Flavour anomalies at LHC(b)

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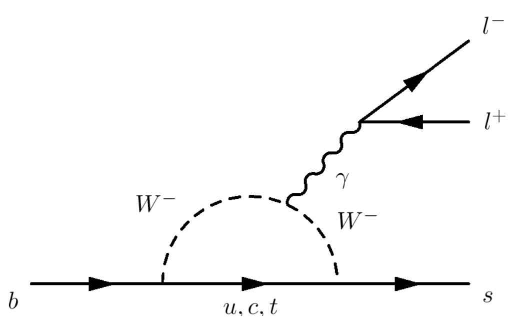
Nikhef

Roma Tre Topical Seminars - Flavour anomalies at LHC and future meson factories

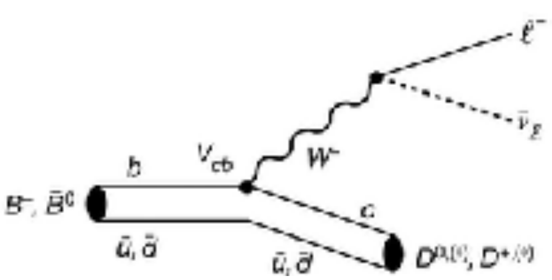
14/12/2017

Outline

- Introduction
- LHCb detectors
- Anomalies in b→sll (l=muon/electron)

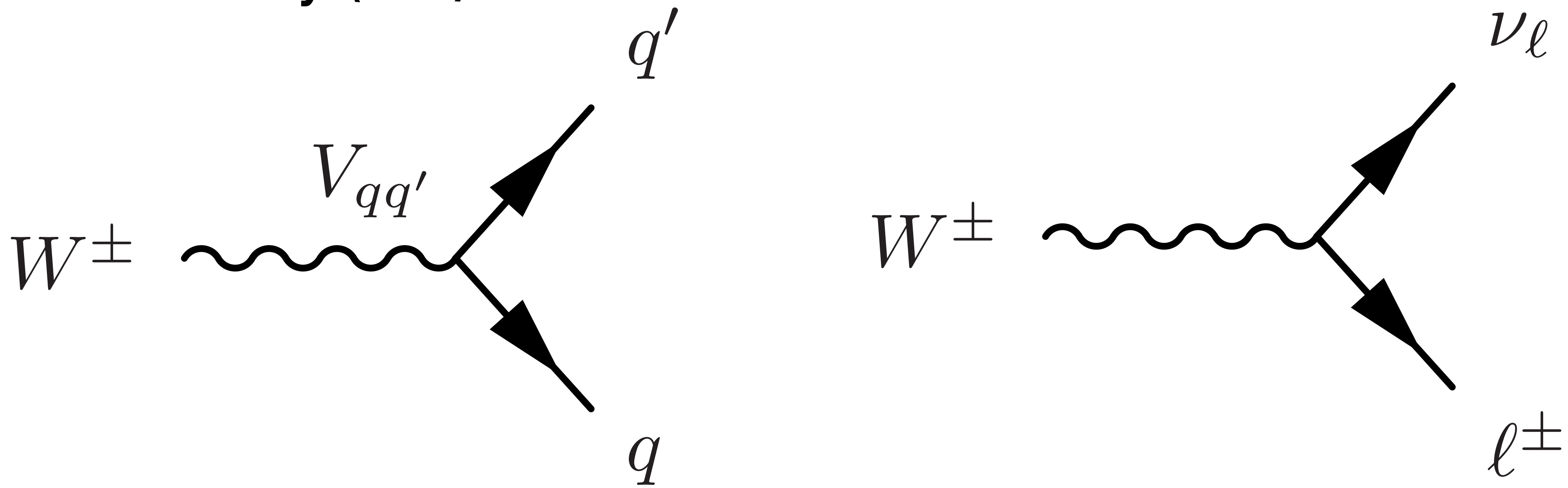


- Anomalies in b→clν$_l$ (l=tau/muon)



Introduction

- Flavour physics is the study of the different generations of fermions and their interactions
- The only relevant difference between them is the interaction with the Higgs field
  - All the other known interactions couple identically with each generation → for leptons this property is called lepton flavour universality (LFU)

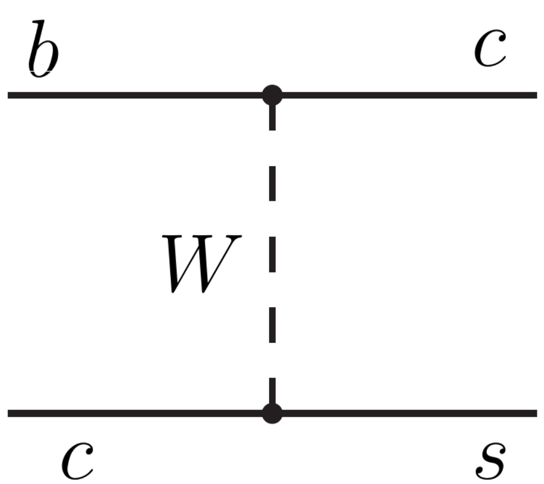


- Virtual particles → probing high mass scales, higher than LHC energy

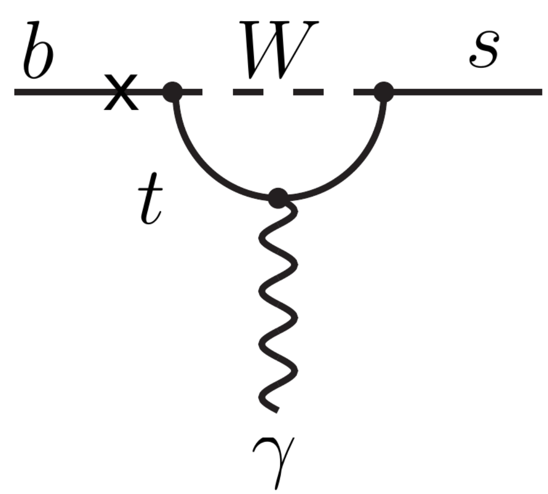
Effective Hamiltonian

- Complex interactions substituted with Fermi-like operators
  - Wilson coeff. $C_i^{(\prime)}$ encode short-distance physics

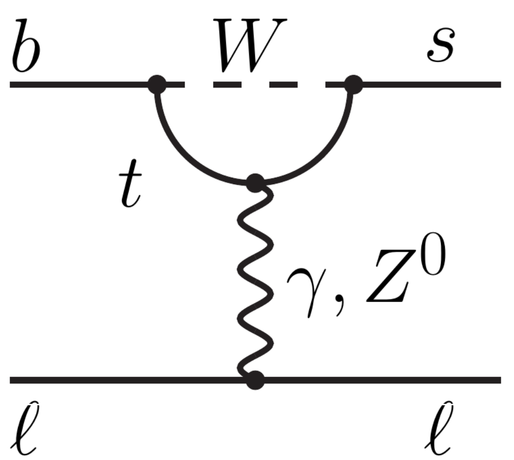
Charged current



Photon penguin



EW penguin



$G_F V_{cb} V_{cs}^* C_2 \bar{c}_L \gamma^\mu b_L \bar{s}_L \gamma_\mu c_L$

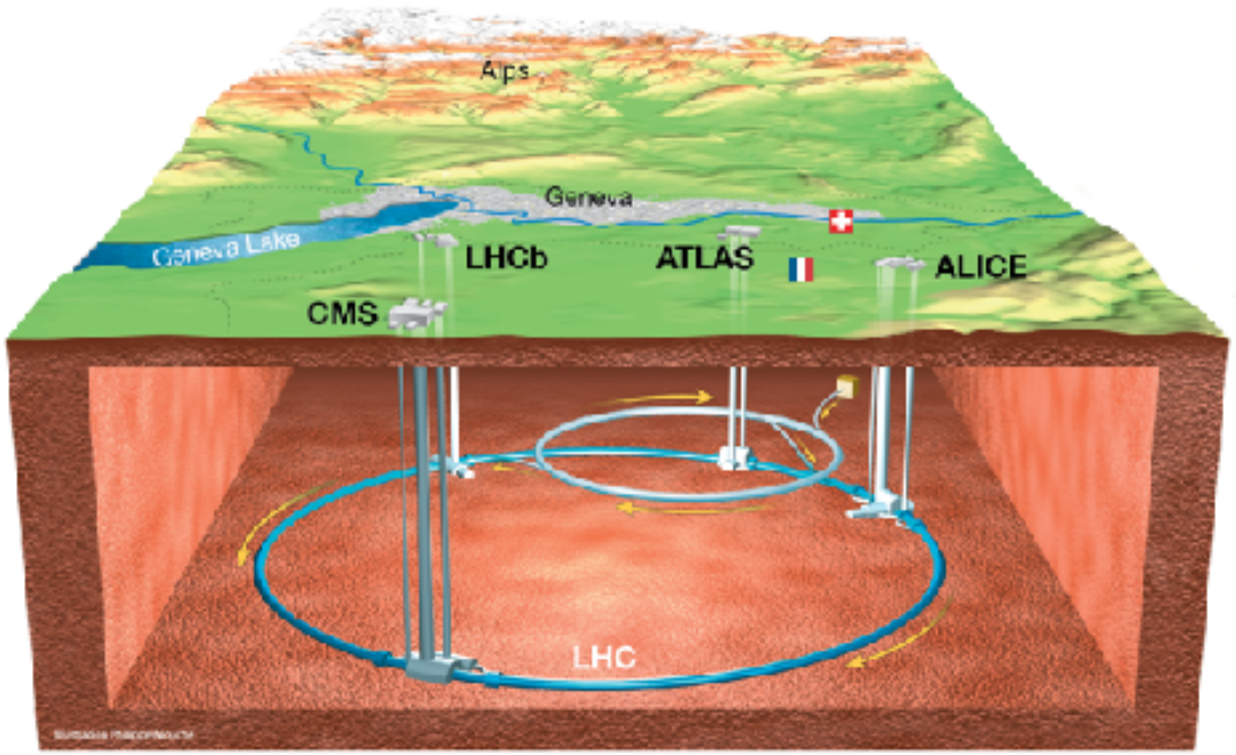
$\frac{e}{4\pi^2} G_F V_{tb} V_{ts}^* m_b C_7 \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$

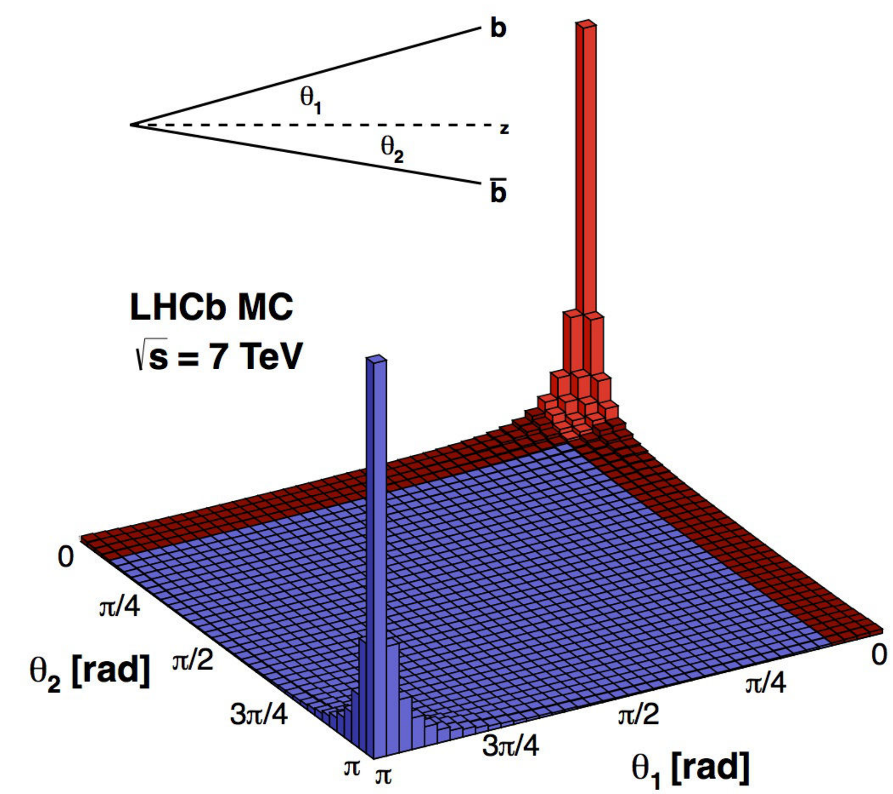
$G_F V_{tb} V_{ts}^* C_{9(10)} \bar{s}_L \gamma^\mu b_L \bar{\ell} \gamma_\mu (\gamma_5) \ell$

- New physics interactions can enter through new operators or modify the coefficients of the SM

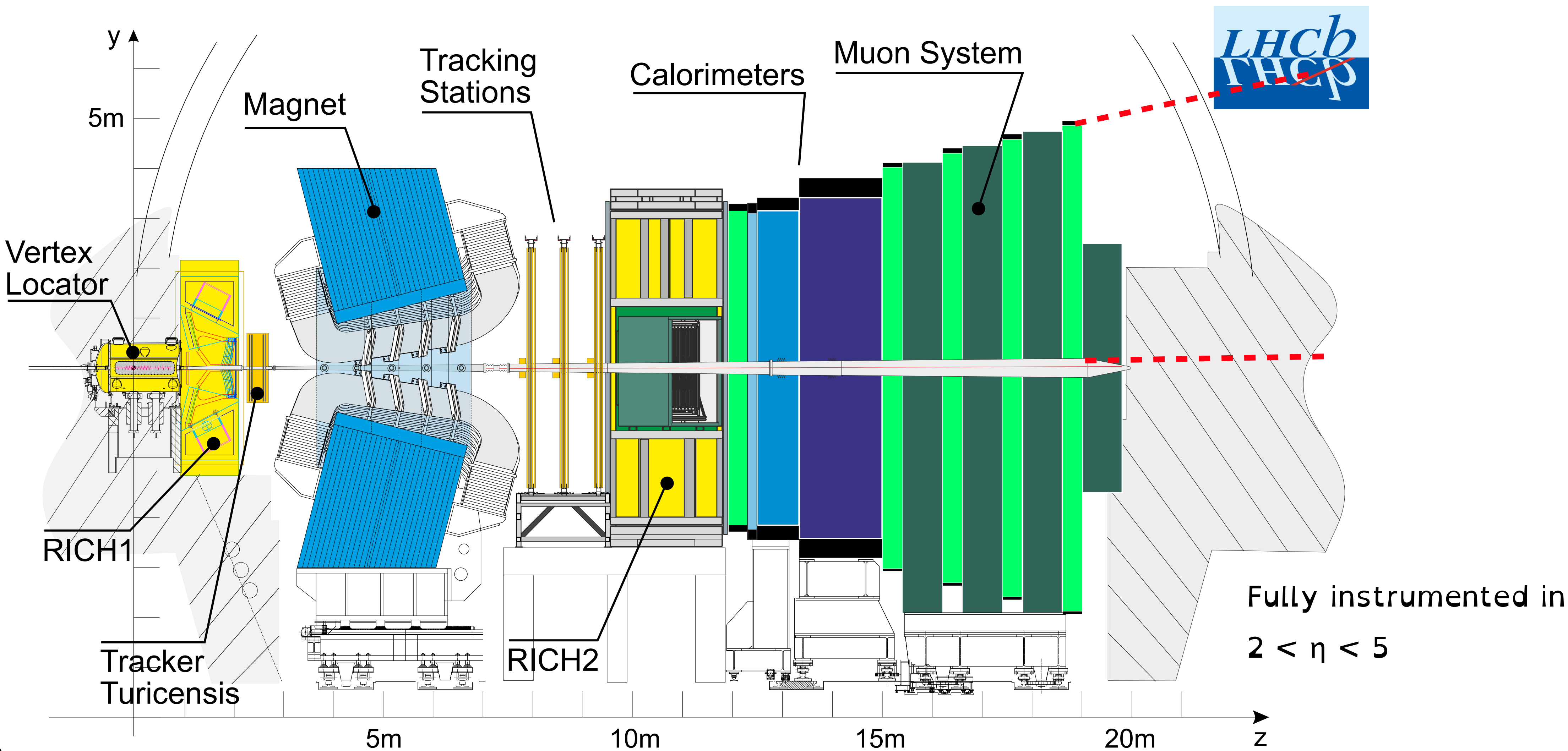
LHCb experiment

- ~1200 members, from 71 institutes in 16 countries
- Dedicated experiment for precision measurements of CP violation and rare decays of heavy-flavoured hadrons
- pp collision at $\sqrt{s}$ = 7, 8, 13 TeV
- $b\bar{b}$ quark pairs produced predominately in the forward (or backward) region





LHCb experiment



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Excellent vertex and IP resolution:

$\sigma(IP) \simeq 24\mu m$ at $p_T = 2GeV$

Good momentum resolution:

$\sigma(p)/p \simeq 0.4\text{-}0.6\%$ for $p \in (0,100) GeV/c$

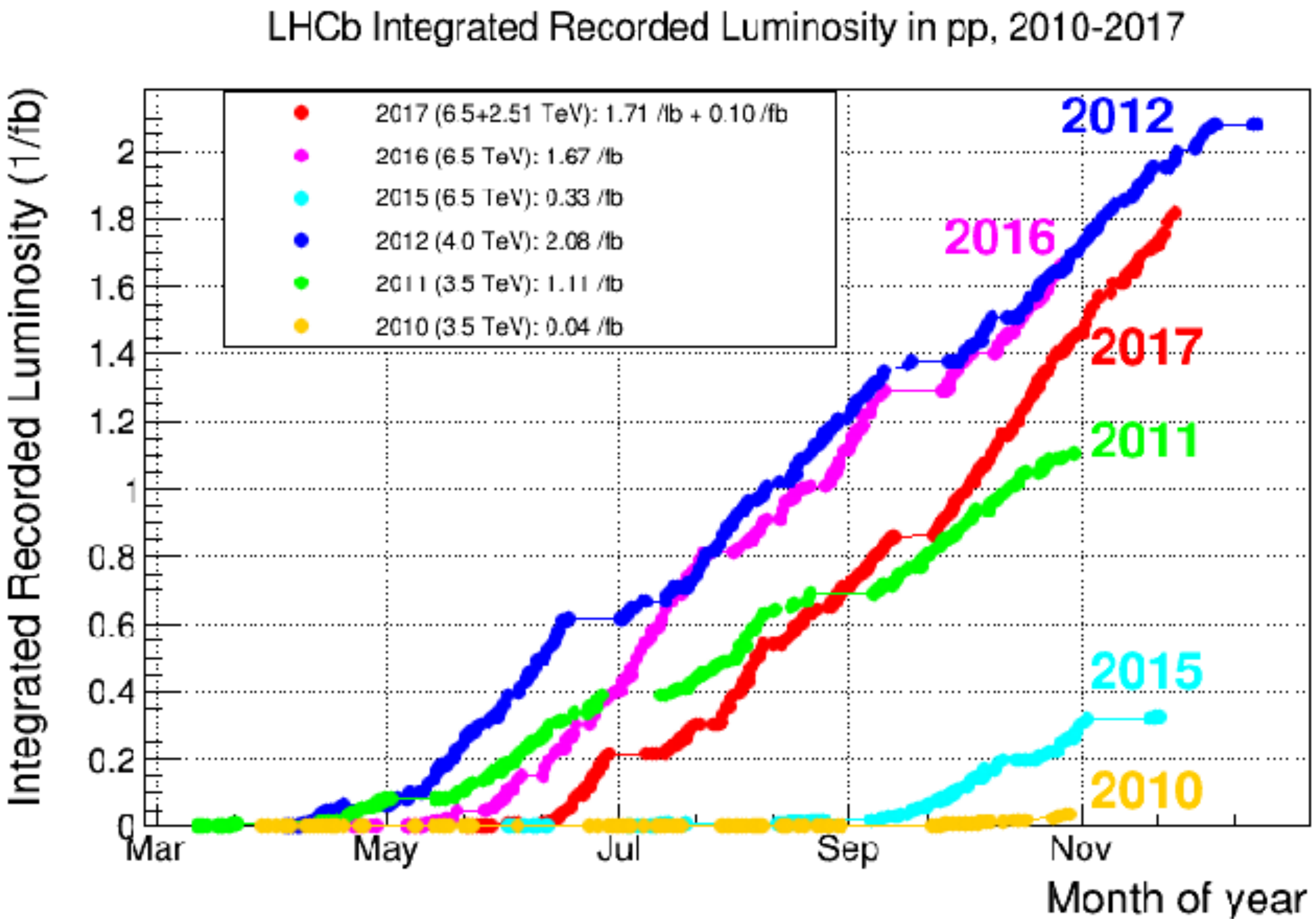
Muon identification:

$\varepsilon_\mu = 98\%$, $\varepsilon_{K\to\mu} = 0.6\%$, $\varepsilon_{\pi\to\mu} = 0.3\%$

Trigger efficiency:

$\varepsilon_\mu = 90\%$ for selected B decays

LHCb experiment

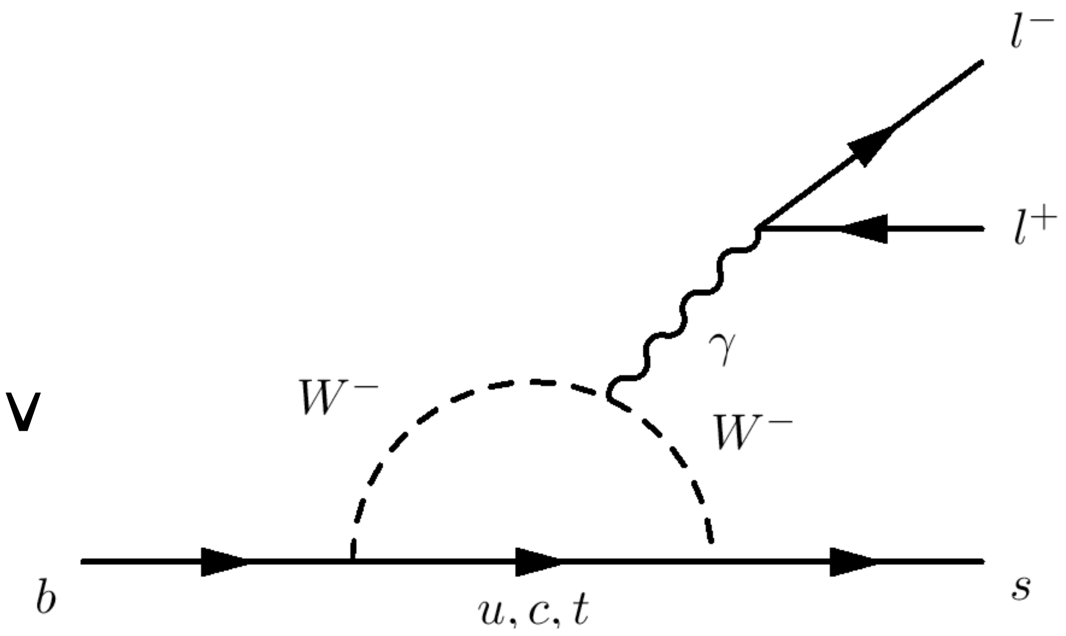


~10^{11} $b\bar{b}$ decays/fb in acceptance

- Luminosity levelled at $4\text{x}10^{32}\text{cm}^{-2}\text{s}^{-1}$ → constant conditions
- Analyses presented today are based on 3/fb collected during Run1

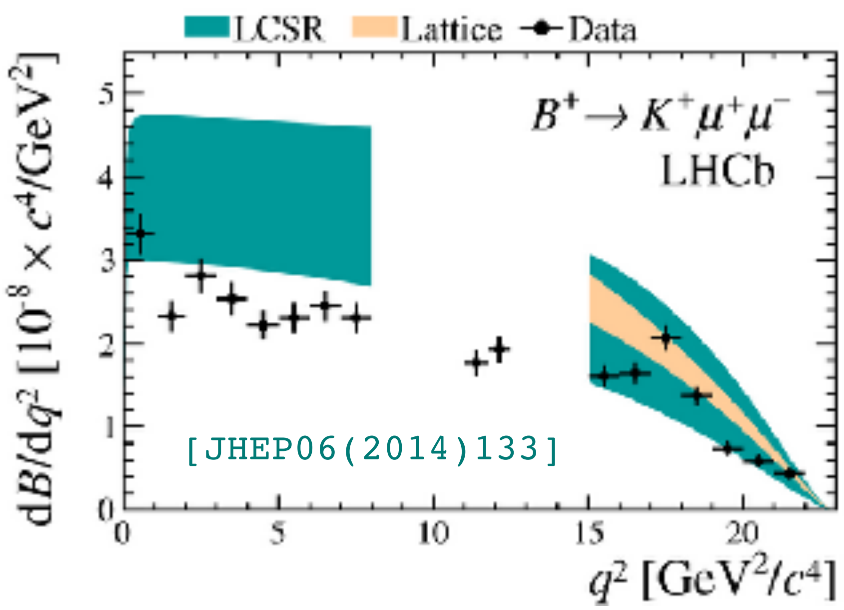
loop-level b→sll transitions

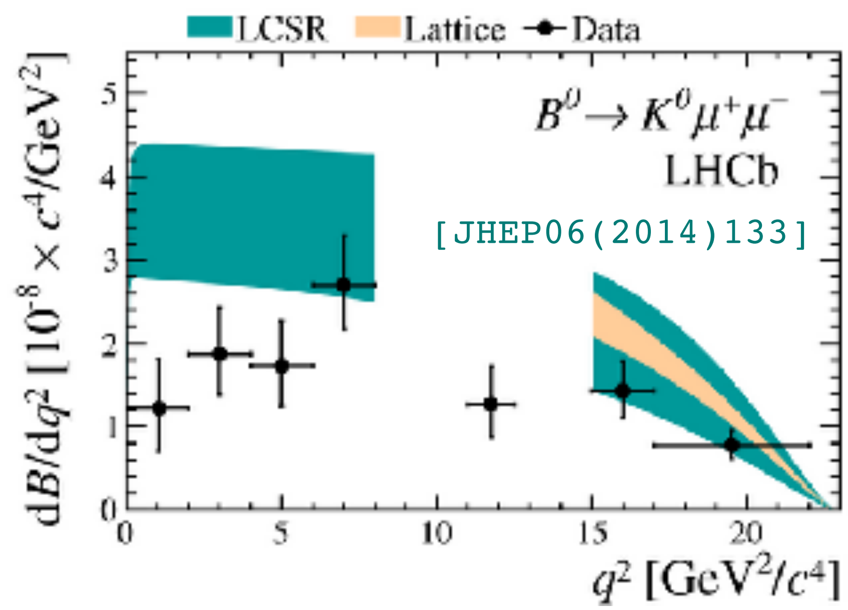
- FCNC forbidden at tree level
- low branching fractions $\sim 10^{-6}$
- NP sensitivity up to about 50TeV

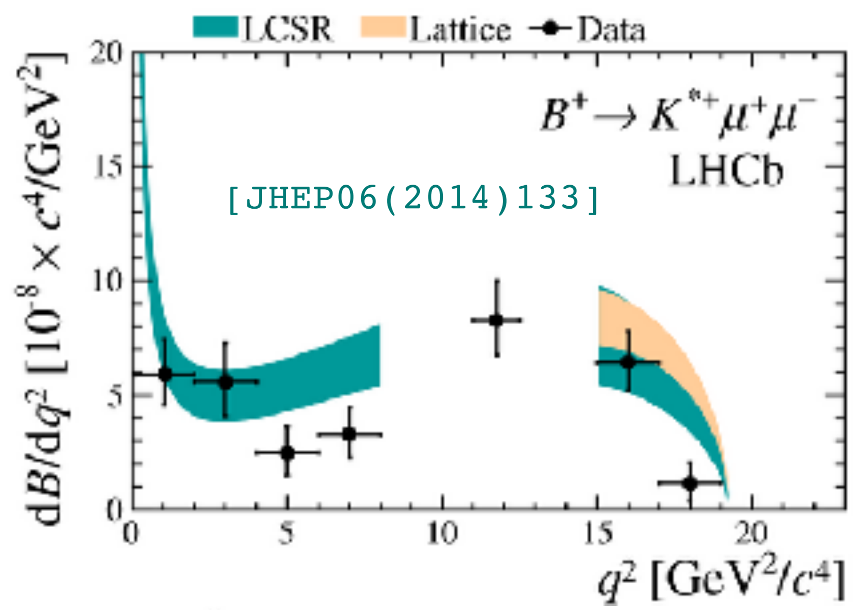


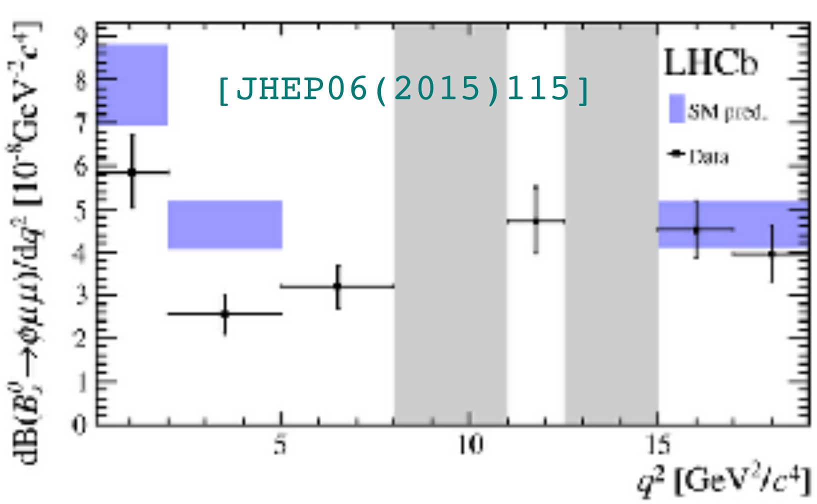
b→sll branching fractions

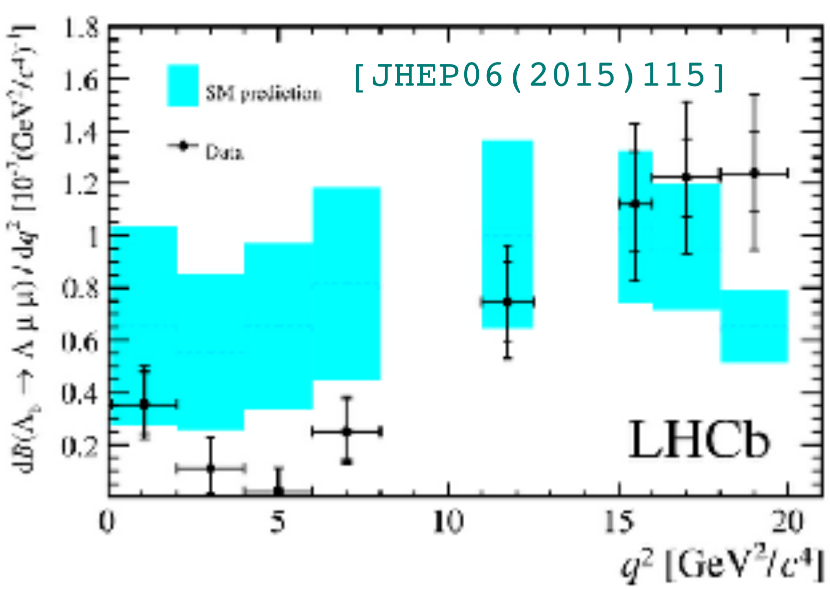
- Measurements of b→sll decay rates systematically below the SM predictions, 2-3 σ depending on the final state

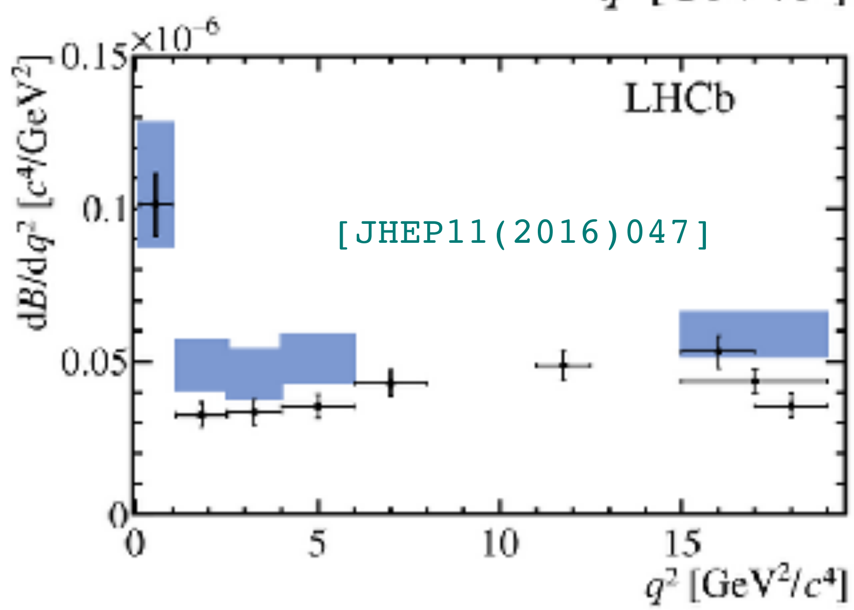










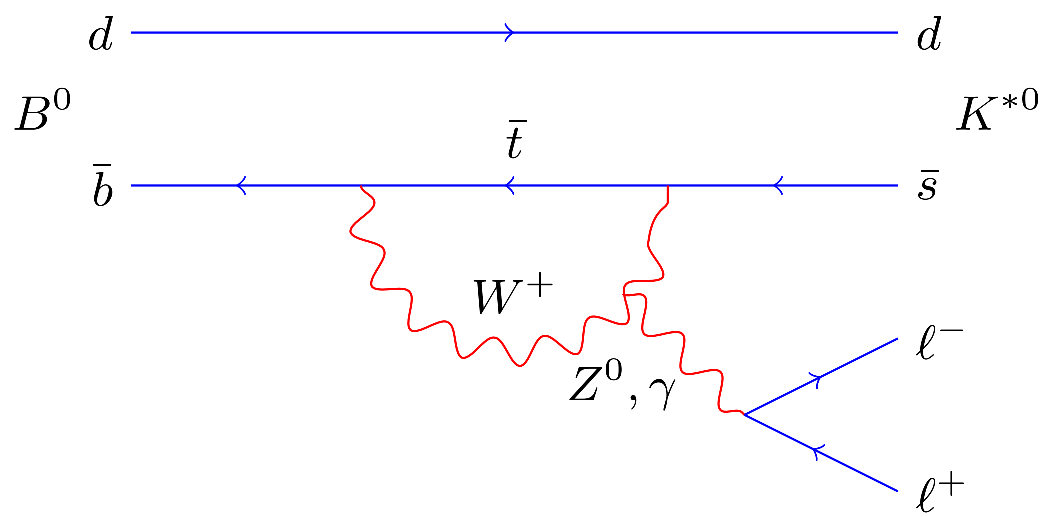


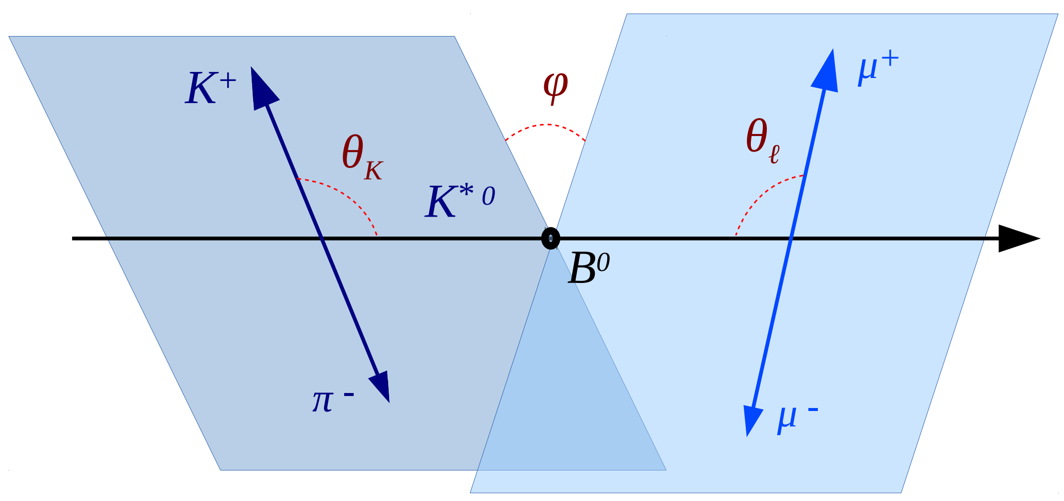
- c9 modification?

q^2 = four-momentum transferred to the di-leptons.

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

- Differential decay rate of $B^0 \to K^{*0}\mu\mu$ as a function of the $q^2 = m_{\ell\ell}$ and three angles ($\theta_K, \theta_\ell, \varphi$)
- Angular coefficients depend on hadronic form factor → significant uncertainty at the leading order





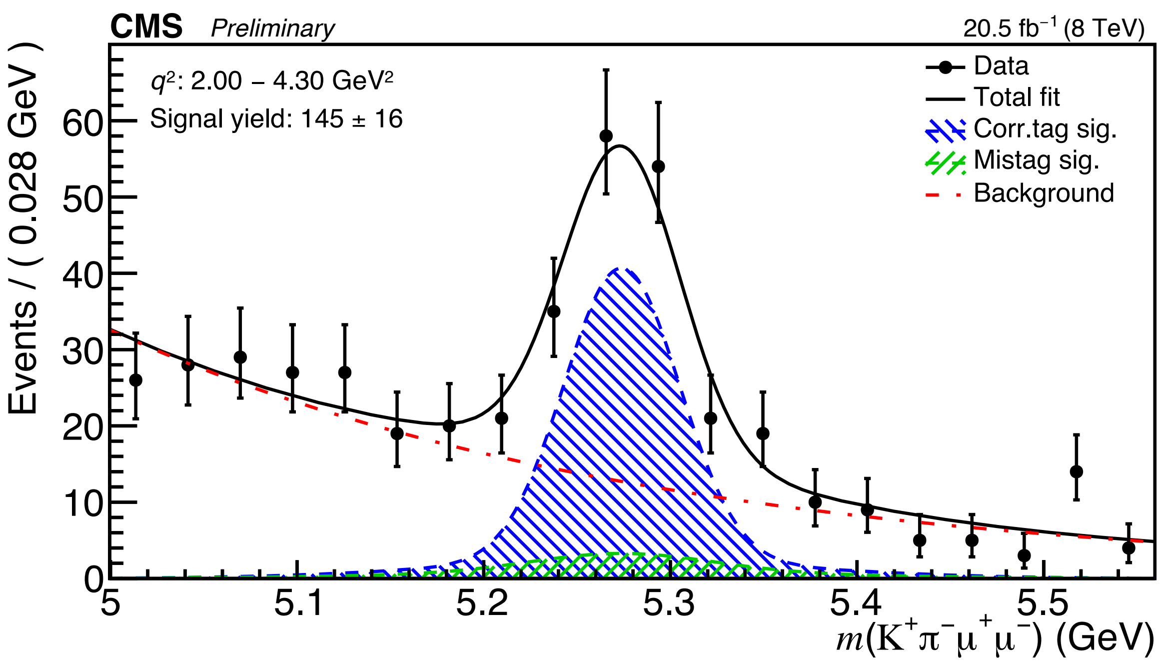
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos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

F_L = fraction of longitudinally polarised K*

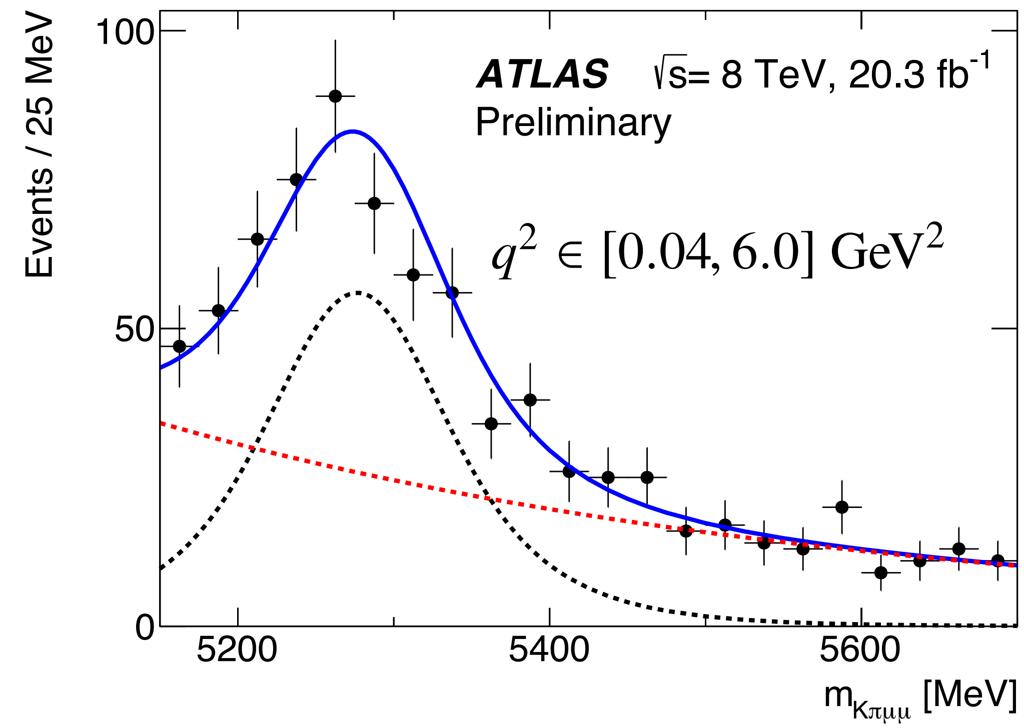
S_i = angular coefficients

Several recents measurements

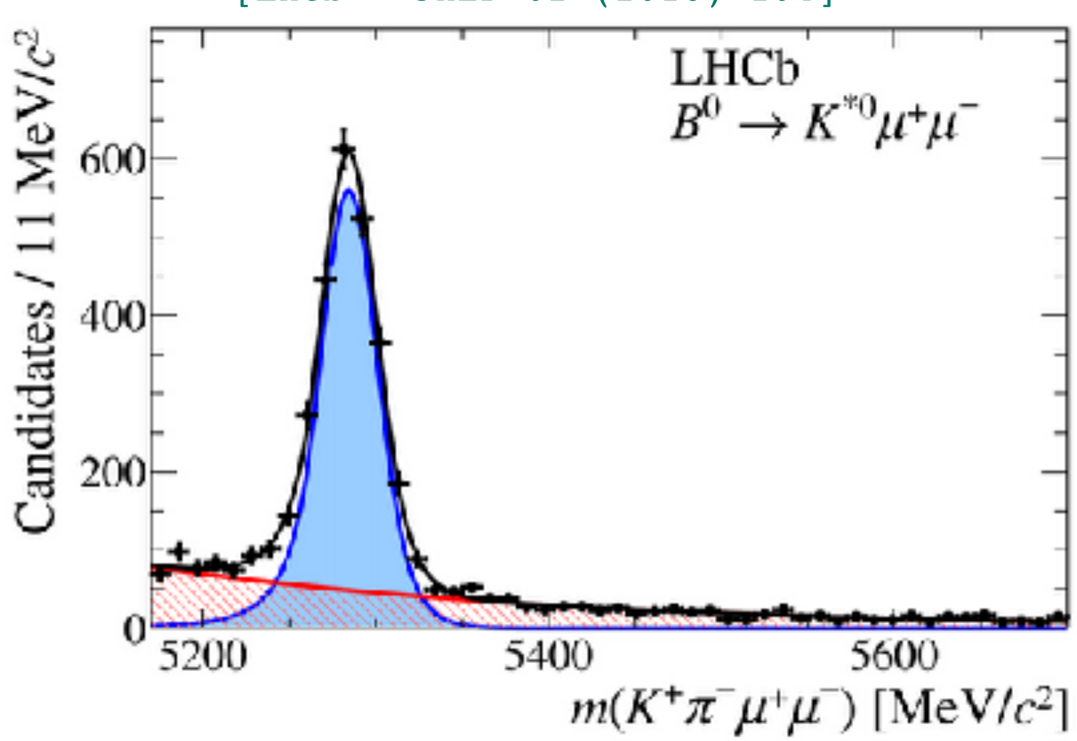
[CMS - CMS-PAS-BPH-15-008]



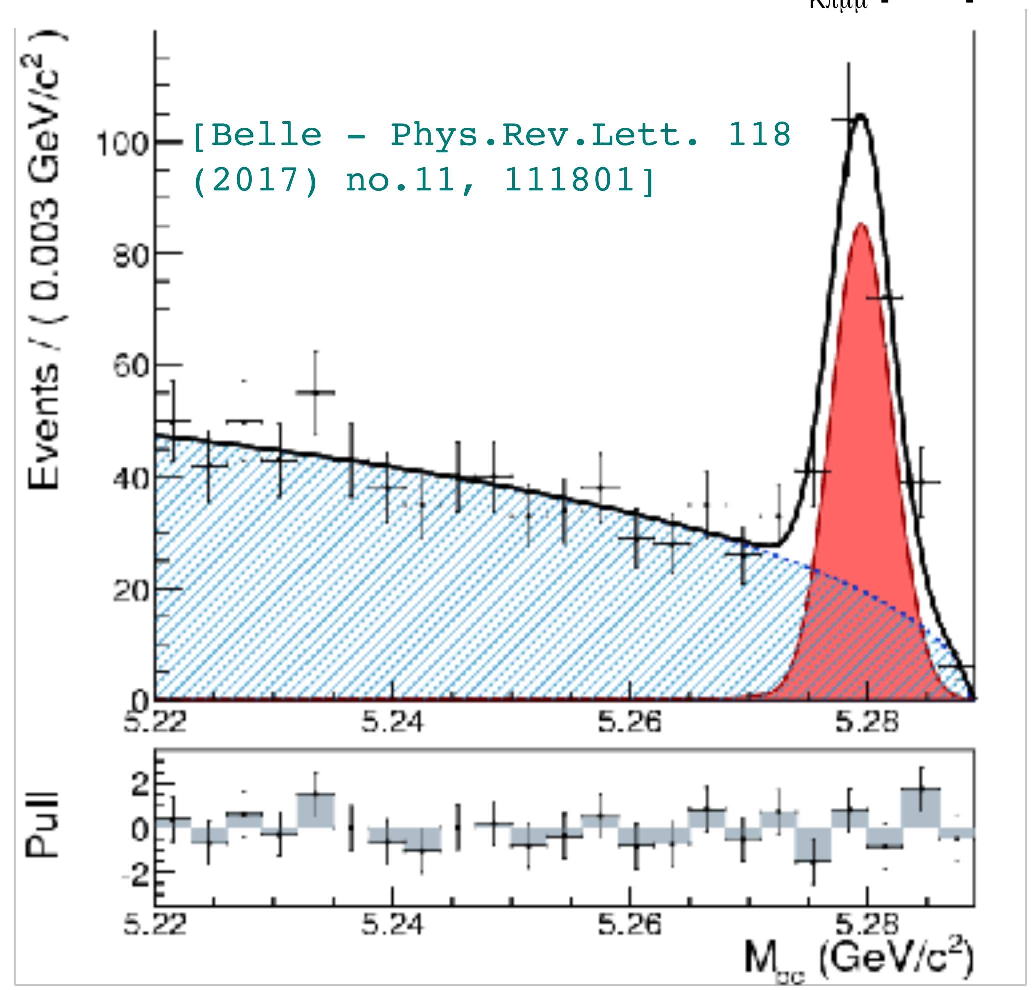
[ATLAS - ATLAS-CONF-2017-023]



[LHCb - JHEP 02 (2016) 104]

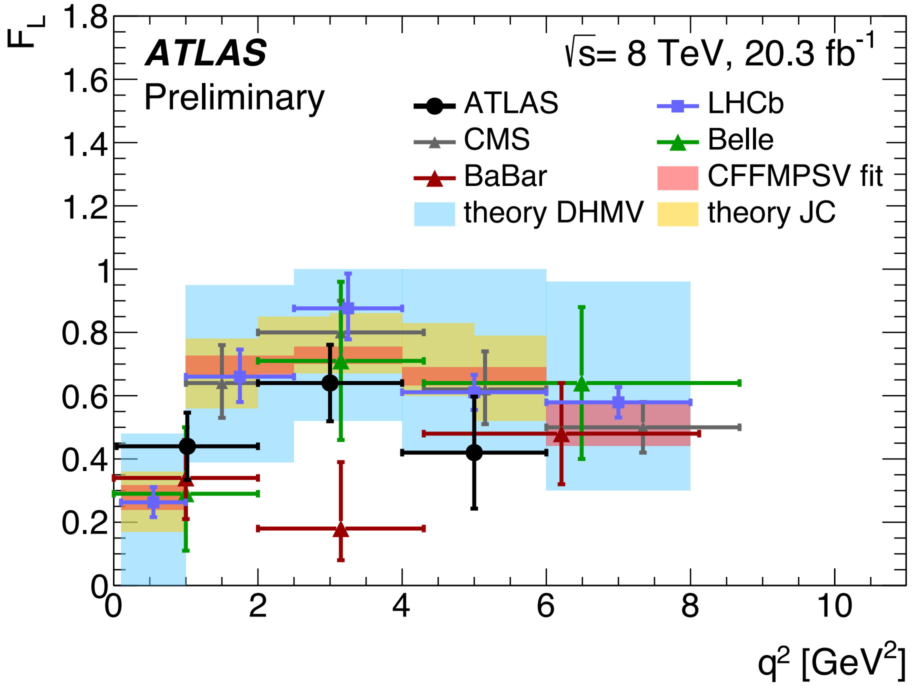


[Belle - Phys.Rev.Lett. 118 (2017) no.11, 111801]

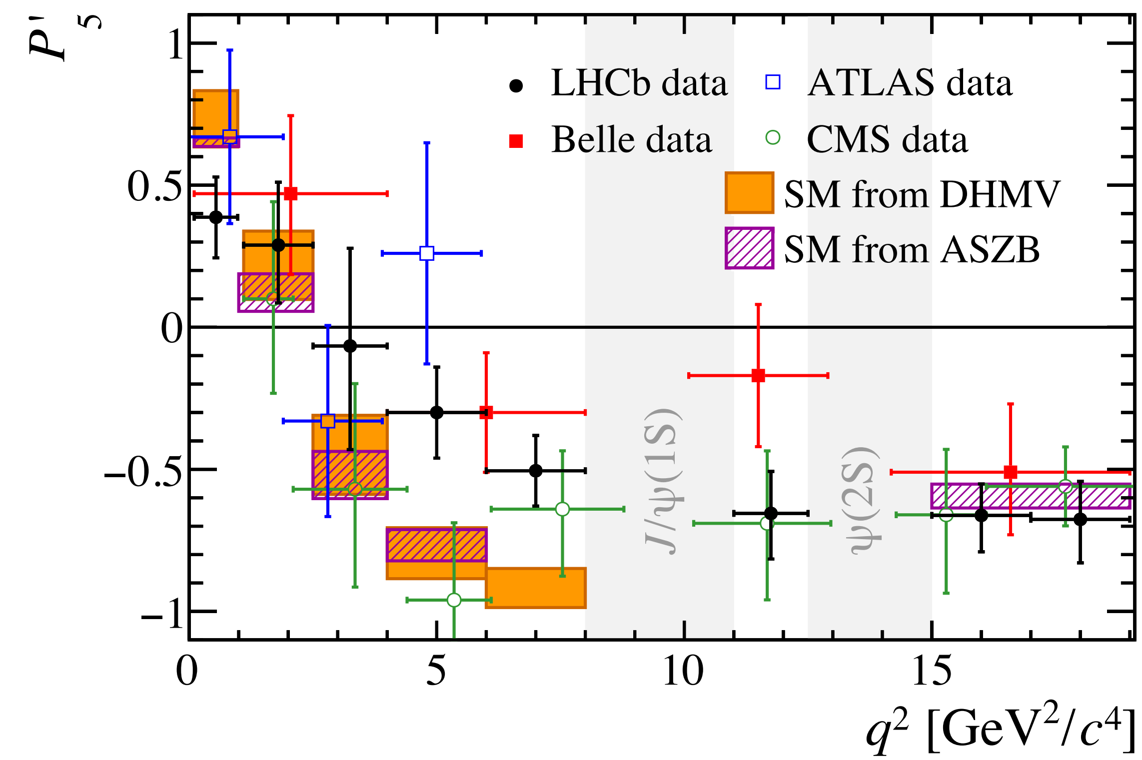


$B^0 \to K^{*0}\mu\mu$ results

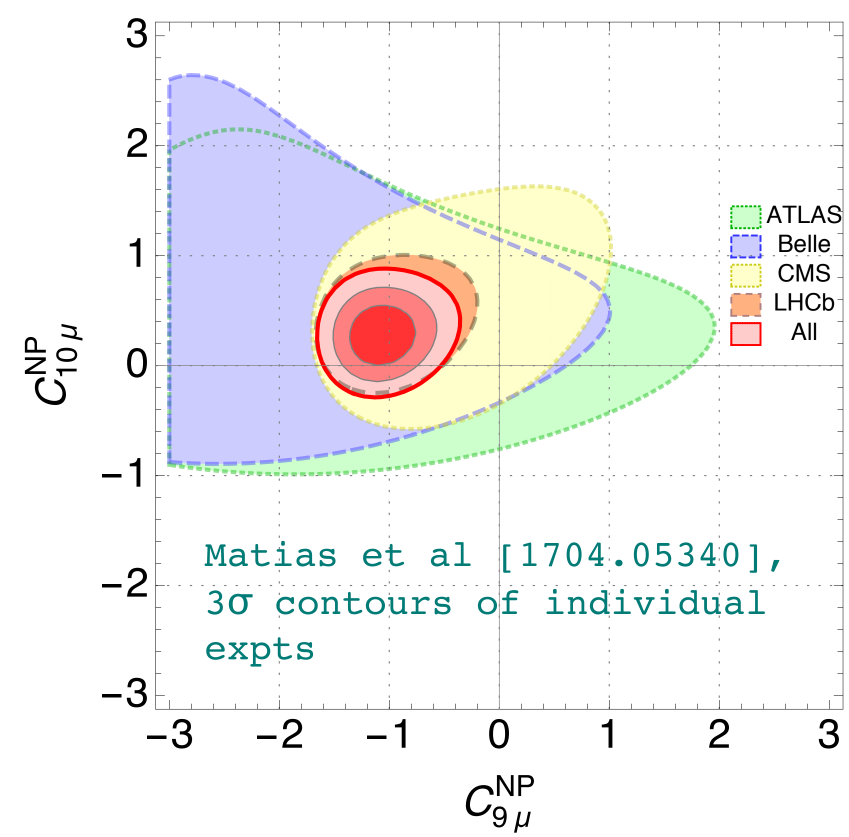
[ATLAS - ATLAS-CONF-2017-023]



ATLAS,CMS,Belle,LHCb at Moriond 2017



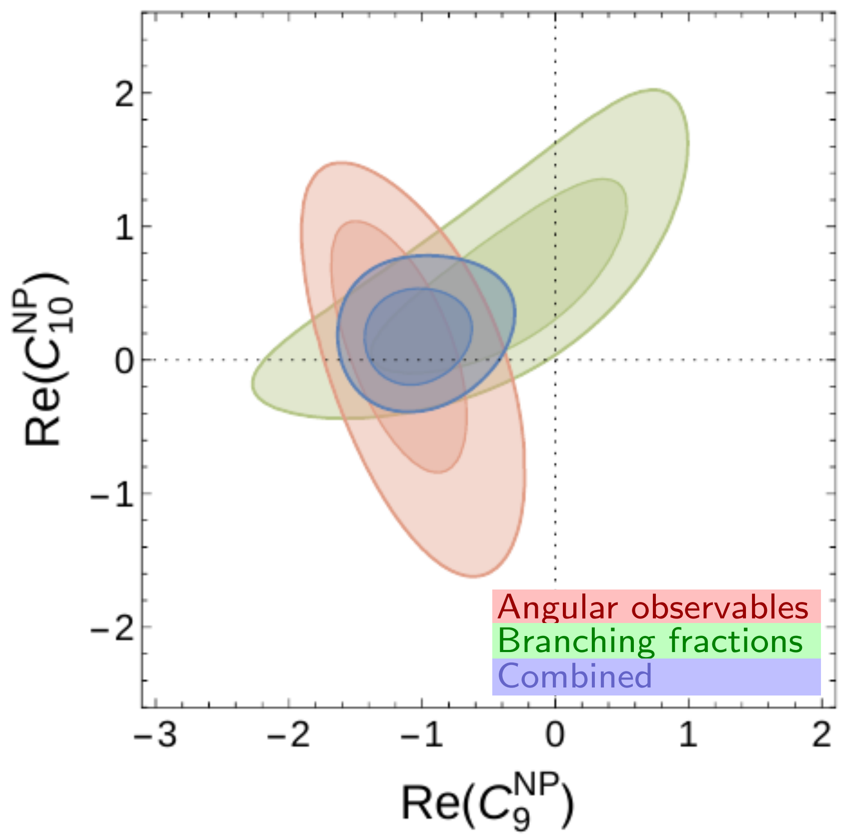
- Re-parametrisation of the angular coefficients in terms of observables with reduced dependency on FF
- P5' shows a significant discrepancy
- Global fits shows strong deviation in dilepton vector coupling C_9 → tension at the level of 4-5 σ



[Altmannshofer et al arXiv:1703.09189, Matias et al arXiv:1704.05340]

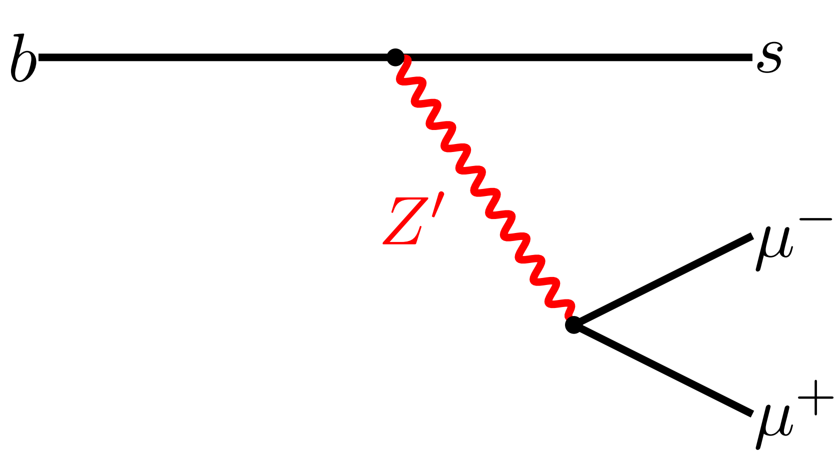
Interpretations

W. Altmannshofer et al., EPJC 75 (2015) 382



- Combine rare semileptonic decay observables in an independent global fit
- Several attempts to interpret the data

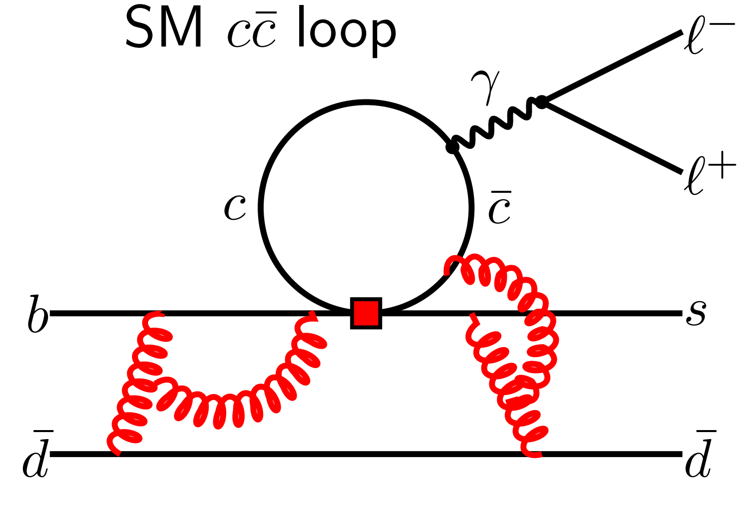
Possible NP



New vector Z', leptoquarks ...

Buttazzo et al [1604.03940]
Bauer et al [PRL116,141802(2016)]
Crivellin et al [PRL114,151801(2015)]
Altmannshofer et al[PRD89(2014)095033]

SM $c\bar{c}$ loop

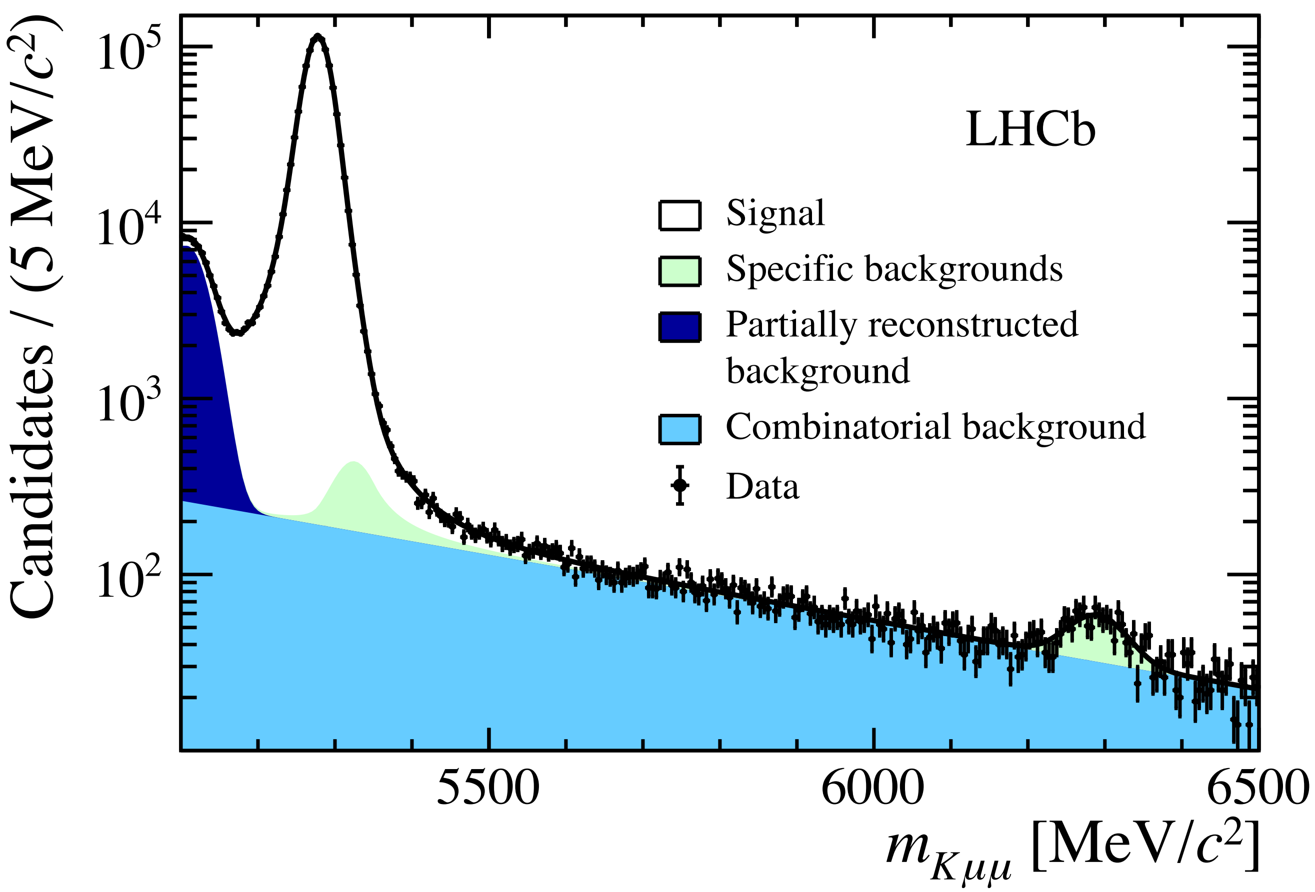


$c\bar{c}$ contribution can mimic vector-like NP effect (corrections to C_9)

Lyon,Zwicky [1406.0566]
Altmannshofer Straub [1503.06199]
Ciuchini et al [1512.07157]

Impact of dilepton vector coupling

- Important to understand how much the long distance contribution from SM and interference with the short distance
- Measurement of the phase difference between the short-distance and narrow resonances in $B^+ \to K^+ \mu^+ \mu^-$



[Eur. Phys.J. C(2017)77:161]

- Dependence of the observables enters through C_9

$$\mathcal{C}_9^{\text{eff}} = \mathcal{C}_9 + Y(q^2)$$

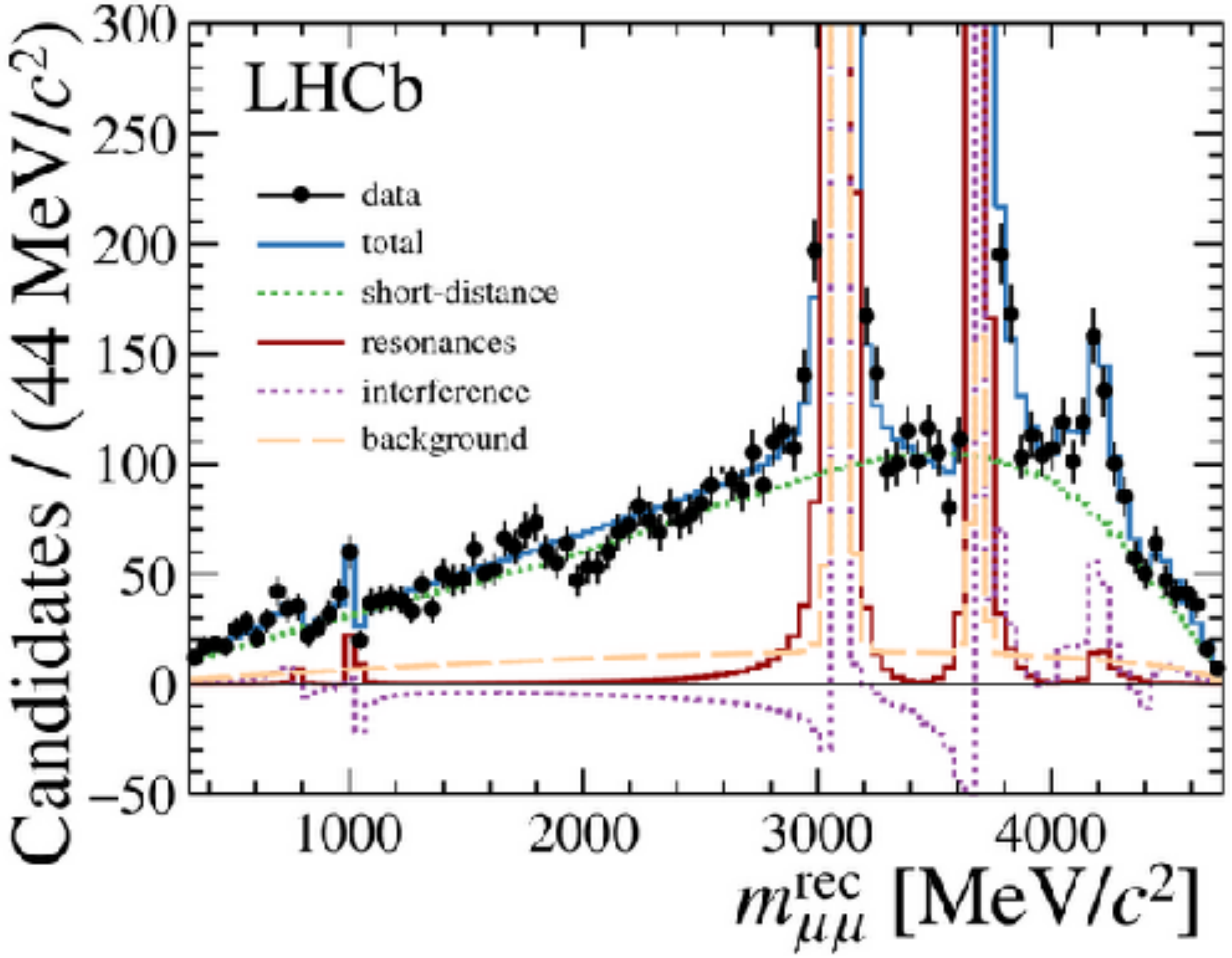
- $Y(q^2)$ summarises contributions from $bsq\bar{q}$ operators
- Main culprit is the large $c\bar{c}$ component such as the J/psi

Measuring phase differences

- Fit to full dimuon mass distribution including:
  - Resonances: ρ, ω, ϕ, J/ψ, ψ(2S)
  - Broad charmonium states: ψ(3770), ψ(4040), ψ(4160), ψ(4415)

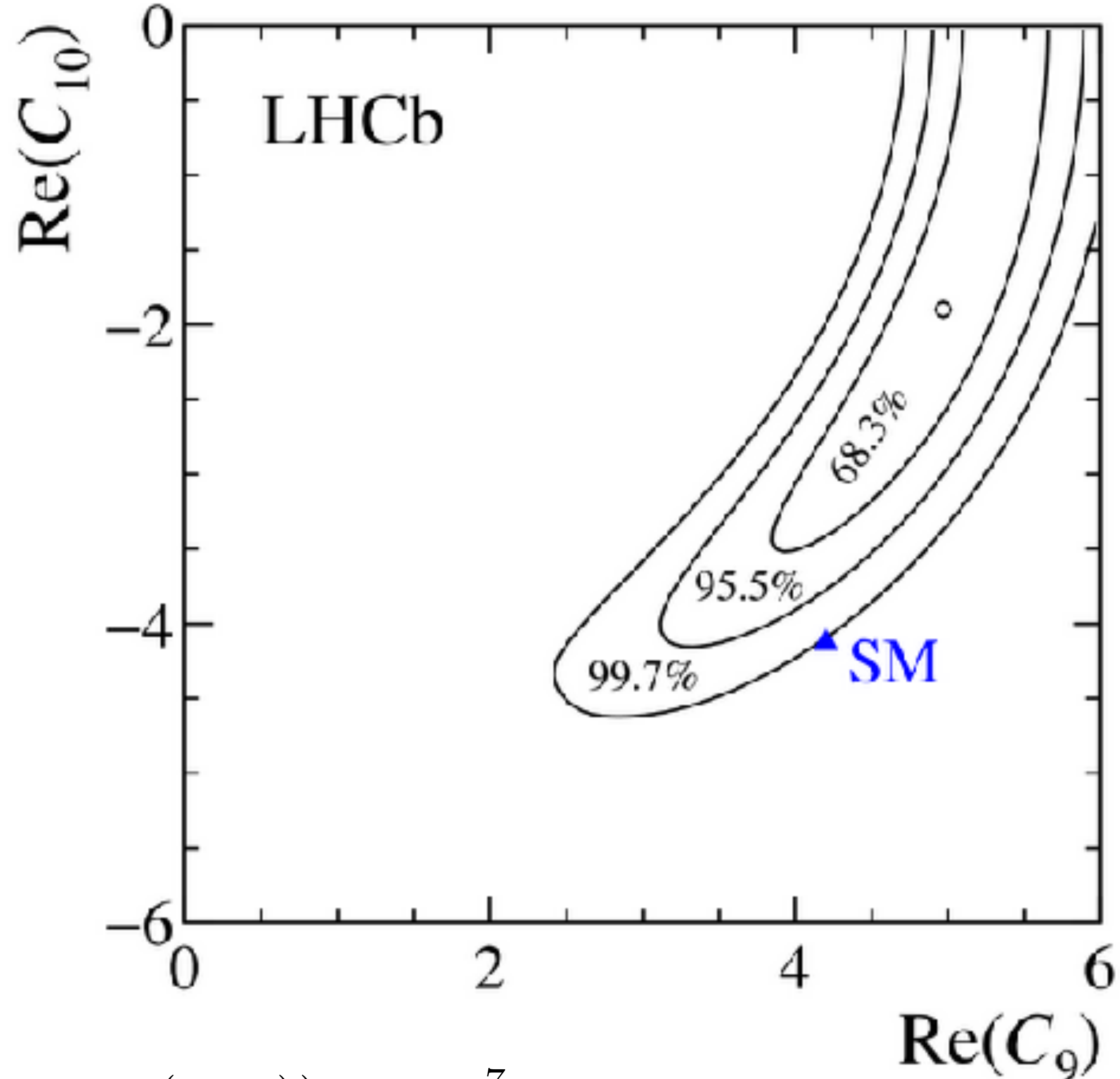
[Eur. Phys.J. C(2017)77:161]

- Four-fold ambiguity in J/ψ and ψ(2S) phases signs:
  - compatible with $\pi/2 \rightarrow$ minimal interference with non resonant
- Dedicated analysis needed for $B^0 \rightarrow K^{*0}\mu^+\mu^-$



Fit to Wilson coefficients

- Non resonant sensitive to C_9 and C_{10}
- Deviation of 3.0σ from SM
- Low $B^+ \to K^+ \mu^+ \mu^-$ BR not explain by resonance interferences
- Its measurement in agreement with previous measurement



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

[Eur. Phys.J. C(2017)77:161]

Lepton Flavour Universality

- Universality: the three charged leptons couple in a universal way to the SM gauge bosons
- In the SM the only flavour non-universal terms are the three lepton masses
- If NP couples in a non-universal way to the three leptons families discoverable through rare decays involving different leptons in the final state

Test of lepton universality using $B^+ \to K^+ll$ decays

- Test of LFU measuring the ratio between the decay rates of $B \to K^{(*)}ll$, cancellation of hadronic form-factors uncertainties in predictions

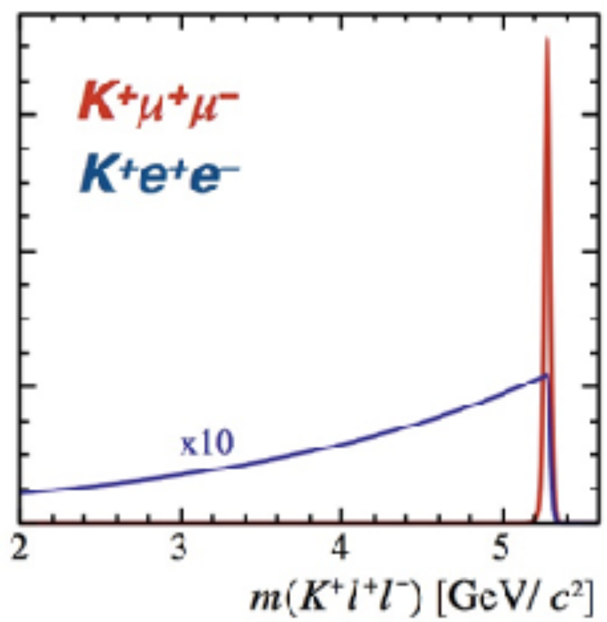
$$R_K = \frac{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \frac{d\Gamma[B^+ \to K^+ e^+ e^-]}{dq^2} dq^2}$$

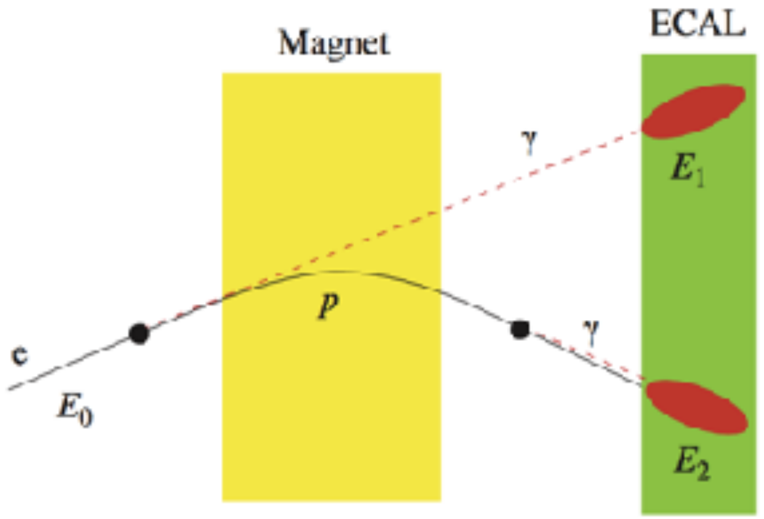
- Masses of leptons small compared with the b-quark
  - $R_{K(*)}$ is close to unity in SM, with very small uncertainties
- QED effects can be large but this is accounted for in the measurements
  - Possible deviation from QED corrections ~1% in the central q^2

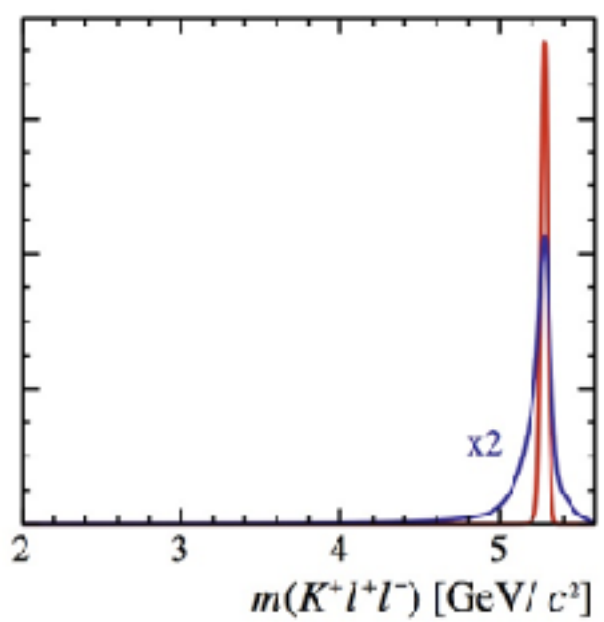
Bordone, M., Isidori, G. & Pattori, A. Eur. Phys. J. C (2016) 76: 440.

Bremsstrahlung issues

- Electrons more difficult than muons due to bremsstrahlung
  - energy recovered exploiting calorimeter information





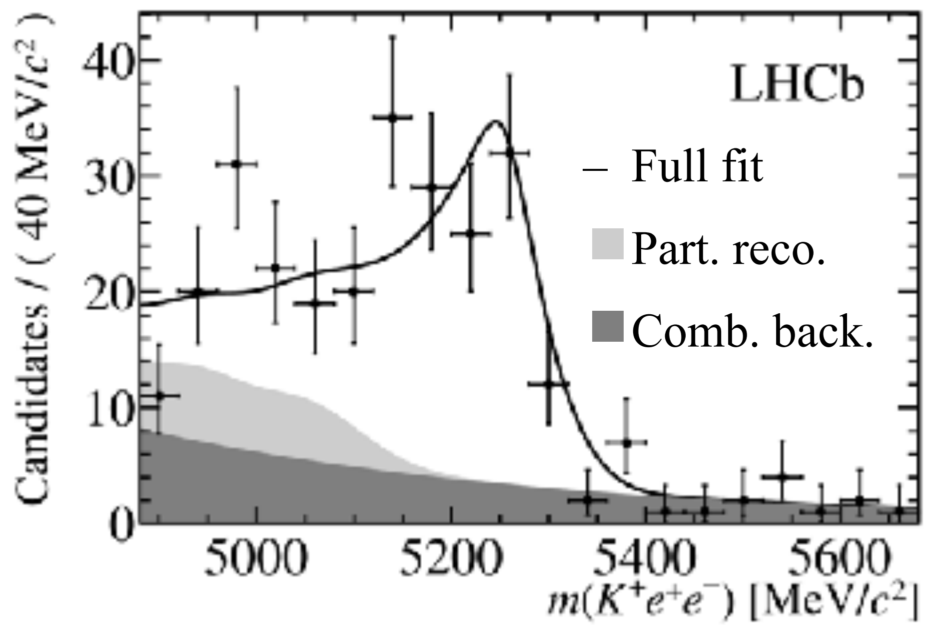


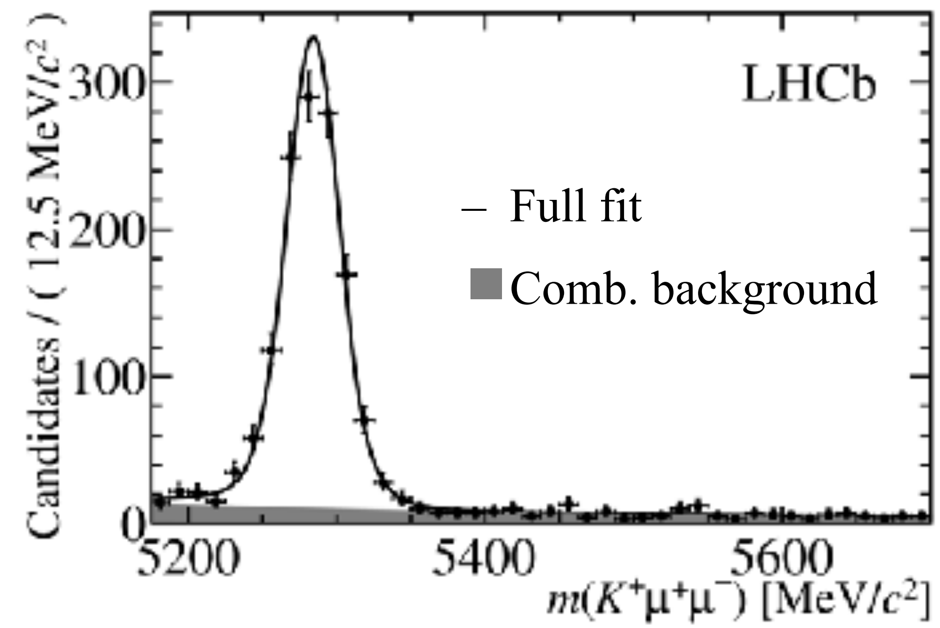
- Low trigger efficiency
  - Trigger by the electron, hadron and other particles in the event
  - Final result from likelihood combination

The R_K measurement

$1\text{GeV}^2/c^4 < q^2 < 6\text{GeV}^2/c^4$

Electron trigger

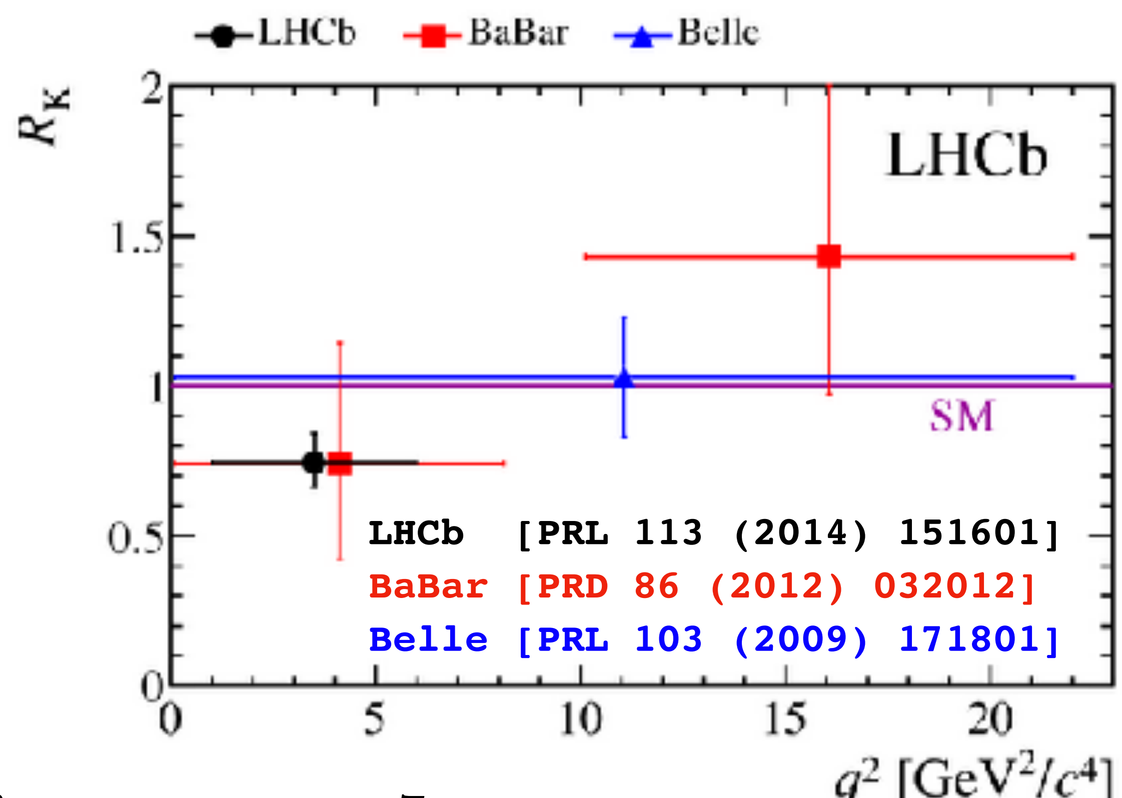




- Combination of the various trigger channels gives:

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

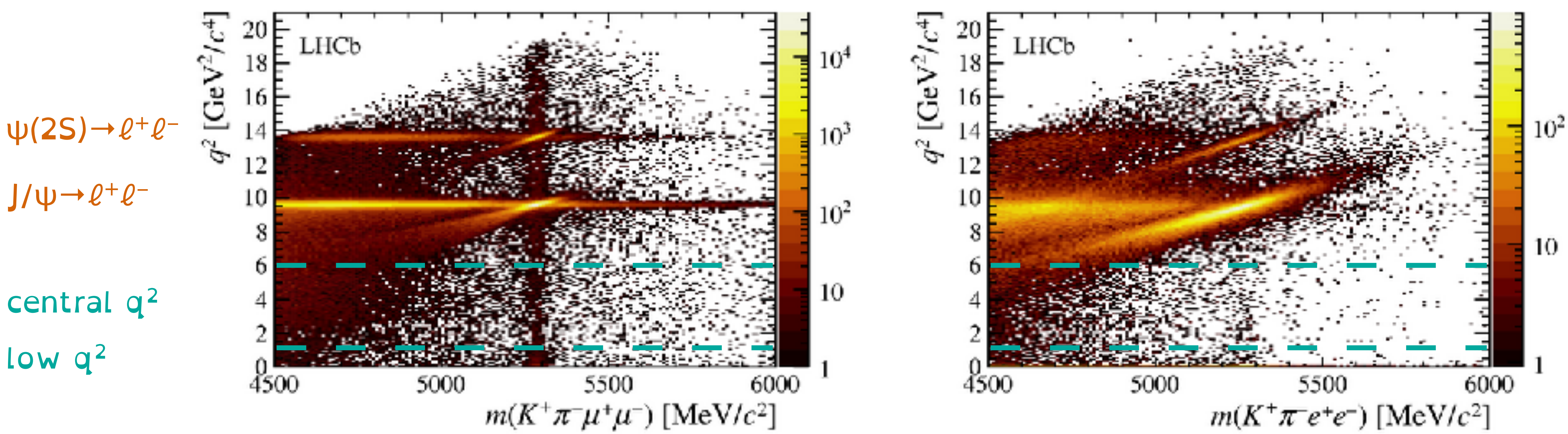
- Compatible with SM at 2.6σ level
- Branching fraction of $B^+ \to K^+e^+e^-$ compatible with the SM



$$\mathcal{B}(B^+ \to K^+e^+e^-) = 1.56^{+0.19}_{-0.15}(\text{stat})^{+0.06}_{-0.05}(\text{syst}) \times 10^{-7}$$

The R_{K*} measurement

- Results use Run1 data ~$3fb^{-1}$ of integrated luminosity
- Measure the double ratio with the resonant mode $B \to K^* J/\psi(\to \ell^+\ell^-)$
  - Systematics due to different experimental efficiencies reduced
- Selection as similar as possible between μμ and ee
- Fit B mass in two q^2 regions: low [0.045-1.1] GeV^2/c^4 and central [1.1-6.0] GeV^2/c^4

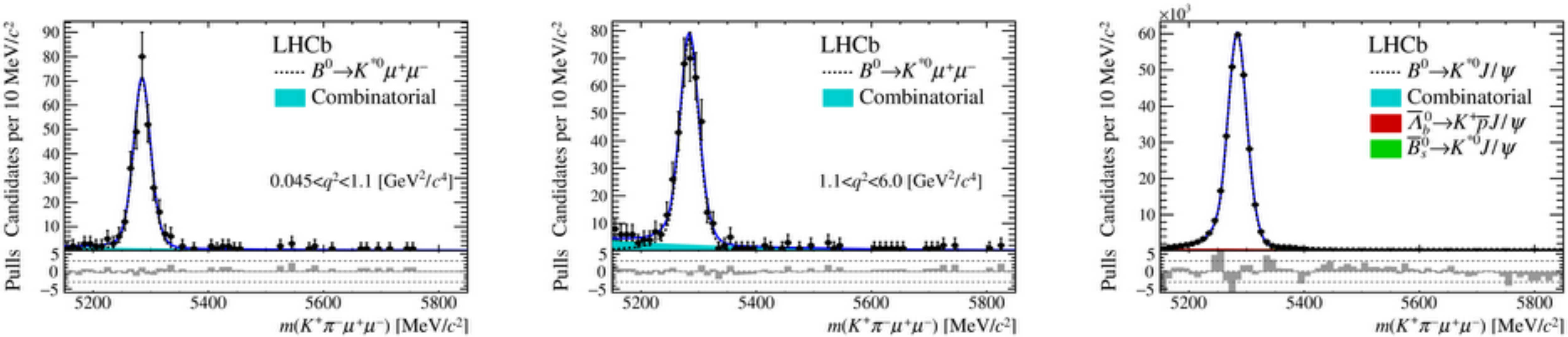


[JHEP 08 (2017) 055]

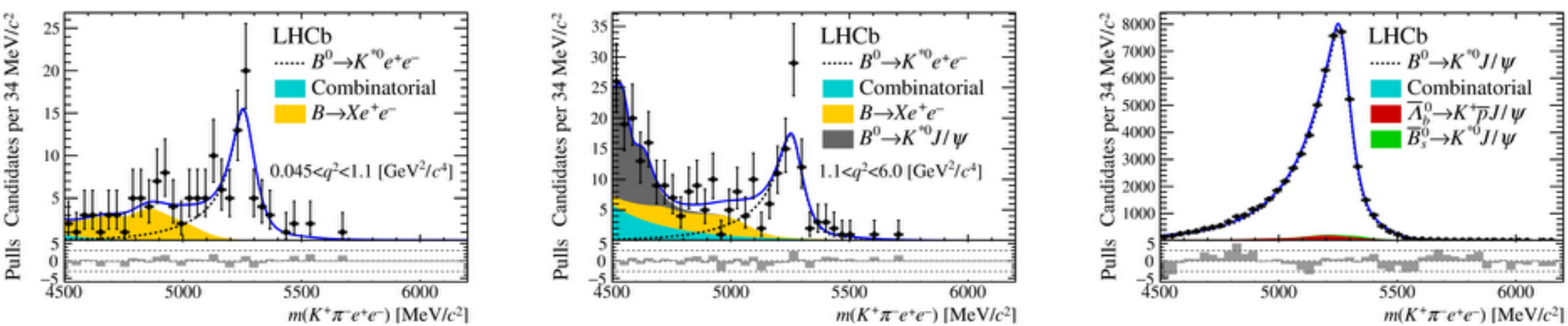
Fit results

[JHEP 08 (2017) 055]

μμ mode



ee mode



Cross-Checks

[JHEP 08 (2017) 055]

- Measure single ratio for the J/ψ mode to control absolute scale of the efficiencies:

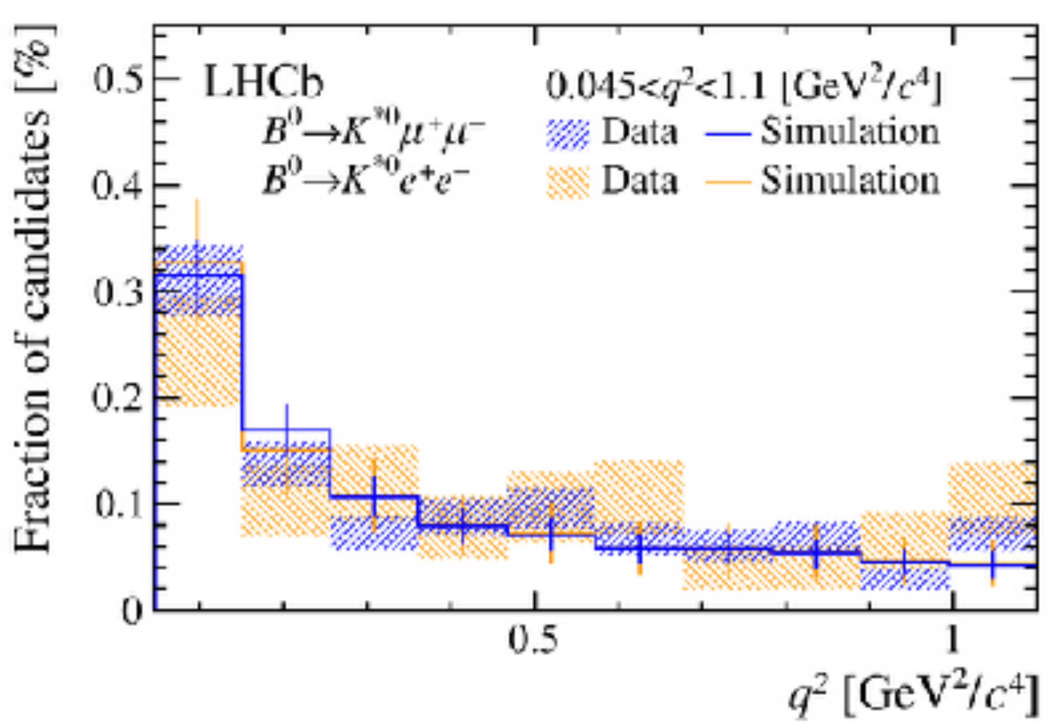
$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))} = 1.043 \pm 0.006(\text{stat}) \pm 0.045(\text{syst})$$

- Additional cross-check from measurement of the ratio:

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

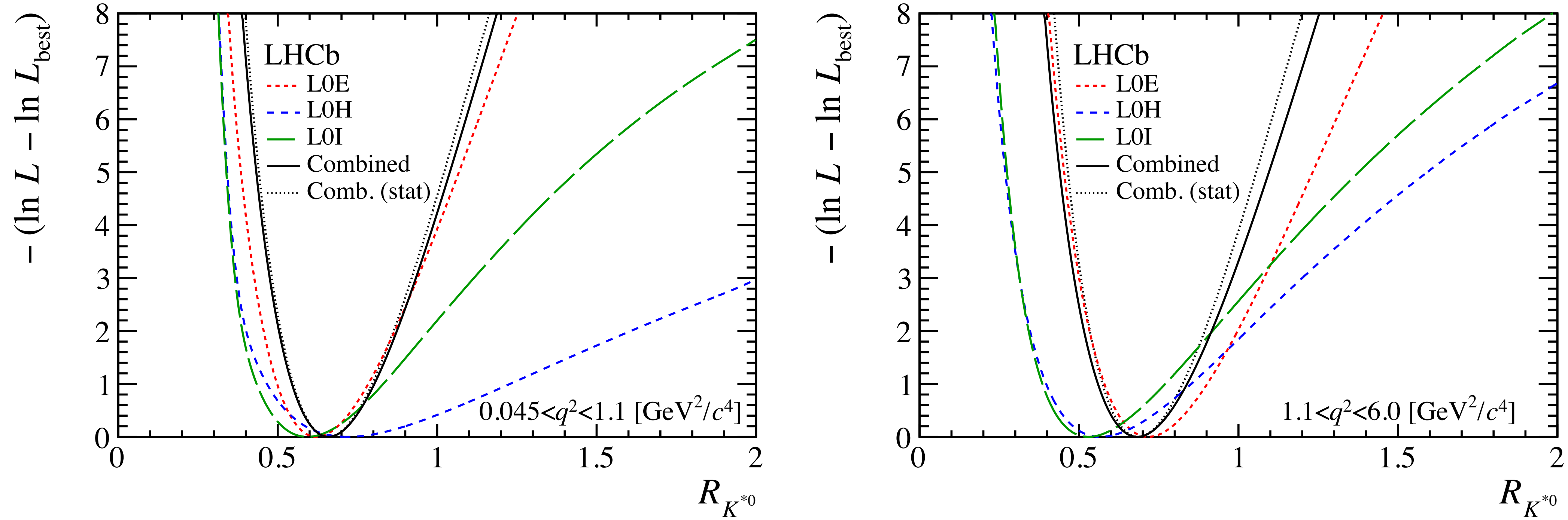
measured with 2% precision

compatible with 1 within 1σ



Splot technique used to statistically subtract background from data → good agreement between data and simulation

Results



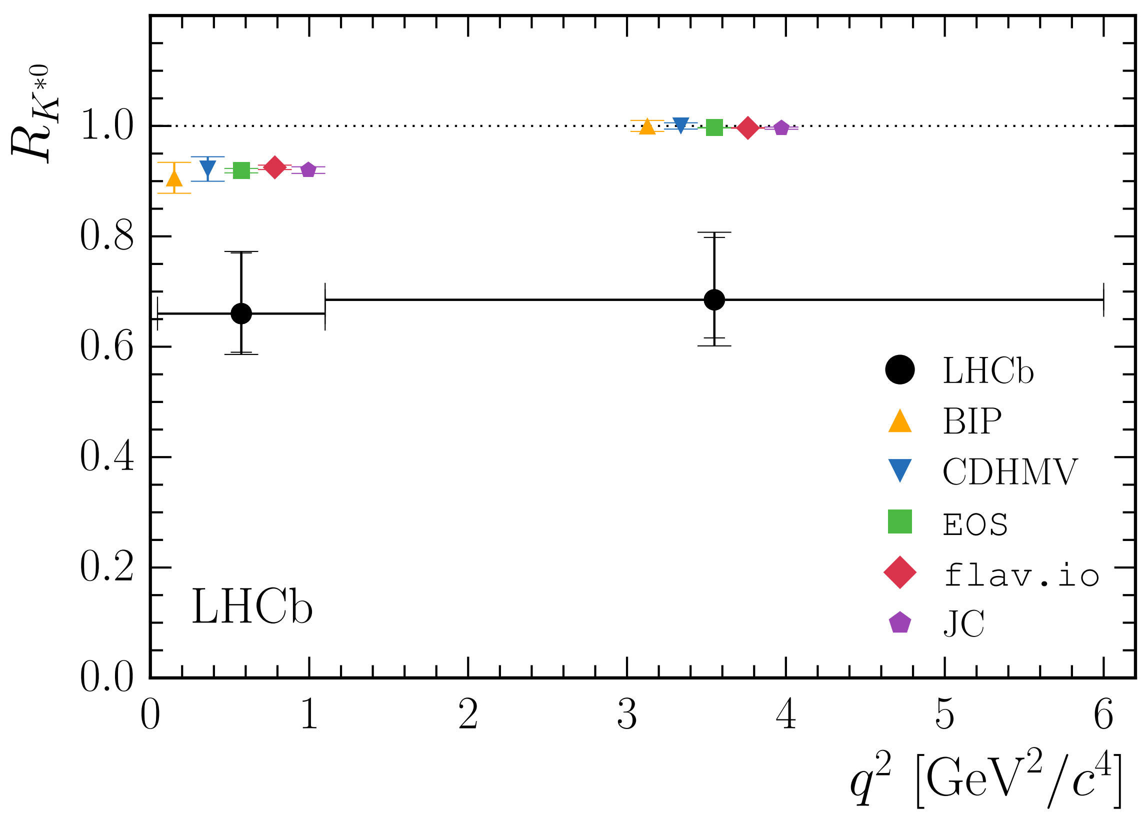
Measured values of R_{K*} in the three trigger categories found in good agreement

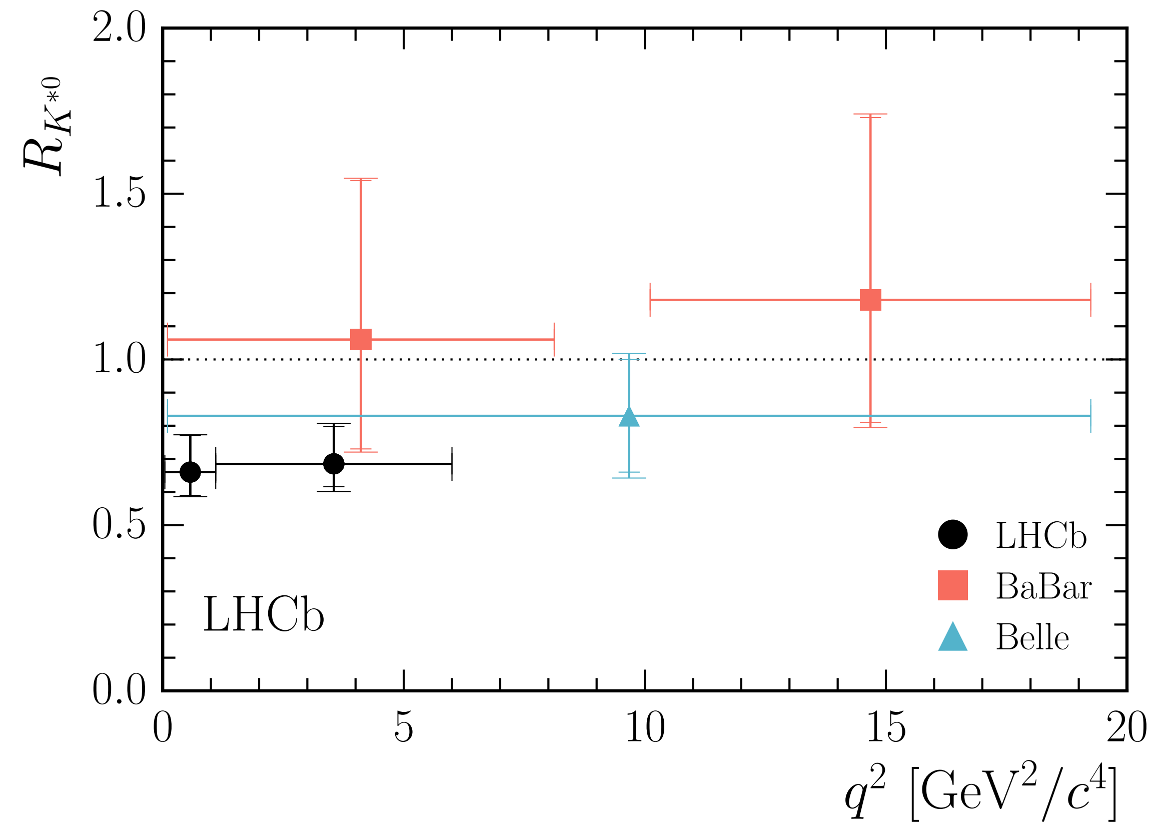
	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66\ ^{+\ 0.11}_{-\ 0.07} \pm 0.03$	$0.69\ ^{+\ 0.11}_{-\ 0.07} \pm 0.05$
95.4% CL	$[0.52, 0.89]$	$[0.53, 0.94]$
99.7% CL	$[0.45, 1.04]$	$[0.46, 1.10]$

[JHEP 08 (2017) 055]

Results (2)

[JHEP 08 (2017) 055]





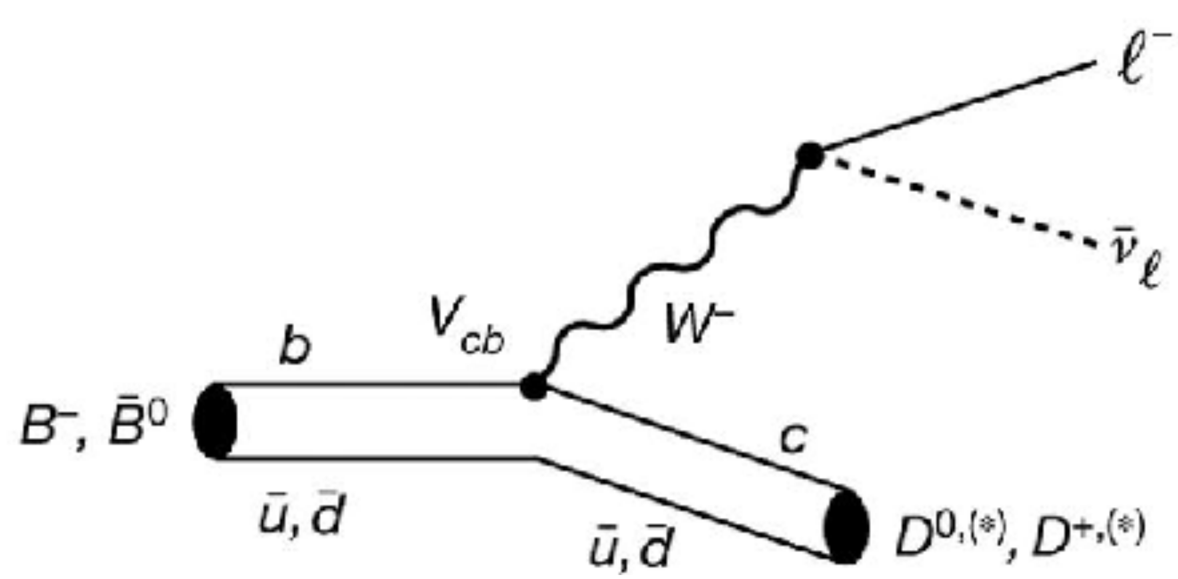
BIP	arXiv:1605.07633
CDHMV	arXiv:1510.04239, 1605.03156, 1701.08672
EOS	arXiv:1610.08761, https://eos.github.io
flav.io	arXiv:1503.05534, 1703.09189, flav-io/flavio
JC	arXiv:1412.3183

BaBar PRD 86 (2012) 032012
Belle PRL 103 (2009) 171801

- Most precise measurement to date
- Error dominated by the statistical uncertainty
- Compatible with the SM at 2.1-2.3σ in the low q^2 and 2.4-2.5σ in the central q^2

tree-level b→clν transitions

- Can proceed via tree-level large BF ~O(%)
- NP sensitivity up to about 1TeV

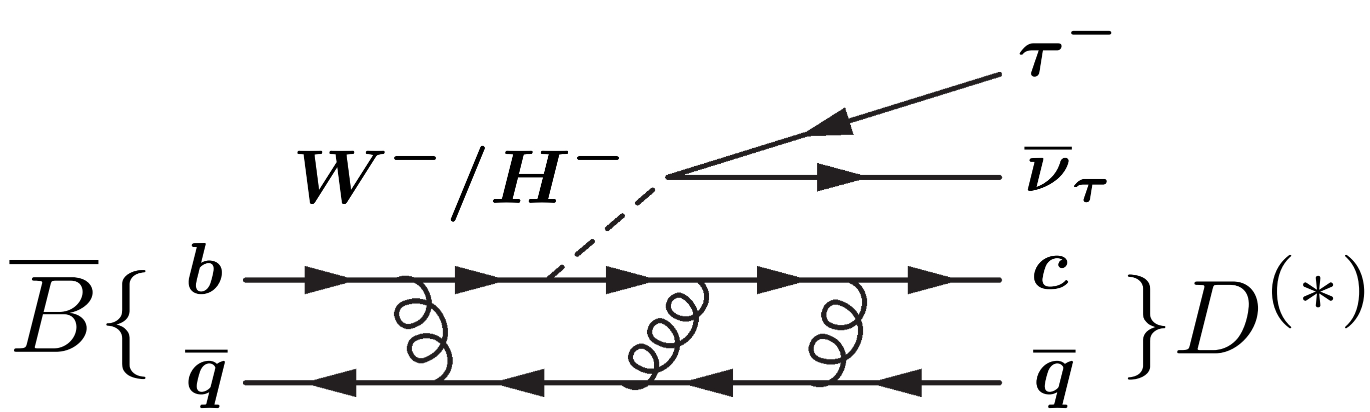


Measurement R(D$^{(*)}$)

- Access to a large rate of charged current decays
- Ratio of decays with different lepton generations
  - Theoretically clean due cancellation of form factor uncertainties
  - Cancellation of experimental uncertainties

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}$$

- Sensitive to any physics model favouring 3rd generation leptons



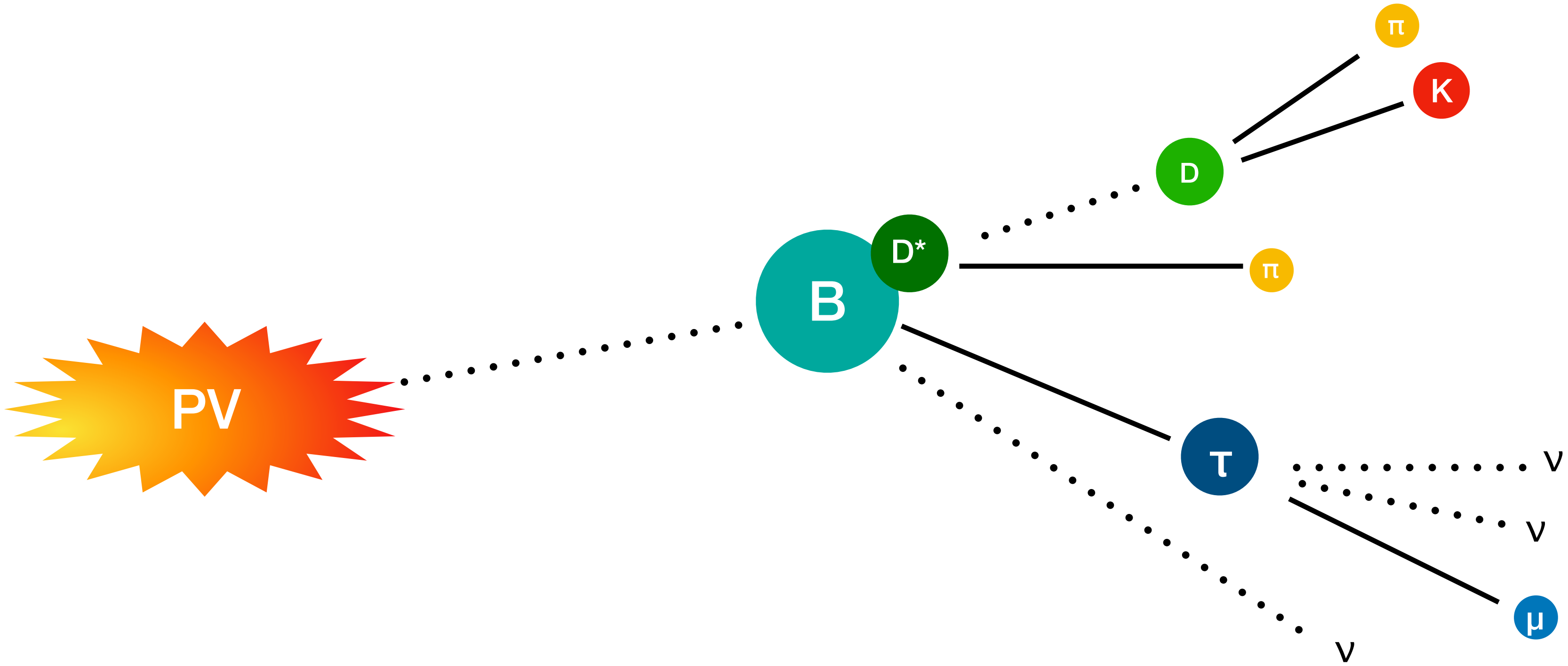
Three competitors

	BaBar	Belle	LHCb
n. B's produced	O(400M)	O(700M)	O(800B)
Production mechanism	$\Upsilon(4S) \to B\overline{B}$	$\Upsilon(4S) \to B\overline{B}$	$pp \to gg \to b\overline{b}$
Pubblications	Phys.Rev.Lett 109, 101802 (2012) Phys. Rev. D 88, 072012 (2013)	Phys.Rev.D 92, 072014 (2015) Phys. Rev. D 94, 072007 (2016)	Phys.Rev.Lett.115, 111803 (2015) LHCb-PAPER-2017, in preparation

- LHCb measurements with muonic and 3prong mode

Challenges at LHCb

- Missing neutrinos → no sharp peak to fit
- large background from partially reconstructed B decays: $B \to D^{**}\mu$, $B \to H_c(\to X\mu)D^{*}X$
- B-factories exploit kinematics of the $e^{+}e^{-} \to \Upsilon(4S) \to B\bar{B}$ reaction
  - Tagging technique provides info of missing system
  - Reduced background from partially reconstructed
  - Low efficiency ($\sim 10^{-3}$)
- More difficult at LHCb, compensate using large boost and huge production

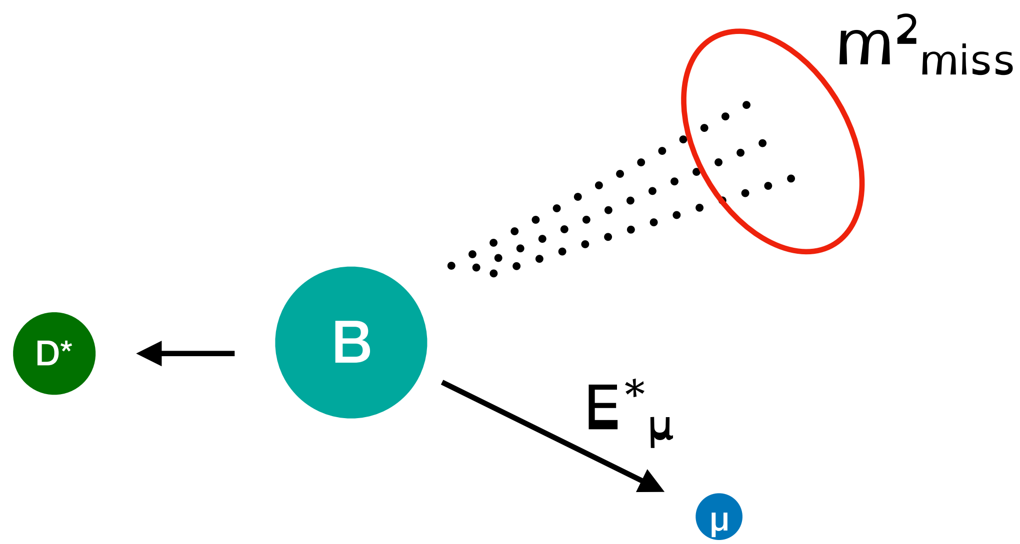


Key features

[PRL 115 (2015) 111803]

- Most discriminating variables E^*_μ, $m^2_{miss} = (p_B - p_{D*} - p_\mu)^2$, and $q^2 = (p_B - p_{D*})^2$
- Missing neutrinos → no analytical solution for p_B
- Rest frame approximation: B boost along z >> boost of the decay products in the B rest frame → $(p_z)_B = m_B/m_{(D*\mu)}(p_z)_{D*\mu}$ → resolution on p_B ~18%

$B^0 \rightarrow D^{*+}\tau^-\bar{\nu}$	$B^0 \rightarrow D^{*+}\mu^-\bar{\nu}$
$m^2_{miss} > 0$	$m^2_{miss} = 0$
E^*_ℓ spectrum is soft	E^*_ℓ spectrum is hard
$m^2_\tau \leq q^2 \leq 10.6$ GeV^2	$0 \leq q^2 \leq 10.6$ GeV^2



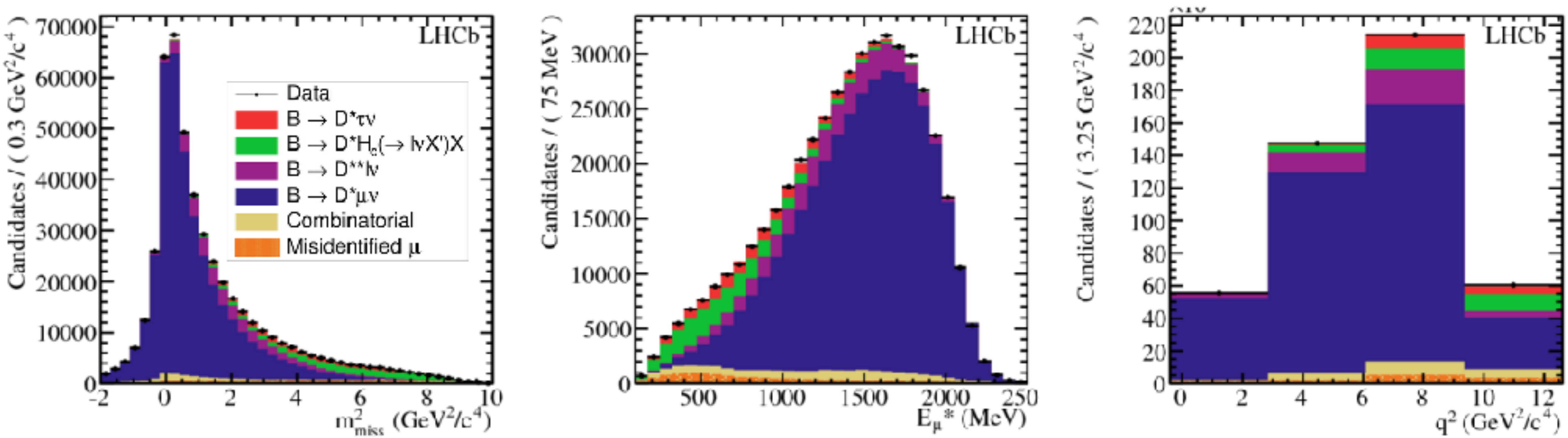
Result

[PRL 115 (2015) 111803]

- Template fit in three variables: m^2_{miss}, E_μ, q^2
  - Simulated samples for signal and physics background
  - Background from μ mis-ID and combinatorial from data

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

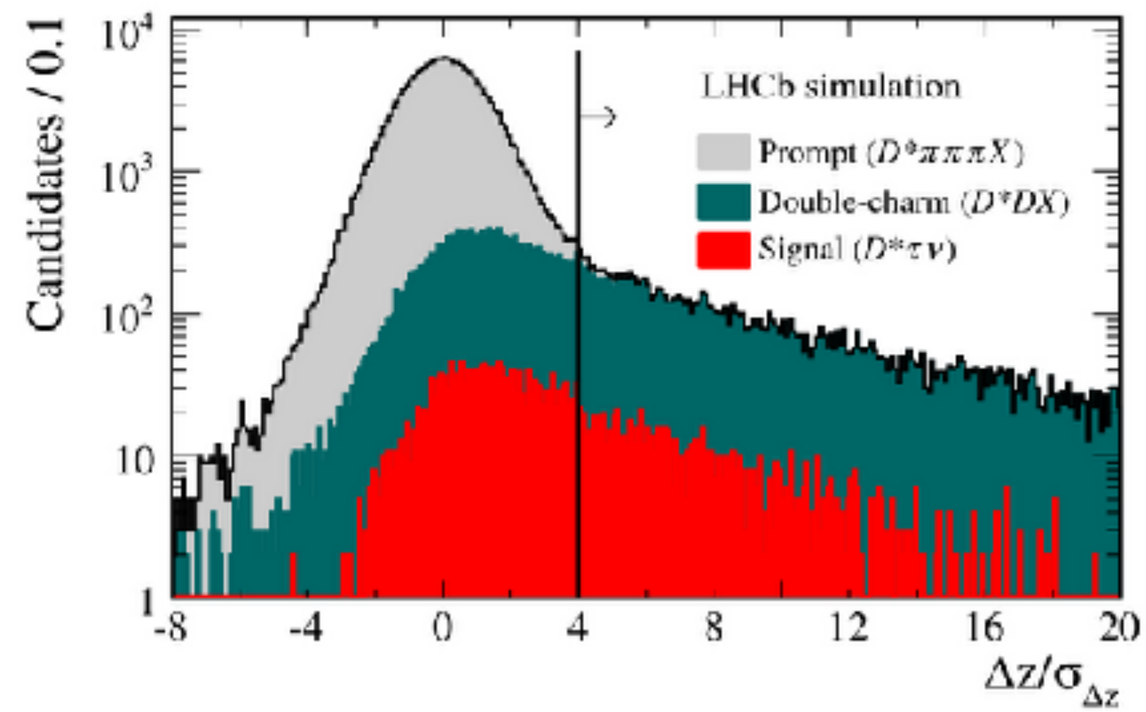
Compatible with the SM
at 2.1σ level



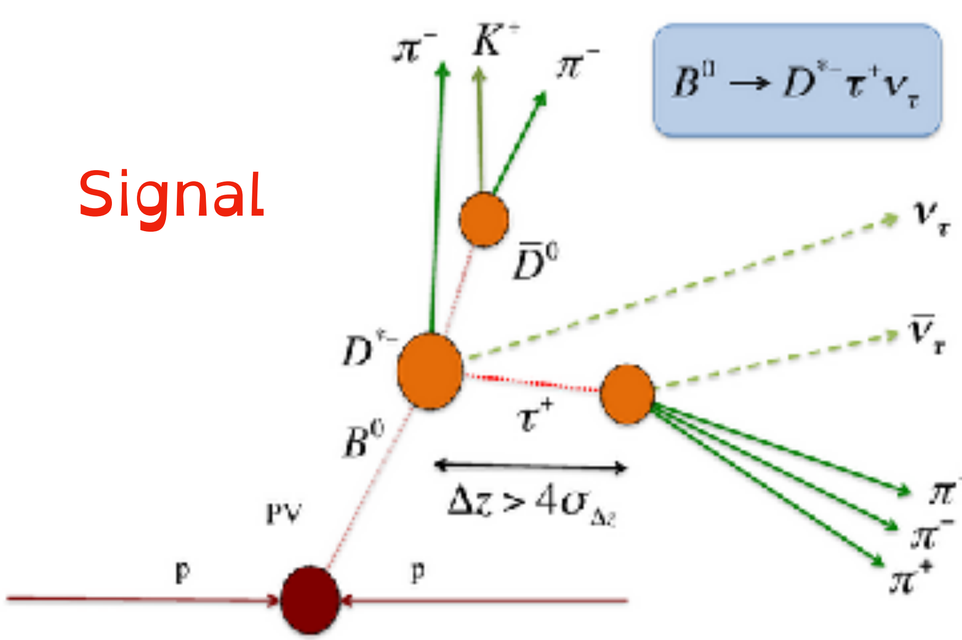
Dominant uncertainties: statistical and size of simulated samples.

R(D*) with 3-prong τ decays

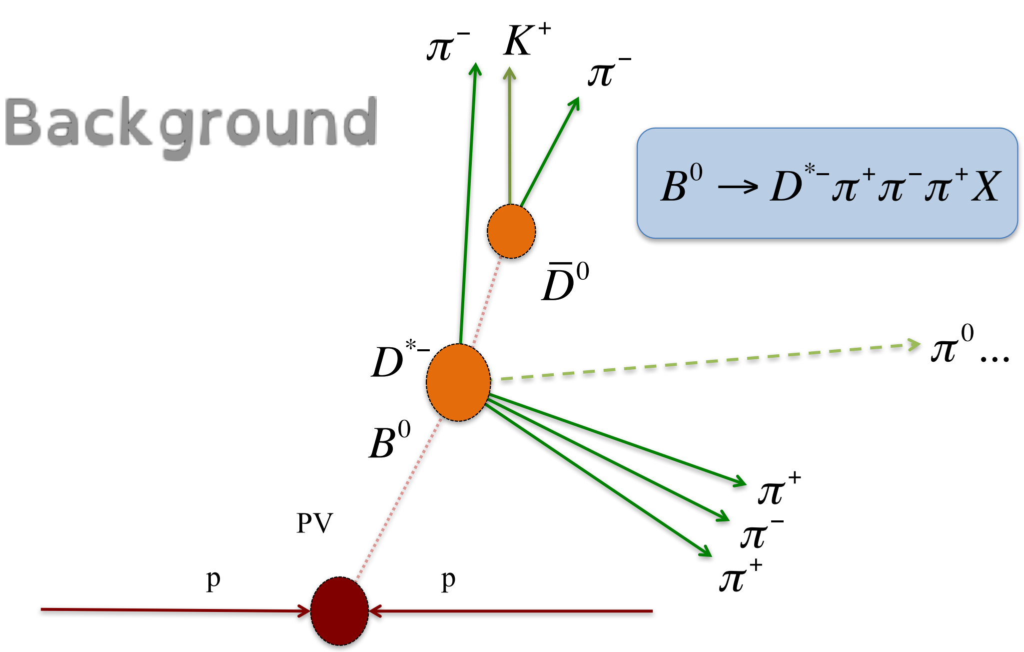
- First measurement of R(D*) using $\tau \to 3\pi\nu$. Using 3fb-1 of Run I data
- No background from $B \to D^{*(*)}\ell\nu$ decays
- Main background from part-reco
  - Exploiting τ lifetime
  - Train BDT agains $B \to D^{*}D_{s}X$ exploiting isolation and kinematic information



Signal



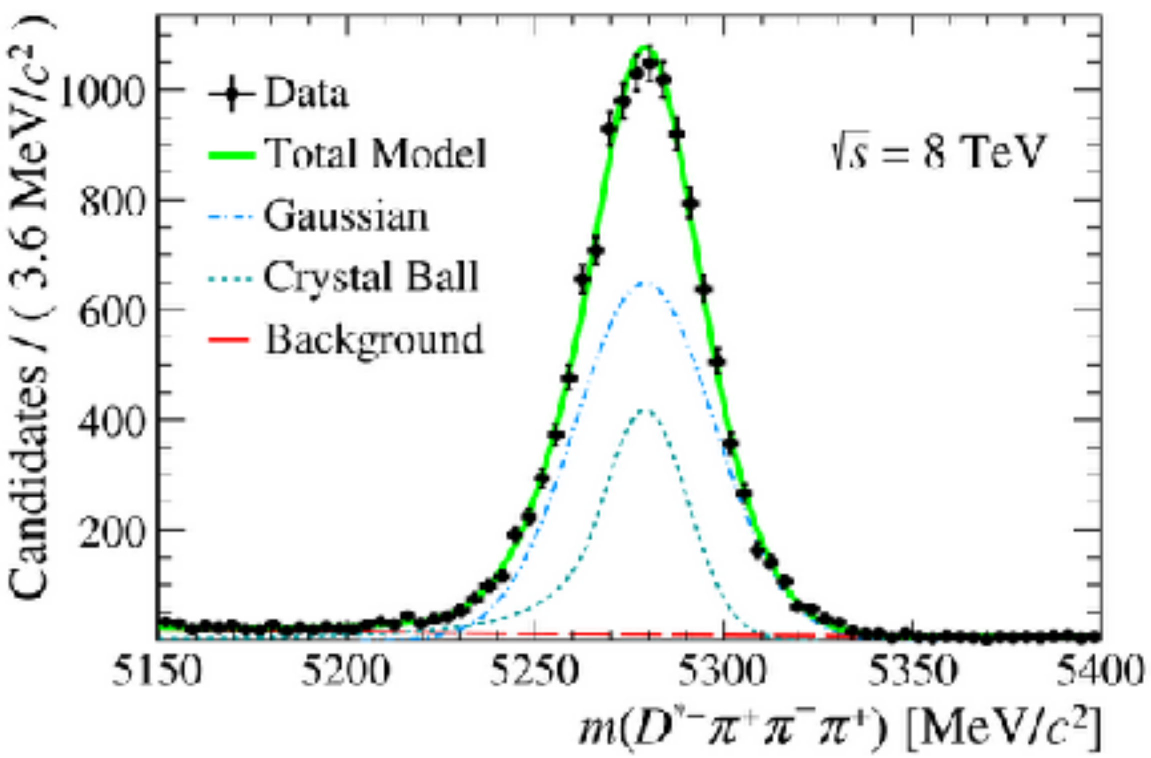
Background



Normalisation

- Normalisation to $B^0 \to D^{*-}\pi^+\pi^-\pi^+$ decays, similar signal topology
  → reduced systematics

$$\mathcal{K}(D^{*-}) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)}$$



- R(D*) measured through:

$$R(D^{*-}) = \mathcal{K}(D^{*-}) \frac{\mathcal{B}(B^0 \to D^{*-}3\pi)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

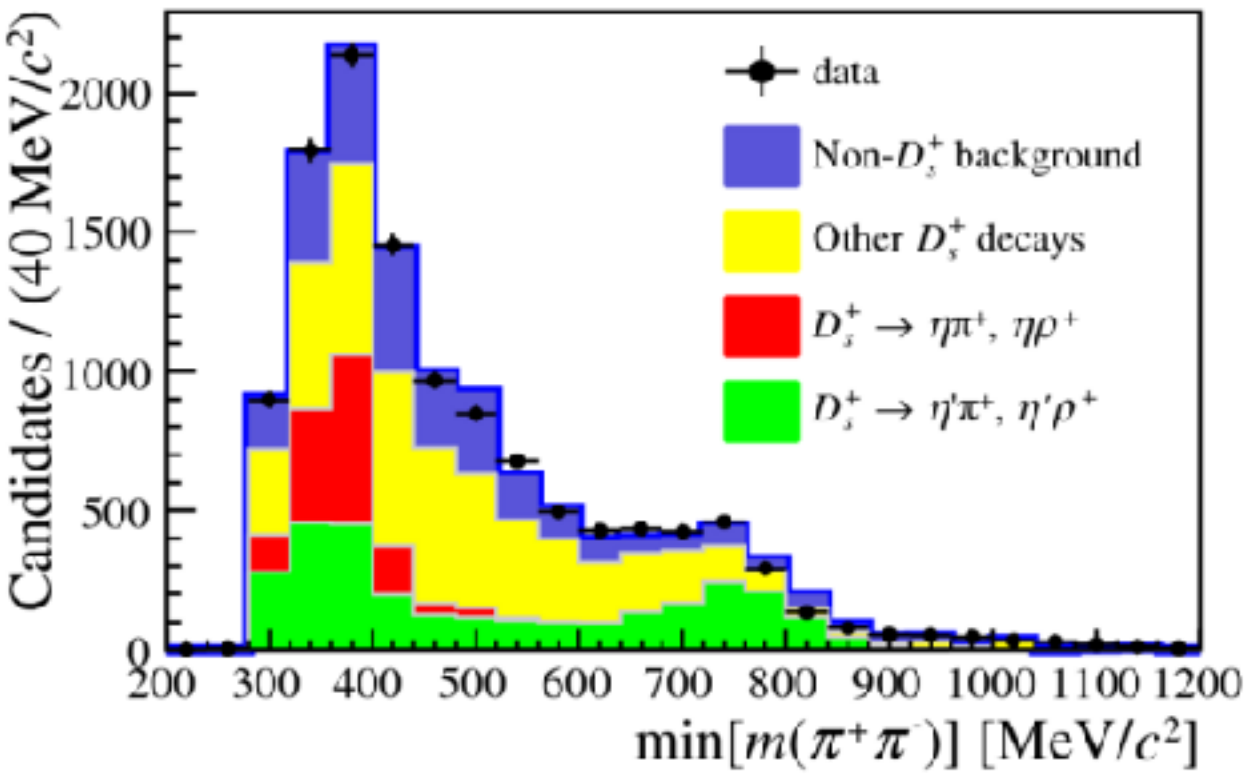
- External inputs:

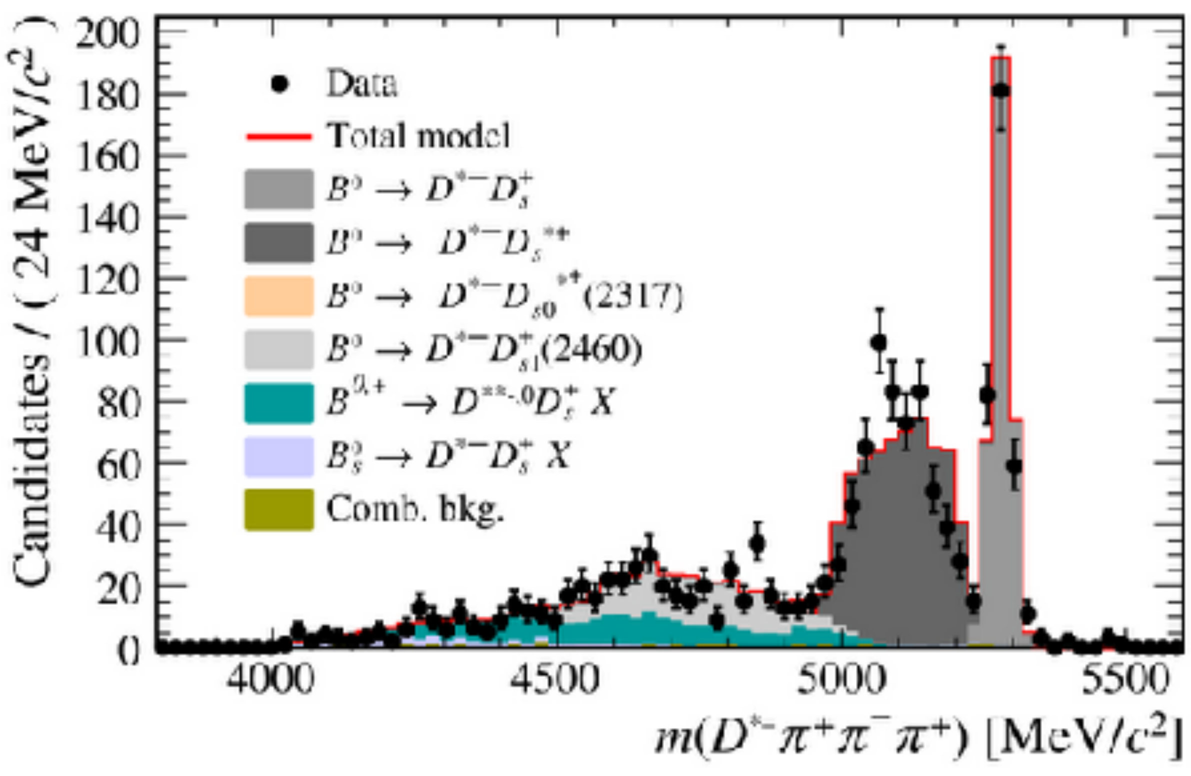
$$\mathcal{B}(B^0 \to D^{*-}3\pi) = (7.23 \pm 0.51) \times 10^{-3}$$ [Phys. Rev. D87 (2013) 092001]

$$\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu) = (4.88 \pm 0.10) \times 10^{-2}$$ [arXiv:1612.07233]

Main backgrounds

- Dominant background $B^0 \to D^* D_s X$
- Evaluated using data





Signal Fit

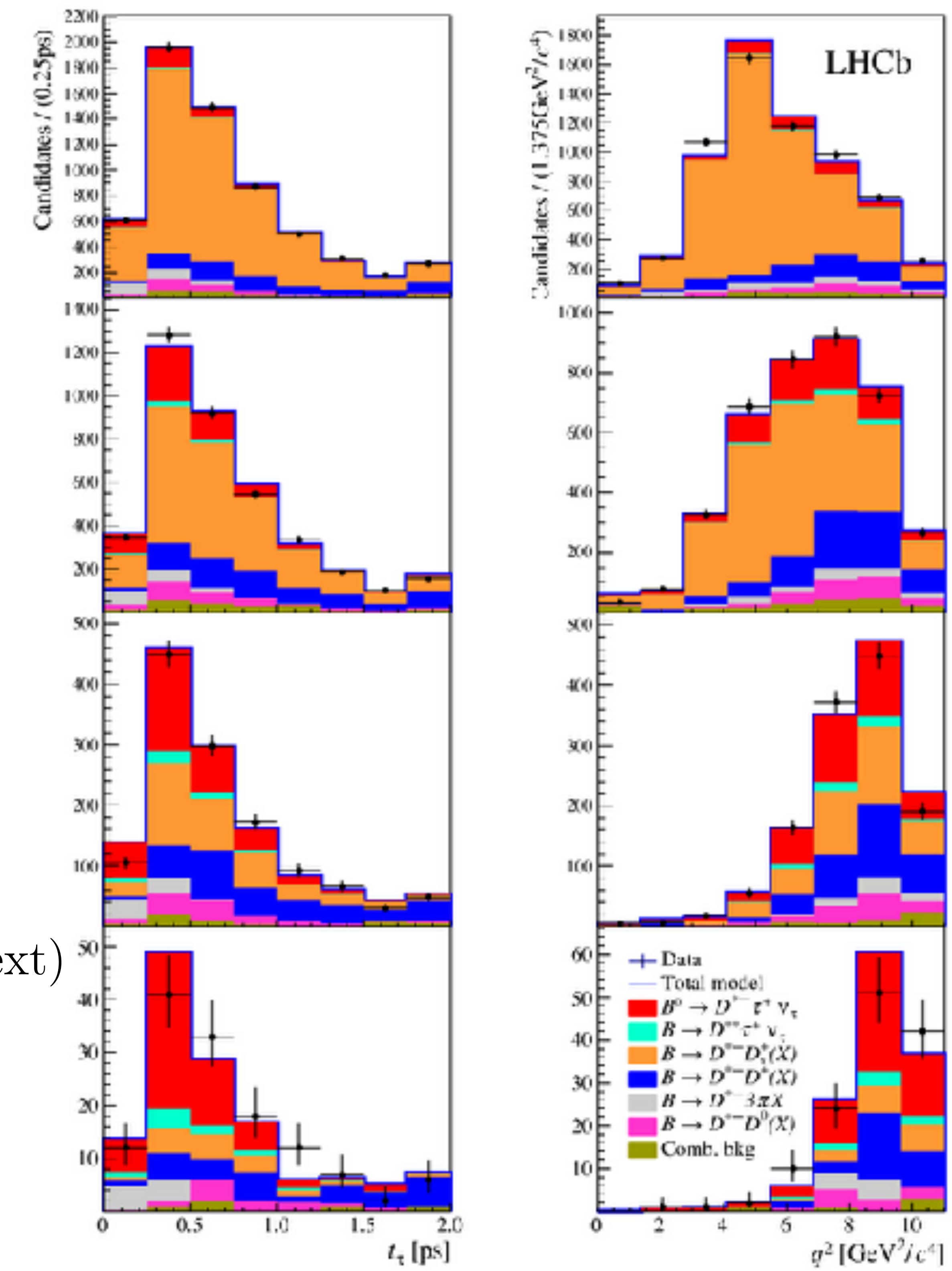
- Perform a 3D template fit to q2 and τ lifetime in bins of BDT response
- Dominant uncertainties: statistics of the simulated sample (efficiency corrections and bkg shapes).

$$\mathcal{K}(D^{*-}) = 1.93 \pm 0.13\,(\mathrm{stat}) \pm 0.18\,(\mathrm{syst})$$

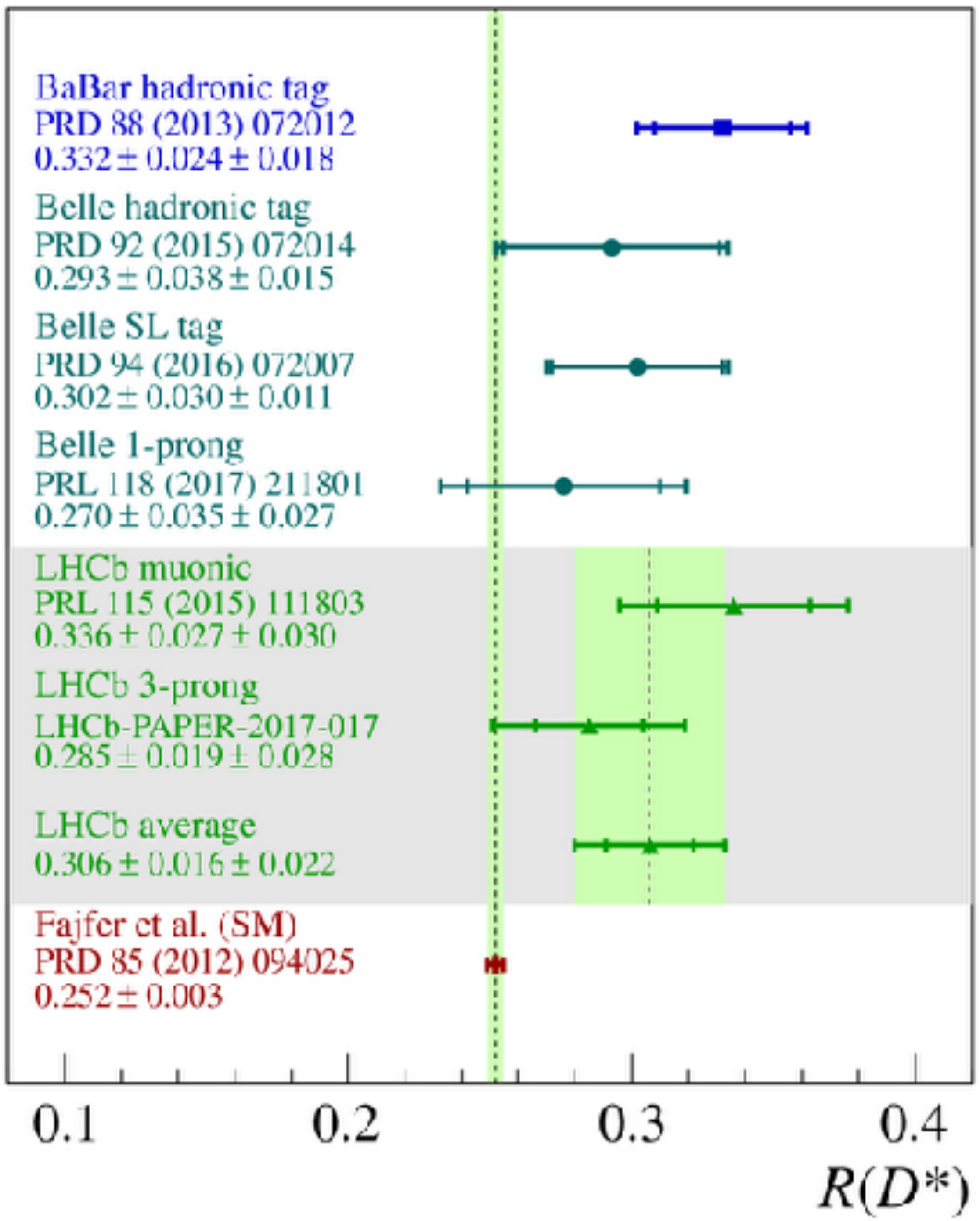
- Result combined with external inputs to determine R(D*)

$$\mathcal{R}(D^{*-}) = 0.286 \pm 0.019\,(\mathrm{stat}) \pm 0.025\,(\mathrm{syst}) \pm 0.021\,(\mathrm{ext})$$

- Compatible with the muonic measurement

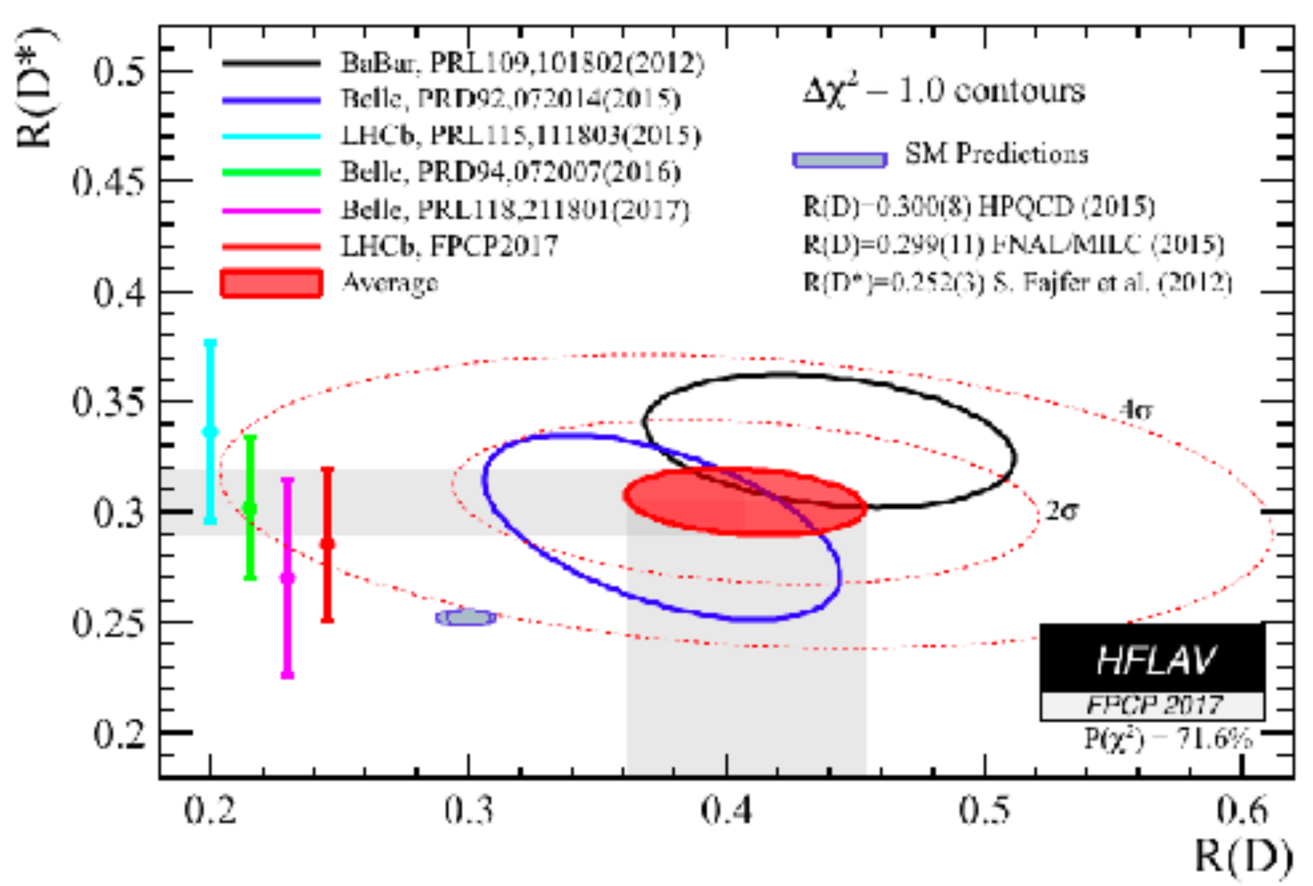


R(D*) summary



- LHCb combination 2.1σ from SM
- All the experiments see an excess of signal w.r.t. SM predictions
- HFLAV average 4.1σ from SM

http://www.slac.stanford.edu/xorg/hfag/semi/fpcp17/RDRDs.html



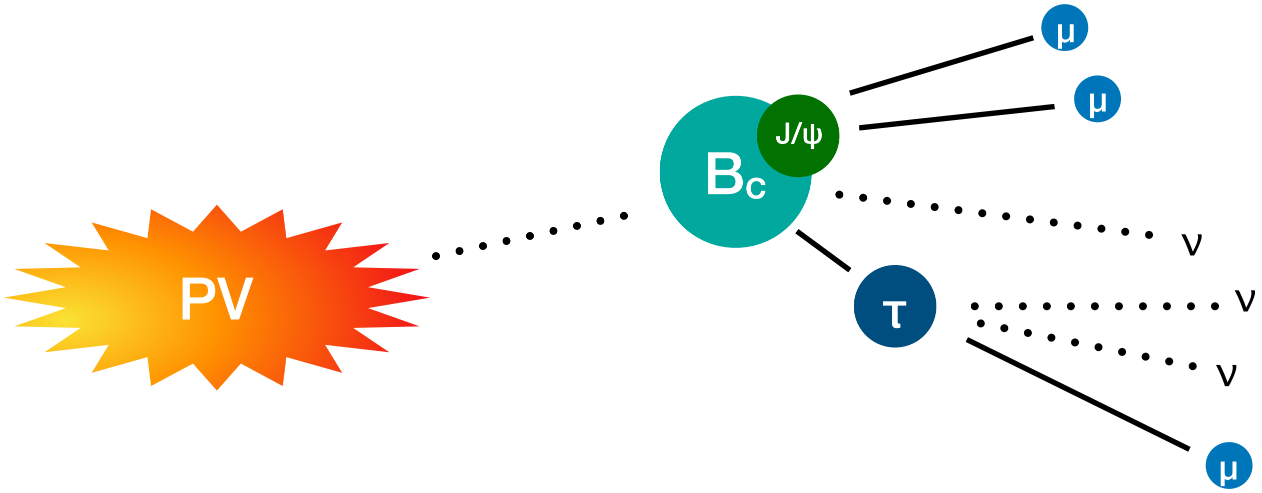
LFU test with Bc decays

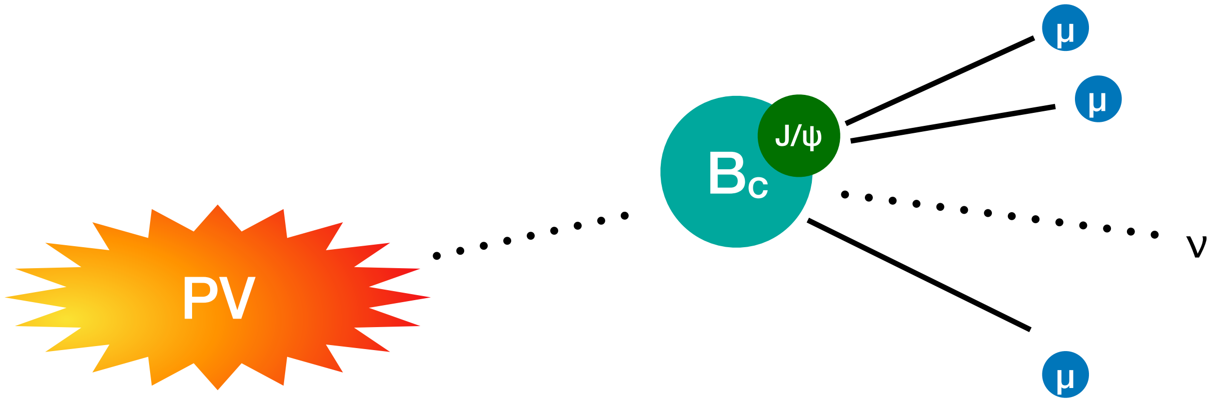
LHCB-PAPER-2017-035

- b-quarks free to hadronise into all sorts of different flavoured particles. B_c/B^0 production ratio ~1/200
- LFU test measuring R(J/ψ)

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} \qquad \tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$$

- Scarce knowledge of form factors → prediction in the range of 0.25 – 0.28
[arXiv:hep-ph/0211021] [Phys. Rev. D73 (2006) 054024] [Phys. Rev. D74 (2006) 074008]
- Similar approach used for R(D*) measurement





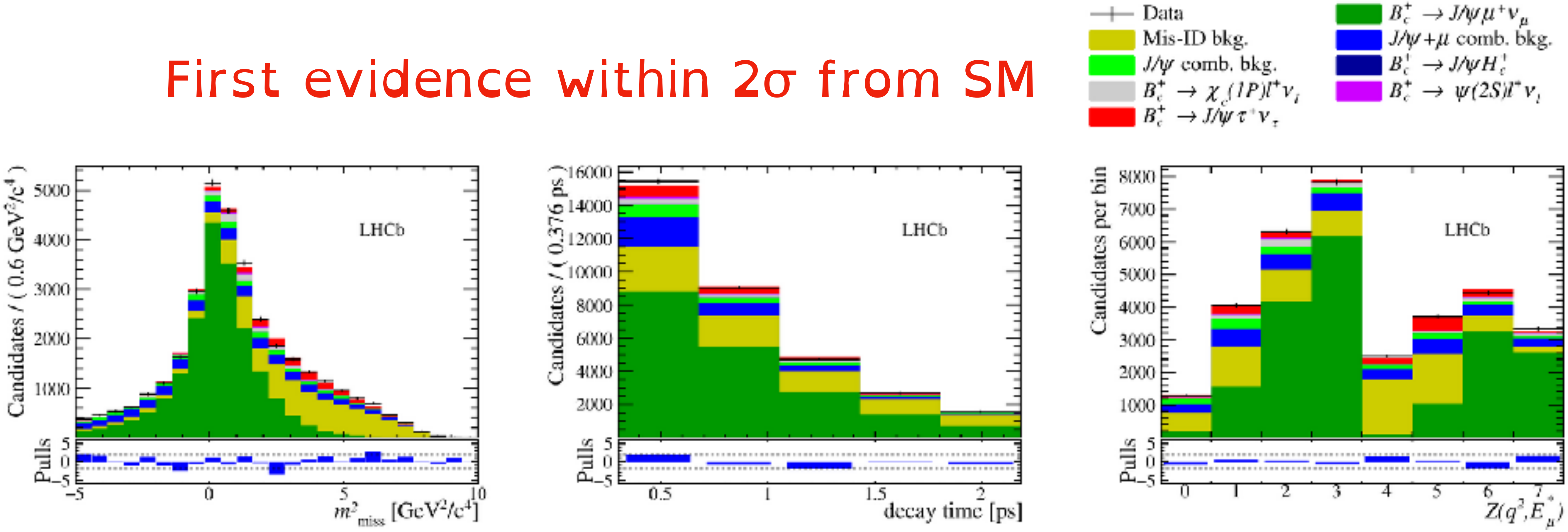
Result

LHCB-PAPER-2017-035

- Main backgrounds: J/ψ + random μ, $B^+ \rightarrow J/\psi h^+$, and $Bc \rightarrow J/\psi H_c$
- 3D template fit. B_c lifetime additional handle against lighter b-hadrons

$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} = 0.71 \pm 0.17\,(\mathrm{stat}) \pm 0.18\,(\mathrm{syst})$$

First evidence within 2σ from SM



- Main systematics: statistical, simulated sample size, form factors

Summary

- Muonic $b \to s\ell\ell$ BFs tend to be below the SM predictions
- R_K and R_{K^*} less then unity
    - NP seems to not couple strongly with the first generation
    - All seems to be related to a change in the C_9 coefficient (or C_9 and C_{10}) → $B_s \to \mu\mu$ crucial role to disentangle NP in C_{10}
- Anomaly more evident in the third generation
- Can $b \to c$ and $b \to s$ anomalies be related?
- Consistent picture BUT there is no single result above 3σ yet → too early to claim for NP?

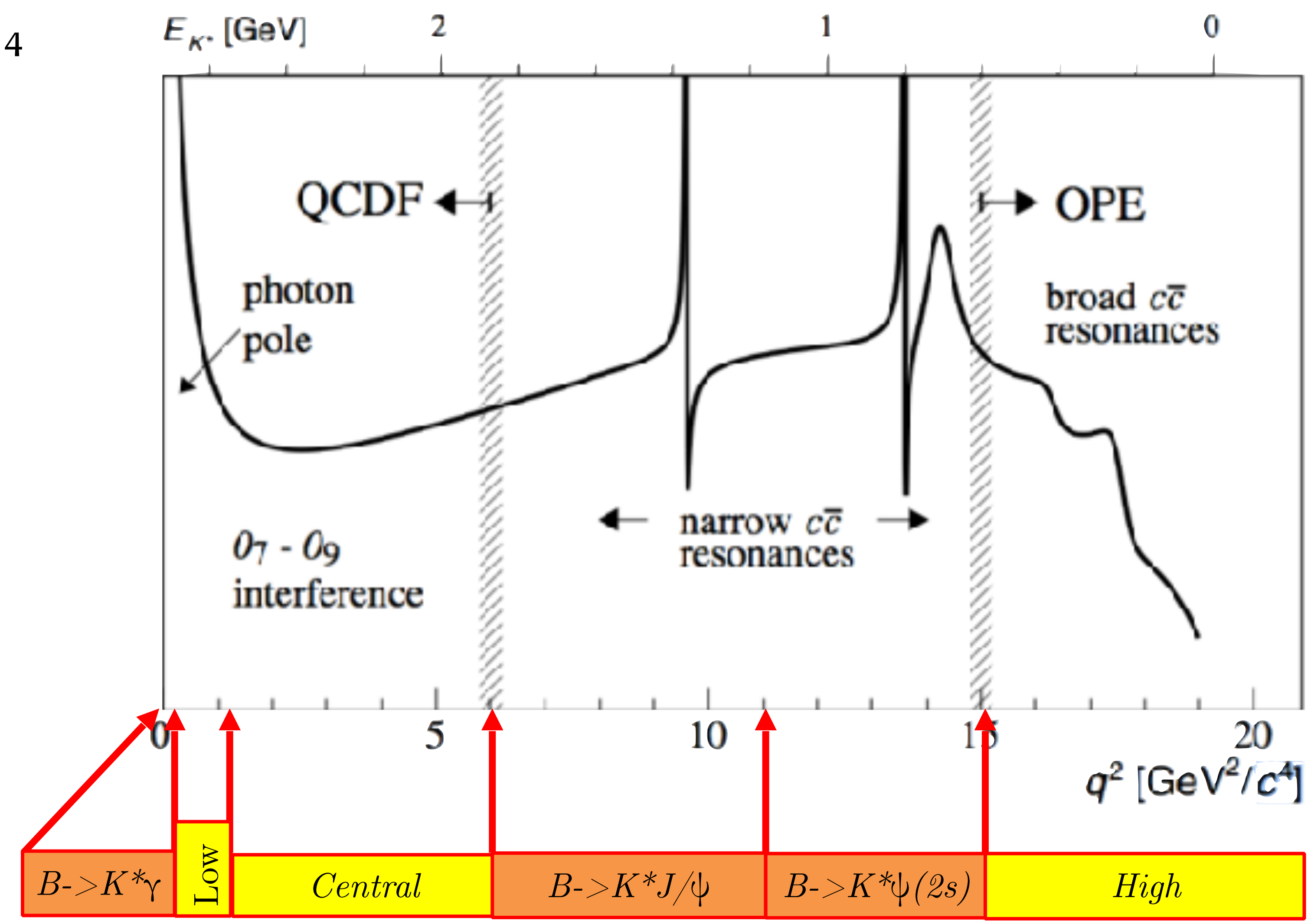
Summary and Outlook

- LFU tests are powerful probes for new physics
    - Anomalies observed in both tree- and loop-level semileptonic B decays
- All the presented measurements are based on Run1 data → 4fb-1 already on tape in Run2 + 2018 data-taking
- Many other observables useful to probe the nature of the NP: BR($B_s \to \mu\mu$), LFV searches, Λ_b decays

Backup

q^2 spectrum

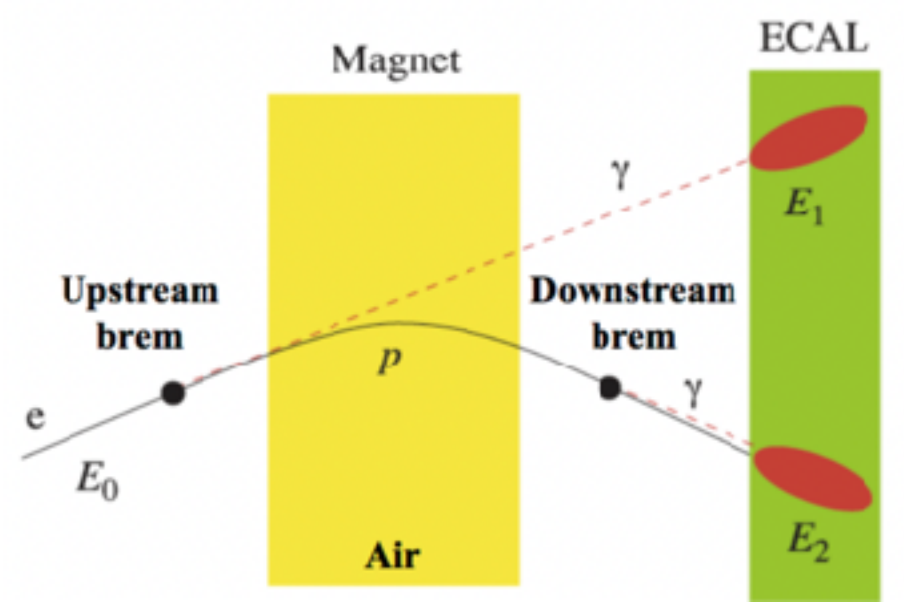
- Three q^2 regions considered:
  - Low-q^2: $0.0004 < q^2 < 1.1$ dominated by the photon pole
  - Central-q^2: $1.1 < q^2 < 6$ most interesting to observe new physics
  - High-q^2: $q^2 > 15 GeV^2/c^4$

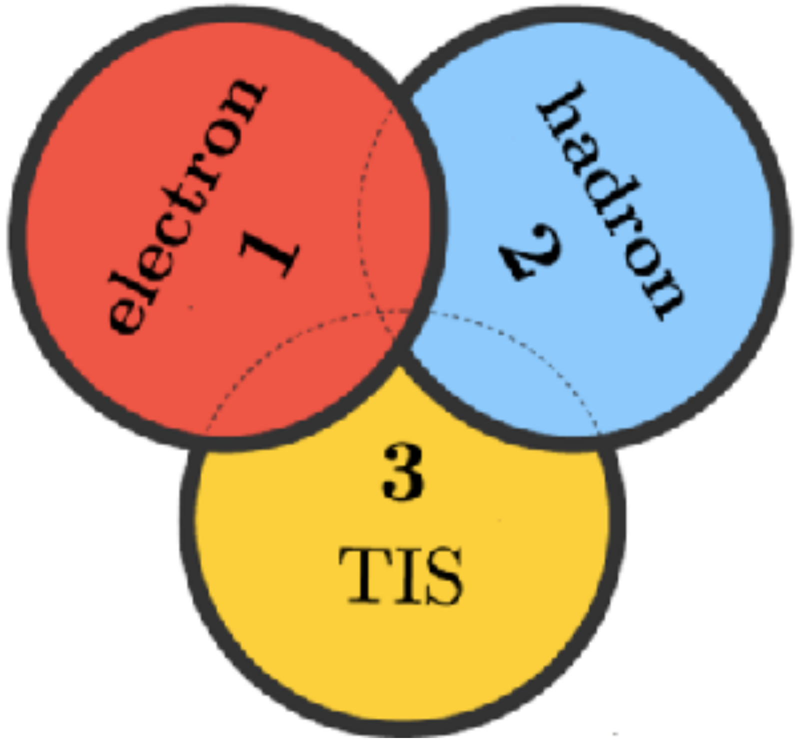


Electrons at LHCb

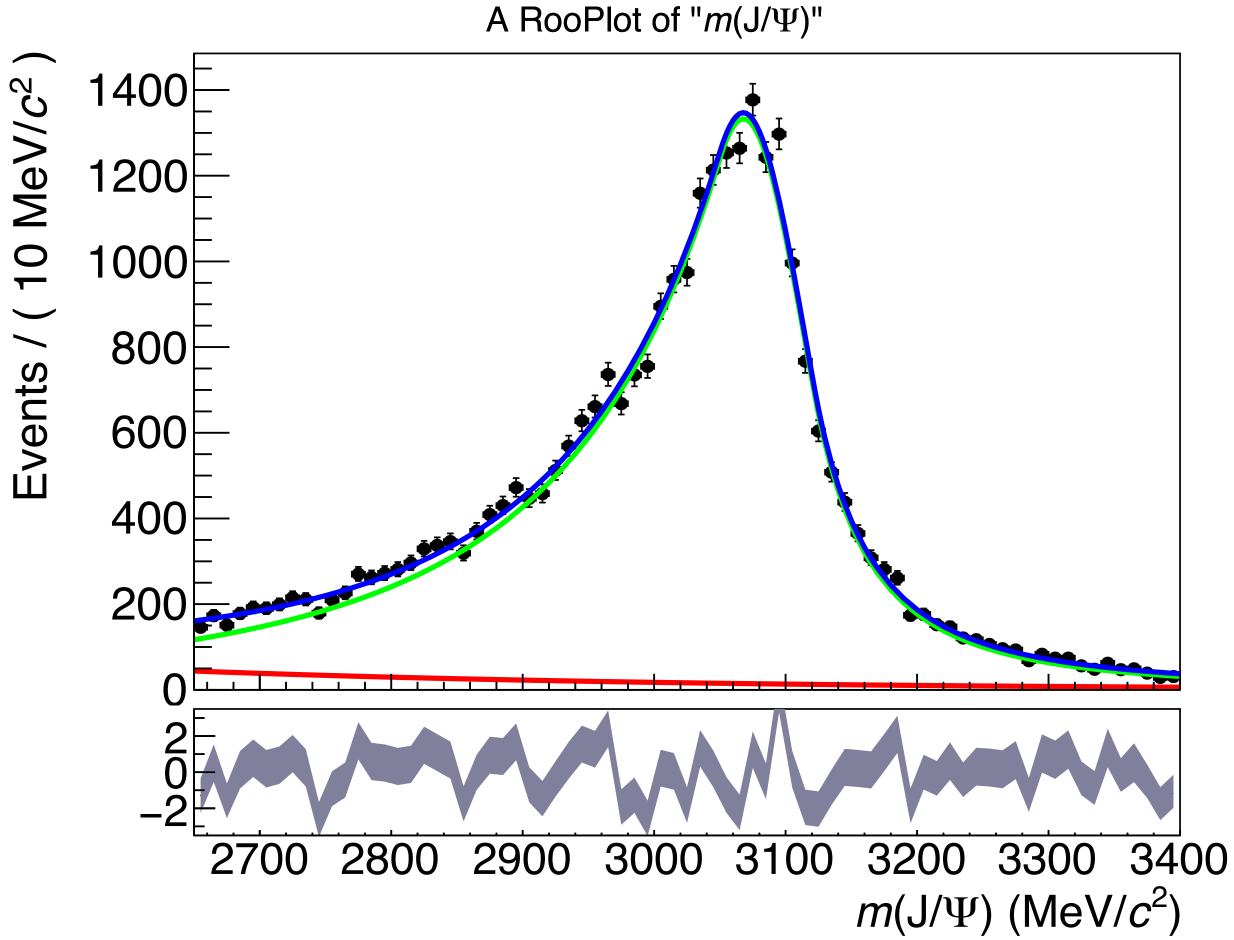
JHEP 08 (2017) 055

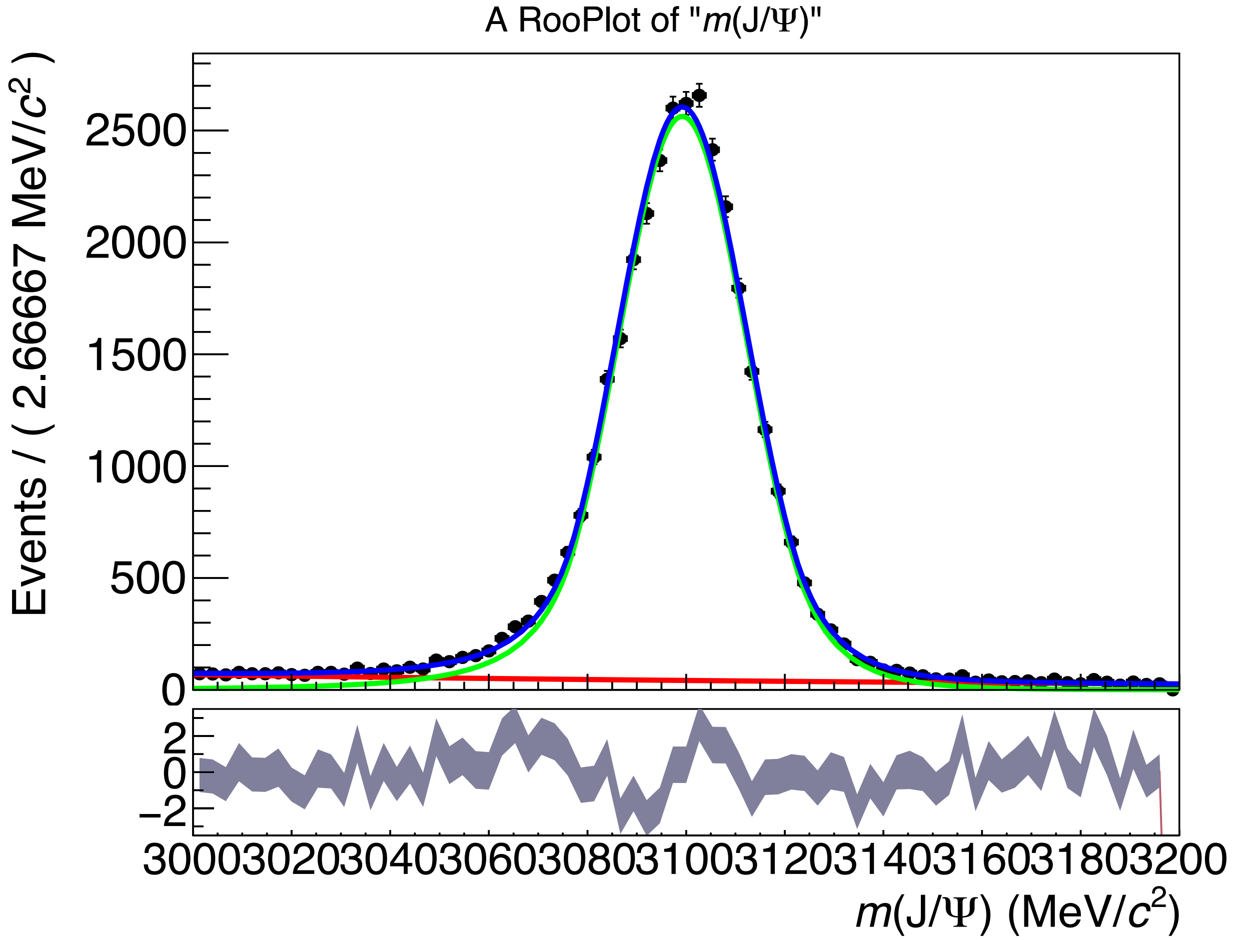
- Lepton identification is anything but universal!
- Electrons emit a large amount of bremsstrahlung, degrading momentum and mass resolution
- Recovery procedure in place for bremsstrahlung but incomplete
- energy threshold of bremsstrahlung photons ET>75 MeV, calorimeter acceptance and resolution, presence of energy deposits wrongly interpreted as bremsstrahlung clusters
- Due to higher occupancy of calorimeters, trigger thresholds are higher for electrons (~2.5 to 3.0 GeV) than for muons (~1.5 to 1.8 GeV) .
- Mitigated by selecting decays with electrons using hadron trigger either fired either by K* products (hadron) or by any other particle in the event not associated with signal (TIS)





J/psi mass resolution





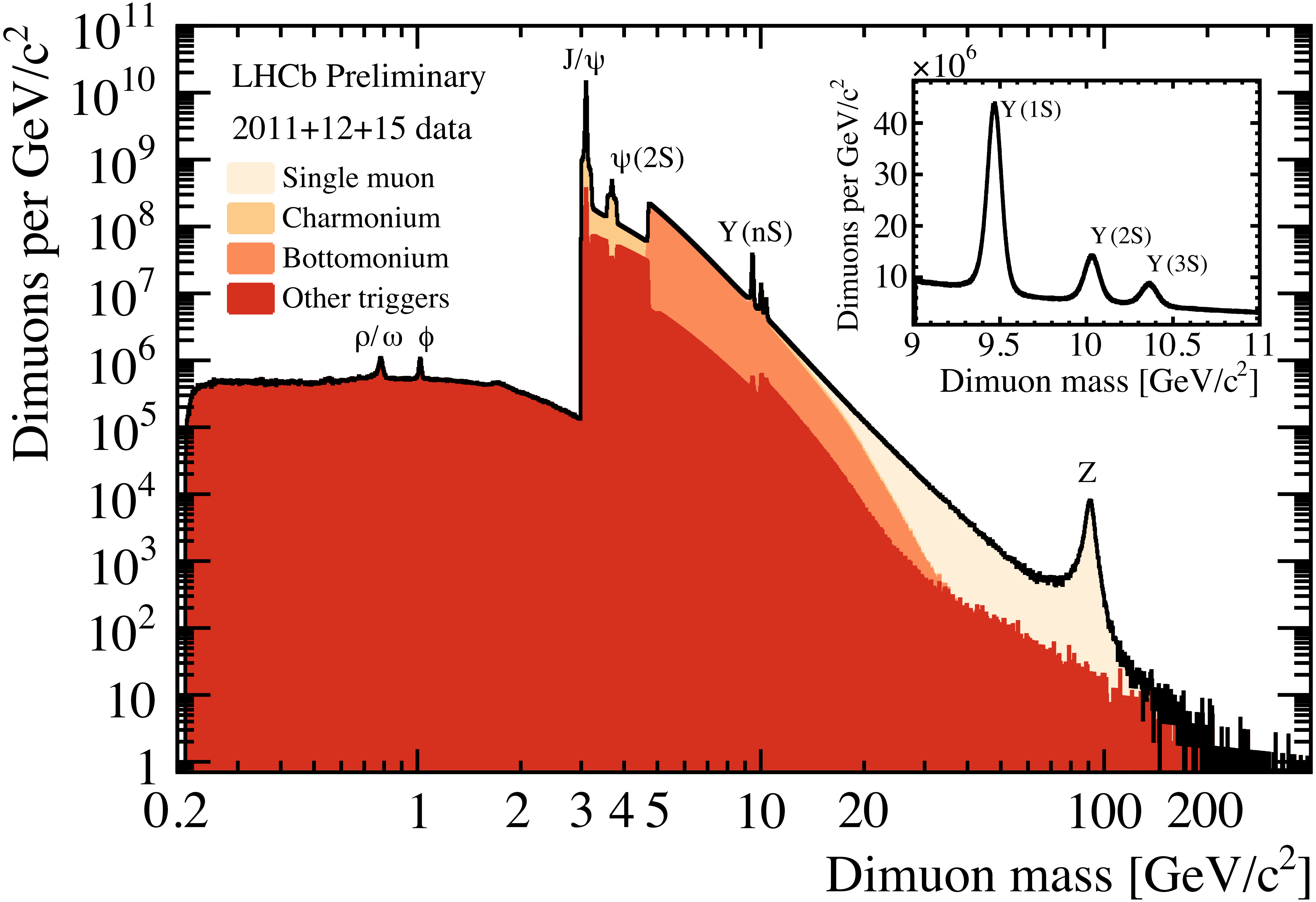
J/psi → ee

resolution ~47MeV/c2

J/psi → μμ

resolution ~13MeV/c2

dimuon @LHCb



LHCb Preliminary
2011+12+15 data
Single muon
Charmonium
Bottomonium
Other triggers
J/ψ
ψ(2S)
ρ/ω
ϕ
Υ(nS)
Z
Dimuons per GeV/c^2
Dimuon mass [GeV/c^2]
×10^6
Υ(1S)
Υ(2S)
Υ(3S)

Outline

- Angular analysis of B->K*μμ and B->ϕμμ -> access to variables with reduced dependency on theoretical uncertainties
- Test of LFU measuring the ratio between the decay rates of B->K*ll, cancellation of hadronic form-factors uncertainties in predictions