technische universität dortmund

Experimentelle Physik V
Teilchenphysik

QUARK FLAVOUR PHYSICS

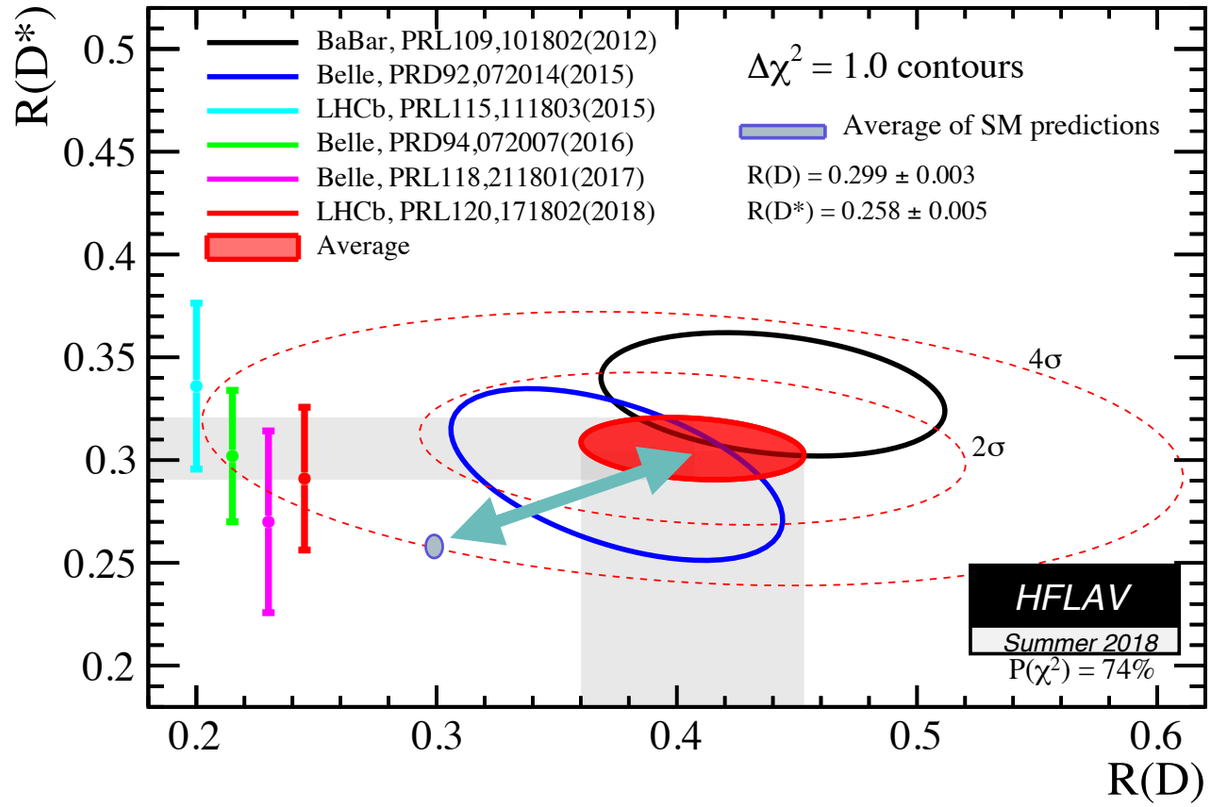
Stefanie Reichert (TU Dortmund) on behalf of the LHCb collaboration

26th International Conference on Supersymmetry and Unification of Fundamental Interactions
Barcelona, Spain
25 July 2018

WHY FLAVOUR?

- Flavour sector enables many null tests of Standard Model (SM)
  - e.g. CKM triangle unitary?
- SM suppressions such as CKM and GIM lead to a variety of interesting rare decays
  → excellent probe for NP
- Anomalies have been observed
  - in $b \to c\ell\nu$ with τ vs. light leptons and
  - in $b \to s\ell\ell$ decays (μ vs. e)

[HFLAV summer 2018]

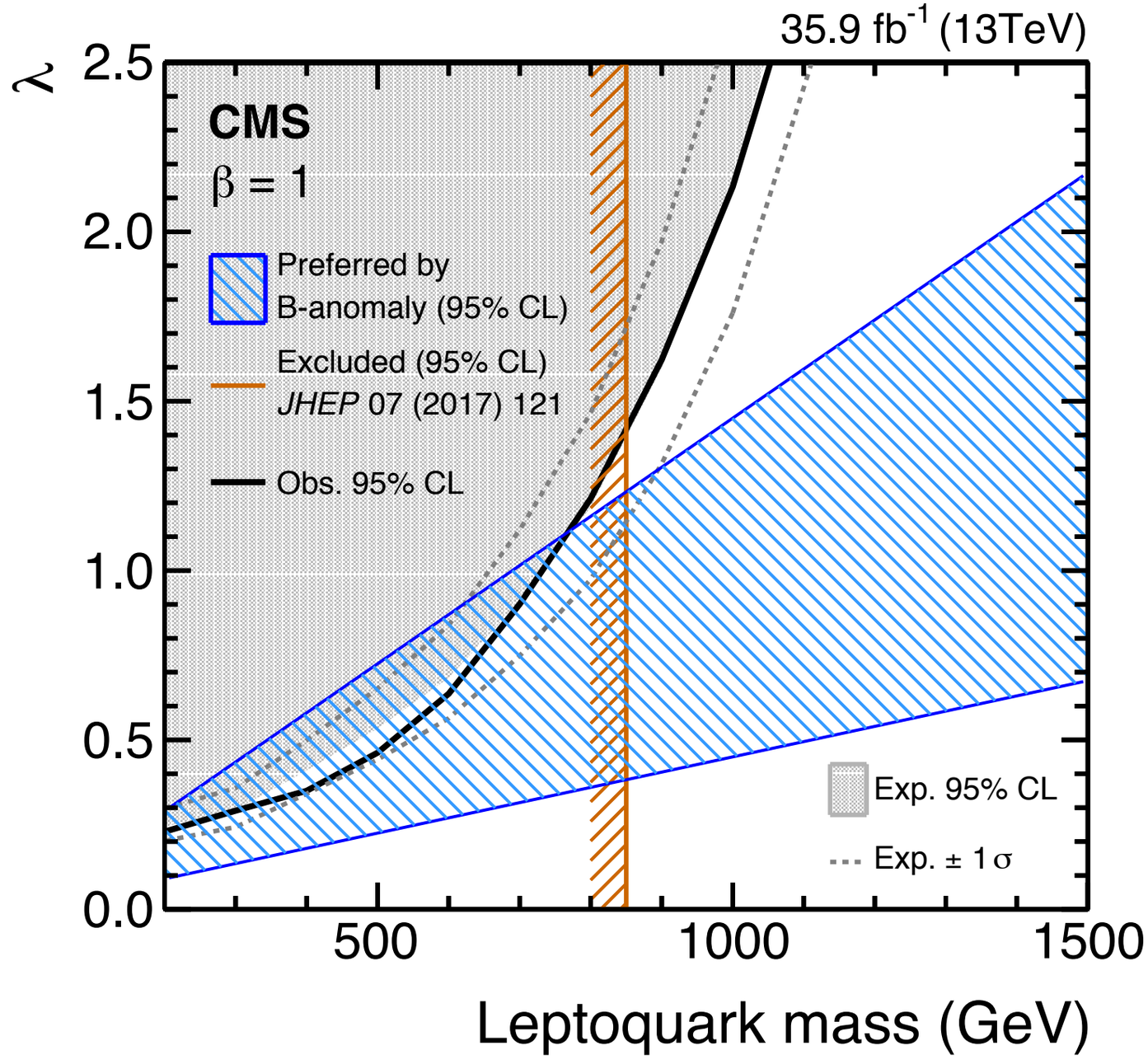


Difference between world average and SM predictions at 3.8σ

See talks by D. Bardhan and G. De Nardo

DIRECT AND INDIRECT SEARCHES

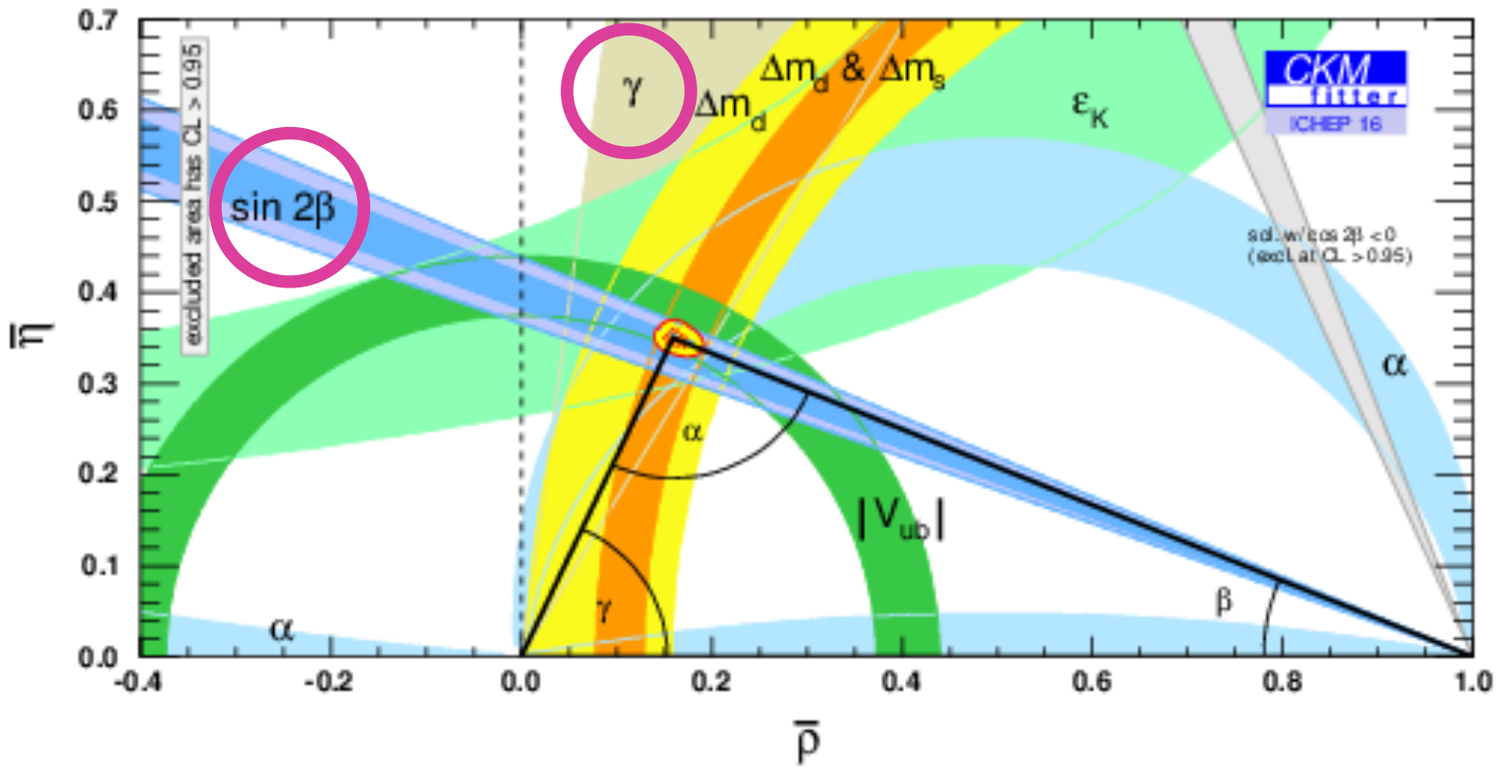
- So far, no sign for new physics (NP) in direct searches e.g. leptoquarks
- Indirect searches allow to probe NP models to much higher mass scales than currently accessible
- NP could affect
  - angular distributions,
  - branching ratios, …



[CMS-EXO-17-029]

WHERE TO LOOK FOR NEW PHYSICS

- Over-constrain CKM triangle to ensure its unitarity; mixing and CP violation in B decays



[CKMFitter for ICHEP 2016]

- Mixing and CP violation in charm decays
- Rare decays as strong SM suppression could be lifted by NP

CKM and CPV

See talk by M. Alexander

See talk by J. Garcia Pardinas

CKM TRIANGLE AMBIGUITY

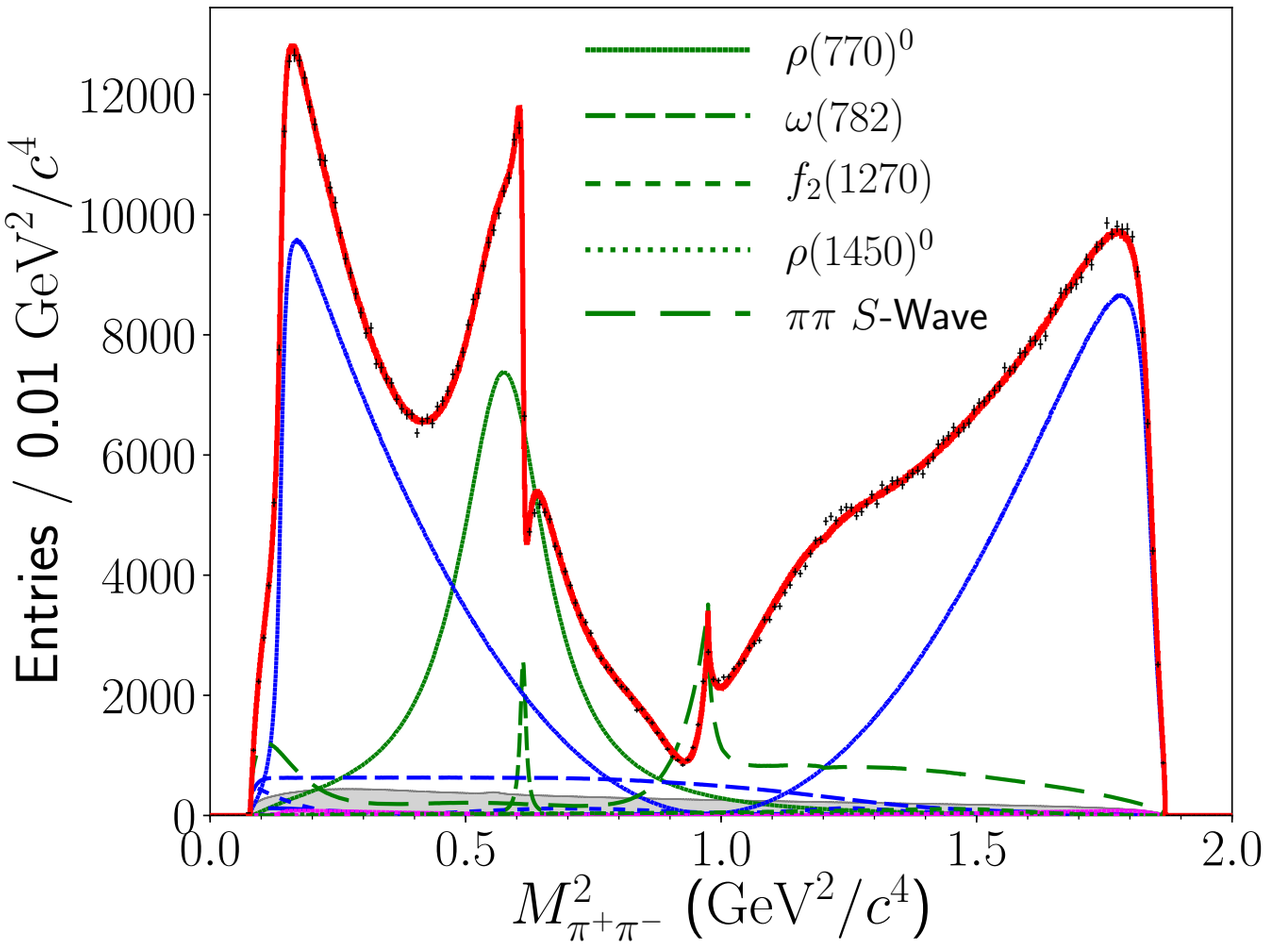
- Measurements of sin(2β) from $B^0 \to J/\psi K^0_S$ decays allow to infer 2β with a two-fold ambiguity:
  2β and π-2β

- Resolve ambiguity in CKM triangle by measuring cos(2β)
  [arXiv:1804.06152 [hep-ex],
  arXiv:1804.06153 [hep-ex]]

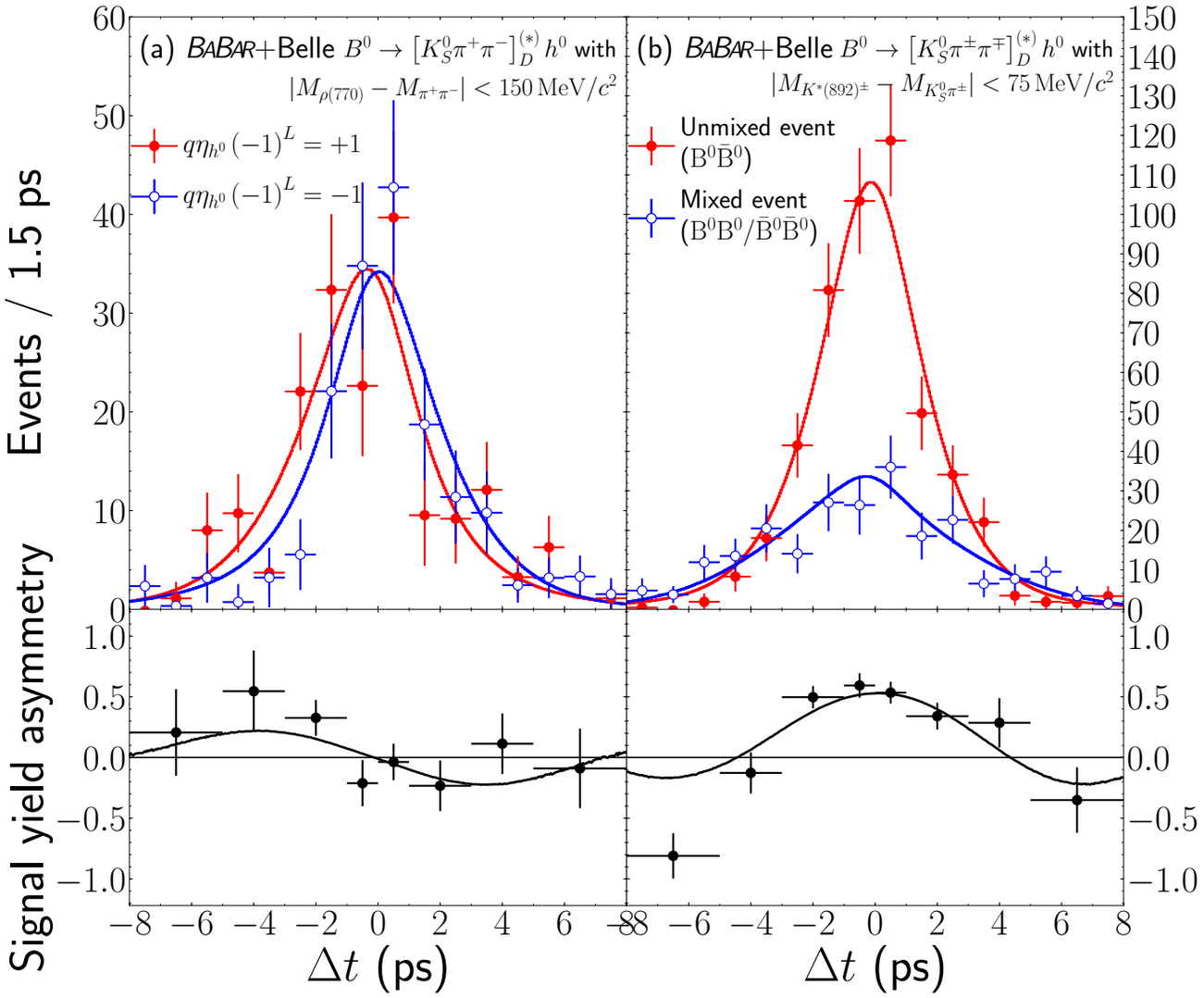
- Time-dependent Dalitz plot analysis of $B^0 \to D^{(*)}h^0$ with $D \to K^0_s\pi^+\pi^-$decays
  (notation includes D^0 and $\overline{D}^0$)

- Combined BaBar and Belle datasets of 1.1ab^{-1} at Y(4S)

[arXiv:1804.06153 [hep-ex]]



[arXiv:1804.06152 [hep-ex]]



Compatible with world average

$\sin(2\beta) = 0.691 \pm 0.017$ [HFLAV]

and LHCb result

$\sin(2\beta) = 0.760 \pm 0.034$ [JHEP 11 (2017) 170]

CKM TRIANGLE AMBIGUITY

- Results in

  $\sin(2\beta) = 0.80 \pm 0.14 \pm 0.06 \pm 0.03$

  $\cos(2\beta) = 0.91 \pm 0.22 \pm 0.09 \pm 0.07$

- Significance of $\cos(2\beta) > 0$ exceeds 3.7σ

- Alternative fit yields

  $\beta = (22.5 \pm 4.4 \pm 1.2 \pm 0.6)^\circ$

  → observation of CPV at 5.1σ in $B^0 \to D^{(*)}h^0$ decays

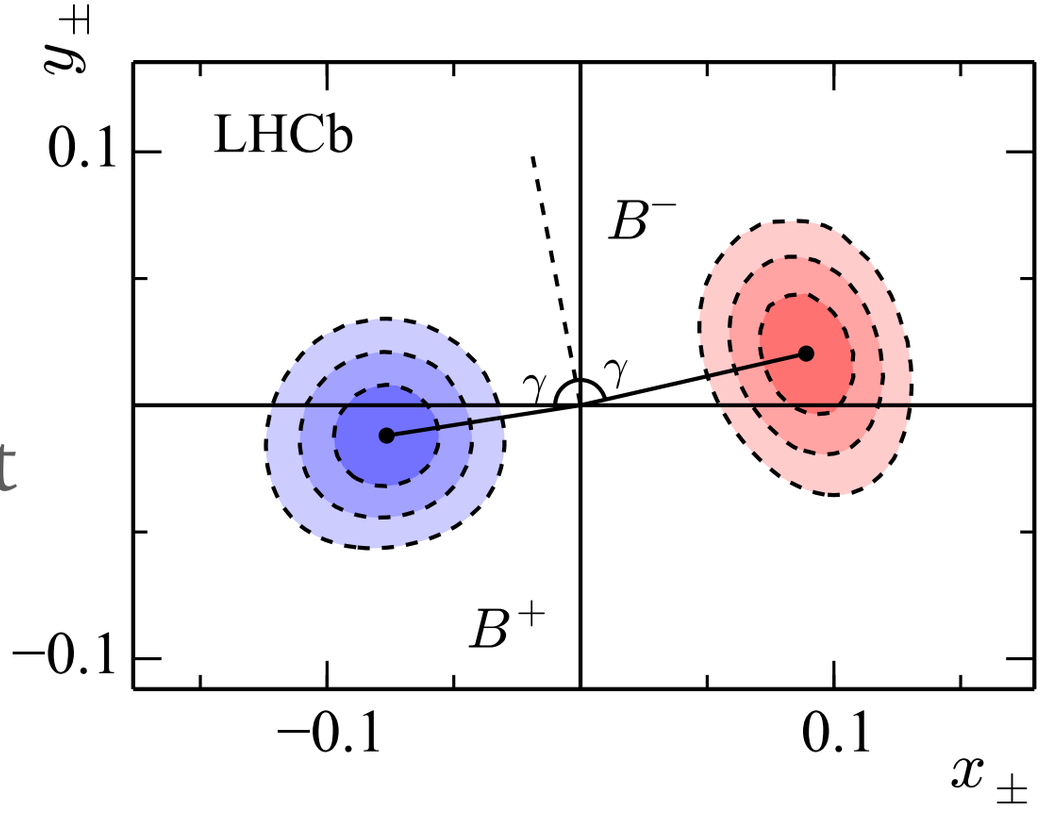
- Excludes ambiguous solution

  $\pi/2 - \beta = (68.1 \pm 0.7)^\circ$

  at level of 7.3σ

CKM CONTINUED

- Extract γ from $B^{\pm} \to DK^{\pm}$ with $D \to K^0_s\pi^+\pi^-$ and $D \to K^0_s K^+K^-$ decays [arXiv:1806:01202 [hep-ex] with 2fb^{-1} LHCb data (Run 2 update)
- Fit to extract cartesian parameters $x_{\pm} = r_B \cos(\delta_B \pm \gamma)$ and $y_{\pm} = r_B \sin(\delta_B \pm \gamma)$ using external input from CLEO
- Non-zero opening angle between (x_-, y_-) and (x_+, y_+) equals 2 γ
- Maximum likelihood fit to extract underlying physics parameters
- For $0° < \gamma < 180°$

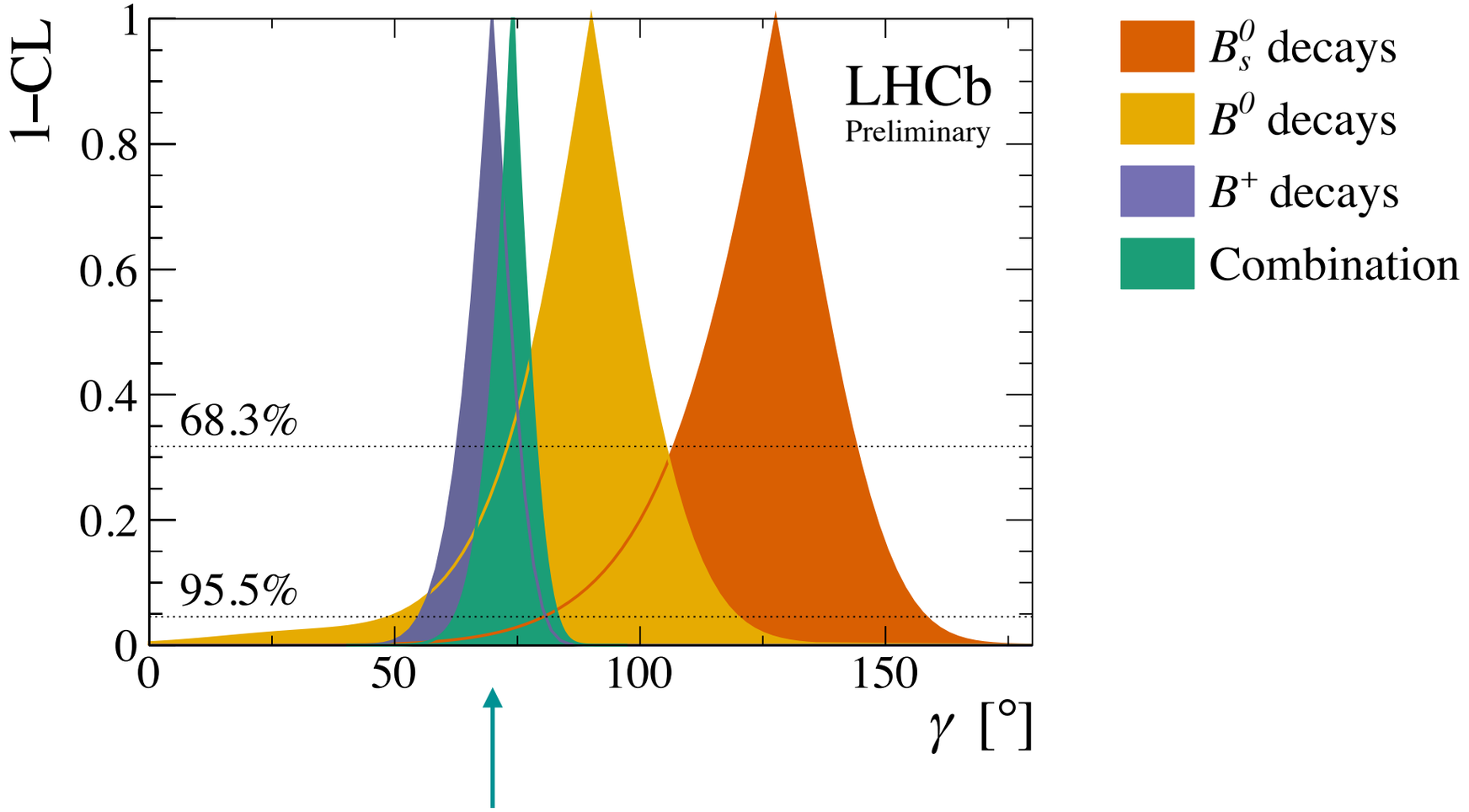


[arXiv:1806:01202 [hep-ex]]

$$\gamma = 87° \,^{+11°}_{-12°}, \quad r_B = 0.087^{+0.013}_{-0.014}, \quad \delta_B = 101° \,^{+11°}_{-11°}$$

CKM COMBINED

- Combination of all γ measurements at LHCb [LHCb-CONF-2018-002]



$$\gamma = \left(74.0^{+5.0}_{-5.8}\right)^\circ$$

γ is becoming a precision measurement

ROOM FOR NEW PHYSICS?

- Quantify new physics (NP) contribution in terms of complex amplitude

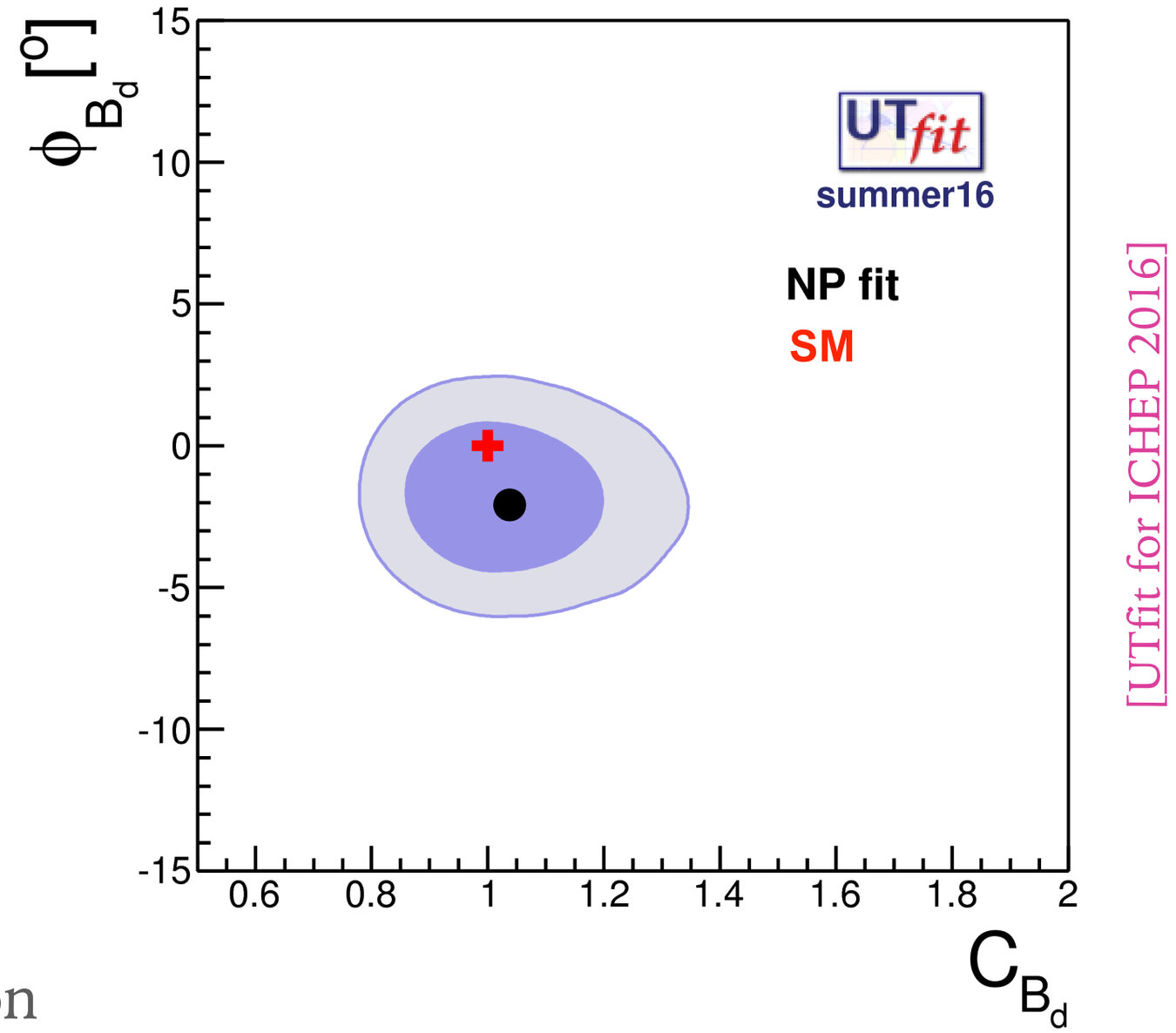
$$C_{B_d} e^{2i\phi_{B_d}} = \frac{\langle B_d^0 | H_{\text{eff}}^{\text{SM+NP}} | \overline{B}_d^0 \rangle}{\langle B_d^0 | H_{\text{eff}}^{\text{SM}} | \overline{B}_d^0 \rangle}$$

- Fit result [UTfit for ICHEP 2016]

$$C_{B_d} = 1.03 \pm 0.11$$

$$\phi_{B_d} = (-1.8 \pm 1.7)^\circ$$

compatible with SM expectation

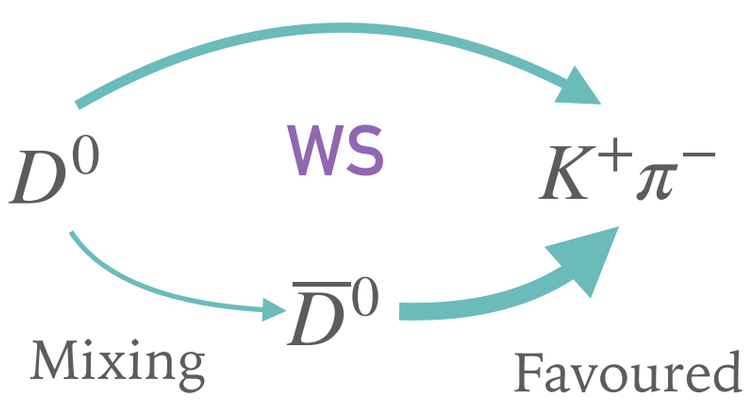


MIXING AND CPV IN CHARM

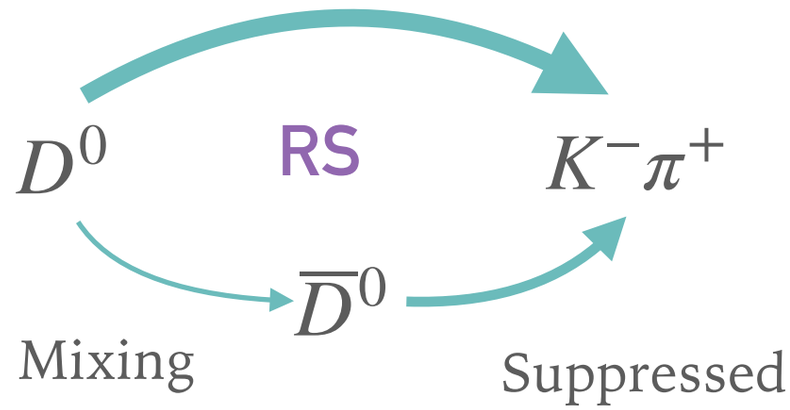
- Update of charm mixing and CPV parameters in $D^0 \to K^+\pi^-$ decays [PR D97 (2018) 031101] on 5fb^{-1} of LHCb data
- Wrong-sign (WS) and right-sign (RS) decays

No CPV in Charm observed yet!

Suppressed



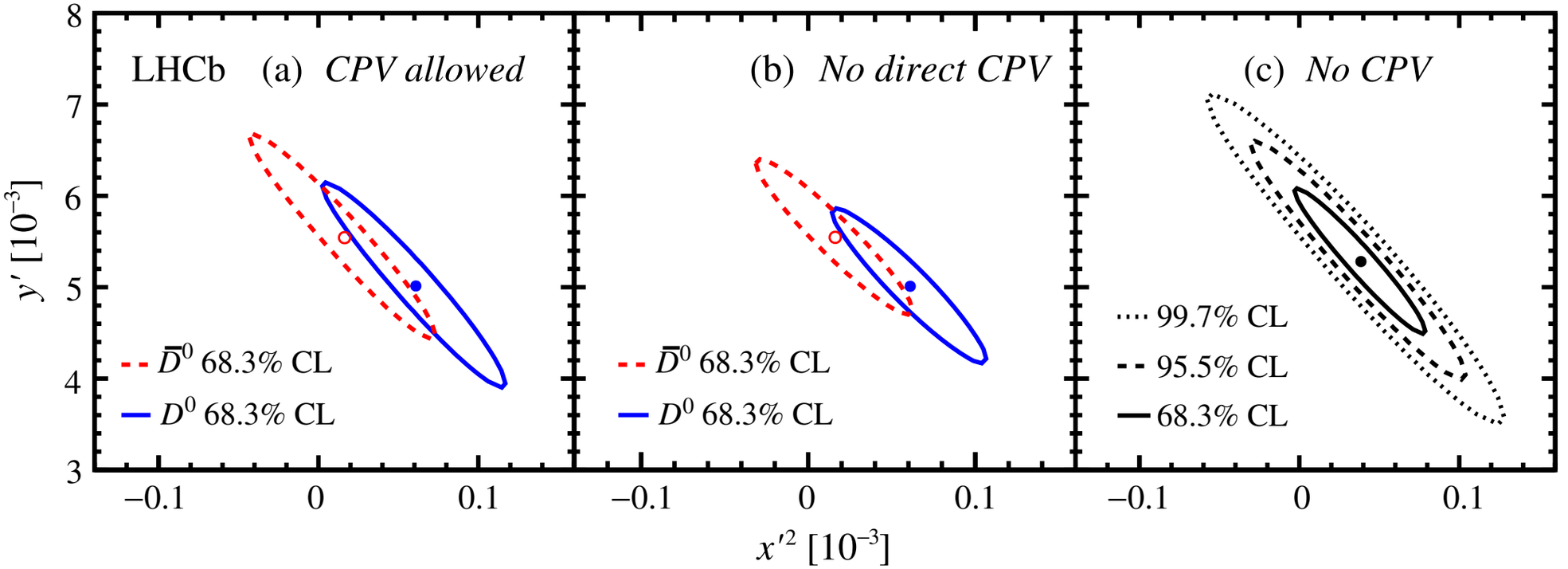
Favoured



- CP-averaged time-dependent ratio of WS to RS

$$R(t) \sim R_D + \sqrt{R_D}y'\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

MIXING AND CPV IN CHARM



[PR D97 (2018) 031101]

CP symmetry

$$x'^2 = (3.9 \pm 2.7) \cdot 10^{-5}$$

$$y' = (5.28 \pm 0.52) \cdot 10^{-3}$$

$$R_D = (3.454 \pm 0.031) \cdot 10^{-3}$$

no CP symmetry

$$A_D = (-0.1 \pm 9.1) \cdot 10^{-3}$$

$$1.00 < |q/p| < 1.35$$

NP could enhance mixing parameters

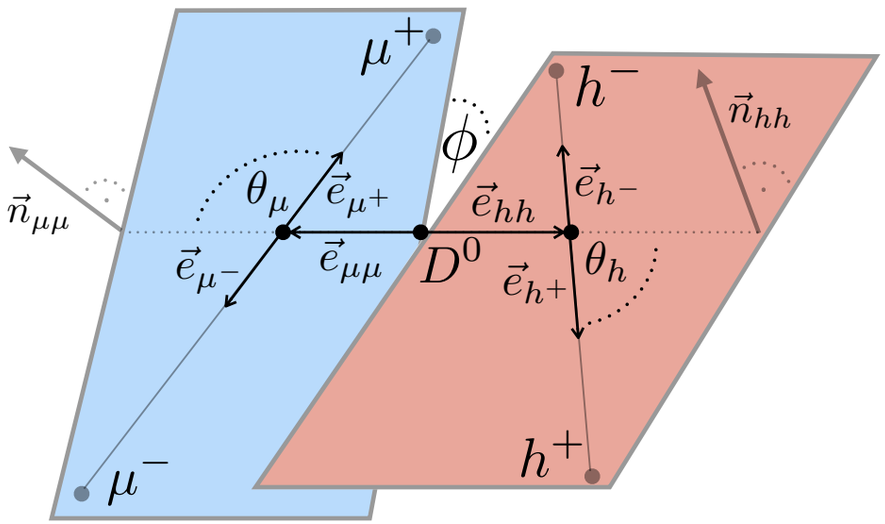
CPV IN RARE CHARM

- Short-distance contributions to inclusive $D^0 \to X\mu^+\mu^-$ decays (FCNCs) sensitive to NP
- Distinguishable from long-distance contributions by studying kinematic correlations and CP asymmetries [arXiv:1806.10793 [hep-ex]]
- Measured on LHCb's 5fb^{-1} dataset

$$A_{\mathrm{FB}} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)}$$

$$A_{2\phi} = \frac{\Gamma(\sin 2\phi > 0) - \Gamma(\sin 2\phi < 0)}{\Gamma(\sin 2\phi > 0) + \Gamma(\sin 2\phi < 0)}$$

$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}$$

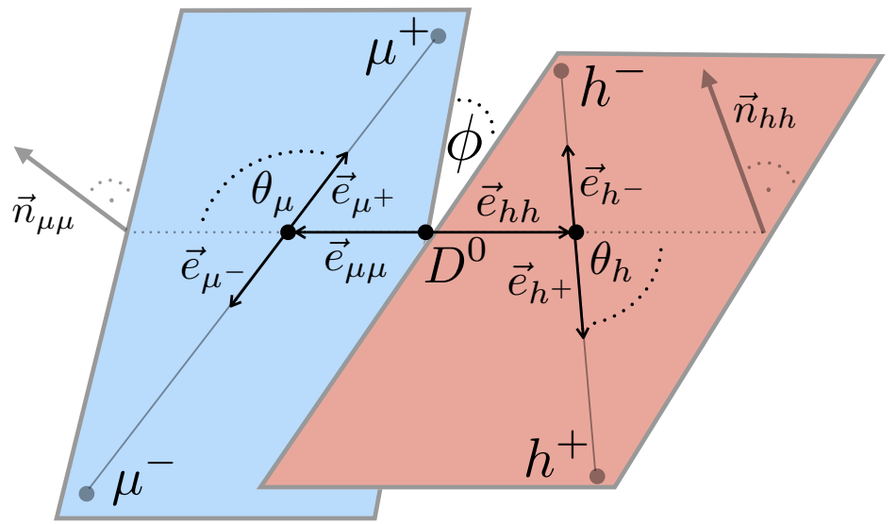


Negligible A_{CP} expected in SM but sizeable in NP.

CPV IN RARE CHARM

- Short-distance contributions to inclusive $D^0 \to X\mu^+\mu^-$ decays (FCNCs) sensitive to NP
- Distinguishable from long-distance contributions by studying kinematic correlations and CP asymmetries [arXiv:1806.10793 [hep-ex]]
- Time- and phase-space integrated:

$$A_{\mathrm{FB}}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (+3.3 \pm 3.7 \pm 0.6)\,\%$$
$$A_{2\phi}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (-0.6 \pm 3.7 \pm 0.6)\,\%$$
$$A_{CP}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (+4.9 \pm 3.8 \pm 0.7)\,\%$$
$$A_{\mathrm{FB}}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\,\%$$
$$A_{2\phi}(D^0 \to K^+K^-\mu^+\mu^-) = (9 \pm 11 \pm 1)\,\%$$
$$A_{CP}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\,\%$$



Negligible A_{CP} expected in SM but sizeable in NP.

Rare decays

See talk by M. Ranos Pernas

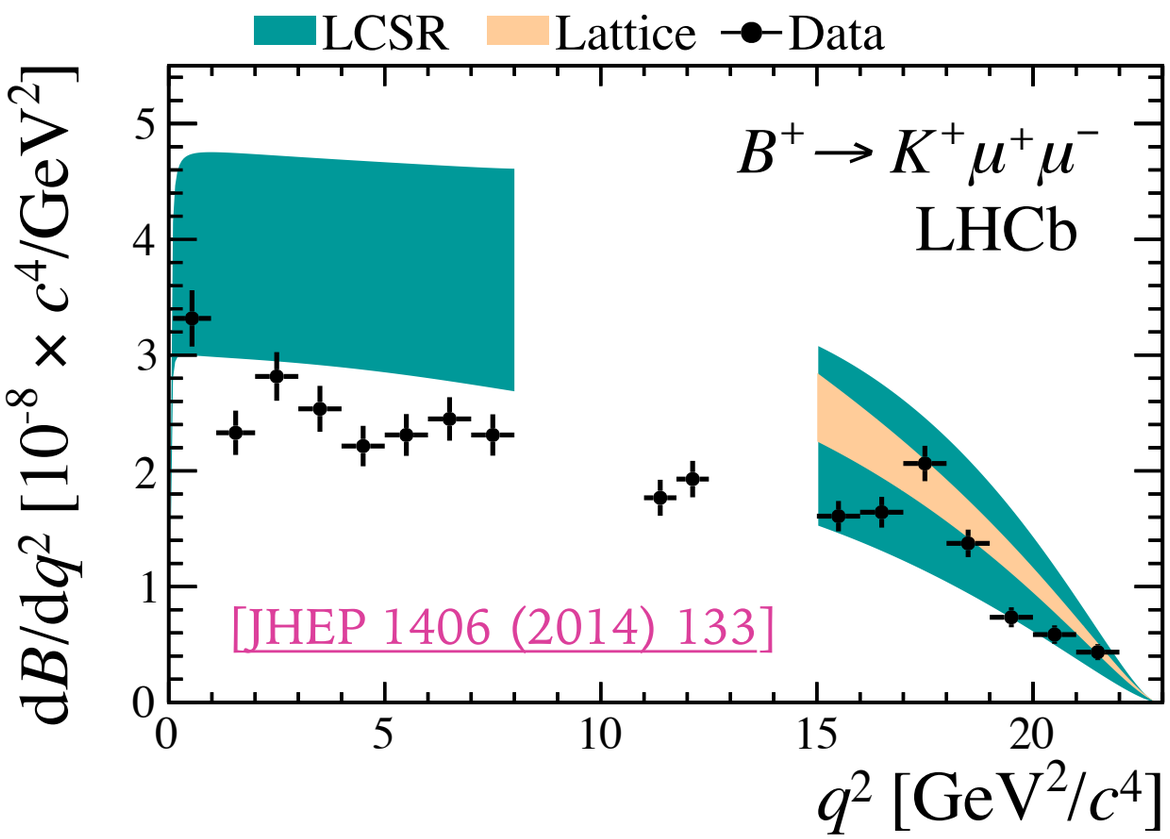
See talk by J. Albert

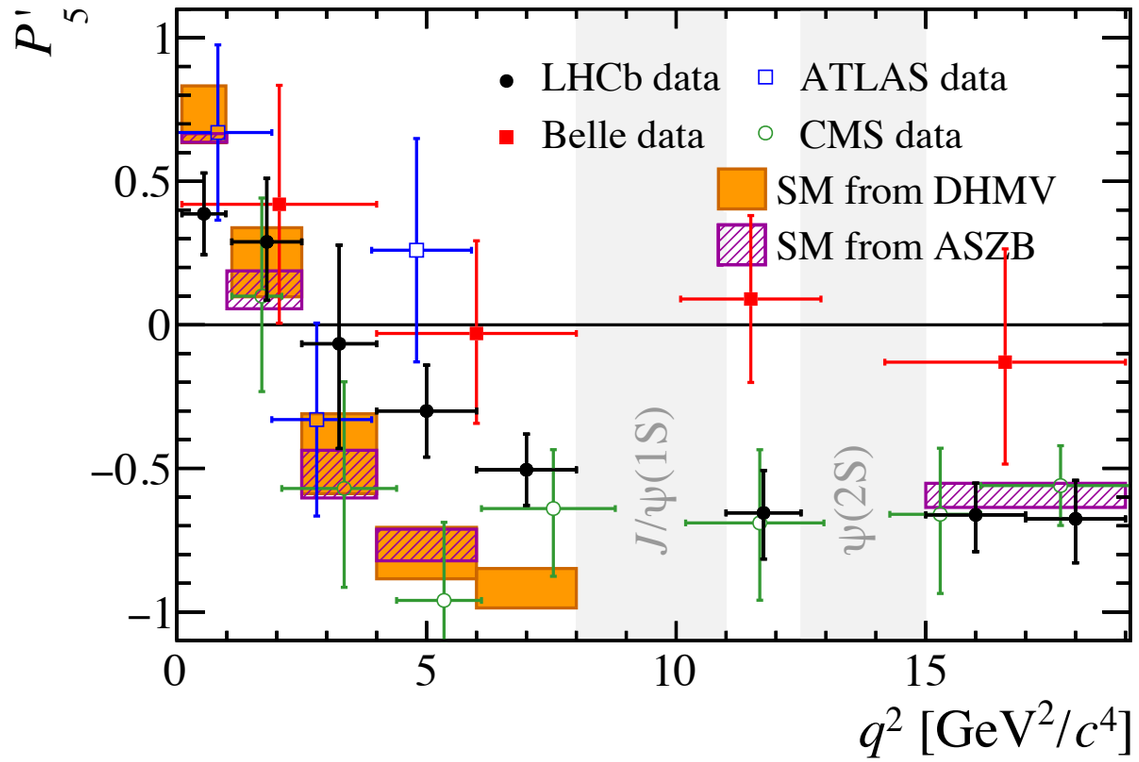
See talk by C. Lazzeroni

FLAVOUR ANOMALIES

- Tensions seen in differential branching fractions and angular observables in $b \to s\mu\mu$ decays

Courtesy of Tom Blake



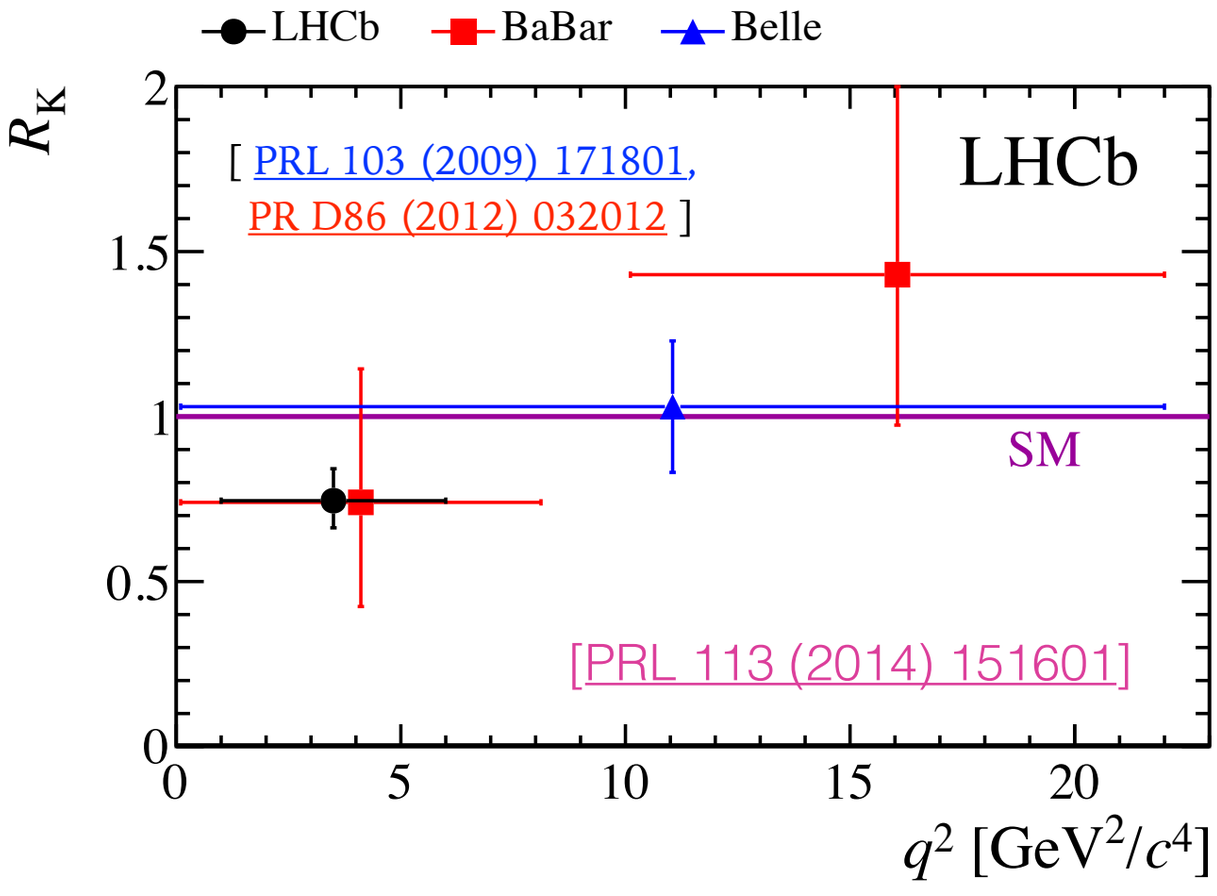


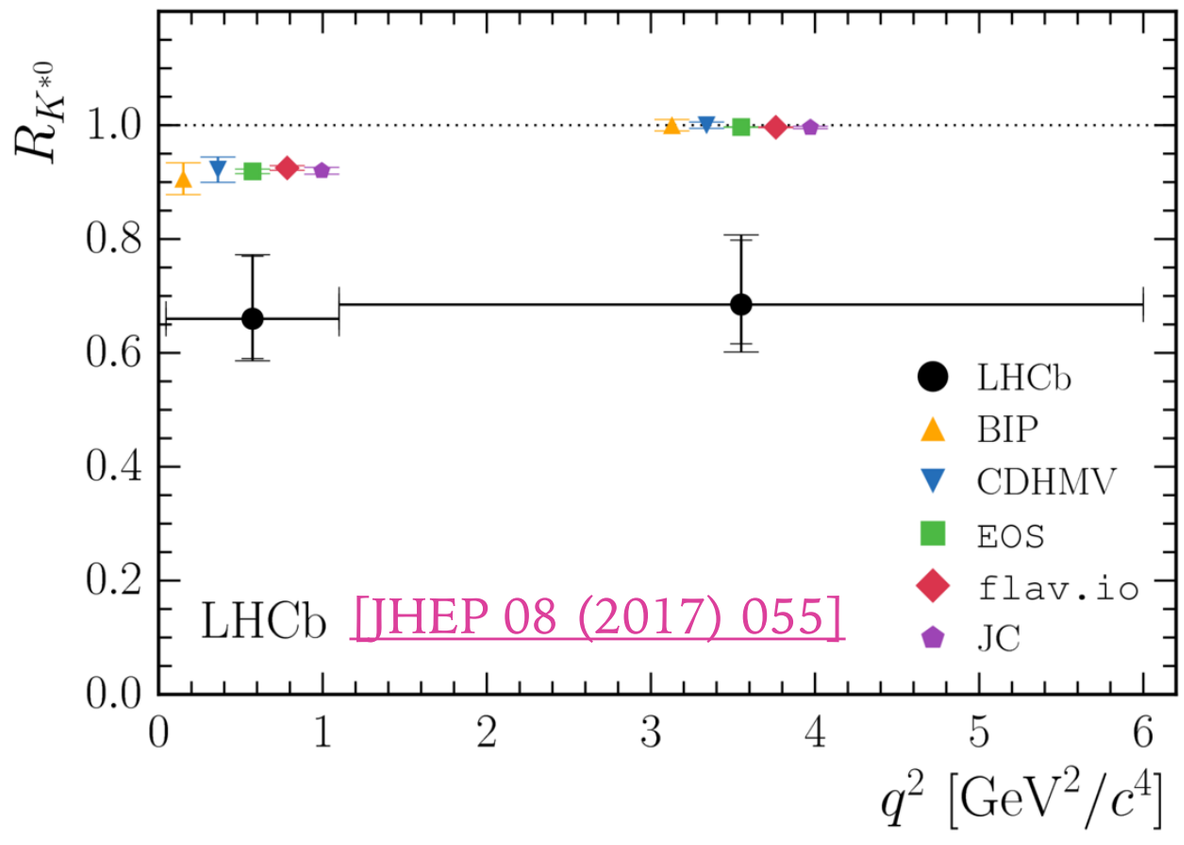
[arXiv:1805.04000 [hep-ex]] [JHEP 02 (2016) 104]

[PL B781 (2018) 517] [PRL 118 (2017) 111801]

FLAVOUR ANOMALIES

- Further tensions observed in related tests of lepton flavour universality



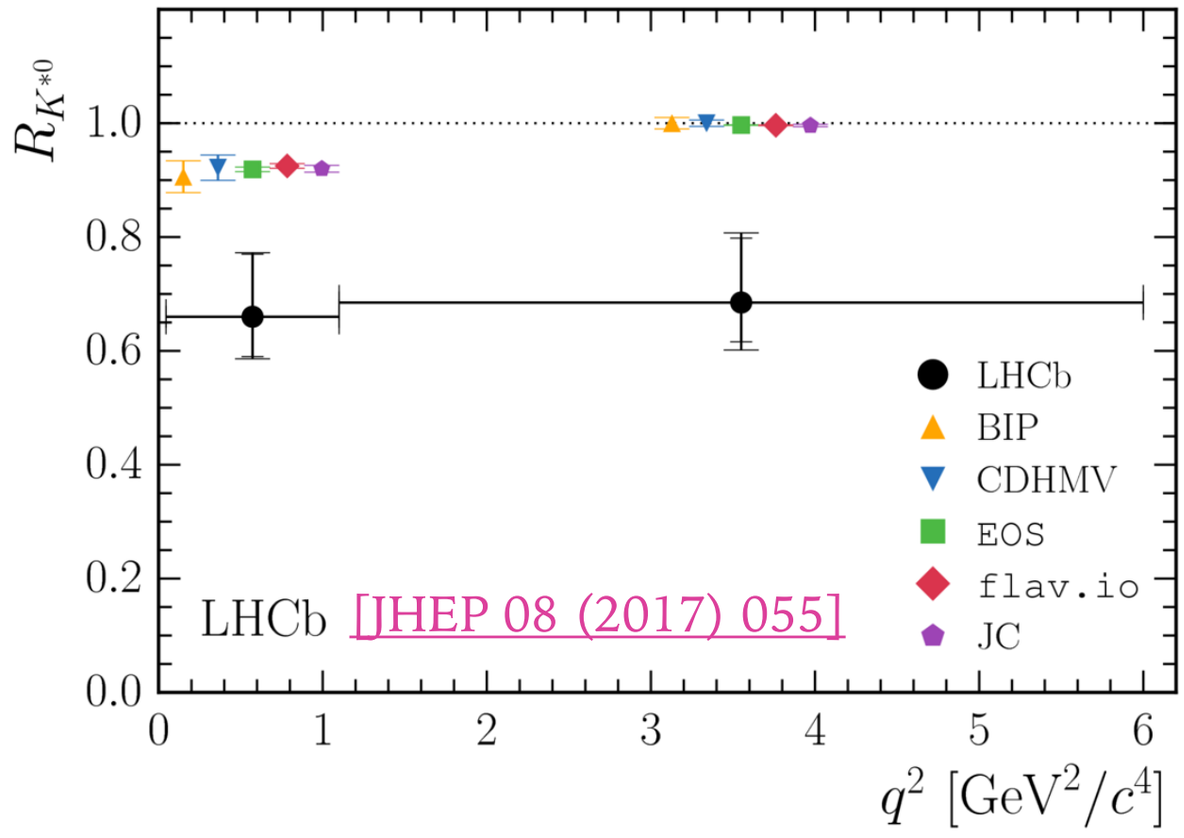


- 2.6σ in R_K and 2.1-2.3σ (2.4-2.5σ) for low (central) q^2 in $R_{K^{*0}}$

FLAVOUR ANOMALIES

- Further tensions observed in related tests of lepton flavour universality

As of beginning of 2018, CMS saves ~10^{10} B decays by triggering on other B in event to measure LFU ratios. Aims for competitive measurement. [LHCC 134]

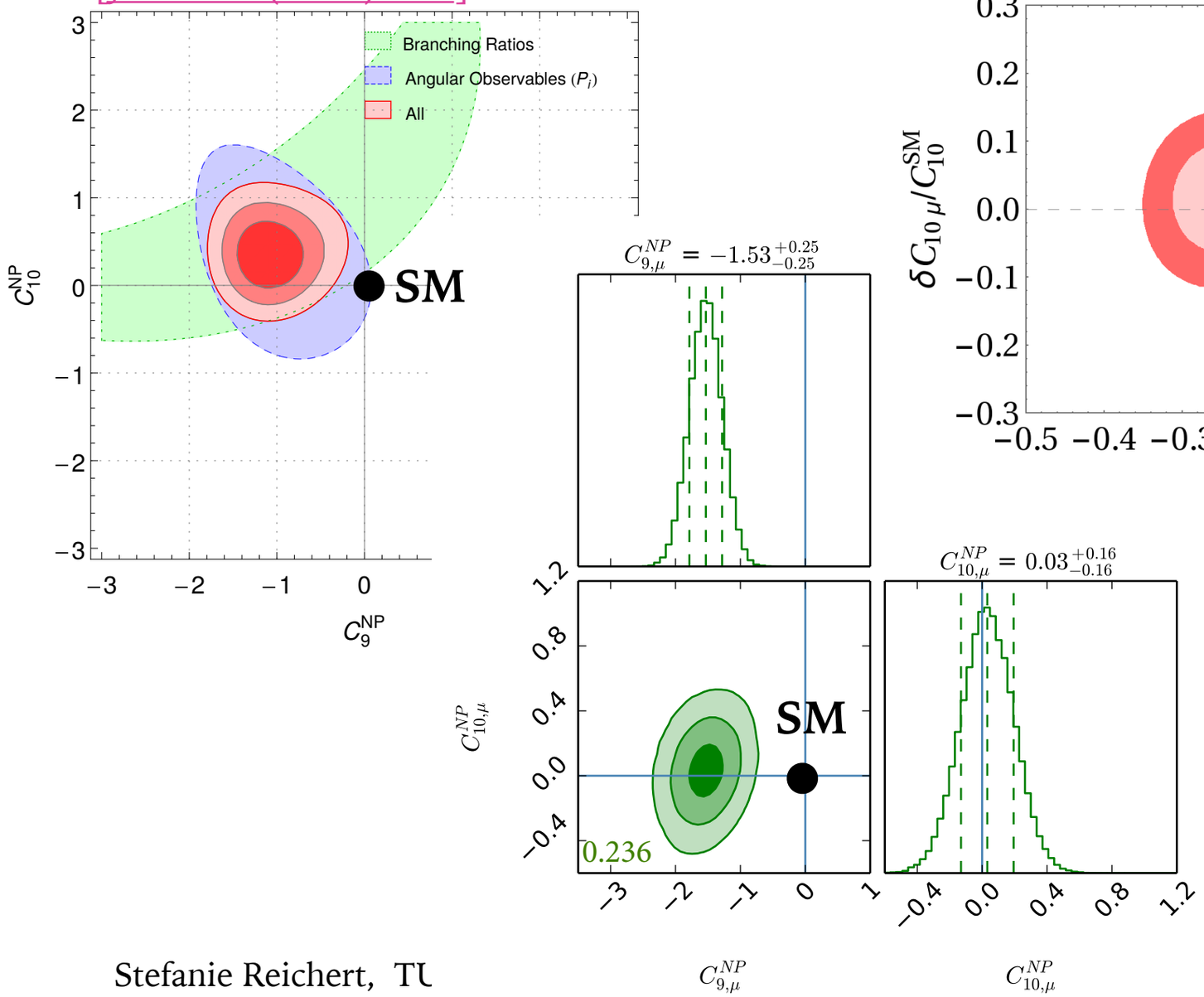


- 2.6σ in R_K and 2.1-2.3σ (2.4-2.5σ) for low (central) q² in $R_{K^{*0}}$

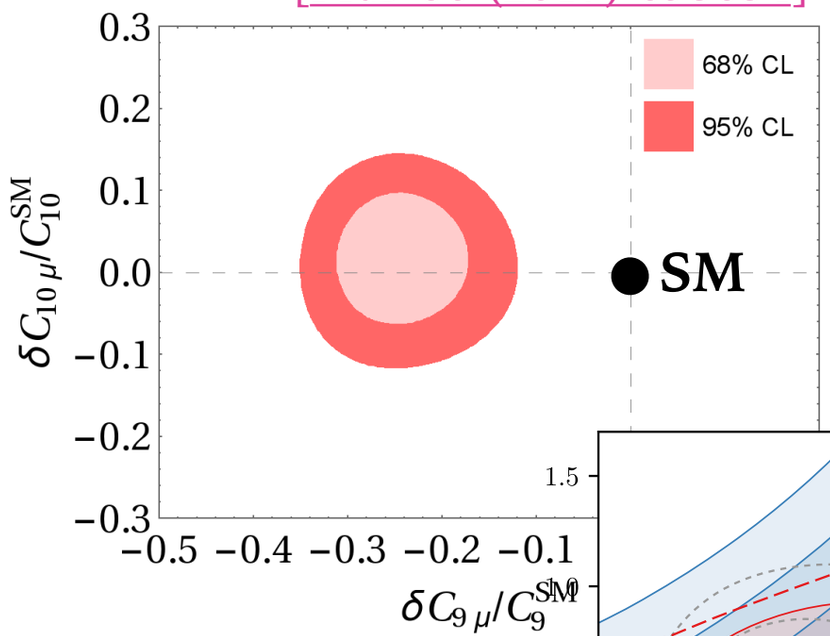
FLAVOUR ANOMALIES

➤ Anomalies in $b \to s\ell\ell$ decays show conclusive pattern

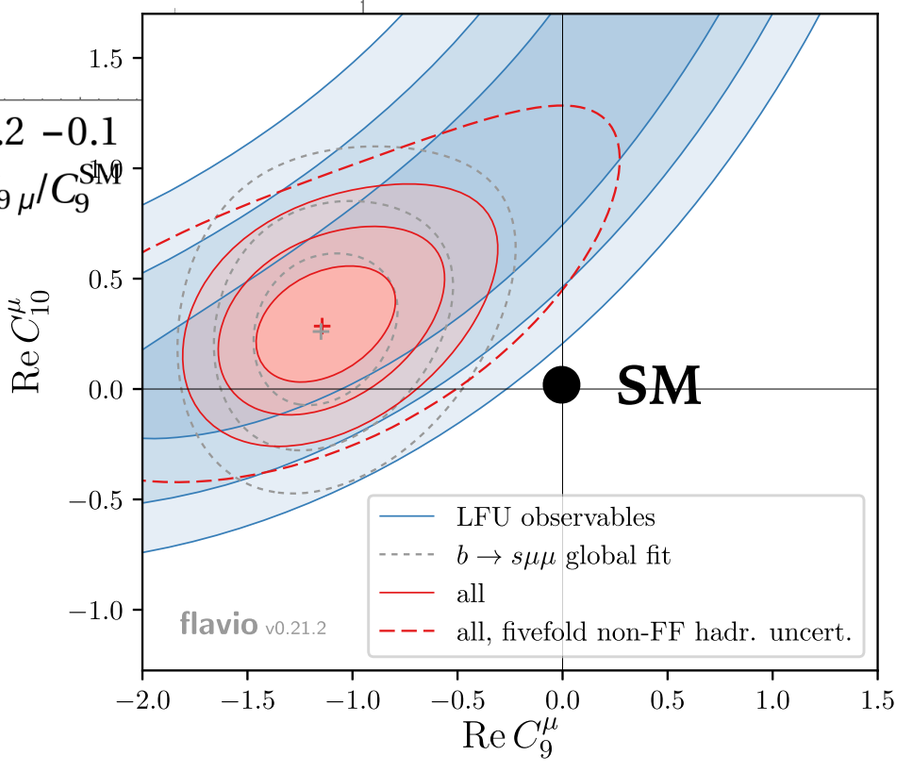
[JHEP 06 (2016) 092]



[PRD 86 (2017) 095034]



[PRD 96 (2017) 055008]



[arXiv:1704.0544 [hep-ex]]

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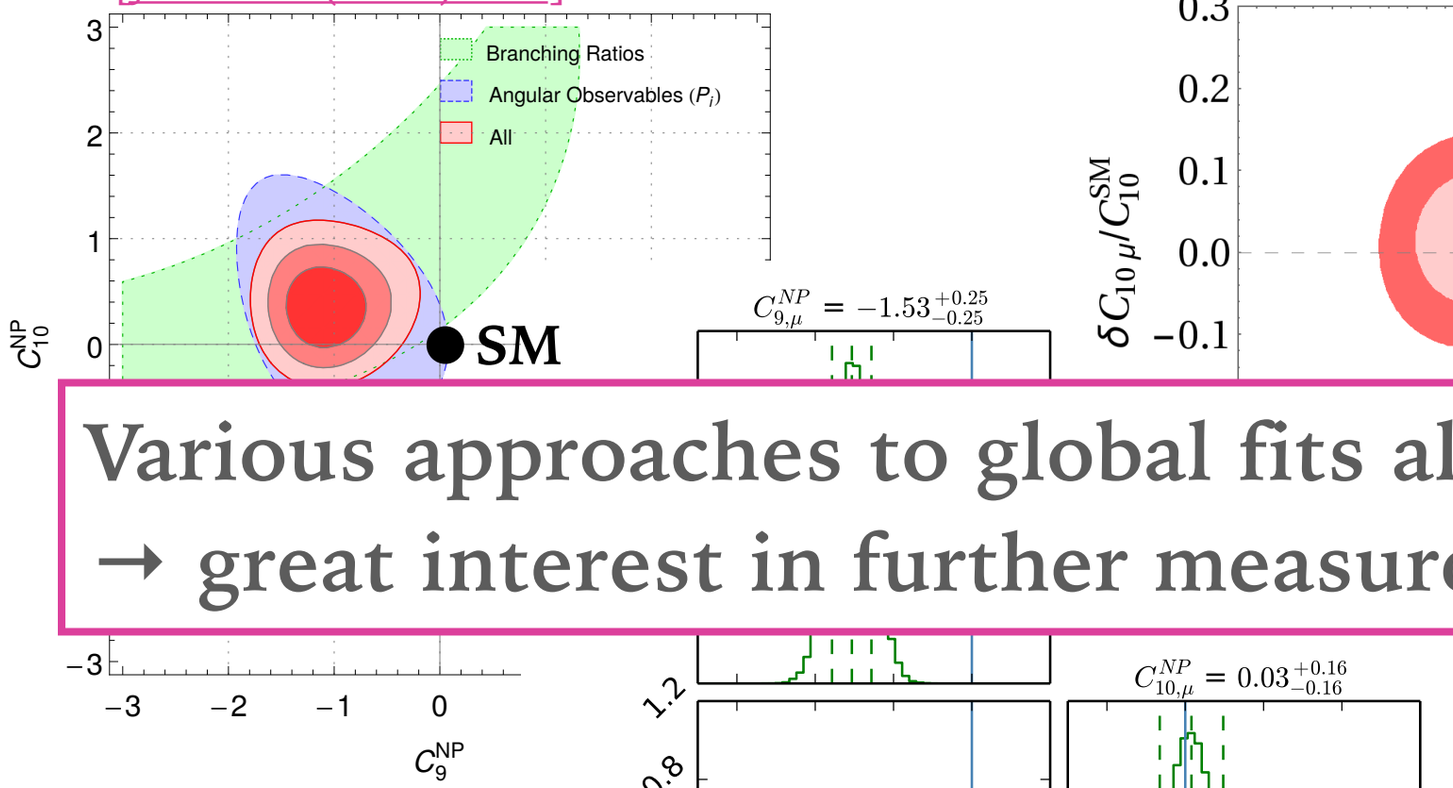

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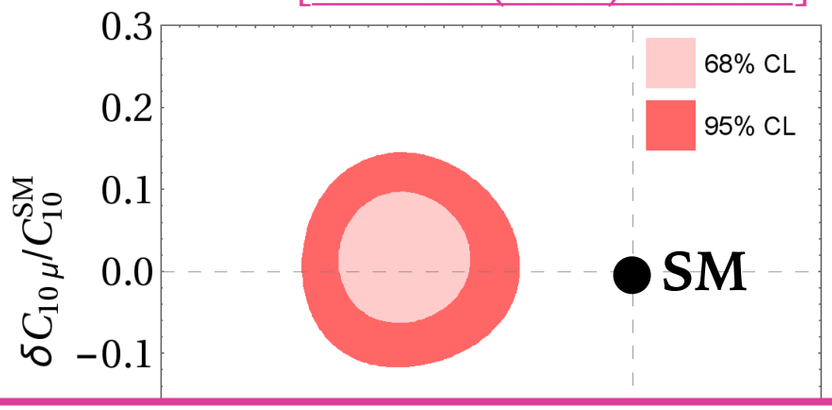
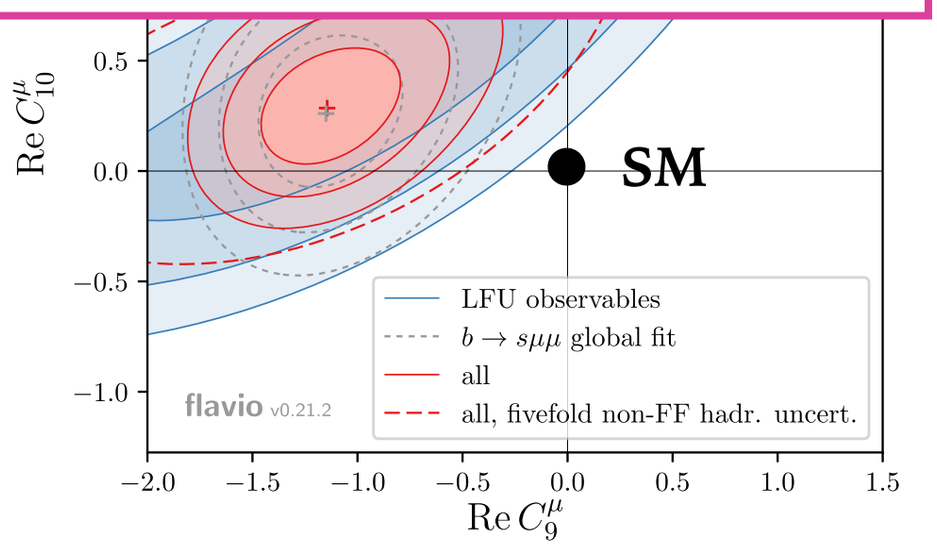


[PRD 96 (2017) 055008]

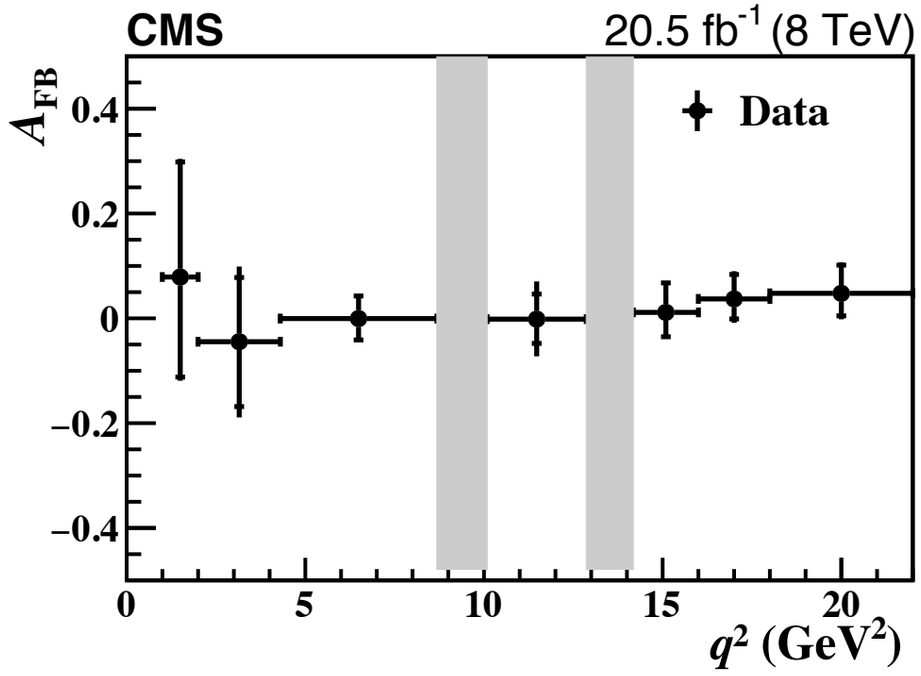
Various approaches to global fits all prefer lowered C_9 value → great interest in further measurements of $b \to s\ell\ell$ decays

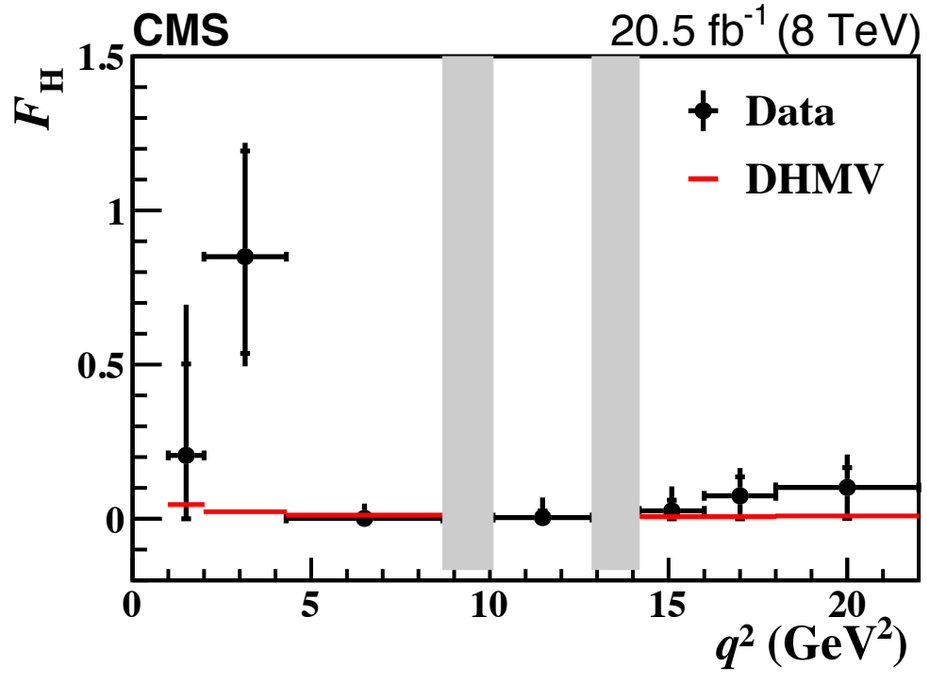
[arXiv:1704.0544 [hep-ex]]



NEW CMS ANGULAR ANALYSIS

- Angular analysis of $B^+ \to K^+\mu^+\mu^-$ decays [arXiv:1806.00636 [hep-ex]] on 20.5fb^{-1} CMS data recorded in 2012
- One-dimensional differential decay rate allows to extract A_{FB} (forward-backward asymmetry) and F_{H} (contribution of (pseudo)scalar and tensor amplitudes to decay width) in q^2-bins





[arXiv:1806.00636 [hep-ex]]

- Compatible with more precise LHCb result [JHEP 05 (2014) 082]

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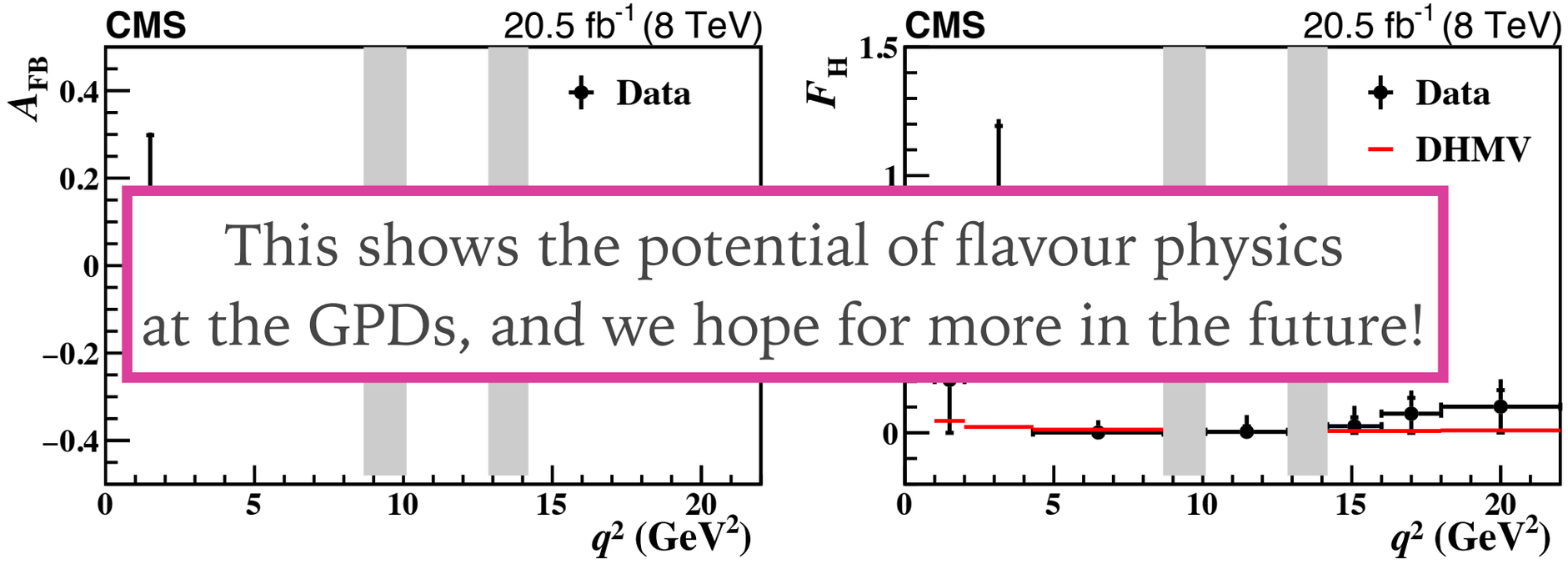


This shows the potential of flavour physics at the GPDs, and we hope for more in the future!

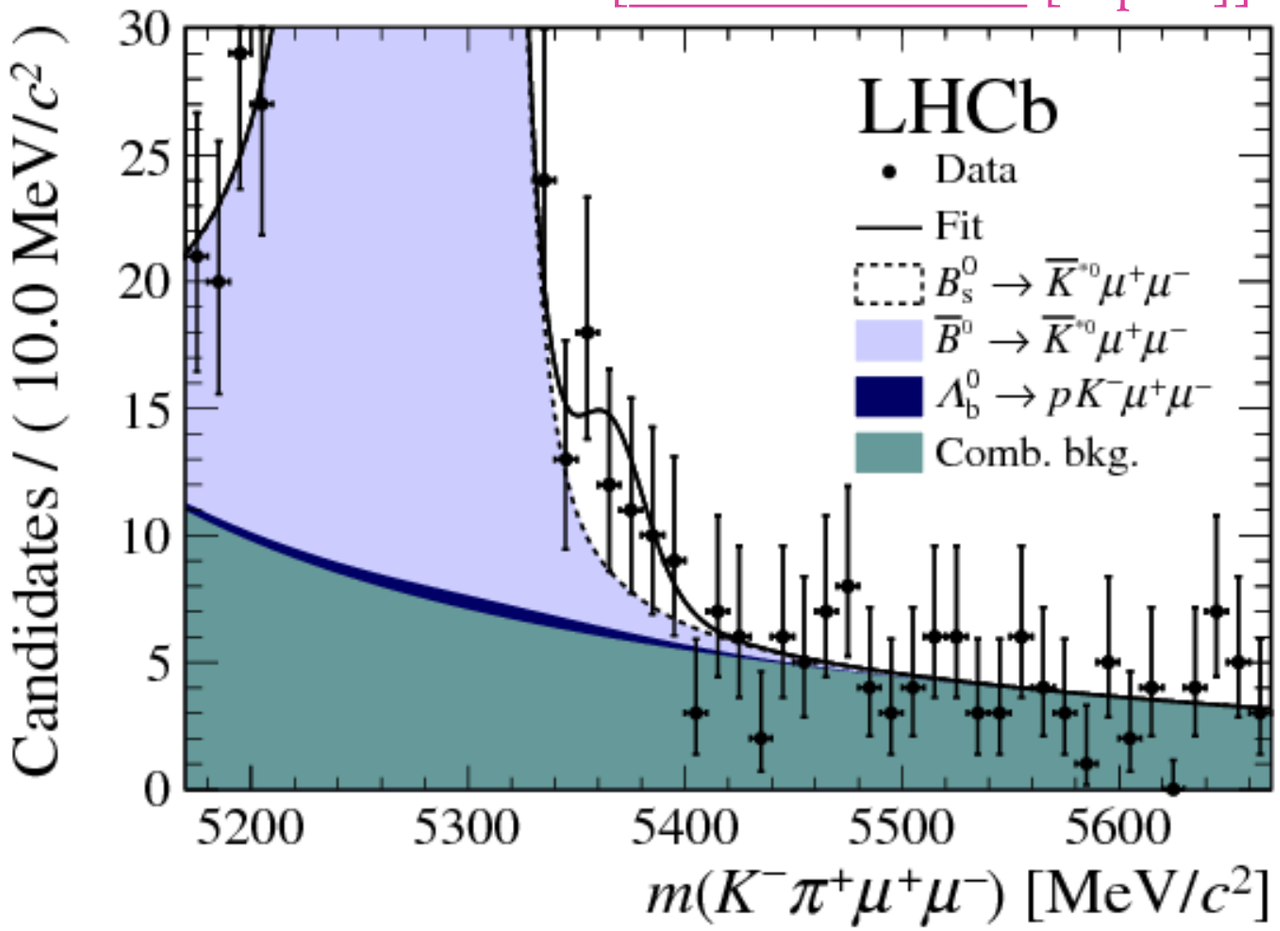
[arXiv:1806.00636 [hep-ex]]

- Compatible with more precise LHCb result [JHEP 05 (2014) 082]

$b \to d\ell\ell$ TRANSITIONS

- Due to $b \to s\ell\ell$ anomalies, increased interest in $b \to d\ell\ell$
- Similar patterns observable in $b \to d$ transitions?
- Evidence for $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$ [arXiv:1804.07167 [hep-ex]] reported by LHCb on dataset of 4.6fb^{-1} with a significance of 3.4σ
- Branching fraction determined to be

[arXiv:1804.07167 [hep-ex]]



No SM prediction but consistent with naive scaling of $\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$ by $|V_{td}/V_{ts}|$

$$\mathcal{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-) = (2.9 \pm 1.0 \pm 0.2 \pm 0.3) \cdot 10^{-8}$$

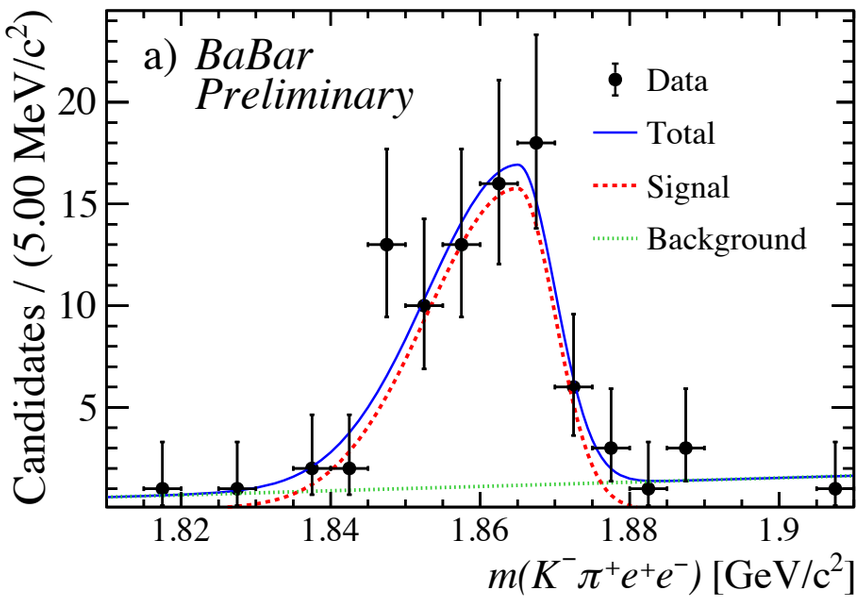
LFU TESTS IN RARE CHARM DECAYS

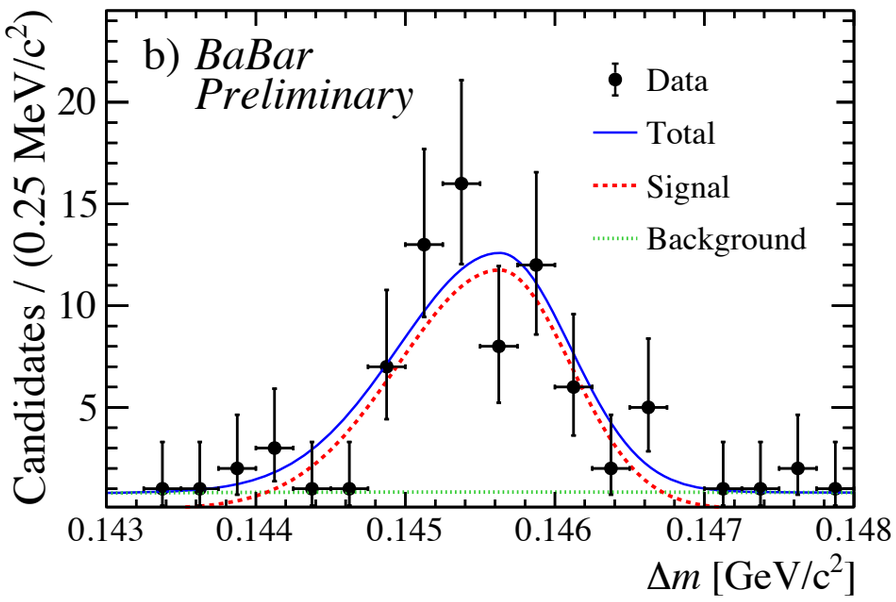
Preliminary

- Hints towards violation of LFU in $b \to s\ell\ell$ and $b \to c\ell\nu$ decays
- What about LFU tests in rare charm?
- LHCb published first observation of $D^0 \to K^-\pi^+\mu^+\mu^-$ with

$$\mathcal{B}(D^+ \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12 \pm 0.40) \cdot 10^{-6}$$ [PL B757 (2016) 558]

- BaBar reports electron final state observation on 424fb^{-1}





with $>10\sigma$

$N_{sig} = 68 \pm 9$

[Talk at ICHEP 2018]

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- BaBar reports electron final state observation on 424fb^{-1}

  → branching fraction measured to be

$$\mathcal{B}(D^+ \to K^-\pi^+e^+e^-) = (3.95 \pm 0.53 \pm 0.16 \pm 0.08) \cdot 10^{-6}$$

  in $0.675 < m(e^+e^-) < 0.875\,\mathrm{GeV}/c^2$

- Branching fractions of both final states agree

  → no hint at violation of LFU in this channel

LFU TESTS IN NOT SO RARE CHARM DECAYS

- Measurement of $D^{0(+)} \to \pi^{-(0)}\mu^+\nu_\mu$ decays and test of lepton flavour universality [arXiv:1802.05492 [hep-ex]] at BESIII in $b \to u\ell\nu$
- Signal/background discrimination with missing mass
- Branching fractions

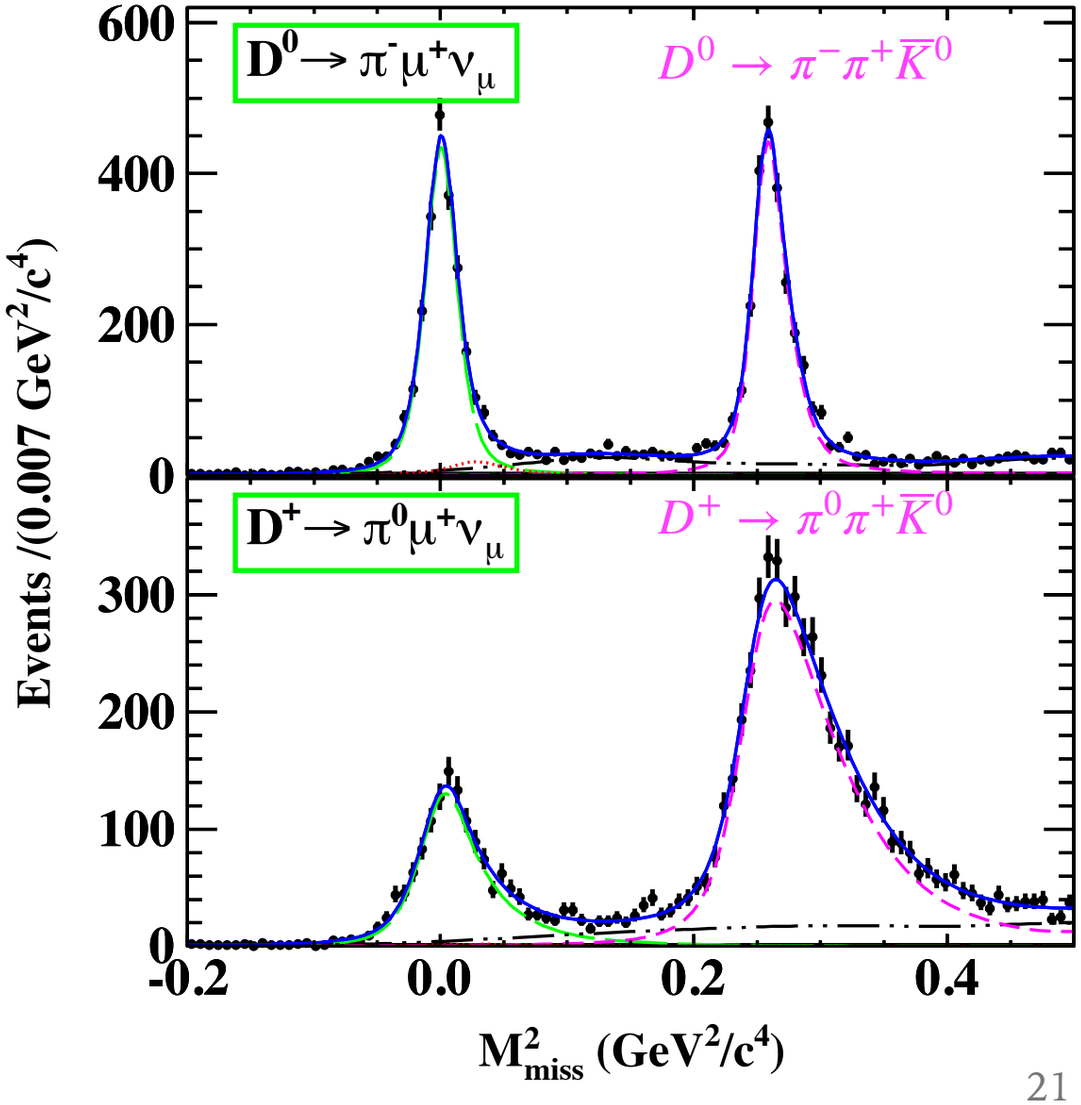
$$\mathcal{B}(D^0 \to \pi^-\mu^+\nu_\mu) = (0.267 \pm 0.007 \pm 0.007)\,\%$$

$$\mathcal{B}(D^+ \to \pi^0\mu^+\nu_\mu) = (0.342 \pm 0.011 \pm 0.010)\,\%$$

combined with results on $D^{0(+)} \to \pi^{-(0)}e^+\nu_e$ decays

[PRD 92 (2015) 072012 (PRD 96 92017) 012002)]

to test for LFU



[arXiv:1802.05492 [hep-ex]]

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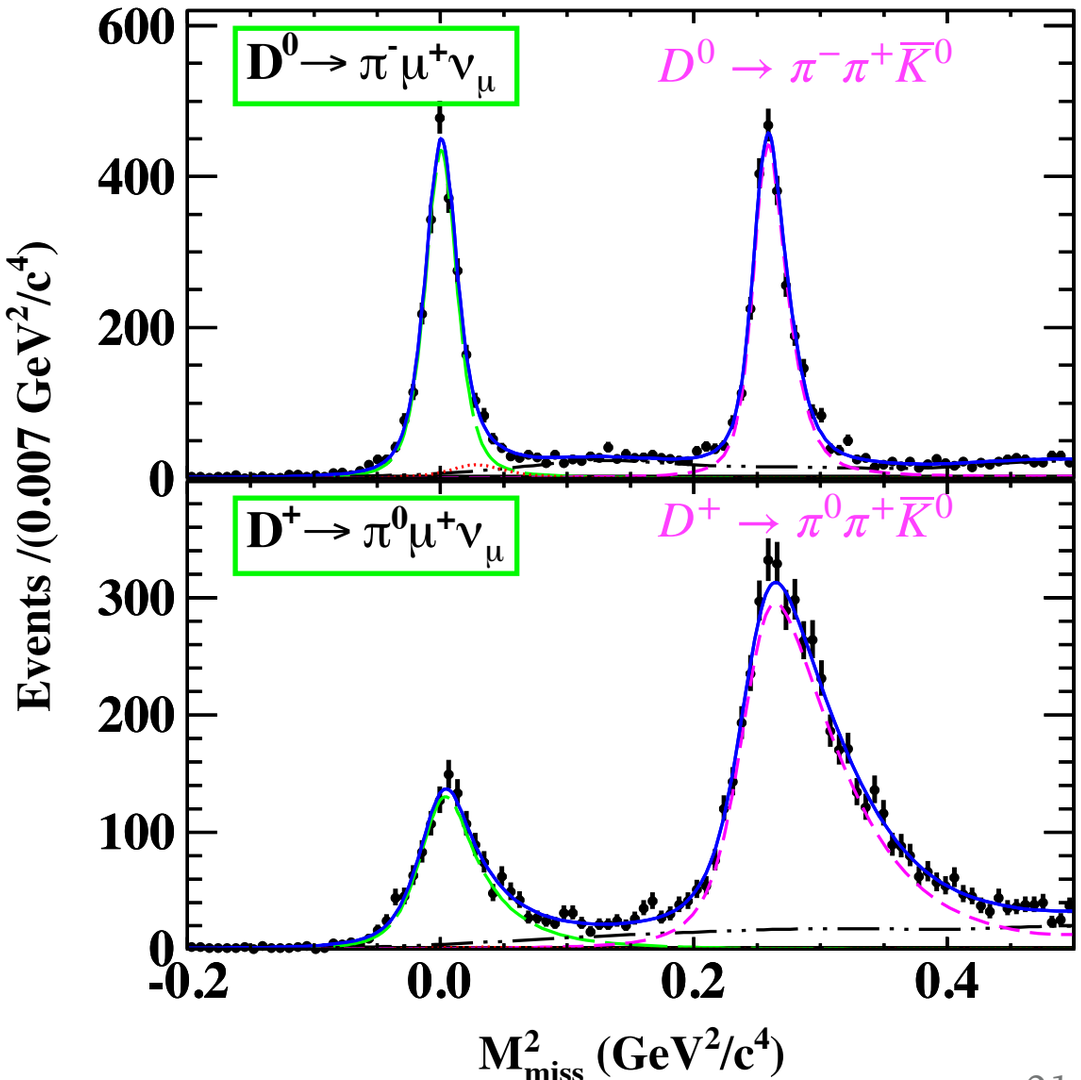
- Signal/background discrimination with missing mass
- Results on LFU ratios:

$$R^0 = 0.905 \pm 0.027 \pm 0.023$$

$$R^+ = 0.942 \pm 0.037 \pm 0.027$$

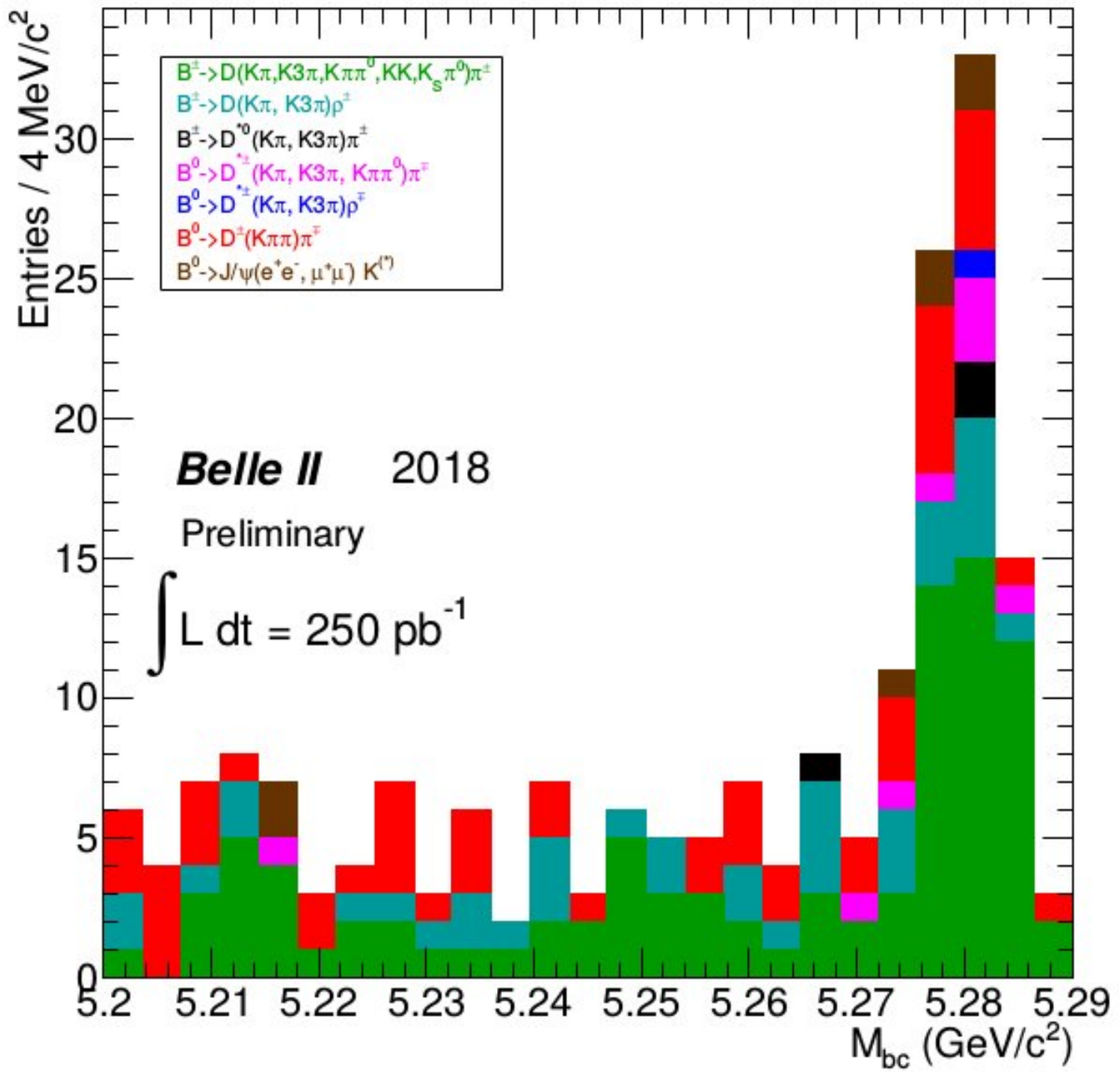
→ compatible with SM at $1.9(0.6)\sigma$



SUMMARY

- Rich flavour physics programme at LHCb, BESIII and B factories - increased interest of CMS and ATLAS
- Anomalies in $b \to s\ell\ell$ follow consistent pattern
  → lowering C_9 by around 25% with respect to SM
- Tensions with respect to SM expectation also seen in $b \to c\ell\nu$

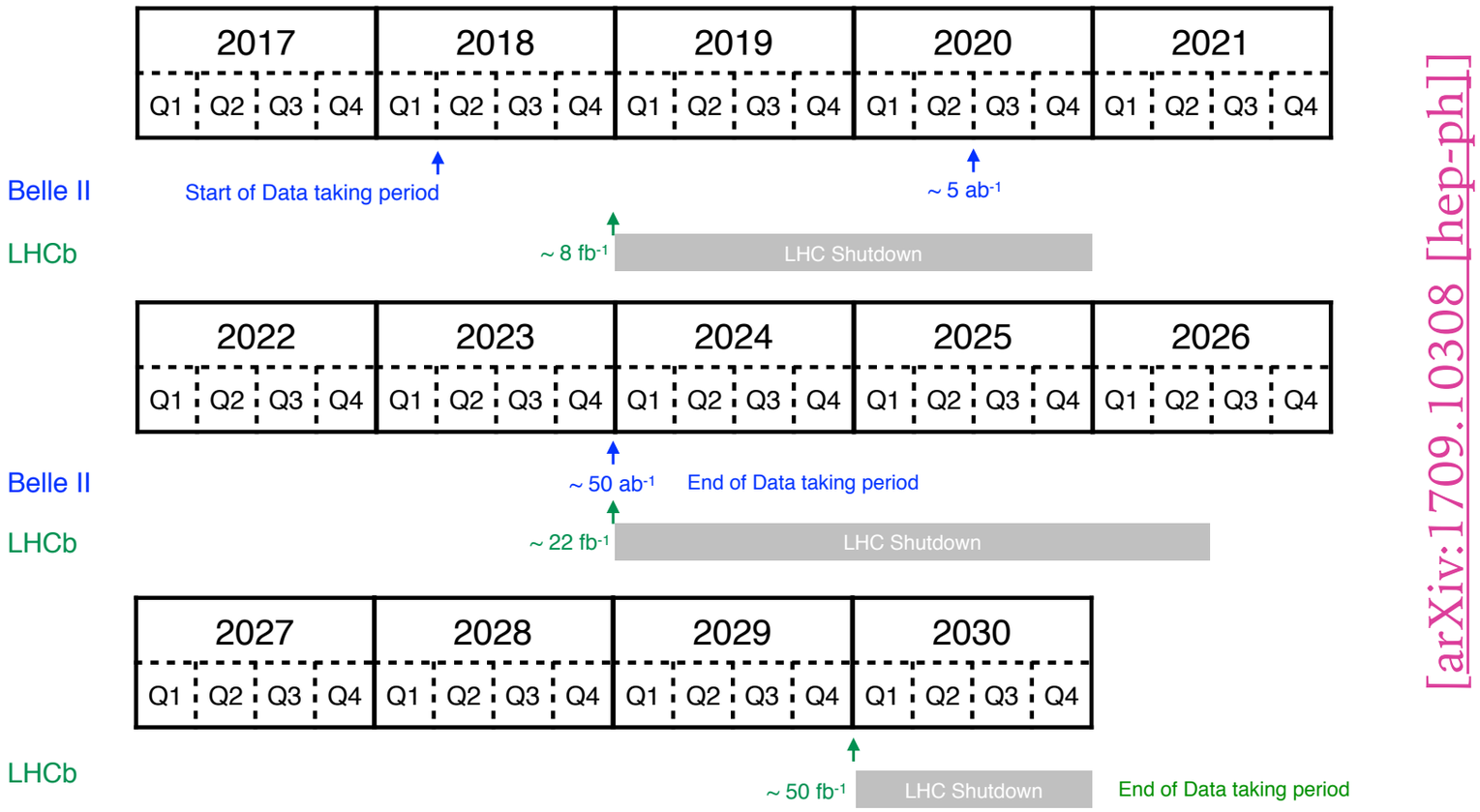
BELLE II IS RAMPING UP AND HAS 'REDISCOVERED' B MESON



[@belle2collab]

OUTLOOK

- LHCb upgrade scheduled in 2019-2020
  → increase in luminosity after shutdown by factor 5 to $2 \cdot 10^{33}\text{cm}^{-2}\text{s}^{-1}$



[arXiv:1709.10308 [hep-ph]]

- With Belle II, upgraded LHCb detector and increased interest of ATLAS and CMS in flavour physics, much more data to analyse!
- Upcoming years will shed light onto nature of anomalies!

Thank you.

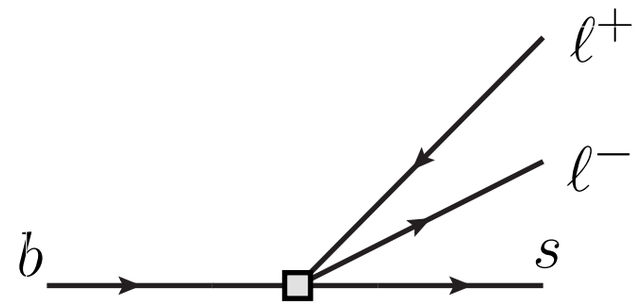
Backup

WILSON COEFFICIENTS

- Effective Hamiltonian for b→sll processes

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

Wilson coefficients



$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

- New physics modify Wilson coefficients $C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$

WILSON COEFFICIENTS

Photon pole enhancement (no pole for $B \to P\ell\ell$ decays)