



DIS 2018

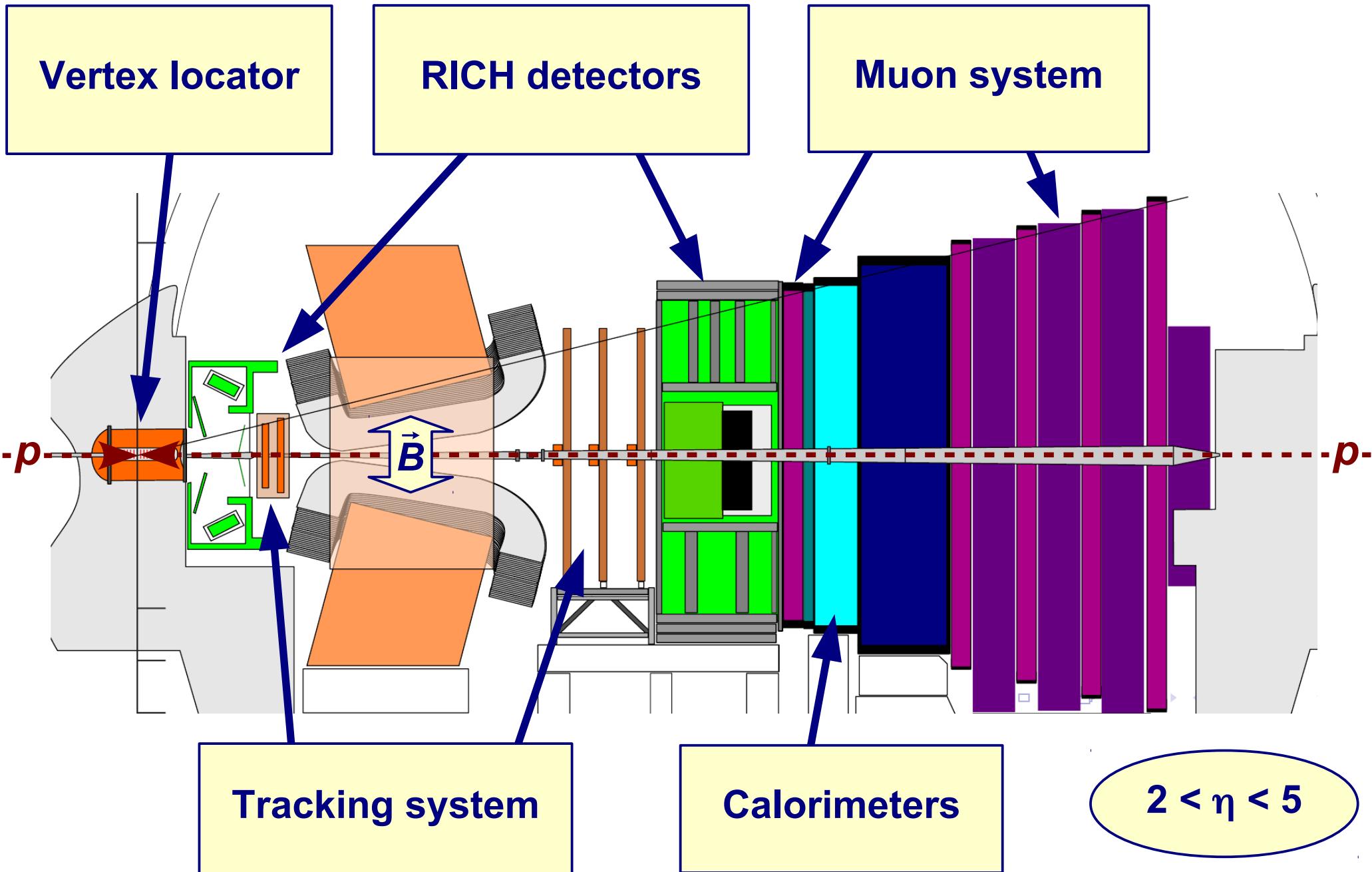
Kobe, Japan, April 16 - 20, 2018

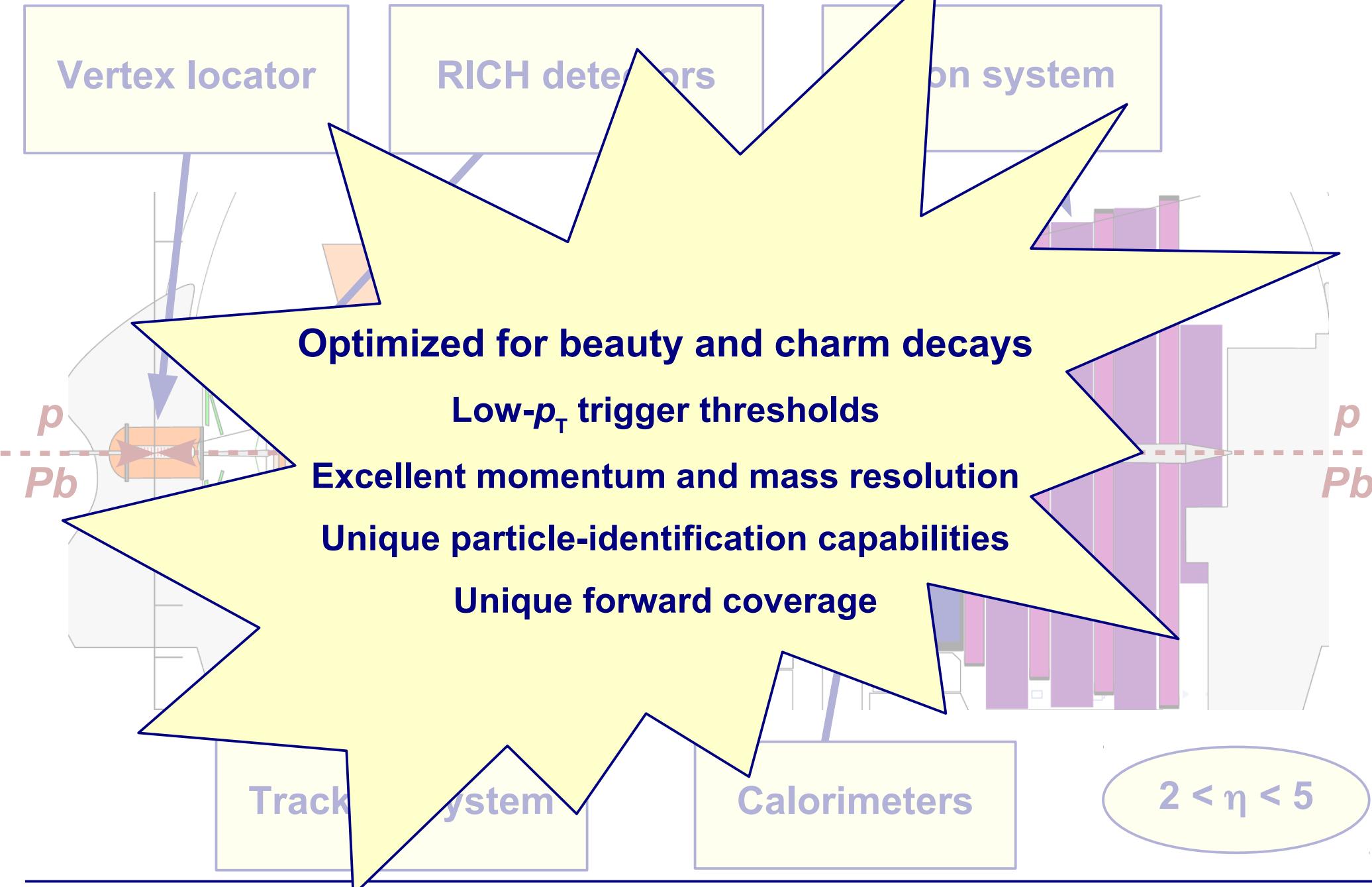
B-flavour anomalies in $b \rightarrow s\ell\ell$ and $b \rightarrow c\ell\nu$ transitions at LHCb

Olaf Steinkamp

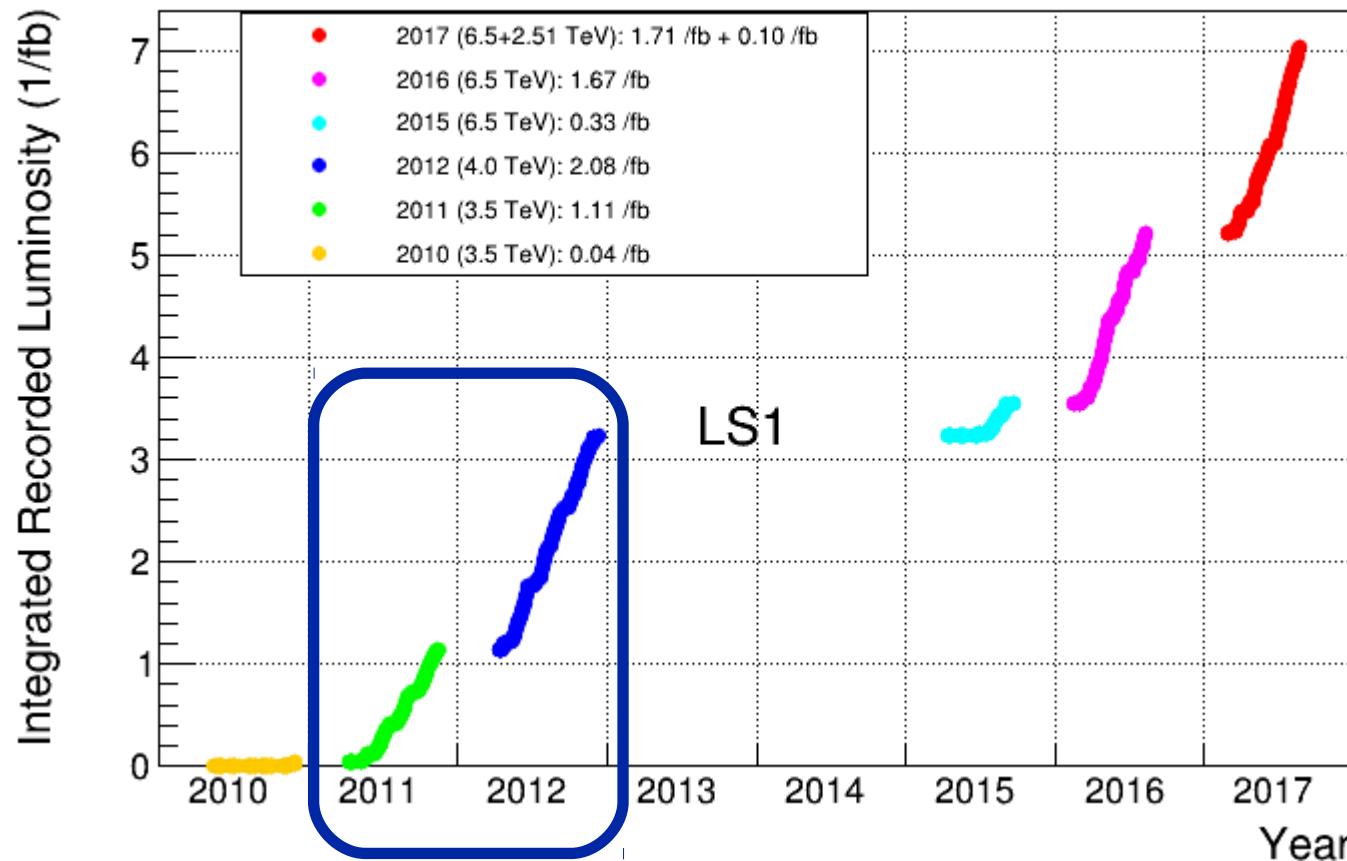
on behalf of the LHCb collaboration

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LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2017



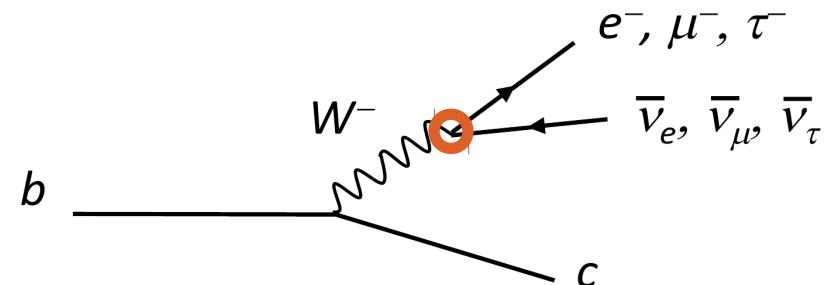
Results presented here based on Run-I data:

1 fb⁻¹ at 7 TeV + 2 fb⁻¹ at 8 TeV

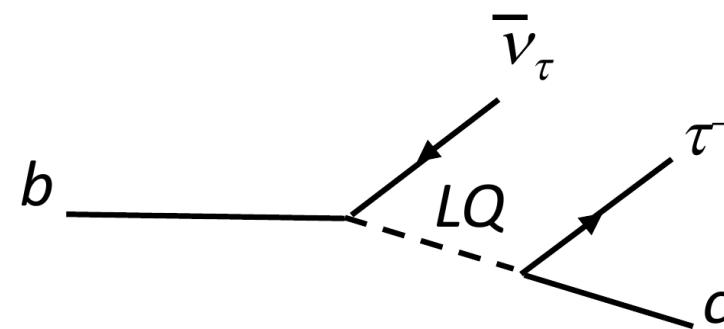
$$b\rightarrow c\,\ell^-\bar\nu_\ell$$

Test Lepton-Flavour Universality:

**Weak coupling constant identical
for all three lepton families**



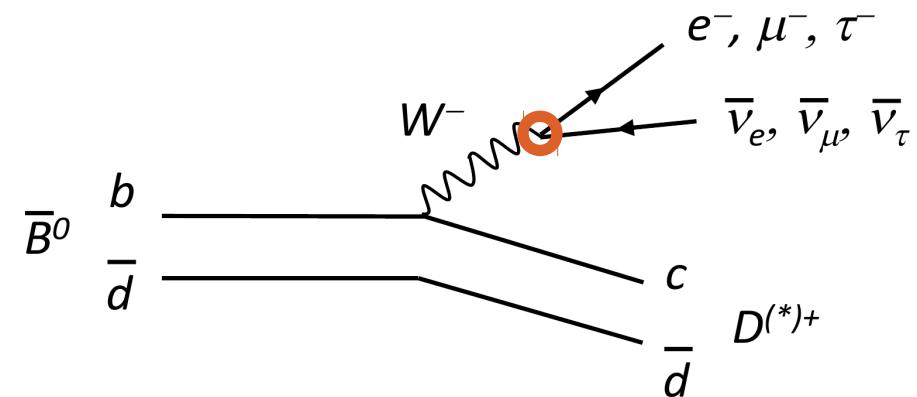
**Possible violation e.g. due to
extended Higgs sector or Leptoquarks:**



Expected to couple predominantly to 3rd family

**Test Lepton-Flavour Universality:
by comparing decay rates, e.g.**

$$R(D^{(*)}) \equiv \frac{\text{BR}(\bar{B}^0 \rightarrow D^{(*)+} \tau^- \bar{\nu}_\tau)}{\text{BR}(\bar{B}^0 \rightarrow D^{(*)+} \mu^- \bar{\nu}_\mu)}$$



“Tree” decays:

- Relatively large branching fractions ($\sim 1.2\%$)
- Well understood in Standard Model → precise predictions

Many systematics cancel to first order in ratio

**But also experimentally challenging:
Multiple neutrinos from W and τ decays**

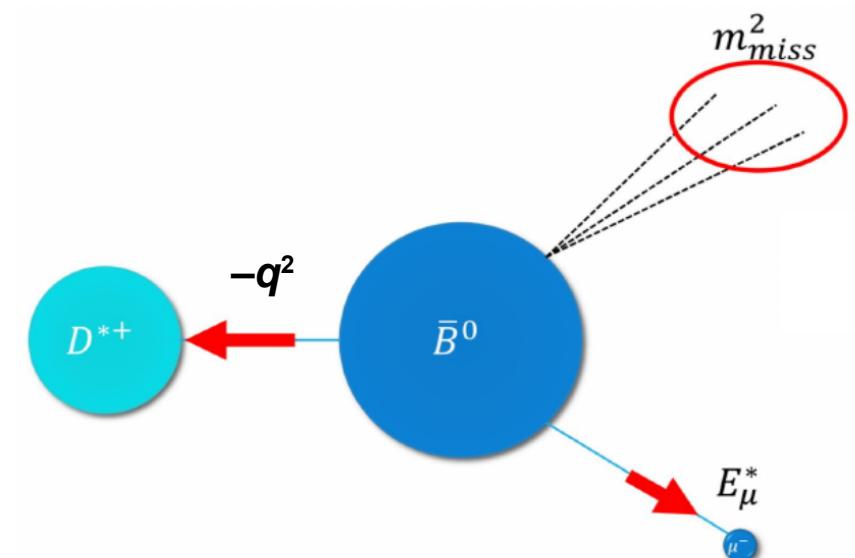
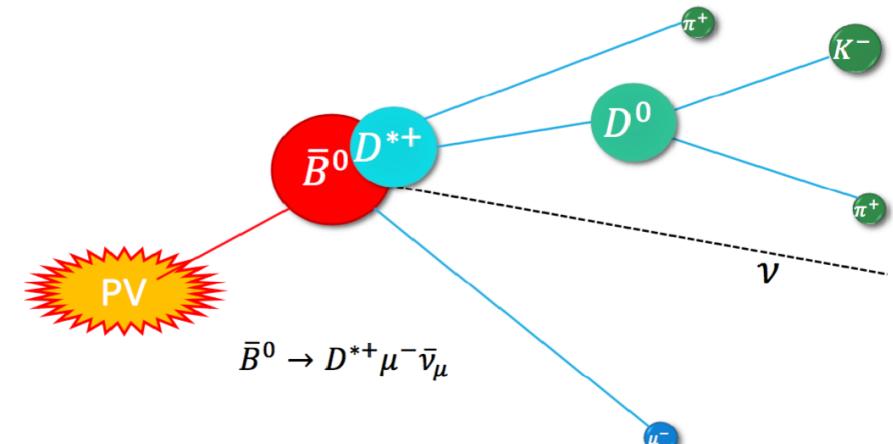
Determine B flight direction from reconstructed vertices

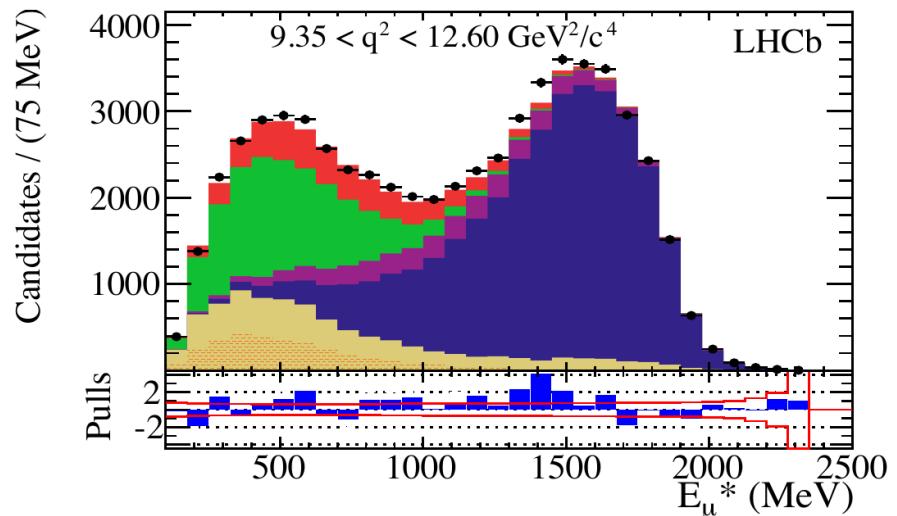
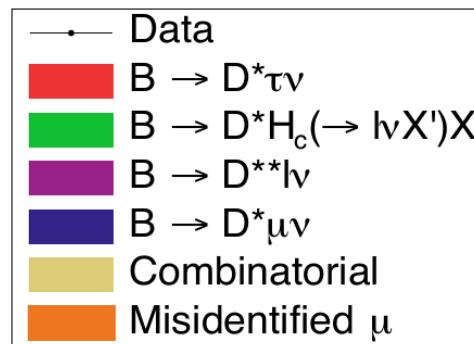
Estimate B momentum as

$$(\mathbf{p}_B)_z \equiv \frac{\mathbf{m}_B}{m_{reco}} \times (\mathbf{p}_{reco})_z$$

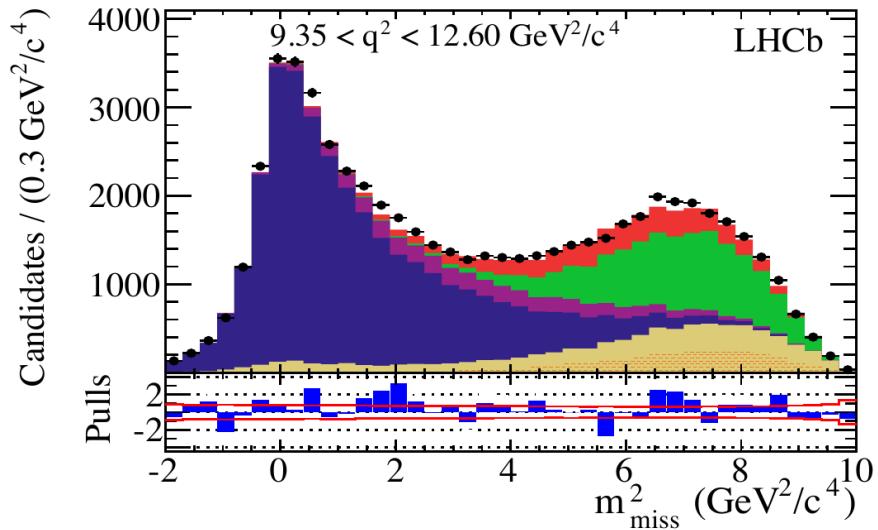
Look at kinematic variables in the B rest frame:

	$D^{*+} \tau^- \bar{\nu}_\tau$	$D^{*+} \mu^- \bar{\nu}_\mu$
E_μ^*	softer	harder
m_{miss}^2	> 0	≈ 0
q^2	$> m_\tau^2$	> 0





	$D^{**+} \tau^- \bar{\nu}_\tau$	$D^{**+} \mu^- \bar{\nu}_\mu$
E_μ^*	softer	harder
m_{miss}^2	> 0	≈ 0
q^2	$> m_\tau^2$	> 0

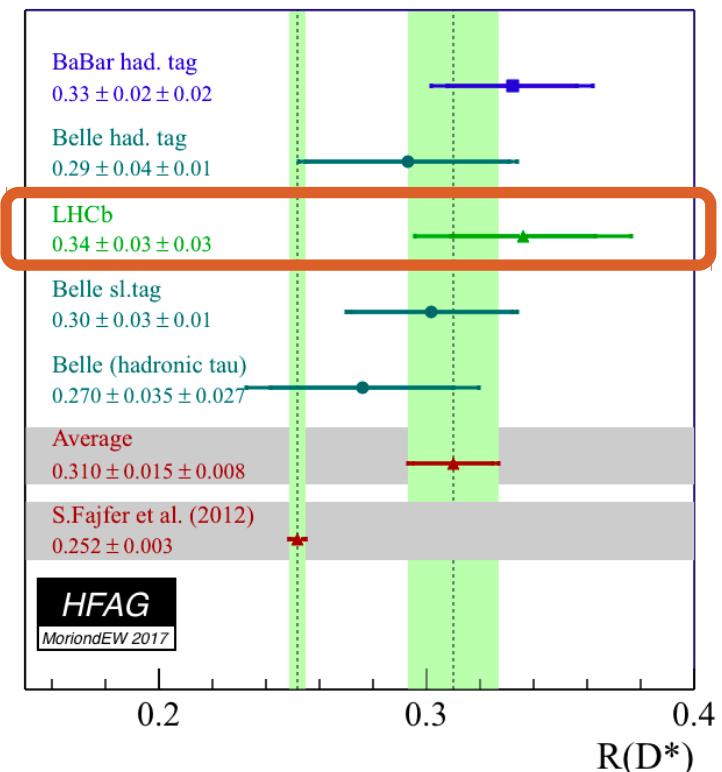


$$R(D^*) = 0.336 \pm 0.027 \text{ (stat)} \pm 0.030 \text{ (syst)}$$

2.1 σ above Standard Model prediction

Compatible with BaBar and Belle

Systematic uncertainty dominated by limited size of simulated event samples



Reconstruct τ decay vertex

Large background from

$$B \rightarrow D^{*+} \pi^- \pi^+ \pi^- X$$

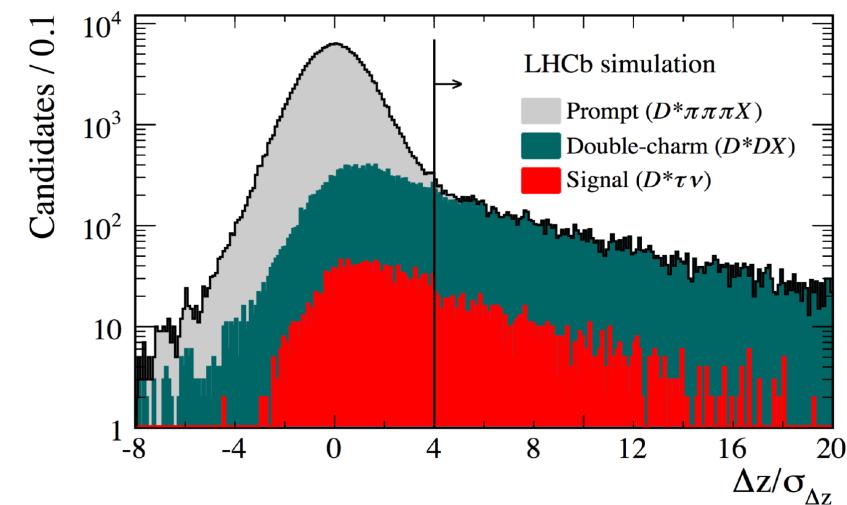
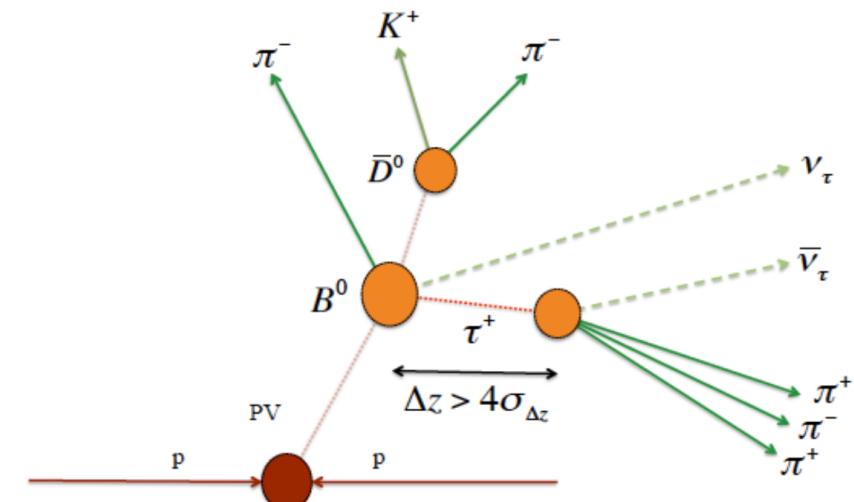
→ Suppress using τ decay length

Long-lived background from

$$B \rightarrow D^{*+} D^-_{(s)} X \text{ with } D^-_{(s)} \rightarrow \pi^- \pi^+ \pi^- X'$$

→ Kinematics, Dalitz structure,
partial reconstruction of D

→ Combine in BDT

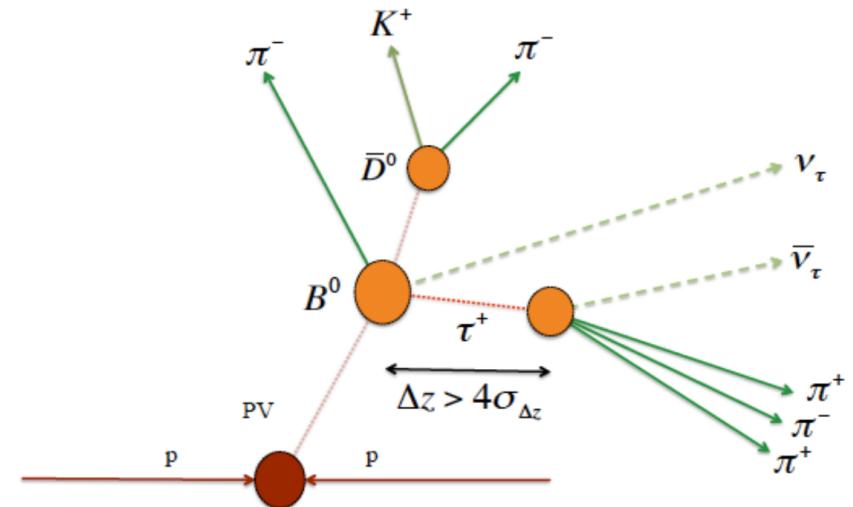


Reconstruct τ decay vertex

Large background from

$$B \rightarrow D^{*+} \pi^- \pi^+ \pi^- X$$

→ Suppress using τ decay length

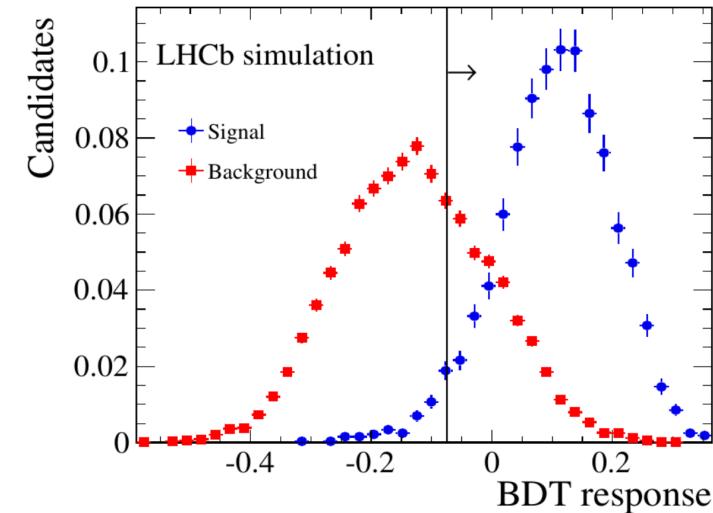


Long-lived background from

$$B \rightarrow D^{*+} D^-_{(s)} X \text{ with } D^-_{(s)} \rightarrow \pi^- \pi^+ \pi^- X'$$

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partial reconstruction of D

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Reconstruct τ decay vertex

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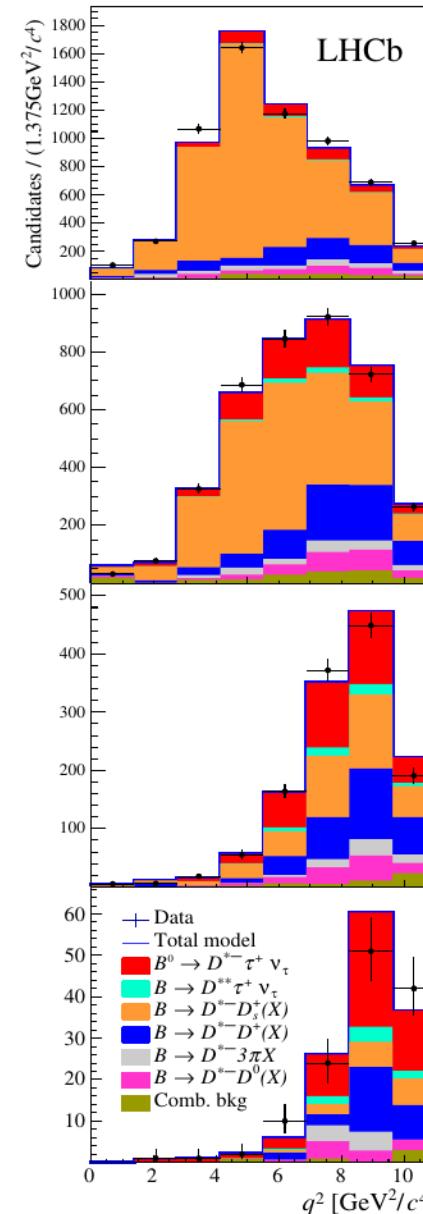
→ Suppress using τ decay length

Long-lived background from

$$B \rightarrow D^{*+} D^-_{(s)} X \text{ with } D^-_{(s)} \rightarrow \pi^- \pi^+ \pi^- X'$$

→ Kinematics, Dalitz structure,
partial reconstruction of D

→ Combine in BDT



increasing BDT output

To reduce systematics, measure BR relative to decay $B^0 \rightarrow D^{*+} \pi^- \pi^+ \pi^-$ with similar final state

$$R(D^*) = \underbrace{\frac{\text{BR}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau)}{\text{BR}(\bar{B}^0 \rightarrow D^{*+} \pi^- \pi^+ \pi^-)}}_{\text{measurement}} \times \underbrace{\frac{\text{BR}(\bar{B}^0 \rightarrow D^{*+} \pi^- \pi^+ \pi^-)}{\text{BR}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)}}_{\text{external inputs}^{(*)}}$$

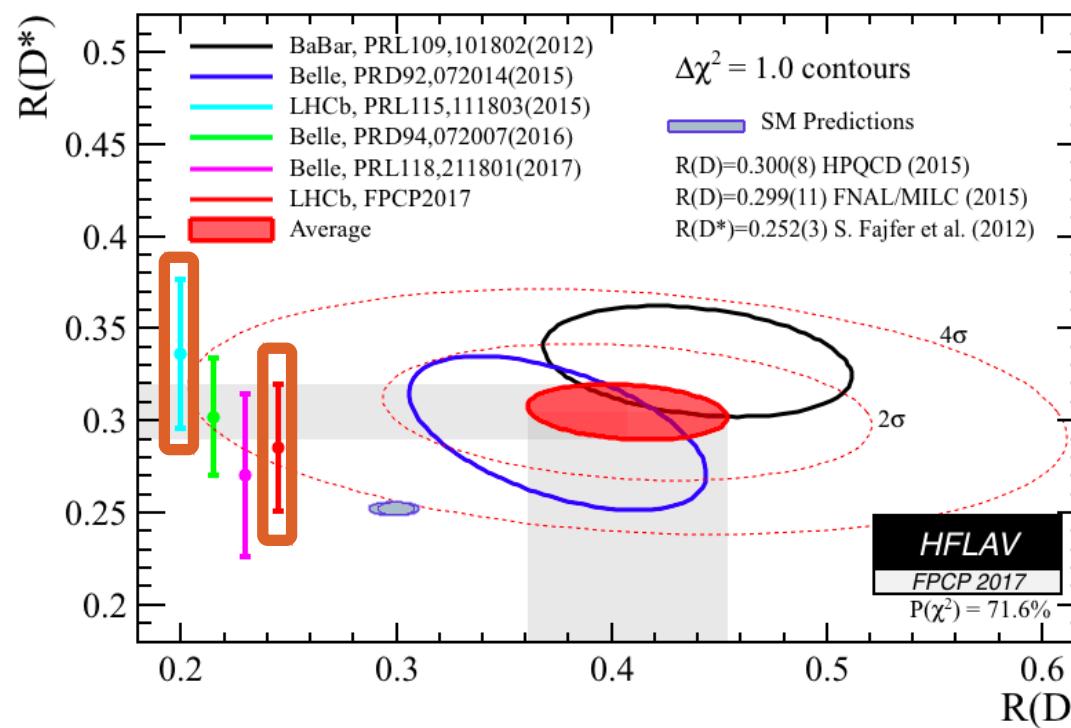
$$R(D^*) = 0.286 \pm 0.019 \text{ (stat)} \pm 0.025 \text{ (syst)} \pm 0.021 \text{ (ext)}$$

Systematic uncertainty again dominated by limited size of simulated event samples

(*) $\text{BR}(\bar{B}^0 \rightarrow D^{*+} \pi^- \pi^+ \pi^-)$: LHCb, [PRD 87 (2013) 092001] $\text{BR}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)$: HFLAV, [arxiv:1612.07233]

$R(D^*)$: Current Status

Combine with measurements of $R(D^*)$ and $R(D)$ from BaBar, Belle



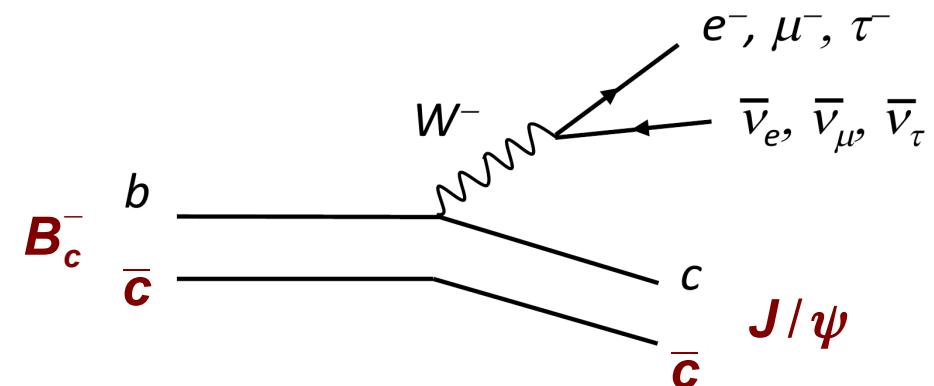
All results above Standard Model predictions

$R(D^*)$ and $R(D)$ combined give $\sim 3 \sigma$ deviation,
using latest Standard-Model predictions

[arXiv:1703.05330, 1707.09509, 1707.09977]

Test other b -systems, e.g.

$$R(J/\psi) \equiv \frac{\text{BR } (B_c^- \rightarrow J/\psi \tau^- \bar{\nu}_\tau)}{\text{BR } (B_c^- \rightarrow J/\psi \mu^- \bar{\nu}_\mu)}$$



Standard Model predictions affected by form-factor uncertainties

$$R_{\text{SM}}(J/\psi) \in [0.25, 0.28]$$

[PLB 452 (1999) 129] [arxiv:hep-ph/0211021] [PRD 73 (2006) 054024] [PRD 74 (2006) 074008]

Small hadronisation fraction
($\approx 0.2\%$ for B_c vs $\approx 40\%$ for B^0)

→ Expect smaller statistics, larger systematic uncertainties

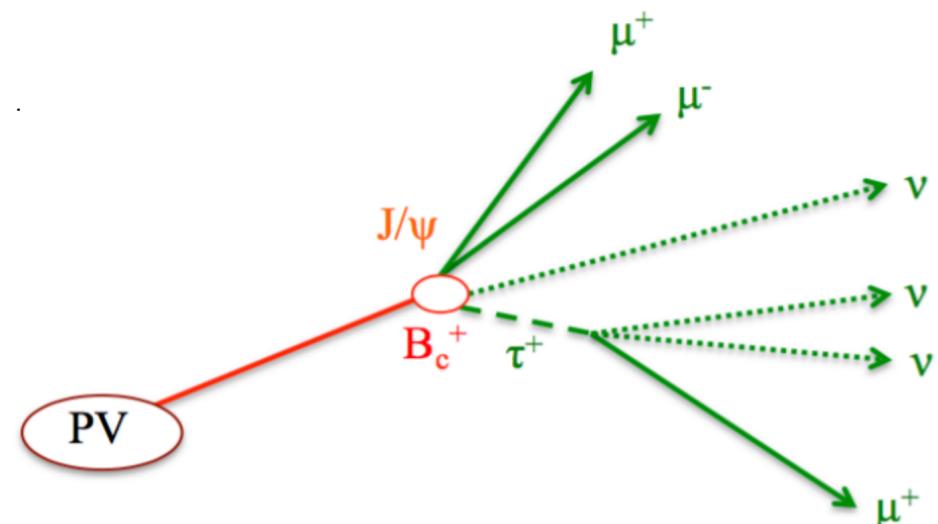
Approach similar to
 $R(D^*)$ measurement:

Reconstruct B_c flight direction
from production and decay vertices

Estimate B_c momentum from

$$(\mathbf{p}_{Bc})_z \equiv \frac{m_{Bc}}{m_{reco}} \times (\mathbf{p}_{reco})_z$$

Extract signal components from fit to
decay time, m_{miss}^2 , $Z(q^2, E_\mu^*)$



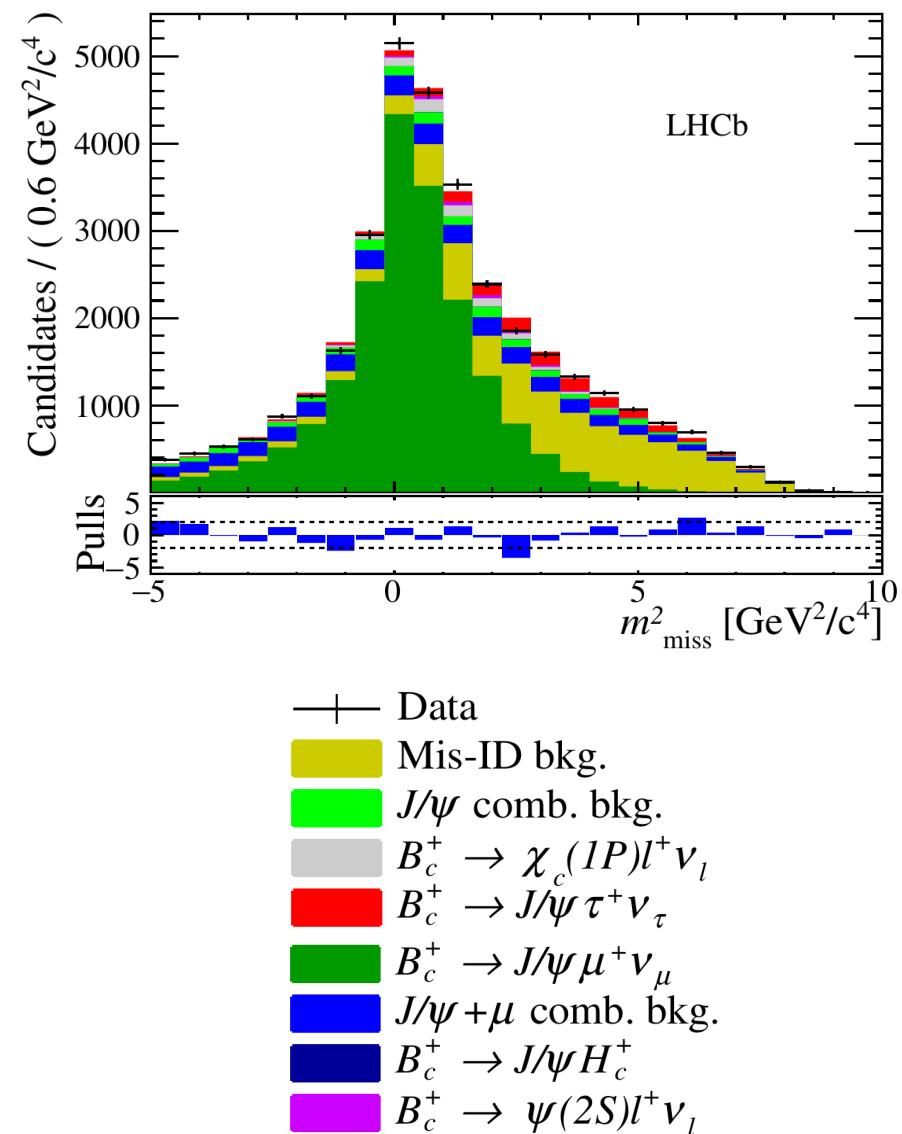
Approach similar to
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Reconstruct B_c flight direction
from production and decay vertices

Estimate B_c momentum from

$$(\mathbf{p}_{Bc})_z \equiv \frac{m_{Bc}}{m_{reco}} \times (\mathbf{p}_{reco})_z$$

Extract signal components from fit to
decay time, m^2_{miss} , $Z(q^2, E_\mu^*)$



Measured value about 2σ above Standard-Model predictions

$$R(J/\psi) = 0.71 \pm 0.17 \text{ (stat)} \pm 0.18 \text{ (syst)}$$

Systematic uncertainty dominated by form-factor uncertainties and size of simulated event samples

Also: first evidence (3σ) for the decay

$$B_c^- \rightarrow J/\psi \tau^- \bar{\nu}_\tau$$

$b \rightarrow s \ell^+ \ell^-$:

R_{K^*} and R_K

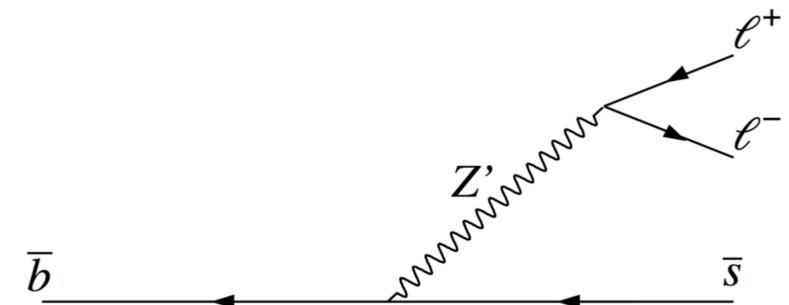
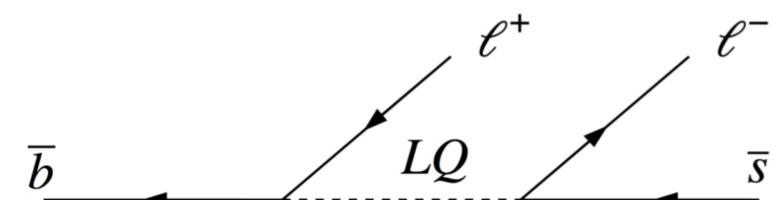
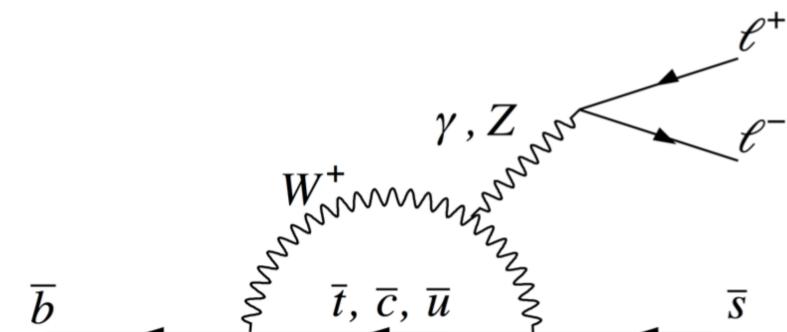
Flavour-Changing Neutral Current decays

Suppressed in Standard Model,
can only occur through loop processes

Excellent sensitivity to possible
“New Physics” contributions

→ Branching fractions

→ Angular distributions



Perform measurements as a function of $q^2 = m^2(\ell^+ \ell^-)$:

Different sensitivity to potential New Physics contributions

New Physics would affect

Wilson coefficients C_i ,

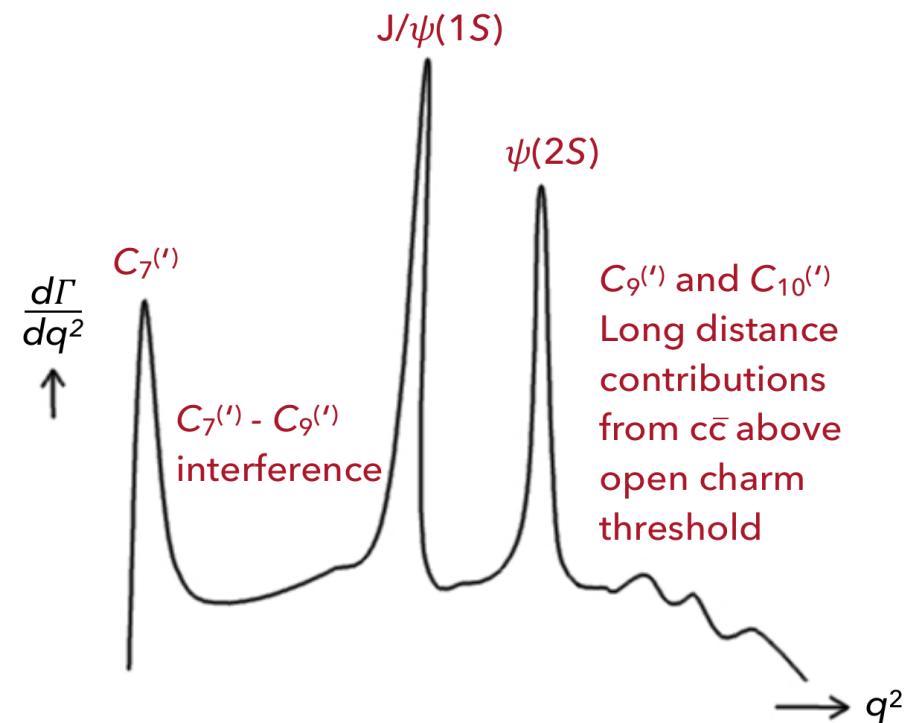
in the effective Hamiltonian:

$$H_{\text{eff}} \equiv -\frac{4 G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left\{ \underbrace{C_i O_i}_{\text{left-handed}} + \underbrace{C_i^\dagger O_i^\dagger}_{\text{right-handed}} \right\}$$

Relevant for $b \rightarrow s \ell^+ \ell^-$:

$i = 7$: photon penguin

$i = 9, 10$: electroweak penguins



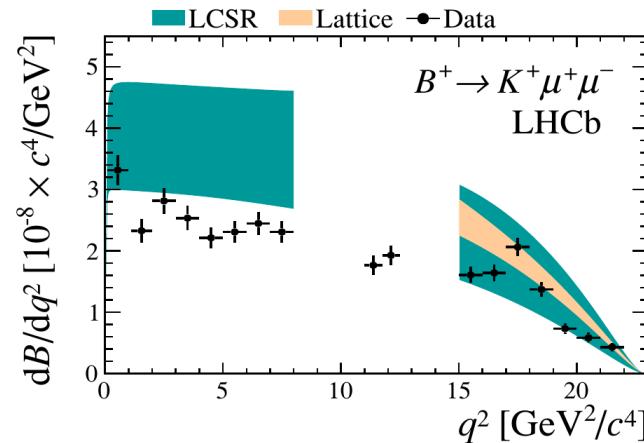
Right-handed contributions strongly suppressed in Standard Model

$b \rightarrow s \mu^+ \mu^-$ Branching Fractions

Measured values in the “interesting” q^2 range consistently below Standard-Model predictions

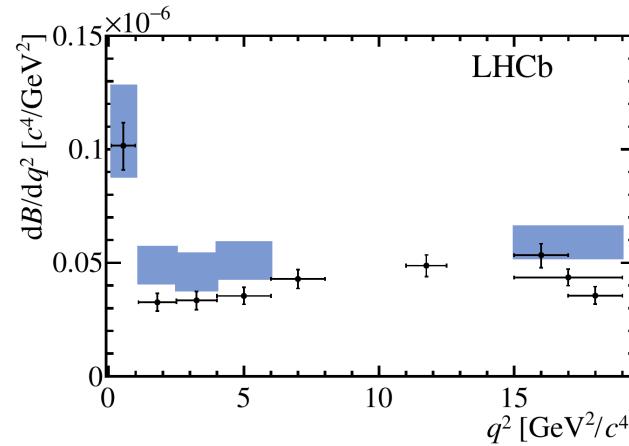
$B^+ \rightarrow K^+ \mu^+ \mu^-$

[JHEP 06(2014)133]



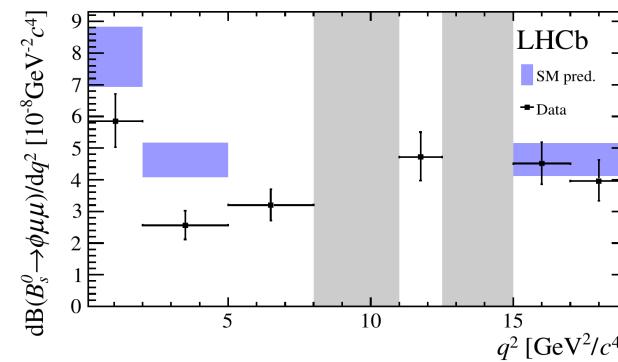
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

[JHEP 04(2017)142]



$B_s^0 \rightarrow \phi \mu^+ \mu^-$

[JHEP 09(2015)179]



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

[JHEP 06(2015)115]

Detmold, Meinel

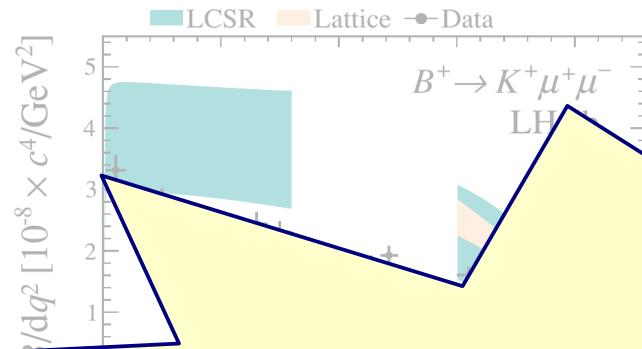
[PRD 93 (2016) 074501]

$b \rightarrow s \mu^+ \mu^-$ Branching Fractions

Measured values in the “interesting” q^2 range consistently below Standard-Model predictions

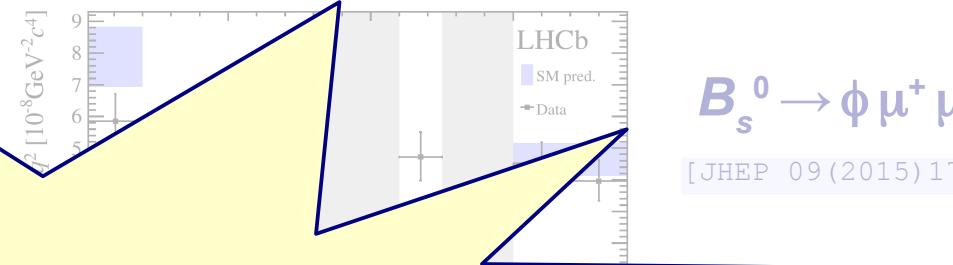
$B^+ \rightarrow K^+ \mu^+ \mu^-$

[JHEP 06(2014)133]



$B_s^0 \rightarrow \phi \mu^+ \mu^-$

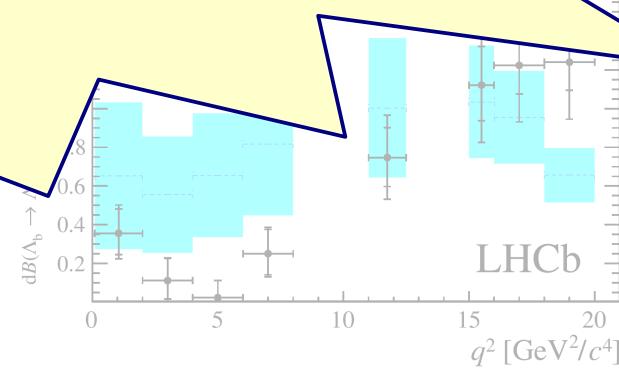
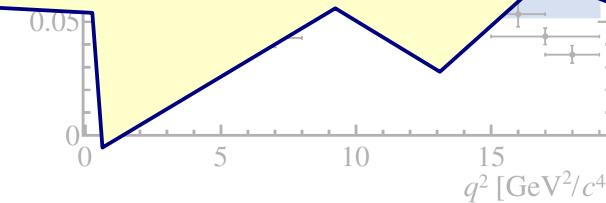
[JHEP 09(2015)179]



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

[JHEP 04(2017)]

But: significant theory uncertainties from hadronic form factors



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

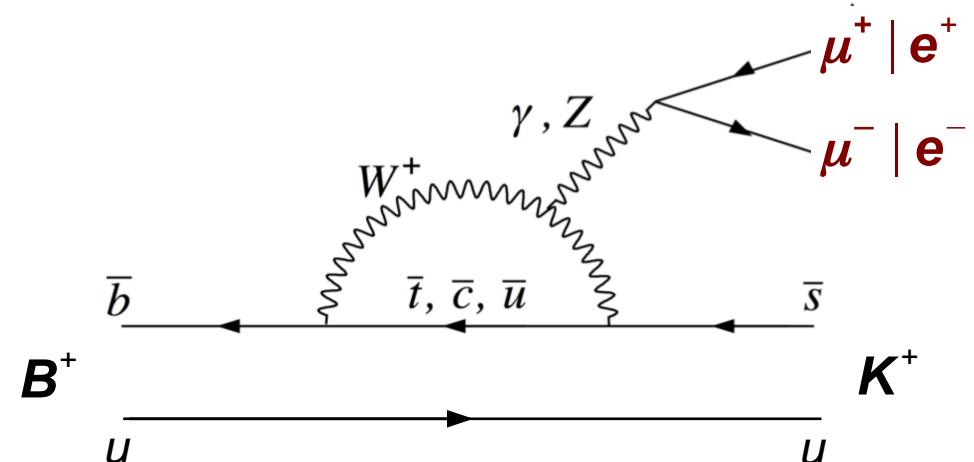
[JHEP 06(2015)115]

Detmold, Meinel

[PRD 93 (2016) 074501]

These form-factor uncertainties
largely cancel in ratios:

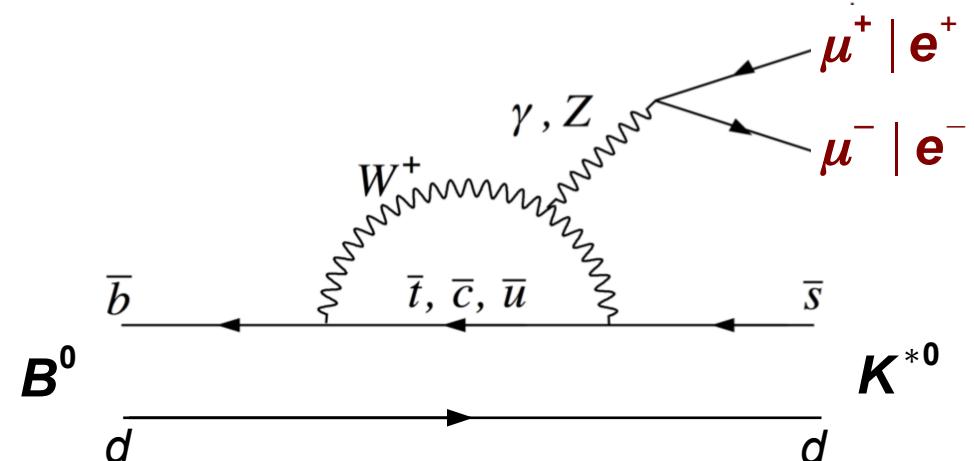
$$R_K \equiv \frac{\text{BR} (B^+ \rightarrow K^+ \mu^+ \mu^-)}{\text{BR} (B^+ \rightarrow K^+ e^+ e^-)}$$



R_K and R_{K^*}

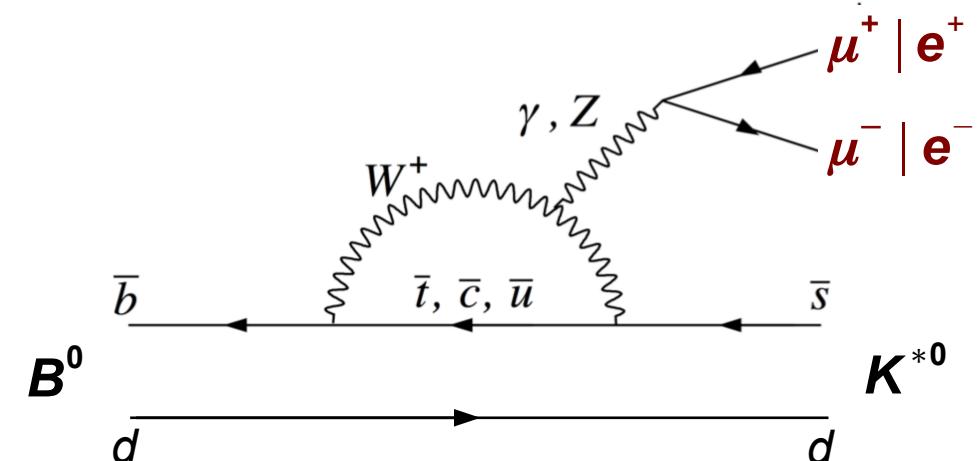
These form-factor uncertainties
largely cancel in ratios:

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



These form-factor uncertainties
largely cancel in ratios:

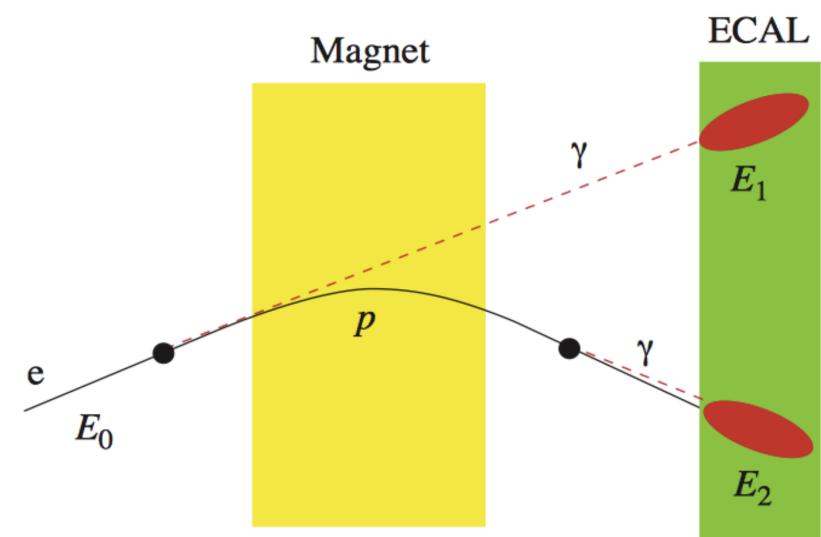
$$R_{K^*} \equiv \frac{\text{BR } (B^0 \rightarrow K^* \mu^+ \mu^-)}{\text{BR } (B^0 \rightarrow K^* e^+ e^-)}$$



→ Tests of Lepton Flavour Universality

Experimental challenge:
Electron reconstruction

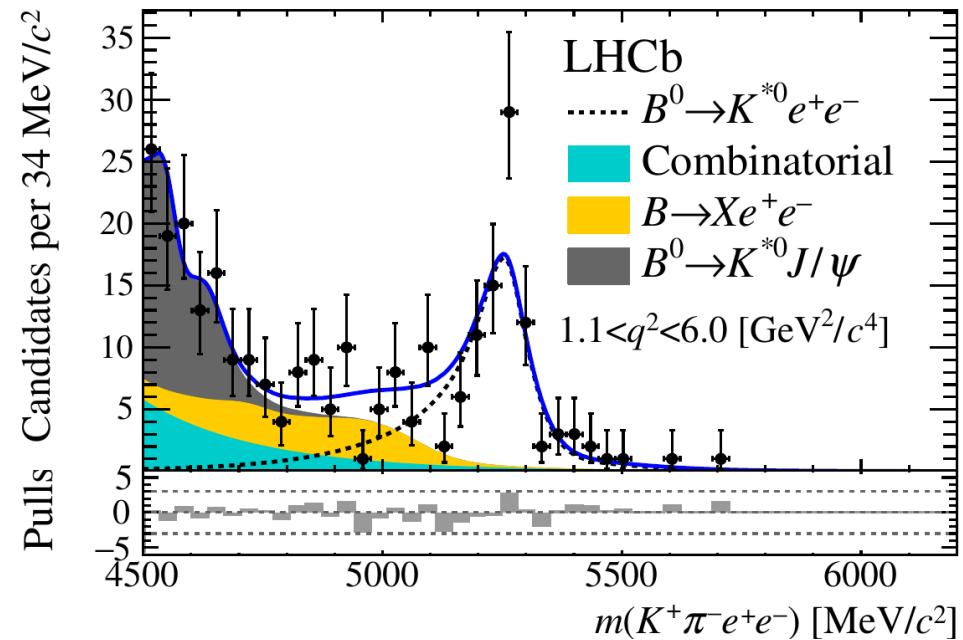
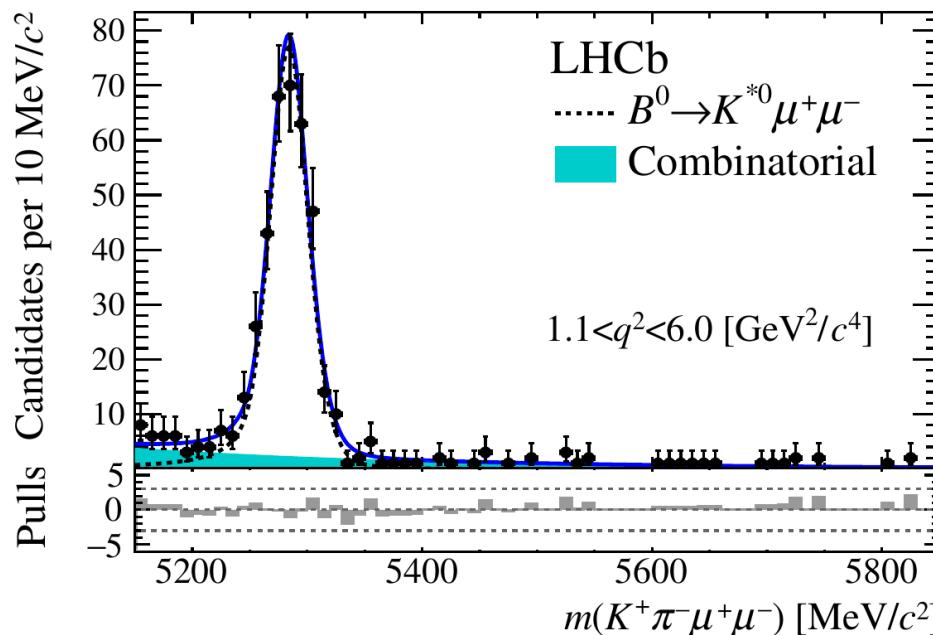
→ Algorithms for
Bremstrahlung recovery,
but never perfect



Lower trigger efficiencies → smaller statistics

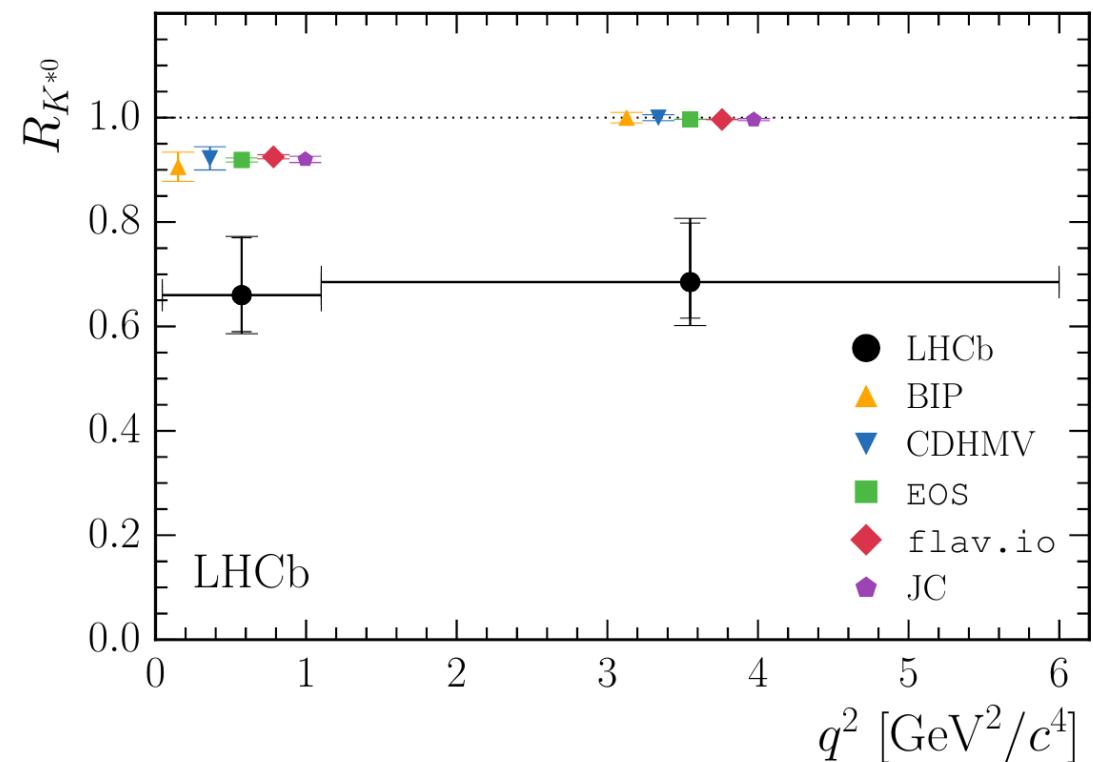
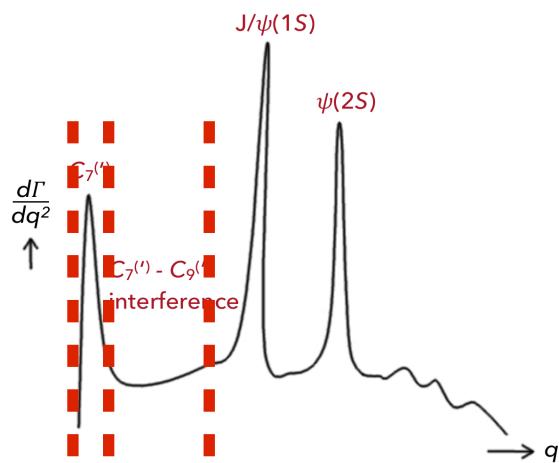
Worse resolution, radiative tail of signal → have to consider partially reconstructed background at lower mass

Additional background from radiative tail of $J/\psi \rightarrow e^+ e^-$



[JHEP 08 (2017) 055]

Measure R_{K^*} in two bins of q^2



**Measured values below Standard Model predictions:
2.1-2.3 σ and 2.4-2.5 σ**

$$R_{K^*} = \begin{cases} 0.66_{-0.07}^{+0.11} (\text{stat}) \pm 0.03 (\text{syst}) ; & 0.045 < q^2 < 1.1 \text{ GeV}^2 c^4 \\ 0.69_{-0.07}^{+0.11} (\text{stat}) \pm 0.05 (\text{syst}) ; & 1.1 < q^2 < 6.0 \text{ GeV}^2 c^4 \end{cases}$$

BaBar and Belle also measured R_{K^*} ,
but larger uncertainties

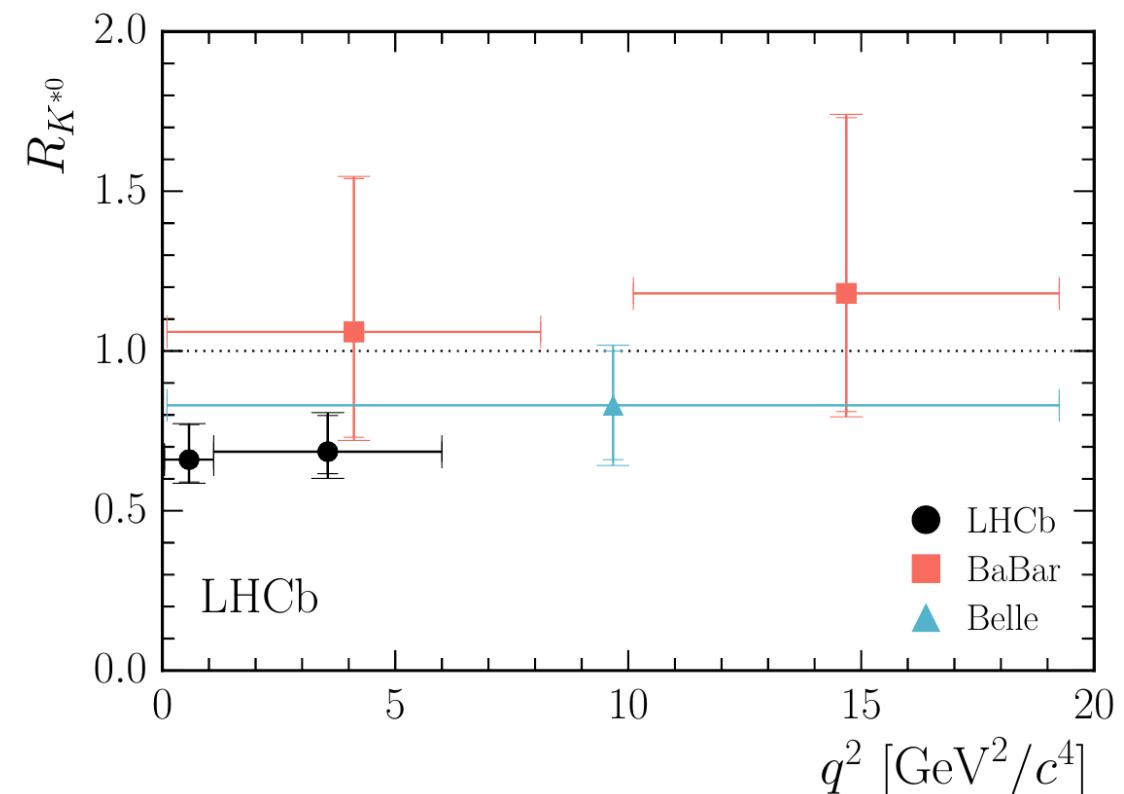
● LHCb

■ BaBar

[PRD 86 (2012) 032012]

▲ Belle

[PRL 103 (2009) 171801]



Earlier measurement of R_K for $1 < q^2 < 6 \text{ GeV}^2 c^4$
also below Standard Model, compatible at 2.6σ

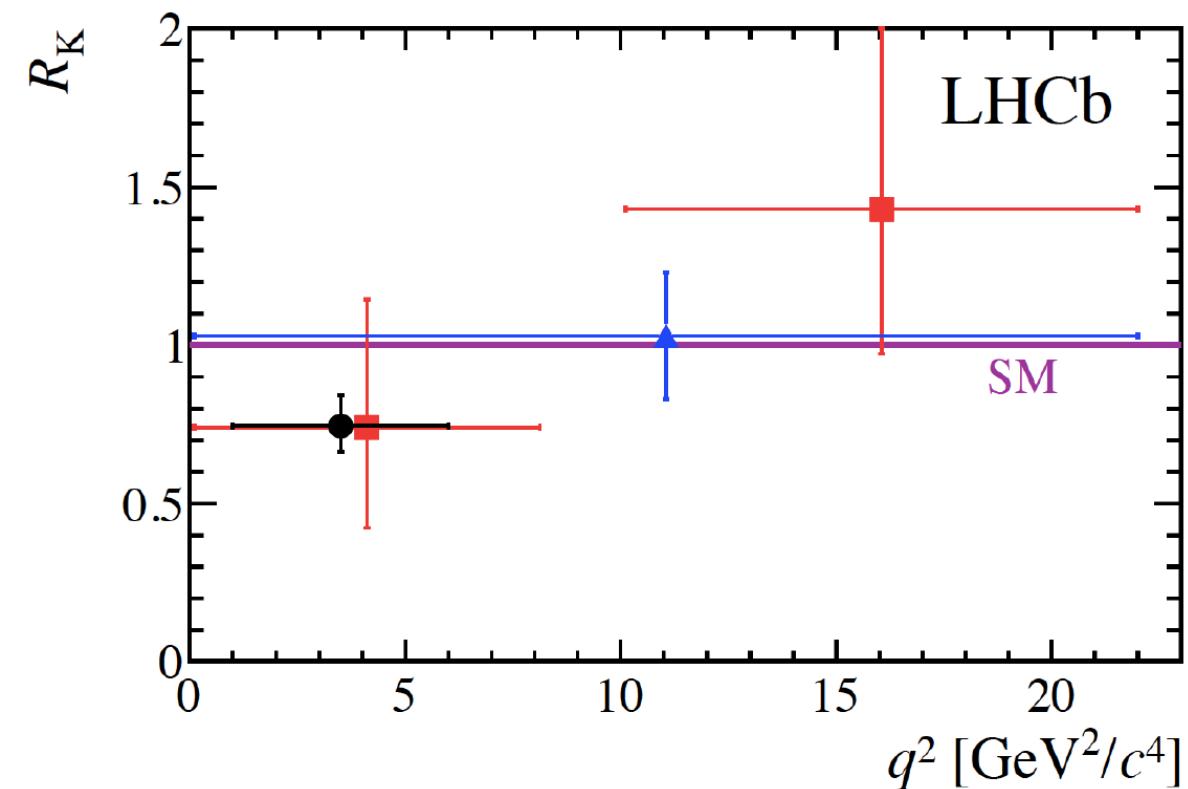
LHCb

BaBar

[PRD 86 (2012) 032012]

Belle

[PRL 103 (2009) 171801]



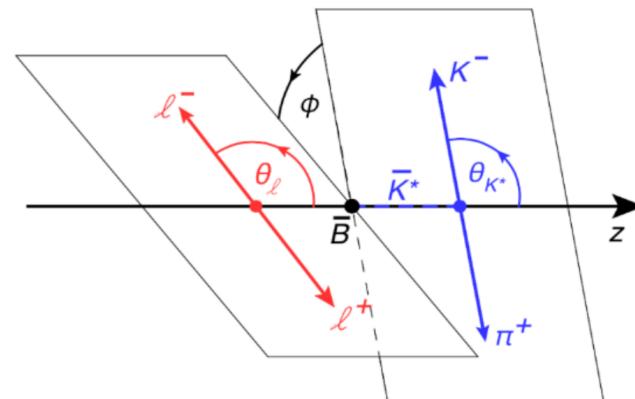
$$R_K = 0.745^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)} ; \quad 1 < q^2 < 6 \text{ GeV}^2 c^4$$

$b \rightarrow s \ell^+ \ell^-$:
angular observables

Reconstruct K^{*0} in its decay to $K^+ \pi^-$

→ four final-state particles

→ three decay angles ($\theta_K, \theta_\ell, \phi$)



Angular distribution
fully described by
8 independent coefficients

These are related to the
underlying Wilson coefficients

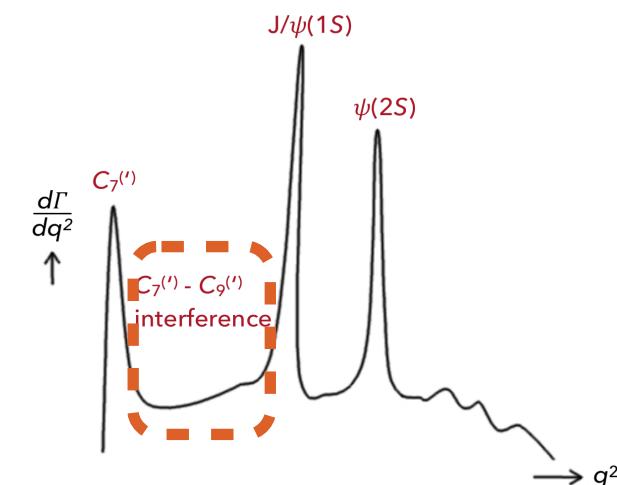
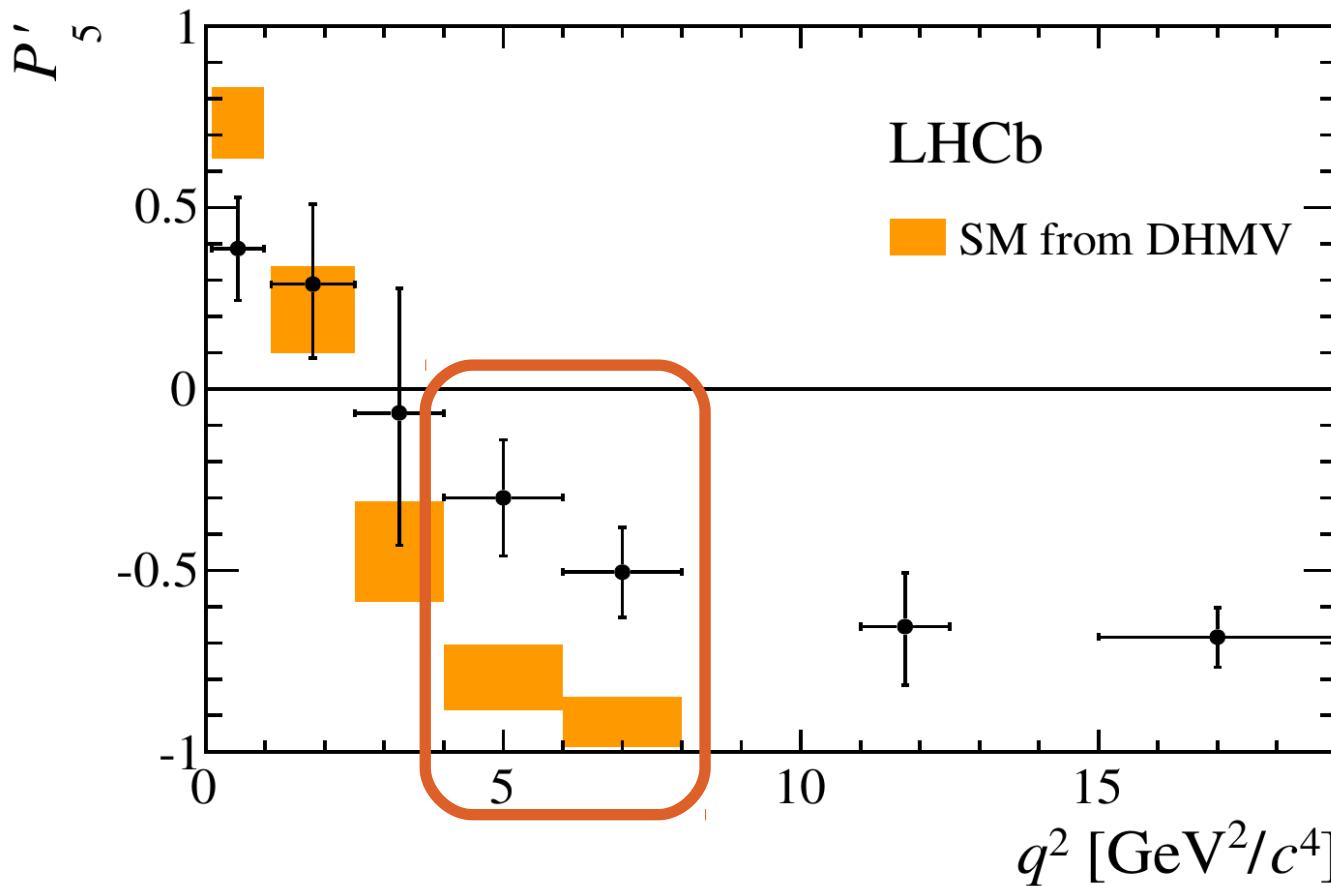
$$\frac{1}{\Gamma} \frac{d^3(\Gamma + \bar{\Gamma})}{d \cos \theta_\ell d \cos \theta_K d\phi} = \frac{9}{32\pi} \left[\frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\ \left. + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell - F_L \cos^2 \theta_K \cos 2\theta_\ell \right. \\ \left. + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi \right. \\ \left. + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi \right. \\ \left. + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi \right. \\ \left. + S_6 \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi \right. \\ \left. + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi \right. \\ \left. + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]$$

To reduce dependence on hadronic form-factors,
construct “optimized” observables such as

$$P'_5 \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

[JHEP 1305 (2013) 137]

Measure the observables in bins of $q^2 = m^2(\ell^+\ell^-)$
→ **Find deviations with local significance of 3.4σ**
for two q^2 bins in the observable P'_5

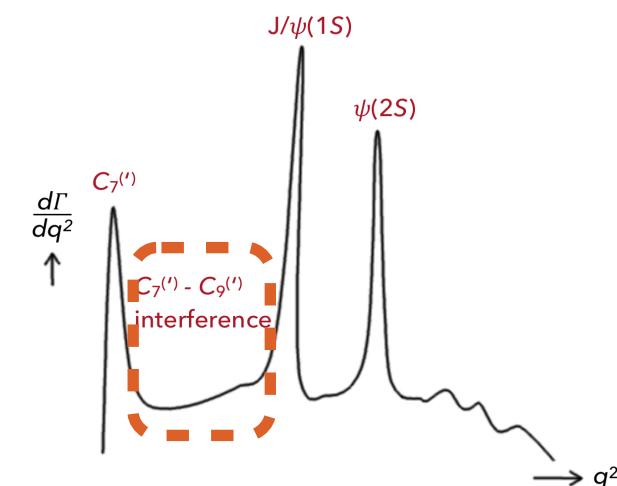
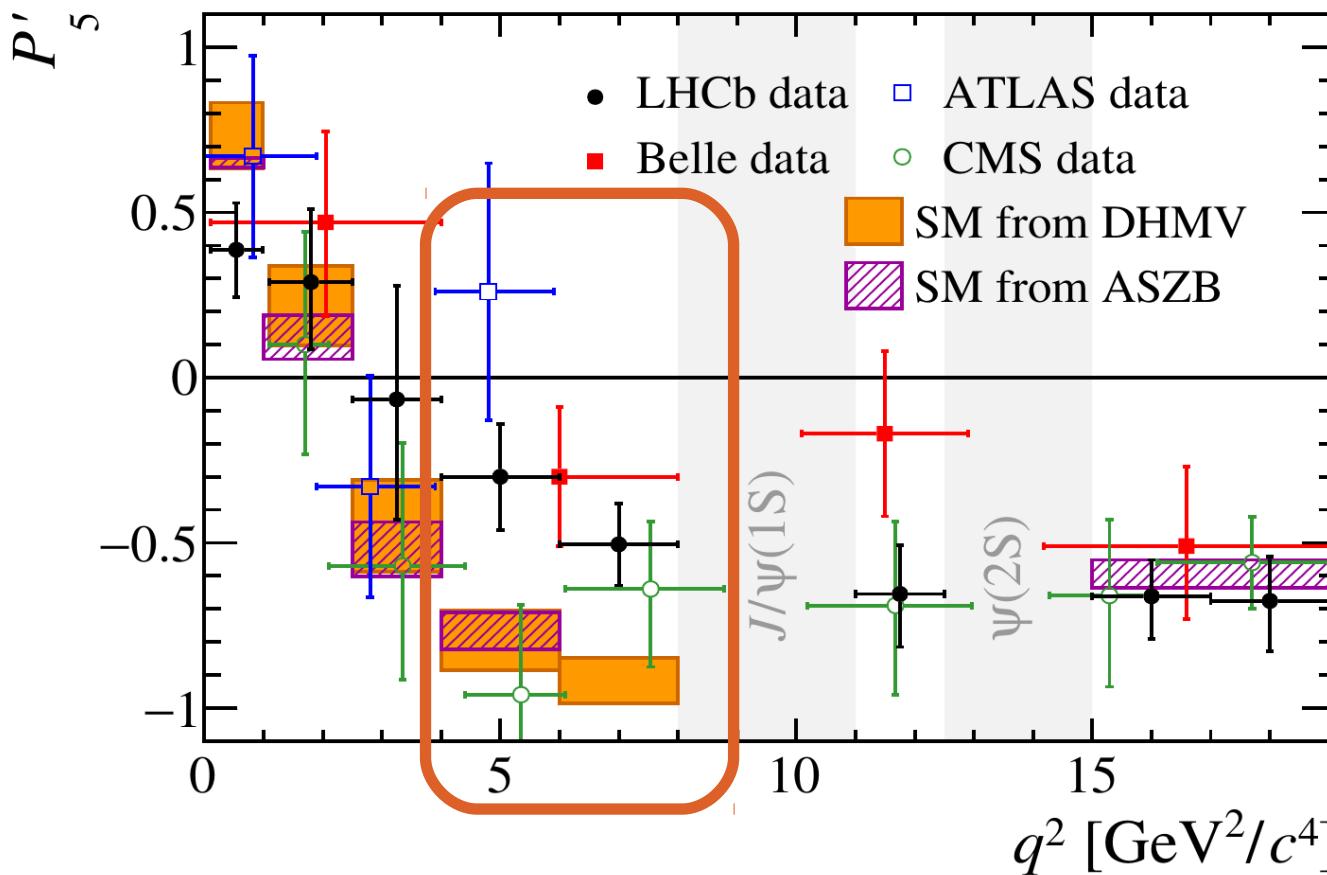


Belle, ATLAS, CMS also look at P'_5 , but larger uncertainties

[PRL 118 (2017) 111801]

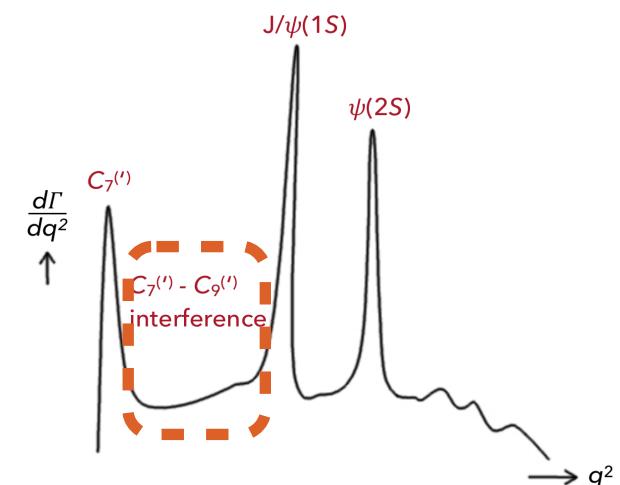
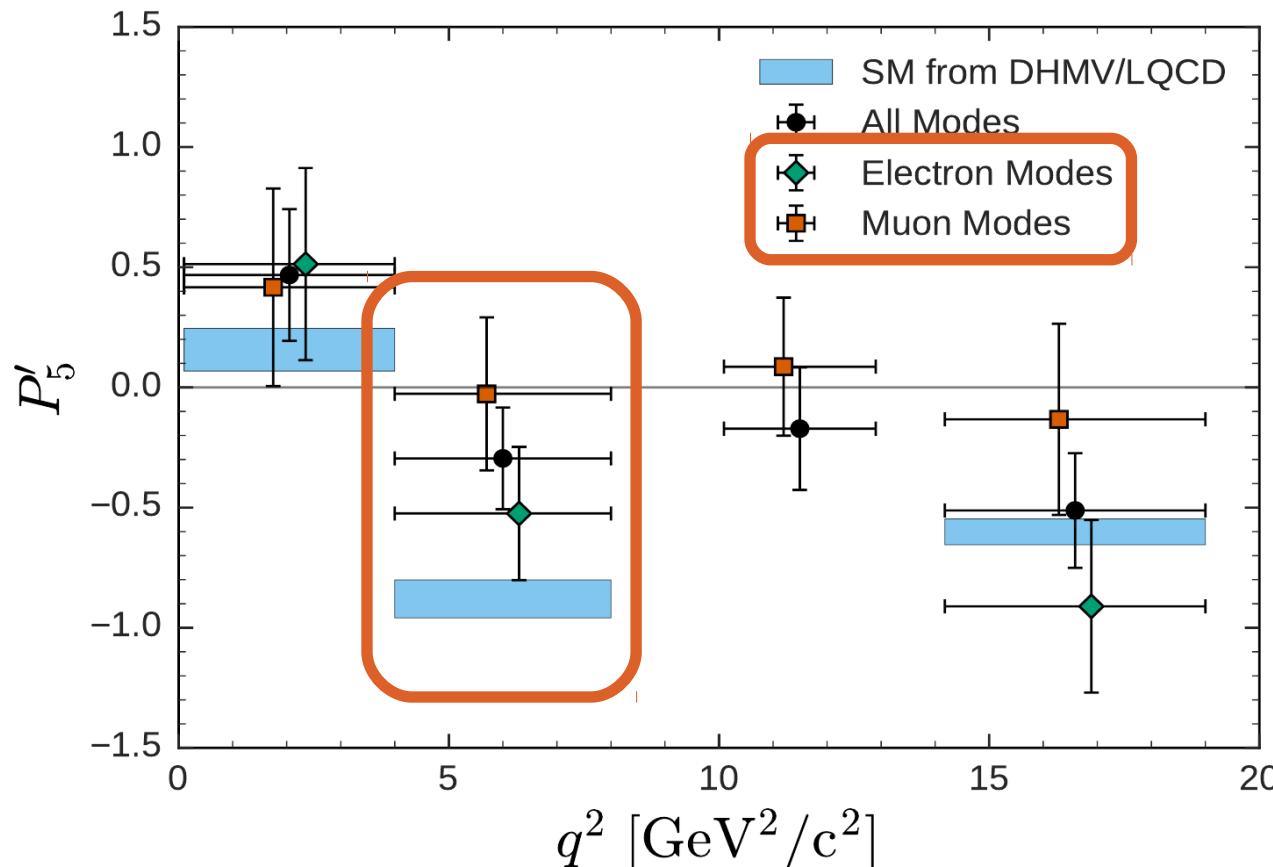
[arXiv:1710.02846]

[ATLAS-CONF-2017-023]



Belle measure $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ AND $B^0 \rightarrow K^{*0} e^+ e^-$

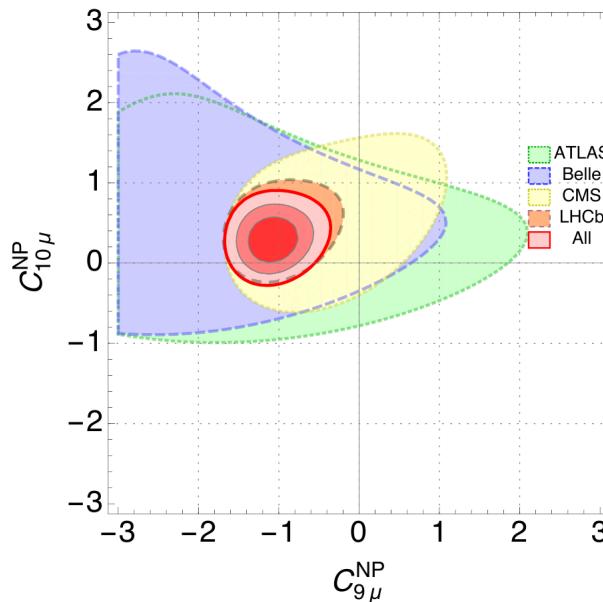
[PRL 118 (2017) 111801]



Possible Interpretations

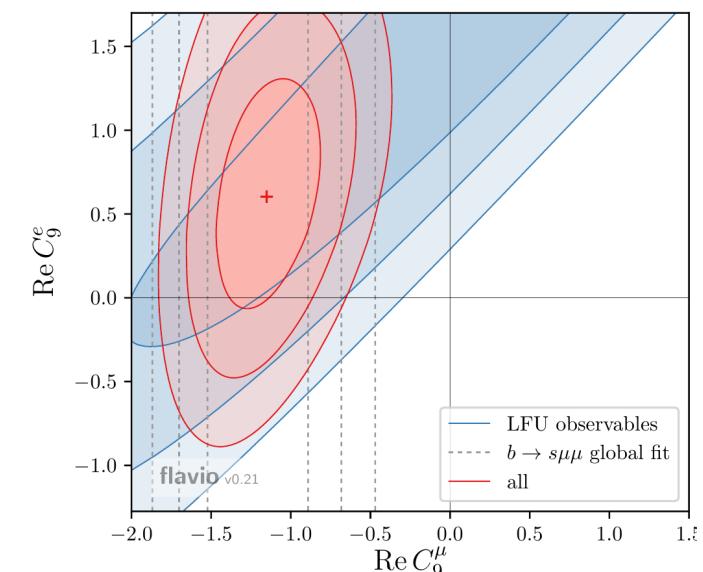
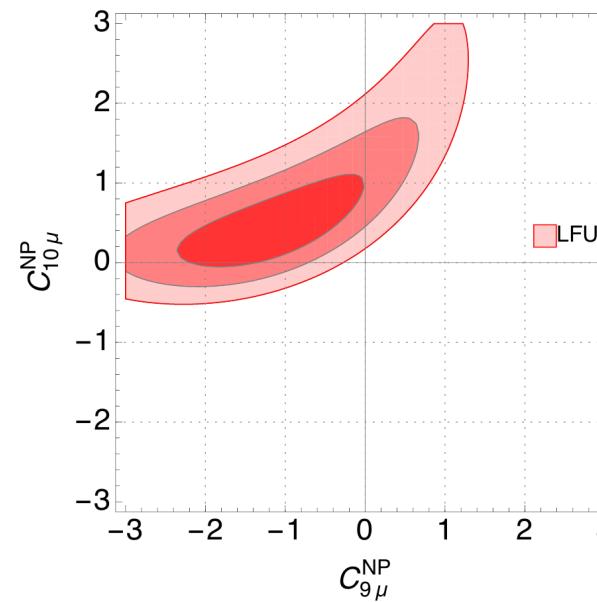
Fits to R_K and R_{K^*} and angular observables give consistent picture:

→ Deviations can be explained with modifications
either to C_9 or to C_9 and C_{10}



Capdevila, Crivellin, Descotes-Genon, Matias, Virto

[JHEP 01 (2018) 93]



Altmannshofer, Stangl, Straub

[PRD 96 (2017) 055008]

Charm-loop effects could contribute to C_9

but cannot explain Lepton-Flavour Universality observables

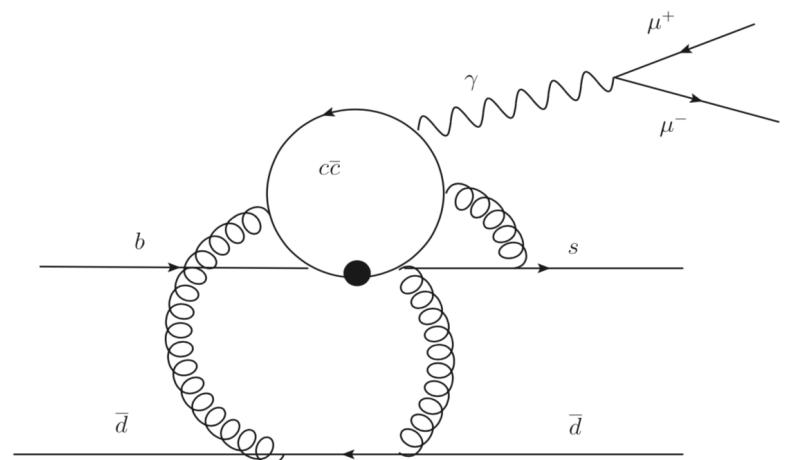
Possible Interpretations

Charm loop:
QCD contribution which at present cannot (yet) be computed reliably

Ciuchini et al. [arXiv:1512.07157]

Altmannshofer, Straub [arXiv:1503.06199]

Lyon, Zwicky [arXiv:1406.0566]



Possible New Physics contribution:
→ **Z' boson or Leptoquark, e.g.**

Bordone et al. [PLB 779 (2018) 317]

Buttazzo et al. [JHEP 08 (2016) 035]

Barbieri et al. [EPJC 76 (2016) 67]

Greljo et al. [JHEP 07 (2015) 142]

Bauer et al. [PRL 116 (2016) 141802]

Crivellin et al. [PRL 114 (2015) 151801]

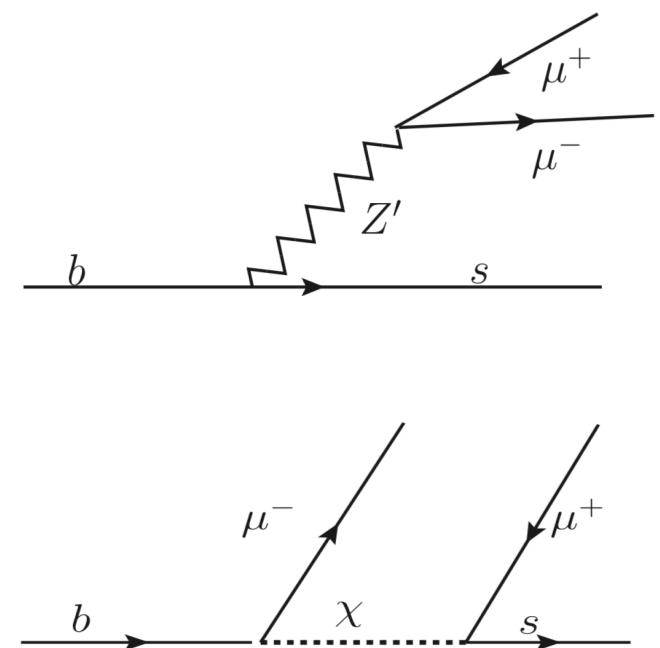
Altmannshofer et al. [PRD 89 (2014) 095033]

Diptomoy et al. [PRD 89 (2014) 071501]

Gould et al. [JHEP 01 (2014) 069]

Descote-Genon et al. [PRD 88 (2013) 074002]

Buras et al. [JHEP 12 (2013) 009]



Outlook

Intriguing tensions with Standard-Model predictions:

- Branching Fractions of $b \rightarrow s \mu^+ \mu^-$ decays
- Angular observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- Lepton Universality in $B^+ \rightarrow K^+ \ell^+ \ell^-$ and $B^0 \rightarrow K^{*0} \ell^+ \ell^-$
- Lepton Universality in tree-level $B \rightarrow D^{(*)} \ell \bar{\nu}_\ell$ decays

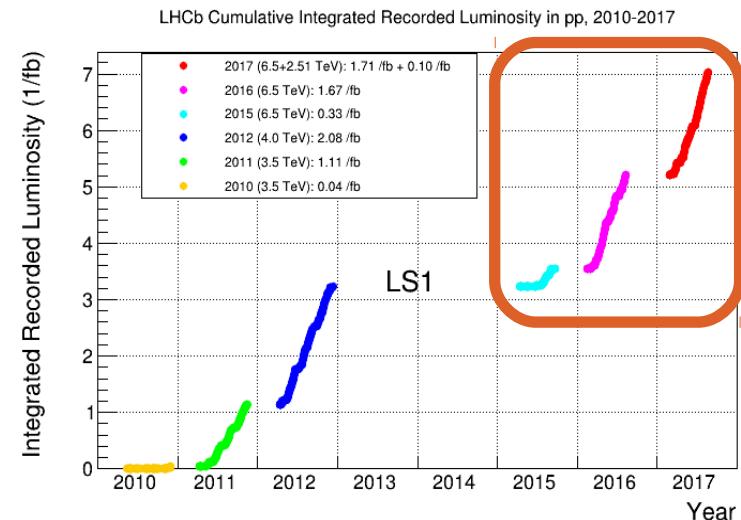
Taken individually, none of these is very significant, taken together they might point to common pattern

Various explanations in terms of “New Physics”:
 Z' boson, lepto-quarks, low-mass resonances, ...

Or poorly understood hadronic effects,
e.g. $c\bar{c}$ interference in $b \rightarrow s \ell\ell$?

Outlook

**Run-2 updates
of all measurements shown here
→ Expect ~ factor five in statistics**



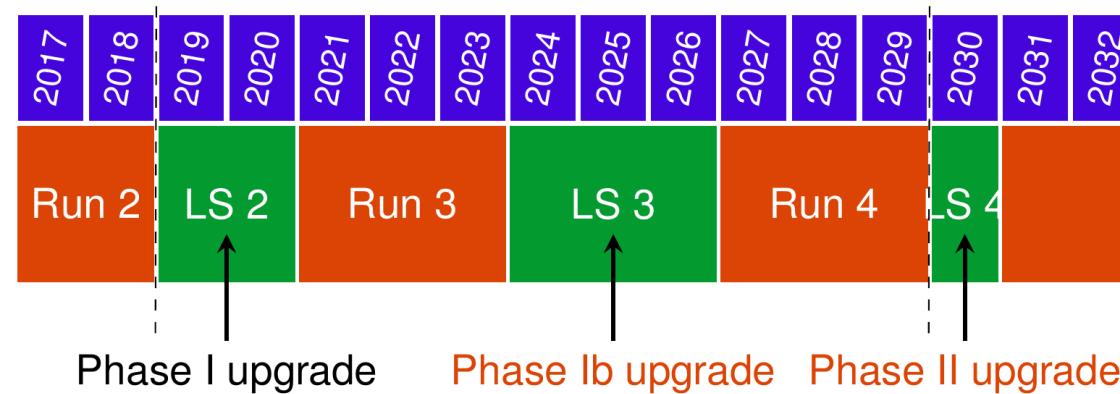
People are also working on other related analyses, e.g.

- $R(D)$, $R(\Lambda_c^+)$**
- Angular observables in $B^0 \rightarrow K^* e^+ e^-$**
- and more ...**

LHCb Upgrade for LHC “long shutdown” (LS2) in 2019/2020:

- Factor 5 in instantaneous luminosity
- Improved trigger efficiency for hadrons

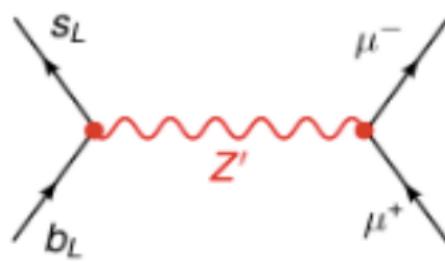
Expression of Interest for further LHCb Upgrades



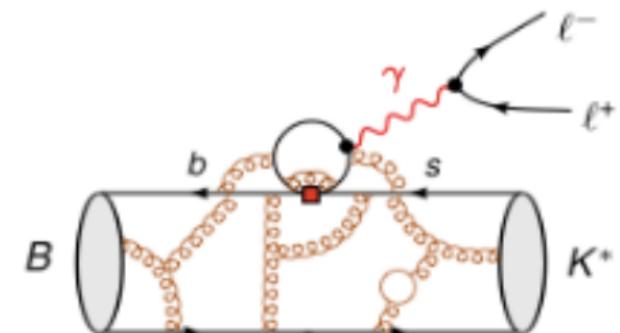
**Looking forward to friendly competition
with Belle II here in Japan**

Close collaboration with theorists is crucial

Optimist's view point

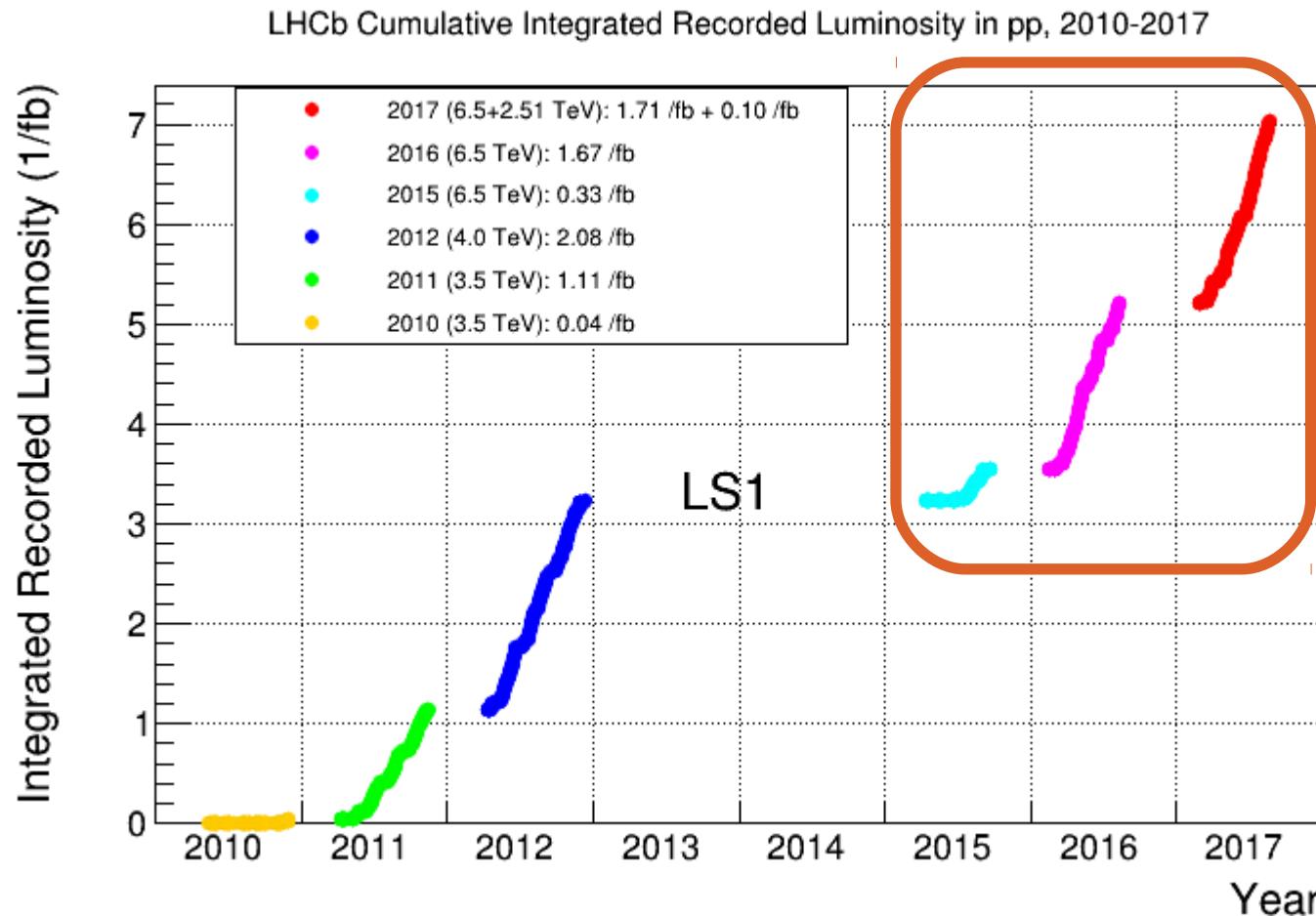


Pessimist's view point





Backup



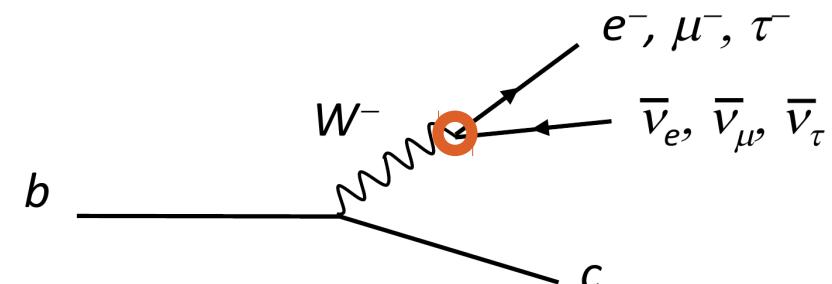
Run II so far: 3.7 fb^{-1} at 13 TeV

$\sigma(pp \rightarrow b\bar{b})$: $300 \mu\text{b}$ @ 7 TeV $\rightarrow 500 \mu\text{b}$ @ 13 TeV

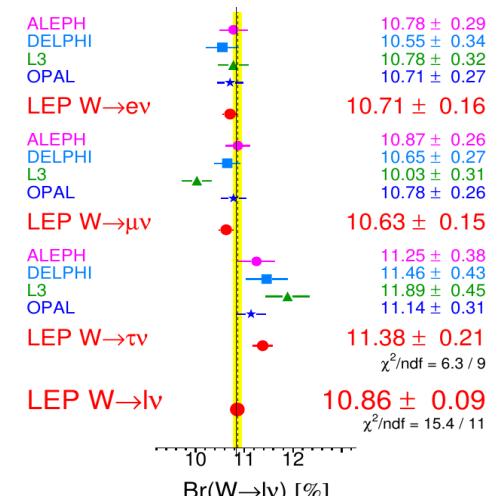
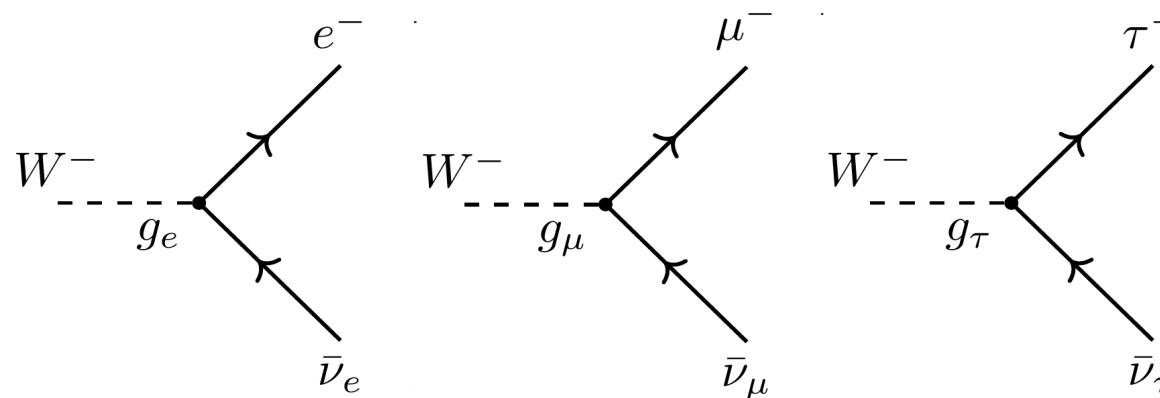
Improvements in trigger and selection efficiencies

Test Lepton-Flavour Universality:

**Weak coupling constant identical
for all three lepton families**



Tested in W decays @ LEP to precision of a few percent

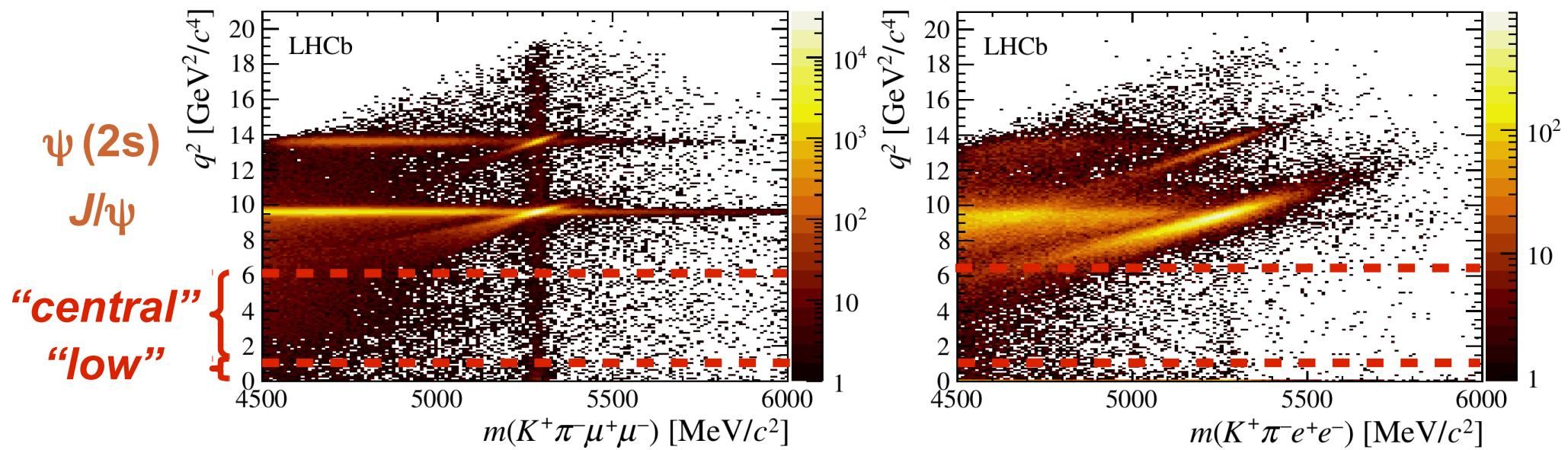


$$\frac{2 \times \text{BR} (W \rightarrow \tau^- \bar{\nu}_\tau)}{\text{BR} (W \rightarrow \mu^- \bar{\nu}_\mu) + \text{BR} (W \rightarrow e^- \bar{\nu}_e)} = 1.066 \pm 0.025 \ (\approx 2.6 \sigma)$$

Lower trigger efficiencies → smaller statistics

Worse resolution, radiative tail of signal → have to consider partially reconstructed background at lower mass

Additional background from radiative tail of $J/\psi \rightarrow e^+ e^-$

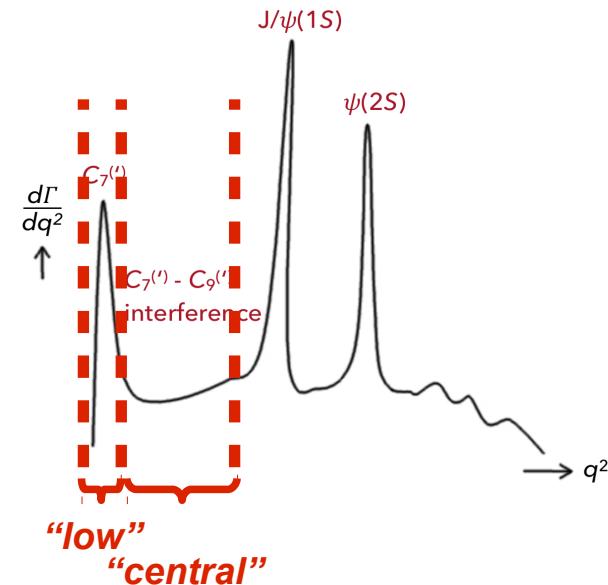


[JHEP 08 (2017) 055]

Measure R_{K^*} in two bins of q^2

To reduce systematics, measure double ratio:

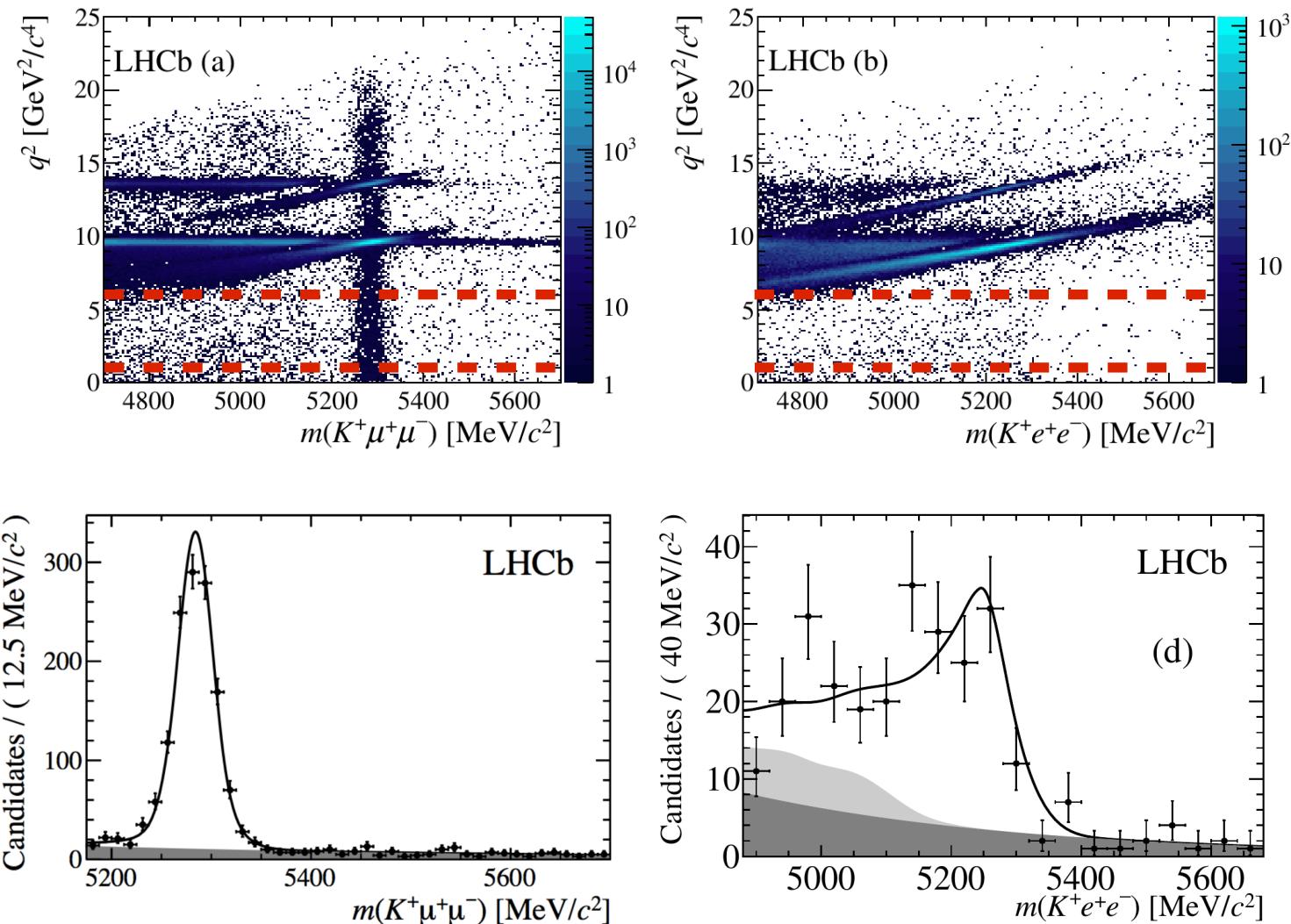
$$R_{K^*} \equiv \frac{\text{BR}(B^0 \rightarrow K^{*0} \mu^+ \mu^-) / \text{BR}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-))}{\text{BR}(B^0 \rightarrow K^{*0} e^+ e^-) / \text{BR}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-))} = 1$$



As a cross-check, determine also:

$$R_{\psi(2s)} \equiv \frac{\text{BR}(B^0 \rightarrow K^{*0} \psi(2s) (\rightarrow \mu^+ \mu^-)) / \text{BR}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-))}{\text{BR}(B^0 \rightarrow K^{*0} \psi(2s) (\rightarrow e^+ e^-)) / \text{BR}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-))}$$

Result compatible with expectation

Earlier measurement of R_K for $1 < q^2 < 6 \text{ GeV}^2 c^4$ 

Angular acceptance in $(\theta_K, \theta_\ell, \phi)$ from simulation,
cross checked on large samples of $B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-)$

