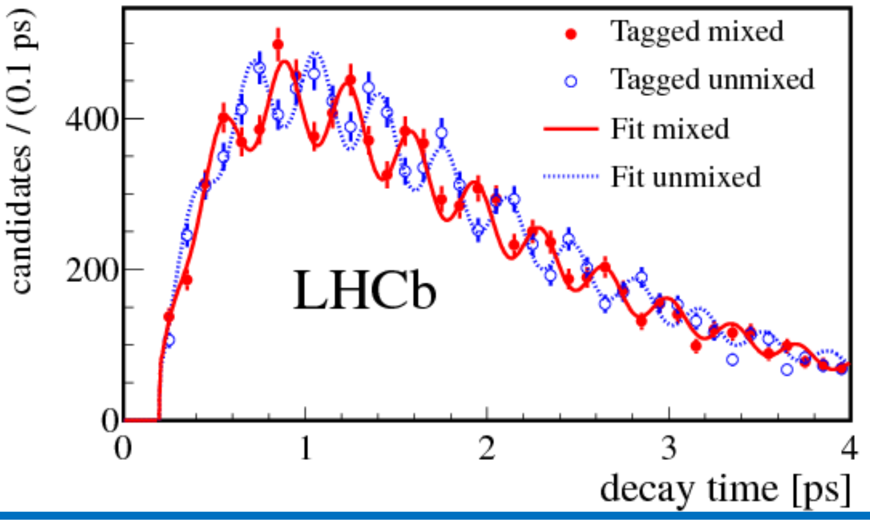




$B_s^0 - \overline{B_s^0}$ mixing

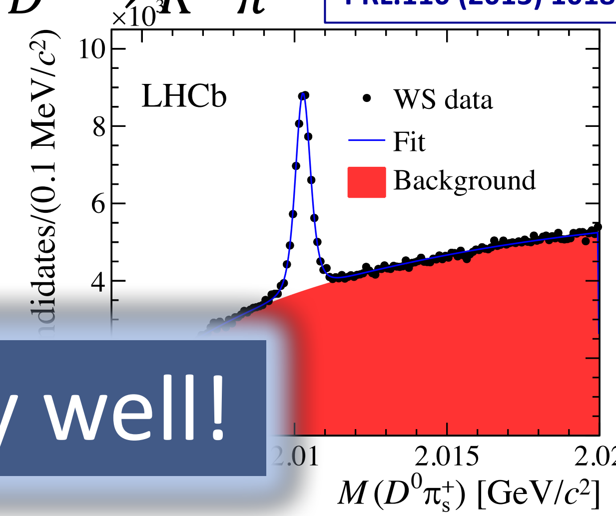
$B_s^0 \rightarrow D_s^- \pi^+$ **New.J.Phys.15 (2013) 053021**

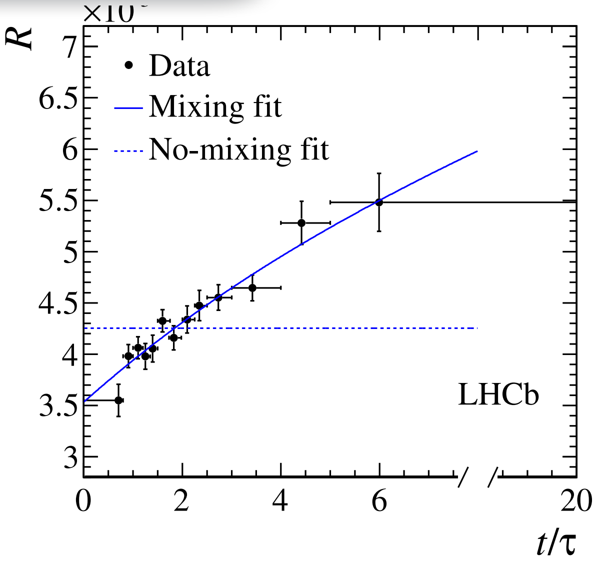




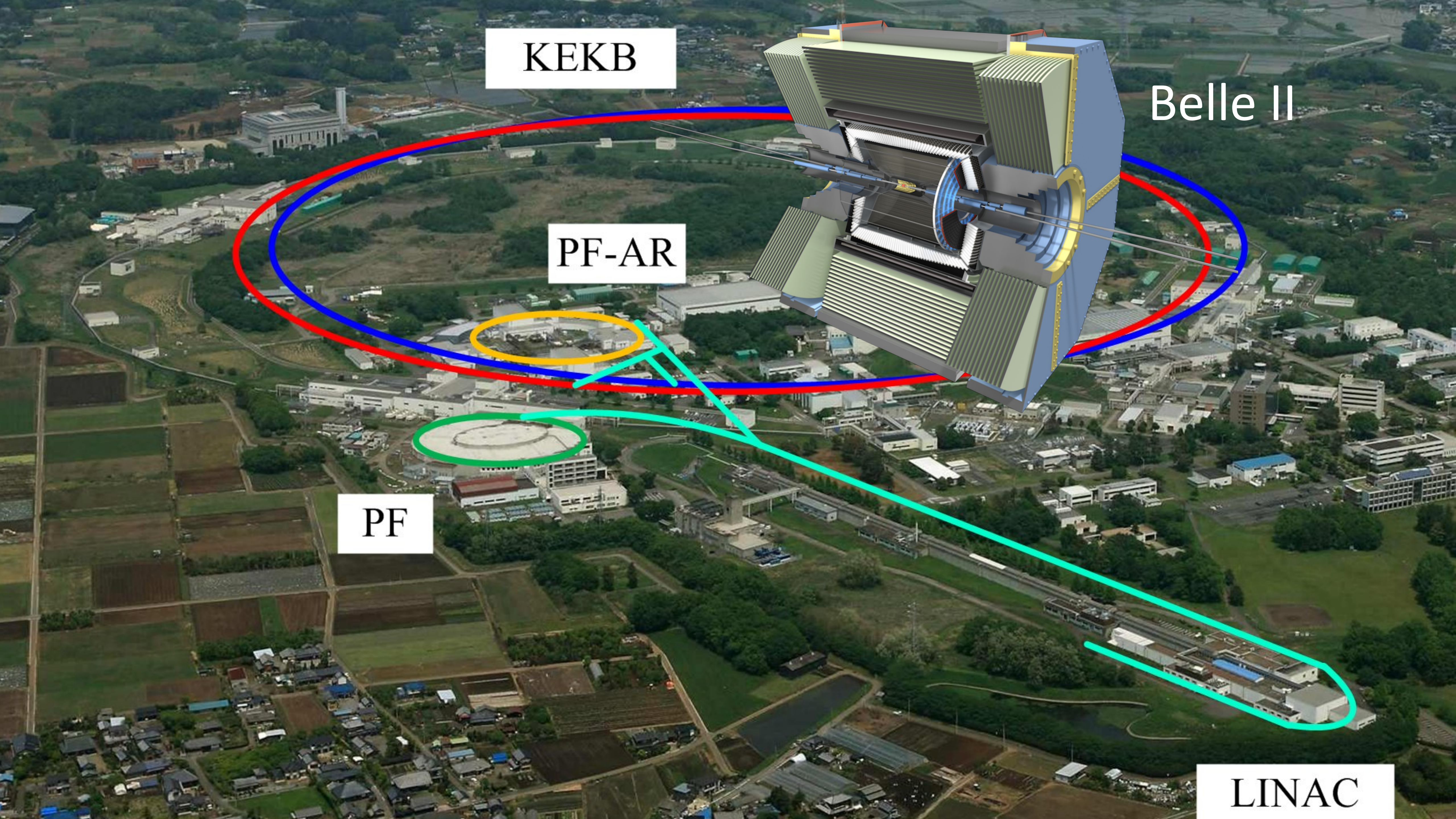
$D^0 \rightarrow \overline{D^0}$ mixing

$D^0 \rightarrow K^+ \pi^-$ **PRL.110 (2013) 101802**





The Experiment works extremely well!

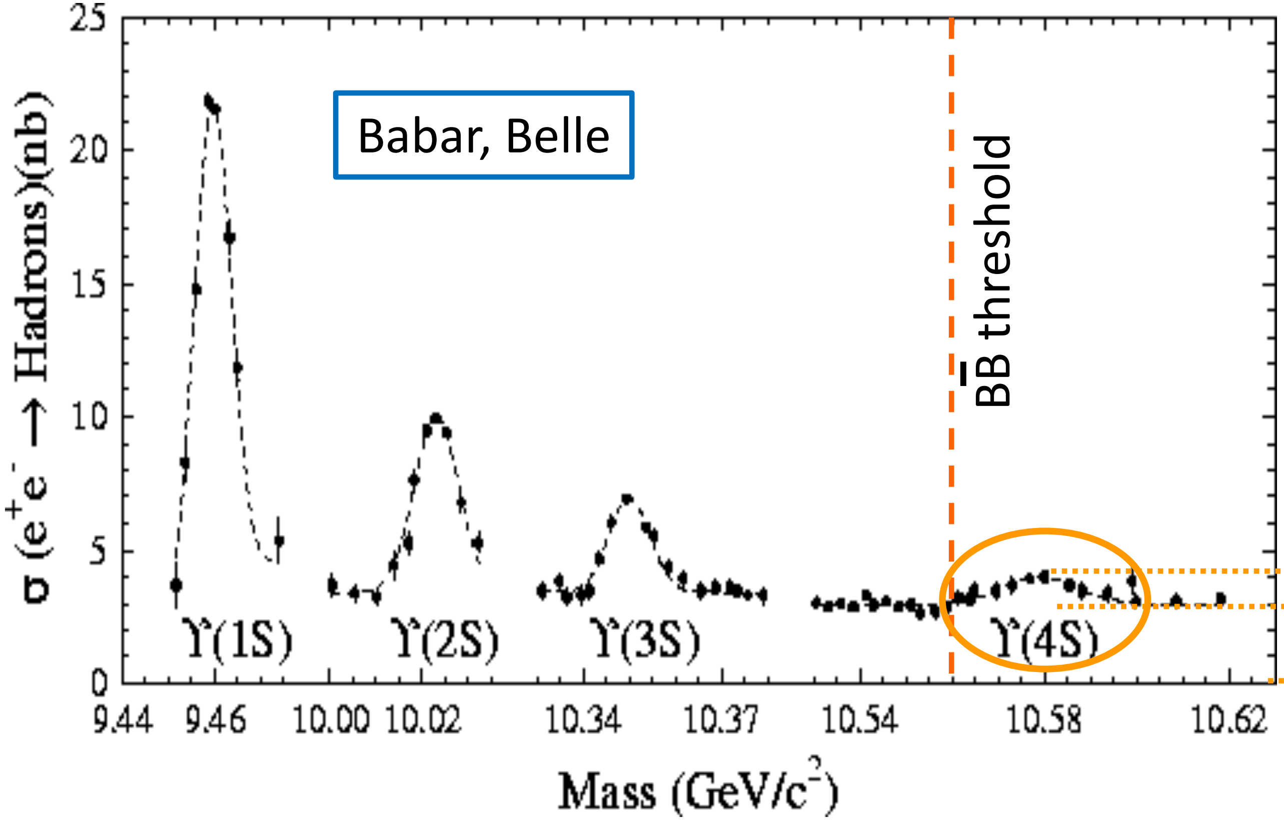

KEKB
Belle II
PF-AR
PF
LINAC

B meson production in e^+e^- Collisions

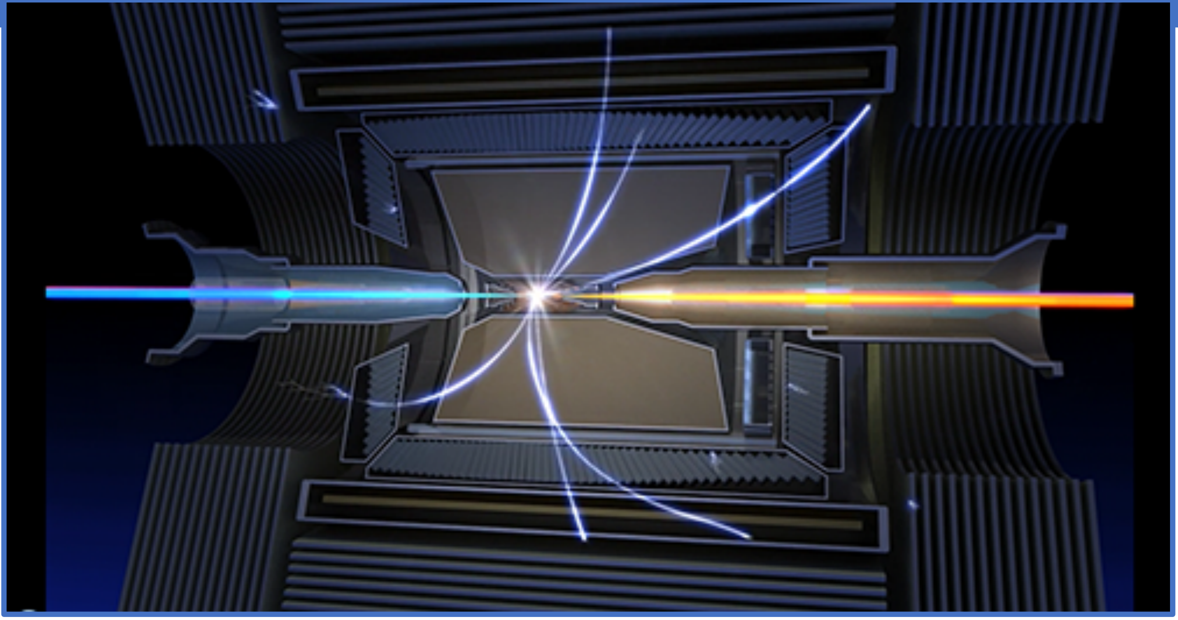
- Electron-Positron collider:

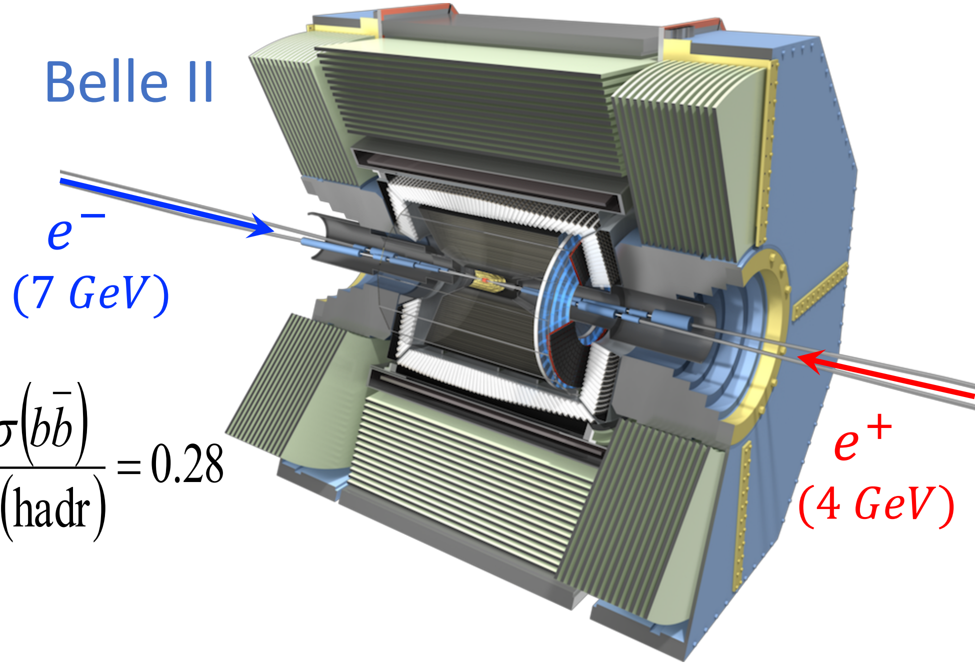
  $e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^0\overline{B^0}$

  – Only 4S resonance or higher produces B meson pair
  – Low B production cross-section: ~1 nb
  – Clean environment, *coherent* $B^0\overline{B^0}$ production



$$\frac{\sigma(b\bar{b})}{\sigma(\text{hadr})} = 0.28$$



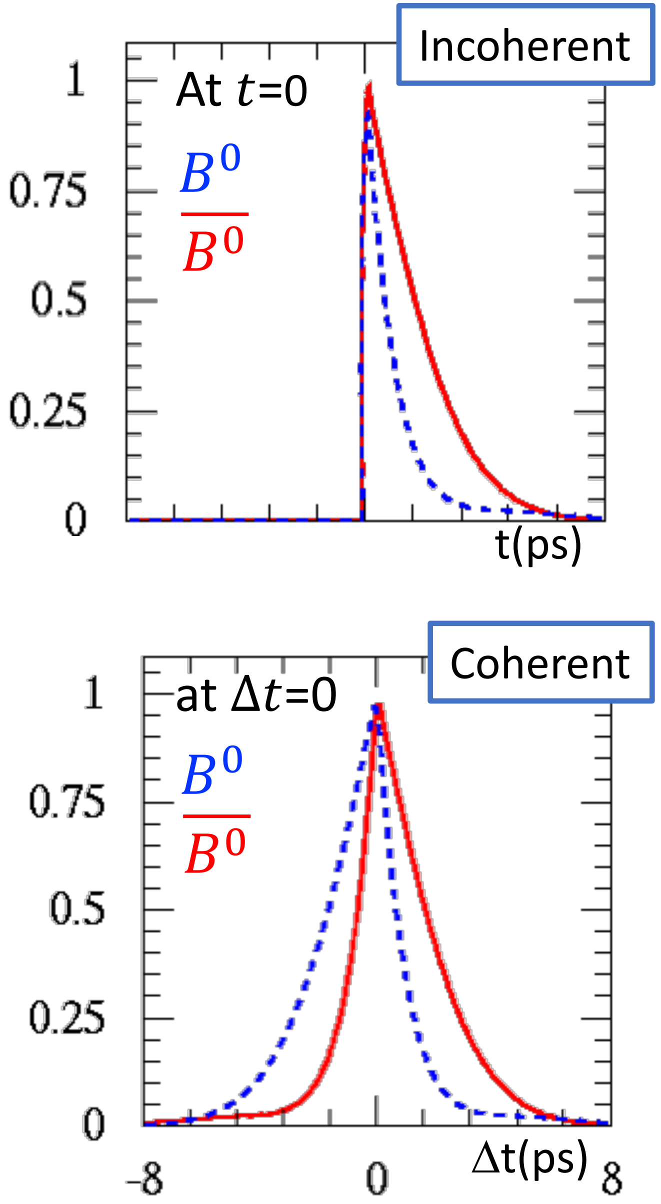


$\Upsilon(4S)$: Coherent B - $\overline{B}$ production

- $B^0\overline{B^0}$ system evolves coherently until one B decays (EPR!)

$$\left|\left(B^0\overline{B^0}\right)_{P=-}(t)\right\rangle = e^{-\Gamma_B t/2}\ \frac{1}{\sqrt{2}}\left|B^0(\vec{k})\,\overline{B^0}(-\vec{k})\right\rangle - \left|B^0(\overline{-\vec{k}})\,\overline{B^0}(\vec{k})\right\rangle$$

- The first decay of the two B's "starts the clock".
- Instead of flavour tag at production, B mesons have opposite flavour at the time the first meson decays.
  - Work with Δt
  - Half of the time the signal B *decays first* ($\Delta t < 0$)
- Coherent production improves flavour tagging performance



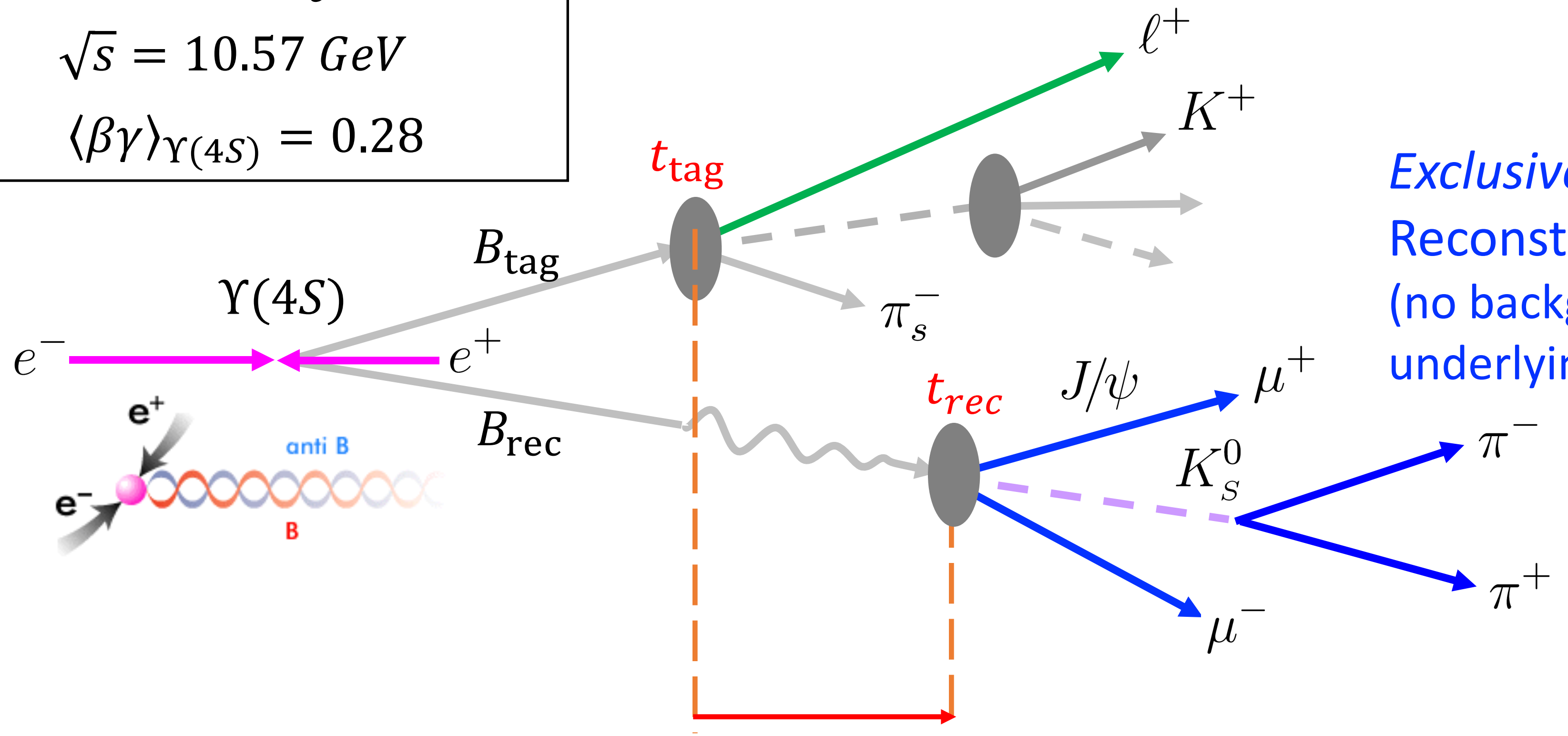
$\Upsilon(4S)$: Coherent B - $\overline{B}$ production (Babar & Belle)

Belle II @ Super KEKB

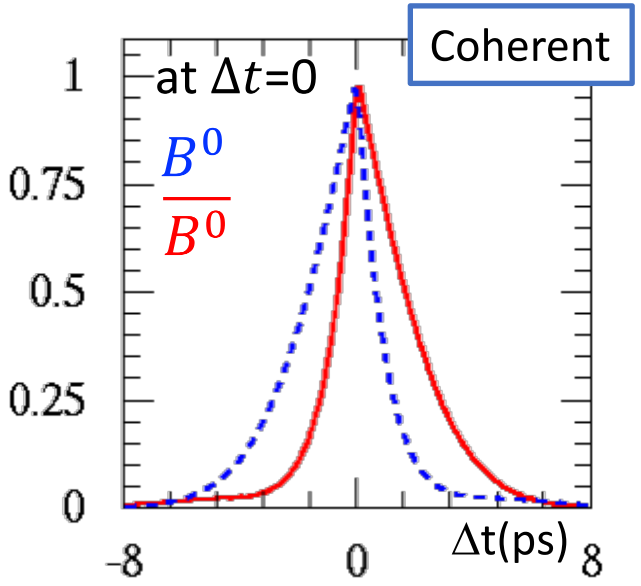
$$E_{e^-} = 7\ GeV \quad ; \quad E_{e^-} = 4\ GeV$$
$$\sqrt{s} = 10.57\ GeV$$
$$\langle \beta\gamma \rangle_{\Upsilon(4S)} = 0.28$$

Flavour tagging of *other* B
(can be 100% pure)

Exclusive B meson
Reconstruction
(no backgrounds from
underlying event)



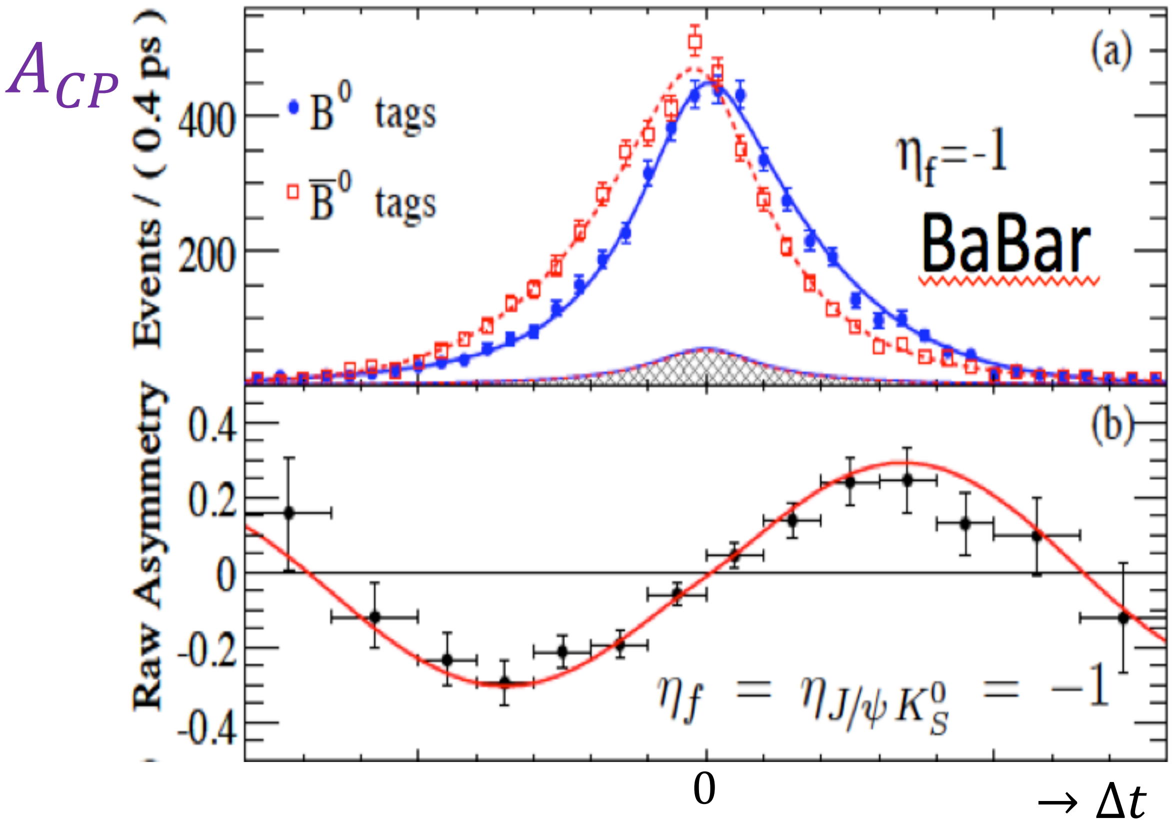
$\Delta t \equiv t_{\rm rec} - t_{\rm tag}$

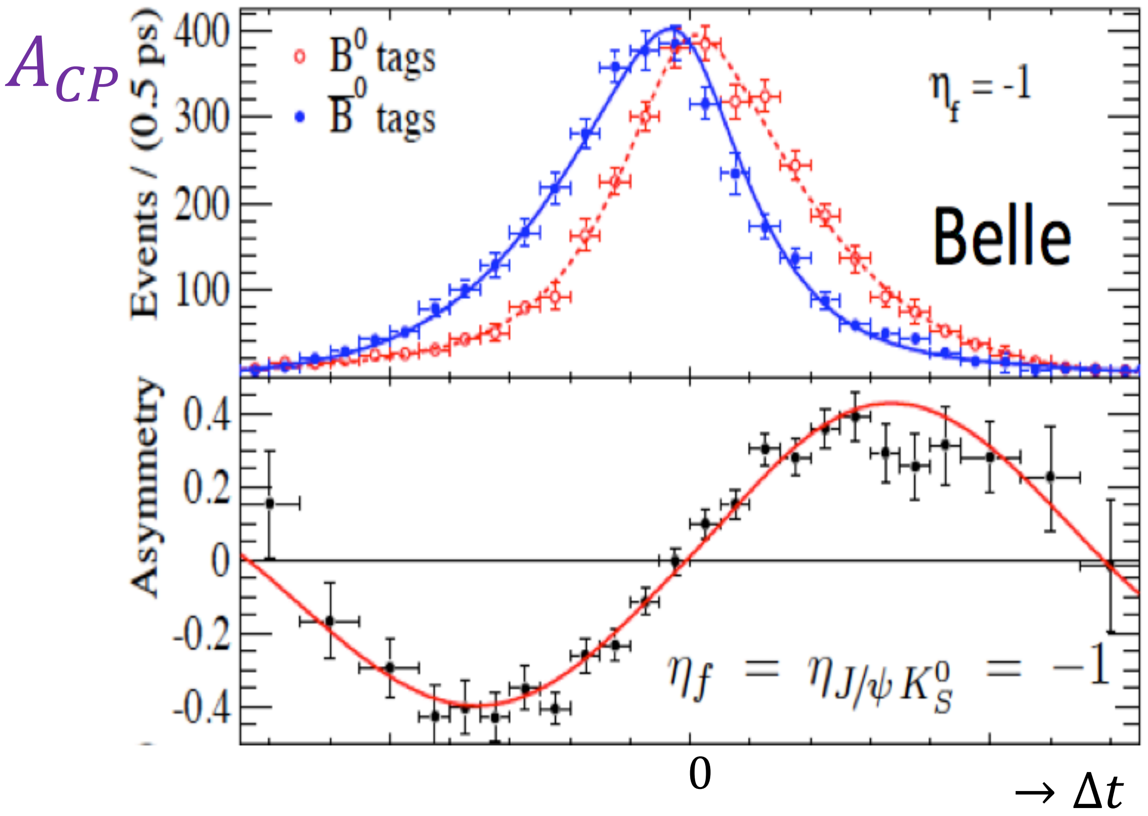


Vertexing and time reconstruction

$\Delta t \approx {}^{\Delta z}/_{c\ \beta\gamma\Upsilon(4S)}$; $(\langle \Delta z \rangle \approx 130\ \mu m)$

CP Asymmetry for "Golden" mode: $B^0 \to J/\psi\ K_S$





$$A_{CP}(t) = \sin 2\beta \sin \Delta m t$$

Babar: $\sin 2\beta = 0.657 \pm 0.036\ (\text{stat}) \pm 0.012\ (\text{syst})$

Belle: $\sin 2\beta = 0.670 \pm 0.029\ (\text{stat}) \pm 0.013\ (syst)$

Babar & Belle

Compare LHC with B-factory for $B^0 \to J/\psi\ K_S$

- *Decay-time dependent*

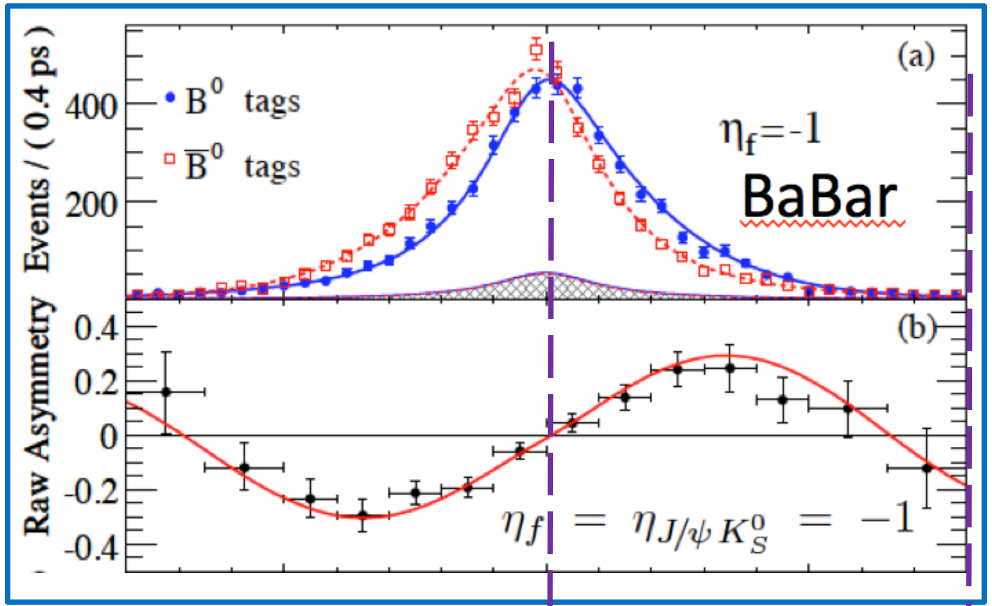
  CP violation:

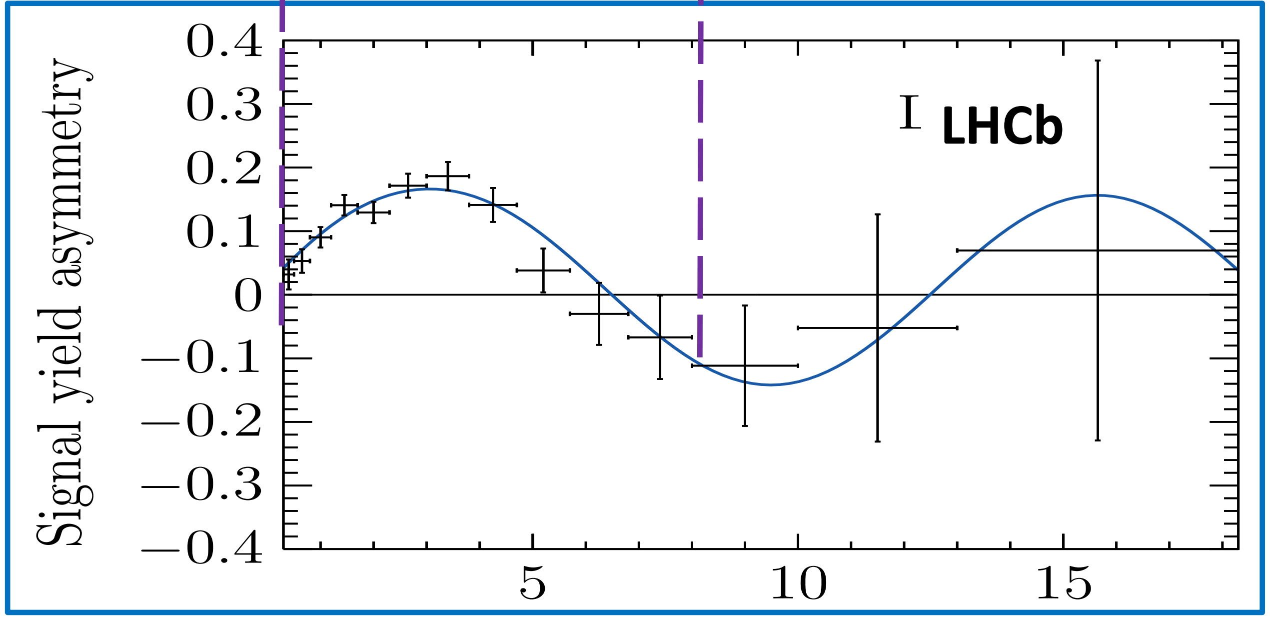
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)}$$

Interfere *direct* and *mixed*

$$B^0 \longrightarrow J/\psi\ K_s$$
$$B^0 \xrightarrow{e^{i2\beta}} \overline{B^0} \longrightarrow J/\psi\ K_s$$

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{tb}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$





Design your own B-meson CP Violation Experiment

- Which type of machine would you use?
  - e^+e^- or pp , pp or $p\overline{p}$ collider or fixed target? Why?
- At which energy do you want to run this machine?
- You will measure CP asymmetry in $B_s \rightarrow D_s^{\mp} K^{\pm}$ with BR=10^{-4}
  - Estimate how many collisions you need for a precision of γ=1^o
- You measure $B_s \rightarrow D_s^{\mp} K^{\pm}$ and $\overline{B_s} \rightarrow D_s^{\mp} K^{\pm}$
  - How do you determine the flavour of the B_s at production?
  - Are there intrinsic limits to this precision?
  - How would you calibrate the wrong tag fraction?
- There is a potential large background from another B_s-decay.
  - Do you know which it could be?
  - With which detector technology would you remove this background?
- What is the formula to reconstruct the B_s meson decay time in an event in observable quantities?
  - Which subdetectors would you require to measure it?

Design your own B-meson CP Violation Experiment

- Which type of machine would you use?
- e^+e^- or pp , pp or $p\overline{p}$ collider or fixed target? Why?
- At which energy do you want to run this machine?

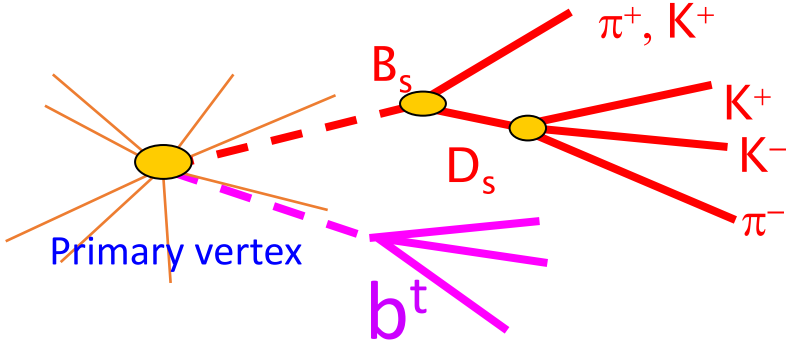
- Points to consider:
  - e^+e^- at $\Upsilon(4S)$: electromagnetic production, clean, *no* B_s, coherent production: B^0 only time dependent CPV, requires asymmetric beams, good flavor tagging.
  - e^+e^- at $\Upsilon(5S)$: B_s, lower cross section, no resolution for time dependent CPV.
  - e^+e^- at Z-peak. Weak production, not coherent, interesting…?
  - pp collisions: Strong production and lots of stat’s, “messy” events, large backgrounds requiring excellent detectors.
  - Fixed target vs collider: low cross section vs long decay distance.
    - b-quark cross section increases with high energy
  - pp vs $p\overline{p}$: ”colour drag” asymmetry. Extra cross check for pp.

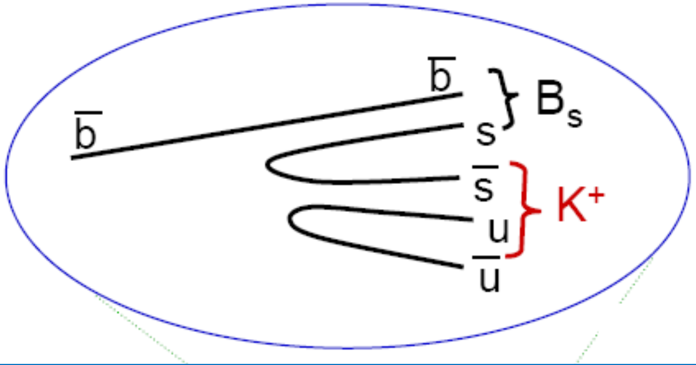
Design your own B-meson CP Violation Experiment

- You will measure CP asymmetry in $B_s \to D_s^{\mp} K^{\pm}$ with BR=10^{-4}.
  - Estimate how many collisions you need for a precision of γ=1°
  - B_s mesons: Let's assume pp collisions at LHC using LHCb
- For ~1% measurement precision (0.01) on asymmetry:
  - Number of perfectly measured $B_s \to D_s^{\mp} K^{\pm}$ events:
    - N ~ 10.000
  - Fraction of collisions that produce b-quarks:
    - ~ 1 in 100
  - Fraction of events where B_s meson is produced from b-quark:
    - 1 in 10
  - Fraction of B_s that decay into $B_s \to D_s^{\mp} K^{\pm}$ channel
    - 1 in 5000 (BR = 2 x 10^{-4})
- ➔ So in total ~ 10.000 x 100 x 10 x 5000 = 5 x 10^{10} perfectly reconstructed events required
- Next, assumed measured by the LHCb experiment:
  - Acceptance x Reconstruction (background, resolution):
    - 1 in 40
  - Trigger:
    - 1 in 3
  - Tagging Power:
    - 4% → 1 in 25
- In total 5 x 10^{10} x 40 x 3 x 25 = 1.5 x 10^{14} pp collisions must be collected
- Assume ~10 MHz collisions, 3 x 10^{6} s/year running time: ~ 5 years of running.

Design your own B-meson CP Violation Experiment

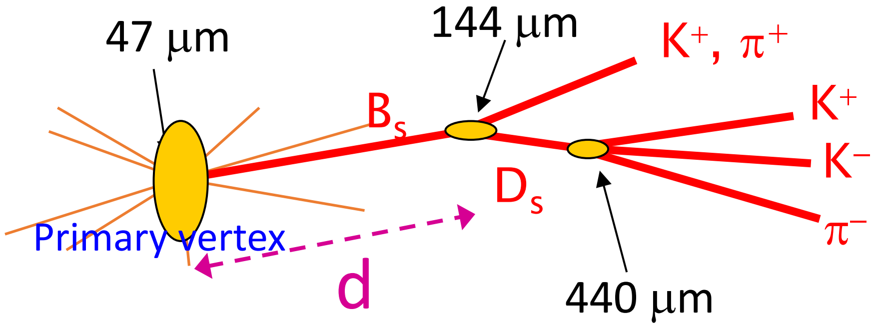
- You measure $B_s \to D_s^{\mp} K^{\pm}$ and $\overline{B_s} \to D_s^{\mp} K^{\pm}$
  - How do you determine the flavour of the B_s at production?
    - Opposite side tag:
      - charge of lepton from b-decay, charge of kaon from b-decay, vertex charge.
    - Same side tag: “closest” kaon in the color string.
  - Are there intrinsic limits to this precision?
    - B-mixing of neutral B:
      - Charged B^+, B^- =perfect, B_d^0= ok-ish, B_s^0 = no information
  - How would you calibrate the wrong tag fraction?
    - Use $B_s \to D_s^- \pi^+$ and $\overline{B_s} \to D_s^+ \pi^-$ Mixing asymmetry has amplitude 1 → calibrate.





Design your own B-meson CP Violation Experiment

- There is a potential large background from another B_s-decay.
  - Do you know which it could be?
    - $B_s \to D_s\pi$
  - With which detector technology would you remove this background?
    - $\pi - \mathrm{K}$ seperation using RICH particle identification
- What is the formula to reconstruct the B_s meson decay time in an event in observable quantities?
    - $t = md/p$
  - Which subdetectors would you require to measure it?
    - $d \;\to$ Vertex detector
    - $p \;\to$ Magnet Tracker
    - $m \to B$ meson mass



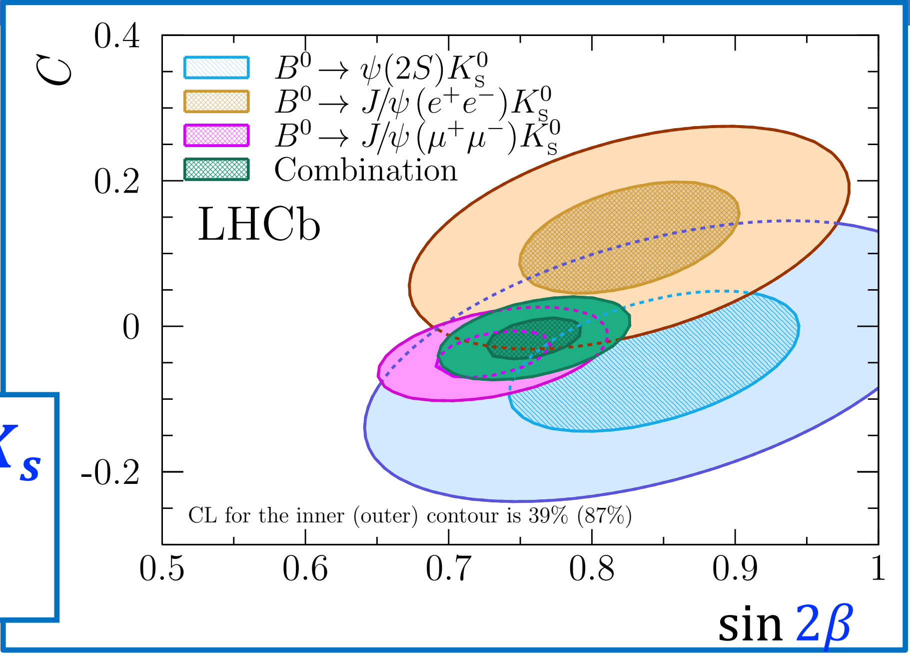
Decay time resolution = 40 fs

Decay time dependent CP violation

- $B^0 \to J/\psi\, K_s$ and $B_s^0 \to J/\psi\, \phi$

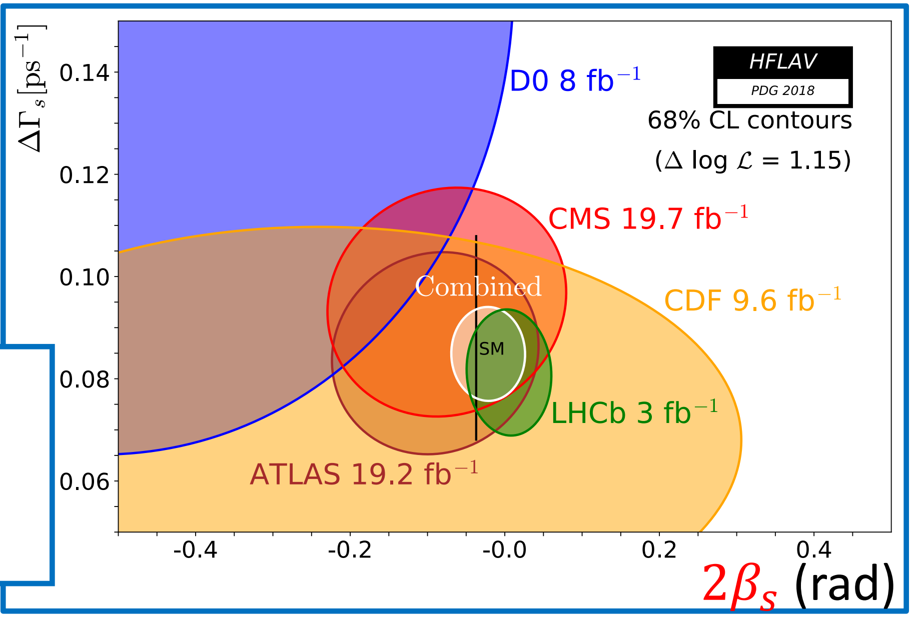
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}_{(s)}\to f}(t) - \Gamma_{B_{(s)}\to f}(t)}{\Gamma_{B_{(s)}\to f}(t) + \Gamma_{B_{(s)}\to f}(t)}$$

$$\begin{tikzcd} B^0 \arrow[rr] \arrow[dr, "e^{i2\beta}"'] & & J/\psi\ K_s \\ & \overline{B^0} \arrow[ur] & \end{tikzcd}$$



$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{tb}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

$$\begin{tikzcd} B_s^0 \arrow[rr] \arrow[dr, "e^{i2\beta_s}"'] & & J/\psi\, \phi \\ & \overline{B_s^0} \arrow[ur] & \end{tikzcd}$$

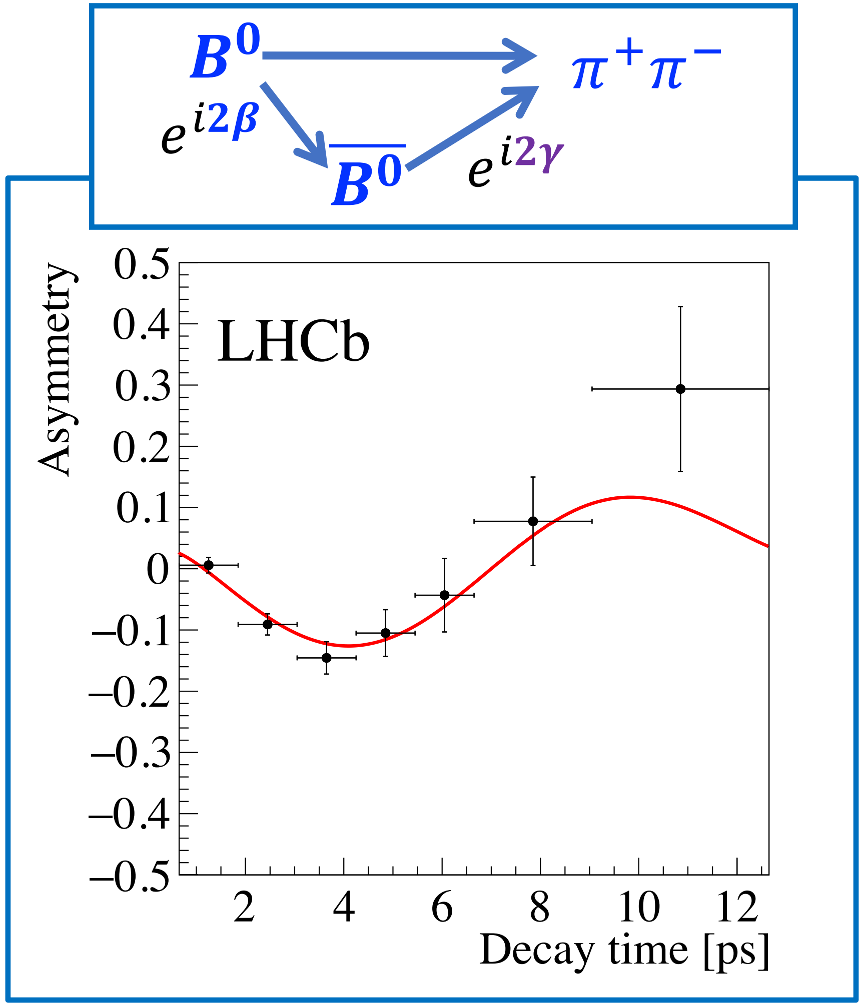


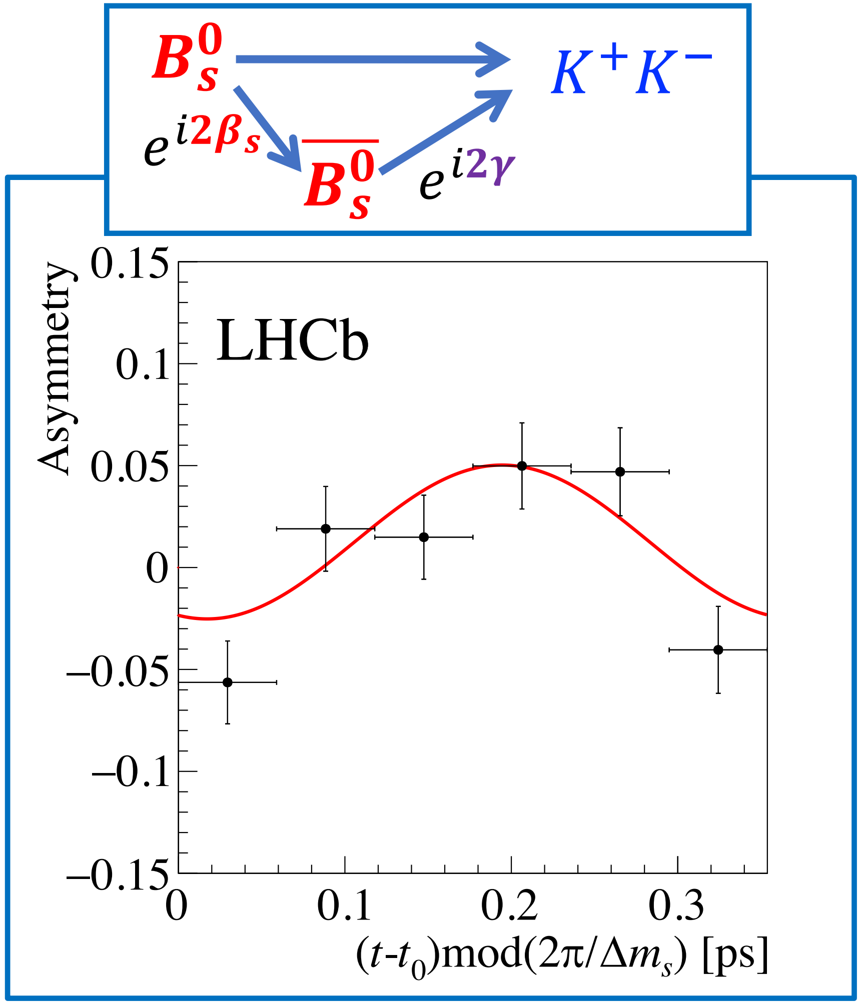
Decay time dependent CP violation

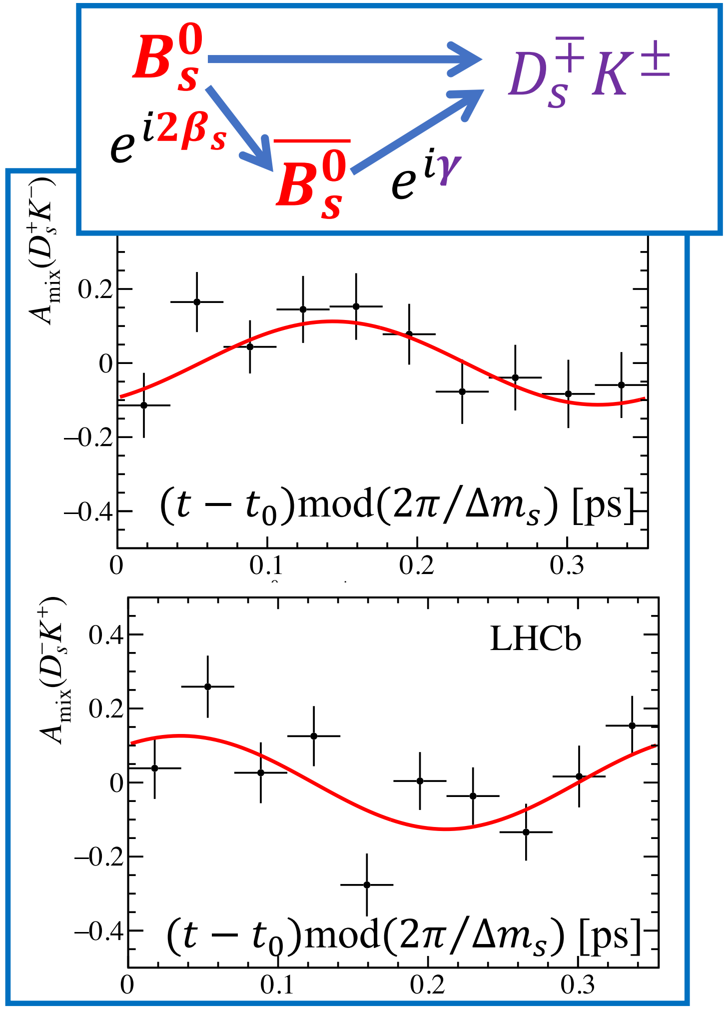
- *Hadronic decay modes (LHCb)*:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{tb}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

Note: $\alpha = \pi - (\beta + \gamma)$

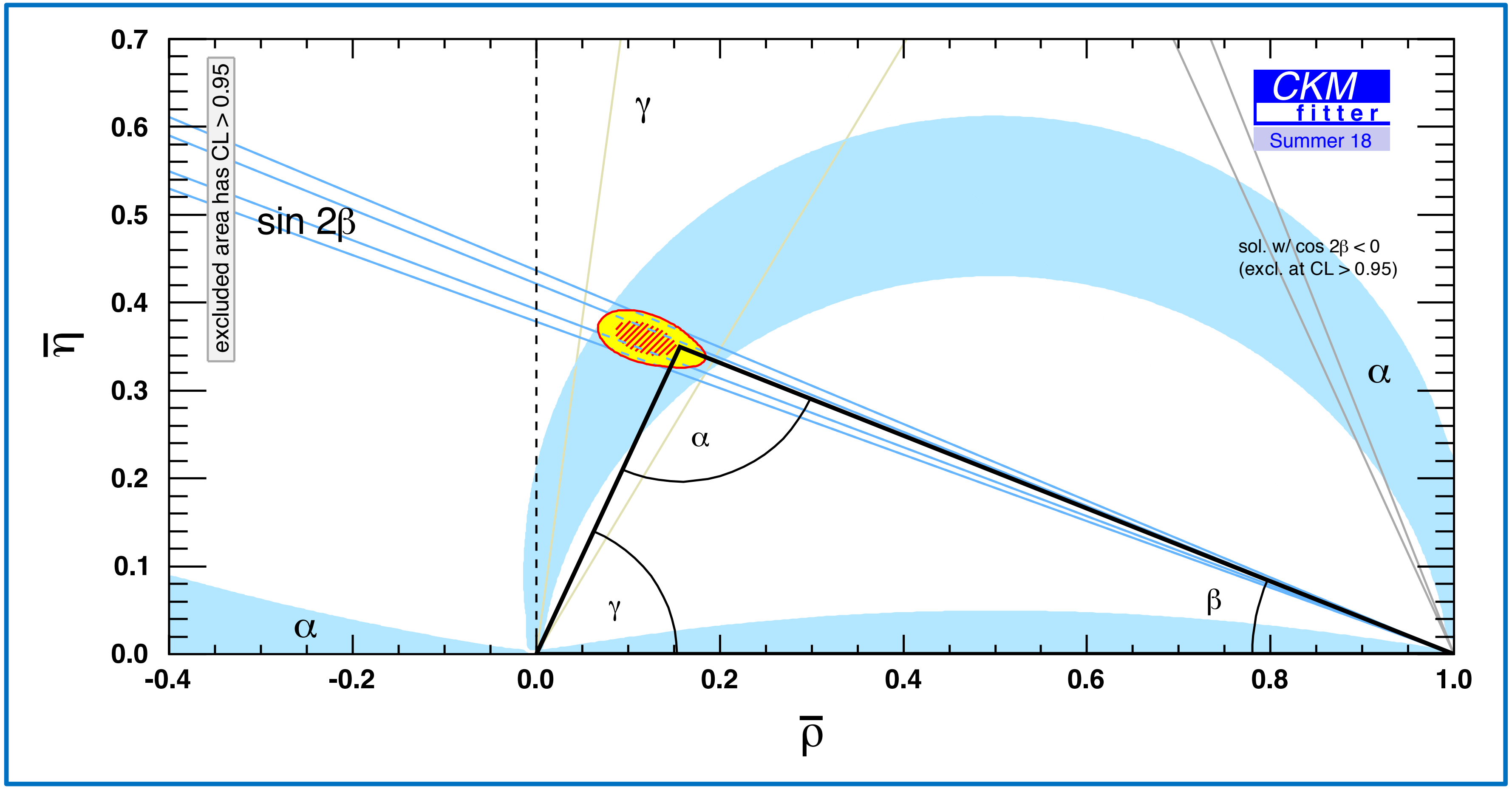






CKM triangle: putting all measurements together

	Measured	CKMfitter prediction	UTfit prediction
β	22.7 ± 0.7	$23.7^{+1.1}_{-1.0}$	23.8 ± 1.4
γ	70.0 ± 4.2	$65.3^{+1.0}_{-2.5}$	65.8 ± 2.2
α	93.1 ± 5.6	$92.1^{+1.5}_{-1.1}$	90.1 ± 2.2



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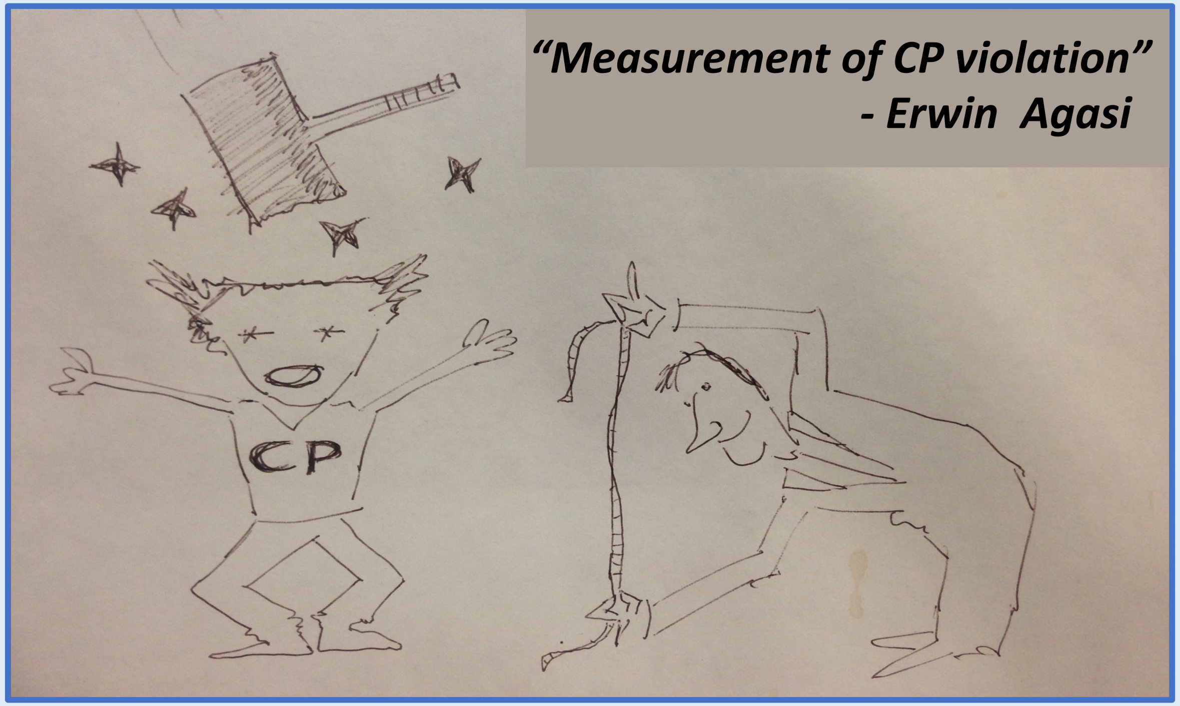
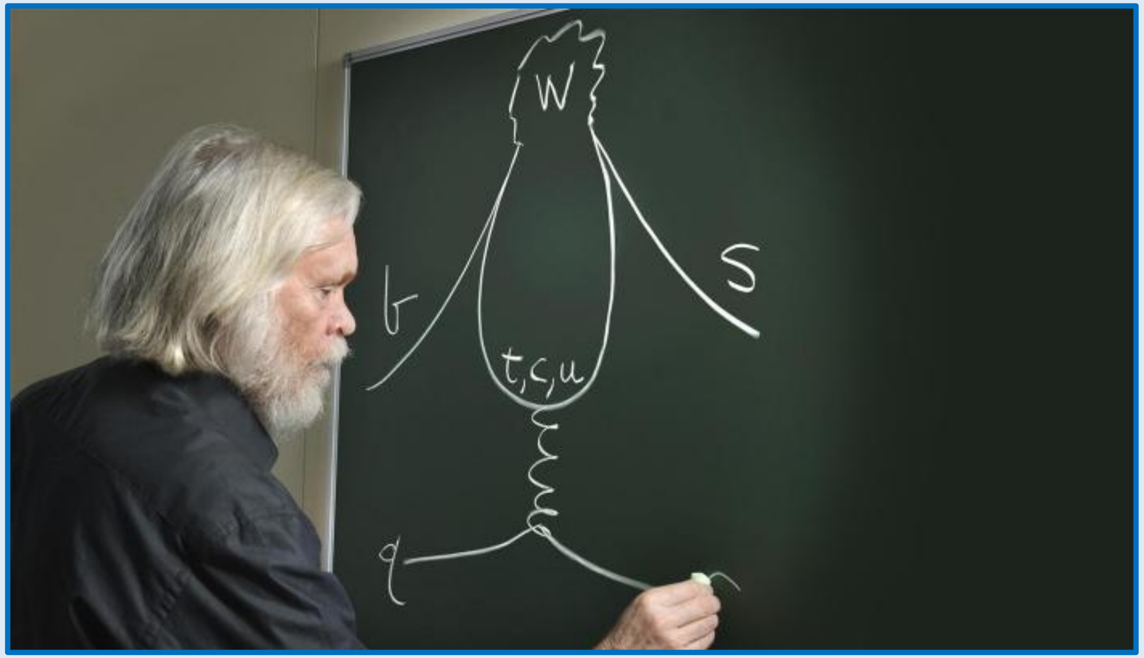


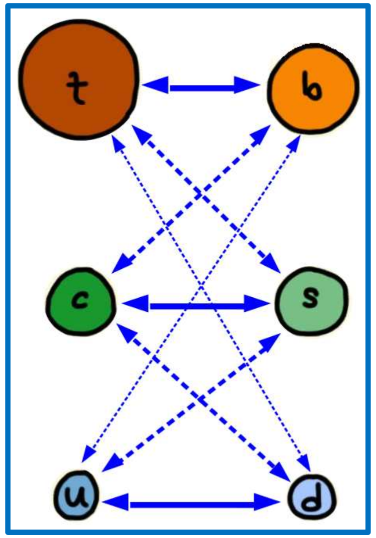
"Measurement of CP violation"
- Erwin Agasi

Contents:

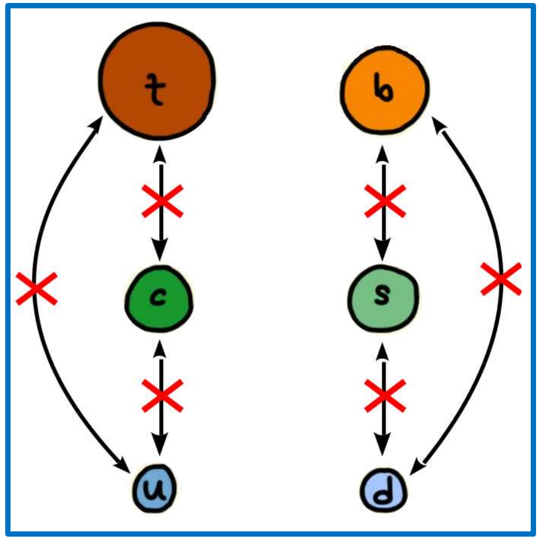


S.M.: No Flavour Changing Neutral Currents (FCNC)

- CKM: Flavour changing *charged* currents

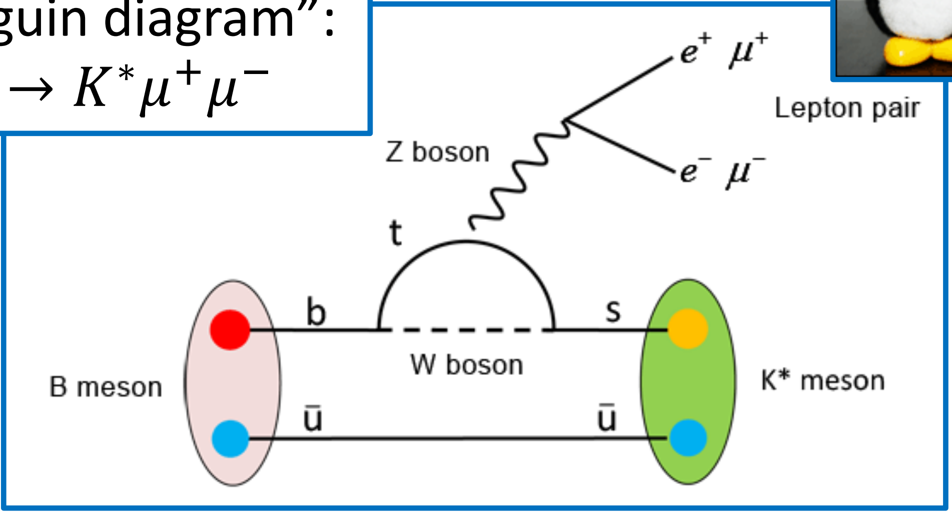


- SM does *not* have Flavour changing *neutral* currents

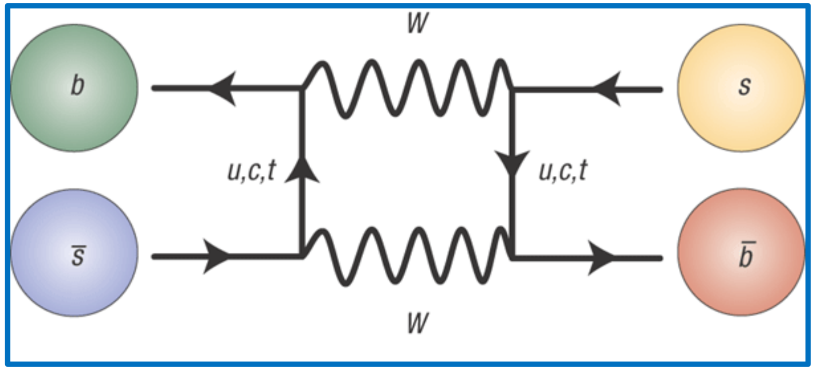


- Neutral currents are possible via higher order processes:

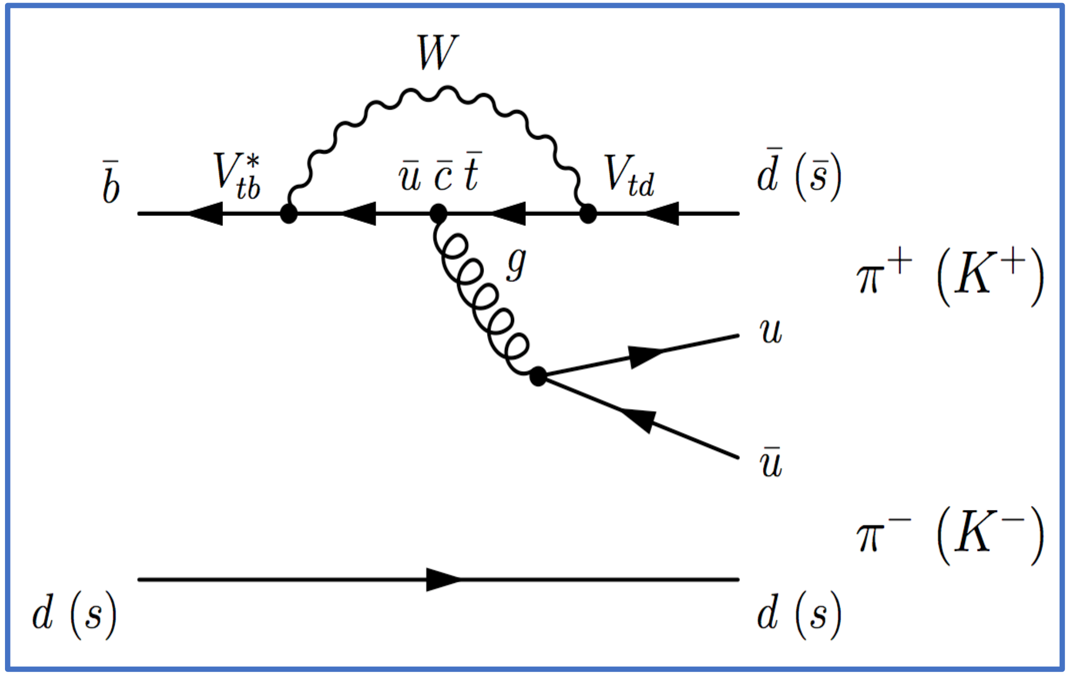
Decay via "Penguin diagram": $B \to K^* \mu^+ \mu^-$

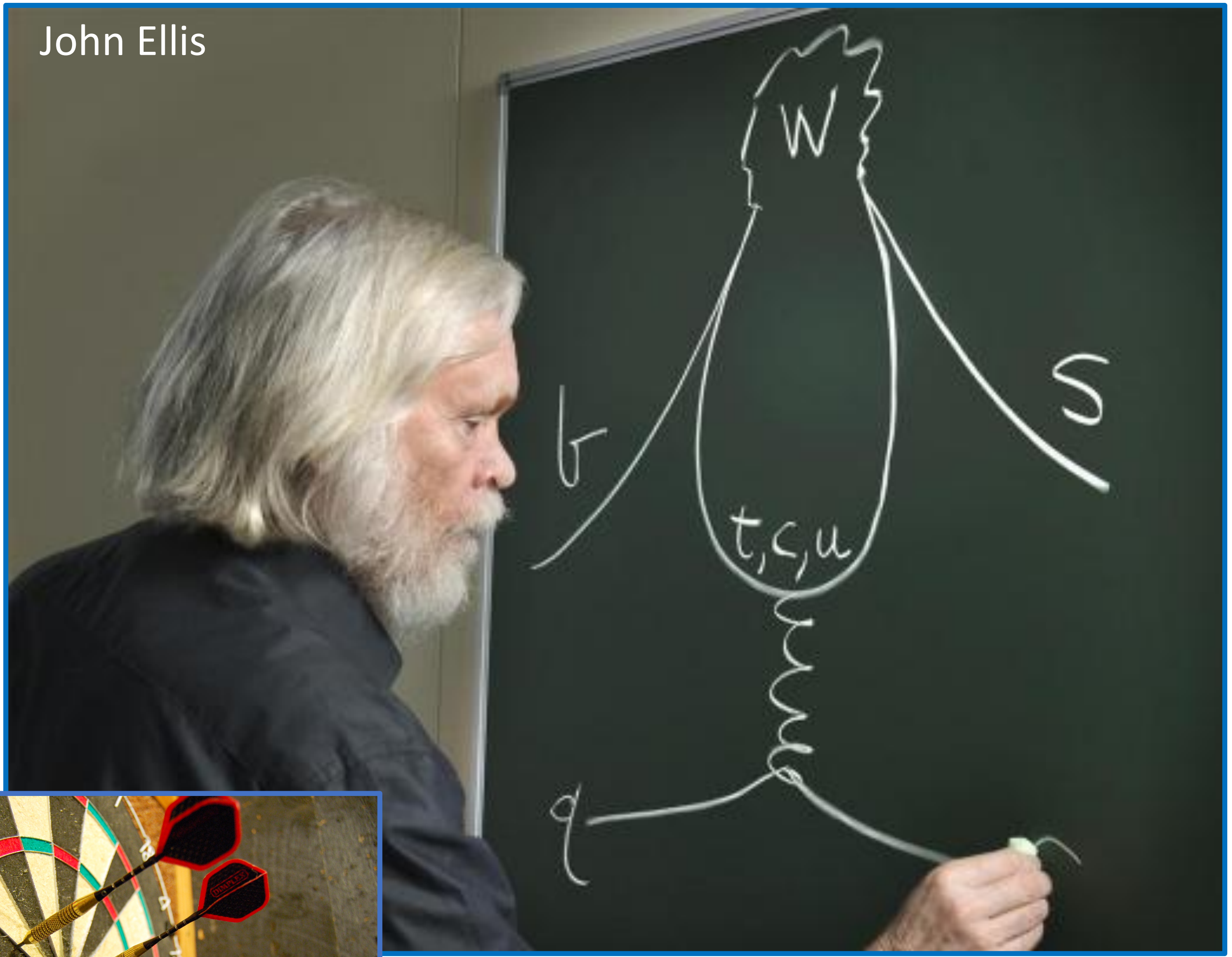


Flavour Oscillation via "Box diagram": $\overline{B_s} \to B_s$



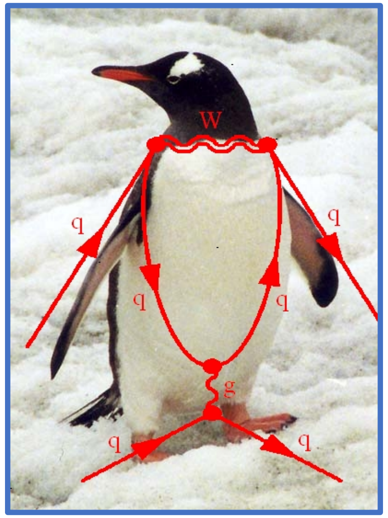
A story on darts and penguins





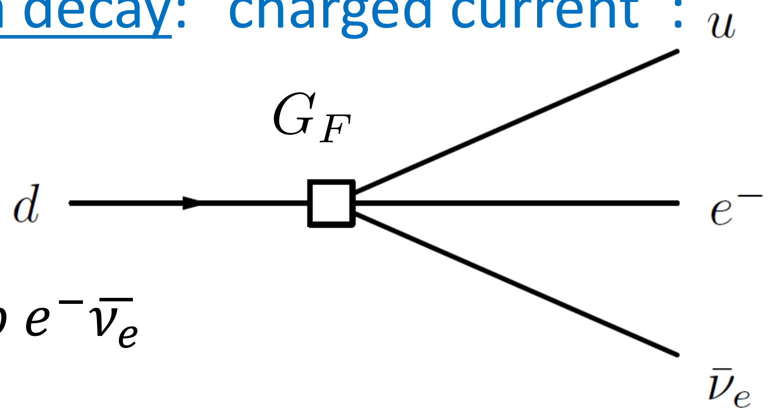
John Ellis


Melissa Franklin



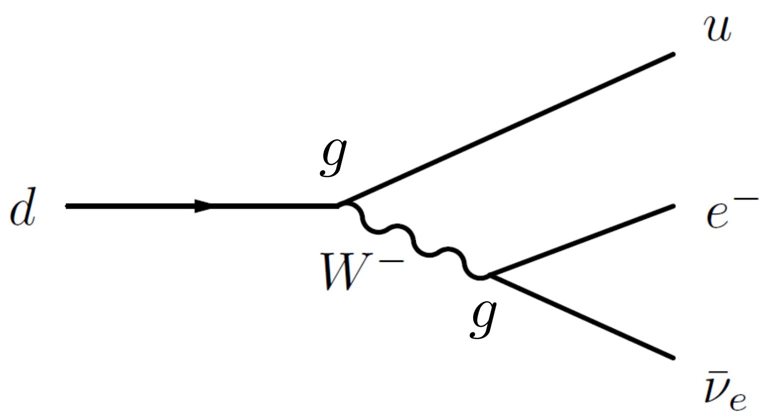
B-decays and effective couplings

- Beta decay: "charged current":

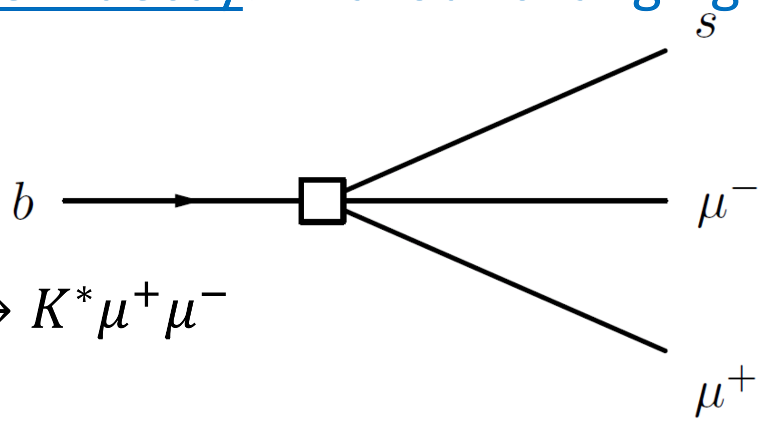


$n \to p\, e^- \overline{\nu}_e$

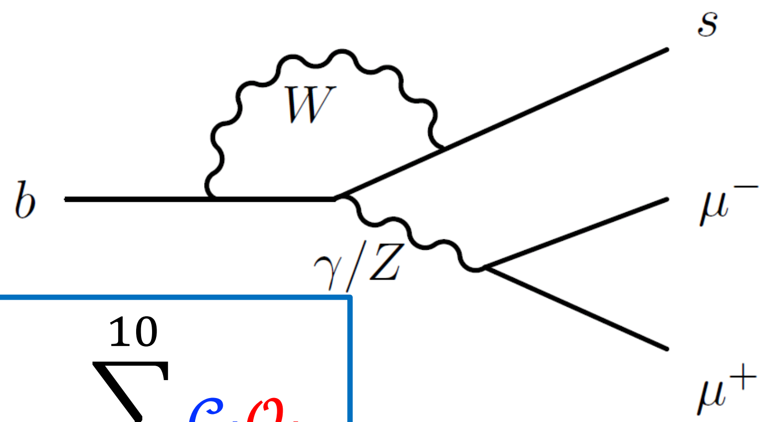
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$



- Rare B decay: "Flavour changing neutral current":



$B^0 \to K^* \mu^+ \mu^-$

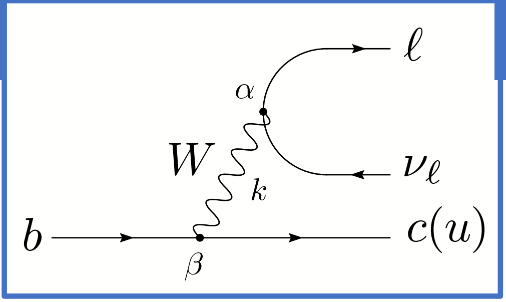


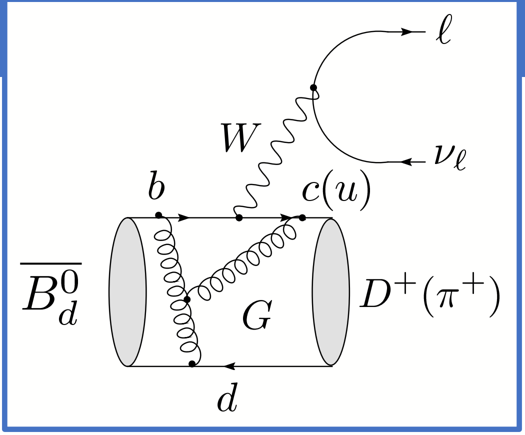
Eff Hamiltonian:

$$\mathcal{H}_{eff} = -\frac{4\,G_F}{\sqrt{2}} V_{CKM} \sum_{i=1}^{10} \mathcal{C}_i \mathcal{O}_i$$

Effective Operators $\mathcal{O}_i$ with Wilson coefficients $\mathcal{C}_i$ predicted by the Standard Model.

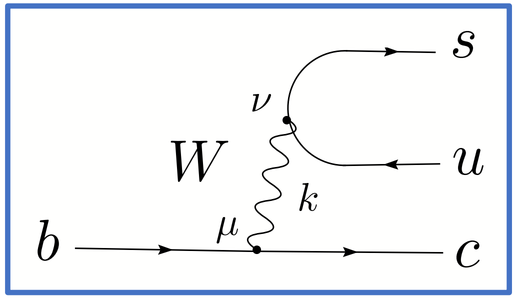
Strong Interaction causes trouble

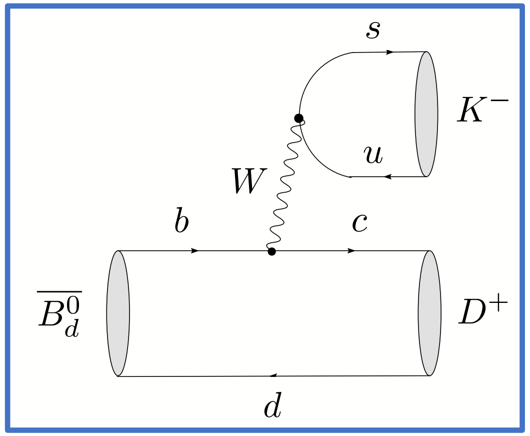




- Semileptonic decays
  - Factorization!

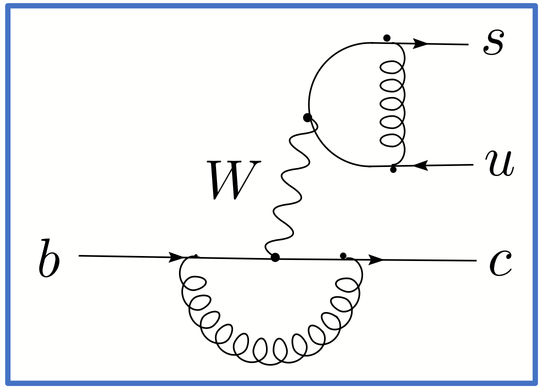
$$\boldsymbol{\mathcal{H}}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb} \underbrace{[\overline{u}_l\, \gamma^{\alpha}(1-\gamma_5)\, u_\nu]}_{\textit{Dirac spinors}} \underbrace{\left[D^+ \middle| \overline{c}\, \gamma^{\beta}(1-\gamma_5)\, b \middle| \overline{B_d^0}\right]}_{\textit{hadronic ME}}$$



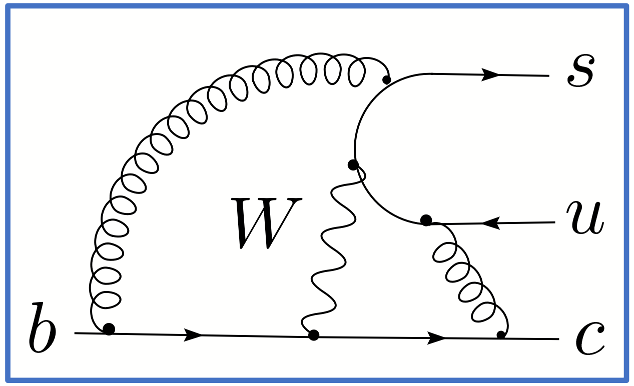


- $\mathcal{H}$adronic decays
  - Factorization?

Factorizable QCD:

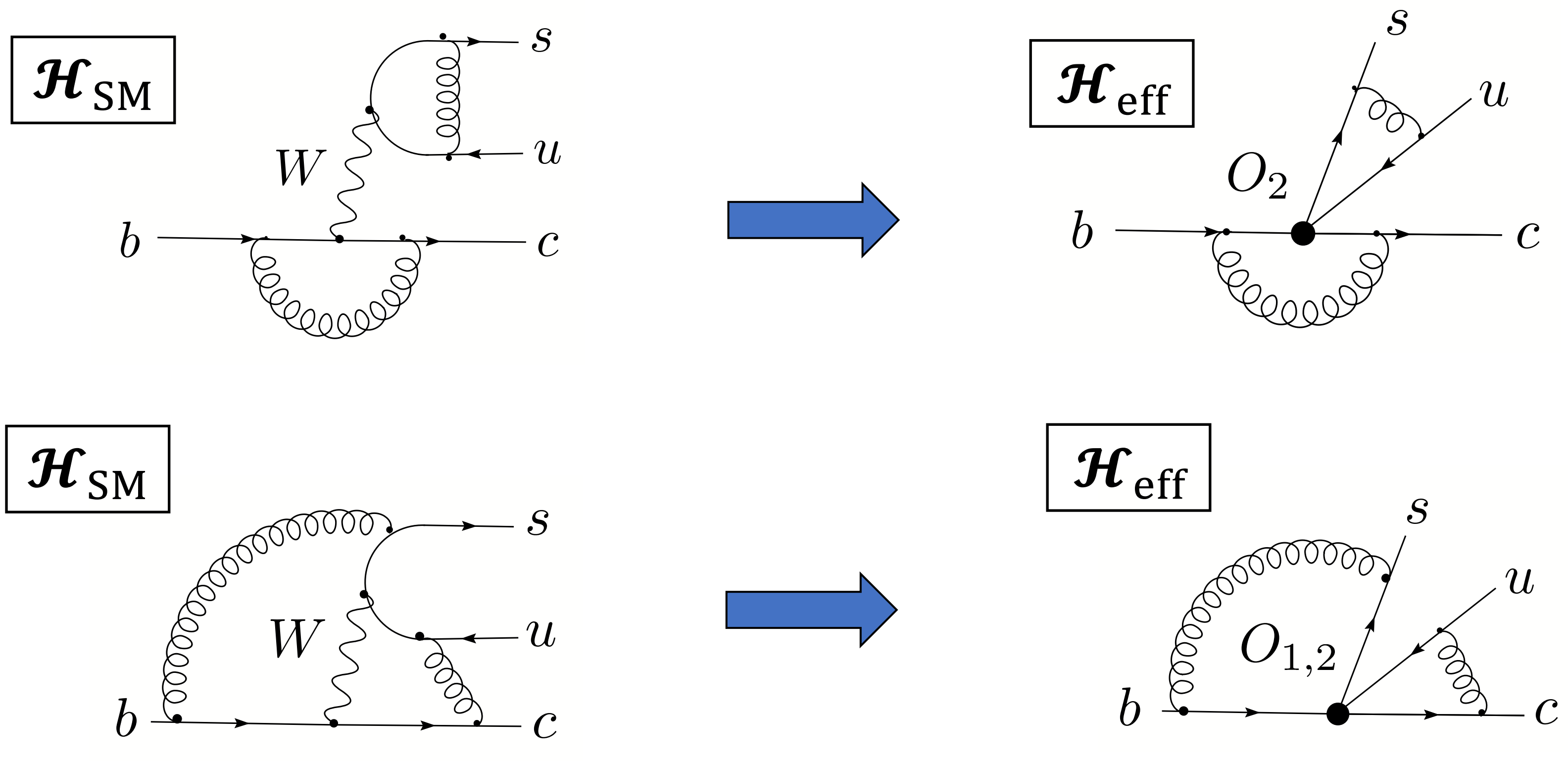


Non-Factorizable QCD:



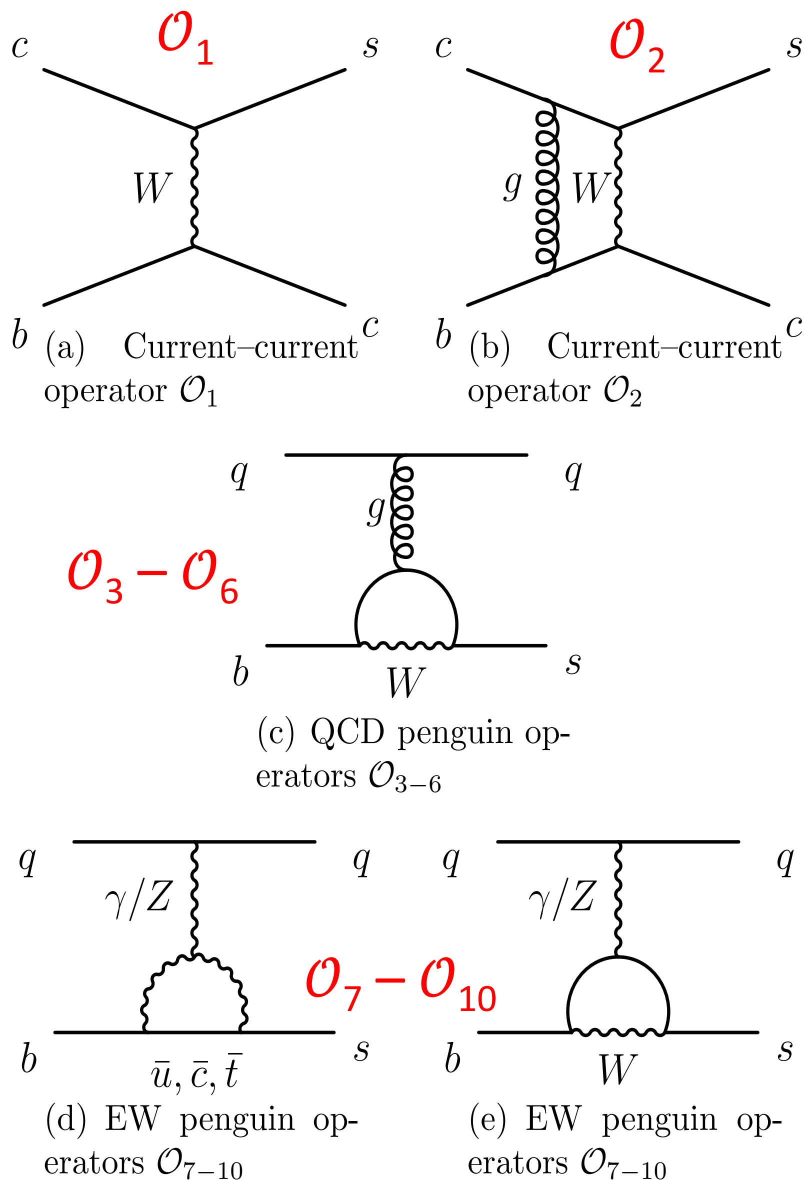
Solution: Effective couplings

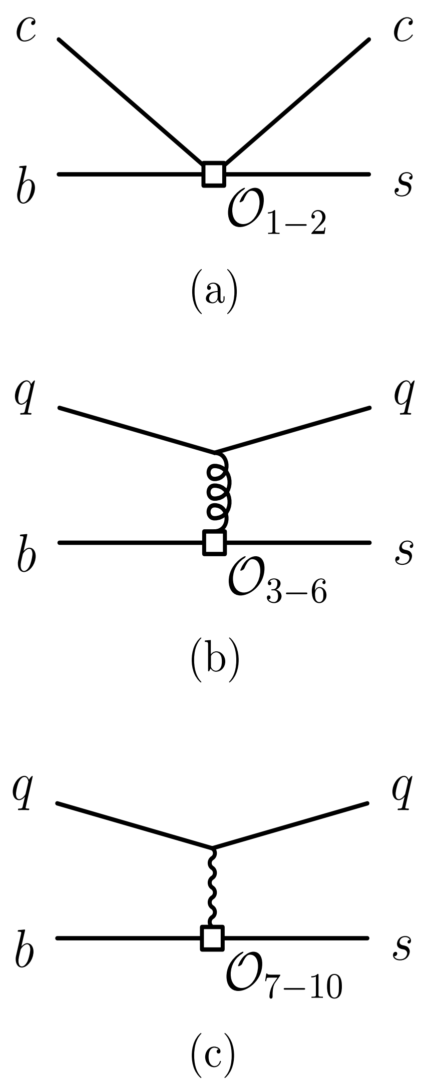
- Operator Product Expansion:
  - Integrate out heavy fields
  - Separate *perturbative* Wilson coefficients $\mathcal{C}_\mathrm{i}$ from *non-perturbative* local operators $\mathcal{O}_\mathrm{i}$



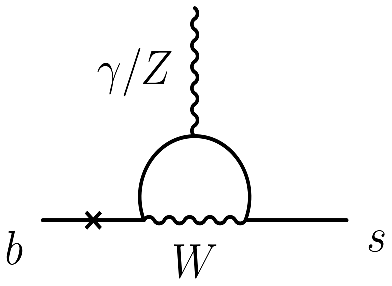
$$\mathcal{H}_{\mathrm{eff}} = \frac{G_F}{\sqrt{2}} V_{us}^* V_{cb} \left[\mathcal{C}_1 \mathcal{O}_1 + \mathcal{C}_2 \mathcal{O}_2\right]$$

Rare B-decays and effective couplings: $b \to sq\bar{q}$



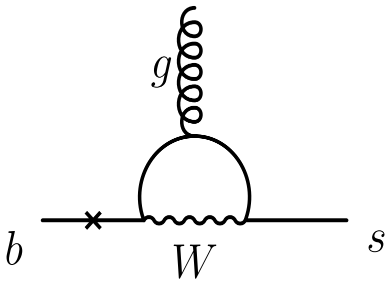


$\mathcal{O}_{7\gamma}$

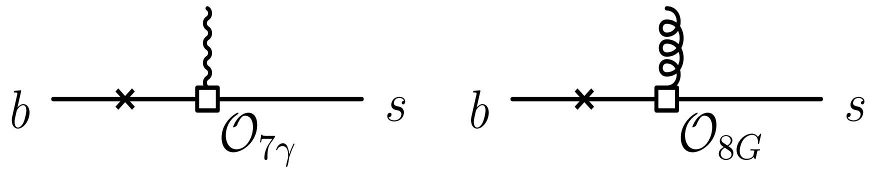


(f) Electromagnetic penguin operator $\mathcal{O}_{7\gamma}$

$\mathcal{O}_{8G}$

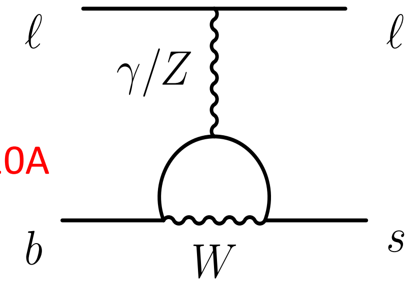


(g) Chromomagnetic penguin operator $\mathcal{O}_{8G}$

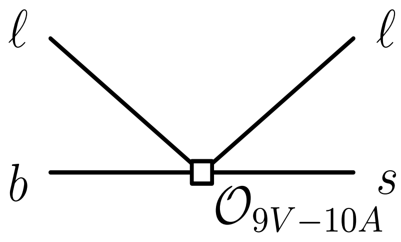


(d) (e)

$\mathcal{O}_{9V} - \mathcal{O}_{10A}$



(h) Semi-leptonic operators $\mathcal{O}_{9V-10A}$



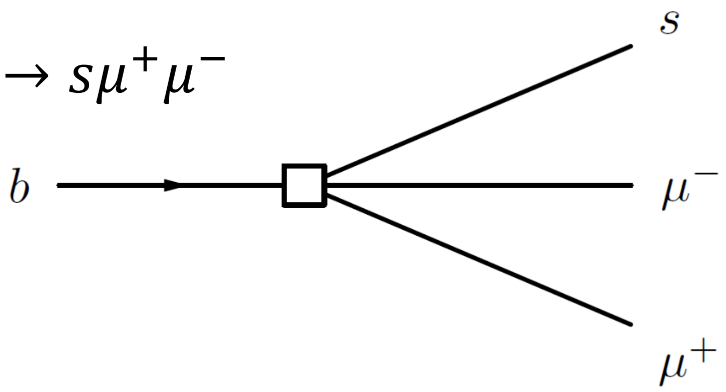
(f)

Rare B-decays and effective couplings: $b \to s\mu^+\mu^-$

- Effective 4-fermion coupling:

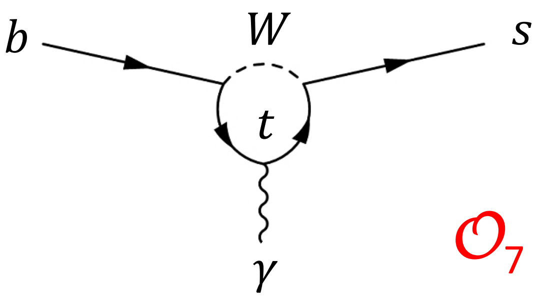
$$\boxed{\mathcal{H}_{eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} \mathcal{C}_i \mathcal{O}_i}$$

$b \to s\mu^+\mu^-$



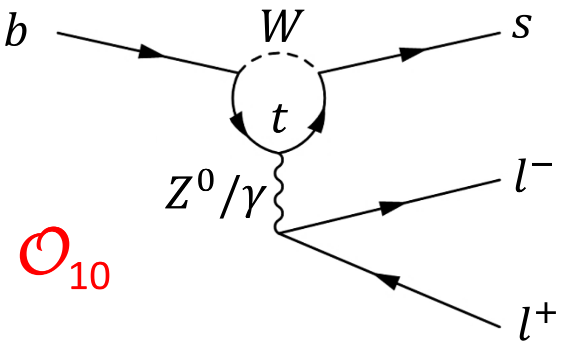
- Standard Model diagrams:

Photon penguin:



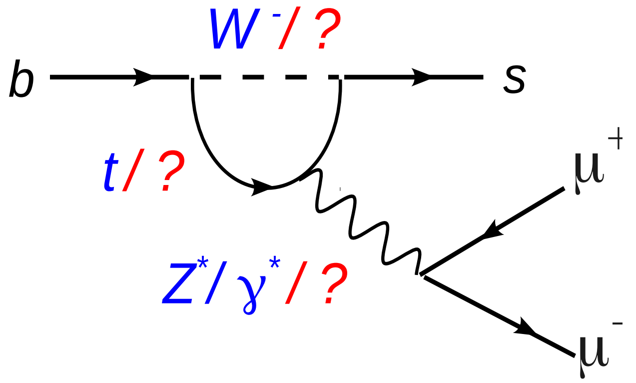
$\mathcal{O}_7$

Vector, Axial vector:



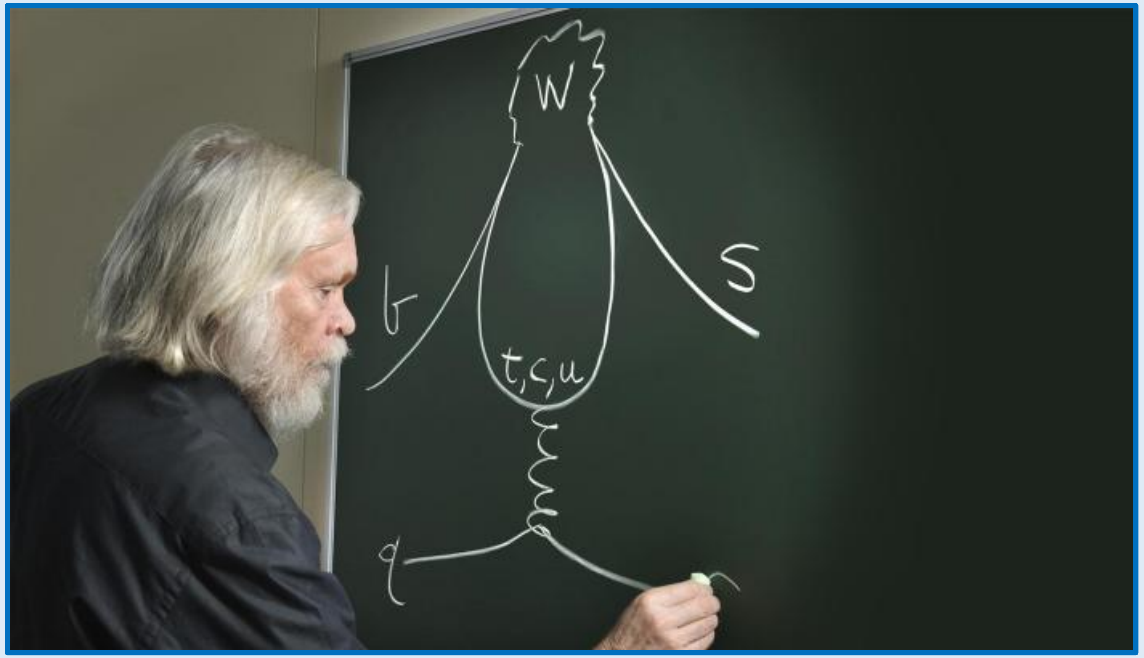
$\mathcal{O}_9$, $\mathcal{O}_{10}$

- Beyond Standard Model:



- Experimental test: Compare calculable C_i coefficients to experimental data
  - Sensitivity for NP in Wilson coefficients C_7, C_9, C_{10}

Contents:



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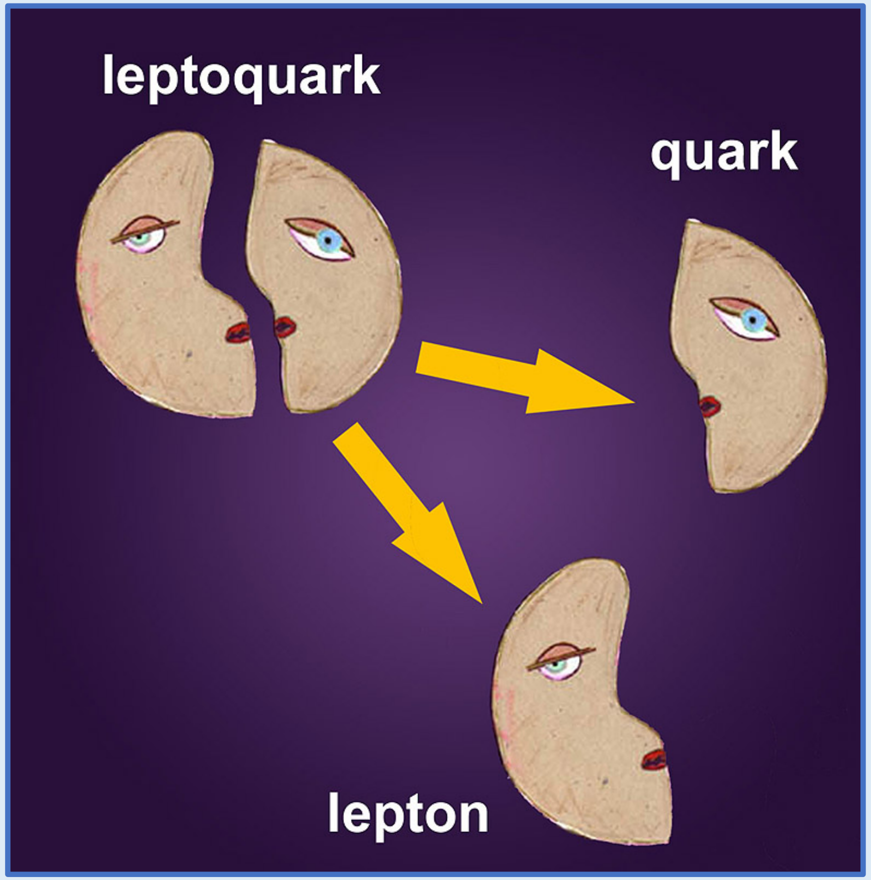
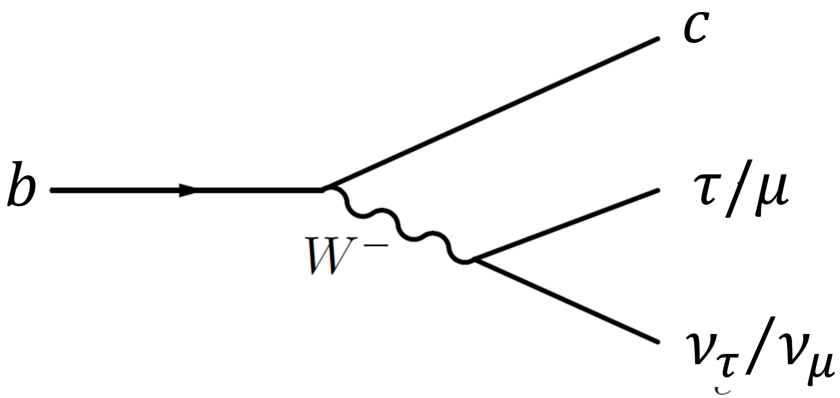


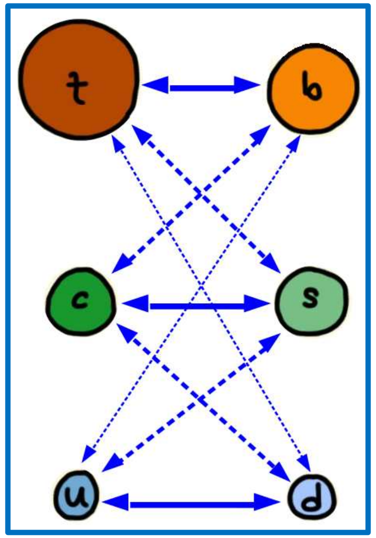
B-decays and lepton universality

- $b \to c\, l\, \nu$ charged current: "Allowed" → large decay rates

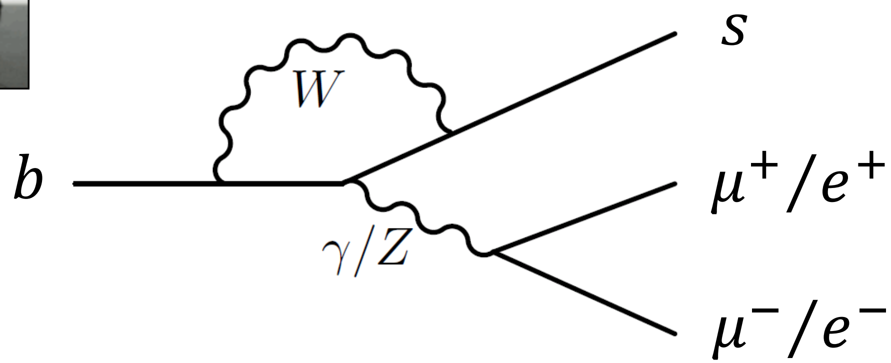


$$R_D = \frac{B \to D\tau\nu}{B \to D\mu\nu}$$

$$R_{D^*} = \frac{B \to D^*\tau\nu}{B \to D^*\mu\nu}$$

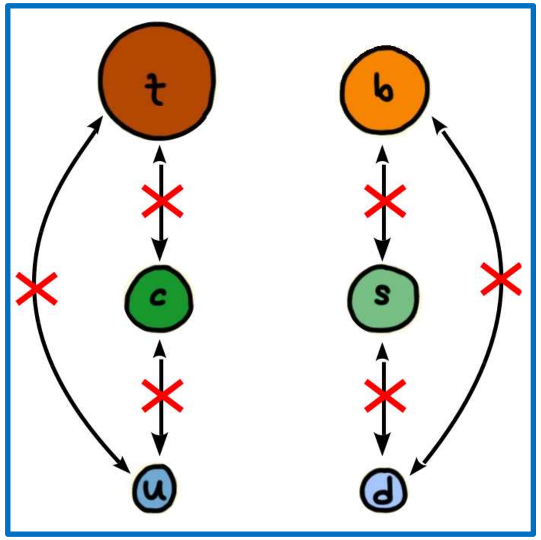


- $b \to s l^+ l^-$ neutral current: "Forbidden" → rare decays



$$R_K = \frac{B^+ \to K^+\mu^+\mu^-}{B^+ \to K^+e^+e^-}$$

$$R_{K^*} = \frac{B^0 \to K^{*0}\mu^+\mu^-}{B^0 \to K^{*0}e^+e^-}$$

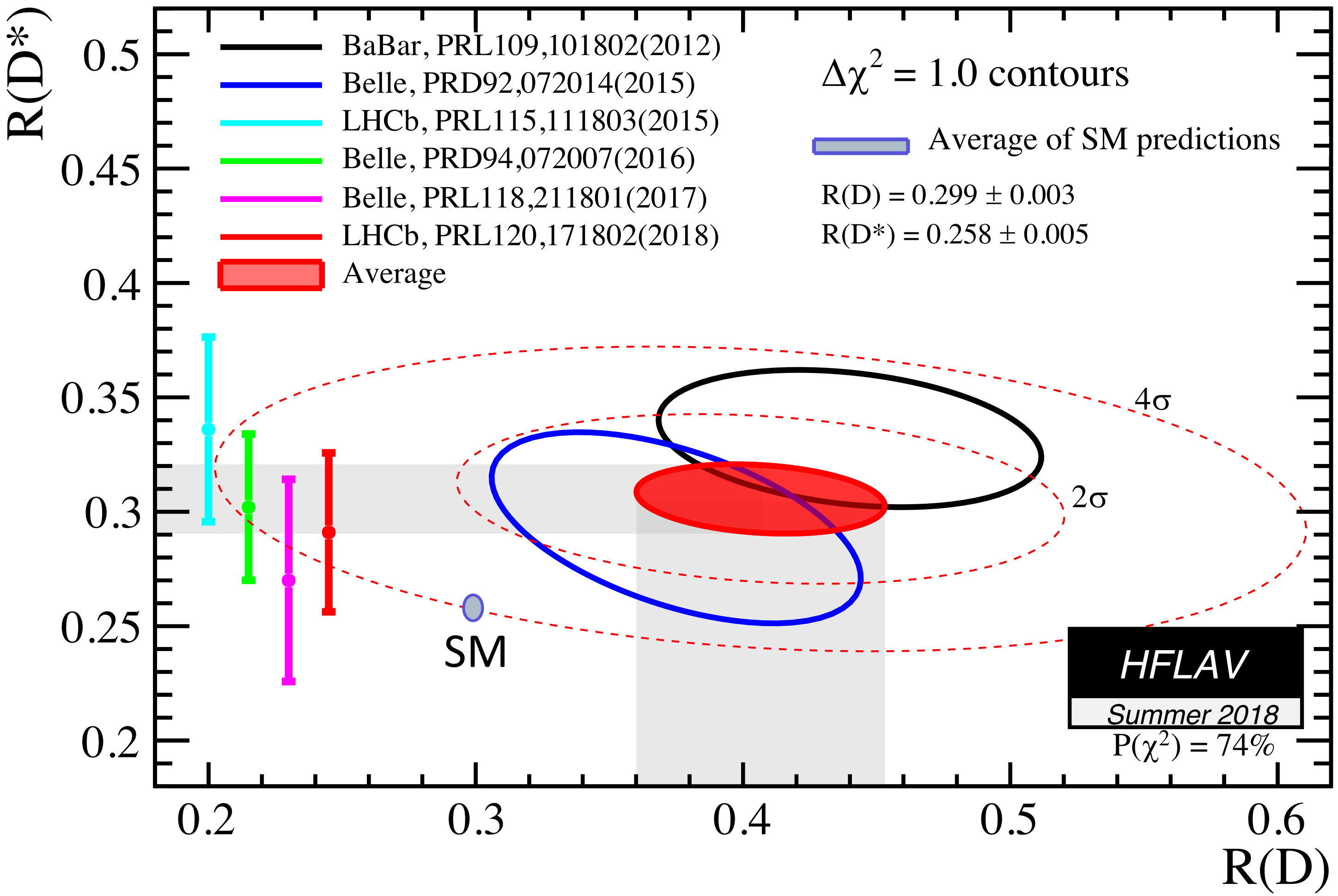


R_D and R_{D^*}

- $b \to c\, l\, \nu$ allowed charged current

$$R\left(D^{(*)}\right) = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\mu\nu)}$$

~ 4σ deviation



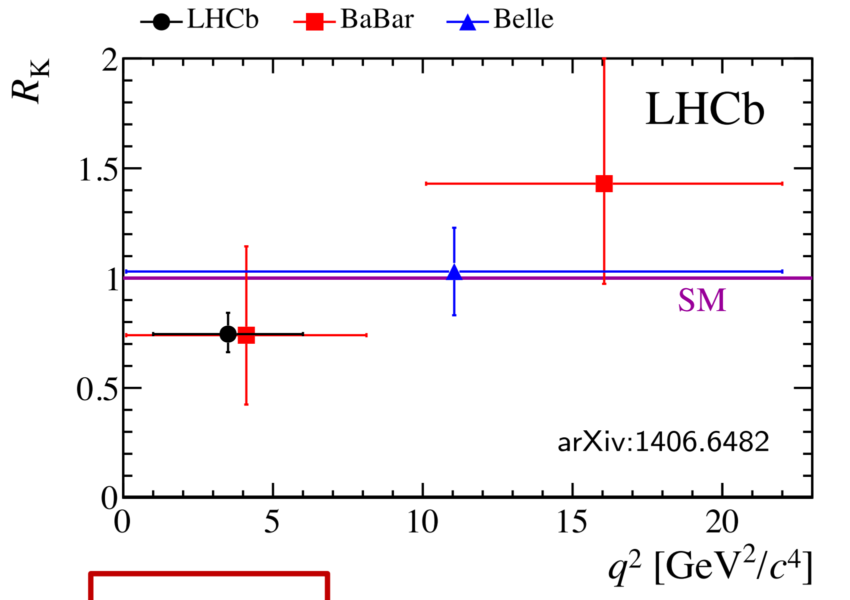
➔ Involves leptons of 2nd and 3rd generation

R_K and R_{K^*}

- $b \to s\, l^+ l^-$ suppressed neutral current

$$R(K) = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)}$$

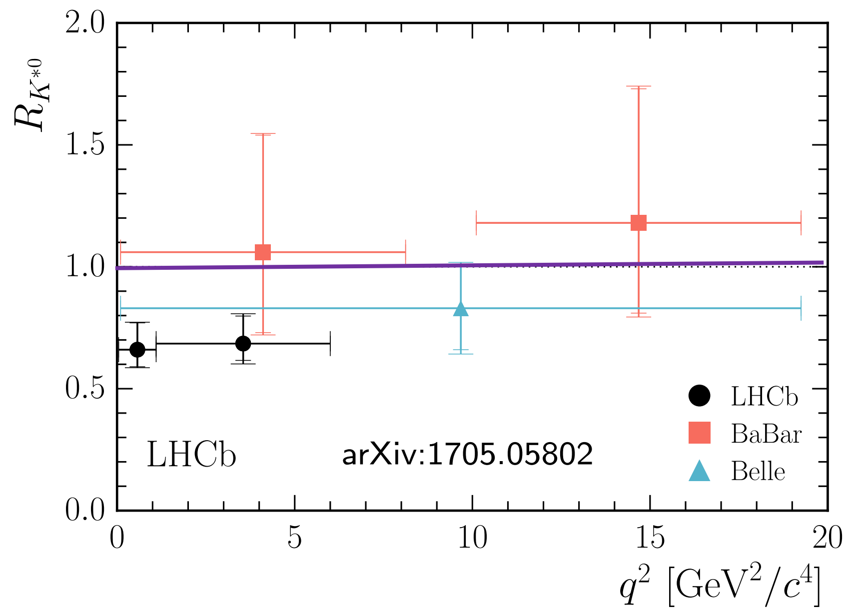
$$R(K) = 0.745\,^{+0.090}_{-0.074}\ (\text{stat}) \pm 0.036\ (\text{syst})$$



~3.5 σ

$$R(K^*) = \frac{BR(B^0 \to K^* \mu^+ \mu^-)}{BR(B^0 \to K^* e^+ e^-)}$$

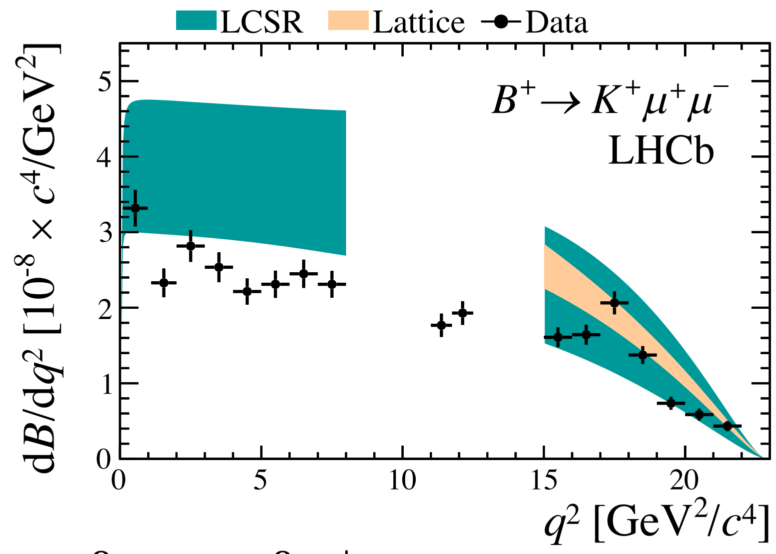
$$R(K^*) = \begin{cases} 0.66\,^{+0.11}_{-0.07}\ (\text{stat}) \pm 0.03\ (\text{syst})\ \text{in bin1} \\ 0.69\,^{+0.11}_{-0.07}\ (\text{stat}) \pm 0.05\ (\text{syst})\ \text{in bin2} \end{cases}$$



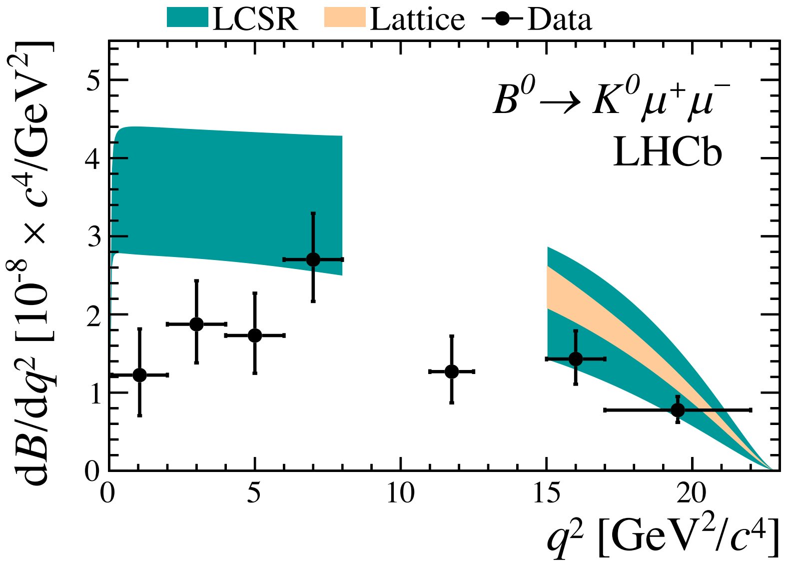
➔ Involves leptons of 1st and 2nd generation

Branching fractions of Rare Decays: $b \to s\,\mu^+\mu^-$

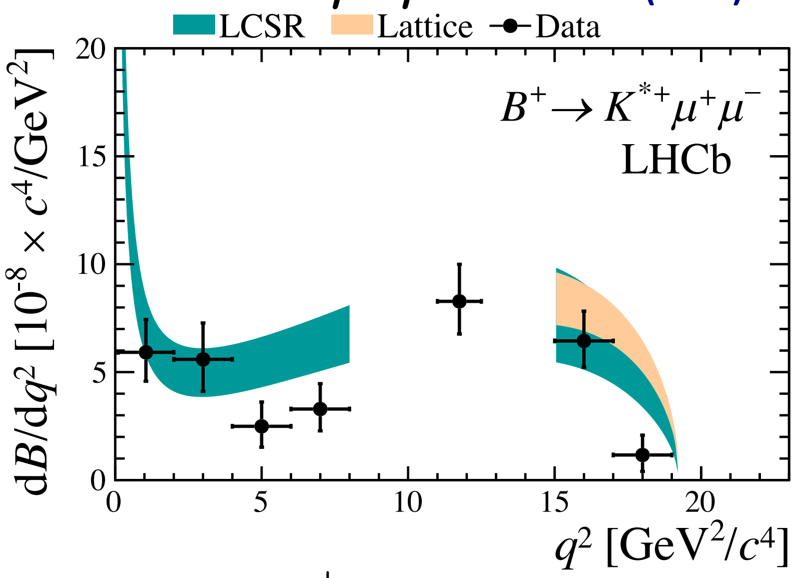
$B^+ \to K^+\mu^+\mu^-$ JHEP 06 (2014) 133



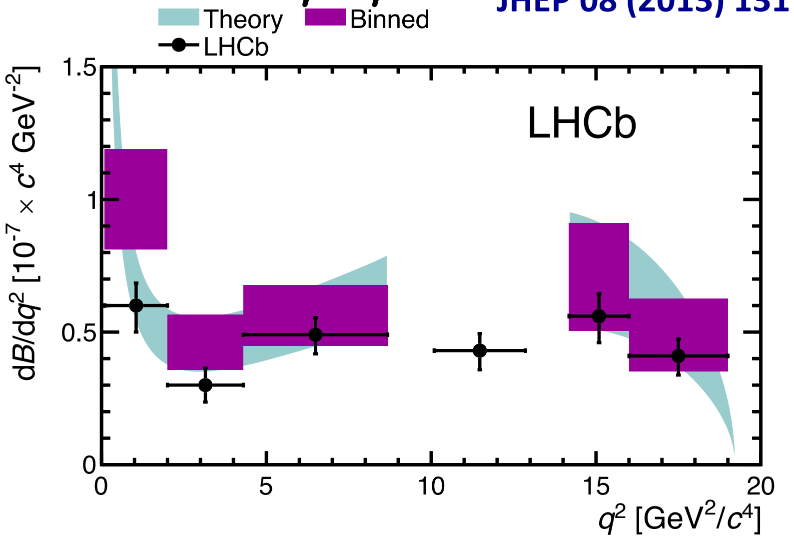
$B^0 \to K^0\mu^+\mu^-$ JHEP 06 (2014) 133



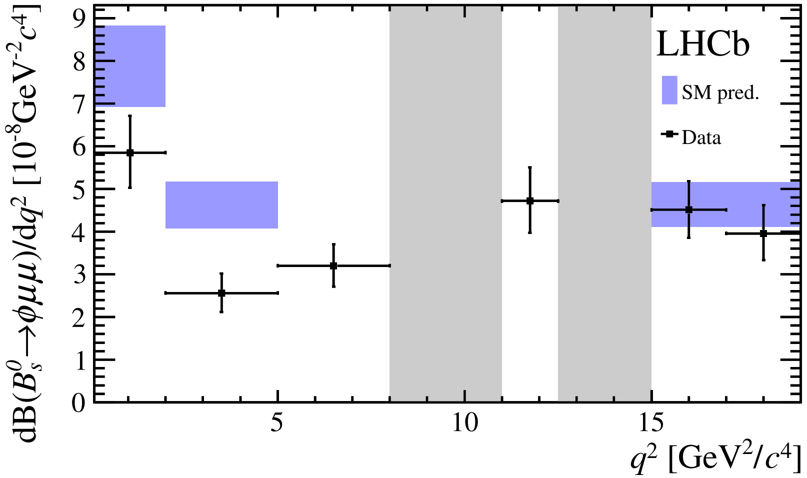
$B^+ \to K^{*+}\mu^+\mu^-$ JHEP 06 (2014) 133



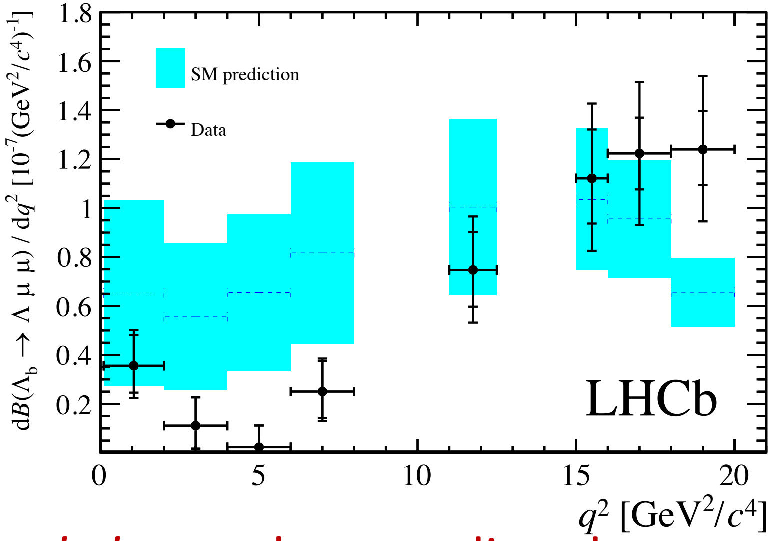
$B^0 \to K^{*0}\mu^+\mu^-$ JHEP 08 (2013) 131



$B_s \to \phi\mu^+\mu^-$ JHEP 09 (2015) 179

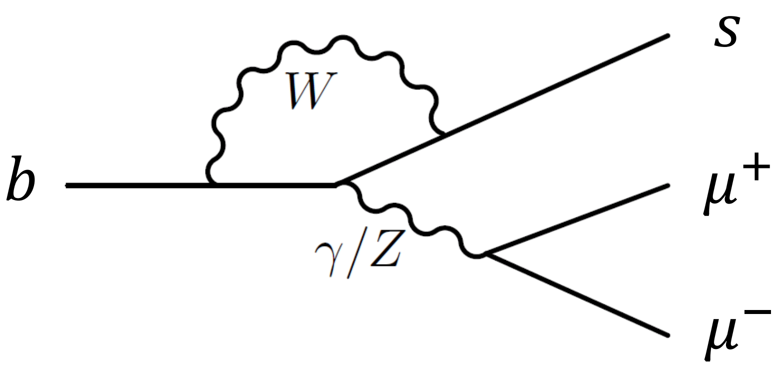


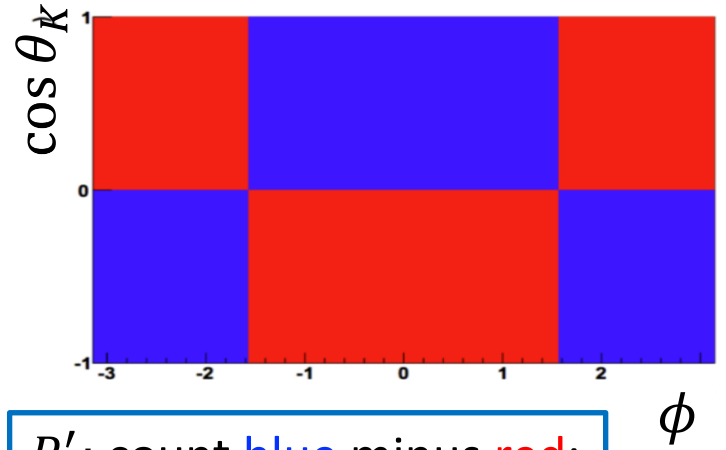
$\Lambda_b \to \Lambda\mu^+\mu^-$ JHEP 06 (2015) 115



- Branching fractions related to $b \to s\,\mu^+\mu^-$ transition *consistently lower* than predicted.

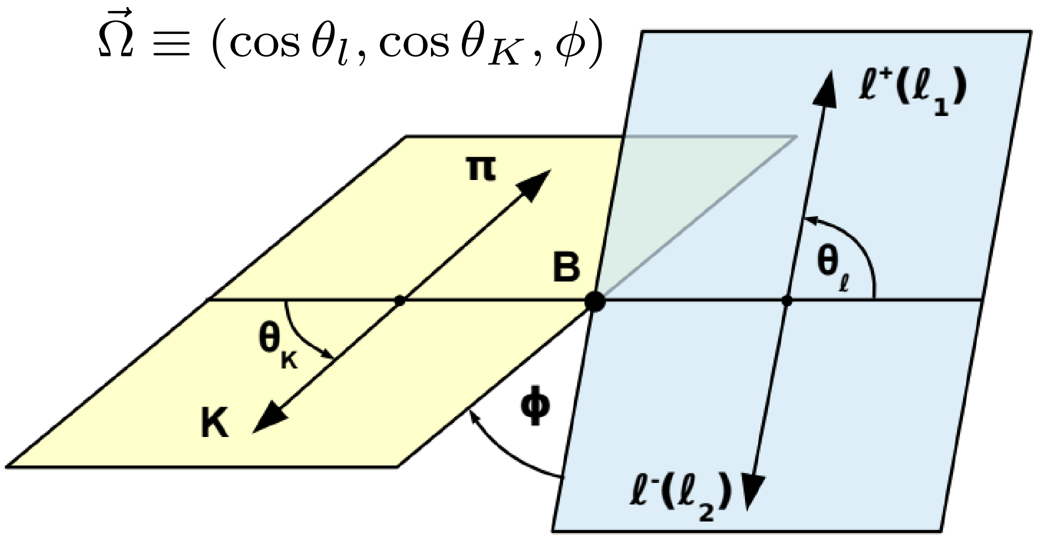
Variable P_5' in $B^0 \to K^{*0}\mu^+\mu^-$

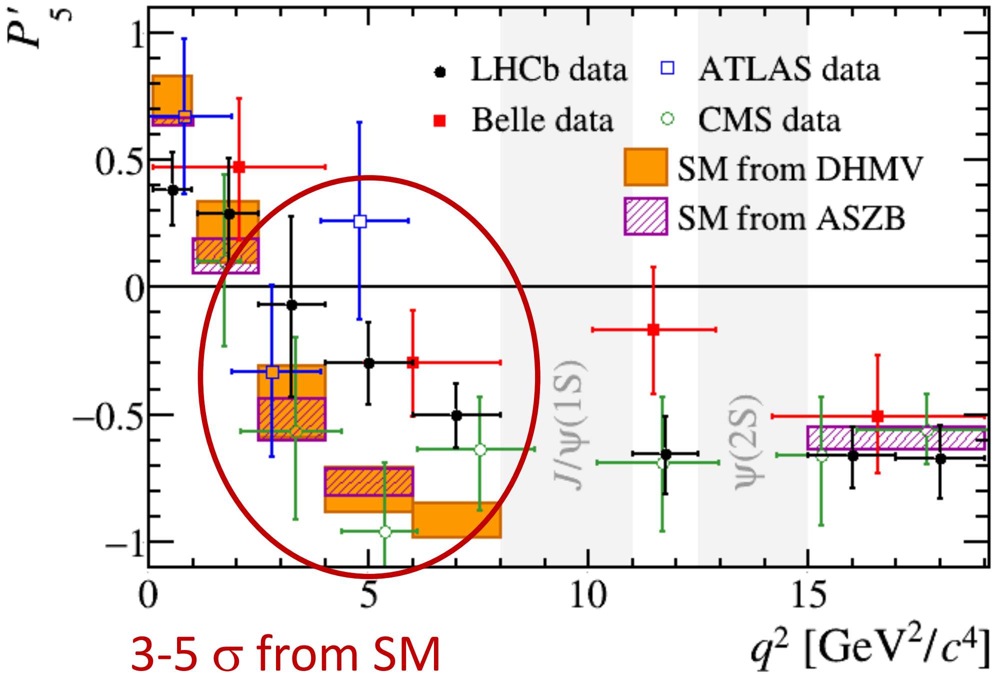




P_5': count blue minus red:

- Study angular distribution of final state particles



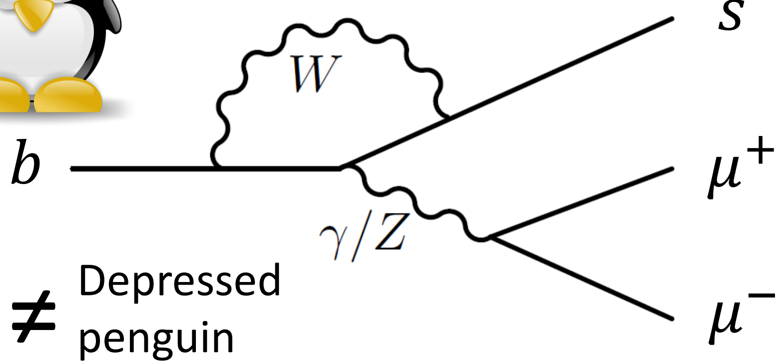


3-5 σ from SM

Global Fit of $b \to s\,\mu^+\mu^-$

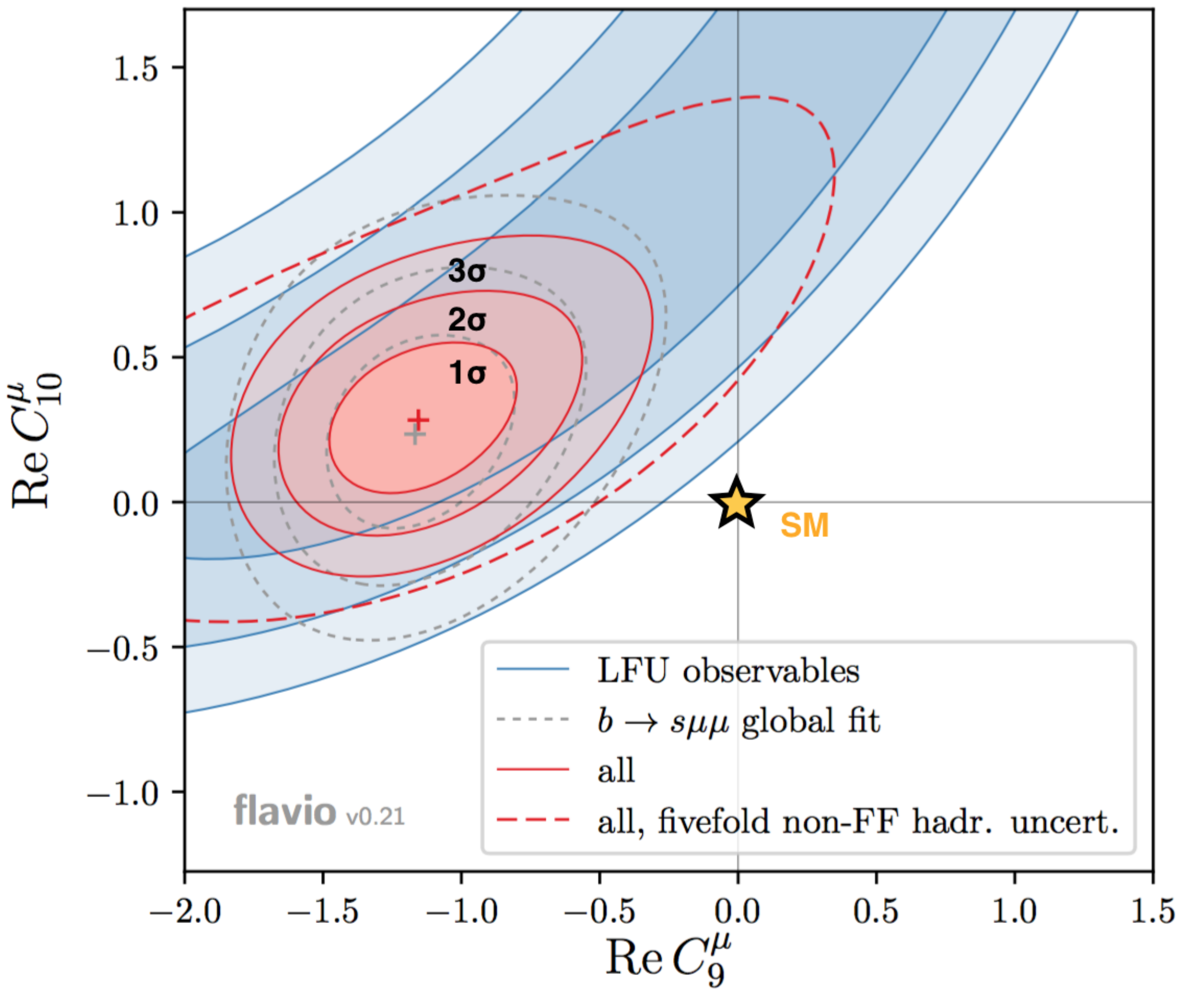
$$\mathcal{H}_{eff} = -\frac{4\,G_F}{\sqrt{2}} V_{CKM} \sum_{i=1}^{10} C_i O_i$$

- Semileptonic Penguin operators: O_9, O_{10}
- Good fit for: $C_9^{NP} = -C_{10}^{NP} \simeq -1$
  - New effective $V - A$ contribution
  - Suppressed $b \to s\,\mu^+\mu^-$ penguin



Note: Suppressed penguin $\neq$ Depressed penguin

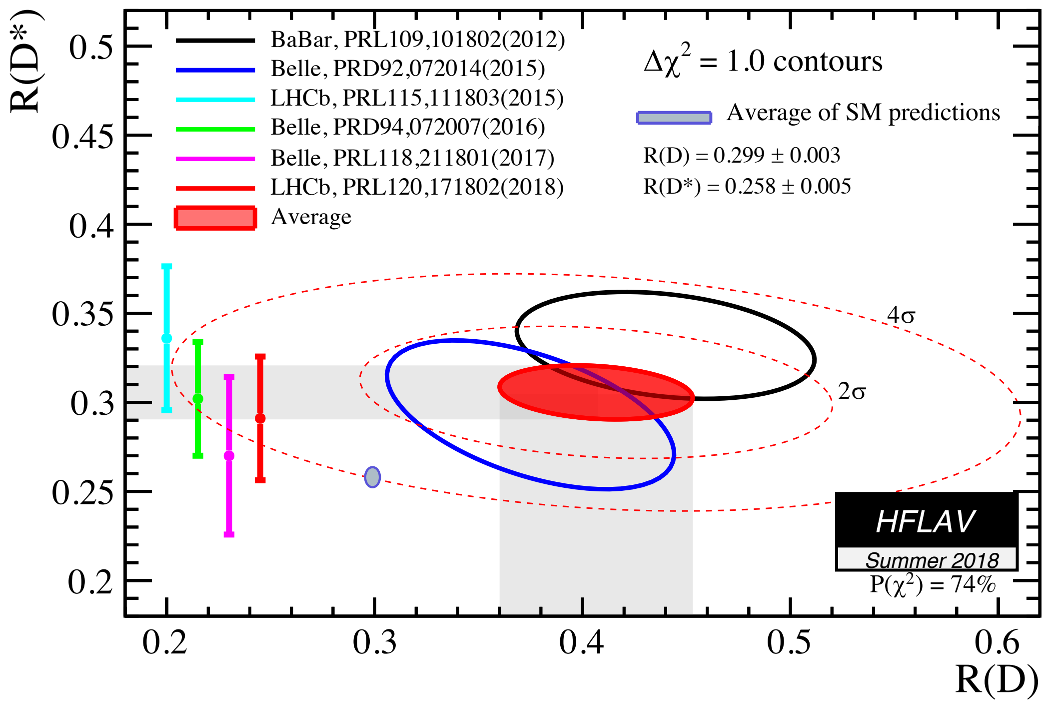
Altmannshofer et al., arXiv:1704.05435



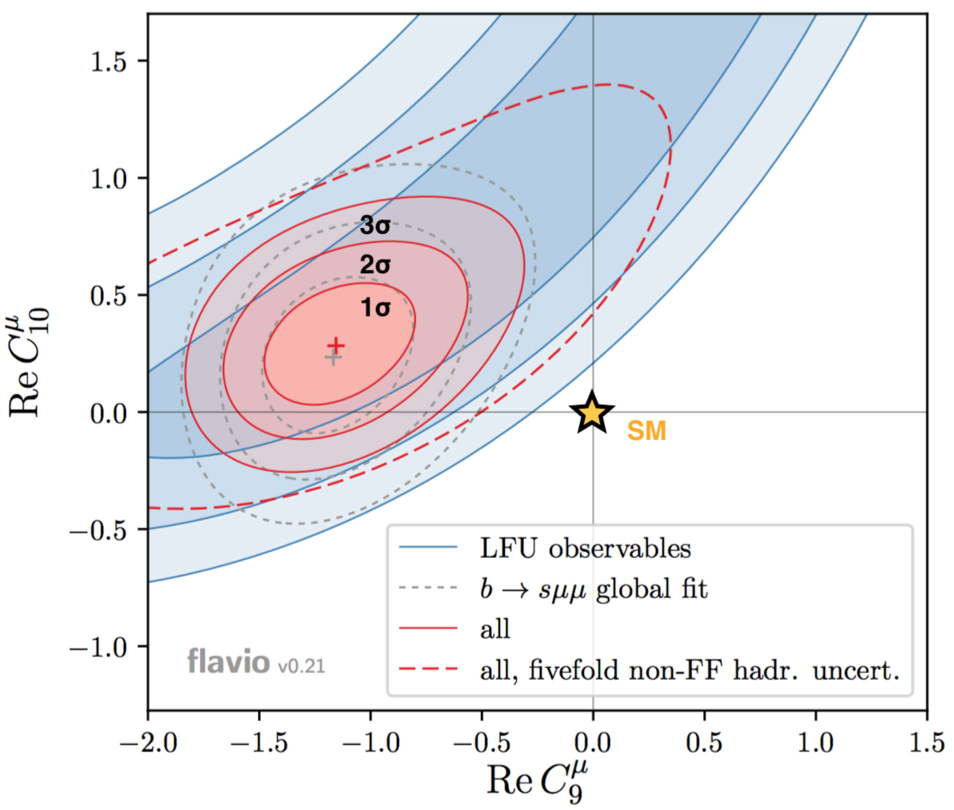
Significance: 4-6 σ

Contradicting universality effects?

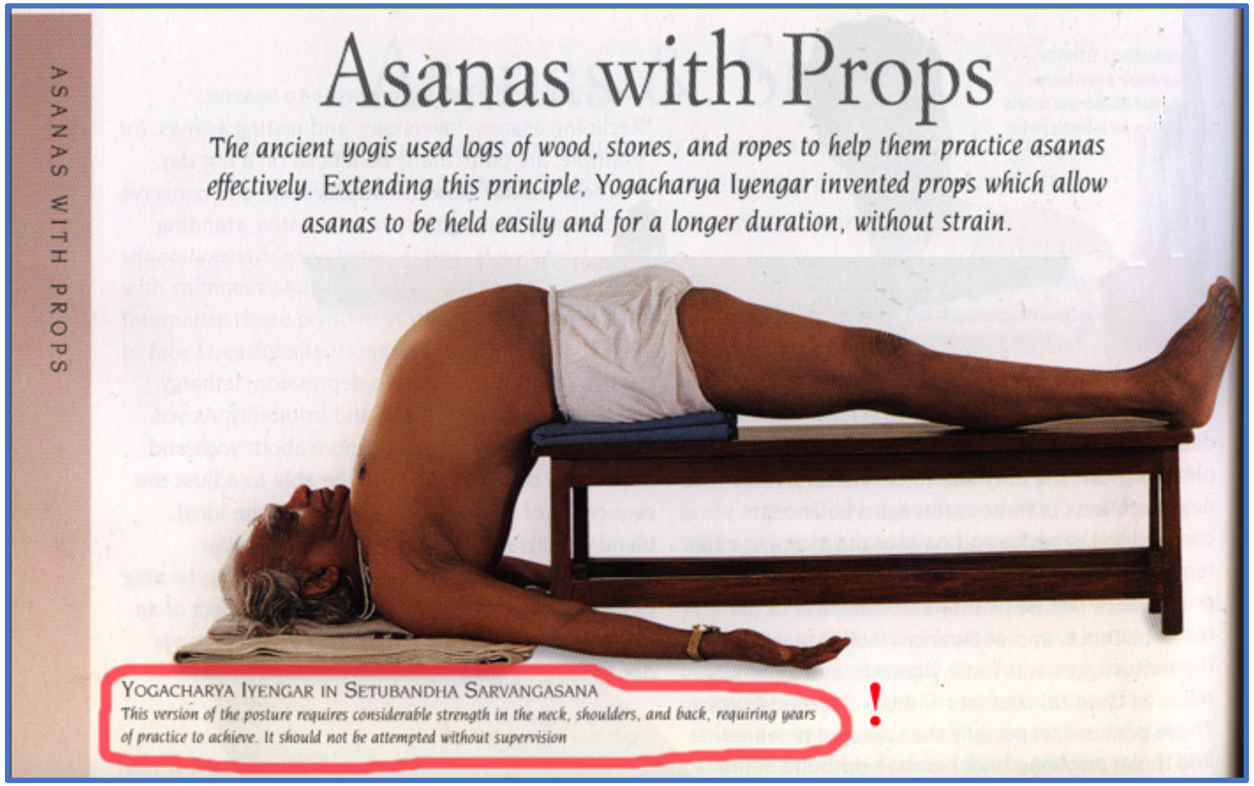
- R_D, R_{D^*}
  - ~ 25% effect at ***tree*** level:
    - ***Large*** new physics effect
    - $M{\sim}3$ TeV



- R_K, R_{K^*}
  - ~ 25% effect at ***penguin*** level:
    - ***Small*** new physics effect
    - $M{\sim}30$ TeV



Universality?



ASANAS WITH PROPS

Asanas with Props

The ancient yogis used logs of wood, stones, and ropes to help them practice asanas effectively. Extending this principle, Yogacharya Iyengar invented props which allow asanas to be held easily and for a longer duration, without strain.

YOGACHARYA IYENGAR IN SETUBANDHA SARVANGASANA

This version of the posture requires considerable strength in the neck, shoulders, and back, requiring years of practice to achieve. It should not be attempted without supervision

!

...Indian Yoga

Russian Yoga...

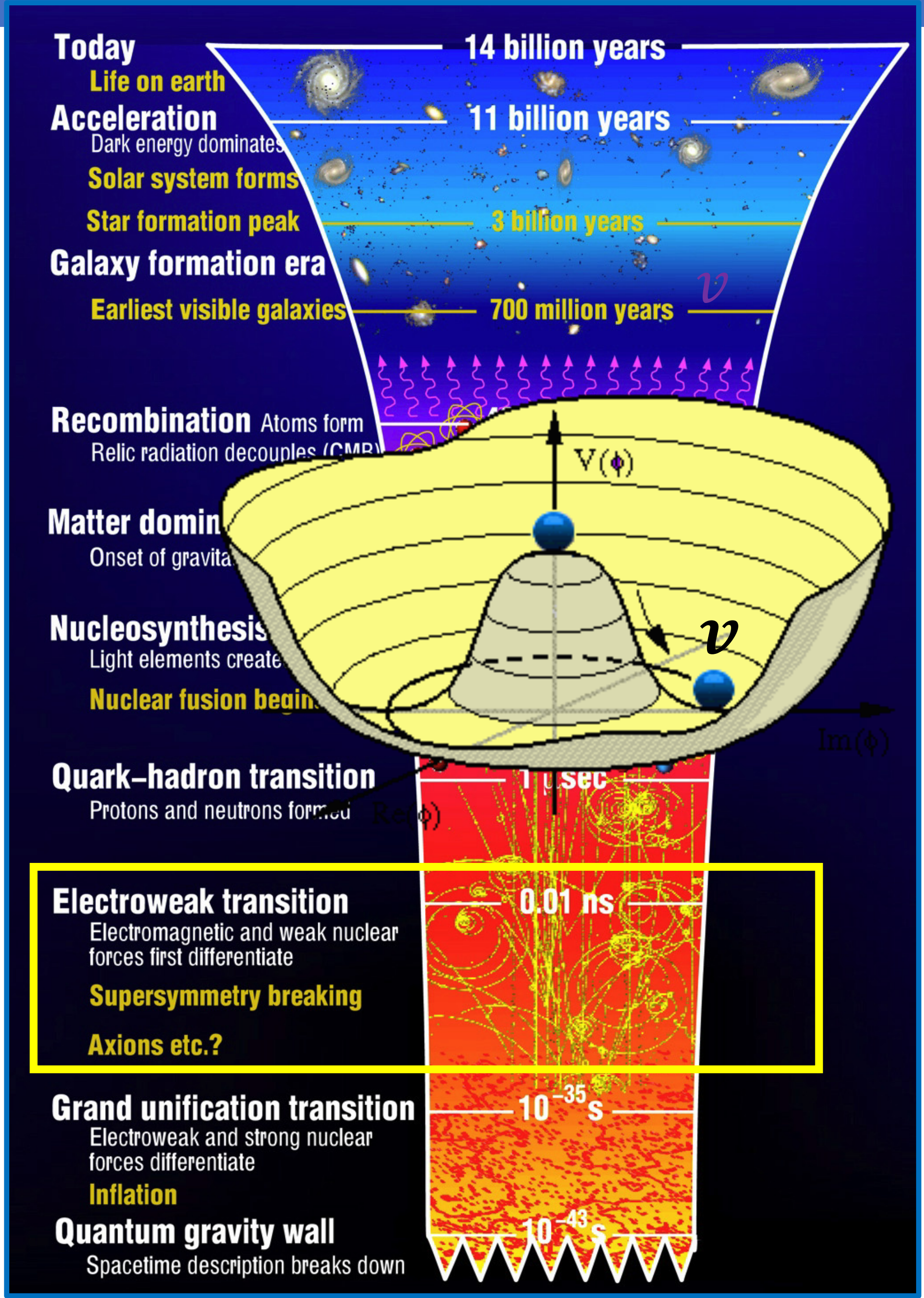
Flavour Physics at high mass: GGL model

- Effective New Physics operators point at *left-handed vector* coupling

- New physics occurs above weak scale (~TeV)
  - Before EWSB: physics that is invariant under $SU(3)_C \times SU(2)_L \times U(1)_Y$
  - *Operates on massless interaction states*

- 3rd generation is special (eg. Y_{top} = 1)

- Glashow, Guagdagnoli, Lane (GGL) model: Operator for NP in 3rd generation:
  - $G\left(\overline{b'}_L\, \gamma_\mu\, b'_L\right)\ \left(\overline{\tau'}_L\, \gamma^\mu\, \tau'_L\right)$

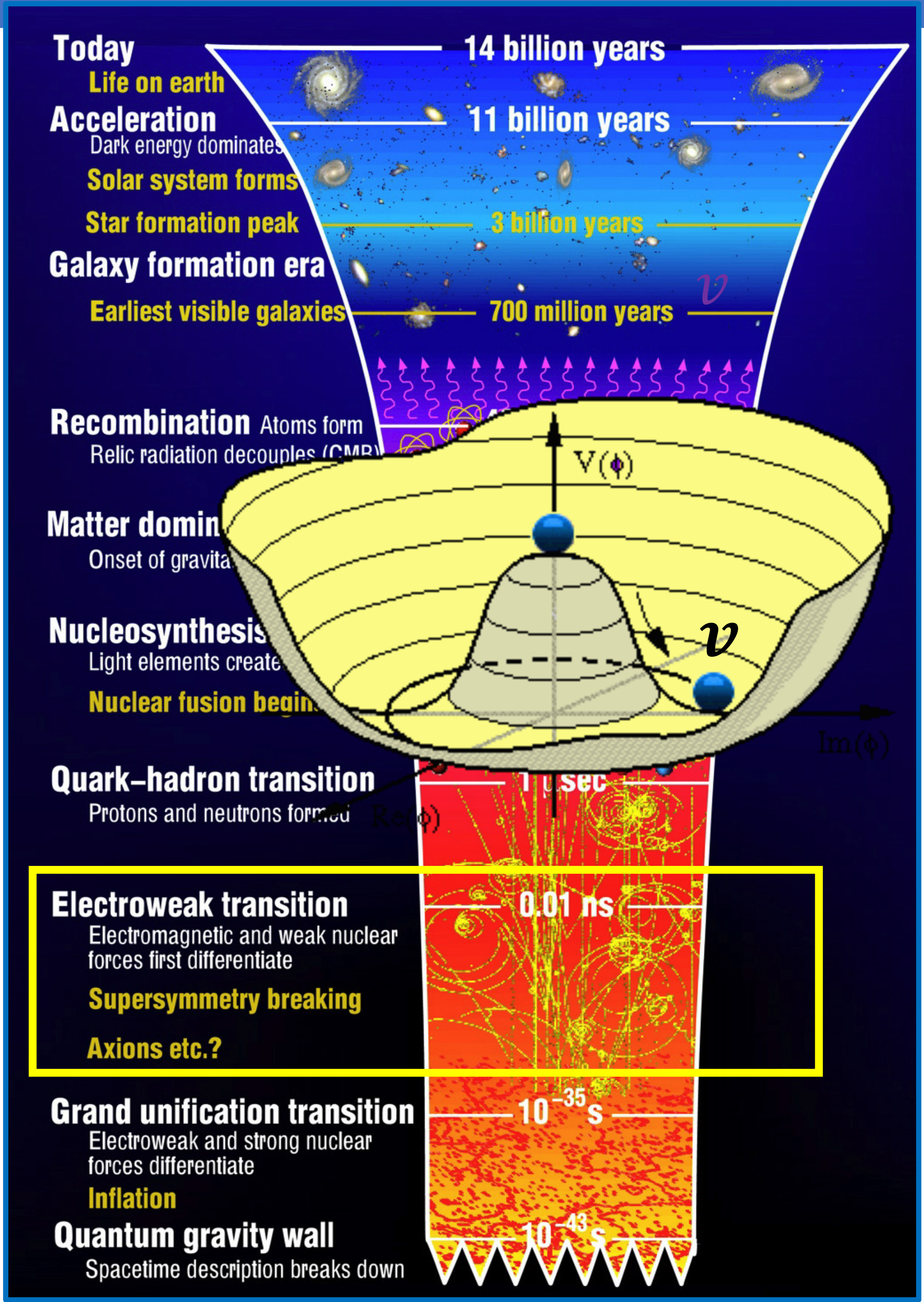


Where does GGL operator come from?

- Glashow, Guagdagnoli, Lane (GGL) model: operator for NP:
  - $G\left(\bar{b'}_L\,\gamma_\mu\,b'_L\right)\;\left(\bar{\tau'}_L\,\gamma^\mu\,\tau'_L\right)$
- Relate massive particles to massless states:
  - $b'_L = V^d_{31}\,d + V^d_{32}\,s + V^d_{33}\,b$ and
  - $\tau'_L = V^l_{31}\,e + V^l_{32}\,\mu + V^l_{33}\,\tau$

$$V_{CKM} = \left(V^u V^{d\dagger}\right)_{ij}$$
$$V_{MNS} = \left(V^\nu V^{l\dagger}\right)_{ij}$$

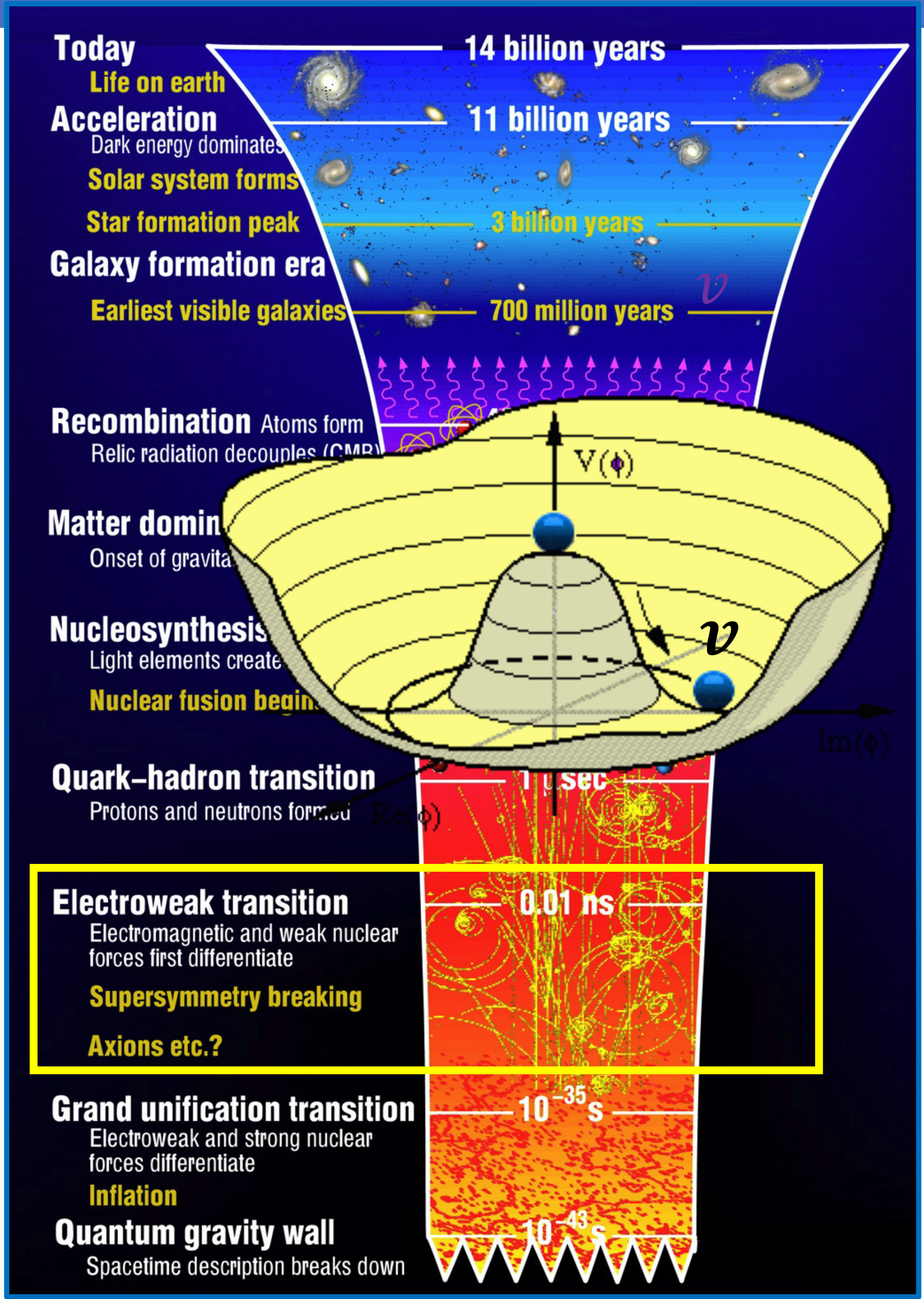
- CKM Hierarchy suggests:
  - $V^d_{33} \simeq V^l_{33} \simeq 1$ and $V^{d,l}_{31} \ll V^{d,l}_{32} \ll 1$
- GGL operator becomes:
  - $G\left[V^d_{33}\,V^{*d}_{32}\,|V_{32}|^2\right]\left(\bar{b}_L\,\gamma_\mu s_L\right)\left(\bar{\mu}_L\gamma^\mu\mu_L\right)$
- *Large* effect in 3rd generation, *small* effect in 2nd generation



GGL operator – more general

- Allow effective operators that are SU(2) x U(1) invariant: $Q' = \begin{pmatrix} t' \\ b' \end{pmatrix}$ and $L' = \begin{pmatrix} \nu_\tau' \\ \tau' \end{pmatrix}$
  - Singlet neutral current:
    - $O_S^{NP} = G_S \left(\overline{Q'}_L \gamma_\mu Q'_L\right) \left(\overline{L'}_L \gamma^\mu L'_L\right)$
  - Triplet neutral current + two charged currents:
    - $O_T^{NP} = G_T \left(\overline{Q'}_L \gamma_\mu \sigma^I Q'_L\right) \left(\overline{L'}_L \gamma^\mu \sigma^I L'_L\right)$

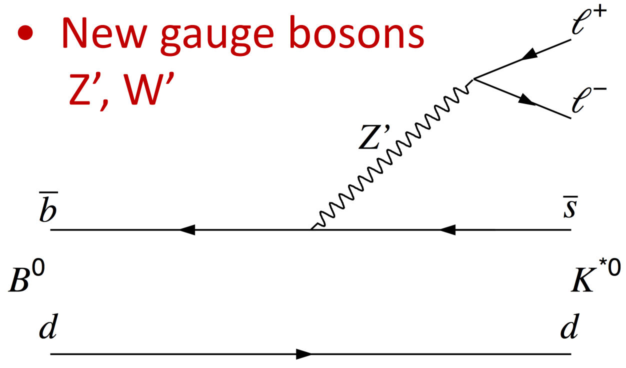
- These operators with CKM hierarchy "naturally" give simultaneous explanation of:
  - R_D , R_{D^*}, charged current, 3rd generation
    - → large effect
  - R_K ,R_{K^*} , $b \to s\, \mu^+\mu^-$,neutral current, 2nd generation
    - → small effect



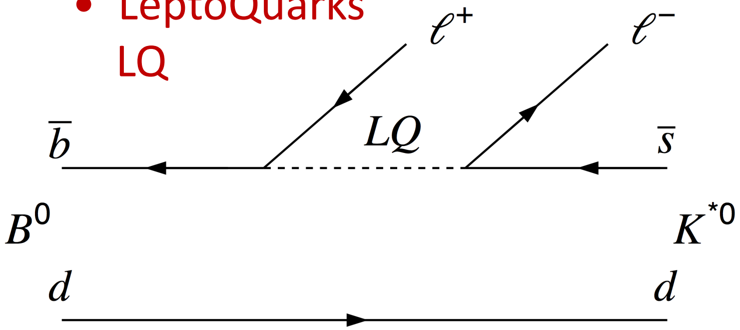
What could it be?

- LFNU is currently a hot topic, many theory papers, see eg. arXiv:1706.07808 for overview.

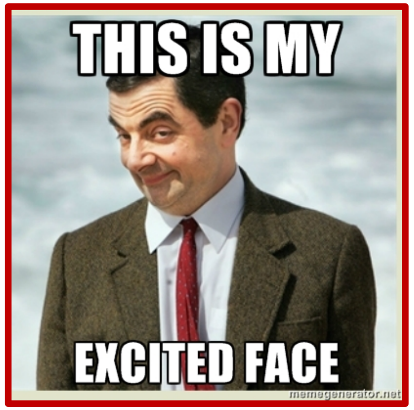
- New gauge bosons
  Z', W'

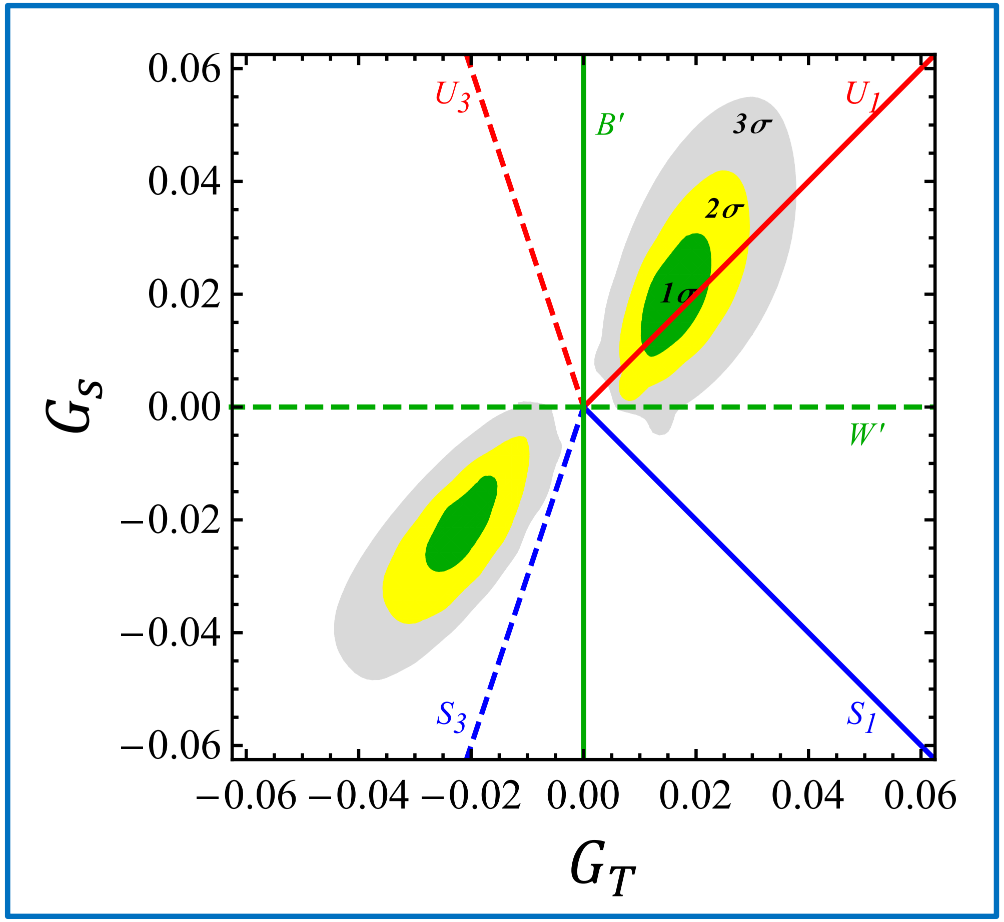


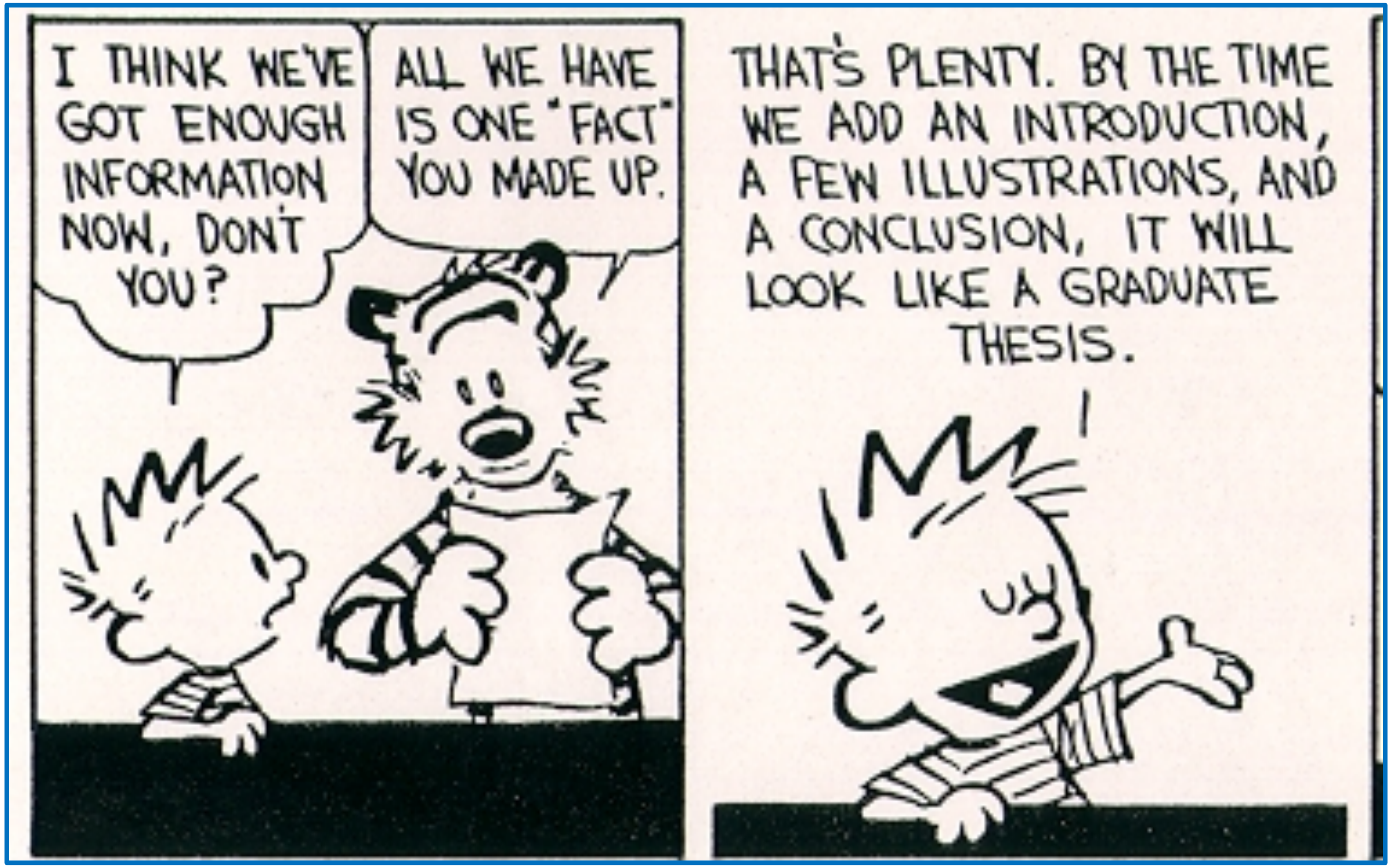
- LeptoQuarks
  LQ



- Best Single LQ model:
  - Vector LQ U1(3,1,2/3)
  - Scale of NP should be ~1.5 TeV
  - Possible UV completions:
    - Pati-Salam models SU(4)
      - Lepton←→4-th color
    - SU(5) GUT
    - 4321 model
    - S_1 & S_3, etc., etc.
  - Shine light on flavour puzzles?!

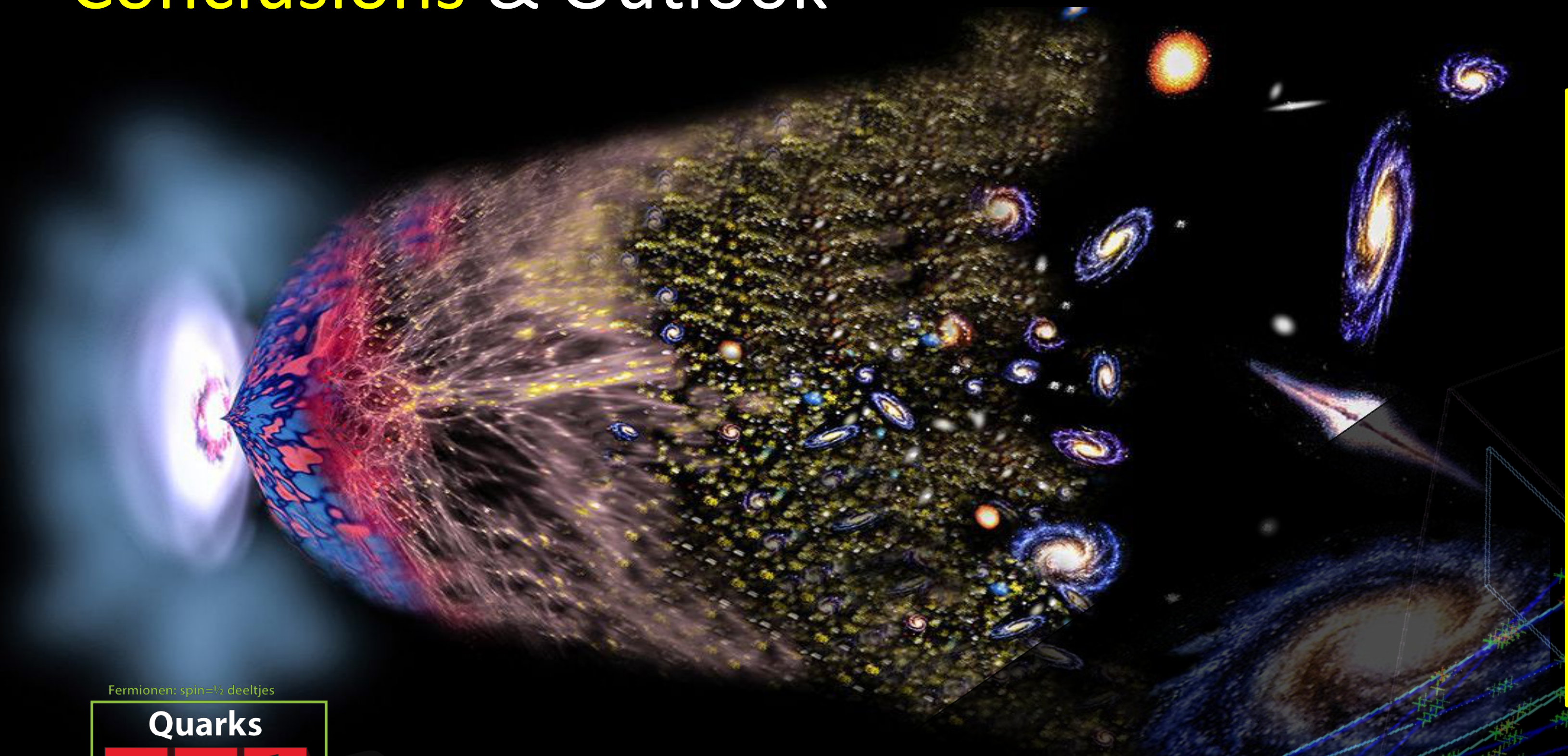


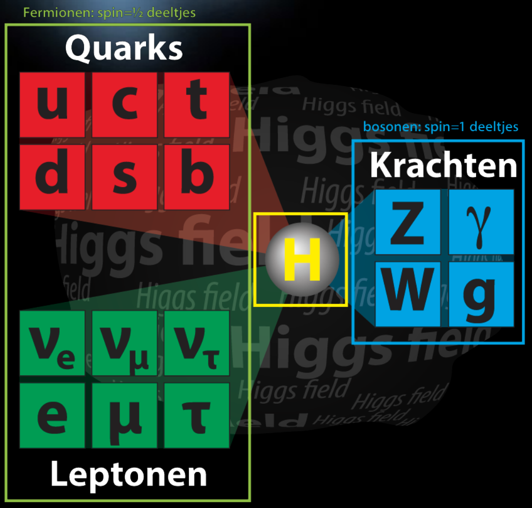



I THINK WE'VE GOT ENOUGH INFORMATION NOW, DON'T YOU?
ALL WE HAVE IS ONE "FACT" YOU MADE UP.
THAT'S PLENTY. BY THE TIME WE ADD AN INTRODUCTION, A FEW ILLUSTRATIONS, AND A CONCLUSION, IT WILL LOOK LIKE A GRADUATE THESIS.

Conclusions & Outlook

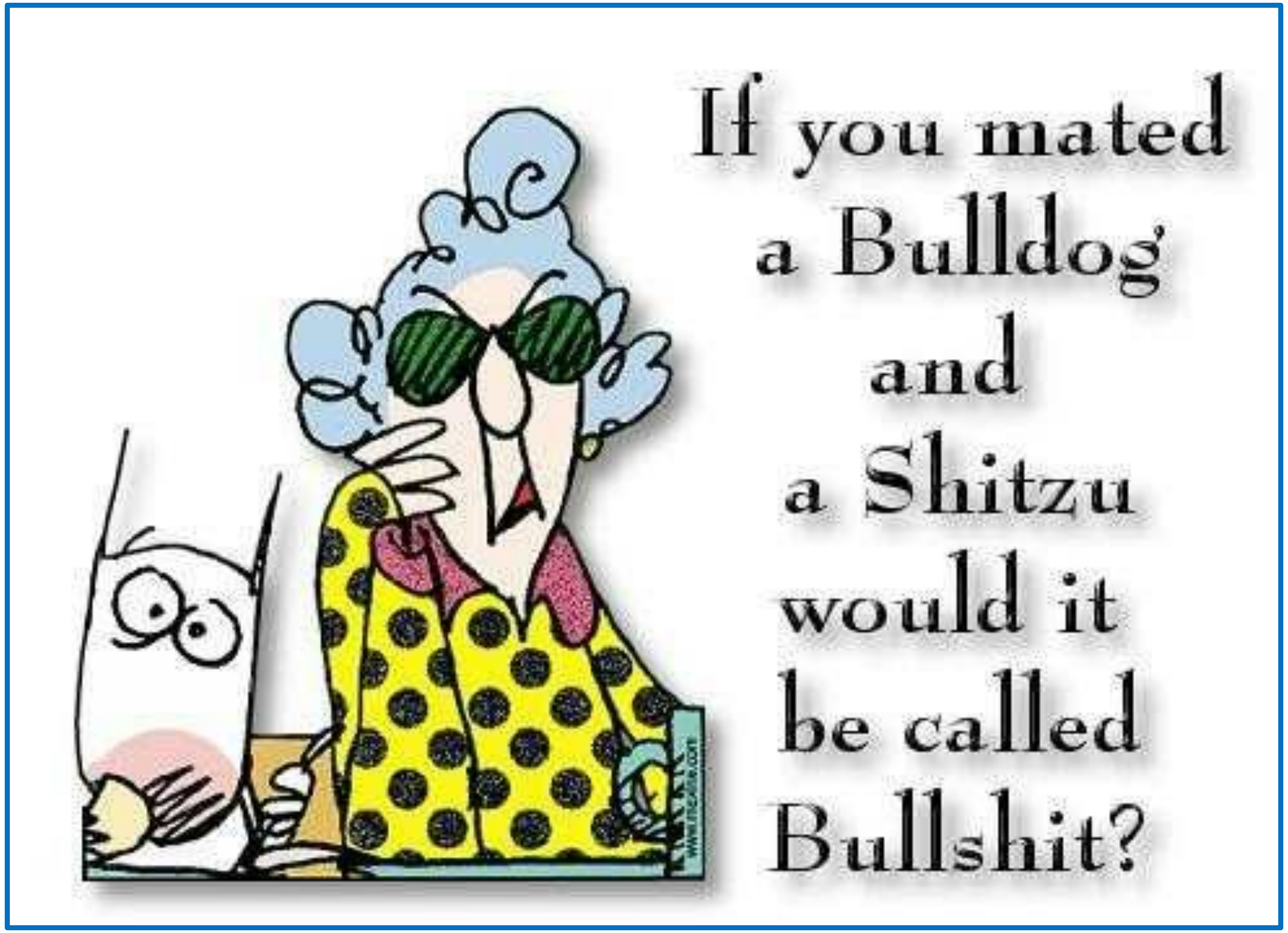
- Why 3? → no antimatter?
- Non Universality → why 3?
- EWSB super interesting
- Flavour probes deeply into quantum (CP, rare decays)
- LHCb→Upgrade1→Upgrade2
- Belle2, …





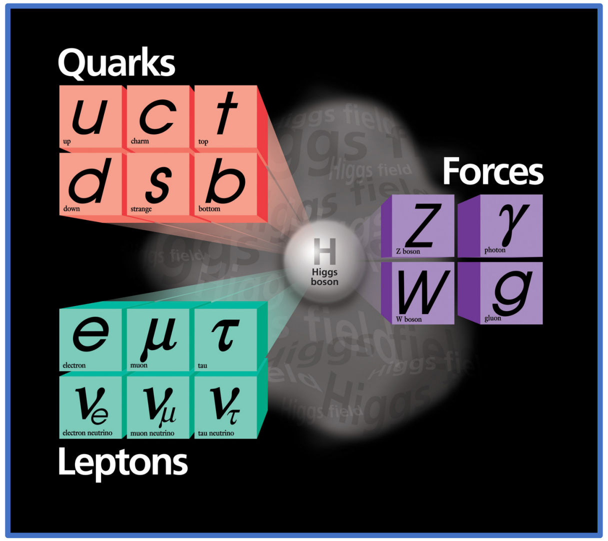
Thank You & Enjoy the Conference

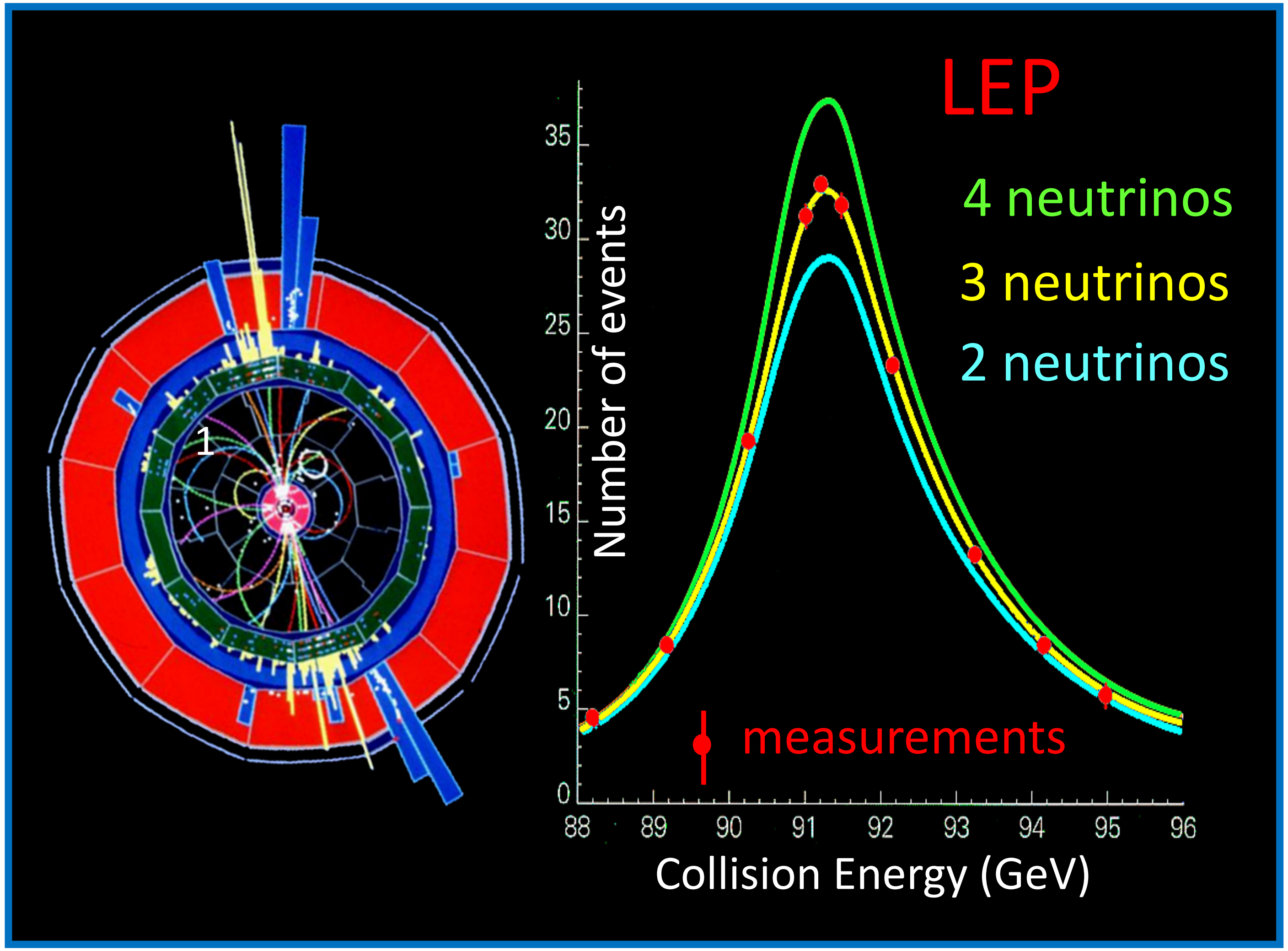
Don’t be afraid to ask questions…



Extra Slides

3 Generations of fundamental particles – How do we know?



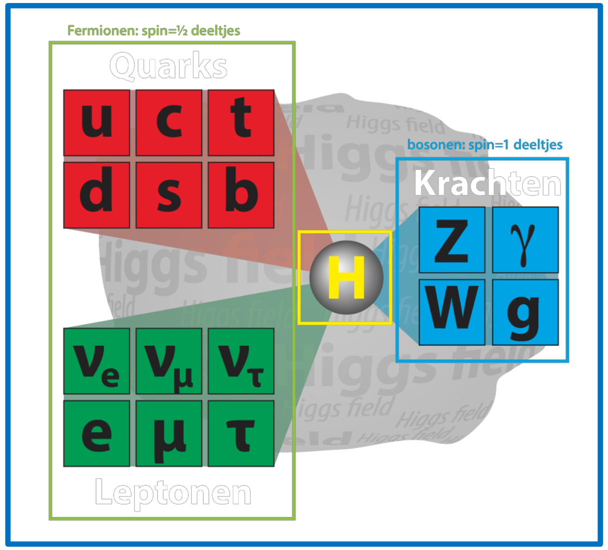


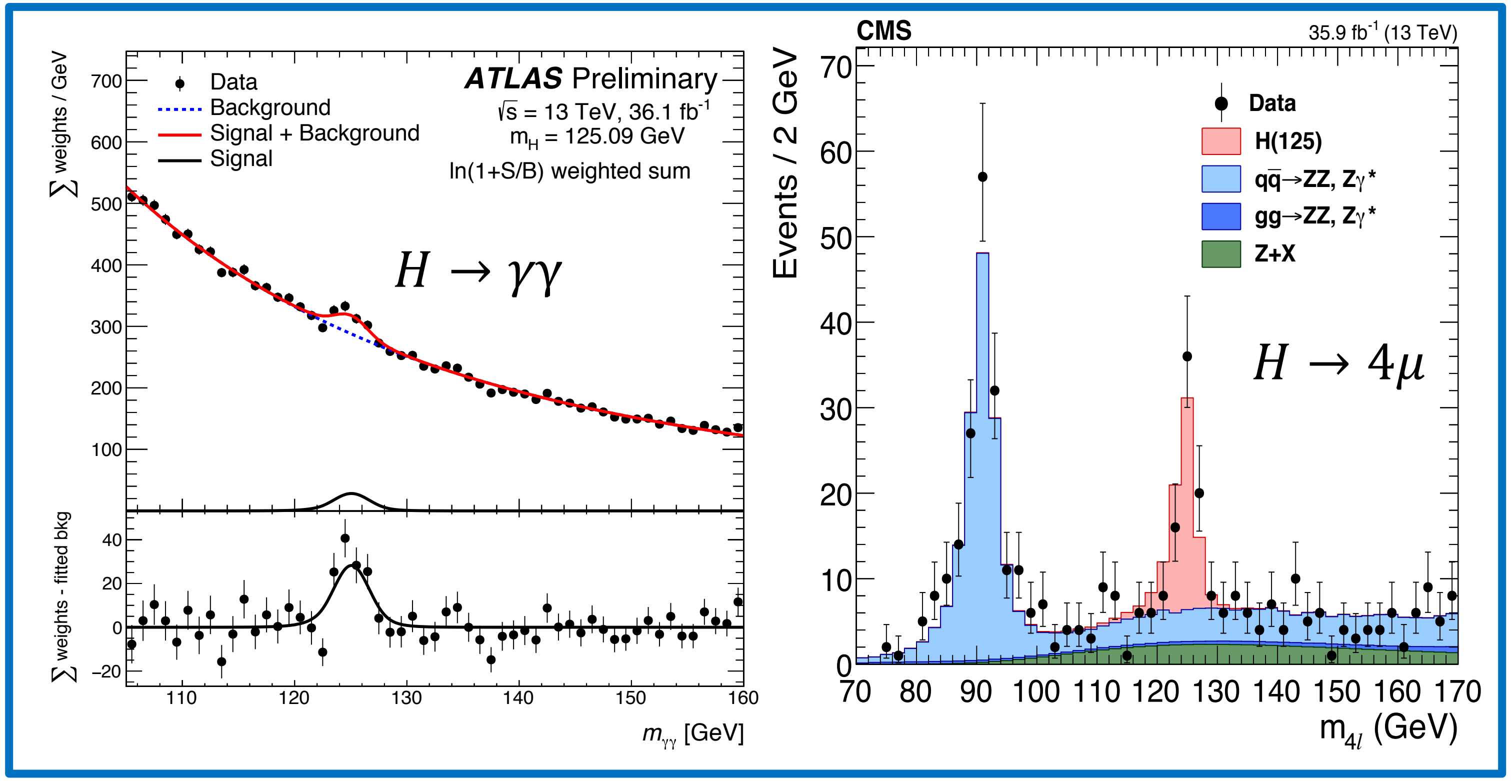
<u>LEP:</u>

Z decays into 3 light neutrino generations

- *Precisely* three

3 Generations of fundamental particles – How do we know?

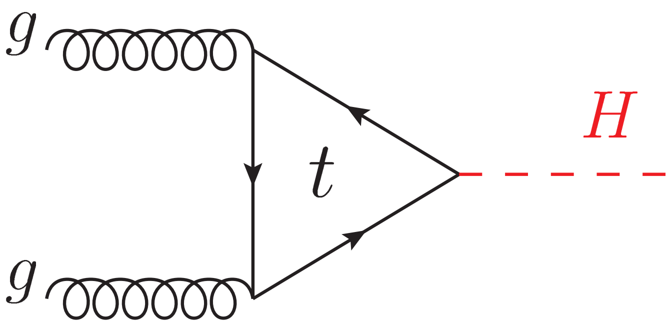




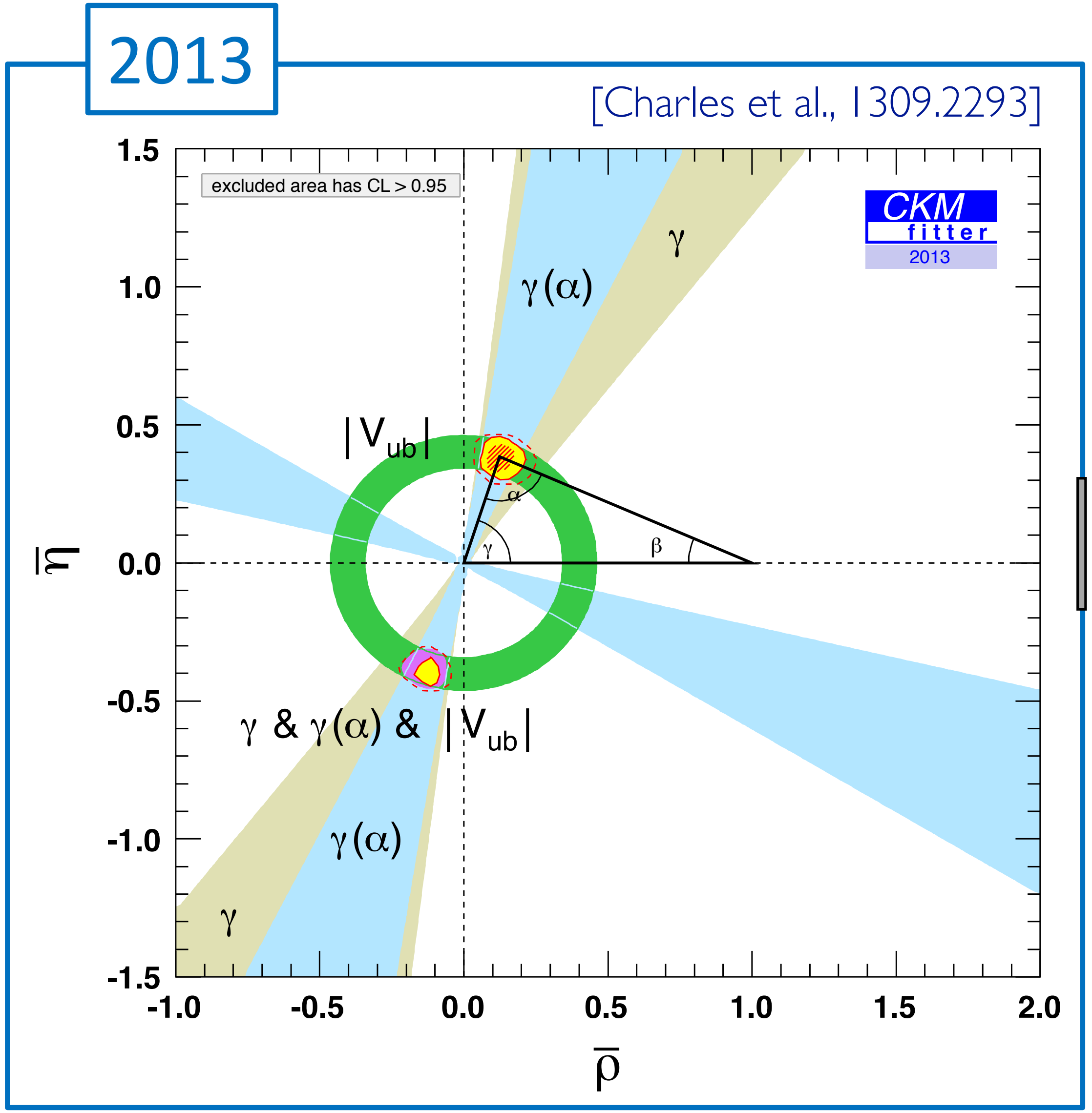
LHC:

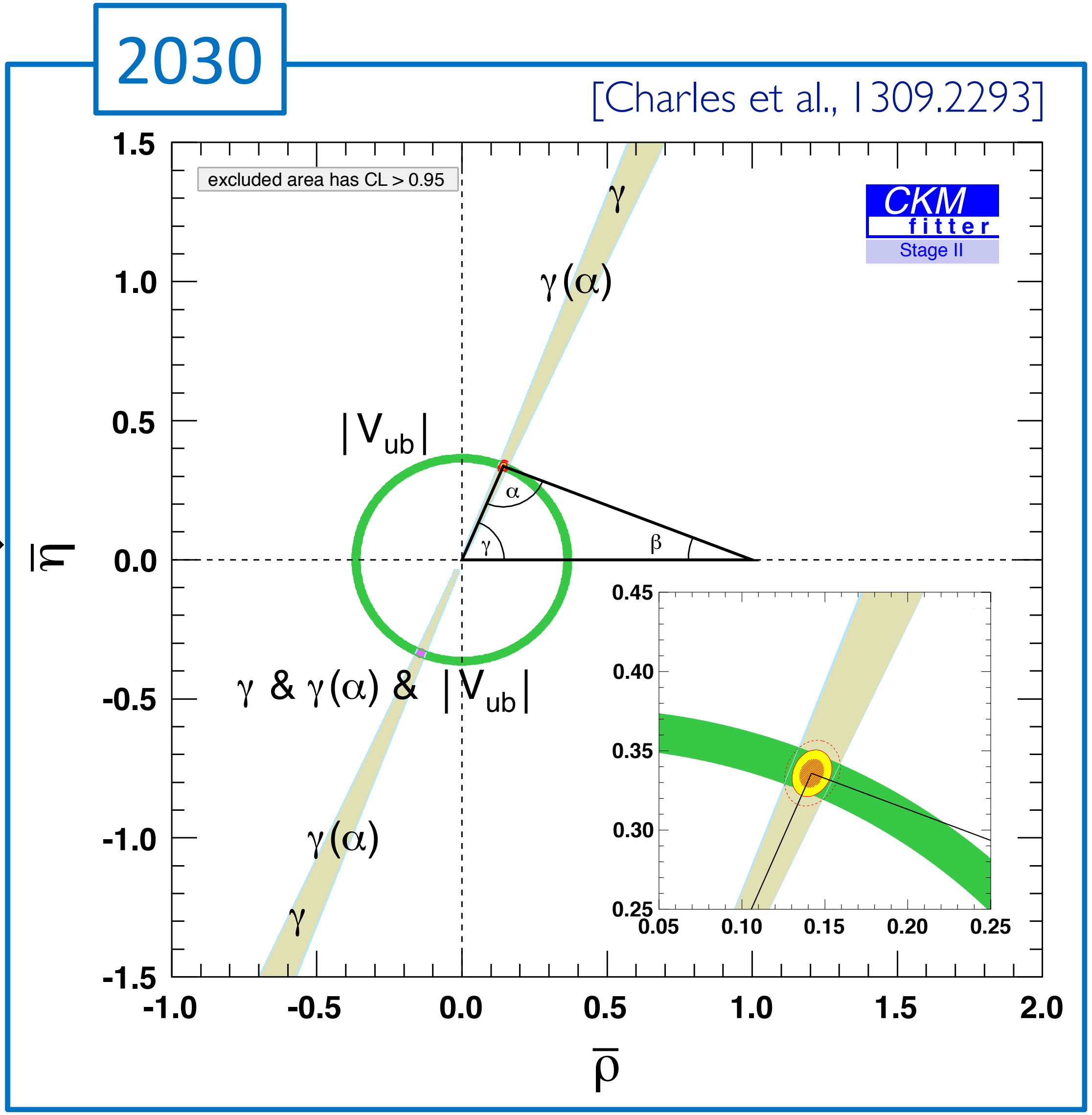
Higgs production:

- *Loop* diagram is proportional to the mass of the heaviest fermion



LHCb: Future sensitivity for CP violation



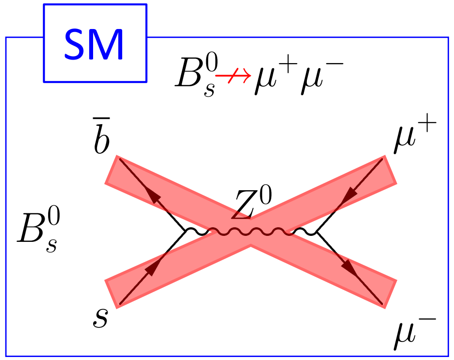


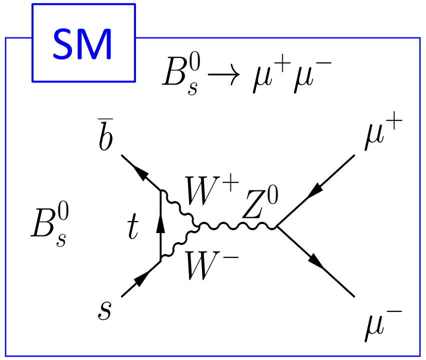
Very Rare Decays

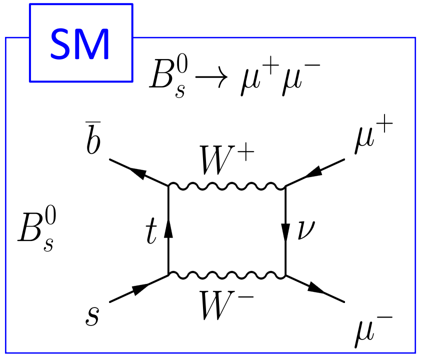
$$B_s^0 \rightarrow \mu^+\mu^-$$
$$B_d^0 \rightarrow \mu^+\mu^-$$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{CKM} \sum_i \mathcal{C}_i \mathcal{O}_i$$

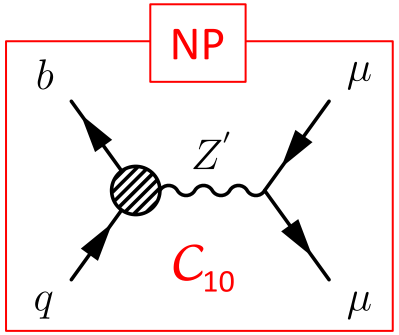
SM: CKM and helicity suppressed: very small B.R.
→ Axial vector coupling C_{10}

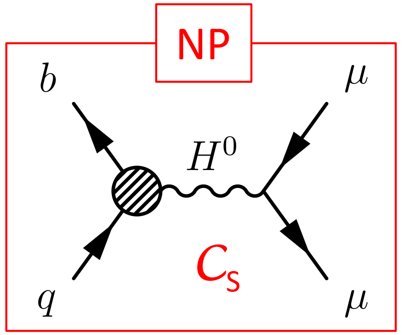


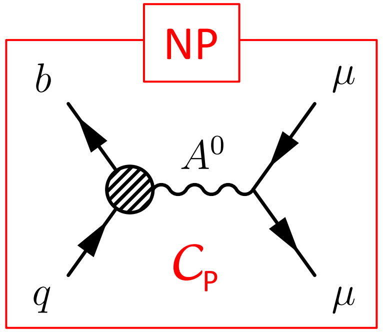




NP: Sensitive to new particles via additional (C_{10}, C_S, C_P) couplings.
→ eg.: Z' , (pseudo-)scalars, …



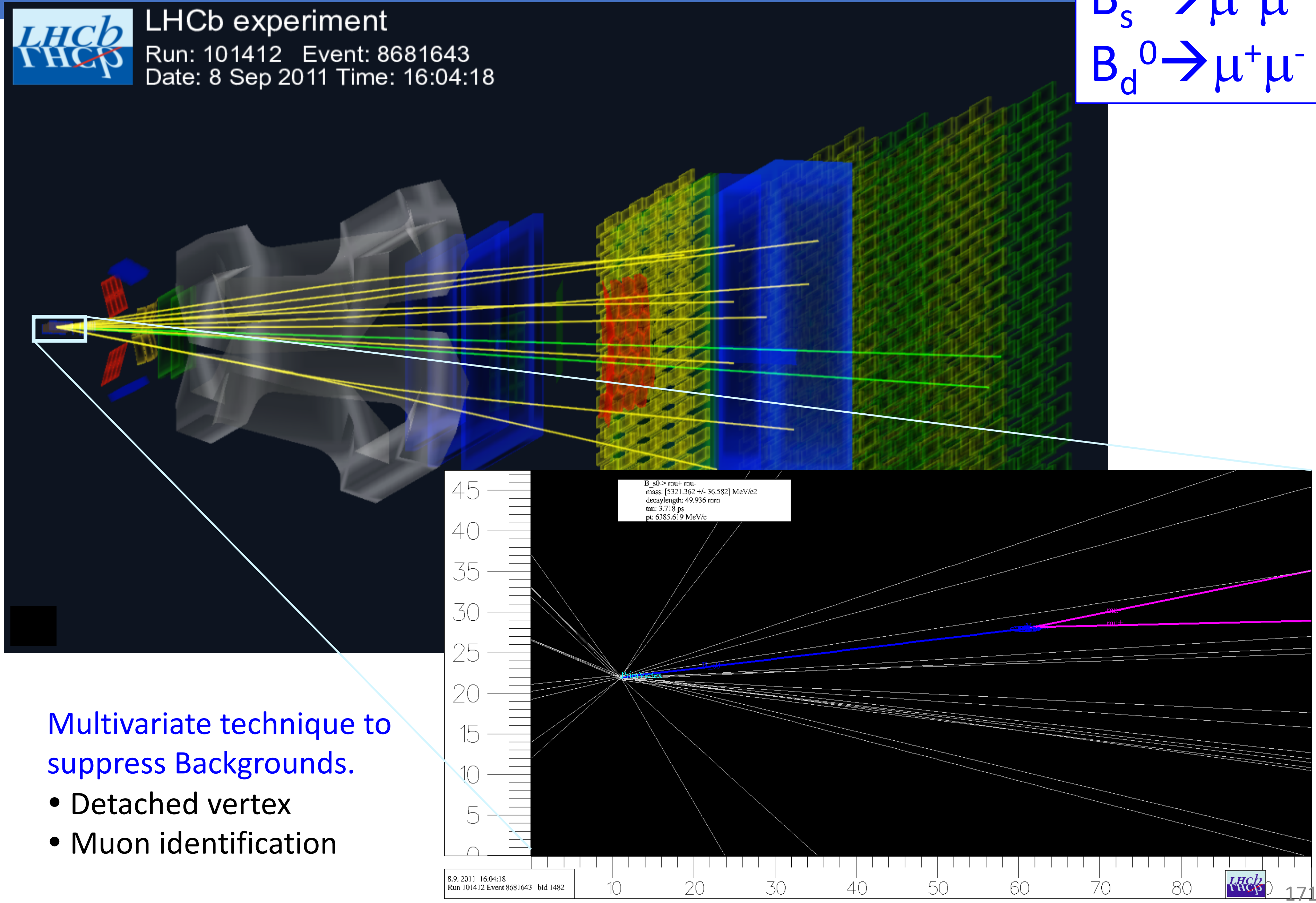




$$BR \propto |V_{tb}V_{tq}|^2 \left[\left(1 - \frac{4m_\mu^2}{M_B^2}\right) \left|C_S - C_S'\right|^2 + \left|(C_P - C_P') + \frac{2m_\mu}{M_B^2}(C_{10} - C_{10}')\right|^2 \right]$$

Very Rare Decays

$B_s^0 \rightarrow \mu^+\mu^-$
$B_d^0 \rightarrow \mu^+\mu^-$



Multivariate technique to suppress Backgrounds.

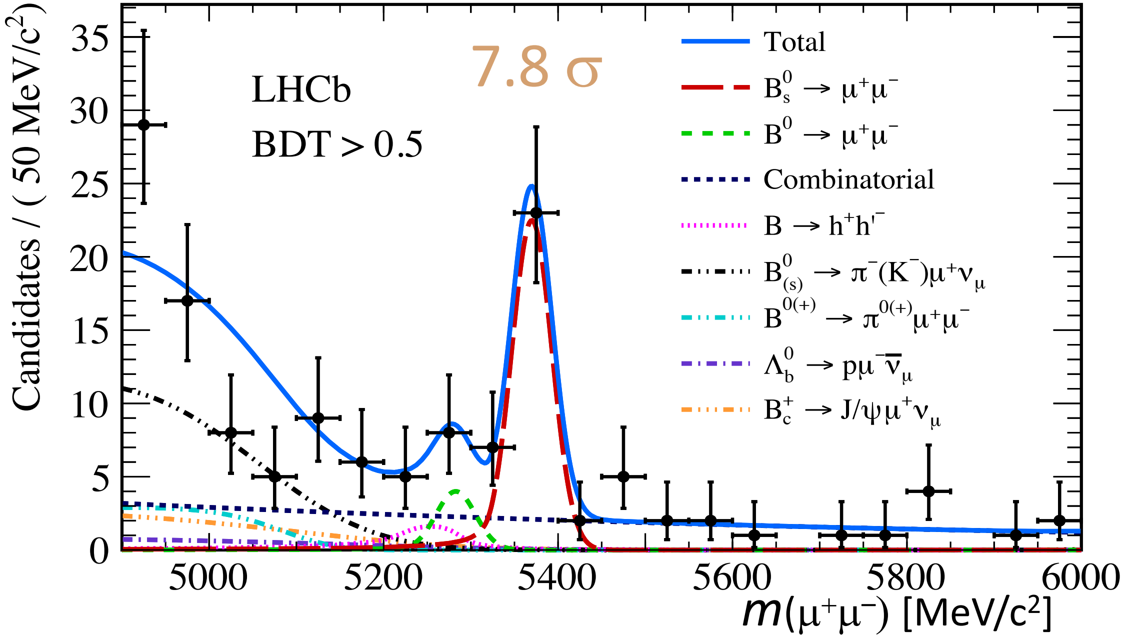
- Detached vertex
- Muon identification

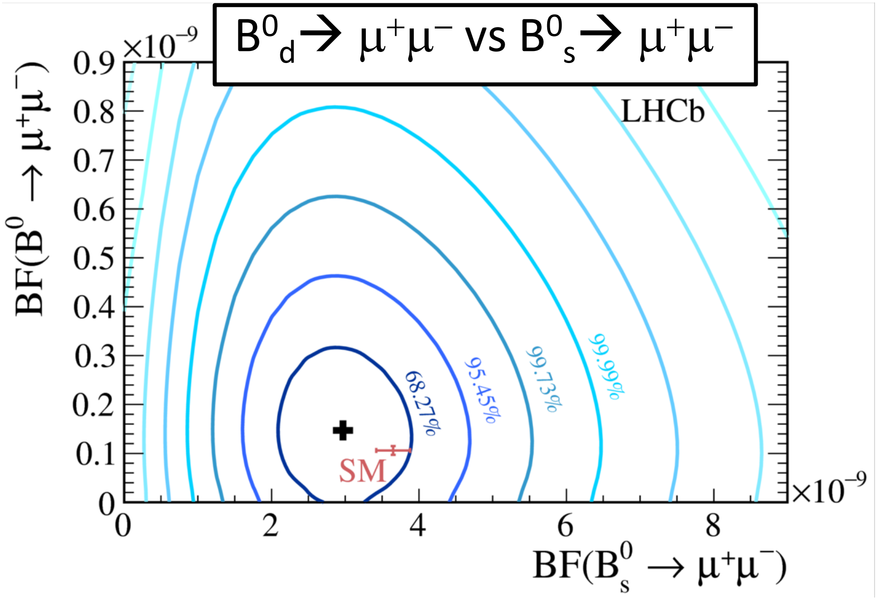
Very Rare Decays

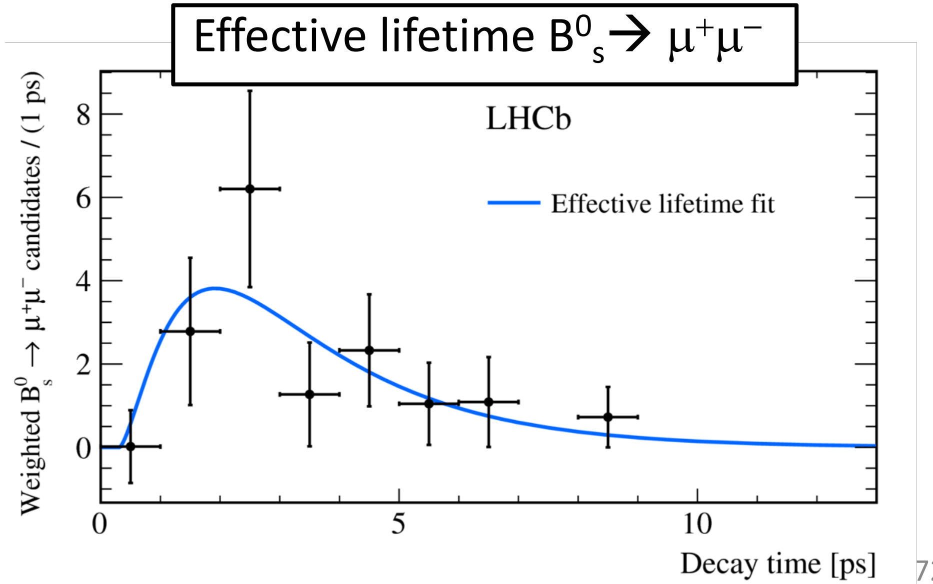
PRL 118 (2017) 191801

$B^0_{d/s} \rightarrow \mu^+\mu^-$

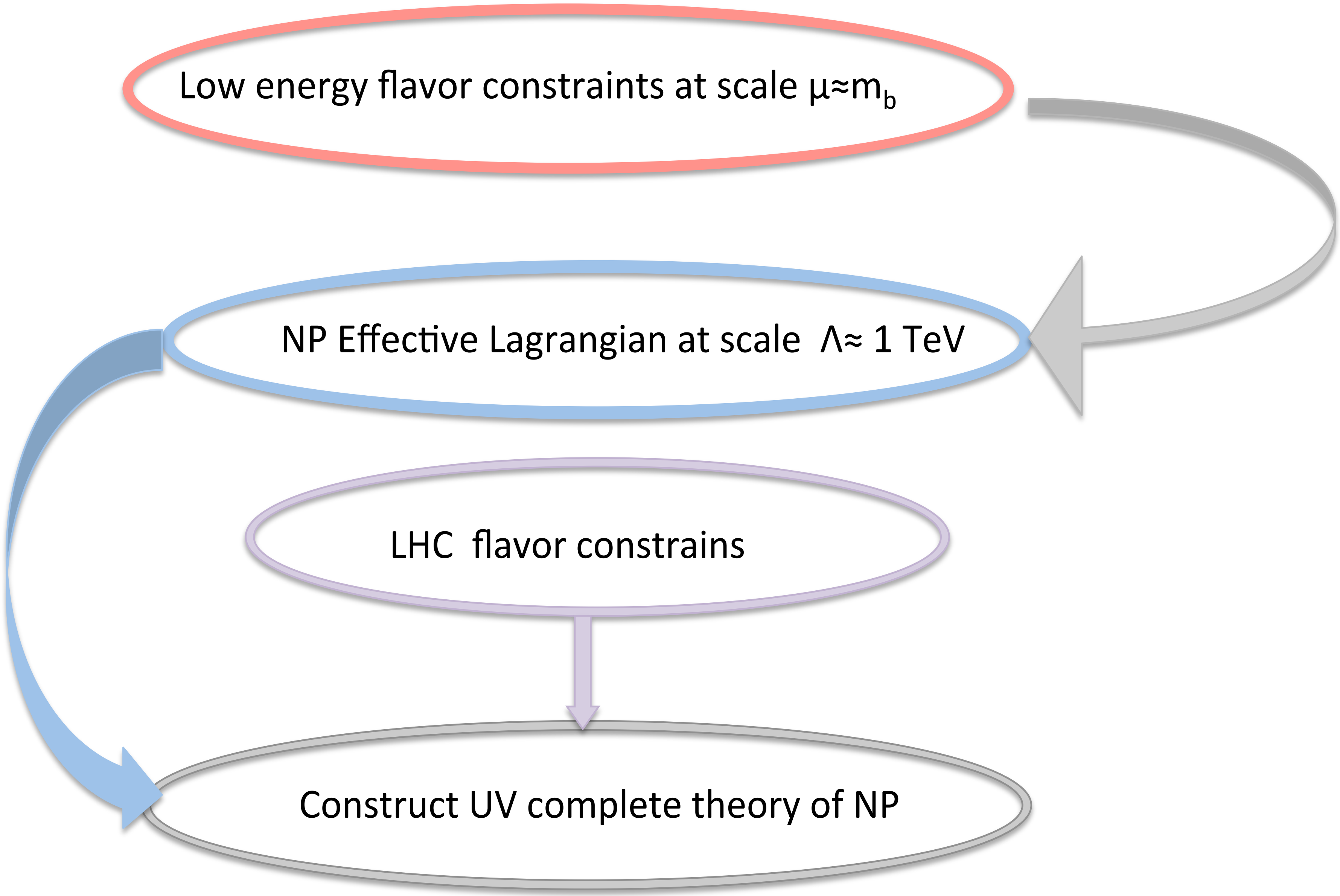
- Very strongly suppressed in the SM
- High sensitivity for physics beyond SM
- Hot topic for LHCb







S. Fajfer, ICHEP2018



S. Fajfer, ICHEP2018

Models at TeV scale explaining both B anomalies

Scalar LQ as pseudo-Nambu-Goldstone boson

Gripaios et al, 1010.3962,
Gripaios et al., 1412.1791,
Marzocca 1803.10972…

Models with scalar LQs

Hiller & Schmaltz, 1408.1627,
Becirevic et al. 1608.08501, SF and Kosnik, 1511.06024, Becirevic et al., 1503.09024,
Dorsner et al, 1706.07779,
Cox et al., 1612.03923,
Crivellin et al.,1703.09226…

W', Z' in warped space

Megias et al.,1707.08014

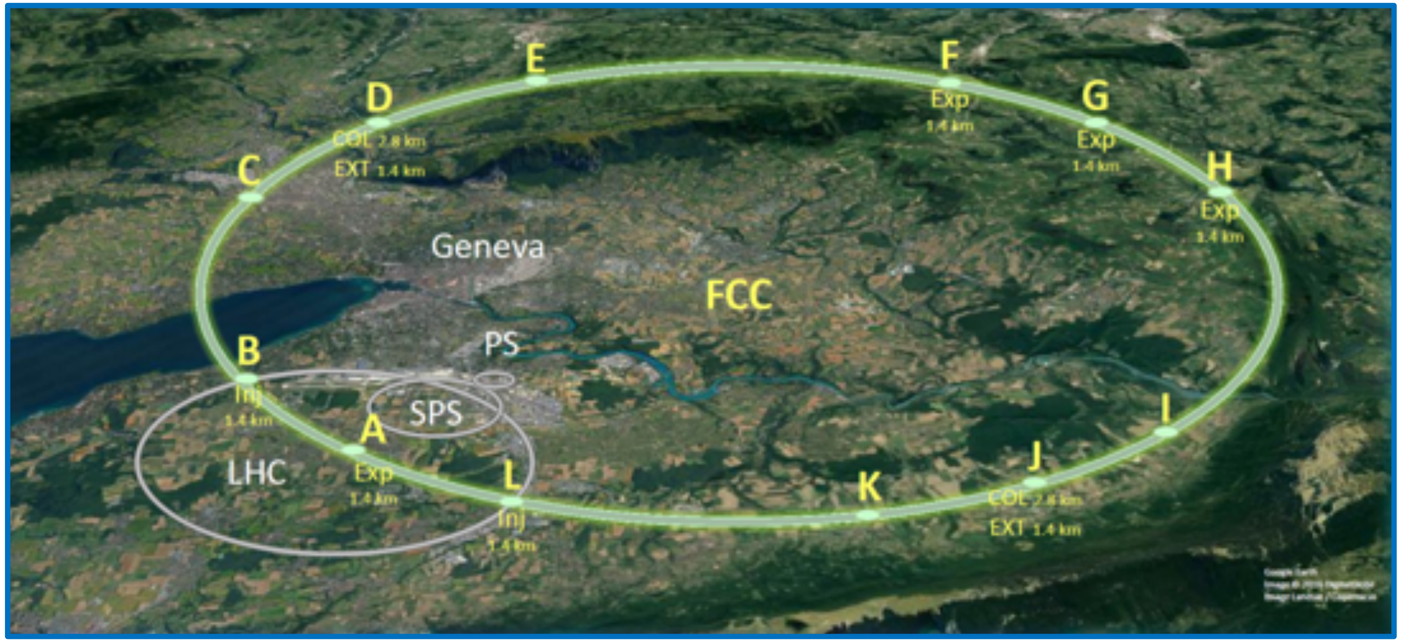
Vector resonances (from techni-fermions)

Barbieri et al.,1506.09201, Buttazzo et al. 1604.03940,
Barbieri et al., 1611.04930
Blanke & Crivellin, 1801.07256,…

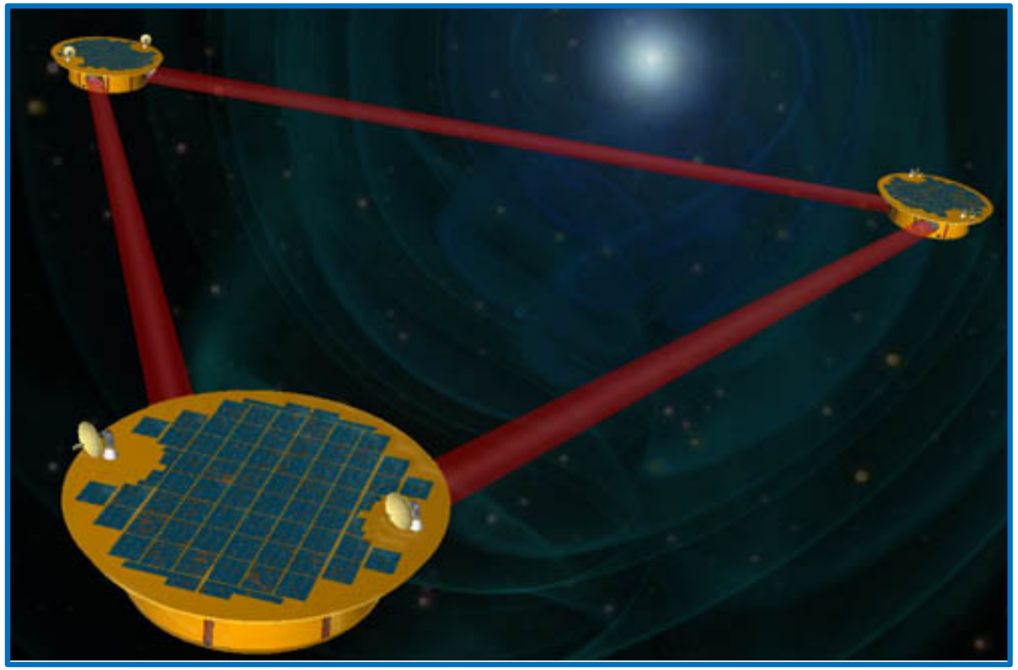
Gauge bosons

Greljo et al., 1804.04642
Cline, Camalich, 1706.08510
Calibbi et al.,1709.00692
Assad et al., 1708.06350
Di Luzio et al.,1708.08450
Bordone et al.,1712.01368, 1805.09328…

How could we probe the EW phase transition?



Circles!



Triangles!