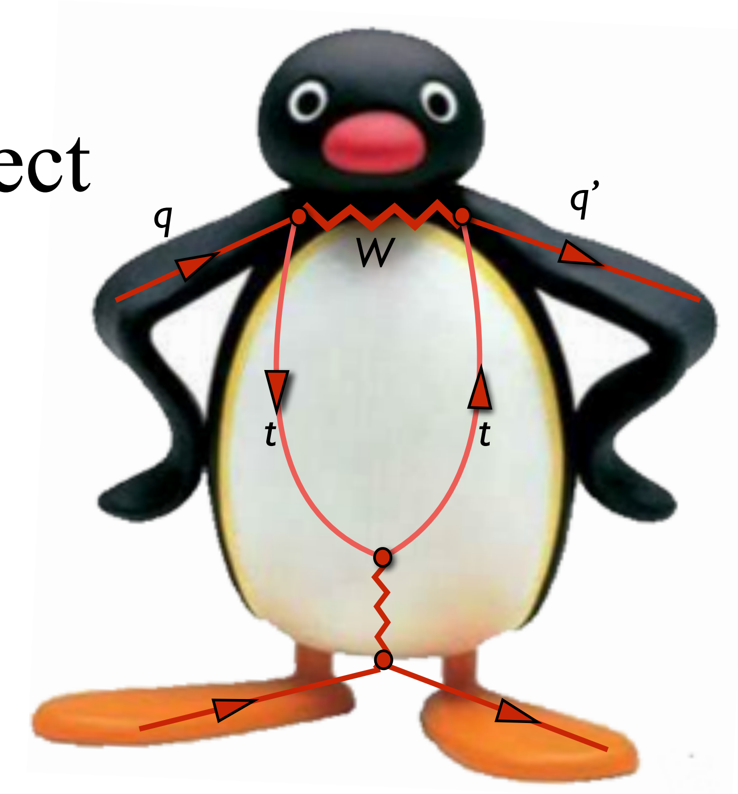
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

LHCb Rare Decays

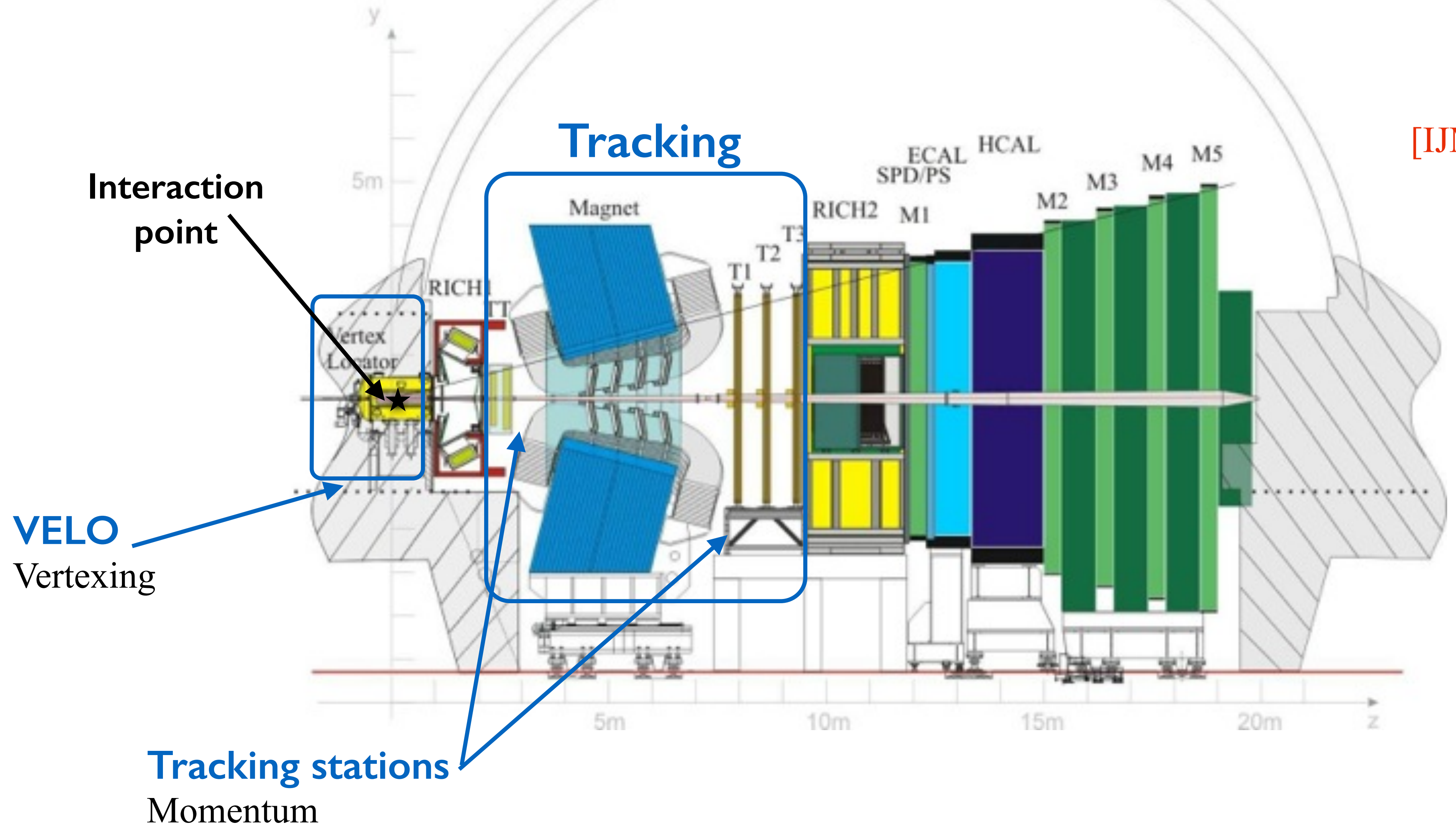
Giovanni Veneziano
on behalf of the LHCb collaboration



- Rare decays are the perfect playground for indirect searches of New Physics (NP)
  - ✓ $BR \sim 10^{-5}$ — 10^{-10} are now accessible
  - ✓ Small effects may cause substantial variations from SM expectations
- The SM relies on lepton universality
  - ✓ Non-SM Higgs-like charged scalars may couple differently to the three lepton generations
- FCNC transitions in the SM are described by loop diagrams sensitive to NP scenarios
  - ✓ Heavy virtual particles may enter the loop and affect the observables (BR, A_{CP})

- LHCb is a forward detector ($2 < \eta < 5$) designed to study *b* physics

[JINST 3 (2008) S08005]
[IJMP A 30 (2015) 1530022]



✓ Very precise vertex location $\sigma_{IP} = 20\ \mu m$

✓ Excellent tracking resolution $\Delta p/p = 0.5 - 1\ \%$

✓ Very good PID performances $\epsilon_{detection}(K) \sim 95\%(85\%)$ with $10\%(3\%)$ π misId

✓ Very efficient muon and dimuon trigger

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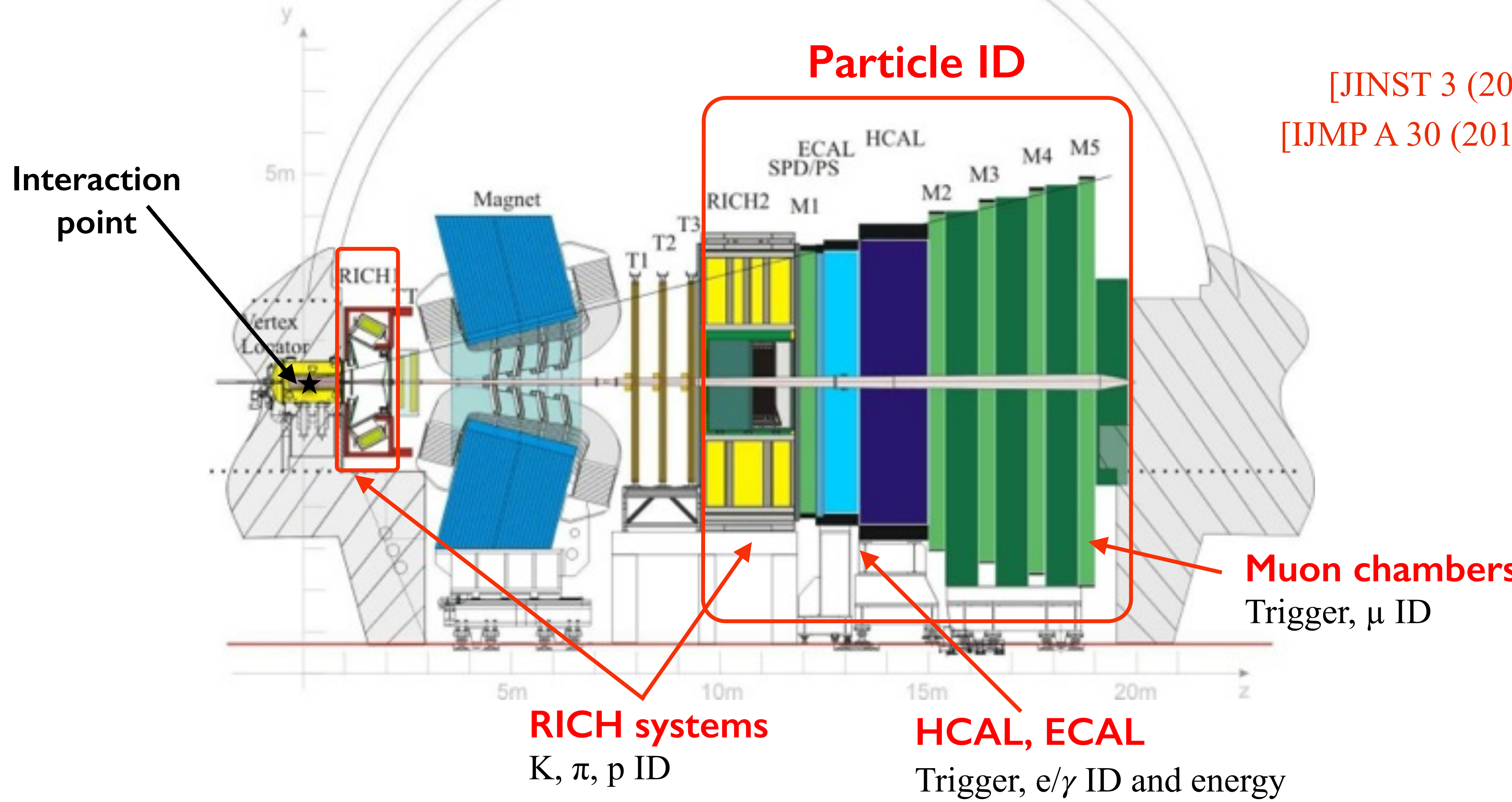

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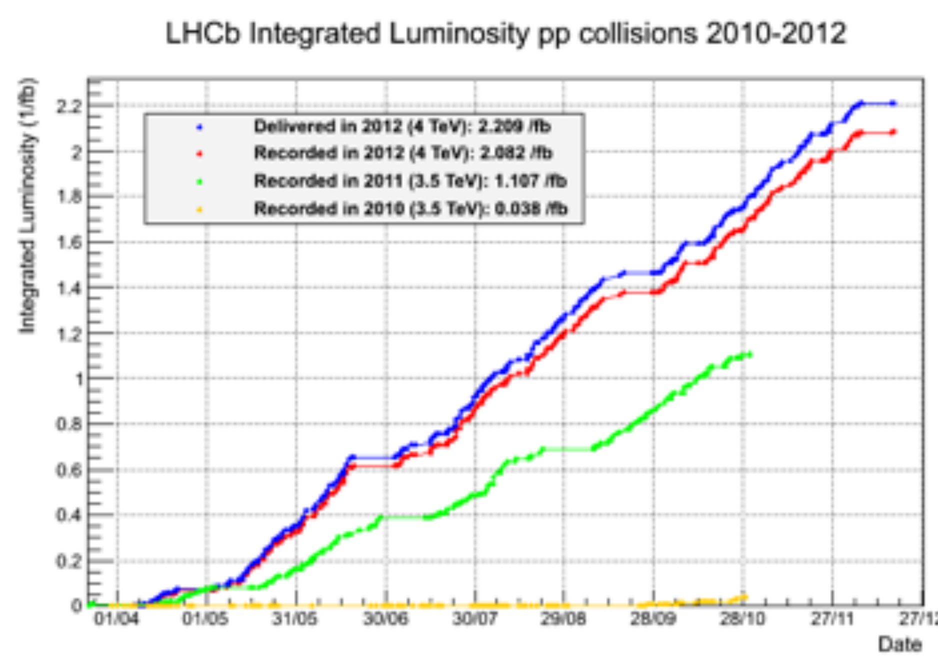

- ✓ A total luminosity of ~ 3 fb^{-1} has been recorded during LHC run I
- ✓ Run II has started

[See LHCb talks from Monday]

$B \to D^{*}\tau\nu$

Measurement of the ratio of branching fractions

$$\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$$

[arXiv:1506.08614, submitted to PRL]

$B_s \to \phi\mu\mu$

Angular analysis and differential branching fraction of the decay $B_s \to \phi\mu^+\mu^-$

[arXiv:1506.08777, to appear in JHEP]

$B \to \pi\mu\mu$

First measurement of the differential branching fraction and CP asymmetry of the $B^+ \to \pi^+\mu^+\mu^-$ decay

[LHCb-PAPER-2015-035, to be submitted to JHEP]

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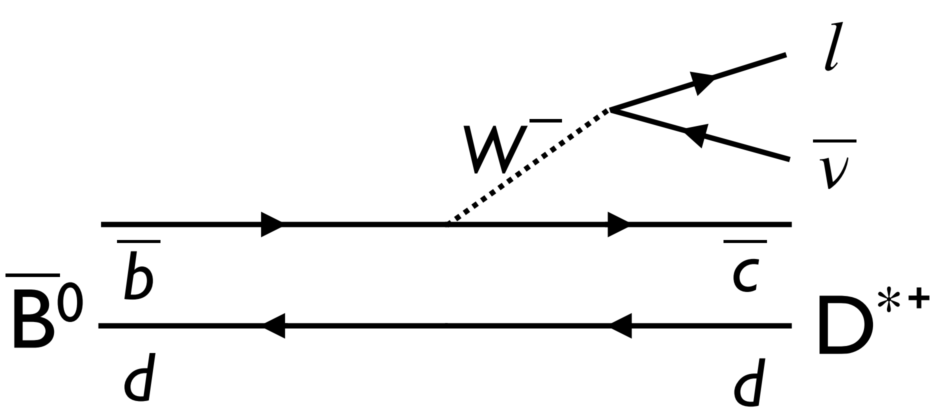
arXiv:1506.08614

B → D*τν

Motivation

- Semileptonic B decays are theoretically well understood
  - ✓ Tree level virtual W emission
  - ✓ Lepton universality implies that the *BR* for the semileptonic decays to *e*, μ and τ differ only for phase-space and helicity-suppressed contributions



$$R(D^*) = \frac{\mathcal{BR}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{BR}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$

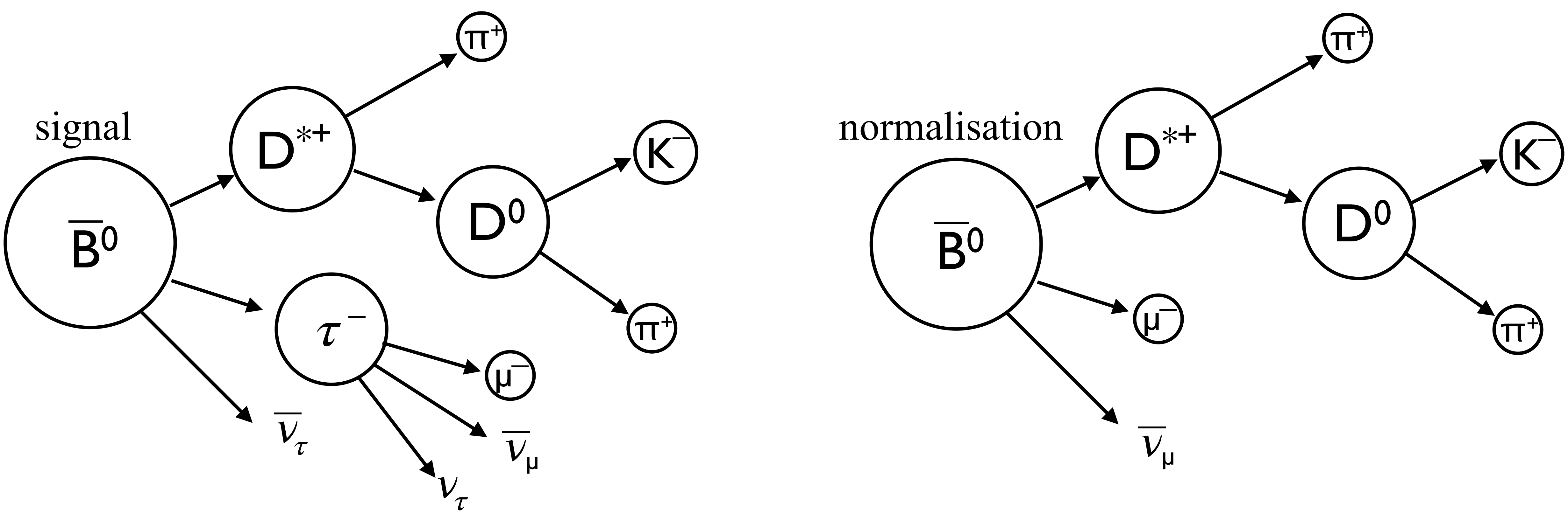
- R(D*) provides a test for lepton universality
  - ✓ Sensitive to non-SM particles coupling to third generation fermions (*e.g.* charged Higgs) [M. Tanaka, Z Phys C67 (1995) 321]
  - ✓ Form factor uncertainties cancellation
  - ✓ First measurement of R(D*) at a hadron collider

arXiv:1506.08614

B → D*τν

Analysis strategy

- Look for $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$
  - ✓ Signal and normalisation channel have the same visible final state
  - ✓ Same reconstruction and selection applied
  - ✓ Signal and normalisation channels are distinguished from the different kinematics



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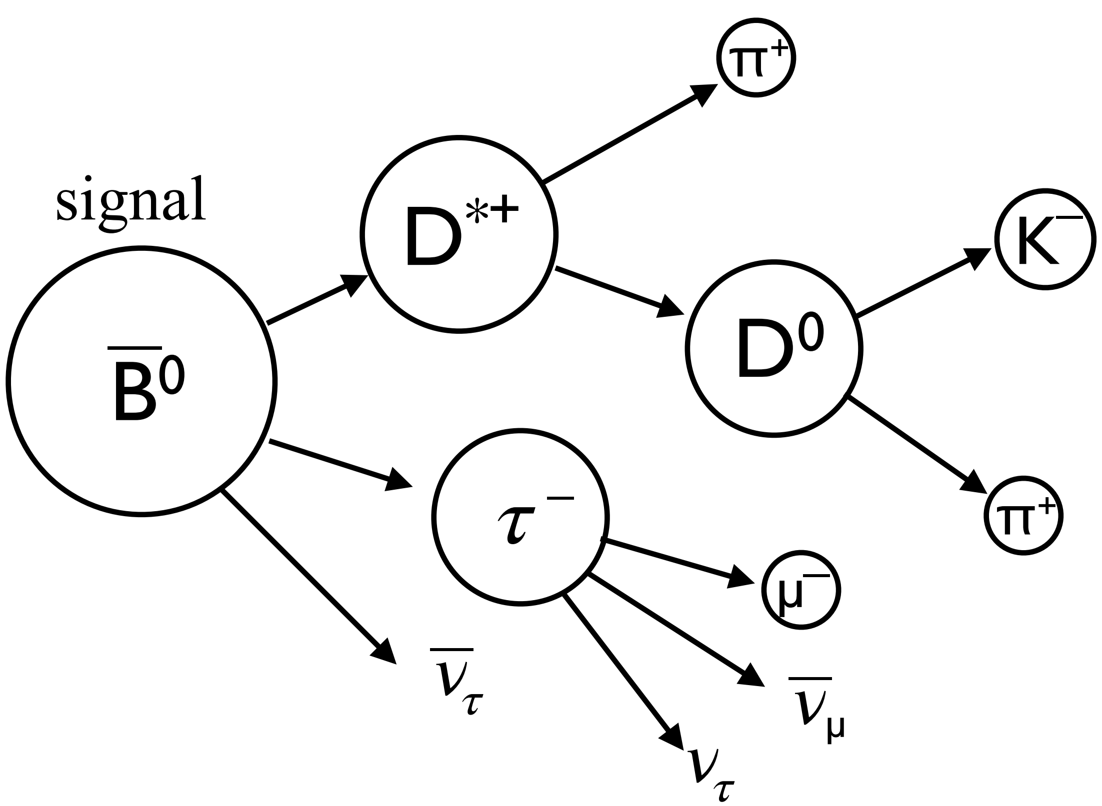


- For the signal in the B rest frame
  - ✓ $m^2_{\rm miss}$ is larger
  - ✓ The q^2 spectrum starts at m^2_τ
  - ✓ E^*_μ spectrum is softer

$$m^2_{\rm miss} = (p^\mu_B - p^\mu_{D^*} - p^\mu_\mu)^2$$

$$q^2 = (p^\mu_B - p^\mu_{D^*})^2$$

E^*_μ is the muon energy

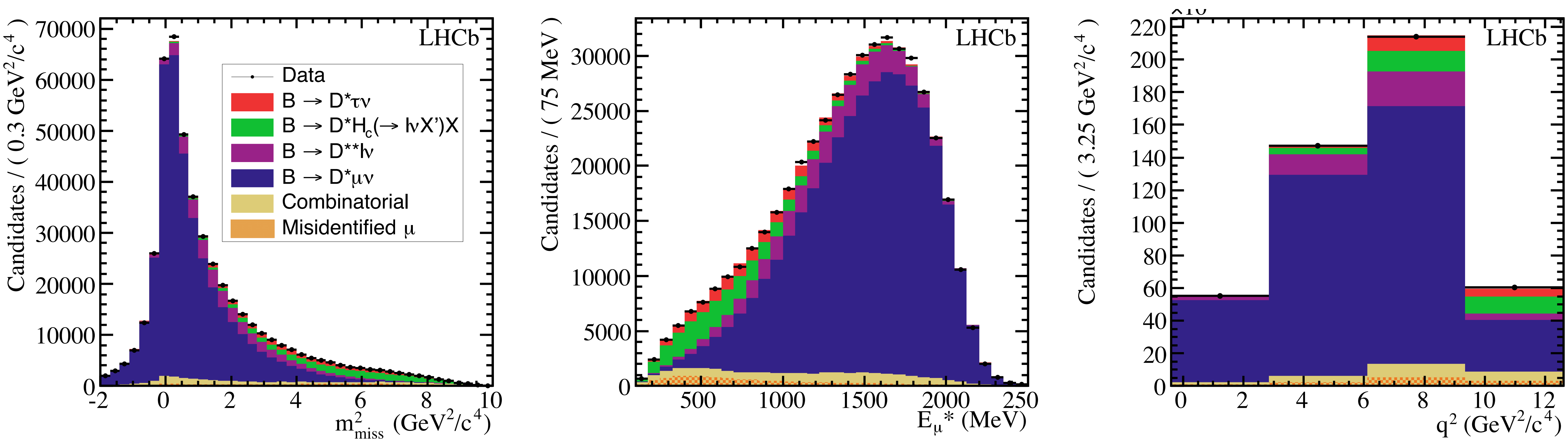
arXiv:1506.08614

B → D*τν

Results

- The projections of the multidimensional maximum likelihood fit are shown
  - ✓ Signal is suppressed wrt normalisation because of phase-space and $\mathcal{BR}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau) \sim 17\%$

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



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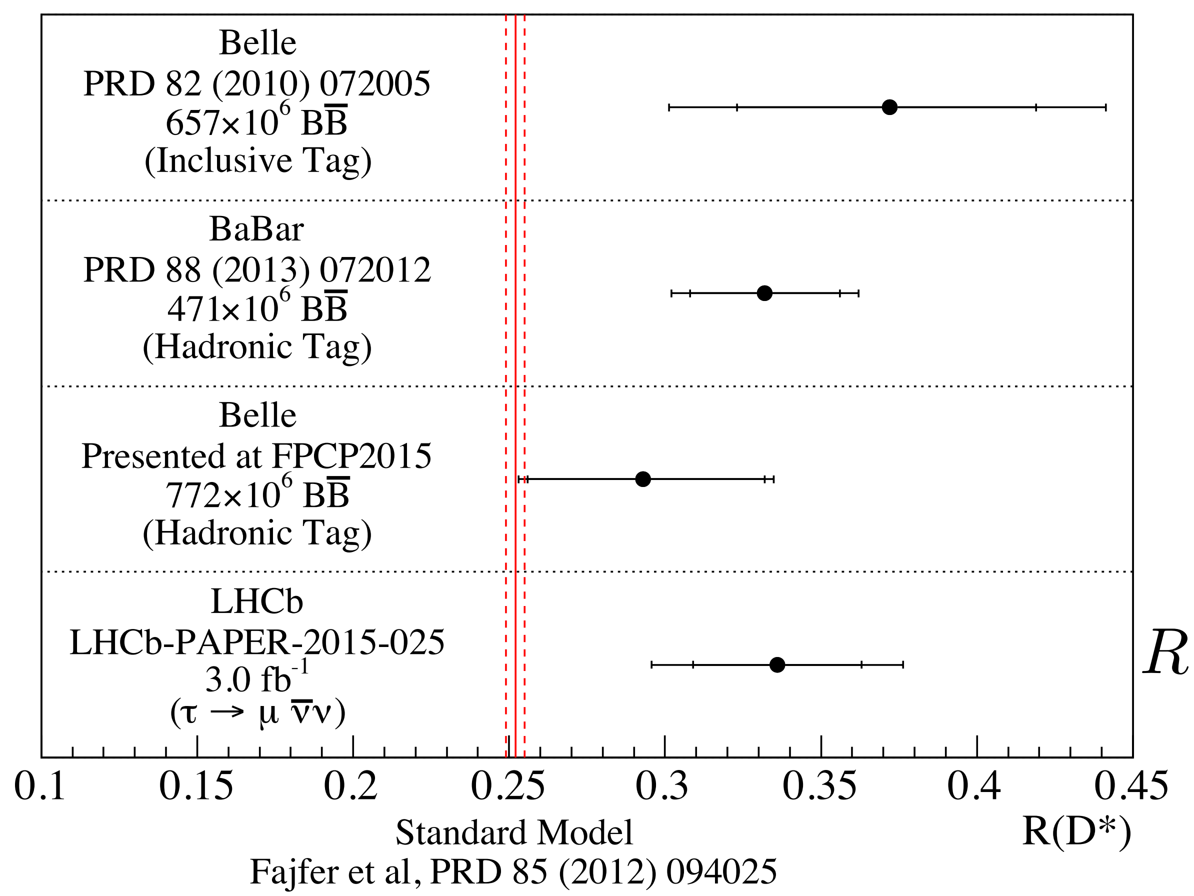

✓ Compatible with the B-factories

✓ 2.1 σ tension with the SM prediction !

$$R(D^*)_{\text{HFAG average}} = 0.322 \pm 0.018(stat) \pm 0.012(syst)$$

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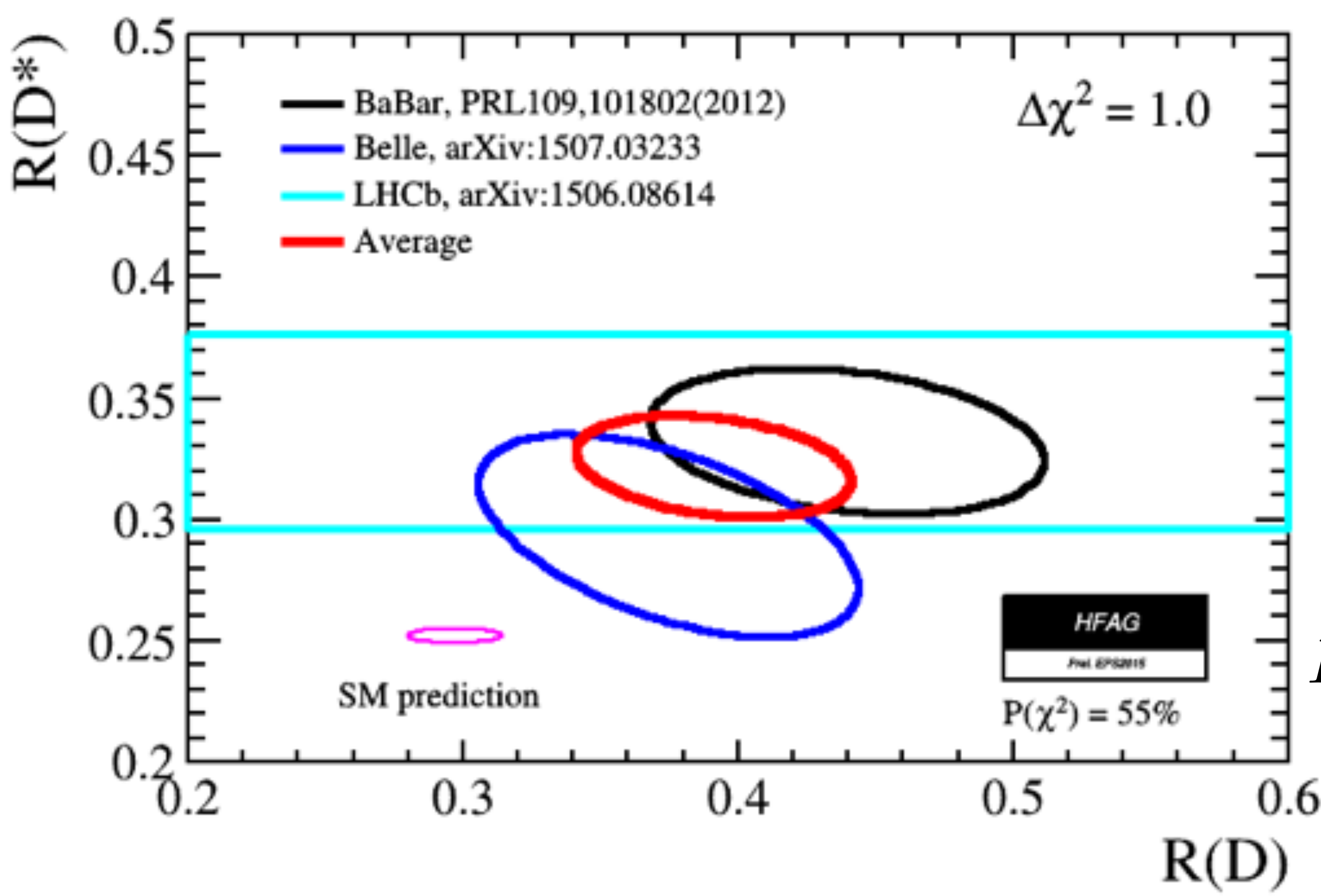

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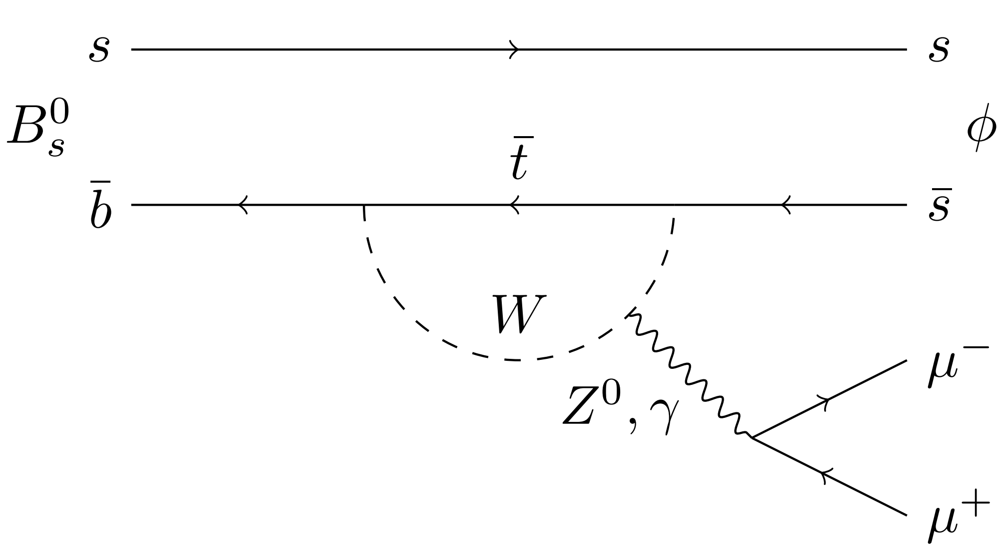
Angular analysis and differential branching fraction of the decay $B_s^0 \to \phi\mu^+\mu^-$

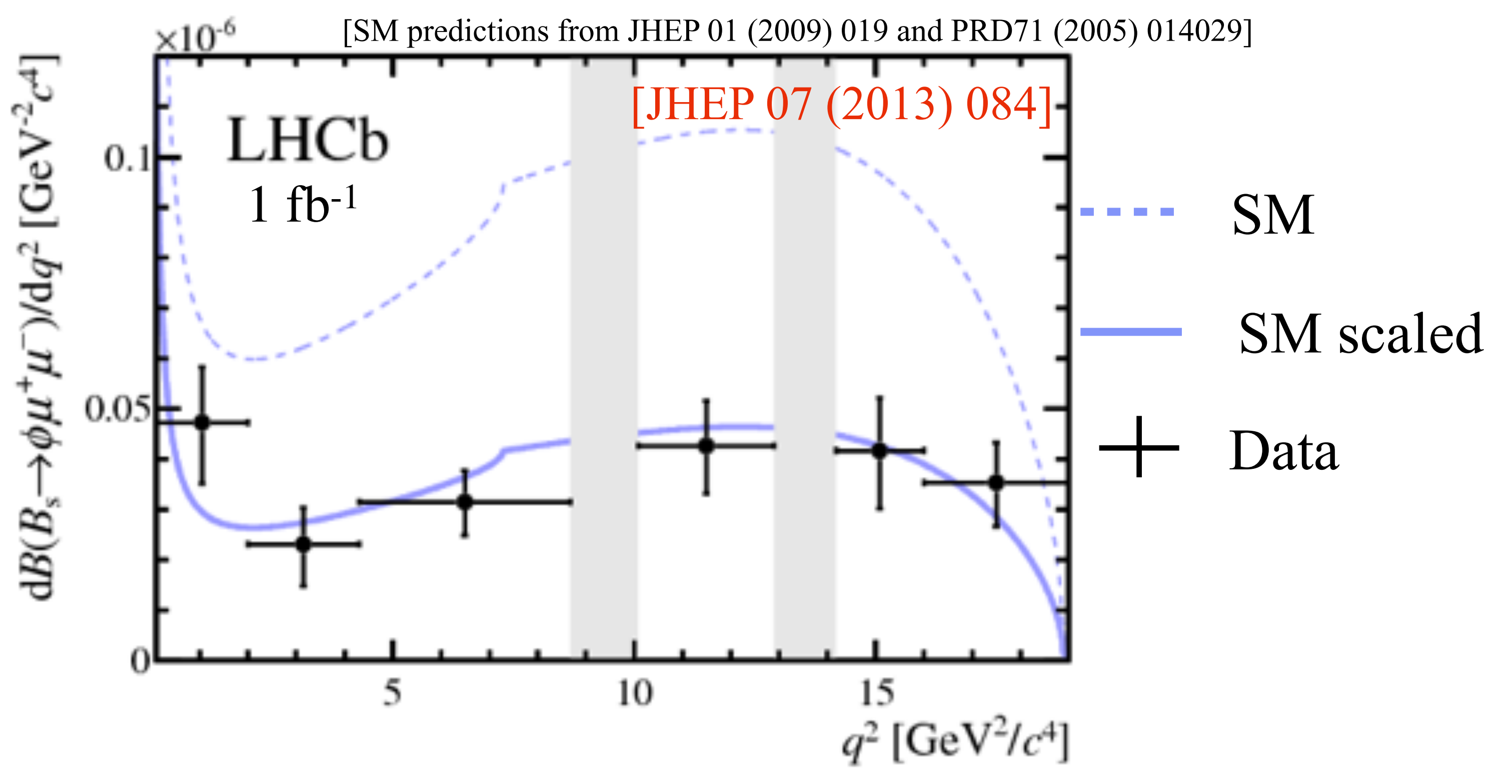
arXiv:1506.08777

$B_s \to \phi\mu\mu$

Motivation

- FCNC b → s transitions sensitive to new physics effects
  - ✓ Branching fraction significantly lower than SM predictions observed in 2011 data (1 fb^{-1})
  - ✓ Same trend observed in other b → sμμ transitions (*e.g.* $B_s \to K^*\mu^+\mu^-$)
  - ✓ 3 fb^{-1} update





arXiv:1506.08777

$B_s \to \phi\mu\mu$

Branching fraction

- The analysis is performed in bins of dimuon invariant mass q^2
  - ✓ Charmonium background decays can be vetoed
    $q^2 \notin [8, 11]\ \mathrm{GeV}^2/c^4$ and $q^2 \notin [12.5, 15]\ \mathrm{GeV}^2/c^4$
- The branching fraction in a q^2 bin is obtained from

$$\frac{\mathrm{d}\mathcal{BR}(\mathrm{B_s} \to \phi\mu\mu)}{\mathrm{dq}^2} = \frac{1}{q^2_{\mathrm{max}} - q^2_{\mathrm{min}}} \times \frac{N_{\phi\mu\mu}}{N_{\phi J\psi}} \times \frac{\epsilon_{\phi J\psi}}{\epsilon_{\phi\mu\mu}} \times \mathcal{BR}(B_s \to \phi J/\psi) \times \mathcal{BR}(J/\psi \to \mu\mu)$$

  - ✓ $\mathrm{B_s} \to \phi\, J/\psi$ is used as normalisation channel
  - ✓ BR($J/\psi \to \mu\mu$) from PDG
  - ✓ relative efficiencies from simulation

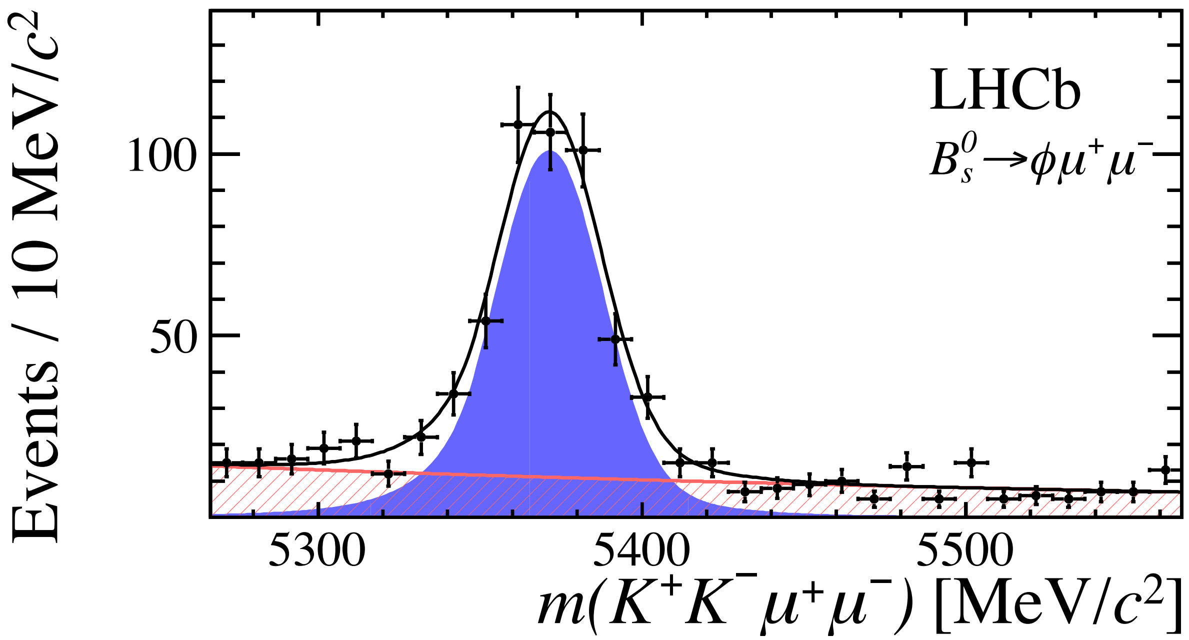
- Yields determined from an unbinned maximum likelihood fit to $m_{\mathrm{B_s}}$

arXiv:1506.08777

$B_s \to \phi\mu\mu$

Branching fraction

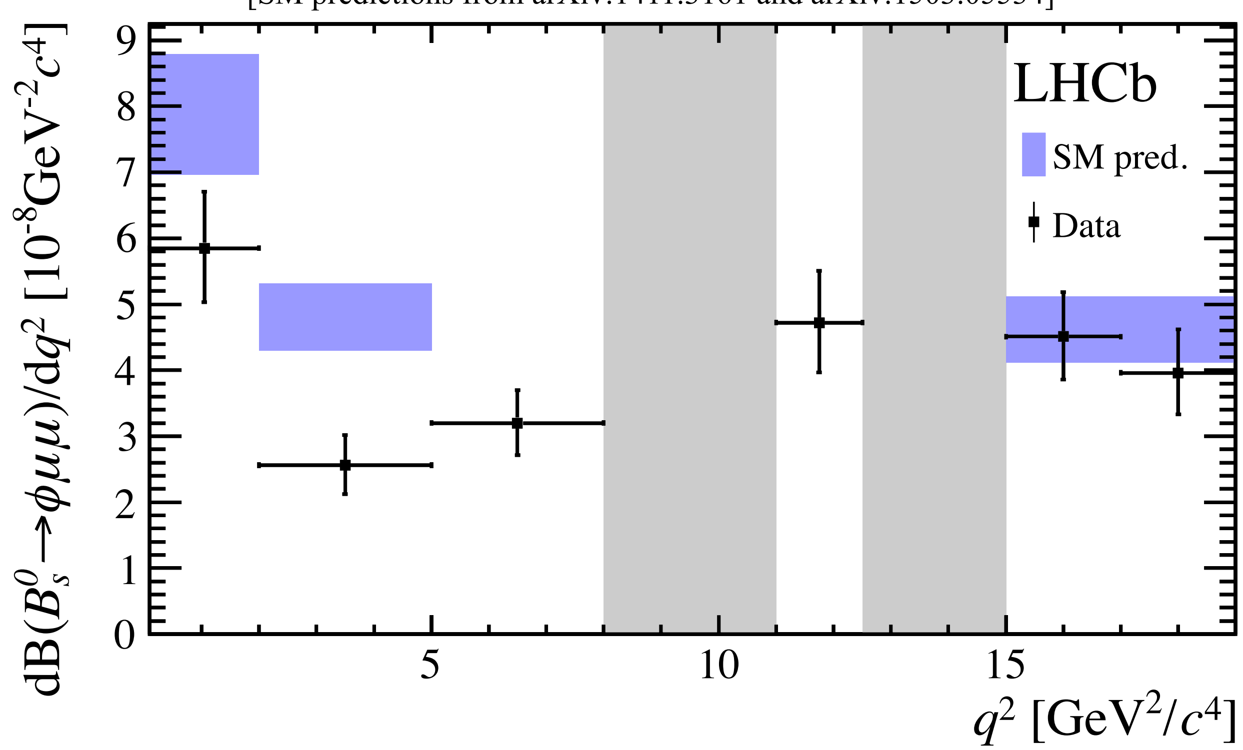
- The mass fit integrated over all the q^2 bins is shown



$$\frac{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to J/\psi\,\phi)} = (7.40^{+0.42}_{-0.40}\,_{\text{stat.}} \pm 0.16_{\text{sys.}} \pm 0.21_{\text{extrapol.}}) \cdot 10^{-4}$$

$$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (7.97^{+0.45}_{-0.43}\,_{\text{stat.}} \pm 0.18_{\text{sys.}} \pm 0.23_{\text{extrapol.}} \pm 0.60_{J/\psi\,\phi}) \cdot 10^{-7}$$

[SM predictions from arXiv:1411.3161 and arXiv:1503.05534]



✓ At low q^2 the $B_s \to \phi\mu^+\mu^-$ branching fraction is 3.5 σ below the SM

✓ New physics in C_9 ?

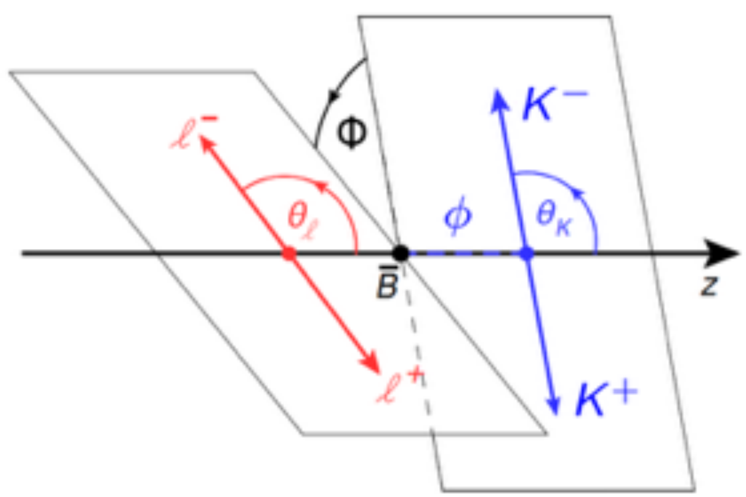
arXiv:1506.08777

$B_s \to \phi\mu\mu$

Angular analysis

- The angular analysis relies on the angles ϑ_l, ϑ_K and ϕ
  - ✓ Eight observables: CP averages (F_L, $S_{3,4,7}$) and CP asymmetries ($A_{5,6,8,9}$)

$$\frac{1}{d\Gamma/dq^2}\frac{d^3\Gamma}{d\cos\theta_l\, d\cos\theta_K\, d\Phi} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_l - F_L\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\Phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\Phi + A_5\sin 2\theta_K\sin\theta_l\cos\Phi + A_6\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\Phi + A_8\sin 2\theta_K\sin 2\theta_l\sin\Phi + A_9\sin^2\theta_K\sin^2\theta_l\sin 2\Phi\Big].$$



[C. Bobeth *et al.*, JHEP 07 (2008) 106]

  - ✓ More than in $K^*\mu\mu$ because $\phi\mu^+\mu^-$ is not flavour-tagged
  - ✓ The asymmetries A_8 and A_9 are zero in the SM, and expected to be sensitive to new physics

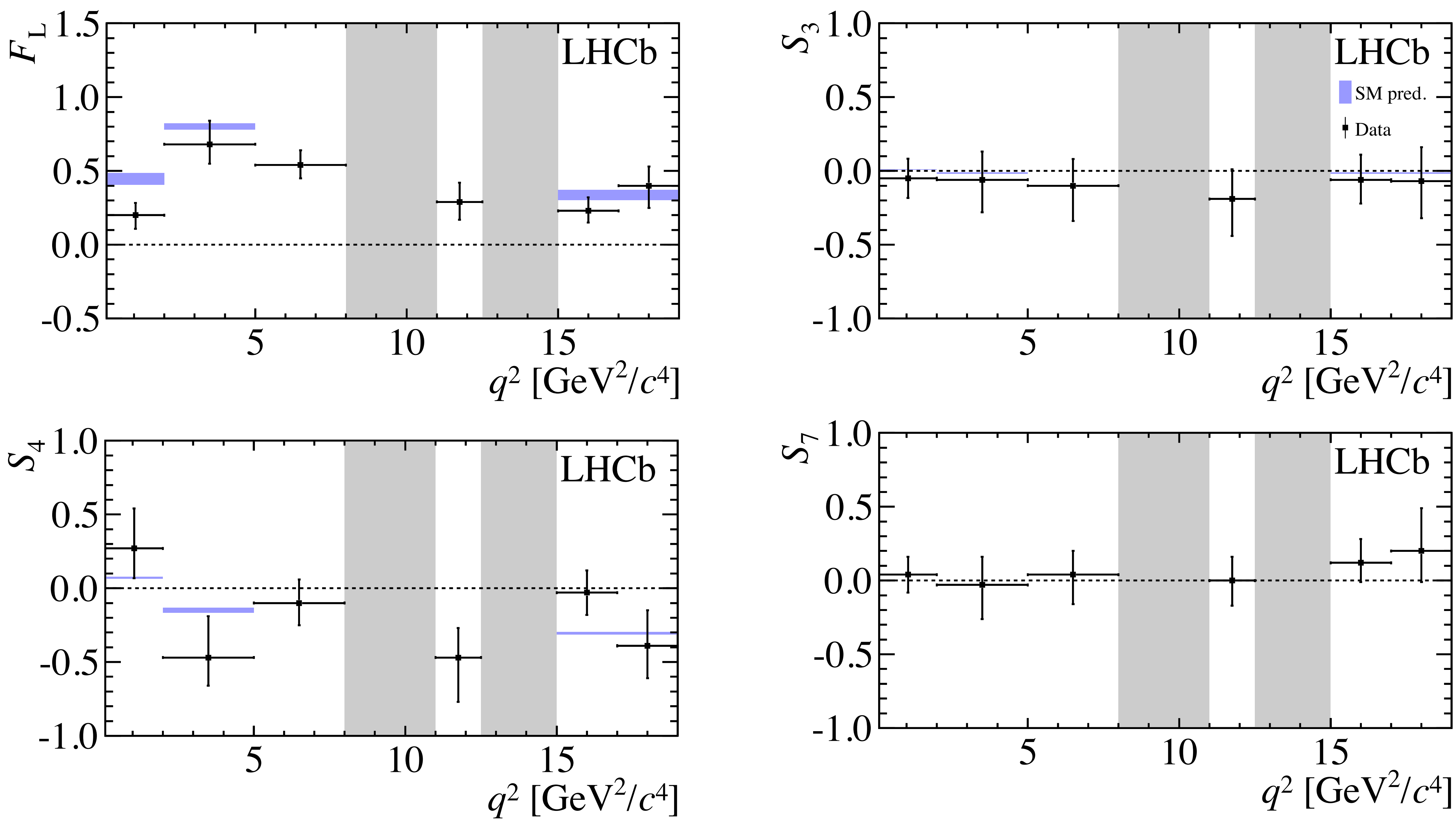
- 3D maximum likelihood fit in bins of q^2

arXiv:1506.08777

$B_s \to \phi\mu\mu$

Angular analysis

- The observables are in agreement with the SM



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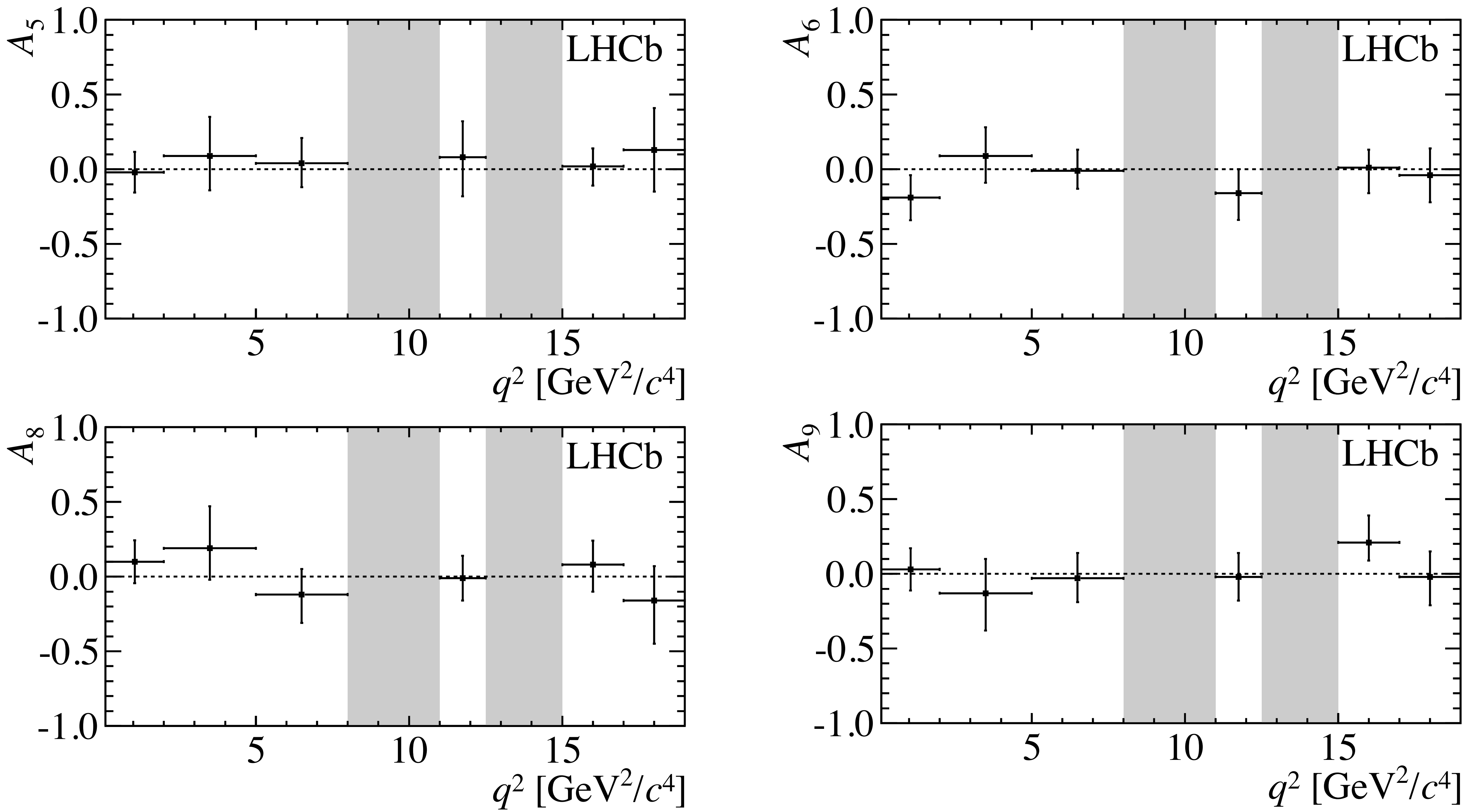


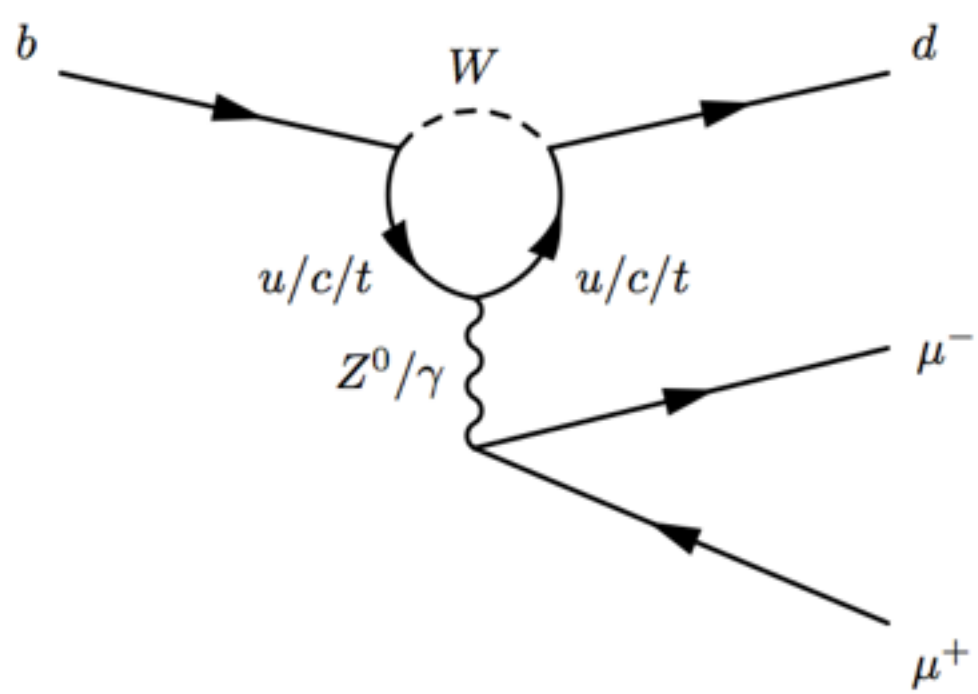
First measurement of the differential branching fraction and CP asymmetry of $B^+ \to \pi^+\mu^+\mu^-$

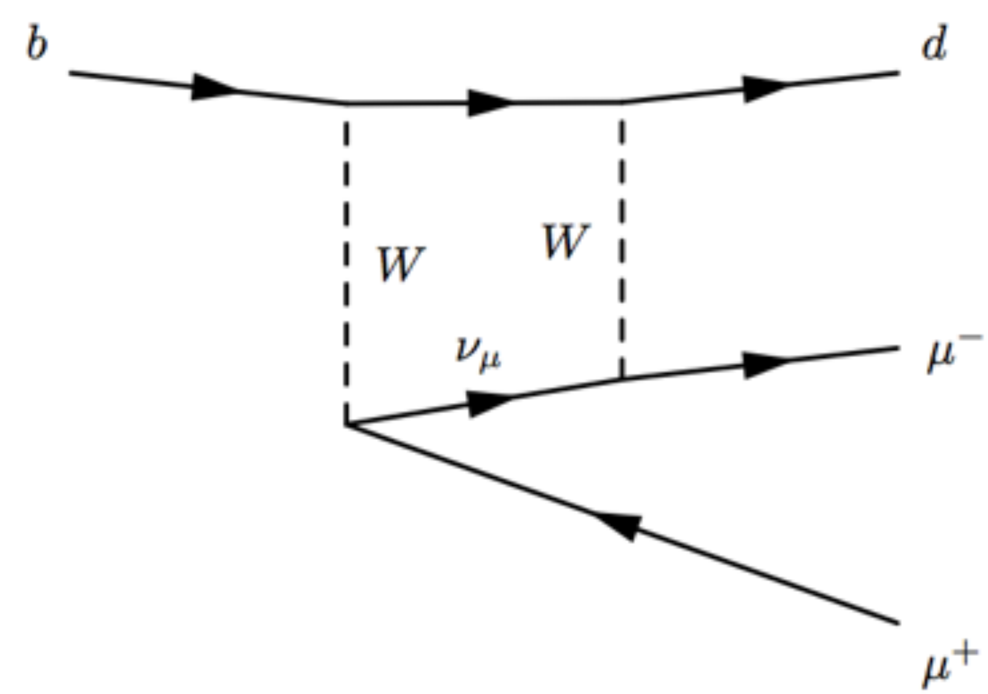
LHCb-PAPER-2015-035

B → πμμ

Motivation

- FCNC b → d transition, sensitive to new physics effects
  - ✓ Measurements of the differential branching fraction in q^2 bins
  - ✓ Computation of CKM elements $|V_{td}|$, $|V_{ts}|$ and their ratio
  - ✓ First A_{CP} measurement in a b → d transition
  - ✓ 3 fb^{-1} update on the branching fraction





LHCb-PAPER-2015-035

Branching fraction

$B \to \pi\mu\mu$

- The differential branching fraction in q^2 bins is evaluated
  - ✓ Charmonium background decays are vetoed

- The $\pi\mu\mu$, $K\mu\mu$ and $KJ/\psi(\to \mu\mu)$ mass distributions are fitted simultaneously
  - ✓ The branching fraction is determined normalising to $B \to K\, J/\psi(\to \mu\mu)$

$$\mathcal{BR}(B \to \pi\mu\mu) = \frac{N_{\pi\mu\mu}}{N_{KJ/\psi}} \times \frac{\epsilon_{KJ/\psi}}{\epsilon_{\pi\mu\mu}} \times \mathcal{BR}(B_s \to KJ/\psi) \times \mathcal{BR}(J/\psi \to \mu\mu)$$

  - ✓ The $B \to K\mu\mu$ normalisation channel is used to determine $|V_{td} / V_{ts}|$ integrating over the form factors

$$\left|\frac{V_{td}}{V_{ts}}\right|^2 = \frac{\mathcal{BR}(B^+ \to \pi^+\mu^+\mu^-)}{\mathcal{BR}(B^+ \to K^+\mu^+\mu^-)} \times \frac{\int \mathrm{d}q^2\, \mathrm{F}_K}{\int \mathrm{d}q^2\, \mathrm{F}_\pi}$$

LHCb-PAPER-2015-035

B → πμμ

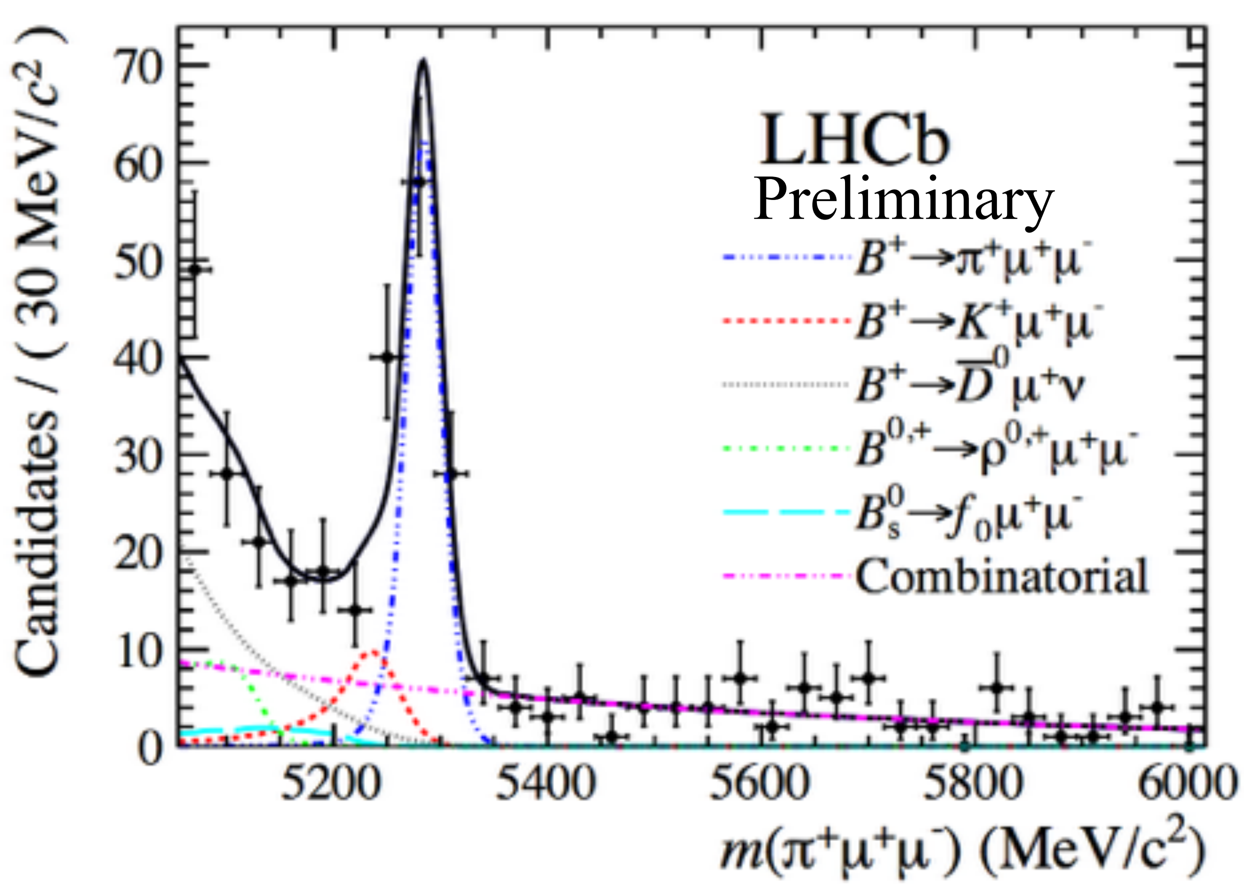
Branching fraction

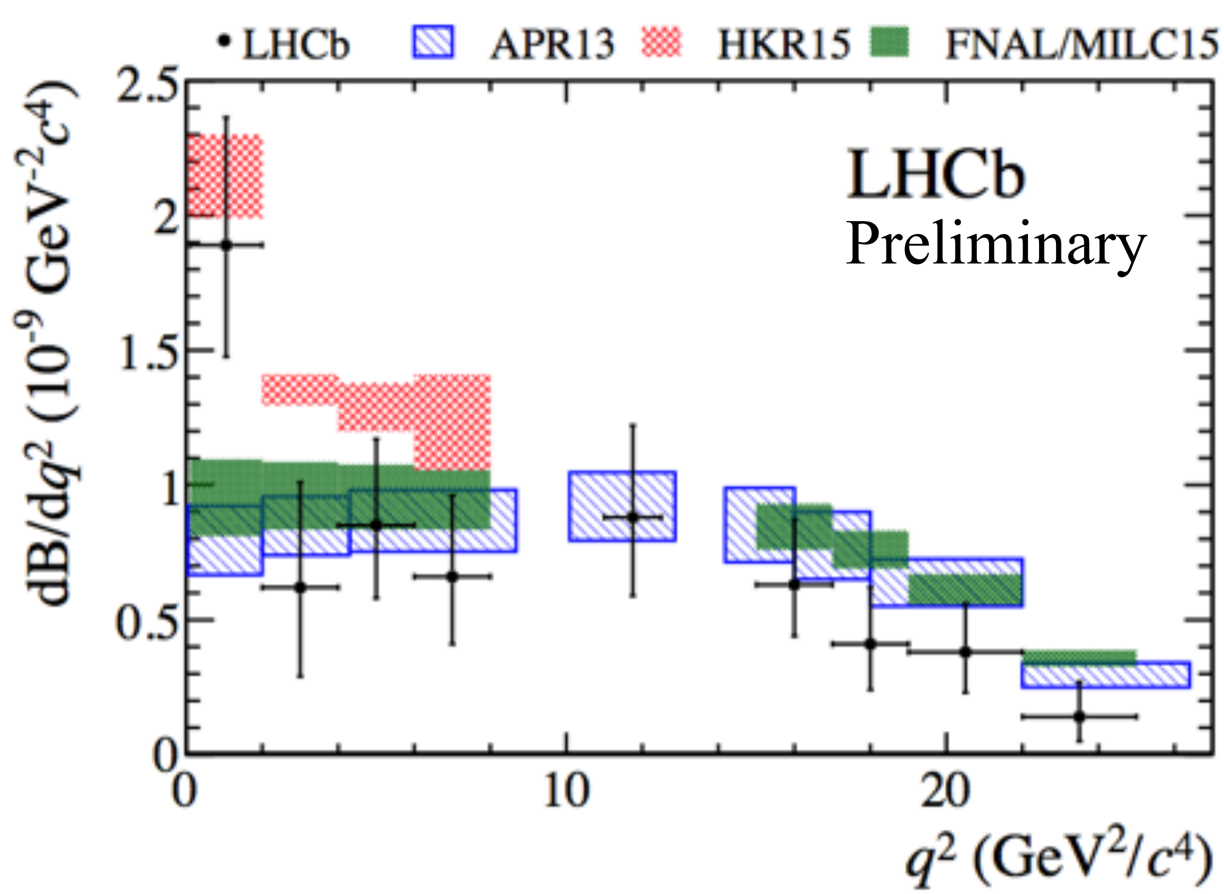
PRELIMINARY

- The branching fraction is found to be

$$\mathcal{BR}(B^+ \to \pi^+\mu^+\mu^-) = (1.83 \pm 0.24(stat) \pm 0.05(syst)) \times 10^{-8}$$

- The differential branching fraction agrees with calculations
  - ✓ The discrepancy is related to how theory models the ρ/ω region





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B → πμμ

Branching fraction

- The ratio of branching fraction BR(B→πμμ) / BR(B→Kμμ) is

$$\frac{\mathcal{BR}(B^+ \to \pi^+\mu^+\mu^-)}{\mathcal{BR}(B^+ \to K^+\mu^+\mu^-)} = \begin{cases} 0.038 \pm 0.009(stat) \pm 0.001(syst) & q^2 \in [1,6]\,\mathrm{GeV}^2/\mathrm{c}^4 \\ 0.037 \pm 0.008(stat) \pm 0.001(syst) & q^2 \in [15,22]\,\mathrm{GeV}^2/\mathrm{c}^4 \end{cases}$$

- The CKM matrix elements are extracted

PRELIMINARY

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.24^{+0.05}_{-0.04}$$

$$|V_{td}| = 7.2^{+0.9}_{-0.8} \times 10^{-3}$$

$$|V_{ts}| = 3.2 \pm 0.4 \times 10^{-2}$$

✓ Errors are statistical plus systematics

✓ Largest error contribution from theory uncertainties

LHCb-PAPER-2015-035

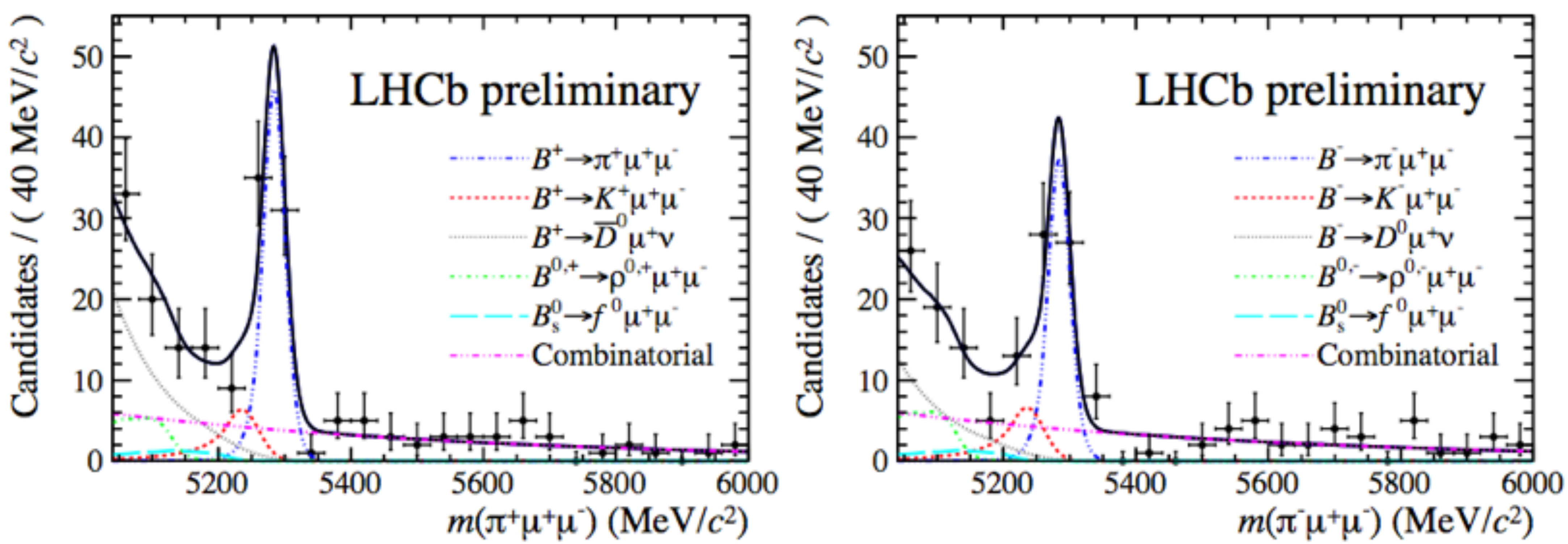
B → πμμ

CP asymmetry

- The CP asymmetry is evaluated for the first time in b → d transitions

$$A_{CP}^{\mathrm{raw}} = \frac{N(B^- \to \pi^-\mu^+\mu^-) - N(B^+ \to \pi^+\mu^+\mu^-)}{N(B^- \to \pi^-\mu^+\mu^-) + N(B^+ \to \pi^+\mu^+\mu^-)}$$

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



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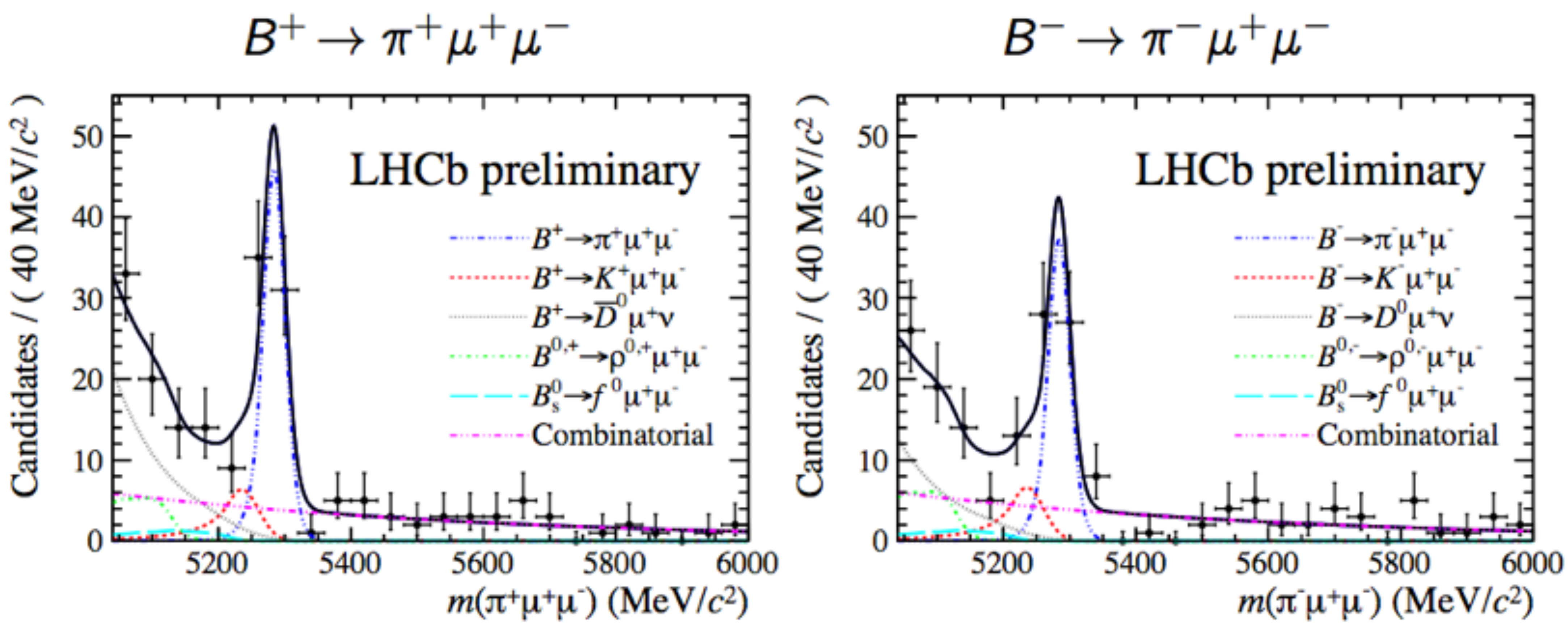
CP asymmetry

B → πμμ

- Adding the corrections for production (from B → K J/ψ) and detection asymmetry (from $D^{*+} \to \pi^+ D^0$) we obtain

$$A_{CP} = -0.11 \pm 0.12(stat) \pm 0.01(syst)$$

PRELIMINARY

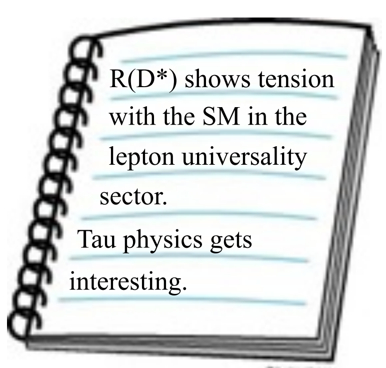


- The SM is being extensively tested at LHCb
  - ✓ many searches for new physics are ongoing
    - Dark bosons in $B^0 \rightarrow K^* \chi\ (\rightarrow \mu\mu)$
    - $B_s \rightarrow \mu\mu$ and $B_d \rightarrow \mu\mu$
    - $B \rightarrow sll$
    - $\Lambda_b \rightarrow \Lambda\mu\mu$
    - R(K)
    - LFV in $\tau \rightarrow \mu\mu\mu$
    - 4th gen majorana neutrinos in $B \rightarrow X\mu\mu$
    - … and many more

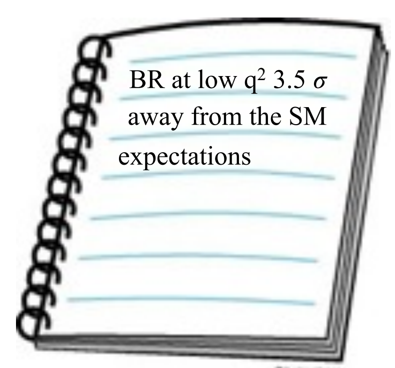
[See talk *BSM searches via rare decays in B physics* on Thursday and the other LHCb talks]

- The SM is being extensively tested at LHCb
  - ✓ many searches for new physics are ongoing
- Lots of interesting results from rare decays
  - ✓ the latest new rare decays results have been presented

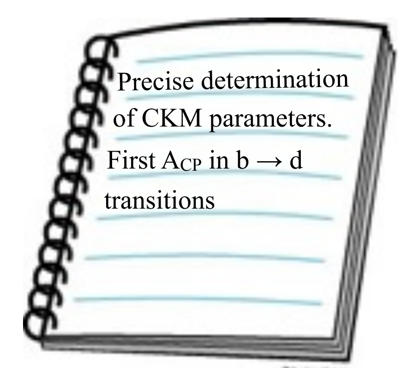
$B \to D^* \tau \nu$



$B_s \to \phi \mu \mu$



$B \to \pi \mu \mu$

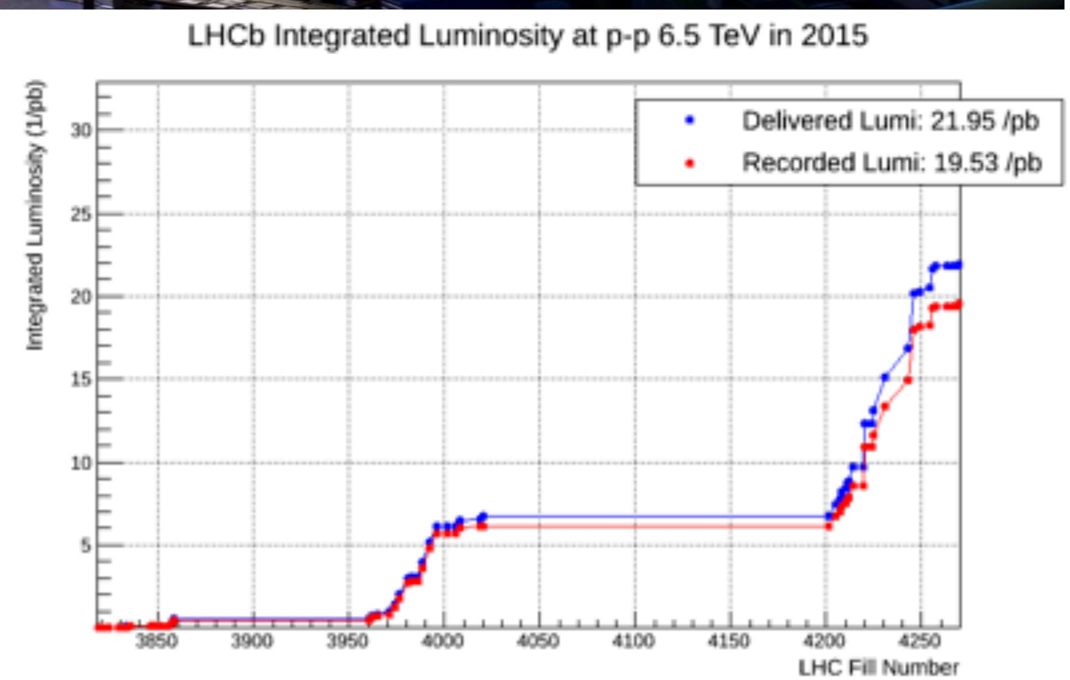


- Much more data in the near future
  - ✓ stay tuned !

Thank you for your attention

backup slides

- LHCb is a forward detector ($2 < \eta < 5$) designed to study *b* physics



✓ A total luminosity of ~ 3 fb^{-1} has been recorded during LHC run I

✓ Run II has started

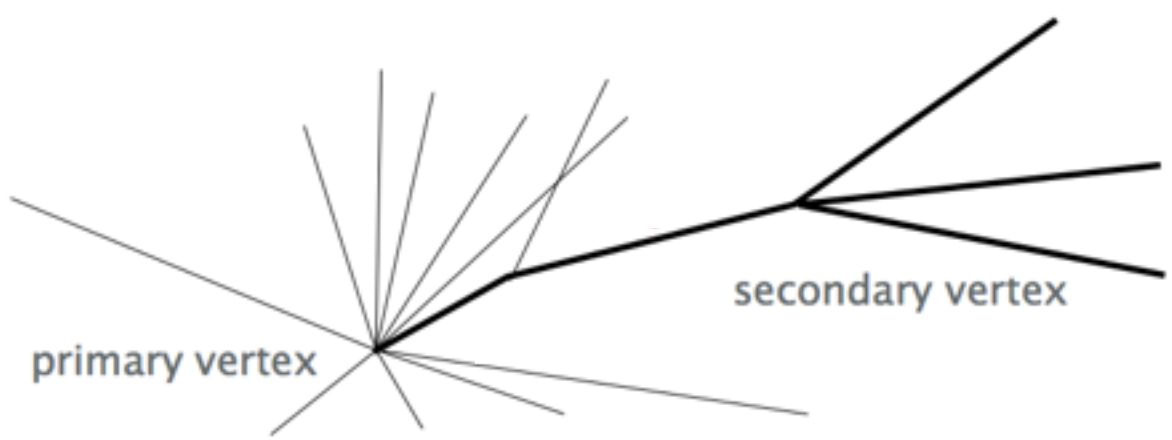
[See LHCb talks from Monday]

arXiv:1506.08614

$B \to D^*\tau\nu$

Selection

- Trigger
  - ✓ No muon p_T requirement in the trigger
  - ✓ Triggered on $D^0 \to K\pi$ with $p_T > 2$ GeV/c (tracks $p_T > 5$ GeV/c)
  - ✓ The displaced D^0 momentum must point toward a PV
- Offline selection
  - ✓ A soft charged pion is added to the D^0 to form the D^{*+} candidate
  - ✓ The muon must be away from the PV and form a good $D^{*+}\mu^-$ vertex
  - ✓ The $D^{*+}\mu^-$ momentum must point toward the PV



arXiv:1506.08614

B → D*τν

Systematics

Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

Expected to be reduced for future $R(D) + R(D^*)$

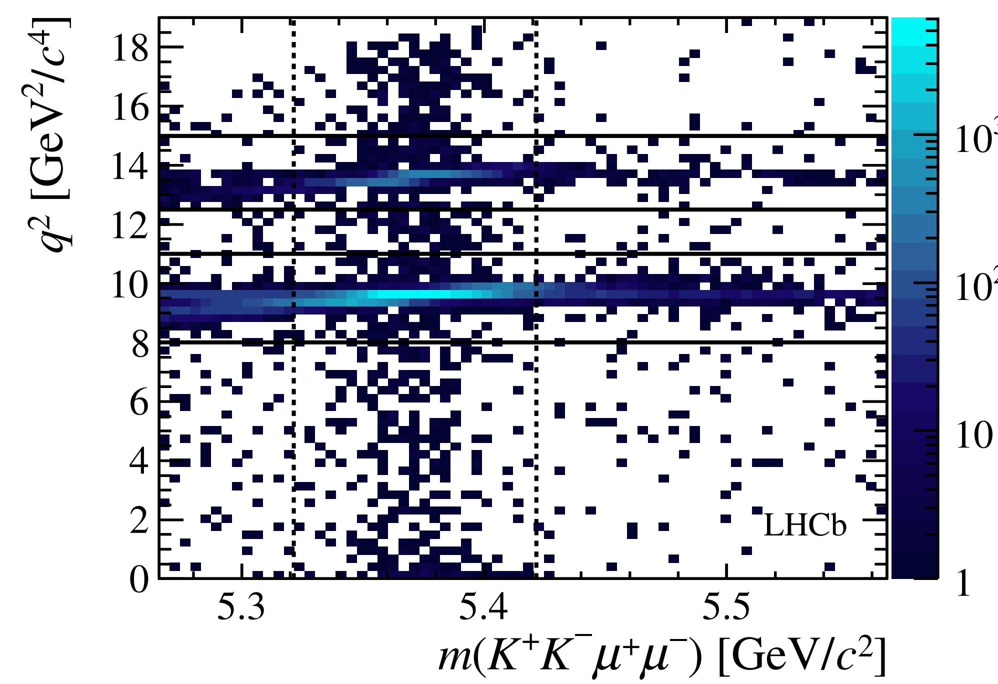
Will scale down with more data (Run2)

arXiv:1506.08777

$B_s \to \phi\mu\mu$

Selection

- Trigger
  - ✓ muon p_T requirements
  - ✓ tracks displaced and not pointing to the PV

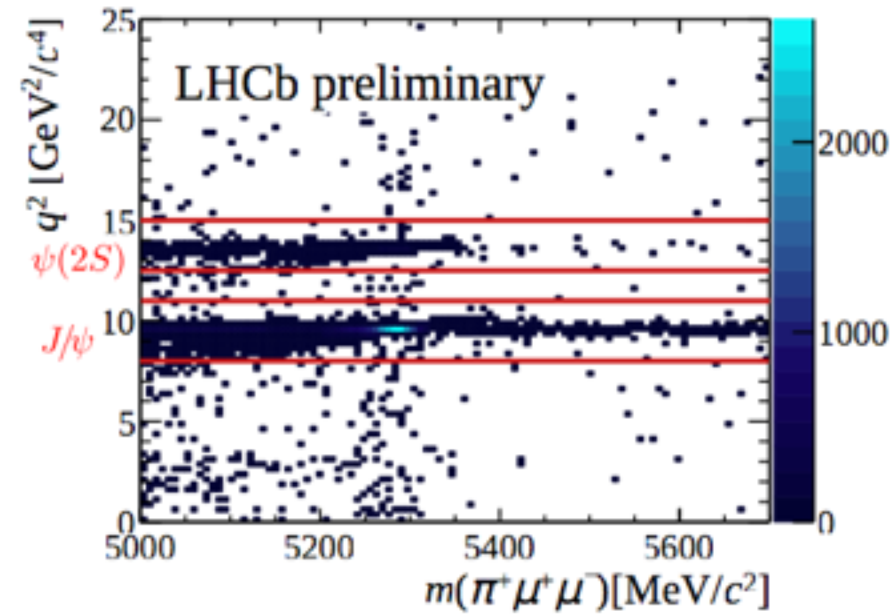


- Offline selection
  - ✓ Narrow ϕ window
  - ✓ Final state tracks must be compatible with the B_s vertex
  - ✓ Mass vetoes to reject partially reconstructed $B_s \to \phi\ J/\psi(\to \mu^+\mu^-)$, and misidentified $B^0 \to K^*\mu\mu$ and $\Lambda_b \to \Lambda\ (\to pK)\ \mu\mu$ backgrounds

- The analysis is performed in bins of dimuon invariant mass q^2
  - ✓ Charmonium background decays can be vetoed

First measurement of the differential branching fraction and CP asymmetry of $B^+ \to \pi^+\mu^+\mu^-$

$B \to \pi\mu\mu$



Selection

- Trigger
  - ✓ muon p_T requirements
  - ✓ tracks displaced and not pointing to the PV
  - ✓ Two+ of the final state particles must form a displaced vertex (SV)

- Offline selection
  - ✓ Final state tracks must be compatible with the B_s vertex
  - ✓ The B_s momentum must point to the PV
  - ✓ MVA (BDT) to remove combinatorial
  - ✓ $\pi\mu\mu$ and $K\mu\mu$ final states are distinguished after the selection by PID algorithms
  - ✓ Charmonium background decays are vetoed

$$q^2 \notin [8, 11]\ \text{GeV}^2/c^4 \quad \text{and} \quad q^2 \notin [12.5, 15]\ \text{GeV}^2/c^4$$