Flavour Puzzles and the LHCb Experiment

Marcel Merk, Bormio 2023

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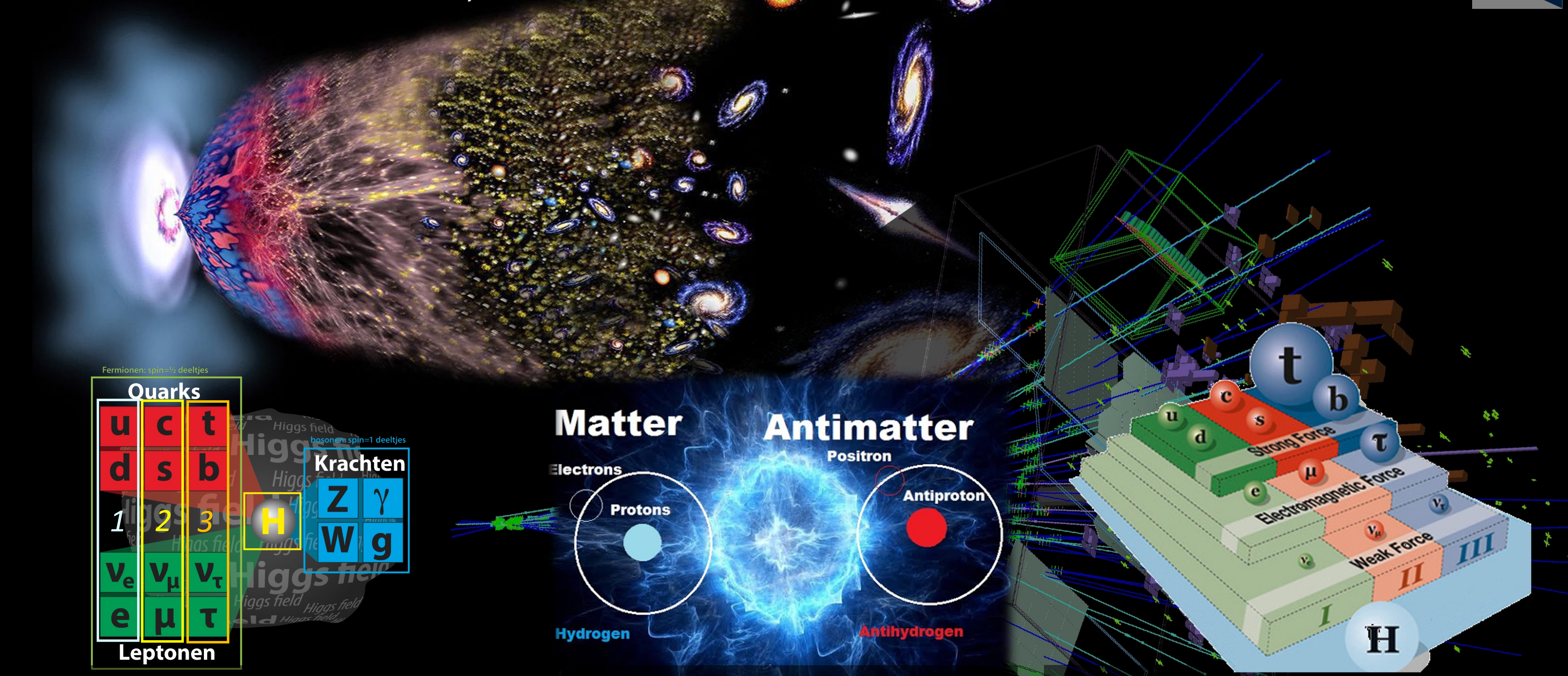

Why three generations of particles? ***Why is there no antimatter?*** ***Why this particle mass hierarchy?***

1) Three generations and the origin of CP violation
2) The amount of CP violation in CKM
3) Measurements of CP violation with LHCb
4) B-decays and Flavour Anomalies
5) Outlook/conclusion

1) **Three generations and the origin of CP violation**
2) The amount of CP violation in CKM
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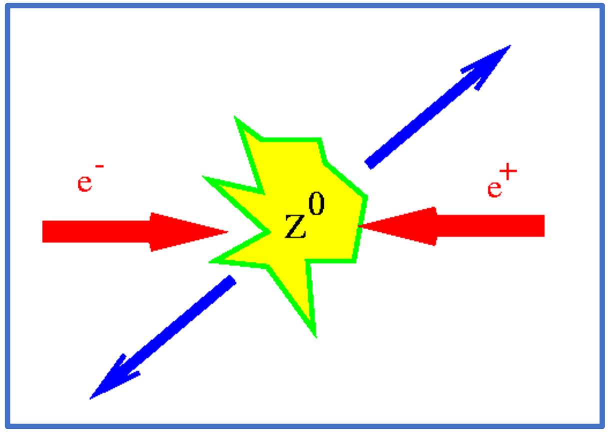
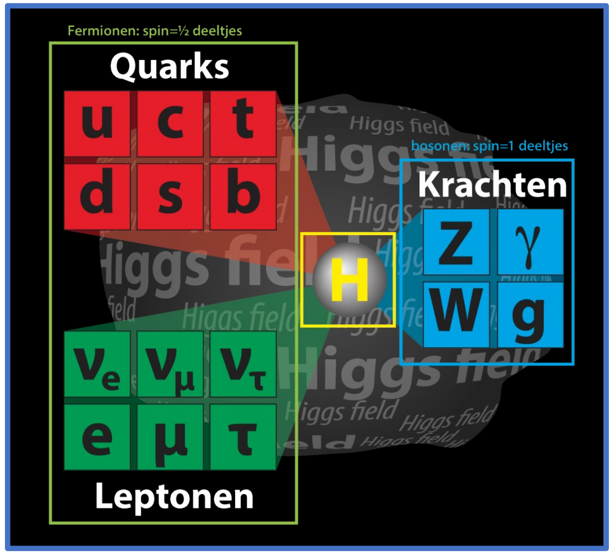
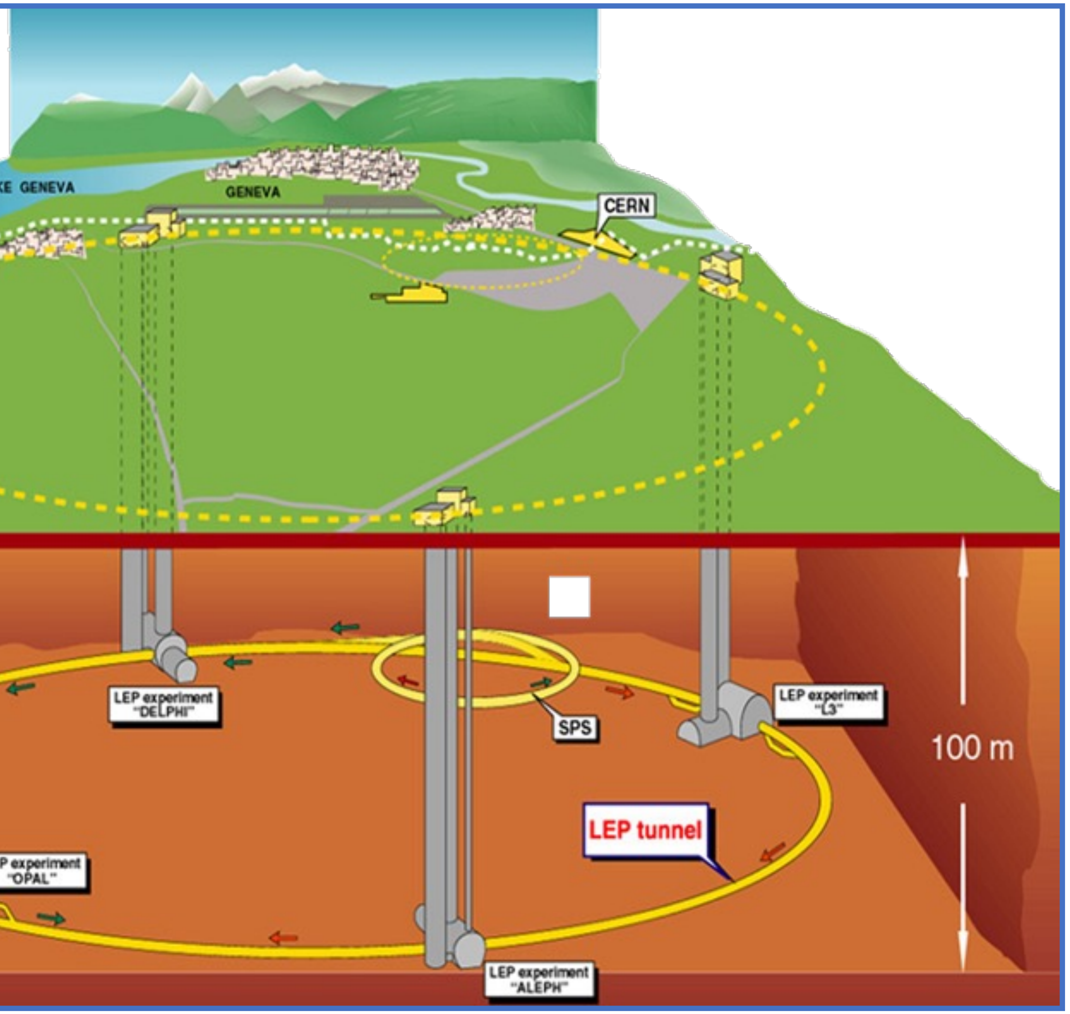
3 Generations of fundamental particles – How do we know?

1) LEP: The heavy Z boson decays into 3 light neutrino types.

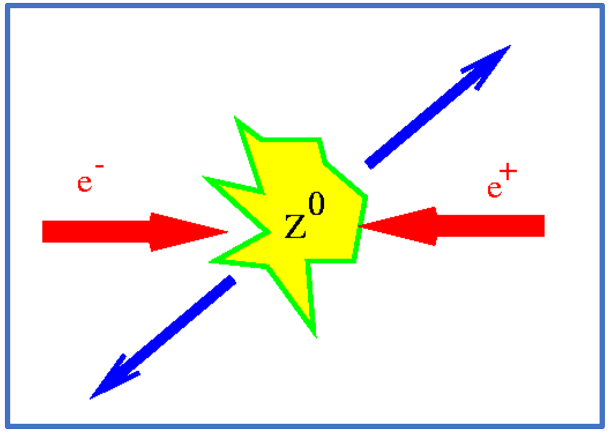


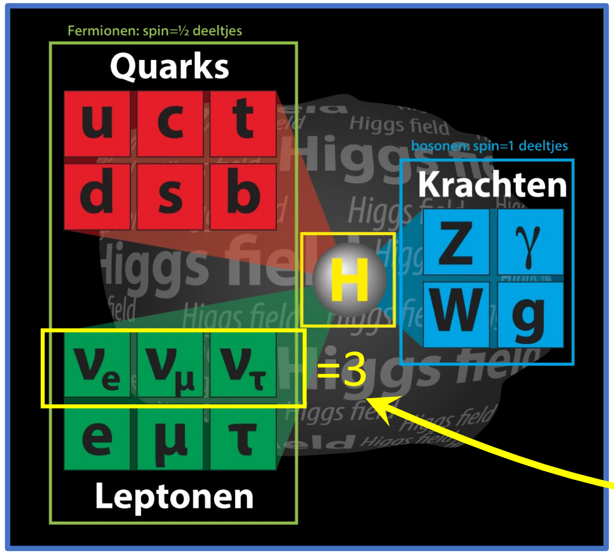


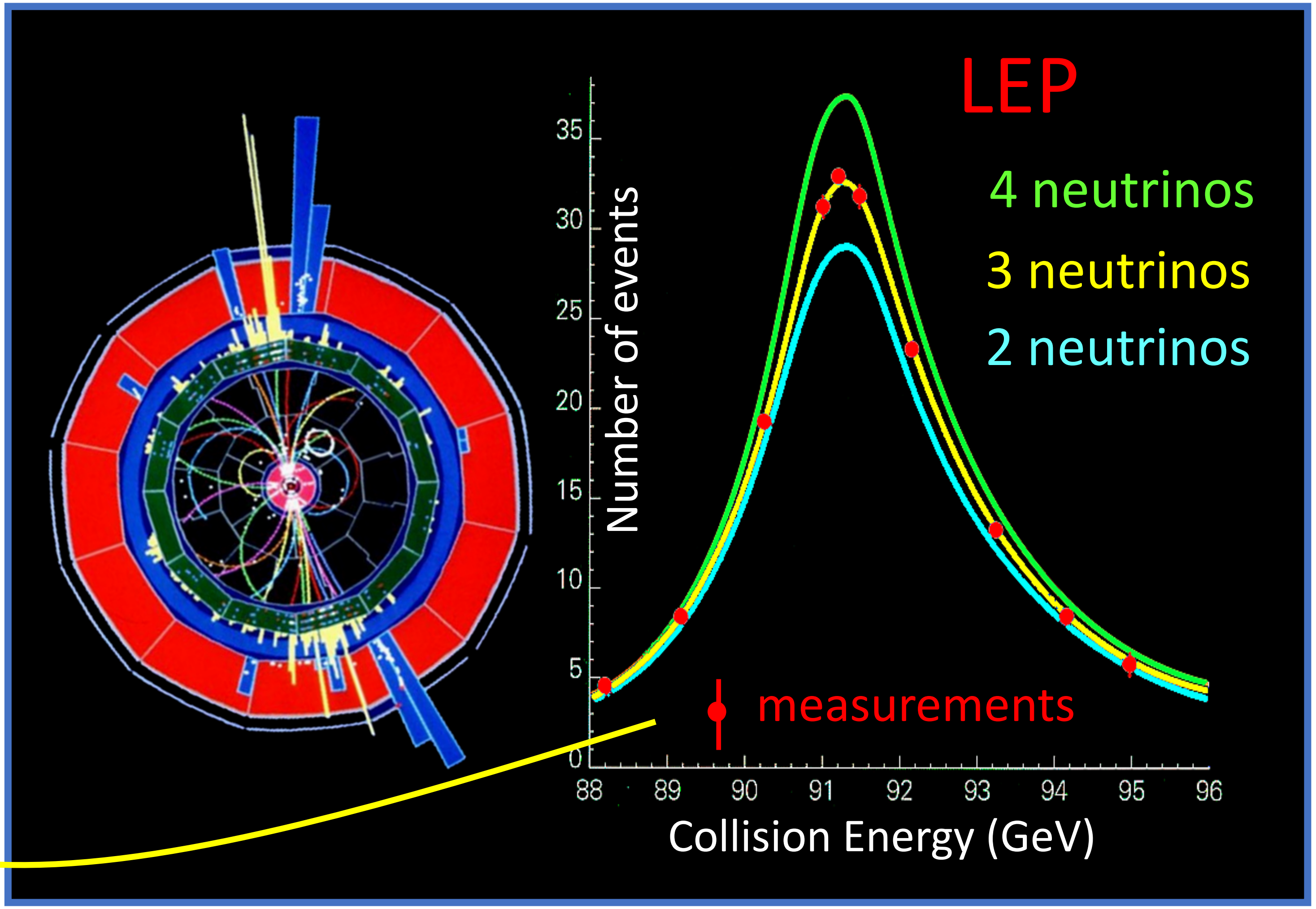
LEP @ CERN:
1989-2000



1) **LEP:** The heavy Z boson decays into 3 light neutrino types.





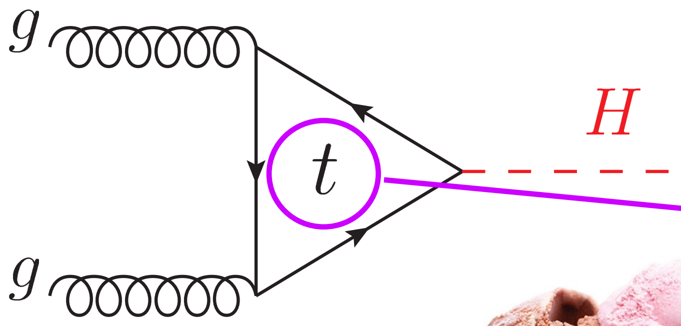


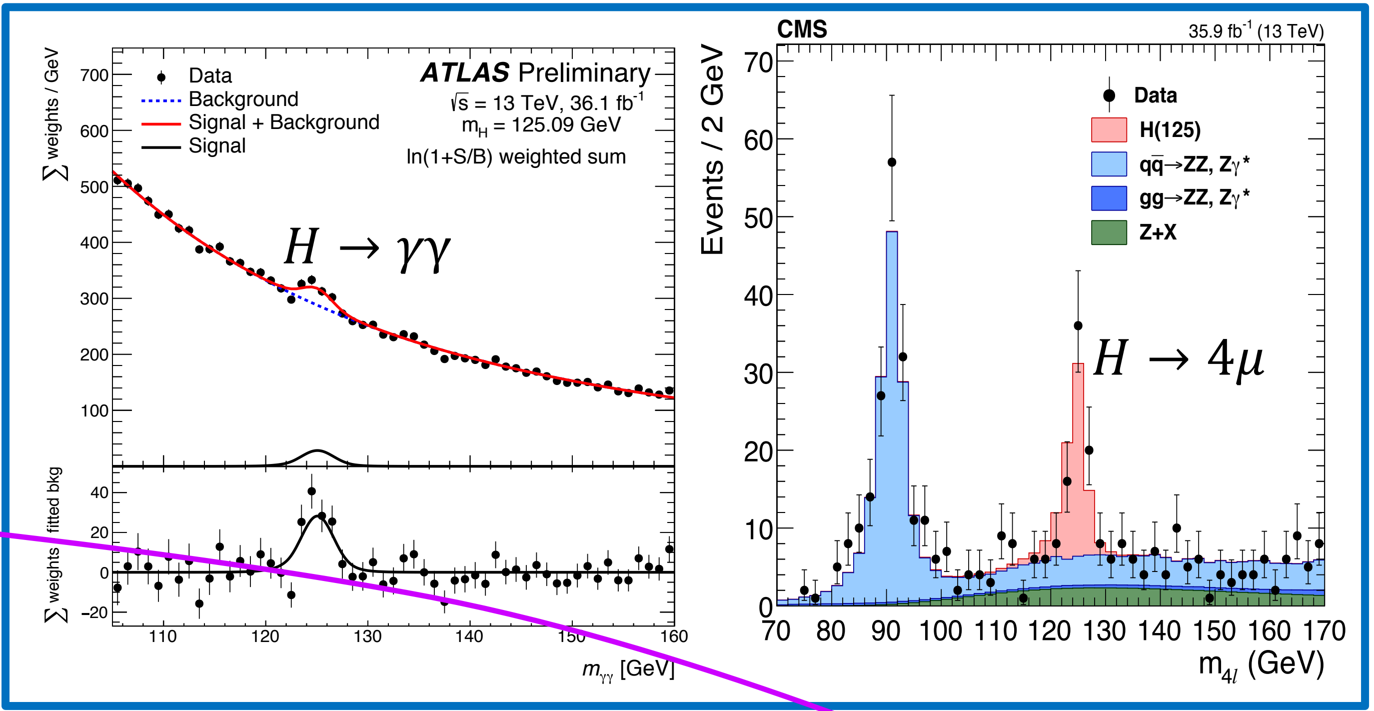
- *No additional weakly interacting **light fermion** generations.*

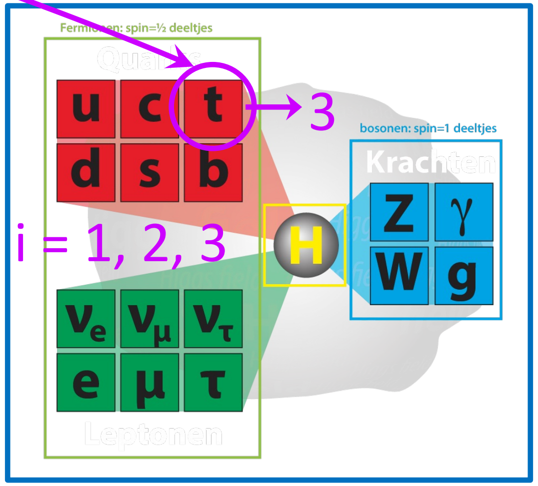
3 Generations of fundamental particles – How do we know?

2) LHC: Higgs production:

Loop diagram is proportional to the mass of the heaviest fermion.





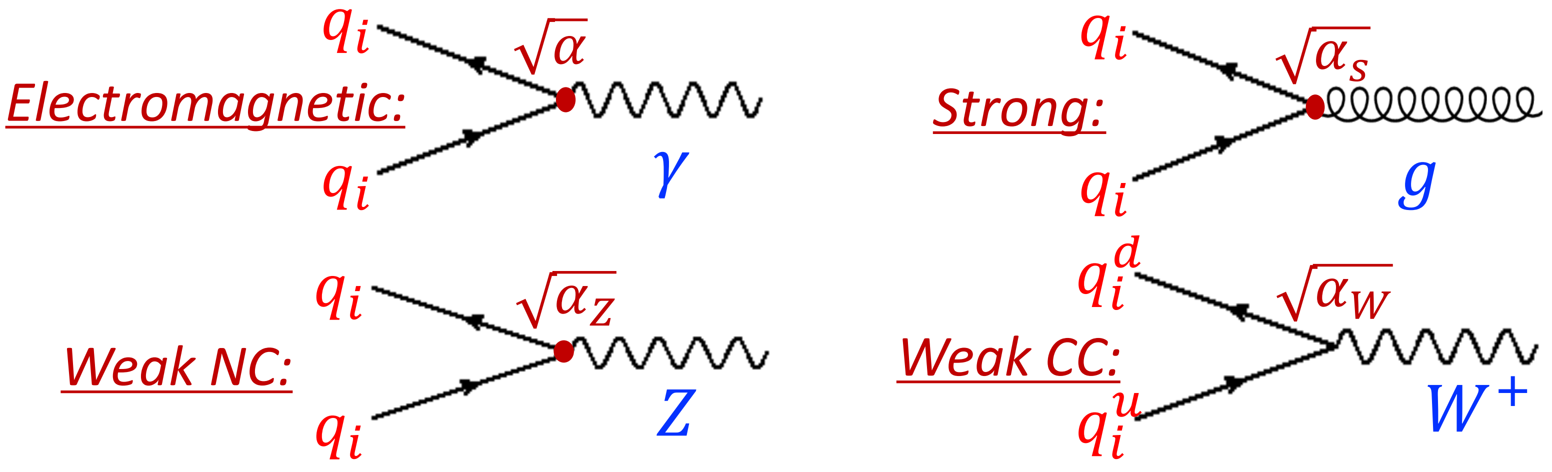


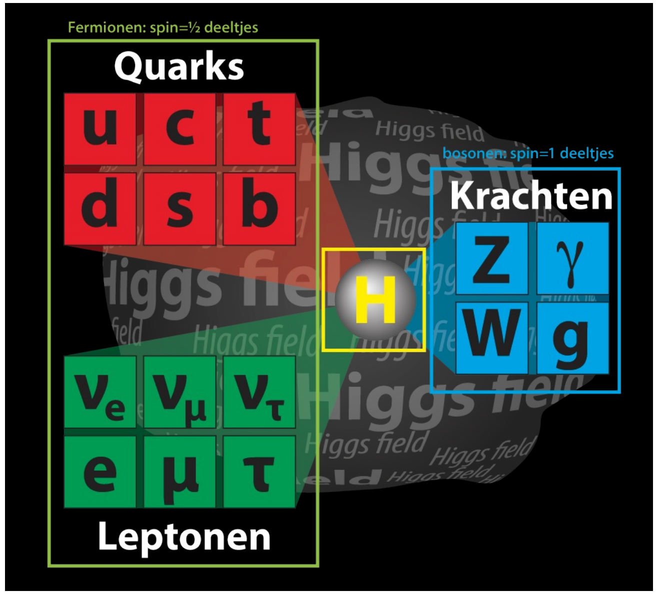
- *Top is the **heaviest fermion** flavour.*

➢ *3 Flavour generations*

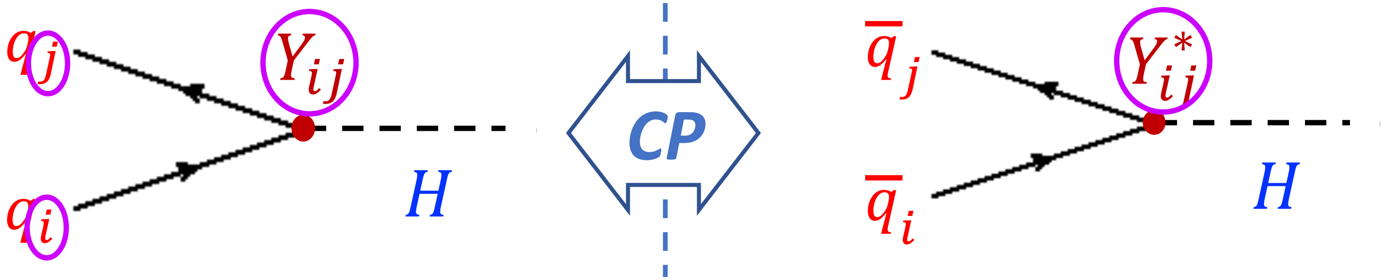
Flavour Universality in the Standard Model

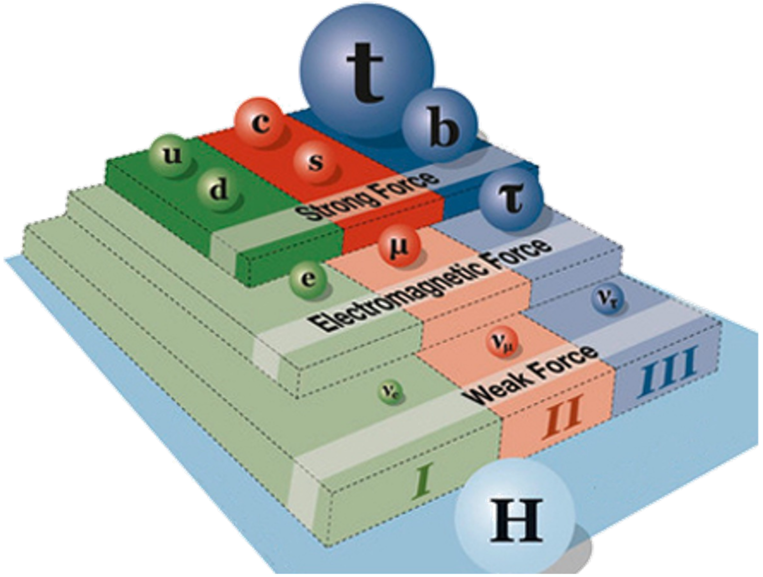
- Quark and lepton generations interact identically
  - No difference between particles of different generation
  - No matter – antimatter asymmetry (CP Violation) by construction





- Universality violation: masses → Higgs !
  - Higgs coupling is *not universal*, and mixes generations $(i \leftrightarrow j)$
  - Complex couplings: allows for CP Violation!

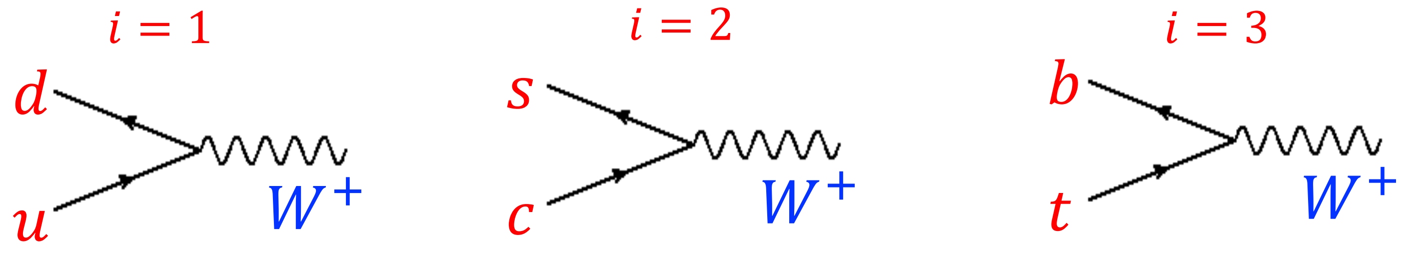




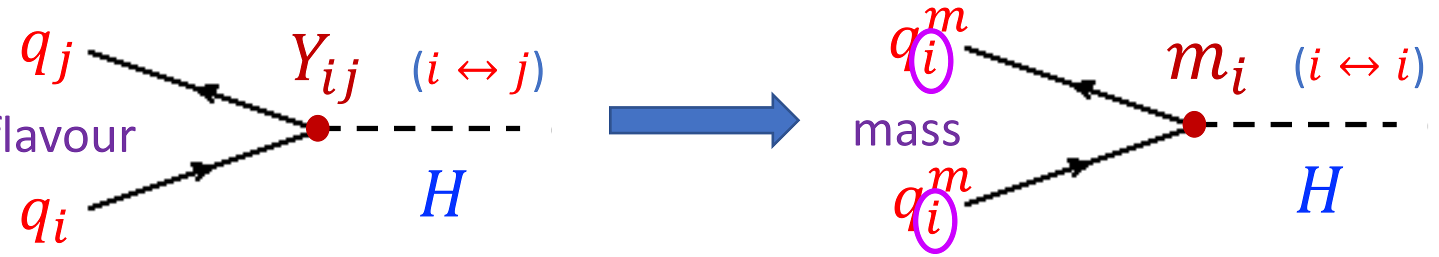
Flavour Universality → Symmetry Breaking

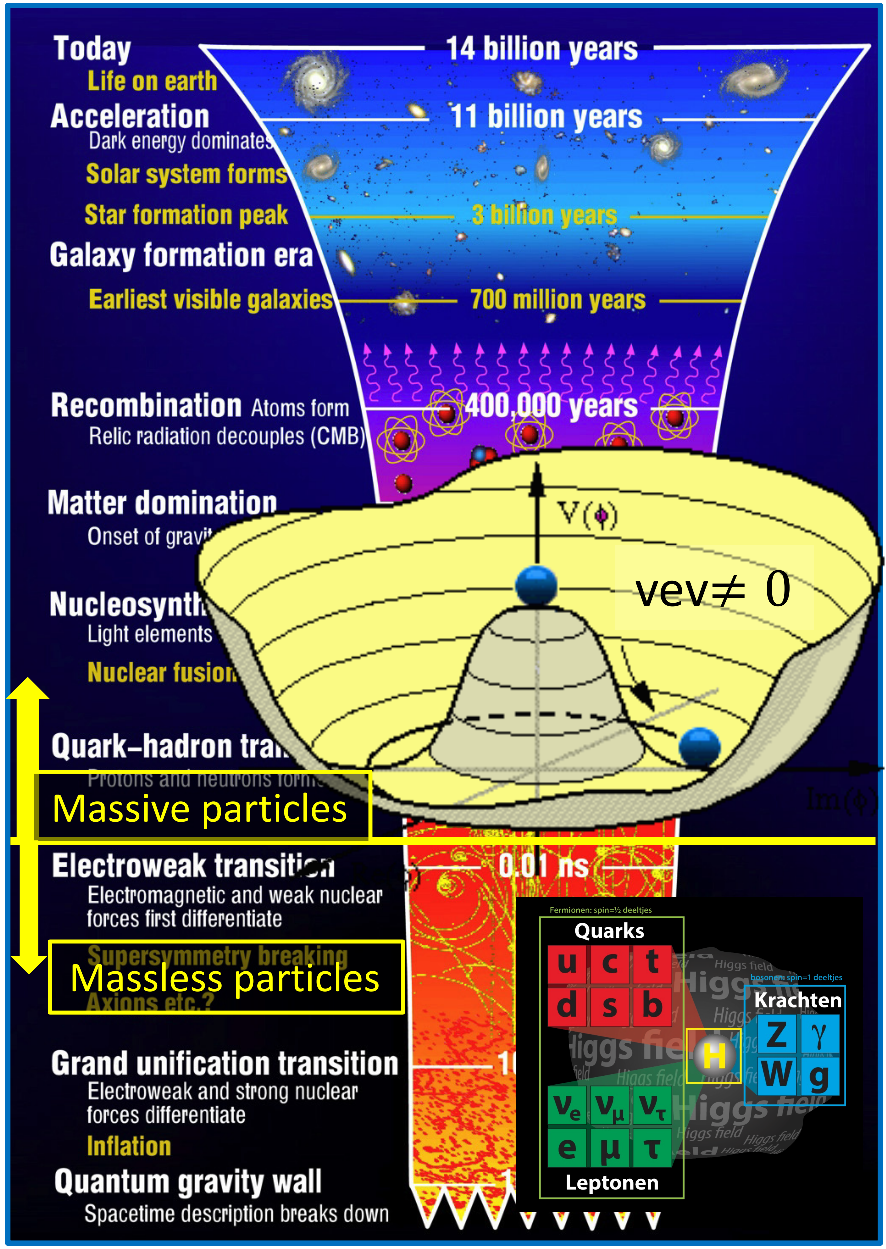
- Weak charged current interaction: $(i \leftrightarrow i)$

Flavour states:



- Higgs: redefines quark states in mass eigenstates:





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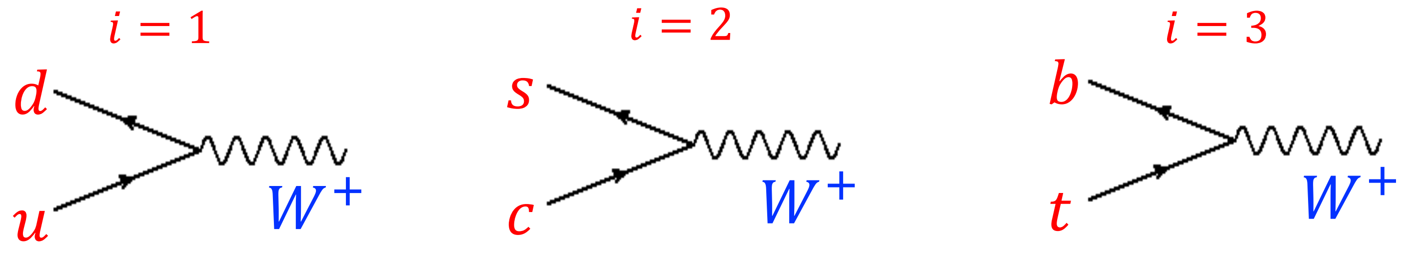
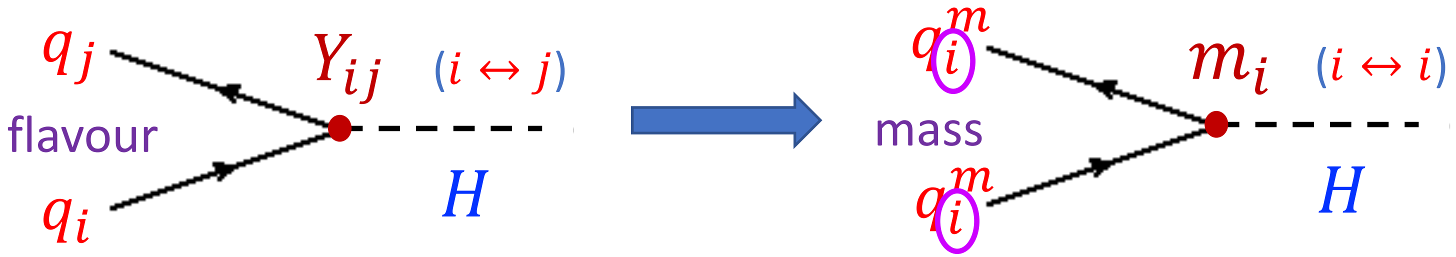
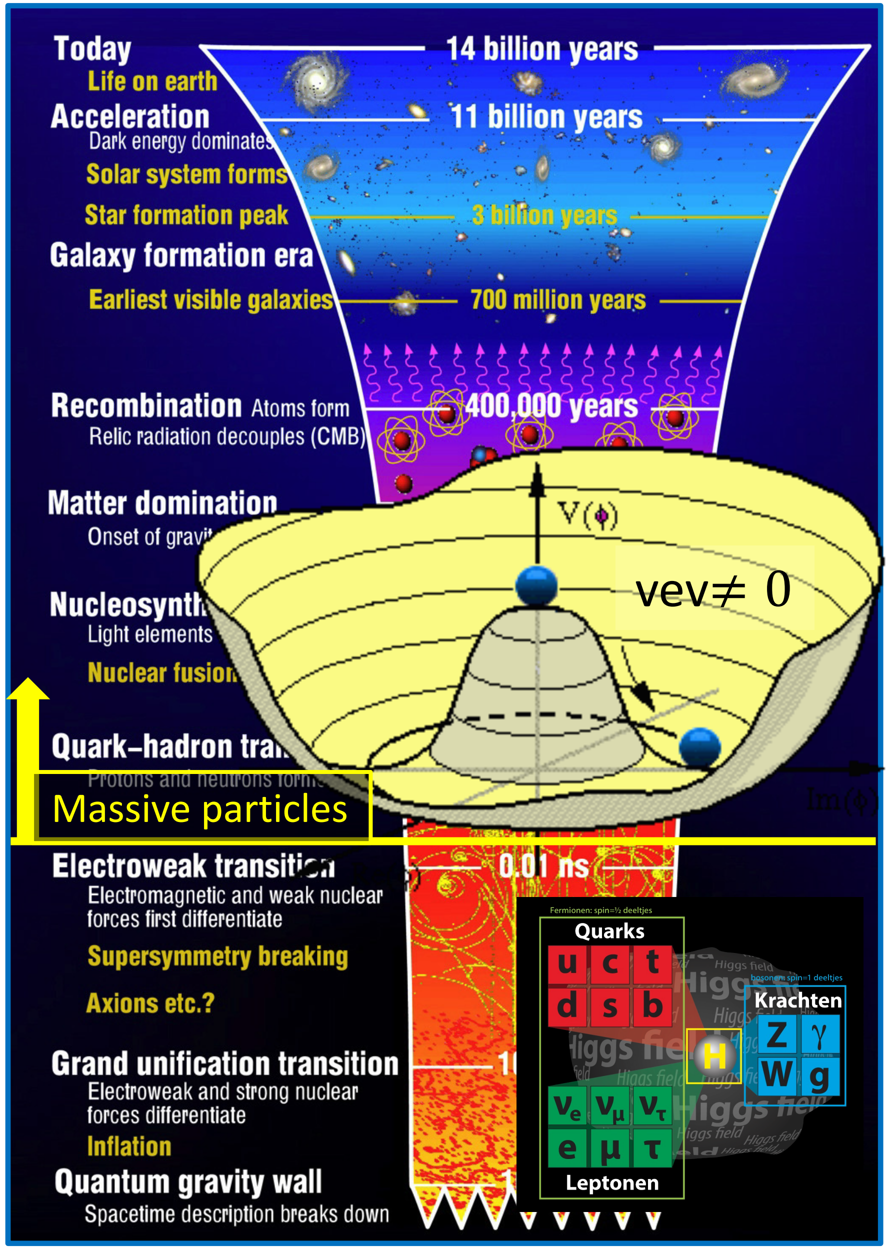


Mass states:

$$|d^m\rangle \equiv V_{ud}\,|d\rangle + V_{us}\,|s\rangle + V_{ub}\,|b\rangle \qquad |u^m\rangle \equiv |u\rangle$$
$$|s^m\rangle \equiv V_{cd}\,|d\rangle + V_{cs}\,|s\rangle + V_{cb}\,|b\rangle \qquad |c^m\rangle \equiv |c\rangle$$
$$|b^m\rangle \equiv V_{td}\,|d\rangle + V_{ts}\,|s\rangle + V_{tb}\,|b\rangle \qquad |t^m\rangle \equiv |t\rangle$$

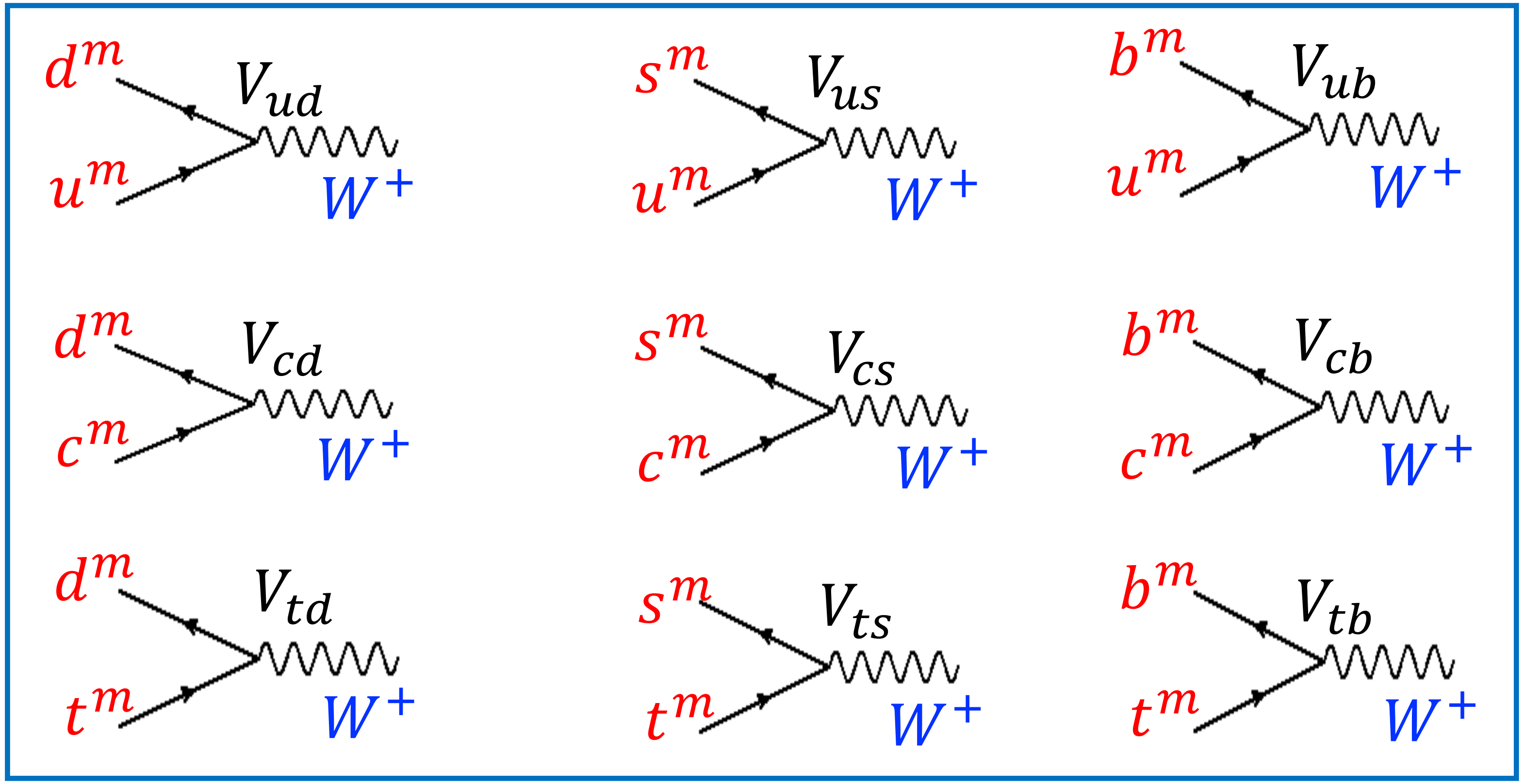
- Higgs: redefines quark states in mass eigenstates:





Flavour Universality → Symmetry Breaking → Flavour Mixing

- Weak charged current interaction: $(i \leftrightarrow j)$



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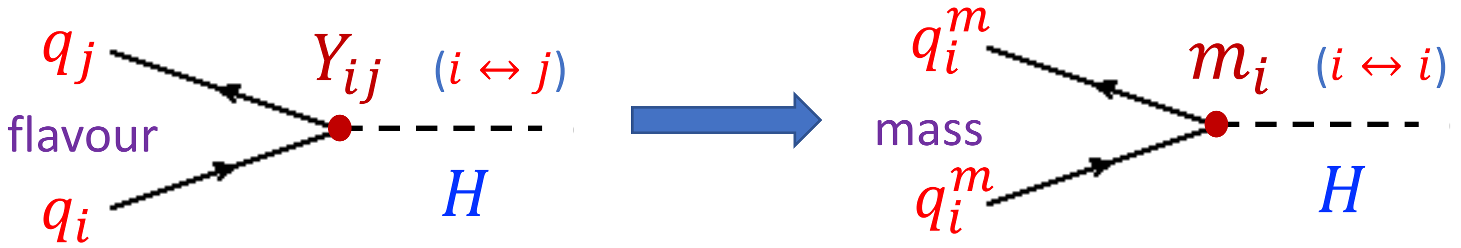

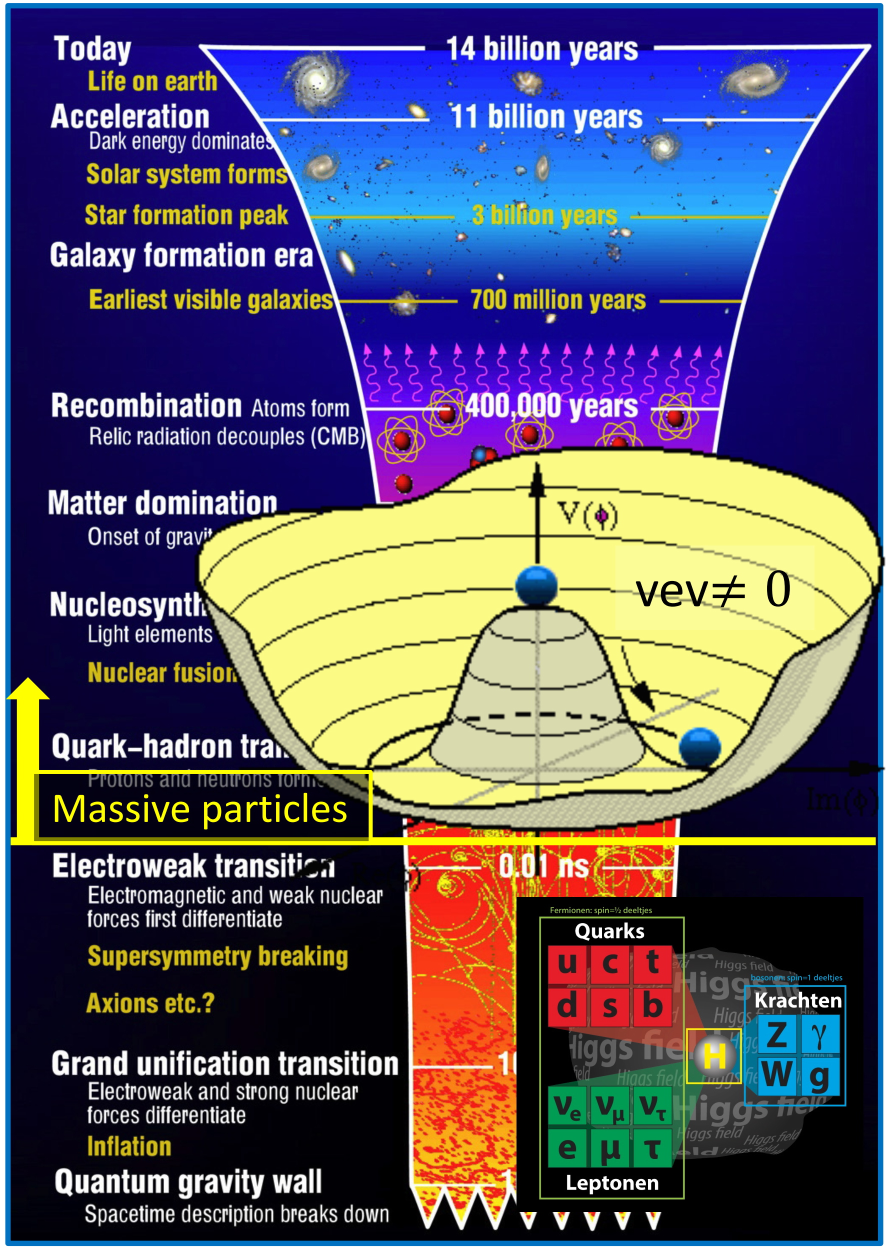

Flavour Universality → Symmetry Breaking → Flavour Mixing

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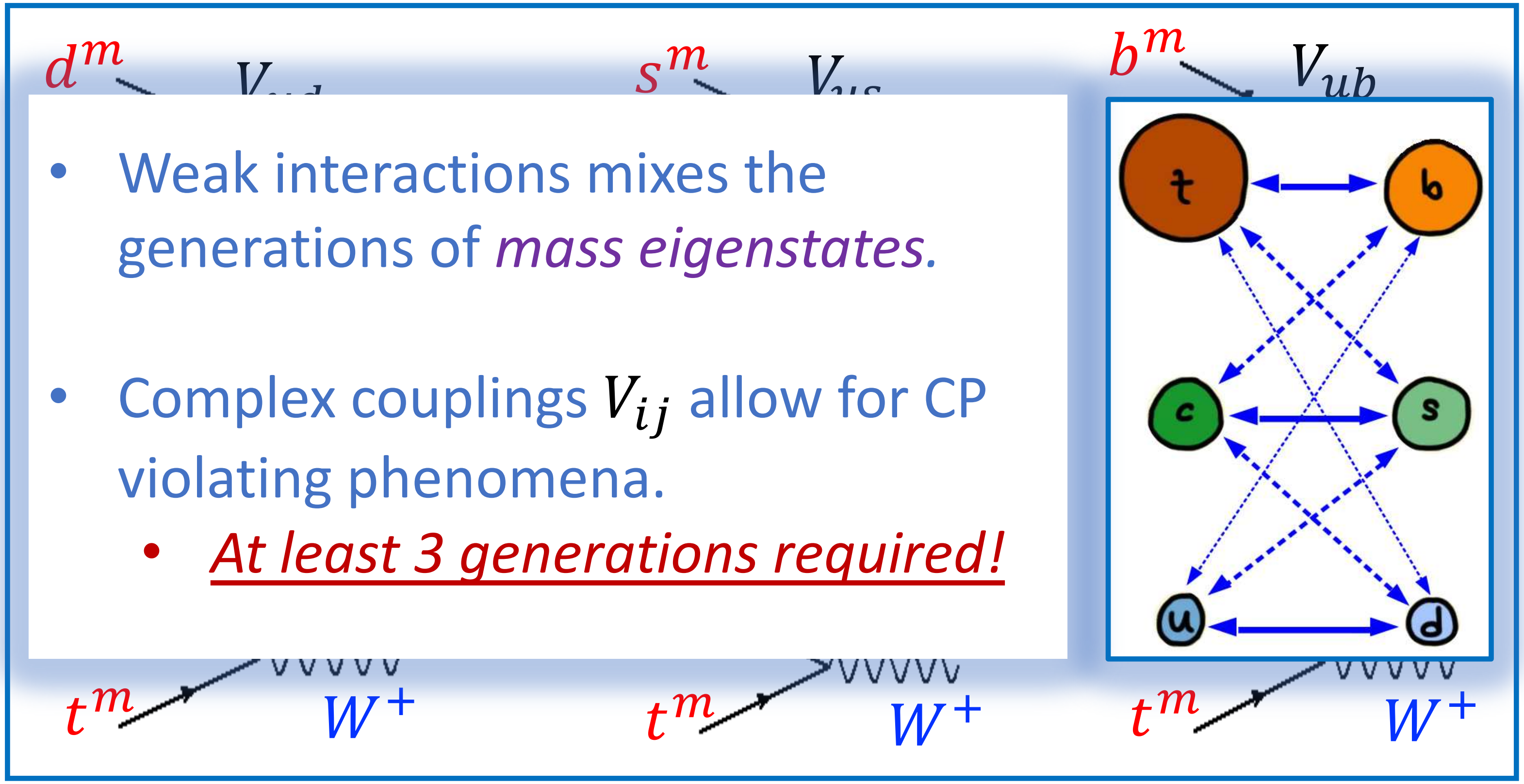
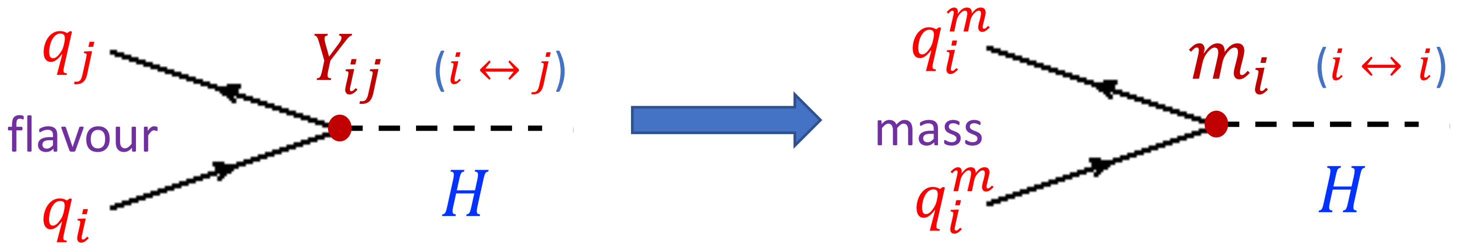
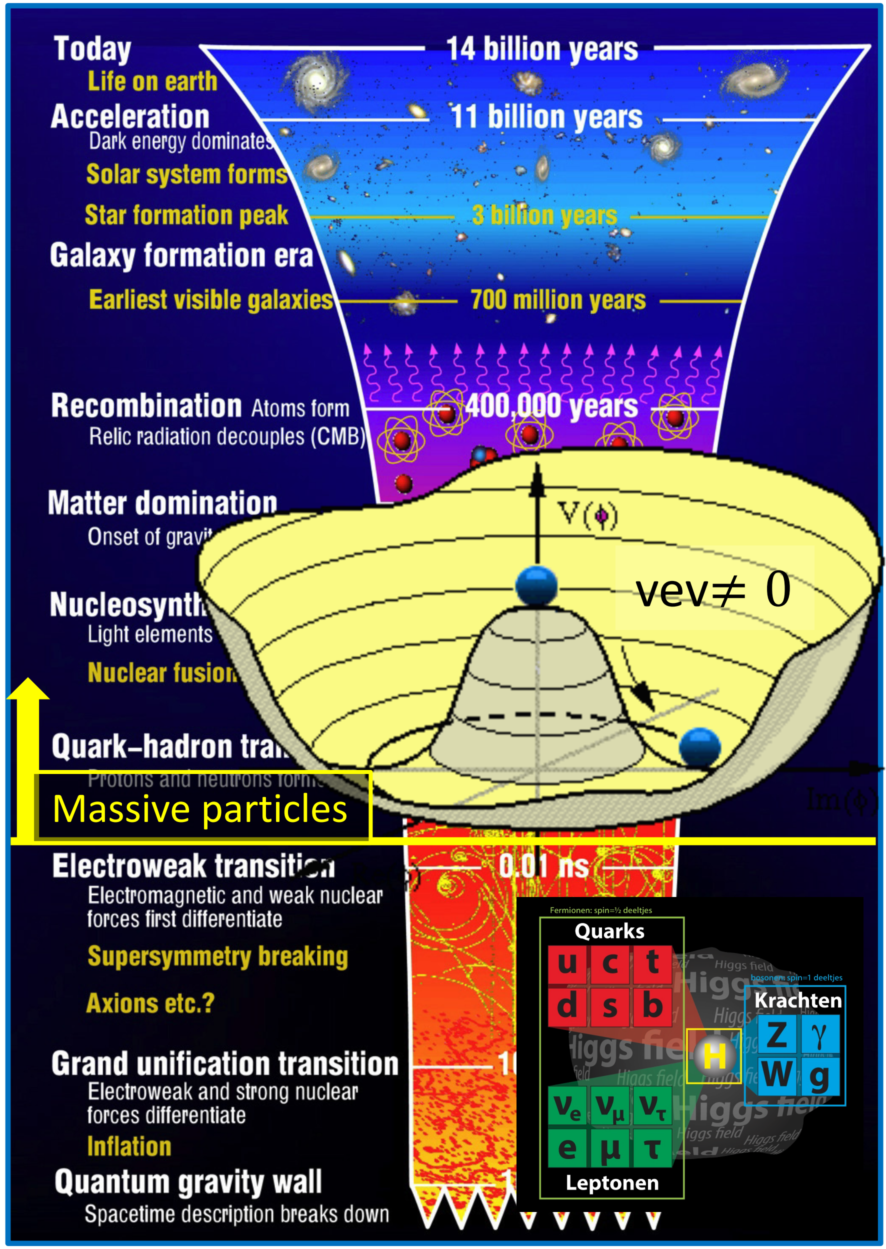


- Weak interactions mixes the generations of *mass eigenstates.*
- Complex couplings V_{ij} allow for CP violating phenomena.
  - *At least 3 generations required!*

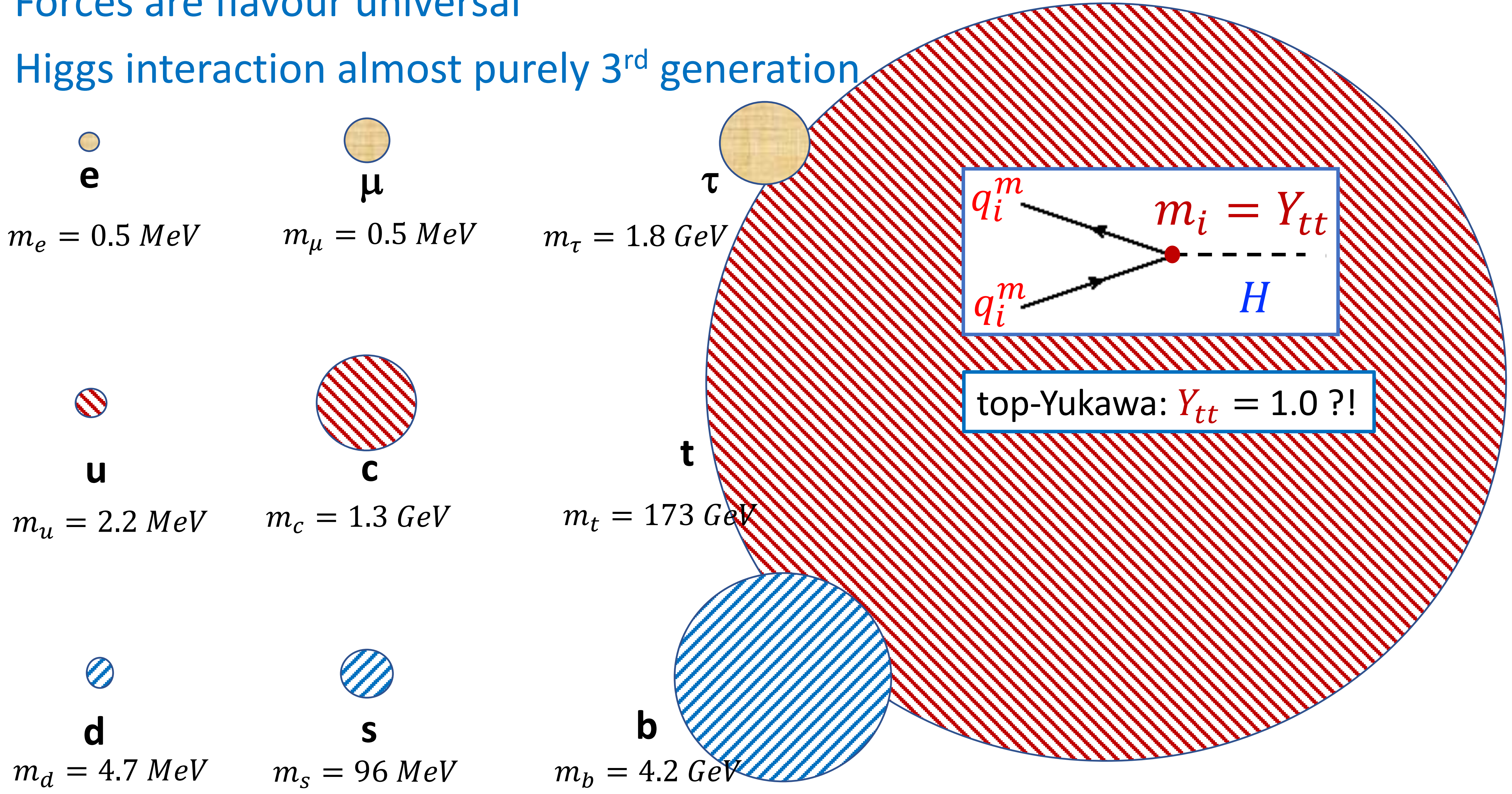
- Higgs: redefines quark states in mass eigenstates:





Flavour Structure: Interactions vs Higgs

- Forces are flavour universal
- Higgs interaction almost purely 3rd generation



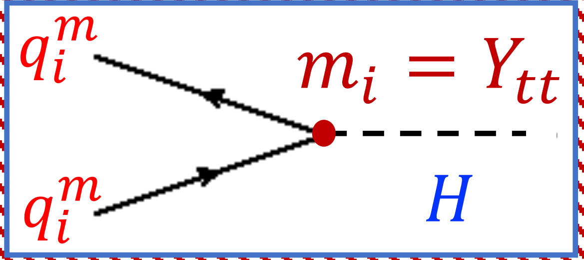
Flavour Structure: Interactions vs Higgs

- Forces are flavour universal
- Higgs interaction almost purely 3rd generation

e $m_e = 0.5\ MeV$

μ $m_\mu = 0.5\ MeV$

τ $m_\tau = 1.8\ GeV$



top-Yukawa: $Y_{tt} = 1.0$?!

Flavour Puzzle: What is the origin of these Higgs couplings across generations?

Higgs coupling is ***large*** for 3rd generation, ***small*** for 2nd generation, ***tiny*** for 1st generation

Perhaps new particles/forces may show a ***similar deviation from flavour universality***?

d $m_d = 4.7\ MeV$

s $m_s = 96\ MeV$

b $m_b = 4.2\ GeV$

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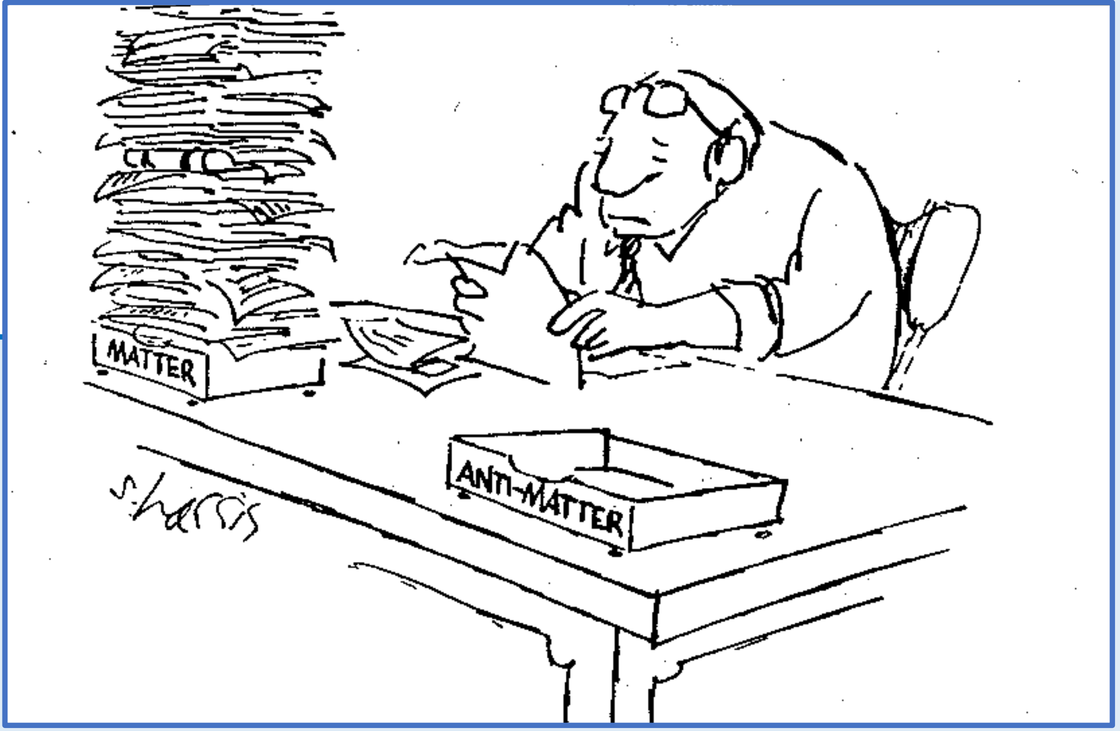
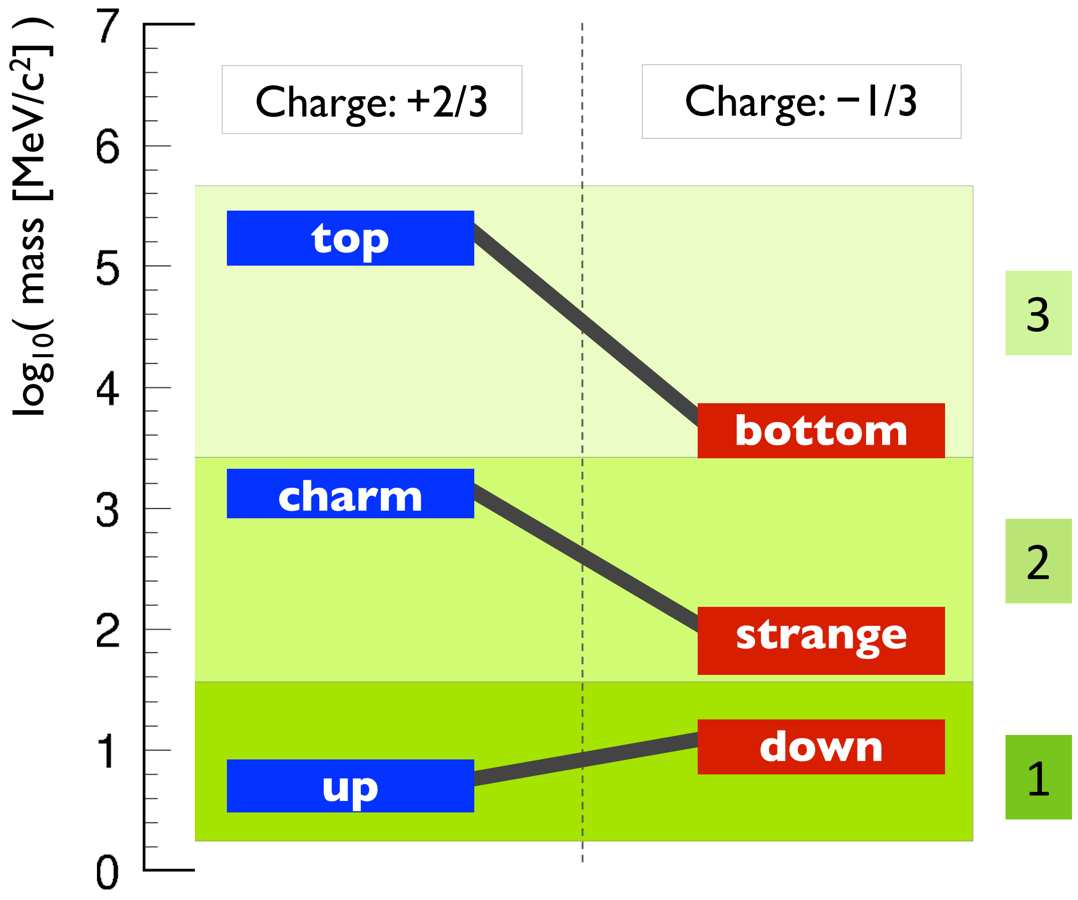
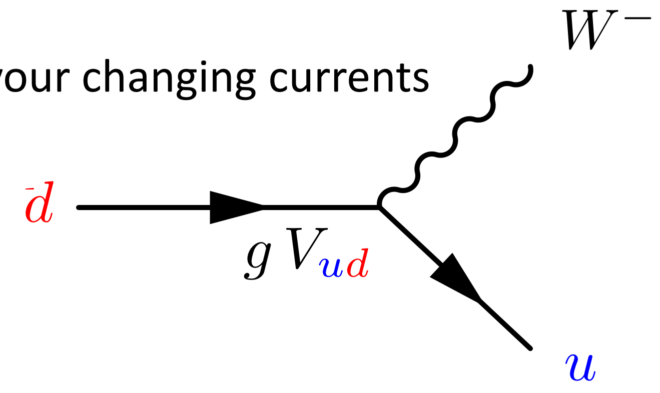


Flavour Changing Quark Interactions

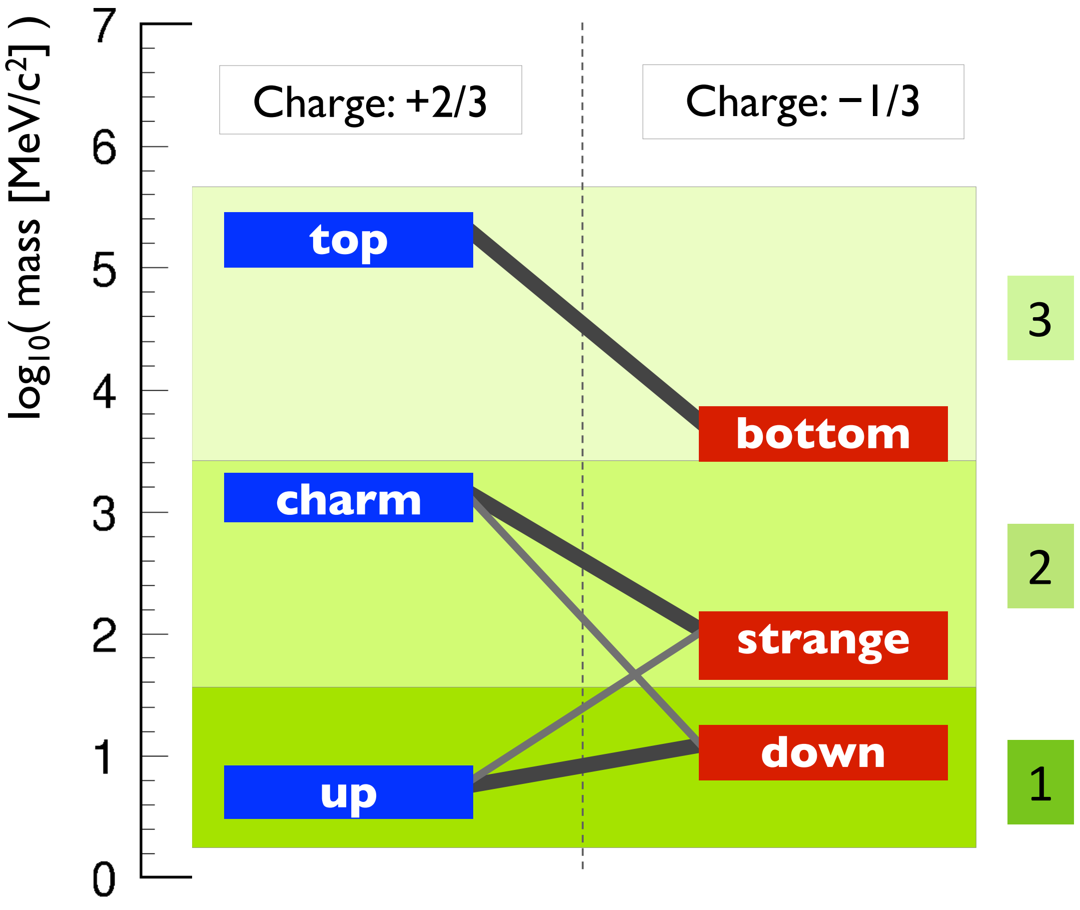


Flavour changing currents

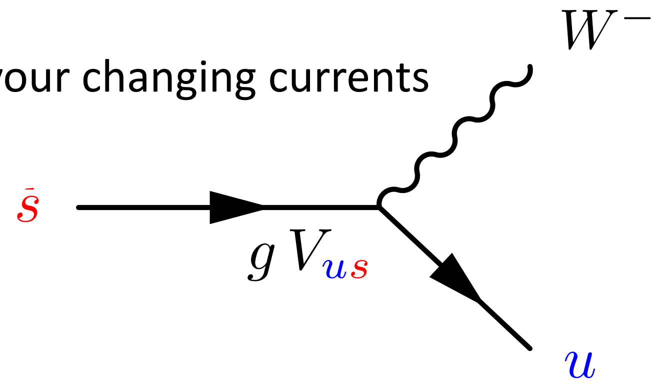


$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & & \\ & V_{cs} & \\ & & V_{tb} \end{pmatrix}$$

Flavour Changing Quark Interactions

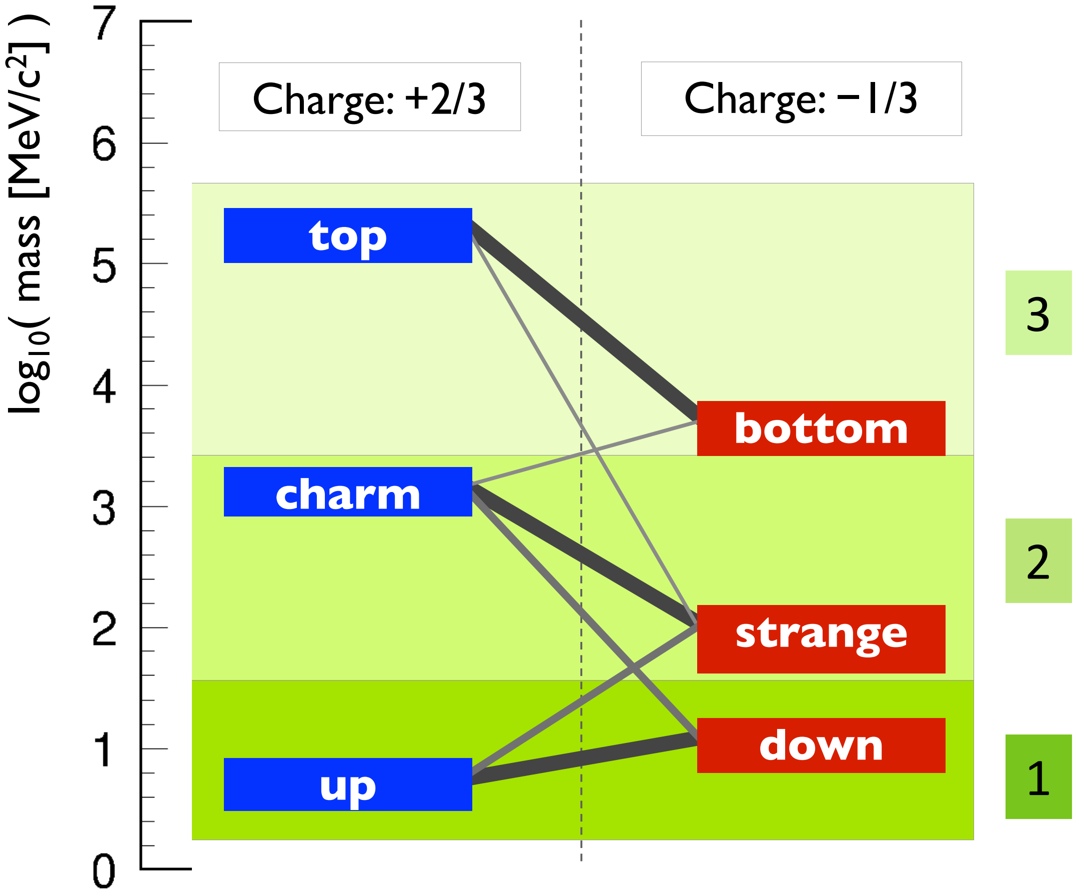


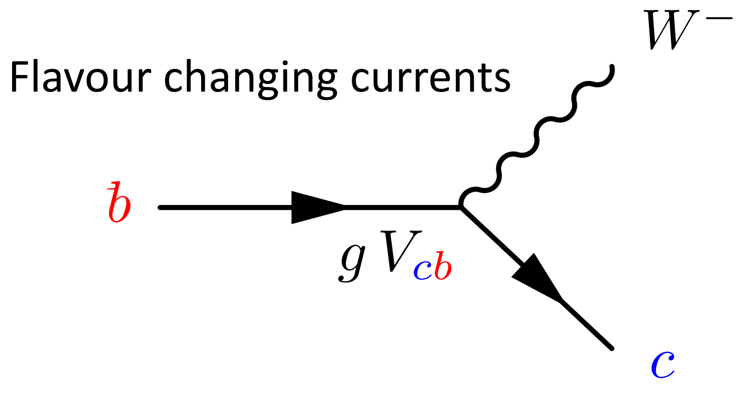
Flavour changing currents



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

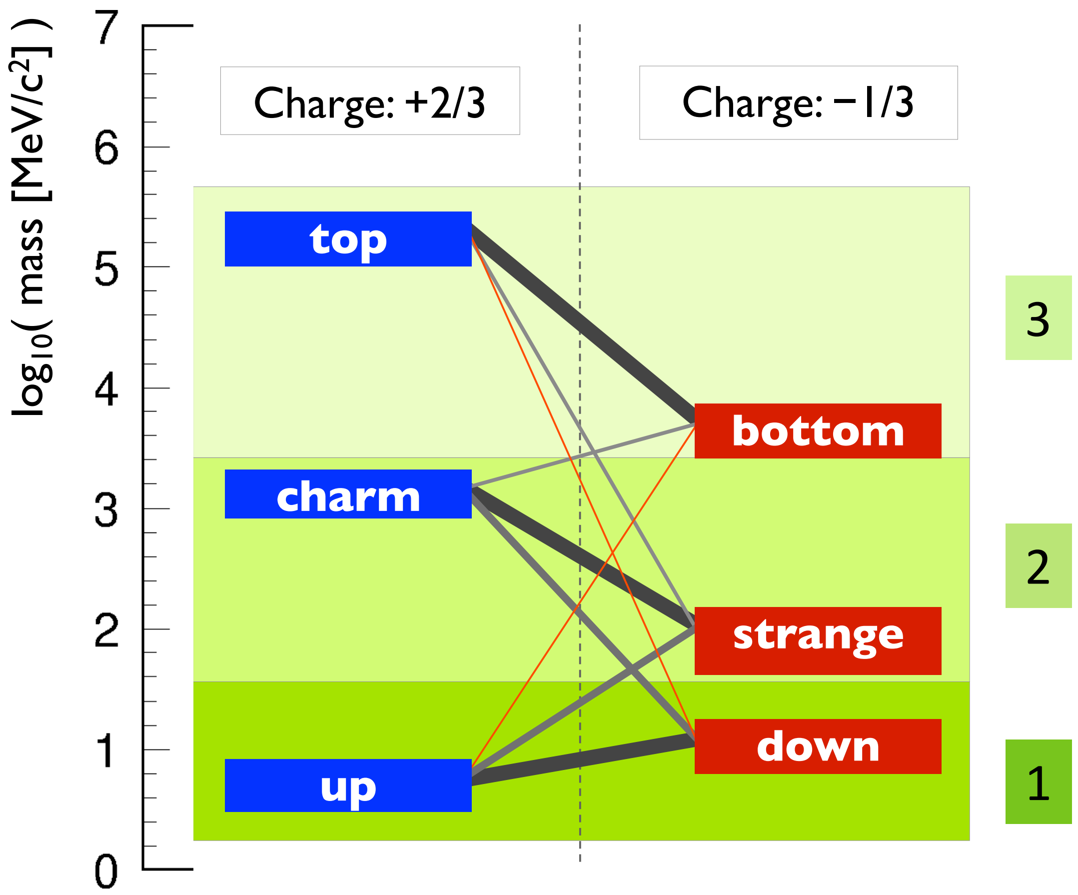
Flavour Changing Quark Interactions

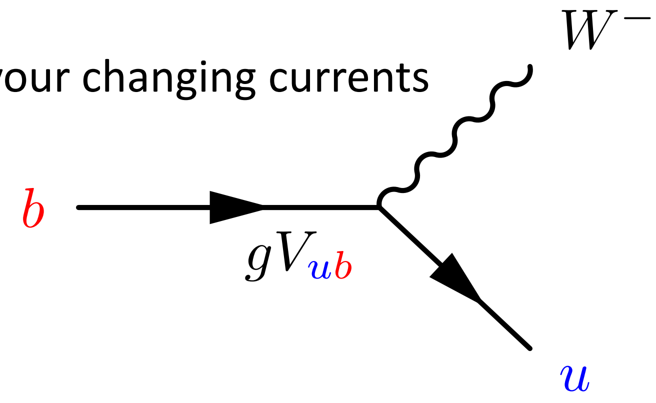




$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & \\ V_{cd} & V_{cs} & V_{cb} \\ & V_{ts} & V_{tb} \end{pmatrix}$$

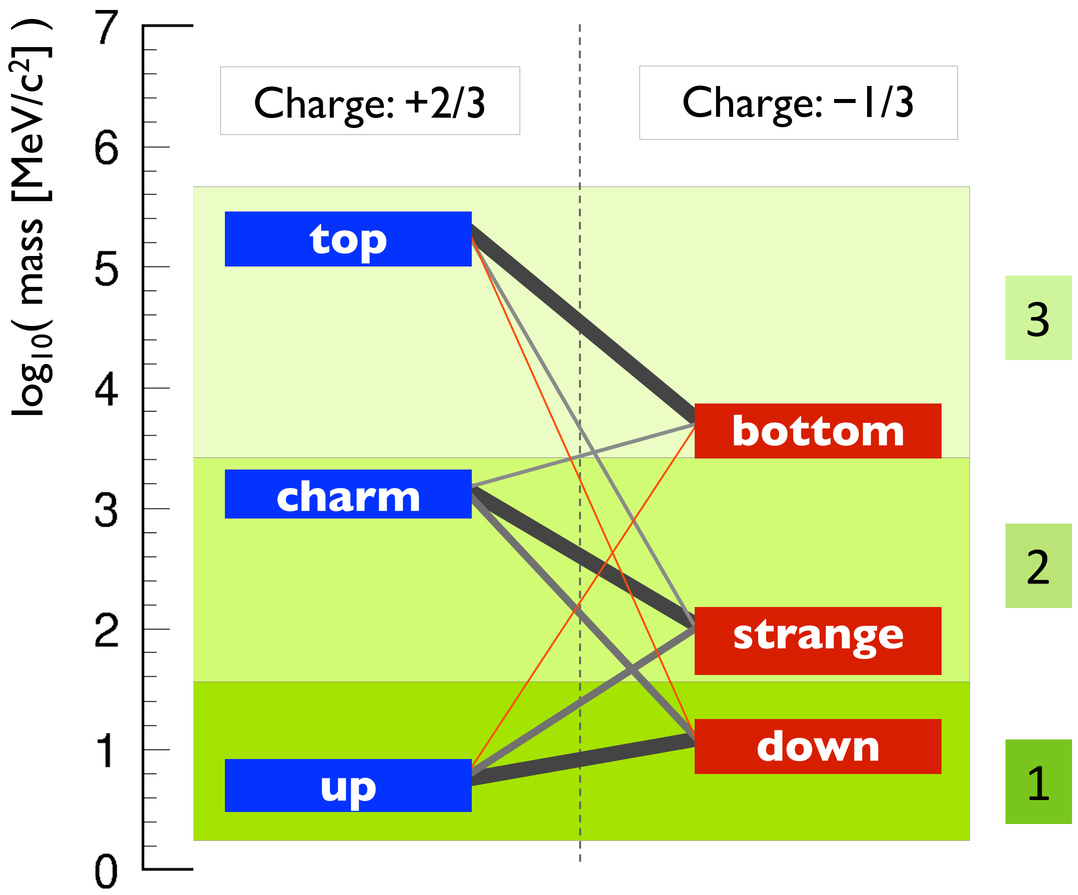
Flavour Changing Quark Interactions

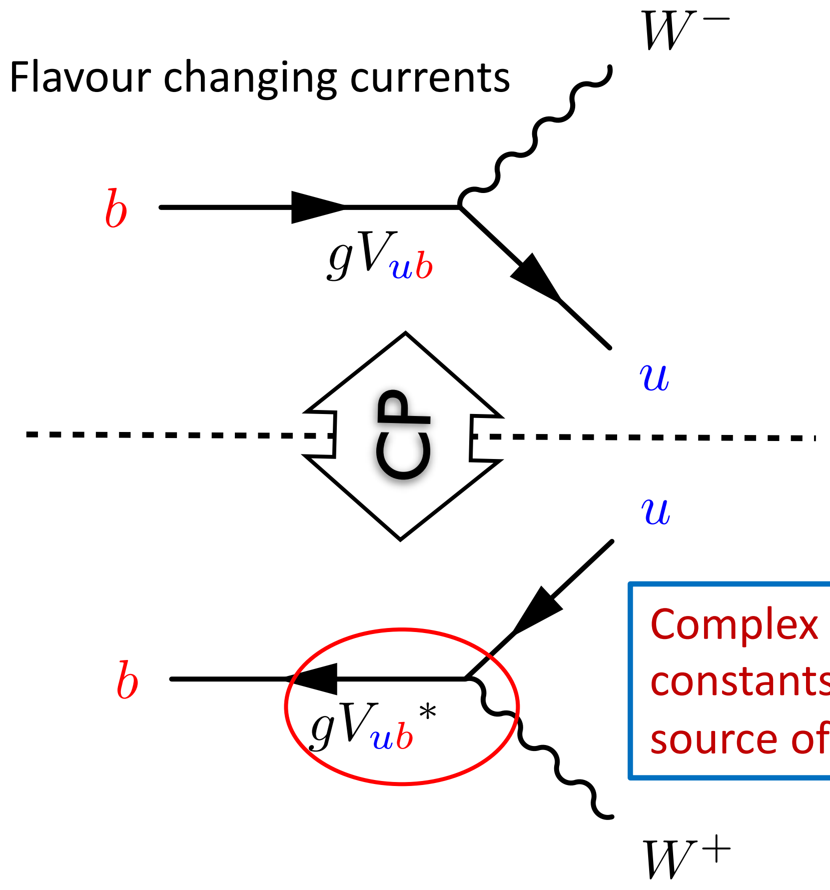




$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Flavour Changing Quark Interactions – CP Violation





Complex coupling constants are the source of CP viol.

- V_{CKM}: Cabibbo Kobayashi Maskawa matrix
- CP violation: particles and antiparticle processes have complex conjugated coupling constants

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

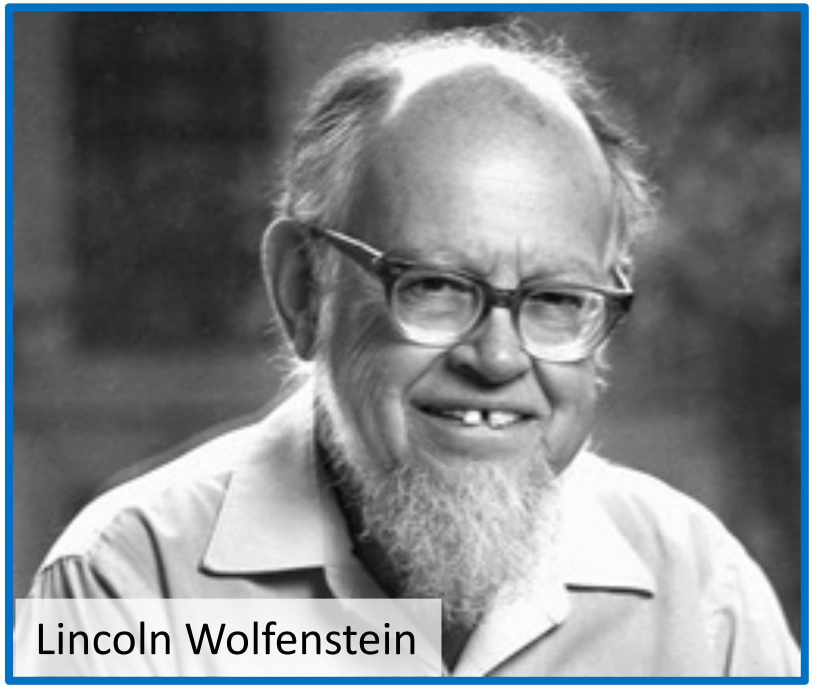
The CKM matrix V_{CKM} - 3 Generations

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

- 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 parameter


Lincoln Wolfenstein

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

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

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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 and unitarity triangle

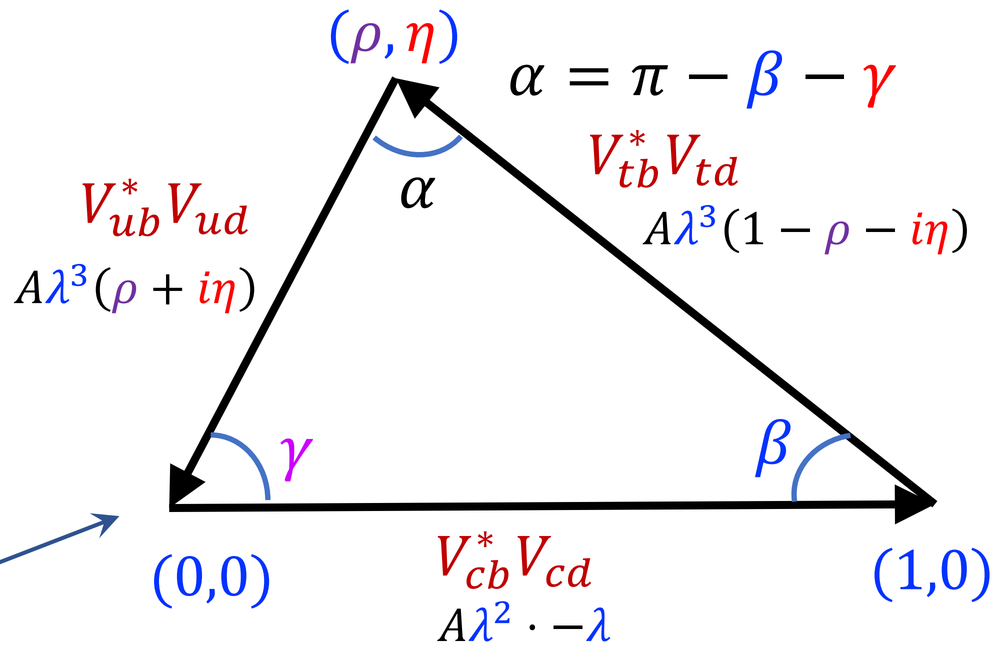
- The CKM is a unitary mixing matrix
  - This implies: $V_{CKM}^{\dagger}\, V_{CKM} = 1$

$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ \boxed{V_{ub}^* \quad V_{cb}^* \quad V_{tb}^*} \end{pmatrix} \begin{pmatrix} \boxed{\begin{matrix} V_{ud} \\ V_{cd} \\ V_{td} \end{matrix}} & \begin{matrix} V_{us} \\ V_{cs} \\ V_{ts} \end{matrix} & \begin{matrix} V_{ub} \\ V_{cb} \\ V_{tb} \end{matrix} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Orthonormality: $V_{cb}^* V_{cd} + V_{tb}^* V_{td} + V_{ub}^* V_{ud} = 0$

$$\longrightarrow \; + \; \nwarrow \; + \; \swarrow \; = 0$$

Triangle in the complex plane:



- Wolfenstein parametrization:

$$V_{CKM} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

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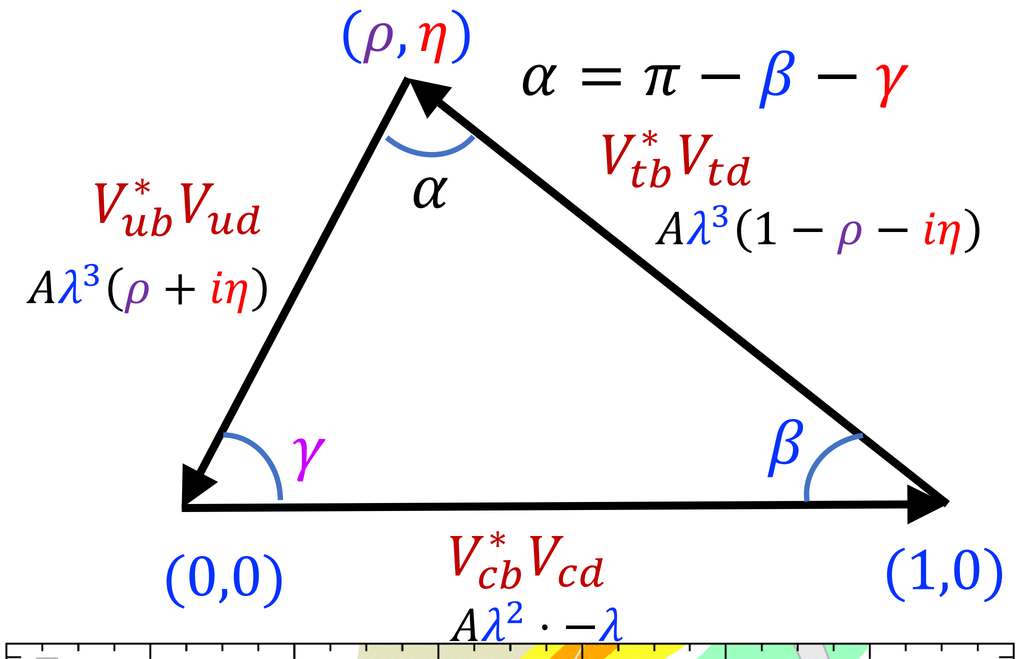

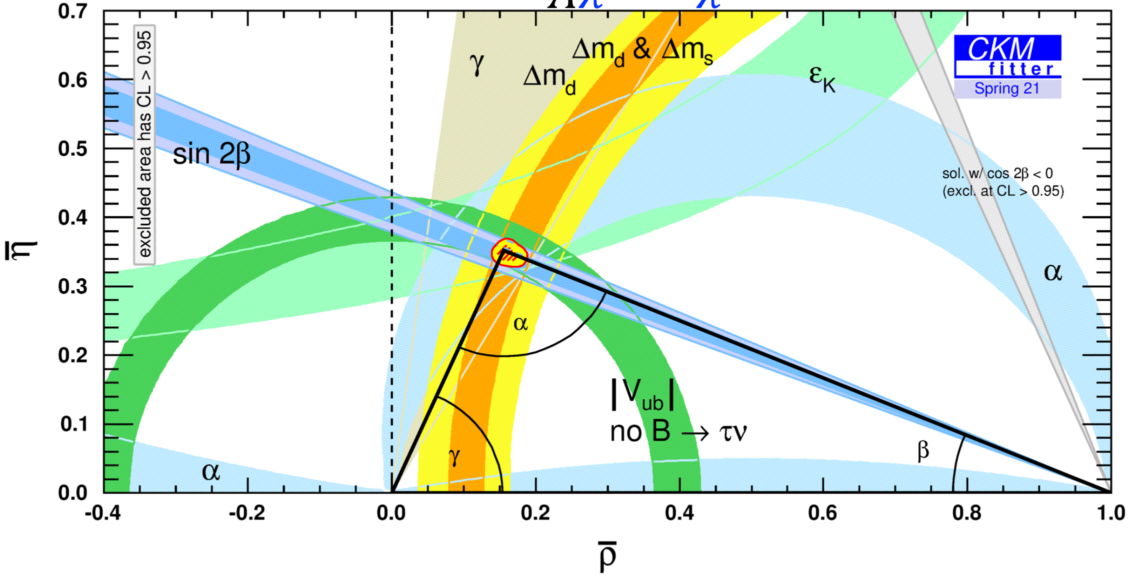

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$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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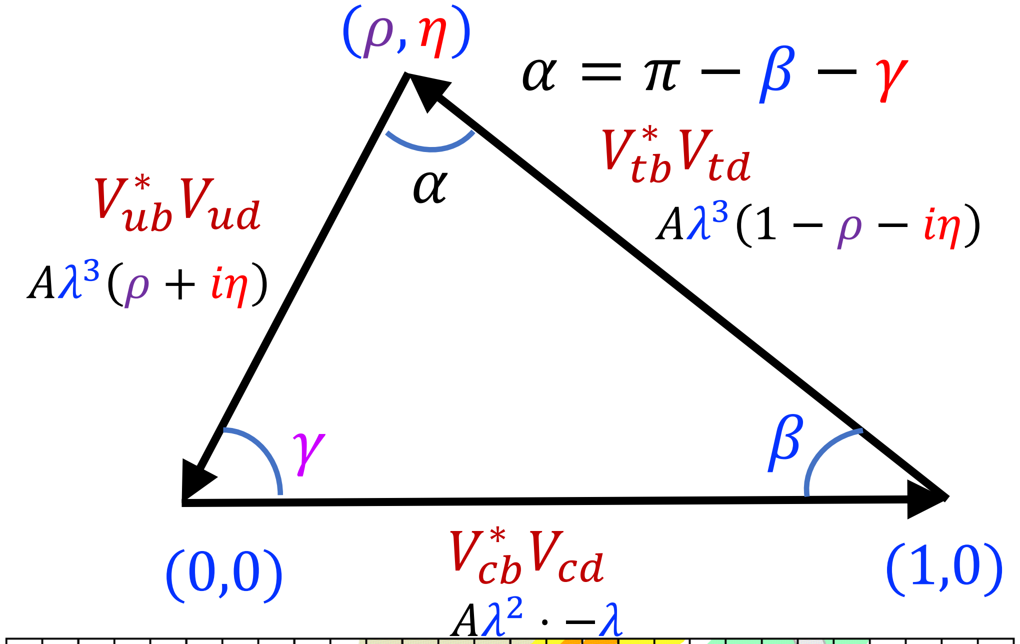
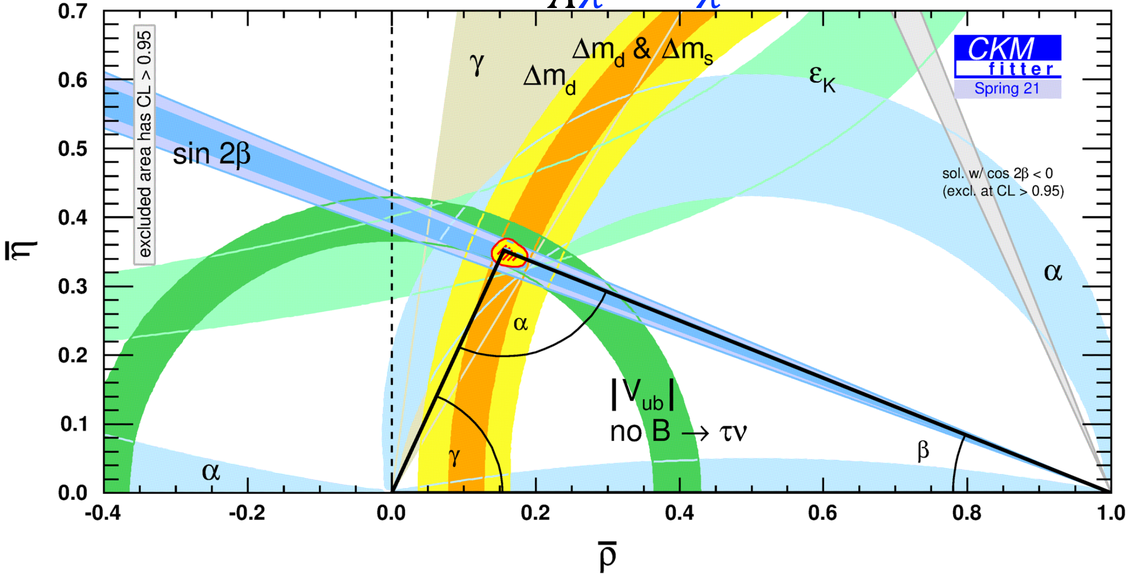
$$\rightarrow \; + \; \nwarrow \; + \; \swarrow \; = 0$$

- <u>Experiment</u>: CKM in terms of ***angles/phases***:
  - The phases are observable in different quark transitions
  - The phases should be consistent with ***one single CP violating freedom*** → test the SM

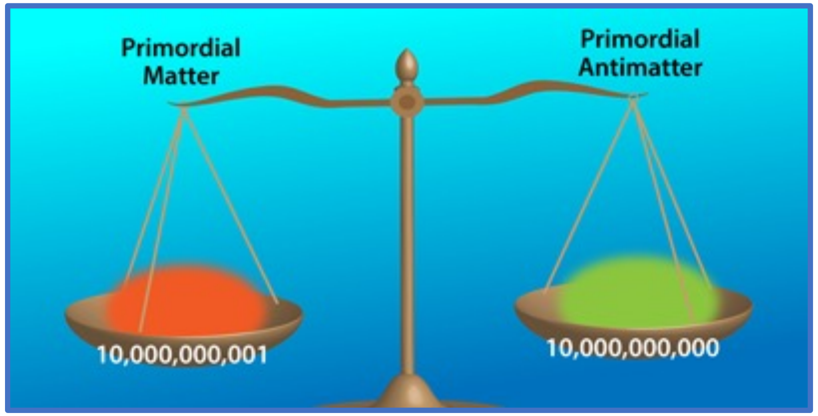
Triangle in the complex plane:

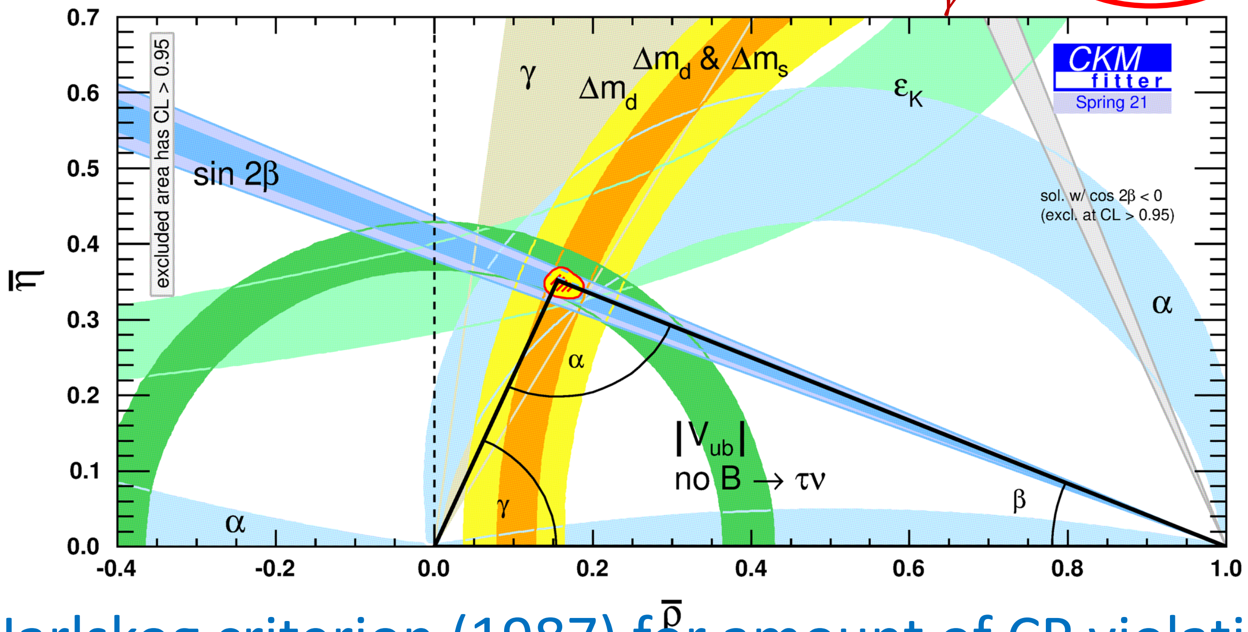




How large is CP violation?

- To explain the absence of antimatter in the universe ***requires*** a primordial baryon asymmetry of: $\frac{\Delta n_B}{n_\gamma} \approx 10^{-10}$





- Large CP violation requires *large mixing* and *large phases* in the CKM matrix.
  - Surface of unitarity triangle

- Jarlskog criterion (1987) for amount of CP violation:

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

From CKM: $A_{CP}/T_c^{12} \approx 10^{-20}$ → **Too small**

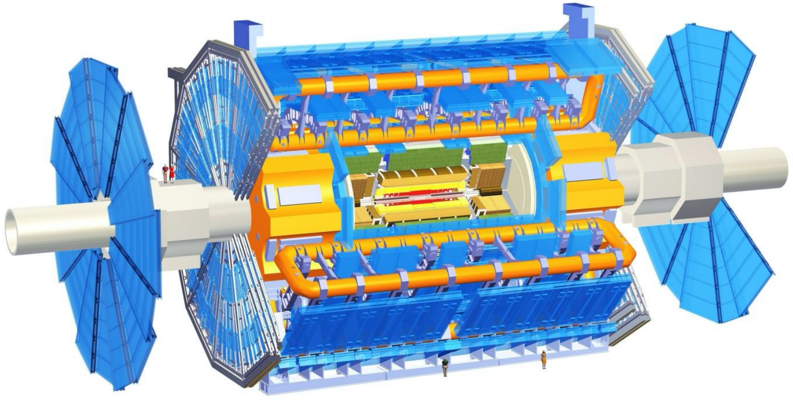
- *Explanation requires existence of **new massive particles**.*

Cecila Jarlskog

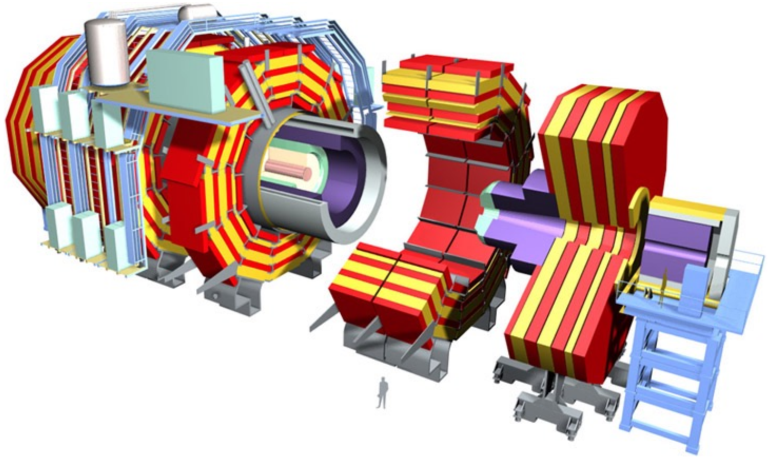
How to search for new massive particles?

1. Direct searches: produce particles on-shell in collisions; '*energy frontier*':

Atlas
@LHC

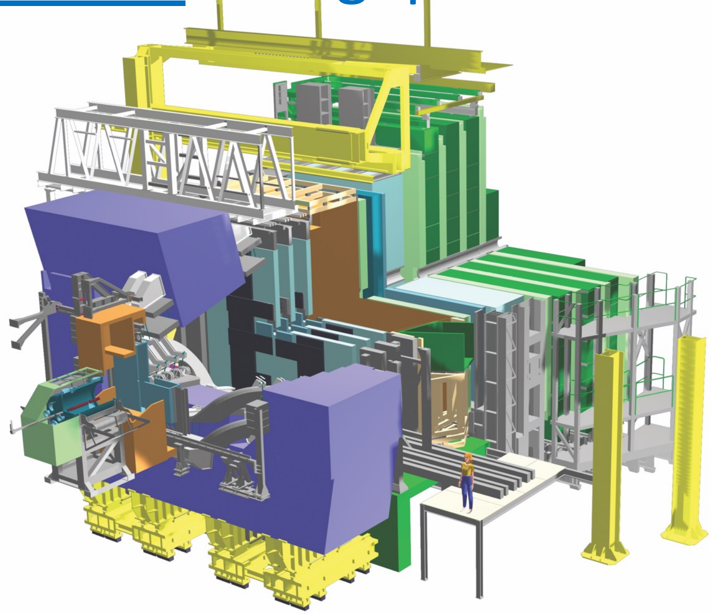


CMS
@LHC

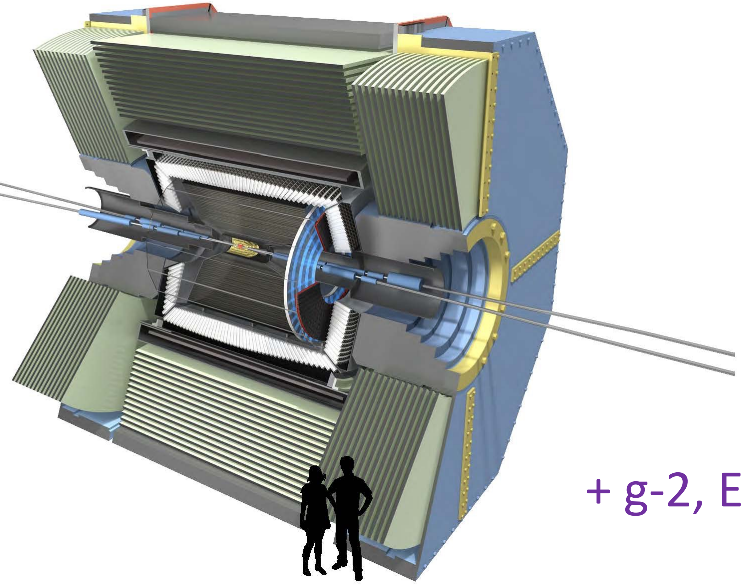


2. Indirect searches: using quantum fluctuations; '*precision frontier*':

LHCb
@LHC

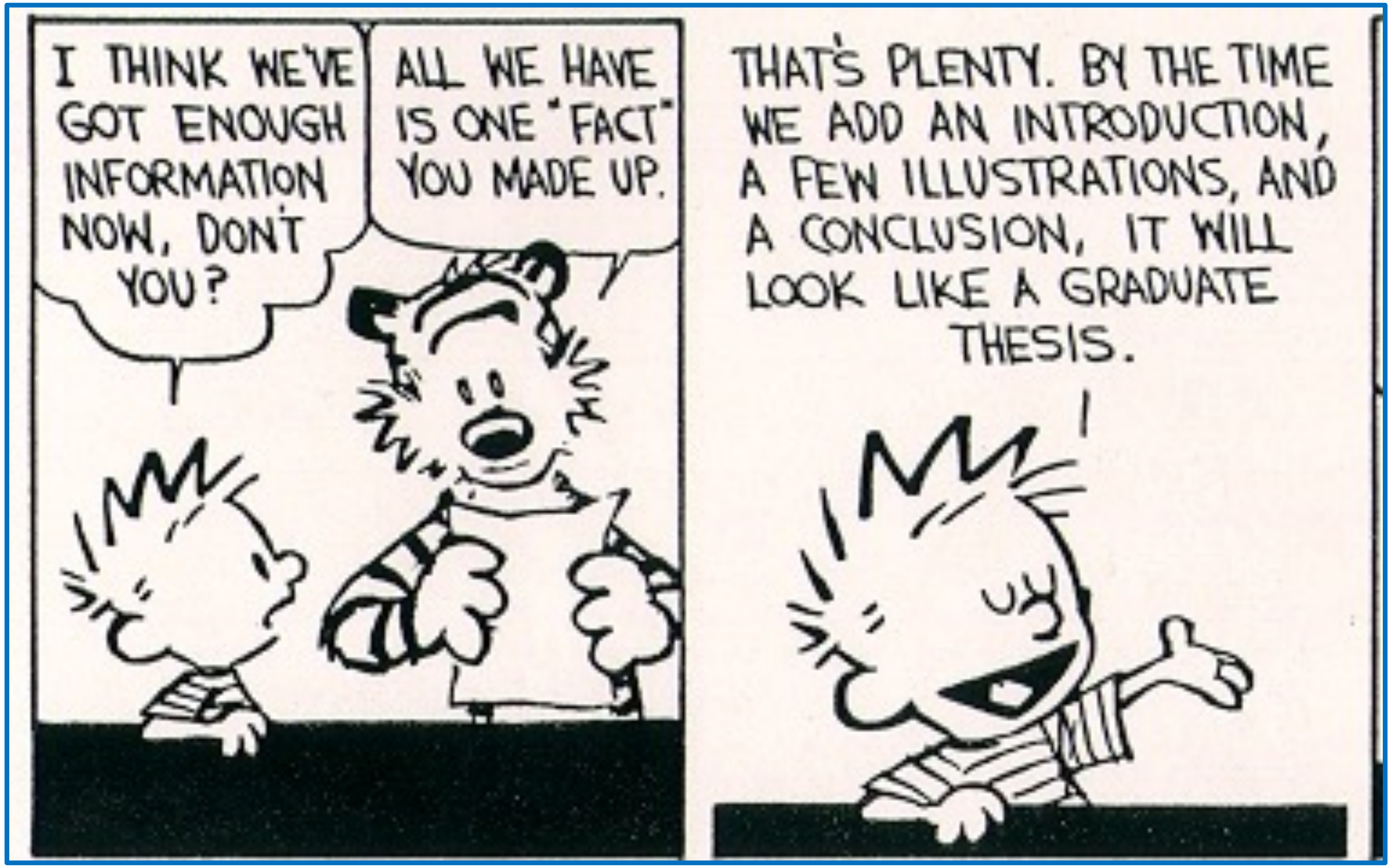


Belle II
@KEK



+ g-2, EDM, …

Note to students



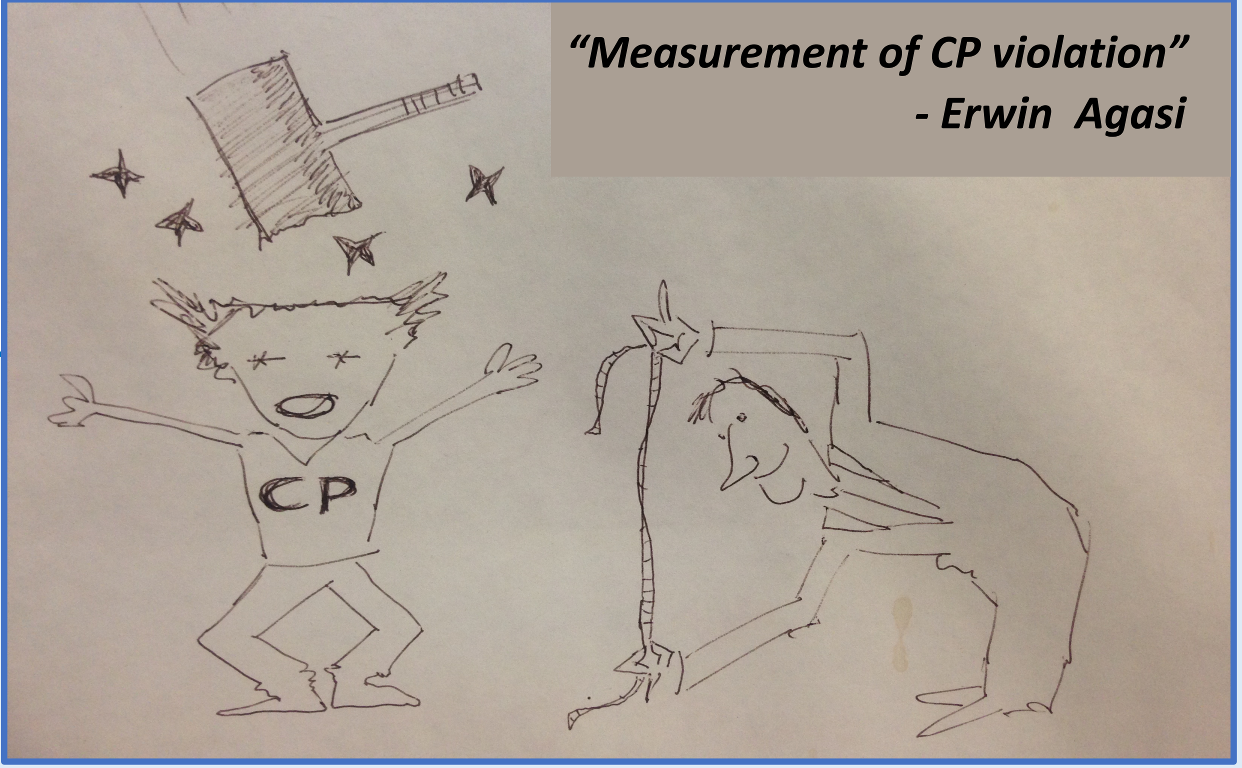
1) Three generations and the origin of CP violation

2) The amount of CP violation in CKM

3) **Measurements of CP violation with LHCb**

4) B-decays and Flavour Anomalies

5) Outlook/conclusion

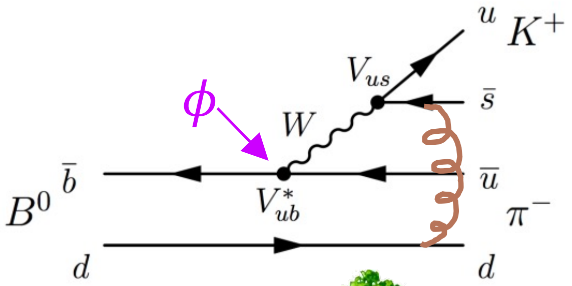


"Measurement of CP violation"
- Erwin Agasi

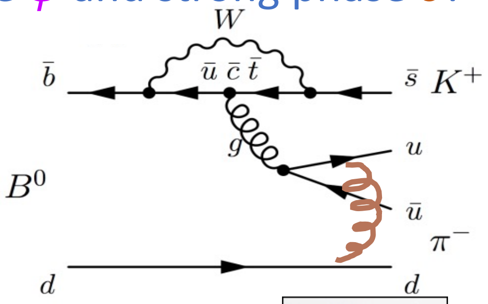
Measurement CP Violation: e.g. B-meson decays

LHCb measurement 2020: arXiv:2012.05319

Decay $B^0 \to K^+\pi^-$ has *two amplitudes* A_T and A_P with a relative complex weak phase ϕ and strong phase δ:

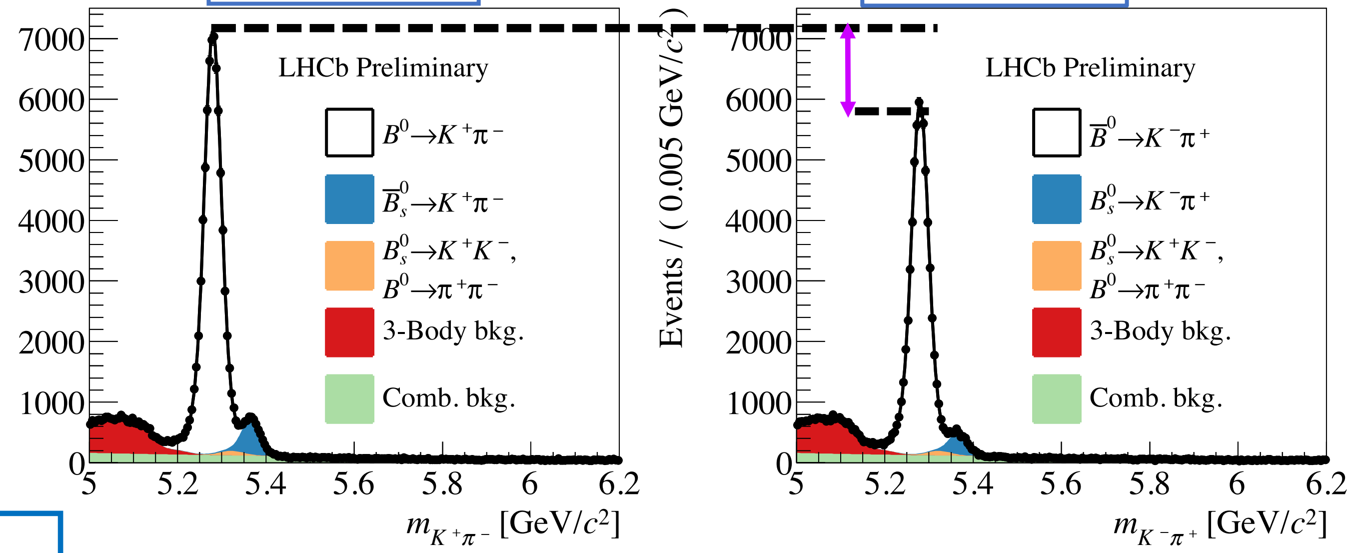


A_T: "Tree"



A_P: "Penguin"

$B^0 \to K^+\pi^-$ CP violation ! $\overline{B}^0 \to K^-\pi^+$



CP Violation

$B^0 \to K^+\pi^-$:

$$A = A_T + A_P e^{i\phi} e^{i\delta}$$

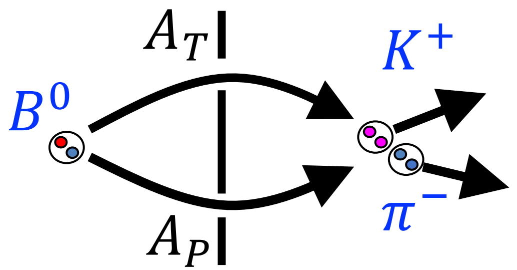
$\overline{B}^0 \to K^-\pi^+$:

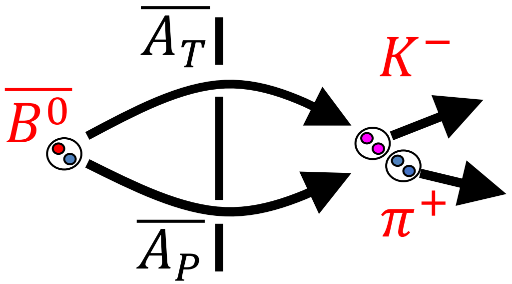
$$\bar{A} = A_T + A_P e^{-i\phi} e^{i\delta}$$

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

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

$$|A - \bar{A}|^2 = 4\, A_T A_P \sin\phi \sin\delta \neq 0$$



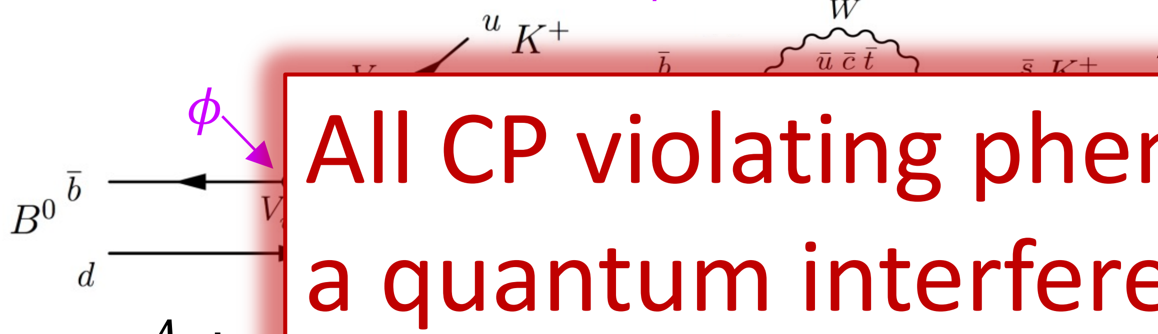


CP violation is a pure *quantum interference* effect

Measurement CP Violation: e.g. B-meson decays

LHCb measurement 2020: arXiv:2012.05319

Decay $B^0 \to K^+\pi^-$ has *two amplitudes* A_T and A_P with a relative complex weak phase ϕ and strong phase δ:

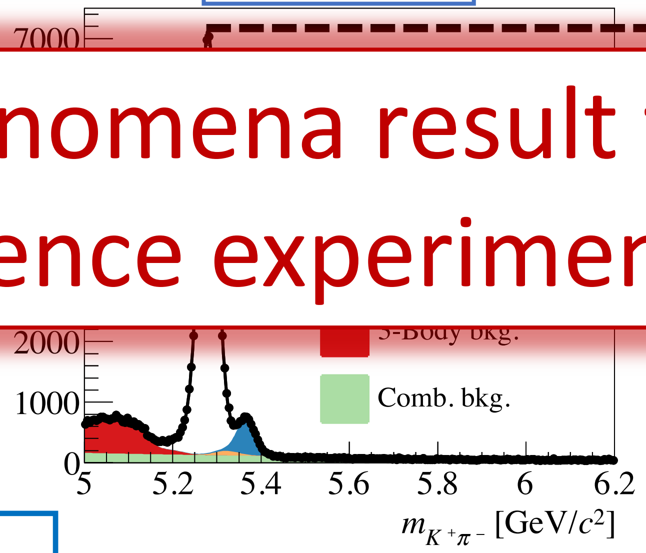


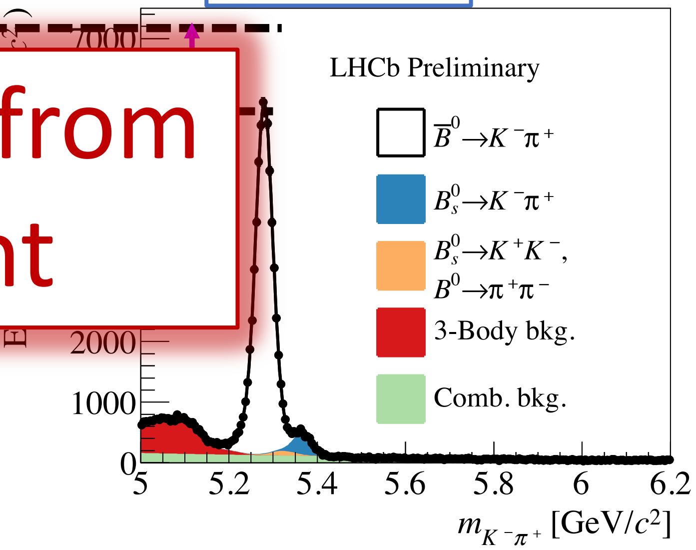
All CP violating phenomena result from a quantum interference experiment

A_T: "Tree"

A_P: "Penguin"

$B^0 \to K^+\pi^-$ CP violation ! $\overline{B}^0 \to K^-\pi^+$





CP Violation

$B^0 \to K^+\pi^-$:

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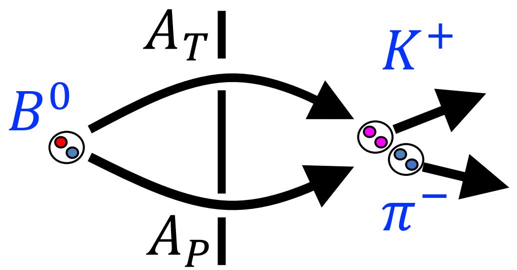
$\overline{B}^0 \to K^-\pi^+$:

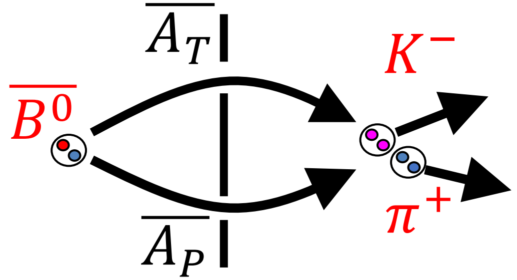
$$\bar{A} = A_T + A_P e^{-i\phi} e^{i\delta}$$

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

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

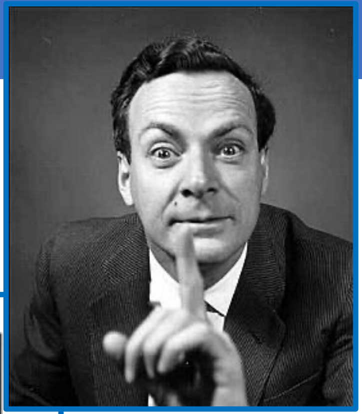
$$|A - \bar{A}|^2 = 4\, A_T A_P \sin\phi \sin\delta \neq 0$$



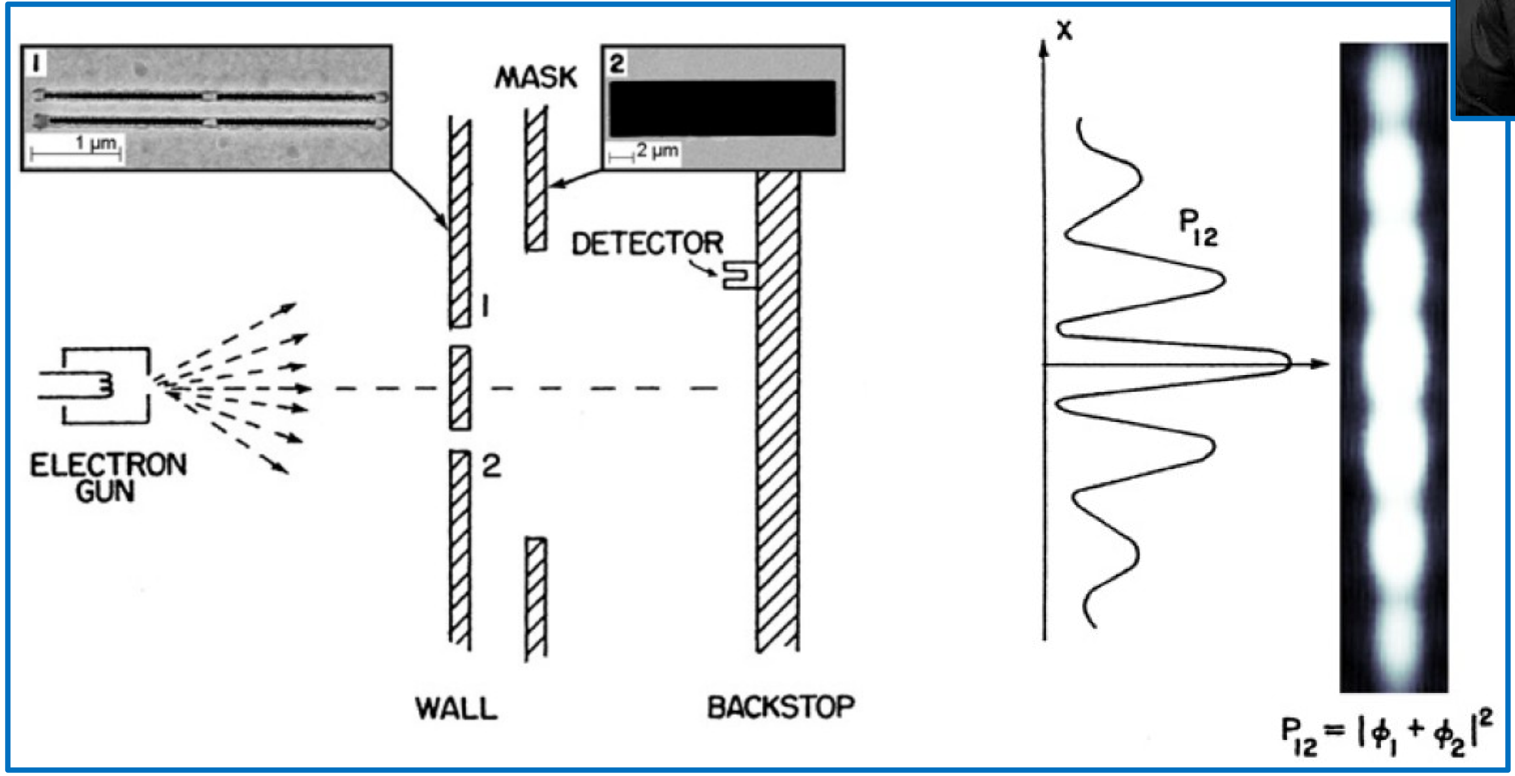


CP violation is a pure *quantum interference* effect

A deeper connection?



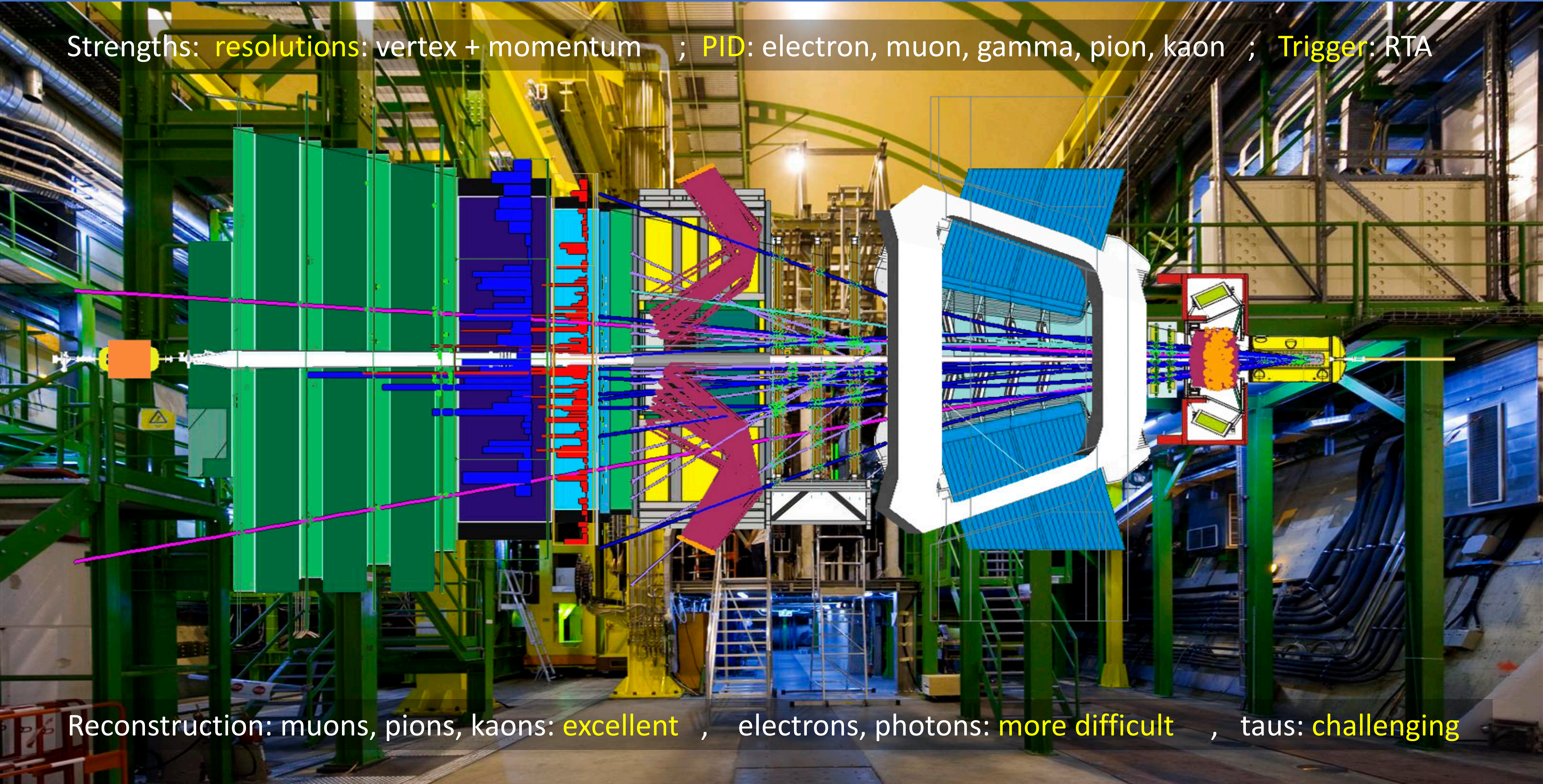
- Feynman: “In the end all quantum phenomena are manifestations of the double slit experiment.”



- *A thought: assuming CPT symmetry: CP violation → T violation*
  Quantum interference ←→ arrow of time?

The LHCb experiment: B-decay precision measurements

Strengths: resolutions: vertex + momentum ; PID: electron, muon, gamma, pion, kaon ; Trigger: RTA

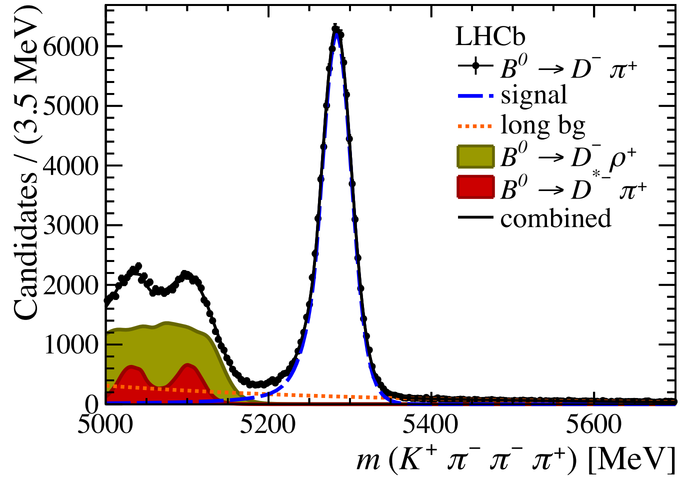


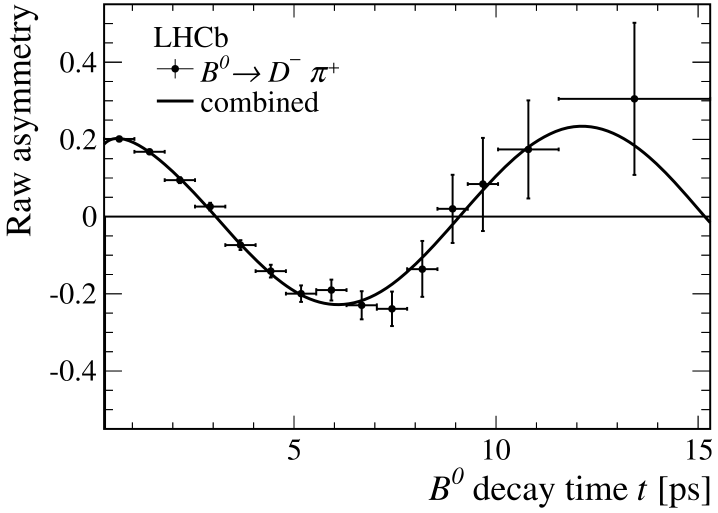
Reconstruction: muons, pions, kaons: excellent , electrons, photons: more difficult , taus: challenging

Meson mixing: does the experiment work?

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

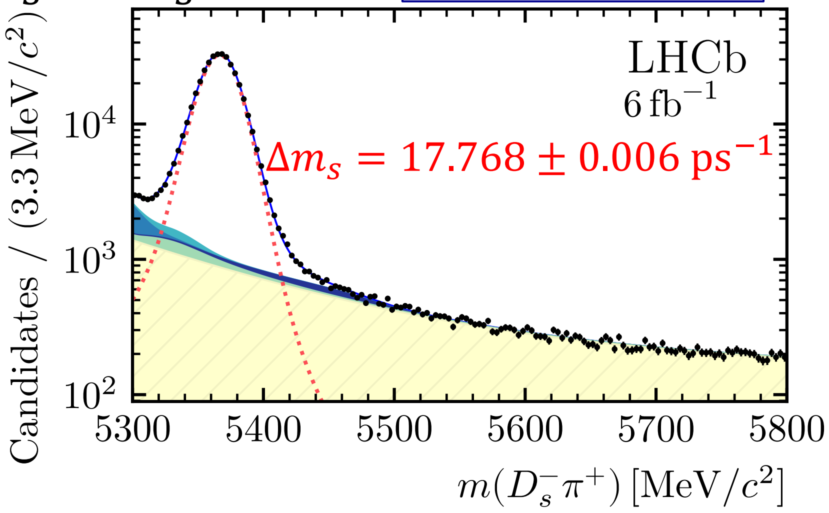
$B^0 \to D^-\pi^+$ **Phys.Lett.B719 (2013) 318**

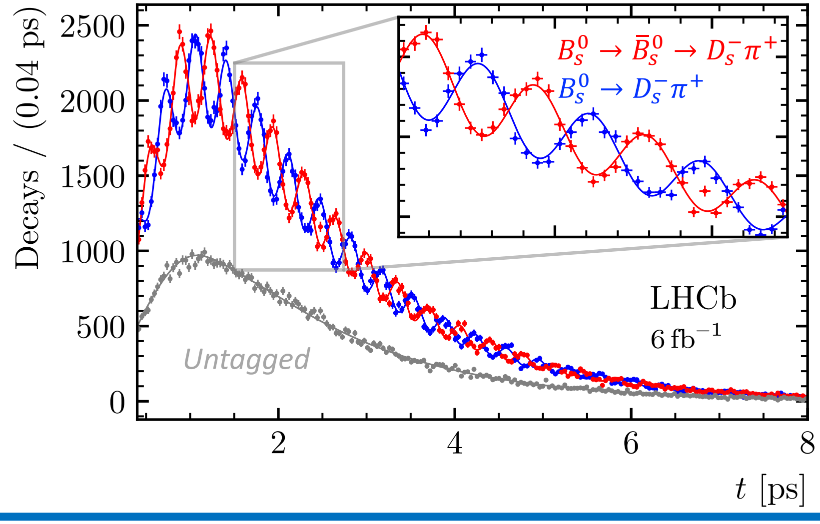




$B_s^0 - \overline{B_s^0}$ mixing

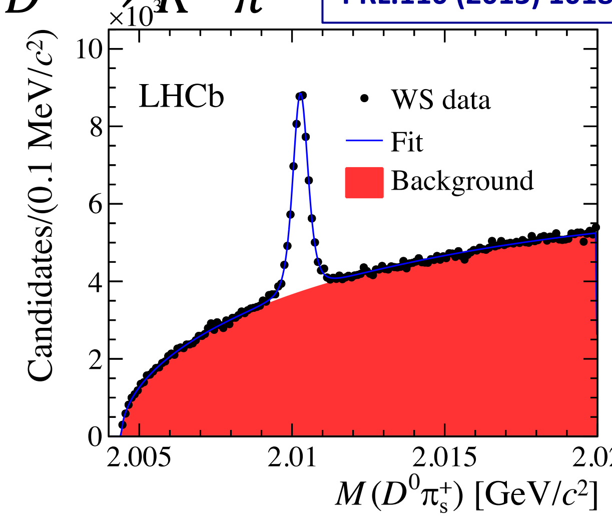
$B_s^0 \to D_s^-\pi^+$ **Nature.Phys.18 (2022) 1**

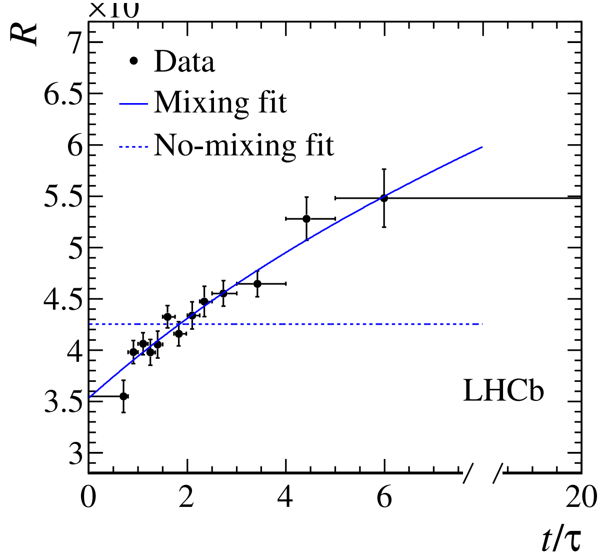




$D^0 \to \overline{D^0}$ mixing

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

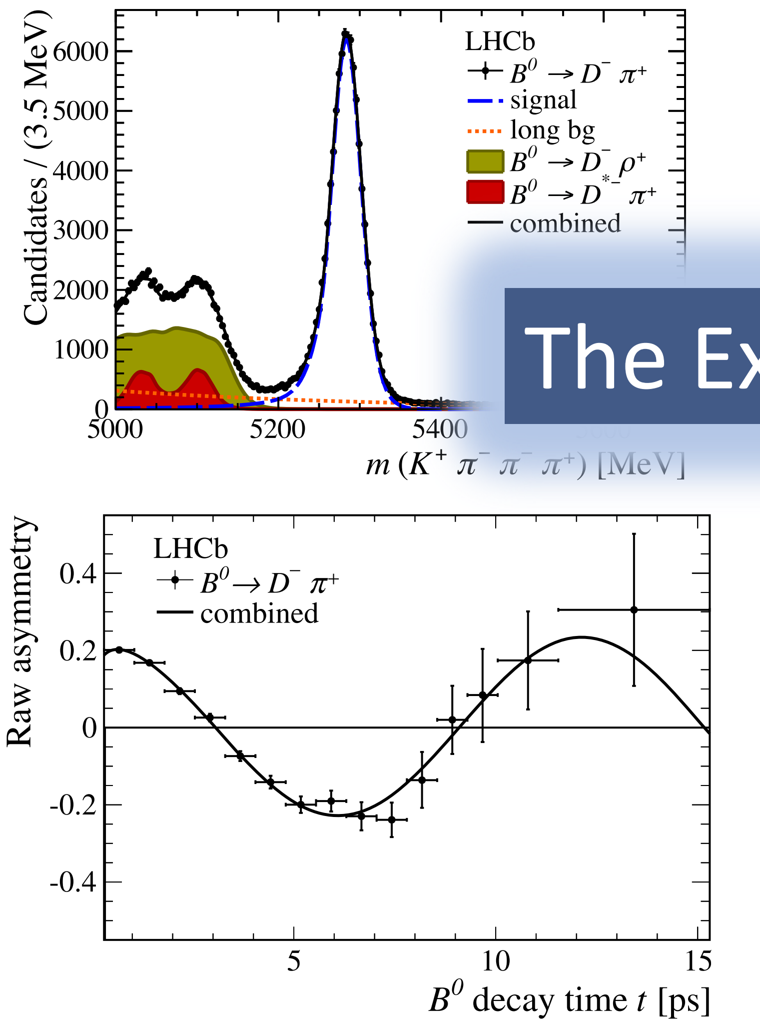




Meson mixing: does the experiment work?

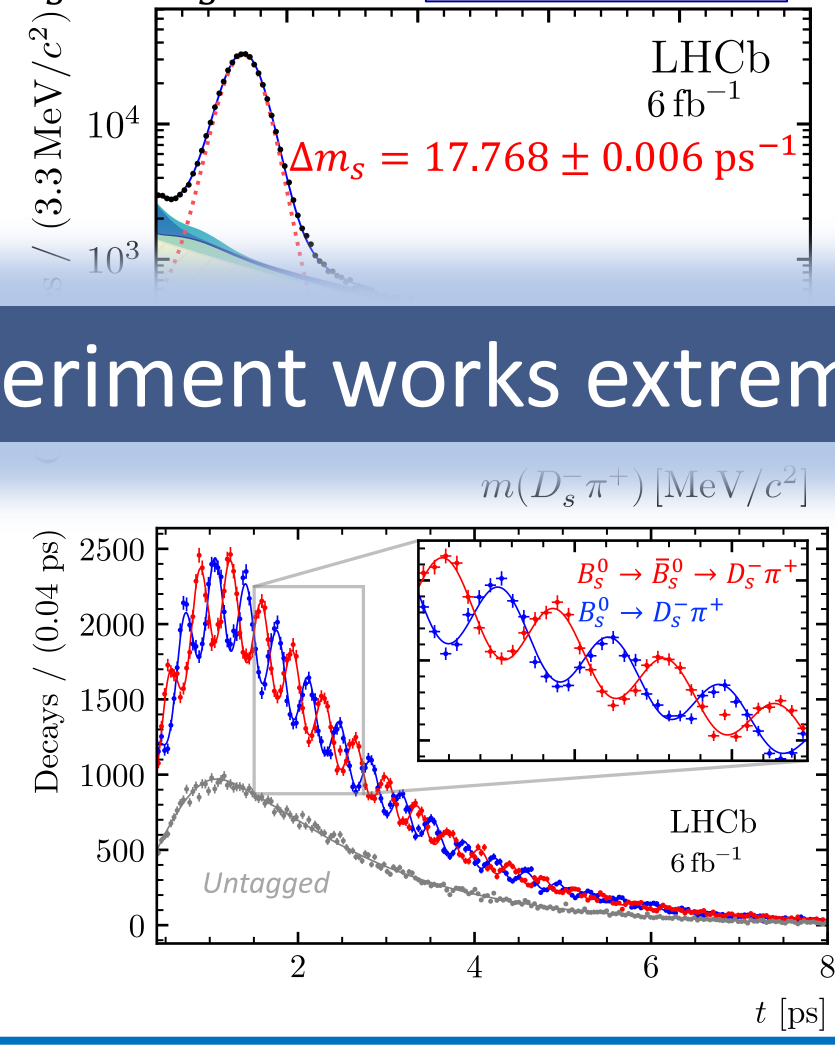
$B^0 - \overline{B^0}$ mixing

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



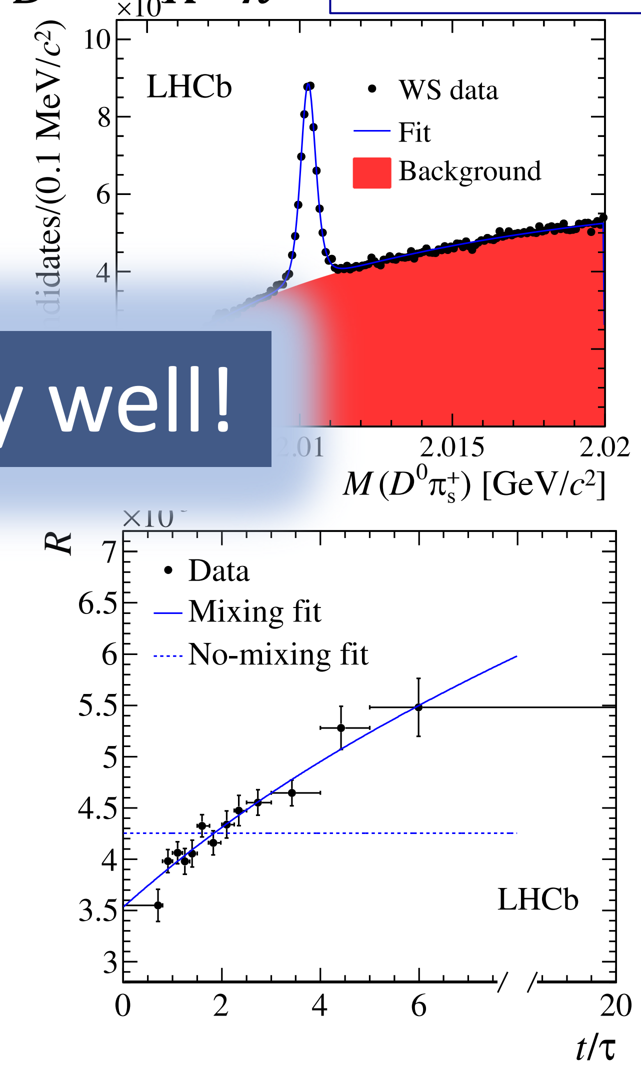
$B_s^0 - \overline{B_s^0}$ mixing

$B_s^0 \to D_s^-\pi^+$ **Nature.Phys.18 (2022) 1**



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

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



The Experiment works extremely well!

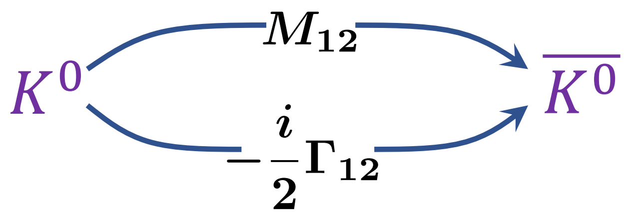
Three types of observable CP violation

a) CP Violation ***"in mixing"*** : 1964 (CCFT)

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

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

Interfere *dispersive* and *absorptive*:



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

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

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

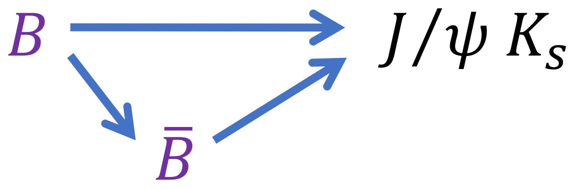
Interfere *decay amplitudes*:

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

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

sin 2β = 0.699 ± 0.017 (PDG)

Interfere *direct and mixed*:



A Bormio induced analogy: Three types of Flavour Violation…

1. “In Mixing”

2. “Direct”

3. “Mixing induced” (interference of 1. and 2.)

(Mirtilli)

(Nonino)

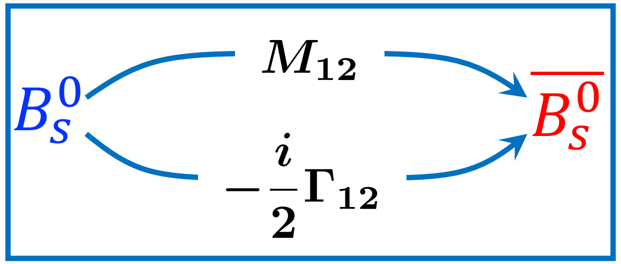
(Braulio)

→ Interference experiments lead to interesting effects!

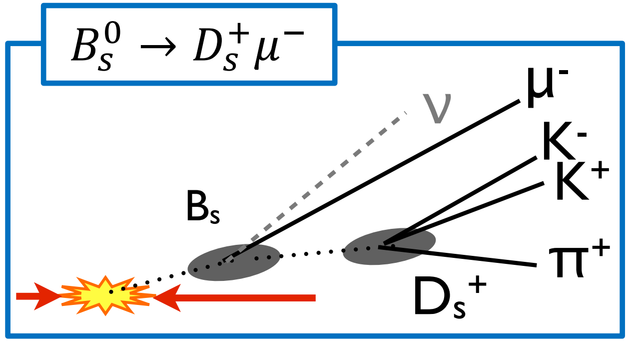
(Constructive or destructive??)

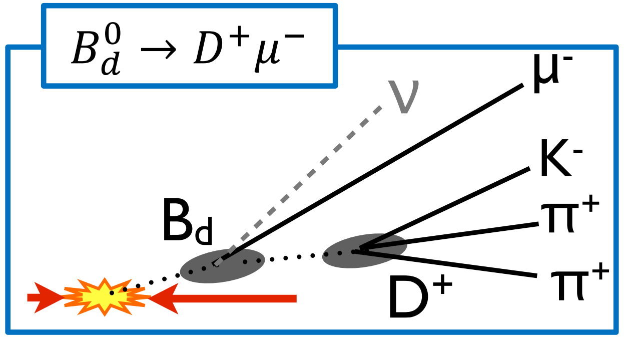
Type-1: CP violation *in mixing*: $A_{SL}(B_d)$ en $A_{SL}(B_s)$

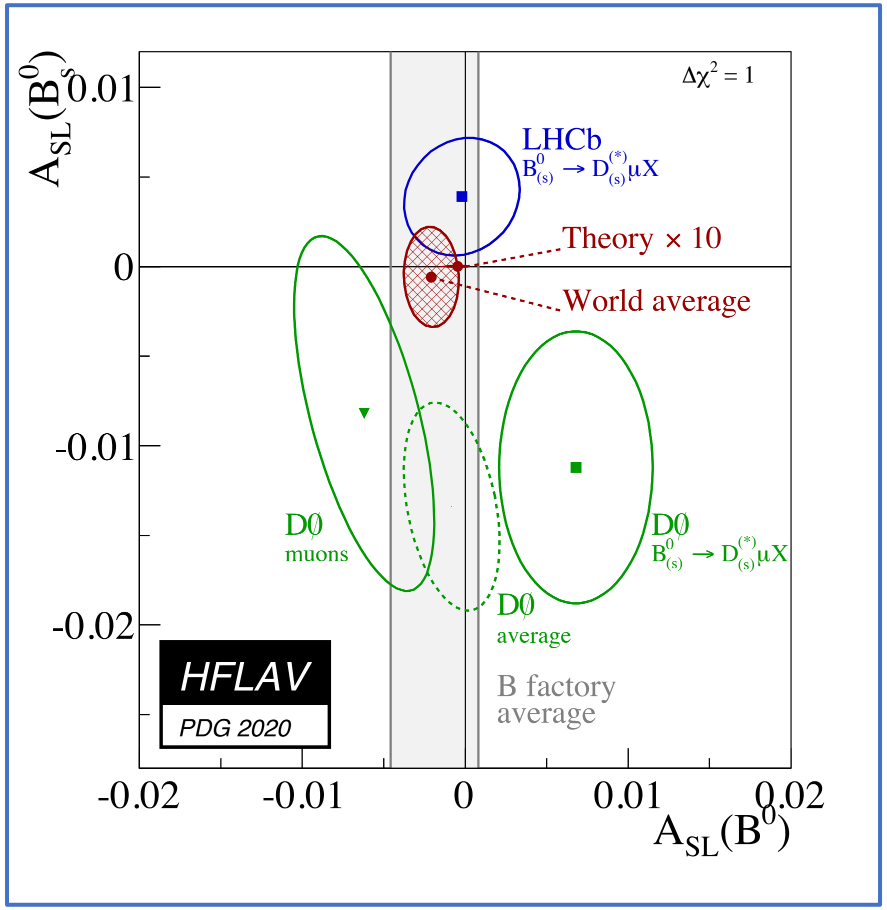
- Interfere dispersive and absorptive:



$$\mathcal{A}_{meas} = \frac{\Gamma_{(D_s^- \mu^+)} - \Gamma_{(D_s^+ \mu^-)}}{\Gamma_{(D_s^- \mu^+)} + \Gamma_{(D_s^+ \mu^-)}}$$







Produce equal amounts of B_s and $\overline{B}_s$. Decays:

$B_s \to D_s^- \mu^+$; $\overline{B}_s \to D_s^+ \mu^-$

If $\mathcal{A}_{meas} \neq 0$, then:

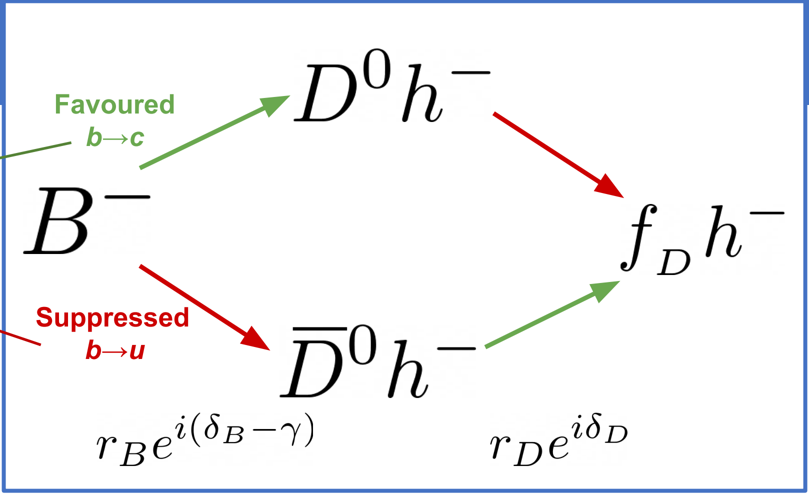
Rates: $B \to \overline{B} \neq \overline{B} \to B$

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

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

LHCb: B_d^0 : PRL 114 (2015) 041601
B_s^0 : PRL 117 (2016) 061803

Type-2: *Direct* CP violation: $B \to Dh$



- Interfere *two decay amplitudes*:

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

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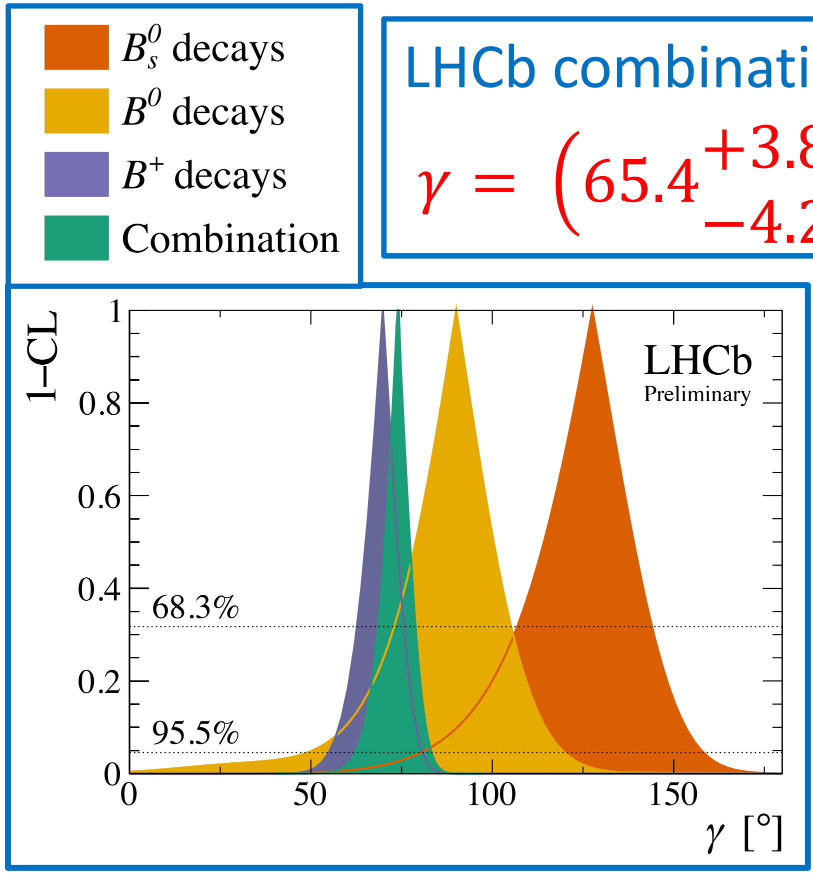
LHCb combination:

$$\gamma = \left(65.4^{+3.8}_{-4.2}\right)^{o}$$



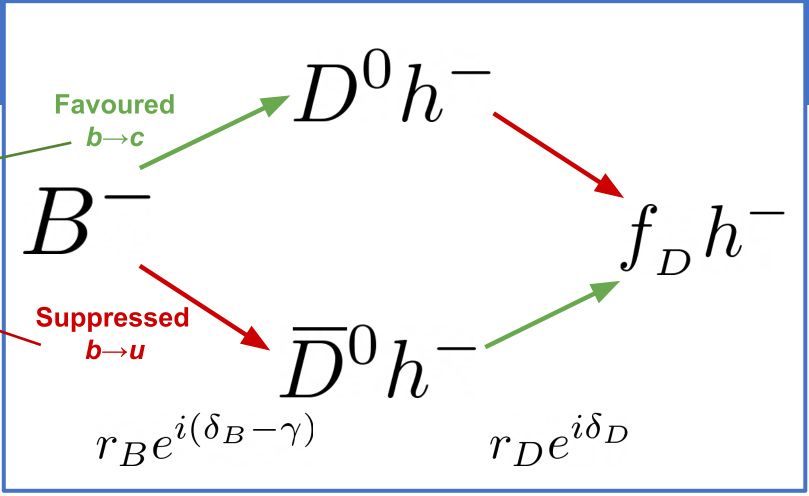
- Measurement of gamma using *many B* decays

B decay	D decay	Ref.	Dataset	Status since Ref. [24]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[28]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[29]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[26]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[30]	Run 1&2	**Updated**
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[31]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[31]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[32]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[33]	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	**New**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[34]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[35]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[36]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[37]	Run 1&2	**New**

Type-2: *Direct* CP violation: $B \to Dh$

- Interfere *two decay amplitudes*:

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



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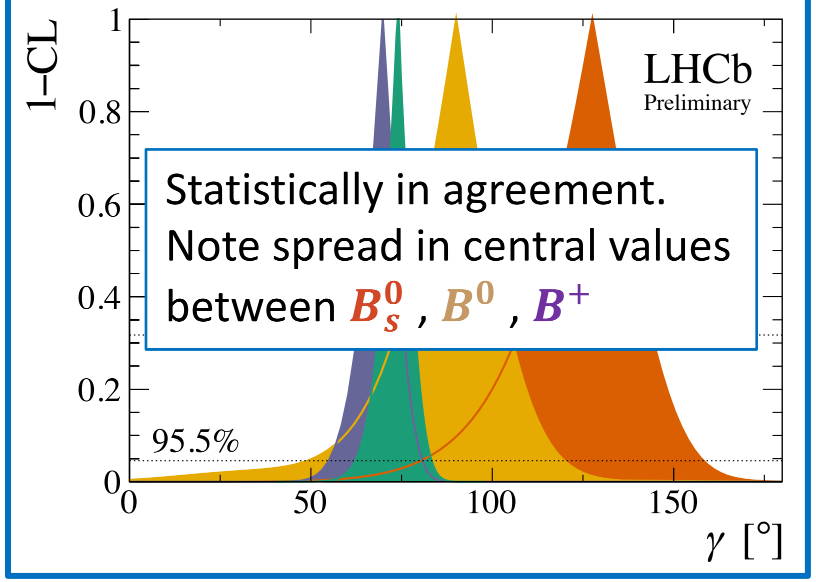
- B_s^0 decays
- B^0 decays
- B^+ decays
- Combination

LHCb combination:

$$\gamma = \left(65.4^{+3.8}_{-4.2}\right)^o$$



Statistically in agreement.
Note spread in central values between B_s^0, B^0, B^+

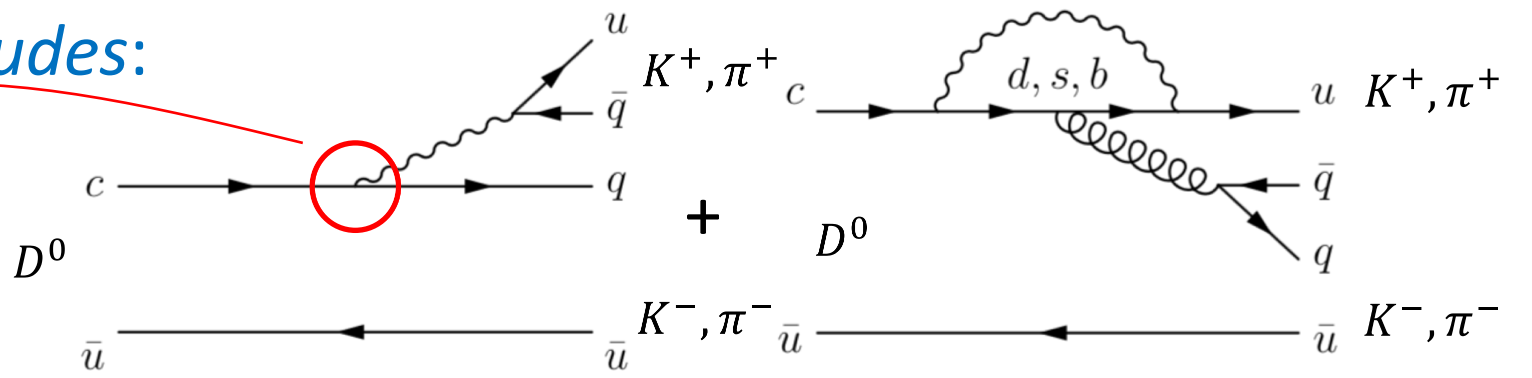
- Measurement of gamma using *many B* decays

B decay	D decay	Ref.	Dataset	Status since Ref. [24]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[28]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[29]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K_S^0 h^+h^-$	[26]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K_S^0 K^\pm\pi^\mp$	[30]	Run 1&2	**Updated**
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[31]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[31]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[32]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[33]	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	**New**
$B^0 \to DK^{*0}$	$D \to K_S^0\pi^+\pi^-$	[34]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[35]	Run 1	As before
$B_s^0 \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[36]	Run 1	As before
$B_s^0 \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[37]	Run 1&2	**New**

Type-2: *Direct* CP violation Charm? $D^0 \to KK$ and $D^0 \to \pi\pi$

- Interfere *two D^0 decay amplitudes*:

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



$D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

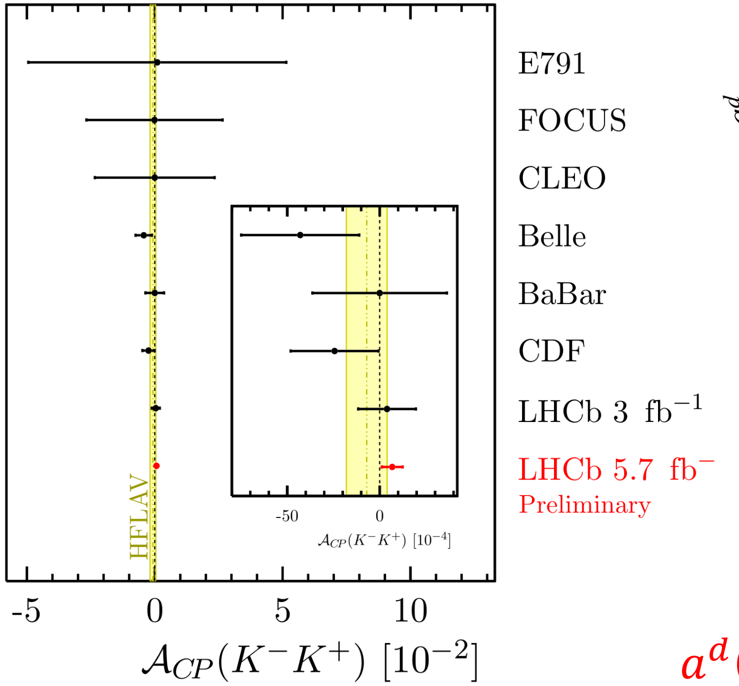
- *2019: Observation* of CP violation **difference** in charm decays **PRL 122.211803**

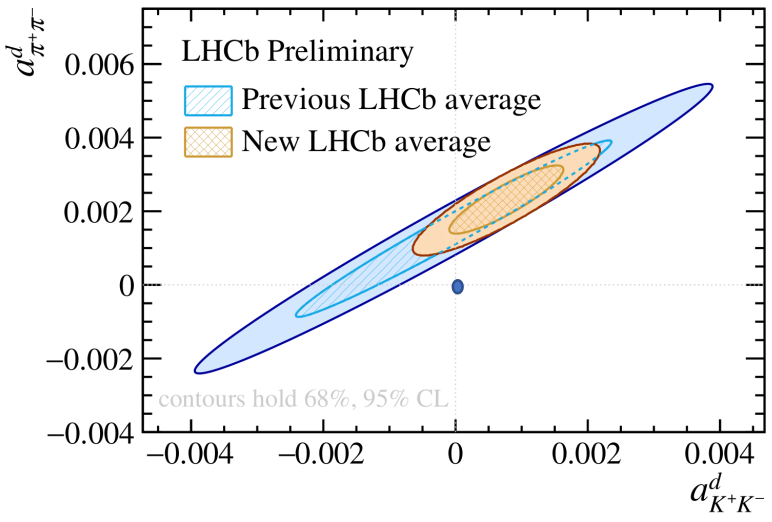
$$\Delta A_{CP} \equiv A_{CP}(D^0 \to KK) - A_{CP}(D^0 \to \pi\pi)$$

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

- *2022: Evidence* of direct CP violation in specific charm decay **PRD D 104 072010**

$$A_{CP}\,(D^0 \to KK) = (6.8 \pm 5.4 \pm 1.6) \times 10^{-4}$$





ICHEP 2022

- Extract ***direct*** CP component using: $A_{CP} = a^d_{hh} + \frac{\langle t_{hh}\rangle}{\tau_{D^0}} \Delta Y$

$$a^d(D^0 \to KK) = (7.7 \pm 5.7) \times 10^{-4}$$

$$a^d(D^0 \to \pi\pi) = (23.2 \pm 6.1) \times 10^{-4}$$

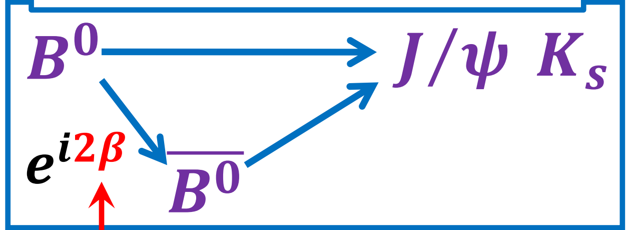
Type-3: CP violation in *interference of mixing and decay*

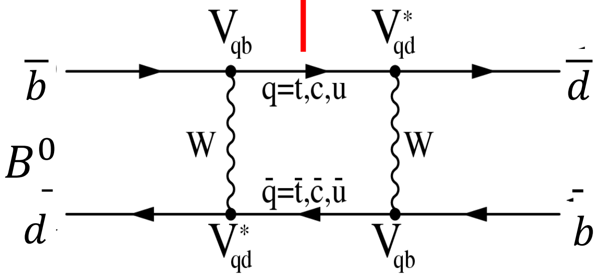
- *Decay-time dependent*

  CP violation:

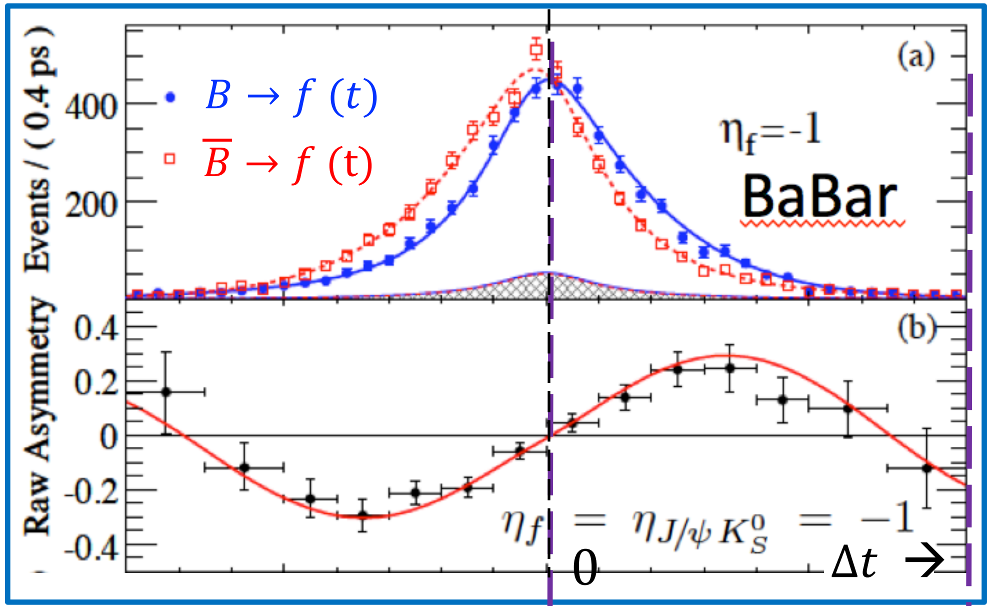
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)}$$

Interfere *direct* and *mixed*





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

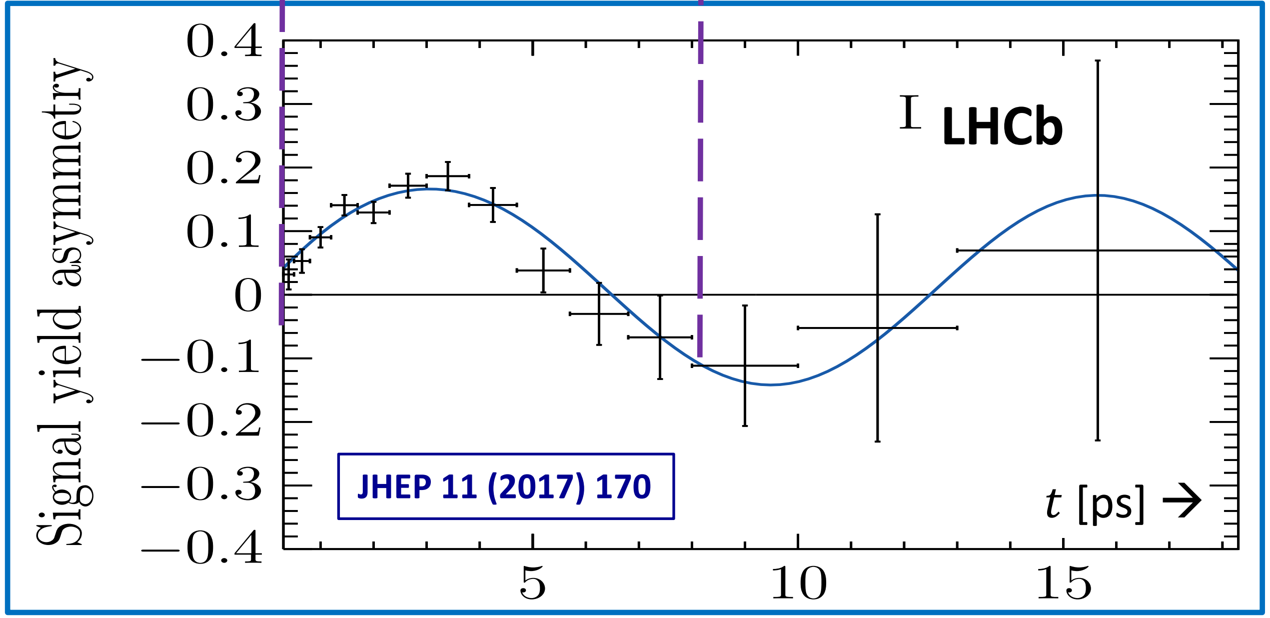


First observation of CP violation in B factories

Belle: PRL 87, 091802

Babar: PRL 87, 091801

Similar measurement LHC



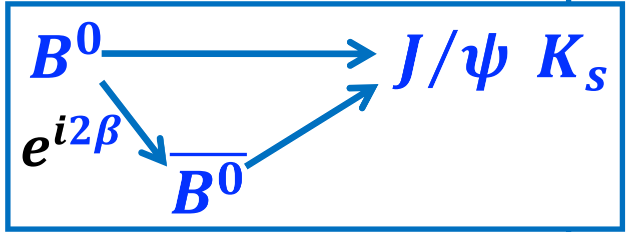
Type-3: CP violation in *interference of mixing and decay*

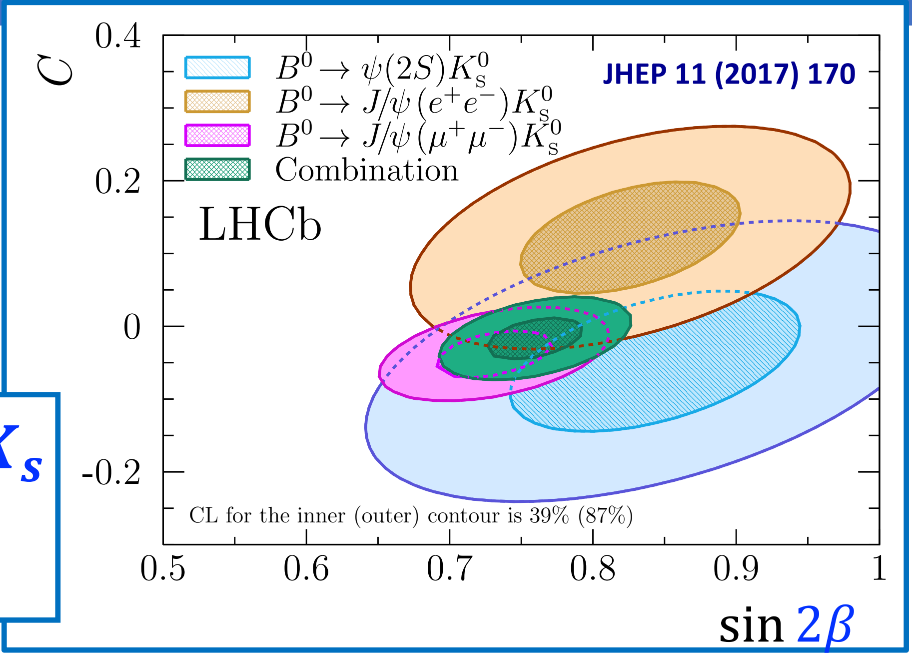
- *Decay-time dependent* CP violation:

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

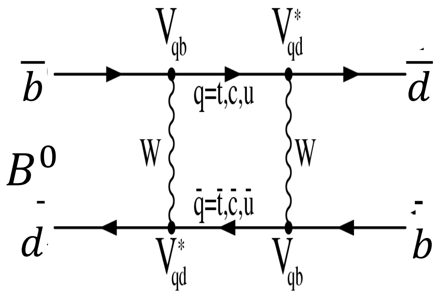
  - Angle β: $B^0 \to J/\psi\, K_S$

    JHEP 11 (2017) 170



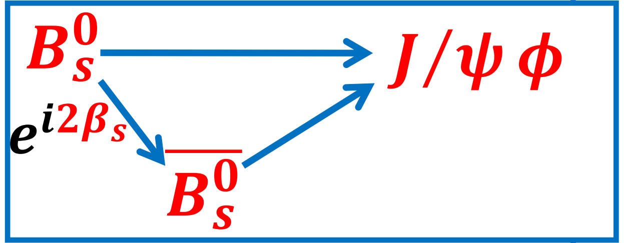


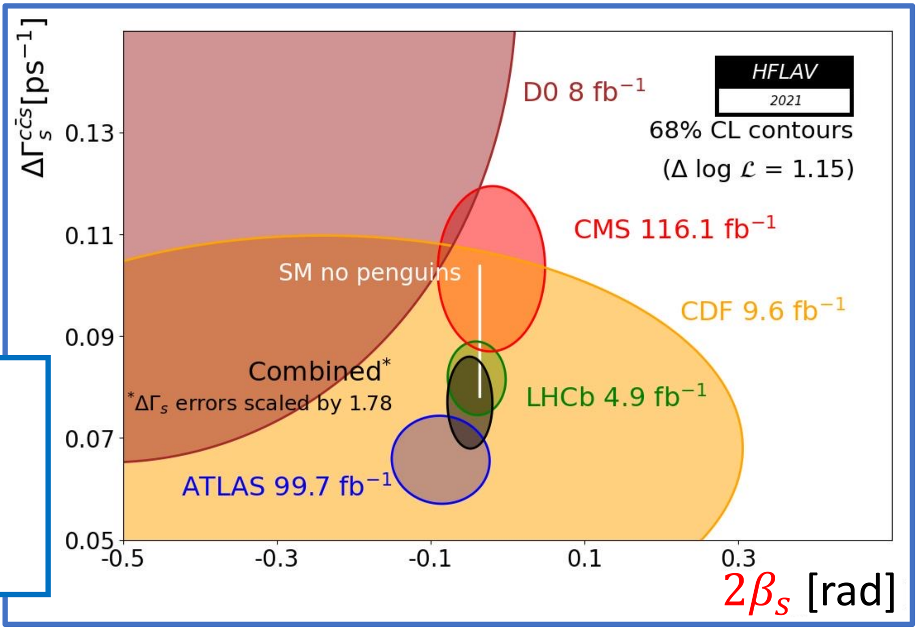
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{tb}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$



  - Angle β_s: $B^0_s \to J/\psi\, \phi$

    Eur. Phys. J. C 79 (2019) 706

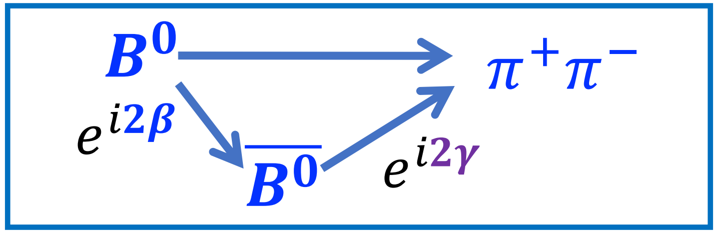


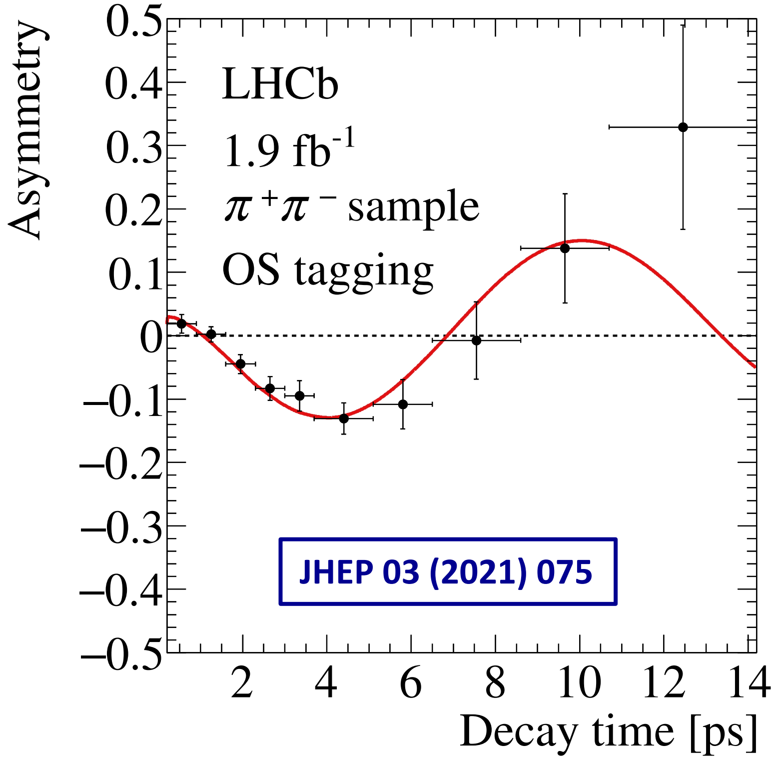


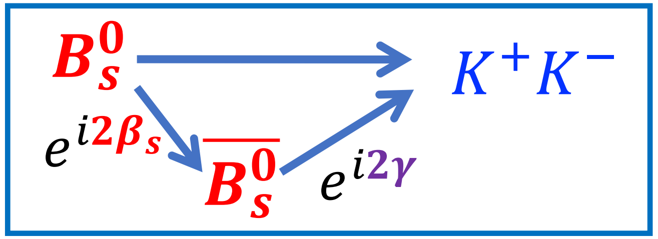
Type-3: CP violation in *interference of mixing and decay*

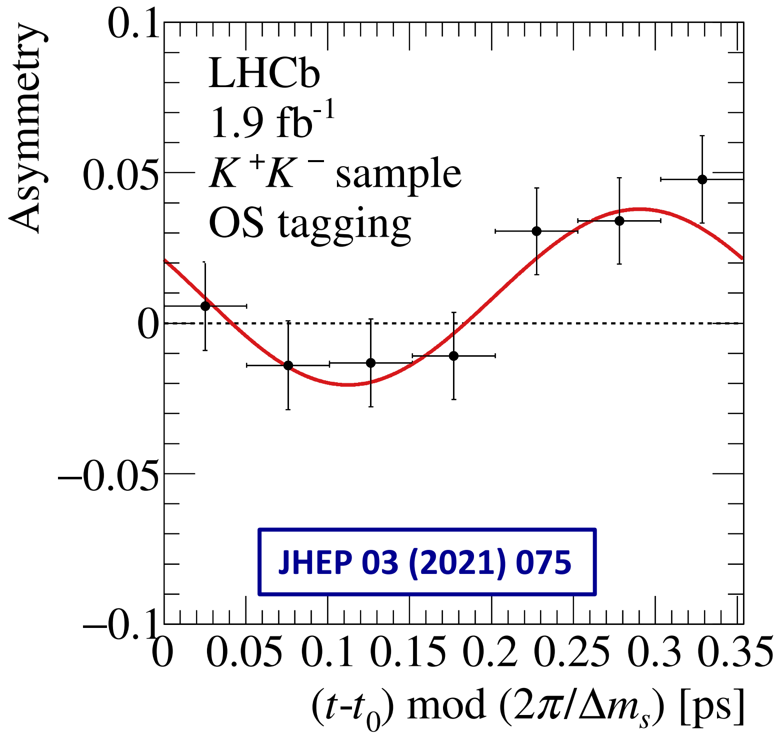
- *Decay-time dependent* CP violation:
  - more similar asymmetry measurements

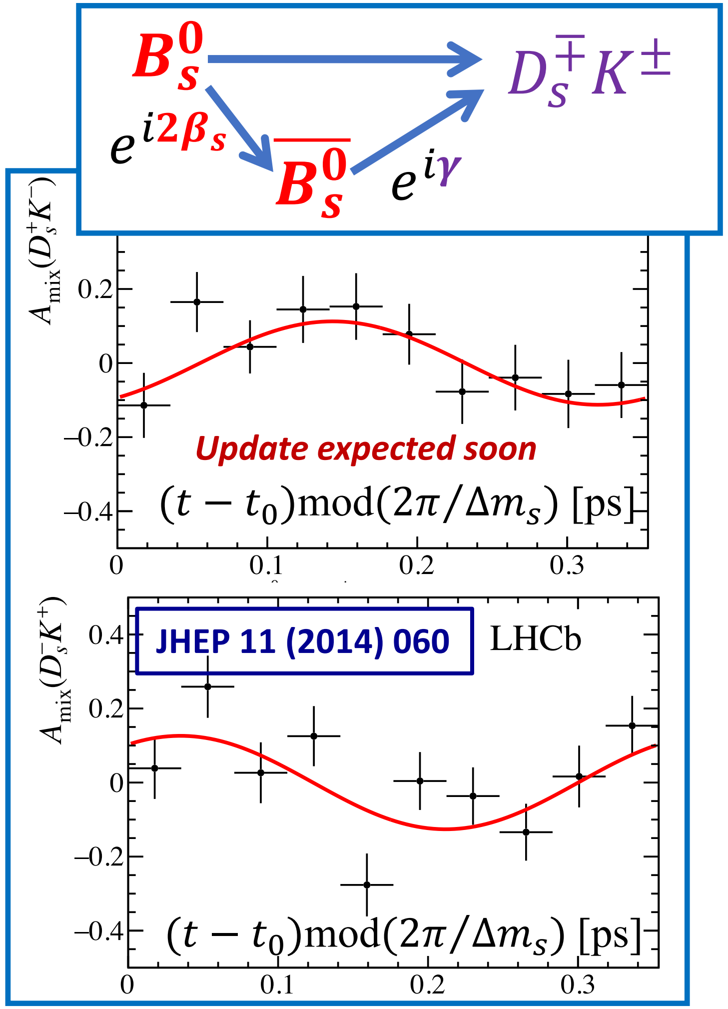
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{tb}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$



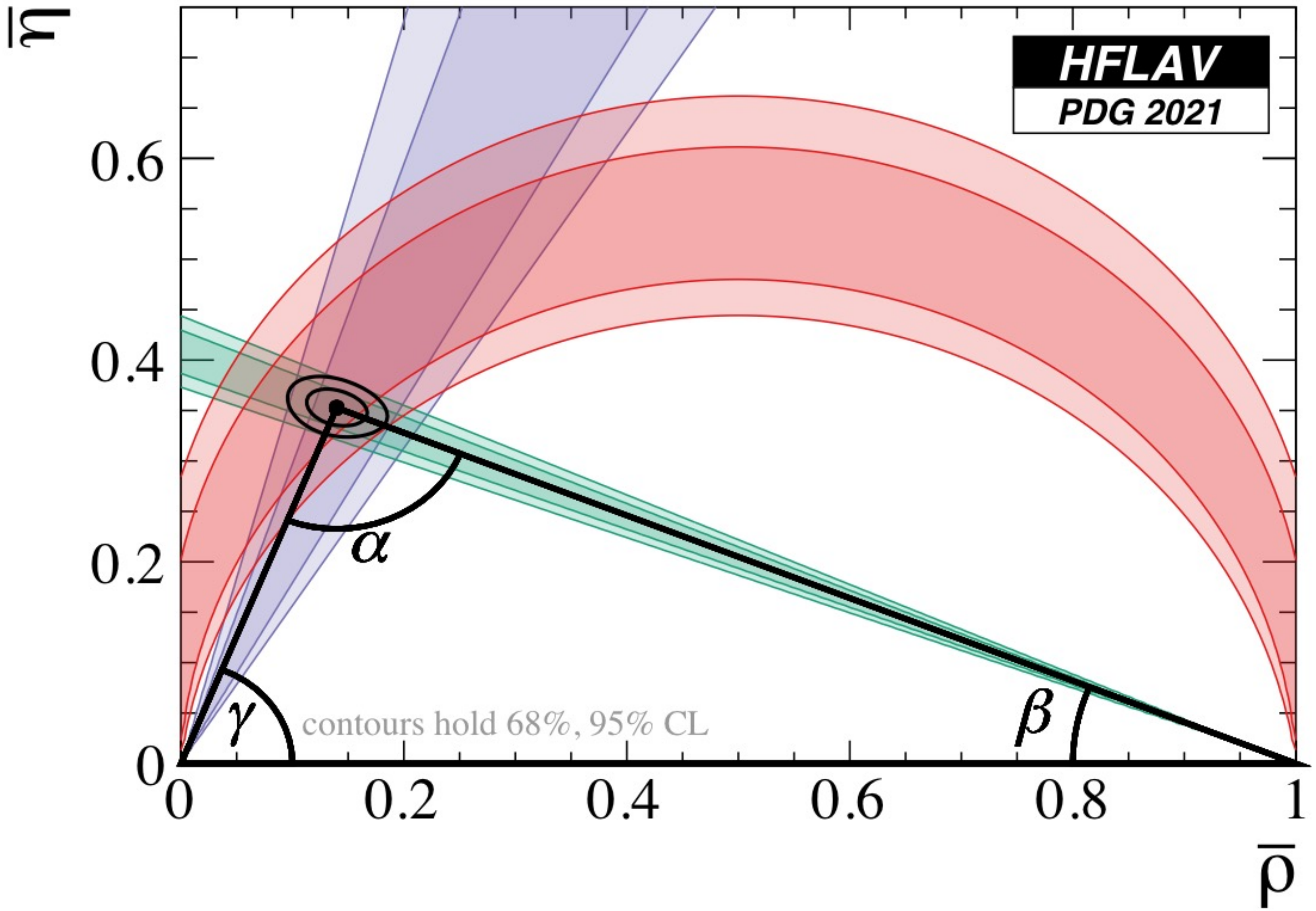








CKM triangle: bringing all together

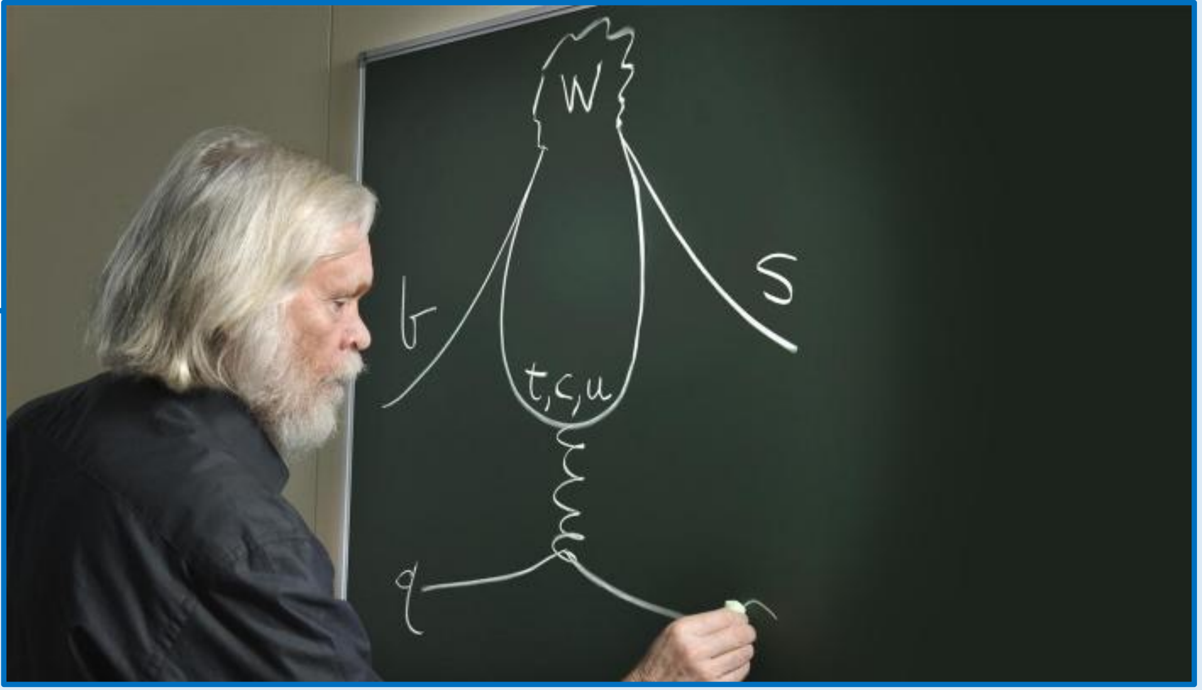


[(My) conclusion on CP observables]

LHCb makes many CP violation measurements. The CKM triangle becomes a precision measurement.

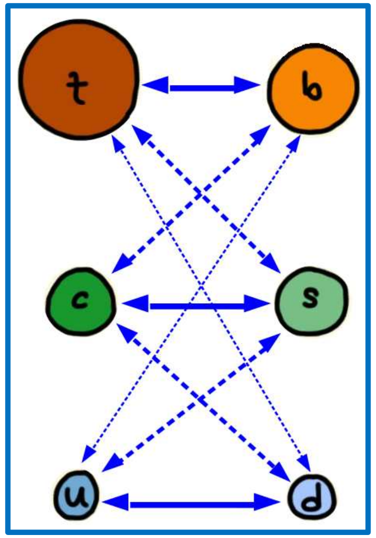
Although some puzzles are open, the CKM prescription sofar survives confrontations with more and more precise data.

1) Three generations and the origin of CP violation
2) The amount of CP violation in CKM
3) Measurements of CP violation with LHCb
4) **B-decays and Flavour Anomalies**
5) Outlook/conclusion

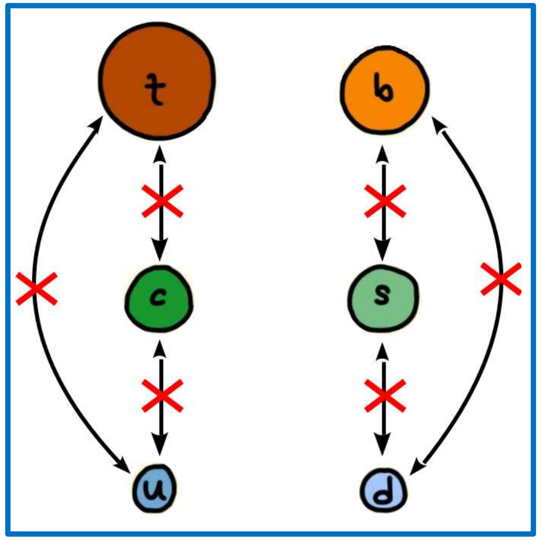


B decays and Flavour anomalies

- CKM: Flavour changing *charged* currents

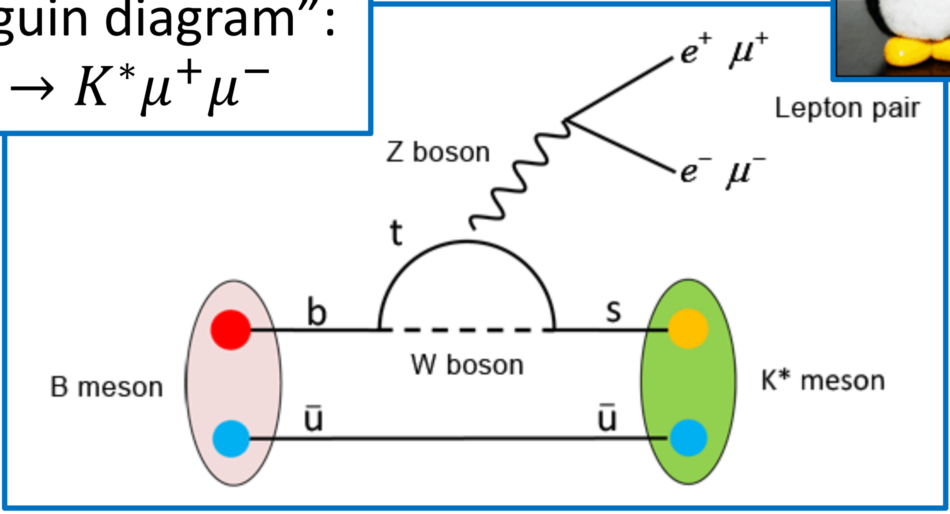


- SM does *not* have Flavour changing *neutral* currents

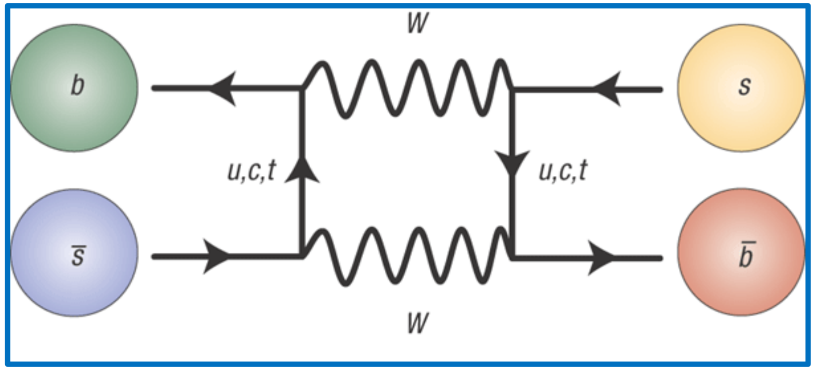


- Neutral currents are possible via higher order processes:

Decay via
“Penguin diagram”:
$B \rightarrow K^{*}\mu^{+}\mu^{-}$

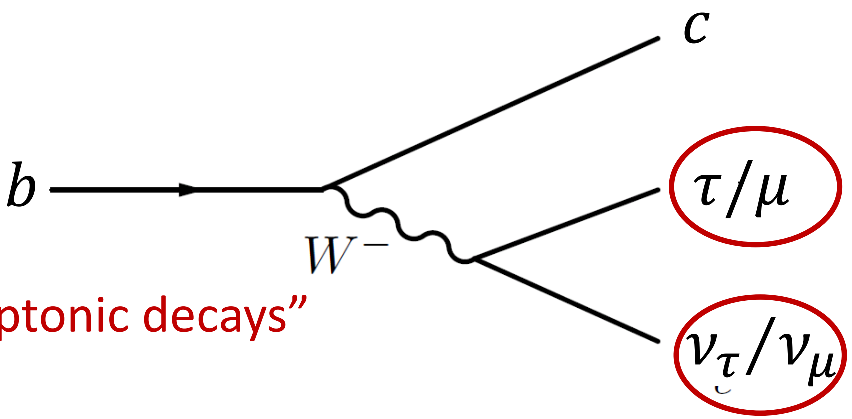


Flavour Oscillation
via “Box diagram”:
$\overline{B_s} \rightarrow B_s$



B decays and Flavour anomalies

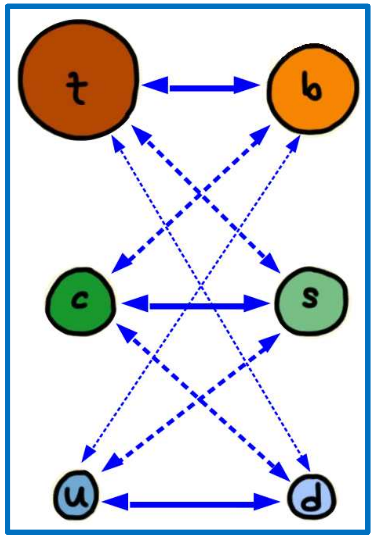
a) $b \rightarrow c\, l\, \nu$ *charged* current: "Allowed" → large decay rates



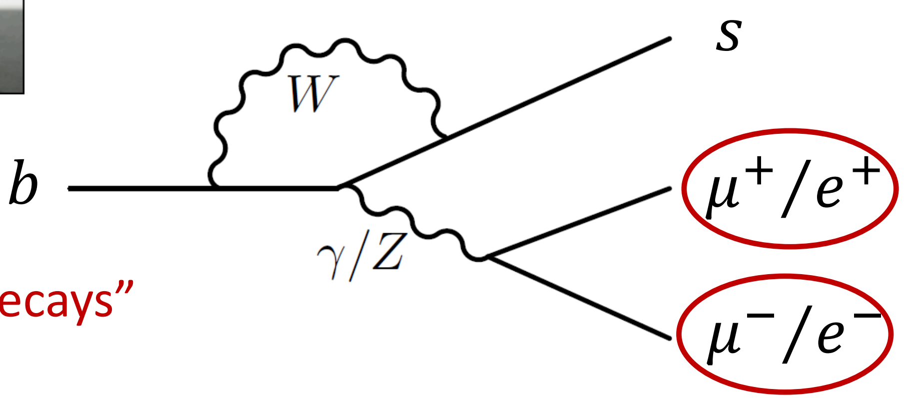
"Semileptonic decays"

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

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



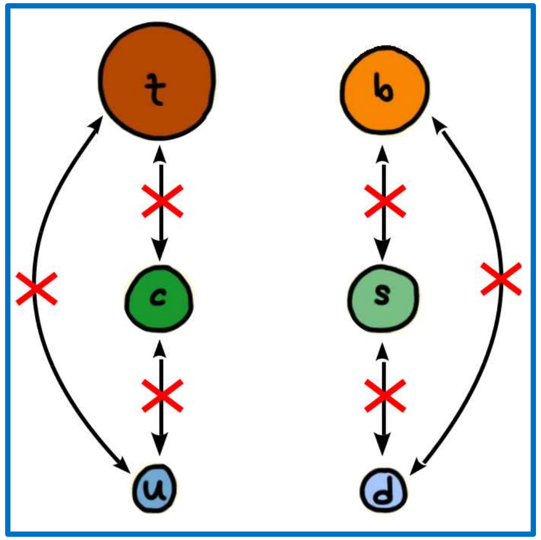
b) $b \rightarrow s l^+ l^-$ *neutral* current: "Suppressed" → rare decays



"Rare decays"

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

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



a) Semileptonics: R_D and R_{D^*}

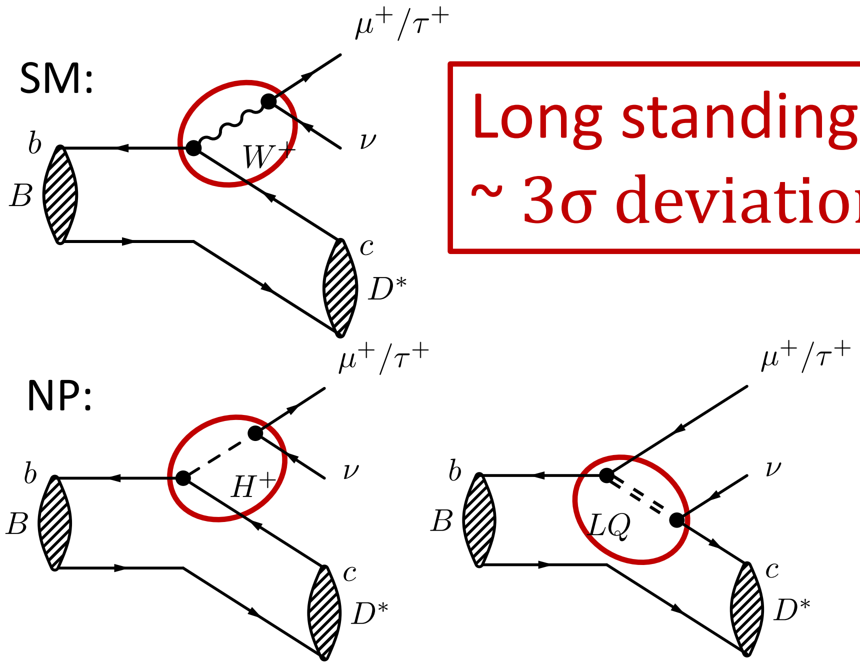
$R(D^*)$ LHCb2015: $\tau \to \mu\, \bar{\nu}_\mu\, \bar{\nu}_\tau$, LHCb2018 : $\tau \to 3\pi\, \bar{\nu}_\tau$

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

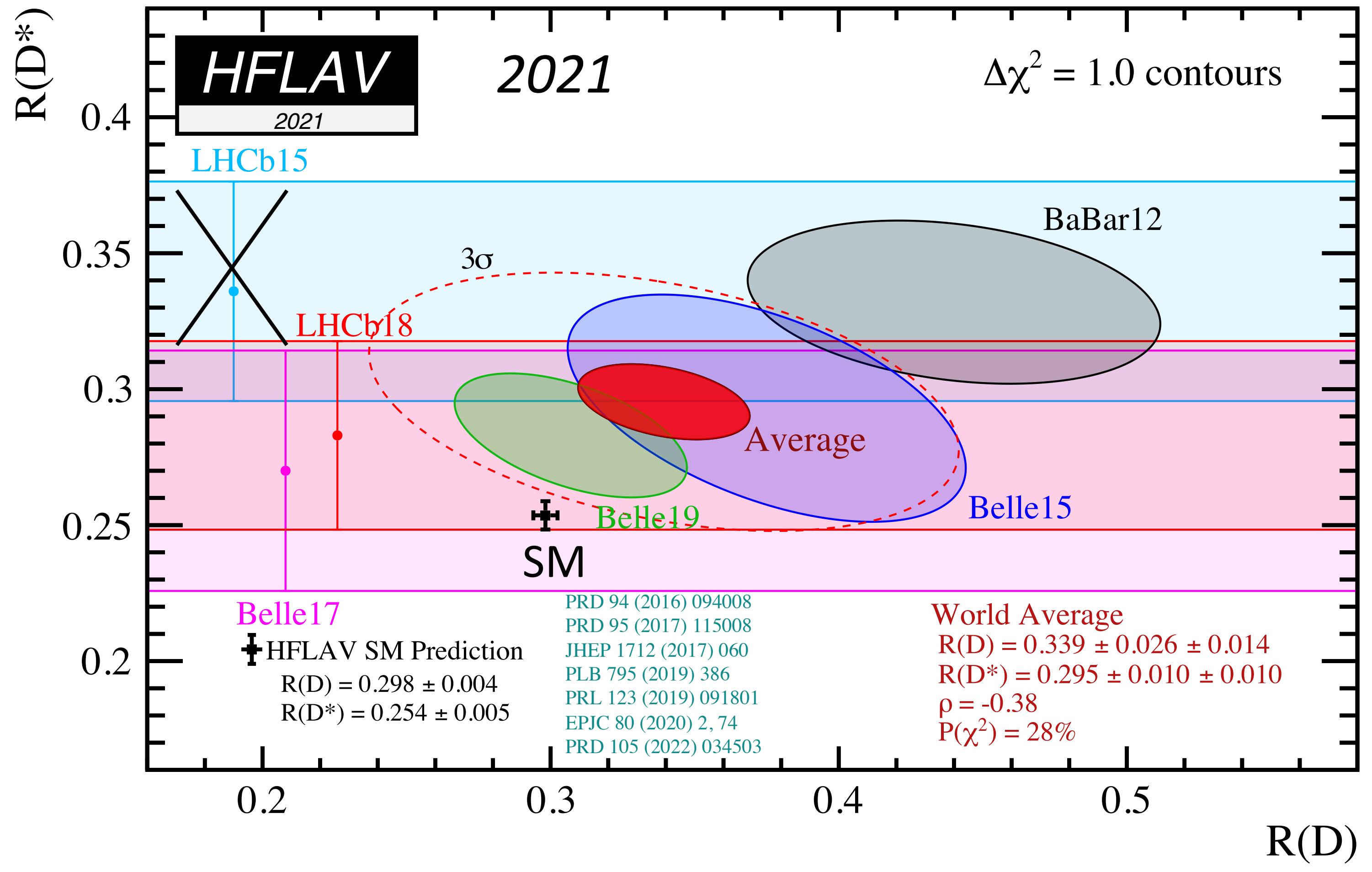
$$R_{D^*} = \frac{BR(B \to D^* \tau \nu)}{BR(B \to D^* \mu \nu)}$$

SM:

NP:



Long standing
~ 3σ deviation



→ New LHCb result replaces LHCb15…

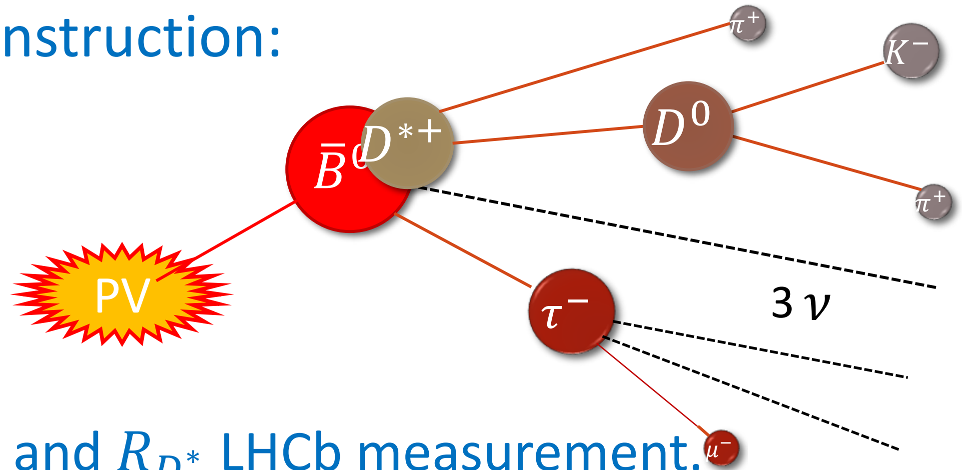
Potential *large* NP effect ➔ Involves 2[nd] and 3[rd] generation leptons

Update R_{D^*} and R_D with $\tau \to \mu\nu_\tau\nu_\mu$

Challenging reconstruction:

- missing neutrinos
- underlying event
- muonic tau only

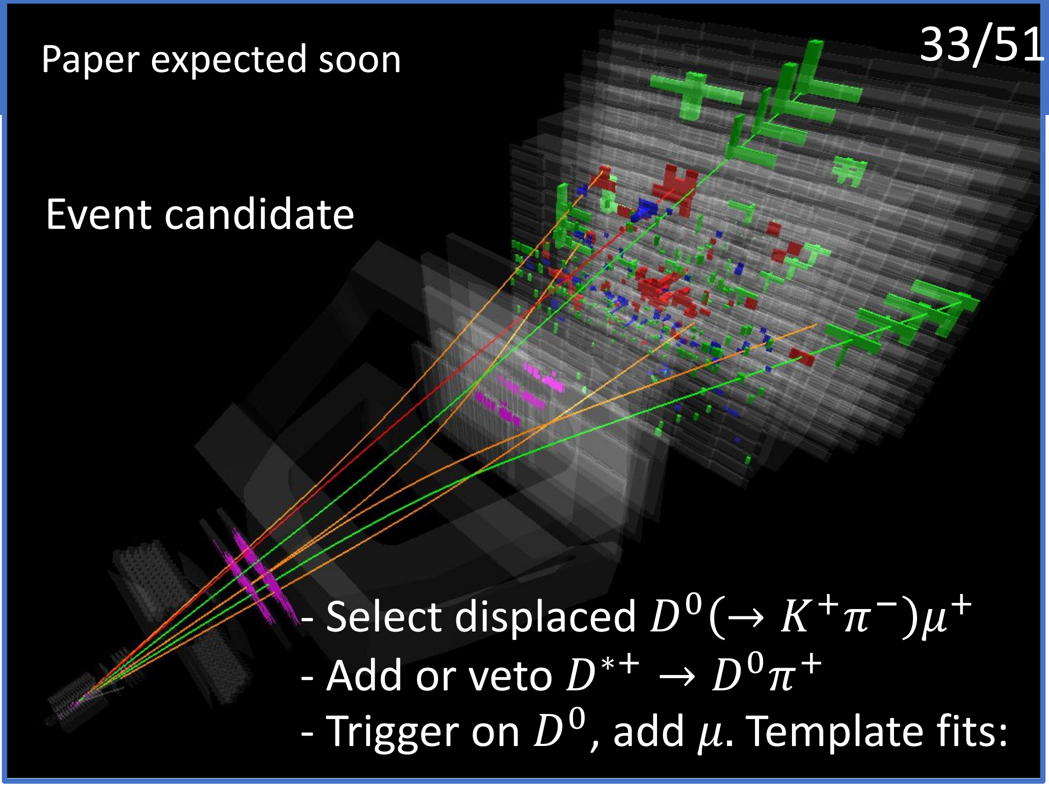
➔ backgrounds!

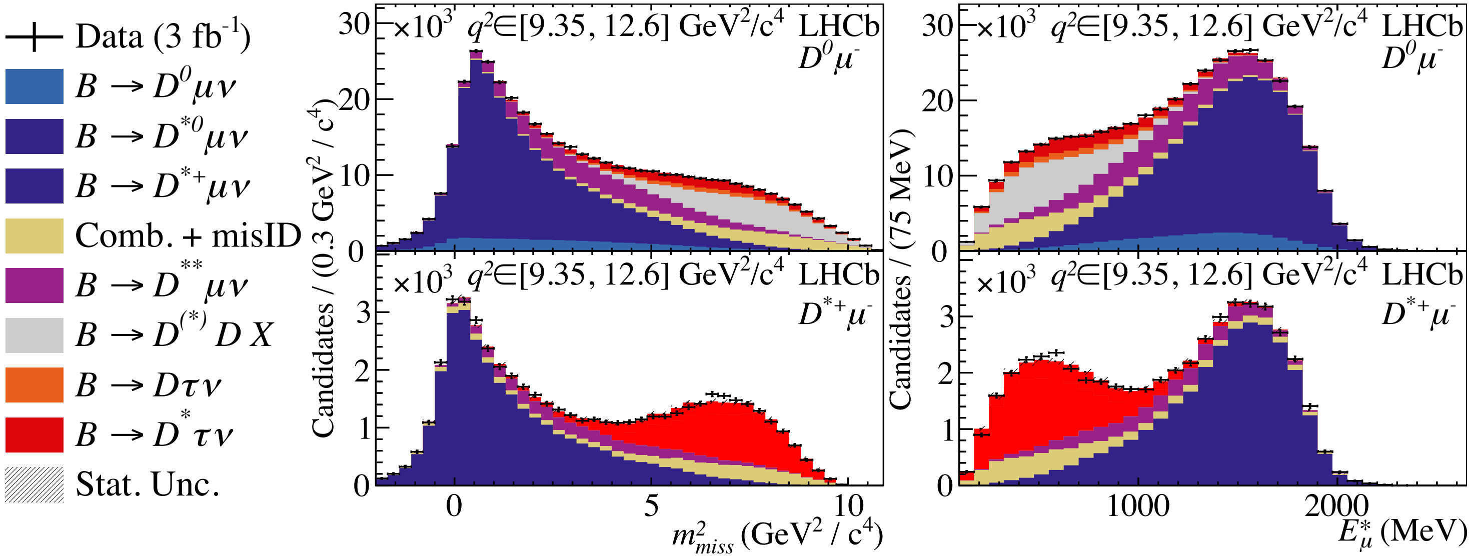


First combined R_D and R_{D^*} LHCb measurement.

Extensive systematic checks:

Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D)}(\times 10^{-2})$
Statistical uncertainty	1.8	6.0
Simulated sample size	1.5	4.5
$B \to D^* DX$ template shape	0.8	3.2
$\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ form-factors	0.7	2.1
$B \to D^{**}\mu^+\nu$ form-factors	0.8	1.2
$\mathcal{B}(B \to D^*(D_s \to \tau\nu)X)$	0.3	1.2
MisID template	0.1	0.8
$\mathcal{B}(B \to D^{**}\tau^+\nu)$	0.5	0.5
Combinatorial	< 0.1	0.1
Resolution	< 0.1	0.1
Additional model uncertainty	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D)}(\times 10^{-2})$
$B \to D^{(*)}DX$ model uncertainty	0.6	0.7
$\bar{B}^0_s \to D_s^{**}\mu^-\bar{\nu}_\mu$ model uncertainty	0.6	2.4
Data/simulation corrections	0.4	0.75
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3
misID template unfolding	0.7	1.2
Baryonic backgrounds	0.7	1.2
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D)}(\times 10^{-2})$
Data/simulation corrections	$0.4 \times \mathcal{R}(D^*)$	$0.6 \times \mathcal{R}(D)$
$\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$ branching fraction	$0.2 \times \mathcal{R}(D^*)$	$0.2 \times \mathcal{R}(D)$
Total uncertainty	3.0	8.9





R_{D^*} and R_D: LHCb 2022 Result

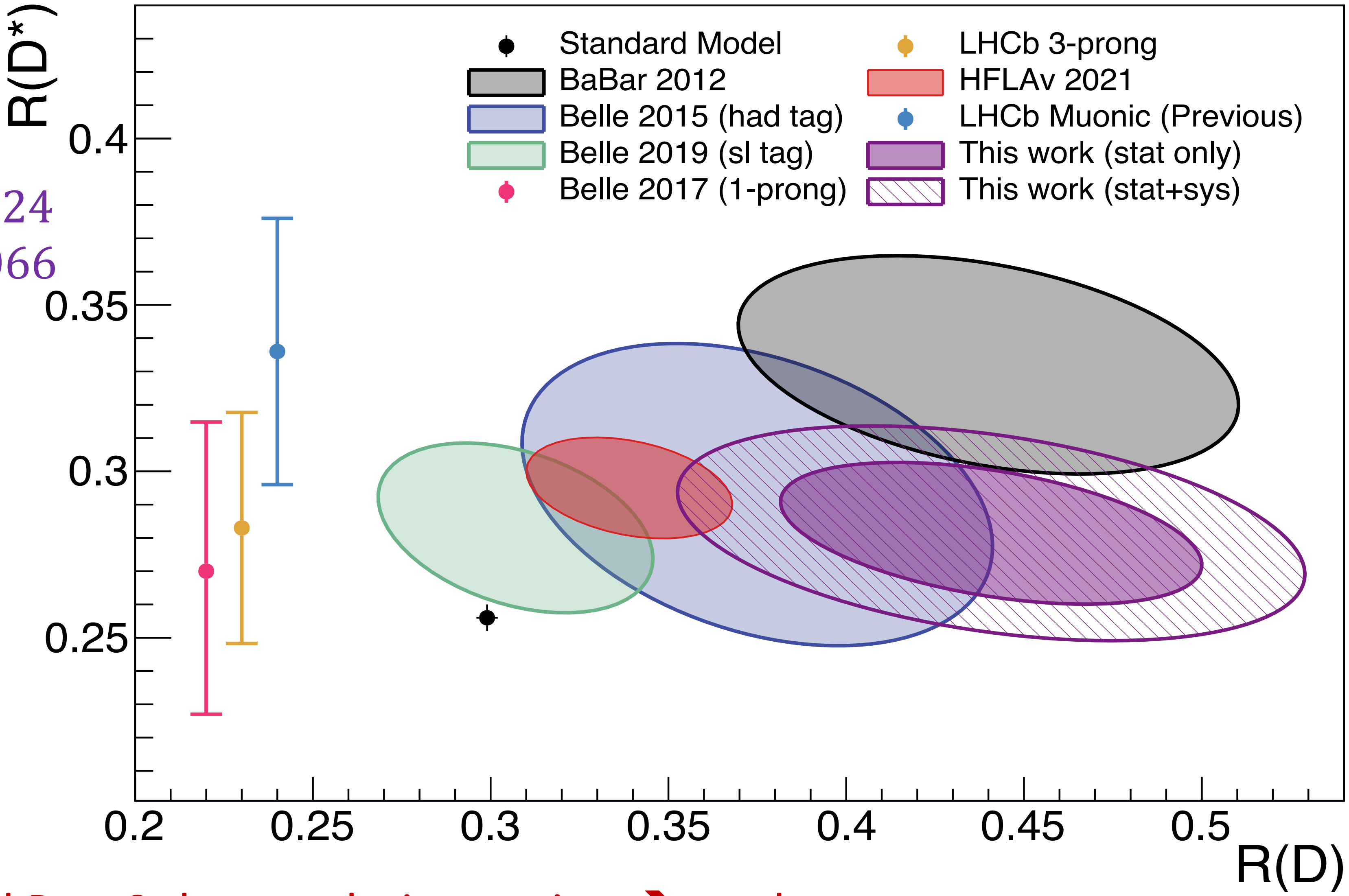
2022 Result:

$$R(D^*) = 0.281 \pm 0.018 \pm 0.024$$
$$R(D^0) = 0.441 \pm 0.060 \pm 0.066$$
$$\rho = -0.43$$

1.9σ agreement with SM

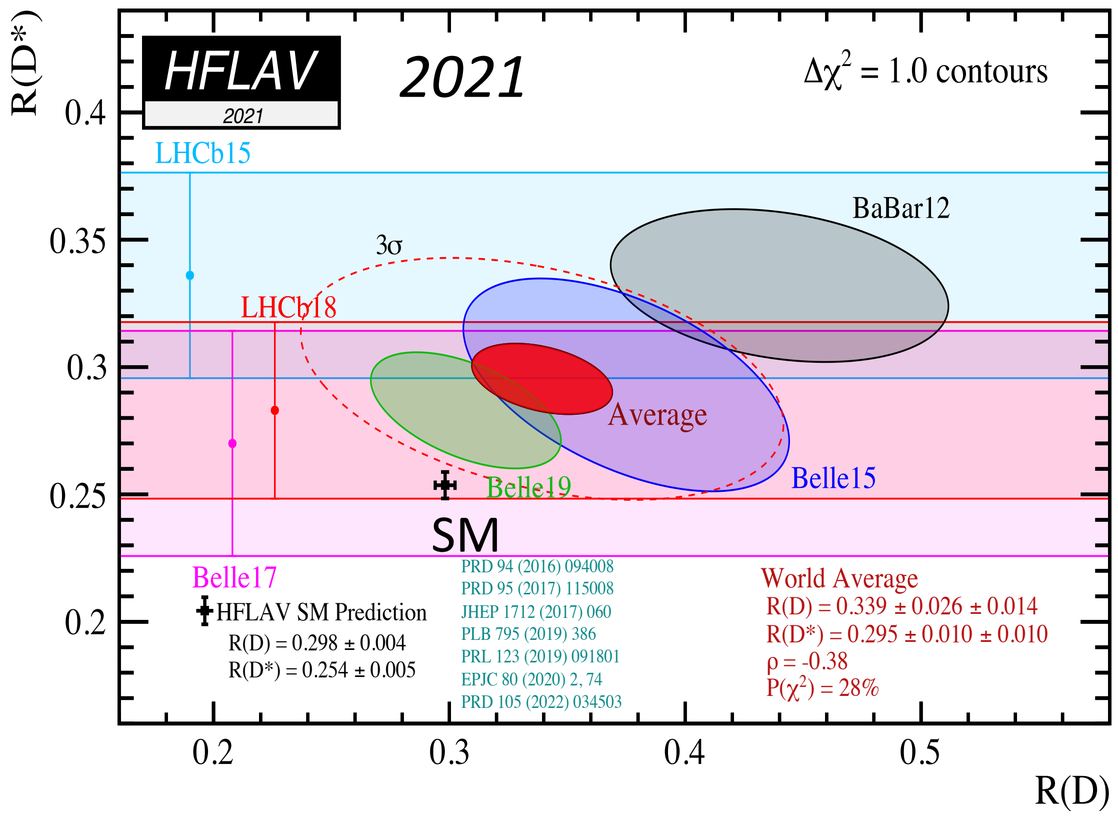
CERN seminar 19-10-2022

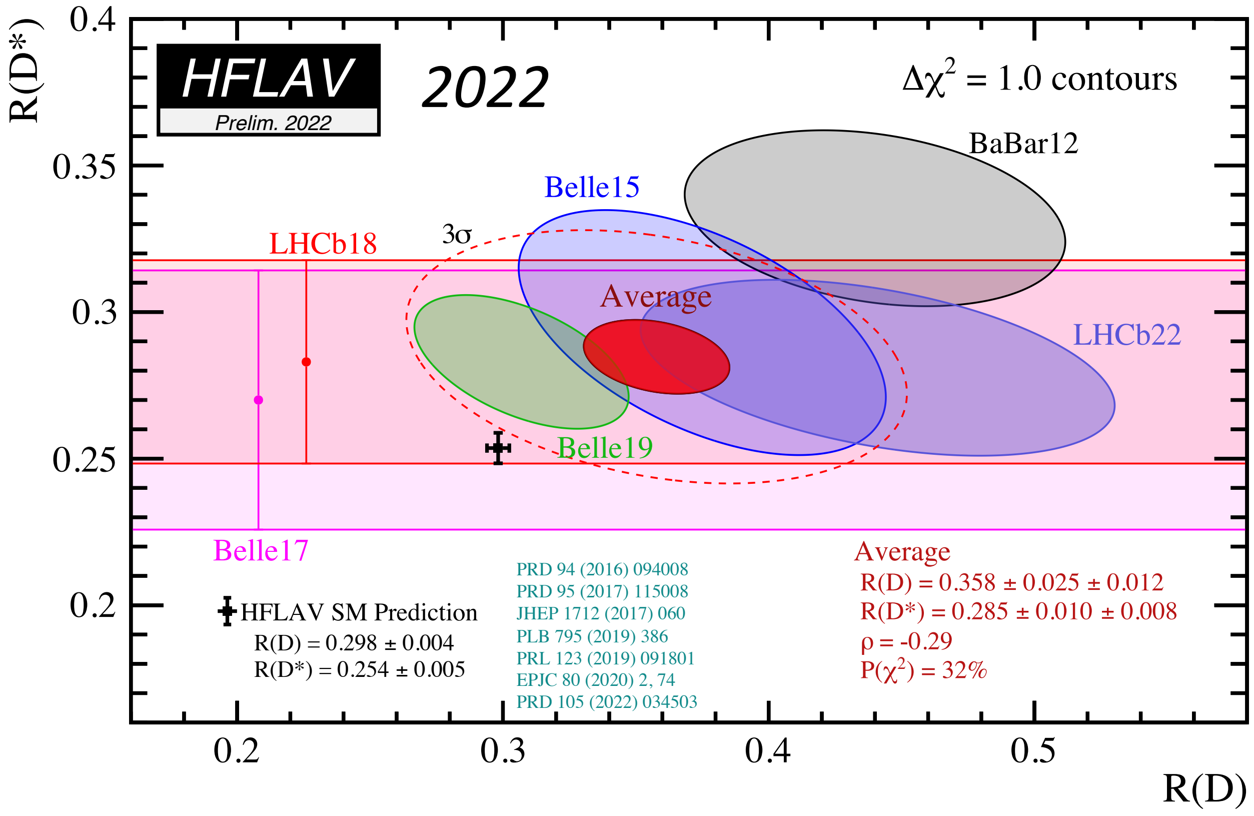
Paper expected soon



Run-1 hadronic taus and Run-2 data analysis ongoing ➔much more to come.

R_{D^*} and R_D: LHCb 2022 Result - Update of HFLAV

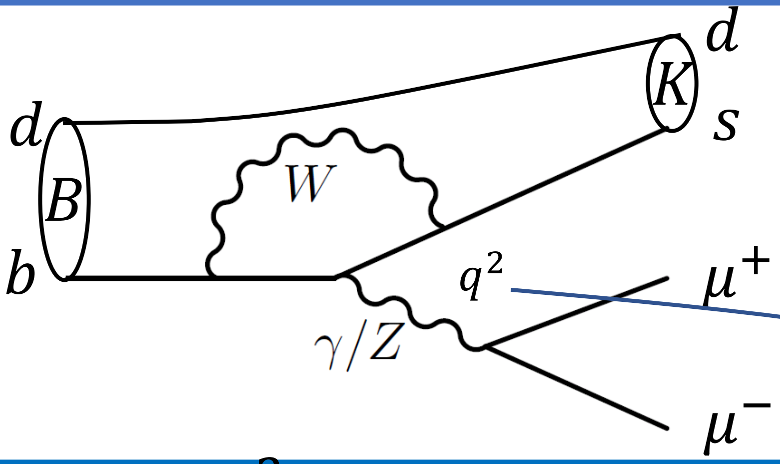




New average: slightly lower $R(D^*)$, slightly higher $R(D)$, reduced correlation.

agreement/tension with the SM: 3.3σ → 3.2σ

b) Rare decays: $b \to s\, l^+ l^-$ transition: suppressed neutral current



Effective Hamiltonian:

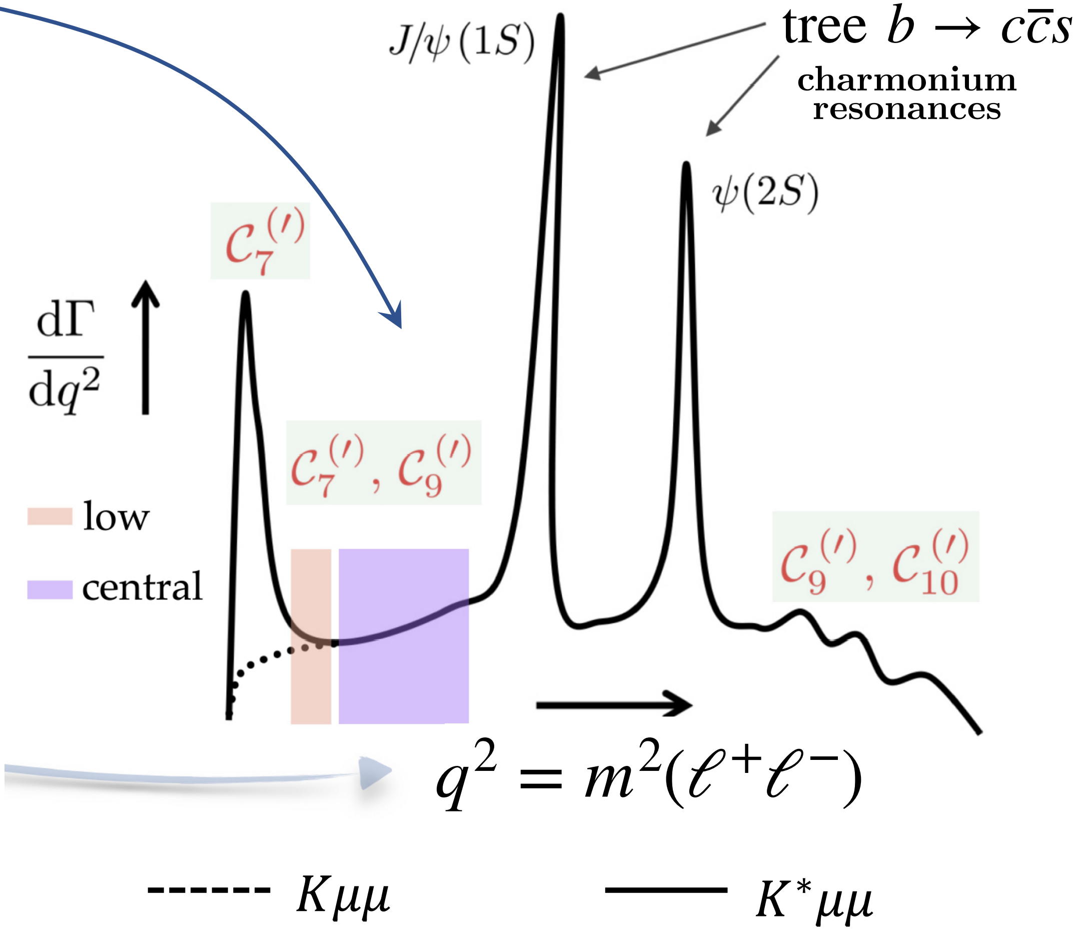
$$H_{eff} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left(C_i^{SM} + \Delta_i^{NP} \right) O_i$$

Wilson coefficients C_i

i. Differential (q^2) decay rates:
- $B^+ \to K^+ \mu^+ \mu^-$, $B^0 \to K^0 \mu^+ \mu^-$,
  $B^+ \to K^{*+} \mu^+ \mu^-$, $B^0 \to K^{*0} \mu^+ \mu^-$,
  $B_s \to \phi \mu^+ \mu^-$, $\Lambda_b \to \Lambda \mu^+ \mu^-$
- Relatively large theory uncertainties

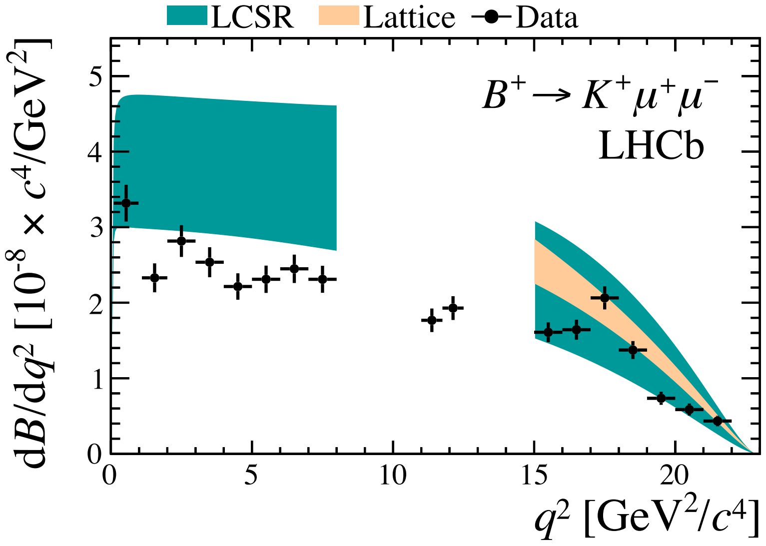
ii. Angular observables (eg P5')
- $B \to K^* \mu^+ \mu^-$, $B^+ \to K^{*+} \mu^+ \mu^-$
- Less theory uncertainty (charm loop)

iii. μ/e Universality ratios R_K, R_{K^*}, …
- Theoretically robust

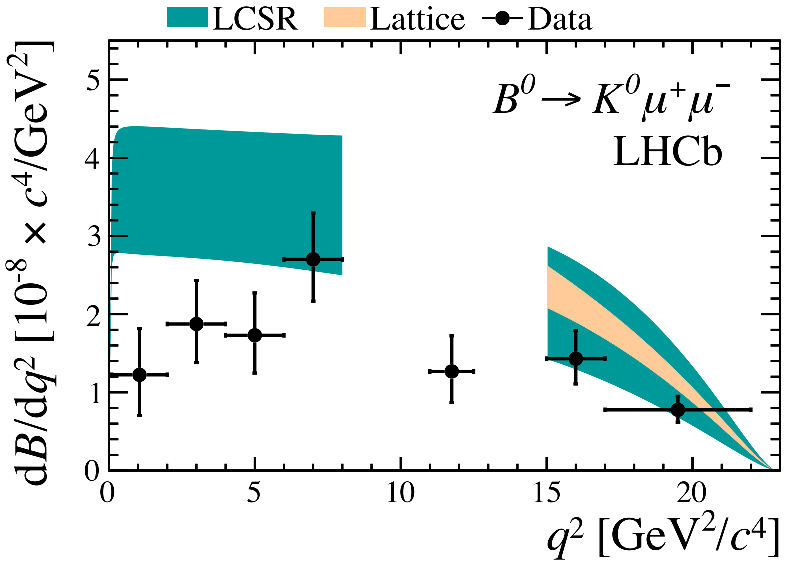


b) i. Differential decay rates of Rare Decays: $b \to s\,\mu^+\mu^-$

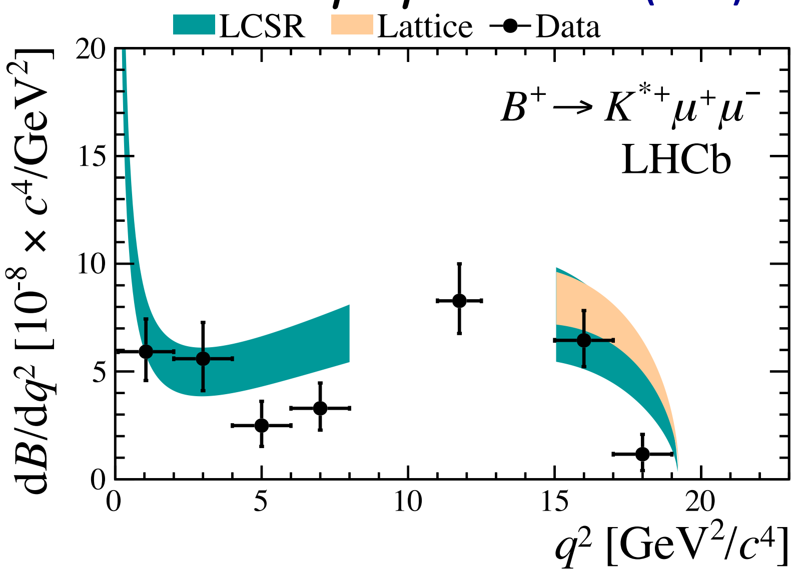
$B^+ \to K^+\mu^+\mu^-$ JHEP 06 (2014) 133



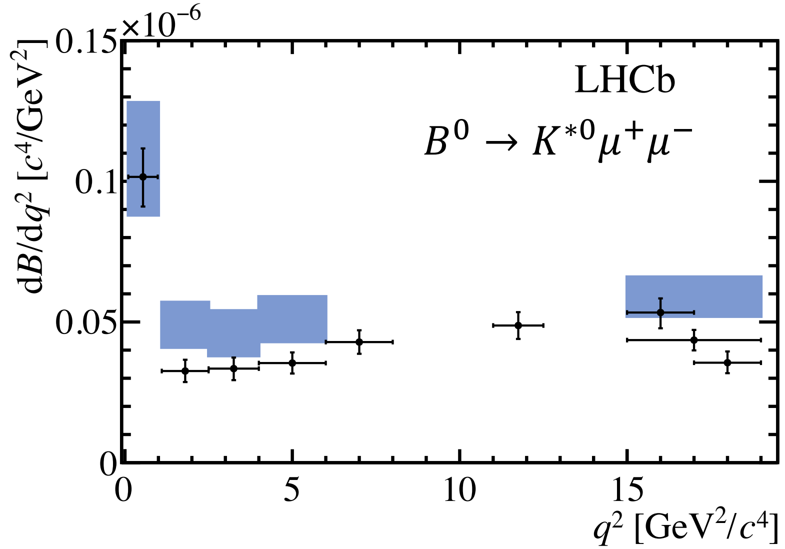
$B^0 \to K^0\mu^+\mu^-$ JHEP 06 (2014) 133



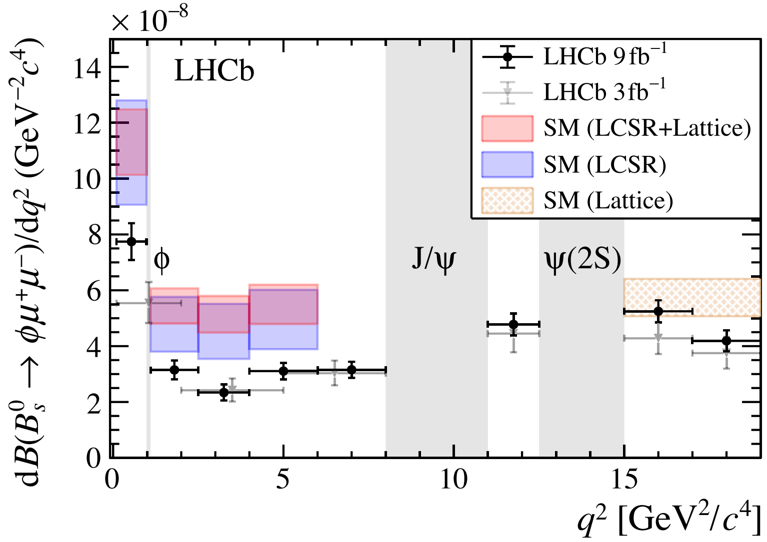
$B^+ \to K^{*+}\mu^+\mu^-$ JHEP 06 (2014) 133



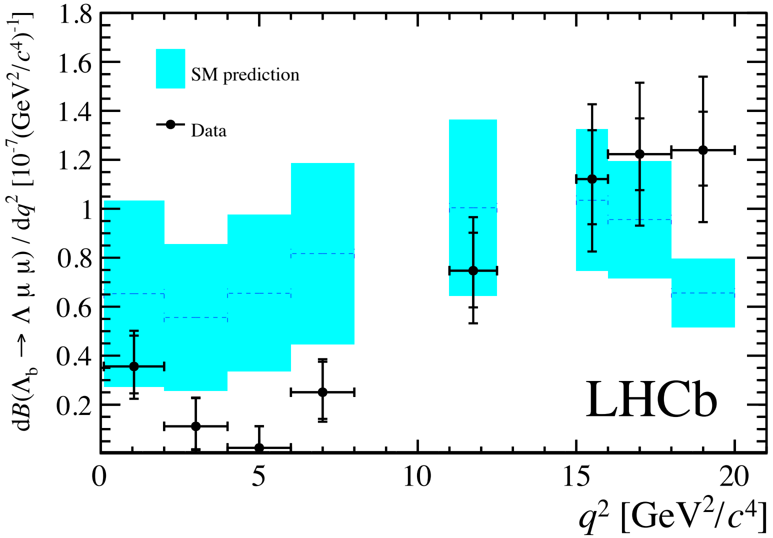
$B^0 \to K^{*0}\mu^+\mu^-$ JHEP 04 (2017) 142



$B_s \to \phi\mu^+\mu^-$ PRL 127 (2021) 111801

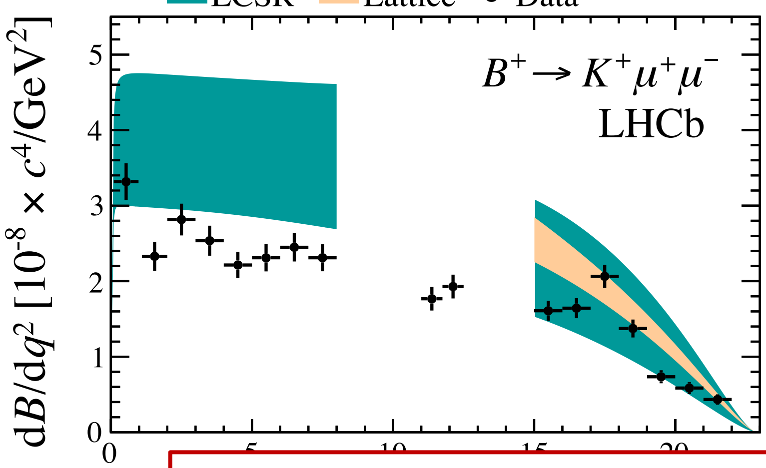


$\Lambda_b \to \Lambda\mu^+\mu^-$ JHEP 06 (2015) 115

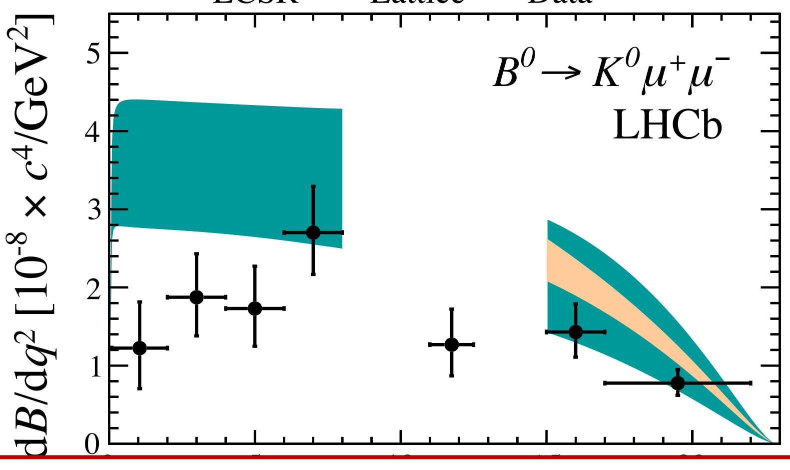


b) i. Differential decay rates of Rare Decays: $b \to s\,\mu^+\mu^-$

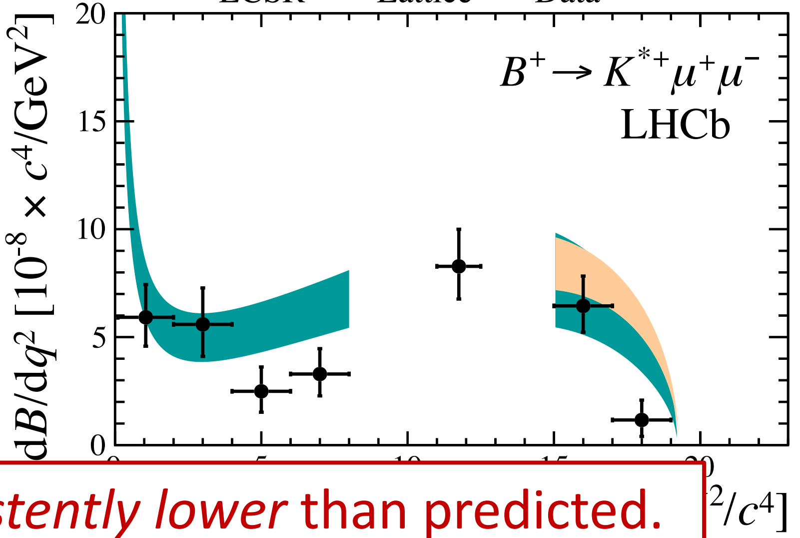
$B^+ \to K^+\mu^+\mu^-$ JHEP 06 (2014) 133



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



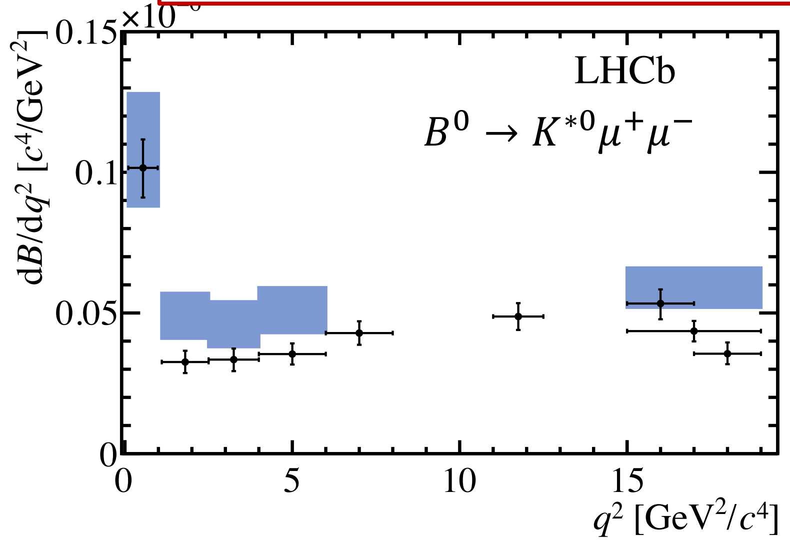
$B^+ \to K^{*+}\mu^+\mu^-$ JHEP 06 (2014) 133

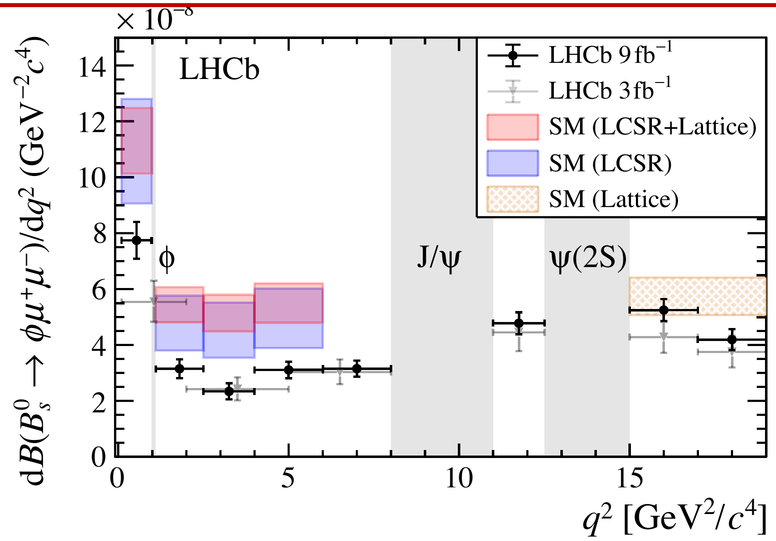


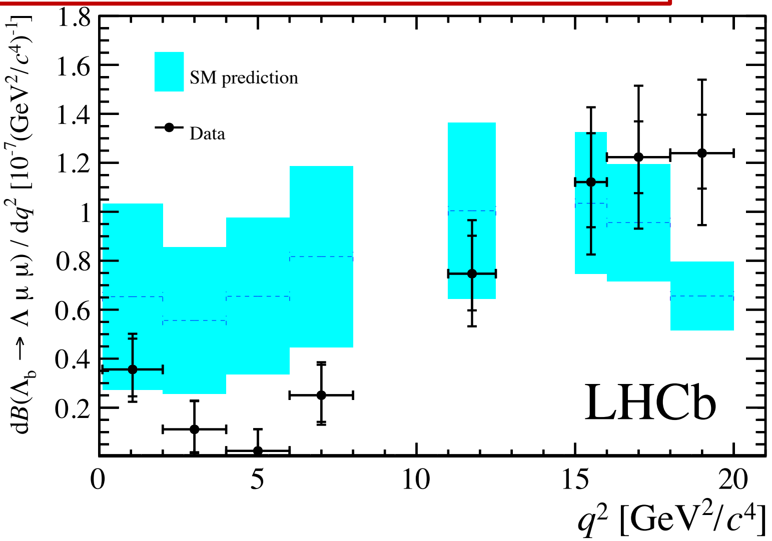
- Branching fractions related to $b \to s\,\mu^+\mu^-$ transition *consistently lower* than predicted.
- Anomaly or common issue with form factors? Theory uncertainty ~ 20 – 30%

$B^0 \to$

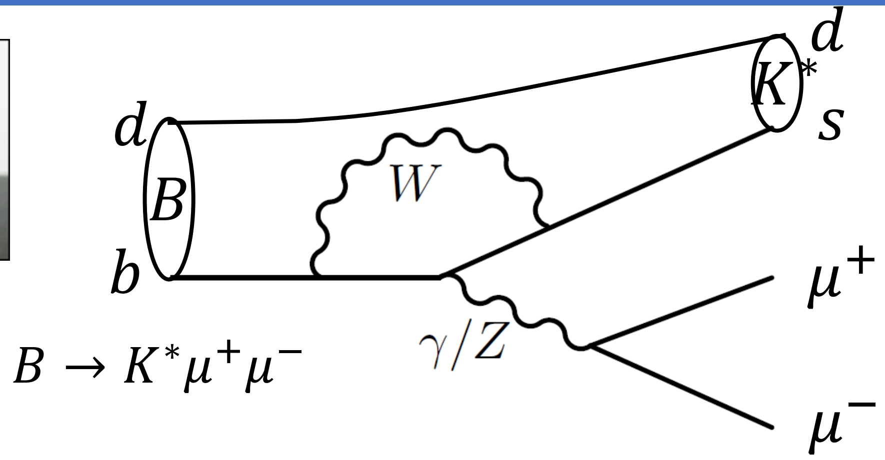
) 115

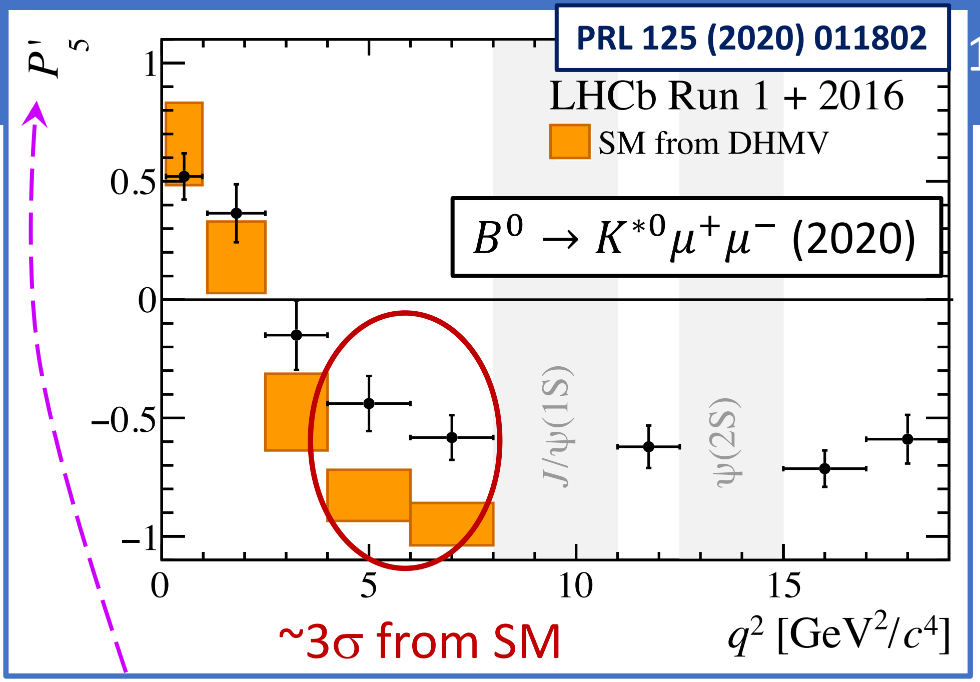




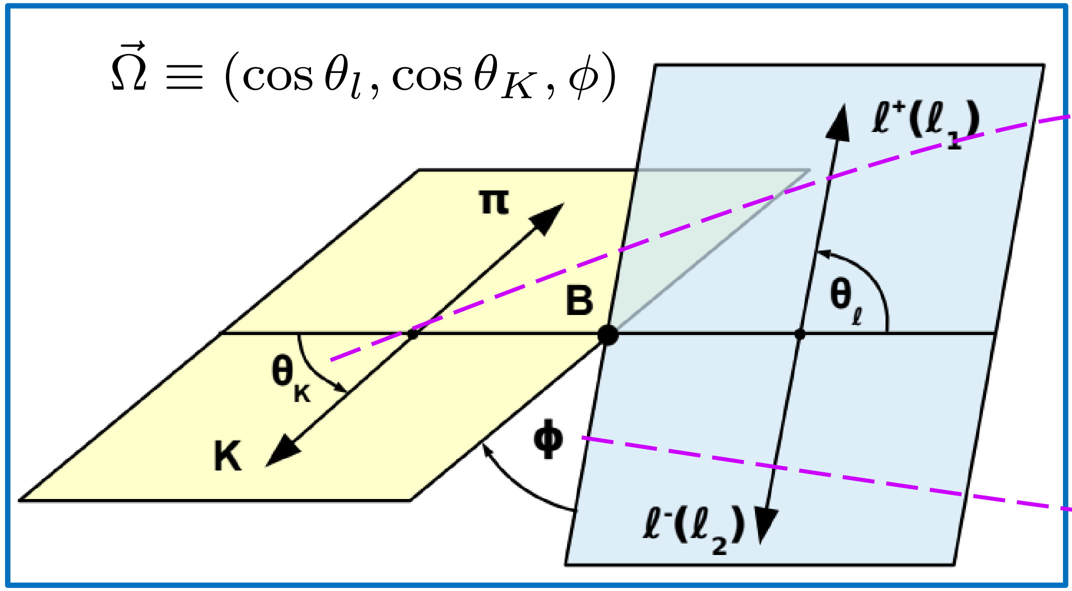


b) ii. Angular observable P_5'

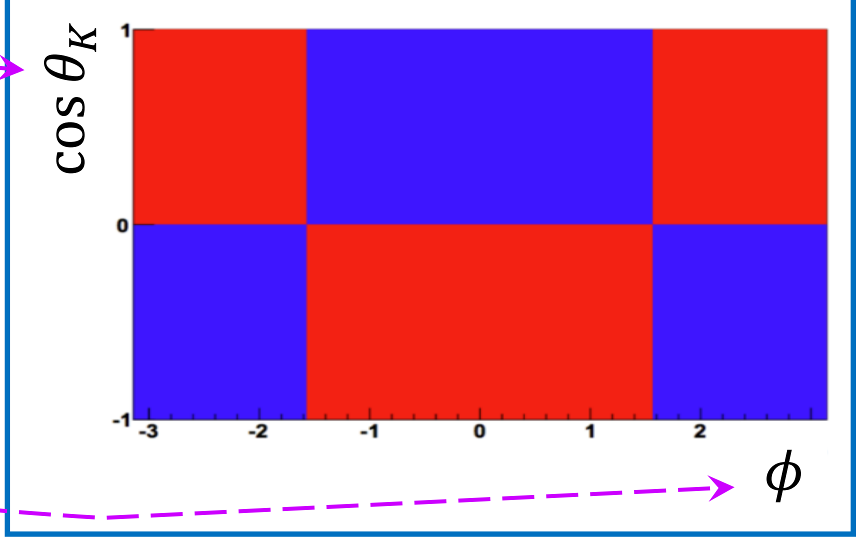




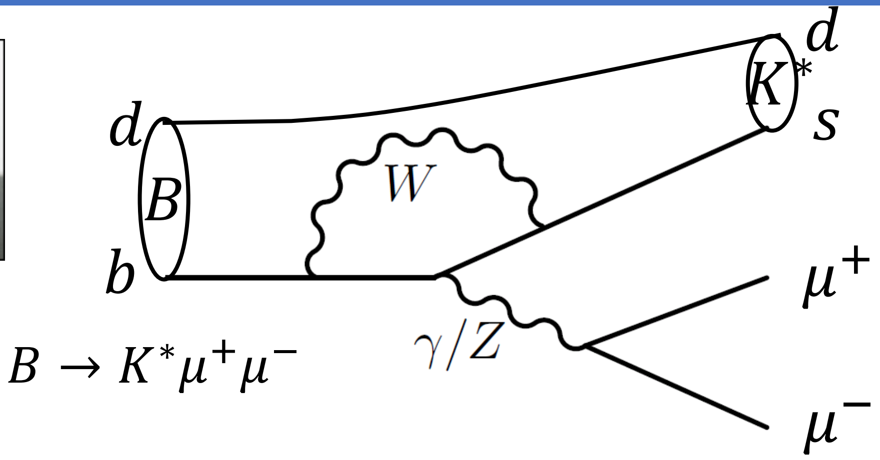
- LHCb: Study angular distribution of the produced particles



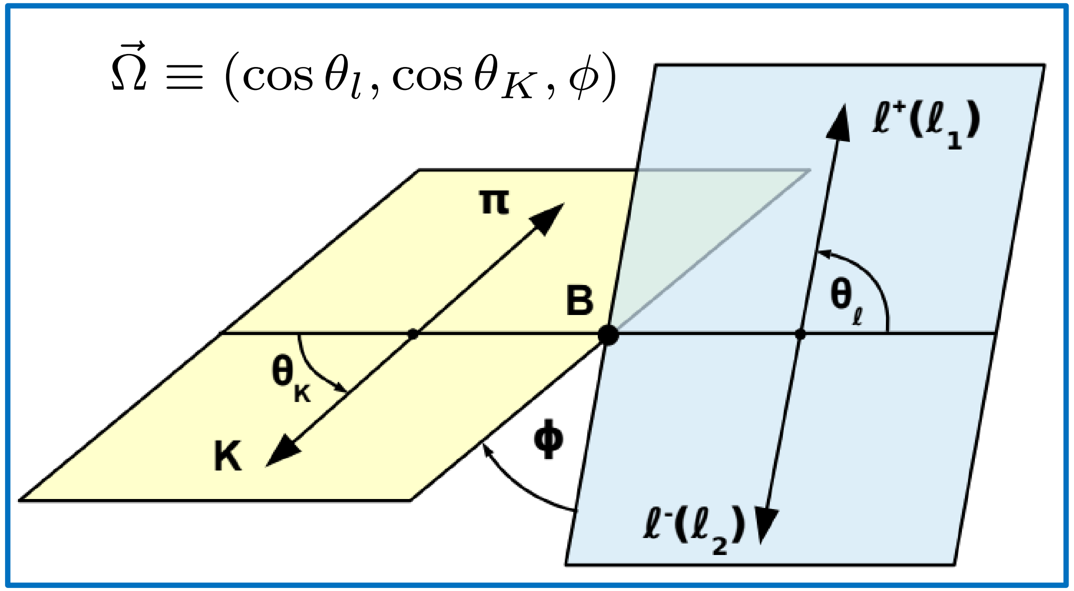
P_5': count blue minus red:

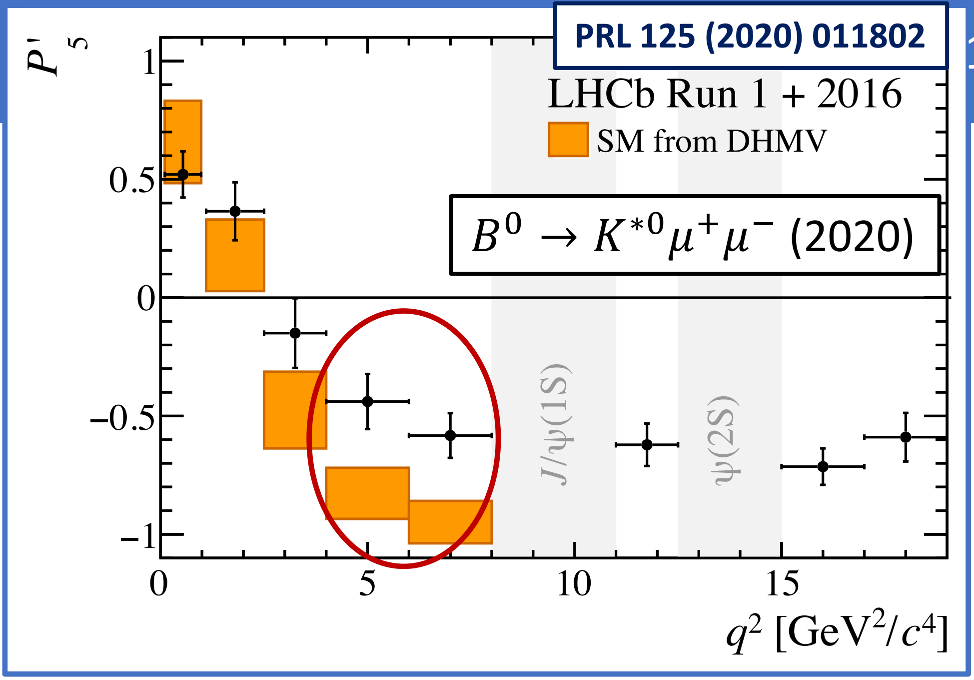


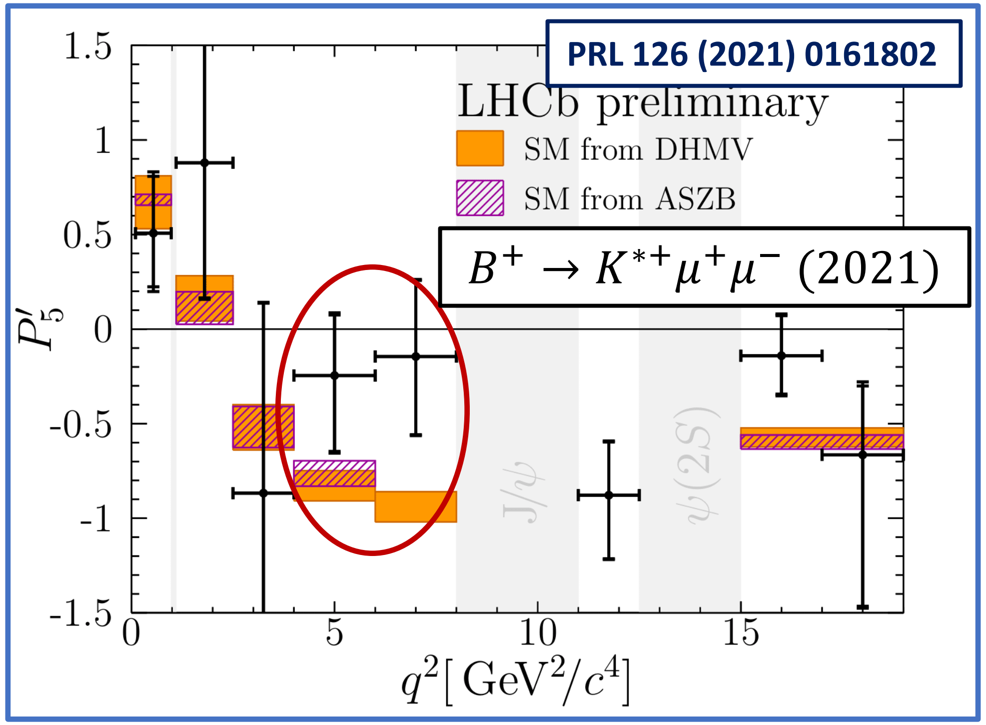
b) ii. Angular observable P'_5



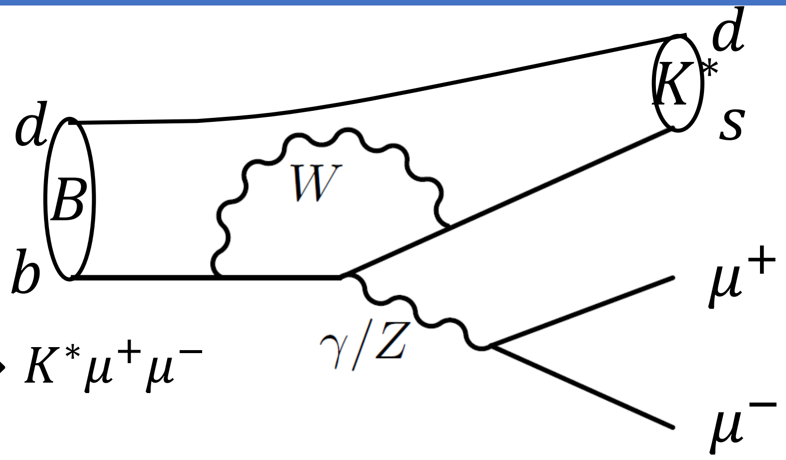
- LHCb: Study angular distribution of the produced particles





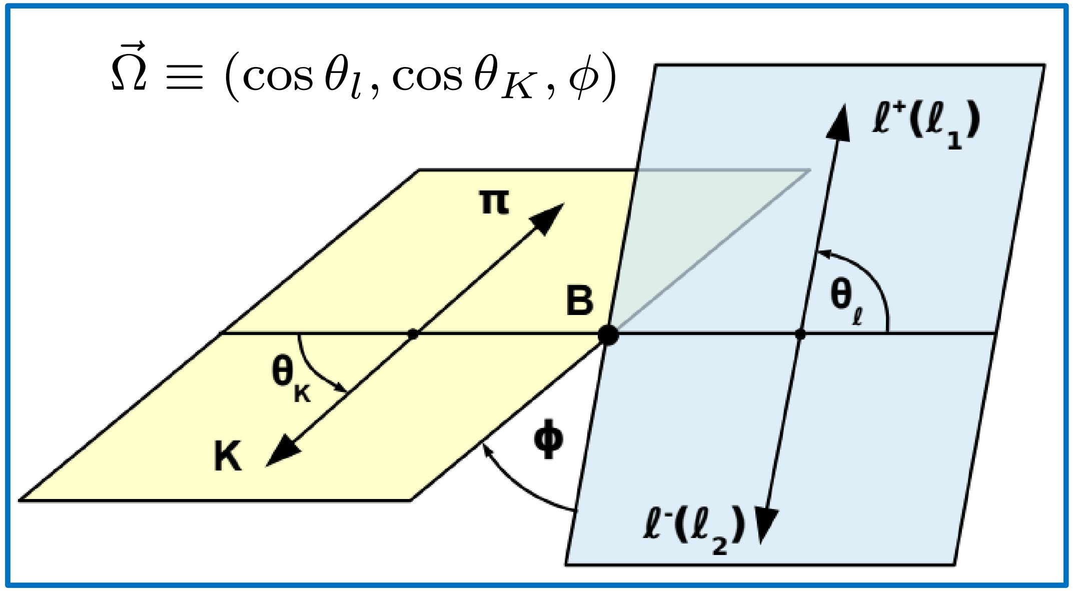


b) ii. Angular observable P_5'



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

- LHCb: Study angular distribution of the produced particles



Recent results:

$B^0 \to K^{*0}\mu^+\mu^-$ with 6 fb^{-1} (~4600 evts)

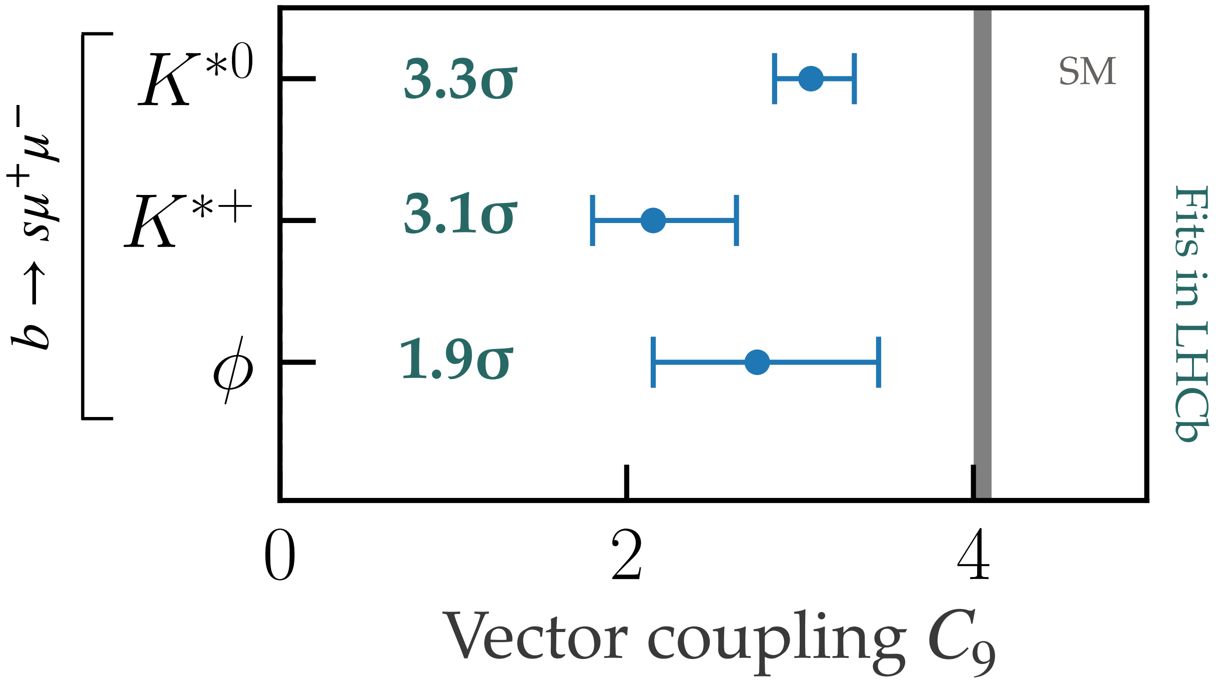
PRL 125 (2020) 011802

$B^+ \to K^{*+}\mu^+\mu^-$ with 9 fb^{-1} (~700 evts)

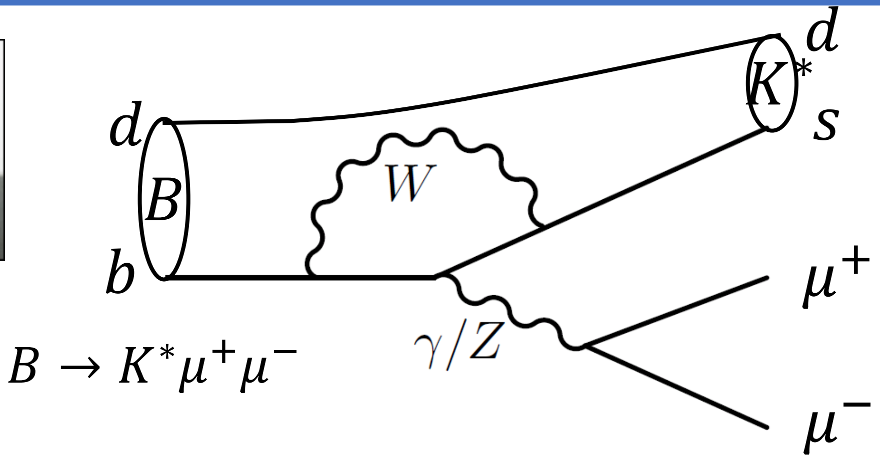
PRL 126 (2021) 161802

$B_s \to \phi\mu^+\mu^-$ with 9 fb^{-1} (~1900 evts)

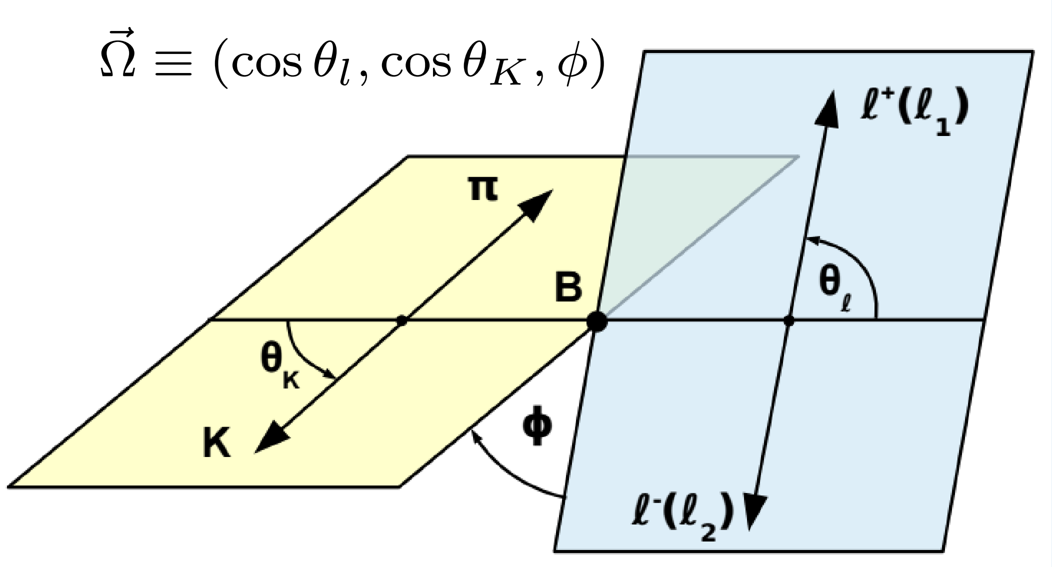
JHEP 11 (2021) 043



b) ii. Angular observable P_5'



- LHCb: Study angular distribution of the produced particles



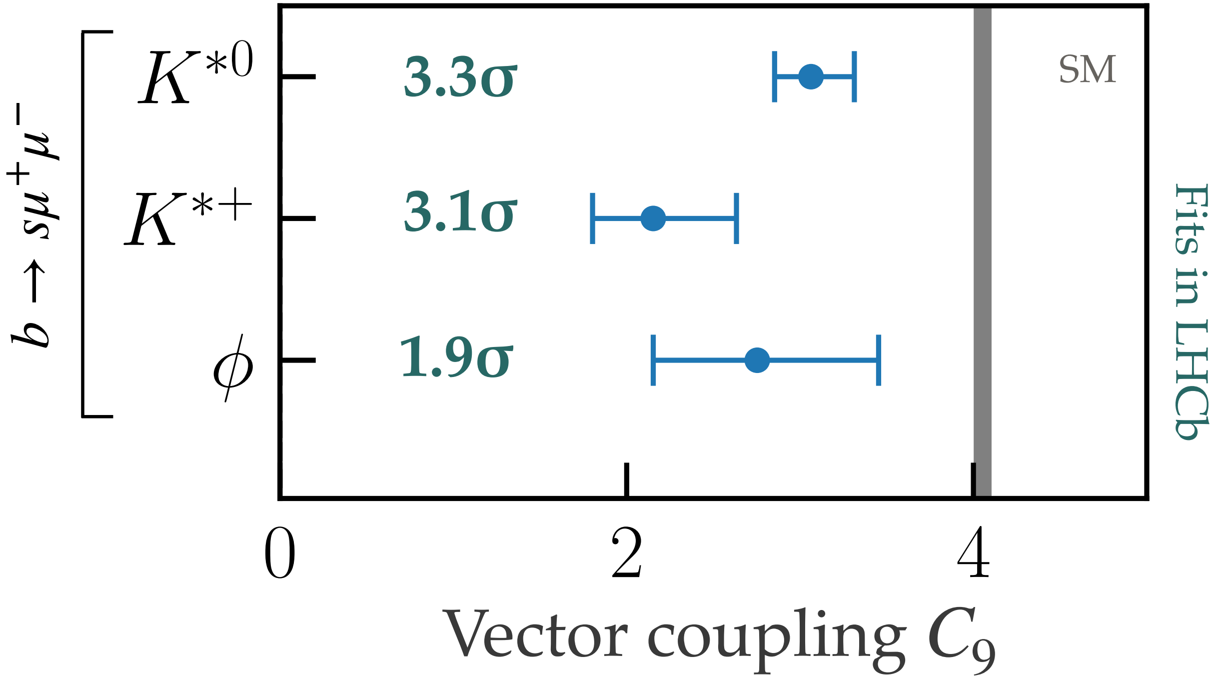
Recent results:

$B^0 \to K^{*0}\mu^+\mu^-$ with 6 fb^{-1} (~4600 evts)

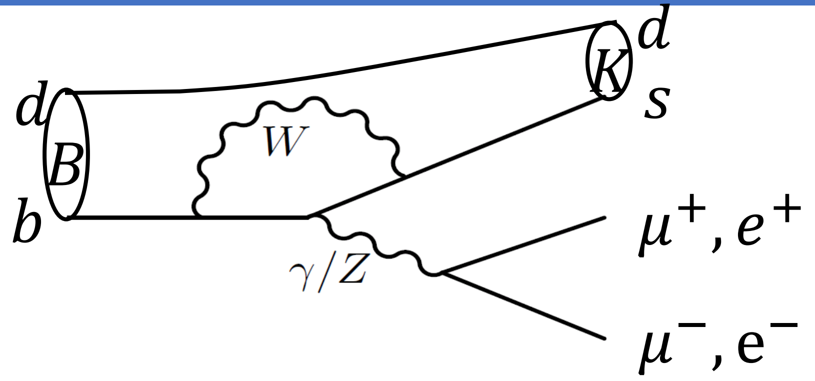
Intruiging coherent and consistent pattern
However, charm loops can mimic shift in $C9$

$B_s \to \phi\mu^+\mu^-$ with 9 fb^{-1} (~1900 evts)

JHEP 11 (2021) 043



b) iii. Universality: R_K and R_{K^*}

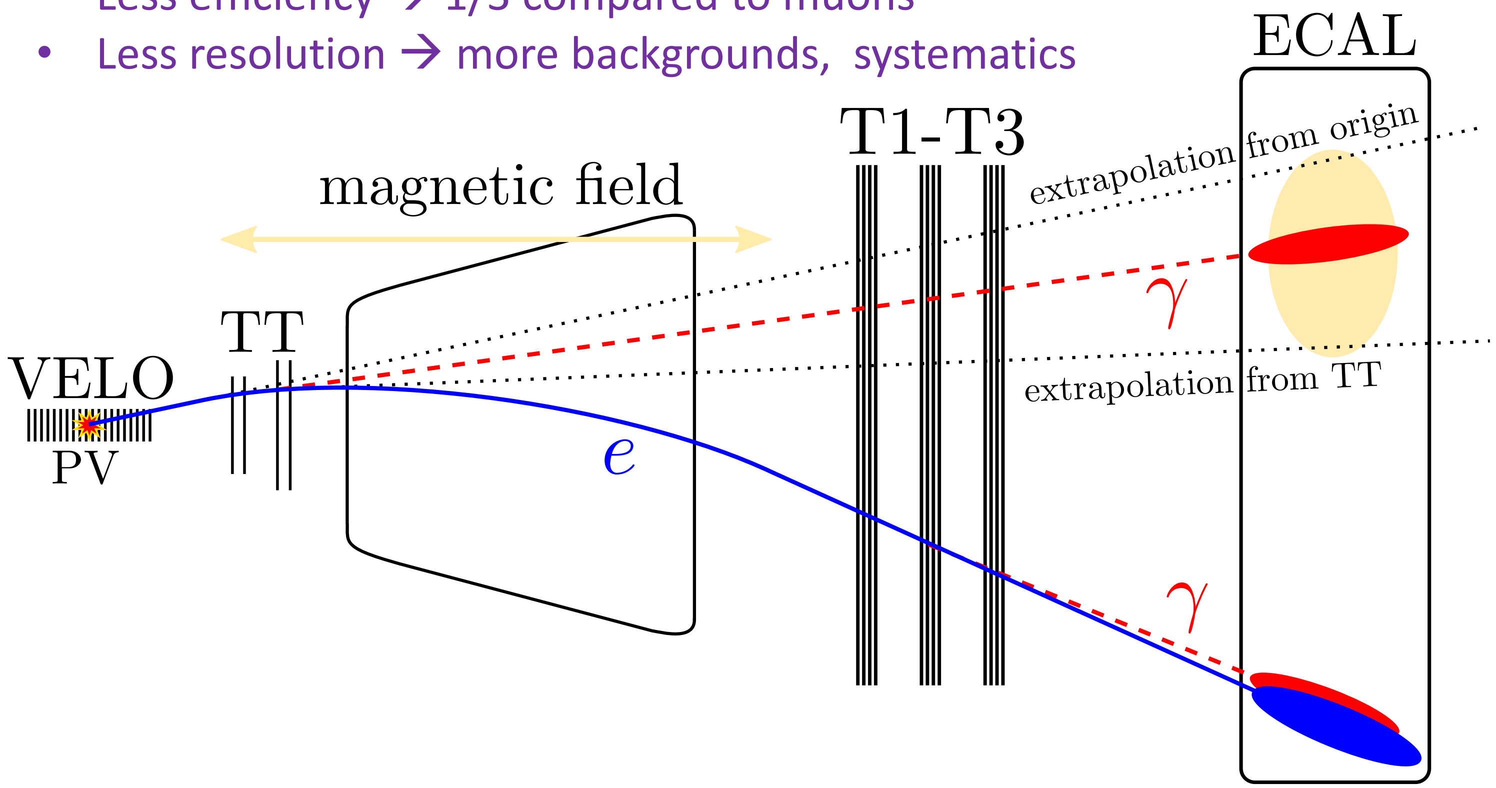


$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)}$$

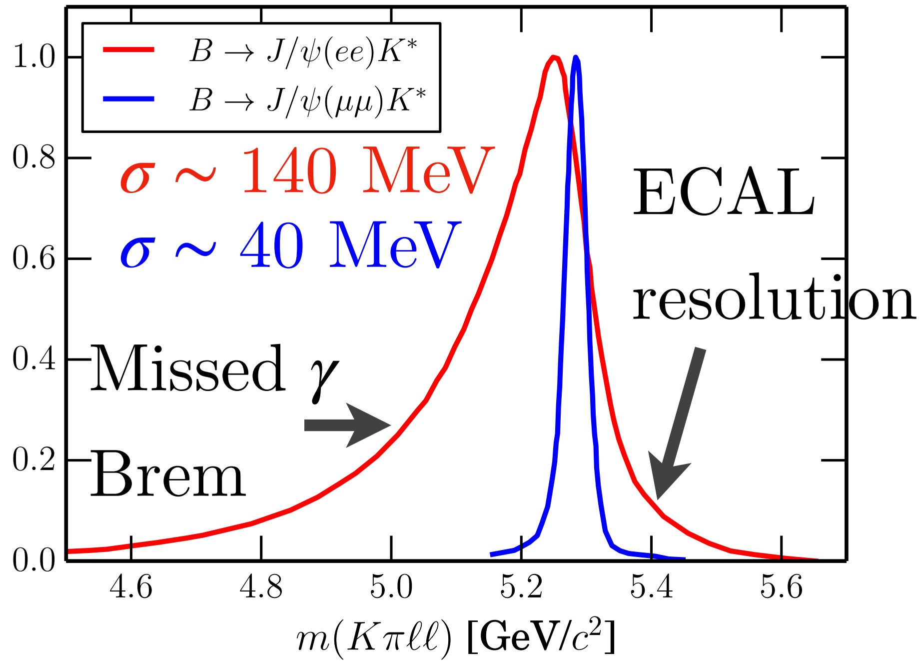
$$R_{K^*} = \frac{BR(B^0 \to K^*\mu^+\mu^-)}{BR(B^0 \to K^*e^+e^-)}$$

Electrons are the limiting factor in the measurement

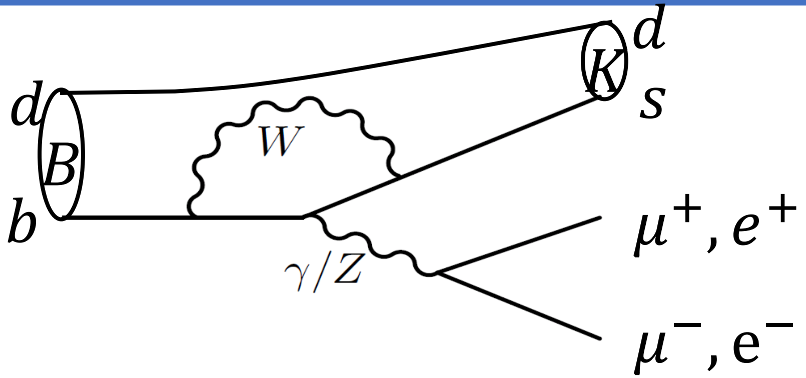
- Less efficiency → 1/3 compared to muons
- Less resolution → more backgrounds, systematics



Mass resolution: muons vs electrons

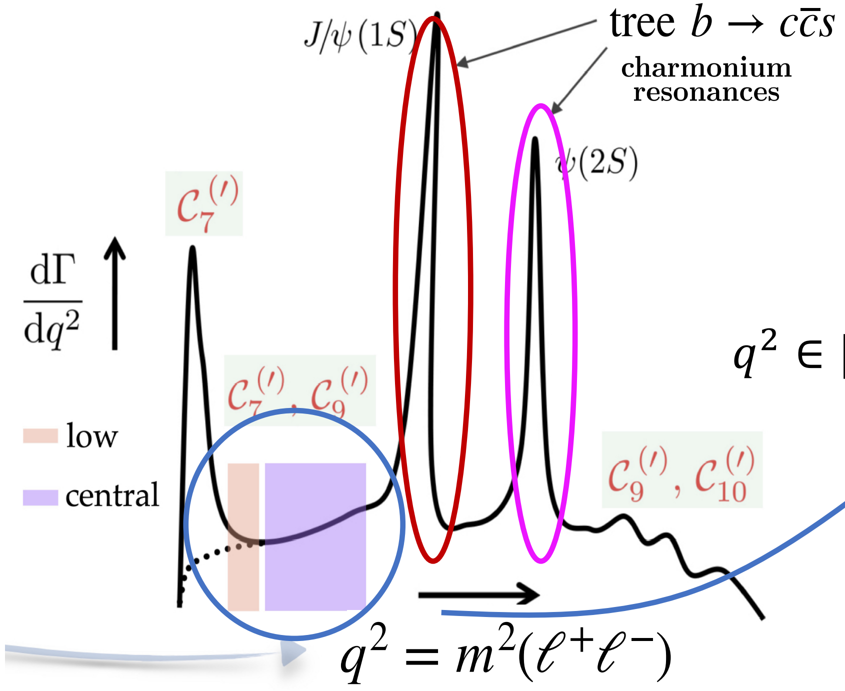


b) iii. Universality: R_K and R_{K^*}

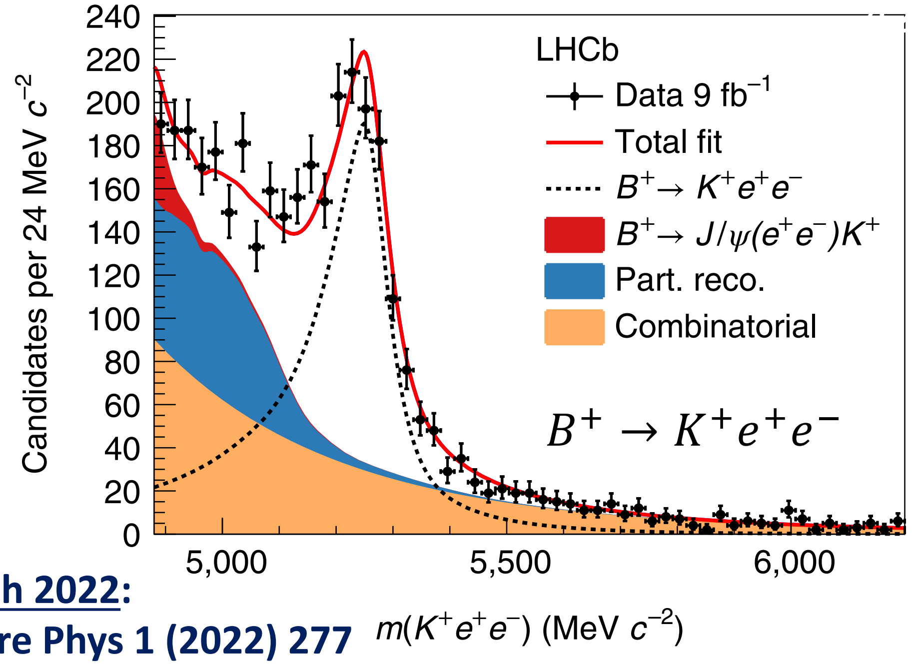


Use resonant modes for control ($R \equiv 1$):

$B \to J/\psi(l^+l^-)K$ and $B \to \psi_{2S}(l^+l^-)$

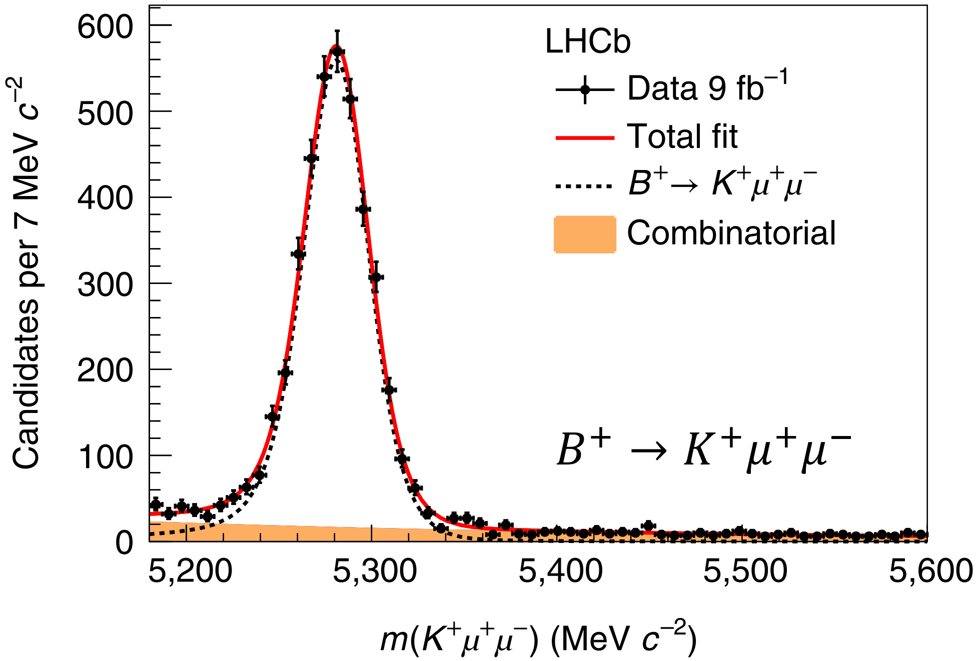


$q^2 \in [1.1\,,\,6]\ \mathrm{GeV}^2/c^4$

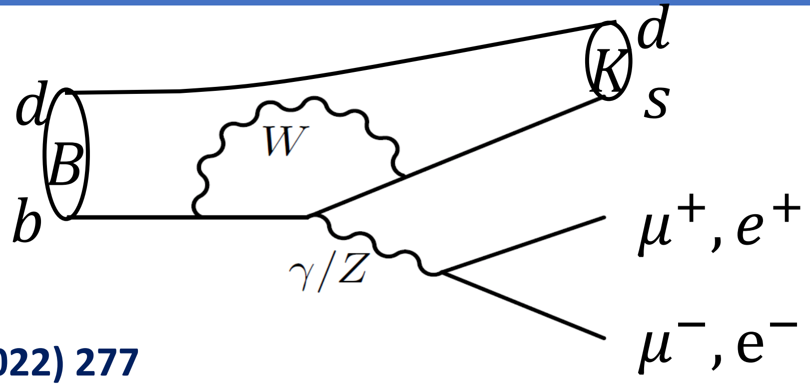


March 2022:

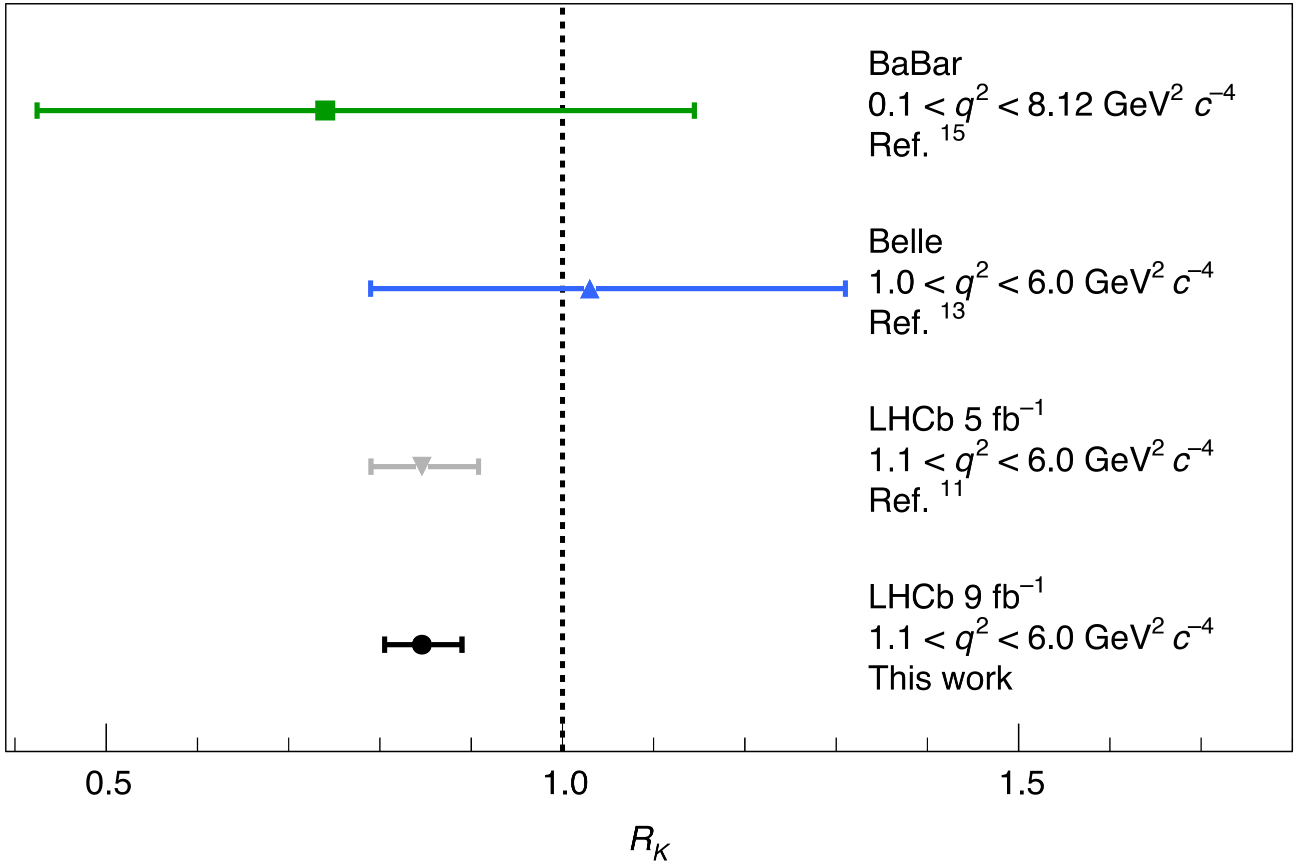
Nature Phys 1 (2022) 277

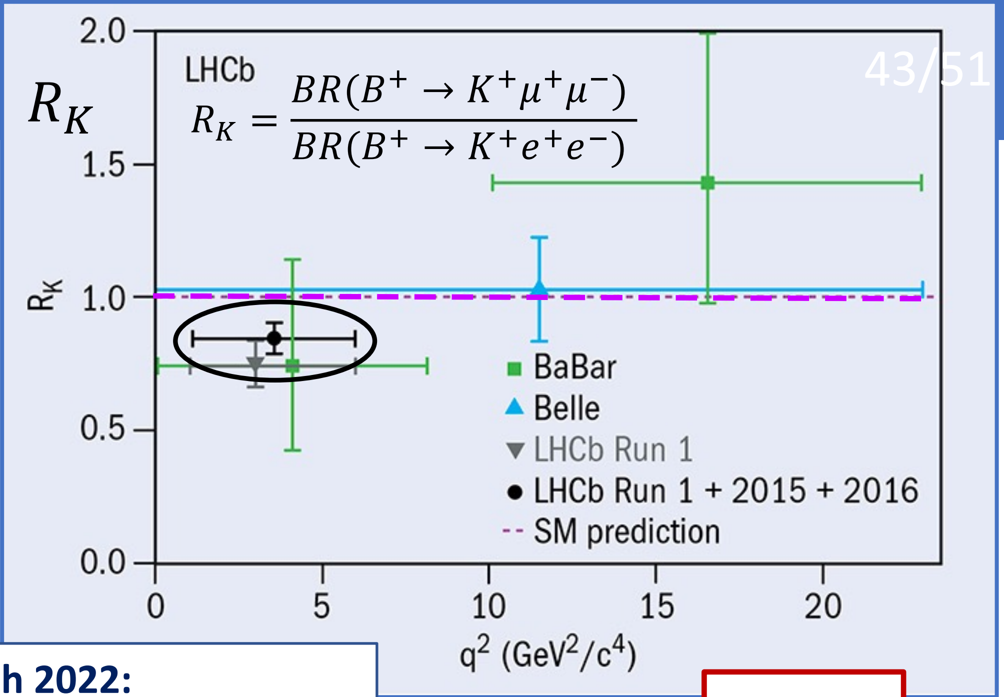


b) iii. Universality: R_K and R_{K^*}



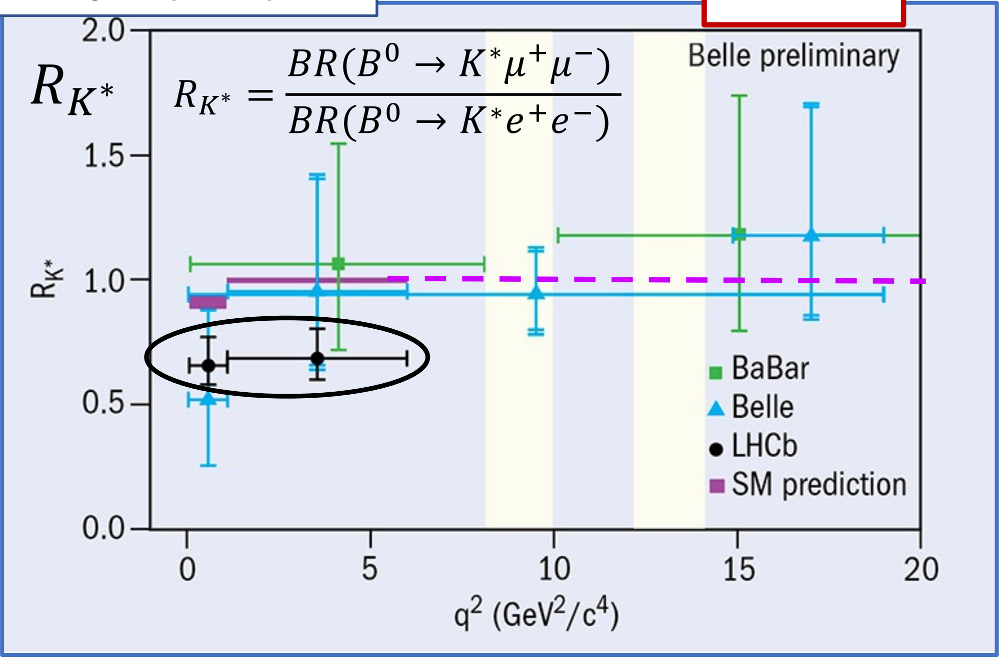
March 2022:
Nature Phys 1 (2022) 277



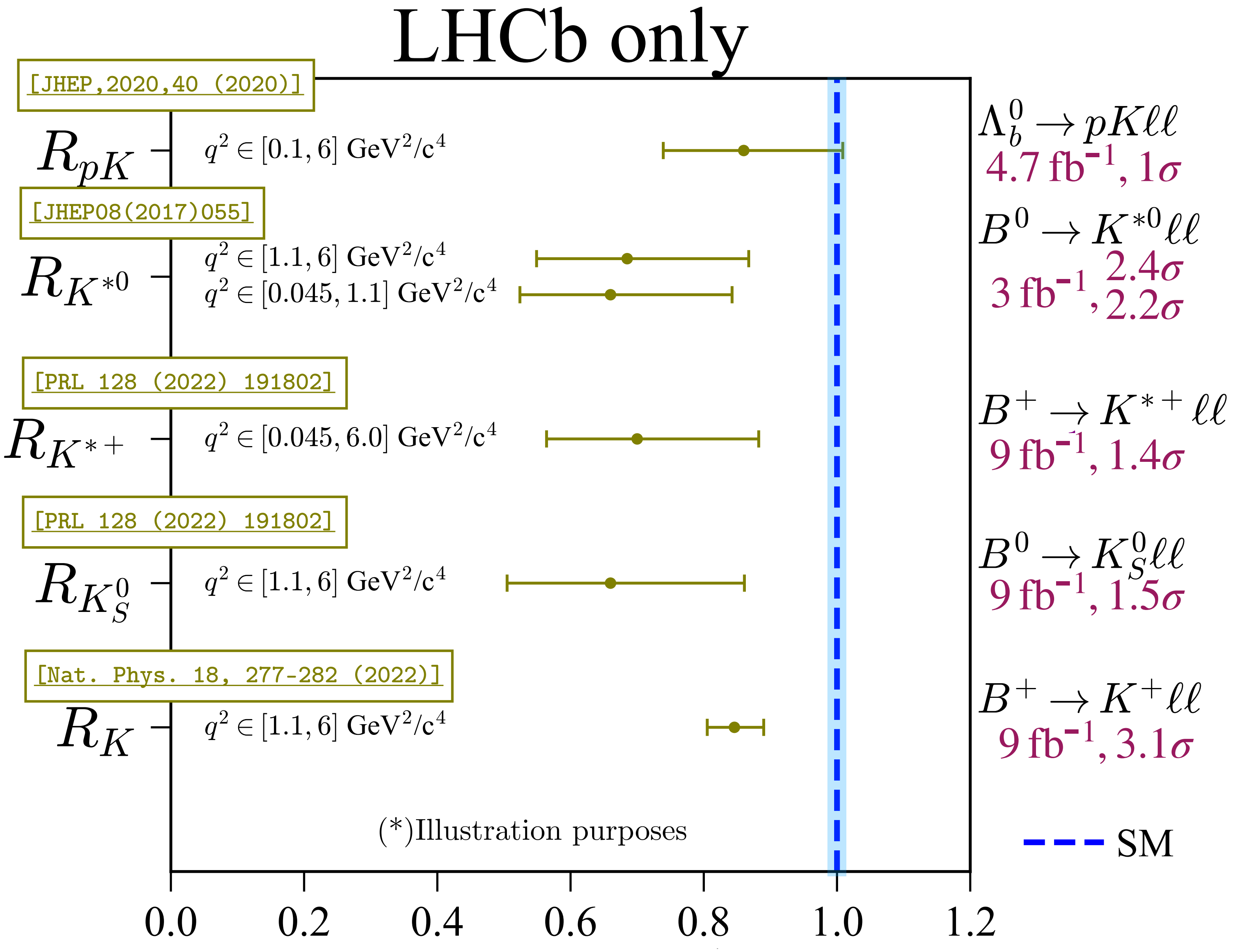


March 2022:
Nature Phys 1 (2022) 277

~ 3 σ



b) iii. Universality: R_K and R_{K^*}

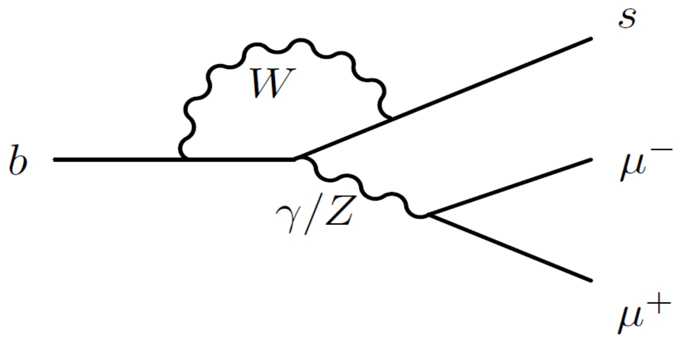


Situation Spring 2022

Together with the P5' and branching ratios: "cautious excitement"

Update Dec 2022 "R_X": simultaneous R_K and R_{K^*}...

b) iii. Universality: R_X



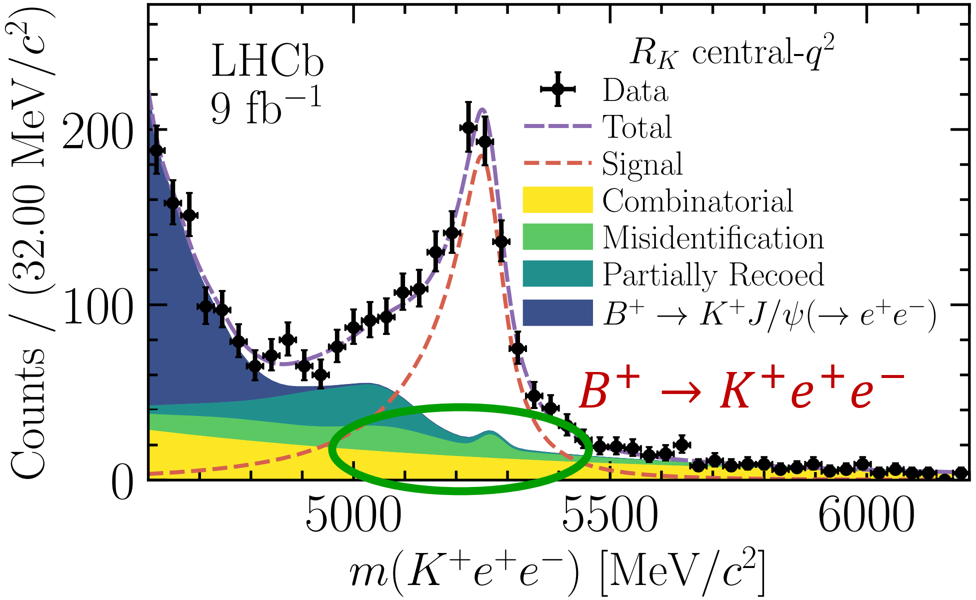
$$R_X = \frac{\mathcal{B}(b \to s\mu^+\mu^-)}{\mathcal{B}(b \to s e^+e^-)}$$

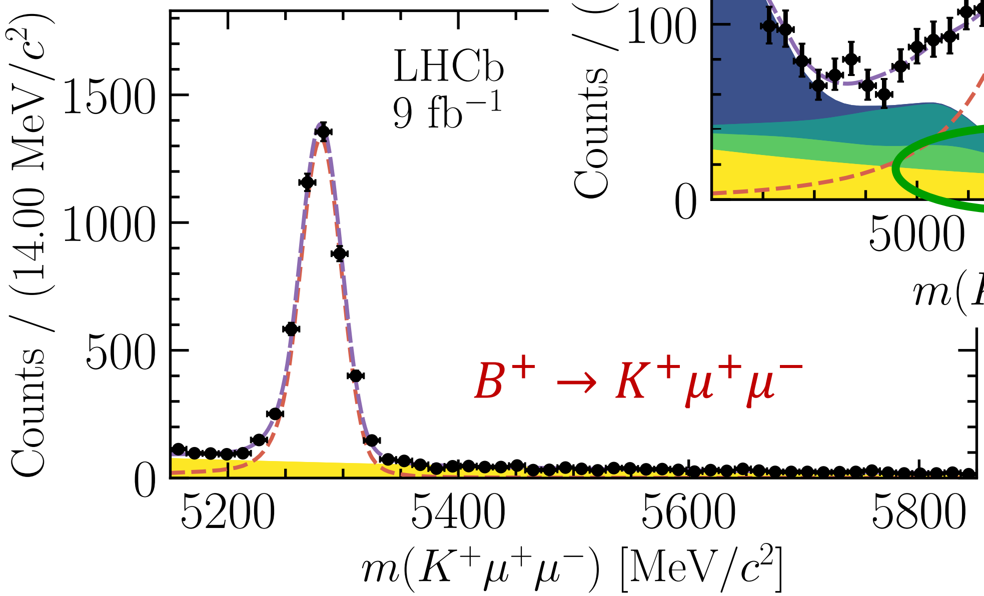
Dec 2022: Simultaneous R_{K^*} and R_K

- New inclusive data-driven mis-ID treatment for $\pi \to e$ and K$\to e$ (affects electron mode)
  - Invert PID electron to pions and kaons
- Low $q^2 \in [0.0, 1.1]\ \mathrm{GeV}^2/c^4$
- Central $q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2/c^4$

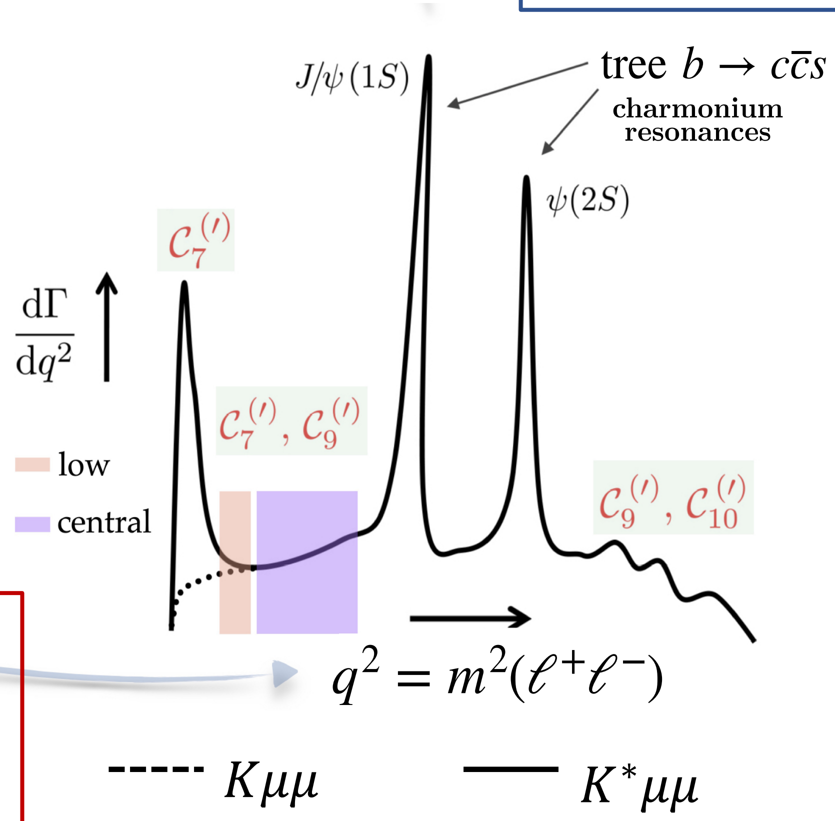
arXiv: 2212.09152v1
arXiv: 2212.09153

Eg.: $B^+ \to K^+ l^+ l^-$
central q^2 bin

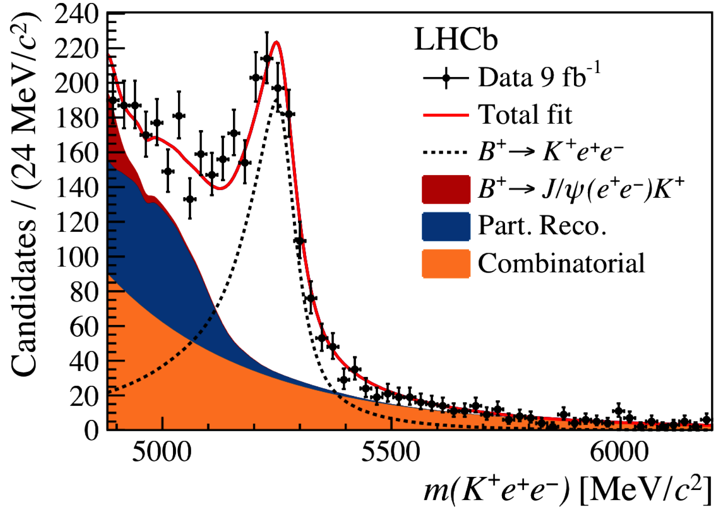




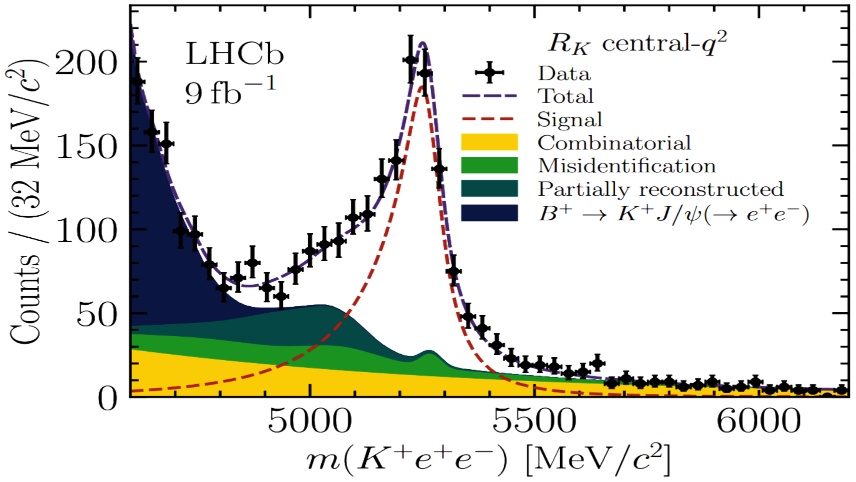
μ –mode:
consistent with before
e – mode:
mis-ID background found



- R_K March 2022: $m(K^+e^+e^-)$

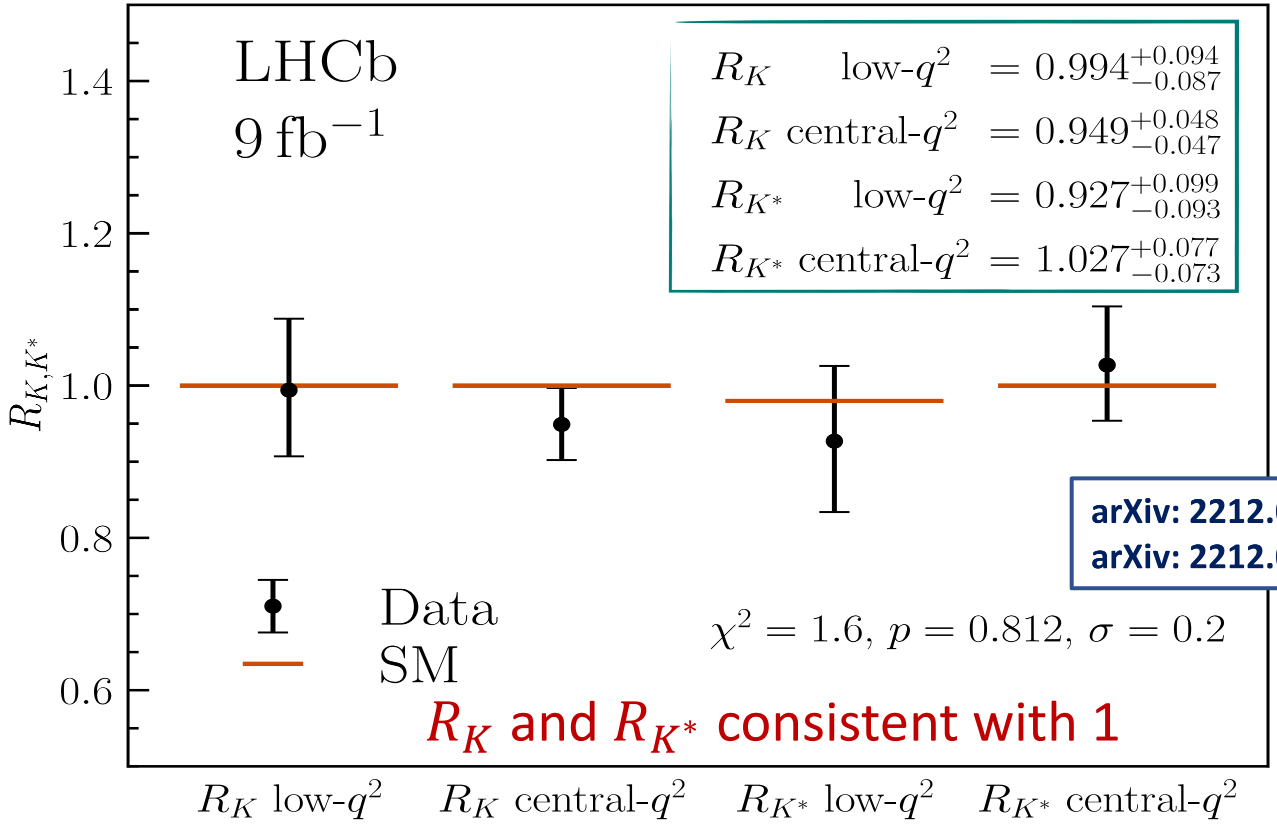


- R_X Dec 2022: $m(K^+e^+e^-)$



Mis-ID rate from $D^{*-} \to (K\pi)\pi$: electron mode reduced -0.1

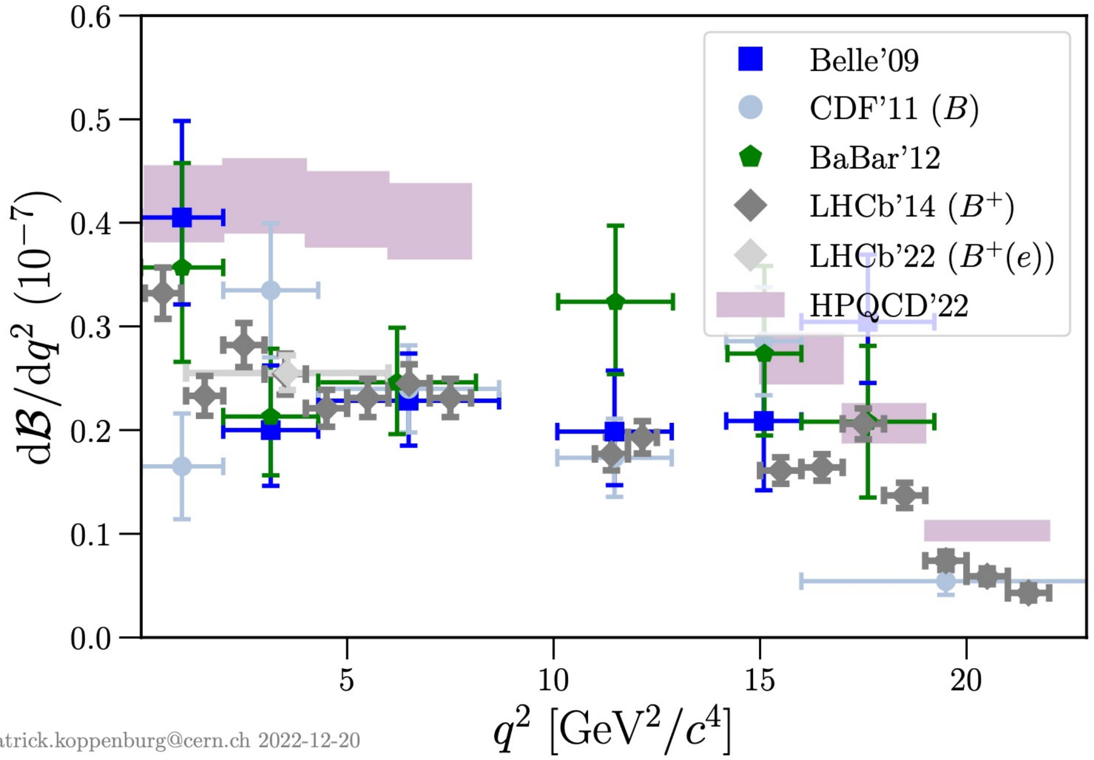
	Sample	$\pi \to e$	$K \to e$
(11+12)	Run 1	1.78 (1.70) %	0.69 (1.24) %
(15+16)	Run 2p1	0.83 (1.51) %	0.18 (1.25) %
(17+18)	Run 2p2	0.80 (1.50) %	0.16 (1.23) %



arXiv: 2212.09152v1
arXiv: 2212.09153

Anomaly situation

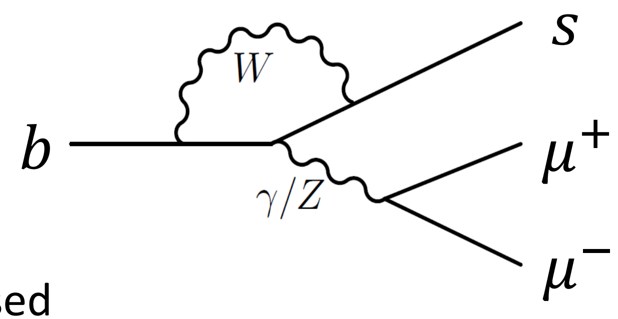
- Excitement about muons
  - Branching ratios low → theory uncertainty?
  - Angular observables deviate → cc-bar loop?
  - Universality ratio → electrons changed



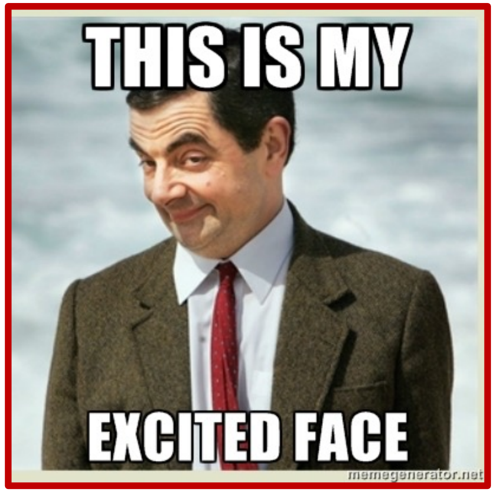
[PRD 86 (2012) 032012], [PRL 103 (2009) 171801], [PRL 107 (2011) 201802], [JHEP 06 (2014) 133], [arXiv:2212.09153], [Parrot, Bouchard, Davies]

- Overall anomaly statues
  - Muons did not change
  - Ball partly back to theory community
  - More to come on taus


Suppressed penguin ≠ Depressed penguin

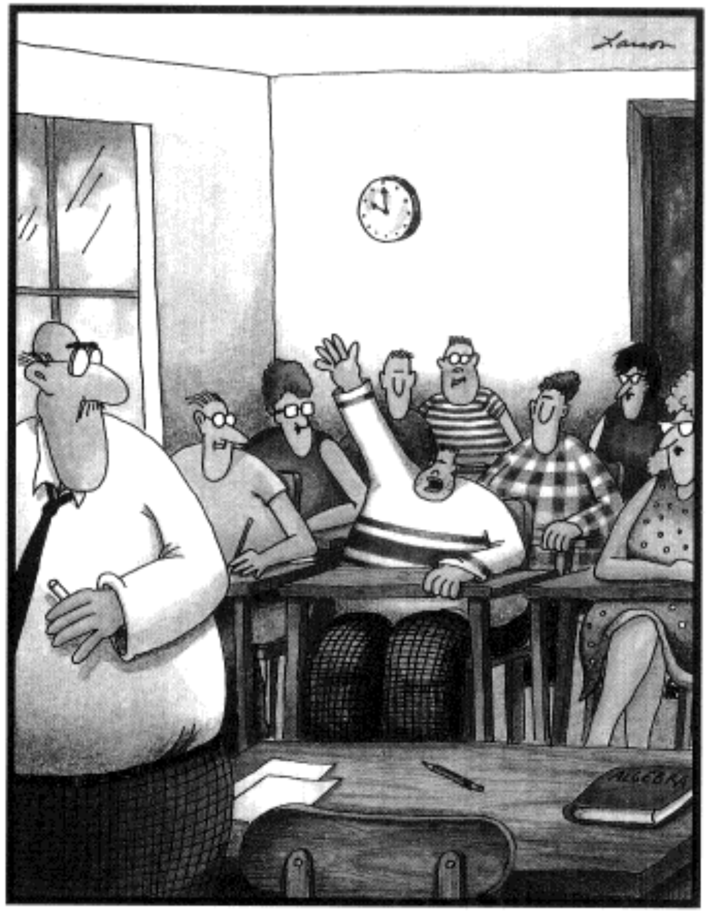


Me: March 2022



Me: Dec 2022

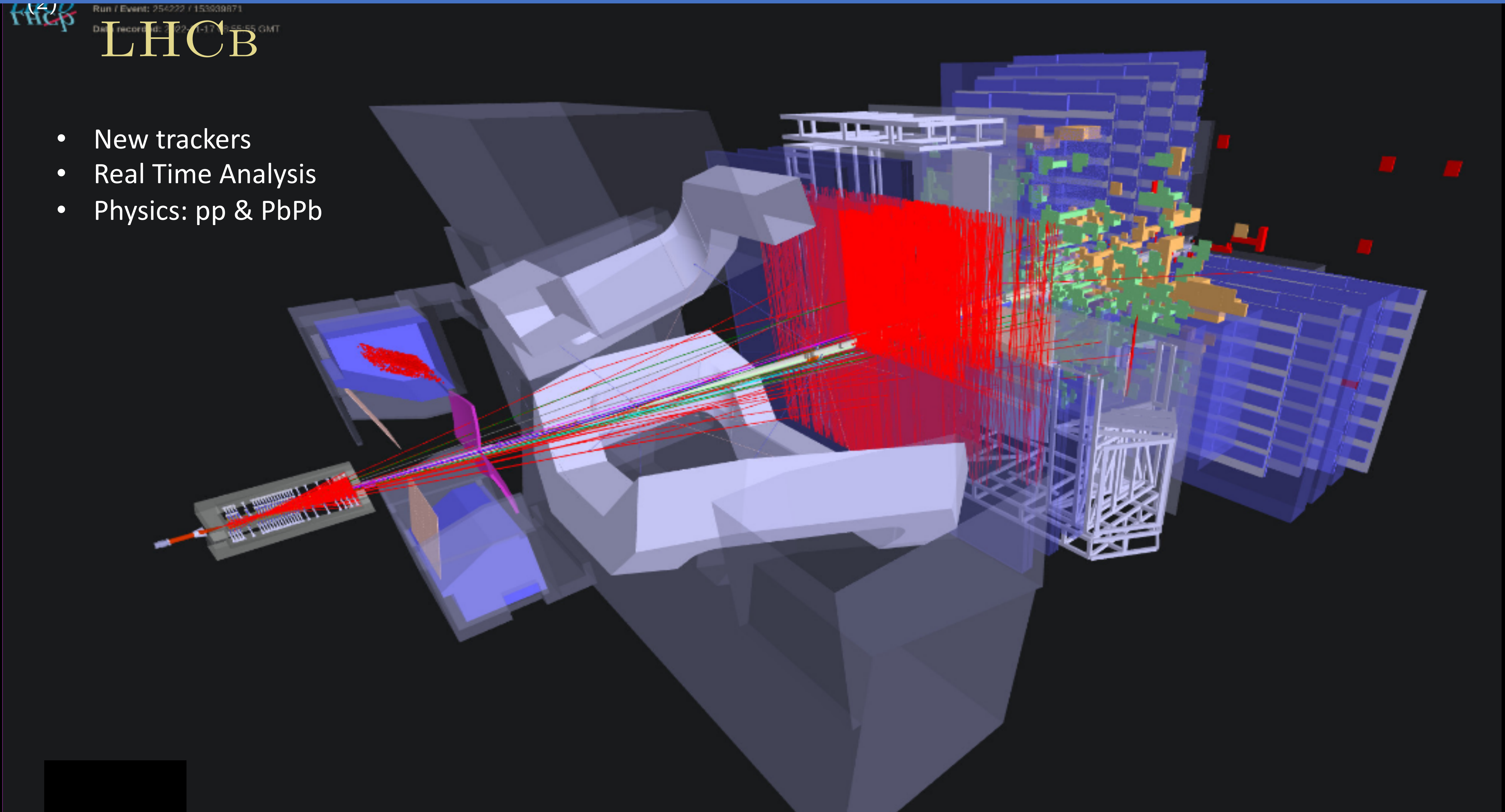
1) Three generations and the origin of CP violation
2) The amount of CP violation in CKM
3) Measurements of CP violation with LHCb
4) B-decays and Flavour Anomalies
5) **Outlook/conclusion**



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

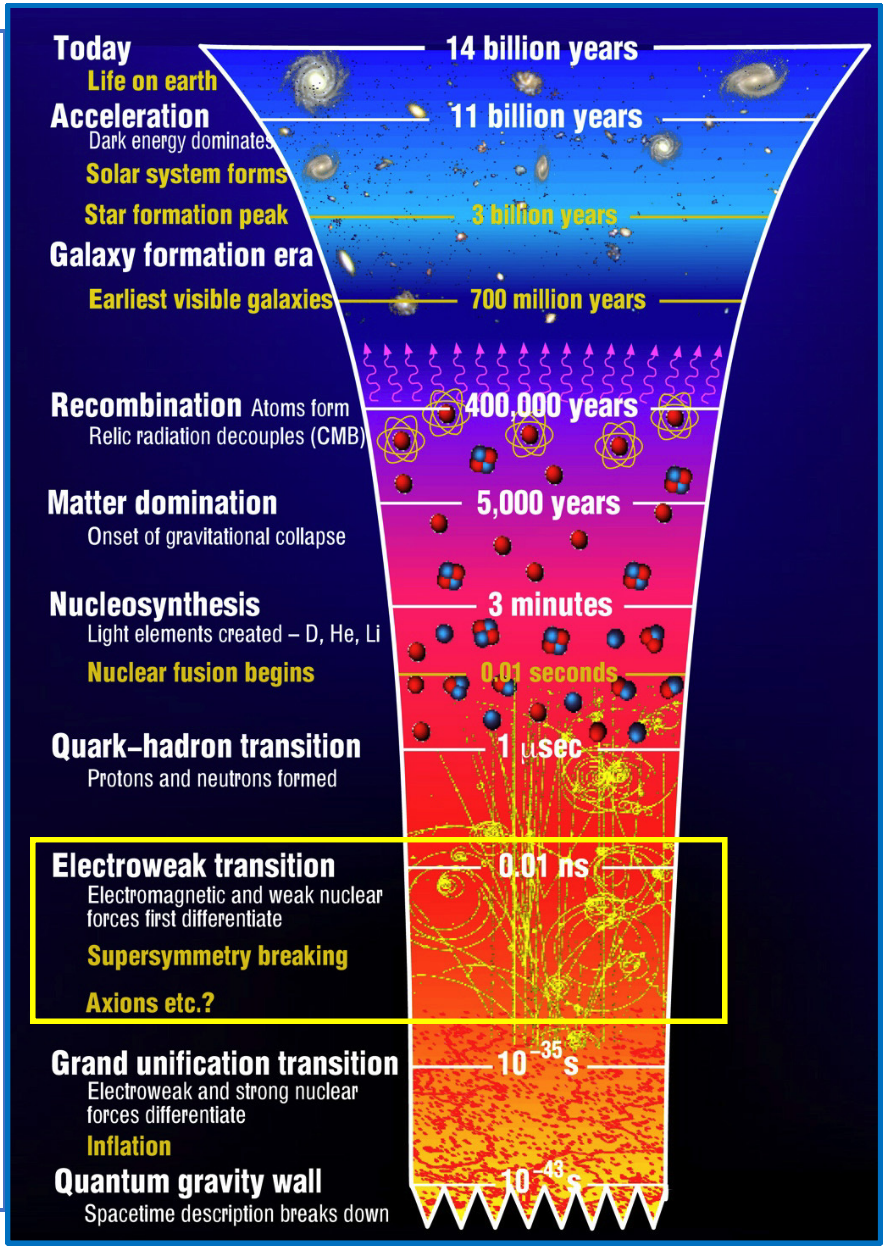
LHCb in Run-3 is a largely new detector

- New trackers
- Real Time Analysis
- Physics: pp & PbPb

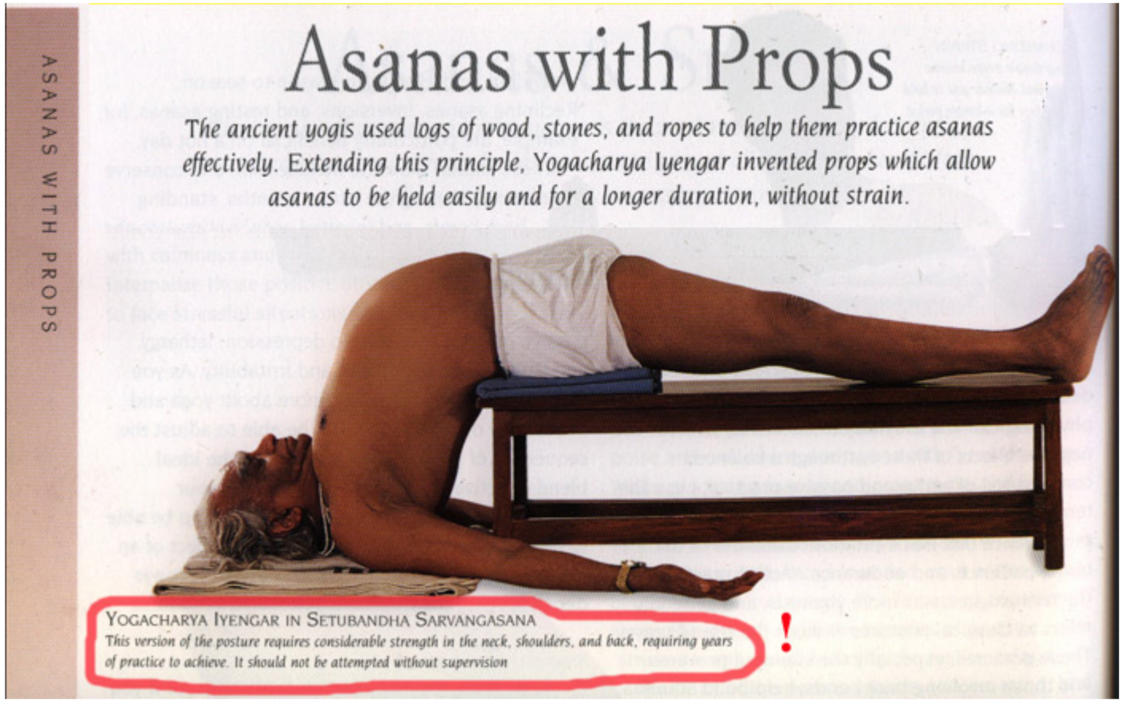


Conclusions

- Flavour puzzle:
  - Origin of generation structure and matter anti-matter asymmetry is still unknown.
- The CKM paradigm for CP violation still stands
  - Experimental tests getting more and more precise
- B-decays are a sensitive tool for searches for BSM quantum fluctuations
  - Semileptonics with taus are intruiging: more to come
  - Rare decays show deviations from theory for muons; but electron/muon universality ratio is consistent with unity.
- Looking forward to more results, in particular run-3



Universality



Extra Slides