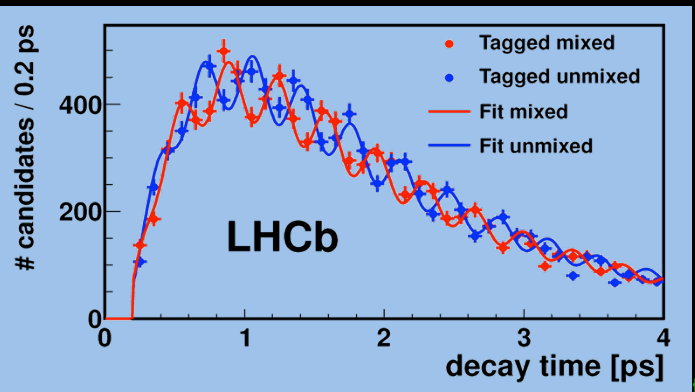
B-Flavour Physics in LHCb



Marcel Merk
On behalf of the LHCb collaboration

54th International Winter Meeting on Nuclear Physics
Bormio, Jan 25-29, 2016

Outline

1. Flavour Physics

2. The LHCb Experiment

3. CP Violation Measurements
   a) CP Violation in B-mixing: a_{sl}^{d} and a_{sl}^{s}

   b) Direct CP Violation: CKM angle γ

   c) Time dependent CP violation: CKM angles ϕ_d and ϕ_s

4. B Decay Rates
   a) Very Rare Decays: $B \rightarrow \mu\mu$

   b) Rare Decays: $b \rightarrow s$ quark transition

   c) Lepton Flavour Universality tests

5. Outlook

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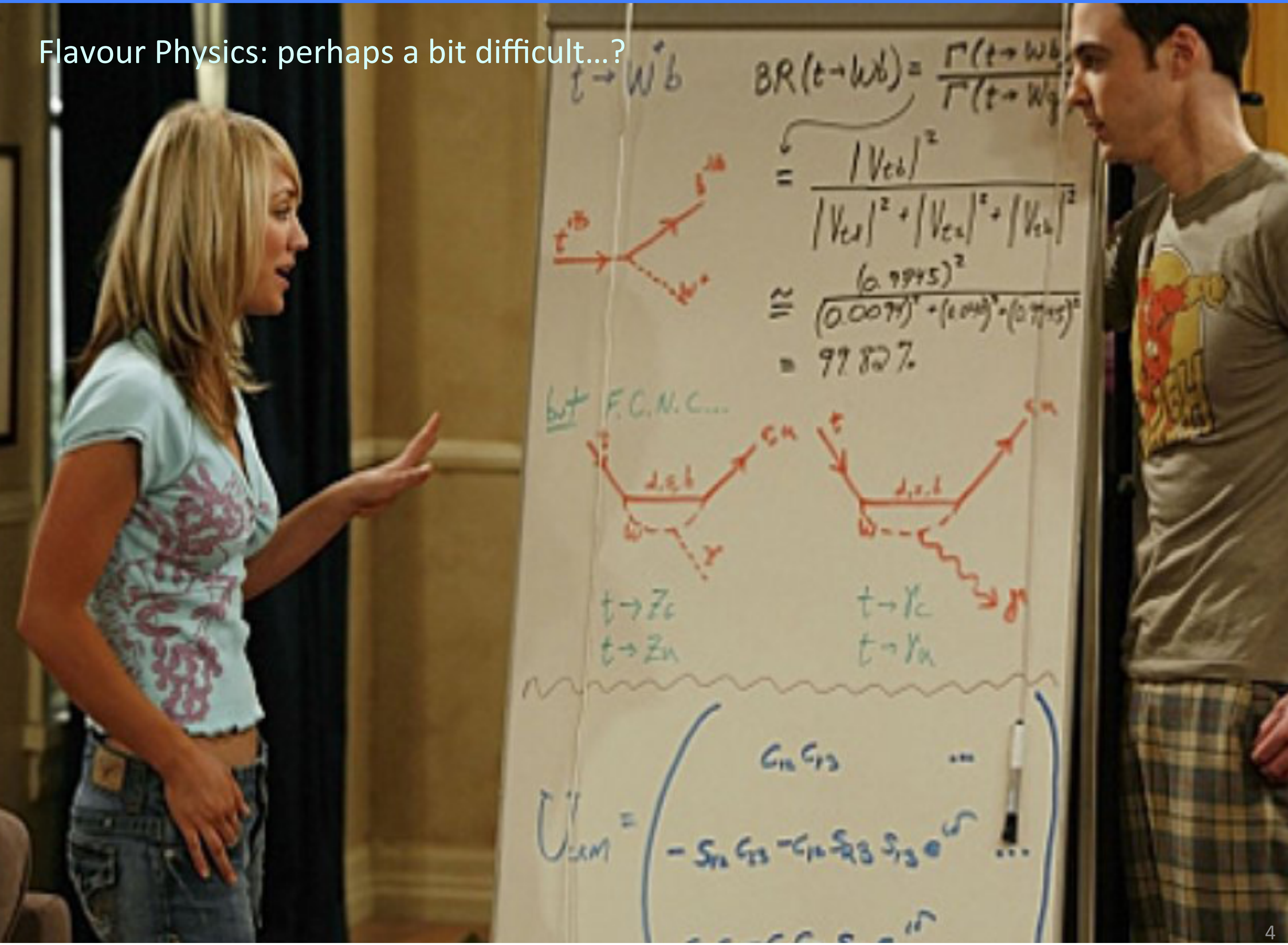
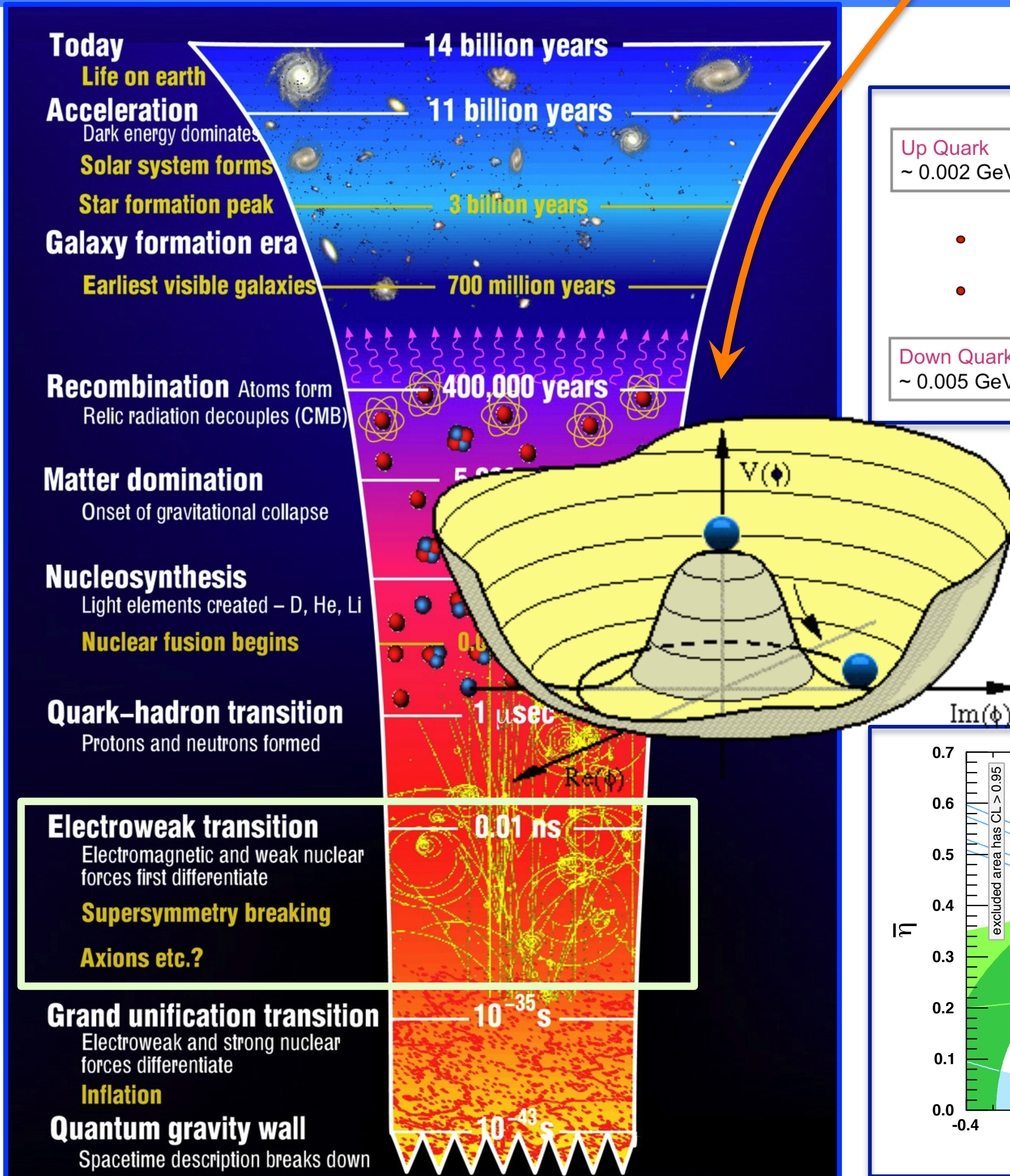
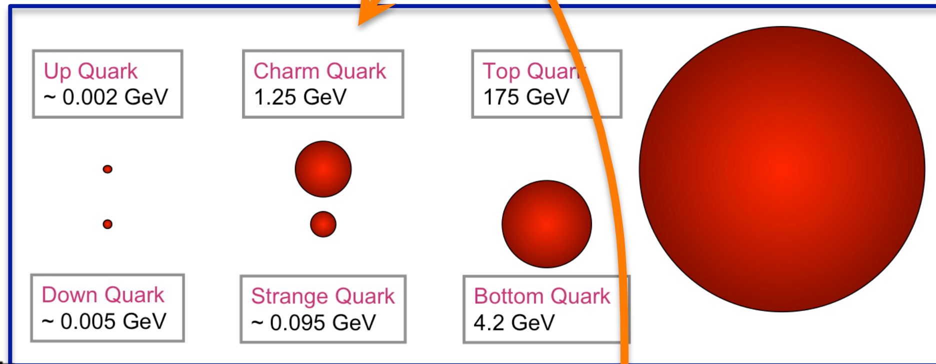
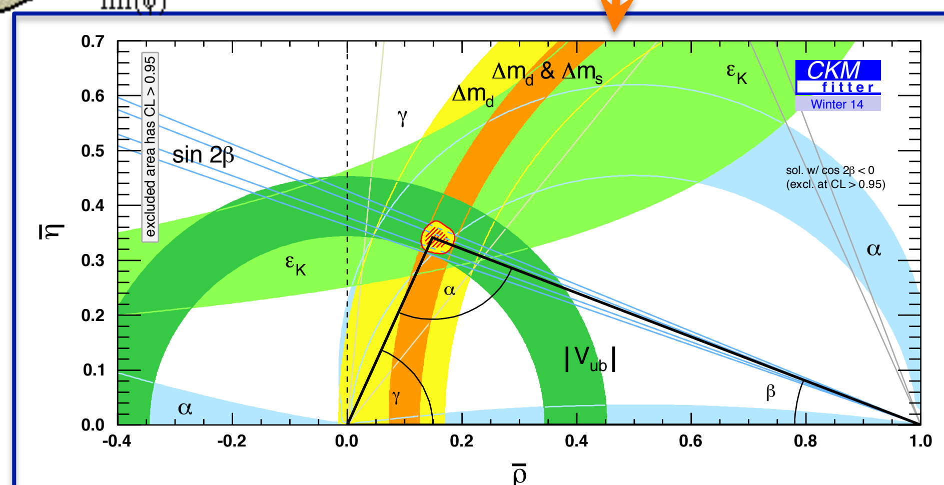
Flavour Physics: perhaps a bit difficult…?



$$\mathcal{L}_{EW} = i\overline{\psi}_L \gamma_\mu D^\mu \psi_L + V(\phi) + Y_{ij}\left(\overline{\psi}^i_L \phi\right)\psi^j_R$$







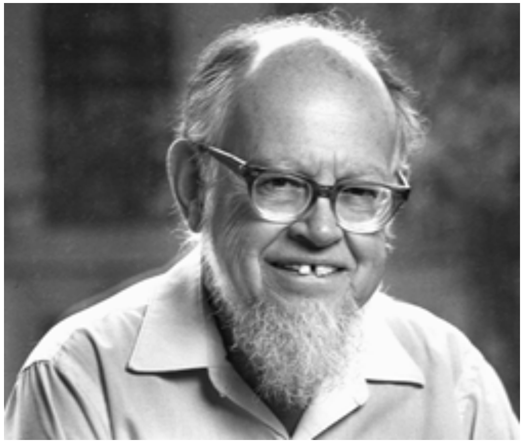
Mass vs Weak Eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- The Higgs interaction $Y_{ij}\,(\overline{\psi}_L \phi)\,\psi_R$ and the W interaction $g\,\overline{\psi}_L\,(\gamma^\mu W_\mu)\,\psi_L$ do not agree on the quark eigenstates.
  - Relation is the CKM matrix V_{CKM},
  - Leads to three mixing angles and one free imaginary CP phase in the CKM.
- Quark CP violation emerged together with mass.

The CKM Matrix V_{CKM}

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



Wolfenstein parametrization: V_{CKM}

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

From unitarity ($V_{CKM} V^{\dagger}_{CKM}=1$)
CKM has four free parameters:
- 3 real: λ (≈ 0.22) , A (≈ 1), ρ
- 1 imaginary: $i\eta$

Particle → Antiparticle: $V_{ij} \rightarrow V_{ij}^*$
=> 1 CP Violating phase

The CKM Matrix V_{CKM}

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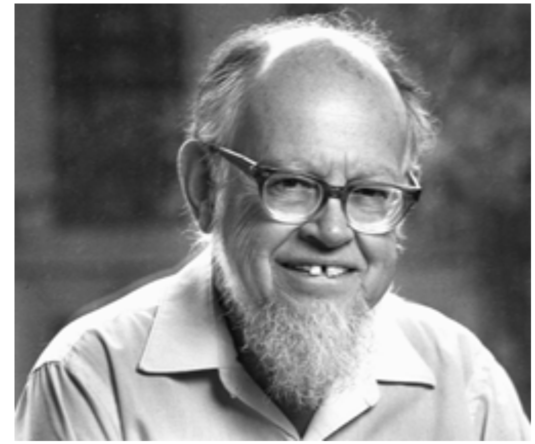

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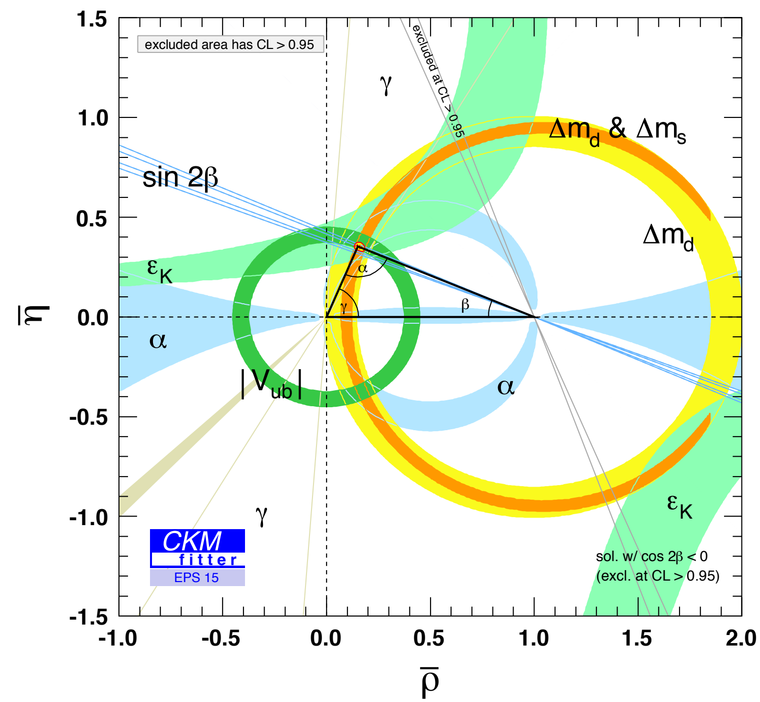

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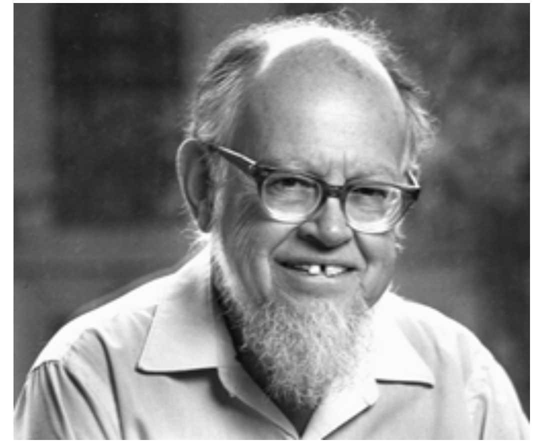
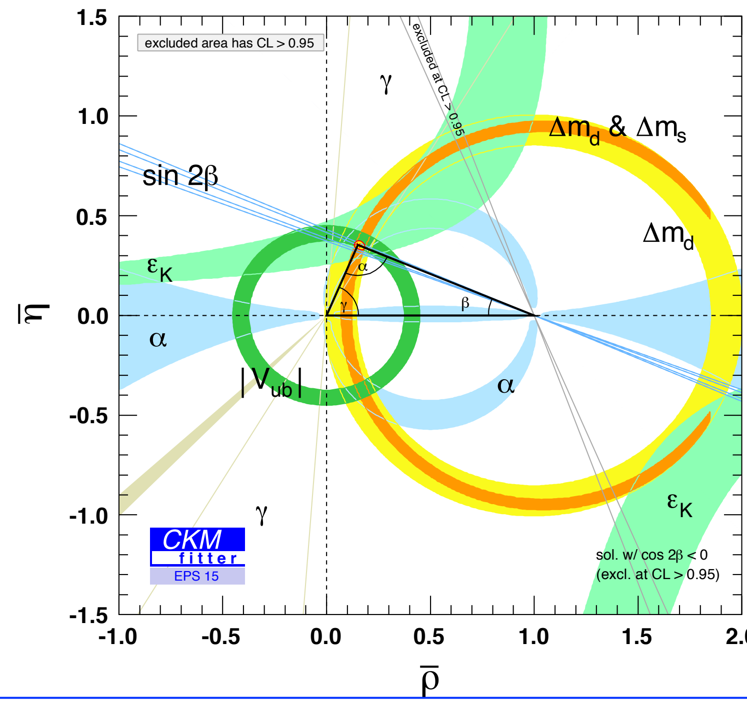


Wolfenstein parametrization: V_{CKM}

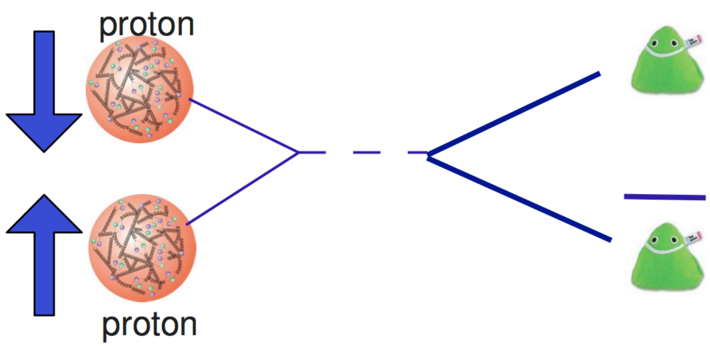
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$



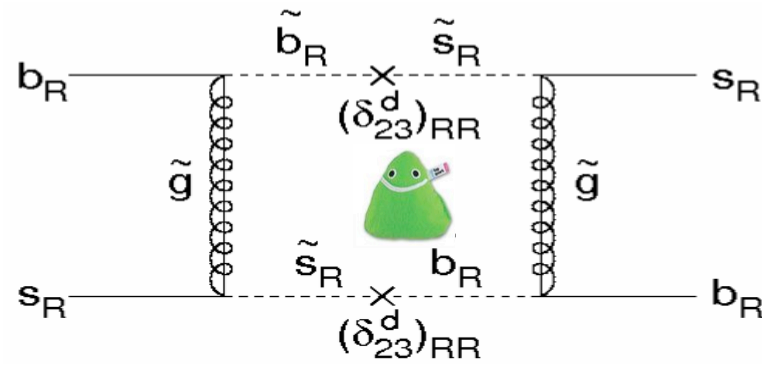
Can flavour physics explain the matter - antimatter asymmetry? ➔ Requires New Physics!

Direct vs Indirect search

The ***absolute*** energy frontier:



The ***virtual*** energy frontier:



- Direct observation:
  - Produce particles on-shell and detect decay products
  - More intuitive(?), "really" produced
  - Limited by collision energy

- Indirect observation:
  - Less intuitive(?), quantum level
  - Limited by precision, not by collision energy
  - CP observables sensitive to imaginary couplings

- Indirect observations in the past:
  - Kaon decay $K^0 \rightarrow \mu\mu$ hints at c-quark via GIM in 1970 (J/Ψ produced in 1974)
  - 3rd quark family predicted 1972 to explain CP violation (b produced in 1977, t in 1994)
  - Neutral current discovered in neutrino experiment in 1973 (Z-boson produced in 1983)
  - $B\bar{B}$ mixing (1987) hints at large top mass, LEP predicts top mass (1990) (top in 1994)

Indirect evidence for top mass and charm quark

$K^0 \rightarrow \mu\mu$ pointed to the **charm** quark

GIM, Phys.Rev.D2,1285,1970

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

…

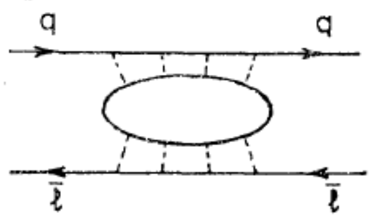
splitting, beginning at order $G(G\Lambda^2)$, as well as contributions to such unobserved decay modes as $K_2 \rightarrow \mu^+ + \mu^-$, $K^+ \rightarrow \pi^+ + l + \bar{l}$, etc., involving neutral lepton

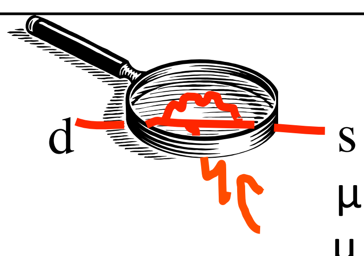
…

We wish to propose a simple model in which the divergences are properly ordered. Our model is founded in a quark model, but one involving four, not three, fundamental fermions; the weak interactions are medi-

…

new quantum number $\mathcal{C}$ for charm.





B^0 mixing pointed to the **top** quark mass

ARGUS Coll, Phys.Lett.B192:245,1987

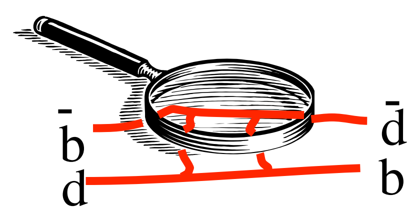
DESY 87-029
April 1987

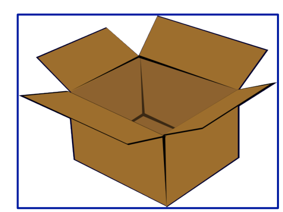
OBSERVATION OF B^0-$\bar{B}^0$ MIXING

The ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson-lepton events on the $\Upsilon(4S)$ leads to the conclusion that B^0-$\bar{B}^0$ mixing has been observed and is substantial.

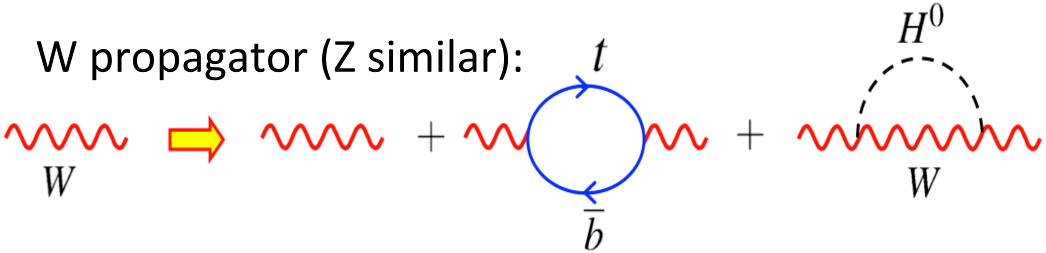
Parameters	Comments
$r > 0.09$ 90%CL	This experiment
$x > 0.44$	This experiment
$B^{\frac{1}{2}} f_B \approx f_\pi < 160$ MeV	B meson (≈ pion) decay constant
$m_b < 5 GeV/c^2$	b-quark mass
$\tau_b < 1.4 \cdot 10^{-12} s$	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi-Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [17]
$m_t > 50 GeV/c^2$	t quark mass





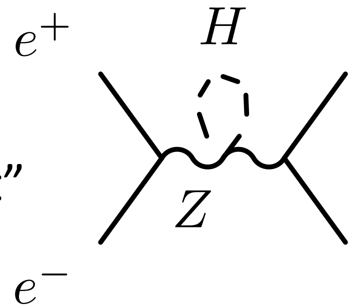
Higgs mass and Electroweak precision measurements

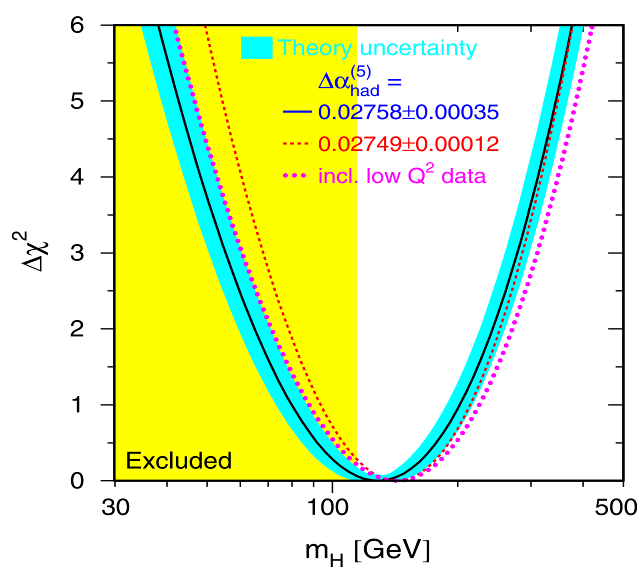
W propagator (Z similar):



$$M_W = M_W^0 + a m_t^2 + b \ln\left(\frac{M_H}{M_W}\right)$$

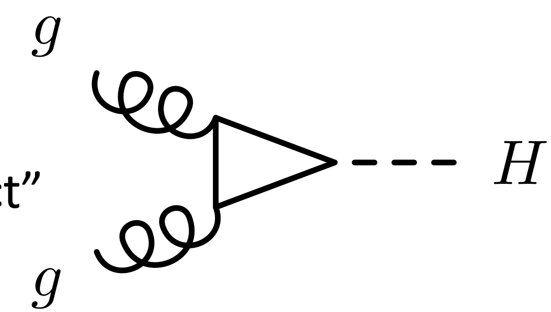
- **LEP**
  "Indirect"

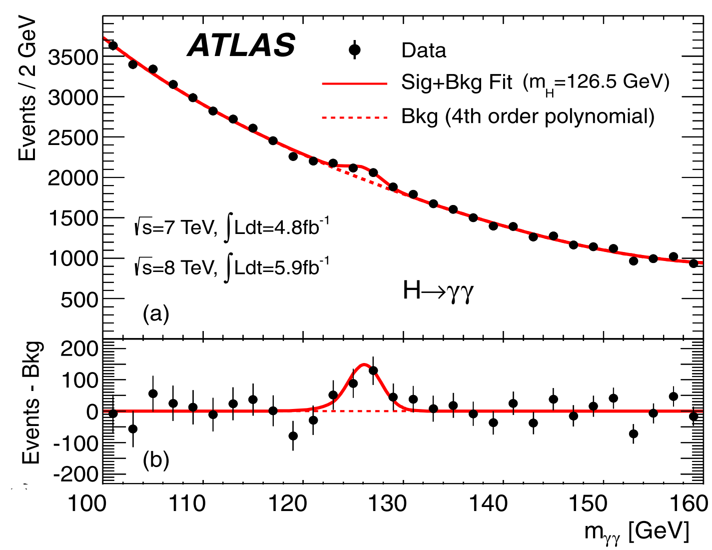




LEP: Phys.Rep.427 (2006) 257

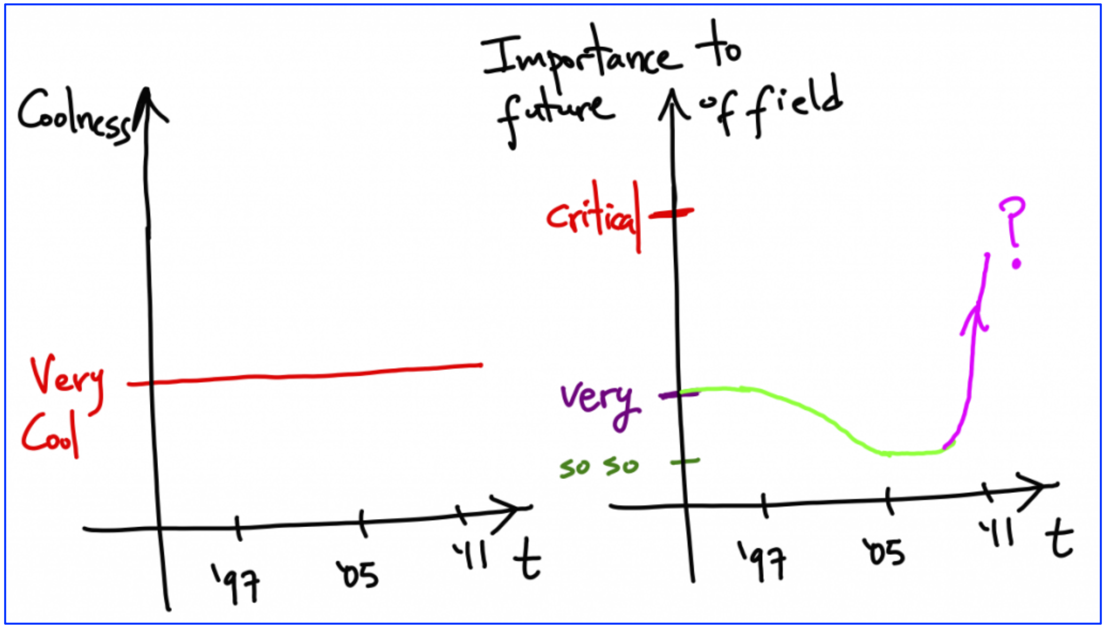
- **LHC**
  "Direct"

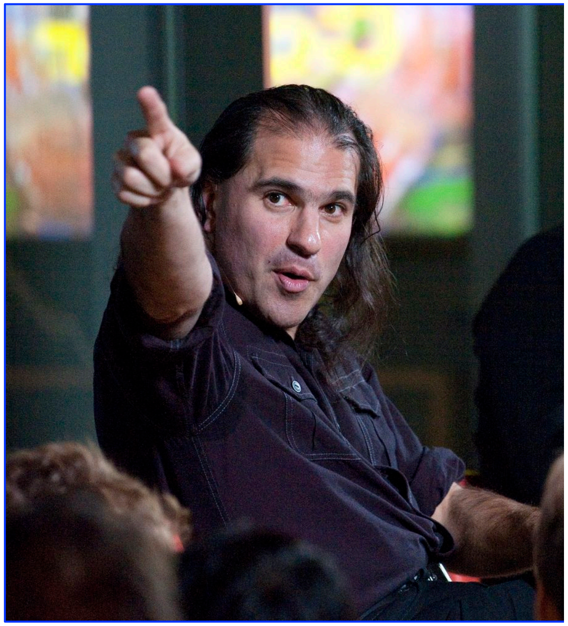




Atlas coll. Phys.Lett.B716 (2012) 1

Why work on Flavor Physics?





(Nima Arkani-Hamed likes it too)

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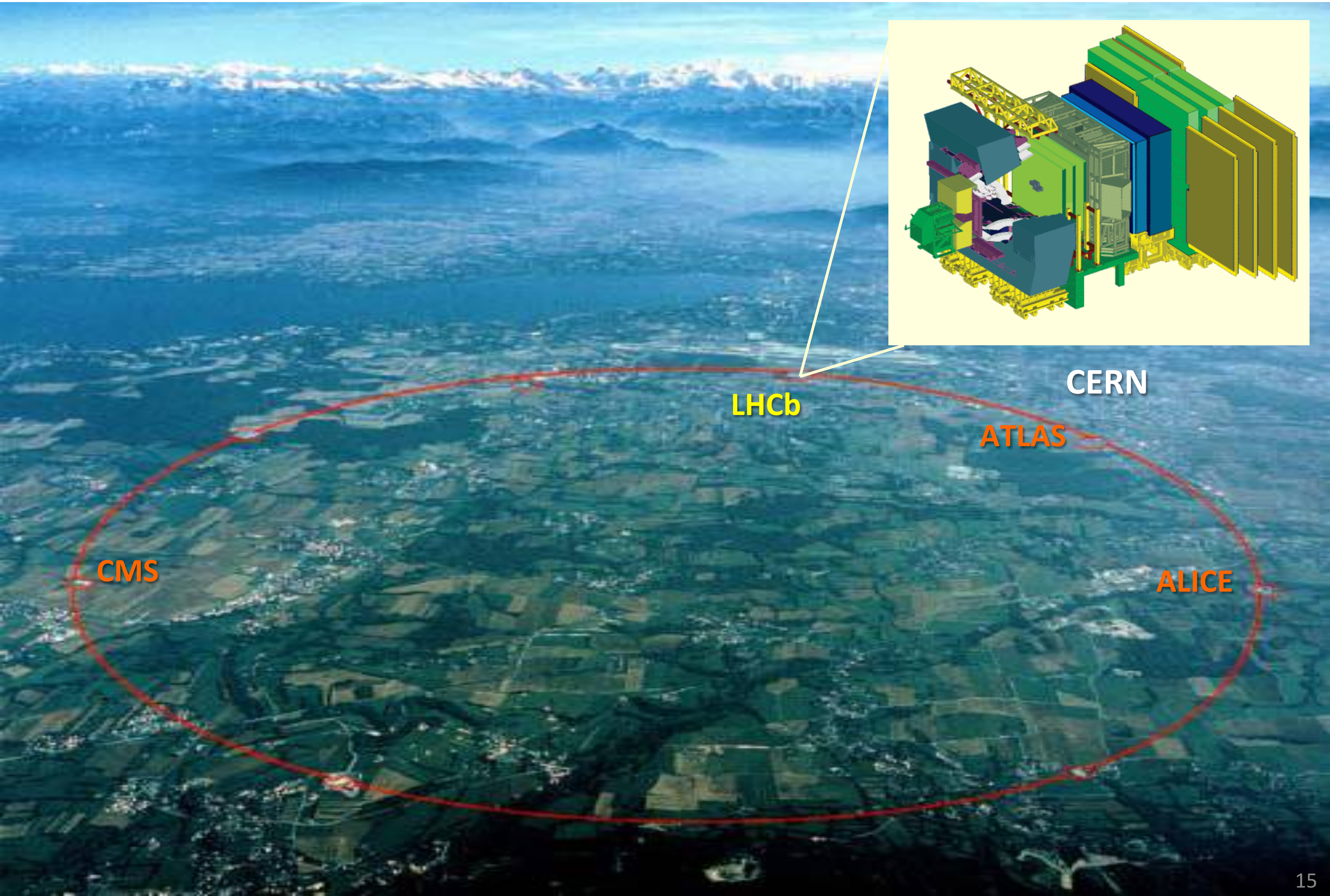
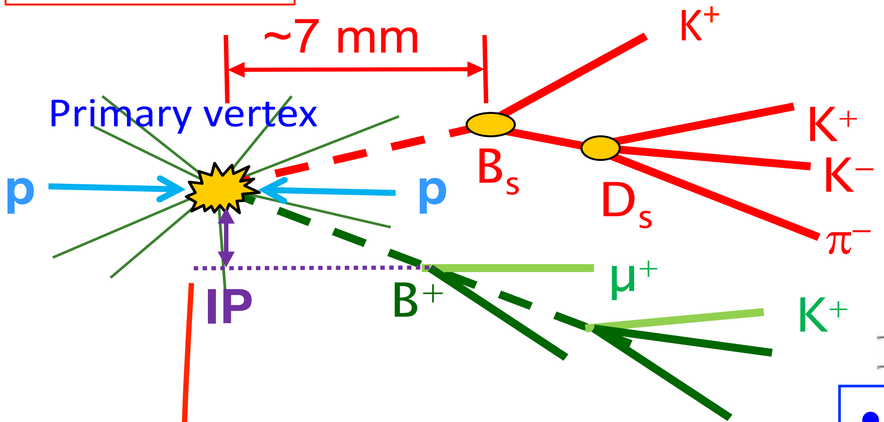
LHCb @ LHC



B Physics @ LHCb

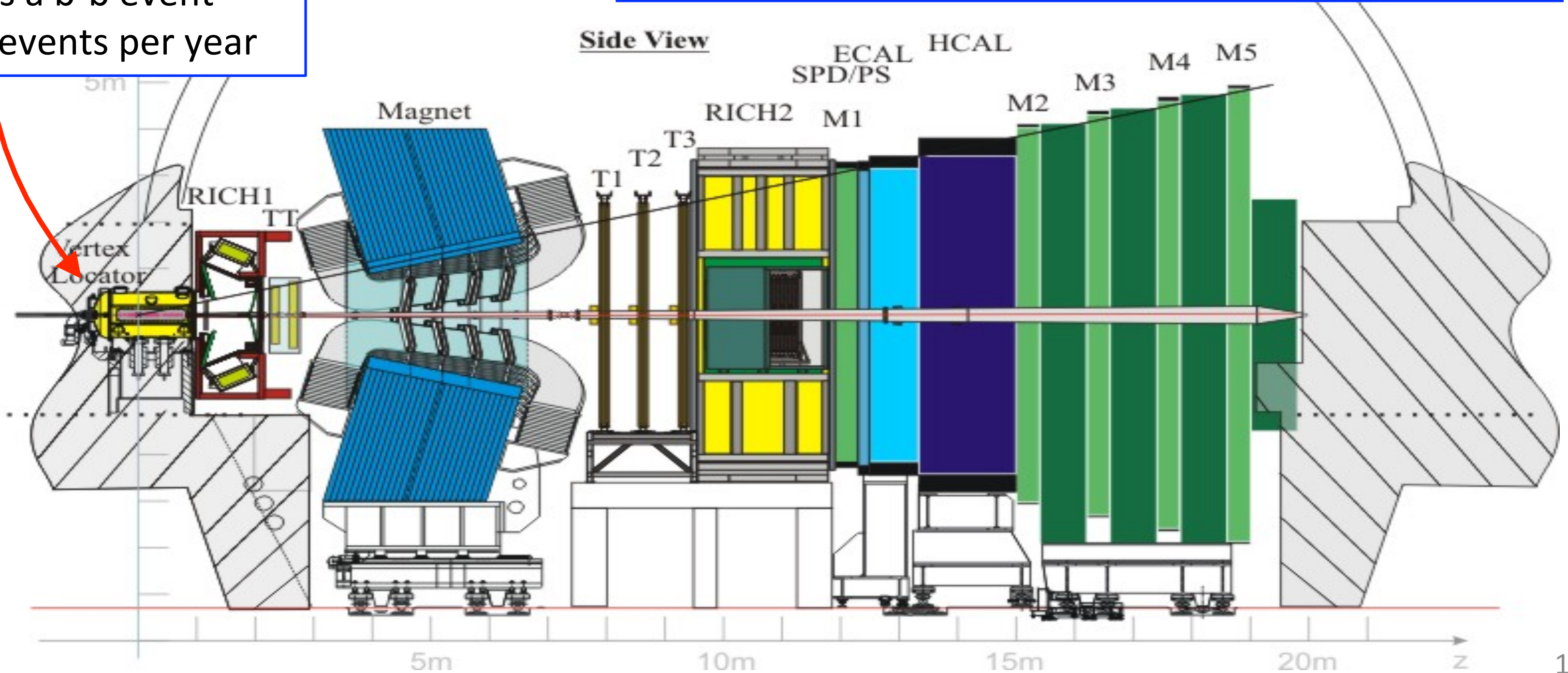
$B_s \rightarrow D_s^- K^+$



- Background Suppression
- Flavour tagging
- Decay time measurement

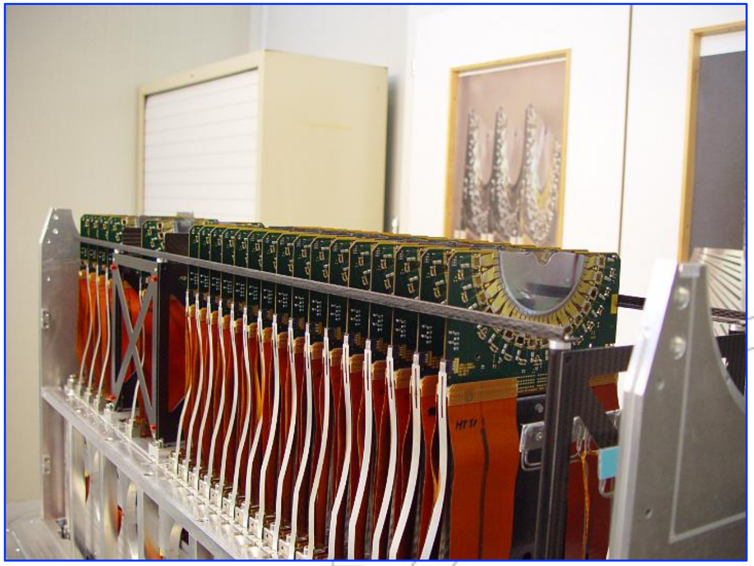
- Vertex and momenta reconstruction
- Particle identification (π, K, μ, e, γ)
- Trigger

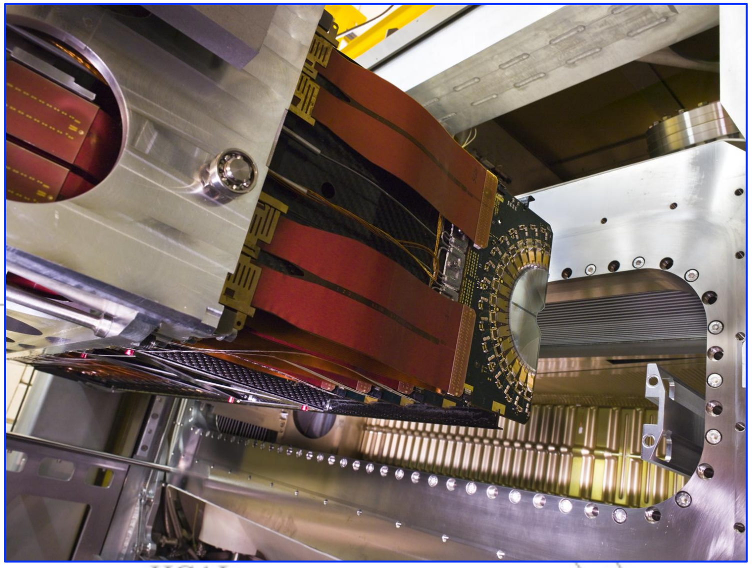
Design:
- LHCb event rate: ~30 MHz
- 1 in 160 is a b-b event
- 10^{12} b-b events per year

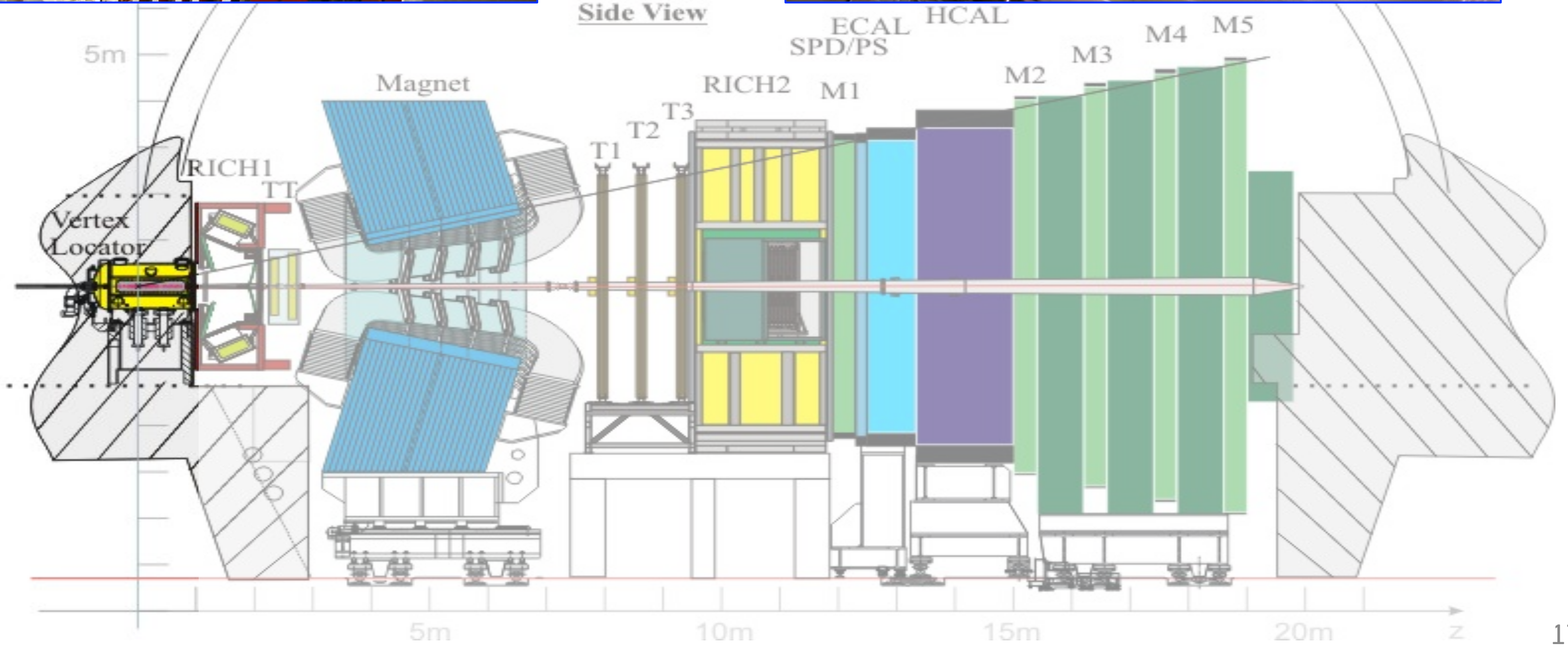


Vertex Topology

Vertex Locator

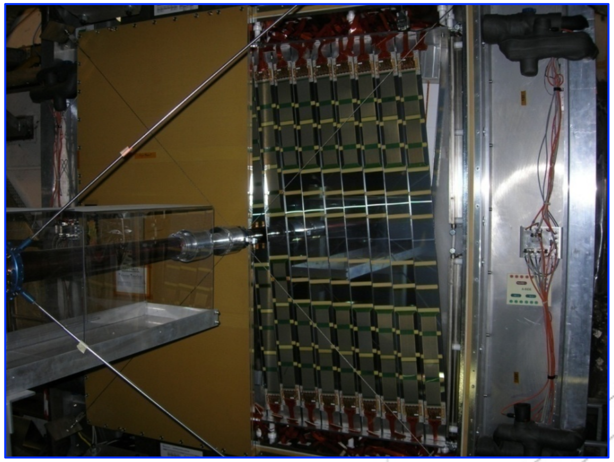




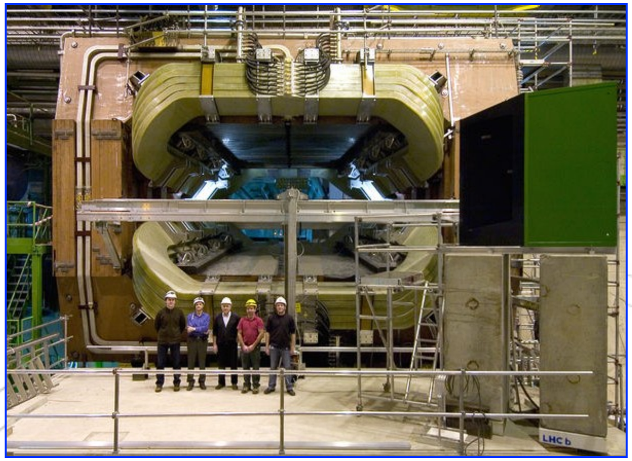


Momentum and Mass Reconstruction

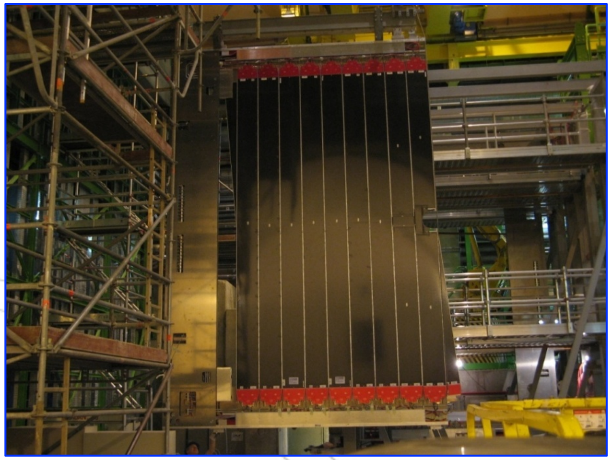
Trigger Tracker

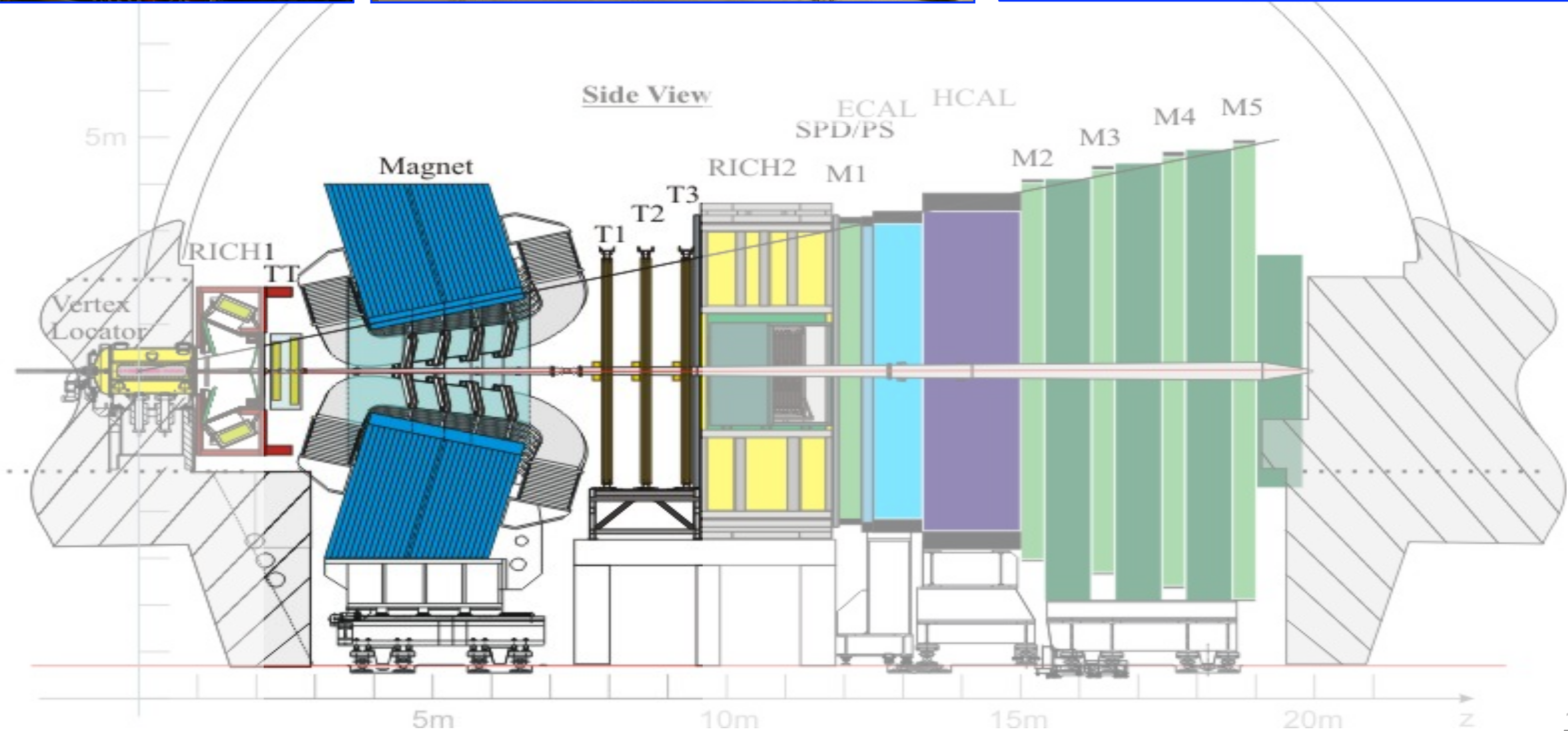


Magnet



Outer Tracker

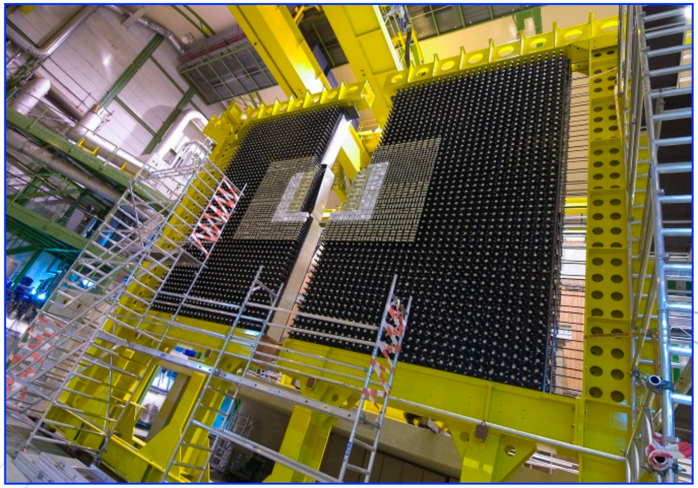




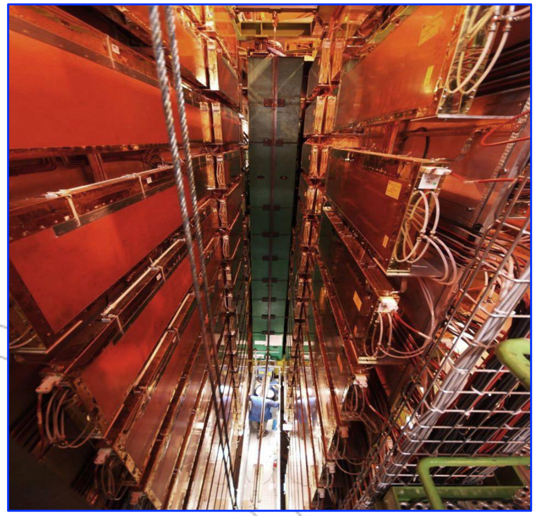
Particle Identification: π, K, μ, γ, e

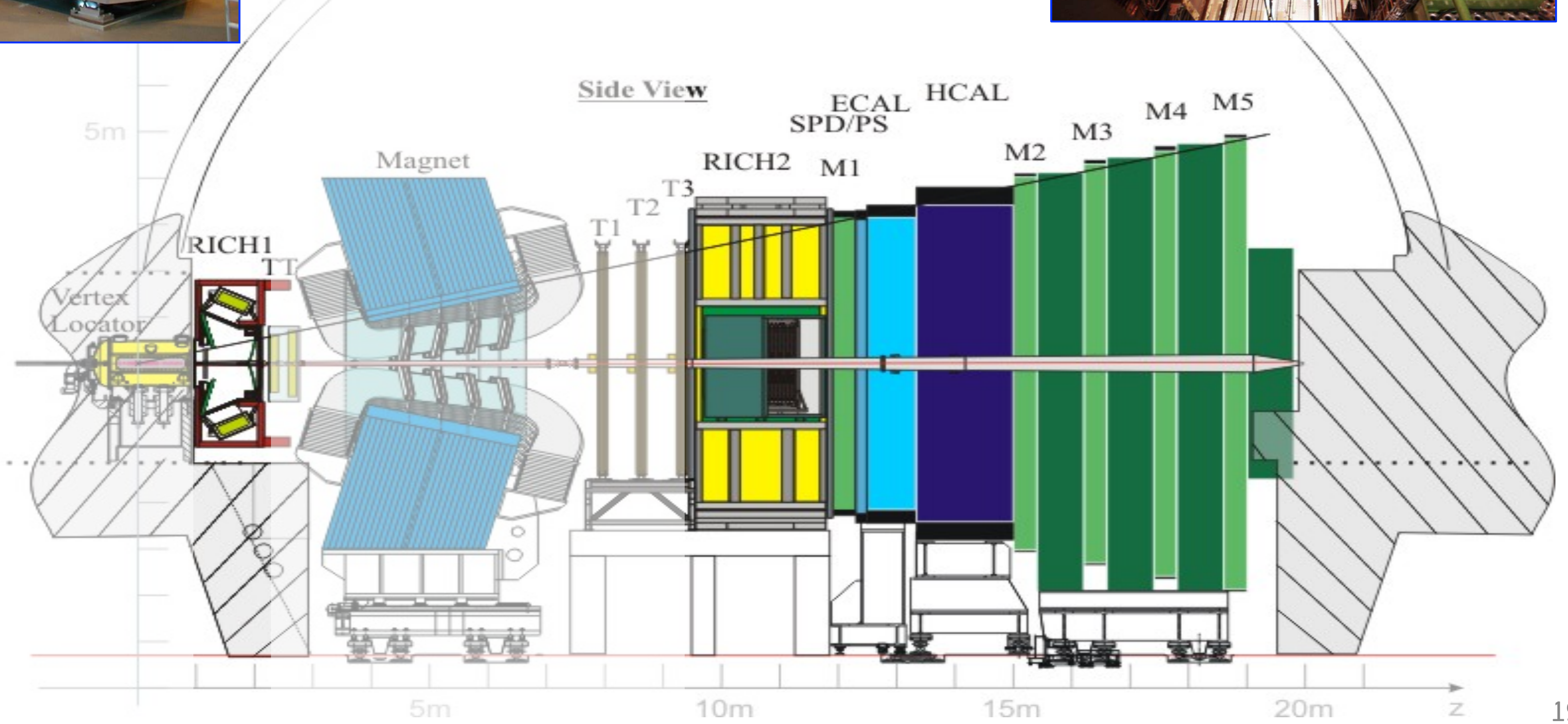
RICH

Calorimeter

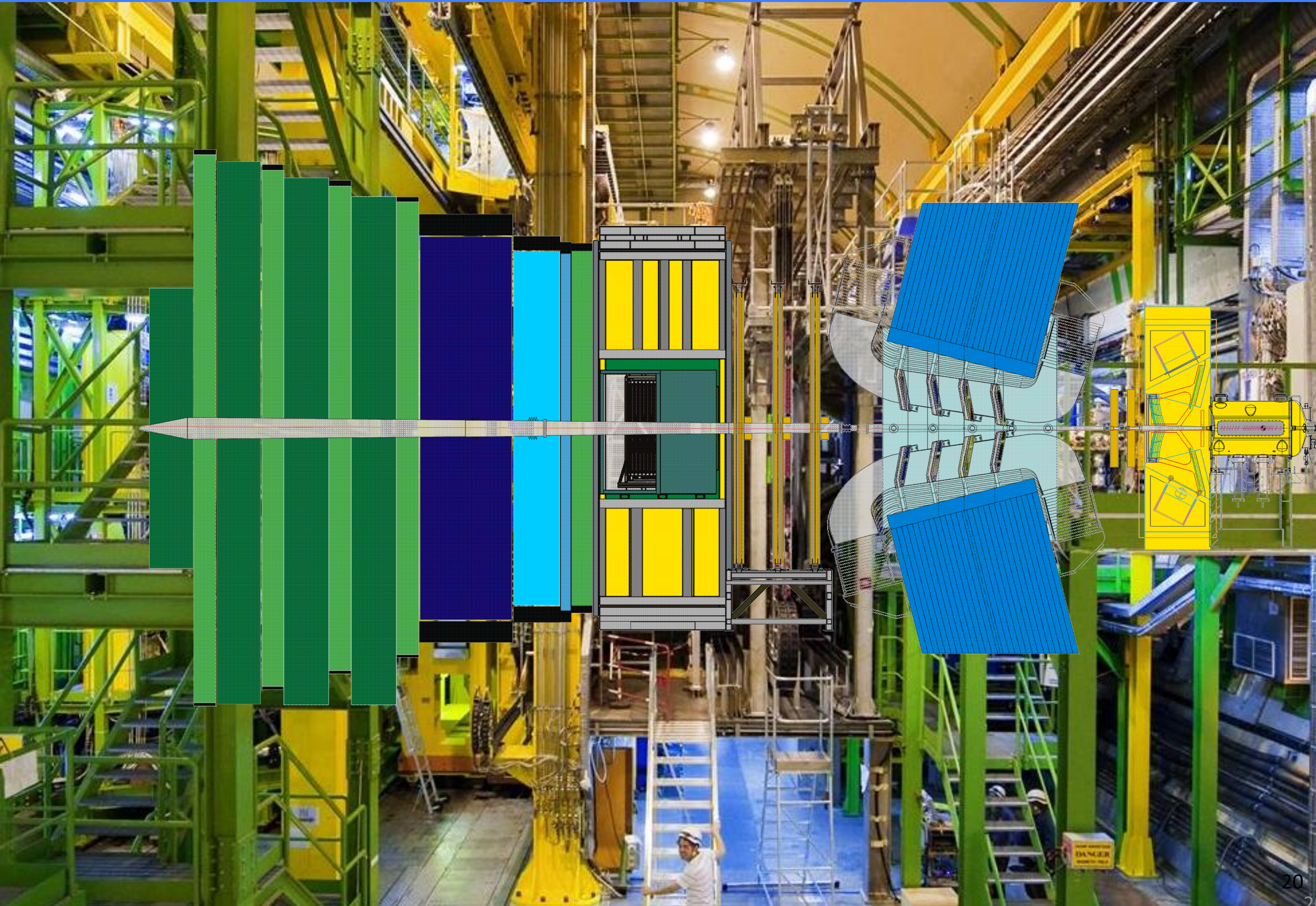


Muon





The LHCb Detector



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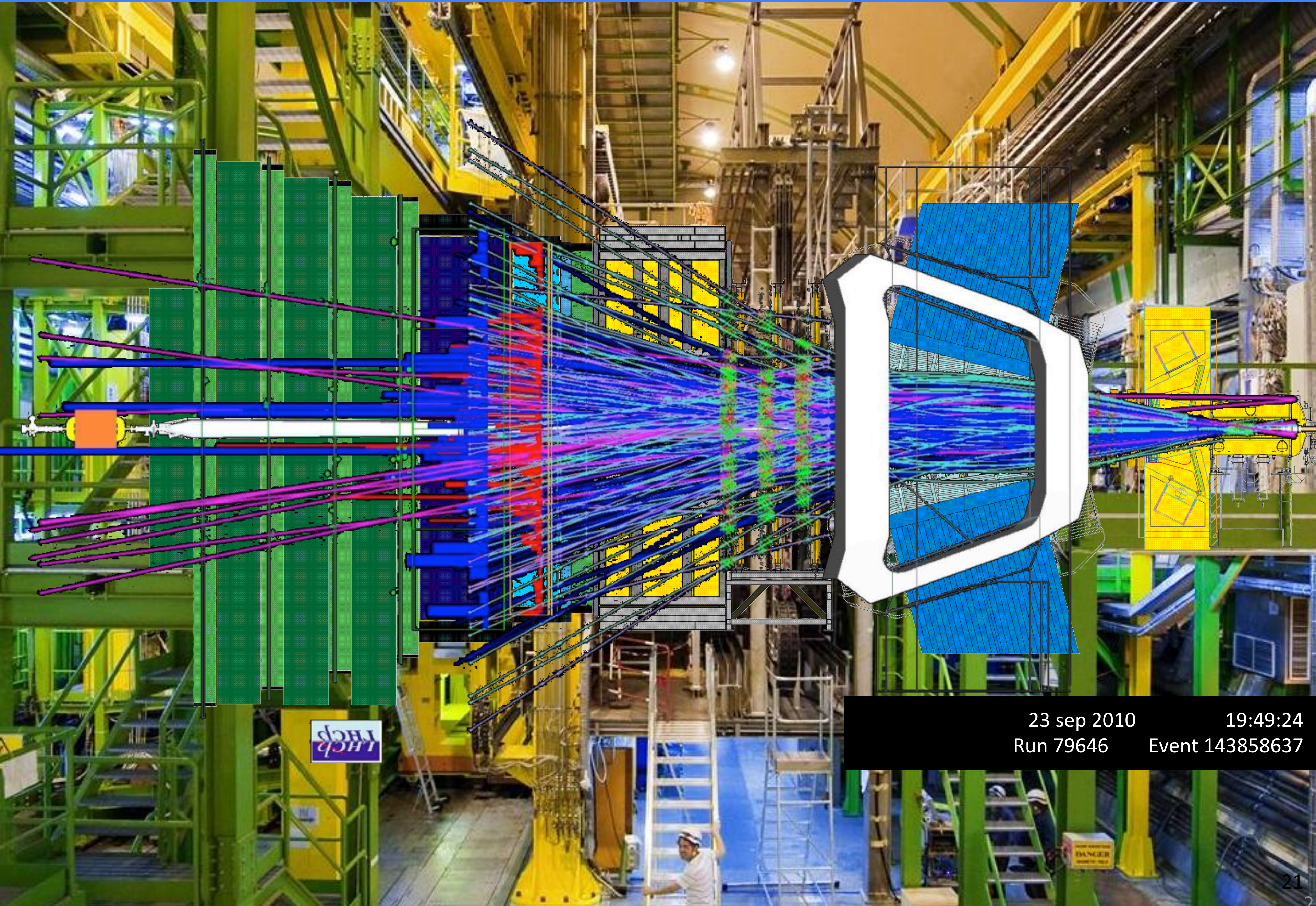

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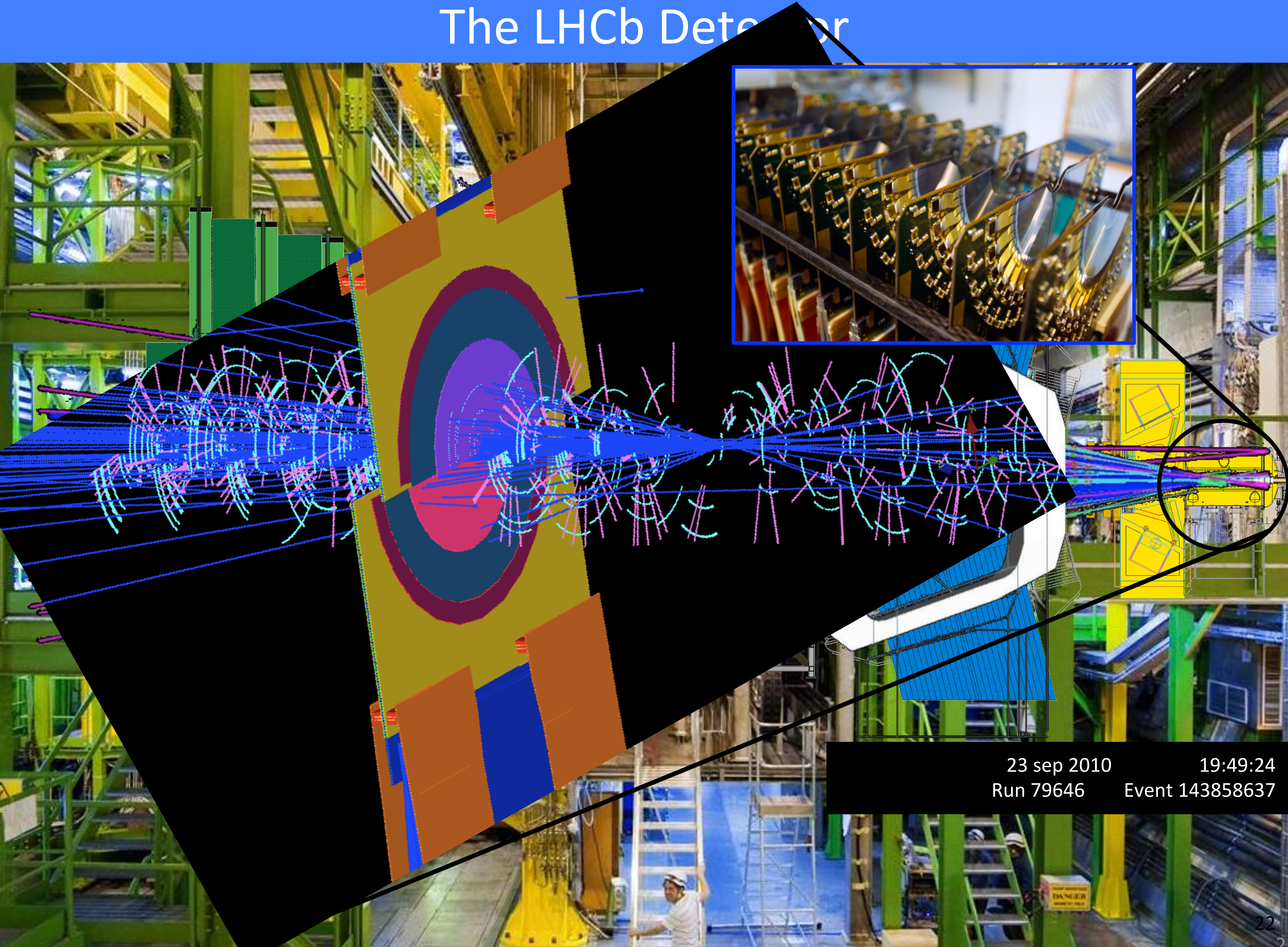


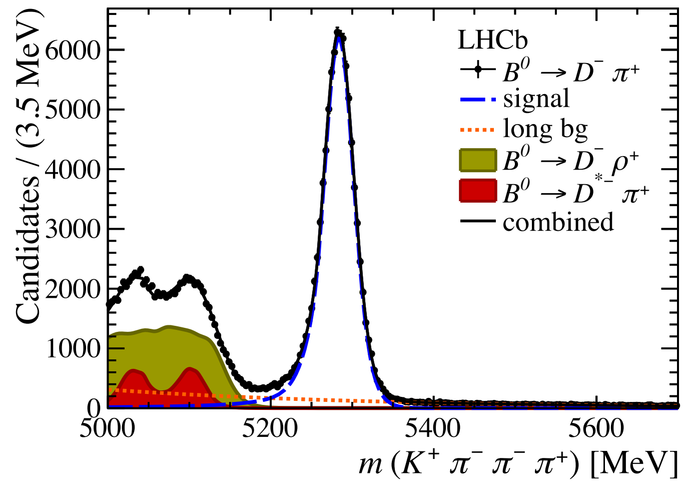
LHCb Performance: $B_{d/s}$ Mixing

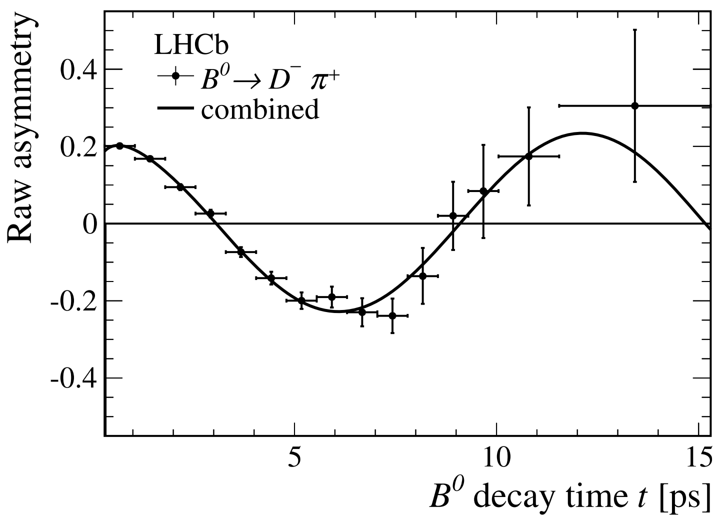
Trigger, background suppression, decay time reconstruction, flavour tagging: ***it works!***

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

$B^0 \rightarrow D^- \pi^+$

Phys.Lett.B719 (2013) 318

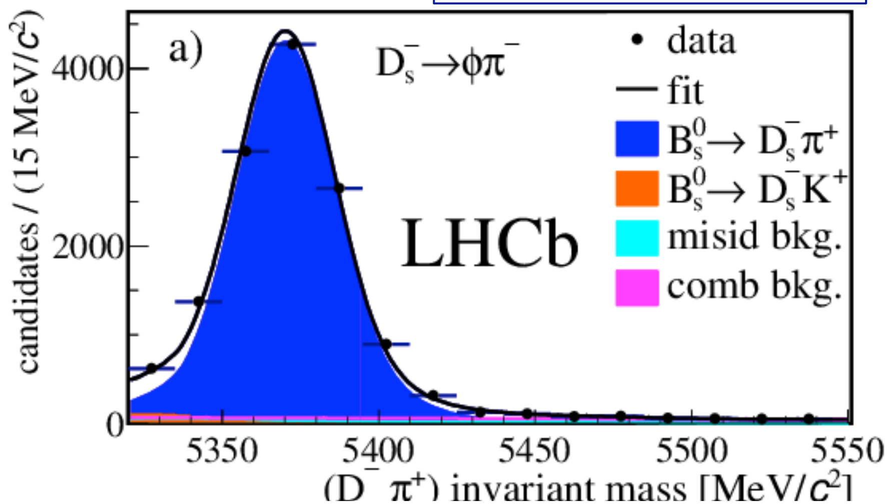


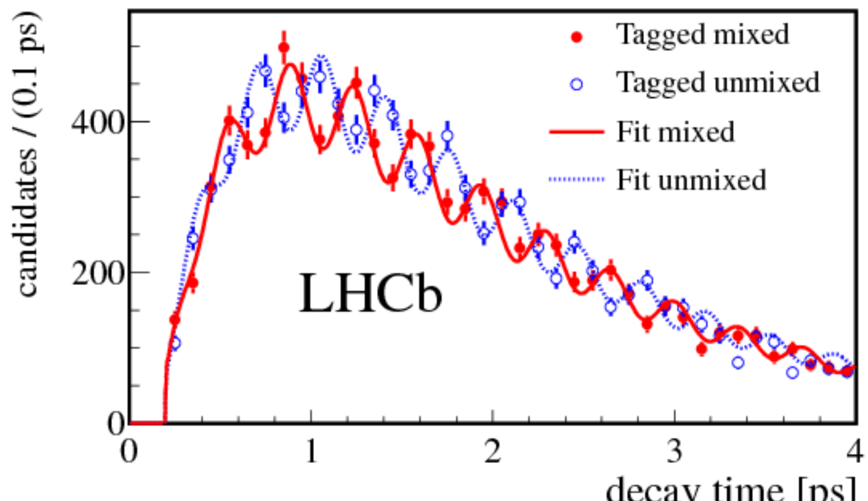


$B_s^0 - \overline{B}_s^0$ mixing

$B_s^0 \rightarrow D_s^- \pi^+$

New.J.Phys.15 (2013) 053021





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A slide of History on CP Violation

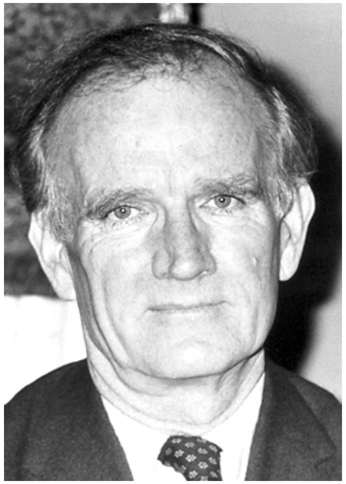
- **Charge Parity Violation in particle physics:**
  - **a) 1964** (CCFT): Discovered in neutral Kaon beam "*indirect* CP violation"
    - Also called: ***CPV in mixing***
    - Prob($K^0 \rightarrow \overline{K}^0$) ≠ Prob ($\overline{K}^0 \rightarrow K^0$)

      $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$ (PDG 2014)
  - **b) 1999** (NA48 & KTeV): Seen in Kaon decays "*direct* CP violation"
    - Also called: ***CPV in decay***
    - Decay rates $\Gamma(K^0 \rightarrow \pi^+\pi^-) \neq \Gamma(\overline{K}^0 \rightarrow \pi^+\pi^-)$

      $Re(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \times 10^{-3}$ (PDG 2014)
  - **c) 2001** (Belle & Babar): Observed in B mesons decays "CP violation in *interference*"
    - Also called: ***mixing induced CPV***

      $\sin 2\beta = 0.682 \pm 0.019$ (PDG 2014)

James Watson Cronin



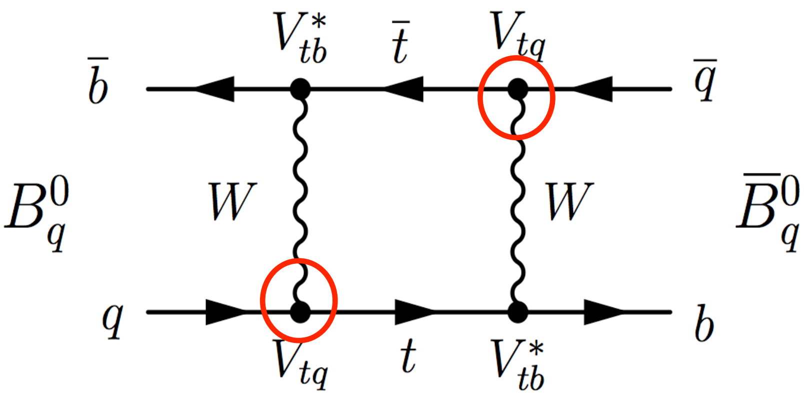
Val Logsdon Fitch

→ Nobel prize 1980

Observing CP Violation in B decays

- CP Violation occurs in *interference of two quantum amplitudes* that have a different CP odd (as well as CP even) phase.
  - Use the phenomenon of B-$\overline{B}$ mixing:
  - Interference of direct decay and decay via mixing leads to CP violation.

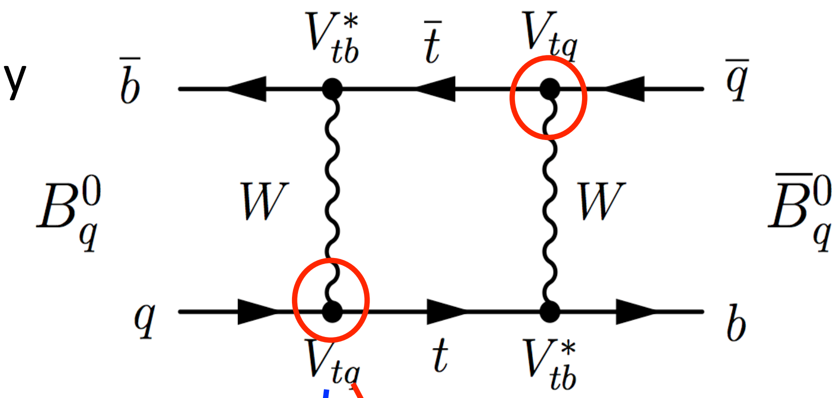
    Standard Model:
    - B^0-$\overline{B}^0$ phase $\phi_d = \arg(V_{td}) = 2\beta$
    - B_s-$\overline{B}_s$ phase $\phi_s = \arg(V_{ts}) = -2\beta_s$

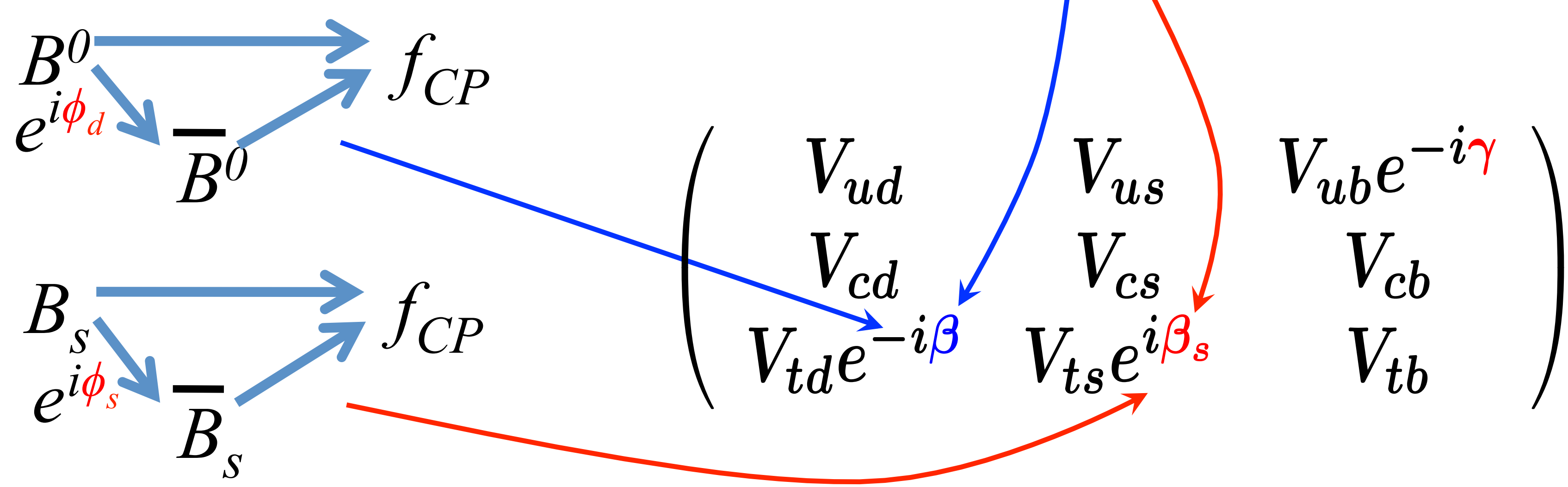


Observing CP Violation in B decays

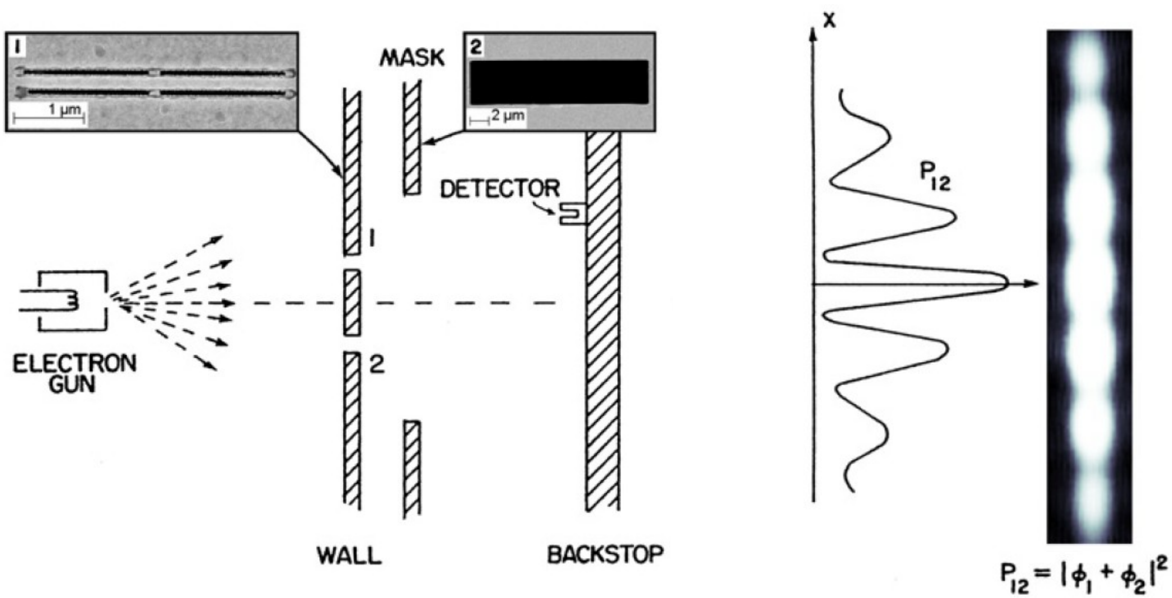
- CP Violation occurs in *interference of two quantum amplitudes* that have a different CP odd (as well as CP even) phase.
  - Use the phenomenon of B-$\bar{B}$ mixing:
  - Interference of direct decay and decay via mixing leads to CP violation.

    Standard Model:
    - B^0-$\bar{B}^0$ phase $\phi_d = \arg(V_{td}) = 2\beta$
    - B_s-$\bar{B}_s$ phase $\phi_s = \arg(V_{ts}) = -2\beta_s$

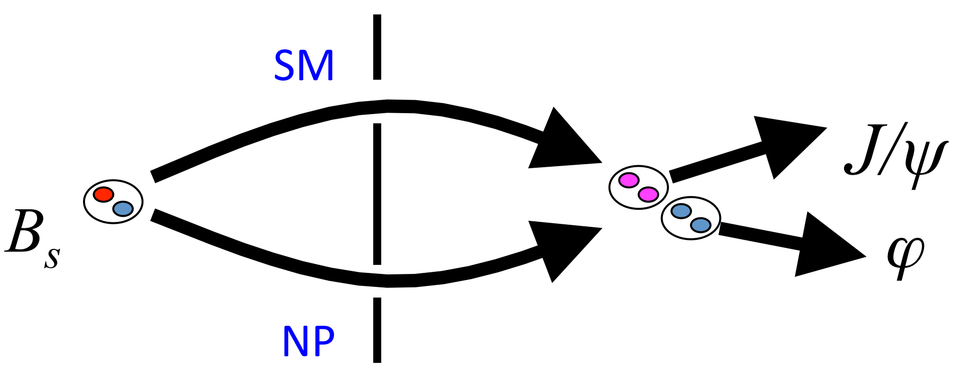


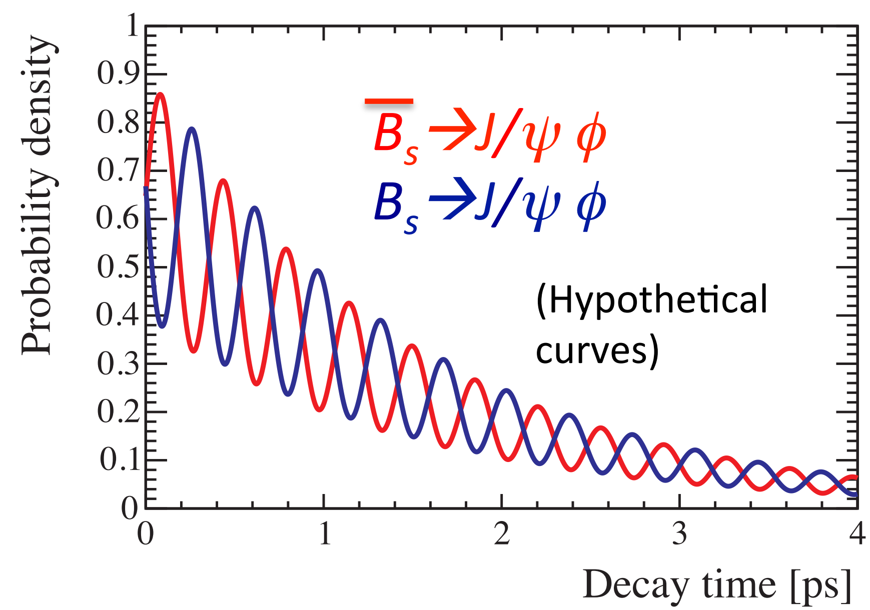


Feynman: “Remember the double slit experiment”



LHCb is a completely analogous interference experiment using B-mesons.

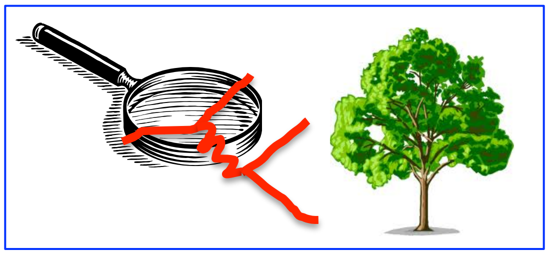


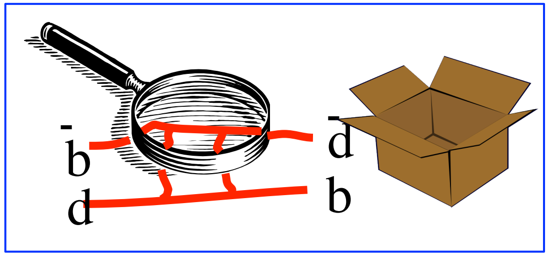


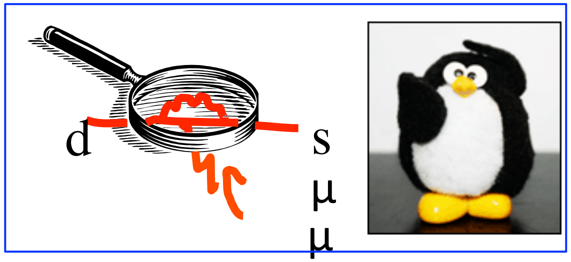
Look for interference of SM with NP

Probing new CP-violation with B mesons

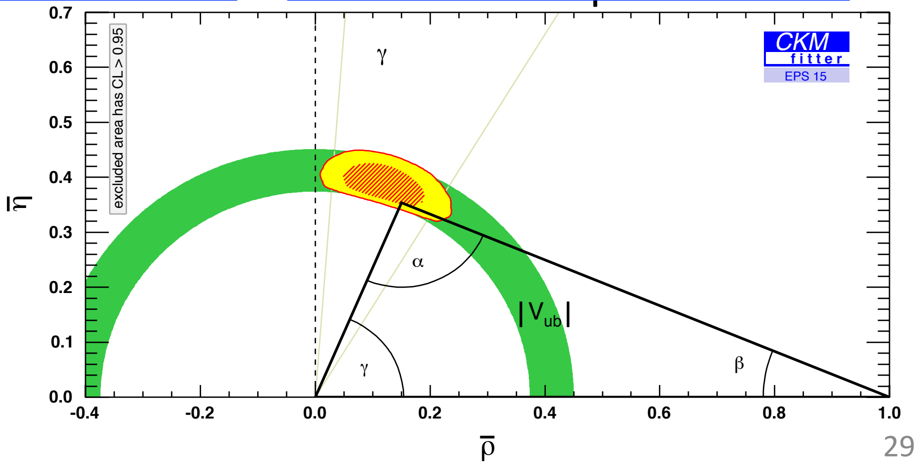
- Look for *interference* of CKM with BSM amplitudes:
  a) SM Prediction: No CP violation a la kaons (*"indirect"* or *"mixing"*)
     - K←→$\bar{K}$ = epsilon ≠ 0 but B←→$\bar{B}$ = 0
  b) Precise measurement of angle γ *"with trees"* vs γ *"with loops"* (*"direct"*)
     - Many decay modes with tree and loop diagrams are available
  c) SM Prediction: B_s box diagram phase $\phi_s = -2\beta_s \approx 0$ (*"mixing induced"*)
     - New Physics "in the box"?







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



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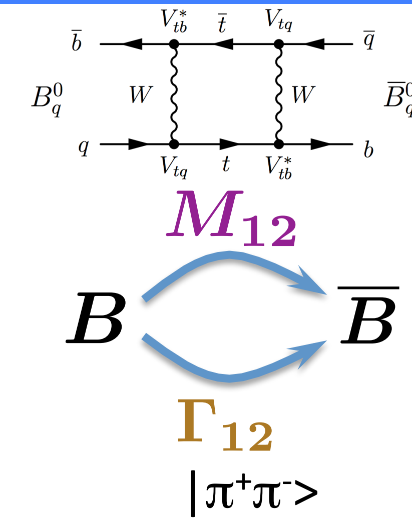
CP Violation in Mixing



- Interference of the *dispersive* and *absorptive* amplitudes
  - Similar to measurement ε in kaon physics
- Hamiltonian:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}\begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix}$$

- Eigenstates:

$$M_L, M_H \quad ; \quad \Delta M = M_H - M_L$$
$$\Gamma_L, \Gamma_H \quad ; \quad \Delta\Gamma = \Gamma_H - \Gamma_L$$

$$\phi_{12} = \arg(-M_{12}/\Gamma_{12})$$

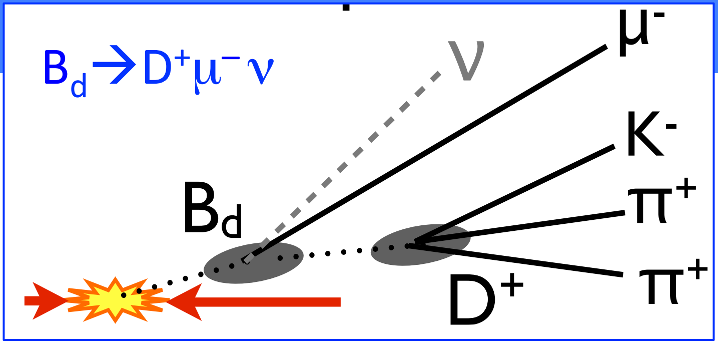
- Observable:

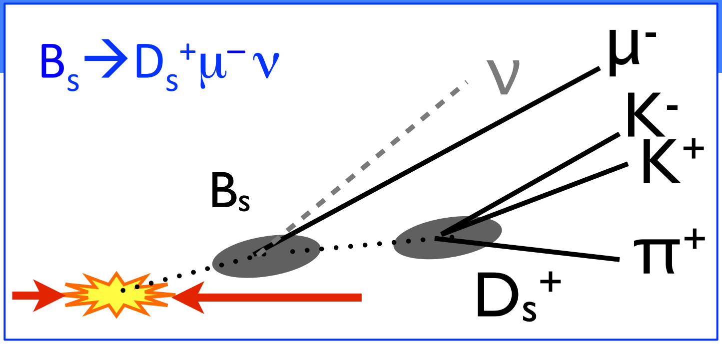
$$a_{sl} = \frac{\Gamma\left(\overline{B}(t) \to f\right) - \Gamma\left(B(t) \to \overline{f}\right)}{\Gamma\left(\overline{B}(t) \to f\right) + \Gamma\left(B(t) \to \overline{f}\right)} = \frac{\Delta\Gamma}{\Delta M}\tan\phi_{12}$$

- In the Standard Model $\phi_{12} \approx 0.2°$ for B_s
- $B_{d,s}$: measure with flavor specific decays: $B_{d,s} \to D_{(s)}^{+} \mu^{-} \nu$ and C.C.

Lenz, Nierste JHEP.06 (2007) 072

B_d vs B_s

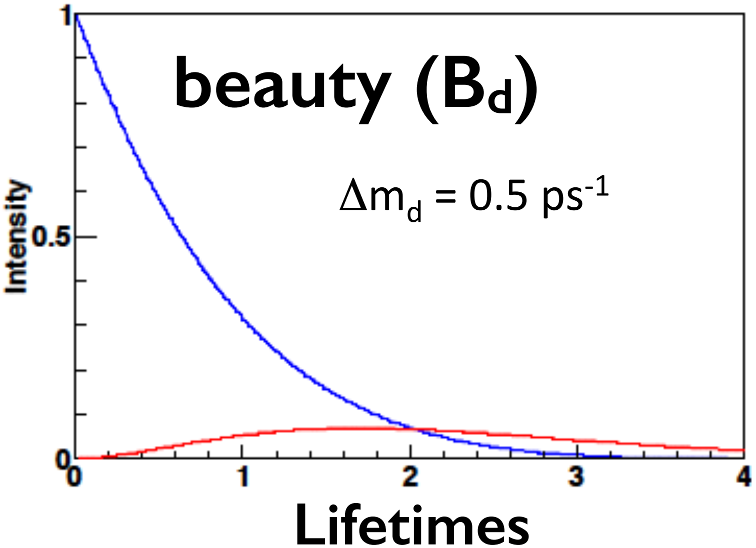


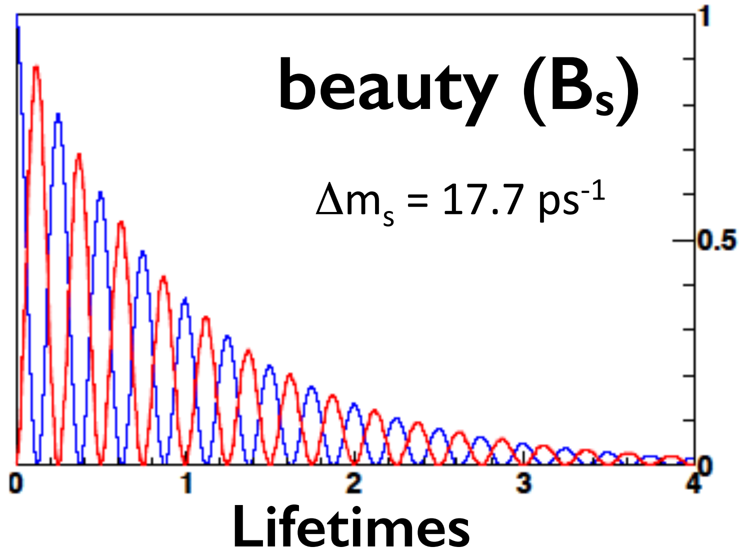


$$\mathcal{A}_{B\overline{B}} = \frac{N(D^-_{(s)}\mu^+,t) - N(D^+_{(s)}\mu^-,t)}{N(D^-_{(s)}\mu^+,t) + N(D^+_{(s)}\mu^-,t)} = \frac{a_{sl}}{2} + \left(a_p + \frac{a_{sl}}{2}\right)\frac{\cos\Delta M t}{\cosh\frac{\Delta\Gamma}{2}t}$$

a^d_{sl} (B_d) : must measure time-dependent

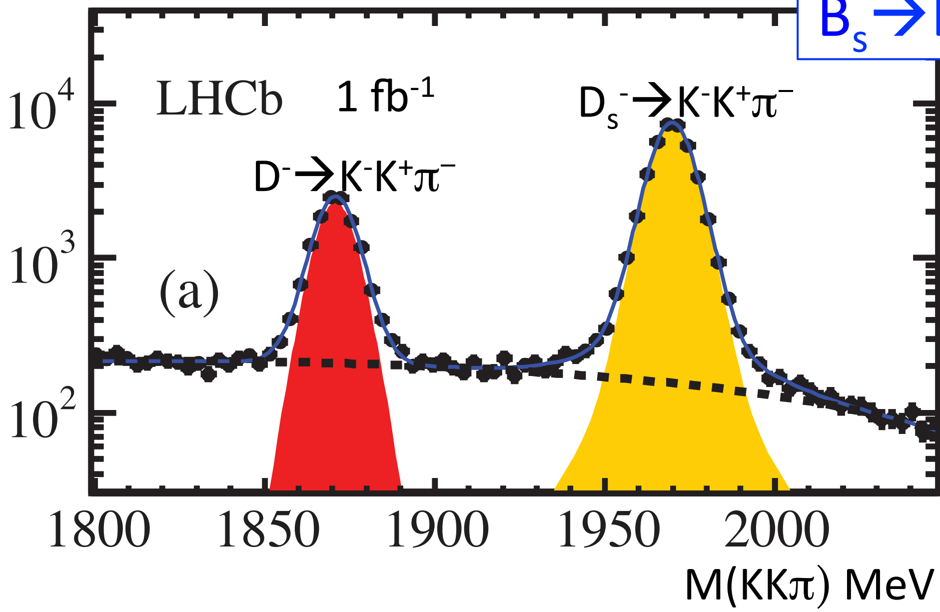
a^s_{sl} (B_s) : washout of fast oscillation factor and production asymmetry





Semileptonic charge asymmetry with B_s: a_{sl}^s

$B_s \rightarrow D_s^+ \mu^- \nu$



$$\mathcal{A}_{\text{meas}} = \frac{\Gamma\left[D_s^- \mu^+\right] - \Gamma\left[D_s^+ \mu^-\right]}{\Gamma\left[D_s^- \mu^+\right] + \Gamma\left[D_s^+ \mu^-\right]} = \frac{a_{sl}^s}{2}$$

Correct for detection asymmetry:

$$\frac{\epsilon\left(D_s^- \mu^+\right)}{\epsilon\left(D_s^+ \mu^-\right)}$$

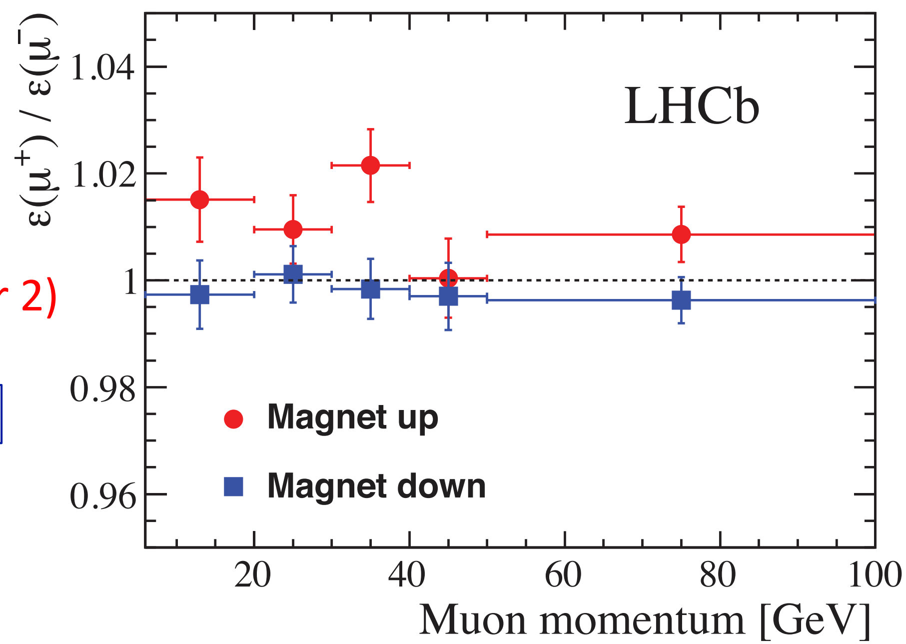
LHCb: PLB 728C (2014) 607

$$a_{sl}^s = (-0.06 \pm 0.50 \pm 0.36)\ \%$$

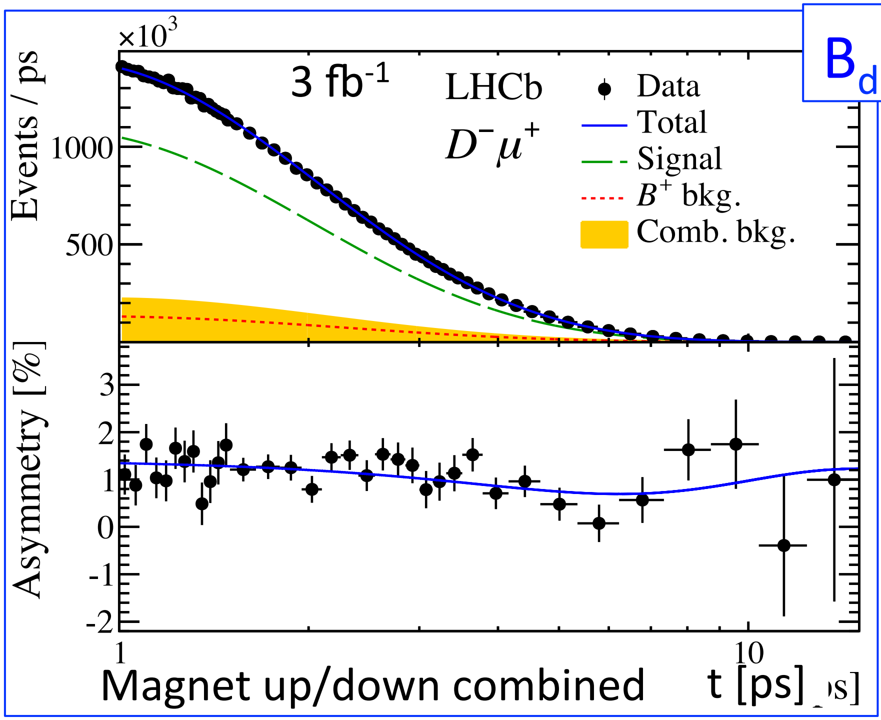
(Update coming soon; error reduces by factor 2)

Standard Model: Lenz, Nierste JHEP.06 (2007) 072

$$a_{sl}^s = (1.9 \pm 0.3) \times 10^{-5}$$



Semileptonic charge asymmetry with B_d: a_{sl}^d



$B_d \rightarrow D^+ \mu^- \nu$

Time dependent analysis:

- Decay time reconstruction with missing neutrino
- Background modelling

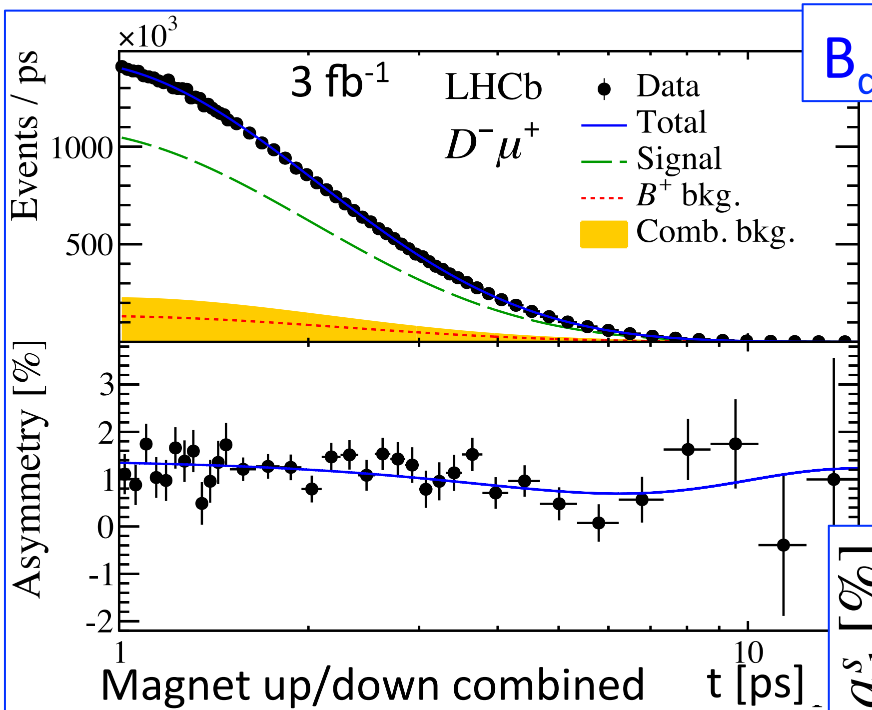
LHCb: PRL 114 (2015) 041601

$$a_{sl}^d = (-0.02 \pm 0.19 \pm 0.30)\,\%$$

Standard Model: Lenz, Nierste JHEP.06 (2007) 072

$$a_{sl}^d = (-4.1 \pm 0.6) \times 10^{-4}$$

Semileptonic charge asymmetry with B_d: a_{sl}^d



$B_d \rightarrow D^+ \mu^- \nu$

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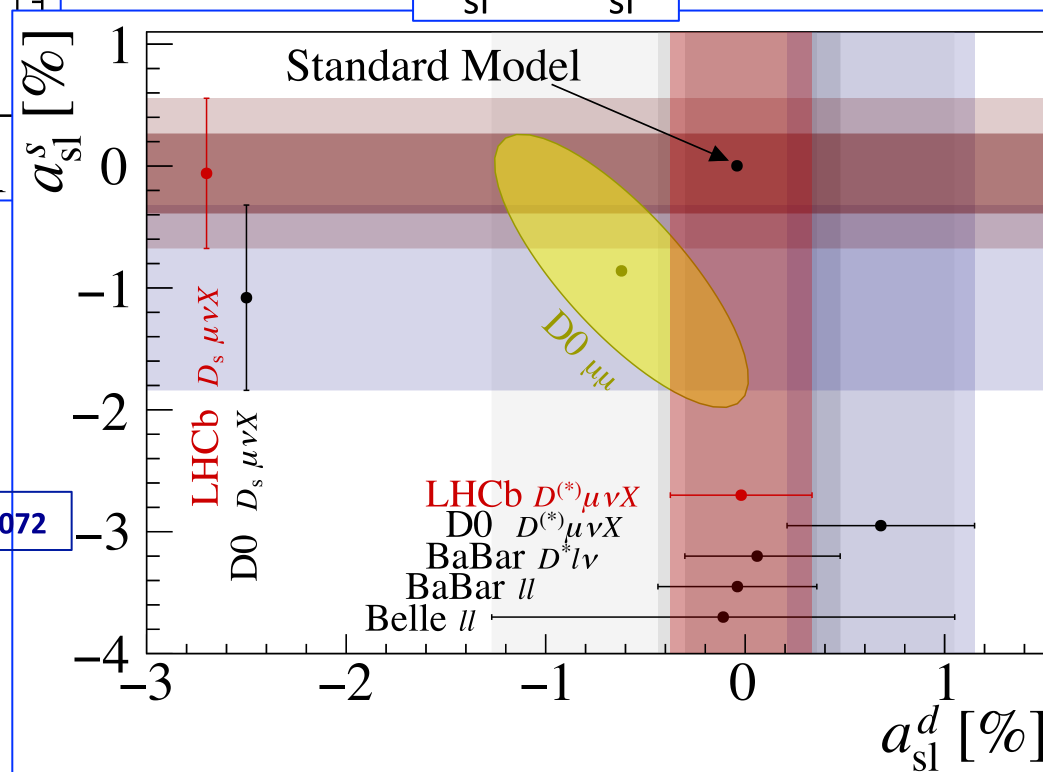
a_{sl}^s vs a_{sl}^d



LHCb:

PRL 114 (2015) 041601

$$a_{sl}^d = (-0.02 \pm 0.19 \pm 0.30)\ \%$$

Standard Model:

Lenz, Nierste JHEP.06 (2007) 072

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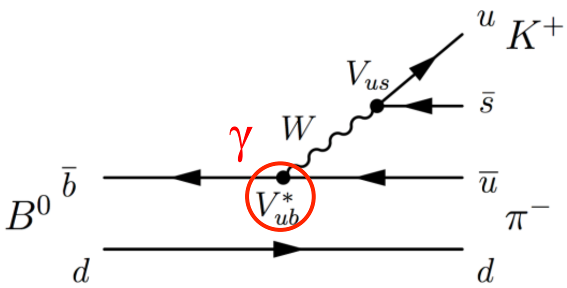
Direct CP Violation with $B_{(s)} \rightarrow K\pi$ ("charmless")



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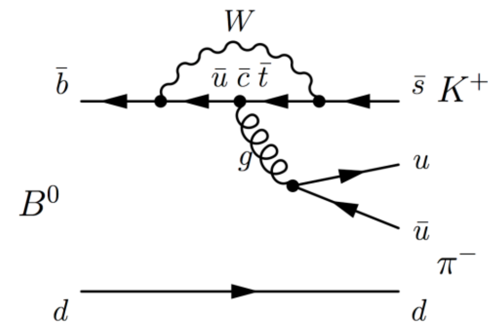


- Interference of trees and penguins
  - New physics can contribute to penguin loop
- Sensitive to V_{ub} phase: CKM angle γ
- Measure the *untagged* CP asymmetry for B^0 and B_s decays:

$$\mathcal{A}_{CP} = \frac{\left(N_{\overline{B}\rightarrow\overline{f}} - N_{B\rightarrow f}\right)}{\left(N_{\overline{B}\rightarrow\overline{f}} + N_{B\rightarrow f}\right)} \qquad B \rightarrow f = \begin{cases} B^0 \rightarrow K^+\pi^- \\ B_s \rightarrow \pi^+K^- \end{cases}$$

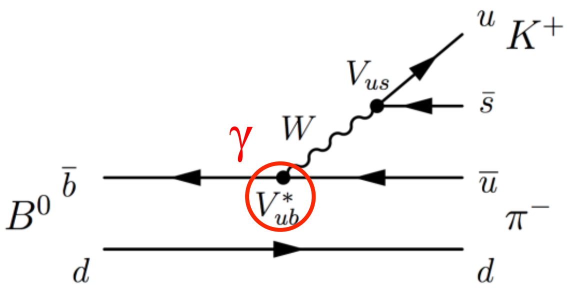
$$\mathcal{A}_{\mathrm{raw}} = \mathcal{A}_{CP} + \mathcal{A}_{\mathrm{det}} + \kappa \cdot \mathcal{A}_{\mathrm{prod}}$$

(The correction factor is O(1%), measured from data)

Instrumental asymmetry

Mixing dilution times production asymmetry

Direct CP Violation with $B_{(s)} \rightarrow K\pi$ (“charmless”)



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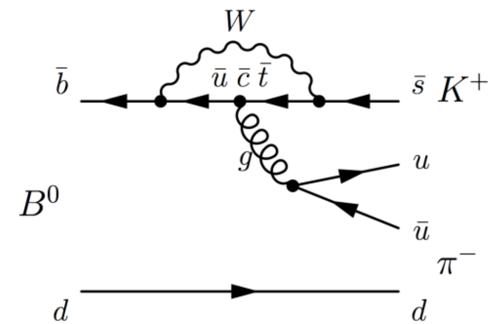


$B^0 \rightarrow K\pi$

PRL 110.221601

A_{CP} = -0.080 ± 0.007 ± 0.003

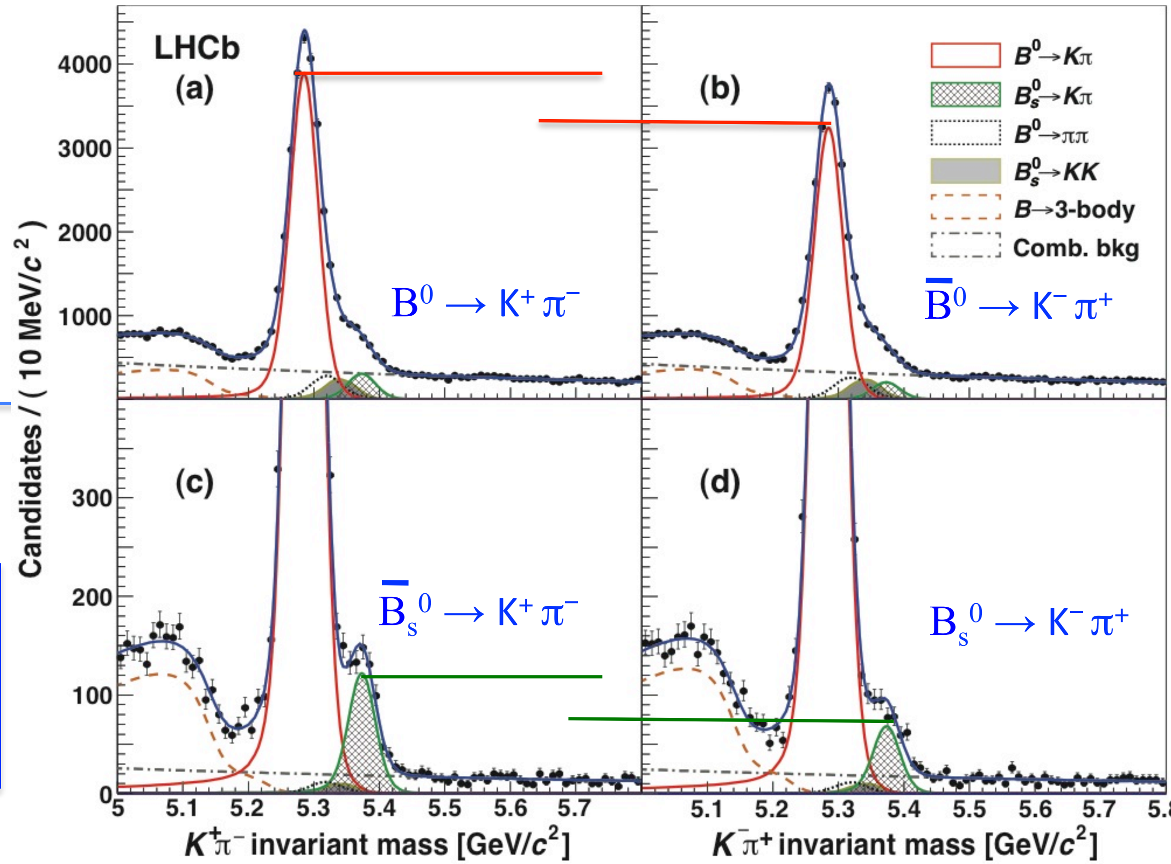
Most precise measurement of CP violation in a hadronic Machine.

$B_s \rightarrow \pi K$

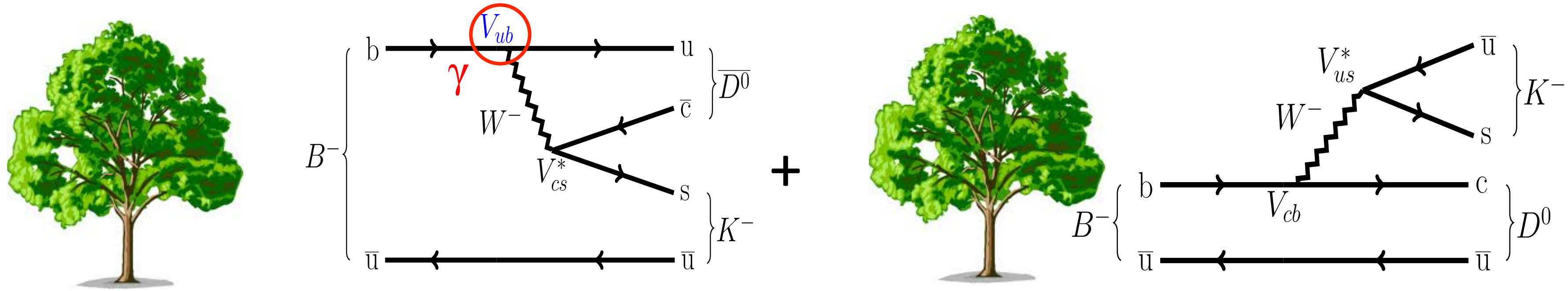
PRL 110.221601

A_{CP} = 0.27 ± 0.04 ± 0.01

First observation of a CP asymmetry in B_s decays



Direct CP Violation with B→DK ("charmed")



- Interference of trees and trees
  - Interfere decays b→c with b→u to final states common to D^0 and D^0
- Sensitive to V_{ub} phase: CKM angle γ :
- Many methods

$$\frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)} = r_B\, e^{i\delta_B}\, e^{-i\gamma}$$

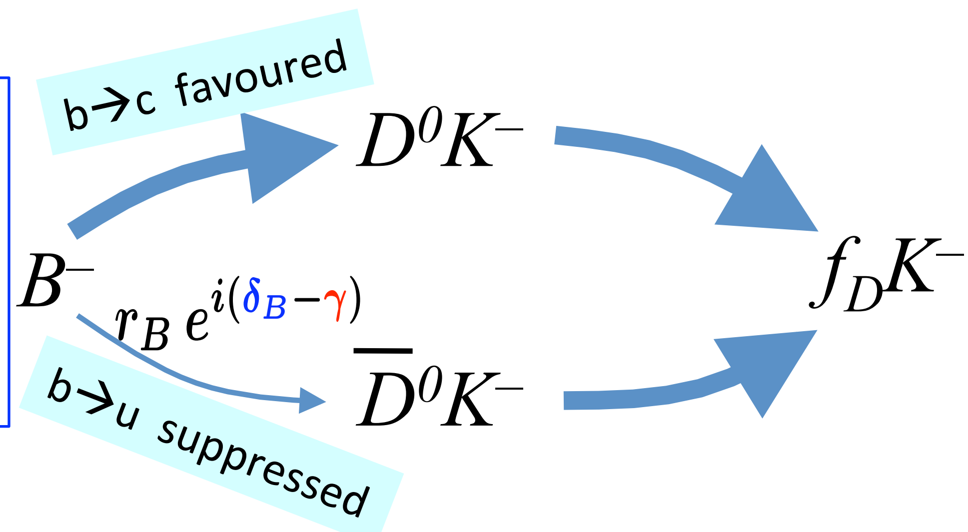
Gronau, London, Wyler: Phys. Lett. B 265, 172 (1991)

<u>GLW method:</u>

f_D is a CP eigenstate common to D^0 and $\overline{D}^0$: $f_D = K^+K^-, \pi^+\pi^-,\ldots$

Interfere: $B \to D^0K$, $B \to \overline{D}^0K$

- Large event rate; small interference



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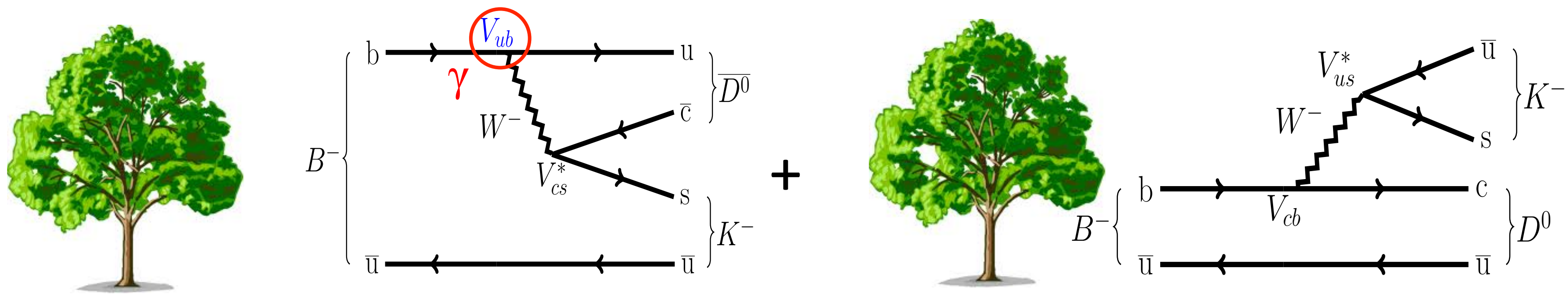

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$$\frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)} = r_B\, e^{i\delta_B}\, e^{-i\gamma}$$

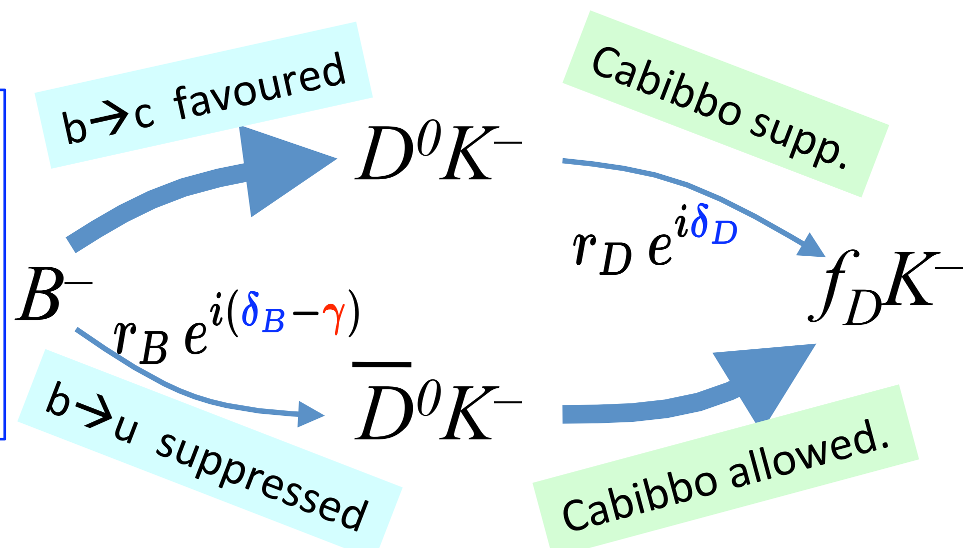
Atwood, Dunietz, Soni:
Phys Rev Lett 78, 3257 (1997)
Phys Rev D 63, 036005 (2001)

ADS method:

Use common flavour state $f_D=(K^+\pi^-)$

Note: decay $D^0 \to K^+\pi^-$ is double Cabibbo suppressed

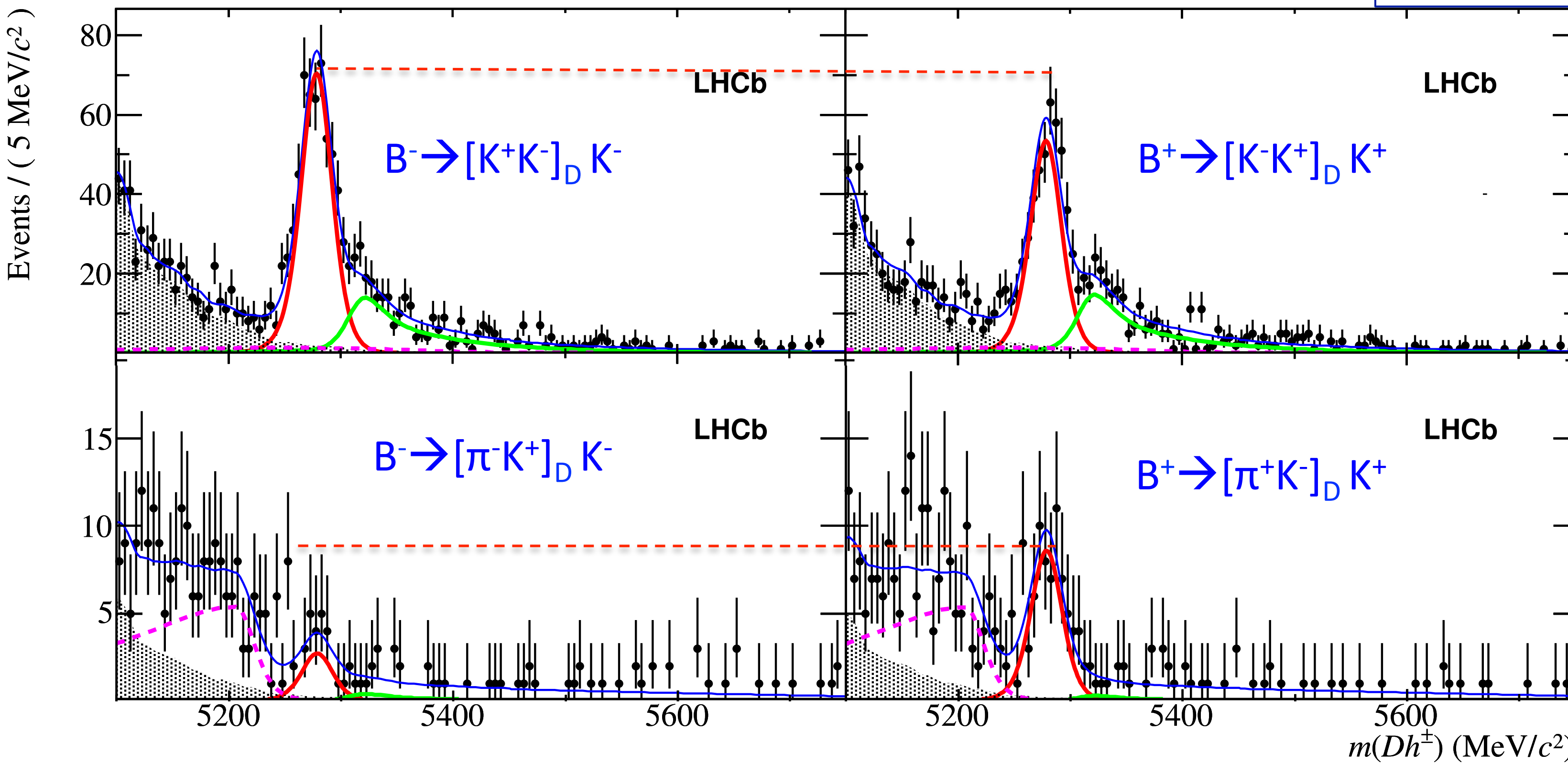
- Lower event rate; large interference



Direct CP Violation with B→DK ("charmed")

Observe ADS mode $B^- \to [\pi^- K^+]_D K^-$ with 10 σ significance

PLB 712 (212) 203
arXiv:1203.3662
LHCb: 1.0 fb^{-1}



GLW

ADS

GLW:

A_{CP+} = 0.145 +- 0.032 +- 0.010
R_{CP+} = 1.007 +- 0.038 +- 0.012

ADS:

A_{ADS} = -0.52 +- 0.15 +- 0.02
R_{ADS} = 0.0152 +- 0.0020 +- 0.0004

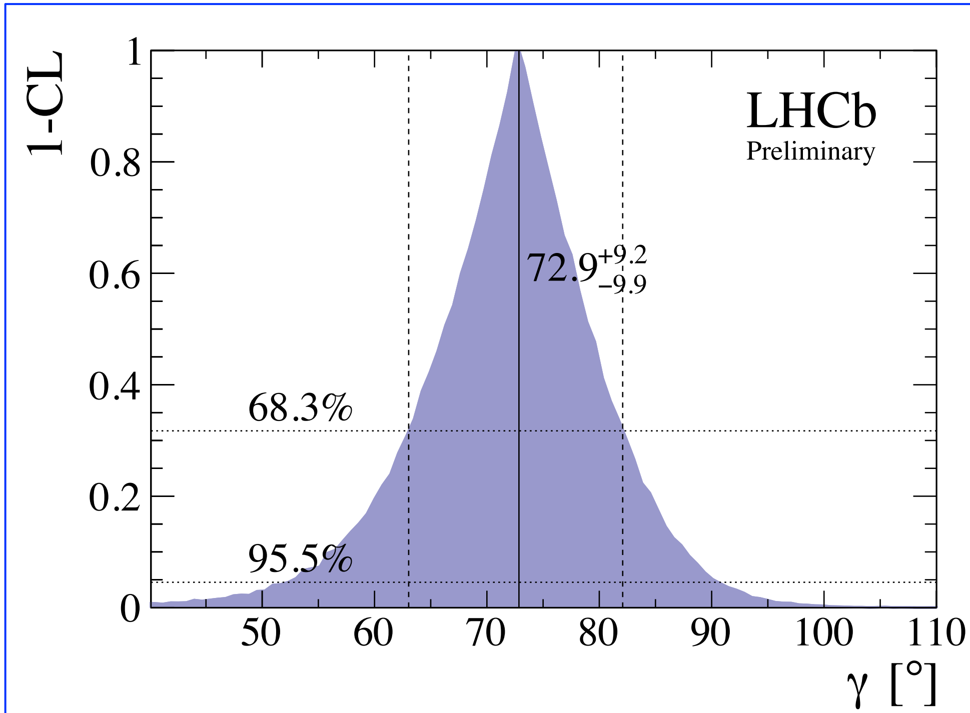
➔ CP violation is observed with 5.8 ***σ***

γ from B→D K and B→D π

More methods/modes available: GLW, ADS, GGSZ, GLS…:

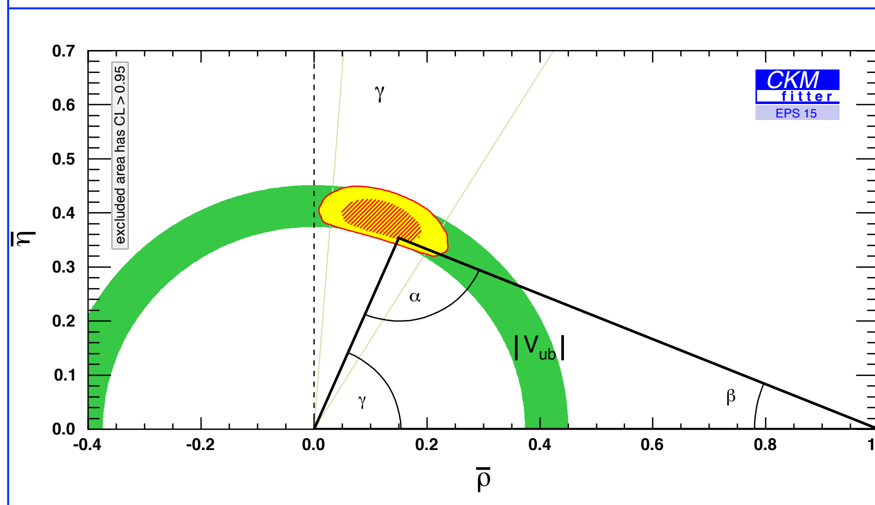
- $B^+ \rightarrow Dh^+$ with $D \rightarrow hh$; GLW/ADS method (2011 data): Phys.Lett.B712(212)203
- $B^+ \rightarrow Dh^+$ with $D \rightarrow K\pi\pi\pi$; ADS method (2011 data) : Phys.Lett.B723(2013)44
- $B^+ \rightarrow DK^+$ with $D \rightarrow K_s^0 hh$; GGSZ method (2011+2012 data) : arXiv:1408.2748
- $B^+ \rightarrow DK^+$ with $D \rightarrow K_s^0 K\pi$; GLS method (2011+2012 data) : Phys.Lett B 733 (2014) 36
- $B^0 \rightarrow D^0 K^{*0}$ with $D \rightarrow hh$; GLW/ADS (2011+2012 data) : arXiv:1407.8136

PLB 726 (2013) 151, LHCb-CONF-2014-004



Most precise γ determination:

$$\gamma_{B\rightarrow Dh} = \left(72.9^{+9.2}_{-9.9}\right)^{o}$$



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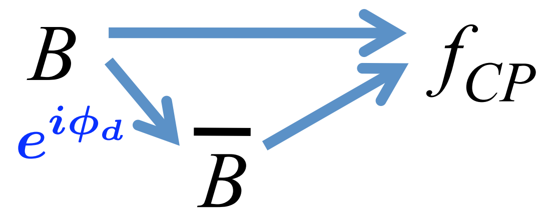
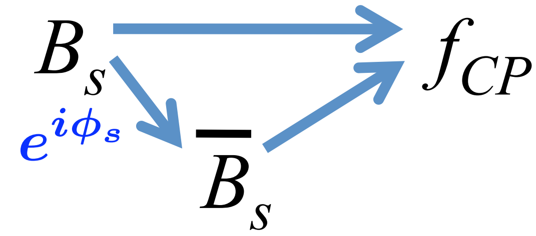
Time Dependent CP Violation: mixing phase



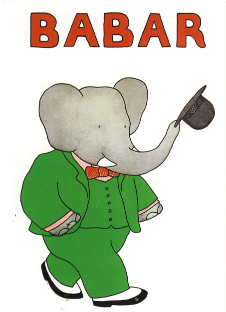


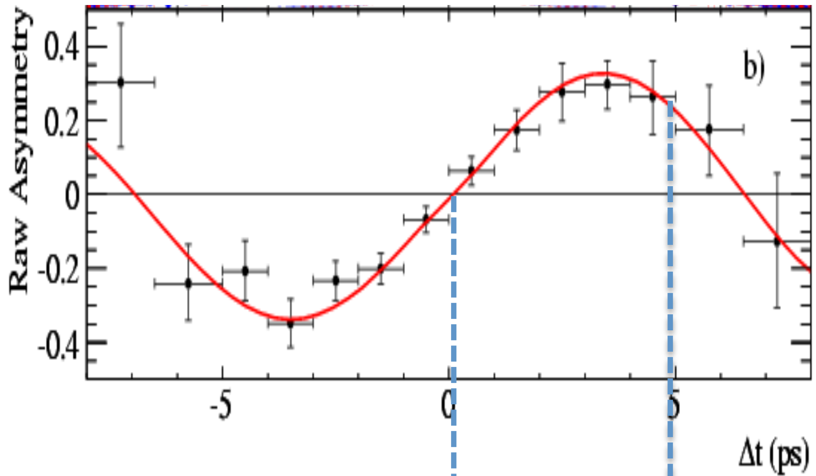
$$\mathcal{A}_{\mathcal{CP}}(t) = \frac{\Gamma_{\overline{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\overline{B}\to f}(t) + \Gamma_{B\to f}(t)} = \frac{\mathcal{A}^{dir}\cos(\Delta\mathrm{M}t) + \mathcal{A}^{mix}\sin(\Delta\mathrm{M}t)}{\cosh\left(\frac{\Delta\Gamma}{2}\mathrm{t}\right) - \mathcal{A}^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma}{2}\mathrm{t}\right)}$$

$$\left(\mathcal{A}^{dir}\right)^2 + \left(\mathcal{A}^{mix}\right)^2 + \left(\mathcal{A}^{\Delta\Gamma}\right)^2 = 1$$

- Extraction of $\mathcal{A}^{dir}$ and $\mathcal{A}^{mix}$ require flavour tagging: knowing the flavour of the B-meson at production
- Measure ϕ_d (SM: $\mathcal{A}^{mix} = \sin 2\beta$) and ϕ_s (SM: $\mathcal{A}^{mix} = -\sin 2\beta_s$)

ϕ_d : B-factory golden mode: $B^0 \to J/\psi\, K_s$



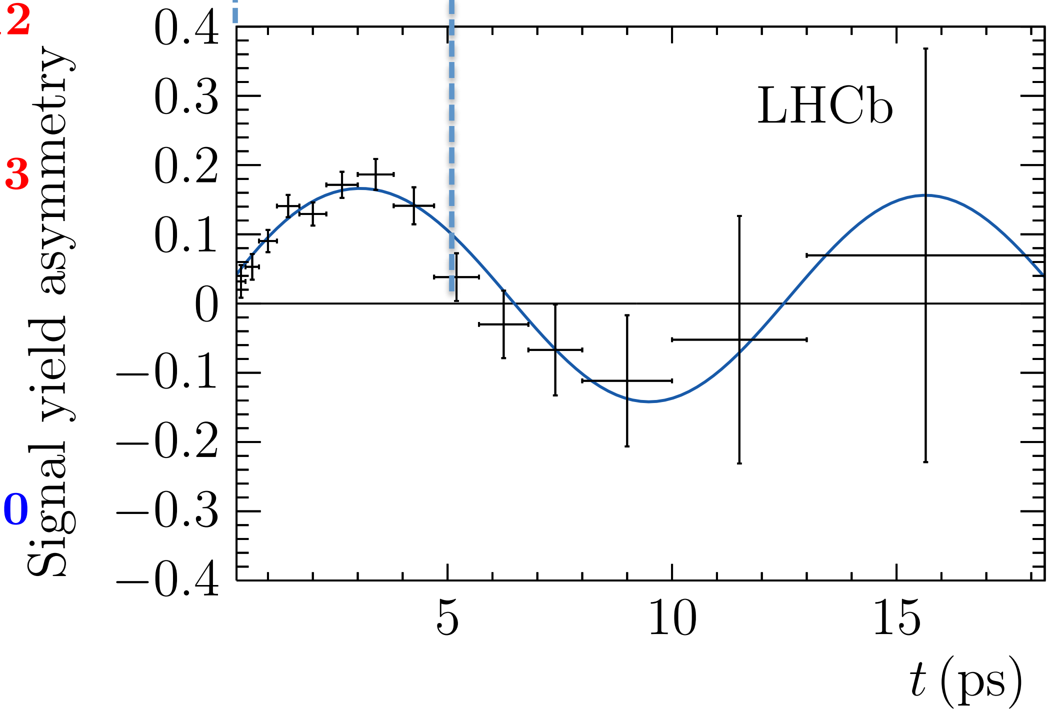


B-factories:

- Coherent production, clean flavour tag

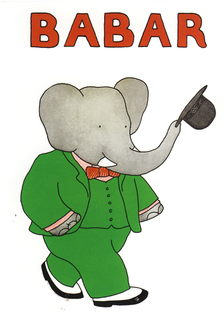
BaBar: Phys.Rev.D79 (2009) 072009
Belle: PRL 108 (2012) 171802

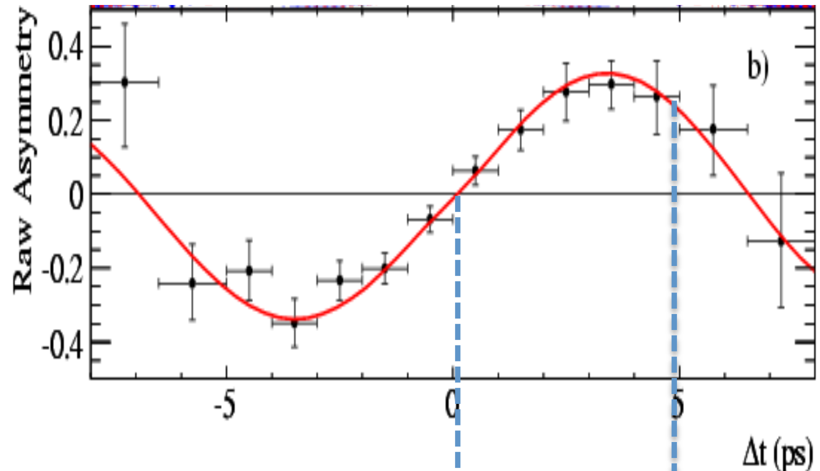
- Babar:
  $\sin 2\beta = 0.662 \pm 0.039 \pm 0.012$
- Belle:
  $\sin 2\beta = 0.670 \pm 0.029 \pm 0.013$
- LHCb: PRL. 115 (2015) 031601
  (Not so golden mode for LHCb: K_s decays often outside Velo)
  $\sin 2\beta = 0.731 \pm 0.035 \pm 0.020$



(CKM Mixing Phase: $\phi_d = 2\beta$)

ϕ_d : B-factory golden mode: $B^0 \rightarrow J/\psi\ K_s$

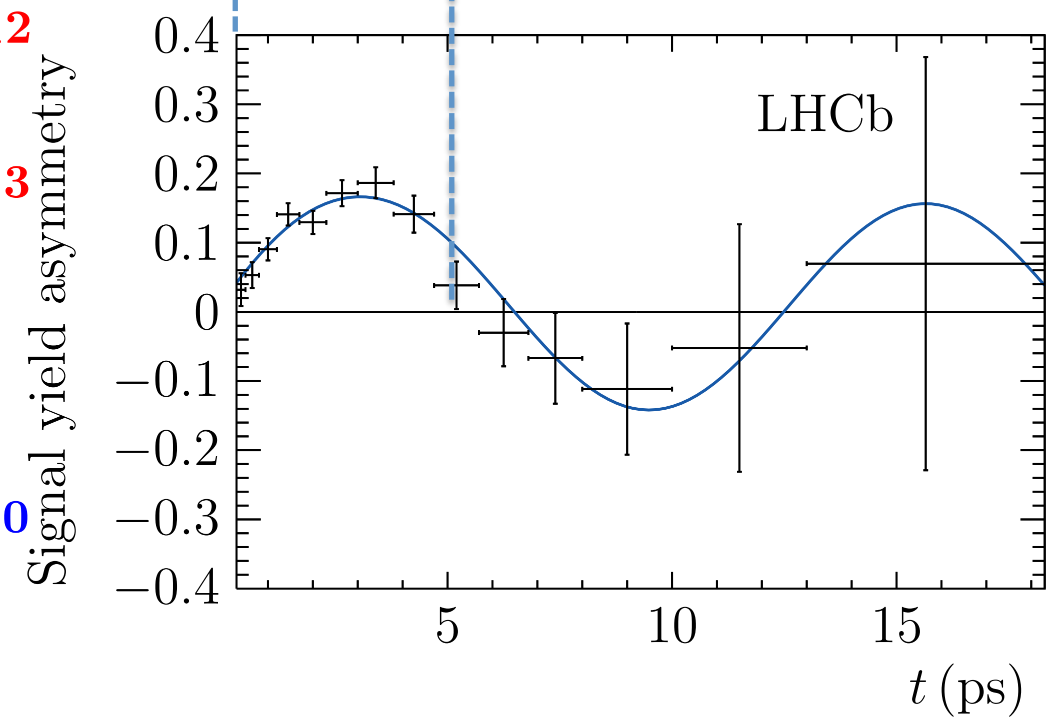




B-factories:
- Coherent production, clean flavour tag

BaBar: Phys.Rev.D79 (2009) 072009
Belle: PRL 108 (2012) 171802

- Babar:
  $\mathbf{\sin 2\beta = 0.662 \pm 0.039 \pm 0.012}$
- Belle:
  $\mathbf{\sin 2\beta = 0.670 \pm 0.029 \pm 0.013}$
- LHCb: PRL. 115 (2015) 031601
  (Not so golden mode for LHCb: K_s decays often outside Velo)
  $\mathbf{\sin 2\beta = 0.731 \pm 0.035 \pm 0.020}$



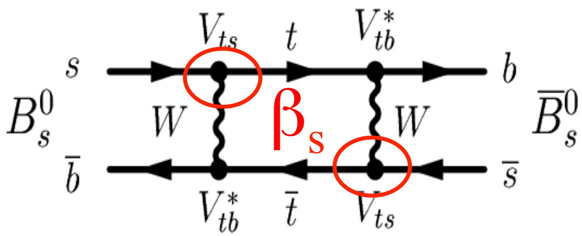
(CKM Mixing Phase: $\phi_d = 2\beta$)

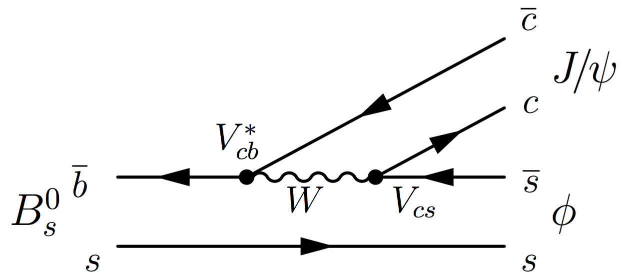
ϕ_s : LHCb golden mode: $B_s \to J/\psi\ \phi$

(CKM Mixing Phase: $\phi_s = -2\beta_s \approx 0$)

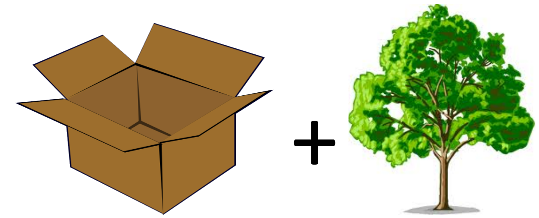
Two decay amplitudes to the same CP eigenstate final state.

1) via mixing $B_s \to \overline{B}_s \to J/\psi\ \phi$:

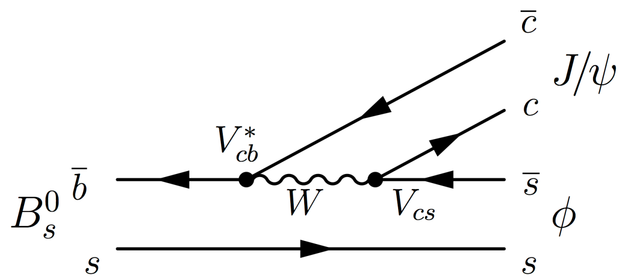




:



2) direct: $B_s \to J/\psi\ \phi$:

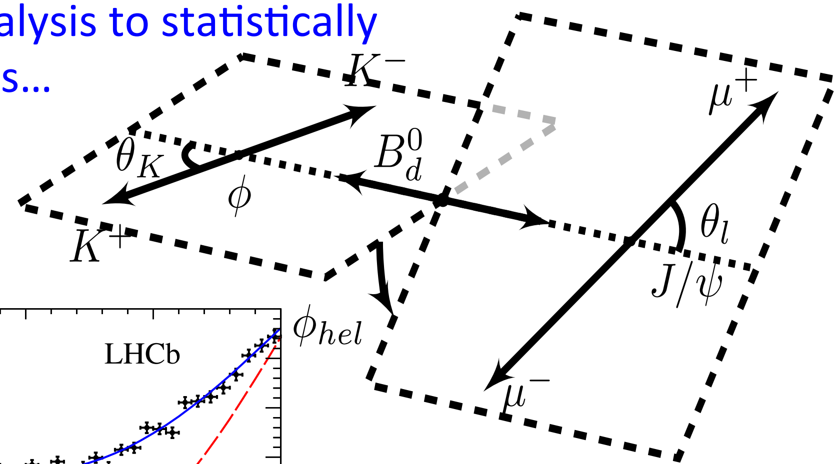


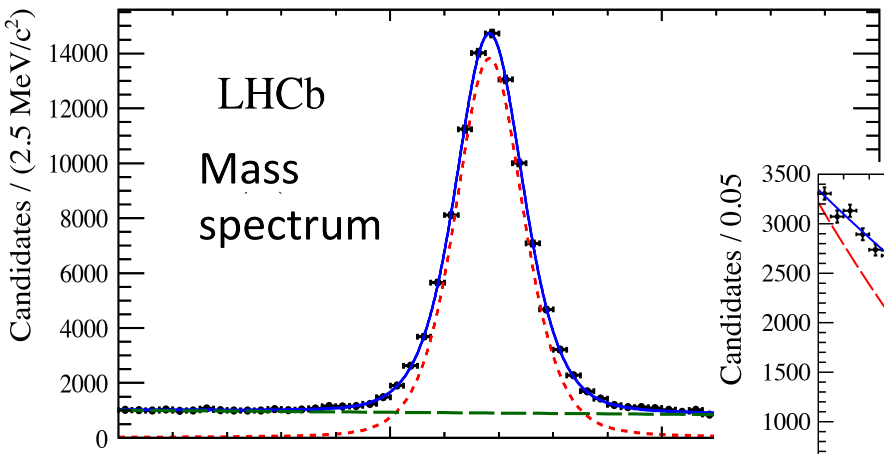
:

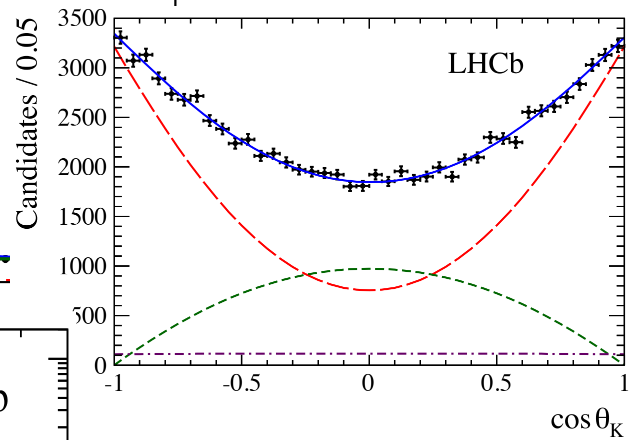
- Golden mode for a time dependent measurement of "ϕ_s via mixing diagram"
  - Hadronic uncertainties small
- Sensitive to new physics that enters via the mixing loop
- B_s is a *pseudoscalar* (s=0) while J/ψ and ϕ are *vector* particles (s=1)
  - Final state is superposition of CP even (L=0 and L=2) CP odd (L=1)
  - Requires angular analysis to disentangle
- Alternative analysis in pure CP odd eigenstate $B_s \to J/\psi\ \pi^+\pi^-$

ϕ_s : LHCb golden mode: $B_s \to J/\psi\ \phi$

- Requires combined decay time and angular analysis to statistically disentangle the CP even and CP odd amplitudes…

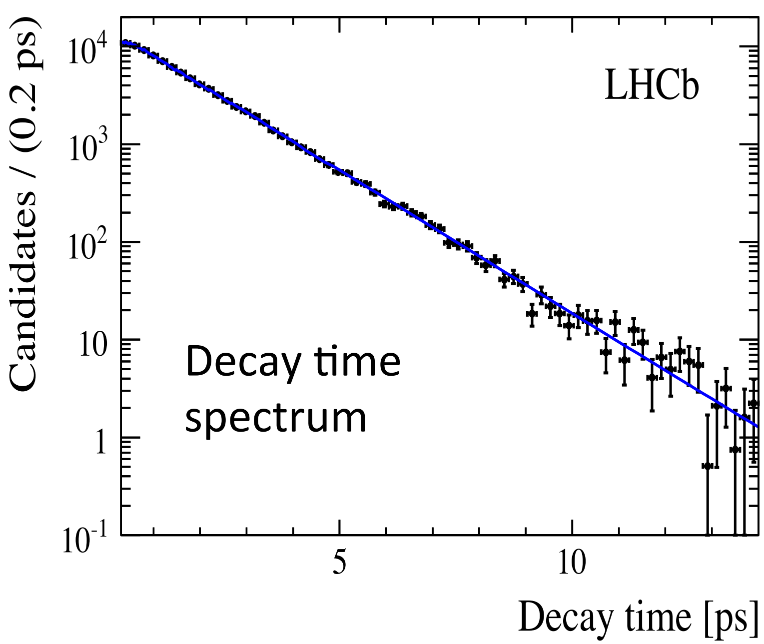


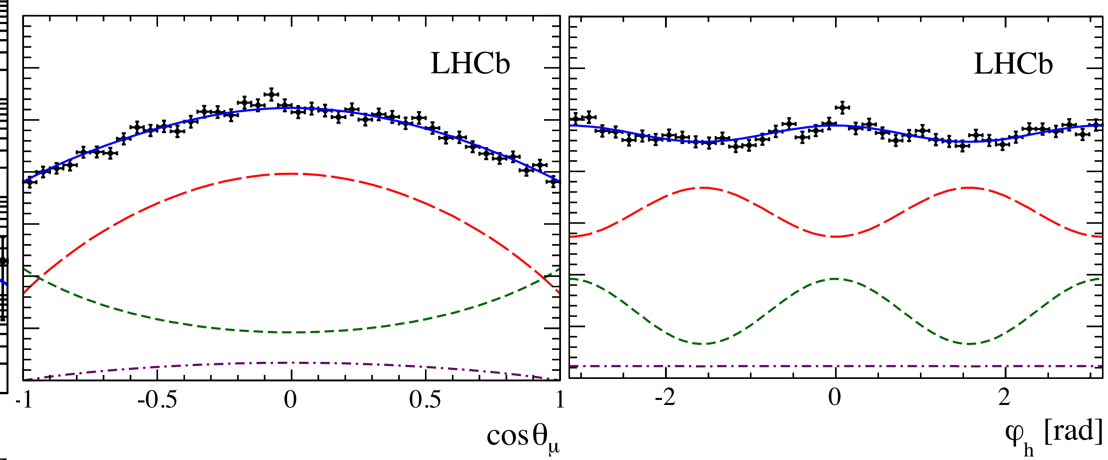




CP even

CP odd





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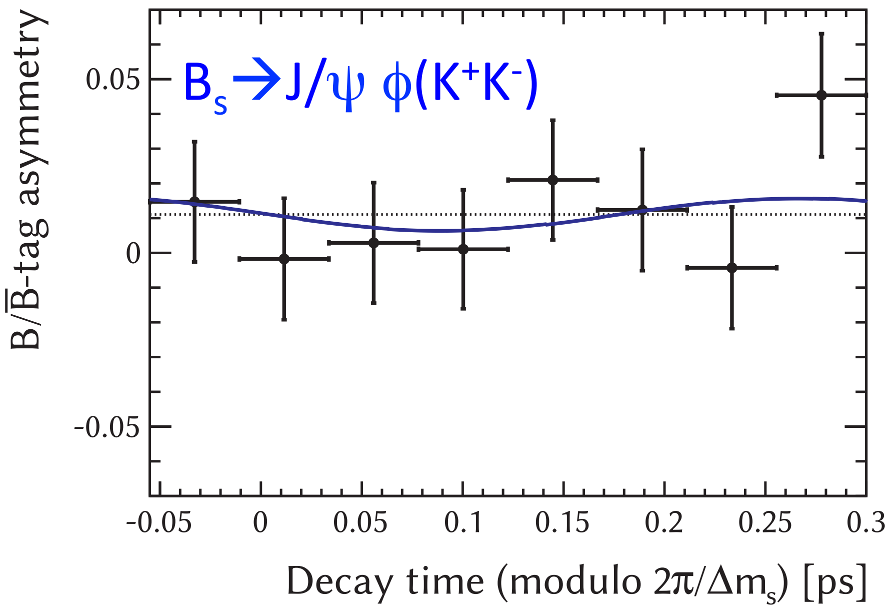

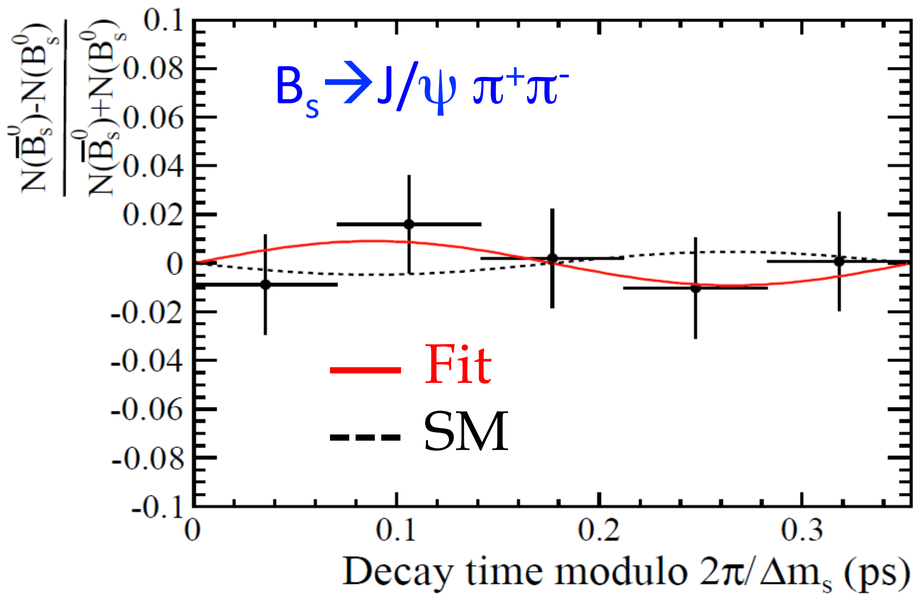

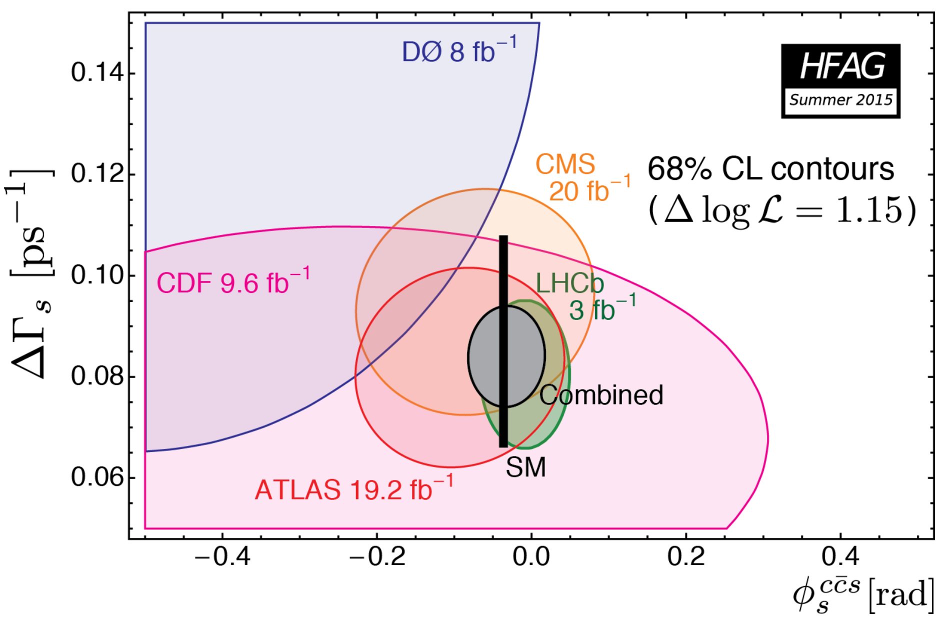

LHCb: **PRL 114 (2015) 041801**

ϕ_s = -0.010 +- 0.039 [rad]

Standard Model: **CKMFitter**

$\phi_s = -2\beta_s$ = -0.0376 +- 0.0008 [rad]

Consistent.

2011 + 2012 data: 3 fb^{-1}

Outline

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   a) Very Rare Decays: $B \rightarrow \mu\mu$

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5. Outlook

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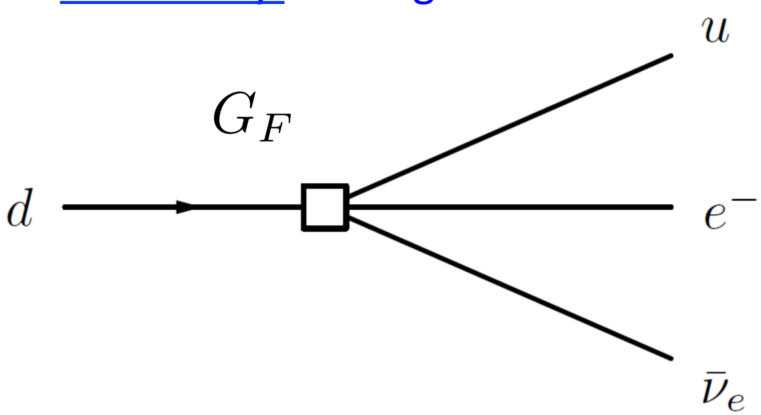
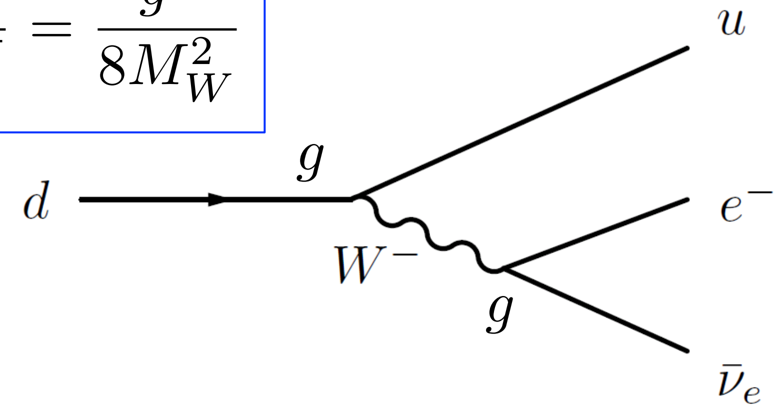
Effective Couplings

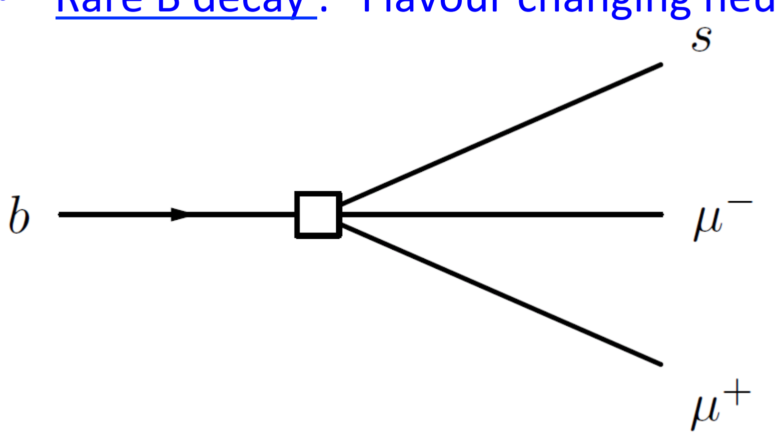
- Beta decay : "charged current":

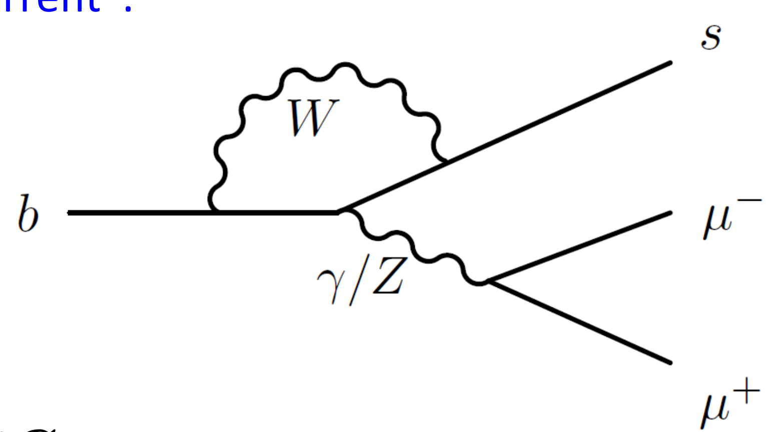
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$





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





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

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

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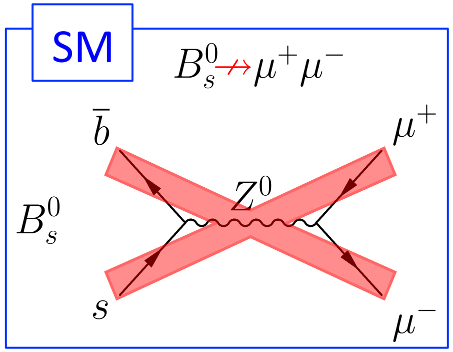
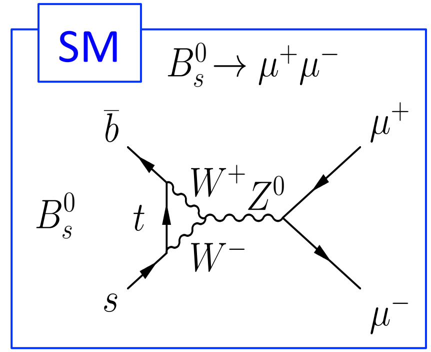
Very Rare Decays

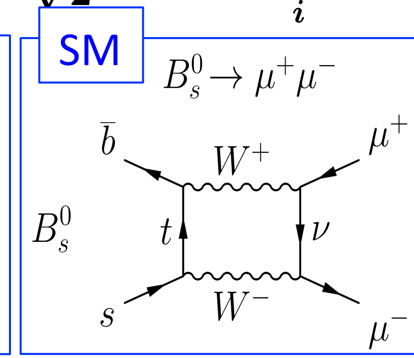
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{CKM} \sum_i \mathcal{C}_i \mathcal{O}_i$$

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

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





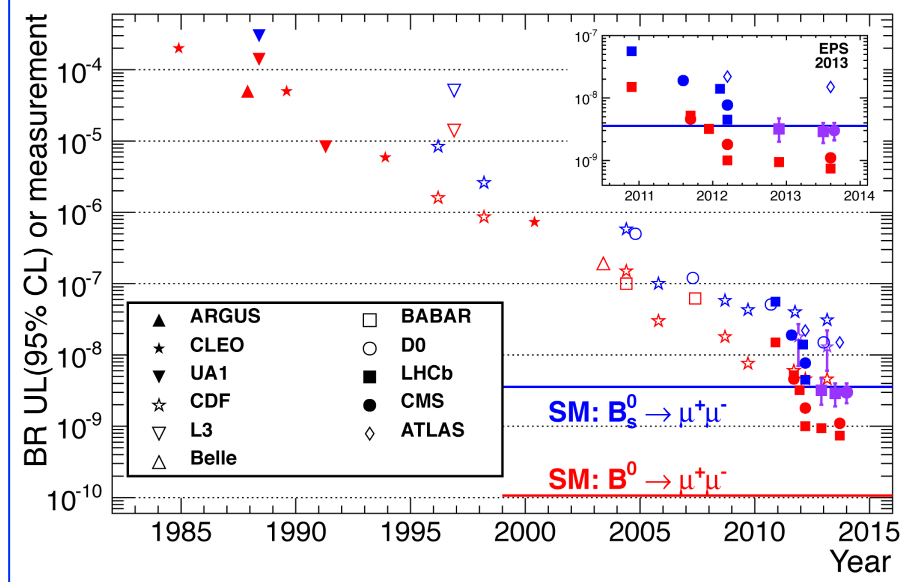


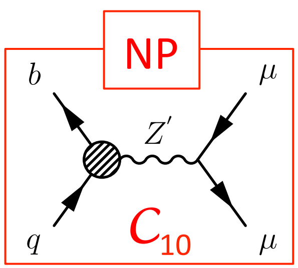
SM: CKM and helicity suppressed: very small B.R.
→ Axial vector coupling C_{10}

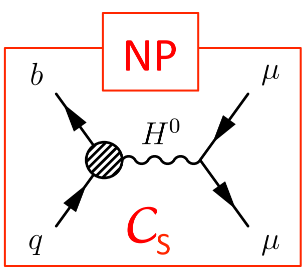
BR ($B_s^0 \rightarrow \mu^+\mu^-$) = $(3.66 \pm 0.23) \times 10^{-9}$
BR ($B_d^0 \rightarrow \mu^+\mu^-$) = $(1.06 \pm 0.09) \times 10^{-10}$

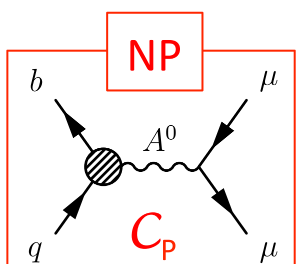
NP: Sensitive to new particles via additional (C_{10}, C_S, C_P) couplings.
→ e.g.: Z' , (pseudo-)scalars, ...

A 30-year quest for very rare decays....



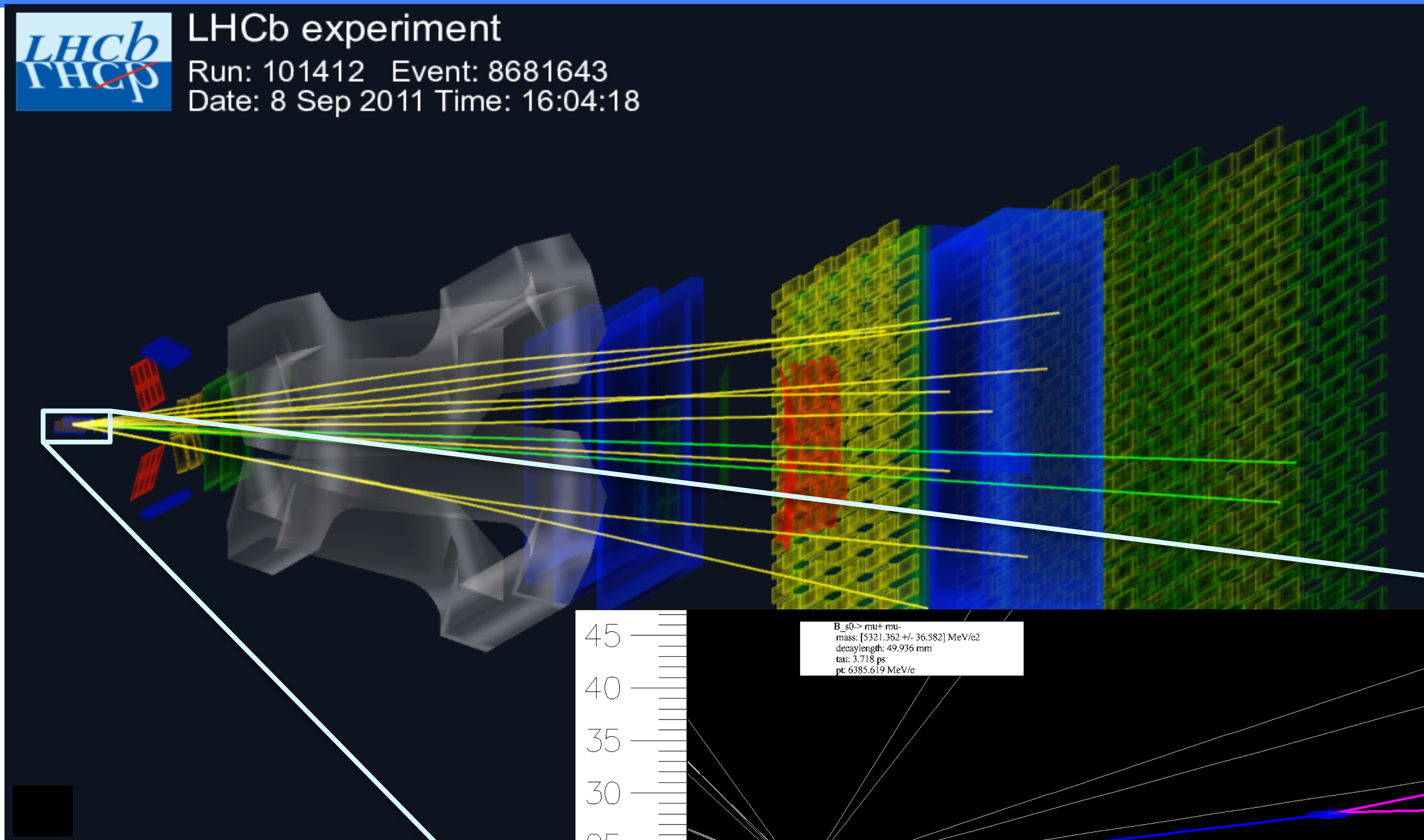


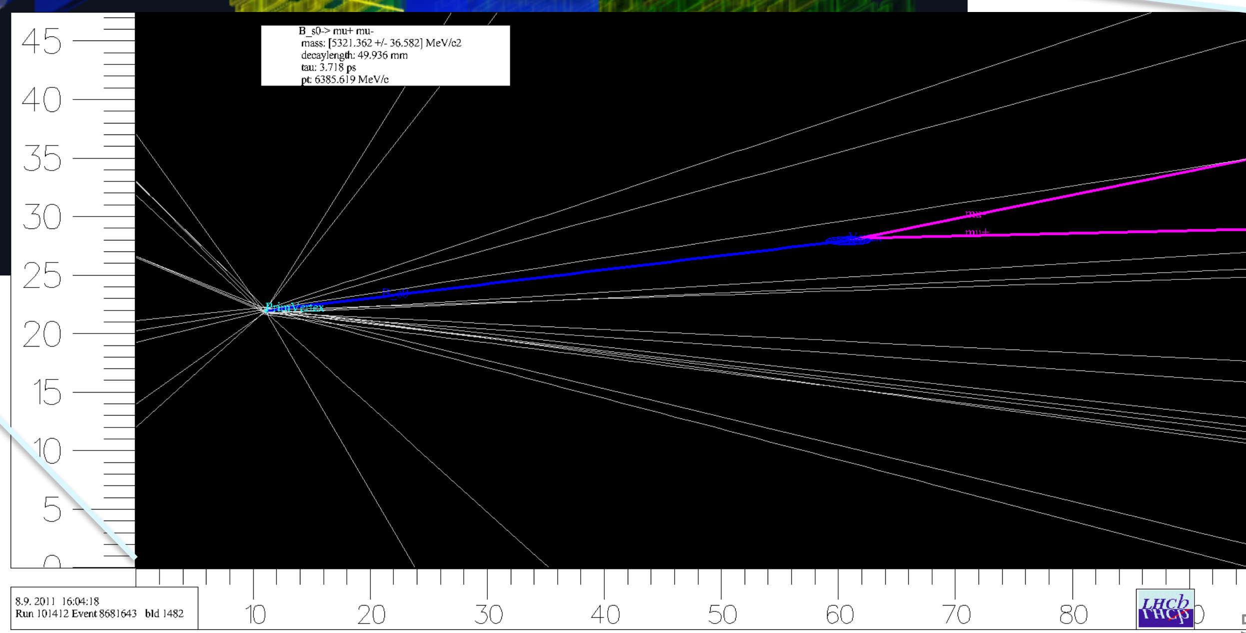




$$BR \propto |V_{tb}V_{tq}|^2 \left[\left(1 - \frac{4m_\mu^2}{M_B^2}\right) |C_S - C_S'|^2 + |(C_P - C_P') + \frac{2m_\mu}{M_B^2}(C_{10} - C_{10}')|^2 \right]$$

Very Rare Decays





Multivariate technique to suppress Backgrounds.

- Detached vertex
- Muon identification

Very Rare Decays

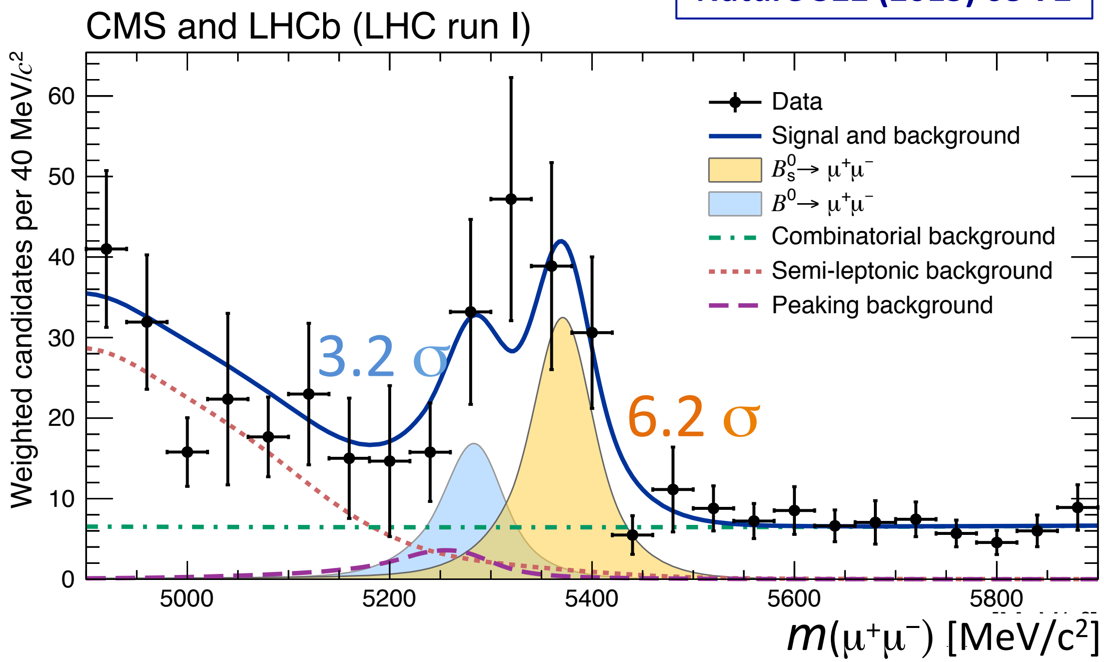
Nature 522 (2015) 68-72

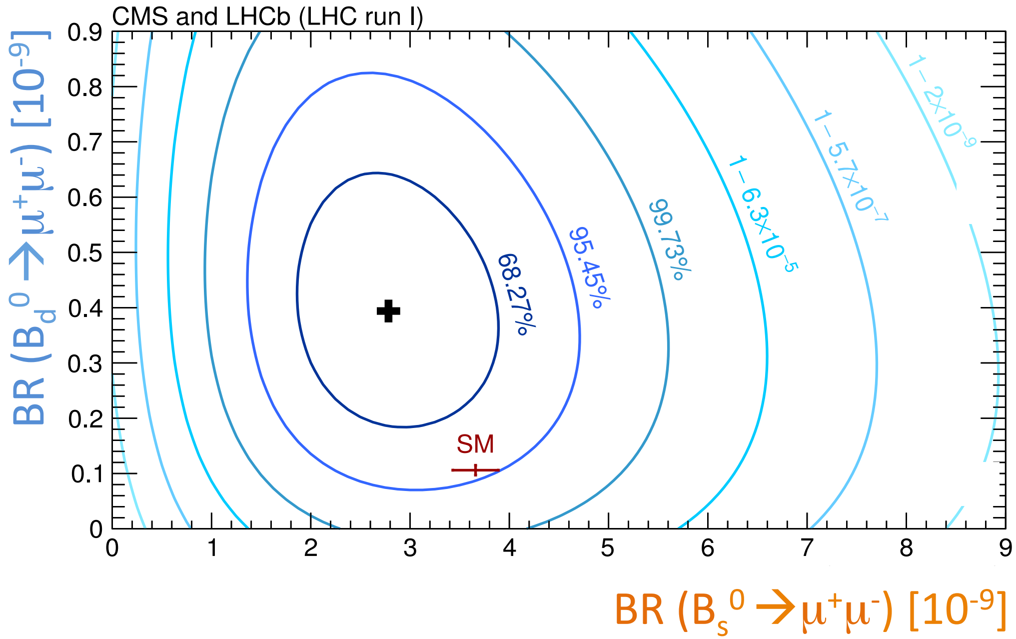
$B^0_{d/s} \rightarrow \mu^+\mu^-$

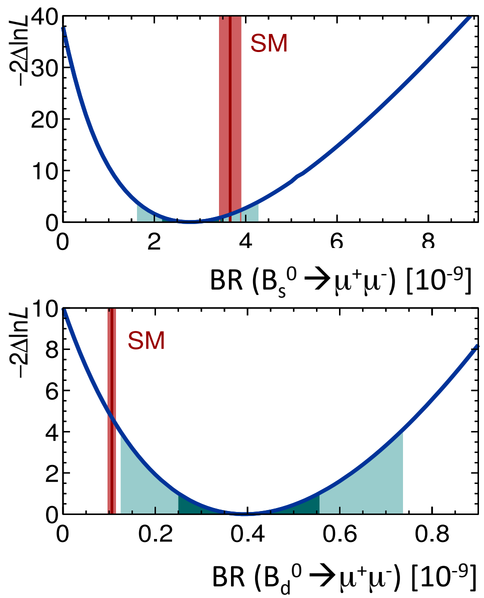
- LHCb + CMS combined signal:

BR ($B_s^0 \rightarrow \mu^+\mu^-$) = (2.8 ± 0.7) x 10^{-9}
BR ($B_d^0 \rightarrow \mu^+\mu^-$) = (3.9 ± 1.5) x 10^{-10}

Consistent with SM at ~ 2σ
Hot topic for LHC Run-2!







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      ◆ Sensitive probe for NP. $\mathcal{B}(B_d)$ too high?
   b) Rare Decays: $b\rightarrow s$ quark transition

   c) Lepton Flavour Universality tests

5. **Outlook**

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   ➔ **b) Rare Decays: b→s quark transition**

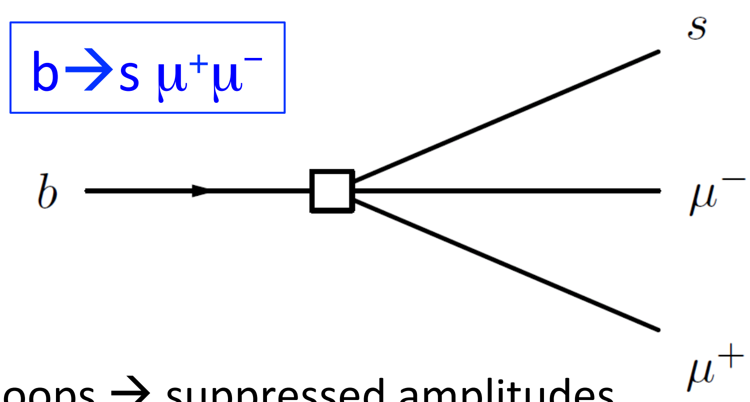
   c) Lepton Flavour Universality tests
5. **Outlook**

b →s quark transition

- Effective 4-fermion coupling:

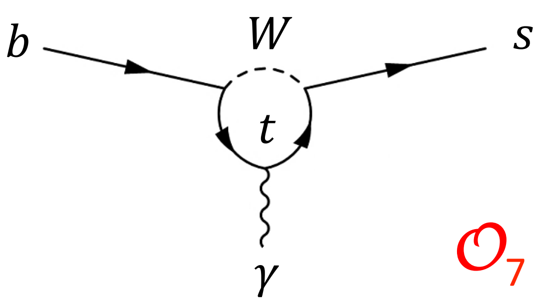
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

b→s $\mu^+\mu^-$

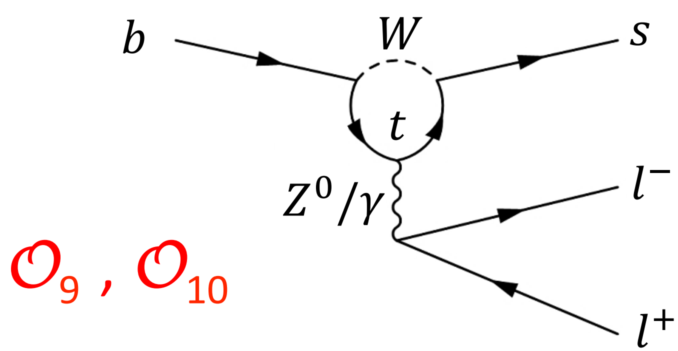


- Standard Model:
  - No flavour changing neutral currents: loops → suppressed amplitudes

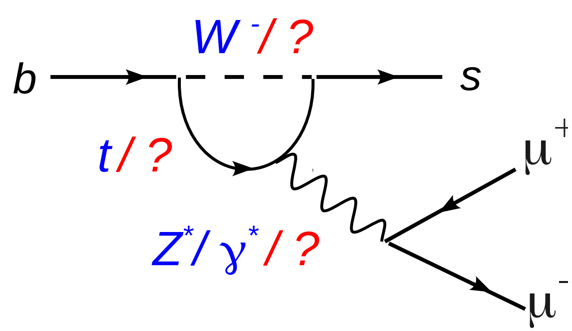
Photon penguin:



Vector, Axial vector:



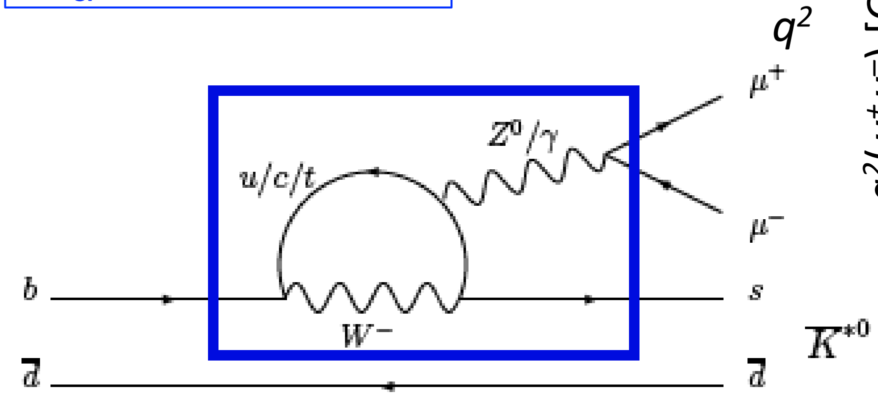
- New Physics:
  - Sensitivity for NP in Wilson coefficients C_7, C_9, C_{10}

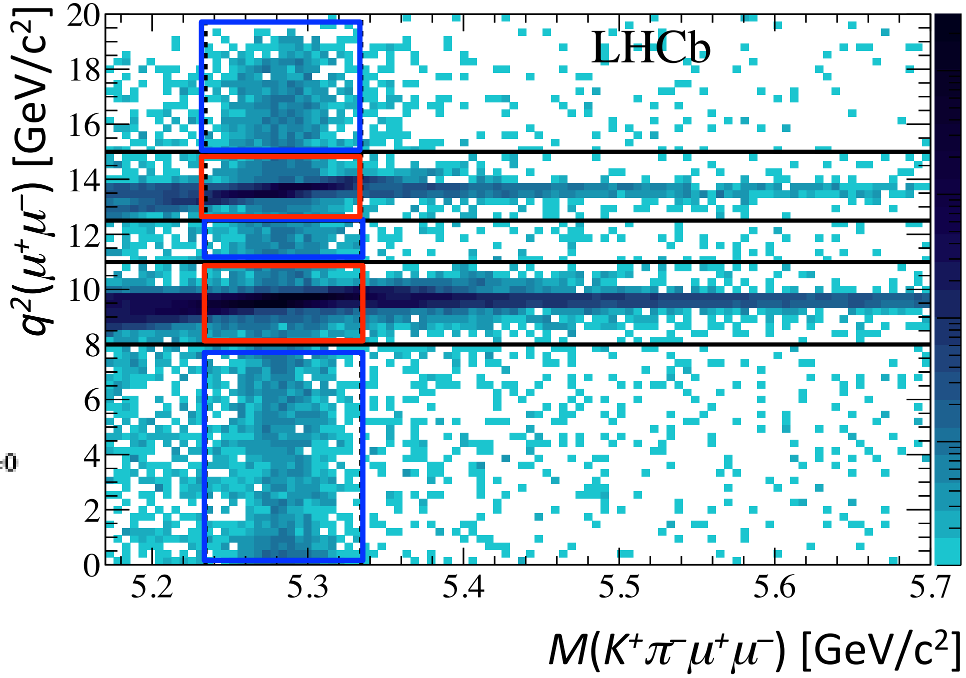


Rare Decays: b → s $\mu^+\mu^-$

arXiv:1512.044442

$B_d^0 \rightarrow K^* \mu^+\mu^-$





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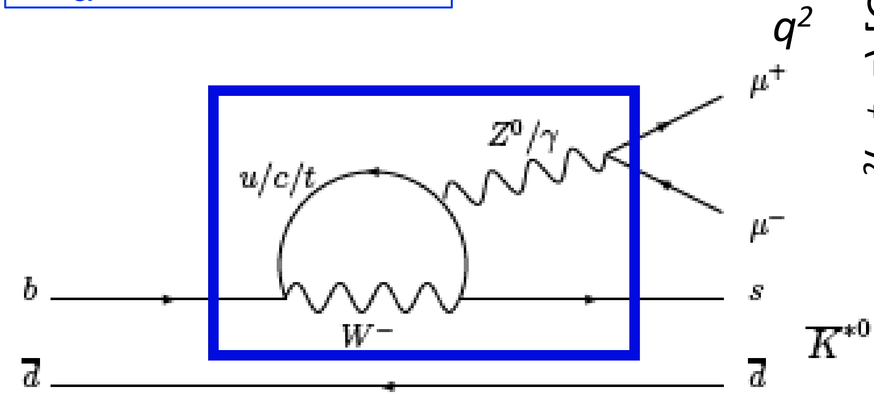
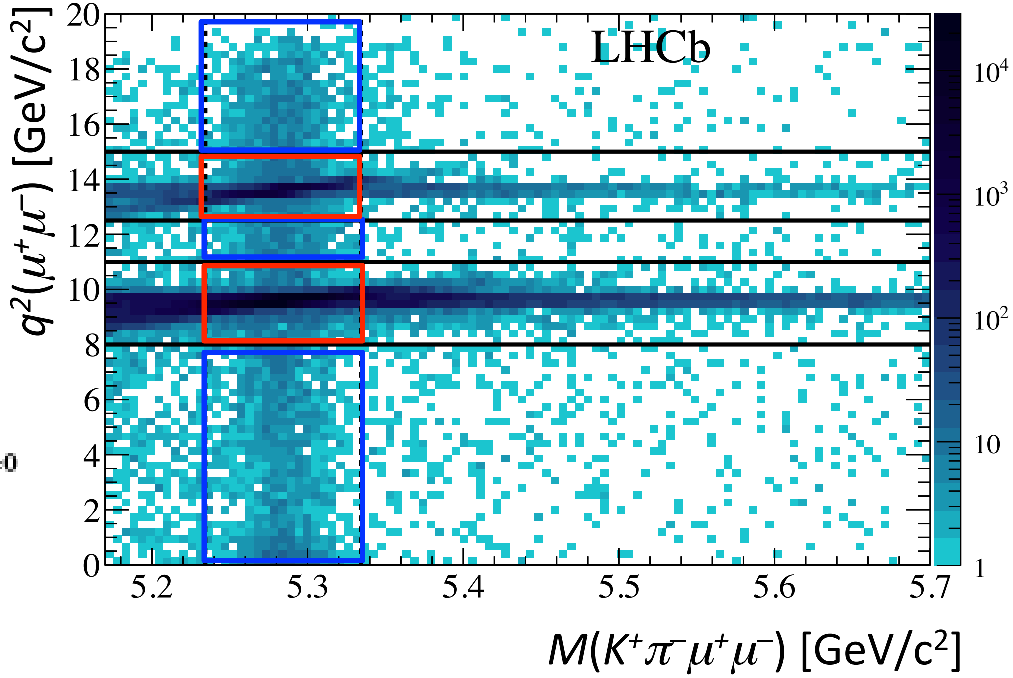
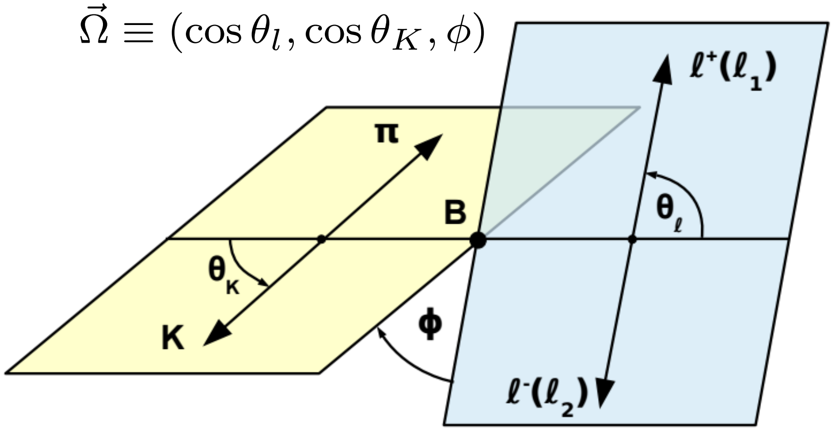




- Study the angular distribution of the final state particles:

$\vec{\Omega} \equiv (\cos\theta_l, \cos\theta_K, \phi)$



$$\frac{d^4\Gamma[\overline{B}^0 \rightarrow K^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi} \sum_j I_j(q^2) f_j(\vec{\Omega})$$

$I_j \rightarrow \overline{I}_j$ for B^0

– Observables:

$$S_j = (I_j + \overline{I}_j) \;/\; \left(\frac{d\Gamma}{dq^2} + \frac{d\overline{\Gamma}}{dq^2}\right)$$

$$A_j = (I_j - \overline{I}_j) \;/\; \left(\frac{d\Gamma}{dq^2} + \frac{d\overline{\Gamma}}{dq^2}\right)$$

Rare Decays: $b \to s \mu^+\mu^-$

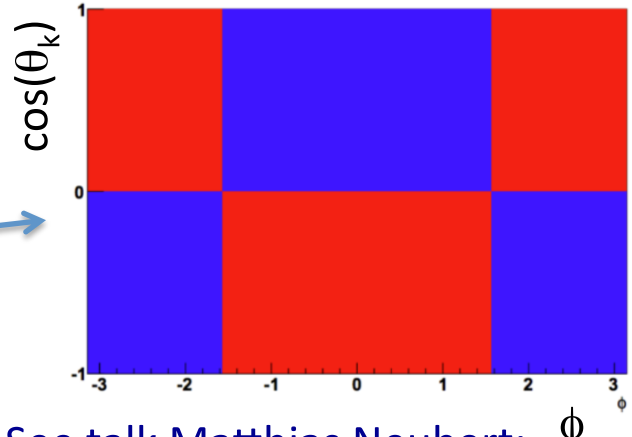
arXiv:1512.044442

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

Observables S_5, P'_5:

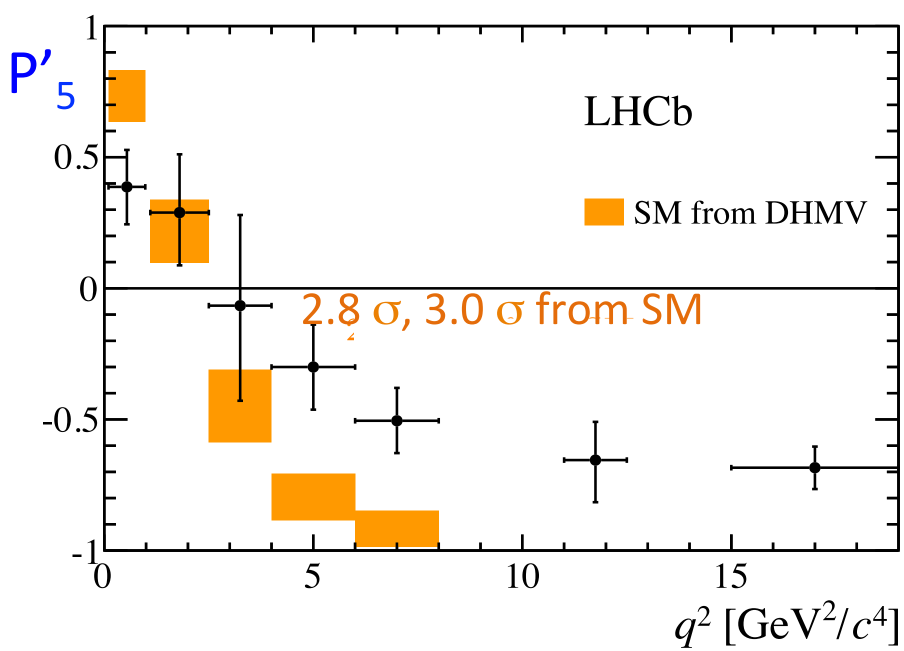
- S_5 variable: count blue minus red
- "Robust" P'_5 variable: $P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$

(F_L = longitudinal polarisation K*)

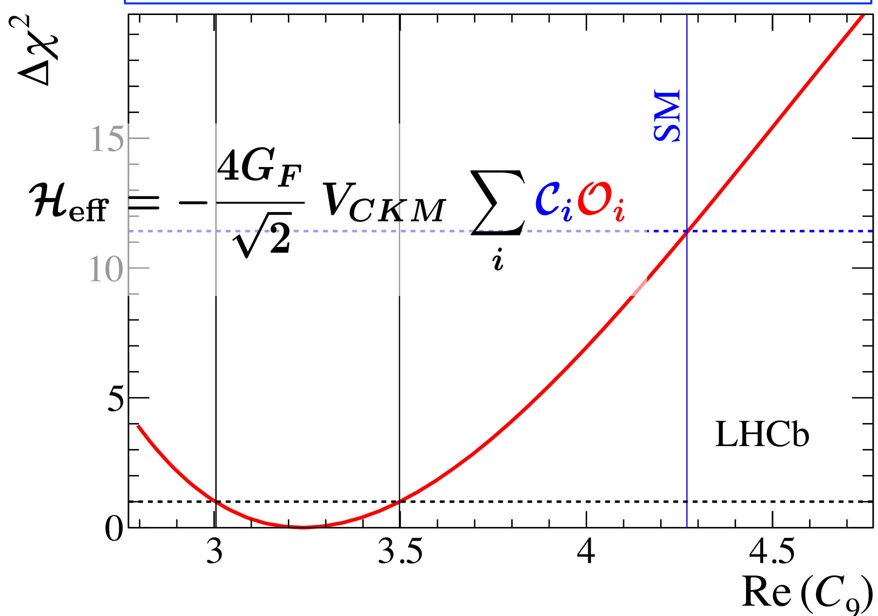


See talk Matthias Neubert:

P'_5 vs q^2 shows deviations from SM:



Fit the value of Wilson coefficient:
$C_9 = C_9^{SM} + C_9^{NP}$ points at $C_9^{NP} \sim -1$



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

Warning: hadronic uncertainties ($c\bar{c}$)

Rare Decays: b → s $\mu^+\mu^-$

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

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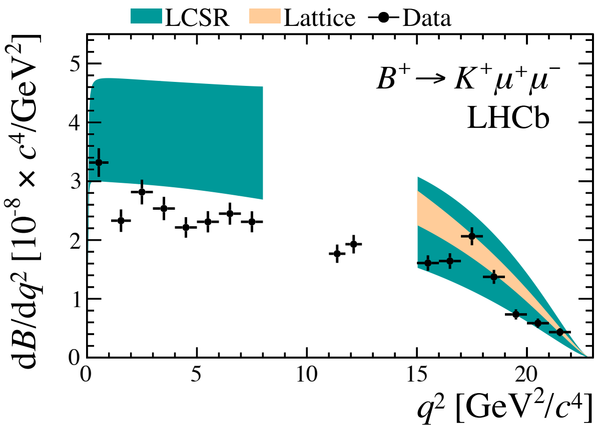

$B^0 \to K^0\mu^+\mu^-$

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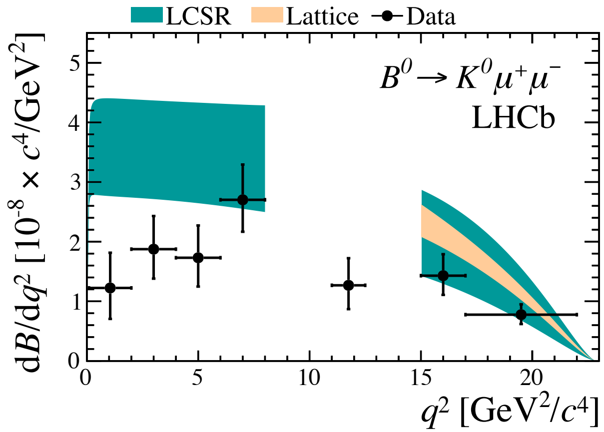

$B^+ \to K^{*+}\mu^+\mu^-$

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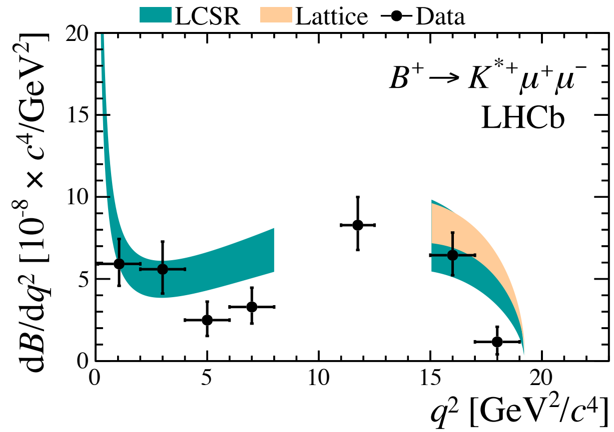

$B^0 \to K^{*0}\mu^+\mu^-$

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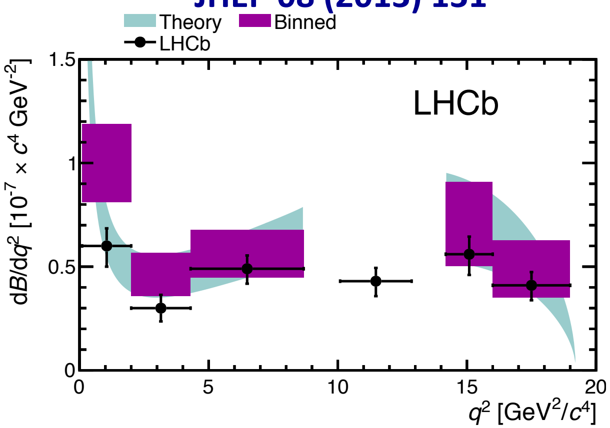
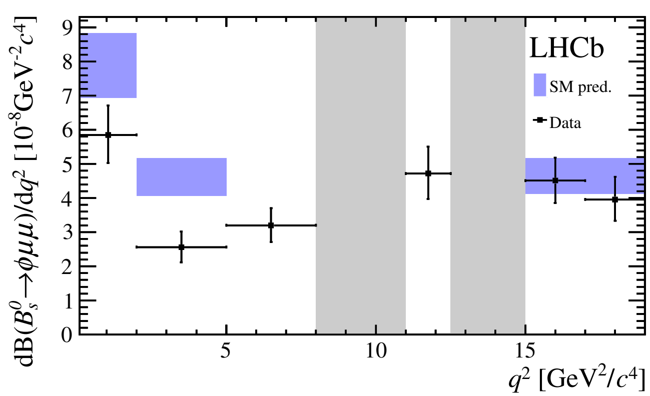


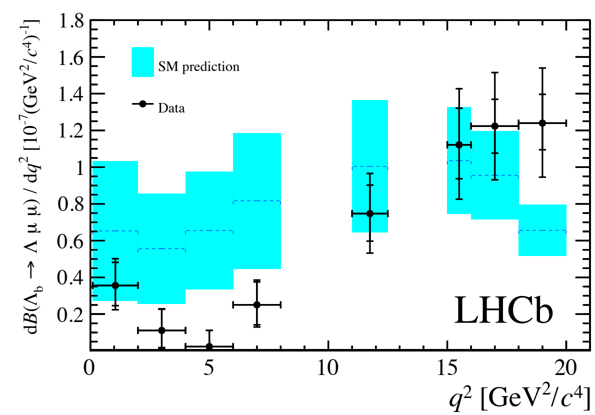
$B_s \to \phi\mu^+\mu^-$

JHEP 09 (2015) 179



$\Lambda_b \to \Lambda\mu^+\mu^-$

JHEP 06 (2015) 115



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

Outline

1. Flavour Physics

2. The LHCb Experiment

3. CP Violation Measurements
   a) CP Violation in B-mixing: a_{sl}^{d} and a_{sl}^{s}
      ◆ Unlike kaons, no large CPV, in agreement with SM.
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4. **B Decay Rates**
   a) Very Rare Decays: $B \rightarrow \mu\mu$
      ◆ Sensitive probe for NP. $\mathcal{B}(B_d)$ too high?
   ➔ **b) Rare Decays: b→s quark transition**
      ◆ ~ 4σ deviations from SM observed. Theory uncertainties?
   c) Lepton Flavour Universality tests

5. **Outlook**

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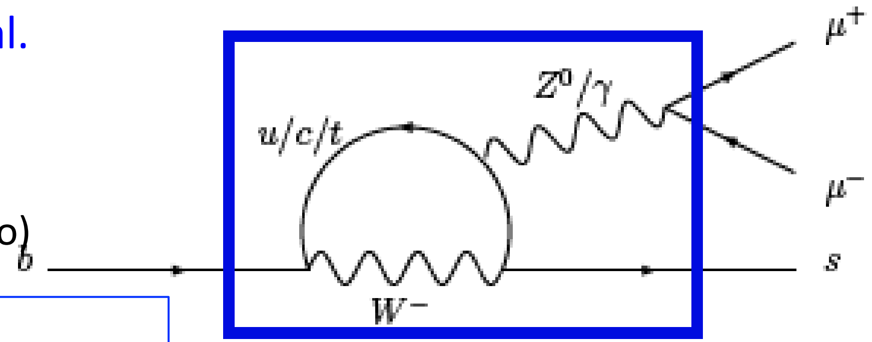
Lepton Universality: $B^+ \to K^+ \mu^+\mu^-$ / $B^+ \to K^+ e^+e^-$

- Standard Model: $b \to s\, l^+l^-$ is flavour universal.
- Expect equal branching fractions for $b \to s\, \mu^+\mu^-$ and $b \to s\, e^+e^-$
  - (Hadronic uncertainties largely cancel in the ratio)



$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \stackrel{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-2})$$

(R_{K^*} coming soon)

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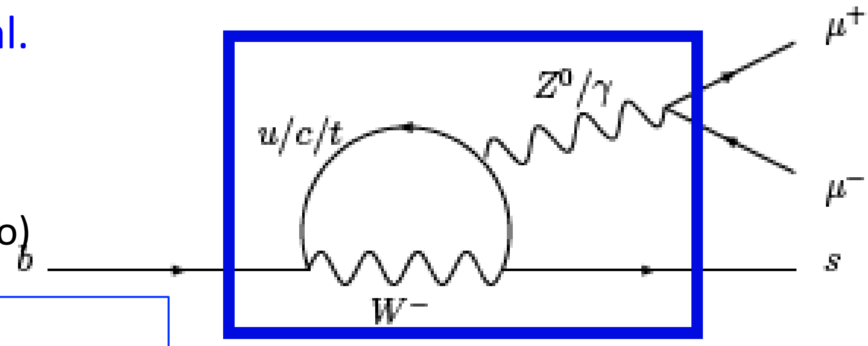

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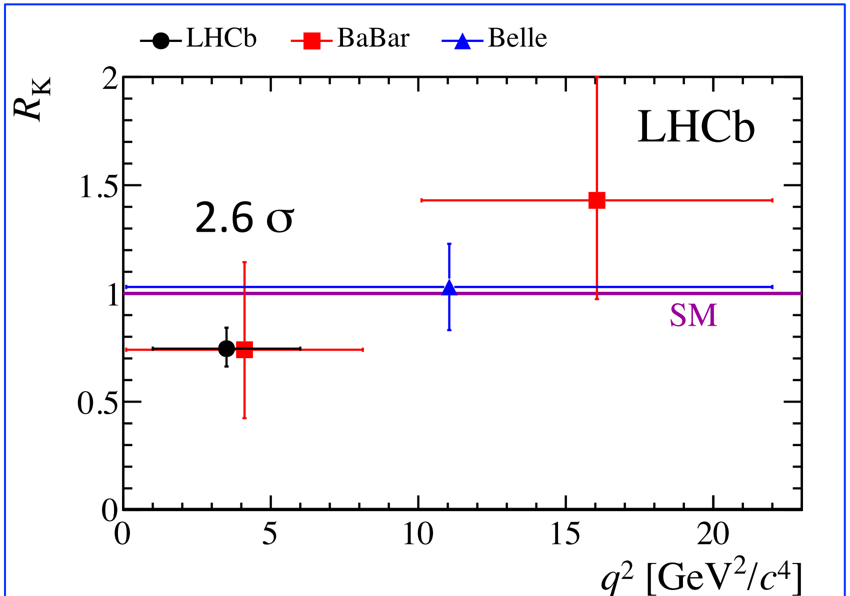
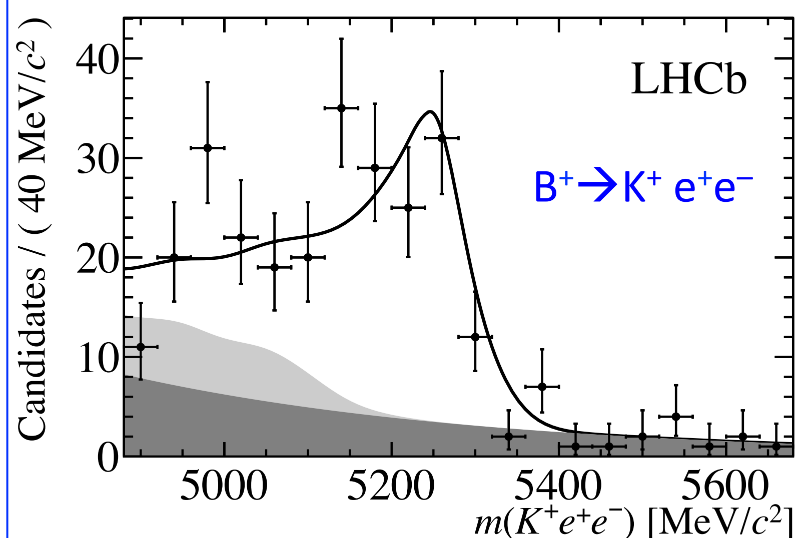
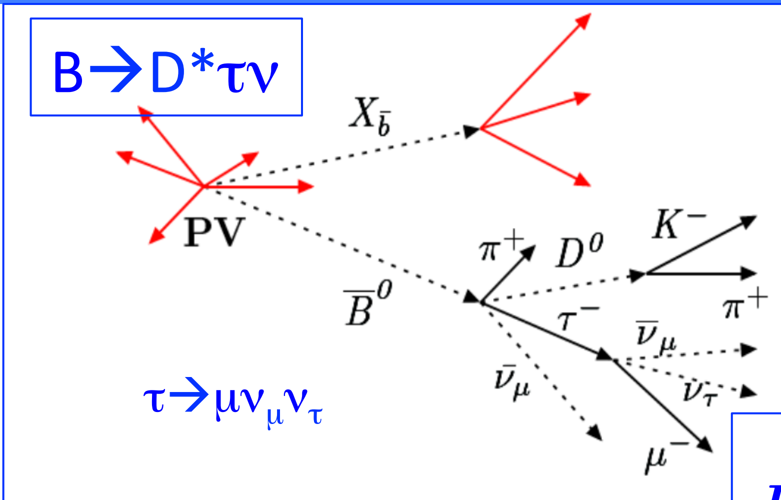


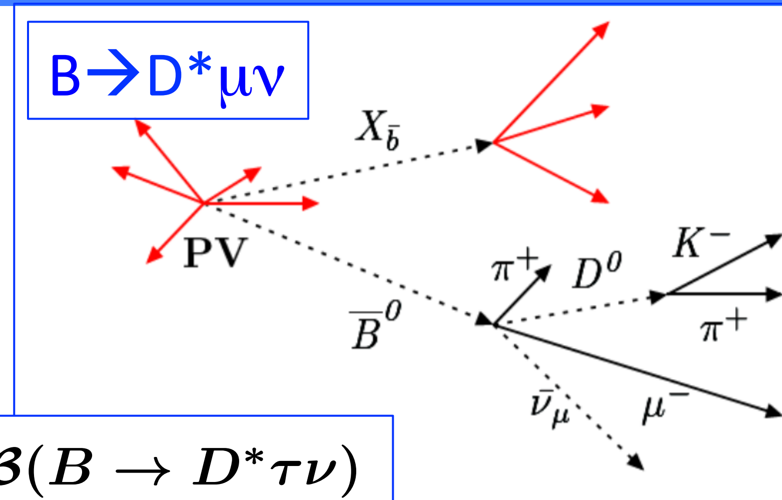


$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$R_K \neq 1$ would imply NP with non-universal lepton couplings.

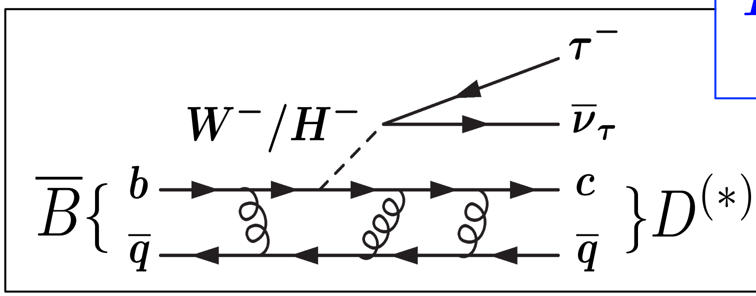
Lepton Universality: B → D*τν / B → D*μν



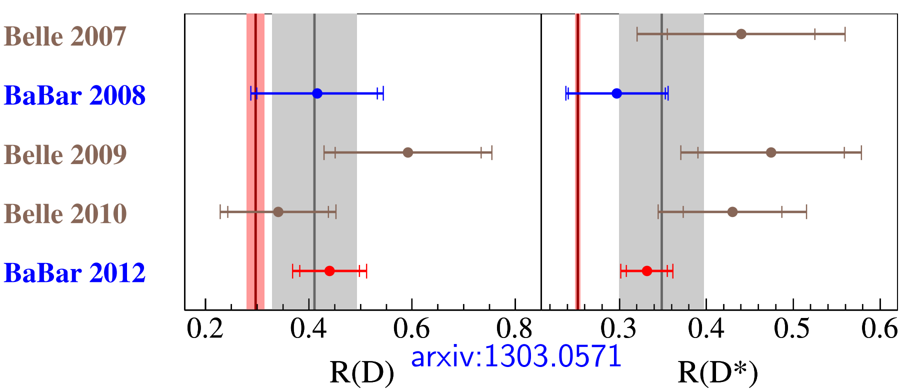


$$R_{D^*} \equiv \frac{\mathcal{B}(B \to D^*\tau\nu)}{\mathcal{B}(B \to D^*\mu\nu)}$$

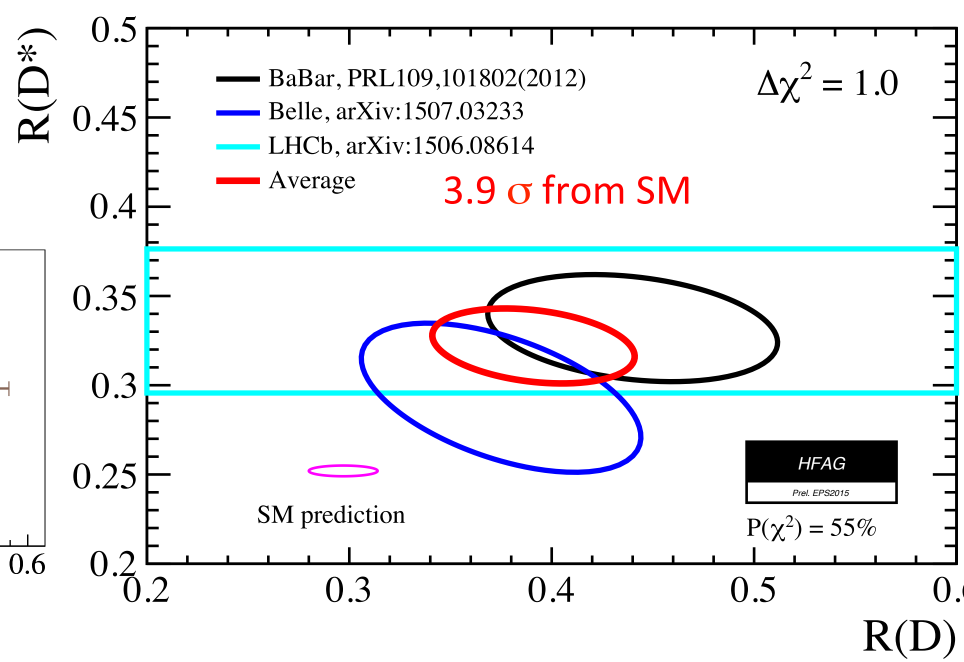
(≠ 1 due to phase space!)



Before LHCb:



arxiv:1303.0571



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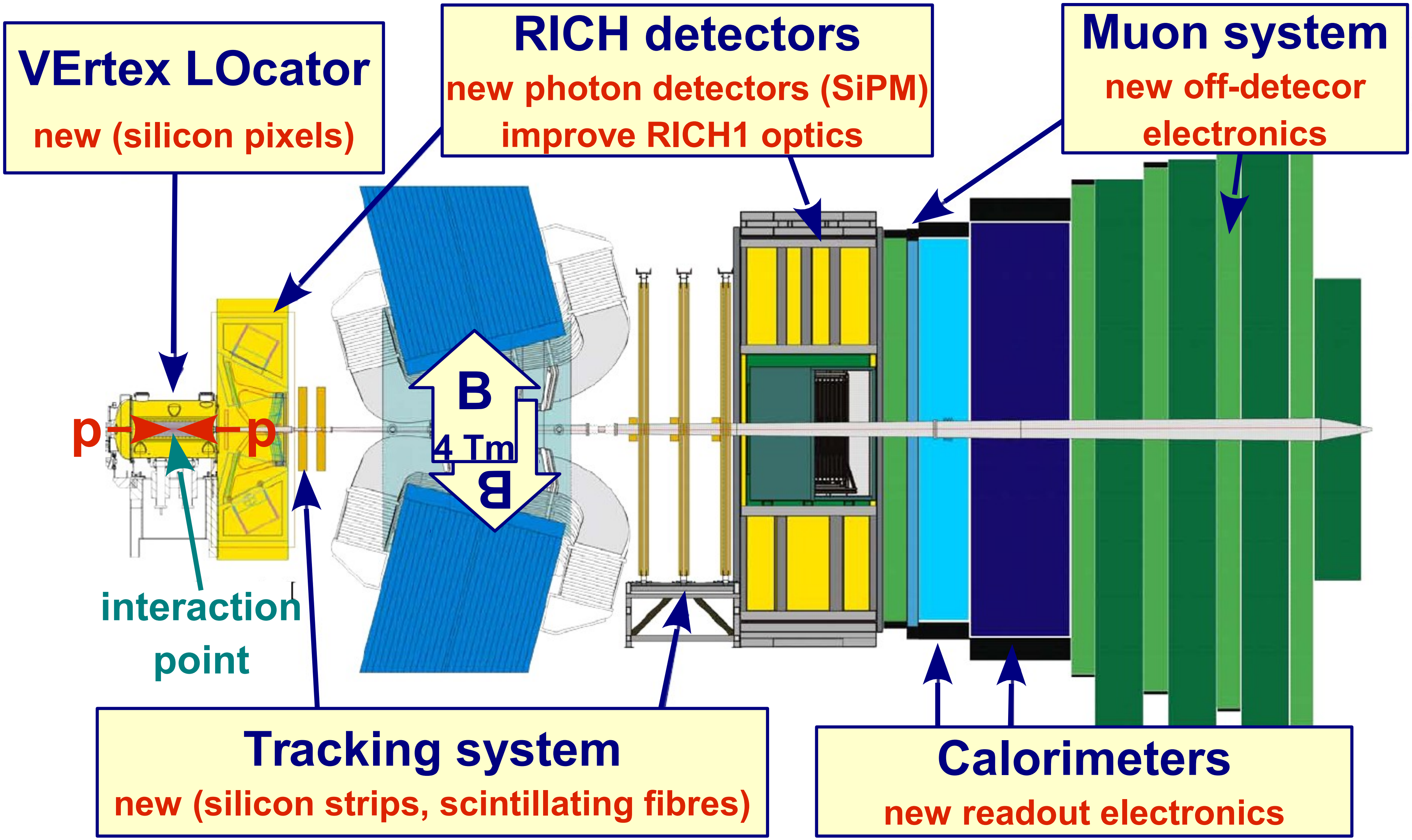
The Future – LHCb Upgrade



The Future – LHCb Upgrade

Triggers today

Triggers in the future

Gligorov 2014

Expected statistical uncertainties before and after upgrade

before upgrade | after upgrade | Theory uncertainty

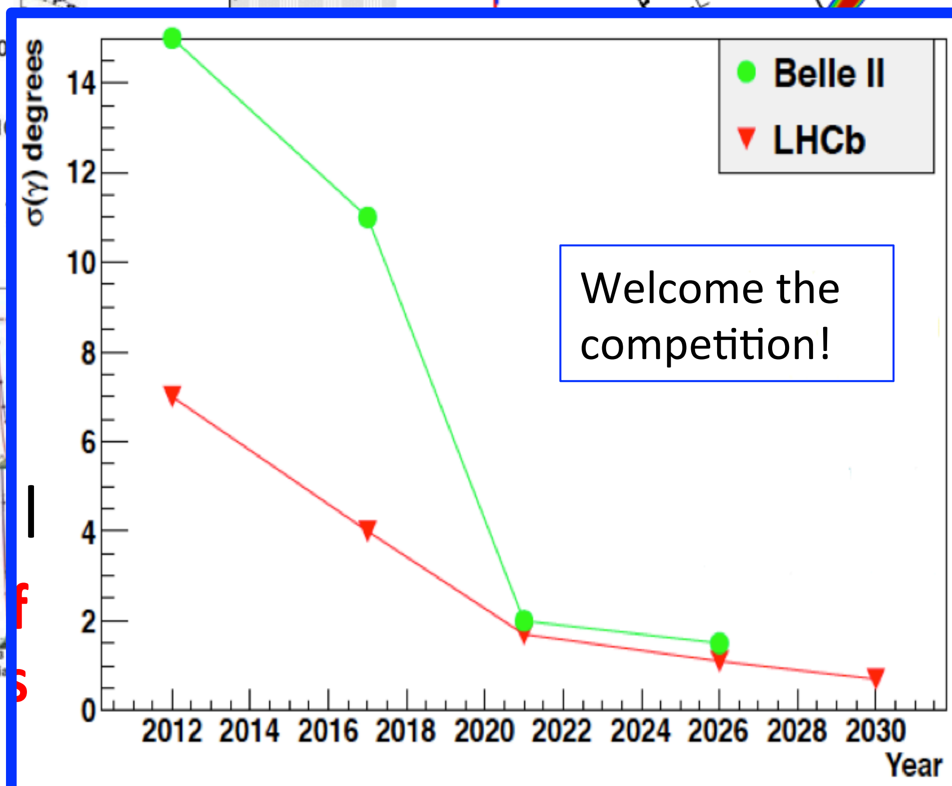
Type	Observable	LHC Run 1	LHCb 2018	Upgrade 50/fb	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

Comparable precision for experiment & theory after upgrade.

LHCb is more than b-physics...

General Purpose detector in the forward region:

- Charm physics
- Electroweak Physics: W, Z
- Exotica & Majorana particles searches
- Spectroscopy (see S. Neubert)
- QCD & Heavy Ion physics (Pb-Pb, p-Pb) (see M. Schmelling)
- Focus on b-physics remains



Thank you for your attention!