Recent results from LHCb and future prospects

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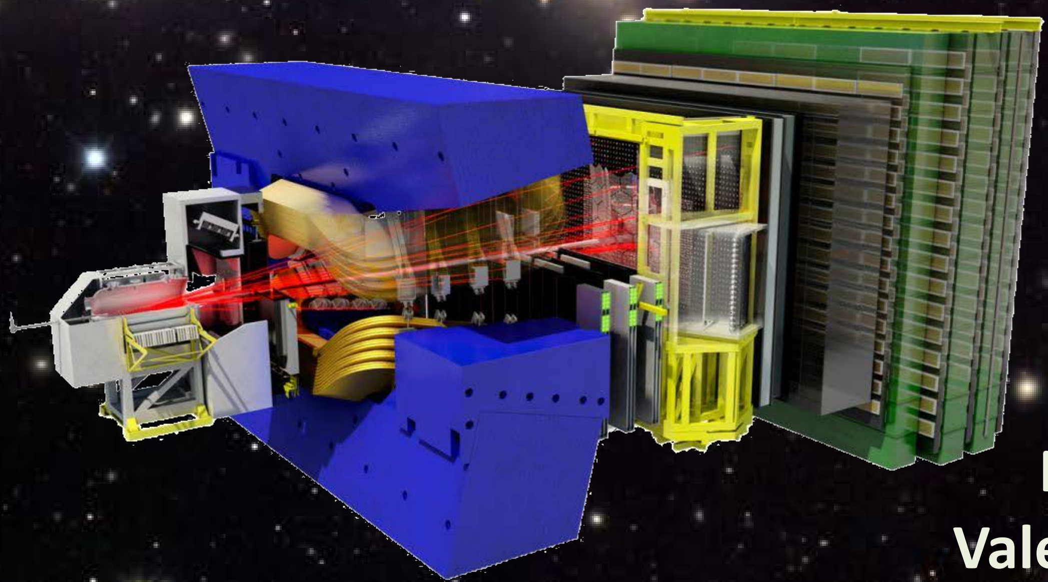
On behalf of the LHCb collaboration



PLANCK 2016
Valencia, May 2016

Solving fundamental questions with the LHCb:

What's matter?

How quarks couple?

Matter vs antimatter?

How leptons couple?

Universe symmetries?

Outline:

New states of matter

[LHCb-CONF-2016-004]

[PRL 115, 072001 (2015)]

CKM matrix element V_{ub}

[Nature Phys. 10 (2015) 1038]

B_d mixing and CP violation

[LHCb-PAPER-2015-031]

[PRL 114 (2015) 041601]

[LHCb-PAPER-2016-013]

Lepton universality

[PRL 113 (2014) 151601]

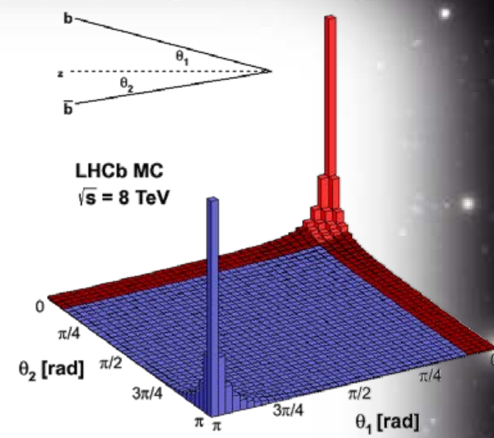
[PRL 115 (2015) 111803]

Lorentz invariance & CPT

[LHCb-PAPER-2016-005]

The LHCb experiment

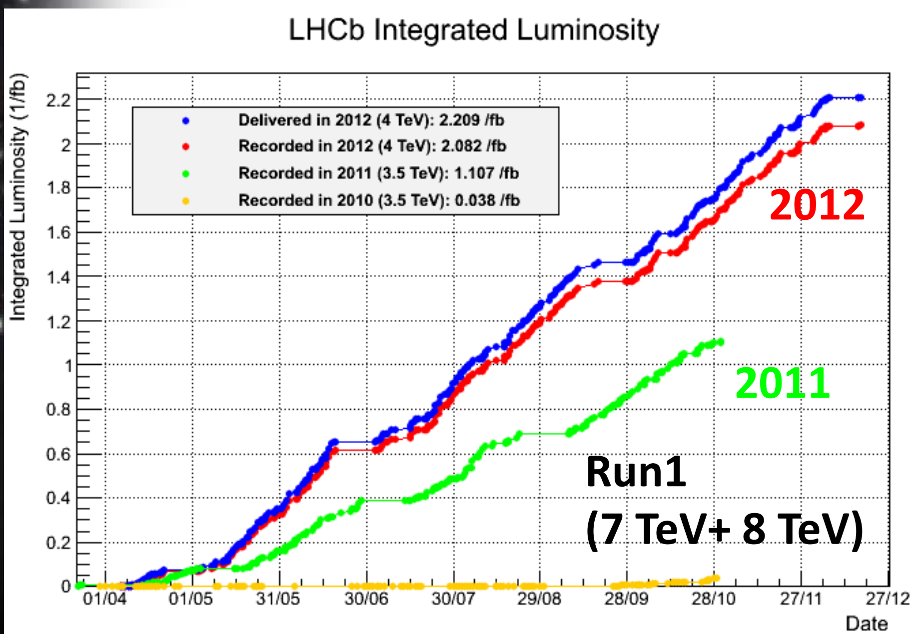
The LHCb experiment

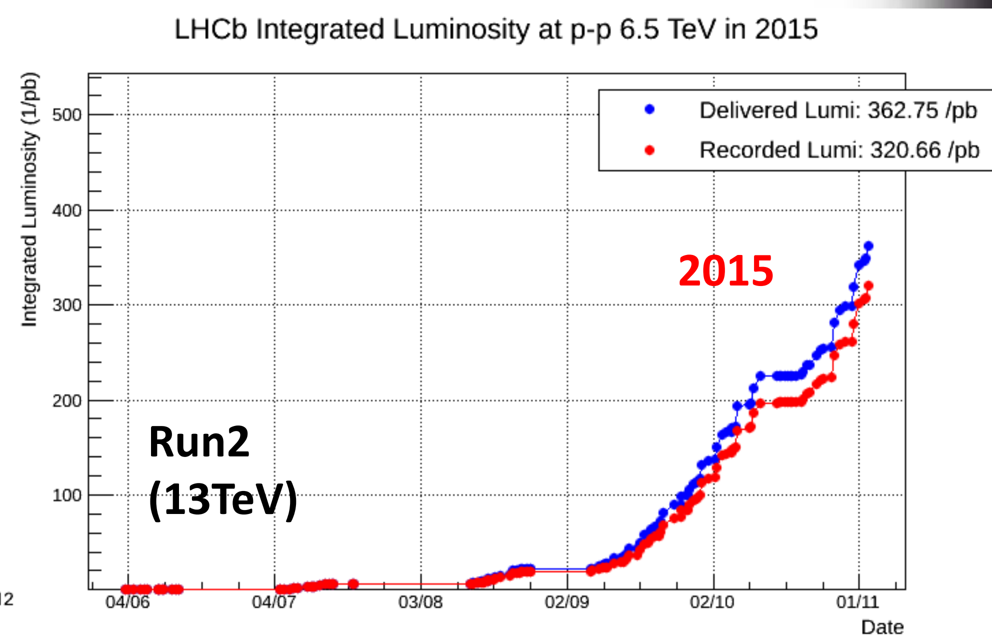


- LHC: Large $b\bar{b}$ cross section in pp collisions (gluon fusion) (~250 μb – 500 μb @ $\sqrt{s}$=7 – 14 TeV):

- LHCb: single-arm forward spectrometer ($2 < \eta < 5$): ~ 4% of the solid angle, ~30% of the *b* hadron production

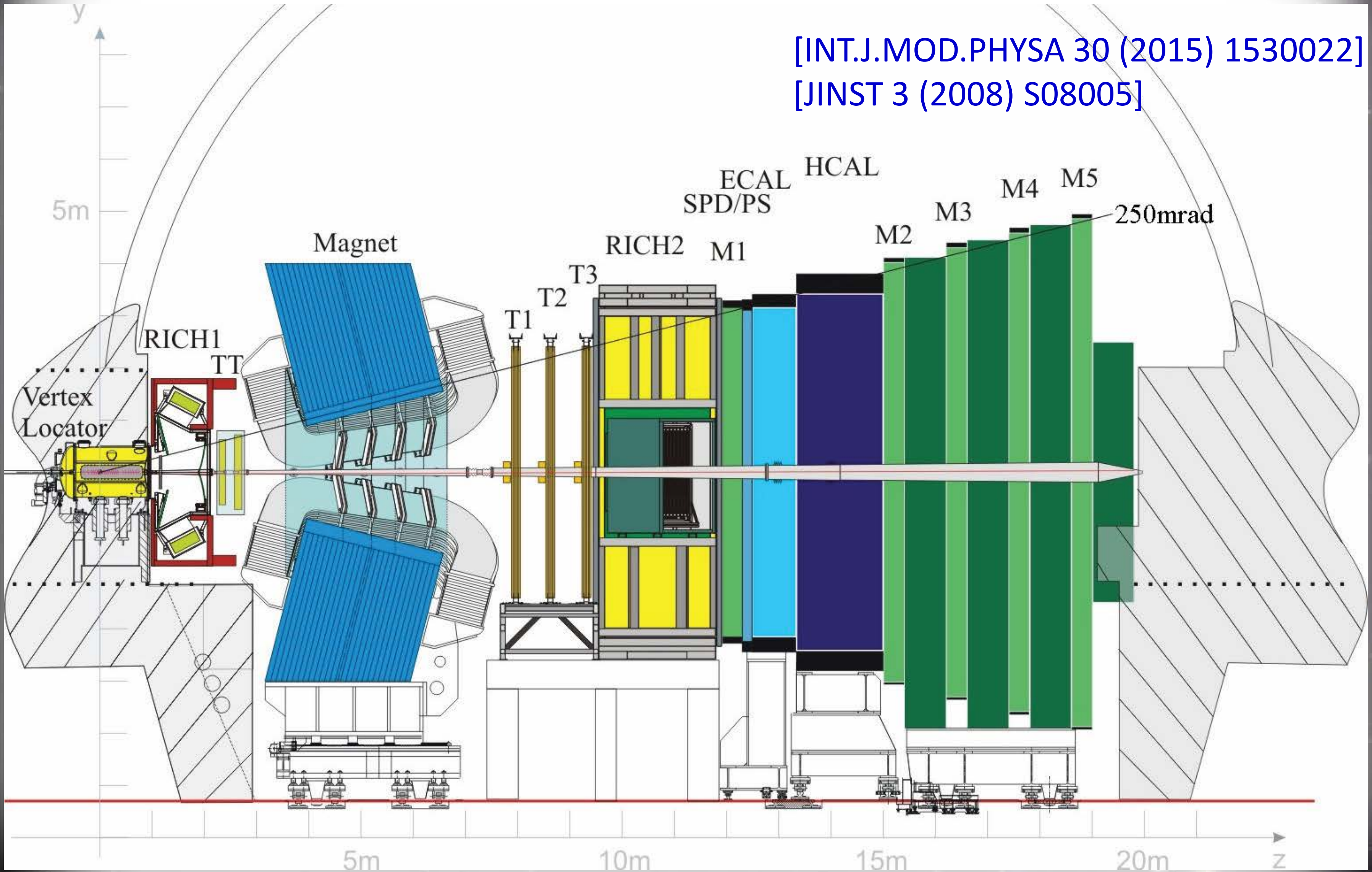
- Very good performance: **3 fb^{-1}** accumulated in Run1, working well for Run2, expected **5 fb^{-1}**





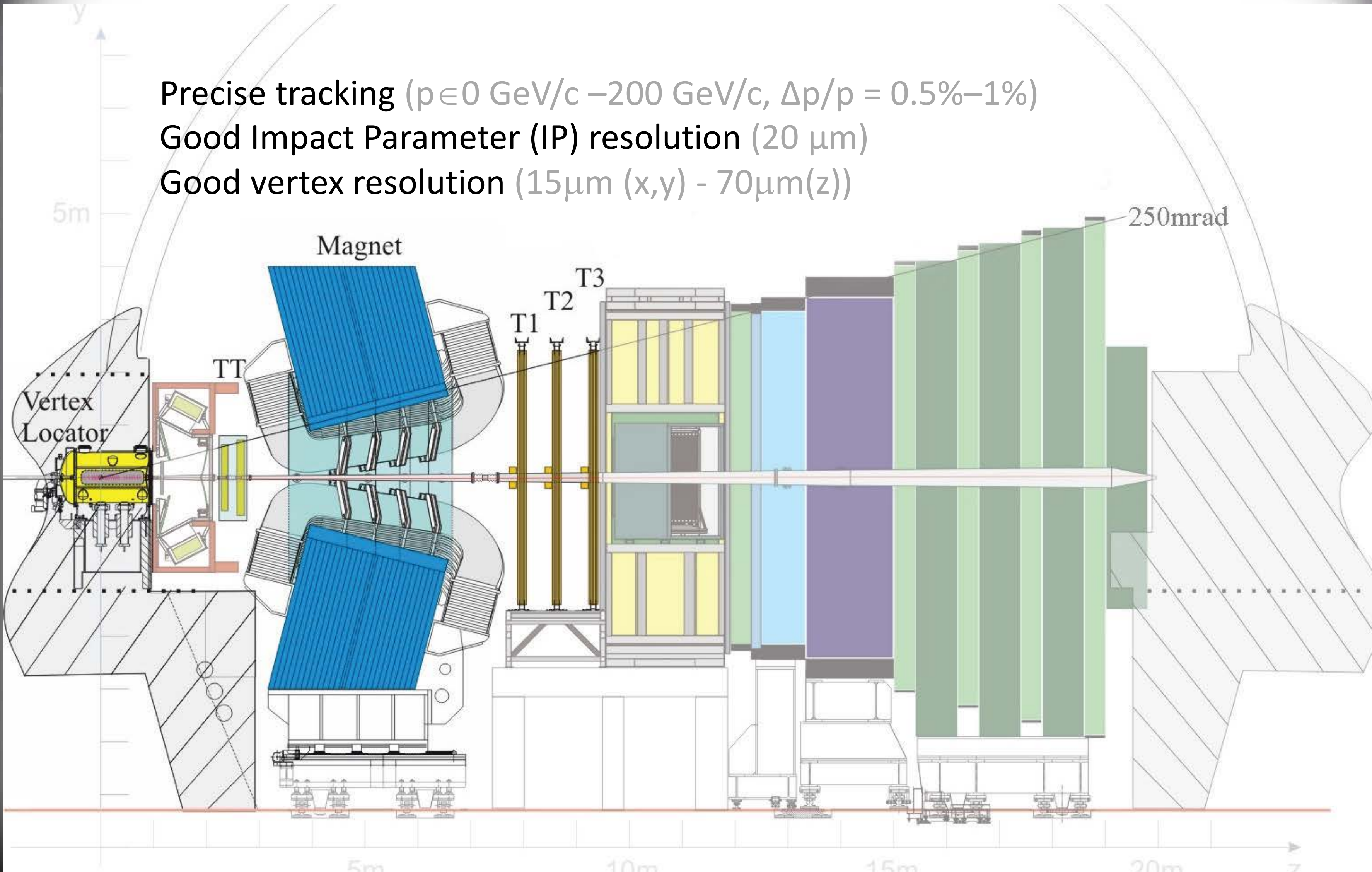
The LHCb experiment

[INT.J.MOD.PHYSA 30 (2015) 1530022]
[JINST 3 (2008) S08005]



The LHCb experiment

Precise tracking (p∈0 GeV/c –200 GeV/c, Δp/p = 0.5%–1%)
Good Impact Parameter (IP) resolution (20 μm)
Good vertex resolution (15μm (x,y) - 70μm(z))

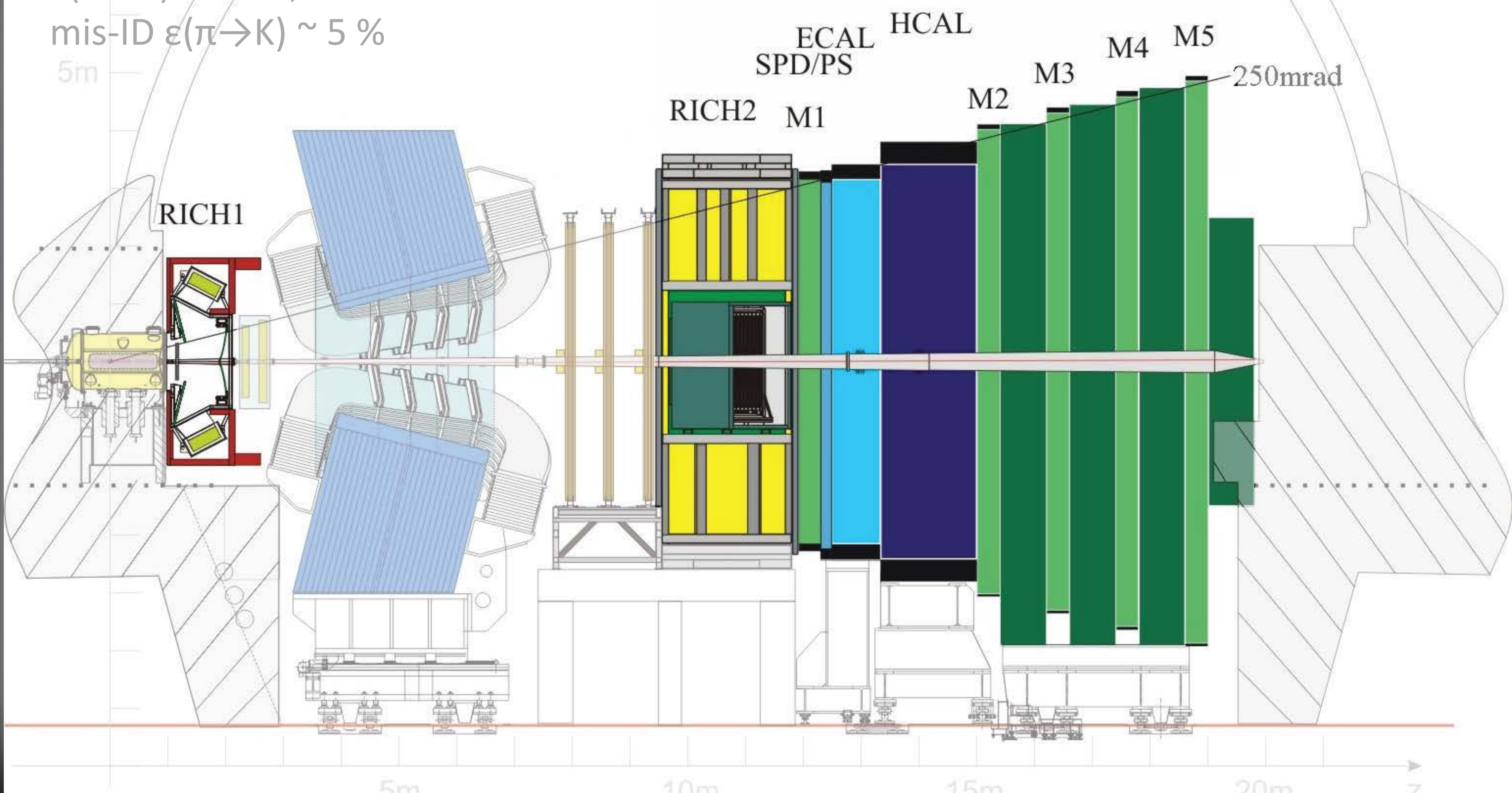


The LHCb experiment

Excellent particle identication
π/K separation over 2-100 GeV
ε(K→K) ~ 95 %,
mis-ID ε(π→K) ~ 5 %

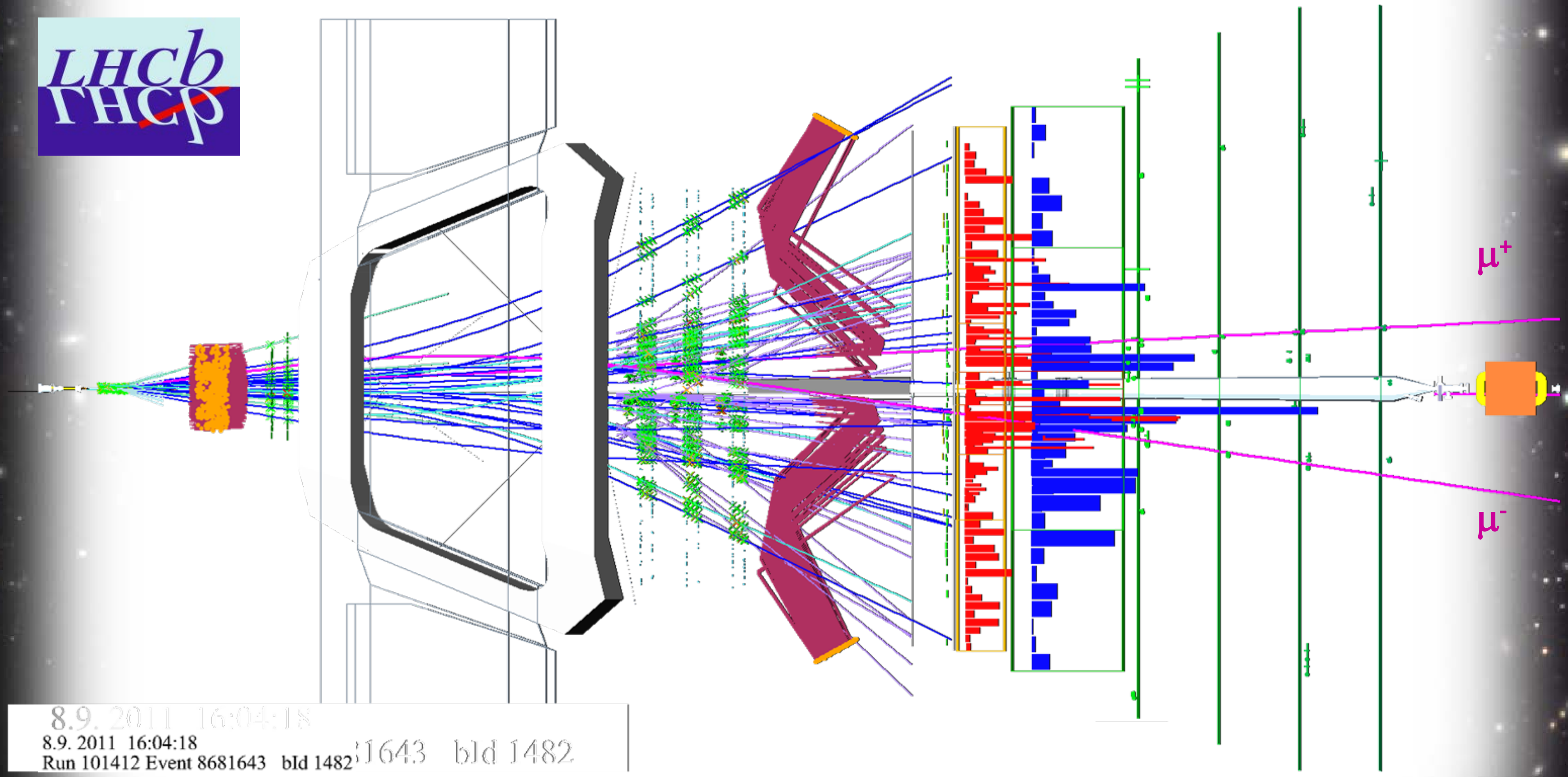
Calorimeter system
ΔE/E = 1 % ⊕10 %/√E (GeV)

Powerful μ identification
ε(μ→μ) ~ 97 %,
mis-ID ε(π→μ) ~ 1-3 %



The LHCb experiment

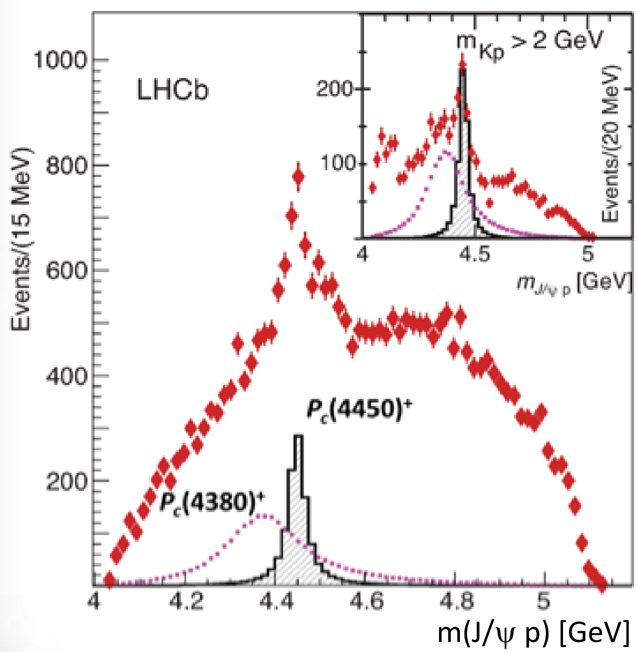
$B_s \to \mu^+\mu^-$ event



New states of matter

$q\bar{q}q\bar{q}$ and $qqqq\bar{q}$ states predicted from the origin of the Quark Model
[M. Gell-Mann, PL8 (1964) 214]

- X(3872)($c\bar{c}u\bar{u}$), Z(4430) ($c\bar{c}u\bar{d}$) observed
- LHCb has observed J/ψ p resonances in $\Lambda_b \rightarrow J/\psi K^- p$ decays: two pentaquarks states: $P_c(4380)^+$ and $P_c(4450)^+$ ($c\bar{c}uud$)

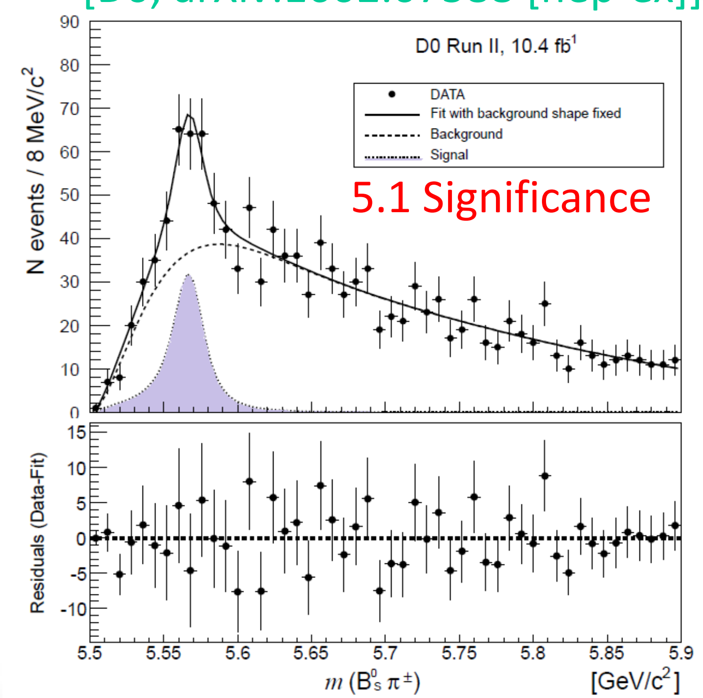


[PRL 115, 072001 (2015)]

- D0 has three months ago announced a new state formed by 4 different valence quarks: b, s, u, d

Tetraquark $X(5568) \rightarrow B_s \pi$

[D0, arXiv:1602.07588 [hep-ex]]



Looking for confirmation at LHCb...

New states of matter

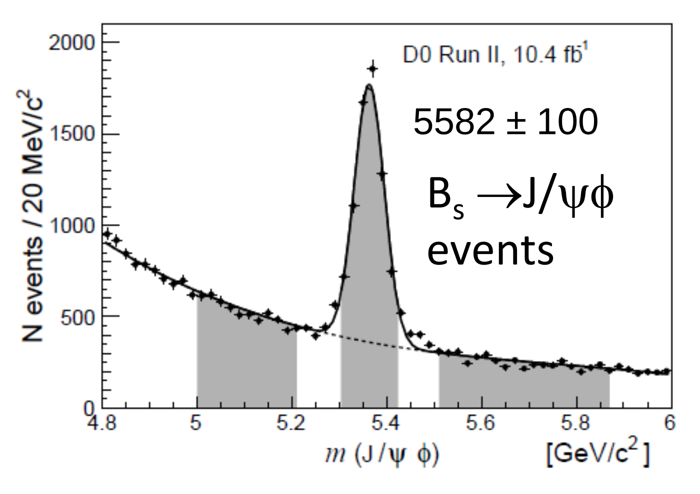
[D0, arXiv:1602.07588 [hep-ex]]

- At D0: X(5568), with $10.4 fb^{-1}$ at $p\bar{p}$, $\sqrt{s}$= 1.96 TeV:

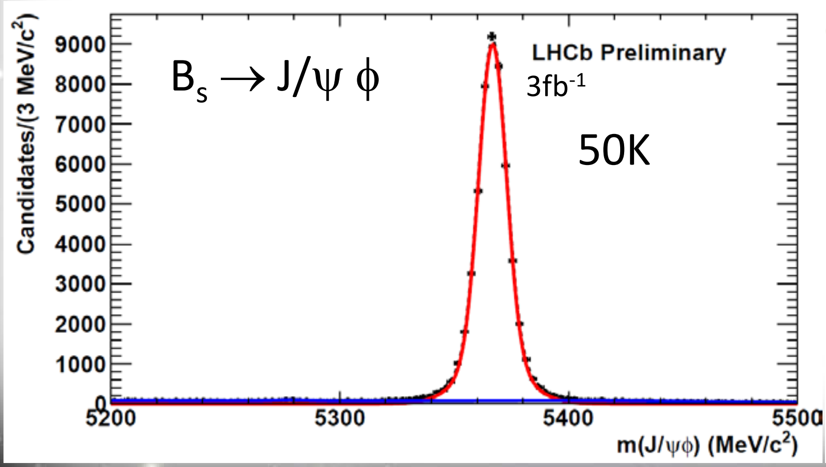
Candidates: $B_s \to J/\psi\ \phi$ (with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$)
+ one π $\to$ X(5568) state:

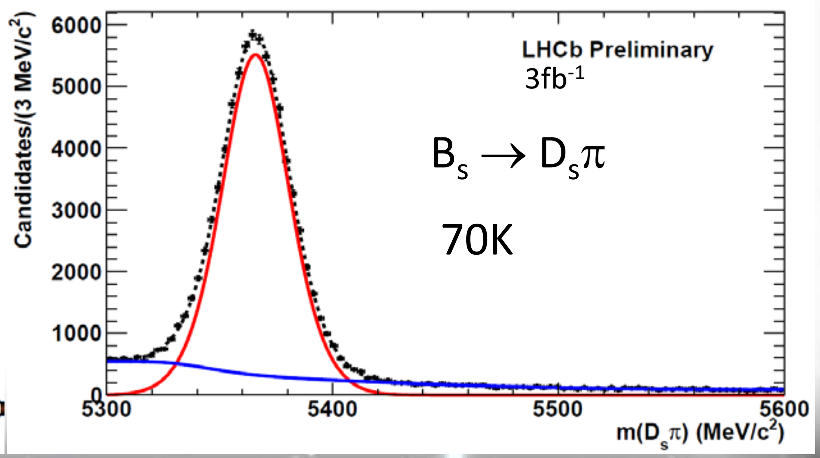
$$m = 5567.8 \pm 2.9\,(\text{stat})^{+0.9}_{-1.9}\,(\text{syst})\ \text{MeV}/c^2$$
$$\Gamma = 21.9 \pm 6.4\,(\text{stat})^{+5.0}_{-2.5}\,(\text{syst})\ \text{MeV}/c^2$$

Relative production fraction to B_s: (8.6 ± 1.9 ± 1.4)%



- At LHCb, with $3 fb^{-1}$ at pp, $\sqrt{s}$= 7 and 8 TeV, we have very large B_s samples [LHCb-CONF-2016-004] (20 larger than D0 samples, better mass resolution)

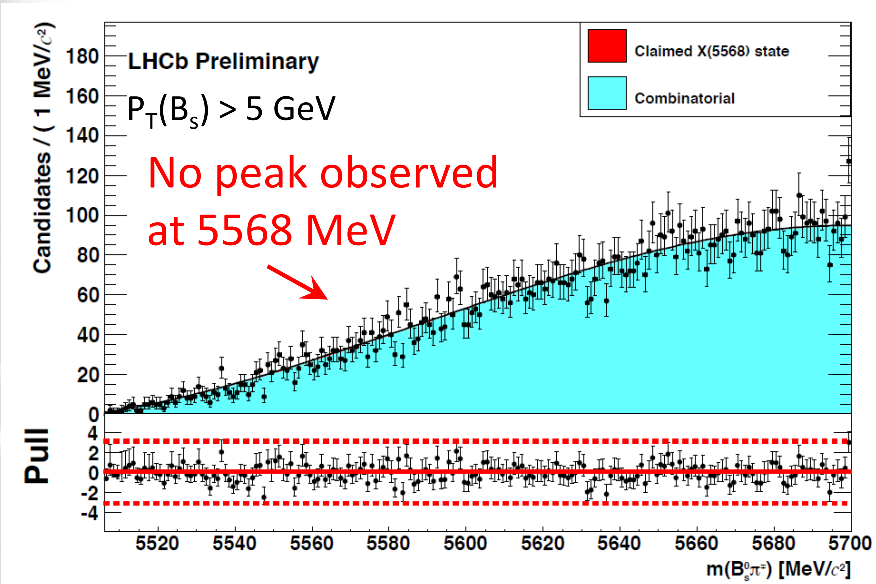




New states of matter

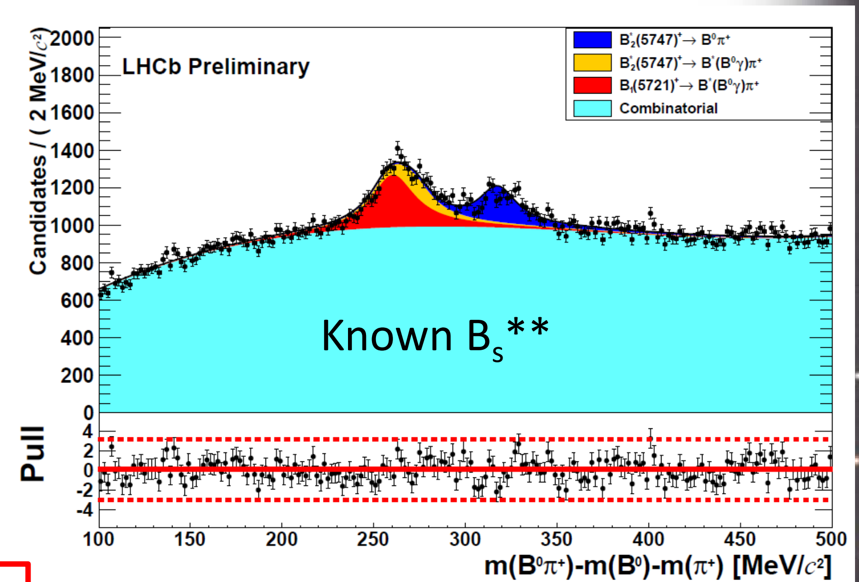
[LHCb-CONF-2016-004]

- Adding a pion to the B_s candidates…
  Fit to the $Q = m(B_s\pi^{\pm}) - m(B_s) - m(\pi^{\pm})$ distribution:



LHCb cannot confirm D0 peak

Cross-check:
Fit to $B\pi^{+}$ candidates obtained with similar selection criteria

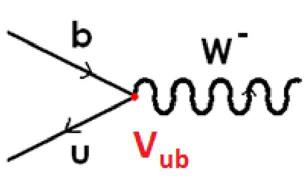


Upper Limit for the relative production fraction:

(B_s p_T>5 GeV): ρ_{LHCb}< 0.01 % at 95%CL
(B_s p_T>10 GeV): ρ_{LHCb} < 0.018 % at 95%CL

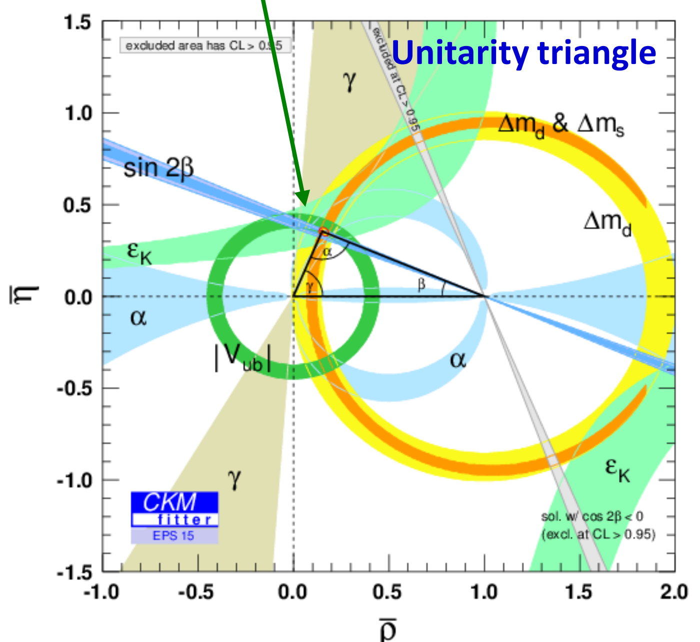
The CKM matrix V_{ub}

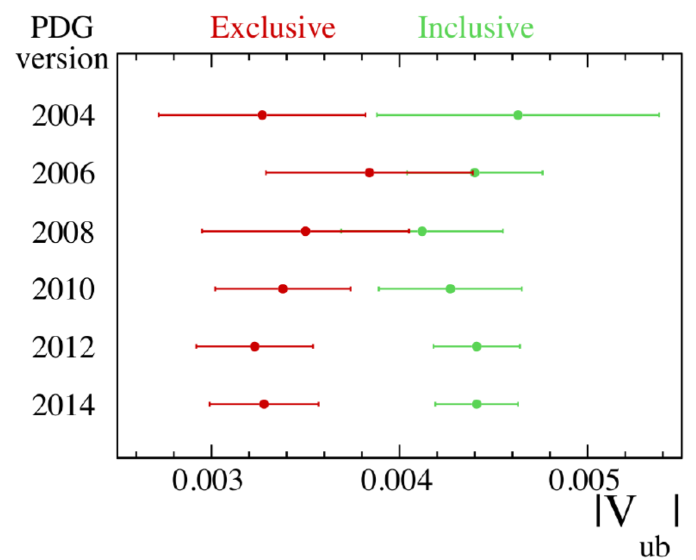
The smallest CKM element (b $\rightarrow$ u coupling) ~ 4‰



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

Key constraint in the flavour picture





Large discrepancies between $|V_{ub}|$ from different determinations (**~3σ**)

http://ckmfitter.in2p3.fr, see also http://www.utfit.org

The CKM matrix V_{ub}

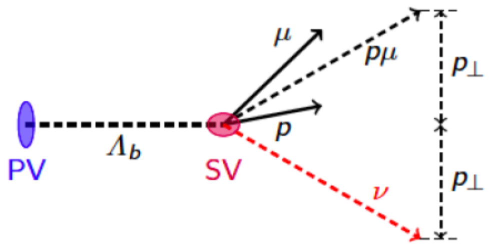
[Nature Physics 10 (2015) 1038]

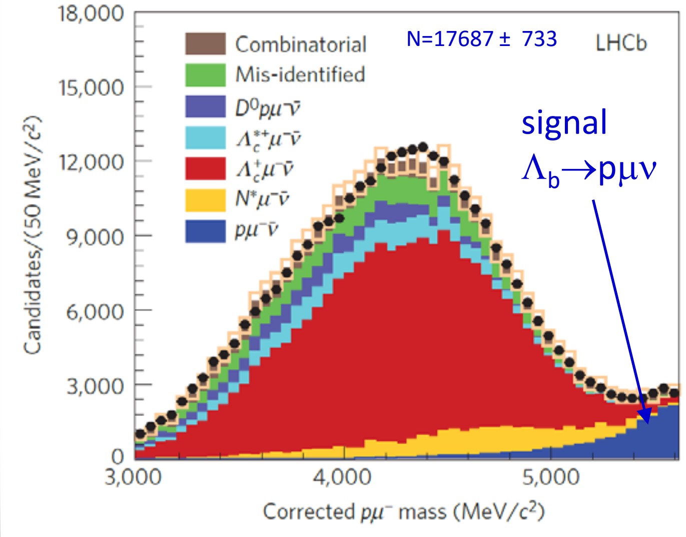
Using semileptonic decays of b-baryons:

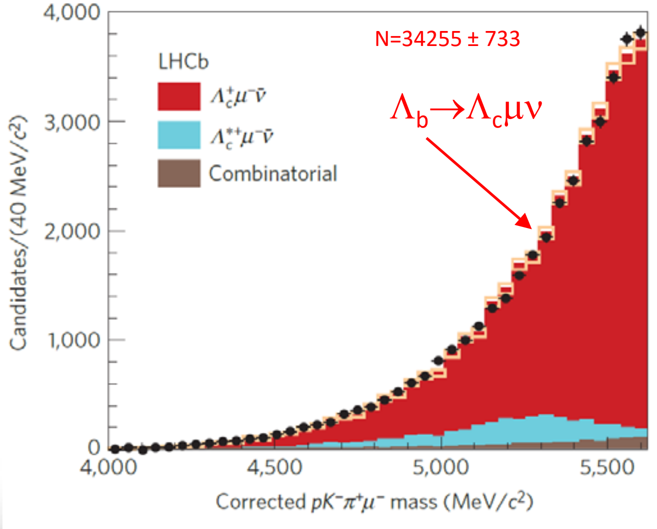
$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} = \frac{|V_{ub}|^2}{|V_{cb}|^2}$$ x Ratio of form factors

(5% accuracy from LQCD)
[PRD 92 (2015) 034503 (2015)]

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







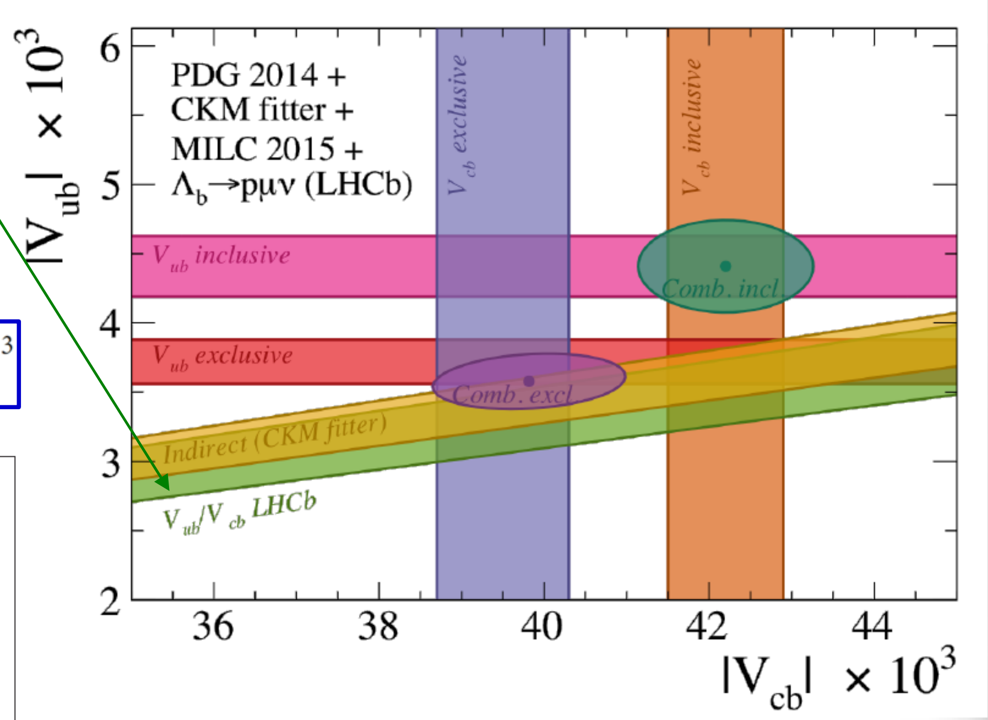
The CKM matrix V_{ub}

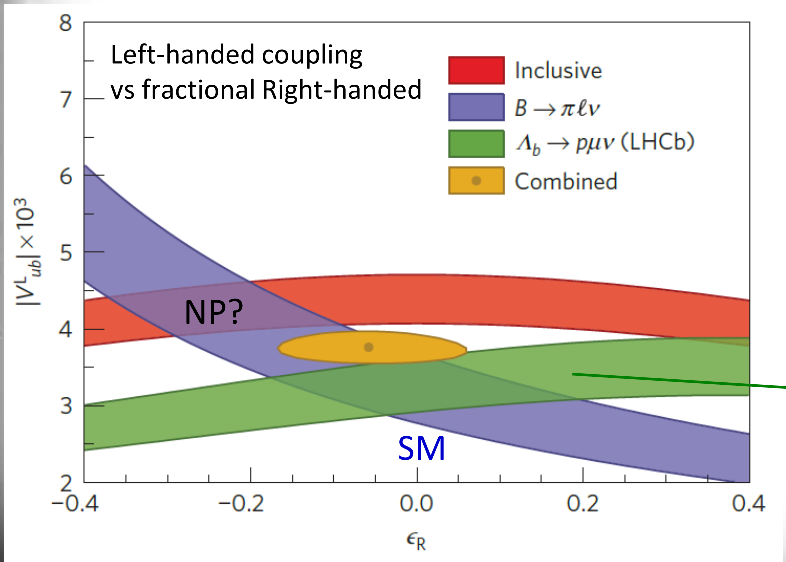
[Nature Physics 10 (2015) 1038]

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

Using the world average from exclusive V_{cb}:

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

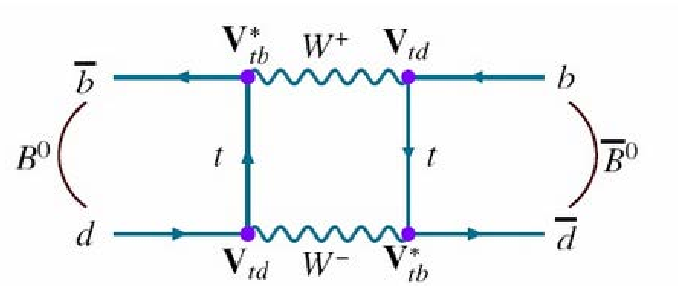




Disfavours models with Right-handed currents

B_d-$\overline{B}_d$ oscillations

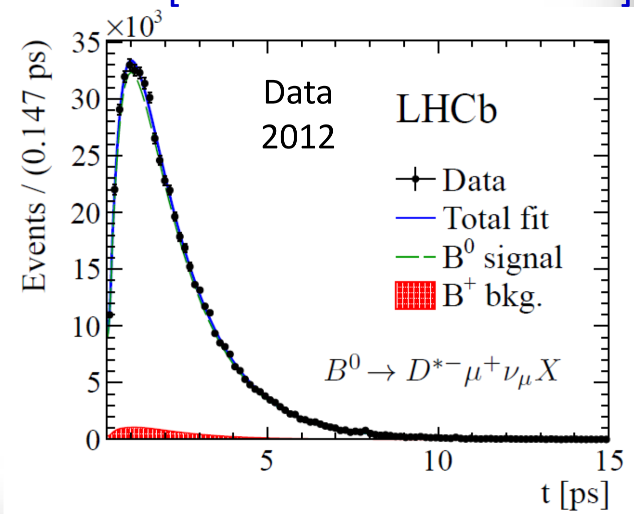
Neutral B mesons oscillate between particle and antiparticle with frequency Δm (mass difference between the mass states B_L, B_H)



The time-dependent asymmetry A(t) of B_d events that changed flavour (mixed) or not (unmixed) is:

[LHCb-PAPER-2015-031]

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



Use semileptonic decays of B decays to D* or D and $\mu\nu$ X with flavour tag to determine Δm_d

$t = M_B L / p(D^{(*)}\mu) \times \kappa_{sim} (D^{(*)}\mu)$

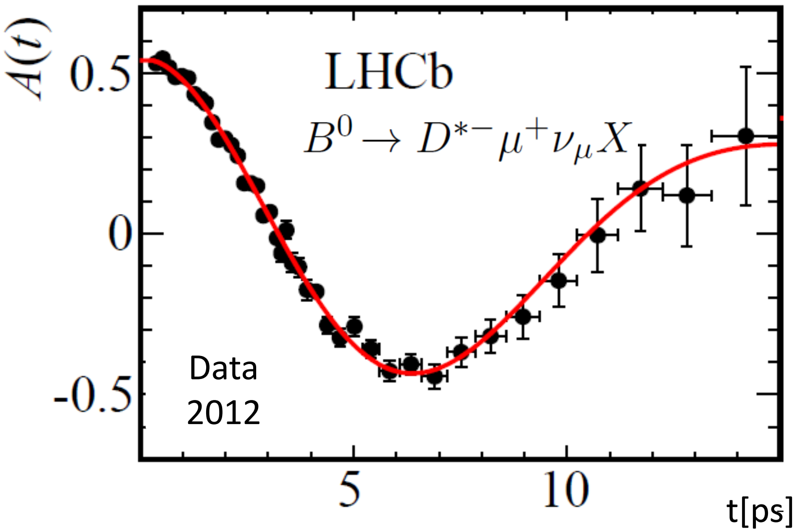
B_d-$\overline{B}_d$ oscillations

[LHCb-PAPER-2015-031]

The most precise single measurement:

$$\Delta m_d = (505.0 \pm 2.1\,(\text{stat}) \pm 1.0\,(\text{syst}))\ \text{ns}^{-1}$$

Consistent with the world average $\Delta m = (510 \pm 3)\ \text{ns}^{-1}$



(best tagging category)

New Lattice results [arXiv:1602.03560] allow stronger constraints on the CKM Unitarity triangle

CP Violation

CP violation in mixing is produced in the B system if the probabilities of **B** $\rightarrow$ $\overline{\mathbf{B}}$ and $\overline{\mathbf{B}}$ $\rightarrow$ **B** are different.

This effect has only been observed, so far, in the neutral kaon system (ε_K=0.2%)

Possible to measure it using B semileptonic decays $B\rightarrow D^{(*)}\mu\nu X$ since the lepton tags the flavour at decay and has large BR.

The semileptonic asymmetry is defined as:

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

Predicted to be very small in the SM:

$a_{\rm sl}^d = (-4.7 \pm 0.6) \times 10^{-4}$ (for the B_d system)

$a_{\rm sl}^s = (2.22 \pm 0.27) \times 10^{-5}$ (for the B_s system)

Artuso, Borissov, Lenz [arXiv:1511.09466]

CP Violation

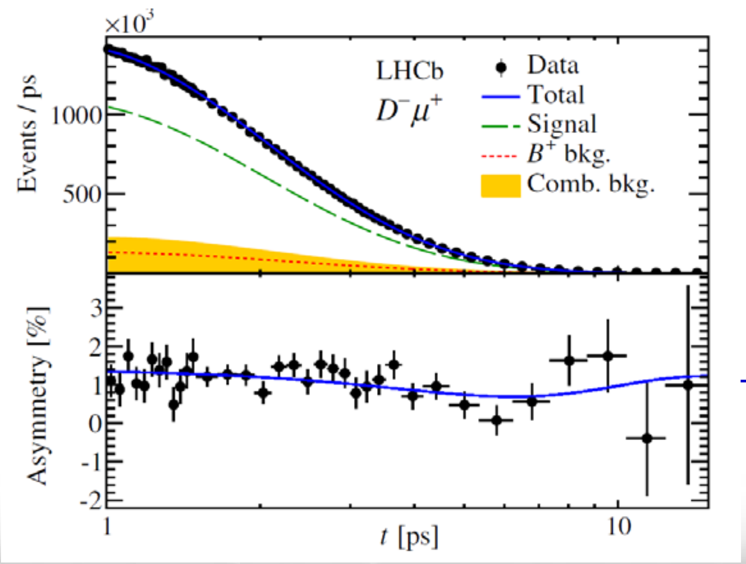
[PRL 114 (2015) 041601]

The untagged CP assymetry is convenient at LHCb to have large statistics:

$$A(t) = \frac{N(f,t) - N(\bar{f},t)}{N(f,t) - N(\bar{f},t)} = A_{\mathrm{D}} + \frac{a_{\mathrm{sl}}}{2} - \left(\frac{a_{\mathrm{sl}}}{2} + A_{\mathrm{P}}\right)\cos(\Delta m\, t)$$

$A_D \equiv$ Detection asymmetry: measured using calibration samples (K,μ,π)

$A_P \equiv$ Production asymmetry: - almost not contributing for the B_s system (large Δm_s)
- measured simultaneously with a_{sl} for B_d (time-dependent)



→ detection and production asymmetries

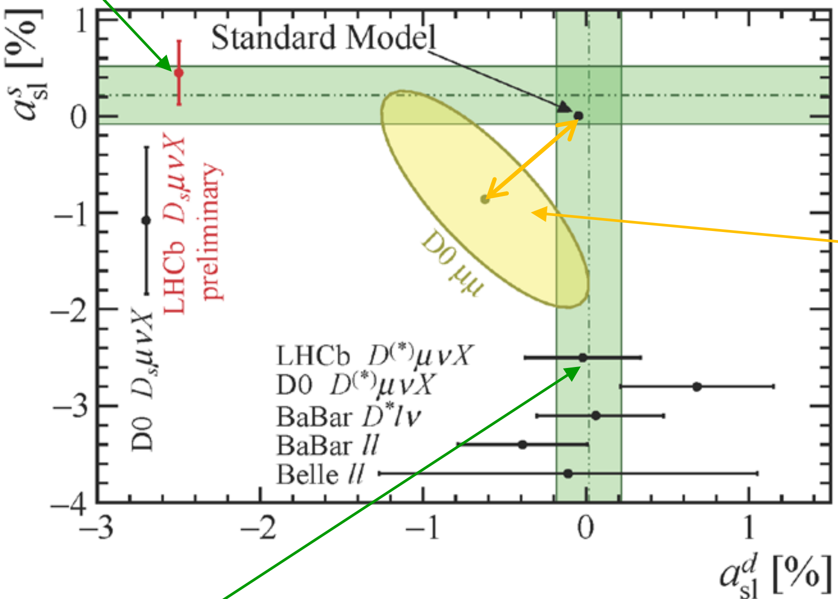
CP Violation

Results: $B_s^0 \to D_s^- X \mu^+ \nu$

$$a_{sl}^s = (0.45 \pm 0.26\,(\text{stat}) \pm 0.20\,(\text{syst}))\%$$

[LHCb-PAPER-2016-013]

(3fb^{-1}) (Preliminary)



D0 CPV ≠ 0 (3.6σ) [PRD89(14) 012002]

$B^0 \to D^{(*)-}\mu^+\nu_\mu X$

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

[PRL 114 (2015) 041601]

(3fb^{-1})

Lepton universality

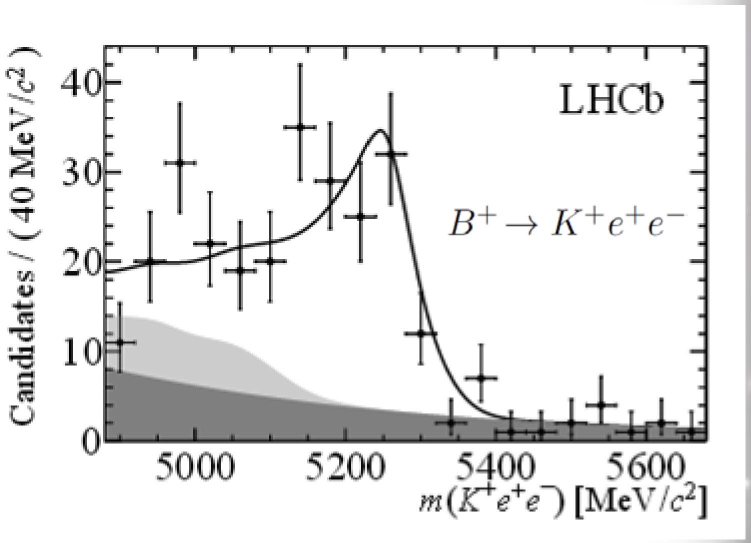
[PRL 113 (2014) 151601]

In the SM all leptons are expected to behave in the same way.
For instance,

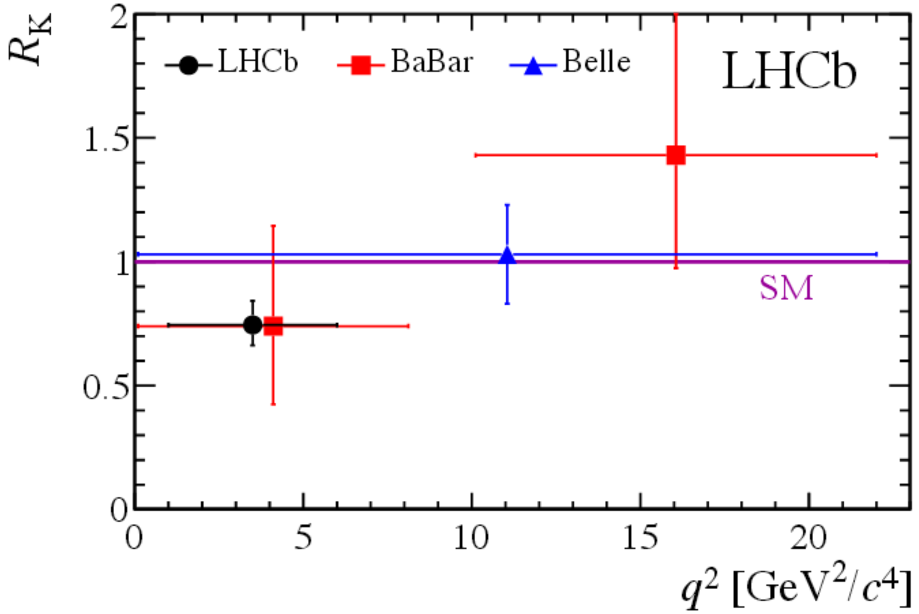
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

$= 1.000 + O(m_\mu^2/m_b^2)$ (SM)

- Precise theory prediction due to cancellation of hadronic form factor uncertainties
- Models with new Z' bosons can make $R_K<1$
- Experimentally, use the $B\to K\, J/\psi(\to ee)$ and $B\to K\, J/\psi(\to \mu\mu)$ to perform a double ratio



Lepton universality



For $1 < q^2 < 6$ GeV^2

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

[PRL 113 (2014) 151601]

$\rightarrow$ Consistent (but lower) than the SM at **2.6σ**

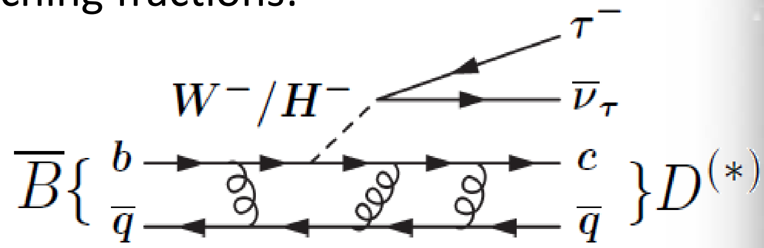
Boost the measurement of other obsevables: R_{K*}, $R_{\Lambda*}$, R_{ϕ} ...

Lepton universality

- Another test of lepton universality:

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

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

$R(D)_{SM}=0.300 \pm 0.008$

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

Based on HQET form factors:
[H. Na et al., PRD 92, 054410 (2015)]
[Fajfer, Kamenic, Nišandižć: PRD85, 094025 (2012)]
and experimental measurements (HFAG)

BaBar measured an excess of $B \to D^{(*)}\tau\nu$ (3σ away from SM) [PRD 88 (2013) 072012]

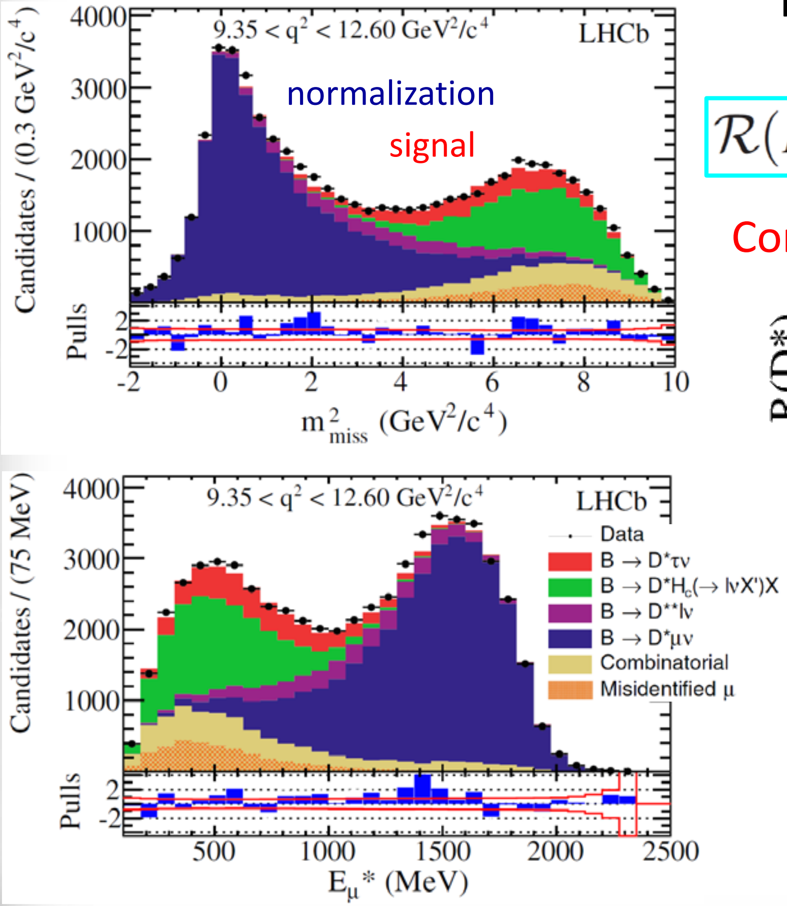
LHCb started with $B \to D^*\tau\nu$, cleaner mode

$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ to reduce experimental uncertainties

Lepton universality

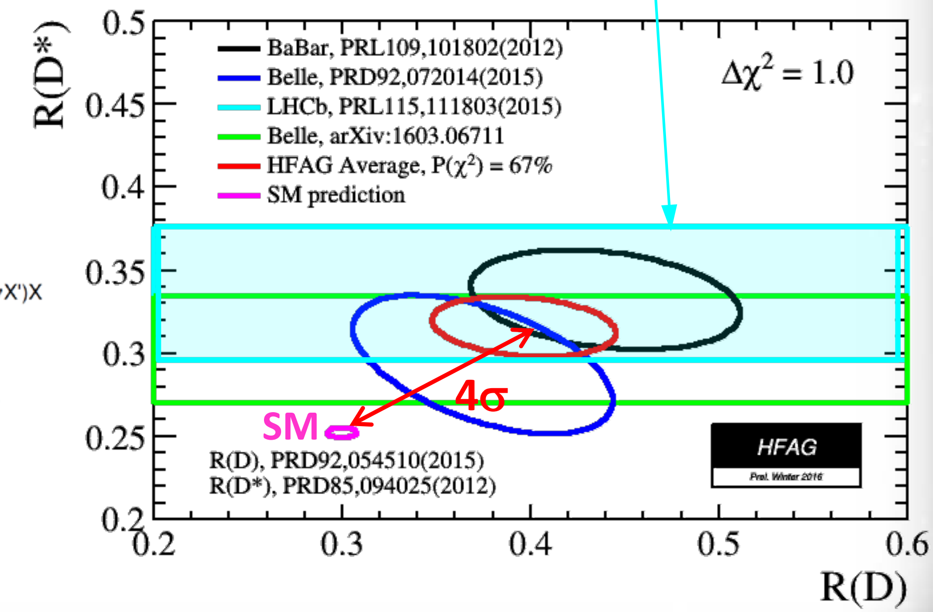
[PRL 115 (2015) 111803]

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



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

Contributes to increase the SM deviation



Lorentz invariance and CPT

- Lorentz invariance and CPT are exact symmetries in the SM
- May be broken in Quantum Theories aiming to describe Planck-scale physics
- CPT symmetry implies equal mass and width for the B^0 and $\overline{B}^0$ mesons

any difference can be characterized by the CPT observable

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

with Δm and $\Delta\Gamma$ being the mass and width different between the mass states

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

and δm and $\delta\Gamma$ the mass and width difference of flavor B and $\overline{\text{B}}$ states

If δm or $\delta\Gamma \neq 0$ (i.e. z $\neq$ 0) $\rightarrow$ CPT violation

Since Δm and $\Delta\Gamma$ are very small, z is very sensitive to CPT-violating effects

Lorentz invariance and CPT

- CPT violation implies Lorentz invariance breaking
- In a low-energy effective field theory, like the Standard Model Extension (SME), the z parameter is expressed in terms or the four-velocity of the B meson (β^{μ})

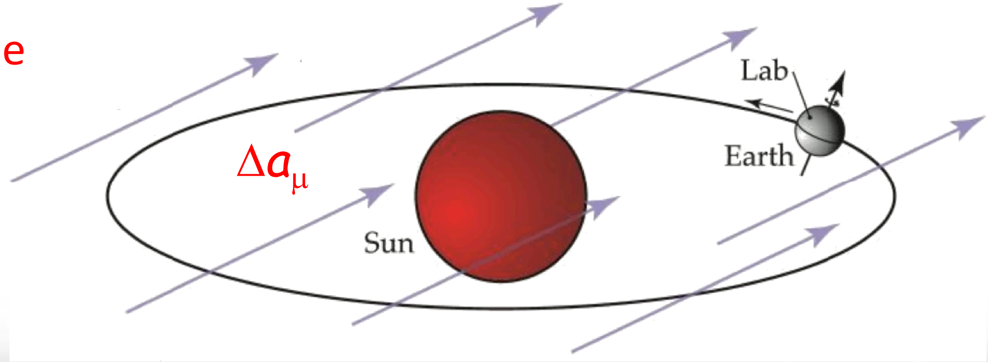
[PRD 55 (1997) 6760, PRD 58 (1998) 116002]

$$z = \frac{\beta^{\mu}\Delta a_{\mu}}{\Delta m + i\Delta\Gamma/2}$$

with Δa_{μ} (SME parameter) the vacuum expectation value (real) describing the coupling with the B mesons.

$\rightarrow$ z is almost real and depends on momentum and direction in space of the B meson in absolute coordinate system [PRD61(2000)016002]

Sun-centred frame



Lorentz invariance and CPT

- Re(z) can be measured using $B^0 \to J/\psi K^0_S$ and $B^0_s \to J/\psi K^+K^-$

[LHCb-PAPER-2016-005]

$$\mathcal{R}e(z) \approx \frac{\gamma}{\Delta m}\Big[\Delta a_0 + \cos(\chi)\Delta a_Z + \sin(\chi)\big[\Delta a_Y \sin(\Omega\hat{t}) + \Delta a_X \cos(\Omega\hat{t})\big]\Big]$$

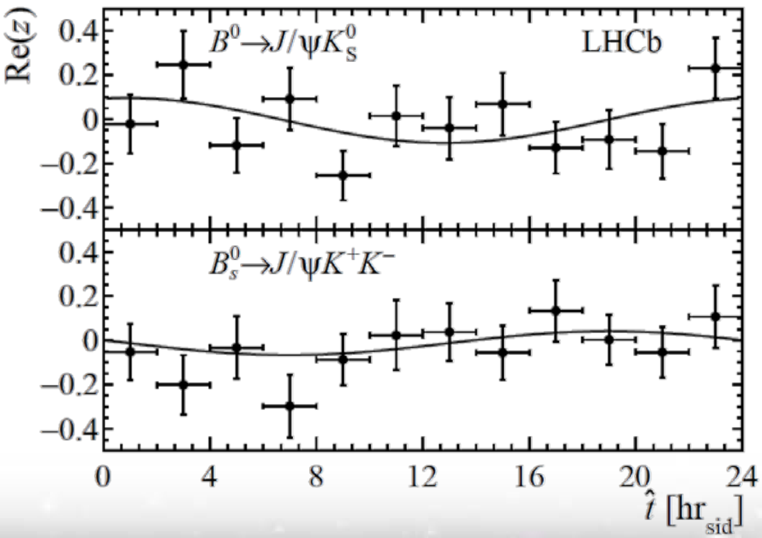
Angle of B meson with Earth rotational axis. B mesons mostly along beam cos (χ) ~ -0.34

Small Δm

Large boost at LHCb <$\beta\gamma$> ~ 20

Sidereal frequency

Re(z) as function of sidereal phase $\hat{t}$ →



No sidereal variation is observed

Lorentz invariance and CPT

- Δa_{μ} values obtained for the B and B_s systems, more precise than results from BaBar (O(10^3)) and D0 (O(10)) experiments

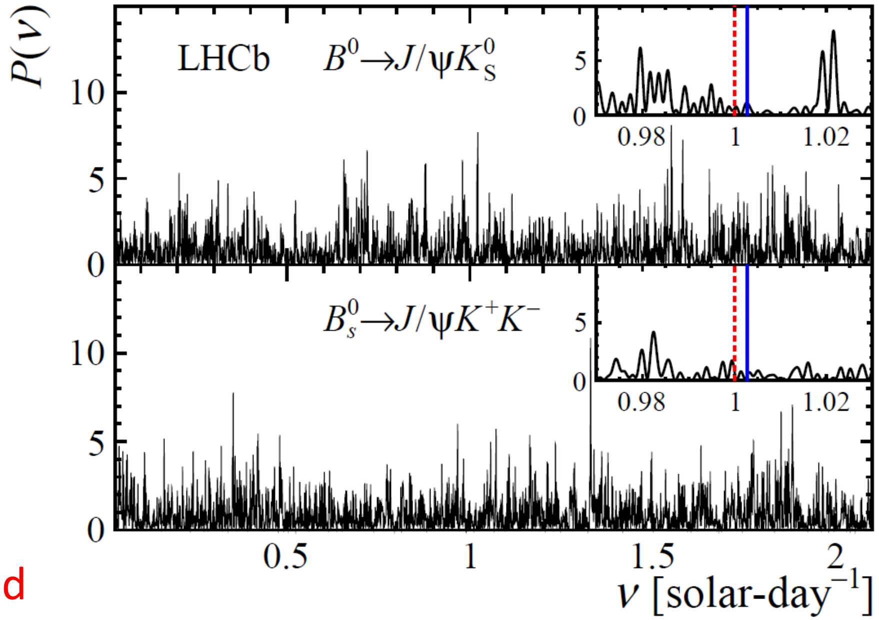
B^0 system
$\Delta a_{\parallel} = (-0.10 \pm 0.82 \pm 0.54) \times 10^{-15}$ GeV
$\Delta a_{\perp} = (-0.20 \pm 0.22 \pm 0.04) \times 10^{-13}$ GeV
$\Delta a_{X} = (+1.97 \pm 1.30 \pm 0.29) \times 10^{-15}$ GeV
$\Delta a_{Y} = (+0.44 \pm 1.26 \pm 0.29) \times 10^{-15}$ GeV

B_s^0 system
$\Delta a_{\parallel} = (-0.89 \pm 1.41 \pm 0.36) \times 10^{-14}$ GeV
$\Delta a_{\perp} = (-0.47 \pm 0.39 \pm 0.08) \times 10^{-12}$ GeV
$\Delta a_{X} = (+1.01 \pm 2.08 \pm 0.71) \times 10^{-14}$ GeV
$\Delta a_{Y} = (-3.83 \pm 2.09 \pm 0.71) \times 10^{-14}$ GeV
$\mathcal{R}e(z) = -0.022 \pm 0.033 \pm 0.003$
$\mathcal{I}m(z) = 0.004 \pm 0.011 \pm 0.002$

- First direct measurement of the z parameter in the B_s system, no Lorentz invariance-assumption

Lorentz invariance and CPT

- A wide range of frequencies scanned around the sidereal frequency (0.03 – 2.10 $day_{\odot}^{-1}$)



No significant peaks found

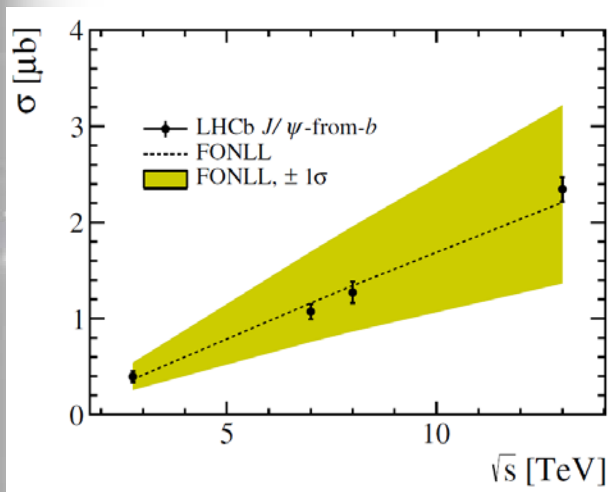
Results consistent with CPT symmetry and Lorentz invariance

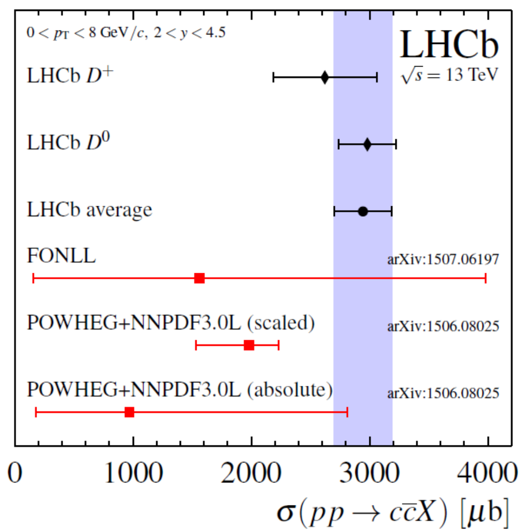
Prospects

- Already results with 13 TeV (2015) data on production cross sections

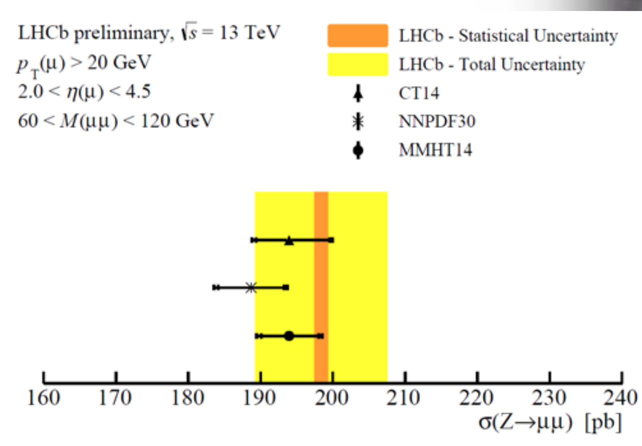
Prompt charm production

J/ ψ production





Z→μμ production



[JHEP 10 (2015) 172] [JHEP 03 (2016) 159] [LHCb-CONF-2016-002]

- Largely benefits from a larger $b\bar{b}$ cross section (Run1 x2) and an improved trigger: Larger farm, online full event reconstruction, real time calibration and alignment

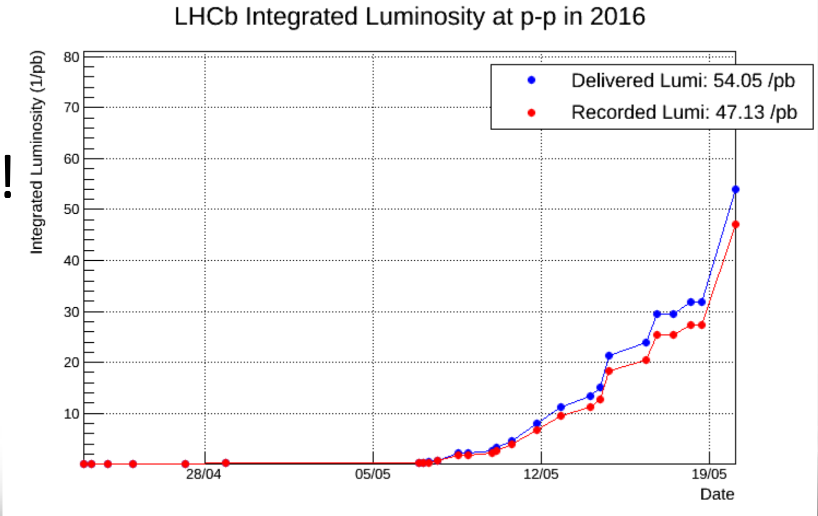
Summary

- Excellent performances of LHCb, plenty of results with Run1 (more than 300 publications), including very challenging channels (with ν's in the final state).

- Deviations from SM in some channels and obsevables, focus on them with Run2 data

- 2016 Run2 already ongoing, with larger $b\bar{b}$ cross section ($\times$2) and improved trigger.

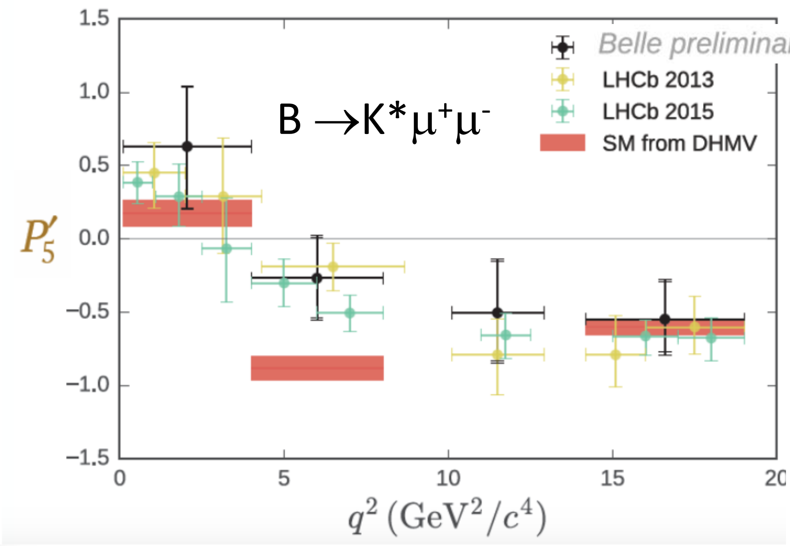
Many things to learn this year!

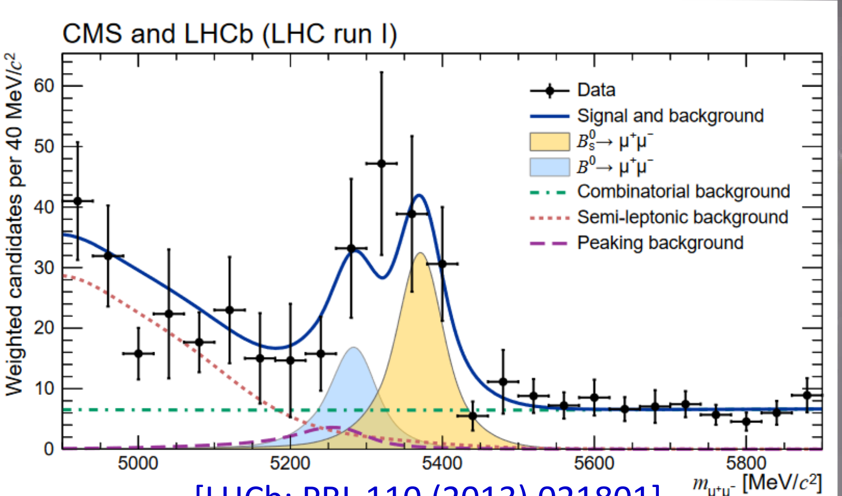


Thank you!

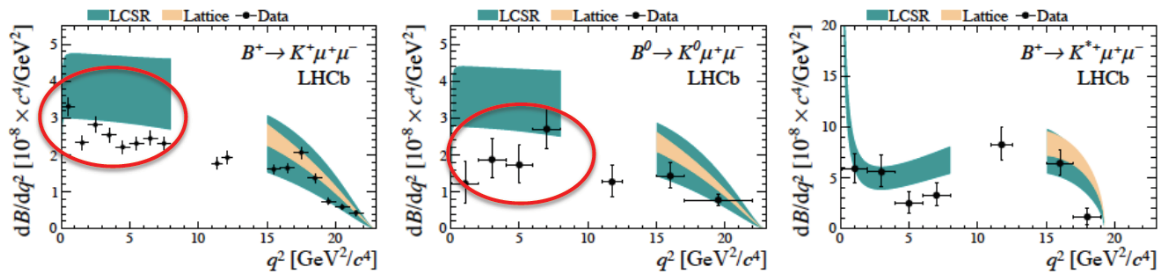
Backup

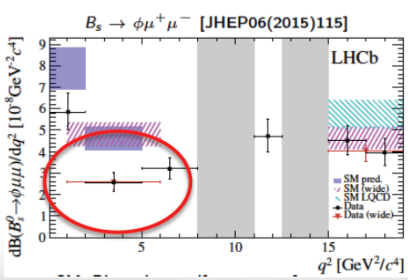
[LHCb: JHEP02(2016)104]

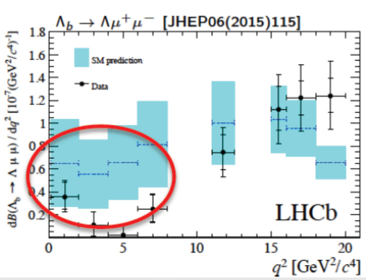




[LHCb: PRL 110 (2013) 021801],
[Nature 522 (2015),68]







Backup

[LHCb-PUB-2014-040]

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	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**	–