

B-anomalies Experimental overview

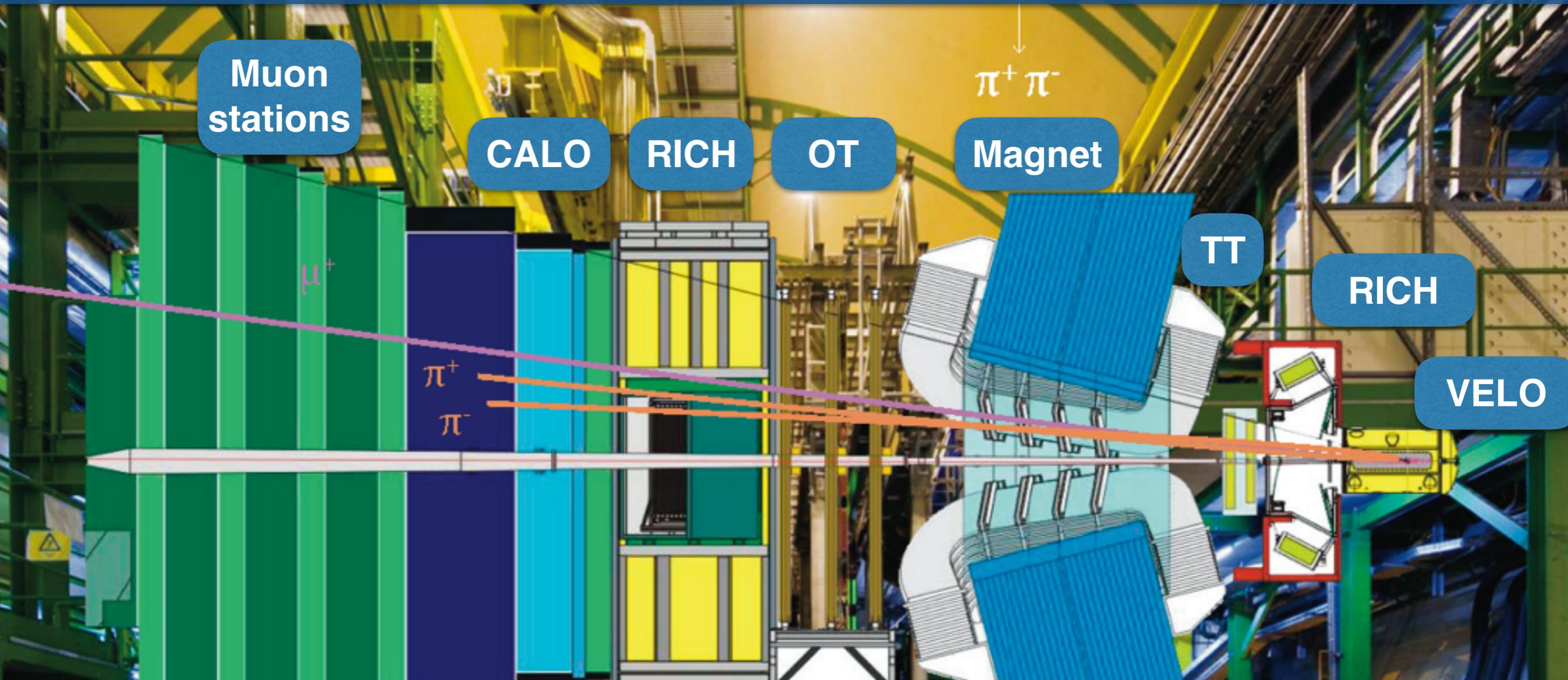
Siim Tolk
on behalf of the LHCb collaboration

PACTS
Tallinn 2018

Anomalies in b quark transitions

- five different **experiments**:
ATLAS, BABAR, BELLE, CMS, LHCb
- vastly different **collision environments** requiring
different analysis strategies: *hadronic (abundant) VS leptonic (clean)*
- processes with different SM contributions:
tree level semi-leptonic decays, loop level FCNC transition
- many **clean observables**:
angular observables, branching fraction ratios

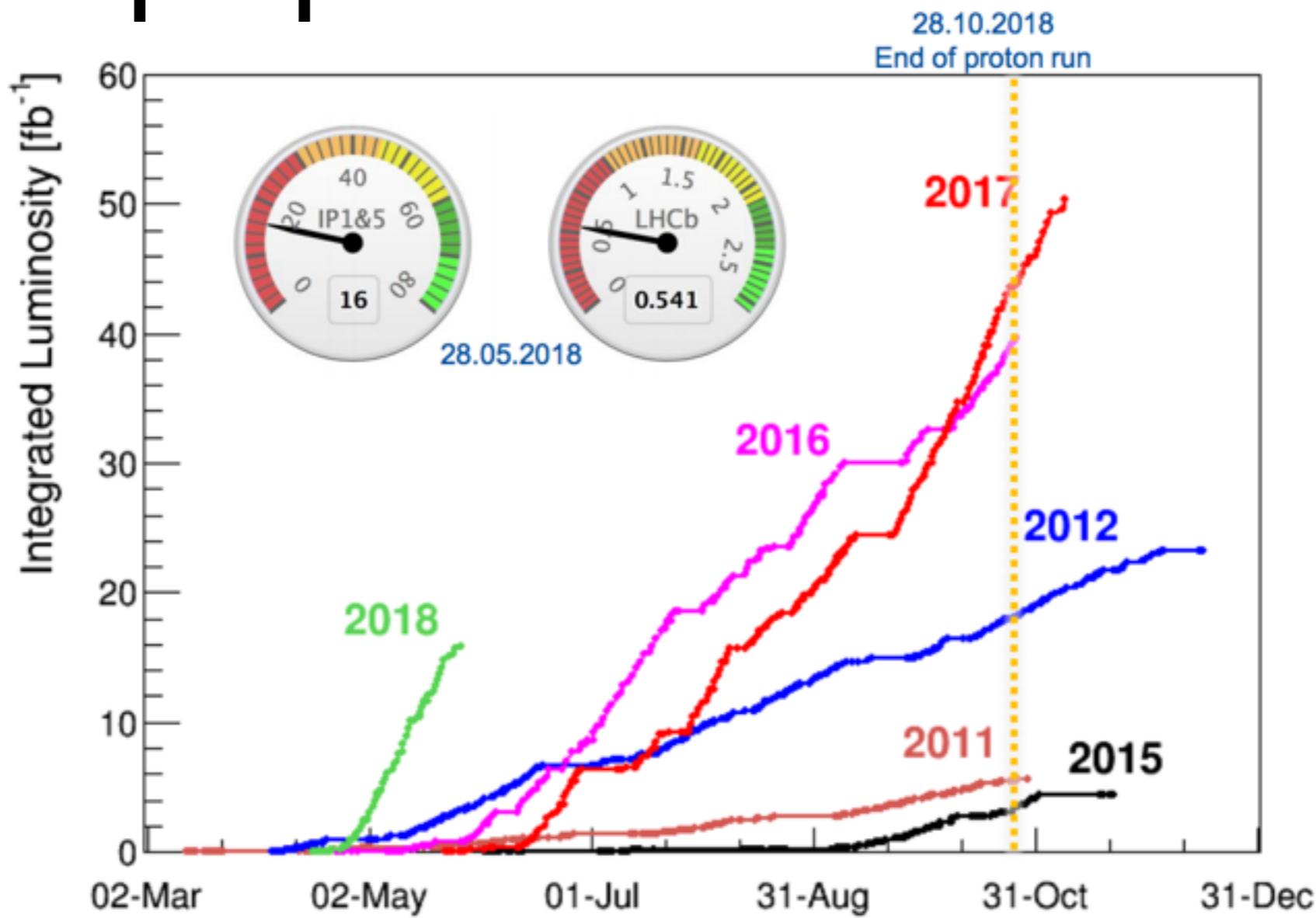
LHCb detector @ LHC



- Clean collision environment ($\mu \sim 1.6$) and high boost ($\gamma \sim 20$)
- Good mass resolution (~ 23 MeV for $B \rightarrow \mu^+ \mu^-$)

And more: excellent charged hadron identification, vertexing, high trigger and tracking efficiencies (> $\sim 90\%$) also in the low p_T range.

A very successful year for the LHC: quick ramp-up and an efficient running

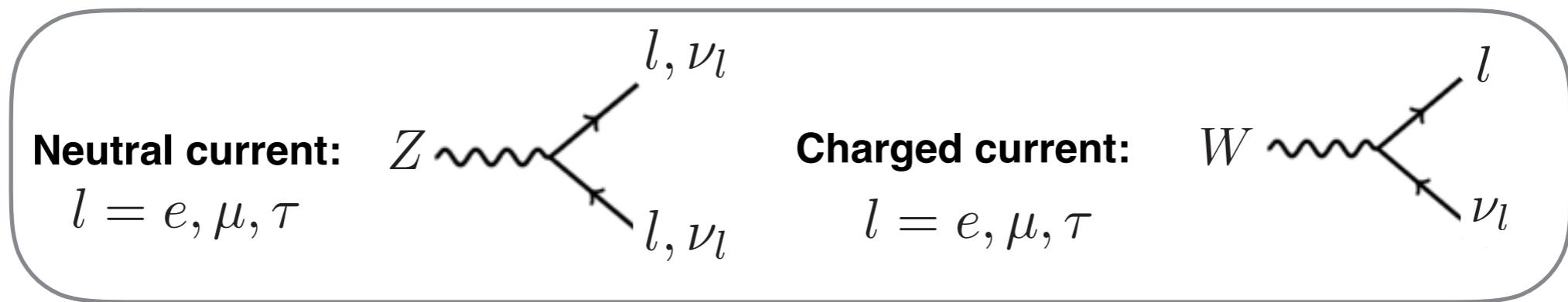


**Aim for 2fb^{-1} for LHCb (~ 1.5 to go)
 60fb^{-1} for ATLAS and CMS**

Lepton Flavour Universality tests with semi-leptonic decays

Lepton Flavour Universality

- In the Standard Model, lepton **couplings** to the gauge bosons are **identical**:



- The branching fractions (BF) to different lepton generations only differ due to **lepton masses**
 - Higgs couplings, phase space, level of helicity suppression
- Lepton Universality has been **thoroughly tested** over the years at LEP, PIENU, NA62, BES-III, CLEO, KEDR and many other experiments.
 - **Neutral Currents** measured to be universal with $<2\%$ precision
 - **Charged Currents** measured to be universal with $<2\%$ precision for the first two generations

Constraints on the charged current couplings to the third lepton generation are weaker.

CERN-PH-EP/2005-051

Assuming only partial lepton universality the ratio between the tau fractions and the average of electrons and muons can also be computed:

$$2\mathcal{B}(W \rightarrow \tau\bar{\nu}_\tau) / (\mathcal{B}(W \rightarrow e\bar{\nu}_e) + \mathcal{B}(W \rightarrow \mu\bar{\nu}_\mu)) = 1.077 \pm 0.026$$

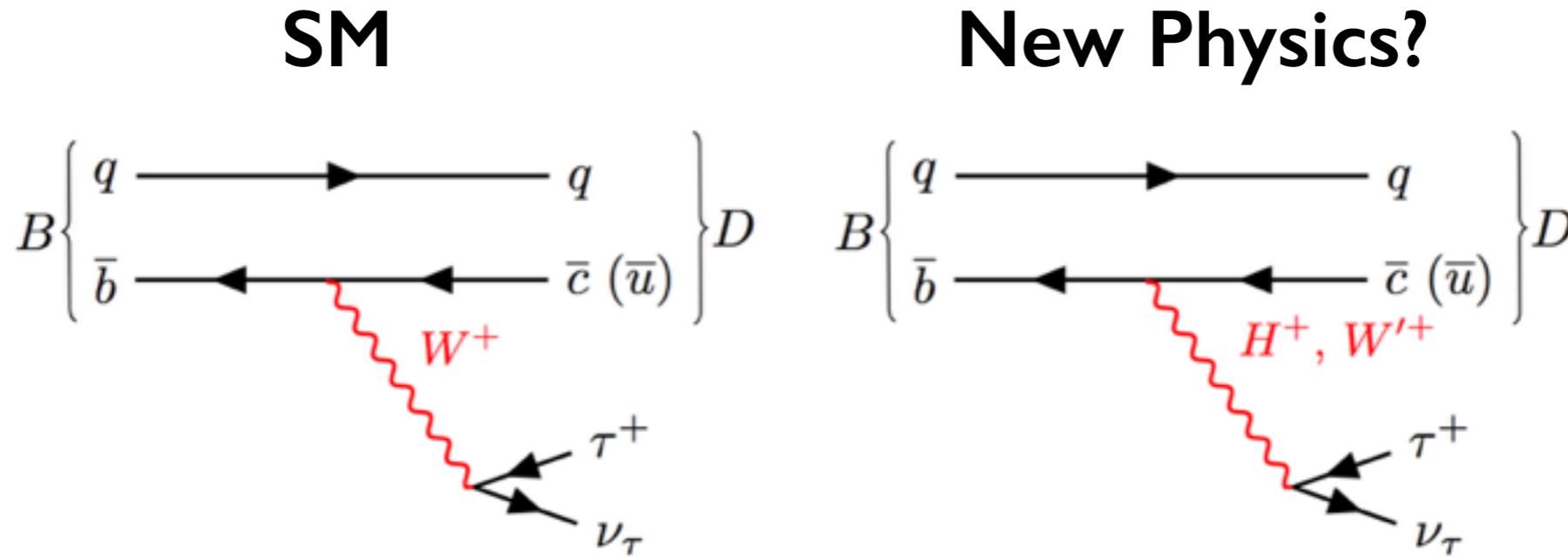
resulting in a poor agreement at the level of 2.8 standard deviations, with all correlations included.

LEP: 2.8σ upward tension in $W \rightarrow \tau\nu_\tau$

Many NP scenarios contain additional interactions and enhanced couplings to the third generation: (charged Higgses, new vectors coupled to SM Higgs doublet, leptoquarks)

- New Physics could evade the strong bounds from the direct searches while preserving the effect on heavy flavour

Tree level **semi-leptonic $b \rightarrow c l \bar{\nu}$ transitions** are excellent test modes for charged currents:



- abundant (crucial for the τ mode) and theoretically well understood
- the ratios of branching fractions are known with a **precision of a few %** and can be precisely measured:

$$\mathcal{R}(D^*) \equiv \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \bar{\nu}_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-} \mu^+ \bar{\nu}_\mu)} = \mathbf{0.260(8)}$$

R(D) and R(D*) at the B-factories

$R(D)$ and $R(D^*)$ at the B-factories

B's are produced bin $e^+e^- \rightarrow Y(4S) \rightarrow BB$

- reconstruct and tag the ‘other’ B
- **kinematically constrain the whole event** and measure the energy lost in neutrinos

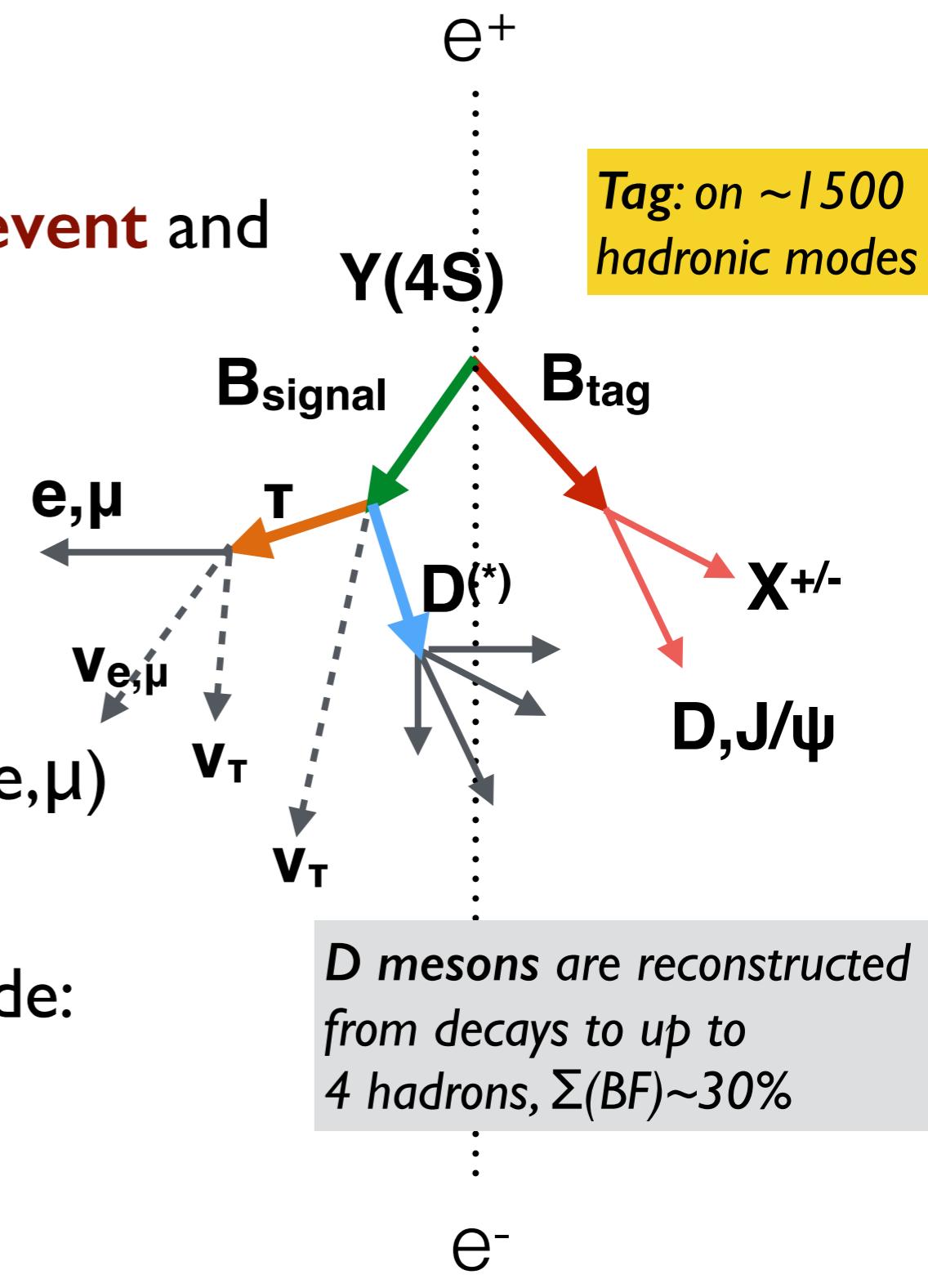
Several independent measurements:

From the tag side:

- tag on exclusive hadronic B decays
- tag on semi-leptonic $B \rightarrow D l \bar{\nu}$ decays (e, μ)

and from the signal side:

- reconstruct τ from semi-leptonic mode:
 $\tau^- \rightarrow l \bar{\nu} \nu$ (e, μ)
- reconstruct τ from hadronic mode:
 $\tau^- \rightarrow \pi^- \nu_\tau, \tau^- \rightarrow \rho^- \nu_\tau, \tau^- \rightarrow 3\pi(\pi^0) \nu_\tau, \dots$



$R(D)$ and $R(D^*)$ at the B-factories

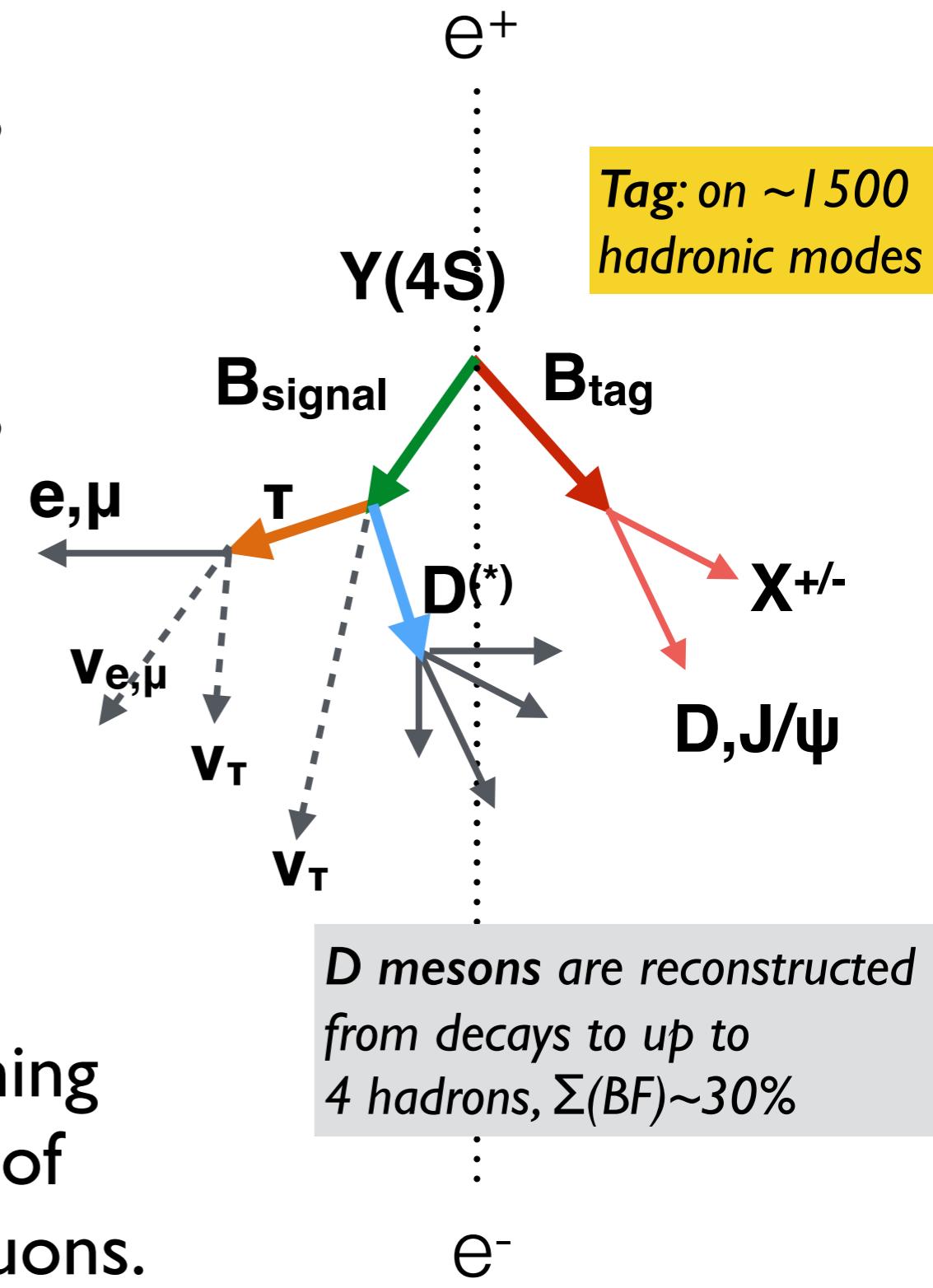
BABAR:

- 2012: $R(D^*)$ and $R(D)$: hadronic tag, leptonic tau

BELLE:

- 2015: $R(D^*)$ and $R(D)$: hadronic tag, leptonic tau
- 2015: $R(D^*)$: semi-leptonic tag, leptonic tau
- 2017: $R(D^*)$: semi-leptonic tag, $\tau^- \rightarrow \pi^- \nu_\tau, \tau^- \rightarrow \rho^- \nu_\tau$

👉 B-factories always quote the branching fraction ratios relative to the average of $B \rightarrow D^{(*)} l \bar{\nu}$ decays to electrons and muons.



$R(D)$ and $R(D^*)$ at LHC

Measuring $R(D)$ and $R(D^*)$ in a **hadronic environment** is challenging: *the decay chain cannot be fully constrained, the B -momentum is not known.*

LHCb has determined $R(D^*)$ independently in **two τ -decay modes**:

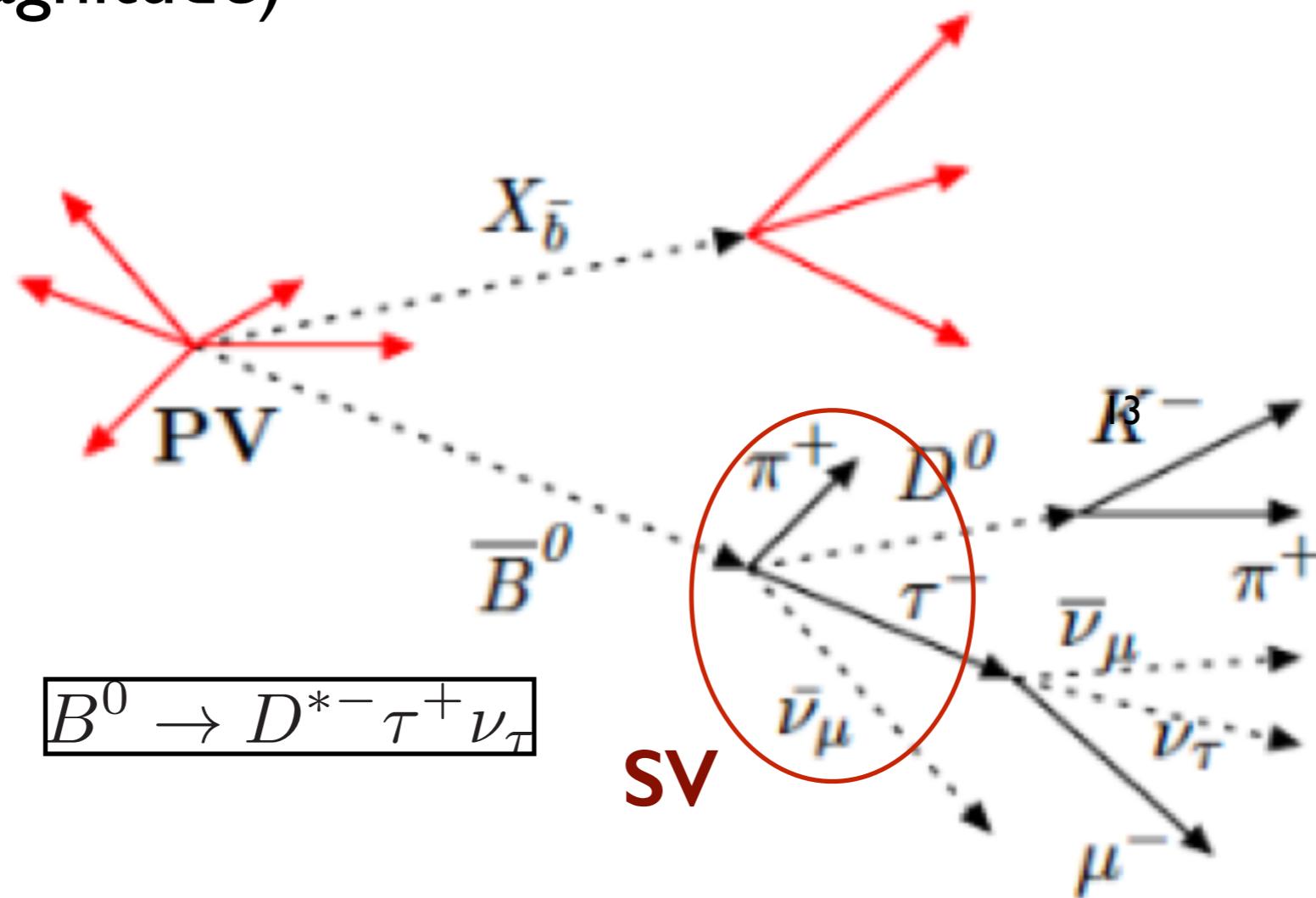
- $\tau \rightarrow \mu \nu \nu$ (*semileptonic*)
- $\tau \rightarrow 3\pi(\pi^0)$ (*hadronic*)

R(D*) at LHCb with $\tau \rightarrow \mu \nu \bar{\nu}$ decays (Run I)

PRL 115, 111803

In the case of R(D*) estimate B-momentum with the help of the $D^* \rightarrow D^0 \pi^+$ decay vertex (SV):

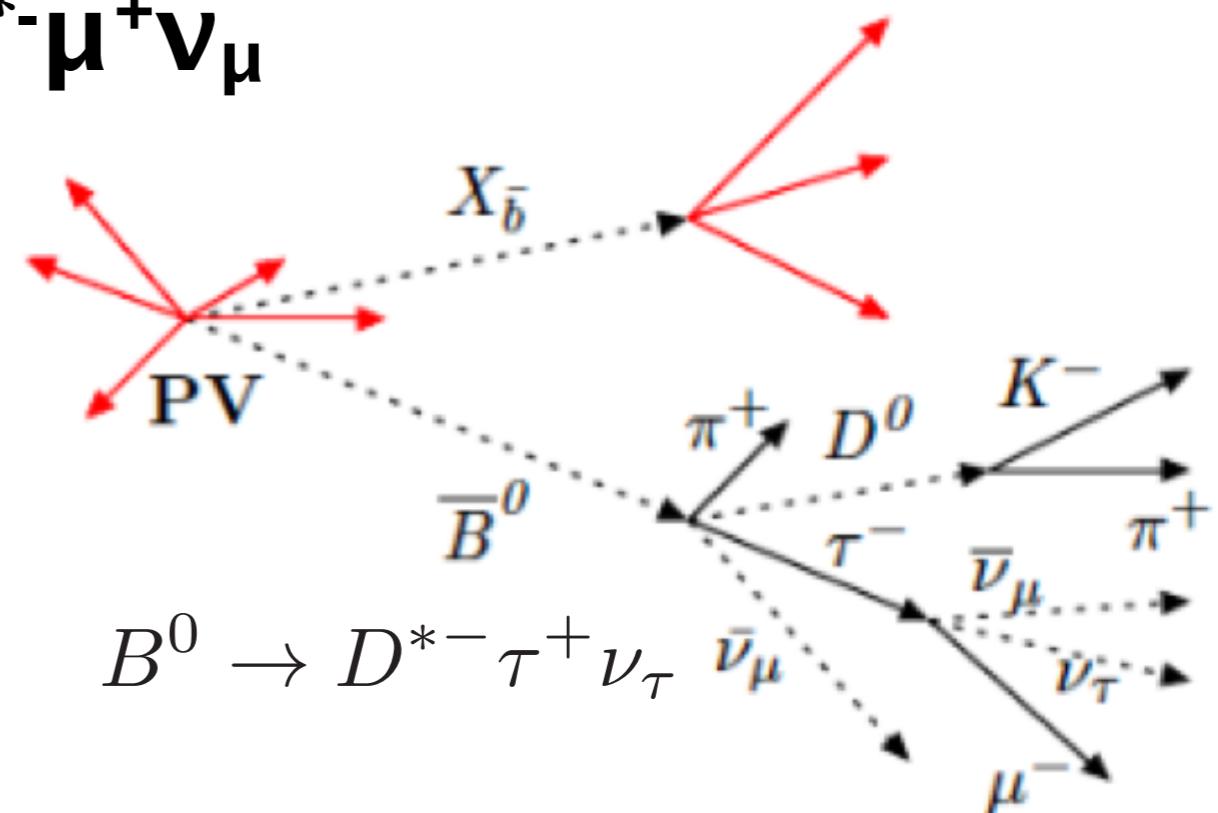
- ☞ Primary-secondary vertex separation (direction)
- ☞ Boost of the reconstructed signal decay products along the beam (magnitude)



$R(D^*)$ at LHCb with $\tau \rightarrow \mu \nu \bar{\nu}$ decays (Run I)

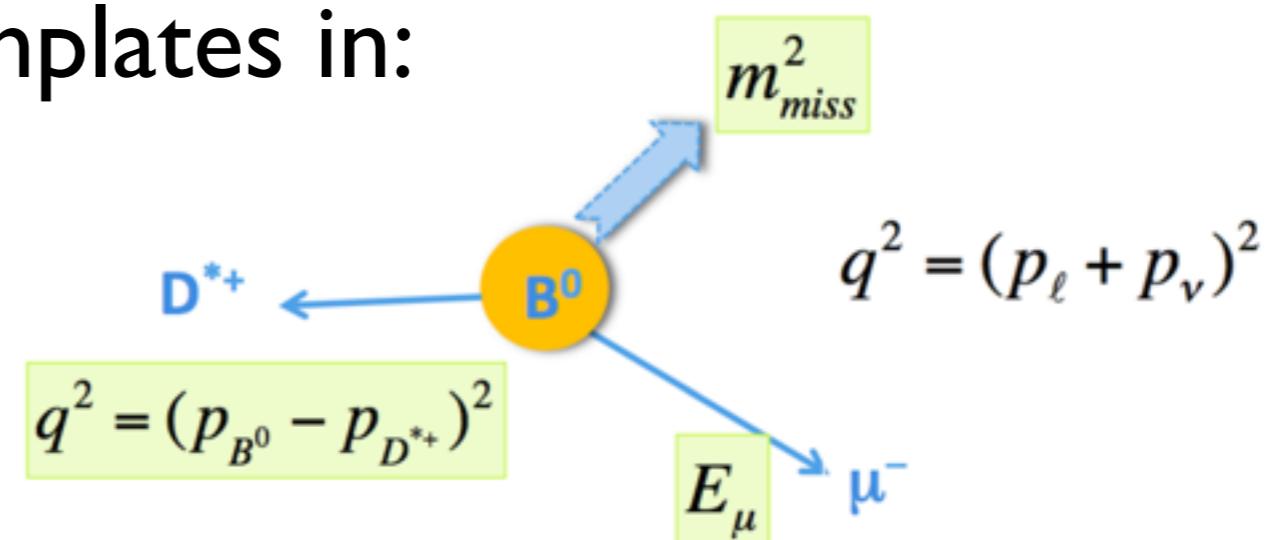
PRL 115, 111803

Normalise exclusively to $B^0 \rightarrow D^* - \mu^+ \nu_\mu$
(same visible final state)



Separate signal,normalisation and background modes
using kinematic distribution templates in:

- the muon energy, (E_μ)
- missing mass squared (m_{miss}^2)
- lepton recoil (q^2)



$R(D^*)$ at LHCb with $\tau \rightarrow 3\pi(\pi^0)$ decays (Run I)

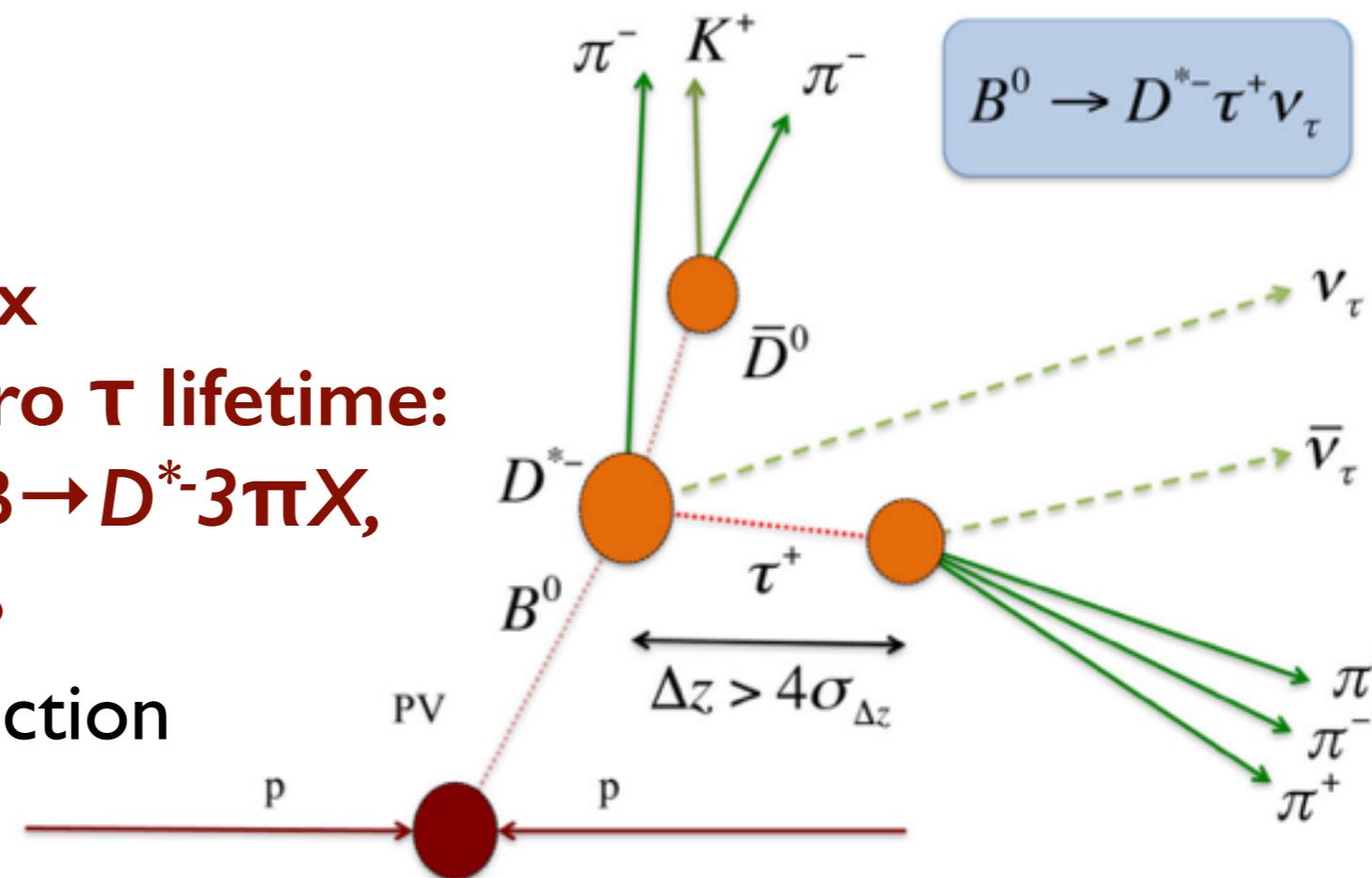
Recent!

The first time $R(D^*)$ is determined with hadronic
 $\tau^- \rightarrow 3\pi(\pi^0)\nu_\tau$ modes.

PRD 97 072013

Benefit from:

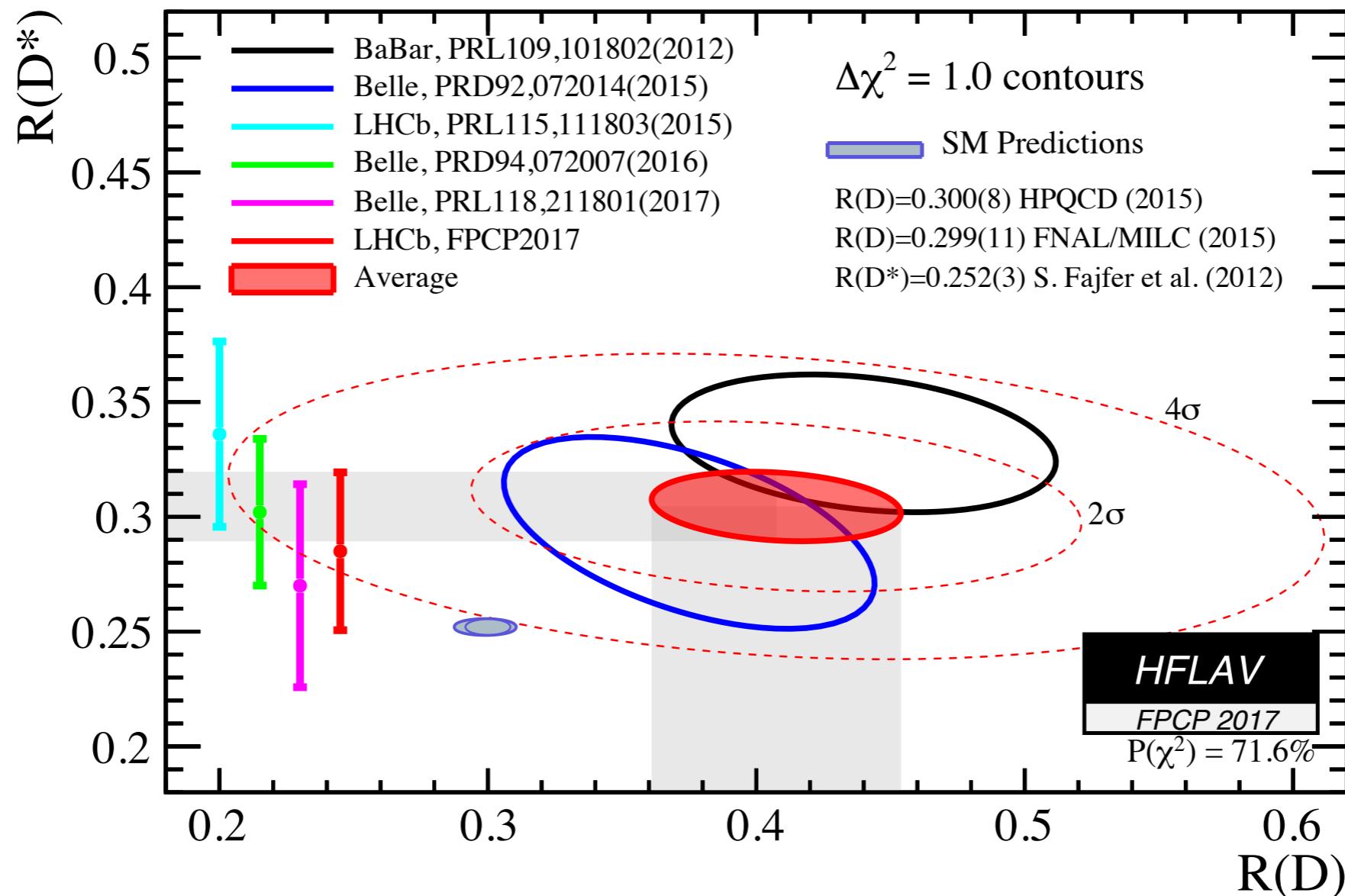
- no charged leptons:
no semi-leptonic background
- **high boost, precise τ -vertex reconstruction and non-zero τ lifetime:**
eliminate background from $B \rightarrow D^ 3\pi X$,
reject 99.9% bkg, retain 40%*
- complete B^0 and τ reconstruction
(*2-fold ambiguity*)



First normalise and then calculate the $R(D^*)$:

- normalise the signal chain branching fraction to $B \rightarrow D^* 3\pi$
- calculate $R(D^*)$ exclusively w.r.t $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$

Combined $R(D^*)$ and $R(D)$ significance is 4.1 σ w.r.t SM ($R(D^*)$ alone 3.4 σ)



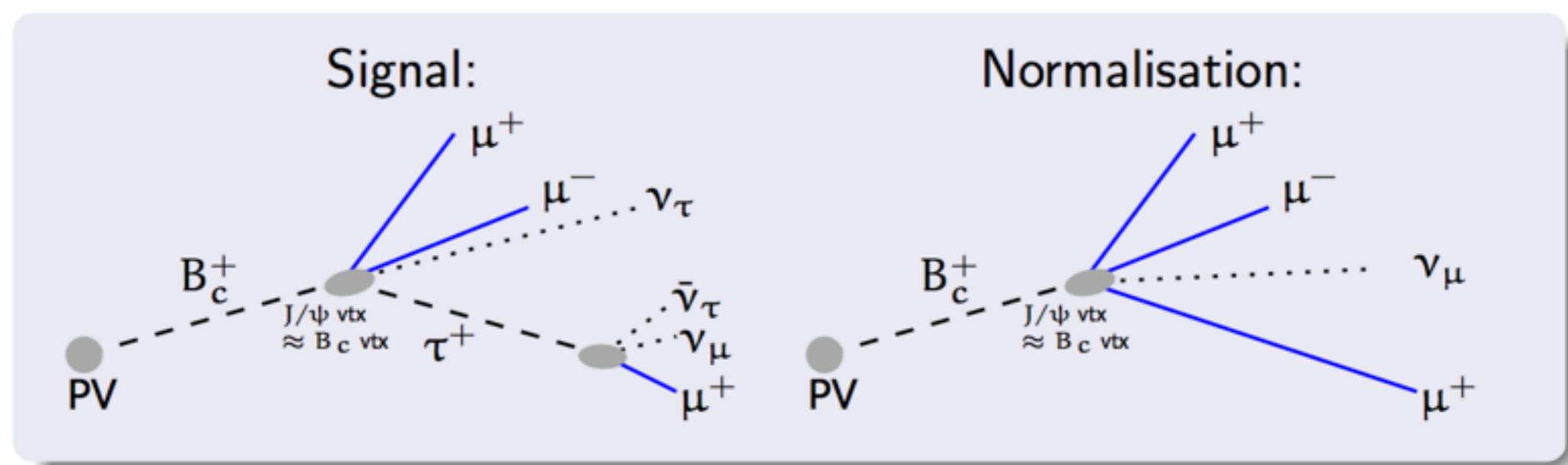
NB! Updates not included (small combined effect on the tension):

- * mild change in the published LHCb $R(D^*)$ from hadronic τ channel
- * updated SM predictions [JHEP 11 (2017) 061]

LHCb has performed similar LFU test with
 $B_c \rightarrow J/\psi l \bar{\nu}_l$ decays: $R(J/\psi)$

Recent!

PRL 120.121801



LFU test results on B_c decays: $R(J/\psi)$

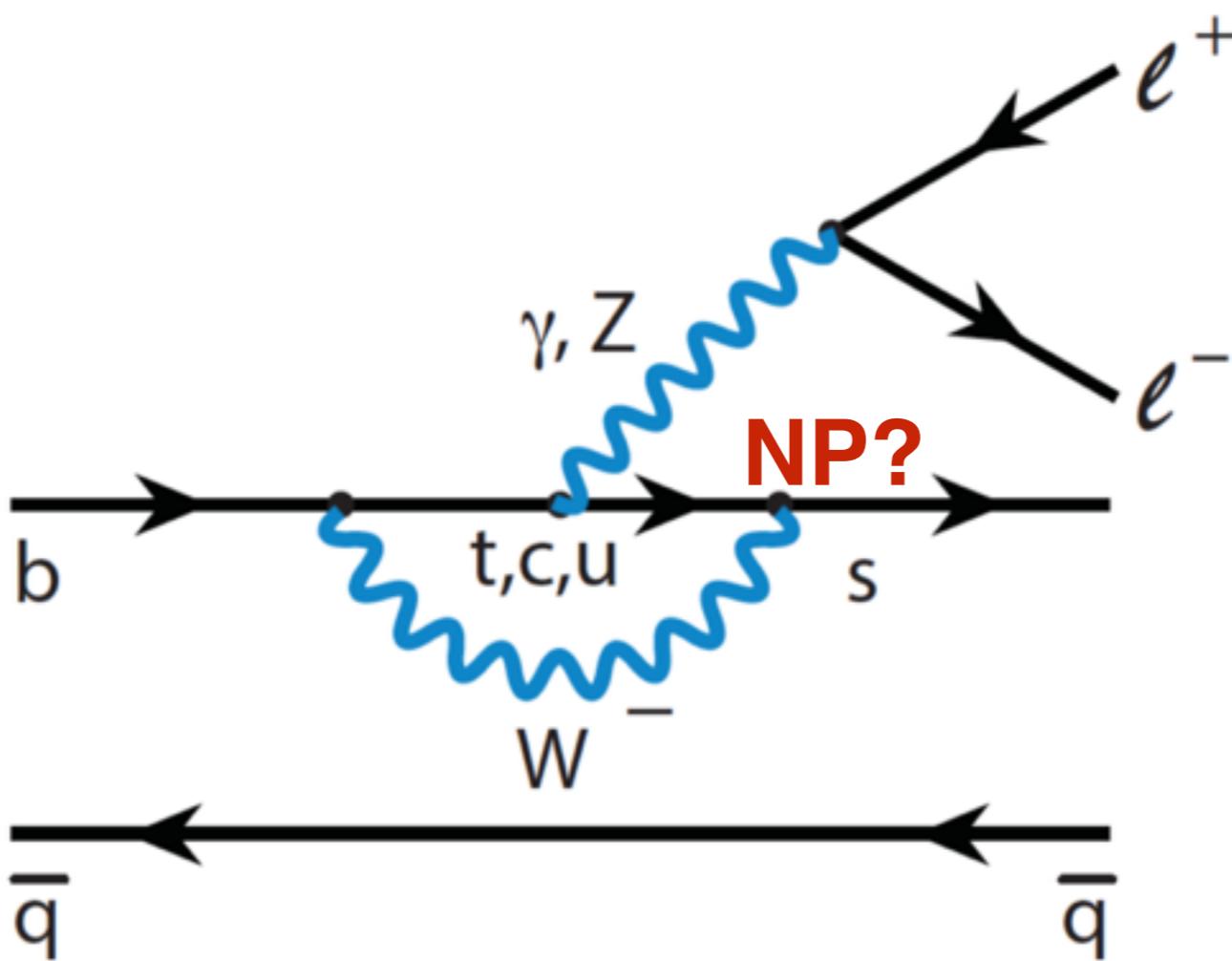
Recent!

PRL 120.121801

- B_c system suffers from:
 - small fragmentation fraction to B_c
 - imprecise $B_c \rightarrow J/\psi$ form factors lead to large theory and experimental uncertainties (*crucial for the kinematic templates*)
- First evidence for $B_c \rightarrow J/\psi \tau^+ \nu_\tau$ decays (3σ)
- $R(J/\psi)$ results on Run I data in a 2σ agreement with the predicted central value range (0.25-0.28):

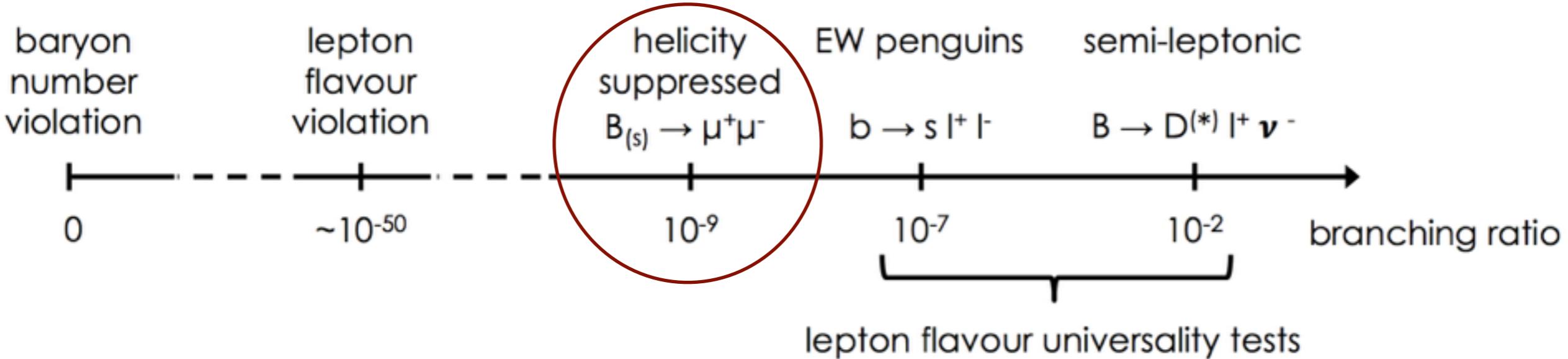
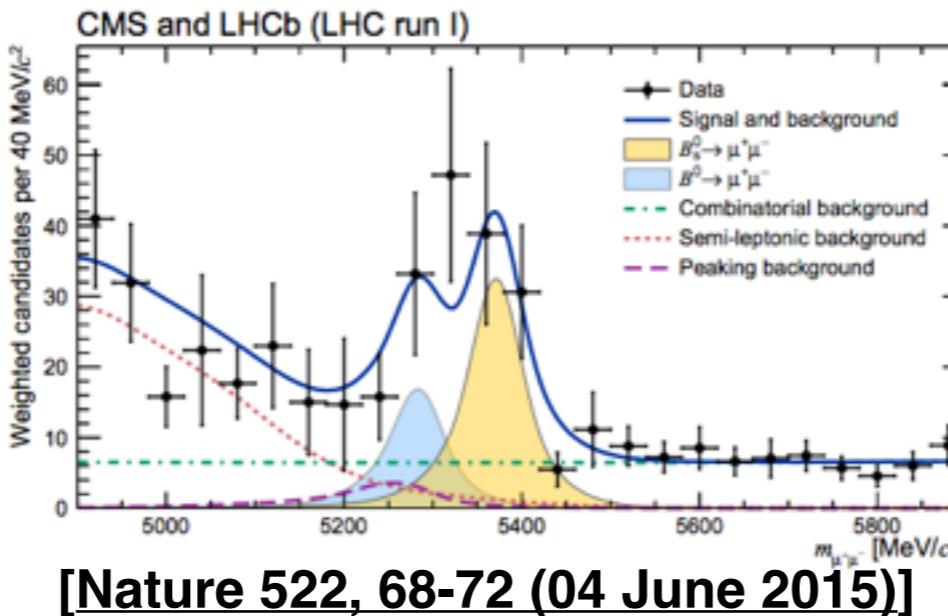
$$\begin{aligned} R(J/\psi) &= \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} \\ &= 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst}). \end{aligned}$$

Flavour anomalies at the loop level



- $b \rightarrow s l^+ l^-$ transitions are rare in the SM (no tree level contributions: GIM, CKM, in some cases helicity suppressed)
- ideally suited for indirect New Physics searches (indirectly sensitive to energy scales $O(100\text{TeV})$)

Large and clean samples of B's have allowed to
(i) observe new rare modes:



(ii) study the rare modes in depth with additional observables:
 effective $B_s \rightarrow \mu\mu$ lifetime, angular observables, asymmetries, branching fraction ratios to less favoured final states
 (as for $B \rightarrow K^*\mu\mu, B \rightarrow K^*ee$)

LFU tests with $B \rightarrow K^{(*)}\mu\mu$ and $B \rightarrow K^{(*)}ee$ decays: $R(K)$ and $R(K^*)$

- Theoretical uncertainties on the exclusive $B \rightarrow K^{(*)}\ell\ell$ branching fractions are **reduced to a per-mille level** in ratios (*hadronic effects cancel*):

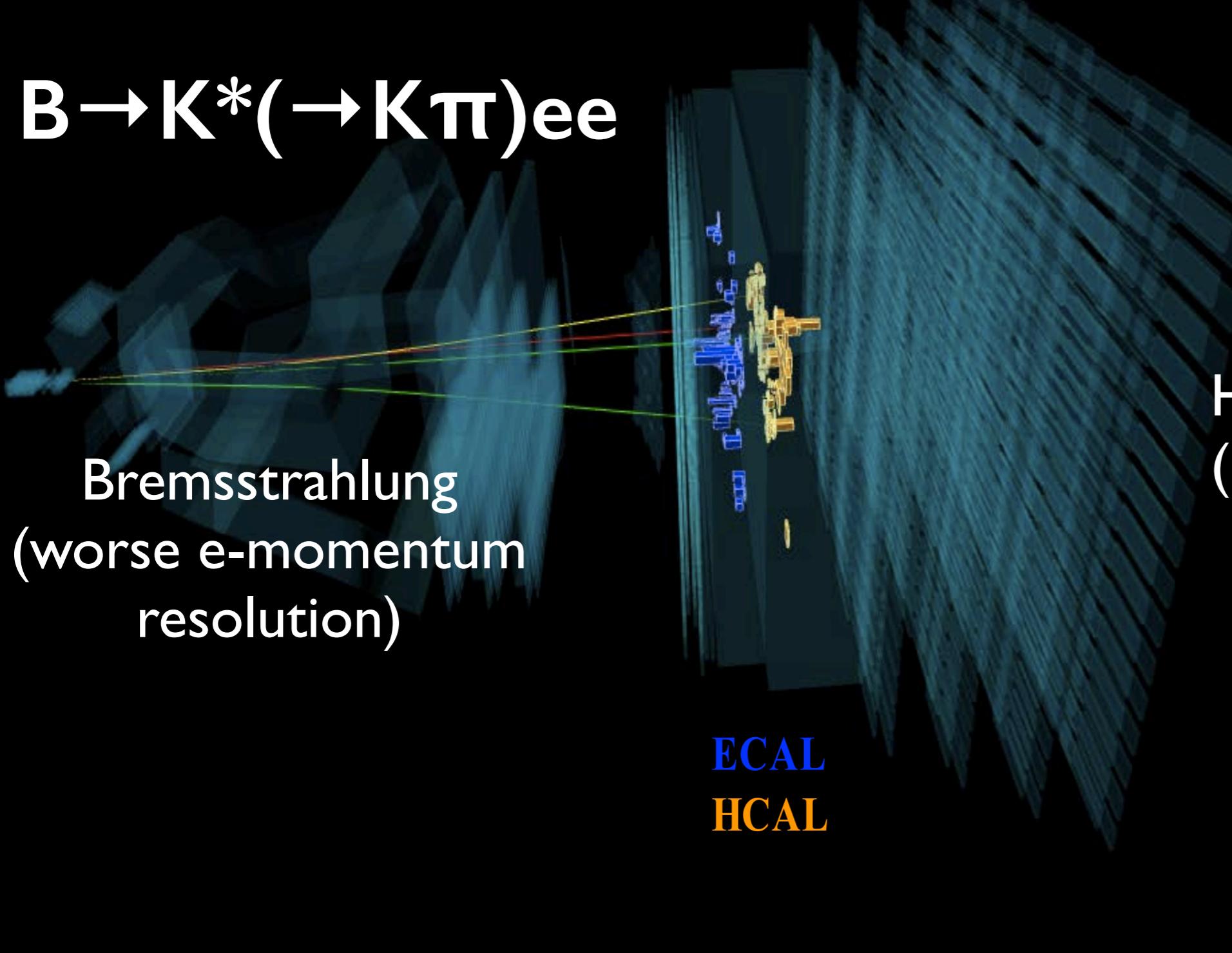
$$R(K) = \frac{B^+ \rightarrow K^+ \mu^+ \mu^-}{B^+ \rightarrow K^+ e^+ e^-} \quad R(K^*) = \frac{B^0 \rightarrow K^{*0} \mu^+ \mu^-}{B^0 \rightarrow K^{*0} e^+ e^-}$$

- SM, $R(K)$ and $R(K^*)$ expected to be close to unity.
- Sensitive to new neutral and heavy gauge bosons, lepto-quarks, Z' models.

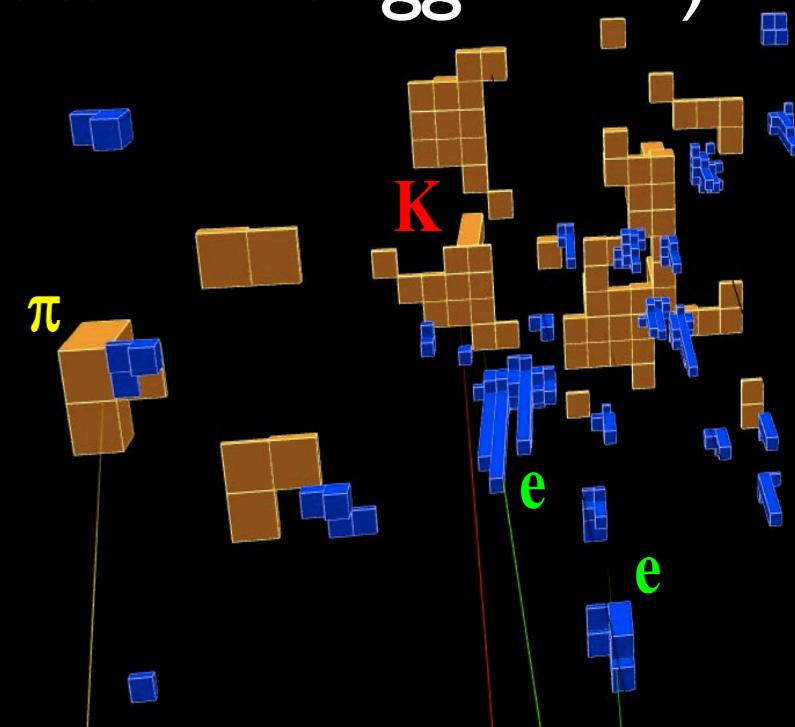
Electron reconstruction in LHCb

Electron and muon detection is far from universal.

$B \rightarrow K^*(\rightarrow K\pi)ee$



High ECAL occupancy
(lower e-trigger eff.)



Electron reconstruction in LHCb

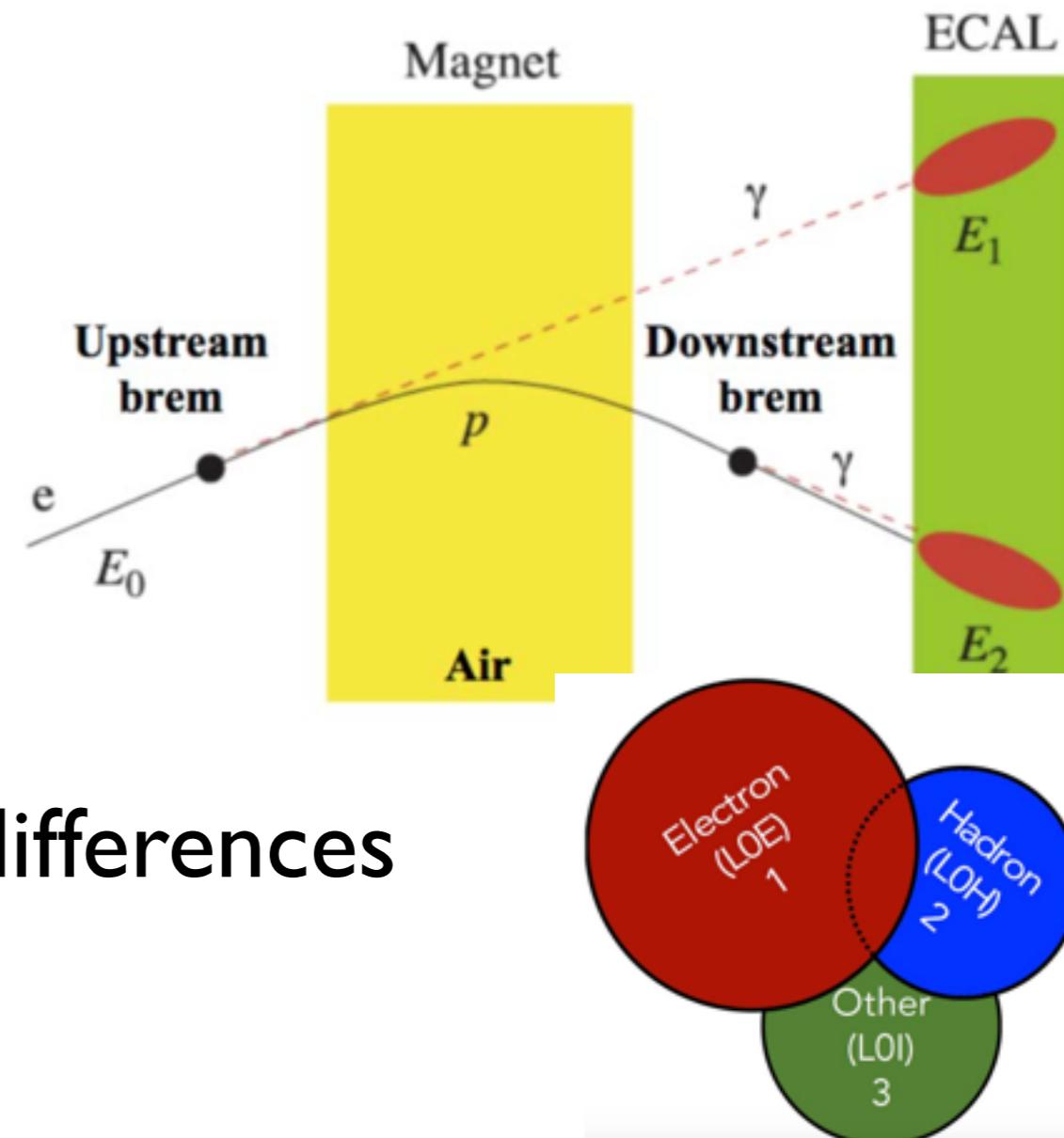
- Reduce the experimental uncertainties by measuring a **double ratio**:

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

- Simulate FSR using PHOTOS
(verified at $\sim 1\%$ level) [EPJ C76 \(2016\)](#)

- Correct for upstream radiation
(fit categories: no-/one-/more- added γ)

- Mitigate $e-\mu$ trigger threshold differences
by including hadron triggers



Convincing cross-checks at LHCb

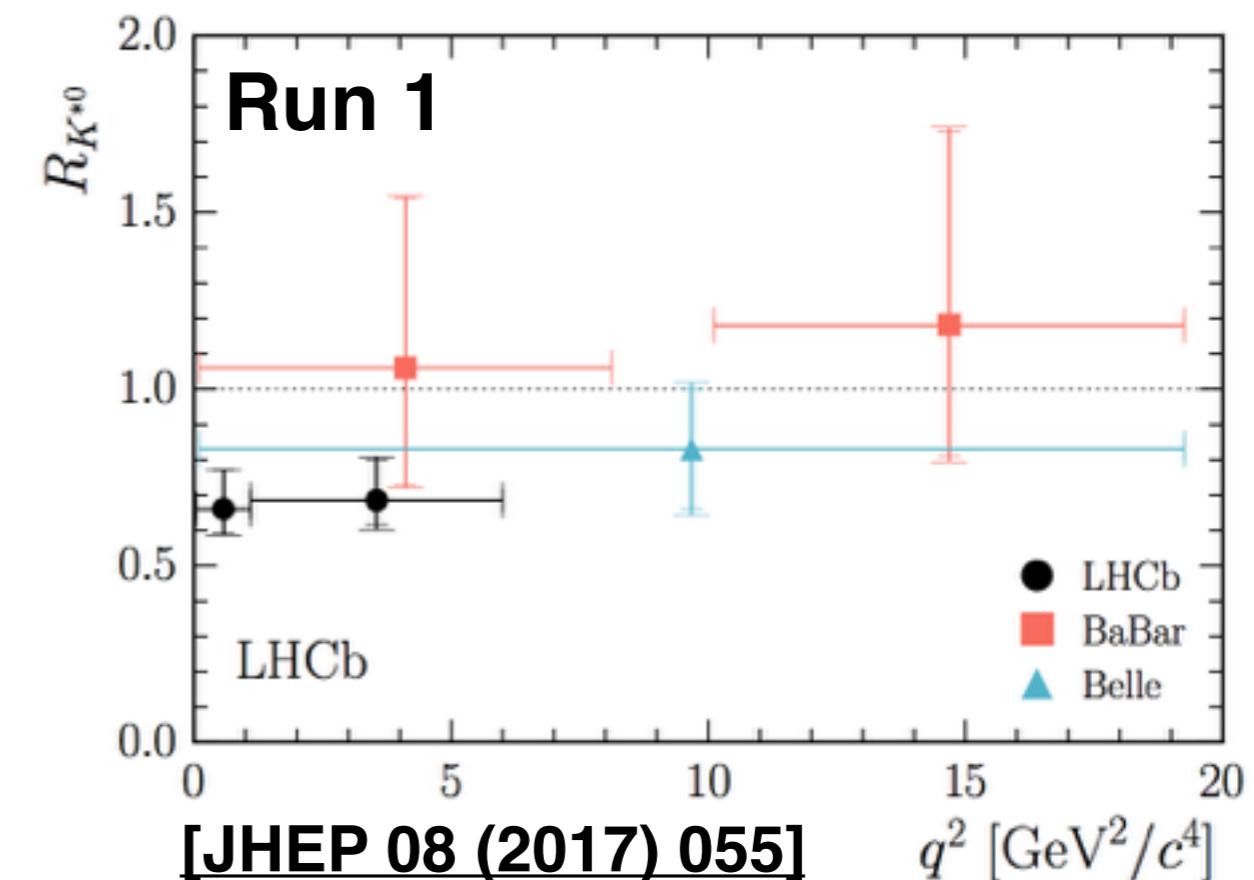
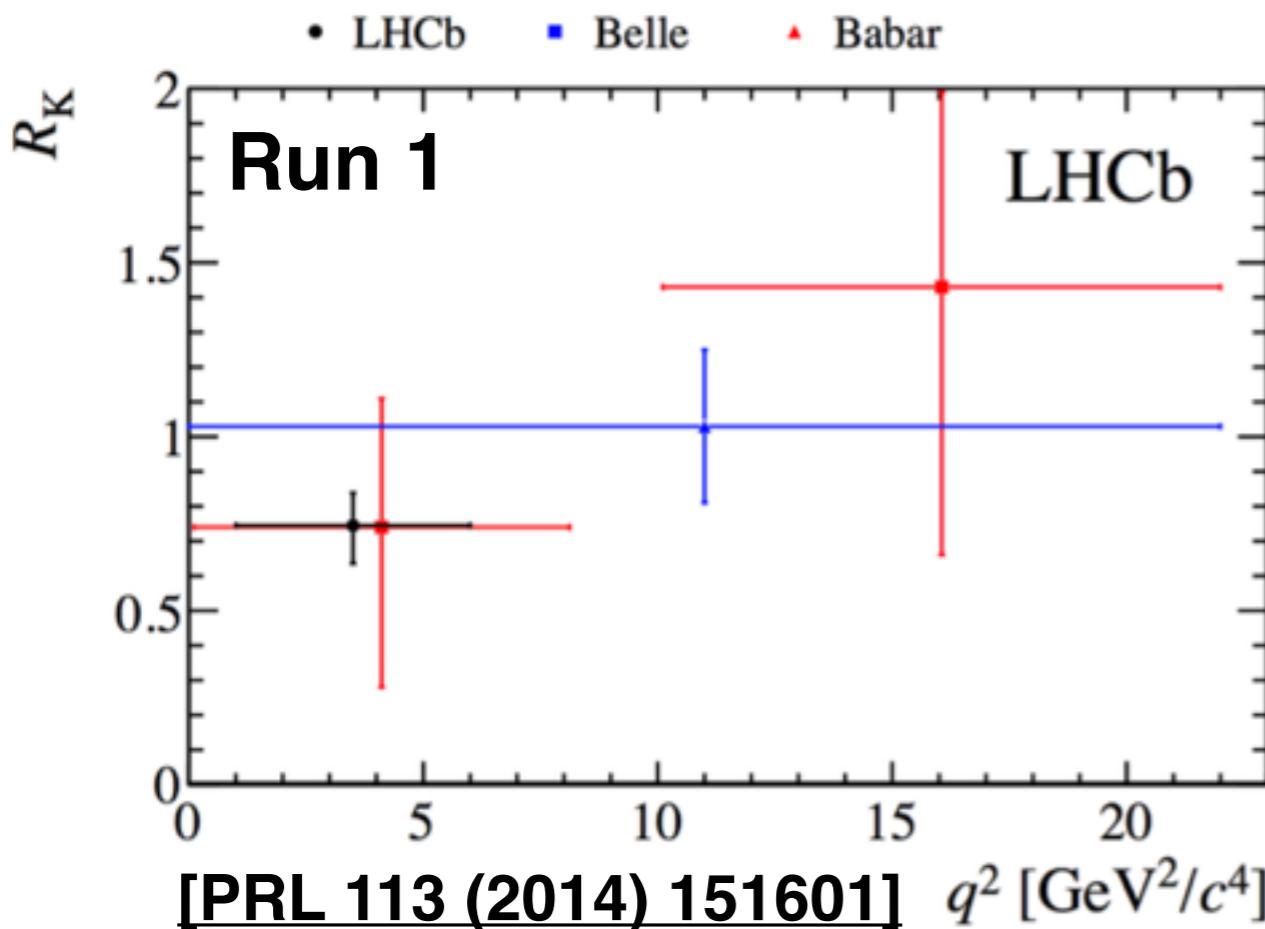
- **Single ratio** of resonant $J/\psi \rightarrow l^+l^-$ modes in good agreement to unity (*a strict test*)

$$r_{J/\psi} = 1.043 \pm 0.006(\text{stat}) \pm 0.045(\text{syst.})$$

- **Double ratio** of resonant $\Psi(2S)$ modes: within one standard deviation from unity (2% precision)
- **Branching fractions** of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ and $B^0 \rightarrow K^{*0}\gamma$ with photon conversion $\gamma \rightarrow e^+e^-$ in agreement with previous measurements and expectations (*validates γ -recovery*)

R(K) and R(K*) results

LHCb focusses on the q^2 regions with reliable theoretical predictions and small contributions from the resonant modes. Precision limited by statistics.



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

2.6 σ

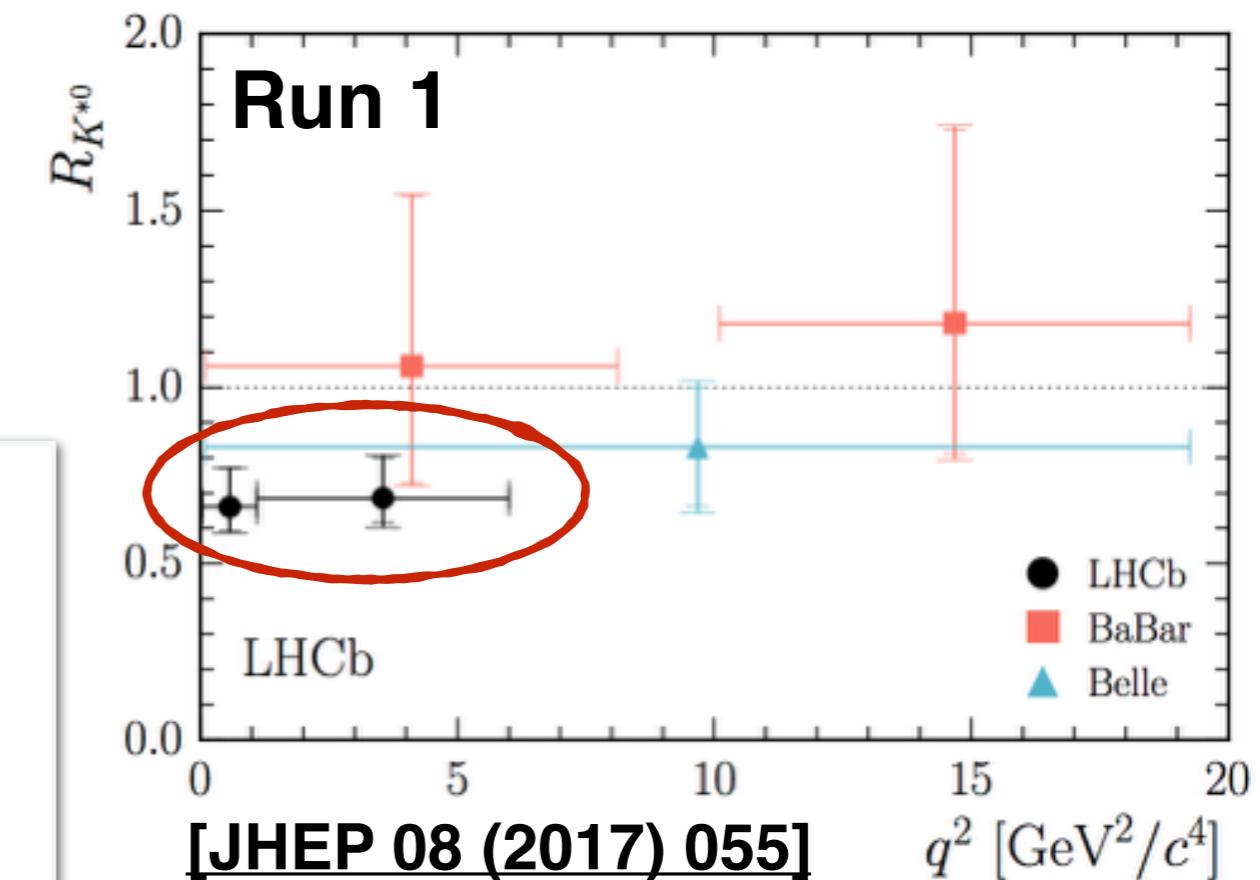
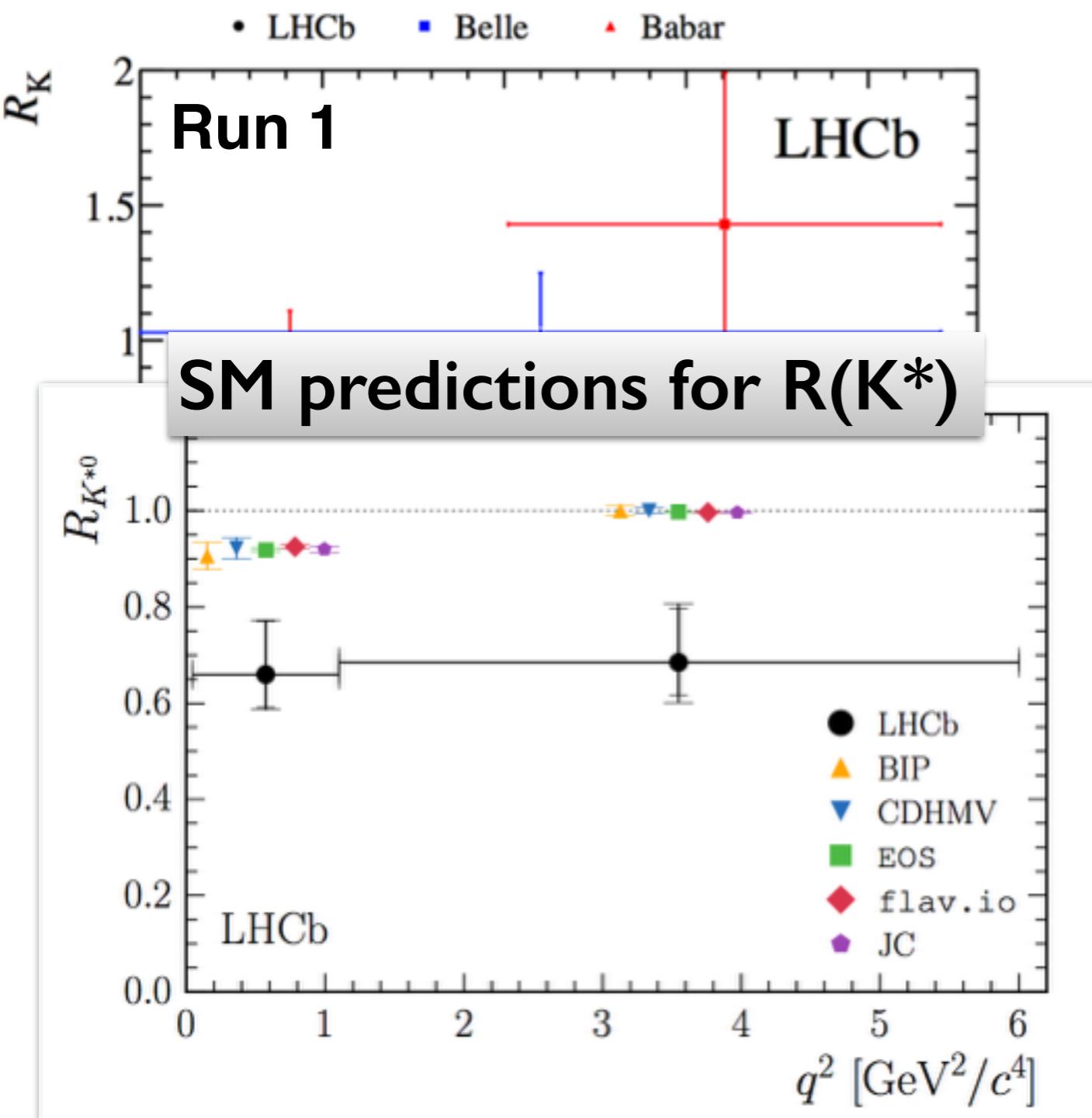
$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}) & \text{for } 0.045 < q^2 < 1.1 \text{ GeV}^2/c^4, \\ 0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05(\text{syst}) & \text{for } 1.1 < q^2 < 6.0 \text{ GeV}^2/c^4. \end{cases}$$

for $0.045 < q^2 < 1.1 \text{ GeV}^2/c^4$,
for $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$.

2.1 - 2.4 σ

$R(K)$ and $R(K^*)$ results

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2.6 σ

for $0.045 < q^2 < 1.1$ GeV $^2/c^4$,
for $1.1 < q^2 < 6.0$ GeV $^2/c^4$. **2.1 - 2.4 σ**

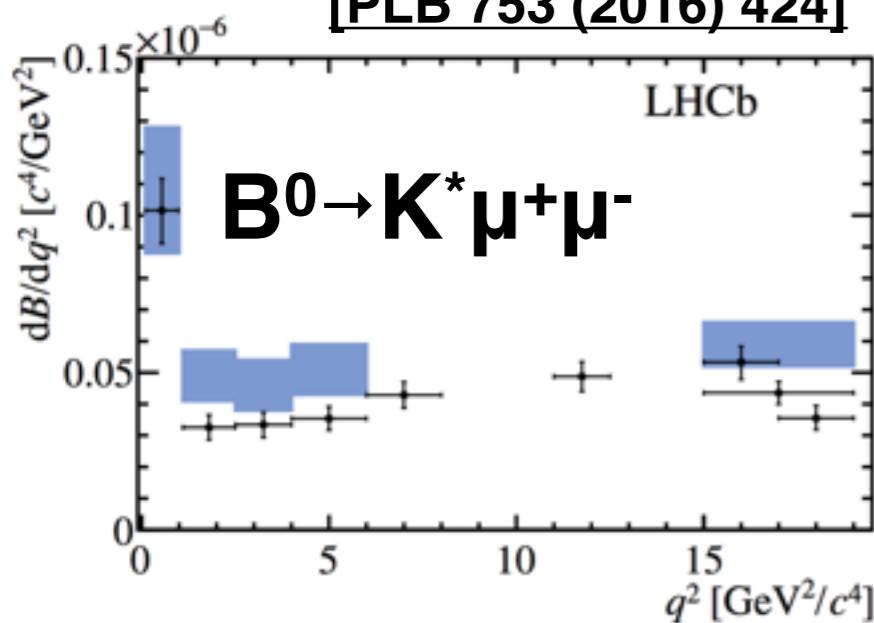
If not of statistical nature, where do the tensions originate from?

- $b \rightarrow s\mu^+\mu^-$?
- $b \rightarrow s e^+e^-$?

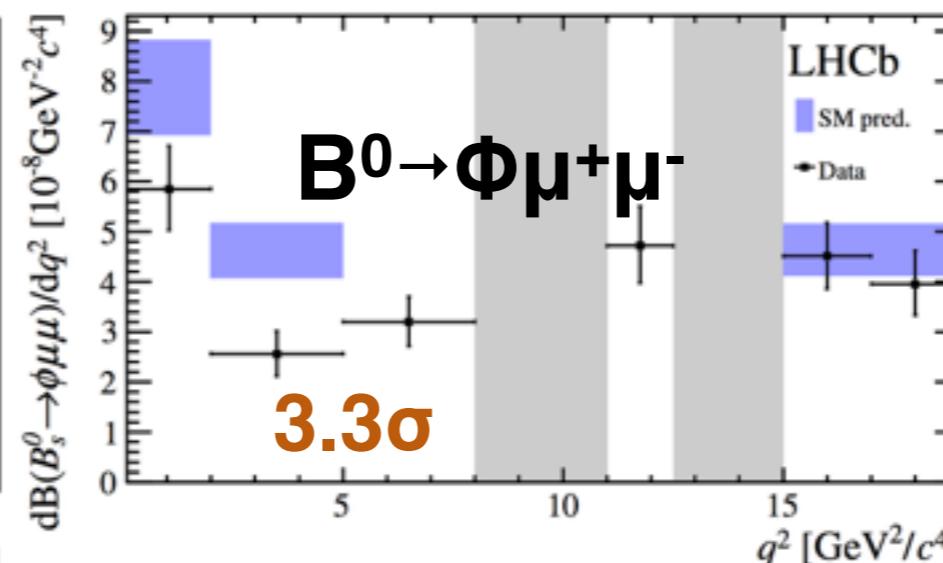
Exclusive $b \rightarrow s \mu^+ \mu^-$ branching fractions on the lower side ($q^2 \sim 5 \text{ GeV}^2$)

[JHEP 04 (2017) 142]

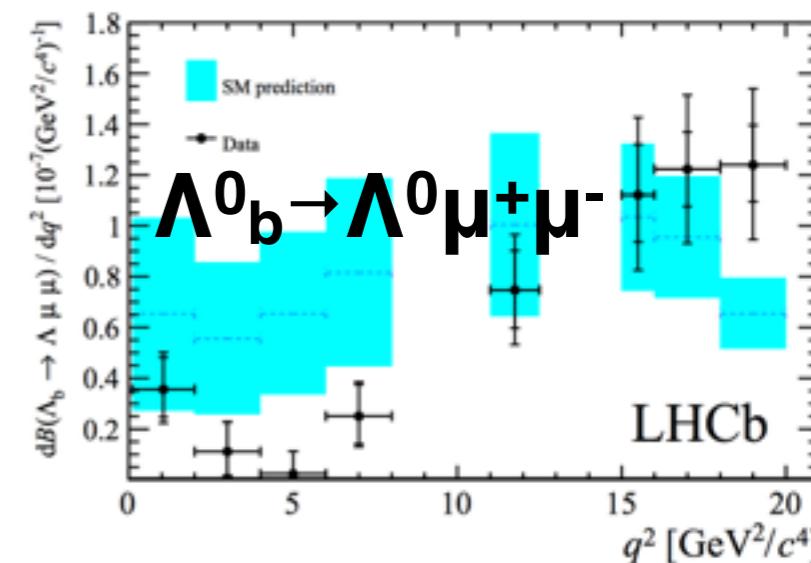
[PLB 753 (2016) 424]



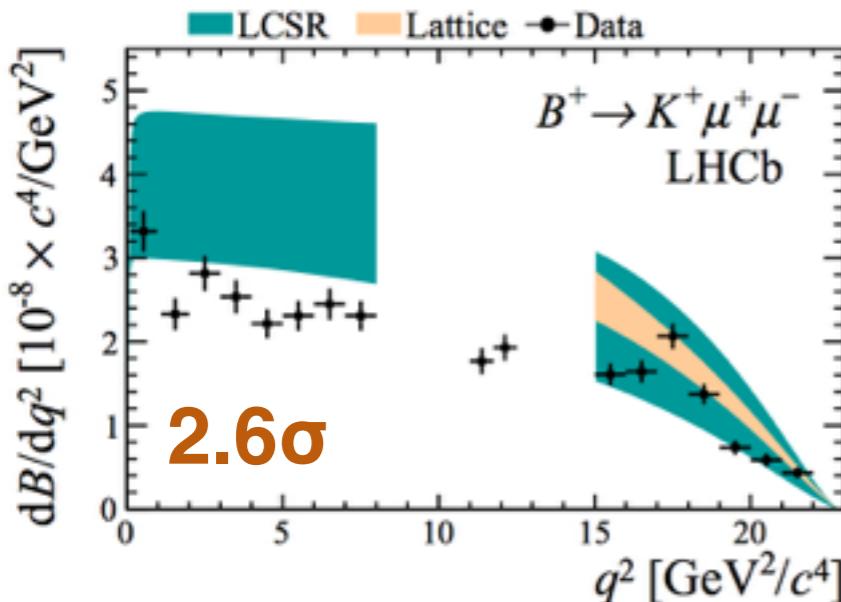
[JHEP 09 (2015) 179]



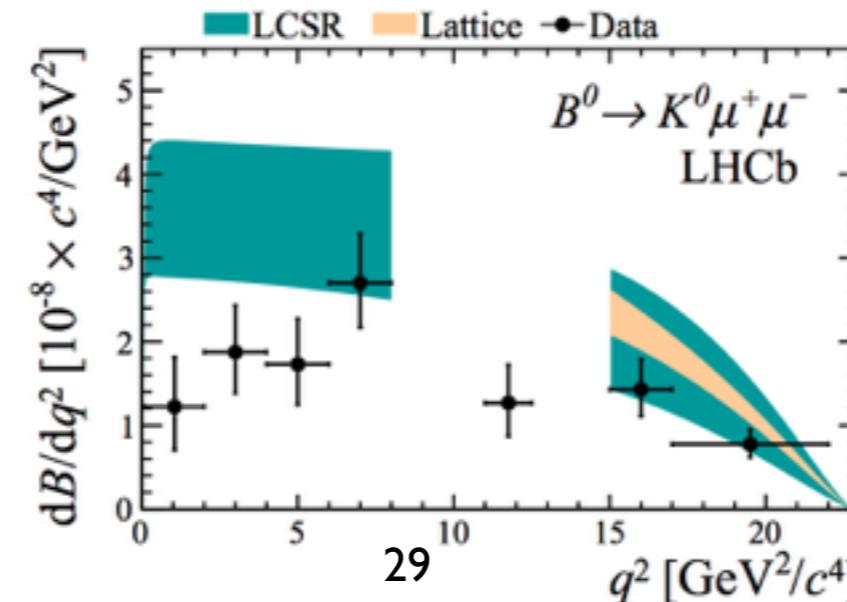
[JHEP 06 (2015) 115]



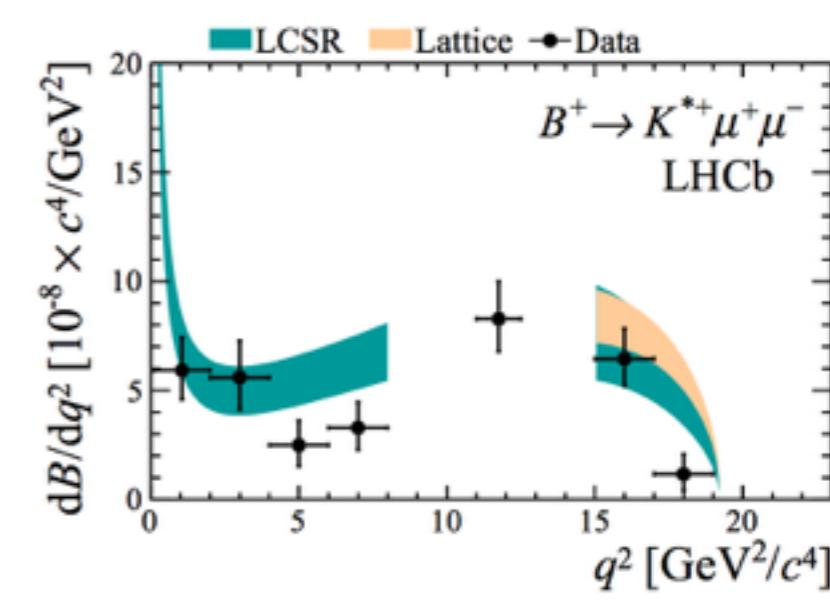
[JHEP 06 (2014) 133]



[JHEP 06 (2014) 133]

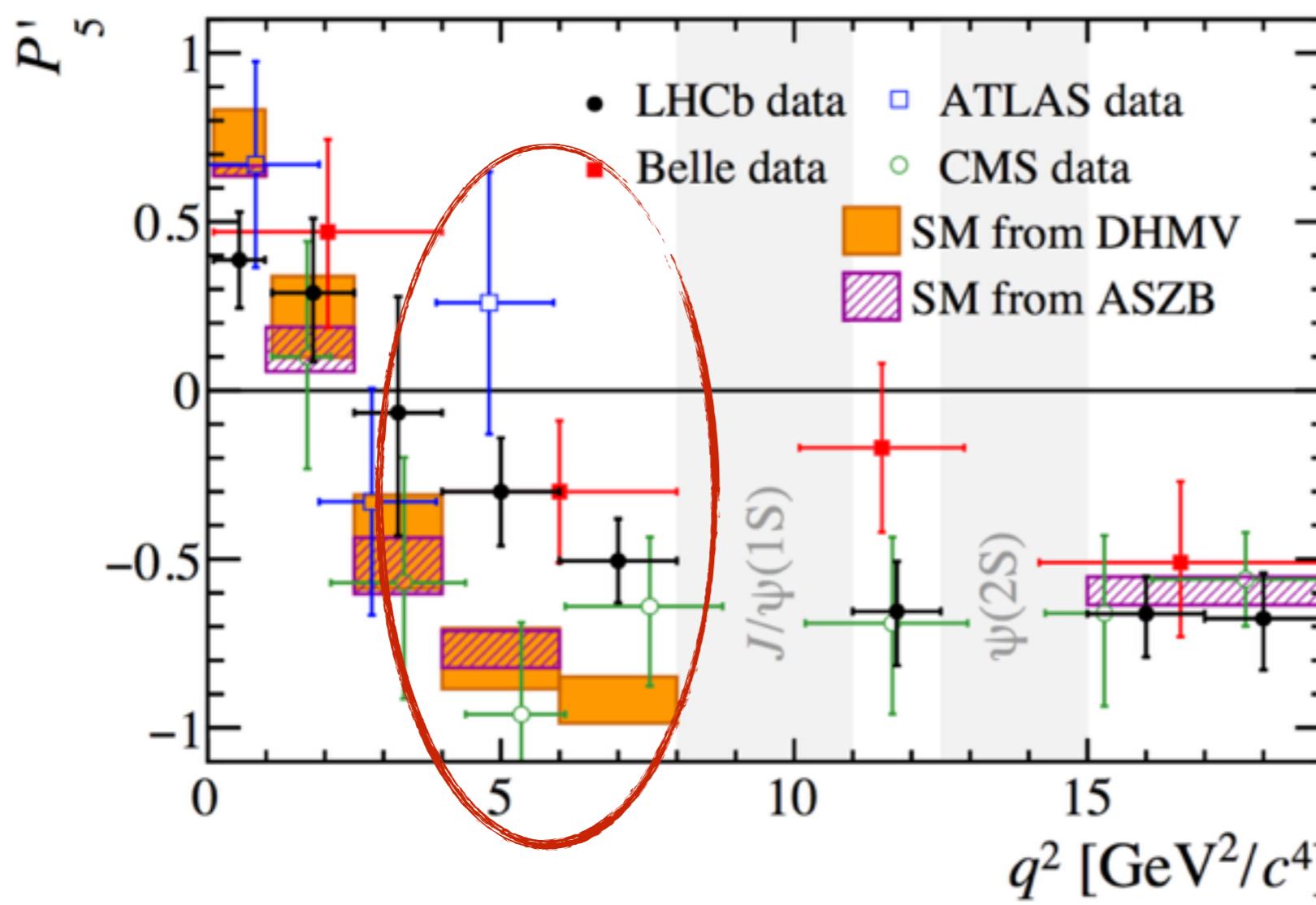


[JHEP 06 (2014) 133]



$B^0 \rightarrow K^* \mu^+ \mu^-$ angular observable (P_5')

- The three decay angles can be parameterised in optimised observables with greatly reduced form factor dependencies.
- One of the cleanest, P_5' , diverges from the predictions ($\sim 3\sigma$) in the same region ($q^2 \sim 5 \text{ GeV}^2$)



LHCb : [\[JHEP 02 \(2016\) 104\]](#)

ATLAS : [\[CERN-EP-2017-161\]](#)

BELLE : [\[PRL 118 \(2017\) 111801\]](#)

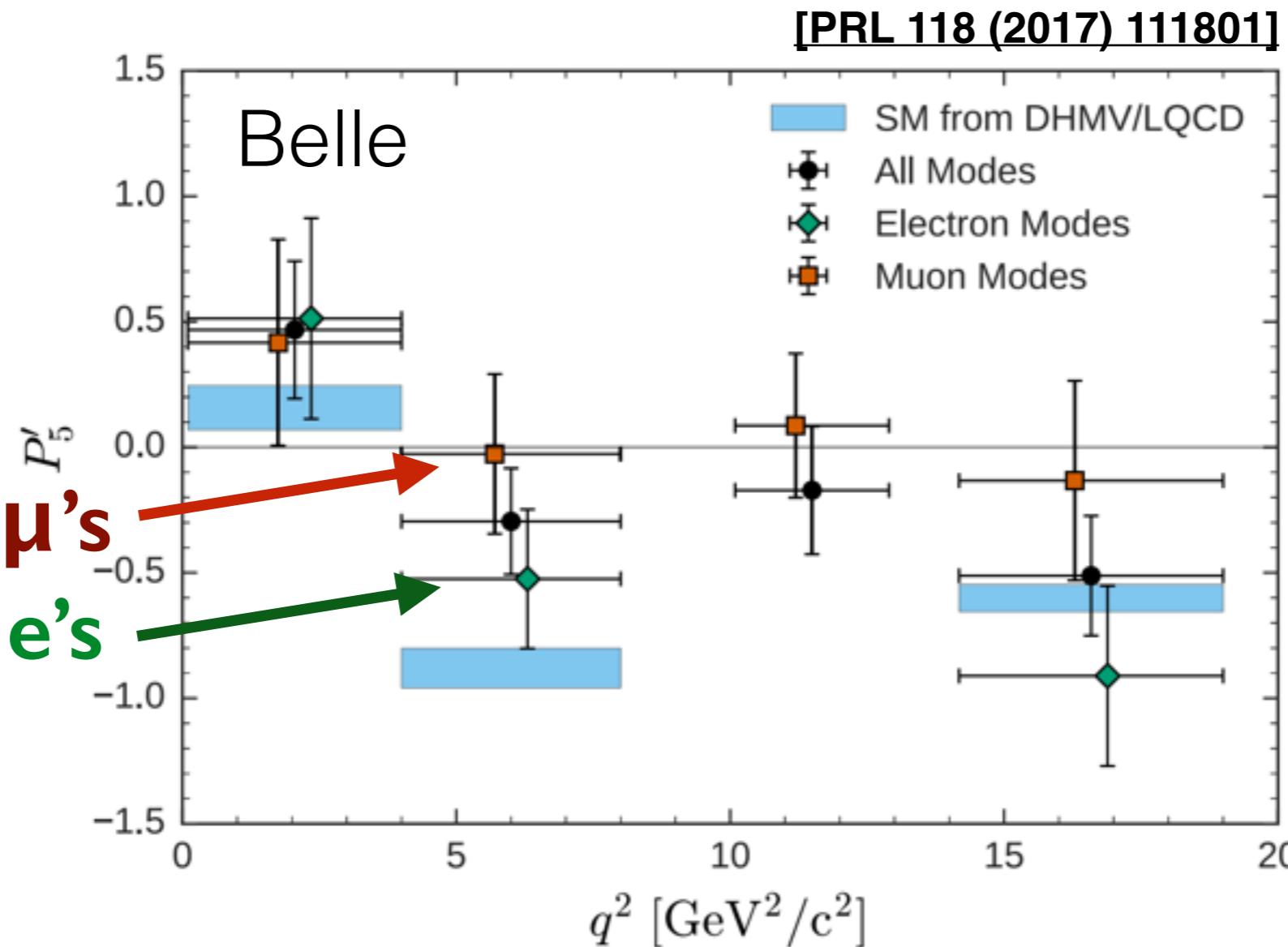
CMS : [\[PRD 97 \(2018\) 095035\]](#)

DHMV : [\[JHEP 12, 125 \(2014\)\]](#)

ASZB : [\[EPJC 75, 382 \(2015\)\]](#)

$B^0 \rightarrow K^* e^+ e^-$ angular observables

- Interestingly for $B^0 \rightarrow K^* e^+ e^-$, BELLE measures a better agreement in P_5' :

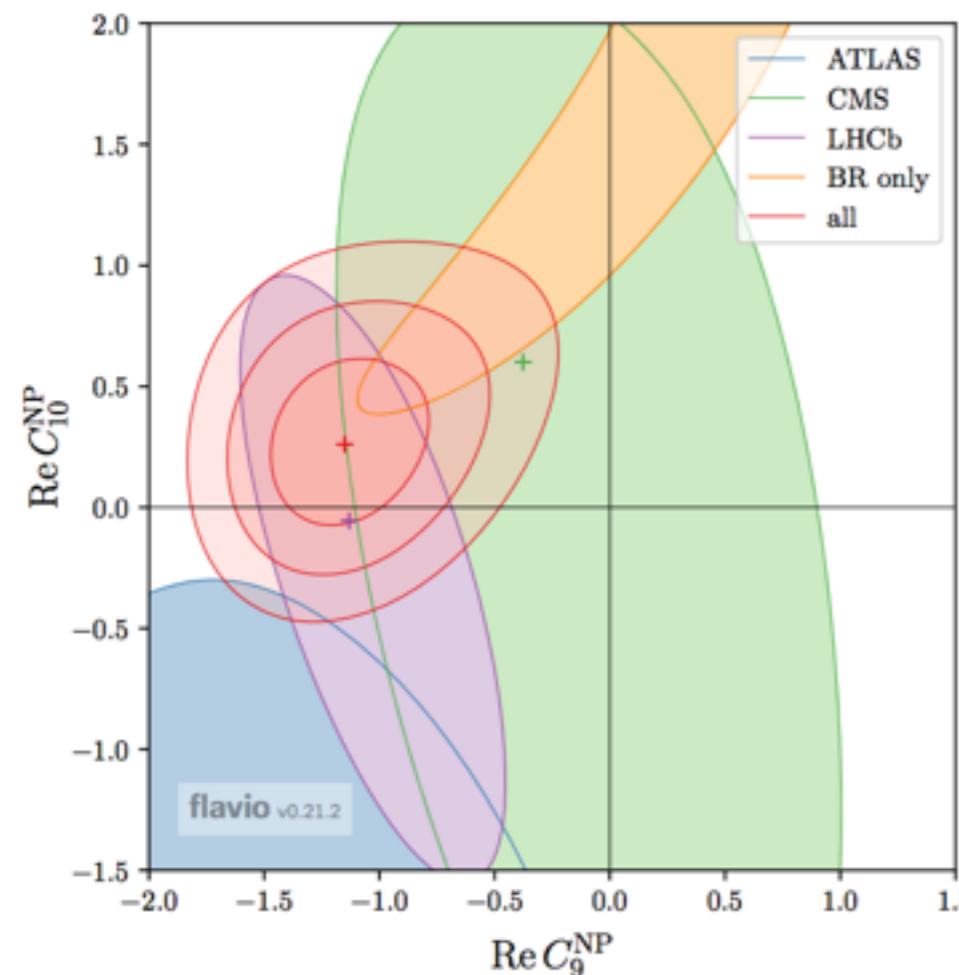


Also LHCb's results from a simplified $B^0 \rightarrow K^* e^+ e^-$ angular analysis' in agreement with SM.

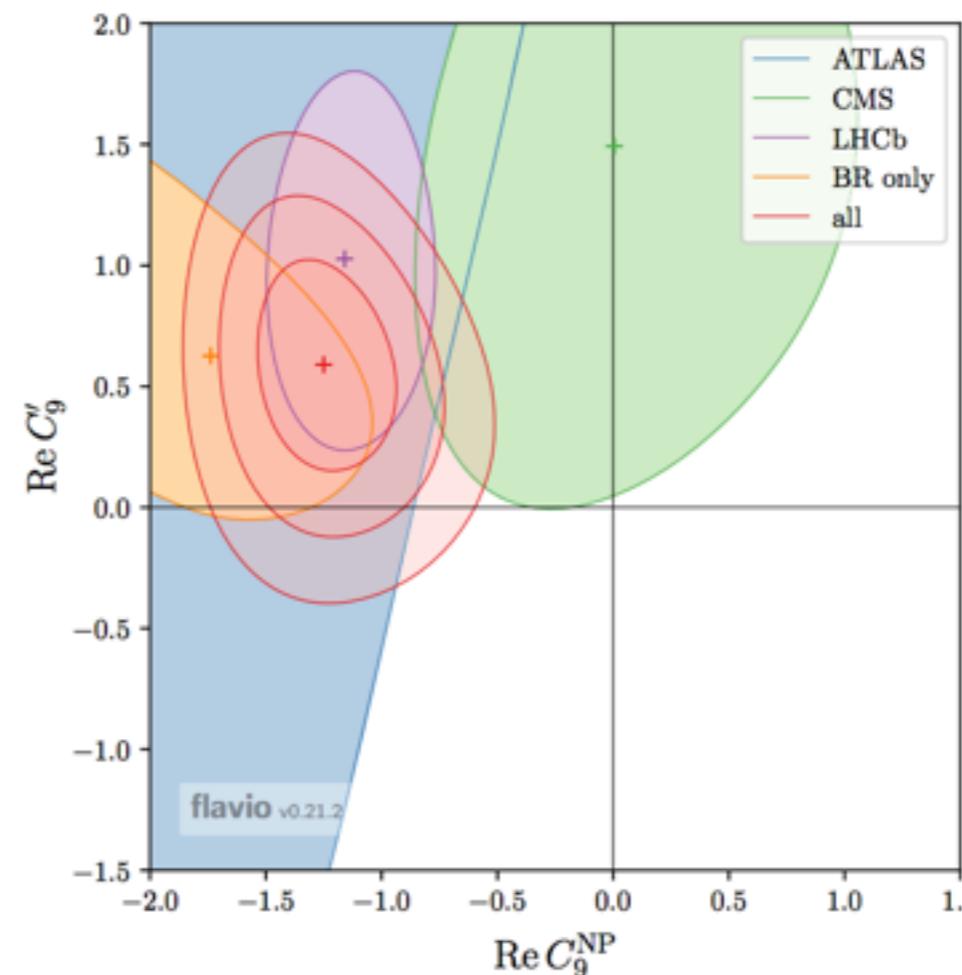
A global model independent analysis of the underlying physics in $b \rightarrow s l^+ l^- (\gamma)$ transitions show a consistent picture with:

- tensions at $4-5\sigma$ level w.r.t SM in left-handed muon couplings
- two favoured (model independent) solutions to the tensions

a) $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$



b) $C_9^{\text{NP}} < 0$



Altmannshofer et al [EPJC (2017) 77:377], Capdevila et al [PSI-PR-17-05]

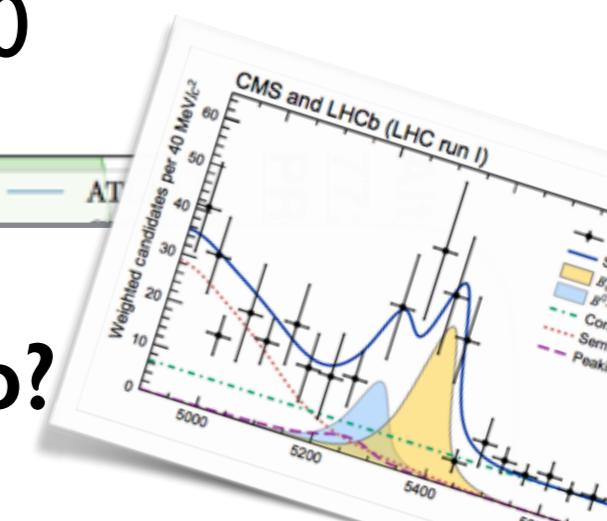
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a) $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$



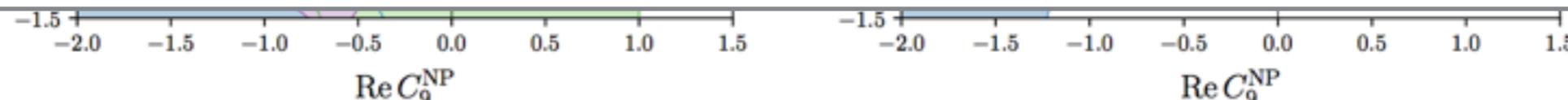
b) $C_9^{\text{NP}} < 0$



Footnote: how to distinguish between a and b?

👉 Improve the $B_s \rightarrow \mu^+ \mu^-$ precision

- sensitive to axial-vector contribution (C_{10}^{NP})
- as well as to new (pseudo-)scalar contributions ($C_{P,S}$ free from helicity suppression)



(~90 measurements e.g. in Descotes-Genon, Hofer, Matias, Virto [[JHEP 06 \(2016\) 092](#)],
Altmannshofer, Straub [[EPJC 75\(8\) \(2015\) 382](#)], Hurth, Mahmoudi, Neshatpour [[arXiv:1603.00865](#)])

Summary (I/2)

Several experiments have recently published compelling results on b-quark transitions.

- The relative rate of $b \rightarrow c\tau\nu$ and $b \rightarrow c\mu\nu$ transitions lower than predicted: *combined WA $R(D^*)$ and $R(D)$ tension at $\sim 4\sigma$, LHCb published first results from B_c decays, $R(J/\Psi)$ are $(2\sigma$, w.r.t predicted central values)*
- The relative rates of FCNC $b \rightarrow s\mu^+\mu^-$ and $b \rightarrow se^+e^-$ transitions lower than predicted:
 $R(K)$ and $R(K^)$ tensions at $2\text{-}3\sigma$*

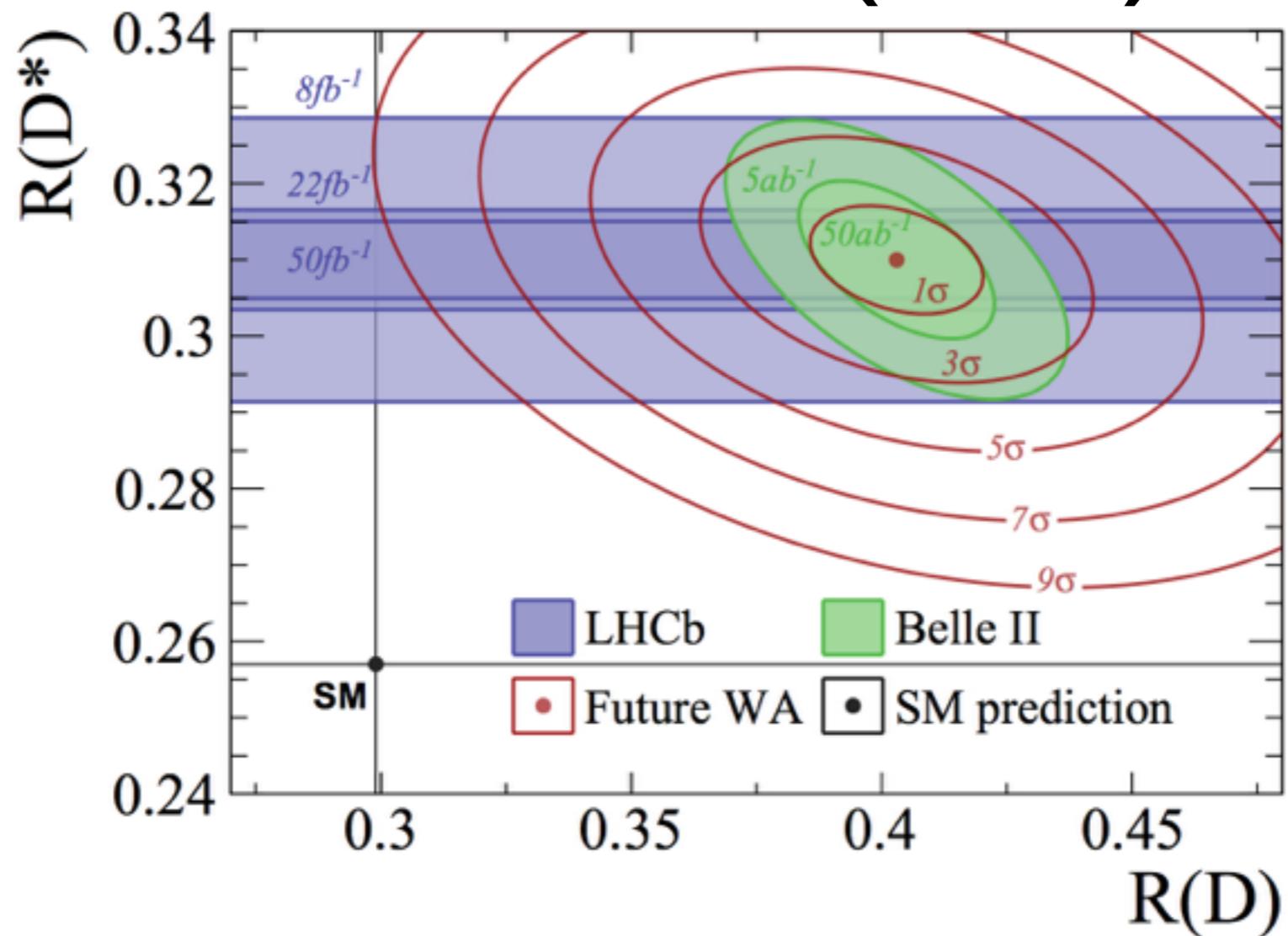
Summary (2/2)

- The measured **branching fractions** of exclusive $b \rightarrow s\mu^+\mu^-$ modes lower than predicted in the q^2 region $\sim 5\text{GeV}$.
- Tension in the $B \rightarrow K^*\mu\mu$ angular observable P^5' in the same q^2 region ($\sim 5\text{GeV}^2$).
- Global model independent $b \rightarrow s l^+l^-(\gamma)$ analysis show at a **consistent picture with tensions in (axial-)vector muon couplings**

Outlook (I/2)

- After RunII, LHCb will have ~ 5.7 x the RunI data.
- Expected uncertainties after LHCb RunII (2019) assuming current central values: [1709.10308v5](#)
 - $R(K)$: 13% -> 6% ($>5\sigma$)
 - $R(K^*)$: 17% -> 7% ($>3.5\sigma$)
- CMS has announced plans to trigger on single muons while the luminosity is low, record $\sim 10B$ B's in 2018 and measure $R(K^{(*)})$; ATLAS testing possible triggers.
- BELLE2 expected to start recording physics data in spring 2019 and collect 4 times the number of B's collected by the B-factories by 2020 (5ab^{-1})

Outlook (2/2)



- Current WA for $R(D^*)$ is 5.5% and $R(D)$ at 11.6%
- Precision of $R(D^*)$ from LHCb (BelleII) after 2019 (2020) expected to be 3.5% (3.2%)
- Precision on $R(D)$ from Belle 2 after 2020 at 5.6%
(possible also in LHCb, precision remains to be seen)