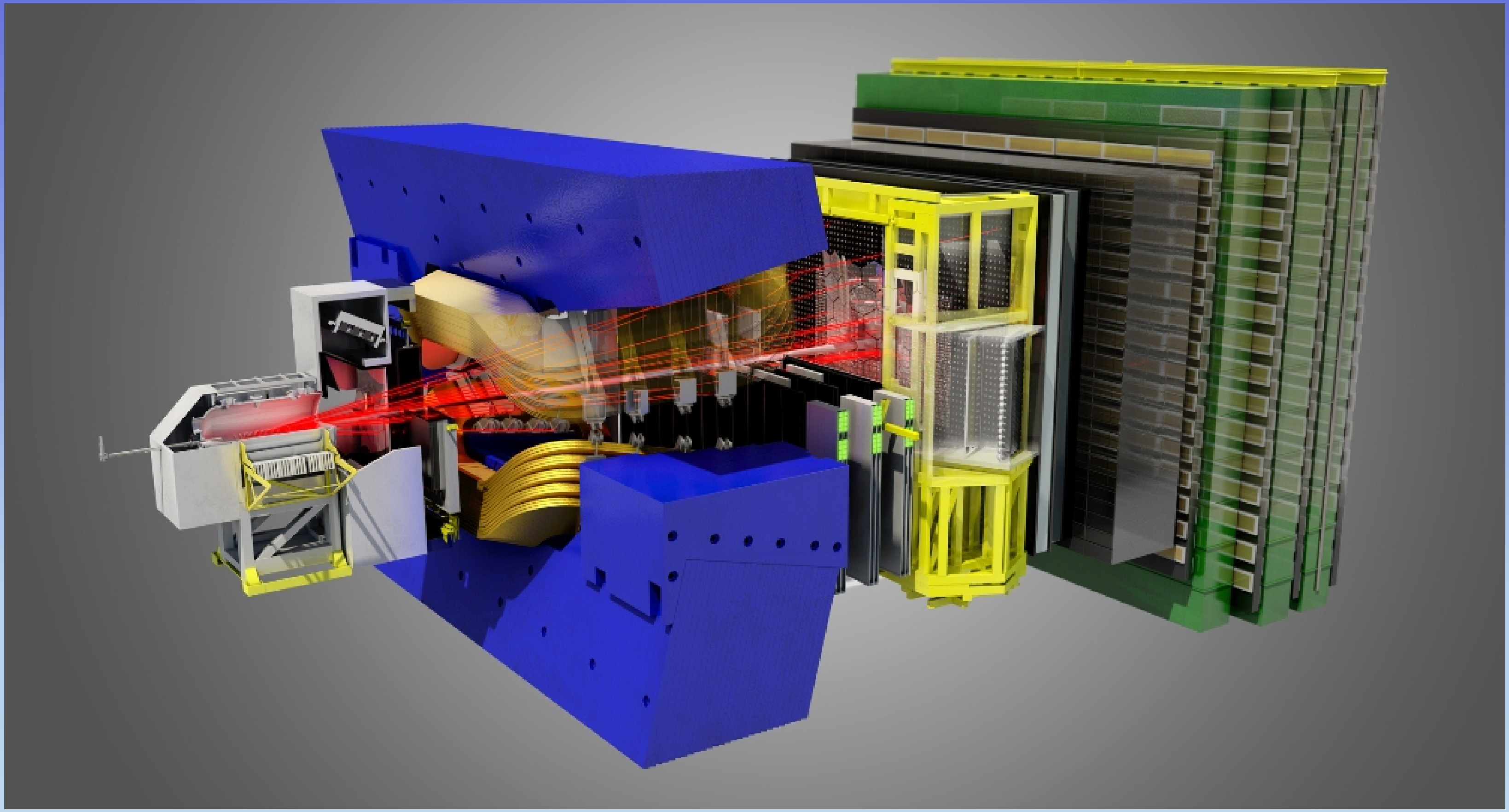
IDPASC 2018, 21st-31st May, Valencia, Spain

Experimental Flavour Physics



Arantza Oyanguren (IFIC – CSIC/UV)

Outline

- Introduction
- The LHCb experiment
- The CKM matrix
- B mixing and CP violation
- Rare decays of B mesons
- Future plans

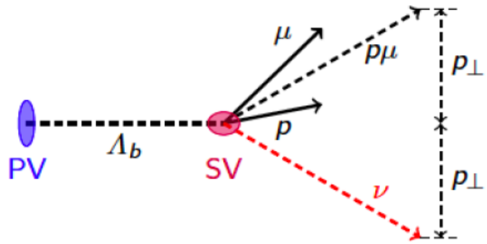
The CKM matrix

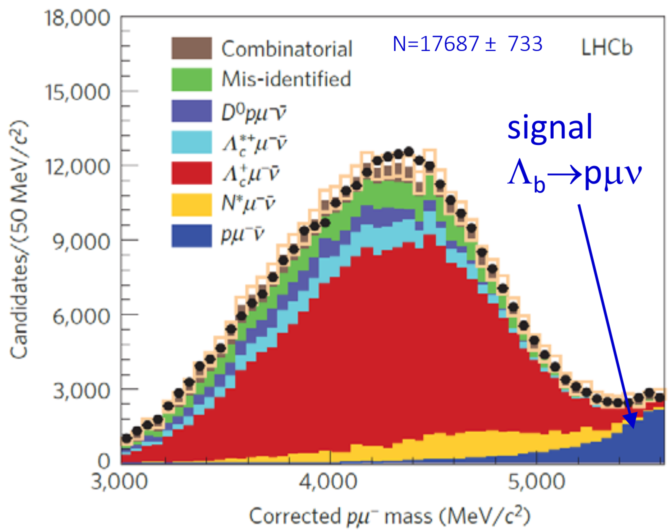
At LHCb very challenging due to the missing neutrino:

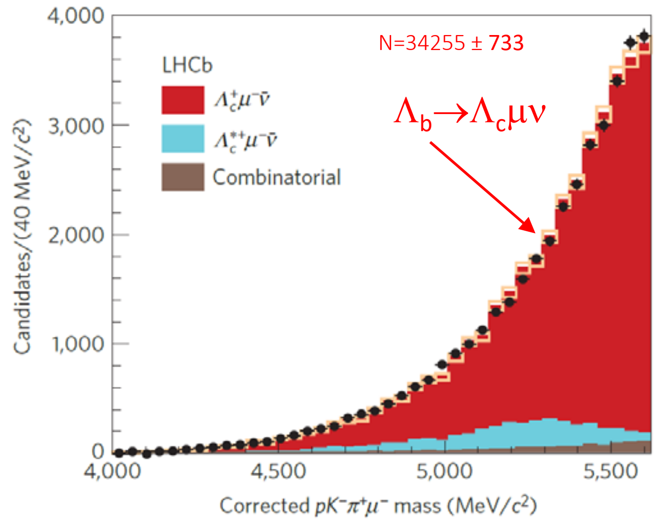
Using semileptonic decays of b-baryons:

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} = \frac{|V_{ub}|^2}{|V_{cb}|^2}$$ x Ratio of form factors ← (5% accuracy from LQCD)

- Use information from displaced vertex
- Select high q^2 region (theory more precise)
- Corrected mass: $m_{\mathrm{corr}} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp$







[Nature Physics 10 (2015) 1038]

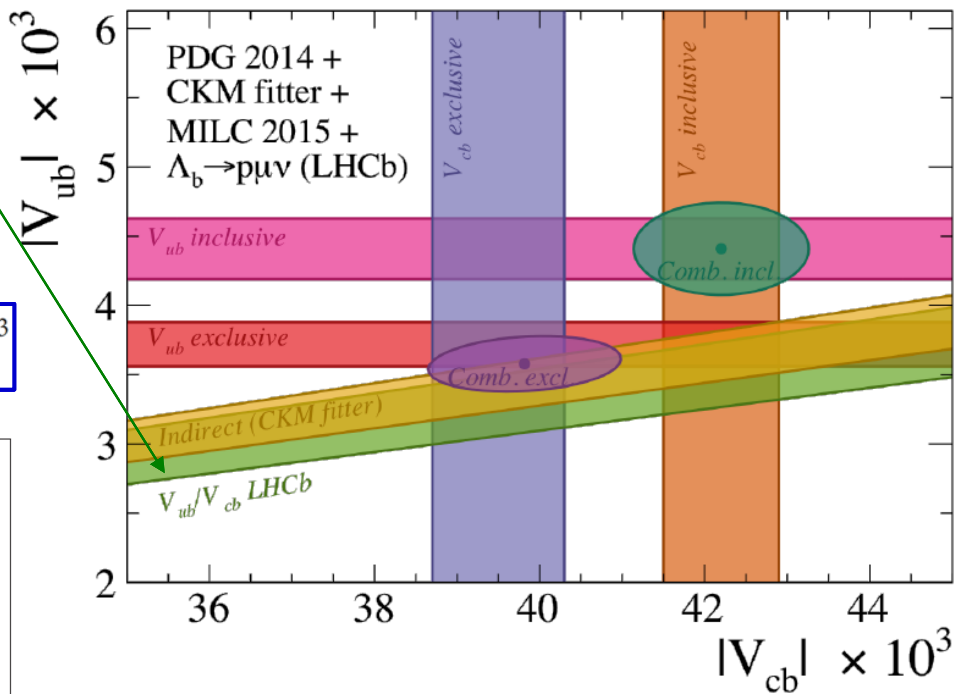
The CKM matrix

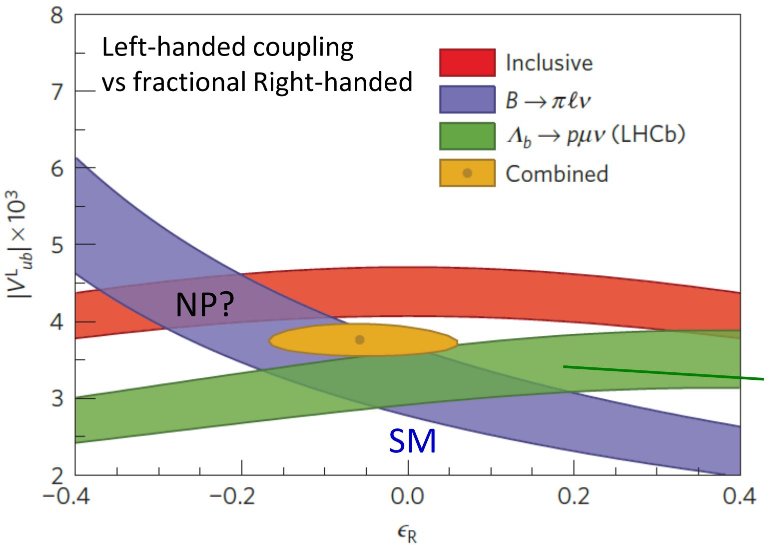
[Nature Physics 10 (2015) 1038]

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004$$

Using the world average from exclusive V_{cb}:

$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$$





Disfavours New Physics models with Right-handed currents

B mixing and CP violation

Mixing of neutral B mesons governed by

$$i\frac{\partial}{\partial t}\begin{pmatrix}a\\b\end{pmatrix}=H\begin{pmatrix}a\\b\end{pmatrix}=\begin{pmatrix}M_{11}-\frac{i}{2}\Gamma_{11} & M_{12}-\frac{i}{2}\Gamma_{12}\\ M_{12}^{*}-\frac{i}{2}\Gamma_{12}^{*} & M_{22}-\frac{i}{2}\Gamma_{22}\end{pmatrix}\begin{pmatrix}a\\b\end{pmatrix}$$

Mass eigenstates:

$$|B_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B^0}\rangle$$

p and q represent the amount of state mixing

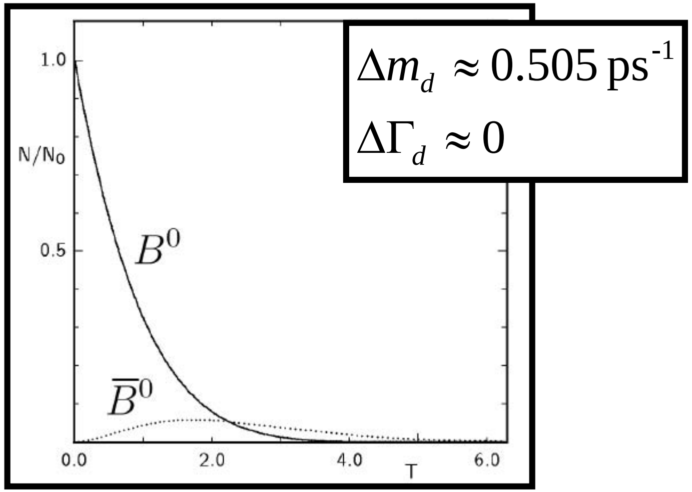
$$|p|^2+|q|^2=1$$

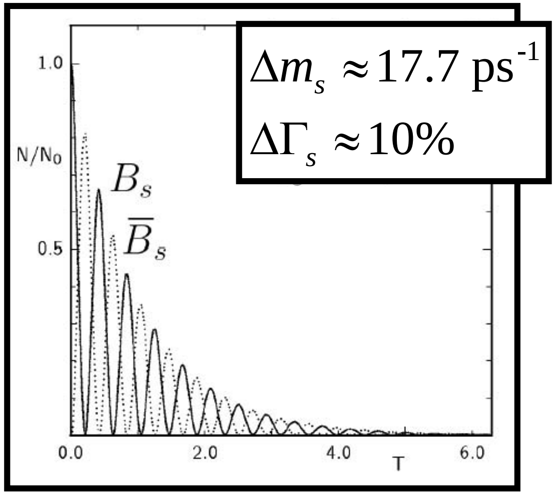
$$|q/p|=1$$

$$\frac{q}{p}=\sqrt{\frac{M_{12}^{*}-\frac{i}{2}\Gamma_{12}^{*}}{M_{12}-\frac{i}{2}\Gamma_{12}}}$$

$$\Delta m = m_H - m_L = 2|M_{12}|$$

$$\Delta\Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|$$



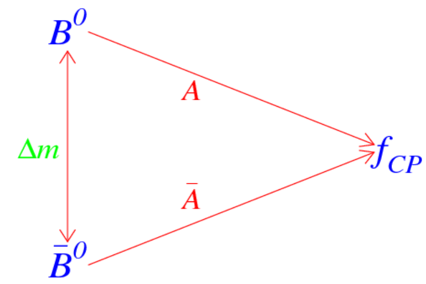


B mixing and CP violation

Decay amplitudes of flavour states decaying to the same final state f

$$A_f = \langle f | H | B^0 \rangle \quad \overline{A}_f = \langle f | H | \overline{B^0} \rangle$$

One can define $\lambda_f = \frac{q}{p} \frac{\overline{A}_f}{A_f}$



$\tau \equiv 1/\Gamma$

$x \equiv \Delta m/\Gamma$

$y \equiv \Delta\Gamma/2\Gamma$

Time dependence of decay rate for initially pure flavour states:

$$\Gamma_f \equiv \left| \langle f | H | B^0(t) \rangle \right|^2 = \frac{1+|\lambda_f|^2}{2} |A_f|^2 e^{-t/\tau} \left[\cosh yt/\tau + A_{\Delta f} \sinh yt/\tau + C_f \cos xt/\tau - S_f \sin xt/\tau \right]$$

$$\overline{\Gamma}_f \equiv \left| \langle f | H | \overline{B}^0(t) \rangle \right|^2 = \frac{1+|\lambda_f|^2}{2} \left| \frac{p}{q} A_f \right|^2 e^{-t/\tau} \left[\cosh yt/\tau + A_{\Delta f} \sinh yt/\tau - C_f \cos xt/\tau + S_f \sin xt/\tau \right]$$

$$S_f \equiv \frac{2\,\mathrm{Im}\lambda_f}{1+|\lambda_f|^2} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad A_{\Delta f}^2 + S_f^2 + C_f^2 = 1$$

B mixing and CP violation

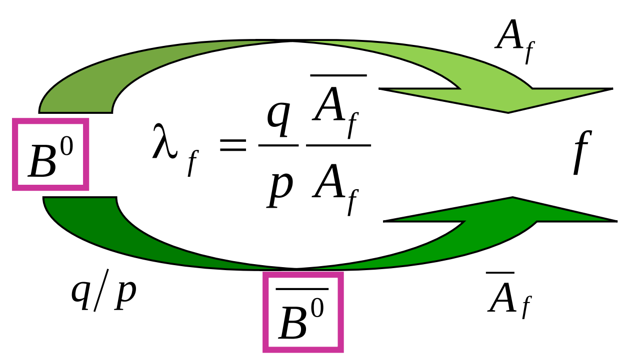
CP Violation $\rightarrow\ \Gamma_f \neq \overline{\Gamma}_f$

Three types:

- **CPV in Decay:** $B^0 \rightarrow f \quad \neq \quad \overline{B^0} \rightarrow \overline{f}$ $\qquad \left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1$
- **CPV in Mixing:** $B^0 \rightarrow \overline{B^0} \quad \neq \quad \overline{B^0} \rightarrow B^0$ $\qquad \left|\frac{q}{p}\right| \neq 1$ $\qquad \mathrm{Im}\left\{\Gamma_{12}^* M_{12}\right\} \neq 0$
- **CPV in Interference between mixing and decay:**

$$\left|\lambda_f\right| = 1, \quad \mathrm{Im}\left\{\lambda_f\right\} \neq 0$$

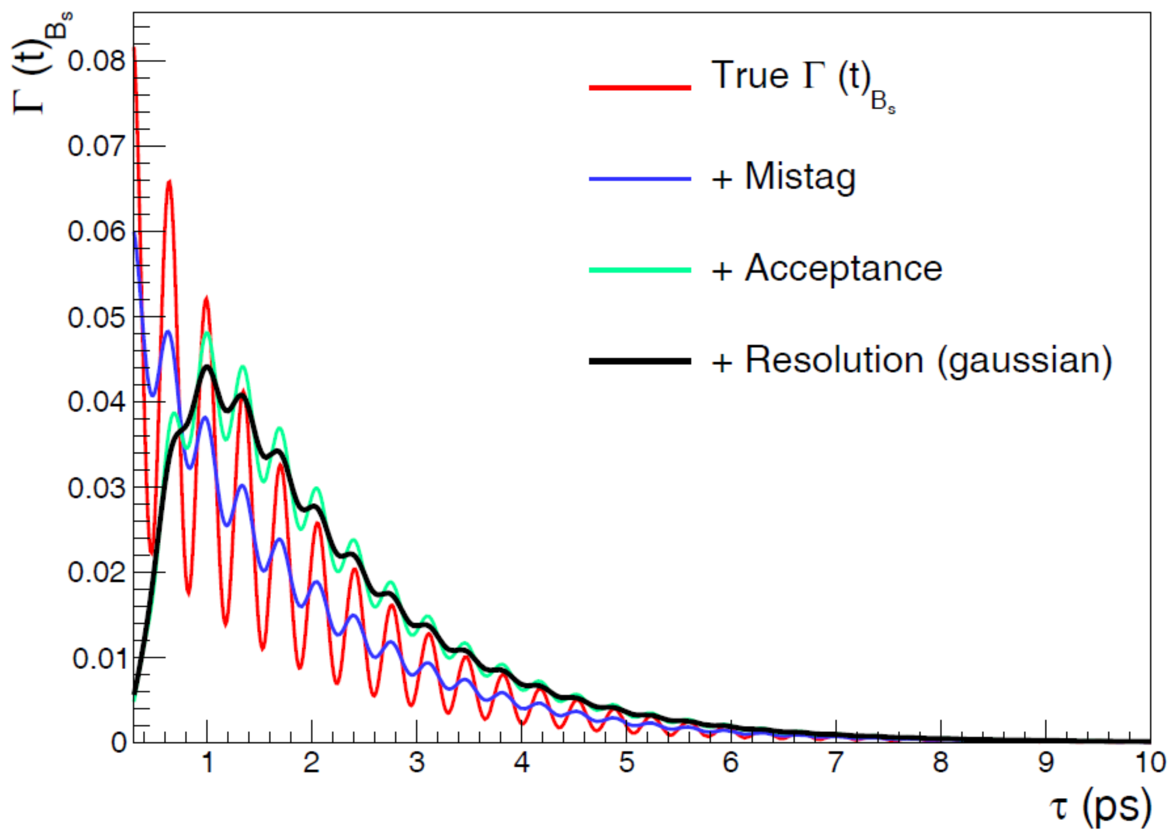
$$A_f^{CP}(t) = \frac{\Gamma_f(t) - \overline{\Gamma}_f(t)}{\Gamma_f(t) + \overline{\Gamma}_f(t)} = \frac{-C_f \cos(\Delta m t) + S_f \sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_{\Delta f} \sinh(\Delta\Gamma t/2)}$$



B mixing and CP violation

- Experimental effects:

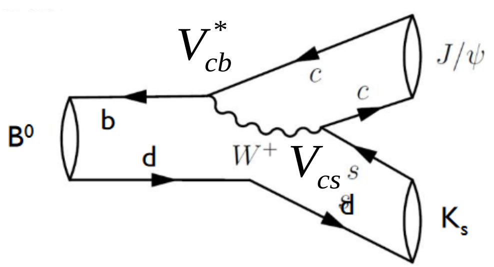
Dilution of the oscillation (lost of sensitivity of the oscillation parameters) due to reconstruction effects

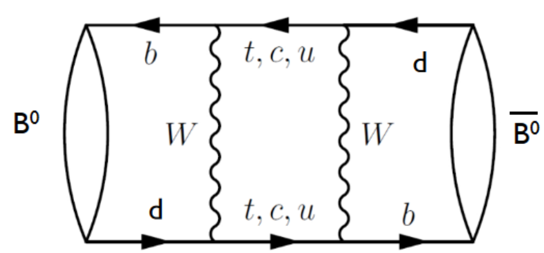


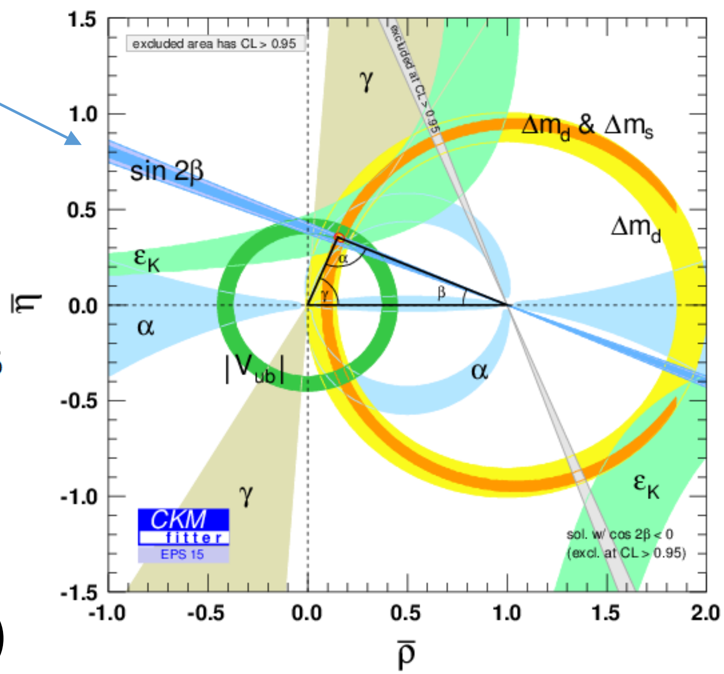
B mixing and CP violation

Measuring the β angle of the CKM triangle

Golden channel: $B^0 \to J/\psi\, K^0$







$$A_f^{CP}(t) = \frac{\Gamma_f(t) - \bar{\Gamma}_f(t)}{\Gamma_f(t) + \bar{\Gamma}_f(t)} = \frac{-C_f \cos(\Delta m t) + S_f \sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_{\Delta f} \sinh(\Delta\Gamma t/2)}$$

$$\sim -C_f \cos(\Delta m t) + S_f \sin(\Delta m t)$$

$$S_f \equiv \frac{2\,\mathrm{Im}\lambda_f}{1 + |\lambda_f|^2}$$

$$\mathrm{Im}\{\lambda_f\} = \mathrm{Im}\{-e^{-2i\beta}\} = \sin 2\beta$$

C_f ~0 in the SM

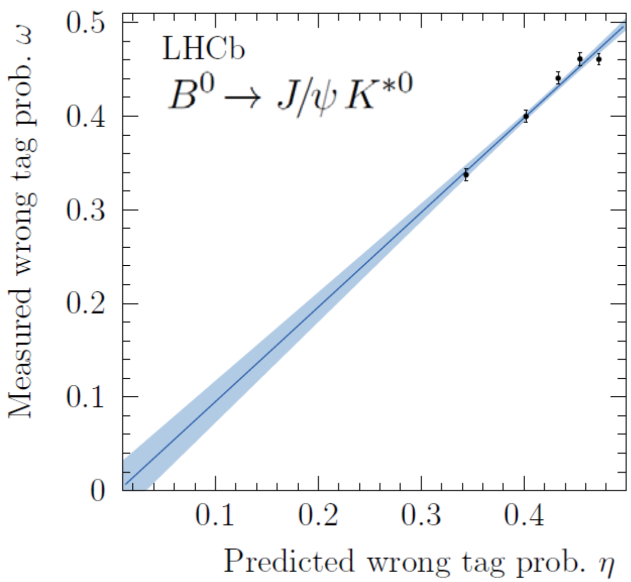
$$A_f^{CP}(t) \sim \sin 2\beta \sin(\Delta m t)$$

B mixing and CP violation

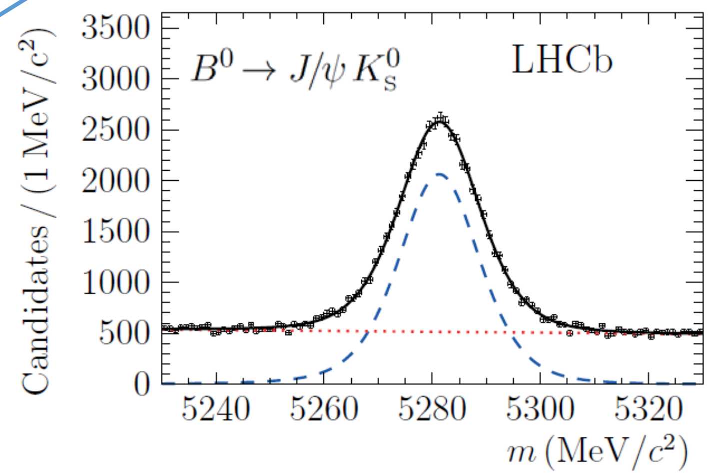
Count number of tagged signal events reconstructed as function of time

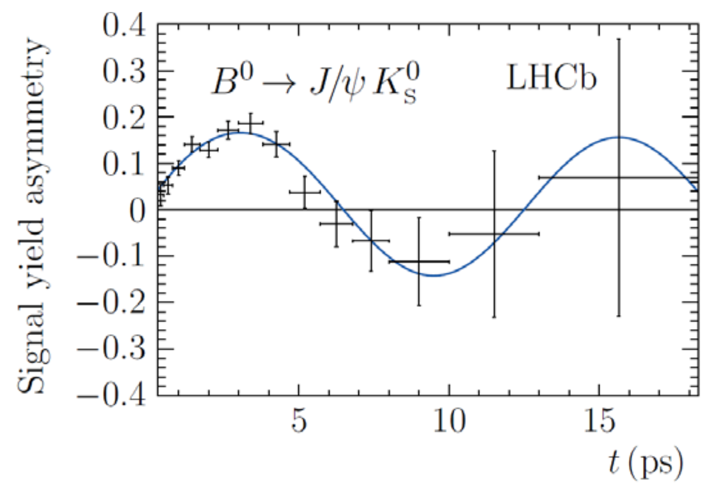
$$A_{CP}(t) = \frac{N\left(B_{tag} = B^0\right) - N\left(B_{tag} = \overline{B}^0\right)}{N\left(B_{tag} = B^0\right) + N\left(B_{tag} = \overline{B}^0\right)} \approx \pm\left\{(1-2\omega) \times \sin 2\beta \times \sin(\Delta m \Delta t)\right\} \otimes \mathrm{R}(\Delta t)$$

Flavour mistag calibrated using a control sample flavour specific ($K^{*0} \rightarrow K^- \pi^+$)

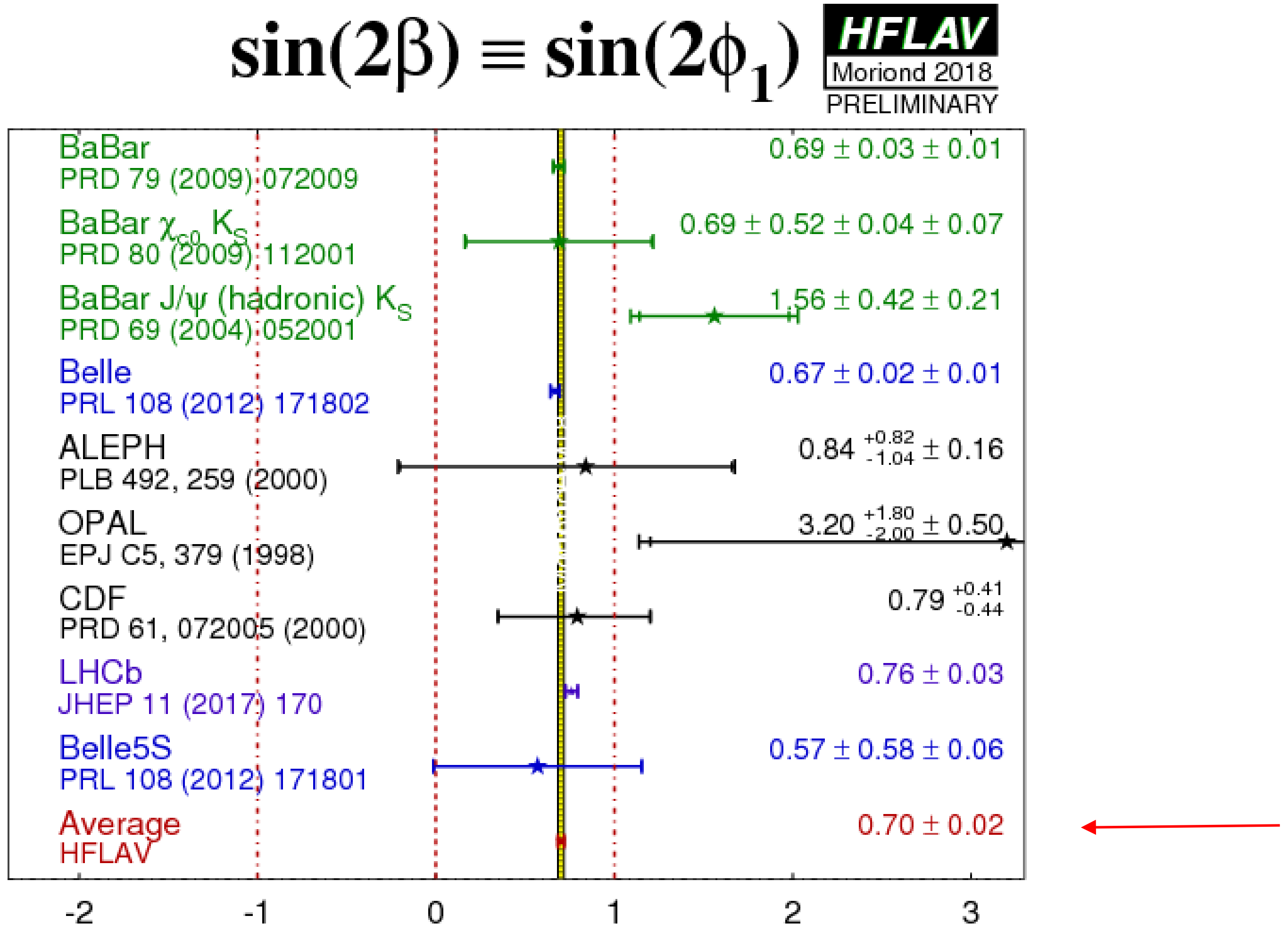


$$\omega = (35.62 \pm 0.12)\,\%$$
$$\varepsilon_{\mathrm{tag}} = (36.54 \pm 0.14)\,\%$$





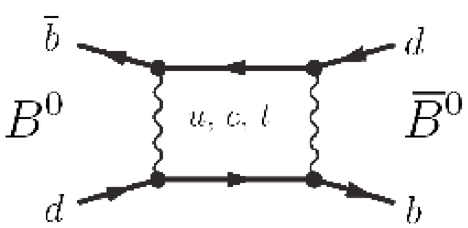
B mixing and CP violation

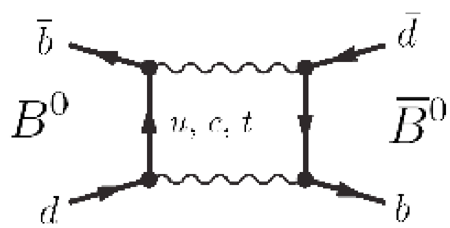


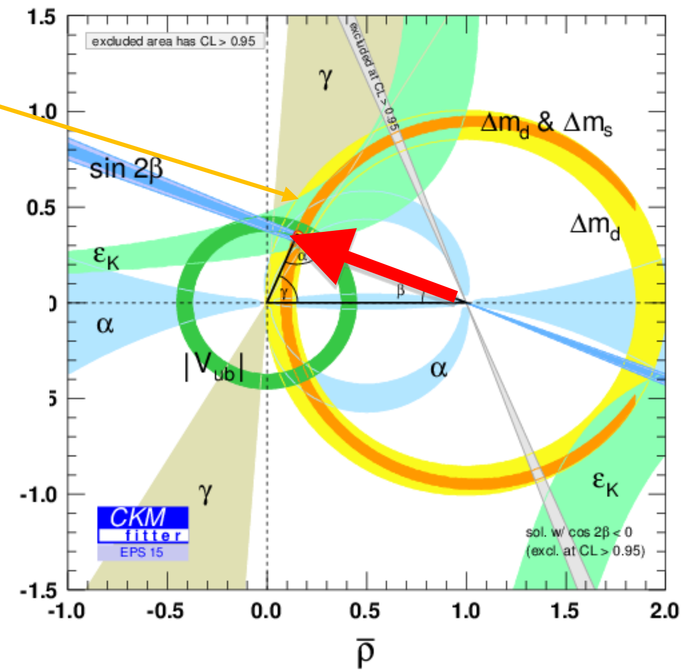
B mixing and CP violation

Measuring the other side of the CKM triangle

- Through the mass difference Δm_d, Δm_s in the box diagrams:





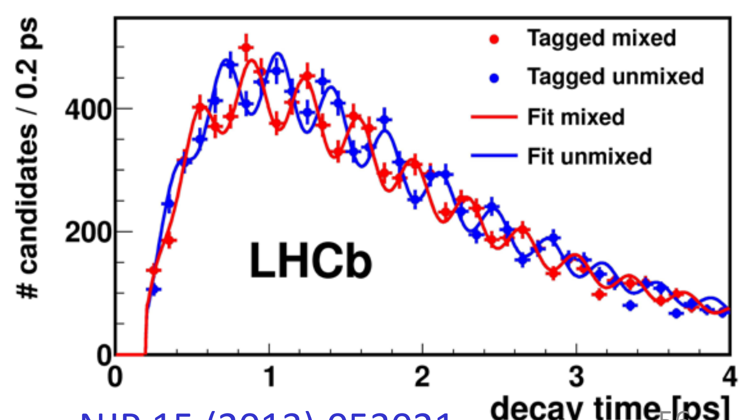


The time-dependent asymmetry A(t) of $B_{d,s}$ events that changed flavour (mixed) or not (unmixed) is:

$$A_{mix}(t)\frac{N^{unmix}(t)-N^{mix}(t)}{N^{unmix}(t)+N^{mix}(t)} = \cos\Delta mt$$

with experimental effects:

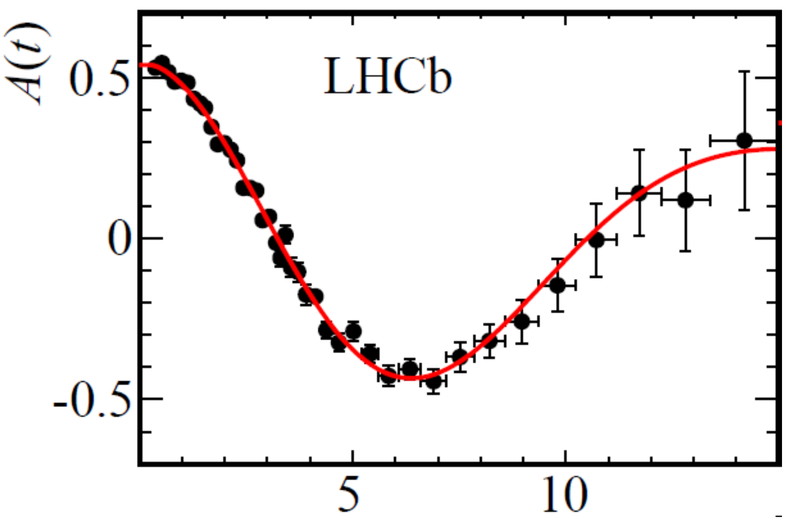
$$= \{(1-2\omega)\times\cos\Delta m\Delta t\}\otimes R(\Delta t)$$



NJP 15 (2013) 053021

B mixing and CP violation

Measuring the other side of the CKM triangle

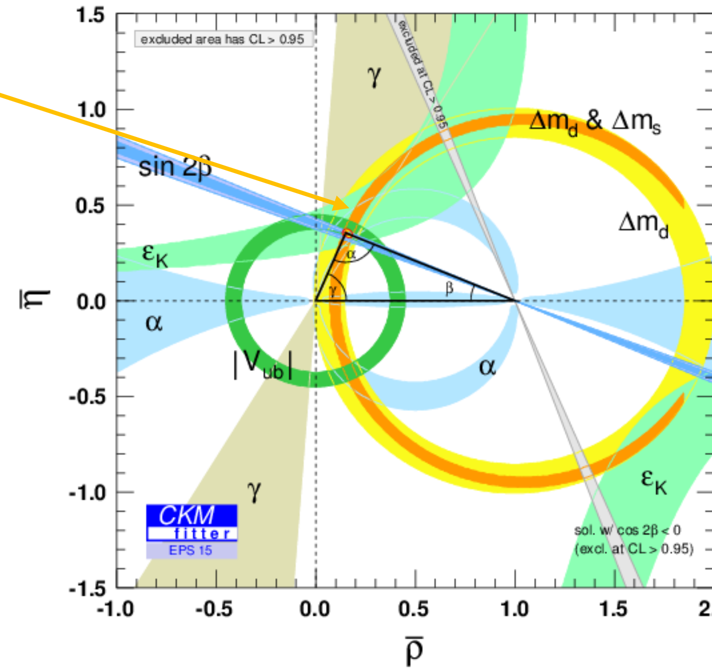


(best tagging category)

[EPJ C (2016) 76]

$\Delta m_d = (0.5050 \pm 0.0021 \pm 0.0010)\ \mathrm{ps}^{-1}$

$\Delta m_s = (17.768 \pm 0.023 \pm 0.006)\ \mathrm{ps}^{-1}$



$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

error from theory

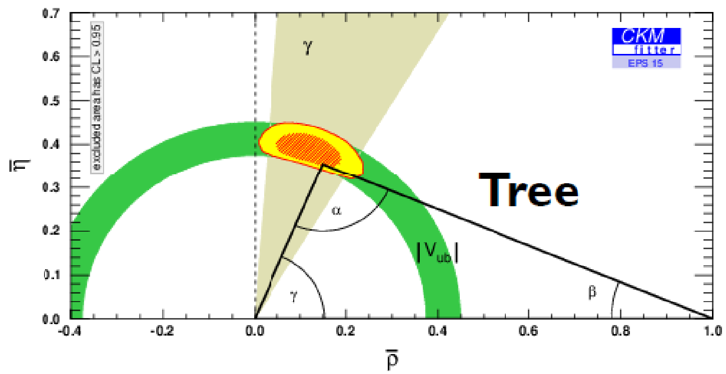
$$|V_{td}/V_{ts}| = 0.216 \pm 0.001 \pm 0.011$$

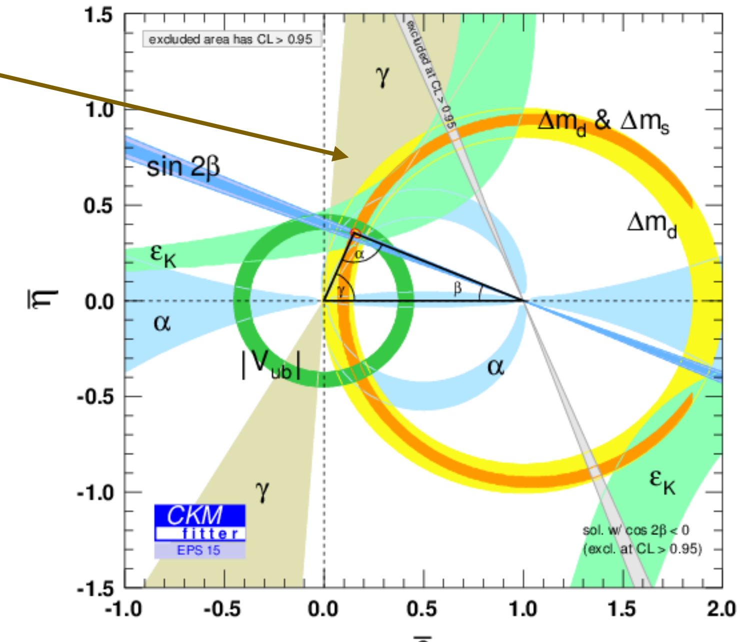
Q : Could you infer the top mass from the measured Δm_d?

B mixing and CP violation

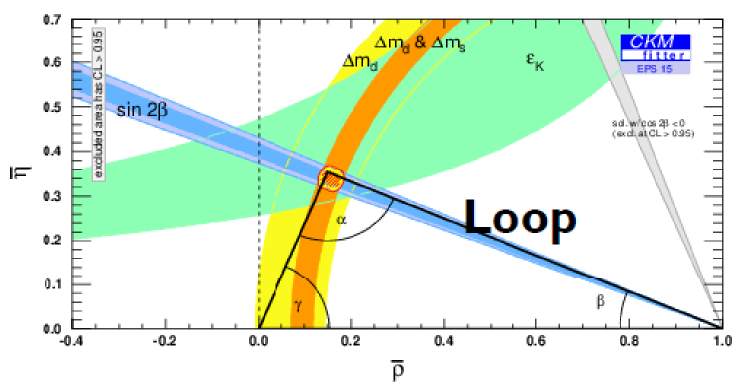
Measuring the γ angle of the CKM triangle

Key to determine the apex from tree level processes, with V_{ub} is the "reference clock"

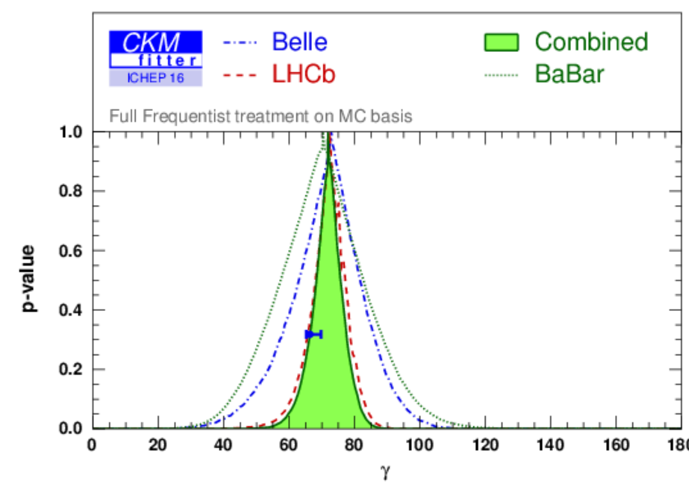




To be compared with constraints from loop processes:



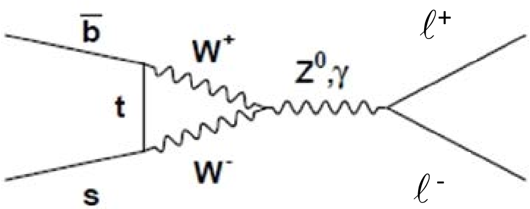
$\gamma = 72.2^{+5.3}_{-5.8}$



Rare decays

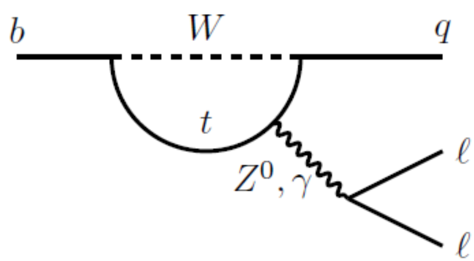
- Processes very suppressed, go through loop diagrams: branching fractions (BR) 10^{-5} – 10^{-10}
- Highly sensitive to New Physics: if one finds more events than expected → new particles

leptonic



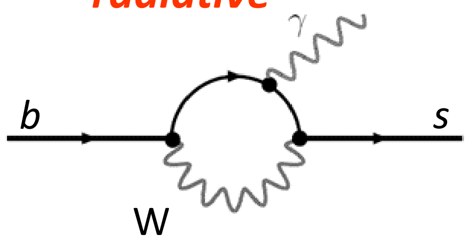
BR ~ 10^{-9}

semileptonic



BR ~ 10^{-7}

radiative

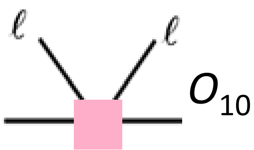


BR ~ 10^{-5}

Experimentally → leptons/photons with high transverse momenta

Theoretically → observables can be calculated in terms of Wilson coefficients

Ex: $\Gamma\left(B_s^0 \to \mu^+\mu^-\right) \sim \frac{G_F^2\alpha^2}{64\pi^3} m_{Bs}^2 f_{Bs}^2 \left|V_{tb}V_{ts}\right|^2 \left|2m_\mu C_{10}\right|^2$

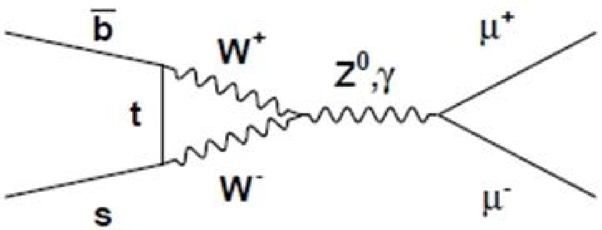


Hadronic uncertainties in decay constants or form factors

Rare decays: leptonic

One of the most relevant channels:

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

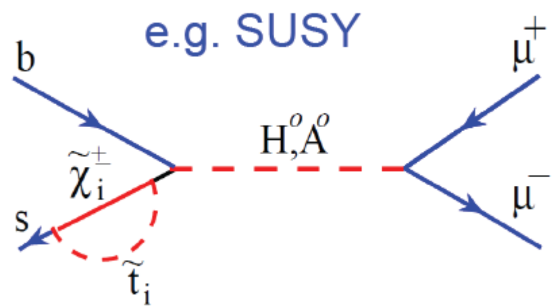


→ FCNC + helicity supressed → **Very Rare decay**:

→ Standard Model prediction:

[PRL 112 101801 (2014)]

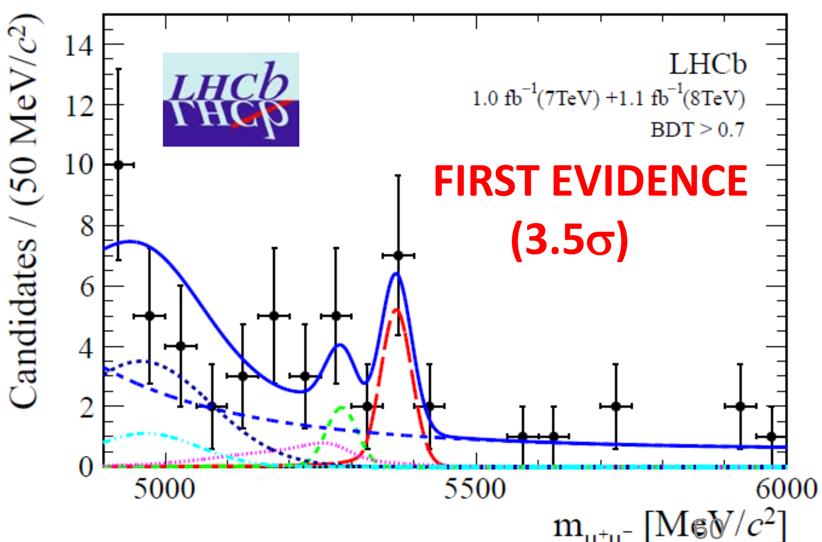
$$\mathcal{B}(B_s^0 \to \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$$



→ Enhanced by New Physics models (e.g. SUSY ~ $tg^6\beta/m^4{}_A$)

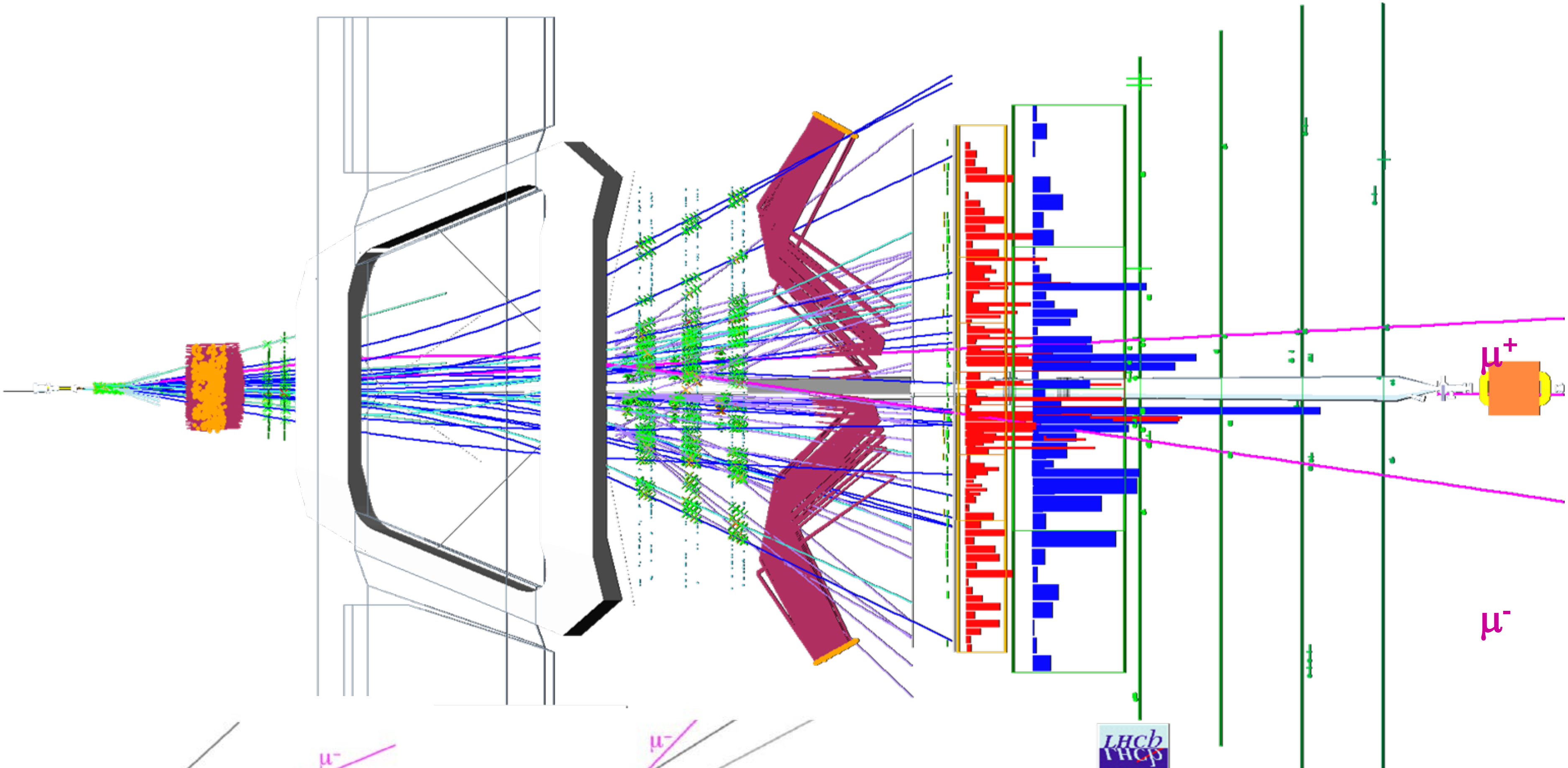
→ First evidence by LHCb in 2012!

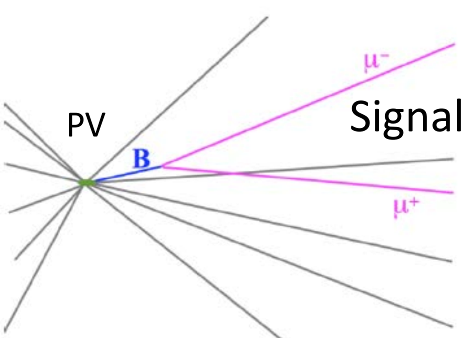
[LHCb, PRL110 (2013)021801] (2fb^{-1})

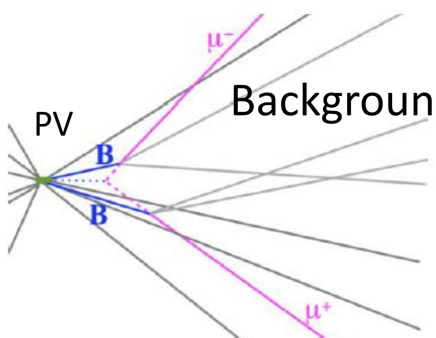


Rare decays: leptonic

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

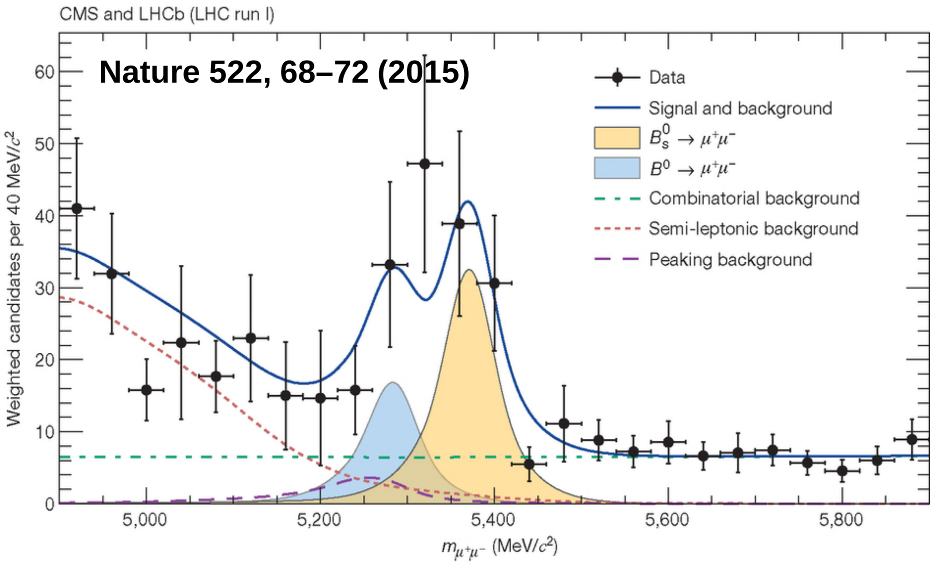






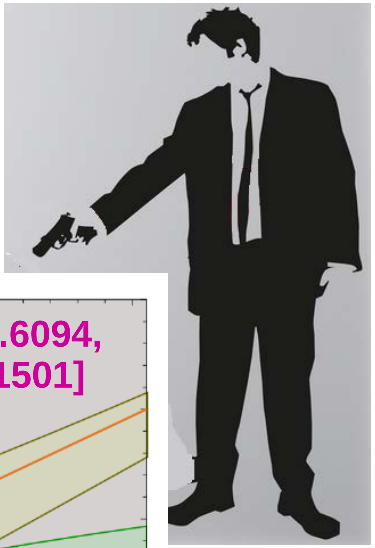
CMS + LHCb

Rare decays: leptonic

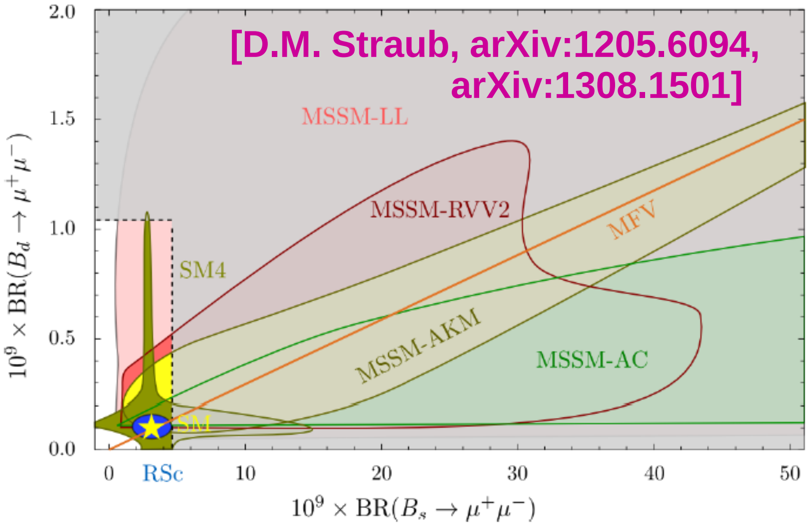


$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$ **6.2σ**

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$ **3.2σ**



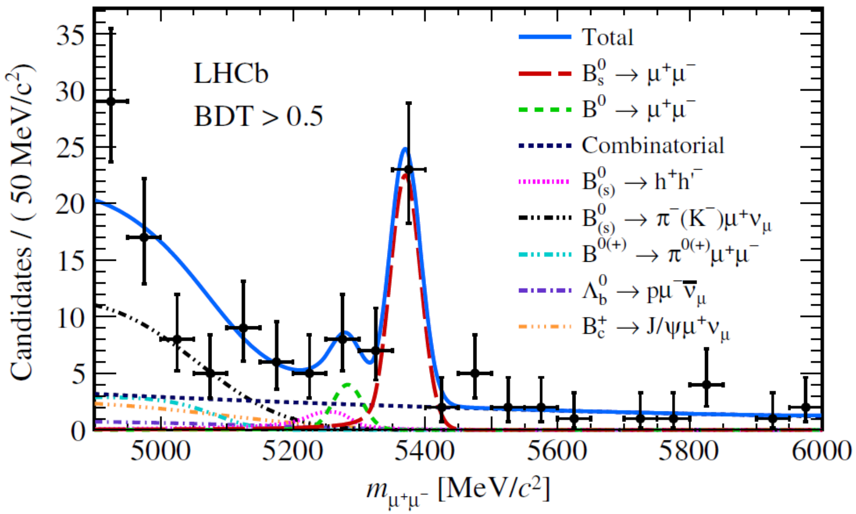
- Known as "the New Physics killer":



Rare decays: leptonic

Updated results:

4.4 fb^{-1} [PRL 118 (2017) 191801]



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ at } 95\%$$

→ **In agreement with the SM**

→ Theoretical uncertainties ($f_{B(s)}$, V_{CKM}) well below statistical uncertainty

- $B_s \to \tau^+\tau^-$ also searched for at LHCb:

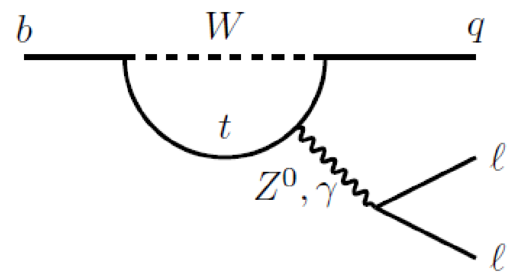
$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ at } 95\%$$

[arXiv:1703.02508 [hep-ex]]

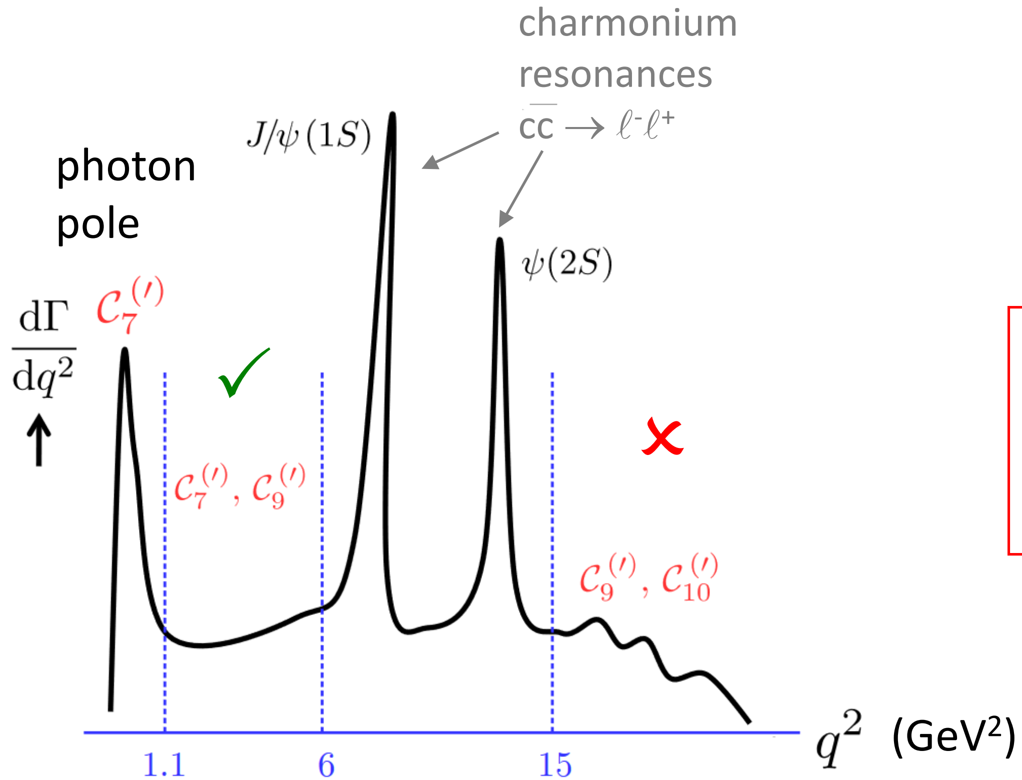
Rare decays: semileptonic

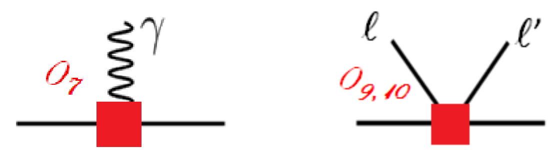
Differential branching fraction: $d\Gamma/dq^2$

Each q^2 region probes different processes



$q^2 = (p_{\ell^+} + p_{\ell^-})^2$





SM values (μ=m_b): C_7 ~ - 0.33
C_9 ~ 4.27
C_{10} ~ - 4.17

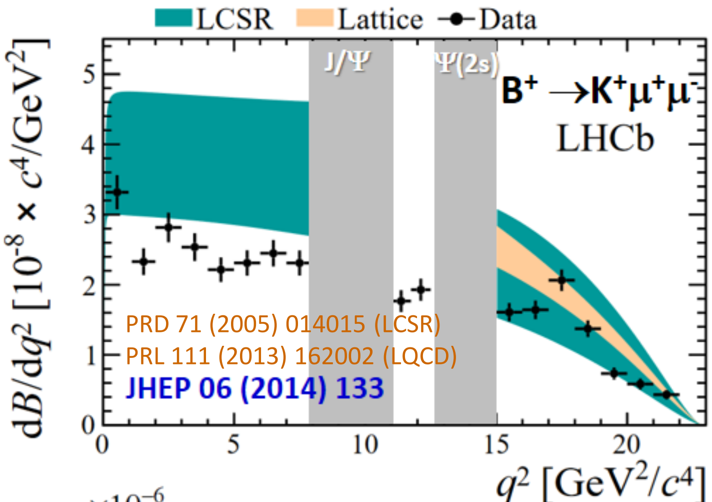
(Everything else small or negligible)

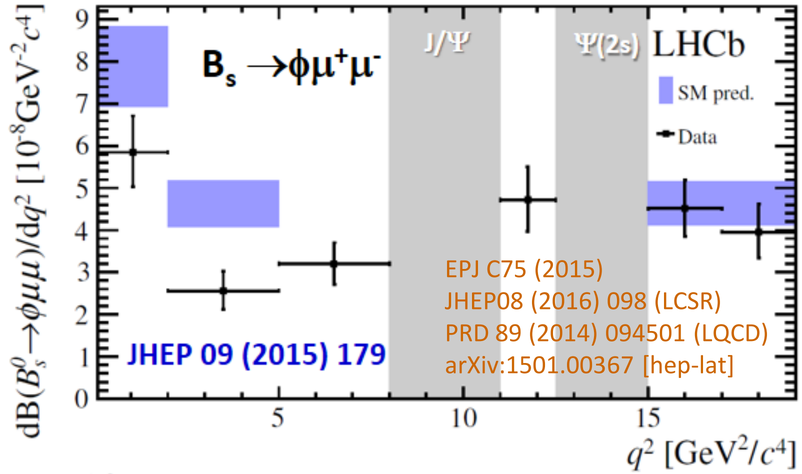
$C_i = C_i^{SM} + C_i^{NP}$

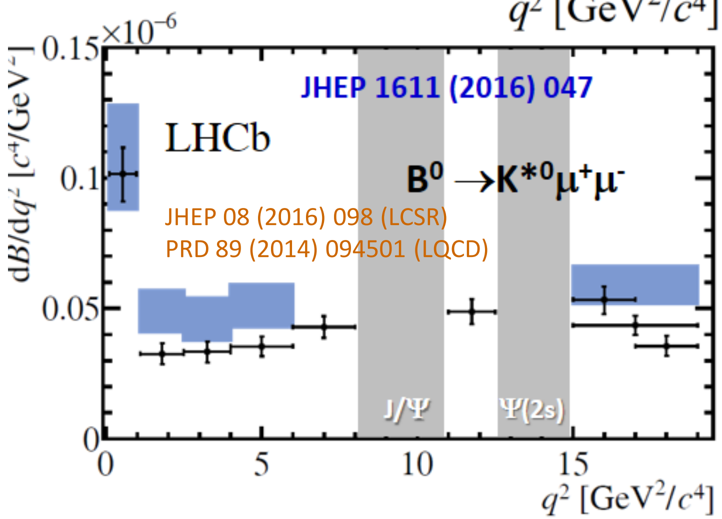
(Primed $C'_i \rightarrow$ right handed currents: suppressed in SM)

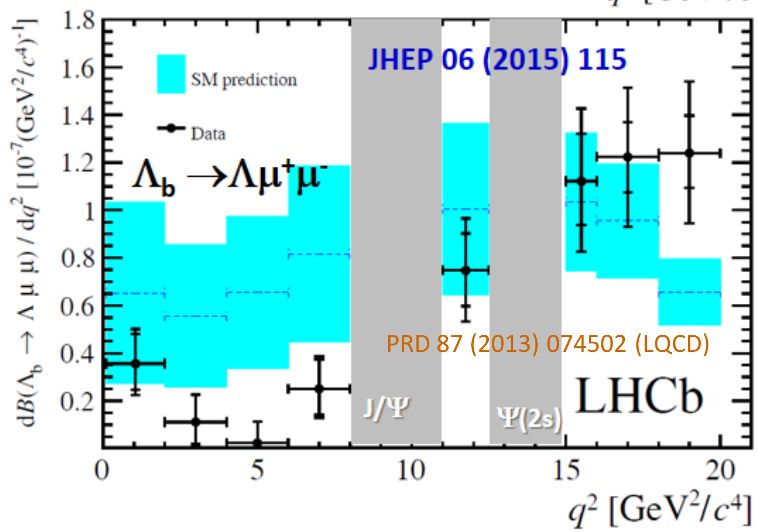
Rare decays: semileptonic

- Differential decay width as function of $q^2 = m^2_{\mu\mu}$







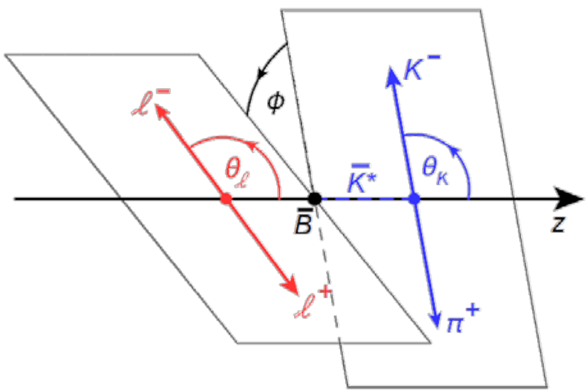


Theory affected by hadronic uncertainties: LCSR + LQCD

Rare decays: semileptonic

- Angular distribution in B→ K*$\ell^-\ell^+$: q^2 and three angles

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$



$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

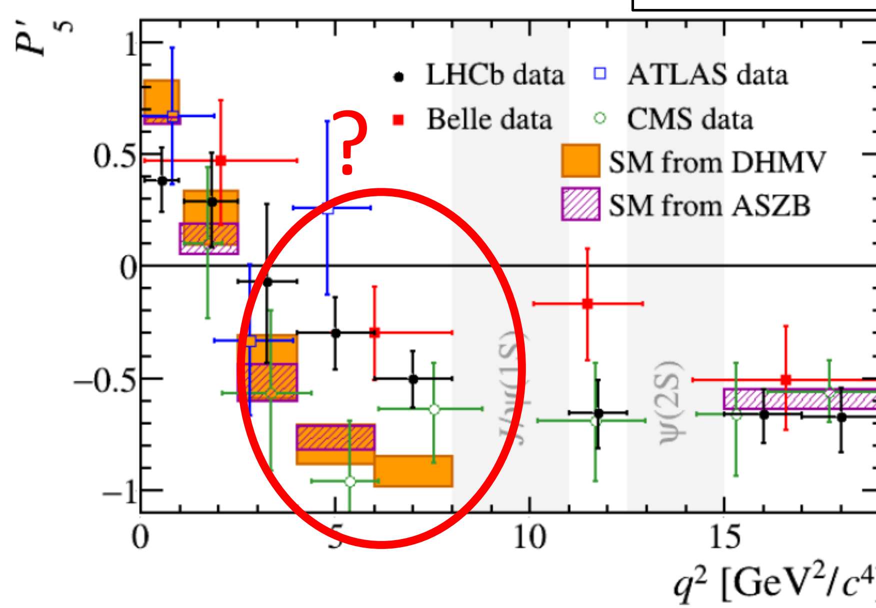
Functions of q^2 and Wilson coef. **C$_i$**

Optimized observables: cancellation of form factor dependencies: P'$_i$

[Descotes-Genon et al, JHEP 05 (2013) 137]

- JHEP 02 (2016) 104
- PRL 118 (2017) 111801
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

→ Deviation from SM ~ **3σ**



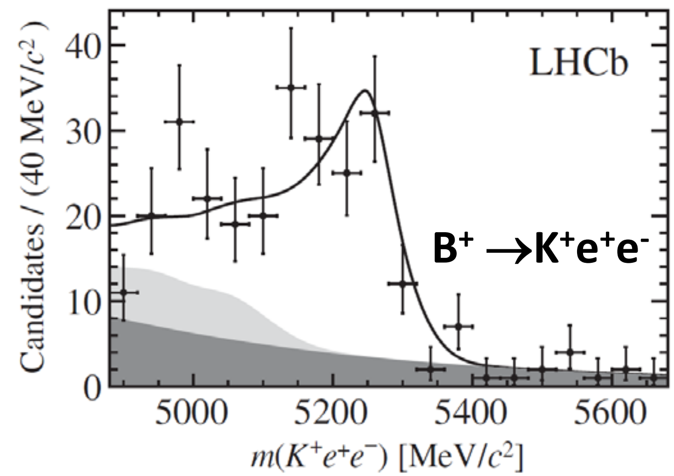
Rare decays: semileptonic

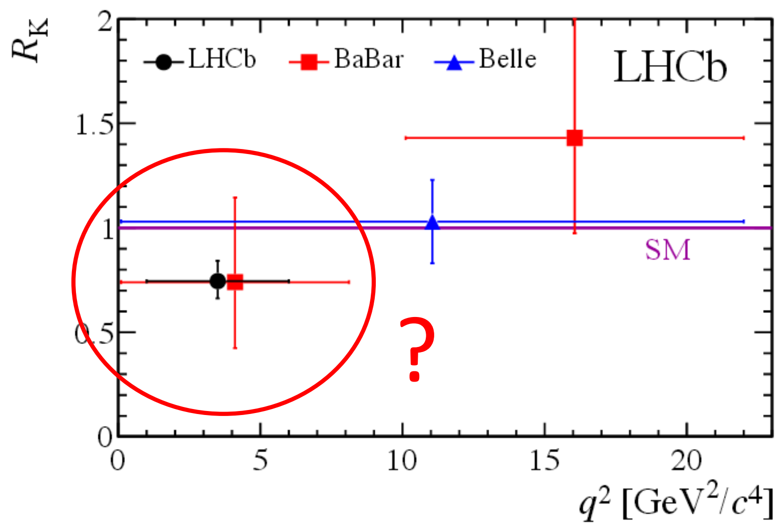
- In the SM all leptons are expected to behave in the same way:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$ = 1.000 + $O(m_\mu^2/m_b^2)$ (SM)

- Experimentally, use the $B^+ \to K^+ J/\psi(\to e^+e^-)$ and $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ to perform a double ratio

- Precise theory prediction due to cancellation of hadronic form factor uncertainties





1 GeV < q^2 < 6 GeV [PRL 113 (2014) 151601]

$$R_K = 0.745^{+0.090}_{-0.074}\,(\mathrm{stat}) \pm 0.036\,(\mathrm{syst})$$

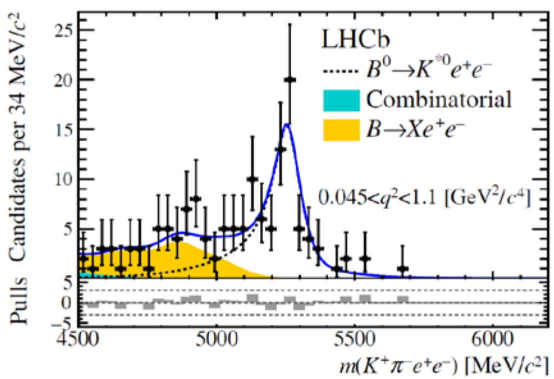
→ Consistent, but lower, than the SM at **2.6σ**

Rare decays: semileptonic

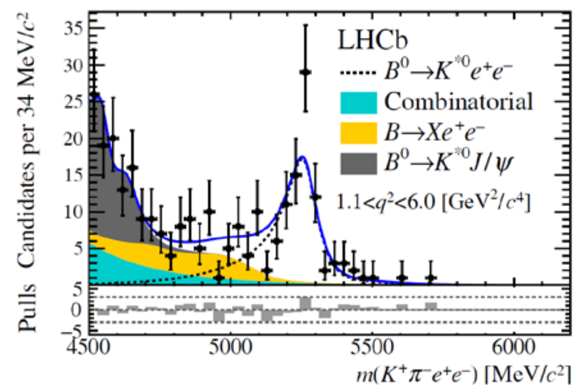
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}$$

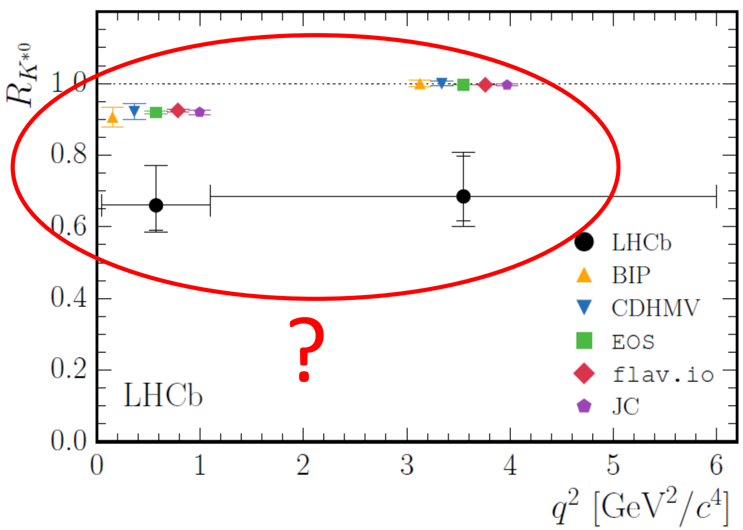
[arXiv:1705.05802 [hep-ex]]

0.045 GeV < q^2 < 1.1 GeV



1.1 GeV < q^2 < 6 GeV





Low q^2: SM = 0.922(22)

$$R_{K^{*0}} = 0.66\,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst})$$

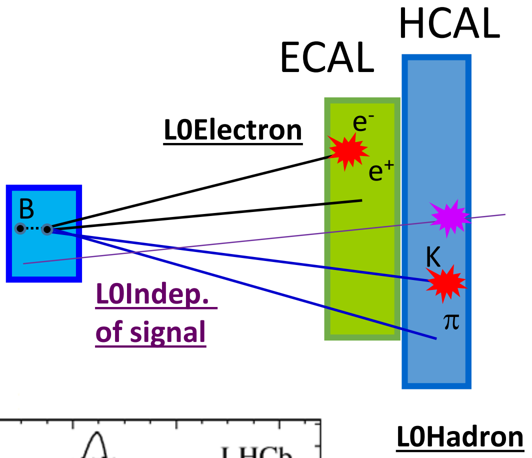
Central q^2: SM = 1.000(6)

$$R_{K^{*0}} = 0.69\,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst})$$

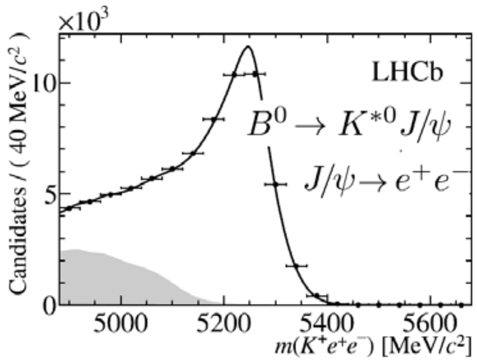
→ Consistent, but lower than the SM at **2.1-2.3σ** (low q^2) and **2.4-2.5σ** (central q^2)

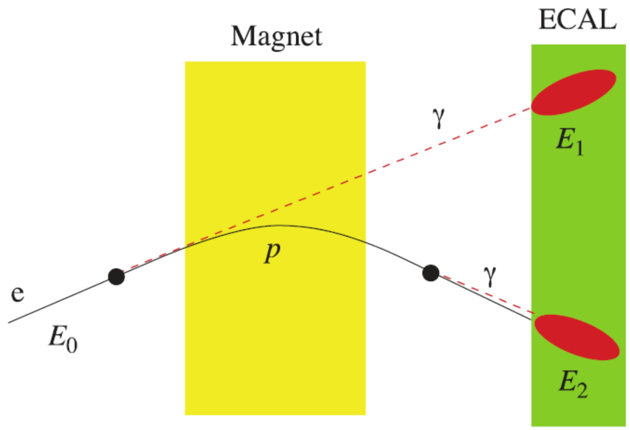
Rare decays

Quick note on experimental issues:

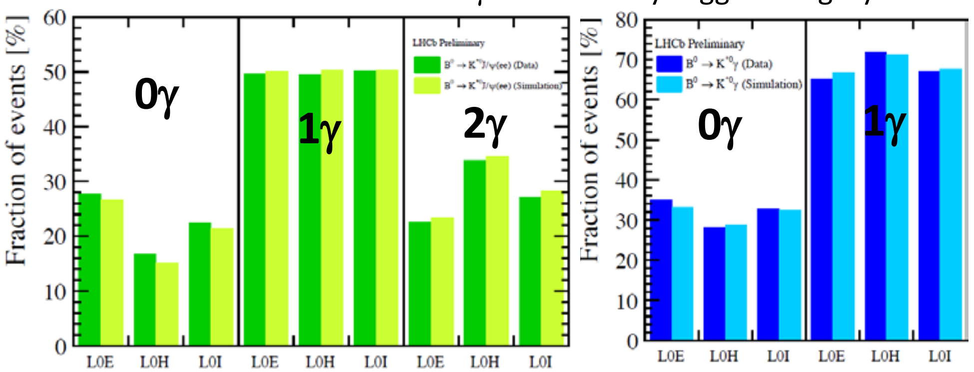


- LHCb is far better with muons than electrons
- *Trigger*, reconstruction, selection and particle identification are harder with electrons
- Mass resolution affected by *e bremsstrahlung* $\rightarrow$ need energy recovery
- Mass shape modelled according to the number of *bremsstrahlung* recovered





Data-MC for the number of γ recovered by trigger category

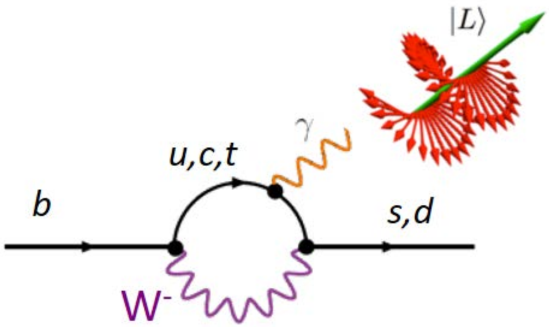


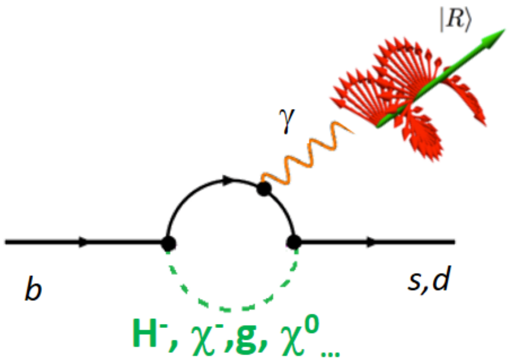
B $\rightarrow$ K* J/Ψ ($\rightarrow$ e⁺e⁻)   B $\rightarrow$ K* γ ($\rightarrow$ e⁺e⁻)

Rare decays: radiative

Probing the spin structure of the photon: $B_s \to \phi\gamma$

- In the Standard Model photons emitted in $b \to s\gamma$ transitions are left-handed polarized
- New particles in the loop could add right-handed contributions





- The polarization of the photon can be inferred from the time evolution of the B_s decay

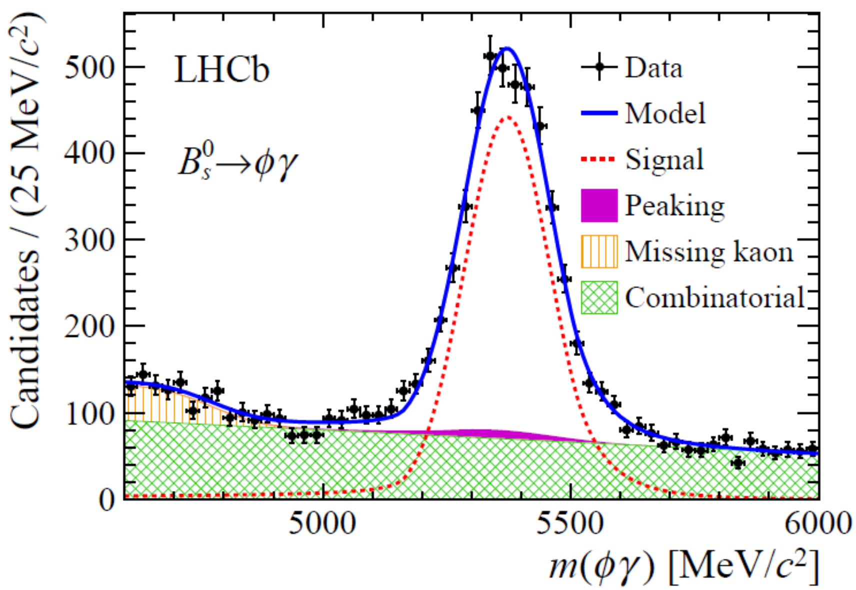
$$\Gamma_{B_s^0}(t) = |A|^2 e^{-\Gamma_s t}\left(\cosh\frac{\Delta\Gamma_s t}{2} - \mathcal{A}^{\Delta}\sinh\frac{\Delta\Gamma_s t}{2}\right)$$

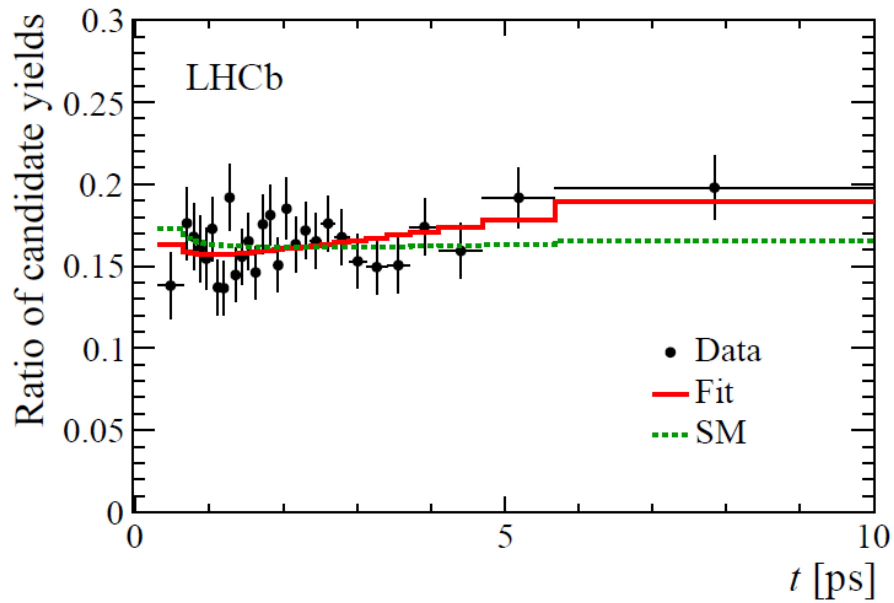
Related to the ratio of right to left handed amplitudes

Rare decays: radiative

This sensitivity comes from the effect of the mixing of $B_s \to \phi\gamma$ and $\overline{B}_s \to \phi\gamma$ with $\phi \to K^+K^-$

Use a control channel with no sensitivity to the photon polarization (ex: a flavor specific channel $B \to K^*\gamma$, with $K^* \to K^-\pi^+$)





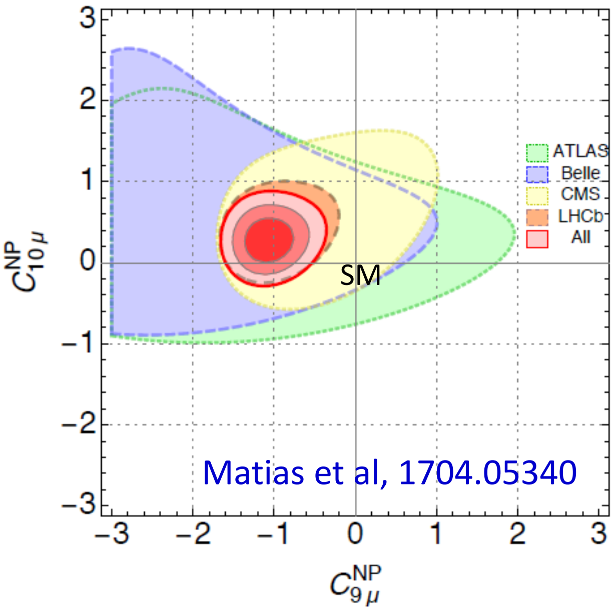
$$\mathcal{A}^{\Delta} = -0.98 \,^{+0.46}_{-0.52}\,^{+0.23}_{-0.20}$$

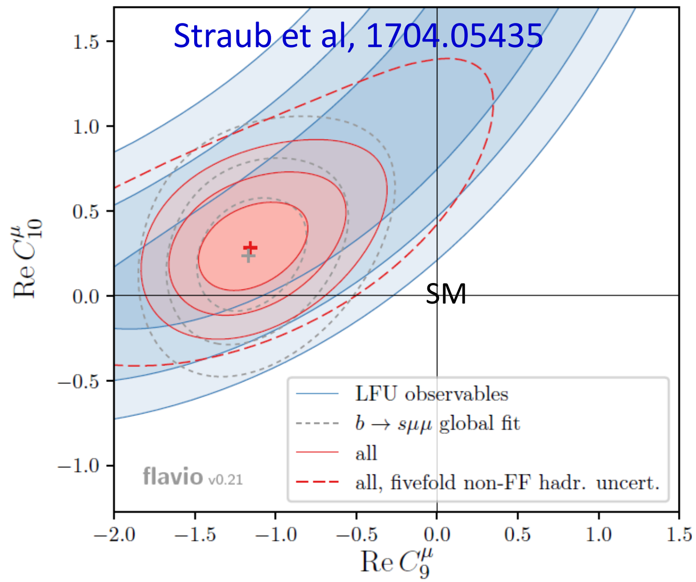
[PRL 118 (2017) 021801]

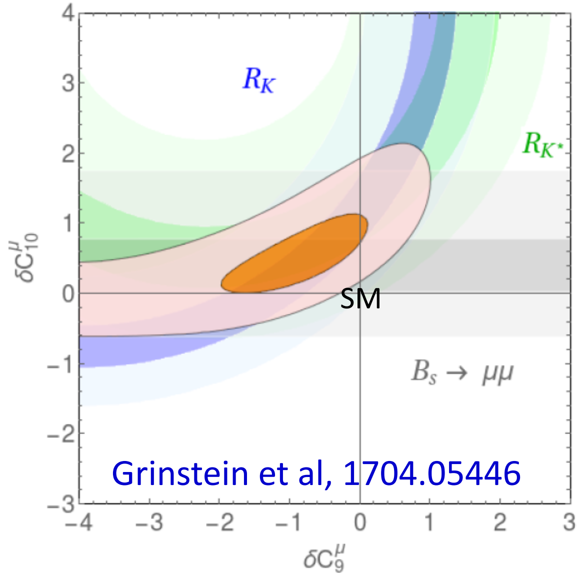
$\mathcal{A}^{\Delta}_{\rm SM} = 0.047\,^{+0.029}_{-0.025}$ → Compatible with the SM within **2σ**

Rare decays

Global fits (some cases with more than 100 observables)







New Physics hypothesis preferred over SM by more than 4 - 5σ

Main effect on the $C_{9\mu}$ coefficient: **4.27^{SM} -1.1^{NP}**

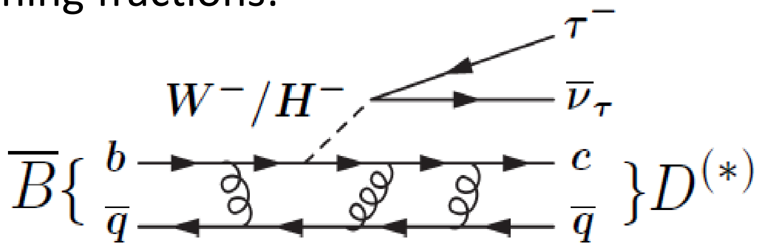
Triggered models with Z’, leptoquarks (LQ), and composite Higgs

Lepton flavour universality

- Another test of lepton universality (now at tree level):

Ratio of semi-tauonic and semi-muonic branching fractions:

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$



Sensitive to charged Higgs bosons and leptoquarks

SM predictions very precise : (V_{cb} and form factors (partially) cancel)

$R(D)_{SM}=0.299 \pm 0.003$

$R(D^*)_{SM}=0.252 \pm 0.003$

BaBar measured an excess of $\overline{B}^0 \to D^{(*)}\tau^-\overline{\nu}_\tau$ (3σ away from SM) [PRD 88 (2013) 072012] [Nature 546(2017)227]

LHCb has performed two analyses:

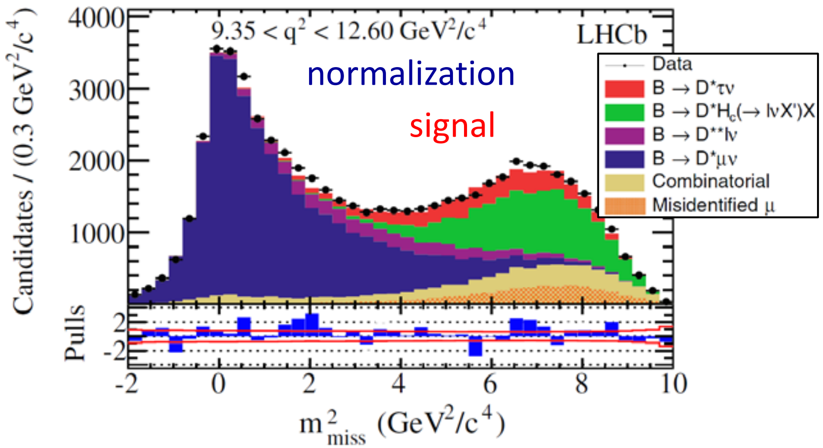
- $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$, with $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ [PRL 115 (2015) 111803]
- $B^0 \to D^{*-}\tau^+\nu$, with $\tau^+ \to \pi^+\pi^-\pi^+\pi^{(0)}\overline{\nu}_\tau$ [JHEP 08 (2017) 055]

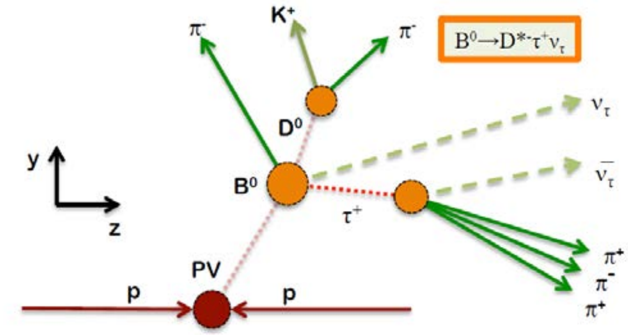
Lepton flavour universality

- Using $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$
- Information from the missing mass squared $m_{miss}^2 = (P_B - P_{D*} - P_\mu)^2$ and muon energy in several q^2 bins

$$\mathcal{R}(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$$

[PRL 115 (2015) 111803]

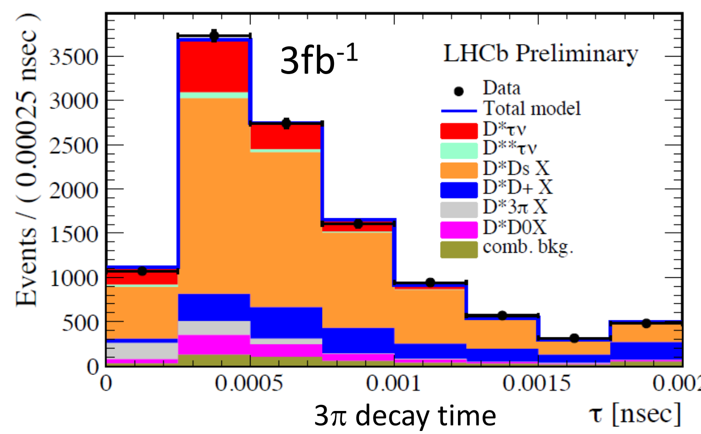




- New analysis by LHCb: using $\tau^+ \to \pi^+ \pi^- \pi^+ \bar{\nu}_\tau$
- Information from the position of the three pions
- Normalized to $B^0 \to D^{*-} \pi^+ \pi^- \pi^+$

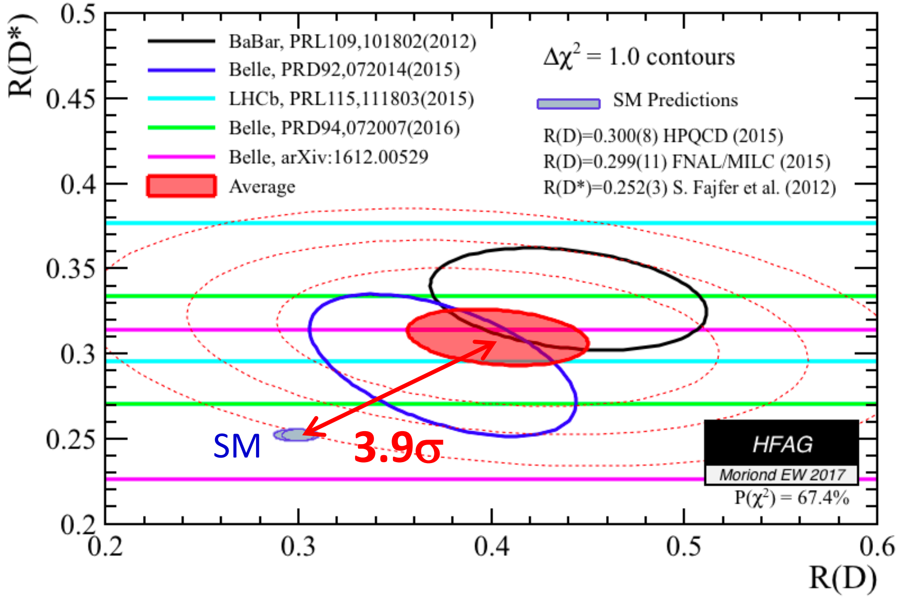
$$\mathcal{R}(D^{*-}) = 0.285 \pm 0.019 \pm 0.025 \pm 0.014$$

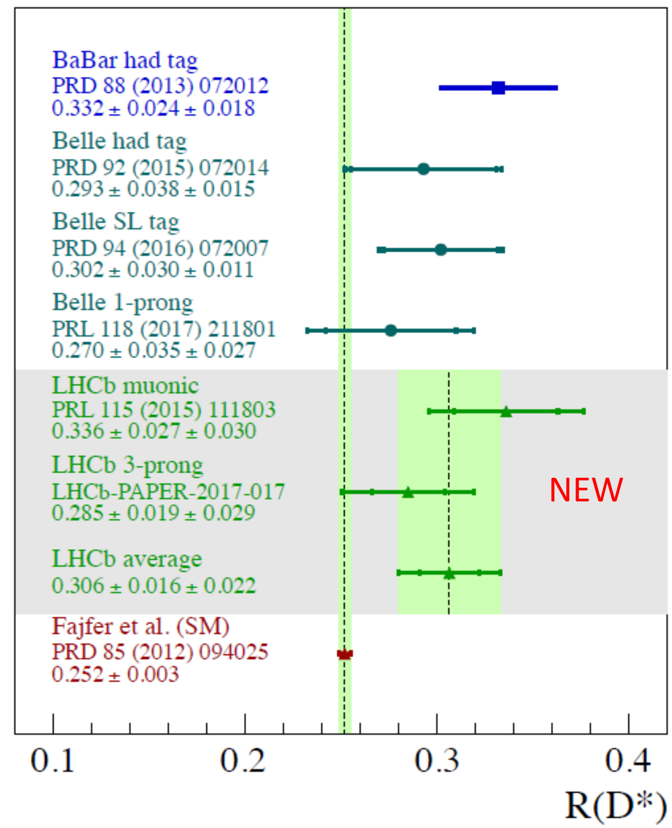
[JHEP 08 (2017) 055]



Lepton flavour universality

- Global picture of R_D and R_{D*}



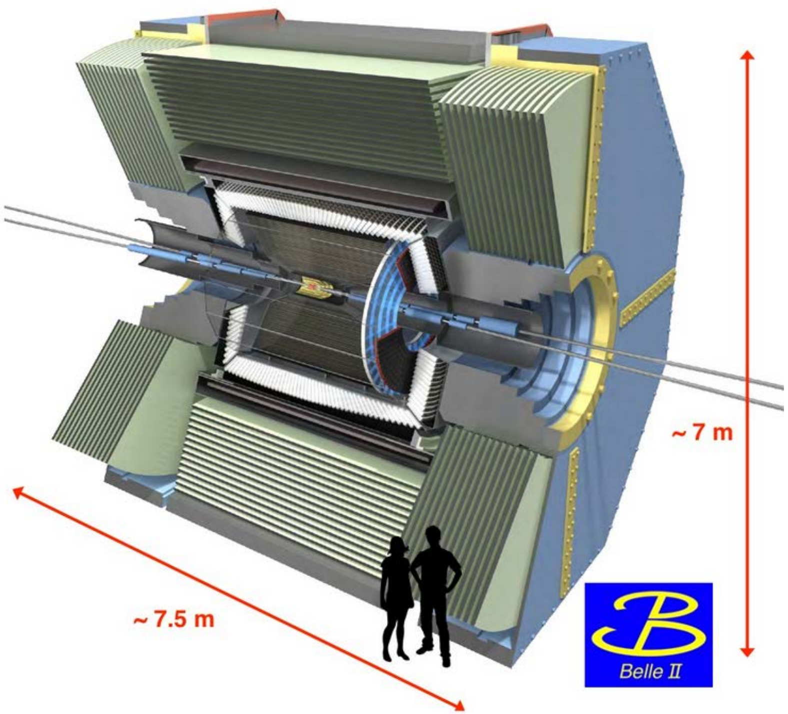


→ About 4σ deviation from SM

Future plans

Belle II

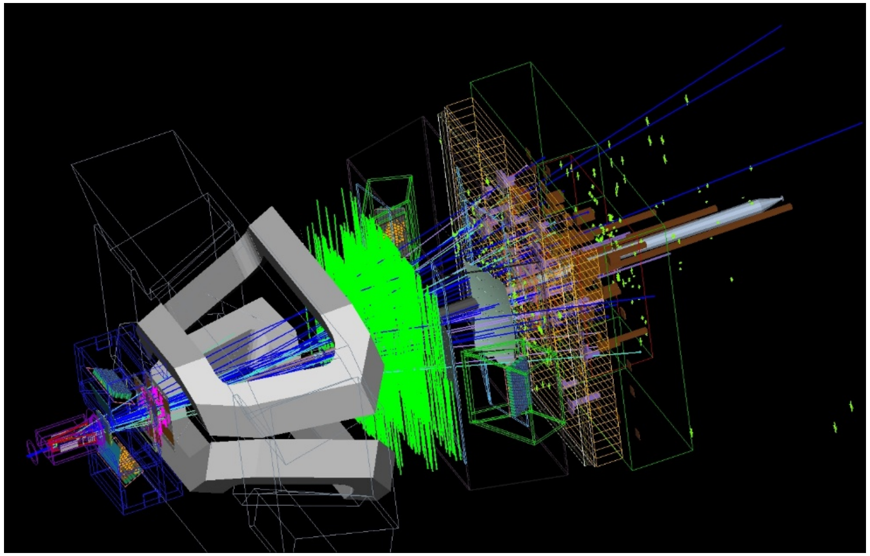
e+e- asymmetric collider (SuperKEK) at the Υ(4S) energy in Tsukuba, Japan



Starting now !

LHCb Upgrade

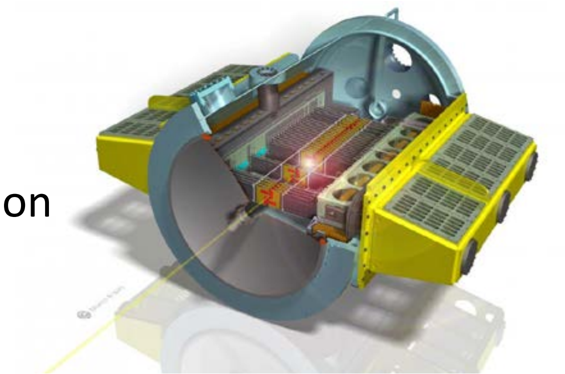
Improved trigger, improved detector



Starting in 2019

Future plans

- At present we did not find evidence for New Phyiscs, but some “anomalies” (let’s cross fingers!!)



- Standard Model deviations are expected to be small
- Most of the measurements are limited by the statisticall precision

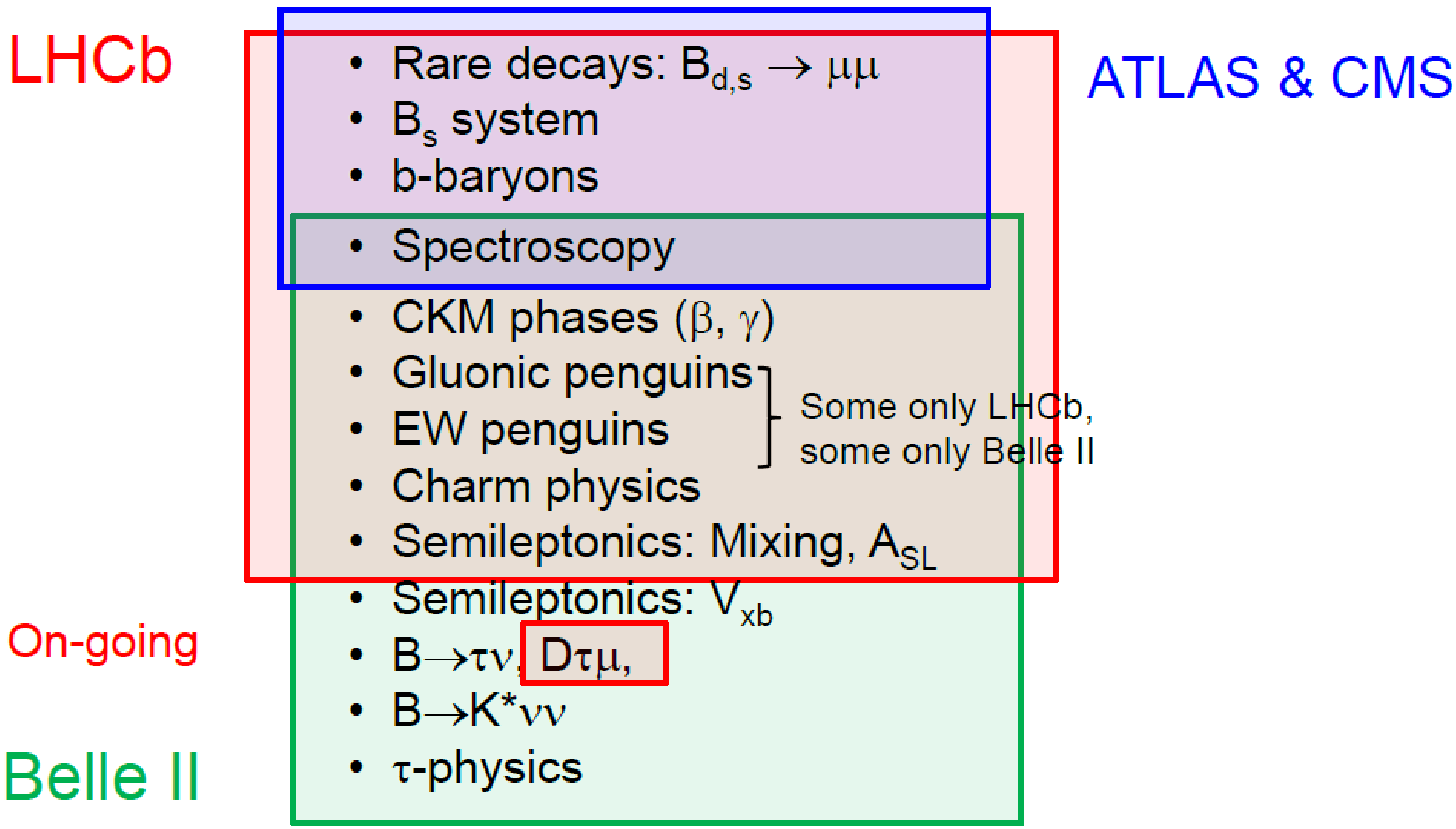
	LHC era		High-lumi LHC era		
	2010-2012	2015-2018	2020-2022	2025-2028	2030+
ATLAS & CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	→	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}
Belle II		0.5 ab^{-1}	25 ab^{-1}	50 ab^{-1}	-

Remember that we have 10^{11} $b\bar{b}$ pairs/fb !

(At Belle II: 10^9 $B\bar{B}$ pairs/ab)

Future plans

Complementarity:



Let’s hope!