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

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

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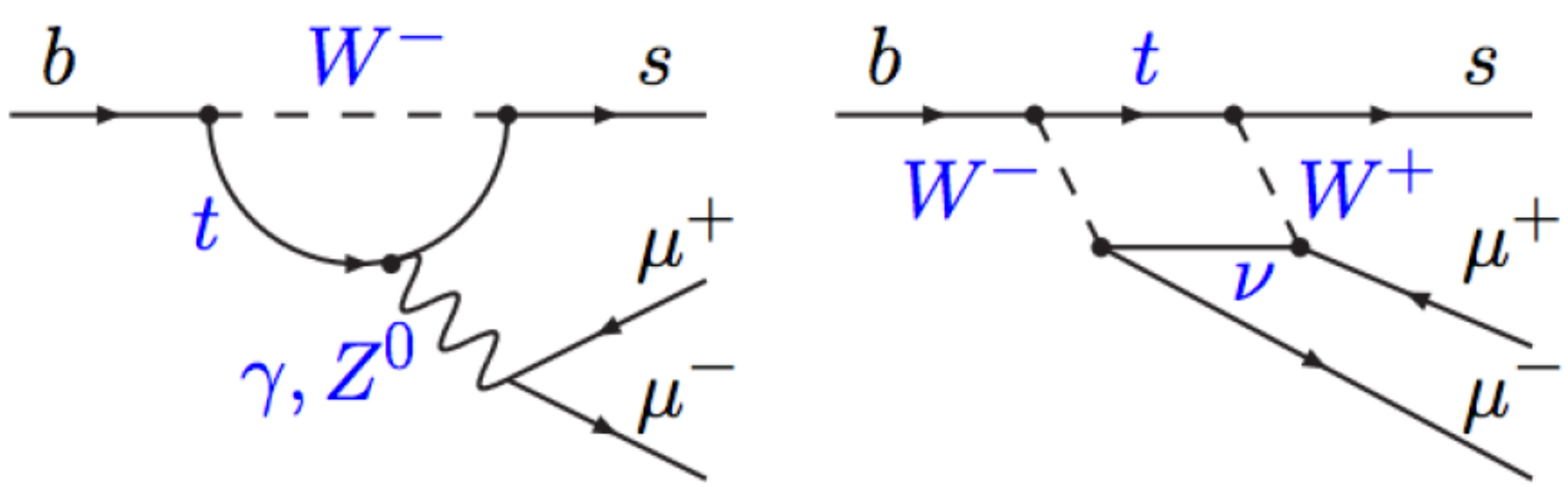
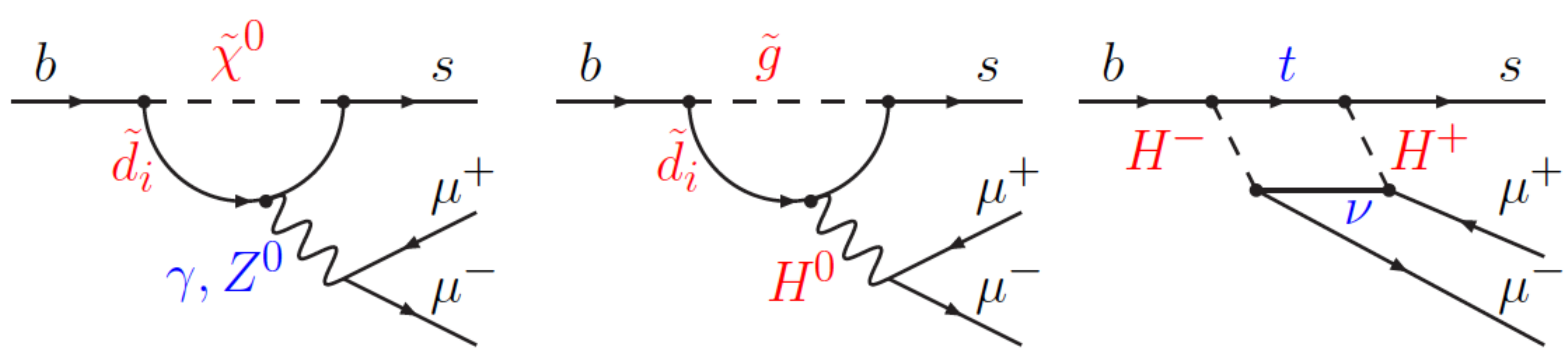
Why rare b decays

- 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

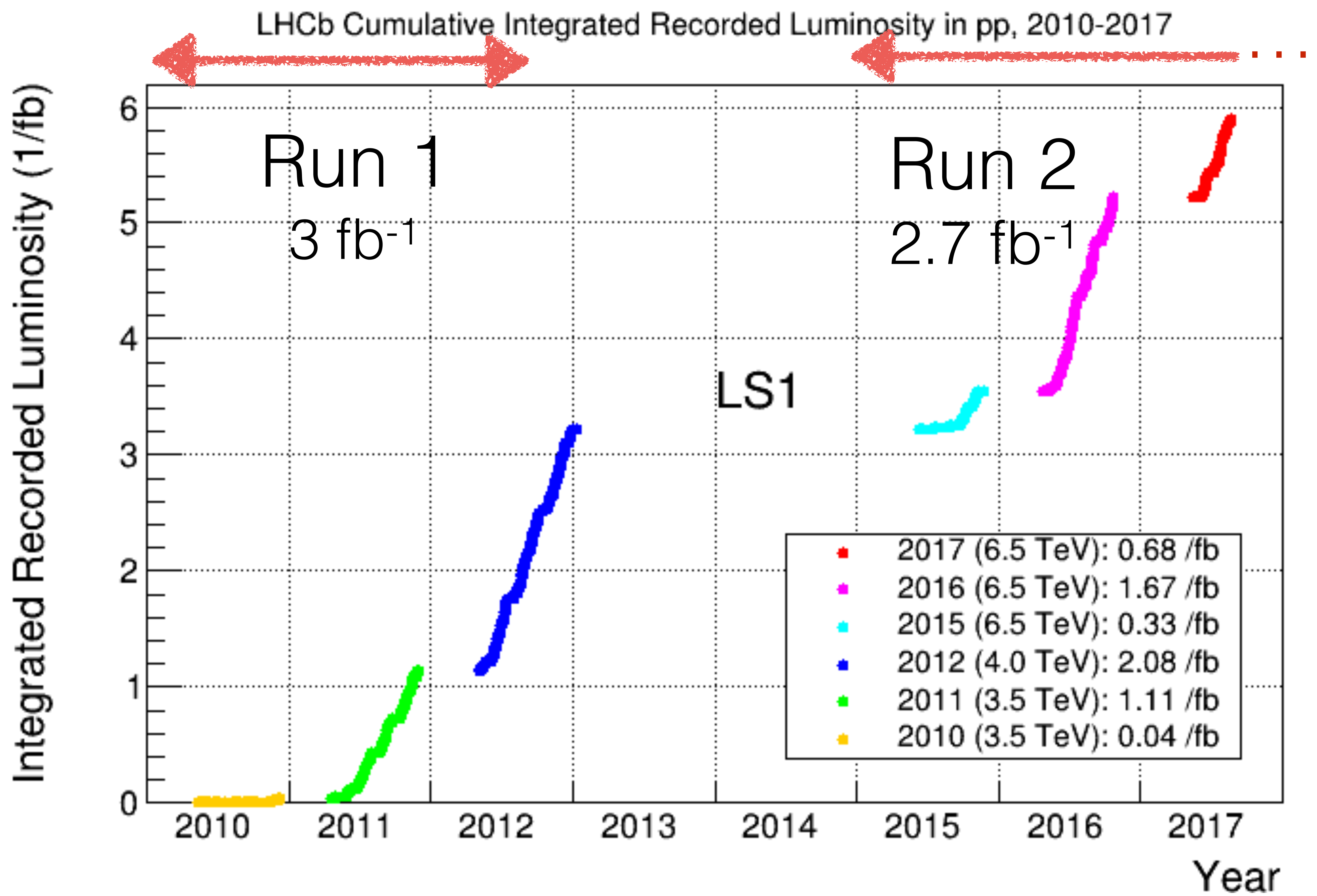
A window on NP at high scales

LHCb: a forward spectrometer for flavour physics

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

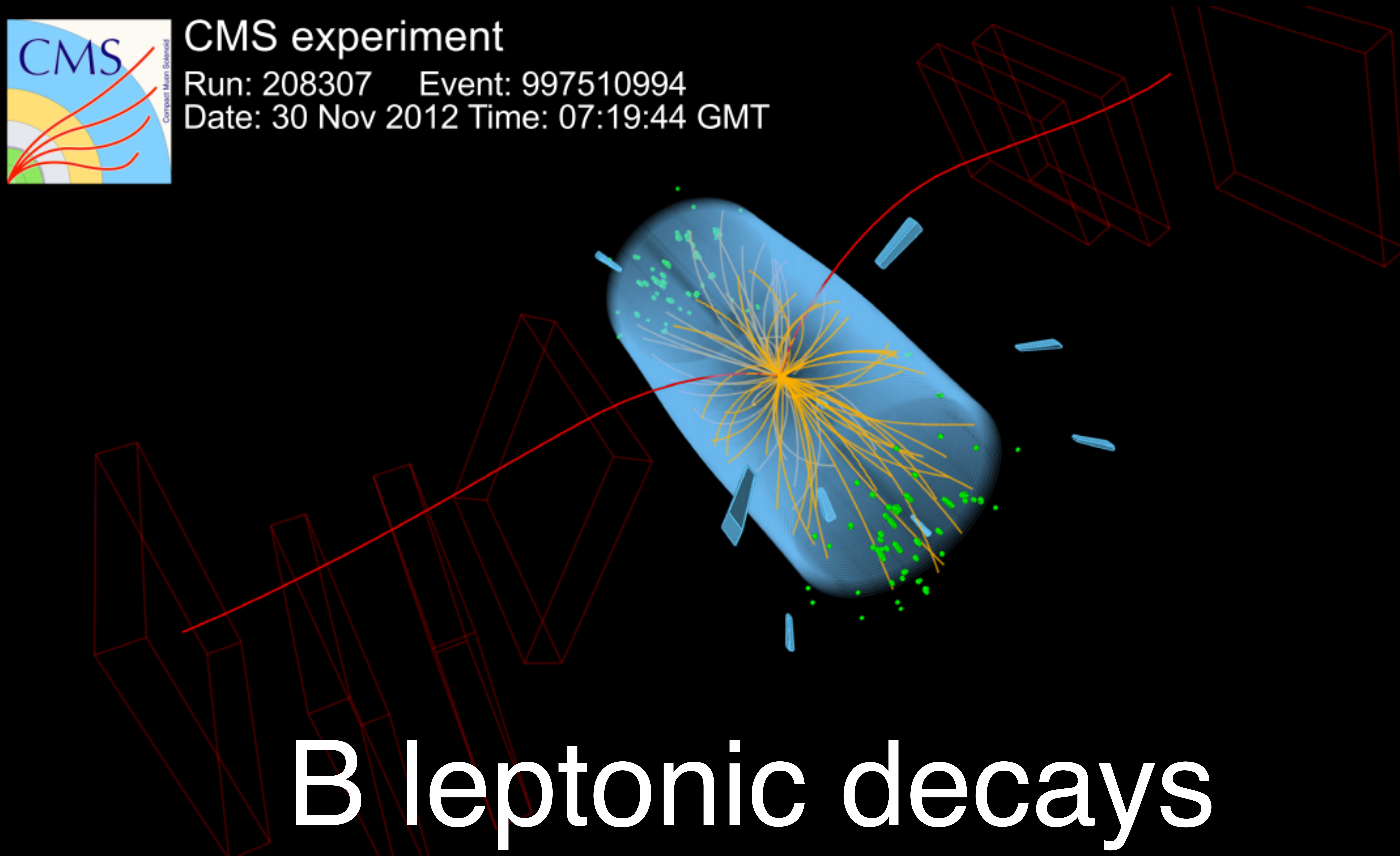
JINST 3 (2008) S08005

Luminosity @ LHCb



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

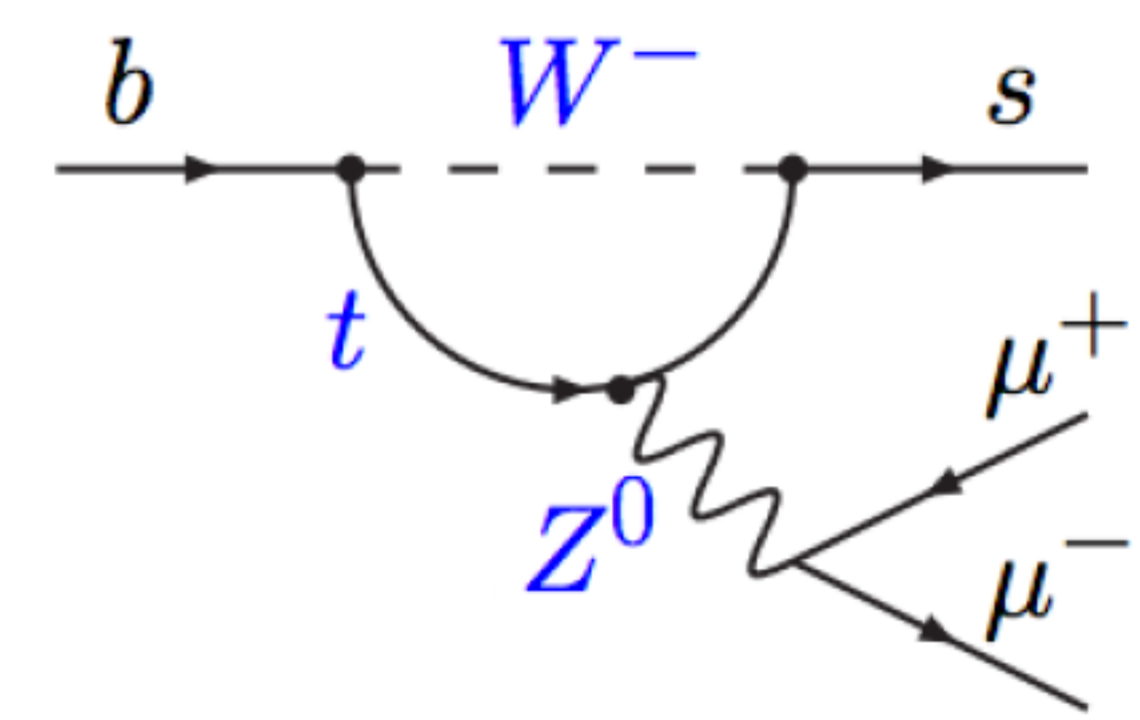
- Experiment designed to run at constant luminosity throughout fills
  - 4×10^{32} cm^{-2} sec^{-1}
  - mean number of interactions/bunch crossing ~1



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 $\sim \left(\frac{m_\mu}{M_B}\right)^2$



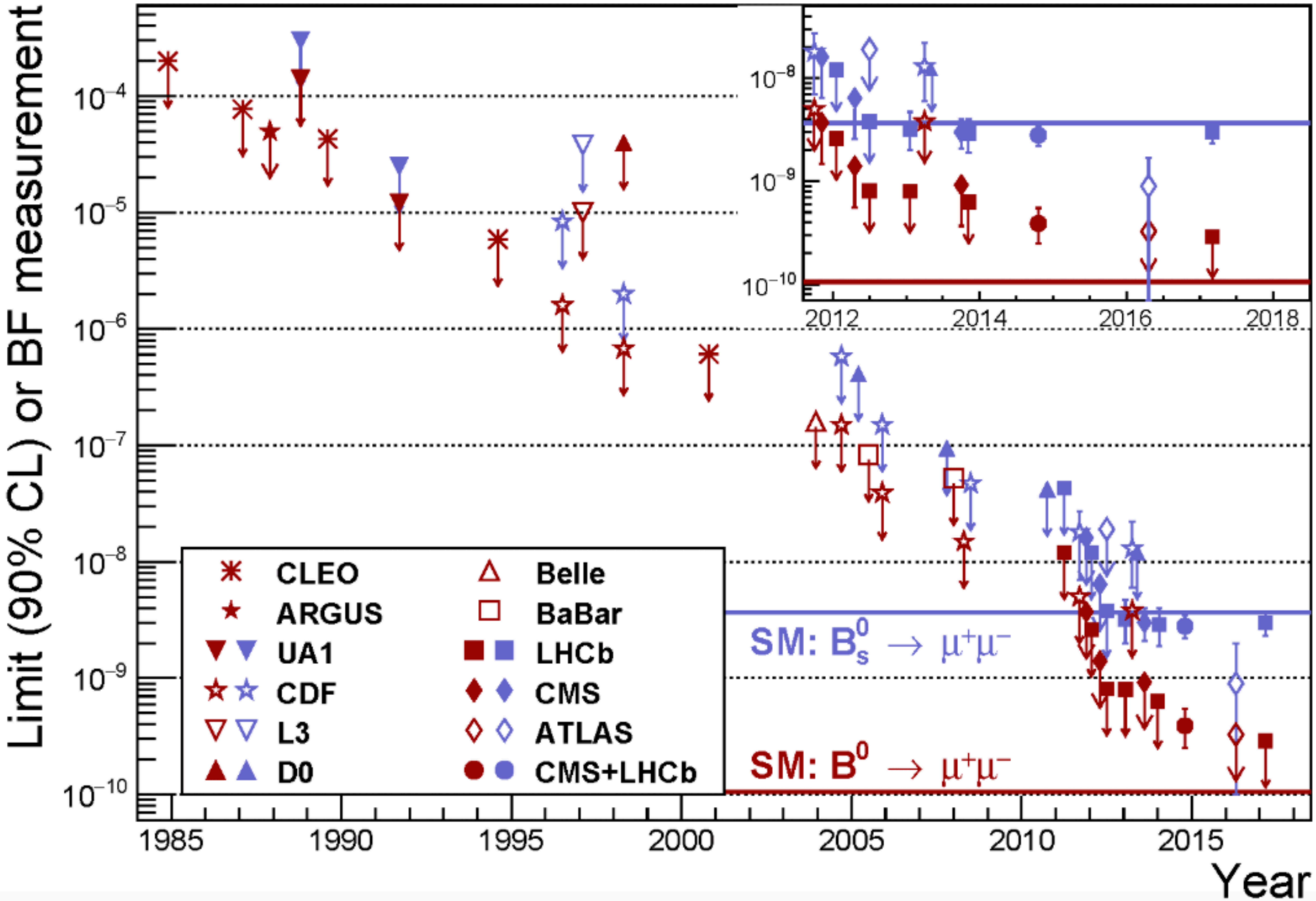
- Theoretically "clean" → precisely predicted

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

Bobeth et al.
PRL 112 (2014) 101801

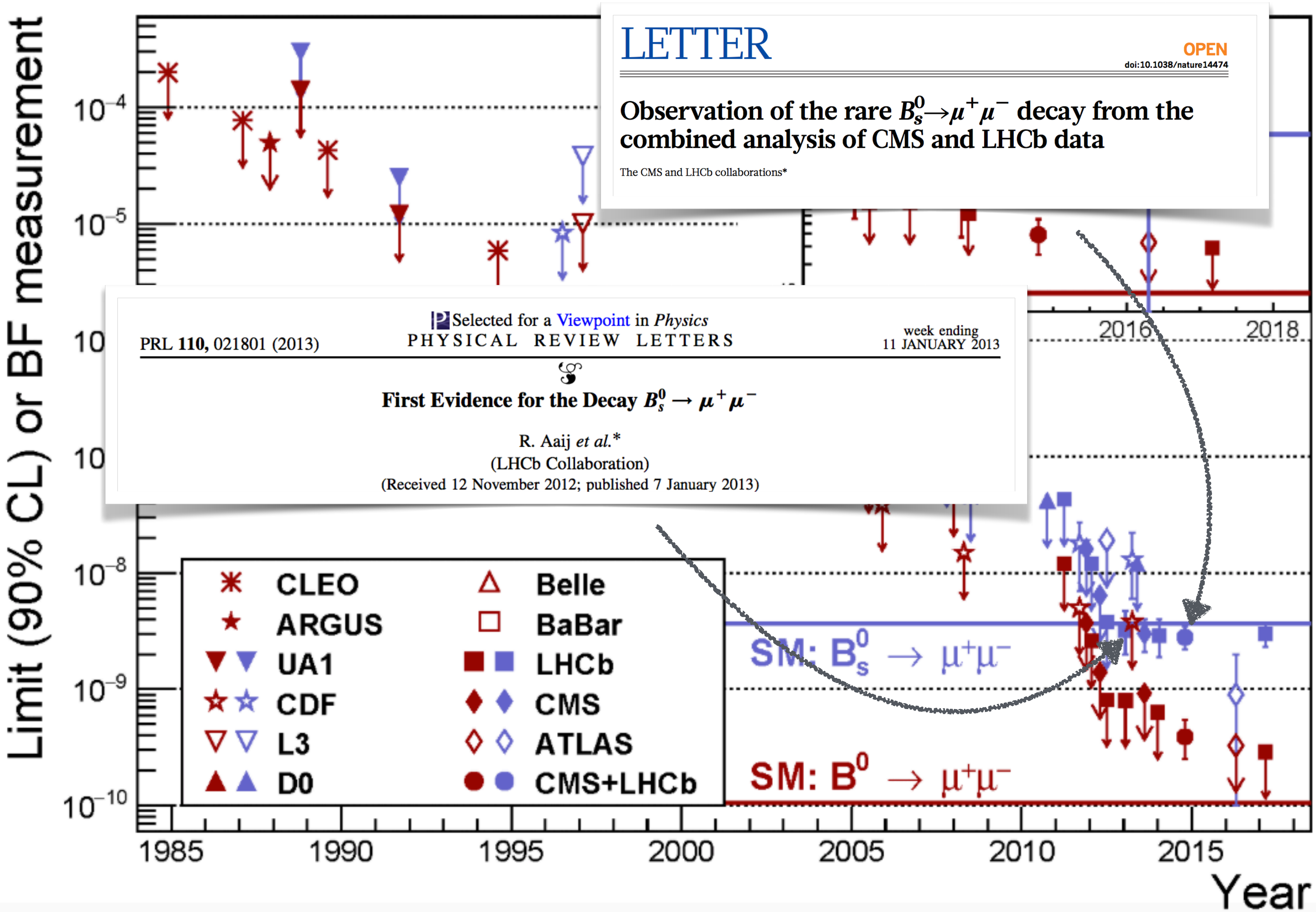
- Sensitive to NP
  - A large class of NP theories, such as SUSY, predict significantly higher values for the $B_{(s)}$ decay probability
- Very clean experimental signature
  - Studied by all high-energy hadron collider experiments

30 years of effort!



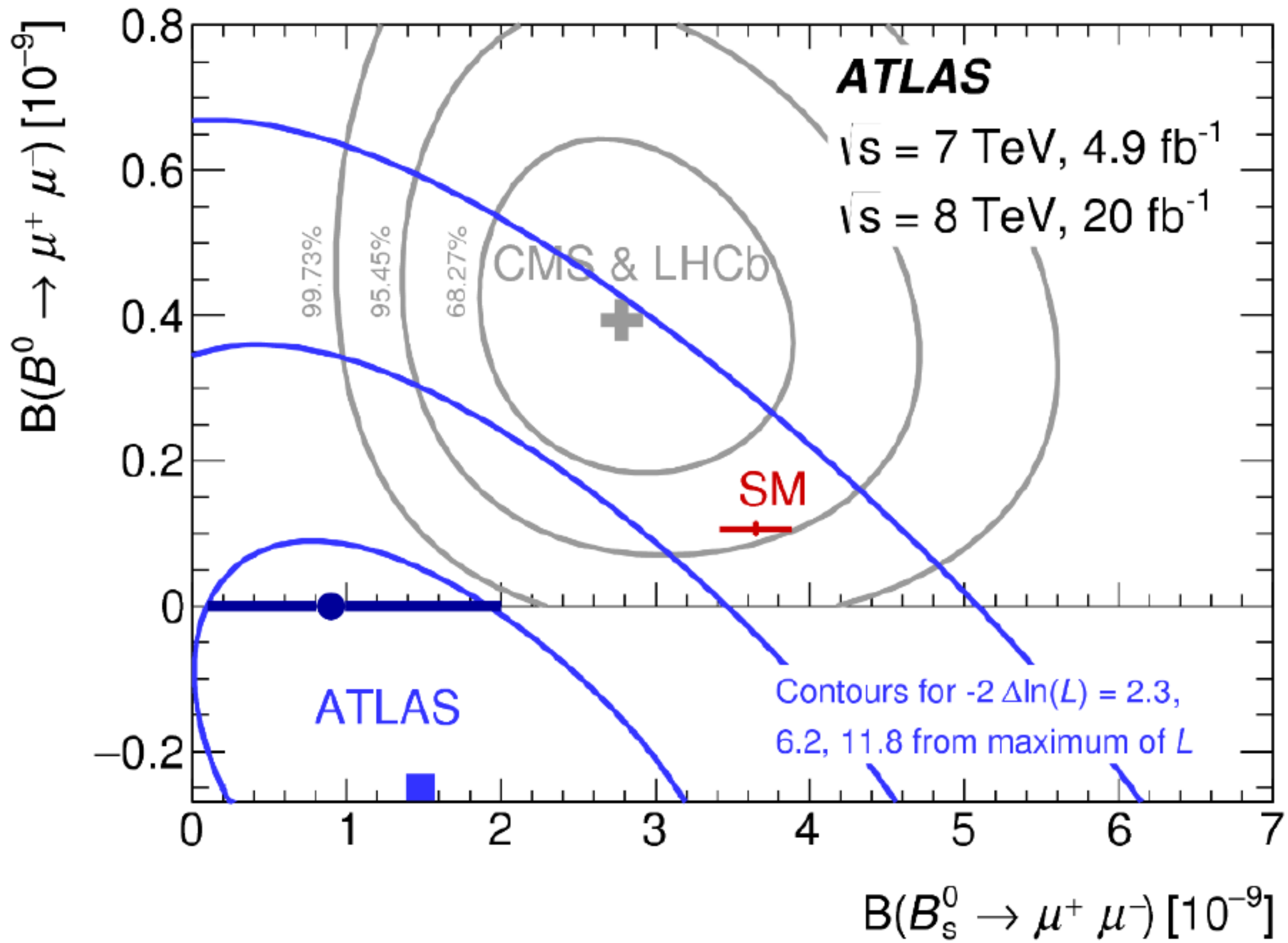
"I'm too old for limits! I want to see signals! " (F.Halzen, EPS 2015)

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

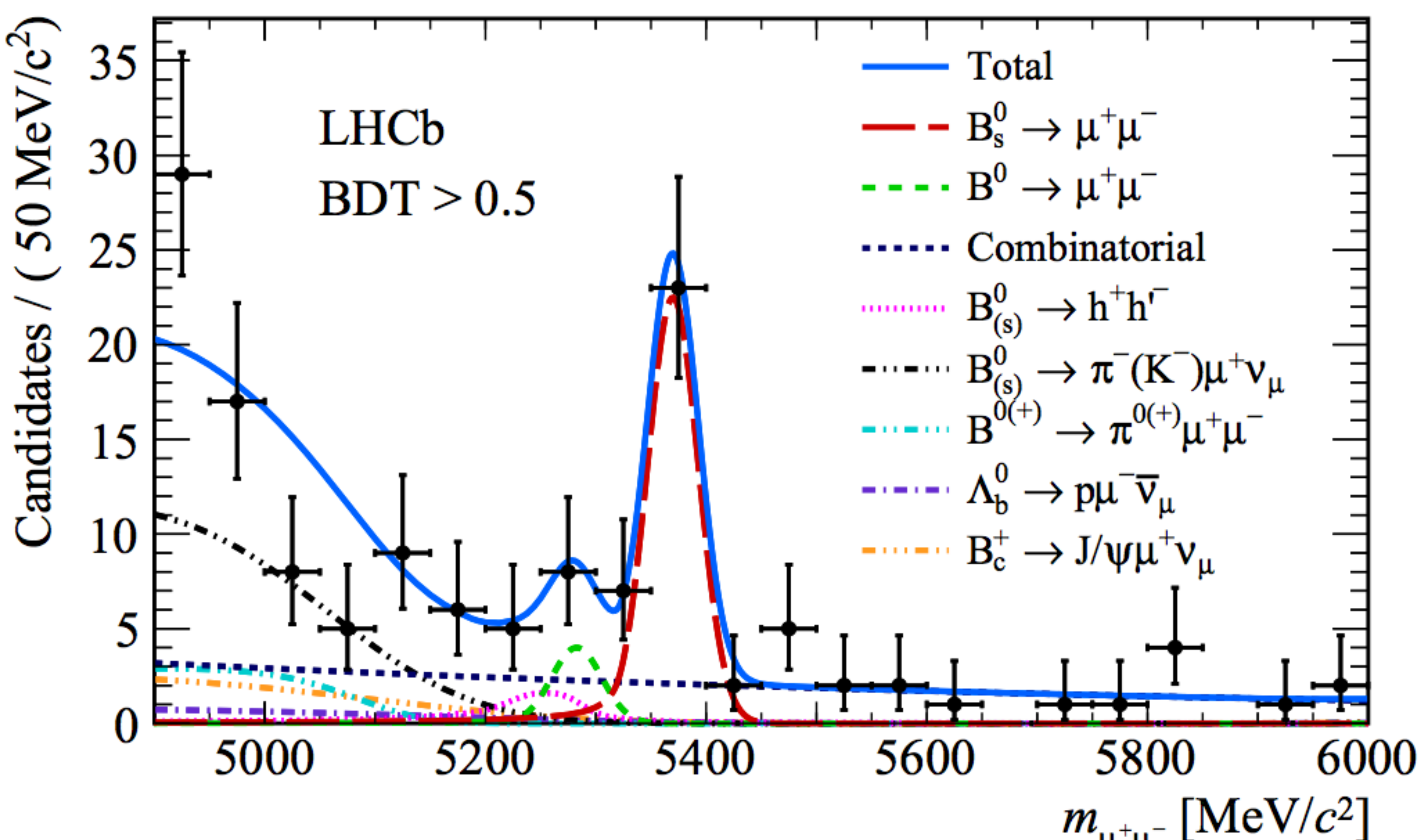
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \quad (\ 20\%)$$

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

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

Bobeth et al.
PRL 112 (2014) 101801

- Consistent with SM expectation at current level of precision

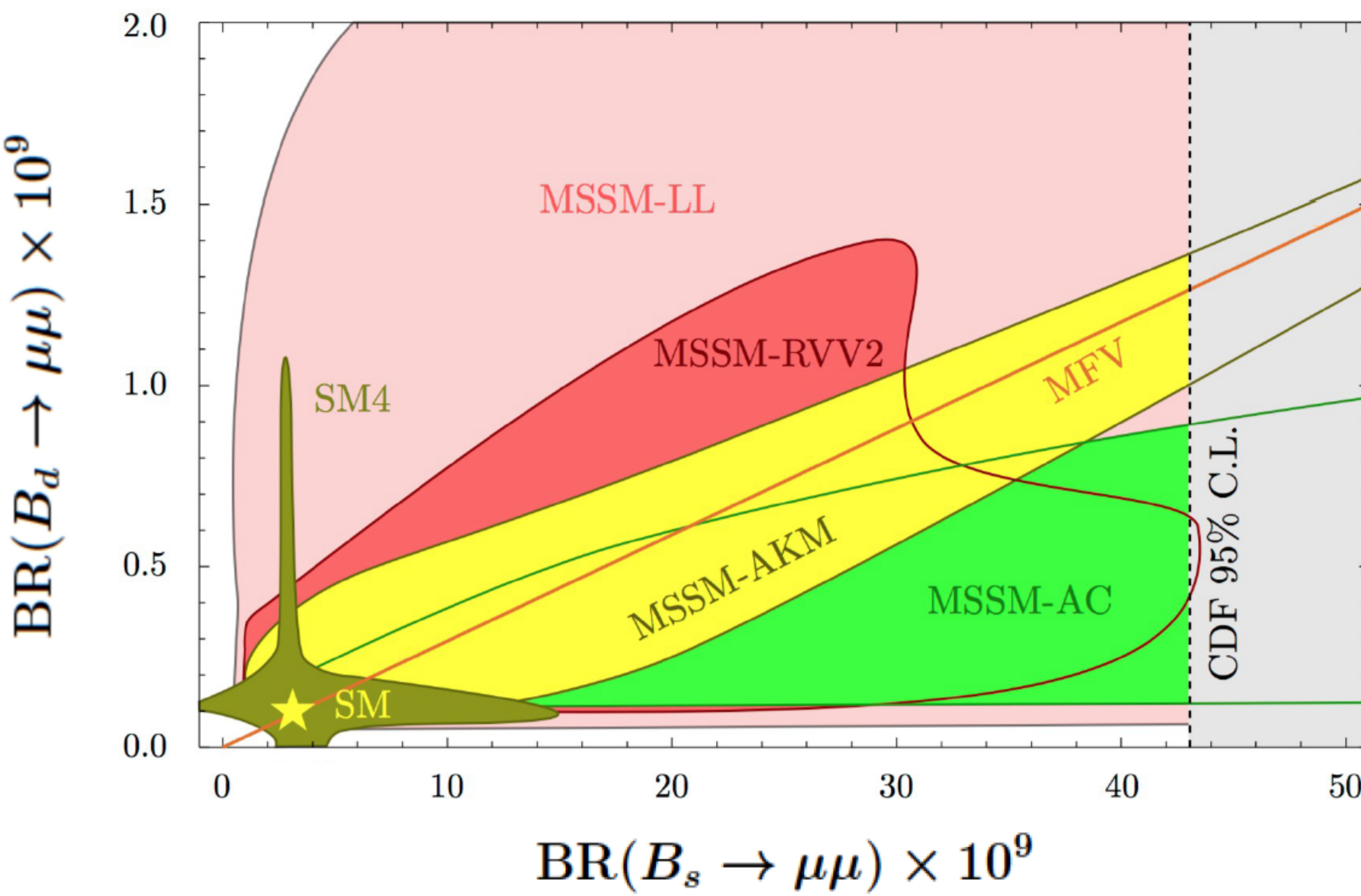


PRL 118 (2017) 191801

The SM stands its ground

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

Straub, arXiv:1107.0266

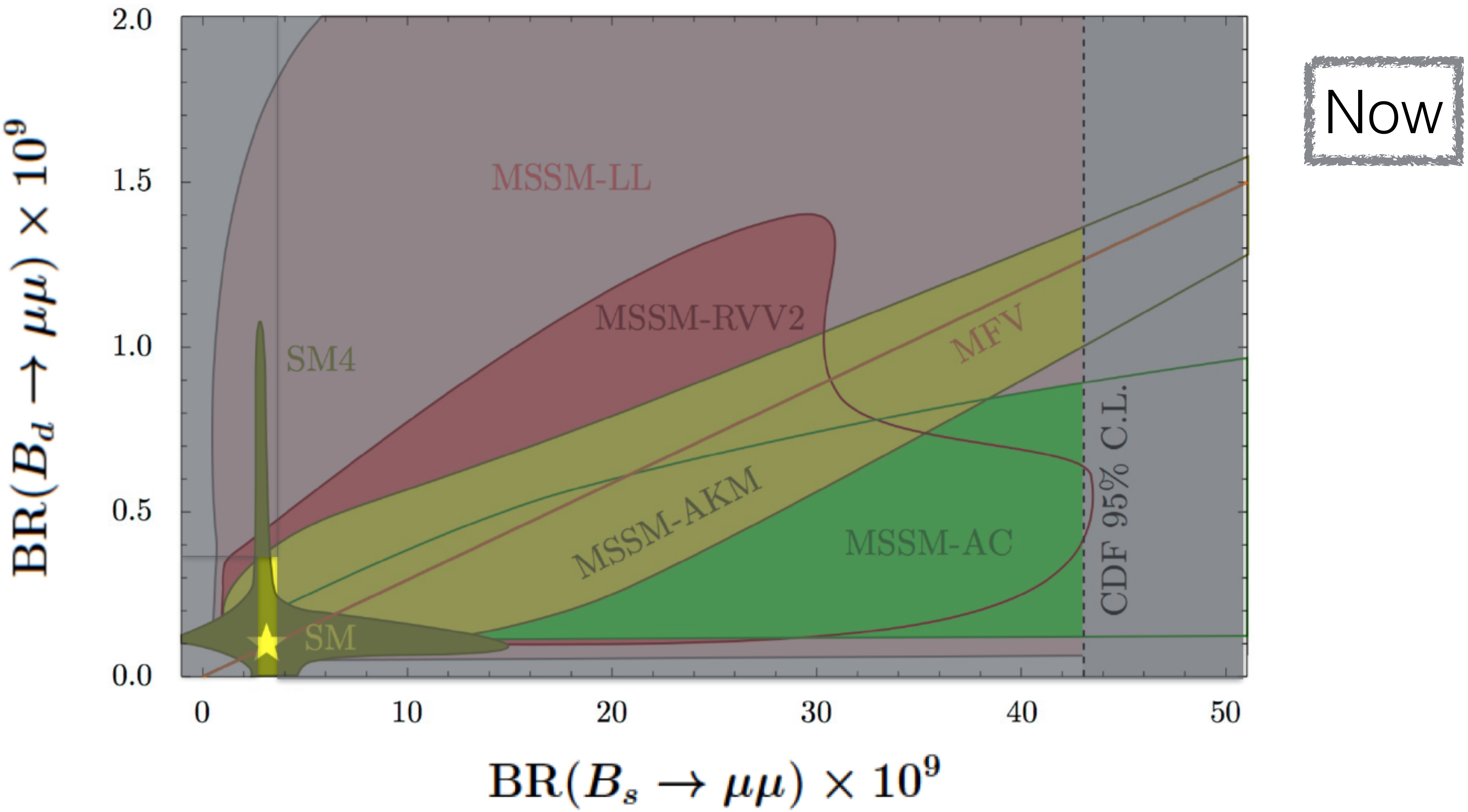


Pre-LHC

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:

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

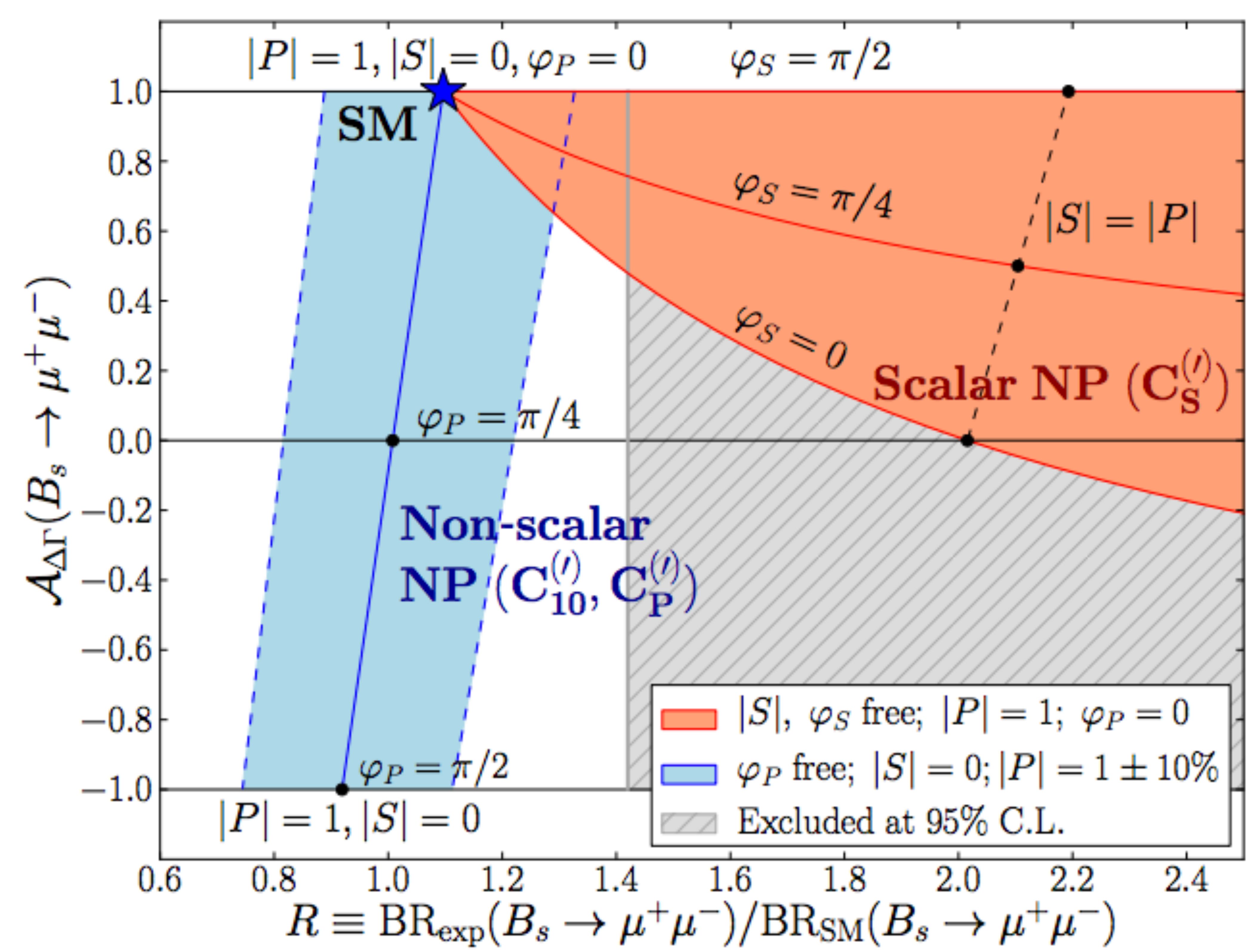
Expectation value of untagged time-dependent rate

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

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]



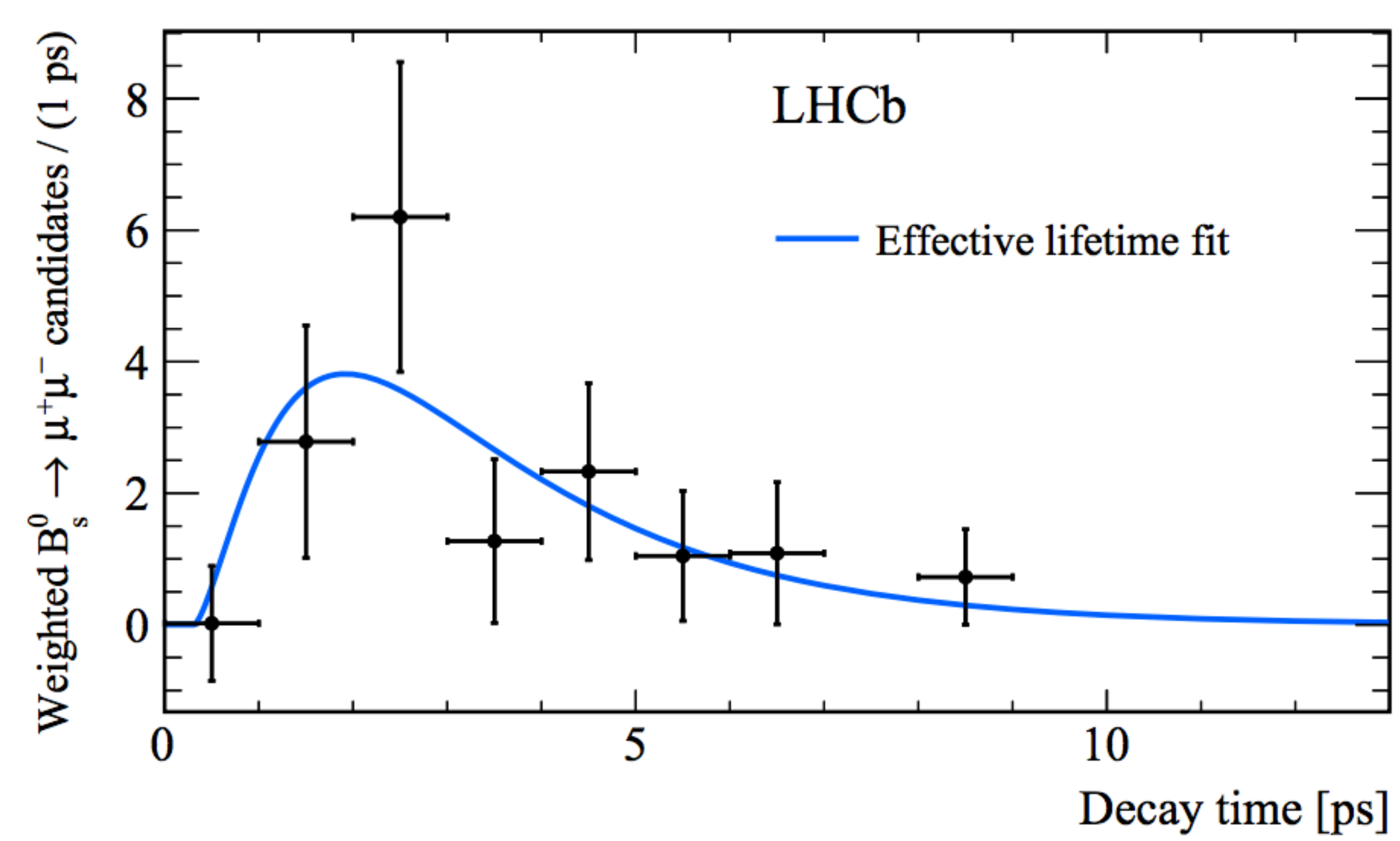
Results on τ_{eff}

- 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

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

$$\tau_{\text{eff}}(B_s(t)\to\mu^+\mu^-) = (2.04 \pm 0.44 \pm 0.05)\,ps$$

- 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

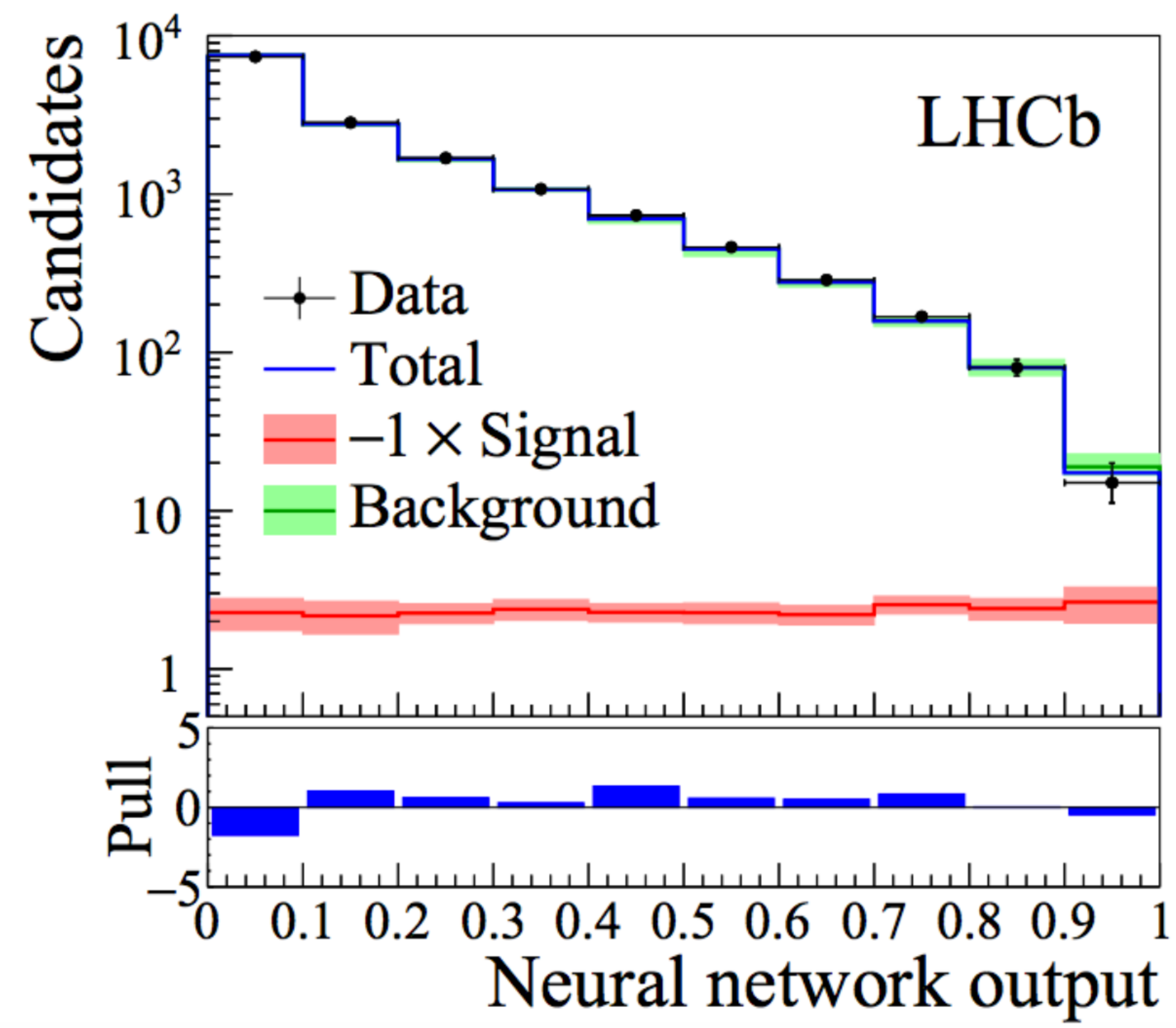
$B_{s,d} \to \tau^+\tau^-$

- 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:

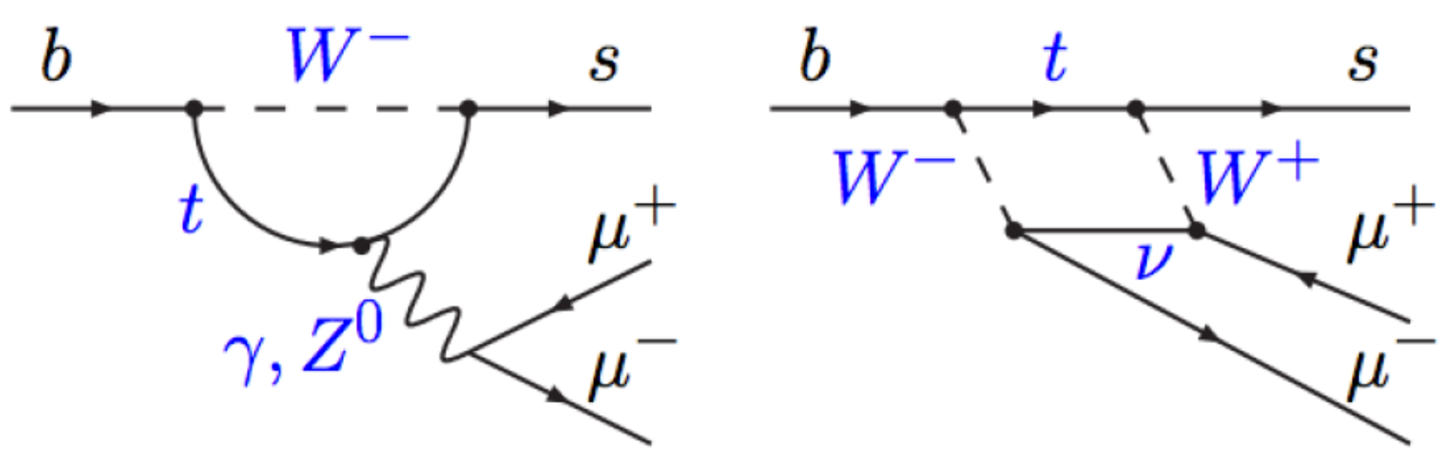
PRL 118 (2017) 251802

$$\mathcal{B}(B_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ at } 95\% \text{ C.L.}$$ → first direct limit
$$\mathcal{B}(B_d \to \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ at } 95\% \text{ C.L.}$$ → best limit

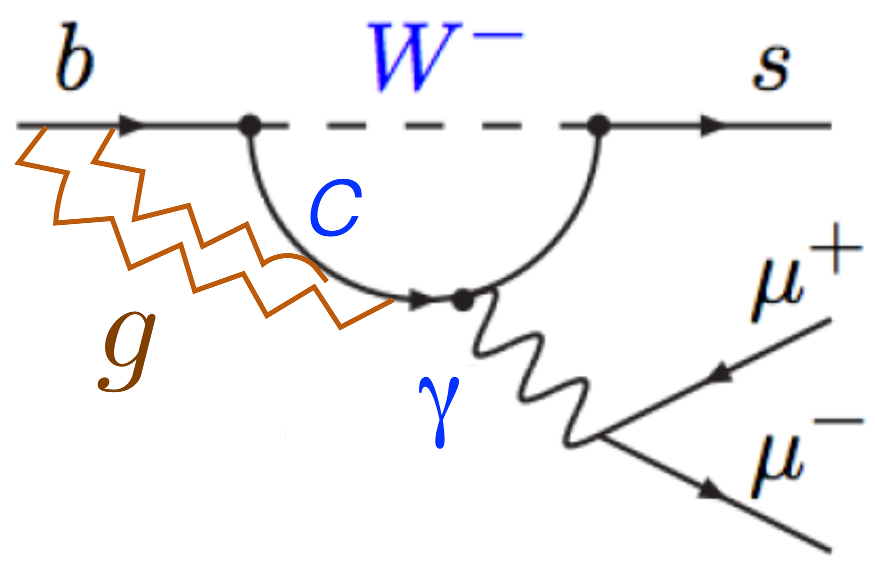
$b \to s\ell^+\ell^-$ transitions

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



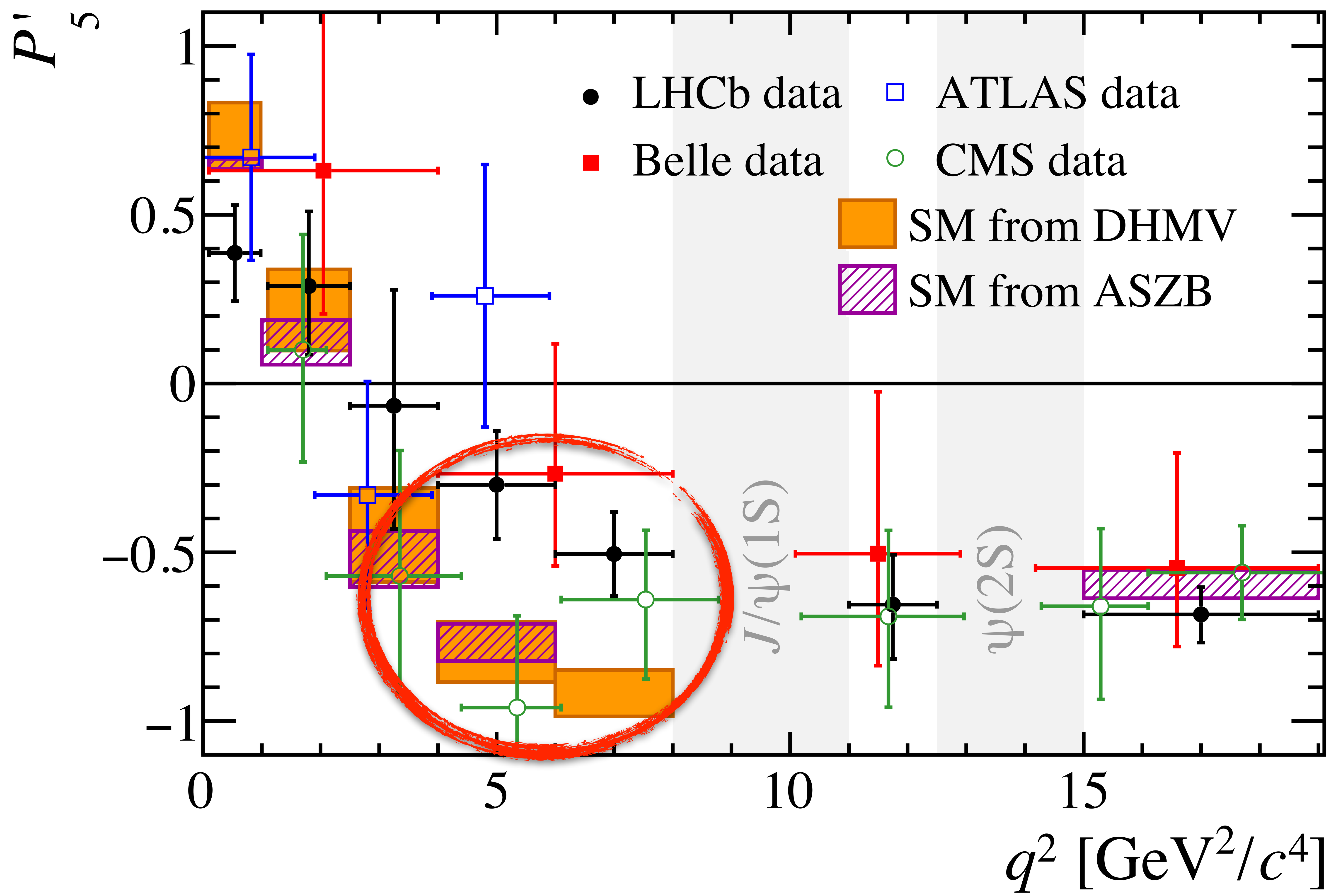
- Four final state particles with rich phenomenology, plethora of observables, which can be built from the measured amplitudes
- Rates, angular distributions and asymmetries sensitive to NP
- A lot of phenomenological work invested in defining observables with "clean" theoretical predictions.
    - Observables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



- Question: how clean?

P_5' anomaly

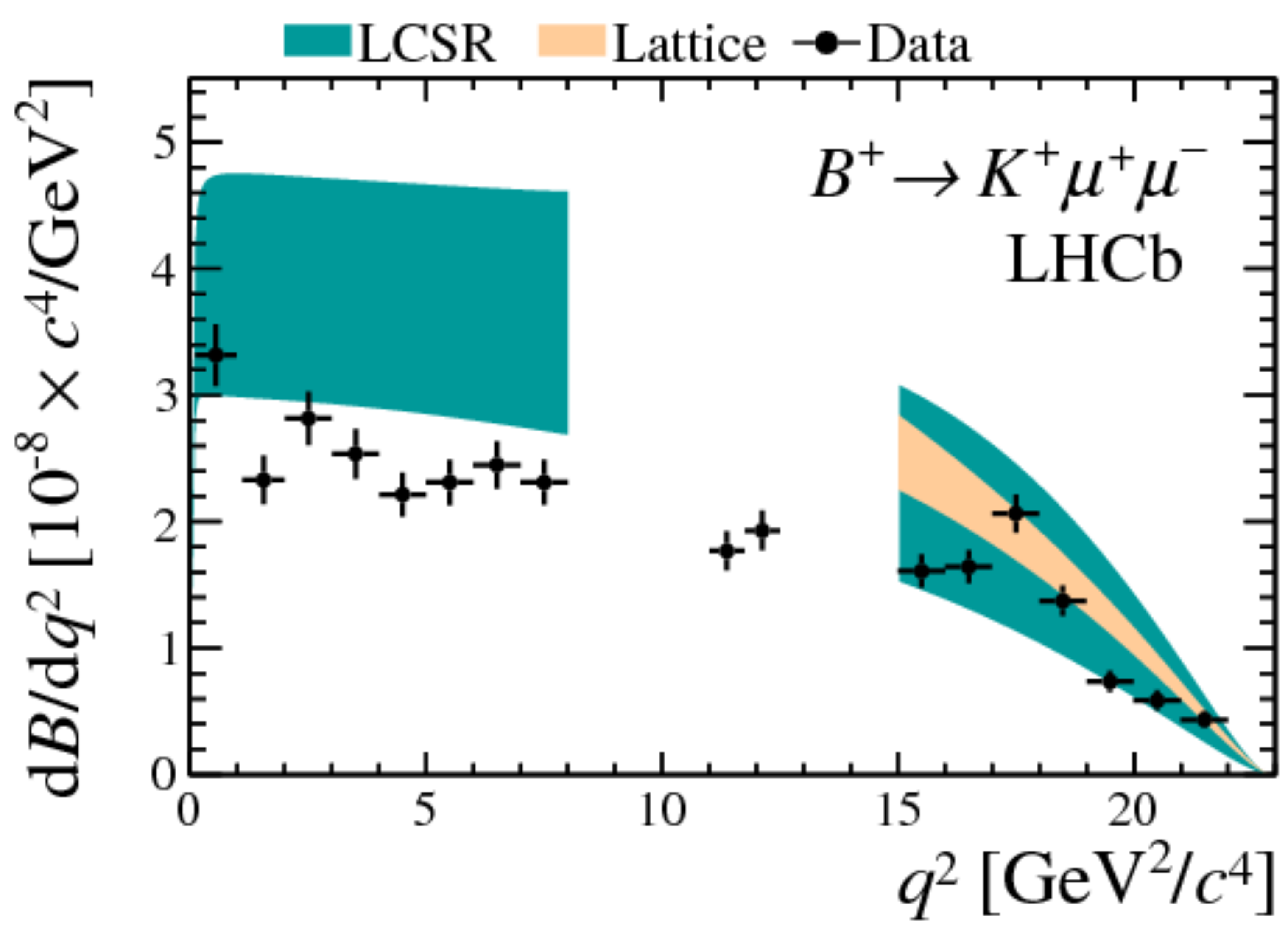
- One such observable is so-called P'_5, not intuitive, but constructed from angular observables to be robust from 'form-factor uncertainties'

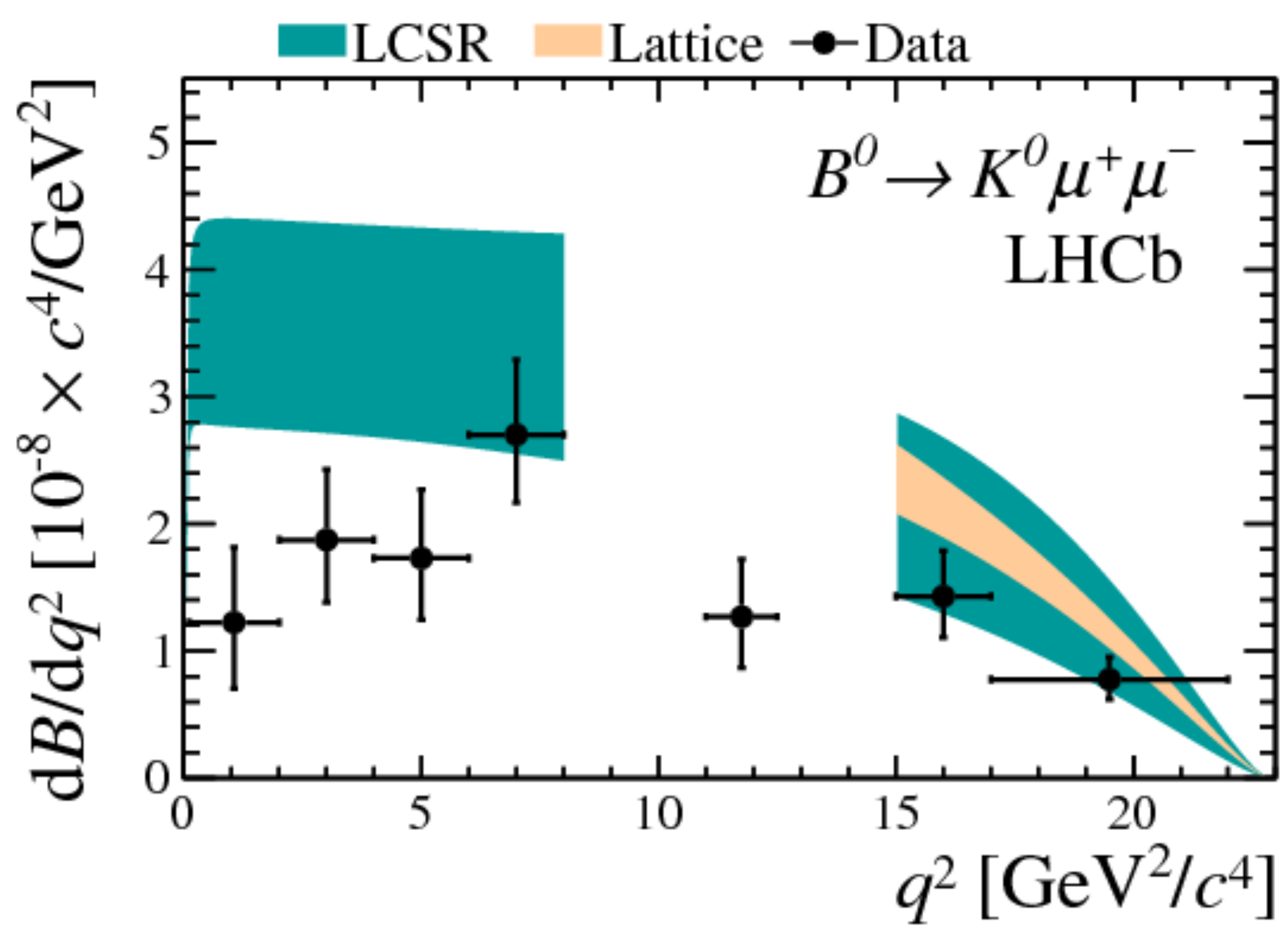


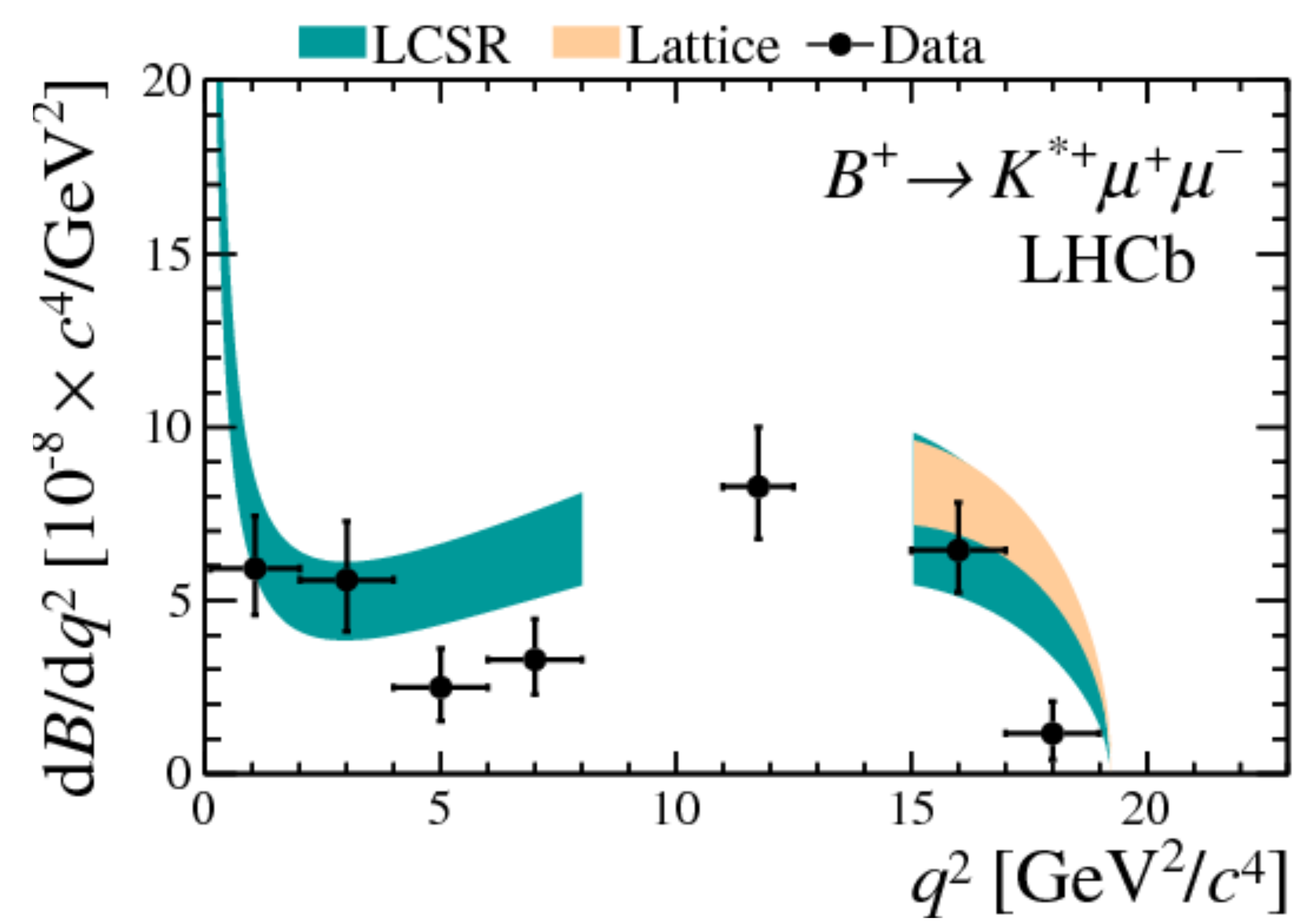
LHCb: JHEP 02 (2016) 104
Belle: PRL 118 (2017) 111801
ATLAS-CONF-2017-023
CMS-PAS-BPH-15-008

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

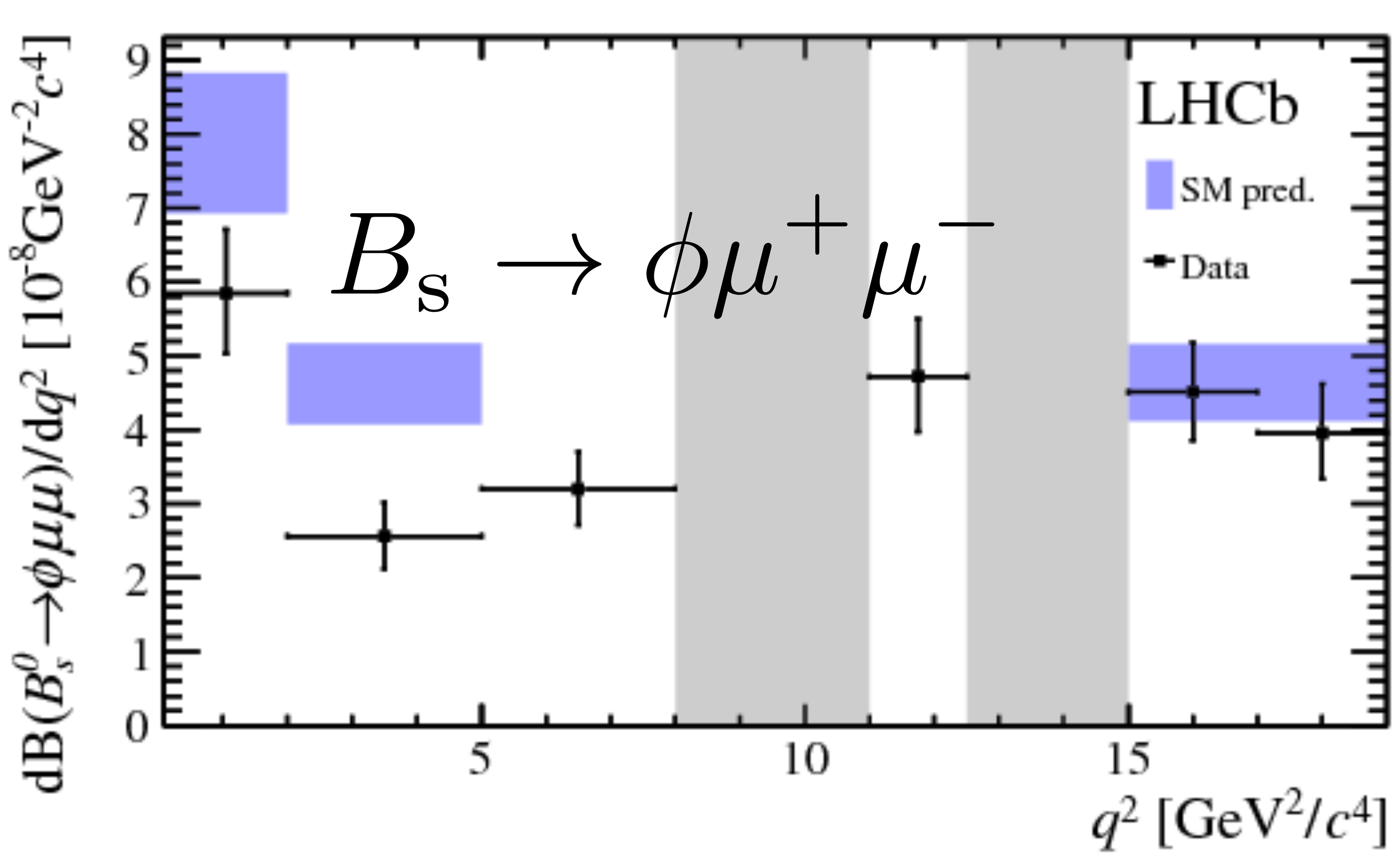
Intriguing set of results in differential branching fractions for b→sμμ transitions

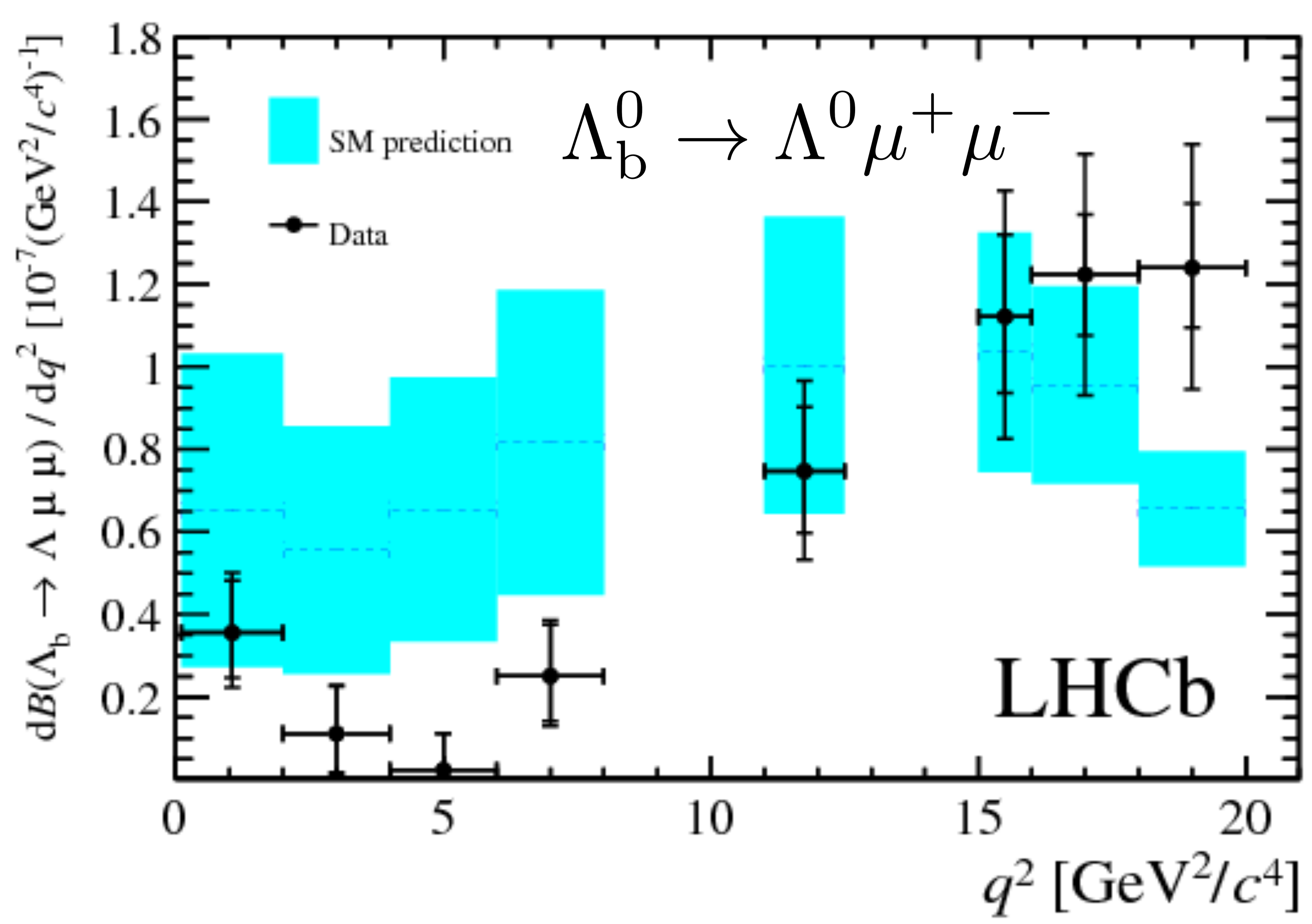


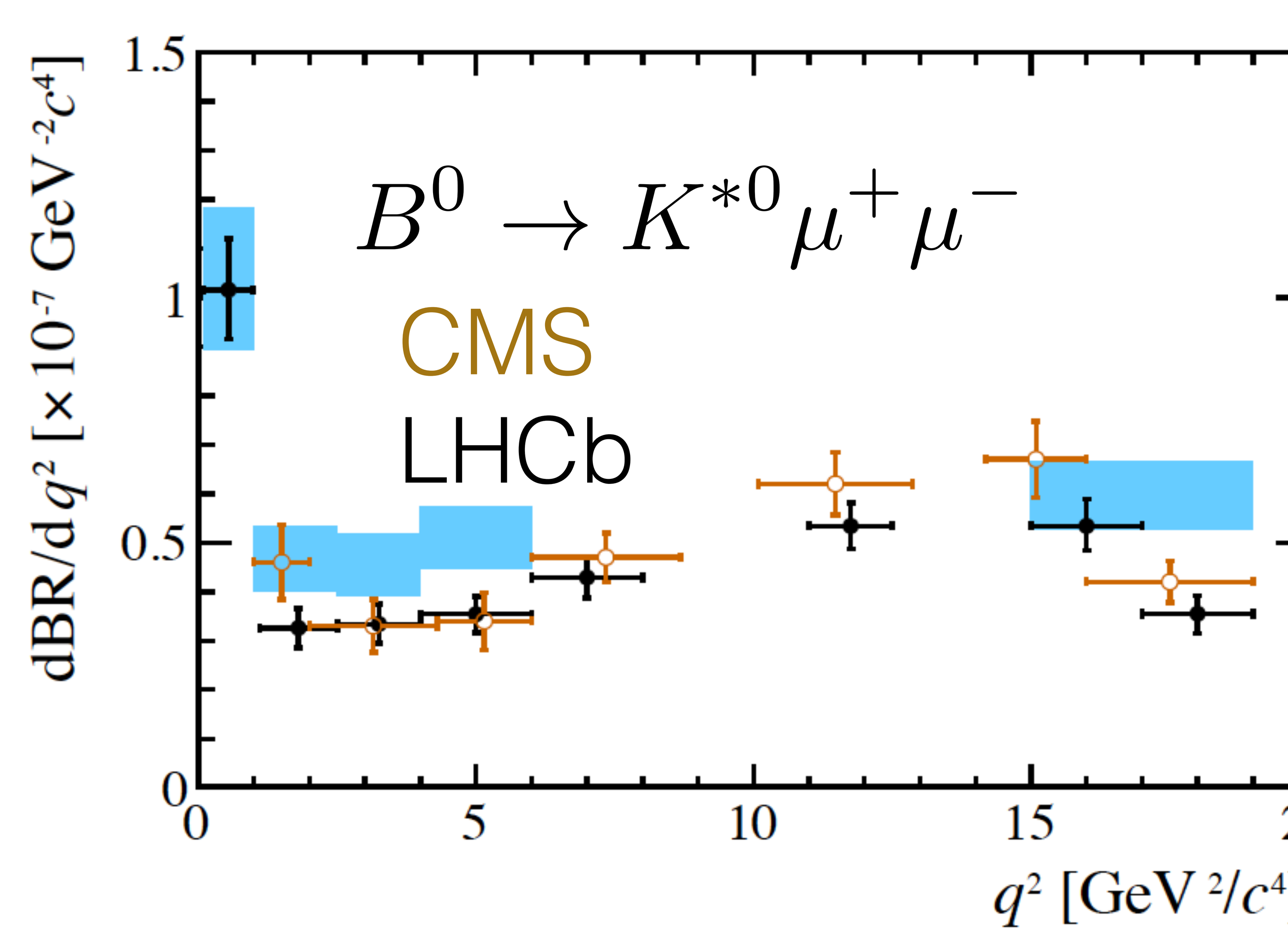




JHEP 06 (2014) 133







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 :

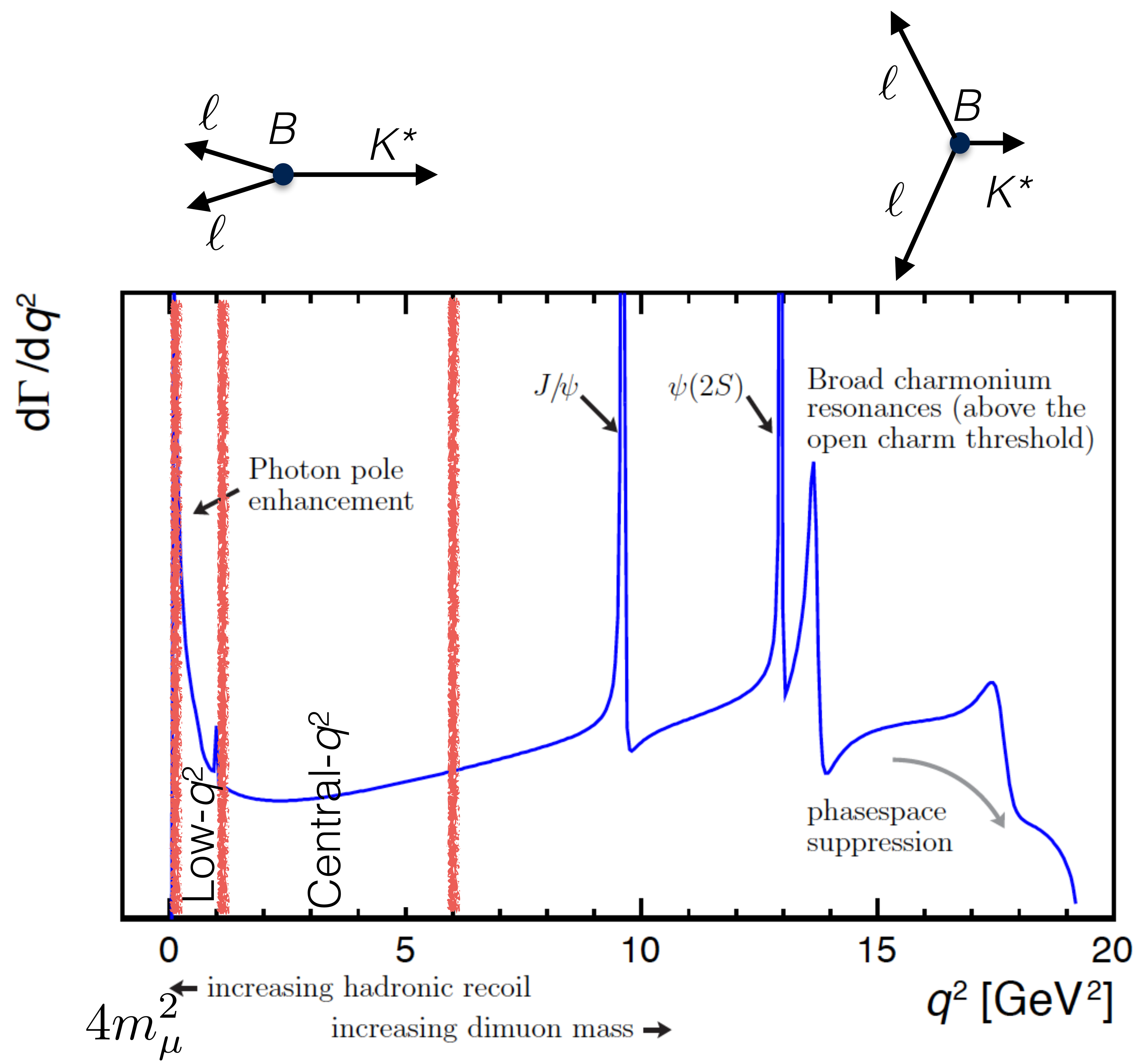
  - Sensitive to possible new interactions that couple in a non-universal way to electrons and muons

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

R_{K^*}

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

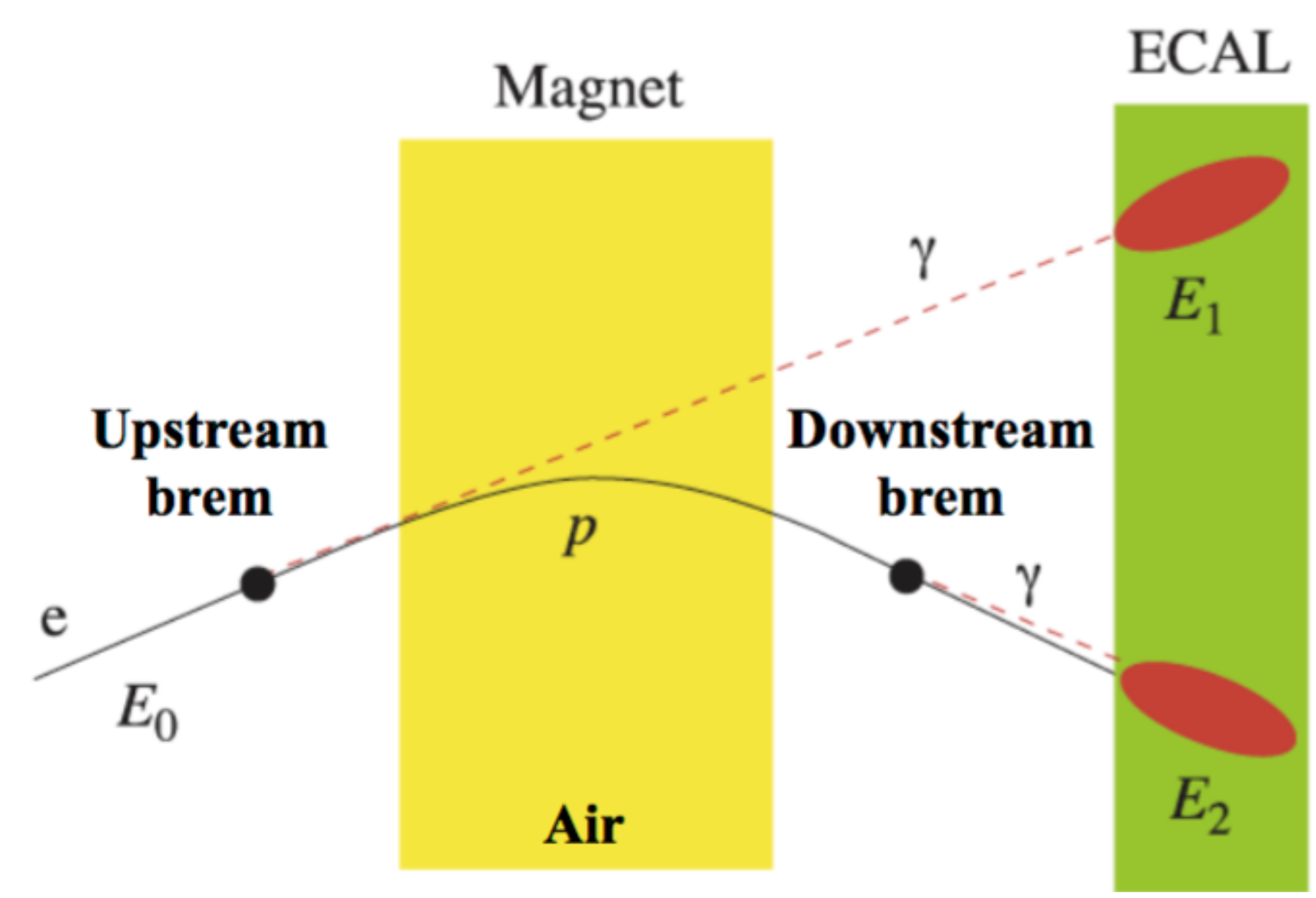
- LHCb performed measurement in two q^2 bins that are sensitive to different NP contributions:
    - Low-q^2 bin: [0.045,1.1] GeV^2
    - Central-q^2 bin: [1.1,6.0] GeV^2

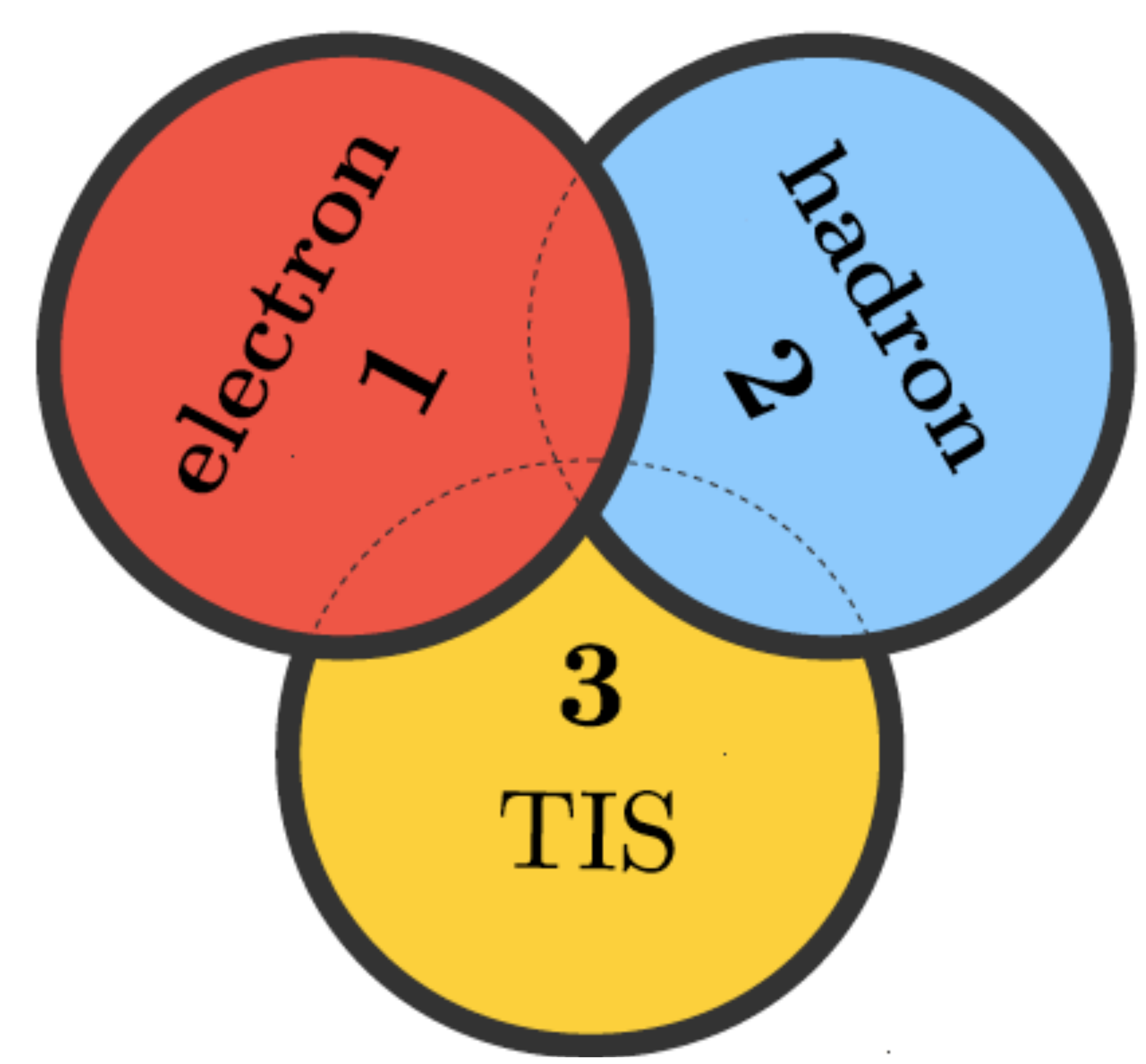


A very challenging measurement

JHEP 08 (2017) 055

- 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) .
  - Mitigated by selecting decays with electrons using hadron trigger either fired either by *K** products (hadron) or by any other particle in the event not associated with signal (TIS)





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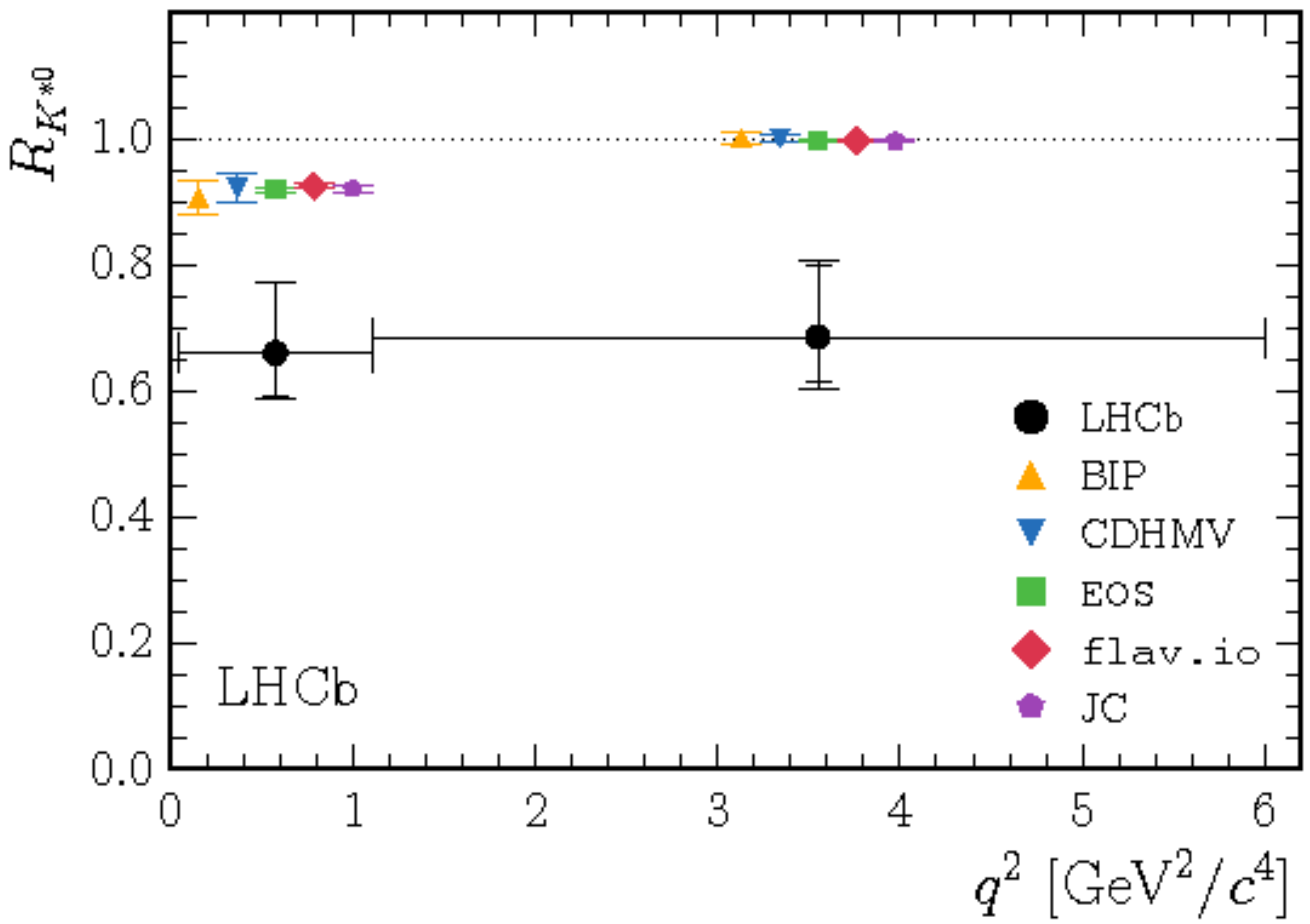
Low-q^2 Central-q^2 $B^0 \to K^* J/\psi(\to \ell^+\ell^-)$

- 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

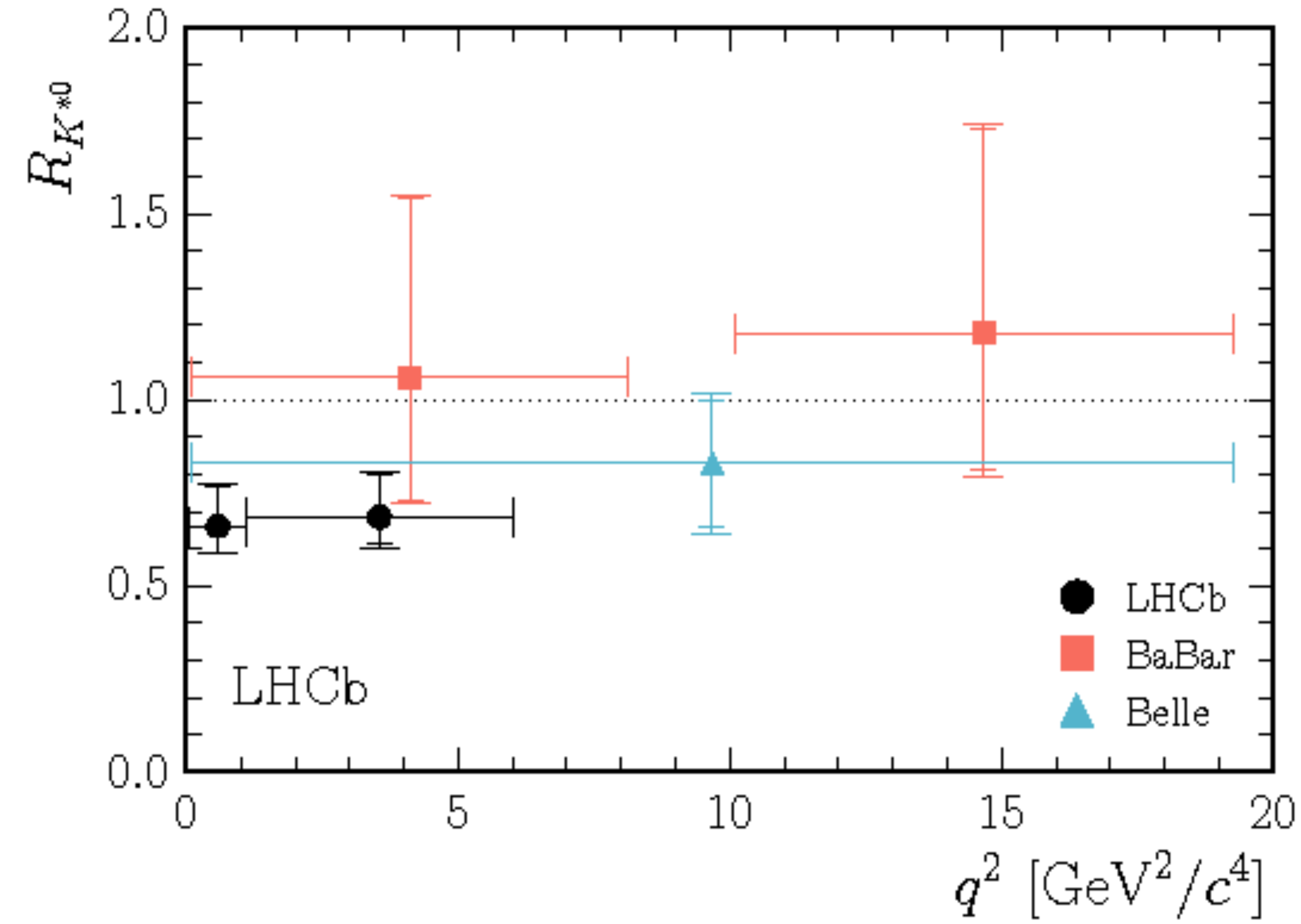
Results

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

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- $r_{J/\psi} = \dfrac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))} = 1.043 \pm 0.006 \pm 0.045$
  - 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
- $R_{\psi(2S)} = \dfrac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))} \Bigg/ \dfrac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$ → 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-q²

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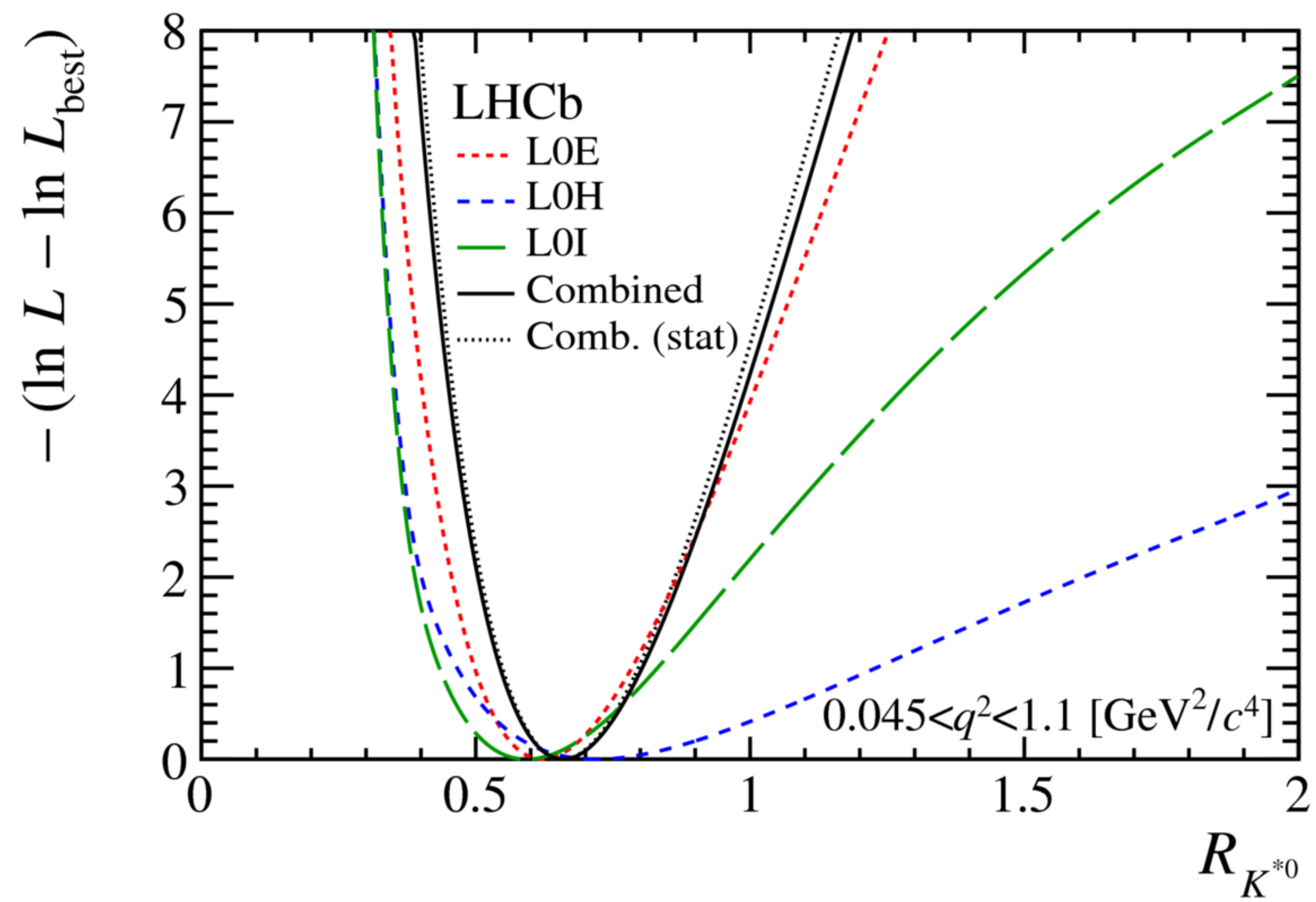
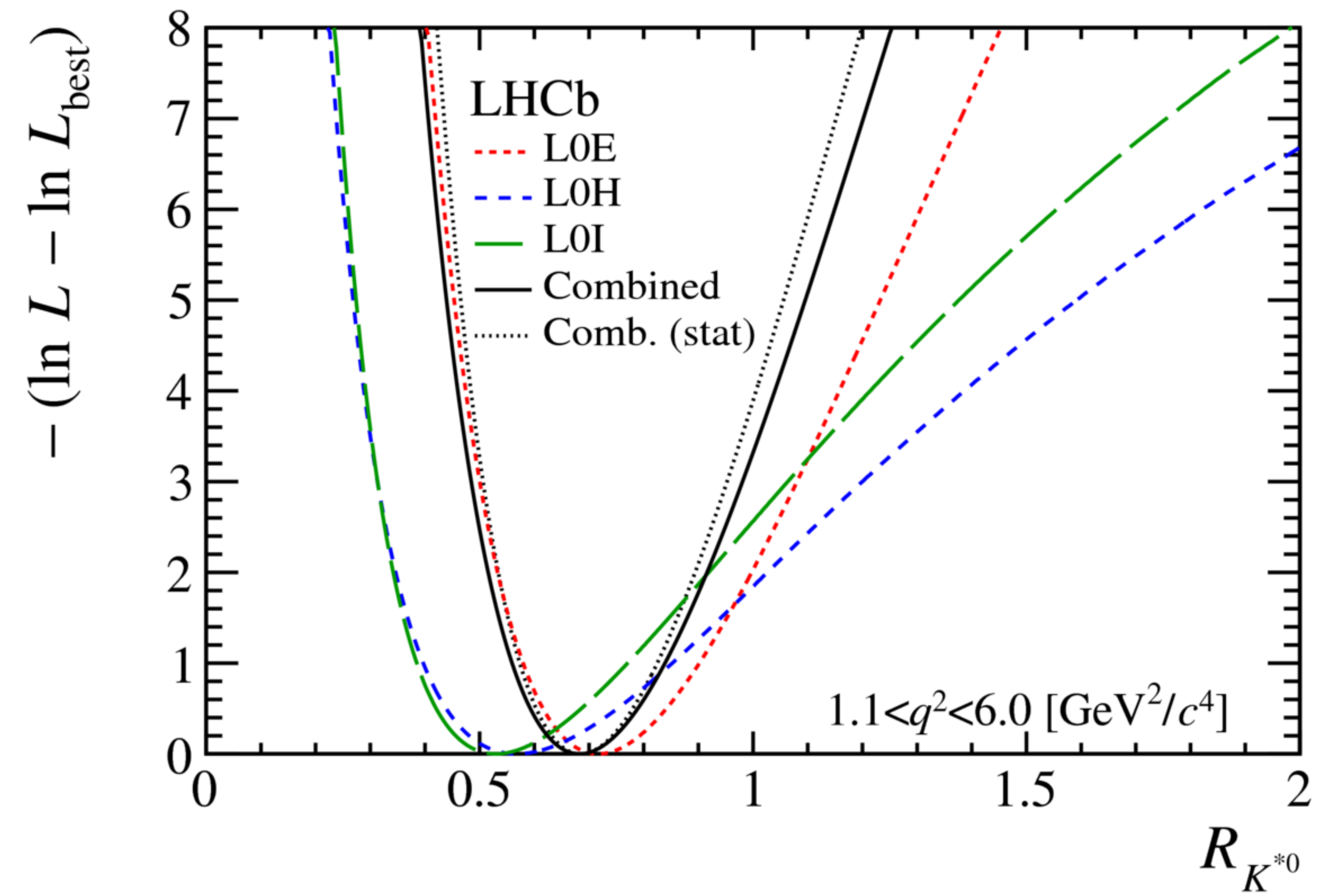
Central-q²

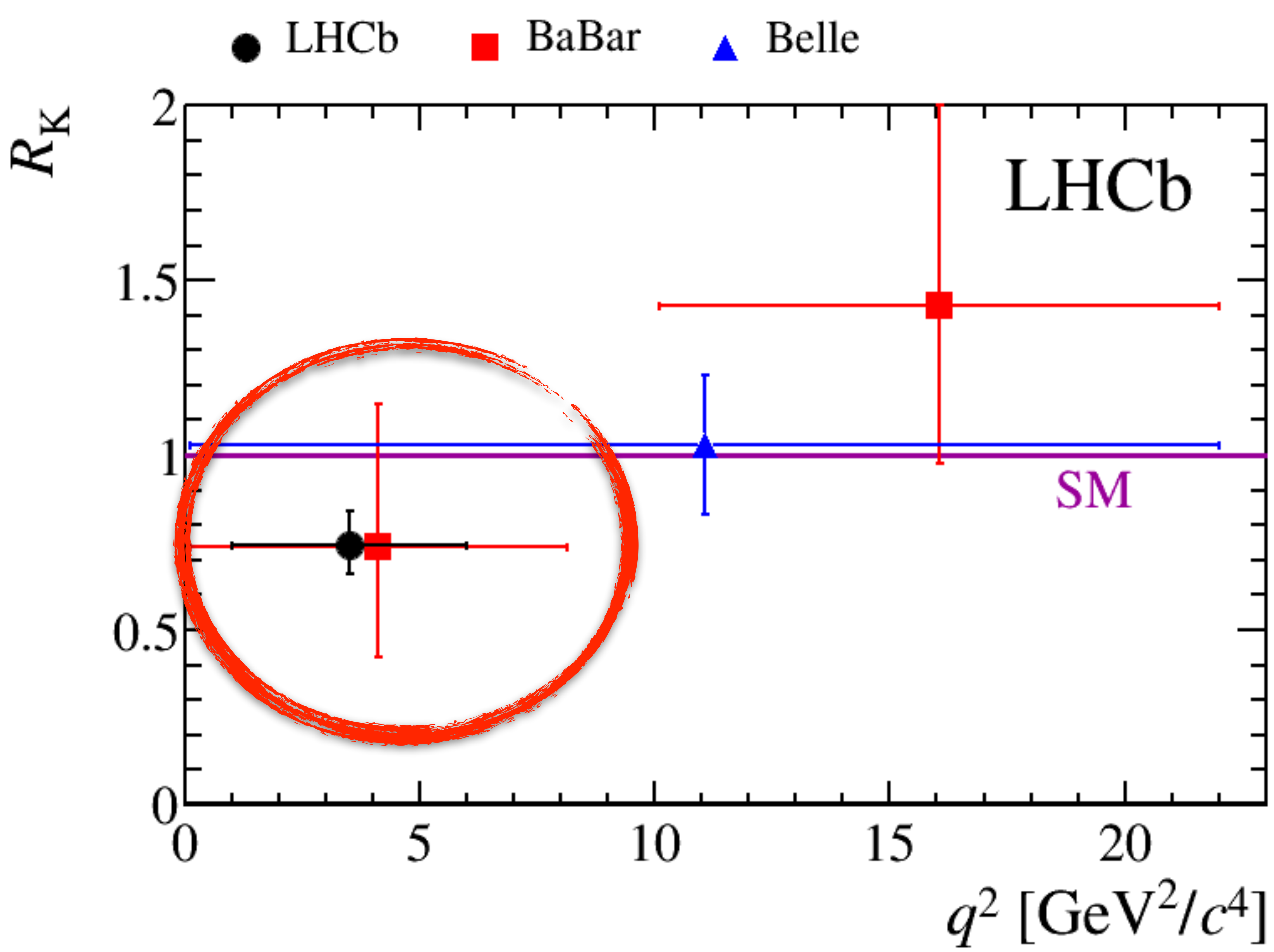




A reminder: R_K

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

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



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

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

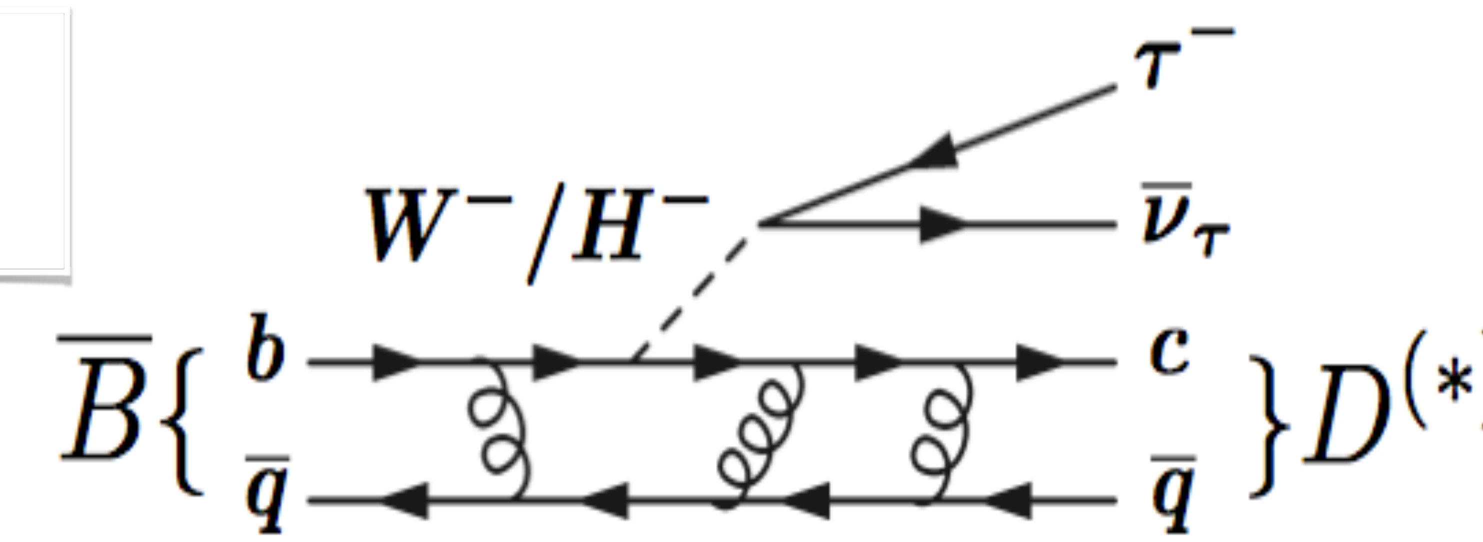
LFU studies in $B \to D^{(*)}\tau\nu$ decays

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

Tree level
b→c transition

- Different class of decays (charged current)
  - precisely predicted:
    $R(D^*)_{\mathrm{SM}} = 0.257 \pm 0.03$

Berlochner et al
arXiv:1703.05330



- 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

~4%

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

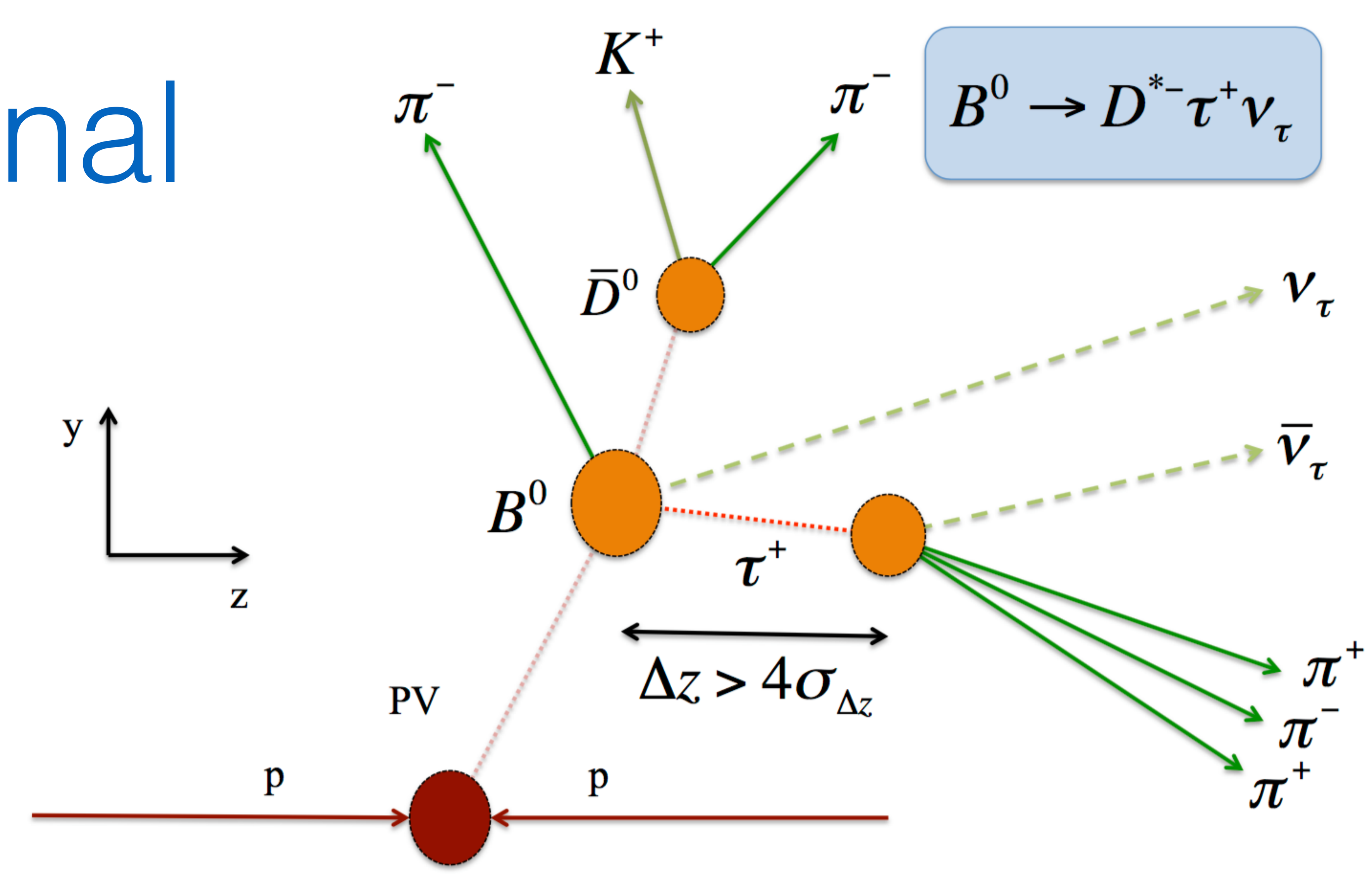
~2%

Measured

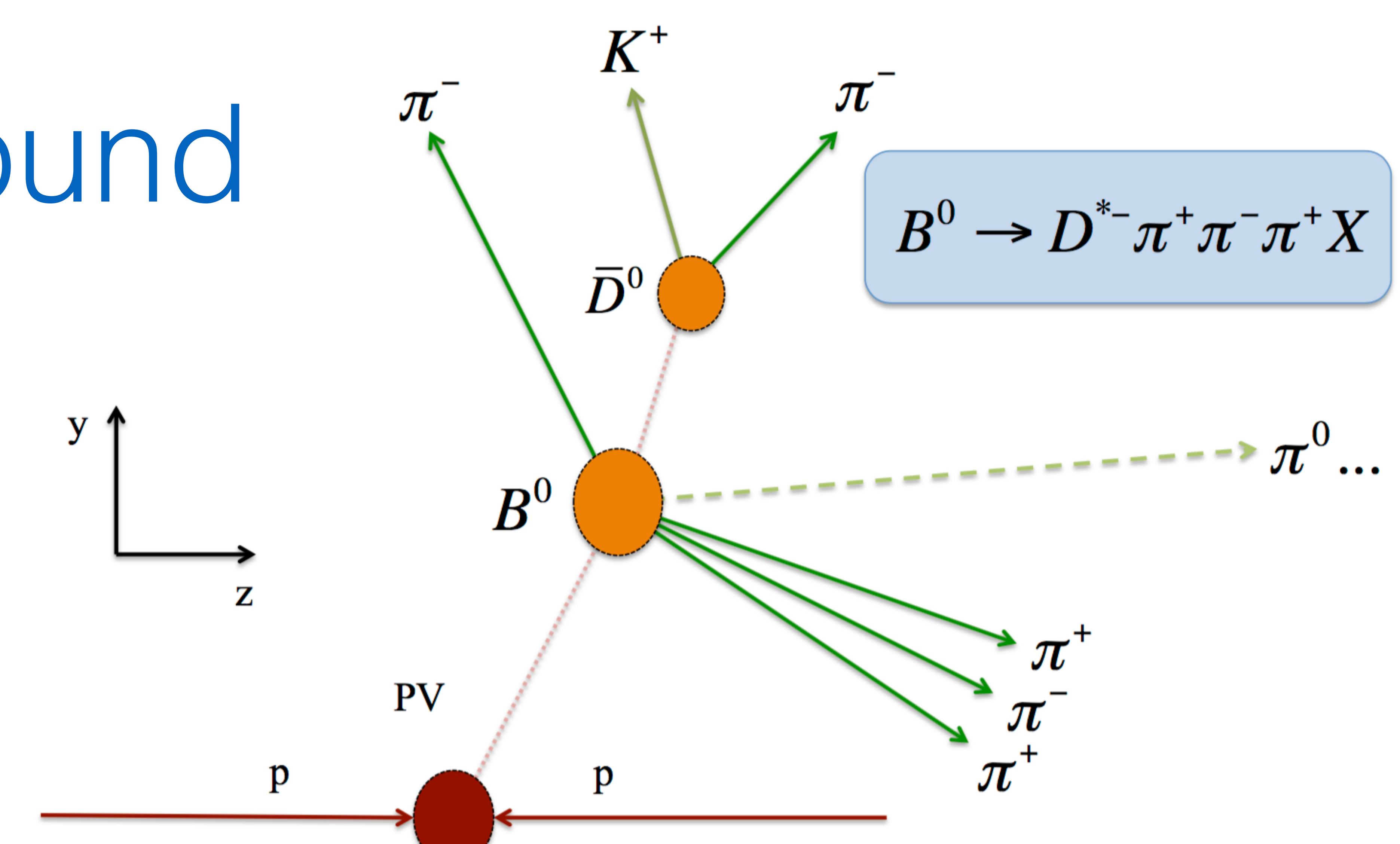
External inputs

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

Signal

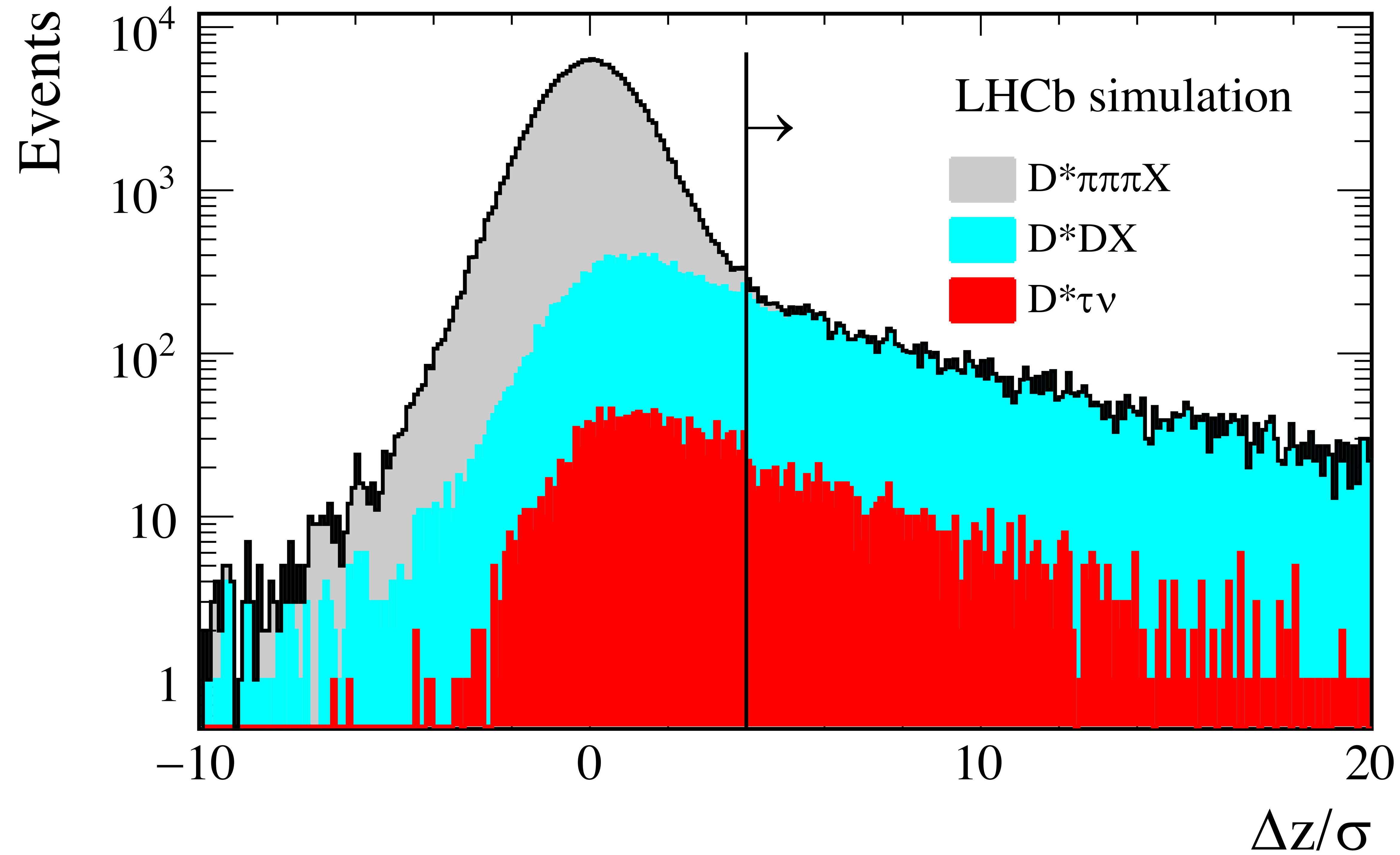


Background



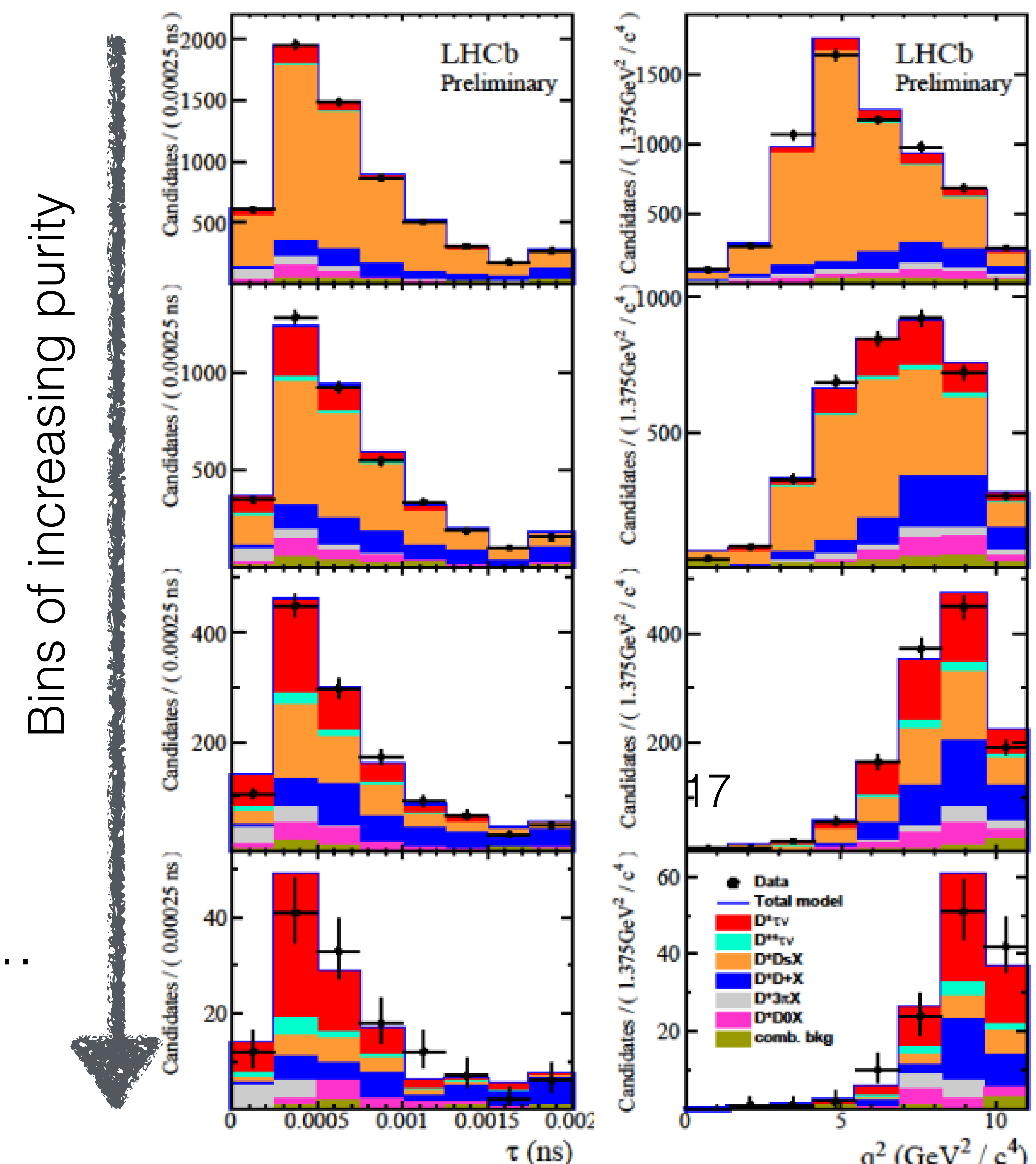
Background reduction

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



arXiv:1708.08856

Signal yield ~1300 events



3π decay time

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

- 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

Results

- 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

arXiv:1708.08856

- LHCb muonic:

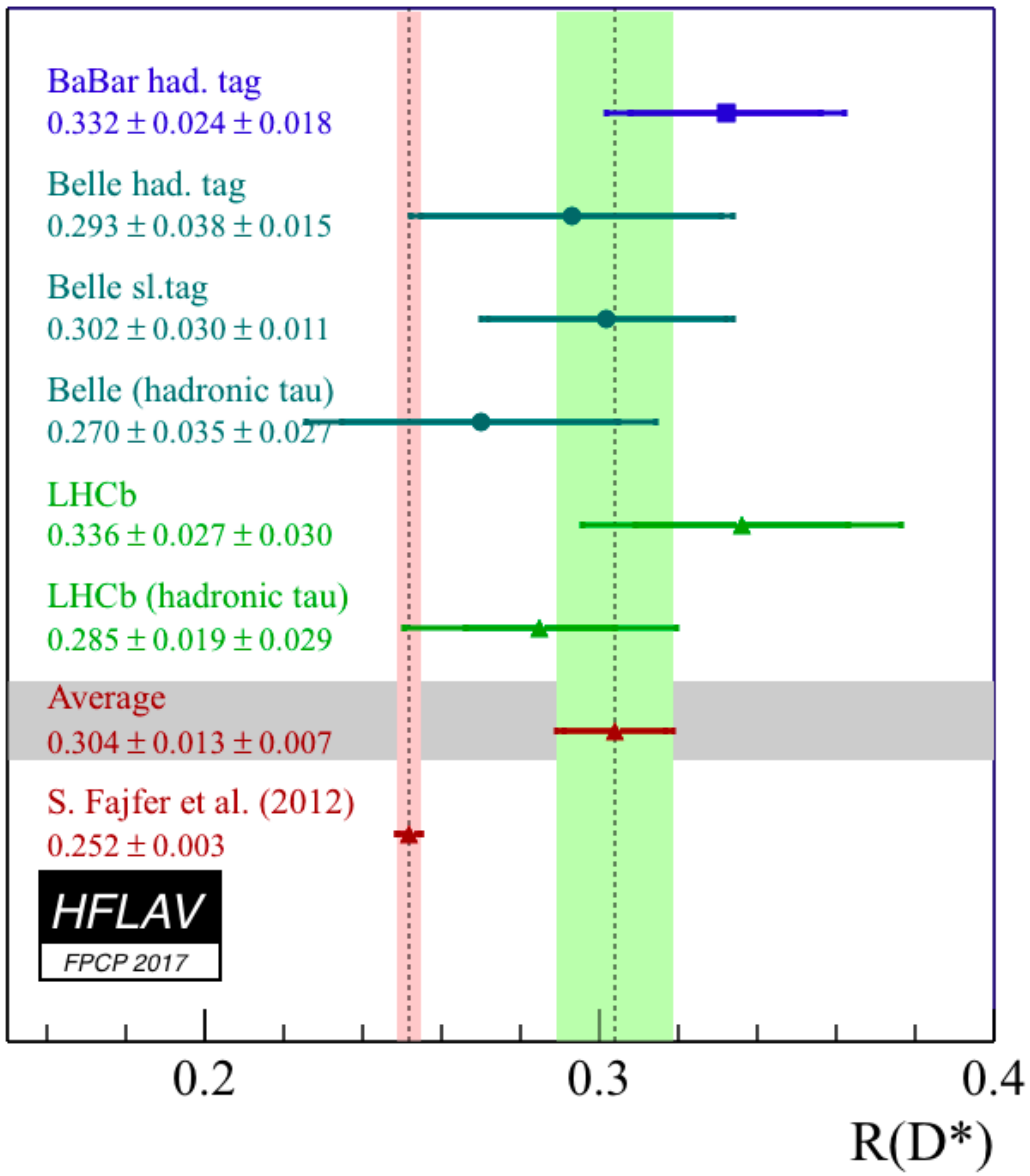
  $R(D^*) = 0.336 \pm 0.027_{\mathrm{stat}} \pm 0.030_{\mathrm{syst}}$

- Preliminary LHCb average:

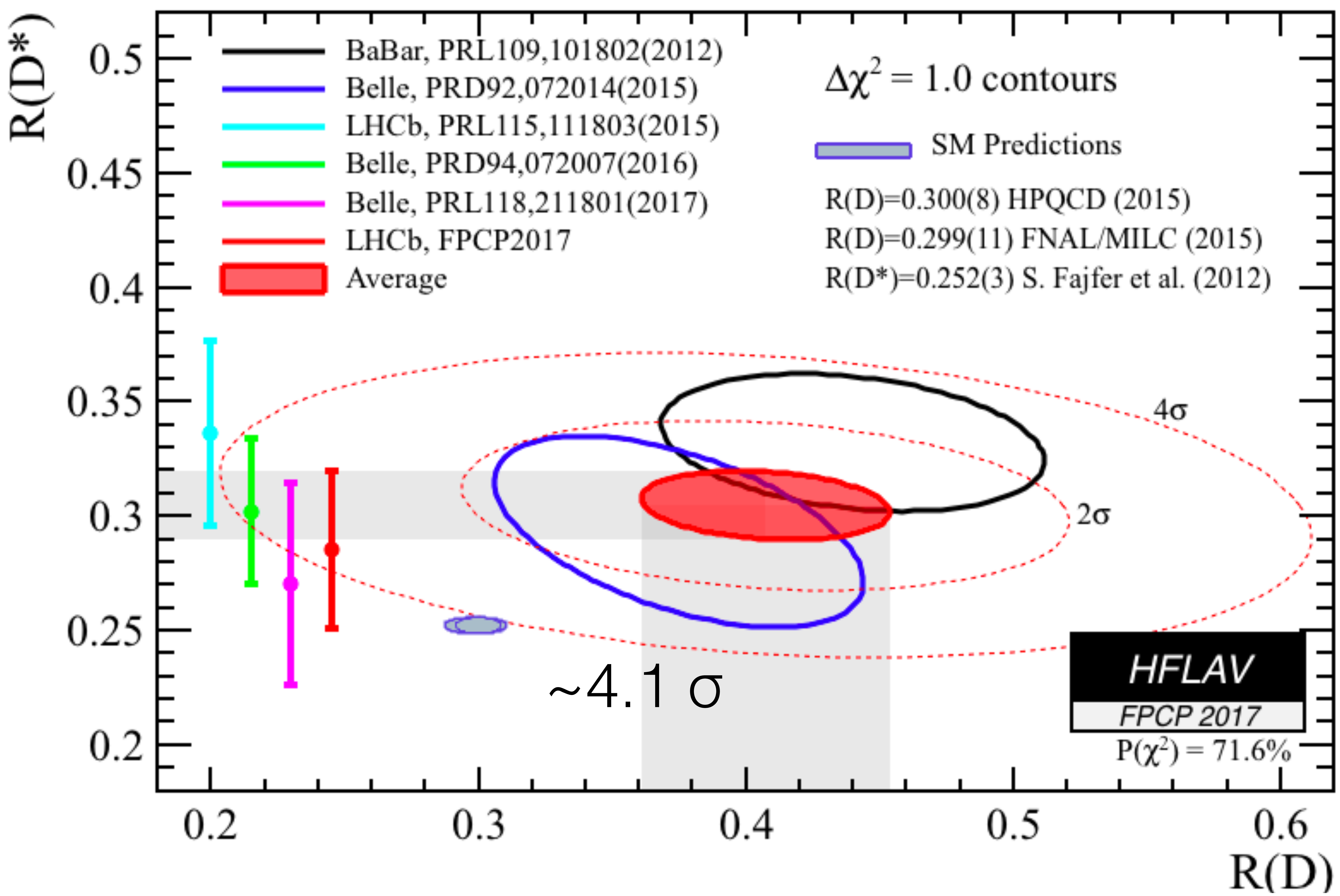
  $R(D^*) = 0.306 \pm 0.027$

- 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 :

$$R(J/\psi) : B_c^+ \to J/\psi\, \tau^+ \nu_\tau$$

$$R(D^-) : B^0 \to D^- \tau^+ \nu_\tau$$

$$R(D^0) : B^+ \to D^0 \tau^+ \nu_\tau$$

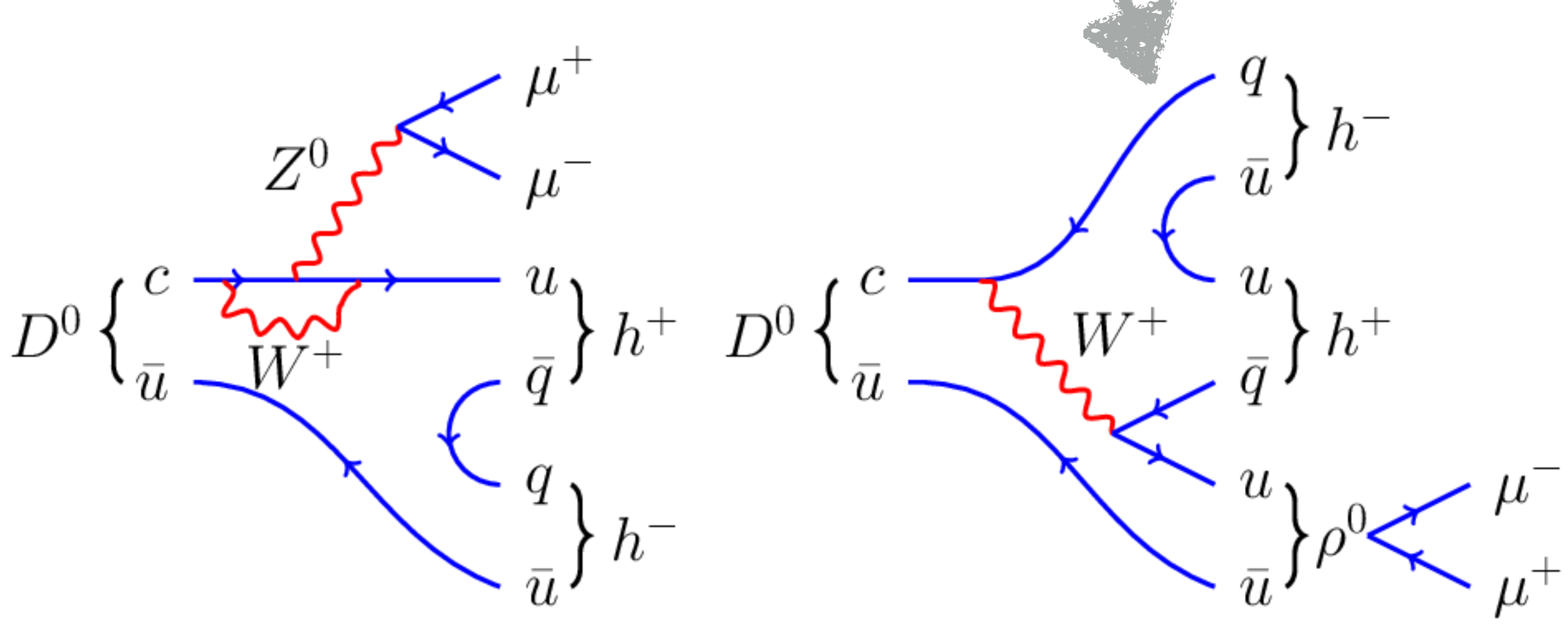
$$R(D_{\rm s}^{(*)}) : B_{\rm s}^0 \to D_{\rm s}^{(*)} \tau^+ \nu_\tau$$

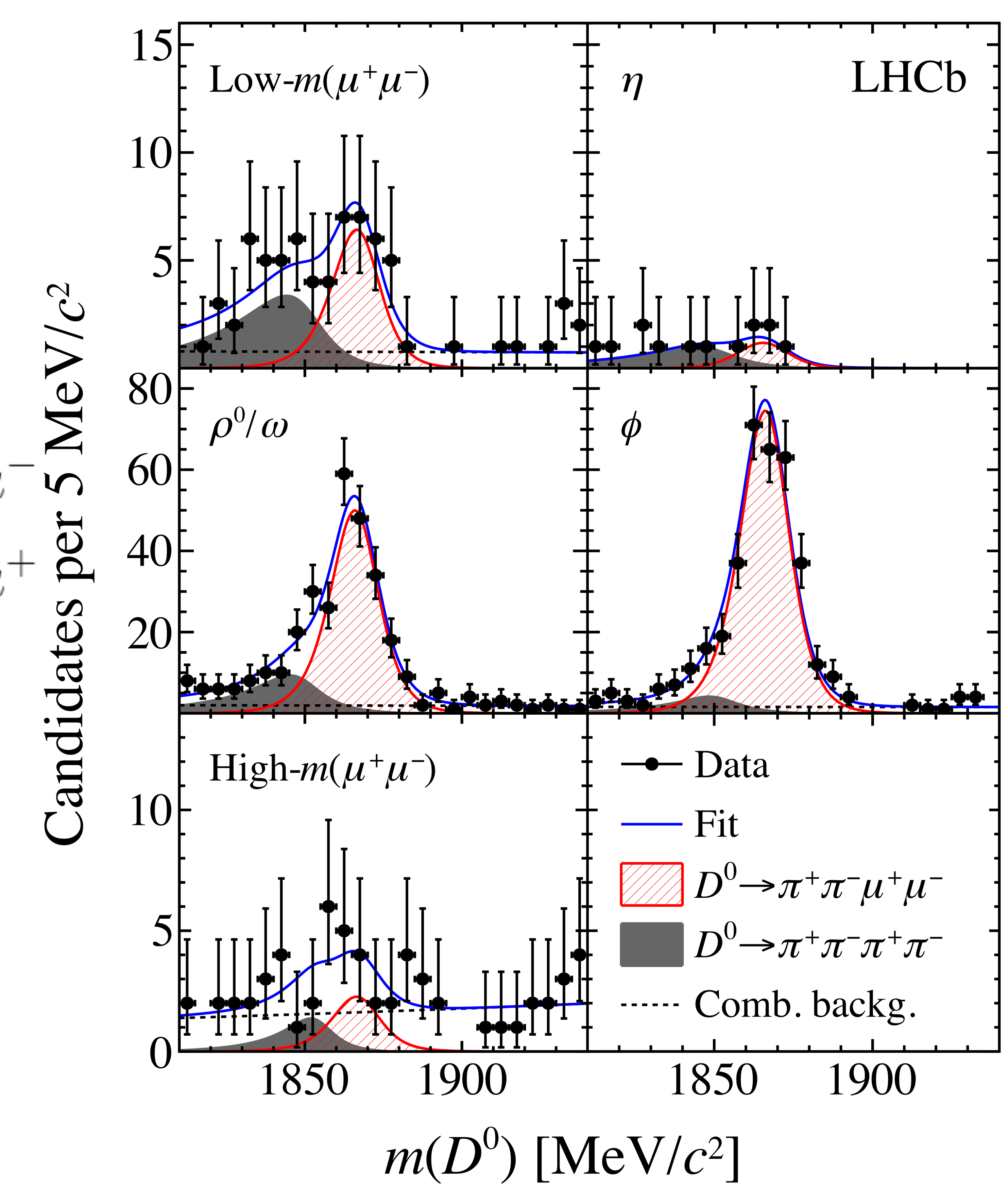
$$R(\Lambda_{\rm b}) : \Lambda_{\rm b} \to \Lambda_{\rm c}^{(*)} \tau^+ \nu_\tau$$

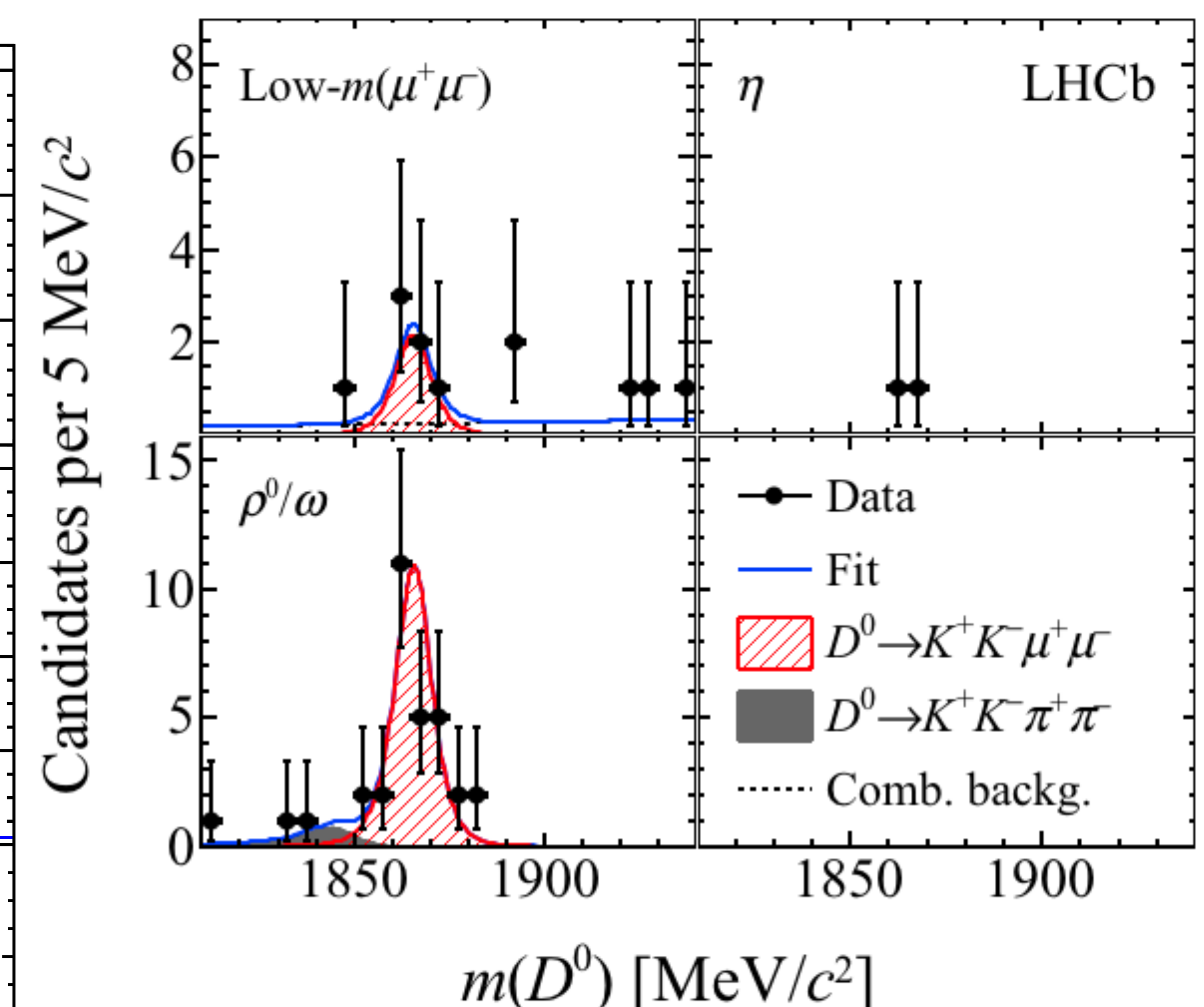
Rarest charm-hadron decays ever observed !

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

- $c \to u\mu^+\mu^-$ 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

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

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

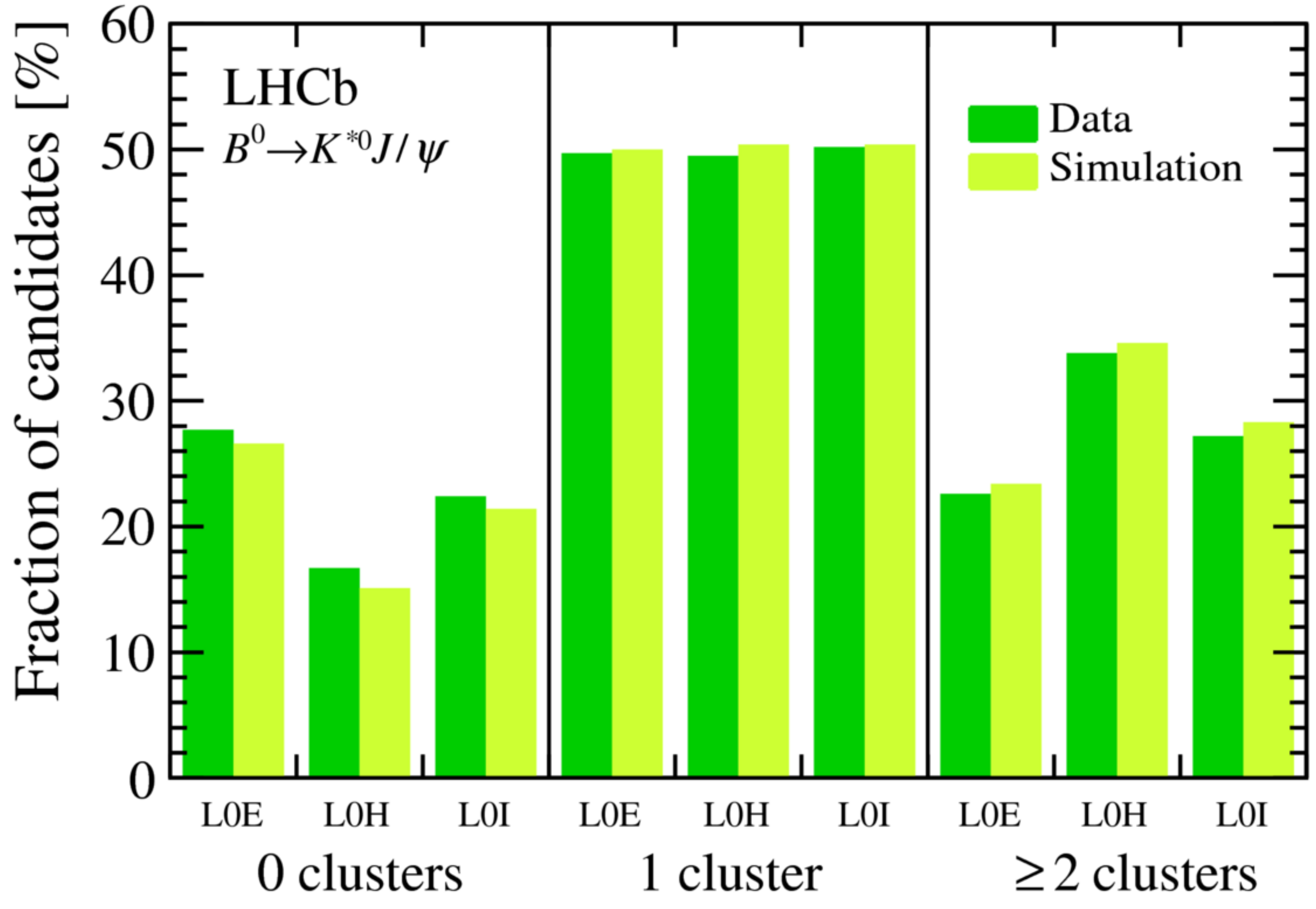
Conclusions

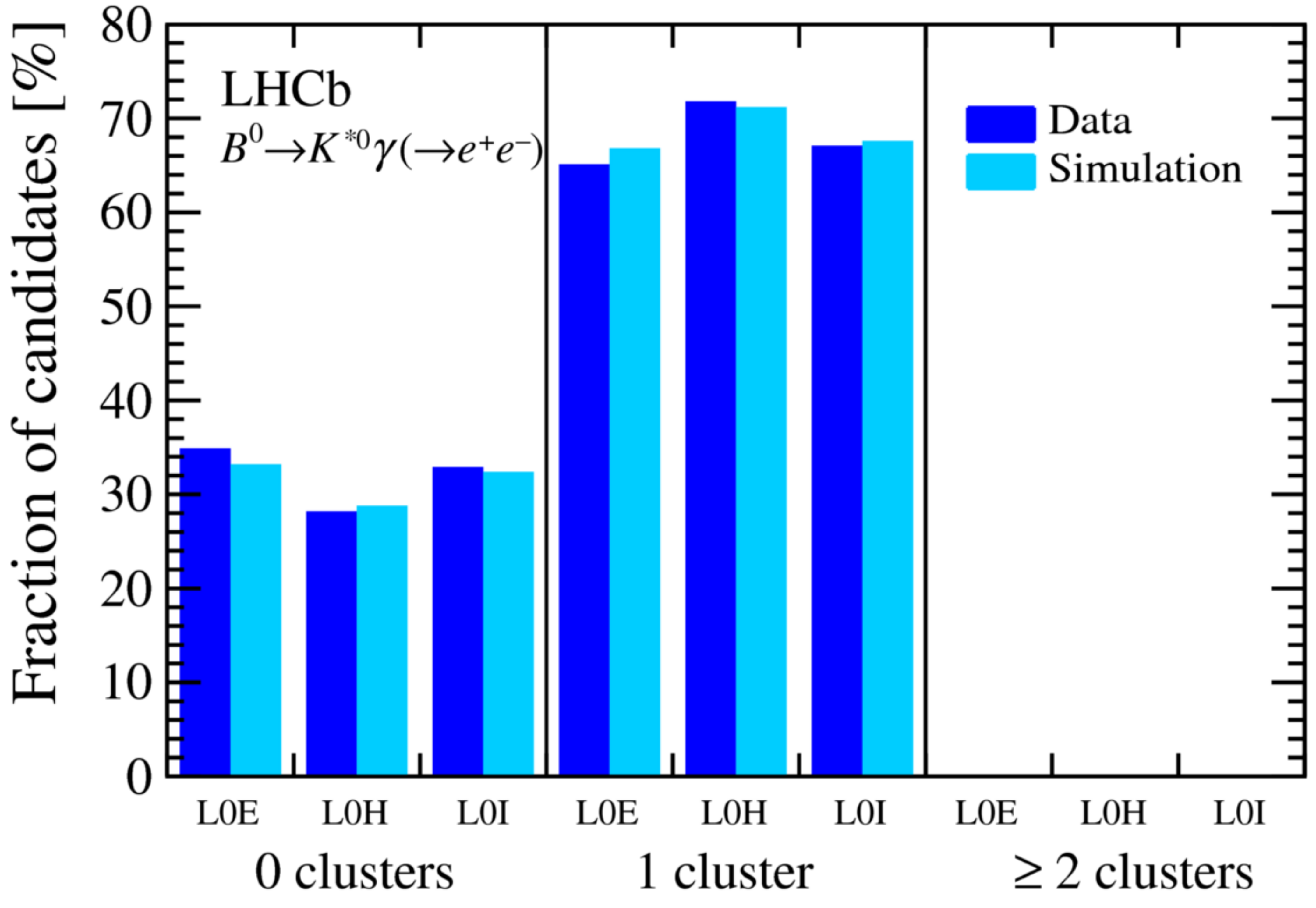
- Precise measurements of flavour observables provide a powerful way to probe for NP effects beyond the SM, complementing direct searches for NP
- Flavour-physics measurements at the LHC, in particular by LHCb, are dramatically adding to the already impressive knowledge accumulated by the B-factories 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





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})

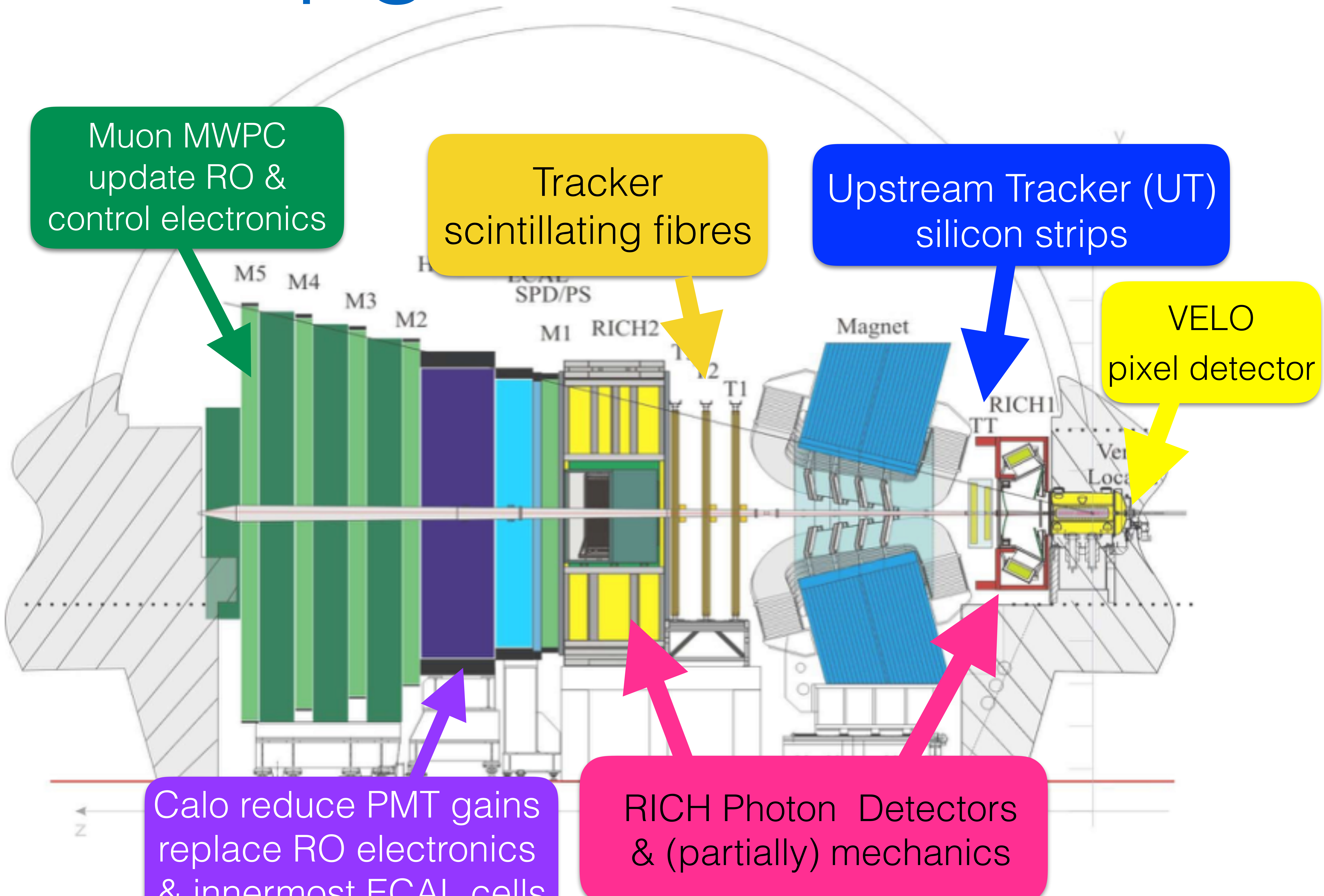
	LHCb	ATLAS/CMS
Run 1	3	30
Run 2	8	100
Run 3	25	300
Run 4	50	…3000

LHCb Upgrade

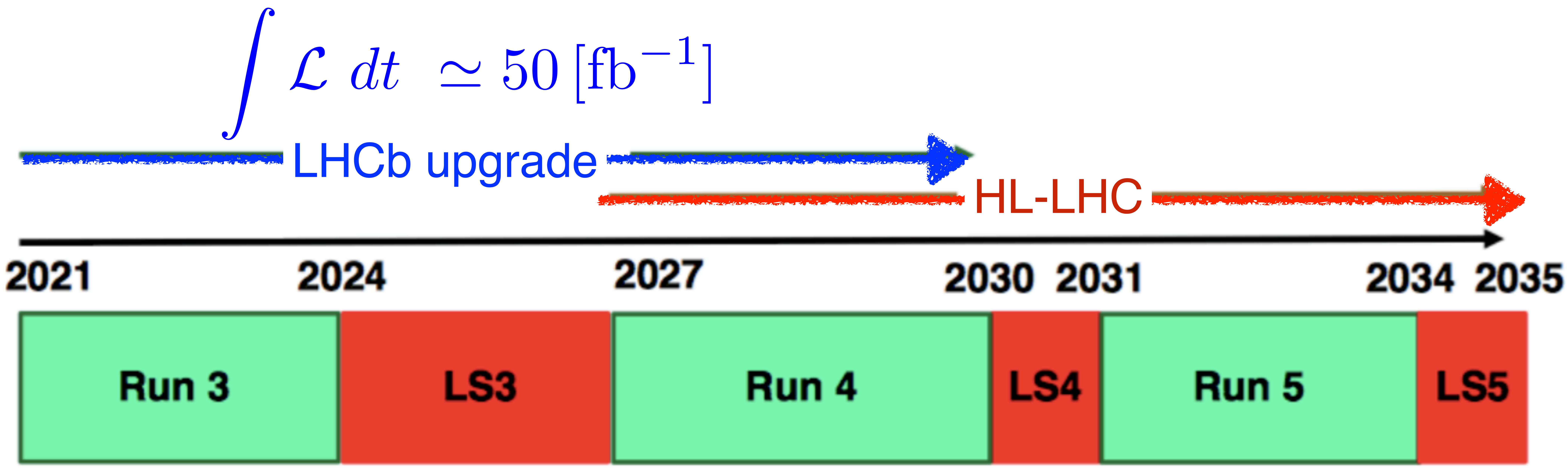
- Requirements:
  - 40 MHz readout
  - Event selection performed by HLT software only
  - $\mathcal{L} = 2 \times 10^{33} \mathrm{cm}^{-2} \mathrm{sec}^{-1}$ (x 5)
    - ➔ 5.5 visible interactions/crossing
    - ➔ Higher track multiplicity (from ~ <70> to <180>)

- 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



- 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 $\mathcal{L}$ [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	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