b anomalies at LHCb

status and prospect

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On behalf of the LHCb collaboration

Beauty, 21-24 September 2020, Japan *(virtual)*

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Outline

- Representation of anomalies in EFT
- Tree-level (semi-leptonic) decays
  - LFU ratios
- Loop $b \to s,d$ decays
  - Angular analyses, LFU ratios
- Leptonic: Branching fractions
- LFV searches
- Summary

Note: most results shown are based on full Run 1 ($3fb^{-1}$) + 2015+2016 ($2\ fb^{-1}$) Run 2 data

Effective Hamiltonians

Derived using Operator Product Expansion + renormalization group to sum up the radiative corrections*

$$H_{eff} = \sum_i V^i_{CKM} C_i(\mu) O_i(\mu)$$

- i = 1,2 : tree diagrams
- i = 3-6 : gluonic penguin
- i = 7-10 : electroweak penguin (7γ, 8G : magnetic-penguin)
- leptonic operators (S,P)
- Box operators : to describe oscillations

Quark flavour couplings (CKM for the SM)

Wilson coefficients, integrate physics from EW scale to μ (~ 1 GeV)

6-dim operators (higher orders negligible)

Matrix elements of operators O_i : non perturbative calculations: source of hadronic uncertainties (decay constants, form factors, etc...)

C_i/O_i mix under RG equations: in practice, use effective C_i^{eff}

For right-handed current, use of primed coefficients, C_i' (beyond SM contributions)

*** For a exhaustive review, see : G.Buchalla et al, Rev.Mod.Phys.68 (1996) 1125-1144 https://arxiv.org/abs/hep-ph/9512380***

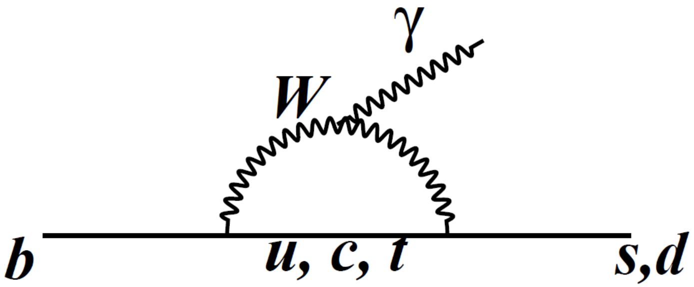
Loop operators and new physics

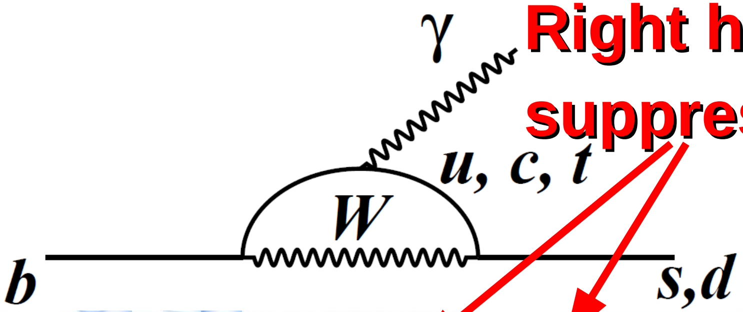
Loop operators → massive (electroweak) virtual particles : New Physics might intervene. Wilson coefficients affected by NP.

$$C_i(') \rightarrow C_i(')+C_i^{NP}$$

See J.Virto, next presentation for details

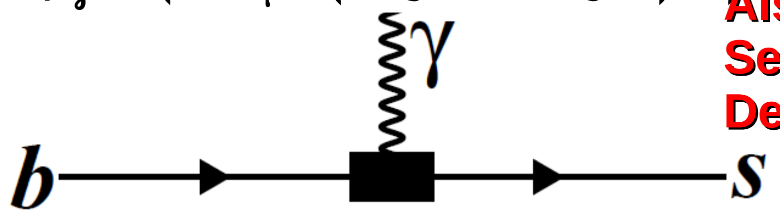
Electromagnetic penguin



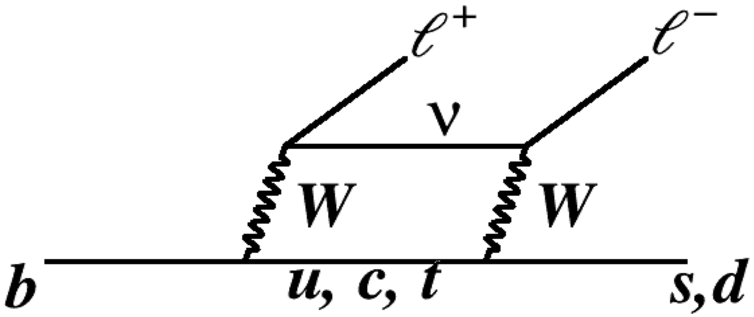


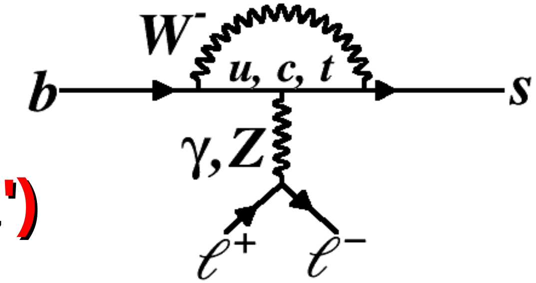
Right handed γ coupling (C_7') suppressed in SM!

$$O_{7\gamma}=\left(\bar{s}\sigma_{\mu\nu}\left(m_b R+m_s L\right)b\right)F^{\mu\nu}$$



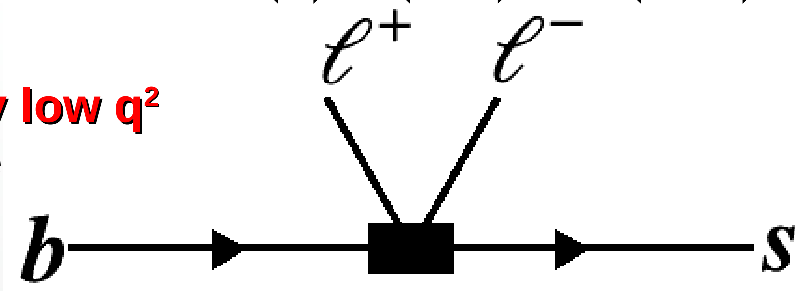
Also b → see at very low q^2
See Da Yu Tou, Rare Decays, Thursday





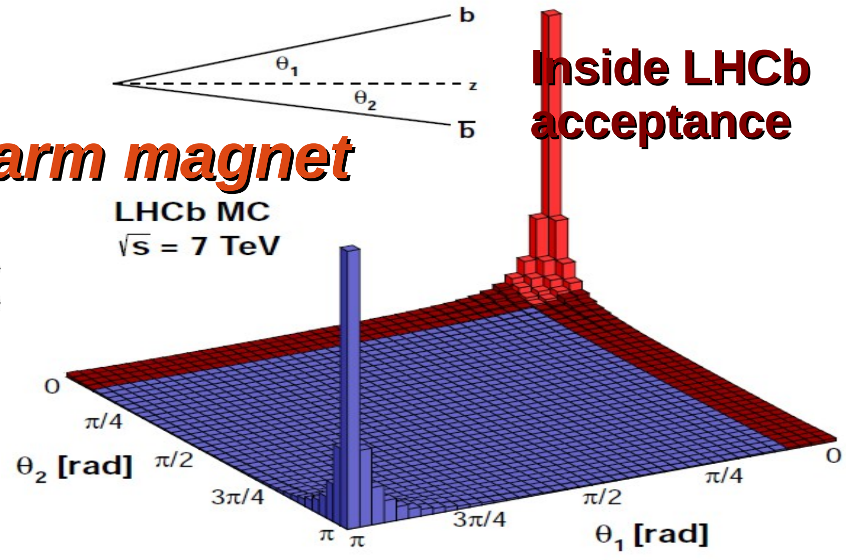
$$O_9(')=\left(\bar{s}b\right)_{V\mp A}\left(\bar{\ell}\ell\right)_V$$

$$O_{10}(')=\left(\bar{s}b\right)_{V\mp A}\left(\bar{\ell}\ell\right)_A$$



A great variety of b hadrons: $B_{u,d}$, B_s, B_c, b baryons, etc...

LHCb detector



Forward single-arm spectrometer with warm magnet (possibility to inverse polarity)

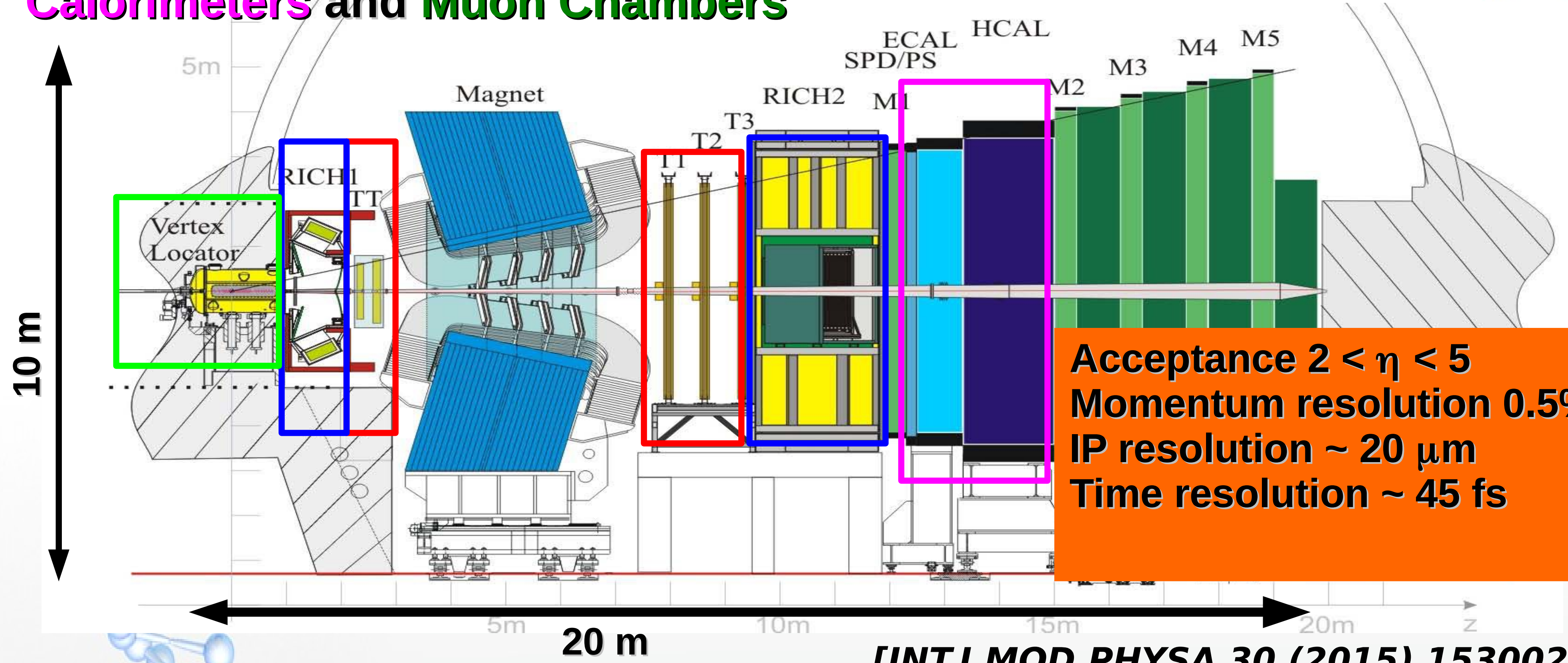
Optimized for b and c hadron studies

Vertexing

Tracking stations

Particle ID Ring Imaging Cherenkov

Calorimeters and Muon Chambers



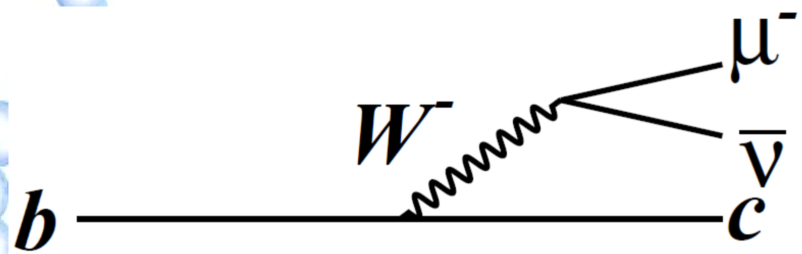
Acceptance 2 < η < 5
Momentum resolution 0.5% to 1%
IP resolution ~ 20 μm
Time resolution ~ 45 fs

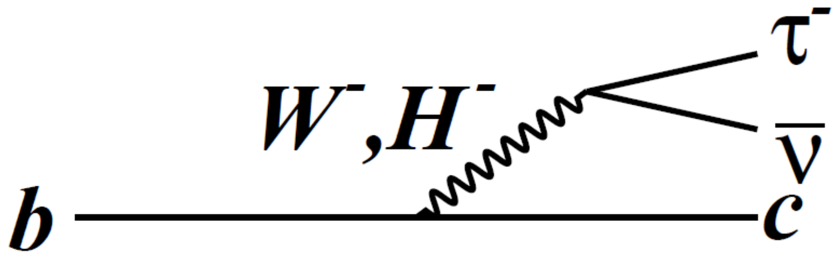
[INT.J.MOD.PHYSA 30 (2015) 1530022]
[JINST 3 (2008) S08005]

Lepton Flavour Universality with Semileptonic tree $b \to c \, \ell \, \nu$

See S.Braun, semileptonic parallel session, Tuesday
Dynamics of Bs semileptonic

$H_b \to H_c^{(*)} \tau \bar{\nu}$ vs $H_b \to H_c^{(*)} \mu \bar{\nu}$





Test of Lepton Flavour Universality in SM. NP might prefer heavy lepton (τ)

Measure:

$$R\left(H_c^{(*)}\right) = \frac{BR\left(H_b \to H_c^{(*)} \tau \bar{\nu}\right)}{BR\left(H_b \to H_c^{(*)} \mu \bar{\nu}\right)}$$

Precise SM-based predictions:

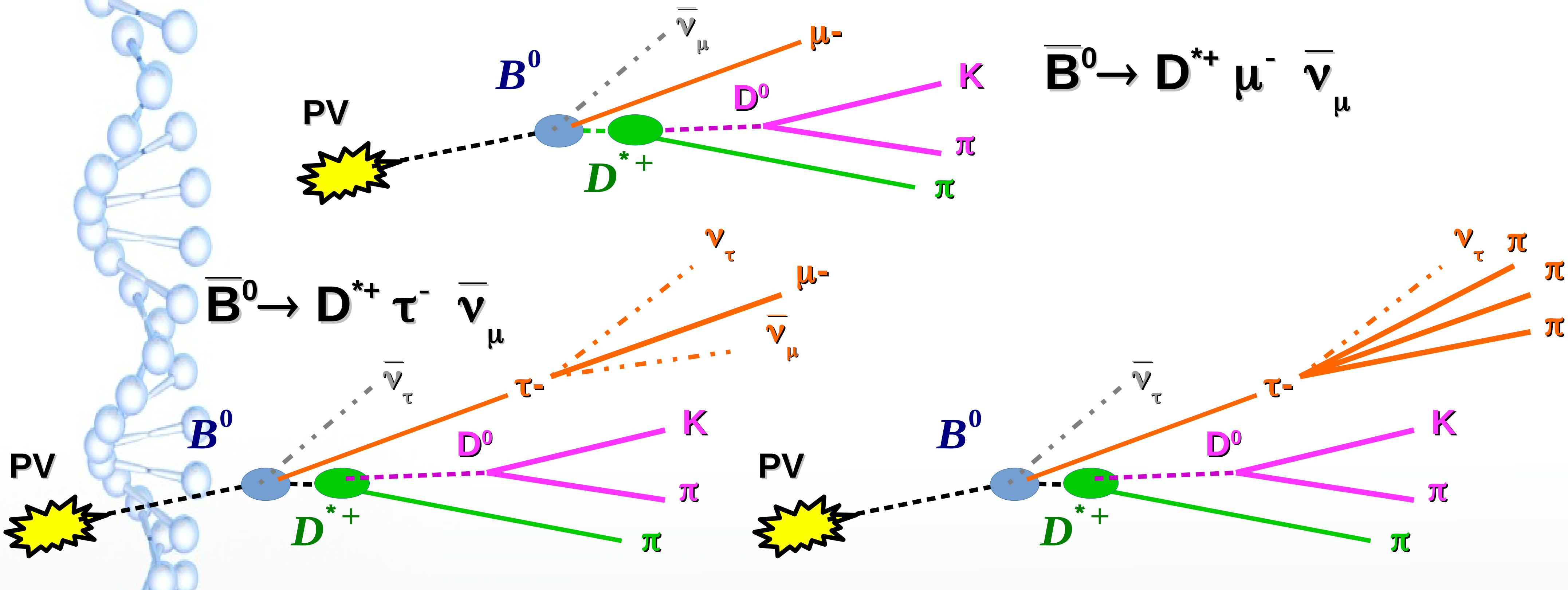
R(D) = 0.299 +/- 0.003
R(D*) = 0.252 +/- 0.003

H. Na et al., PRD 92(2015) 054510
Fajfer, Kamenic, Nišandižć, PRD85 (2012) 094025
D.Bigi, Gambino, PRD 94 (2016) 094008

LHCb $\overline{B}^0 \rightarrow D^{*+} \tau^- \overline{\nu}_\tau$ vs $\overline{B}^0 \rightarrow D^{*+} \mu^- \overline{\nu}_\mu$

Very specific topologies for different τ decays (leptonic vs hadronic)

Use of missing mass, muon energy, momentum transfer q, and τ decay time (hadronic mode)



LEPTONIC $\tau^- \rightarrow \mu^- \overline{\nu}_\mu \nu_\tau$ **HADRONIC** $\tau^- \rightarrow \pi^-\pi^+\pi^-(\pi^0)\,\nu_\tau$

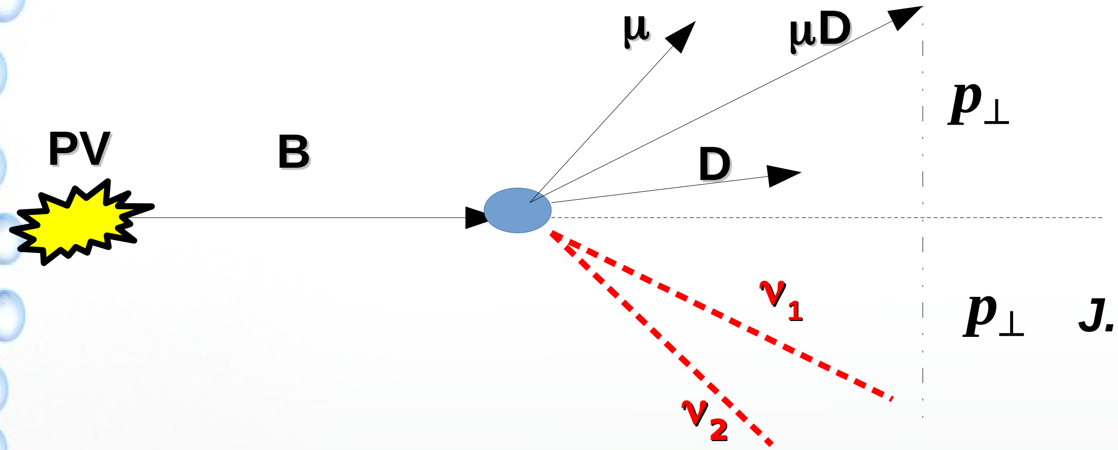
PRL 115 (2015) 111803, 2015-025 *PRL 120 (2018)171802, 2017-017*

$\overline{B}^0 \to D^{*+} \tau^- \overline{\nu}_\tau$ vs $\overline{B}^0 \to D^{*+} \mu^- \overline{\nu}_\mu$

Specific variables and neutrino reconstruction

$$m^2_{miss} = (P_B - P_{D^*} - P_\mu)^2 \quad q^2 = (P_B - P_{D^*})^2$$

Use approximation of P_B, infer the neutrino 4-momentum from geometrical considerations



$p_\perp$

$p_\perp$

Two folds ambiguity for the determination of $p_{//}(\nu)$, resolved with a regression method.

J. High Energ. Phys. (2017) 2017: 21

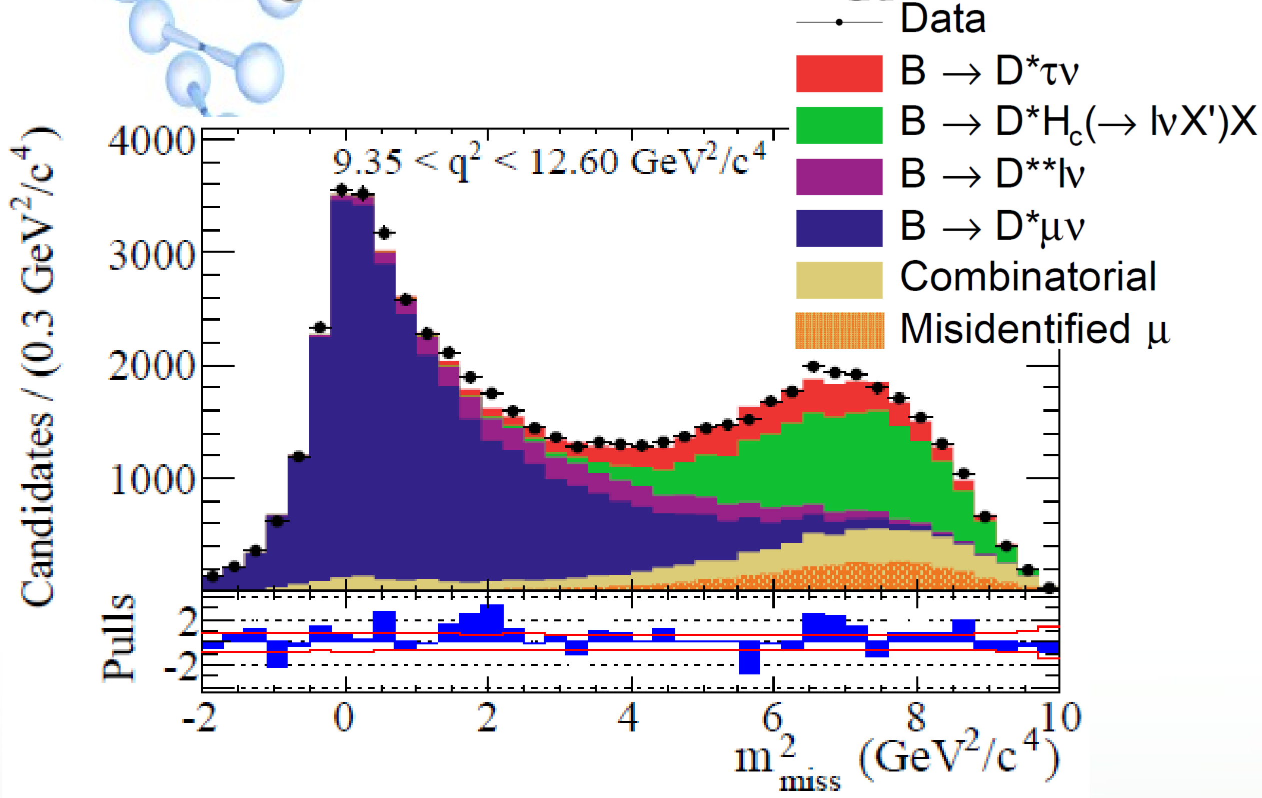
$\overline{B}^0 \to D^{*+} \tau^- \overline{\nu}_\tau$ vs $\overline{B}^0 \to D^{*+} \mu^- \overline{\nu}_\mu$

LHCb

$\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$

PRL 115 (2015) 111803

2D missing mass – muon energy fit



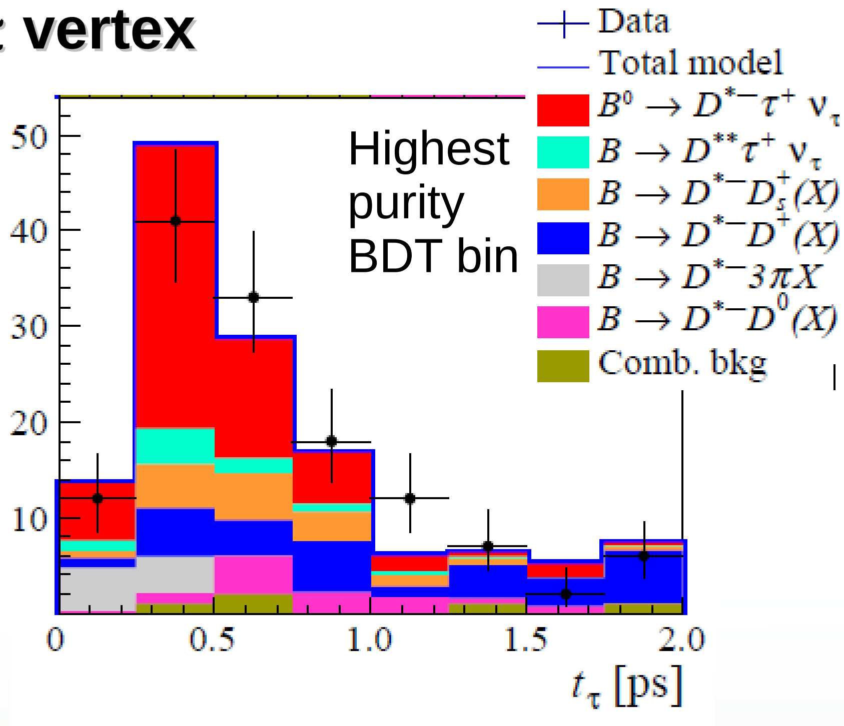
R(D*)=0.336±0.027(stat)±0.030(syst)

$\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\, \nu_\tau$

PRL 120 (2018)171802

$\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-$ as normalization

2D fit q^2 – tau decay time from 3π vertex

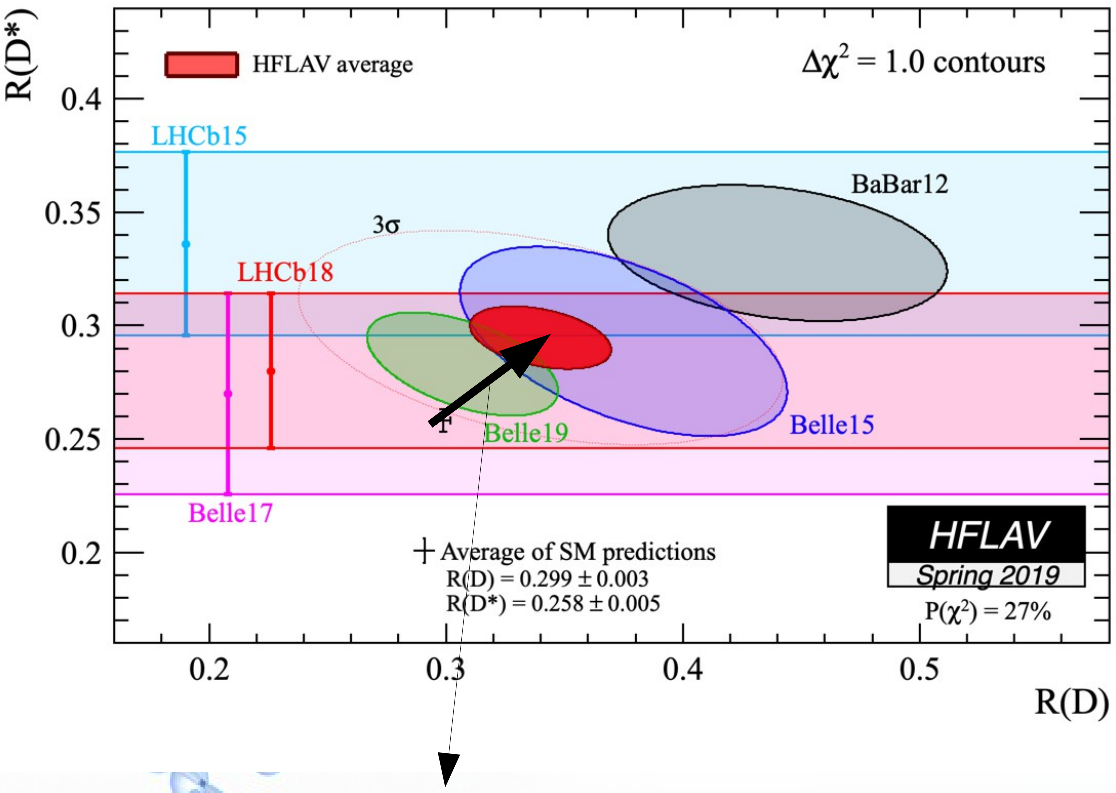


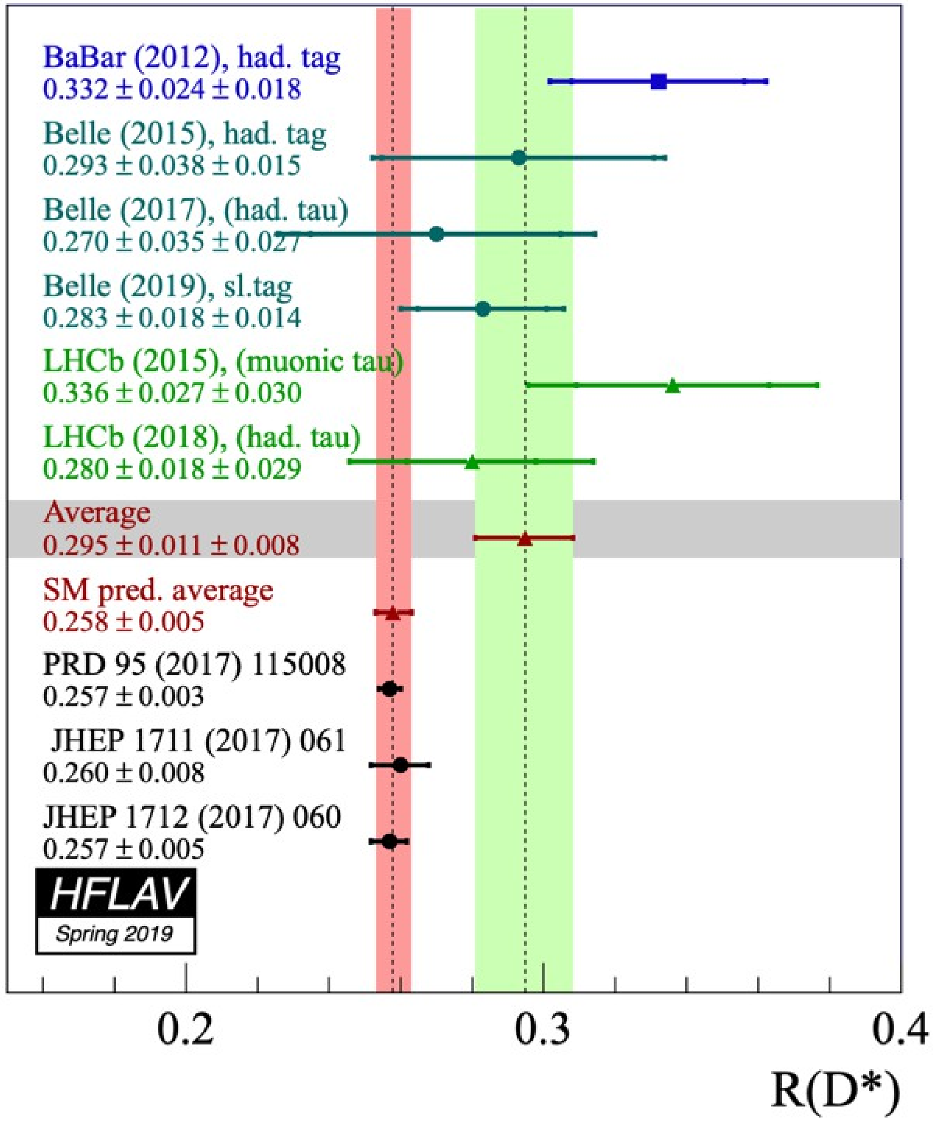
R(D*)=0.291±0.021(stat)±0.026(syst)±0.013(BR)

Complicated analyses with huge MC samples, and many background sources

Global situation for $R(D^{(*)})$

LHCb 2D R(D) & R(D*) analysis currently in internal review



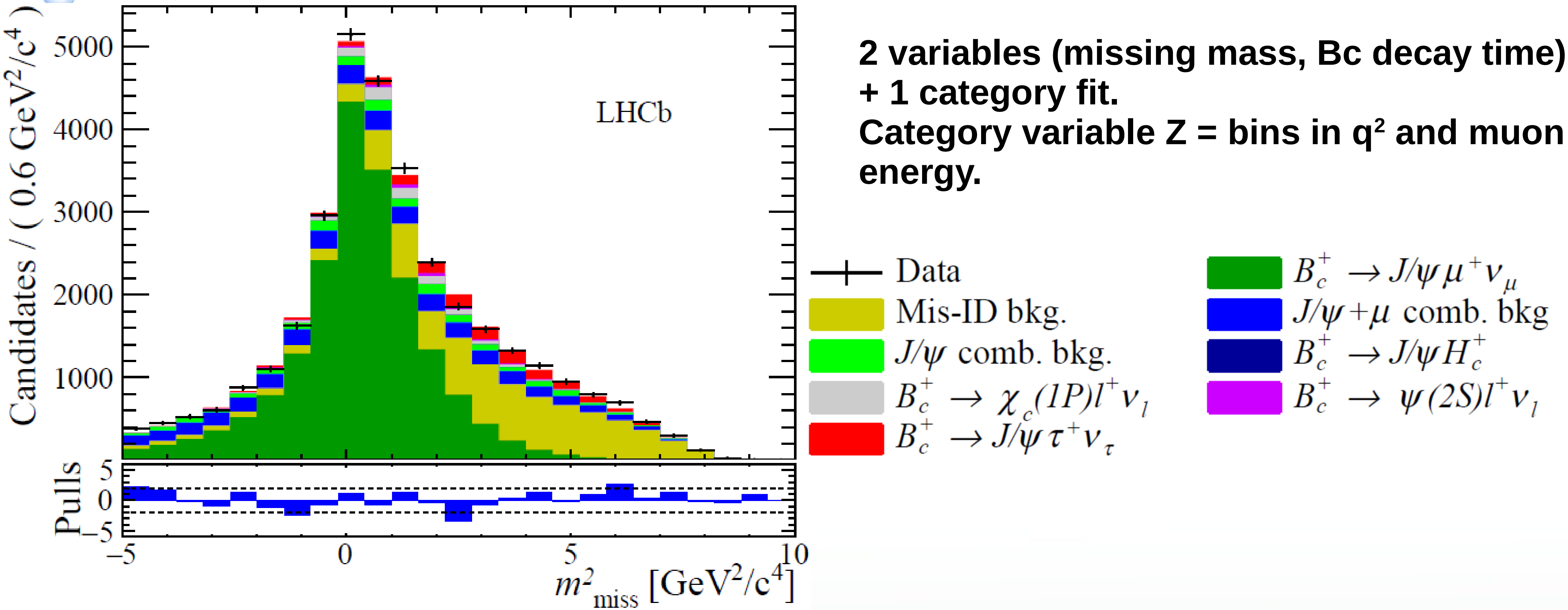


After recent (Belle) result, discrepancy is 3.1σ wrt SM.

$B_c^+ \to J/\psi\, \tau^- \bar{\nu}_\tau$ vs $B_c^+ \to J/\psi\, \mu^- \bar{\nu}_\mu$

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

PRL 120 (2018) 121801
LHCb-PAPER-2017-035



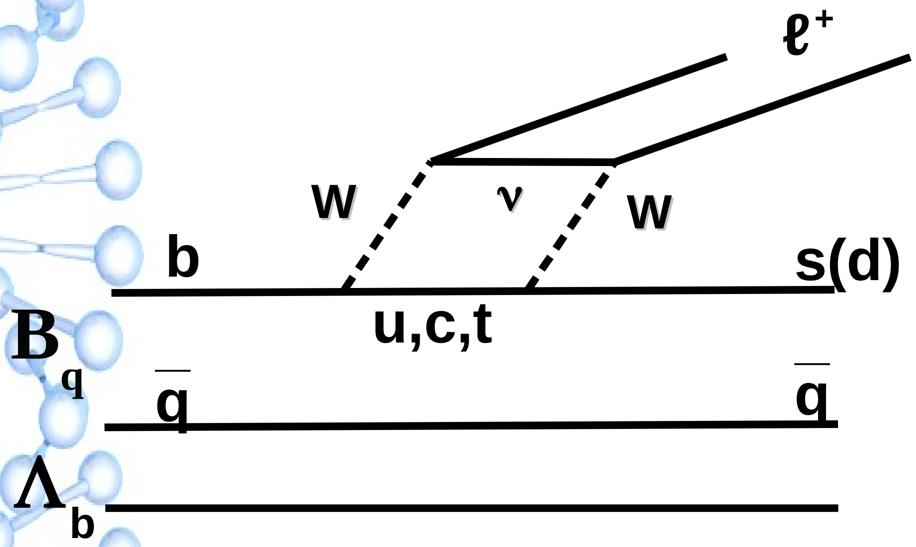
2 variables (missing mass, Bc decay time) + 1 category fit.
Category variable Z = bins in q^2 and muon energy.

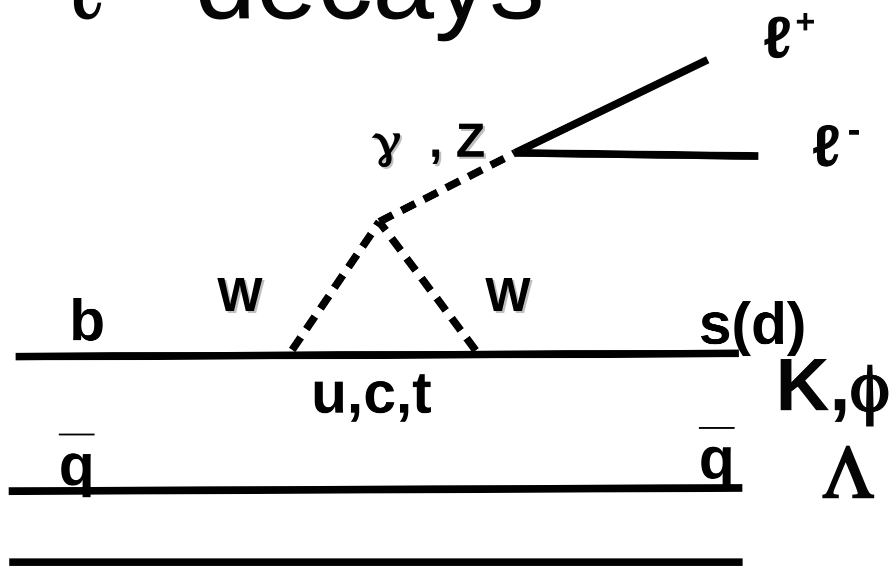
R(J/ψ)=0.71±0.17(stat)±0.18(syst)

2σ above the range of predictions

Available SM-based predictions in the range 0.25 -0.28 e.g. PLB452 (1999) 129, PRD73 (2006) 054024, PRD74 (2006) 074008

$b \to s(d)\ell^+\ell^-$ decays

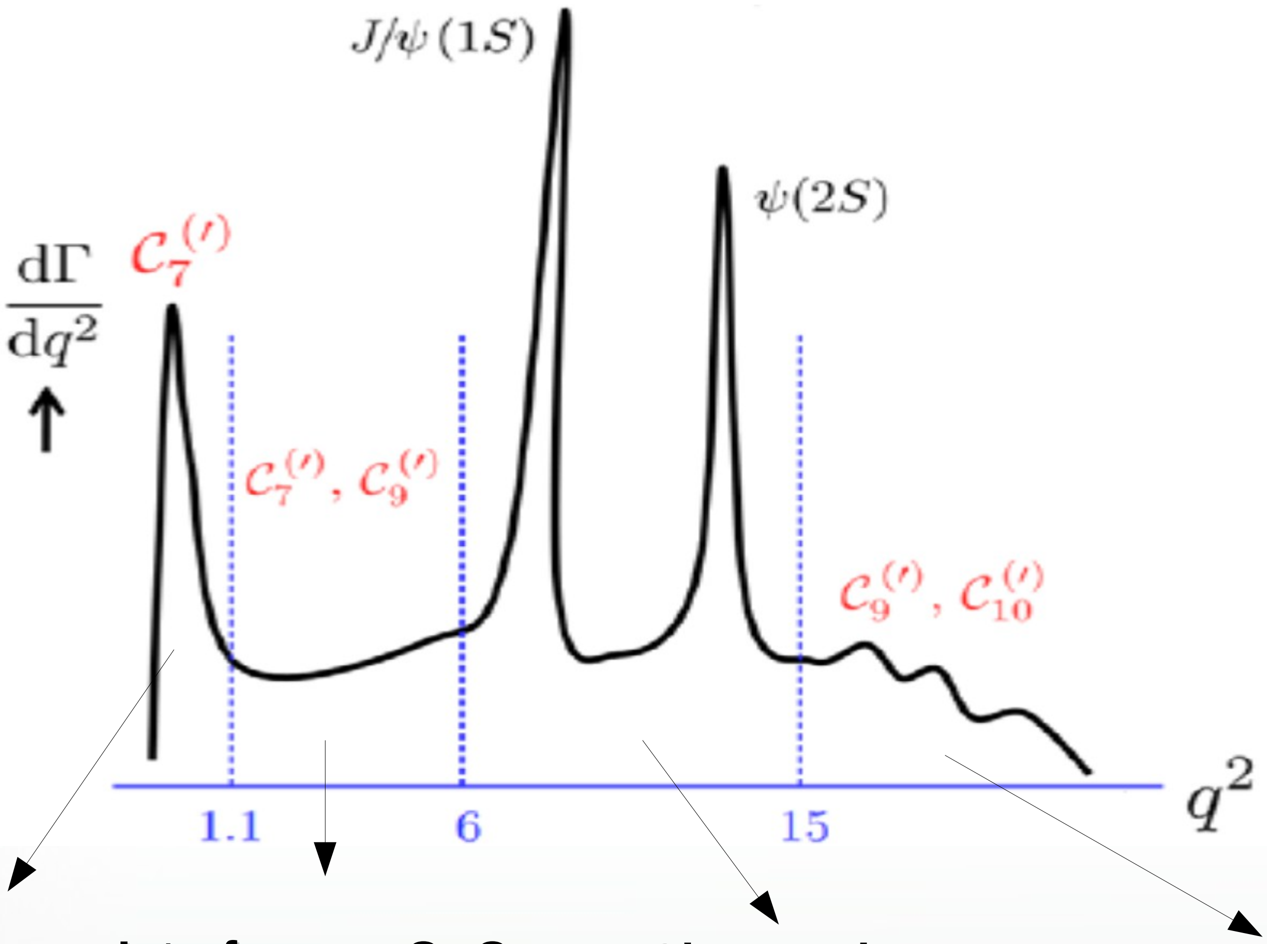




New physics can intervene in the loops/boxes
Can be probed through the analysis of the dynamics of the decays
Or testing, e.g., lepton universality $b \to s\, e^+e^- / b \to s\mu^+\mu^-$
Dominated by O_7, O_9, O_{10} operators

See Da Yu Tou, Rare Decays parallel session, Tuesday

$b \to s(d)\ell^+\ell^-$: contribution of operators vs q^2



O_7 dominated Photon pole (e.g., for K* mode) below 0.045 GeV^2

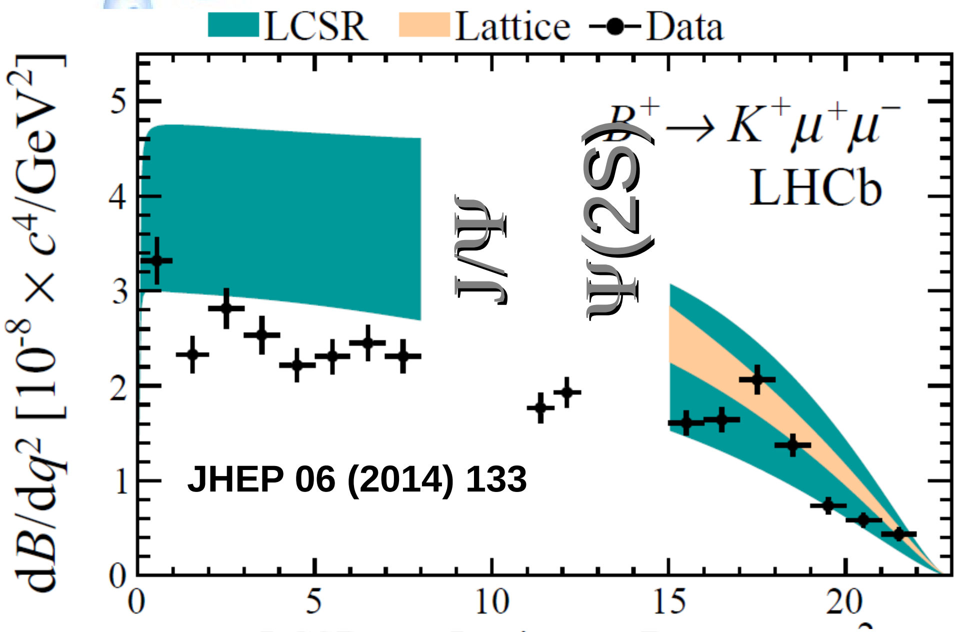
Interference O_7-O_9

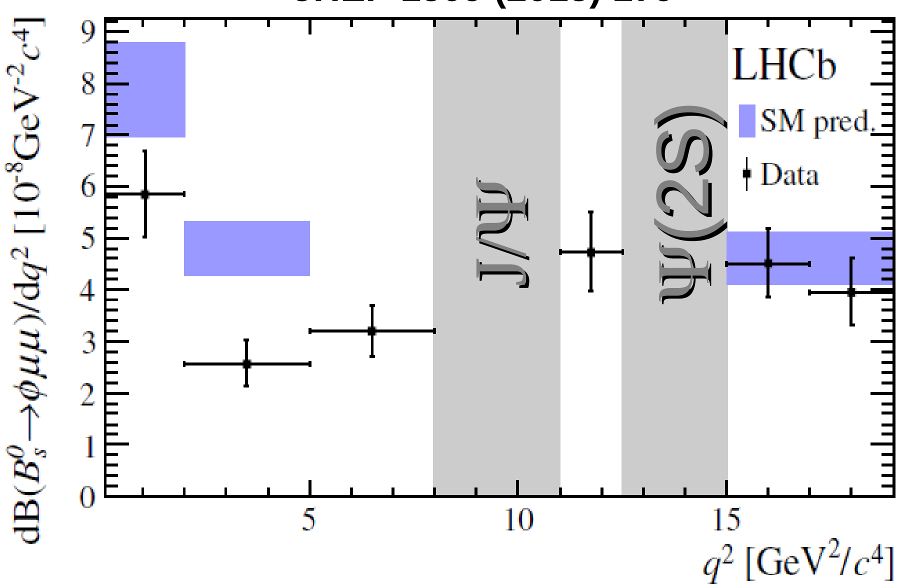
Charmonium

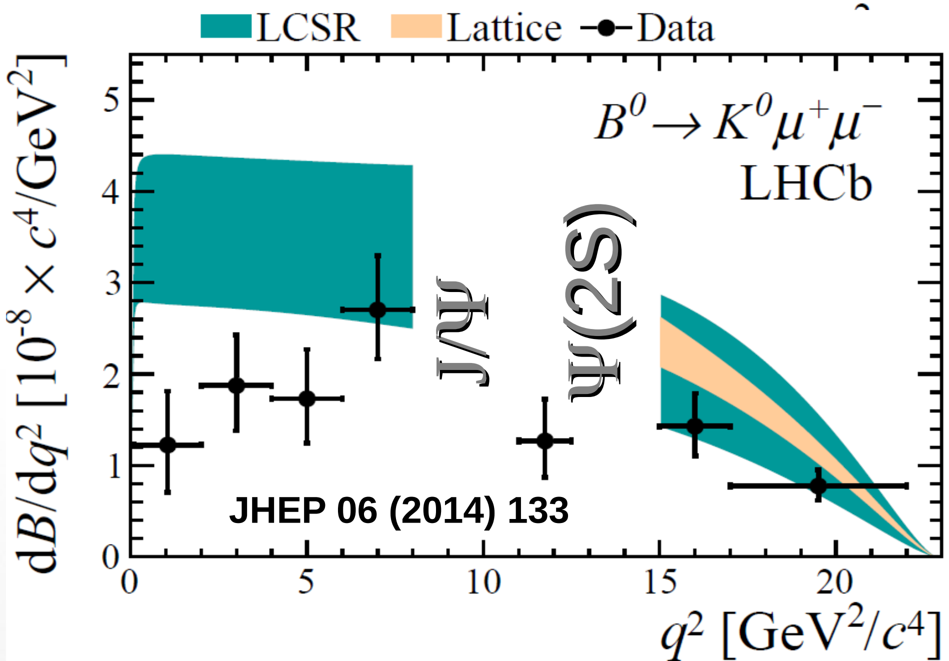
Interference O_9-O_{10}

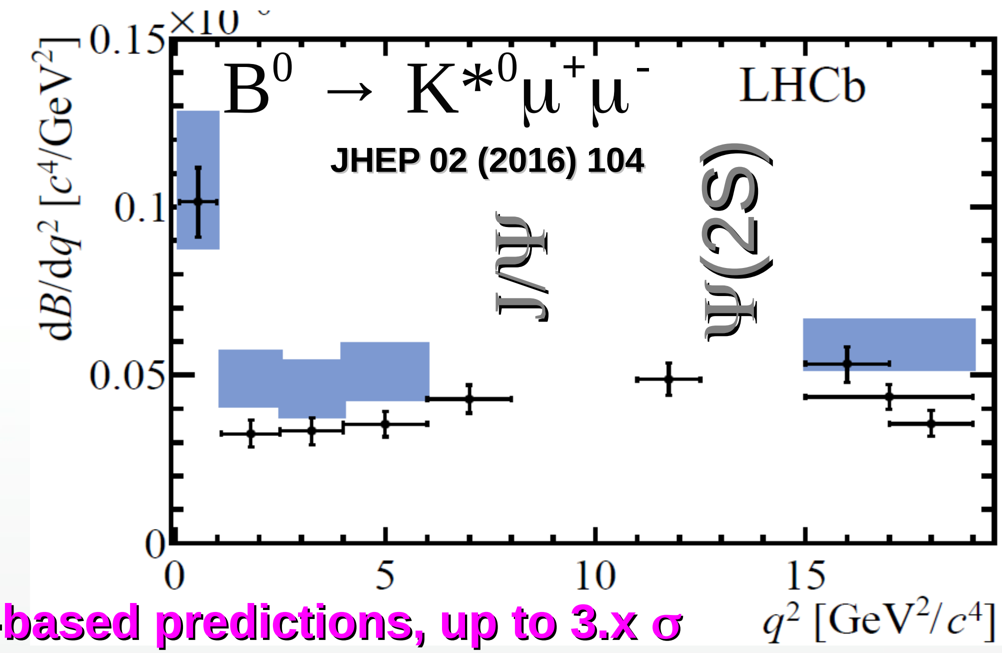
$B \rightarrow X\,\mu^{+}\mu^{-}$ $d\Gamma/dq^2$ spectra

$$q^2 = (P_B - P_X)^2$$









Data tends to be systematically below the SM-based predictions, up to 3.x σ

Dynamics for $B^0 \to K^{*0}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$

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

$q^2 = \mu^+\mu^-$ invariant mass squared

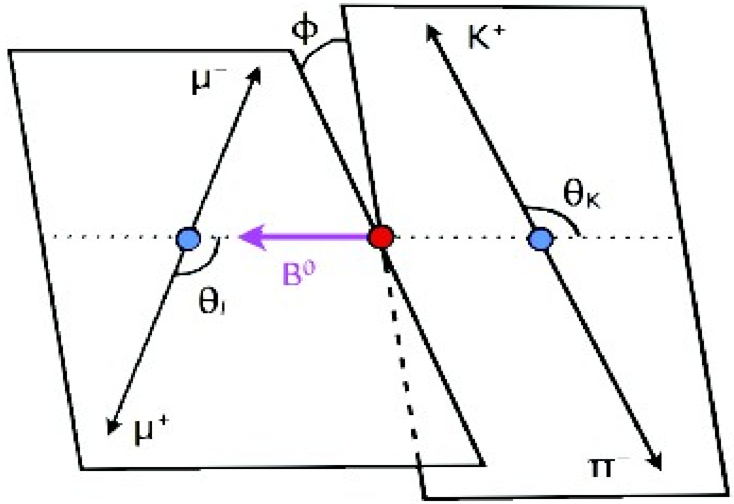
Formula slightly different between K* (self-tagging) and ϕ

F_L: fraction of longitudinal polarization of K*/ϕ

A_{FB} = forward-backward asymmetry of the dimuon system

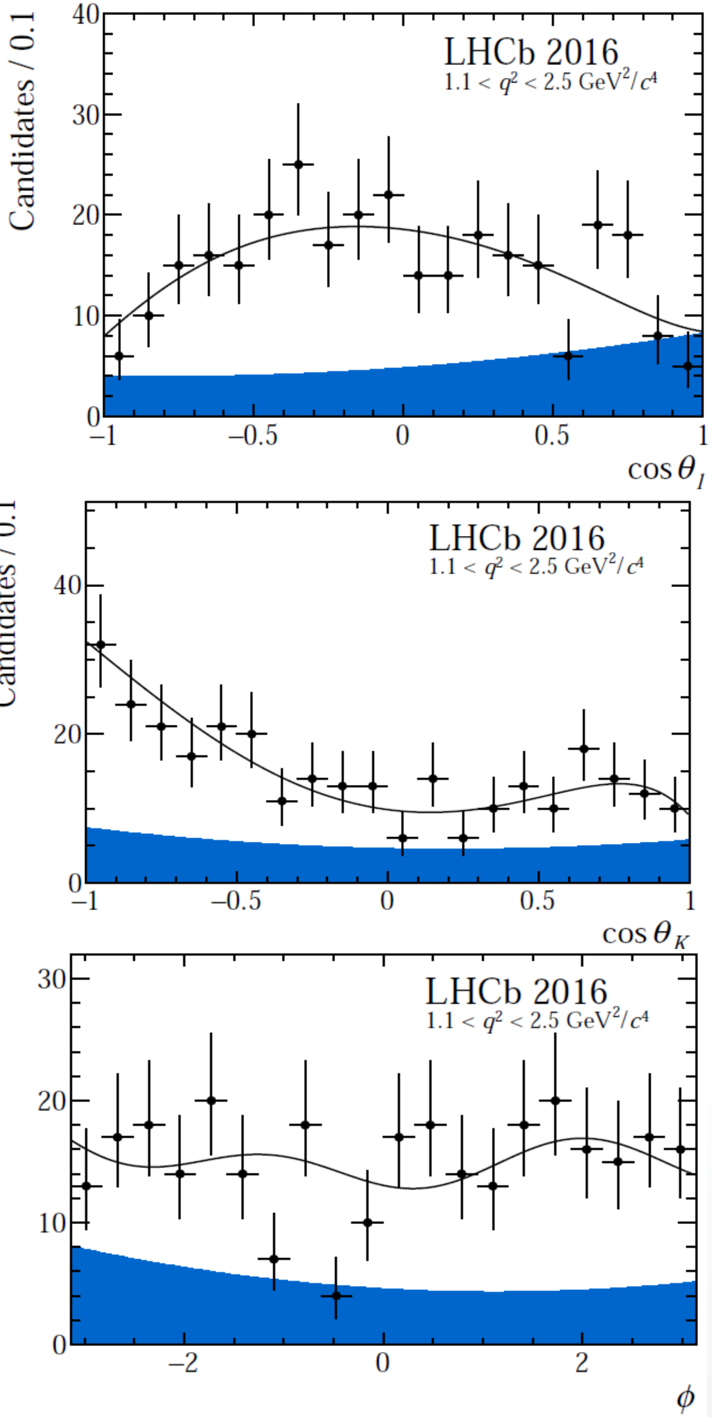
$S_5 = A_5$ in the case of ϕ

They depend on B→K*/ϕ form factors and Wilson Coefficients of the OPE



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

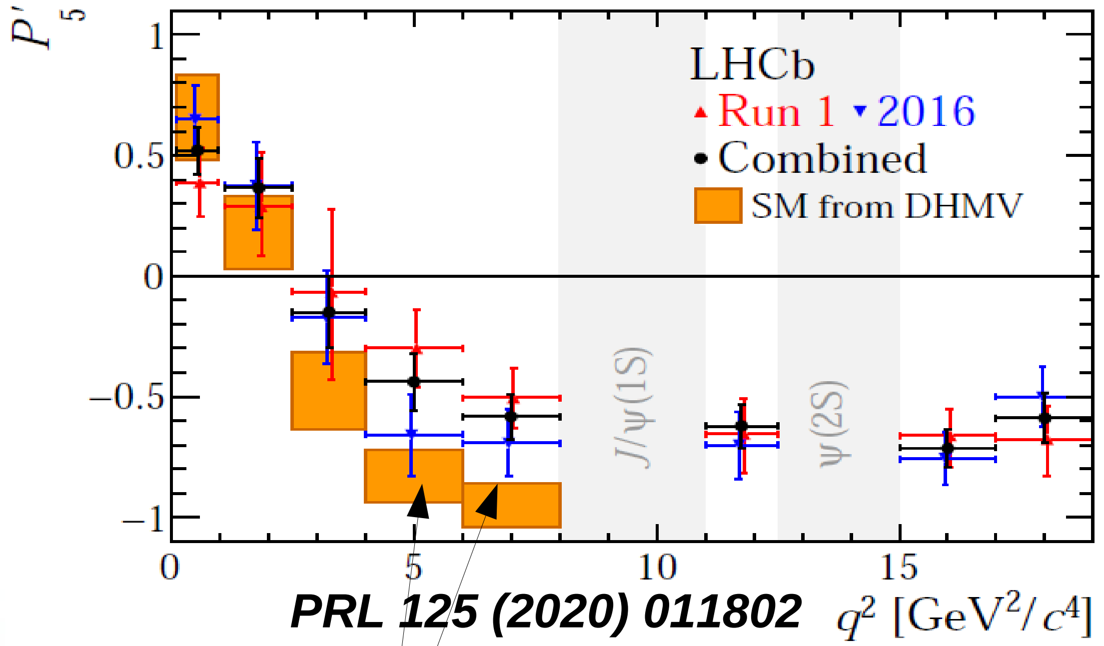
(Run1+2016)



Form-factor independent (LO):

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_{\rm L}(1-F_{\rm L})}} \qquad P'_6 = \frac{S_7}{\sqrt{F_{\rm L}(1-F_{\rm L})}}$$

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



PRL 125 (2020) 011802

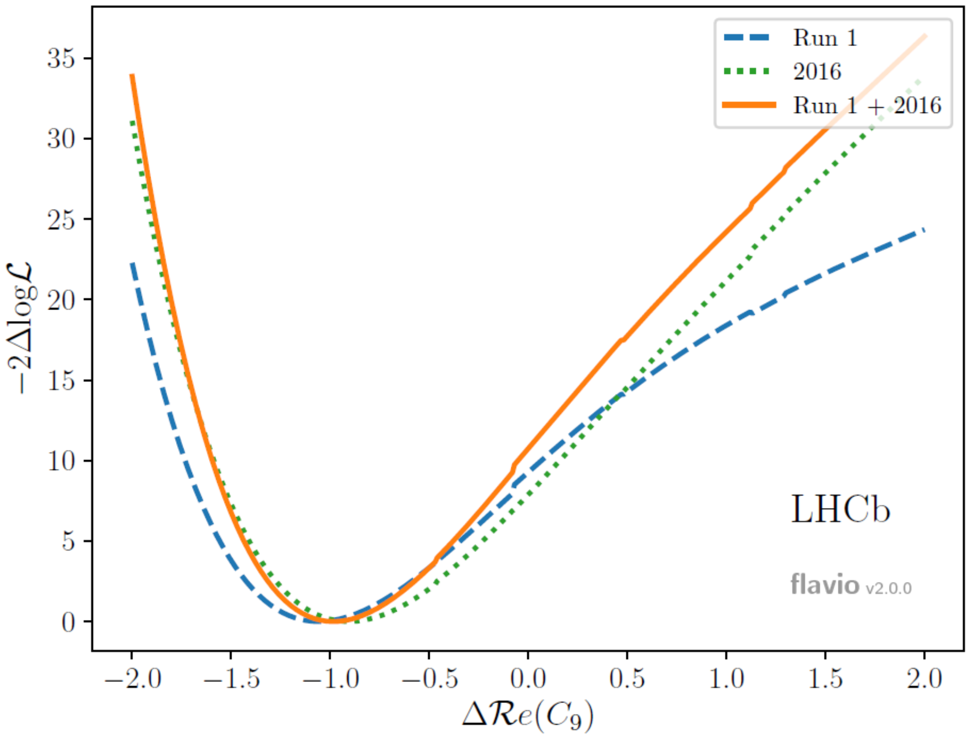
2.5, 2.9σ local discrepancies

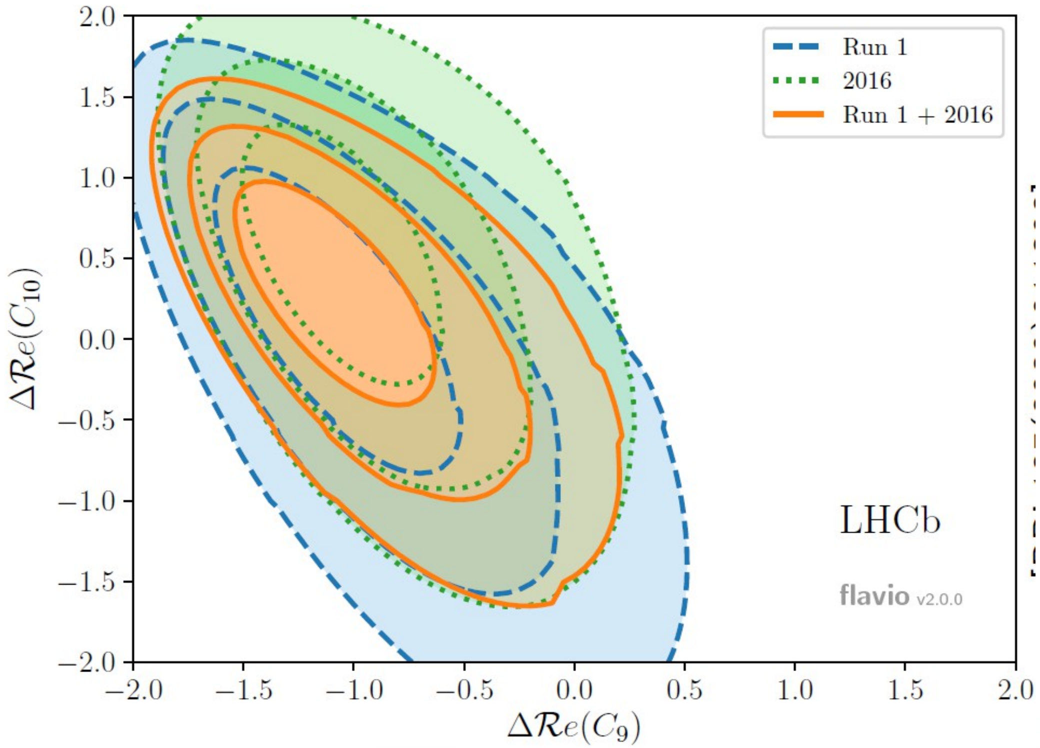
$B^0 \rightarrow K^{*0}\mu^+\mu^-$ fit to Wilson coefficients

combining angular coefficients

$\Delta C_i = C_i - C_i^{SM}$

flavio arXiv:1810.08132





Fit favours ΔC_9 ~-1, discrepancy wrt SM: 3.3σ

R_X ratios

Test of Lepton Flavour Universality: R_K(SM)= 1 (+corrections order < 10^{-3})
(excluding the γ pole for K* mode)

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

PRL 122 (2019) 191801

$$R_{K^{*0}} = \frac{BR(B^0 \to K^{*0} \mu^+ \mu^-)}{BR(B^0 \to K^{*0} e^+ e^-)}$$

JHEP 08 (2017) 055

Experimentally:

$$R_X = \frac{BR(B \to X \mu^+ \mu^-)}{BR(B \to X J/\psi(\mu^+ \mu^-))} / \frac{BR(B \to X e^+ e^-)}{BR(B \to X J/\psi(e^+ e^-))}$$

Minimize systematic uncertainties

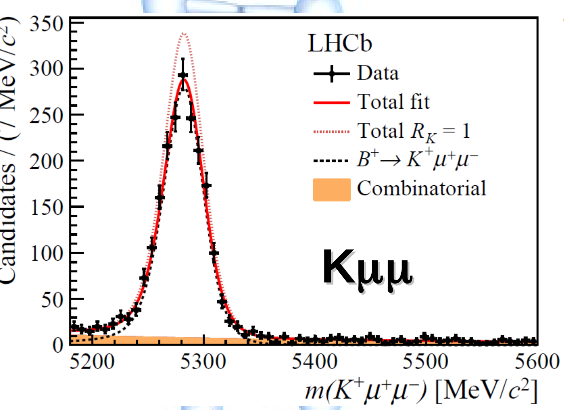
study of $r_{J/\psi} = \frac{BR(B \to X J/\psi(\mu^+ \mu^-))}{BR(B \to X J/\psi(e^+ e^-))}$ **with high accuracy**

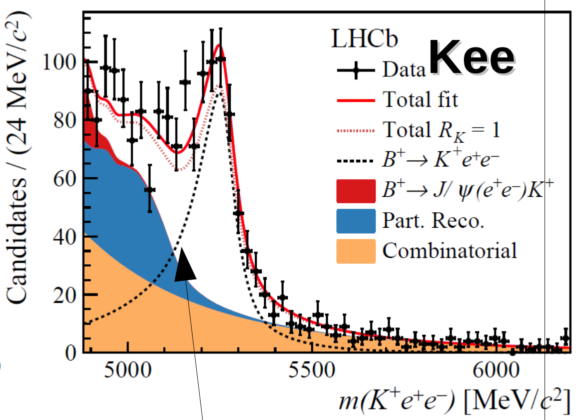
q^2 range: above γ pole and background of type B → φ(→ ℓℓ) K and below J/Ψ radiative tail

R_X ratios - fits

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

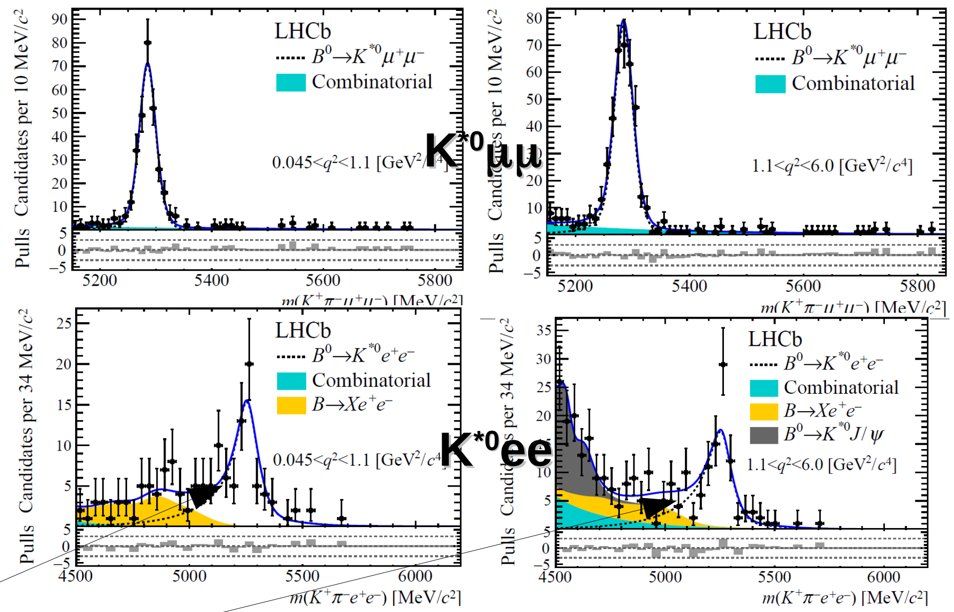
1.1 GeV² < q²< 6 GeV²





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

0.045 GeV² < q²< 1.1 GeV² **1.1 GeV² < q²< 6 GeV²**

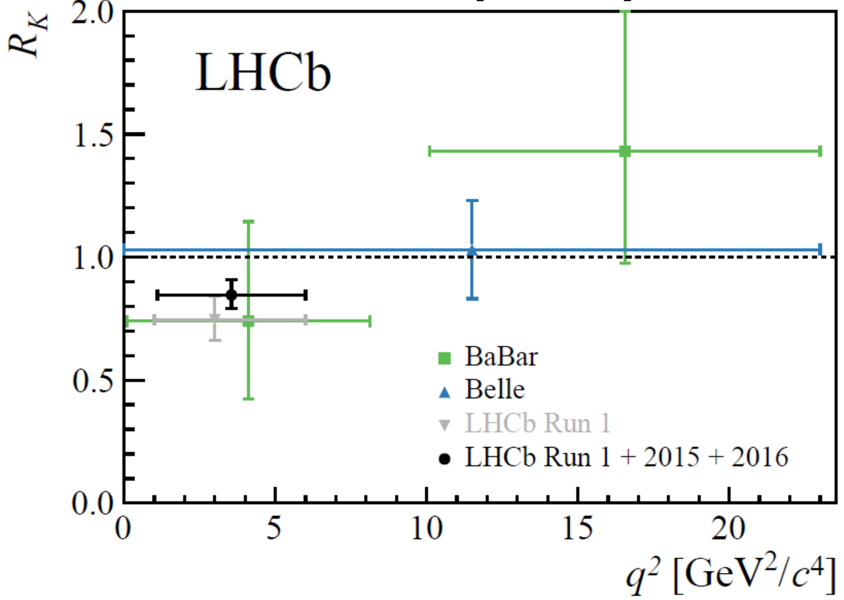


Radiative Bremsstrahlung tail for electron modes

R_X ratios, results

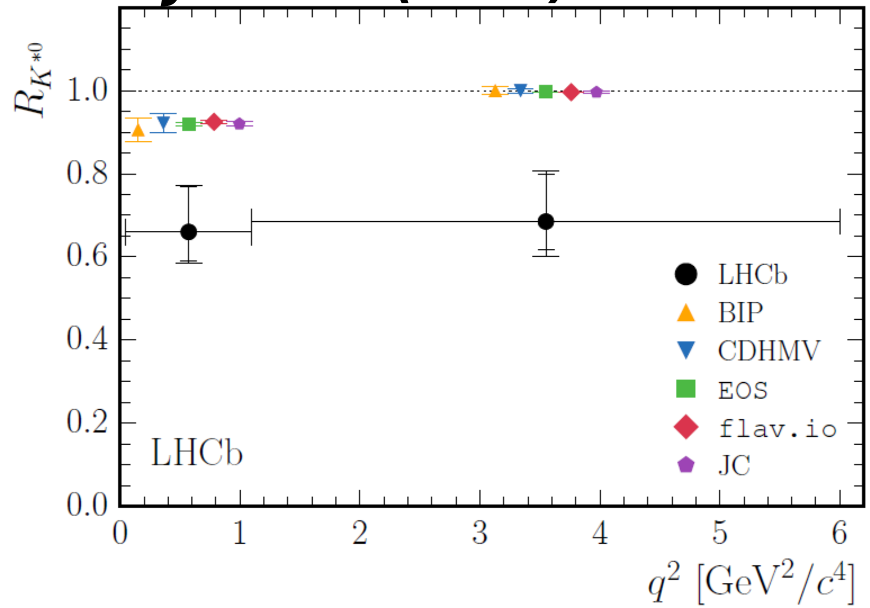
$B^+ \to K^+\ell^+\ell^-$

PRL 122 (2019) 191801



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

JHEP 08 (2017) 055



$$R_K = 0.846^{+0.060}_{+0.054}(stat.)^{+0.016}_{+0.014}(syst.)$$

2.5σ below SM-based predictions

Update with full Run1+Run2 currently in internal review

$0.045\ GeV^2 < q^2 < 1.1\ GeV^2$

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

2.1-2.3σ below SM

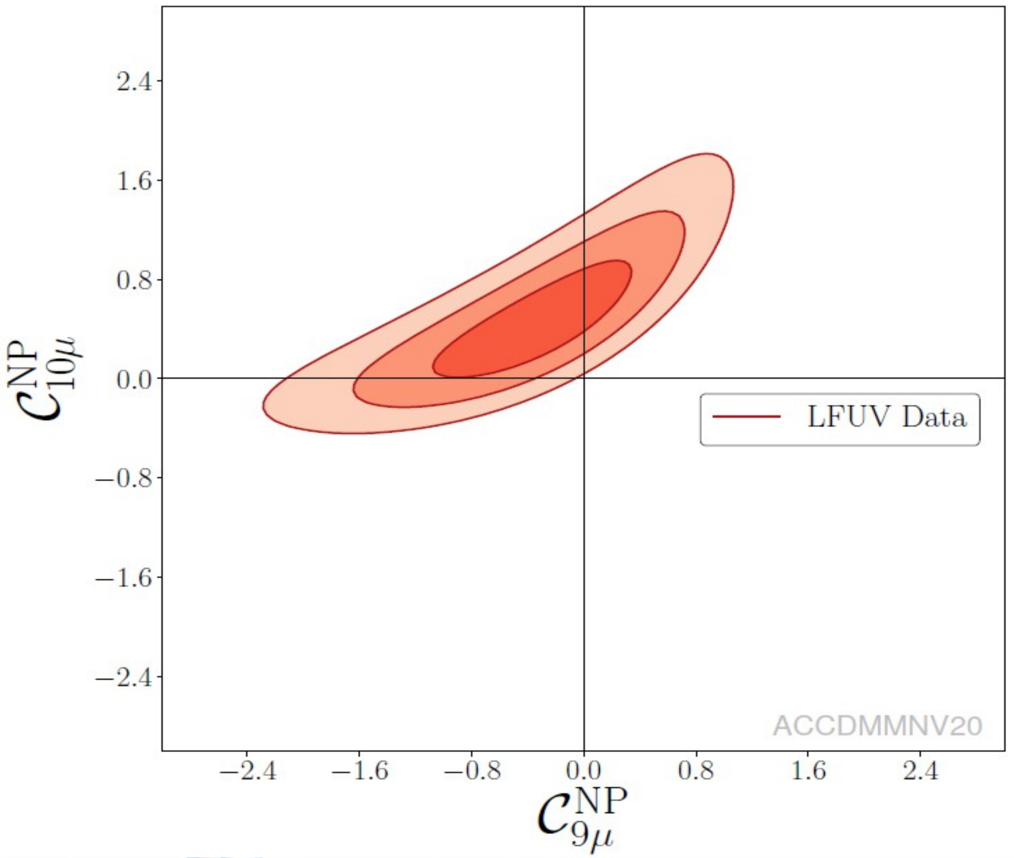
$1.1\ GeV^2 < q^2 < 6\ GeV^2$

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

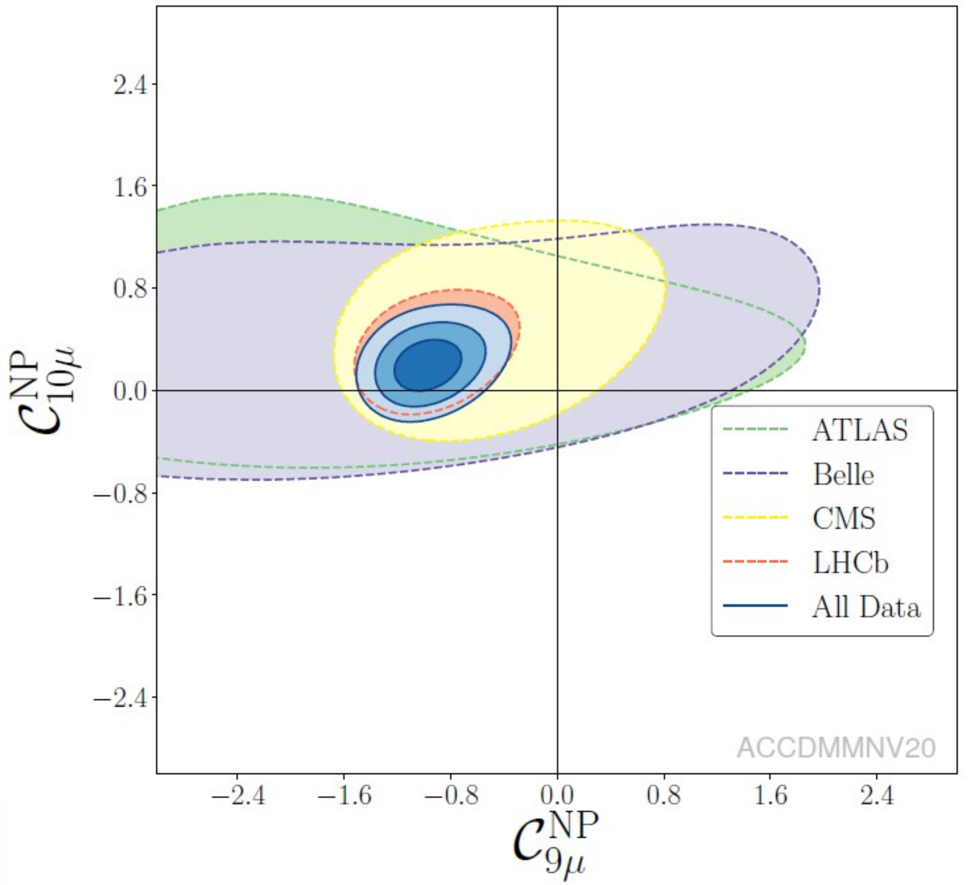
2.4-2.5σ below SM

From R_K and R_{K*} to fits to Wilson coefficients

LFUV only
Belle and LHCb data involved



LFUV + angular analyses



EPJC 79, 714 (2019)

Updated June 2020 https://arxiv.org/abs/1903.09578 v6

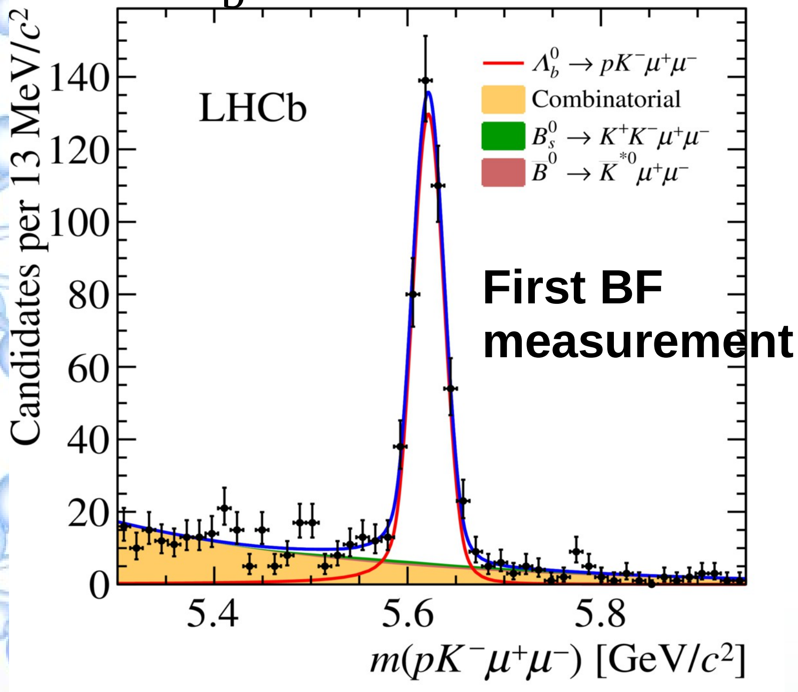
JHEP05 (2020) 040

R(pK), $\Lambda_b \rightarrow pK\ell^+\ell^-$

$0.1 < q^2 < 6.0$ GeV^2
m(pK)<2600 MeV/c^2

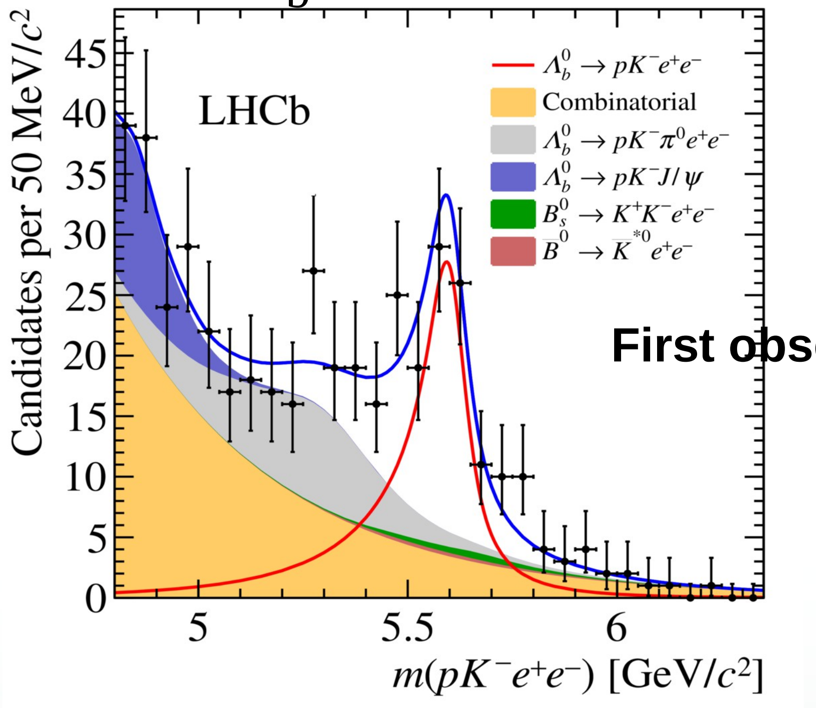
Same technique as for R_K, use of J/Ψ mode as normalization to reduce systematics

$\Lambda_b \rightarrow pK\mu^+\mu^-$



First BF measurement

$\Lambda_b \rightarrow pKe^+e^-$

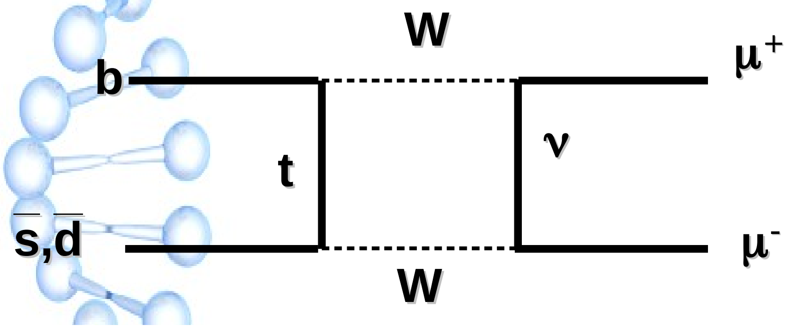


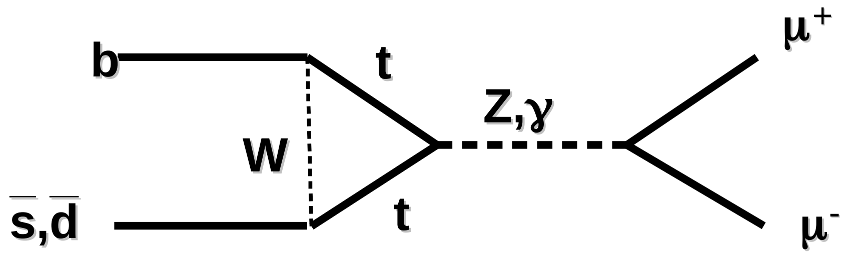
First observation

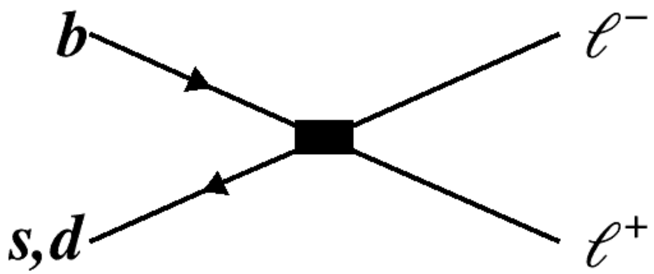
$$R_{pK} = 0.86^{+0.14}_{+0.11}(stat.) \pm 0.05(syst.)$$

Compatible with unity for now

$B \to \ell^+ \ell^-$ decays







Contribution from $O_{10}(')$
and

$$O_S(') = (\bar{s}\, b)_{V \pm A} (\bar{\ell}\, \ell)$$
$$O_P(') = (\bar{s}\, b)_{V \pm A} (\bar{\ell}\, \ell)_P$$

SM-based predictions:

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

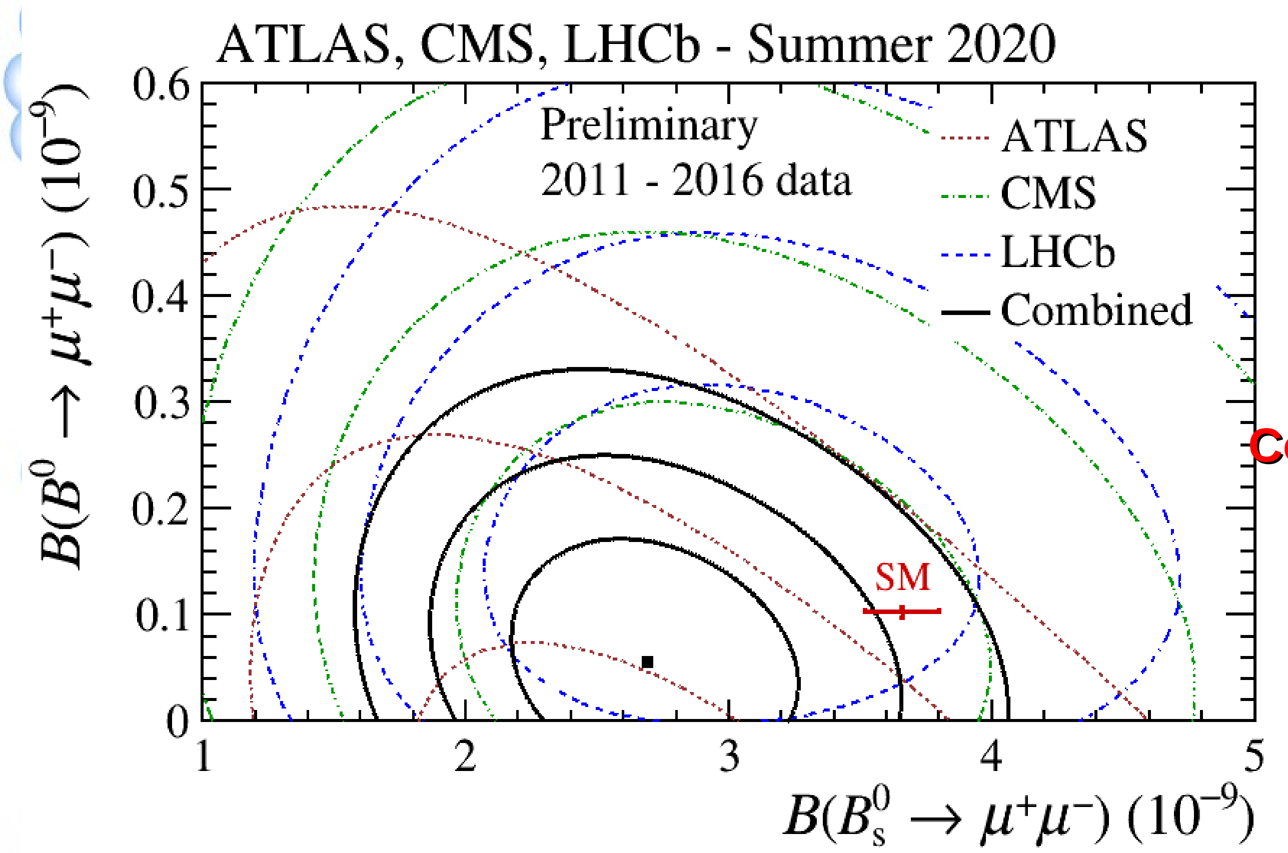
See I.Williams, Rare Decays parallel session, Tuesday
For details on experimental status

C.Bobeth et al., PRL 112 (2014) 101801

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

Recent combination (08/2020)
LHCb-CONF-2020-002
CMS PAS BPH-20-003
ATLAS-CONF-2020-049

Based on
LHCb (PRL 118 (2017) 191801)
ATLAS (JHEP 04 (2019) 098)
CMS JHEP 04 (2020) 188



Combination within 2.1σ of SM

On going:
LHCb full Run 1 + Run 2 results

$$BR(B_s^0 \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$$

$$BR(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10}\ @\ 95\%\ CL$$

LHCb
PRL 124 (2020) 211802

$B \to e^{+}e^{-}$

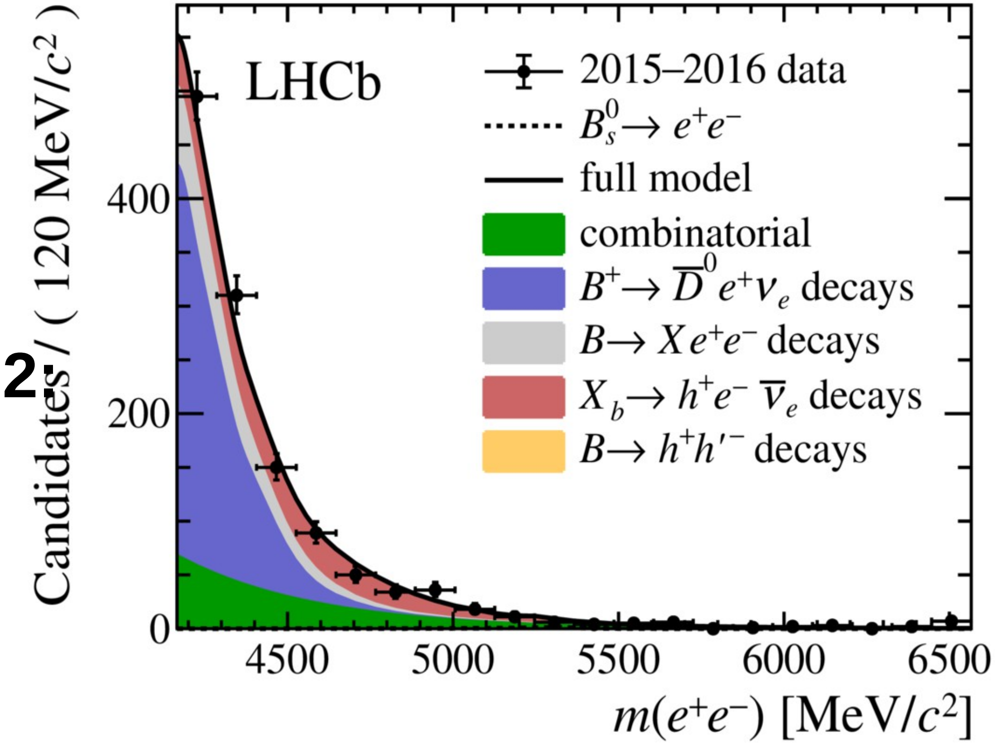
SM-based predictions:

$$BR(B^0 \to e^+ e^-) = (2.41 \pm 0.13) \times 10^{-15}$$
$$BR(B_s^0 \to e^+ e^-) = (8.60 \pm 0.36) \times 10^{-14}$$

M. Beneke et al., JHEP 10 (2019) 232
Fleischer et al., JHEP 05 (2017) 156

Analysis with Run 1 + part of Run 2:

No excess of events/background



$$BR(B_s^0 \to e^+ e^-) < 9.4\,(11.2) \times 10^{-9} \;@\; 90\,(95)\,\%\,CL$$

$$BR(B^0 \to e^+ e^-) < 2.5\,(3.0) \times 10^{-9} \;@\; 90\,(95)\,\%\,CL$$

LFV searches

If LFUV confirmed, what about LFV?, e.g.:
B → ℓℓ’, b → (s,d)ℓℓ’

Recent LHCb searches:

$B^0_{(s)} \to \tau^+\mu^-$ *PRL 123 (2019) 211801*

$$BR(B^0 \to \tau^+\mu^-) < 1.4 \times 10^{-5} @ 95\% CL$$

$$BR(B^0_s \to \tau^+\mu^-) < 4.2 \times 10^{-5} @ 95\% CL$$

$B^+ \to K^+ \mu^\pm e^\mp$ *PRL 123 (2019) 241802*

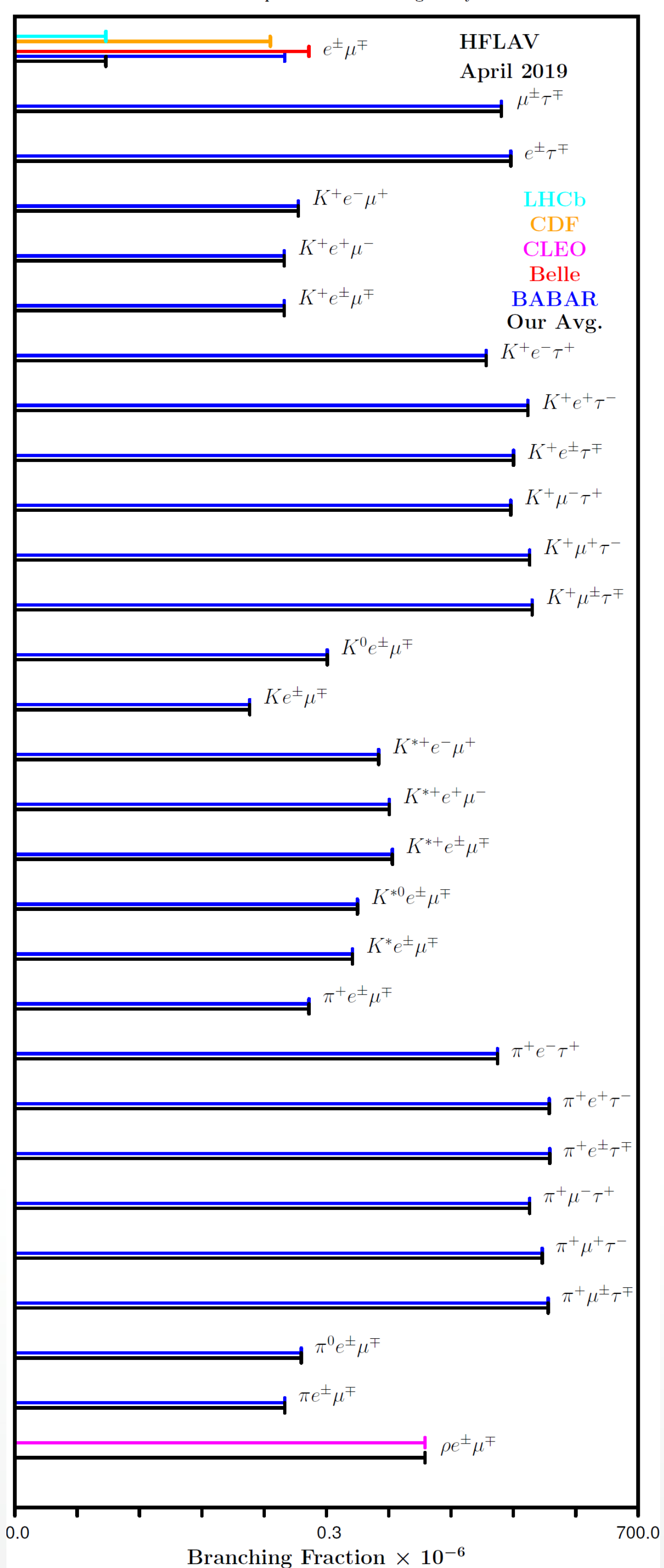
$$BR(B^+ \to K^+\mu^- e^+) < 9.5 \times 10^{-9} @ 95\ CL$$

$$BR(B^+ \to K^+\mu^+ e^-) < 8.8 \times 10^{-9} @ 95\ CL$$

$B^+ \to K^+ \mu^- \tau^+$ *JHEP 06 (2020) 129*

$$BR(B^+ \to K^+\mu^-\tau^+) < 4.5 \times 10^{-5} @ 95\ CL$$

See I.Williams, Rare Decays parallel session, Tuesday



Prospects for LFU – finishing Run 2

Semileptonic LFU, ongoing effort:

$R(D^0)$: $B^+ \rightarrow D^0 \tau \nu$
$R(D^+)$: $B^0 \rightarrow D^+ \tau \nu$
$R(Ds^{(*)})$: $B_s \rightarrow D_s^{(*)} \tau \nu$
$R(\Lambda_c^{(*)})$: $\Lambda_b \rightarrow \Lambda_c^{(*)} \tau \nu$
$R(J/\Psi)$: $B_c \rightarrow J/\Psi \tau \nu$
$R(p)$: $\Lambda_b \rightarrow p \tau \nu$

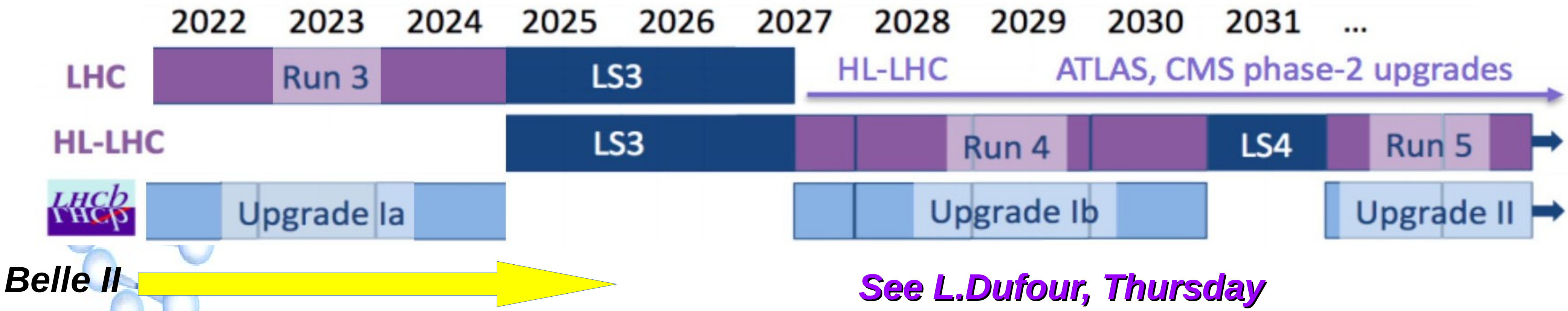
EW Penguin:

Expected precisions with full Run1+Run2

R_X precision	9 fb^{-1}
R_K	0.043
$R_{K^{*0}}$	0.052
R_ϕ	0.130
R_{pK}	0.105
R_π	0.302

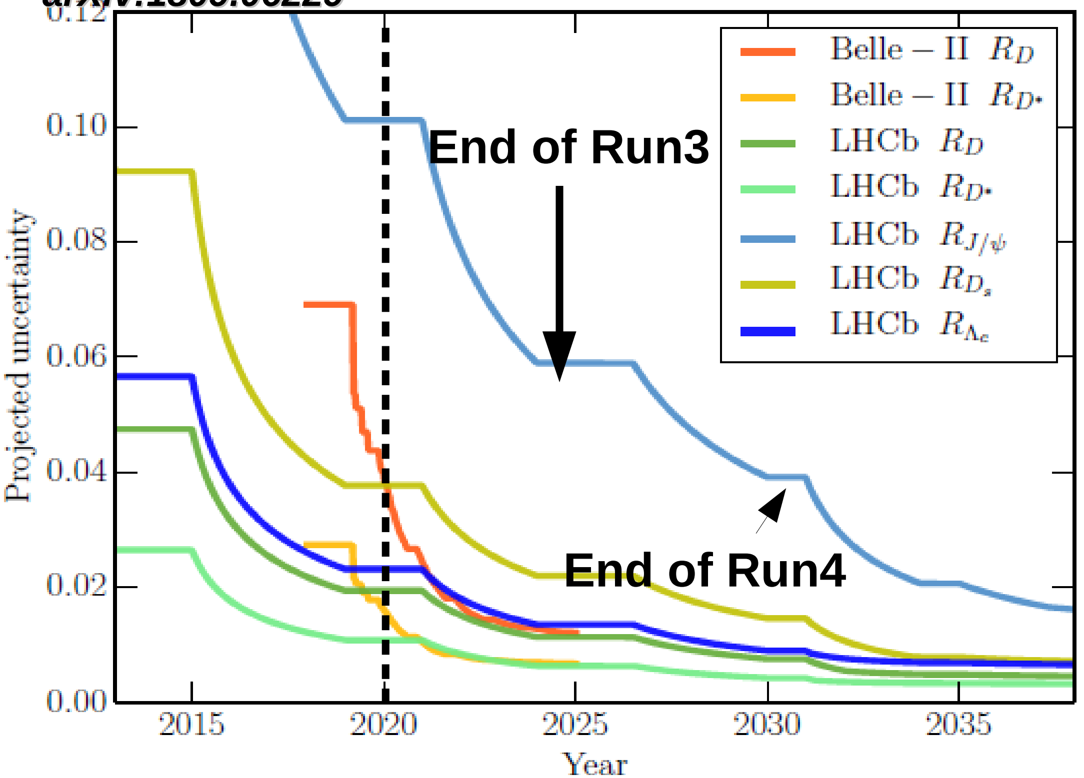
CERN-LHCC-2018-027, LHCB-PUB-2018-009, arXiv:1808.08865

Prospects for LFU, upgrades



See L.Dufour, Thursday
HL-LHC upgrade & LHCb

J. Phys. G: Nucl. Part. Phys. 46 (2019) 023001
arXiv:1809.06229



Tree b → c ℓ ν

	Run3	Run4	Run5
precision	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
R_K	0.025	0.017	0.007
$R_{K^{*0}}$	0.031	0.020	0.008
R_ϕ	0.076	0.050	0.020
R_{pK}	0.061	0..041	0.016
R_π	0.176	0.117	0.047

CERN-LHCC-2018-027, LHCB-PUB-2018-009, arXiv:1808.08865

Loop b → s(d)$\ell^+\ell^-$

Conclusion

- Some persisting anomalies
  - LFUV tests 2-4 σ discrepancies
  - No LFV so far
- EFT analyses are becoming more and more accurate
  - Significance of NP contributions to Wilson coefficients becoming intriguing, e.g. for C_9
  - Global fit to WC are model-independent but models involving vector leptoquarks (JHEP 11 (2017) 044) or 4321 model (PRD 96, (2017) 115011, JHEP 11 (2018) 081) are regularly put forward
  - Any model is constrained by B_s mixing for $b \to s$ transitions (LFU EW penguins) and B_c lifetime for $b \to c$ (semileptonic LFU)
- Near future: more results and combinations are coming with analysis of the second half of Run 2
- Excellent prospects for Run 3 and after, fundamental role of Flavour Physics

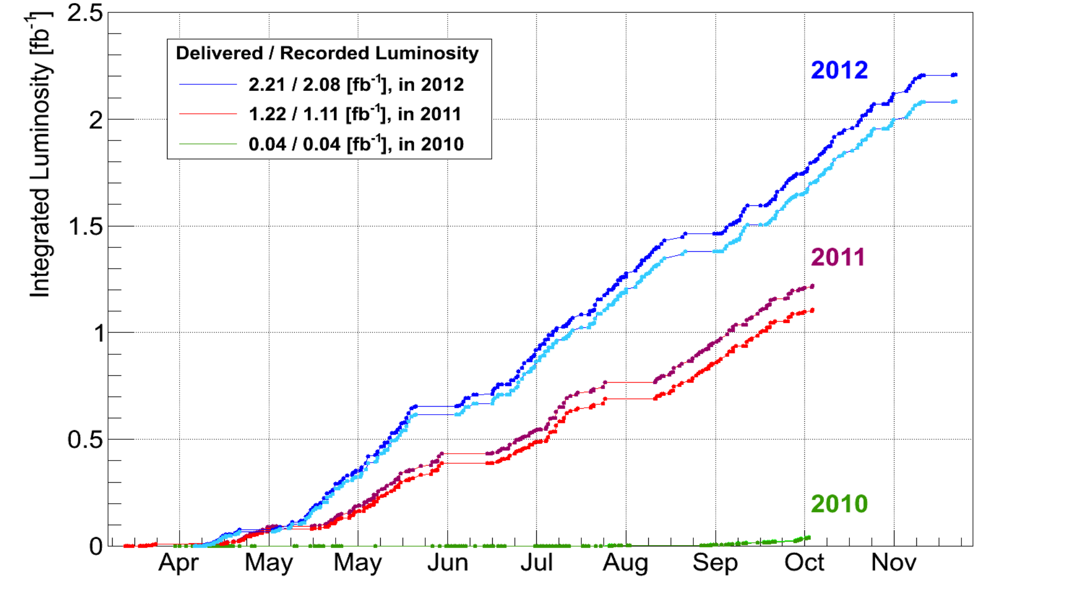
Back up

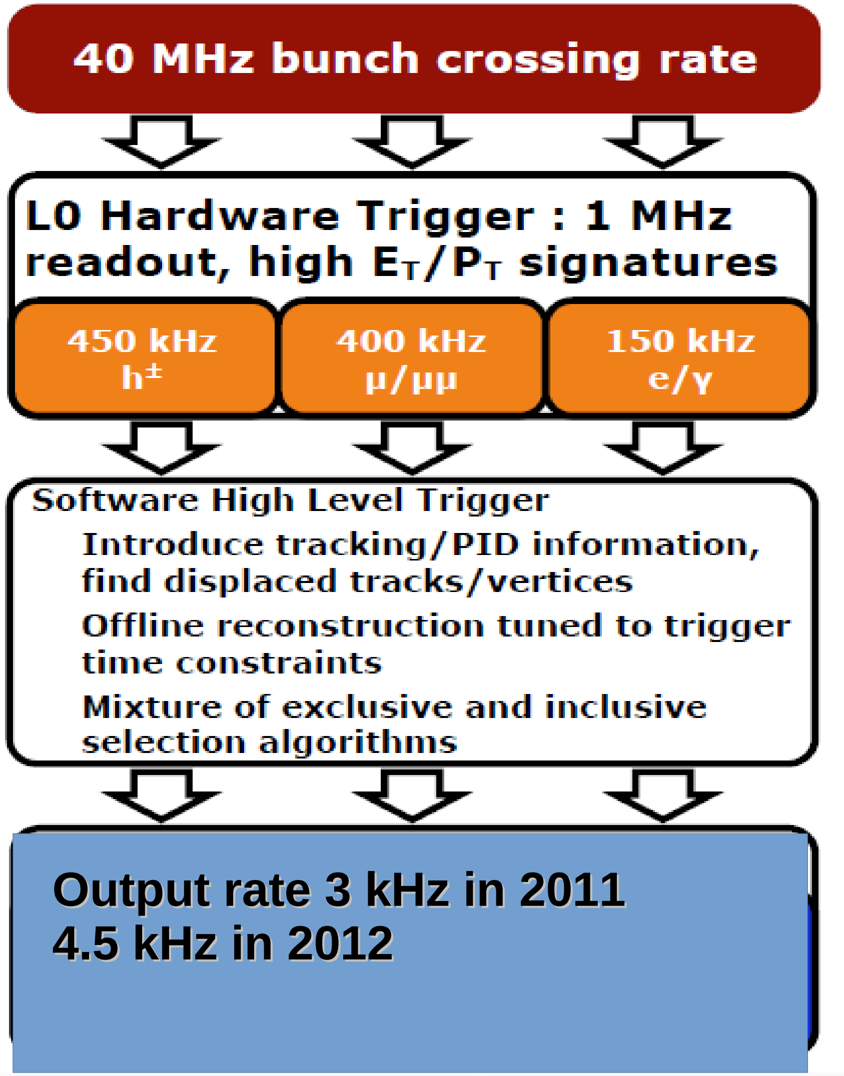
LHCb data (2011+2012) – Run I

10^{11} protons per bunch colliding at 7 (2011) and 8 (2012) TeV

Luminosity at IP8 (LHCb): 2-4 x 10^{32} cm^{-2} s^{-1}
About 1500 charged particles produced at each pp collision
$\sigma(b\bar{b})$ ~ 75 μb @ 7 TeV* in LHCb acceptance
J. High Energy Phys.08 (2013) 117

Dominated by B^+ (f_u) and B^0 (f_d) species but also B_s, $f_s/(f_u + f_d)$ ~ 0.134, b-baryons ($f(\Lambda_b)/(f_u + f_d)$ ~ 0.240)
Traces of Bc, Eur. Phys. J. C77 (2017) 895





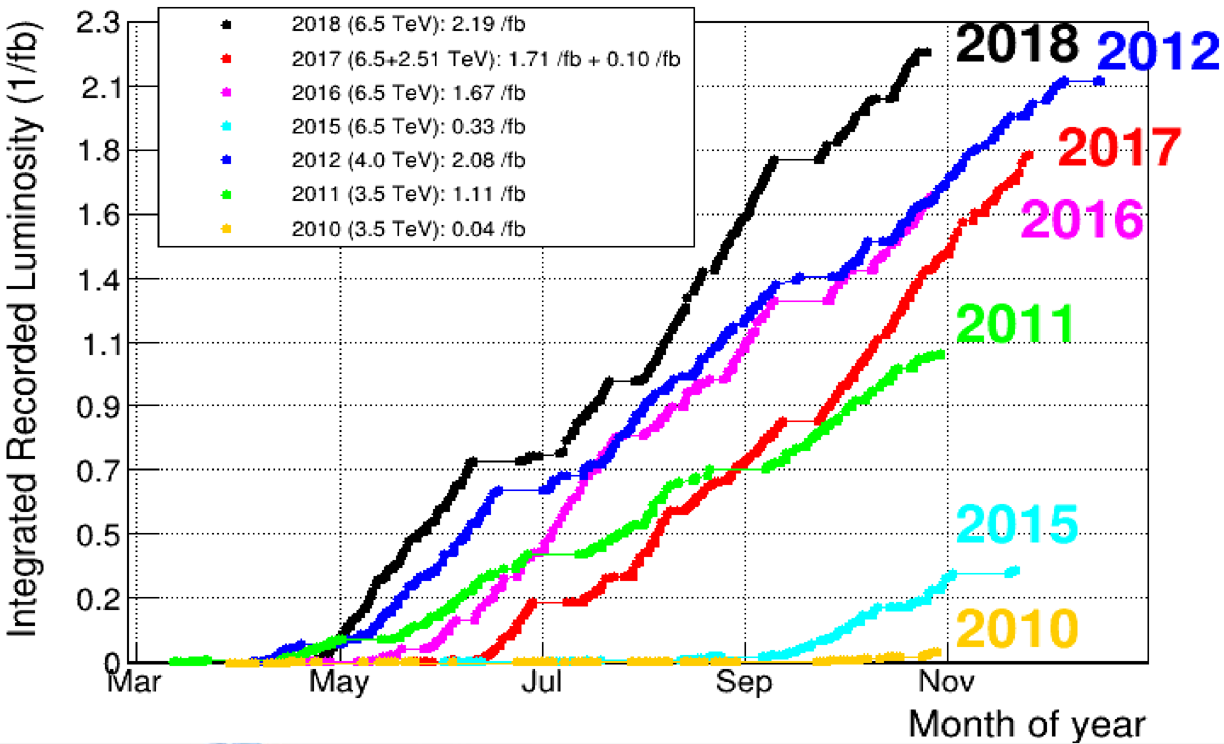
LHCb data (2015-2018) – Run II

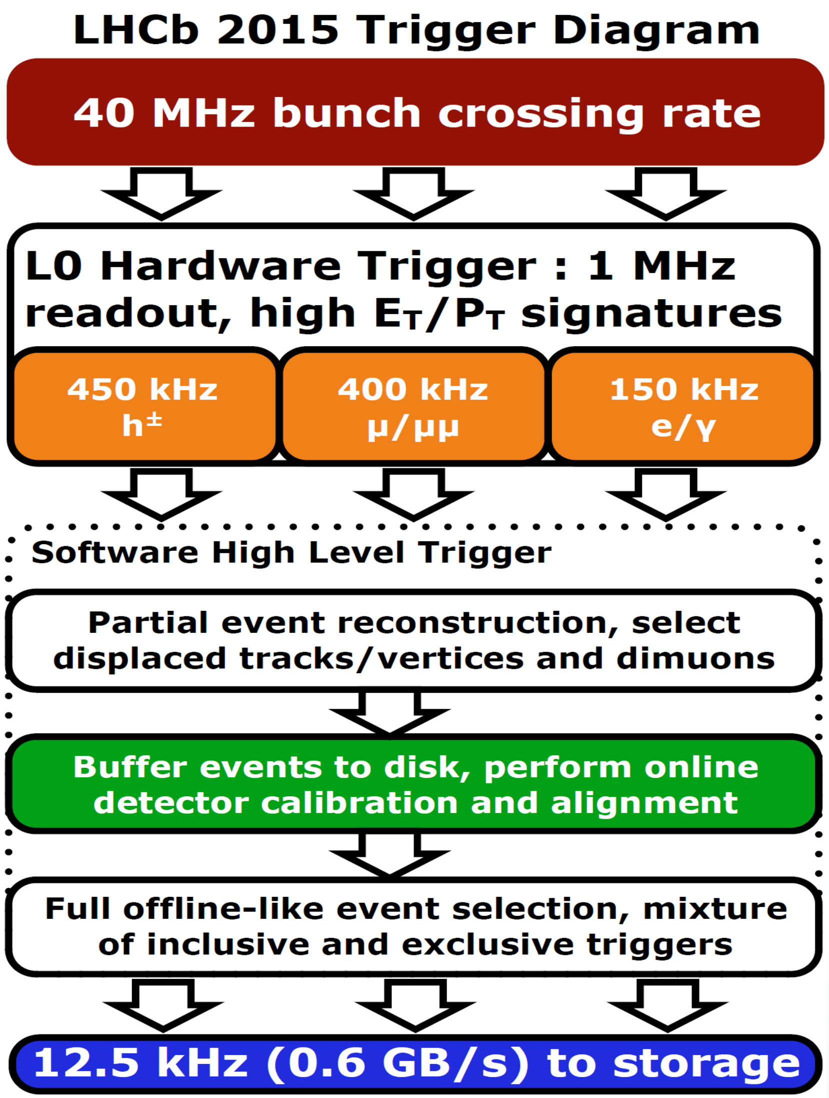
Bunch colliding at 13 TeV

$\sigma(b\bar{b})$ ~ 165 μb @ 13 TeV* in LHCb acceptance
About 2.3 times the value @ 7-8 TeV

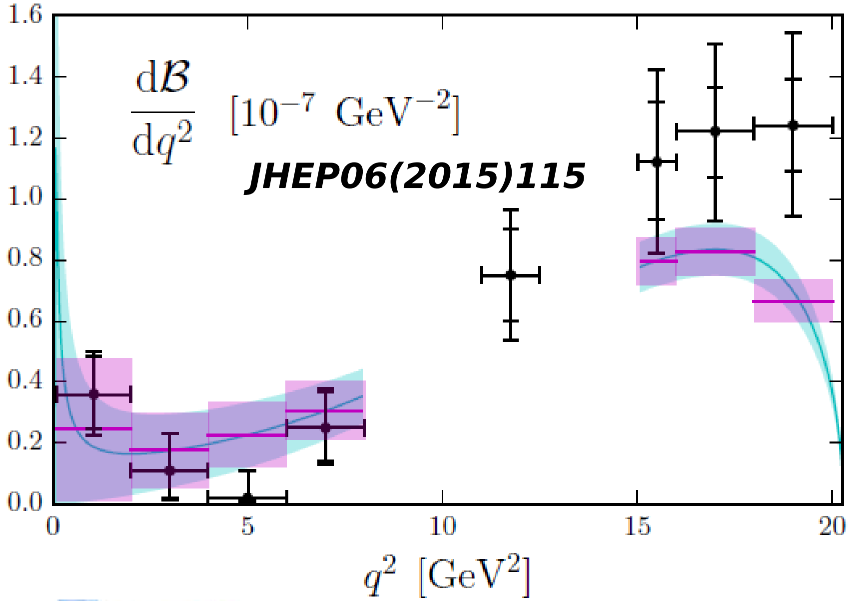
**** Phys. Rev. Lett. 118, 052002 (2017)***

LHCb recorded luminosity in pp collisions / year





$\Lambda_b \rightarrow \Lambda\, \mu^+\mu^-$: q^2 and angular spectra

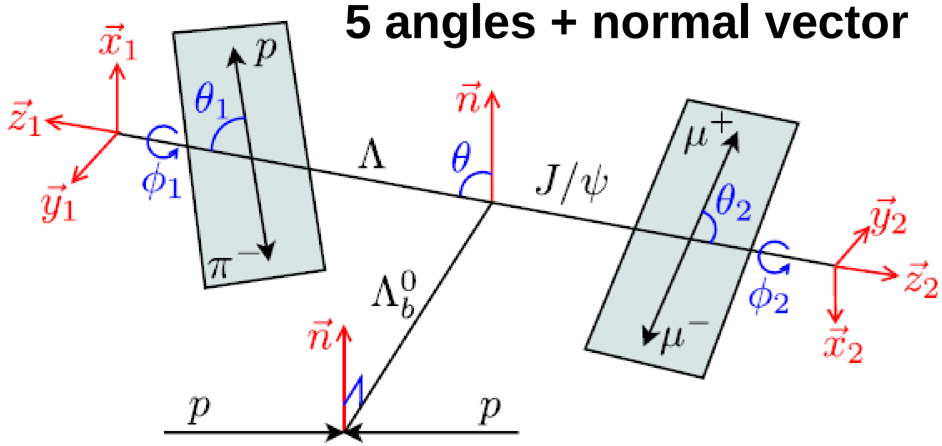


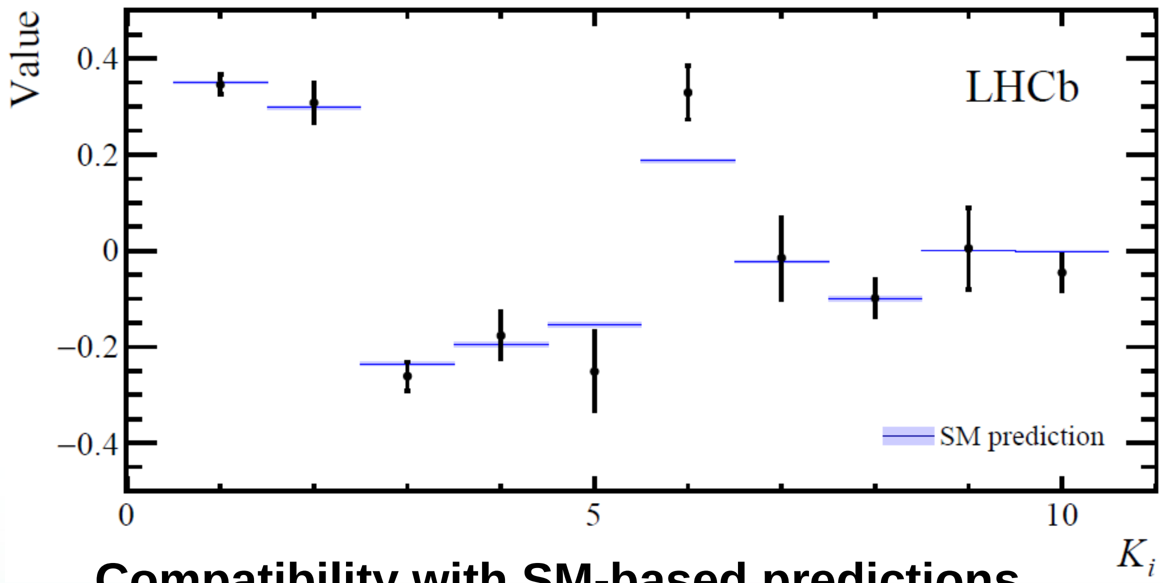
JHEP 09 (2018) 146

$$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi^2}\sum_i^{34} K_i(q^2) f_i(\vec{\Omega})$$

Performed with Run 1 + Run 2 data

5 angles + normal vector





Compatibility with SM-based predictions
Boër et al, JHEP01 (2015) 155
Detmold et al., PRD93 (2016) 074501

Radiative b → s γ

Let handed γ favoured, right handed suppressed by m_s/m_b
Mixing induced CP asymmetry suppressed similarly
Any substantial value of the parameters of time-dependent CP asymmetry would be an indication of NP

$$\Gamma_B(t)/\Gamma_{\bar{B}}(t) \propto \left[\cosh(\Delta\Gamma t/2) - A^{\Delta\Gamma}\sinh(\Delta\Gamma t/2) \pm C\cos(\Delta m t/2) \mp S\sin(\Delta m t/2)\right]$$

Photon helicity and weak phases

CP violation in the decay

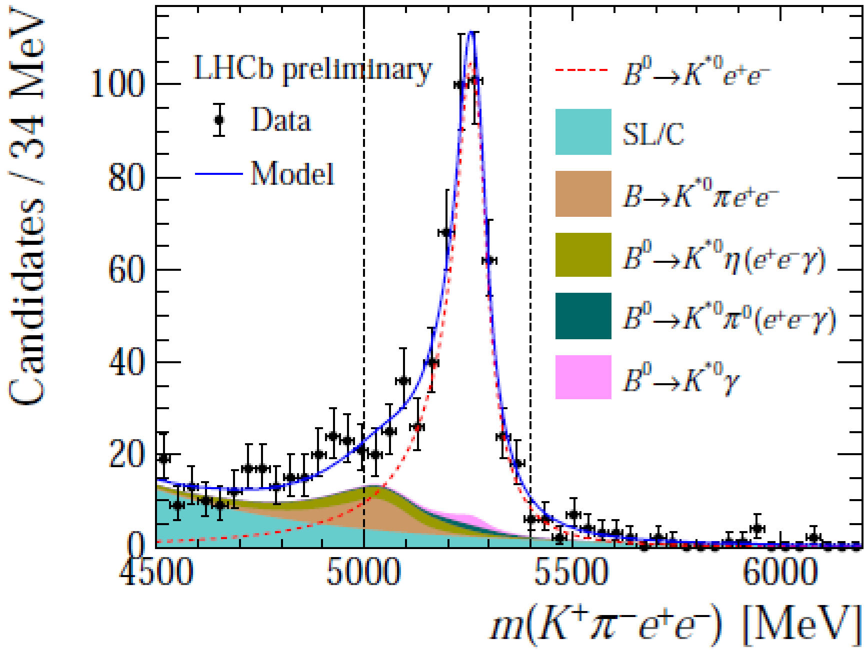
Expected to be close to zero within SM (e.g., PLB664 (2008) 174)

LHCb-PAPER-2020-020 in preparation

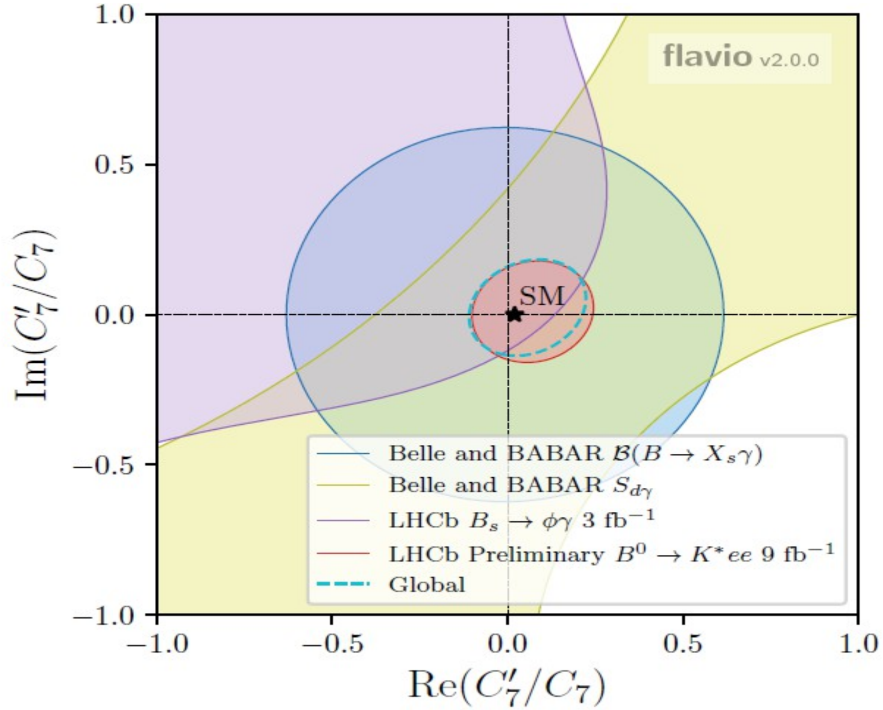
$B^0 \to K^{*0}e^+e^-$ at very low q^2

Sensitivity to γ polarization (operator O_7):
enhancement of RH current? (NP...)

$0.0008 < q^2 < 0.257$ GeV^2



Fit to b → sγ decays + low q^2 ee



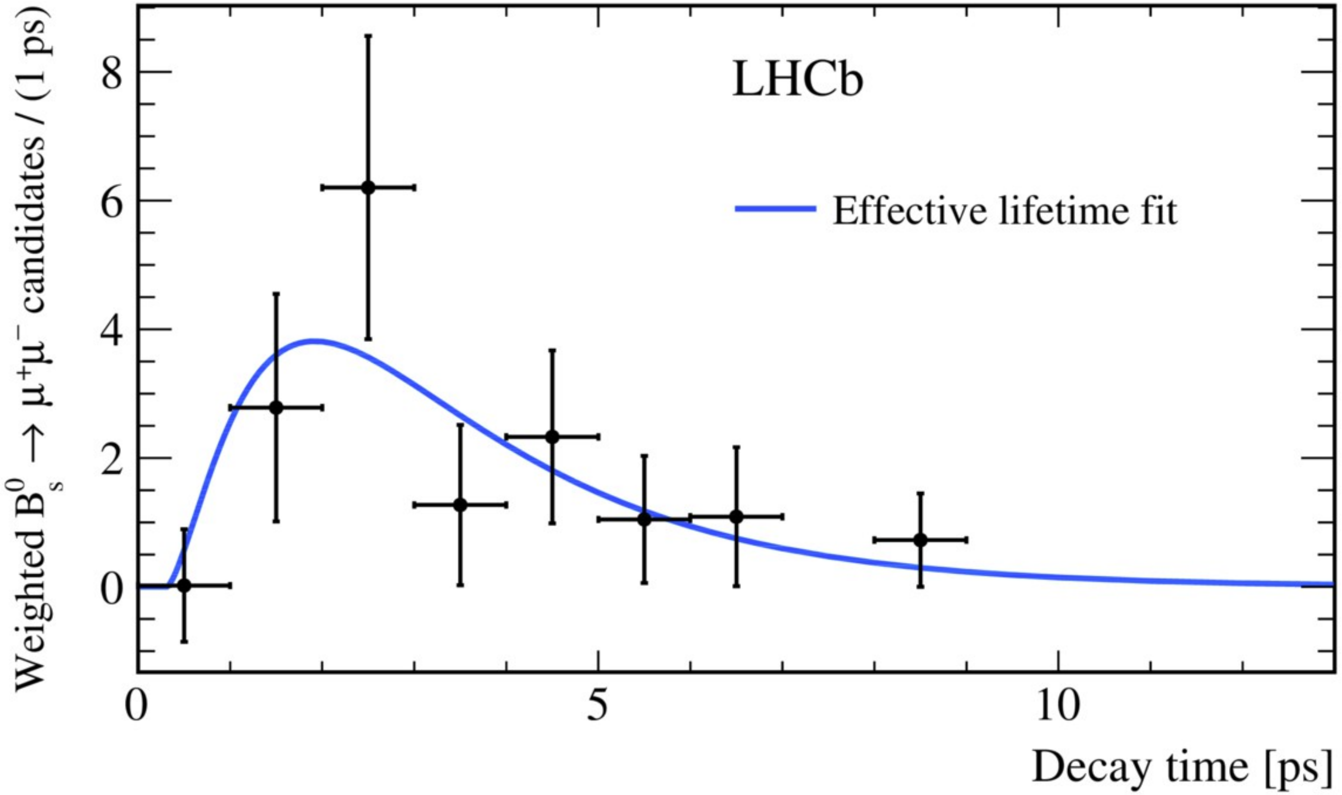
flavio arXiv:1810.08132

Folder angular analysis, coefficients compatible with SM.

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

LHCb (PRL 118 (2017) 191801)

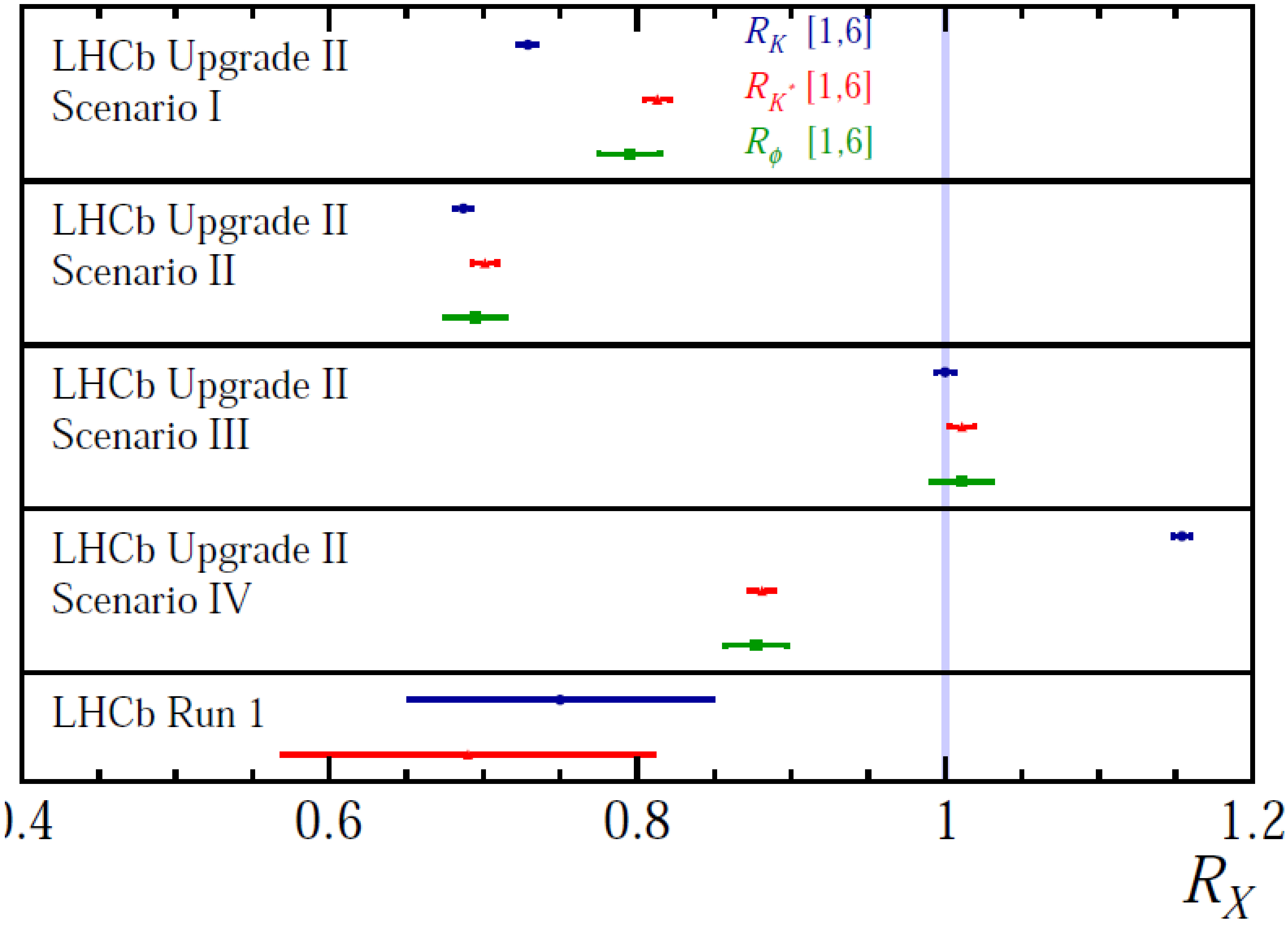
$$\tau_{\mu^+\mu^-} \equiv \int_0^\infty t\,\Gamma(B_s(t)\to\mu^+\mu^-)\,dt / \int_0^\infty \Gamma(B_s(t)\to\mu^+\mu^-)\,dt$$



$\tau(B_s \to \mu^+\mu^-)$=2.04 ± 0.44 ± 0.05 ps

R_X scenarios for Upgrade II

CERN-LHCC-2018-027, LHCB-PUB-2018-009, arXiv:1808.08865



Upgrade DAQ scheme