Sum-of-exclusive $b \to s\ell\ell$ and $b \to d\ell\ell$ decays

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Flavorful opportunities in Semileptonic B decays: Connecting Theory and Experiment

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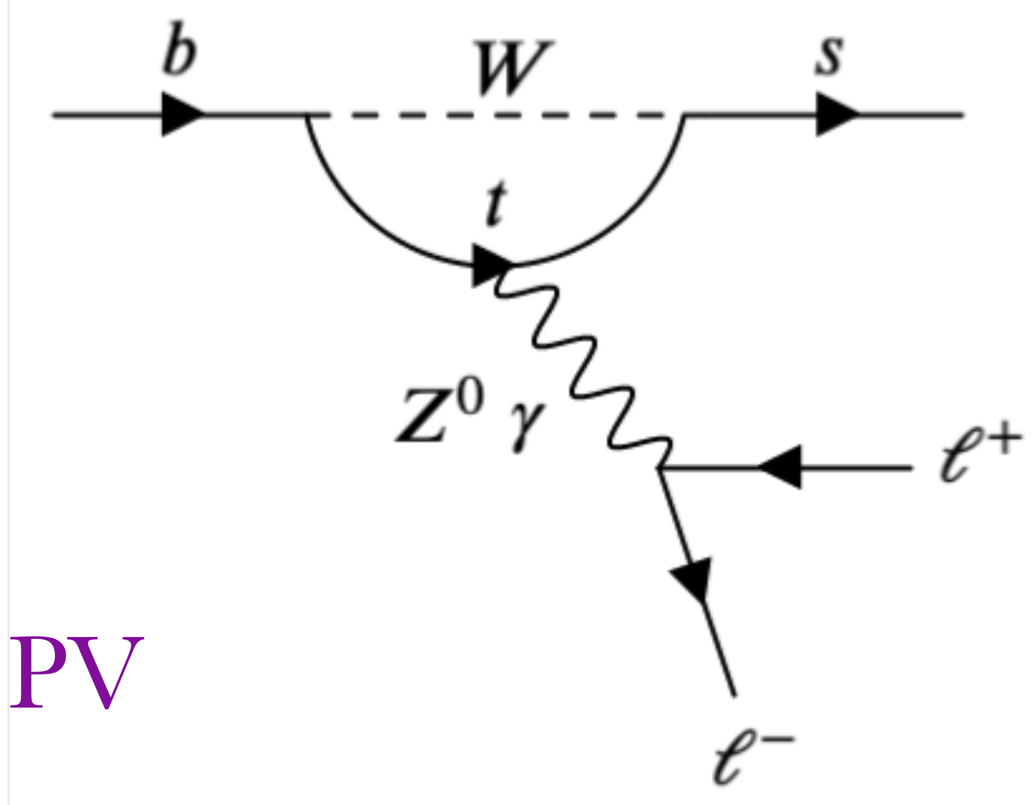
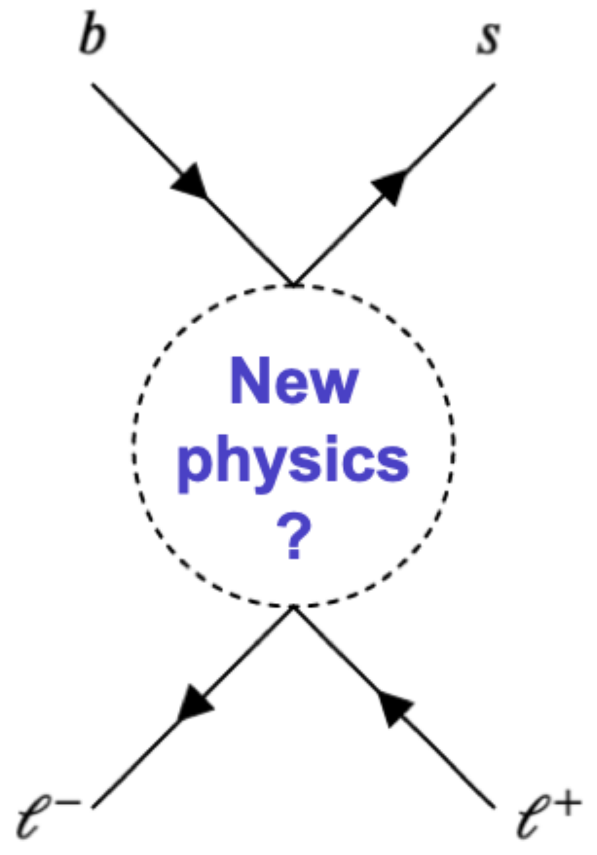
Outline

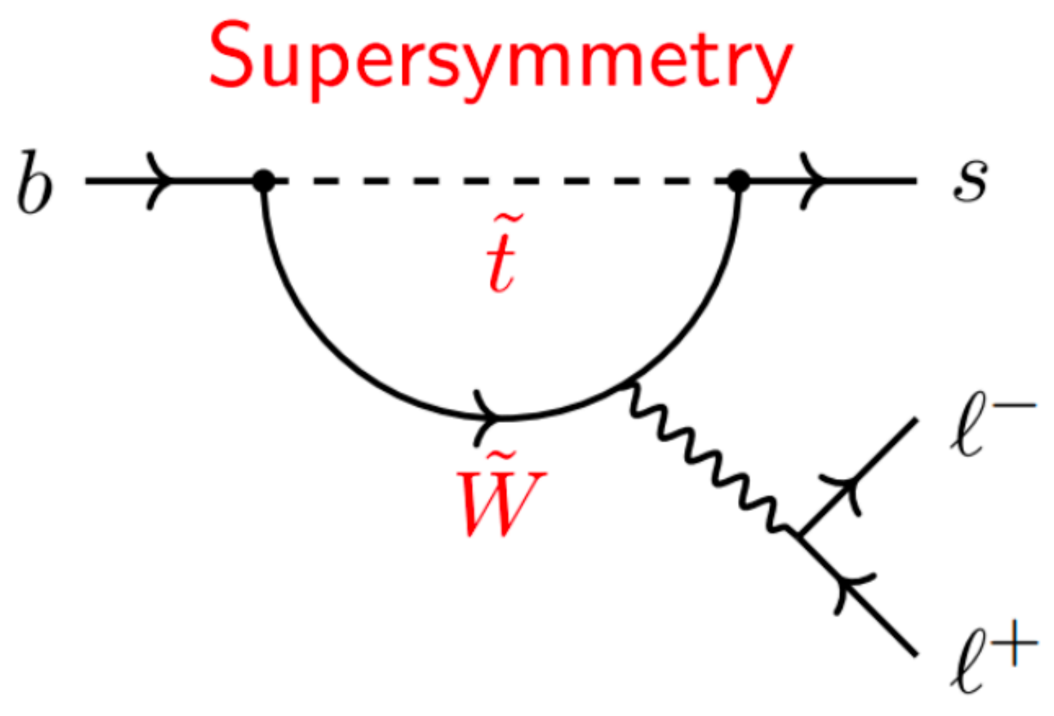
- $b \to s\ell\ell$
  - Current status & motivation
  - Inclusive & sum-of-exclusive measurements
  - Prospects for LHCb & FCC-ee
- $b \to d\ell\ell$
  - Some recent results & discussion

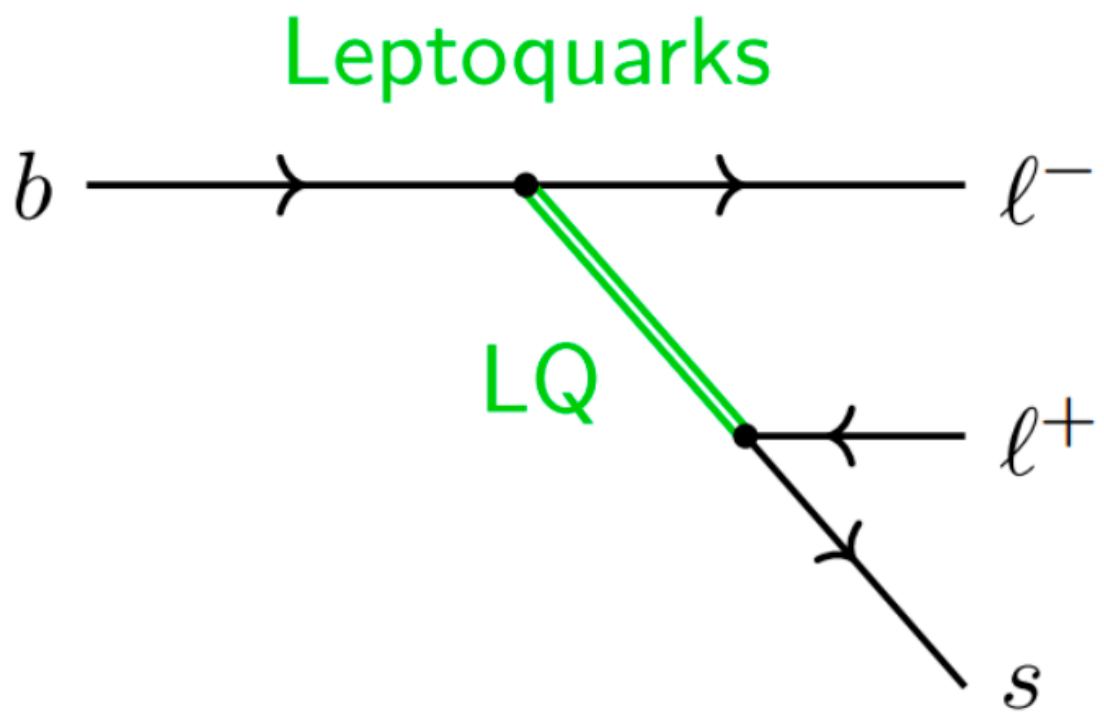
Rare decays with $b \to s\ell\ell$ transitions

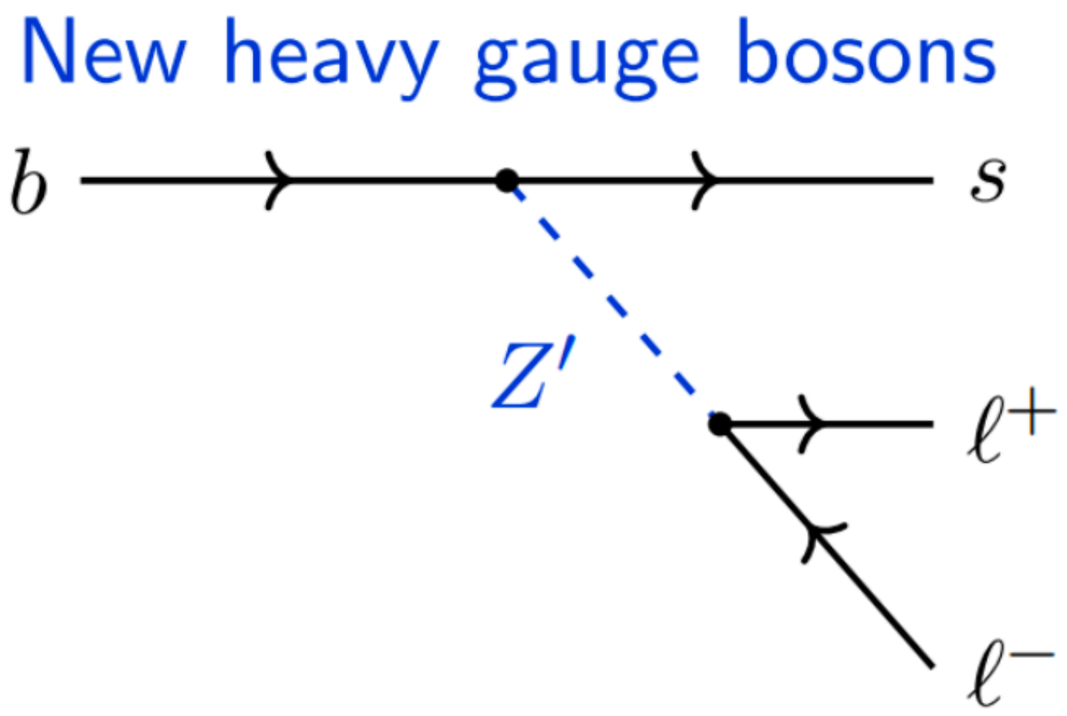
- FCNC processes
  - Forbidden at tree-level, dominated by penguin or box SM diagrams
  - New particles may contribute at loop or even tree-level
  - New Physics: decay rates, angular distributions and new sources of CPV











Effective description of rare b-decays

- Rare b-decays described with effect Hamiltonian in Weak Effective Theory (WET)

Wilson coefficients (effective couplings) encode short-distance physics

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

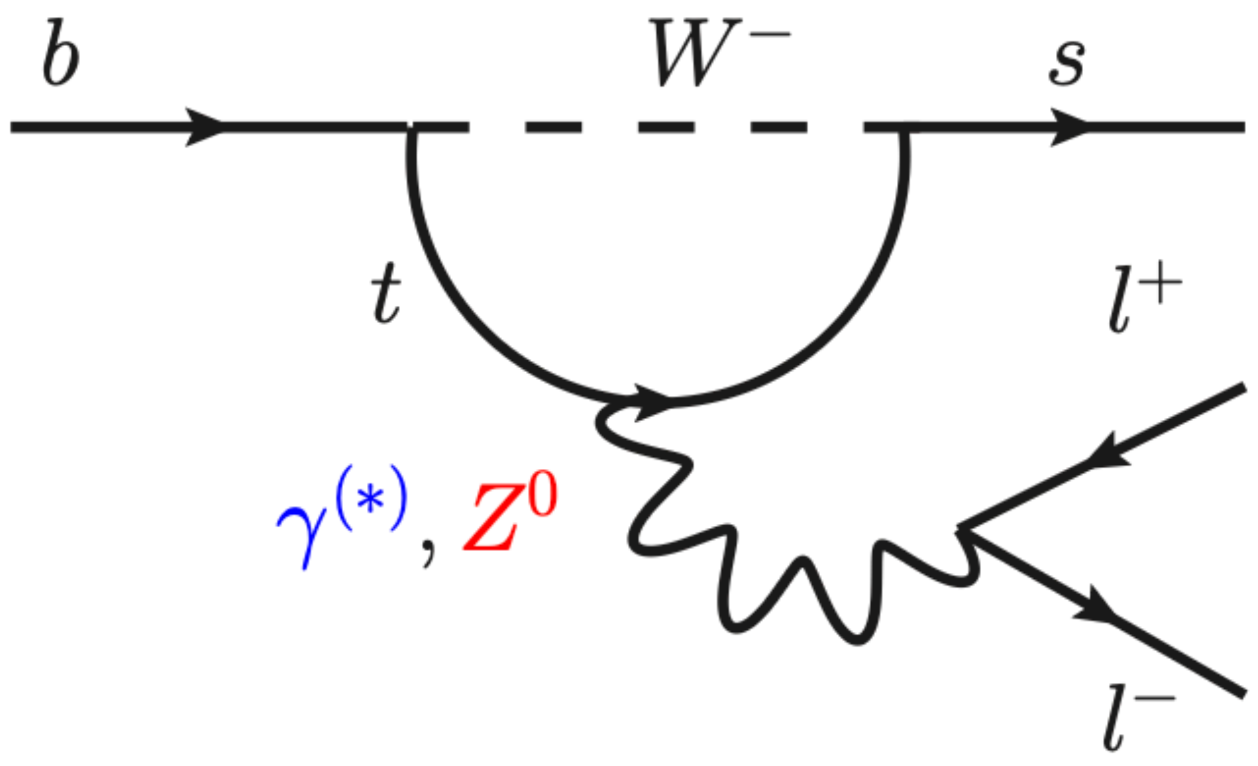
Local operators low-energy interaction basis

i = 1,2	Tree
i = 3 – 6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin

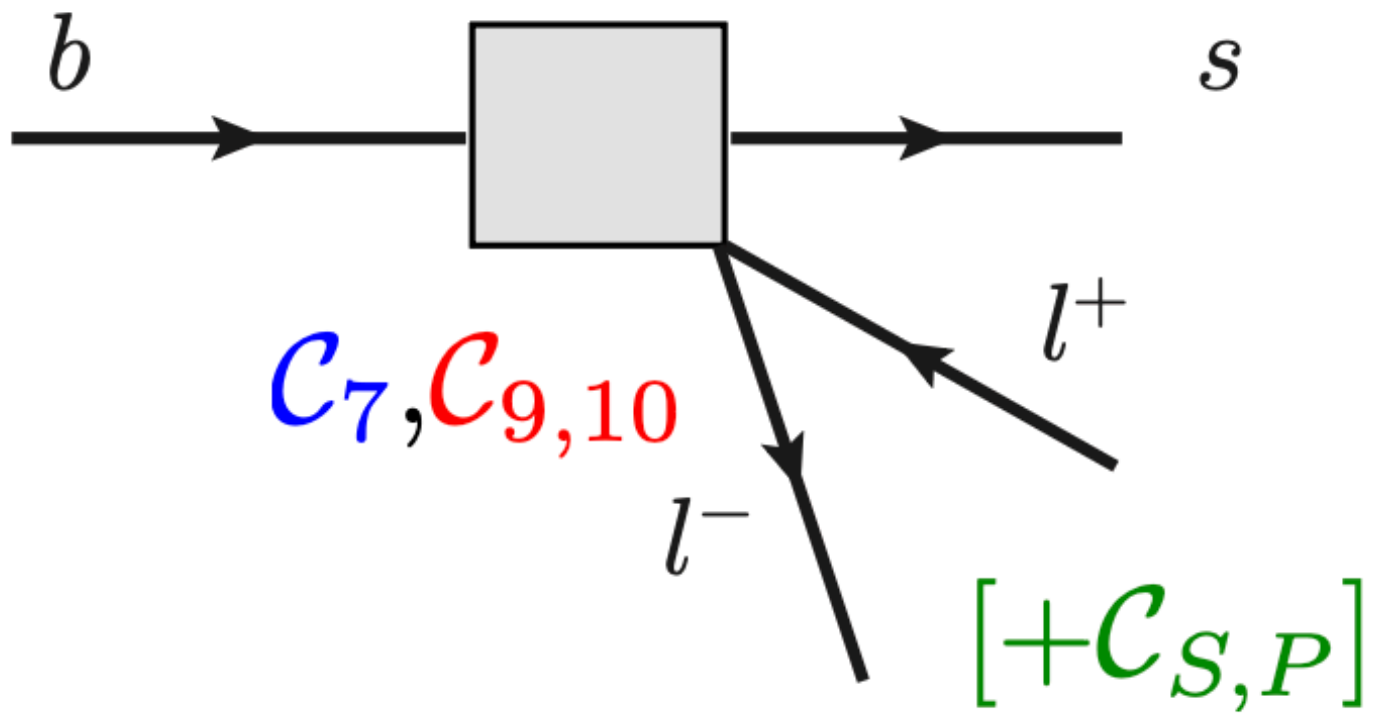
Flavour-violating coupling

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

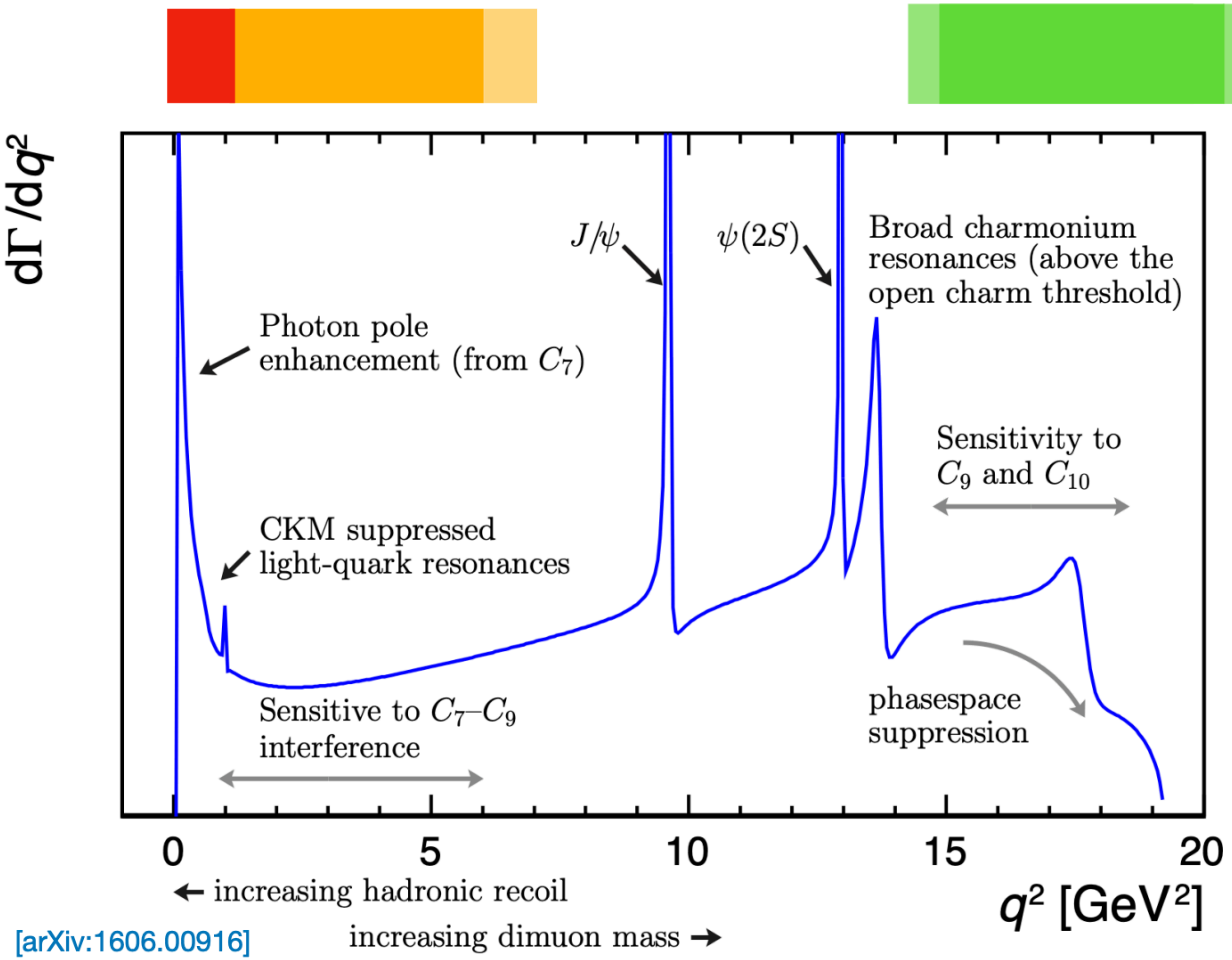
NP scale ($\Lambda^2_{NP} \gg m_W \gg m_b \gg \Lambda_{QCD}$)



"integrate out heavy degrees of freedom"



Differential decay rates / q^2 dependence



[arXiv:1606.00916]

$q^2 = m^2(\ell^+\ell^-)$-regions allow to study different types of couplings to New Physics

Low-q^2 bin: [0.1,1.1] GeV²

Close to the photon pole, sensitive to dipole currents C_7

Central-q^2 bin: [1.1,6] GeV²

Dominantly sensitive to C_9 and C_{10}

High-q^2 bin: [14.3 or 15,19] GeV²

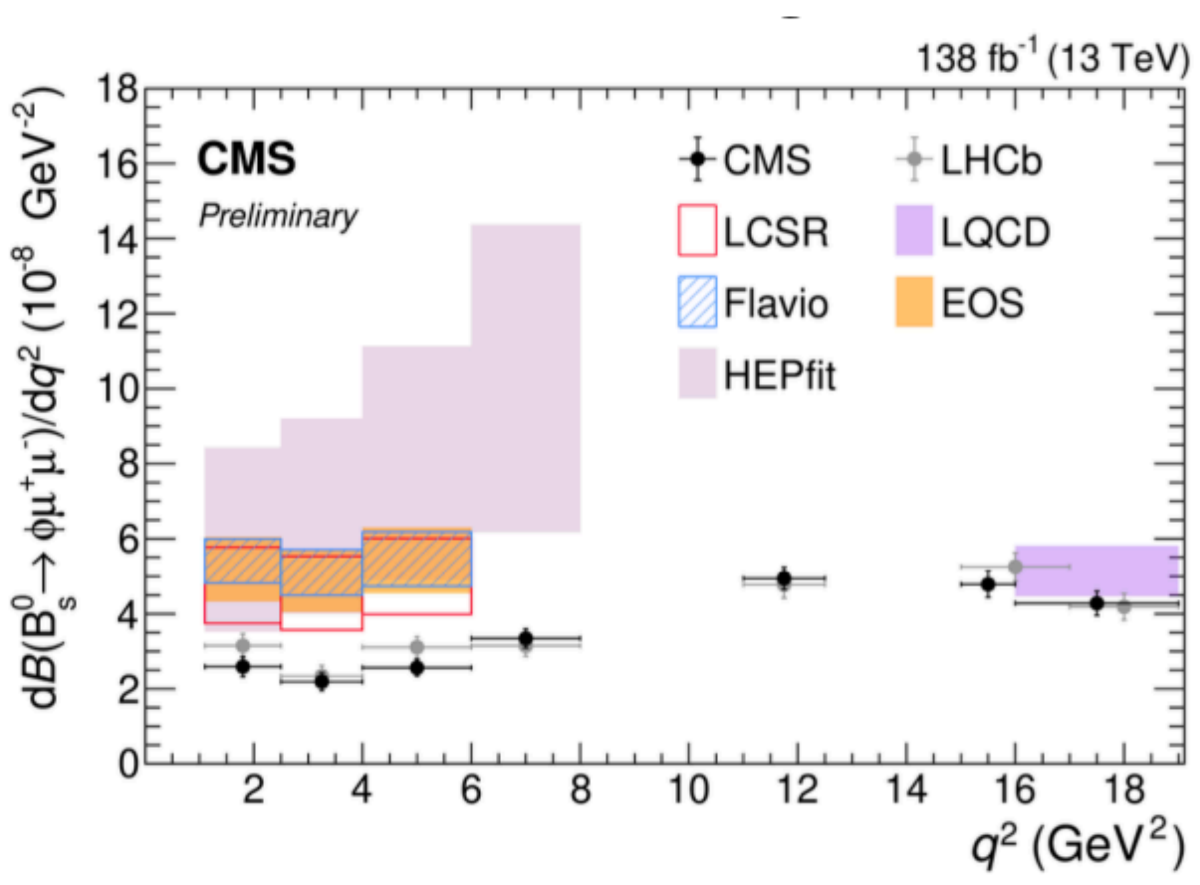
Clean probe of C_9, C_{10}

Experimental status

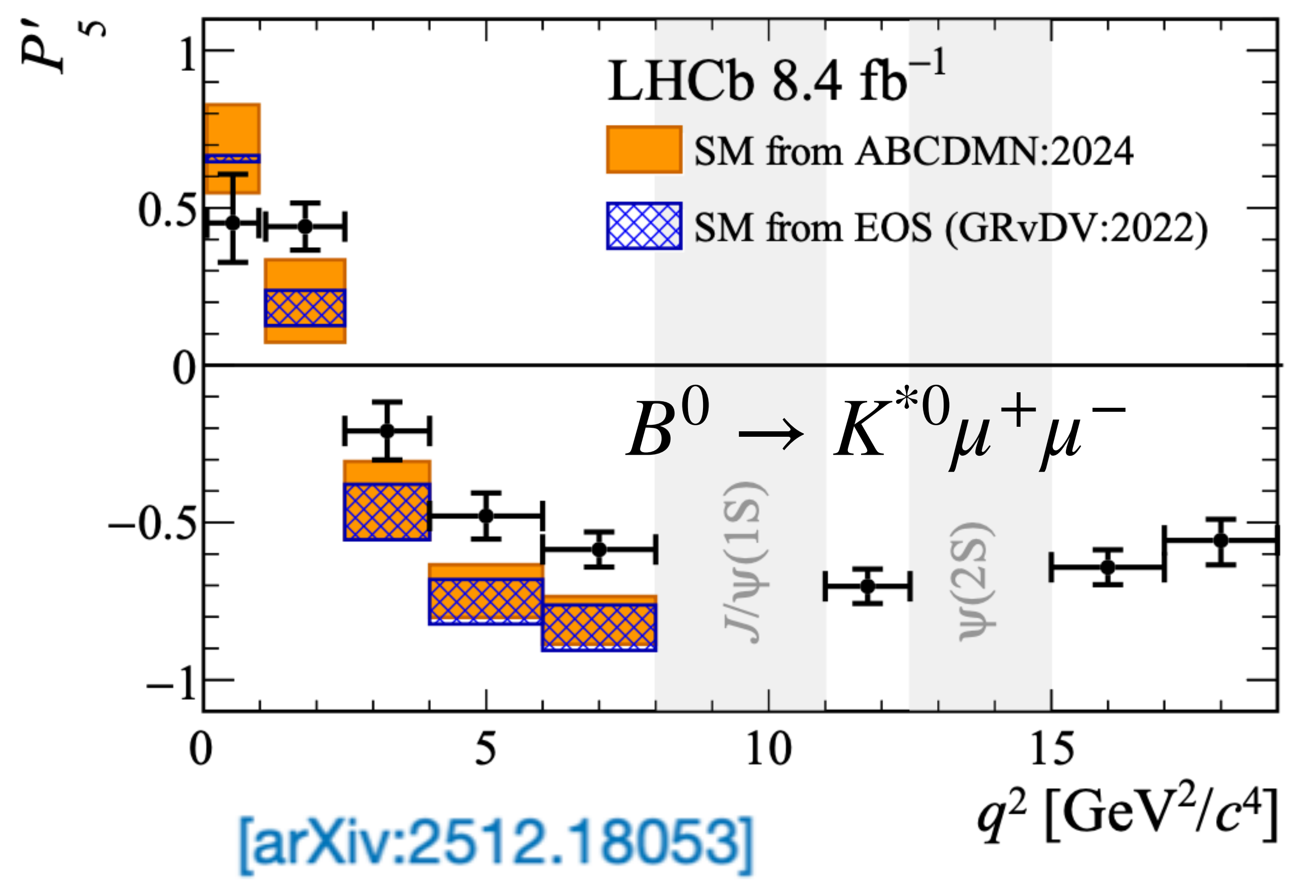
Higher theory uncertainties

Lower theory uncertainties

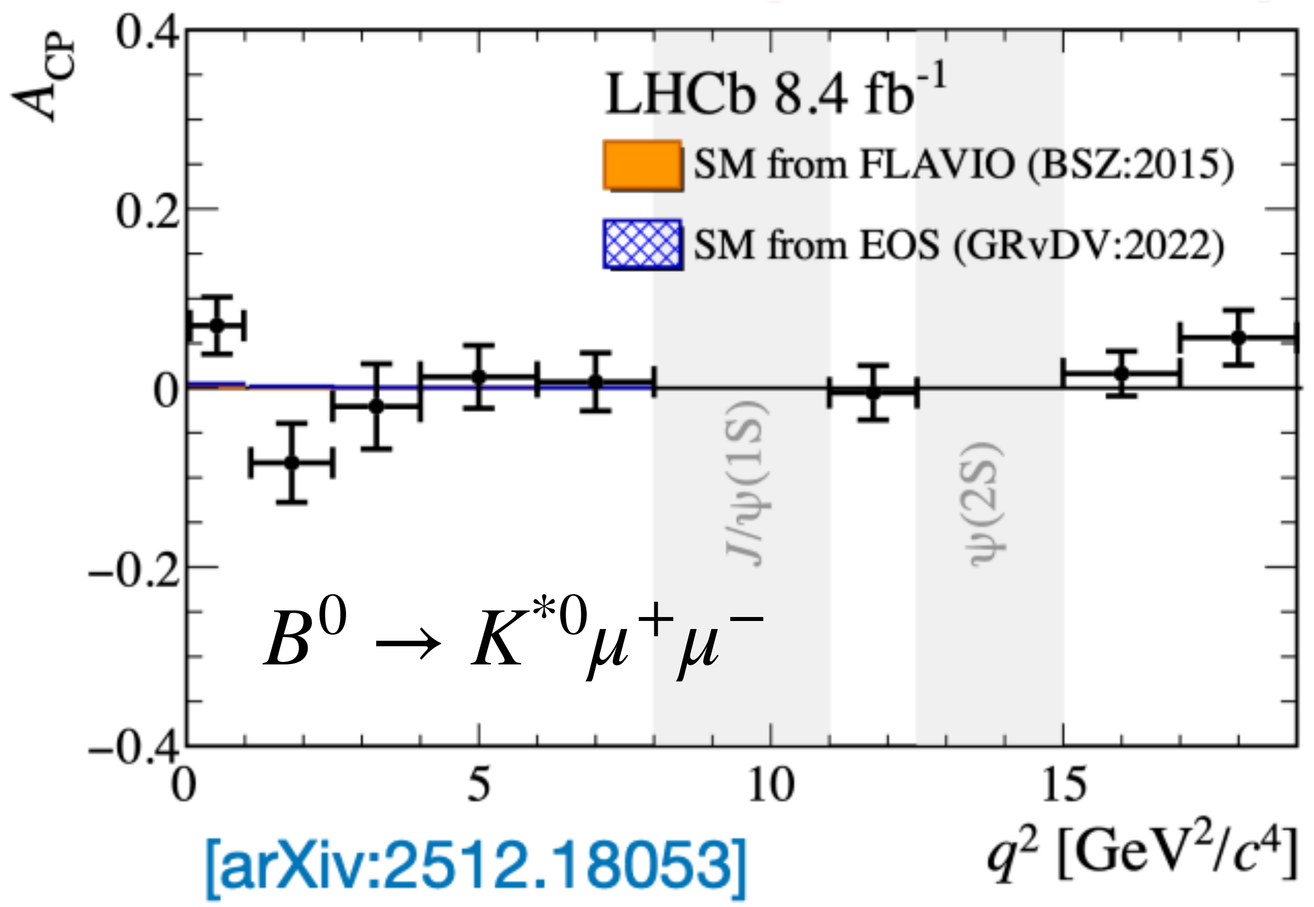
Differential decay rates



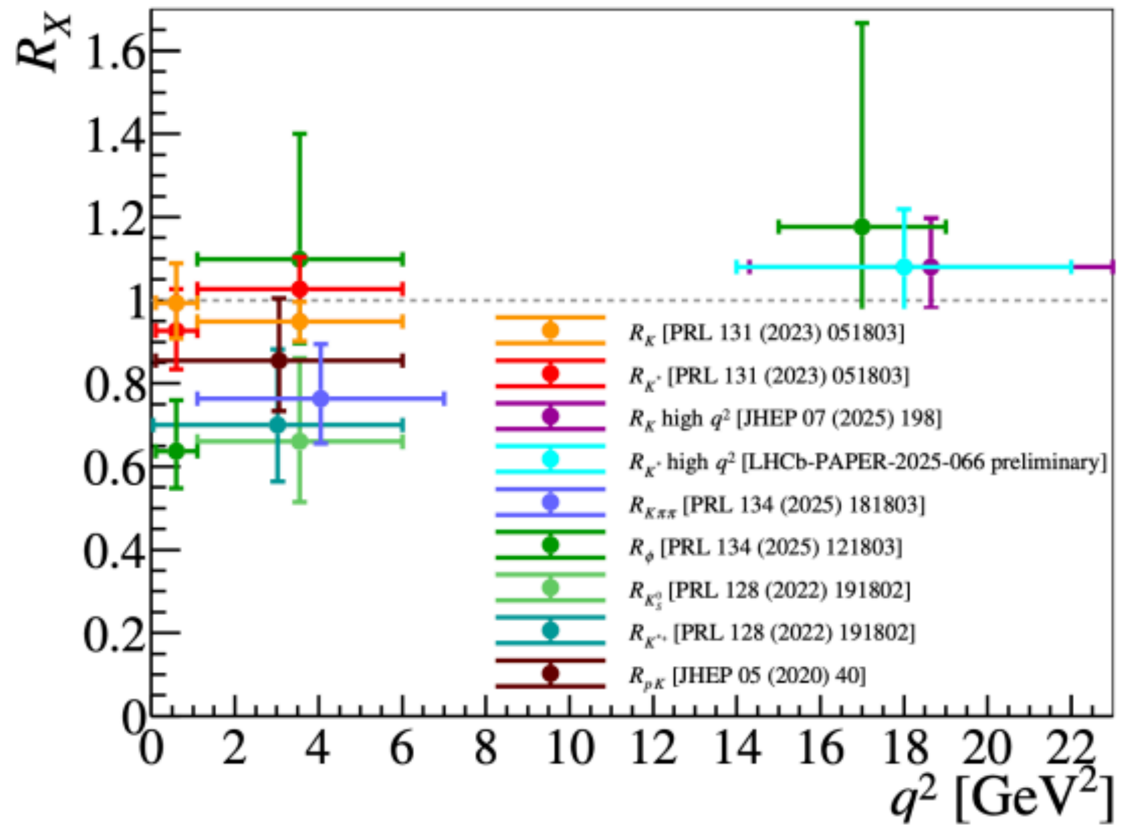
Angular observables



CP asymmetries



LFU tests

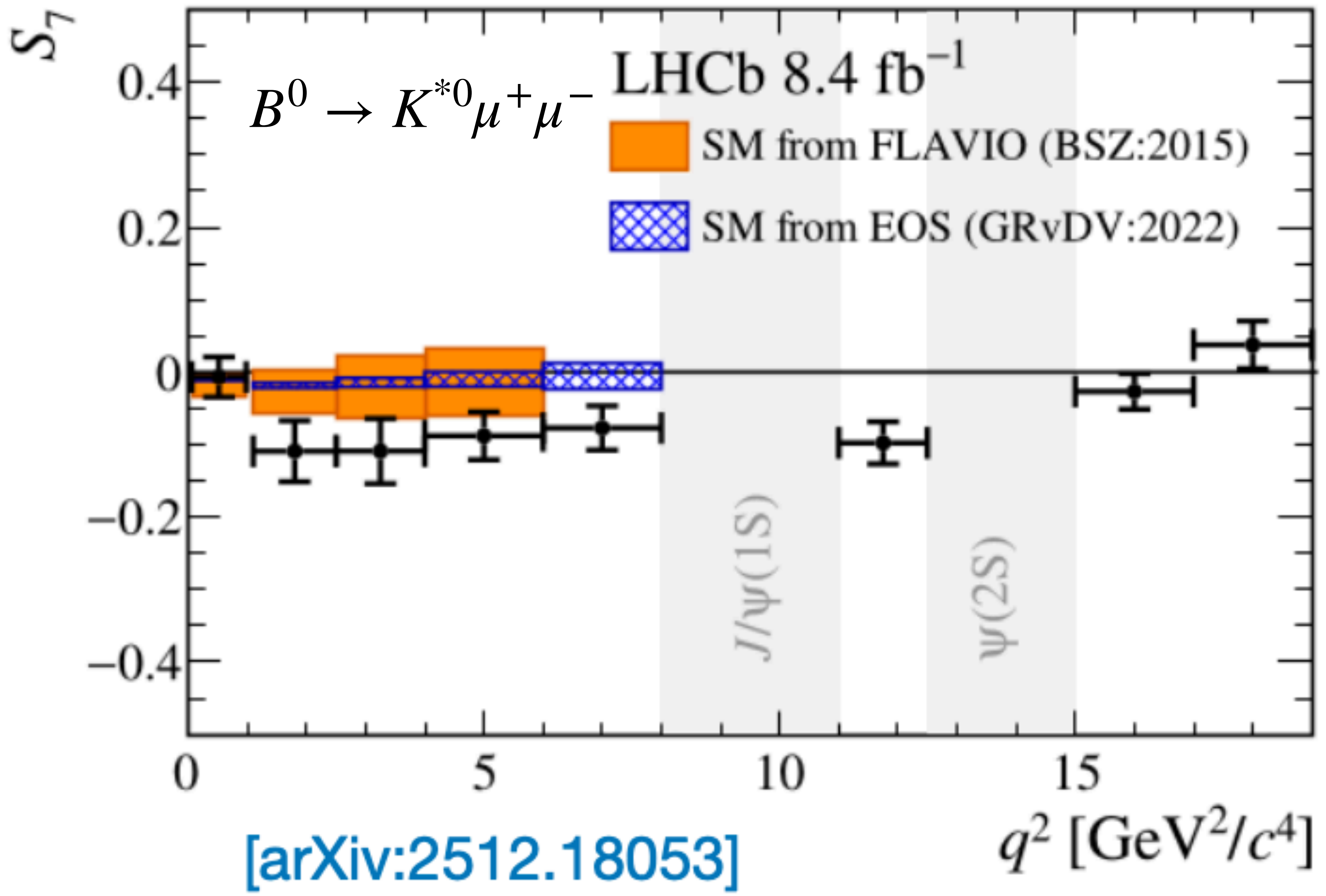


Tensions observed by many experiments (CMS, LHCb, Belle) in low & central q^2 bin in the BFs for several decay modes ($B^0 \to K^{*0}\mu^+\mu^-$, $B^+ \to K^+\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$, …) and in angular observables (P'_5, A_{FB}) in $B^0 \to K^{*0}\mu^+\mu^-$

Experimental status

New concerns about the understanding of the hadronic uncertainties from tensions in S_7 in $B^0 \to K^{*0}\mu^+\mu^-$
[Altmannshofer et. al.: arXiv:2603.27753]

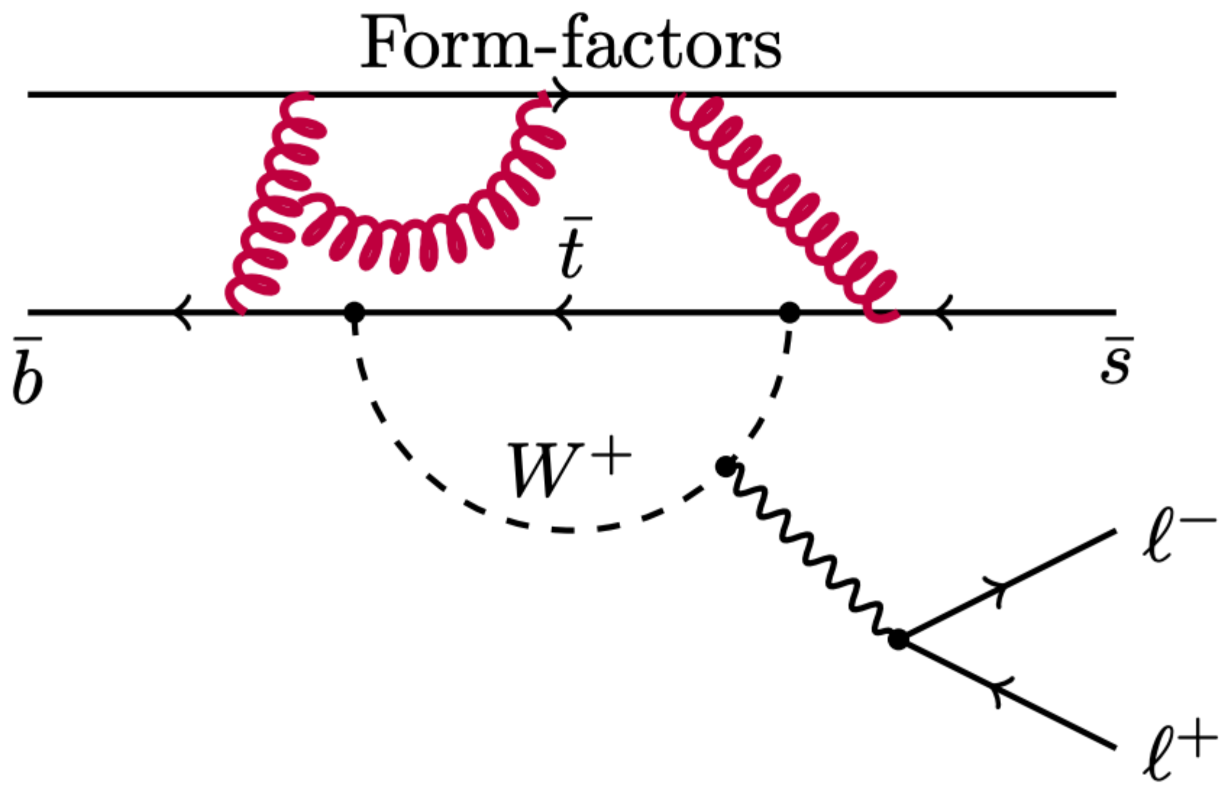
"We stress that a non-zero S_7 cannot be explained by heavy new physics but requires a sizable hadronic effect that introduces a strong phase"



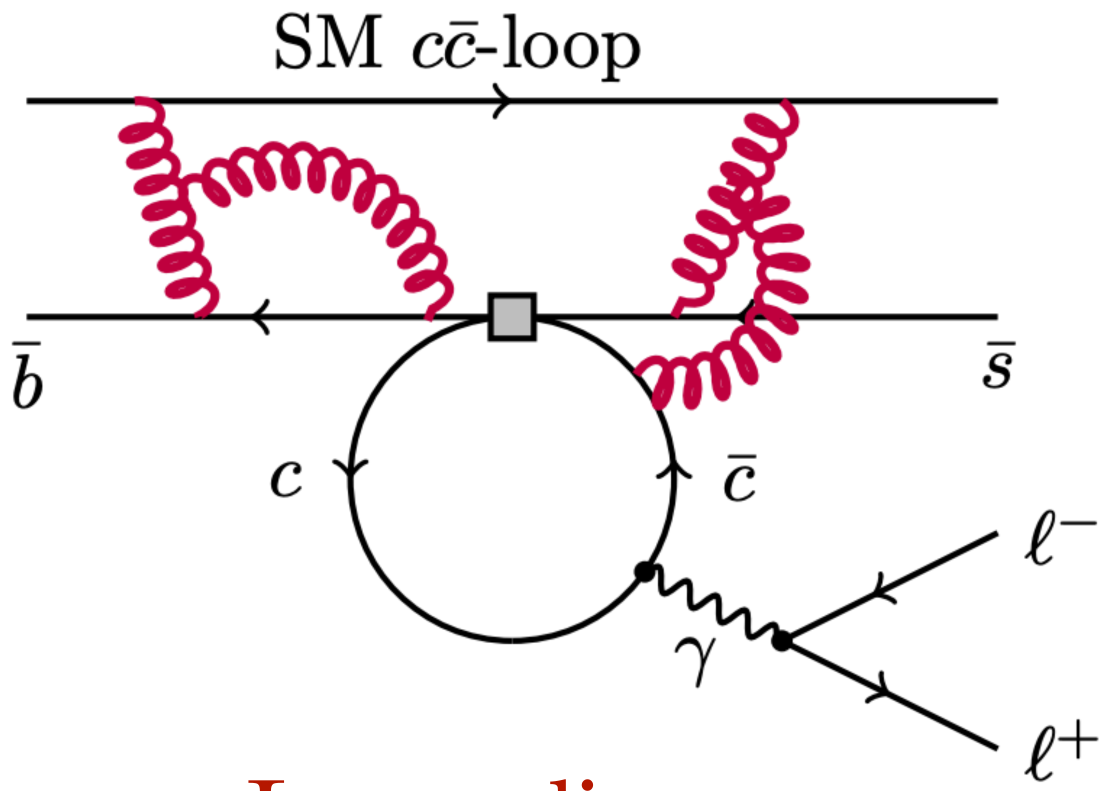
[arXiv:2512.18053]

Hadronic uncertainties

- Before interpreting these deviations as New Physics, we must understand the hadronic uncertainties



Local hadronic form factors



Long-distance
non-local contributions
can mimic shifts in Wilson coefficients

$$\mathscr{A} \propto \underbrace{C_i}_{\text{Short-distance}} \times \underbrace{\langle H_s | O_i | H_b \rangle}_{\text{Hadronic matrix elements}}$$

- Understanding the QCD hadronic uncertainties is crucial for understanding the experimental results
- Both local and non-local hadronic contributions exhibit a non-trivial q^2 dependence

How can we disentangle New Physics from hadronic effects?

- What is behind the observed tensions?
  - Charm-loop effects?
  - Unknown hadronic effects?
  - New Physics?

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- An ideal observable should provide:
  - Independent hadronic systematics
  - Cleaner theoretical description
  - Complementary sensitivity to New Physics
  - Experimental feasibility

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  - Cleaner theoretical description ✓
  - Complementary sensitivity to New Physics ✓
  - Experimental feasibility ⚠

→ Inclusive $B \to X_s \ell\ell$

Experimental challenges

- Ideal approach:
  - Fully inclusive reconstruction ($\ell^+\ell^-$ only)
  - No extrapolation to missing final states
  - Direct comparison with SM predictions
- Experimentally challenging:
  - Large partially reconstructed backgrounds
  - Large combinatorial background (hadron colliders)
  - Inclusive signal difficult to isolate using only $\ell^+\ell^-$

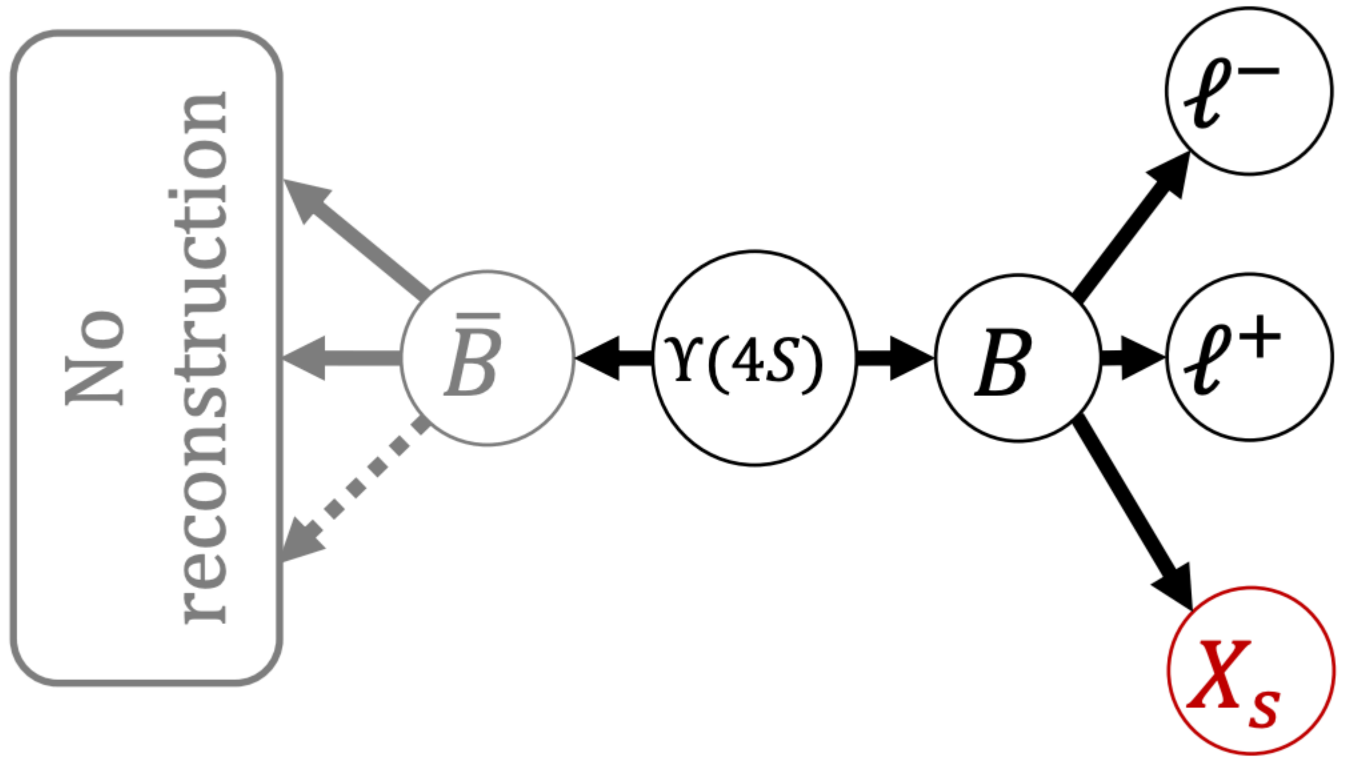
Current experimental solution

- Sum-of-exclusive approach:
  - Reconstruct many exclusive X_s final states
  - Combine their yields & estimate the visible rate
  - Extrapolate to the full inclusive rate
- Remaining challenges:
  - Missing X_s states, extrapolations
    - Model dependence
  - Cuts in m_{X_s} to control backgrounds → limited m_{X_s} acceptance
  - Efficiency corrections

Preliminary results from Belle II

[Check Z. Wang talk at Moriond EW 2026]

- Some preliminary results from Belle II
  - 2019-2022 Belle II data (365 fb^{-1})



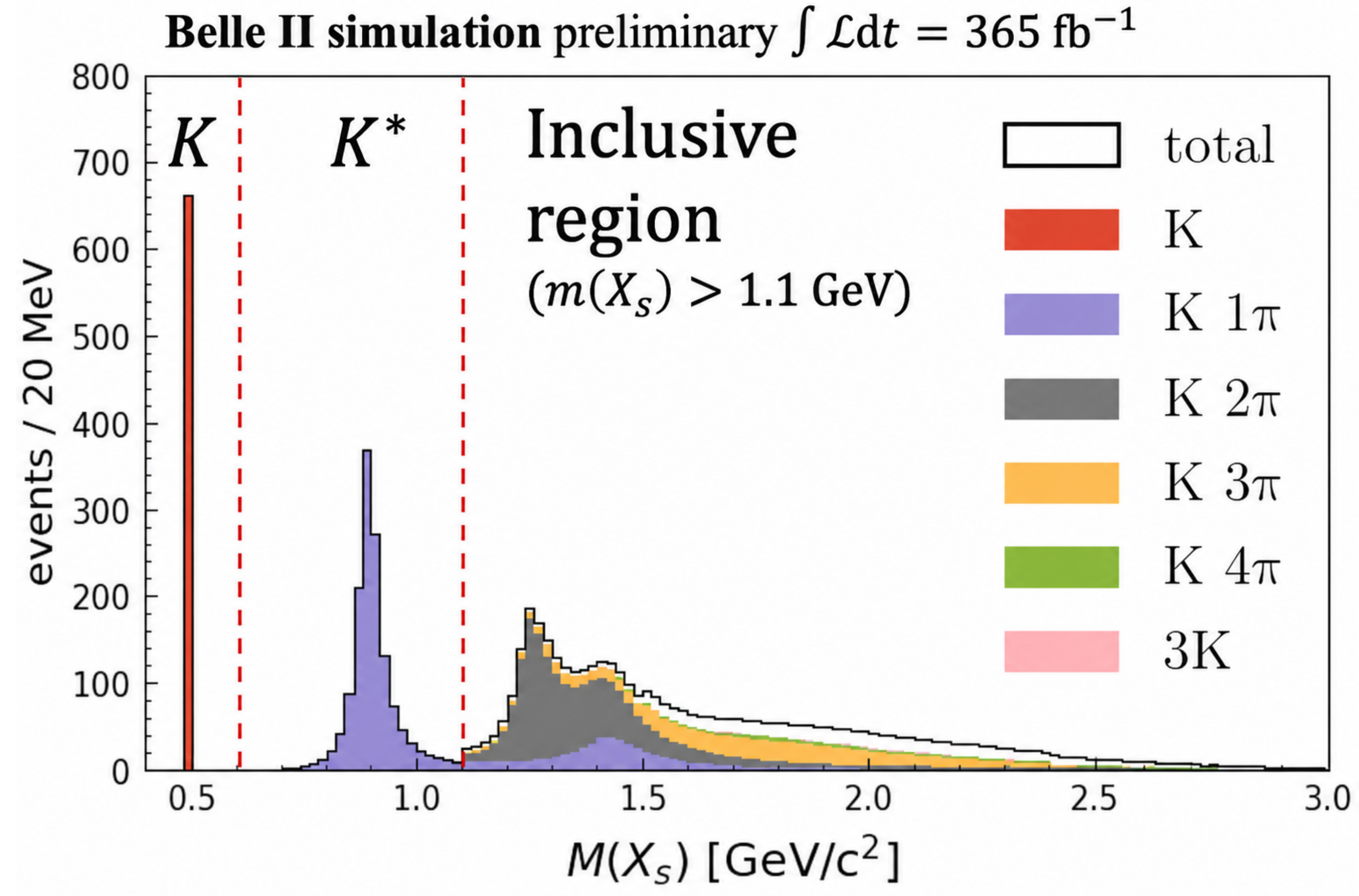
- Sum-of-exclusive: X_s reconstructed from 20 modes in $m_X < 1.8$ GeV$/c^2$ region

- $$\mathscr{B}(B \to X_s \ell\ell) = \frac{N_{sig}}{\epsilon \cdot f_{visi} \cdot 2N_{B\bar{B}}}$$

Visible fraction (by Pythia, Lund String model)

Efficiency of the reconstructed modes (simulation)

	$B^0, \bar{B}^0$		$B^\pm$	
K	K_S		$K^\pm$	
$K\pi$	$K^\pm\pi^\mp$	$K_S\pi^0$	$K^\pm\pi^0$	$K_S\pi^\pm$
$K2\pi$	$K^\pm\pi^\mp\pi^0$	$K_S\pi^\mp\pi^\pm$	$K^\pm\pi^\mp\pi^\pm$	$K_S\pi^\pm\pi^0$
$K3\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp$	$K_S\pi^\mp\pi^\pm\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^0$	$K_S\pi^\mp\pi^\pm\pi^\pm$
$K4\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^0$	$K_S\pi^\mp\pi^\pm\pi^\mp\pi^\pm$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^\pm$	$K_S\pi^\mp\pi^\pm\pi^\mp\pi^0$
$3K$	$K_SK^\pm K^\mp$		$K^\pm K^\pm K^\mp$	



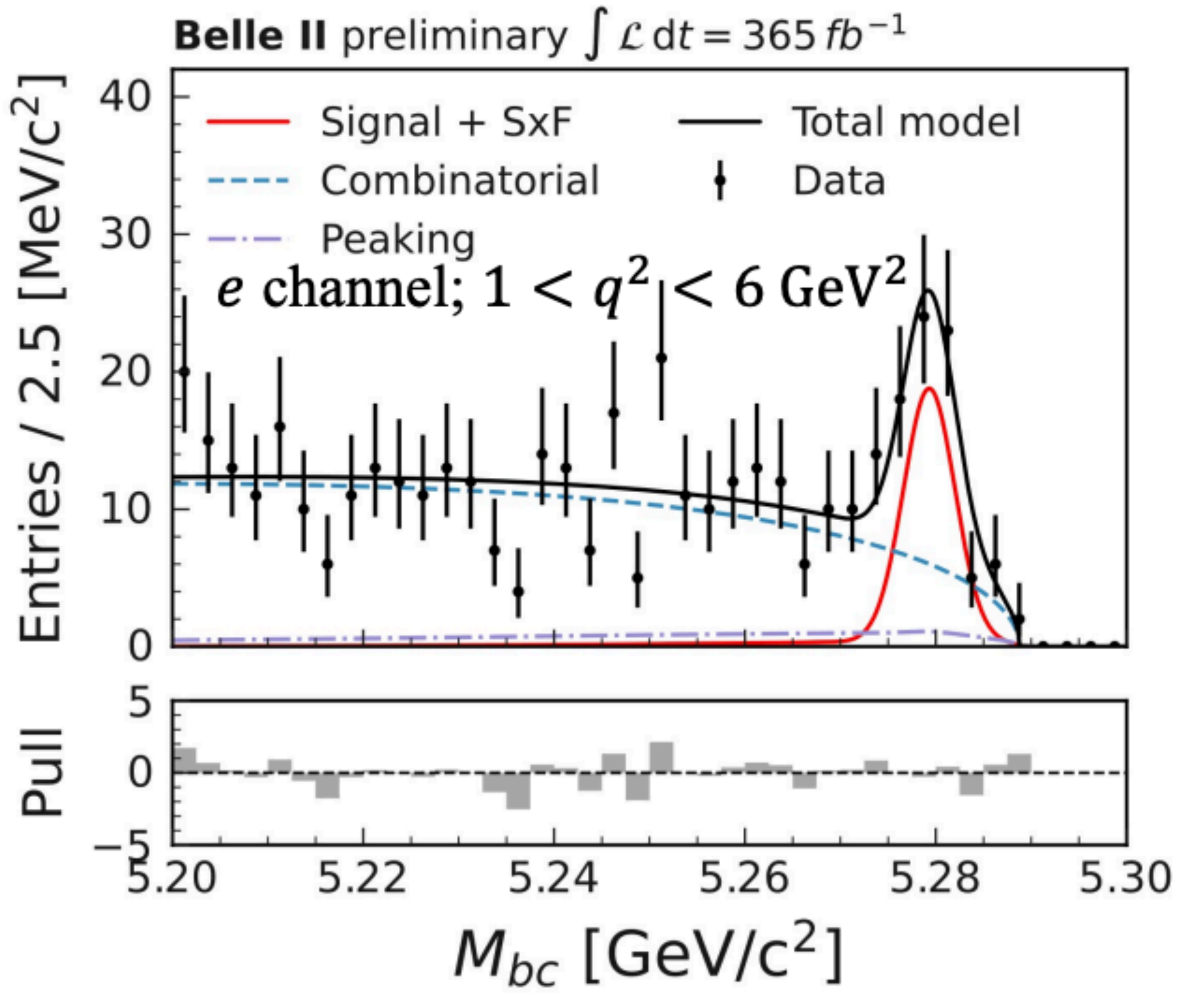
Preliminary results from Belle II

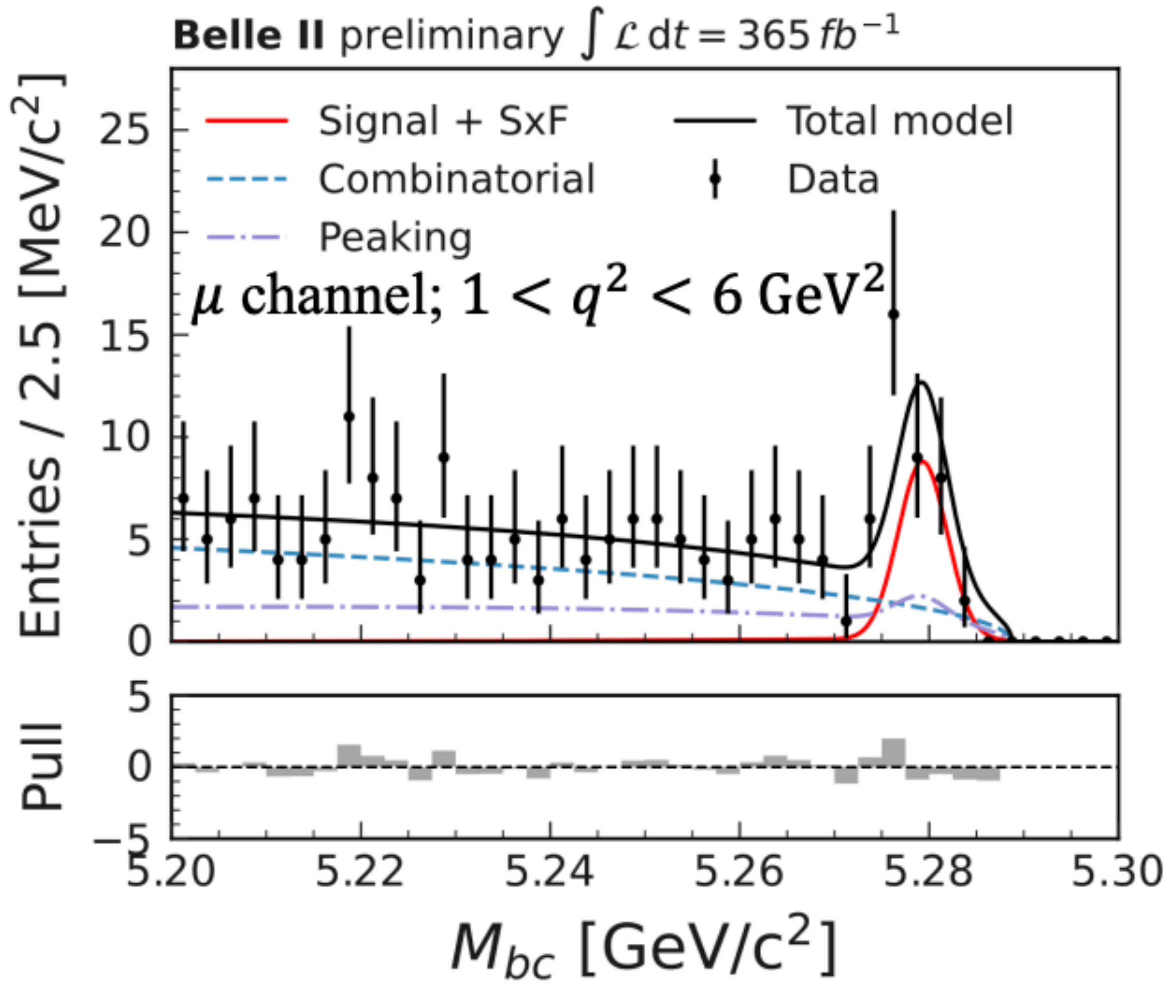
[Check Z. Wang talk at Moriond EW 2026]

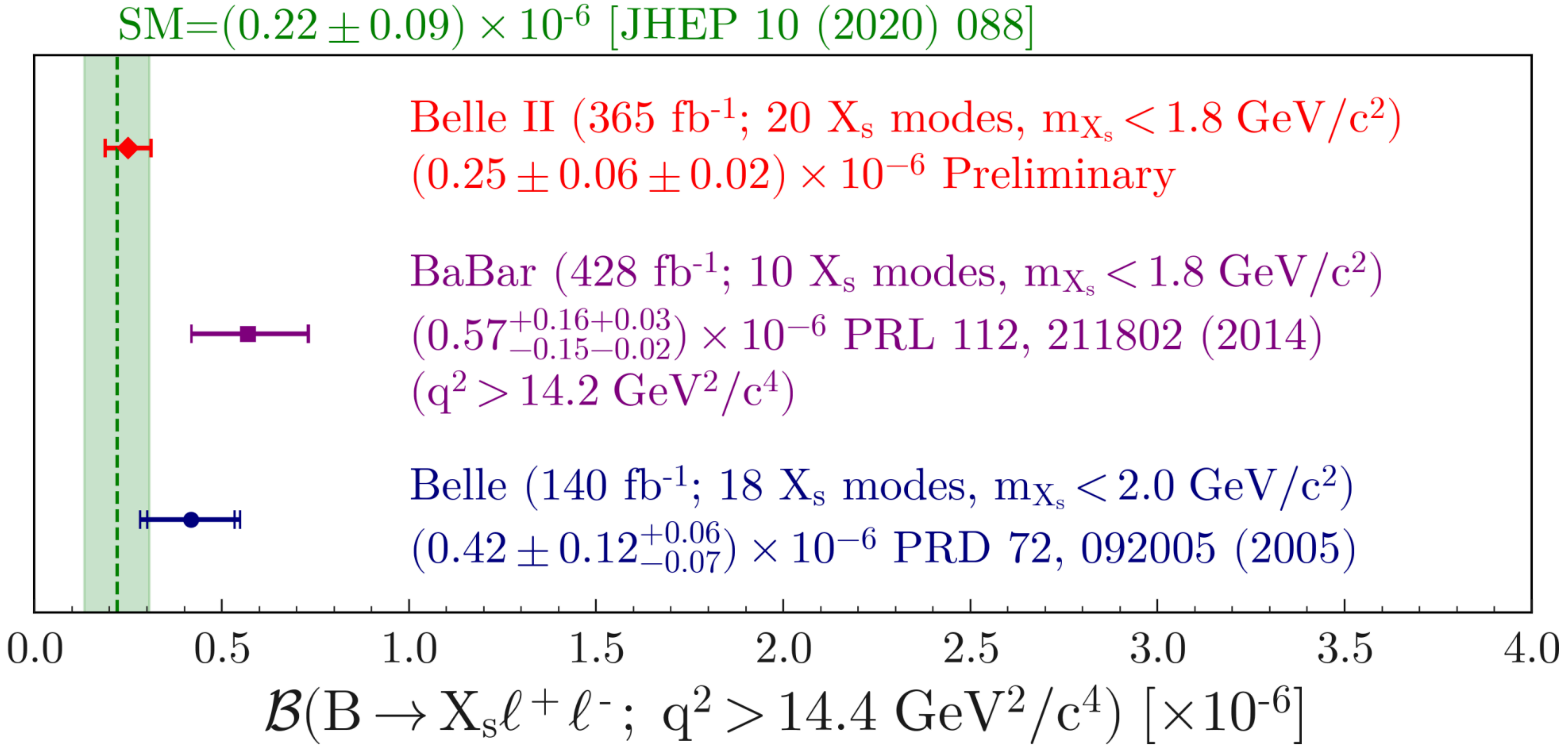
- Fragmentation correction obtained in a data-driven way
  - Control samples $B \to X_s\gamma$ and $B \to X_s J/\psi$
  - Calibrate the hadronic fragmentation model

$\approx$ 180 events in total

$$M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$$







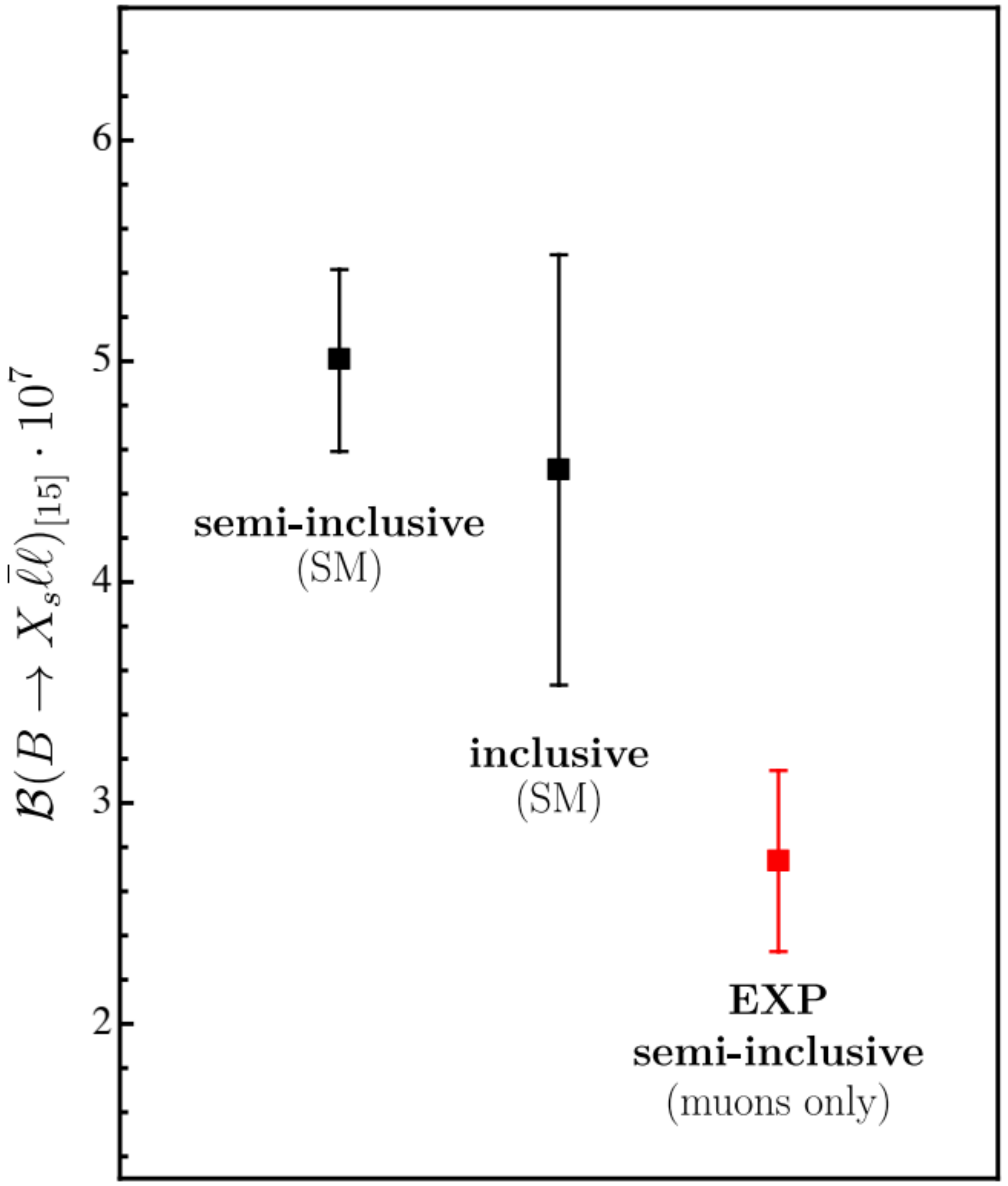
Sum-of-exclusive approaches at LHCb?

[Y. Amhris, P. Owen, EPJC 82 (2022) 371]

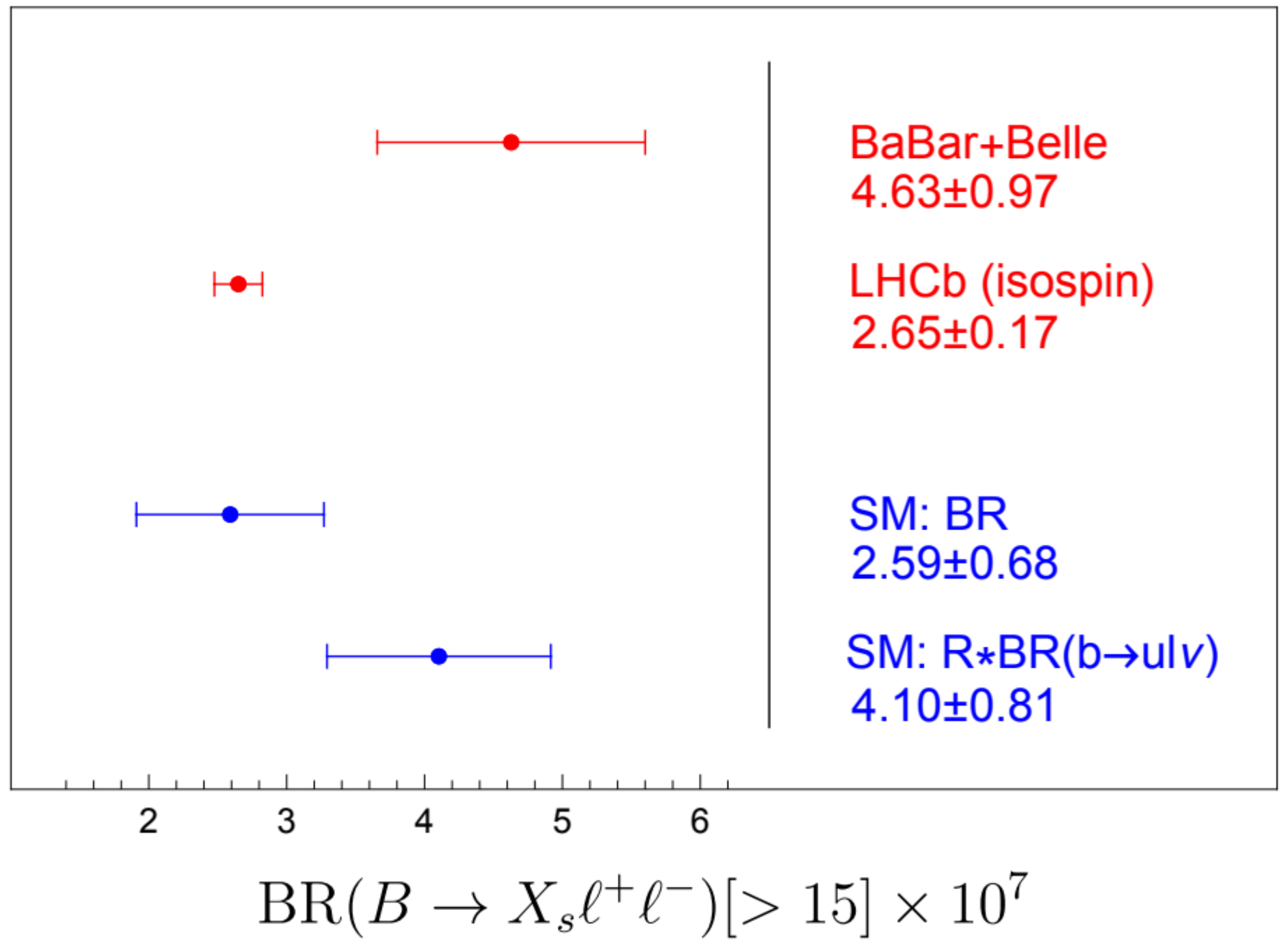
- Reconstruct instead $K^+\ell^+\ell^-X$
  - Require one kaon in addition to the dilepton pair
- Experimental advantages
  - Better defined decay-vertex and background rejection
  - Self-tagged, high-yield inclusive signature
- From $K^+\ell^+\ell^-X$ to $X_s\ell\ell$
  - Use isospin symmetry to account for neutral-kaon final states in B^0 and B^+ decays
  - Treat B_s^0 and Λ_b^0 contributions as backgrounds, to be subtracted using dedicated inclusive or semi-inclusive measurements

Tensions in (semi-) inclusive approaches at high-q^2

- Similar tension observed also in the inclusive $b \to s\bar{\mu}\mu$ rates at high q^2
  - *Insensitive* to hadronic form factors
  - Independent verification of this phenomenon
- More precise measurements at high-q^2 can also provide further input to clarify these tensions



G. Isidori, Z. Polonsky, A. Tinari ([Phys. Rev. D 108 (2023)])

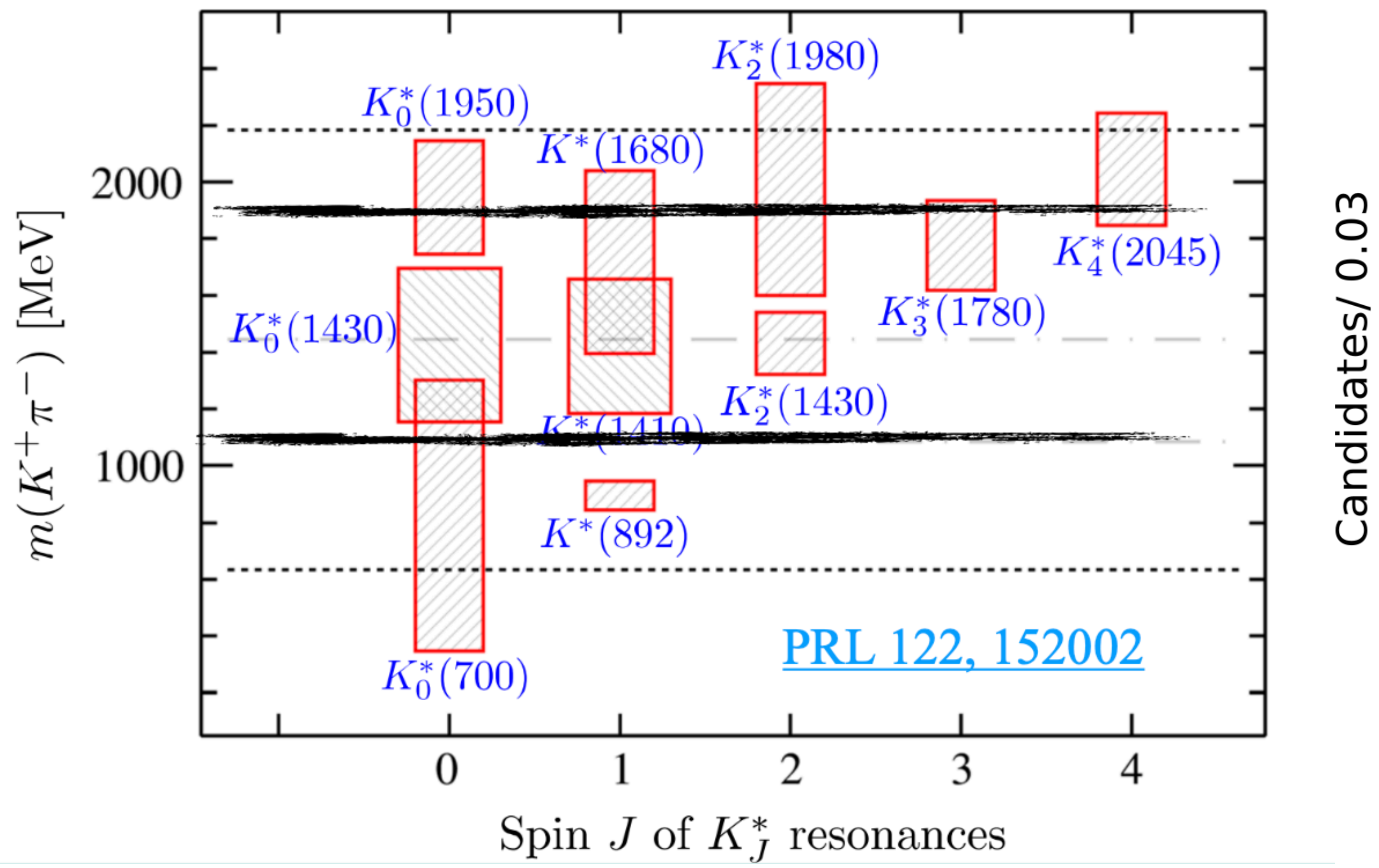


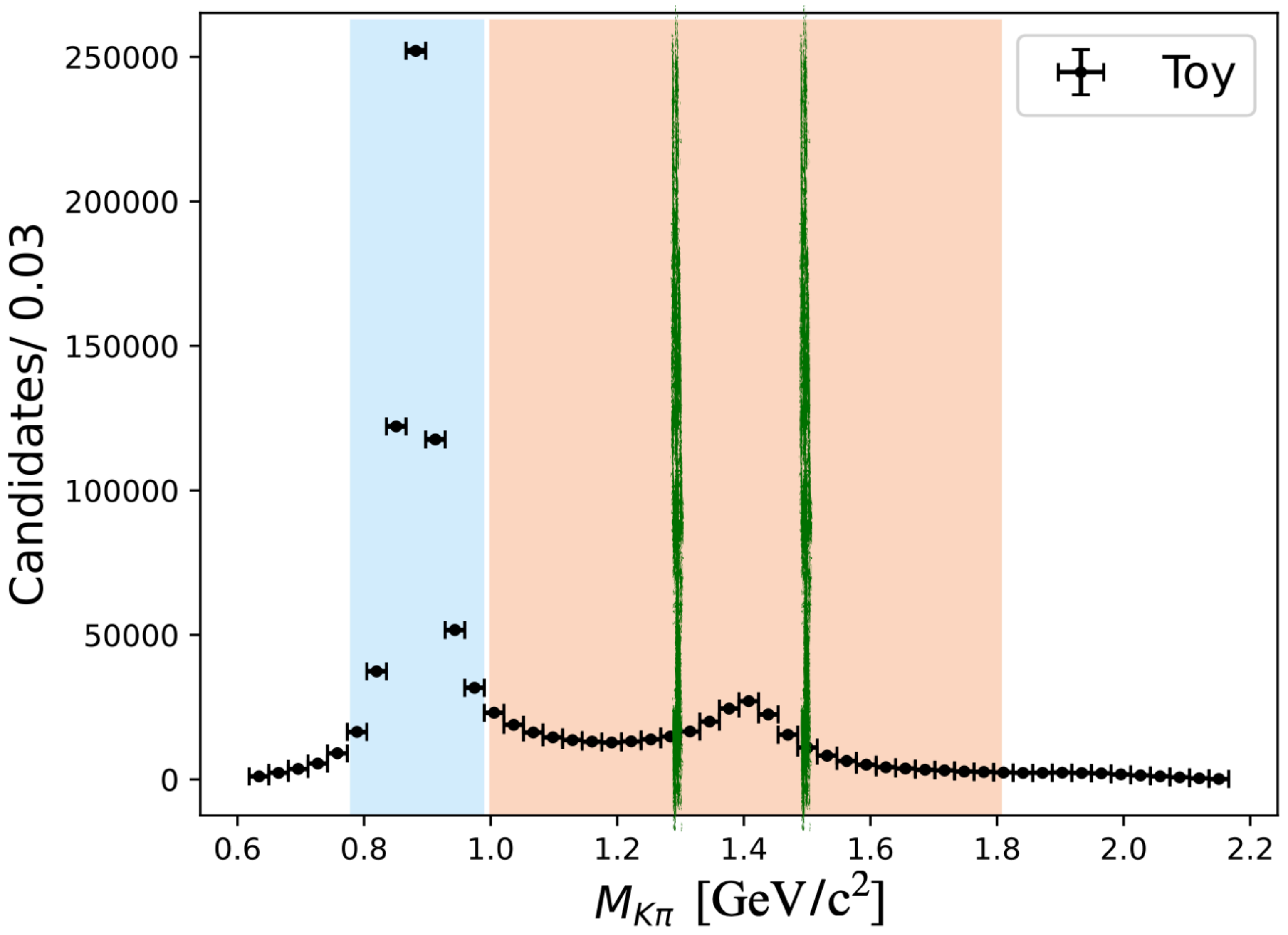
T. Huber, J. Jenkins, et al. ([Phys. Rev. D 108 (2023)])

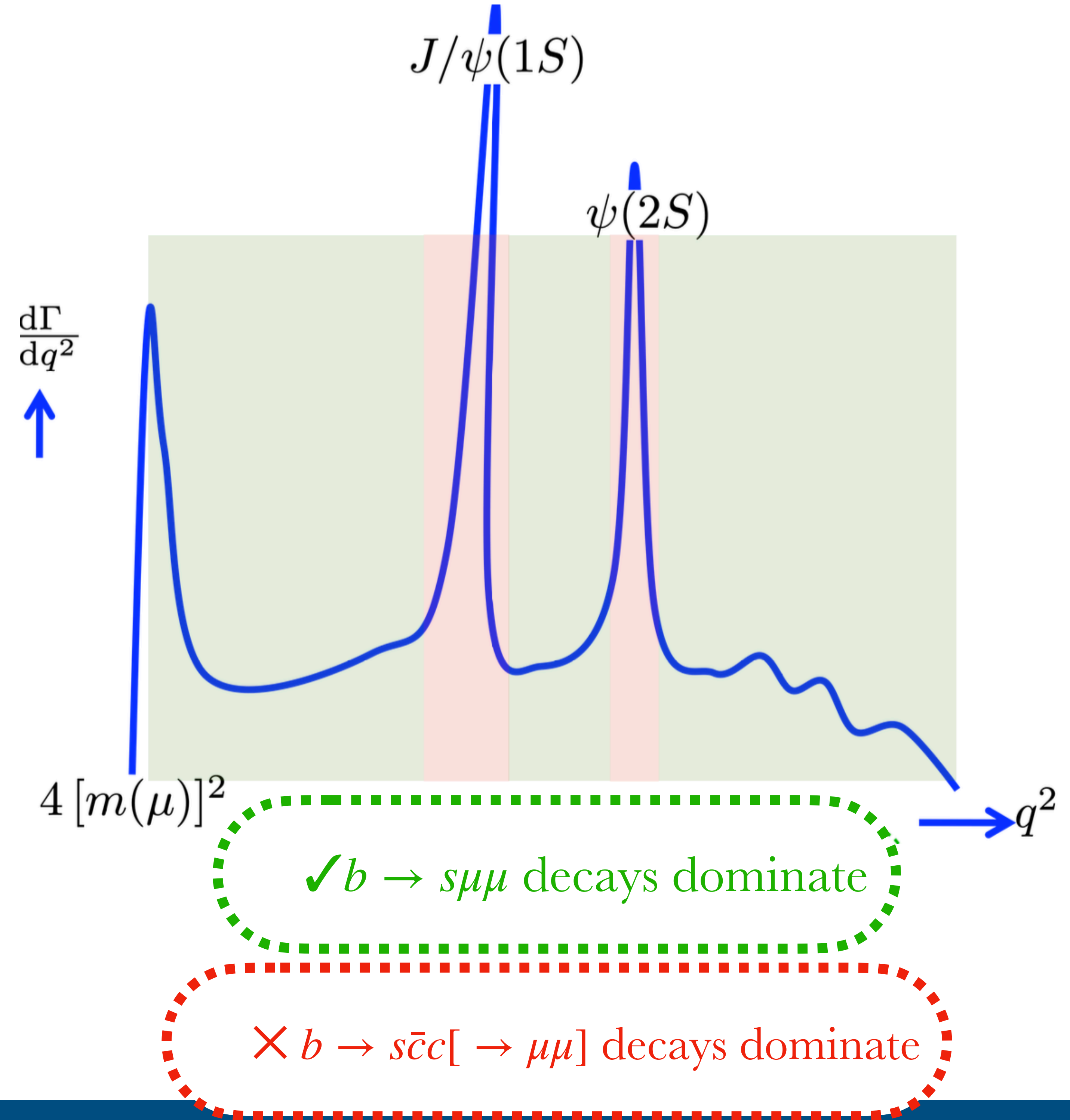
Some new results from LHCb…

$B^0 \to K^+\pi^-\mu^+\mu^-$ at high $m(K\pi)$ mass (8.4 fb^{-1})

- Most measurements of this final state are in the $K^{*0}(892)$ resonance
  - Now we have explored the upper mass region, composed of many resonances
- Previous measurement in Run1 data with $m(K\pi)$ in 1330-1530 MeV (JHEP 12 (2016) 065)
  - Not previously done at high-q^2 in this region

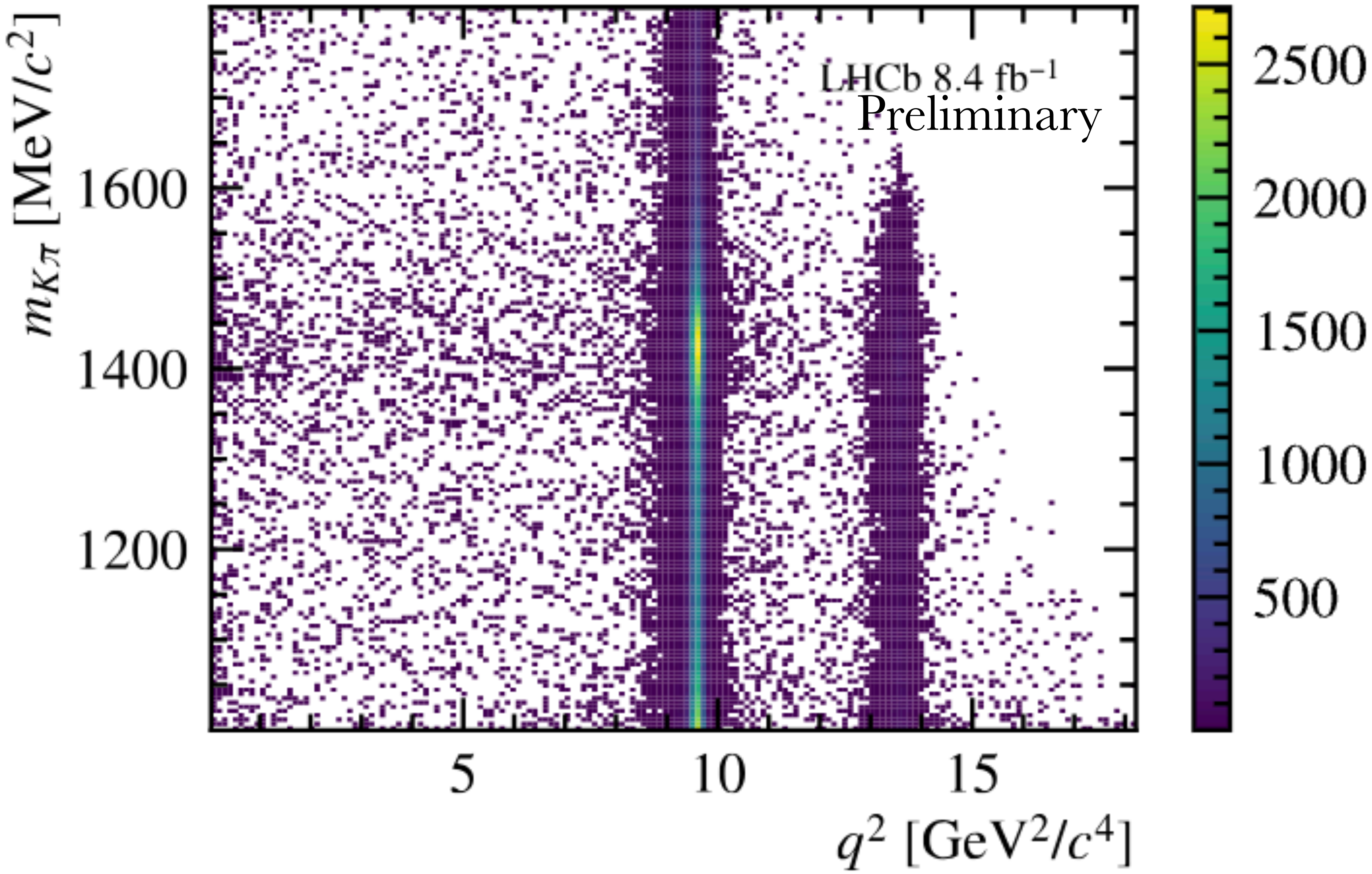






$B^0 \to K^+\pi^-\mu^+\mu^-$ at high $m(K\pi)$ mass (8.4 fb^{-1})

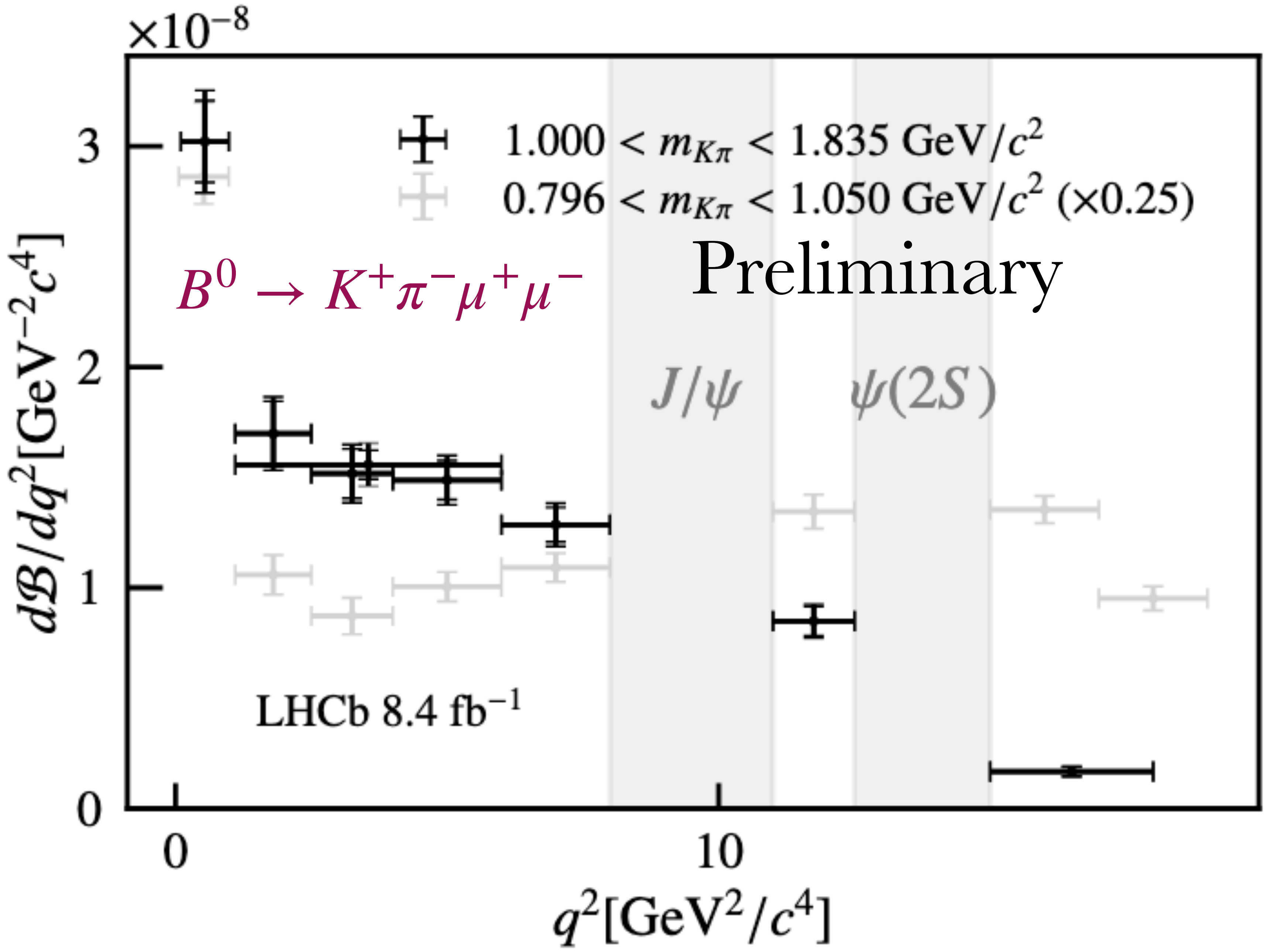
- Data from pp collisions collected by LHCb between 2011 and 2018 (8.4 fb^{-1})
  - 7 and 8 TeV in Run 1 (2011-2012) and 13 TeV for Run 2 (2015-2018)

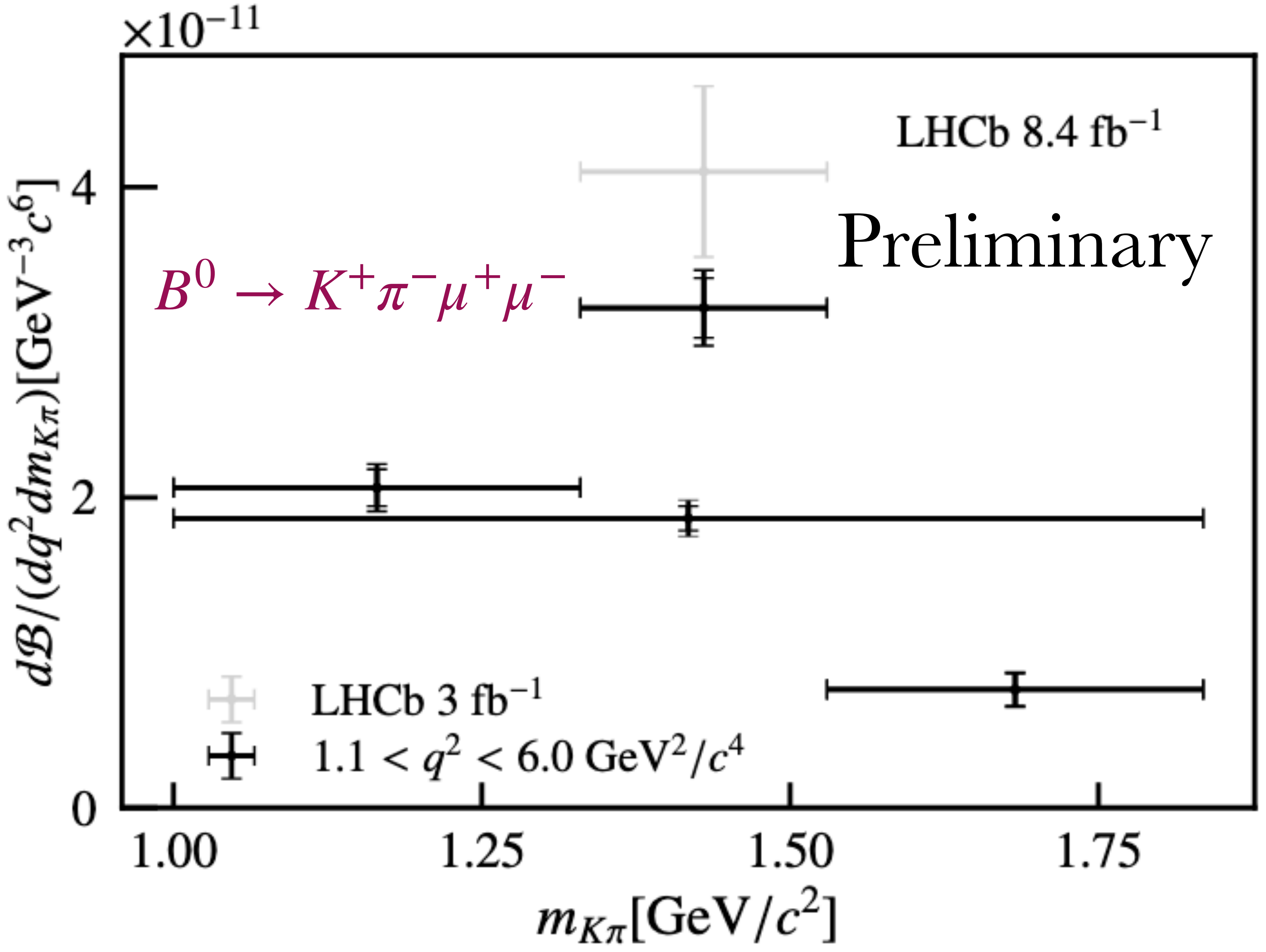


$m(K^+\pi^-)$ [MeV/c^2]	q^2 [GeV^2/c^4]
1000-1835	0.10-0.98
1000-1835	1.1-6.0
1000-1330	1.1-6.0
1330-1530	1.1-6.0
1530-1835	1.1-6.0
1000-1835	1.1-2.5
1000-1835	2.5-4.0
1000-1835	4.0-6.0
1000-1835	6.0-8.0
1000-1835	11.0-12.5
1000-1835	15.0-18.0

$B^0 \to K^+\pi^-\mu^+\mu^-$ at high $m(K\pi)$ mass (8.4 fb^{-1})

- First observation of $B^0 \to K^+\pi^-\mu^+\mu^-$ in two regions of q^2 above the J/ψ resonance
- Theory predictions above 1 GeV/c² are needed to check for compatibility with SM
- First complete determination of the $B^0 \to K^+\pi^-\mu^+\mu^-$ decay width
- Updated semi-inclusive experimental $b \to s\mu\mu$ rate, for comparison with theoretical predictions at high-q^2





$B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$ (8.4 fb^{-1})

$B^+ \to K^+\pi^+\pi^-\mu^+\mu^-$ (8.4 fb^{-1})

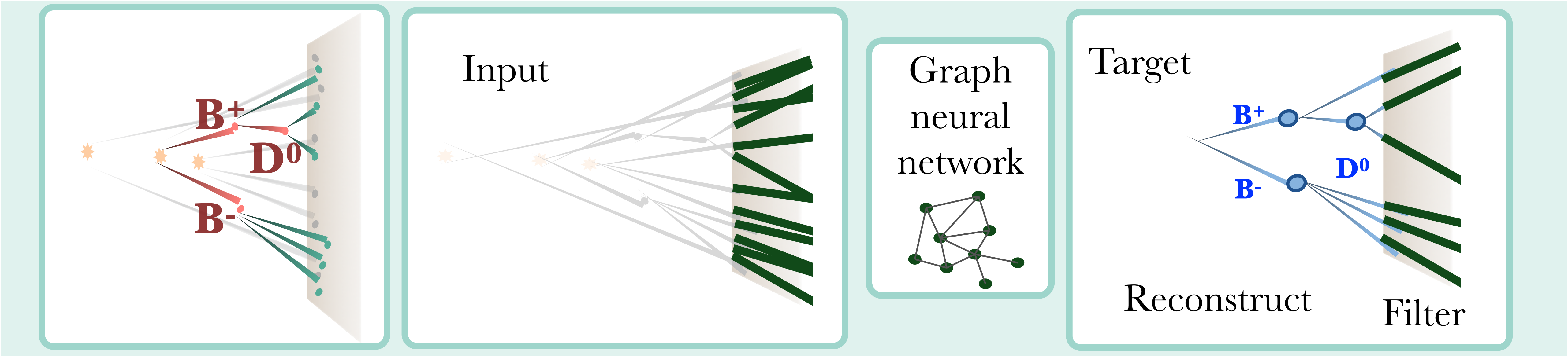
Results still blinded & not public…

But should be out in a few months, stay tuned!

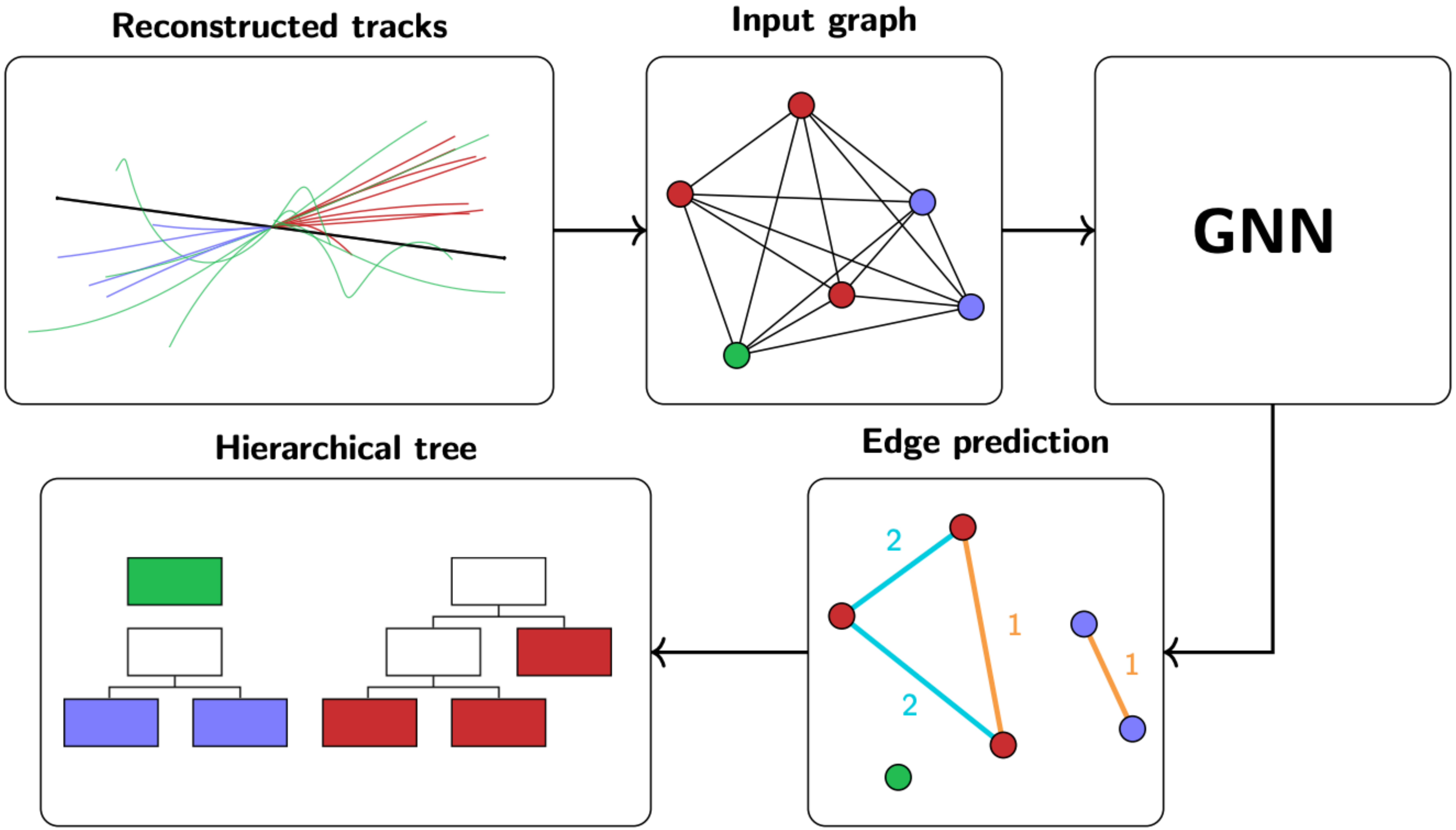
Towards a more inclusive approach…

Deep-learning based Full Event Interpretation (DFEI)

- Event reconstruction proposal for the LHCb Upgrade II
  - Graph-Neural-Network (GNN)-based
  - Input features: charged particles and its measured properties (nodes) and their relations (edges)
  - Hierarchical, automatized and inclusive reconstruction of heavy-hadron decay chains
  - Safely discard rest of event, with minimal loss for analyses → powerful event size reduction in a multi-signal environment
  - Tool for background classification & suppression, useful for analysis



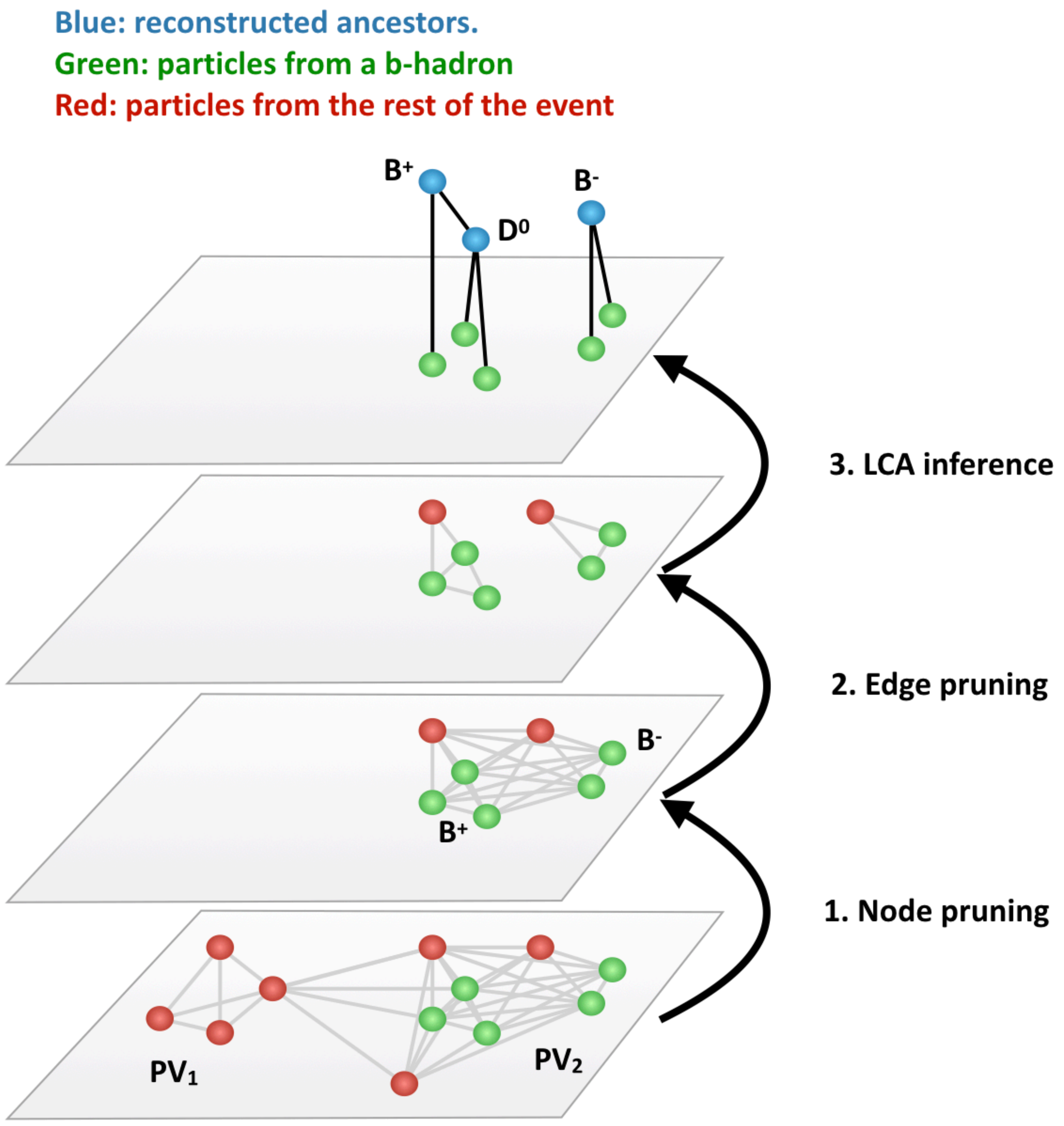
From tracks to hierarchical tree

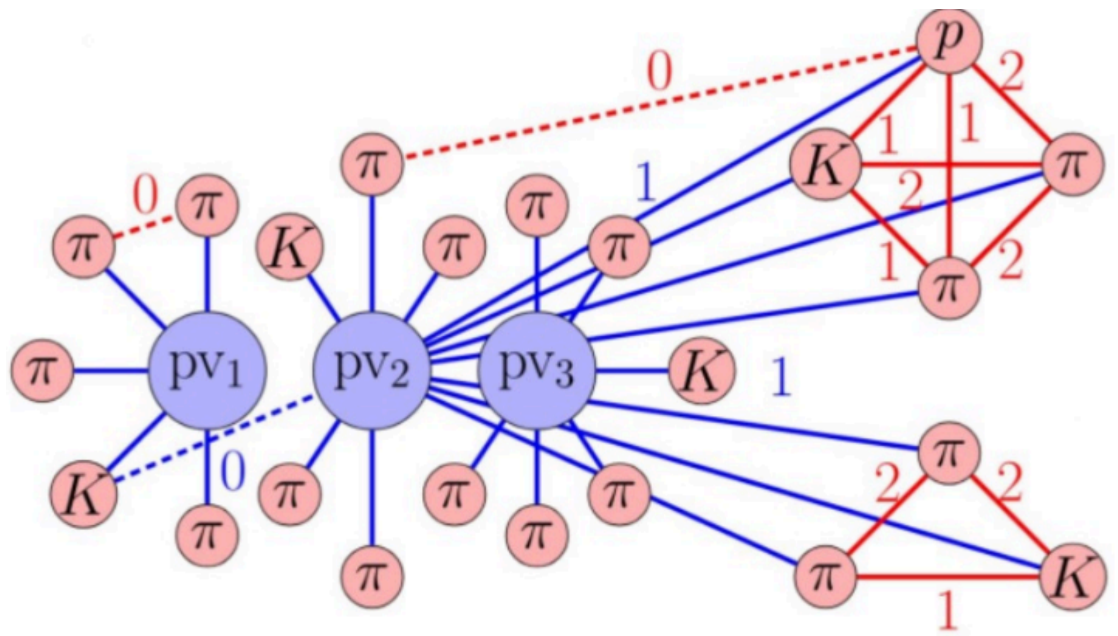


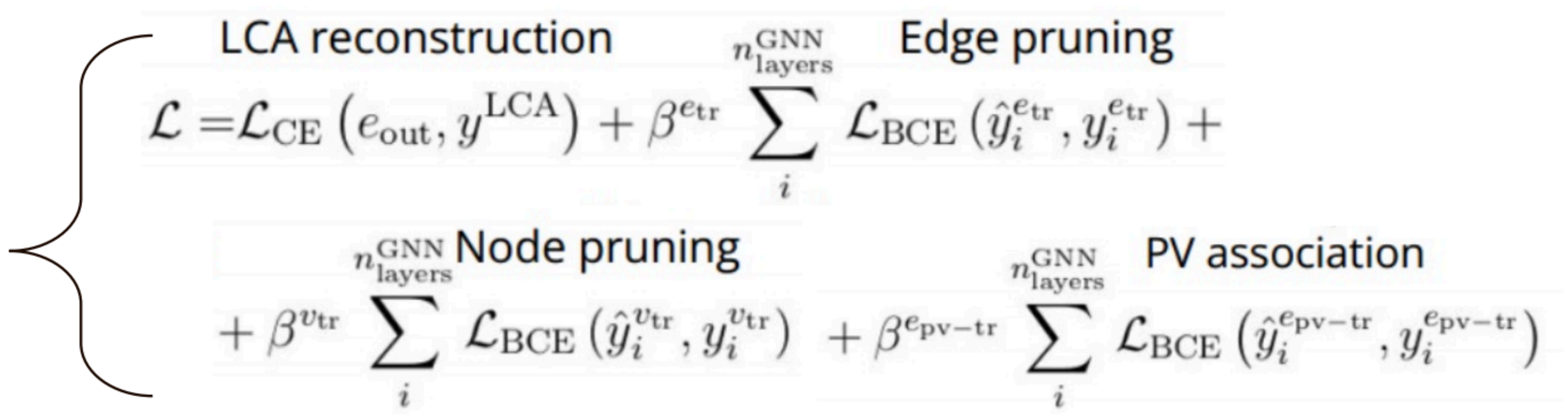
Deep-learning based Full Event Interpretation (DFEI)

[Comput.Softw.Big Sci. 7 (2023) 1, 12]

[Mach. Learn.: Sci. Technol. 6 045060]







$$\mathcal{L} = \mathcal{L}_{\mathrm{CE}}\left(e_{\mathrm{out}}, y^{\mathrm{LCA}}\right) + \beta^{e_{\mathrm{tr}}} \sum_i^{n_{\mathrm{layers}}^{\mathrm{GNN}}} \mathcal{L}_{\mathrm{BCE}}\left(\hat{y}_i^{e_{\mathrm{tr}}}, y_i^{e_{\mathrm{tr}}}\right) + \beta^{v_{\mathrm{tr}}} \sum_i^{n_{\mathrm{layers}}^{\mathrm{GNN}}} \mathcal{L}_{\mathrm{BCE}}\left(\hat{y}_i^{v_{\mathrm{tr}}}, y_i^{v_{\mathrm{tr}}}\right) + \beta^{e_{\mathrm{pv-tr}}} \sum_i^{n_{\mathrm{layers}}^{\mathrm{GNN}}} \mathcal{L}_{\mathrm{BCE}}\left(\hat{y}_i^{e_{\mathrm{pv-tr}}}, y_i^{e_{\mathrm{pv-tr}}}\right)$$

- Updated model: HGNN
  - Performs key tasks simultaneously
    - Graph pruning (nodes & edges)
    - Primary vertex association
    - Beauty hadron decays reconstruction

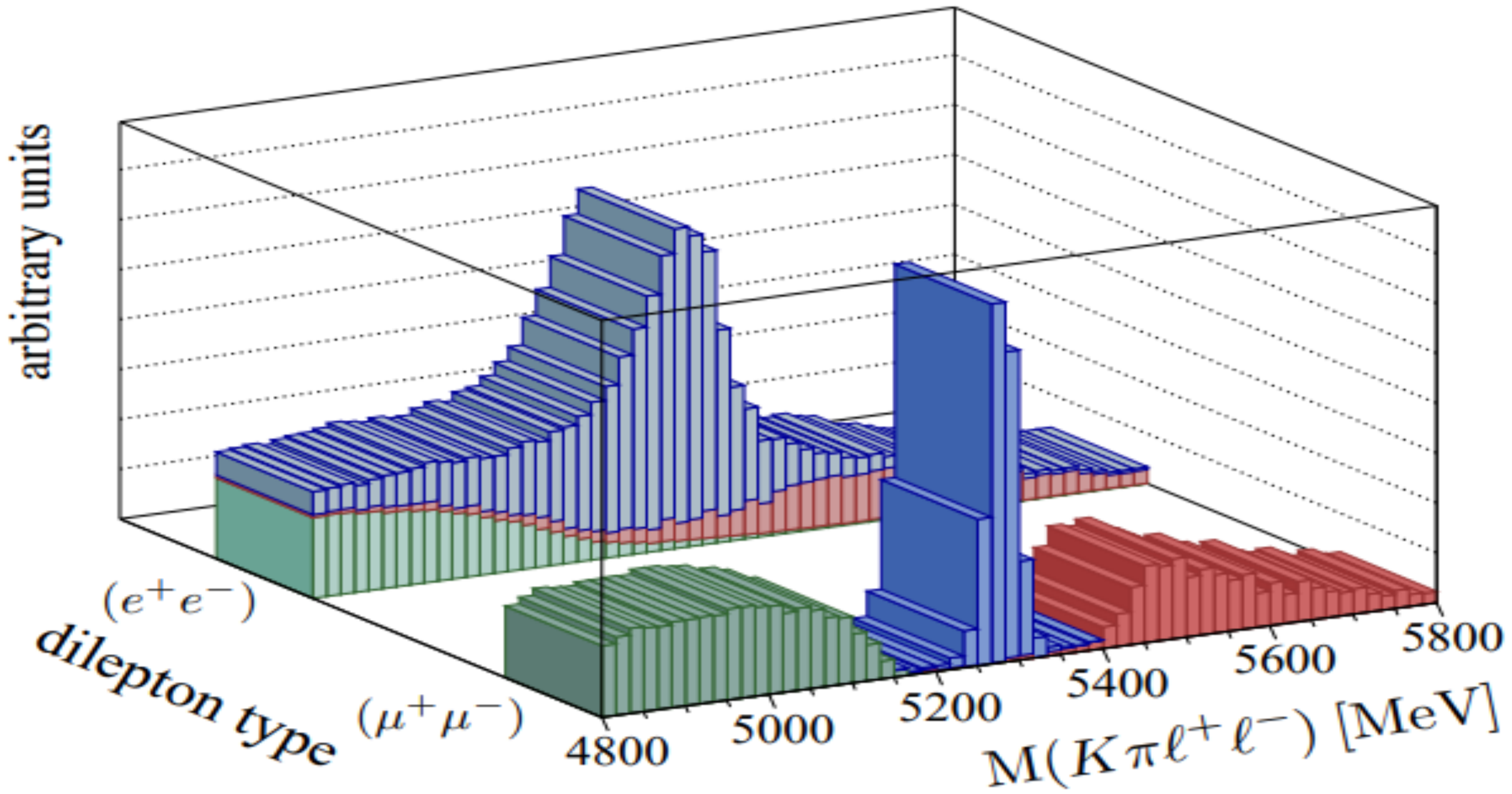
Standard vs DFEI analysis

- Standard exclusive analysis: identification of signal decay → fine-tuned selection
  - Possible contamination from similar partially-, over-reconstructed or poorly identified decays

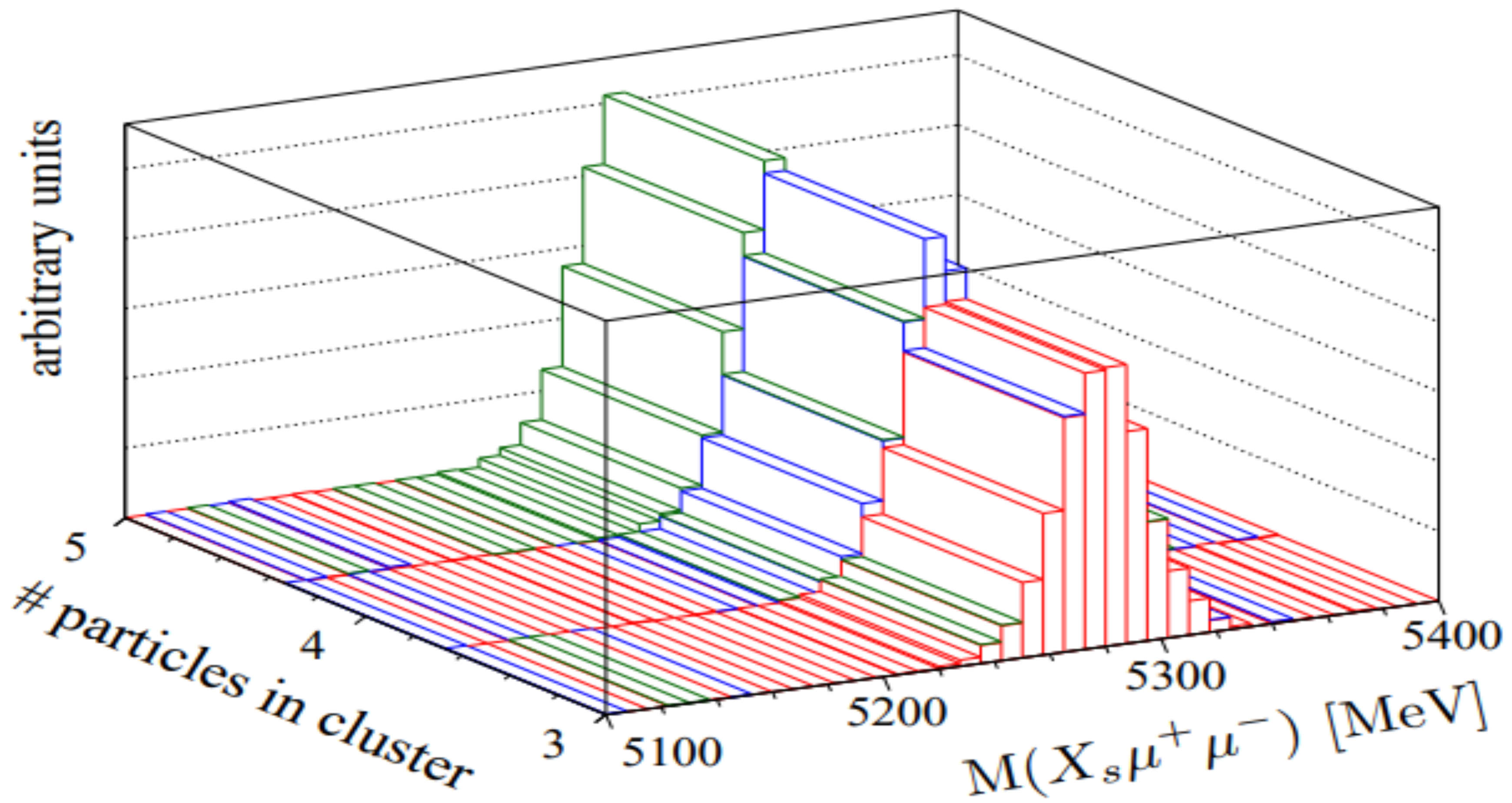
- In DFEI, the algorithm is trained to inclusively identify and reconstruct decay chains originating from a b-hadron → independently of the type of the decay chain or of the number of particles in the final state
  - Partially- and over-reconstructed decays in standard analysis are fully reconstructed in DFEI
  - These contributions are classified in reconstructed clusters of different numbers of particles
  - DFEI seems to mitigate partially- and over-reconstructed background

DFEI: (semi-)inclusive reconstruction

$B^+ \to K^+\pi^-\pi^+\ell^+\ell^-$
$B^0 \to K^+\pi^-\ell^+\ell^-$
$B^+ \to K^+\ell^+\ell^-$



Standard



DFEI-based

A novel path towards a semi-inclusive approach in LHCb?

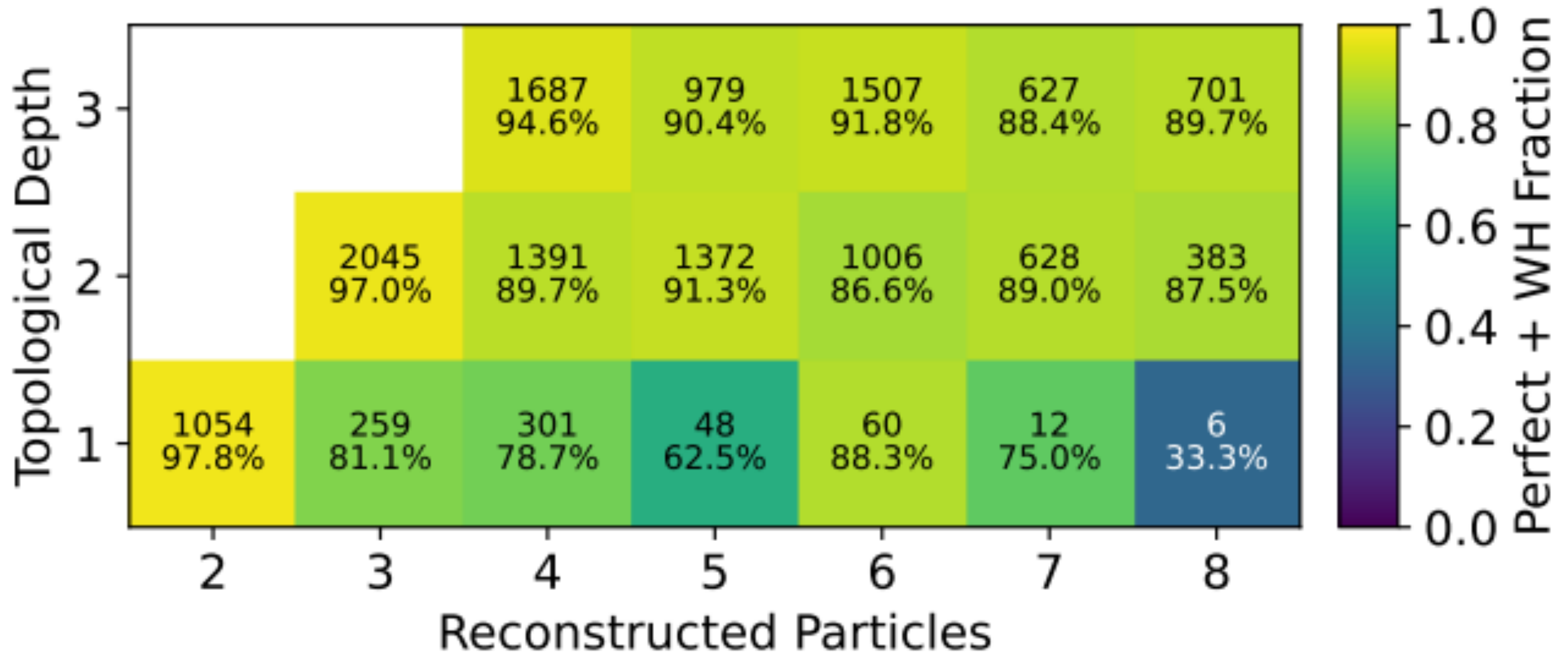
Questions for a semi-inclusive measurement

- Normalization mode?
  - One normalization per topology?
  - Would it make sense to have a "semi-inclusive" normalization?
    - $B \to X_s J/\psi$?
- Efficiency?
  - Parametrize as a function of multiplicity & number of neutral particles (+ kinematics)
- Inclusive CP measurement: could it be useful?
  - u-spin symmetry, final-state rescattering, …

Prototype DFEI for IDEA detector at FCC-*ee*

[Check Samuel Morand's talk at Flavours at FCC Workshop]

- Fast simulations of FCC-ee events using PYTHIA8 [6], EVTGEN [7] and DELPHES [8] for the IDEA detector concept [9].
- Centrally produced inclusive samples available for training and evaluation : $e^+e^- \to Z \to b\bar{b}$ at $\sqrt{s} = 91$ GeV.
- Exclusive channel samples are generated locally for testing.
- Only charged reconstructed particles are considered.
- Benchmark B-physics channels used for comparison with the literature [3, 10].



$B^0 \to K^{*0}[K^+\pi^-]\mu^+\mu^-$	$B^+ \to \bar{D}^0[K^+\pi^-\pi^+\pi^-]\pi^+$
$B^0 \to K^+\pi^-$	$B^+ \to \bar{D}^0[K^+\pi^-]\pi^+$
$B^+ \to K^+K^-\pi^+$	$B^+ \to D_s^+[K^+K^-\pi^+]\bar{D}^0[K^+\pi^-]$
$B_s^0 \to J/\psi[\mu^+\mu^-]\phi[K^+K^-]$	$B^+ \to J/\psi[e^+e^-]K^+$
$B_s^0 \to D_s^-[K^+K^-\pi^-]\pi^+$	$B^+ \to J/\psi[\mu^+\mu^-]K^+$
$B_s^0 \to D^+[K^-\pi^+\pi^+]D^-[K^+\pi^-\pi^-]$	$\Lambda_b \to \Lambda_c^+[pK^-\pi^+]\pi^-$
$\Lambda_b \to pK^-$	$\Lambda_b \to pK^-\mu^+\mu^-$

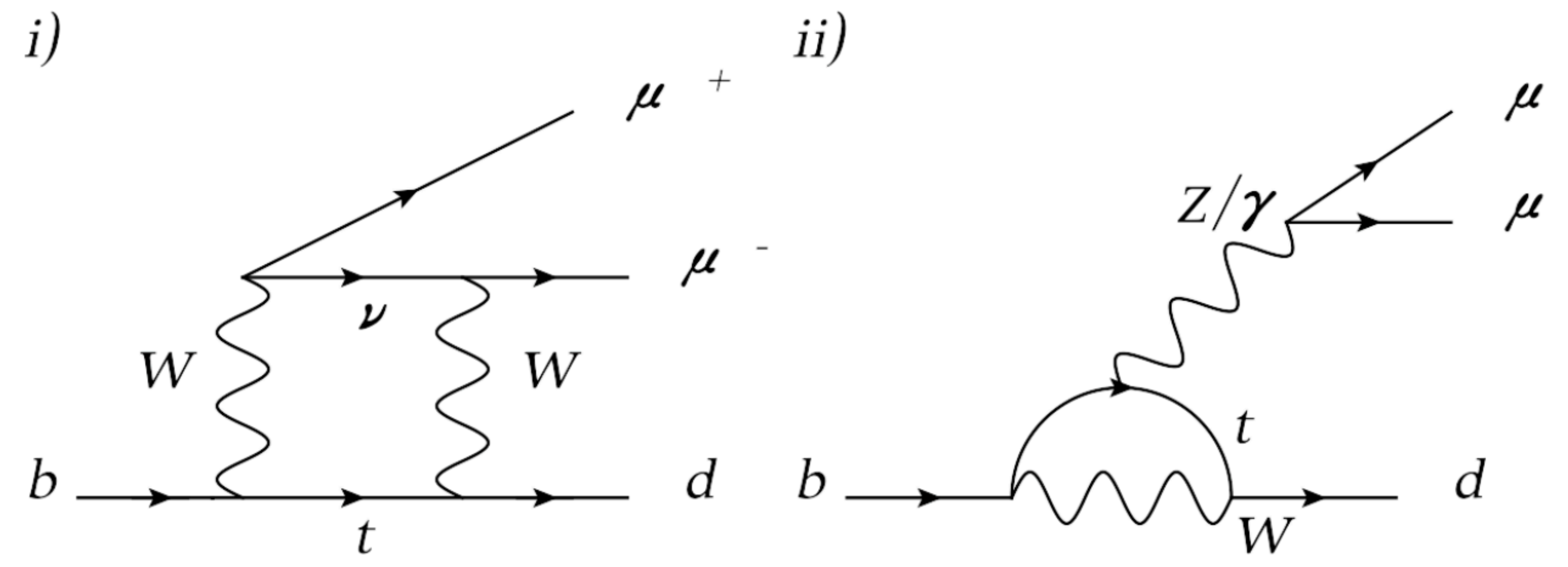
Channel	Perfect	WH	Perfect + WH
$B^0 \to D^+[K^-\pi^+\pi^+]D^-[K^+\pi^-\pi^-]$	81%	16%	**97%**
$B^0 \to K^+\pi^-$	97%	0%	**97%**
$B^0 \to K^{*0}[K^+\pi^-]\mu^+\mu^-$	86%	9%	**94%**
$B^+ \to \bar{D}^0[K^+\pi^-\pi^+\pi^-]\pi^+$	93%	3%	**97%**
$B^+ \to \bar{D}^0[K^+\pi^-]\pi^+$	86%	10%	**96%**
$B^+ \to D_s^+[K^+K^-\pi^+]\bar{D}^0[K^+\pi^-]$	83%	13%	**96%**
$B^+ \to J/\psi[e^+e^-]K^+$	88%	8%	**96%**
$B^+ \to J/\psi[\mu^+\mu^-]K^+$	90%	6%	**96%**
$B^+ \to K^+K^-\pi^+$	82%	13%	**95%**
$B_s^0 \to D_s^-[K^+K^-\pi^-]\pi^+$	86%	10%	**96%**
$B_s^0 \to J/\psi[\mu^+\mu^-]\phi[K^+K^-]$	82%	11%	**93%**
$\Lambda_b \to \Lambda_c^+[pK^-\pi^+]\pi^-$	76%	20%	**96%**
$\Lambda_b \to pK^-$	97%	0%	**97%**
$\Lambda_b \to pK^-\mu^+\mu^-$	89%	5%	**94%**

$b \to d\ell\ell$

Rare decays with $b \to d\ell\ell$ transitions

- Like $b \to s\ell\ell$ transitions, $b \to d\ell\ell$ are highly suppressed in the SM
  - FCNC: loop diagrams in the SM
  - But further CKM suppression from $|V_{td}/V_{ts}|^2$
  - Good probe for new physics: decay rates, angular observables and CPV

- Diagrams of same order of magnitude
  - Interference can produce large CP asymmetry



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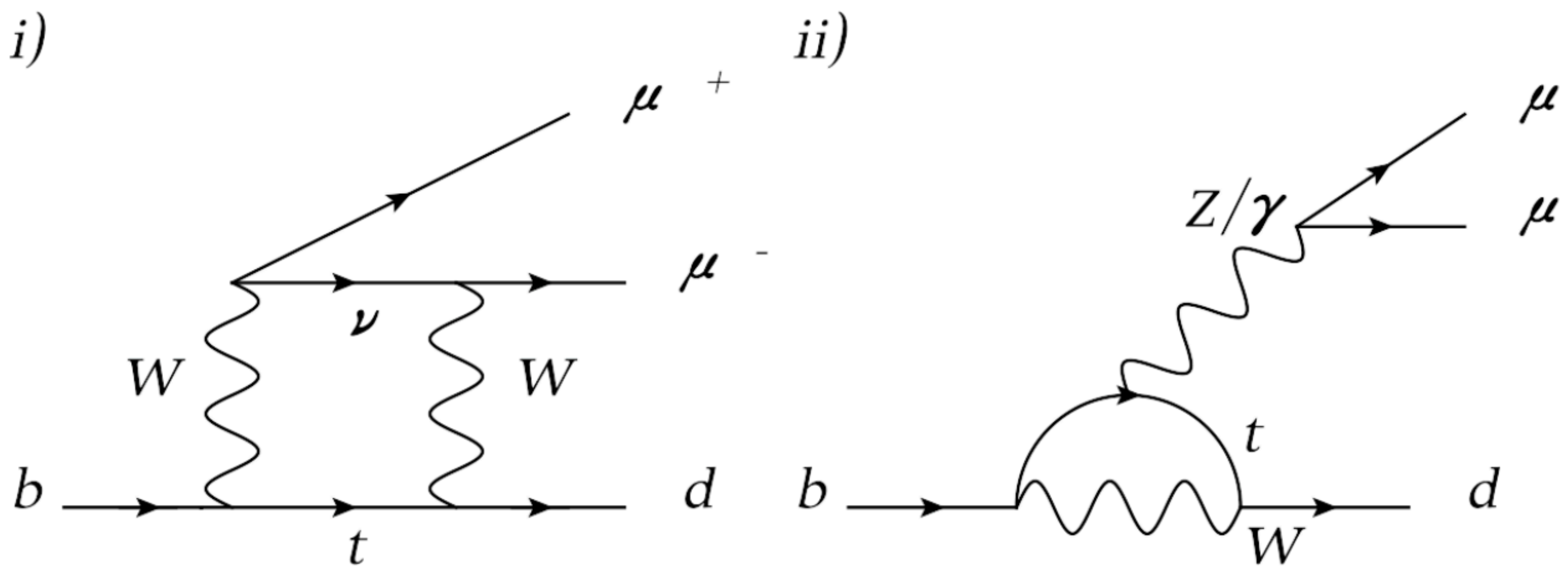
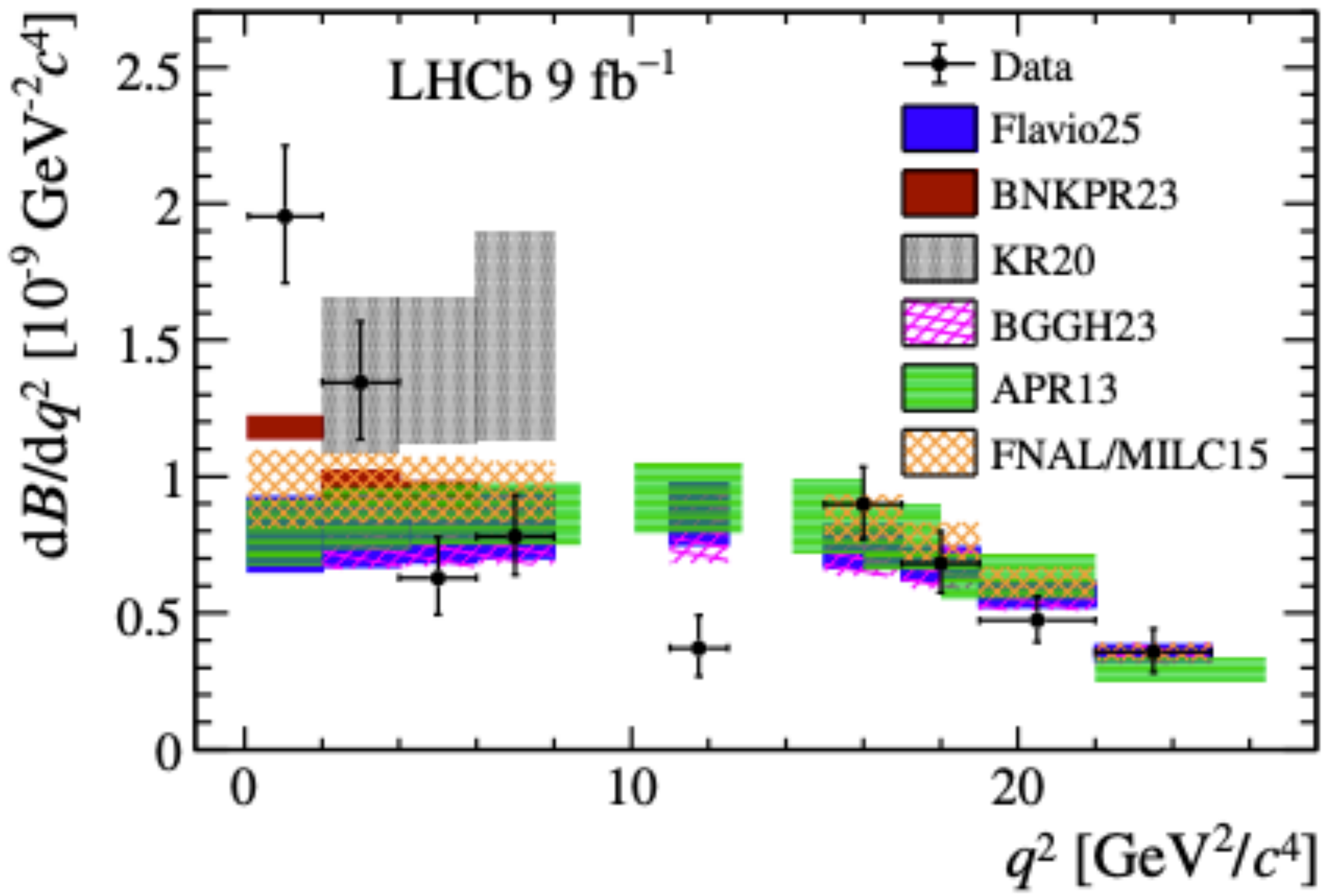
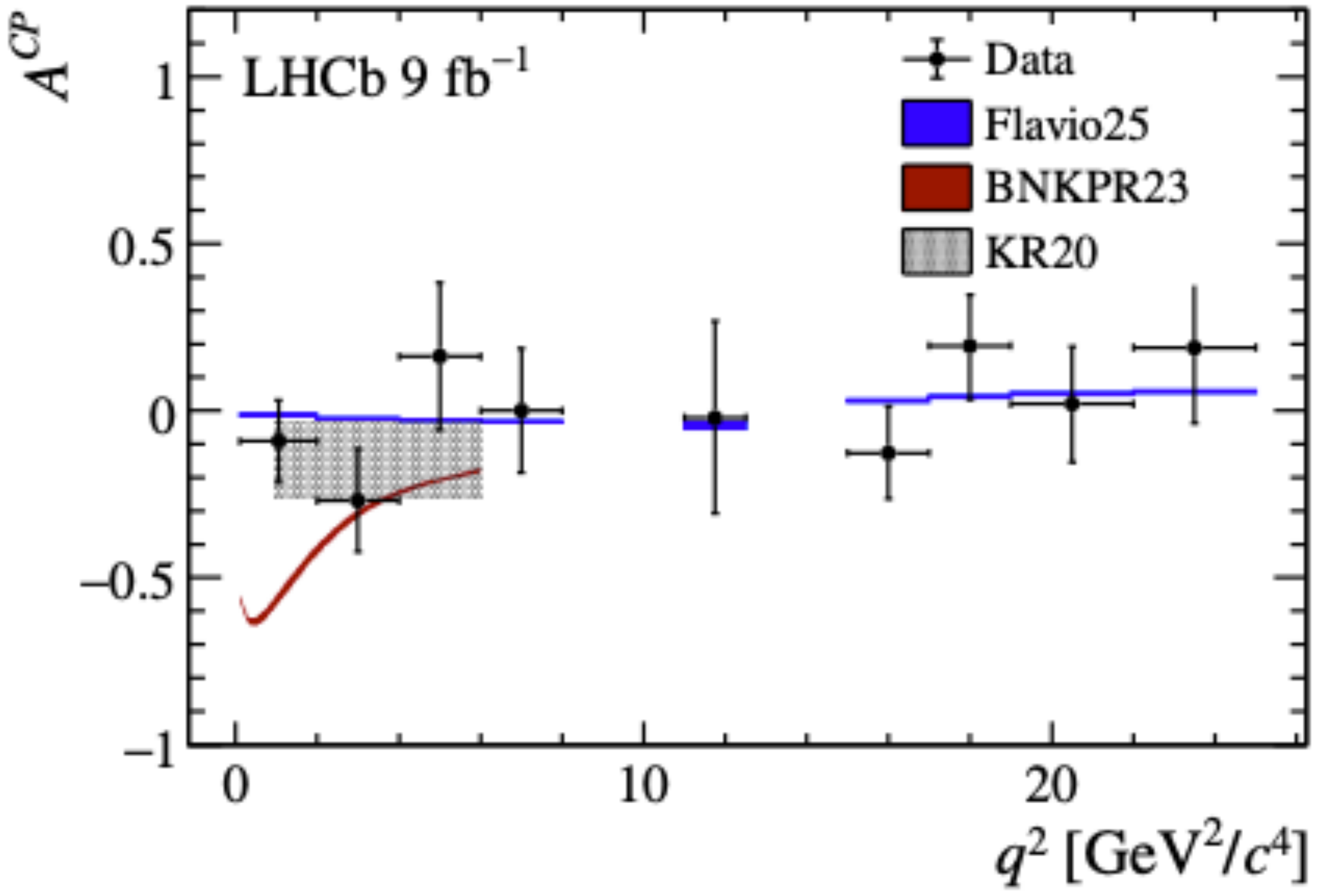
Complementary way to probe anomalies observed in $b \to s\ell\ell$ decays!

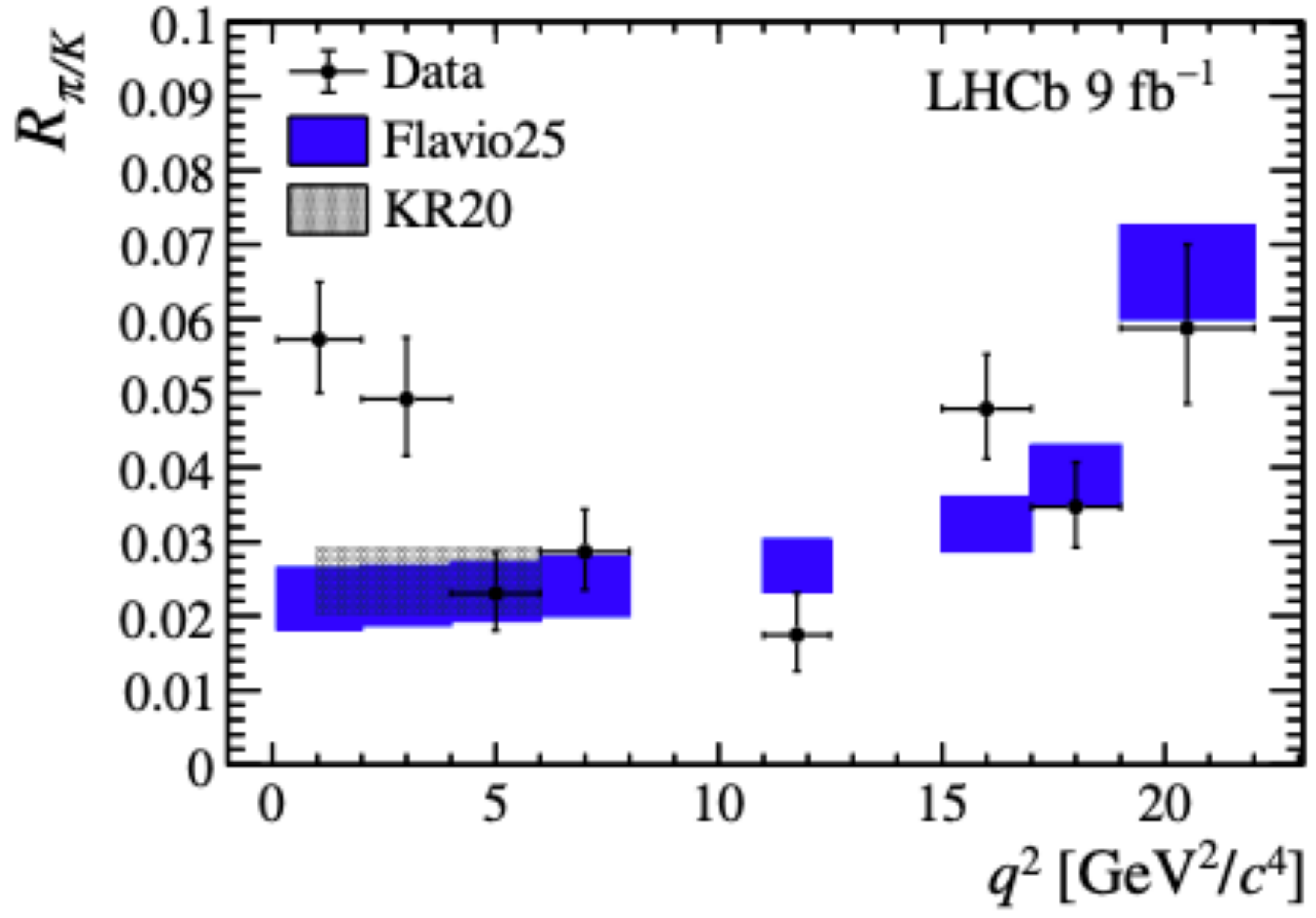


$B^+ \to \pi^+\mu^+\mu^-$ updated $BF + A_{CP}$ measurement

- Updated LHCb measurement using Runs 1 and 2 data (arXiv:2606.23646)







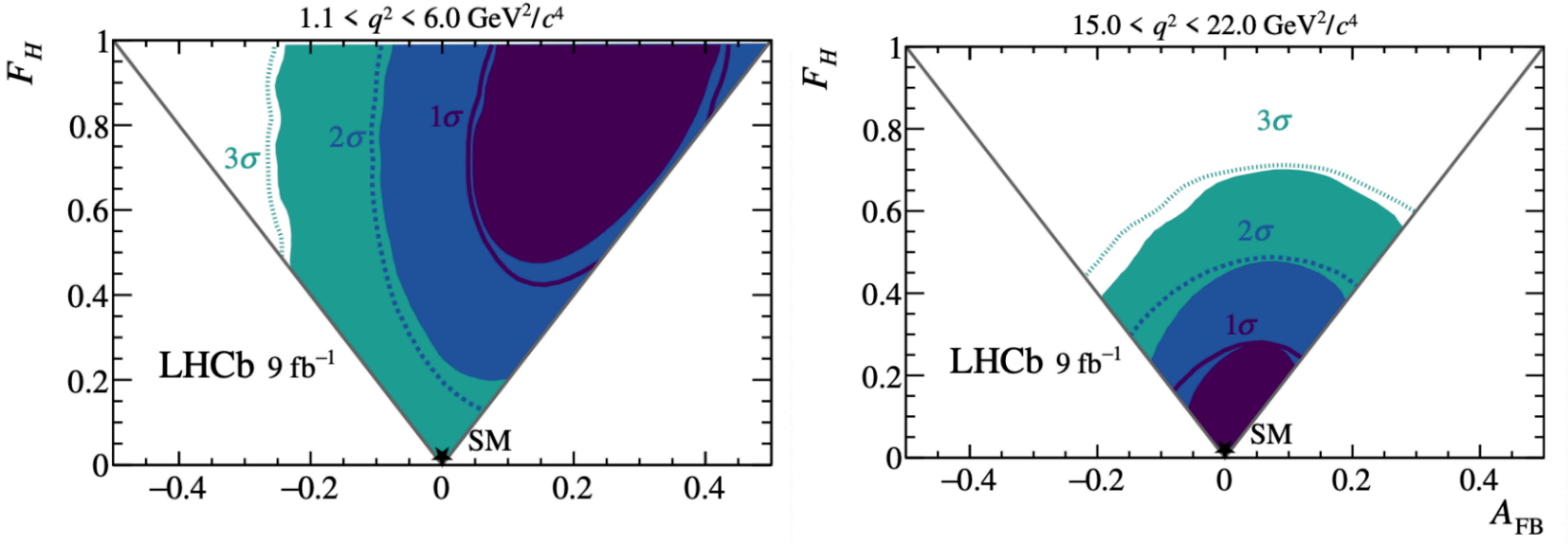
- Localised deviations from the SM predicitions are seen up to the level of 3σ
  - Short-distance contribution seems not enough to explain the data
  - We need input from theory!

$B^+ \to \pi^+\mu^+\mu^-$ angular observables

- Large offset in flavio prediction → absence of light-quark and charmonia modeling
- Angular analysis in two q^2 bins, measuring F_H and A_{FB}

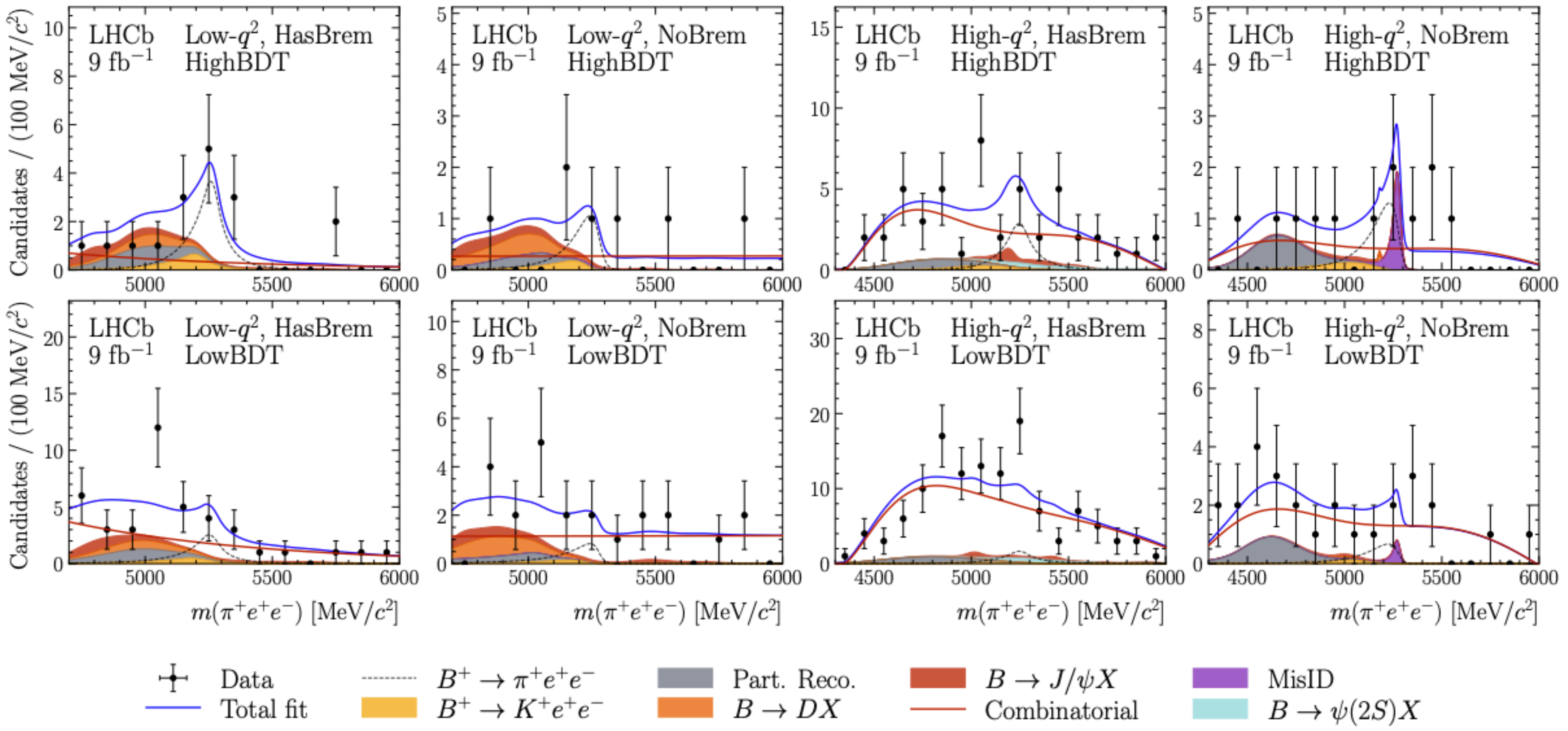
$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_l} = \frac{3}{4}(1-\boxed{F_H})(1-\cos^2\theta_l) + \frac{\boxed{F_H}}{2} + \boxed{A_{\mathrm{FB}}}\cos\theta_l$$

[arXiv:2604.21987]



$B^+ \to \pi^+ e^+ e^-$ decays updated search

- BR estimation from the muon mode:
  - $\mathcal{B}_{\mathrm{SM}}(B^+ \to \pi^+ e^+ e^-) \sim 1.8 \times 10^{-8}$
- Full Run 1&2 LHCb analysis (arXiv:2604.26784)
  - First evidence (3.2σ)!
  - $\mathcal{B}(B^+ \to \pi^+ e^+ e^-) = (2.4^{+0.9+0.4}_{-0.8-0.2}) \times 10^{-8}$
  - $\mathcal{B}(B^+ \to \pi^+ e^+ e^-)^{[0.045,6]\ \mathrm{GeV}^2/c^4} = (0.76^{+0.30+0.14}_{-0.27-0.08}) \times 10^{-8}$
  - $\mathcal{B}(B^+ \to \pi^+ e^+ e^-)^{[15,25]\ \mathrm{GeV}^2/c^4} = (0.40^{+0.52+0.24}_{-0.45-0.22}) \times 10^{-8}$



Prospects & questions in $b \to d\ell\ell$

- CPV wrt $B \to K\mu\mu$? [arXiv:2403.13056]
  - CP asymmetries $\Gamma - \bar{\Gamma} \propto \mathrm{Im}(Y_{u\bar{u}} - Y_{c\bar{c}})$
  - U-spin limit

$$R^{CP}_{K/\pi} \equiv \frac{d\Gamma_K/dq^2 - d\bar{\Gamma}_K/dq^2}{d\Gamma_\pi/dq^2 - d\bar{\Gamma}_\pi/dq^2}$$

$$Y^{(K)}_{u\bar{u}}(q^2) = Y^{(\pi)}_{u\bar{u}}(q^2), \qquad Y^{(K)}_{c\bar{c}}(q^2) = Y^{(\pi)}_{c\bar{c}}(q^2)$$

$$R^{CP}_{K/\pi}\Big|_{U\text{-spin}} = \left(\frac{\lambda_K}{\lambda_\pi}\right)^{3/2} \left(\frac{f_+^{(K)}}{f_+^{(\pi)}}\right)^2 \left[1 + \frac{C_7^{\mathrm{SM}}\left(\tilde{f}_T^{(K)} - \tilde{f}_T^{(\pi)}\right)}{C_9^{\mathrm{SM}} + C_7^{\mathrm{SM}}\tilde{f}_T^{(\pi)}}\right]$$

Non-local amplitudes and CKM factors cancel in the U-spin limit

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Is this relevant?

Non-local amplitudes and CKM factors cancel in the U-spin limit

Conclusions & prospects

- Rare b-meson decays are promising probes for new physics
  - Anomalies in $b \to s\bar{\mu}\mu$ still there, $b \to d\ell\ell$ offer complementary probes
  - More and more precise experimental results needed to better understand the scenario
- Interesting new results incoming:
  - $B^+ \to K^+\pi^-\mu^+\mu^-$ at high $K\pi$ mass with Runs 1&2
  - $B^+ \to \pi^+\mu^+\mu^-$ and $B^+ \to \pi^+e^+e^-$ with Runs 1&2
  - Other studies ongoing; interplay with theorists is crucial
  - A huge LHCb dataset collected during Run 3 has still to be explored — stay tuned!

Thank you!

Backup

$B^+ \to \pi^+\mu^+\mu^-$ decays

- First observed at LHCb with 2011 data [JHEP12(2012)125], later measured with all Run1 data [JHEP10(2015)034]

$$\mathcal{B}\left(B^+ \to \pi^+\mu^+\mu^-\right) = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$$

$$A_{\mathrm{CP}}\left(B^+ \to \pi^+\mu^+\mu^-\right) = -0.11 \pm 0.12 \pm 0.01$$

- The ratio between the CKM elements can be obtained as

$$\left|\frac{V_{td}}{V_{ts}}\right|^2 = \frac{\mathcal{B}\left(B^+ \to \pi^+\mu^+\mu^-\right)}{\mathcal{B}\left(B^+ \to K^+\mu^+\mu^-\right)} \times \frac{\int F_K \, dq^2}{\int F_\pi \, dq^2},$$

Can be computed with the EOS package and $B \to \pi(K)$ form factors

$$|V_{td}|^2 = \frac{\mathcal{B}\left(B^+ \to \pi^+\mu^+\mu^-\right)}{\int F_\pi \, dq^2}, \qquad |V_{ts}|^2 = \frac{\mathcal{B}\left(B^+ \to K^+\mu^+\mu^-\right)}{\int F_K \, dq^2},$$

- In Run1: $\left|\frac{V_{td}}{V_{ts}}\right| = 0.24^{+0.05}_{-0.04}, \quad |V_{td}| = 7.2^{+0.9}_{-0.8} \times 10^{-3}, \quad |V_{ts}| = 3.2^{+0.4}_{-0.4} \times 10^{-2}$