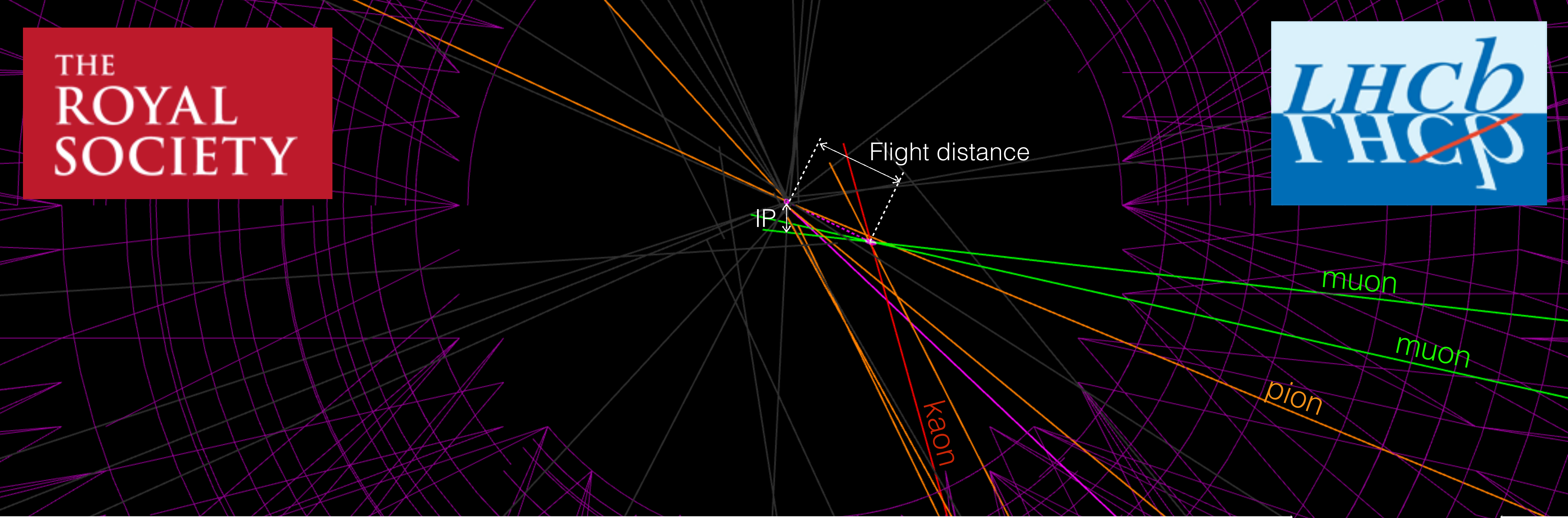

THE ROYAL SOCIETY

LHCb

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Experimental review of flavour anomalies in b-hadron decays

T. Blake for the LHCb collaboration

CKM 2018, Heidelberg

Flavour anomalies

1. $b \to s\ell^+\ell^-$ processes

   ➡ Rate and angular distribution of exclusive $b \to s\mu^+\mu^-$ decays.

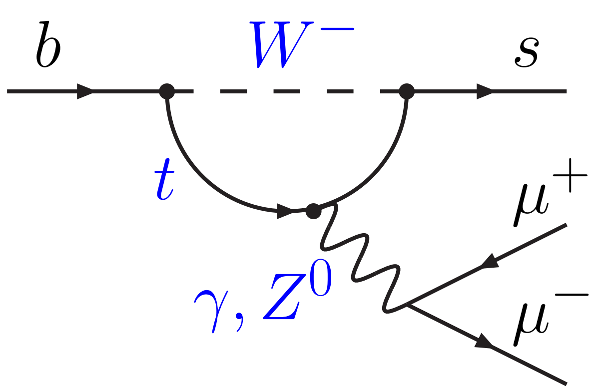
   ➡ Relative rates of $b \to se^+e^-$ and $b \to s\mu^+\mu^-$ decays ($R_{K^{(*)}}$)

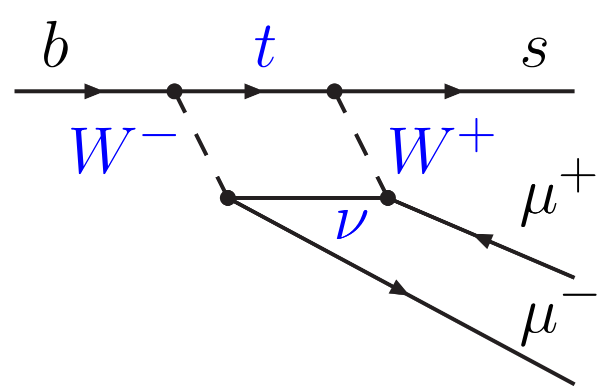
2. $b \to c\tau^-\bar{\nu}_\tau$ decays

   ➡ Rate of $b \to c\tau^-\bar{\nu}_\tau$ decays versus decays with e/μ ($R(D^{(*)})$).

Electroweak penguin decays

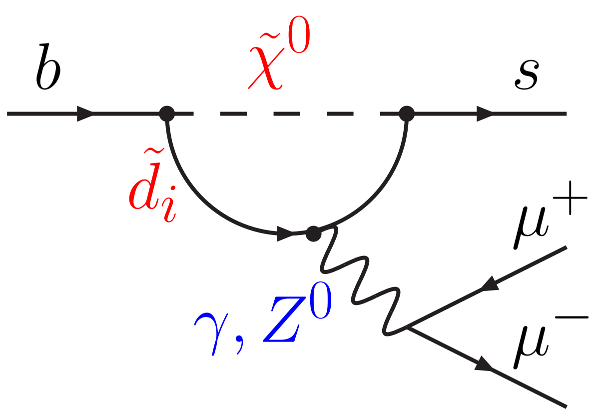
- Flavour changing neutral current transitions that only occur at loop order (and beyond) in the SM.

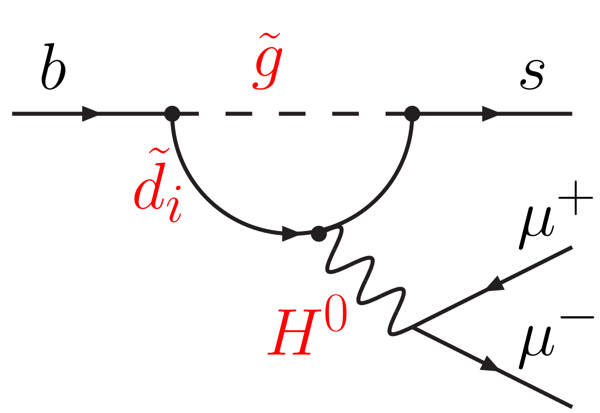


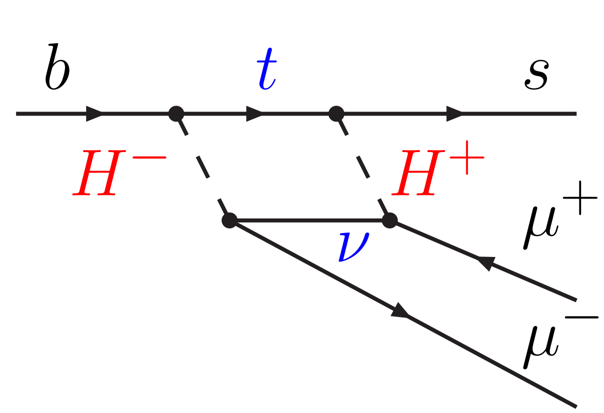


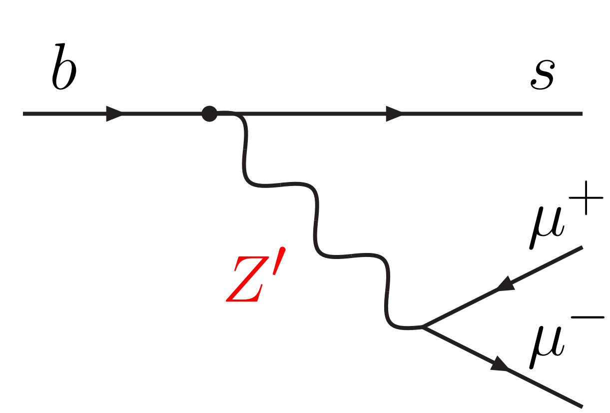
SM diagrams involve the charged current interaction.

- New particles can also contribute:



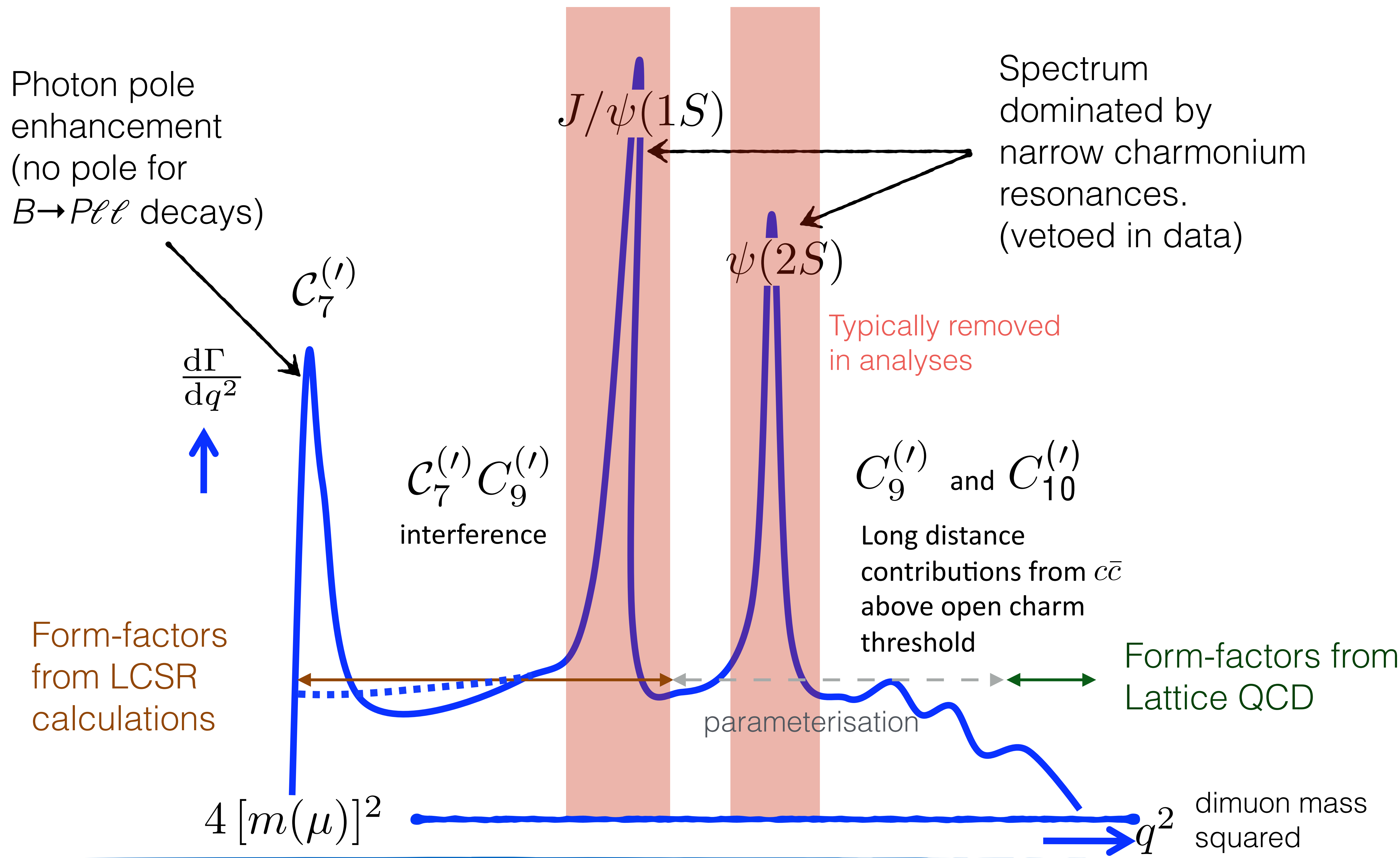






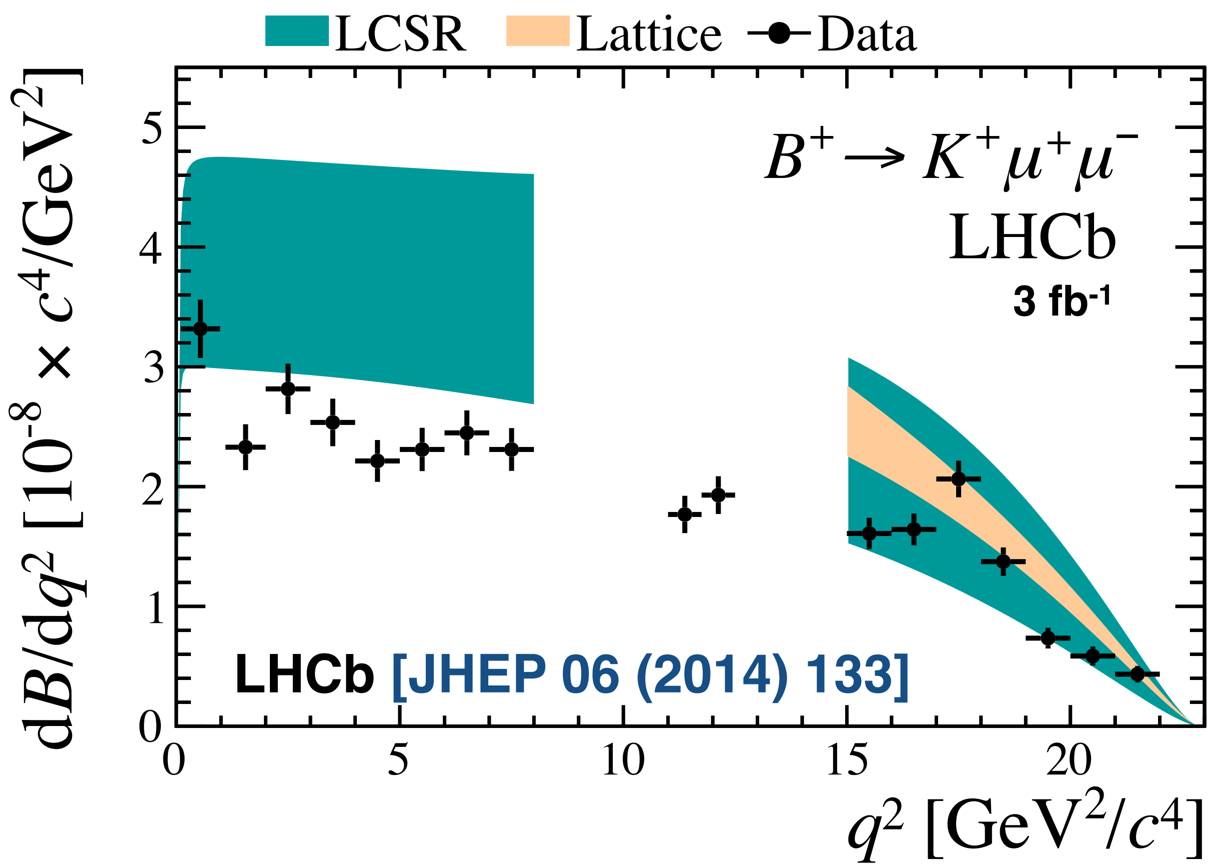
enhancing/suppressing decay rates, introducing new sources of *CP* violation and/or modifying the angular distribution of the final-state particles.

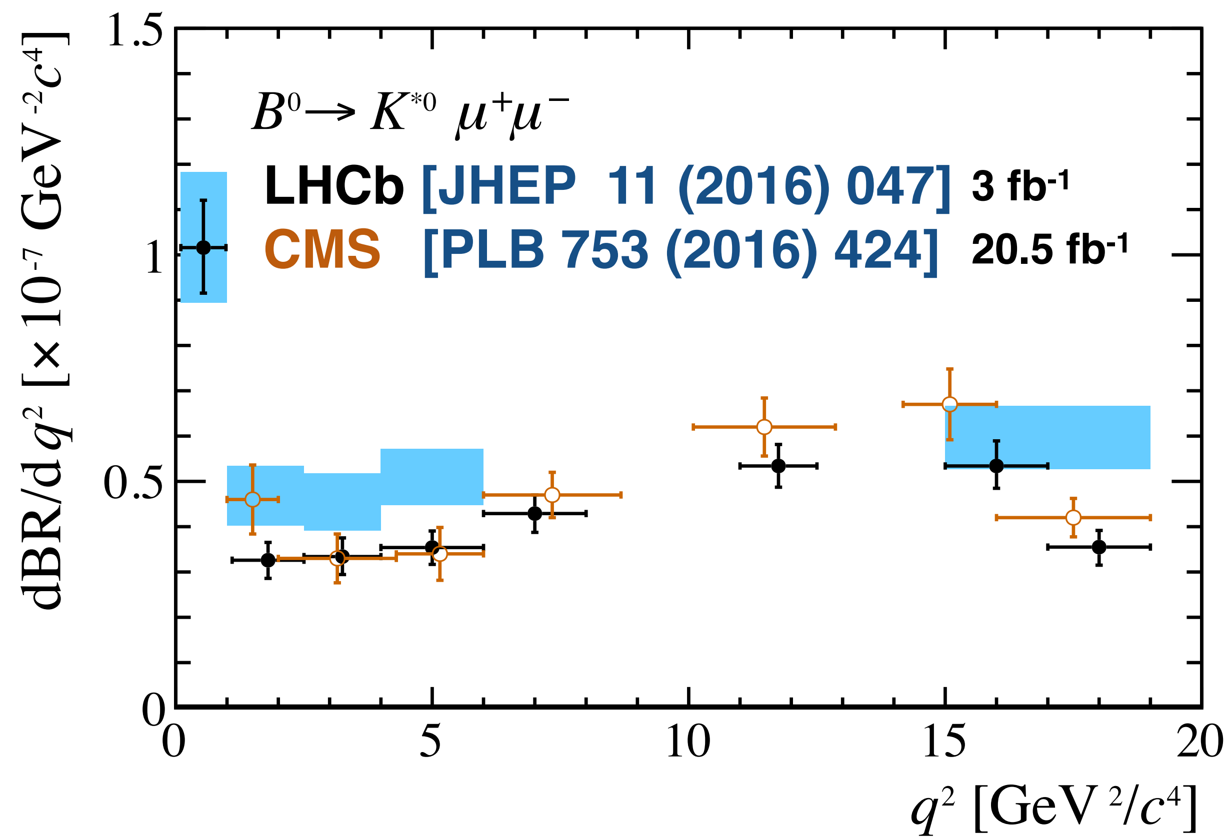
Expected $\mathrm{d}\Gamma/\mathrm{d}q^2$ spectrum



Branching fraction measurements

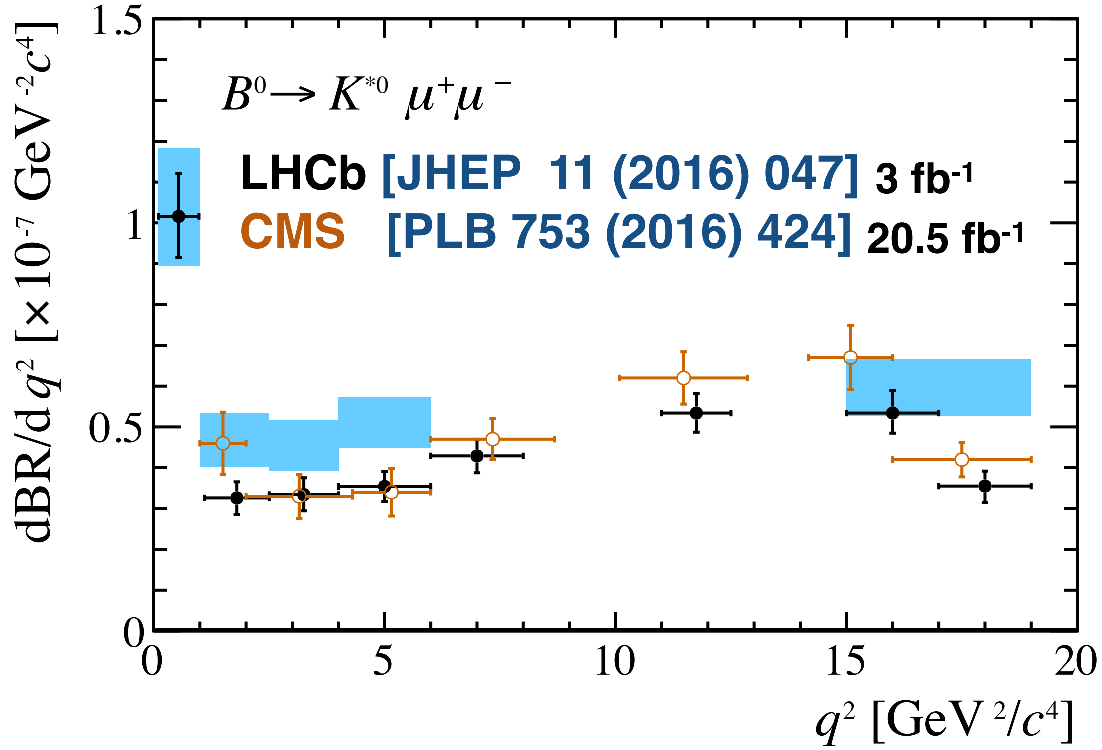
- We already have precise measurements of branching fractions from the Run1 data, with at least comparable precision to SM expectations:

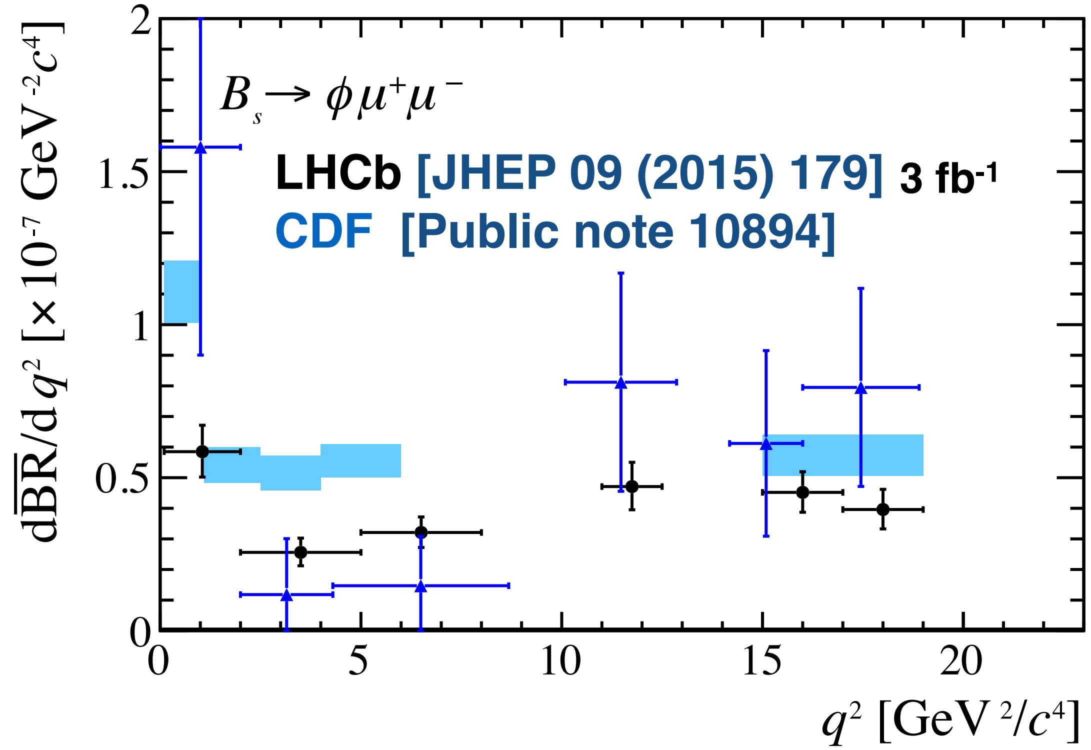


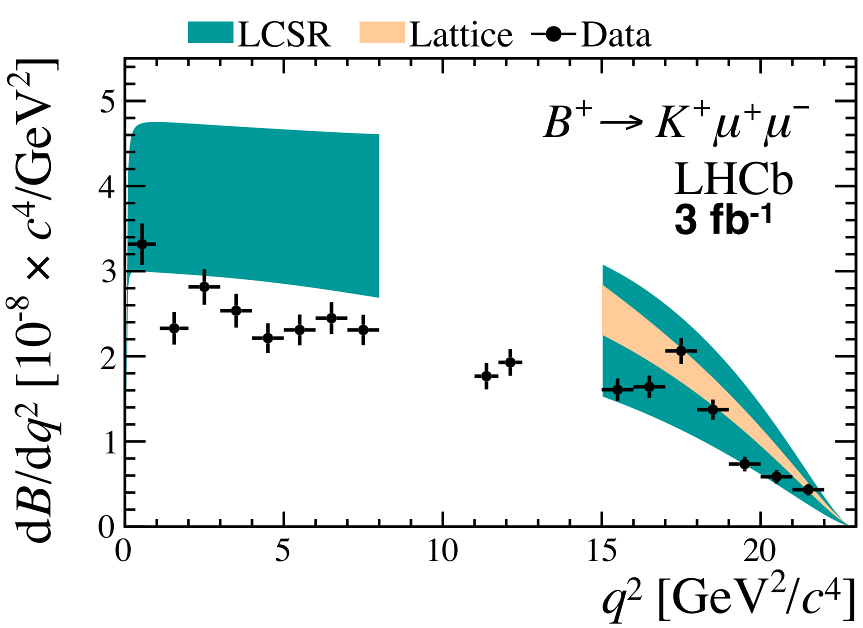


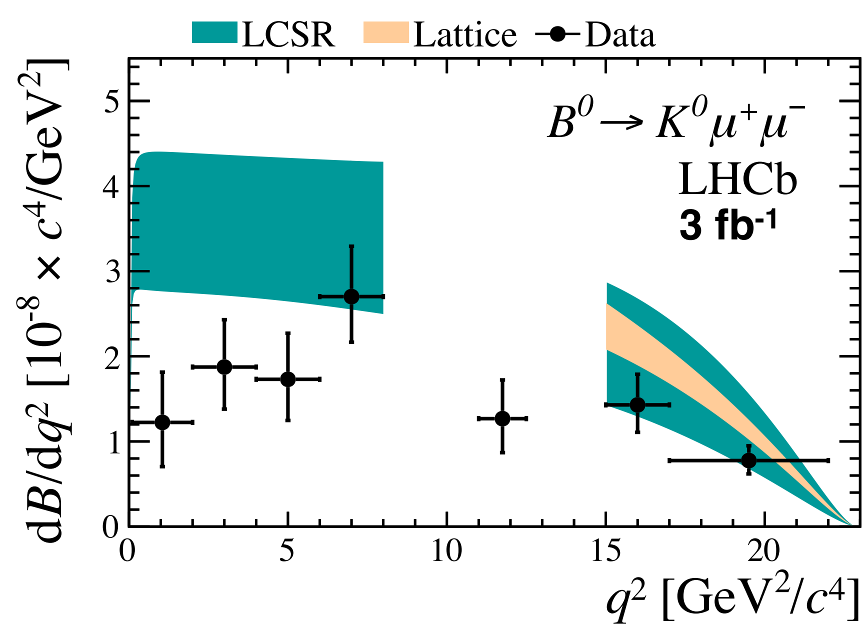
- SM predictions have large theoretical uncertainties from hadronic form factors (3 for $B \to K$ and 7 for $B \to K^*$ decays). For details see **Bobeth et al [JHEP 01 (2012) 107], Bouchard et al. [PRL111 (2013) 162002], Altmannshofer & Straub [EPJC (2015) 75 382]**.

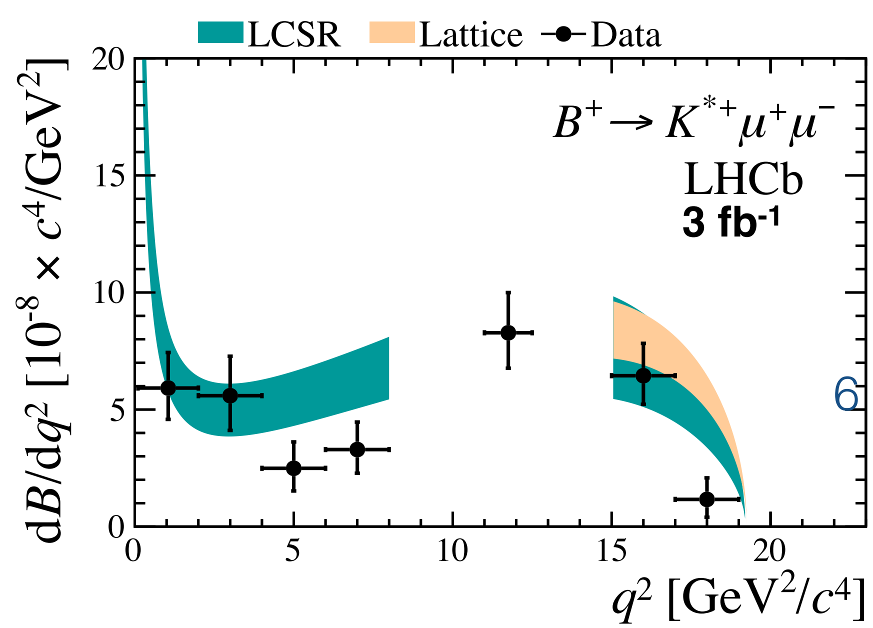
Branching fraction measurements











[JHEP 06 (2014) 133]

Measure smaller branching fractions than predicted by the SM

$B^0 \to K^{*0}\mu^+\mu^-$ angular distribution

Complex angular distribution, described by three angles:

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

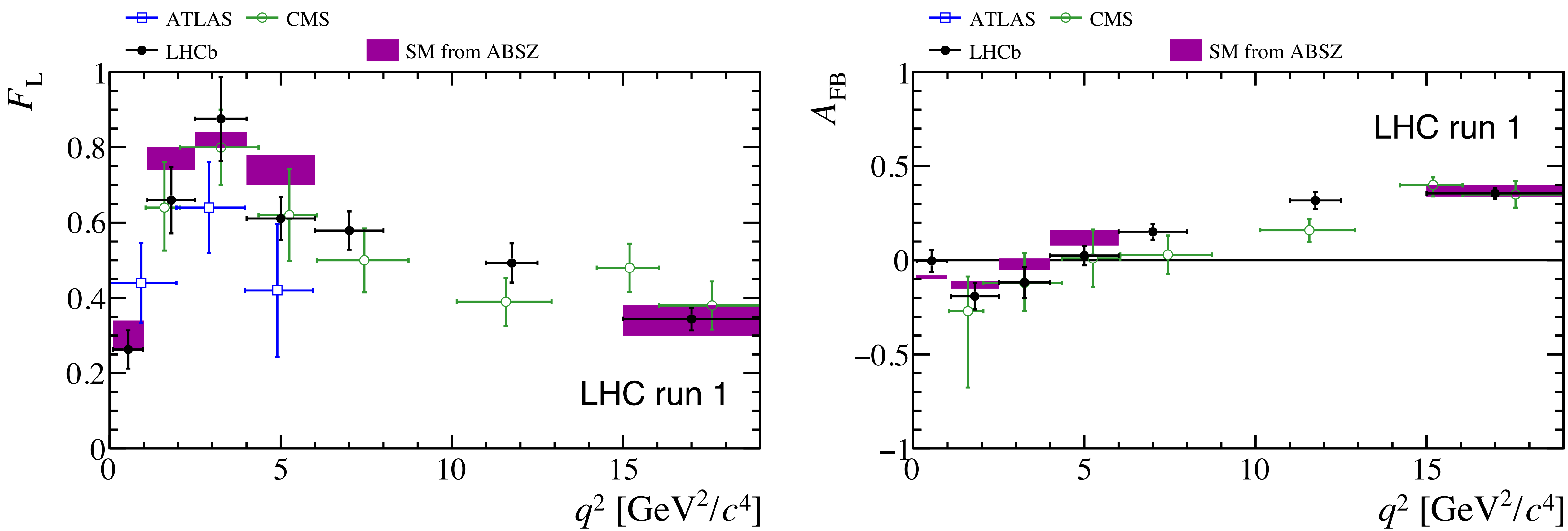
fraction of longitudinal polarisation of the K^* (F_{L})

forward-backward asymmetry of the dilepton system (A_{FB})

The observables depend on form-factors for the $B \to K^*$ transition plus the underlying short distance physics (Wilson coefficients).

Experiments can reduce the complexity by folding the angular distribution, see **LHCb [PRL 111 (2013) 191801]**

$B^0 \to K^{*0}\mu^+\mu^-$ angular observables

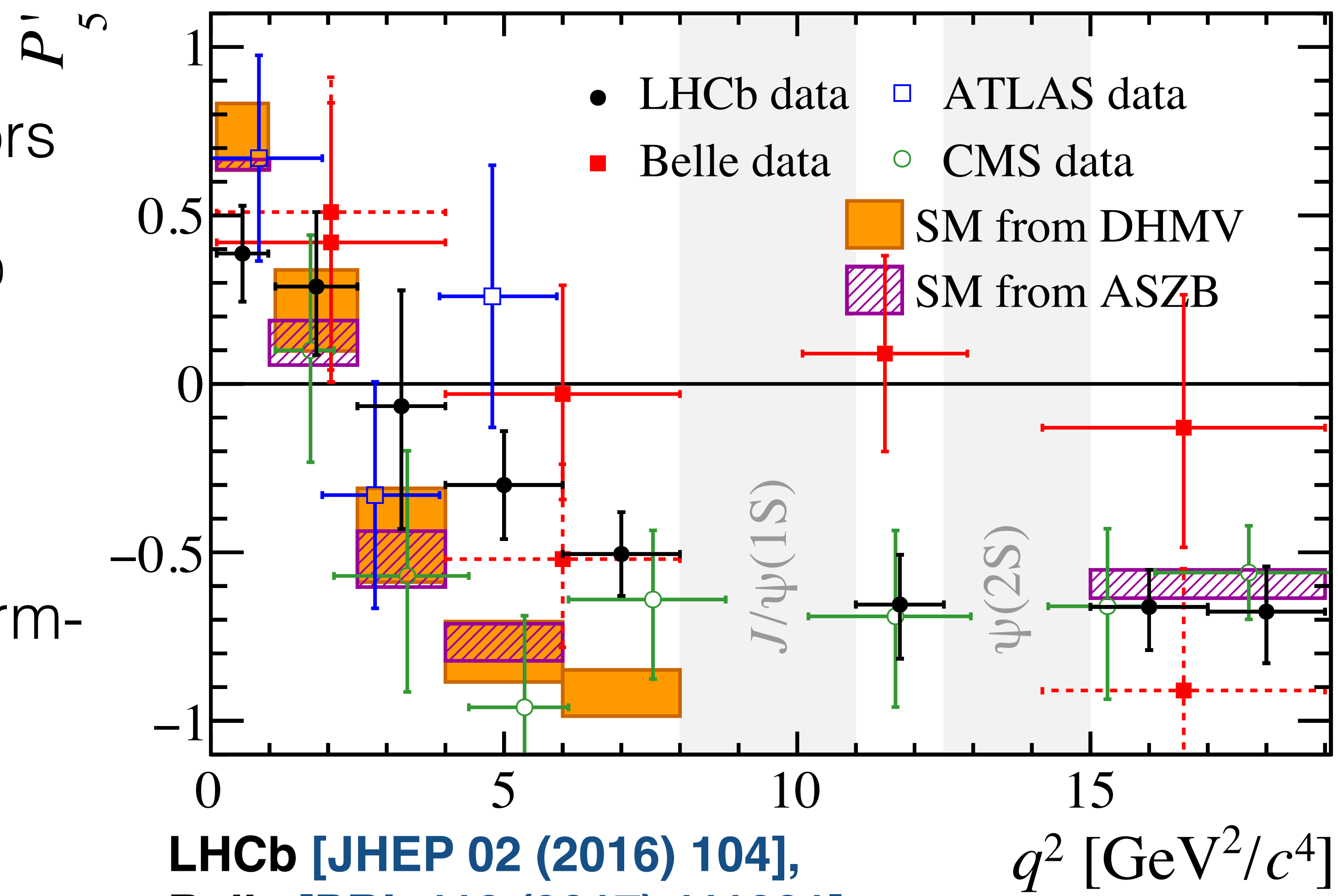


- Overlaying results for F_L and A_{FB} from LHCb **[JHEP 02 (2016) 104]** , CMS **[PLB 753 (2016) 424]** and ATLAS **[ATLAS-CONF-2017-023]**.
- SM predictions based on
  Altmannshofer & Straub [EPJC 75 (2015) 382]
  LCSR form-factors from Bharucha, Straub & Zwicky, [JHEP 08 (2016) 98]
  Lattice form-factors from Horgan, Liu, Meinel & Wingate [arXiv:1501.00367] } Joint fit performed

Form-factor "free" observables

- In QCD factorisation/SCET there are only two form-factors
  - ➡ One is associated with A_0 and the other $A_{||}$ and $A_{\perp}$.
- Can then construct ratios of observables which are independent of these soft form-factors at leading order, e.g.

$$P'_5 = S_5/\sqrt{F_{\rm L}(1-F_{\rm L})}$$



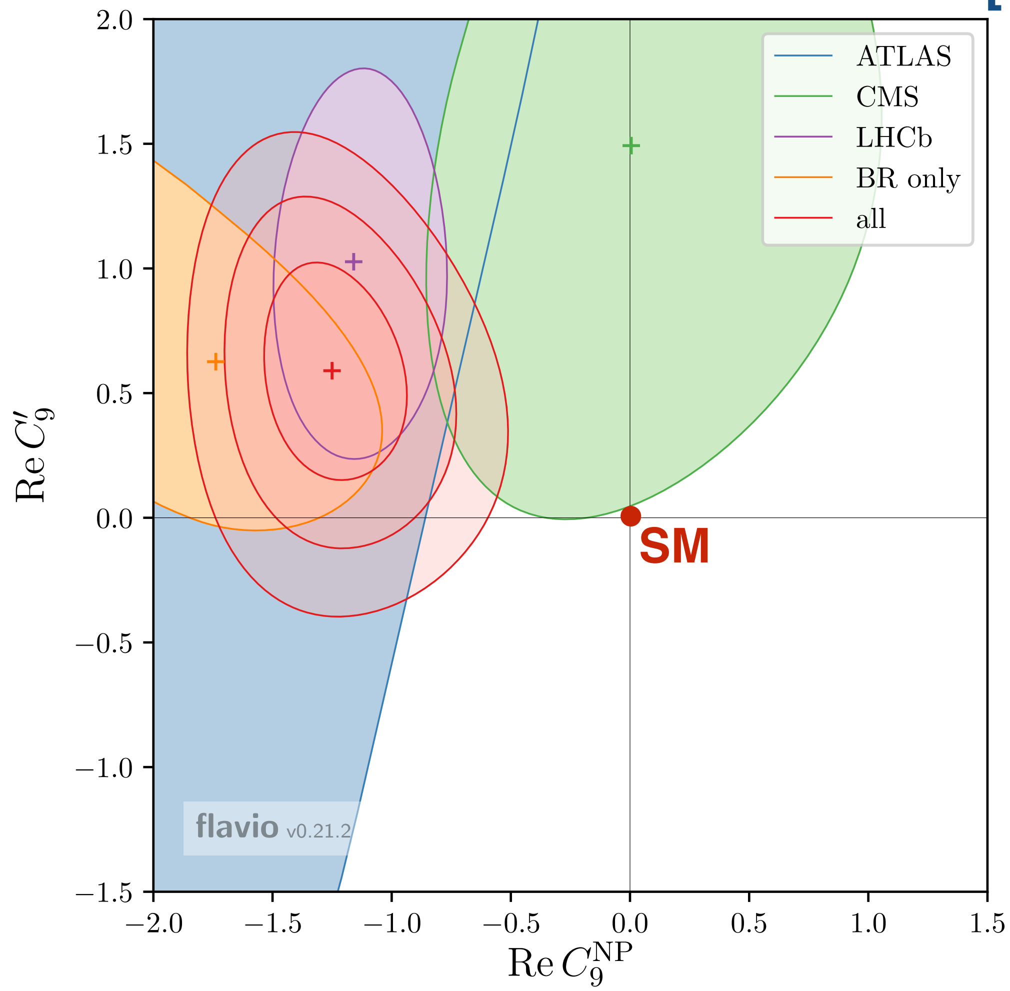
LHCb [JHEP 02 (2016) 104], Belle [PRL 118 (2017) 111801], ATLAS [ATLAS-CONF-2017-023], CMS [PLB 781 (2018) 517].

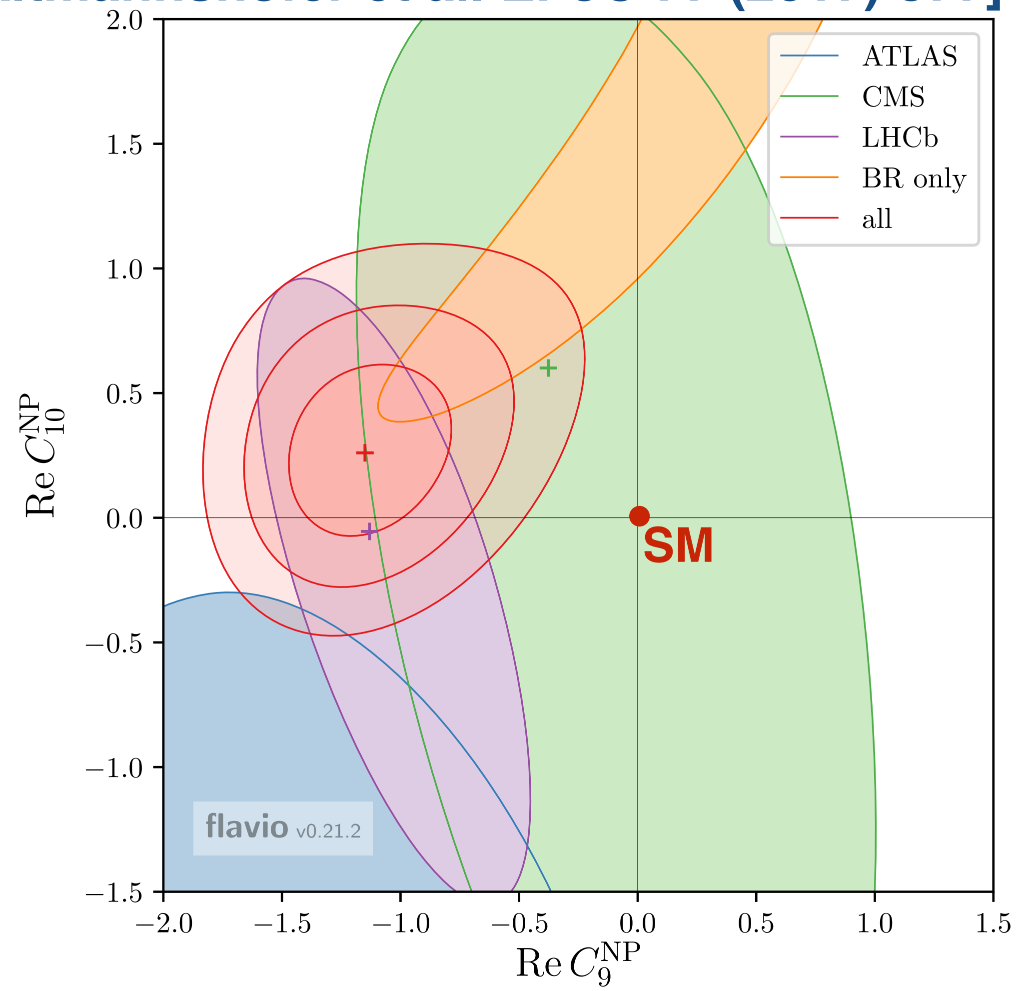
- P'_5 is one of a set of so-called form-factor free observables that can be measured **Descotes-Genon et al. [JHEP 04 (2012) 104]**.

Global fits

- Several attempts to interpret our results through global fits to $b \to s$ data.

[W. Altmannshofer et al. EPJC 77 (2017) 377]





Data are consistent between experiments/measurements and favour a modified vector coupling ($C_9^{NP} \neq 0$) at 4-5σ.

see talk by Danny van Dyk (and talk by David Straub)

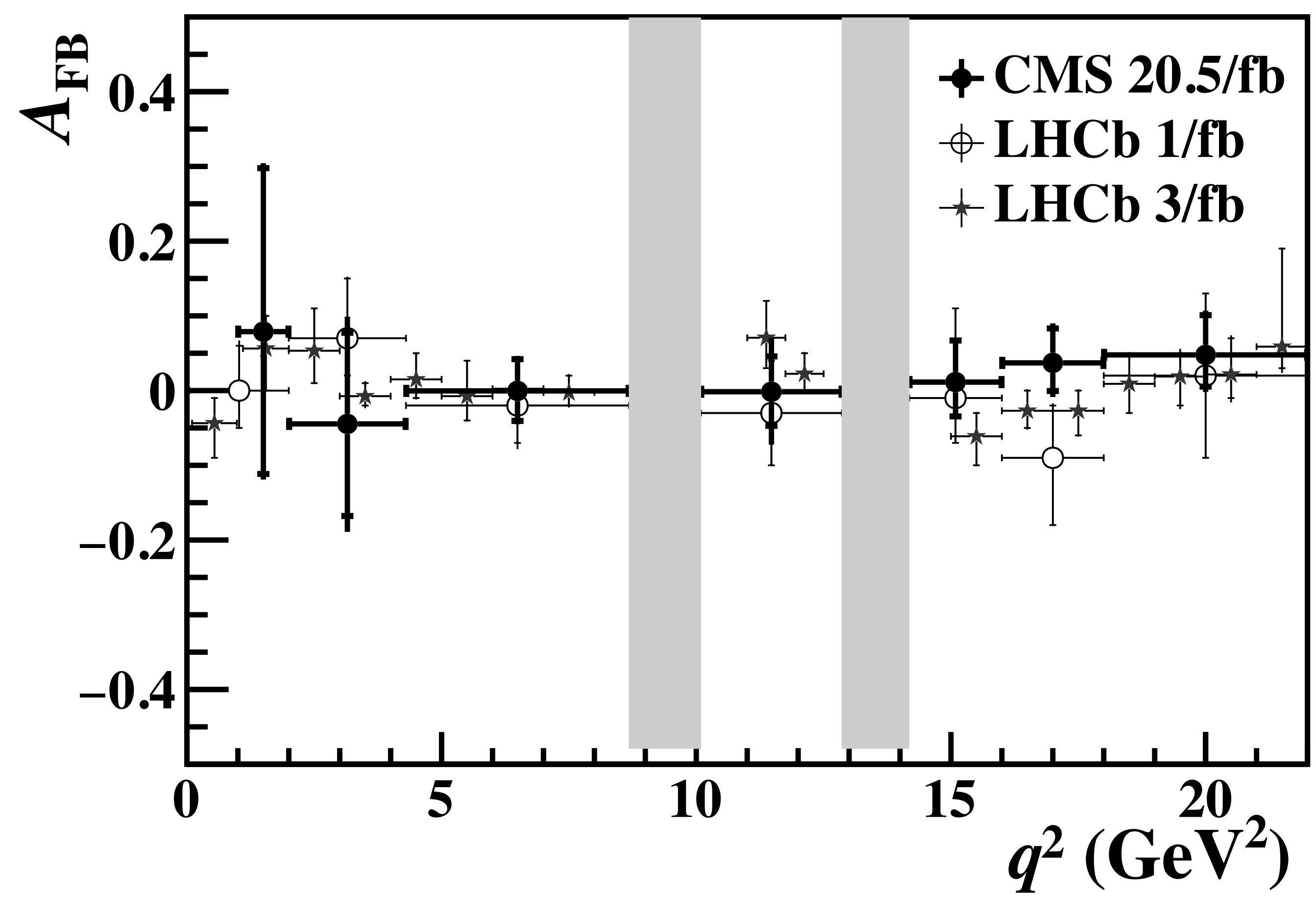
$B^+ \rightarrow K^+ \mu^+ \mu^-$ decay

- Decay described by single angle θ_l and q^2:

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_l} = \frac{3}{4}(1-F_{\mathrm{H}})(1-\cos^2\theta_l) + \frac{F_{\mathrm{H}}}{2} + A_{\mathrm{FB}}\cos\theta_l$$

- In the SM operator basis $A_{\mathrm{FB}} = 0$ and $F_{\mathrm{H}} \approx 0$.
- Only non-zero if there are new scalar/pseudoscalar or tensor contributions.
- Data consistent with a SM-like picture.
- We also know from $\mathcal{B}(B_s \to \mu^+\mu^-)$ that scalar & pseudoscalar contributions are very small.

CMS [arXiv:1806.00636], LHCb [JHEP 05 (2014) 082]



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

- First observed by the CDF collaboration in **[PRL 107 (2011) 201802]**
- Decay has unique phenomenology:
  - ➡ Diquark pair as a spectator rather than single quark;
  - ➡ Λ_b can be produced polarised in *pp* collisions;
  - ➡ and the Λ baryon decays via the weak interaction.
- Based on **[JHEP 06 (2015) 115]**, expect signal predominantly at low hadronic-recoil ($15<q^2<20$ GeV^2/c^4).

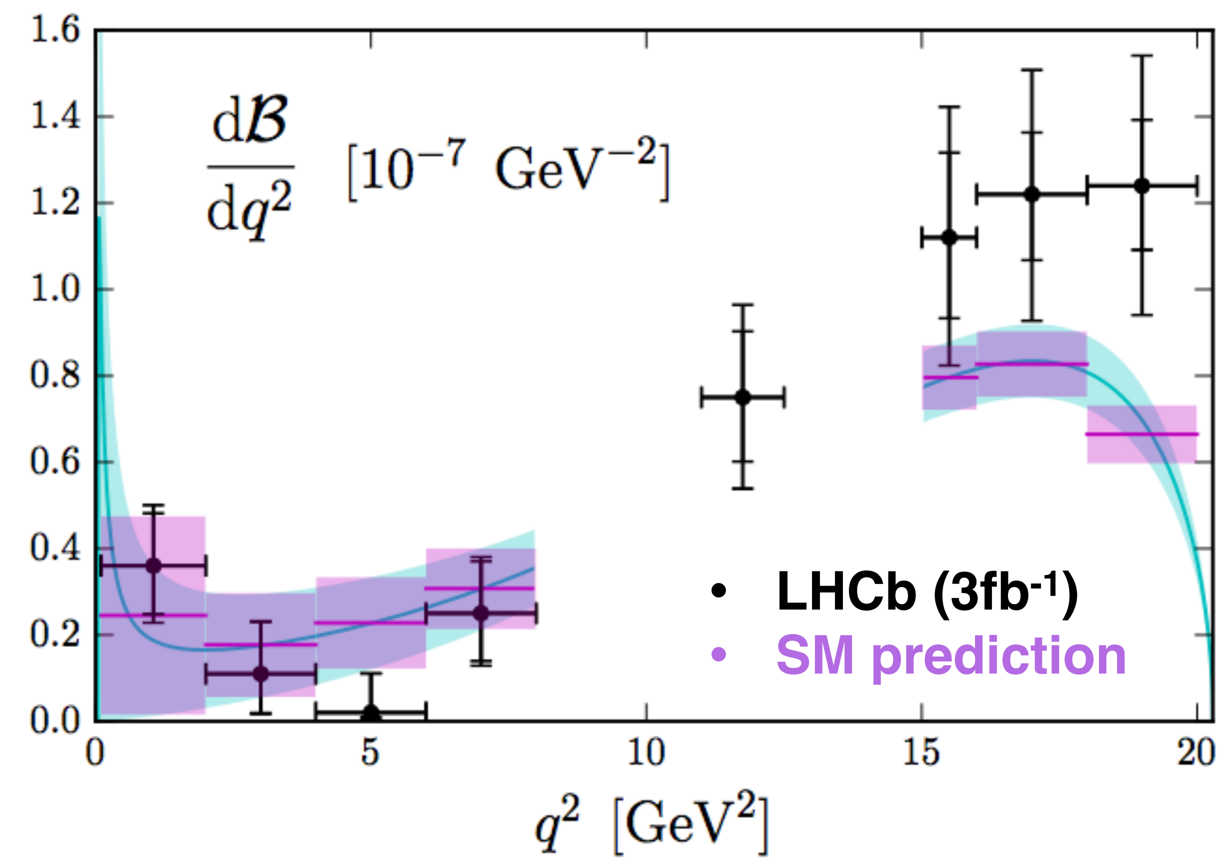


Figure and SM prediction from:
Detmold et al. [PRD 93 (2016) 074501]

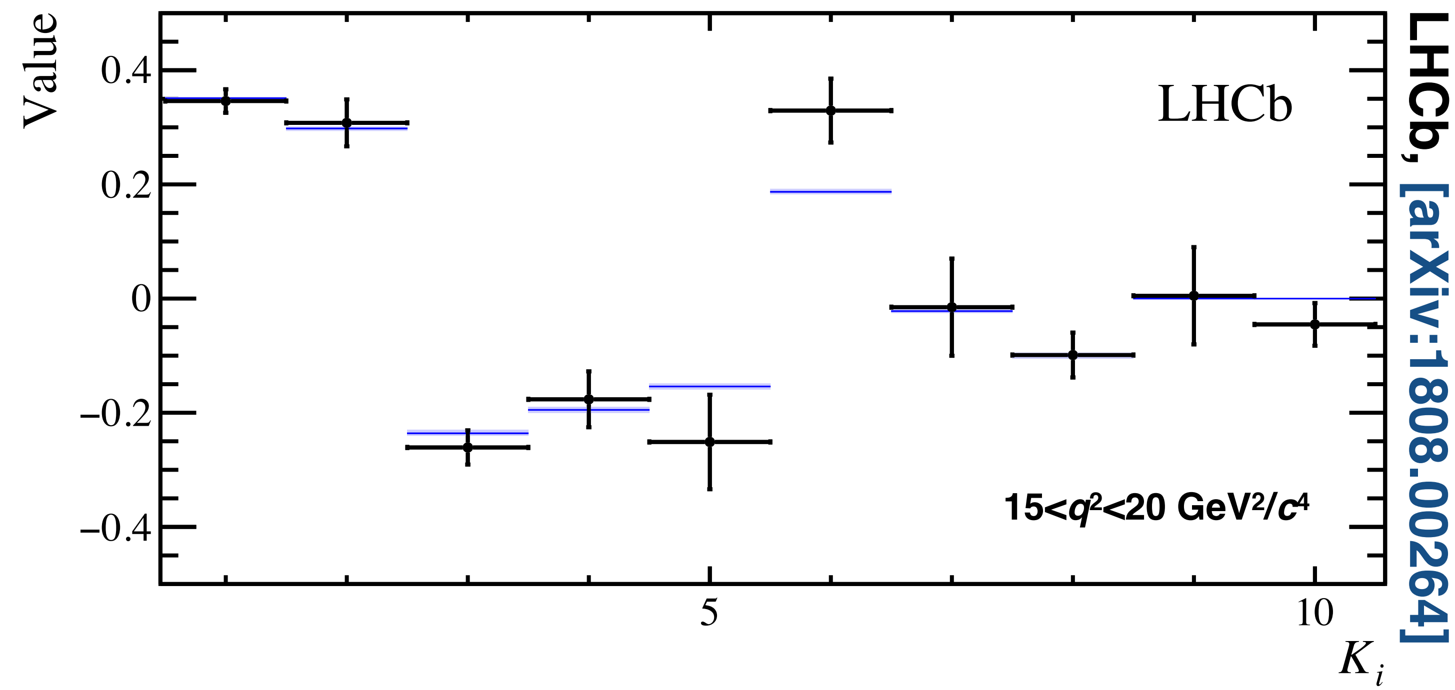
Data from:
LHCb [JHEP 06 (2015) 115]

$\Lambda_b \to \Lambda \mu^+ \mu^-$ angular distribution

- First measurement of the full set of angular observables for $\Lambda_b \to \Lambda \mu^+ \mu^-$.
- Decay is described by 5 angles and a normal-vector:

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

- K_{11} — K_{34} are consistent with having a small production polarisation (i.e. consistent with zero).



Data are consistent with SM predictions from

Boër et al. [JHEP 01 (2015) 155]
Detmold et al. [PRD 93 (2016) 074501]

Lepton universality tests

- In the SM, ratios

$$R_{\rm K} = \frac{\int {\rm d}\Gamma[B^+ \to K^+\mu^+\mu^-]/{\rm d}q^2 \cdot {\rm d}q^2}{\int {\rm d}\Gamma[B^+ \to K^+e^+e^-]/{\rm d}q^2 \cdot {\rm d}q^2}$$

  only differ from unity by phase space — the dominant SM processes couple equally to the different lepton flavours.

- Theoretically clean since hadronic uncertainties cancel in the ratio.

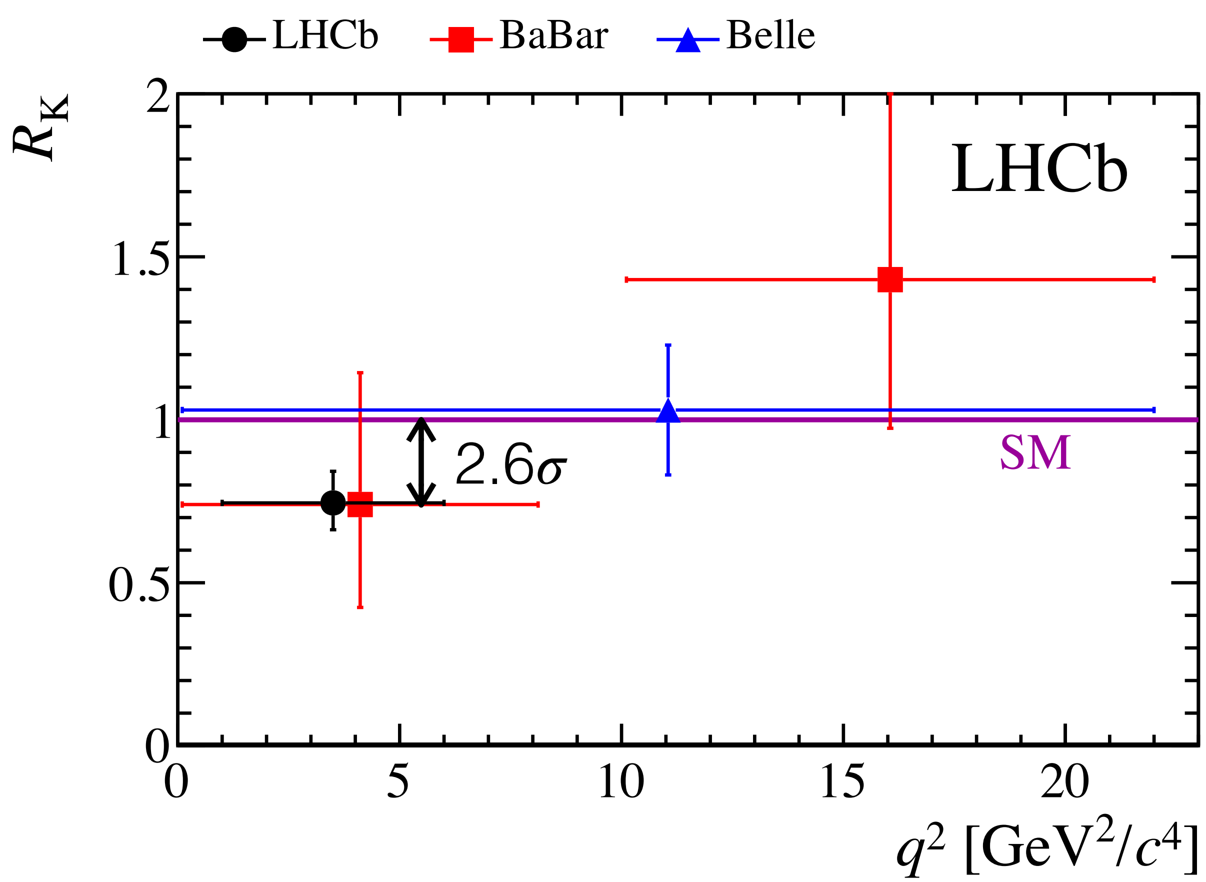
- Experimentally challenging due to differences in muon/electron reconstruction (in particular Bremsstrahlung from the electrons).

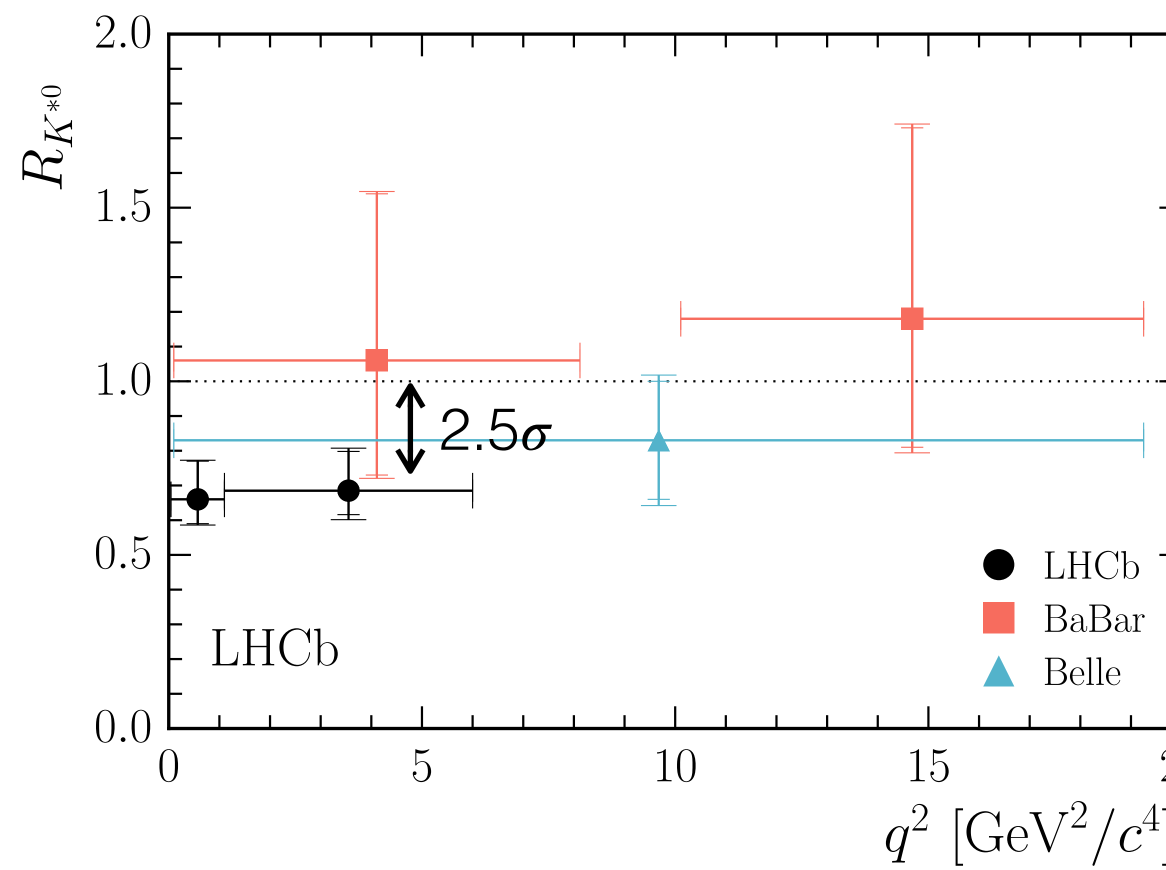
  ➡ Take double ratios with $B\to J/\psi K^{(*)}$ decays to cancel possible sources of systematic uncertainty.

  ➡ Correct for migration of events in q^2 due to FSR/Bremsstrahlung using MC (with PHOTOS).

Lepton universality tests

- Interesting hints of non-universal lepton couplings in LHCb's run 1 dataset:





LHCb [PRL113 (2014) 151601]
LHCb [LHCb-PAPER-2017-013]
BaBar [PRD 86 (2012) 032012]
Belle [PRL 103 (2009) 171801]

NB $R_K \simeq 0.8$ was a prediction of one class of model explaining the $B^0 \to K^{*0}\mu^+\mu^-$ angular observables, see L_μ - L_τ models
W. Altmannshofer et al. [PRD 89 (2014) 095033]

Flavour anomalies

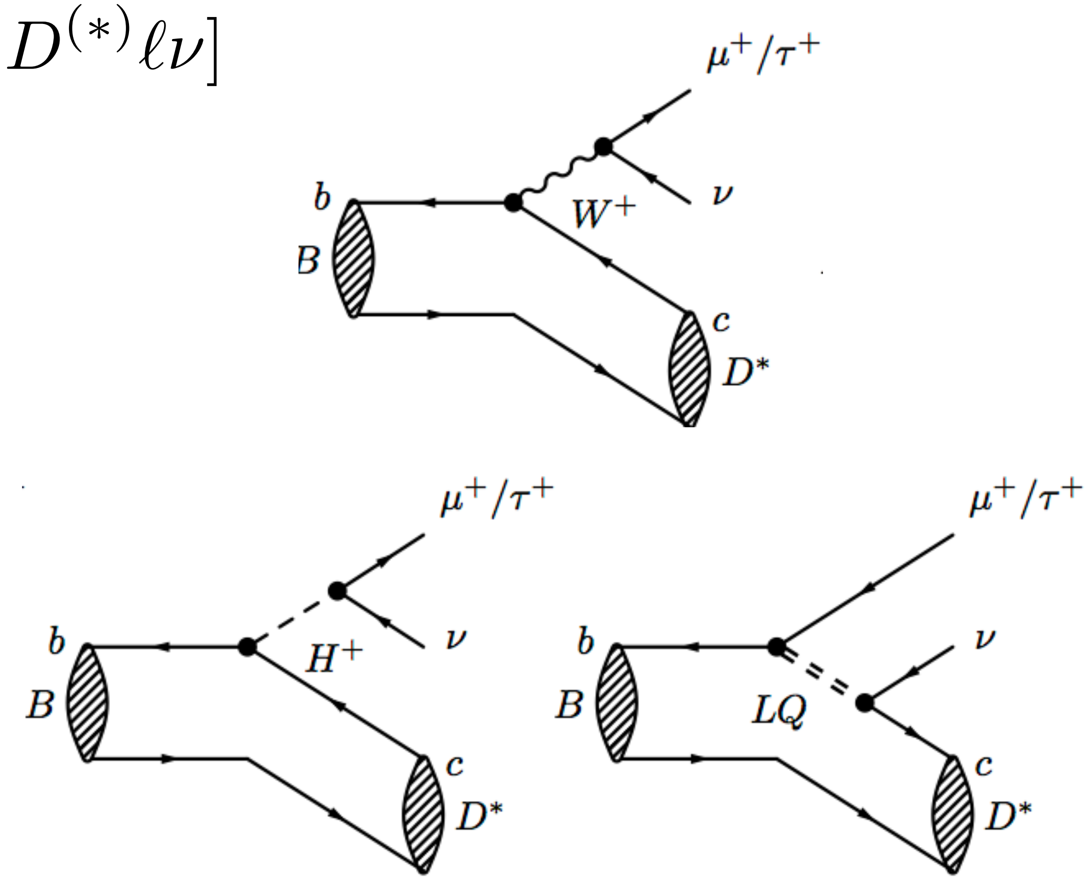
1. $b \to s\ell^+\ell^-$ processes
   - ➡ Rate and angular distribution of exclusive $b \to s\mu^+\mu^-$ decays.
   - ➡ Relative rates of $b \to se^+e^-$ and $b \to s\mu^+\mu^-$ decays ($R_{K^{(*)}}$)

2. $b \to c\tau^-\bar{\nu}_\tau$ decays
   - ➡ Rate of $b \to c\tau^-\bar{\nu}_\tau$ decays versus decays with e/μ ($R(D^{(*)})$).

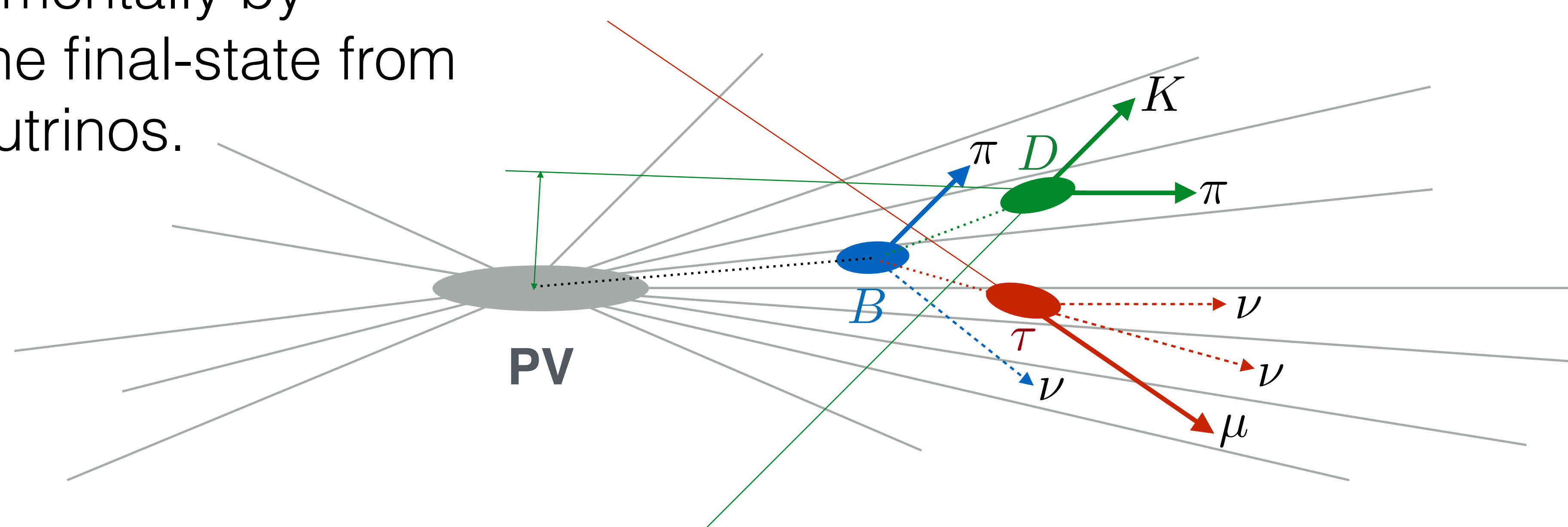
$b \to c\tau\nu$ decays

- Ratios $R(D^{(*)}) = \Gamma[B \to D^{(*)}\tau\nu]/\Gamma[B \to D^{(*)}\ell\nu]$ are also theoretically clean in the SM:
  - ➡ Coupling to leptons is universal.
  - ➡ Hadronic uncertainties and $|V_{cb}|$ cancel in the ratio.

  and can be enhanced in extensions of the SM (*e.g.* with charged Higgs).



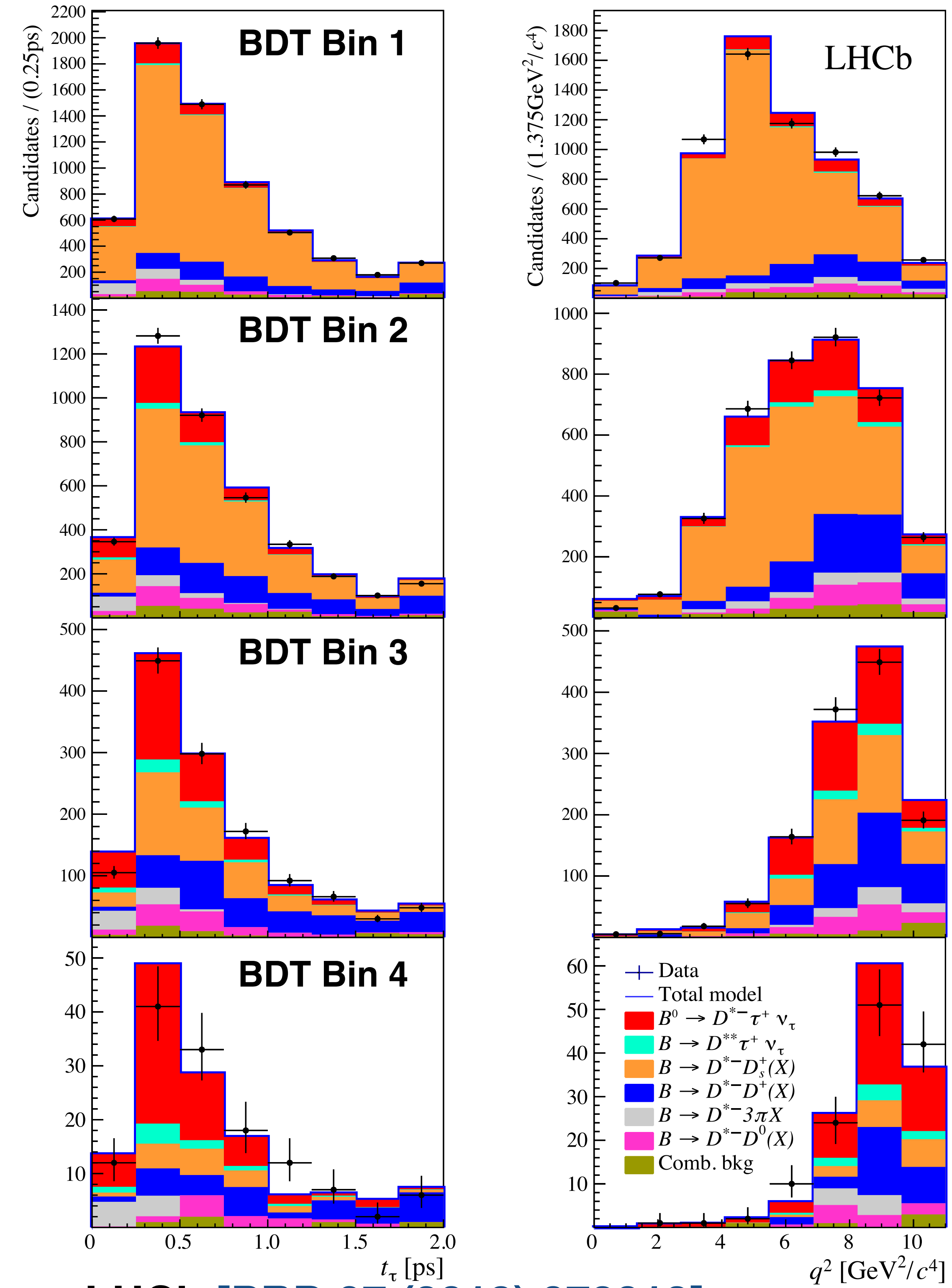
- Complicated experimentally by missing energy in the final-state from multiple missing neutrinos.



$R(D^*)$ with $\tau \to 3\pi(\pi^0)\nu$

- Experimental challenge is to separate signal from backgrounds.
  - ➡ Use missing mass, lepton energy, q^2 and multivariate discriminants.
  - ➡ Can use boost approximation to determine kinematic quantities ($(\beta_z\gamma)_{\rm vis} \approx (\beta_z\gamma)_B$).
- *B*-factory experiments can exploit leptonic/hadronic tag of the other *B* in the event and centre-of-mass constraints.

Modelling of *D* and hadronic backgrounds is important**

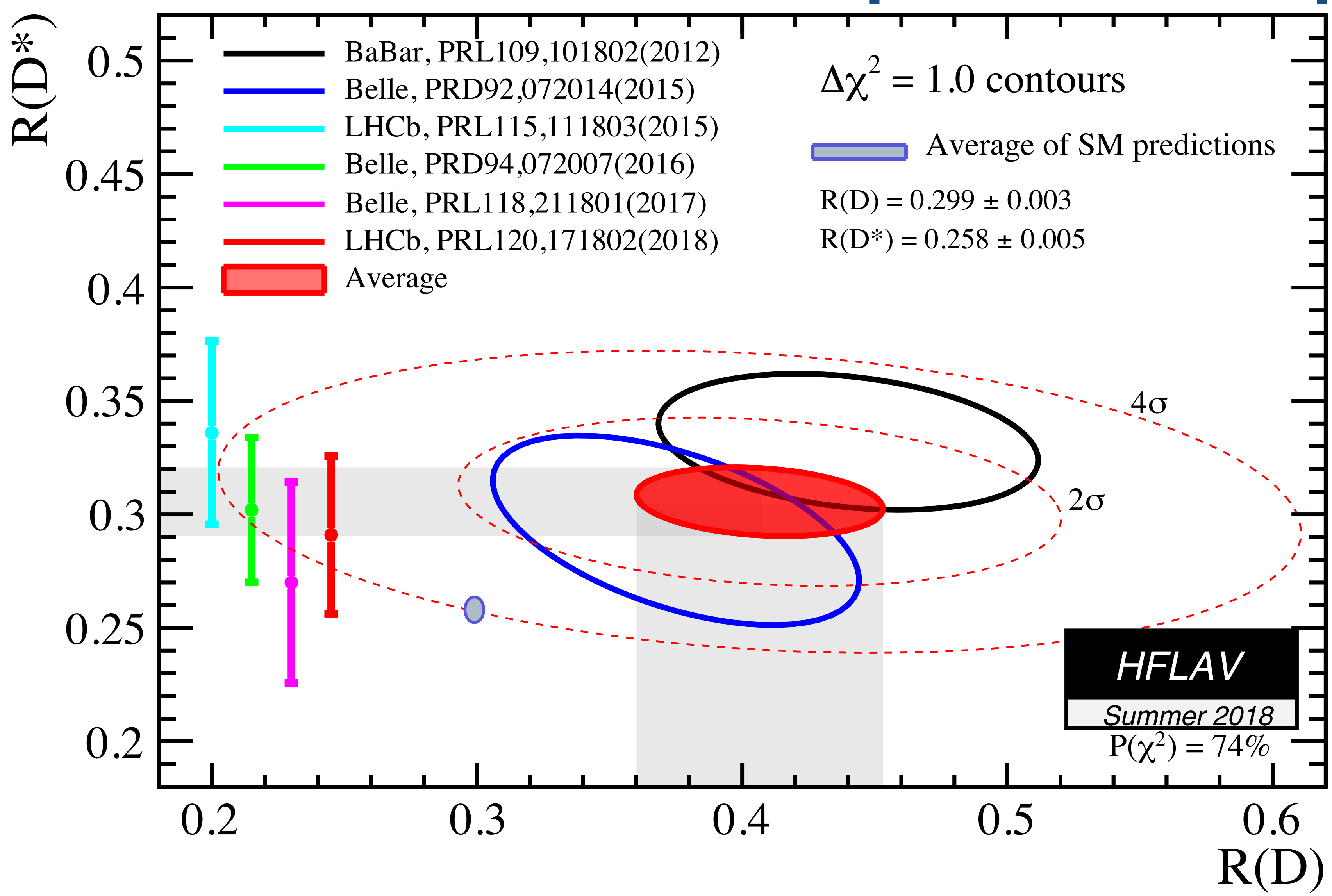


LHCb [PRD 97 (2018) 072013]

R(D) versus *R(D*)*

[hflav-eos.web.cern.ch]

Combination of *R(D)* and *R(D*)* is 3.8σ from the corresponding SM prediction.



- SM predictions:
  - ➡ *R(D)* from **FLAG working group [EPJC 77 (2017) 112]**.
  - ➡ *R(D*)* from **S. Fajfer et al. [PRD 85 (2012) 094025]**.

$R(J/\psi)$

- LHCb has also measured a similar ratio using B_c decays:

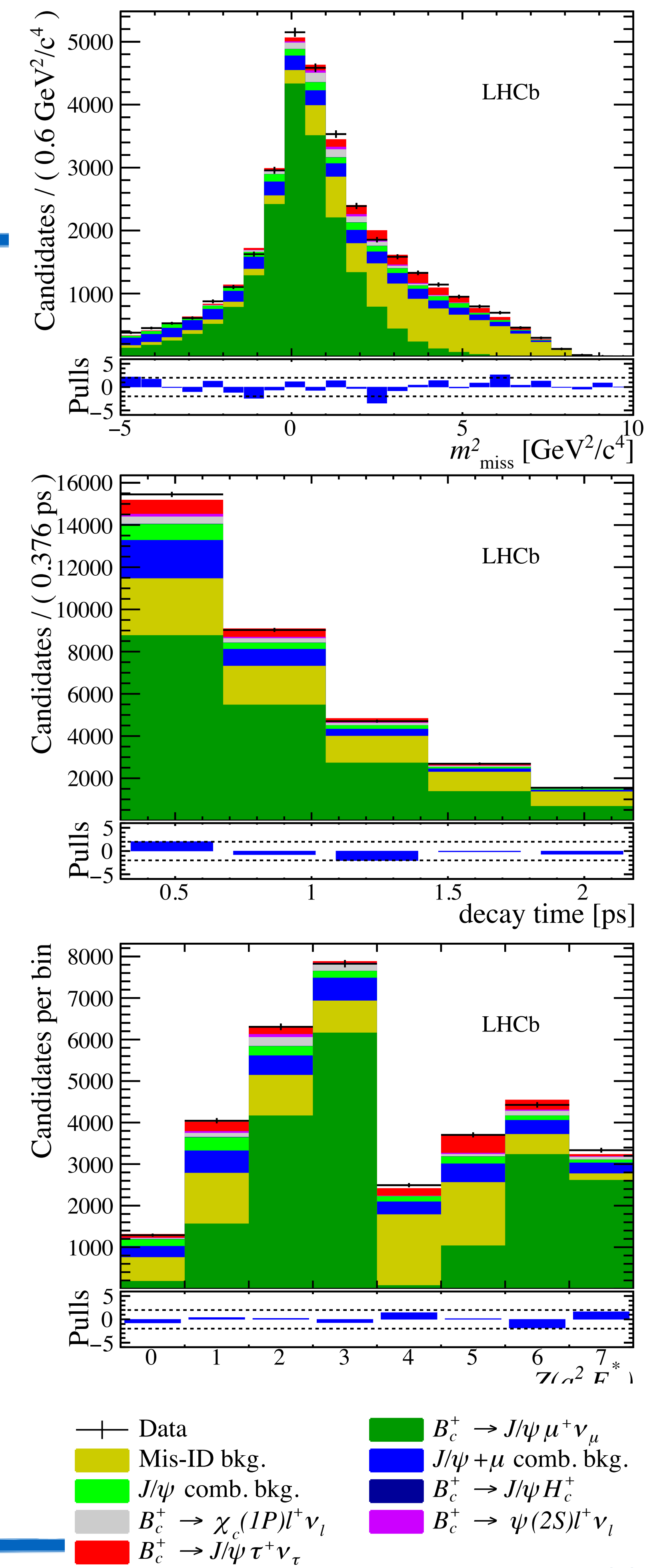
$$R(J/\psi) = \frac{\Gamma[B_c^+ \to J/\psi \tau^+ \nu_\tau]}{\Gamma[B_c^+ \to J/\psi \mu^+ \nu_\mu]}$$
$$= 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$$

[LHCb, PRL120 (2018) 121801]

- Perform a template fit to the B_c decay time, to m^2_{miss} and a category label $Z(q^2, E^*_\mu)$.

- SM predictions based on the quark-model/QCD sum rules are in the range 0.25–0.28.

- Systematic uncertainty driven by knowledge of the $B_c^+ \to J/\psi$ form-factors and the size of the simulated samples used to derive the templates.

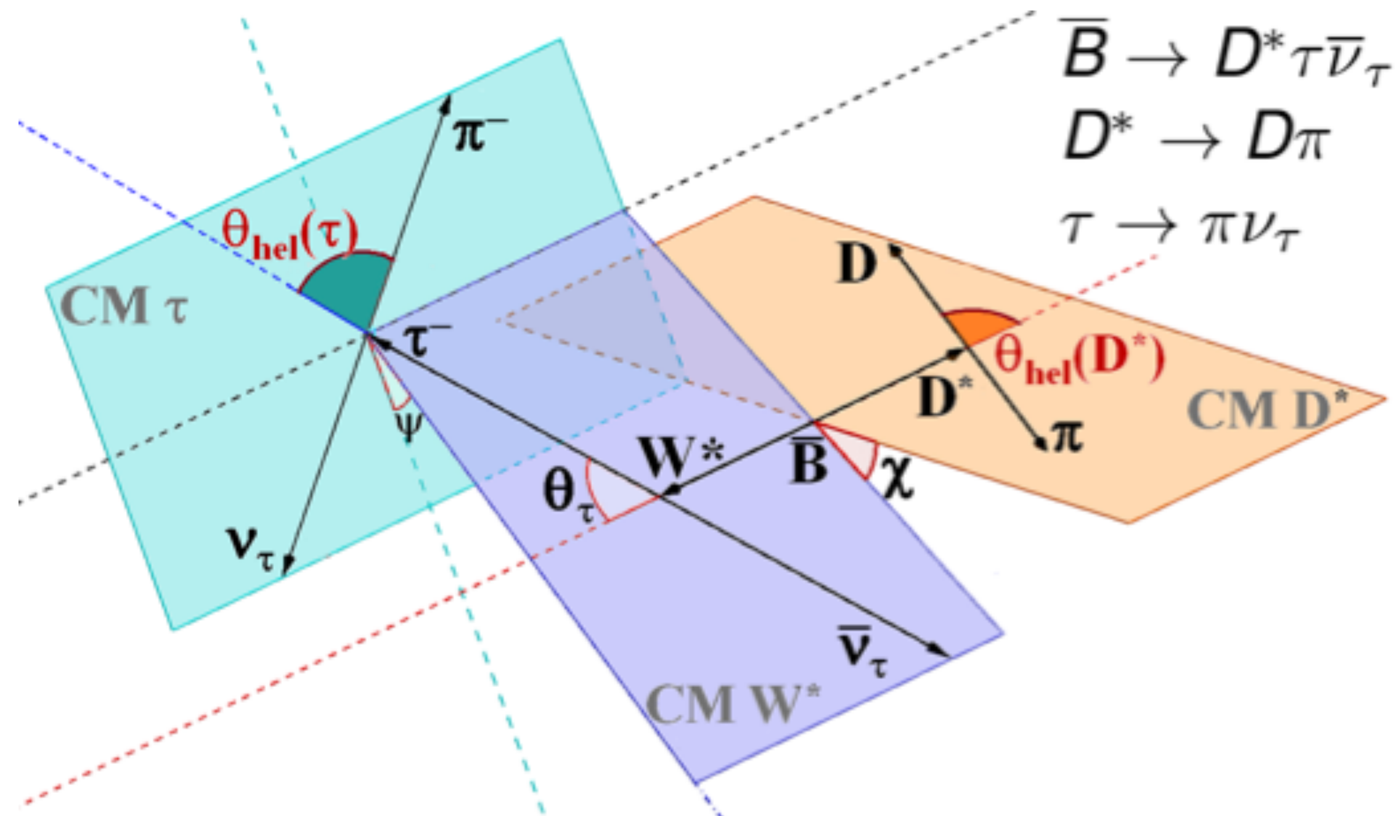


$B \to D^{*}\tau\nu$ angular distribution

- Can also look at the angular distribution of the final-state particles.

eg Can measure $\theta_{\rm hel}(\tau)$ and $\theta_{\rm hel}(D^{*})$ using hadronic τ decays.

- Angular projections:



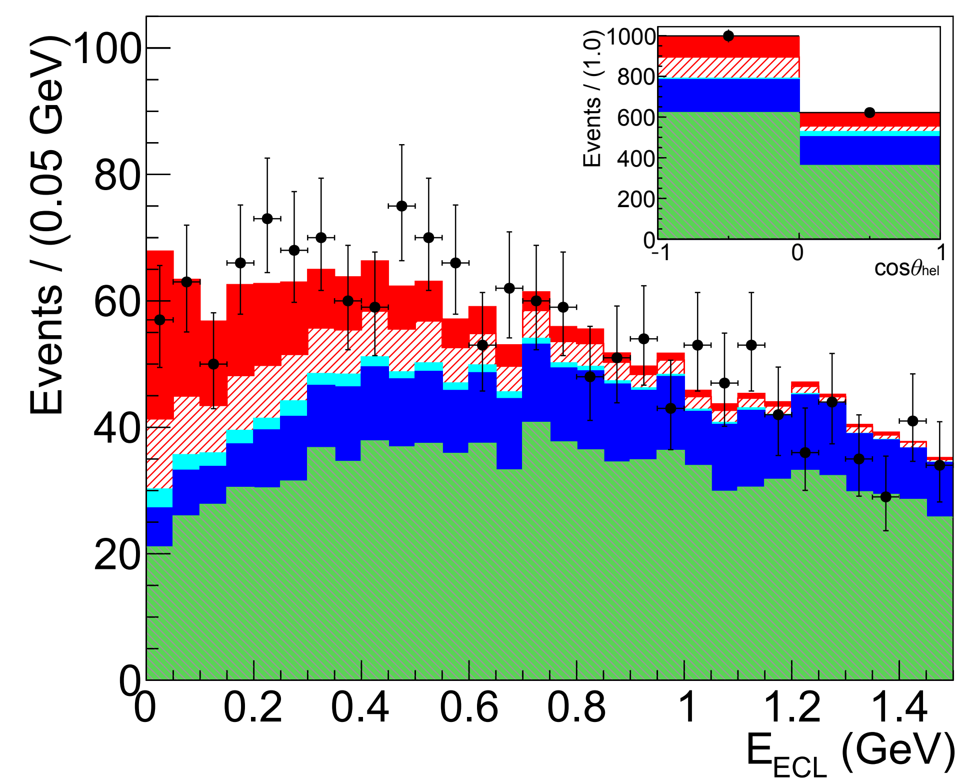
From talk by Karol Adamczyk

$$\frac{d\Gamma}{d\cos\theta_{\rm hel}(\tau)} = \frac{1}{2}\left(1 + \alpha P_{\tau}\cos\theta_{\rm hel}(\tau)\right)$$

$$\frac{d\Gamma}{d\cos\theta_{\rm hel}(D^{*})} = \frac{3}{4}\left(2F_{\rm L}\cos^{2}\theta_{\rm hel}(D^{*}) + (1 - F_{\rm L})\sin^{2}\theta_{\rm hel}(D^{*})\right)$$

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

Belle [PRL 118 (2017) 211801]



- From the forward-backward asymmetry of 1-prong decays Belle measures:

$$P_\tau(D^*) = -0.38 \pm 0.51\,(\text{stat})^{+0.21}_{-0.16}\,(\text{syst})$$

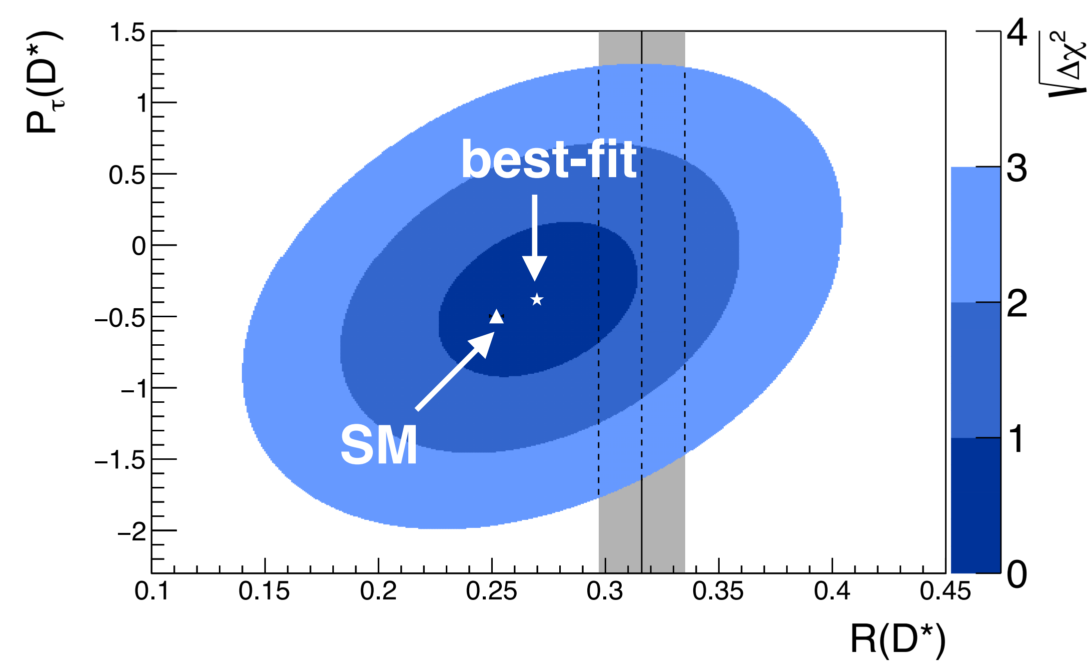
with **[PRL118 (2017) 211801]**.

- *Preliminary* measurement of F_L also shown for the first time at CKM 2018:

$$F_{\rm L} = 0.60 \pm 0.08\,(\text{stat}) \pm 0.035\,(\text{syst})$$

[see talk by K. Adamczyk].

- Measured value of F_L consistent with SM predictions within 2σ e.g. **Alok et al. [PRD 95 (2017) 115038]**.



Summary

- Anomalies in $b \to s\ell^+\ell^-$ processes:
  - Branching fractions of $b \to s\mu^+\mu^-$ processes systematically below SM predictions (inclusive branching fraction is consistent).
  - *R*$_K$ and *R*$_{K^*}$ different from unity.
  - *P'*$_5$ anomaly in the angular distribution of $B^0 \to K^{*0}\mu^+\mu^-$.

} $\mathcal{O}(20\%\ \mathrm{SM})$ on loop-order process

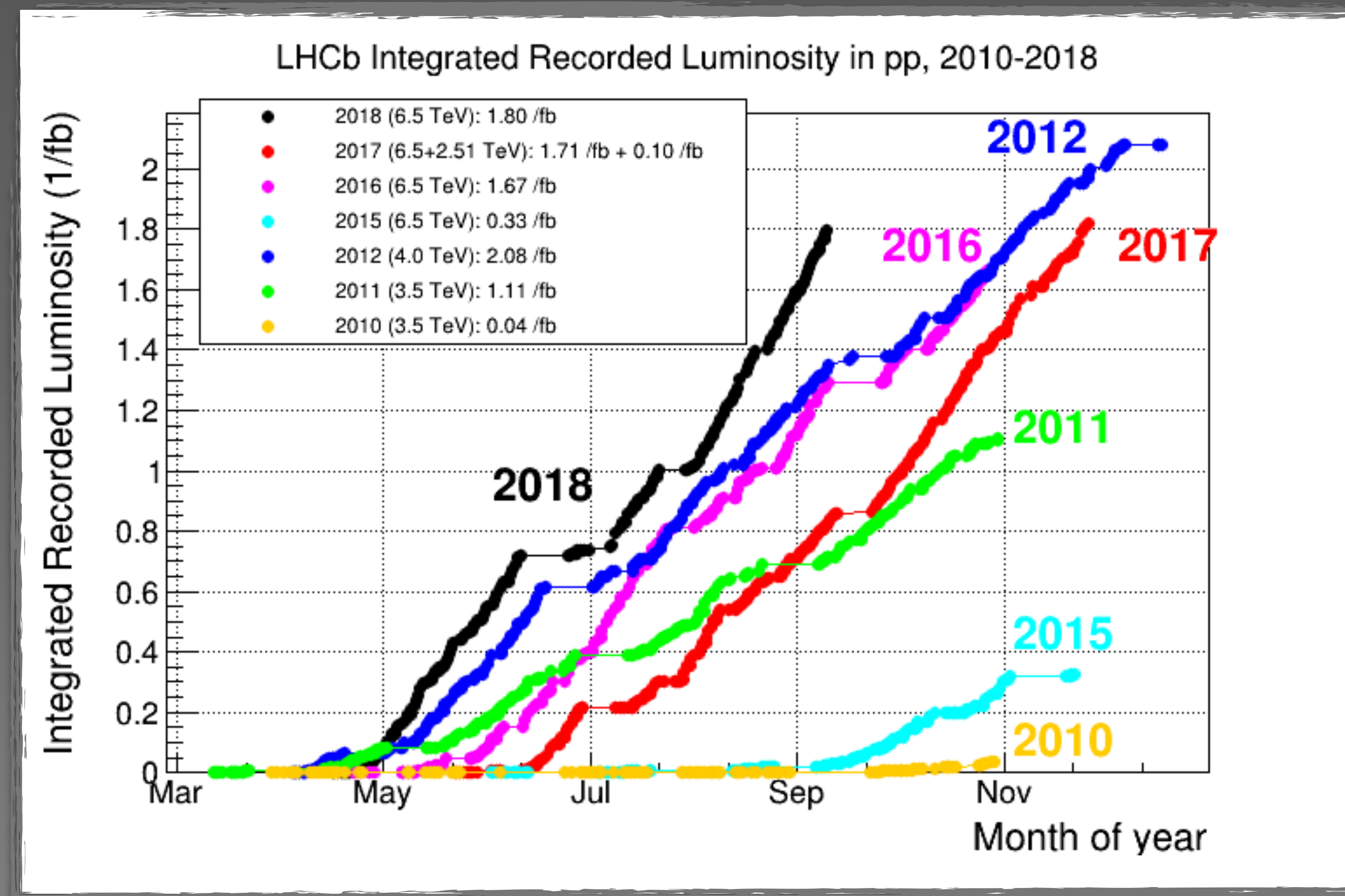
- Anomalies in $b \to c\ell^-\bar{\nu}_\ell$ processes:
  - *R(D)* and *R(D*)* larger than SM predictions.

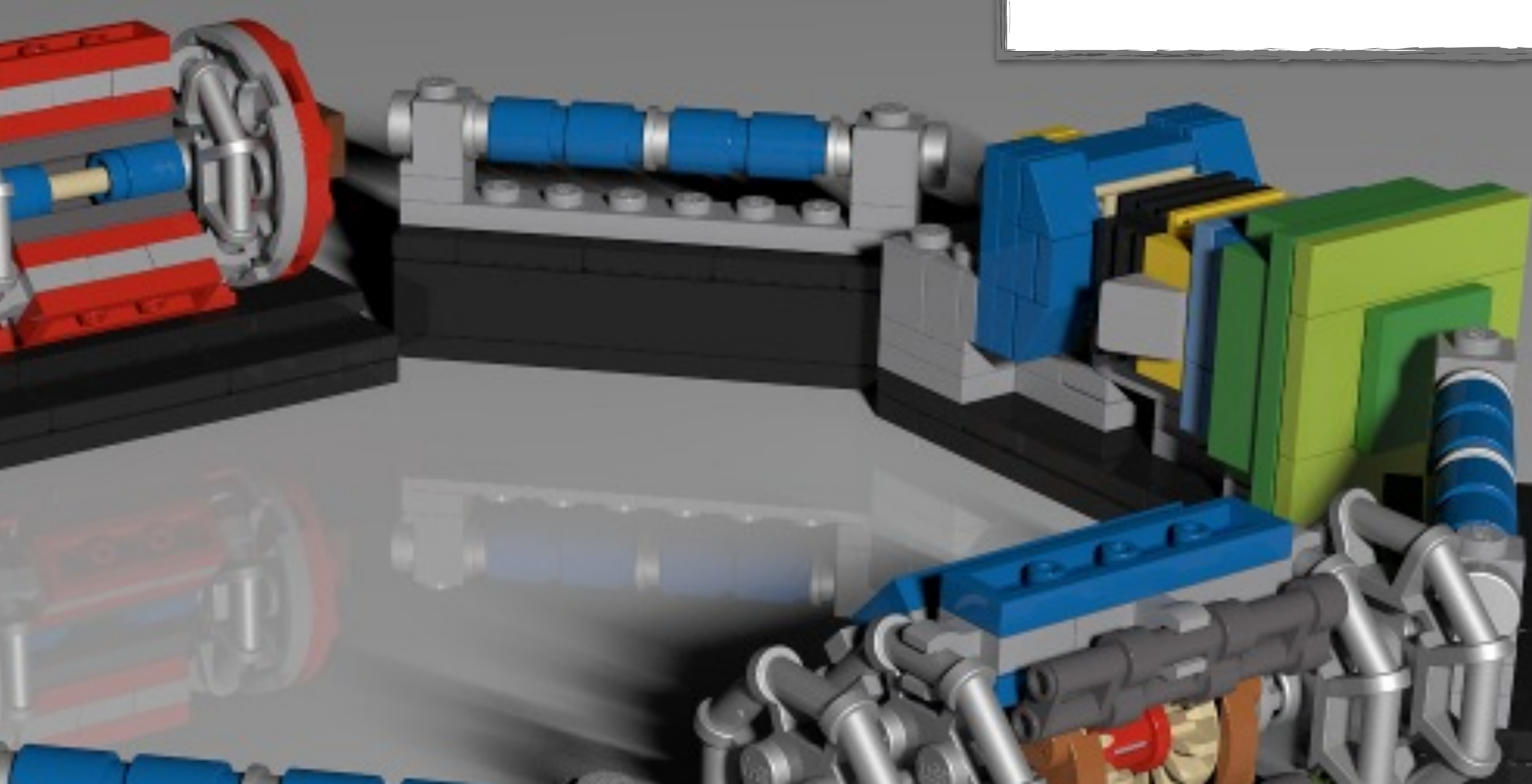
} $\mathcal{O}(20\%\ \mathrm{SM})$ on tree-level process

- Long-standing tension between inclusive and exclusive determinations of $|V_{ub}|$ and $|V_{cb}|$.

Summary

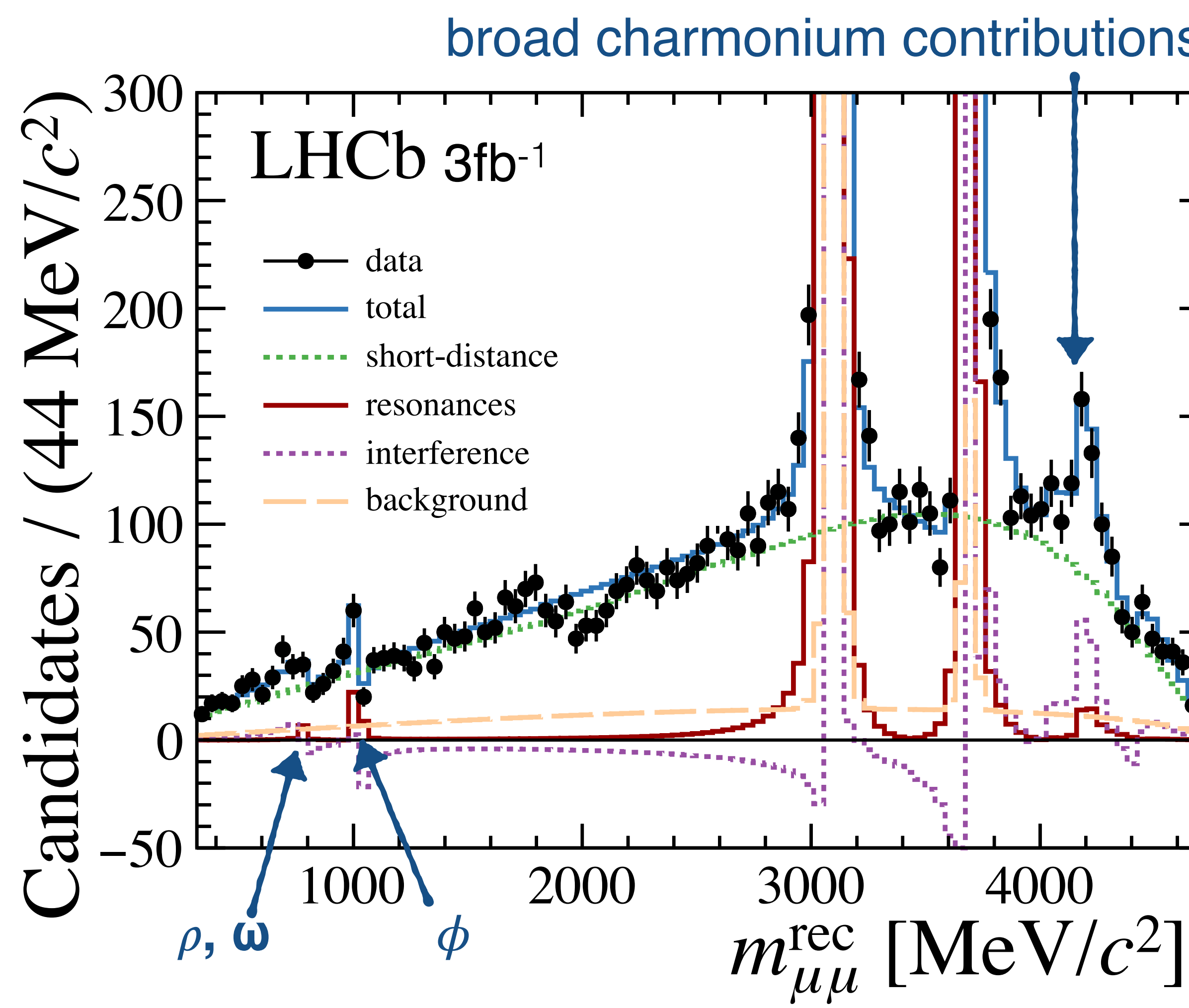
- Huge progress expected in the next five years with new data from the LHC experiments (including parked datasets) and from Belle II.





Resonant contributions

- With the large LHC datasets can also explore the shape of the $d\Gamma/dq^2$ spectrum in detail.
- See evidence for broad charmonium states and light quark contributions.
- Can determine relative magnitude/phases of the different contributions.



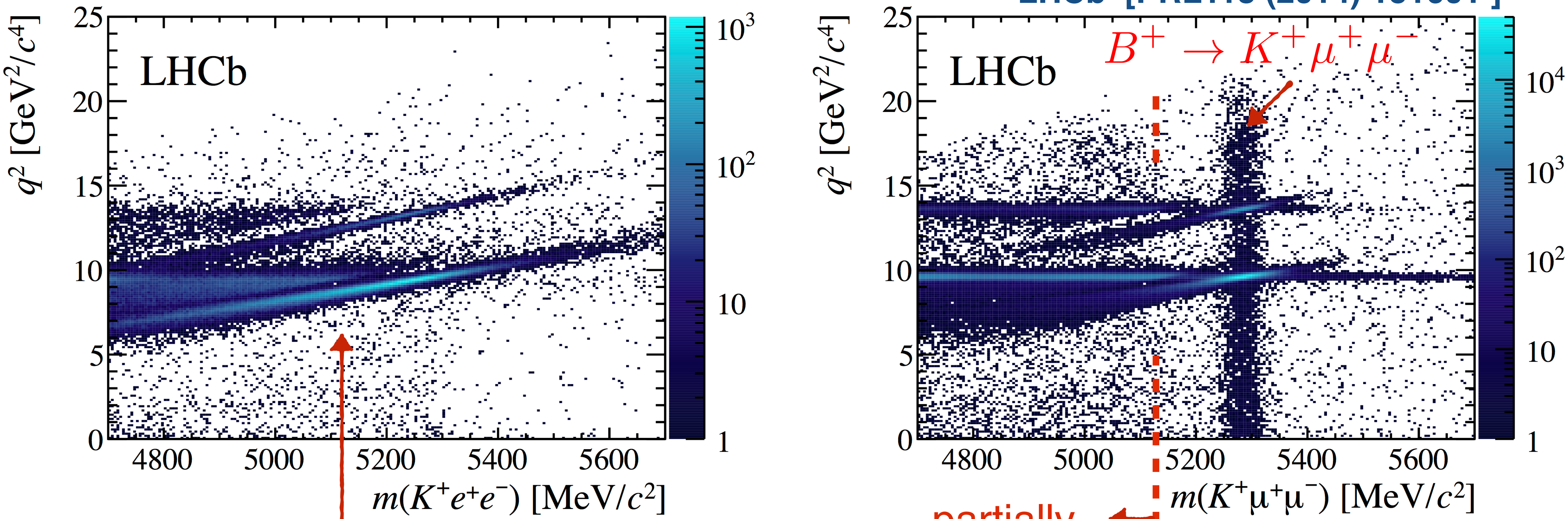
[LHCb, EPJC (2017) 77 161]

- Data could be used to exclude models proposing new GeV-scale particles as an explanation for R_K/R_{K^*}. **[F. Sala & D. Straub, arXiv:1704.06188]**

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

- Even after Bremsstrahlung recovery there are significant differences between dielectron and dimuon final states:

LHCb [PRL113 (2014) 151601]



Large radiative tail and migration of events (even after Brem. recovery).

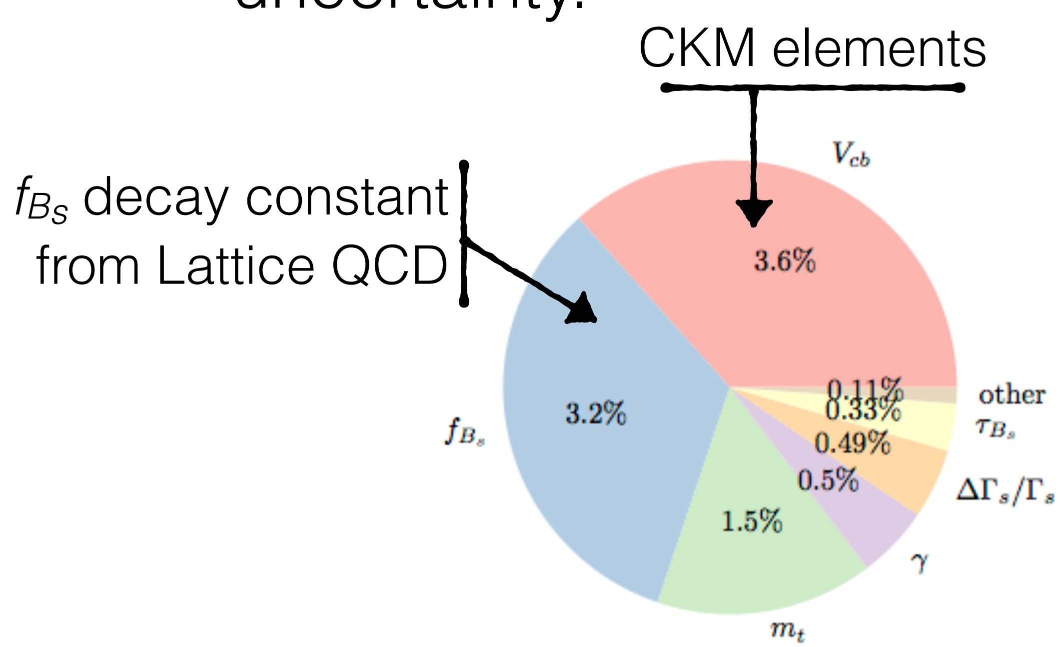
partially reconstructed decays

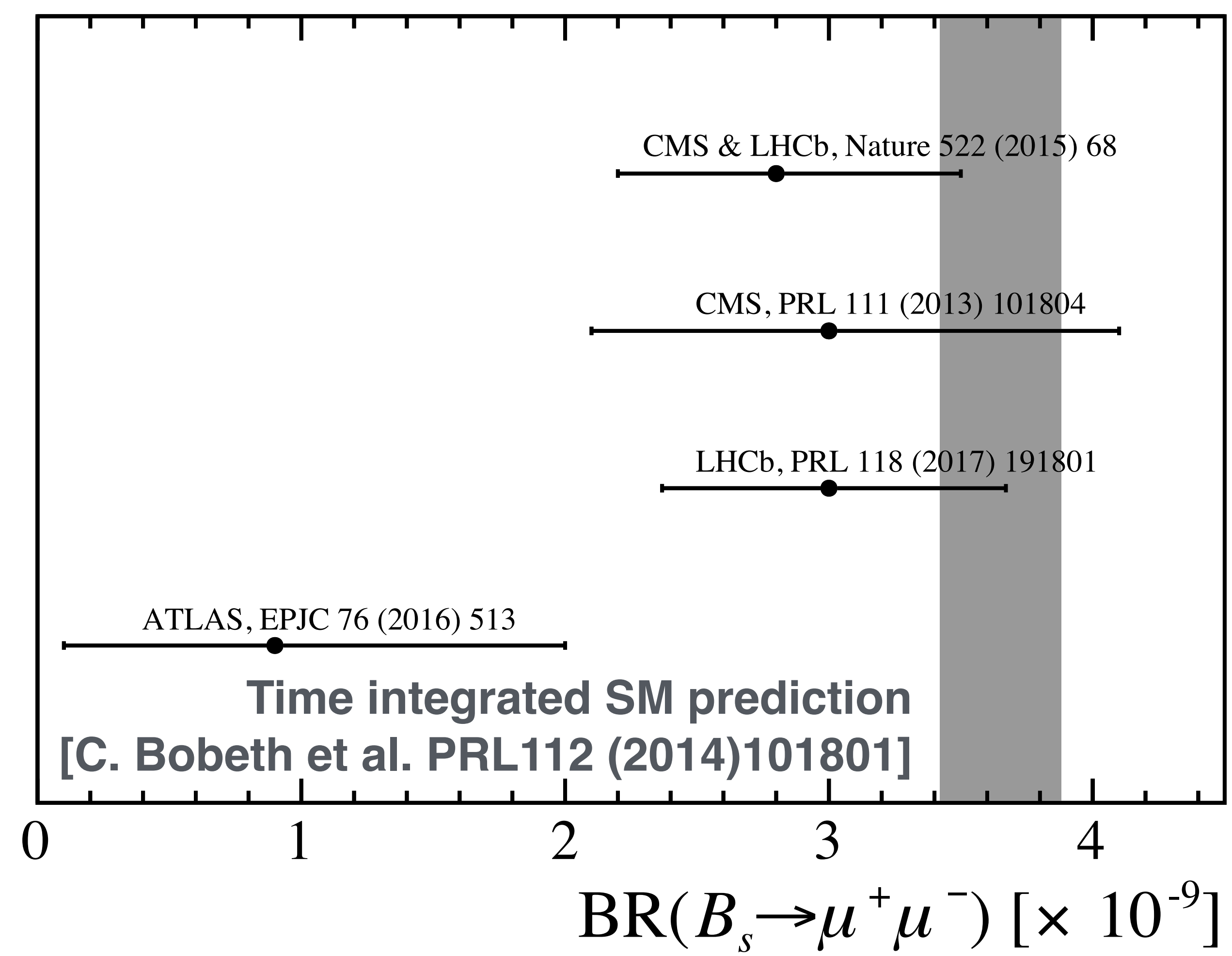
$B_s \to \mu^+\mu^-$

- Recent LHCb analysis using run 1 and 2 data (3fb^{-1} +1.4fb^{-1}) provided the first single experiment observation of $B_s \to \mu^+\mu^-$ at more than 7σ.
  [LHCb, PRL 118 (2017) 191801]

- Measurements are all consistent with the SM expectation.
  - ➡ Can exclude large scalar contributions.

- Branching fraction predicted precisely in the SM with a ~6% uncertainty.





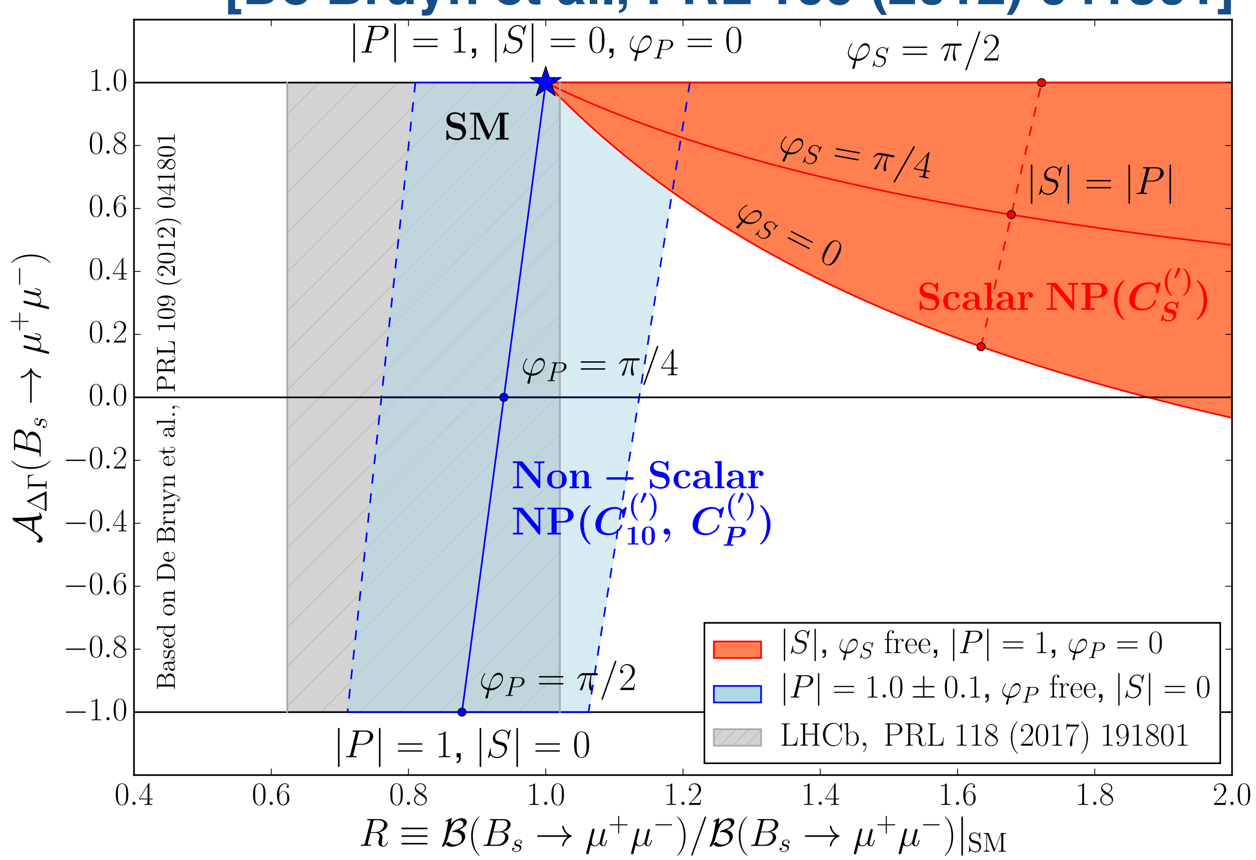
Effective lifetime

- The untagged time dependent decay rate is

$$\Gamma[B_s(t) \to \mu^+\mu^-] + \Gamma[\bar{B}_s(t) \to \mu^+\mu^-] \propto$$
$$e^{-t/\tau_{B_s}} \left\{ \cosh\left(\frac{\Delta\Gamma_s}{2} t\right) + A_{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_s}{2} t\right) \right\}$$

- $A_{\Delta\Gamma}$ provides additional separation between scalar and pesudoscalar contributions.
- In the SM $A_{\Delta\Gamma} = 1$ such that the system evolves with the lifetime of the heavy B_s mass eigenstate.

[De Bruyn et al., PRL 109 (2012) 041801]



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

- The $A_{\Delta\Gamma}$ parameter modifies the effective lifetime of the decay:

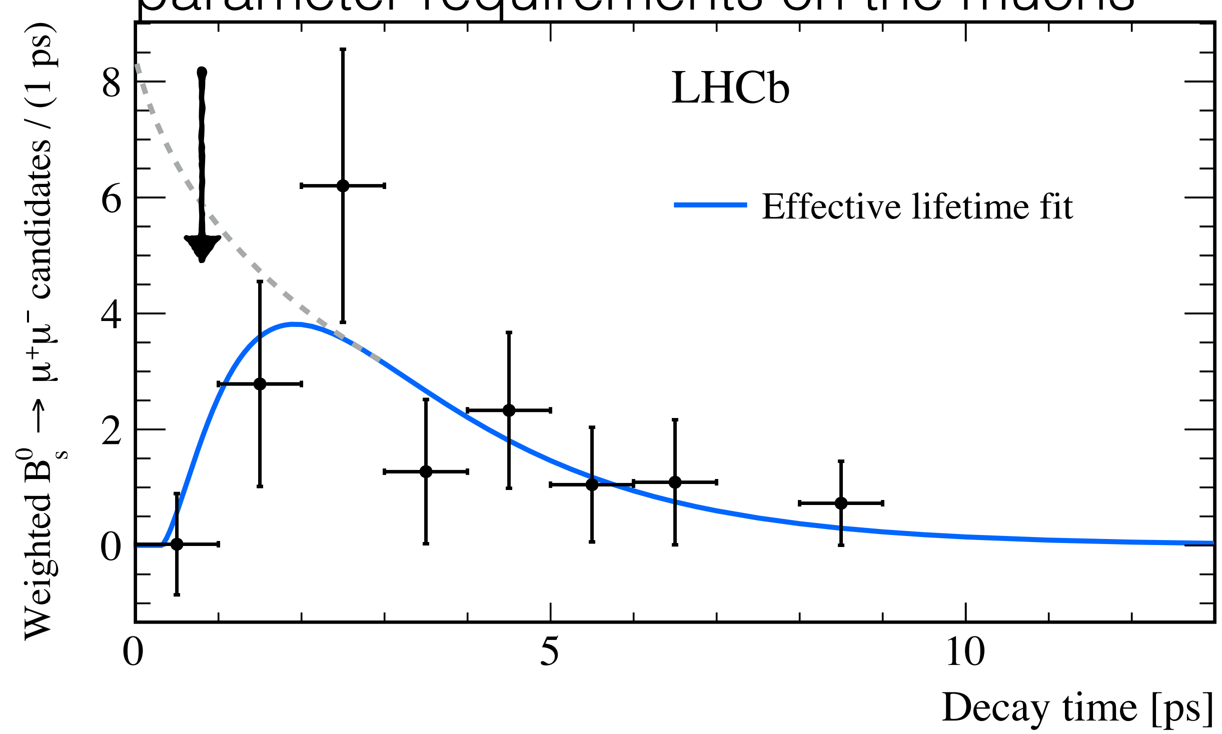
$$\tau_{\rm eff} = \frac{\tau_{B_s}}{1-y_s^2}\left(\frac{1+2A_{\Delta\Gamma}\,y_s+y_s^2}{1+A_{\Delta\Gamma}\,y_s}\right) \quad \text{where} \quad y_s = \tau_{B_s}\frac{\Delta\Gamma}{2}$$

- LHCb have performed a first measurement of $\tau_{\rm eff}$, giving

$$\tau[B_s^0\to\mu^+\mu^-] = 2.04\pm0.44\pm0.05\,{\rm ps}$$

NB Not yet sensitive to $A_{\Delta\Gamma}$ (the stat. uncertainty is larger than the change in the lifetime from $\Delta\Gamma_s$). This will become more interesting during runs 3 and 4.

lifetime acceptance, due to impact parameter requirements on the muons

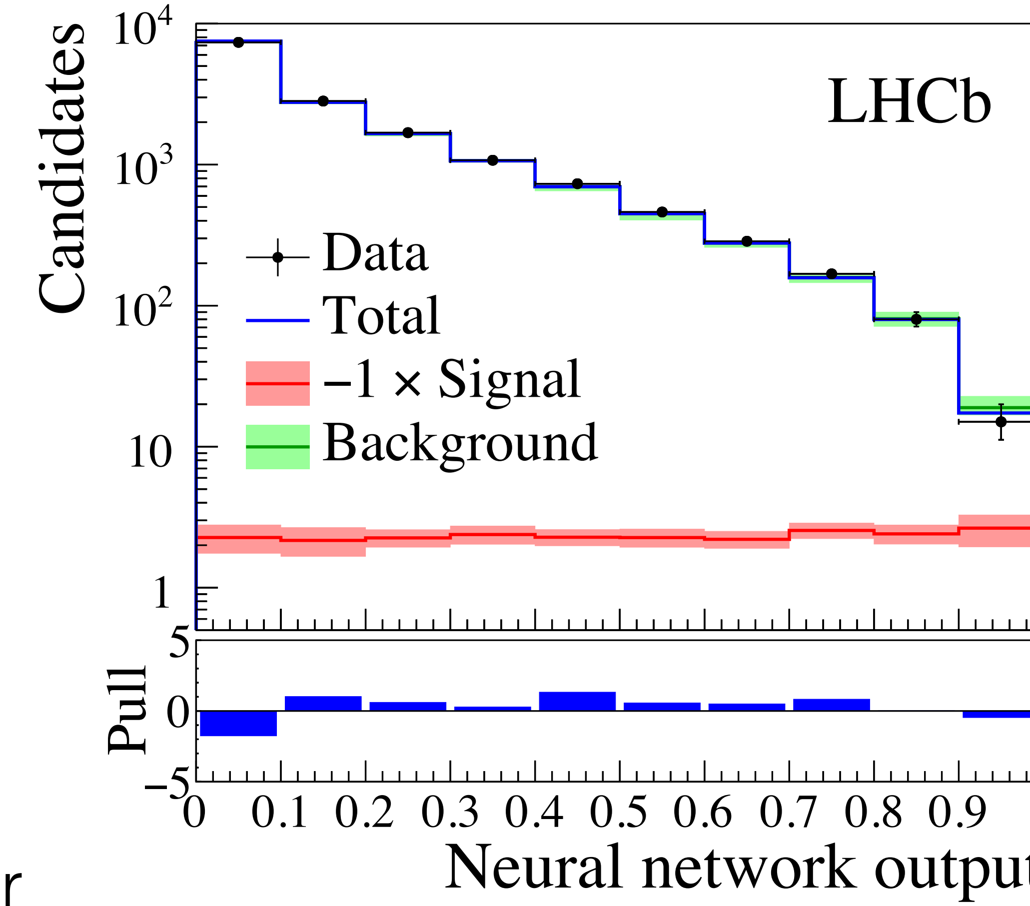


[LHCb, PRL 118 (2017) 191801]

$B_{(s,d)} \to \tau^+\tau^-$

- LHCb performs a search for $B_{(s,d)} \to \tau^+\tau^-$ decays using $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$.
    - ➡ Exploit the $\tau^- \to a_1(1260)^-\nu_\tau$ and $a_1(1260)^- \to \rho(770)^0\pi^-$ decays to select signal/control regions of dipion mass.
- Fit Neural network response to discriminate signal from background.
    - ➡ Ditau mass is not a good discriminator due to missing neutrino energy.
- LHCb sets limits on:

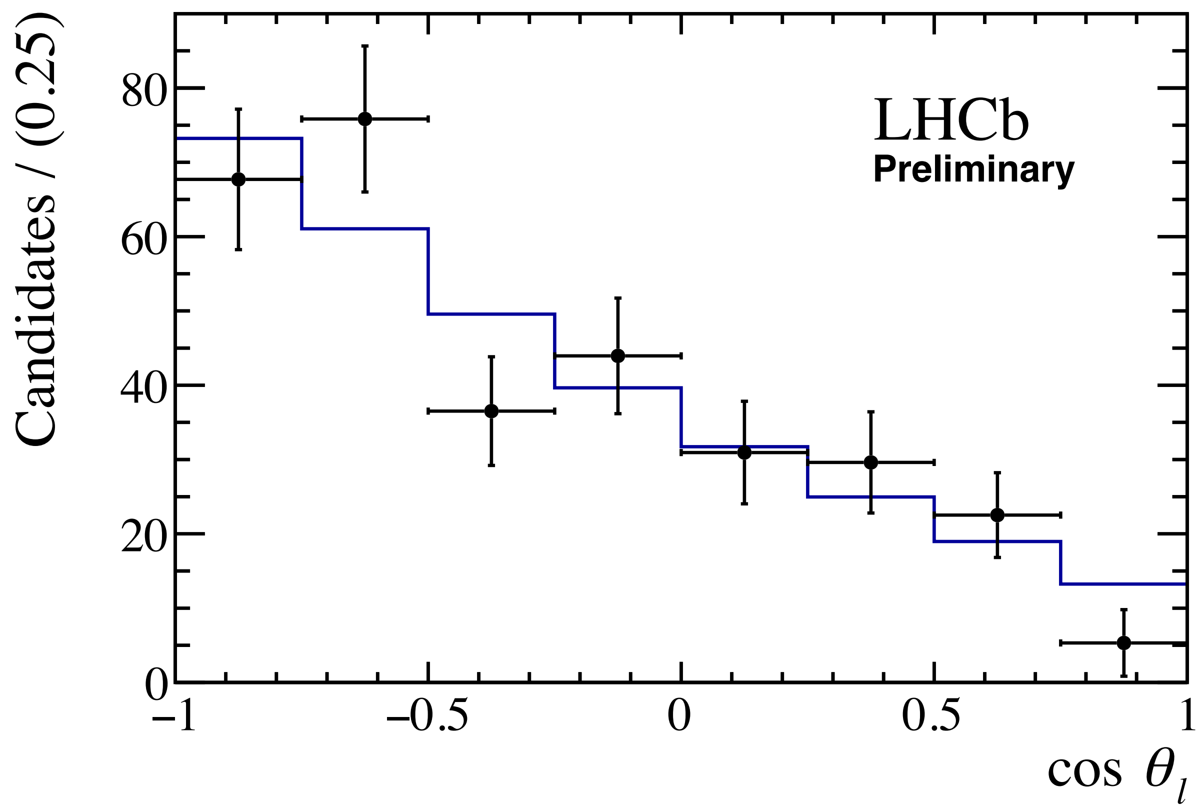
$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3}\ (95\%\ \mathrm{CL})$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3}\ (95\%\ \mathrm{CL})$$

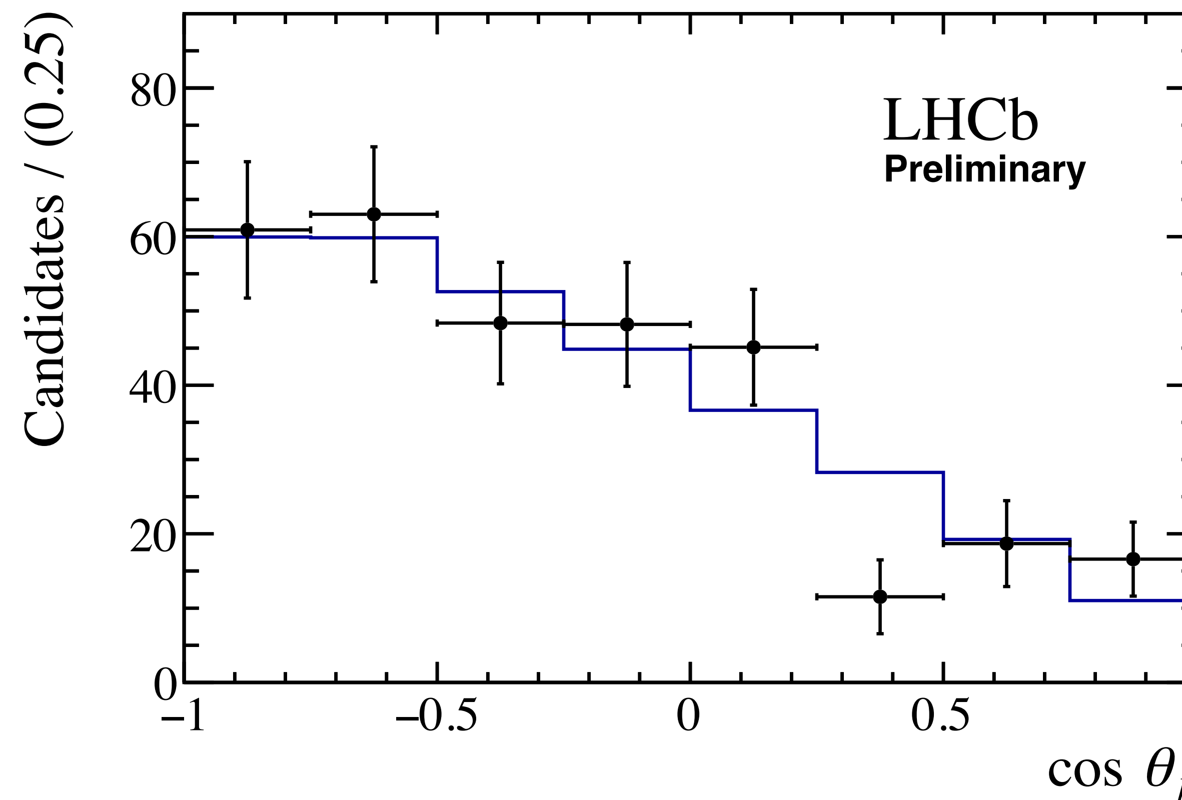


[LHCb, PRL 118 (2017) 251802]

First limit on $B_s \to \tau^+\tau^-$ and worlds best limit on $B^0 \to \tau^+\tau^-$

$\Lambda_b \to \Lambda\mu^+\mu^-$ angular distribution





[LHCb-PAPER-2018-029]

- Large asymmetries on both the lepton- and hadron-side:

$$A_{\rm FB}^{\ell} = -0.39 \pm 0.04\,({\rm stat}) \pm 0.01\,({\rm syst})$$ **Preliminary**

$$A_{\rm FB}^{h} = -0.30 \pm 0.05\,({\rm stat}) \pm 0.02\,({\rm syst})$$ **Preliminary**

$$A_{\rm FB}^{\ell h} = +0.25 \pm 0.04\,({\rm stat}) \pm 0.01\,({\rm syst})$$ **Preliminary**

} Consistent with SM predictions **[PRD 93 (2016) 074501]** ($A_{\rm FB}^{\ell h}$ is ~2σ from its prediction)

- Hadron-side asymmetry due to the weak decay of the Λ baryon.

Effective theory

- Can write a Hamiltonian for an effective theory of $b \to s$ processes:

Wilson coefficient (integrating out scales above μ)

Local 4 fermion operators with different Lorentz structures

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \frac{\alpha_e}{4\pi} \sum_i C_i(\mu) \mathcal{O}_i(\mu),$$

$$\Delta\mathcal{H}_{\text{eff}} = \frac{\kappa_{\text{NP}}}{\Lambda_{\text{NP}}^2} \mathcal{O}_{\text{NP}}$$

NP scale

NP can modify SM contribution or introduce new operators

κ_{NP} can have all/some/none of the suppression of the SM, e.g MFV inherits SM CKM suppression.

c.f. Fermi theory of weak interaction where at low energies:

$$\lim_{q^2 \to 0} \left(\frac{g^2}{m_W^2 - q^2} \right) = \frac{g^2}{m_W^2}$$

i.e. the full theory can be replaced by a 4-fermion operator and a coupling constant, G_F.

Operators

- Different processes are sensitive to different 4-fermion operators.
  - ➡ Can exploit this to over-constrain the system.

$$\mathcal{O}_7 = (m_b/e)\,(\bar{s}\sigma^{\mu\nu}P_R b F_{\mu\nu})$$

photon (constrained by radiative decays and $b \to s\ell^+\ell^-$ processes at small q^2)

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

vector current (constrained by $b \to s\ell^+\ell^-$ processes)

$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

axial vector current (constrained by leptonic decays and $b \to s\ell^+\ell^-$ processes)

$$\mathcal{O}_S = (\bar{s}P_R b)(\bar{\ell}\ell)$$
$$\mathcal{O}_P = (\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell)$$

scalar and pseudoscalar operators (constrained primarily by leptonic decays)

e.g.

$B^0_s \to \mu^+\mu^-$ constrains $C_{10} - C'_{10},\ C_S - C'_S,\ C_P - C'_P$

$B^+ \to K^+\mu^+\mu^-$ constrains $C_9 + C'_9,\ C_{10} + C'_{10}$

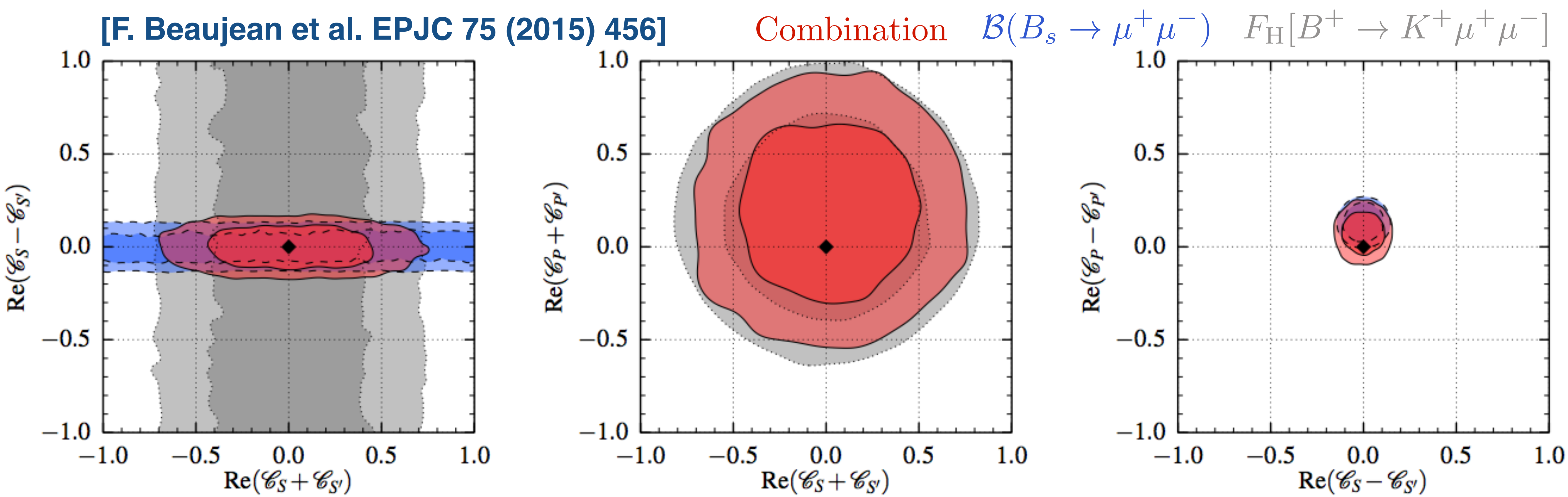
$B^0 \to K^{*0}\mu^+\mu^-$ constrains $C_7 \pm C'_7,\ C_9 \pm C'_9,\ C_{10} \pm C'_{10}$

The primes denote right-handed counterparts of the operators whose contribution is small in the SM.

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

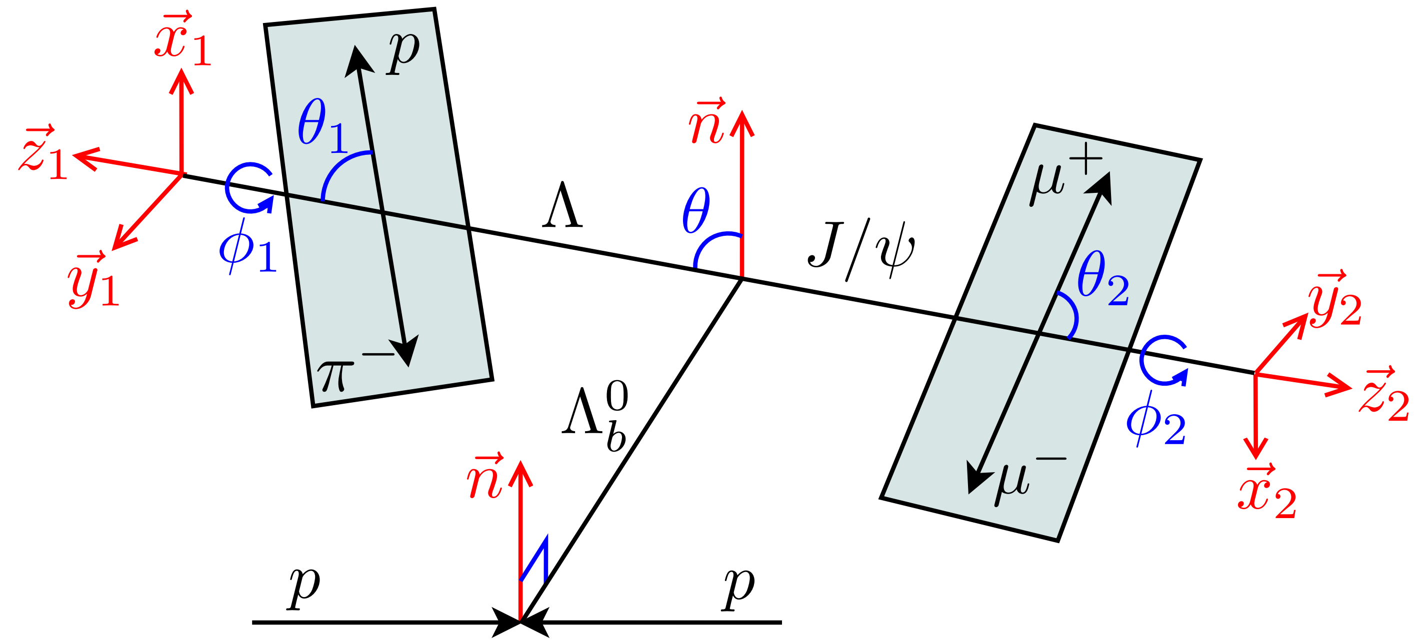
- Angular distribution of $B^+ \to K^+\ell^+\ell^-$ is a null test of SM, but can be sensitive to new scalar/pseudoscalar/tensor contributions, e.g.

[F. Beaujean et al. EPJC 75 (2015) 456]



$\Lambda_b \to \Lambda\mu^+\mu^-$ angular distribution

- If the Λ_b is produced polarised the decay is described by 5 angles and normal-vector, $\hat{n}$.



- Large number of observables:

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

where K_{11}—K_{34} are zero if the Λ_b is unpolarised. **[Blake et al. JHEP 11 (2017) 138]**

- Determine observables using the *method of moments* and a set of orthogonal weighing functions.

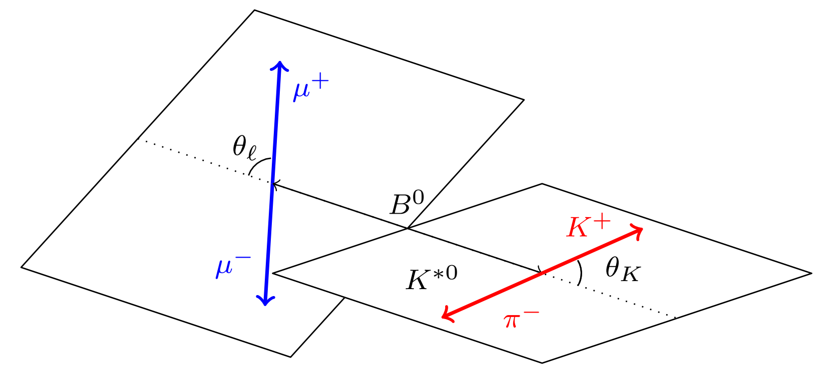
- Correct for angular efficiency using per-candidate weights determined on simulated phasespace events.

- Analysis cross-checked using $B^0 \to J/\psi K_S$ and $\Lambda_b \to J/\psi\Lambda$ decays selected in same way as the signal.

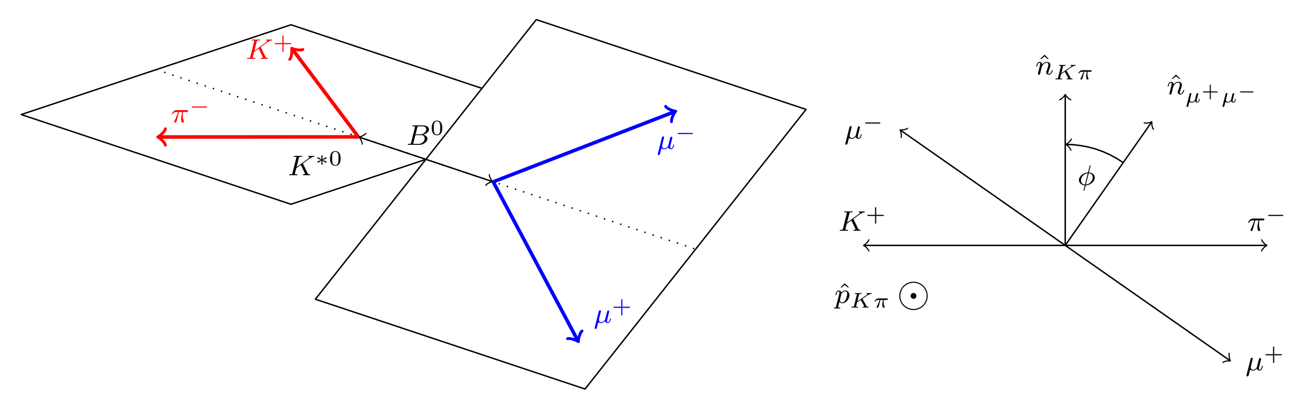
Angular observables

- Angular distribution provides many observables that are sensitive to BSM effects.
- Constraints are orthogonal to branching fraction measurements, both in their impact in global fits and in terms of experimental uncertainties.

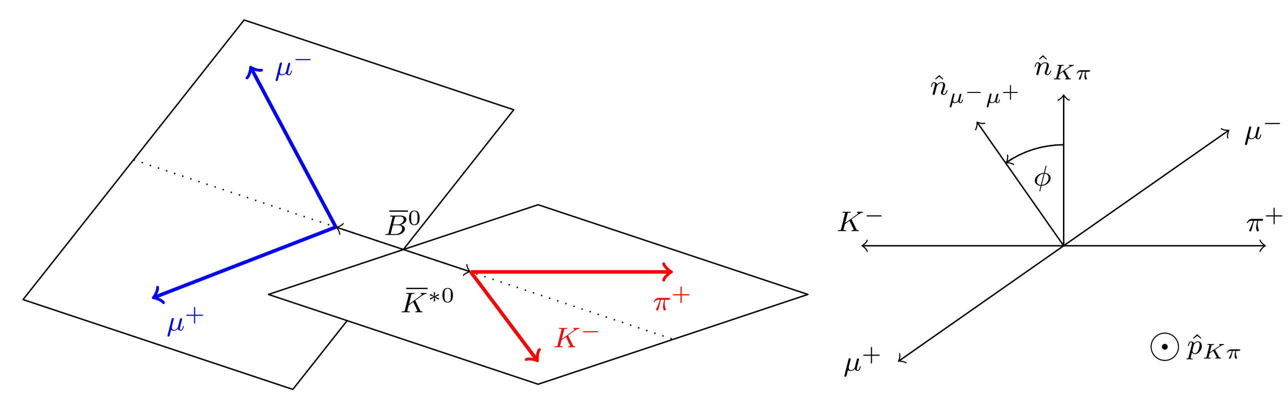
eg $B \to K^{*0}\mu^+\mu^-$ decay described by three angles and q^2.



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay



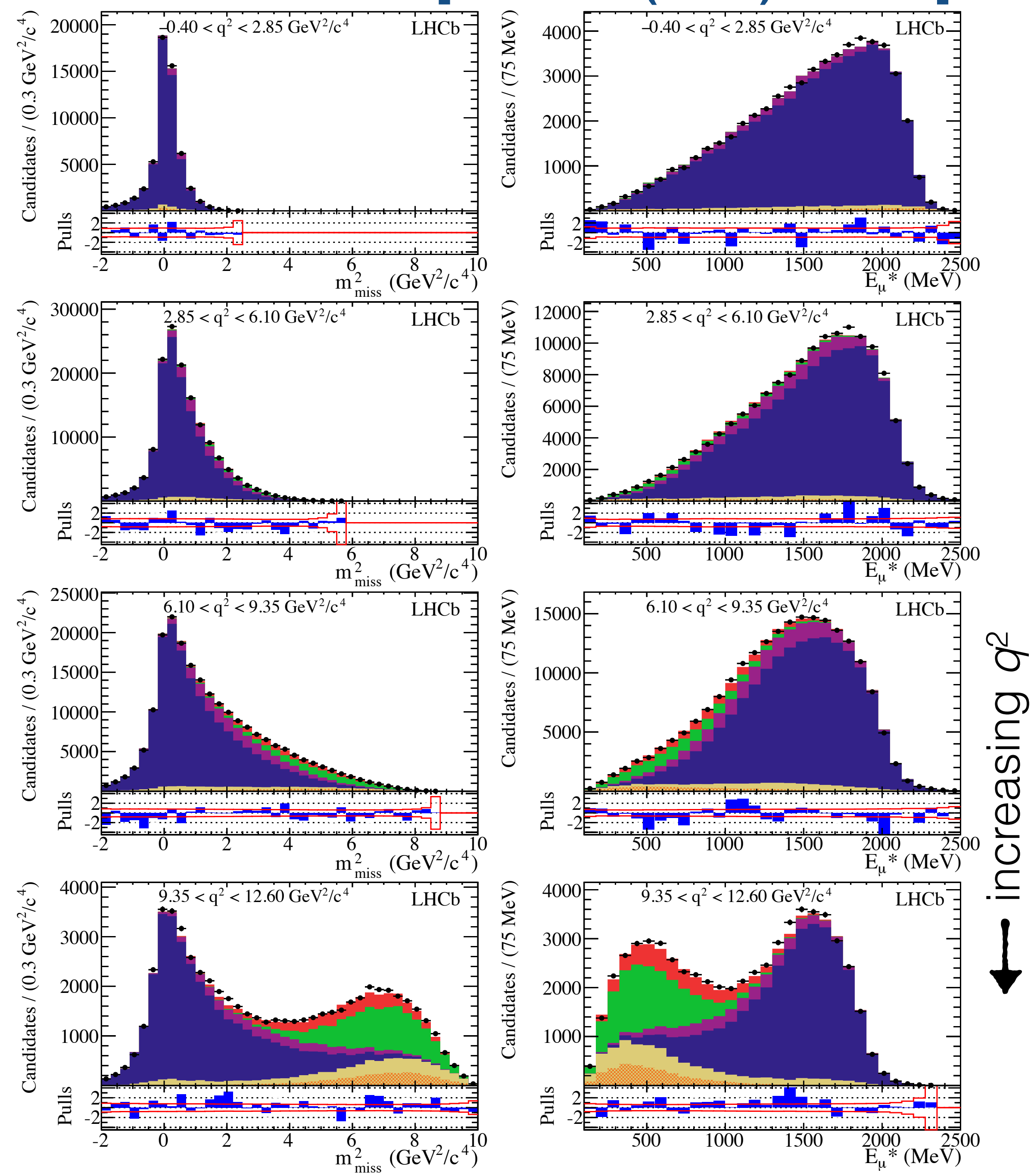
(c) ϕ definition for the $\overline{B}^0$ decay

$R(D^*)$ with $\tau \to \mu\nu$

LHCb [PRL 115 (2015) 111803]

- Experimental challenge is to separate signal from backgrounds.
  - ➡ Use missing mass, lepton energy, q^2 and multivariate discriminants.
  - ➡ Can use boost approximation to determine kinematic quantities ($(\beta_z\gamma)_{\rm vis} \approx (\beta_z\gamma)_B$).
- *B*-factory experiments can exploit leptonic/hadronic tag of the other *B* in the event and centre-of-mass constraints.

Modelling of *D* and hadronic background is important**



B* → *D** τν**, ***B* → *D** *H*c(→ μν *X*') *X, ***B* → *D***μν**,
***B* → *D**μν**, **combinatorial**, **misidentified**

V_{ub} and V_{cb}

[hflav.web.cern.ch]

- Long-standing tension between inclusive and exclusive determinations of V_{ub} and V_{cb}.