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

Monica Pepe Altarelli (CERN)

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

Corfu Summer Institute 2019, August 31-September 11

The LHCb collaboration

- ~1350 members from 79 institutes in 18 countries
- ~490 publications, some with very high impact
- Main focus on heavy quark flavour…but plenty of other physics in the forward direction

The LHCb collaboration

- ~1250 members from 79 institutes in 18 countries
- ~450 publications, some with very high impact
- Main focus on heavy quark flavour…but plenty of other physics in the forward direction

CKM & CPV

EW and QCD

Rare decays

Spectroscopy

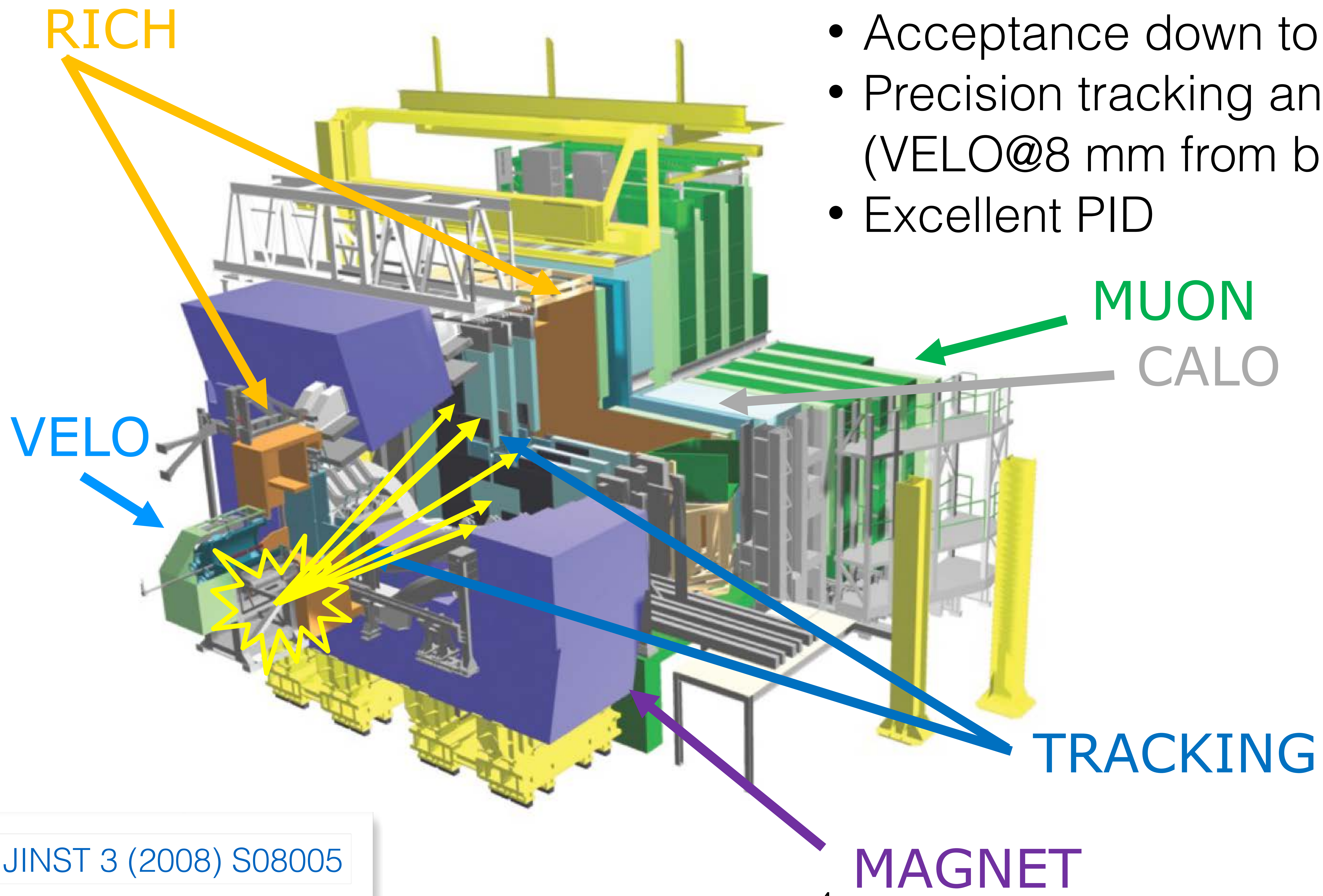
Semileptonic decays

Ions and fixed target

Exotica searches

LHCb detector: the essentials

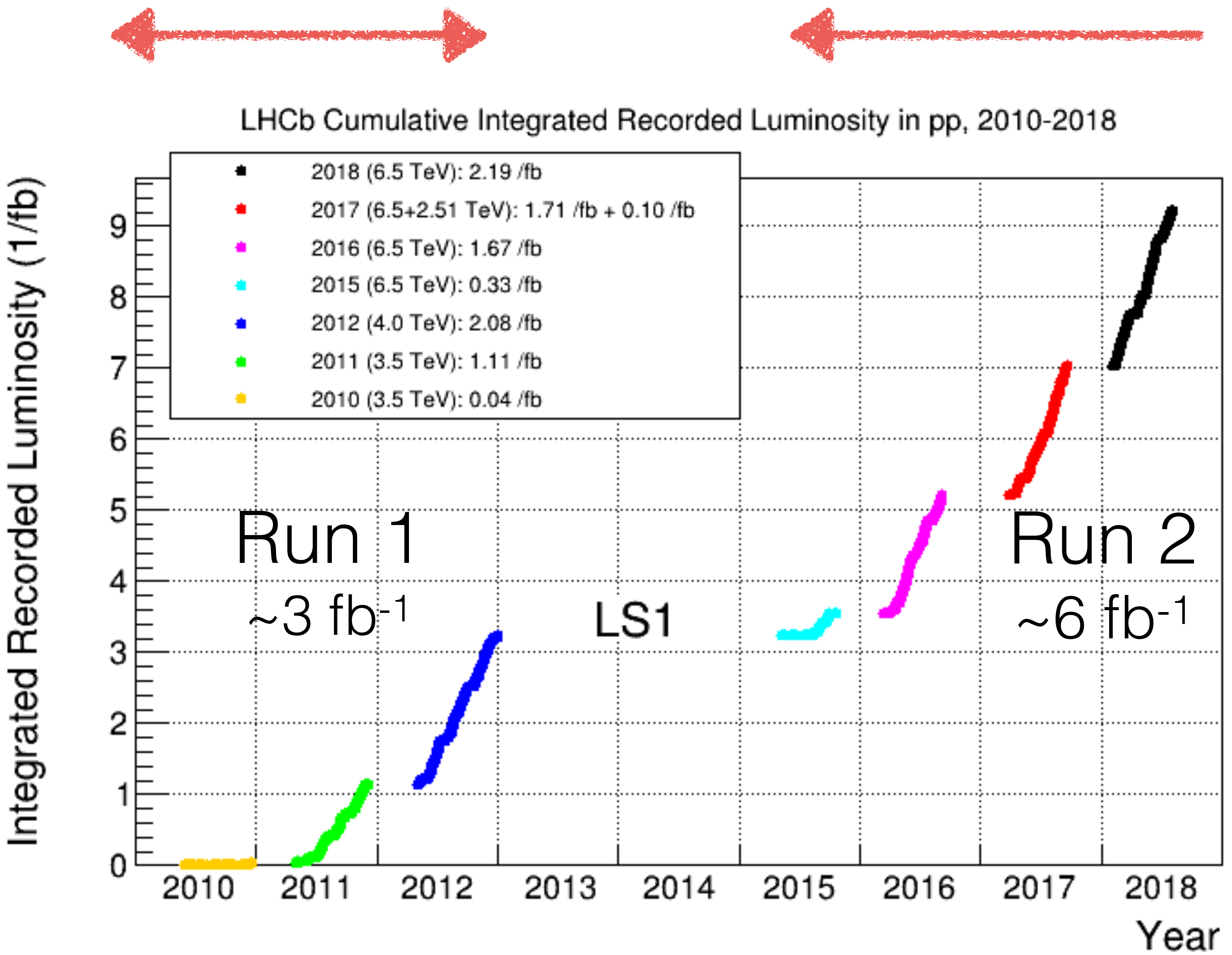
- Forward acceptance
- Efficient trigger for hadronic and leptonic modes
- Acceptance down to low p_T
- Precision tracking and vertexing (VELO@8 mm from beam)
- Excellent PID



JINST 3 (2008) S08005

Luminosity @ LHCb

$$\int \mathcal{L}\,\mathrm{d}t \sim 9\,\mathrm{fb}^{-1}$$



Run 1

~3 fb^{-1}

LS1

Run 2

~6 fb^{-1}

~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 2 x10^{33} cm^{-2} sec^{-1} in Run 3)
  - mean number of interactions/bunch crossing ~1

2018: last year of LHCb as we know it!

LHCb Upgrade

We are here !

HL-LHC

2012 2014 2018 19-20 2023 24-25 2029 30-31 2034

Run1 LS1 Run2 LS2 Run3 LS3 Run4 LS4 Run5 LS5

7,8 TeV 13 TeV 14 TeV

Belle II

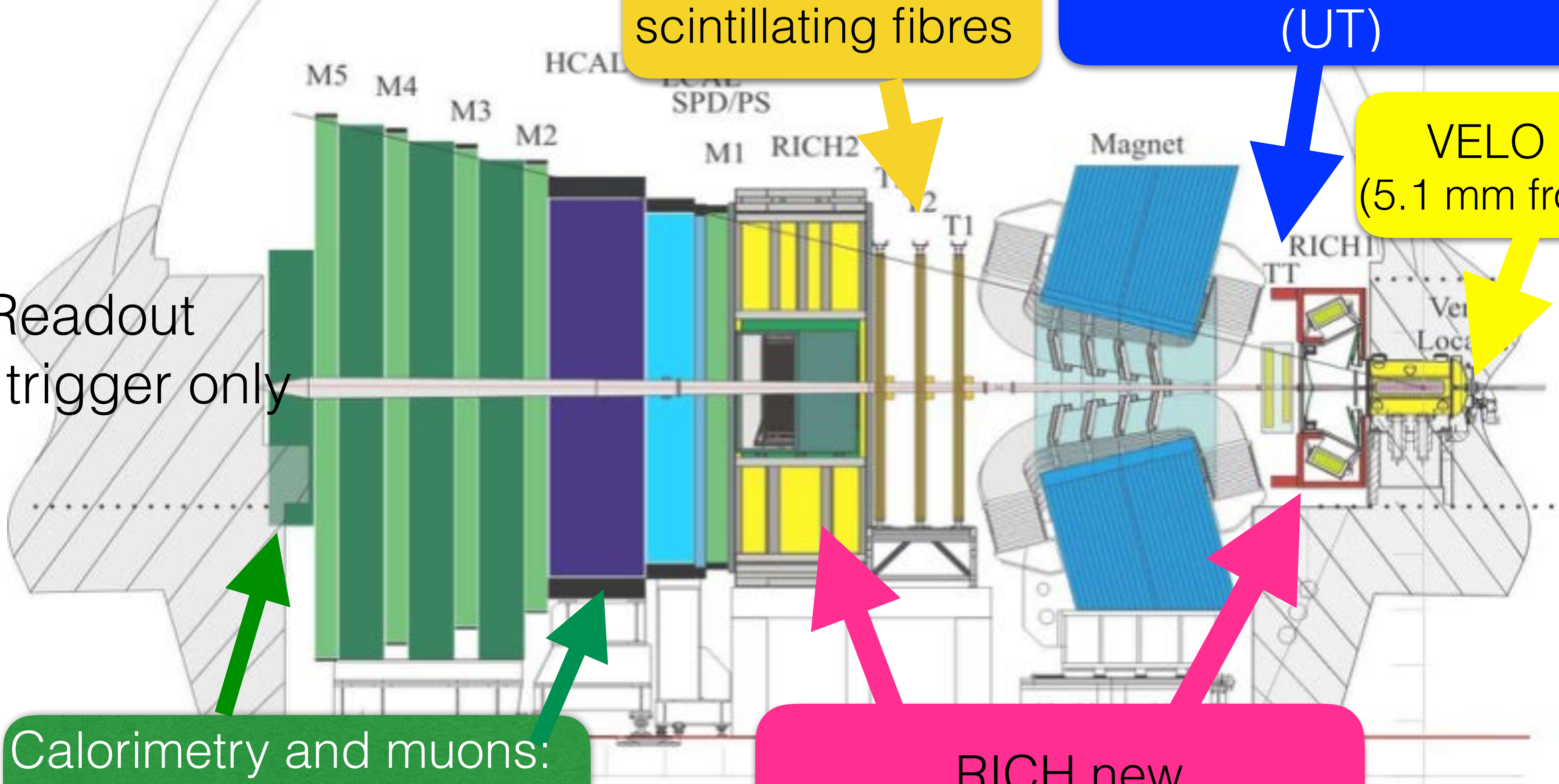
- **LHCb is building and installing its Upgrade I during LS2 (2019-20)→**
  - **Higher Lumi: 4 x10^{32} →2 x10^{33} cm^{-2} sec^{-1}**
  - **more interactions per beam crossing: ~1→~5**

- Possible LHCb detector consolidation and modest enhancements in LS3 (2025) - ATLAS/CMS Phase II upgrades also in LS3

- Major LHCb Upgrade II in LS4 (2030) →Factor ~10 increase in $\mathcal{L}$ ~1.5 x10^{34} /cm^{2} /s (Expression of Interest: CERN/LHCC 2017-003)

The upgraded detector

- Less than 10% of all channels will be kept!
- NEW RO electronics
- NEW DAQ & data centre



40 MHz Readout
Software trigger only

Tracker
scintillating fibres

Upstream Tracker
(UT)

VELO pixels
(5.1 mm from beam)

Calorimetry and muons:
replace RO electronics
& remove redundant
components

RICH new
photodetectors

The NEW detector

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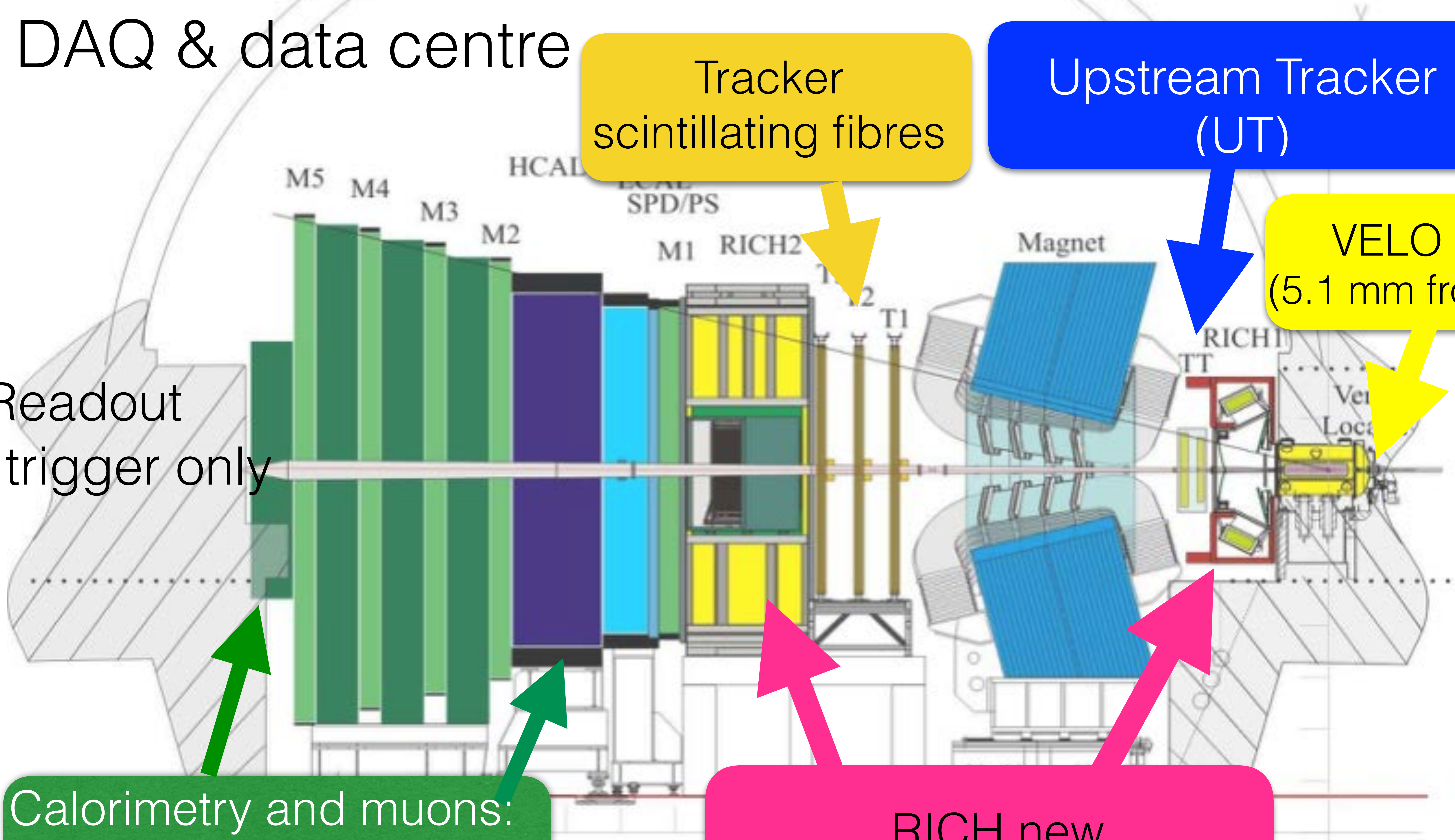


Tracker scintillating fibres

Upstream Tracker (UT)

VELO pixels (5.1 mm from beam)

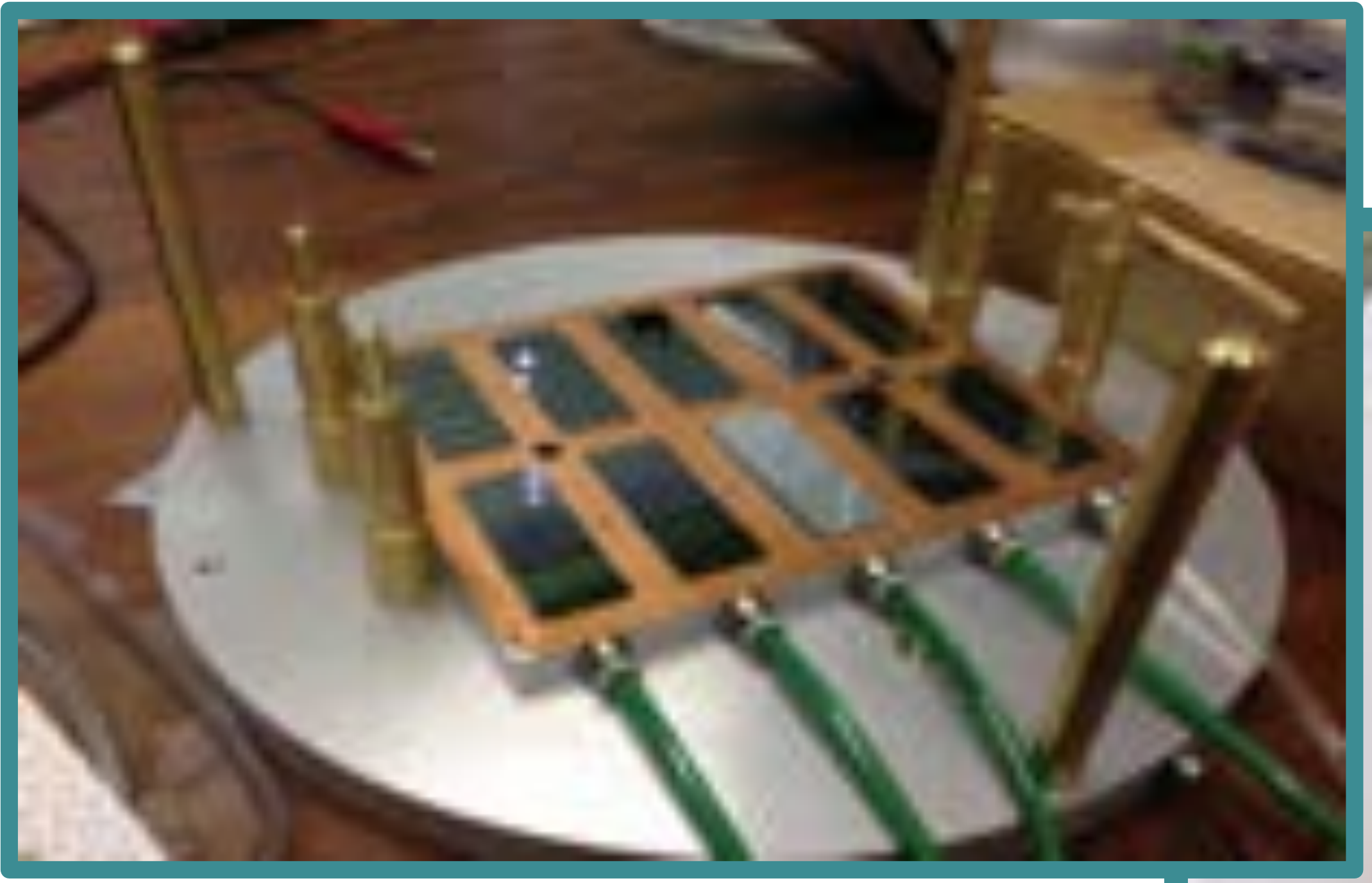
40 MHz Readout
Software trigger only

Calorimetry and muons: replace RO electronics & remove redundant components

RICH new photodetectors

Dismantling and installation ongoing! Very tight timescale!

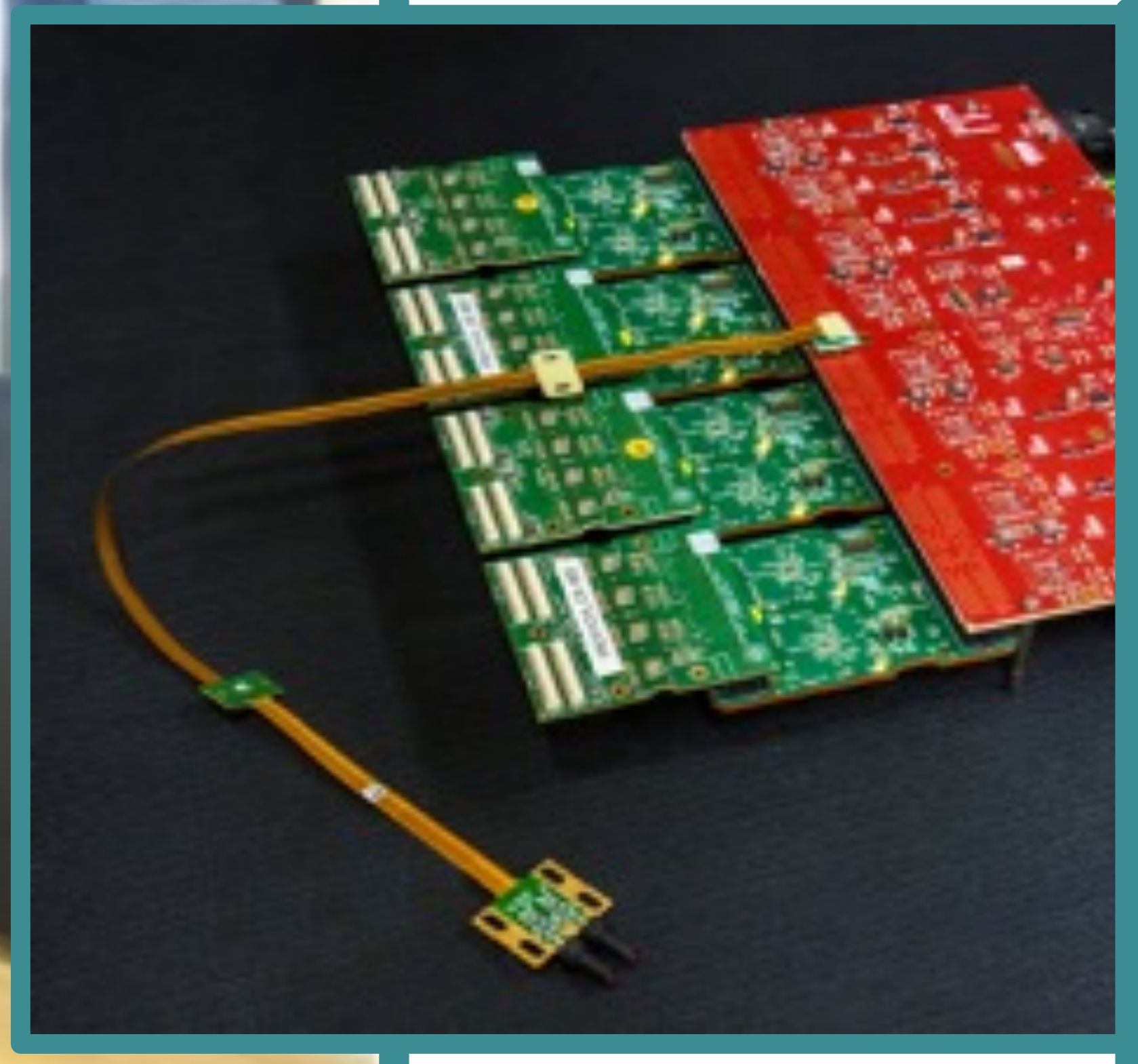
VELO sensor tiles testing device



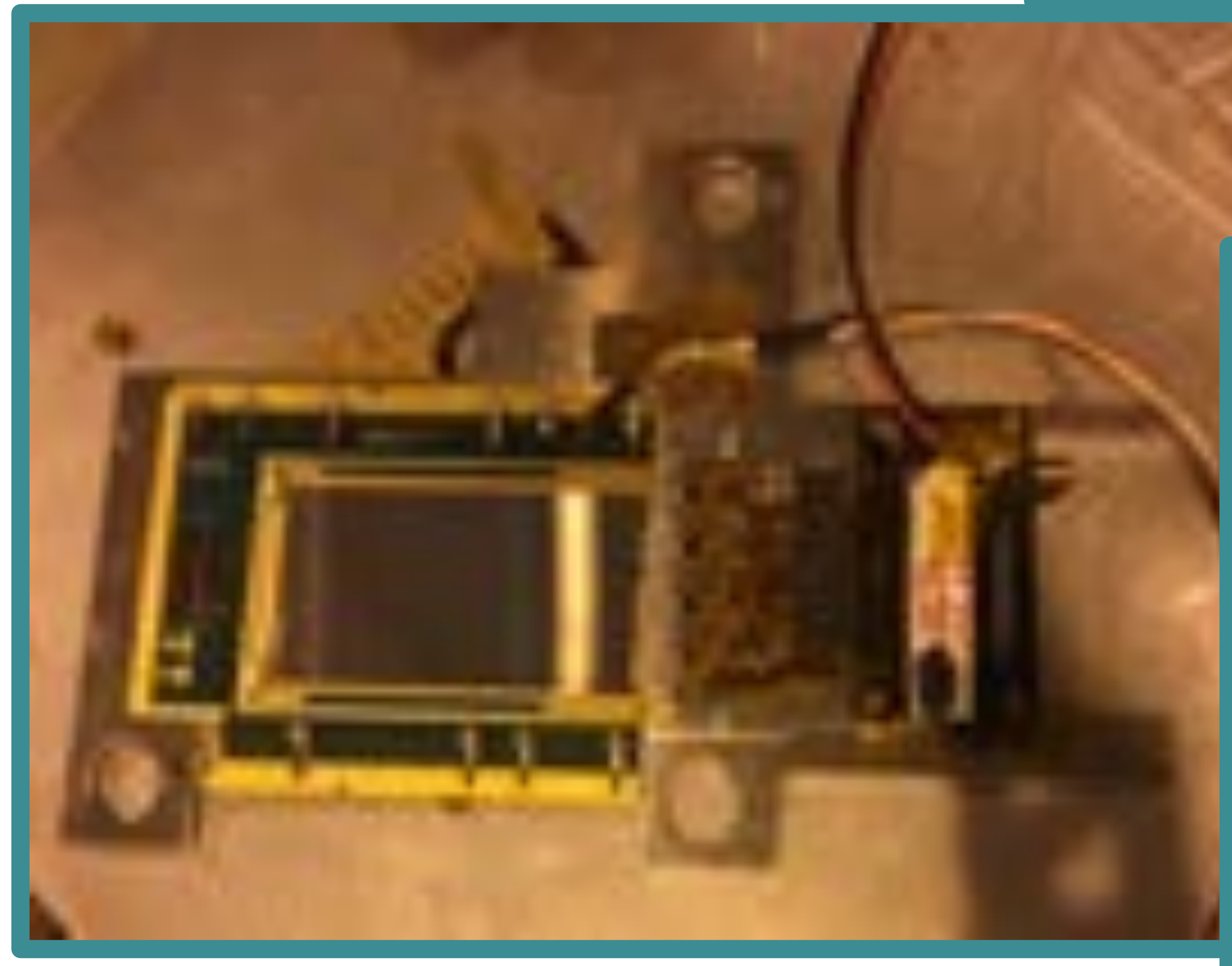
VELO module

SciFI module

SciFI Readoout

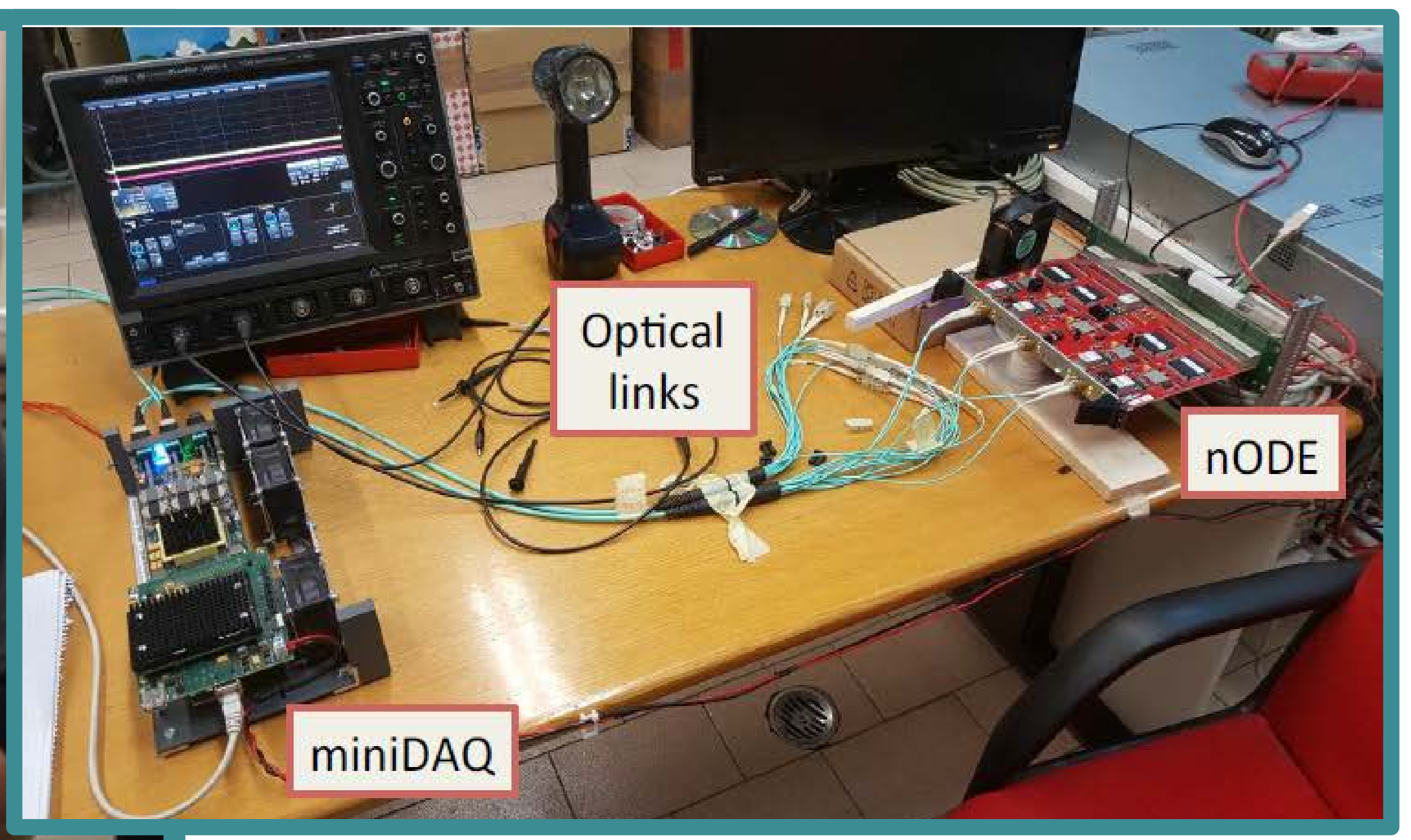


CALO electronics



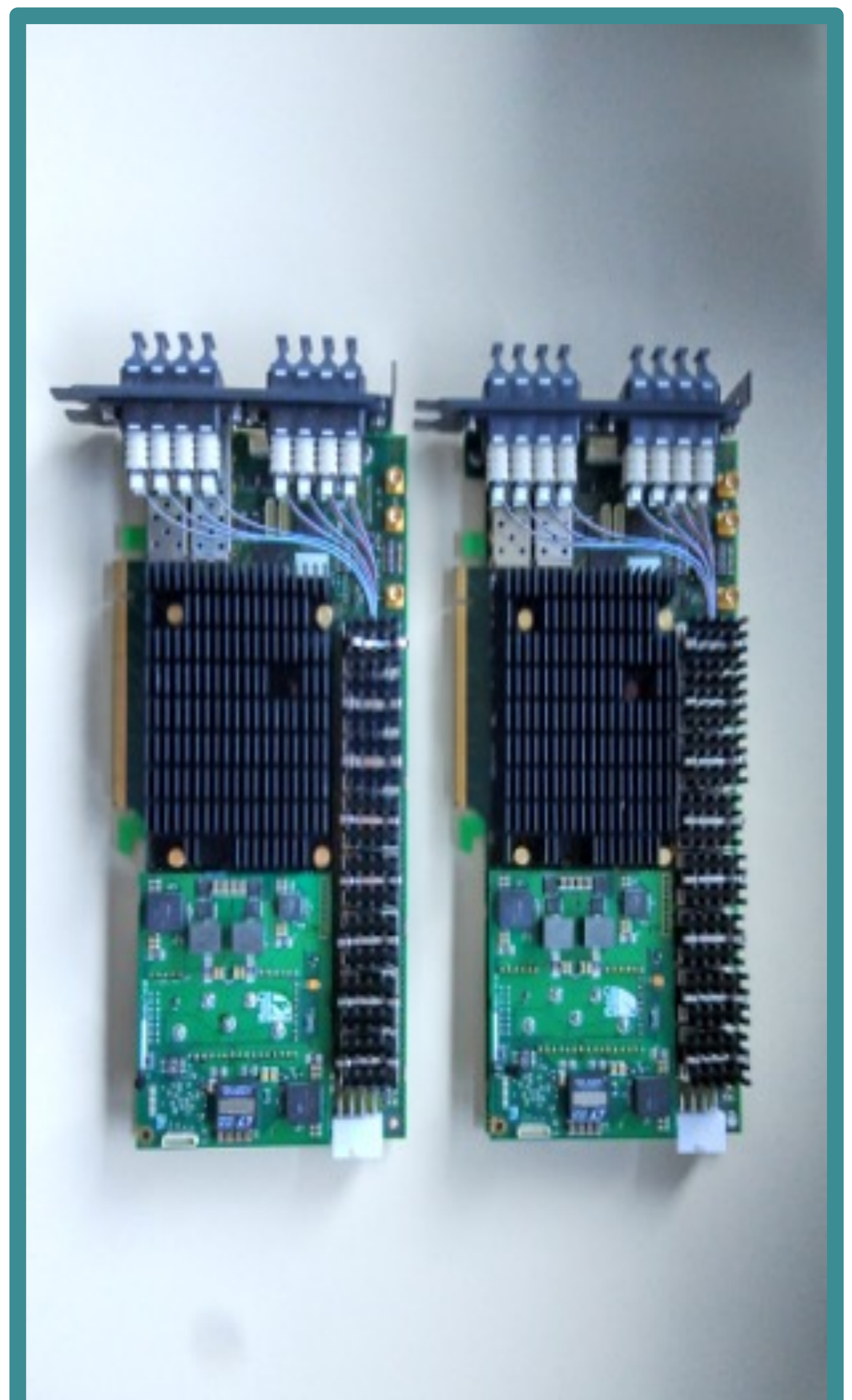
UT sensor

UT staves construction



Test of MUON electronics

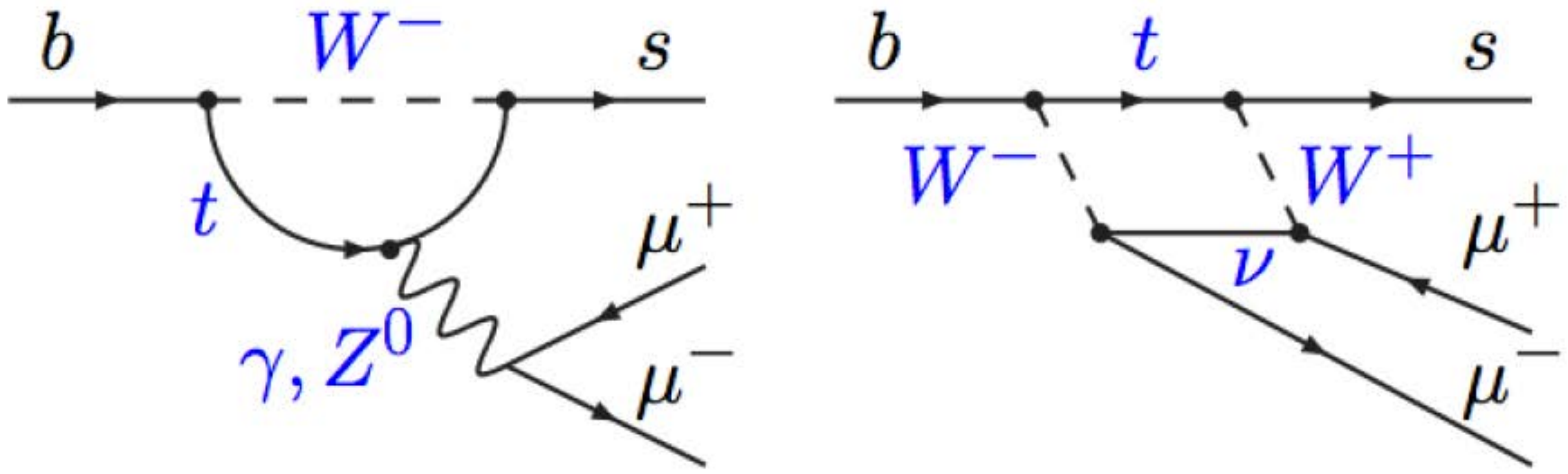
RICH MaPMTs under test



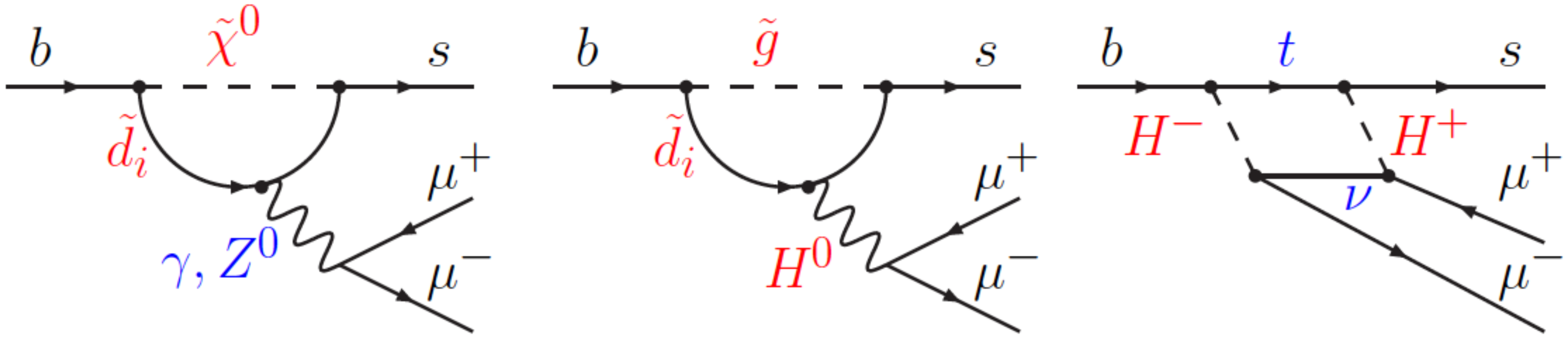
PCIe40 boards

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



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

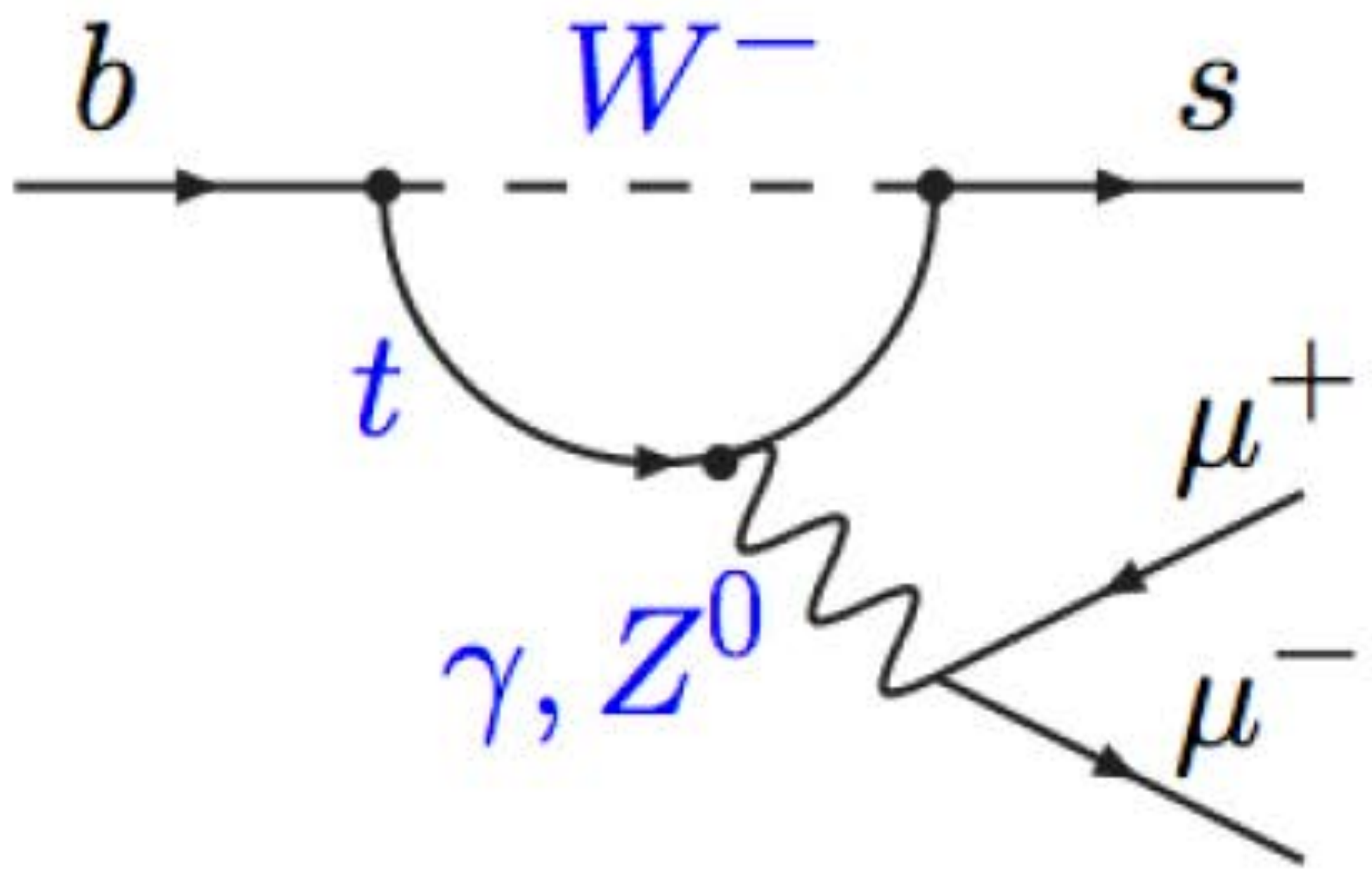


- Strategy: use well-predicted observables to look for deviations
- Indirect approach to New Physics searches, complementary to that of ATLAS/CMS and particularly relevant at this point!

A window on NP at high scales

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

LHCb update with Run 2 data

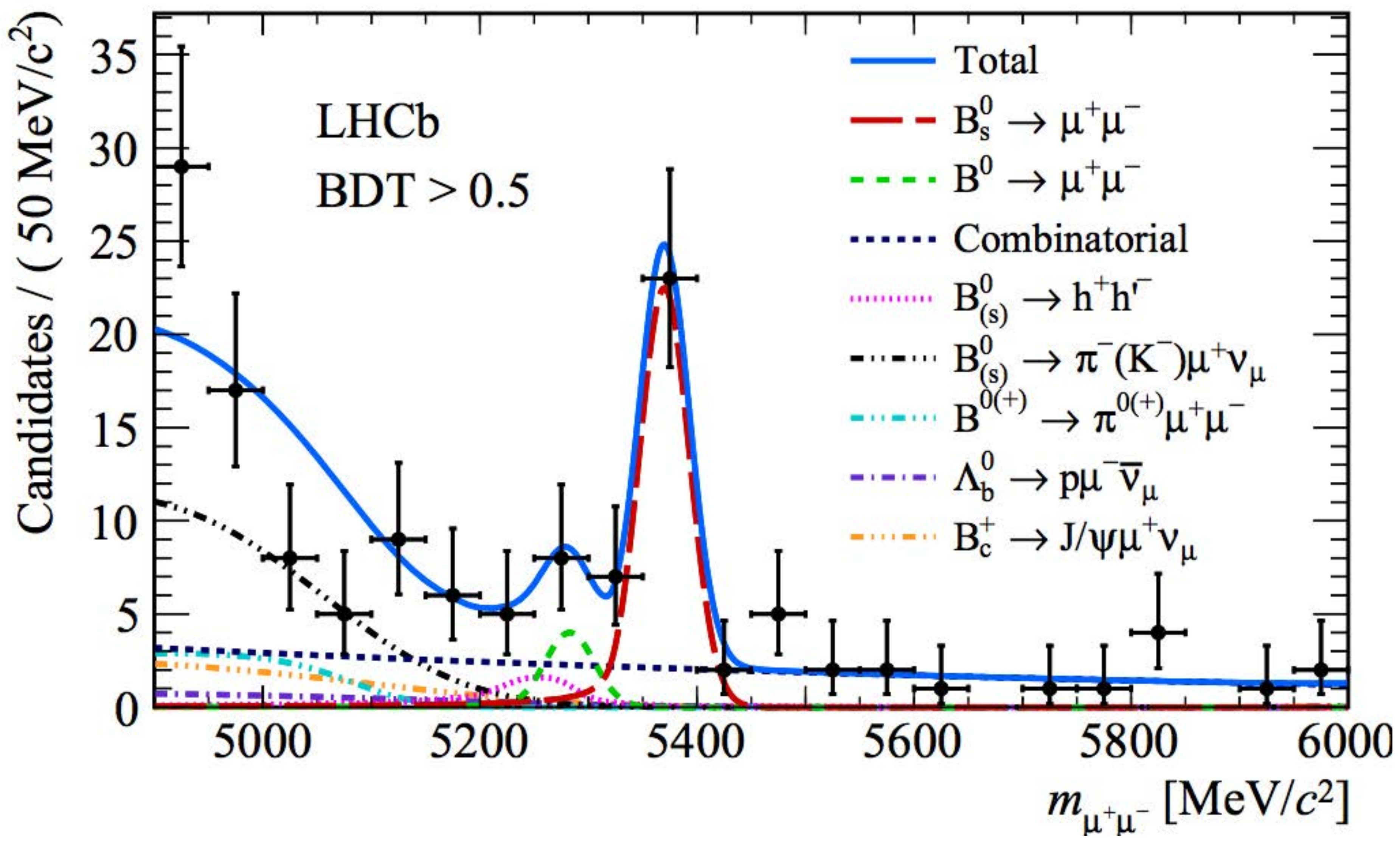
- LHCb analysis based on Run 1 and Run 2 data (3+1.4 fb^{-1})
- First observation from a single experiment with a significance of 7.8 σ

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \quad (\ \ 20\%) \qquad \mathcal{B}_{\rm SM} = (3.65 \pm 0.23) \times 10^{-9}$$

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

- Consistent with SM expectation at current level of precision
- Main sources of systematic uncertainties
  - $B_s^0 \to \mu^+\mu^-$: knowledge of b-quark fragmentation probability ratio f_s/f_d (~6%)
  - $B^0 \to \mu^+\mu^-$: exclusive background

PRL 118 (2017) 191801



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

- **LHCb**, PRL 118 (2017) 191801

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

$$B(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \,@\, 95\,\%\,\mathrm{C.L.}$$

- **CMS**, PRL 111, 101804 (2013)

$$B(B_s^0 \to \mu^+\mu^-) = (2.8^{+1.1}_{-0.9}) \times 10^{-9}$$

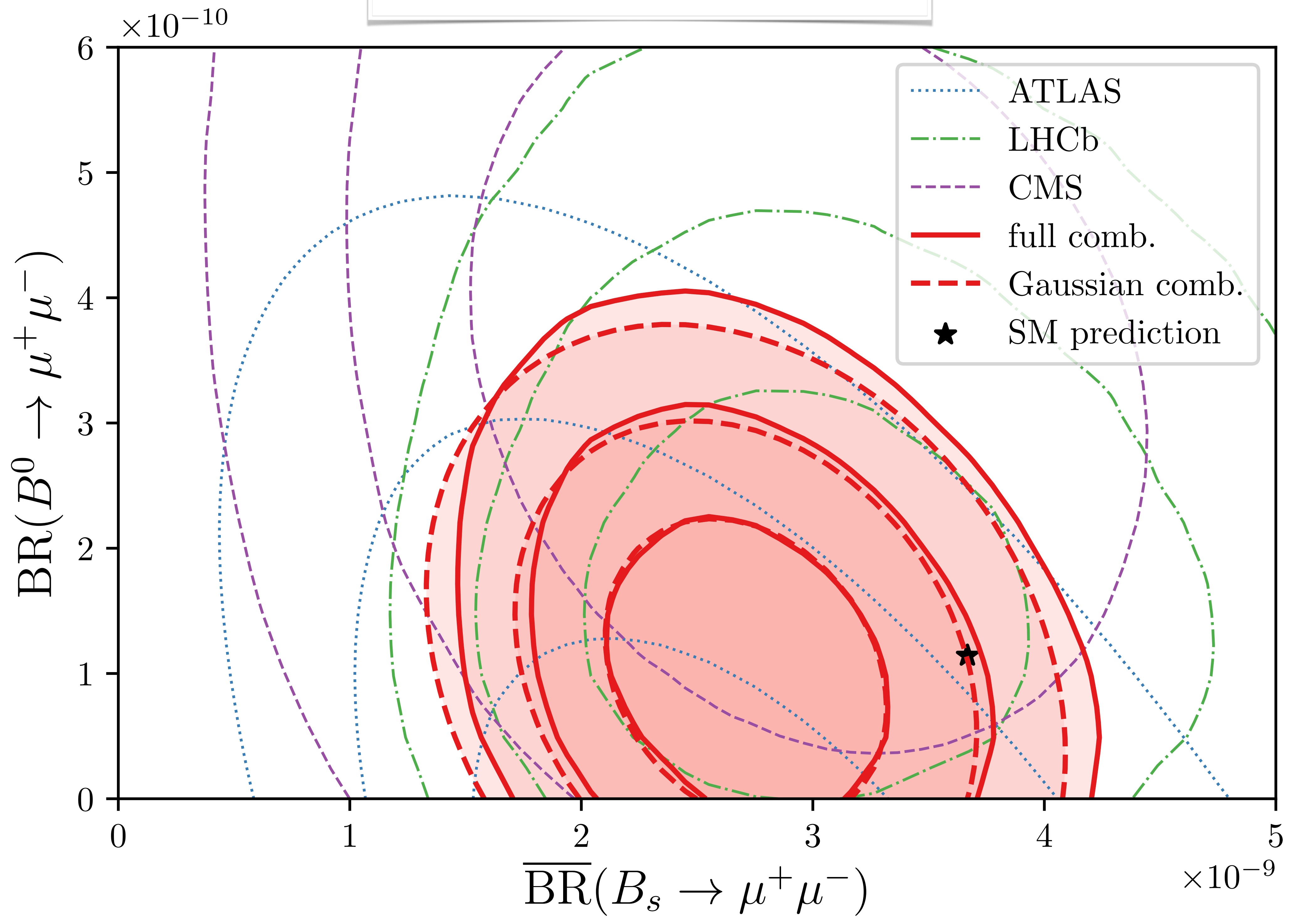
$$B(B^0 \to \mu^+\mu^-) = (4.4^{+2.2}_{-1.9}) \times 10^{-10}$$

- **ATLAS**, JHEP 04 (2019) 098

$$B(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10} \,@\, 95\,\%\,\mathrm{C.L.}$$

Aebischer et al
arXiv:1903.10434



- Naive combination from the three experiments gives:

$$B(B_s^0 \to \mu^+\mu^-) = (2.7^{+0.5}_{-0.4}) \times 10^{-9}$$

roughly 2σ below
SM prediction

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

New CMS result (Lepton Photon 2019)
CMS PAS BPH-16-004

$$B(B_s^0 \to \mu^+\mu^-) = (2.9^{+0.7}_{-0.6} \pm 0.2(f_s/f_d)) \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) < 3.6 \times 10^{-10} \text{ @ } 95\,\%\,\text{C.L.}$$

- **LHCb**, PRL 118 (2017) 19180

$$B(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 1$$

$$B(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ @ } 95\,\%\,\text{C.L.}$$

- **CMS**, PRL 111, 101804 (2013)

$$B(B_s^0 \to \mu^+\mu^-) = (2.8^{+1.1}_{-0.9}) \times 10^{-9}$$

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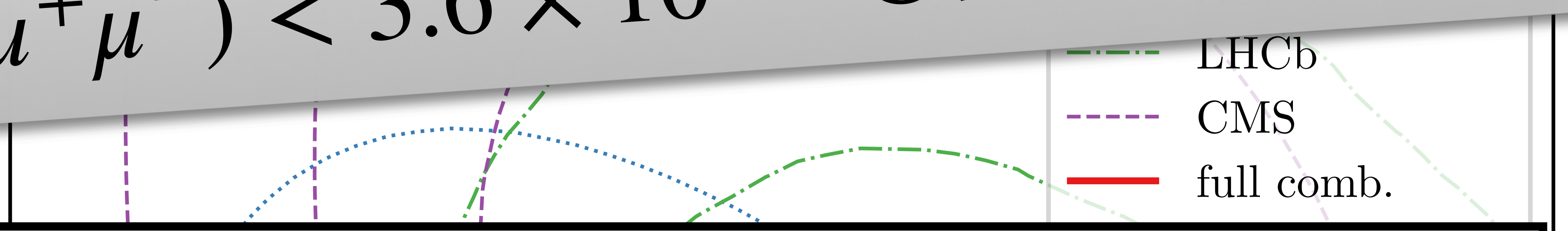
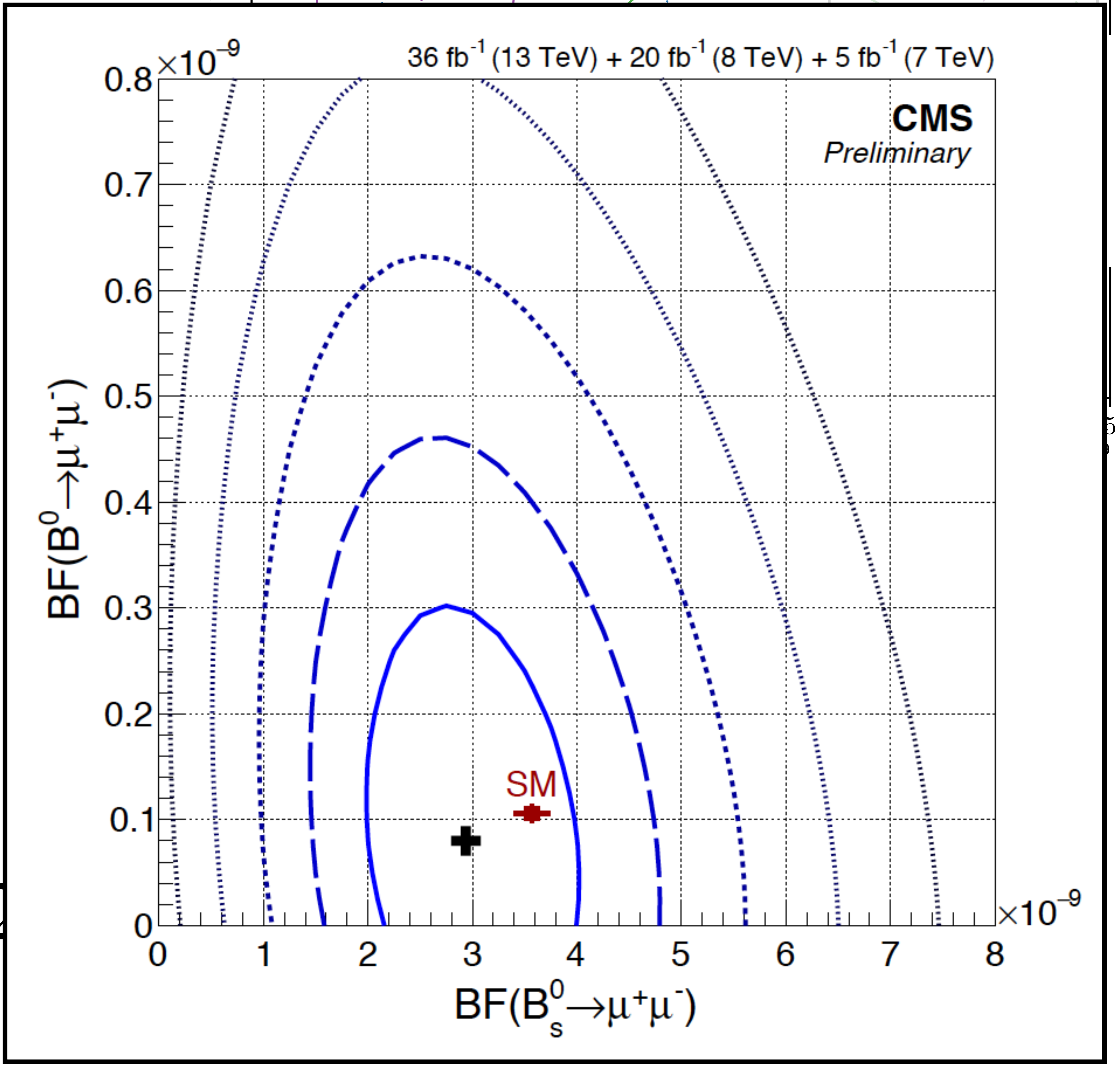
- Naive combination from the three

$$B(B_s^0 \to \mu^+\mu^-) = (2$$





Effective B_s lifetime

- An 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

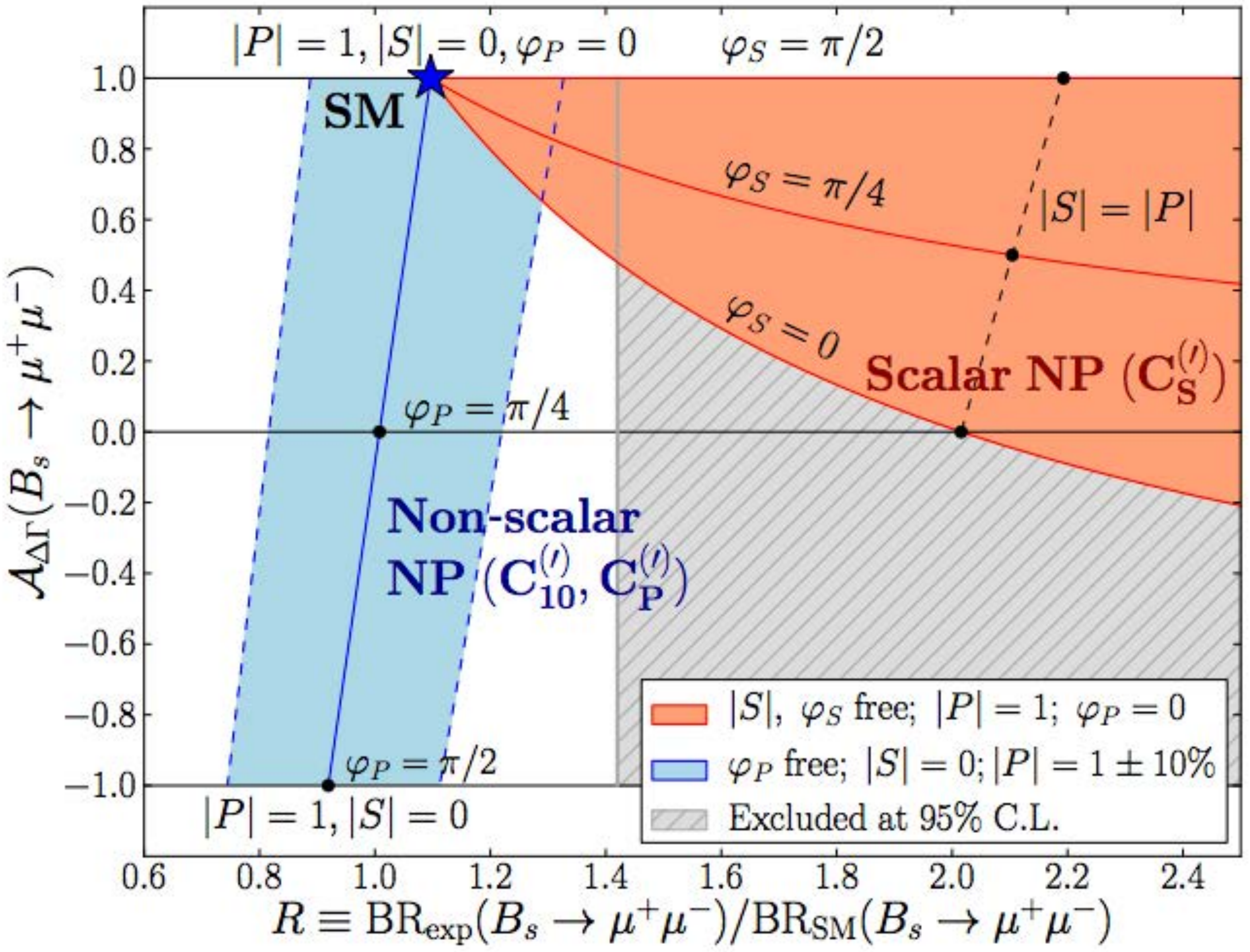
$$\Gamma(B_s(t)\to\mu^+\mu^-) \equiv \Gamma(B_s^0(t)\to\mu^+\mu^-) + \Gamma(\overline{B}_s^0(t)\to\mu^+\mu^-)$$

$$\propto (1-A_{\Delta\Gamma_s})e^{-\Gamma_L t} + (1+A_{\Delta\Gamma_s})e^{-\Gamma_H t}$$

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]



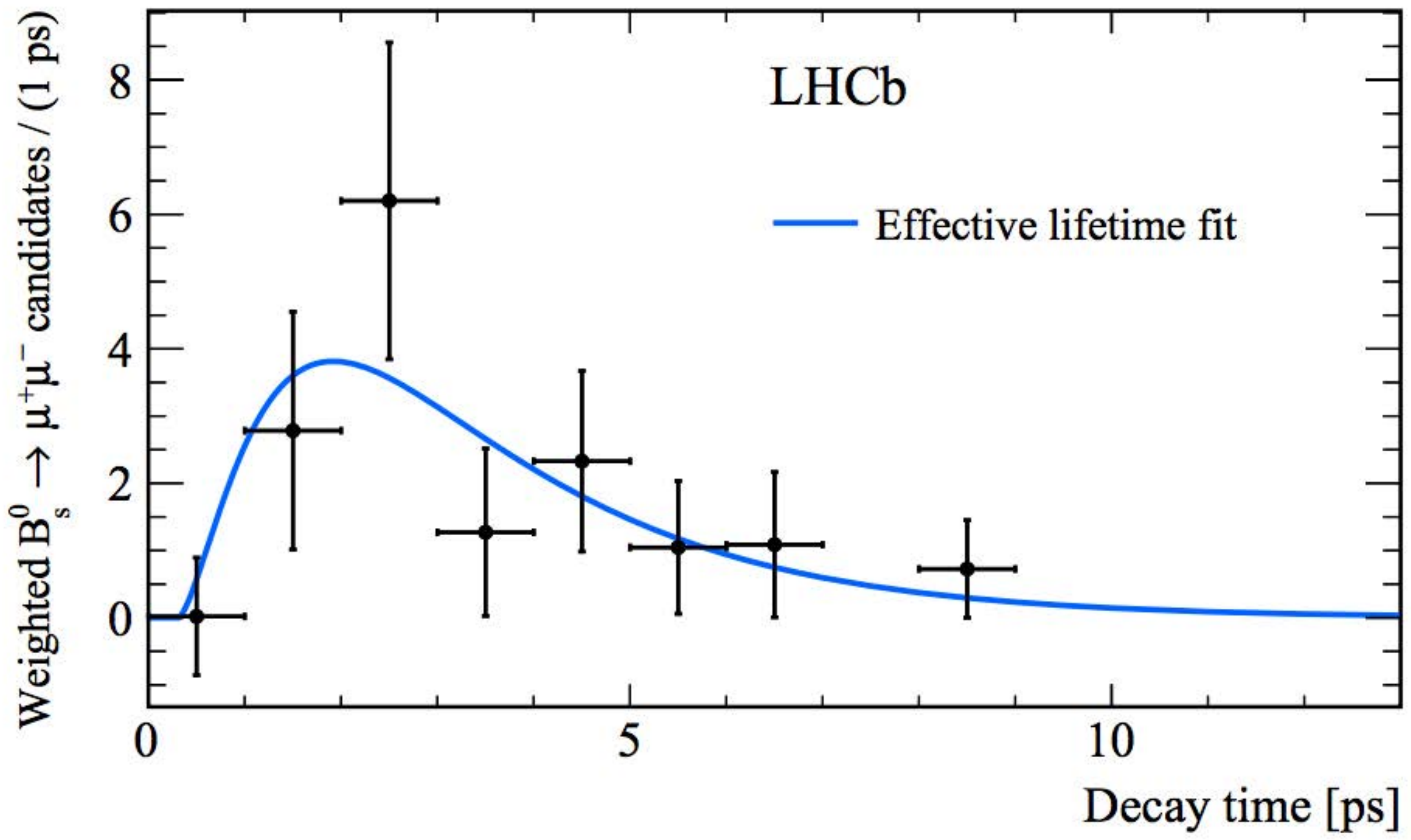
Results on τ_{eff}

- 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 $$y_s = \tau_{B_s}\frac{\Delta\Gamma}{2}$$

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

- 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

Results on

New CMS result (Lepton Photon 2019)
CMS PAS BPH-16-004

$$\tau_{\mu^+\mu^-} = 1.70^{+0.61}_{-0.44}\,\mathrm{ps}$$

e from the d

ts used for

exponentia

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

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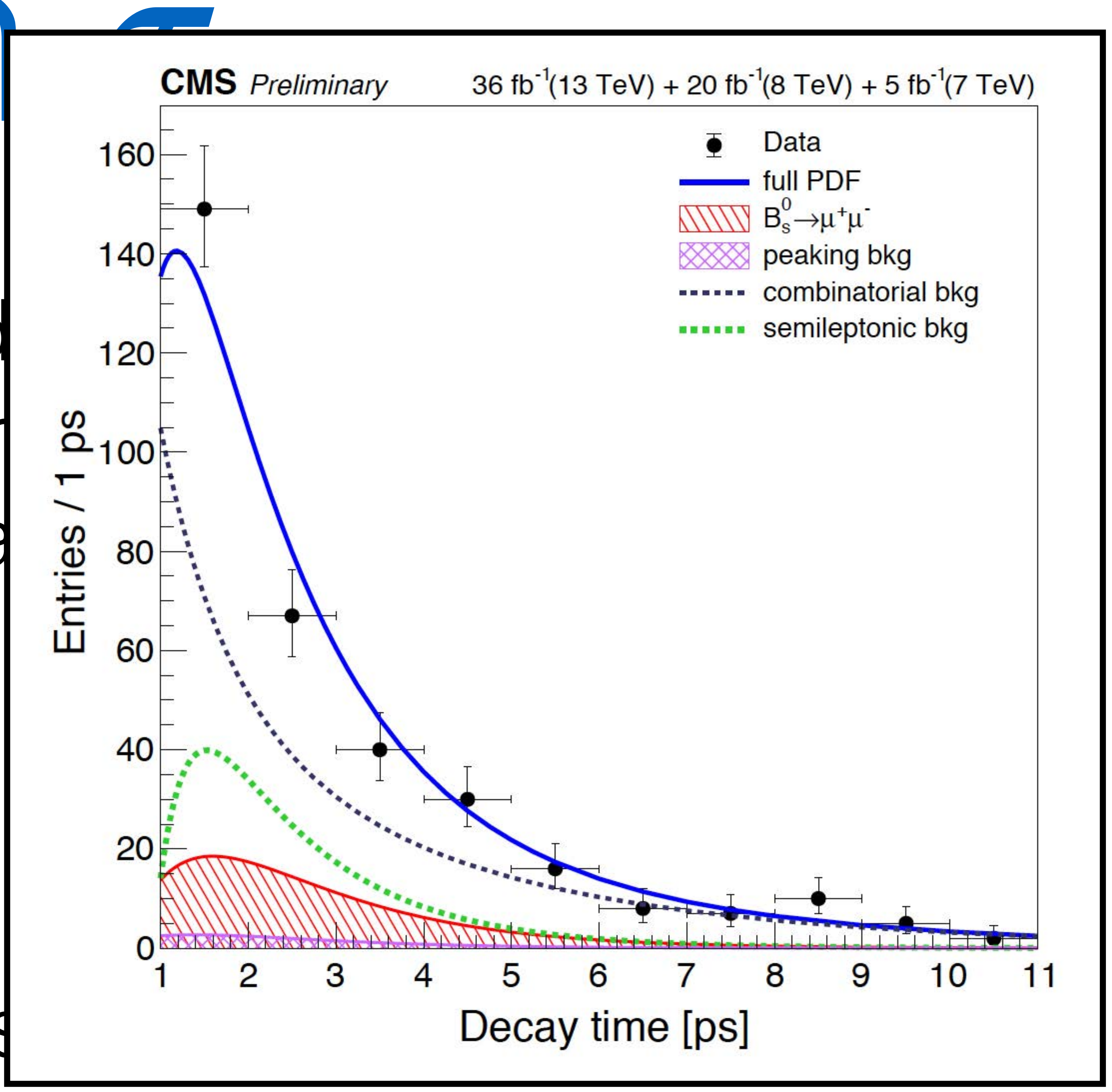
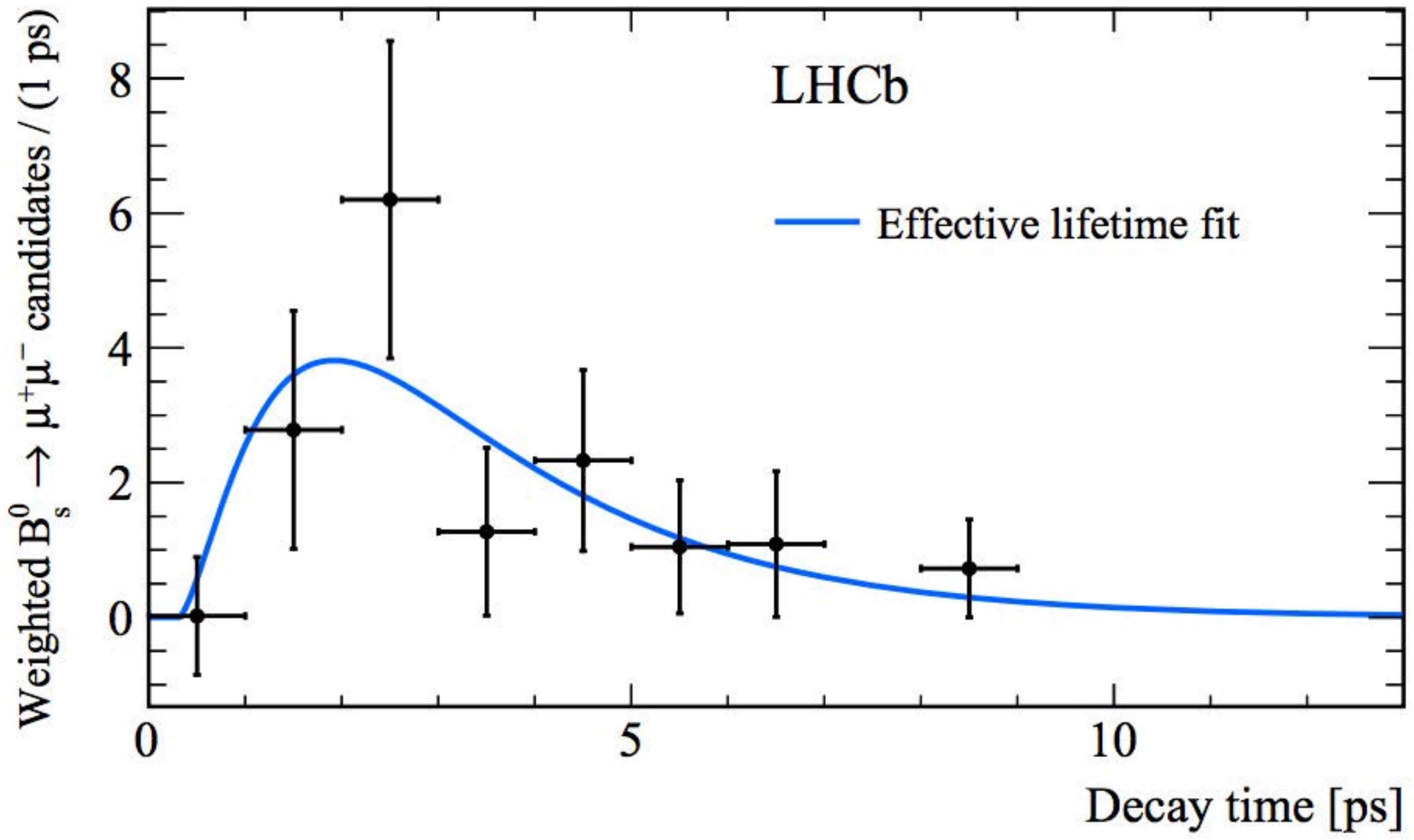
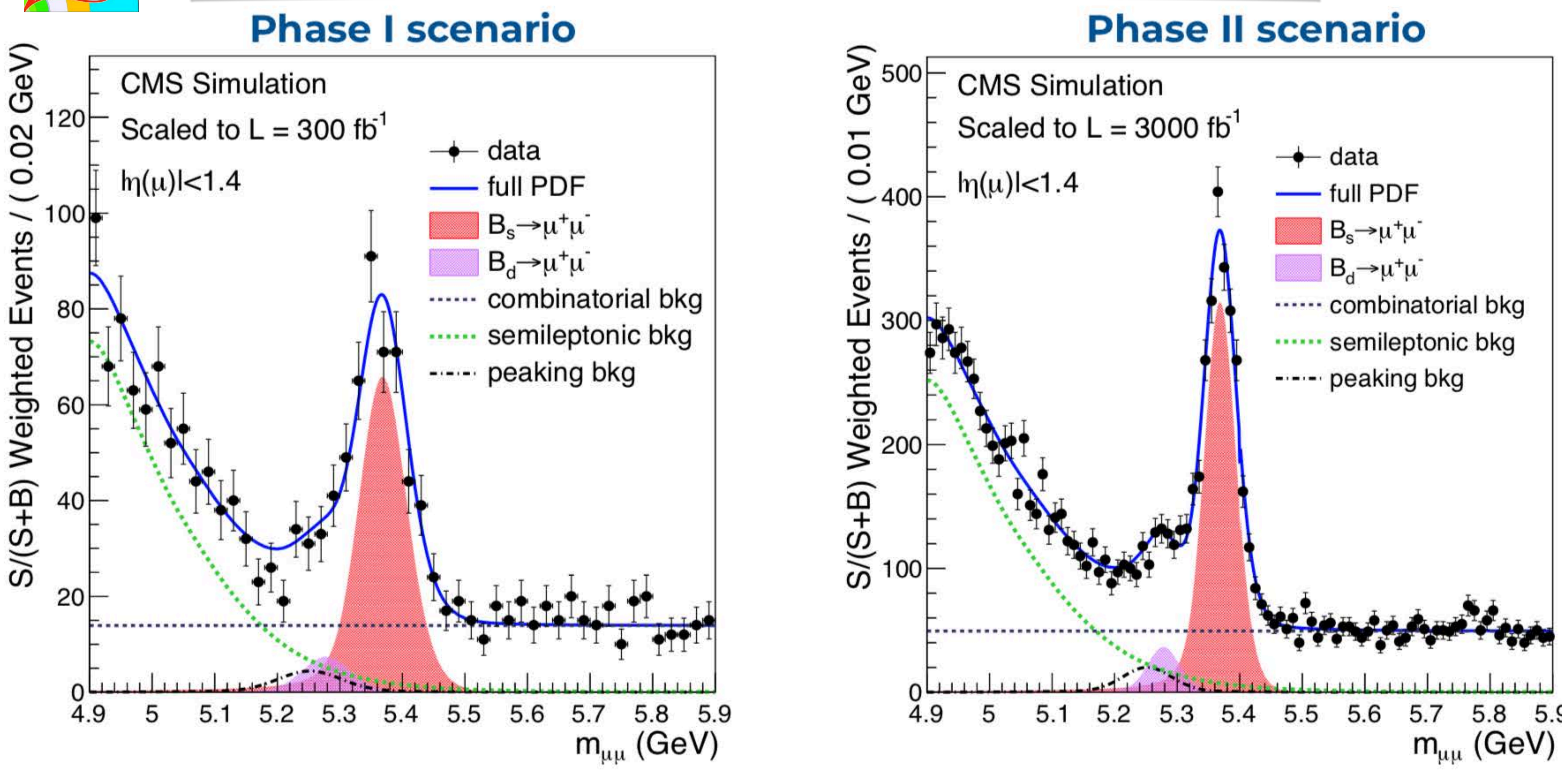




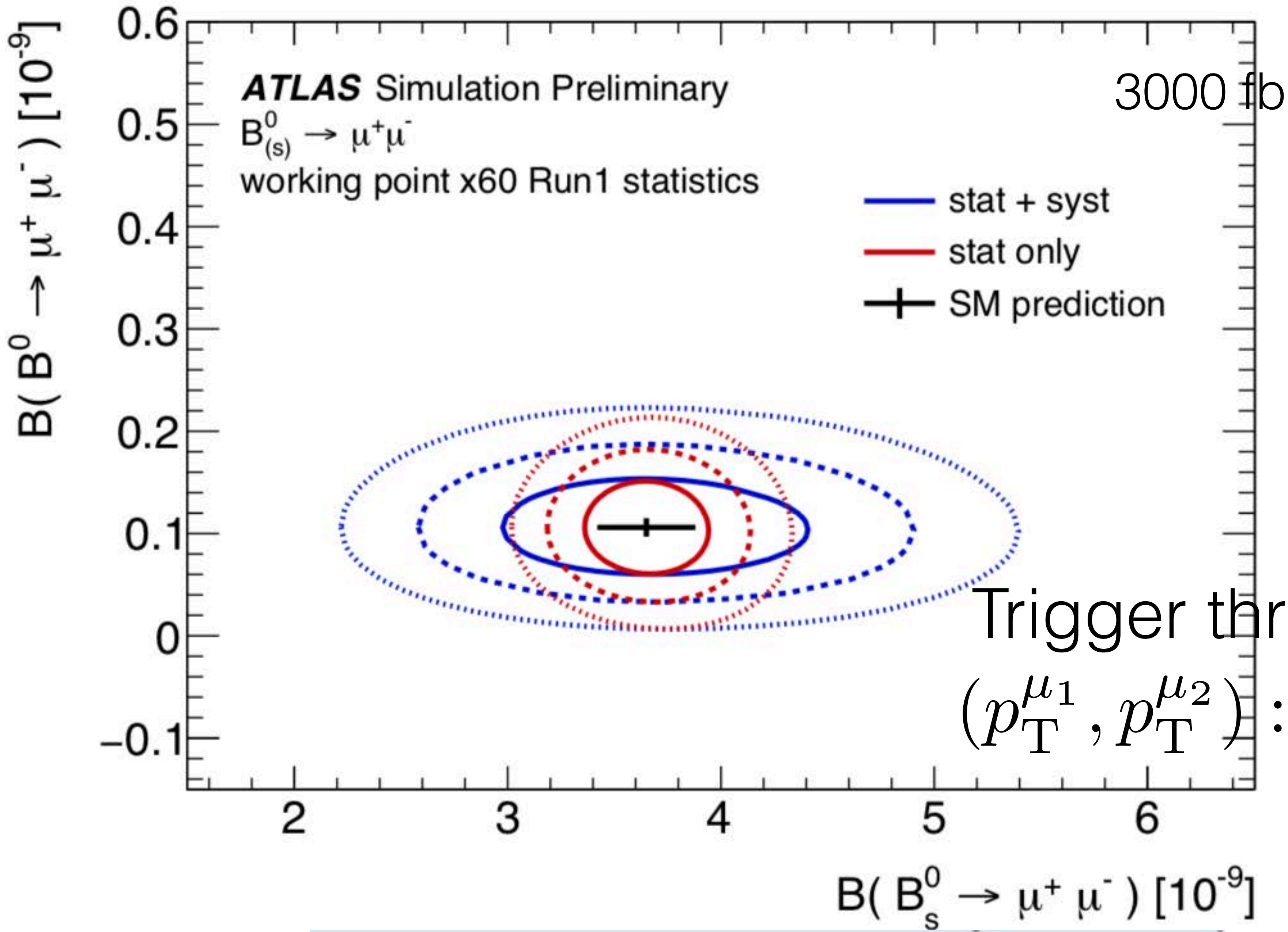
PRL 118 (2017) 191801

$B_{(s)} \to \mu^+\mu^-$ projections

CMS PAS FTR-14-015



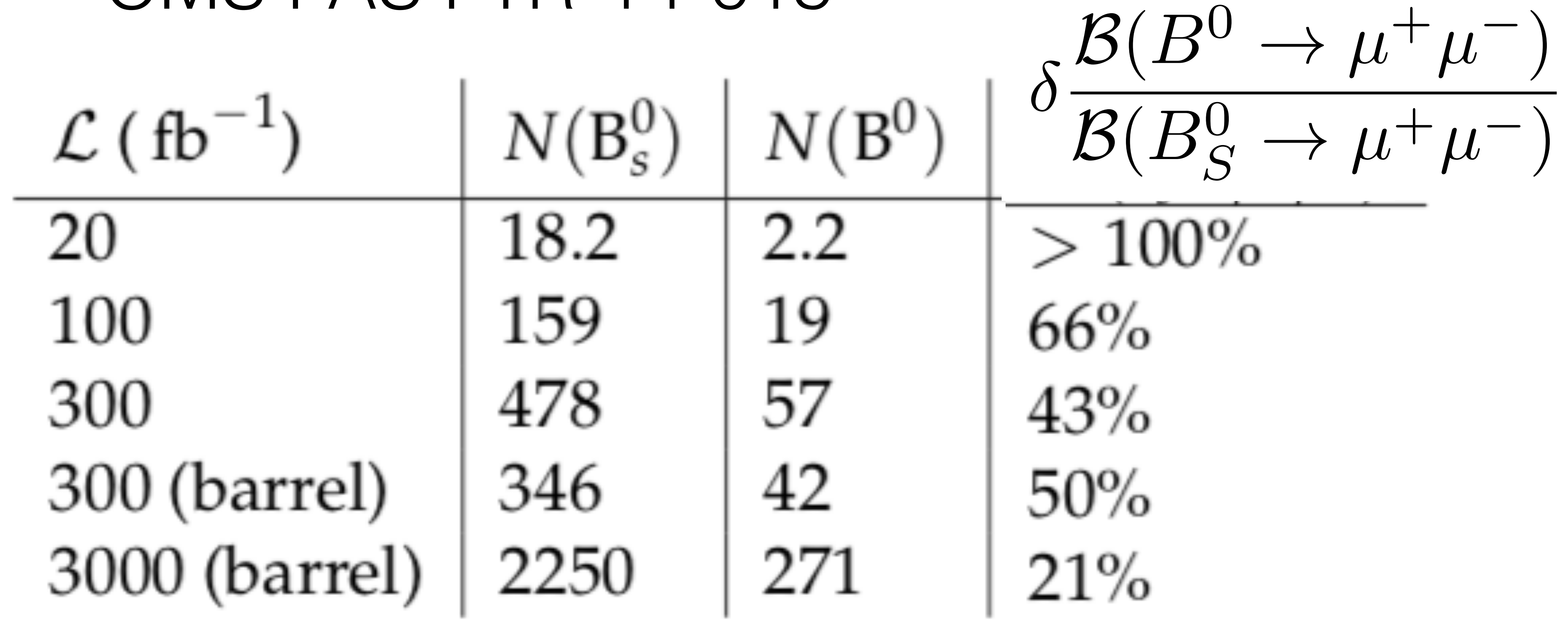
ATLAS-PHYS-PUB-2018-005



Trigger thresholds:

$(p_T^{\mu_1}, p_T^{\mu_2}) : (6\,\mathrm{GeV},\ 10\,\mathrm{GeV})$

CMS PAS FTR-14-015

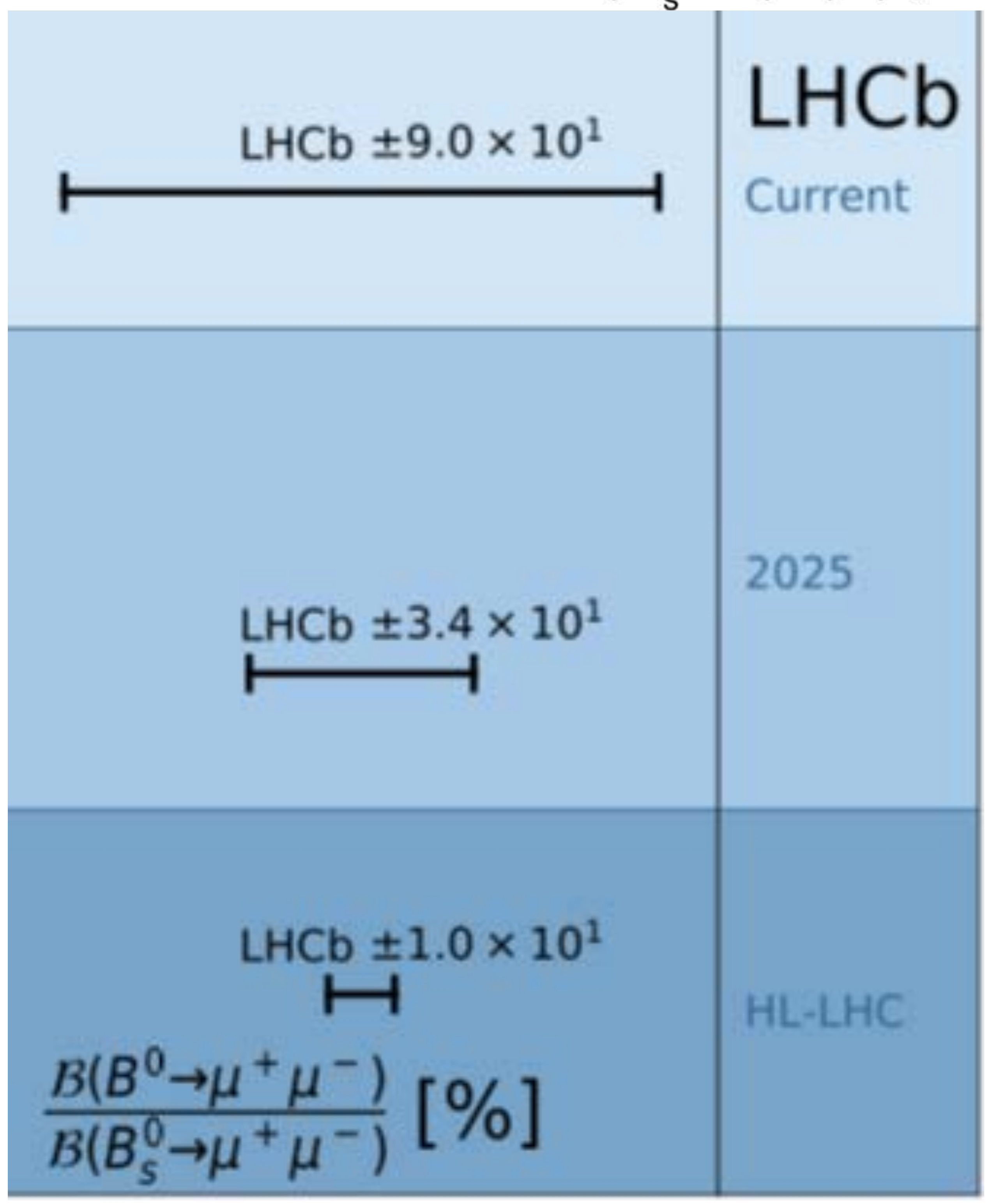


$\mathcal{L}$ (fb^{-1})	$N(B^0_s)$	$N(B^0)$	$\delta\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B^0_S\to\mu^+\mu^-)}$
20	18.2	2.2	> 100%
100	159	19	66%
300	478	57	43%
300 (barrel)	346	42	50%
3000 (barrel)	2250	271	21%

LHCb (23/300 fb^{-1})

~34 %

~10 %



τ_{eff}

~8 %

~2 %

LHCb: Physics case for an LHCb Upgrade II, CERN/LHCC 2018-027

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

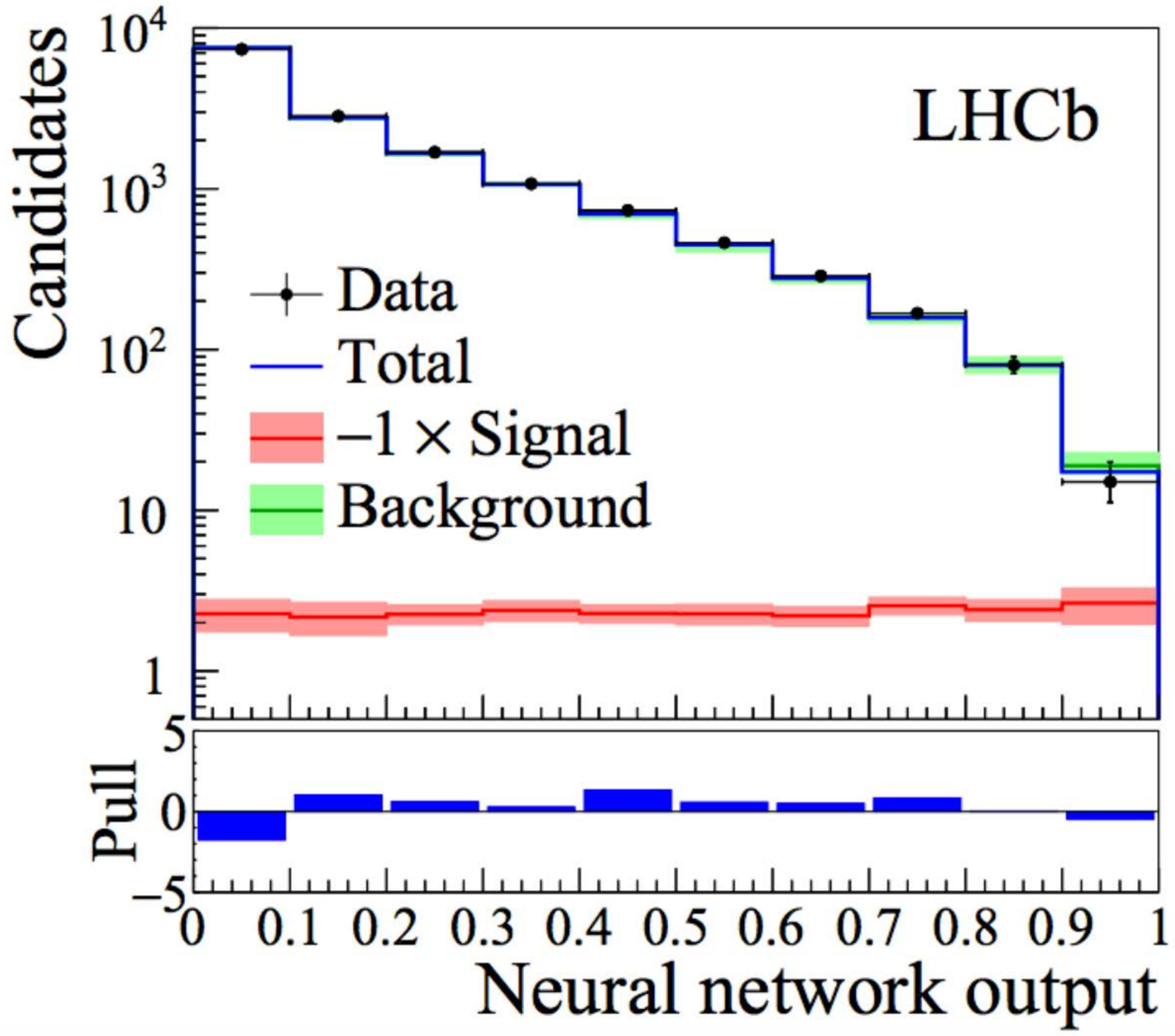
- In the SM, larger BF due to larger τ mass $(m_\tau^2/M_\mathrm{B}^2)$

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

Bobeth et al.
PRL 112 (2014) 101801

- Experimentally challenging due to undetected neutrinos in final state

- Searched by LHCb through the decay
$$\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$$
- $B_{\mathrm{s,d}}$ 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 (Run1 data):

PRL 118 (2017) 251802

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

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

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

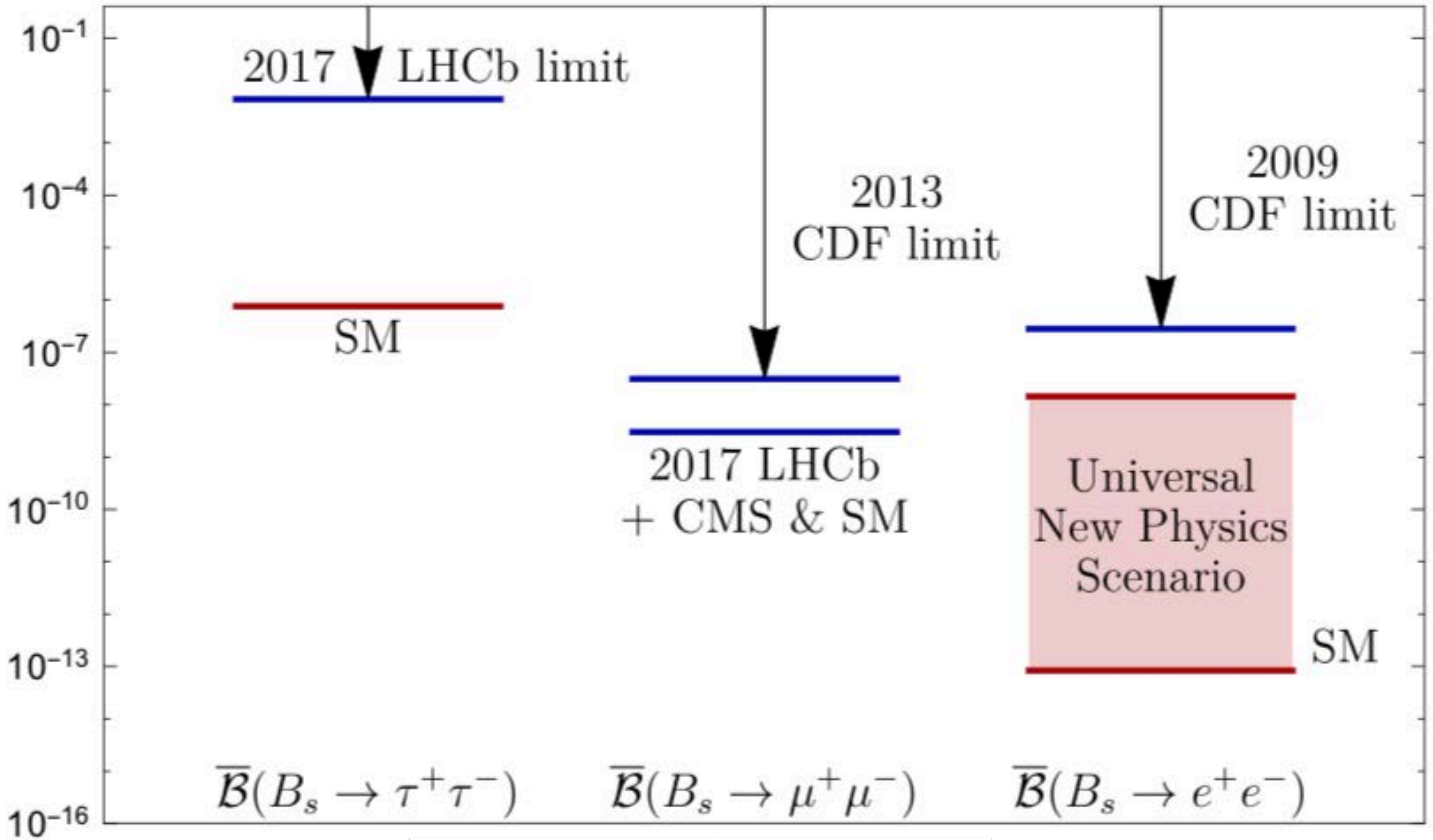
- In SM, smaller BF wrt $B(B_s \to \mu^+\mu^-)$ due to tiny $(m_e)^2$ factor
  $B_s \to e^+e^- = (8.54 \pm 0.55) \times 10^{-14}$

Bobeth et al.
PRL 112 (2014) 101801

  - out of reach from the experimental point of view →very little attention
  - current limit by CDF (from 2009) $B_s \to e^+e^- = < 2.8 \times 10^{-7}$ @ 90 % CL

CDF: PRD102 (2009)201801

- Ongoing LHCb measurement based on Run1 and partial Run 2 relative to $B^+ \to K^+ J/\psi(\to e^+e^-)$
- Analysis in advanced stage, with Interesting projected sensitivity

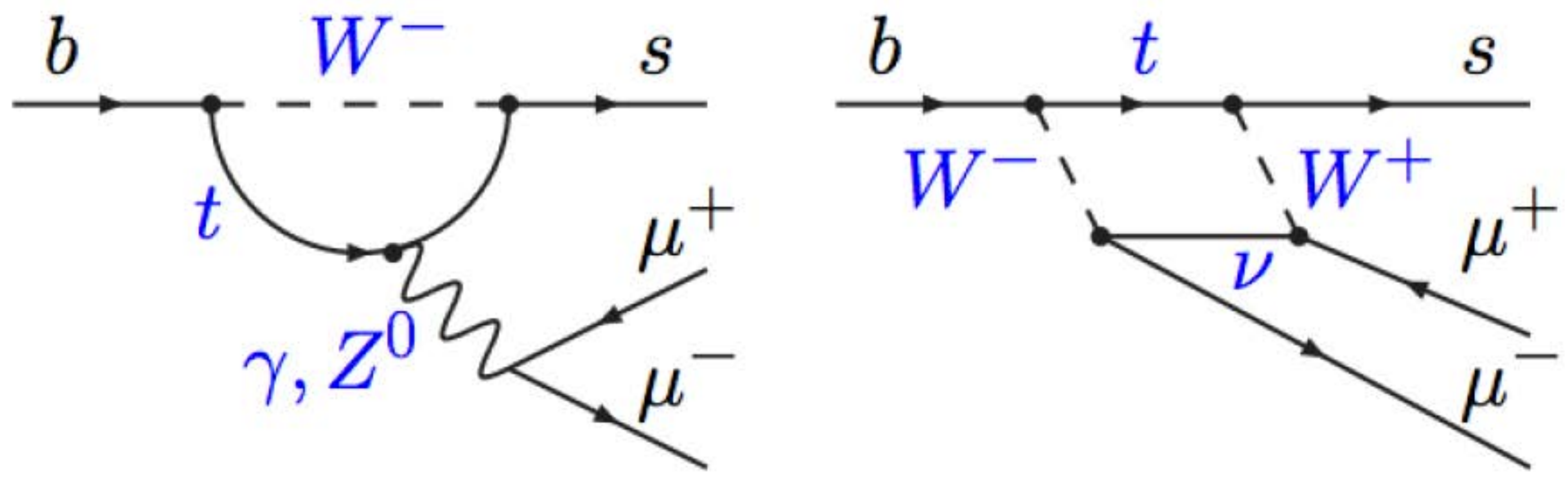


Fleicher et al.
JHEP05 (2017)156

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

Event 27196644
Run 116153
Tue, 22 May 2012 09:02:21

Other interesting rare decays: $b \to s\ell^+\ell^-$ transitions

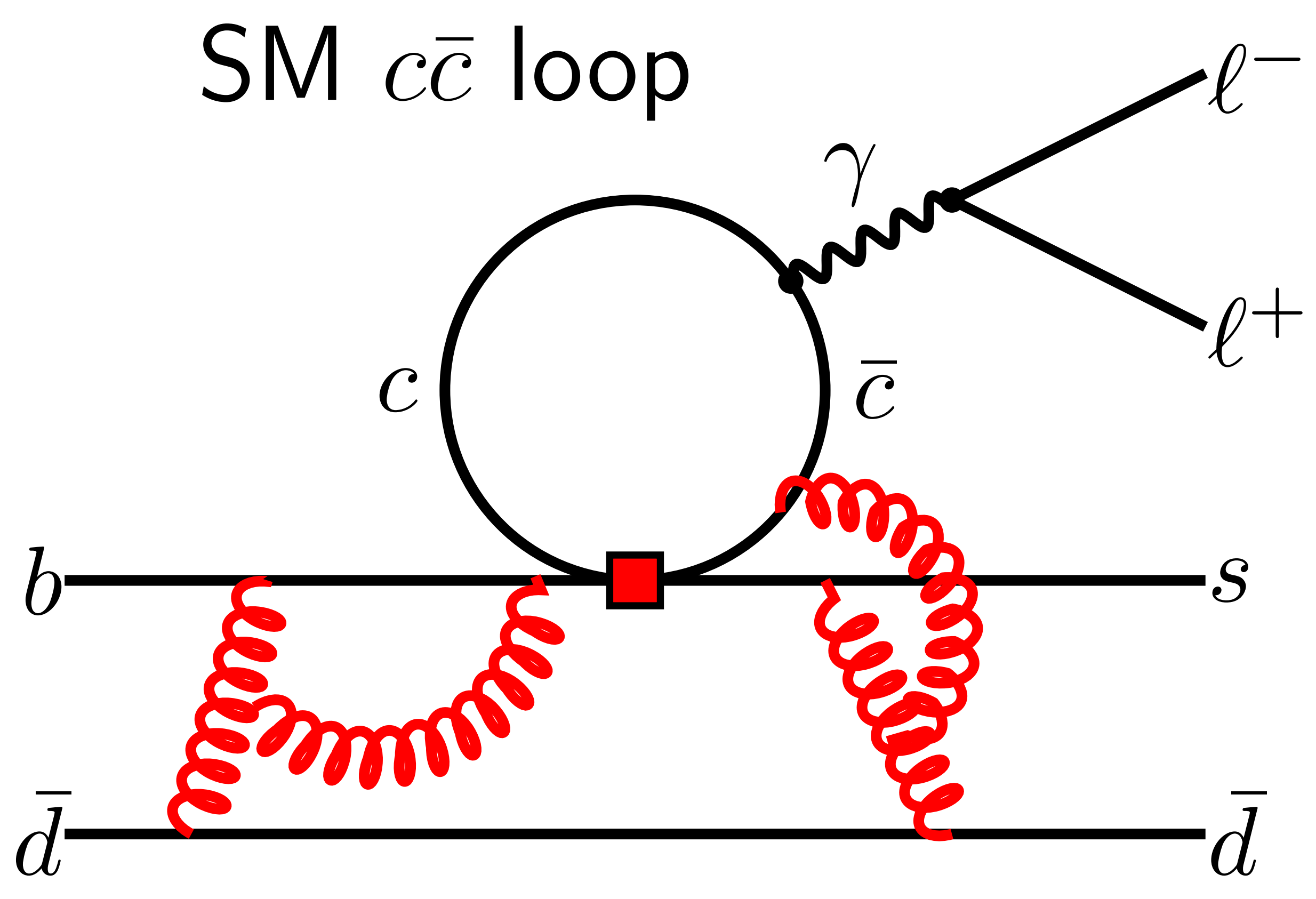


- Can only proceed via loop diagrams

- NP can be competitive with SM processes

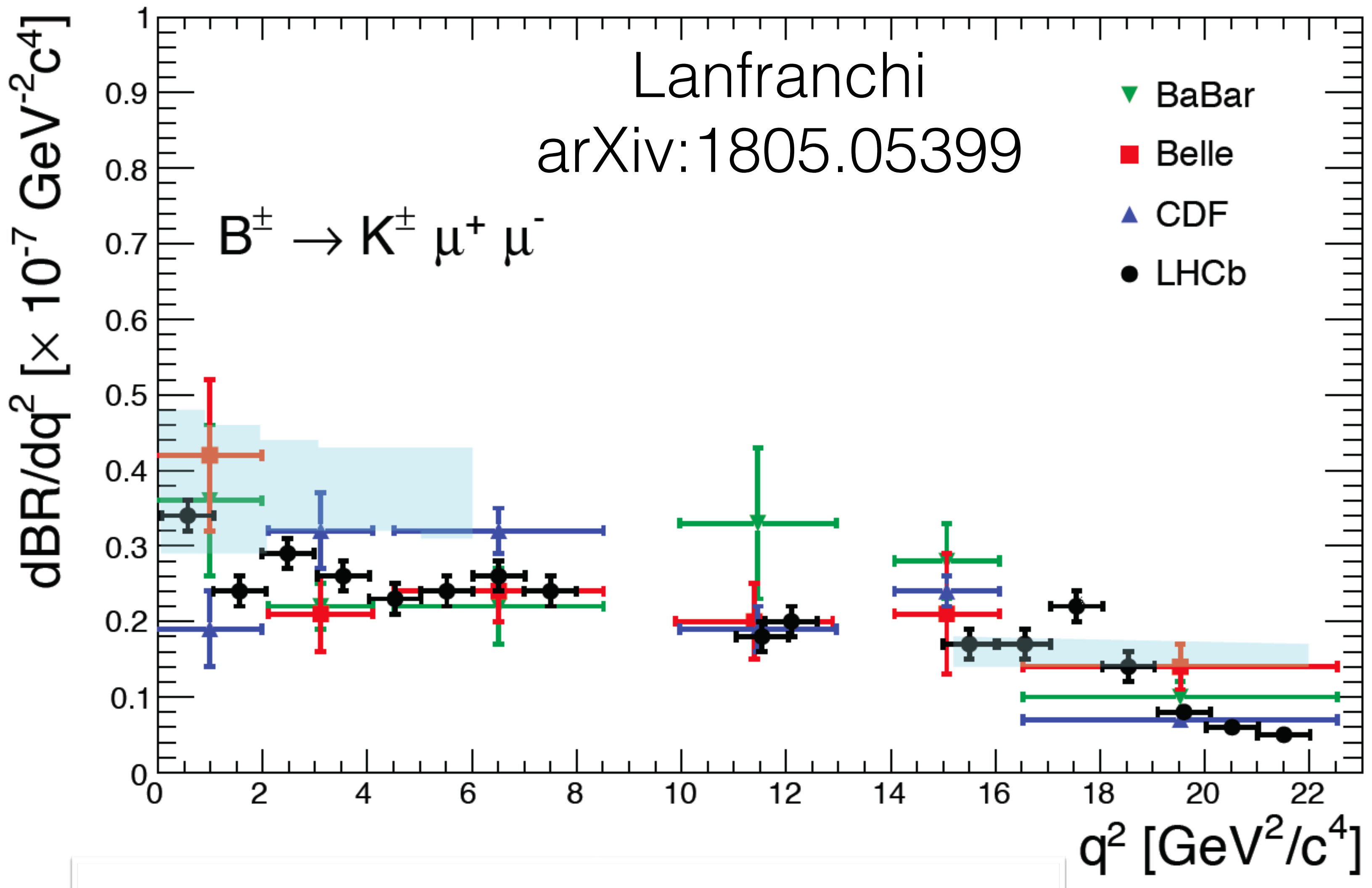
- Rates, angular distributions and asymmetries sensitive to NP

- 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
  - E.g: Are we estimating correctly contributions from charm loops that produce a $\ell^+\ell^-$ pair via a virtual photon?

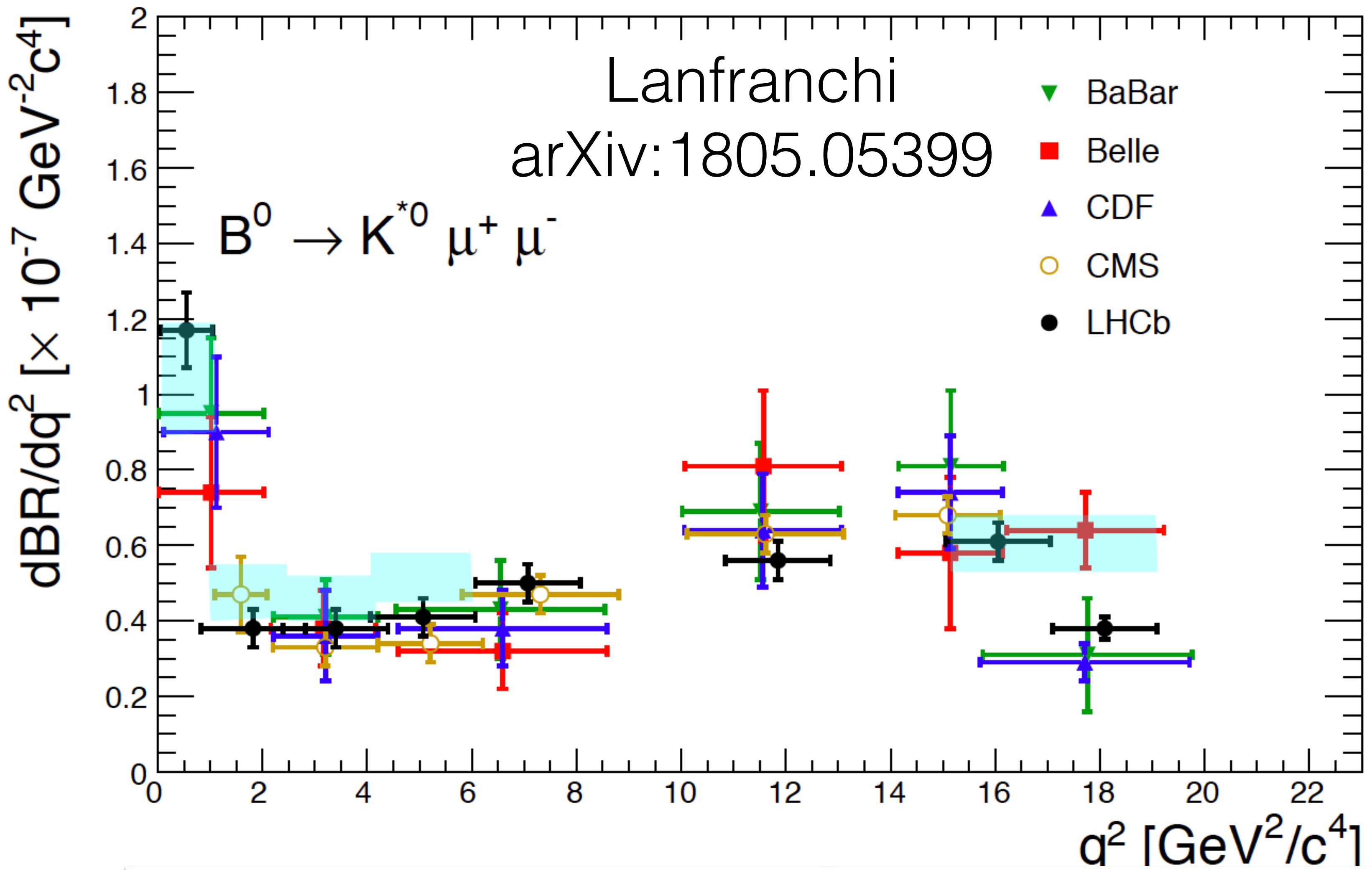


- Question: how clean?

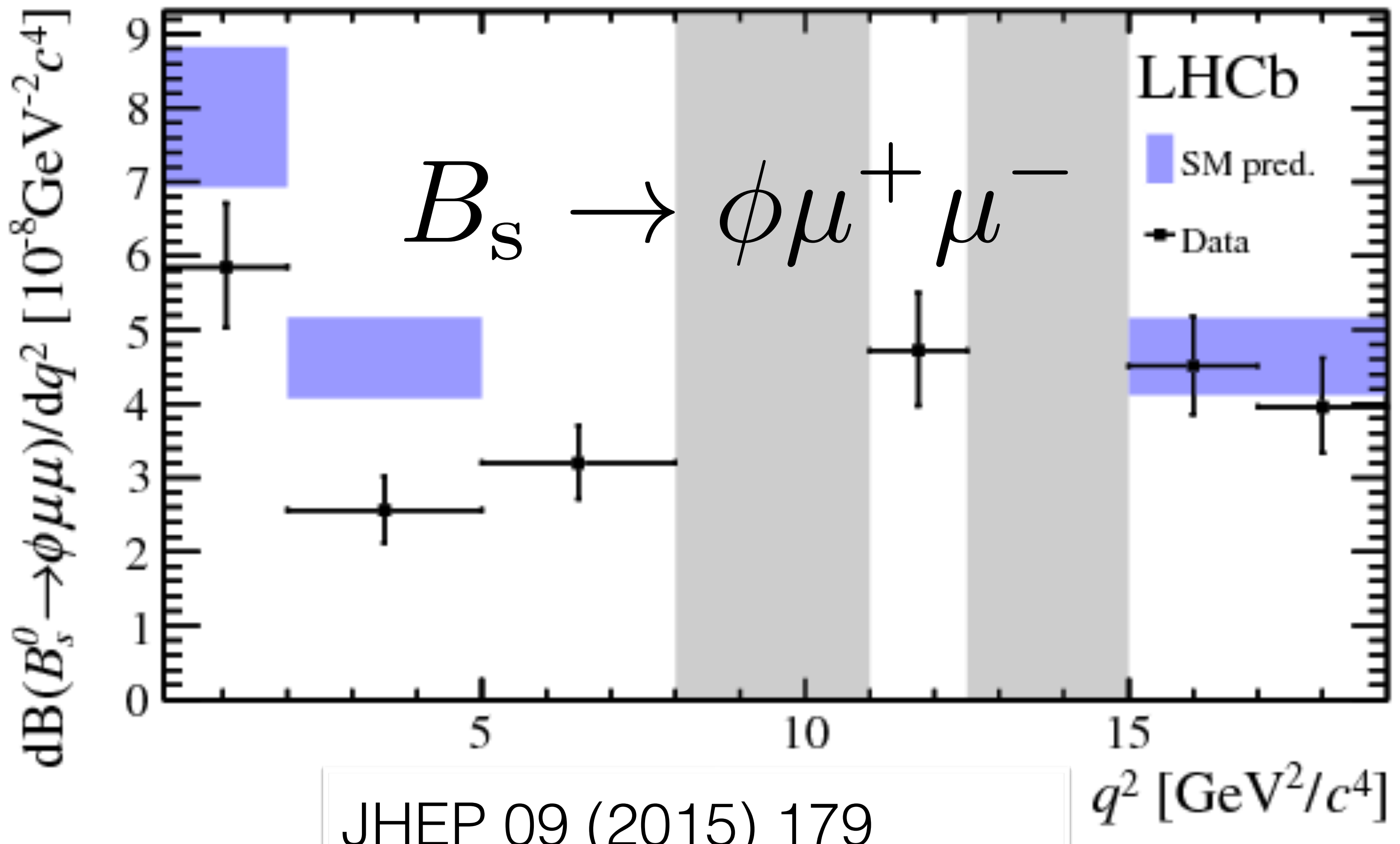
Intriguing set of results in differential branching fractions for b→sμμ transitions



LHCb: JHEP 06 (2014) 133
BaBar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801
CDF: PRL 107 (2011) 201802



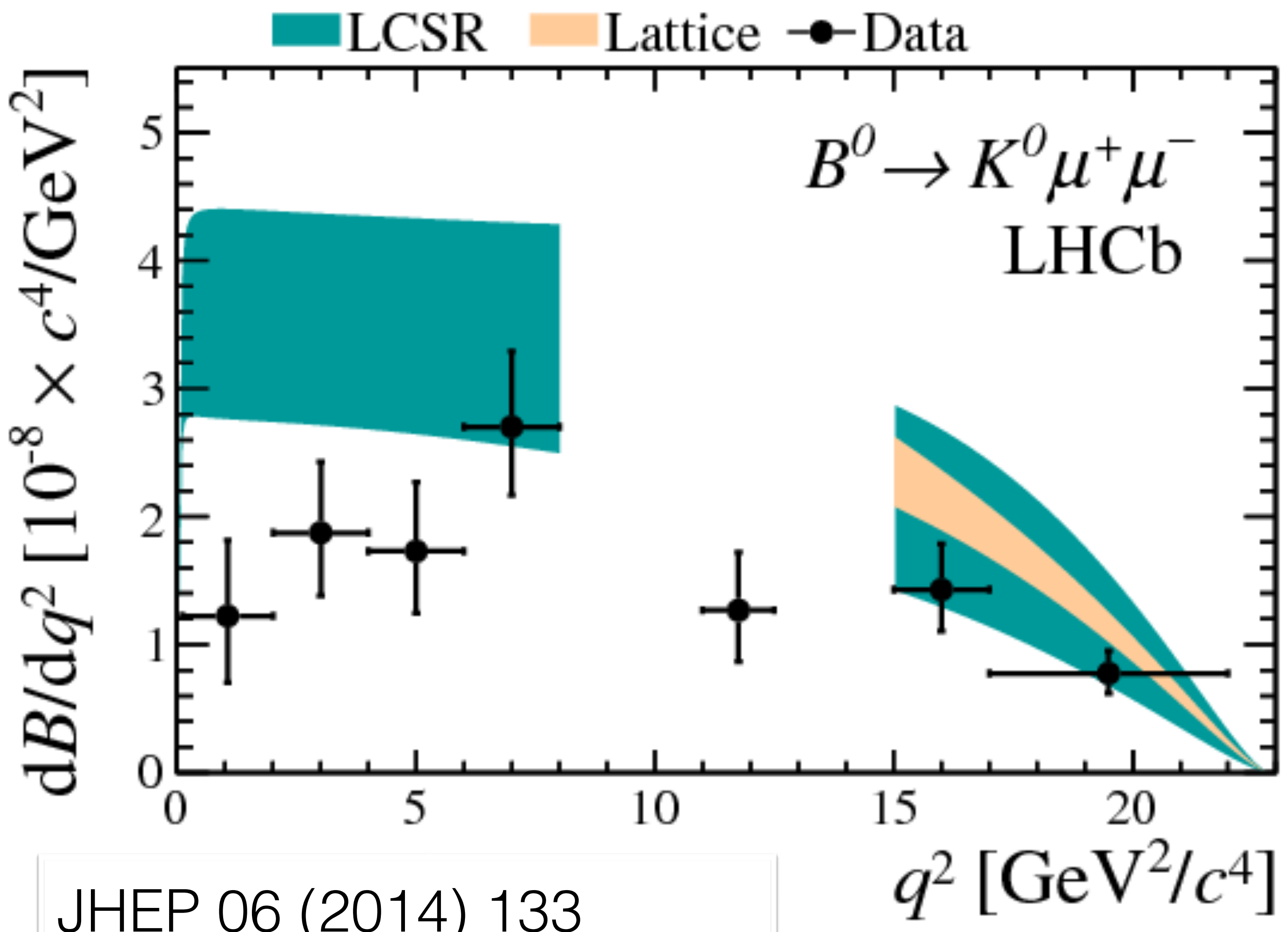
CMS: PLB 753 (2016) 424
LHCb: JHEP 11 (2016) 047, JHEP 04 (2017) 142
BaBar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801
CDF: PRL 107 (2011) 201802



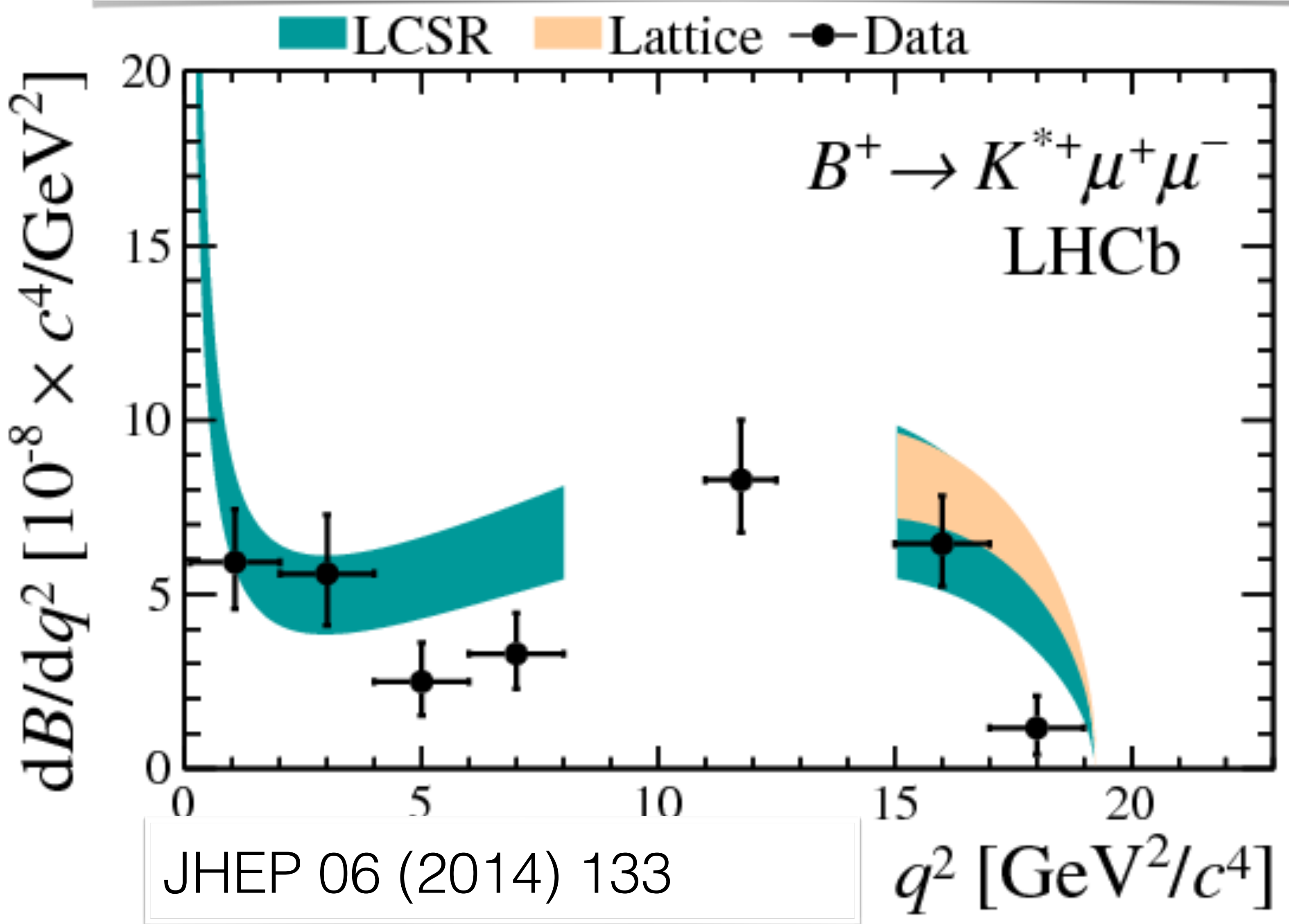
JHEP 09 (2015) 179

$$q^2 = m^2_{\mu^+\mu^-}$$

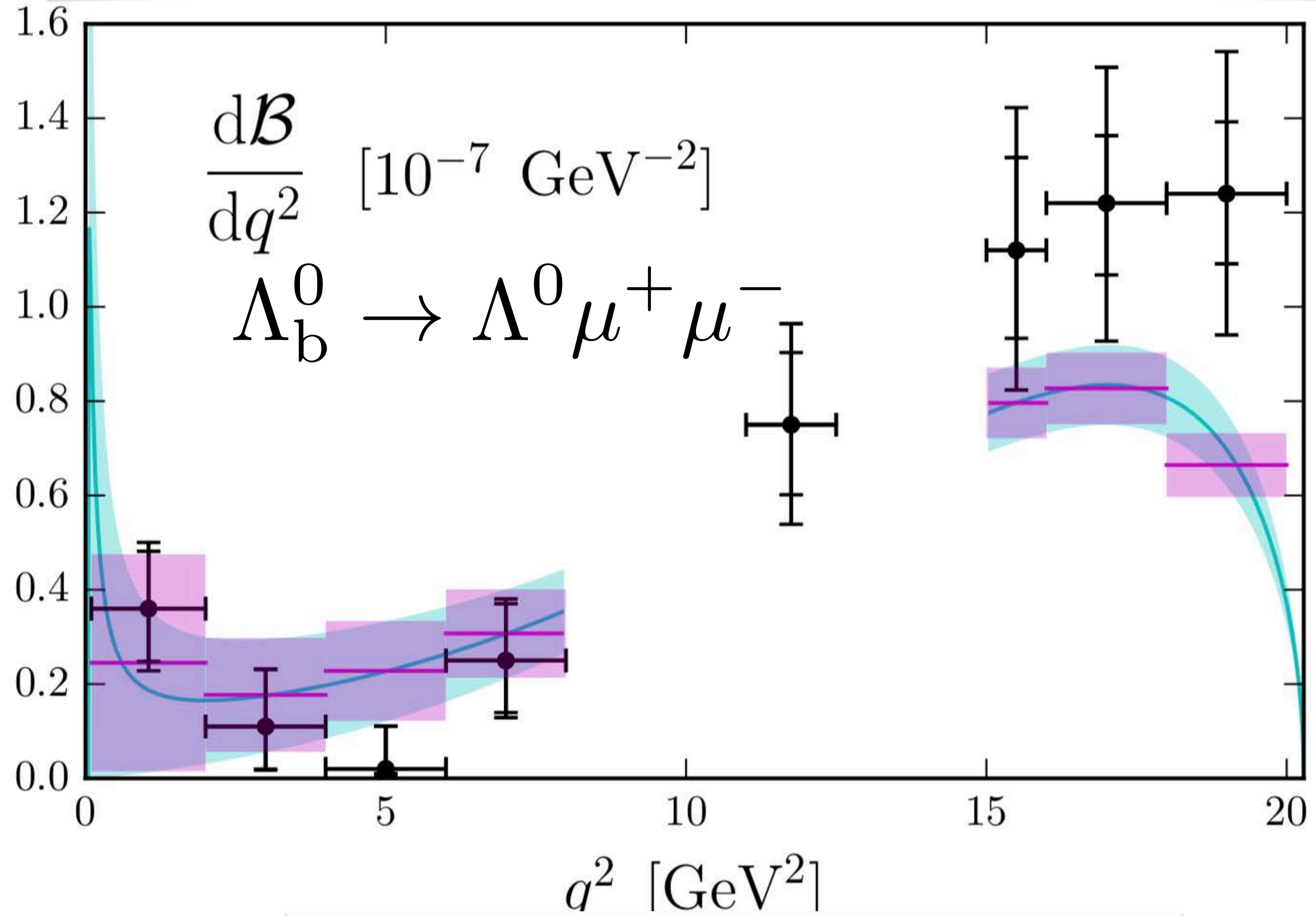
Detmold and Meinel, PRD93 074501 (2016)



JHEP 06 (2014) 133



JHEP 06 (2014) 133

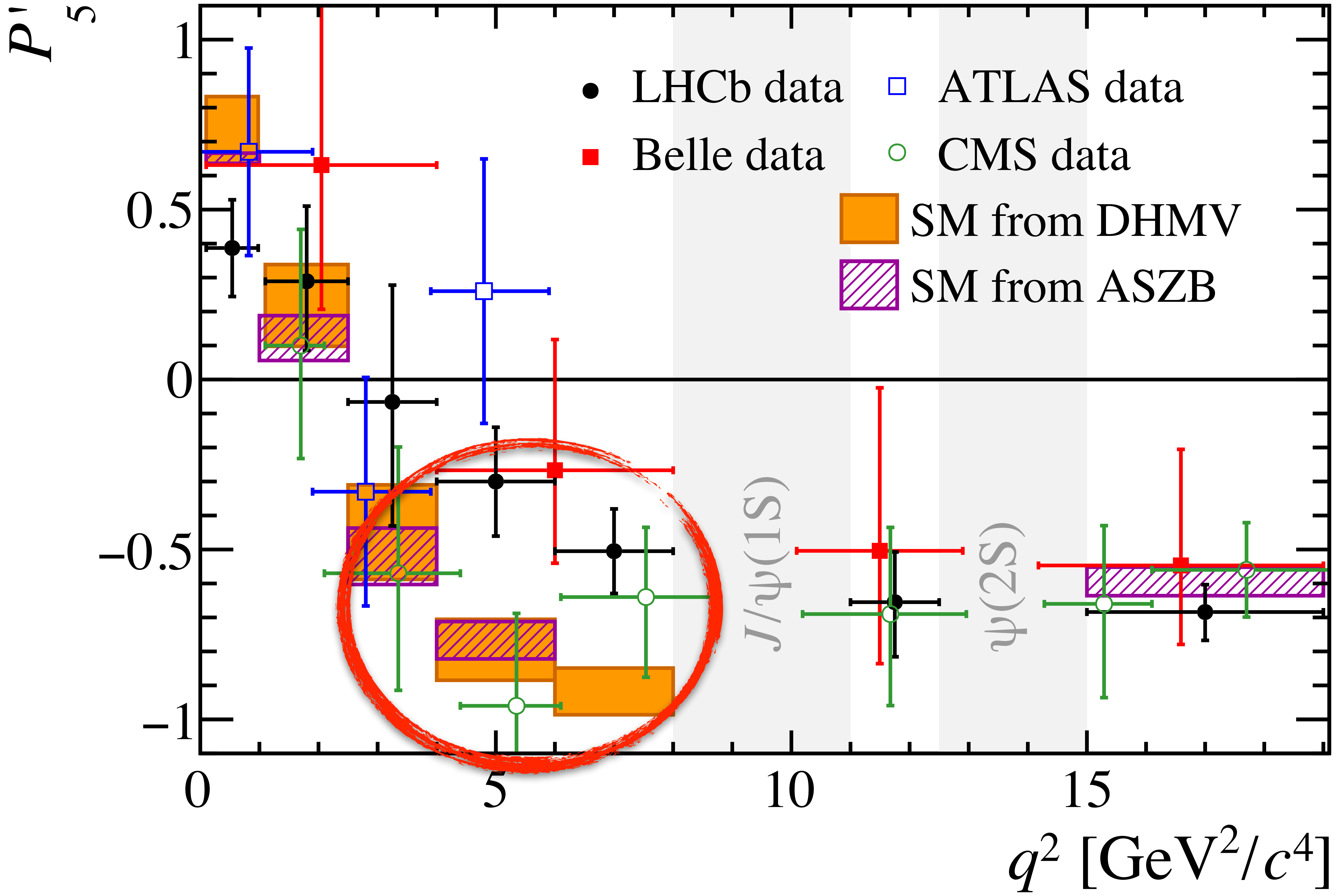


JHEP 06 (2015) 115

- In general, data tend to be lower than theory predictions at low q^2
- Comparison limited by theoretical knowledge of form factors

The curious case of P_5'

- 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: arXiv:1805.04000
CMS-PAS-BPH-15-008

- Is the SM prediction less precise than what is claimed?
- Ongoing work to update analysis of LHCb data up to 2016

Other intriguing results in 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: m_τ, m_μ, m_e ↔ 3477 / 207/ 1

- 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)

- Test LFU in $b \to s\ell^+\ell^-$ transitions, i.e. flavour-changing neutral currents with amplitudes involving loop diagrams

The family of R ratios

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

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

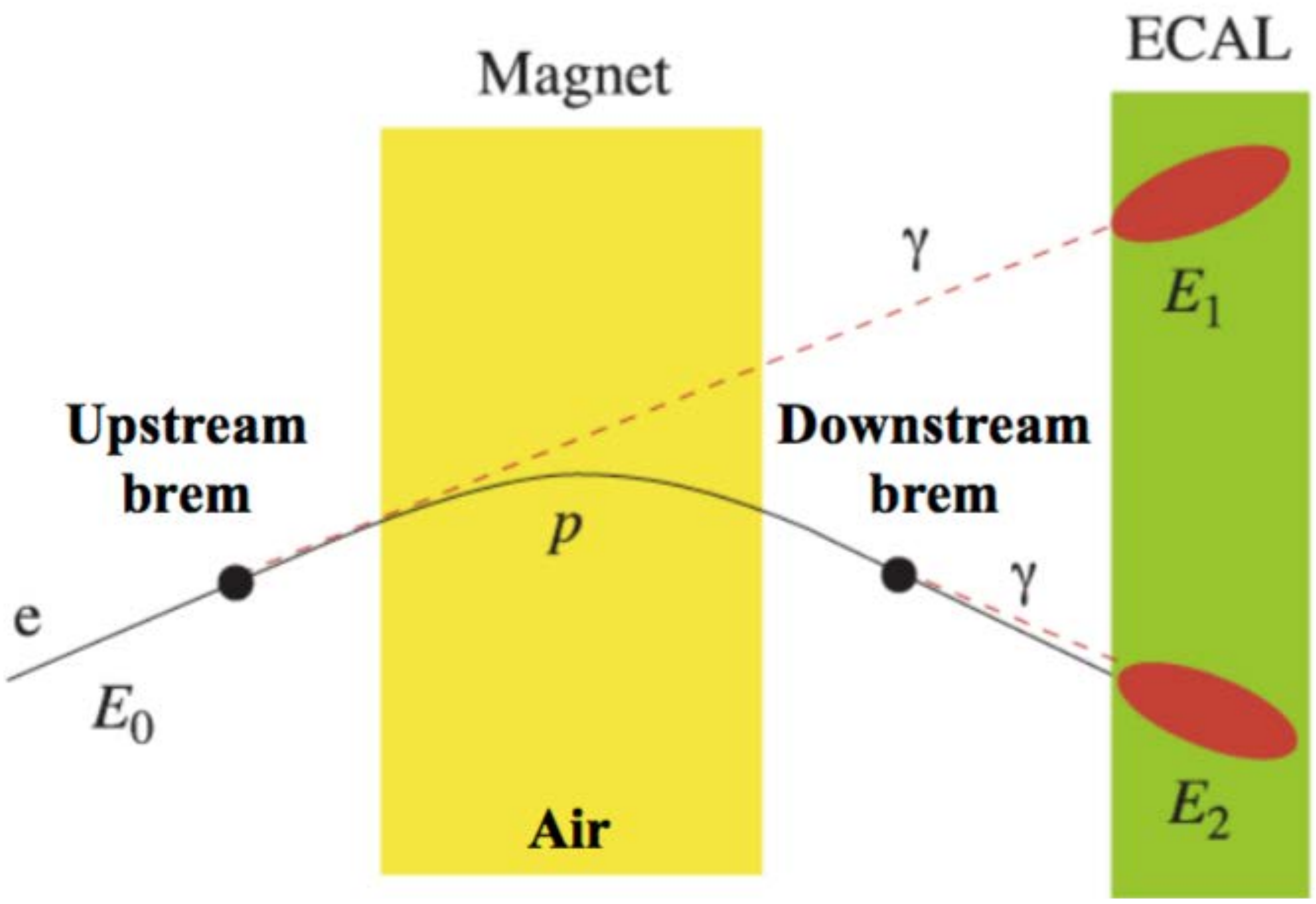
$$H = K, K^*, \phi, \ldots$$

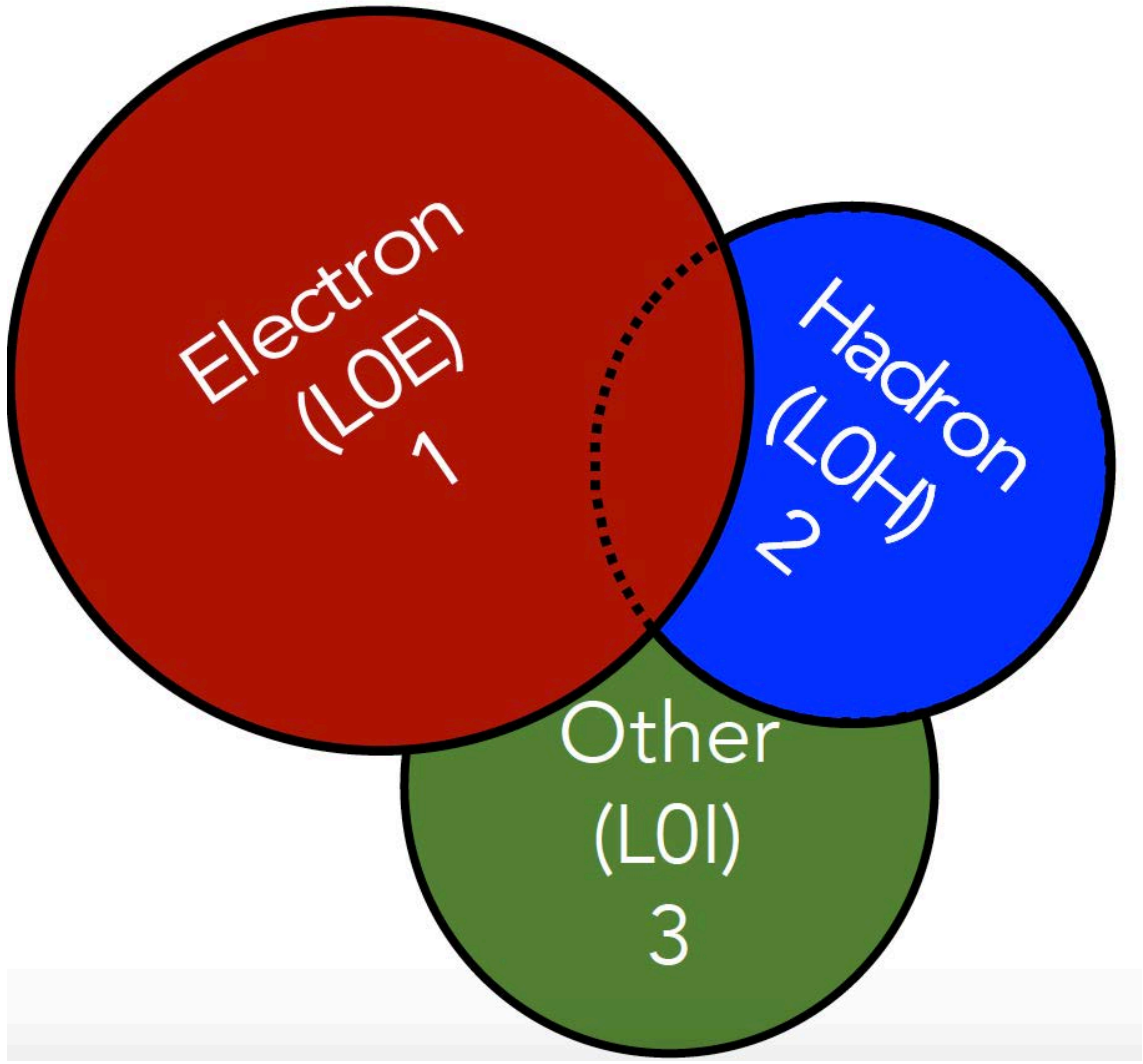
- These ratios are clean probes of NP :
  - Sensitive to possible new interactions that couple in a non-universal way to electrons and muons
  - Small theoretical uncertainties because hadronic uncertainties cancel : $R_\mathrm{H} = 1$ in SM, neglecting lepton masses, with QED corrections at ~% level

Very challenging measurements

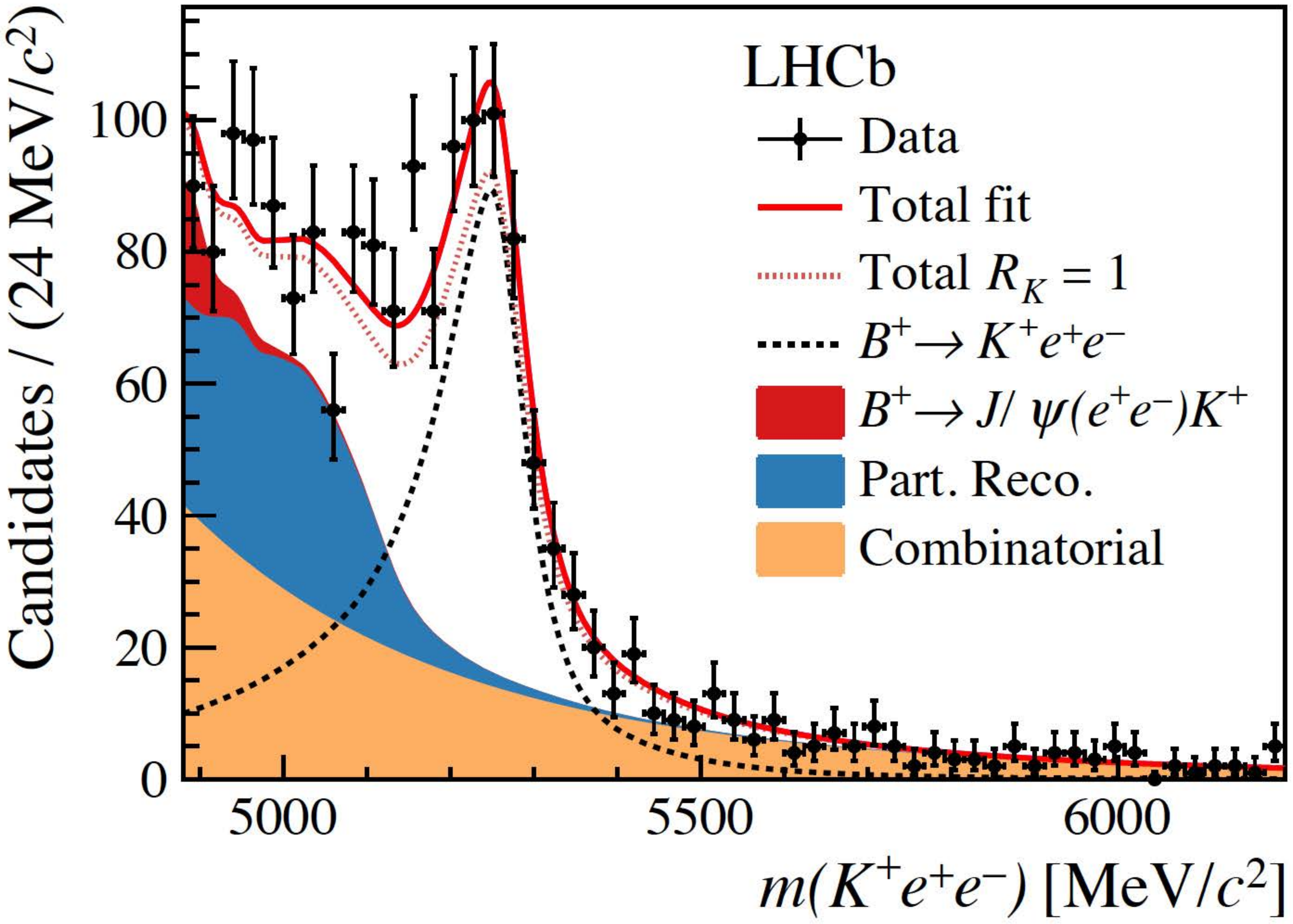
- Lepton identification is anything but universal!
  - Electrons emit a large amount of bremsstrahlung, degrading momentum and mass resolution→ bremsstrahlung recovery can partially fix this
  - Higher occupancy of calorimeters → trigger thresholds are higher for electrons (~2.5 to 3.0 GeV) than for muons (~1.5 to 1.8 GeV) → Mitigate including decays with electrons also selected using hadron trigger either fired by K^* products or by any other particle in the event not associated with signal

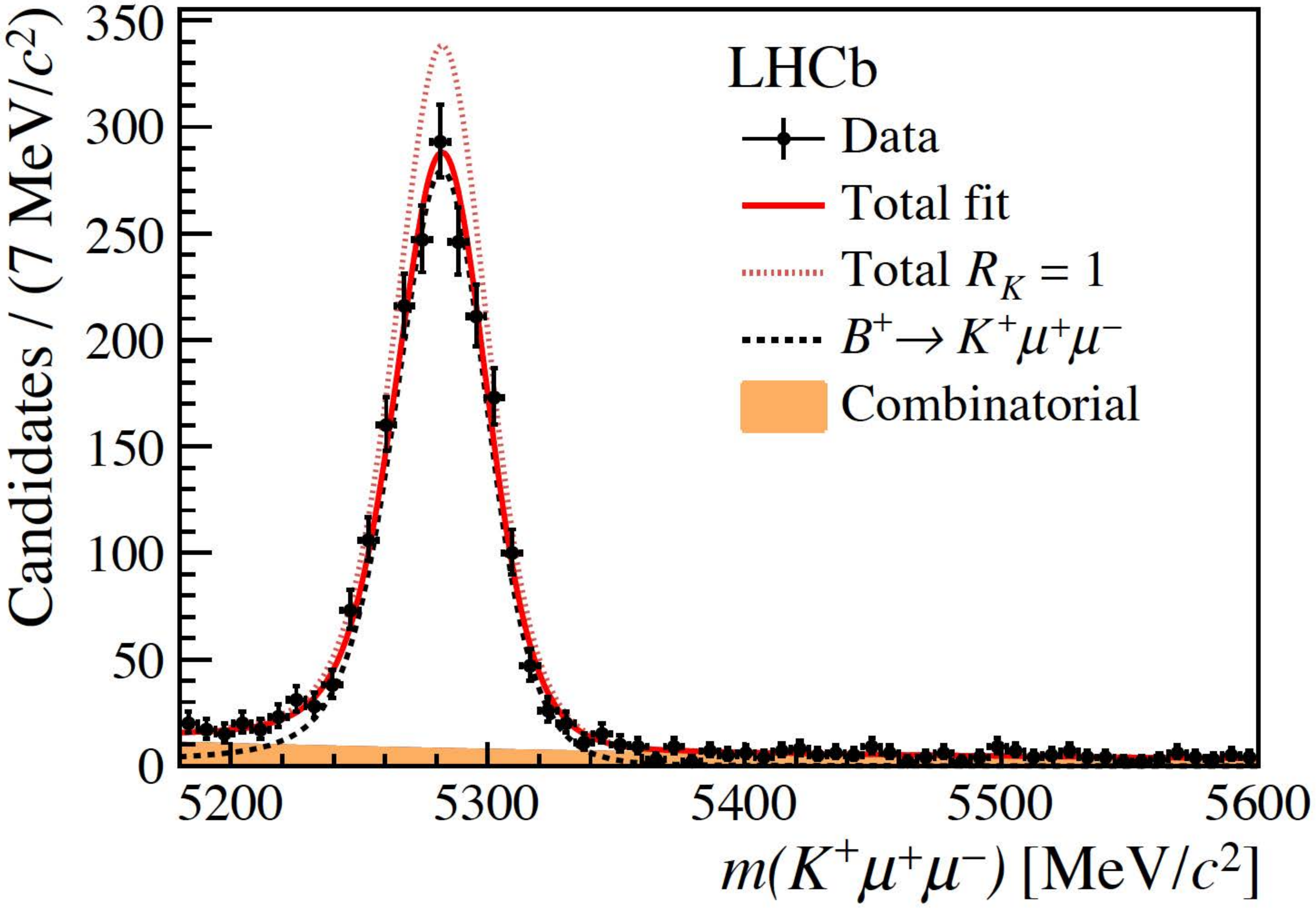
JHEP 08 (2017) 055





electrons vs muons





PRL 122 (2019)191801

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 $B^0 \to J/\psi H$ which are not expected to be affected by NP:

$$R_{\mathrm{H}} = \frac{\mathcal{B}(B^0 \to H\mu^+\mu^-)}{\mathcal{B}(B^0 \to HJ/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to He^+e^-)}{\mathcal{B}(B^0 \to HJ/\psi(\to e^+e^-))}$$

→ Relevant experimental quantities: yields & (trigger, reconstruction and selection) efficiencies for the four decay modes

→ $r_{J/\psi} = \dfrac{B(B \to HJ/\psi(\mu^+\mu^-))}{B(B \to HJ/\psi(e^+e^-))} = 1$ (within 0.4%)

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

- Analyses performed blind

The R_K ratio

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

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

in q^2 interval: $1.1 < q^2 < 6\,\mathrm{GeV}^2$

LHCb: PRL 113 (2014) 151601

- Result compatible with SM at 2.6 σ : $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$
- Performed a re-optimised analysis of 2011-2016 data (total of 5 fb^{-1}) in $1.1 < q^2 < 6\,\mathrm{GeV}^2$
- Factor 2 larger yields than in previous analysis, still statistically dominated by electron mode (~760 e^+e^- candidates vs~1940 $\mu^+\mu^-$ candidates)

Updated R_K result

PRL 122 (2019) 191801

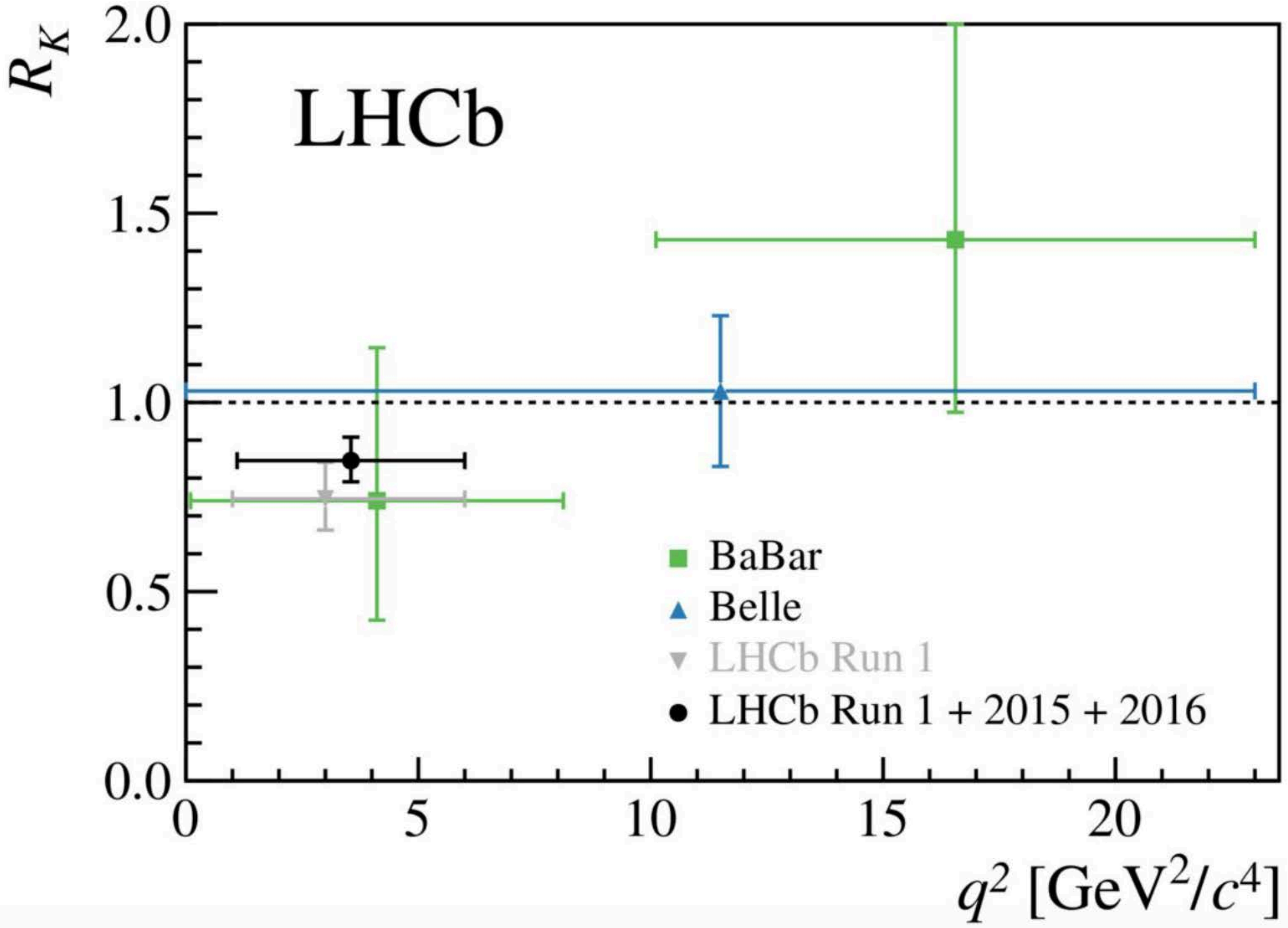
- New result compatible with previous analysis and ~2.5 σ from SM

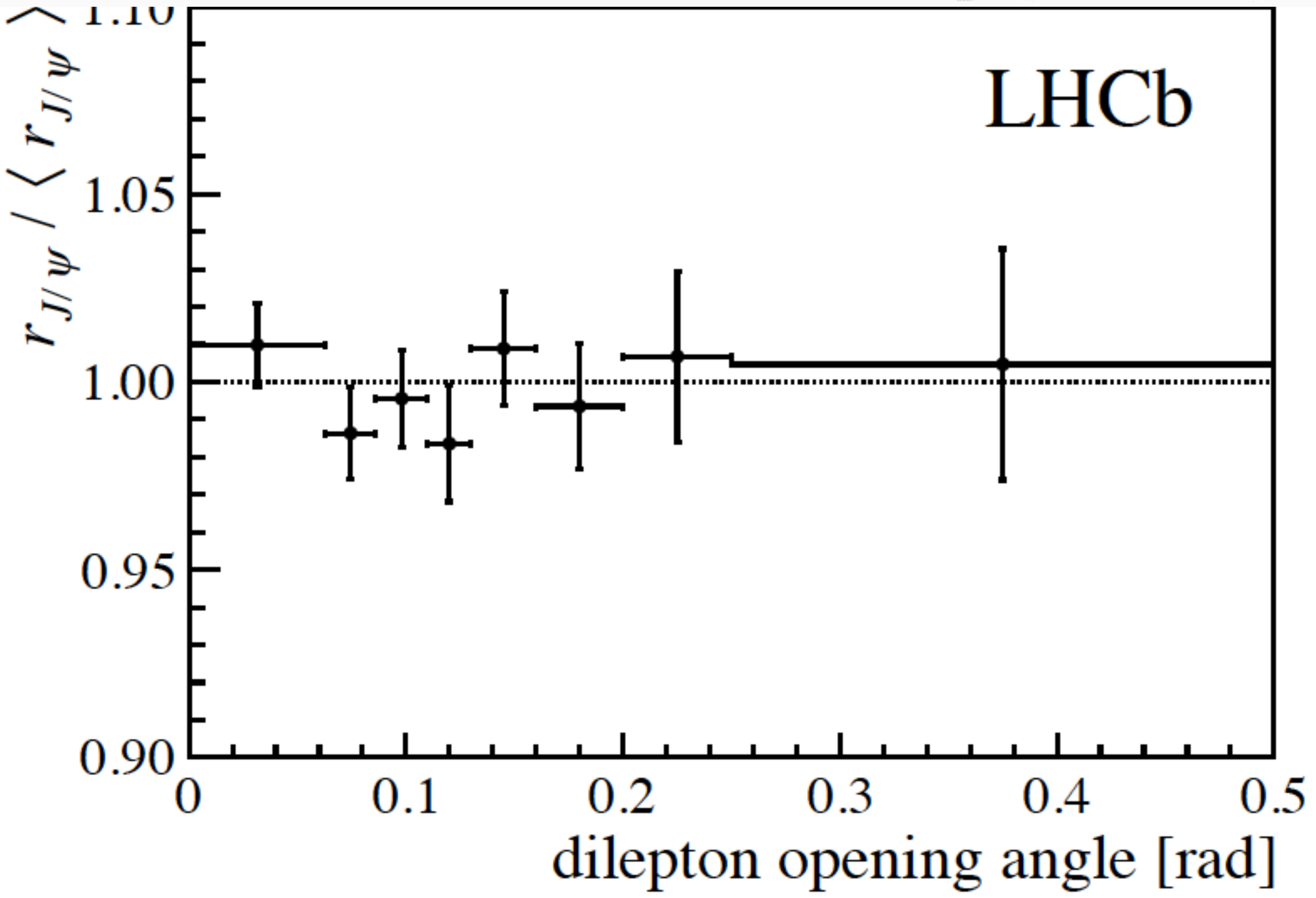
$$R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$$

- $r_{J/\psi}$ cross-check:

$$r_{J/\psi} = 1.014 \pm 0.035$$

- Still x2 B decays recorded by LHCb to be analysed



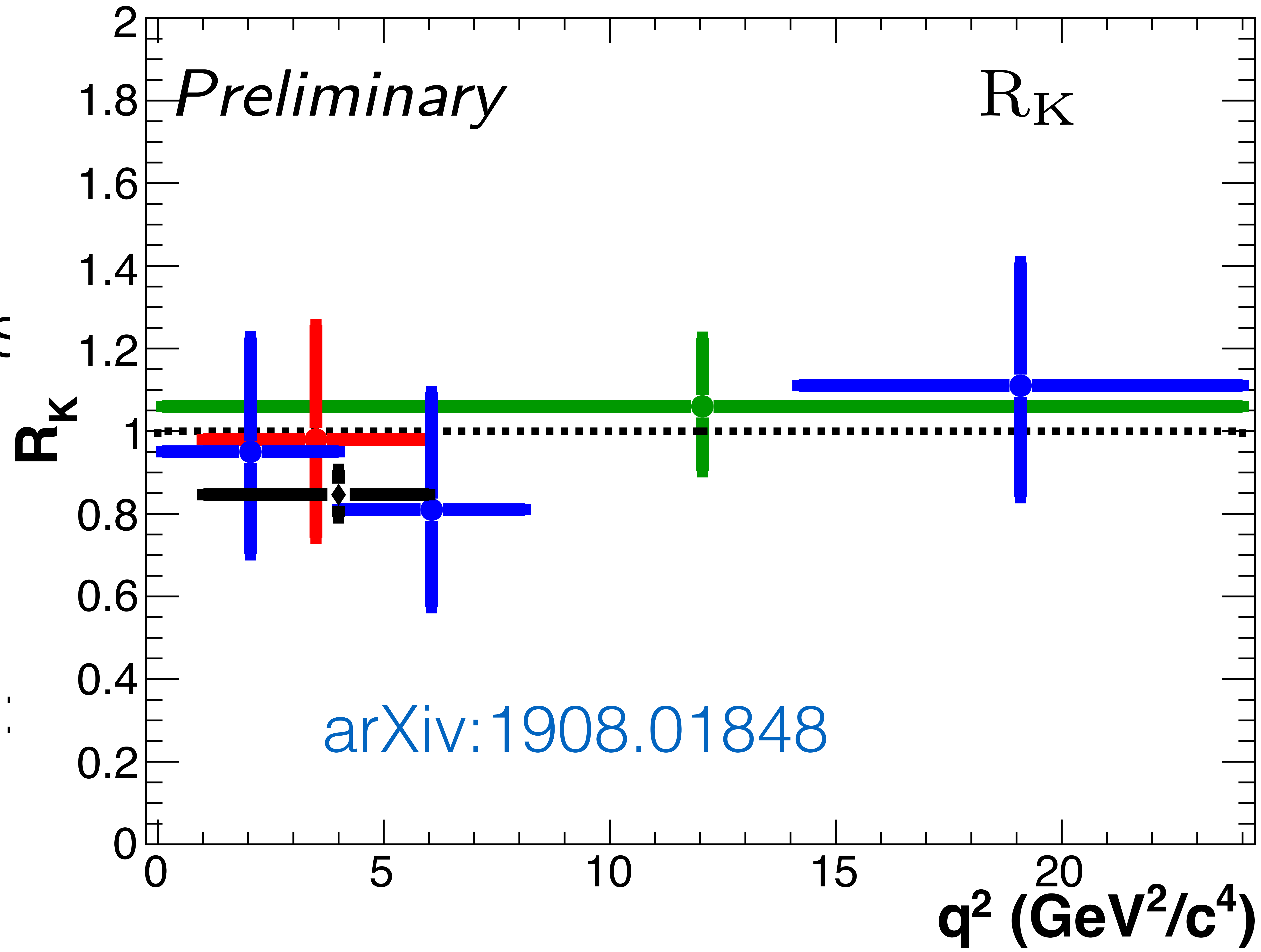


Updated R_K from Belle

- New results from Belle based on full data sample (711 fb^{-1})

- Both charged and neutral modes (K^+, K_s^0) and R_K measured as the weighted average

- R_K measured in various q^2 bins: $[0.1\ ,\ 4.0]$,$[4.0\ ,\ 8.12]$, $[1.0\ ,\ 6.0]$, > 14.18 and > 0.1



- $R_K = 0.98^{+0.27}_{-0.23} \pm 0.06$ for $1.0 < q^2 < 6\,\mathrm{GeV}^2$

- Results compatible with SM expectations and with LHCb

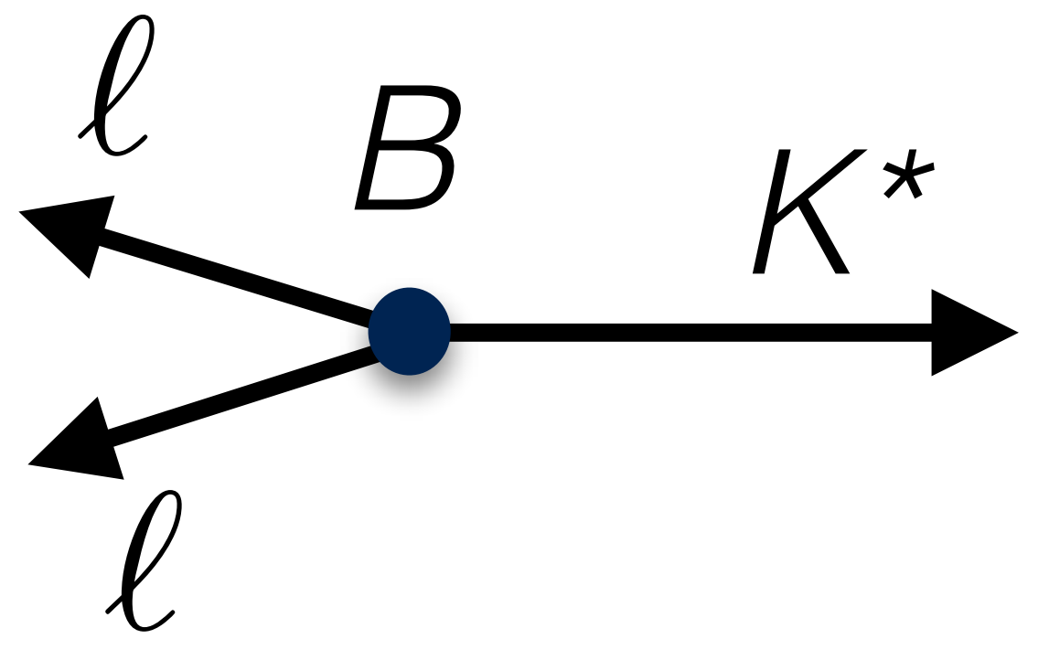
Another ratio: R_{K*}

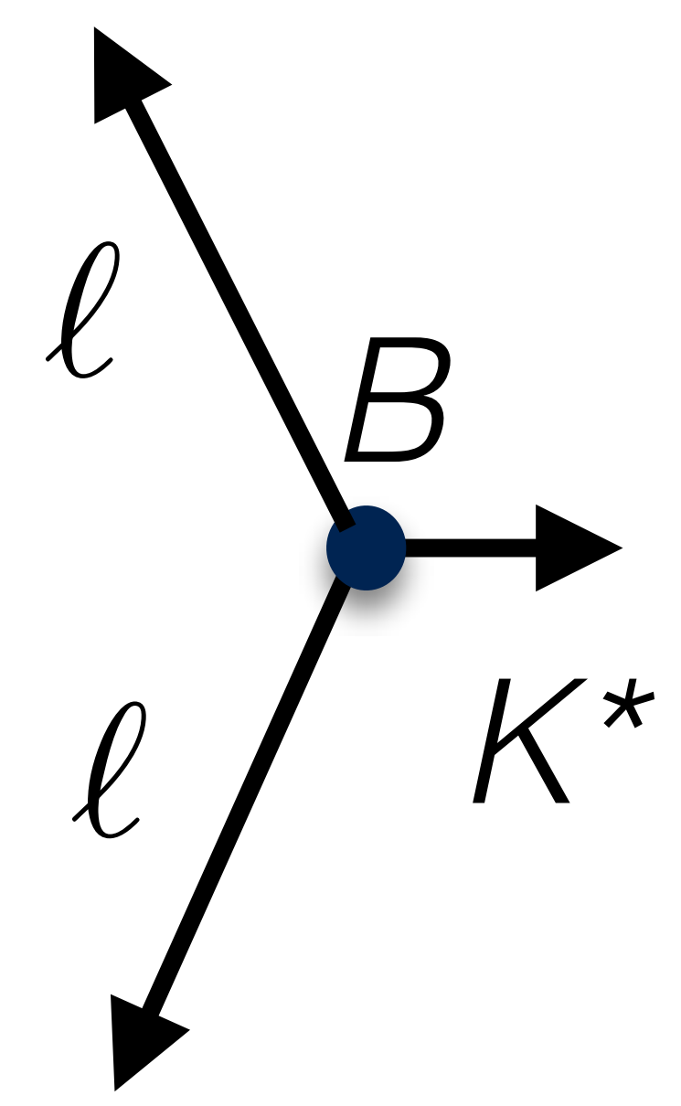
$$R_{\mathrm{K}^*} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

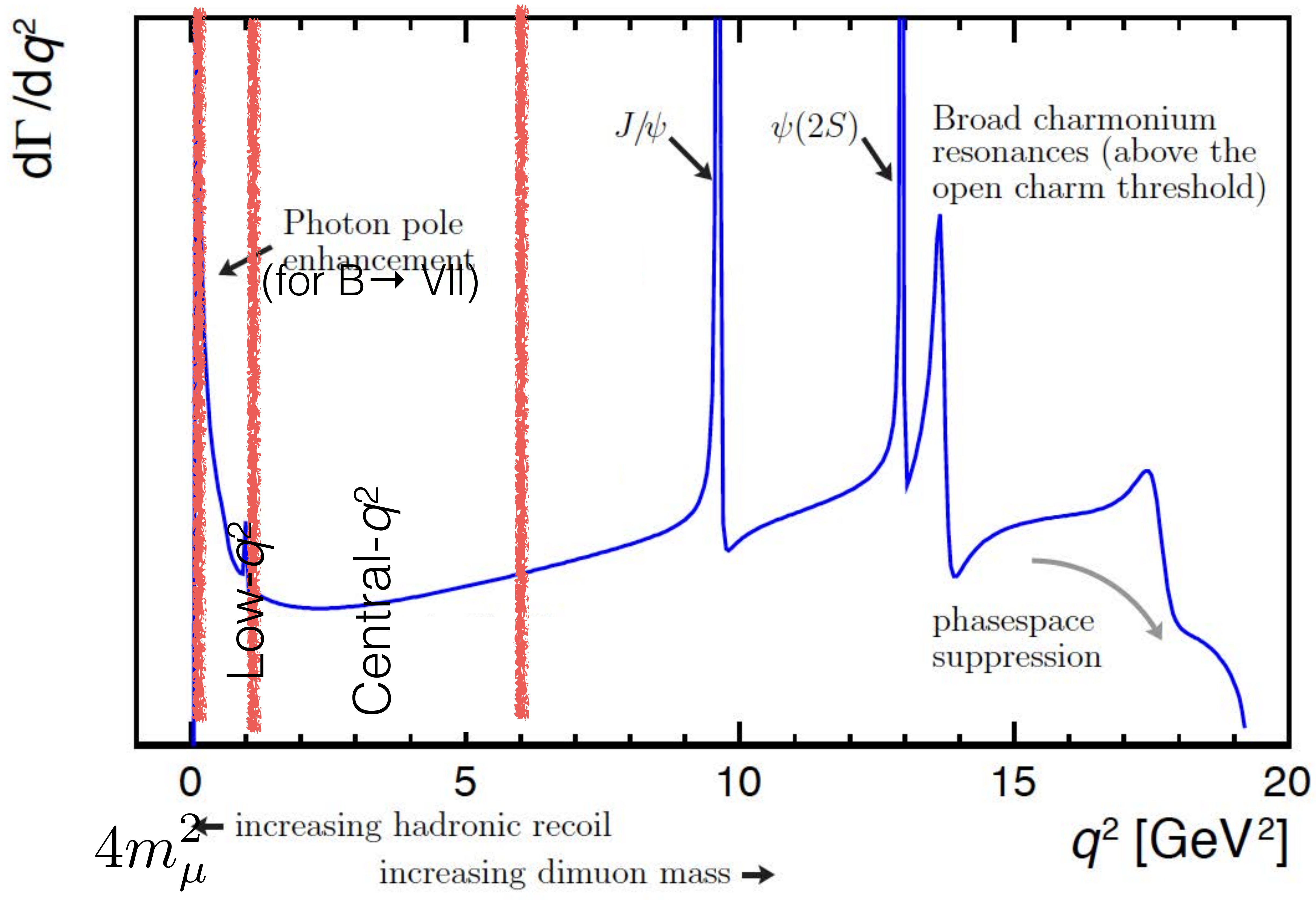
$$K^{*0}(892) \to K^+\pi^-$$

- LHCb performed measurement in two q^2 bins that are sensitive to different NP contributions (Run 1 data, 3 fb^{-1}):
  - Low-q^2 bin: [0.045,1.1] GeV^2
  - Central-q^2 bin: [1.1,6.0] GeV^2

JHEP 08 (2017) 055







Fit to the invariant masses

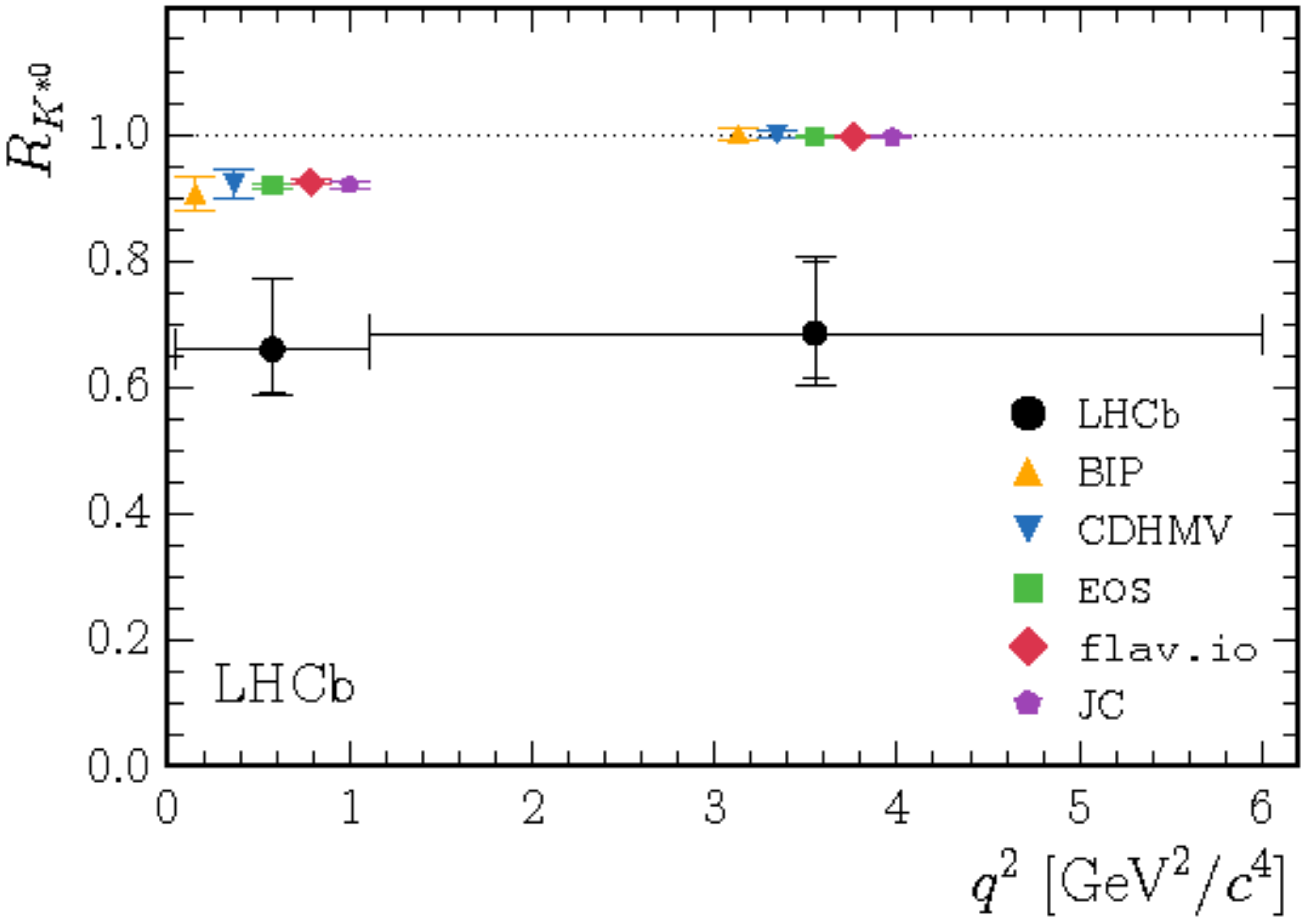
JHEP 08 (2017) 055

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-q² and central-q² , muon sample 3-5 times larger

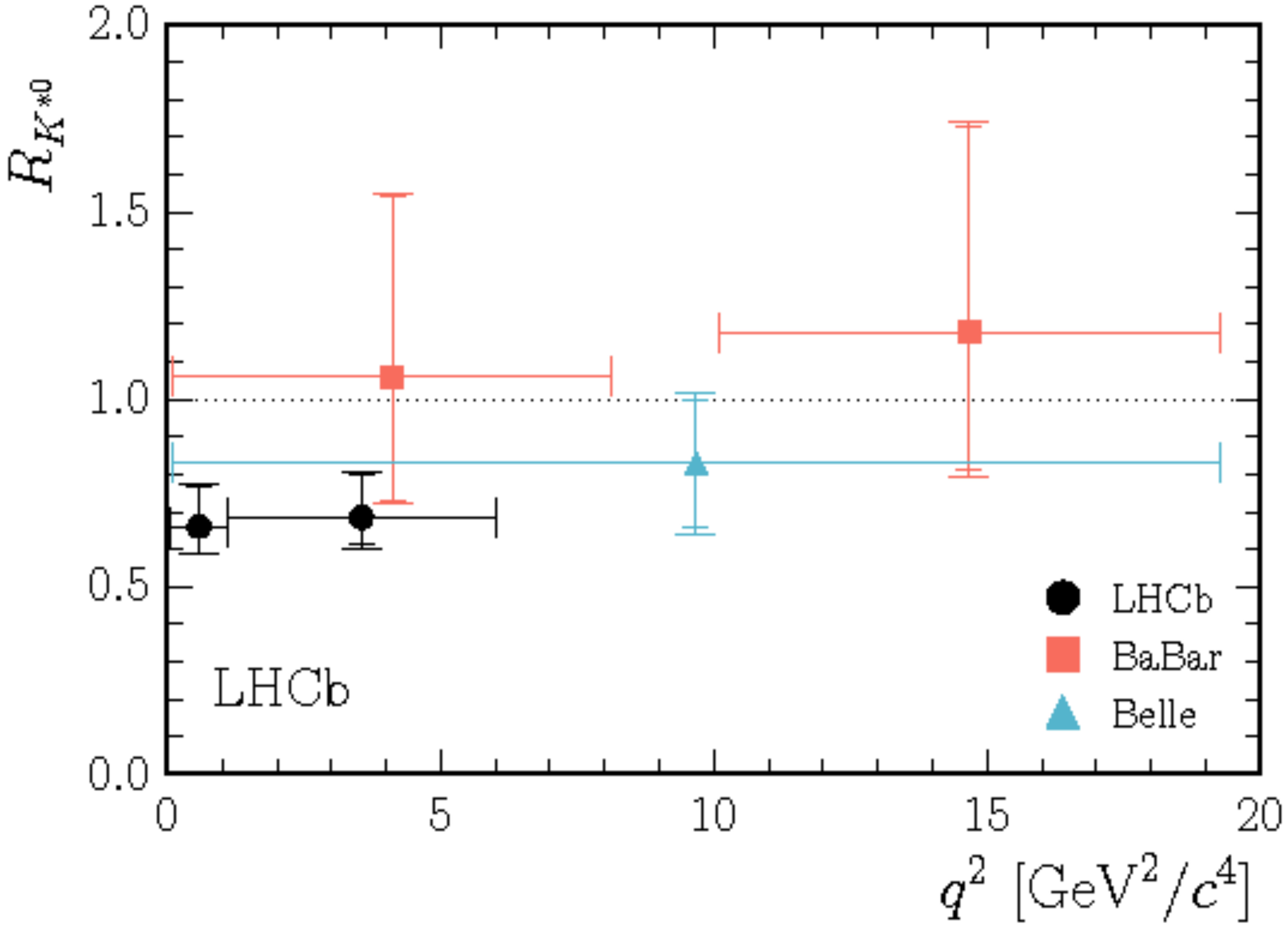
R_{K^*} results

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

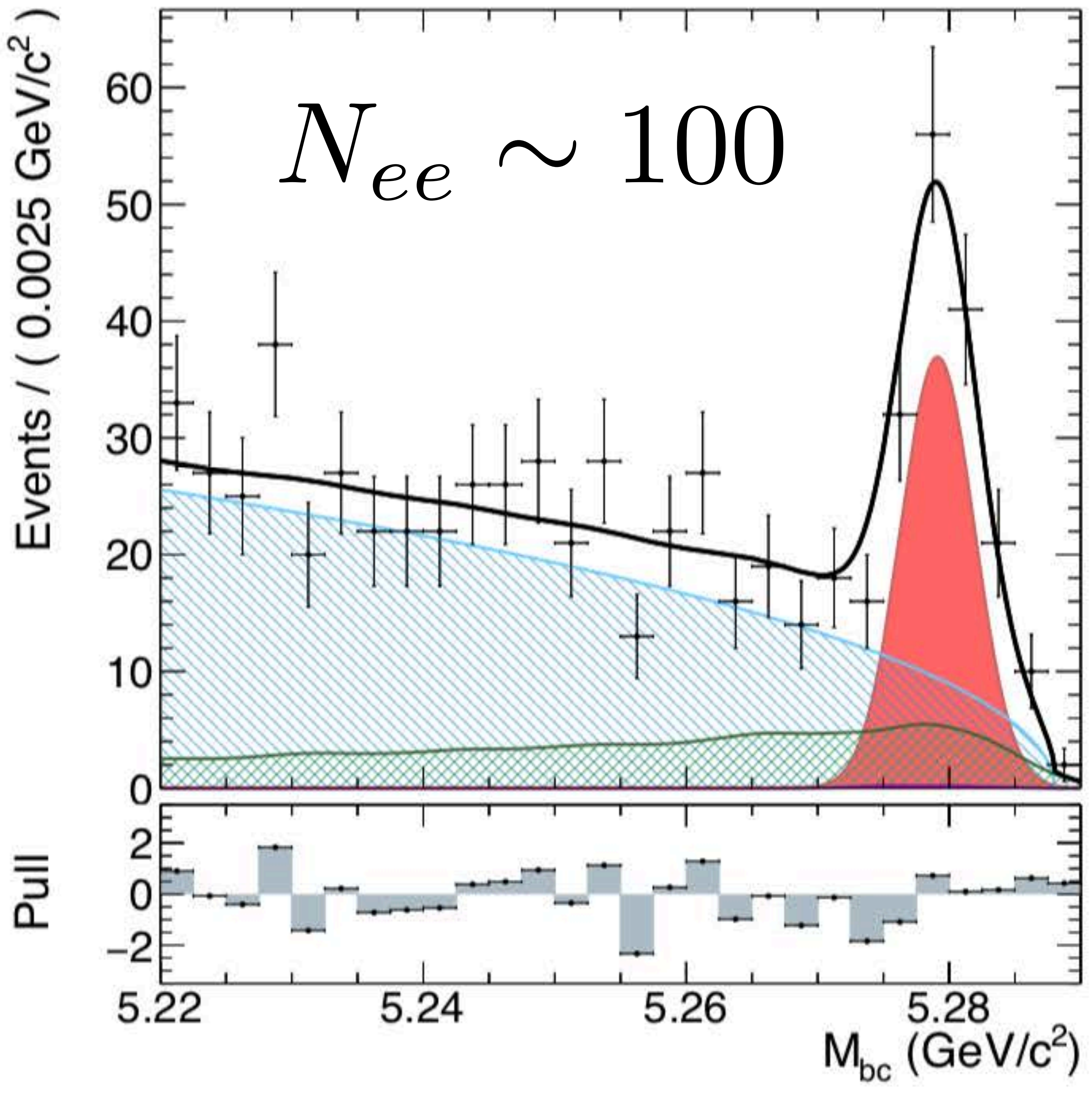
Updated R_{K^*} from Belle

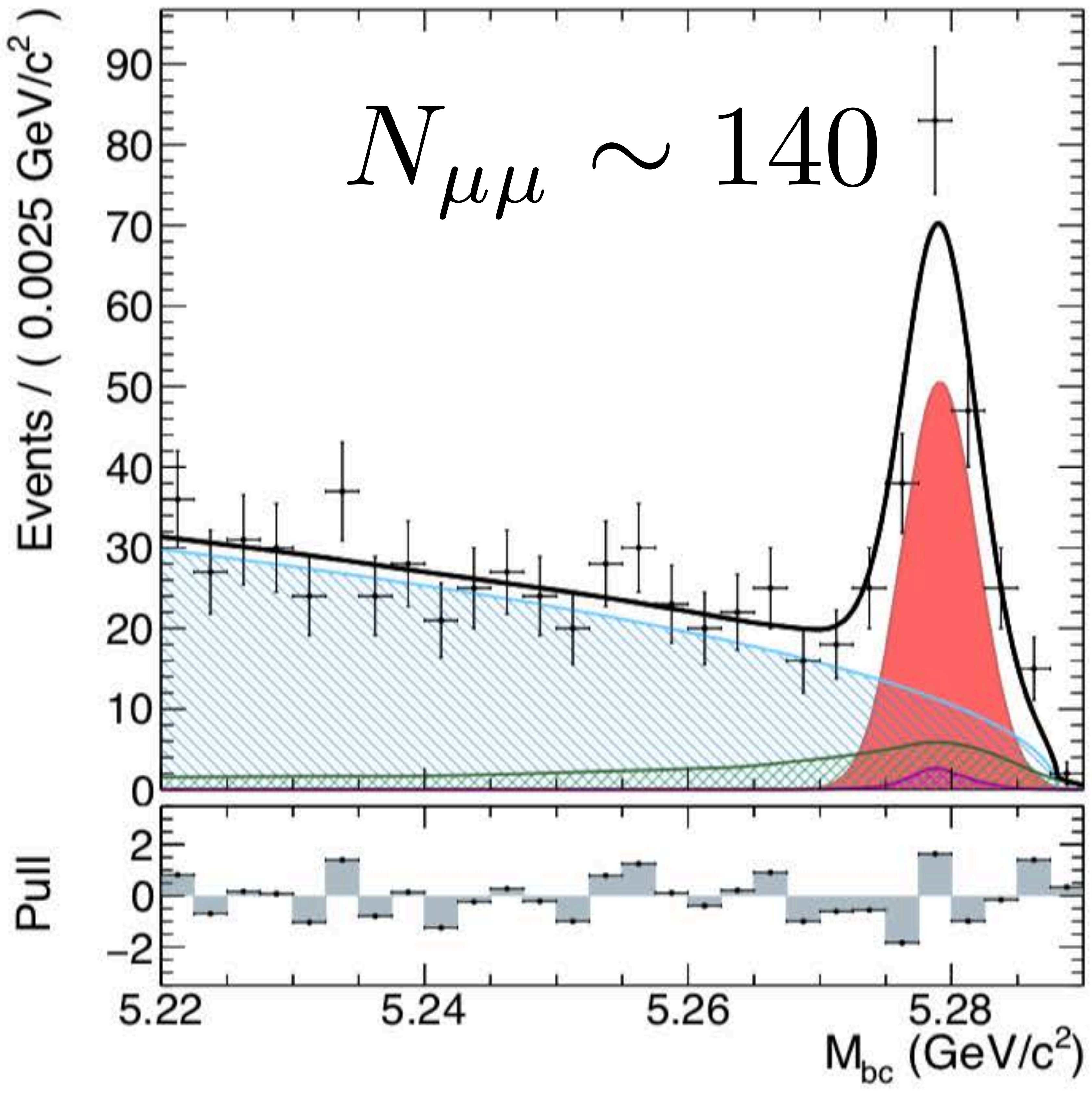
- Full data set analysed using neutral and charged modes :

$$B^0 \to K^{*0}\ell^+\ell^- \qquad K^{*0} \to K^+\pi^-,\ K^{*+} \to K^+\pi^0,\ K^{*+} \to K^0_s\pi^+$$

$$B^+ \to K^{*+}\ell^+\ell^-$$

- R_{K^*} measured as single ratio, but stringent cross-checks performed
  - $B(B \to K^*J/\psi)$ in agreement with world averages
  - $r_{J/\psi} = 1.015 \pm 0.025 \pm 0.038$, validating efficiency measurement



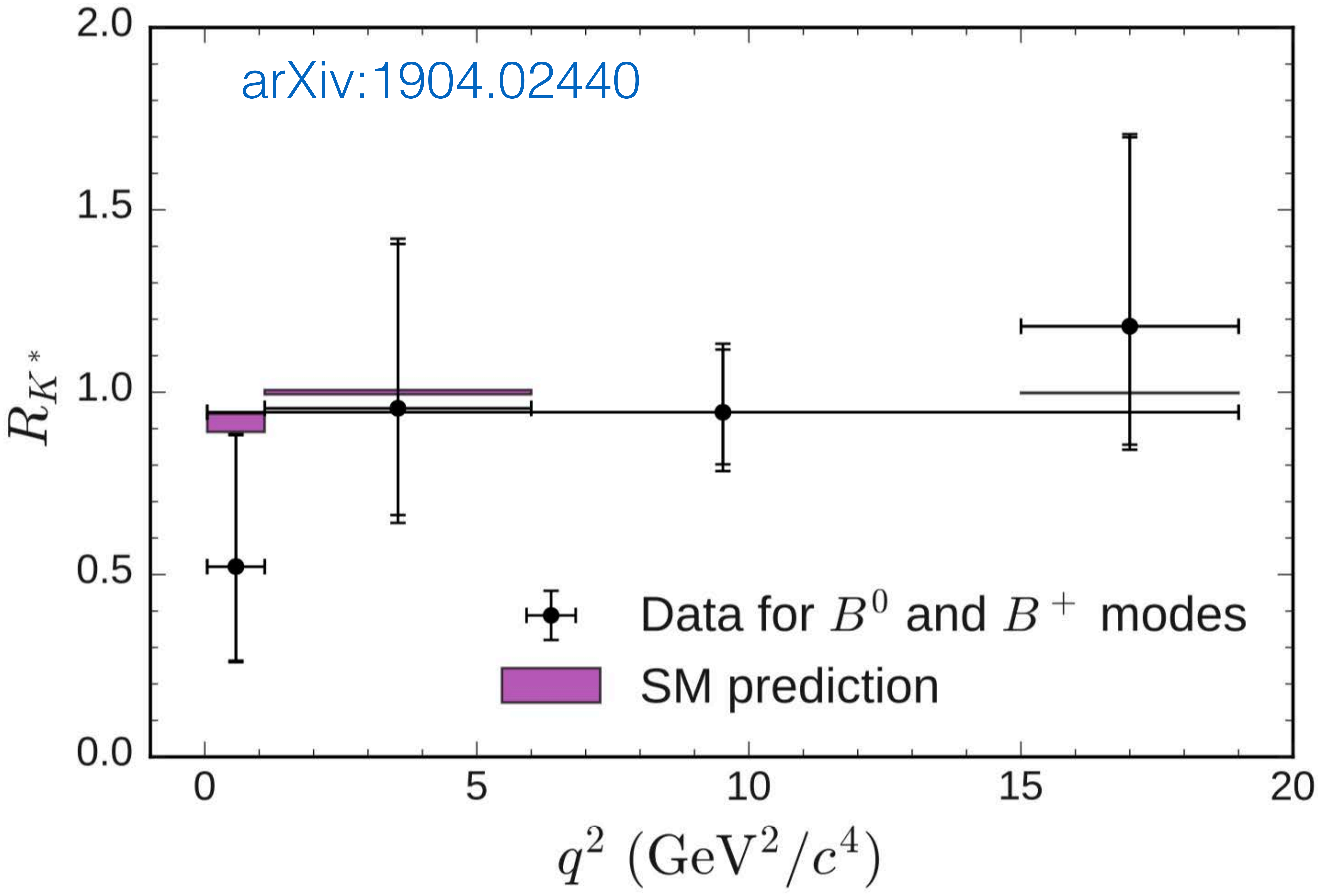


$$q^2 > 0.045\,\mathrm{GeV}^2$$

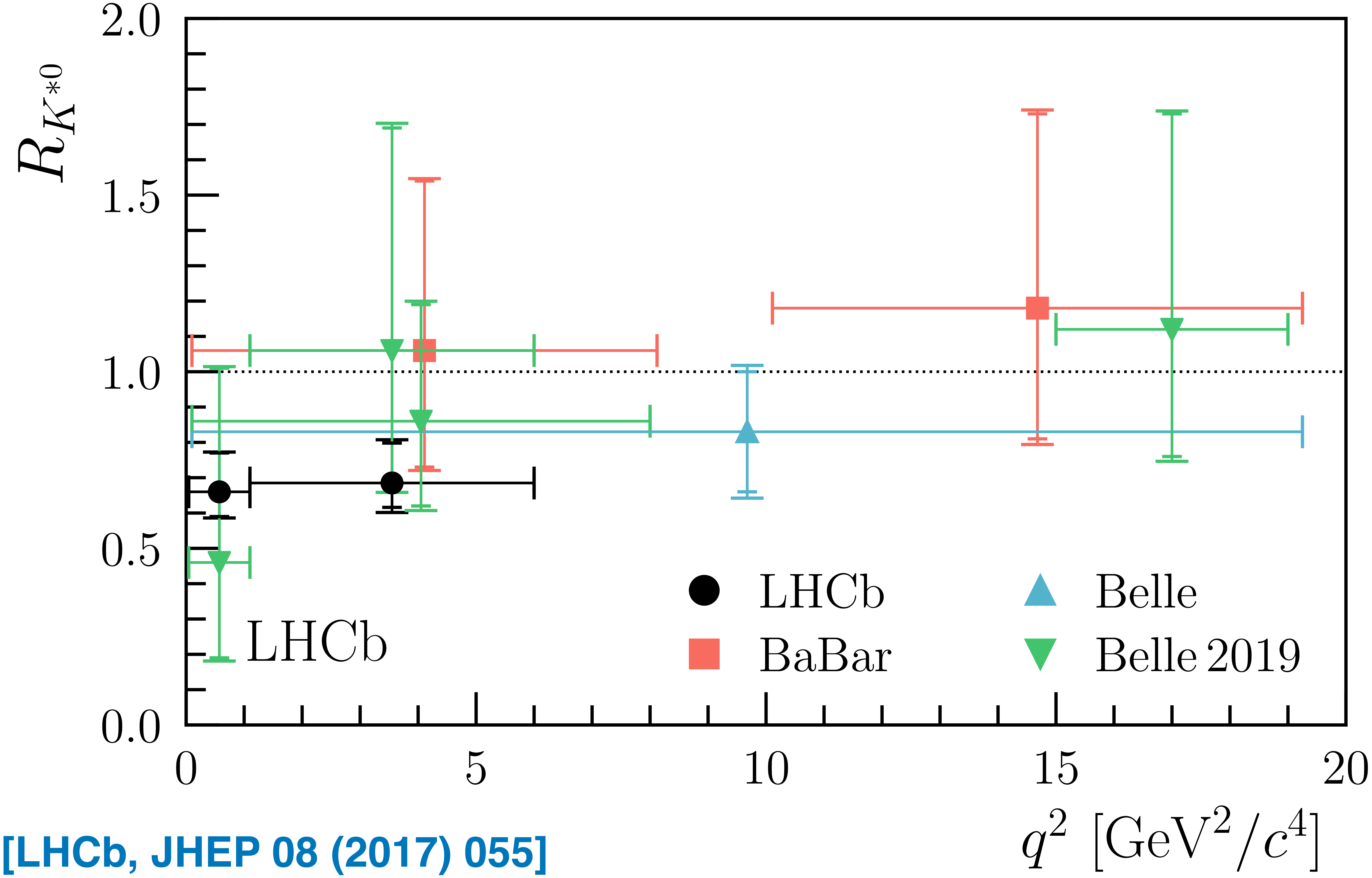
arXiv:1904.02440

Updated R_{K^*} from Belle

- Results compatible with SM



R_{K*} ..putting everything together…



[LHCb, JHEP 08 (2017) 055]
[BaBar, PRD 86 (2012) 032012]
[Belle, PRL 103 (2009) 171801]
[Belle, arXiv:1904.02440]

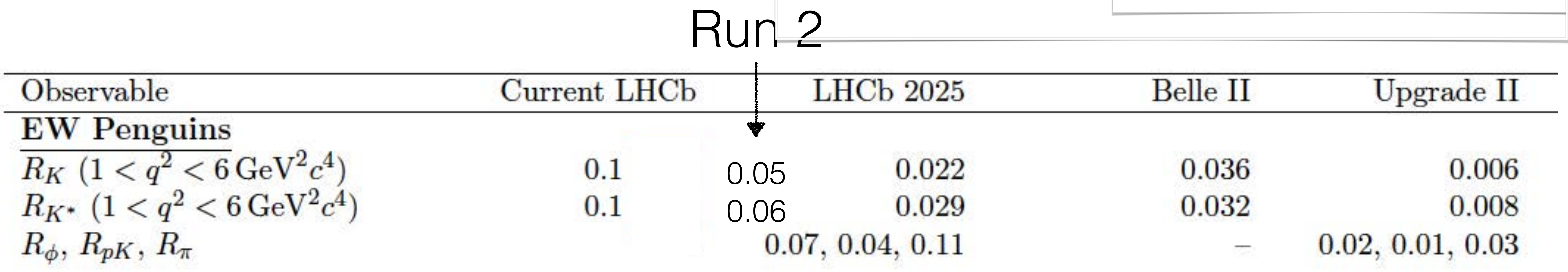
What happens next?

Shorter term

- Run 2 updates of R_K, R_{K*}
- Can make analogous measurement with $R_\phi(B_s \to \phi\ell^+\ell^-)$ and other similar modes

- LHCb: Physics case for an LHCb Upgrade II, CERN/LHCC 2018-027
- The Belle II Physics Book, arXiv:1808.10567

Long term

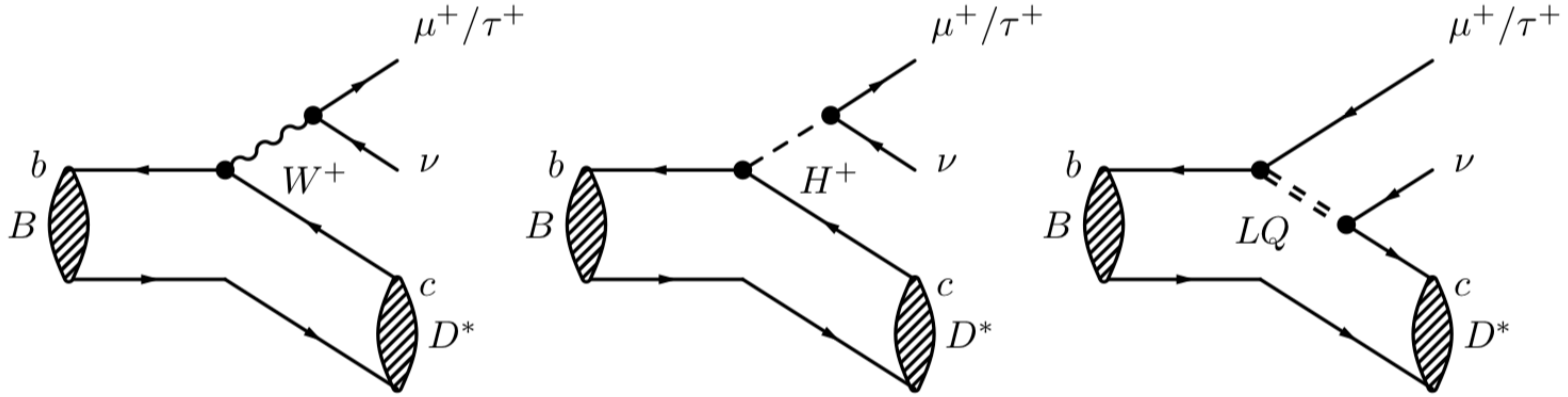


Observable	Current LHCb	Run 2	LHCb 2025	Belle II	Upgrade II
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1	0.05	0.022	0.036	0.006
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1	0.06	0.029	0.032	0.008
R_ϕ, R_{pK}, R_π			0.07, 0.04, 0.11	–	0.02, 0.01, 0.03

- ATLAS/CMS also getting more interested, e.g. CMS devised a new strategy of parking a very large sample of ~10^{10} B hadrons to be able to measure R_K, R_{K*} in a competitive way (→ no prompt reconstruction, opportunistic reconstruction during LS2)

Another puzzling result in tree-level b → c transitions

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



- Different class of decays (tree-level charged current with V_{cb} suppression)
- Not at all rare: $B(B^0 \to D^{*-}\tau^+\nu_\tau) \sim 1\,\%$, problem is the background
- Lepton-universality ratio R(D*) : $R(D*) = \dfrac{B(B^0 \to D^{*-}\tau^+\nu_\tau)}{B(B^0 \to D^{*-}\mu^+\nu_\mu)}$
  - sensitive to any NP model coupling preferentially to third generation leptons
- Predicted theoretically at ~1%: $R(D)_{\mathrm{SM}} = 0.299 \pm 0.003$
  $R(D^*)_{\mathrm{SM}} = 0.258 \pm 0.005$

HFLAV average, 2019

- Studied by Belle, BaBar and LHCb

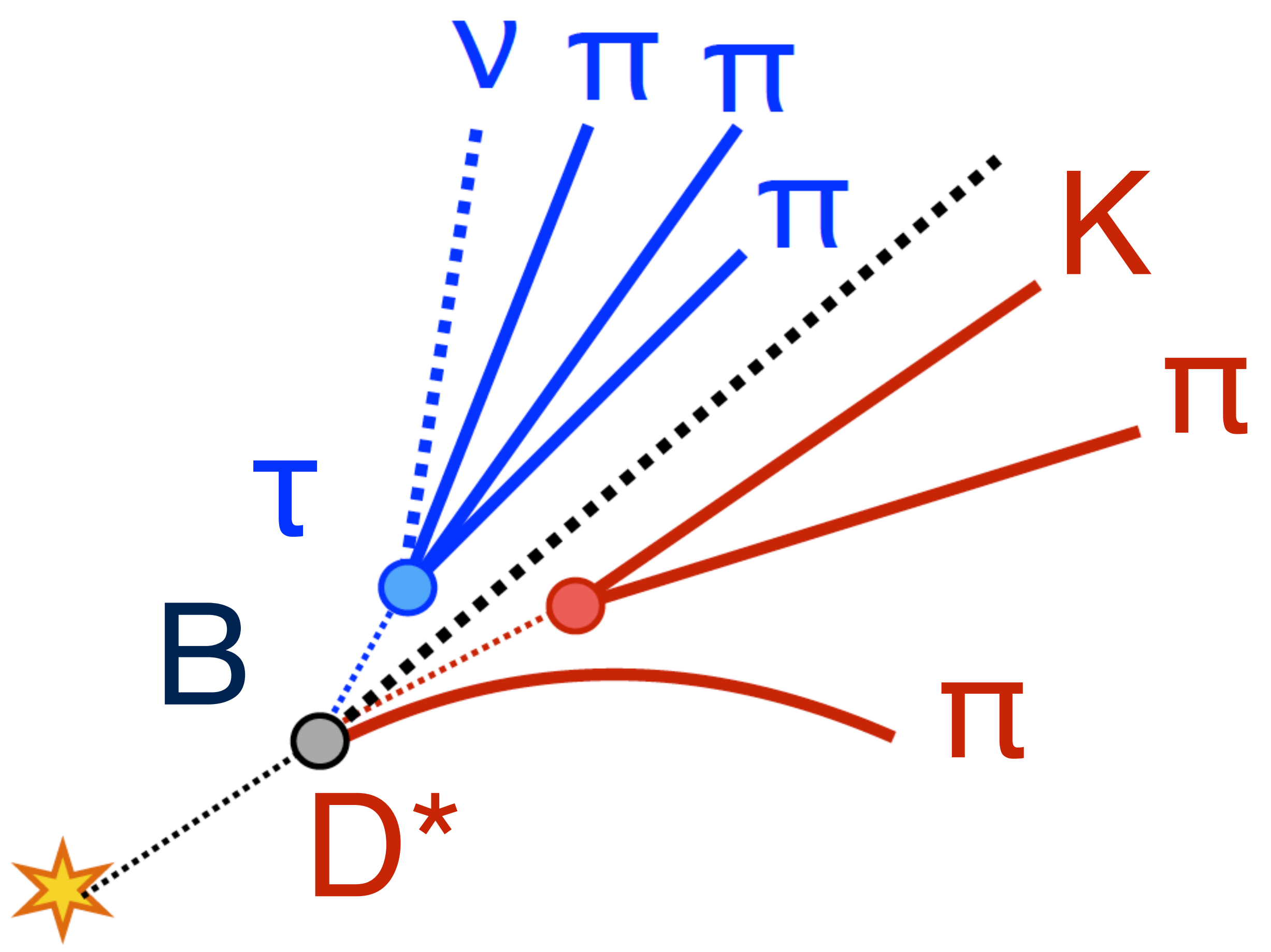
Experimental challenges

- At least two neutrinos in the final state (three if using $\tau \to \mu\nu\nu$)

- At the LHC, as opposed to B factories, the rest of the event does not provide any useful kinematic constraint. However, profit from large boost and huge B production

- Latest LHCb measurement:

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



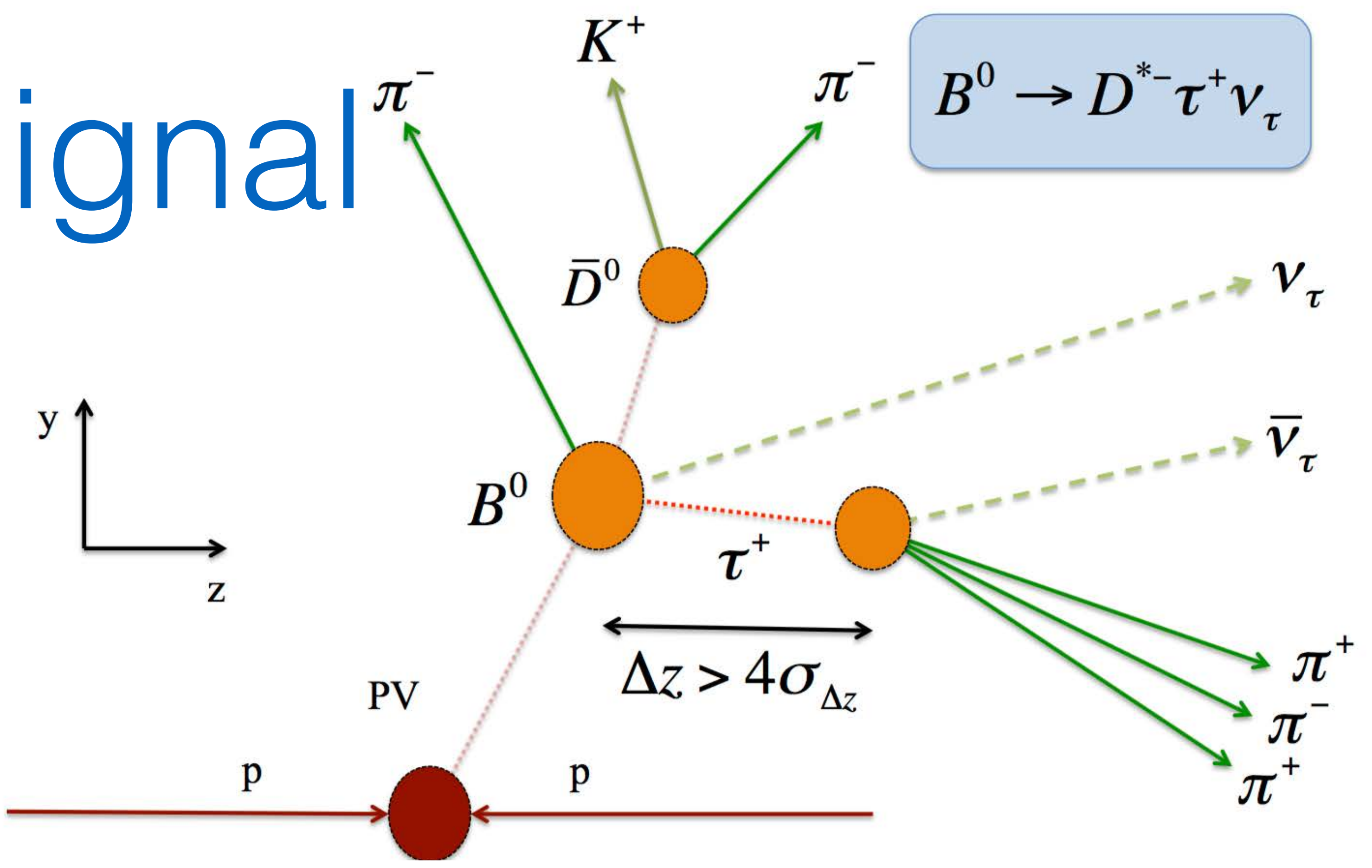
Three-prong mode used for the first time!

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

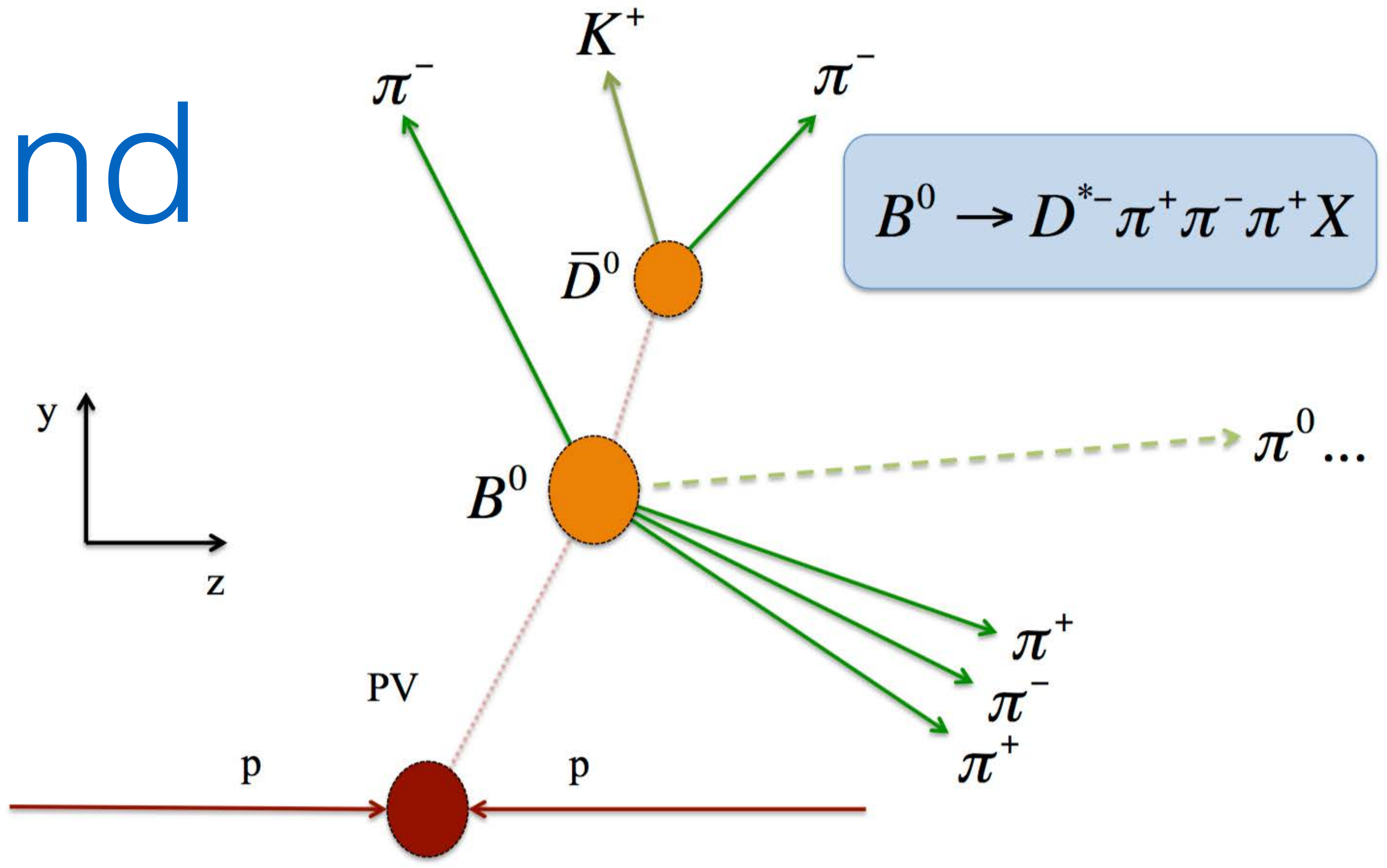
Background reduction

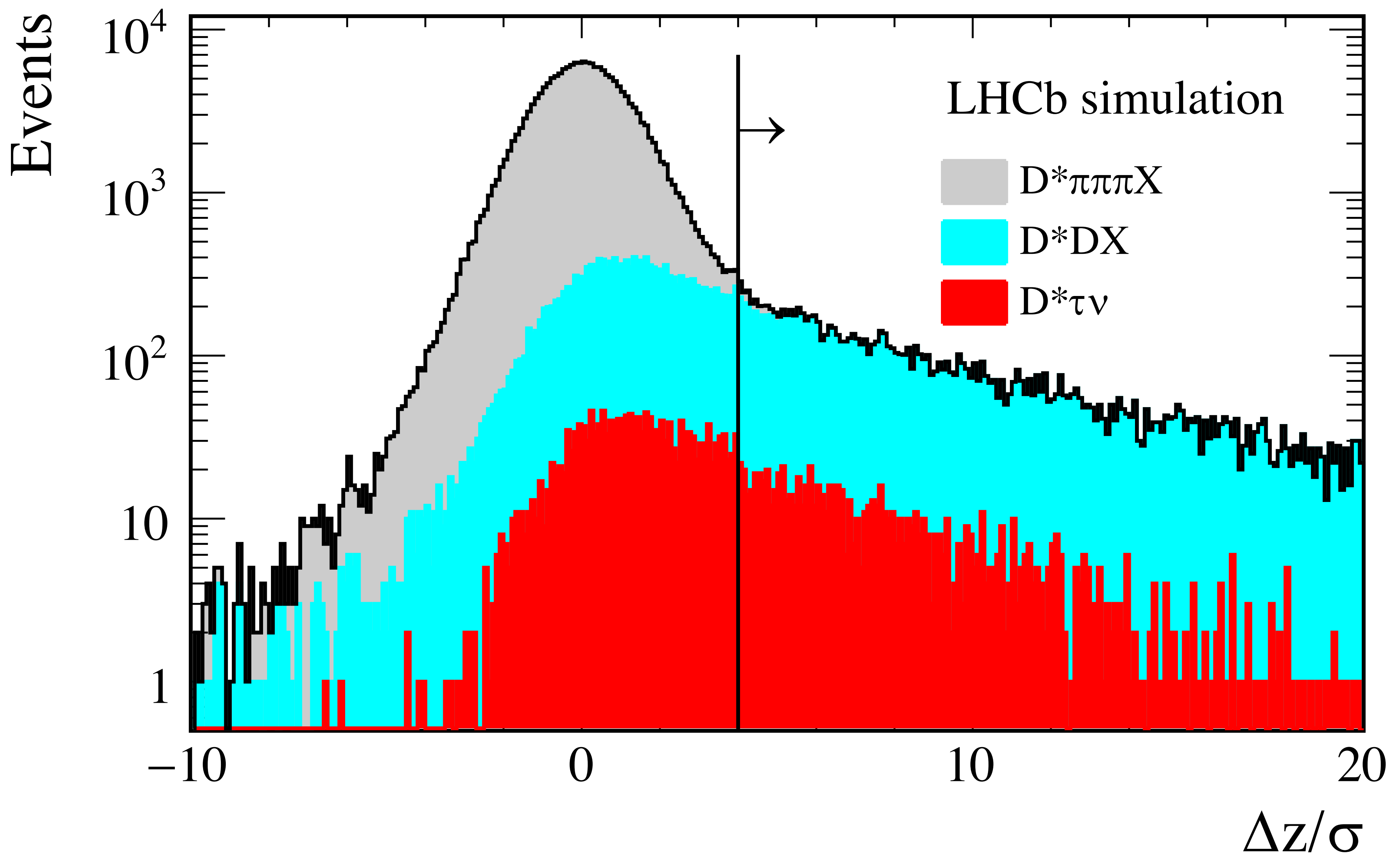
- Separation between B and 3π vertices ($\Delta z > 4\sigma_{\Delta z}$) crucial to obtain the required rejection of $B \to D^* 3\pi X$

Signal



Background



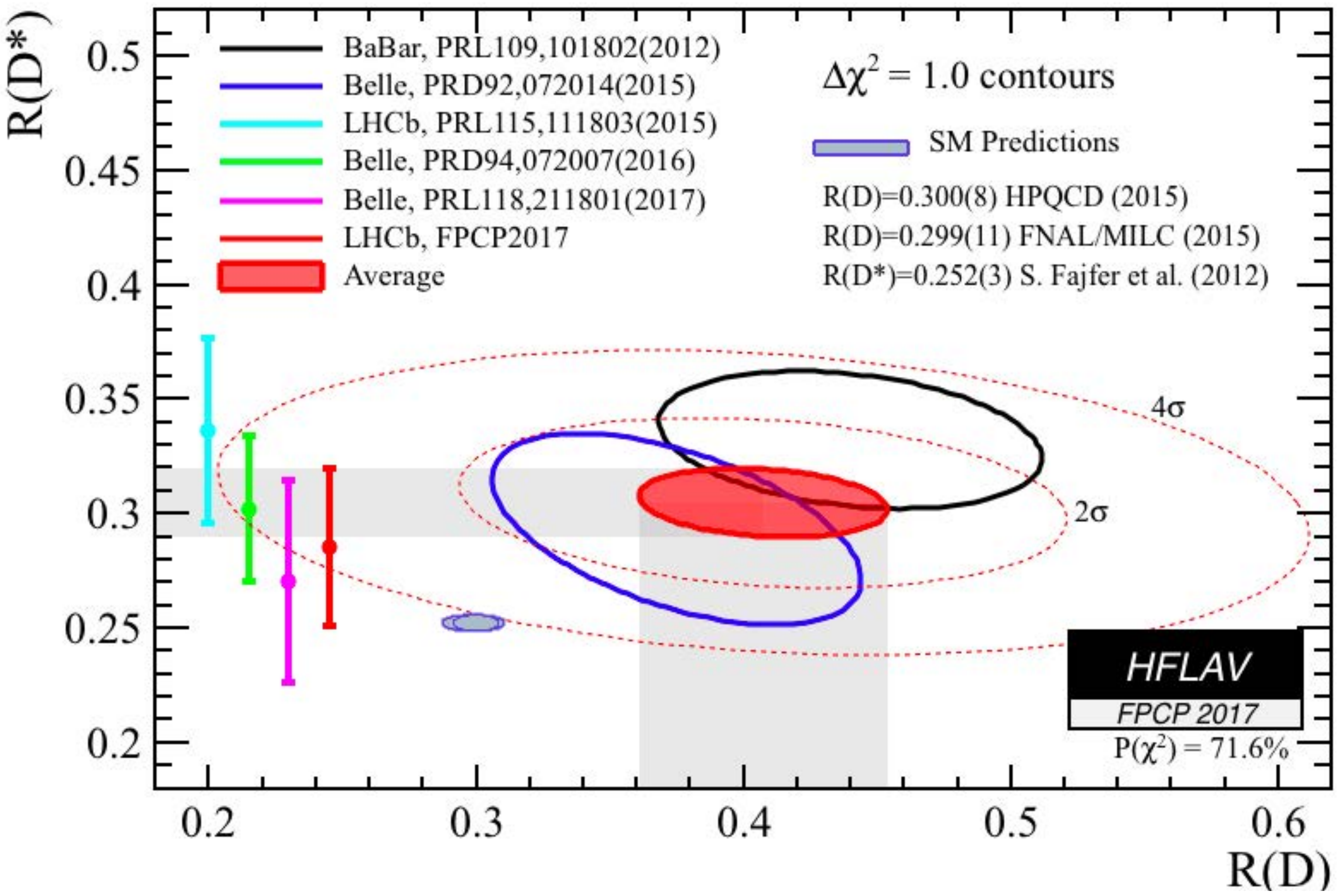


- Remaining double-charm background ($D^*D_{(s)}X$) suppressed by employing a multivariate classifier
- Signal normalised to $B \to D^{*-}3\pi$ to minimize experimental systematics

PRL120 (2018) 171802
PRD 97 (2018) 072013

$$R(D^{*-}) = 0.291 \pm 0.019\,(\text{stat}) \pm 0.026\,(\text{syst}) \pm 0.013\,(\text{ext})$$ ~1.1σ > SM

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



Prospects (LHCb)

- Extend to full Run2 statistics
  - from ~1300 to ~6000 events
  - goal is to be competitive with world average
- A whole programme of semi-tauonic measurements, e.g.

$$\left\{\begin{array}{l} R(D) : B^+ \to D^0\tau^+\nu_\tau \\ R(D^*) : B^0 \to D^{*-}\tau^+\nu_\tau \end{array}\right.$$

$$R(D_s^{(*)}) : B_s^0 \to D_s^{(*)}\tau^+\nu_\tau$$

$$R(\Lambda_b) : \Lambda_b \to \Lambda_c^{(*)}\tau^+\nu_\tau$$

Waiting for Belle II

- ~1.5% projected sensitivity on $R(D^*)$ with 5 ab^{-1}

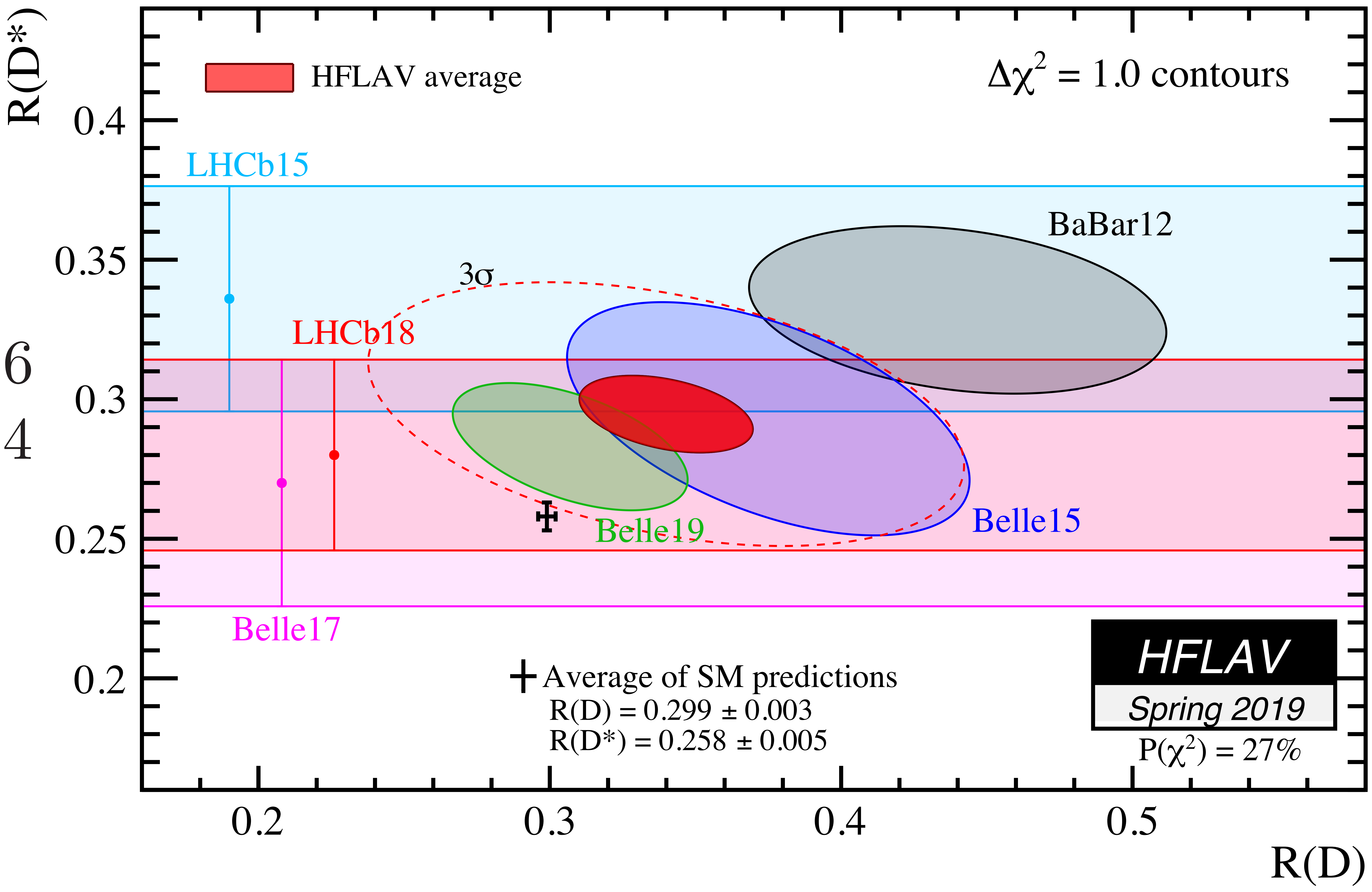
- All experiments see an excess wrt SM predictions
- Tension $\lesssim 4\sigma$
- ~20% effect on $R(D^*)$

Belle: Update of $R(D)$ & $R(D^*)$

- Simultaneously measure R(D) and R(D*) with SL tagging, using the full $Y(4S)$ statistics

arXiv:1904.08794

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

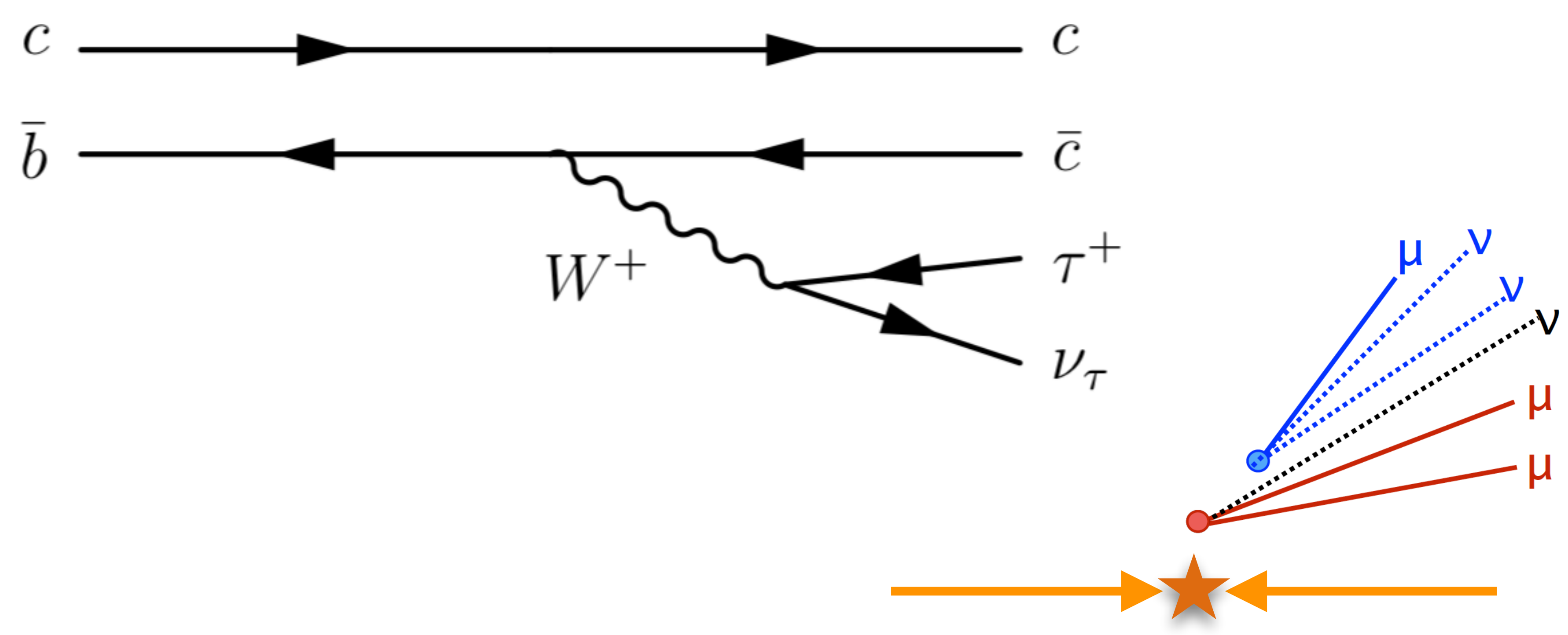


- New HFLAV average: 3.1~ away from SM

Testing LFU with B_c decays

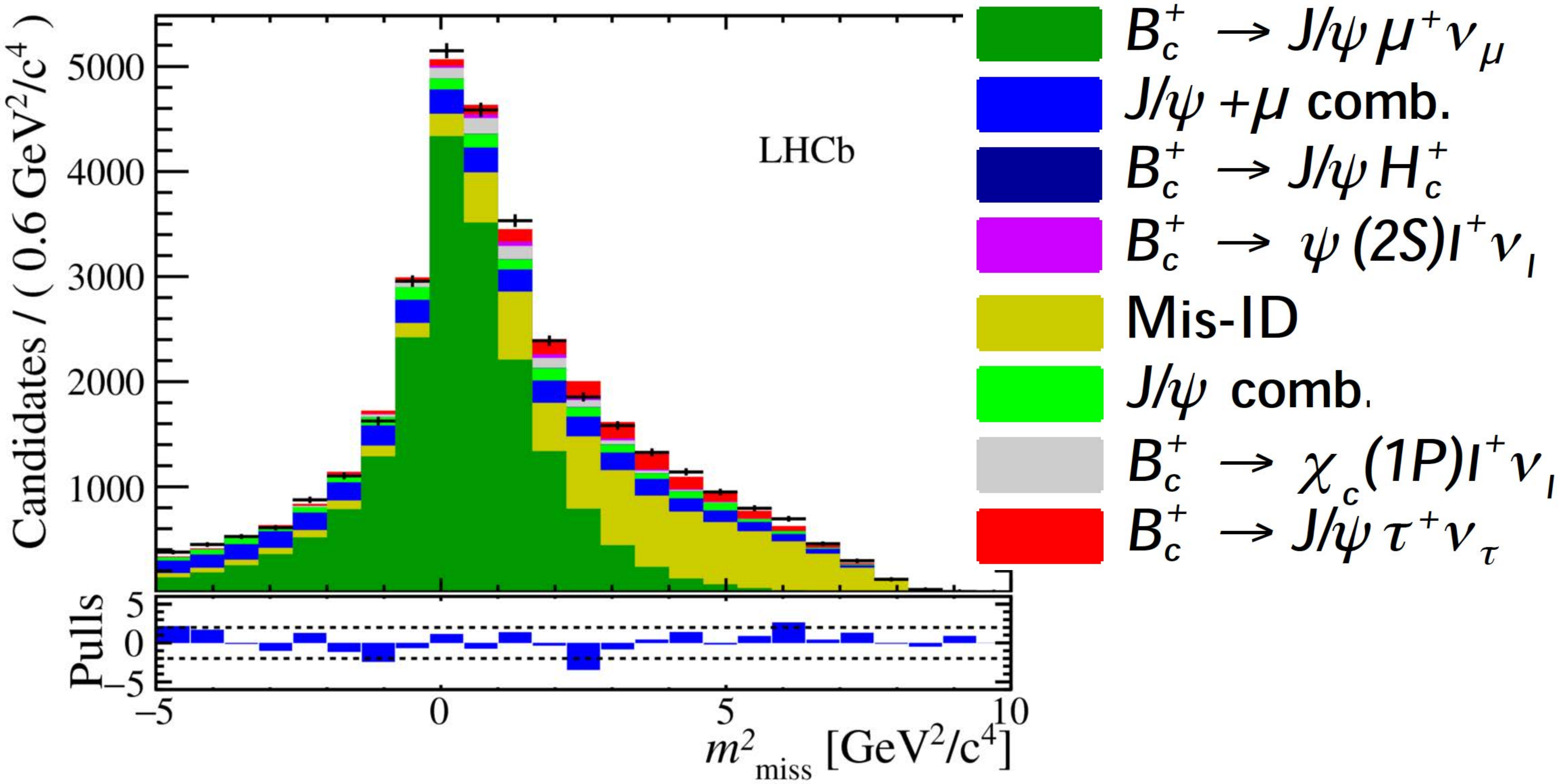
- Generalization of $R(D^*)$ to B_c:

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$



- Signal reconstructed using τ→μνν, $B_c^+ \to J/\psi\mu^+\nu_\mu$ as normalisation

- Largest background from light b hadrons to J/ψ with a π or K misidentified as μ



PRL120 (2018) 121801

$$R(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$$

2σ away from SM prediction (0.25-0.28)

A word on LFV

- Many models proposed to explain these tensions naturally allow for LFV processes with rates that are experimentally accessible

- $B^0_{(s)} \to \tau^+\mu^-$

arXiv:1905.06614

$$\mathcal{B}(B^0 \to \tau^+\mu^-) < 1.4 \cdot 10^{-5}\ @95\%\ \mathrm{CL}$$ → Best limit

$$\mathcal{B}(B^0_s \to \tau^+\mu^-) < 4.2 \cdot 10^{-5}\ @95\%\ \mathrm{CL}$$ → First limit

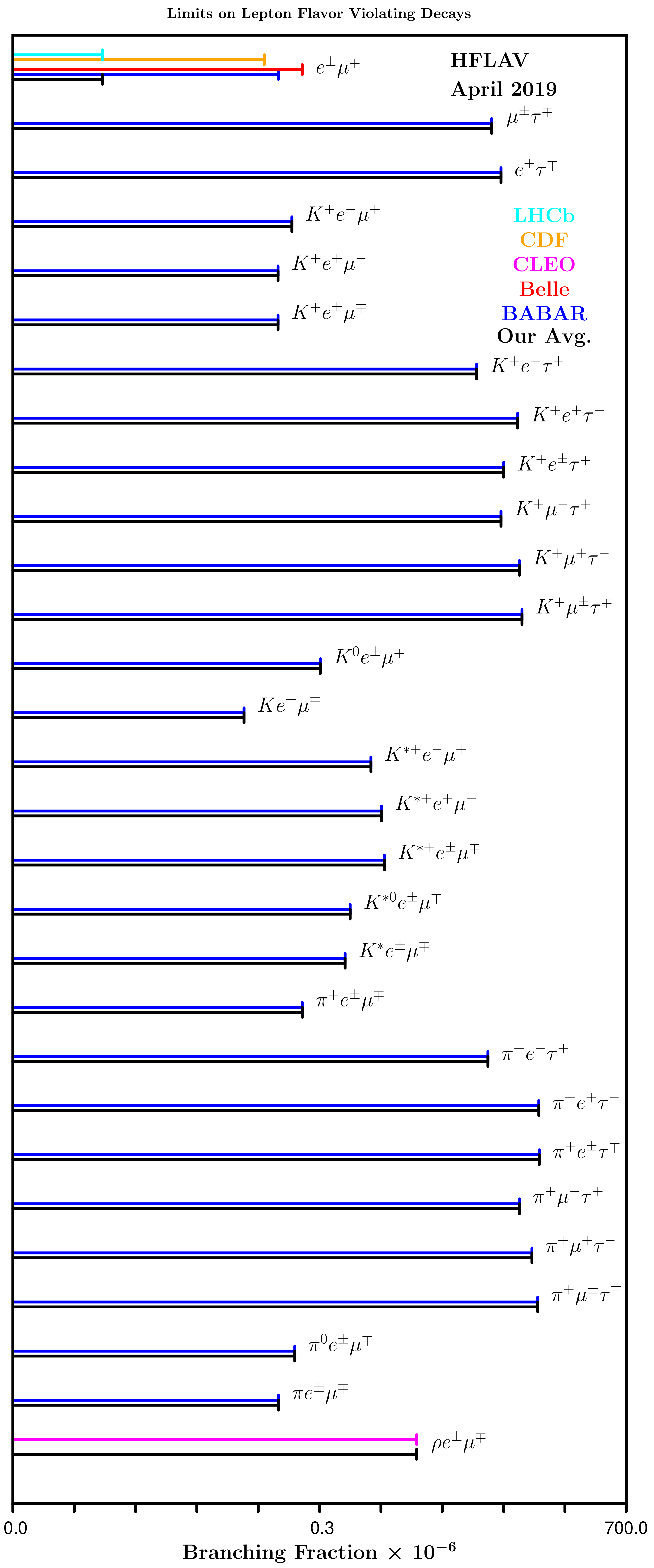
- $B^+ \to K^+\mu^\pm e^\mp$

LHCb-PAPER-2019-022

$$\mathcal{B}(B^+ \to K^+\mu^- e^+) < 9.5 \cdot 10^{-9}\ @95\%\ \mathrm{CL}$$

$$\mathcal{B}(B^+ \to K^+\mu^+ e^-) < 8.8 \cdot 10^{-9}\ @95\%\ \mathrm{CL}$$

→ Improving limits by one order of magnitude



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. Healthy competition from Belle II, ATLAS & CMS very welcome!
- 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 have emerged
- Need more data to test these hints: full analysis of Run 2, while waiting for the high-precision results from the LHCb upgrade and Belle II