

Flavour anomalies in B decays at LHCb

in modes involving leptons

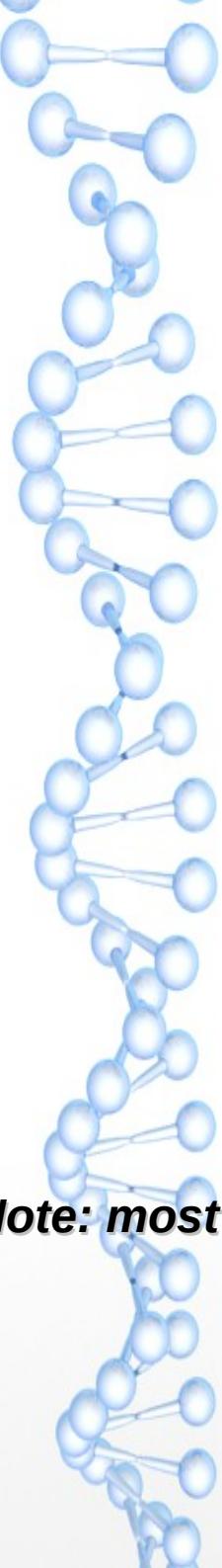
A. Hicheur

U.Constantine/UF Rio de Janeiro

On behalf of the LHCb collaboration

NuFACT, 25-31 August 2019, Daegu, South Korea

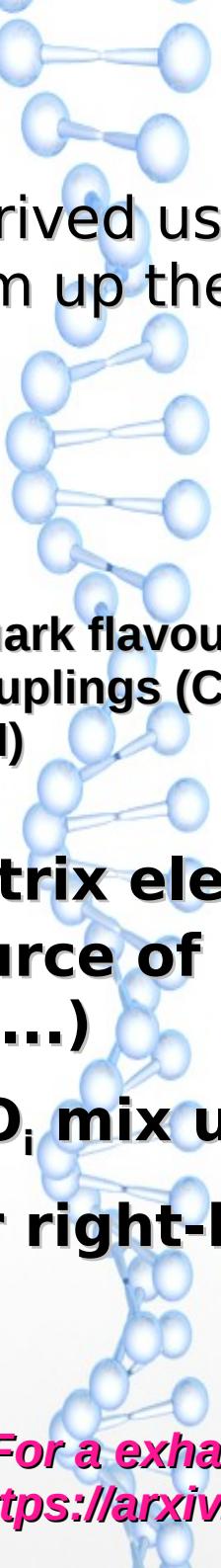




Outline

- Representation of anomalies in EFT
 - Tree-level (semi-leptonic) decays
 - Loop $b \rightarrow s,d$ decays
 - Leptonic
 - Glimpse at LFV searches
 - Summary
- LFUV

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*

$$H_{\text{eff}} = \sum_i V_{\text{CKM}}^i C_i(\mu) O_i(\mu)$$

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

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

Type of operators

Historically, numbered according to the type of decay they intervene in :

- $i = 1, 2$: tree diagrams. E.g, semileptonic tree
- $i = 3-6$: gluonic penguin
- $i = 7-10$: electroweak penguin (7 γ , 8G : magnetic-penguin)
Loop operators
- leptonic operators
- Box operators : to describe oscillations

Represented by effective vertices :



$$O_1 = (\bar{b}_i c_j)_{V-A} (\bar{u}_j d_i)_{V-A}$$



$$O_2 = (\bar{b} c)_{V-A} (\bar{u} d)_{V-A}$$

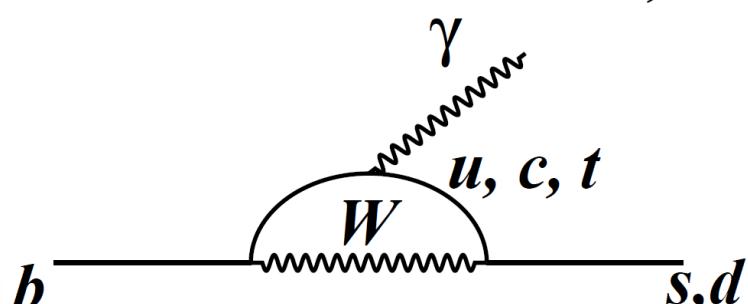
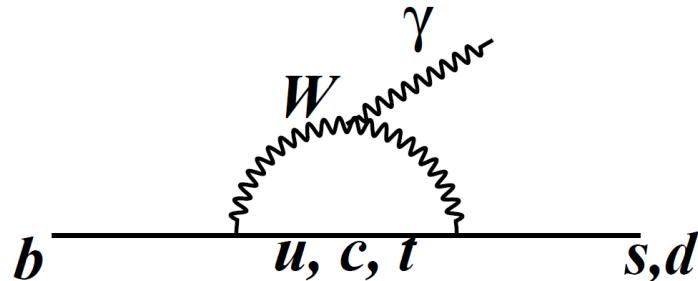
Here color indices are crossed due to gluon exchange

Loop operators and new physics

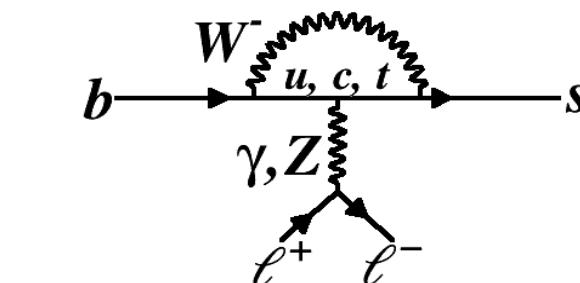
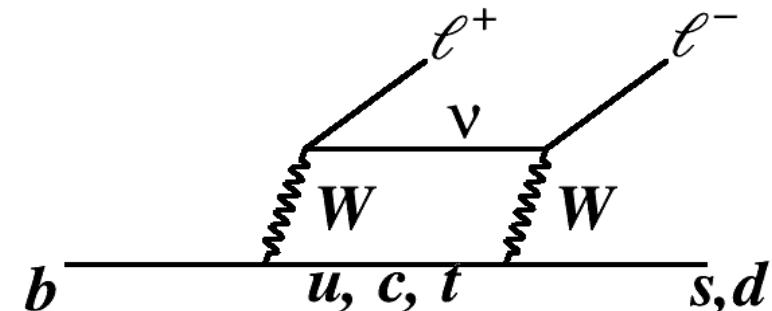
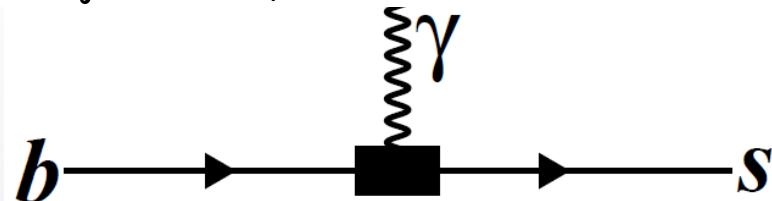
Loop operators → massive (electroweak) virtual particles : New Physics might intervene. Wilson coefficients affected by NP.

$$C_i(\prime) \rightarrow C_i(\prime) + C_i^{\text{NP}}$$

Electromagnetic penguin



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



$$O_9(\prime) = (\bar{s}b)_{V+A}(\bar{\ell}\ell)_V$$

$$O_{10}(\prime) = (\bar{s}b)_{V+A}(\bar{\ell}\ell)_A$$



LHCb detector

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

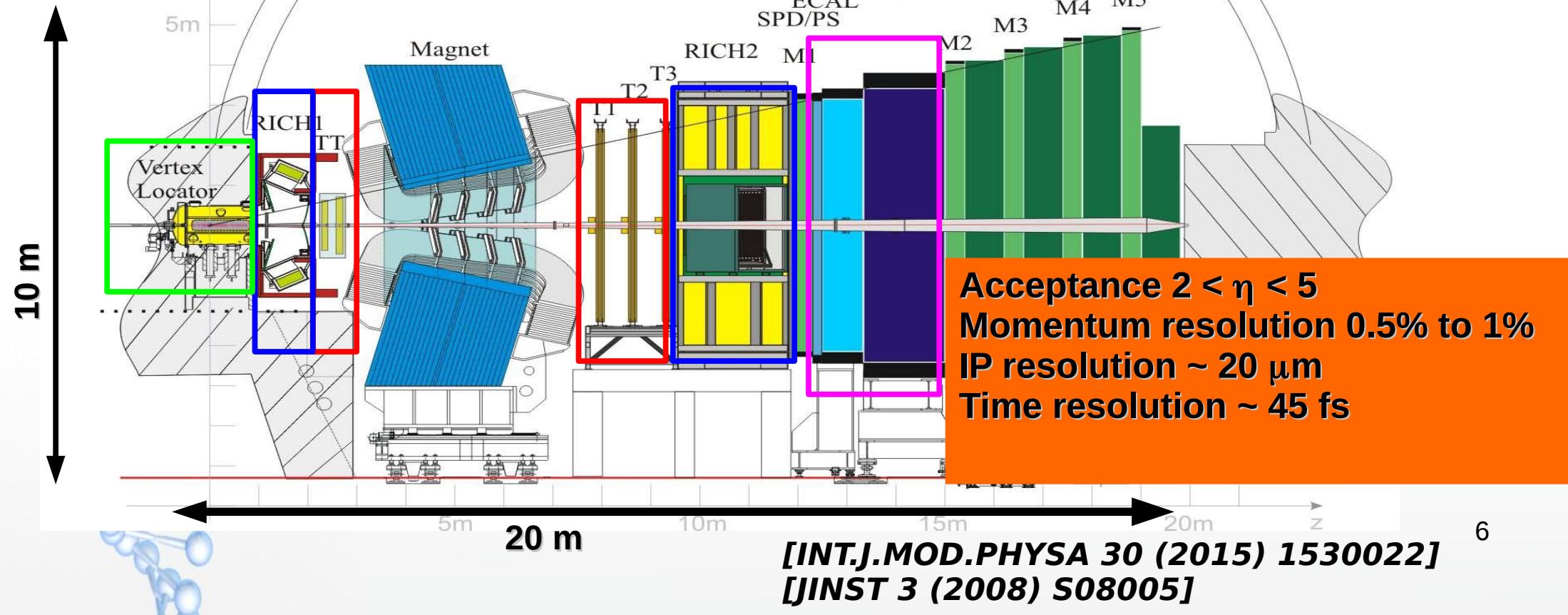
Optimized for b and c hadron studies

Vertexing

Tracking stations

Particle ID Ring Imaging Cherenkov

Calorimeters and Muon Chambers



LHCb data (2011+2012) – Run I

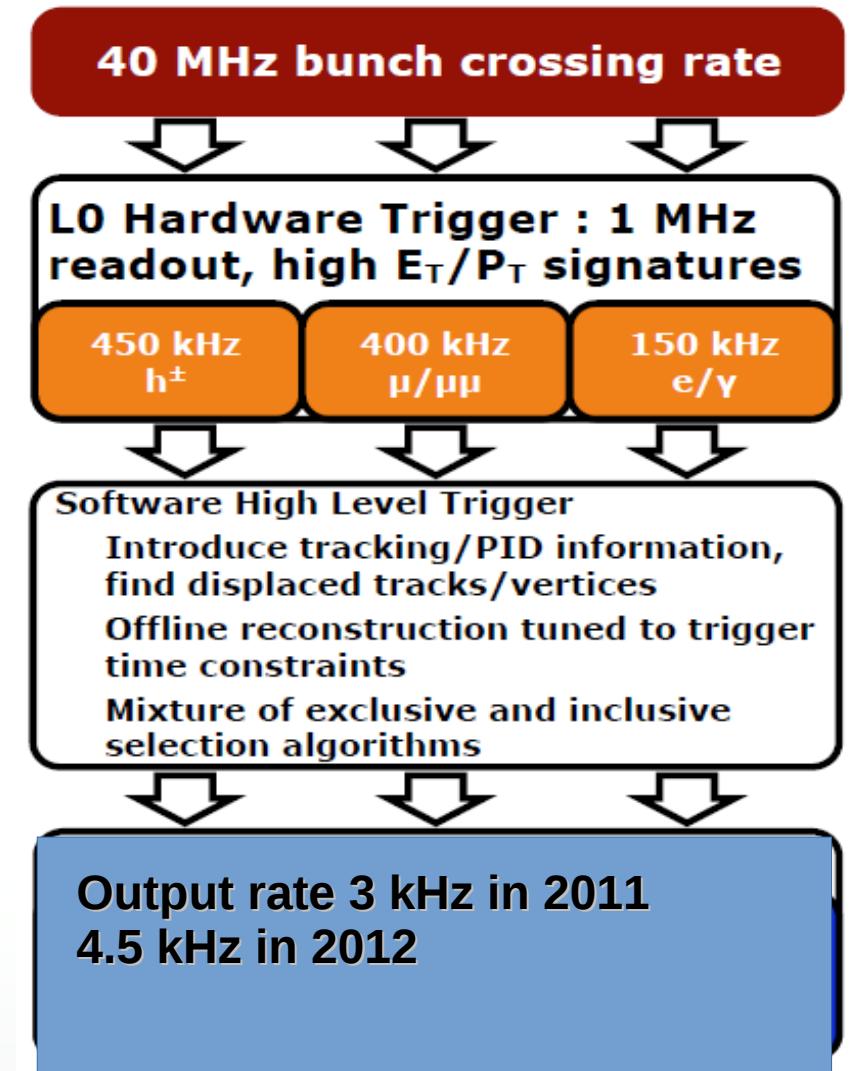
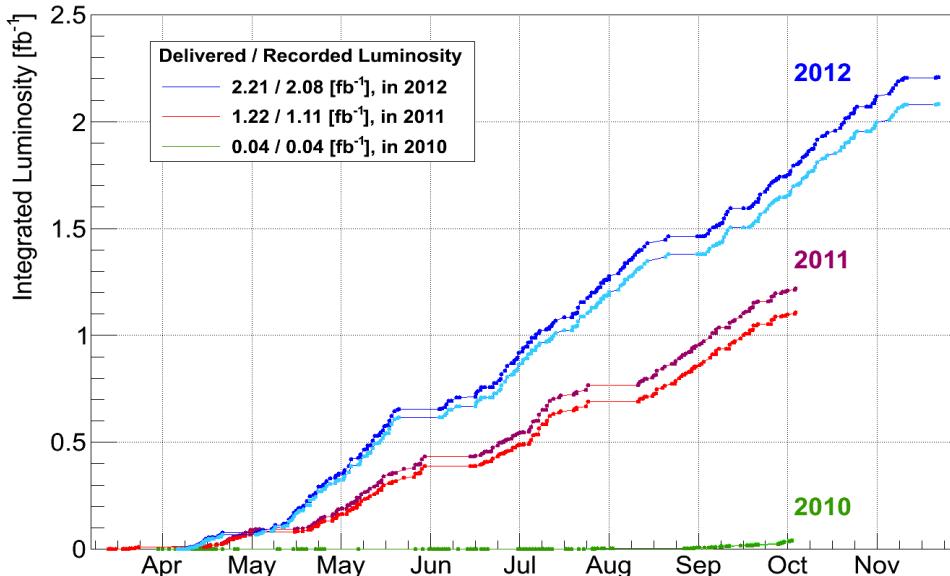
10^{11} protons per bunch colliding at 7 (2011) and 8 (2012) TeV

Luminosity at IP8 (LHCb): $2\text{--}4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

About 1500 charged particles produced at each pp collision

$\sigma(\text{bb}) \sim 75 \mu\text{b}$ @ 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 ,
 $f_s/(f_u + f_d) \sim 0.134$, b-baryons ($f(\Lambda_b)/(f_u + f_d) \sim 0.240$)
Traces of B_c , *Eur. Phys. J. C77 (2017) 895*



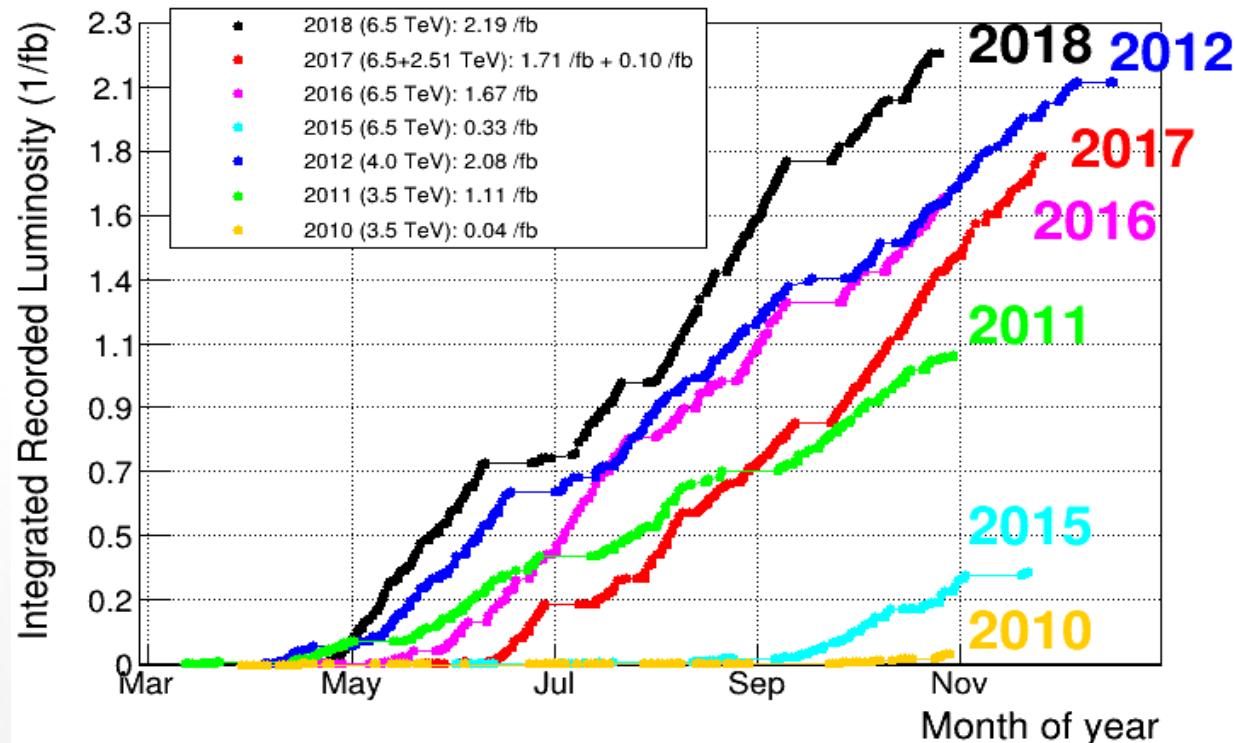
LHCb data (2015-2018) – Run II

Bunch colliding at 13 TeV

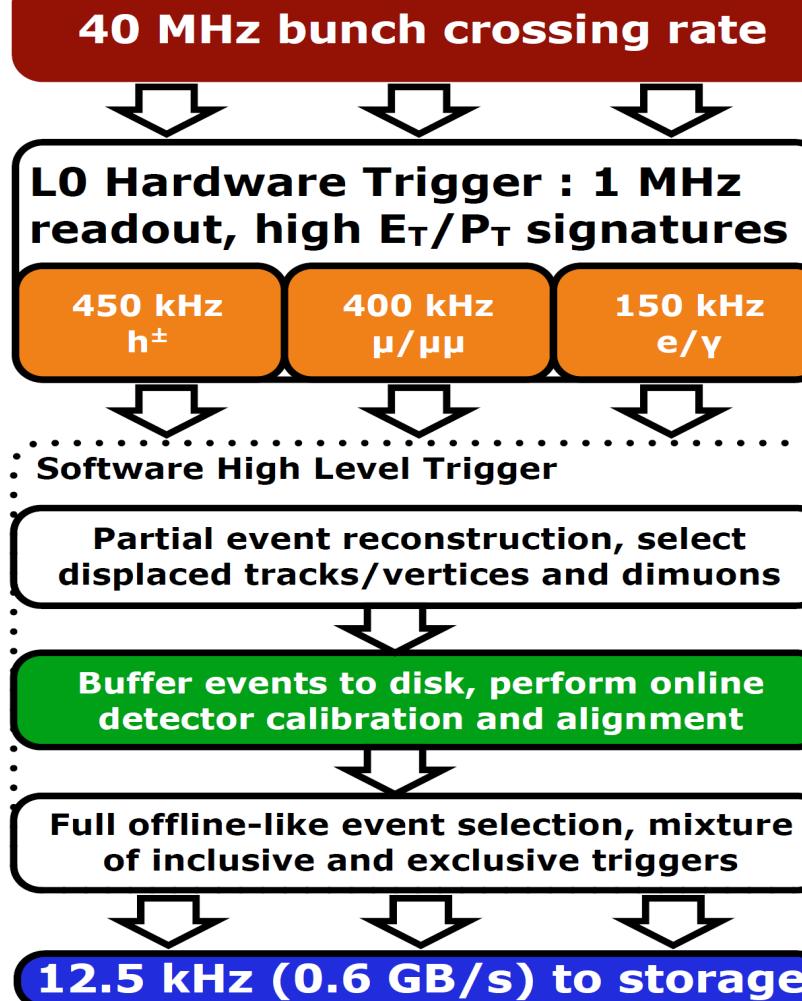
$\sigma(bb) \sim 165 \mu b$ @ 13 TeV* in LHCb acceptance
About 2.3 times the value @ 7-8 TeV

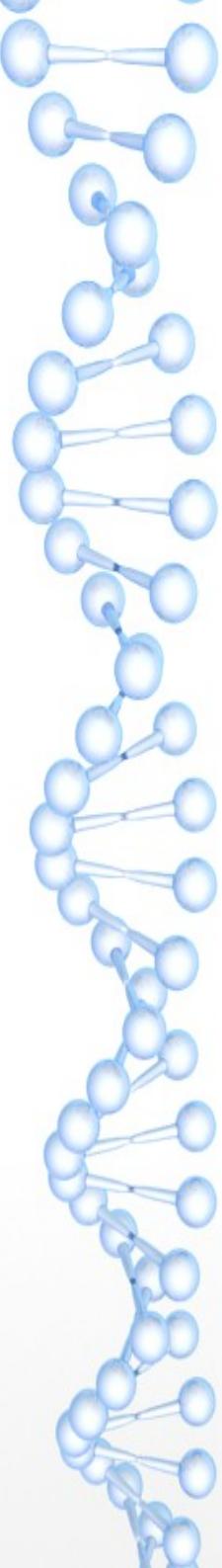
* *Phys. Rev. Lett.* 118, 052002 (2017)

LHCb recorded luminosity in pp collisions / year



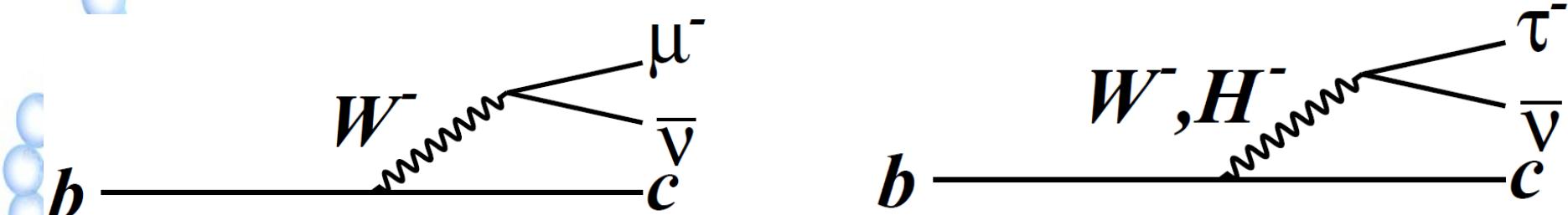
LHCb 2015 Trigger Diagram





Semileptonic tree $b \rightarrow c \ell \nu$

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



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

Measure:

$$R(H_c^{(*)}) = \frac{BR(H_b \rightarrow H_c^{(*)} \tau^- \bar{\nu})}{BR(H_b \rightarrow H_c^{(*)} \mu^- \bar{\nu})}$$

Precise SM-based predictions:

$$R(D) = 0.299 \pm 0.003$$

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

H. Na et al., PRD 92(2015) 054510

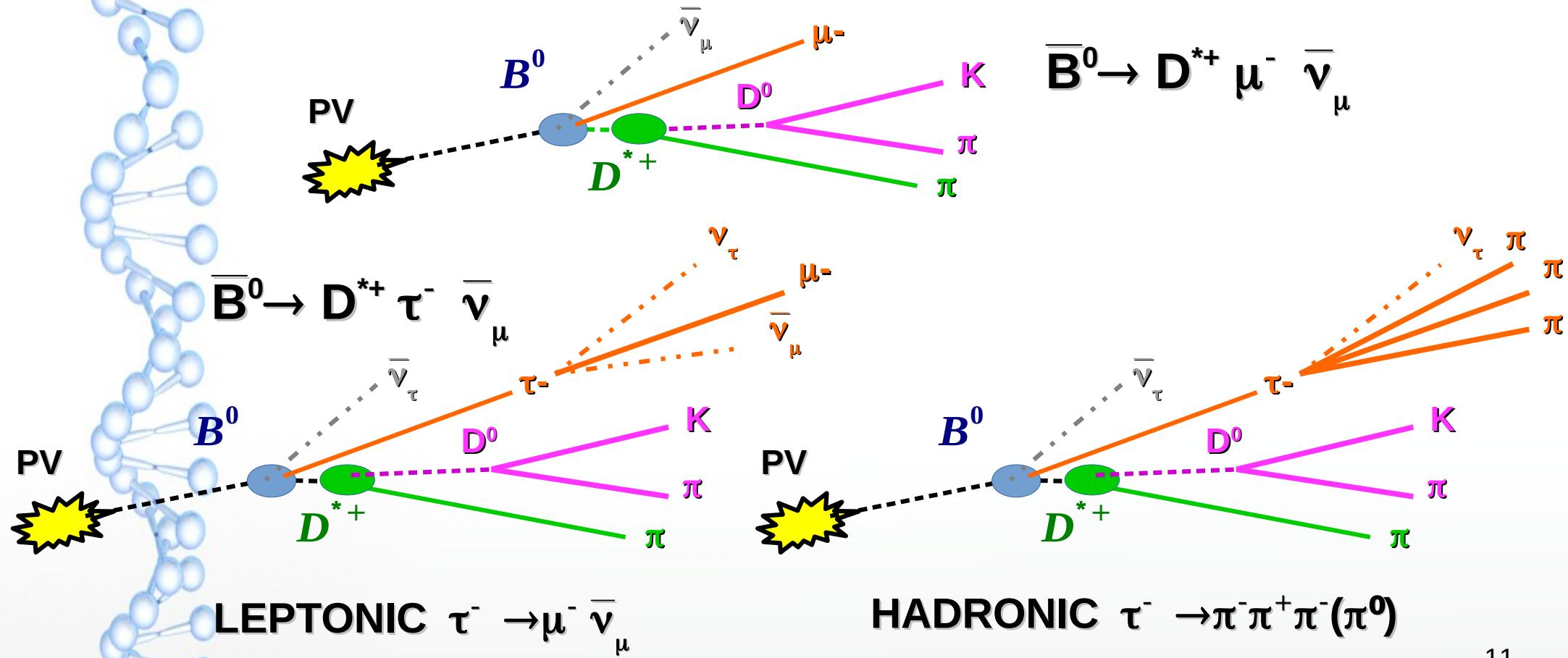
Fajfer, Kamenic, Nišandić, PRD85 (2012) 094025

D.Bigi, Gambino, PRD 94 (2016) 094008

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

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)

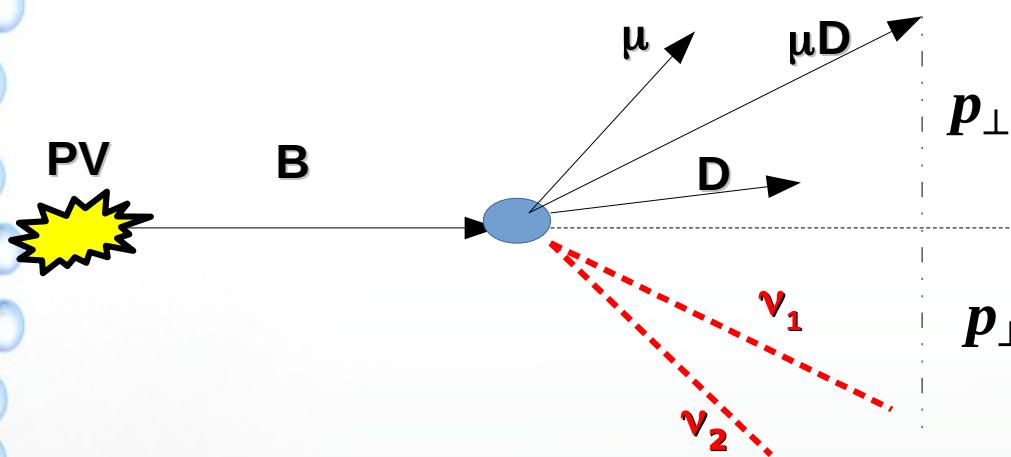


$\overline{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$ vs $\overline{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu$

Specific variables and neutrino reconstruction

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

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



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

p_{\perp} *J. High Energ. Phys. (2017) 2017: 21*

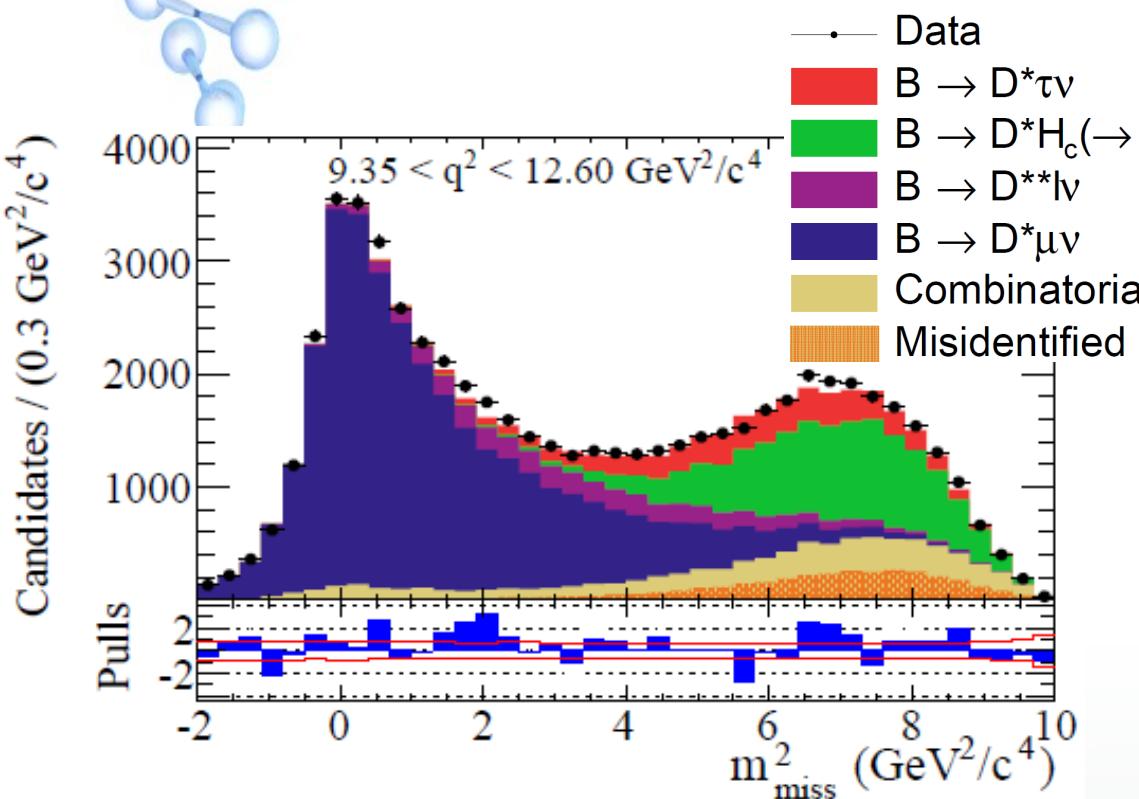
LHCb

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

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

PRL 115 (2015) 111803

2D missing mass – muon energy fit



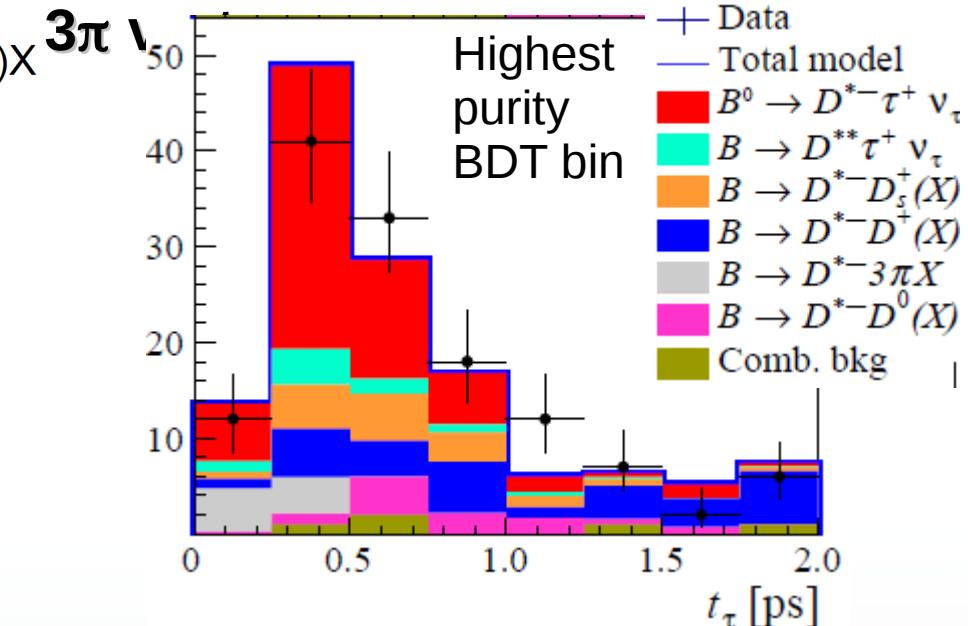
$$R(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$$

$$\tau^- \rightarrow \pi^- \pi^+ \pi^- (\pi^0)$$

PRL 120 (2018) 171802

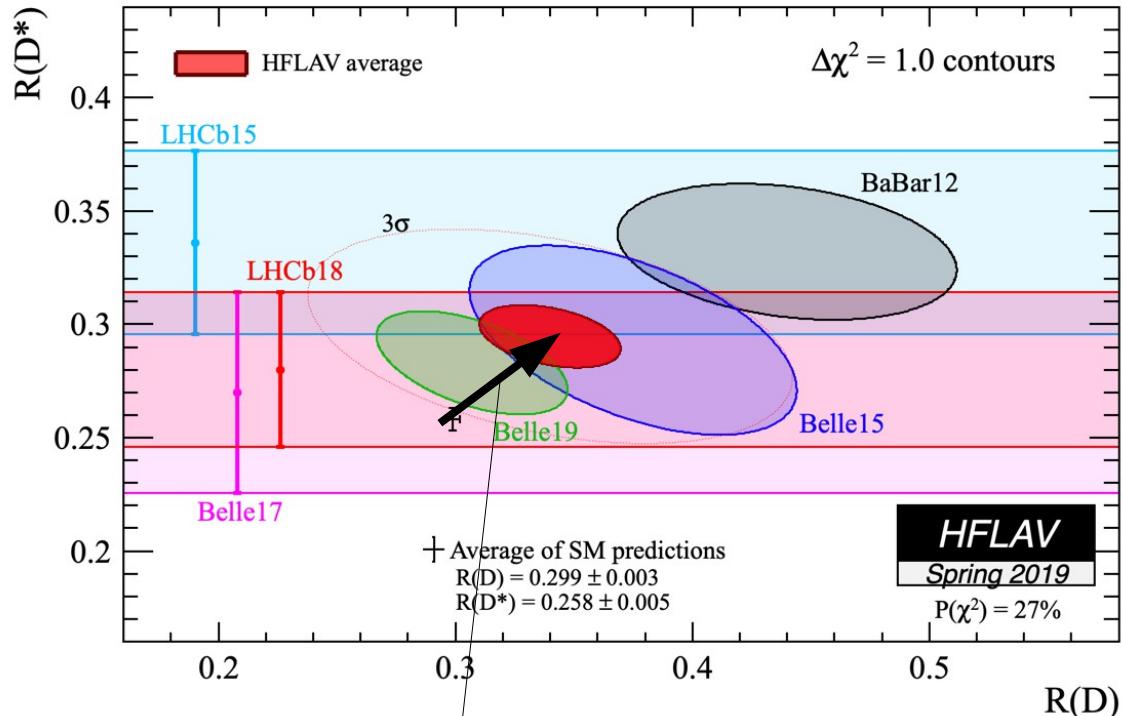
$\overline{B}^0 \rightarrow D^{*+} \pi^- \pi^+ \pi^-$ as normalization

2D fit q^2 – tau decay time from

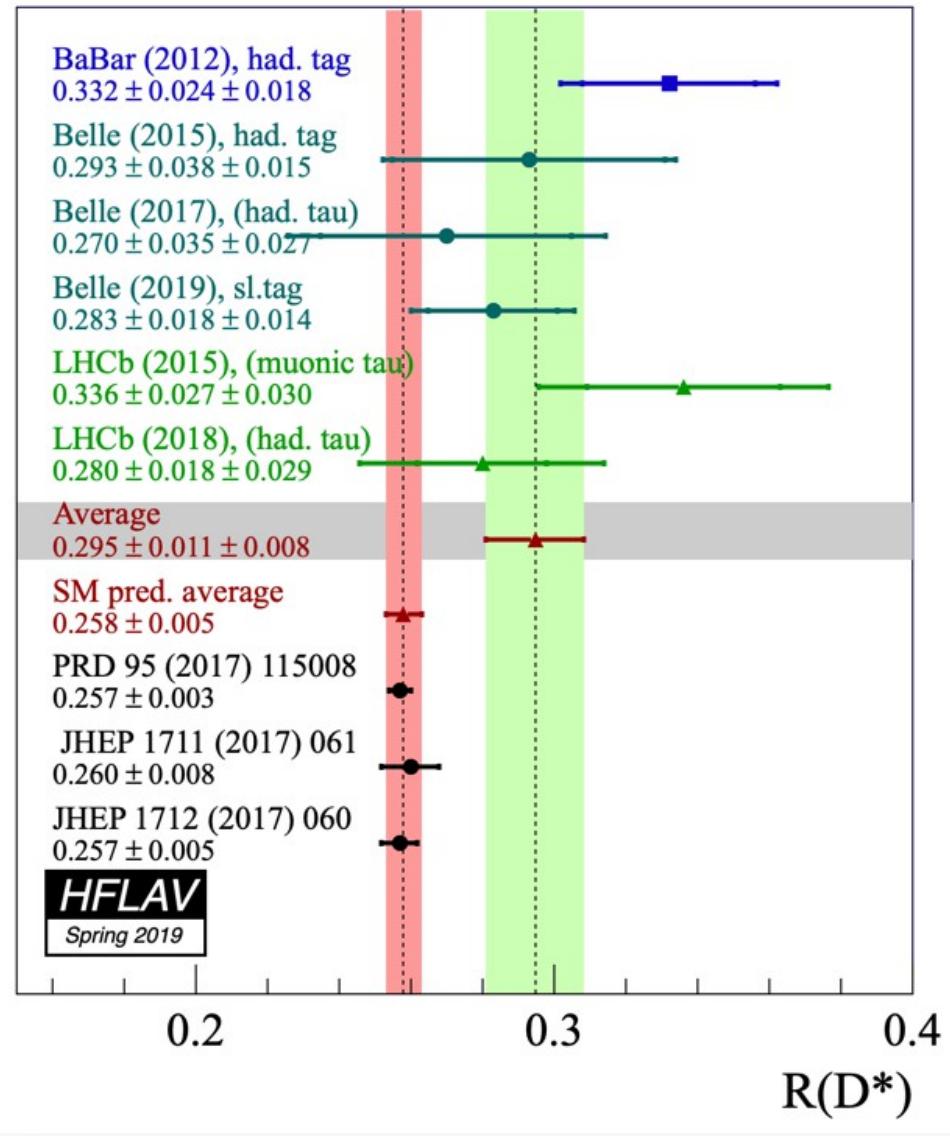


$$R(D^*) = 0.291 \pm 0.021(\text{stat}) \pm 0.026(\text{syst}) \pm 0.013(\text{BR})$$

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



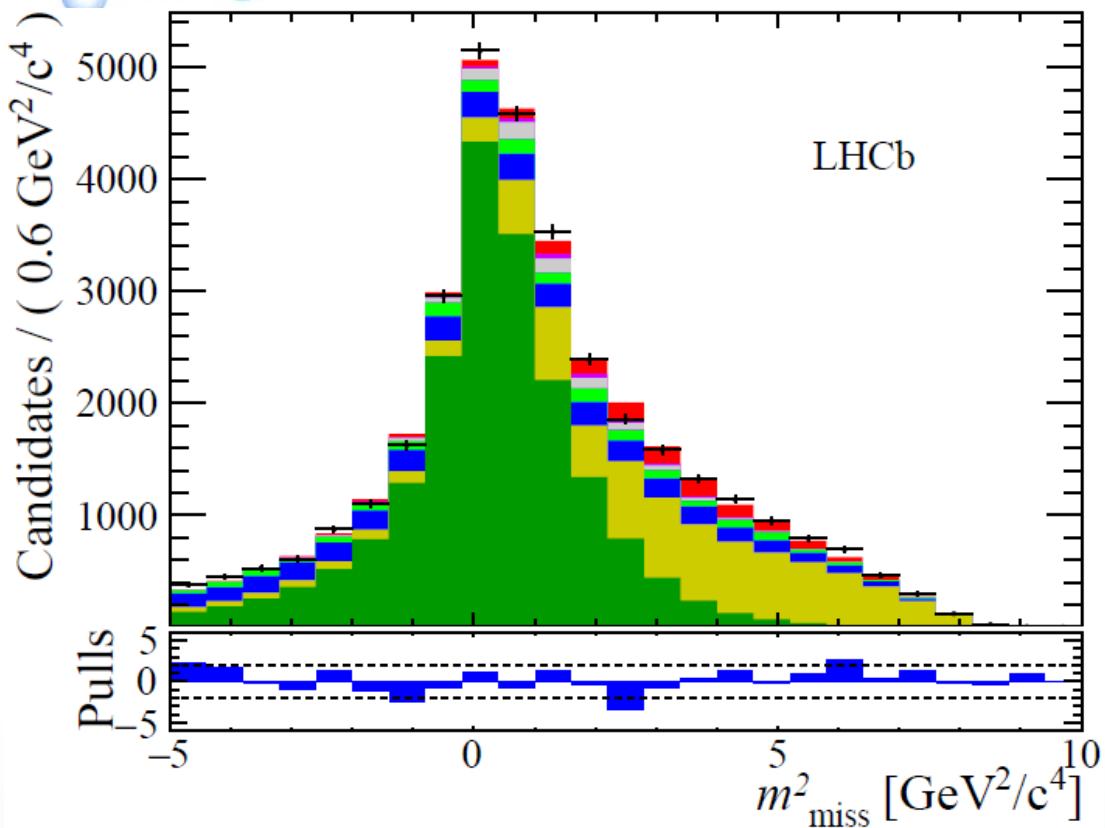
After recent (**Belle**) result, discrepancy went from 3.8σ to 3.1σ wrt SM.



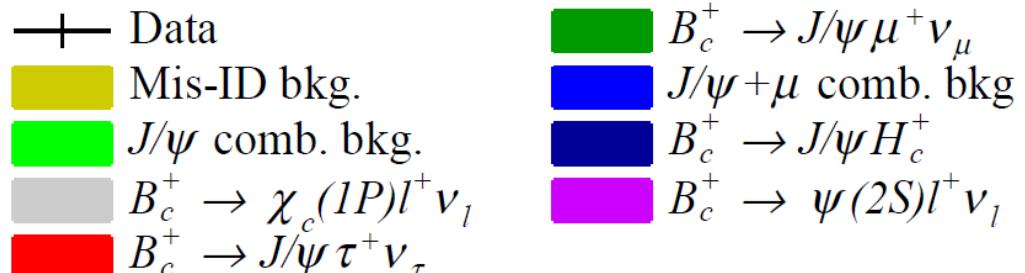
$B_c \rightarrow J/\Psi \tau^- \bar{\nu}_\tau$
 $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$

$B_c \rightarrow J/\Psi \mu^- \bar{\nu}_\mu$

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

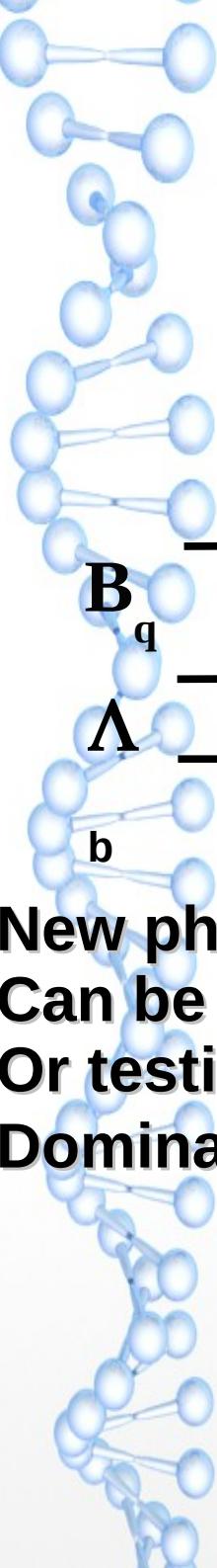


2 variables (missing mass, B_c decay time)
+ 1 category fit.
Category variable Z = bins in q^2 and muon energy.

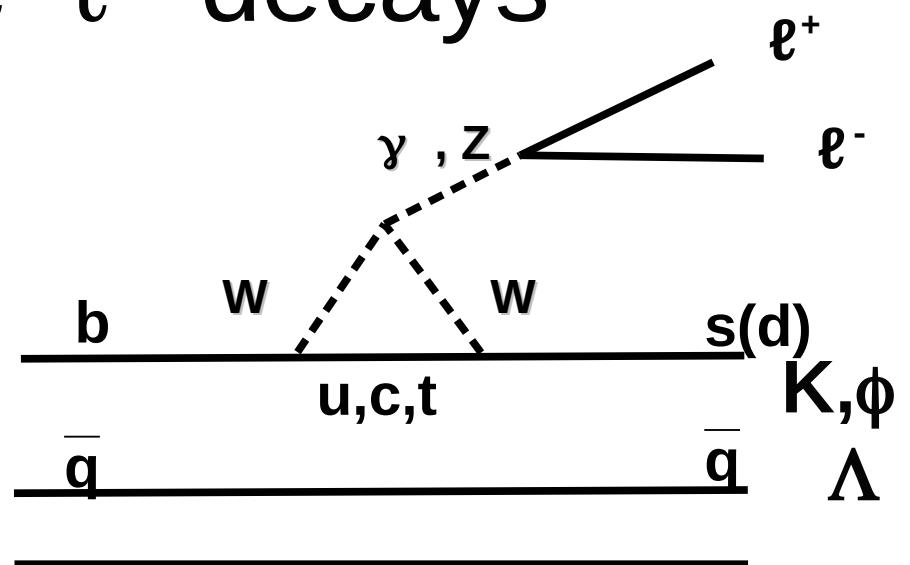
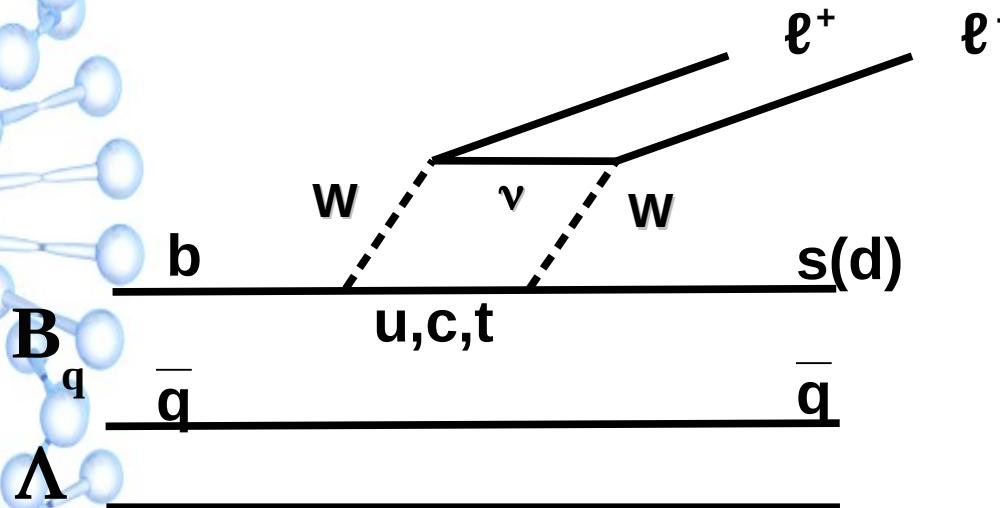


$R(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$
2 σ above the range of predictions

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



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

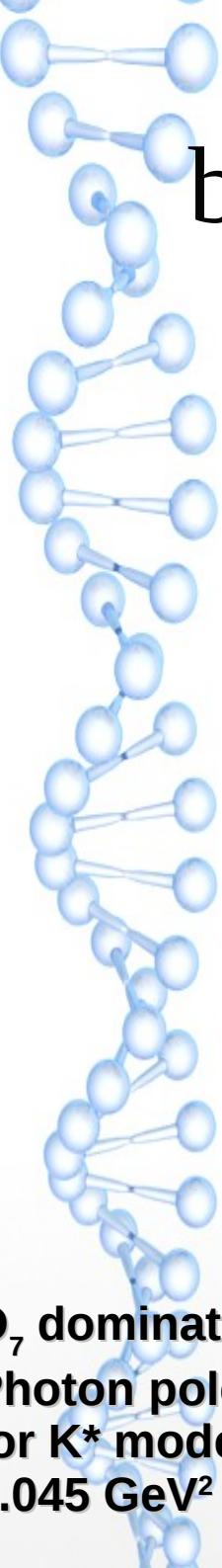


New physics can intervene in the loops/boxes

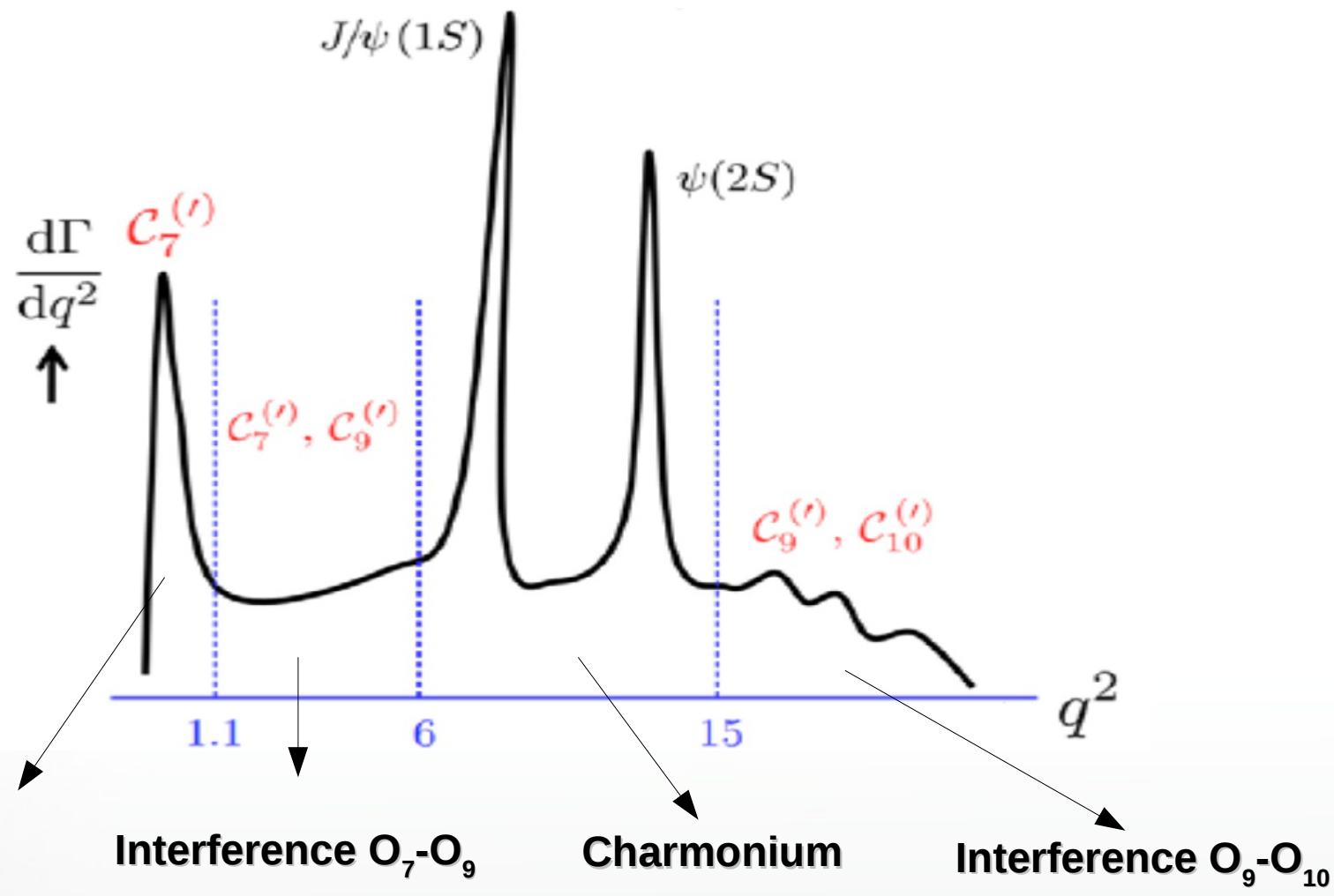
Can be probed through the analysis of the dynamics of the decays

Or testing, e.g., lepton universality $b \rightarrow s e^+ e^- / b \rightarrow s \mu^+ \mu^-$

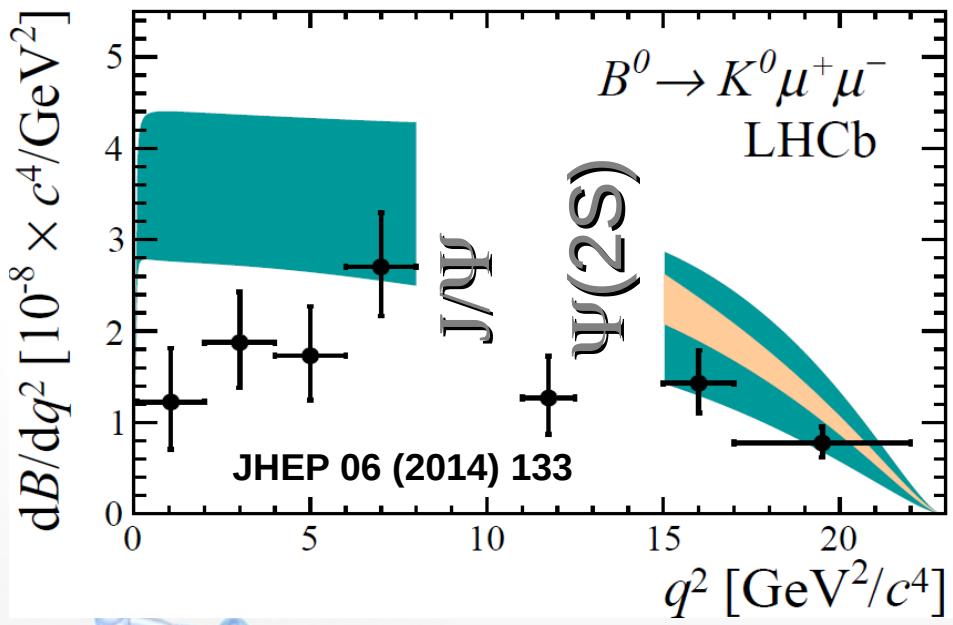
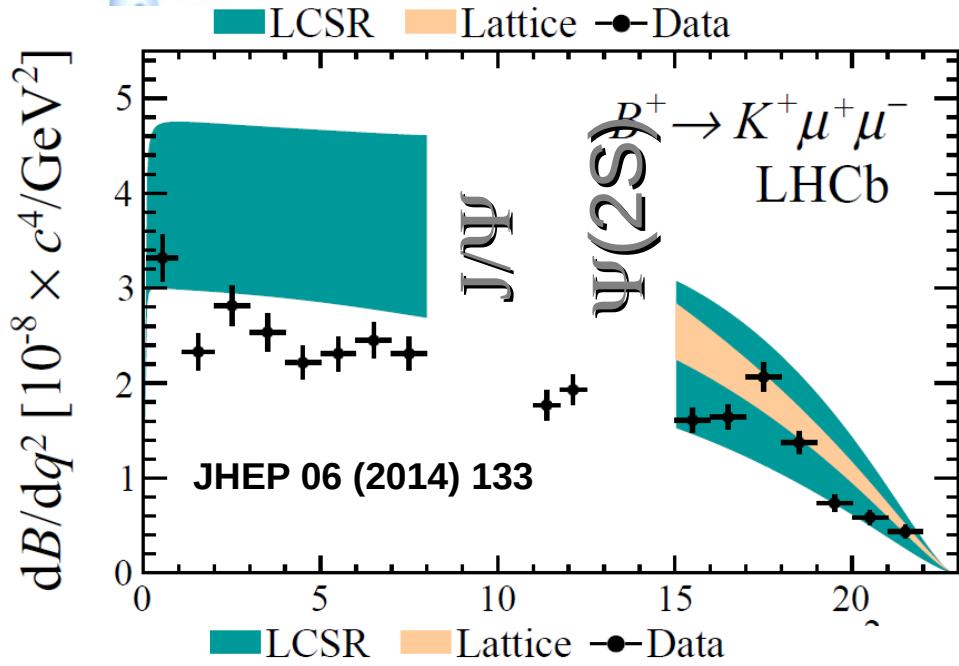
Dominated by O_7, O_9, O_{10} operators



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



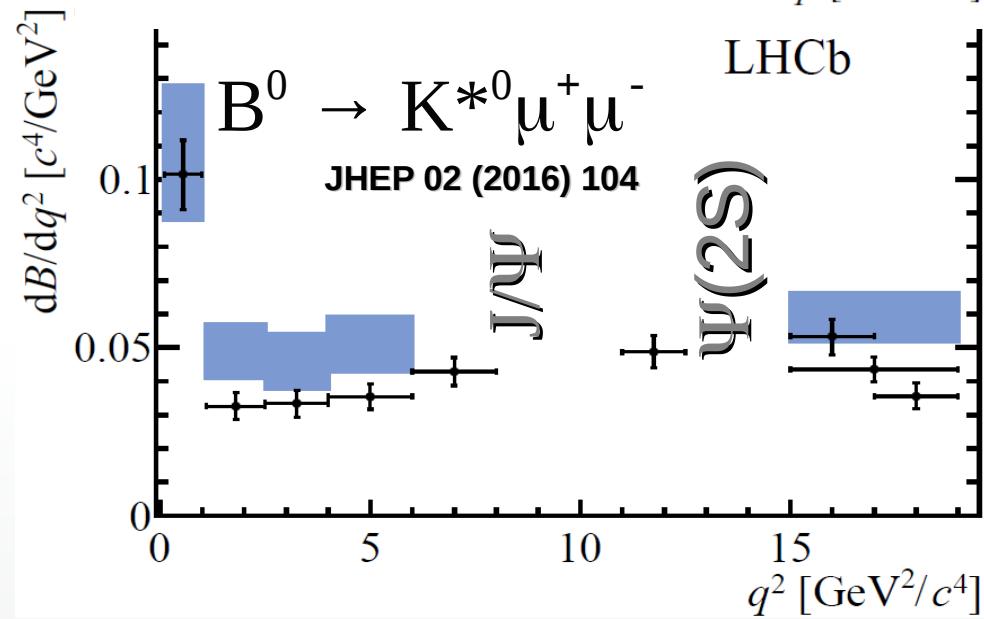
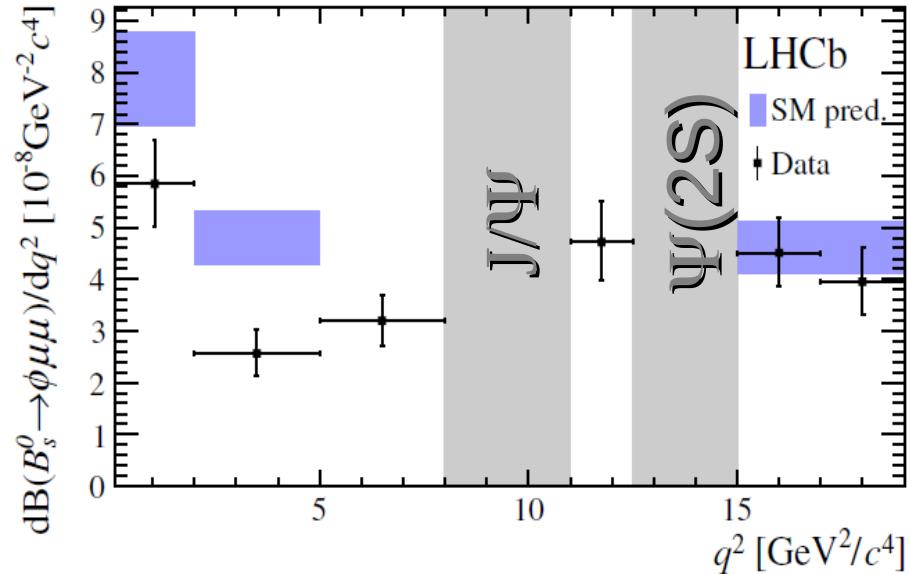
$B \rightarrow X \mu^+ \mu^-$ $d\Gamma/dq^2$ spectra



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

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

JHEP 1509 (2015) 179



Data tends to be systematically below the SM-based predictions, up to 3.0σ

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

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right.$$

$$+ \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_l$$

$$- F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi$$

$$+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi$$

$$+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi$$

$$+ S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \Big]$$

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

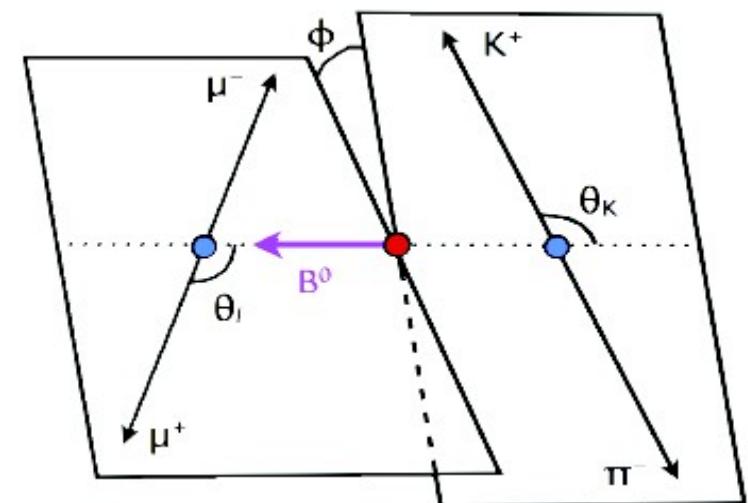
F_L : fraction of longitudinal polarization of K^*/ϕ

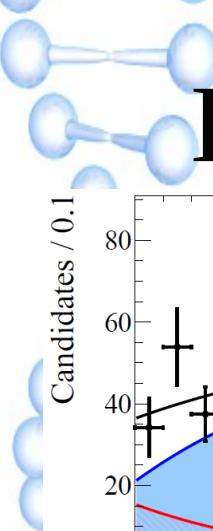
A_{FB} = forward-backward

asymmetry of the dimuon system

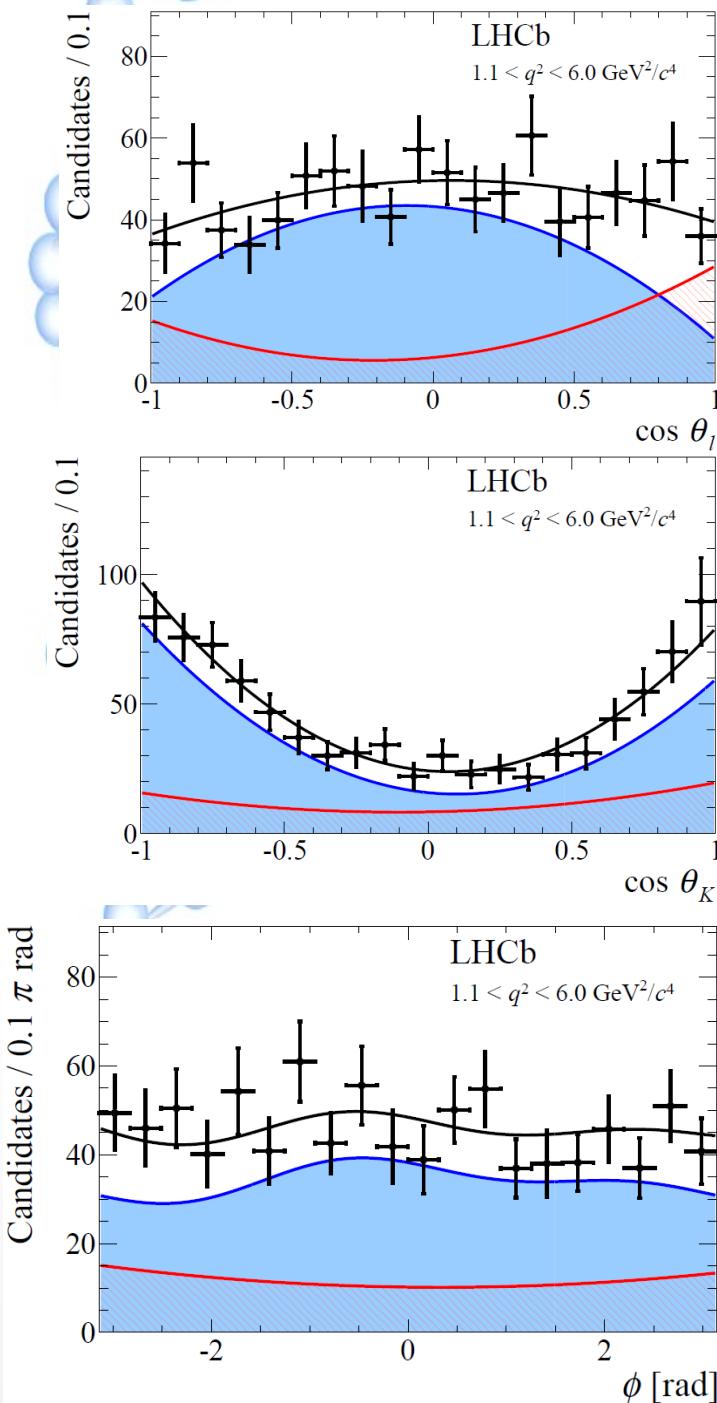
$S_5 = A_5$ in the case of ϕ

They depend on $B \rightarrow K^*/\phi$ form factors and Wilson Coefficients of the OPE





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

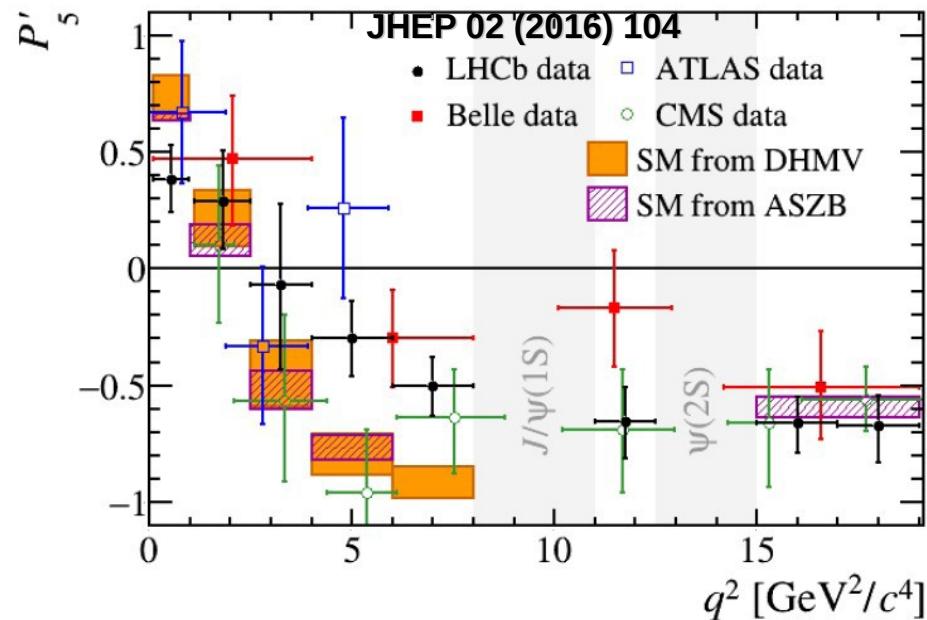


Form-factor independent (LO):

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

$$P'_6 = \frac{S_7}{\sqrt{F_L(1 - F_L)}}$$

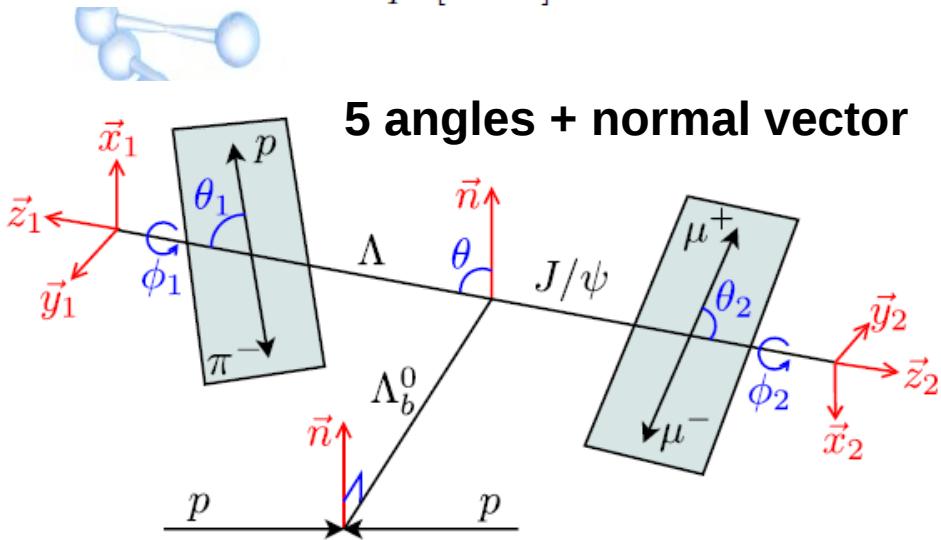
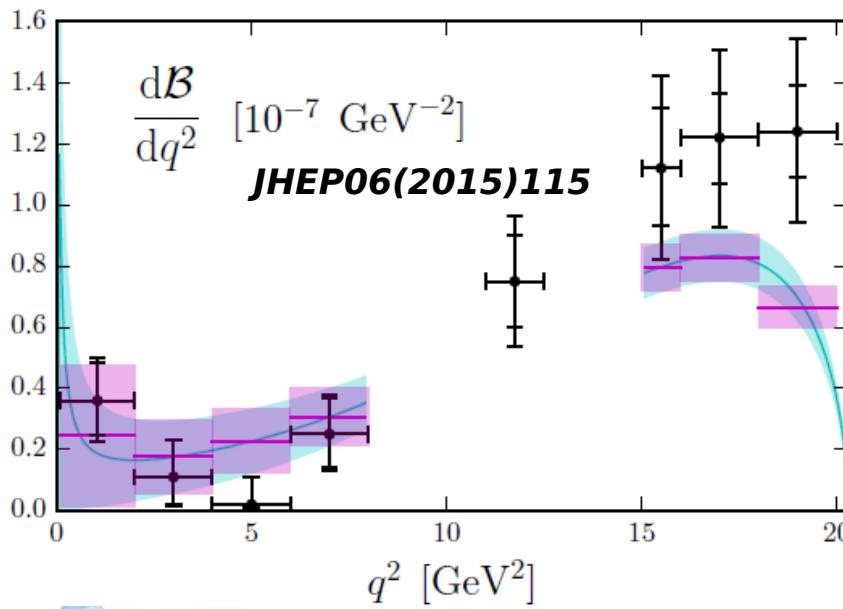
Descotes-Genon et al, JHEP 05 (2013)137



PRL 118 (2017)111801

3 σ local discrepancies

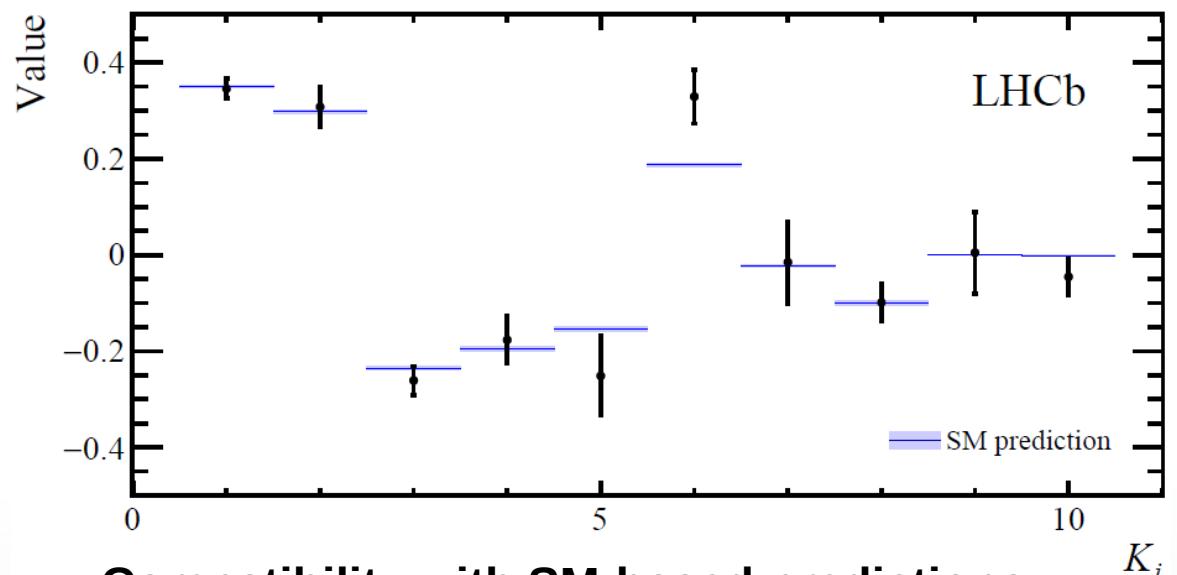
$\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$: q^2 and angular spectra



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



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

R_K ratios

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

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

PRL 122 (2019) 191801

New (Spring 2019)

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

JHEP 08 (2017) 055

Experimentally:

$$R_K = \frac{BR(B \rightarrow K \mu^+ \mu^-)}{BR(B \rightarrow K J/\Psi(\mu^+ \mu^-))} / \frac{BR(B \rightarrow K e^+ e^-)}{BR(B \rightarrow K J/\Psi(e^+ e^-))}$$

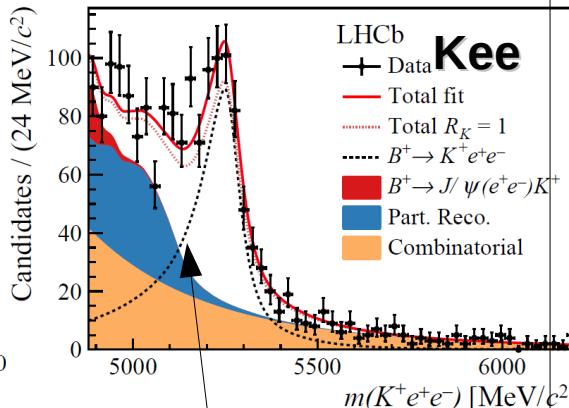
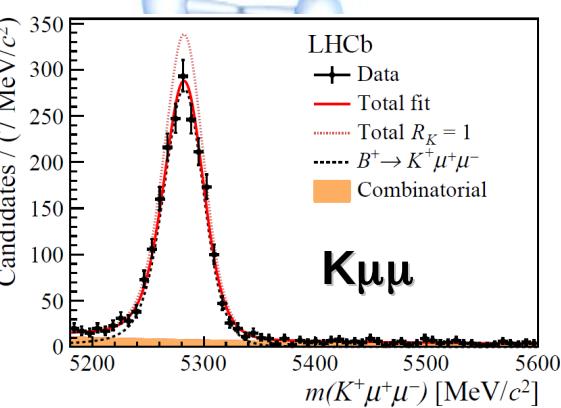
Minimize systematic uncertainties

q² range: above γ pole and background of type $B \rightarrow \phi(\rightarrow \ell\ell) K$
and below J/ Ψ radiative tail

R_K ratios - fits

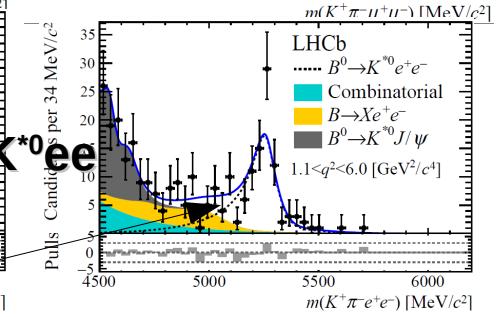
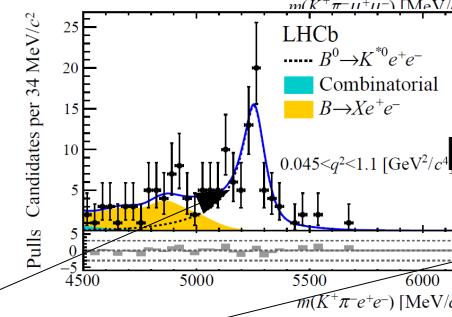
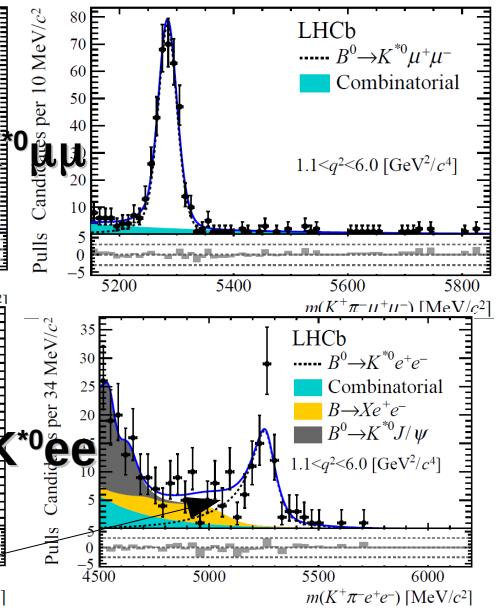
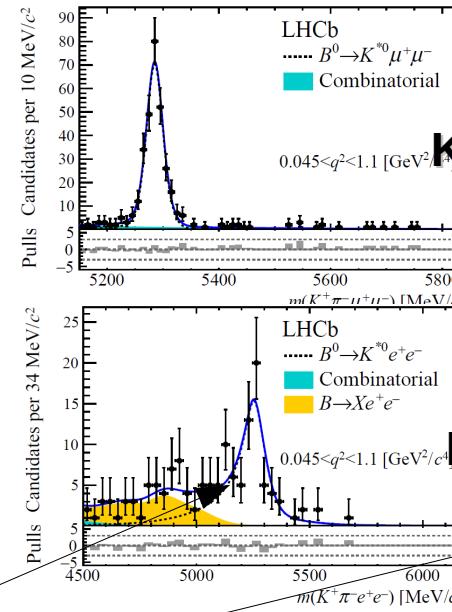
$$B^+ \rightarrow K^+ \ell^+ \ell^-$$

$1.1 \text{ GeV}^2 < q^2 < 6 \text{ GeV}^2$



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

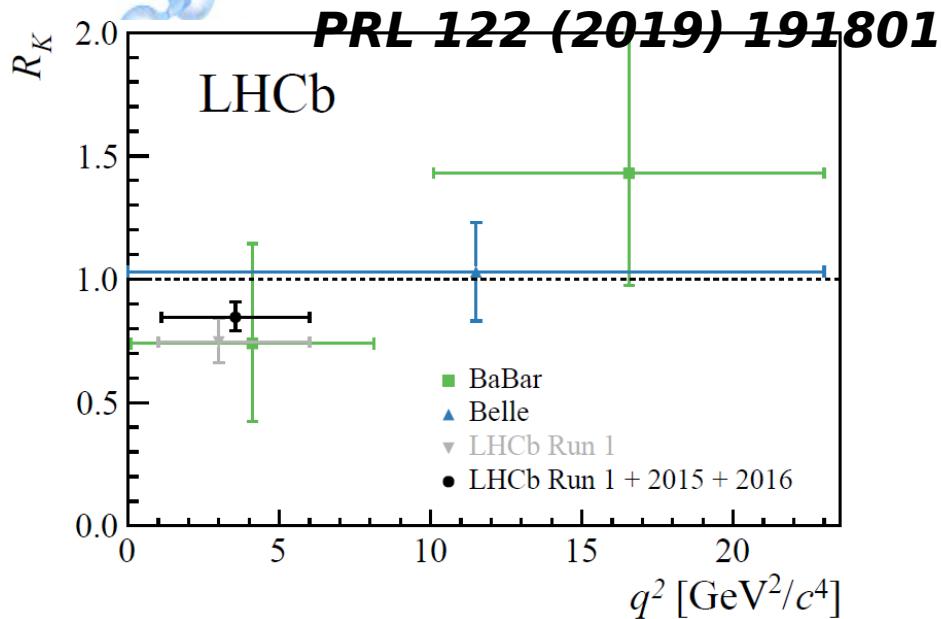
$0.045 \text{ GeV}^2 < q^2 < 1.1 \text{ GeV}^2$ $1.1 \text{ GeV}^2 < q^2 < 6 \text{ GeV}^2$



Radiative Bremsstrahlung tail for electron modes

R_K ratios, results

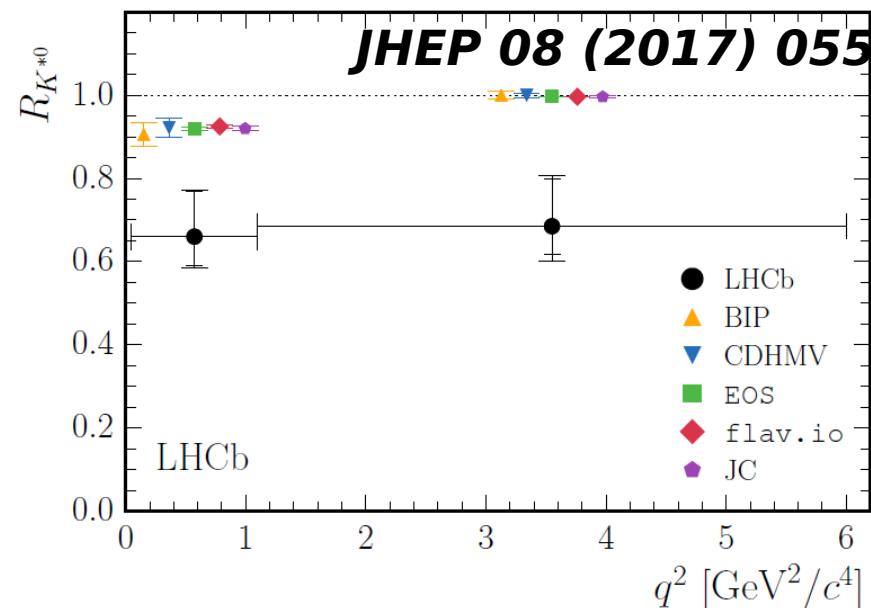
$B^+ \rightarrow K^+ \ell^+ \ell^-$



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

2.5 σ below SM-based predictions

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



$$0.045 \text{ GeV}^2 < q^2 < 1.1 \text{ GeV}^2$$

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

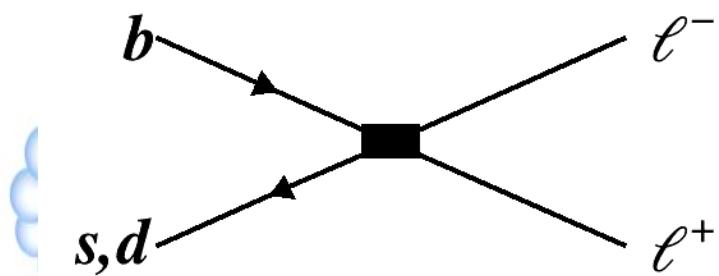
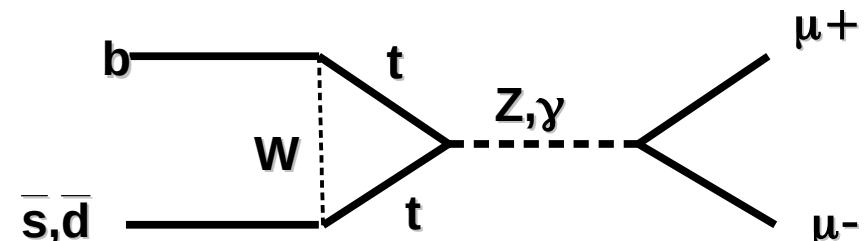
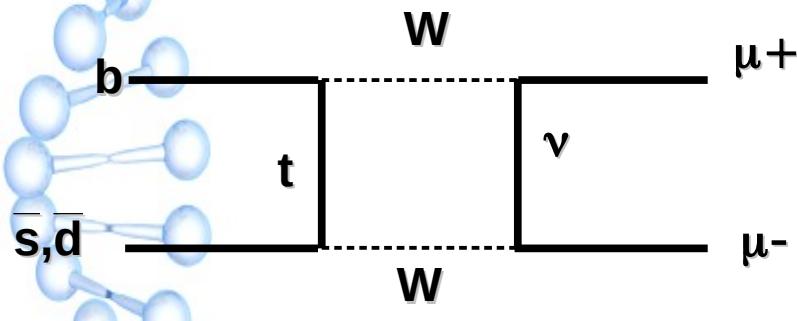
2.1-2.3 σ below SM

$$1.1 \text{ GeV}^2 < q^2 < 6 \text{ GeV}^2$$

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

2.4-2.5 σ below SM

B → ℓ⁺ℓ⁻ decays



Contribution from $O_{10}(\cdot)$
and

$$O_S(\cdot) = (\bar{s} b)_{V \pm A} (\bar{\ell} \ell)$$

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

SM-based predictions:

$$BR(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

$$BR(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$

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

B → μ⁺μ⁻ status

LHCb (PRL 118 (2017) 191801)

$$BR(B^0 \rightarrow \mu^+ \mu^-) < 3.4 \times 10^{-10} @ 95\% CL$$

$$BR(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.5(stat)_{-0.2}^{+0.3}(syst)) \times 10^{-9}$$

ATLAS (JHEP 04 (2019) 098)

$$BR(B^0 \rightarrow \mu^+ \mu^-) < 2.1 \times 10^{-10} @ 95\% CL$$

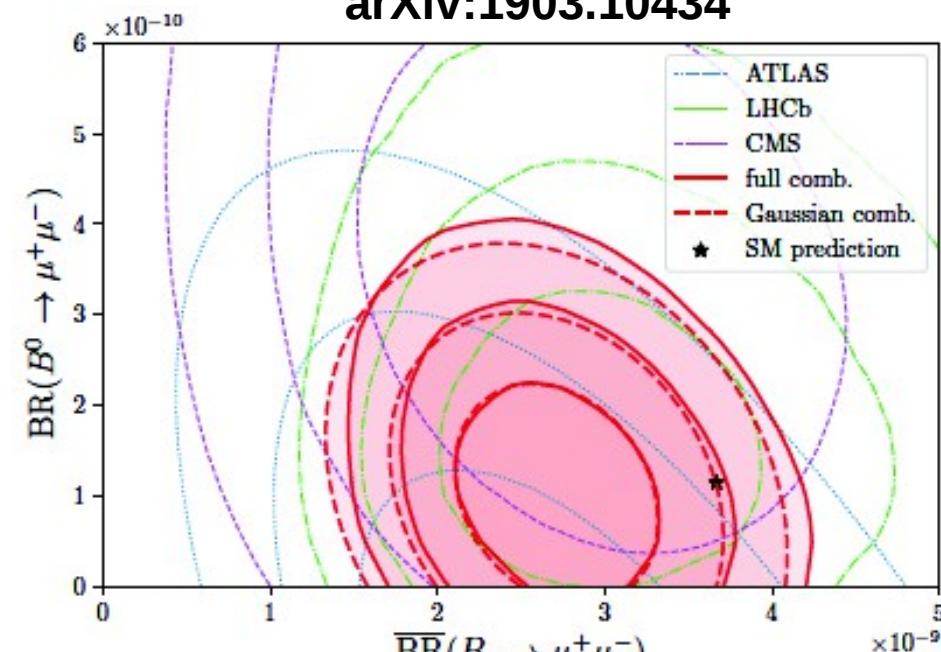
$$BR(B_s^0 \rightarrow \mu^+ \mu^-) = (3.2_{-1.0}^{+1.1}) \times 10^{-9}$$

CMS (PRL 111, 101804 (2013))

$$BR(B^0 \rightarrow \mu^+ \mu^-) = (4.4_{-1.9}^{+2.2}) \times 10^{-10}$$

$$BR(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8_{-0.9}^{+1.1}) \times 10^{-9}$$

arXiv:1903.10434



Combination gives Bs mode 2σ below SM

Very recent CMS update
(08/2019), CMS-PAS-BPH-16-004

$$BR(B^0 \rightarrow \mu^+ \mu^-) < 3.6 \times 10^{-10} @ 95\% CL$$

$$BR(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9_{-0.6}^{+0.7} \pm (0.2)(f_s/f_u)) \times 10^{-9}$$

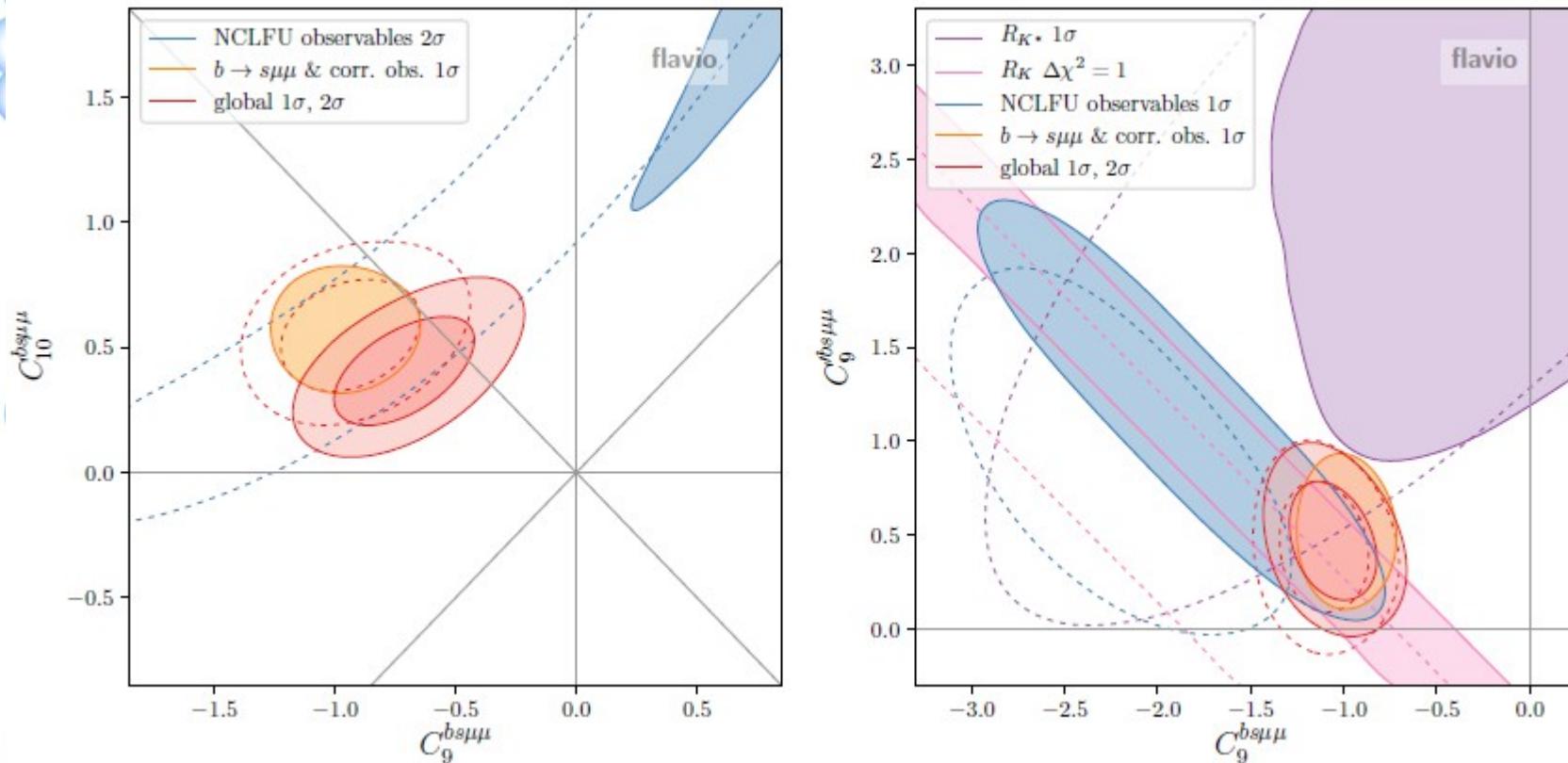


ONGOING UPDATE OF COMBINATION

Global fits to Wilson coefficients

A huge number of observables included

Example of arXiv:1903.10434, D.Straub et al.



Some configurations lead to significant enhancement of right-handed currents wrt SM-based predictions : triggers intense activity related to NP scenarios (New vector Z', Leptoquarks, ...)

A word on LFV

If LFUV confirmed, what about LFV?, e.g.:

$$B \rightarrow \ell\ell', b \rightarrow (s,d)\ell\ell'$$

e.g. recent LHCb searches

$$B_{(s)}^0 \rightarrow \tau^+ \mu^- \text{ arXiv:1905.06614}$$

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

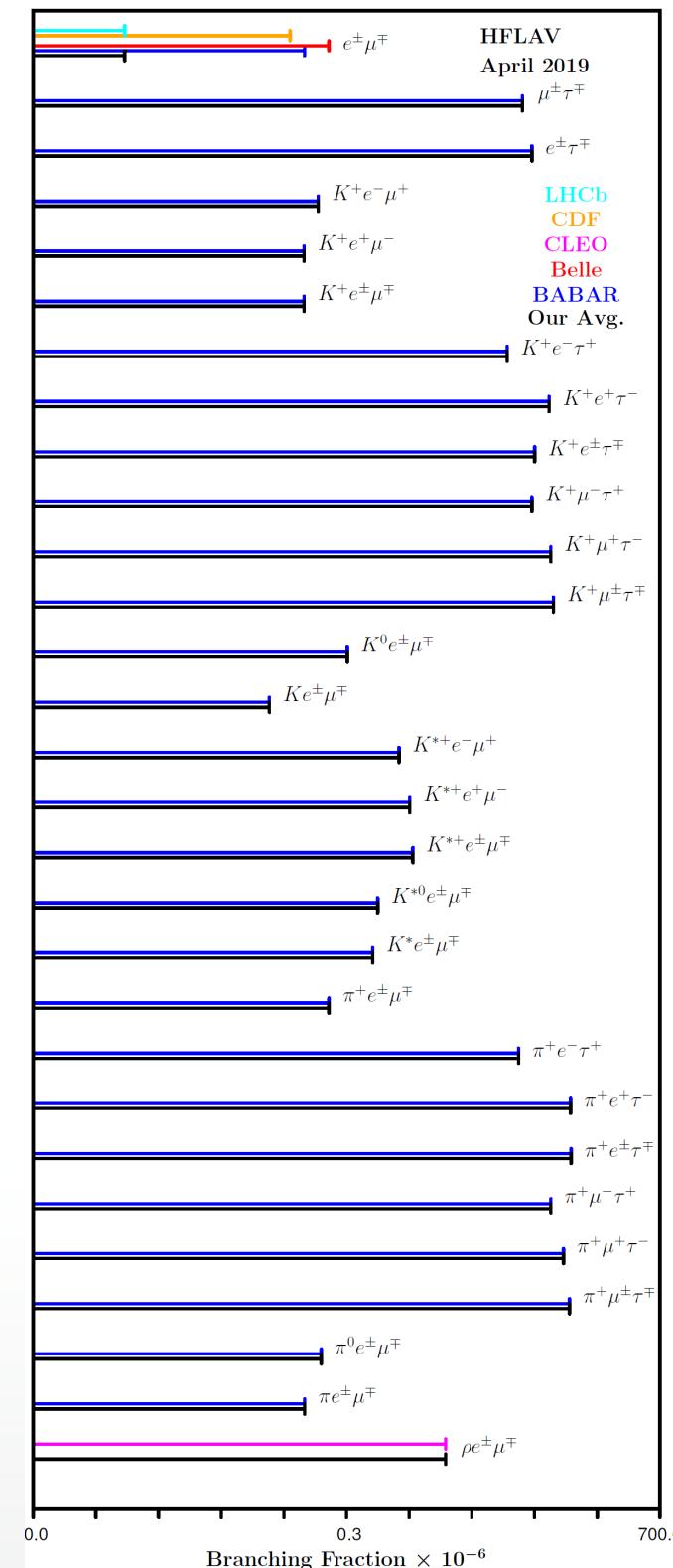
$$BR(B_s^0 \rightarrow \tau^+ \mu^-) < 4.2 \times 10^{-5} \text{ @ 95% CL}$$

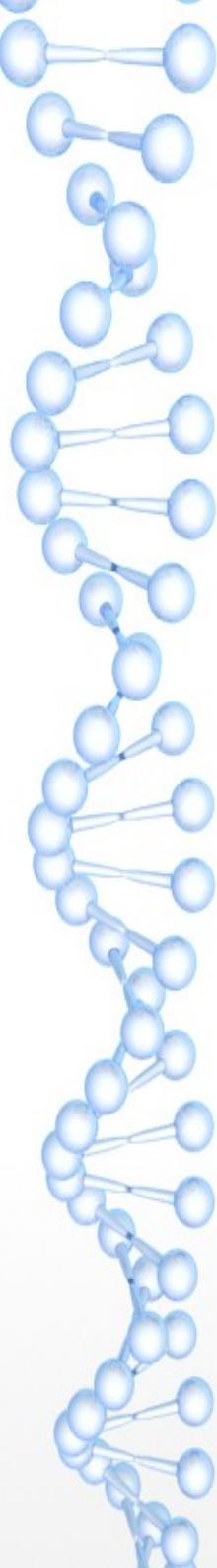
$$B^+ \rightarrow K^+ \mu^\pm e^\mp \text{ LHCb-PAPER-2019-022}$$

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

$$BR(B^+ \rightarrow K^+ \mu^+ e^-) < 9.1 \times 10^{-9} \text{ @ 95% CL}$$

→ NEW, preliminary, on its way to submission





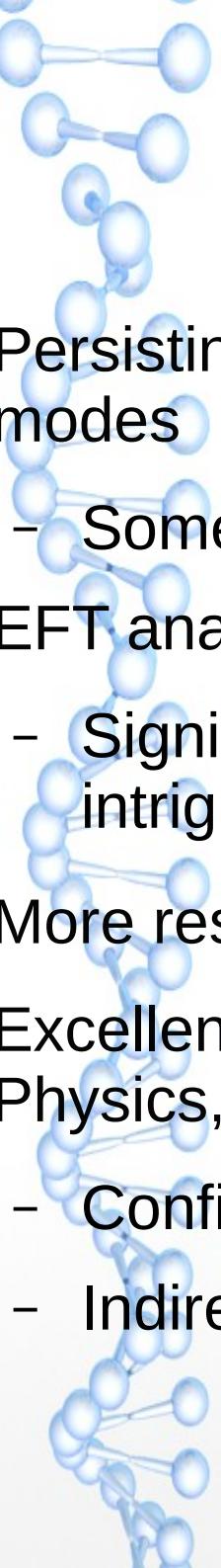
Some theoretical papers (non-exhaustive) on LFUV/LFV

G. Hiller et al., ***Leptoquark Flavor Patterns & B Decay Anomalies***, JHEP 12 (2016) 027, arXiv:1609.08895

A. Crivellin et al., ***Lepton-flavour violating B decays in generic Z' models***, Phys. Rev. D92 (2015) 054013, arXiv:1504.07928

S. M. Boucenna et al., ***Are the B decay anomalies related to neutrino oscillations?***, Phys.Let.B (2015) 09 040, arXiv:1503.07099

See also R.Volkas on Thursday; WG5; *Radiative neutrino mass models and the flavour anomalies*



Conclusion

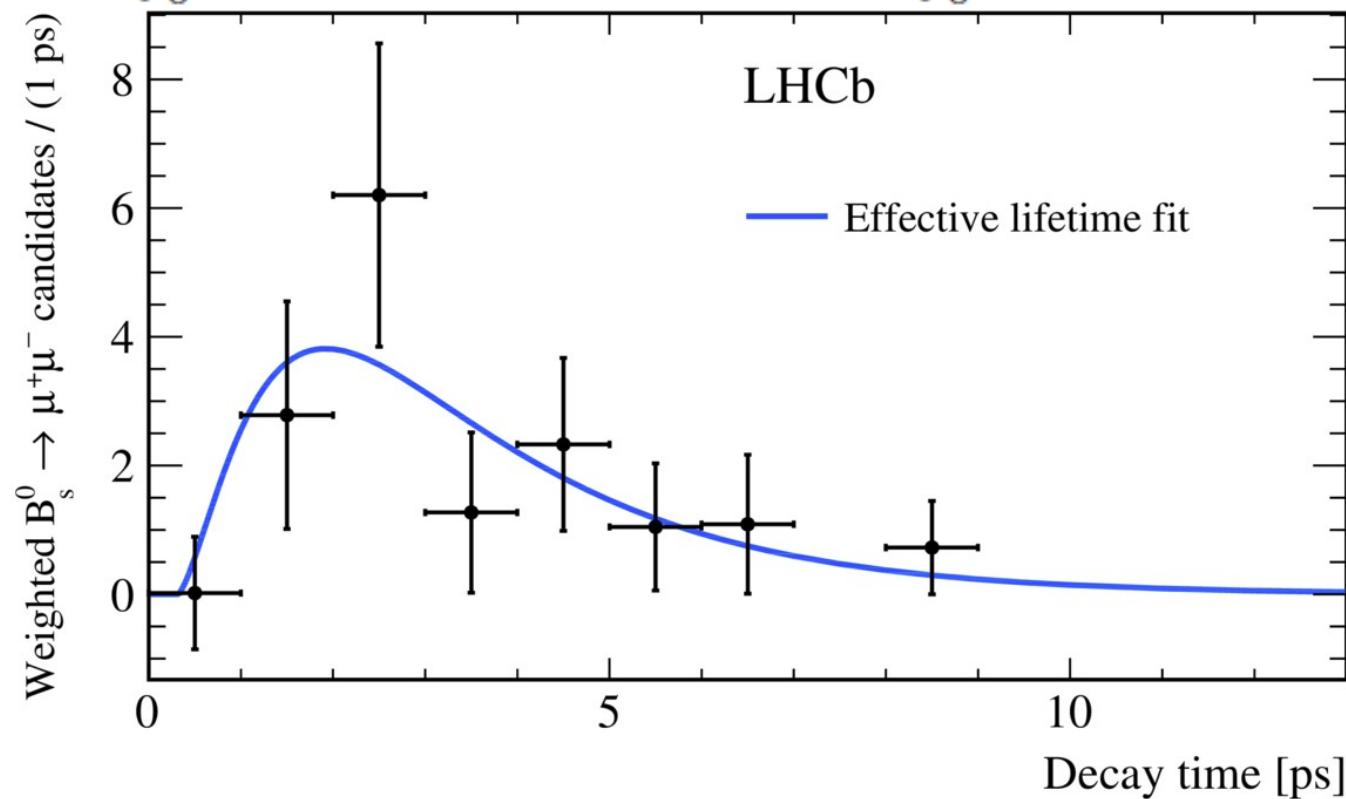
- Persisting anomalies for several observables of leptonic and semi-leptonic modes
 - Some bridges with neutrino physics through LFV searches
- EFT analyses are becoming more and more accurate
 - Significance of NP contributions to Wilson coefficients becoming intriguing, e.g. for C_9
- More results and combinations are coming with analysis of full Run 2
- Excellent prospects for Run 3 and after, fundamental role of Flavour Physics, either ways:
 - Confirmation of anomalies or
 - Indirect constraint on high energy scales

Back up

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

LHCb (PRL 118 (2017) 191801)

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



$$\tau(B_s \rightarrow \mu^+ \mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

News on radiative $b \rightarrow s \gamma$

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

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

Photon helicity and weak phases

CP violation in the decay

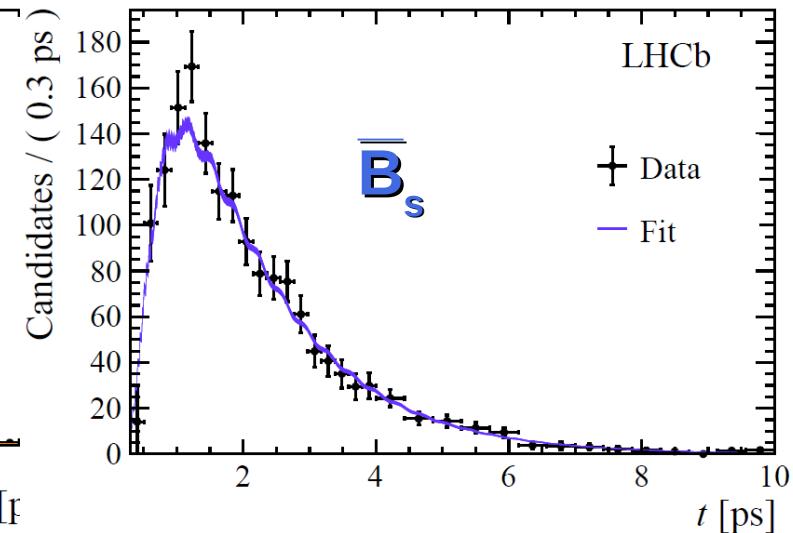
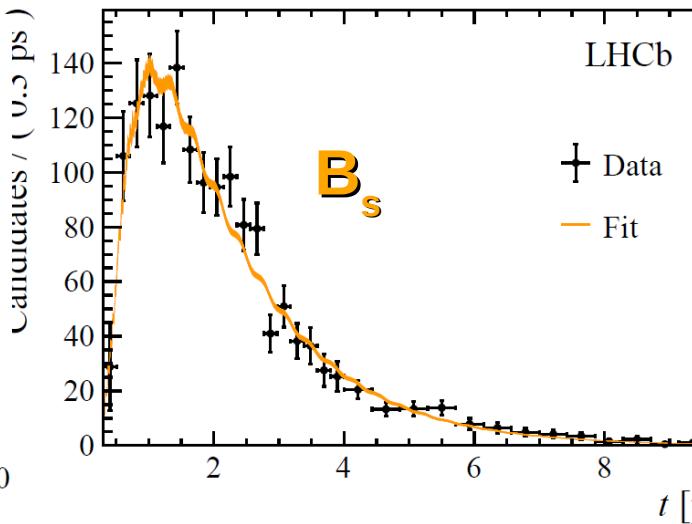
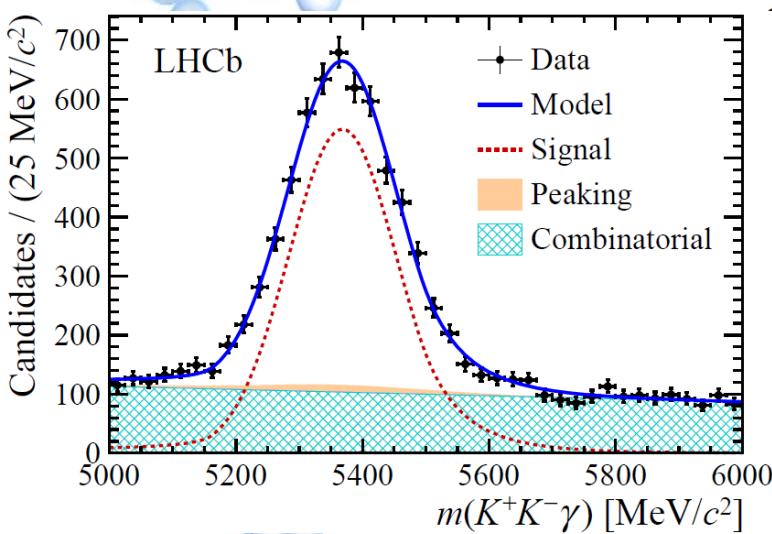
Expected to be close to zero within SM (e.g., PLB664 (2008) 174)

New (Spring 2019):

arXiv:1905.06284, accepted by PRL

$$B_s \rightarrow \phi(KK) \gamma$$

$B^0 \rightarrow K^{*0}(K^+\pi^-)\gamma$ selected with similar requirements to control the time-dependent efficiency

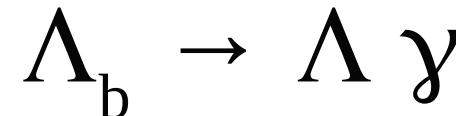


$$A_{\phi\gamma}^{\Delta\Gamma} = -0.67^{+0.37}_{-0.41} \pm 0.17, C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11, S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11$$

First measurements of those parameters for B_s meson radiative decay
Compatible with SM within current accuracy

New (spring 2019)

arXiv:1904.06697, PRL123 (2019) 031801



$B^0 \rightarrow K^{*0} (K^+ \pi^-) \gamma$ used as normalization channel

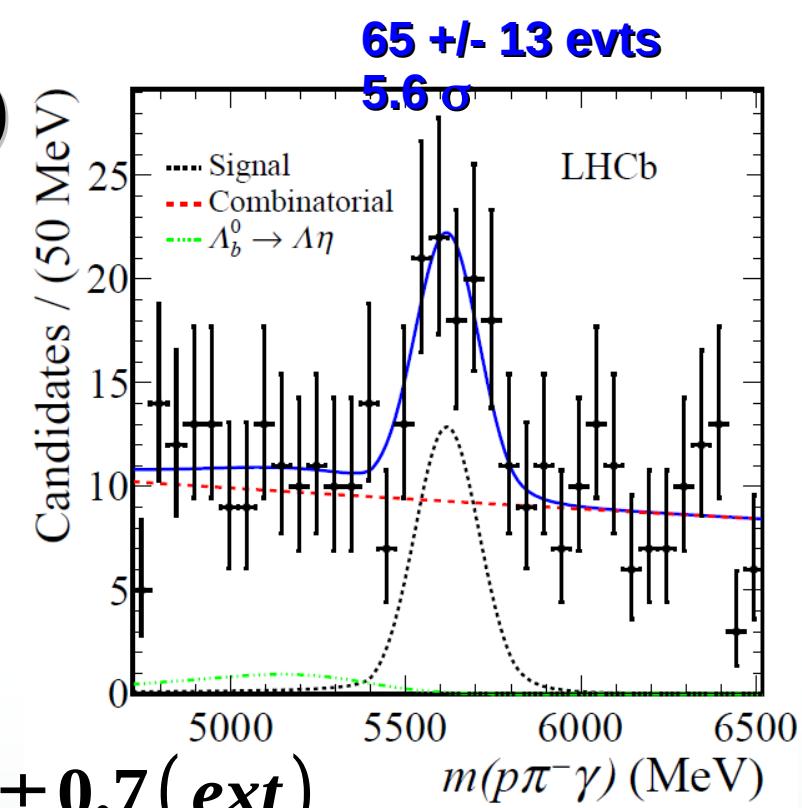
No proper vertex reconstructible (flying Λ and γ): require small DOCA between Λ_b and Λ , assuming Λ_b originates from closest PV to Λ trajectory

Analysis with reduced Run 2 sample (1.7 fb^{-1})

First observation of a b-baryon radiative decay

$$BR(\Lambda_b \rightarrow \Lambda \gamma) = 7.1 \pm 1.5 (\text{stat}) \pm 0.6 (\text{syst}) \pm 0.7 (\text{ext})$$

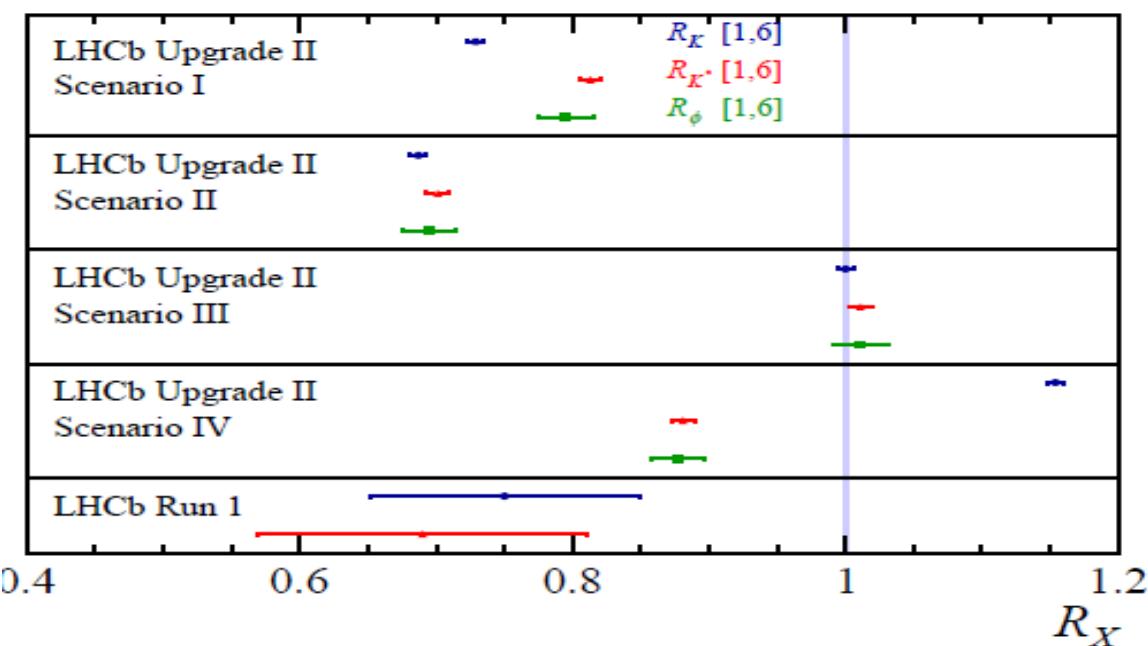
Compatible with SM



Projections for the future

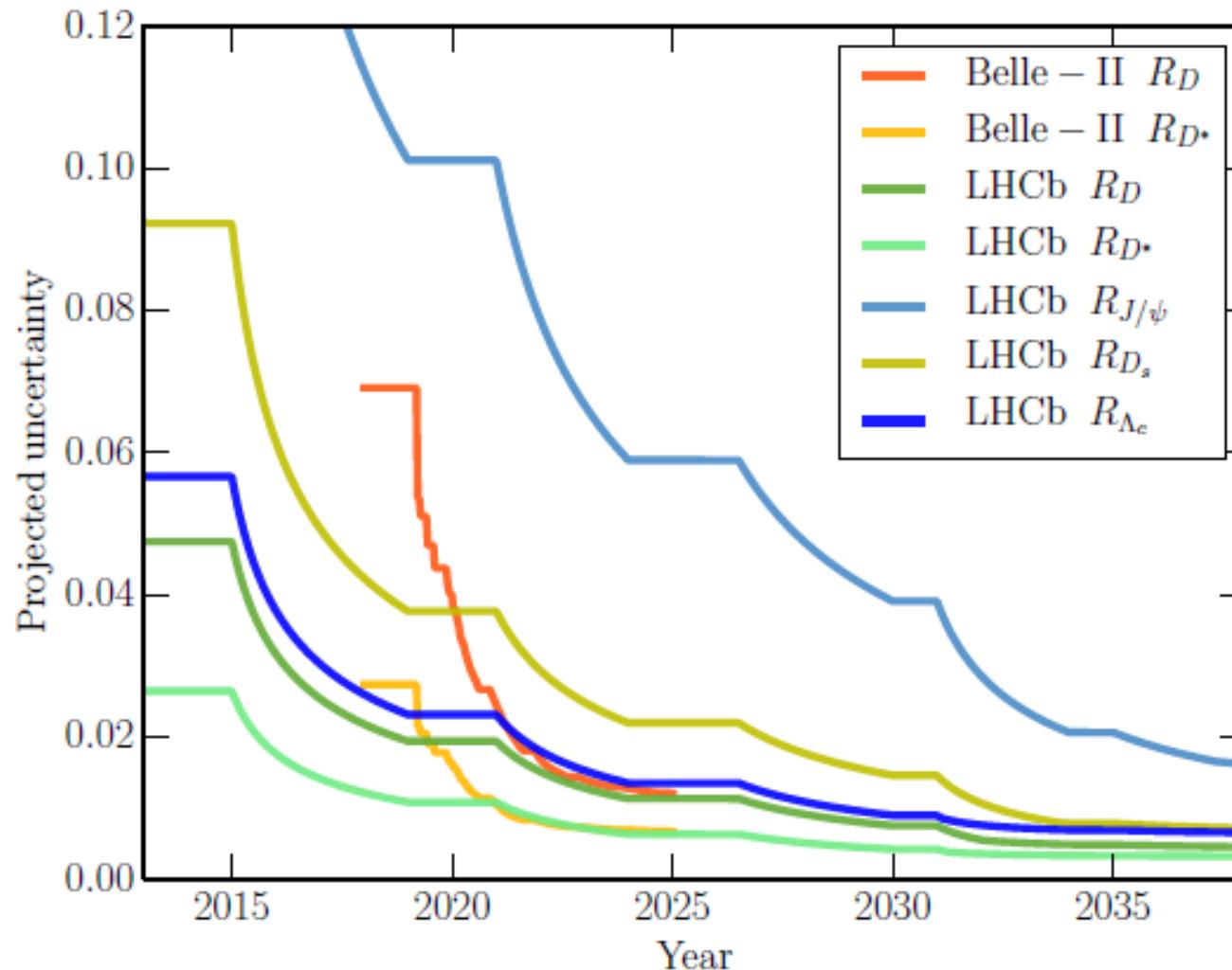
CERN-LHCC-2018-027, LHCb-PUB-2018-009, arXiv:1808.08865

Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \rightarrow K^+ e^+ e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
$B^0 \rightarrow K^{*0} e^+ e^-$	111 ± 14 [275]	490	1 400	3 300	20 000
$B_s^0 \rightarrow \phi e^+ e^-$	–	80	230	530	3 300
$\Lambda_b^0 \rightarrow p K e^+ e^-$	–	120	360	820	5 000
$B^+ \rightarrow \pi^+ e^+ e^-$	–	20	70	150	900
R_X precision	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
R_K	$0.745 \pm 0.090 \pm 0.036$ [274]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [275]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047



Prospects for R(X)

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



Upgrade DAQ scheme

LHCb Upgrade Trigger Diagram

**30 MHz inelastic event rate
(full rate event building)**



Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections



Buffer events to disk, perform online detector calibration and alignment



Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage