Lepton Flavour Universality tests and Lepton Flavour Violation searches at LHCb

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On behalf of the LHCb collaboration

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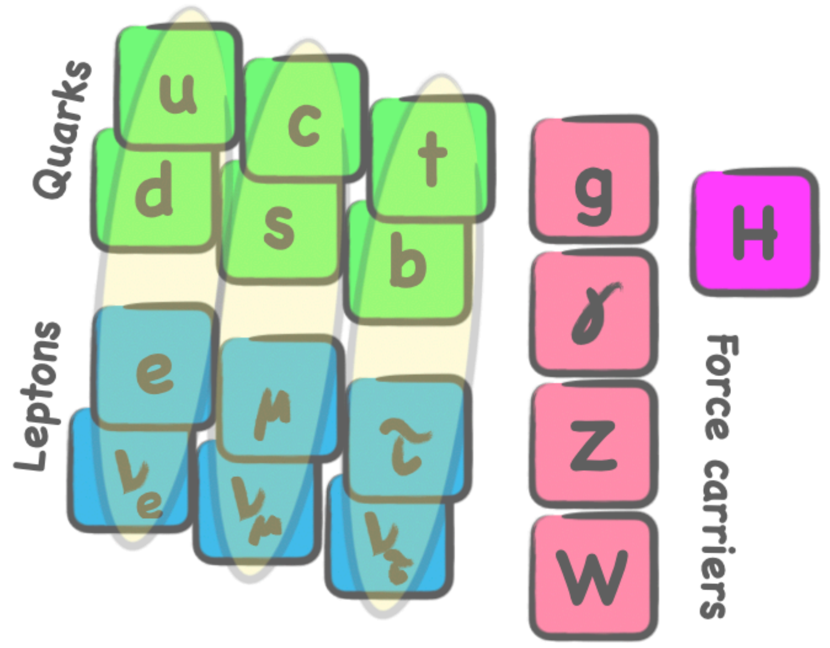
Outline

- The flavour puzzle
- Lepton Flavour Universality tests
  - $b \to s\ell\ell$ decays (Neutral Current)
  - $b \to c\ell\nu$ decays (Charged Current)
- Lepton Flavour Violating Decays
- Conclusion & Outlook

The flavour puzzle

$\psi = Q_L, u_r, d_r, L_L, e_r$

$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$



$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}}(\psi_i, A_a) + \mathcal{L}_{\text{Higgs}}(\psi_i, A_a, H)$$

$$\mathcal{L}_{\text{gauge}} = \sum_a \frac{-1}{4g_a^2}(F_{\mu\nu})^2 + \sum_{i=1}^{3} \bar{\psi}_i i \not{D} \psi_i$$

$$\mathcal{L}_{\text{Higgs}} = \mathcal{L}_H + \mathcal{L}_{Yukawa}$$

Only Yukawa interaction distinguishes the families

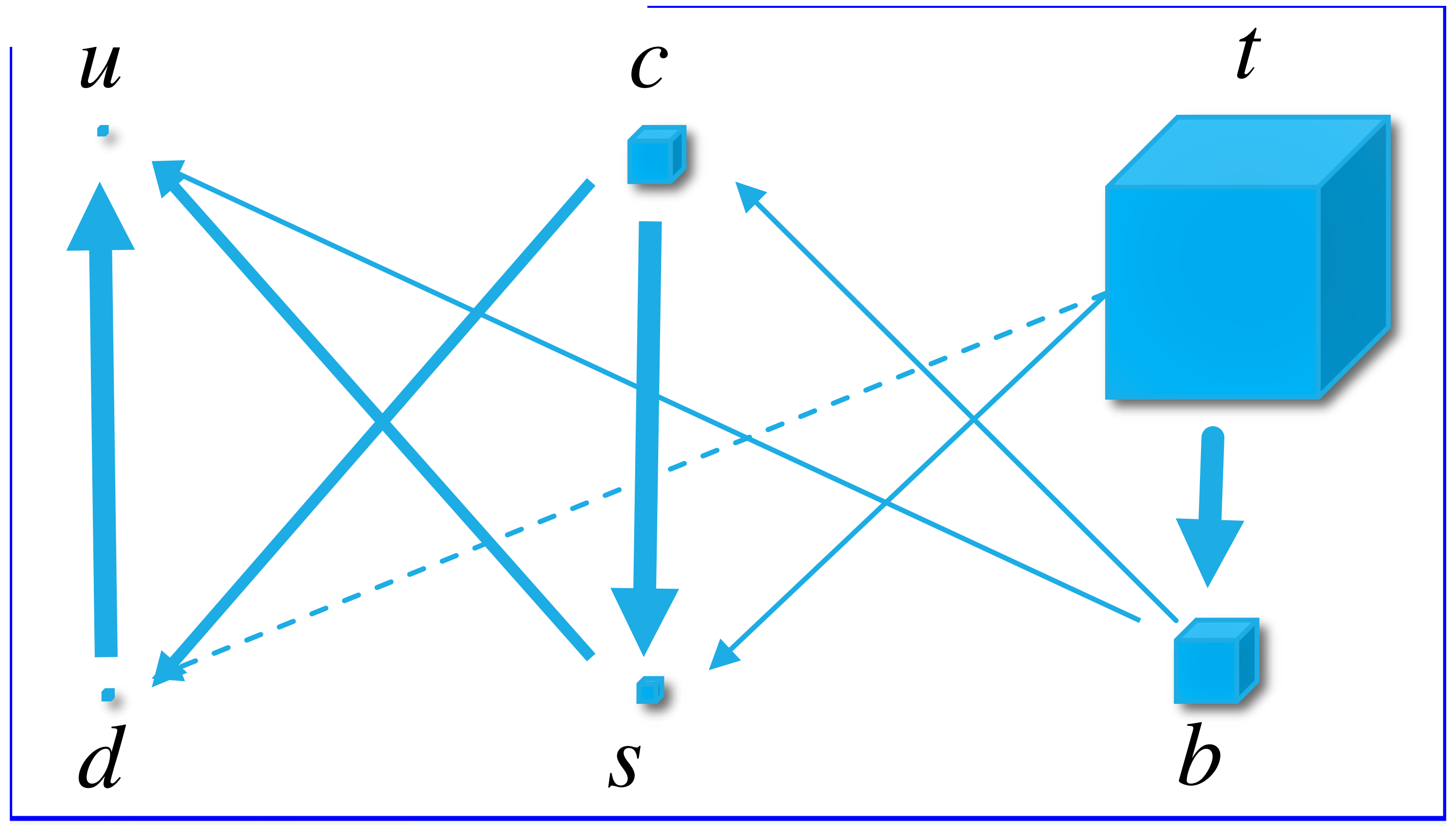
3 identical replica ($i = 1,2,3$) of the same family differing only in mass

Gauge interactions have the same amplitude for all the families: **Lepton Flavour Universality (LFU)**

Flavour is conserved: stringent limits on **Lepton Flavour Violating (LFV)** decays

- **Why 3 generations?**
- **What is the origin of their different mass?**

V_{CKM} nearly diagonal



- **What is the origin of the hierarchy in quark-mixing?**

The flavour puzzle

$$\mathscr{L}_{\text{SM}} = \mathscr{L}_{\text{gauge}}(\psi_i, A_a) + \mathscr{L}_{\text{Higgs}}(\psi_i, A_a, H)$$

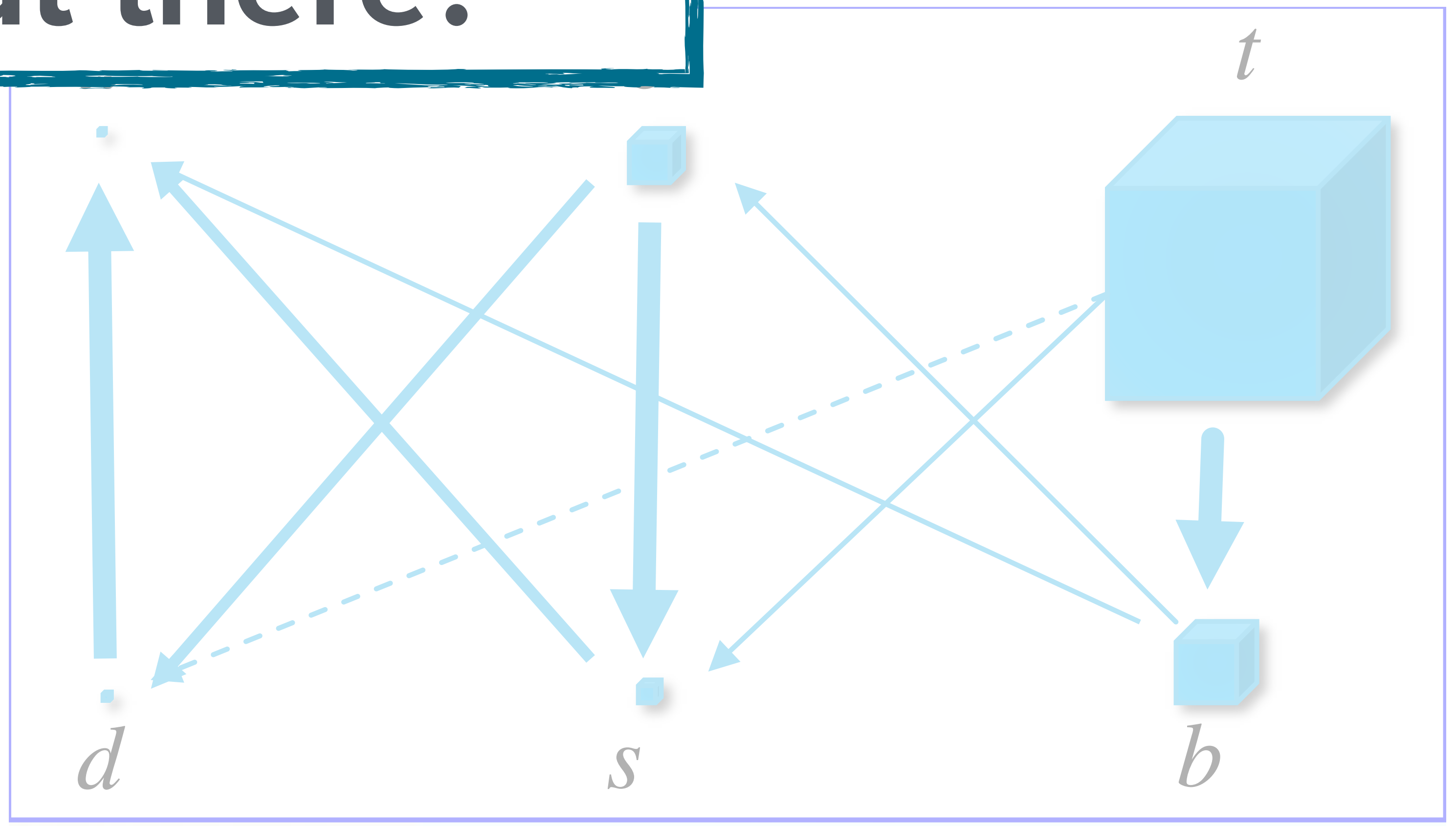
$$\mathscr{L}_{\text{gauge}} = \sum_a \frac{-1}{4g_a^2}(F_{\mu\nu})^2 + \sum_{i=1}^{3} \bar{\psi}_i i \not{D} \psi_i$$

$$\mathscr{L}_{\text{Higgs}} = \mathscr{L}_H + \mathscr{L}_{Yukawa}$$

Only Yukawa interaction distinguishes the families

3 identical replica ($i = 1$
family **differing only in m**

Is there New Physics out there?



Gauge interactions have the same amplitude for all the families: **Lepton Flavour Universality (LFU)**

Flavour is conserved: stringent limits on **Lepton Flavour Violating (LFV)** decays

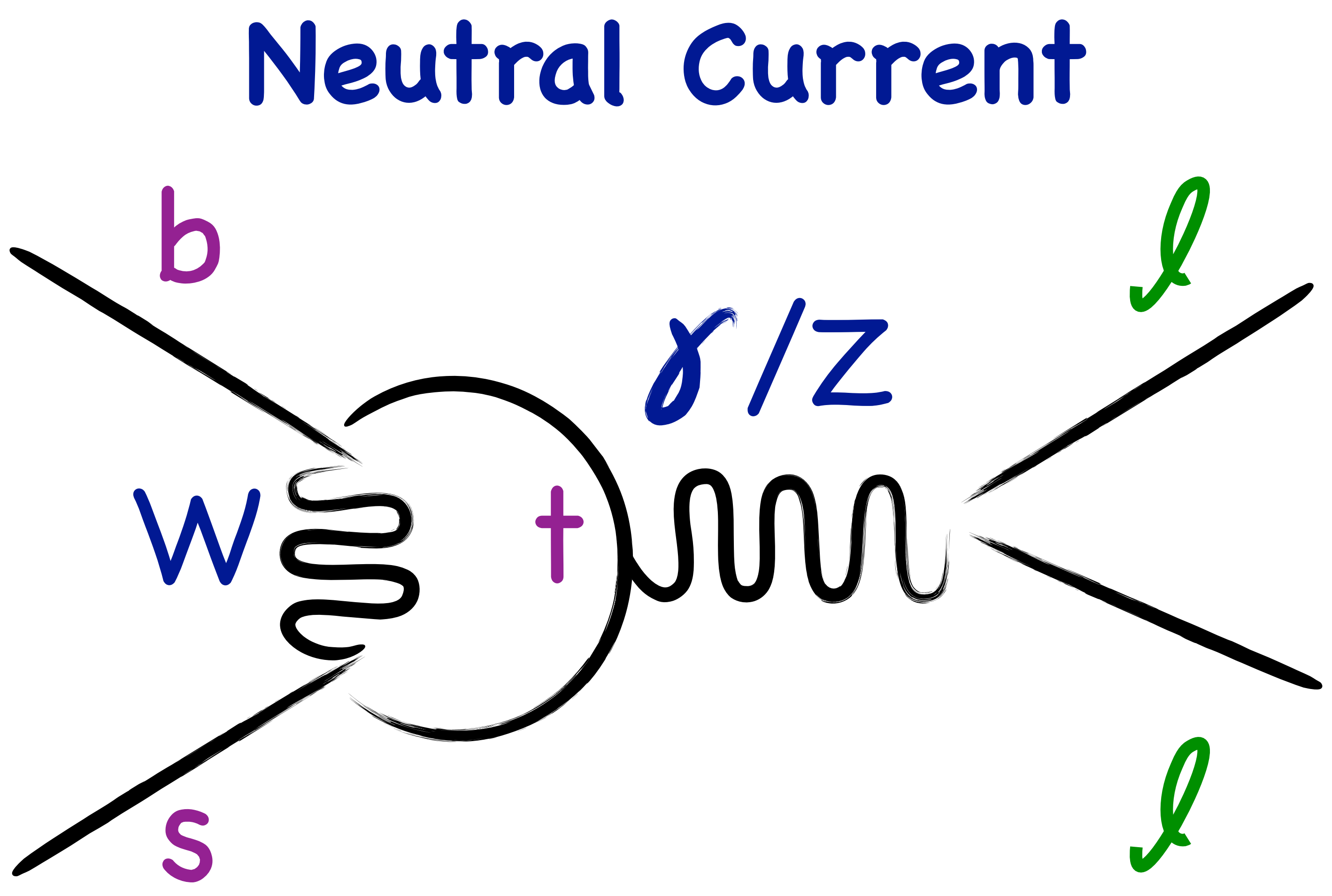
- **Why 3 generations?**
- **What is the origin of their different mass?**
- **What is the origin of the hierarchy in quark-mixing?**

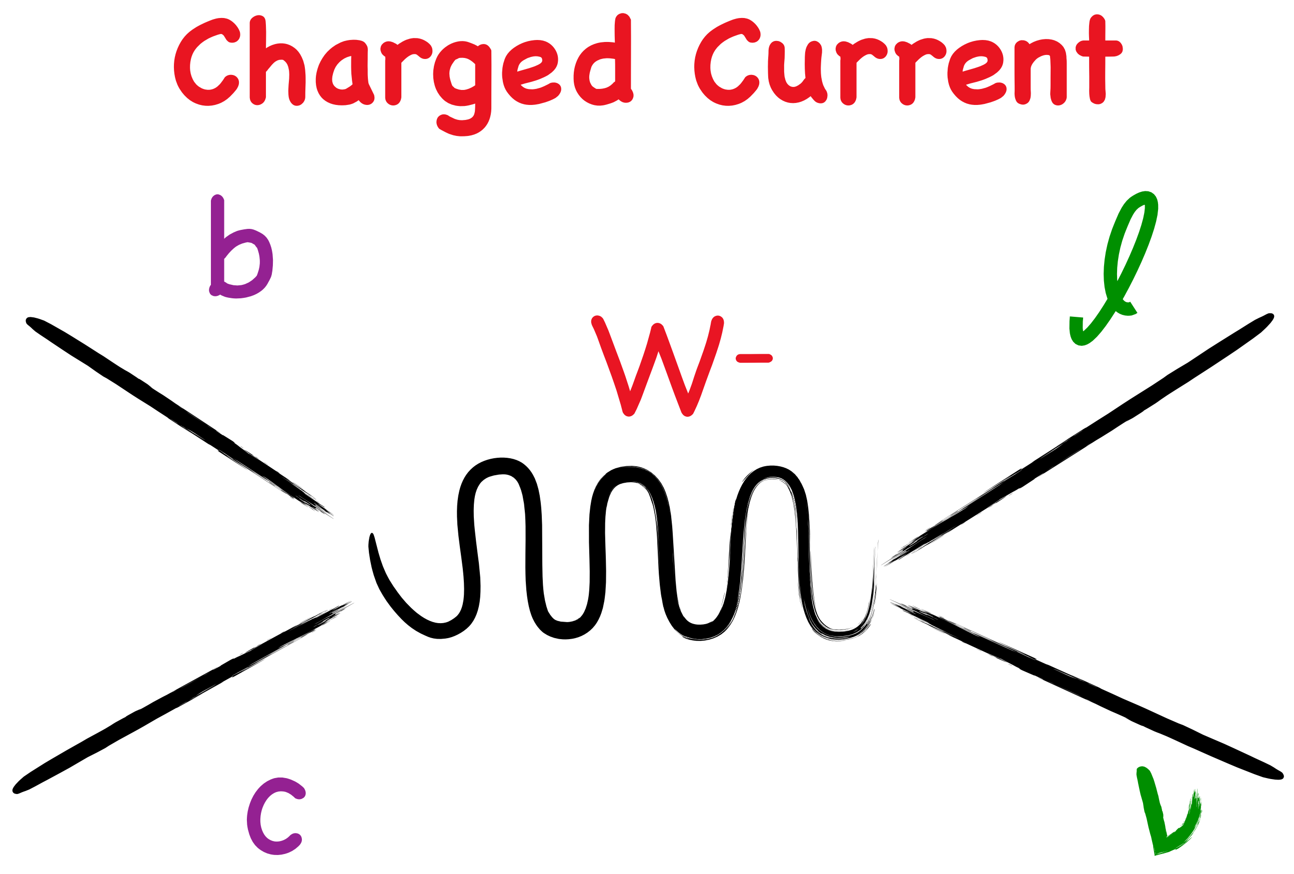
b decays

- Precision measurements in b rare decays can be sensitive to possible New Physics contribution

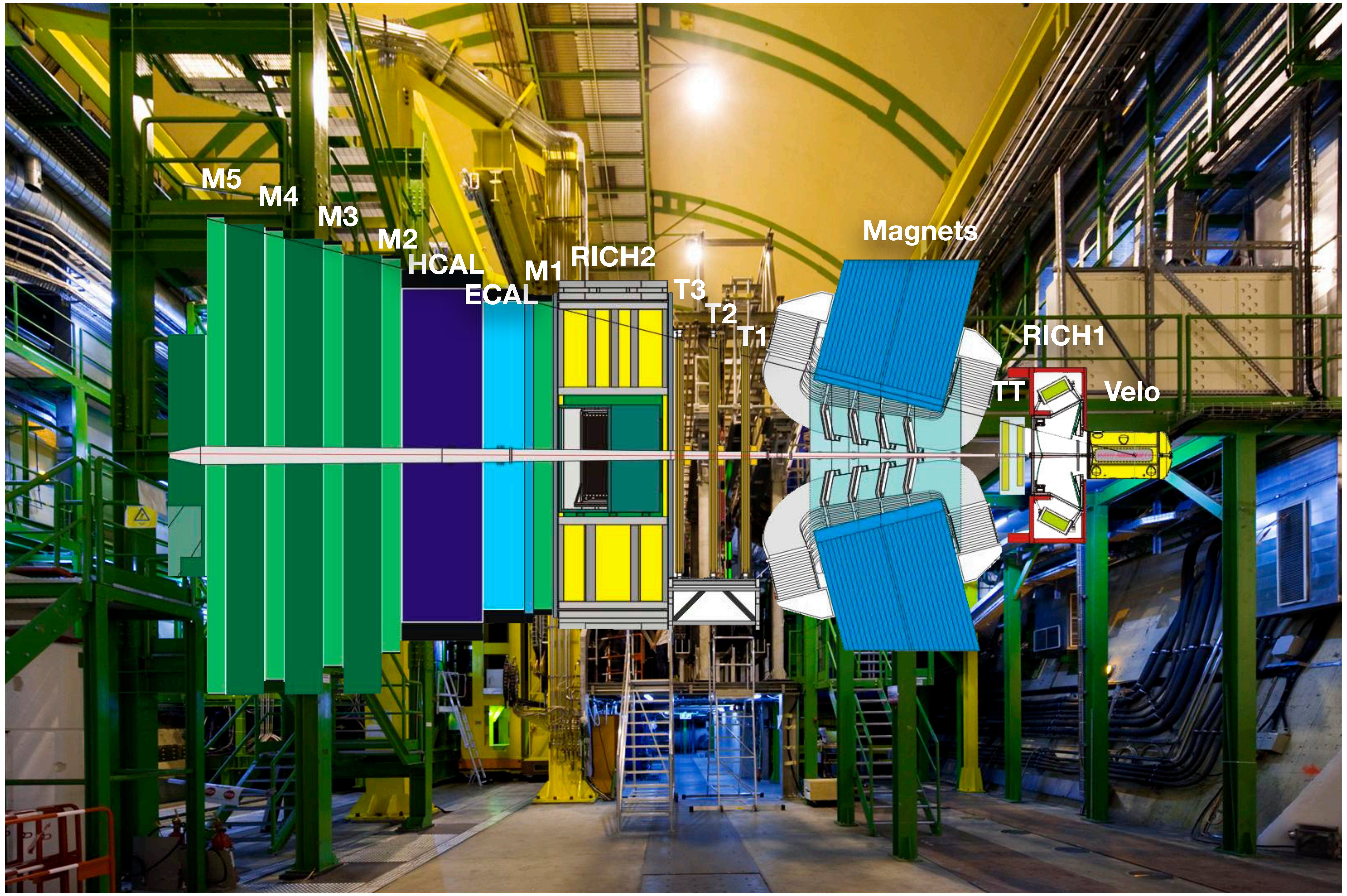
  - $b \to s\ell\ell$ processes
    - Suppressed in the SM (they can happen only via loop or boxes): small BR ~10^{-7} - 10^{-6}
    - New physics mediators can enter in the loops and modify the amplitudes

  - $b \to c\ell\bar{\nu}$ decays
    - Tree level processes: large BR (few %)
    - Clean Standard Model predictions





b decays @LHCb



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- LHCb forward detector: 27% of b hadrons produced from pp collision inside acceptance ($B^+, B^0, B_s, B_c, \Lambda_b \ldots$)
- Good trigger on displaced tracks (e.g. heavy meson decays), especially for di-muons channel (~90 % efficiency)
- Good PID performances from RICH 1,2 , ECAL and Muon Stations
  - Electron ID ~ 90 % for ~ 5 % e→h mis-id
  - Kaon ID ~ 95 % for ~ 5 % π→K mis-id
  - Muon ID ~ 97 % for 1-3 % π→μ mis-id
- Excellent tracking performances (~96% efficiency for long tracks)
  - Δ p / p = 0.5 % at low momentum
  - Impact parameter resolution: (15 +29/ pT[GeV]) μm

b decays

- Precision measurements in b rare decays can be sensitive to possible New Physics contribution
  - $b \to s\ell\ell$ **processes**
    - Suppressed in the SM (they can happen only via loop or boxes): small BR ~10^{-7} - 10^{-6}
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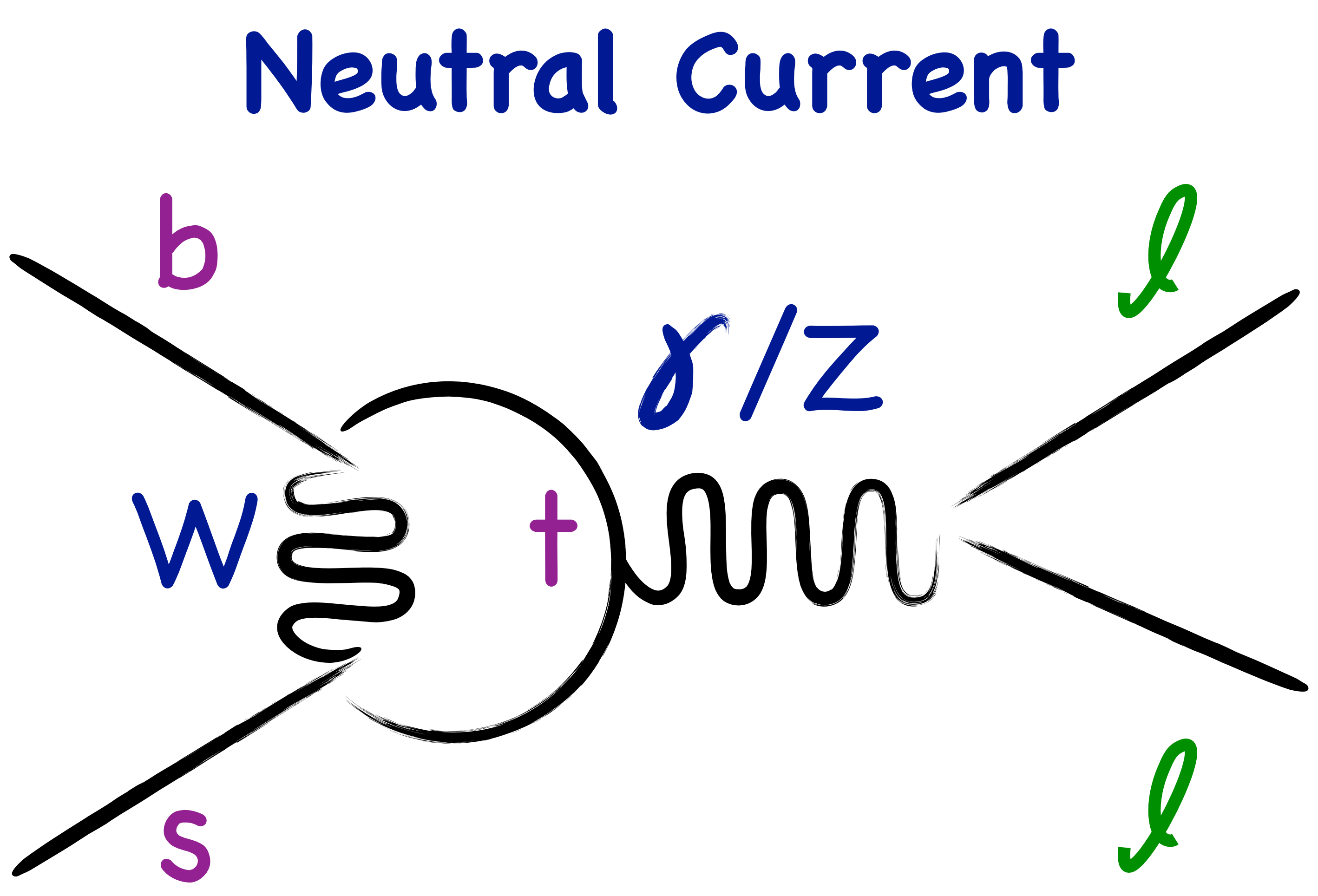
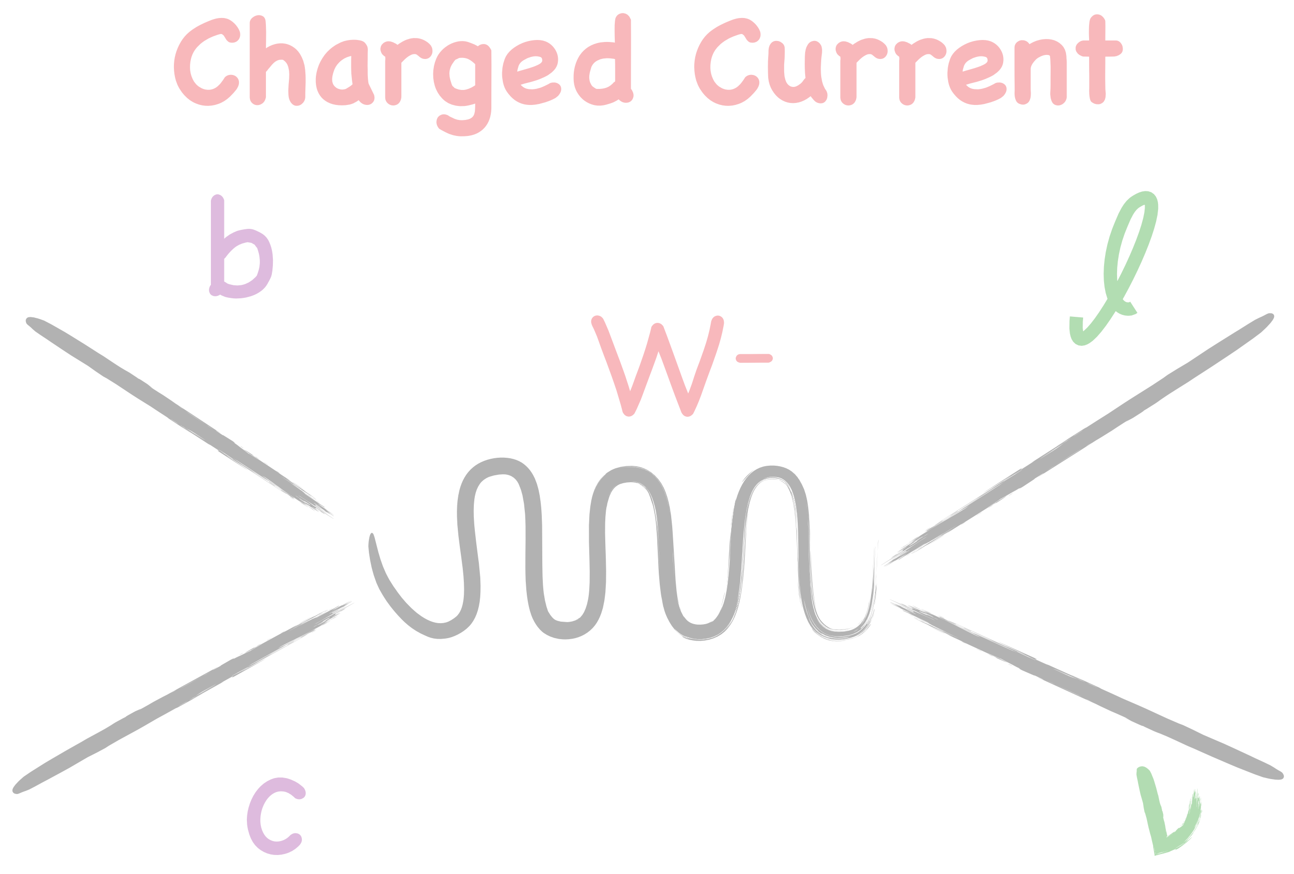




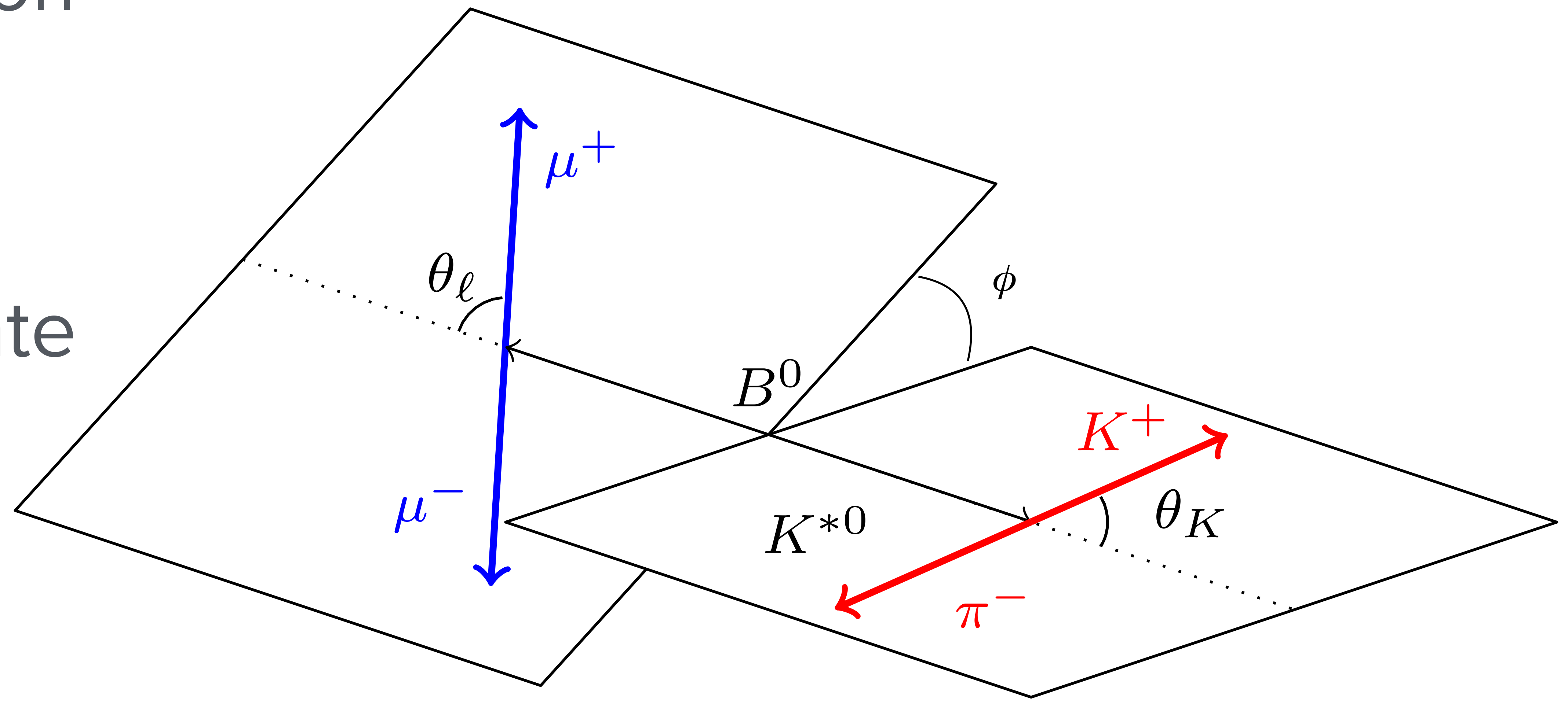
$b \to s\ell\ell$ decays

- Large variety of observables available:
  - **Relative rates** of $b \to s\mu^+\mu^-$ and $b \to se^+e^-$, of the form

EPJ C76 (2016) 8 440

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-2})$$

    - are clean: QCD uncertainties cancels out in the ratio
    - are predicted by the SM with very high precision
  - **Angular distributions**:
    - Study the angular information of the final state particles (e.g. in $B \to K^*\mu^+\mu^-$)

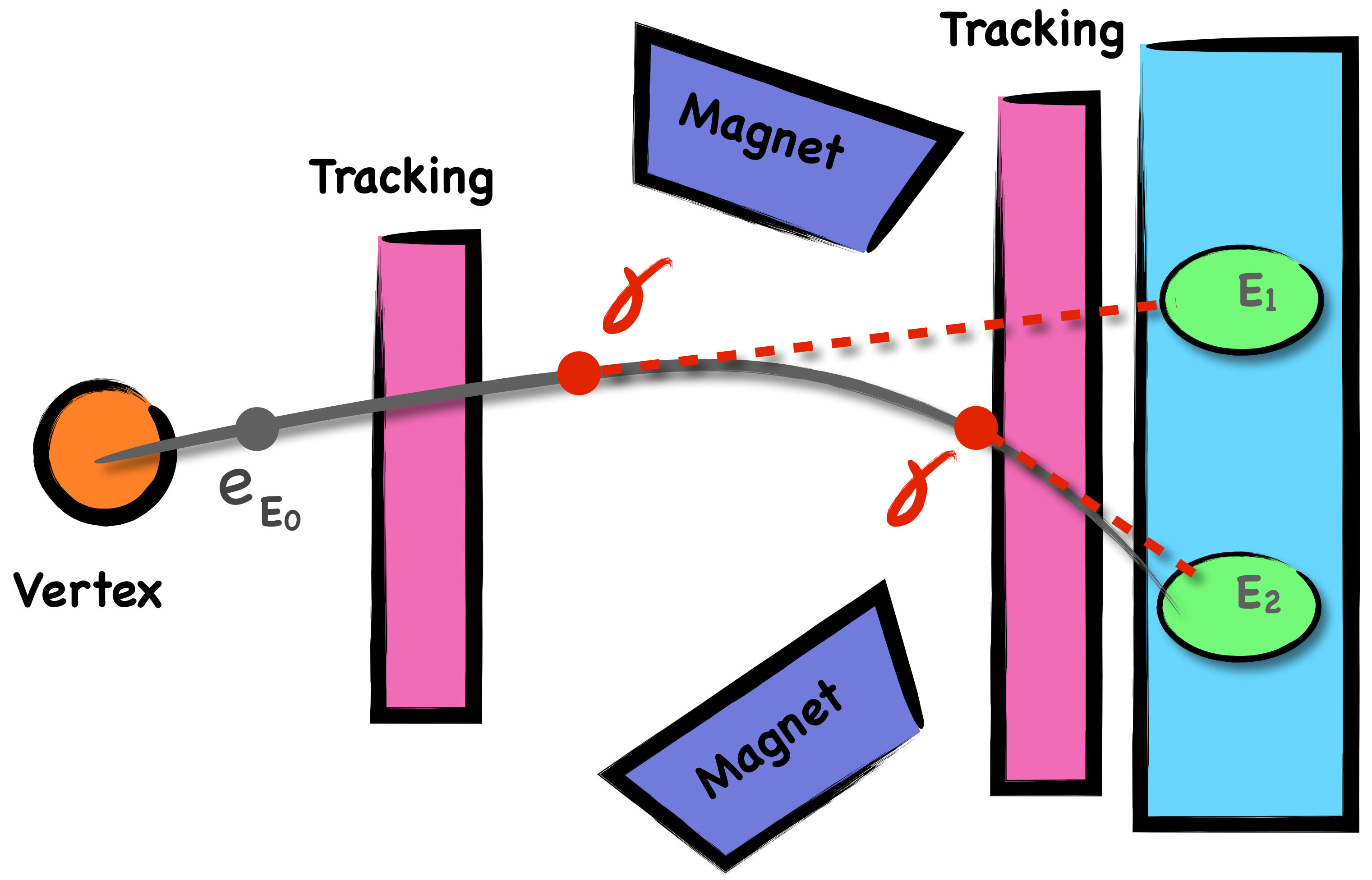


  - Single **branching fractions**:
    - e.g. $B \to K^*\mu^+\mu^-, B_s \to \phi\mu^+\mu^- \ldots$
    - Suffer the most from theory uncertainties

LFU ratios: Electron vs Muon

- Relative rates are sensitive to differences between leptons:

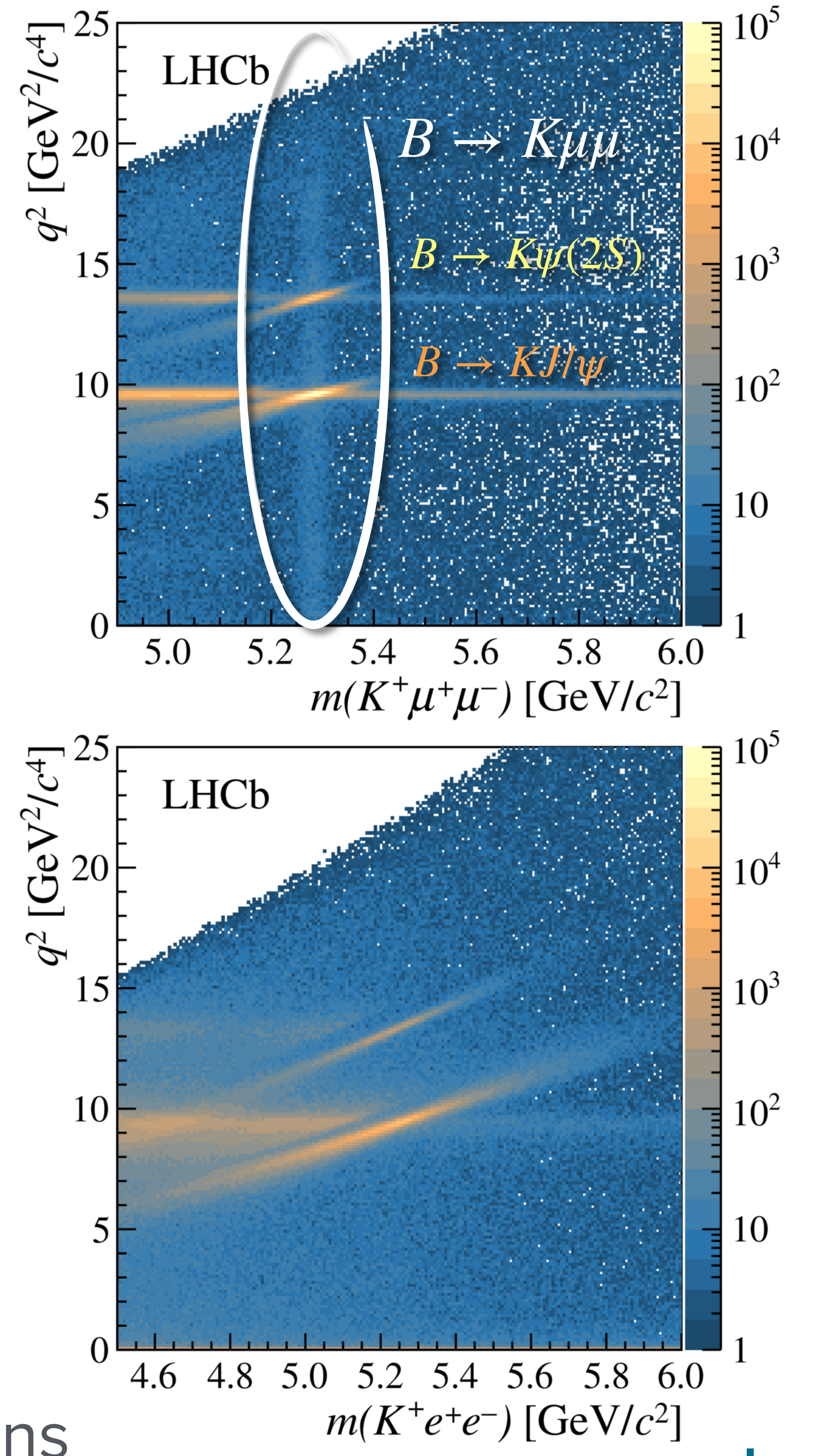
$$R_X = \frac{\mathcal{N}_{B\to X\mu^+\mu^-}}{\mathcal{N}_{B\to Xe^+e^-}} \cdot \frac{\epsilon_{B\to Xe^+e^-}}{\epsilon_{B\to X\mu^+\mu^-}}$$



- Most electrons emit **bremsstrahlung** photons before the magnet:
  - Need to recover the photon cluster energy
- High occupancy in the electron calorimeter:
  - Higher energy thresholds → lower statistics
  - Three exclusive trigger categories defined:
    - $e^\pm$ from the B candidate; $K^\pm$ from the B candidate; rest of the event
- Worse p resolution, lower PID and tracking efficiencies than for muons

Crucial to control e/μ differences

$q^2 = m^2(\ell^+\ell^-)$ PRL 122 (2019) 191801

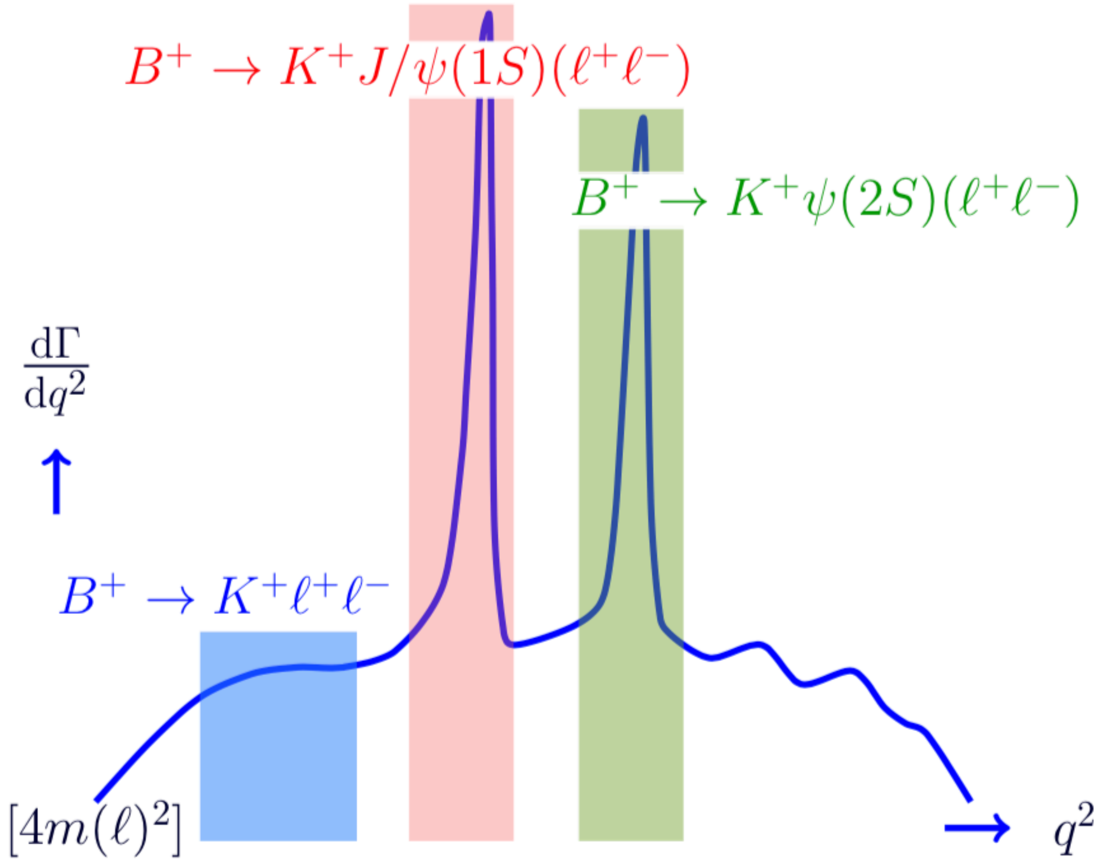


Experimental strategy

- Relative rates are measured as **double ratios**

$$R_X = \frac{\mathcal{N}_{B\to X\mu^+\mu^-}}{\mathcal{N}_{B\to X(J/\psi\to\mu^+\mu^-)}} \cdot \frac{\mathcal{N}_{B\to X(J/\psi\to e^+e^-)}}{\mathcal{N}_{B\to Xe^+e^-}} \cdot \frac{\epsilon_{B\to X(J/\psi\to\mu^+\mu^-)}}{\epsilon_{B\to X\mu^+\mu^-}} \cdot \frac{\epsilon_{B\to Xe^+e^-}}{\epsilon_{B\to X(J/\psi\to e^+e^-)}}$$

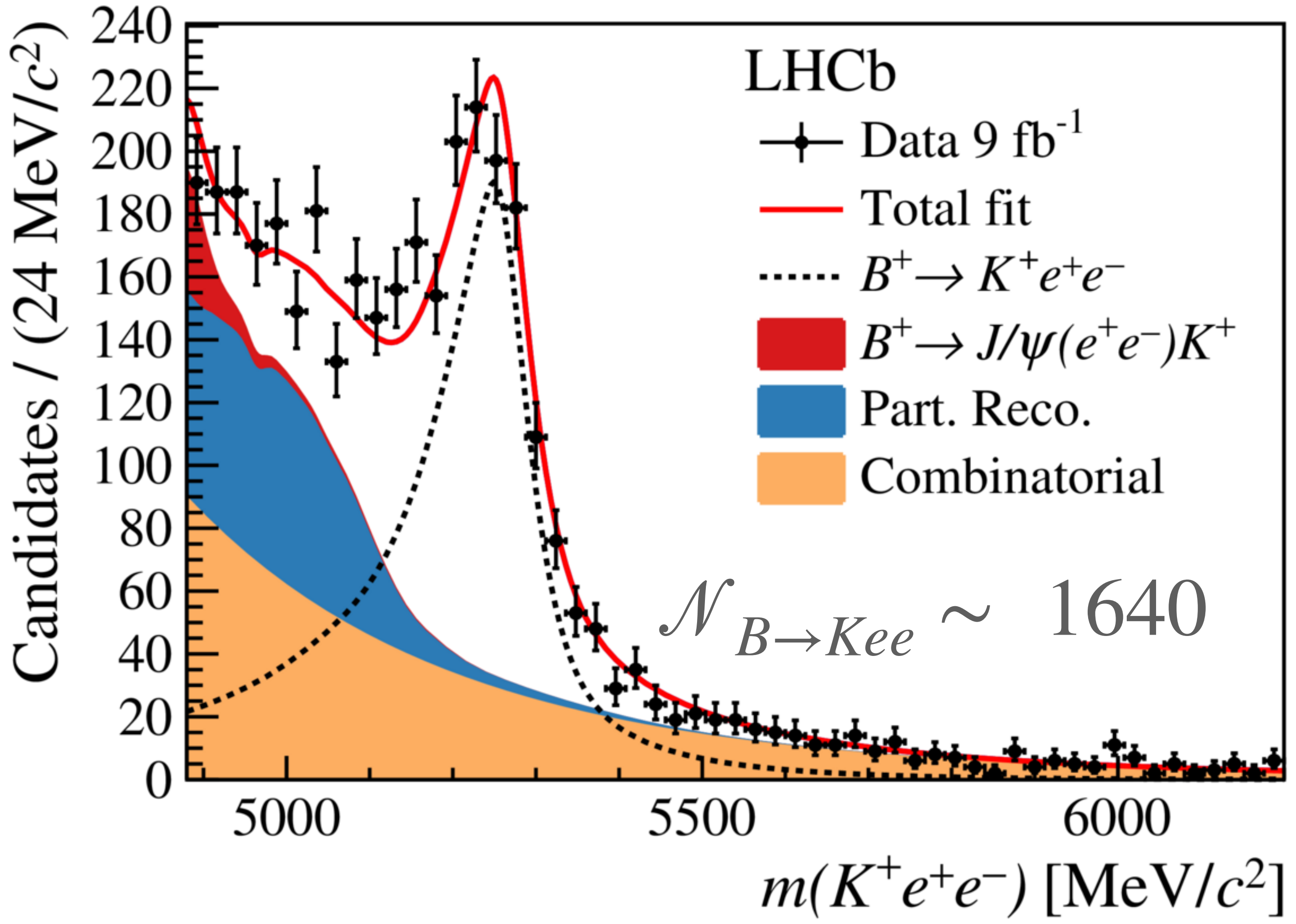
$X = K, K^*, \Lambda_b \ldots$

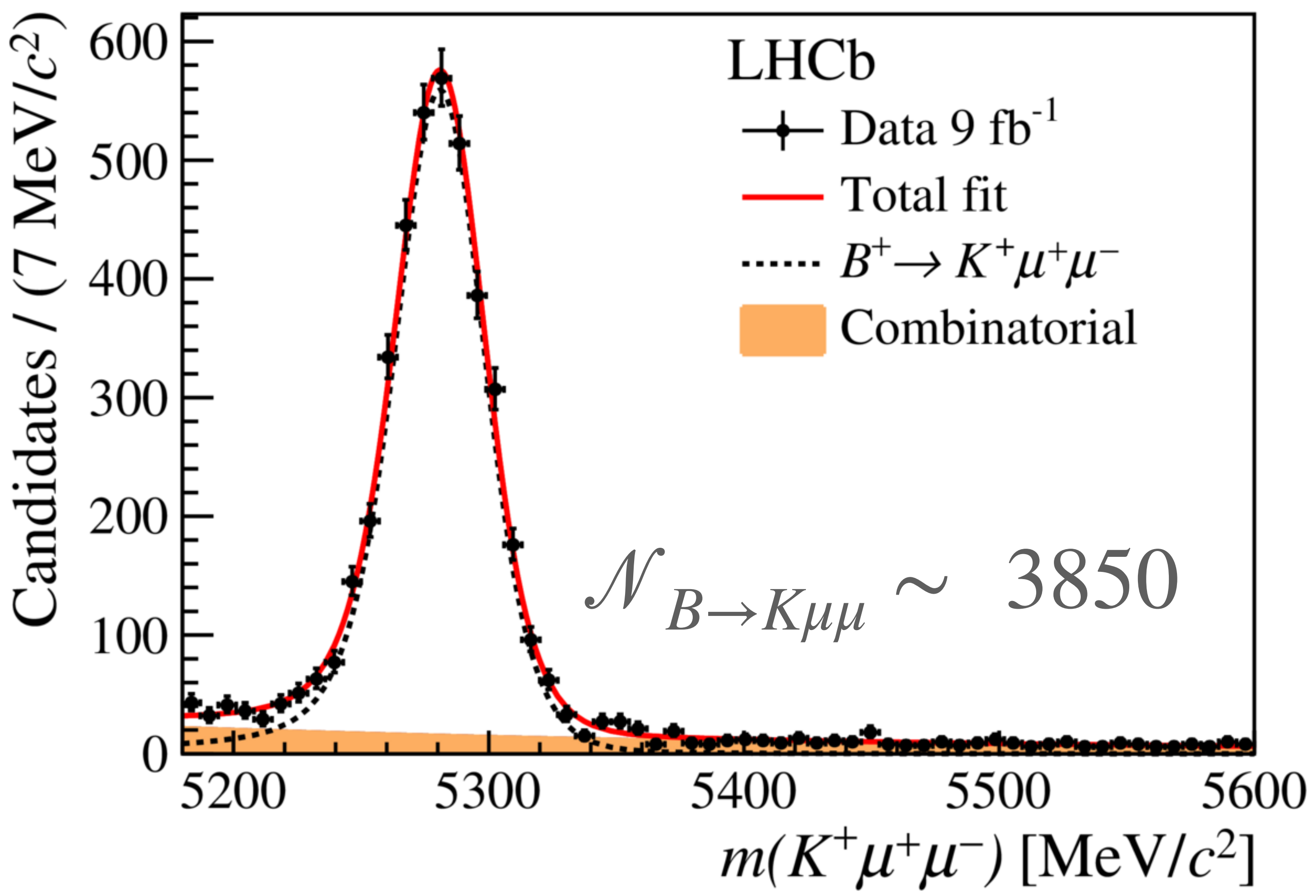


- $J/\psi \to \ell\ell$ satisfies lepton universality at 0.4% precision (PDG)
- Reduced systematics due to leptons reconstruction differences

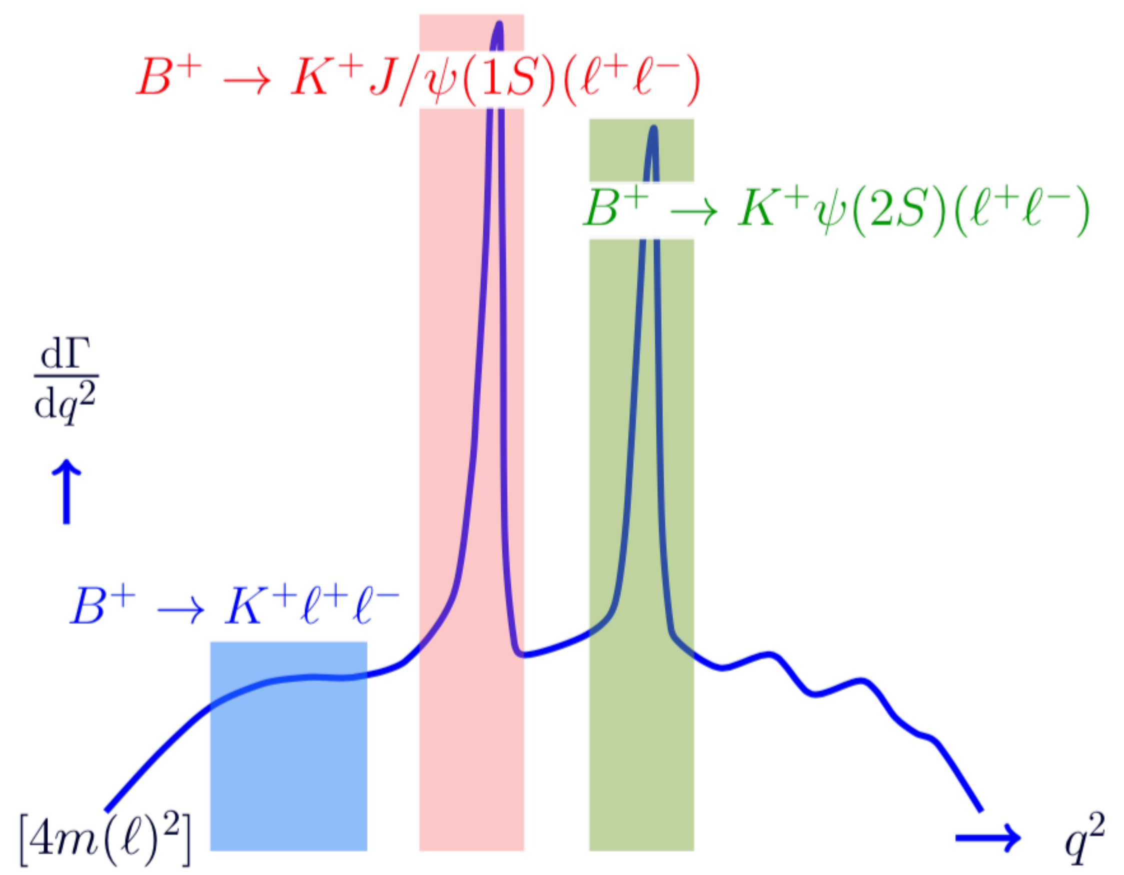
arXiv:2103.11769

- Two ingredients:
  - ▶ Double ratio of yields:
    - ❖ Fits to the invariant mass of the final state particles
  - ▶ Efficiencies of the four decay modes:
    - ❖ Computed from simulation (calibrated using data from resonant channels)





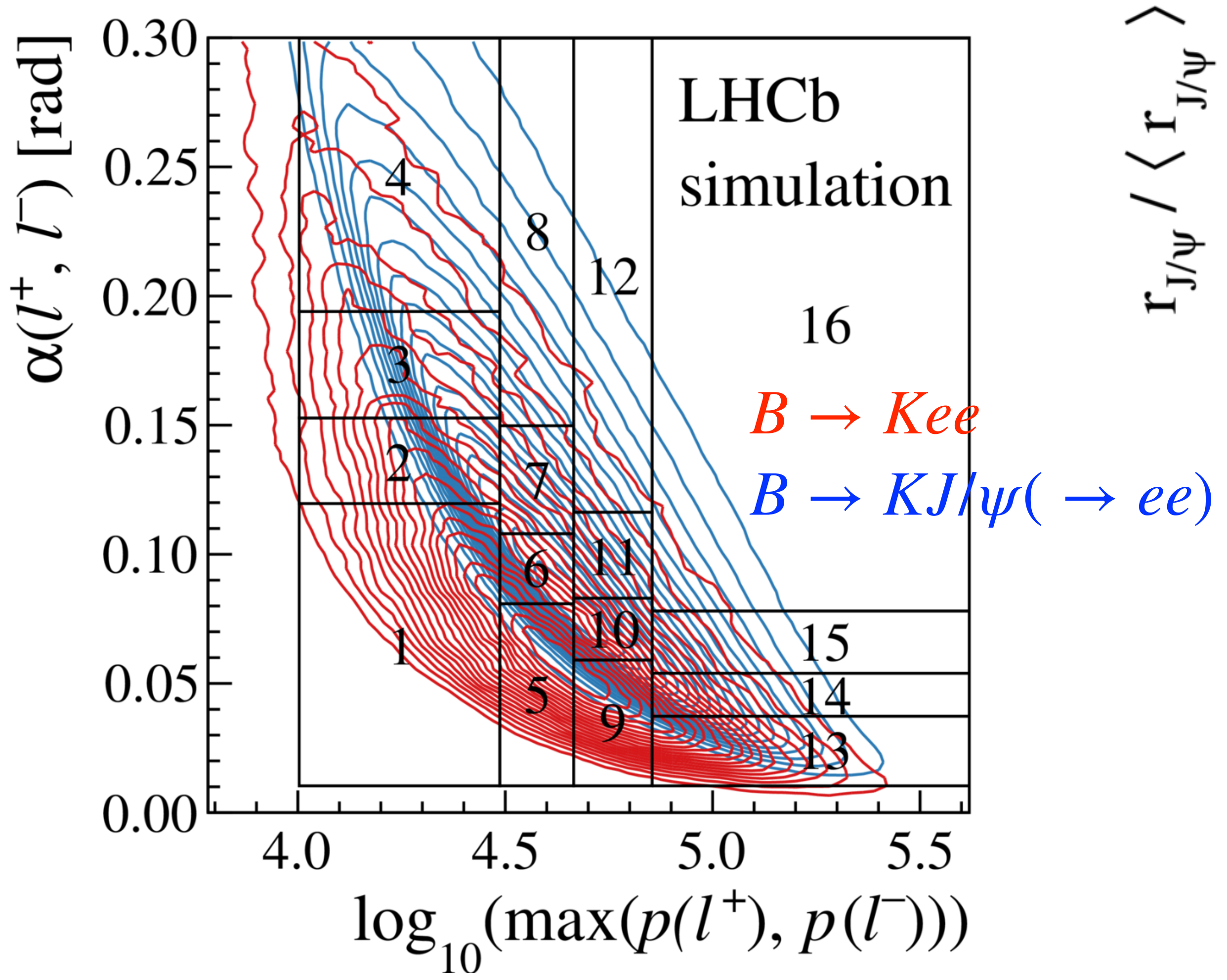
Cross-checks: $r_{J/\psi}$ and $R_{\psi(2S)}$

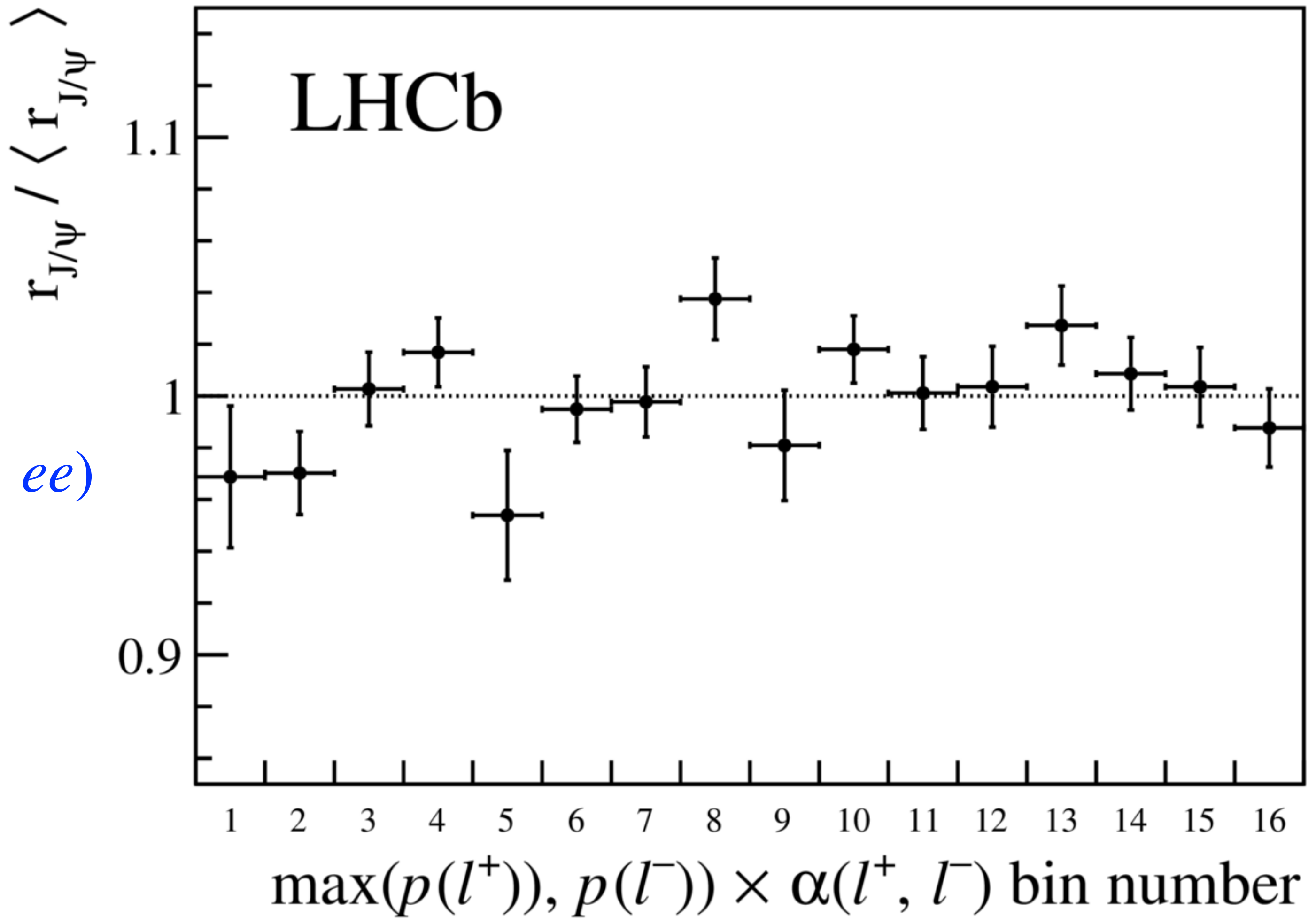


- Extensive use of $B \to X_s(J/\psi \to \ell^+\ell^-)$ and $B \to X_s(\psi(2S) \to \ell^+\ell^-)$ to check that efficiencies are under control

▶ Check: $r_{J/\psi} \equiv \dfrac{\mathcal{B}(B \to X\, J/\psi\, (\to \mu^+\mu^-))}{\mathcal{B}(B \to X\, J/\psi\, (\to e^+e^-))} \overset{\text{SM}}{=} 1$ [0.4% precision (PDG)]

+ absence of trends on any kinematics variables





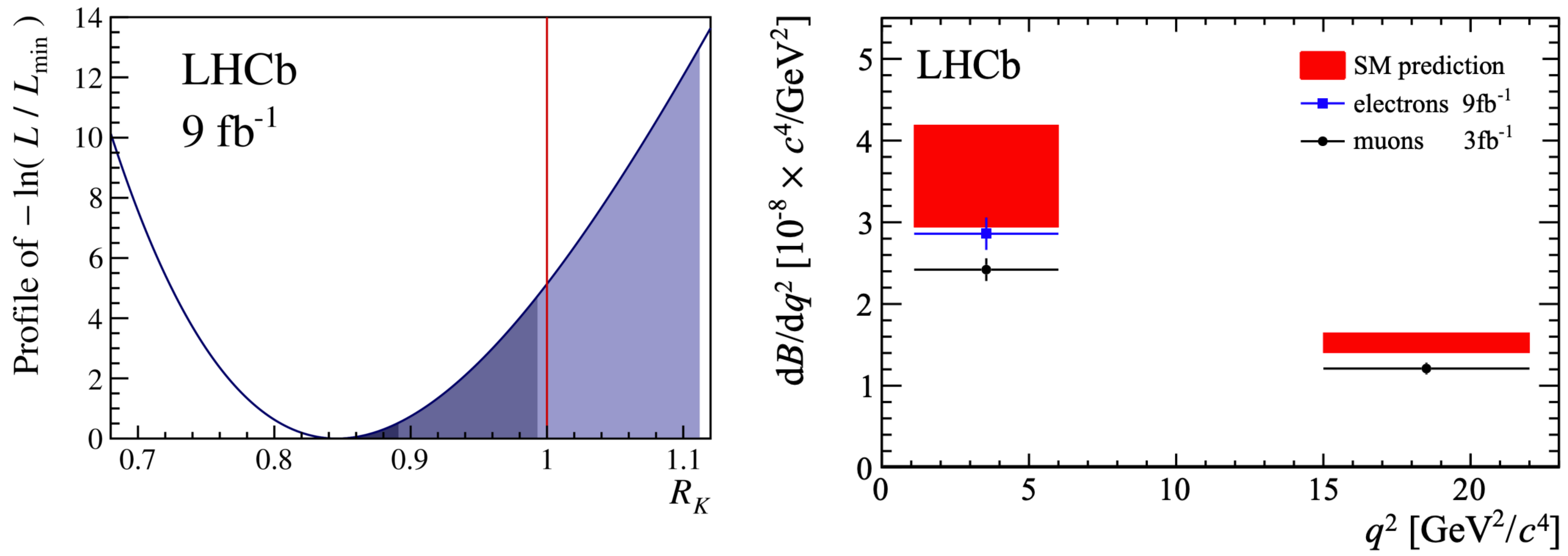
arXiv:2103.11769

▶ Check: $R_{\psi(2S)} = \dfrac{\mathcal{B}(B \to X(\psi(2S) \to \mu\mu))}{\mathcal{B}(B \to X(J/\psi \to \mu\mu))} \cdot \dfrac{\mathcal{B}(B \to X(J/\psi \to ee))}{\mathcal{B}(B \to X(\psi(2S) \to ee))} \overset{\text{SM}}{=} 1$ [~ 1% precision (PDG)]

Validation of the double ratio procedure (effective cancelation of syst uncertainties)

$b \to s\ell\ell$ ratios status

- LHCb recently updated the measurement of R_K using 9fb^{-1}
  - 3.1σ from SM: **evidence of LFU violation**
  - Electron seems to behave more SM like than muons



arXiv:2103.11769

$1.1 < m^2(\ell^+\ell^-) < 6\ \text{GeV}^2$

$$R_K = 0.846^{+0.042}_{-0.039}(\text{stat})^{+0.013}_{-0.012}(\text{sys})$$

$$r_{J/\psi} = 0.981 \pm 0.020(stat + sys)$$

$$R_{\psi(2S)} = 0.997 \pm 0.011(stat + sys)$$

- Other LFU ratio @LHCb:

JHEP 08 (2017) 055

$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07} \pm 0.03 & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2 \\ 0.69^{+0.11}_{-0.07} \pm 0.05 & \text{for } 1.1 < q^2 < 6.0\ \text{GeV}^2 \end{cases}$$

Run1: $2.1\sigma(2.4\sigma)$ from SM

JHEP 05 (2020) 040

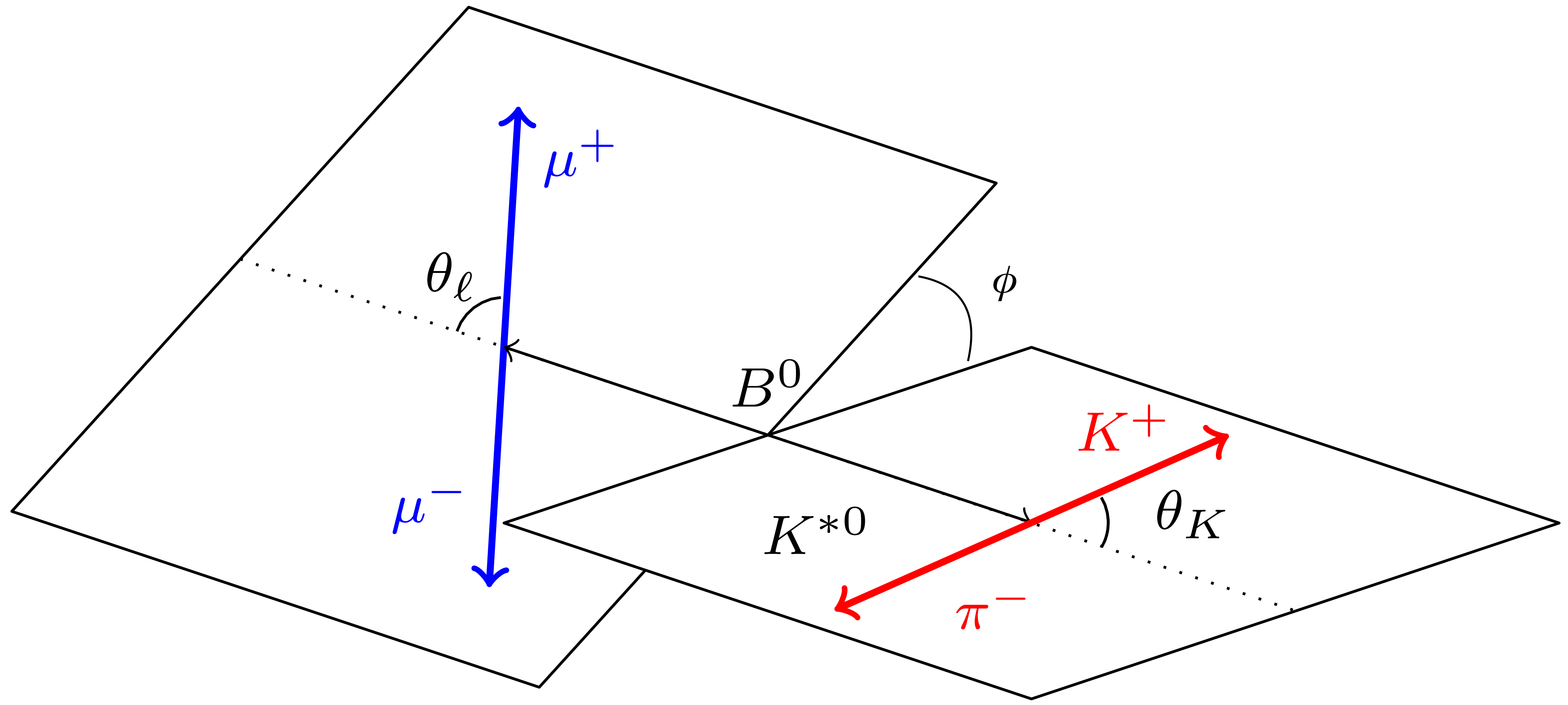
$R^{-1}_{pK} = 1.17^{+0.18}_{-0.16} \pm 0.07$ for $0.1 < m^2(\ell^+\ell^-) < 6\ \text{GeV}^2$

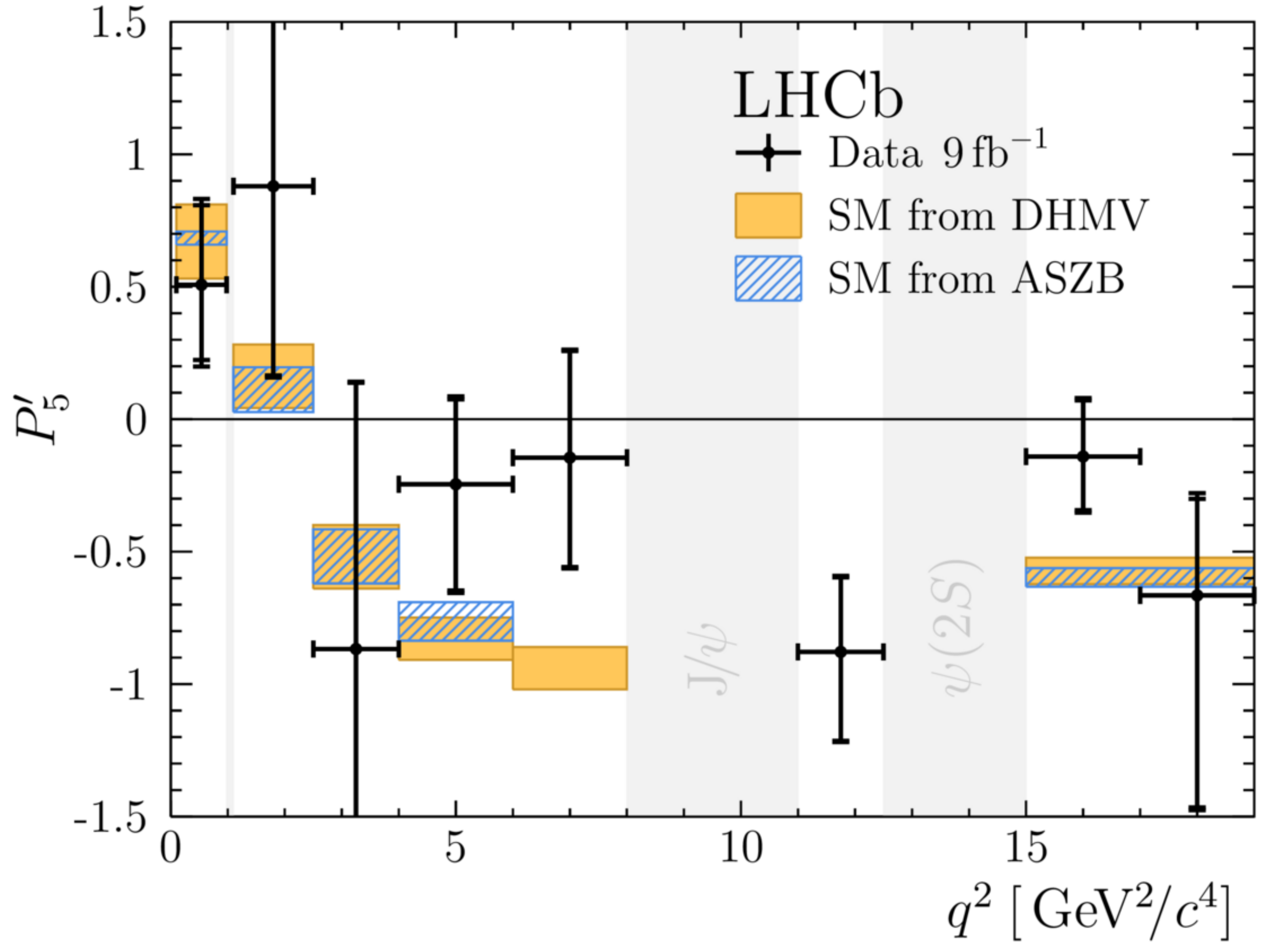
Run1 + 2016: compatible with the SM

- Near future:
  - Update of $R_{K^{*0}}$ with the full data set
  - Ratio measurements with many more decay channels: $R_{K_s}, R_\phi, R_{K\pi\pi}\dots$

$B \to K^*\mu^+\mu^-$ angular distributions

- The angular distributions of the $B \to K^*\mu^+\mu^-$ decay is described with $cos(\theta_\ell), cos(\theta_K), \phi$
- The coefficients F_L, A_{FB}, S_i are sensitive to New Physics
- New basis of P_i' operator to reduce form factors uncertainties: e.g. $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$





- Recent angular analysis of $B \to K^{*+}\mu^+\mu^-$ (9fb^{-1}) showed tension in the SM consistent with that found in $B \to K^{*0}\mu^+\mu^-$
- Global significance of 3.1σ
- Near future:
  - Angular analysis with electrons: $B \to K^*ee$, $B \to K^+ee$

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Coherent pattern?

- Also $b \to s\mu\mu$ BR are measured to be consistently lower than the SM prediction…
  - Many decays studied: $B^{0(+)} \to K^{0(+)}\mu^+\mu^-$, $B^{0(+)} \to K^{*0(+)}\mu^+\mu^-$, $B^0 \to \mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$

[JHEP 06 (2014) 133] [JHEP 04 (2017) 142] [JHEP 09 (2015) 179] [JHEP 06 (2015) 115]

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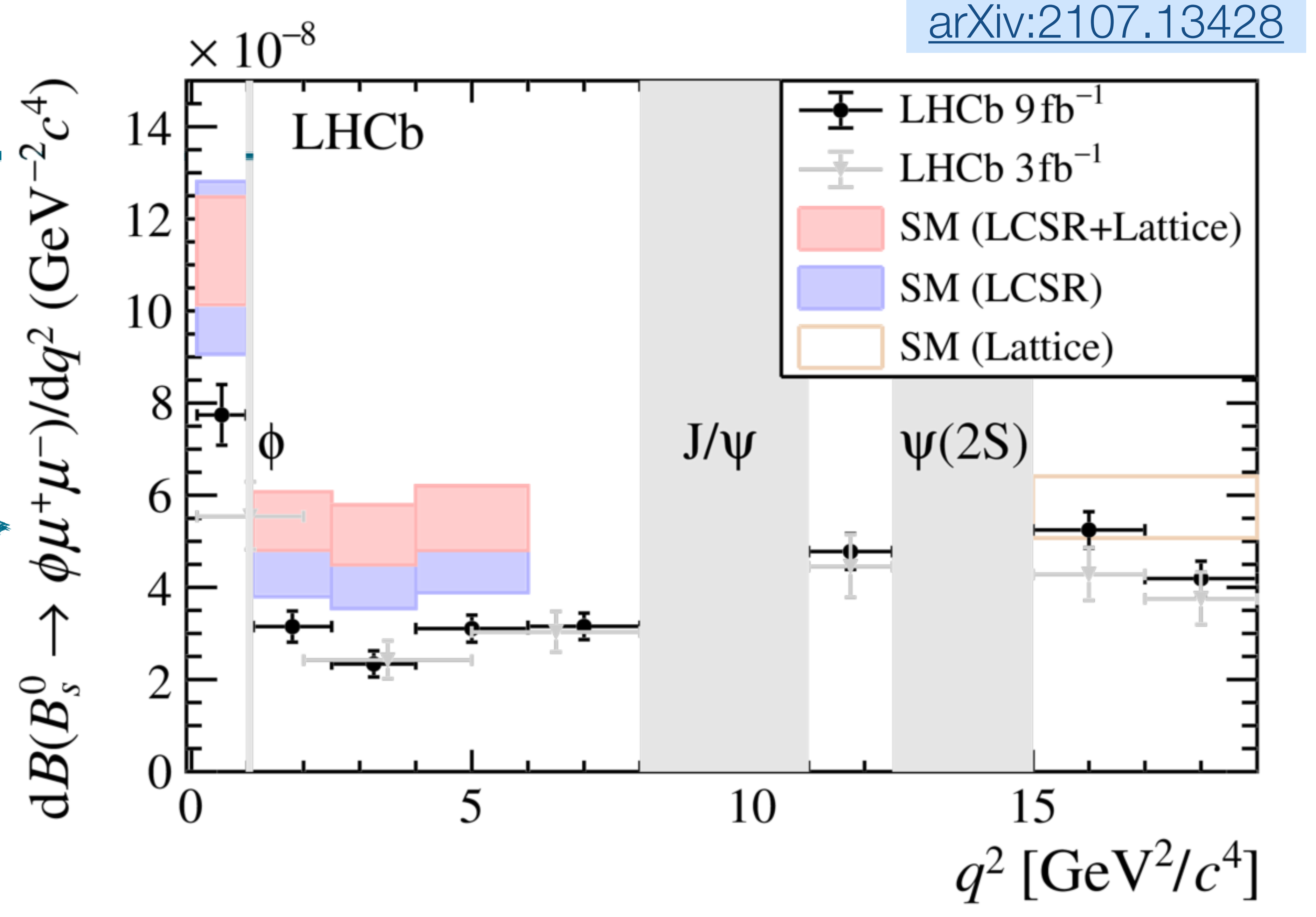
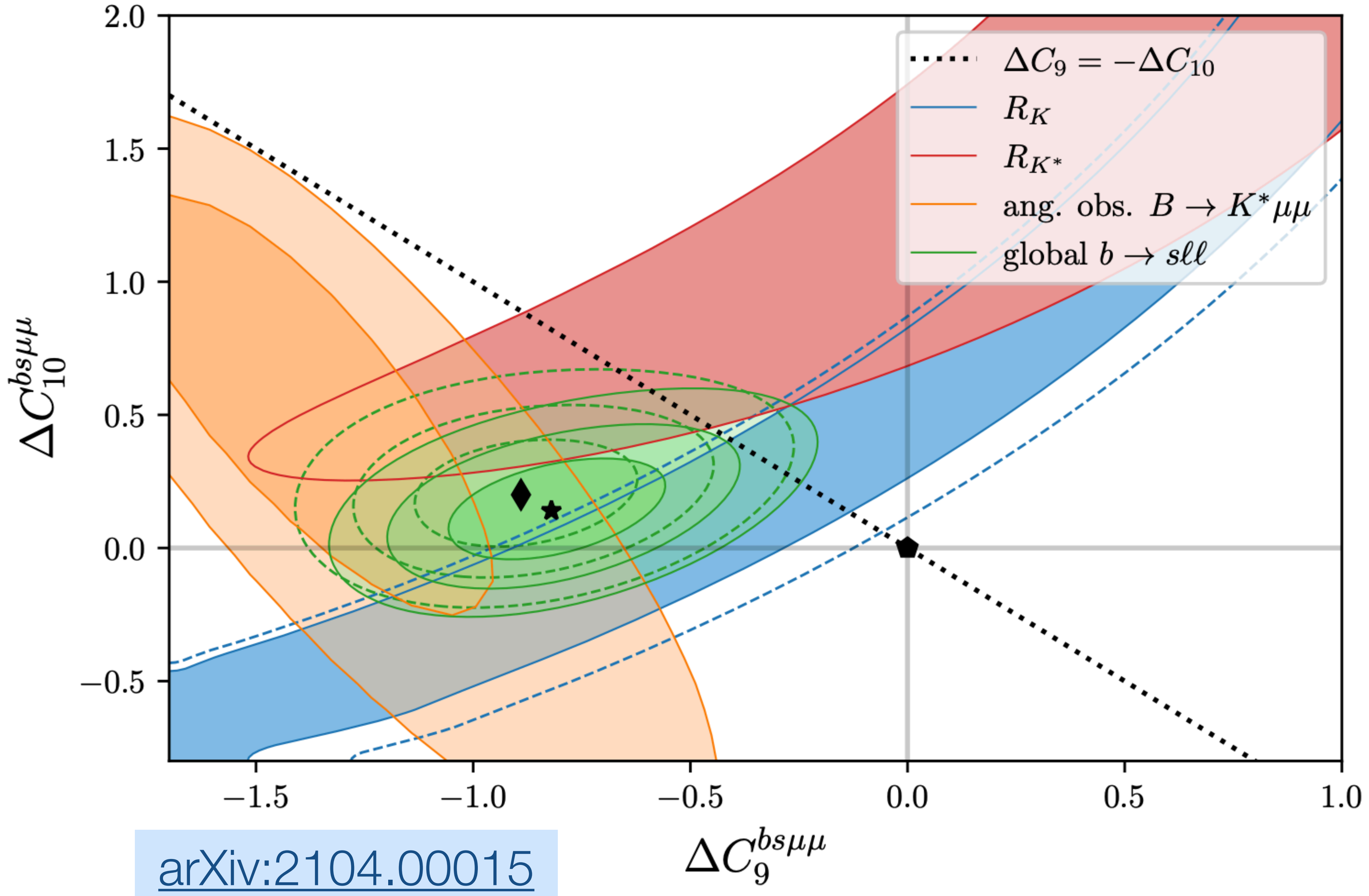


- All the anomalies are pointing to the same effects: a shift of C_9 and C_{10} Wilson coefficients
  - New physics is contributing to $b \to s\ell\ell$ process?
  - Can these effects be attributed to incorrectly estimated charm loop?
  - More measures needed (and coming) to help solving the puzzle

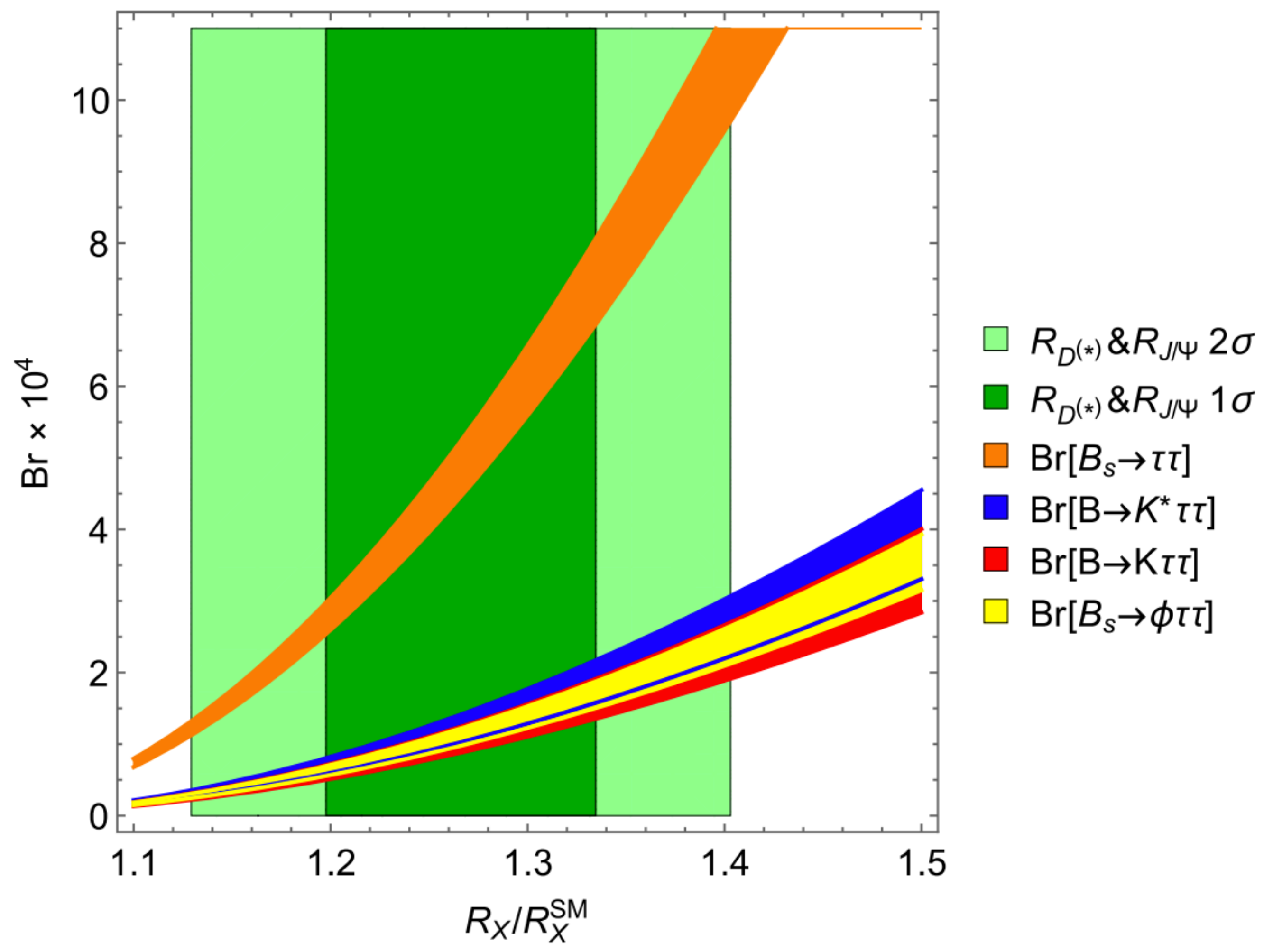


arXiv:2104.00015

Exciting times ahead!

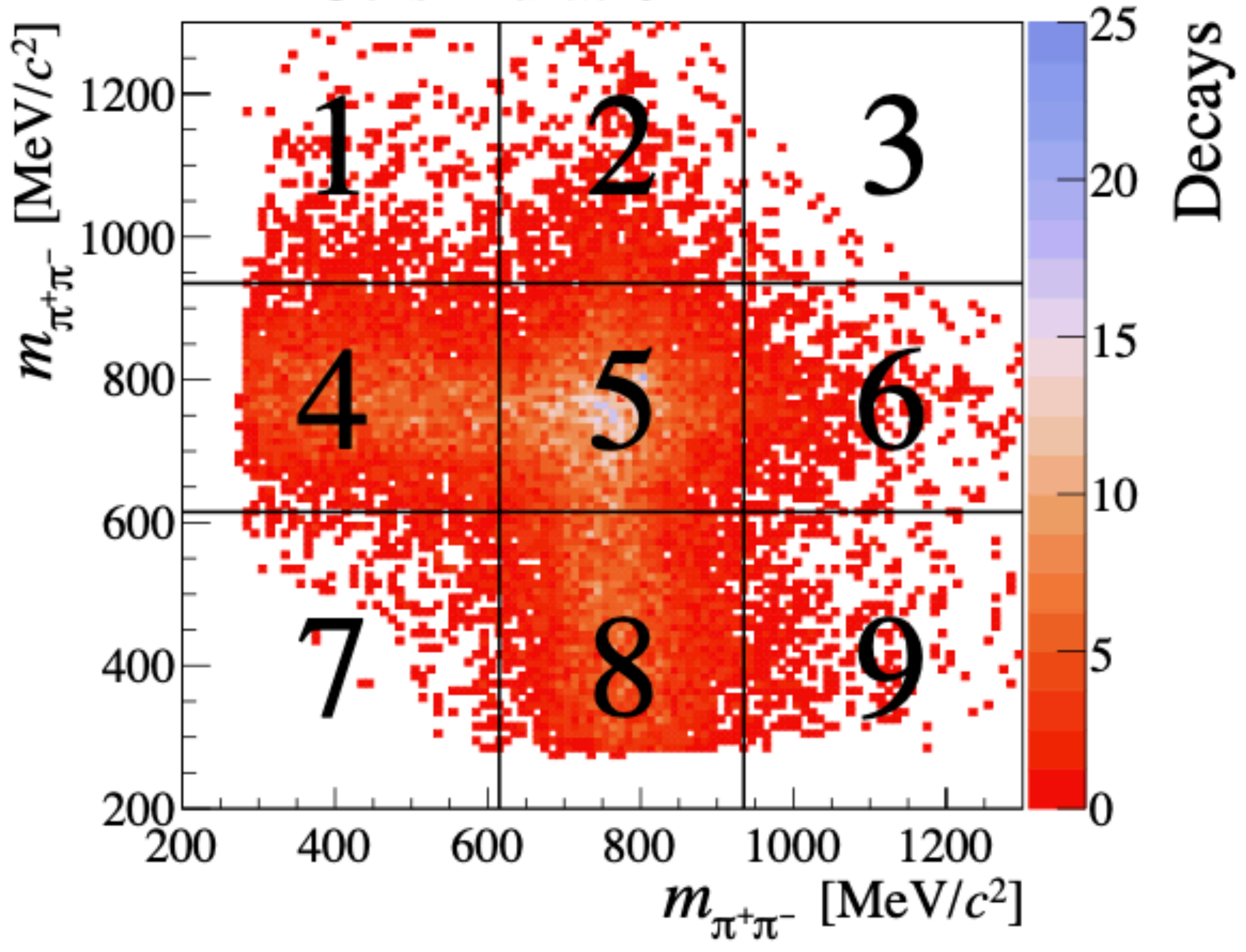
Why not $b \to s\tau^+\tau^-$?

PRL 120 (2018) 181802



- taus could be the most sensitive to NP, still largely unexplored
- More complex experimentally
  - Neutrinos in the final state, $m(\tau\tau)$ weak discriminant
  - No 4π coverage at LHCb
- Usually searched with : $\tau \to a_1(1260)^-\nu_\tau \to \rho(770)^0\pi^-\nu_\tau \to \pi^-\pi^+\pi^-\nu_\tau$
  - Study intermediate resonance forms cross-shape
- Exploit a large variety of MVA techniques
  - Isolation, selection and fit variables
- Difficult choice of control regions to model the background
  - Pseudo-Dalitz plane: define signal and background boxes

$B \to \tau\tau$



Decay	SM prediction	Limits @90% CL
$B^0 \to \tau\tau$	$(2.22 \pm 0.19) \cdot 10^{-8}$	$< 1.6 \cdot 10^{-3}$ (LHCb)
$B^0_s \to \tau\tau$	$(7.73 \pm 0.49) \cdot 10^{-7}$	$< 5.2 \cdot 10^{-3}$ (LHCb)
$B^0 \to K^{*0}\tau\tau$	$(0.98 \pm 0.10) \cdot 10^{-7}$	Ongoing
$B^+ \to K^+\tau\tau$	$(1.20 \pm 0.12) \cdot 10^{-7}$	$< 2.3 \cdot 10^{-3}$ (BaBar)

LHC + LHCb upgrades → 2x yields for fully hadronic decays!

PRL 118 (2017) 251802 PRL 118 (2017) 031802

b decays

- Precision measurement in b rare decays can be sensitive to possible New Physics contribution
  - $b \to s\ell\ell$ processes
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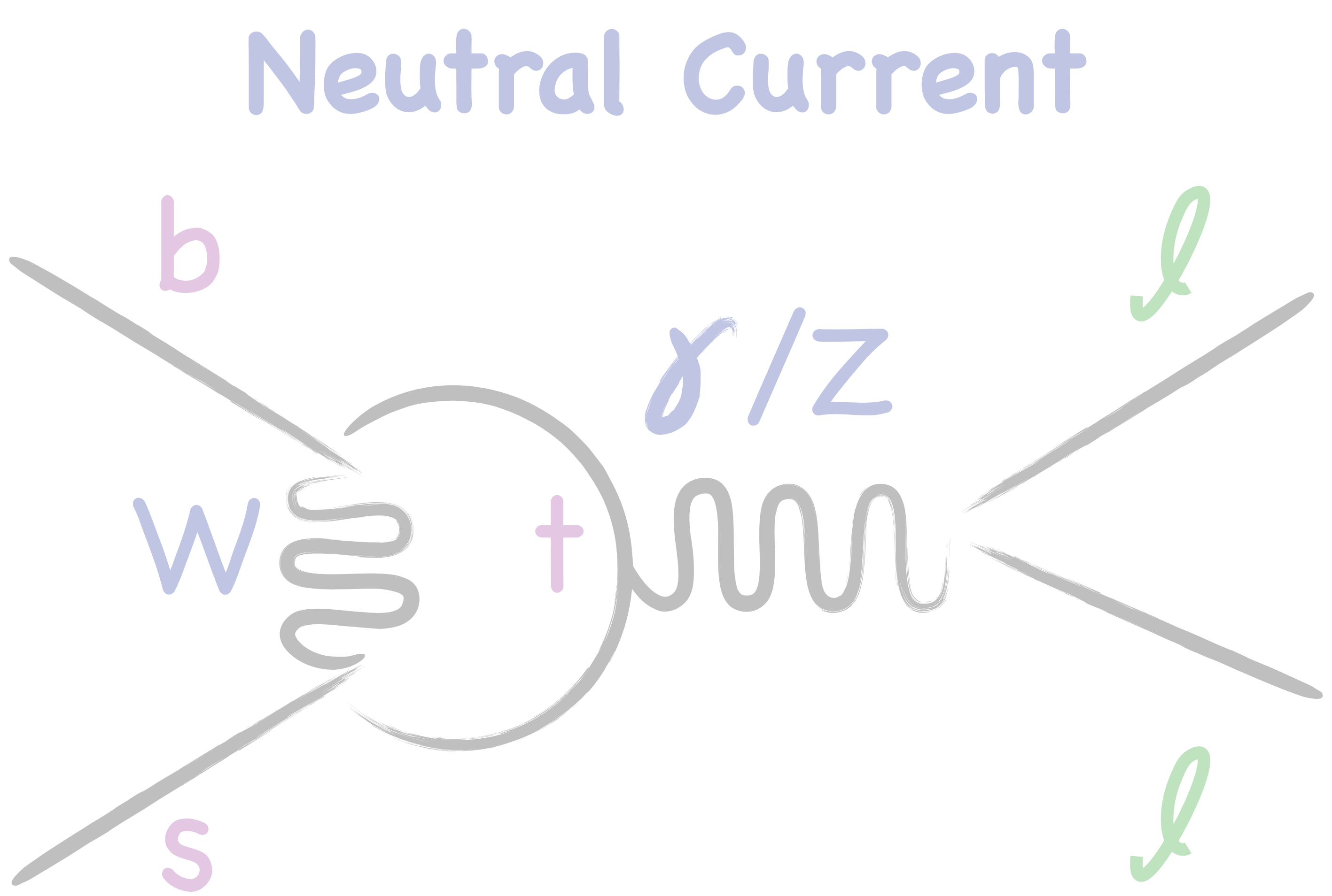
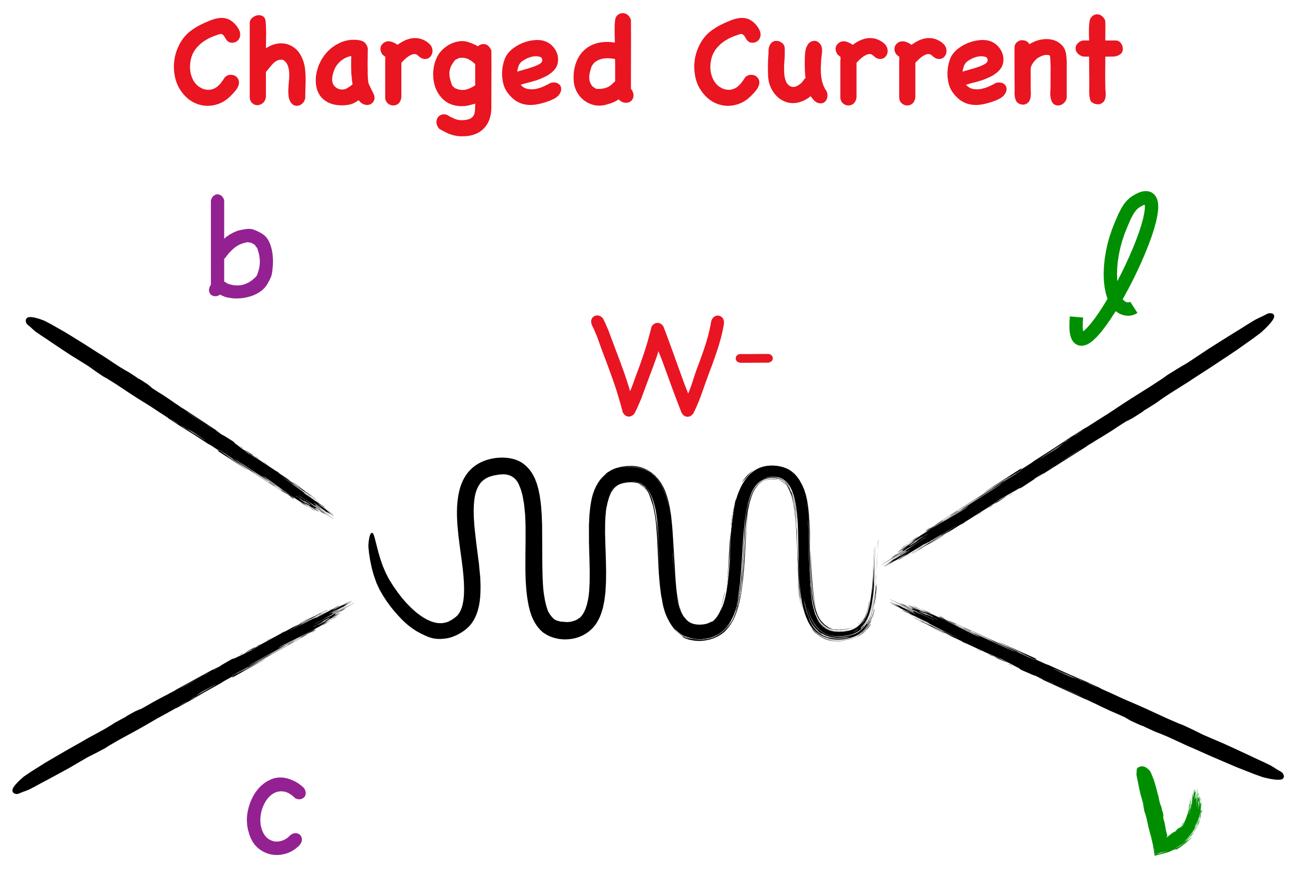


  - $b \to c\ell\bar{\nu}$ decays
    - Tree level processes: large BR (few %)
    - Clean Standard Model predictions

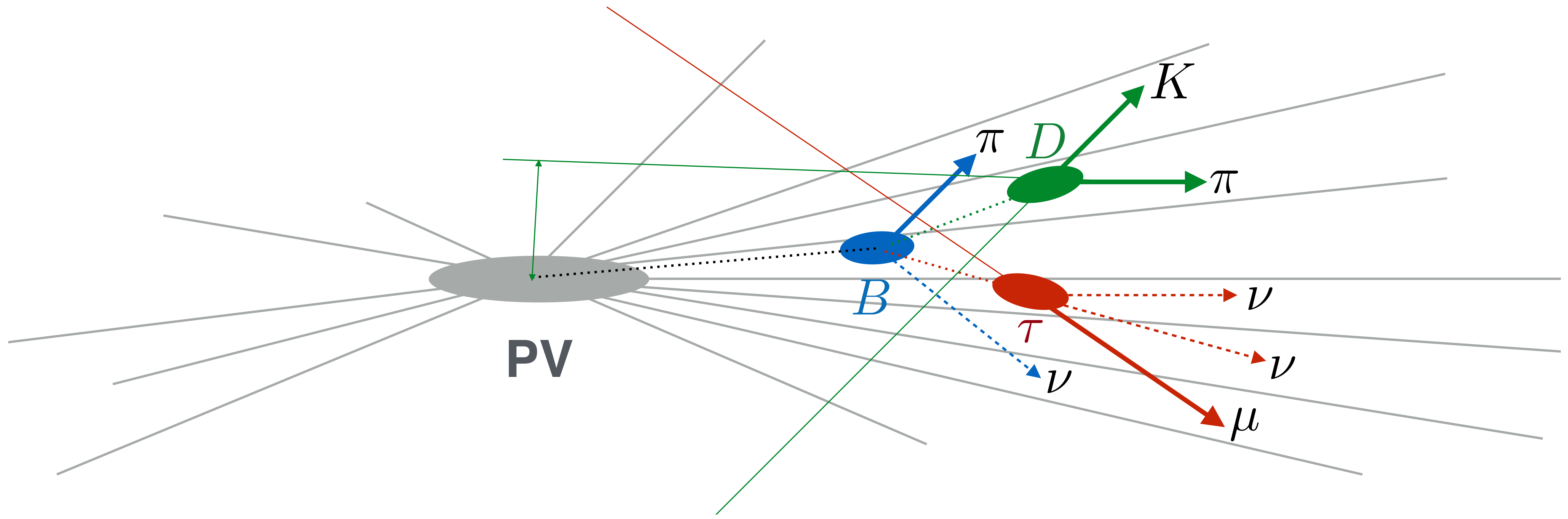


LFU with $b \to c\ell\nu$

- Observables:
  - Relative rates of $b \to c\tau^-\bar{\nu}_\tau$ versus e/μ decays, of the form:

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)} \overset{\text{SM}}{=} 0.258 \pm 0.05$$

  - clean: hadronic uncertainties and $|V_{cb}|$ cancel out

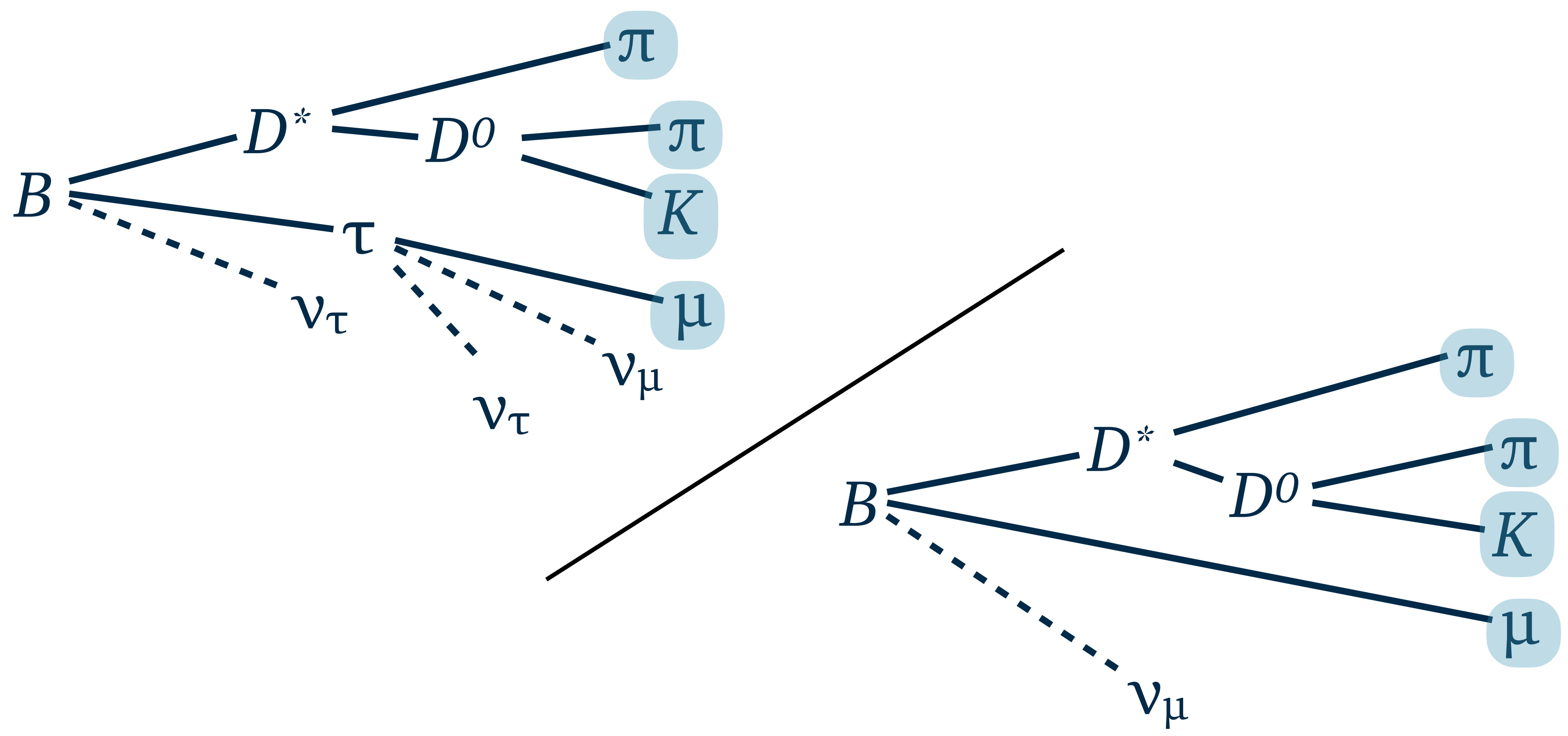


- Complicate final state due to missing energy from neutrinos
- Very busy environment, B momentum unknown
- Large statistics

R_{D^*} @LHCb

'Muonic' $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$

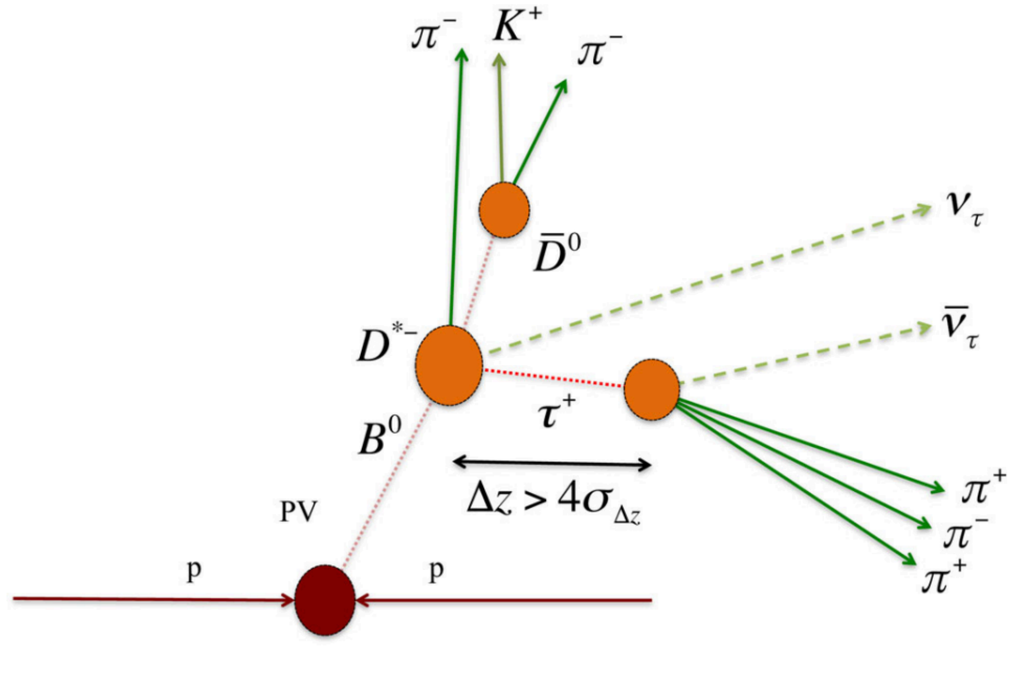
PRL 115 (2015) 111803



- Normalisation and signal channels with same visible final state
  - reduced experimental systematics

'Hadronic' $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
$\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$

PRL 120 (2018) 171802



A normalisation channel with similar final state

Measured: $K(D^{*-}) = \dfrac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}$

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

From LHCb Belle BaBar ~4%

From HFLAV ~2%

- Precise reconstruction of displaced τ vertex
- Precise B and τ line of flights reconstruction (only one ν)
- Good signal/background ratio (no semileptonic bkg)

R_{D^*} @LHCb

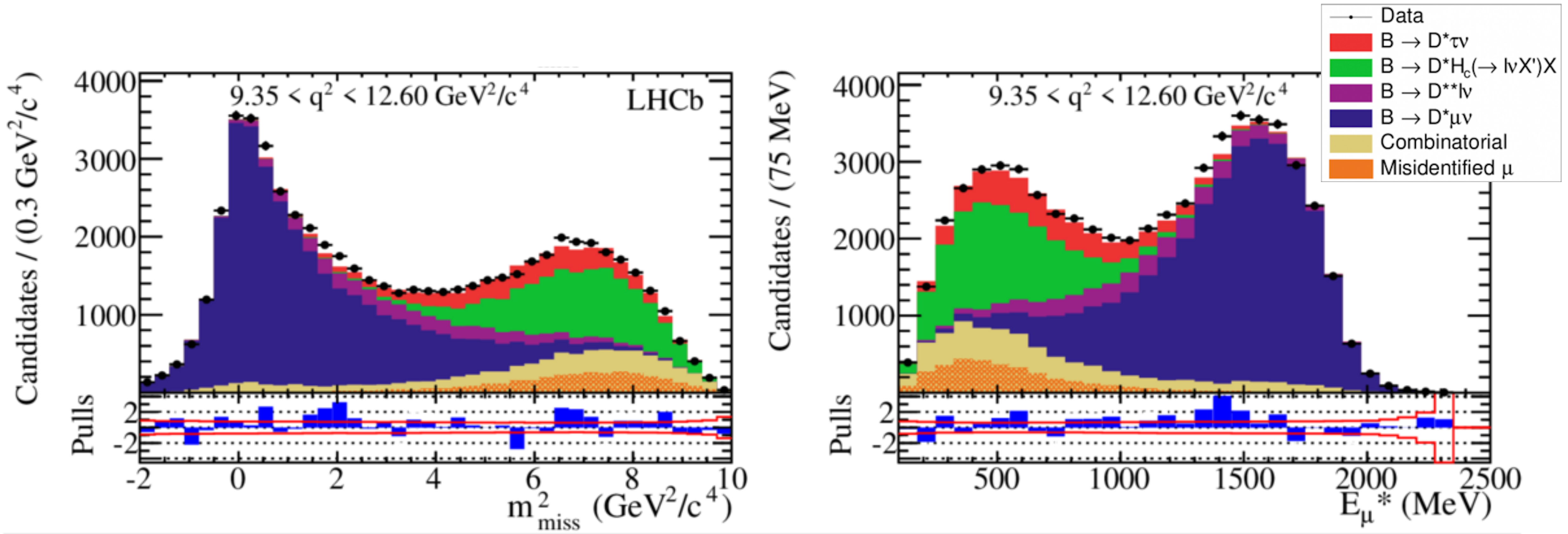
Run1 3fb^{-1}

'Muonic' $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$

PRL 115 (2015) 111803

Fit variables:

$m^2_{\text{miss}} = (p_B - p_{D^*} - p_\mu)^2$, $q^2 = (p_B - p_{D^*})^2$, E^*_μ in B rest frame



- E^*_μ spectrum softer when μ comes from the τ decay
- $m^2_{\text{miss}} = 0$ in $B \to D^* \mu \nu_\mu$

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

2.1σ **above than SM**

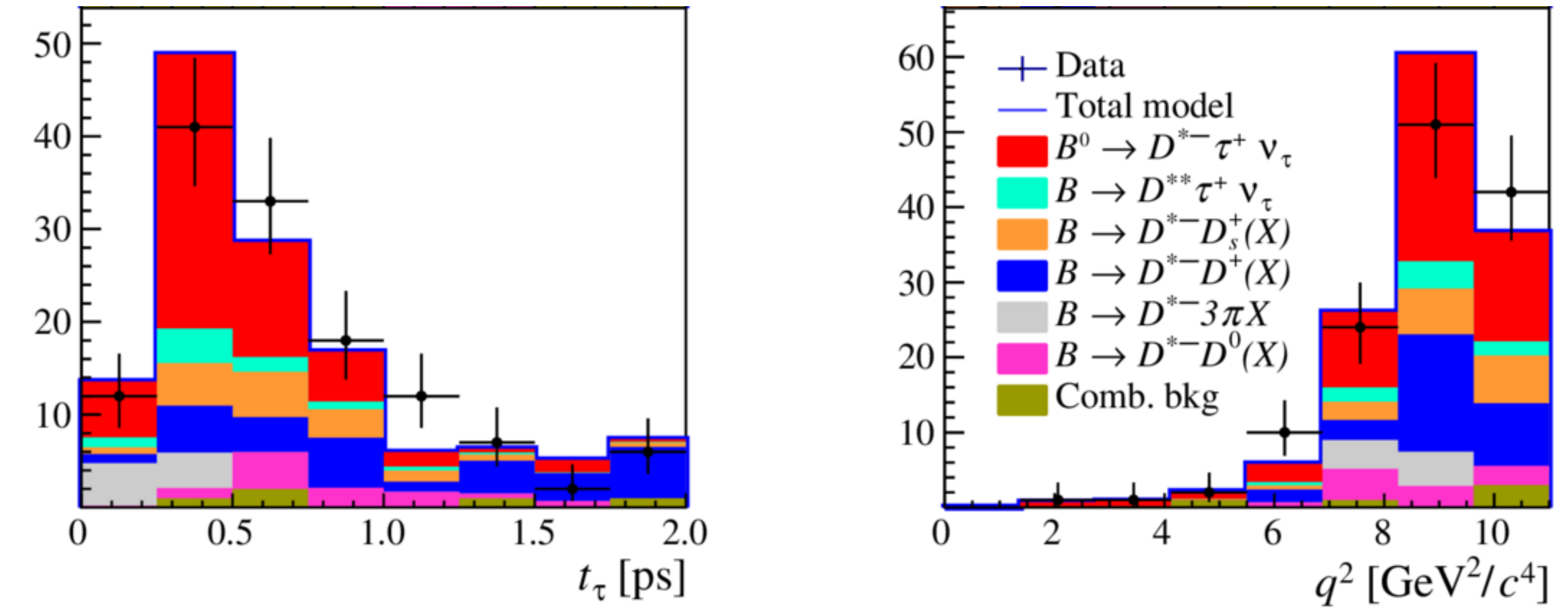
'Hadronic' $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$, $\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$

PRL 120 (2018) 171802

Fit variables:

$\text{BDT}_{\text{output}}$, $q^2 = (p_B - p_{D^*})^2$, t_τ τ decay time

Projections in the bin with the hardest $\text{BDT}_{\text{output}}$



$$\mathcal{R}(D^*) = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$$

$\sim 1\sigma$ **above the SM**

$R_{J/\psi}$ @LHCb

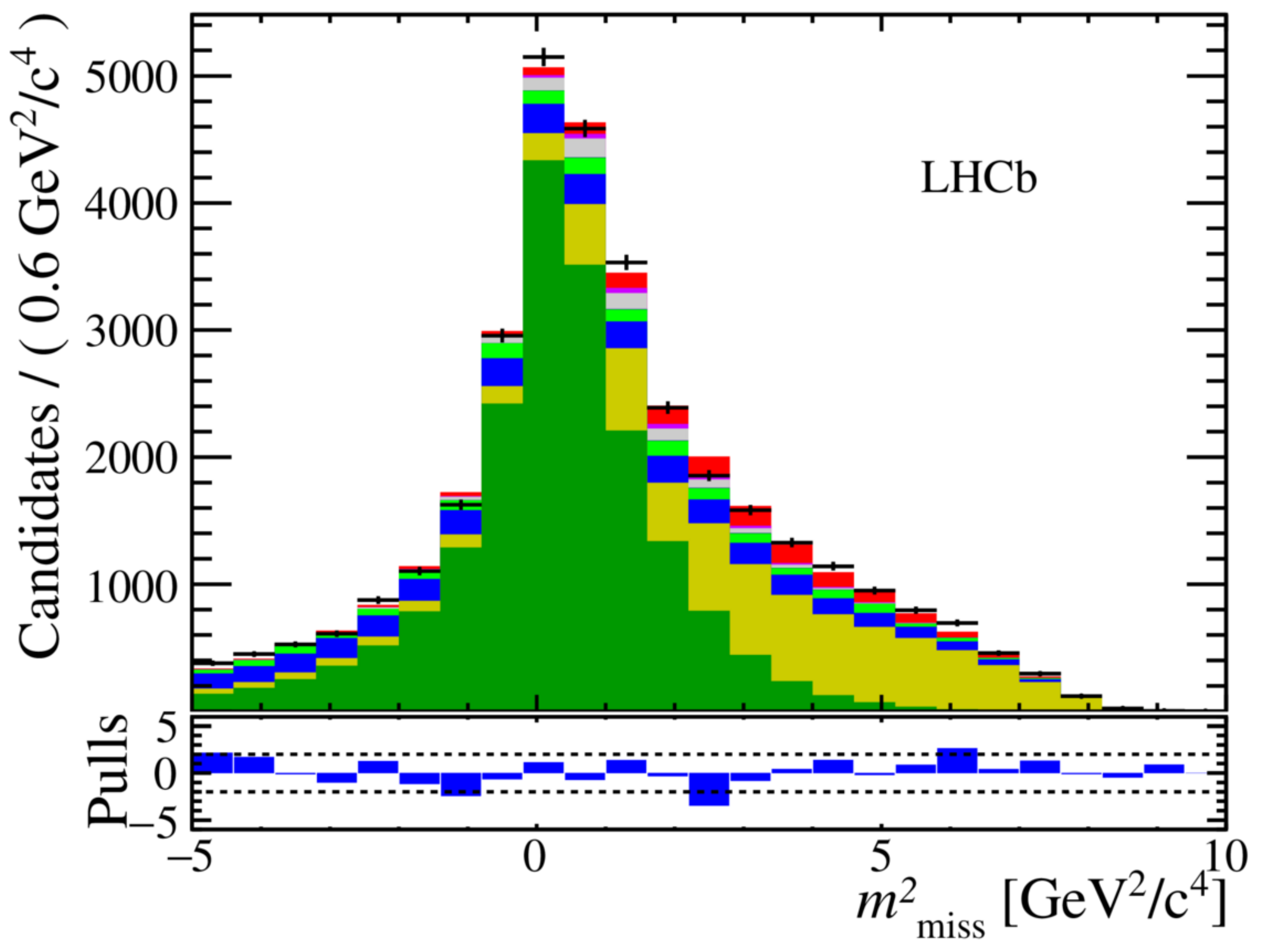
PRL 120 (2017) 121801

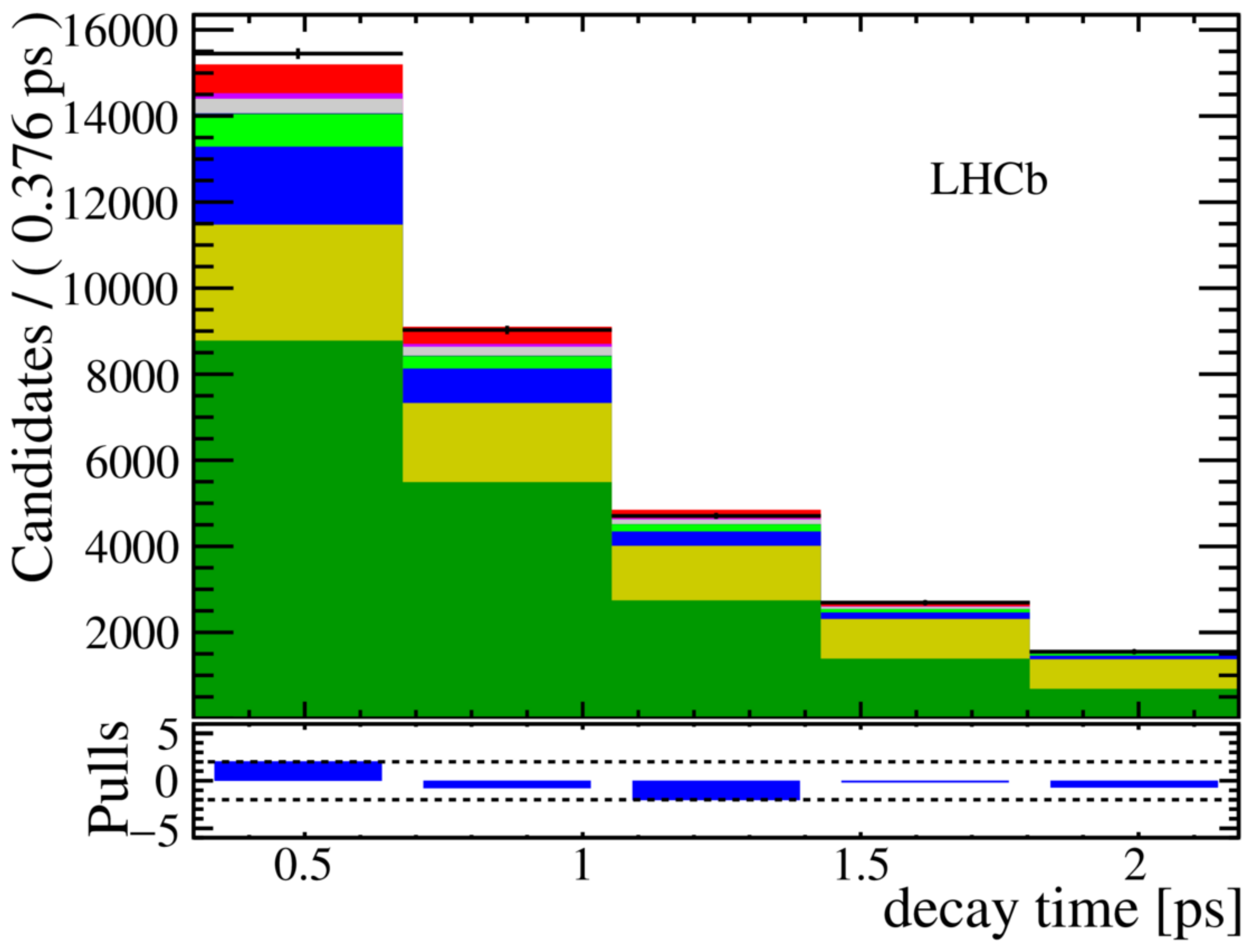
Run1 3fb^{-1}

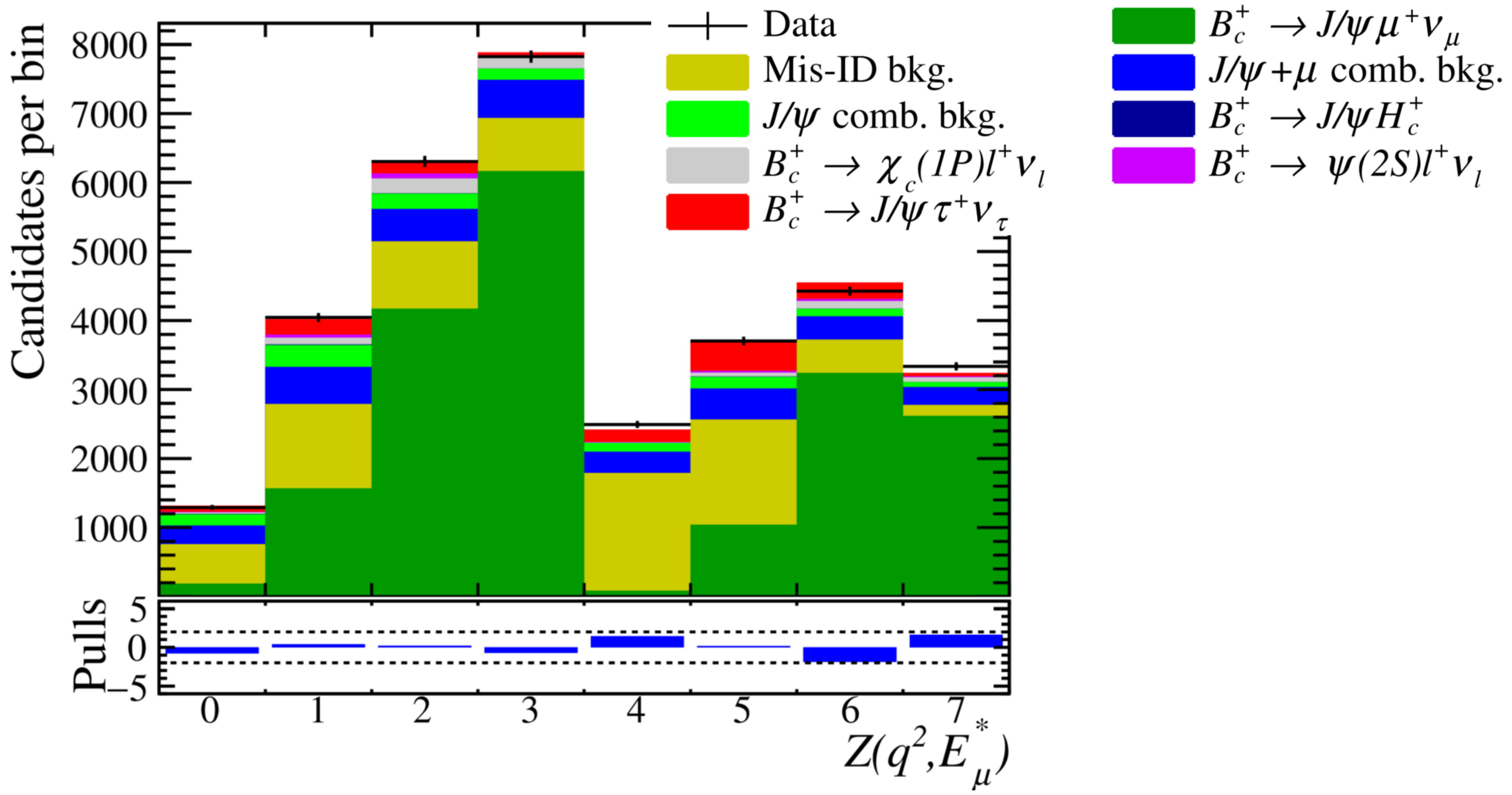
- LFU test with different spectator quark $R_{J/\psi} = \frac{\mathcal{B}(B_c \to J/\psi\tau\nu)}{\mathcal{B}(B_c \to J/\psi\mu\nu)}^{\text{SM}} = [0.25, 0.28]$

Interval due to the choice of the model for form factors

- τ reconstructed via 'muonic' mode: $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$
- Fit variables: $m^2_{\text{miss}} = (p_{B_c} - p_{J/\psi} - p_\mu)^2$, $q^2 = (p_{B_c} - p_{J/\psi})^2$, E^*_μ in B rest frame, decay time of the B_c





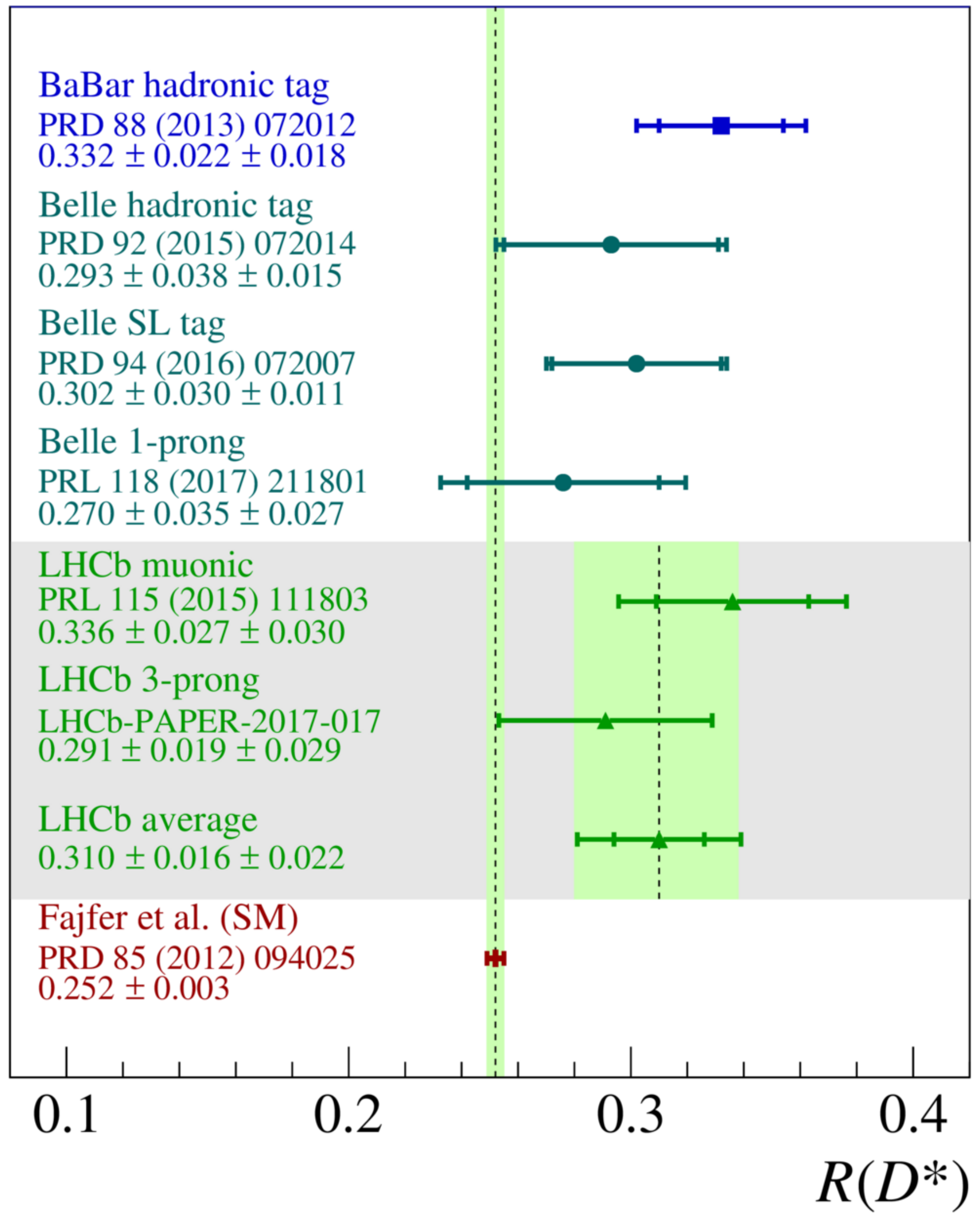


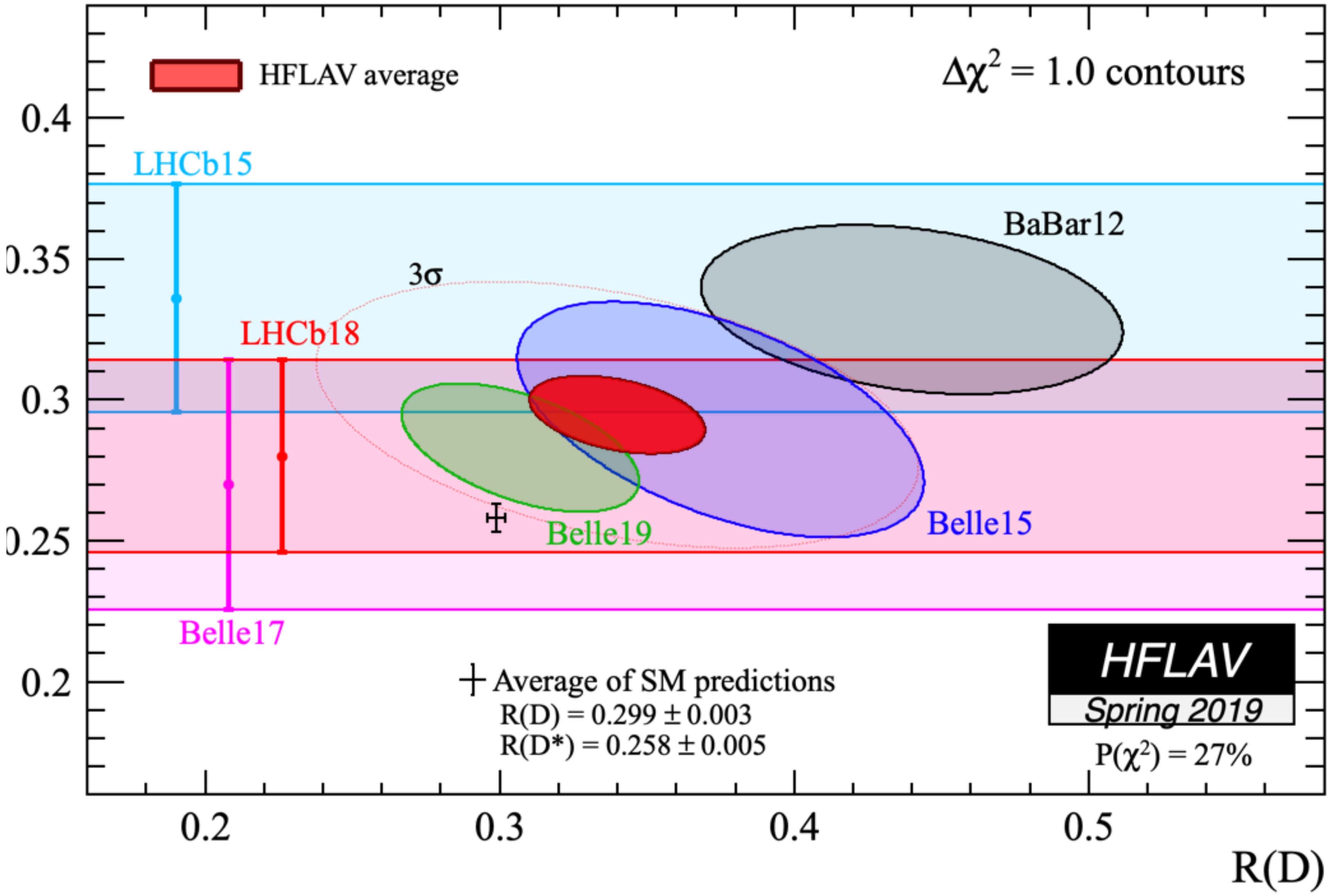
$$R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$$

2σ **above the SM**

Status of LFU $b \to c\ell\nu$ @LHCb

- The combination of R_D and R_{D*} measured from LHCb, Belle and BaBar shows a 3σ tensions with the SM





- Near future:
  - Update measurements with $\mathrm{Run2}$ data ($3.5 \times B$ meson + better trigger efficiency)
  - Simultaneous measurements of R_{D*} & R_{D^0} and R_{D*} & R_{D^+}
  - Exploring other channels: R_{Λ_c}, R_{D_s} … as well as angular observables
  - Add latest theory inputs from form factors

LFU and LFV

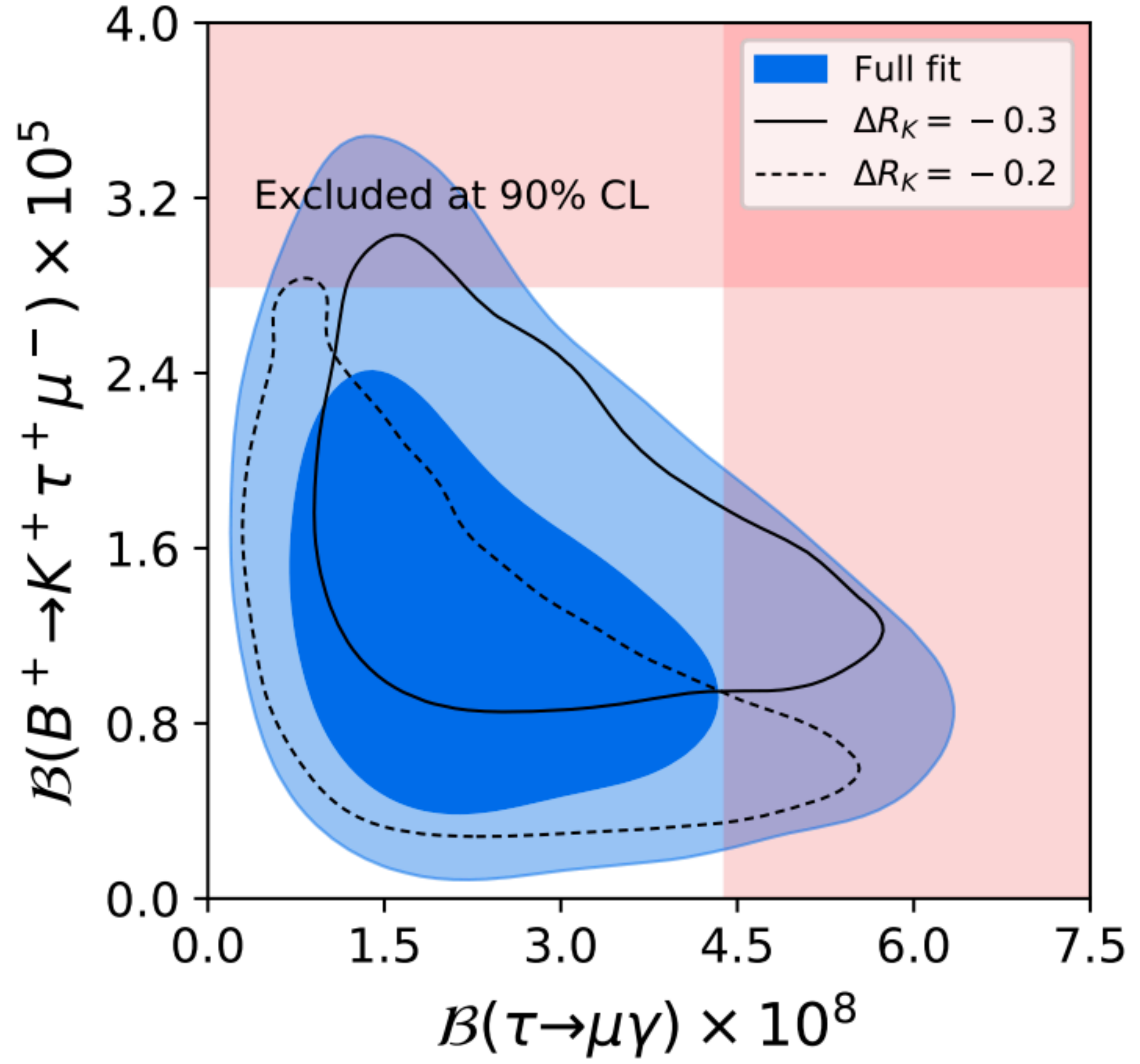
- LFU anomalies observed in $b \to s\ell\ell$ and $b \to c\ell\nu$ decays renew the interests for LFV
  - LFUV generally implies LFV
- Same models (e.g. Leptoquark) can explain both LFU ratios and lead to sizeable LFV:

$$\mathcal{B}(B \to K\mu^{\pm}\tau^{\mp}) \simeq 2 \cdot 10^{-8} \left(\frac{1 - R_K}{0.23}\right)^2$$

arXiv 1503.01084

- Measures of rates for such decays can help to constrain Beyond Standard Model theories
  - NP predicted rates accessible to current experimental reach

arXiv 1805.09328



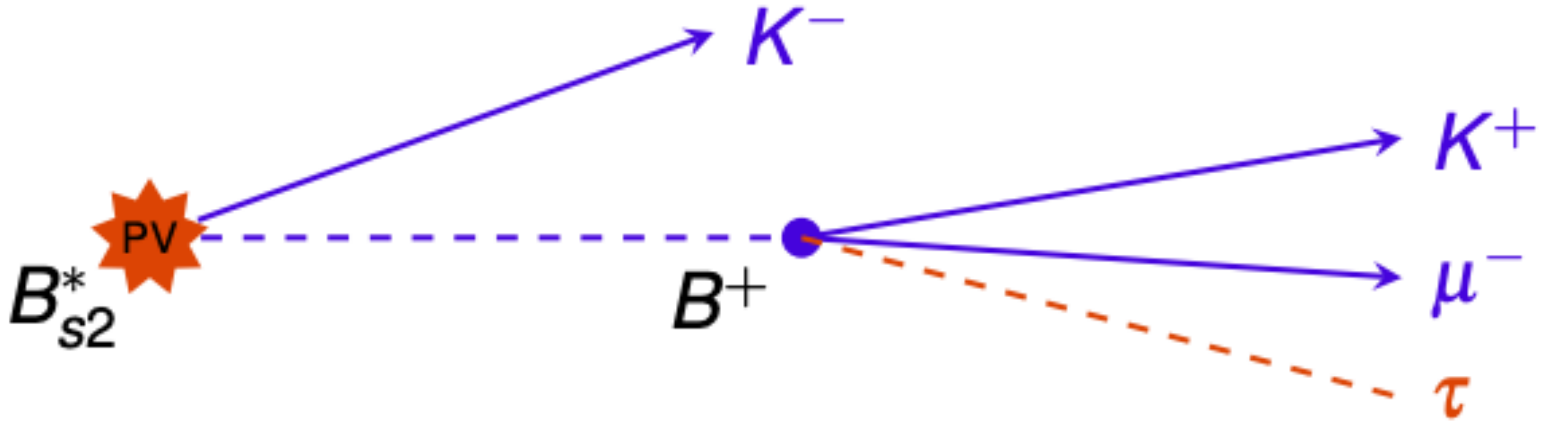
LFV with taus

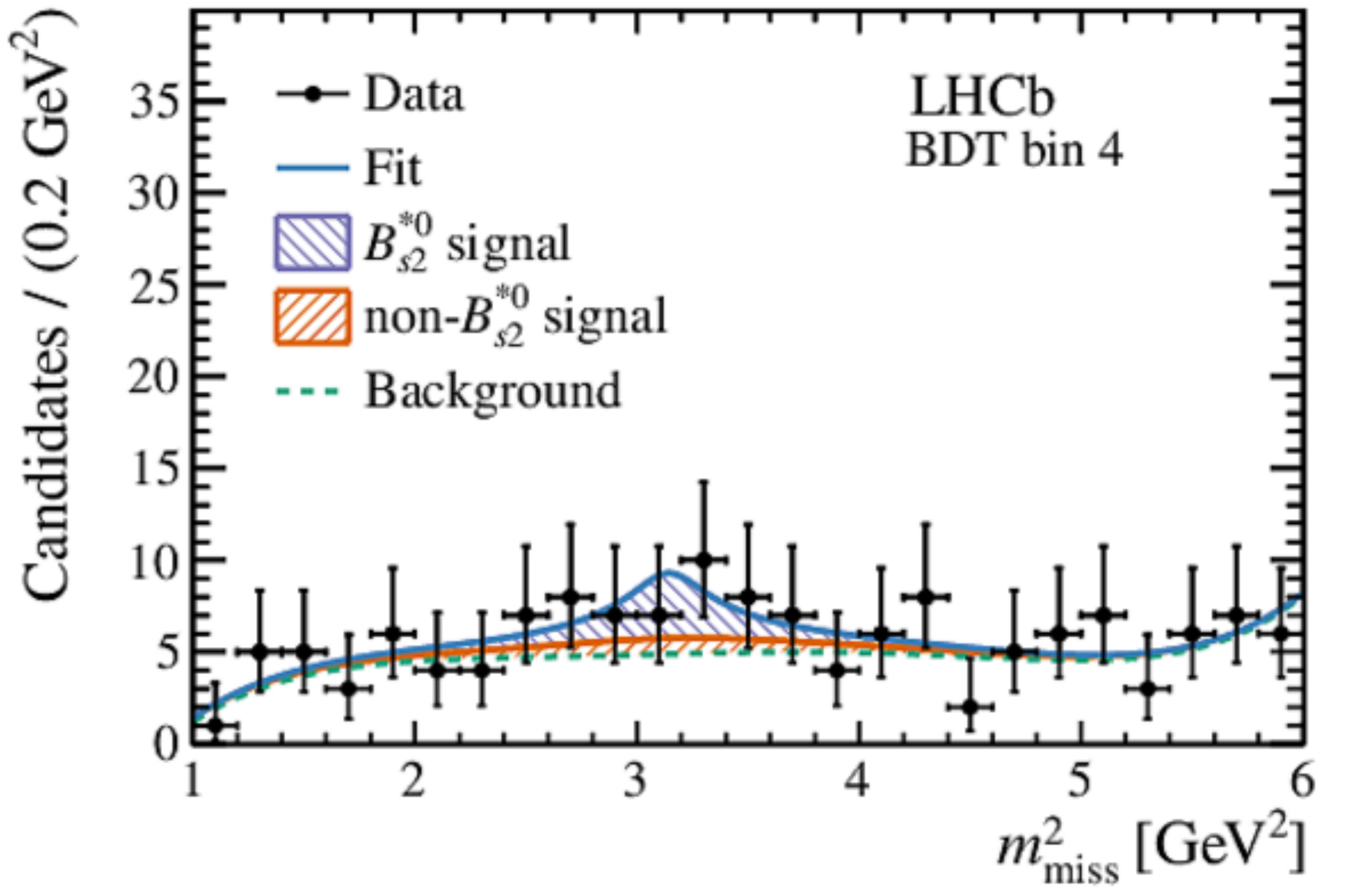
JHEP 06 (2020) 129

Run1+2 9fb^{-1}

$B^+ \to K^+\mu^-\tau^+$

- Use $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$
- New technique for τ reconstruction: use B^+ from B_{s2}^{*0}
  - B^+ flight direction and energy from mass constrains and PV and $K^+\mu^-$ vertex info
  - K^- momenta (two-fold ambiguity)
  - Resolve the ambiguity requiring missing energy > τ track energy (75% of confidence)
- BDT against combinatorial background
  - Control sample adding a prompt kaon of the same sign as the one in the $K^+\mu^-$ pair (SSK)
- Fit to the missing mass distribution in BDT bins





$$\mathcal{B}(B^+ \to K^+\mu^-\tau^+) < 4.5 \times 10^{-5} \text{ at } 95\% \text{ CL}$$

Comparable with the world-best limit

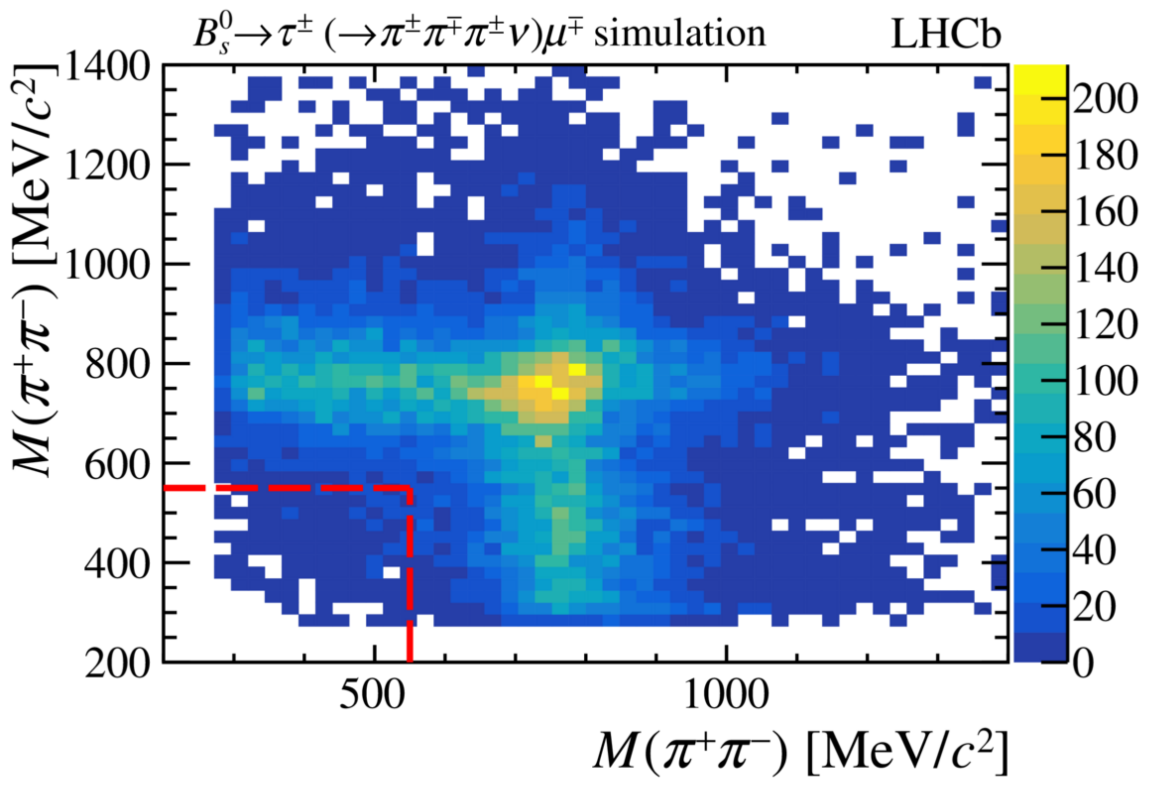
LFV with taus

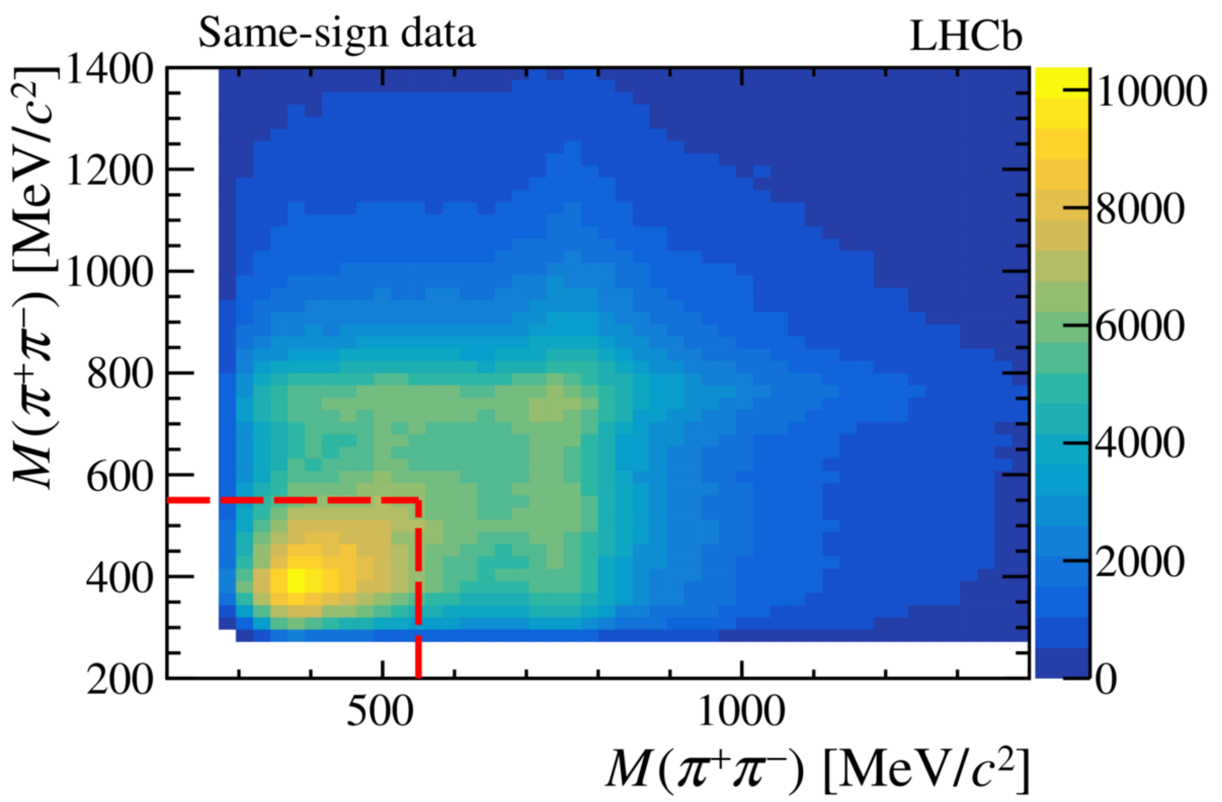
PRL 123 (2019) 211801

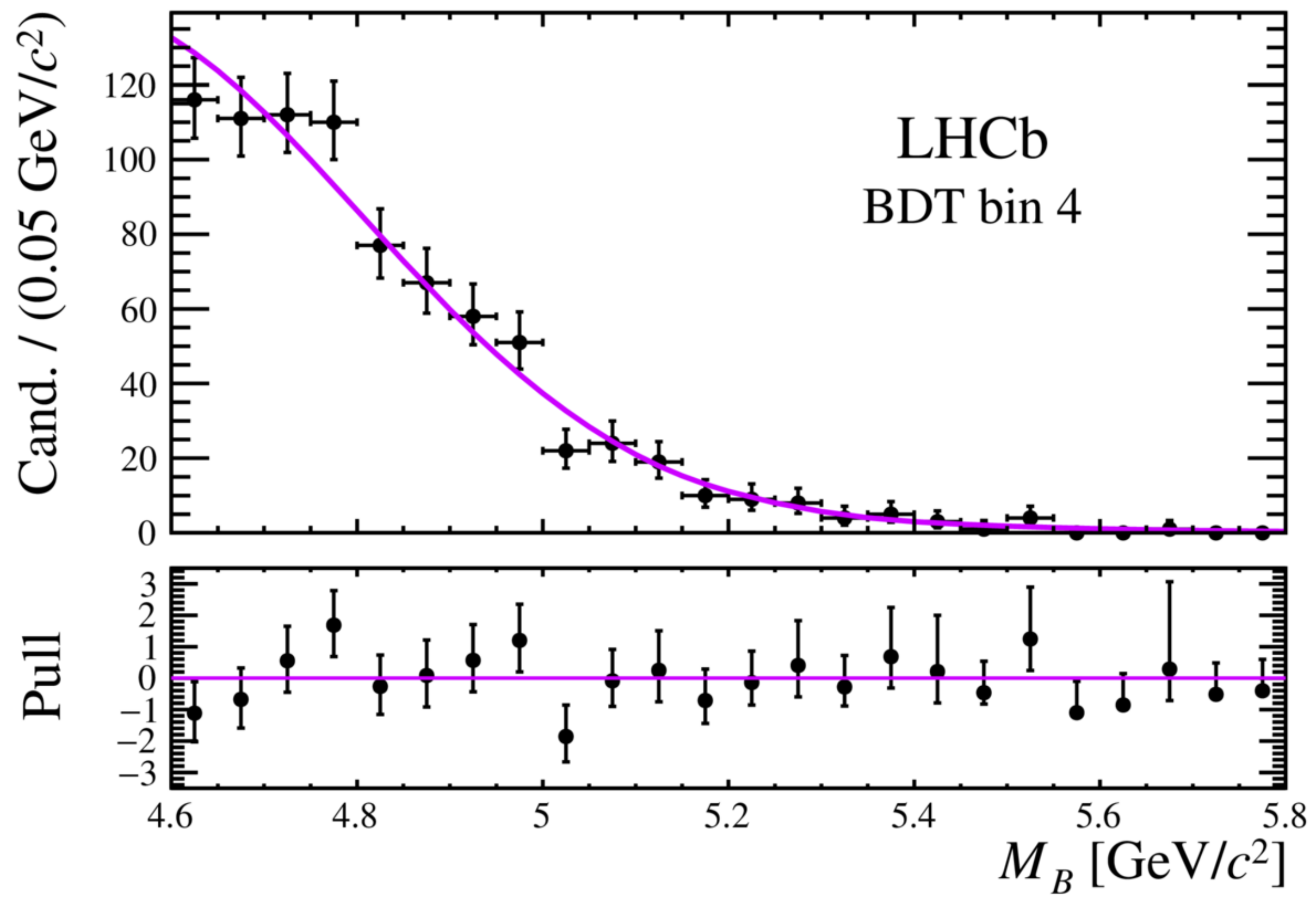
Run1 $3\mathrm{fb}^{-1}$

$B^0_{(s)} \to \tau^\pm \mu^\mp$

- Use $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$
- B mass analytically reconstructed from kinematics constrains
- Background proxy from same-sign data
  - BDT anti-combinatorial + isolation-based BDT
  - Decay time cut to reduce partially reconstructed decays
- 'Final' BDT: Same Sign data vs MC
- Simultaneous fit in bins of BDT and B mass







Most stringent → $\mathcal{B}(B^0 \to \tau^\pm\mu^\mp) < 1.4 \times 10^{-5}$

First limit → $\mathcal{B}(B^0_s \to \tau^\pm\mu^\mp) < 4.2 \times 10^{-5}$

@ 95 % CL

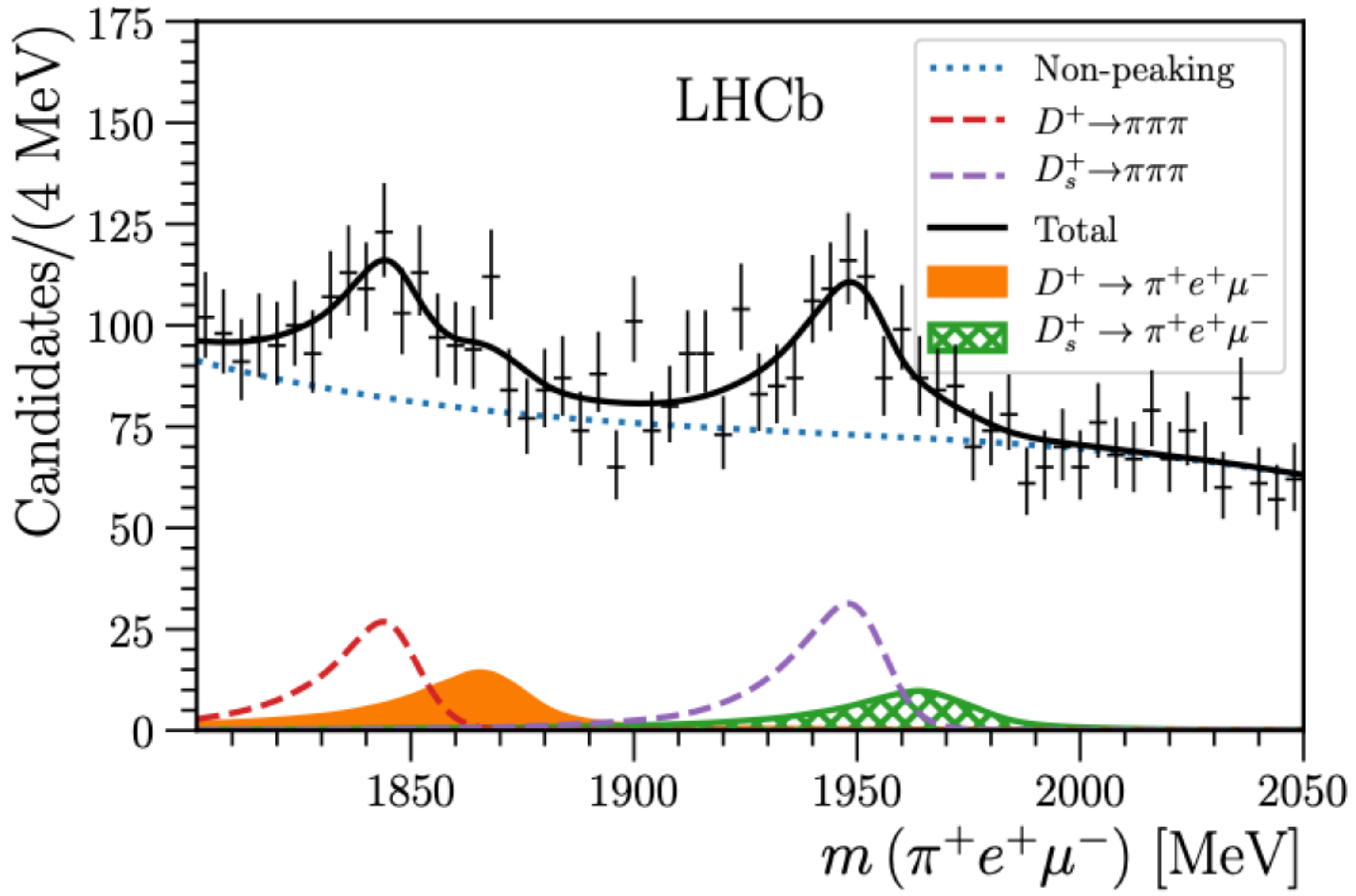
LFV with e, μ

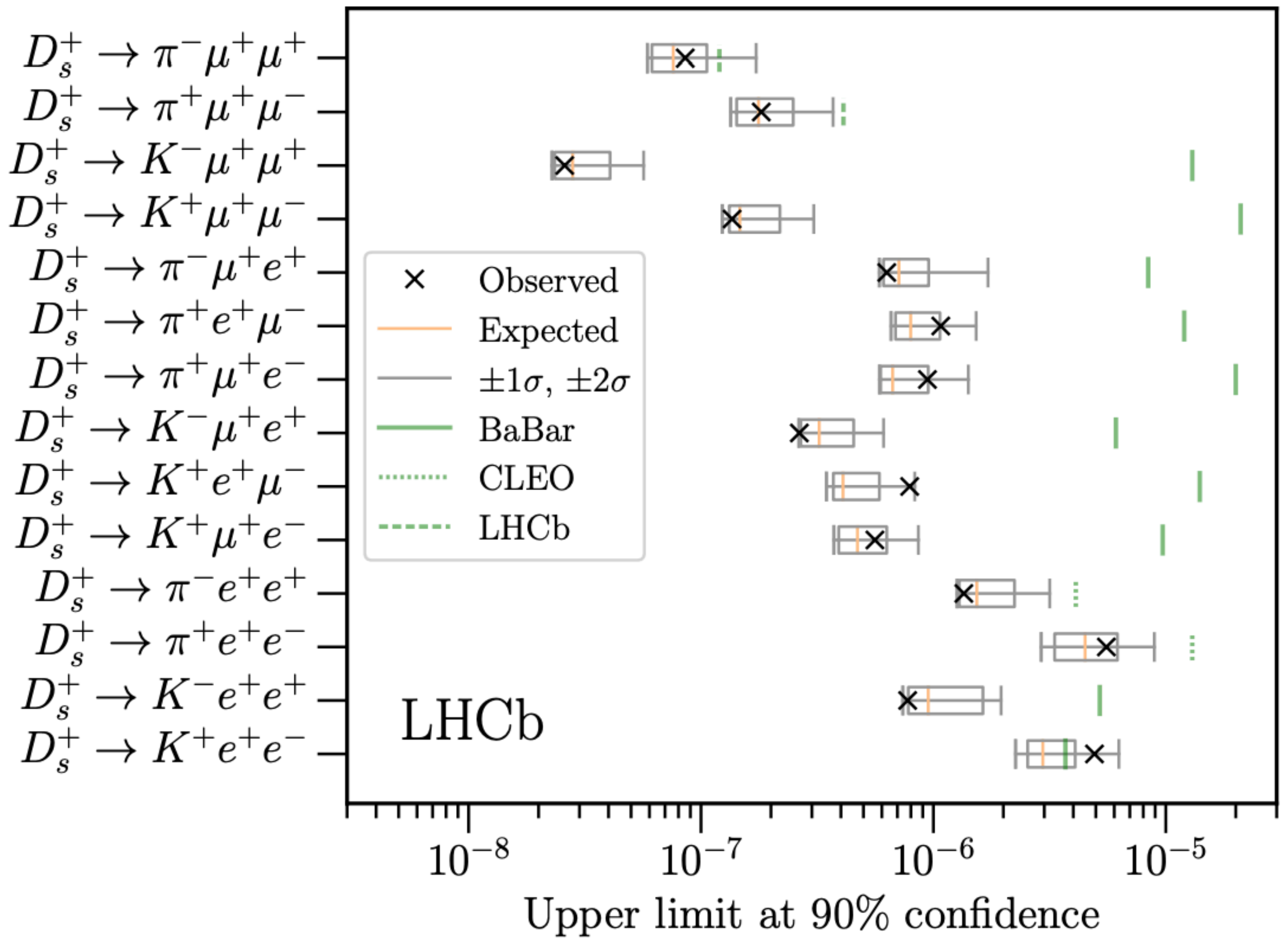
$D^+_{(s)} \to h^\pm \ell^+ \ell'^\mp$, with $\ell = e, \mu$ $h = \pi, K$

2016 1.7fb^{-1}

- Normalisation $D^+ \to \pi^+\phi(\to \ell^+\ell^-)$
- Fit to the 3-body invariant mass
- Limits set between 1.4×10^{-8} and 6.4×10^{-6}

JHEP 06 (2021) 044





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

Run1 3fb^{-1}

PRL 123 (2019) 241802

- Normalisation $B^+ \to K^+J/\psi(\to \ell^+\ell^-)$

$\mathcal{B}(B^+ \to K^+\mu^-e^+)/10^{-9}$	7.0	90% C. L.
$\mathcal{B}(B^+ \to K^+\mu^+e^-)/10^{-9}$	6.4	

world-best limits

$B^0_{(s)} \to \mu^\pm e^\mp$

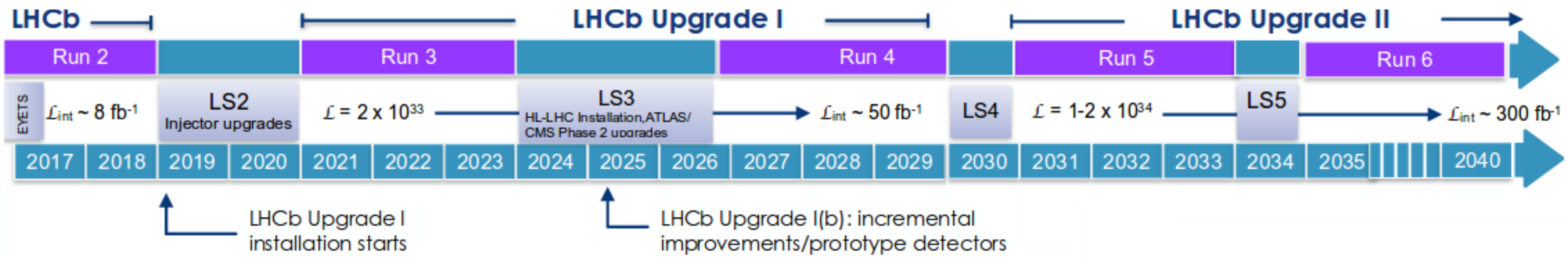
Run1 3fb^{-1}

JHEP 03 (2018) 078

channel	expected	observed
$\mathcal{B}(B^0_s \to e^\pm\mu^\mp)$	$5.0\,(3.9) \times 10^{-9}$	$6.3\,(5.4) \times 10^{-9}$
$\mathcal{B}(B^0 \to e^\pm\mu^\mp)$	$1.2\,(0.9) \times 10^{-9}$	$1.3\,(1.0) \times 10^{-9}$

world-best limits

Conclusion & outlook



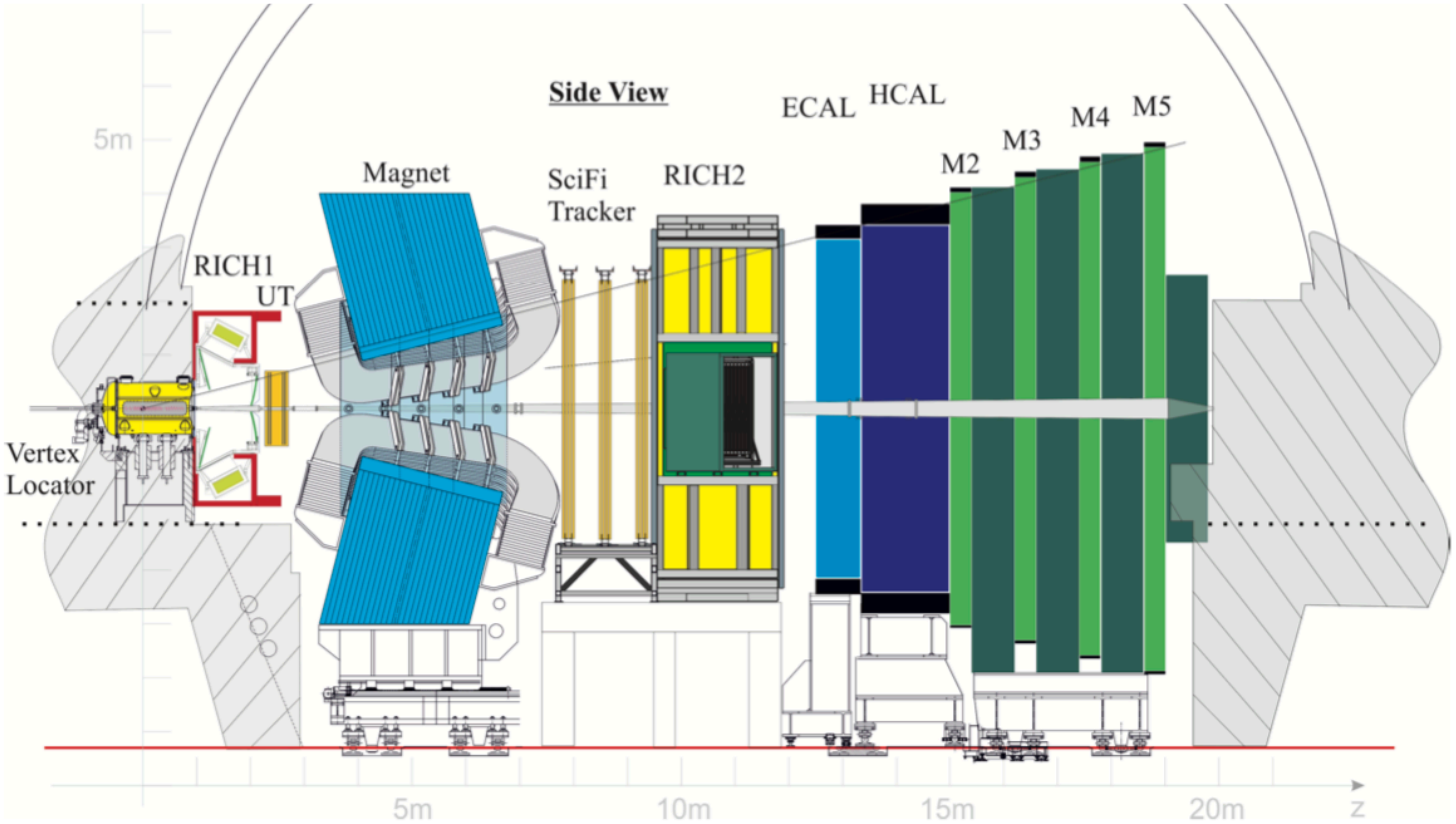
- Flavour physics is one of the most interesting area for NP searches
  - Flavour Anomalies can be confirmed or disproved in very near future
- LHCb is going to give its contribution!
  - Several LHCb measurements to be updated with the full dataset
  - Run3 is about to start (~3 times data in 3 years)
  - LHCb detector undergoing staged upgrades
    - Replaced vertex, tracking detectors: Better vertex resolution
    - Removed hardware trigger: Better efficiency
- Belle II work will be fundamental for NP searches (next talk)

Reduce statistical + data-driven models uncertainties

Reduce background from charged and neutral tracks
Electron modes more accessible

Backup

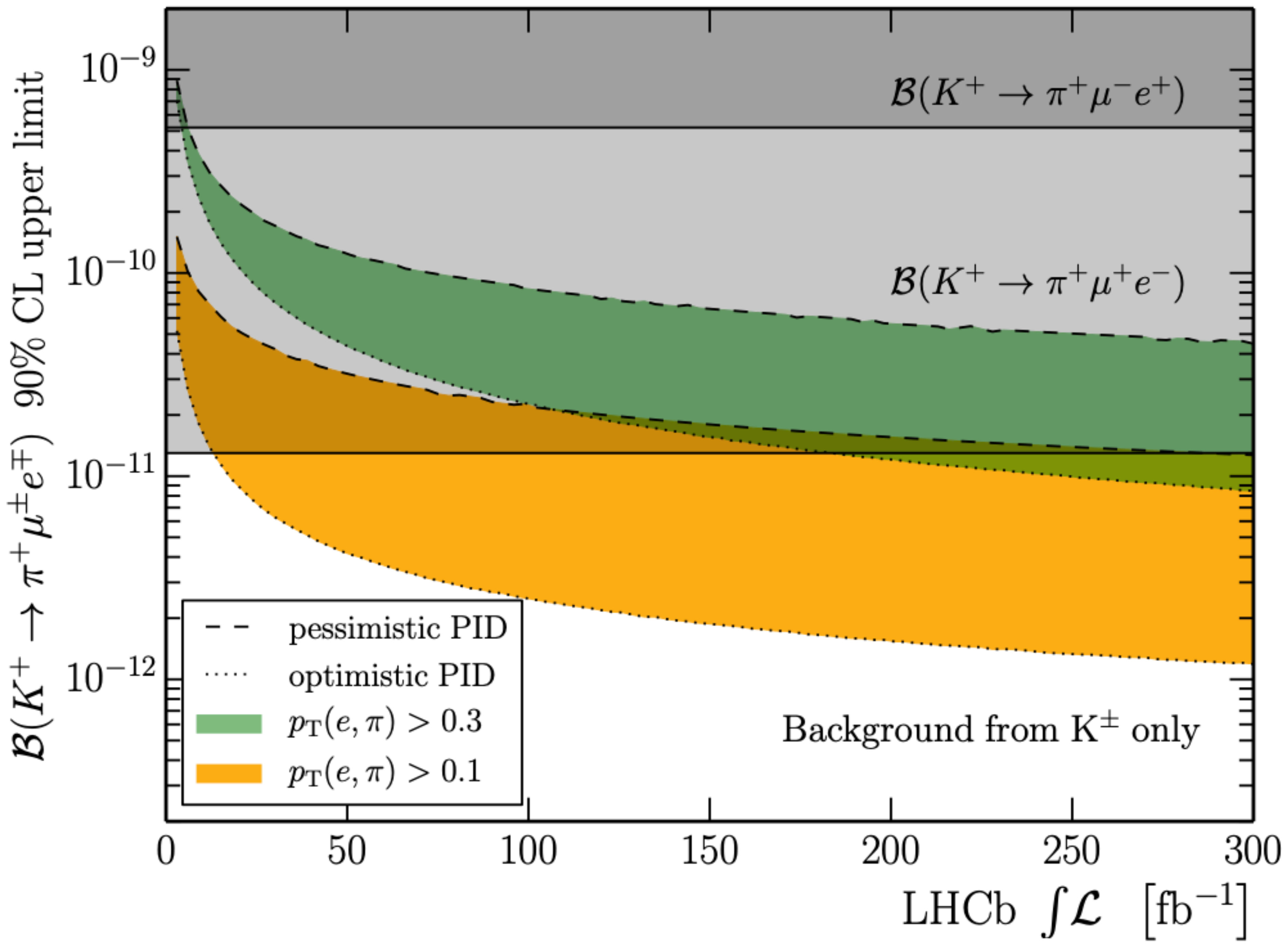
LHCb upgrade - Phase I



- New Vertex Detector
  - Pixel silicon detector
- Trigger-less readout
  - Software HLT on GPU
- New tracking stations:
  - Scintillating Fibers (SciFi) and Silicon micro-strips (UT)
- RICH: New PMTs + new electronics
- Calorimeters
  - PMT gain reduced by a factor 5, FEE redeveloped
- Muon system
  - FEE redeveloped

LFV and LFU prospects

arXiv 1812.07638



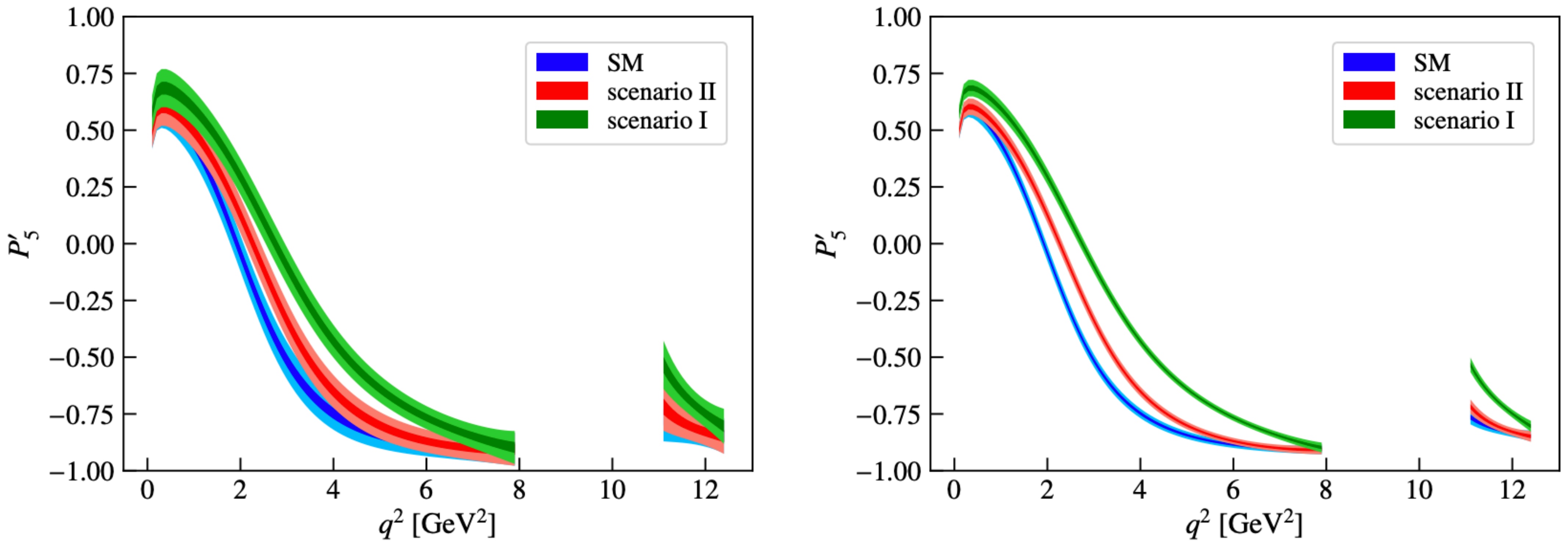


Fig. 49: Total experimental sensitivity, including systematics, at LHCb to the P_5' angular observable in the SM, Scenarios I and II for the Run 3 (left) and the Upgrade II (right) data sets. The sensitivity is computed assuming that the charm-loop contribution is determined from the data.

scenario	C_9^{NP}	C_{10}^{NP}	C_9'	C_{10}'
I	−1.4	0	0	0
II	−0.7	0.7	0	0
III	0	0	0.3	0.3
IV	0	0	0.3	−0.3

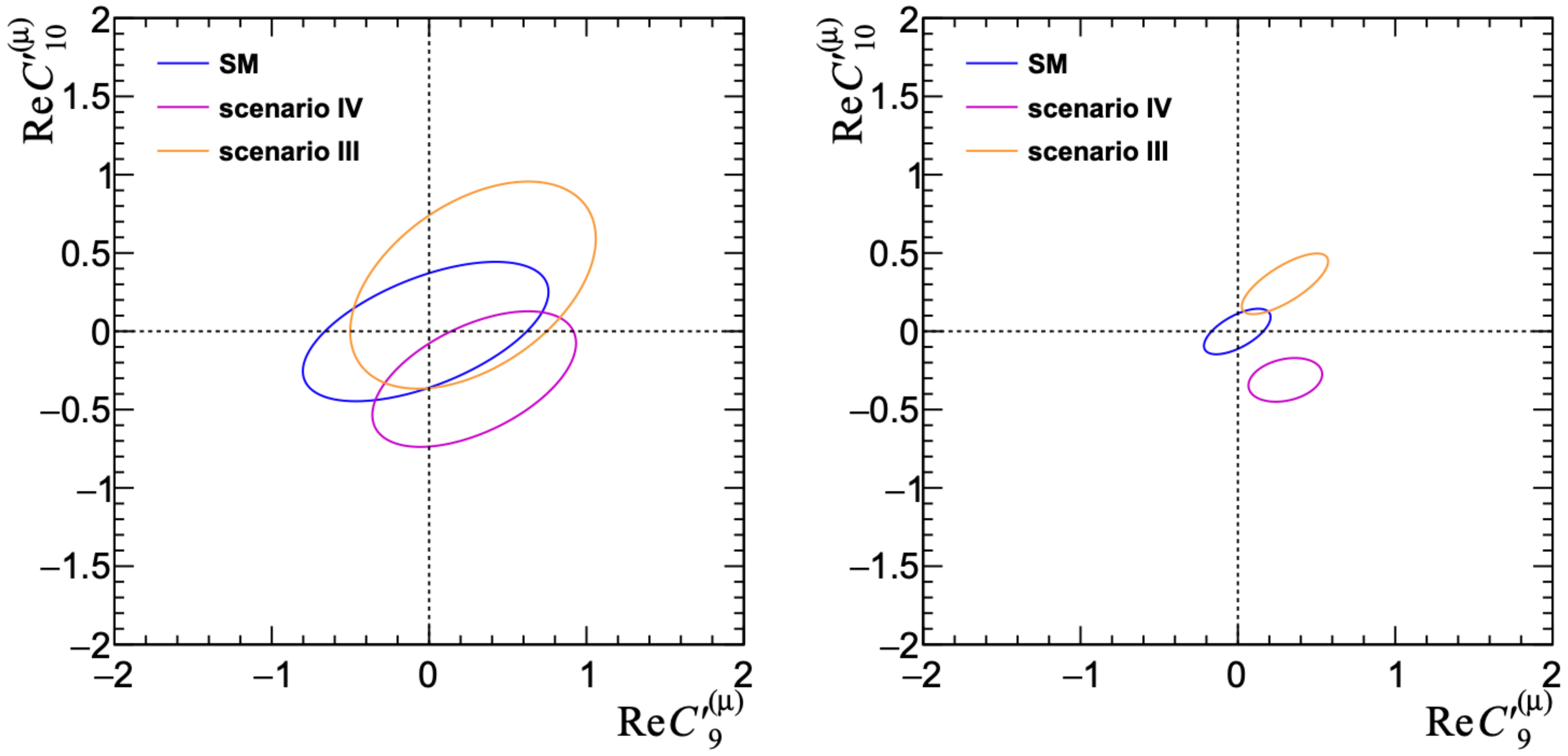
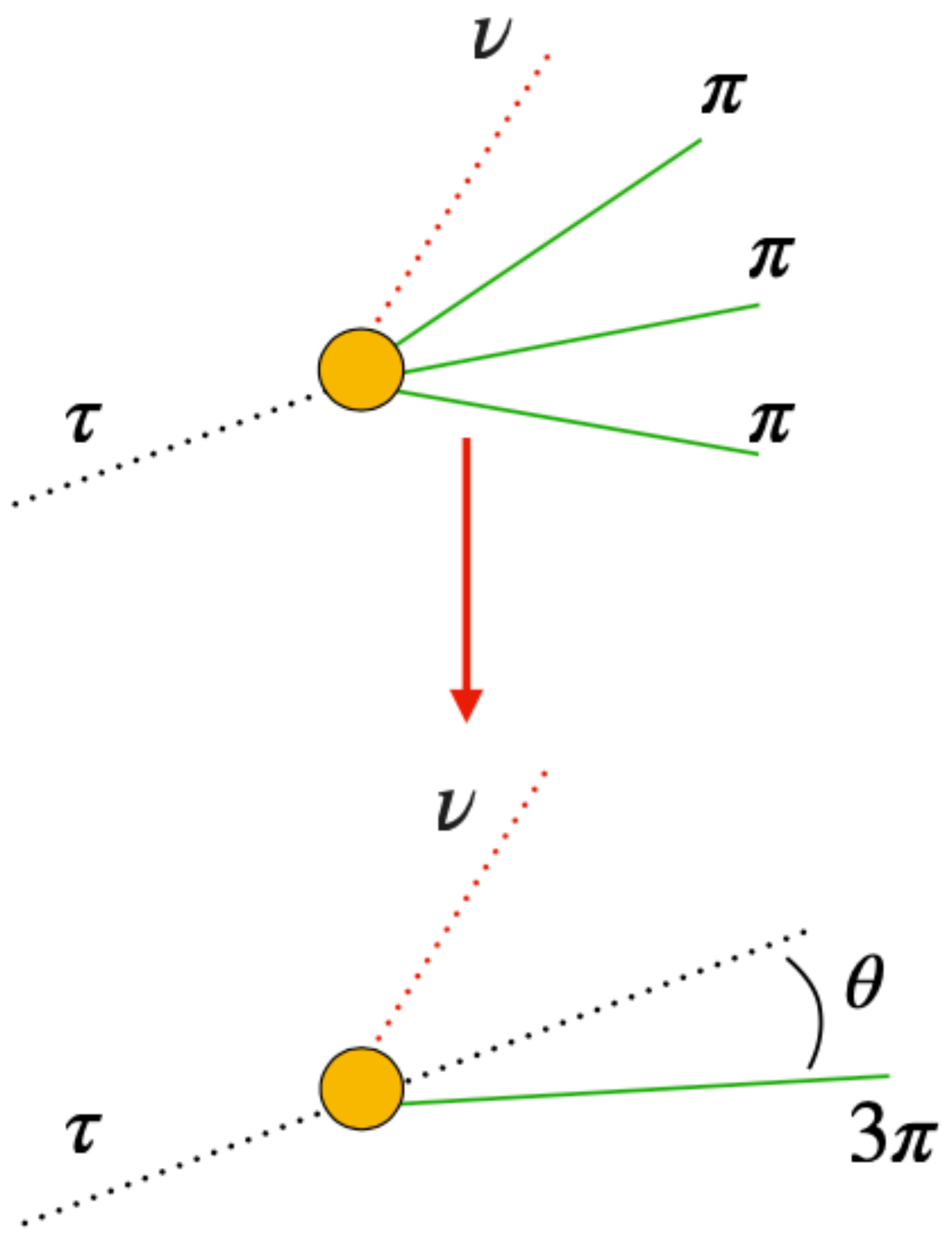


Fig. 50: Expected sensitivity to the Wilson coefficients C_9' and C_{10}' from the future LHCb analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay. The ellipses correspond to $3\,\sigma$ contours for the SM, Scenario III and Scenario IV for the Run 3 (left) and the Upgrade II (right) data sets.

Why not $b \to s\tau^+\tau^-$?

- Decay vertex position reconstructed from pions tracks
  - **Minimally corrected mass**: $M_c = \sqrt{M_{vis}^2 + p_{vis}^2 \sin^2\theta} + p_{vis}\sin\theta$
- Hadronic decays can be reconstructed analytically
  - Impose the constraint $m_\tau = 1776.86$ MeV
  - $|\vec{p_\tau}| = \dfrac{(m_\tau^2 + m_{3\pi}^2)|\vec{p}_{3\pi}|\cos\theta \pm E_{3\pi}\sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2|\vec{p}_{3\pi}|^2\sin^2\theta}}{2(E_{3\pi}^2 - |\vec{p_{3\pi}}|^2\cos^2\theta)}$
- Momentum direction from tau and B decay vertices



- Refit of the decay chain applying **mass constraints:**
  - Improve mass resolution
  - Need to initialize the fitter, analytic reconstruction can be used
  - Fitter can fail, reduced efficiency

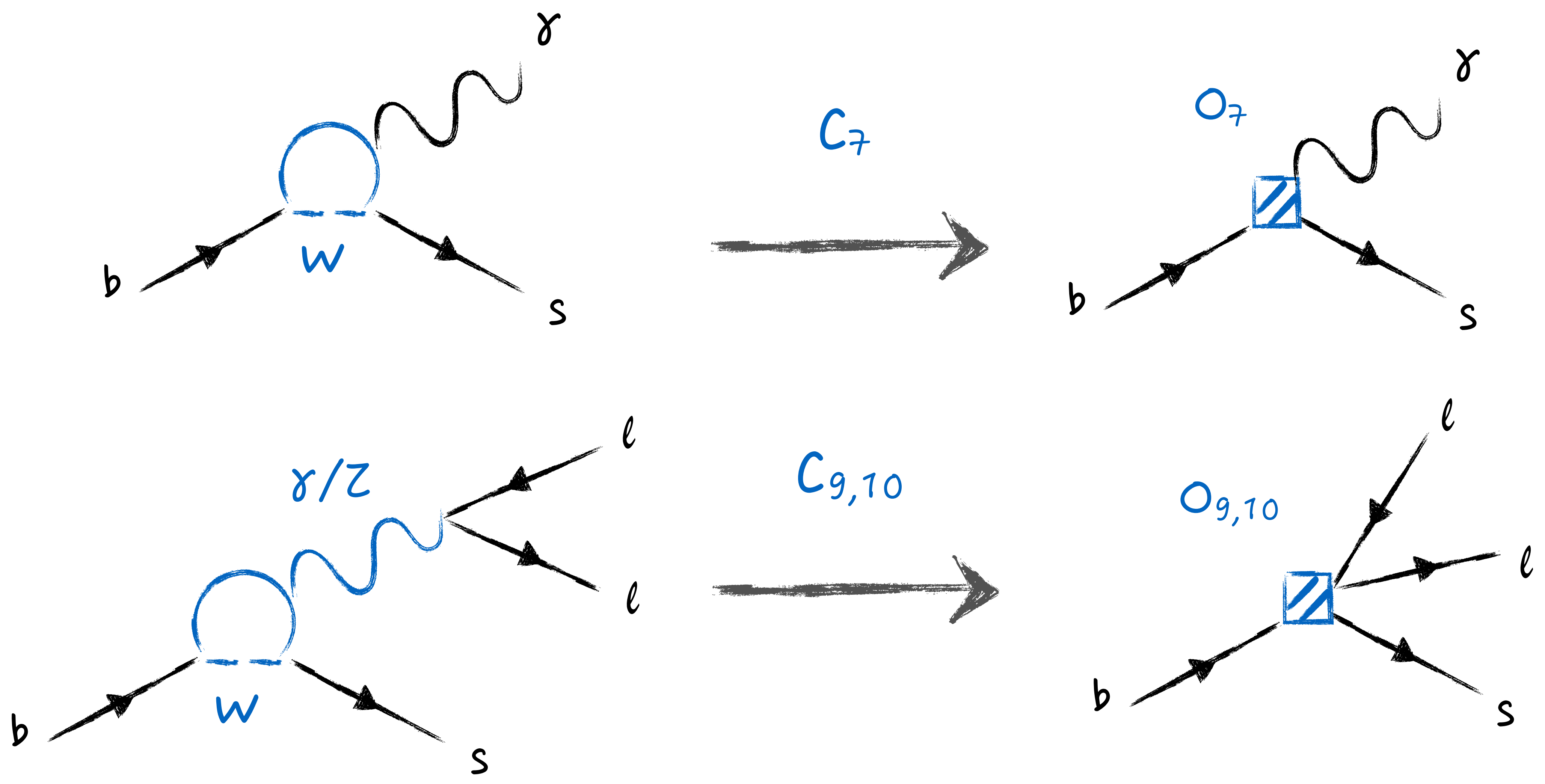
Rare b decays

- Precision measurement in b rare decays can be sensitive to possible New Physics contribution
- They can be described by an **effective theory** (low energy process):

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

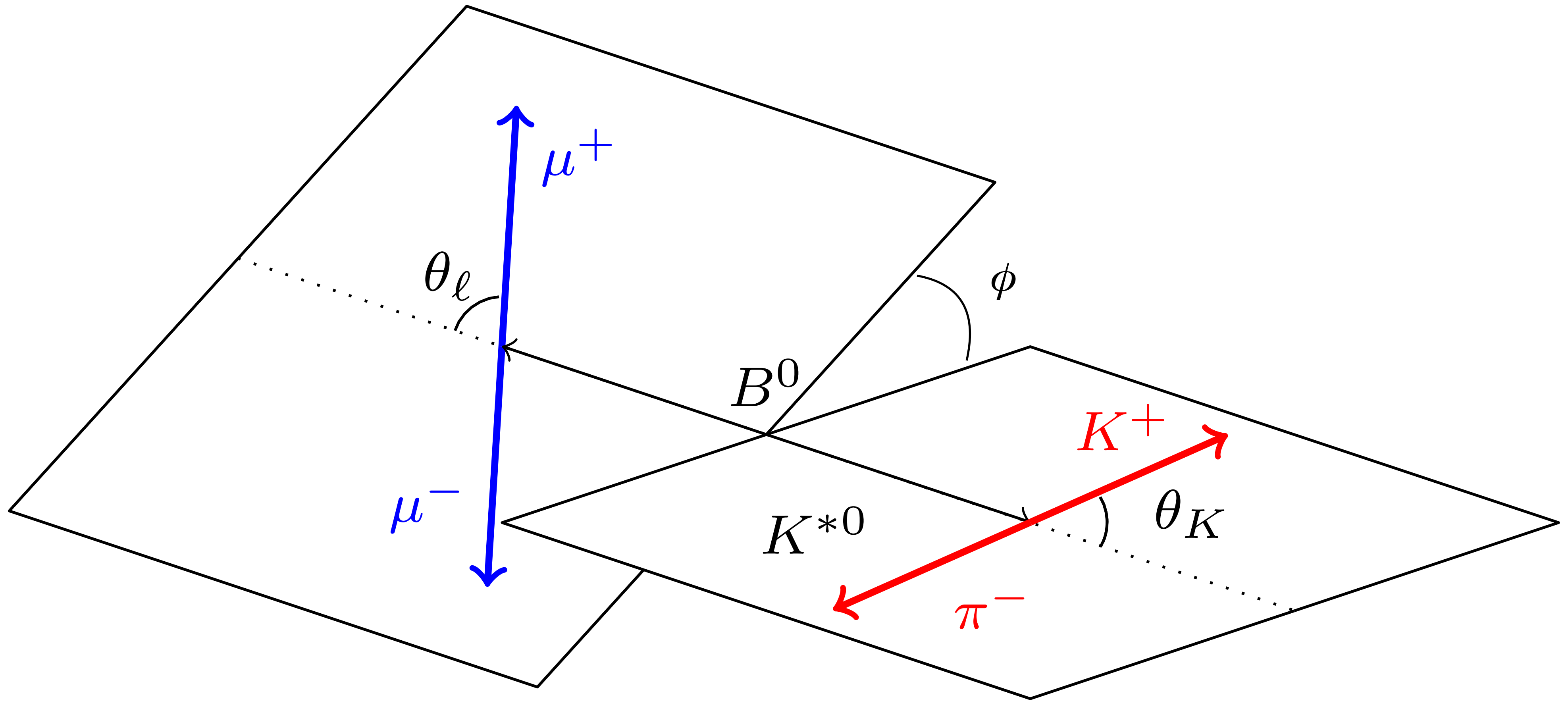
$C_i = C_i^{SM} + C_i^{NP}$ Effective coupling: 'Wilson Coefficient'

O_i Local operators



- NP can introduce new operators or modify the Wilson coefficients, depending on its structure

$B \to K^{*}\mu^{+}\mu^{-}$ angular distributions



$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_l$$
$$-F_\mathrm{L}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\frac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

The flavour puzzle

$$\mathscr{L}_{\text{SM}} = \mathscr{L}_{\text{gauge}}(\psi_i, A_a) + \mathscr{L}_{\text{Higgs}}(\psi_i, A_a, H)$$

$$\mathscr{L}_{\text{gauge}} = \sum_a \frac{-1}{4g_a^2}(F_{\mu\nu})^2 + \sum_{i=1}^{3} \bar{\psi}_i i \not{D}_i \psi_i$$

3 identical replica ($i = 1,2,3$) of the basic fermion family differing only in mass

Gauge interactions are the same for all the families

- **Why 3 generations?**
- **What is the origin of their different masses?**
- **What is the origin of the hierarchy in quark-mixing?**

$$\mathscr{L}_{\text{Higgs}} = \mathscr{L}_H + \mathscr{L}_{Yukawa}$$

Only Yukawa interaction distinguishes the families

Quark sector:

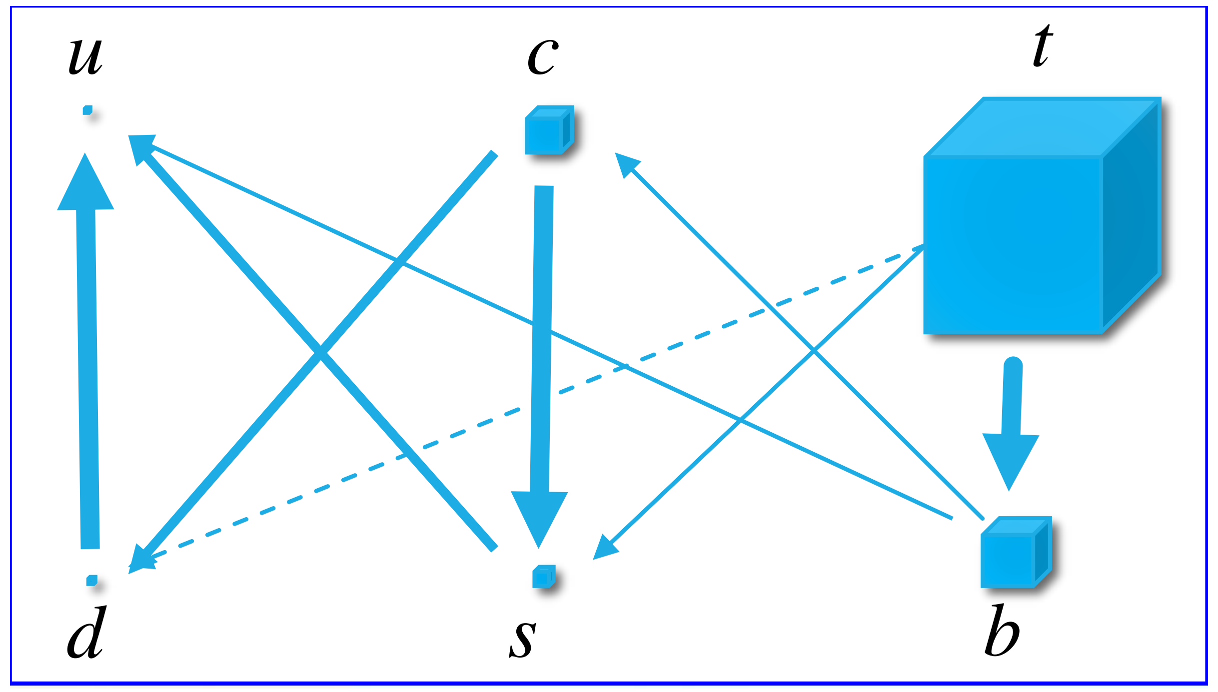
$$\bar{Q}_L^{\,i}\, Y_D^{ik}\, d_R^{\,k}\, \text{H} + h.c. \rightarrow \bar{d}_L^{\,i}\, M_D^{ik}\, d_R^{\,k} + \ldots$$

$$\bar{Q}_L^{\,i}\, Y_U^{ik}\, u_R^{\,k}\, \text{H}_c + h.c. \rightarrow \bar{u}_L^{\,i}\, M_U^{ik}\, u_R^{\,k} + \ldots$$

Only one mass matrix at time can be diagonalised (for gauge flavour invariance)

$$M_D = \text{diag}(m_d, m_s, m_b)$$

$$M_U = V^{+} \times \text{diag}(m_u, m_c, m_t)$$



V_CKM appears in charged-current gauge interaction (mixing u and d)