Tests of Lepton Flavor Universality

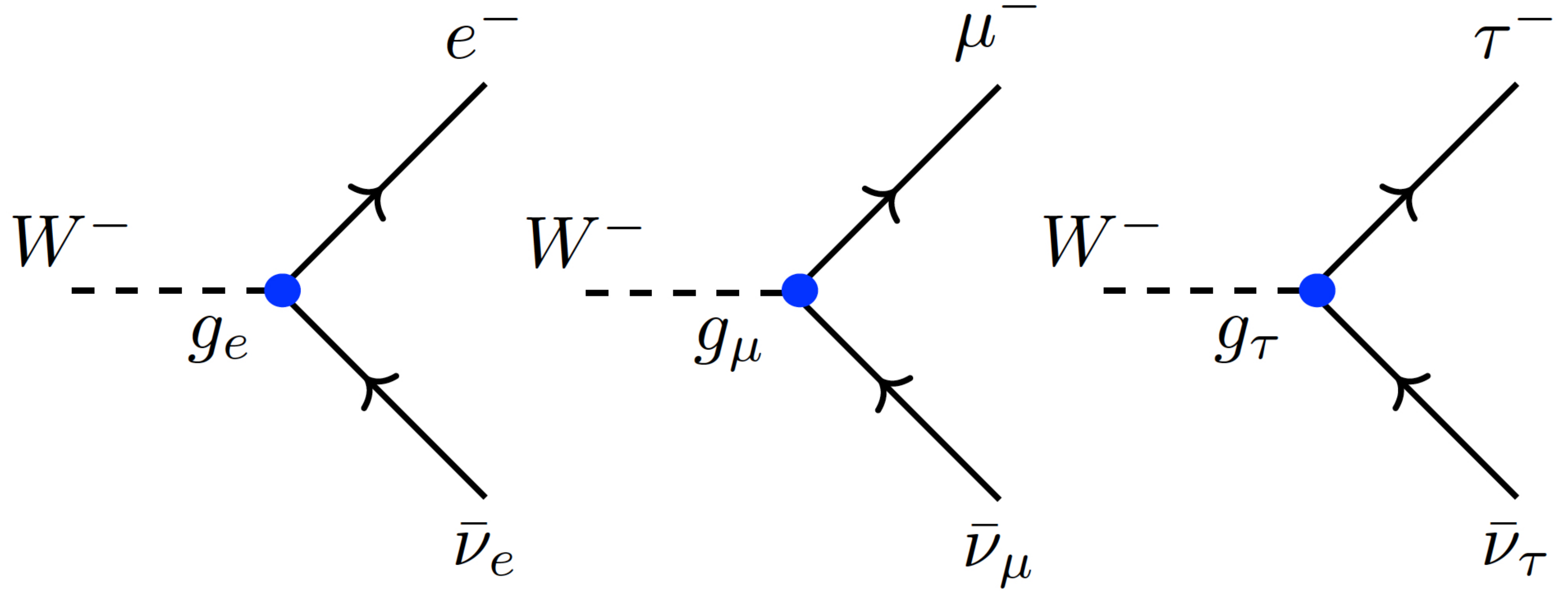
Renato Quagliani (EPFL) on behalf of the LHCb collaboration

Outline

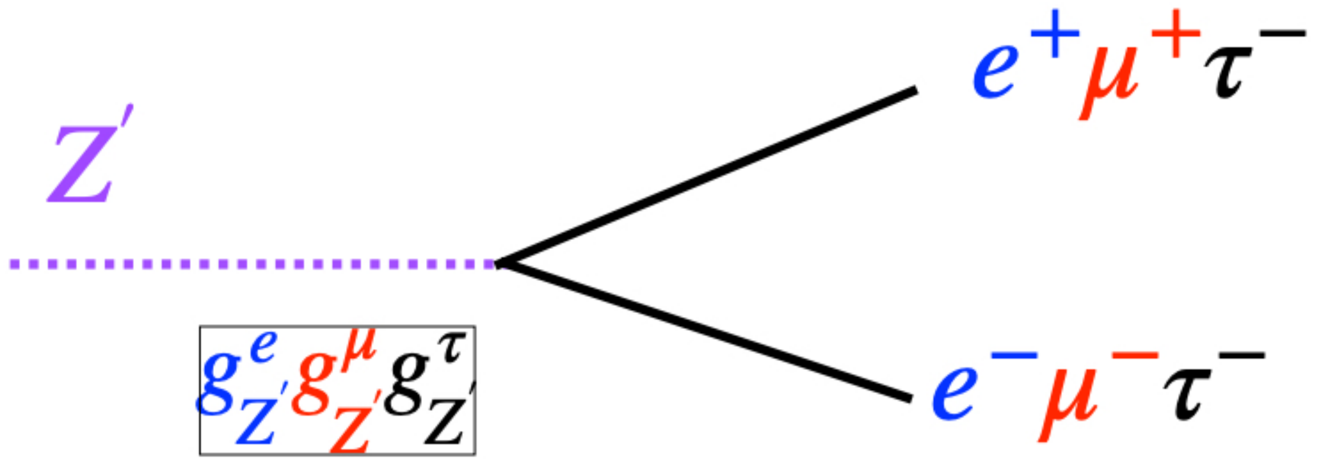
1. Lepton Flavour Universality and LHCb detector
2. LFU tests in $b \to s\ell\ell$
3. LFU tests in $b \to c\ell\nu$
4. Prospect and conclusions

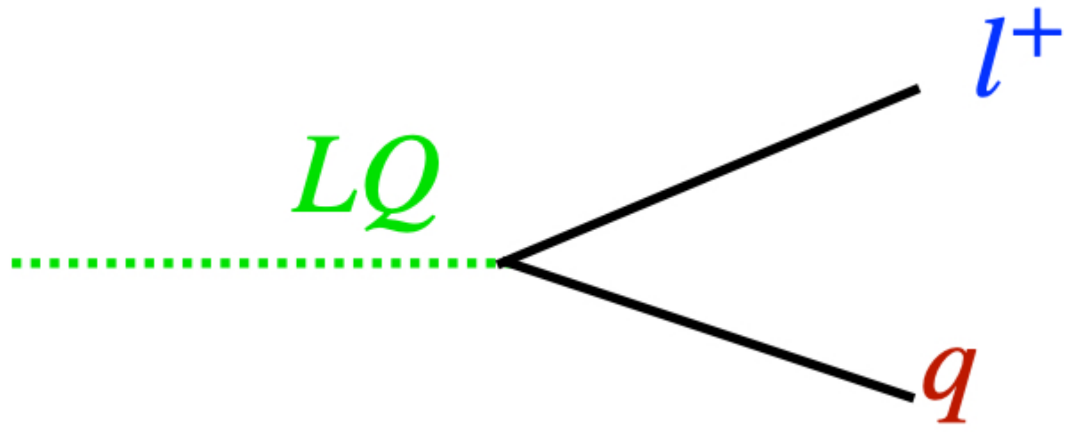
Lepton Flavour Universality (LFU)

- In the SM, EW couplings are independent from lepton flavours

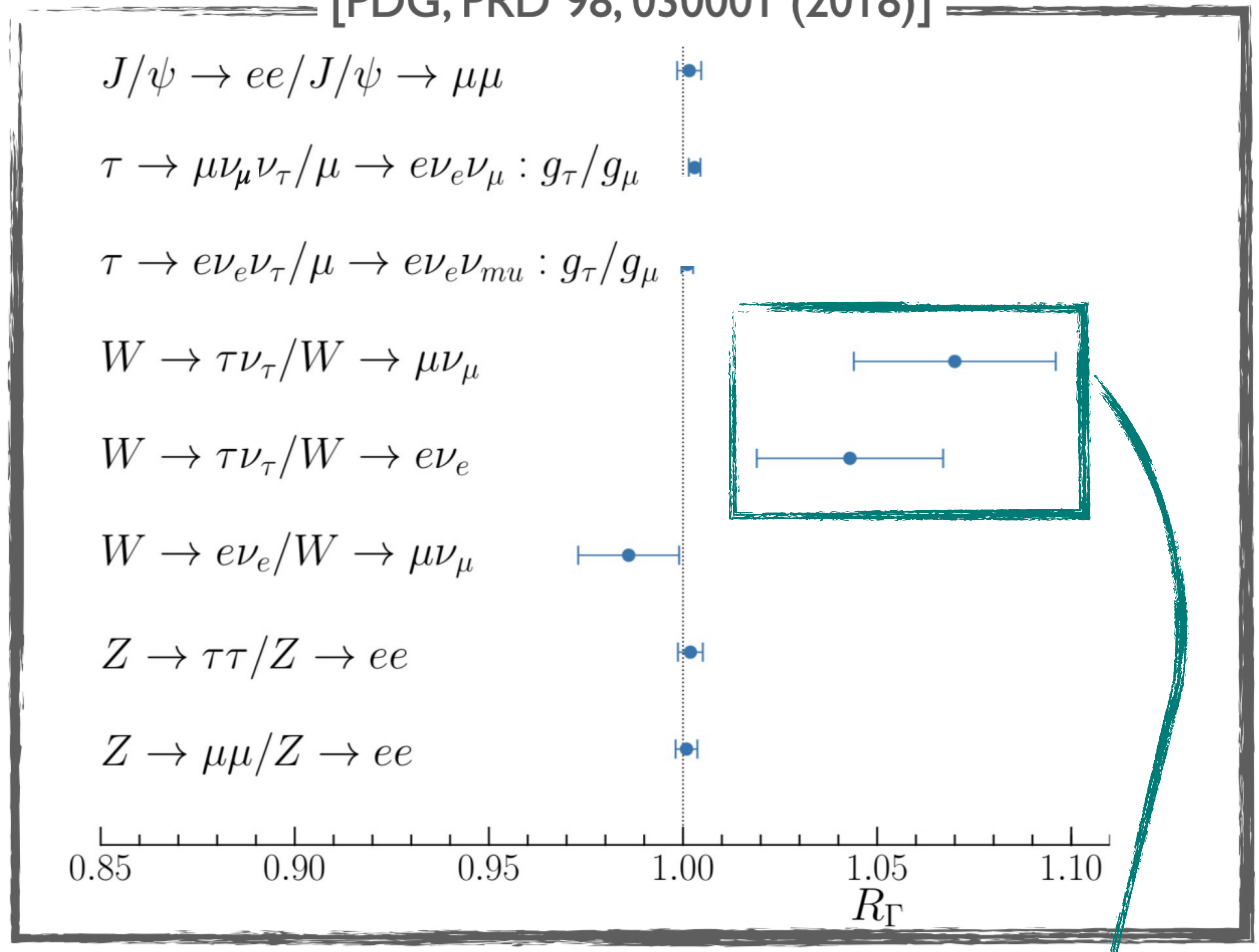


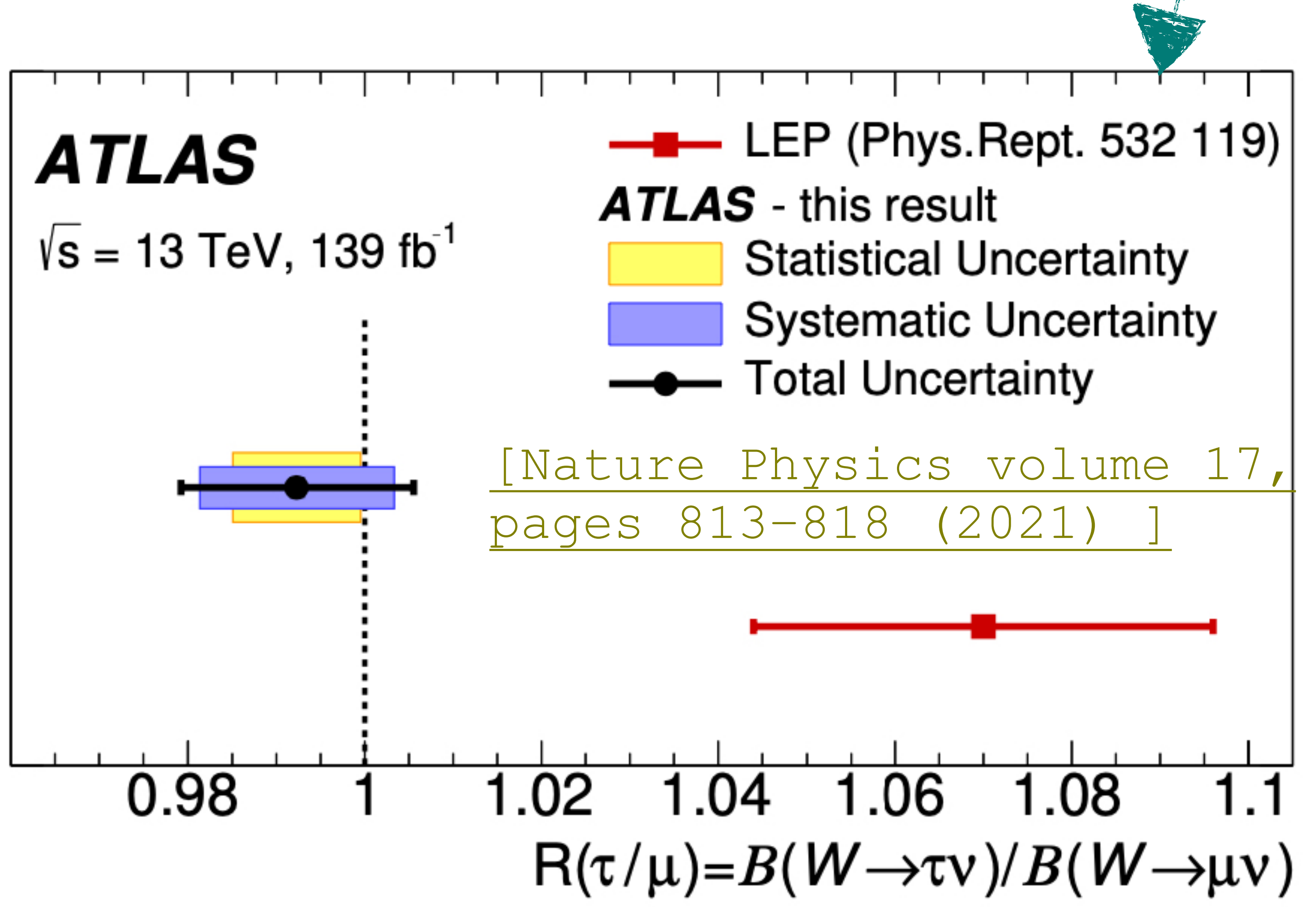
- Extensively verified in $Z \to \ell\ell, \tau \to l\nu\nu, J/\psi \to \ell\ell, \pi \to l\nu, K \to \pi\ell\nu$
- **EW couplings universality verified at per-mille level** since LEP
  - ✦ $W \to \tau\nu$ longstanding tension of 2.5σ solved by recent ATLAS measurement
- BSM new particles can break **LFU at high energy scales**





[PDG, PRD 98, 030001 (2018)]





[Nature Physics volume 17, pages 813-818 (2021)]

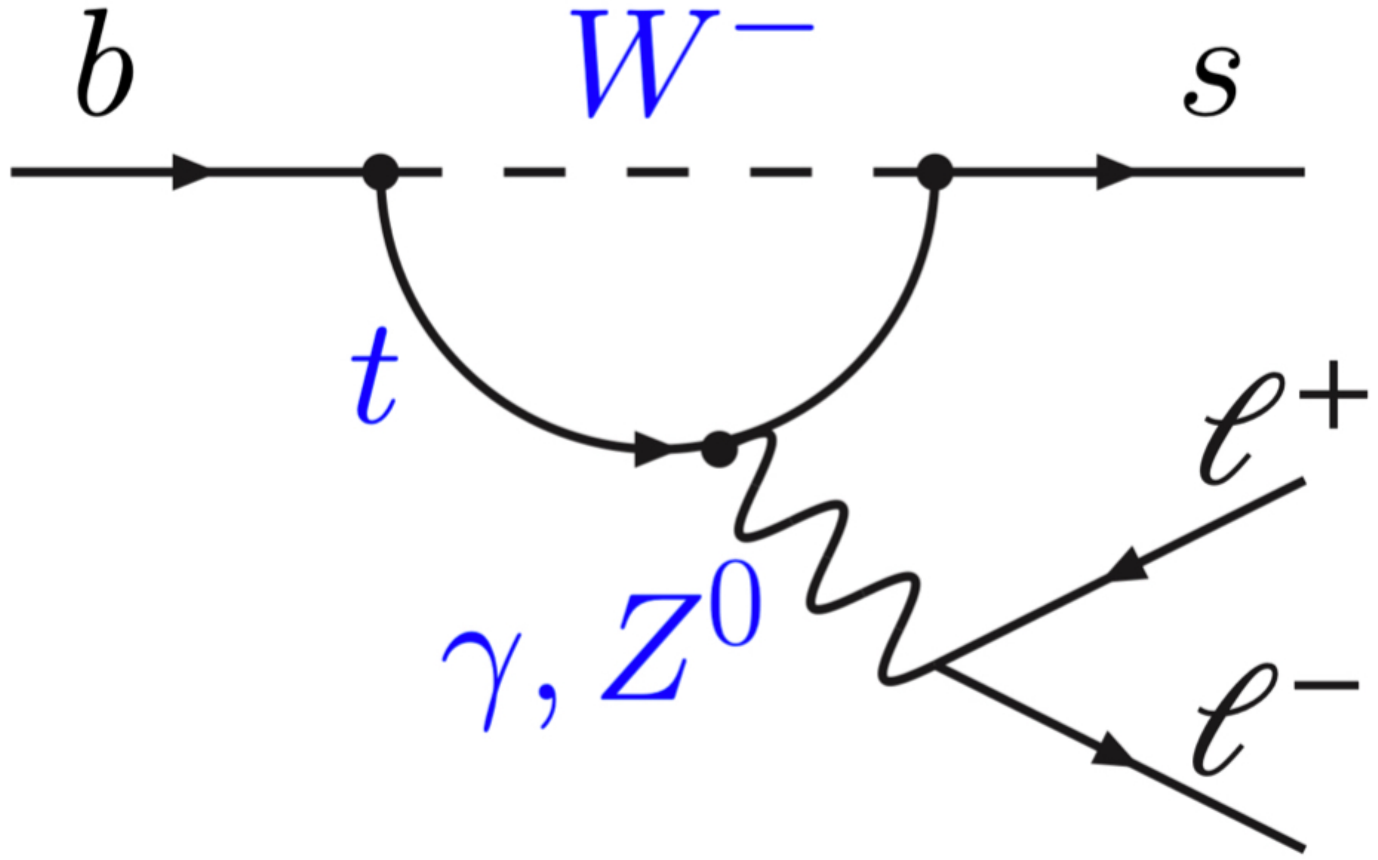
Lepton Flavour Universality tests with B decays

LFU tests in $b \to s\ell\ell$

- **$\mathcal{B} \sim \mathcal{O}(10^{-6})$, suppressed at tree level**
- **Highly sensitive to NP (10-100 TeV scale)**
  - Λ_{NP} probed depends on NP structure (LFUV, LFU universal)
- **NP can affect:**
  - decay rates and differential decay rates
  - angular distributions

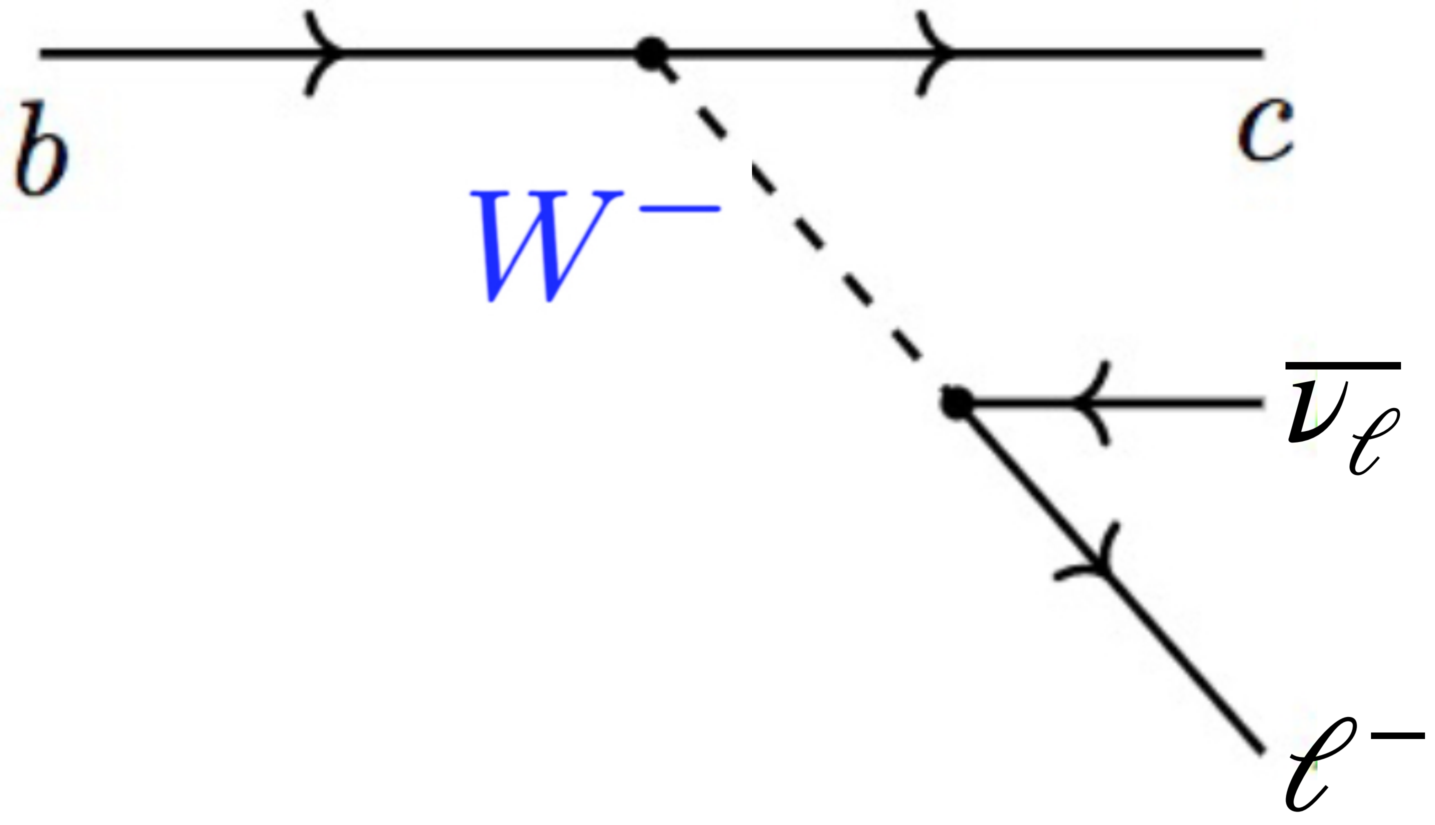
⚠ **not in this talk**

- Is BSM physics hierarchical in lepton sector?
  - **LFU tests with μ/e**



LFU tests also in $b \to c\ell\nu$ at LHCb

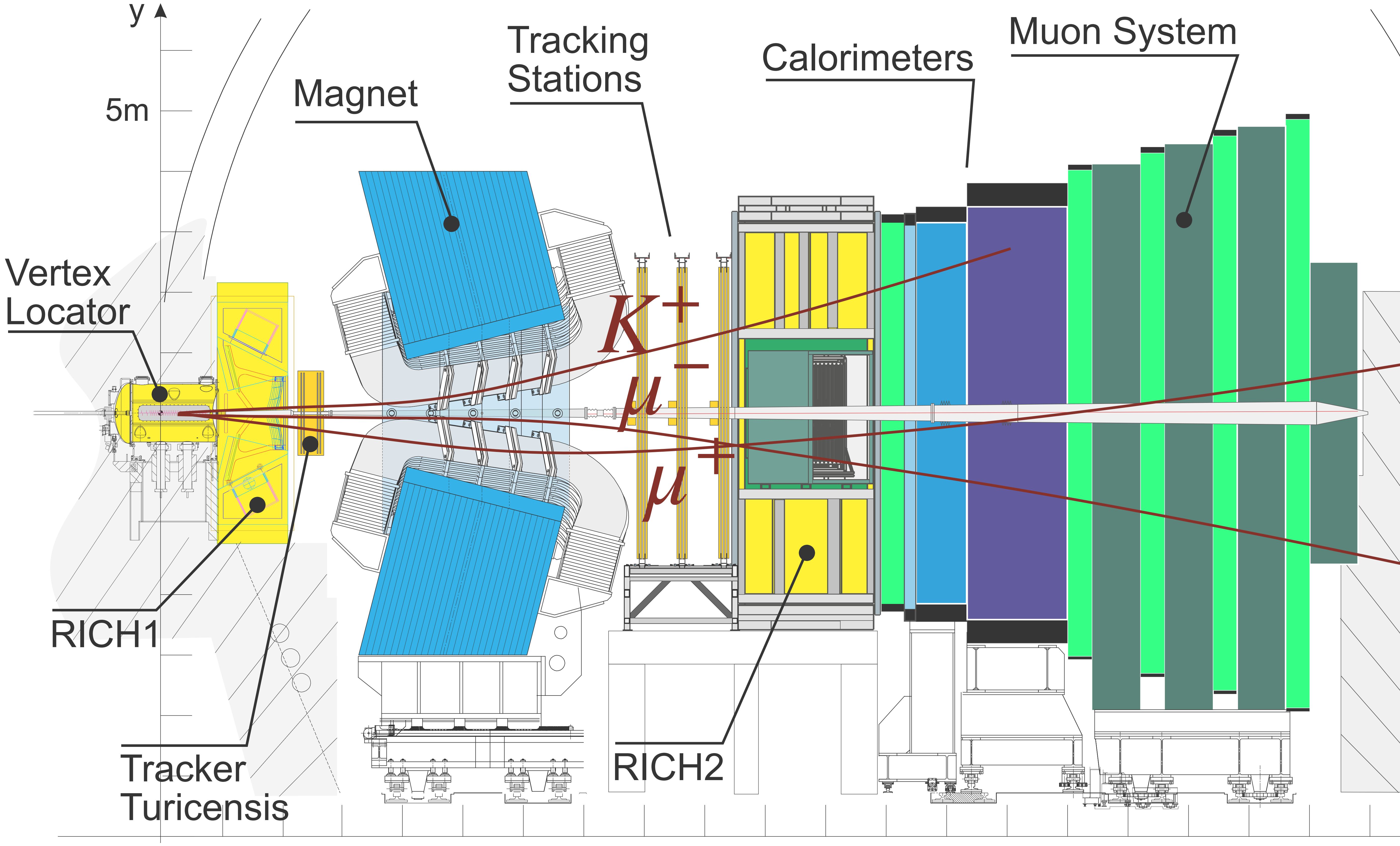
- Large $\mathcal{B}$, tree level processes
- Tree level transition, missing neutrino makes it experimentally challenging
- τ/μ , τ/e

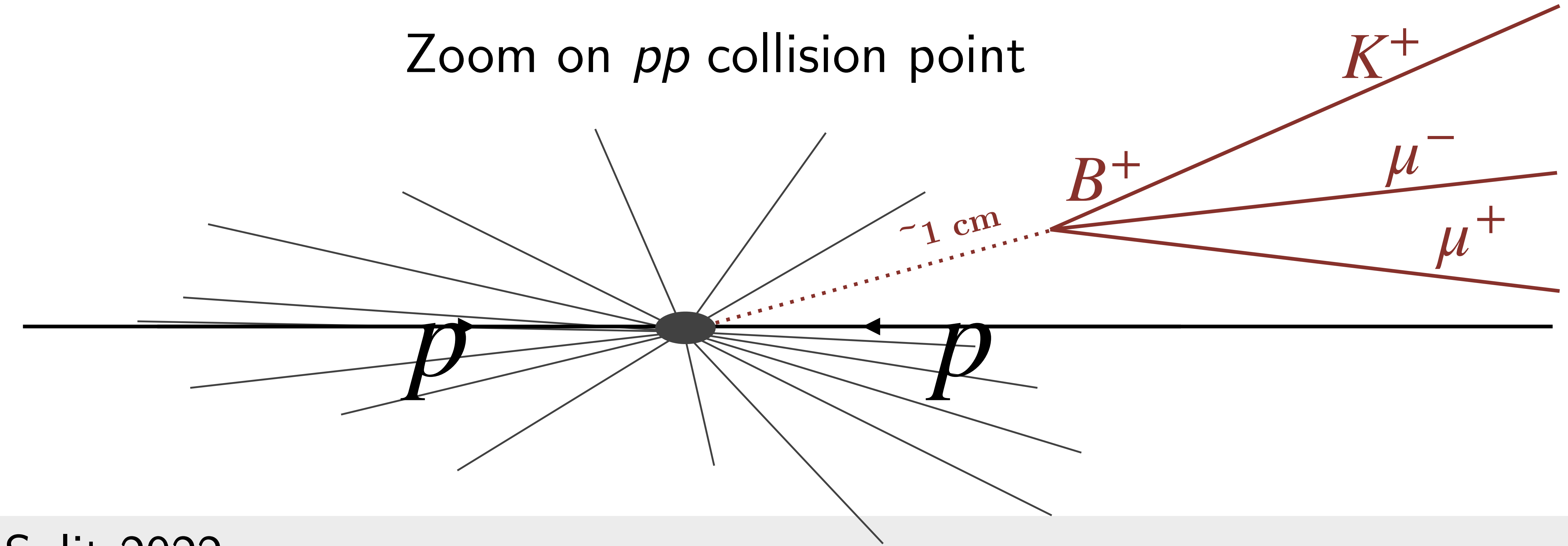


The LHCb experiment

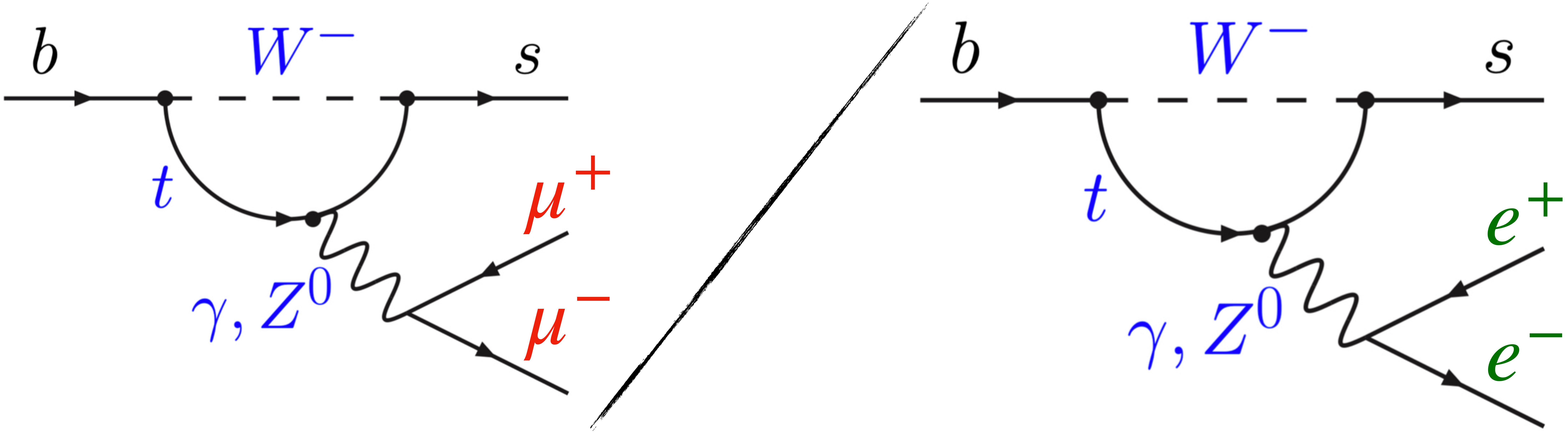
[Int.J.Mod.Phys. A 30, 1530022 (2015)]

- Lower luminosity than ATLAS/CMS for $\langle \mu \rangle \simeq 1.7$, $\mathscr{L}^{\text{LHCb}} \simeq 3.5 \times 10^{32}\ \text{cm}^{-2}\text{s}^{-1}$ → $\mathcal{O}(10^{12})$ b hadrons in LHCb acceptance in RunI/II (2011-2018)
- Acceptance in forward region of pp collisions $(2 < \eta < 5)$
  - Excellent displaced vertex identification
  - Low-p_{T} triggers (few GeV)
- Dipole magnet with **very precise tracking detectors** $\sigma_p/p \sim 0.5\,\%$
  - Particle ID with calorimeters, muon system and Cherenkov detectors (RICH)



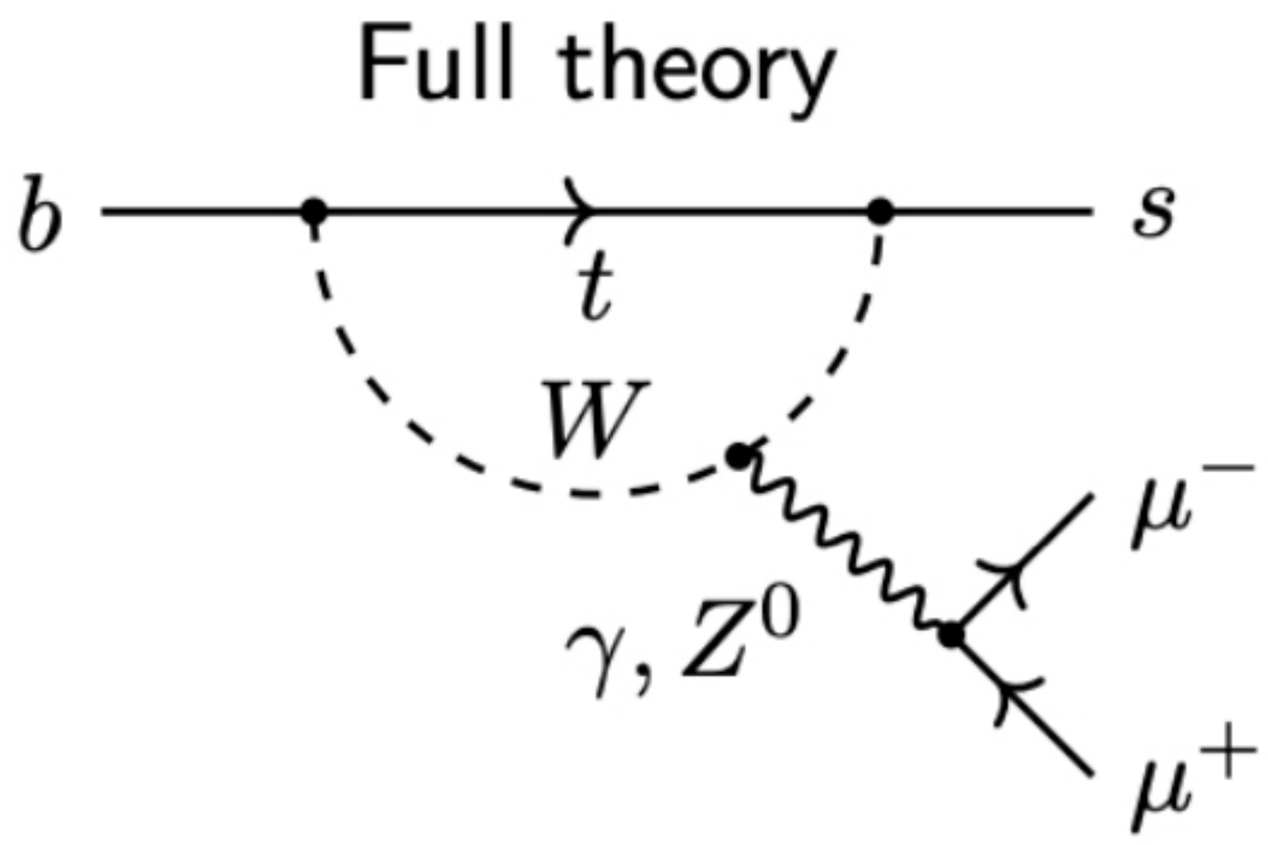

Zoom on pp collision point

LFU tests in $b \to s\ell\ell$



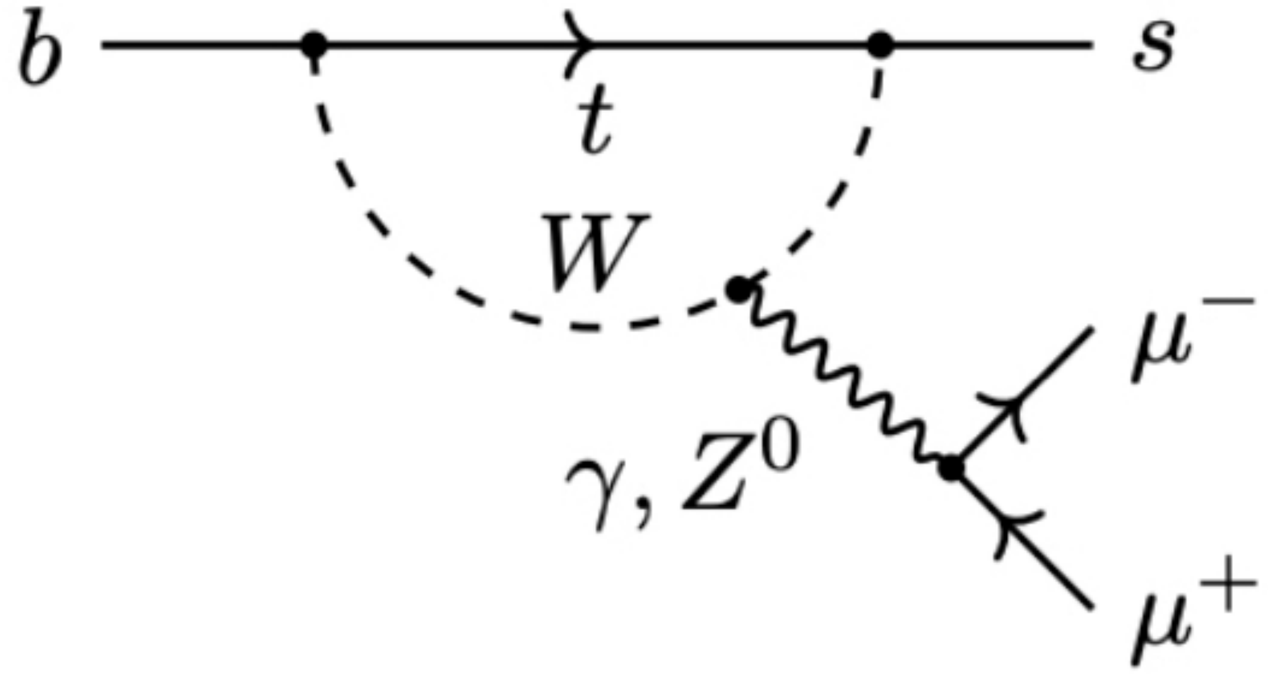
$$R_H = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B\to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B\to He^+e^-)}{dq^2} dq^2} \overset{?}{\simeq} 1$$

$b \to s\ell\ell$ phenomenology and sensitivity to NP



$b \to s\ell\ell$ phenomenology and sensitivity to NP

Full theory

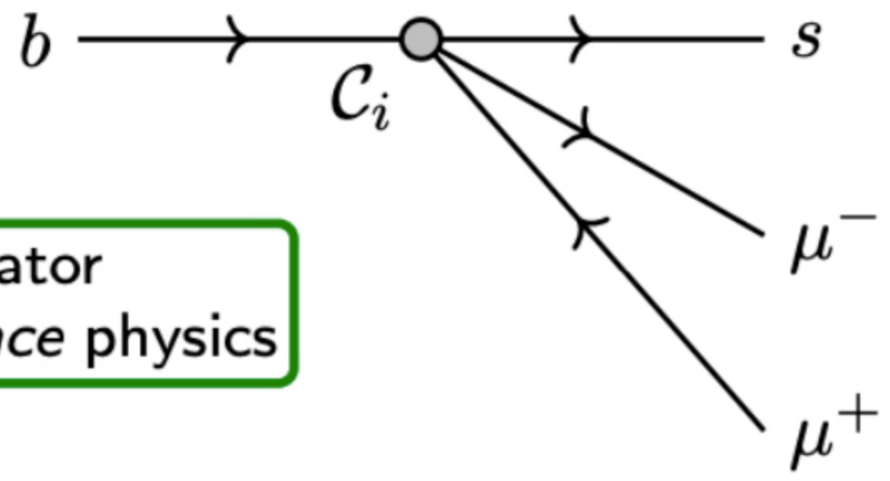


$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^* \sum_i \boxed{\mathcal{C}_i} \boxed{\mathcal{O}_i}$$

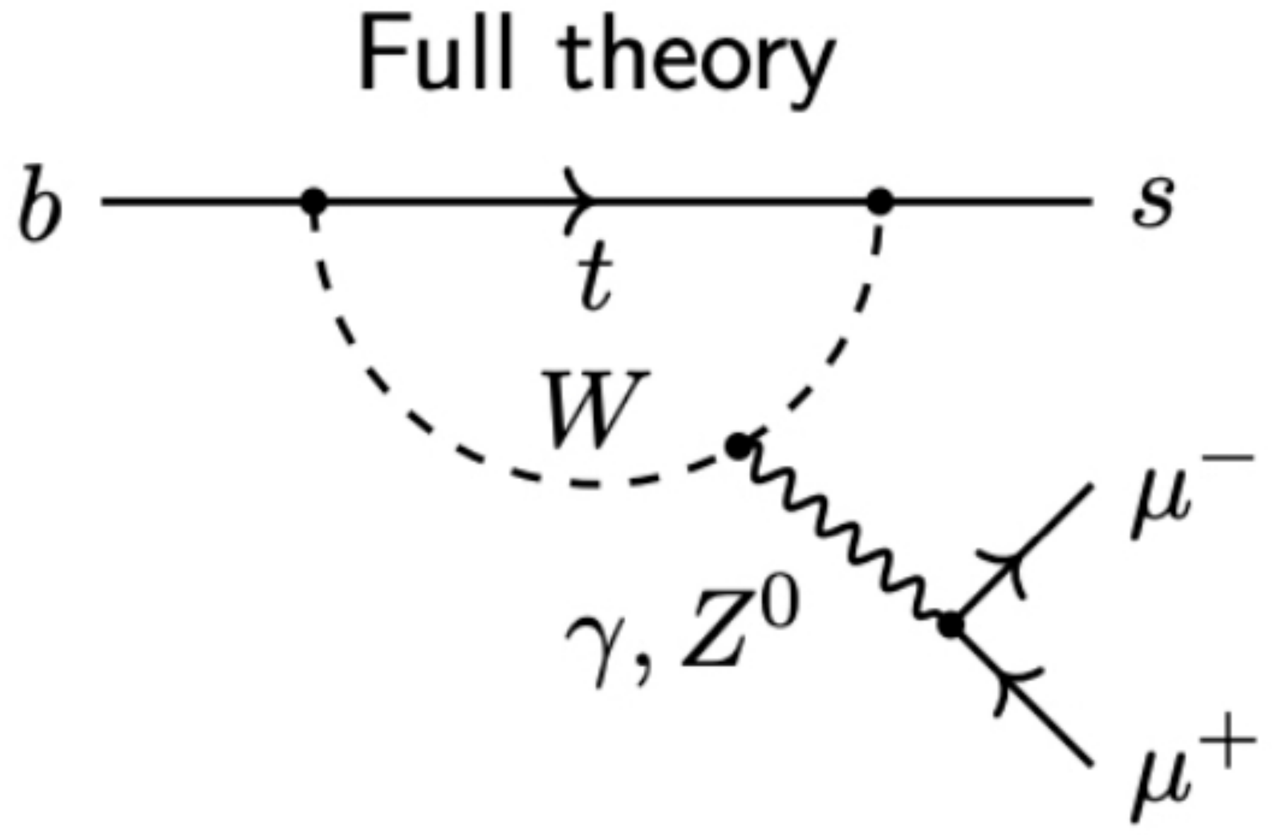
Effective coupling
"Wilson-coefficient"
short distance physics

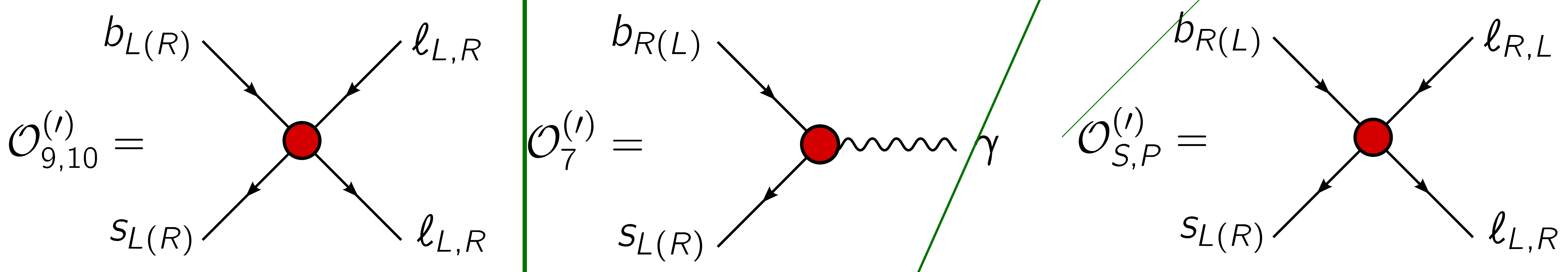
Local operator
long distance physics

Effective description



$b \to s\ell\ell$ phenomenology and sensitivity to NP


Full theory



V-A (EW penguin)

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{\mathrm{L(R)}} b)(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{\mathrm{L(R)}} b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)$$

dipole (e.m. penguin)

$$\mathcal{O}_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{\mathrm{R(L)}}b)F^{\mu\nu}$$

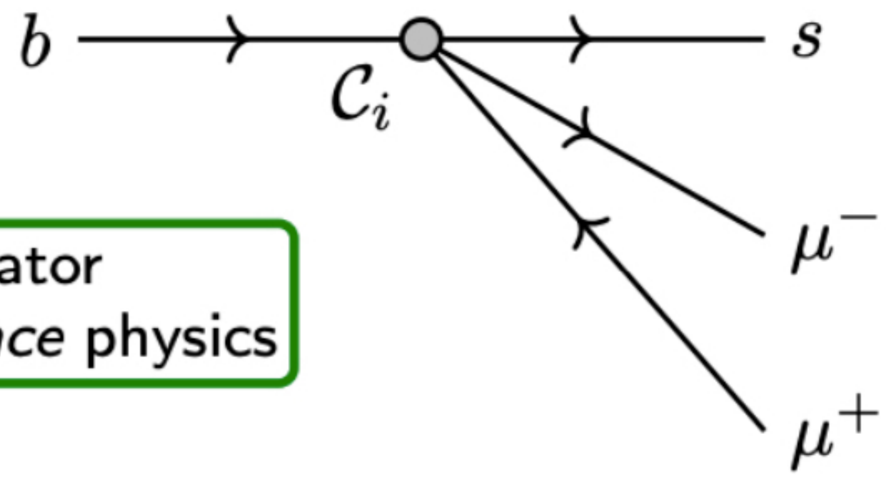
scalar, pseudo-scalar

$$\mathcal{O}_{\mathrm{S}}^{(\prime)} = \bar{s}P_{R(L)}b\,\bar{\ell}\ell$$
$$\mathcal{O}_{\mathrm{P}}^{(\prime)} = \bar{s}P_{R(L)}b\,\bar{\ell}\gamma_5\ell$$

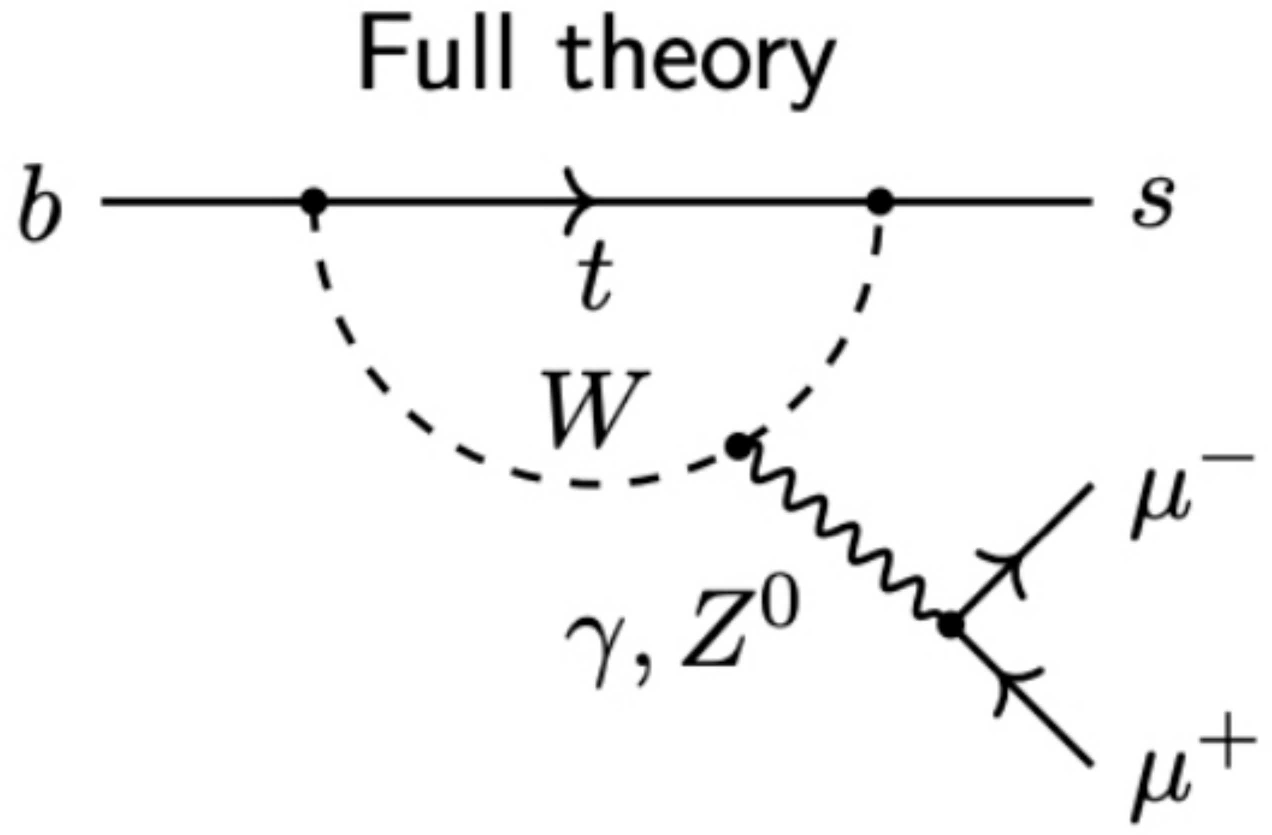
$$\mathcal{H}_{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}}V_{\mathrm{tb}}V_{\mathrm{ts}}^{*}\sum_i \boxed{\mathcal{C}_i}\,\boxed{\mathcal{O}_i}$$

Effective coupling
"Wilson-coefficient"
short distance physics

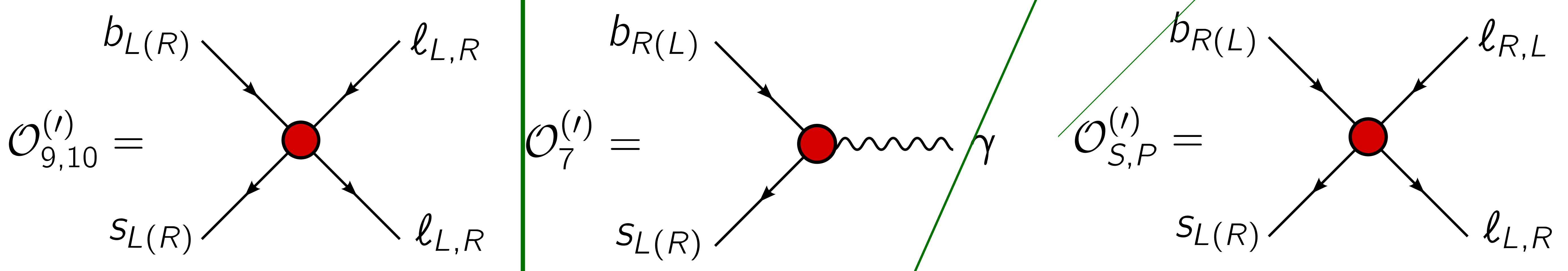
Local operator
long distance physics


Effective description

$b \to s\ell\ell$ phenomenology and sensitivity to NP



V-A (EW penguin) | dipole (e.m. penguin) | scalar, pseudo-scalar



$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{\mathrm{L(R)}} b)(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{\mathrm{L(R)}} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

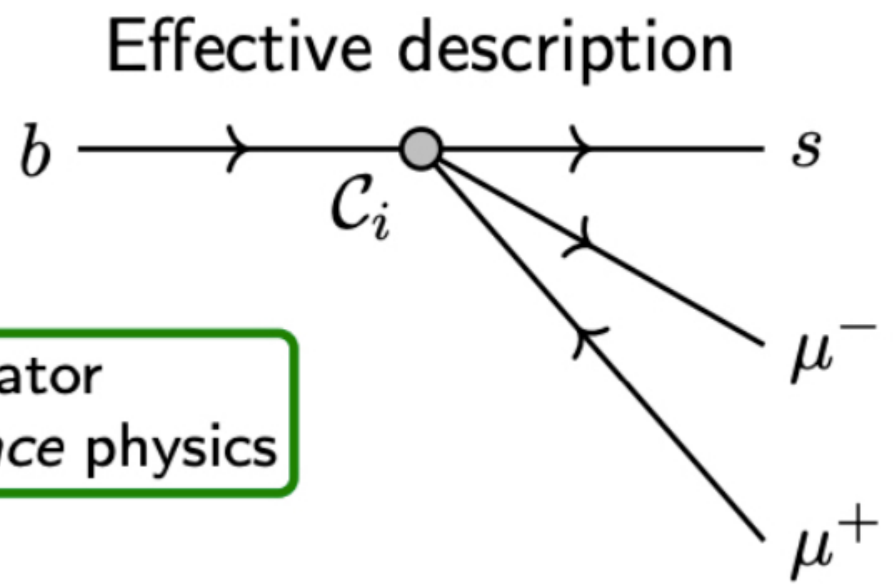
$$\mathcal{O}_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu} P_{\mathrm{R(L)}} b)F^{\mu\nu}$$

$$\mathcal{O}_{\mathrm{S}}^{(\prime)} = \bar{s}P_{R(L)} b\, \bar{\ell}\ell$$
$$\mathcal{O}_{\mathrm{P}}^{(\prime)} = \bar{s}P_{R(L)} b\, \bar{\ell}\gamma_5\ell$$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^* \sum_i \boxed{\mathcal{C}_i}\,\boxed{\mathcal{O}_i}$$

Effective coupling
"Wilson-coefficient"
short distance physics

Local operator
long distance physics



$$\Delta\mathcal{H}_{\text{NP}} = \frac{\boxed{c}}{\boxed{\Lambda^2_{\text{NP}}}}\mathcal{O}_i$$

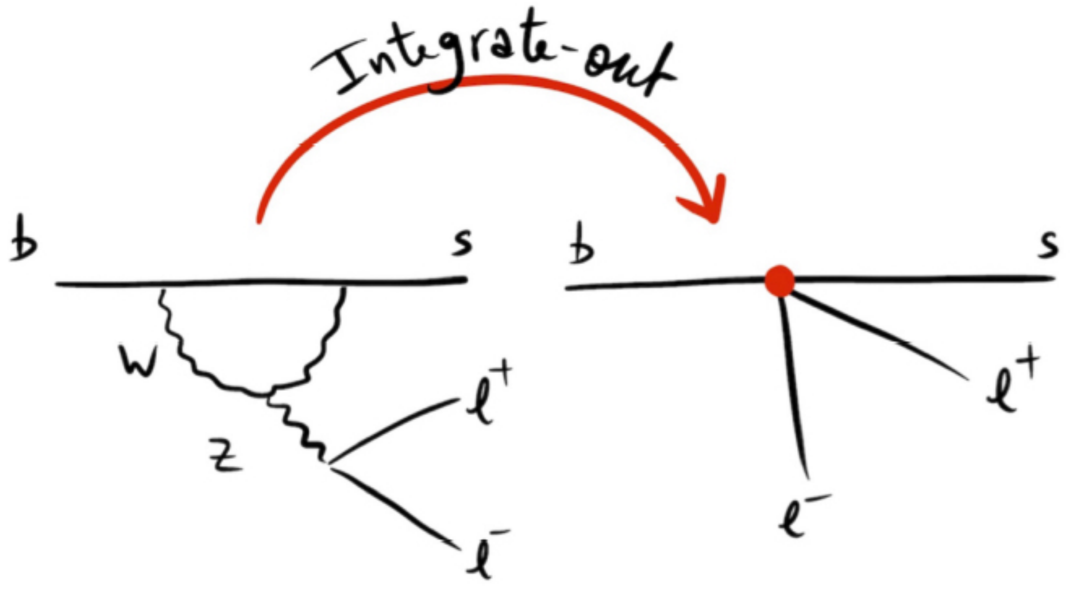
Flavour-violating coupling

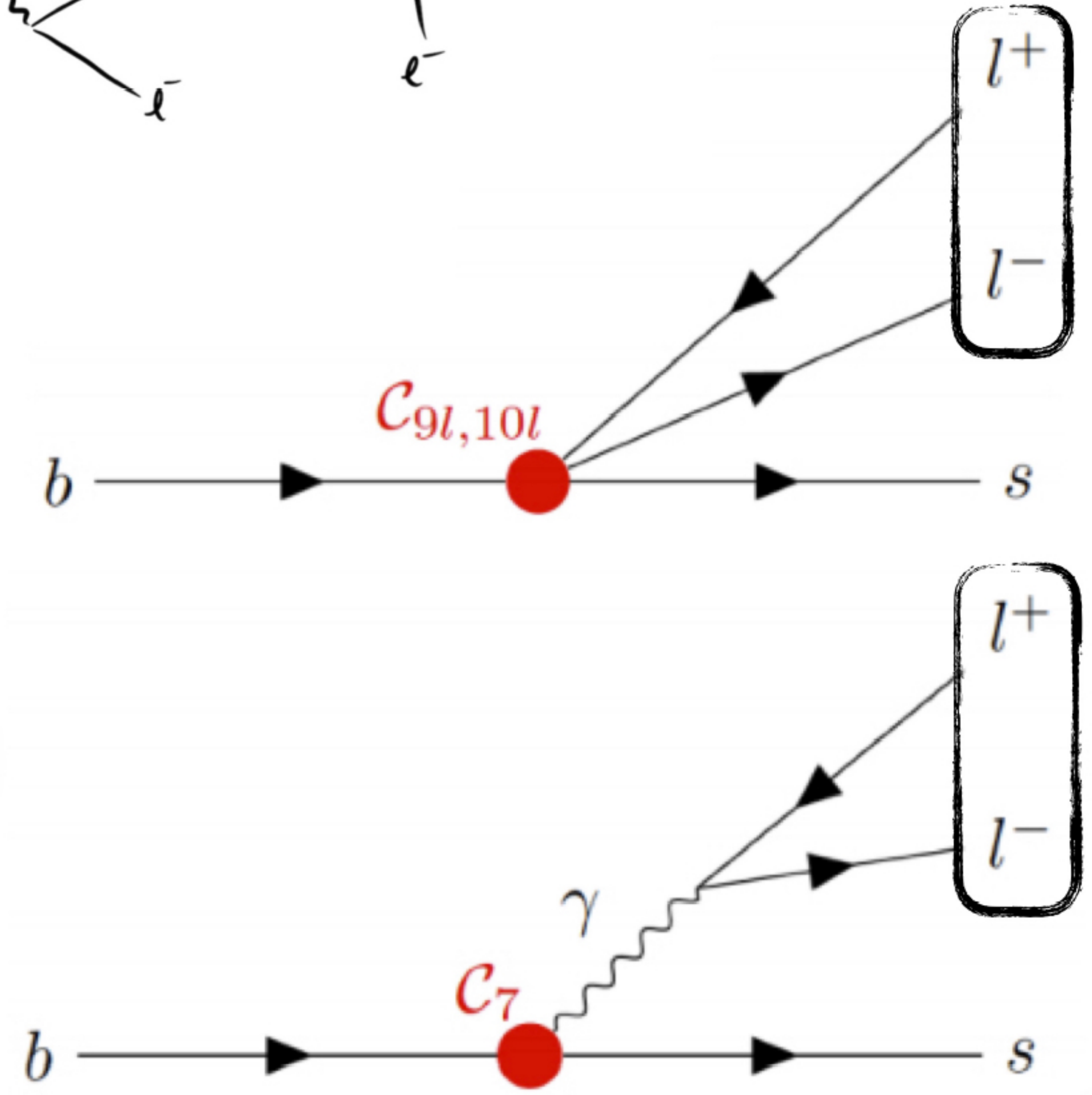
NP scale

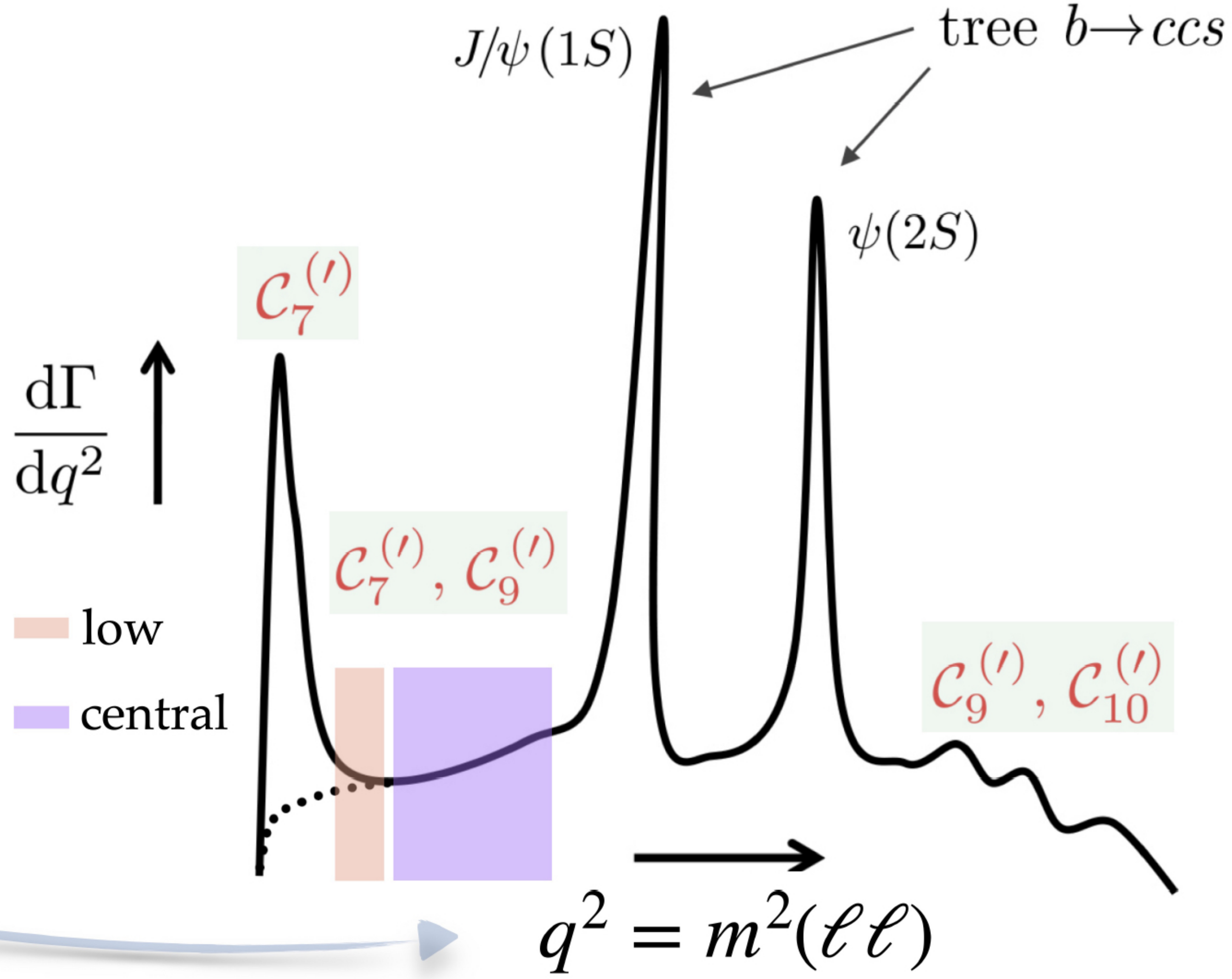
Coupling	$b \to s\gamma$	$B \to \mu\mu$	$b \to s\ell\ell$
$\mathcal{C}_7^{(\prime)}$	✓		✓
$\mathcal{C}_9^{(\prime)}$			✓
$\mathcal{C}_{10}^{(\prime)}$		✓	✓
$\mathcal{C}_S^{(\prime)}$		✓	
$\mathcal{C}_P^{(\prime)}$		✓	

$b \to s\ell\ell$ phenomenology and sensitivity to NP

$$H_{eff} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left(C_i^{SM} + \Delta_i^{NP} \right) O_i$$





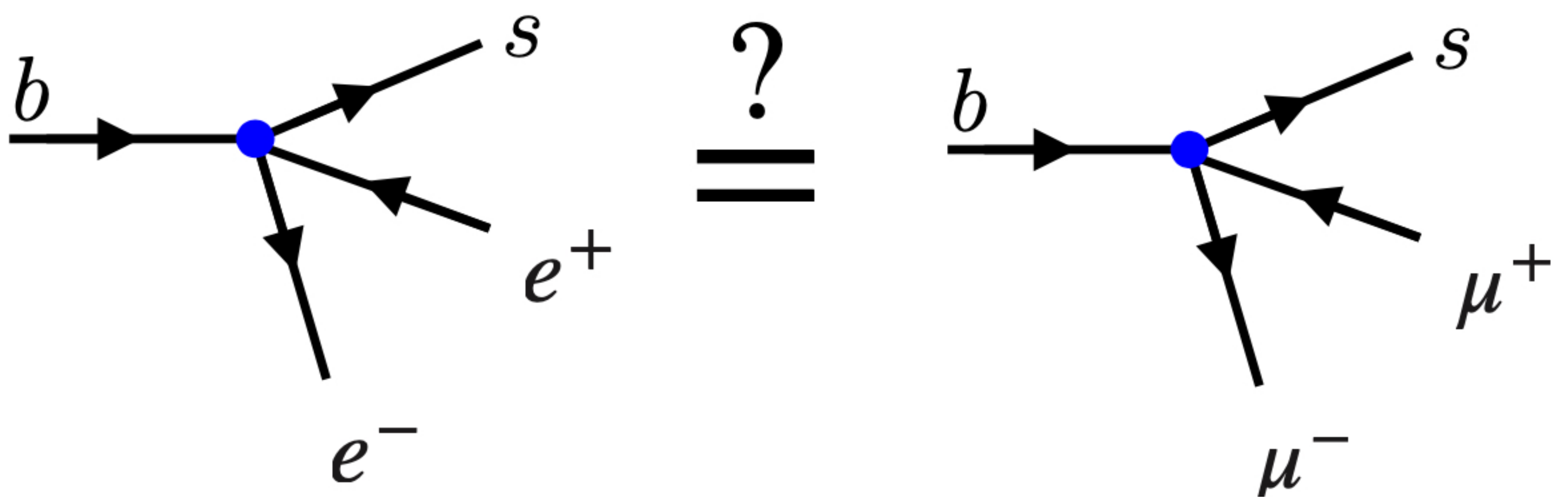


···· : with PseudoScalar H_s in final state, K_s^0, K^+

— : with Vector H_s in final state, $K^{*0}, K^{*+}, \phi, \ldots$

Lepton Flavour Universality in $b \to s\ell\ell$: the actors at LHCb

$$R_H = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B\to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B\to He^+e^-)}{dq^2} dq^2} \overset{?}{\simeq} 1$$

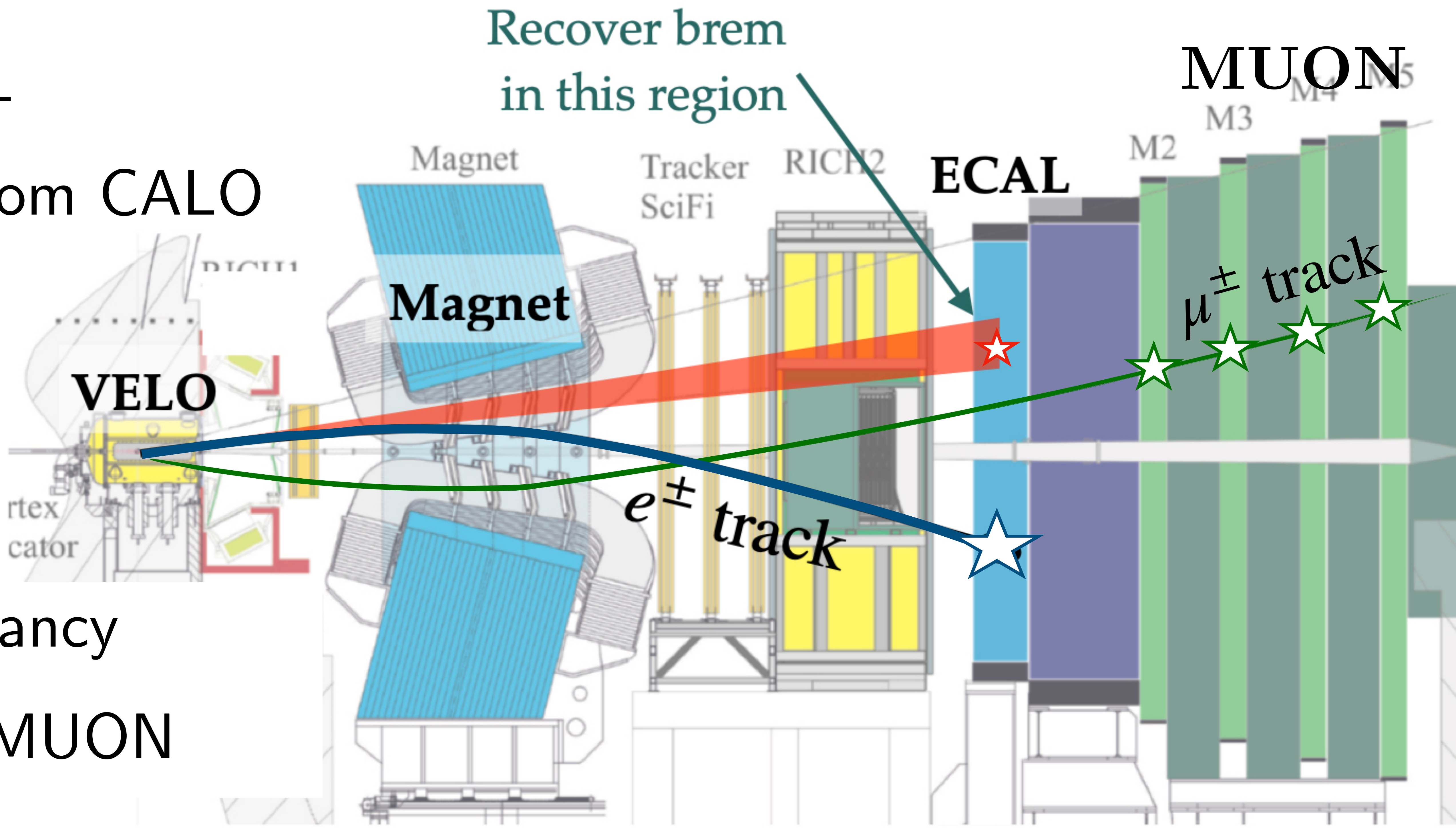


▸ Electrons at LHCb

- ✦ Emits bremmshtralung γ, high occupancy in ECAL
- ✦ **ECAL tight trigger thresholds** and ID mostly from CALO
- ✦ ε_{reco} and $\frac{\sigma_p}{p}$ worse than μ

▸ Muons at LHCb

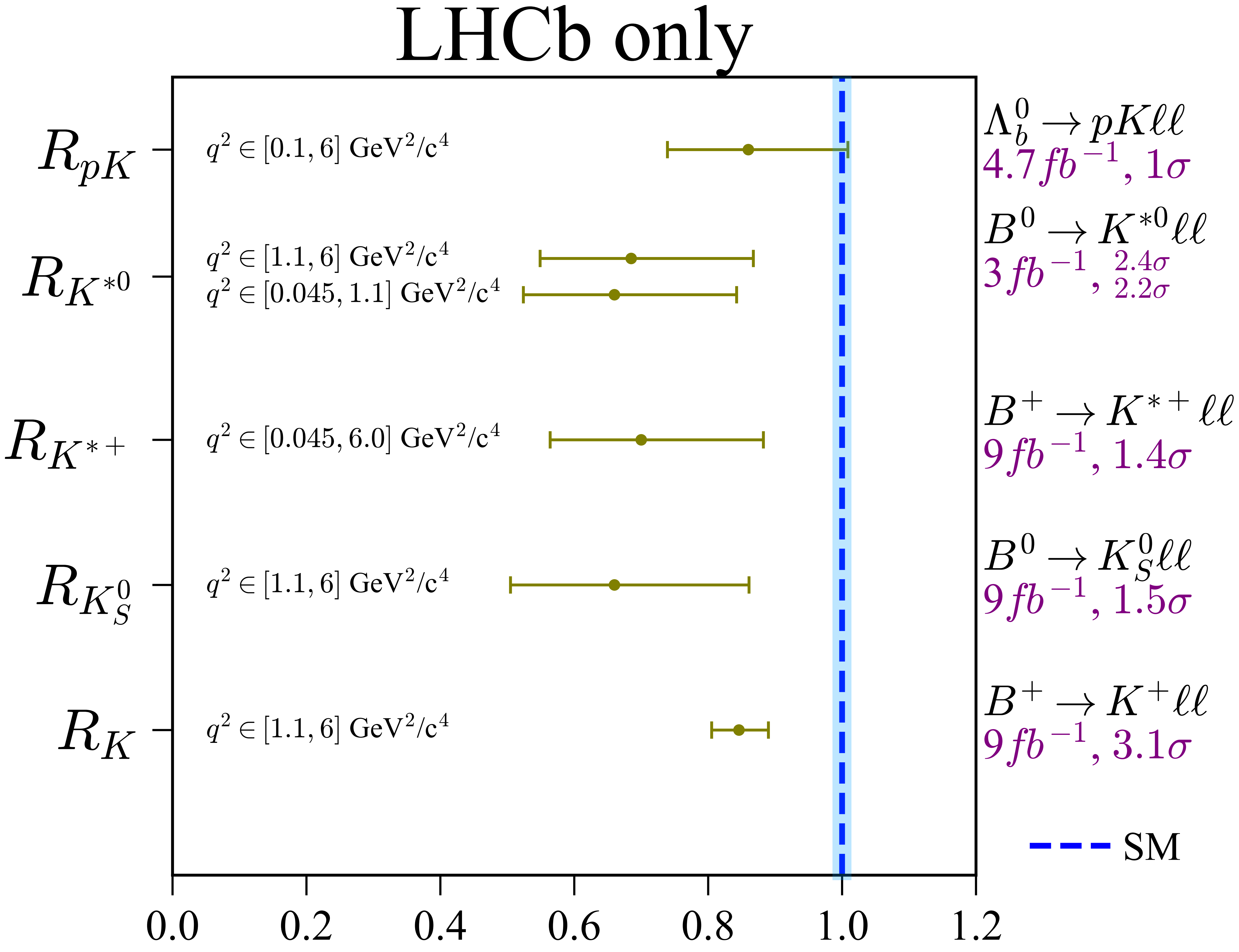
- ✦ Negligible bremmshtralung, MUON has low occupancy
- ✦ Muon soft trigger thresholds and ID mostly from MUON
- ✦ Excellent ε_{reco} and $\frac{\sigma_p}{p}$



Overall, a ratio of ~ 3:1 of reconstructed muons to electrons in LHCb in Run1/2 data taking

Pattern of deviation from LHCb in LFU tests

- Coherent pattern of tension to SM in LFU tests with $b \to s\ell\ell$ transition:
  - R_X **ratios :** $\frac{\mu}{e}$ **decay rates**
- R_X **ratio extremely well predicted in SM**
  - Cancellation of hadronic uncertainties at 10^{-4}
  - $\mathcal{O}(1\%)$ QED corrections [Bordone et al arXiv:1605.07633]
  - Experimentally only statistically limited
- **Any departure from unity is a clear sign of new physics**



$$R_X = \frac{\mathcal{B}(b \to s\mu\mu)}{\mathcal{B}(b \to see)}$$

(*) Measurements from Belle excluded (larger statistical uncertainties)

How is R_X measured in LHCb?

$$R_X = \underbrace{\frac{\boxed{\mathcal{N}^{q^2_{bin}}_{B\to X\mu^+\mu^-}}}{\boxed{\mathcal{N}_{B\to XJ/\psi(\to\mu^+\mu^-)}}} \cdot \frac{\boxed{\mathcal{N}_{B\to XJ/\psi(\to e^+e^-)}}}{\boxed{\mathcal{N}^{q^2_{bin}}_{B\to Xe^+e^-}}}}_{\text{mass fits}} \cdot \underbrace{\frac{\boxed{\mathcal{E}^{q^2_{bin}}_{B\to Xe^+e^-}}}{\boxed{\mathcal{E}_{B\to XJ/\psi(\to e^+e^-)}}} \cdot \frac{\boxed{\mathcal{E}_{B\to XJ/\psi(\to\mu^+\mu^-)}}}{\boxed{\mathcal{E}^{q^2_{bin}}_{B\to X\mu^+\mu^-}}}}_{\text{corrected simulation samples}}$$

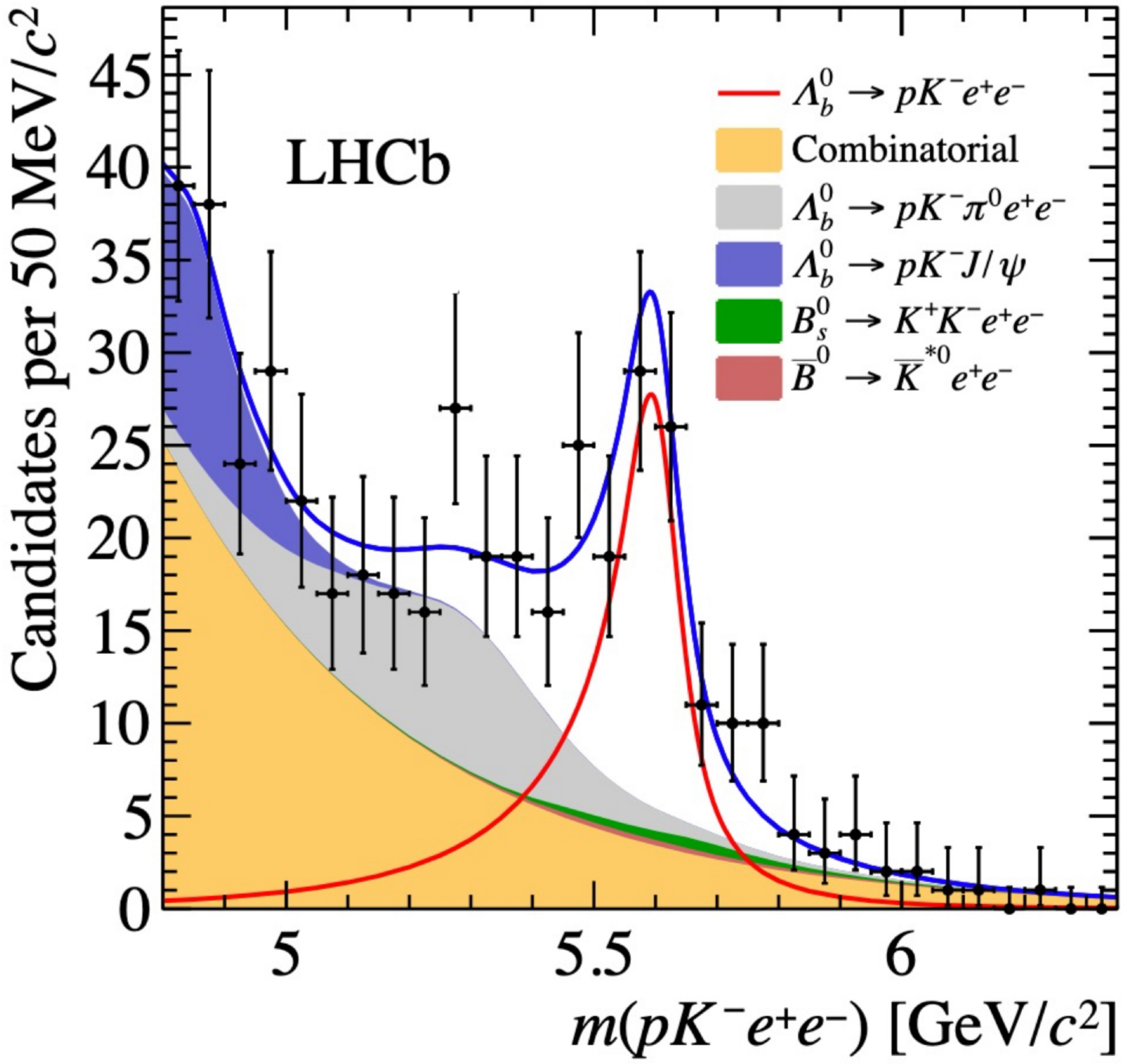
- **$\mathcal{N}$ from mass fits, ε evaluated from data-driven corrected simulation**
- **$B \to XJ/\psi(\ell\ell)$: normalisation and ε calibration mode**
  - Take advantage of $\dfrac{\mathcal{B}(J/\psi \to \mu\mu)}{\mathcal{B}(J/\psi \to ee)} = 1$ for double-ratio and $\sigma^{\varepsilon}_{syst}$ cancellation in $\varepsilon(\mu)/\varepsilon(e)$
- **$\varepsilon(e/\mu)$ goodness of calibration tested**
  - Measuring $r(J/\psi) = \dfrac{\mathcal{B}(B \to XJ/\psi(\mu\mu))}{\mathcal{B}(B \to XJ/\psi(ee))}$=1 ?
  - Measuring $R(\psi(2s)) = \dfrac{\mathcal{B}(B \to X\psi(2S)(\mu\mu))}{\mathcal{B}(B \to X\psi(2S)(ee))}$=1 ? [using the double-ratio approach]
- **Backgrounds vs q^2 specific analysis dependent**

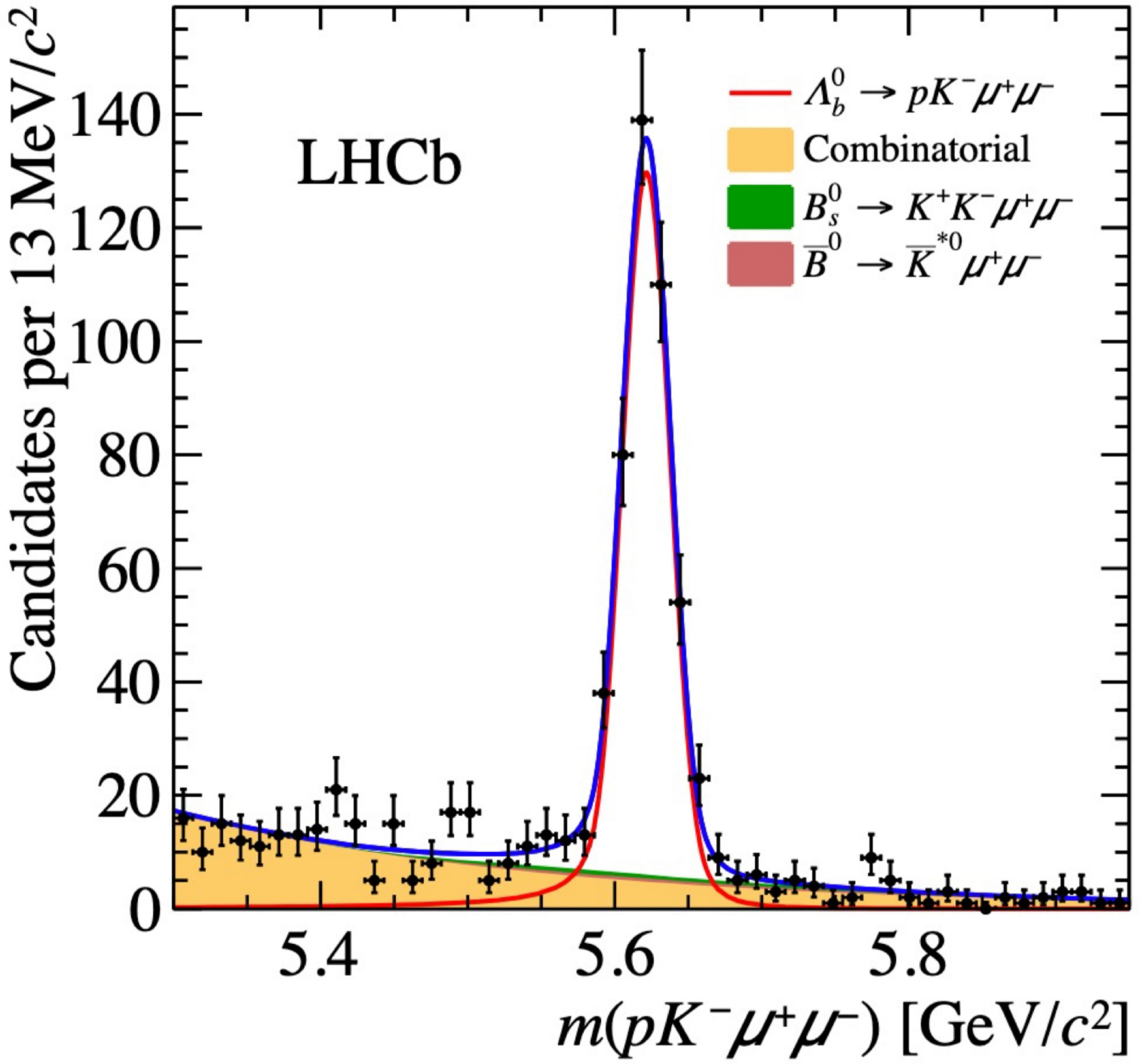
Pattern of deviation from LHCb in LFU tests

[JHEP,2020,40 (2020)]

R_{pK} ($\Lambda_b \to pK\ell\ell$)

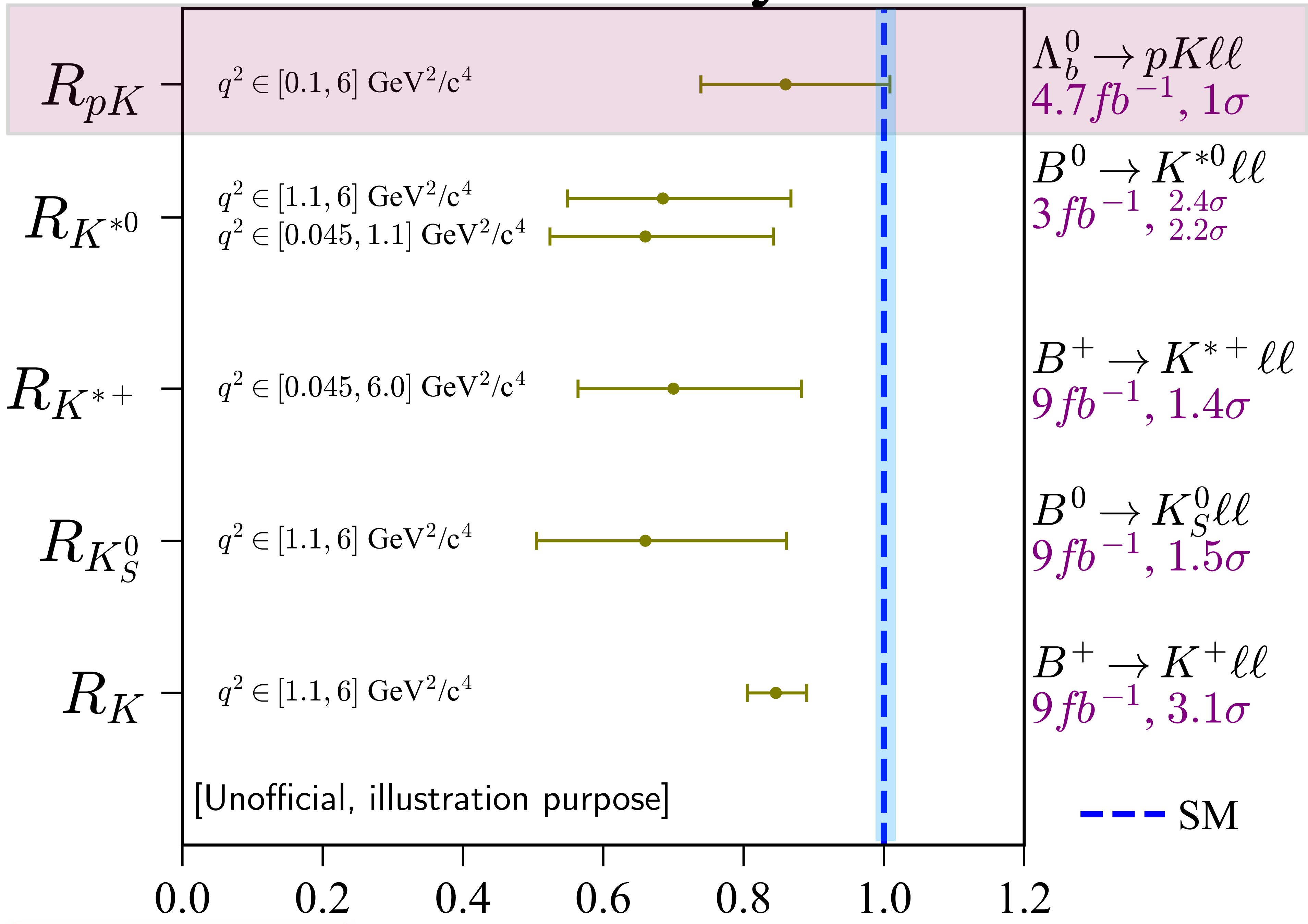
- **LHCb Run1** (3fb^{-1})**+2016**(1.7fb^{-1}) **data**





- First LFU test in baryonic decays (unique at LHCb)
- Systematics dominated by background modelling
- $q^2 \in [0.1,6.0]$ GeV^2/c^4 , $m(pK) < 2400\ MeV/c^2$

LHCb only



Validation

- $r_{J/\psi}^{-1} = 0.96 \pm 0.05$ (stat. $\oplus$ syst.)
- $R_{\psi(2S)}$ compatible with unity within $1\,\sigma$.)

Result

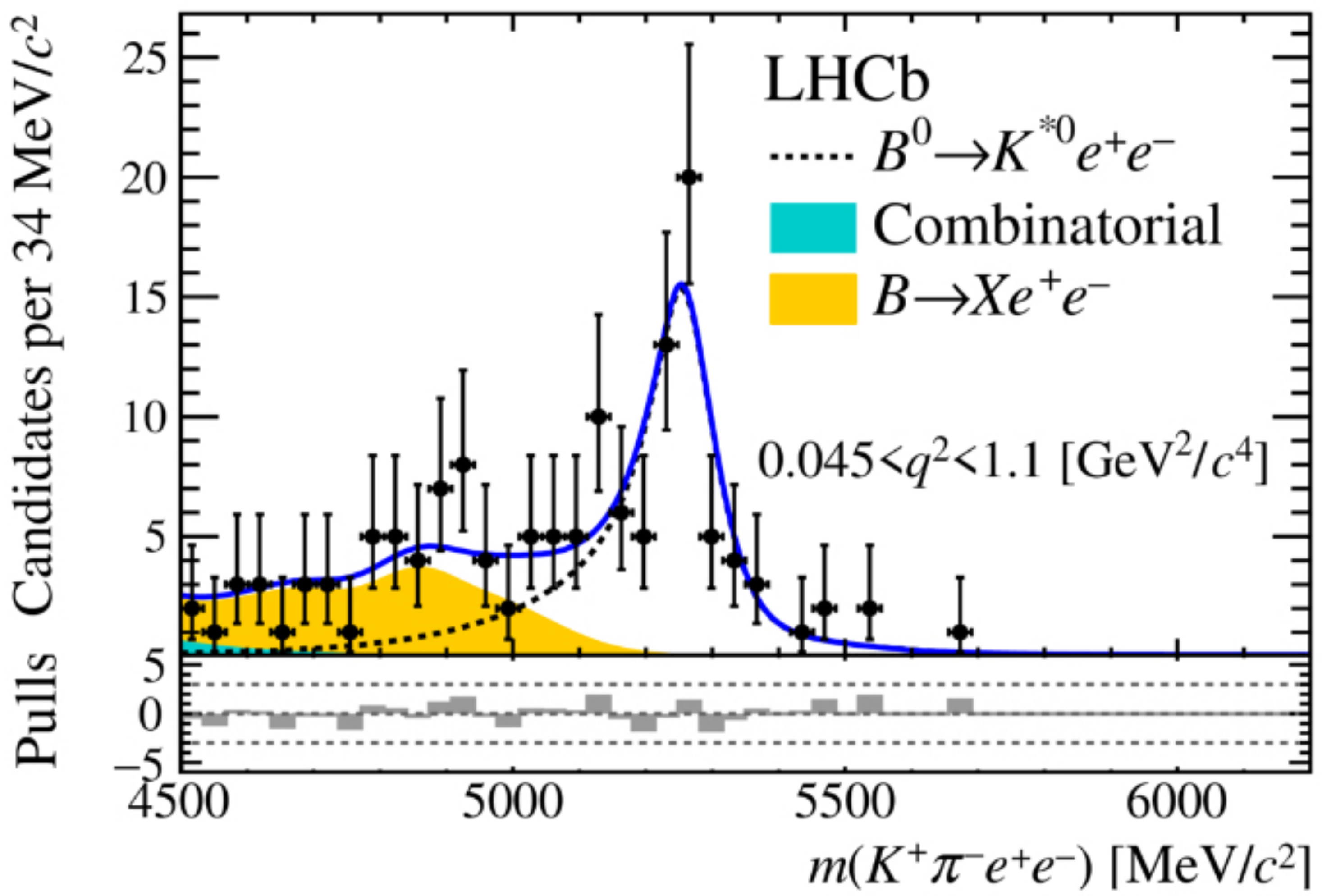
- $R_{pK} = 0.86^{+0.14}_{-0.11}$ (stat.) $\pm\, 0.05$ (syst.)
- Agreement with SM at $< 1\,\sigma$ level

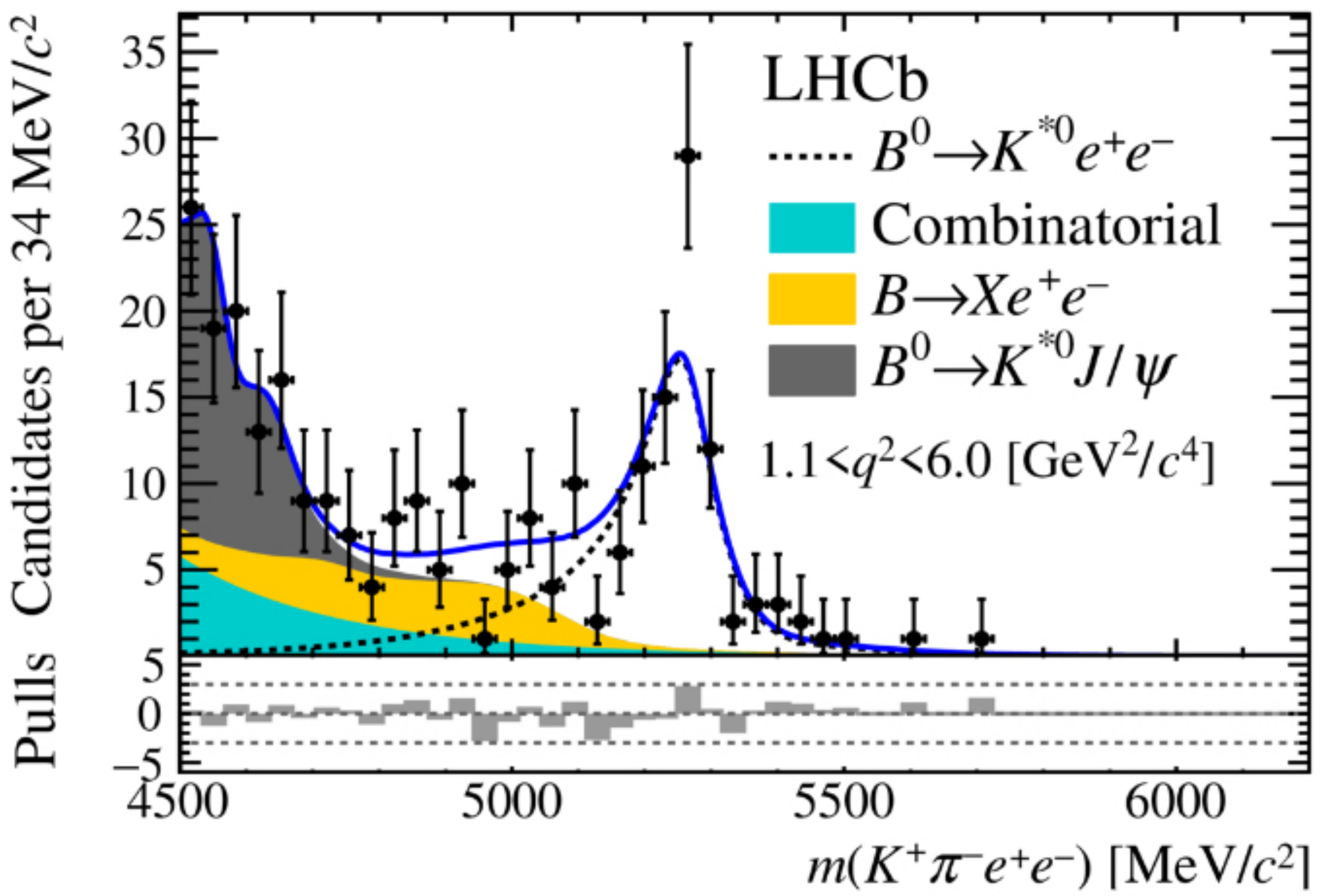
Pattern of deviation from LHCb in LFU tests

[JHEP08(2017)055]

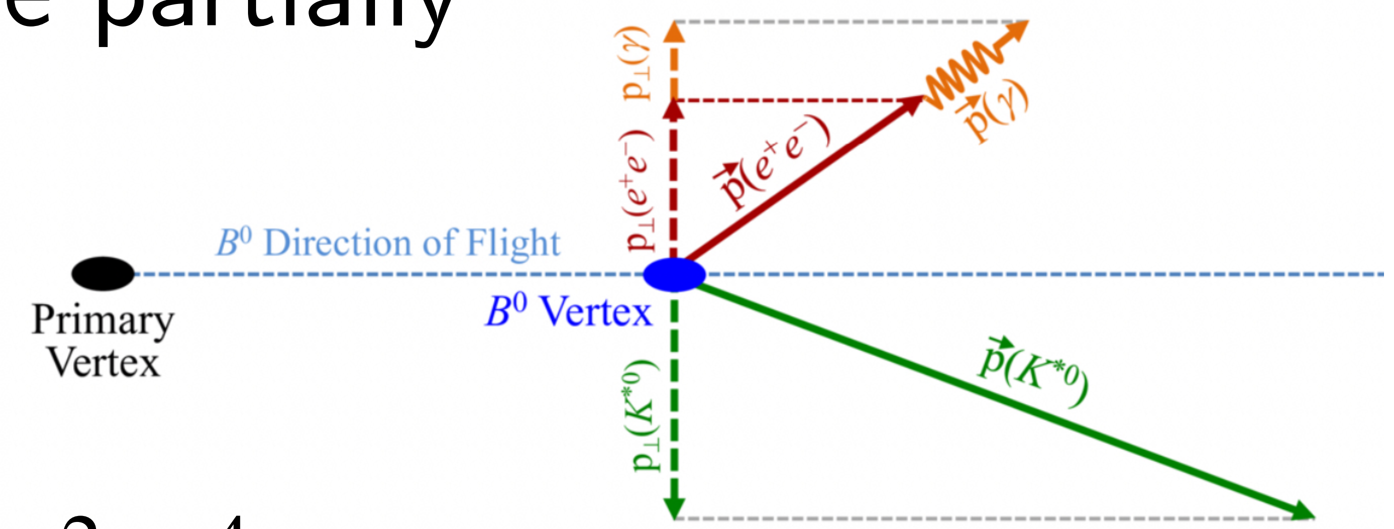
$R_{K^{*0}}$ ($B^0 \to K^{*0}\ell\ell$)

- **LHCb Run1** (3fb^{-1}) **data used**

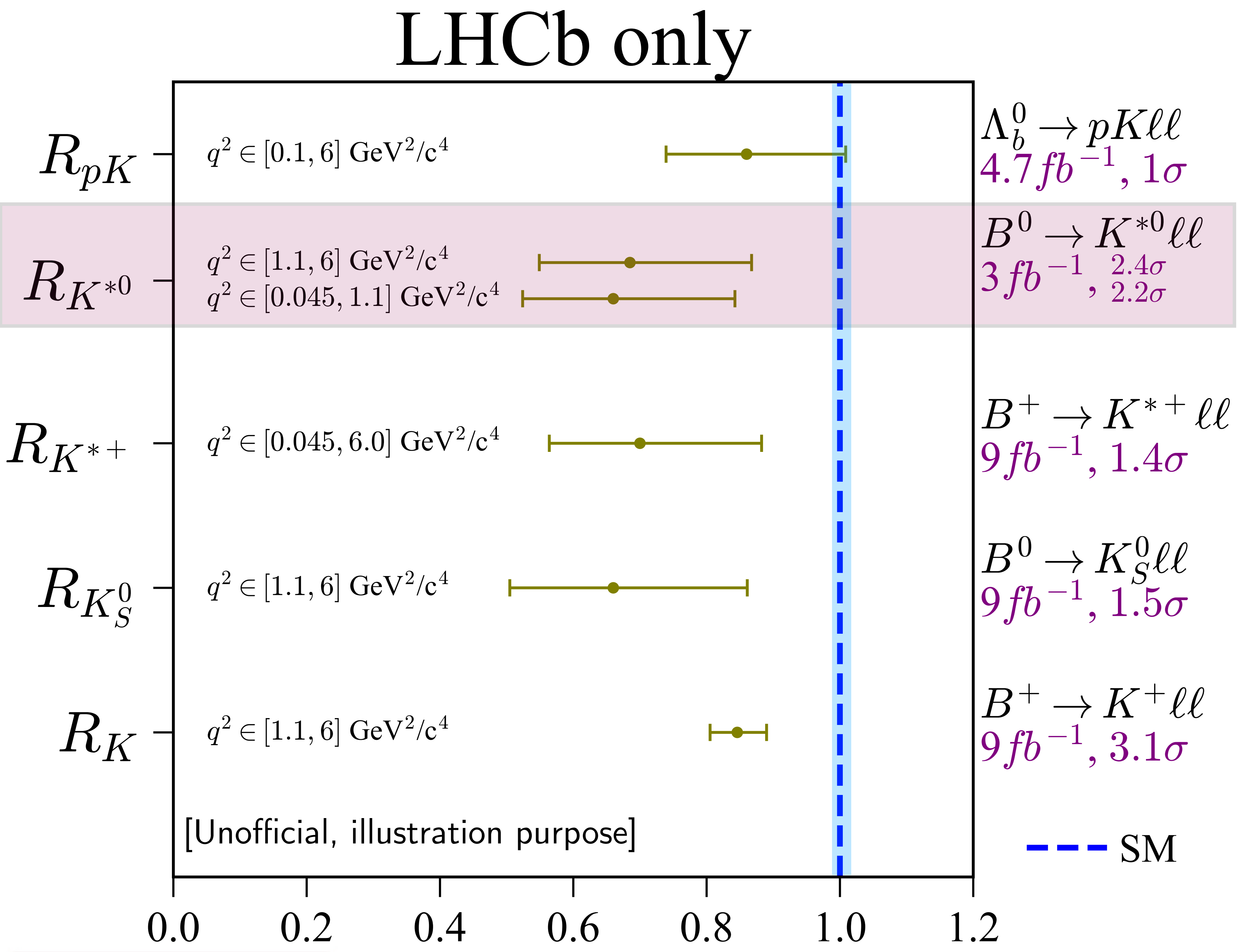




- Dedicated kinematic cut to reduce partially reconstructed background
- Measurement in 2 q^2 regions
  - *low* $q^2 \in [0.045,1.1]\ \mathrm{GeV}^2/c^4$
  - *central* $q^2 \in [\ \ 1.1,6.0]\ \mathrm{GeV}^2/c^4$



LHCb only



Validation

- $r_{J/\psi} = 1.043 \pm 0.006\,(\text{stat.}) \pm 0.045\,(\text{syst.})$
- $R_{\psi(2S)}$ compatible with unity within $1\,\sigma$

Result

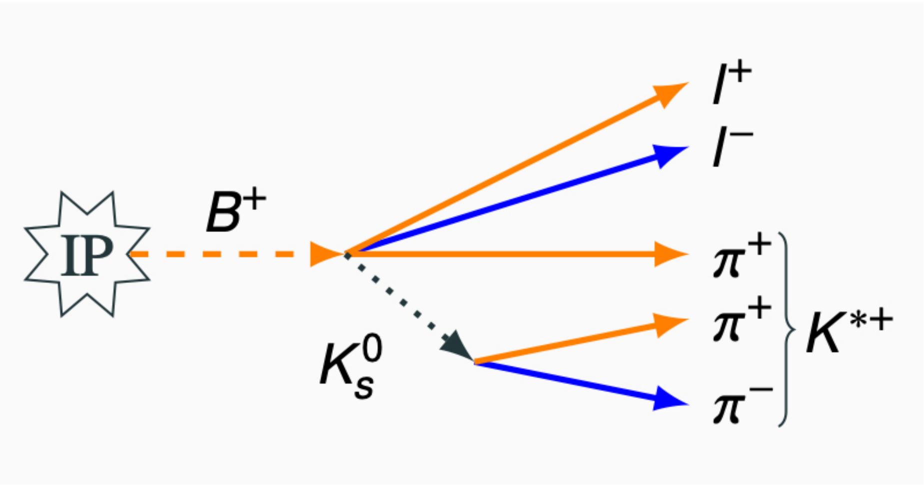
$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07}(\text{stat.}) \pm 0.03(\text{syst.}), \text{low} & 2.2\sigma \\ 0.69^{+0.11}_{-0.07}(\text{stat.}) \pm 0.05(\text{syst.}), \text{central} & 2.4\sigma \end{cases}$$

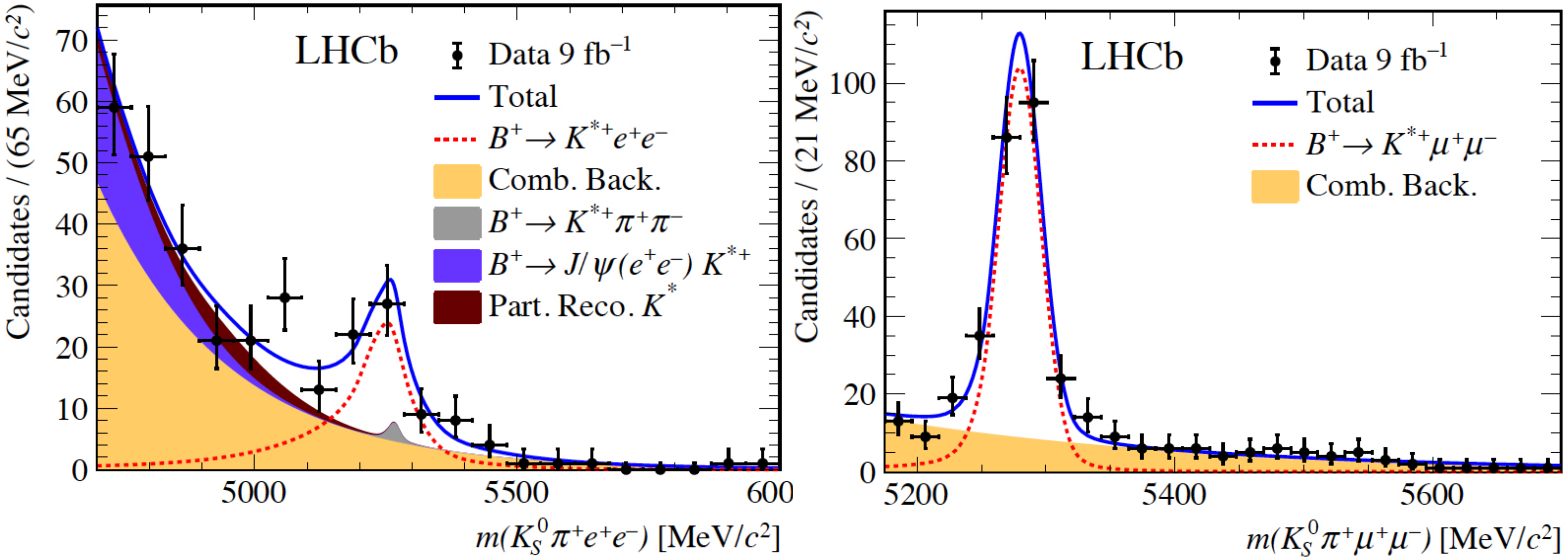
Pattern of deviation from LHCb in LFU tests

[Phys. Rev. Lett. 128 (2022) 191802]

$R_{K^{*+}}$ ($B^+ \to K^{*+}(K_s\pi)\ell\ell$)

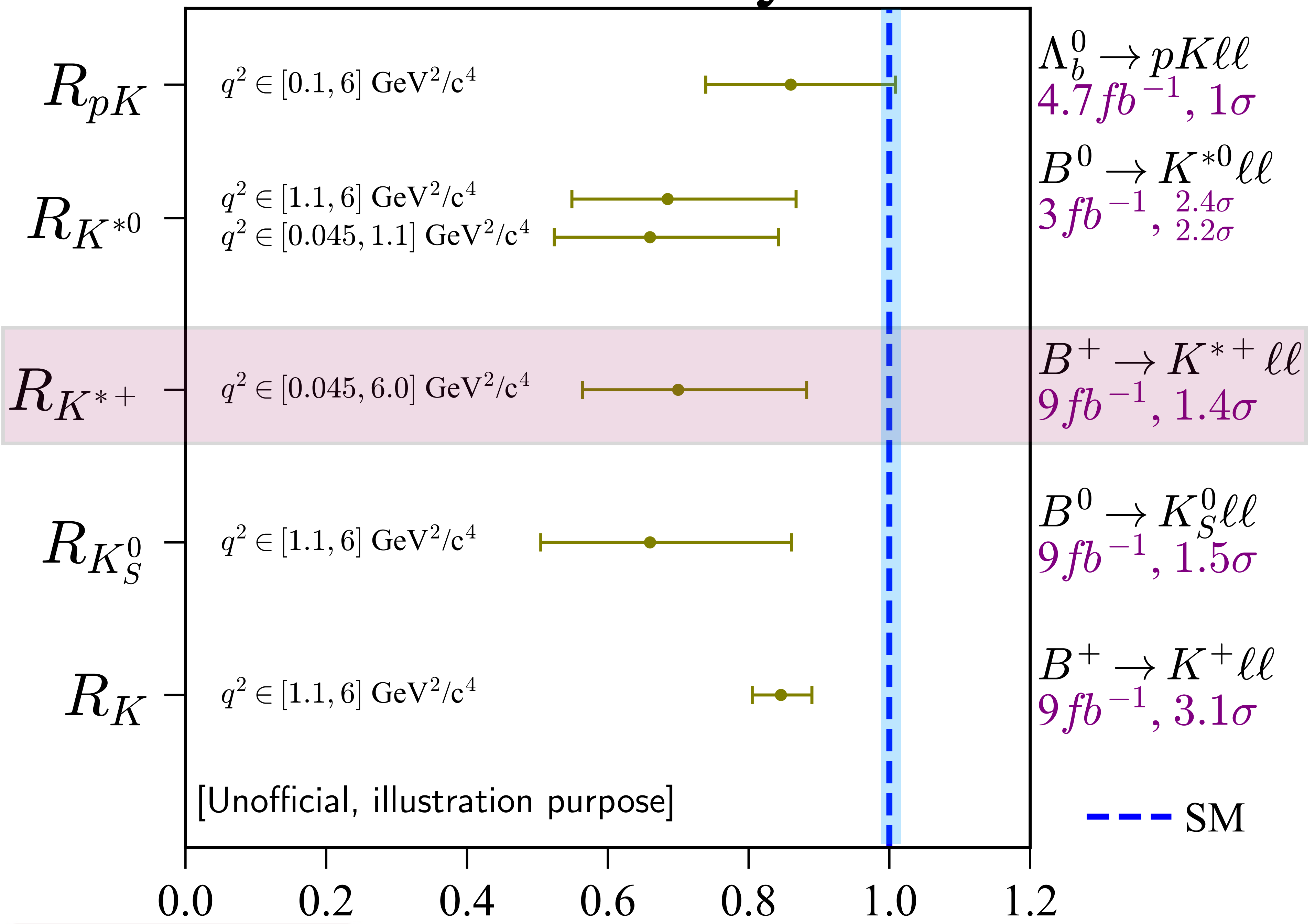
- **All LHCb data used** $(9\mathrm{fb}^{-1})$





- $K_s^0(\to \pi\pi)$ in final states: 2/3 of them decays after the VELO
- **First observation of** $B^+ \to K^{*+}ee$
- $q^2 \in [0.045, 6.0]\ \mathrm{GeV}^2/\mathrm{c}^4$

LHCb only



Validation

- $r_{J/\psi}^{-1} = 0.965 \pm 0.011(\mathrm{stat.}) \pm 0.032(\mathrm{syst.})$
- $R_{\psi(2S)}^{-1} = 1.017 \pm 0.045(\mathrm{stat.}) \pm 0.023(\mathrm{syst.})$

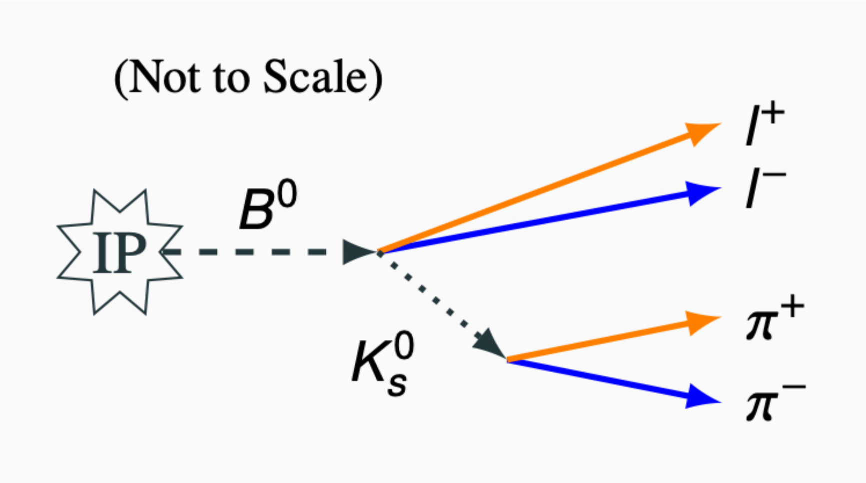
Result

- $R_{K^{*+}} = 0.70^{+0.18}_{-0.13}\,(\mathrm{stat.})\,^{+0.03}_{-0.04}\,(\mathrm{syst.})$
- Agreement with SM at $1.4\,\sigma$ level

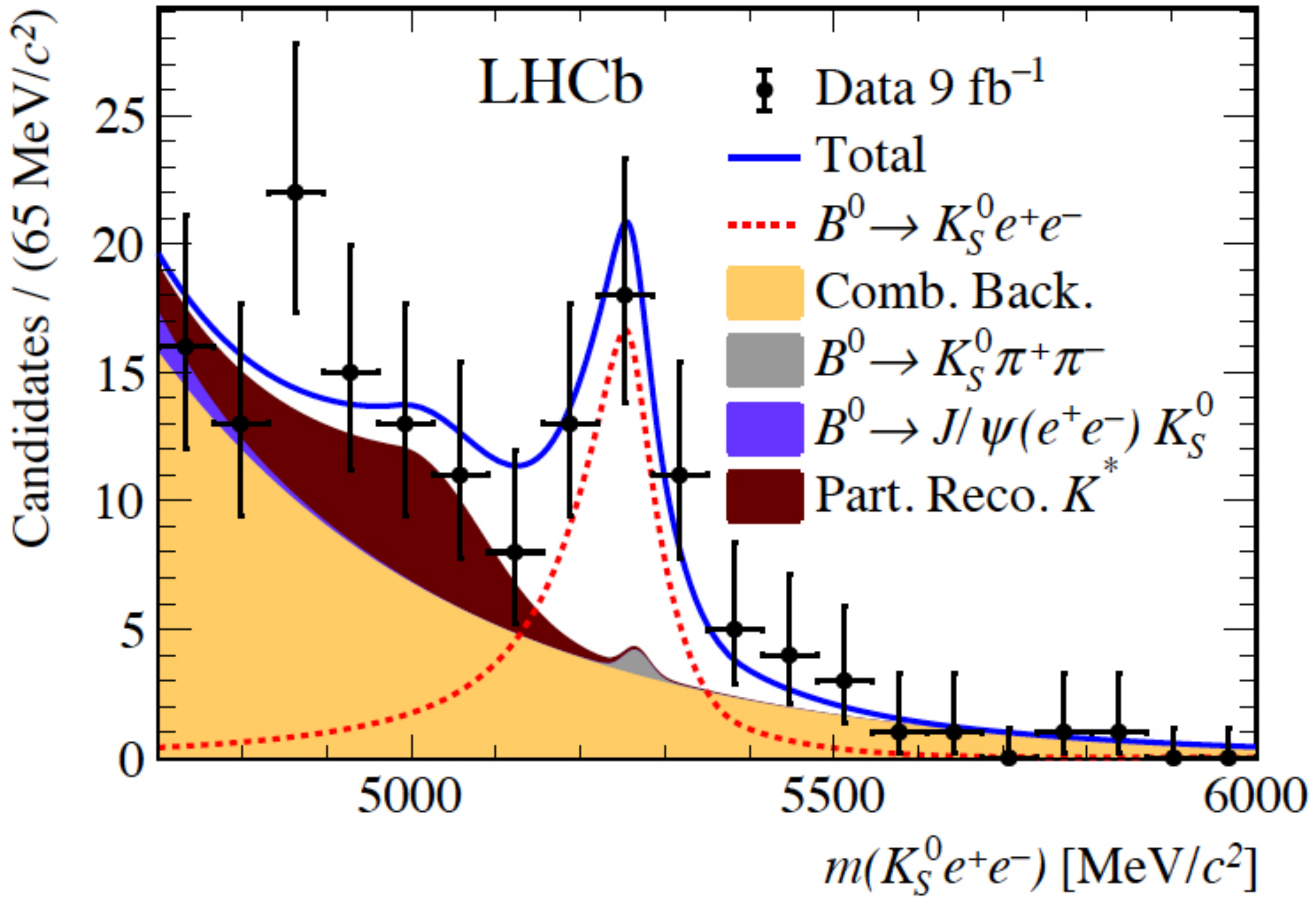
Pattern of deviation from LHCb in LFU tests

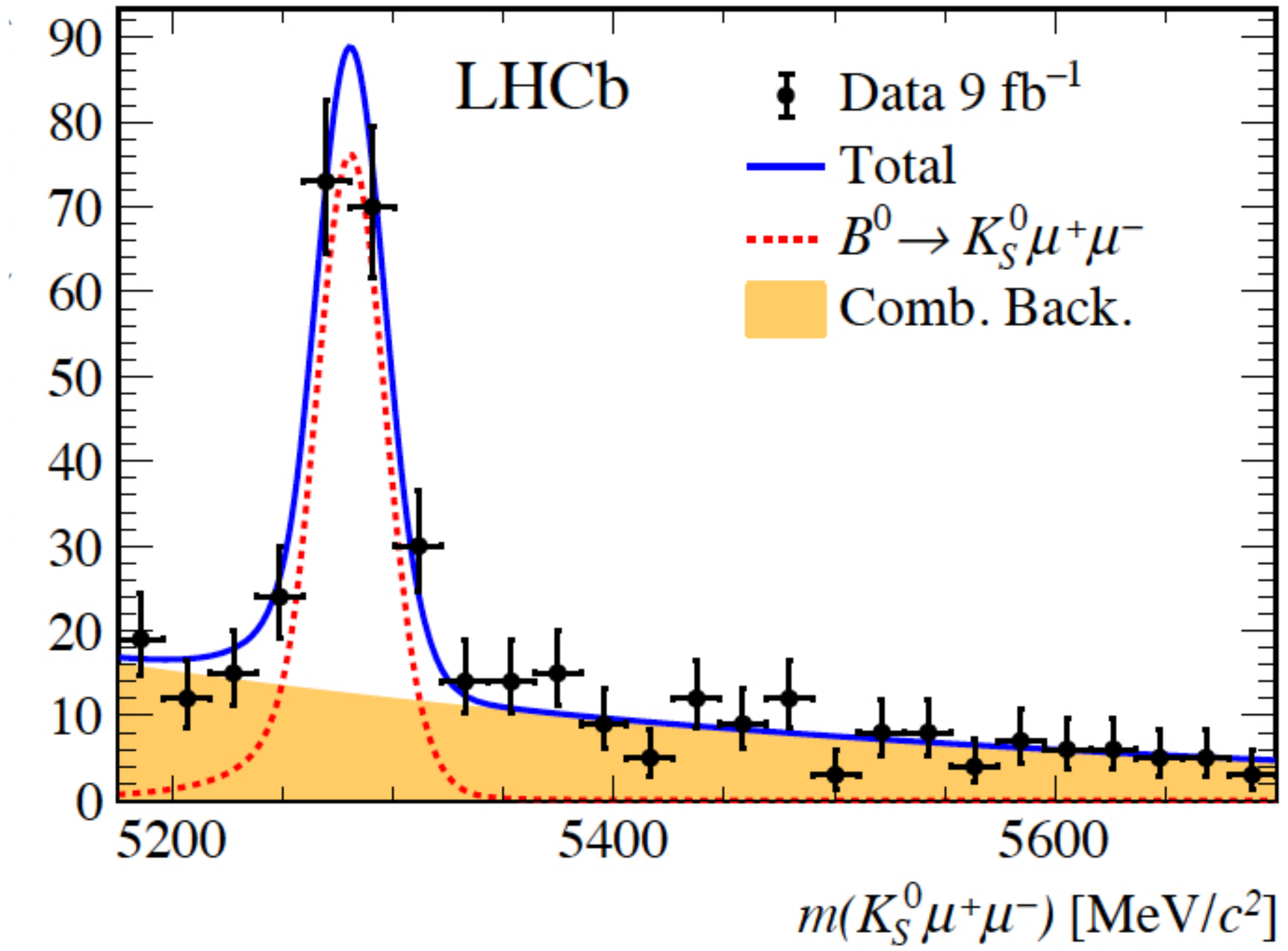
[Phys. Rev. Lett. 128 (2022) 191802]

R_{K_s} ($B^0 \to K_s^0 \ell\ell$)

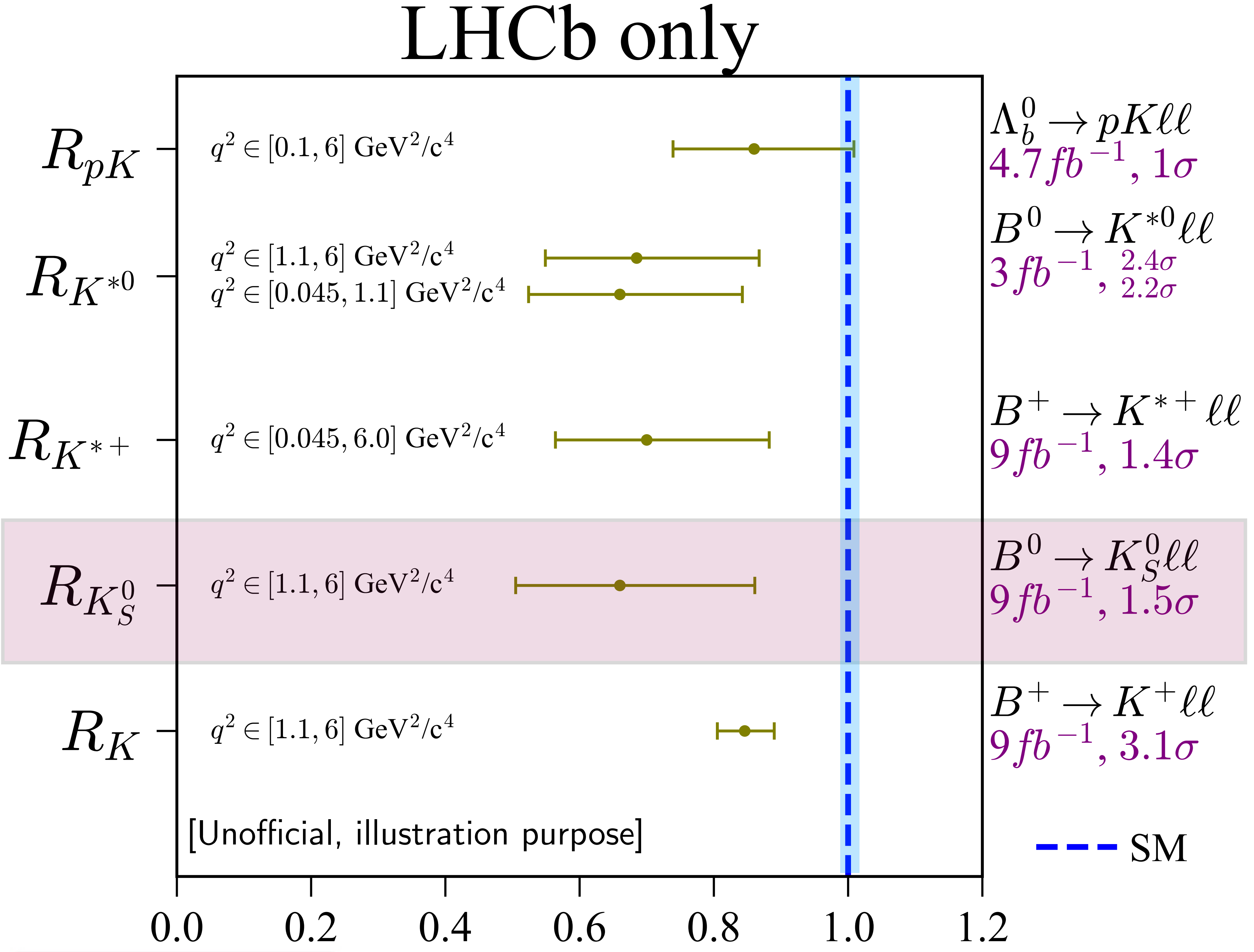


- **All LHCb data used** (9fb^{-1})





- $K_s^0(\to \pi\pi)$ in final states: 2/3 of them decays after the VELO
- **First observation of** $B^0 \to K_s^0 ee$
- $q^2 \in [1.0{,}6.0]\ \text{GeV}^2/\text{c}^4$



Validation

- $r_{J/\psi}^{-1} = 0.977 \pm 0.008(\text{stat.}) \pm 0.027(\text{syst.})$
- $R_{\psi(2S)}^{-1} = 1.014 \pm 0.030(\text{stat.}) \pm 0.020(\text{syst.})$

Result

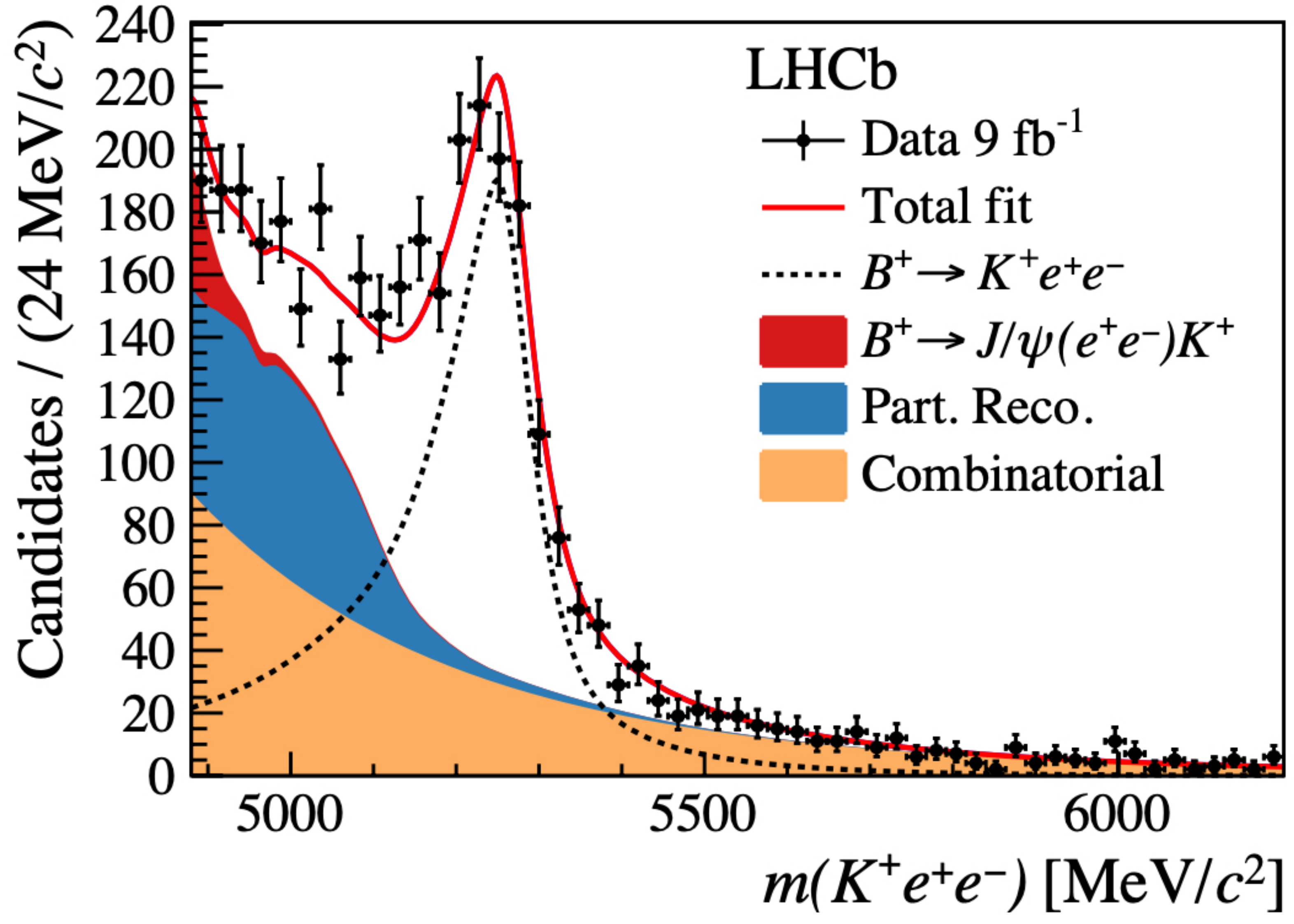
- $R_{K_S^0} = 0.66^{+0.20}_{-0.14}\,(\text{stat.})\,^{+0.02}_{-0.04}\,(\text{syst.})$
- Agreement with SM at $1.5\,\sigma$ level

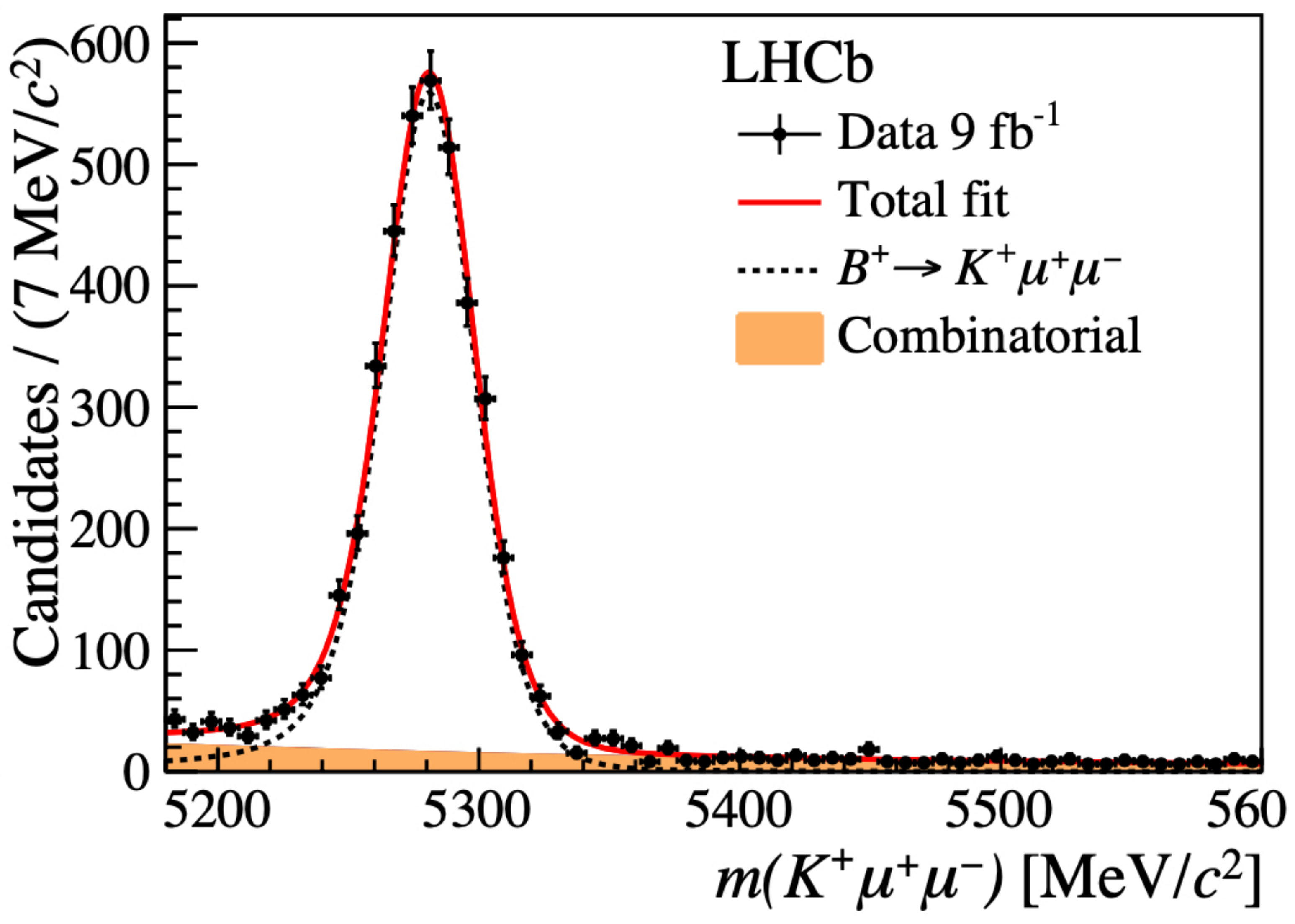
Pattern of deviation from LHCb in LFU tests

[Nat. Phys. 18, 277-282 (2022)]

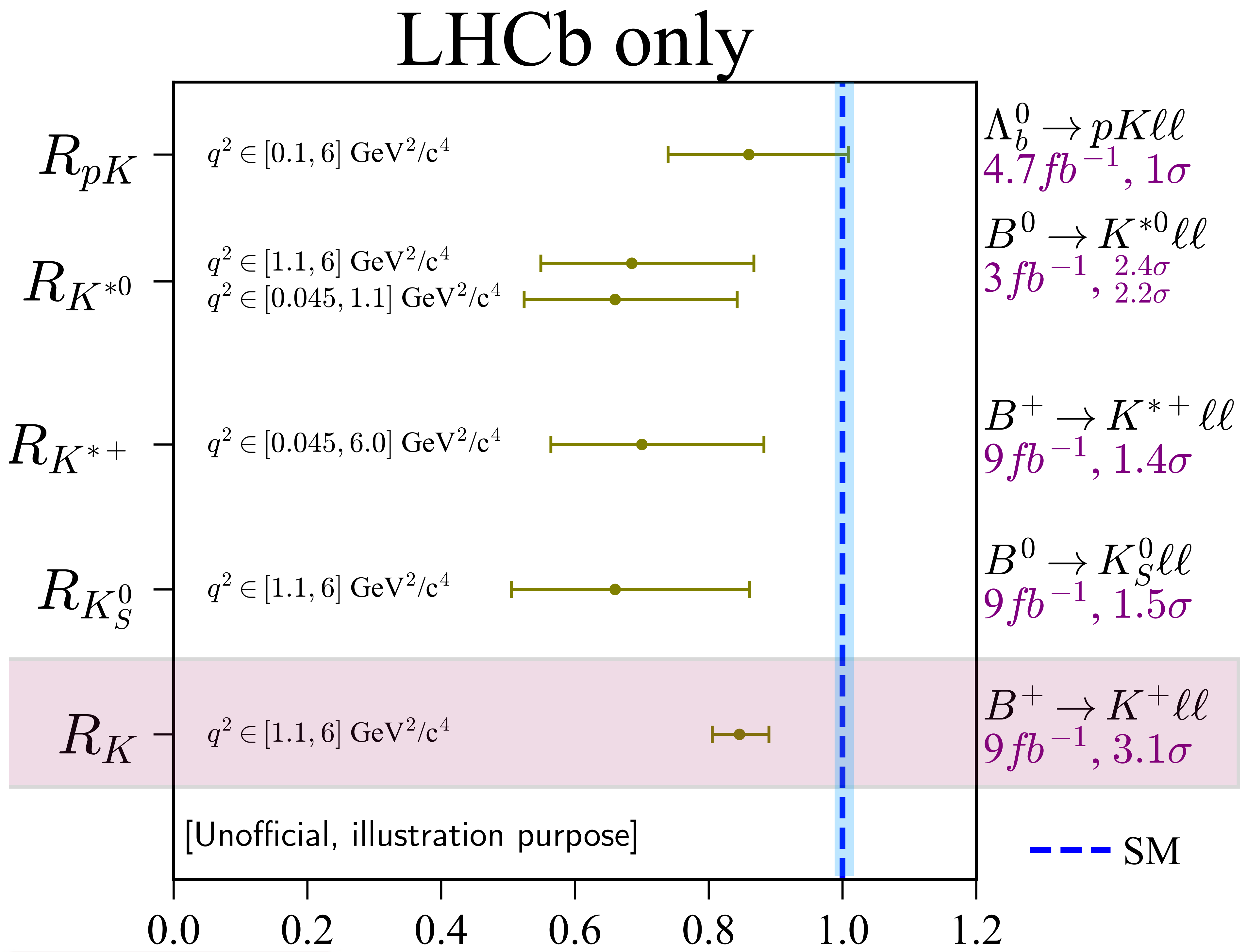
R_{K+} ($B^+ \to K^+\ell\ell$)

- **All LHCb data used** (9fb^{-1})





- Together with K^{*0} mode, the highest statistical yield achievable at LHCb
- $q^2 \in [1.1{,}6.0]$ GeV^2/c^4



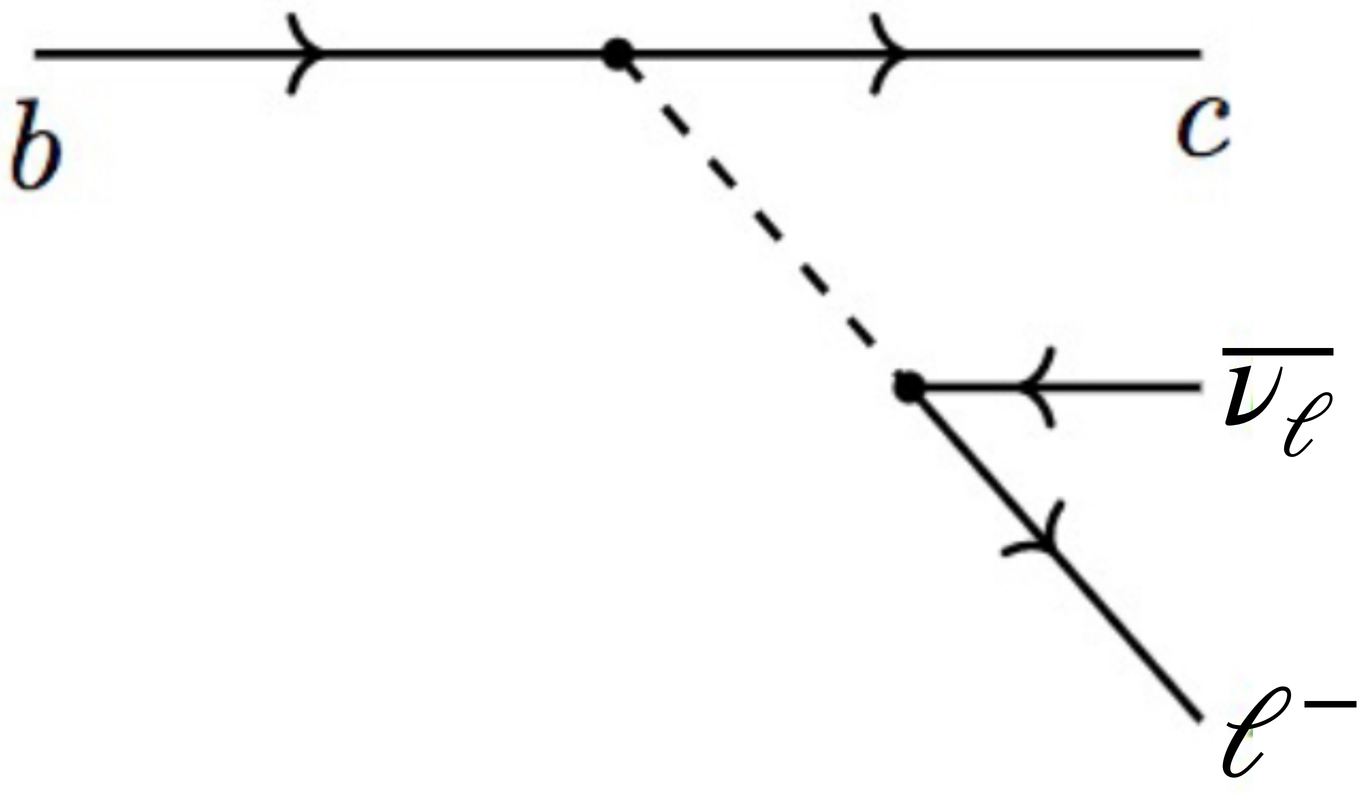
Validation

- $r_{J/\psi} = 0.981 \pm 0.020$ (stat. $\oplus$ syst.)
- $R_{\psi(2S)} = 0.997 \pm 0.011$ (stat. $\oplus$ syst.) .)

Result

- $R_K = 0.846^{+0.042}_{-0.039}\,(\text{stat.})\,^{+0.013}_{-0.012}\,(\text{syst.})$
- Tension of 3.1 σ with the SM

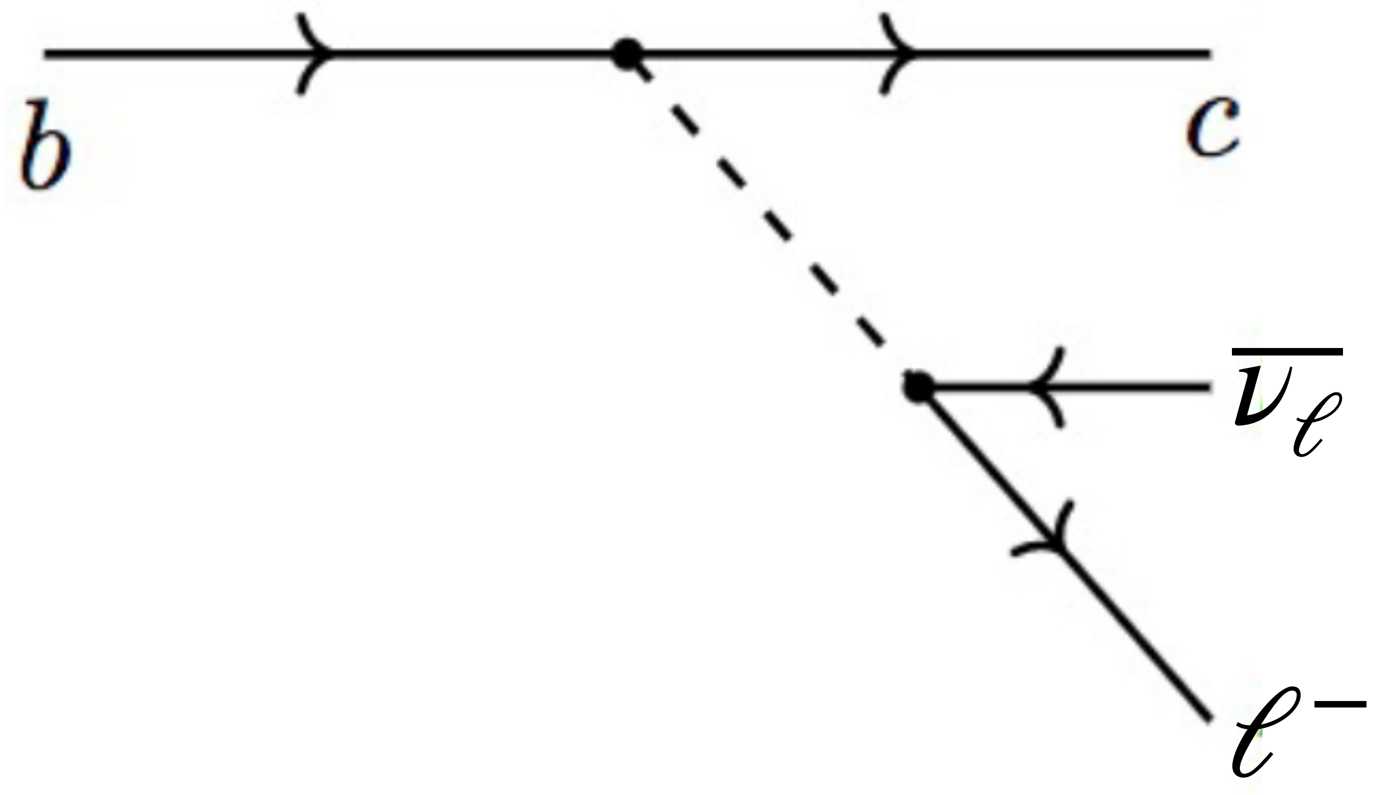
LFU tests in $b \to c\ell\nu$



$\ell = \tau$

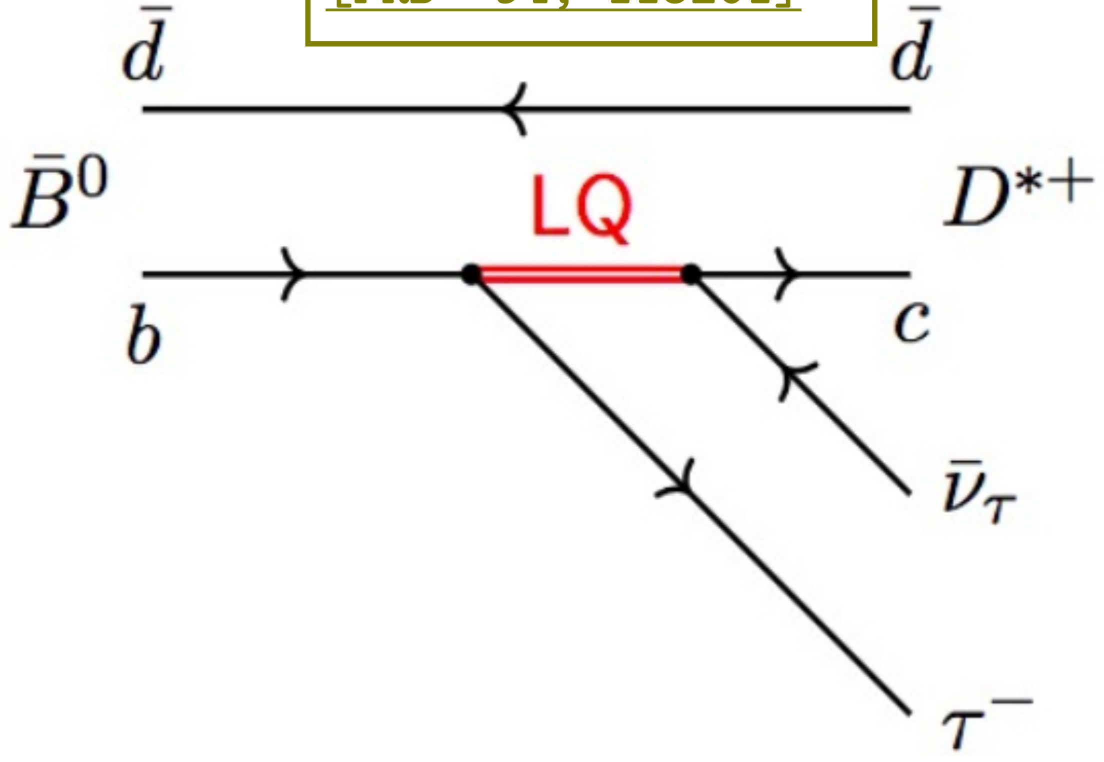
$\ell = \mu/e$

μ – only @ LHCb
μ, e @ B – Factories



Ratio sensitive to possible NP coupling to 3rd generation (e.g. LQ)

[PRL 116, 081801]
[PRD 94, 115201]



$$R(H_c) = \frac{\mathscr{B}(H_b \to H_c \tau \overline{\nu_\tau})}{\mathscr{B}(H_b \to H_c \ell \overline{\nu_\tau})}$$

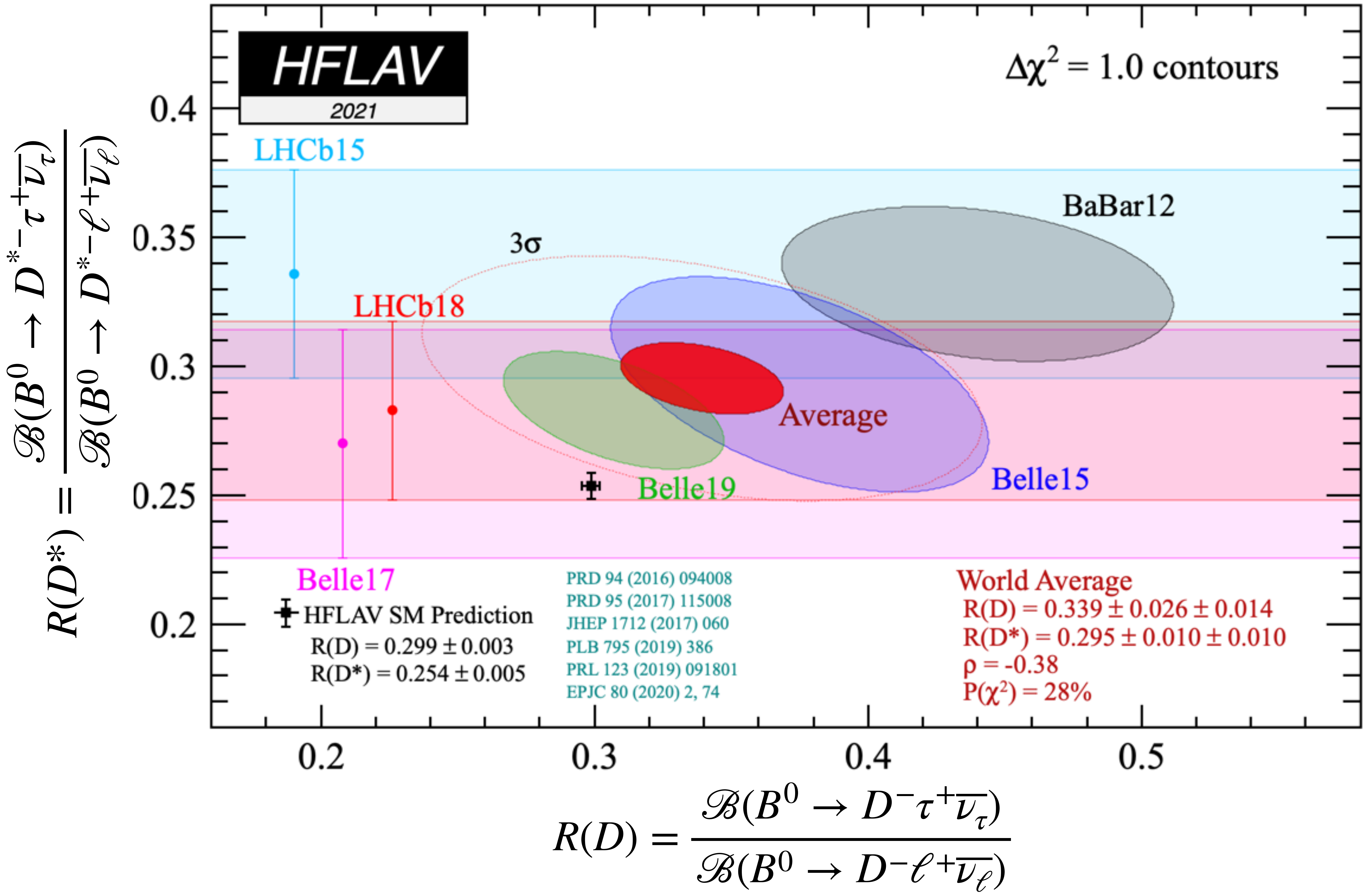
$$H_c = D^{*,+}, D^0, D^+, D_s^+, \Lambda_c^+, J/\psi$$

$$H_b = B^0, B^+, \boxed{B_s^0, B_c, \Lambda_b}$$

Unique at LHCb

$$\boxed{\Xi_b, \Omega_b}$$

$R(D) - R(D^*)$



$\ell = \mu, e$ for B – factories

$\ell = \mu$ for LHCb

- **Using muonic $\tau \to \mu\nu\nu$** [PRL 115,111803 (2015)]
  - ✦ $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
    (2.1σ above SM)

- **With 3-prong hadronic** [PRD 97, 072013 (2018)] [PRL 120, 171802 (2018)]
  $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\overline{\nu_\tau}$
  - ✦ $R(D^*) = 0.280 \pm 0.018 \pm 0.026 \pm 0.013$
    (1σ above SM)

3.3 σ above SM

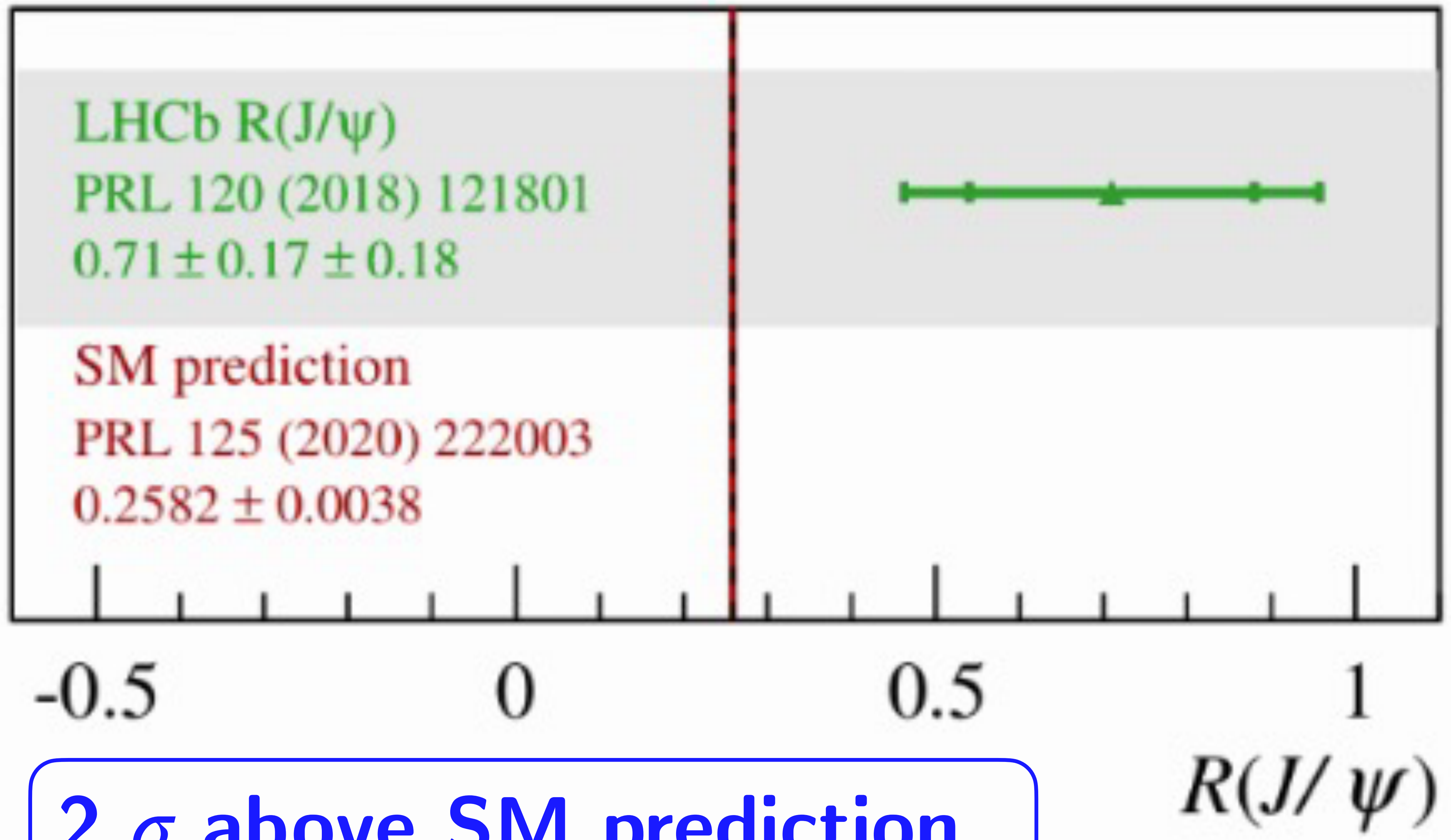
(in combination with all measurements from B-factories)

$R(J/\psi)$ [using B_c decays, leptonic τ]

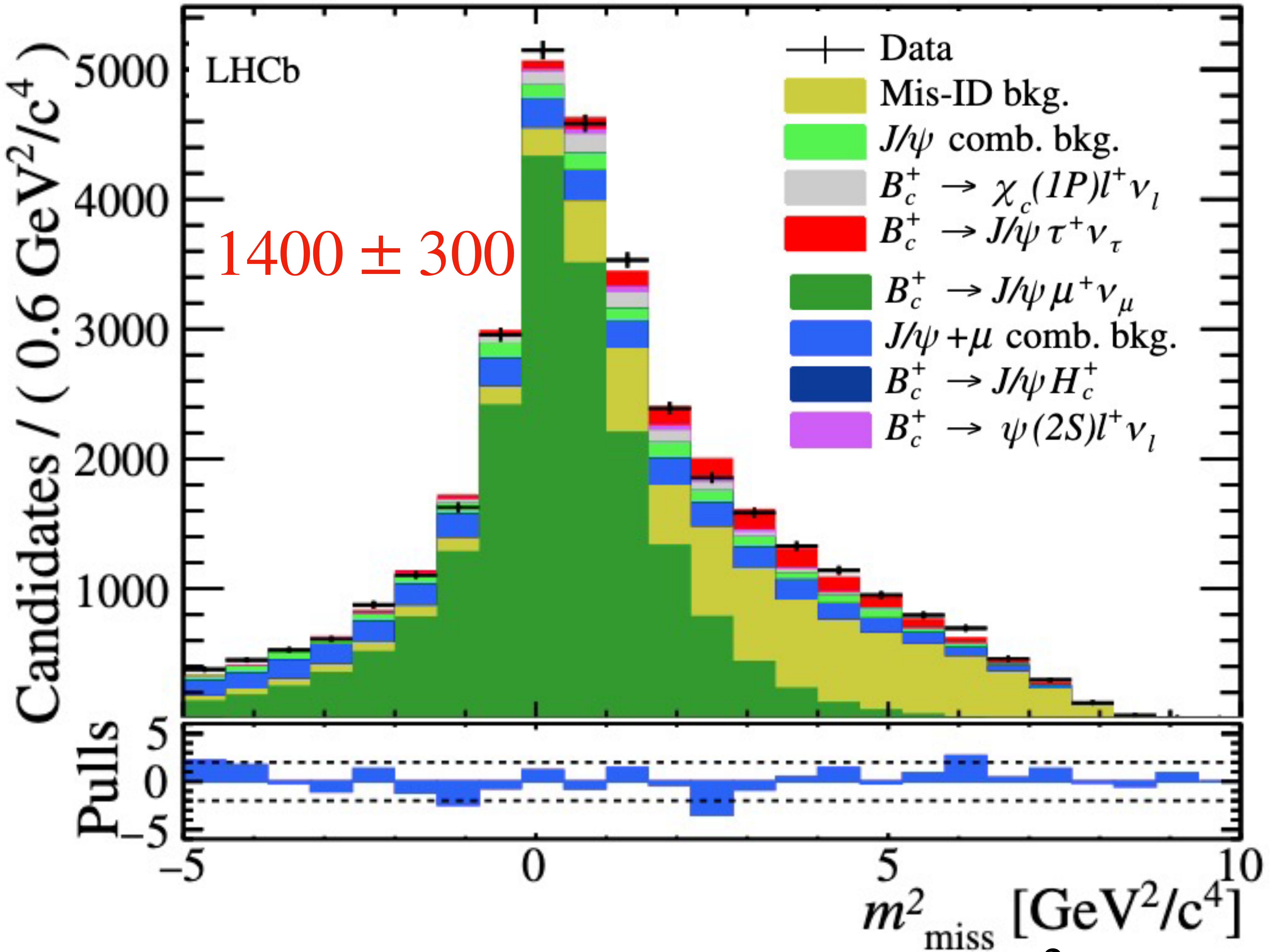
[PRL 120,121801 (2018)]

- $R(J/\psi) = \dfrac{\mathcal{B}(B_c^- \to J/\psi\tau^-\overline{\nu_\tau})}{\mathcal{B}(B_c^- \to J/\psi\mu^-\overline{\nu_\mu})}$ ✦ $\tau^- \to \mu^-\overline{\nu_\mu}\nu_\tau$

- **Use Run1** ($3\ \text{fb}^{-1}$) **data**
  - ✦ **First LFU test in B_c mesons**
  - ✦ **Observation of $B_c \to J/\psi\tau\overline{\nu_\tau}$ with 3σ significance**
  - ✦ σ_{syst} **driven by MC-stat and B_c form factors**



2 σ above SM prediction



Result

3D binned Template fit (Z, m^2_{miss}, t_τ)

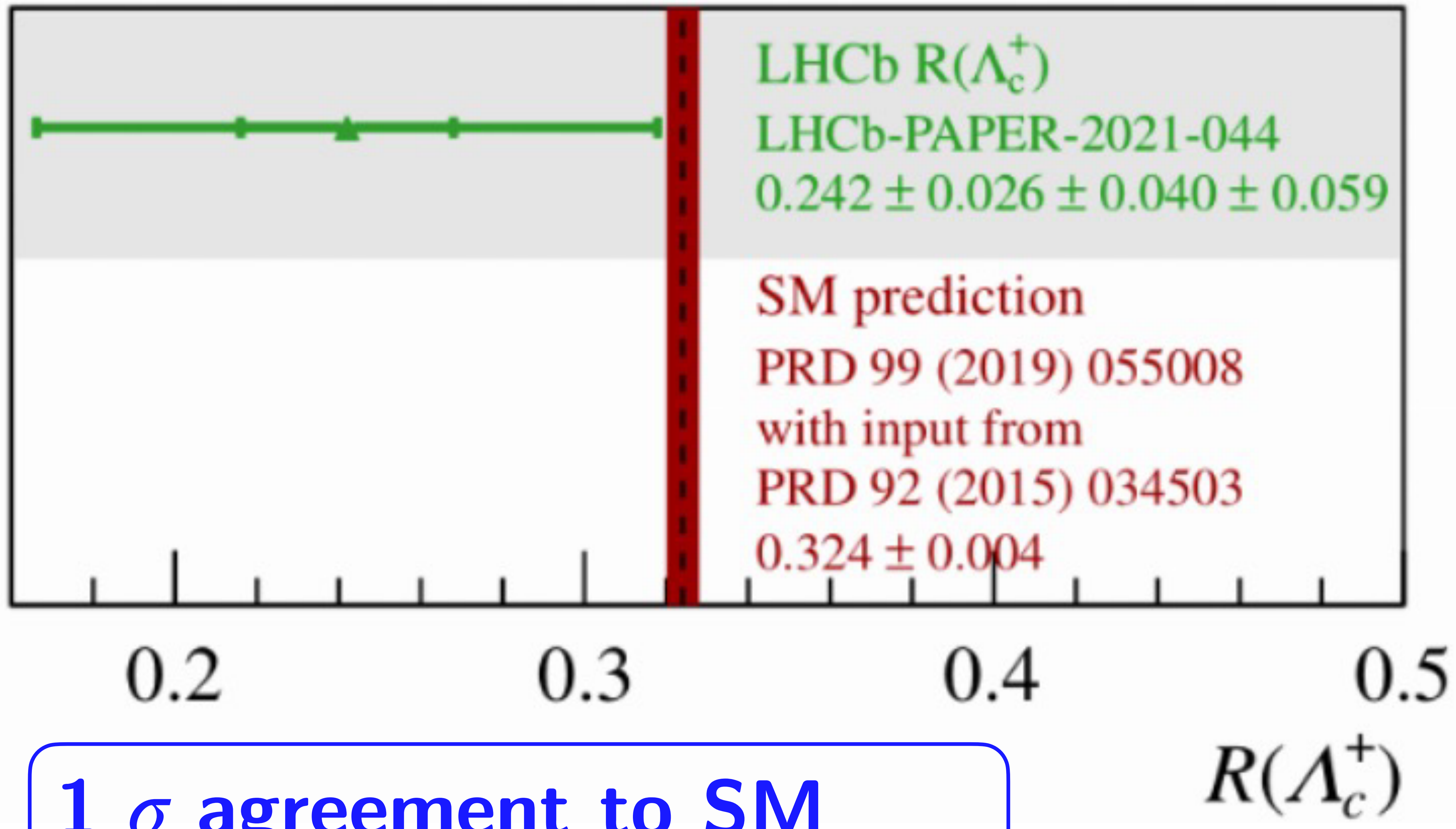
- $R(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$
- $R_{SM}(J/\psi) = 0.2583 \pm 0.0038$ [PRL,125,222003(2020)]

$R(\Lambda_c)$ [using Λ_b decays, hadronic τ]

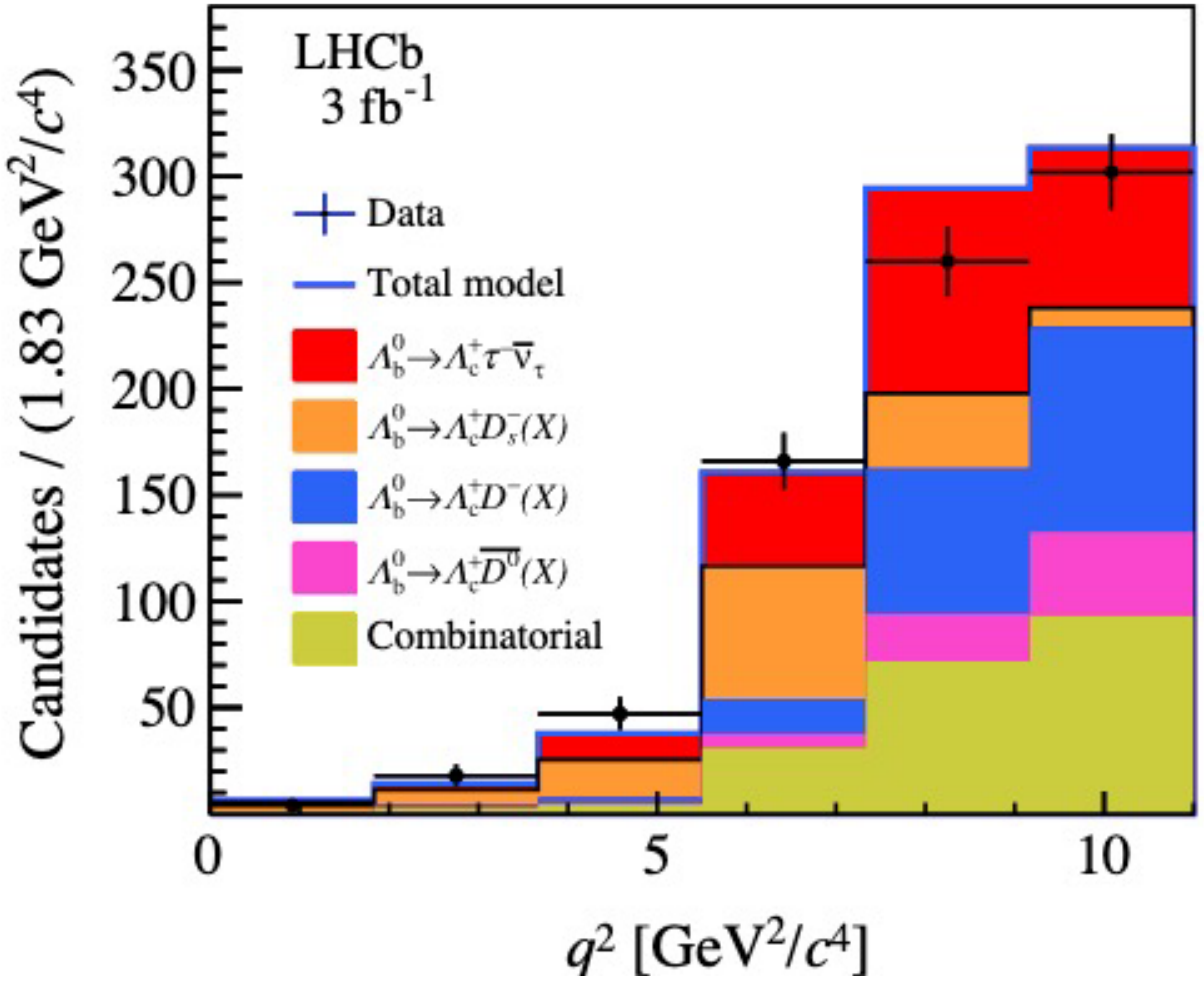
[PRL 128, 191803 (2022)]

- $R(\Lambda_c) = \dfrac{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \tau^- \overline{\nu_\tau})}{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \overline{\nu_\mu})}$ ✦ $\tau^- \to \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$

- **Use Run1 ($3\ \mathrm{fb}^{-1}$) data**
  - ✦ **First LFU test in a baryonic $b \to c\ell\nu$**
  - ✦ **Initial state $S = 1/2$: NP coupling could be different**
  - ✦ σ_{syst} **driven by double-charm background**



1 σ agreement to SM



Result

3D binned Template fit (BDT, q^2, t_τ)

- $R(\Lambda_c^+) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059(\text{ext.})$
- $R_{SM}(\Lambda_c^+) = 0.324 \pm 0.004$ [PRD, 99, 055008]

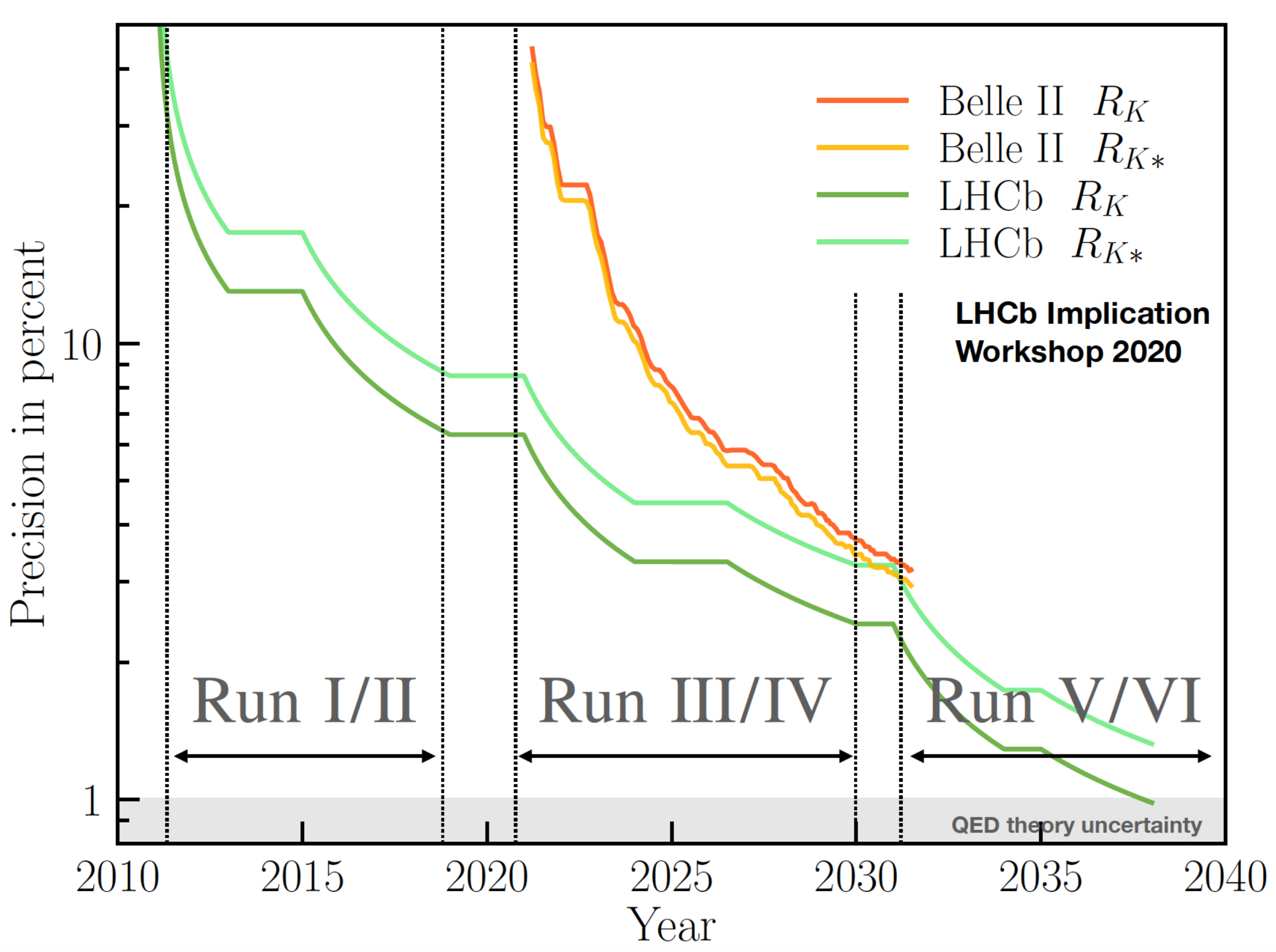
Prospects of LFU tests

$b \to s\ell\ell$

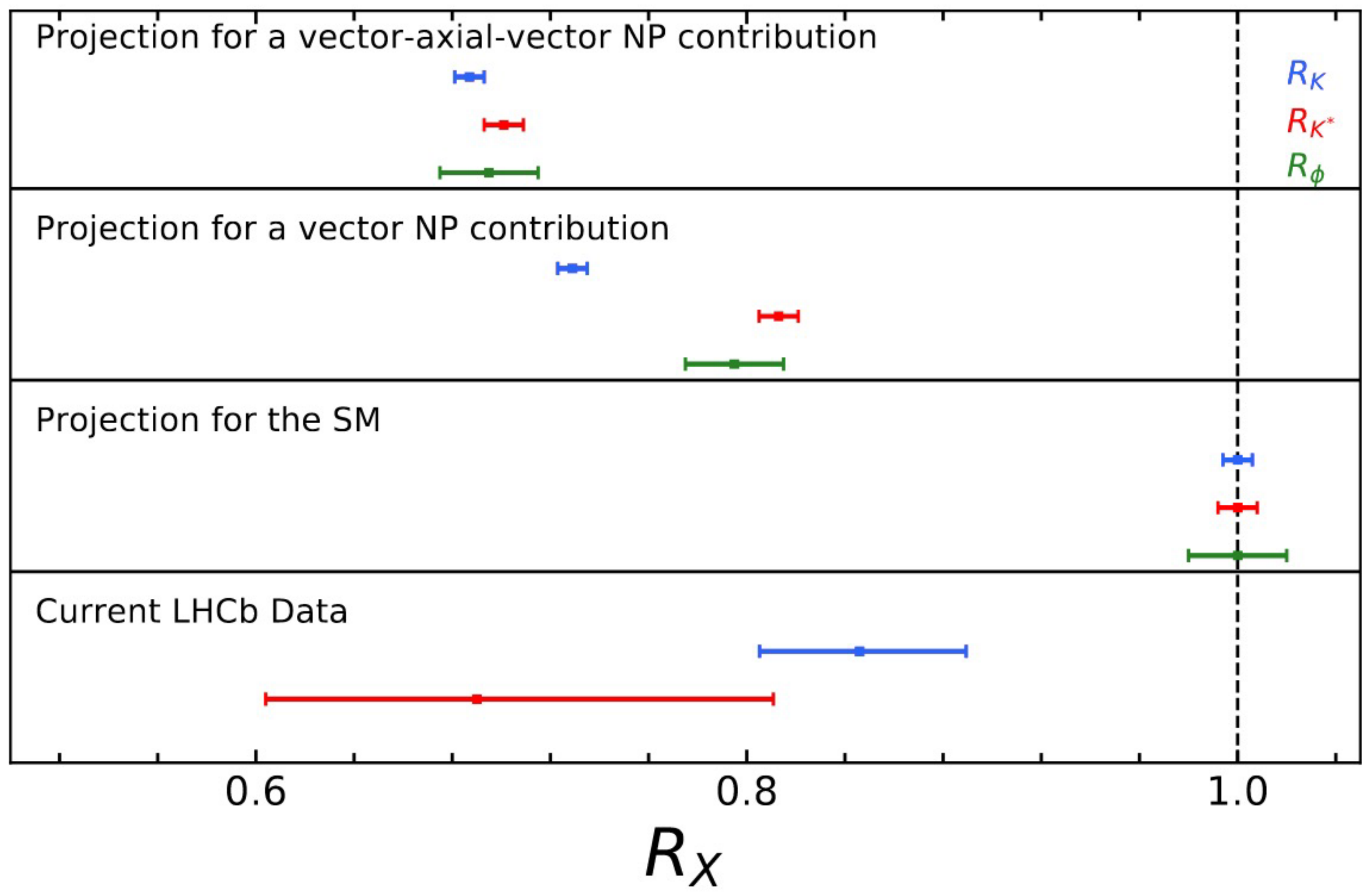
▸ LHCb plans to also include

- Combined $R(K)/R(K^{*,0})$ with 9fb^{-1}
- R_ϕ [$B_s \to \phi\ell\ell$] , full dataset R_{pK}
- $R_{K\pi\pi}$ and high q^2 bins in $R(K)/R(K^{*0})$
- Reach O(%) precision in coming years with Belle-II and LHCb Run III.

[LHCb Implication Workshop 2020]



[LHCb Upgrade II TDR]



$b \to c\ell\nu$

▸ LHCb plans to also include

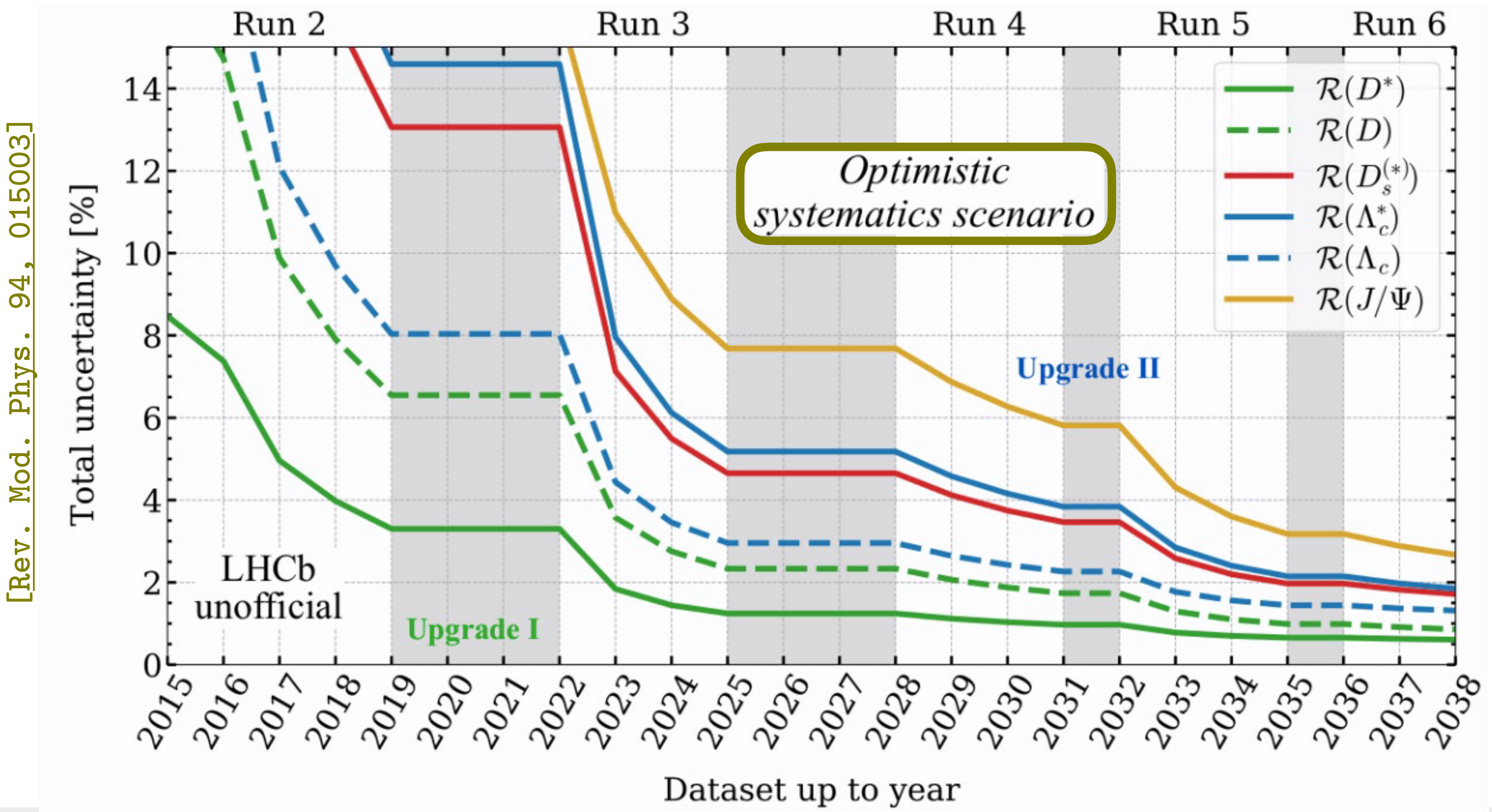
- $R(D^+)$, $R(D^*)$ e/μ
- Combined $R(D^*) - R(D)$
- $R(D^{**})$
- $R(D_s^*)$
- $R(\Lambda_c^{**})$

Exploiting new observables beyond $\mathscr{B}$:

Angular observables for spin structure

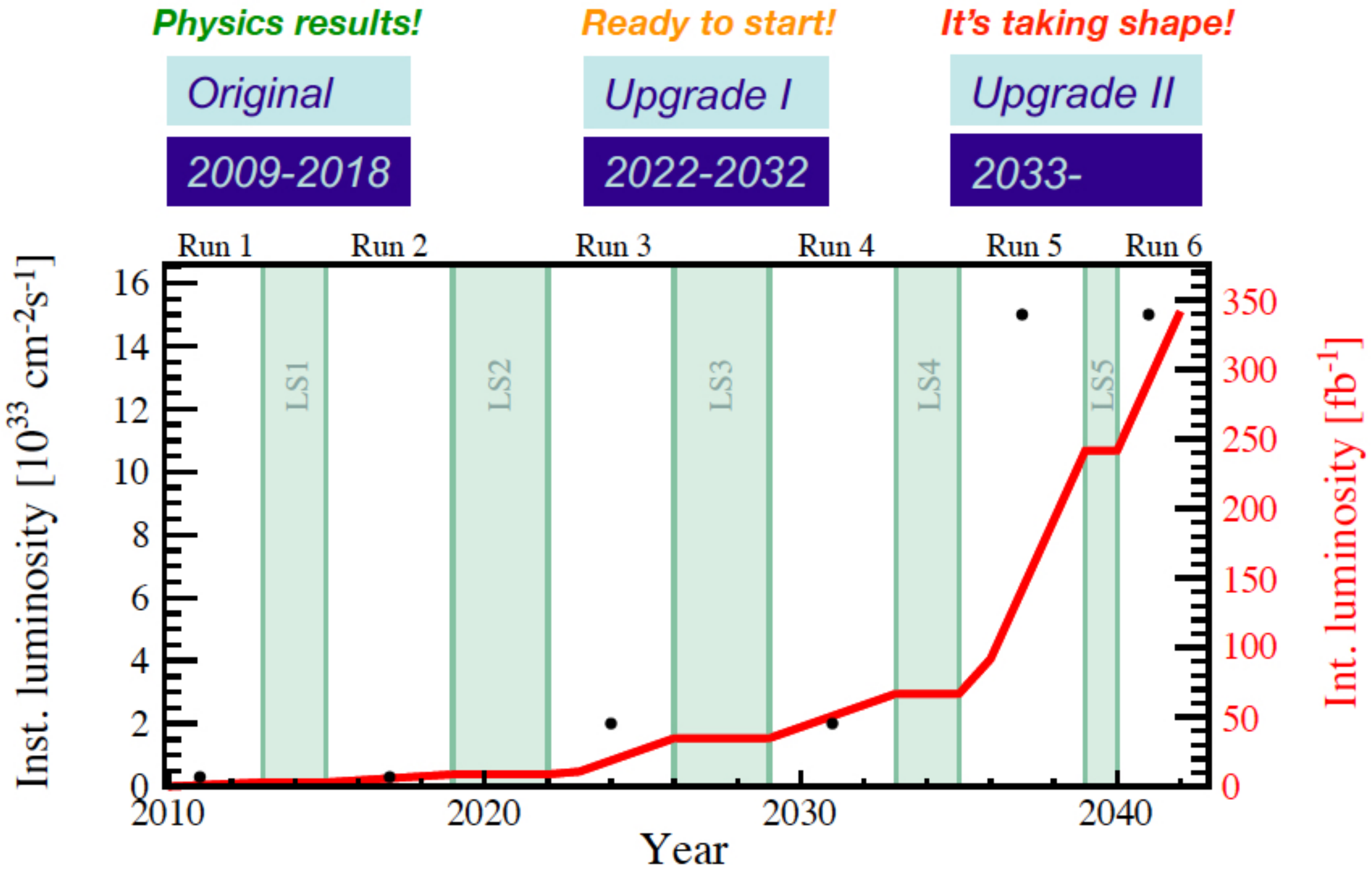
Irreducible systematic of 0.5% on R(D*) and 2% on other ratios

[Rev. Mod. Phys. 94, 015003]



Conclusion

- ***Intriguing pattern of LFU(V) in several exclusive measurements at LHCb in $b \to s\ell\ell$***
  - High priority on a combined $R(K)/R(K^*)$ with full dataset with a deeper understanding of systematics from LHCb as well as adding other decay modes and q^2 regions
- ***Several modes studied and still under studies also in $b \to c\ell\nu$ at LHCb***
  - Starting analysing not only $\mathscr{B}$ ratios, but also other observables such as angular observables

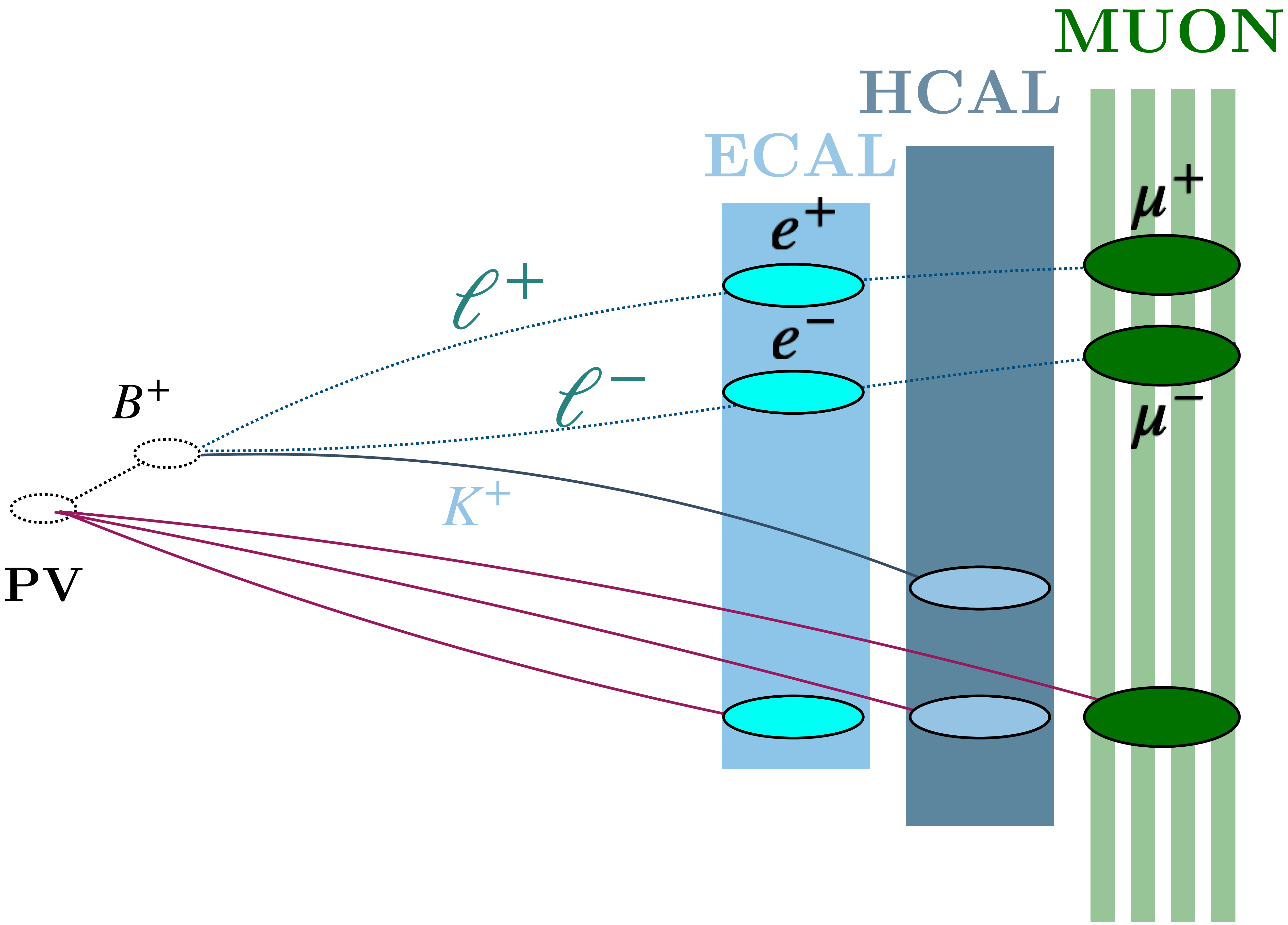


- While focus is on having "legacy" 9fb^{-1}results, ***the Run III has just started***
  - LHCb Run III : 3 x more stat than in Run I/II in 2.5yr
  - Almost a brand new detector with improved performance
  - Belle II will be competing/complement LHCb physics program in next years
- ***Stay tuned for results***

Backup

Trigger strategy

- Hardware triggers in LHCb [ECAL, HCAL, MUON] have different threshold cuts



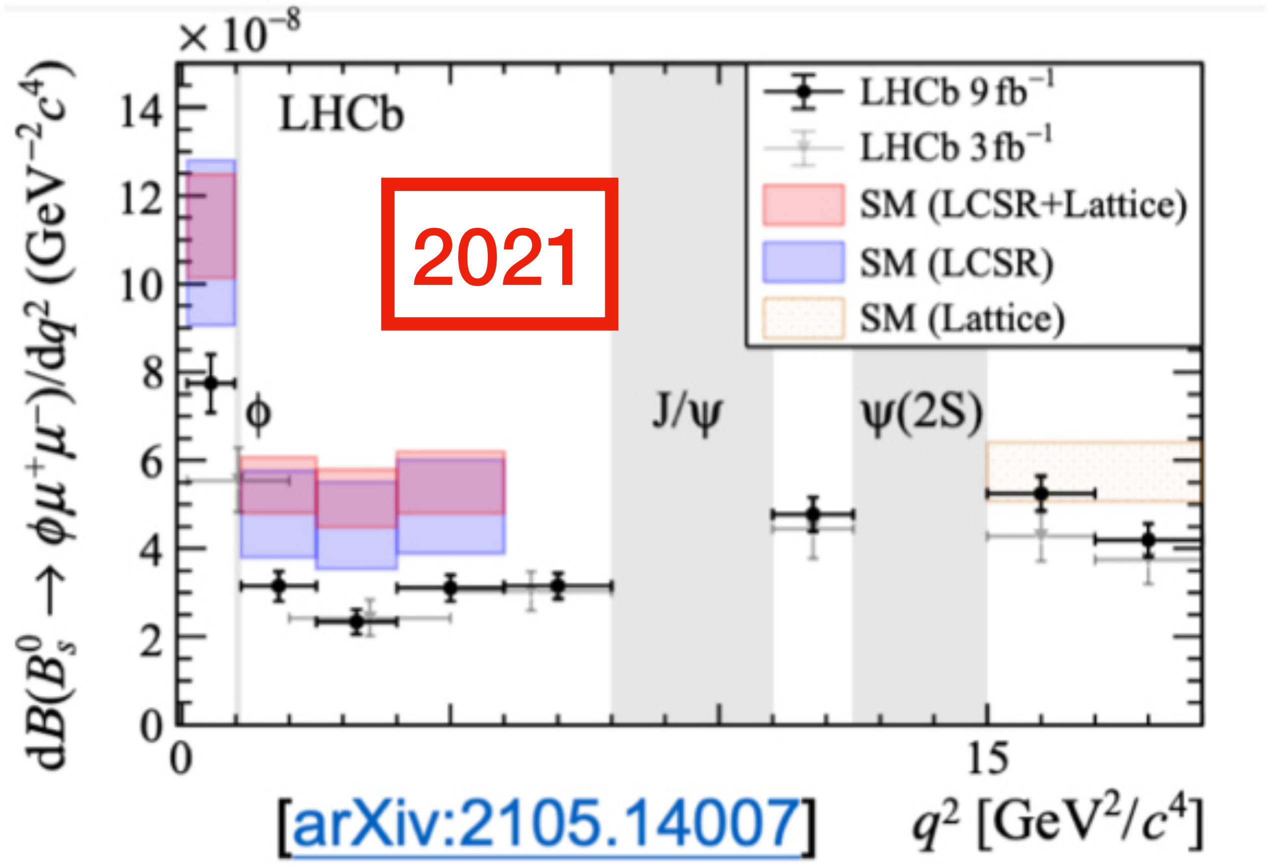
Muon $p_T > 1\text{GeV}$
HCAL/ECAL $E_T > 2.7$ GeV

Trigger selection

- e-mode
  - **L0E**: $e^{\pm}$ fires ECAL trigger
  - **L0H**: K^+ fires HCAL trigger
  - **L0I** : Other tracks in event fires MUON/ECAL/HCAL
- μ-mode
  - **L0M**: $\mu^{\pm}$ fires MUON trigger

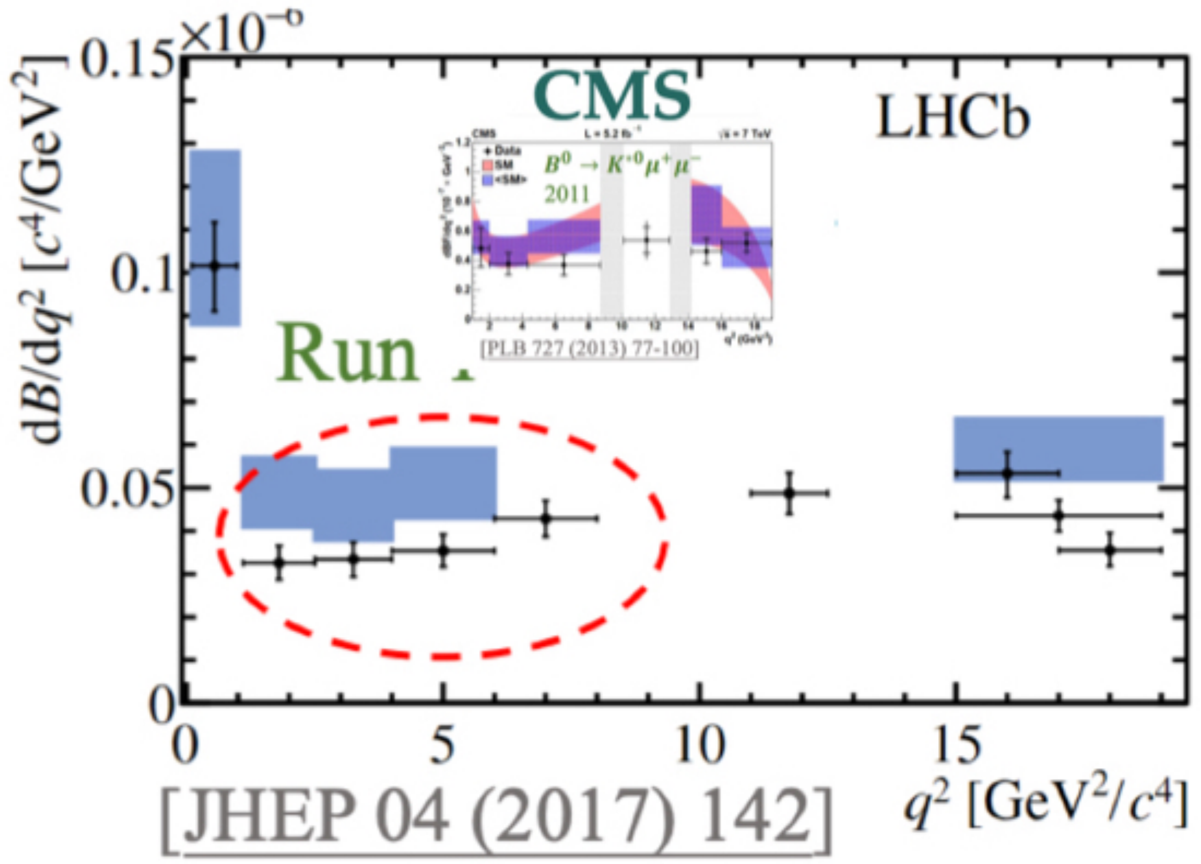
R-Ratio from $\left\langle \frac{L0M}{L0E}, \frac{L0M}{L0H}, \frac{L0M}{L0I} \right\rangle$

$d\mathscr{B}/dq^2$ in $b \to s\mu\mu$



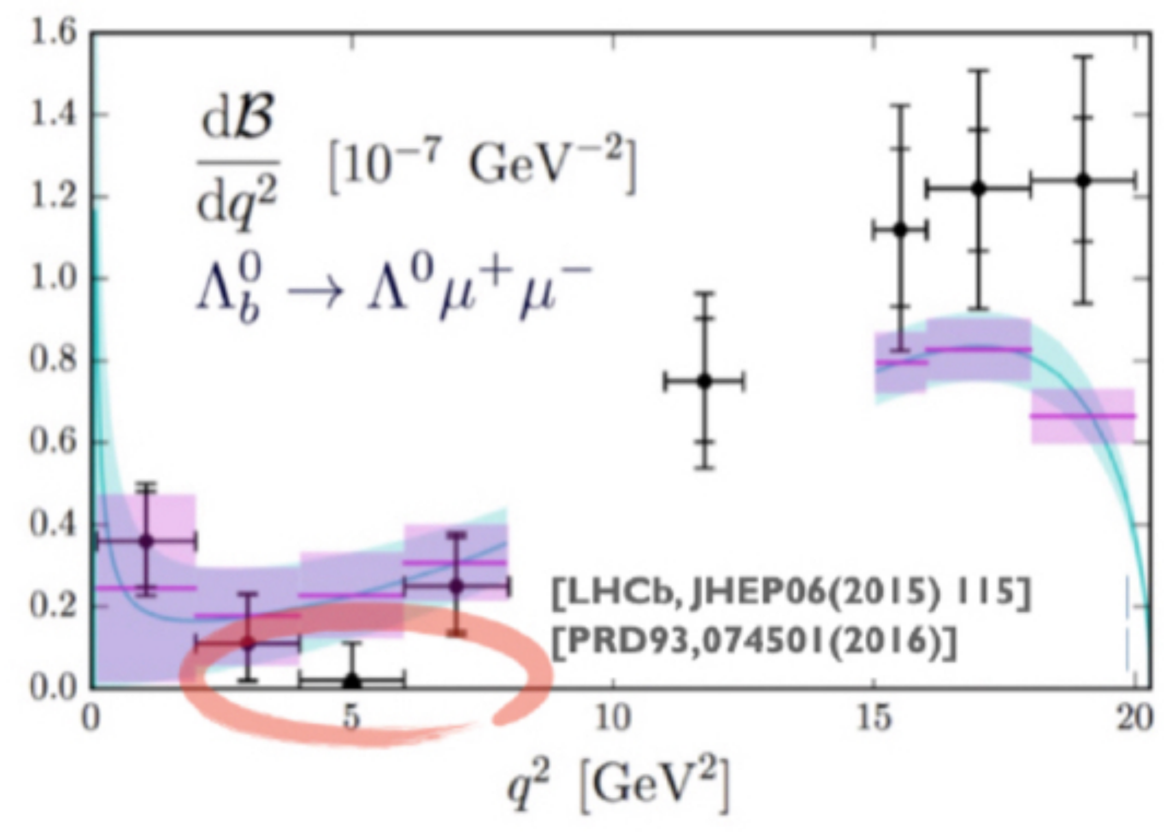
[arXiv:2105.14007]

$B_s \to \phi\mu\mu$

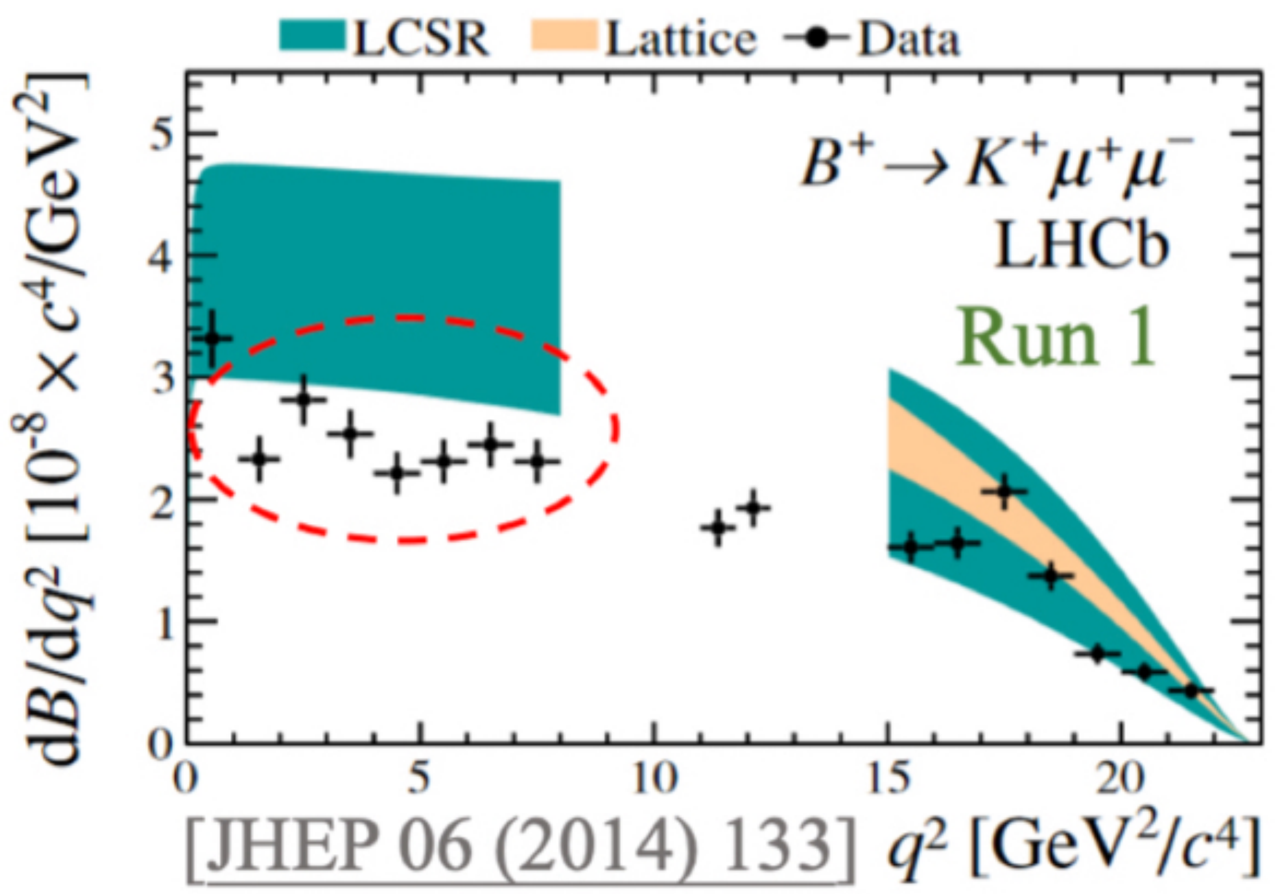


[JHEP 04 (2017) 142]

$B^0 \to K^{*0}\mu\mu$

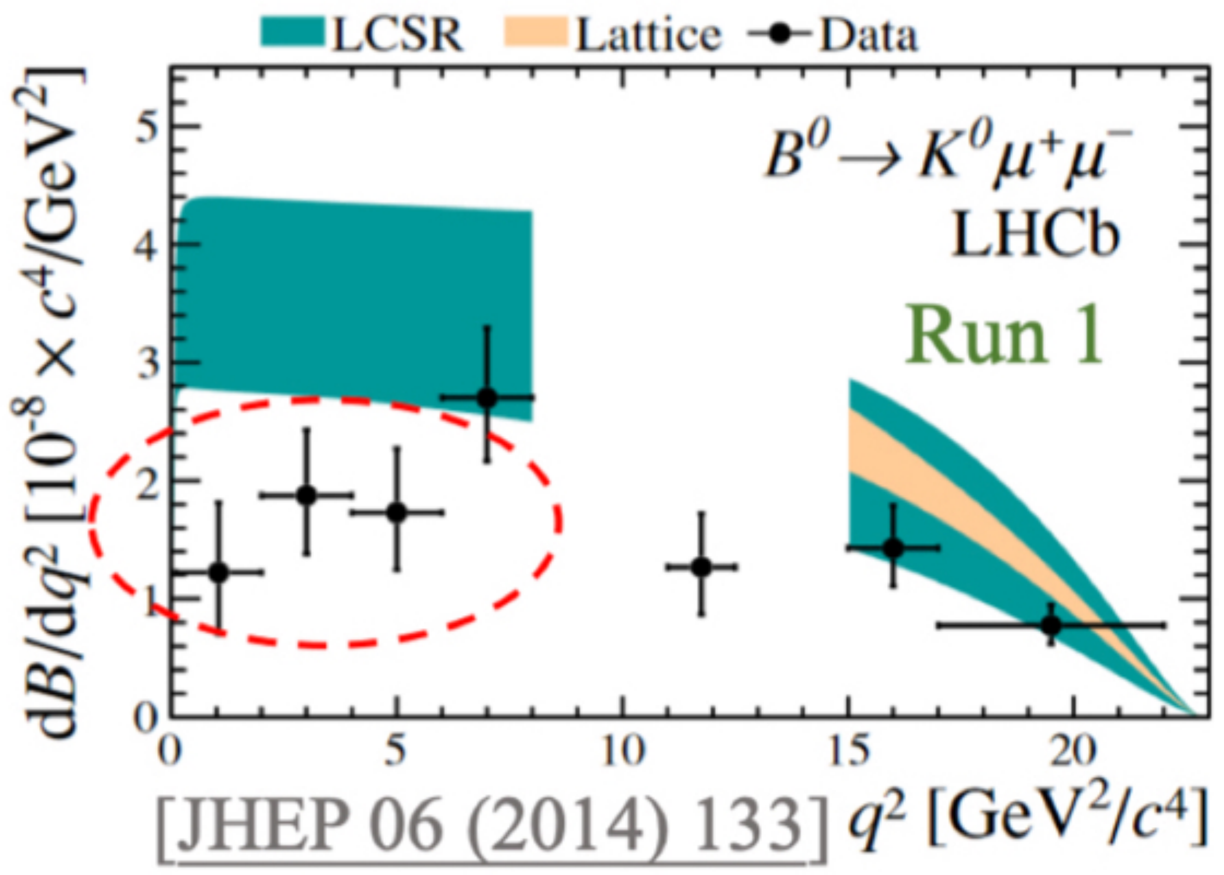


$\Lambda_b \to \Lambda\mu\mu$



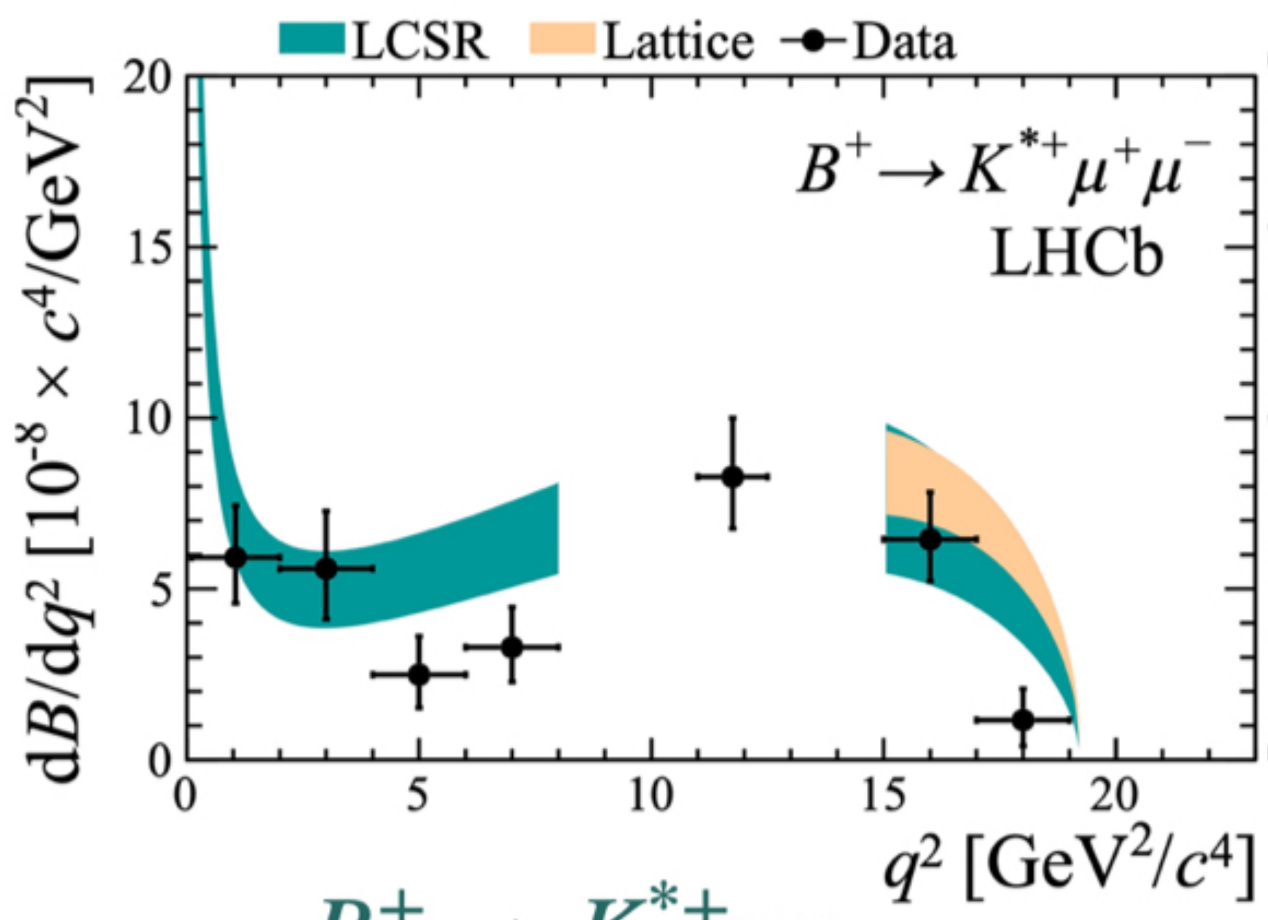
[JHEP 06 (2014) 133]

$B^0 \to K^+\mu\mu$



[JHEP 06 (2014) 133]

$B^0 \to K^0\mu\mu$



[JHEP06(2014)133]
[PRD71(2005)014029]
[JHEP09(2010)089]
[PRD88(2013)054509]
[PRD89(2014)094501]
[PRL111(2013)162002]
[PRL112(2014)212003]

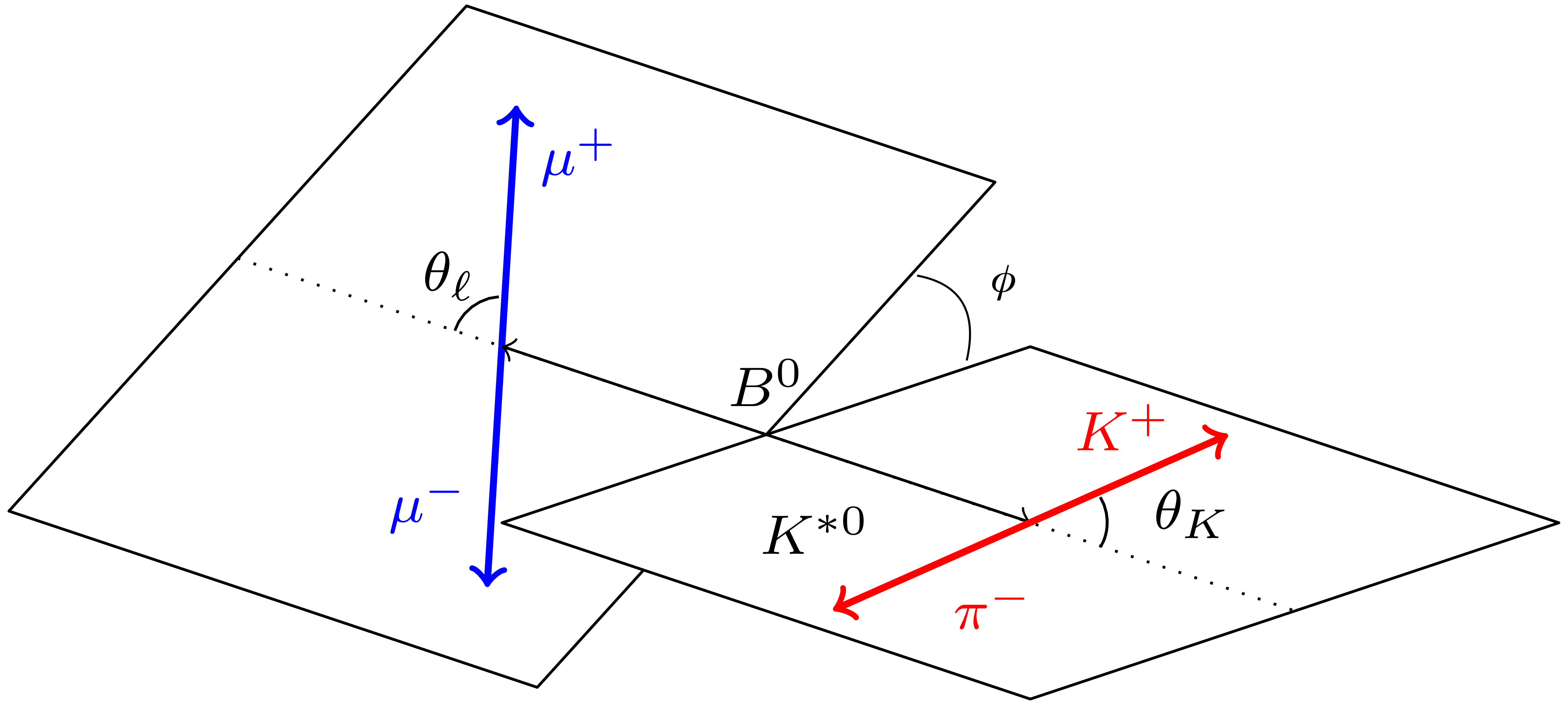
$B^+ \to K^{*+}\mu\mu$

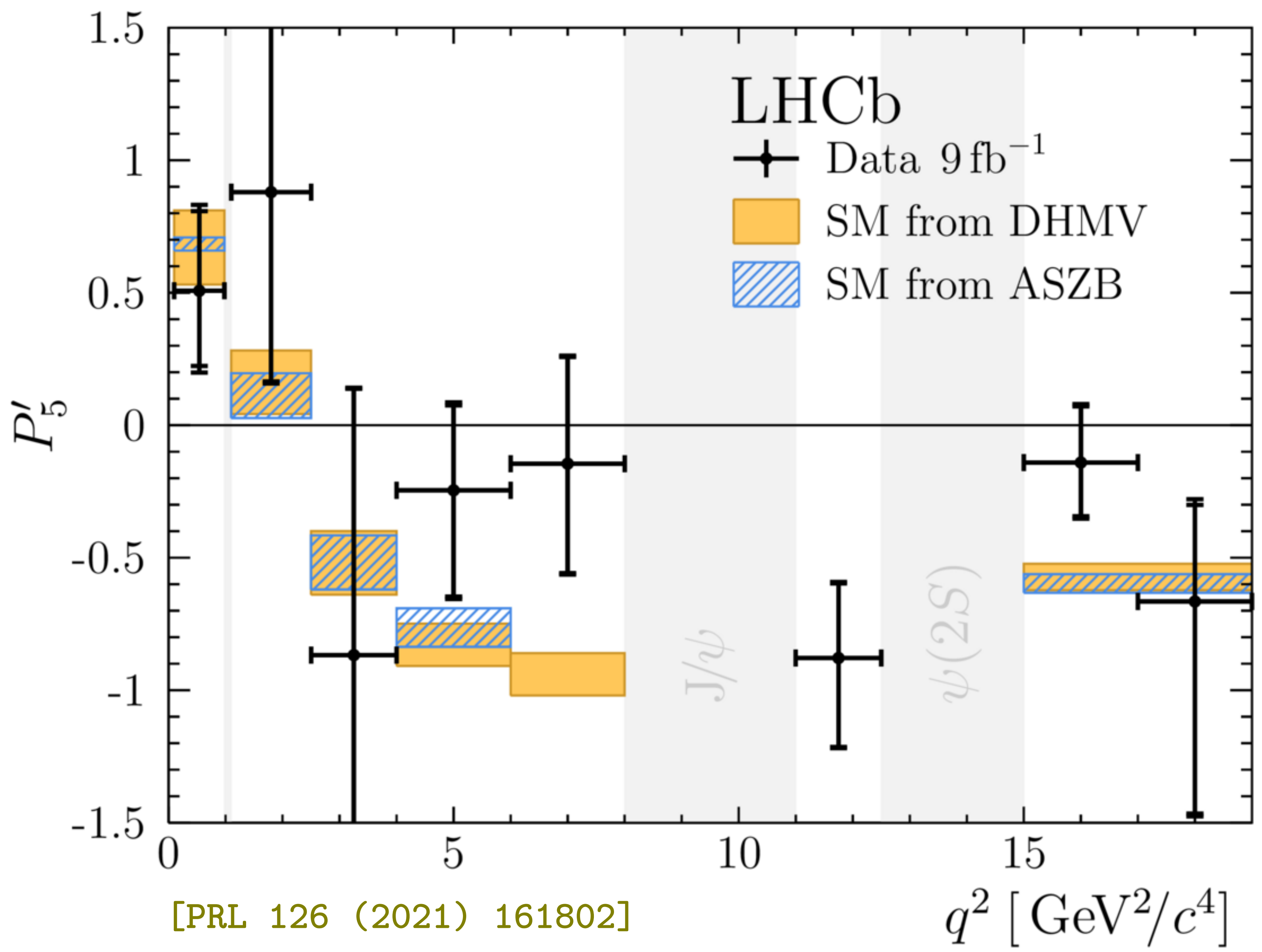
- dB/dq^2 in exclusive $b \to s\mu\mu$ **seems to undershoot SM predictions**
- Coherent pattern but large theory predictions uncertainties (20-30 %) on hadronic form factors

Flavour anomalies in angular $b \to s\mu\mu$

- The angular distributions of the $B \to K^{*}\mu^{+}\mu^{-}$ decay is described with $cos(\theta_{\ell})$, $cos(\theta_{K})$, ϕ
- The coefficients F_L, A_{FB}, S_i are sensitive to New Physics
- Optimised P_i' operator to reduce form factors uncertainties: e.g.

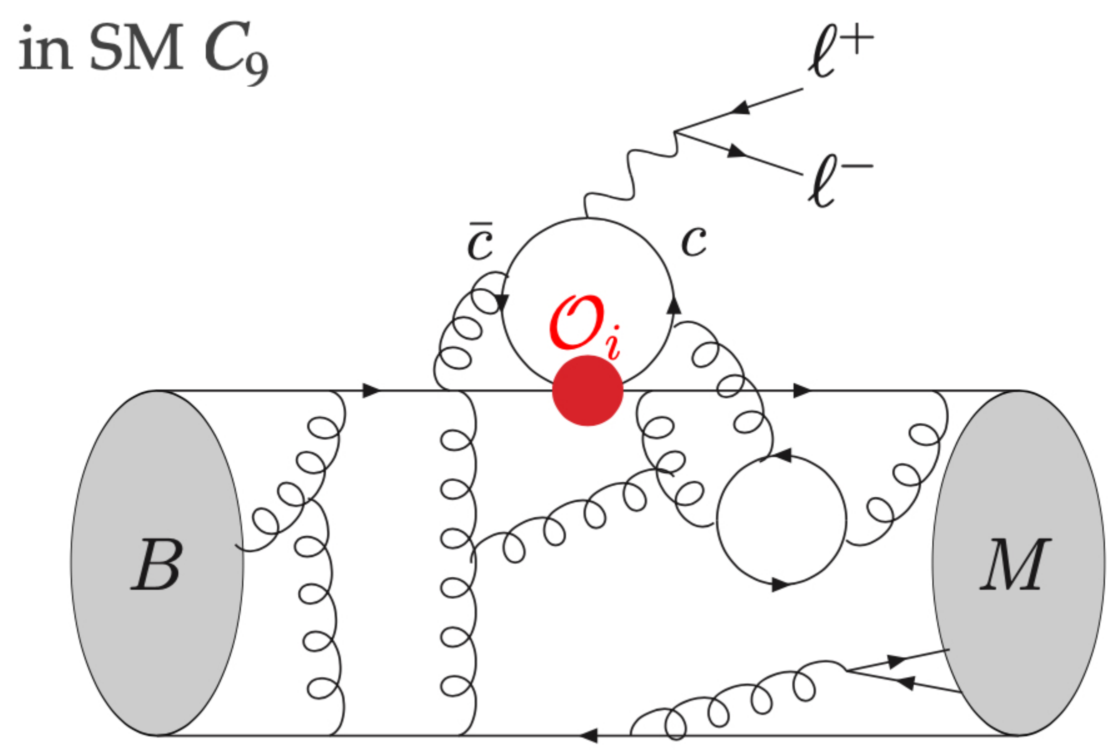
$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$





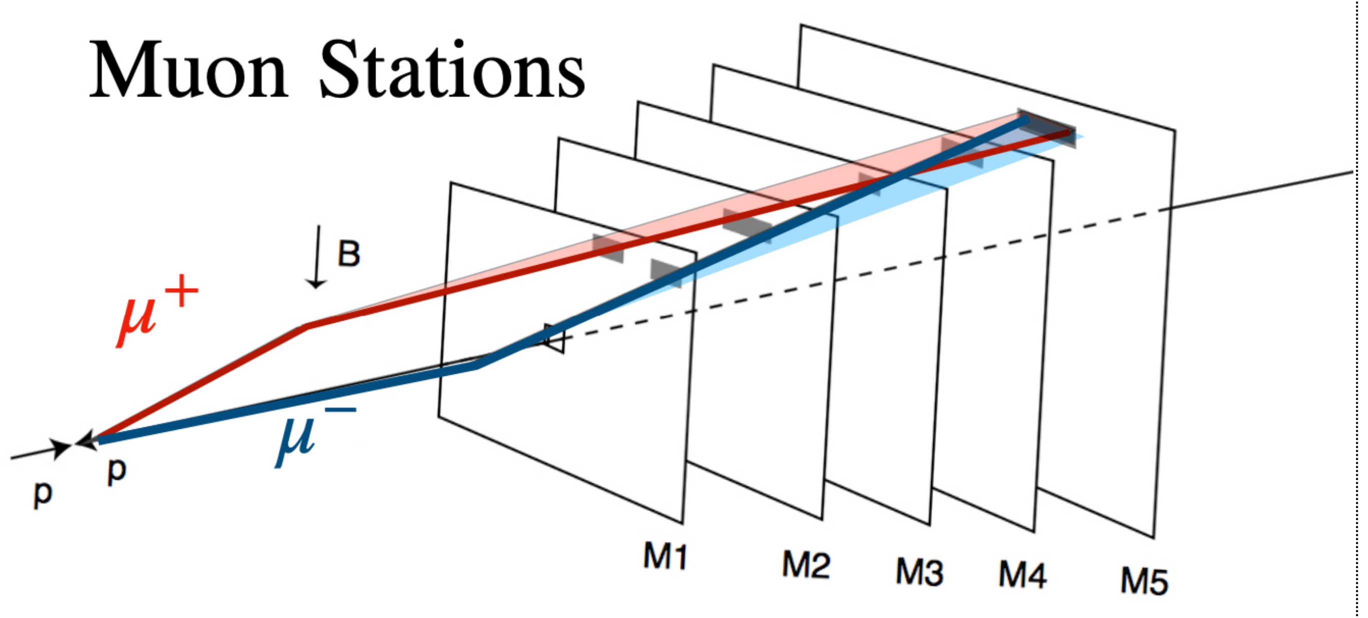
[PRL 126 (2021) 161802]

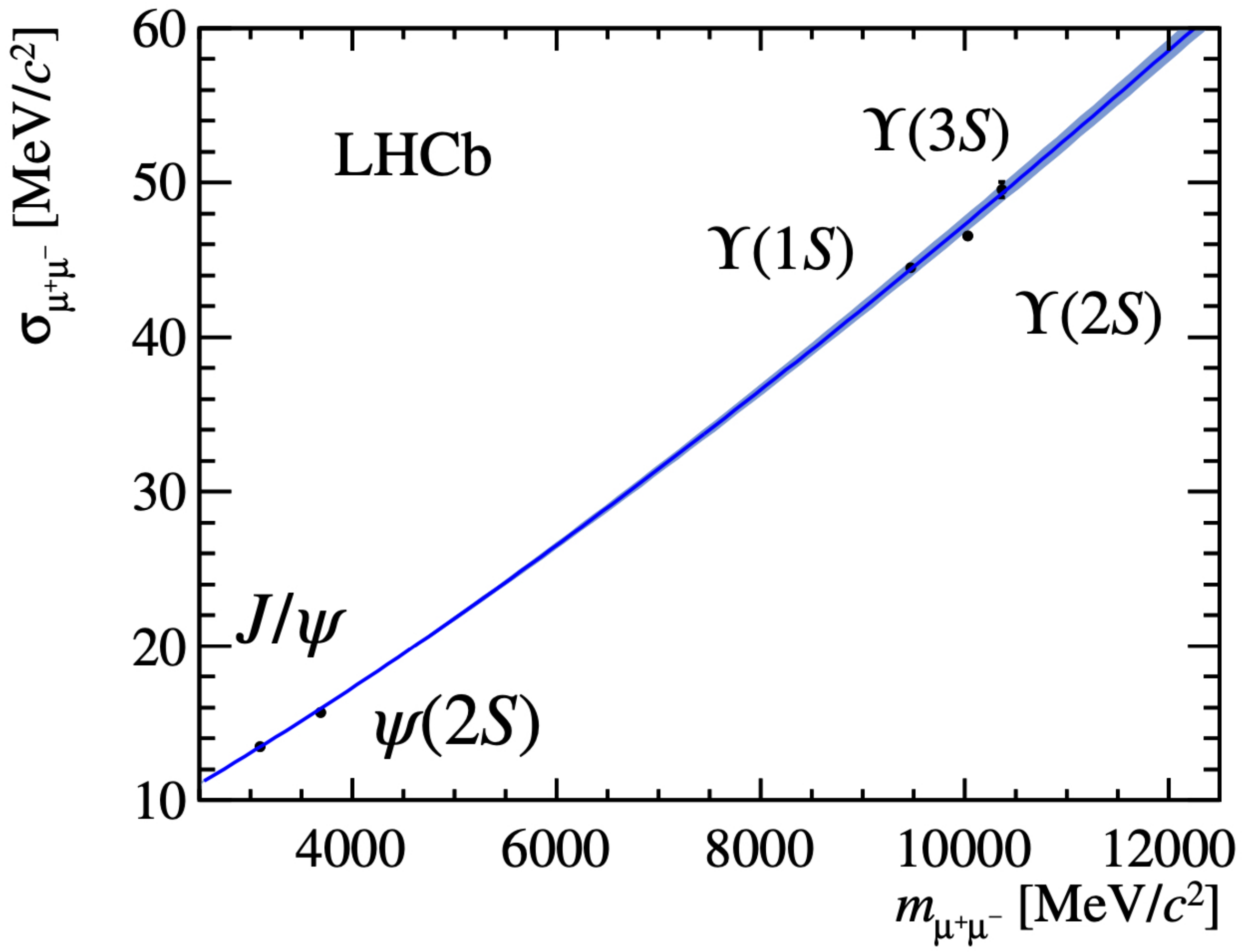
- Latest angular analysis of $B \to K^{*+}\mu^{+}\mu^{-}$ ($9\mathrm{fb}^{-1}$) showed tension in the SM consistent with that found in $B \to K^{*0}\mu^{+}\mu^{-}$
- **Global significance of 3.1σ**
- **Theory uncertainties under scrutiny (role of non-local charmonium loops)**



e/μ in LHCb

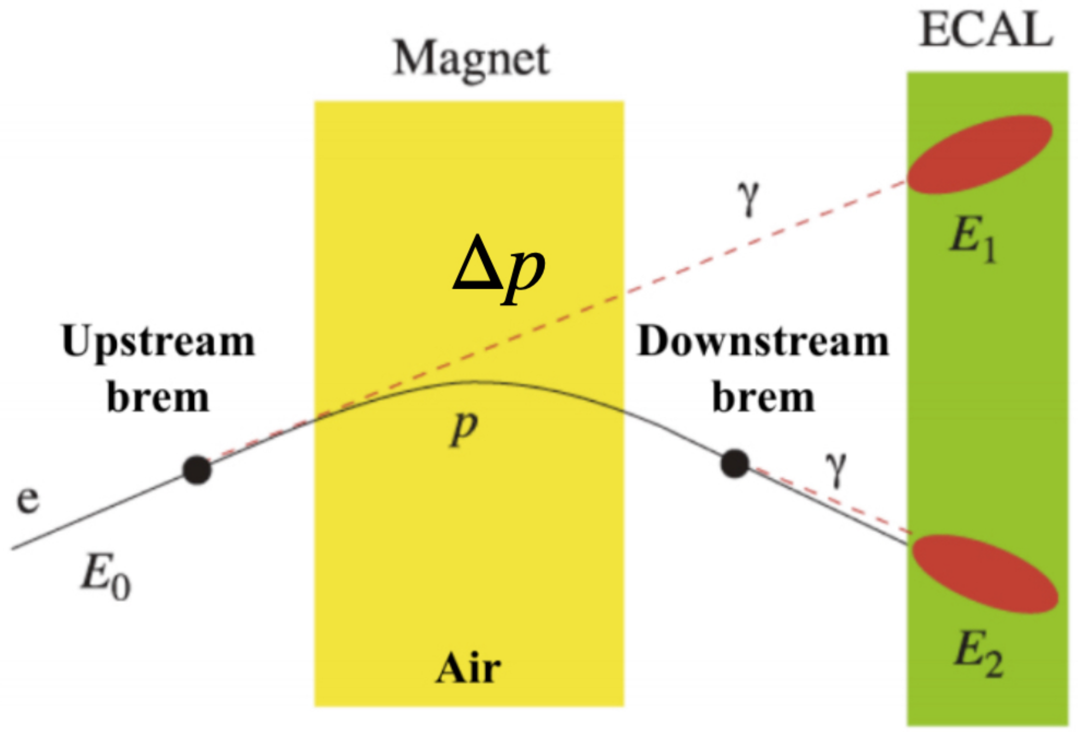
Muons

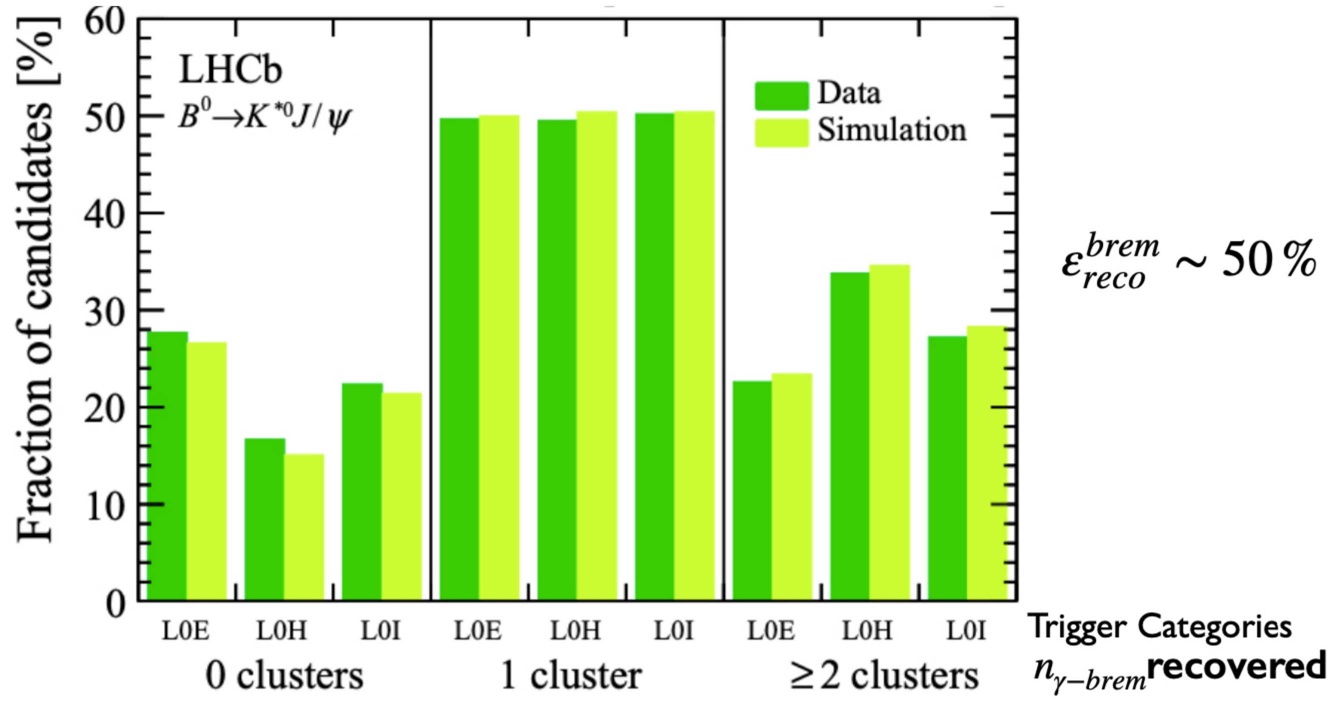




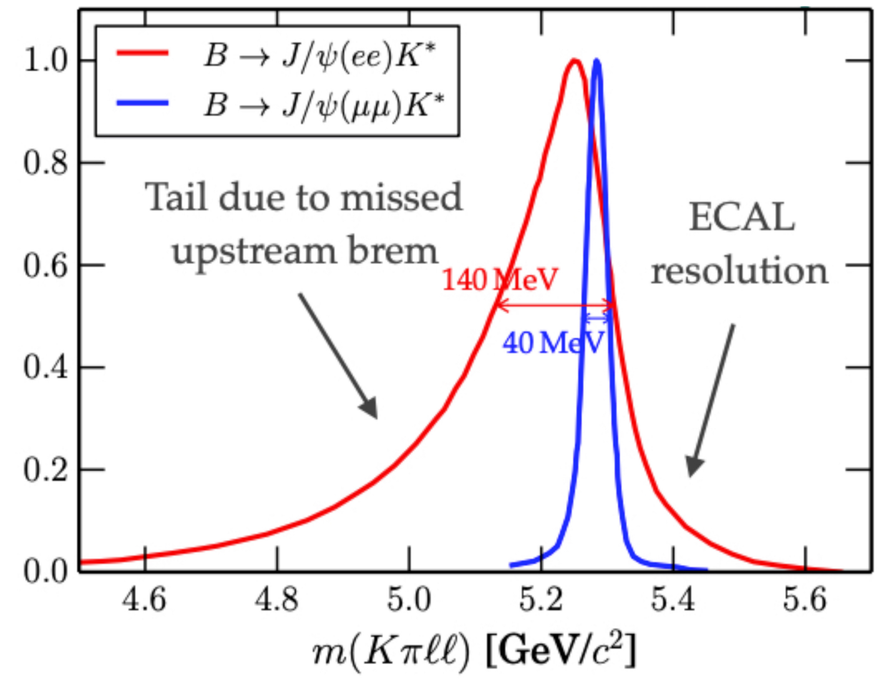
Electrons

[arxiv:1705.05802]

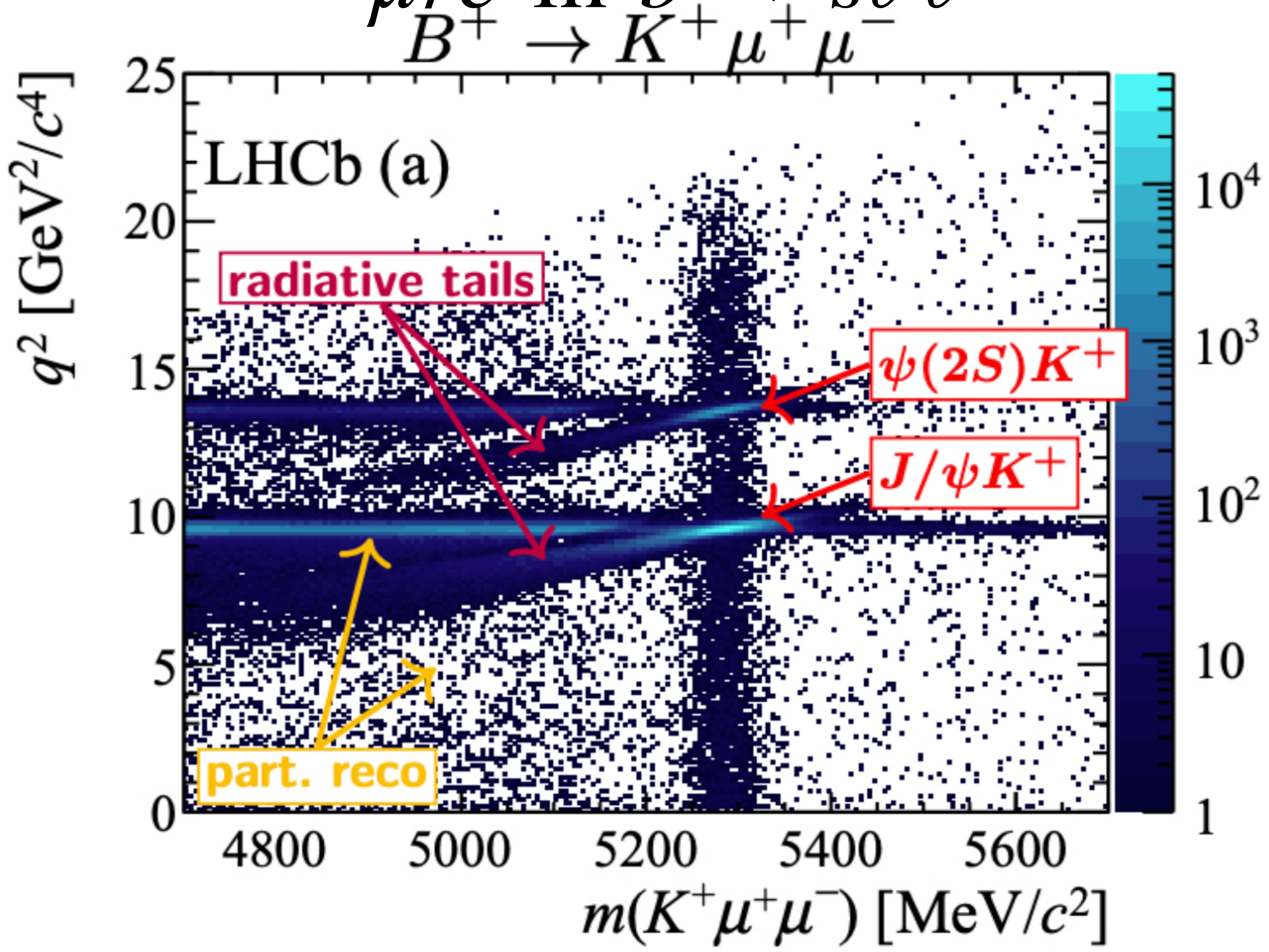


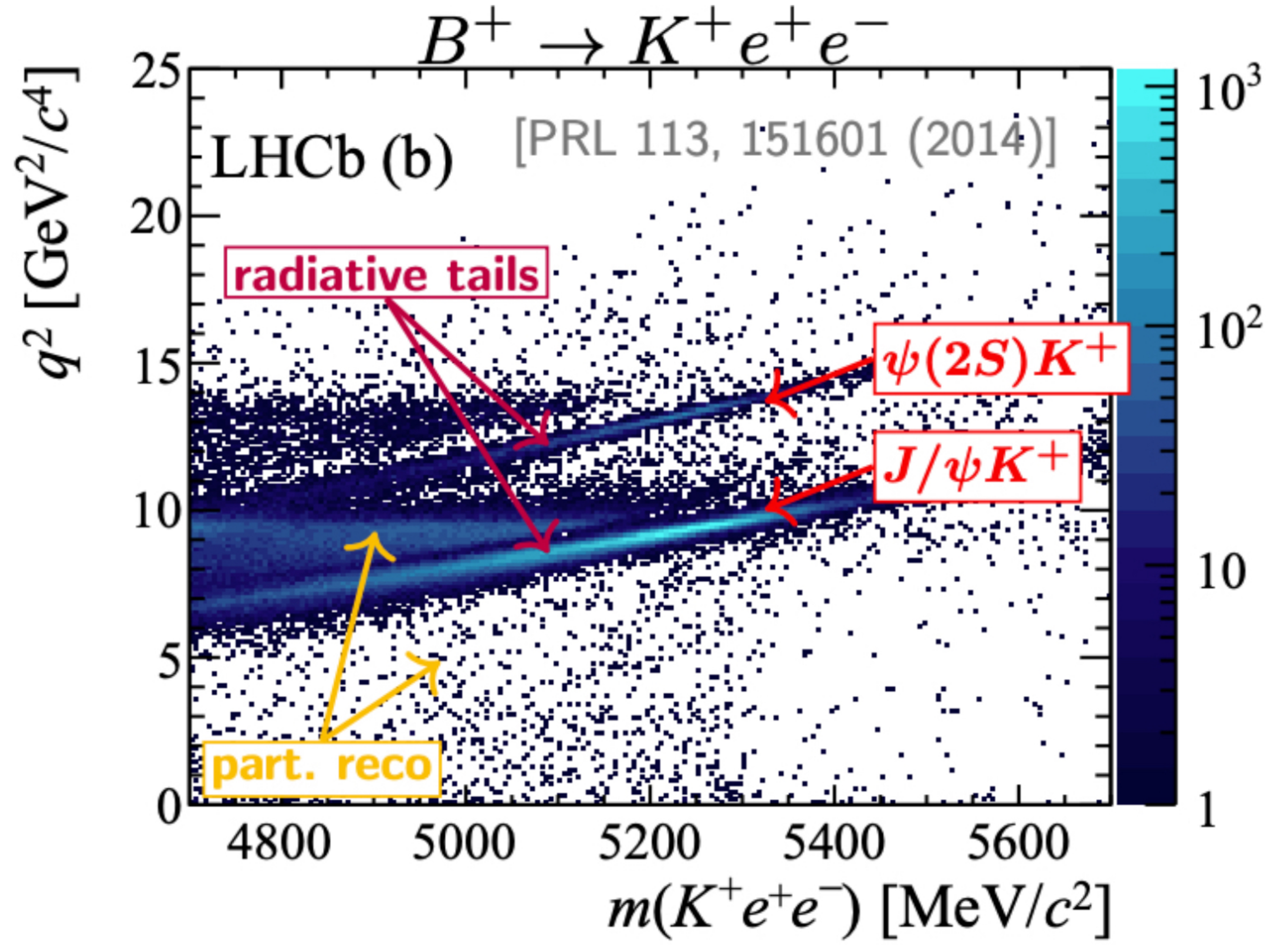


$\epsilon^{brem}_{reco} \sim 50\,\%$



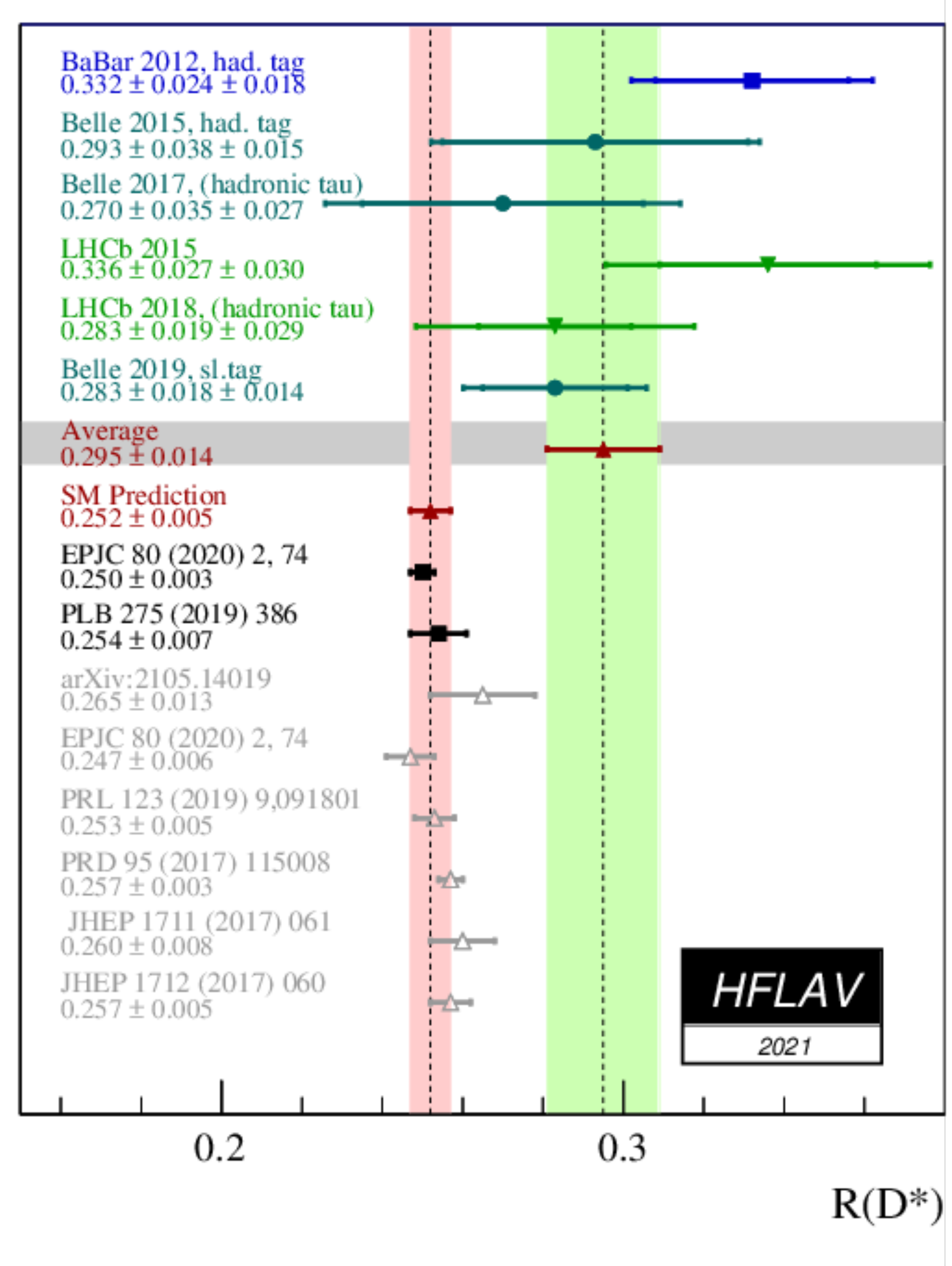
μ/e in $b \to s\ell\ell$

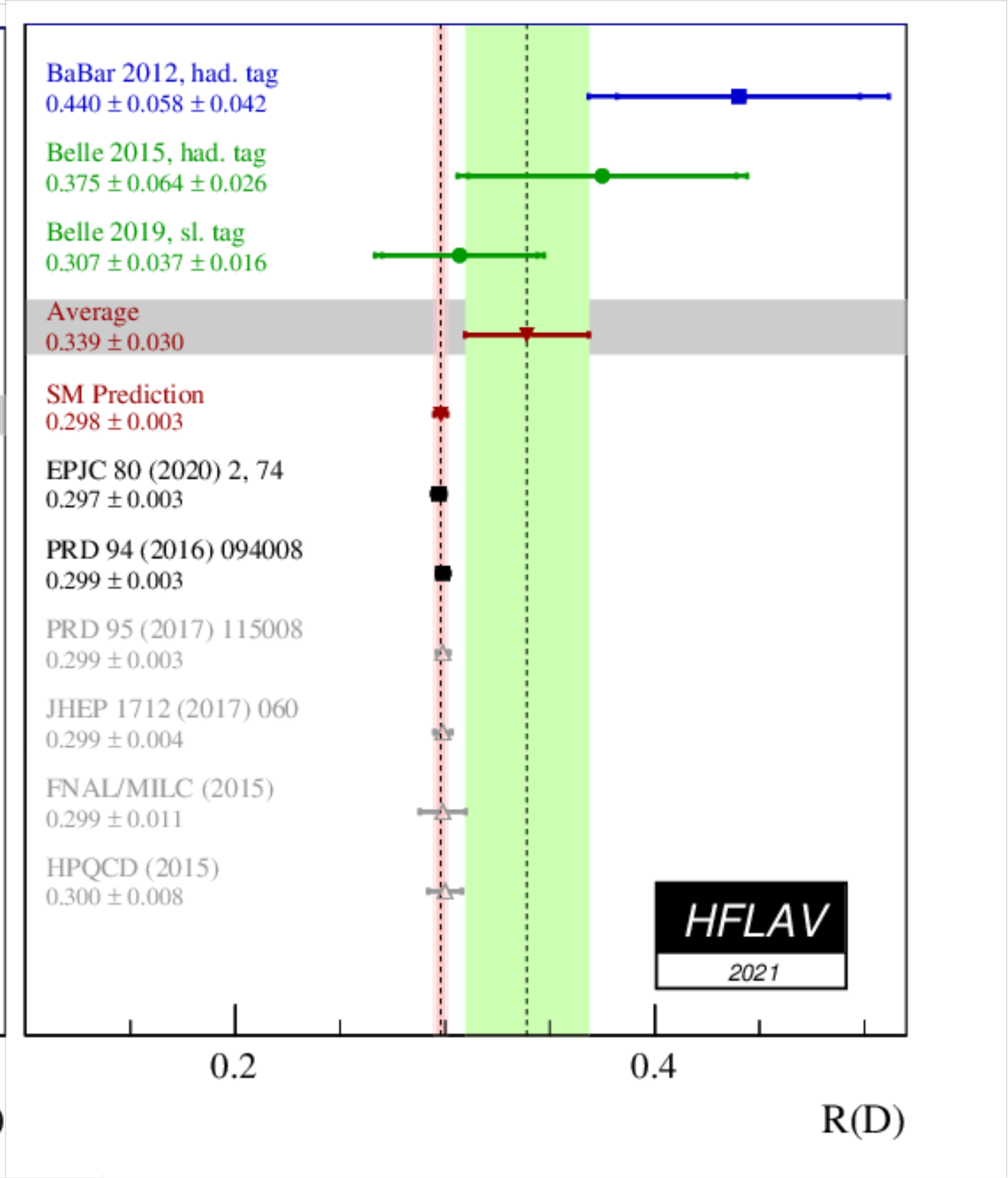




[PRL 113, 151601 (2014)]

R(D*) , R(D)





- All lies above SM

$R(\Lambda_c)$ [using Λ_b decays, leptonic τ]

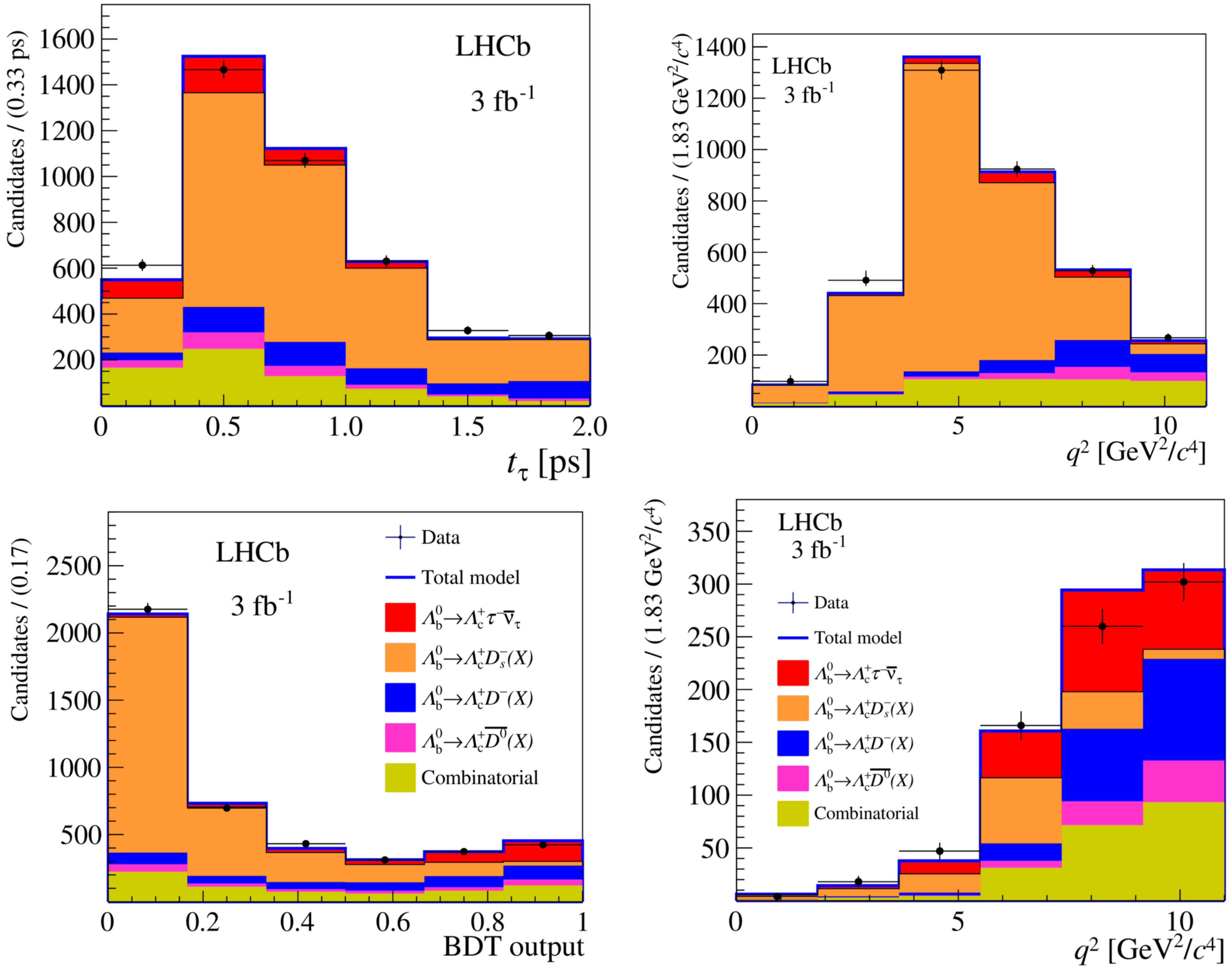
[PRL 128, 191803 (2022)]

Binned template fit Simulation

$$\kappa(\Lambda_c) \equiv \frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-\right)} = \frac{N_{\mathrm{sig}}}{N_{\mathrm{norm}}} \cdot \frac{\epsilon_{\mathrm{sig}}}{\epsilon_{\mathrm{norm}}} \cdot \frac{1}{\mathcal{B}\left(\tau^+ \to \pi^+ \pi^- \pi^+ (\pi^0) \overline{\nu}_\tau\right)}$$

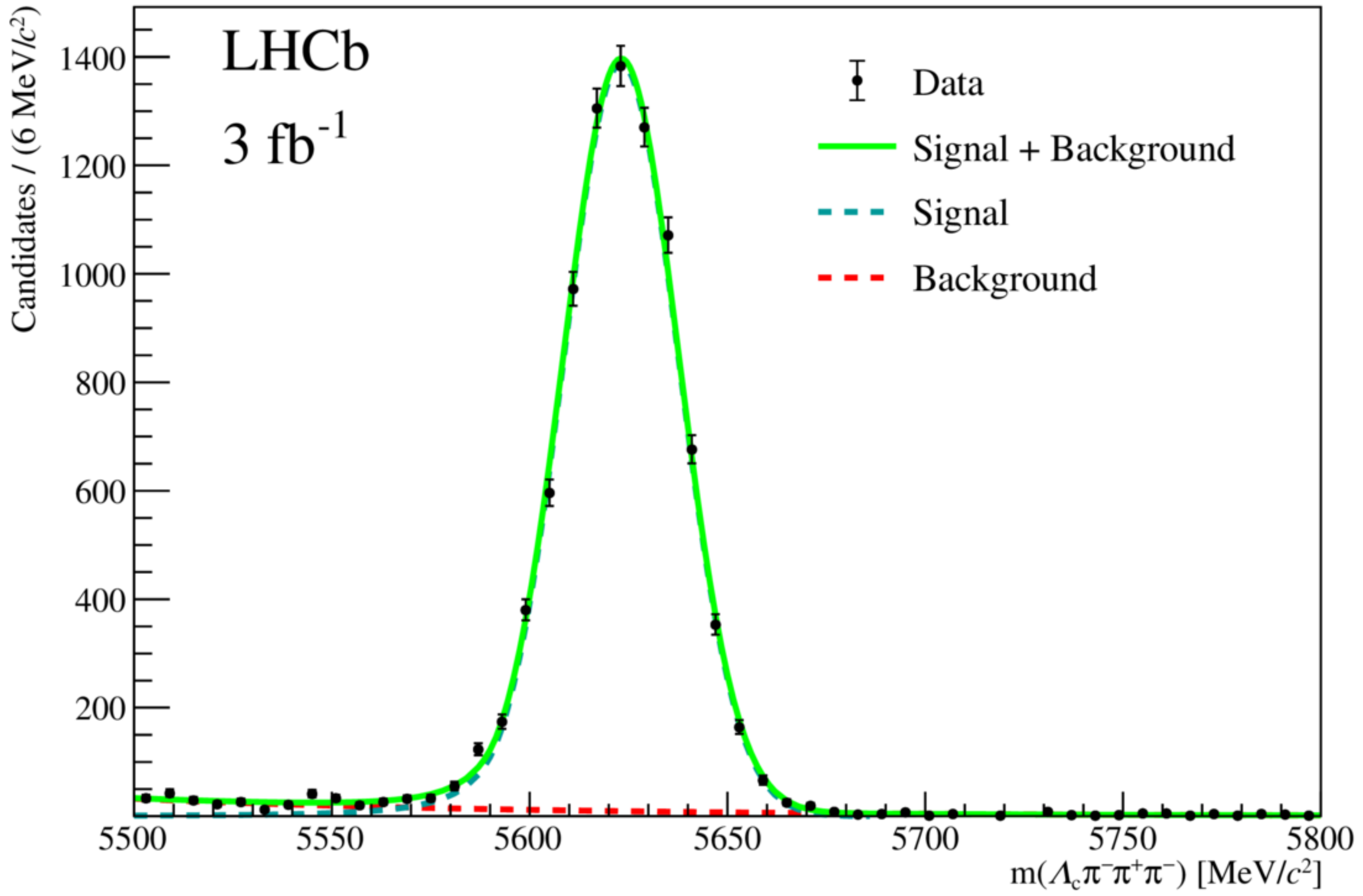
Unbinned maximum likelihood fit External input

$$\mathcal{R}(\Lambda_c) = \kappa(\Lambda_c) \frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^- \pi^+ \pi^- \pi^+\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^- \mu^+ \nu_\mu\right)}$$



Source	$\delta\mathcal{K}(\Lambda_c^+)/\mathcal{K}(\Lambda_c^+)[\%]$
Simulated sample size	3.8
Fit bias	3.9
Signal modelling	2.0
$\Lambda_b^0 \to \Lambda_c^{*+} \tau^- \overline{\nu}_\tau$ feeddown	2.5
$D_s^- \to 3\pi Y$ decay model	2.5
$\Lambda_b^0 \to \Lambda_c^+ D_s^- X$, $\Lambda_b^0 \to \Lambda_c^+ D^- X$, $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 X$ background	4.7
Combinatorial background	0.5
Particle identification and trigger corrections	1.5
Isolation BDT classifier and vertex selection requirements	4.5
D_s^- , D^- , $\overline{D}^0$ template shapes	13.0
Efficiency ratio	2.8
normalization channel efficiency (modelling of $\Lambda_b^0 \to \Lambda_c^+ 3\pi$)	3.0
Total uncertainty	16.5

$\Lambda_b \to \Lambda_c 3\pi$



$R(J/\psi)$ [using B_c decays, leptonic τ]

[PRL 120,121801 (2018)]

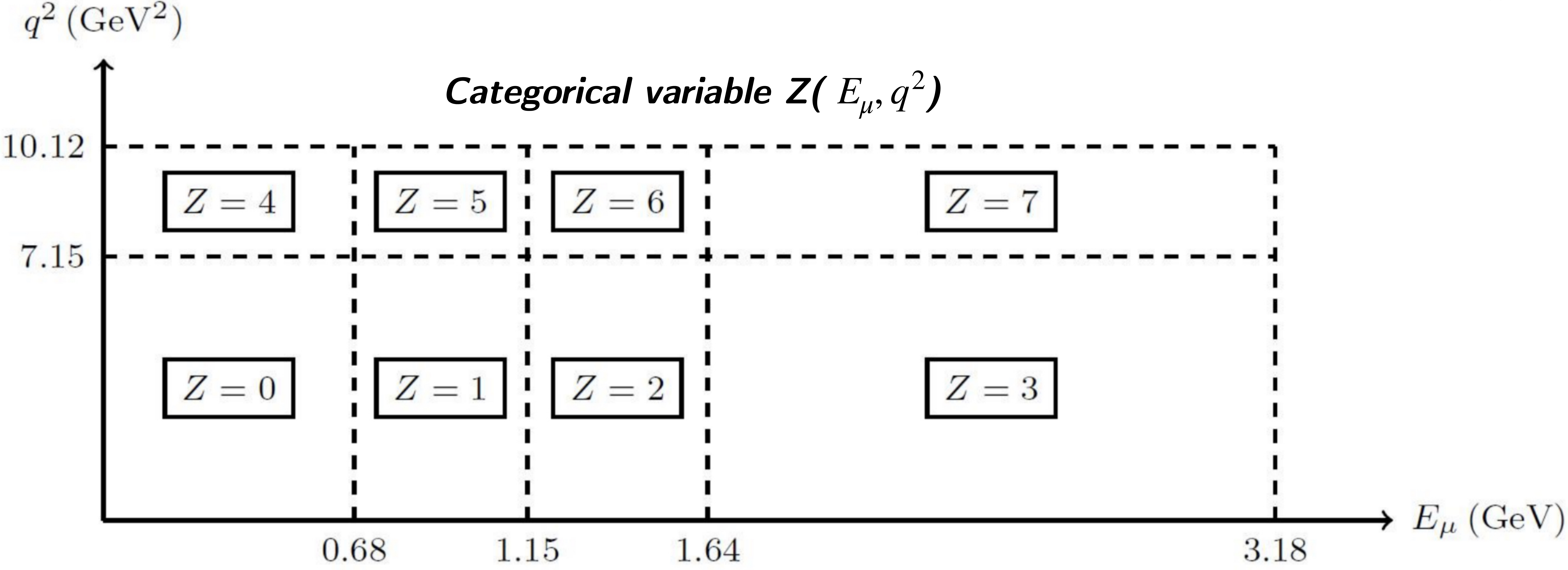
3D binned

Template fit

(Z, m^2_{miss}, t_τ)

- $R(J/\psi) = \dfrac{\mathcal{B}(B_c^- \to J/\psi \tau^- \overline{\nu_\tau})}{\mathcal{B}(B_c^- \to J/\psi \mu^- \overline{\nu_\mu})}$ ✦ $\tau^- \to \mu^- \overline{\nu_\mu} \nu_\tau$

Categorical variable Z(E_μ, q^2)



$R(J/\psi)$ [using B_c decays, leptonic τ], m^2_{miss} projections

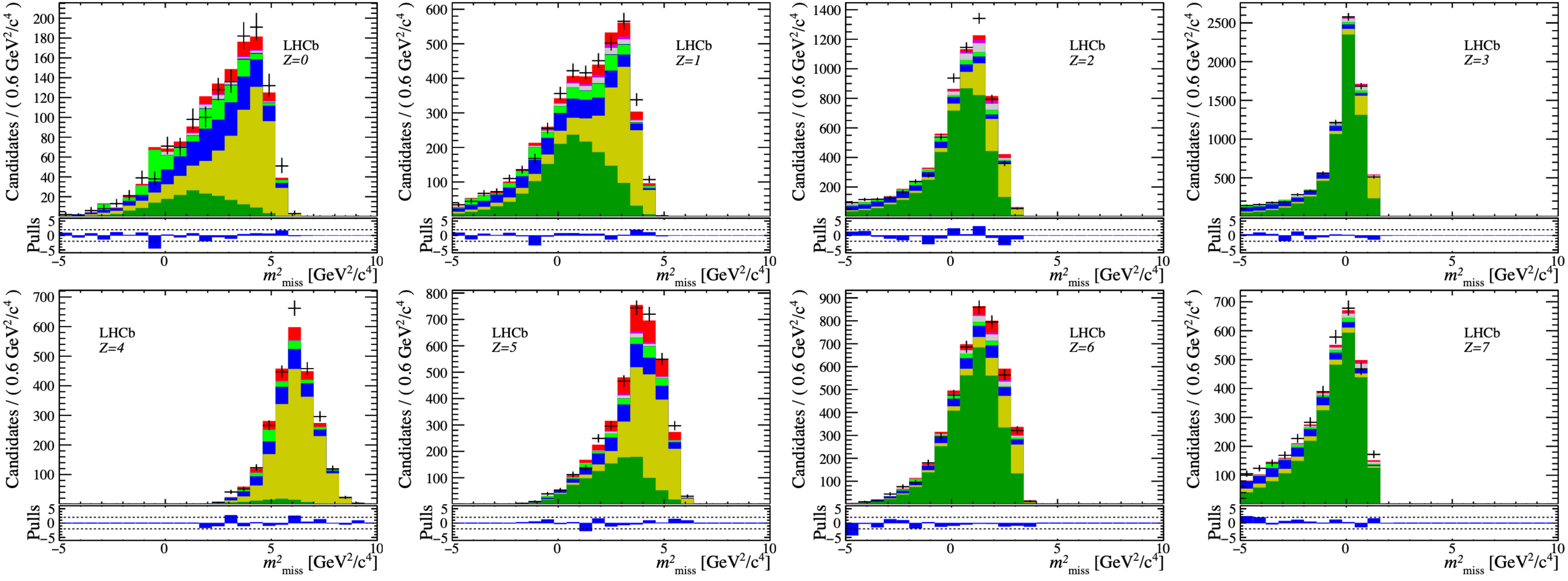
- $R(J/\psi) = \dfrac{\mathcal{B}(B_c^- \to J/\psi \tau^- \overline{\nu_\tau})}{\mathcal{B}(B_c^- \to J/\psi \mu^- \overline{\nu_\mu})}$

┼ Data
🟨 Mis-ID bkg.
🟩 J/ψ comb. bkg.
⬜ $B_c^+ \to \chi_c(1P) l^+ \nu_l$
🟥 $B_c^+ \to J/\psi \tau^+ \nu_\tau$
🟩 $B_c^+ \to J/\psi \mu^+ \nu_\mu$
🟦 $J/\psi + \mu$ comb. bkg.
🟦 $B_c^+ \to J/\psi H_c^+$
🟪 $B_c^+ \to \psi(2S) l^+ \nu_l$

3D binned

Template fit

(Z, m^2_{miss}, t_τ)



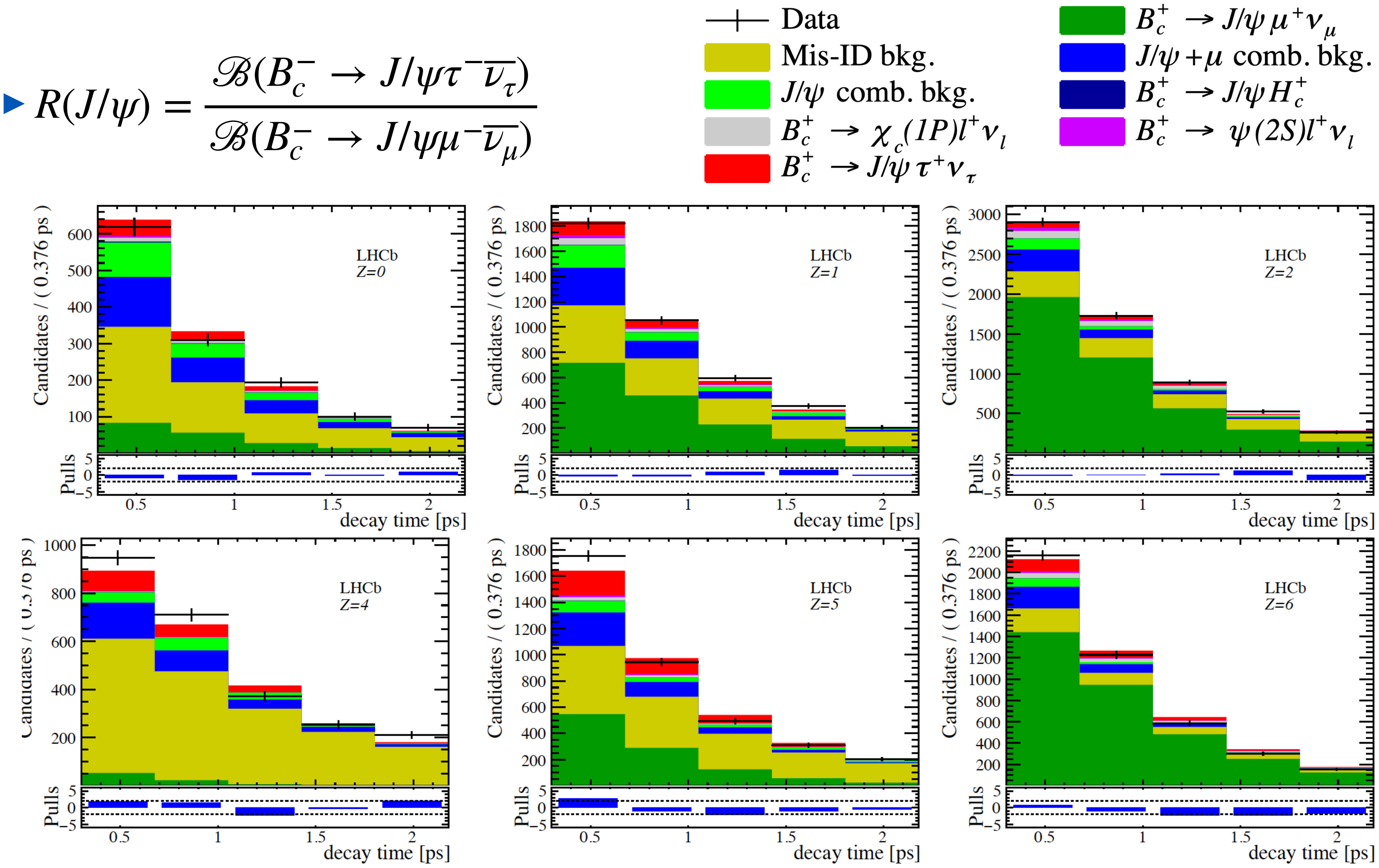
$R(J/\psi)$ [using B_c decays, leptonic τ], t_τ projections

- $R(J/\psi) = \dfrac{\mathscr{B}(B_c^- \to J/\psi \tau^- \overline{\nu_\tau})}{\mathscr{B}(B_c^- \to J/\psi \mu^- \overline{\nu_\mu})}$

3D binned

Template fit

(Z, m^2_{miss}, t_τ)



$R(J/\psi)$ [using B_c decays, leptonic τ], systematics

- $R(J/\psi) = \dfrac{\mathcal{B}(B_c^- \to J/\psi \tau^- \overline{\nu}_\tau)}{\mathcal{B}(B_c^- \to J/\psi \mu^- \overline{\nu}_\mu)}$

Source of uncertainty	Size ($\times 10^{-2}$)
Finite simulation size	8.0
$B_c^+ \to J/\psi$ form factors	12.1
$B_c^+ \to \psi(2S)$ form factors	3.2
Fit bias correction	5.4
Z binning strategy	5.6
Mis-ID background strategy	5.6
combinatorial background cocktail	4.5
combinatorial J/ψ background scaling	0.9
$B_c^+ \to J/\psi H_c X$ contribution	3.6
$\psi(2S)$ and χ_c feed-down	0.9
Weighting of simulation samples	1.6
Efficiency ratio	0.6
$\mathcal{B}(\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau)$	0.2
Systematic uncertainty	17.7
Statistical uncertainty	17.3