Rare decays and tests of lepton flavour universality in (b-)quark flavour physics

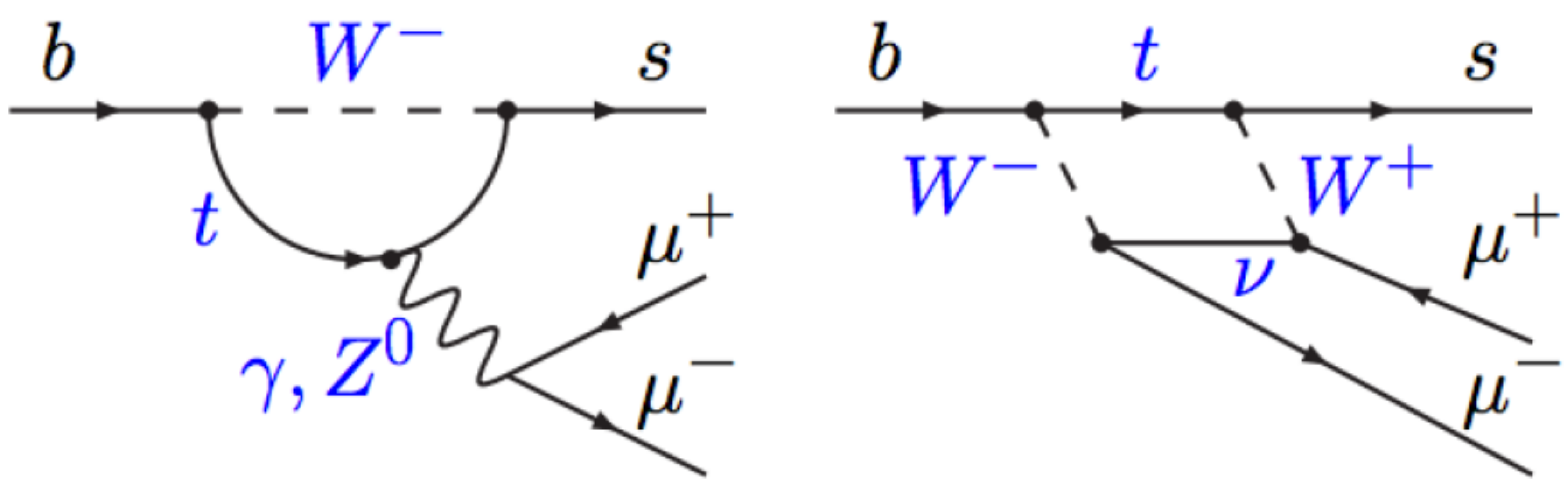
Monica Pepe Altarelli (CERN)

On behalf of LHCb,
also including material from Belle, BaBar, ATLAS and CMS

Corfu Summer Institute
Workshop on the Standard Model and Beyond, September 2-10 2017

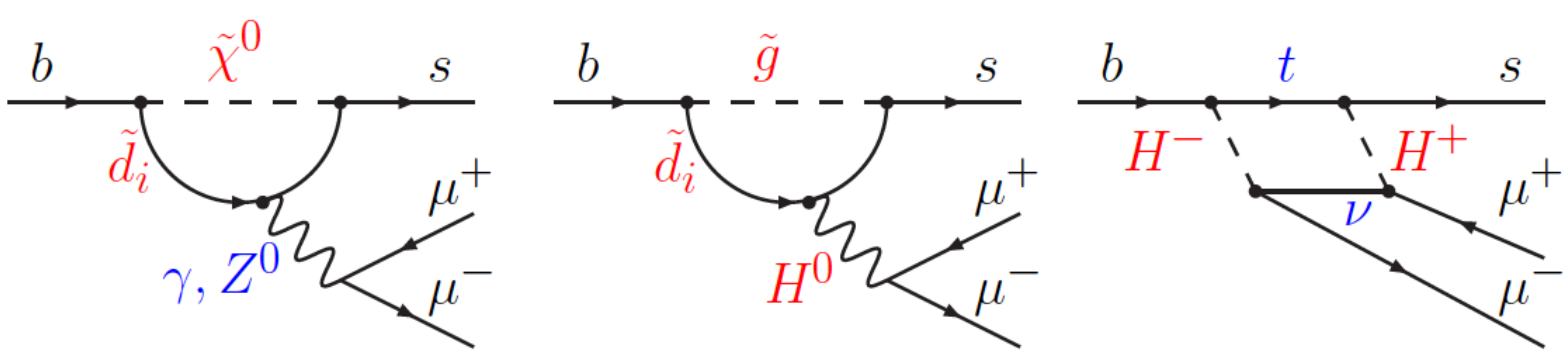
Why rare b decays

- In the SM, processes involving flavour changes between two up-type quarks (u,c,t) or between two down-type quarks (d,s,b) are forbidden at tree level and can only occur at loop level (penguin and box) → Rare



No tree-level flavour changing neutral currents, FCNC

- A new particle, too heavy to be produced at the LHC, can give sizeable effects when exchanged in a loop



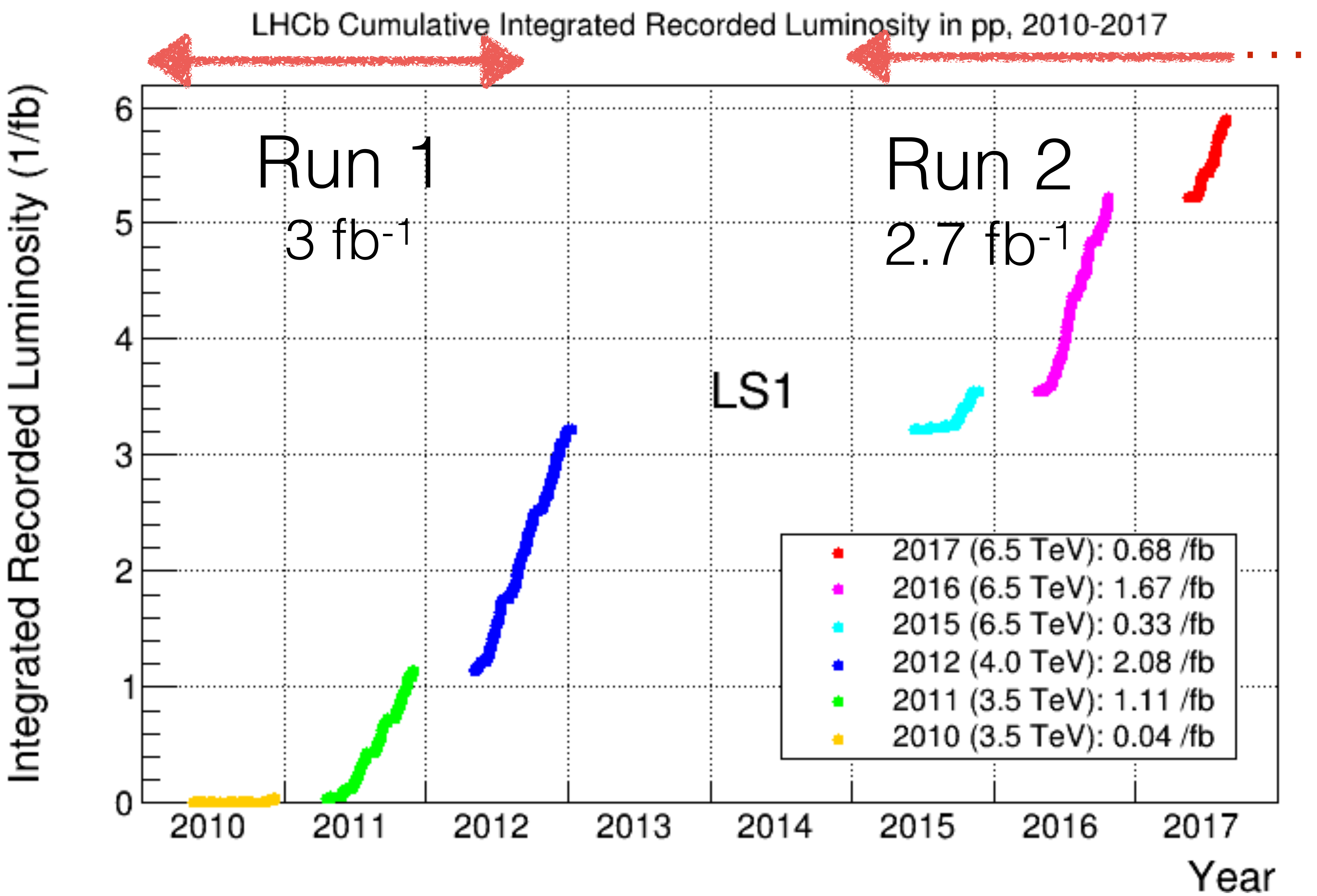
- Indirect approach to New Physics searches, complementary to that of ATLAS/CMS
- Strategy: use well-predicted observables to look for deviations

A window on NP at high scales

LHCb: a forward spectrometer for mainly (but not only) the study of beauty and charm

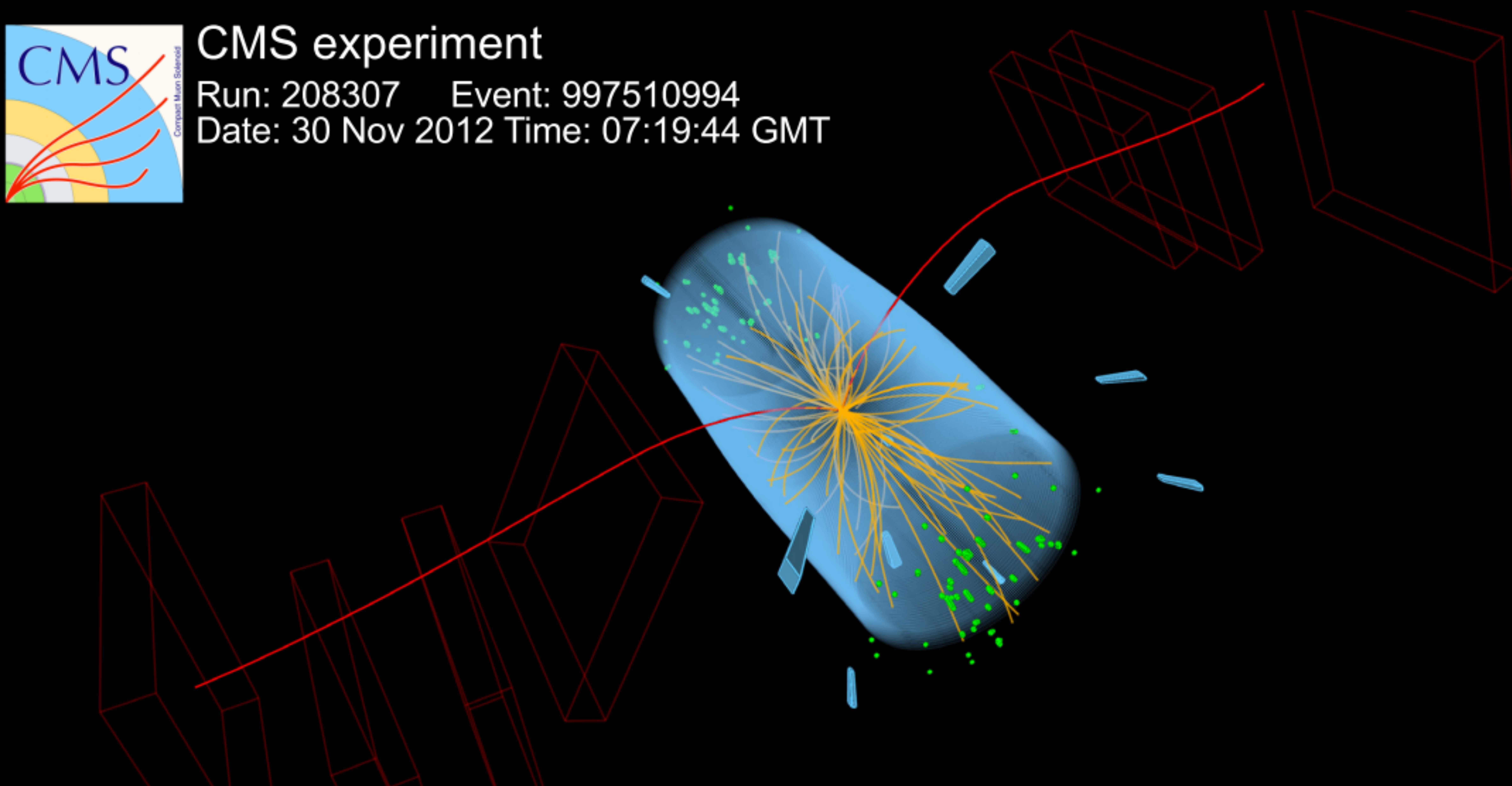
- **Forwards acceptance**
- **Efficient trigger for leptonic and hadronic modes**
- **Precision tracking & vertexing (Vertex Locator @ 8 mm from beam)**
- **Excellent PID**

Luminosity @ LHCb



~10^{11} $b\bar{b}$ decays/fb in acceptance
~10^{12} $c\bar{c}$ decays/fb

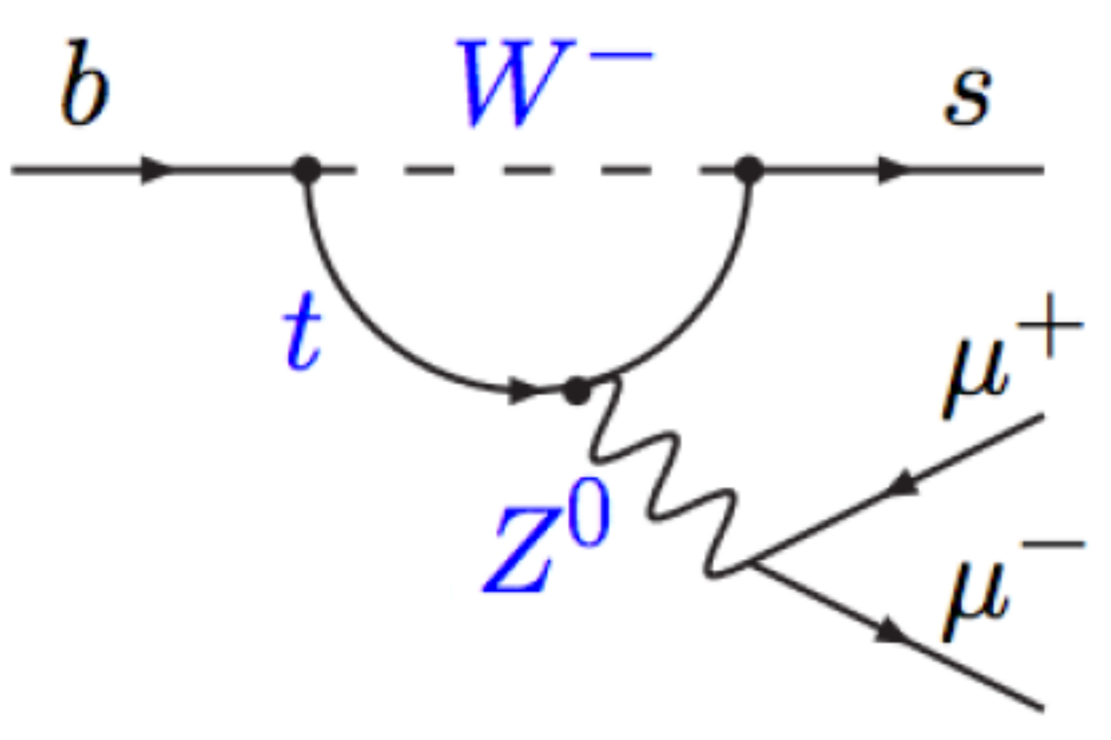
- Experiment designed to run at constant luminosity throughout fills
  - 4 x10^{32} cm^{-2} sec^{-1} (to be raised to 4 x10^{33} cm^{-2} sec^{-1} in Run 3)
  - mean number of interactions/bunch crossing ~1



B leptonic decays

One of the milestones of flavour programme $B_{(s)} \to \mu^+\mu^-$

- Very suppressed in the SM
  - Loop, CKM ($|V_{ts}|^2$ for B_s) and helicity $\sim \left(\frac{m_\mu}{M_B}\right)^2$



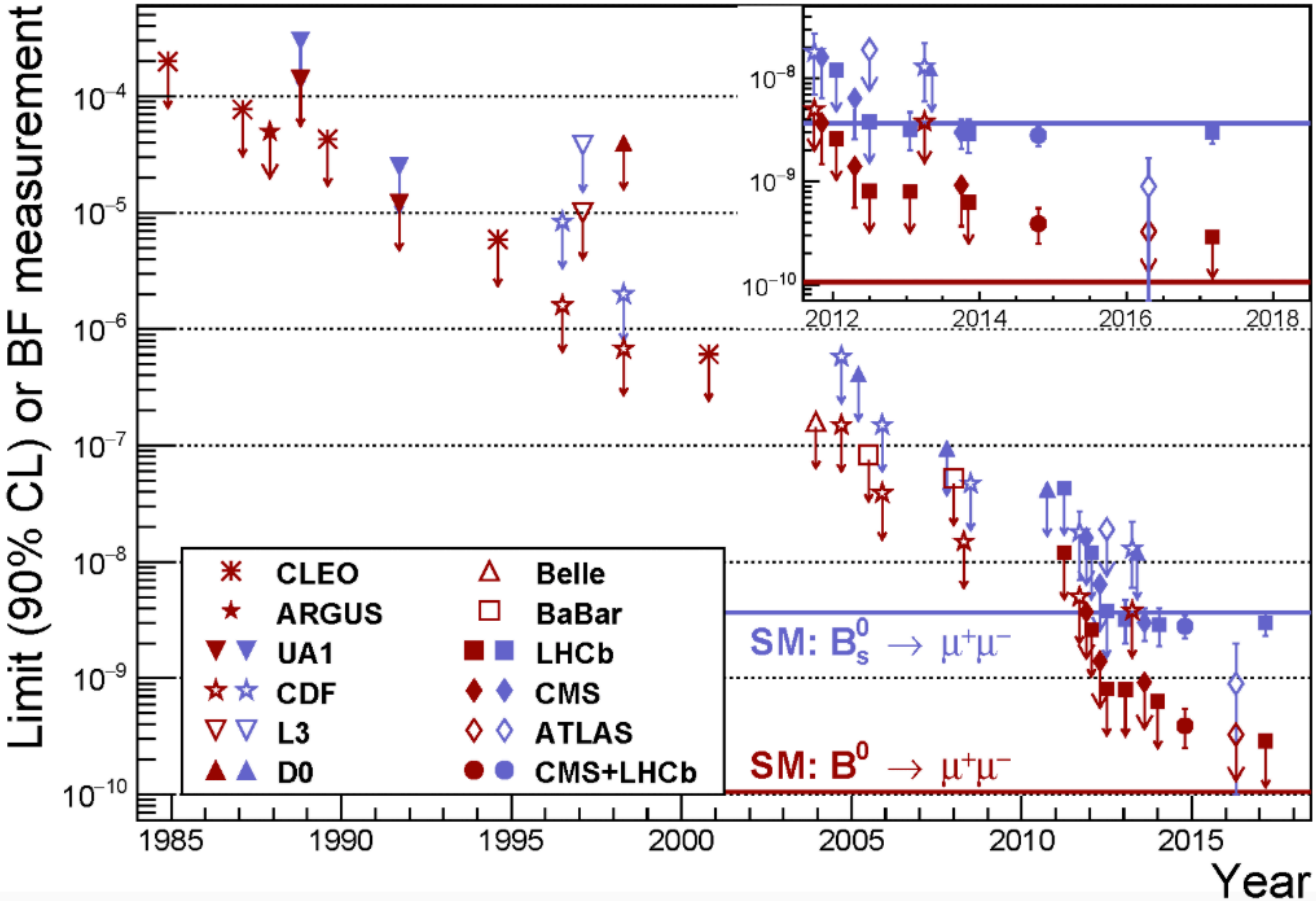
- Theoretically "clean" → precisely predicted

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9} \quad (\sim 6\%)$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Bobeth et al.
PRL 112 (2014) 101801

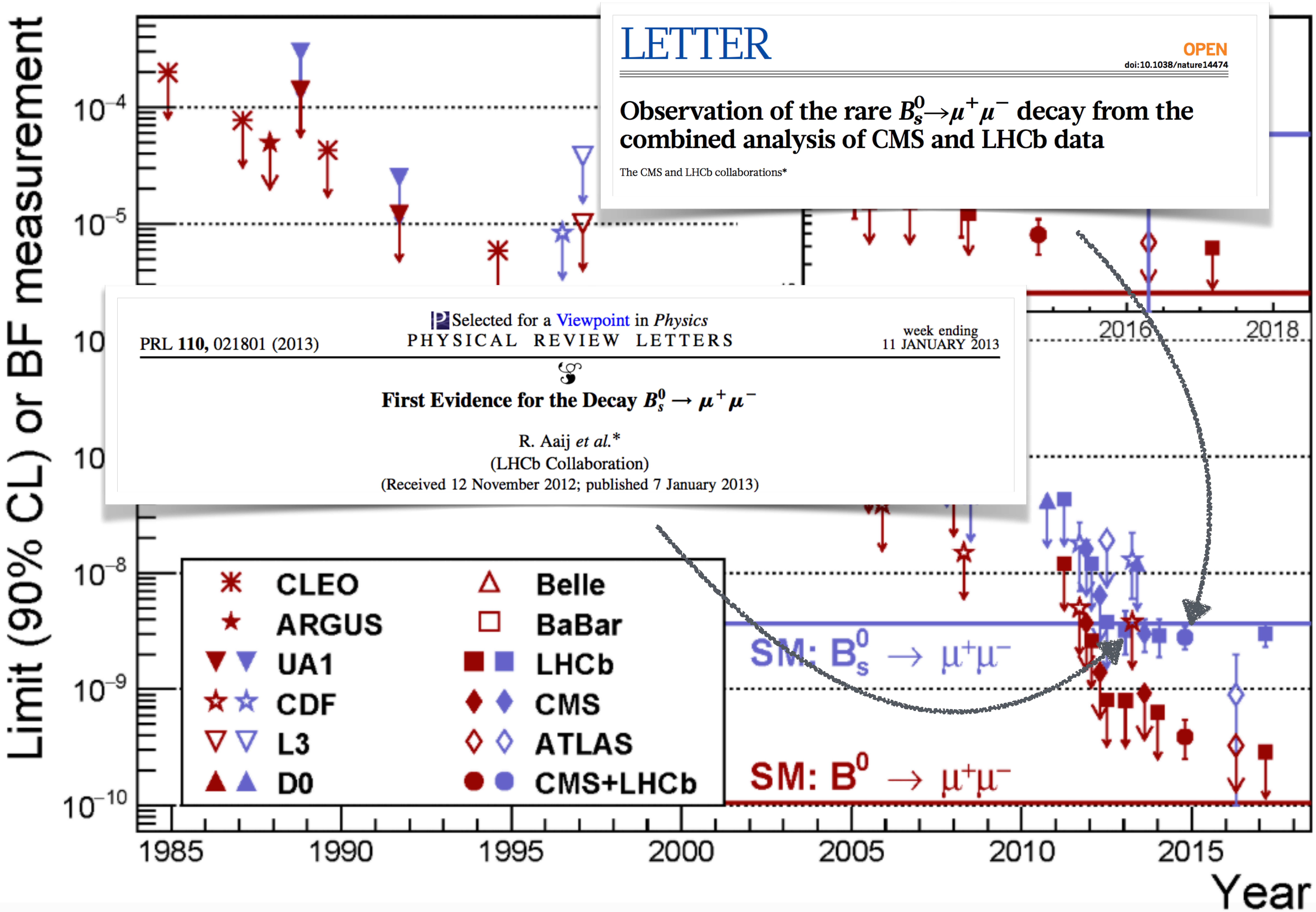
- Sensitive to NP
  - A large class of NP theories, such as SUSY, predict significantly higher values for the $B_{(s)}$ decay probability
- Very clean experimental signature
  - Studied by all high-energy hadron collider experiments

30 years of effort!



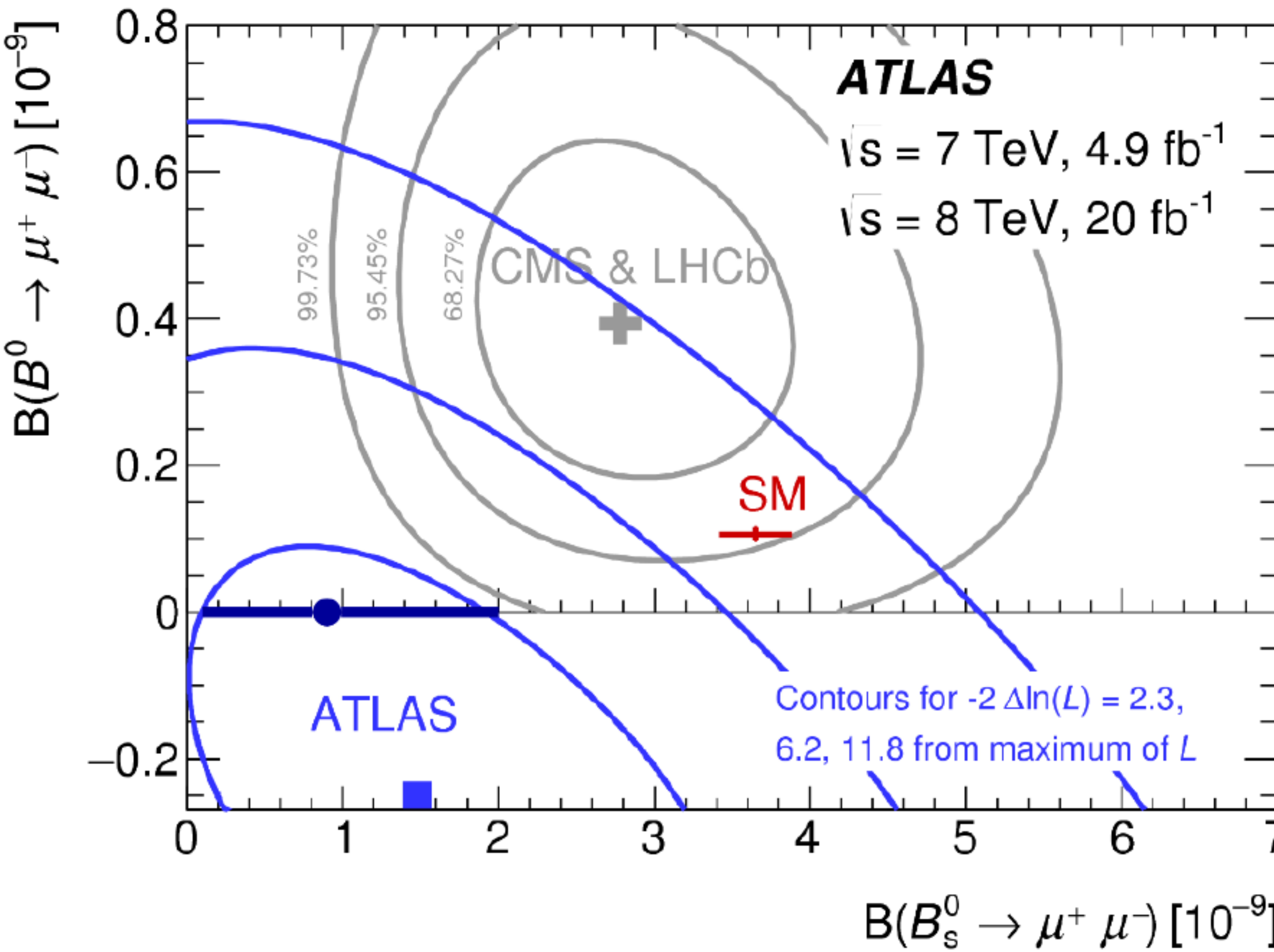
"I'm too old for limits! I want to see signals! " (F.Halzen, EPS 2015)

30 years of effort!



"I'm too old for limits! I want to see signals! " (F.Halzen, EPS 2015)

Era of precision measurements of $B_{(s)} \to \mu^+\mu^-$



ATLAS, EPJC 76 (2016) 513
CMS & LHCb, Nature 522 (2015) 68

Finding a needle in a haystack!

LHCb update with Run 2 data

- Recent LHCb analysis based on Run 1 and Run 2 data (3+1.4 fb^{-1})
- First observation from a single experiment with a significance of 7.8 σ

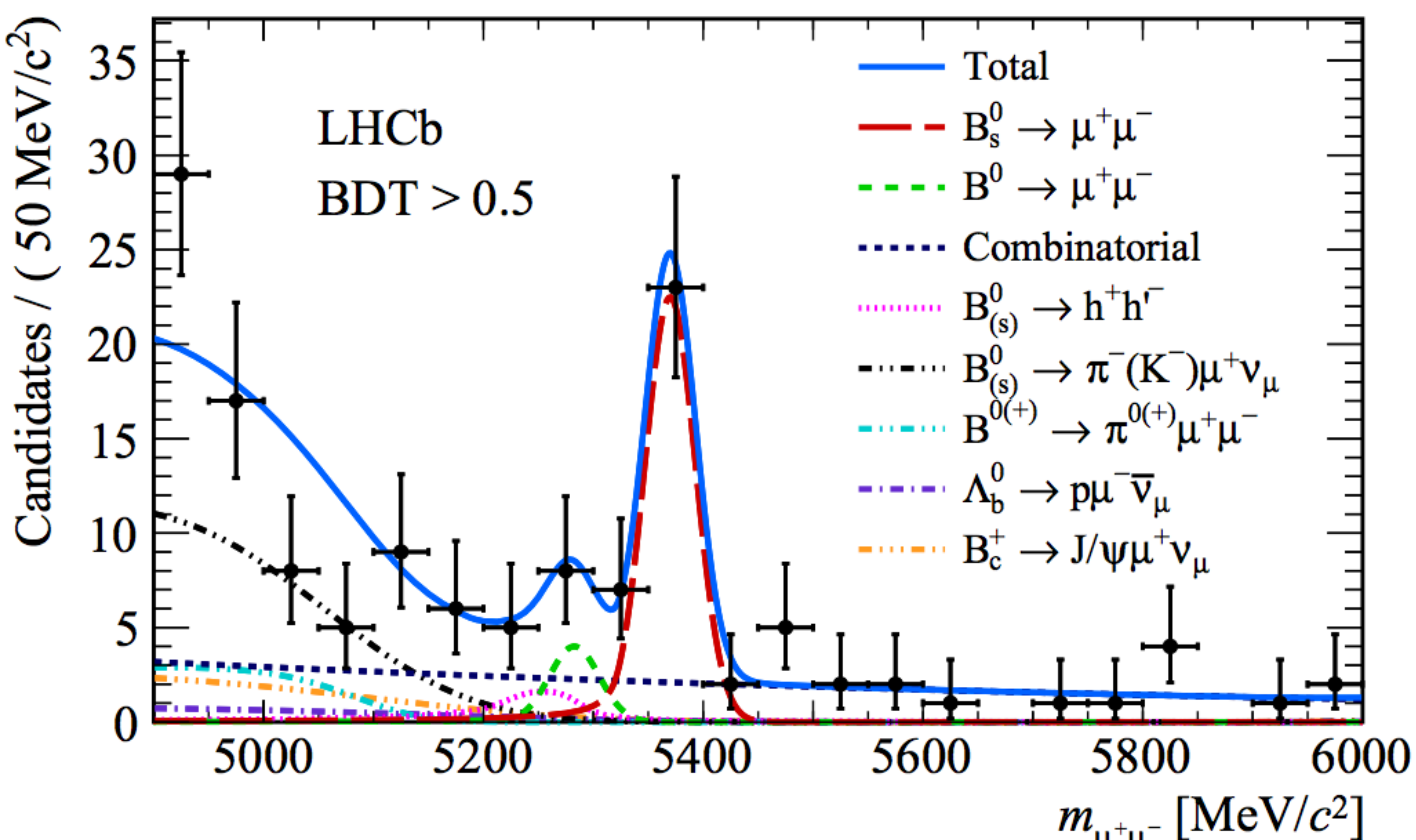
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \quad (\ 20\%)$$

$$\mathcal{B}_{\rm SM} = (3.65 \pm 0.23) \times 10^{-9}$$

Bobeth et al.
PRL 112 (2014) 101801

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

- Consistent with SM expectation at current level of precision

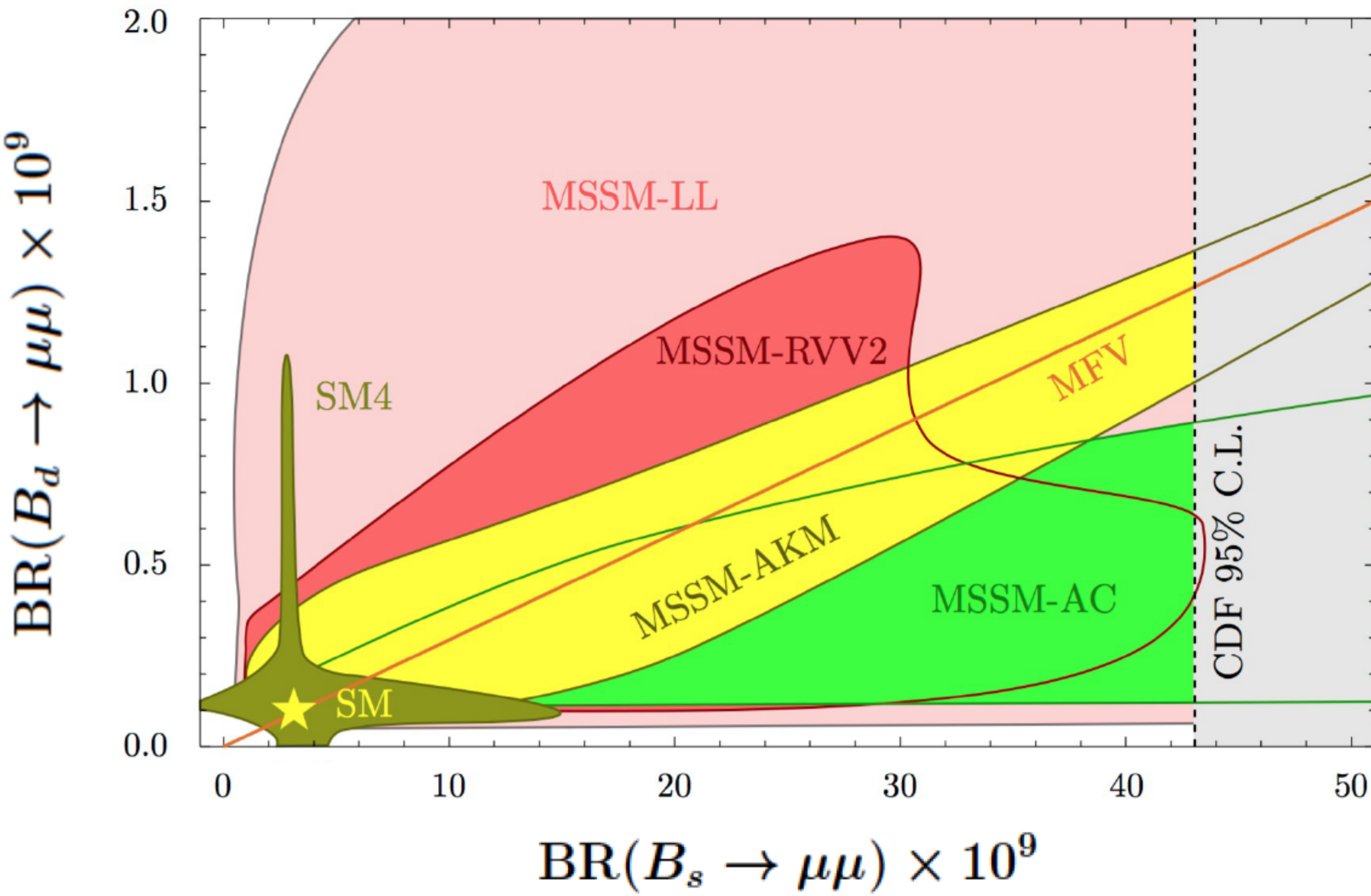


PRL 118 (2017) 191801

The SM stands its ground

- Sizeable effects expected in many MSSM models (cancellation of helicity suppression)

Straub, arXiv:1107.0266

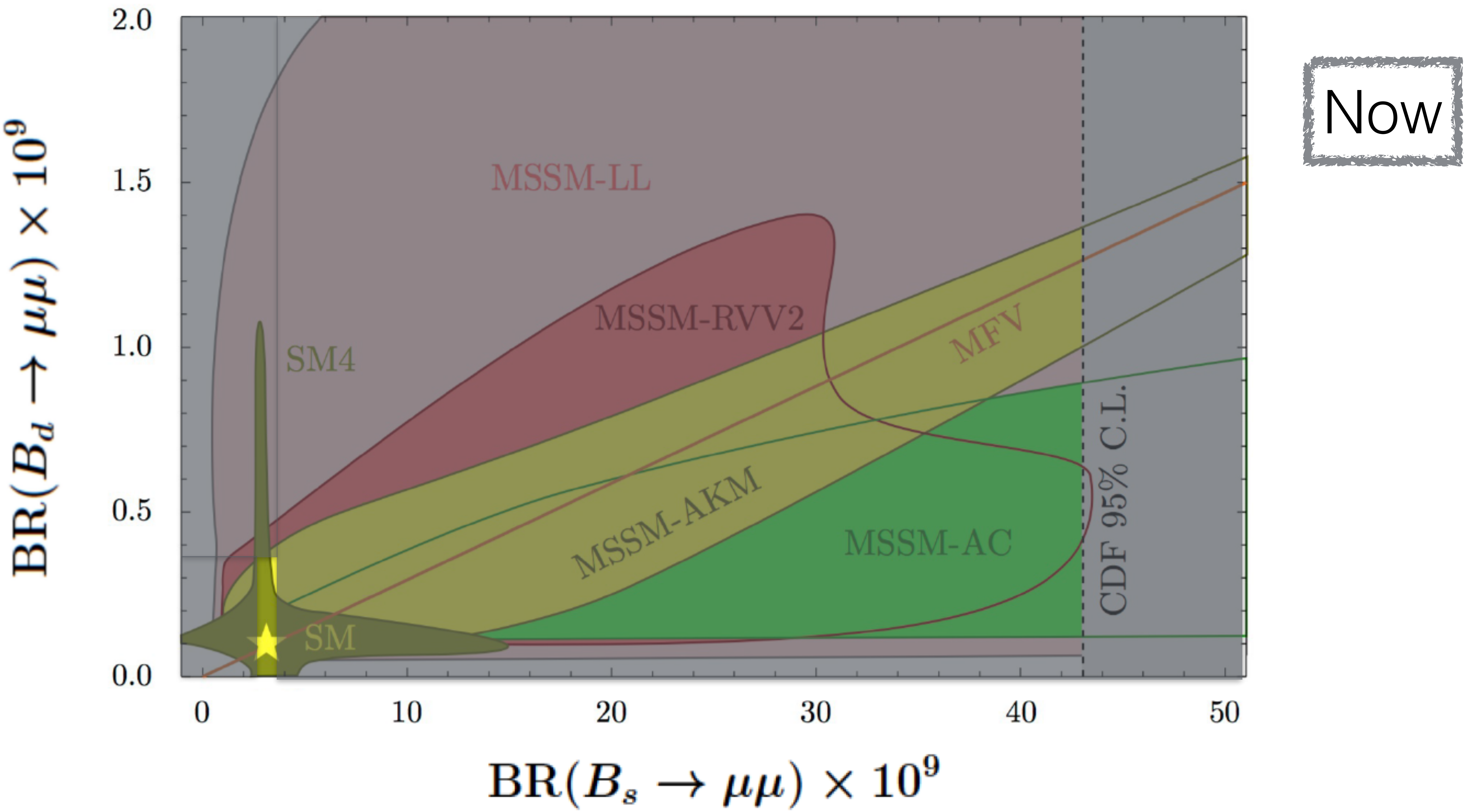


Pre-LHC

The SM stands its ground

- Sizeable effects expected in many MSSM models (cancellation of helicity suppression)

Straub, arXiv:1107.0266



Effective B_s lifetime

- A new observable sensitive to NP and complementary to branching fraction
- For B_s mesons, the sizeable difference between the decay widths of the light and heavy mass eigenstates $\Delta\Gamma_s$ allows us to define:

$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\Gamma(B_s(t)\to\mu^+\mu^-)dt}{\int_0^\infty \Gamma(B_s(t)\to\mu^+\mu^-)dt}$$

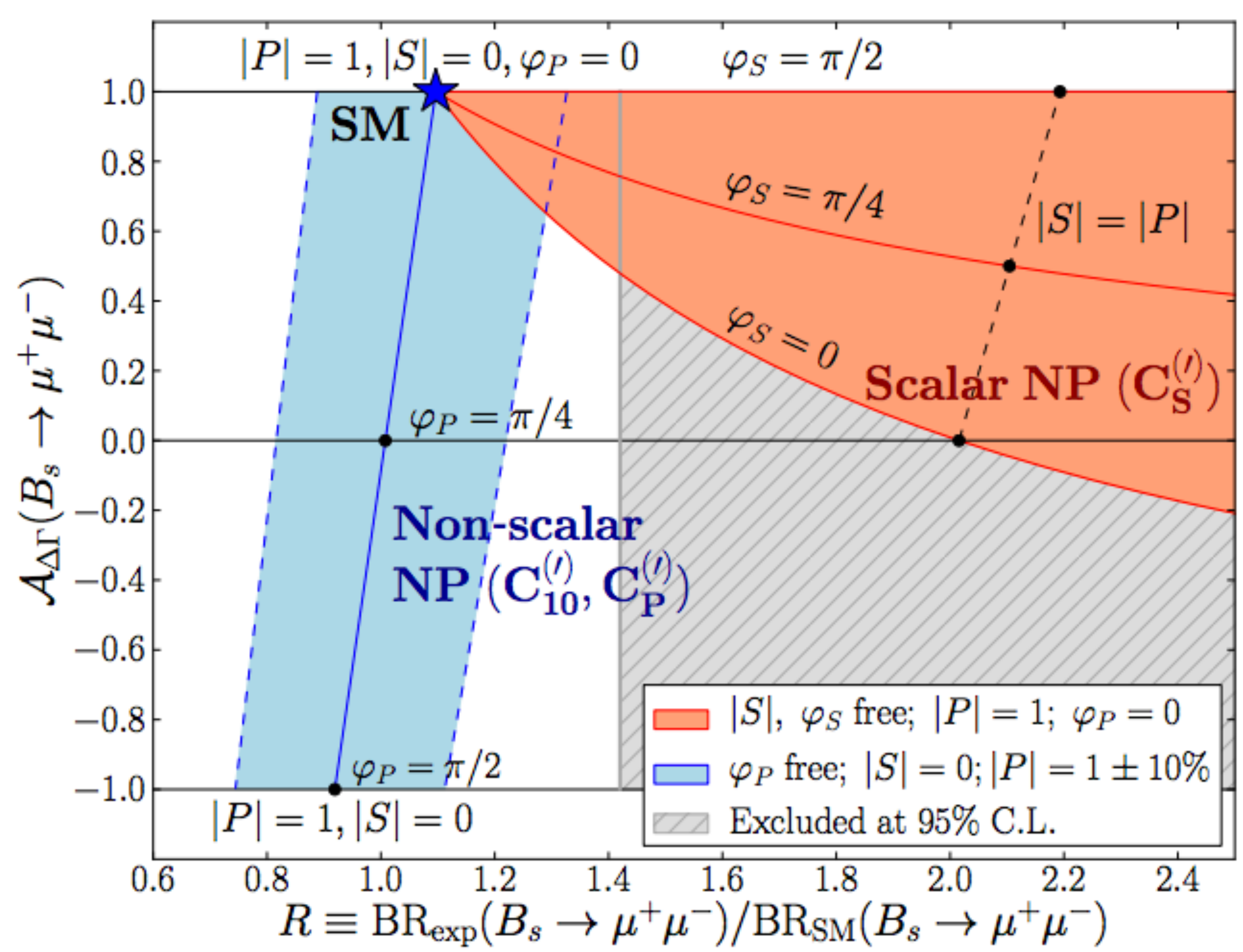
Expectation value of untagged time-dependent rate

$$\Gamma(B_s(t)\to\mu^+\mu^-) \equiv \Gamma(B_s^0(t)\to\mu^+\mu^-) + \Gamma(\overline{B}_s^0(t)\to\mu^+\mu^-)$$
$$\propto (1-A_{\Delta\Gamma_s})e^{-\Gamma_L t} + (1+A_{\Delta\Gamma_s})e^{-\Gamma_H t}$$

De Bruyn et al, PRL 109 (2012) 041801

$$A_{\Delta\Gamma} \equiv \frac{\Gamma(B_s^H\to\mu^+\mu^-) - \Gamma(B_s^L\to\mu^+\mu^-)}{\Gamma(B_s^H\to\mu^+\mu^-) + \Gamma(B_s^L\to\mu^+\mu^-)}$$

- In SM $A_{\Delta\Gamma}= 1$, i.e. B_s system evolves with the lifetime of the heavy B_s mass eigenstate, but in NP scenarios $A_{\Delta\Gamma}$ could be anywhere in range [-1,1]



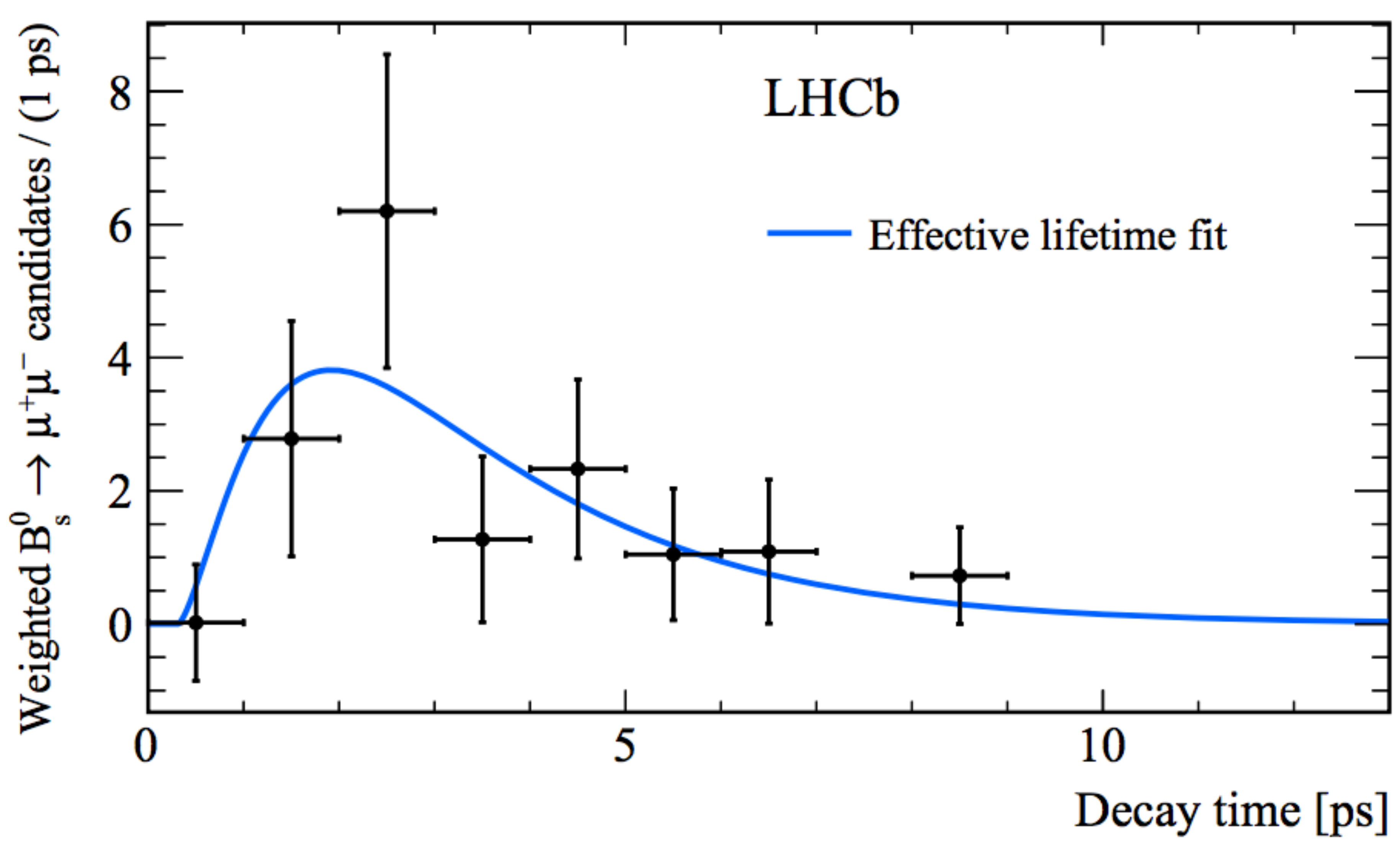
Results on $\tau_{\rm eff}$

- LHCb measured effective lifetime from the decay time distributions of the samples of untagged B_s events used for the branching fraction measurements by fitting a single exponential function

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

$$\tau_{\rm eff}(B_s(t)\to\mu^+\mu^-) = (2.04\pm0.44\pm0.05)\,ps$$

- First measurement by LHCb, not yet sensitive to $A_{\Delta\Gamma}$, but interesting as a proof-of-principle measurement, which can be scaled to higher luminosities



PRL 118 (2017) 191801

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

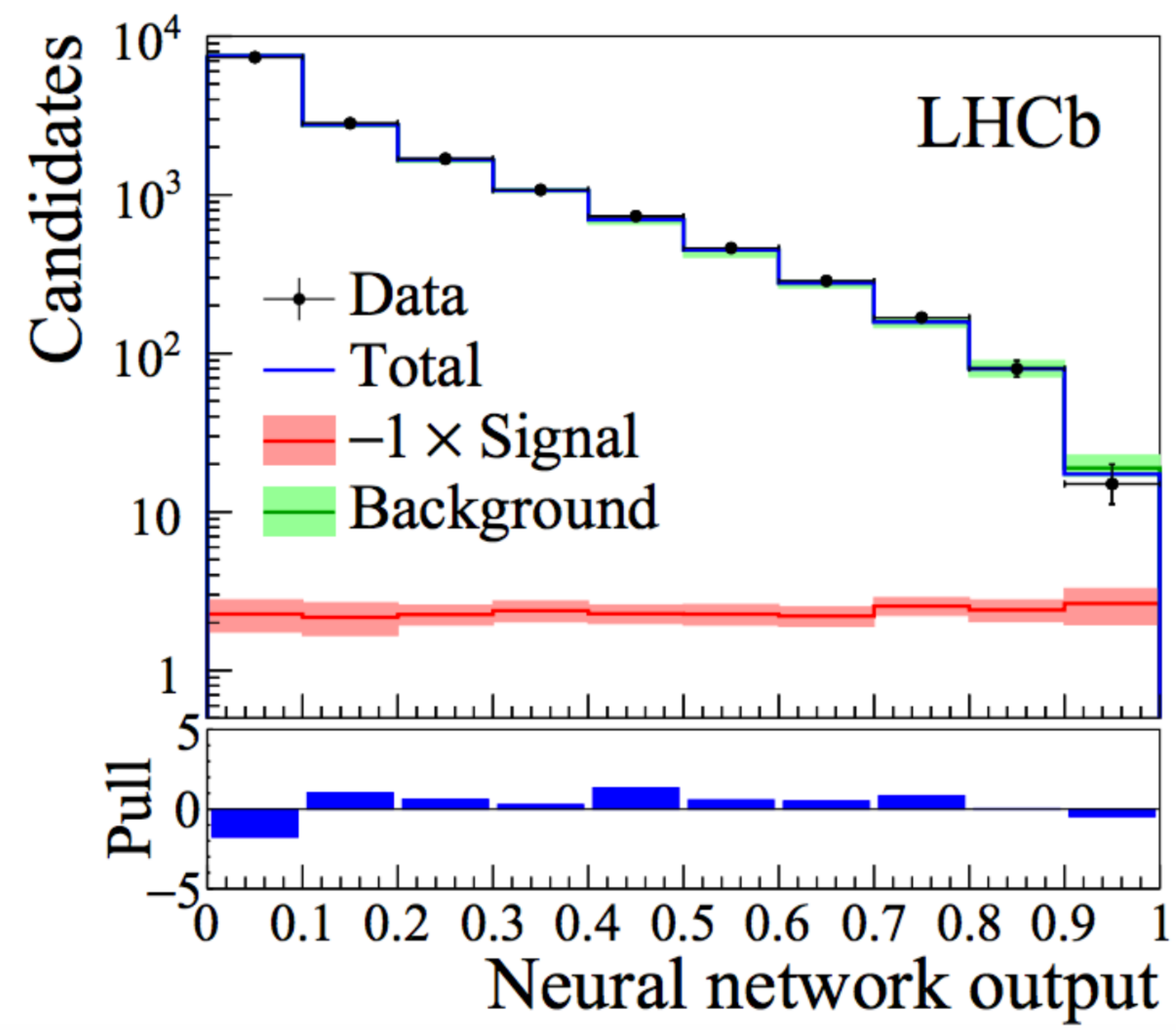
- In the SM, larger BF due to larger τ mass (m_τ^2/M_B^2)

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8}$$

Bobeth et al.
PRL 112 (2014) 101801

- But experimentally challenging due to undetected neutrinos in final state

- Searched by LHCb through the decay $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
- $B_{s,d}$ unresolvable in mass → analysis optimised for B_s
- Exploit intermediate $\rho(770)^0$ resonance to define signal/control regions of $m_{\pi^-\pi^+}$, then fit MVA



- Limits set: PRL 118 (2017) 251802

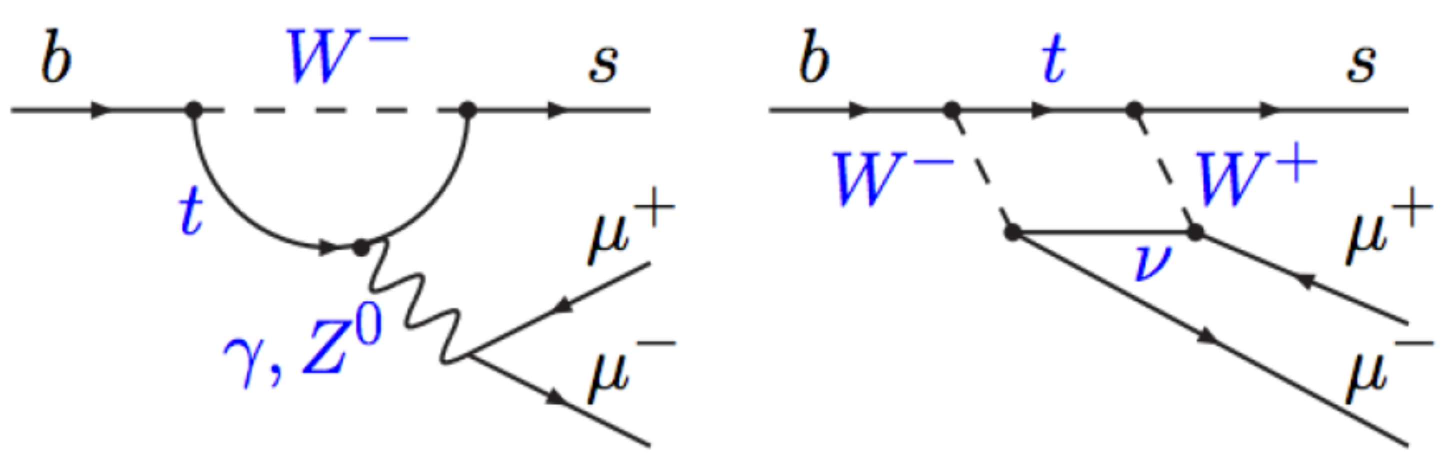
$\mathcal{B}(B_s \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ at 95% C.L. → first direct limit

$\mathcal{B}(B_d \to \tau^+\tau^-) < 2.1 \times 10^{-3}$ at 95% C.L. → best limit

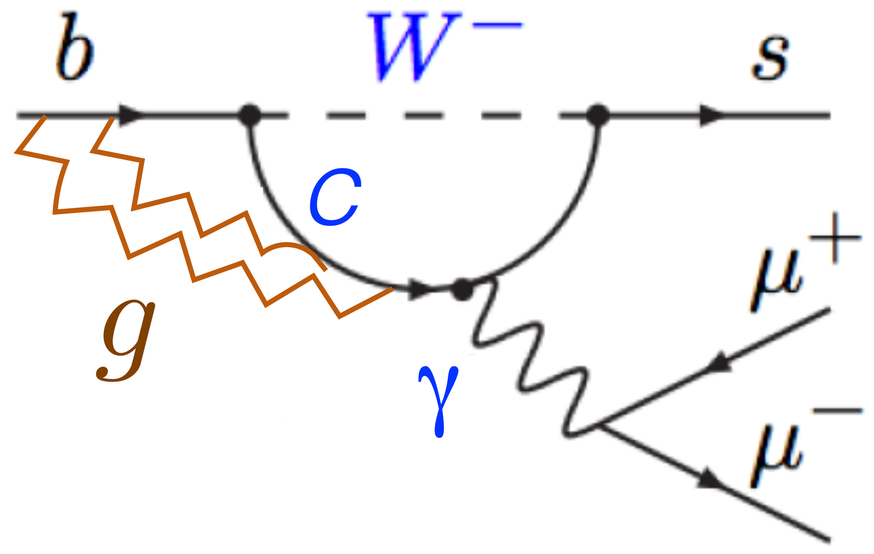
$b \to s\ell^+\ell^-$ transitions

Another interesting rare decay: $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

- A b →s transition that only proceeds via loop diagrams
- NP can be competitive with SM processes



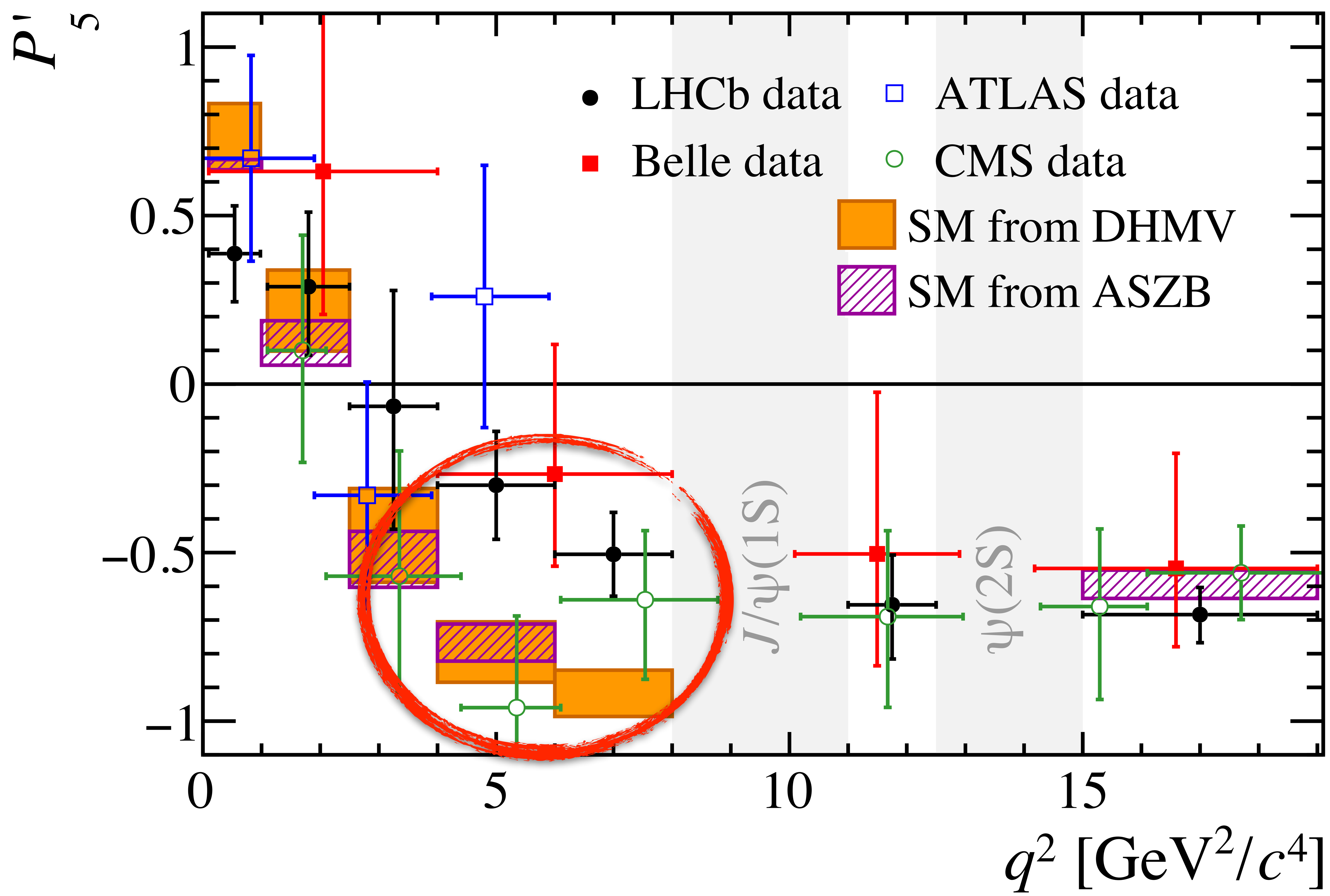
- Four final state particles with rich phenomenology, plethora of observables, which can be built from the measured amplitudes
- Rates, angular distributions and asymmetries sensitive to NP
- A lot of phenomenological work invested in defining observables with "clean" theoretical predictions.
  - Observables form-factor free at leading order
  - Still susceptible to non-factorisable corrections



- Question: how clean?

P_5' anomaly

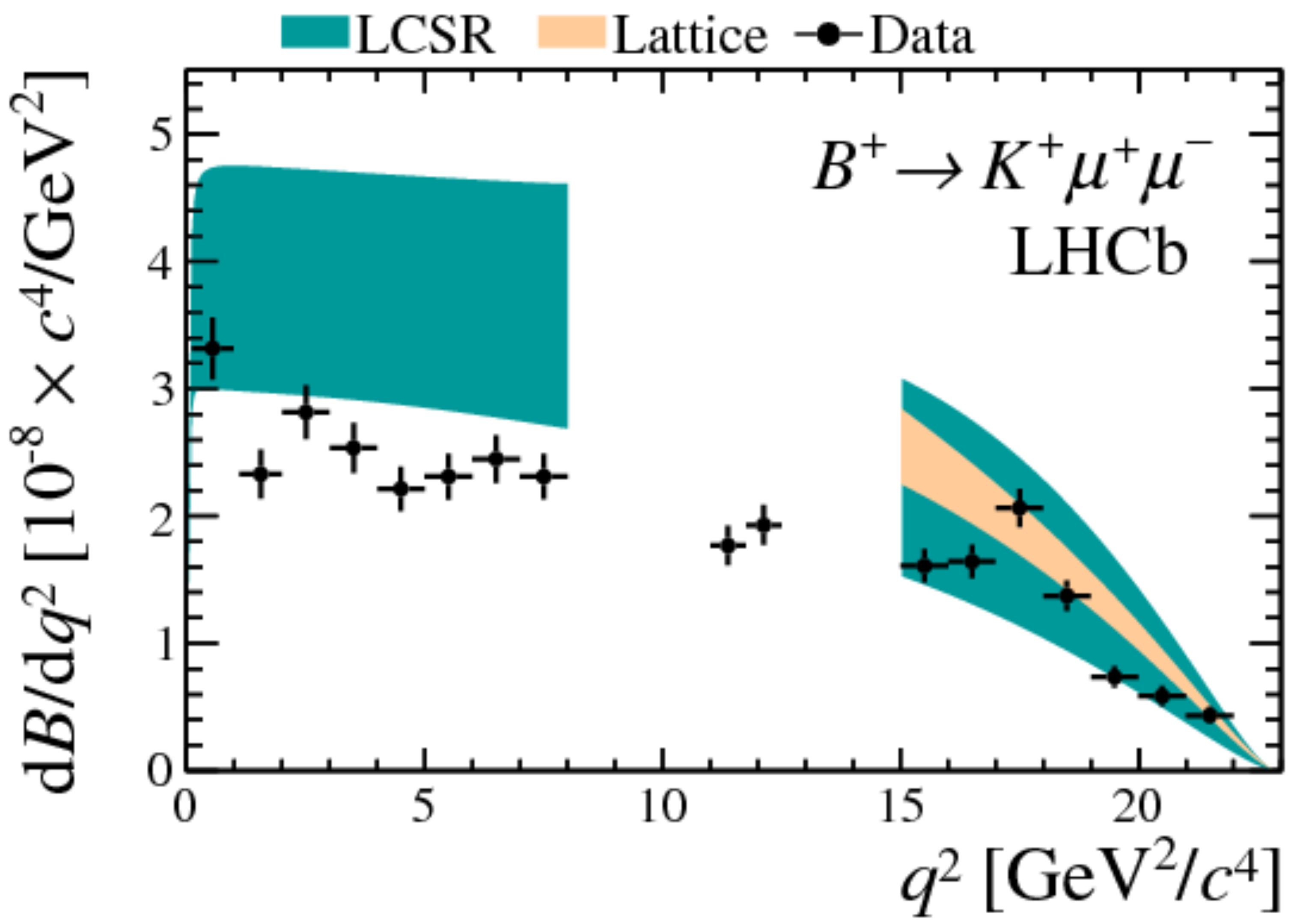
- One such observable is so-called P'$_5$, not intuitive, but constructed from angular observables to be robust from 'form-factor uncertainties'

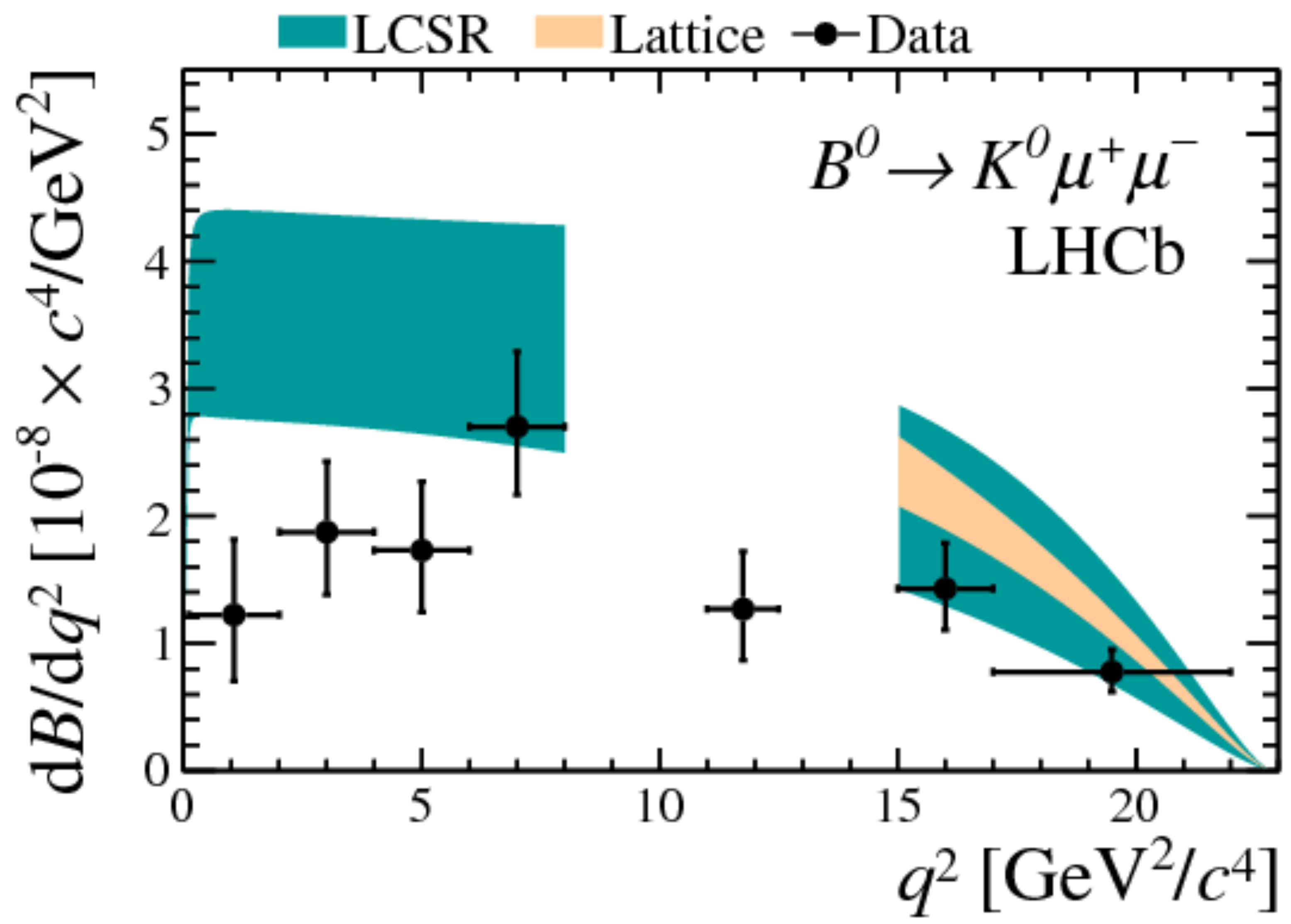


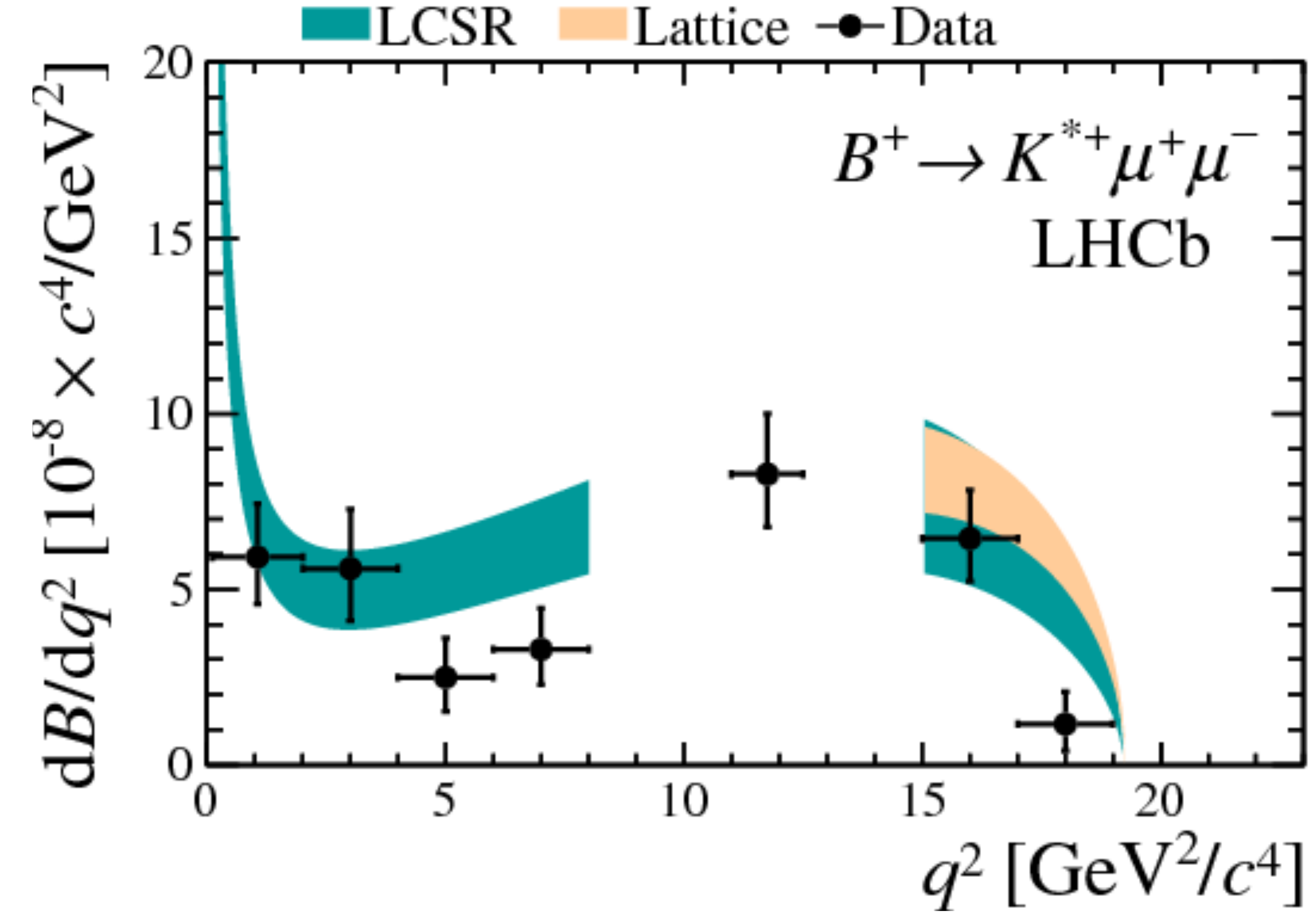
LHCb: JHEP 02 (2016) 104
Belle: PRL 118 (2017) 111801
ATLAS-CONF-2017-023
CMS-PAS-BPH-15-008

- Is the SM prediction less precise than what is claimed?

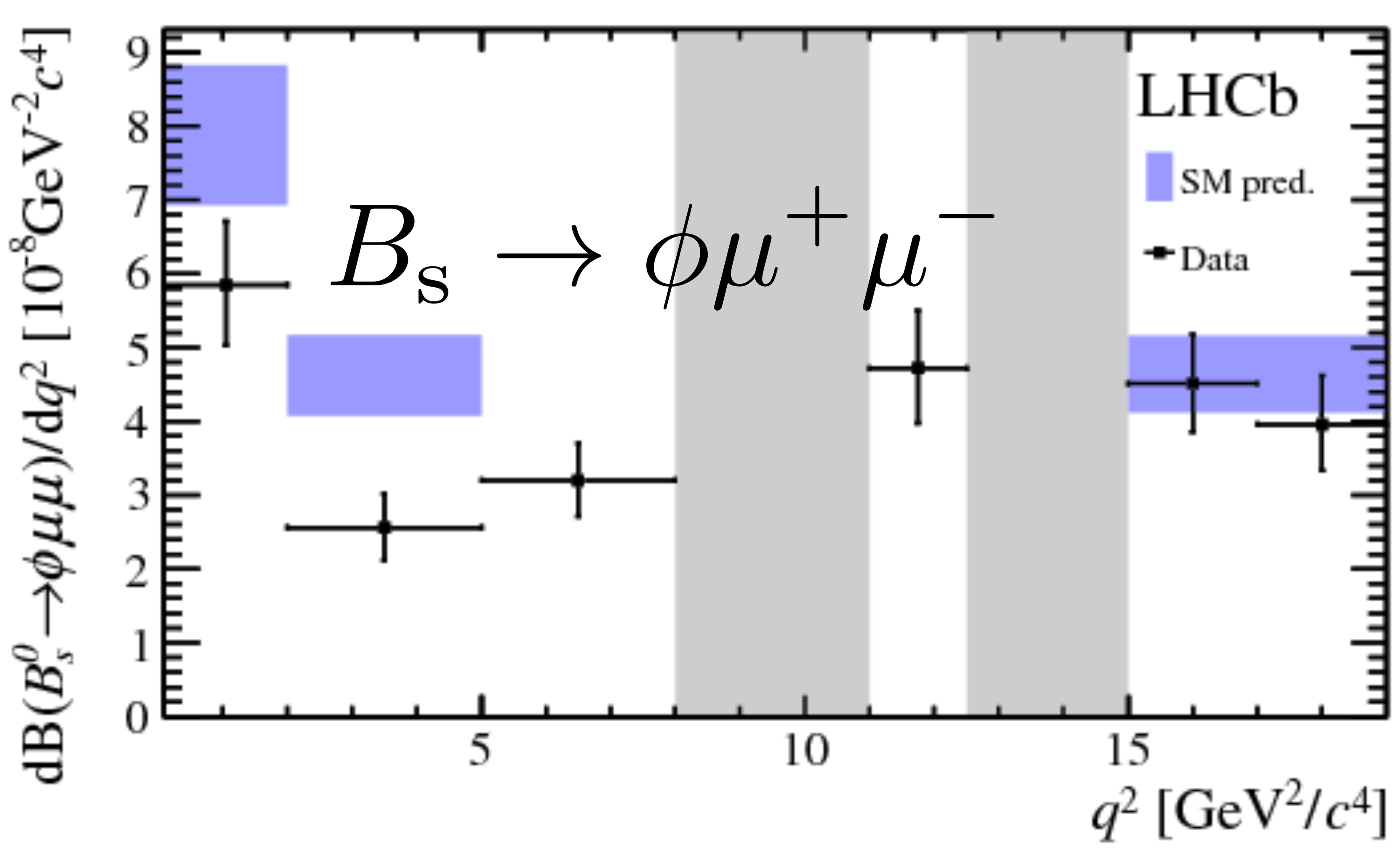
Intriguing set of results in differential branching fractions for b→sμμ transitions

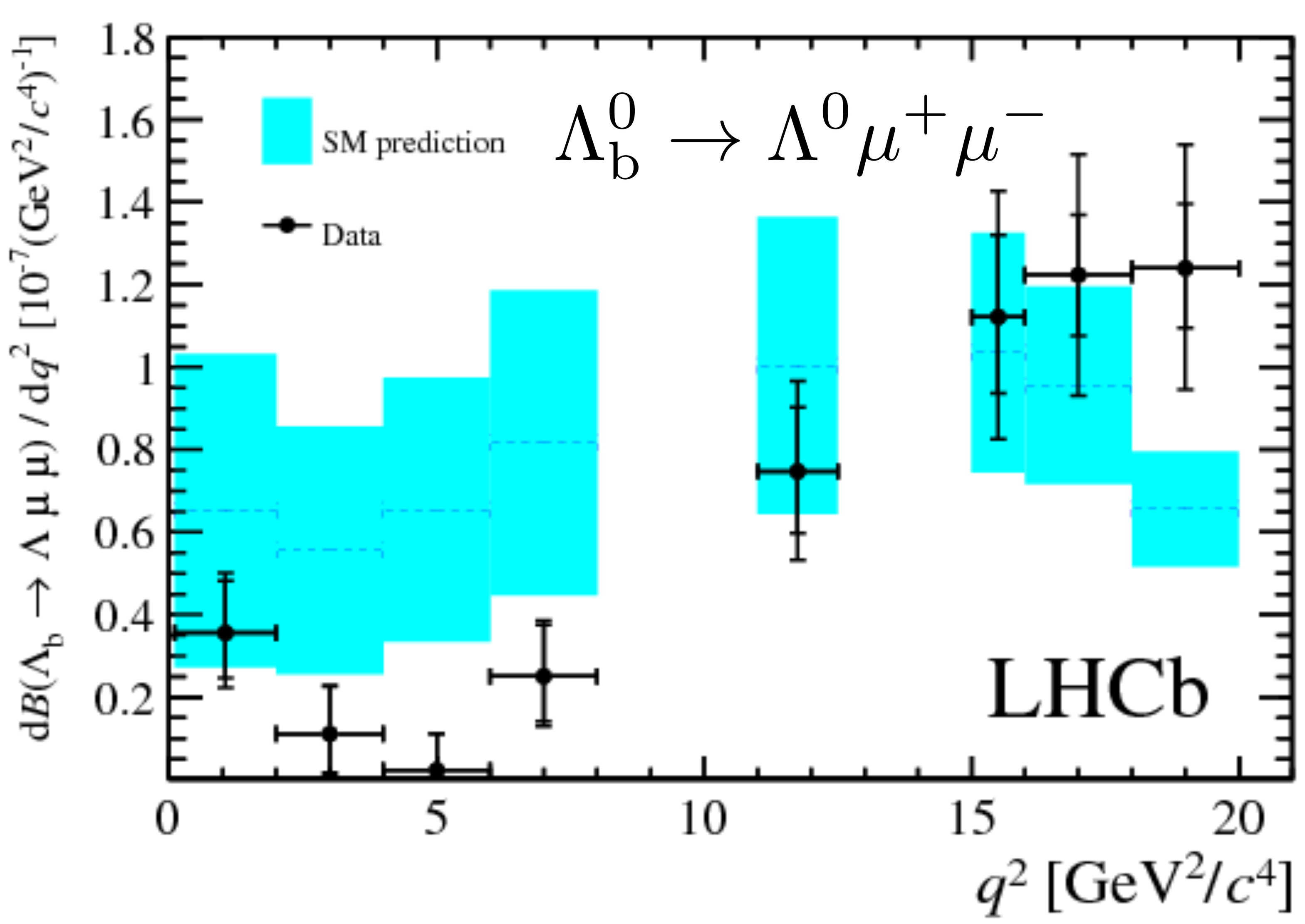


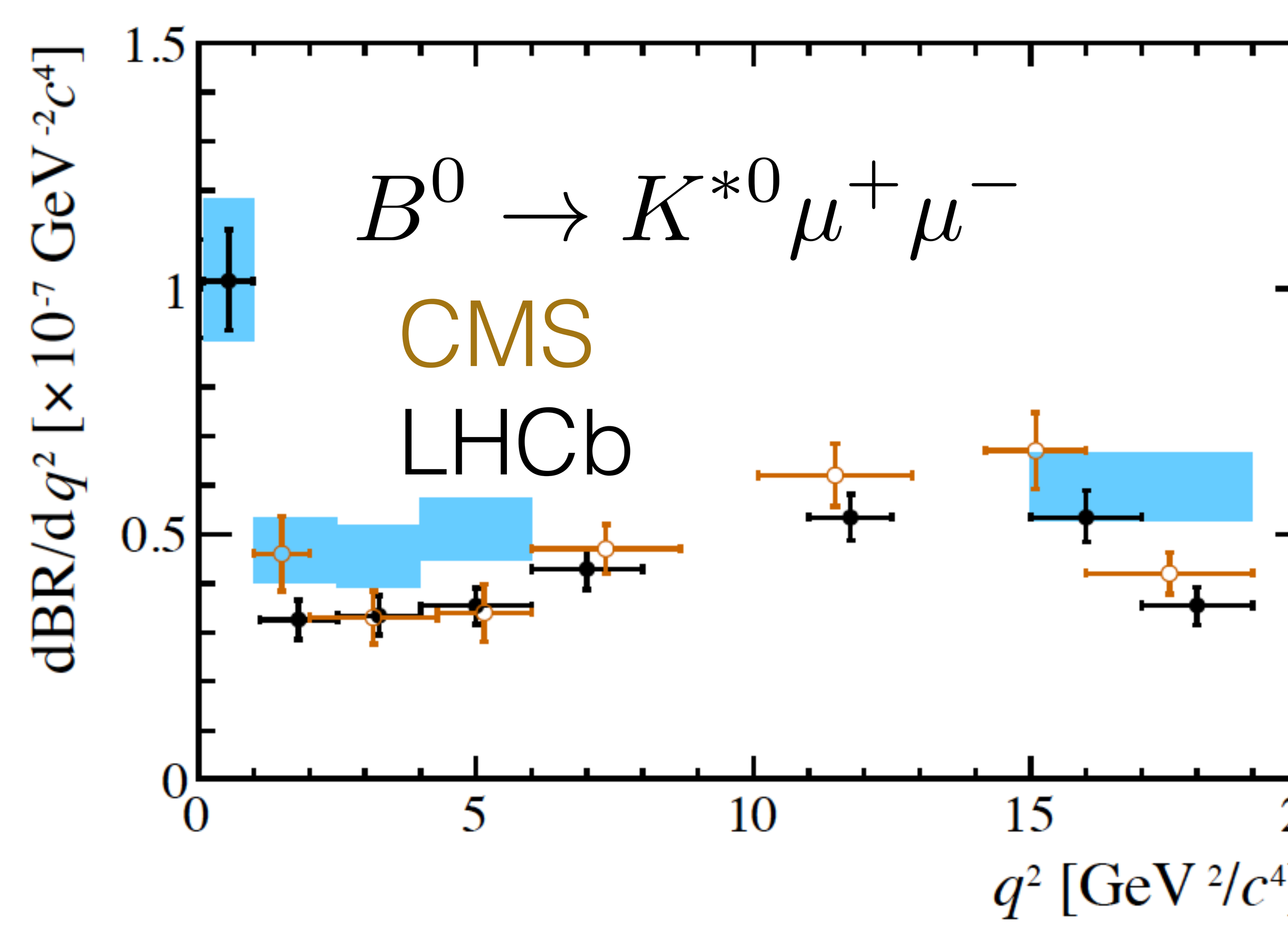




JHEP 06 (2014) 133







JHEP 09 (2015) 179

JHEP 06 (2015) 115

LHCb: JHEP 11 (2016) 047, JHEP 04 (2017) 142
CMS: PLB 753 (2016) 424

- In general, data tend to be lower than theory predictions

Tests of Lepton Flavour Universality

Lepton Flavour Universality

- The property that the three charged leptons (**e**, μ , τ) 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 lepton families, then we can discover it by comparing classes of rare decays involving different lepton pairs (e.g. **e**/μ or μ/τ)

The family of R ratios

- Comparing the rates of $B \to H\mu^+\mu^-$ and $B \to He^+e^-$ allows precise testing of lepton flavour universality

$$R_{\rm H}\left[q^2_{\rm min}, q^2_{\rm max}\right] = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} {\rm d}q^2 \frac{{\rm d}\Gamma(B\to H\mu^+\mu^-)}{{\rm d}q^2}}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} {\rm d}q^2 \frac{{\rm d}\Gamma(B\to He^+e^-)}{{\rm d}q^2}} \, , \quad q^2 = m^2(\ell\ell)$$

$$H = K, K^*, \phi, ...$$

- $b \to s\ell\ell$ flavour-changing neutral currents with amplitudes involving loop diagrams

- These ratios are clean probes of NP :

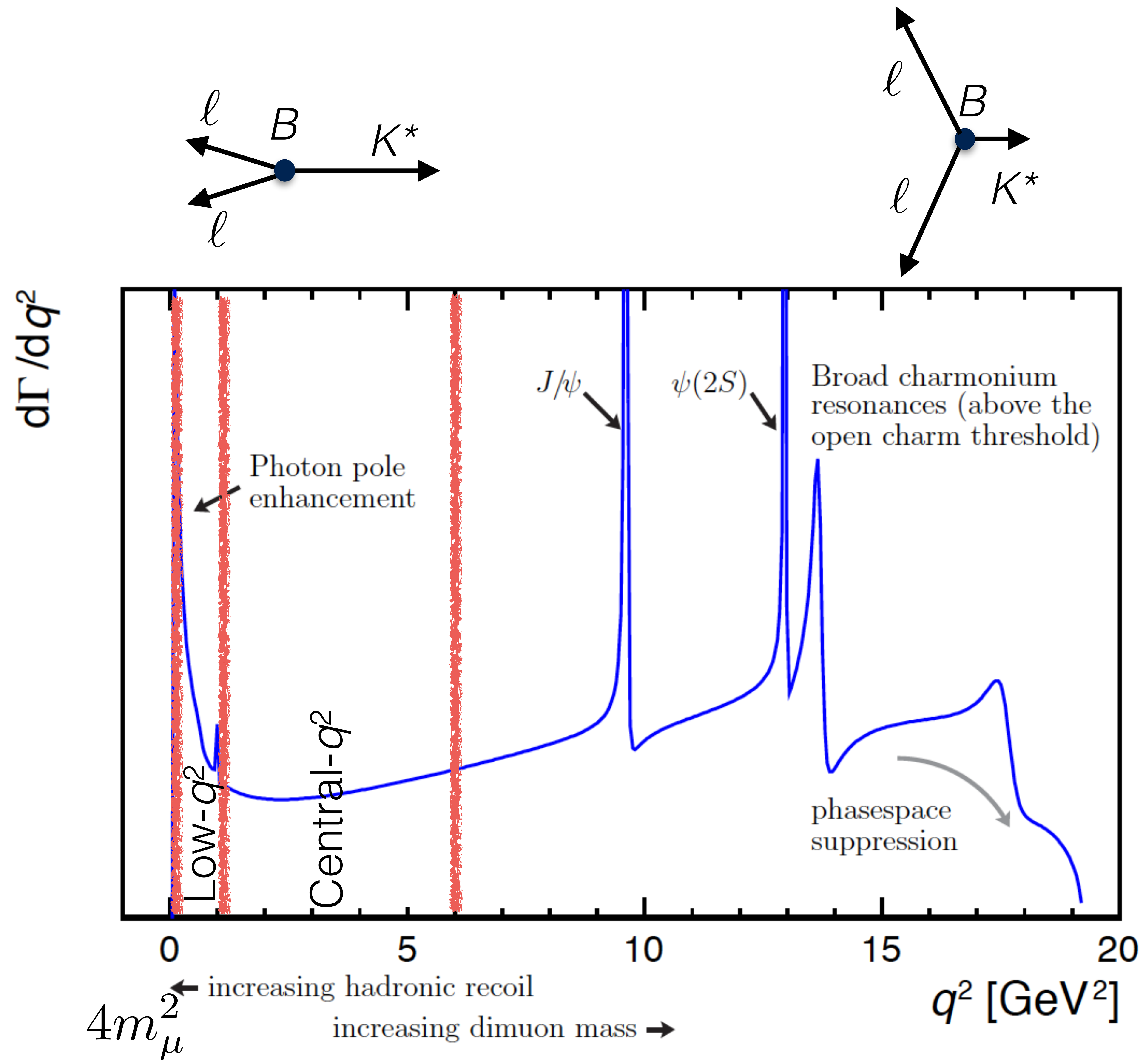
  - Sensitive to possible new interactions that couple in a non-universal way to electrons and muons

  - Small theoretical uncertainties because hadronic uncertainties cancel: in SM, $R_{\rm H} = 1$ neglecting lepton masses, with QED corrections at ~% level

R_{K^*}

$$R_{K^{*0}}\left[q^2_{\min}, q^2_{\max}\right] = \frac{\int_{q^2_{\min}}^{q^2_{\max}} dq^2 \frac{d\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{dq^2}}{\int_{q^2_{\min}}^{q^2_{\max}} dq^2 \frac{d\Gamma(B^0 \to K^{*0}e^+e^-)}{dq^2}}, \quad K^*(892)^0 \to K^+\pi^-$$

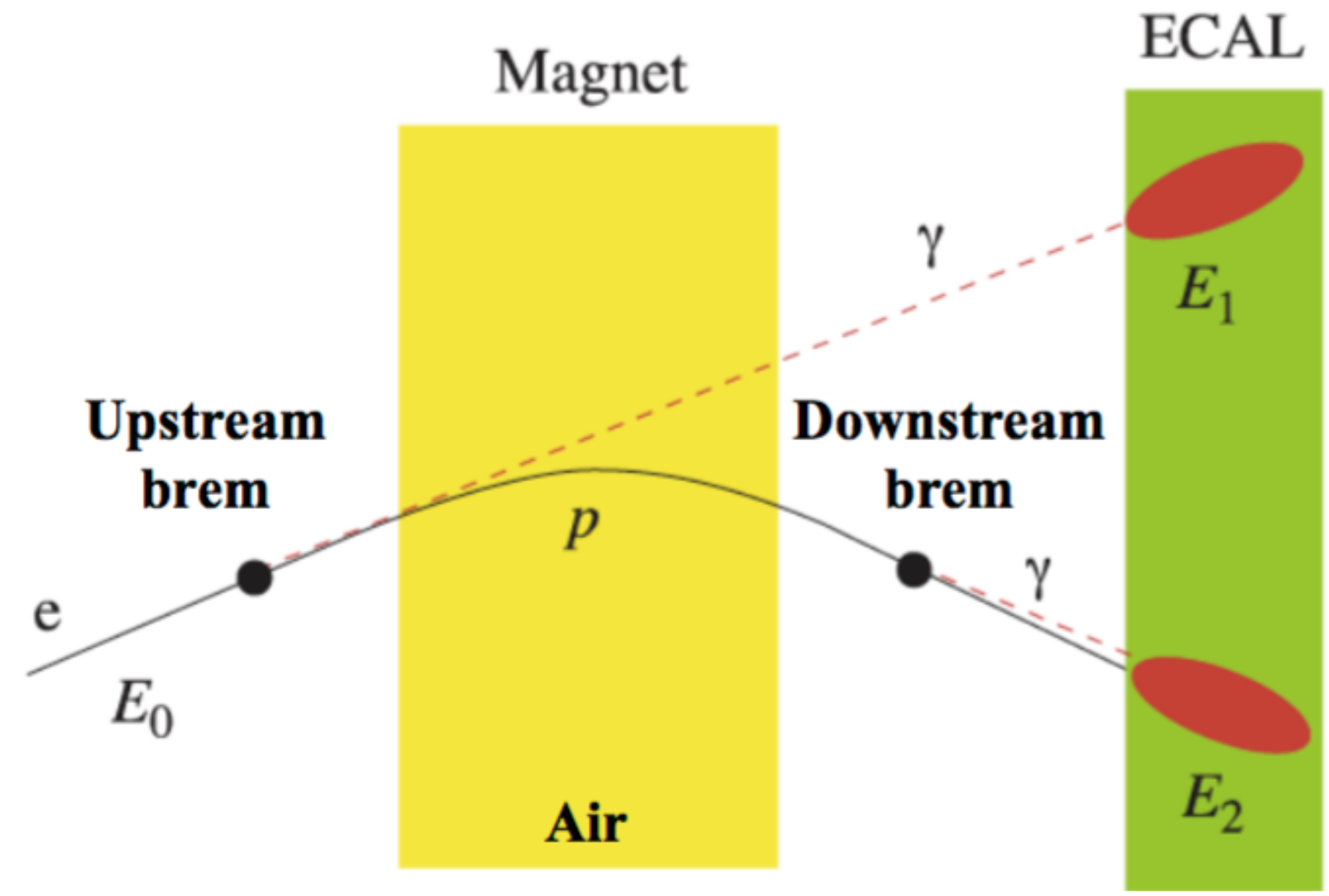
- LHCb performed measurement in two q^2 bins that are sensitive to different NP contributions:
  - Low-q^2 bin: [0.045,1.1] GeV^2
  - Central-q^2 bin: [1.1,6.0] GeV^2

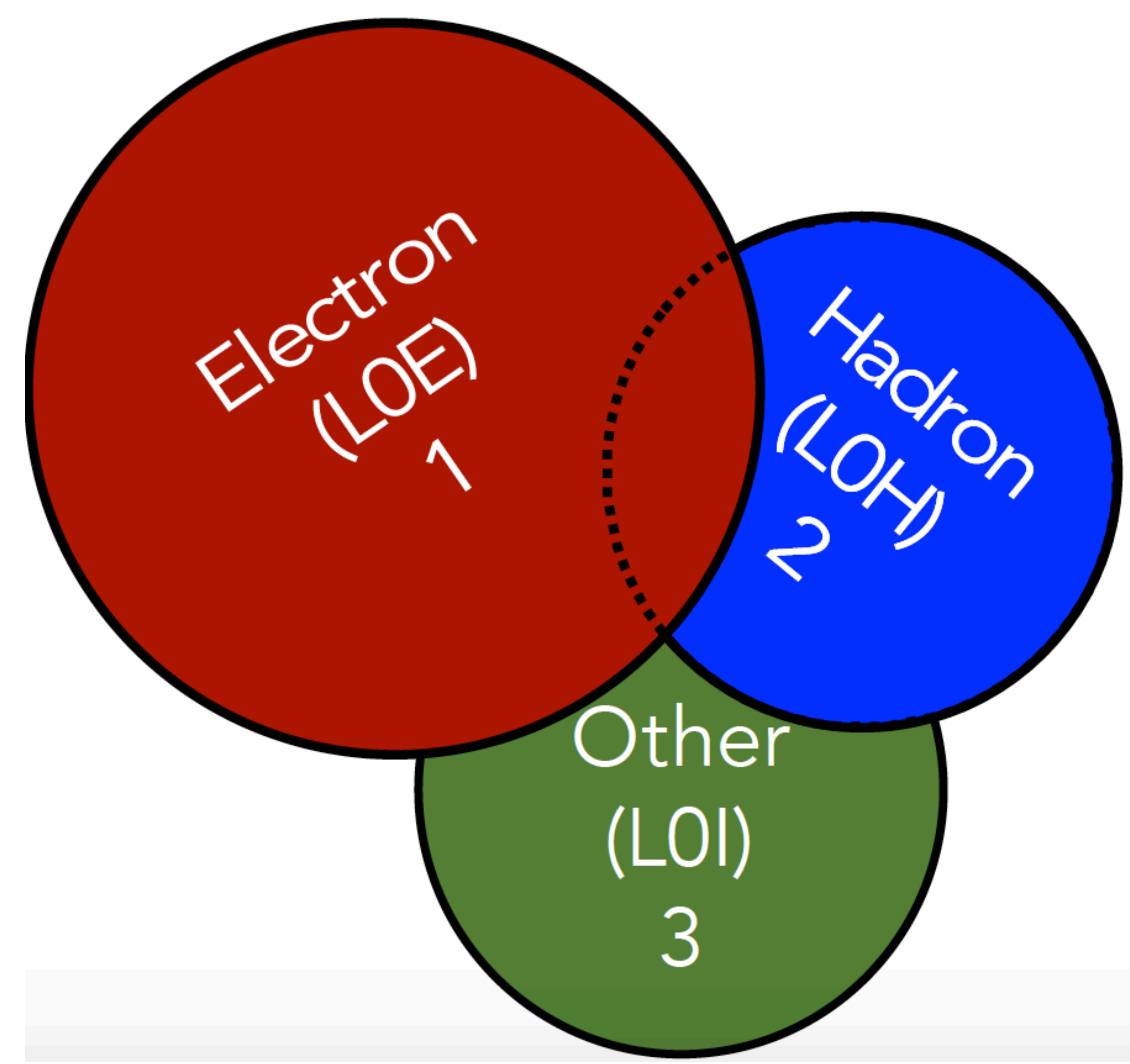


A very challenging measurement

- 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 E_T>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) .
  - To mitigate this, decays with electrons also selected using hadron trigger either fired either by *K** products (LOH) or by any other particle in the event not associated with signal (LOI)

JHEP 08 (2017) 055





A very challenging measurement

Number of candidates for $B^0 \to K^{*0}\mu^+\mu^-$

Number of candidates for $B^0 \to K^{*0}e^+e^-$

JHEP 08 (2017) 055

- Due to bremsstrahlung the reconstructed B mass is shifted towards lower values and events leak into the central-q² bins

Measure as a double ratio

- To mitigate muon and electron differences due to bremsstrahlung and trigger, measurement performed as a double ratio with "resonant" control modes $B^0 \to J/\psi K^*$ which are not expected to be affected by NP:

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

→ Relevant experimental quantities: yields & efficiencies for the four decays

- Similarities between the experimental efficiencies of the non resonant and resonant modes ensure a substantial reduction of systematic uncertainties in the double ratio

- Efficiencies evaluated from simulation, tuned to data using dedicated control samples

- Blind analysis to avoid experimental biases

Fit to the invariant masses

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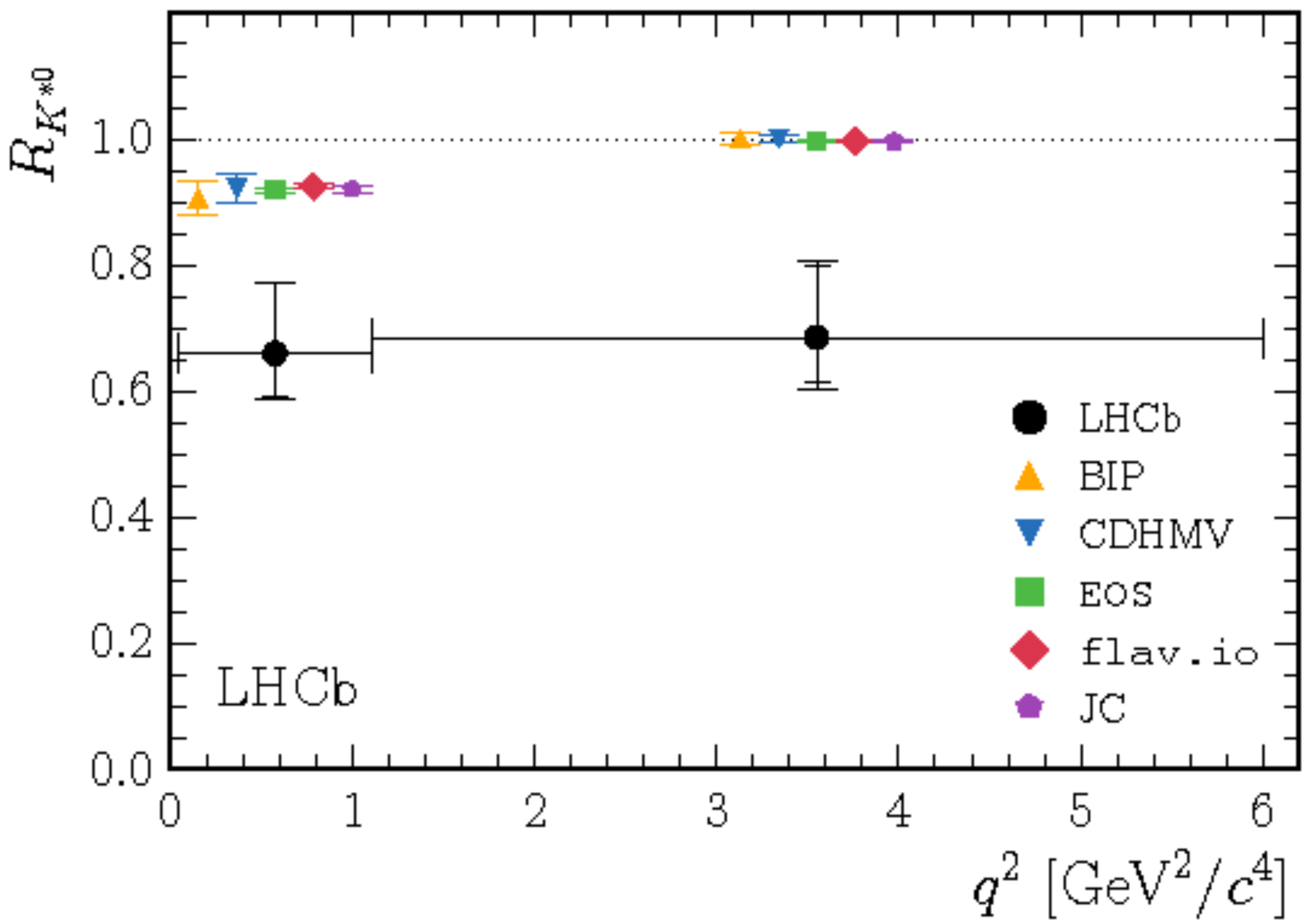
Low-q^2 | Central-q^2 | $B^0 \to K^* J/\psi(\to \ell^+\ell^-)$

- Precision of measurement driven by statistics of electron sample : ~90 and 110 signal candidates in low-q^2 and central-q^2 , muon sample 3-5 times larger

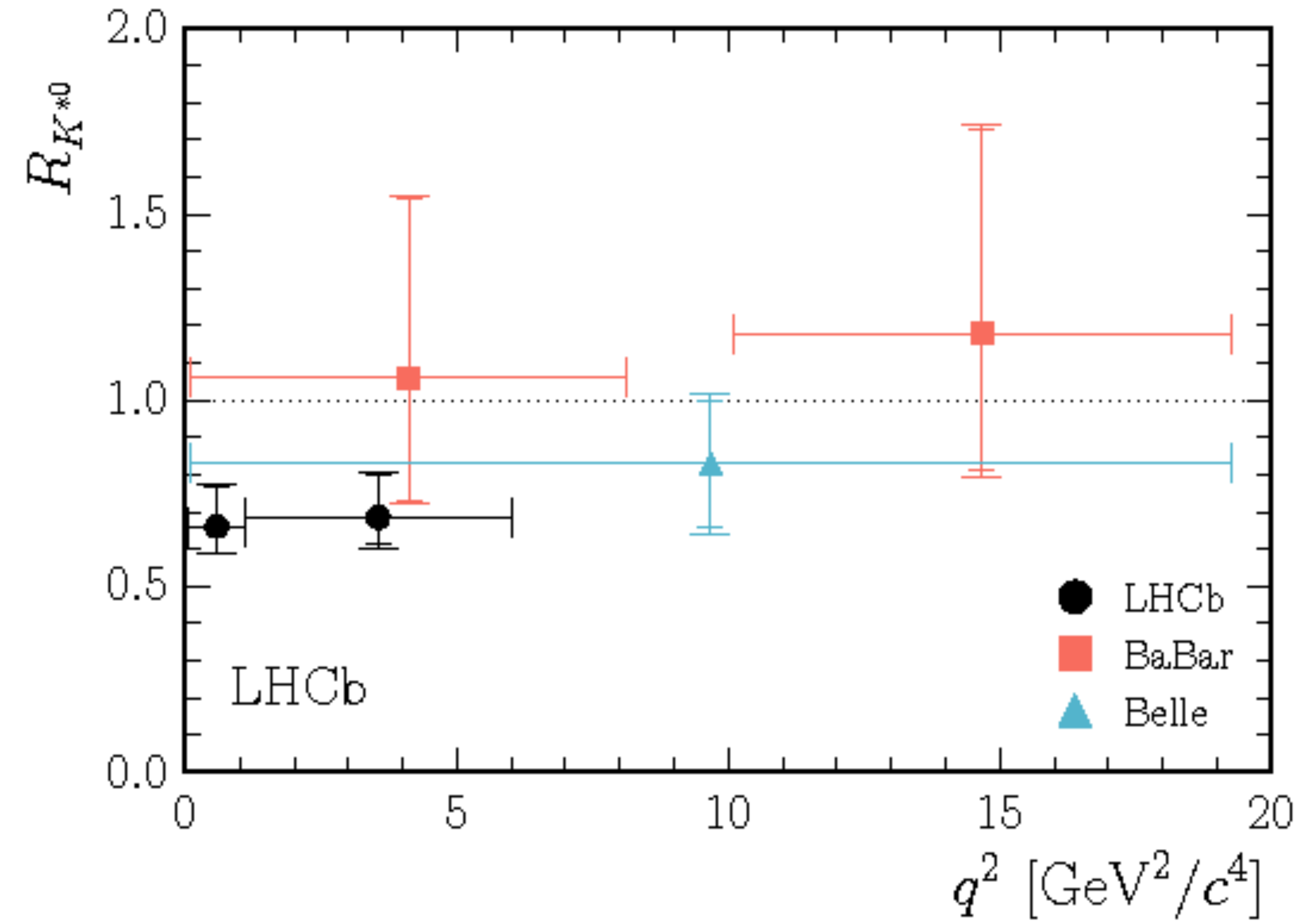
Results

Comparison with SM predictions



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

Comparison with BaBar & Belle



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

LHCb: JHEP 08 (2017) 055

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

2.1 - 2.3 σ
2.4 - 2.5 σ

Crosschecks

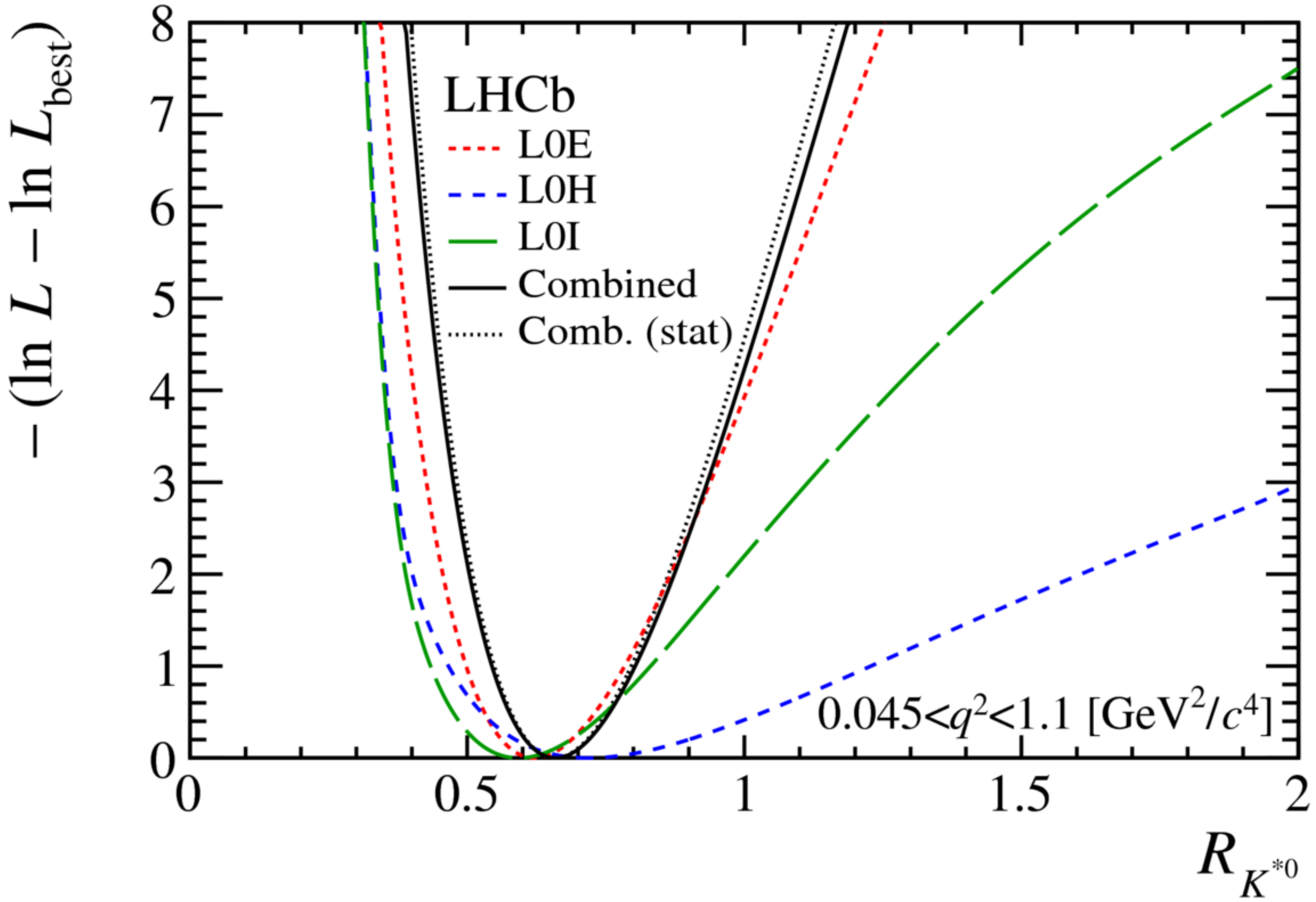
JHEP 08 (2017) 055

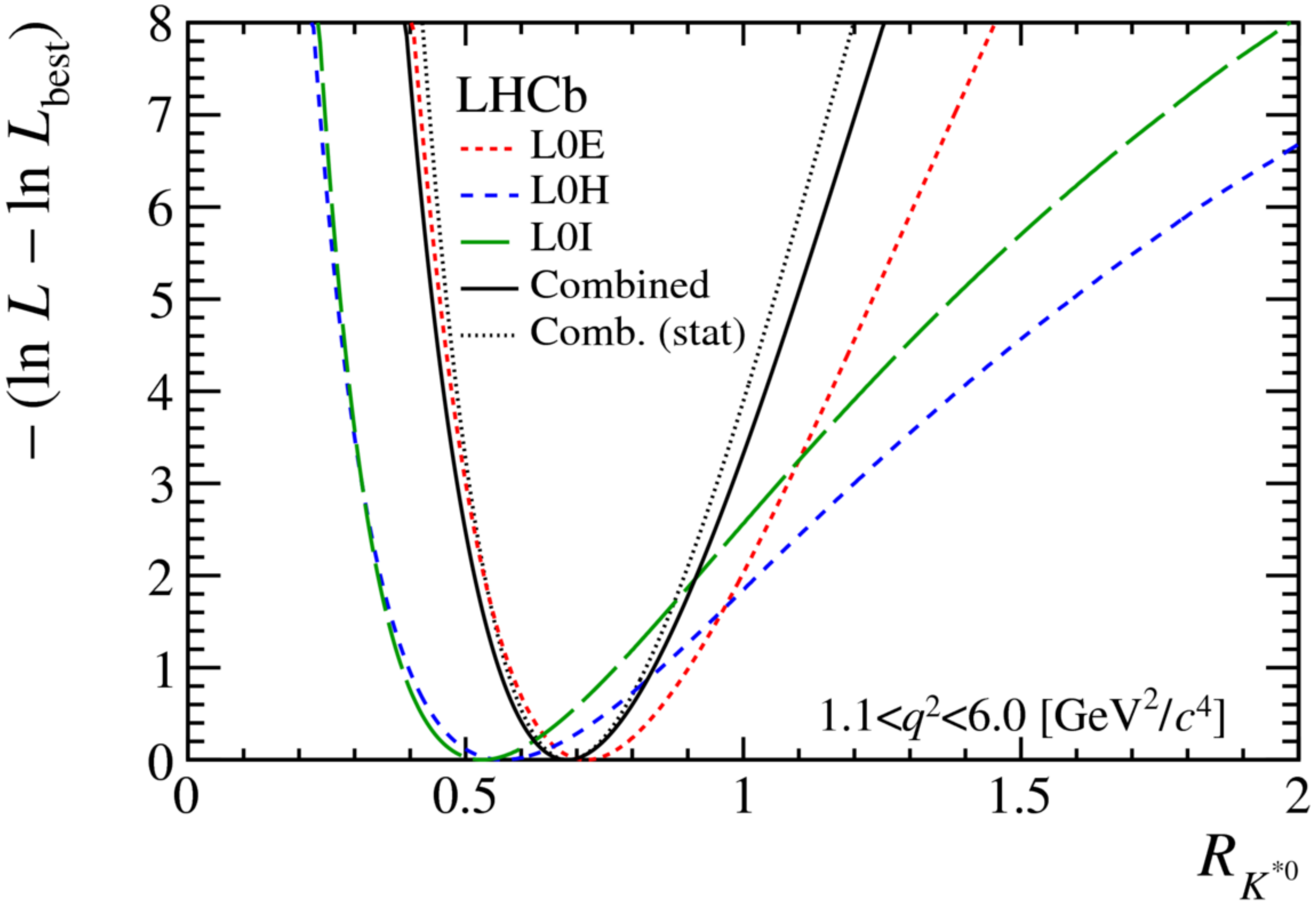
- $r_{J/\psi} = \dfrac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))} = 1.043 \pm 0.006 \pm 0.045$
  - very stringent test of absolute scale of efficiencies that does not benefit from the cancellation of the experimental systematics from the double ratio
  - compatible with being independent of decay kinematics (p_T, η of the B^0 candidate) and track multiplicity
- $R_{\psi(2S)} = \dfrac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))} \Big/ \dfrac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$ → compatible with expectation
- $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$ in agreement with JHEP 04 (2017) 142
- $\mathcal{B}(B^0 \to K^{*0}\gamma)$ compatible with expectations
- If corrections to simulation are not accounted for, the ratio of the efficiencies (and thus R_{K^*}) changes by less than 5%

Electron-trigger categories

- Delta log-likelihood for the three electron-trigger categories, separately and combined

Low-q^2 JHEP 08 (2017) 055 Central-q^2

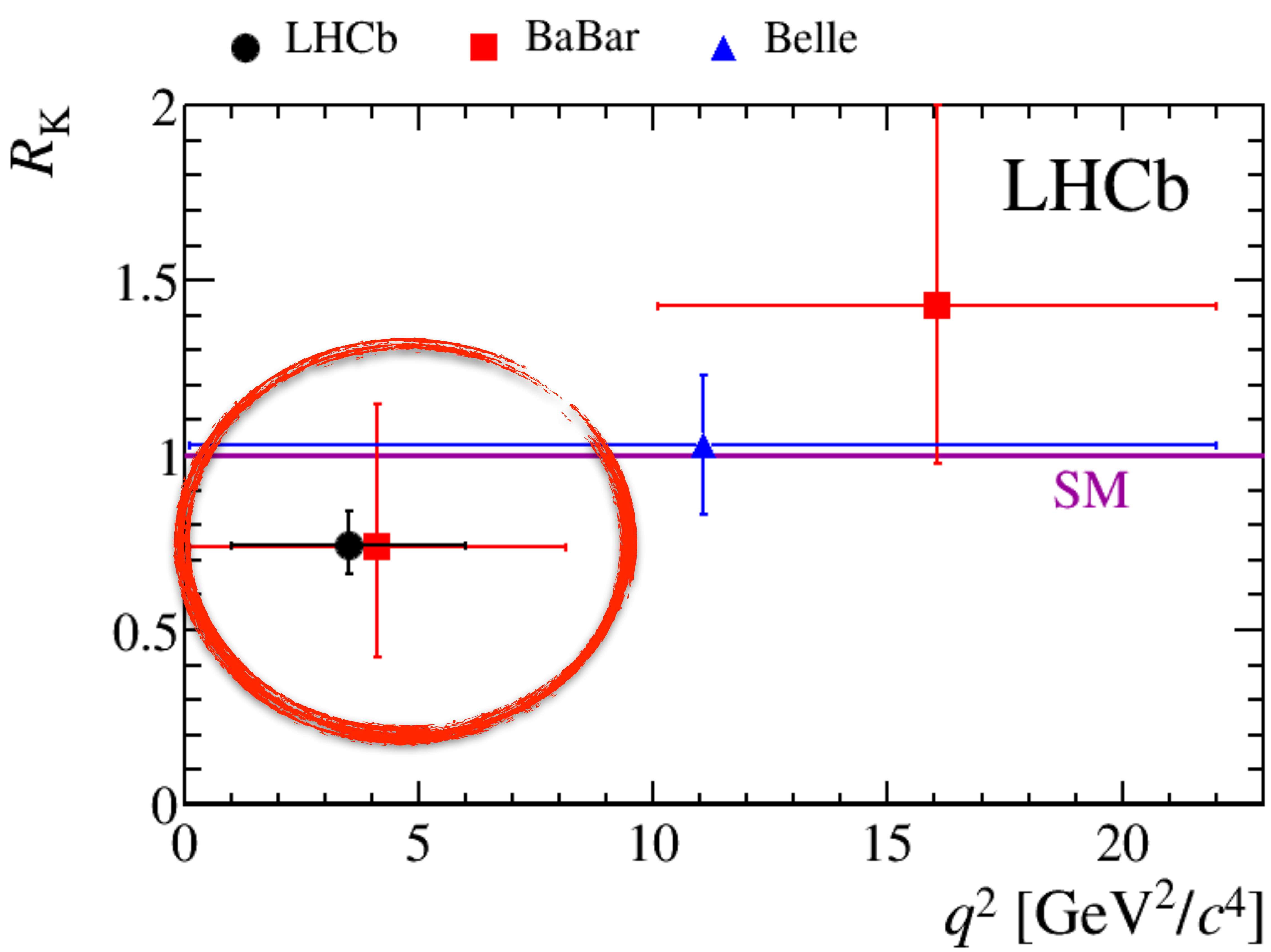




A reminder: R_K

- LHCb published an analysis of R_K based on Run 1 data:

$$R_K\left[q^2_{\rm min}, q^2_{\rm max}\right] = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \frac{d\Gamma(B^+\to K^+\mu^+\mu^-)}{dq^2}}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \frac{d\Gamma(B^+\to K^+e^+e^-)}{dq^2}}, \quad 1 < q^2 < 6\,\mathrm{GeV}^2$$



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

LHCb: PRL 113 (2014) 151601

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

- Compatible with SM at 2.6 σ

What happens next?

- Work in progress in LHCb to update R_K with additional Run 2 data
  - from ~250 $B^+ \to e^+e^-$ candidates to ~800, plus analysis is being improved
- Can make analogous measurement with $B_s \to \phi\ell^+\ell^- \to R_\phi$ and other similar modes
- Run 2 update of R_{K^*}
- Extend the analysis to high-q^2 region, above $\psi(2S)$
- Available data should be sufficient to clarify the picture

Another puzzling result in tree-level $b \to c$ transitions

LFU studies in $B \to D^{(*)}\tau\nu$ decays

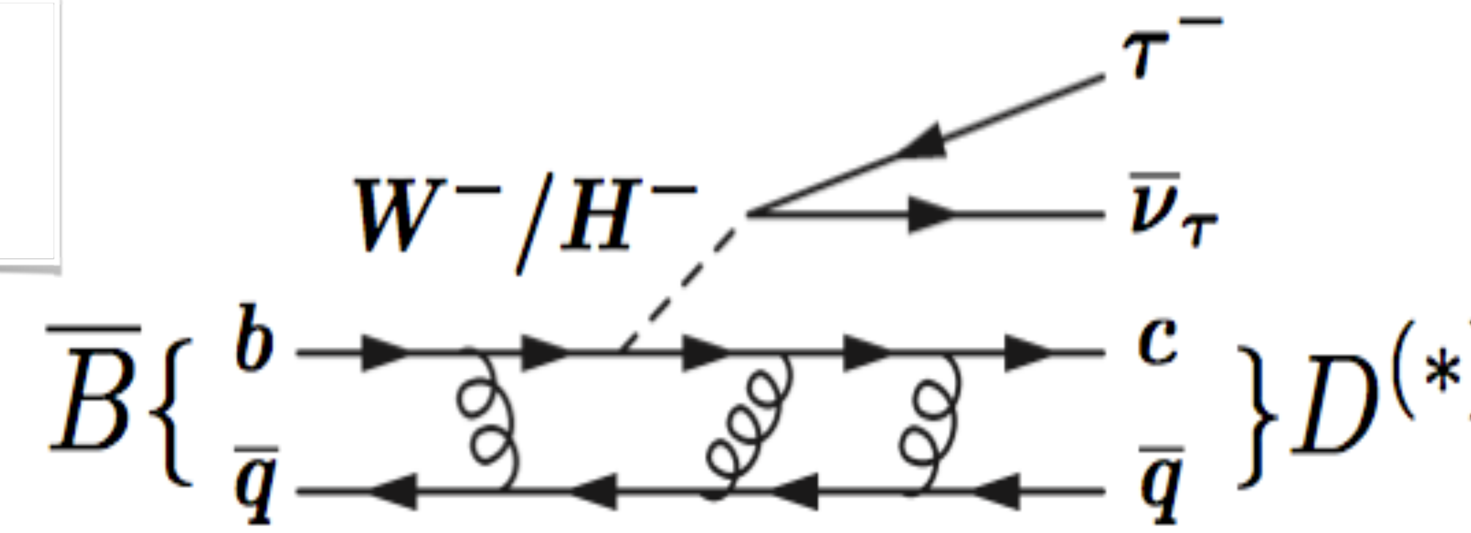
- $R(D^*) = \mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)/\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$

Tree level
b→c transition

- Different class of decays (charged current)
  - precisely predicted:

Berlochner et al
arXiv:1703.05330

$$R(D*)_{\rm SM} = 0.257 \pm 0.003$$



- Latest LHCb measurement : $\begin{cases} \tau^+ & \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau \\ D^{*-} & \to \overline{D}^0(\to K^+\pi^-)\pi^- \end{cases}$

3-prong

  - A semileptonic decay with no (charged) lepton in final state (one K, five π) → Zero background from $B^0 \to D^{*-}\mu^+\nu_\mu X$

- $\mathcal{B}\left(B^0 \to D^{*-}\tau^+(\to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau)\nu_\tau\right) \simeq 0.2\%$ → not at all rare!
  - However, signal to noise ratio less than 1% → need at least 10^3 rejection!
  - Large background, notably from $B \to D^{*-}3\pi X$ (BF~100 x signal) and $B \to D^{*-}D_s^+(X)$ (BF~10 x signal)

Analysis strategy

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

Measured

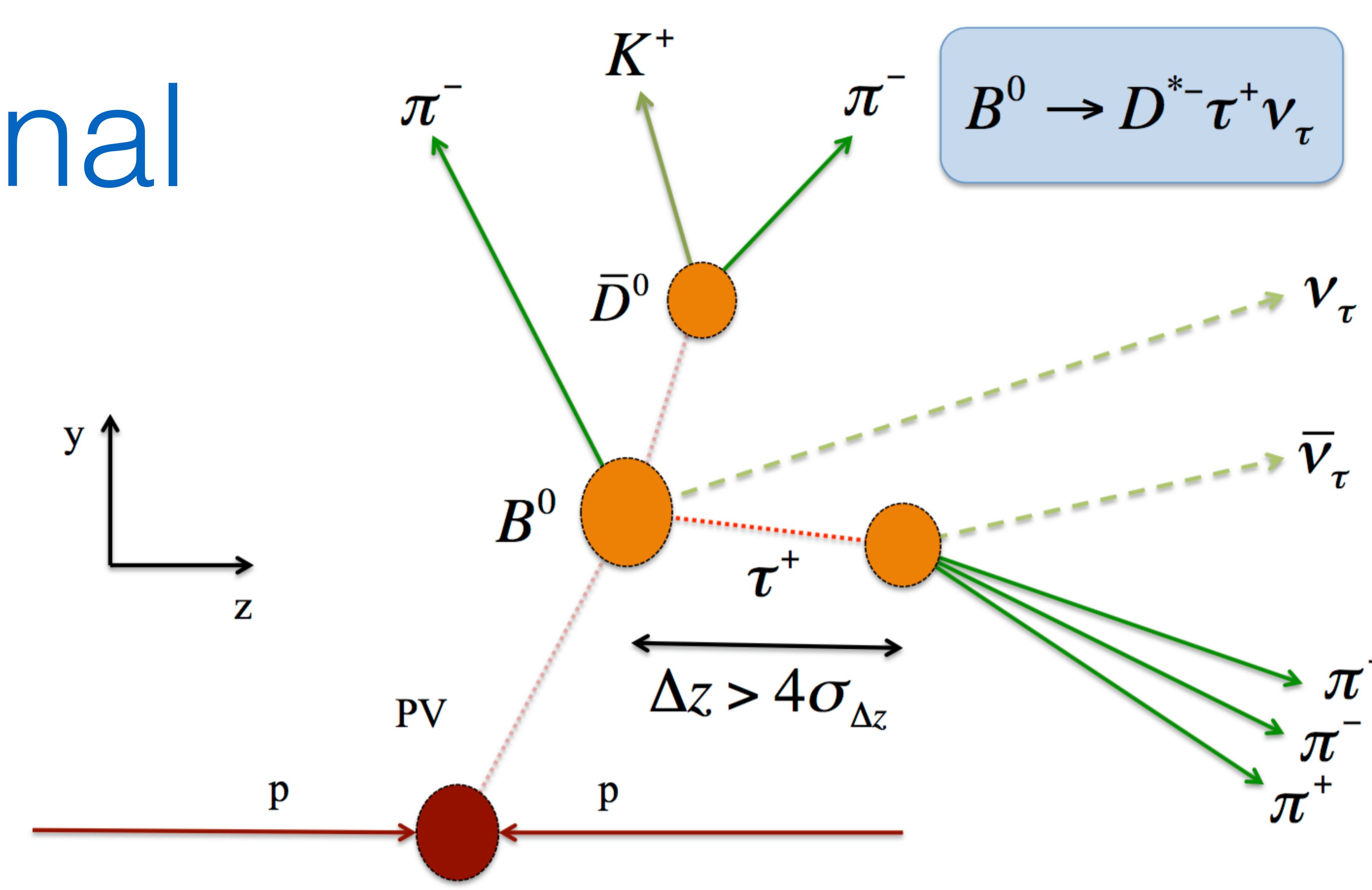
~4%

~2%

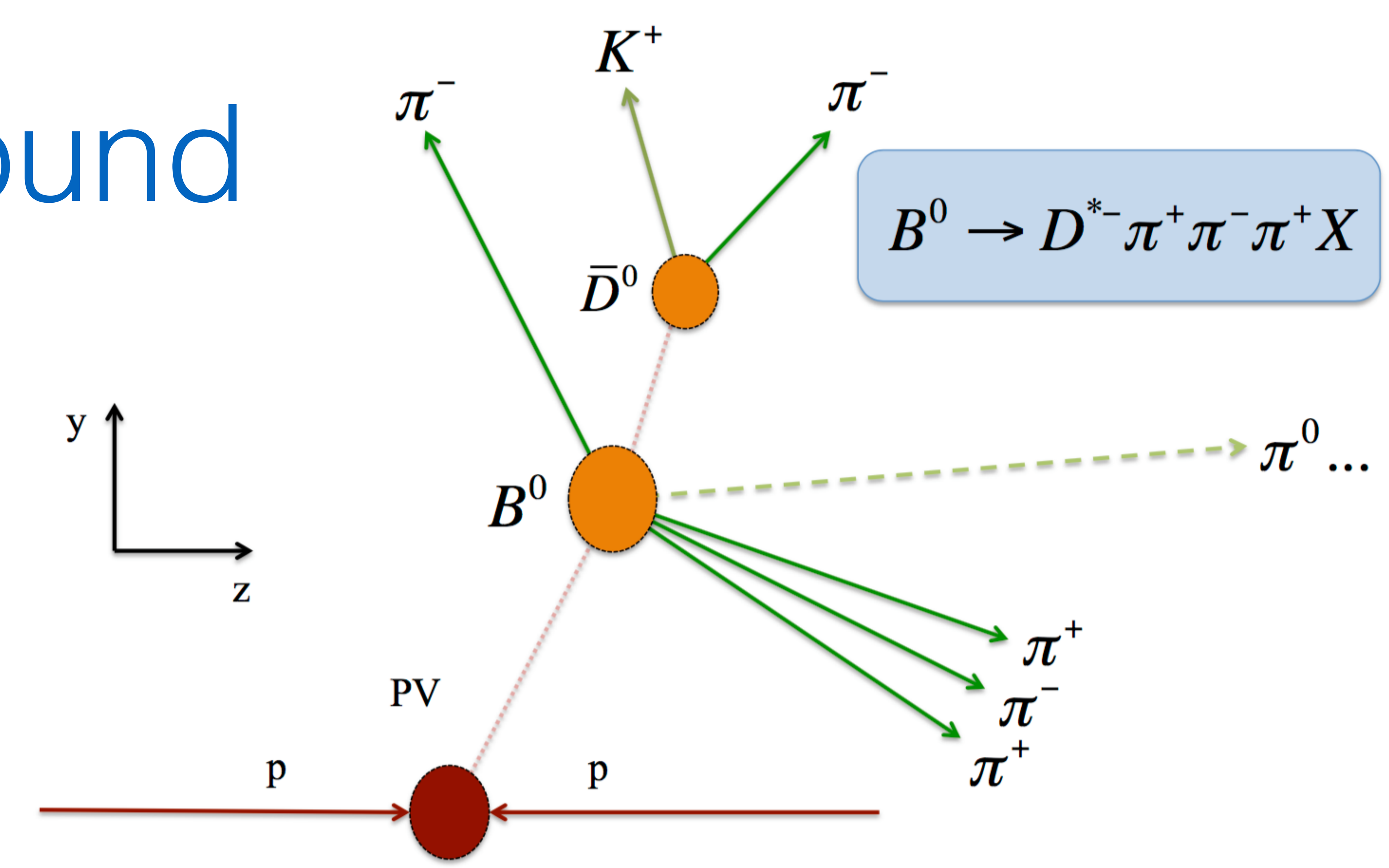
External inputs

- Signal and normalization channel share same final state → most systematics cancel in ratio (trigger, PID, selection…)
- Separation between *B* and 3π vertices ($\Delta z > 4\sigma_{\Delta z}$) crucial to obtain the required rejection of $B \to D^* 3\pi X$)

Signal



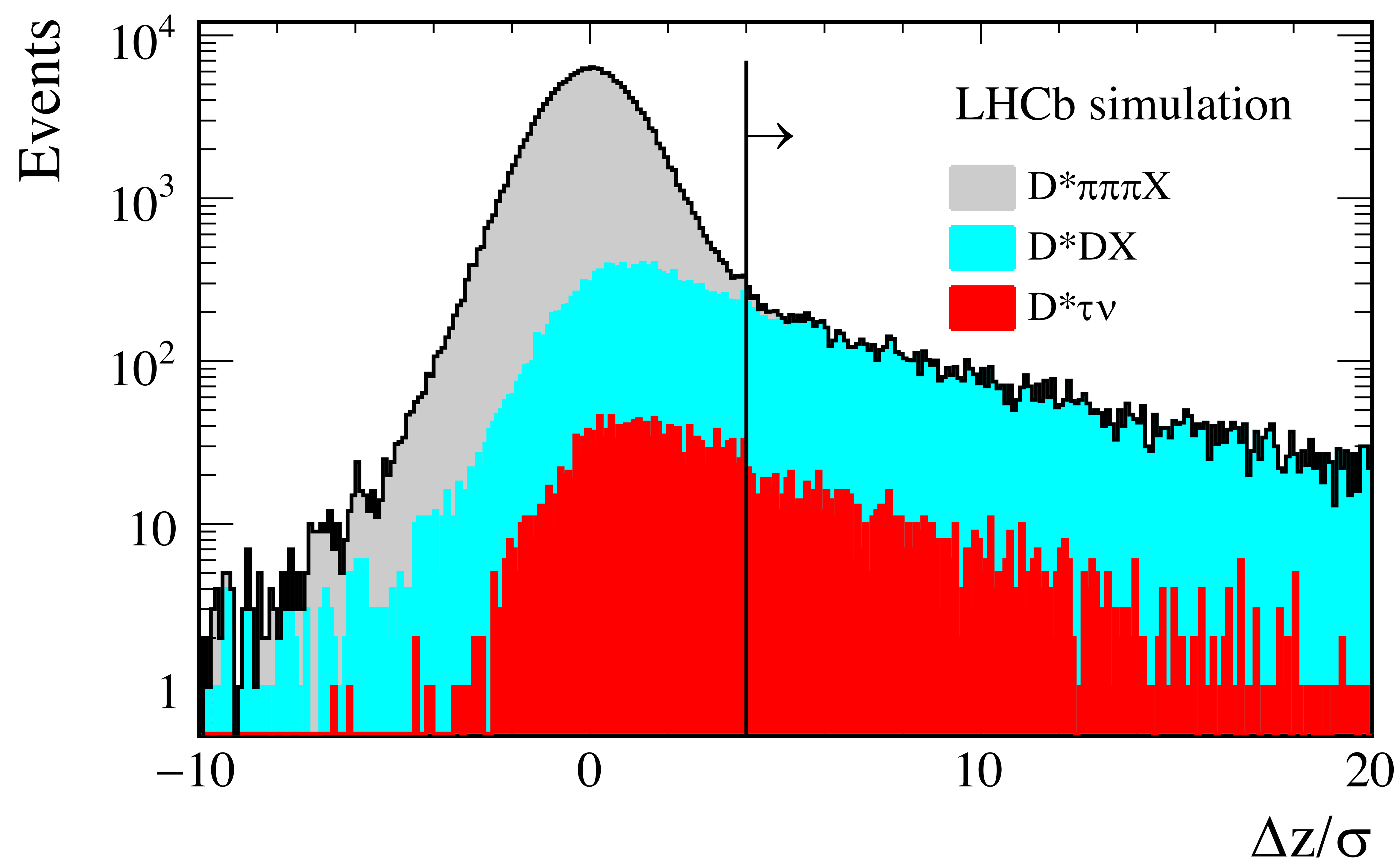
Background



Background reduction

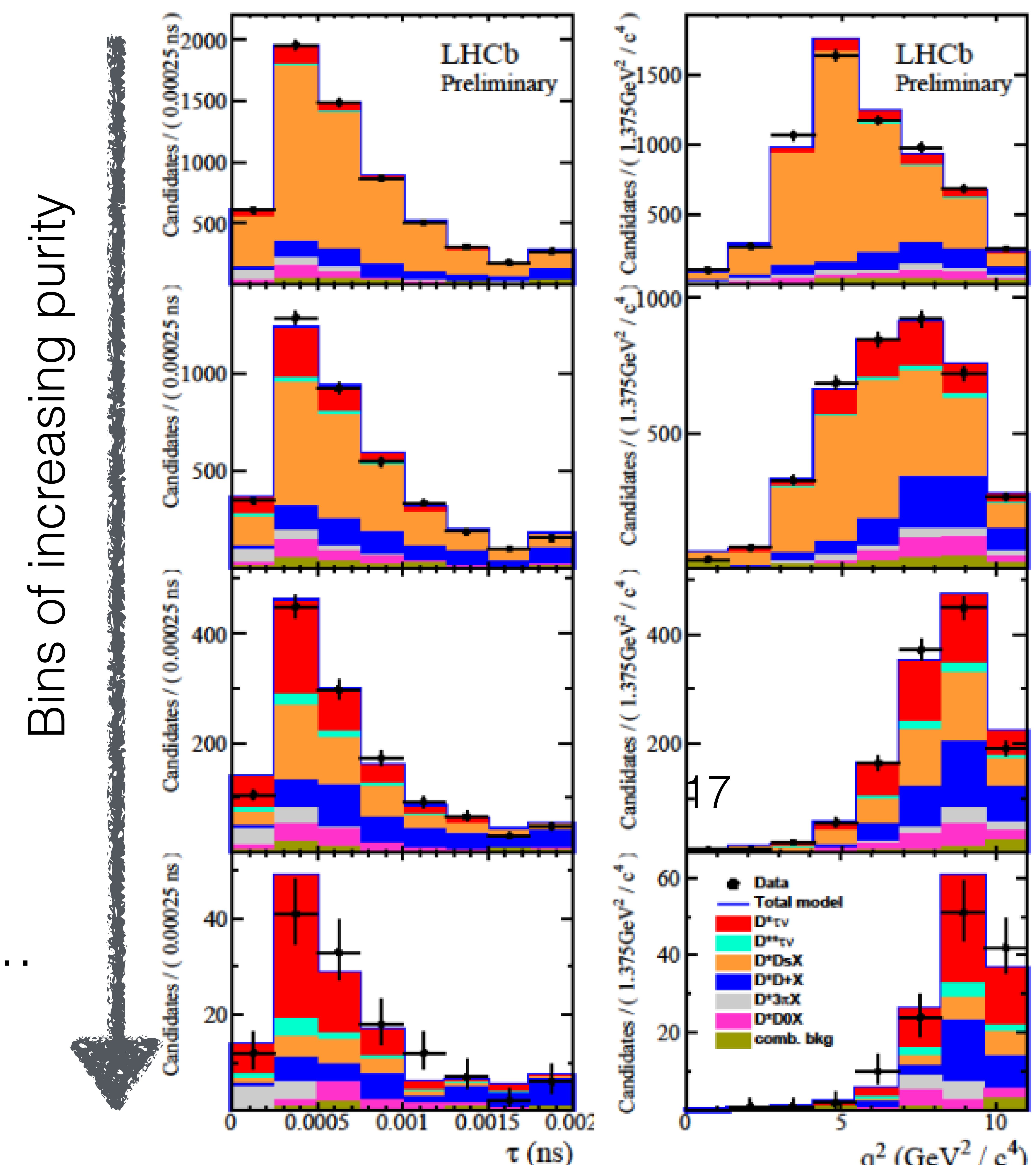
- Requiring a minimum distance between B and τ vertices gives factor 10^3 suppression while retaining ~35% of signal

arXiv:1708.08856



- Remaining double-charm background ($D^*D_{(s)}X$) suppressed by employing a multivariate analysis based on isolation variables, 3π dynamics, reconstruction under signal and background hypotheses….
- Blind analysis

Signal yield ~1300 events



3π decay time

$$q^2 = (p_{\rm B} - p_{\rm D^*})^2$$

Results

arXiv:1708.08856

- This measurement:

  $R(D^*) = 0.285 \pm 0.019_{\mathrm{stat}} \pm 0.025_{\mathrm{syst}} \pm 0.014_{\mathrm{ext}}$

  consistent with SM and with previous determinations

- LHCb muonic:

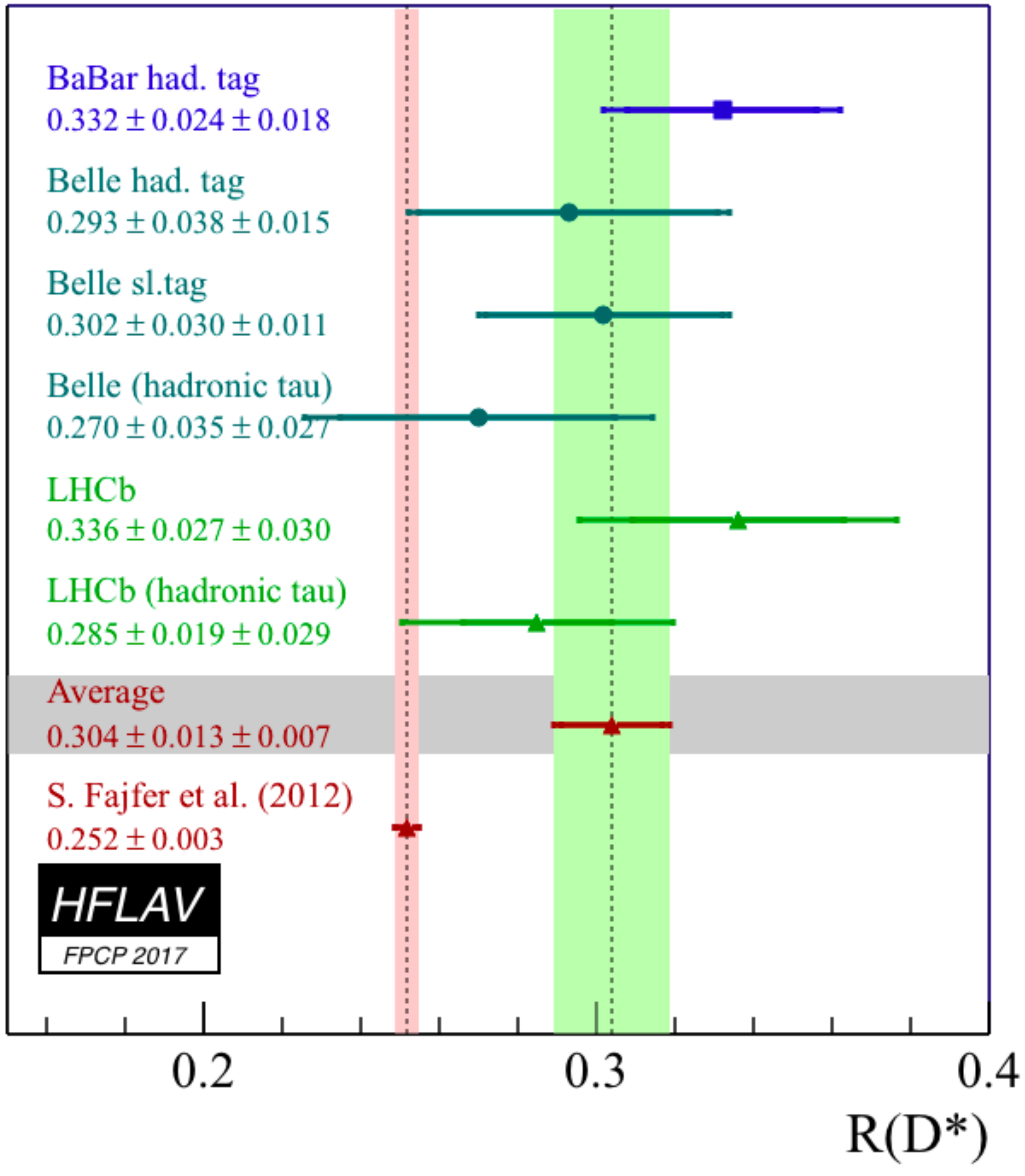
  $R(D^*) = 0.336 \pm 0.027_{\mathrm{stat}} \pm 0.030_{\mathrm{syst}}$

- Preliminary LHCb average:

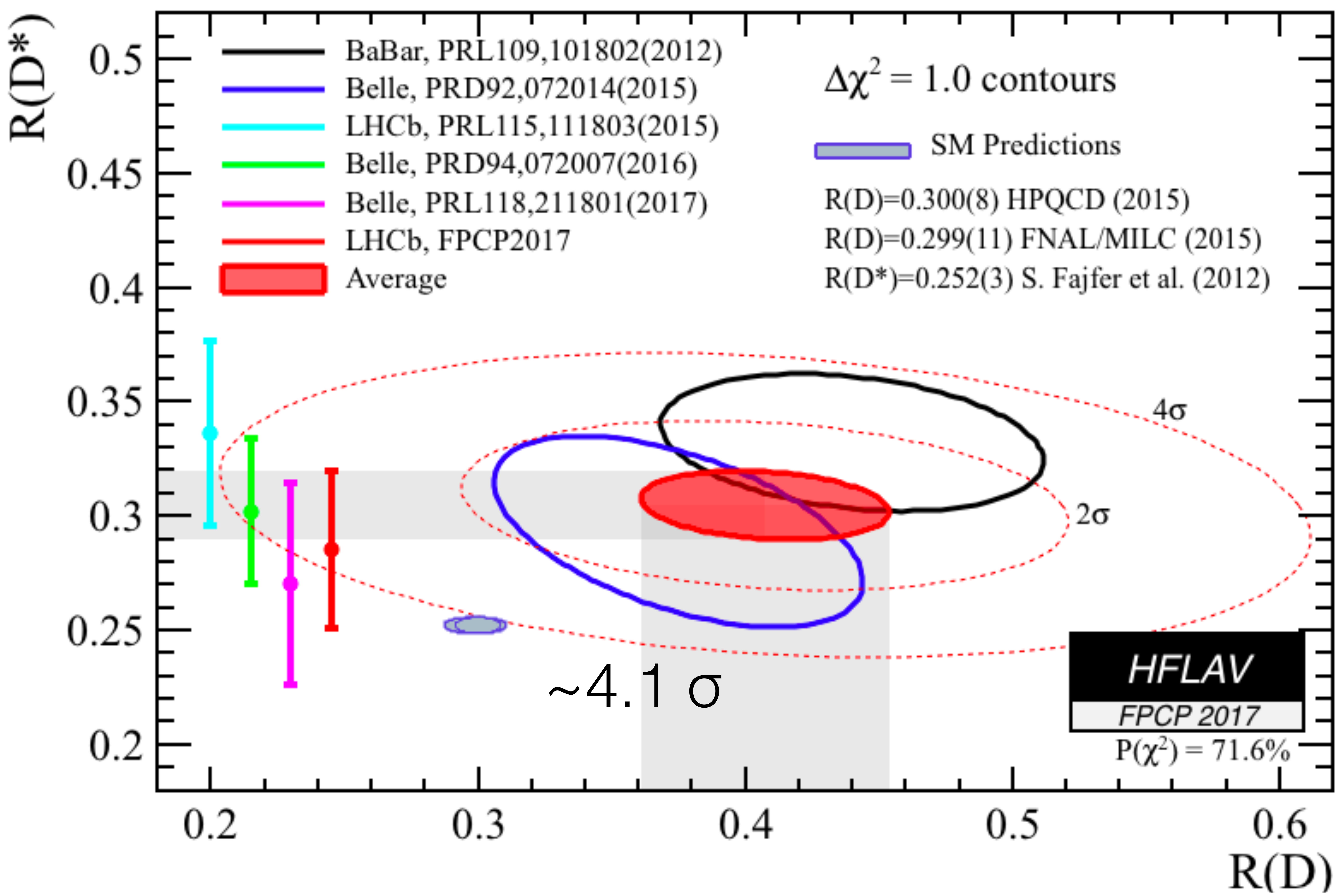
  $R(D^*) = 0.306 \pm 0.027$

- New HFLAV preliminary world average

  $R(D^*) = 0.304 \pm 0.015$ ~3.4 σ



$R(D)$ vs $R(D^*)$



Prospects

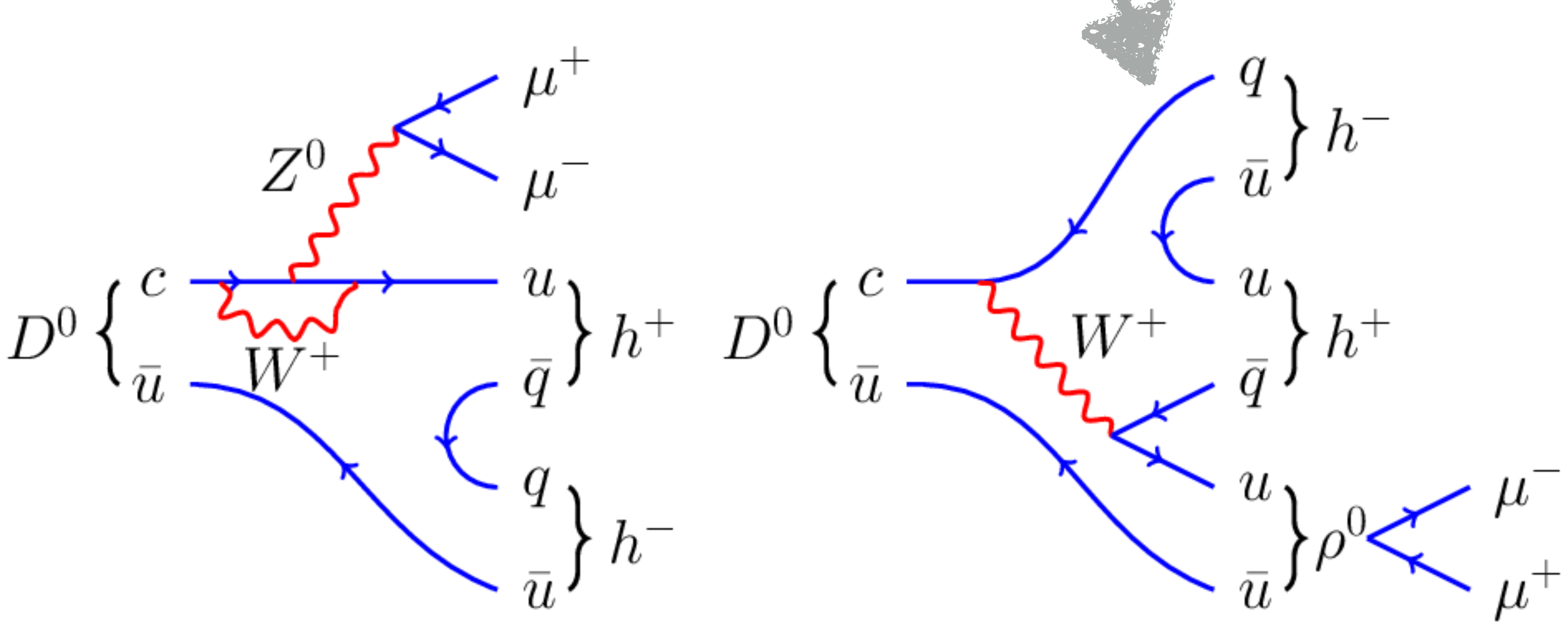
- LHCb: a whole programme of semi-tauonic measurements :

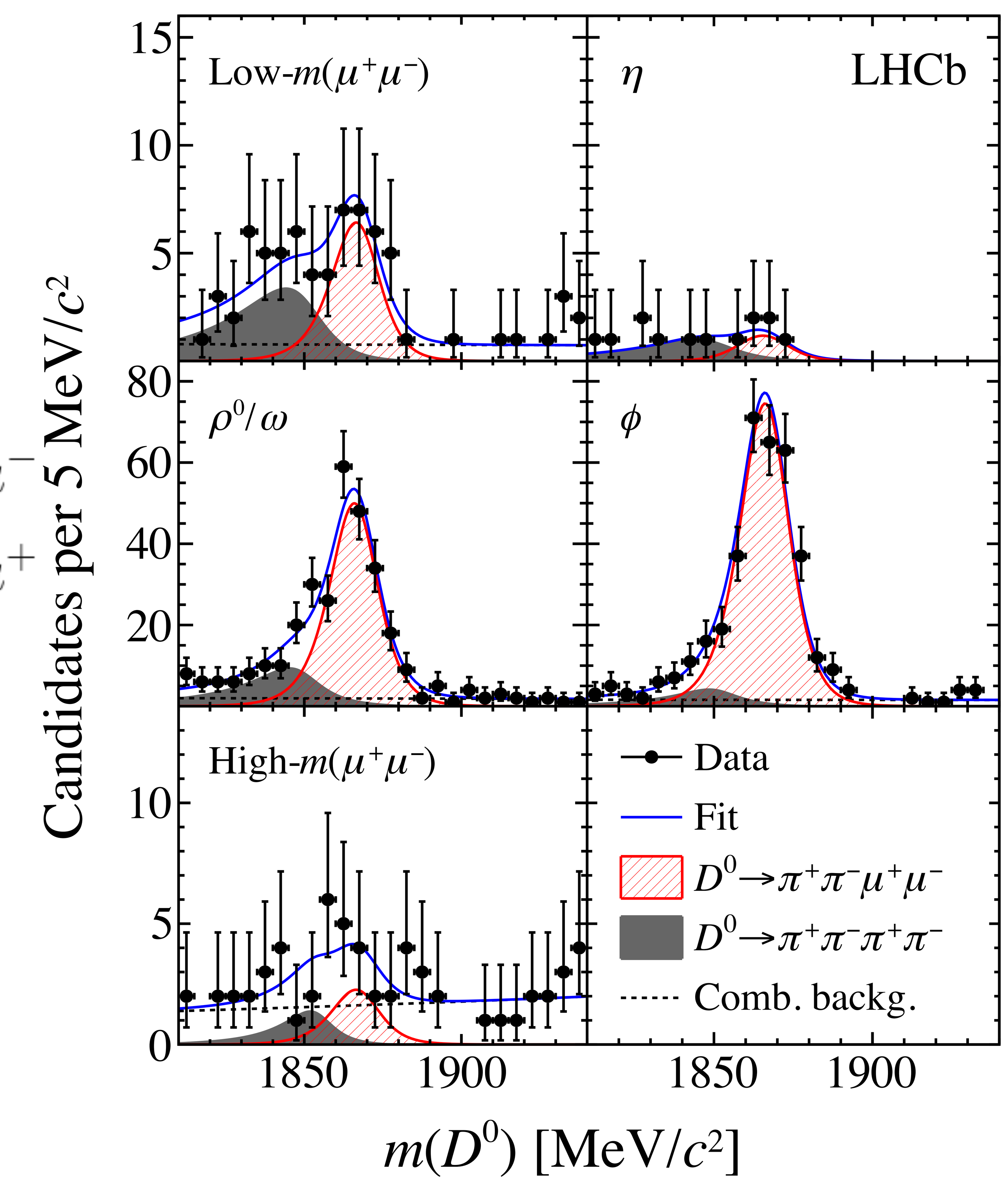
$$R(J/\psi) : B_c^+ \to J/\psi\, \tau^+ \nu_\tau$$
$$R(D^-) : B^0 \to D^- \tau^+ \nu_\tau$$
$$R(D^0) : B^+ \to D^0 \tau^+ \nu_\tau$$
$$R(D_s^{(*)}) : B_s^0 \to D_s^{(*)} \tau^+ \nu_\tau$$
$$R(\Lambda_b) : \Lambda_b \to \Lambda_c^{(*)} \tau^+ \nu_\tau$$

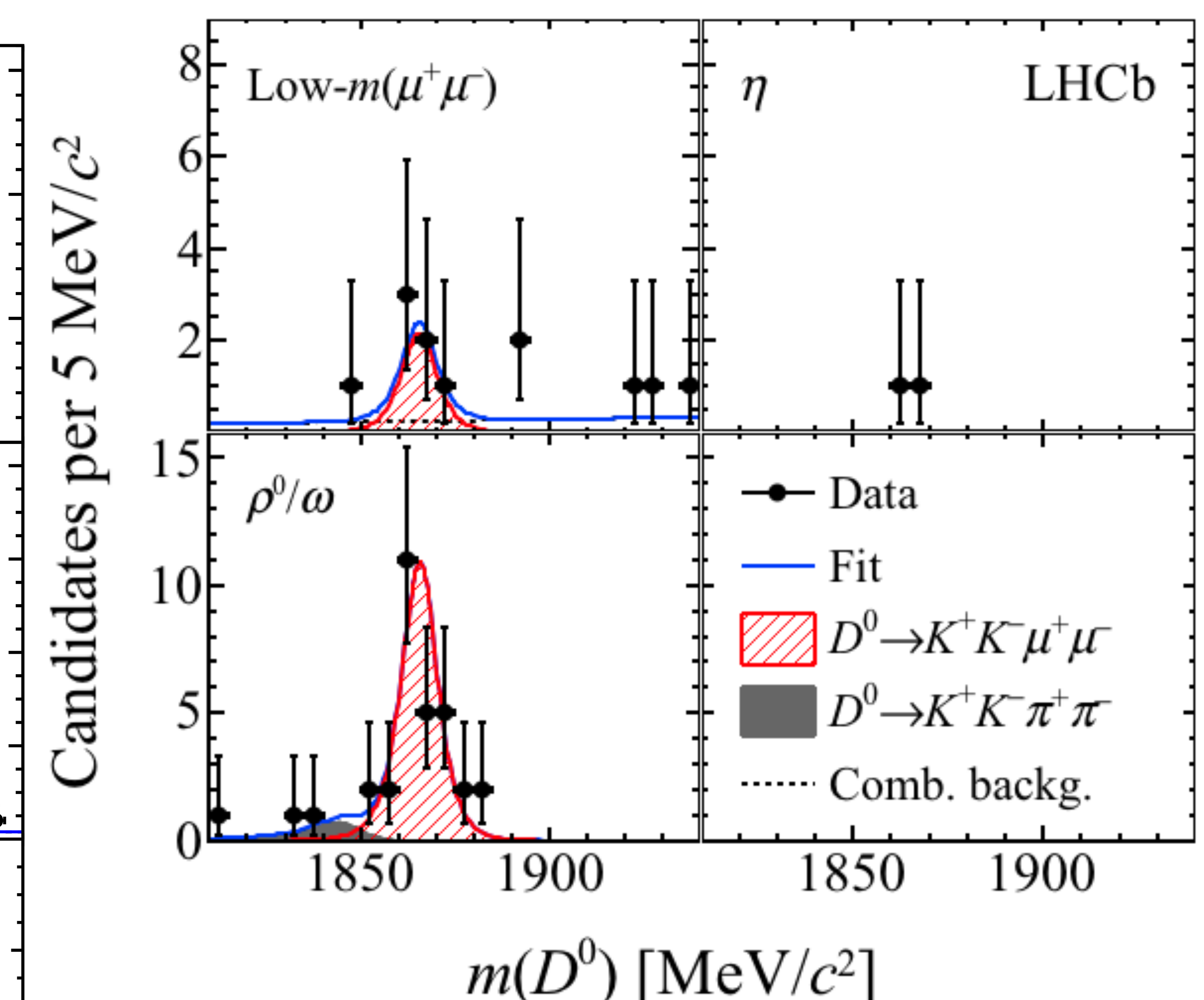
Rarest charm-hadron decays ever observed !

$D^0 \to \pi^+\pi^-\mu^+\mu^-\,,\ D^0 \to K^+K^-\mu^+\mu^-$

- $c \to u\mu^+\mu^-$ FCNC transitions ($\mathcal{O}(10^{-9})$ in SM), potentially sensitive to NP
- However, "long-distance" contributions, are expected to be large, reducing sensitivity to short-distance amplitudes







arXiv:1707.08377
submitted to PRL

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48_{\rm stat} \pm 0.51_{\rm syst} \pm 0.97_{\rm norm}) \times 10^{-7}$$

$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27_{\rm stat} \pm 0.09_{\rm syst} \pm 0.16_{\rm norm}) \times 10^{-7}$$

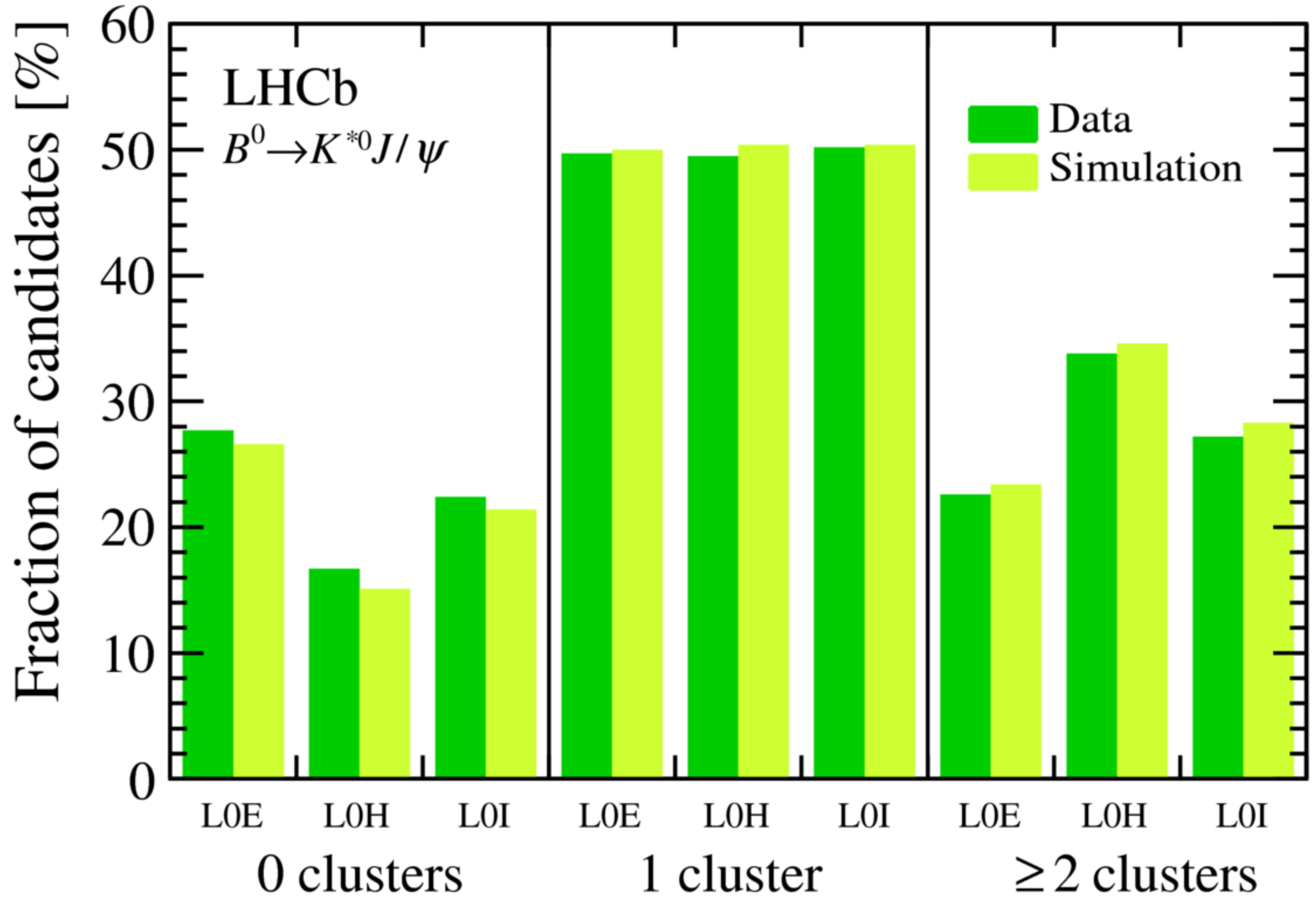
Conclusions

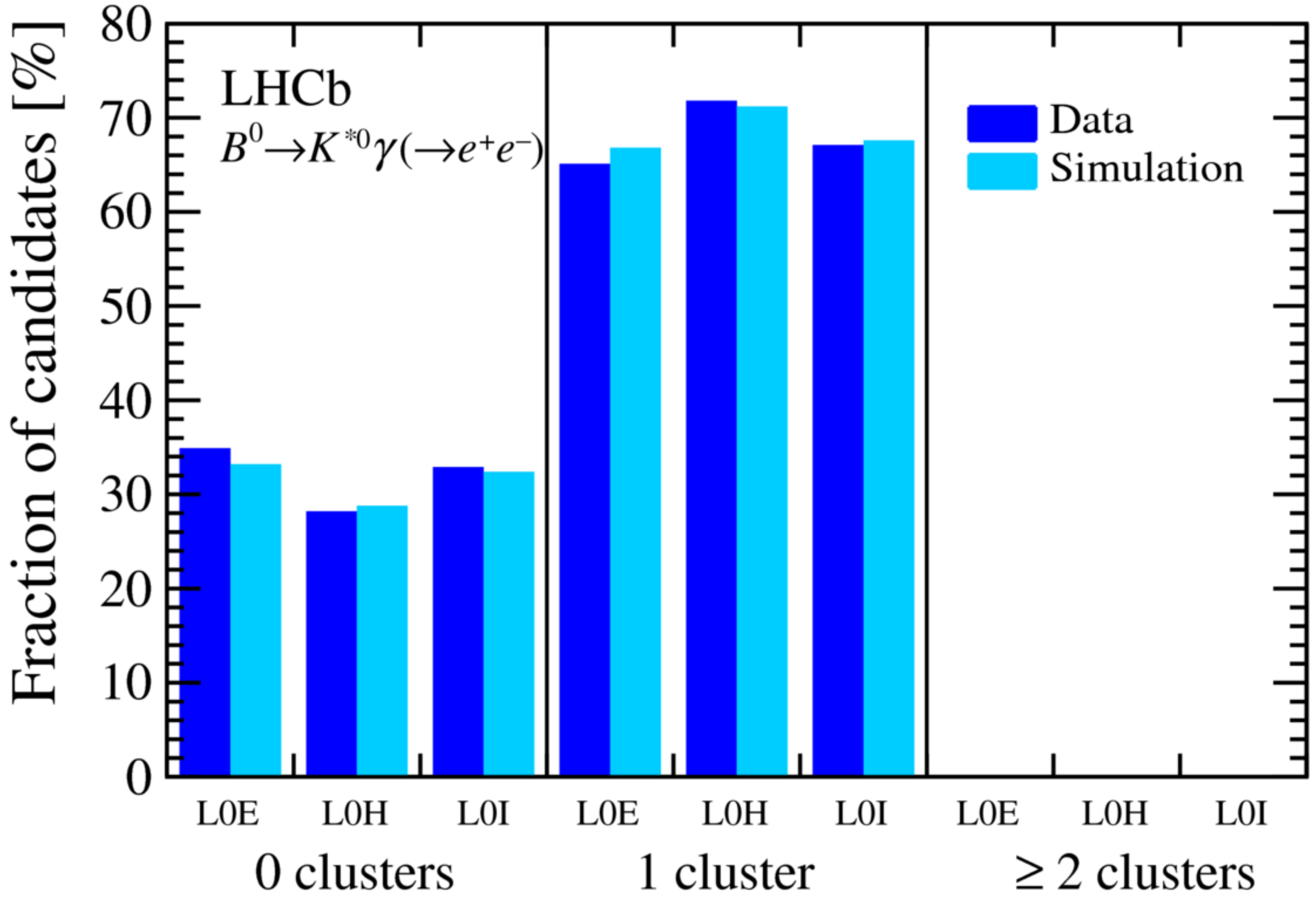
- Precise measurements of flavour observables provide a powerful way to probe for NP effects beyond the SM, complementing direct searches for NP
- Flavour-physics measurements at the LHC, in particular by LHCb, are dramatically adding to the already impressive knowledge accumulated by the B-factories and Tevatron
- Many world record results. For some topics we have moved from exploration to precision measurements
- Most of these results show good compatibility with the SM, but some signs of tension are emerging
- Need more data to test these hints. These data are arriving in Run 2!

A few extra slides

Crosschecks on bremsstrahlung recovery

- Relative population of bremsstrahlung categories compared between data and simulation using $B^0 \to K^{*0} J/\psi(ee)$ and $B^0 \to K^{*0} \gamma(ee)$ events





Relative systematic uncertainty on R(K*)

	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ ratio	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

Relative systematic uncertainty on R(D*)

Table 1: Relative systematic uncertainties on $\mathcal{R}(D^{*-})$.

Source	$\delta R(D^{*-})/R(D^{*-})[\%]$
Simulated sample size	4.7
Empty bins in templates	1.3
Signal decay model	1.8
$D^{**}\tau\nu$ and $D_s^{**}\tau\nu$ feeddowns	2.7
$D_s^+ \to 3\pi X$ decay model	2.5
$B \to D^{*-}D_s^+X$, $B \to D^{*-}D^+X$, $B \to D^{*-}D^0X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*-}3\pi X$ background	2.8
Efficiency ratio	3.9
Total uncertainty	8.9

LHC Schedule & LHCb

- LHCb is currently building its upgrade to be installed in LS2
- Aim: to collect 50 fb^{-1} at

$\mathscr{L} = 2 \times 10^{33}\ cm^{-2}\ s^{-1}$

Integrated Luminosity (fb^{-1})

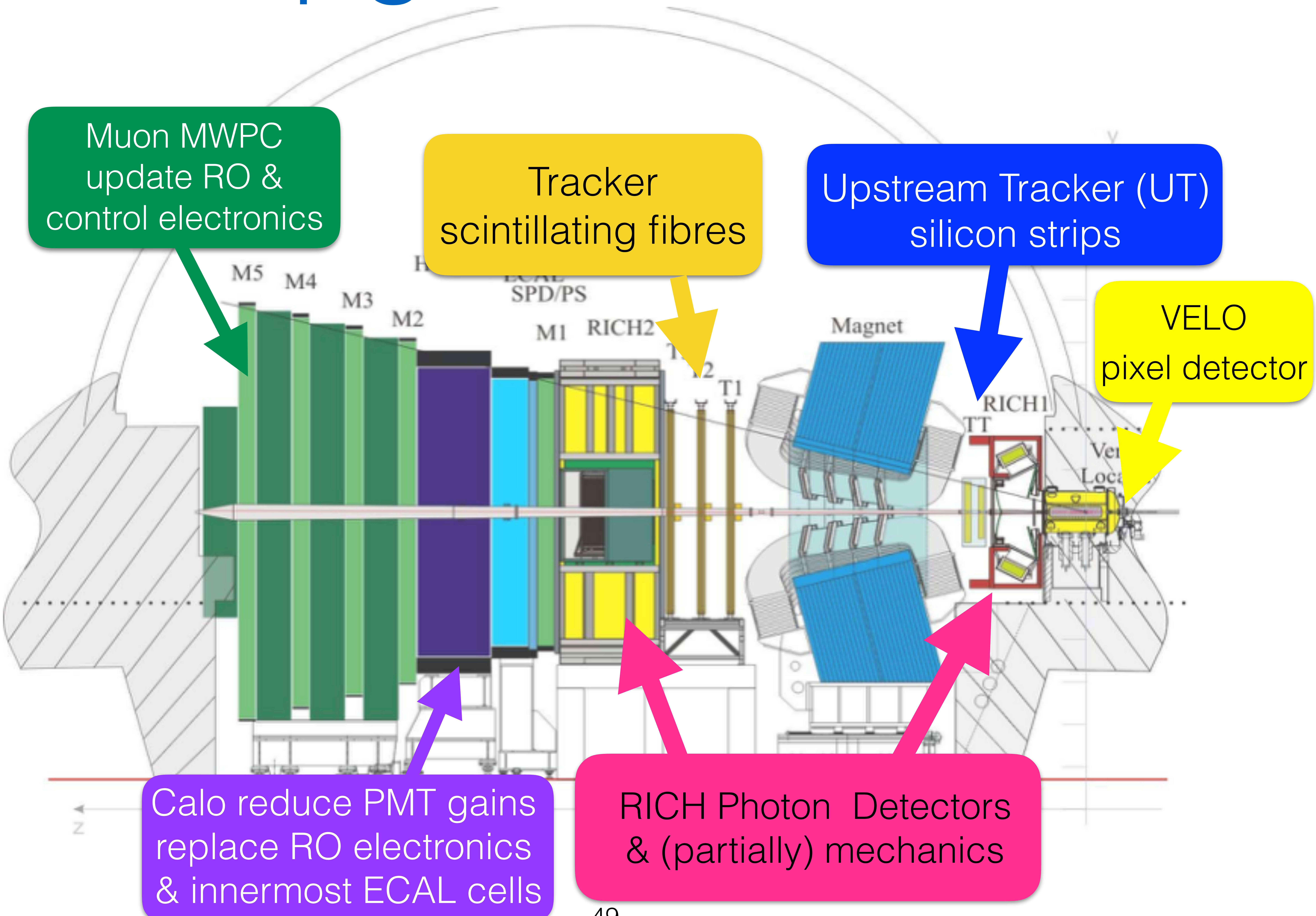
	LHCb	ATLAS/CMS
Run 1	3	30
Run 2	8	100
Run 3	25	300
Run 4	50	…3000

LHCb Upgrade

- Requirements:
  - 40 MHz readout
  - Event selection performed by HLT software only
  - $\mathcal{L} = 2 \times 10^{33} \mathrm{cm}^{-2} \mathrm{sec}^{-1}$ (x 5)
    - ➔ 5.5 visible interactions/crossing
    - ➔ Higher track multiplicity (from ~ <70> to <180>)

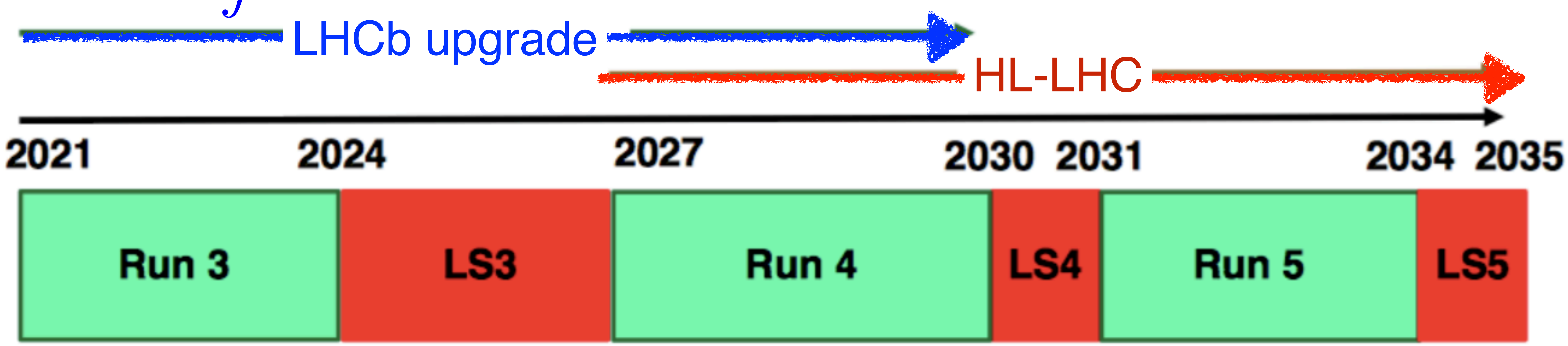
- Implications:
  - New detector front-end electronics because of new readout requirement
  - New HLT farm and network
  - New trackers with finer granularity to reduce occupancy
  - What is not changed needs to be consolidated to sustain higher Luminosity

The upgraded detector



The future after the future

$$\int \mathcal{L}\, dt \simeq 50\, [\mathrm{fb}^{-1}]$$



- While working for the upgrade, discussion started on what to do during the very long shutdown for HL-LHC (LS3) planned for 2024
- Several ideas on the table to consolidate and enhance LHCb with new capabilities that will bring extended physics opportunities in Run 4
- Lay the foundations for a phase-2 Upgrade to be installed during LS4 with a target Lumi of ~2 x 10^{34} cm^{-2} s^{-1} (x10 wrt phase-1 upgrade) integrating 300 fb^{-1}. With pileup of ~50, adding timing information will be key

	LHC Run	Period of data taking	Maximum $\mathcal{L}$ [$cm^{-2}s^{-1}$]	Cumulative $\int \mathcal{L}\,dt$ [fb^{-1}]
Current detector	1 & 2	2010–2012, 2015–2018	4×10^{32}	8
Phase-I Upgrade	3 & 4	2021–2023, 2026–2029	2×10^{33}	50
Phase-II Upgrade	5 $\rightarrow$	2031–2033, 2035 $\rightarrow$	2×10^{34}	300

Strong arguments to continue flavour physics after Run 3
Many measurements of suppressed decays of heavy-flavoured hadrons, which are interesting to probe New Physics effects, will still be statistically limited after the LHCb phase-1 upgrade