Physics of Beauty at LHCb

Yuehong Xie

Central China Normal University

On behalf of LHCb Collaboration

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Outline

- Flavour physics & LHCb experiment
- CP violation
- Rare decays & lepton universality
- Summary and outlook

Quark mixing & CKM

$$\mathcal{L}_{SM} = \underbrace{\mathcal{L}_G(\psi, W, \phi)}_{\text{kinetic energy + gauge IA}} + \underbrace{\mathcal{L}_H(\phi)}_{\text{Higgs potential} \rightarrow \text{spontaneous symmetry breaking}} + \underbrace{\mathcal{L}_Y(\psi, \phi)}_{\text{Yukawa IA} \rightarrow \text{fermion masses}}$$

EWSB & diagonalisation of Yukawa mass matrix
⇒ CKM quark mixing matrix

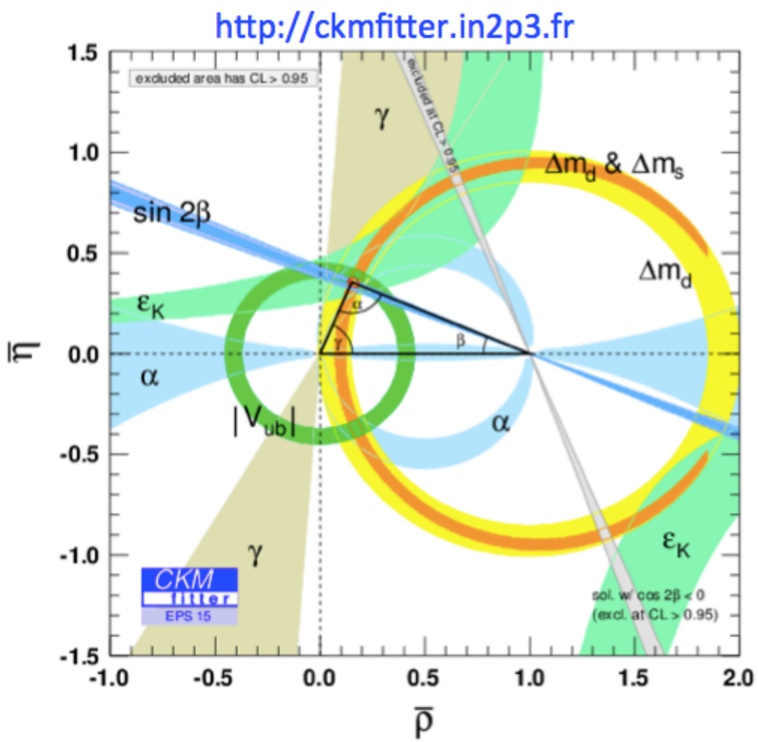
$$\boxed{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}}$$

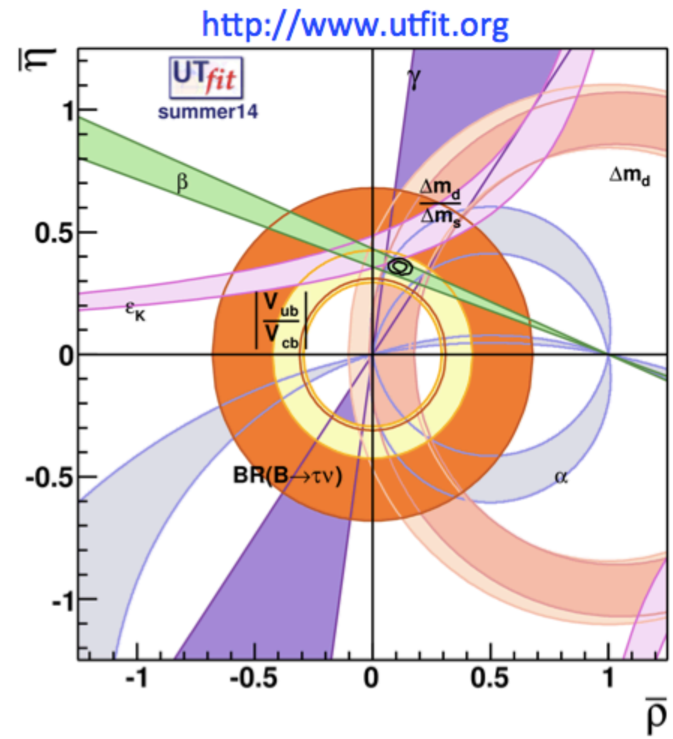
$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

L.Wolfenstein PRL 51 (1983) 1945

$\eta \neq 0$ ⇒ complex matrix element
⇒ CP violation (CPV) in weak interactions

Where we are with CKM





Very successful to describe collider data. However,

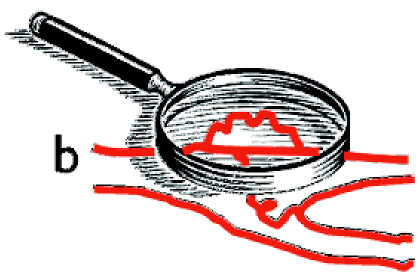
- CPV from CKM short by 10^{10} to explain the observed matter −antimatter asymmetry
- Dynamic origin of patterns of fermion masses and mixing unclear

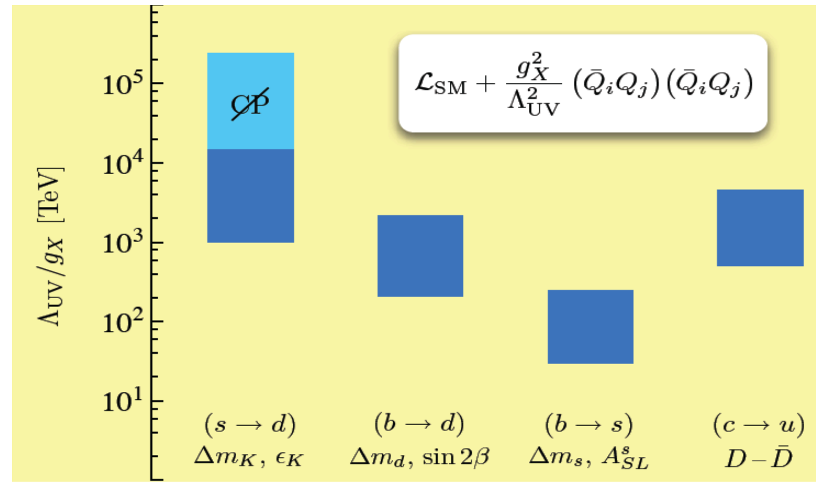
New physics (NP) beyond standard model (SM) at higher energy scale

Opportunities in flavour sector

Flavour as a window to NP, complementary to direct searches

- Exploring NP scale >> TeV
- Distinguishing NP models





Generic bounds on New Physics scale (for g_X~1)

NP could have significant effect in processes where SM contribution is suppressed and well understood

- Mixing processes
- Rare loop decays
- SM forbidden decays

- Decay rates
- CP asymmetries
- Angular correlations

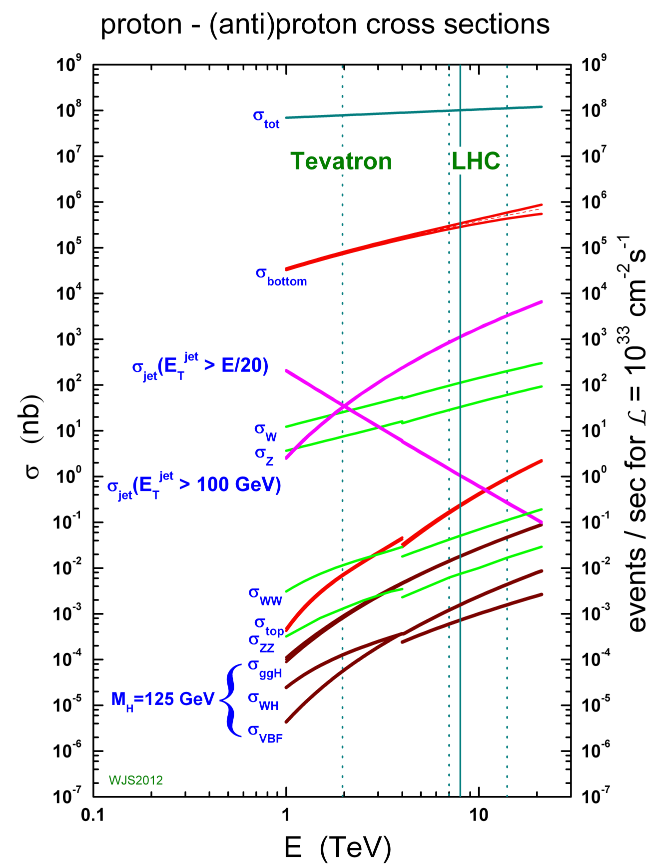
LHC：a flavour factory

Huge numbers of beauty and charm hadrons produced

$\sigma_{b\bar{b}} \sim$ 1% of total pp cross section

- A few×10^8 beauty pairs/hour generated at LHCb luminosity
- All species: B^0, $B^\pm$, B_s, B_c, Λ_b, …

About 20 times more charm!



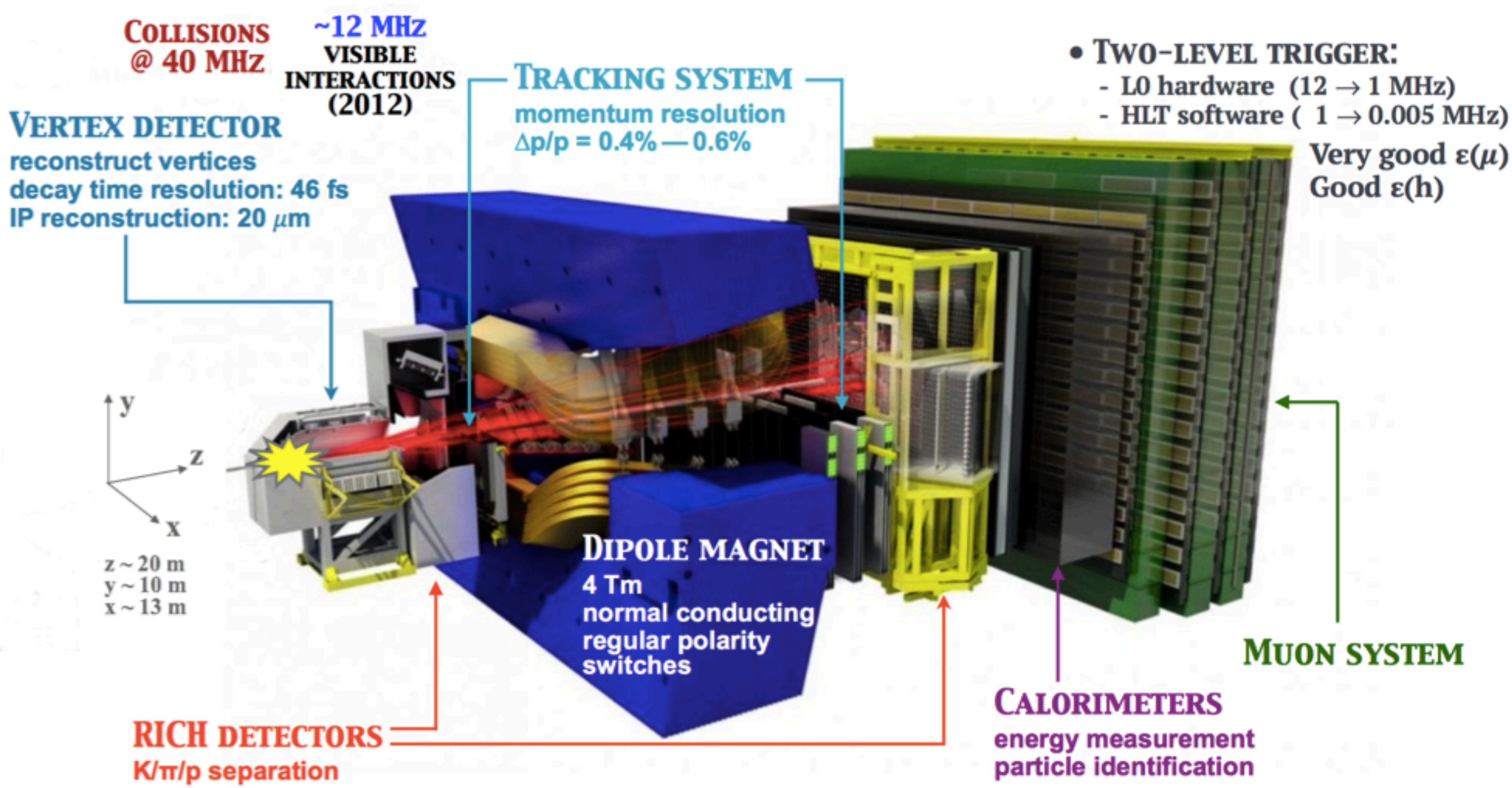
Detectors

LHCb: forward single arm detector for study of heavy flavour physics

ATLAS, CMS: general purpose, covering some flavour physics topics

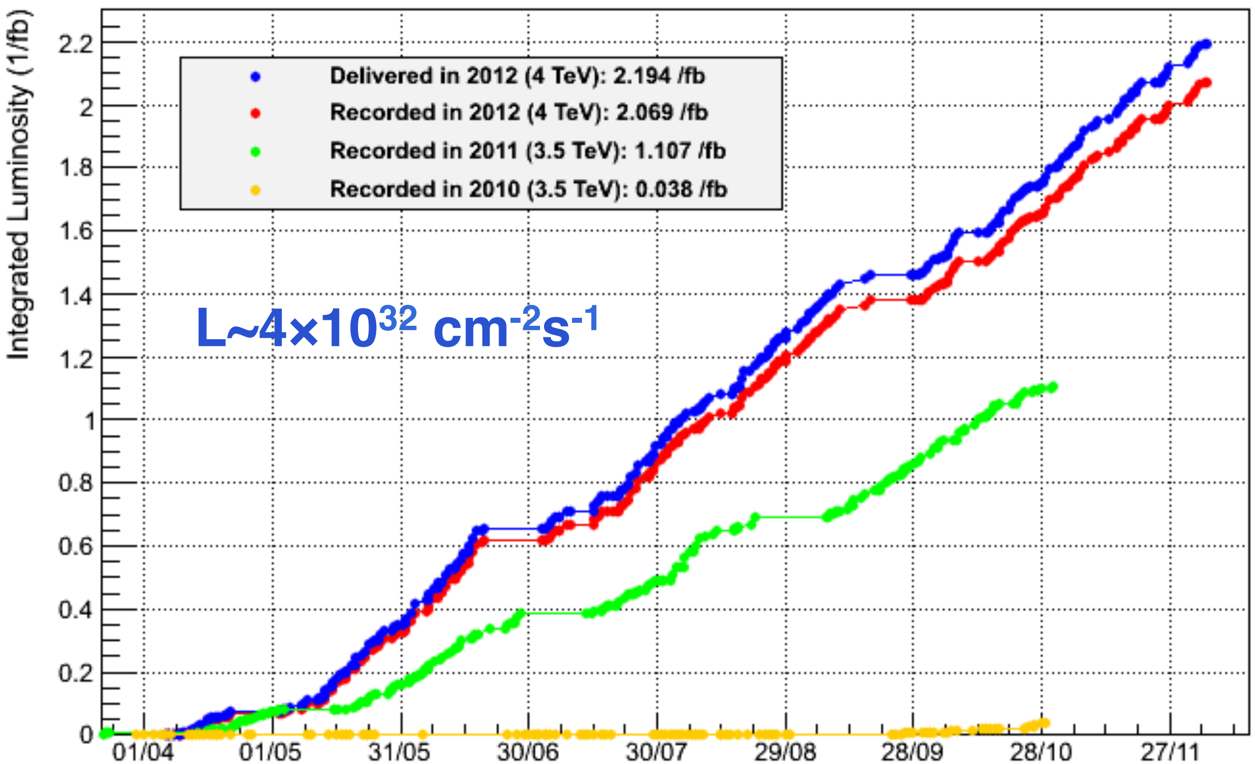
This talk will be mostly about LHCb results on B physics

LHCb spectrometer



Excellent tracking, vertexing and particle identification.
Powerful trigger at low transverse momentum.

Run 1 pp data–taking at 7/8 TeV



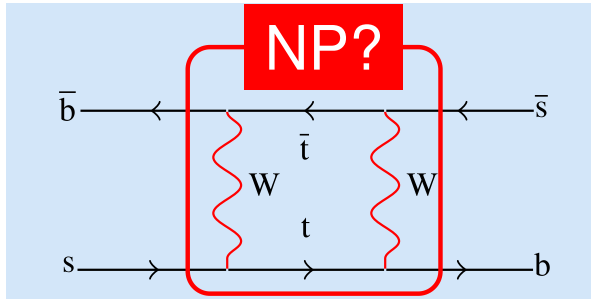
Results of this talk are based on run 1 data: 3 fb^{-1}

CP violation

Neutral B mixing

Weak states mix via box diagram： flavour oscillation

$$|B_q\rangle = |\bar{b}q\rangle$$



$$|\bar{B}_q\rangle = |b\bar{q}\rangle$$

Mass eigenstaes

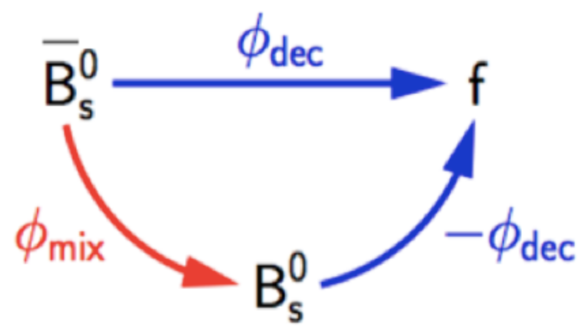
$\Delta m_q = m_H - m_L$, $\Delta\Gamma_q = \Gamma_L - \Gamma_H$

$$|B_L^q\rangle = p|B_q\rangle + q|\bar{B}_q\rangle$$

$$|B_H^q\rangle = p|B_q\rangle - q|\bar{B}_q\rangle$$

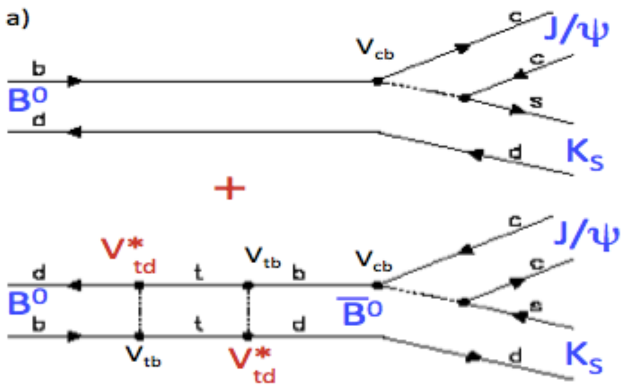
CPV observables

- CPV in mixing: a^q_{sl}
- Mixing–induced CPV： ϕ_s, $\phi_d = 2\beta$



a^q_{sl}, ϕ_q and Δm_q are very sensitive to NP in mixing

sin2β: a milestone in particle physics



$B_d \to J/\psi K_S$

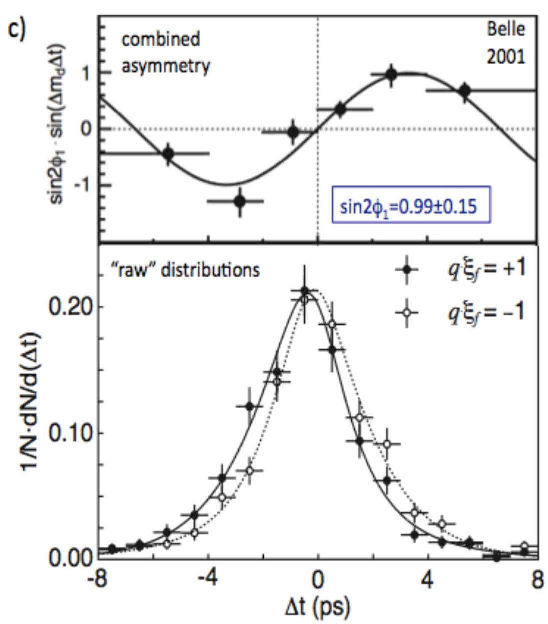
Babar, PRL 87 (2001) 091801

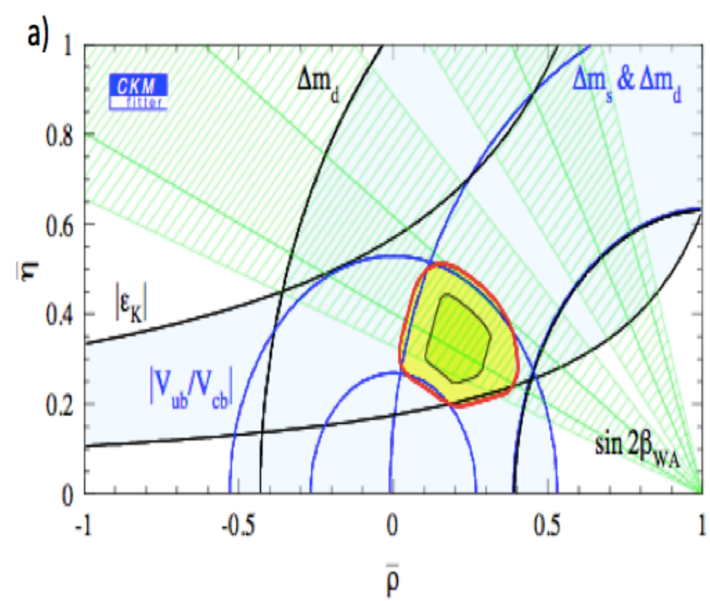
$\sin\phi_d = \sin 2\beta = 0.59 \pm 0.14 \pm 0.05$

Belle, PRL 87 (2001) 091802

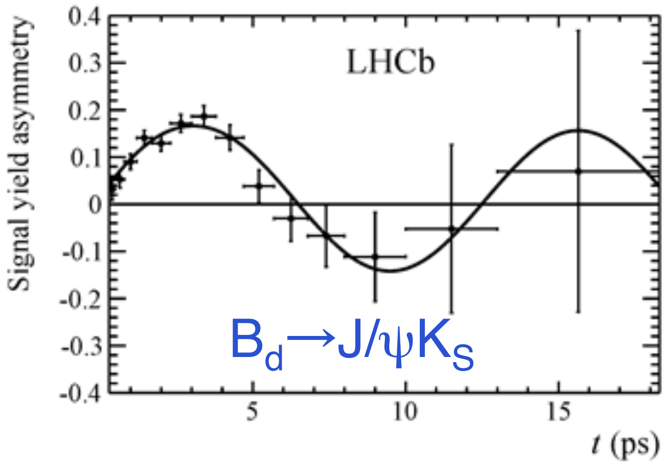
$\sin\phi_d = \sin\phi_1 = 0.99 \pm 0.14 \pm 0.06$

First observation of CPV in B decays confirms SM prediction!





LHCb result of sin2β

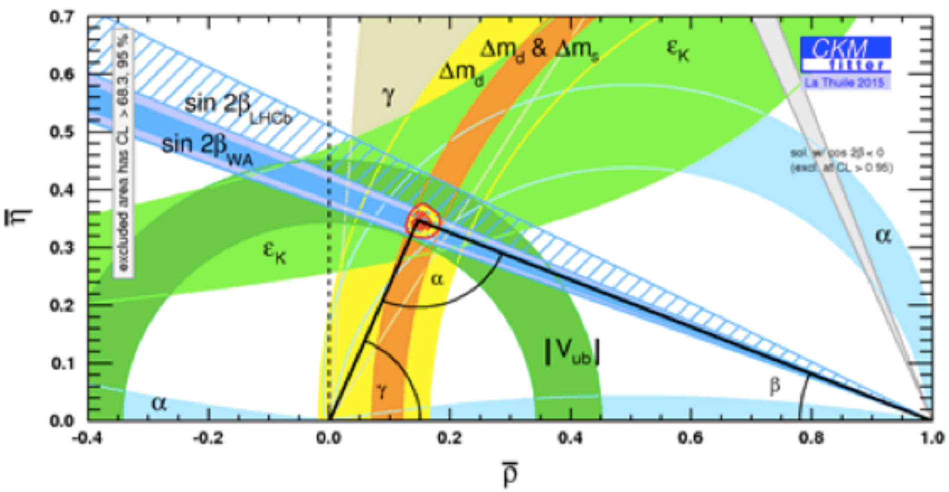


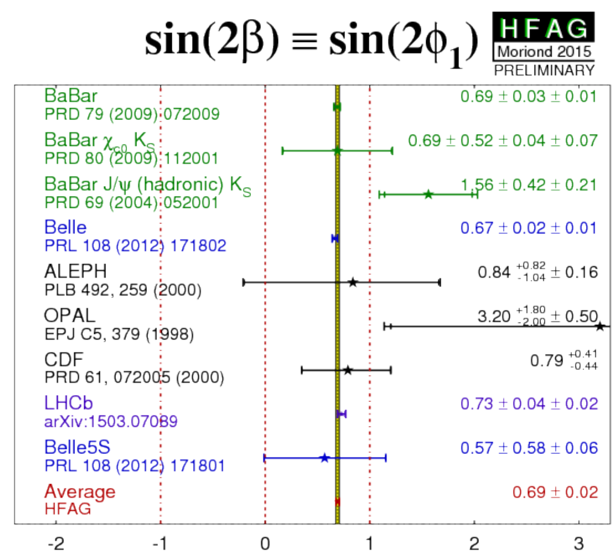
LHCb, PRL 115 (2015) 031601

$\sin 2\beta = 0.731 \pm 0.035 \pm 0.020$

Indirect fit in SM:

$\sin 2\beta = 0.771^{+0.017}_{-0.041}$



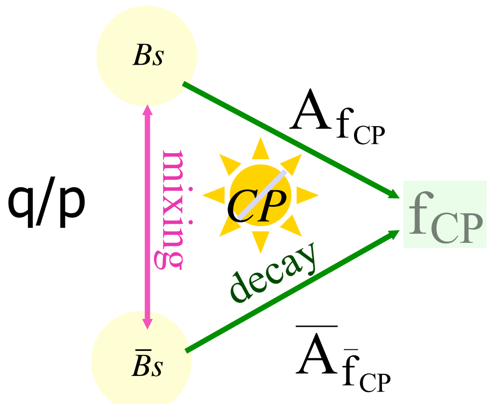


LHCb precision approaches that of B factories

ϕ_s: a crucial goal of LHCb

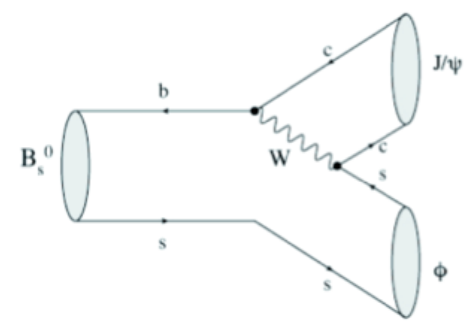
10% of b-hadrons in pp collisions are B_s mesons!

Measuring B_s CPV is LHC(b) territory.



For $b \to c\bar{c}s$ decay such as $B_s \to J/\psi\phi$

$$\phi_s \equiv -\arg\left(\eta_{f_{CP}} \frac{q}{p} \cdot \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}\right)$$



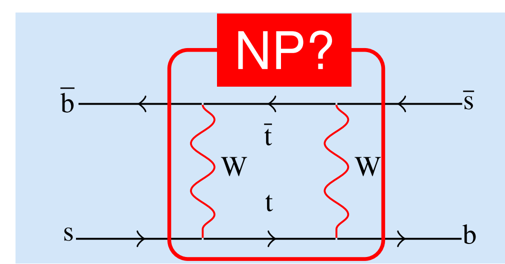
ϕ_s is precisely predicted in SM

$$\phi_s^{SM} = -0.038 \pm 0.001 \text{ rad}$$

(up to small correction for penguins)

ϕ_s is very sensitive to NP in mixing

$$\phi_s = \phi_s^{SM} + \Delta\phi^{NP}$$

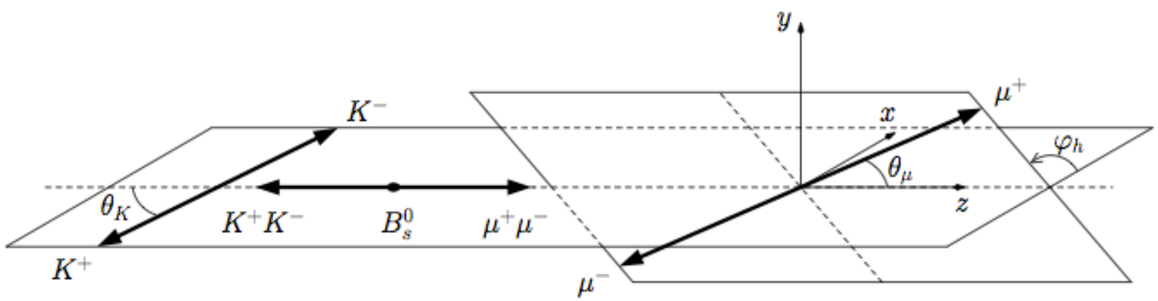


Analysis strategy of $B_s \to J/\psi\phi$

$$A_{\mathrm{CP}} \equiv \frac{\Gamma\left(\boxed{\overline{B}{}_s^0} \to f\right) - \Gamma\left(\boxed{B_s^0} \to f\right)}{\Gamma\left(\overline{B}{}_s^0 \to f\right) + \Gamma\left(B_s^0 \to f\right)} \sim \boxed{\eta_f} \sin\phi_s \boxed{\sin(\Delta m_s t)}$$

Requirements

- Good performance to tag initial flavour of B_s
- Good time resolution to resolve fast B_s oscillation and determine Δm_s
- Angular analysis to separate CP eigenstates

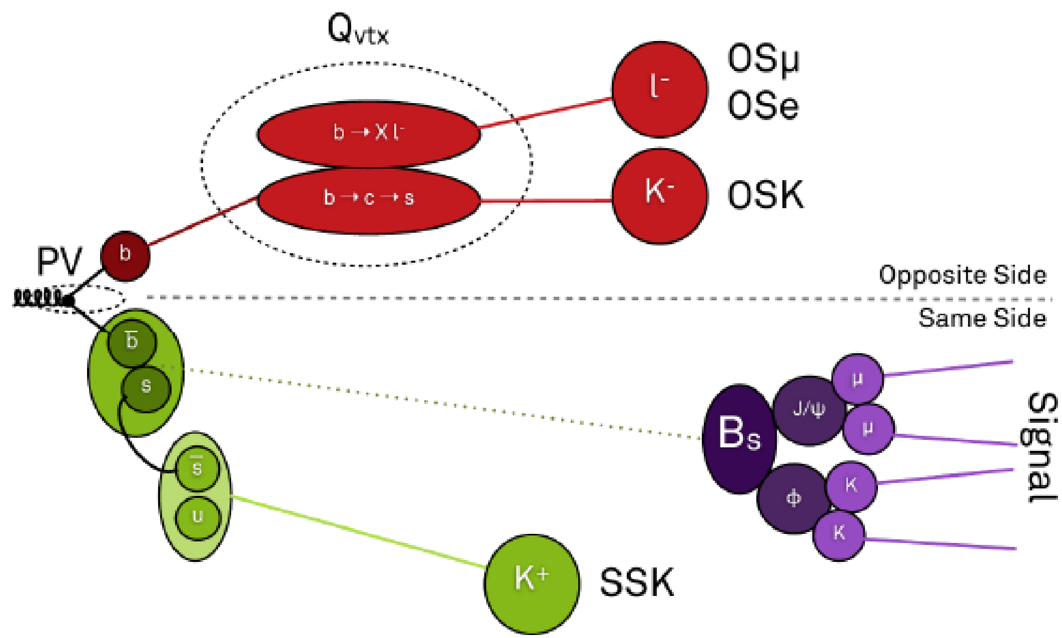


Tagging the initial flavour

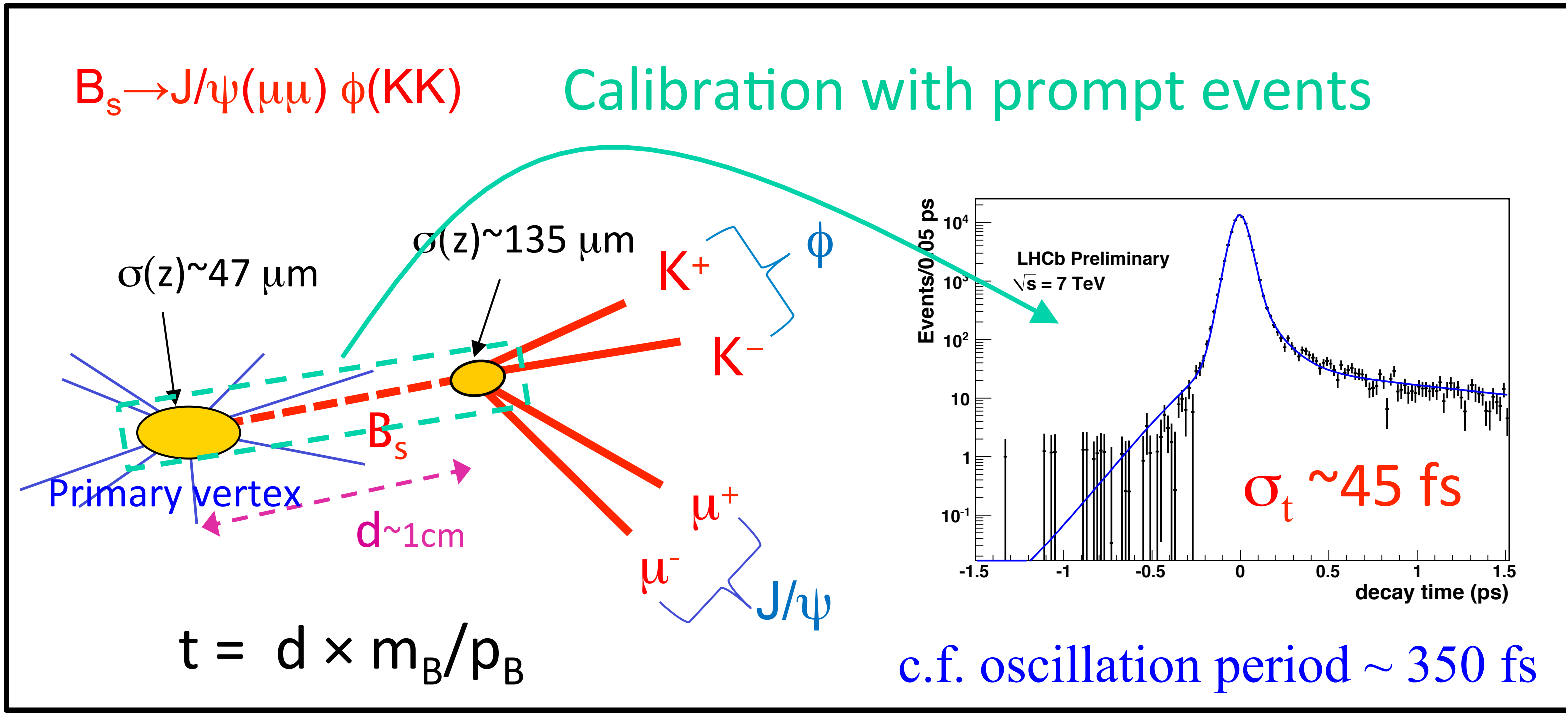
Opposite side (OS): using charges of decay products of the other B hadron LHCb, EPJC 72 (2012) 2022

Same side (SS): using charges of particles produced in association with the signal B LHCb, JINST 11 (2016) P05010

category	Effective $\varepsilon(1-2\omega)^2$ (%)
only OS tagged	1.19 ± 0.06
only SS tagged	0.84 ± 0.11
OS&SS tagged	1.7 ± 0.08
Total	3.73 ± 0.15



Decay time reconstruction



Impact of decay time resolution, $\Delta m_s \approx 17.7\ \mathrm{ps}^{-1}$

- If $\sigma_t = 45$ fs, dilution factor $\exp(-\Delta m_s^2 \sigma_t^2/2) \approx 0.73$
- If $\sigma_t = 90$ fs, dilution factor $\exp(-\Delta m_s^2 \sigma_t^2/2) \approx 0.28$

Method to measure $\Delta m_{s/d}$

- Choose a flavour specific decay mode

  e.g., $B^0 \rightarrow D^{(*)-} \mu^+ \nu$, $B_s \rightarrow D_s^- \pi^+$

$$
\begin{array}{ccc}
B^0 & \longrightarrow & f \\
\overline{B^0} & \not\longrightarrow & f \\
& \searrow B^0 \nearrow &
\end{array}
$$

- For each event
  - Identify the initial B flavour (at production point)
  - Reconstruct the decay time *t*

- Measure the decay rate as a function of *t*, and determine the oscillation frequency $\Delta m_{s/d}$

$$N^{\text{unmix}}(t) = N\left(B^0 \to D^{(*)-}\mu^+\nu_\mu X\right)(t) \propto e^{-\Gamma_d t}\left[1 + \cos(\Delta m_d t)\right]$$

$$N^{\text{mix}}(t) = N\left(B^0 \to \bar{B}^0 \to D^{(*)+}\mu^-\bar{\nu}_\mu X\right)(t) \propto e^{-\Gamma_d t}\left[1 + \cos(\Delta m_d t)\right]$$

$$A(t) = \frac{N^{\text{unmix}} - N^{\text{mix}}}{N^{\text{unmix}} + N^{\text{mix}}} = \cos(\Delta m_d t)$$

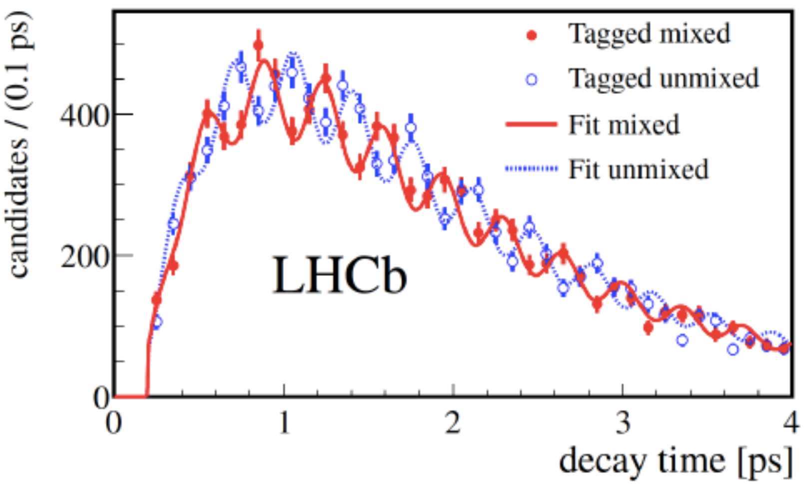
$\Delta m_{s/d}$ measurements

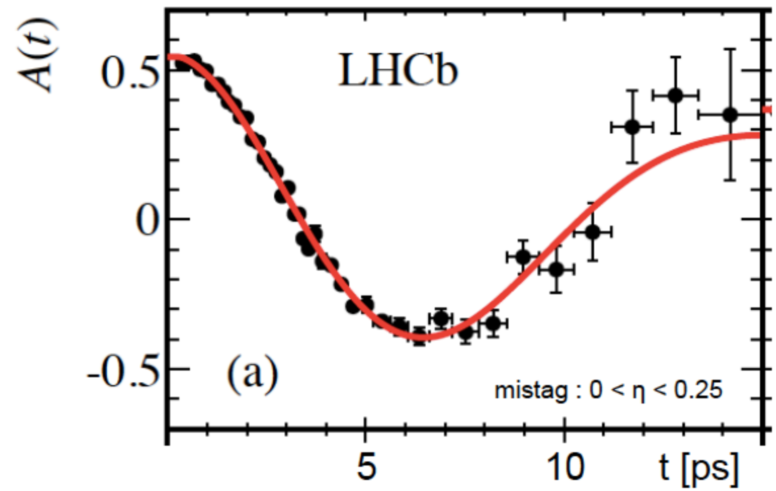
$B_s \to D_s^- \pi^+$ (1 fb^{-1})

LHCb, New J.Phys. 15 (2015) 053201

$B^0 \to D^{(*)-} \mu^+ \bar{\nu}$ (3 fb^{-1}) NEW

LHCb, EPJC 76 (2016) 412





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

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

SM: $\Delta m_s = 16.3 \pm 1.1$ ps^{-1}

SM: $\Delta m_d = 0.566^{+0.035}_{-0.043}$ ps^{-1}

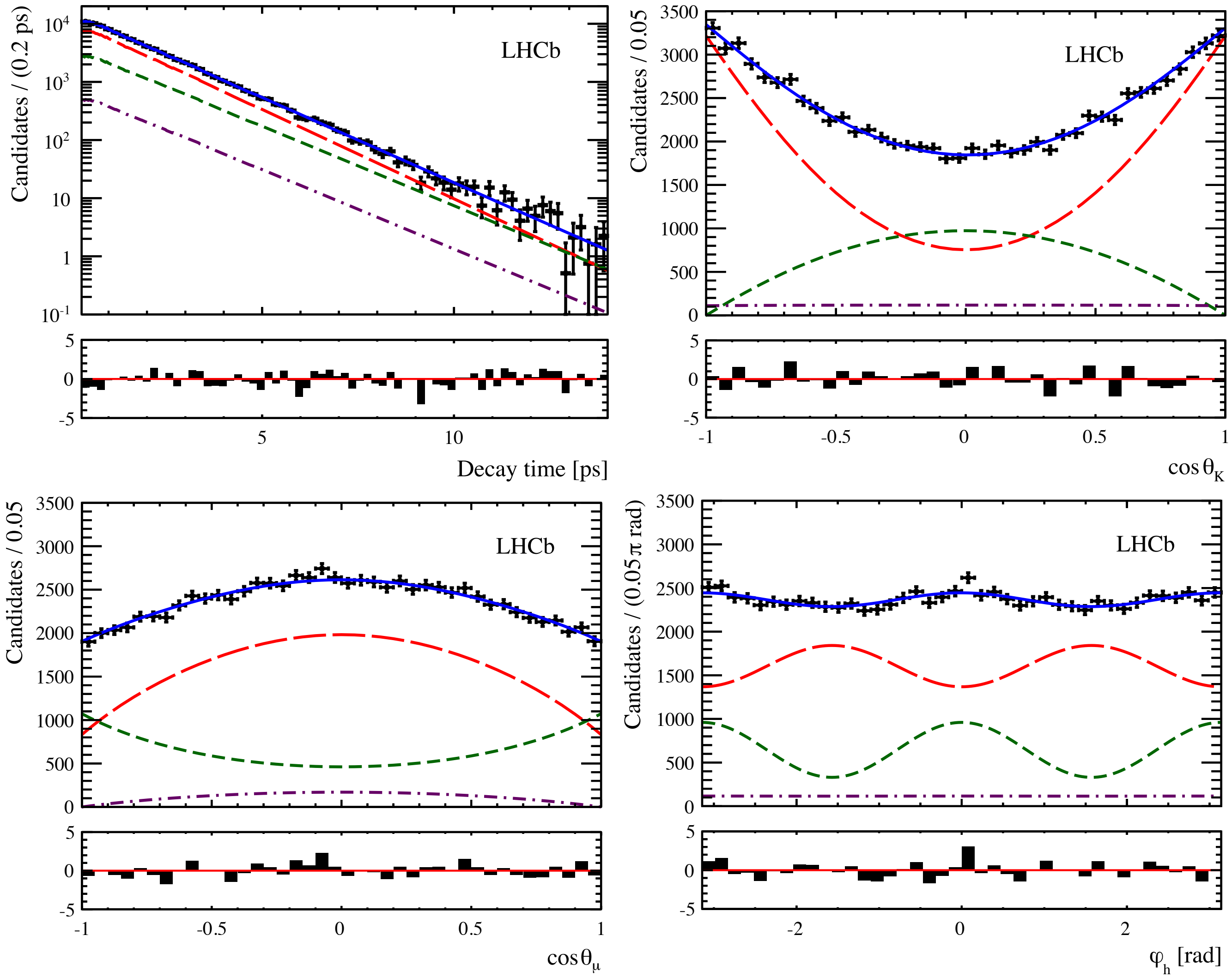
SM predictions suffer large uncertainties in Lattice QCD calculation of hadronic parameters

Time−dependent angular analysis

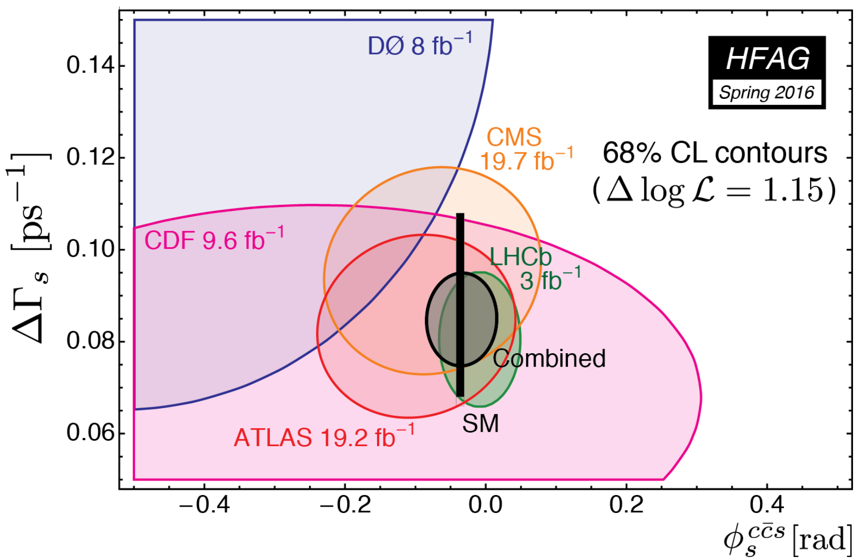
CP Even

CP Odd

S-wave (KK)



ϕ_s results



LHCb, PRL 114（2014）041801

$B_s \to J/\psi\phi$, $J/\psi\pi^+\pi^-$:

ϕ_s = -0.010 ± 0.039 rad

In agreement with

ϕ_s^{SM} = -0.038 ± 0.001 rad

LHCb result most precise but still statistically limited

Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps^{-1})	Ref.
CDF	$J/\psi\phi$	9.6 fb^{-1}	[−0.60, +0.12], 68% CL	$+0.068 \pm 0.026 \pm 0.009$	Phys. Rev. Lett. **109**, 171802 (2012)
D0	$J/\psi\phi$	8.0 fb^{-1}	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$	Phys. Rev. **D85**, 032006 (2012)
ATLAS	$J/\psi\phi$	4.9 fb^{-1}	$+0.12 \pm 0.25 \pm 0.05$	$+0.053 \pm 0.021 \pm 0.010$	Phys. Rev. **D90**, 052007 (2014)
ATLAS	$J/\psi\phi$	14.3 fb^{-1}	$-0.123 \pm 0.089 \pm 0.041$	$+0.096 \pm 0.013 \pm 0.007$	arXiv:1601.03297
ATLAS	above 2 combined		$-0.098 \pm 0.084 \pm 0.040$	$+0.083 \pm 0.011 \pm 0.007$	arXiv:1601.03297
CMS	$J/\psi\phi$	19.7 fb^{-1}	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$	Phys. Lett. **B757**, 97–120 (2016)
LHCb	$J/\psi K^+K^-$	3.0 fb^{-1}	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0033$	Phys. Rev. Lett. **114**, 041801 (2015)
LHCb	$J/\psi\pi^+\pi^-$	3.0 fb^{-1}	$+0.070 \pm 0.068 \pm 0.008$	—	Phys. Lett. **B736**, 186 (2014)
LHCb	above 2 combined		-0.010 ± 0.039(tot)	—	Phys. Rev. Lett. **114**, 041801 (2015)
LHCb	$D_s^+D_s^-$	3.0 fb^{-1}	$+0.02 \pm 0.17 \pm 0.02$	—	Phys. Rev. Lett. **113**, 211801 (2014)
All combined			-0.033 ± 0.033	$+0.084 \pm 0.007$	

More $b \to c\bar{c}s$ modes for ϕ_s

- $B_s \to D_s^+ D_s^-$: supplementary mode

  $\phi_s = 0.02 \pm 0.17 \pm 0.02$ rad LHCb, PRL 113 (2014) 211801

- $B_s \to \psi(2S)\phi$: supplementary mode

  NEW

  $\phi_s = 0.23 \pm 0.29 \pm 0.02$ rad LHCb-PAPER-2016-027, in prep.

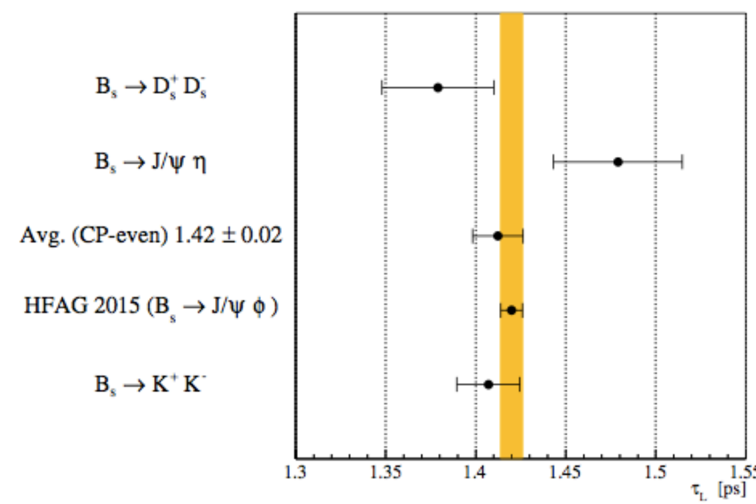
- $B_s \to J/\psi\eta$: CP-even mode, lifetime measured so far

  $\tau(J/\psi\eta) = 1.479 \pm 0.034 \pm 0.011$ ps

  LHCb-PAPER-2016-017 NEW

- More analyses underway

  $B_s \to J/\psi K^+K^-$ above $\phi(1020)$ region,
  $B_s \to \eta_c\phi$, $B_s \to J/\psi\phi$ with $J/\psi \to e^+e^-$, …



Adding these modes can improve ϕ_s precision by ~20%

Semi-leptonic asymmetries

Semi-leptonic asymmetry a^q_{sl} quantifies CPV in mixing.

a^q_{sl} is precisely predicted to be tiny in SM: ~$O(10^{-4})$,
can be enhanced by NP

$$a_{\rm sl} = \frac{N(\bar{B}\to B \to f) - N(B\to\bar{B} \to \bar{f})}{N(\bar{B}\to B \to f) + N(B\to\bar{B} \to \bar{f})}$$

$$\begin{array}{ccc} B^0_q & \longrightarrow & f \\ \overline{B^0_q} & \not\longrightarrow & f \\ \searrow & B^0_q & \nearrow \end{array}$$

(1) Measure time-integrated raw asymmetry

$$A_{\rm raw} = \frac{N(D_s^- \mu^+) - N(D_s^+ \mu^-)}{N(D_s^- \mu^+) + N(D_s^+ \mu^-)}$$

(2) Correct for detection asymmetry and background effect

$$a^s_{\rm sl} = \frac{2}{1 - f_{\rm bkg}}(A_{\rm raw} - A_{\rm det} - f_{\rm bkg} A_{\rm bkg})$$

For B_d, also correct for production asymmetry

LHCb results of a^q_{sl}

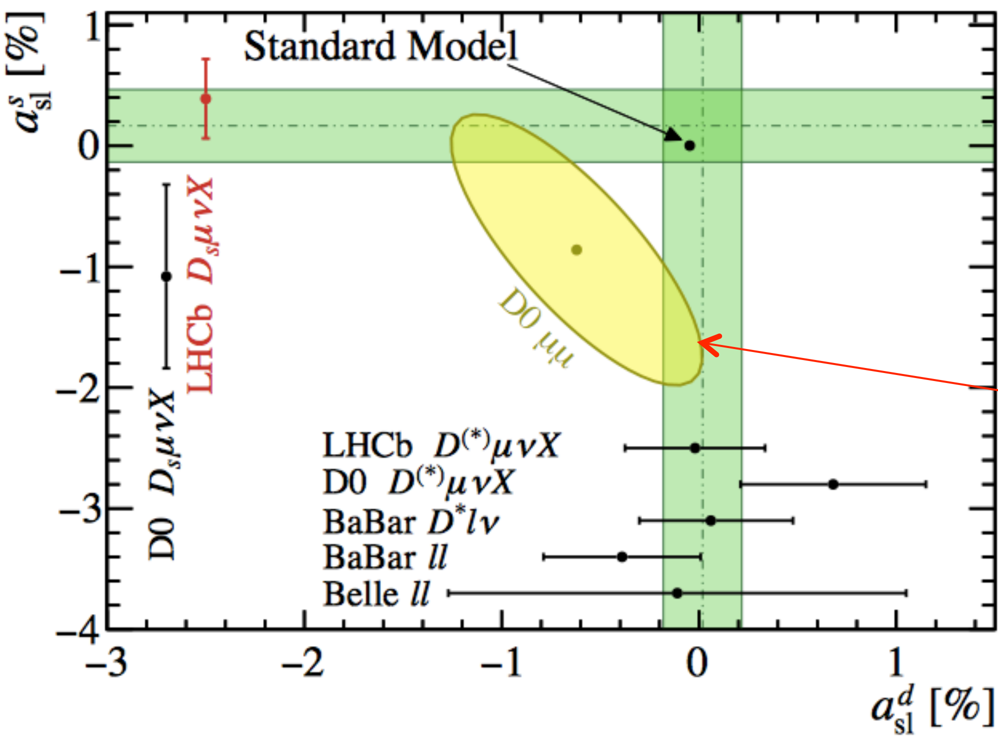
$B_s \to D_s^- \mu^+ \overline{\nu}$: $a^s_{sl} = (0.39 \pm 0.26 \pm 0.20)$ %

LHCb, PRL 117 (2016) 061803

NEW

$B_d \to D^{(*)-} \mu^+ \overline{\nu}$: $a^d_{sl} = (-0.02 \pm 0.19 \pm 0.30)$ %

LHCb, PRL 114 (2014) 041601



Consistent with SM prediction & CP conservation

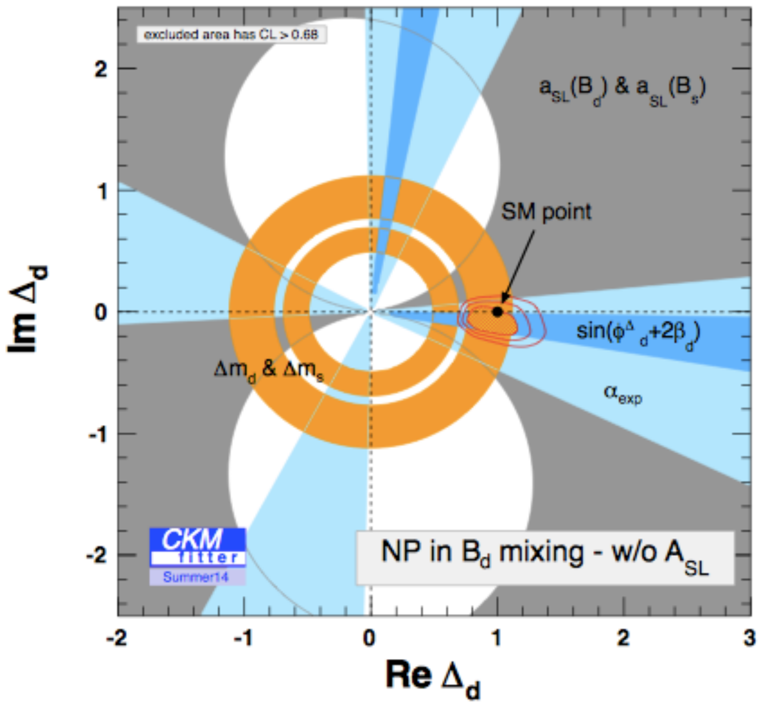
In tension with D0 dimuon asymmetry

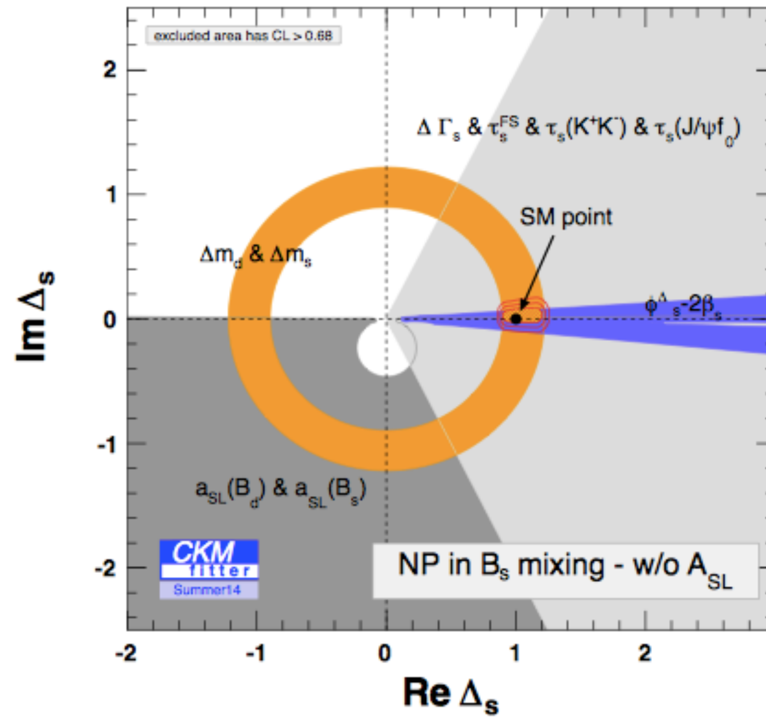
$A^b_{sl} = c_1\, a^s_{sl} + c_1\, a^s_{sl}$
$= (0.957 \pm 0.251 \pm 0.146)$%

D0, PRL 105 (2010) 081801

Constraints on NP in B mixing

$$M_{12}^q \equiv M_{12}^{\mathrm{SM},q} \cdot \Delta_q$$





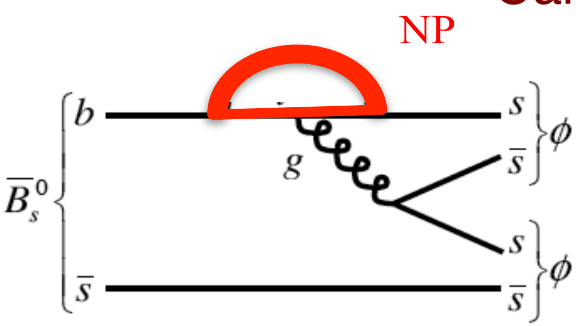
No sign of NP. Data still allow NP contributions in B mixing up to 30-40% at 3σ level

CPV in loop decays

$B_s \to \phi\phi$

b→s decay. Weak phase |ϕ|<0.02 in SM.

Can be affected by NP in decay and/or mixing.

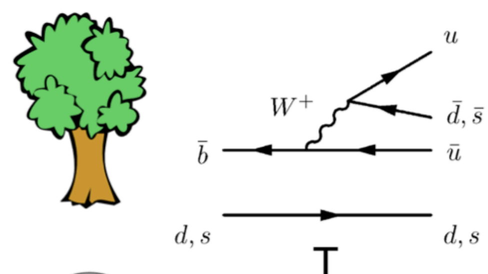


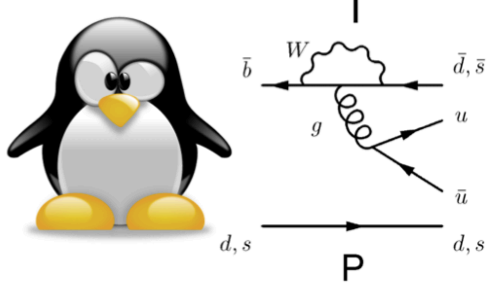
$\phi = -0.17 \pm 0.15 \pm 0.03$ rad

LHCb, PRD 90 (2014) 052011

$B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$

$1fb^{-1}$ CPV results	K^+K^-	$\pi^+\pi^-$
Direct CPV	0.14 ± 0.11	-0.30 ± 0.05
Mixing induced CPV	0.30 ± 0.13	-0.66 ± 0.06





Allowing 50% U-spin breaking, using γ from B→Dh

$\phi_s = -0.12^{+0.14}_{-0.16}$ rad

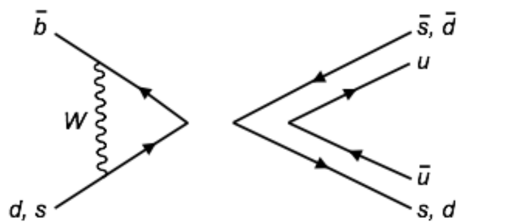
LHCb, PLB 741 (2015) 1

Consistent with tree-level determination

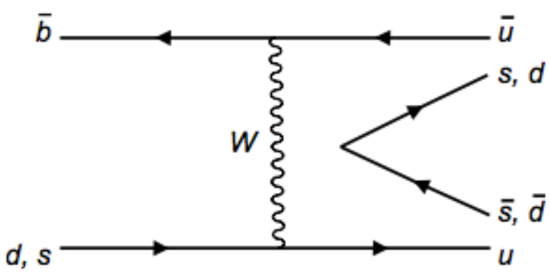
$\phi_s^{\,b\to ccs} = -0.033 \pm 0.033$ rad

Observation of $B_d \to K^+K^-$

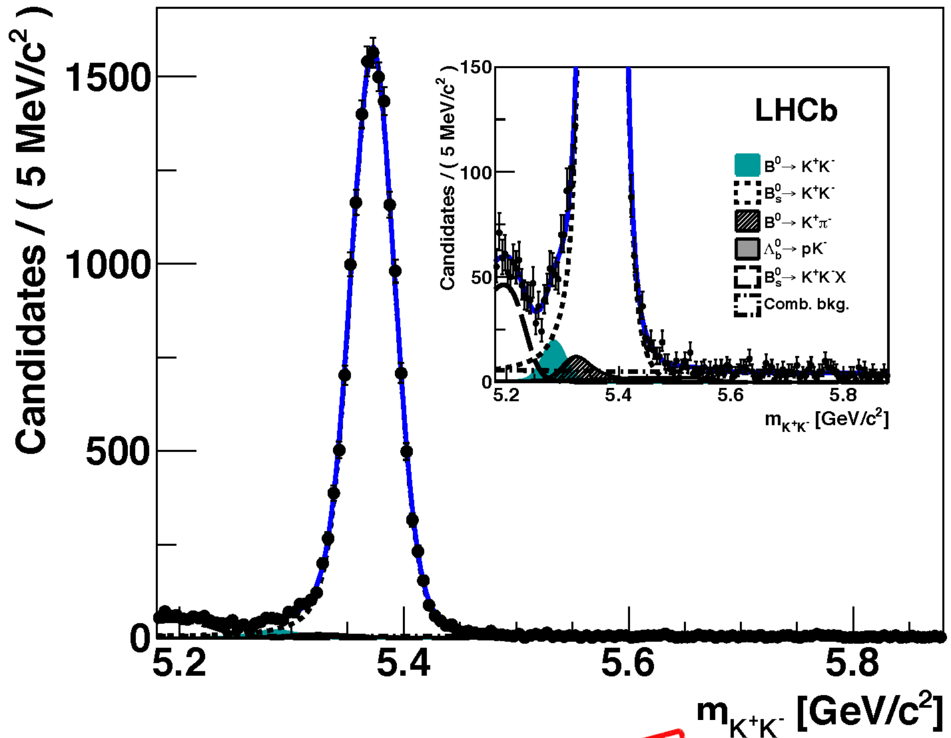
Highly suppressed decay, test of QCD computation



Penguin Annihilation (PA)



W-Exchange(E)



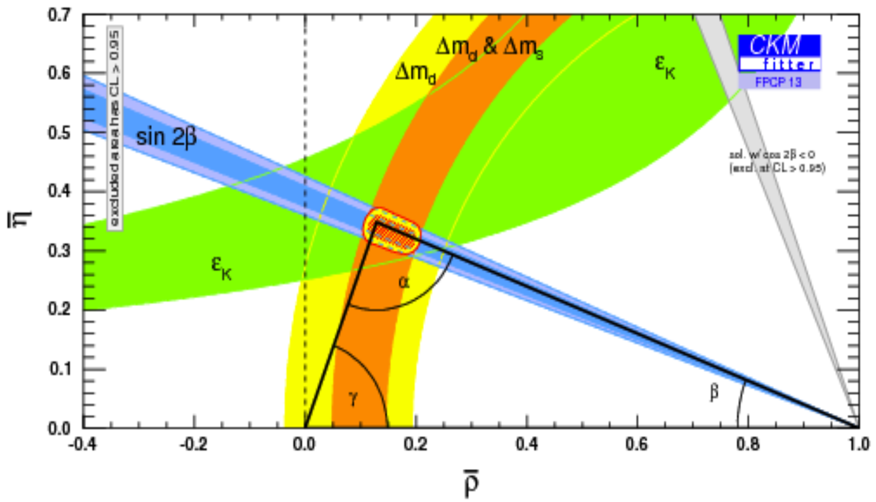
$B(B_d \to K^+K^-) = (7.80 \pm 1.27 \pm 0.21) \times 10^{-8}$

The rarest B decay into hadronic final state ever observed!

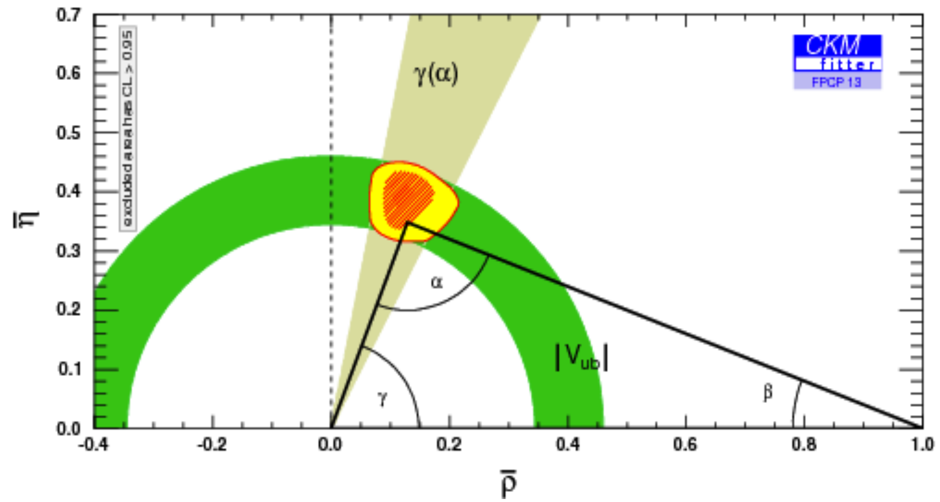
(5.8σ significance) LHCb-PAPER-2016-036, in prep.

Unitarity triangle

Measurements from “loop”



Measurements from “tree”

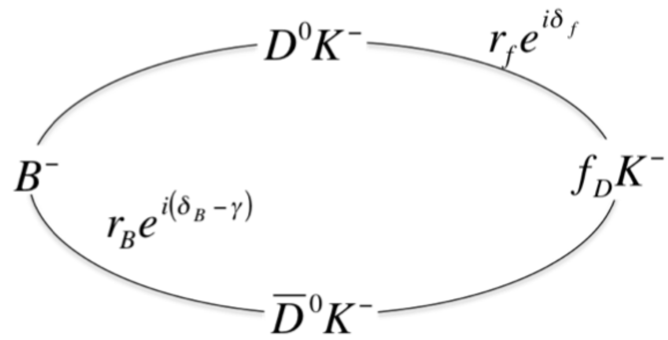


Need significant improvement of γ and $|V_{ub}|$ precision

CPV in B→Dh for γ measurement

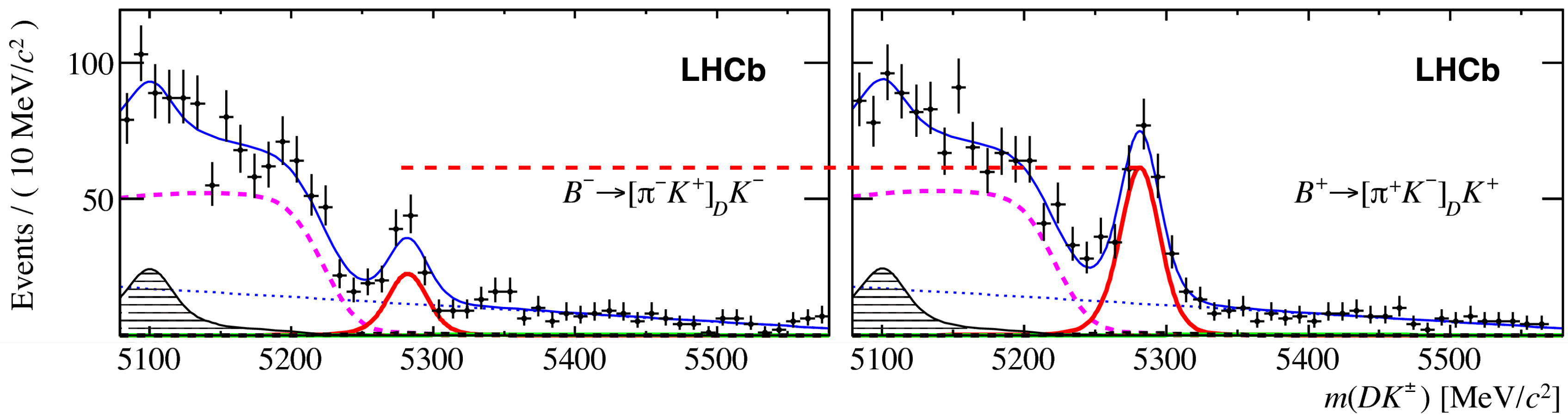
Large CPV if r_f is small

e.g. with $D^0 \to K^+\pi^-$



sensitivity to γ

$$\frac{N(B^-) - N(B^+)}{N(B^-) + N(B^+)} = A_{CP+} = \frac{1}{R_{CP+}} 2r_B(2F_+ - 1)\sin(\delta_B)\sin(\gamma)$$



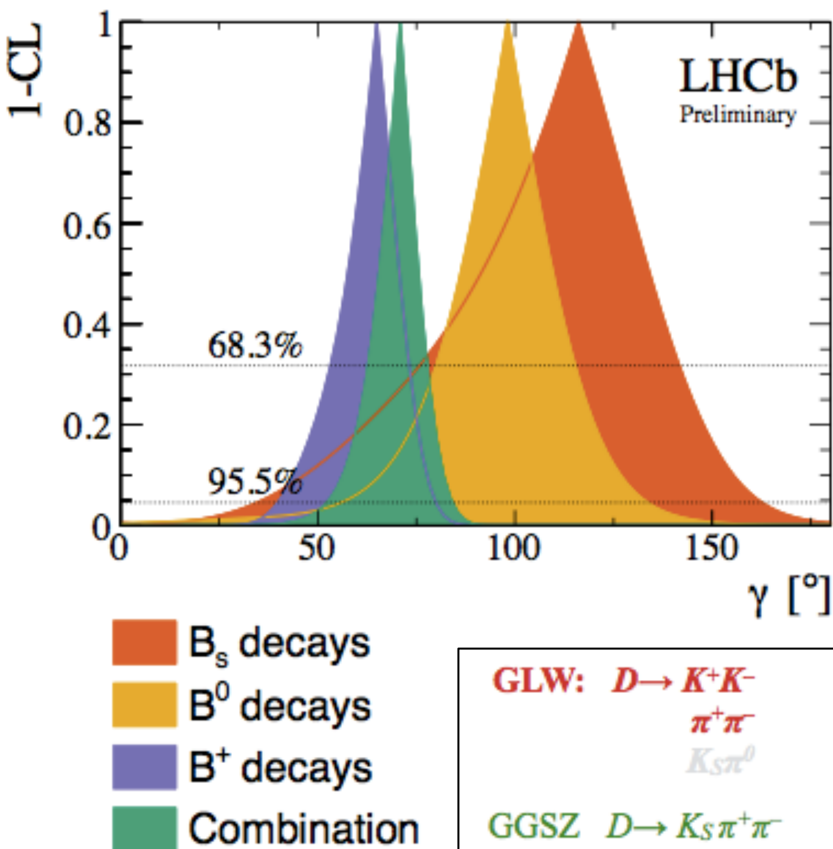
Suppressed ADS mode $B^\pm \to [\pi K]_D K^\pm$ with $D^0 \to K^+\pi^-$

A_{CP}= -0.403 ±0.056 ± 0.011 LHCb, PLB 760 (2016) 117

γ combination at LHCb

Determine γ from CPV measurements

- in many B & D decay modes
- using external inputs of D decay parameters: r_f and δ_f



LHCb-PAPER-2016-032

$$\gamma = (70.9^{+7.1}_{-8.5})^\circ$$

NEW

BaBar: $\gamma = (70\pm18)^\circ$

Belle: $\gamma = (73^{+13}{}_{-15})^\circ$

Used D decay modes

GLW: $D \to K^+K^-$, $\pi^+\pi^-$, $K_S\pi^0$

ADS: $D \to \pi^-K^+$

quasi-ADS $D \to \pi^-K^+\pi^+\pi^-$, $\pi^-K^+\pi^0$

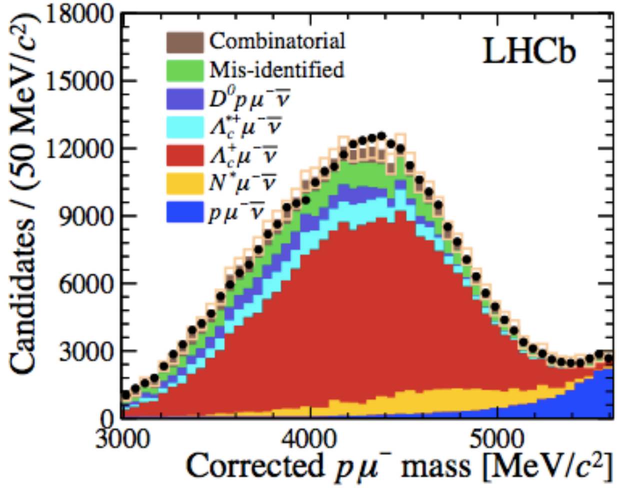
quasi-GLW $D \to \pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^0$, $\pi^+\pi^-\pi^0$

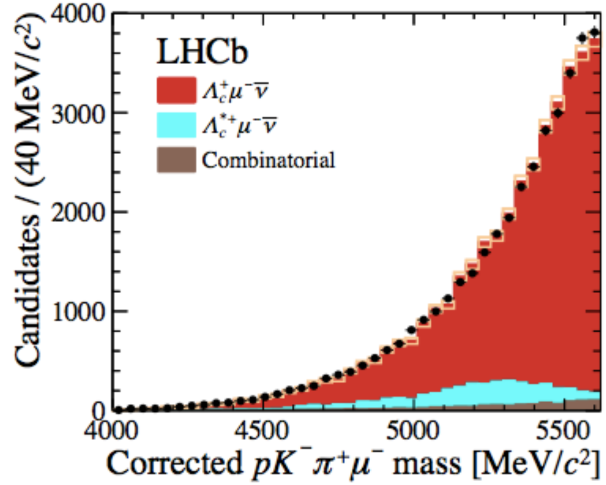
GGSZ $D \to K_S\pi^+\pi^-$, $K_SK^+K^-$

GLS $D \to K_SK^-\pi^+$, $K_S\pi^-K^+$

$|V_{ub}|$ from $\Lambda_b \to p\mu^- \nu$

Partial reconstruction of $\Lambda_b \to p\mu^- \nu$ and $\Lambda_b \to \Lambda_c^+ \mu^- \nu$





Signal: 17687 ± 733

Normalization: 34255 ± 571

Determine $|V_{ub}|^2/|V_{cb}|^2$

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\ GeV^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\ GeV^2}} \cdot R_{\mathrm{FF}}$$

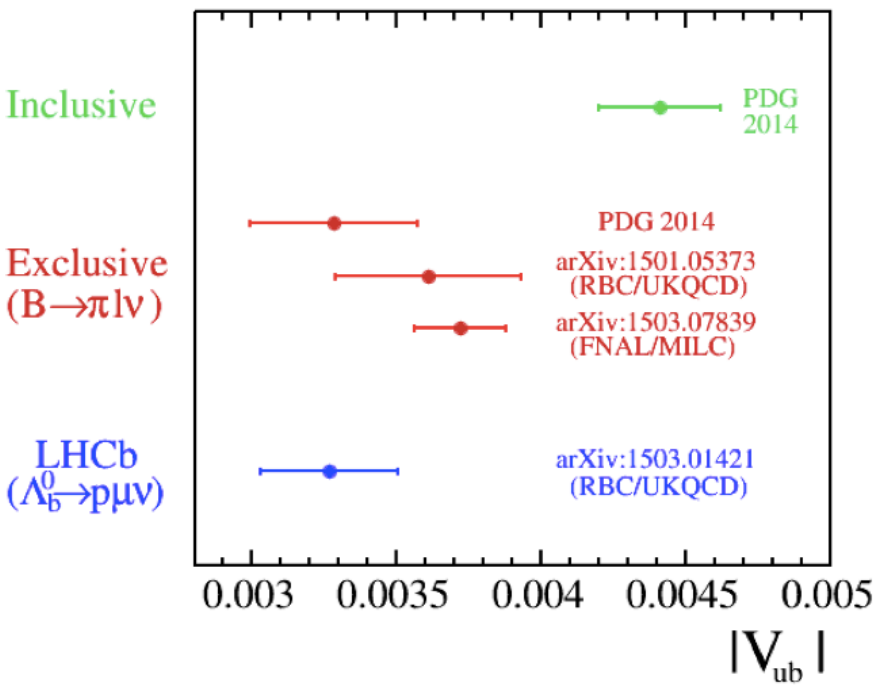
form factor ratio
5% uncertainty
on $|V_{ub}|$

LHCb $|V_{ub}|$ result

Using PDG exclusive average of $|V_{cb}|$

$$|V_{ub}| = (3.27 \pm 0.15_{\exp} \pm 0.17_{theory} \pm 0.06_{|Vcb|}) \times 10^{-3}$$

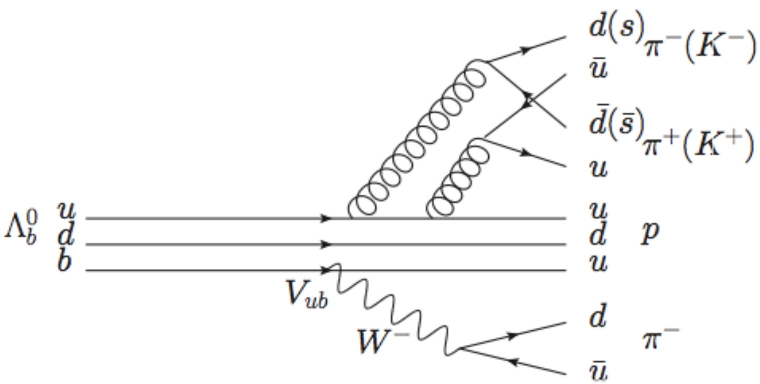
LHCb, Nature Physics 11 (2015) 743



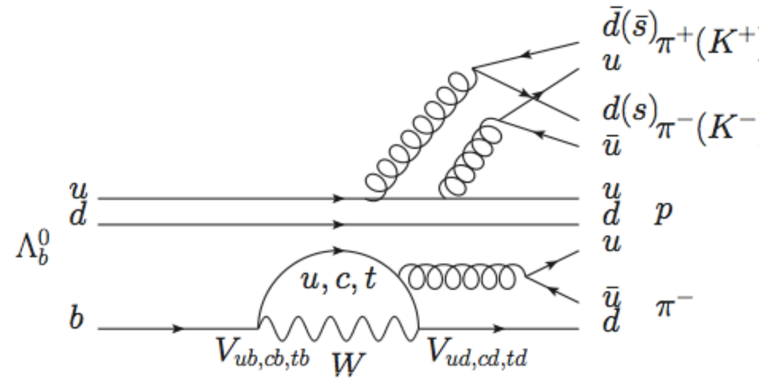
Consistent with previous exclusive measurements

Baryon decay $\Lambda_b \to p\pi^- h^+h^-$

- CPV has never been observed in baryon sector
- $A_{CP} \sim 20\%$ expected in charmless Λ_b decays in SM
  Y. K. Hsiao et al., PRD 91 (2015) 116007
- $\Lambda_b \to p\pi^- h^+h^-$ has comparable tree and loops contributions



Tree $\propto |V_{ub}| \sim \lambda^3$



Penguin $\propto \sum_{x=u,c,t} V_{bx} V_{xd} \sim \lambda^3$

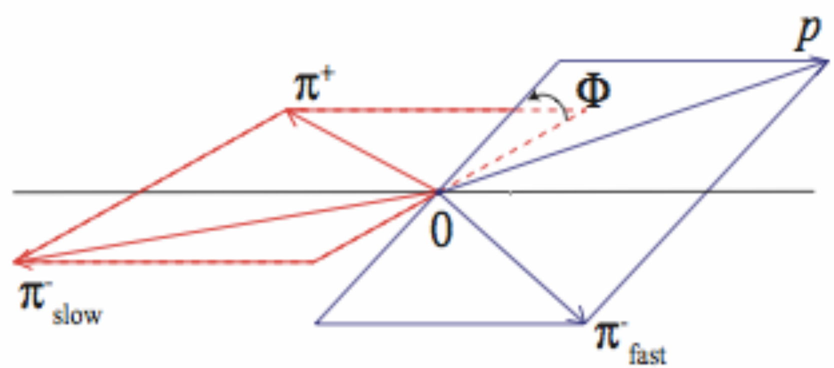
V_{ub} has large phase γ

Triple product asymmetry

Search for CPV using triple product asymmetry (TPA)

Triple products in the Λ_b rest frame:

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h-} \times \vec{p}_{h+}) \propto \sin\Phi$$
$$\overline{C}_{\hat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h+} \times \vec{p}_{h-}) \propto \sin\overline{\Phi}$$



$\hat{T}$-odd asymmetries:

$$A_{\hat{T}} = \frac{N_{\Lambda_b^0}(C_{\hat{T}}>0) - N_{\Lambda_b^0}(C_{\hat{T}}<0)}{N_{\Lambda_b^0}(C_{\hat{T}}>0) + N_{\Lambda_b^0}(C_{\hat{T}}<0)}$$

$$\overline{A}_{\hat{T}} = \frac{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}>0) - N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}<0)}{N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}>0) + N_{\overline{\Lambda}_b^0}(-\overline{C}_{\hat{T}}<0)}$$

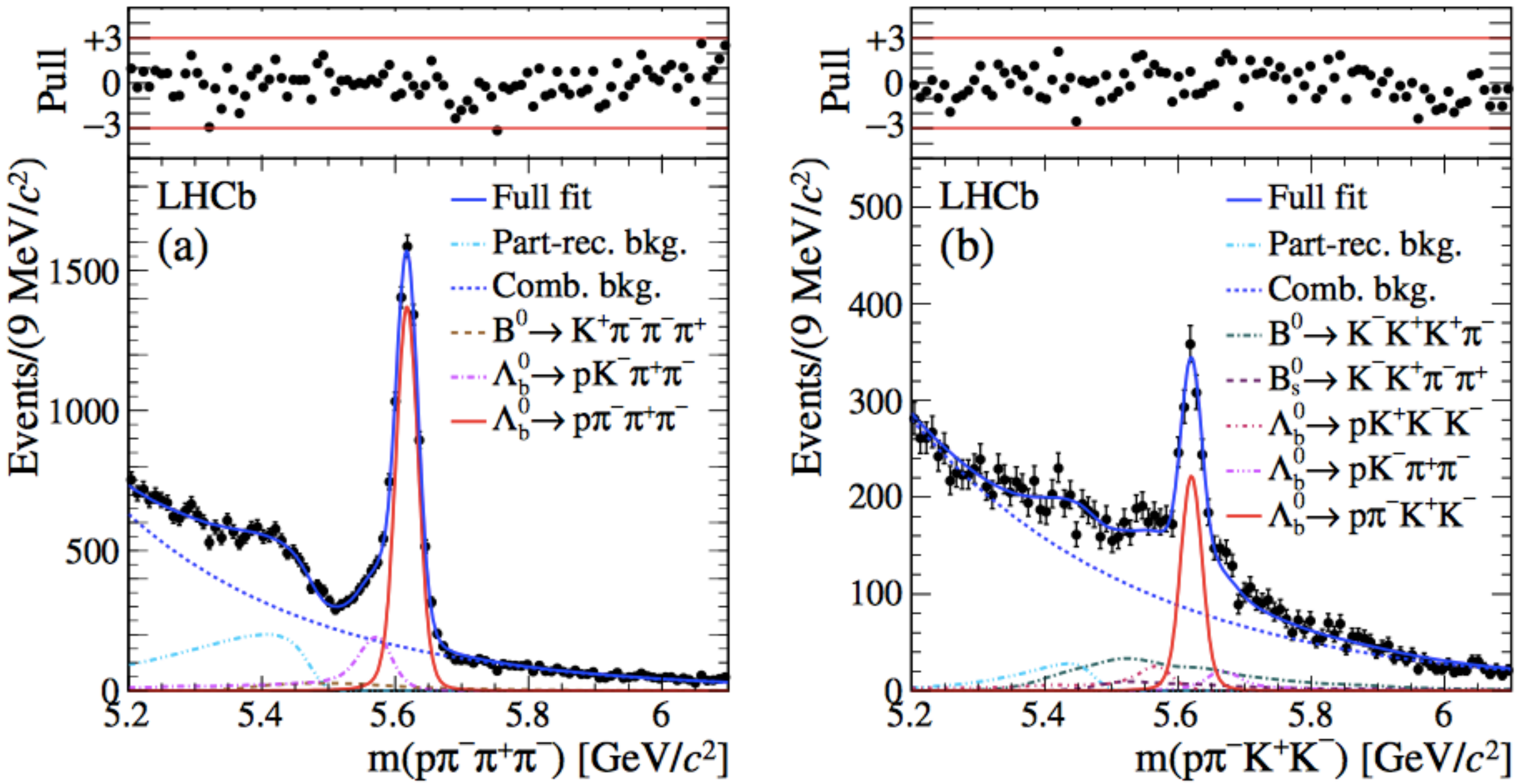
CP-violating observable:

$$\mathbf{a}_{\mathbf{CP}}^{\hat{\mathbf{T}}-\mathbf{odd}} = \frac{1}{2}(\mathbf{A}_{\hat{\mathbf{T}}} - \overline{\mathbf{A}}_{\hat{\mathbf{T}}})$$

P-violating observable:

$$\mathbf{a}_{\mathbf{P}}^{\hat{\mathbf{T}}-\mathbf{odd}} = \frac{1}{2}(\mathbf{A}_{\hat{\mathbf{T}}} + \overline{\mathbf{A}}_{\hat{\mathbf{T}}})$$

$\Lambda_b \to p\pi^- h^+h^-$: signal yields



$$N_{\Lambda_b^0 \to p\pi^-\pi^+\pi^-} = 6646 \pm 105(\text{stat})$$

$$N_{\Lambda_b^0 \to p\pi^-K^+K^-} = 1030 \pm 56(\text{stat})$$

(full run-1 sample) LHCb-PAPER-2016-030, in prep.

CPV in baryon decays

Measurements integrated over phase space

- No significant CPV

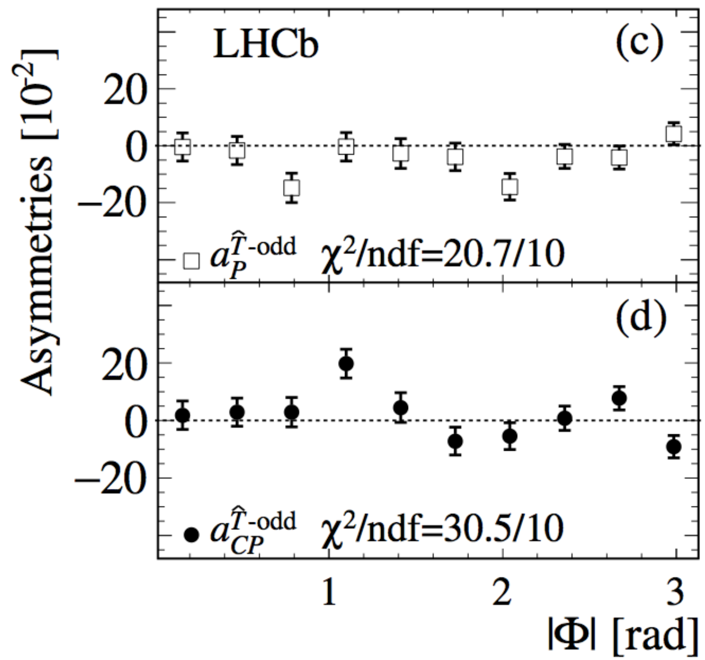
Λ_b^0 decay	$A_{\widehat{T}}$ [%]	$\overline{A}_{\widehat{T}}$ [%]	$a_{CP}^{\widehat{T}\text{-odd}}$ ($a_P^{\widehat{T}\text{-odd}}$) [%]
$p\pi^-\pi^+\pi^-$	$-2.56 \pm 2.06 \pm 0.45$	$-4.86 \pm 2.06 \pm 0.44$	$1.15(-3.71) \pm 1.45 \pm 0.32$
$p\pi^-K^-K^+$	$+2.68 \pm 6.76 \pm 0.85$	$+4.55 \pm 6.07 \pm 0.52$	$-0.93(+3.62) \pm 4.54 \pm 0.42$

Local Measurements

- Binning in $|\Phi|$
- 3.3σ significance of localized CPV in $\Lambda_b \to p\pi^-\pi^+\pi^-$
- Compatible with SM

NEW

LHCb-PAPER-2016-030, in prep.



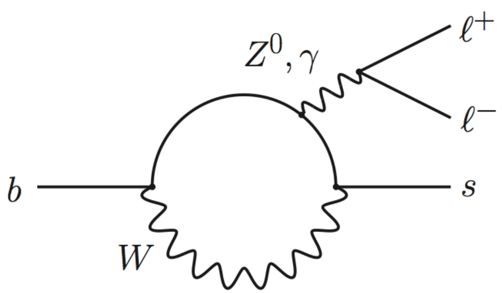
First evidence of CPV in baryon decays!

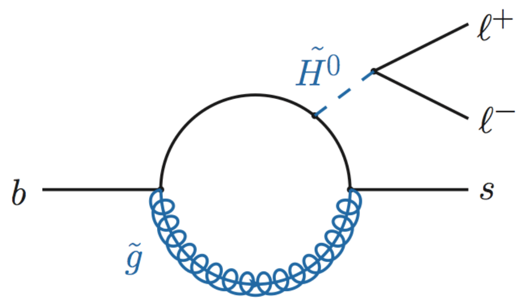
Rare decays and lepton universality

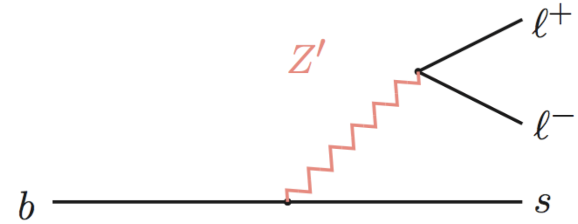
Motivation

b → sl^+l^- transitions are FCNC processes where

- ➢ SM contribution is suppressed
- ➢ NP effect could be pronounced



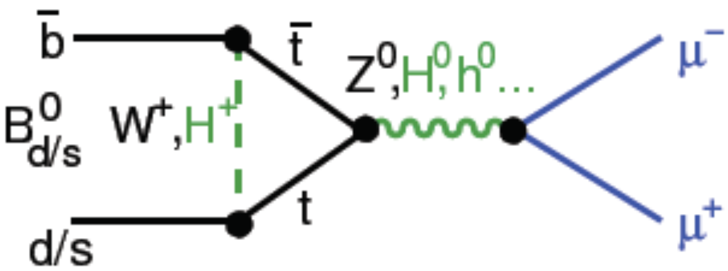


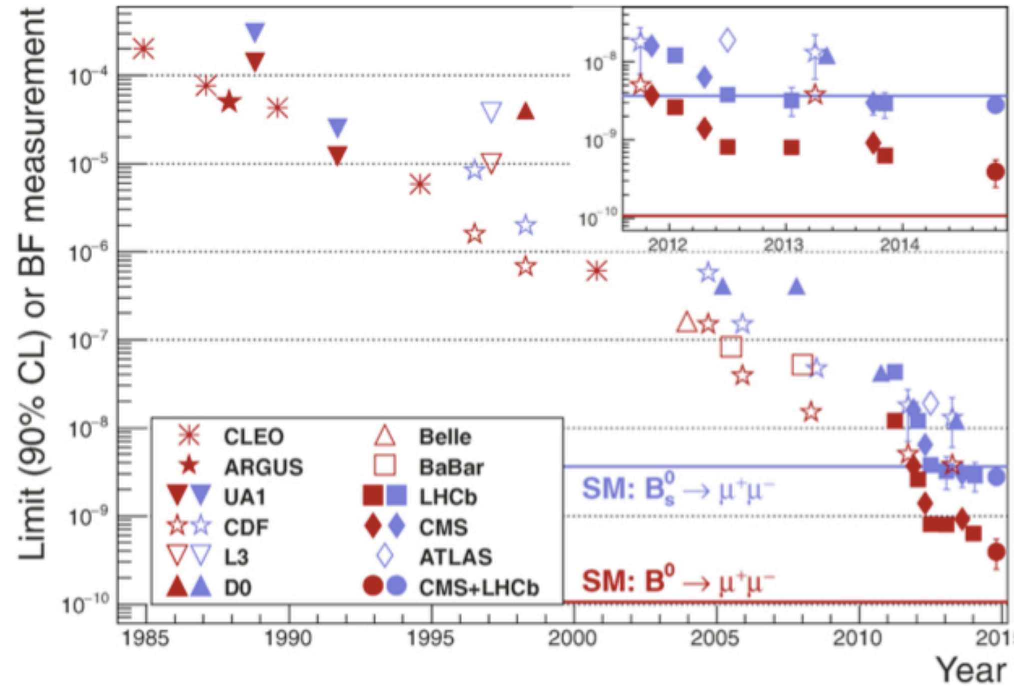


Lepton universality

- ➢ In the SM, ratio like $\Gamma(B^+ \rightarrow K^+\mu^+\mu^-)/\Gamma(B^+ \rightarrow K^+e^+e^-)$ differs from unity only because of phase space difference

$B_{s/d} \to \mu^+\mu^-$

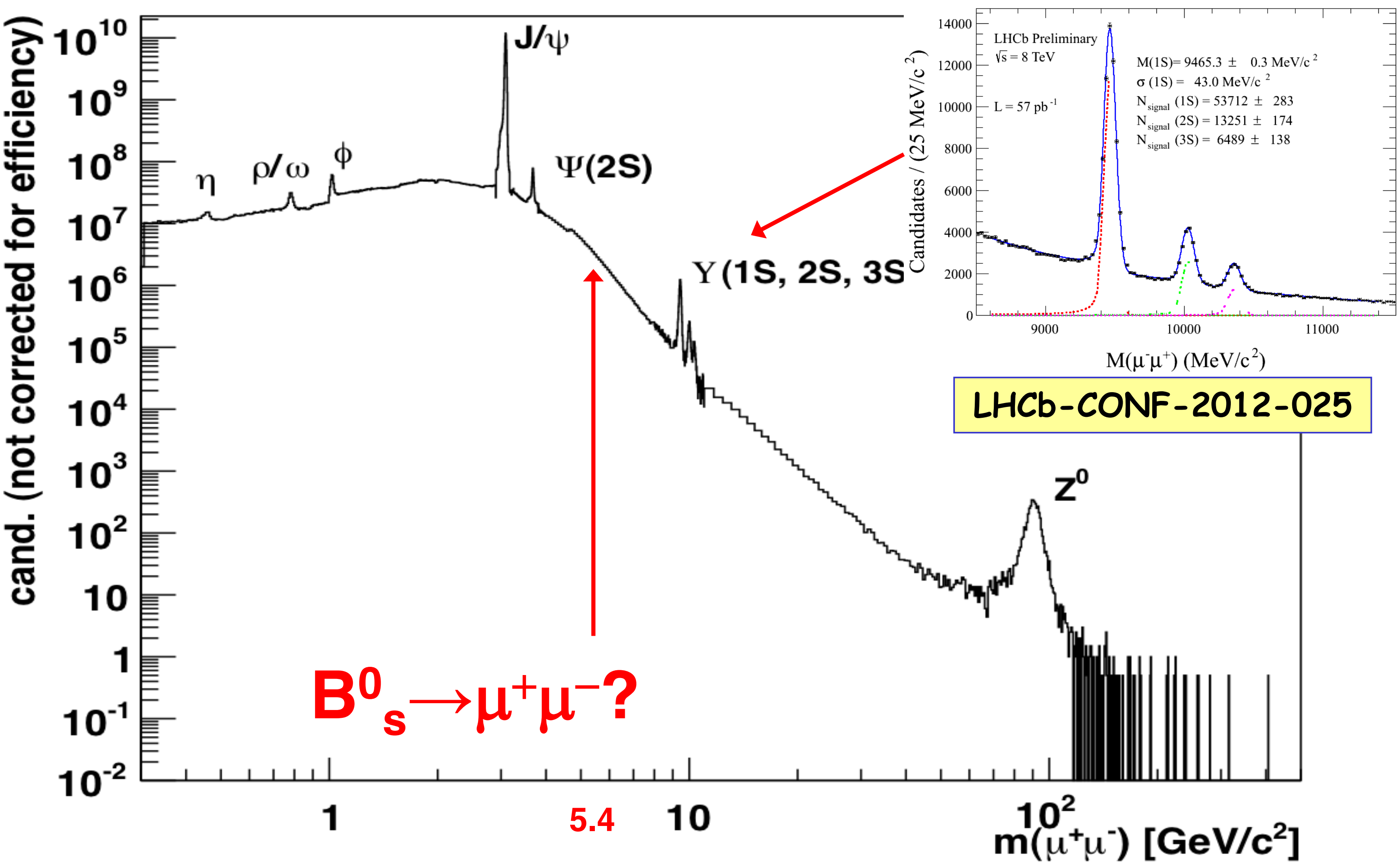




A key physics goal of flavour sector

- Dominated by short distance interactions
- Very rare in SM (~10^{-9} with CKM, GIM and helicity suppression)
- Particularly sensitive to NP in scalar sector

Needle in haystack

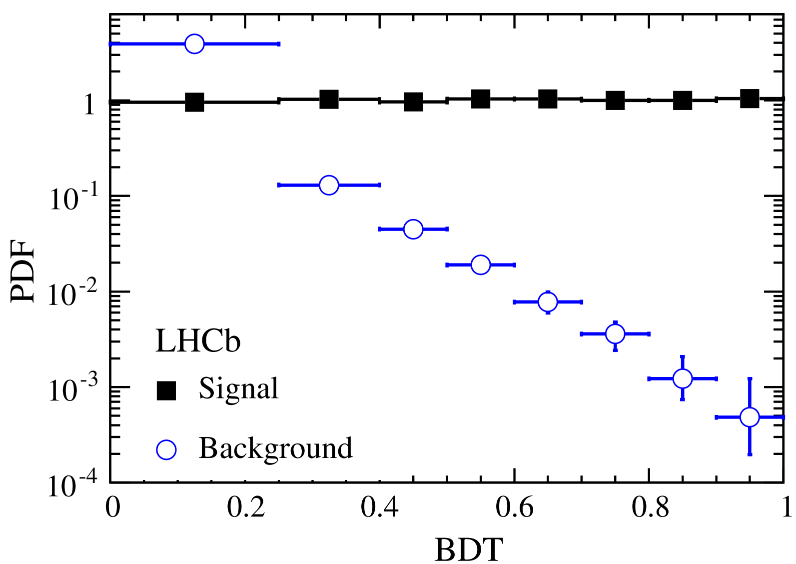


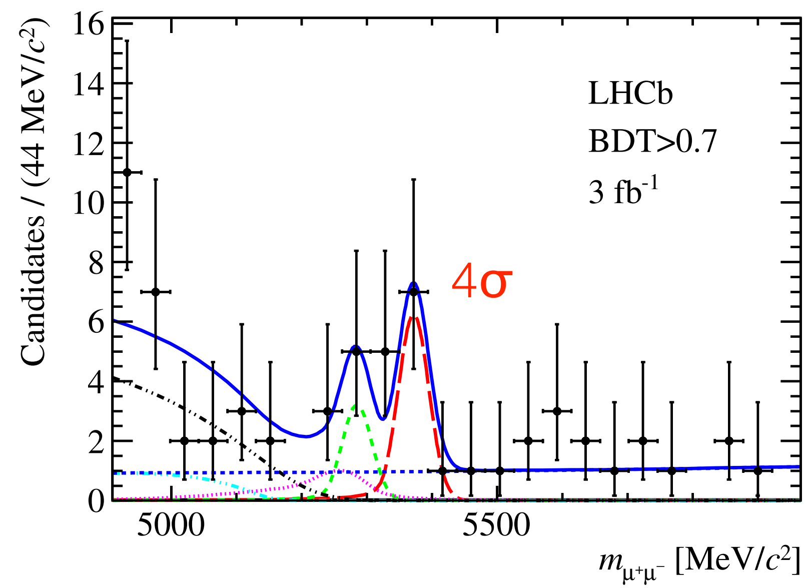
LHCb-CONF-2012-025

LHCb selection of $B_{s/d} \to \mu^+\mu^-$

Signal and background separation

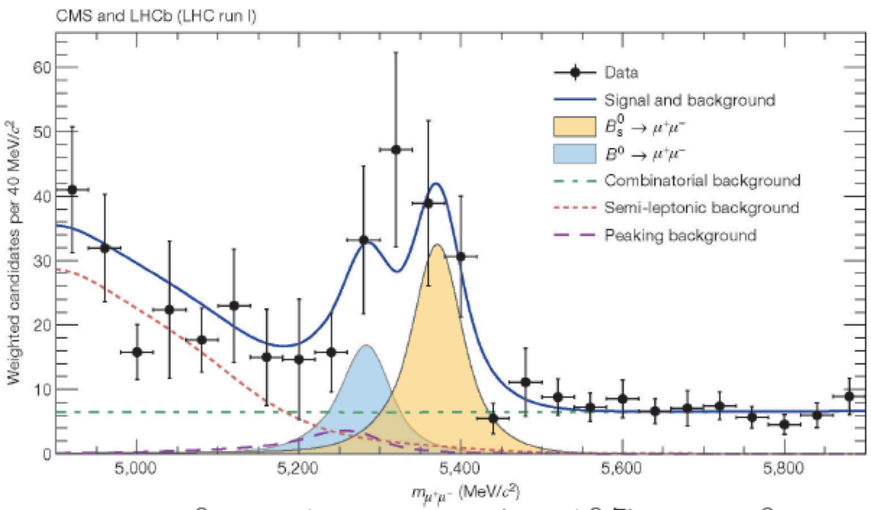
- ✧ Combine various kinematic and topological variables using boosted decision tree technique (BDT）
- ✧ Simultaneously fit $\mu^+\mu^-$ invariant mass distributions in different BDT bins





LHCb, PRL 111 (2013) 101805

LHCb+CMS combination



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$$

CMS+LHCb, Nature 522 (2015) 68

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

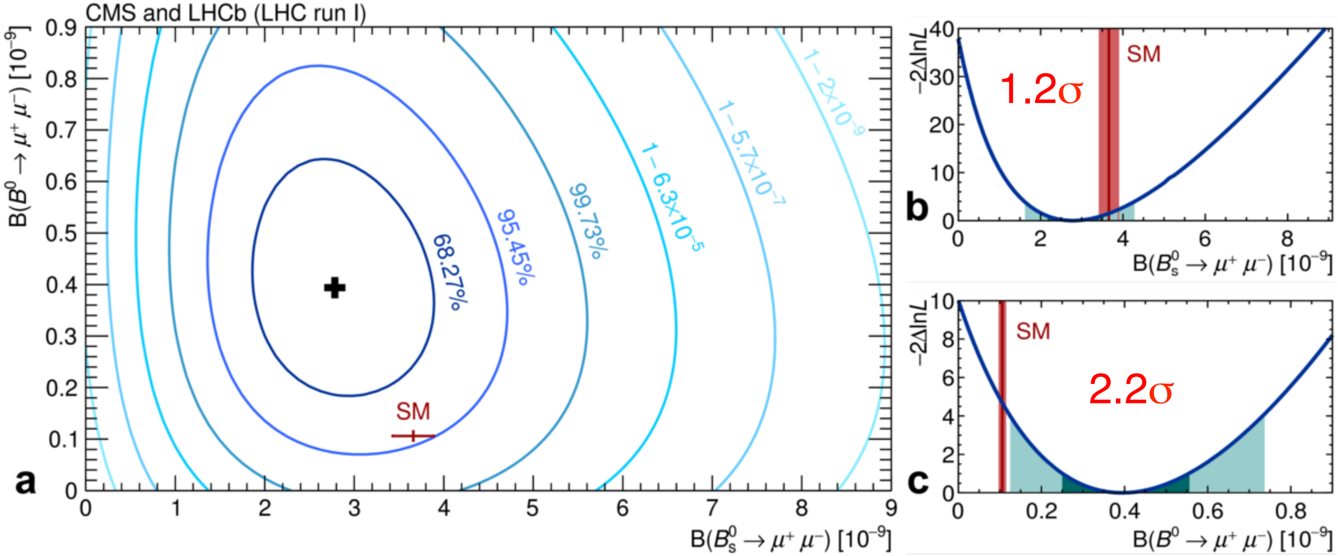
first observation,6.2σ significance

$B_d \to \mu^+\mu^-$

3.0σ significance

SM expectations:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$



ATLAS result of $B_{s/d} \to \mu^+\mu^-$

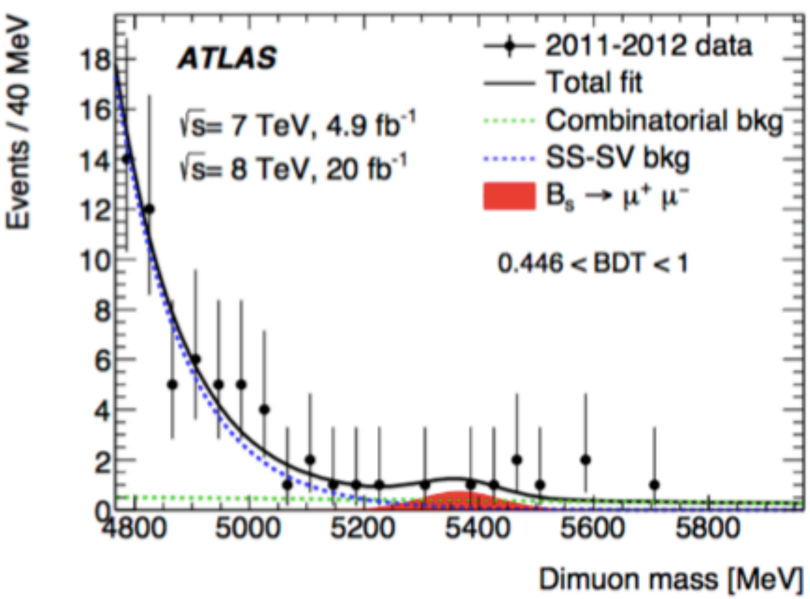
ATLAS published run 1 search result: no significant signal

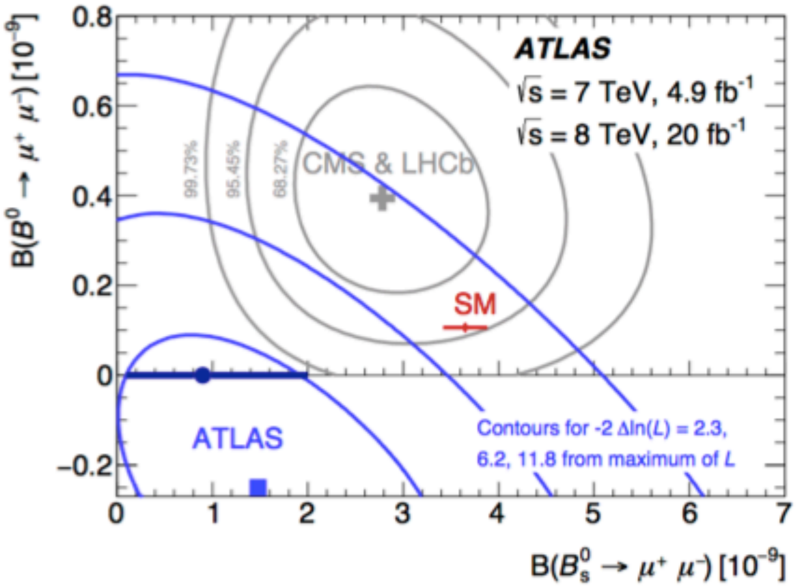
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(0.9^{+1.1}_{-0.8}\right) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10} \ (95\% \ \mathrm{CL})$$

P-value of 4.8% for compatibility with SM predictions

arXiv:1604.04263

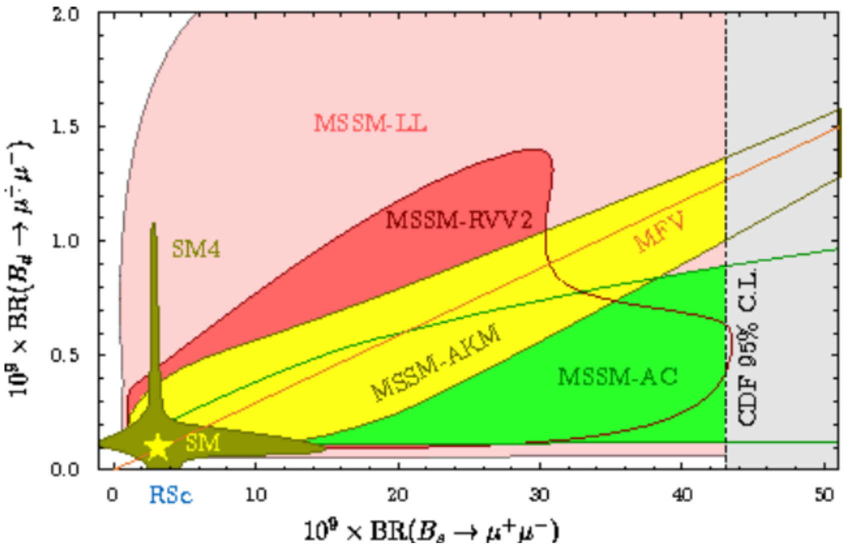




NP model killing

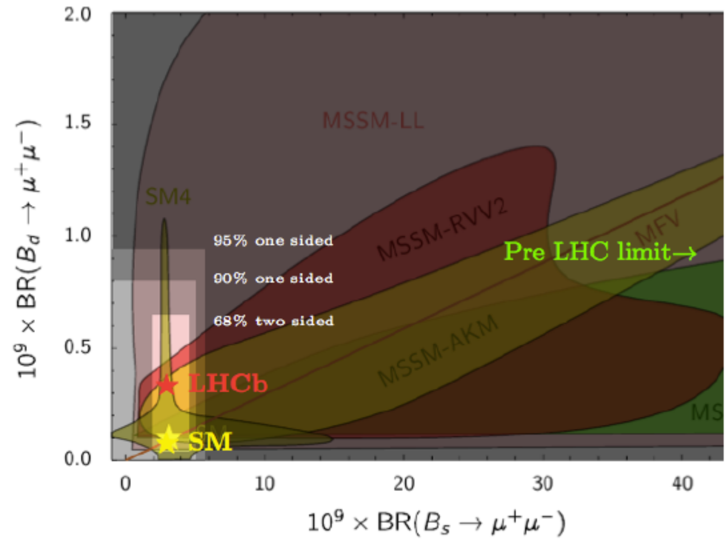
Before the LHC results

[D.Straub arXiv:1205.6094]



After the LHC results

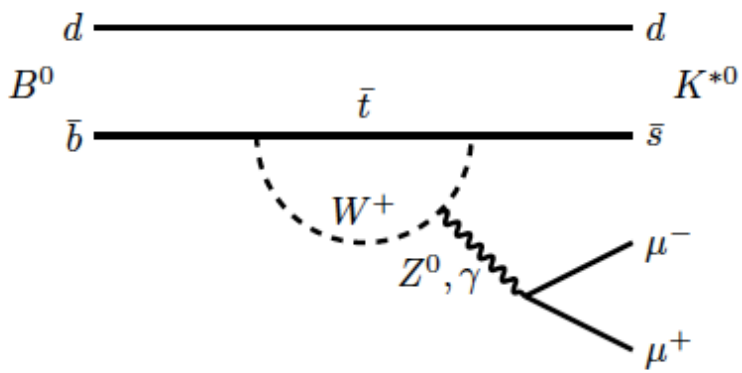
Cartoon of plot from
[D.Straub arXiv:1205.6094]

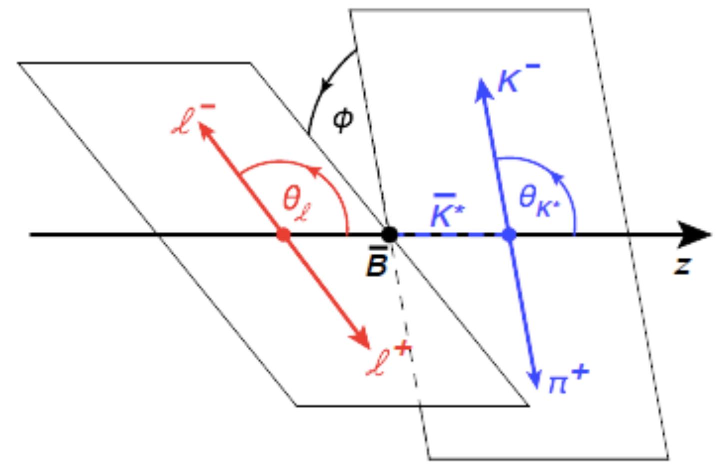


Run II and upgrade goals

- $\mathrm{Br}(B_s \to \mu^+\mu^-) / \mathrm{Br}(B_d \to \mu^+\mu^-)$ to test MFV
- Effective lifetime and CP violation in $B_s \to \mu^+\mu^-$

Angular analysis of $B \to K^{*0}\,\mu^+\mu^-$





$B^0 \to K^{*0}\ l^+l^-$ described by three angles (θ_K, θ_l, Φ) and di-muon mass squared, q^2:

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

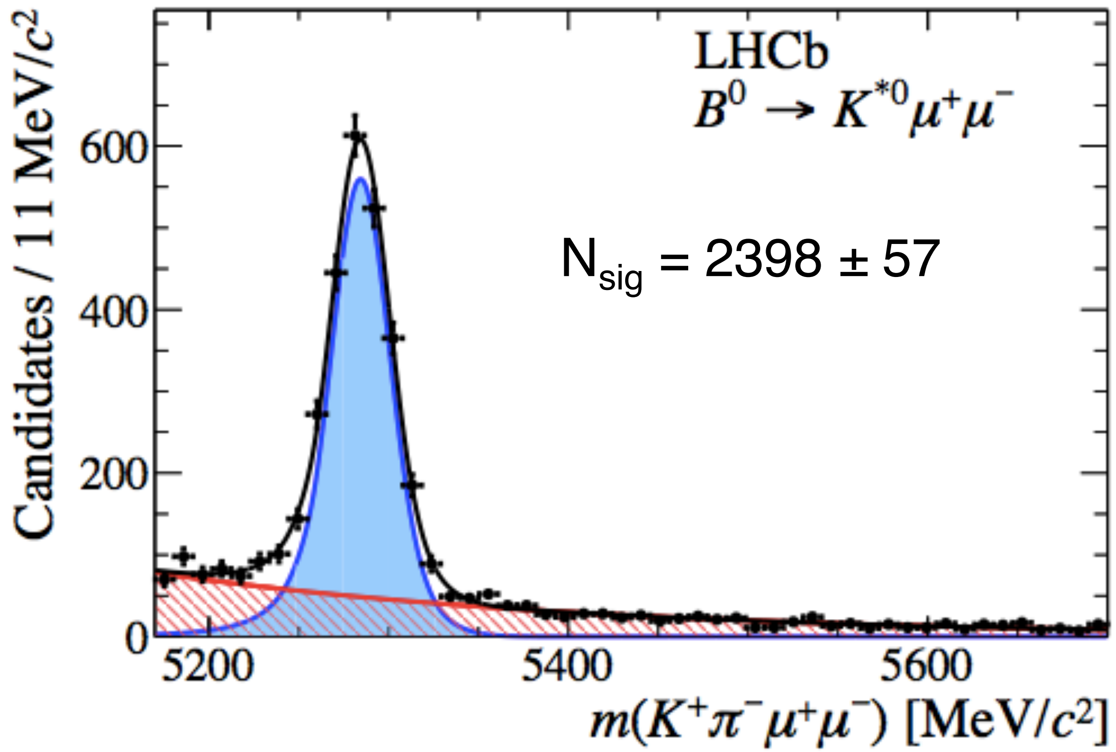
Observables: A_{FB}, S_i, F_L

Or different notations, e.g. $P'_{i=4,5,6,8} = \dfrac{S_{j=4,5,7,8}}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}$

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

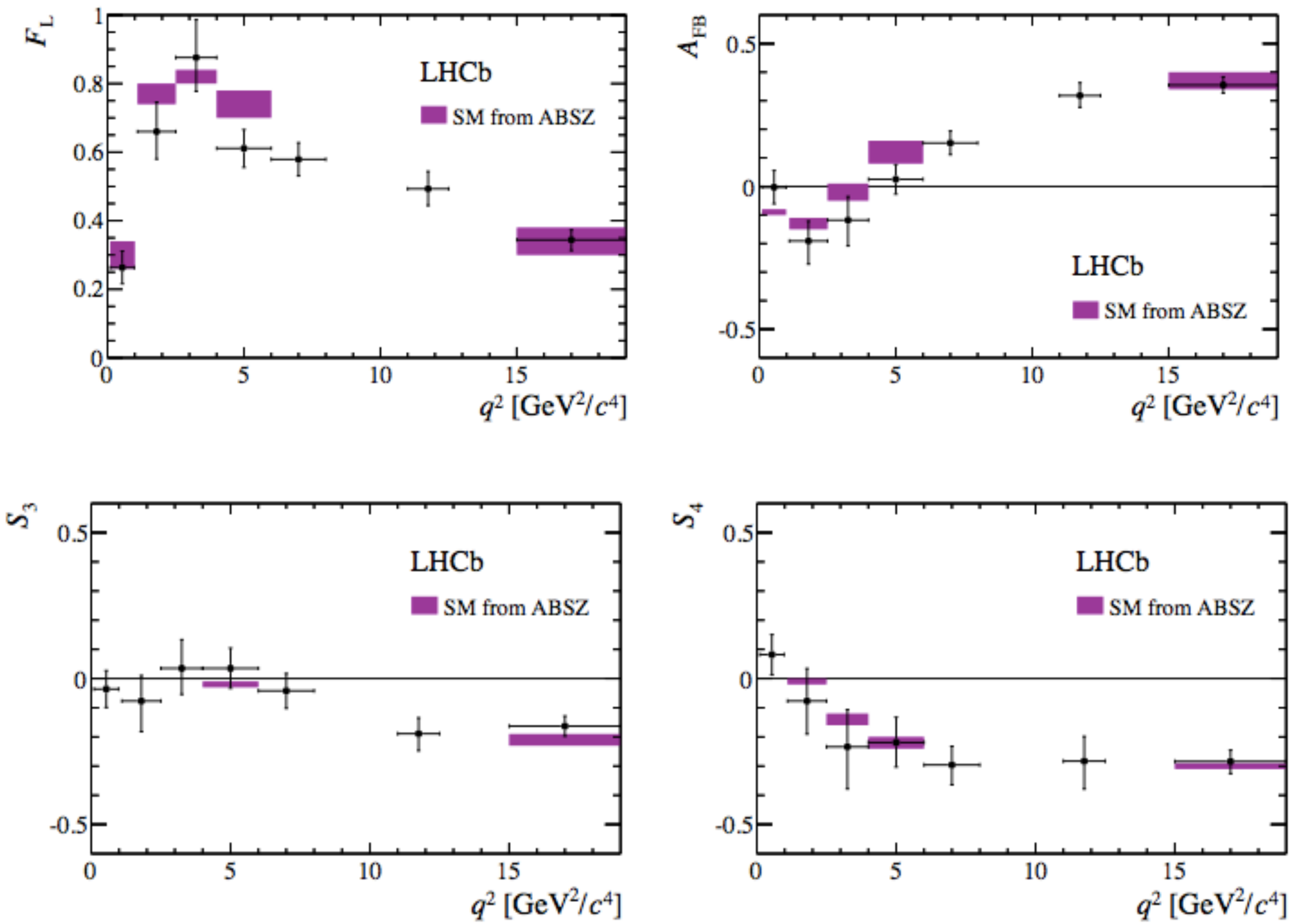
LHCb, JHEP 02 (2016) 104

Update: $1fb^{-1} \to 3fb^{-1}$



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

LHCb, JHEP 02 (2016) 104



Basically consistent with SM, except S_5 …

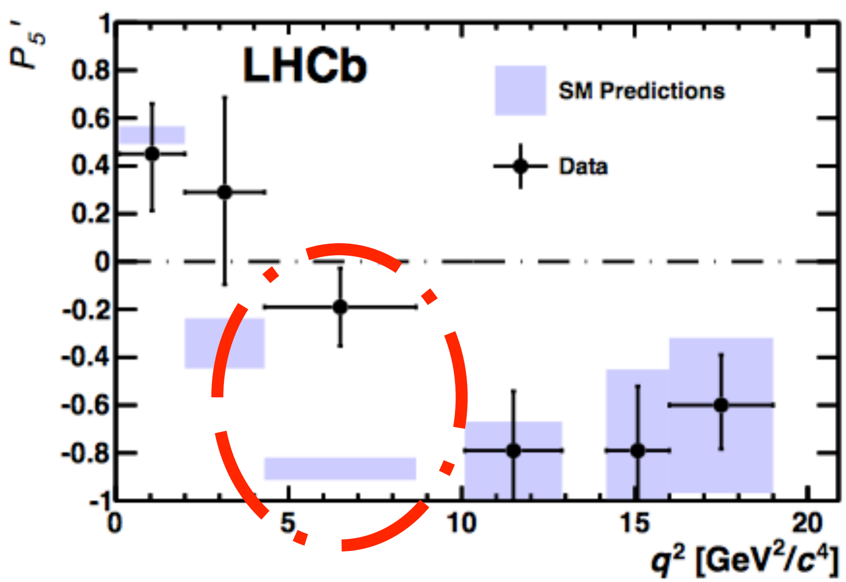
P_5' anomaly

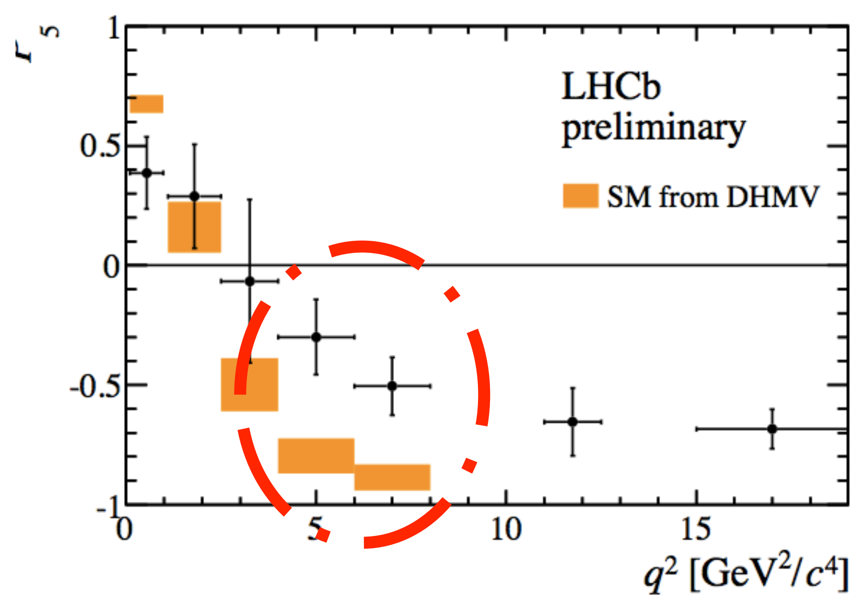
theoretically clean variable

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L))}}$$

1 fb^{-1} LHCb, PRL 111(2014)191801

3 fb^{-1} LHCb, JHEP 02 (2016) 104

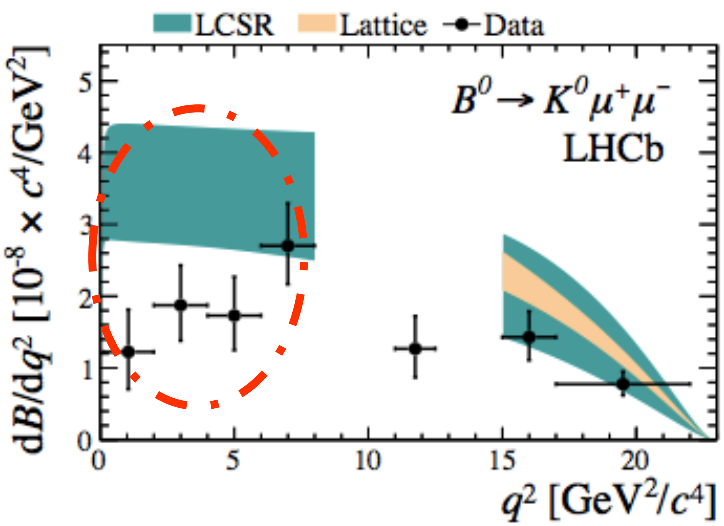


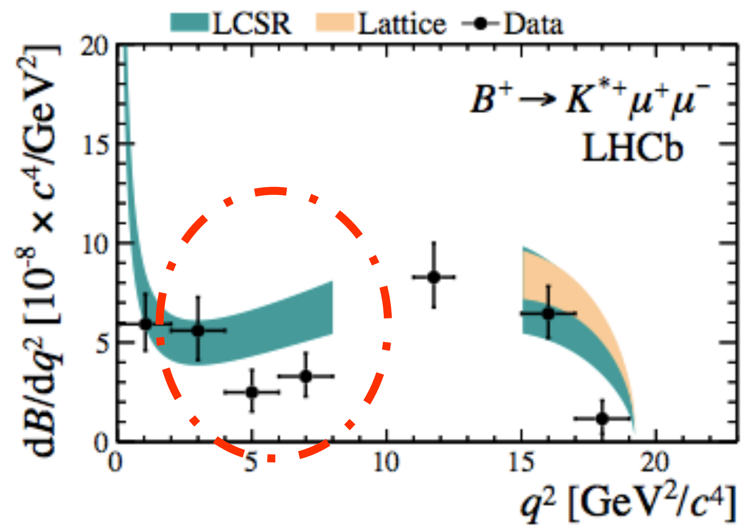


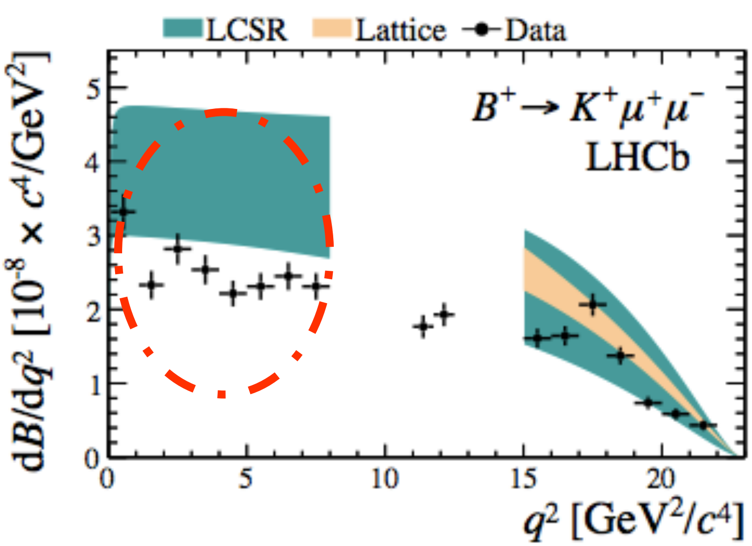
Tension with SM prediction remains (3.4σ local discrepancy)

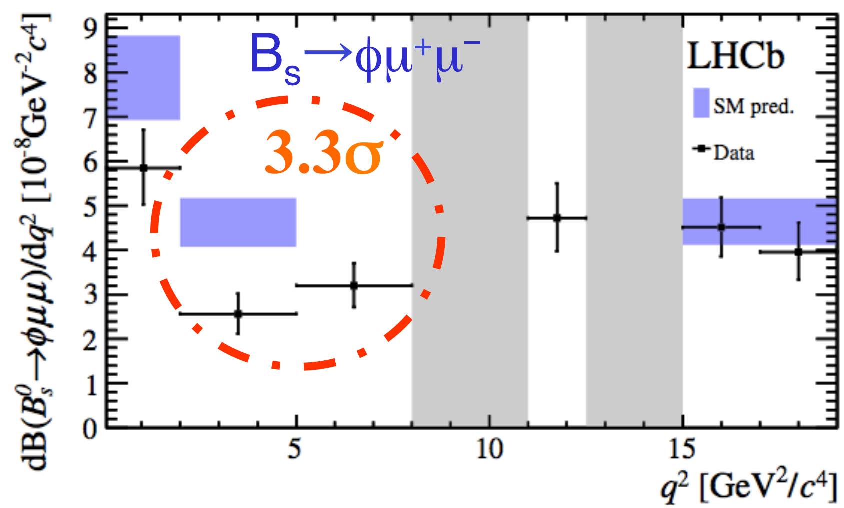
Puzzles in differential rates

LHCb, JHEP 06 (2014) 133, JHEP 09 (2015) 179







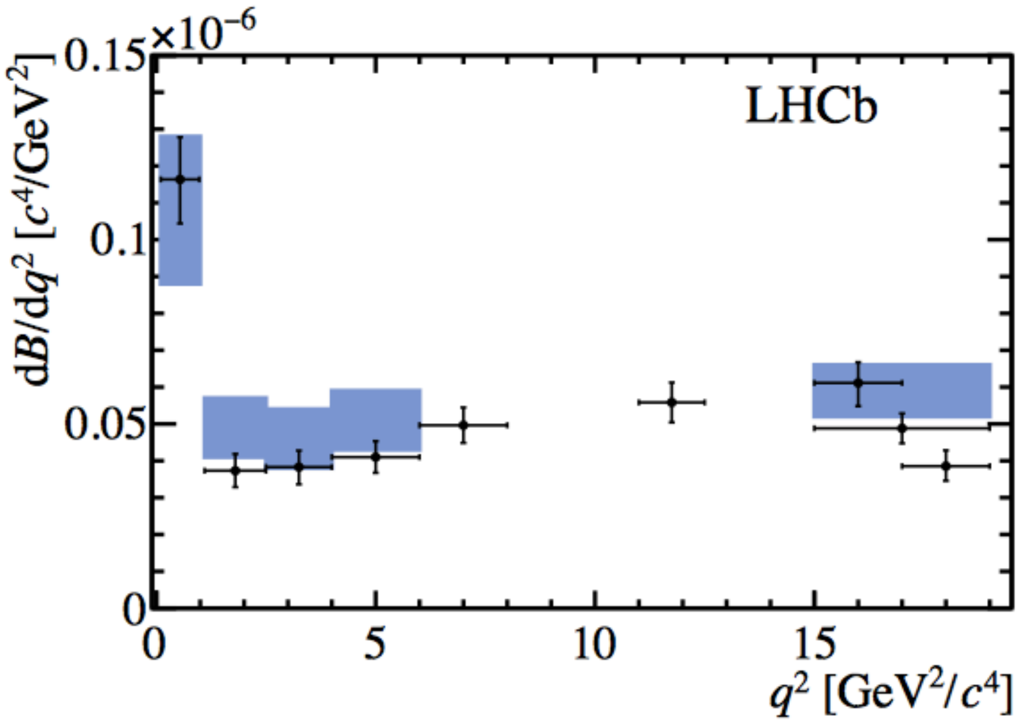


Differential rate of $B^0 \to K^{*0} \mu^+\mu^-$

LHCb-PAPER-2016-012

3 fb^{-1}, including $K\pi$ S wave

NEW



Good agreement with SM predictions from

Bharucha et al., arXiv: 1503.05534

Horgan et al., PRD 98(2014) 094501

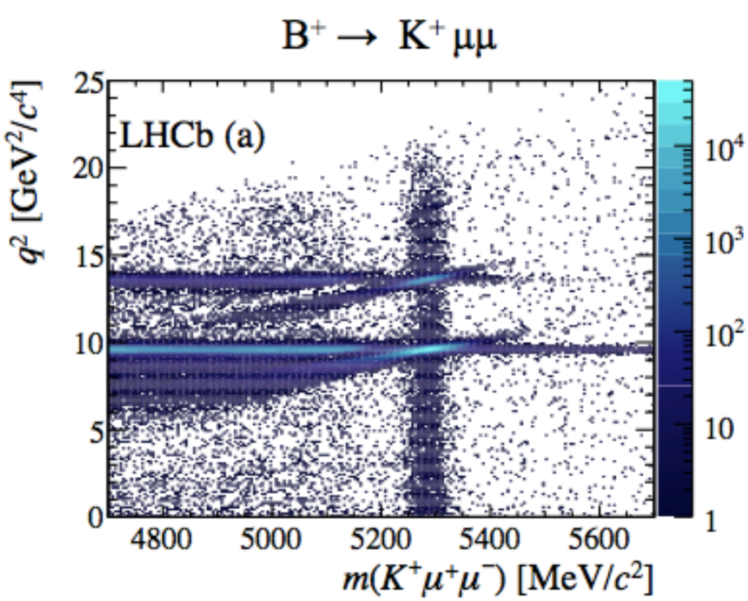
Lepton universality in $B^+ \to K^+ l^+ l^-$

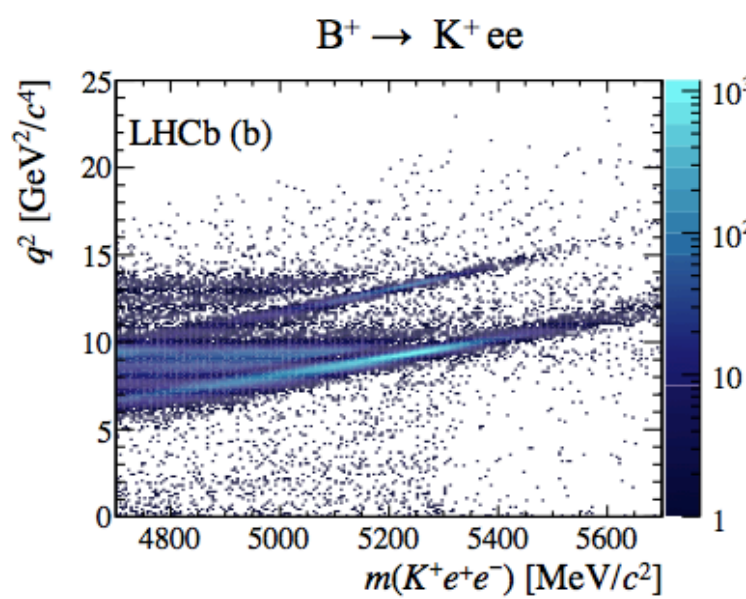
$$R_K = \frac{\Gamma(B^+ \to K^+ \mu^+ \mu^-)}{\Gamma(B^+ \to K^+ e^+ e^-)}$$

SM lepton universality: $R_k = 1$ within $O(10^{-3})$

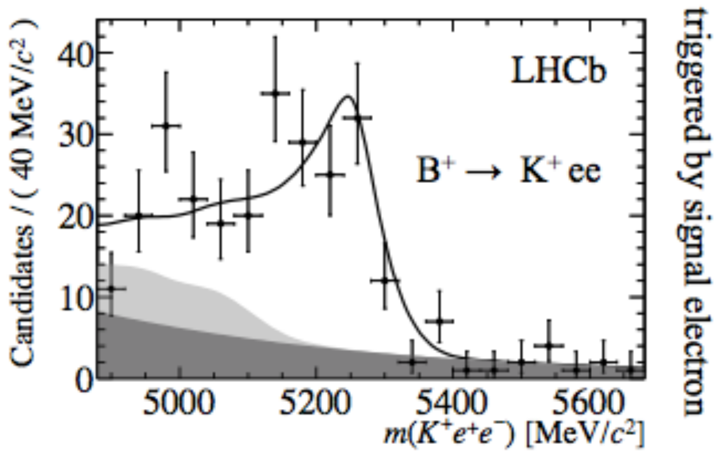
- hardly affected by hadronic uncertainty

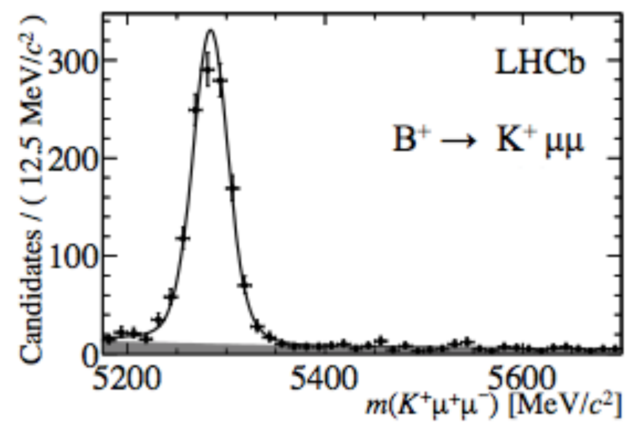
Experimental Challenge: bremsstrahlung effect for the electron mode

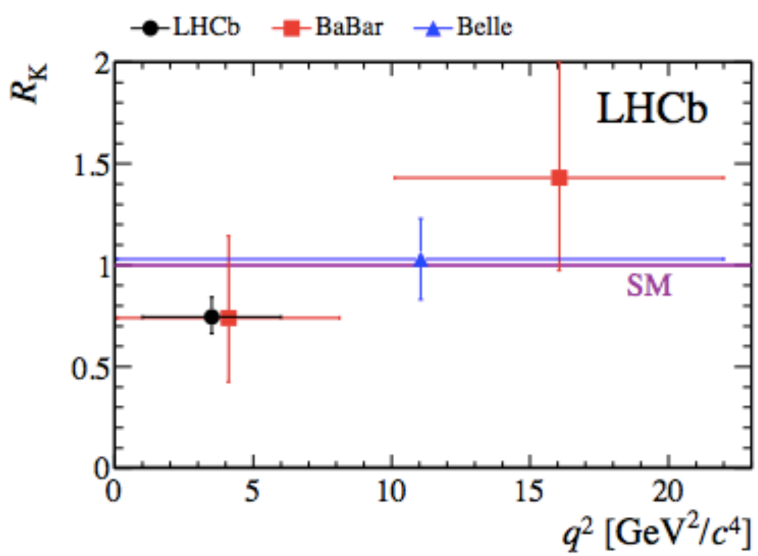




R_K result







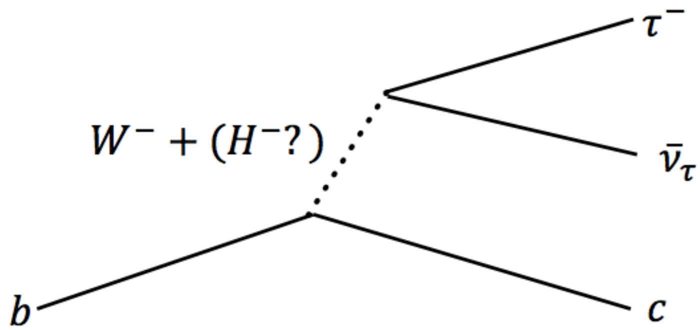
LHCb, PRL 113 (2014) 151601

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

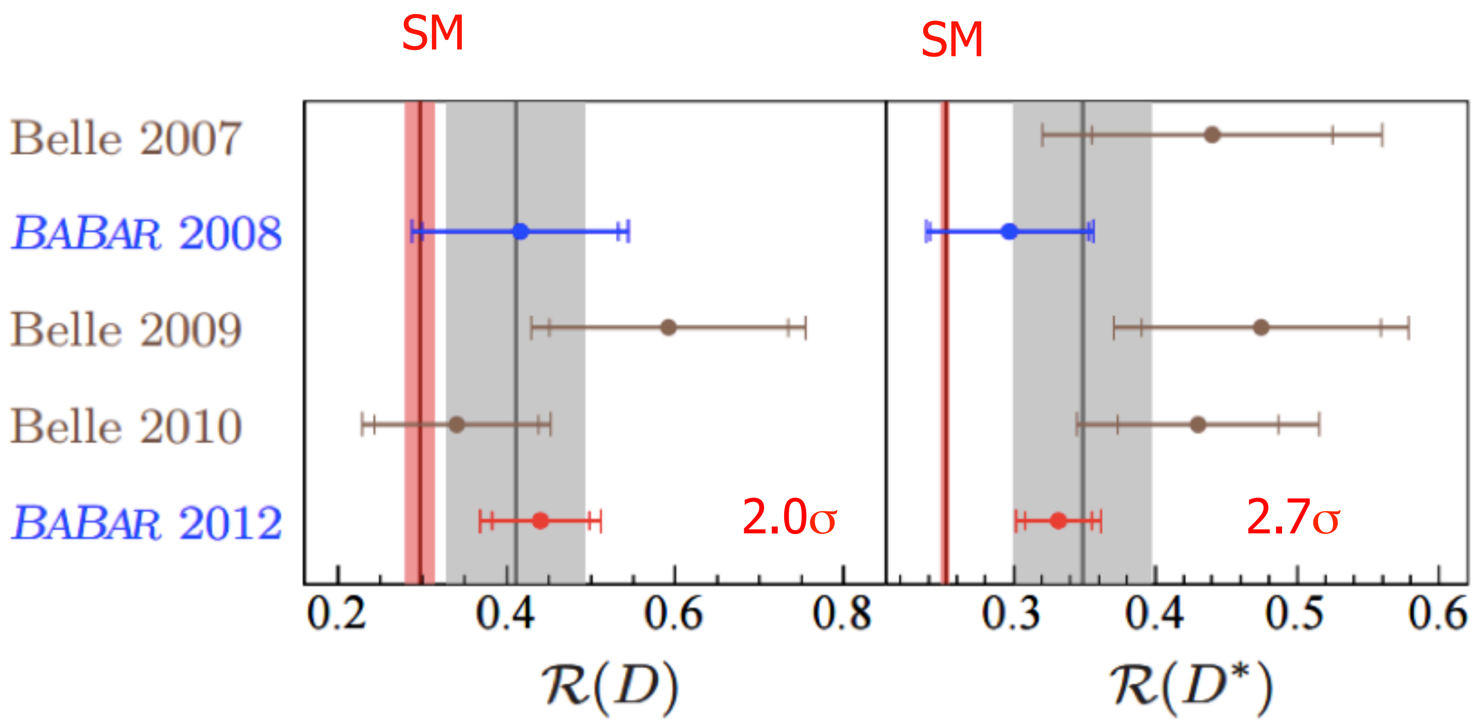
Consistent with SM within 2.6σ

R(K*) , R(ϕ) and others are coming

Lepton universality: B → D$^{(*)}$lν



$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}(\mu \text{ or } e)\nu)}$$



$B^0 \to D^{*+}\tau^-\nu$ partial reconstruction

Leptonic mode: $\tau \to \mu\nu_\tau\bar{\nu}_\mu$

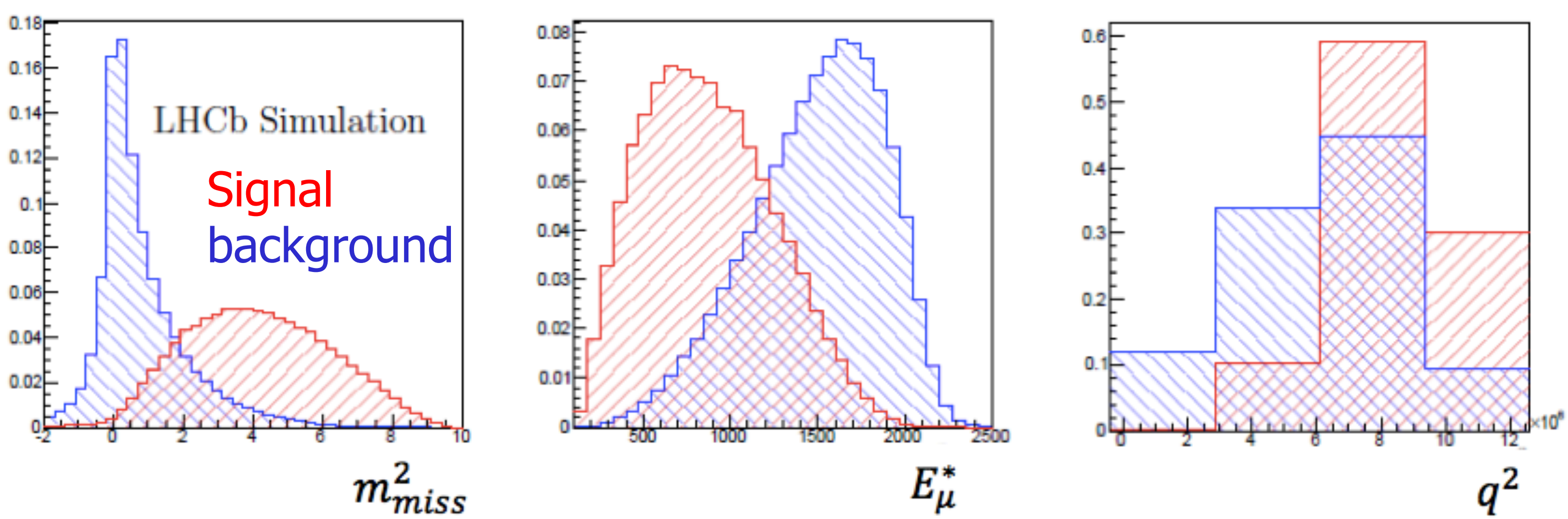
Kinematic variables estimated assuming

$$(p_B)_z = \frac{m_B}{m_{\rm reco}}(p_{\rm reco})_z$$

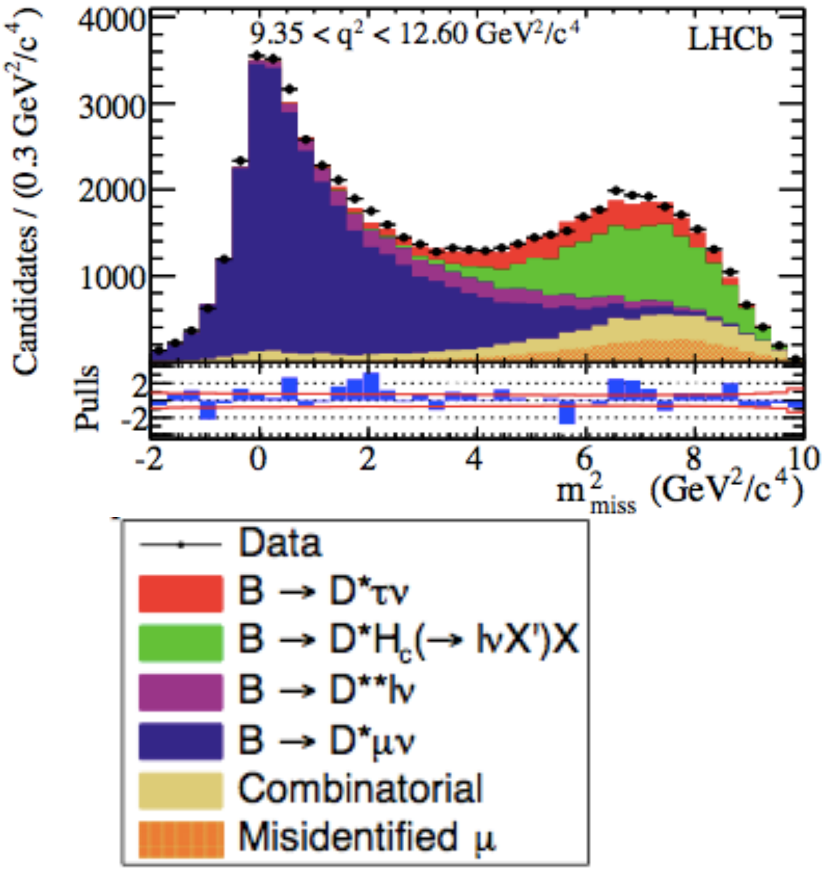
m_{miss}: invariant mass of the invisible part

E_μ^*: μ energy in B rest frame

q^2: squared 4-momentum of $\tau\nu$



LHCb R(D∗) result

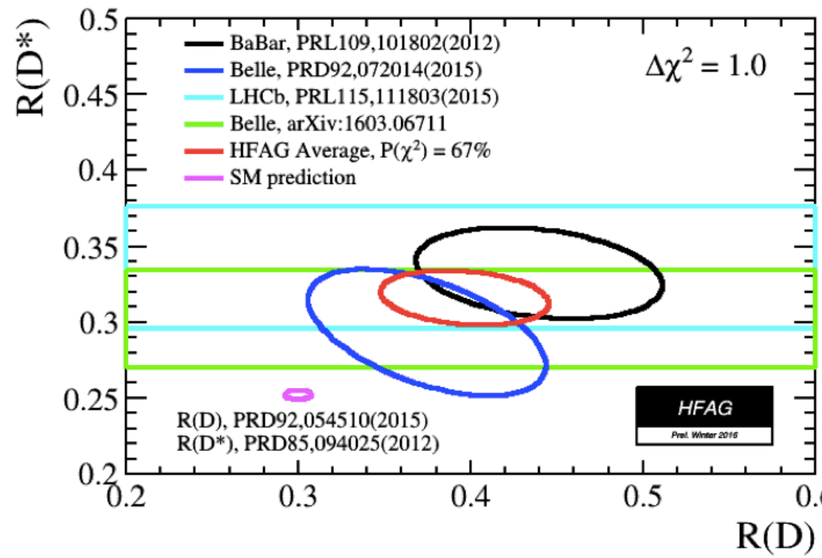


$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

LHCb, PRL 115 (2015) 111803

2.1σ above SM prediction

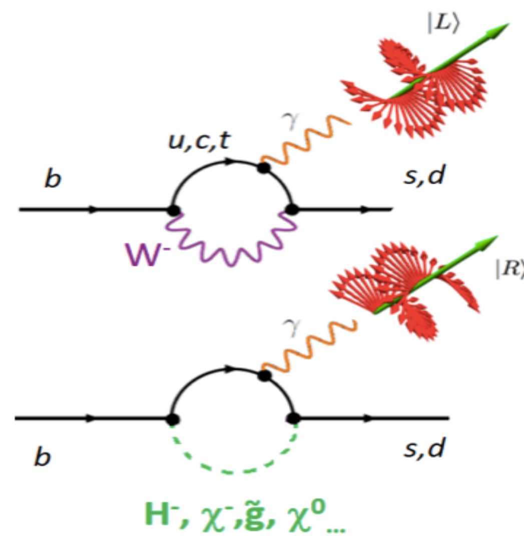
$R(D^*) = 0.252 \pm 0.003$



Babar/Belle results confirmed

Photon polarization

- Photons in $b \to s\gamma$ are predominantly left-handed since W boson couples to left-handed quarks
- New particles in the loop can enhance right-handed contribution



Wilson coefficients C_7 and C_7' are related to related to left- and right-handed photons

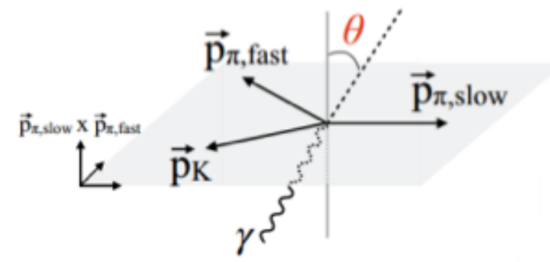
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (\underbrace{C_i \mathcal{O}_i}_{\text{left-handed}} + \underbrace{C_i' \mathcal{O}_i'}_{\text{right-handed}}) + h.c.$$

$$\frac{\mathcal{C}_7'}{\mathcal{C}_7} \stackrel{\text{SM}}{=} \mathcal{O}\left(\frac{m_s}{m_b}\right)$$

$$\mathcal{O}_7^{(\prime)} = \frac{e^2}{16\pi^2} m_b \left[\bar{s}\sigma_{\mu\nu} P_{R(L)} b\right] F^{\mu\nu}$$

Results of photon polarization

Up-down asymmetry in $B^+ \to K^+ \pi^- \pi^- \gamma$



$|C_7'|^2 \neq |C_7|^2$ at 5.2σ

LHCb, PRL 112 (2014) 161801

Angular analysis of $B^0 \to K^{*0} e^+ e^-$ at low q^2

$$A_T^{(2)}(q^2 \to 0) = \frac{2\,\mathrm{Re}\,(\mathcal{C}_7 \mathcal{C}_7'^{*})}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$

$$A_T^{\mathrm{Im}}(q^2 \to 0) = \frac{2\,\mathrm{Im}\,(\mathcal{C}_7 \mathcal{C}_7'^{*})}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$

$$A_T^{(2)} = -0.23 \pm 0.23 \pm 0.05$$

$$A_T^{\mathrm{Im}} = +0.14 \pm 0.22 \pm 0.05$$

Compatible with SM ($\simeq 0$)

LHCb, PRL 112 (2014) 161801

Time-dependent analysis of $B^0 \to K^{*0} (K_S \pi^0) \gamma$

$S(K^{*0}\gamma) \approx -2\,|C_7'/C_7| \sin 2\beta$

$S(K^{*0}\gamma) = -0.16 \pm 0.22$

Consistent with SM (≈ 0)

HFAG, average of Babar+Belle

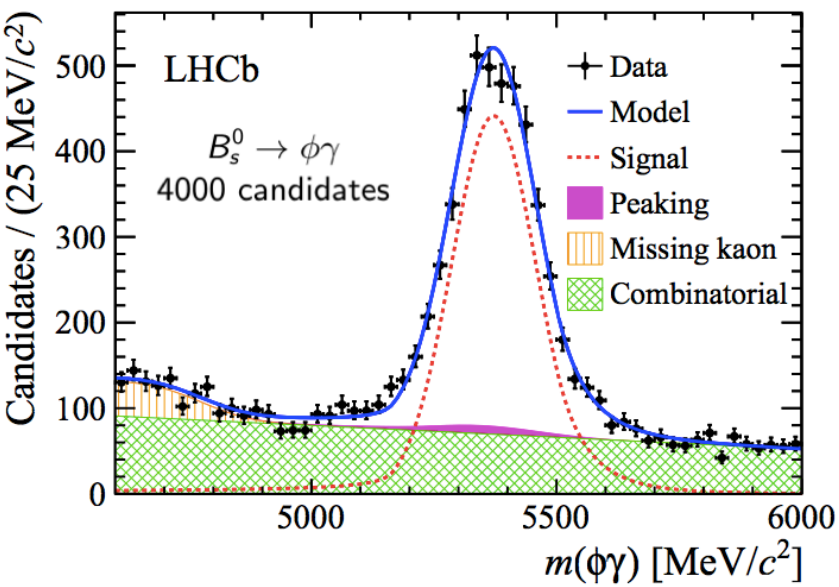
Photon polarization in $B_s \to \phi\gamma$

First measurement of photon polarization in B_s decays

New observable in untagged time-dependent rate

Muheim, Xie, Zwicky, PLB 664 (2008) 174

$$\Gamma_{B_s^0 \to \phi\gamma}(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\Delta\Gamma_s t/2\right) - \mathcal{A}^{\Delta} \sinh\left(\Delta\Gamma_s t/2\right)\right]$$



$$\mathcal{A}^{\Delta} \simeq \frac{2\,\mathrm{Re}\left(e^{-i\phi_s}\,\mathcal{C}_7\,\mathcal{C}_7'\right)}{|\mathcal{C}_7|^2 + |\mathcal{C}_7'|^2}$$

NEW

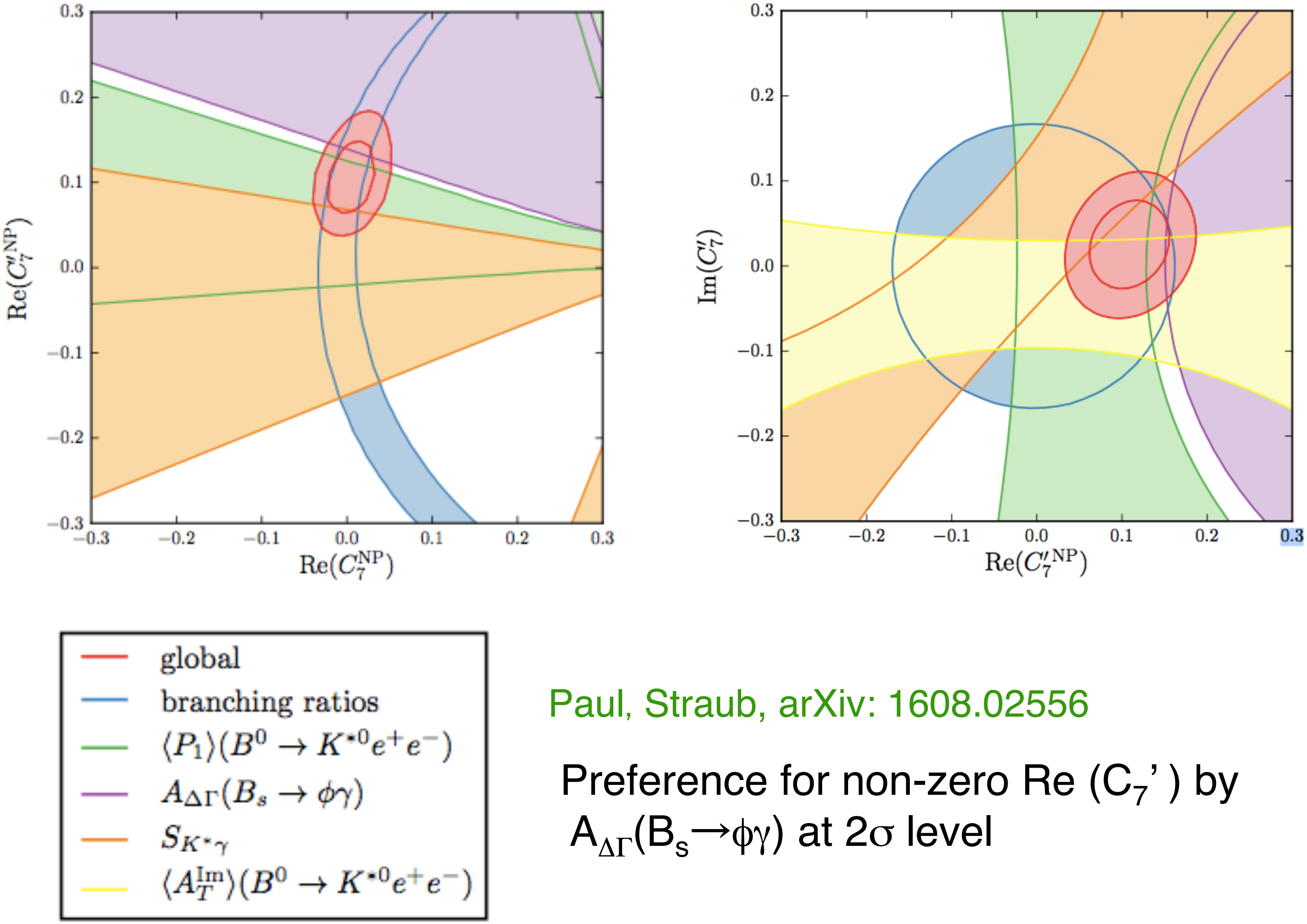
$$\mathcal{A}^{\Delta} = -0.98\;^{+0.46}_{-0.52}(\mathrm{stat.})^{+0.23}_{-0.20}(\mathrm{syst.})$$

LHCb–PAPER-2016-034, in prep.

Compatible with SM within 2σ

$$\mathcal{A}^{\Delta}_{\mathrm{SM}} = 0.047^{+0.029}_{-0.025}$$

Constraints on right-handed NP



Paul, Straub, arXiv: 1608.02556

Preference for non-zero Re (C_7') by $A_{\Delta\Gamma}(B_s \to \phi\gamma)$ at 2σ level

Forbidden decays

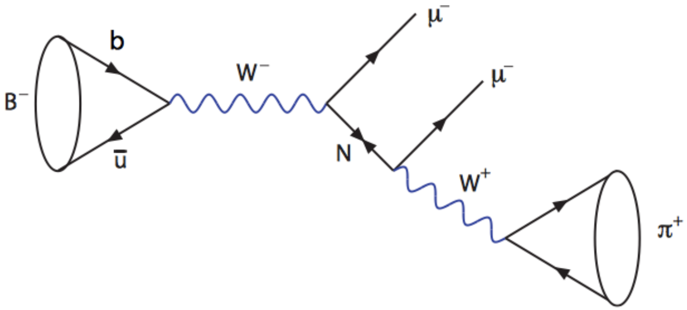
Some 1 fb^{-1} results on lepton flavour/number violation

LHCb, PRL 111 (2013) 141801

Mode	Limit	90 % C.L.	95 % C.L.
$B_s^0 \to e^\pm \mu^\mp$	Expected	1.5×10^{-8}	1.8×10^{-8}
	Observed	1.1×10^{-8}	1.4×10^{-8}
$B^0 \to e^\pm \mu^\mp$	Expected	3.8×10^{-9}	4.8×10^{-9}
	Observed	2.8×10^{-9}	3.7×10^{-9}

LHCb, PRL 112 (2014) 131802

$$\mathcal{B}(B^- \to \pi^+ \mu^- \mu^-) < 4.0 \cdot 10^{-9} \ (95\%\mathrm{CL})$$



LHCb run 2 can improve these limits

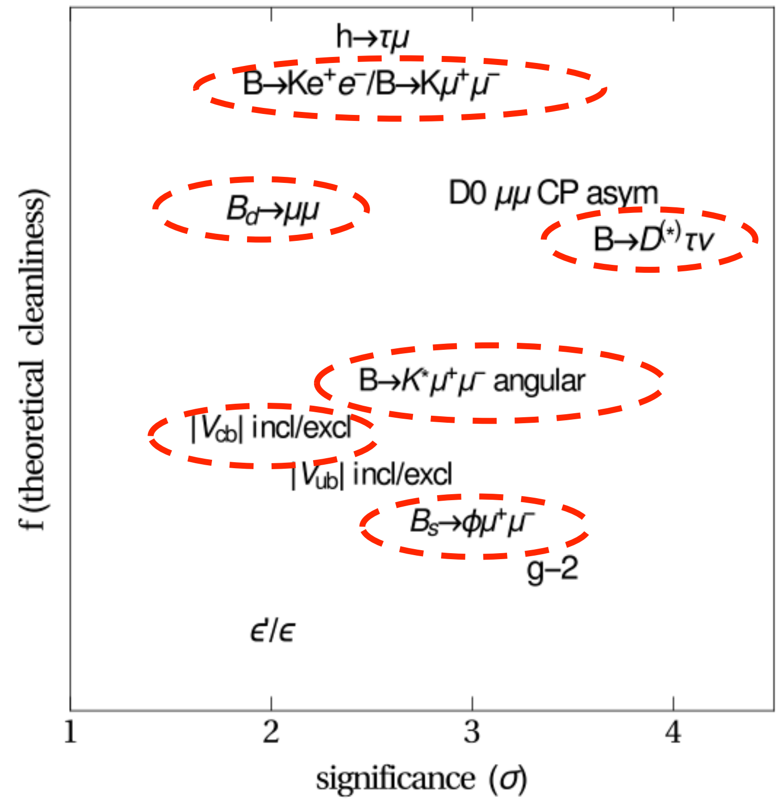
$$\mathcal{B}(B^+ \to K^+ e^\pm \mu^\mp) < 9,1 \times 10^{-8}$$
$$\mathcal{B}(B^+ \to K^+ e^\pm \tau^\mp) < 3,0 \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^+ \tau^\pm \mu^\mp) < 4,8 \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^*(892)^+ e^\pm \mu^\mp) < 1,4 \times 10^{-6}$$
$$\mathcal{B}(B \to K^*(892)^0 e^\pm \mu^\mp) < 5,8 \times 10^{-7}$$
$$\mathcal{B}(B \to K e^\pm \mu^\mp) < 2,7 \times 10^{-7}$$

Summary and outlook

Picture after LHCb run 1

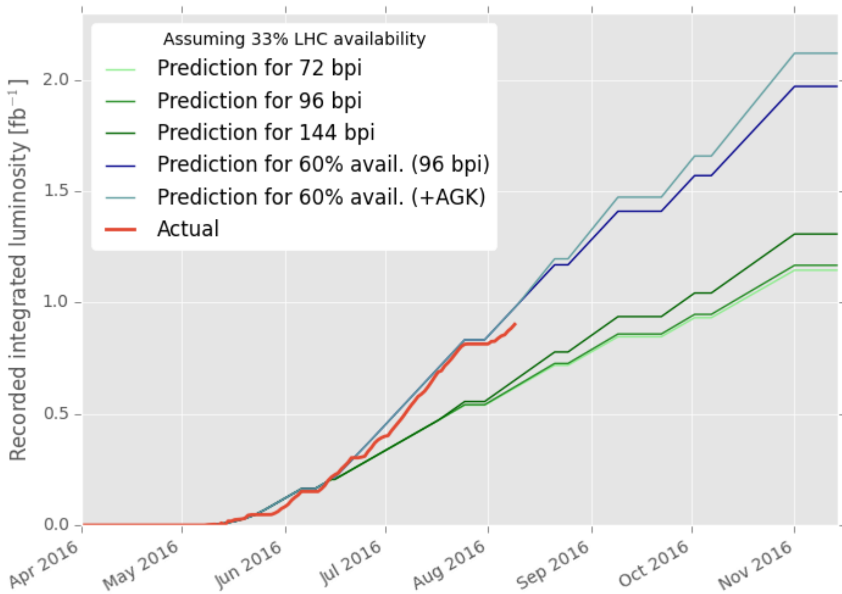
LHCb has studied CPV and rare B decays with unprecedented sensitivity in a wide scope

- Overall picture is SM-like
- Some anomalies await clarification



Z. Ligeti, arXiv: 1606.02756

Run 2 data−taking at 13 TeV



0.33 fb^{-1} in 2015
1.04 fb^{-1} this year.

σ_{bb} (13 TeV) ~ 2 σ_{bb} (7/8 TeV)

Expect 2 fb^{-1} in 2016 and 6 fb^{-1} data in run 2

Improve measurement precisions by factor of two in run 2

New results may appear in early 2017

Upgrade

LHCb detector upgrade during LS2 (2019-2020)

- 40 MHz readout of all sub-detectors and software trigger
- 10 times higher luminosity

Expect 50 fb^{-1} in run 3 and run 4

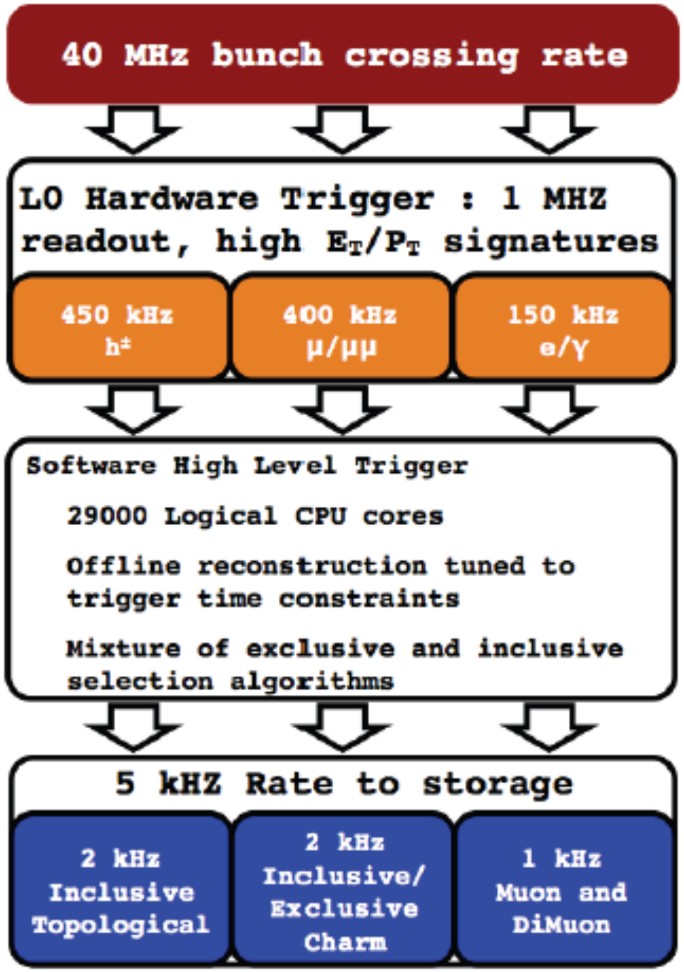
- 6 times precision improvement compared with run 1
- Much wider scope of study than now

Some crucial goals of upgrade

- CPV in $B_s \to \mu^+\mu^-$
- Precision measurement of photon polarization in $B_s \to \phi\gamma$
- Precision measurement of CPV in $B_s \to \phi\phi$

Backup slides

Powerful trigger



B hadrons are long−lived

– well separate PV and SV

B hadrons have large masses

– decay products with high pT

- Level-0: hardware
  - high pT objects (Calo, Muon)
- High-Level: software
  - HLT1: add vertex info
  - HLT2: global reconstruction

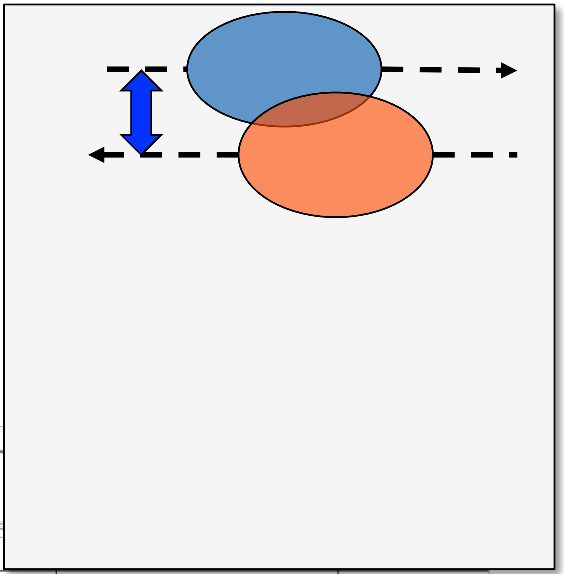
Trigger efficiency: ~90% for dimuon events
~30% for hadronic final states

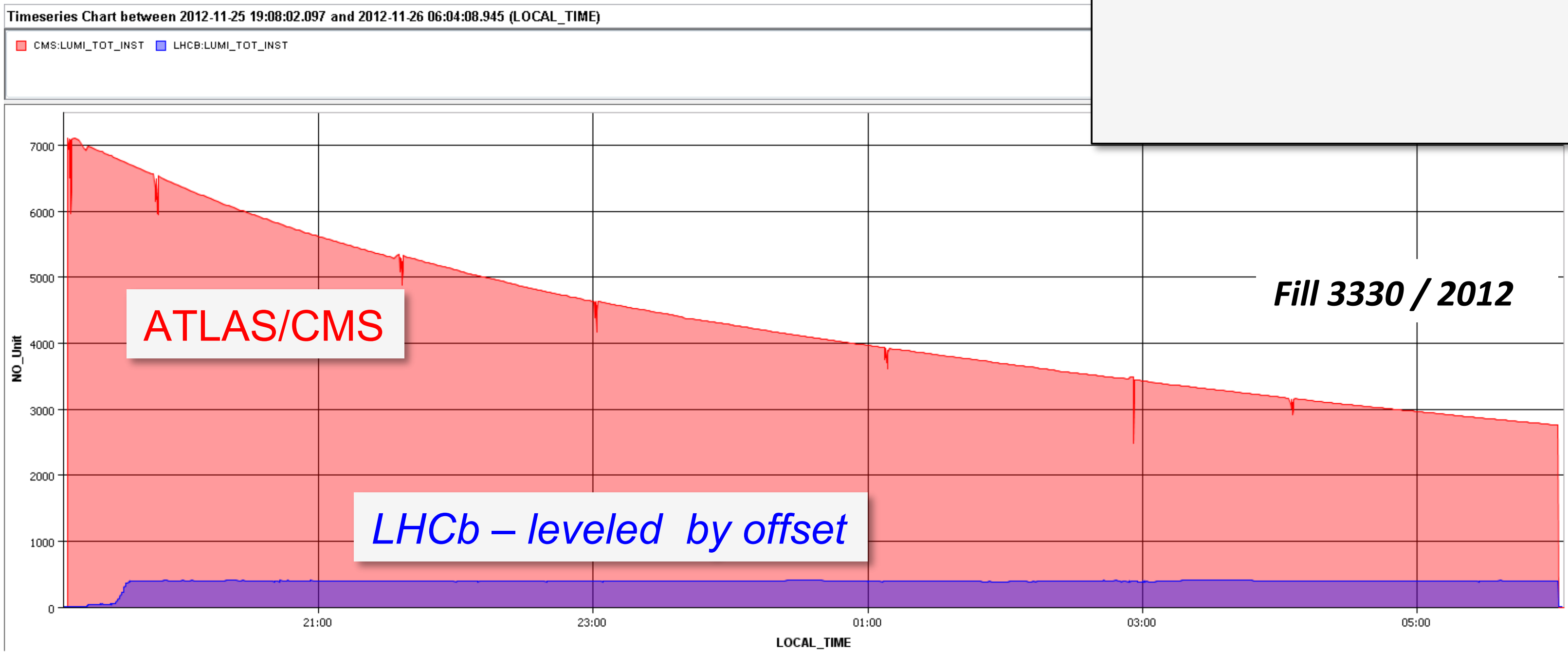
LHCb luminosity leveling

Reduce the peak luminosity on purpose by

- Offset leveling

Constant at ~4×10^{32} $cm^{-2}s^{-1}$, 2 times design luminosity, an order of magnitude lower than ATLAS and CMS



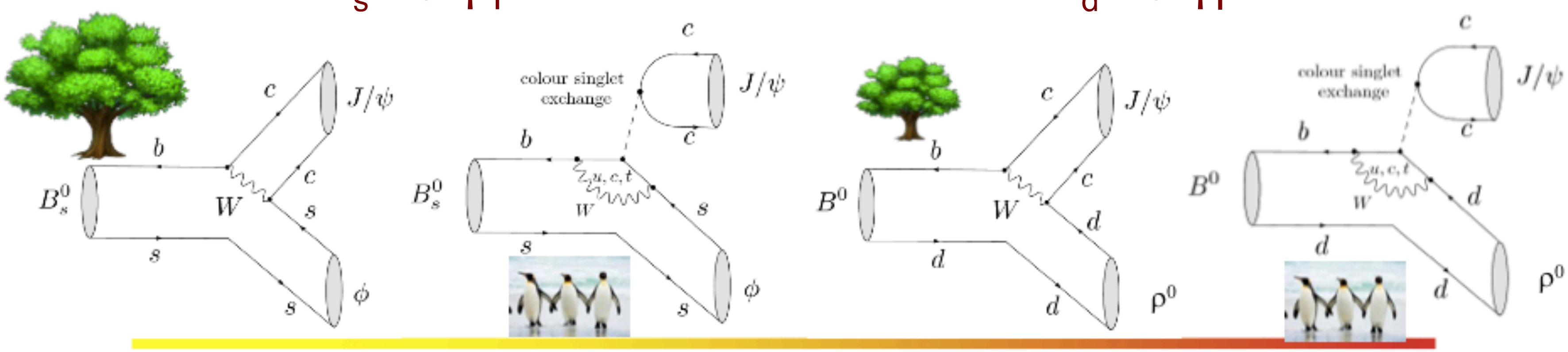


Control of penguin pollution

Penguin contribution small but hard to quantify from theory

- Use SU(3) flavour symmetry: s $\rightarrow$ d

$B_s \rightarrow J/\psi\phi$ $B_d \rightarrow J/\psi\rho$



1 $a\,\lambda^2 e^{-i\gamma} e^{i\theta}$ λ $a\,\lambda e^{-i\gamma} e^{i\theta}$

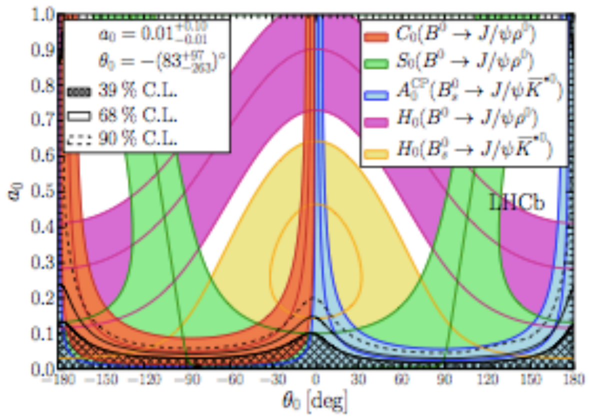
Measure $A_{CP}(B_d \rightarrow J/\psi\rho)$ to constrain a and θ, and put limit on shift of ϕ_s due to neglecting penguins in $B_d \rightarrow J/\psi\phi$:

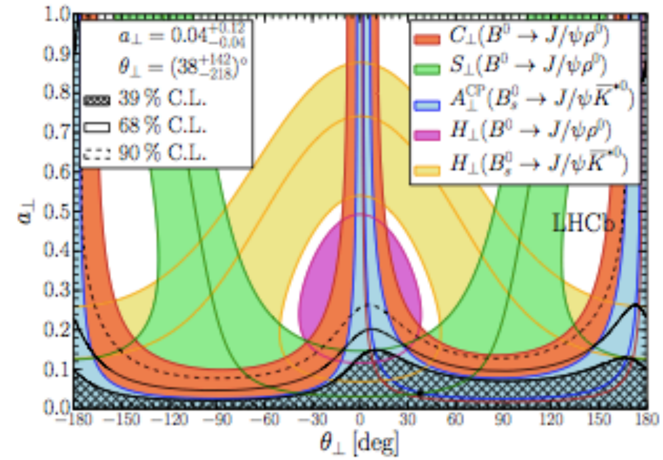
$|\delta_P| < 0.018$ rad@95%CL LHCb, Phys. Lett. B742 (2015) 38

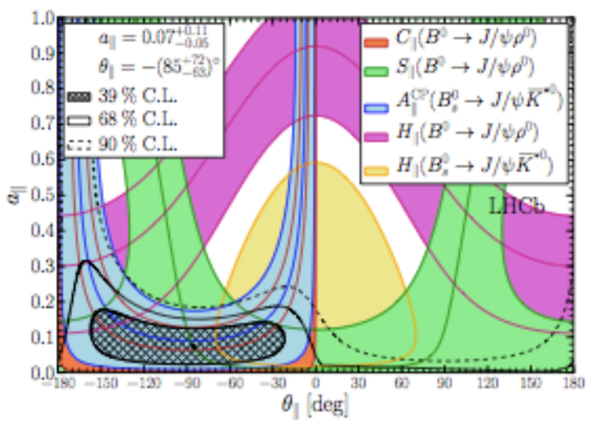
Adding constraint from $B_s \to J/\psi \bar{K}^{*0}$

LHCb, JHEP1511（2015）082

- Results dominated by $B^0 \to J/\psi\rho^0$ (SU(3) flavor symmetry broken by 20% – 30%):







[LHCb, PLB 742 (2015) 38-49] [LHCb, JHEP 11 (2015) 082]

$$\delta_P^0 = 0.000 \,{}^{+0.009}_{-0.011}\,{}^{+0.004}_{-0.009}\ \text{rad}$$

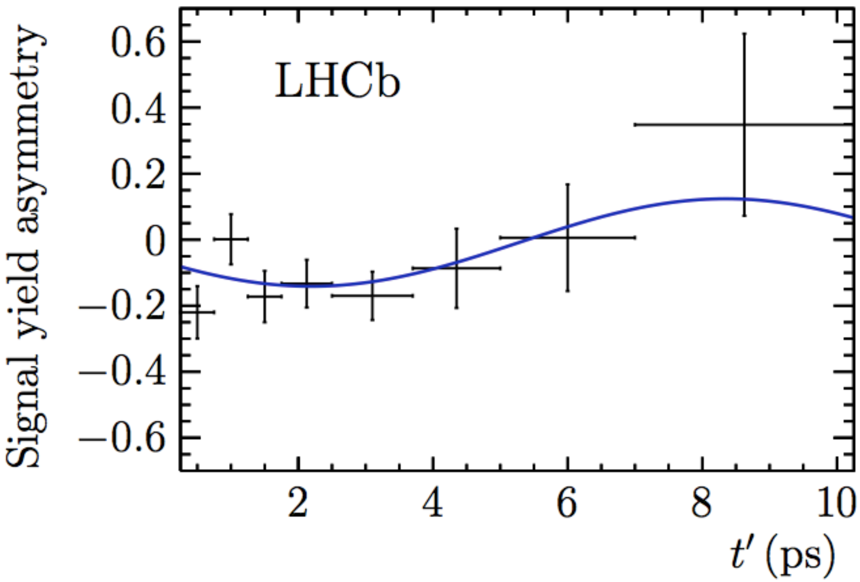
$$\delta_P^\parallel = 0.001 \,{}^{+0.010}_{-0.014} \pm 0.008\ \text{rad}$$

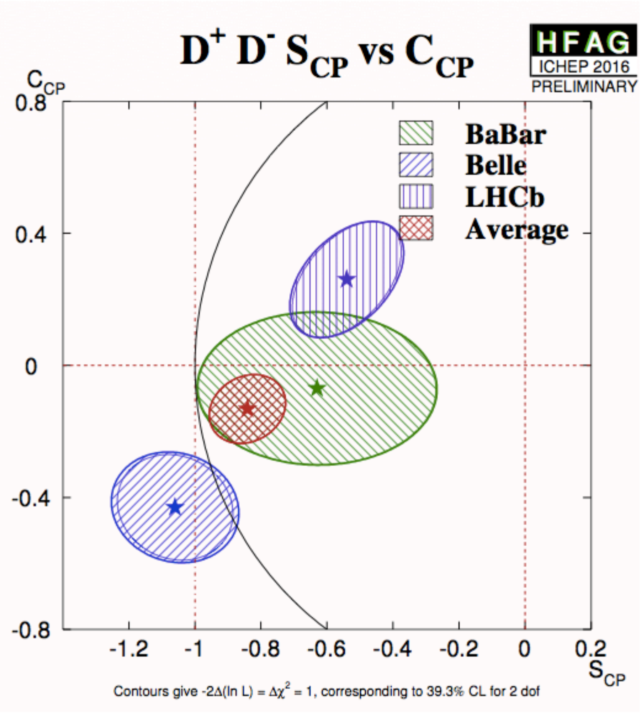
$$\delta_P^\perp = 0.003 \,{}^{+0.010}_{-0.014} \pm 0.008\ \text{rad}$$

Penguin pollution in $\phi_s^{c\bar{c}s}$ is small and under control!

CPV in $B_d \to D^+D^-$

Measurement of CPV in this $b \to c\bar{c}d$ transition can help control penguin effect on the ϕ_s measurement in $B_s \to D_s^+ D_s^-$





LHCb−PAPER-2016-037, in prep.

$$S = -0.54\,^{+0.17}_{-0.16}\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst})$$
$$C = 0.26\,^{+0.18}_{-0.17}\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})$$

$$S_{CP}/\sqrt{1 - C_{CP}^2} = -\sin(\varphi_d + \Delta\varphi)$$

$$\sin(\phi_d + \Delta\phi) = 0.56\,^{+0.16}_{-0.17}$$

CPT& Lorentz violation

Is there a mass difference between B^0_q and $\bar{B}^0_q$?

- Fit the time–dependent decay rate to see if z is nonzero

$$|B_L\rangle = p\sqrt{1-z}|B^0\rangle + q\sqrt{1+z}|\bar{B}^0\rangle$$
$$|B_H\rangle = p\sqrt{1+z}|B^0\rangle - q\sqrt{1-z}|\bar{B}^0\rangle$$

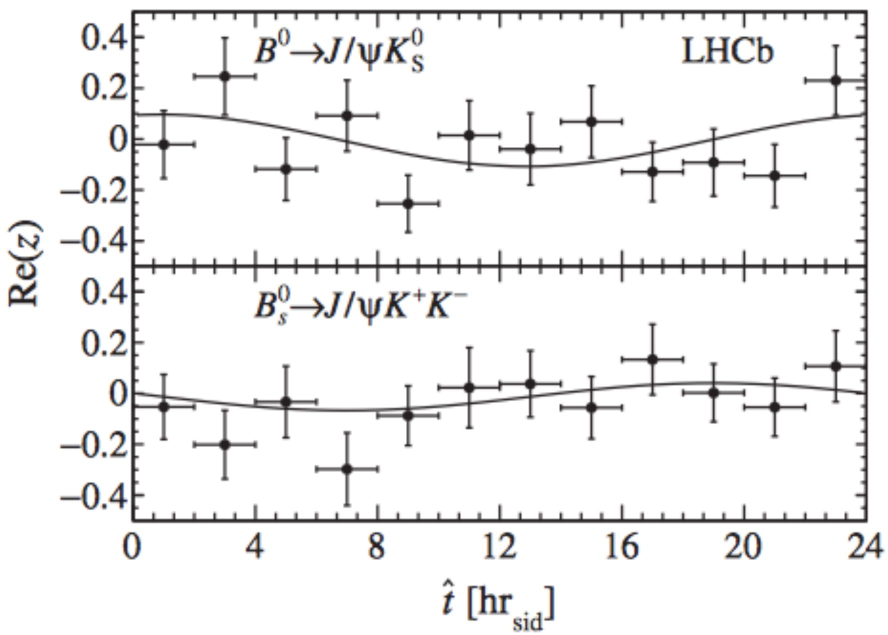
$$z = \frac{\delta m - i\delta\Gamma/2}{\Delta m - i\Delta\Gamma/2}$$

$$\delta m \equiv (M_{11} - M_{22})/2 \quad \delta\Gamma \equiv (\Gamma_{11} - \Gamma_{22})/2$$

Does the mass difference vary due to Earth's rotation?

- Check for periodic dependence of z on sidereal time

CPT& Lorentz violation



LHCb, PRL 116 (2016) 241601

No periodic variation of mass difference.
Average mass difference consistent with zero.

Stringent constraint on CPT violation.

$$\mathcal{R}e(z^{B^0_s}) = -0.022 \pm 0.033(\text{stat}) \pm 0.003(\text{syst}),$$

$$\mathcal{I}m(z^{B^0_s}) = 0.004 \pm 0.011(\text{stat}) \pm 0.002(\text{syst}).$$

Inputs to γ combination

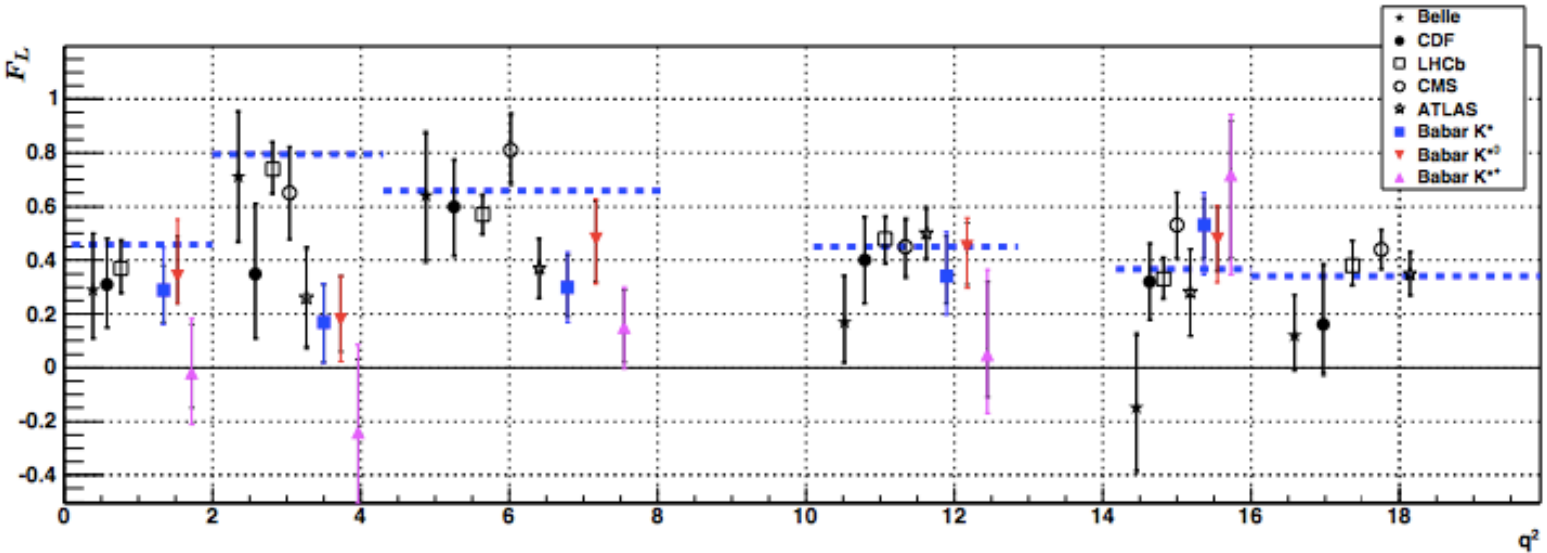
Four new papers

Constraints on the unitarity triangle angle γ from Dalitz plot analysis of $B^0 \to DK^+\pi^-$ decays	LHCb-PAPER-2015-059 arXiv:1602.03455	$B^0 \to [K^+K^-]K\pi$ $B^0 \to [\pi^+\pi^-]K\pi$
Measurement of *CP* observables in $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ with two- and four-body D decays	LHCb-PAPER-2016-003	$B^\pm \to [h^\pm h^\pm]h^\pm$ $B^\pm \to [K^+\pi^-\pi^+\pi^-]h^\pm$ $B^\pm \to [\pi^+\pi^-\pi^+\pi^-]h^\pm$
Model-independent measurement of the CKM angle γ using $B^0 \to DK^{*0}$, $D \to K^0_S\pi^+\pi^-$, $K^0_S K^+K^-$ decays	LHCb-PAPER-2016-006	$B^0 \to [K_S^0 h^+h^-]K^{*0}$
Measurement of the CKM angle γ using $B^0 \to DK^{*0}$ with $D \to K^0_S\pi^+\pi^-$ decays	LHCb-PAPER-2016-007	$B^0 \to [K_S^0\pi^+\pi^-]K^{*0}$

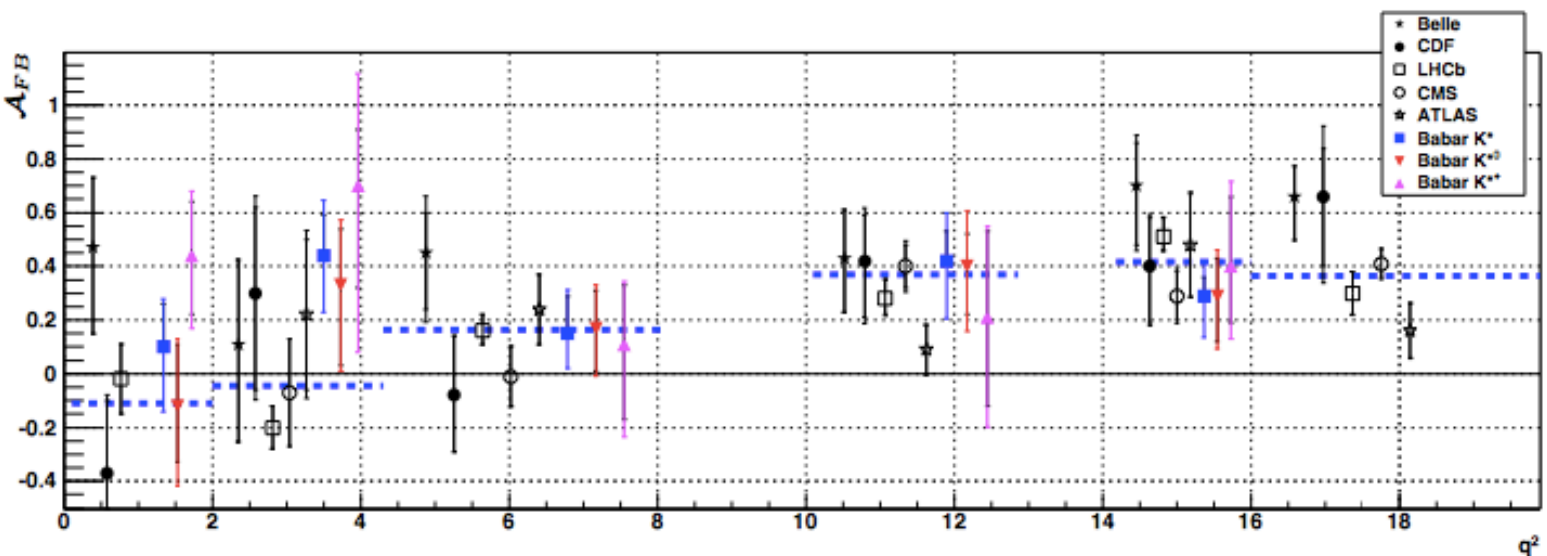
which add to five published papers,

A study of *CP* violation in $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ decays with $D \to K_S^0 K^\pm\pi^\mp$ final states Phys. Lett. B733 (2014) 36 arXiv:1402.2982	$B^\pm \to [K_S^0 K^+\pi^-]h^\pm$
Measurement of *CP* asymmetry in $B_s^0 \to D_s^\mp K^\pm$ decays JHEP 11 (2014) 060 arXiv:1407.6127	$B_s \to D_s K$
Measurement of *CP* violation parameters in $B^0 \to DK^{*0}$ decays Phys. Rev. D90 (2014) 112002 arXiv:1407.8136	$B^0 \to [K^\pm\pi^\pm]K^{*0}$
Measurement of the CKM angle γ using $B^\pm \to DK^\pm$ with $D \to K_S^0\pi^+\pi^-$, $K_S^0 K^+K^-$ decays JHEP 10 (2014) 097 arXiv:1408.2748	$B^\pm \to [K_S^0 h^+h^-]K^\pm$
A study of *CP* violation in $B^\mp \to Dh^\mp$ ($h=K,\pi$) with the modes $D \to K^\mp\pi^\pm\pi^0$, $D \to \pi^+\pi^-\pi^0$ and $D \to K^+K^-\pi^0$ Phys. Rev. D91 (2015) 112014 arXiv:1504.05442	$B^\pm \to [h^\pm h^\pm\pi^0]h^\pm$

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

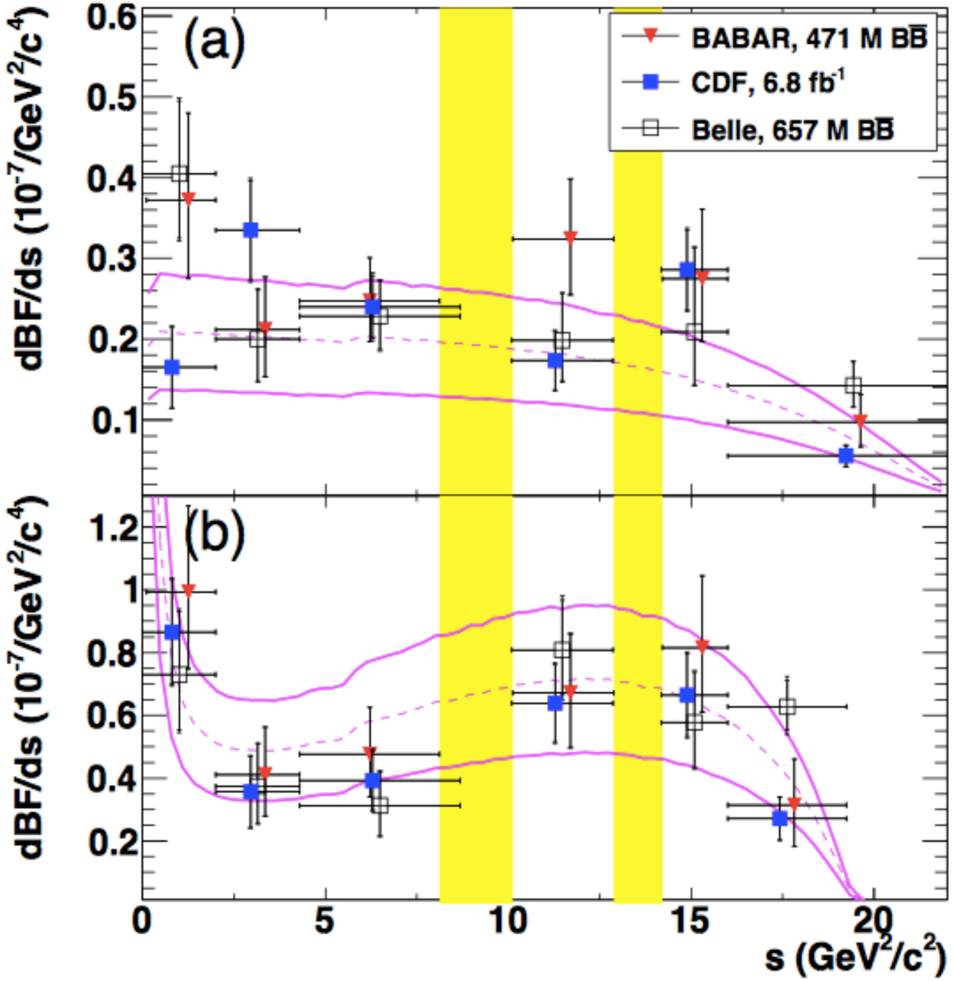


(a) F_L.



(b) $\mathcal{A}_{FB}$.

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



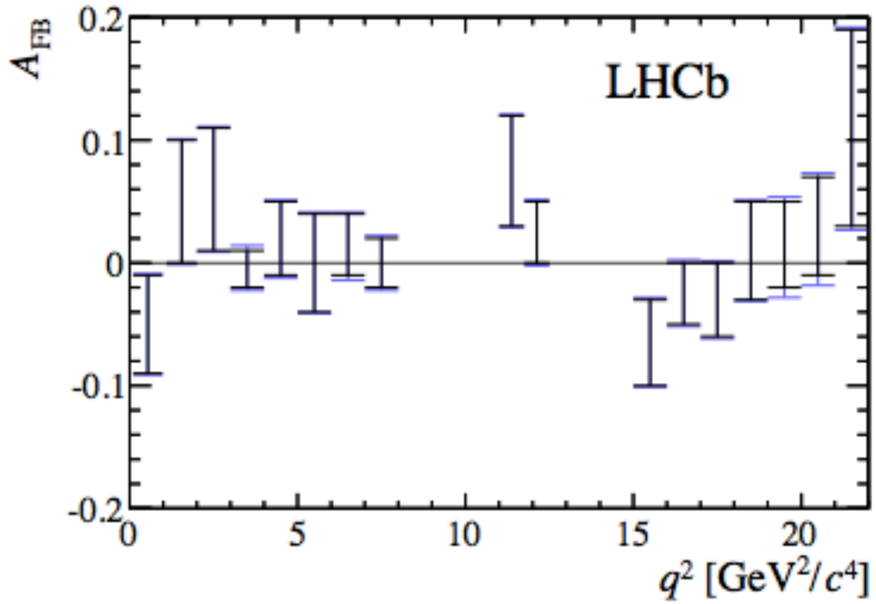
(a)
(b)
BABAR, 471 M BB̄
CDF, 6.8 fb-1
Belle, 657 M BB̄
dBF/ds (10-7/GeV2/c4)
s (GeV2/c2)

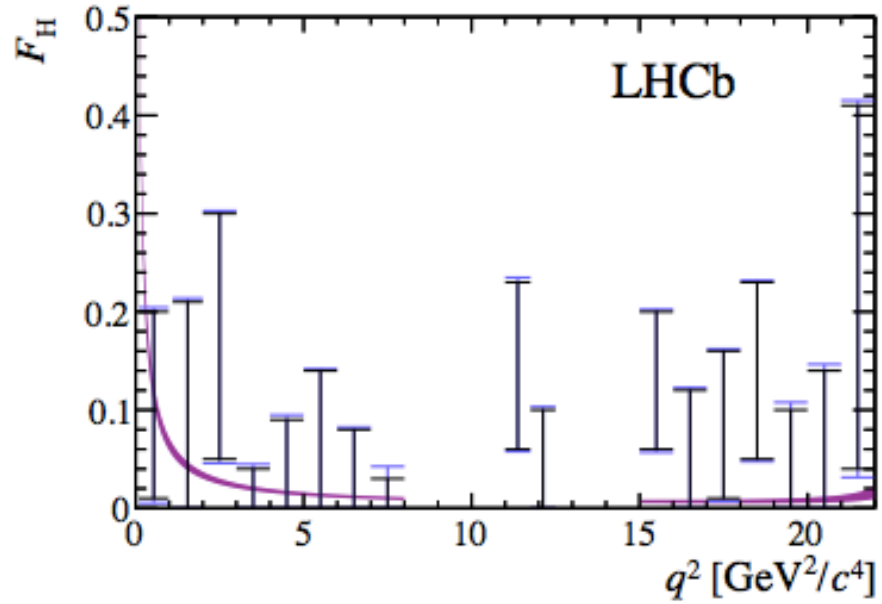
Angular analysis of $B^+ \to K^+\mu^+\mu^-$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_l} = \frac{3}{4}(1-F_H)(1-\cos^2\theta_l) + \frac{1}{2}F_H + A_{FB}\cos\theta_l$$

$1fb^{-1}$ result of $B^+ \to K^+\mu^+\mu^-$ LHCb, JHEP 1405 (2014) 082

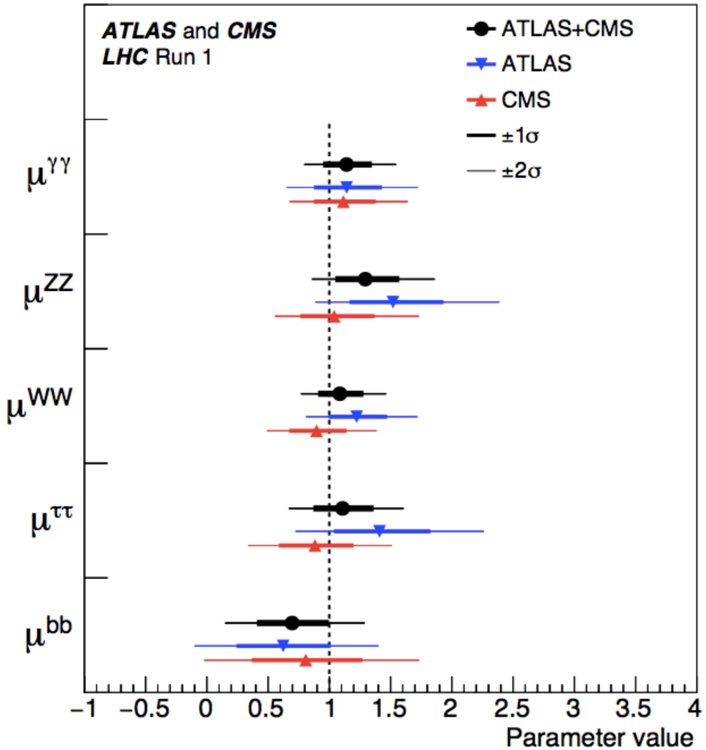
Consistent with SM SM predictions: $R_K \cong 1$ & $F_H \sim 0$

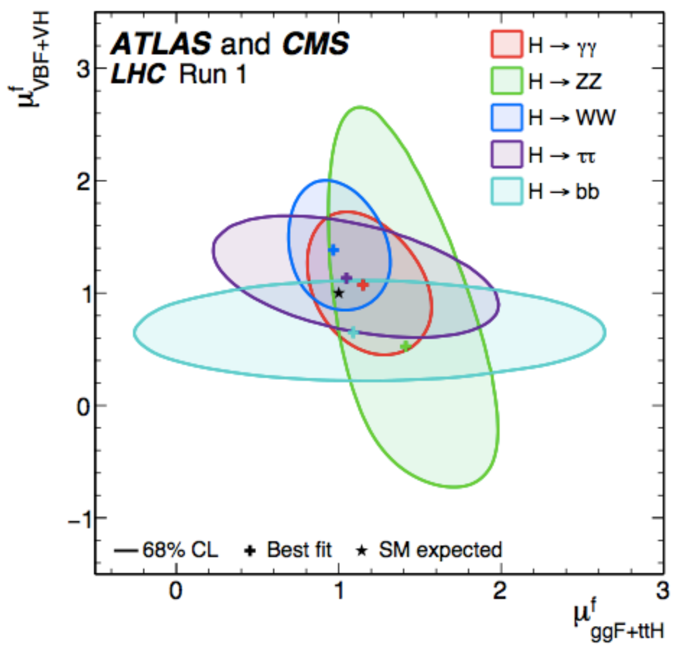




Angular analysis of $B^+ \to K^+e^+e^-$ not possible yet

Properties of the Higgs





- Couplings to heavy particles consistent with SM: mass generation of heavy particles roughly understood
- Not much information about light fermions
  - Little sensitivity from ATLAS/CMS data
  - Study quark mixing to test Yukawa interactions