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LHCb Results on Flavour Physics

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On behalf of the LHCb Collaboration

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Outline

- Introduction to Flavour and LHCb
- 2016 selected highlights on mixing, CPV and FCNC
  - Mixing and CPV with B semileptonic decays
  - CKM angle gamma
  - CPV in baryonic decays
  - CPV search with charm mesons
  - Anomalies in $B^0 \to K^{*0} \mu\mu$
- Other recent anomalies and tensions
  - Lepton Flavour Universality
  - $B_{s,d} \to \mu\mu$
- Future LHCb prospects

Focus of this talk: new physics searches at LHCb with beauty and charm hadrons

Other important LHCb physics results (spectroscopy, heavy ions) will be covered in the talk by Giovanni Passaleva

Flavour in Valtellina

If you Google for Flavour …

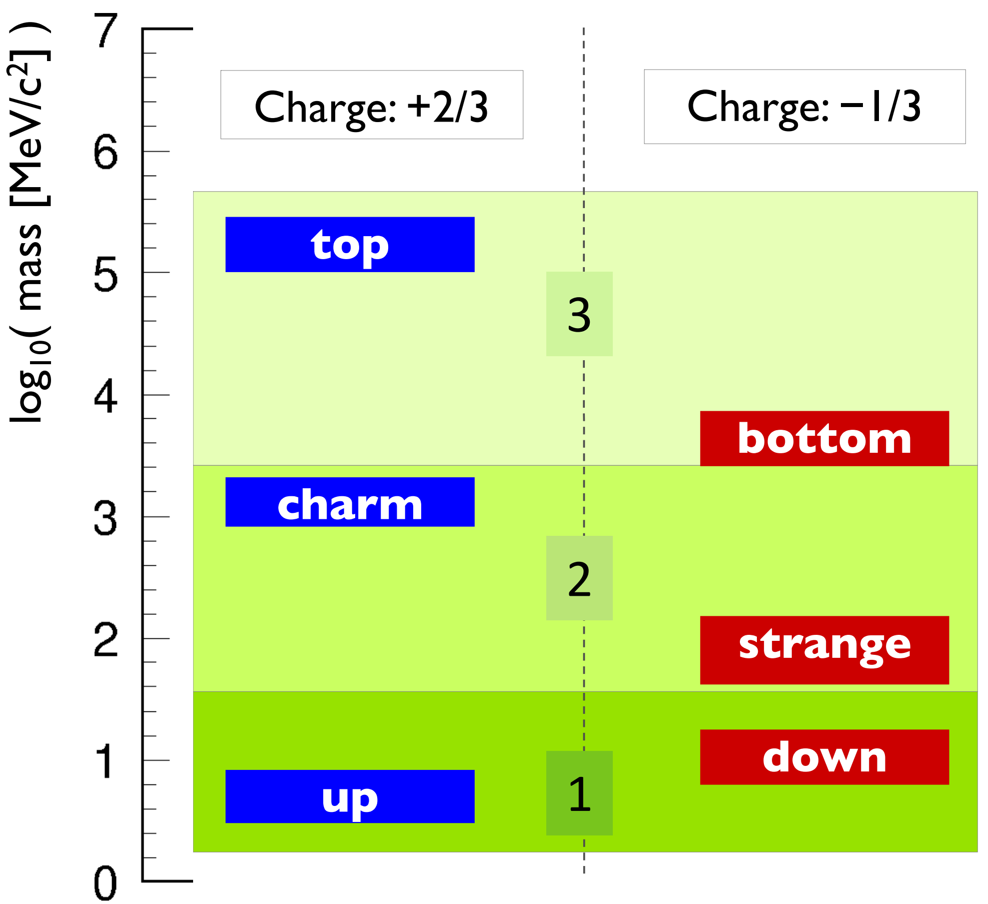
Different flavours…of slopes

Great excitement with just *u* and *d* quarks!

3 generations: hic est flavour physics!

"Flavour" == several copies of the same gauge representation

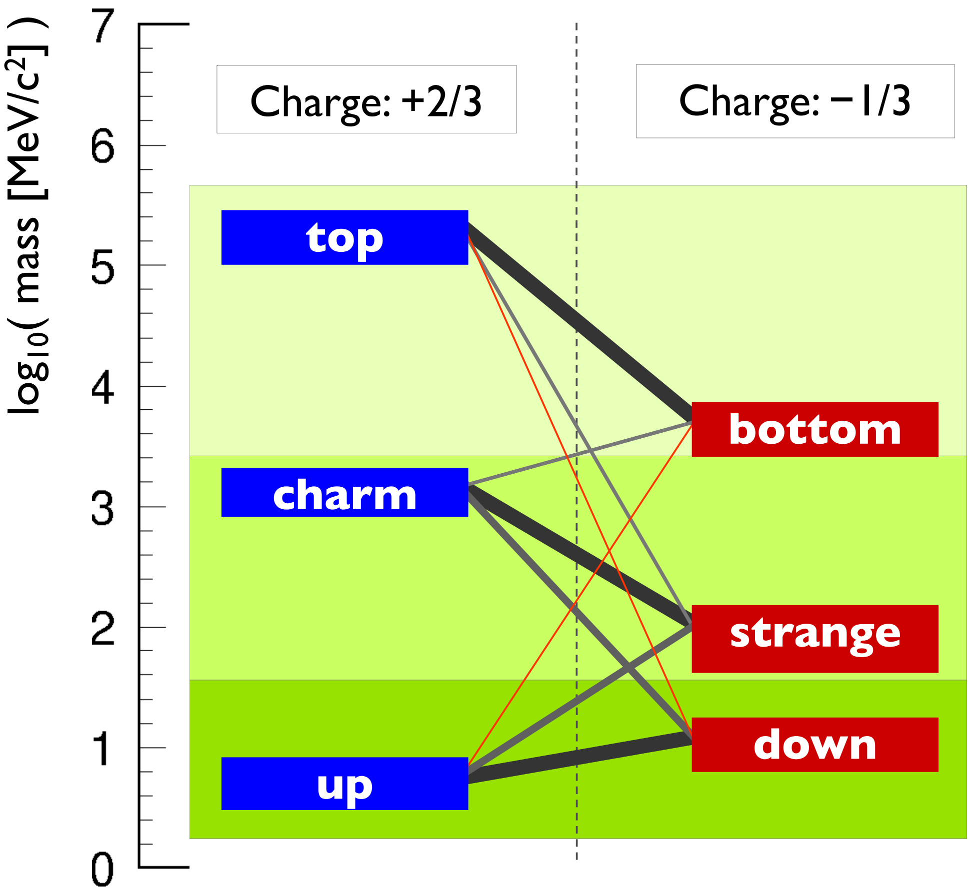
3 up-type and 3-down type quarks with same quantum charges but **different masses**

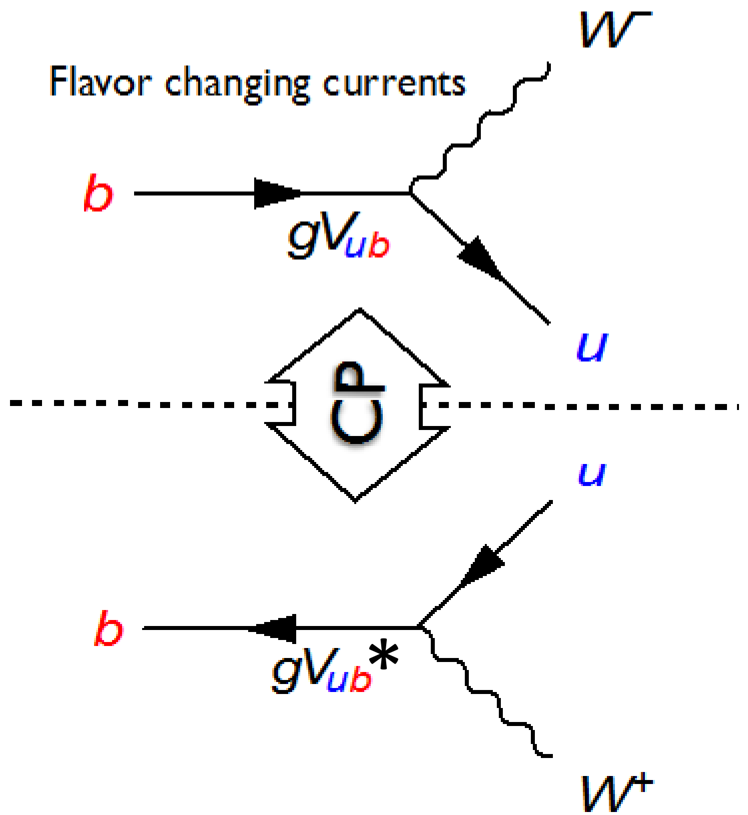


3 generations: hic est flavour physics!

"Flavour" == several copies of the same gauge representation

3 up-type and 3-down type quarks with same quantum charges but **different masses** and **different couplings** to W boson



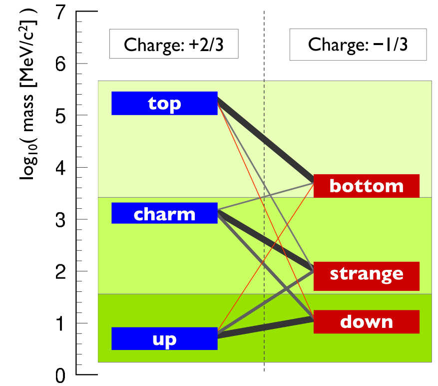


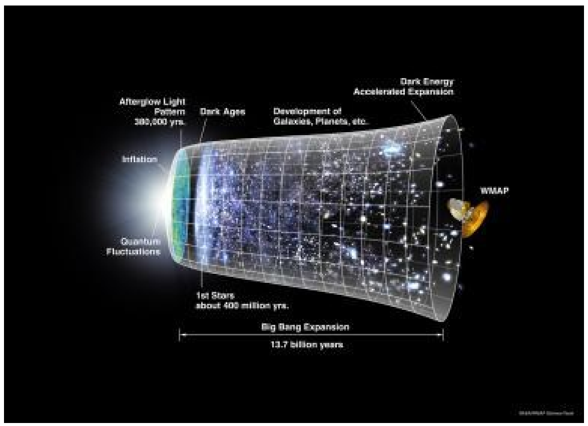
Complex couplings ⇒CP violation

Why is flavour physics interesting?

- Standard Model flavour puzzle: why 3 generations, what is the origin of the hierarchy observed in the fermion masses and quark mixing parameters

  (and why so different from lepton mixing anarchy?)



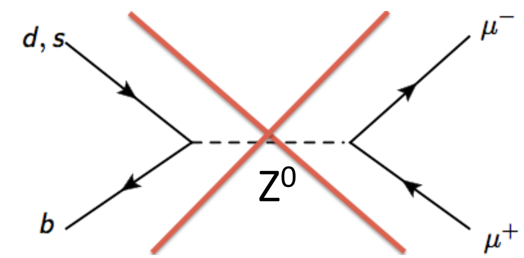


- Cosmology

  Amount of CPV in Standard Model not sufficient to explain the observed matter-antimatter asymmetry in the Universe. New sources of CPV required by baryogenesis.

- Discovery potential far beyond the energy frontier via studies of forbidden or SM suppressed processes, such as FCNC

FCNC
Flavour Changing Neutral Current
forbidden at tree-level in SM

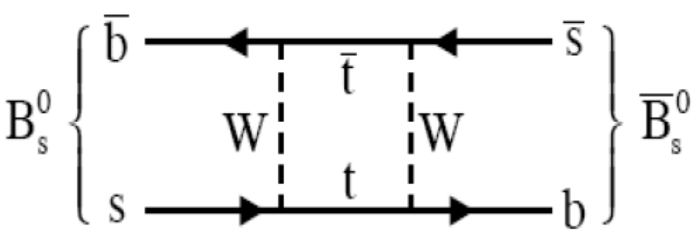


Indirect searches for New Physics

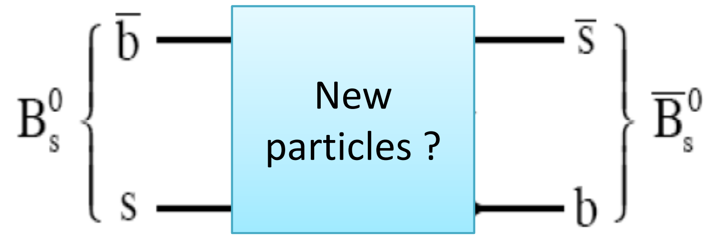
FCNC occur only at loop level: box or penguin diagrams. Sensitive to BSM contributions from new particles that can mediate the loops. Two examples:

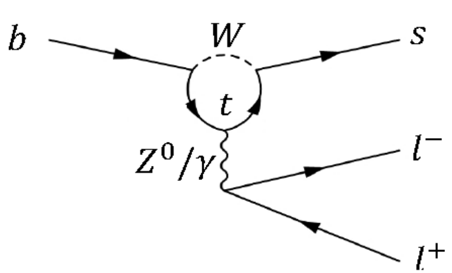
SM

BSM

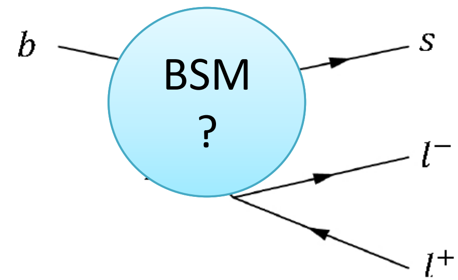


Flavour mixing





Rare decay



New particles can be virtually produced $\Rightarrow$ sensitivity limited by precision, not by collision energy. Sensitivity to new particles up to ~100 TeV can be reached at LHCb

[A. Buras et al. JHEP1411(2014)121]

Why beauty and charm?

PRODUCTION

Large beauty and charm cross-sections in pp collisions at LHC 7-13 TeV center of mass energy

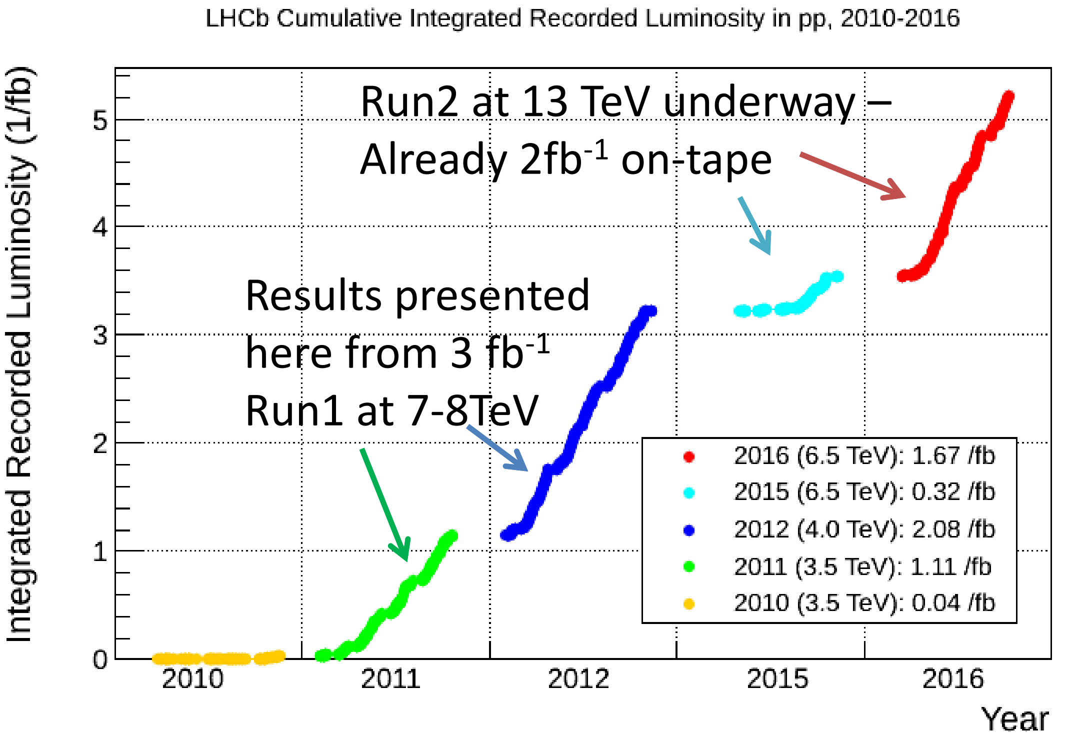
In LHCb acceptance:

$\sigma(c\bar{c})$ = 1500-3000 μb

$\Rightarrow$ O(10^{12}) $c\bar{c}$ pairs/fb^{-1}

$\sigma(b\bar{b})$ = 250-500 μb

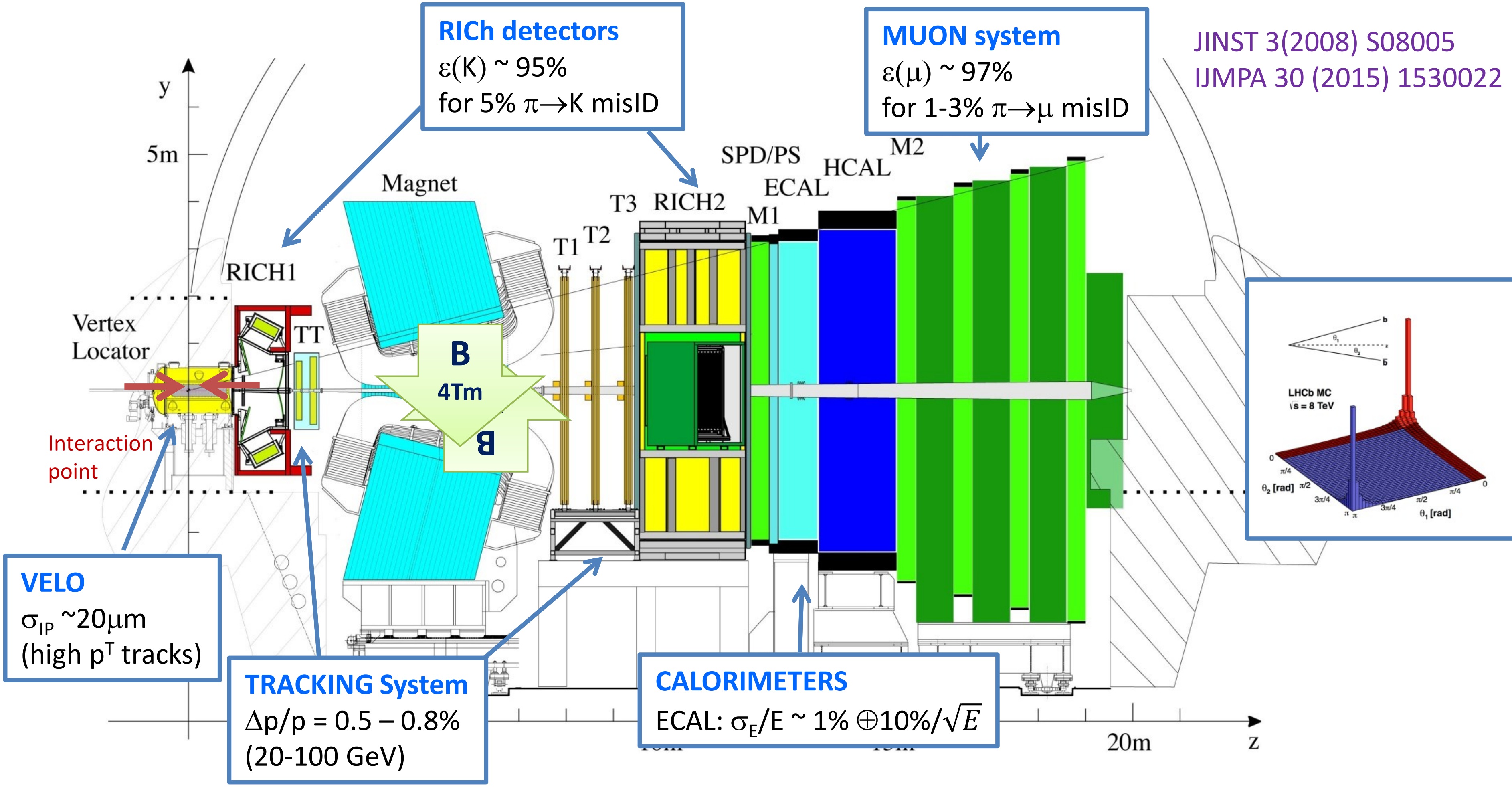
$\Rightarrow$ O(10^{11}) $b\bar{b}$ pairs/fb^{-1}



DECAY

- b and c are the heaviest quarks that form bound hadrons
- Many decay channels
- Long lifetime O(10^{-12} s) enables precise measurement of production and decay vertex

LHCb detector



JINST 3(2008) S08005
IJMPA 30 (2015) 1530022

Single arm forward spectrometer, large acceptance for $b\bar{b}$ in forward region $2<\eta<5$

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B-MIXING

B_s mixing

B flavour eigenstates do not coincide with mass eigenstates, i.e.,

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

$\Rightarrow$ B-mixing or B-flavour oscillation = periodical transformation of a B (B^0 or B_s) into its own antiparticle as a function of time. Oscillation frequency $\Delta m = m_H - m_L$

- B_s fast oscillation requires: excellent decay time reconstruction
- Clean samples of self-tagged decays

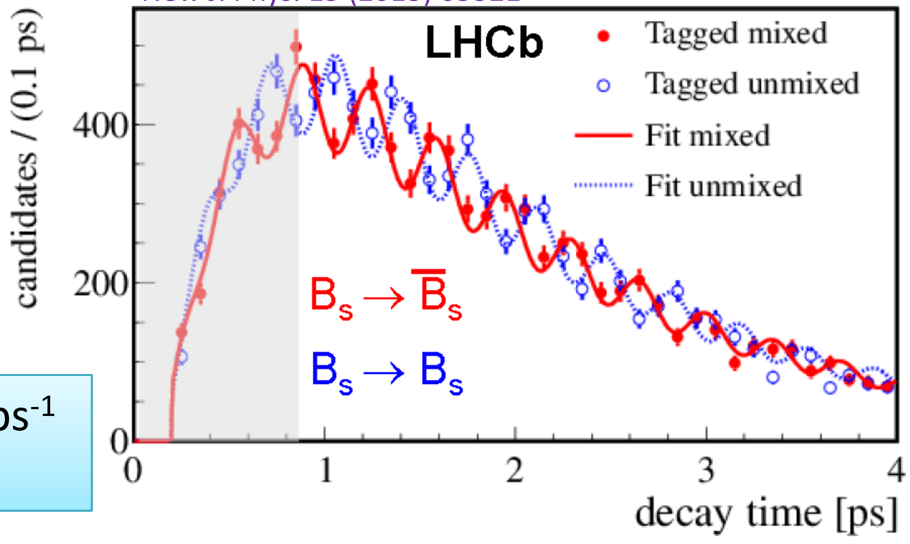
$B_s \rightarrow D_s^- \pi^+$ and $\overline{B}_s \rightarrow D_s^+ \pi^-$

- Flavour-Tag production

Mixed if different flavour at decay and production

Unmixed if equal flavour at decay and production

New J. Phys. 15 (2013) 05321



LHCb(1 fb^{-1}) : $\Delta m_s = 17.768 \pm 0.023 \pm 0.006$ ps^{-1}
most precise measurement to date

SM: $\Delta m_s = 17.3 \pm 1.5$ ps^{-1}

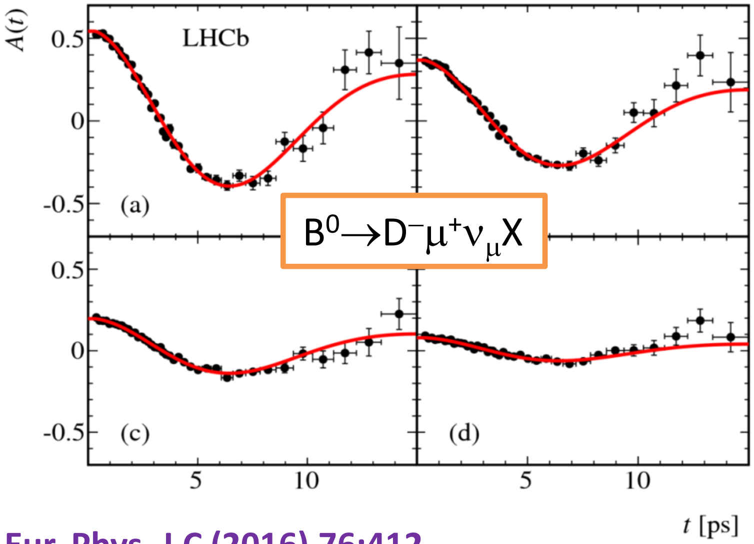
B^0 mixing

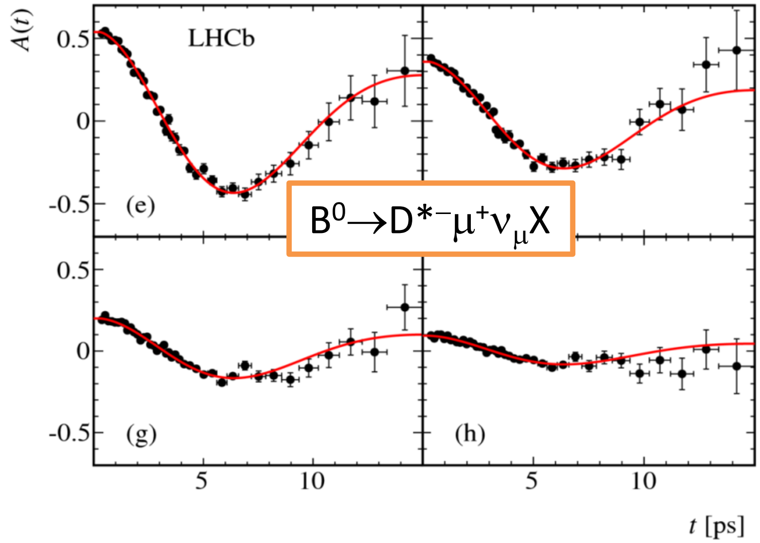
3fb^{-1} update in 2016

Δm_d measured with full Run-1 data sample (3 fb^{-1}) and semileptonic B^0 decays
Mixing frequency directly related to mixing asymmetry

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

Mixing asymmetry projections in 4 tagging categories with different mistag rates:





Eur. Phys. J.C (2016) 76:412

$\Delta m_d = 505.0 \pm 2.1 \pm 1.0$ ns^{-1}
Most precise single measurement - compatible and similar precision to world average

CPV in B mixing

3fb^{-1} update in 2016

CPV in B mixing if $P(B_q \to \overline{B_q}) \neq P(\overline{B_q} \to B_q)$, q=s,d

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

Predicted to be very small in SM

$a_{sl}^s = 2.22 \pm 0.27 \times 10^{-5}$

$a_{sl}^d = -4.7 \pm 0.6 \times 10^{-4}$

D0 measurement of like-sign dimuon

3.2σ from SM PRL105(2010)081801

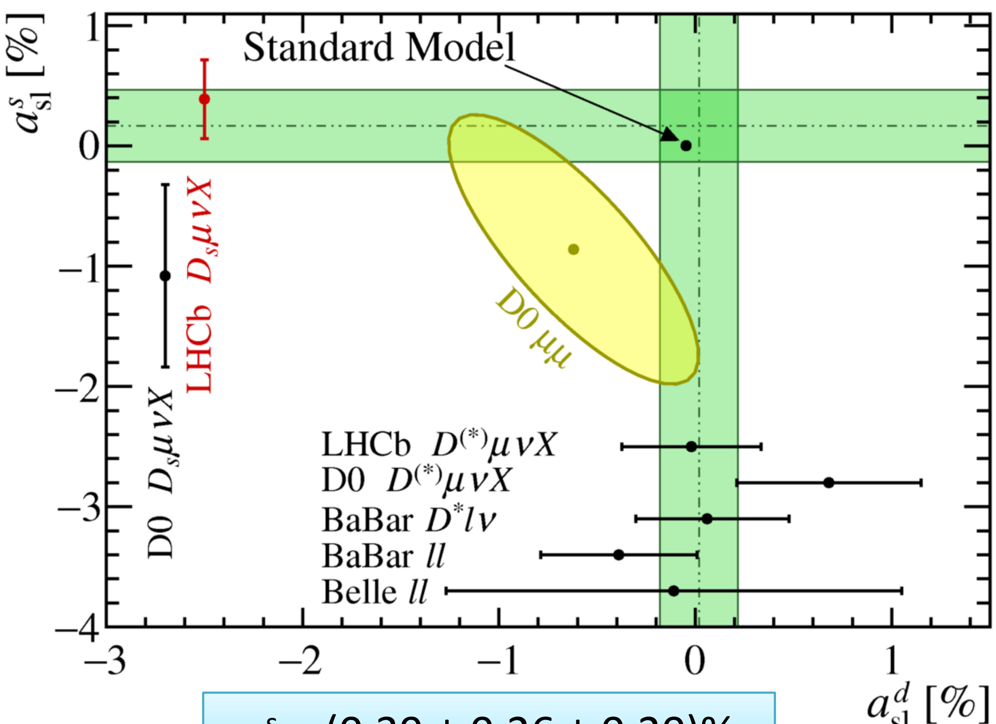
sensitive to both a_{sl}^d and a_{sl}^s

LHCb measures a_{sl}^s using untagged semileptonic decays: $B_s \to D_s^- \mu^+ \nu X$

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

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

PRL 117 (2016) 061803



$a_{sl}^s = (0.39 \pm 0.26 \pm 0.20)\%$

Most precise measurement to date

And in good agreement with SM

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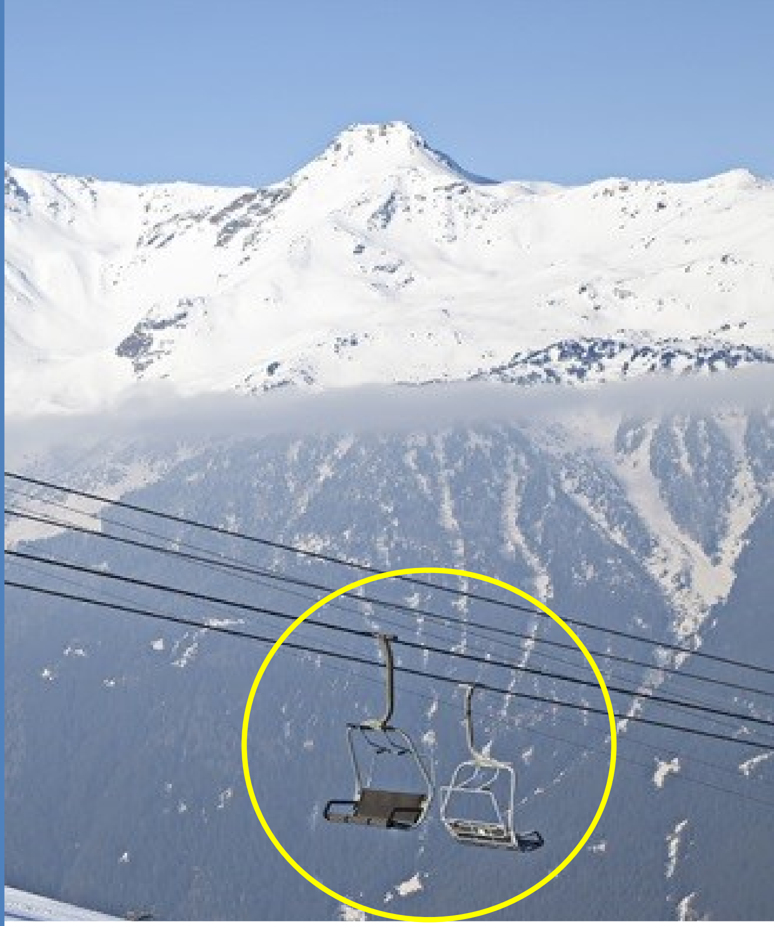
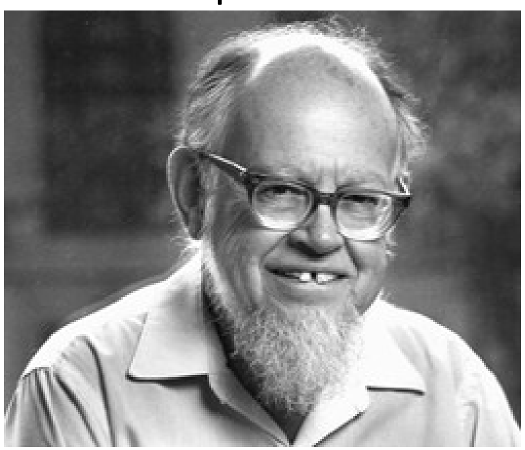


MORE ON CPV

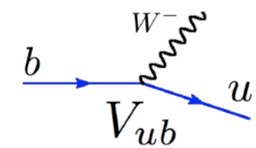
CKM Unitarity Triangle- Reminder

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

Wolfenstein parameterisation

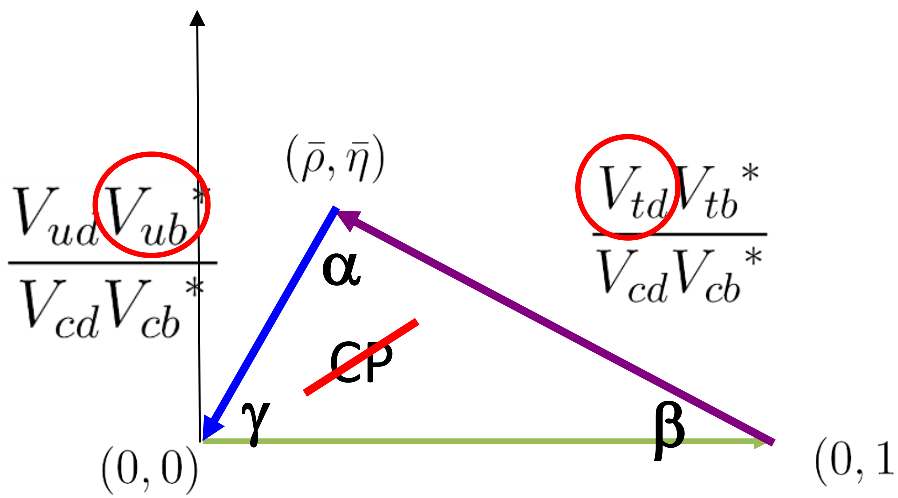


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & \boxed{V_{ub}} \\ V_{cd} & V_{cs} & V_{cb} \\ \boxed{V_{td}} & V_{ts} & V_{tb} \end{pmatrix}$$



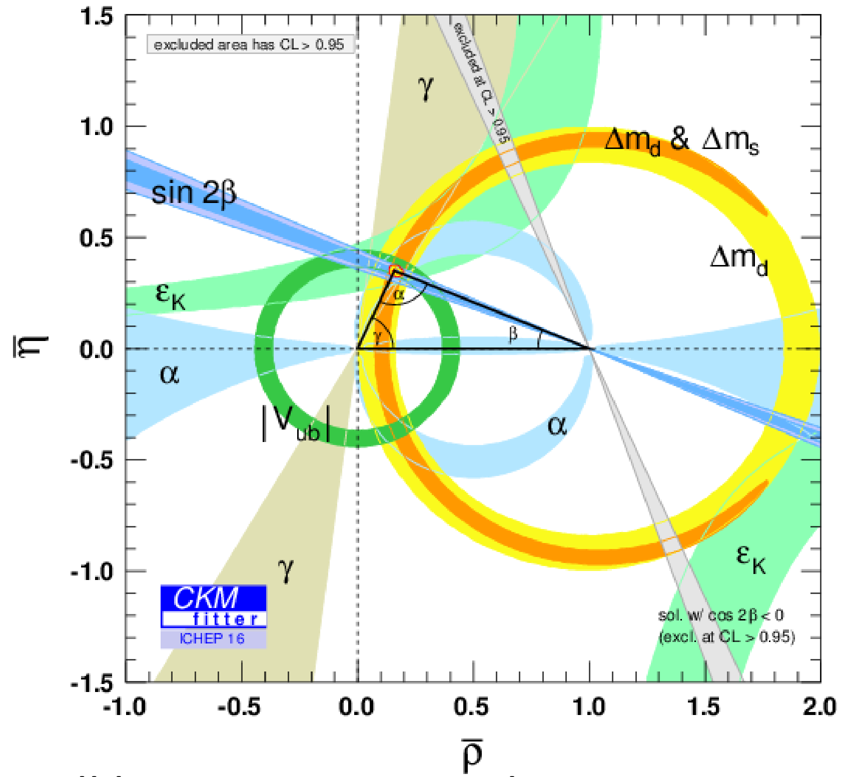
$$\Downarrow \quad \boxed{VV^\dagger = 1} \quad \Downarrow$$

$$\boxed{V_{ud}V_{ub}{}^* + V_{cd}V_{cb}{}^* + V_{td}V_{tb}{}^* = 0}$$



CKM angle γ

$$\gamma = arg\left(-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)$$



Still large experimental uncertainty on γ from direct measurements

CKMFITTER $\gamma = 72.1\,^{+5.4}_{-5.8}\,°$

UTFIT $\gamma = 70.5 \pm 5.7°$

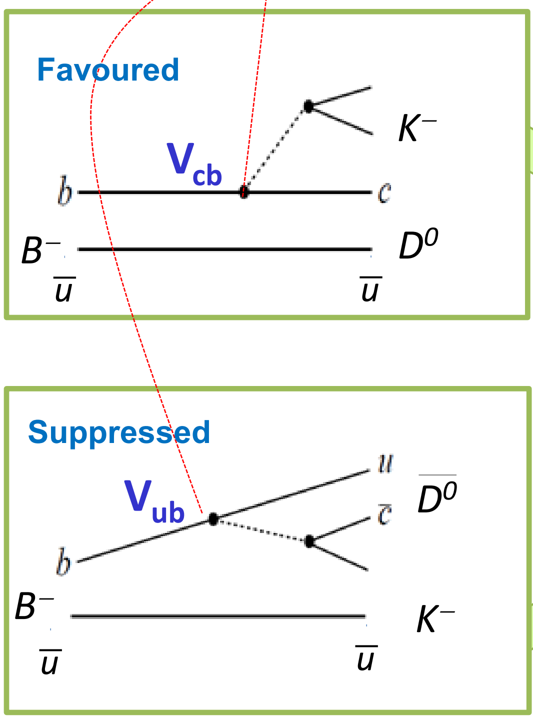
Above averages dominated by LHCb results

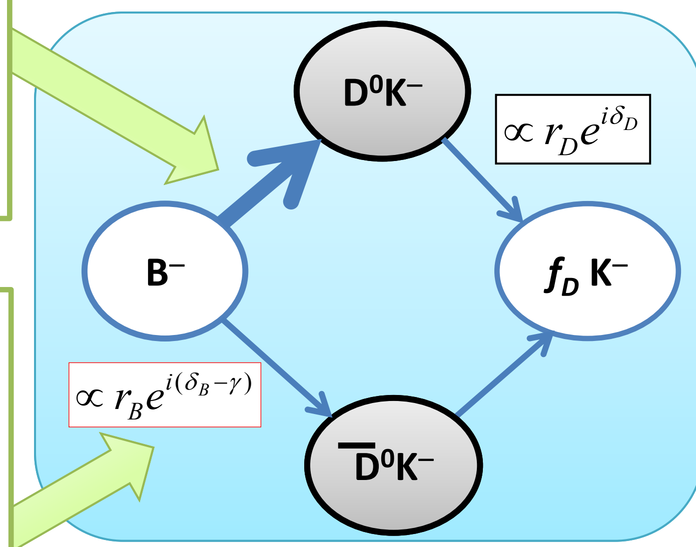
An increasingly precise picture..but still room for New Physics at O(20%) level

Precision CKM metrology required

- γ can be measured from tree level decays only $\Rightarrow$SM benchmark
  - negligible BSM contributions
  - negligible theoretical uncertainties
- Several experimental challenges
  - V_{ub} mediated transitions $\Rightarrow$ Small BF involved
  - Fully hadronic decays

CKM angle γ from $B^\pm \to DK^\pm$





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

$$r_D e^{i\delta_D} \equiv \frac{A(D^0 \to f_D)}{A(\overline{D}^0 \to f_D)}$$

All unknowns from data

$\Rightarrow$ No hadronic uncertainties

Methods and D final states

GLW : $f_D = KK, \pi\pi$ [Gronau-London-Wyler] PLB 253,483(1991), PLB 265,172 1991)

ADS : $f_D = K\pi, K\pi\pi\pi$ [Atwood-Dunietz-Soni] PRL 78,257(1997), PRD 63,036005(2001)

GGSZ : $f_D = K_S\pi\pi, K_SKK$ [Giri-Grossman-Soffer-Zupan] PRD 68,054018(2003)

GLS : $f_D = K_SK\pi$ [Grossman-Ligeti-Soffer] PRD 67,071301(2003)

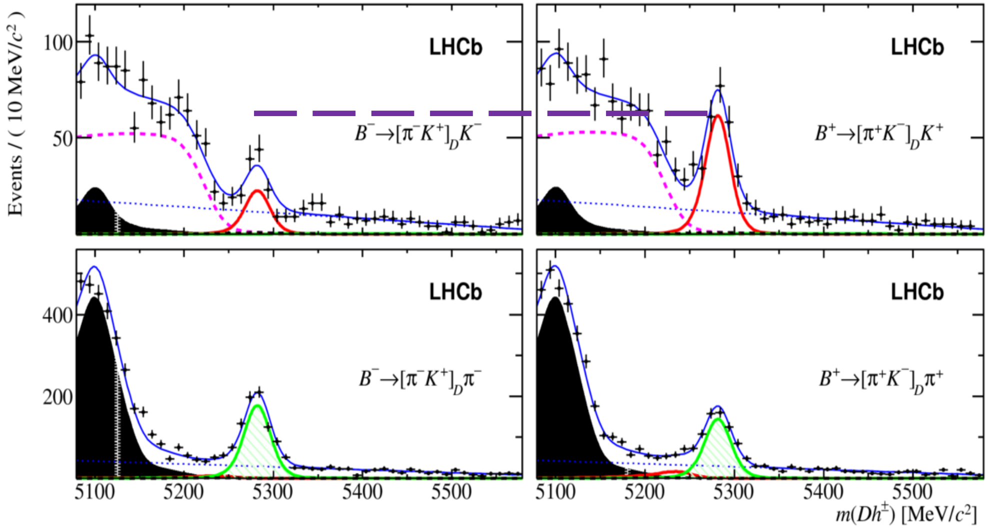
Same methods apply to $B^- \to D\pi^-$, but interference smaller

CKM angle γ from $B^\pm \to DK^\pm$

3fb^{-1} update in 2016

PLB 760 (2016) 117

Analysis includes: D to KK, $\pi\pi$, Kπ, K3π, 4π



D$\to$Kπ ADS suppressed-mode
Small yields but large asymmetry

$B^\pm\to[\pi^\pm K^\mp]\,K^\pm$ 553 ± 34 events
$B^\pm\to[\pi^\pm K^\mp]\,\pi^\pm$ 1360 ± 44 events

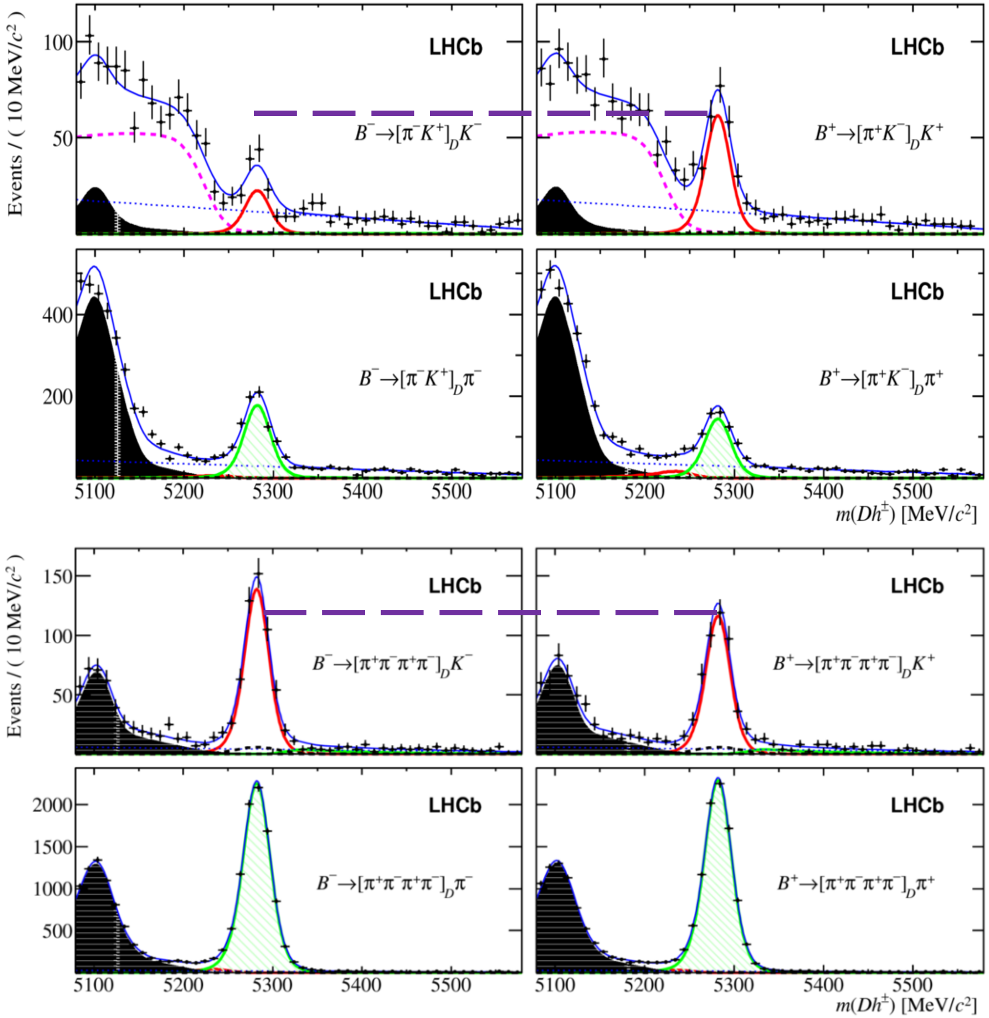
CPV at 8σ in B$\to$ DK

CKM angle γ from $B^{\pm} \to DK^{\pm}$

$3fb^{-1}$ update in 2016

PLB 760 (2016) 117

Analysis includes: D to KK, $\pi\pi$, $K\pi$, $K3\pi$, 4π



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$B^{\pm} \to [\pi^{\pm}K^{\mp}]\ \pi^{\pm}$ 1360 ± 44 events

CPV at 8σ in B→ DK

First measurement of CP parameters from D →4π. Large yields

$B^{\pm} \to [\pi^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}]\ K^{\pm}$ 1497 ± 60 events
$B^{\pm} \to [\pi^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}]\ \pi^{\pm}$ 19300 ± 150 events

CP fraction $F_+ = 0.737 +/- 0.028$
(External input from CLEO)
CPV at 2.7σ in B→ DK
Opposite sign to ADS as expected
From predominantly CP-even GLW

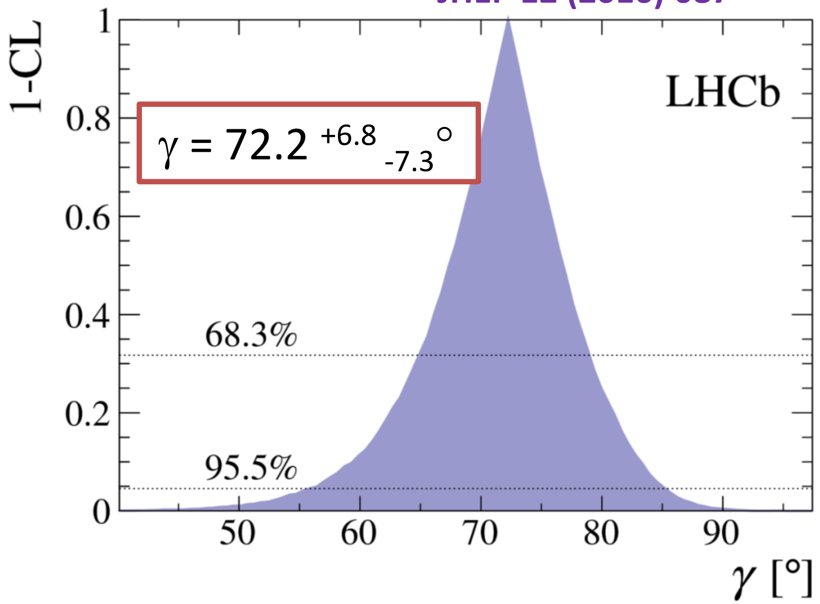
γ: combination of B→DK results

New update in 2016

Frequentist method combining 71 observables depending on 32 parameters
Compatible results obtained also with alternative Bayesian approach

B decay	D decay	Method
$B^+ \to Dh^+$	$D \to h^+h^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS
$B^+ \to Dh^+$	$D \to h^+h^-\pi^0$	GLW/ADS
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ
$B^+ \to DK^+$	$D \to K^0_S K^-\pi^+$	GLS
$B^+ \to Dh^+\pi^-\pi^+$	$D \to h^+h^-$	GLW/ADS
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD

JHEP 12 (2016) 087



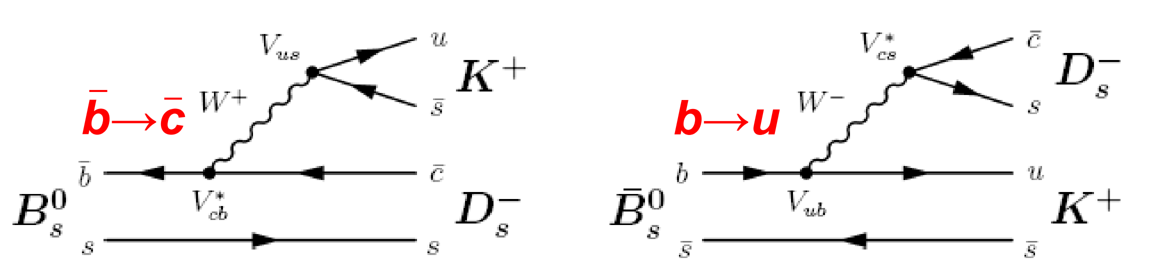
Most precise determination of γ from a single experiment

As all input measurements are statistically limited, uncertainty should reach ~4° with Run2

γ from $B_s \to D_sK$ update, not yet in γ combination

3fb^{-1} update in 2016

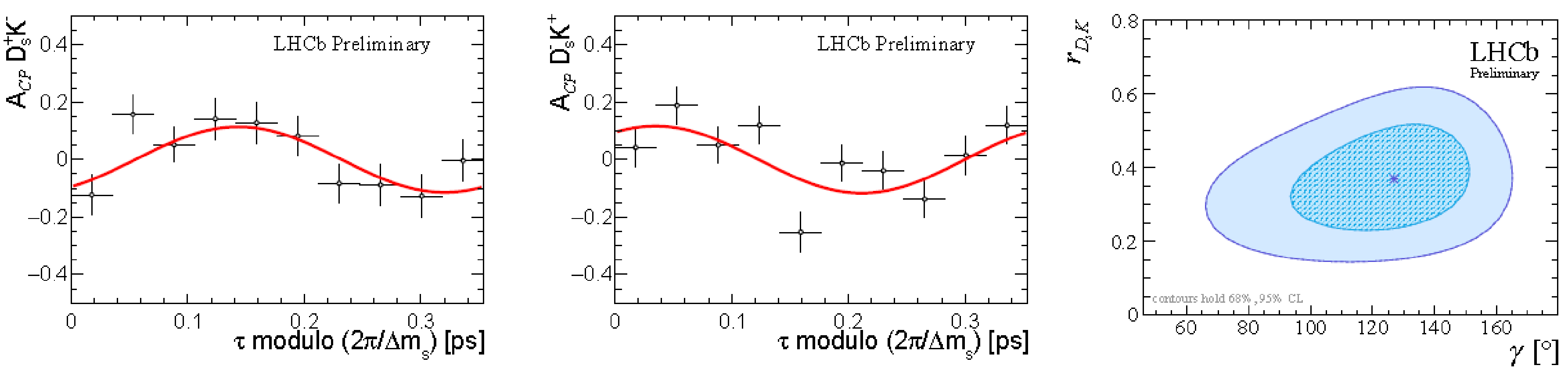
$D_s^{\pm}K^{\mp}$ not self-tagged,
both B^0_s and $\overline{B^0}_s$ can decay to it
$\Rightarrow$ Time-dependent required
Measurement unique to LHCb



$$A_{CP}(t) \equiv \frac{\Gamma(B_s^0(t=0)\to D_s^+K^-) - \Gamma(\overline{B}_s^0(t=0)\to D_s^+K^-)}{\Gamma(B_s^0(t=0)\to D_s^+K^-) + \Gamma(\overline{B}_s^0(t=0)\to D_s^+K^-)} = \frac{C\cos(\Delta m_s t) - S\sin(\Delta m_s t)}{\cosh(\Delta\Gamma_s t/2) + A\sinh(\Delta\Gamma_s t/2)}$$

$$S = \frac{2r}{1+r^2}\sin(\delta - (\gamma - 2\beta_s)) \qquad A = \frac{2r}{1+r^2}\cos(\delta - (\gamma - 2\beta_s)) \qquad C = -\frac{1-r^2}{1+r^2}$$

LHCb-CONF-2016-015



CPV in baryons decay

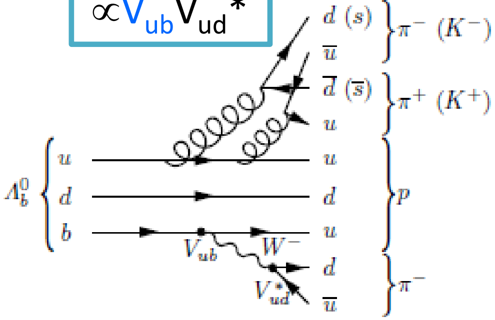
New in 2016

arXiv:1609.05216

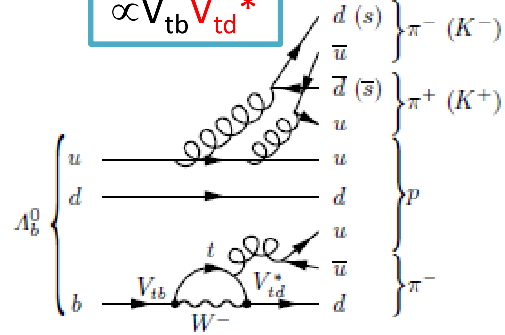
Non-negligible CPV effects predicted within SM in charmless Λ_b decays

Interfering amplitudes with similar size and large relative weak phase in $\Lambda_b \to p\pi\pi\pi$ or $\Lambda_b \to p\pi KK$

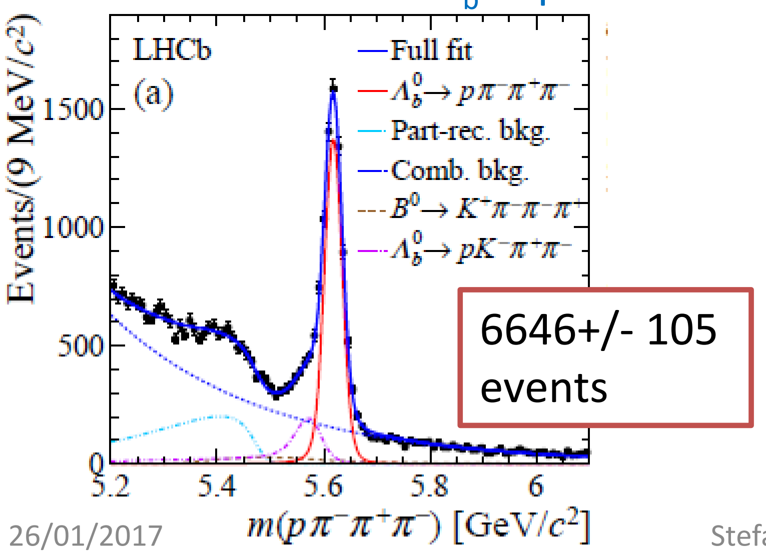
$\propto V_{ub}V_{ud}^*$



$\propto V_{tb}V_{td}^*$



First observation of $\Lambda_b \to p\pi\pi\pi$



4-body final states

Triple product asymmetries

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+})$$

$$\overline{C}_{\hat{T}} = \vec{p}_{\bar{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-})$$

$$A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}, \quad \Lambda_b$$

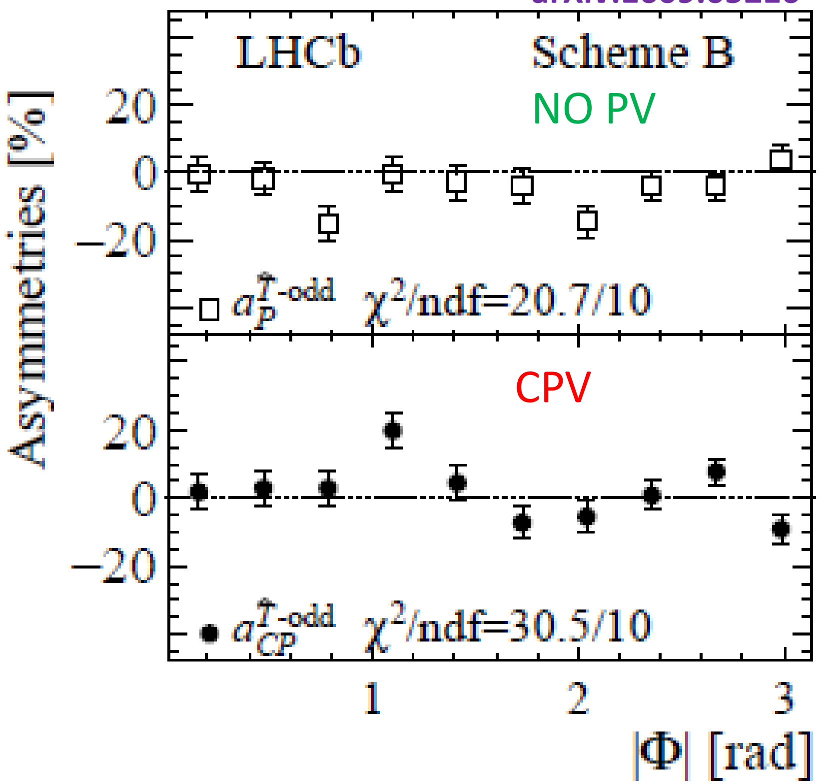
$$\overline{A}_{\hat{T}}(\overline{C}_{\hat{T}}) = \frac{\overline{N}(-\overline{C}_{\hat{T}} > 0) - \overline{N}(-\overline{C}_{\hat{T}} < 0)}{\overline{N}(-\overline{C}_{\hat{T}} > 0) + \overline{N}(-\overline{C}_{\hat{T}} < 0)}, \quad \overline{\Lambda}_b$$

Observables largely insensitive to production and charge detection asymmetries (advantage over simple decay rates)

CPV with baryons

New in 2016

arXiv:1609.05216

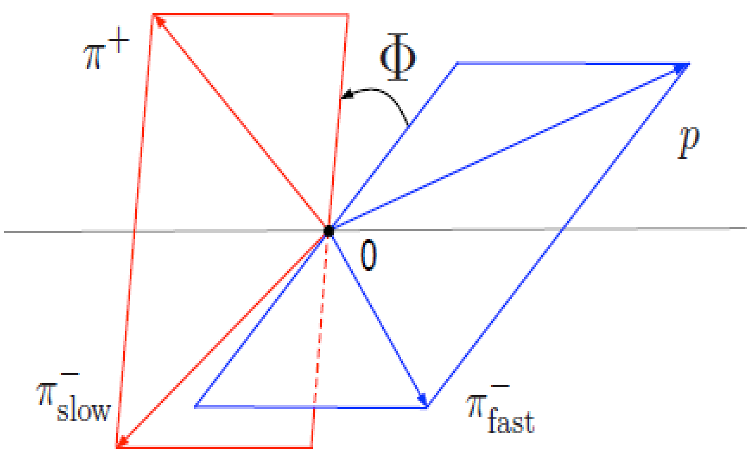


Observables:

$$a_P^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} + \overline{A}_{\hat{T}}\right), \quad \neq 0 \Rightarrow \text{PV}$$

$$a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} - \overline{A}_{\hat{T}}\right), \quad \neq 0 \Rightarrow \text{CPV}$$

Searches of localised P- and CP-violating asymmetries in distinct region of the phase-space. Two different binning schemes used.



Data consistent with NO P violation

CPV at 3.3σ level (combining both schemes)

First evidence of CPV in baryon sector

No CPV in charm yet

3fb^{-1} update in 2016

- LHCb largest data sample of charm decays to charged tracks
- Unique environment with up-type quarks
  - D^0 mixing firmly established
  - Expected tiny level of CPV in SM <10^{-2}, which could be enhanced by NP

$$\boxed{\Delta A_{CP}} = \boxed{A_{CP}}(D^0 \to K^+K^-) - \boxed{A_{CP}}(D^0 \to \pi^+\pi^-) \qquad \boxed{A_{CP}} = \frac{\Gamma(D\to f) - \Gamma(\bar{D}\to \bar{f})}{\Gamma(D\to f) + \Gamma(\bar{D}\to \bar{f})}$$

- LHCb 0.6 fb^{-1} : ΔA_{CP} = (-0.82 ± 0.21)% , evidence of CPV PRL108(2012)111602

3fb^{-1} update in 2016, using $D^{*+} \to D^0\pi^+$ and $D^{*-} \to \overline{D^0}\pi^-$ samples

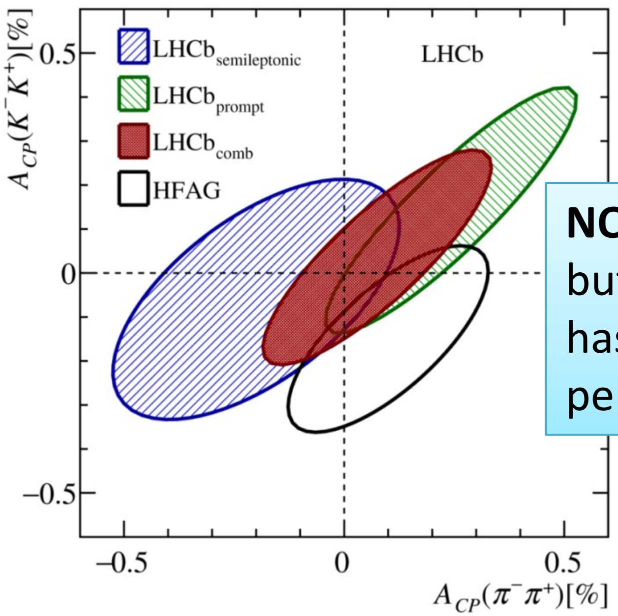
PRL 116 191601 (2016)

$$\Delta A_{CP} = (0.10 \pm 0.08 \pm 0.03)\%$$

supercedes our previous measurement

arXiV:1610.09476

$$A_{CP}(KK) = (0.04 \pm 0.12 \pm 0.10)\%$$
$$A_{CP}(\pi\pi) = (0.07 \pm 0.14 \pm 0.11)\%$$



NO CPV
but sensitivity has reached per mill level

Time-dependent CPV with $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

Preliminary
$3fb^{-1}$,2016

LHCB-CONF-2016-009

- D^* tagged sample, $O(10^6)$ decays
- Asymmetry $A_{CP}(t)$ measured in bins of decay proper-time

$$A_{CP}(t) \cong a_{CP}^{dir} - \frac{t}{\tau_D} A_\Gamma$$

- Slope A_Γ measures indirect CP violation
- Detection asymmetries corrections checked on $D^0 \to K^-\pi^+$ control sample

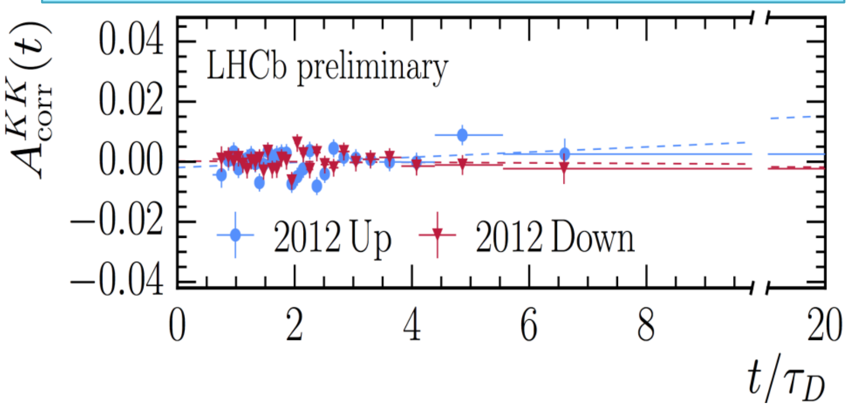
$$A_\Gamma(D^0 \to K^+K^-) = (-0.30 \pm 0.32 \pm 0.14) \times 10^{-3}$$
$$A_\Gamma(D^0 \to \pi^+\pi^-) = (\ \ 0.46 \pm 0.58 \pm 0.16) \times 10^{-3}$$

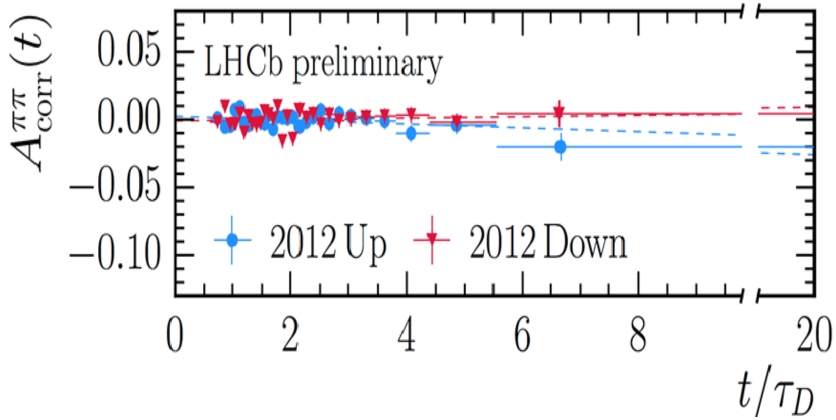
Most precise measurement of these observables

Also unbinned analysis available on same data sample, consistent results (LHCB-CONF-2016-010)

Data split by magnet polarities and years

Consistent results, no slope ⇒ no CPV





- Introduction to Flavour and LHCb
- 2016 selected highlights on mixing, CPV and FCNC
    - B-Mixing and CPV
    - CKM angle gamma
    - CPV in baryonic decays
    - CPV search in charm
    - **Anomalies in $B^0 \to K^{*0}\mu\mu$**
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- Future LHCb prospects

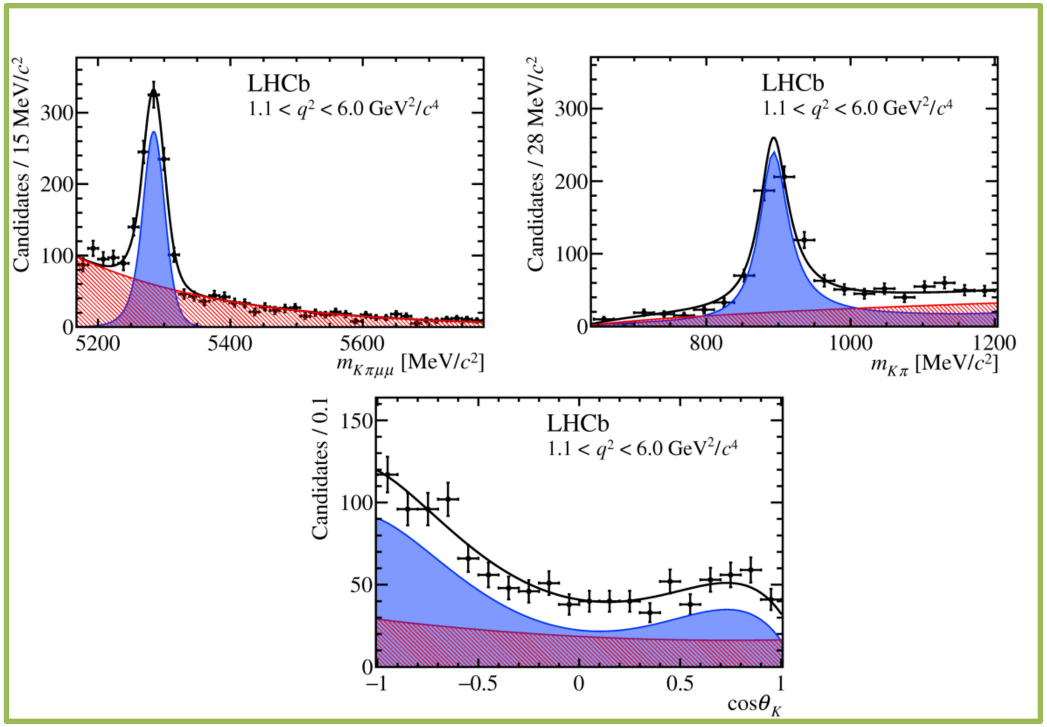
RARE DECAYS

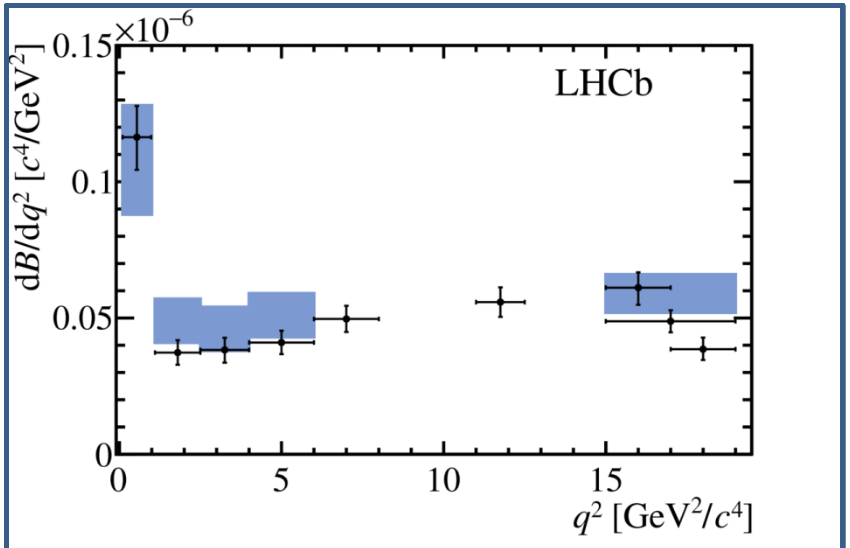
$B^0 \to K^{*0}(892)\mu^+\mu^-$

3fb^{-1} update in 2016

JHEP 11 (2016) 047

- Differential branching fraction of $B^0 \to K^{*0}(892)\mu^+\mu^-$
  - P-wave only determined for the first time
- Measured S-wave fraction, F_S
  - Fit to $M(K\pi\mu\mu)$, $M(K\pi)$ and helicity angle $\cos(\theta_K)$
  - $F_S = 0.101 \pm 0.017 \pm 0.009$ for $796 < M(K\pi) < 996$ MeV and $1.1 < q^2 < 6.0$ GeV^2





Most precise measurements of the differential branching fraction to date
In good agreement with the SM predictions

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

3fb^{-1} update in 2016

- Four-body final states
- System described by dimuon invariant mass q^2 and $\Omega=(\theta_l, \theta_K, \phi)$
  - Angular distributions sensitive to New Physics

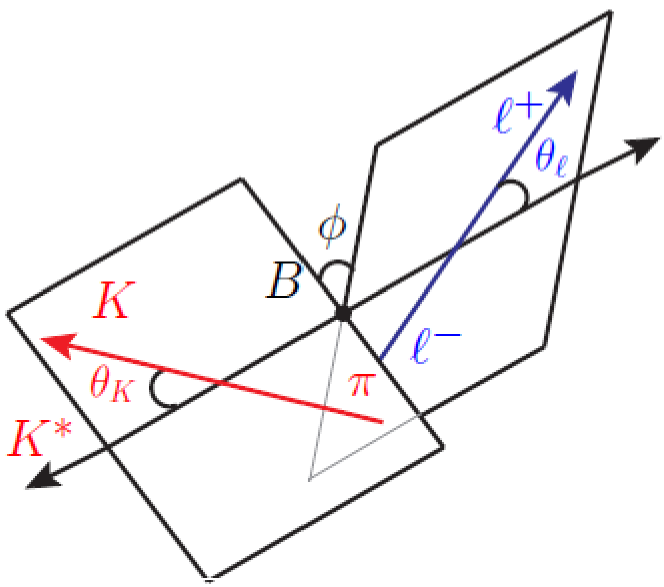
$$\frac{\mathrm{d}^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega})$$

$I_i \to \overline{I^i}$ for B^0

Observables:

$$S_i = (I_i + \bar{I}_i) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)$$

$$A_i = (I_i - \bar{I}_i) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)$$



The observables depend on Wilson coefficients (short-distance physics, evaluated perturbatively, universal) and on hadronic form factors for $B \to K^*$ transition (long-distance physics, evaluated through lattice QCD or LCSR)

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

JHEP 02(2016) 104

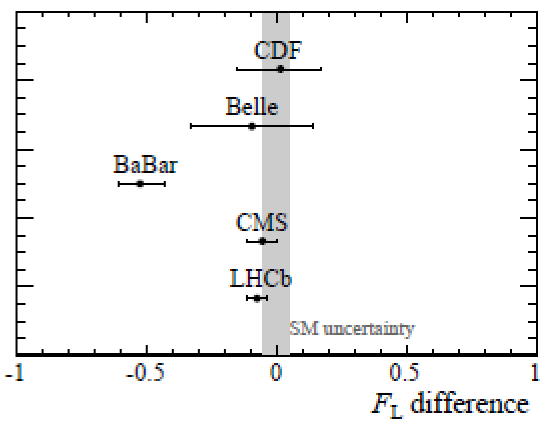
The CP-averaged angular distribution can be explicitely written as

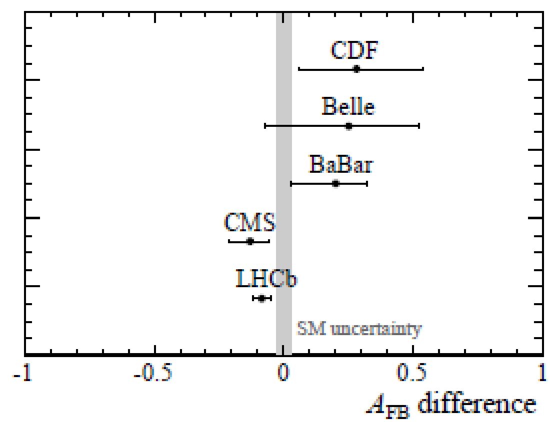
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-\boxed{F_{\rm L}})\sin^2\theta_K + \boxed{F_{\rm L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-\boxed{F_{\rm L}})\sin^2\theta_K\cos 2\theta_l$$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

F_L = Fraction of longitudinal polarisation of the K^{*0}

A_{FB} = Forward-backward asymmetry of dimuon system

LHCb
F_L and A_{FB} in good agreement with SM





Blake, Lanfranchi, Straub
Prog.Part.Nucl.Phys. 92 (2017) 50-91

$B^0 \to K^{*0}\mu^+\mu^-$, P_5' observable

3fb^{-1} update in 2016

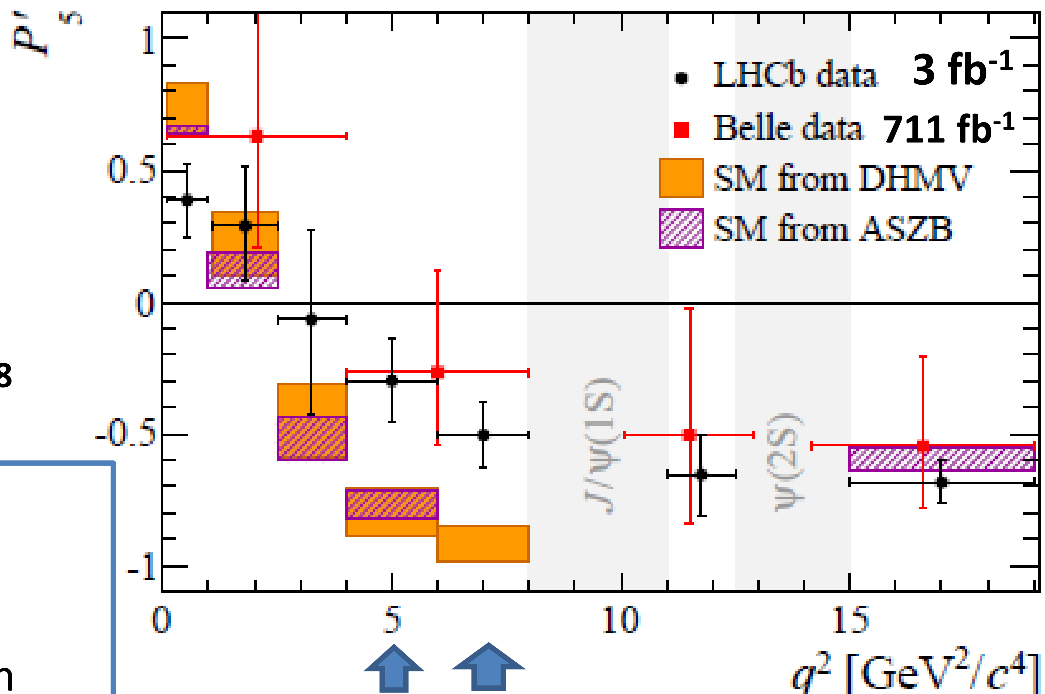
JHEP 02(2016) 104

Set of observables with reduced hadronic uncertainties can be defined using ratios

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

Independent of form-factors at leading order

S.Descotes-Genon et al., JHEP01(2013)048



LHCb has performed the first full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$
Global analysis of LHCb results on CP-averaged observables at **3.4σ** from SM

LHCb local tension with SM prediction

Belle data consistent with LHCb

2.1σ from SM, arXiV:1604.04042

Global fits to b⟶s data

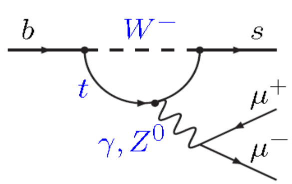
In OPE , *B* decay amplitude is expressed by:

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{CKM} \sum_i C_i O_i$$

O_i describe long-distance physics (non-perturbative)

C_i Wilson coefficients, short-distance physics (perturbative)

i = 1,2	Tree
i = 3 – 6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin



$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$ Vector

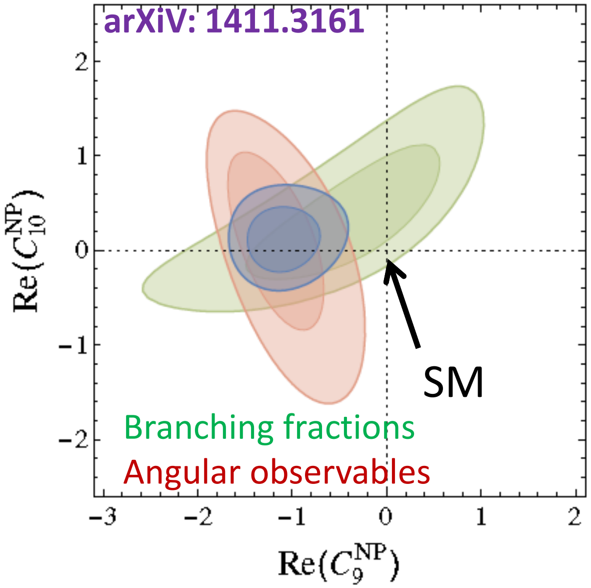
$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$ Axial-vector

Two examples of global fits to b⟶s data: constraints on Wilson coefficients

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

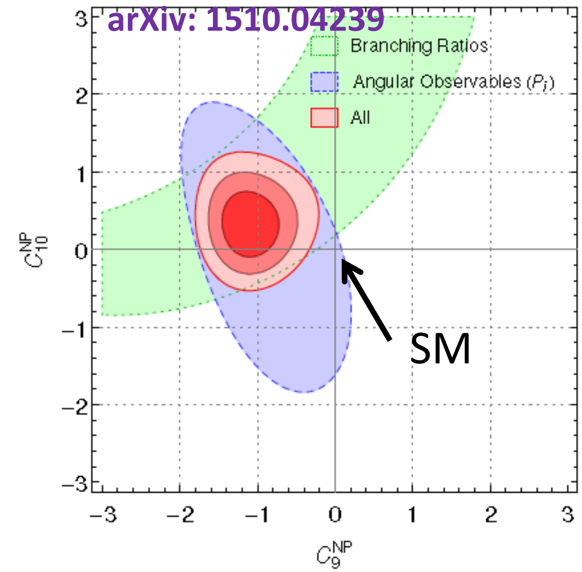
Altamannshofer and Straub

arXiv: 1411.3161



Descotes-Genon et al

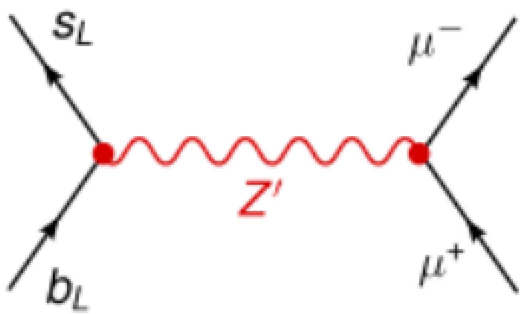
arXiv: 1510.04239



Consistent picture:
data favours modified vector coupling C_9
$C_9^{NP} \neq 0$ at about 4σ

Interpretation of b⟶s anomalies

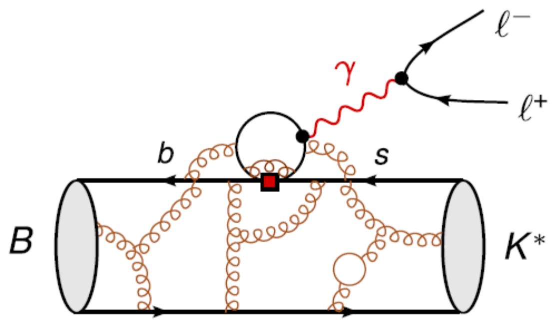
NP



Vector-like contribution could come from a Z' with a mass of a few TeV

OR?

SM



Vector-like contribution could be mimicked by poorly understood charm-loop contributions that may produce a di-muon pair via a virtual photon

Lyon and Zwicky, arXiv:1406.0566
Altmannshofer, W. & Straub, D.M. Eur. Phys. J. C (2015)
Ciuchini et al., JHEP 06(2016)116

More effort on-going to clarify picture: e.g., measure $C_9(q^2)$ dependence (different from charm loops and NP contribution) –
Current statistics not sufficient to draw conclusions

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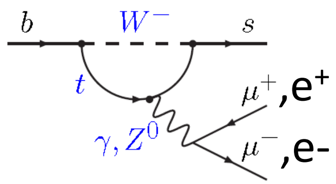
OTHER ANOMALIES

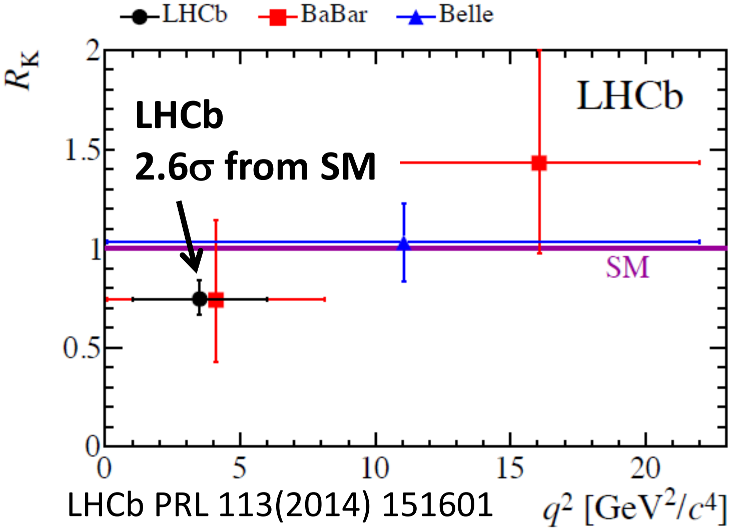
Lepton Universality Test: e/μ



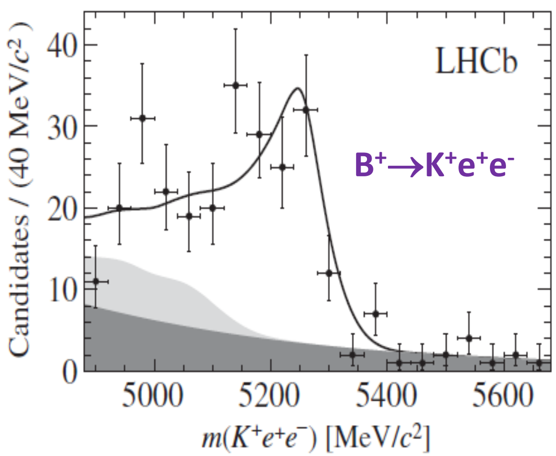
SM b→sll flavour universality
⇒ Expect:

$$R_K = \frac{BF(B^+ \to K^+\mu^-\mu^+)}{BF(B^+ \to K^+e^-e^+)} = 1 \pm O(10^{-3})$$

- Theoretically clean: hadronic uncertainties cancel in the ratio
- Experimentally challenging: electron-reconstruction (Bremsstrahlung tail)



LHCb PRL 113(2014) 151601
BaBar PRD 86(2012)032012
Belle PRL 103 (2009) 171801



LHCb Run-1 (3 fb^{-1}) for $1<q^2<6$ GeV^2:

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

R_K=0.8 consistent with angular anomalies in b→sμμ in some class of NP models
E.g [Altmannshofer et al, PRD 89 (2014) 095033]

Lepton Universality Test: μ/τ

$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\upsilon)}{\Gamma(B \to D^{(*)}\mu\upsilon)}$$

≠1 due to phase-space

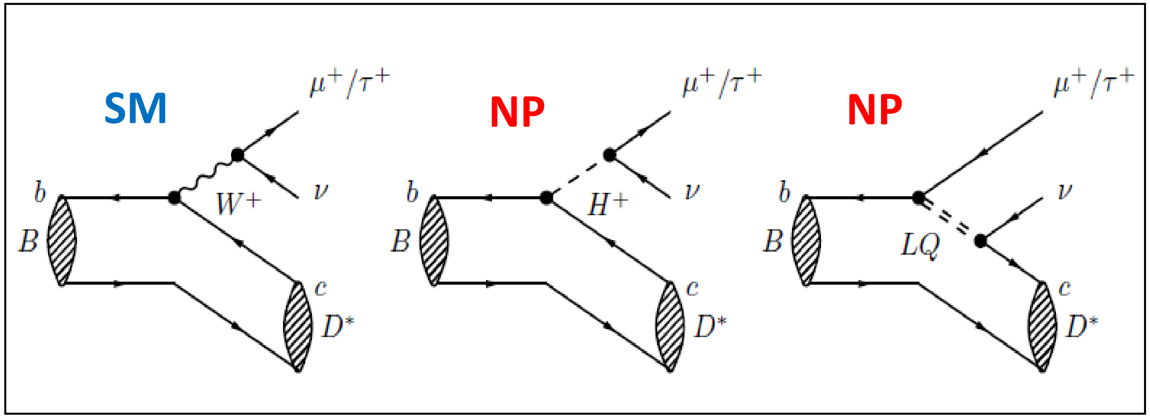
SM prediction theoretically very clean
Sensitive to NP: e.g. charged Higgs, leptoquark

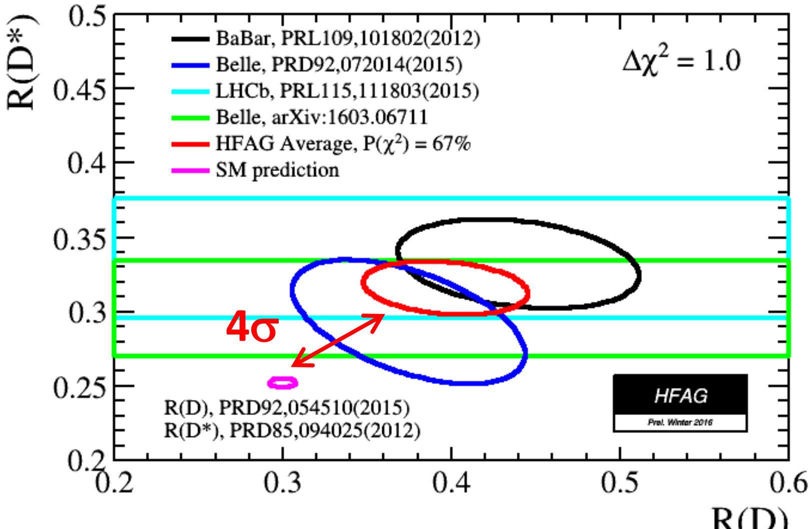
LHCb measured R(D*) with $\tau \to \mu\nu\nu$
Experimental challenge:
missing neutrinos

LHCb result at 2.1σ from SM

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

LHCb, PRL115,111803(2015)



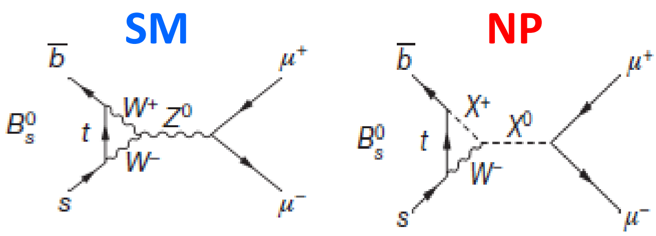


HFAG average of all R(D) and R(D*), including Belle, Babar, LHCb
4σ from expectations

More measurements of other $b \to c\tau\nu$ processes under way at LHCb.
Also using B_s, B_c, Λ_b decays

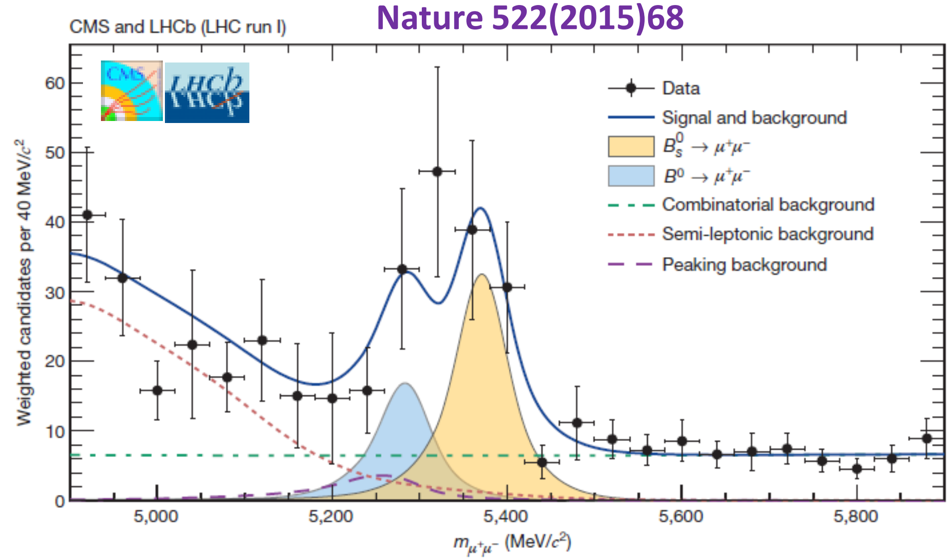
First observation of $B_s \to \mu^+\mu^-$

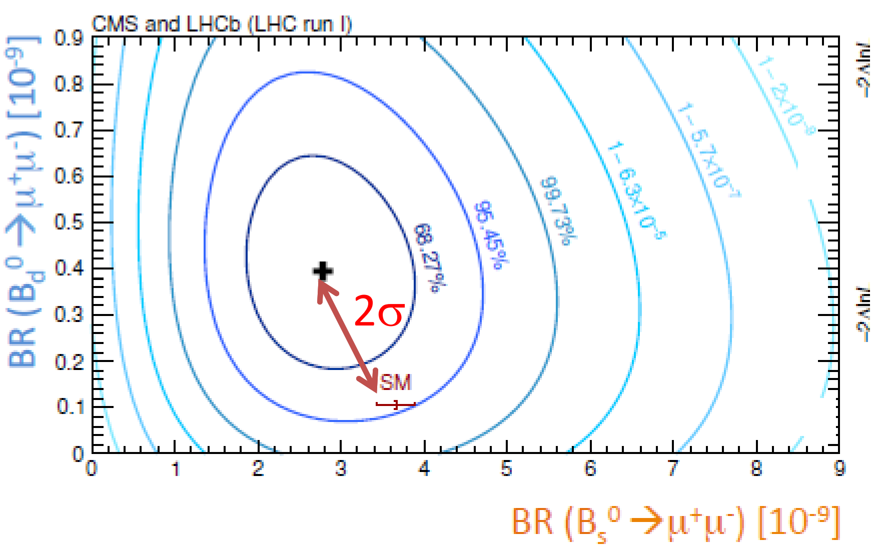
FCNC decay, very rare in SM



BF can be significantly altered in many BSM models

Nature 522(2015)68





First observation (6.2 σ) of $B_s \to \mu^+\mu^-$

- BR = $(2.8^{+0.7}_{-0.6}) \times 10^{-9}$

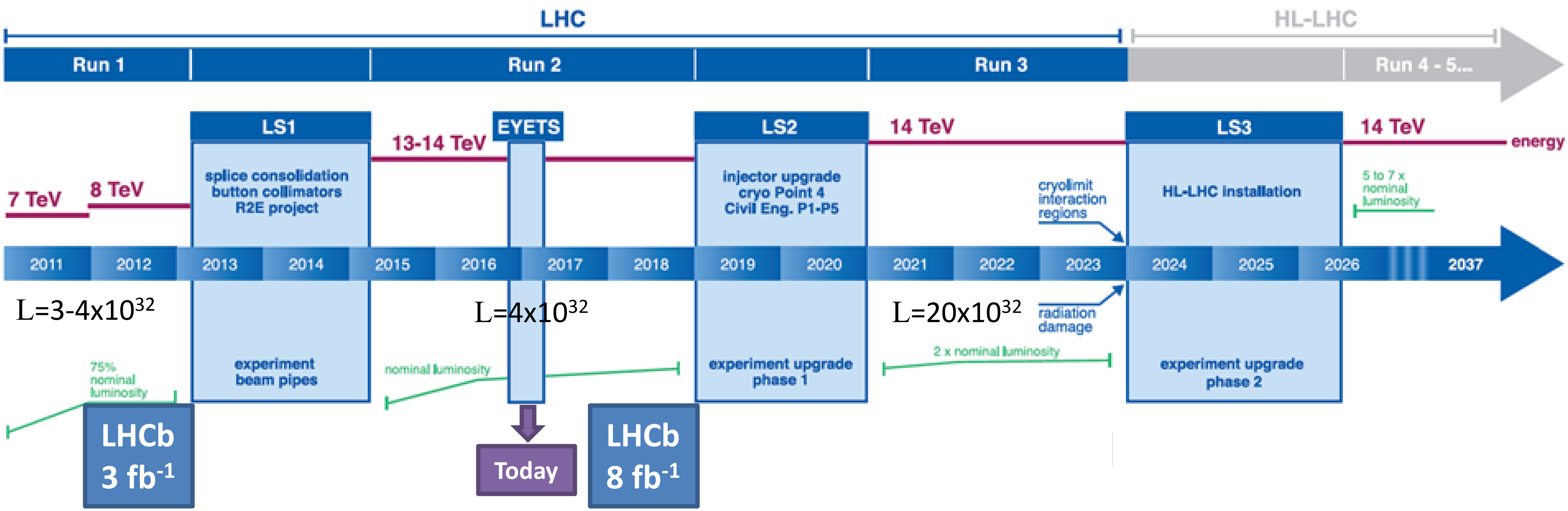
compatible with SM at 1.2σ

First evidence (3σ) of $B^0 \to \mu^+\mu^-$

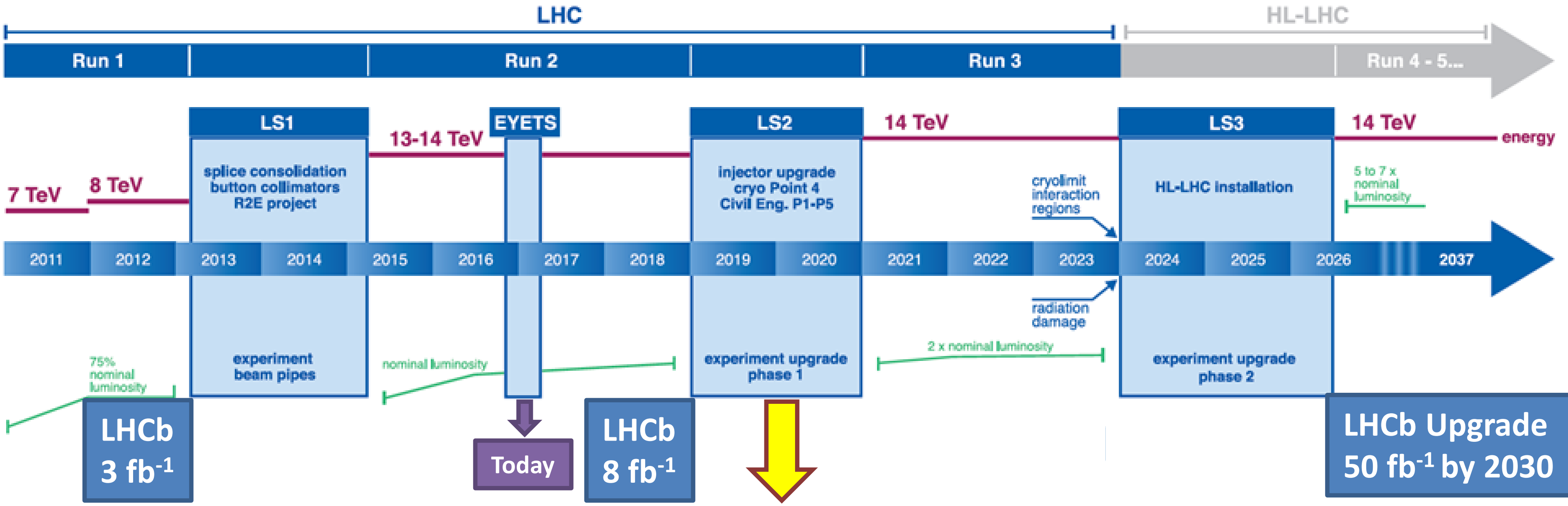
- BR = $(3.9^{+1.6}_{-1.4}) \times 10^{-10}$

compatible with SM at 2.2σ

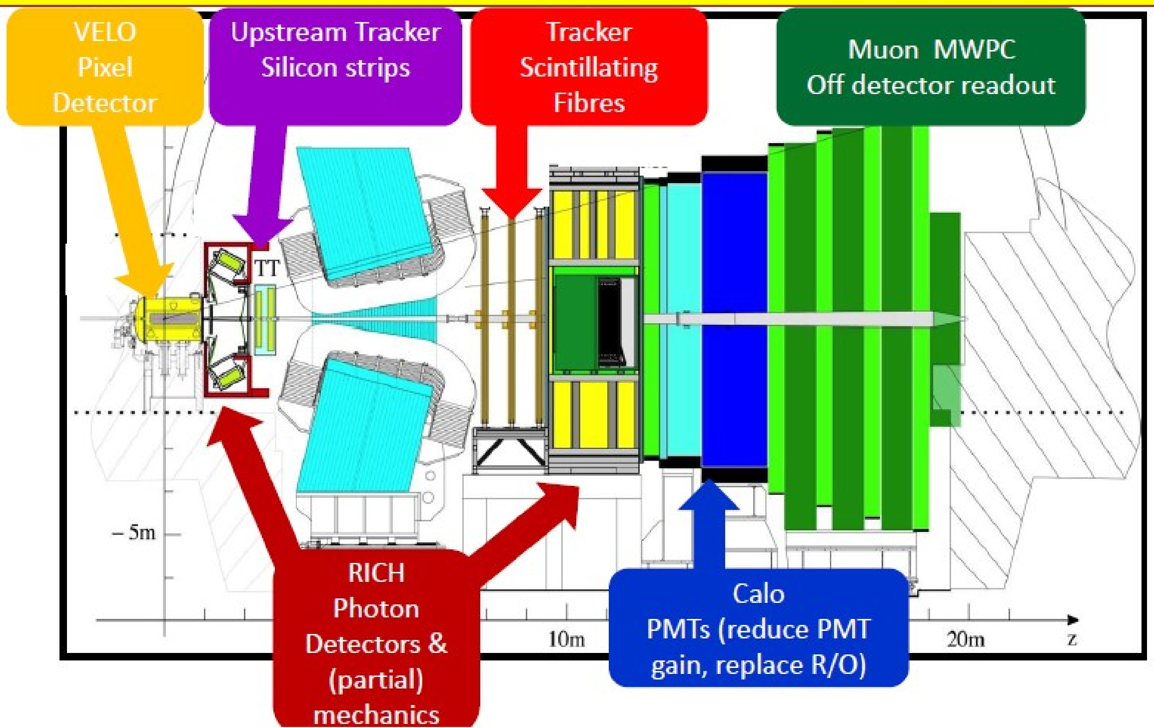
FUTURE PROSPECTS



LHC Operation PLAN



LHCb upgrade: new 40 MHz read-out with fully software trigger



LHCb projected statistical uncertainties

	LHCb Run 1&2 - 2018 8 fb^{-1}	LHCb Upgrade- Run3&4 - ~2030 50 fb^{-1}	Theory
$\frac{BF(B_d \to \mu\mu)}{BF(B_s \to \mu\mu)}$	~100%	~35%	~5%
s_0 $A_{FB}(B_d \to K^*\mu\mu)$	6%	2%	7%
$\gamma\ (B \to DK)$	4°	0.9°	negligible
$\phi_s\ (B_s \to J/\psi\phi)$	0.025	0.008	~0.003
$A_\Gamma(D \to KK)$	0.2 x 10^{-3}	0.05 x 10^{-3}	-

LHCb-PUB-2014-040

Statistical uncertainties will stay larger than theoretical ones for many years!

Conclusions

- Many new LHCb results published this year (>50 papers!)– Only a few, selected ones, presented here
- Increasing experimental precision and good agreement with SM for most of the flavour observables:
  - Mixing in the B_d (and B_s) system
  - CPV in mixing with semileptonic Bs decays (asl_s)
  - CKM-γ from direct CPV in $B \rightarrow DK$ decays
  - First evidence of CPV in baryonic decays (Λ_b)
  - No observation of CPV in D^0 decays
- Some measurements showing interesting tensions with SM:
  - Some exclusive $b \rightarrow s\mu^+\mu^-$ branching fractions
  - $B^0 \rightarrow K^{*0}\mu^+\mu^-$ angular distributions (2016 first full angular analsys)
  - Hints of lepton non universality in $B \rightarrow Kll$ and $B \rightarrow Dl\nu$ decays
  - $B^0 \rightarrow \mu^+\mu^-$ branching fraction (too high?)

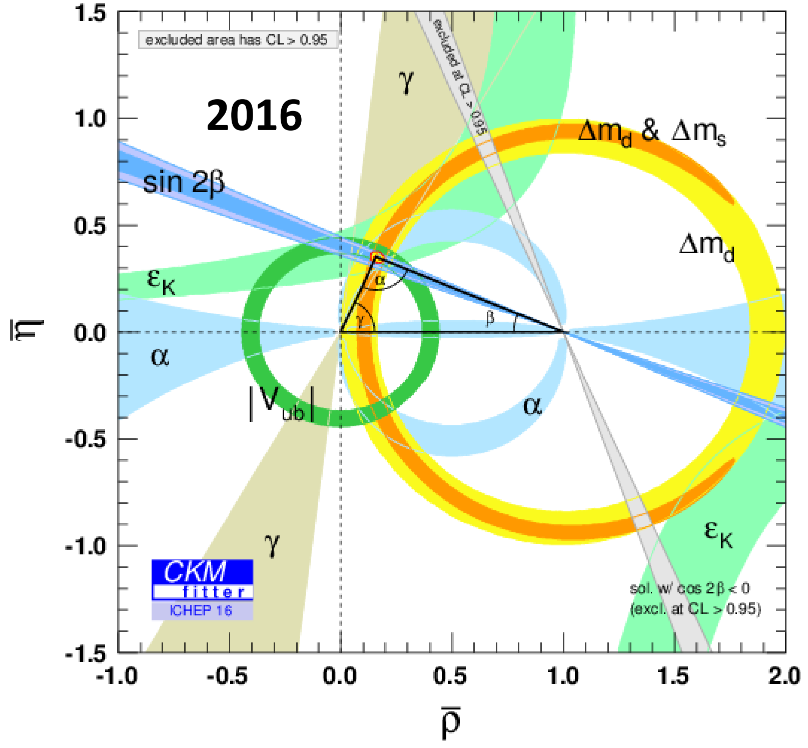
  New Physics or unaccounted uncertainties or statistical fluctuations?
- Most results using LHC Run-1, $3fb^{-1}$; b and c-quark data-samples from Run-2 on tape is already more than twice larger (accounting for larger cross-sections at 13TeV)
- Plans to collect $50fb^{-1}$ by end of LHC Run-4 (2030) with upgraded detector

89
THANK YOU

Flavour physics indirect discoveries

- 1970: c-quark predicted (GIM mechanism) to explain smallness of $K_L \to \mu\mu$
  - 1974: first J/ψ observation
- 1973: 3rd generation introduced (Kobayashi & Maskawa) to explain CP violation in kaon decays, ε_K
  - 1977: first b-quark observed
  - 1994: first top-quark observed
- 1974: charm mass predicted from Δm_K (K^0-mixing)
- 1987: Argus hints of large top mass from Δm_B (B^0-mixing)
  - 1994: top-mass measured

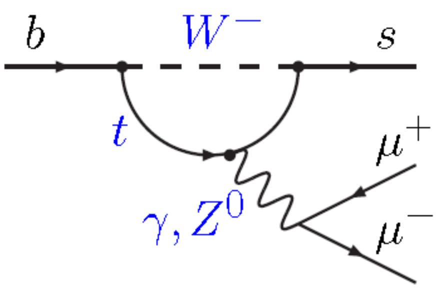
CKM constraints evolution



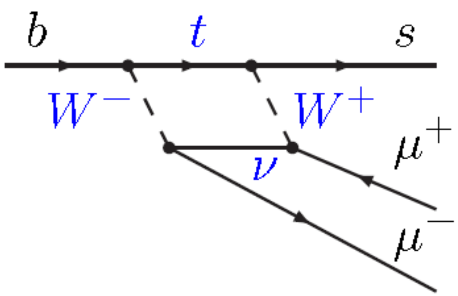
An increasingly precise picture..

FCNC b→sμμ decays

b→s (and b →d) transitions
only occur at loop level in SM

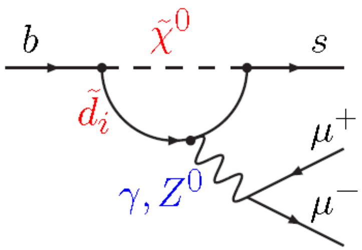


Penguin diagram

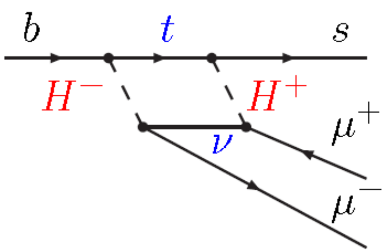


Box diagram

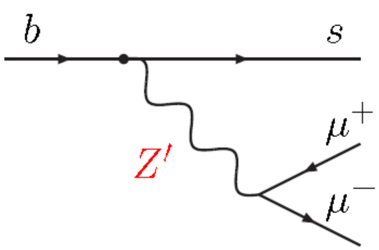
b→s (and b →d) transitions
at loop or tree level via NP. E.g.,



Penguin diagram



Box diagram

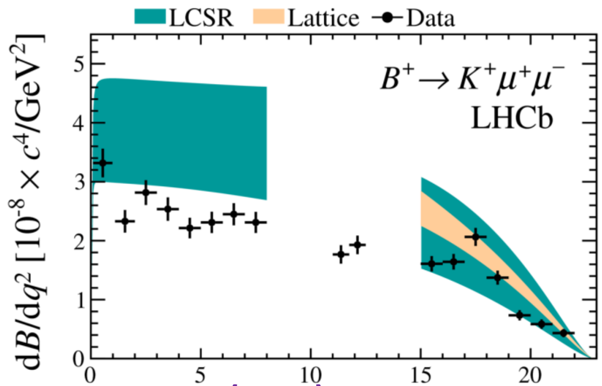


Tree diagram

Several observables: decay rates, CP asymmetries, angular distributions

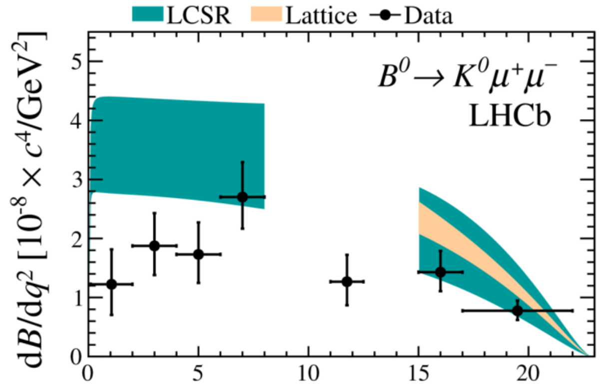
Exclusive b→sμ⁺μ⁻ decay rates

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



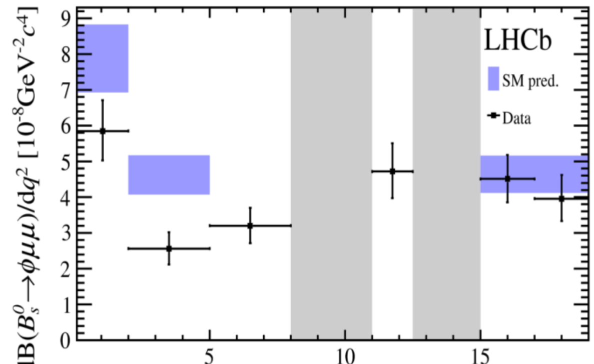
JHEP 06 (2014) 133

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



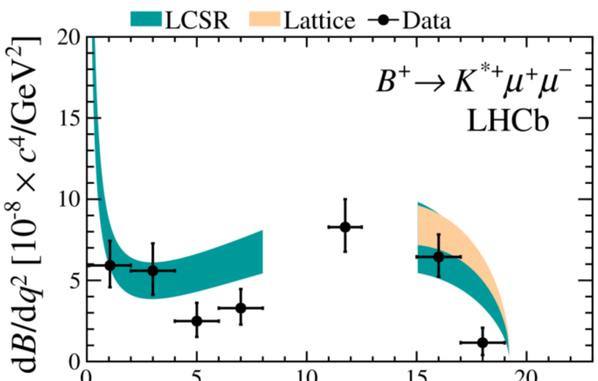
JHEP 06 (2014) 133

$B^0_s \to \phi\mu^+\mu^-$



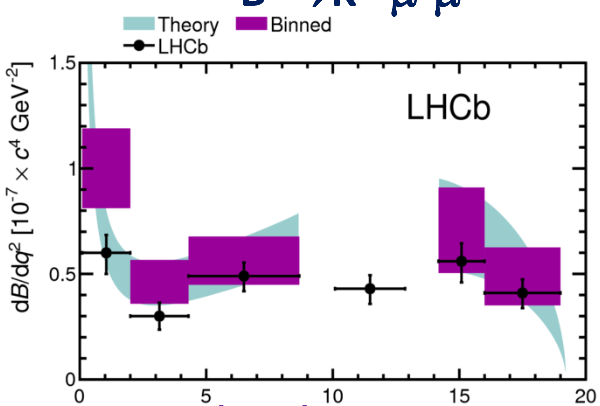
JHEP 09(2015) 179

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



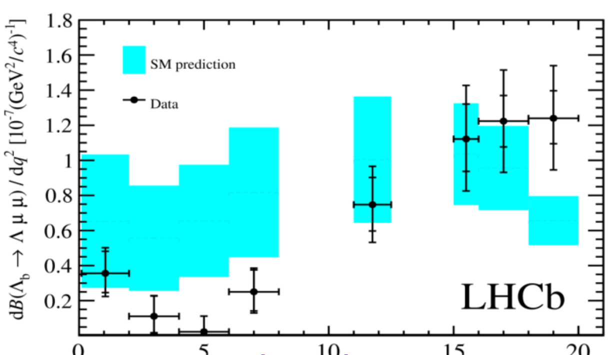
JHEP 06 (2014) 133

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



JHEP 08 (2013) 131

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



JHEP 06 (2015) 115

All lower than predicted!

But large uncertainties in the SM prediction from hadronic form factors

Amplitude phase-differences in $B^+ \to K^+\mu^+\mu^-$

New arXiv 1612.06764
Submitted to EPJC

Observed tensions need sizeable long-distance effects in dimuon mass regions far from the pole-masses of the resonances to be explained in terms of charm-loop contributions

First measurement of the phase difference between the short-distance and the narrow resonant contributions to the $B^+ \to K^+\mu\mu$ decay

Fit to dimuon mass-distribution:

- Long distance (resonances) contributions modelled with relativistic Breit-Wigner with individual magnitude and phases
- Short distance with effective field theory: C_9 and C_{10} floating, $B \to K$ form factors from predictions

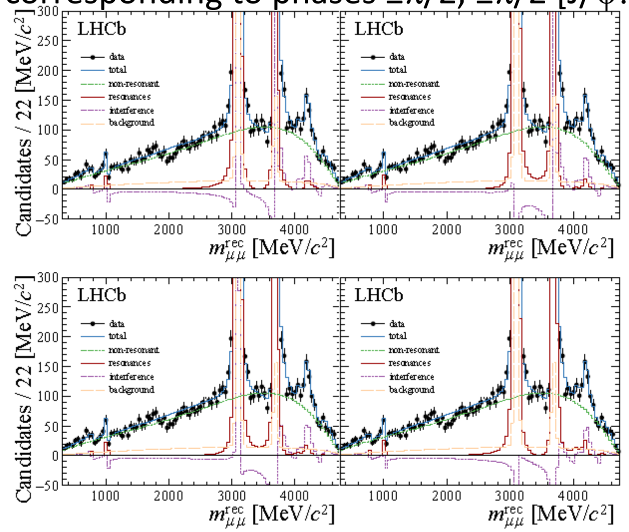
Same strategy could be applied to $B^0 \to K^{*0}\mu\mu$ (complicated due to different helicity amplitudes contributing with different phases)

Also BF measurement of non-resonant component

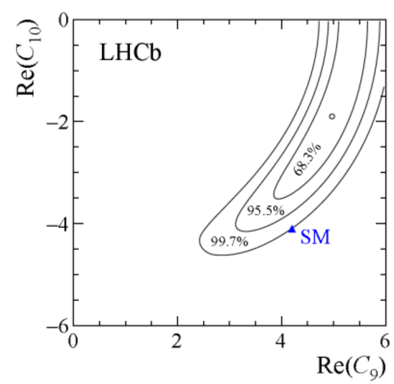
$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37 \pm 0.15\,(\text{stat}) \pm 0.23\,(\text{syst})) \times 10^{-7}$$

compatible with previous but smaller than SM

4 degenerate solutions corresponding to phases $\pm\pi/2$, $\pm\pi/2$ [J/ψ. $\psi(2S)$]



Negligible interference far from pole



If C_{10} set to 0, fit favours region with $C_9 < C_9^{SM}$