LFU measurement and flavour anomalies at LHCb

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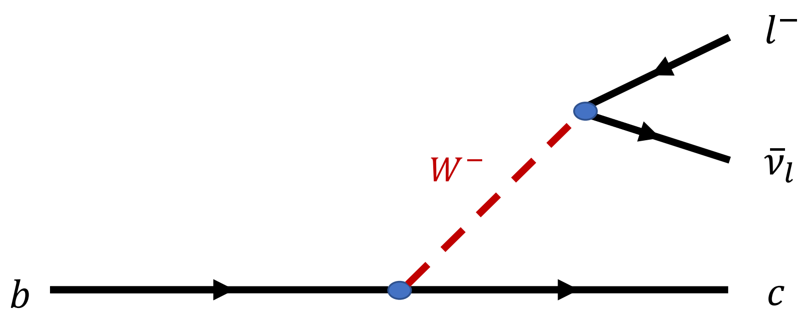
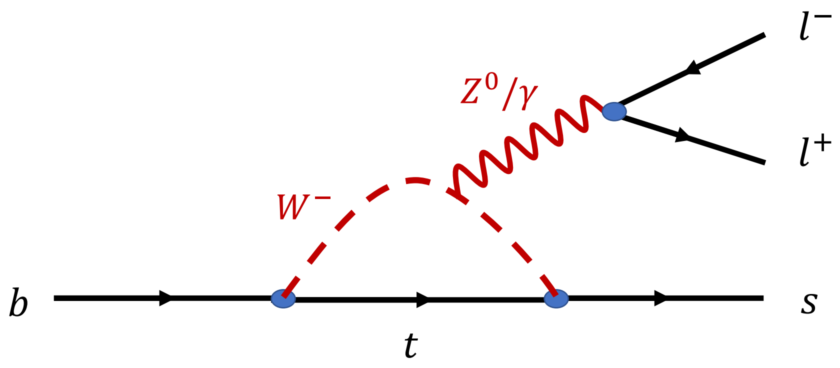
12th Edition of the Large Hadron Collider Physics Conference

June 4th 2024

Flavour anomalies

Tensions with the Standard Model (SM) have been seen in recent years in decays involving $b \to c l \bar{\nu}_l$ and $b \to sll$ transitions

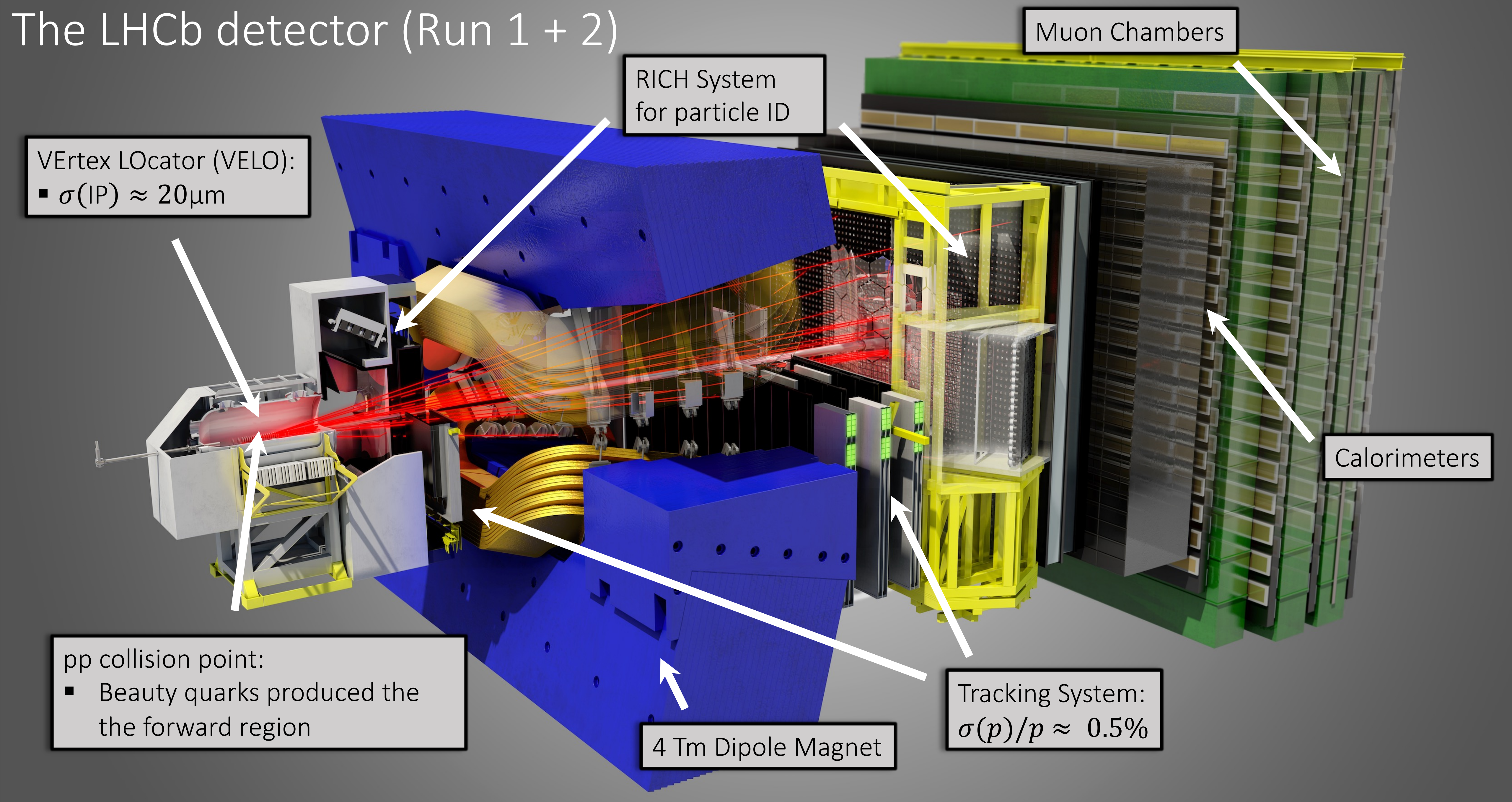




- Tree-level semileptonic decay:
  - 👍 $\mathcal{B} \sim 10\%$ → high signal yields
  - 👍 Probe 3rd generation of leptons with potential enhanced NP coupling
  - 👎 Non-reconstructed neutrinos → challenging analyses with substantial background

- Rare penguin decay:
  - 👍 Fully reconstructible final state
  - 👍 Probe higher-order diagrams where New Physics (NP) particles can appear
  - 👎 $\mathcal{B} \sim 10^{-6}$ → low signal yields

The LHCb detector (Run 1 + 2)



[Int.J.Mod.Phys.**A30**,1530022(2015)]

Outline of the talk

- Measurement of the branching fraction ratios $R(D^{+})$ and $R(D^{*+})$ using muonic τ decays [LHCb-PAPER-2024-007, in preparation]
- Comprehensive analysis of local and nonlocal amplitudes in the $B^{0} \to K^{*0}\mu^{+}\mu^{-}$ decay [LHCb-PAPER-2024-011]

Measurement of the branching fraction ratios $R(D^+)$ and $R(D^{*+})$ using muonic τ decays [LHCb-PAPER-2024-007, in preparation]

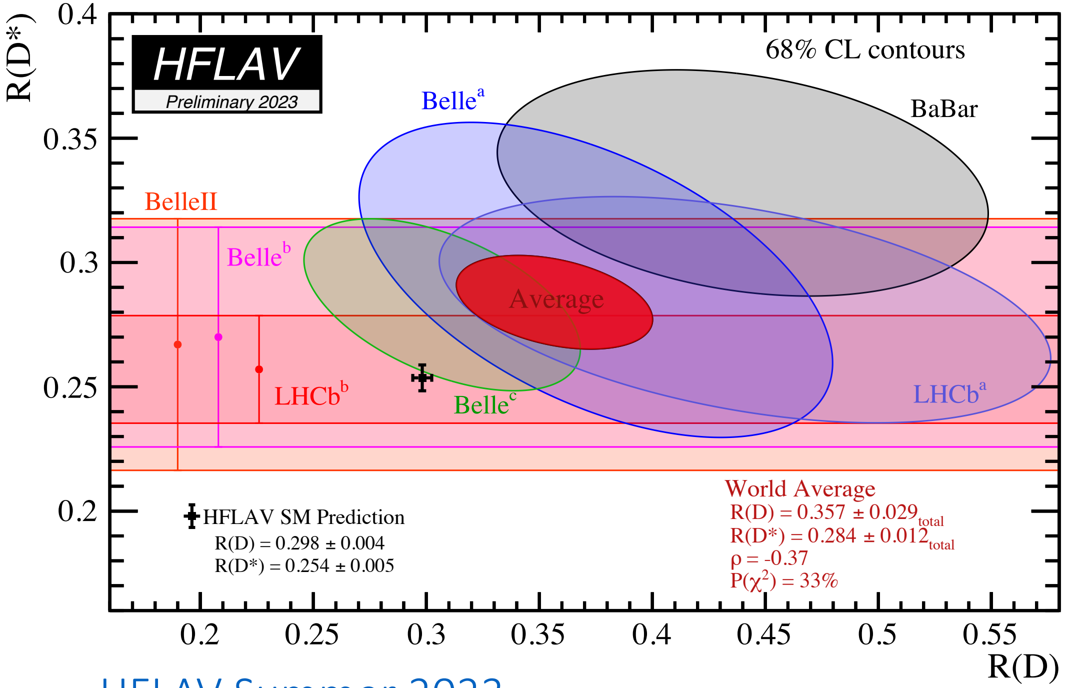
Lepton Flavour Universality (LFU) tests in $b \to cl\nu$ transitions

- LFU in the Standard Model (SM): coupling to e, μ and τ is universal. Differences are only driven by lepton masses
- New Physics can be manifested through experimental departures from LFU
- Experimental LFU test through $R(H_c)$ ratio:

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \nu_\tau)}{\mathcal{B}(H_b \to H_c \mu \nu_\mu)} \qquad H_b = B^0, B^+_{(c)}, B^0_s, \Lambda^0_b \qquad H_c = D^*, D^0, D^+, D_s, J/\psi$$

- Ratio improves theoretical and experimental precision
- Most precise measurements seen in $R(D) - R(D^*)$:
  - HFLAV Summer 2023: 3.3σ tension from SM
  - Recent LHCb measurements with leptonic [PRL 131 (2023) 111802] and hadronic [PRD 108 (2023) 012018] τ decays
  - D^* longitudinal polarization in $B^0 \to D^{*-}\tau^+\nu_\tau$ decays [LHCB-PAPER-2023-020]

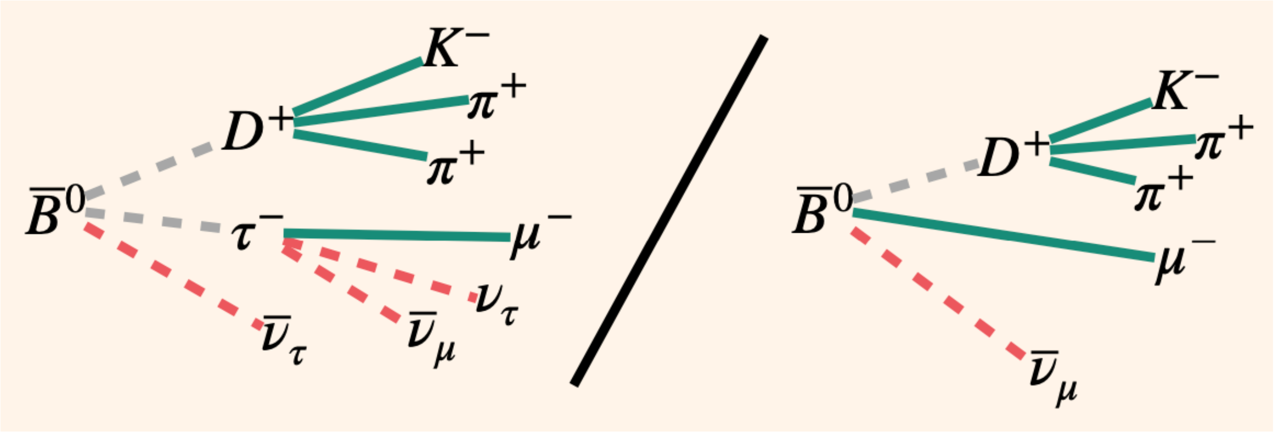
Prior to the analysis presented in this talk



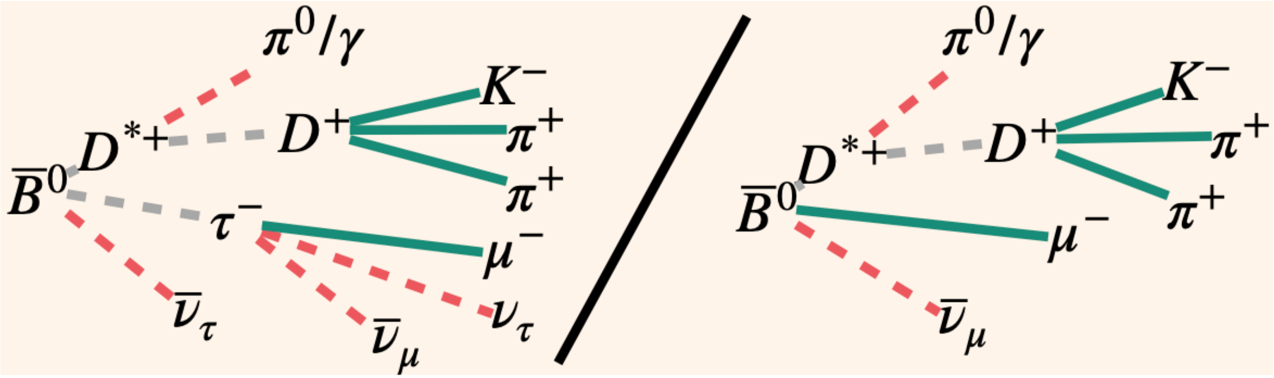
HFLAV Summer 2023

Branching fraction ratios $R(D^+)$ and $R(D^{*+})$: decay topology

$R(D^+) =$



$R(D^{*+}) =$



- Use $D^{*+} \to D^+\pi^0$
- $K^-\pi^+\pi^+\mu^-$ final state common to all four modes.

$$R(D^{(*)+}) = \frac{\epsilon_\mu^{D^{(*)+}}}{\epsilon_\tau^{D^{(*)+}}} \frac{N_\tau^{D^{(*)+}}}{N_\mu^{D^{(*)+}}} \frac{1}{\mathcal{B}(\tau^- \to \mu^-\nu_\tau)}$$

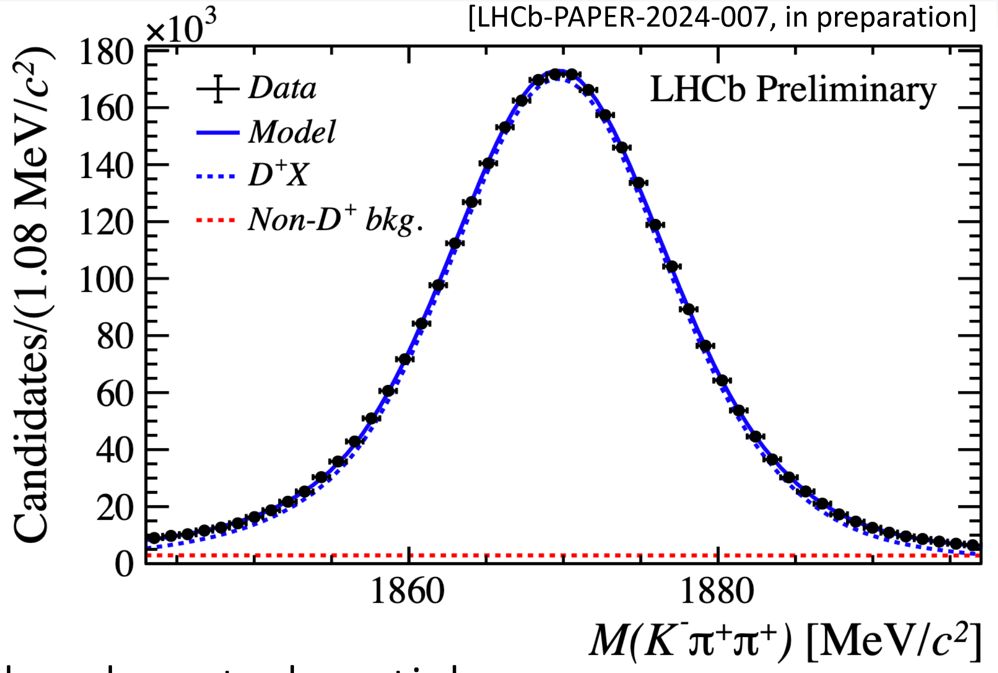
Efficiency ratio determined from MC

Yield ratio from data through a fit to m^2_{miss}, E_μ and $q^2 = (p_B - p_D)^2$

- Main challenges:
  - Non-reconstructed ν and π^0/γ
  - Big data samples (> 3M candidates) → Sensitive to small mis-modelings

Sample selection

- Dataset: 2015 + 2016 (2.0fb^{-1})
- Requirements on $K^-\pi^+\pi^+\mu^-$ candidates:
  - Kinematic
  - Topologic
  - Particle identification
- Fit $m(K^-\pi^+\pi^+)$ and apply sPlot technique to remove fake D^+ bkg.

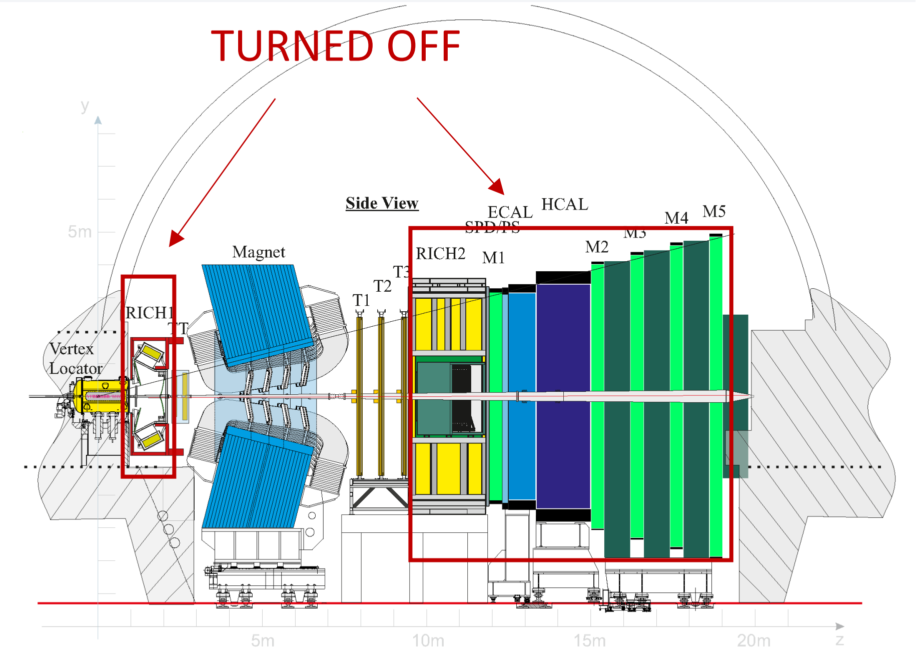


- BDT-based isolation tool against bkg with additional charged and neutral particles:
  - Create four samples enriched with different bkg contributions
  - Final fit performed simultaneously in the four samples

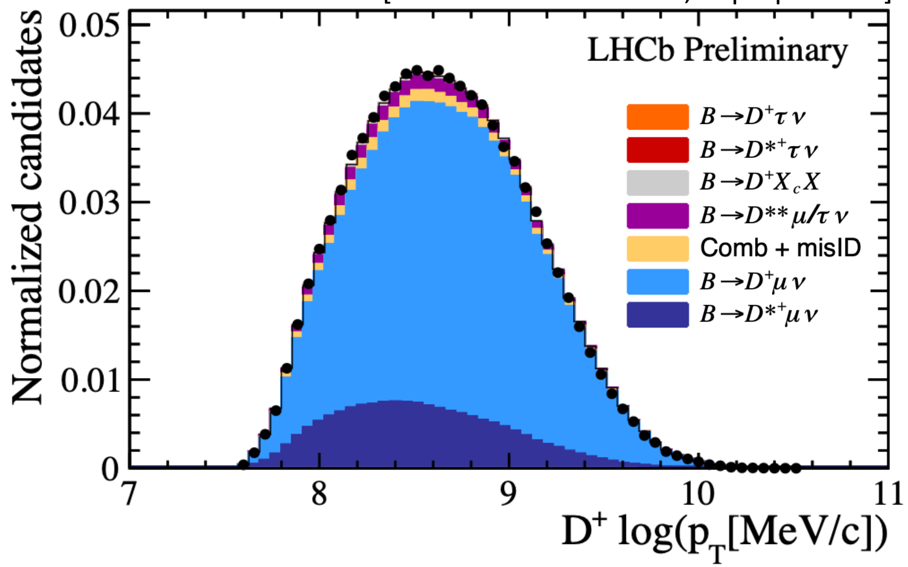
Signal sample $D^+\mu^-$	1π sample $D^+\mu^-\pi^\pm$	2π sample $D^+\mu^-\pi^+\pi^-$	$1K$ sample $D^+\mu^-K^\pm$
	Ex: $B \to D_0^*(2300)(\to D\pi^\pm)\mu\nu_\mu$	Ex: $B \to D^*(2640)^\pm(\to D^*(2010)^+\pi^+\pi^-)\mu\nu_\mu$	$B \to D^+H_c(\to \mu\nu_\mu X)X'$

Simulation

- Role: Obtain efficiencies and fit templates
- Huge statistics needed: not feasible with full LHCb simulation.
- Solution: Use *Tracker-Only* simulation
  - Missing detector effects emulated offline
  - $\times 8$ faster than full LHCb simulation
- Simulation corrections to match data distributions:
  - Reweighting of kinematics and $D^+ \to K^- \pi^+ \pi^+$ Dalitz resonances
  - QED effects through soft-photon corrections [PRL 120 (2018) 261804]
- Excellent Data/simulation agreement reached!



[LHCb-PAPER-2024-007, in preparation]



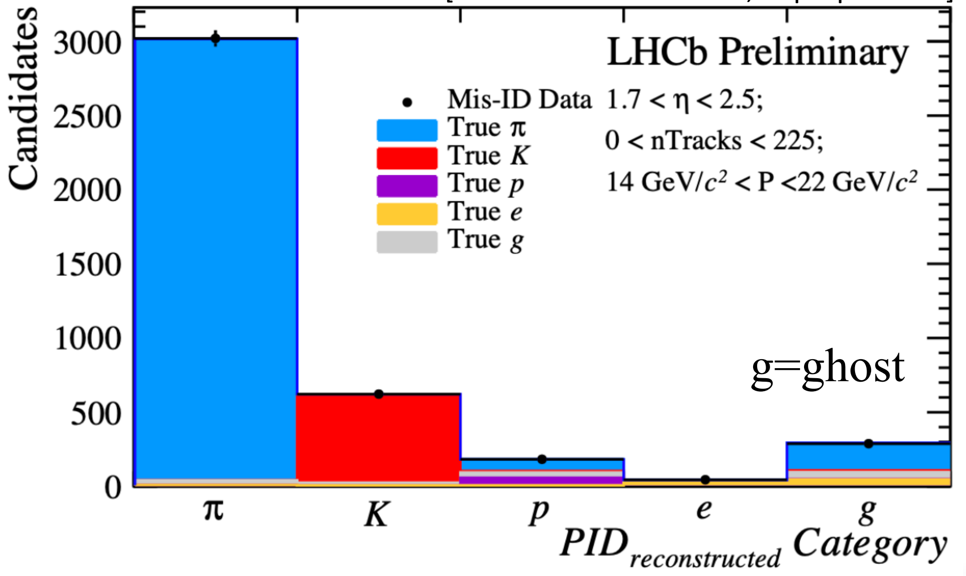
Templates building and form factors

- Simulation templates:
  - Signal ($B \to D^{(*)} l \nu_l$). Form factors from BGL [PRD 94 (2016) 094008, Eur. Phys. J. C (2022) 82:1141]
  - Bkg from $B \to D^{**} X$ decays. Form factors from BLR [PRD 95 (2017) 014022]
  - Double-charm bkg
  - $\Lambda_b^0 \to n D^+ \mu^- \bar{\nu}_\mu$ bkg

First analysis to use and implement HAMMER through RooHammerTool [Eur. Phys. J. C (2020) 80:883, JINST 17 (2022) T04006]
→ **Fast and exact form factors variations in the fit model!**

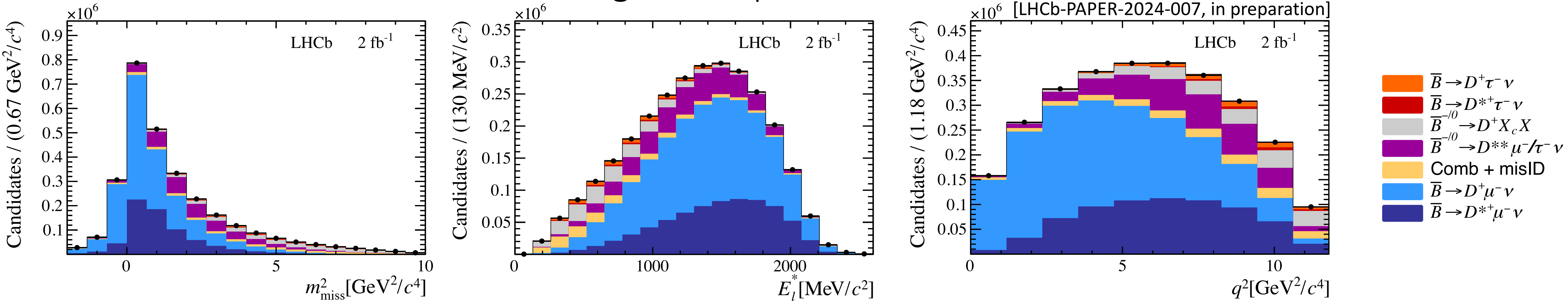
- Data templates:
  - Combinatorial bkg: Obtained from same-sign $D^+ \mu^+$ data
  - Muon mis-identification: Obtained from non-muonic control control samples

[LHCb-PAPER-2024-007, in preparation]



Results

Signal sample



- Analysis results:

$$R(D^+) = 0.249 \pm 0.043_{\rm stat} \pm 0.047_{\rm sys}$$
$$R(D^{*+}) = 0.402 \pm 0.081_{\rm stat} \pm 0.085_{\rm sys}$$

$\rho = -0.39$

- Main systematics from form-factor parametrisations and bkg modelings.

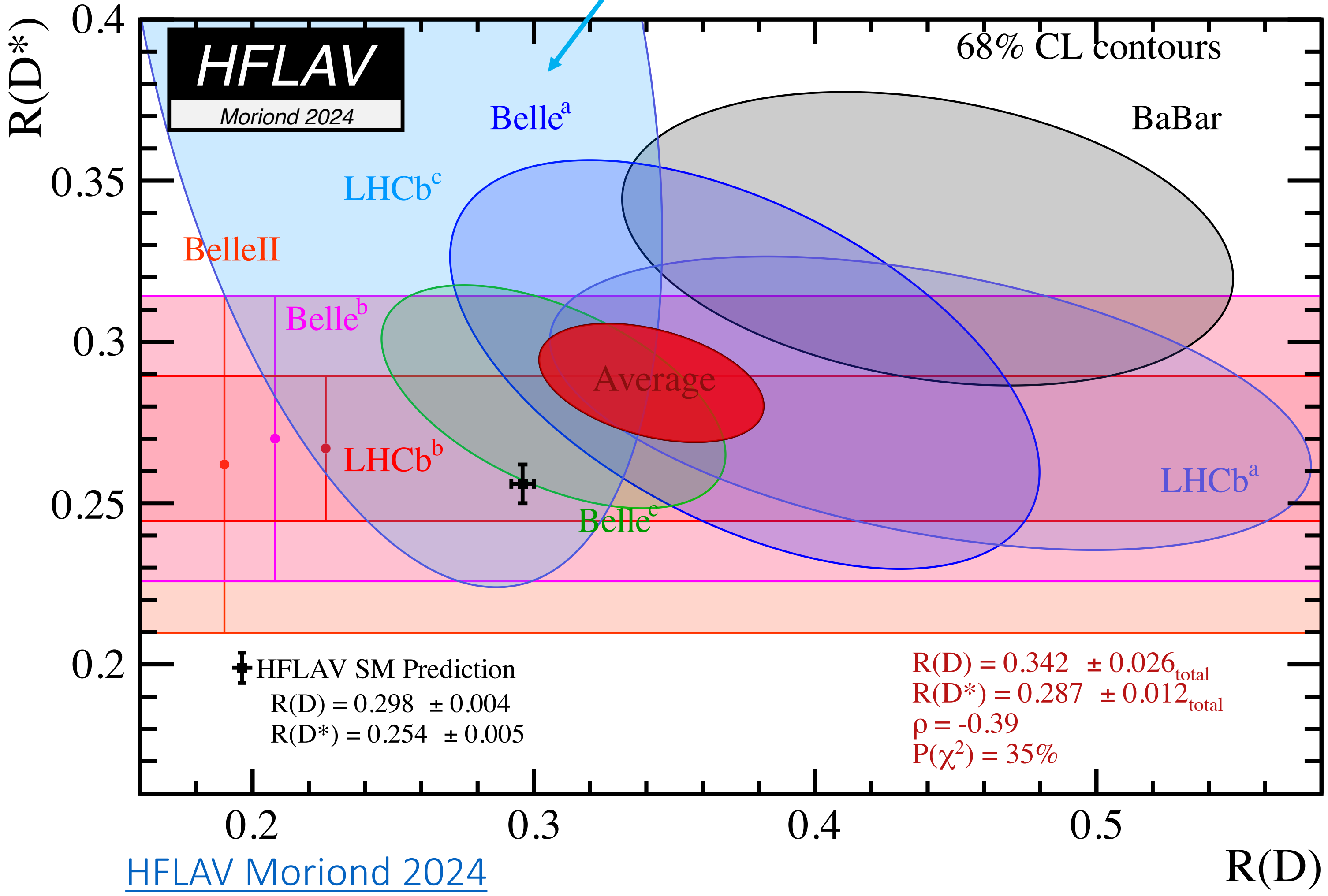
Systematic uncertainties

Source	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$
Form factors	0.023	0.035
$\overline{B}\to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$\overline{B}^{+/0}\to D^+X_cX$ fraction	0.020	0.034
Misidentification	0.019	0.012
Simulation size	0.009	0.030
Combinatorial background	0.005	0.020
Data/simulation agreement	0.016	0.011
Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	0.047	0.086

New $R(D) - R(D^*)$ HFLAV average

- New result compatible with World Average (WA) and SM
- New tension with SM: 3.17σ

New result



HFLAV Moriond 2024

Comprehensive analysis of local and nonlocal amplitudes in the $B^0 \to K^{*0}\mu^+\mu^-$ decay

[LHCb-PAPER-2024-011, arXiv:2405.17347]

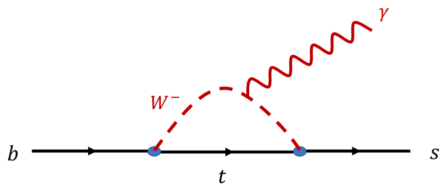
$B^0 \to K^{*0}\mu^+\mu^-$: some intriguing effects

- Described by $b \to s\mu\mu$ penguin transitions:

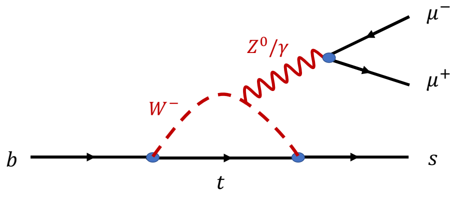
$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i [C_i O_i + C_i' O_i']$$

Left chirality — Right chilarity, suppresed by SM

C_7 = Penguin photon



$C_{9/10}$ = Electroweak penguin

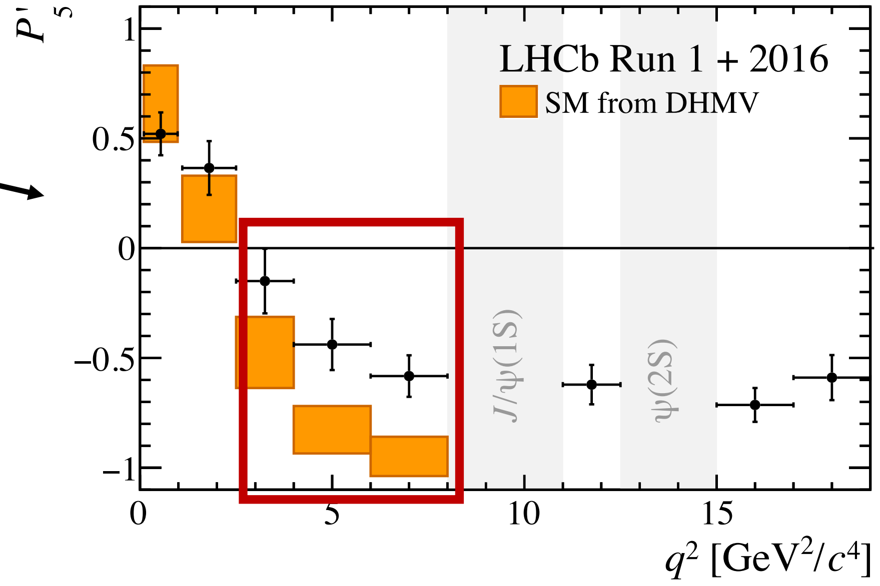


$C_i^{(\prime)}$ (Wilson coeff.): short-distance, sensitive to NP through $C_i = C_i^{SM} + \Delta C_i^{NP}$

O_i' (Operators): long-distance, dependent to QCD form factors

$$q^2 = m_{\mu\mu}^2$$

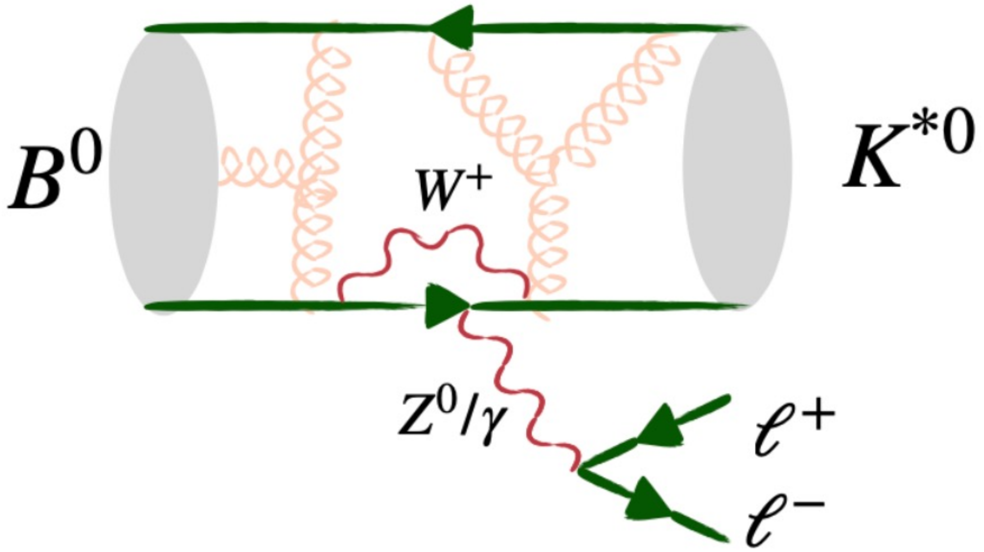
- Tensions with SM are present in angular observables and differential decay rates of $B^0 \to K^{*0}\mu^+\mu^-$
- Points to a NP vector contribution through $\Delta C_9^{\text{NP}} \neq 0$ [Eur. Phys. J. C (2023) 83:648]
- Important question: Is this a genuine NP effect and a mis-modelled QCD contribution?



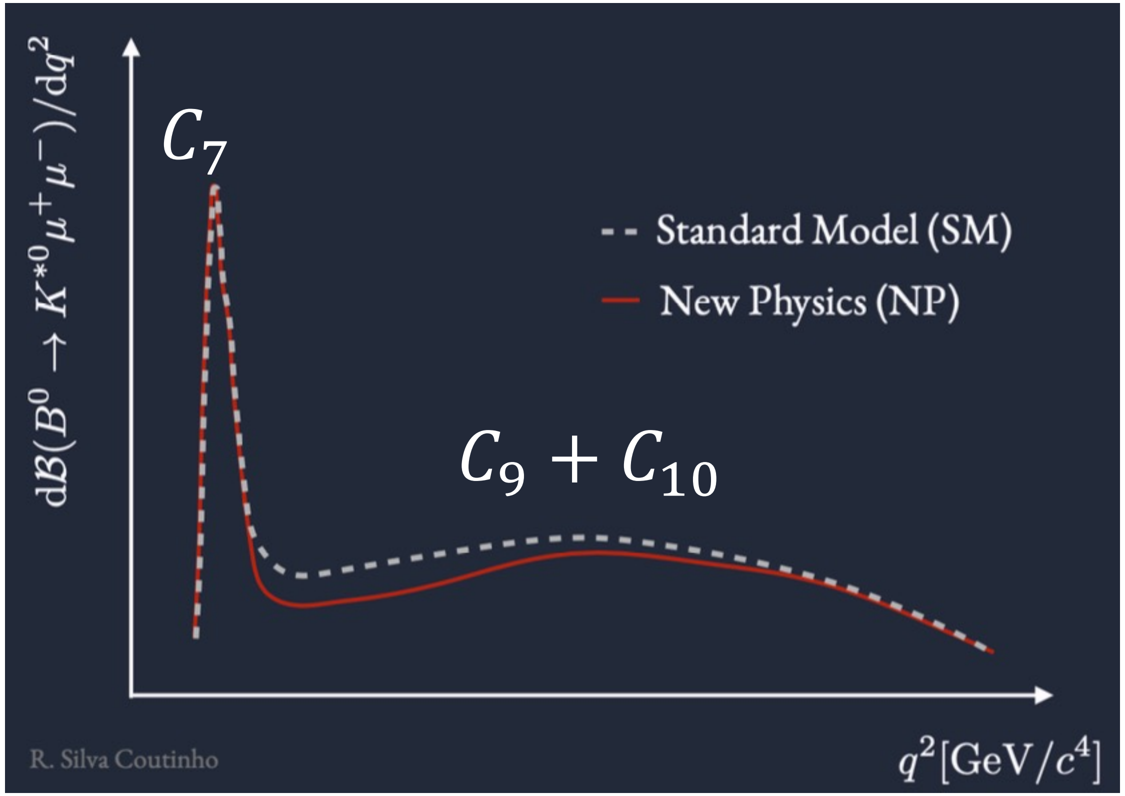
PRL 125 (2020) 011802

$B^0 \to K^{*0}\mu^+\mu^-$: a complex system

Non-resonant $b \to s\mu\mu$
penguin transitions

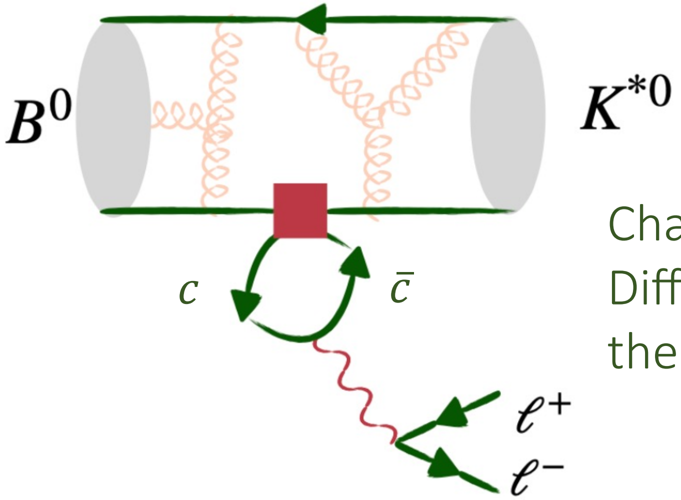


Local amplitudes



$B^0 \to K^{*0}\mu^+\mu^-$: a complex system

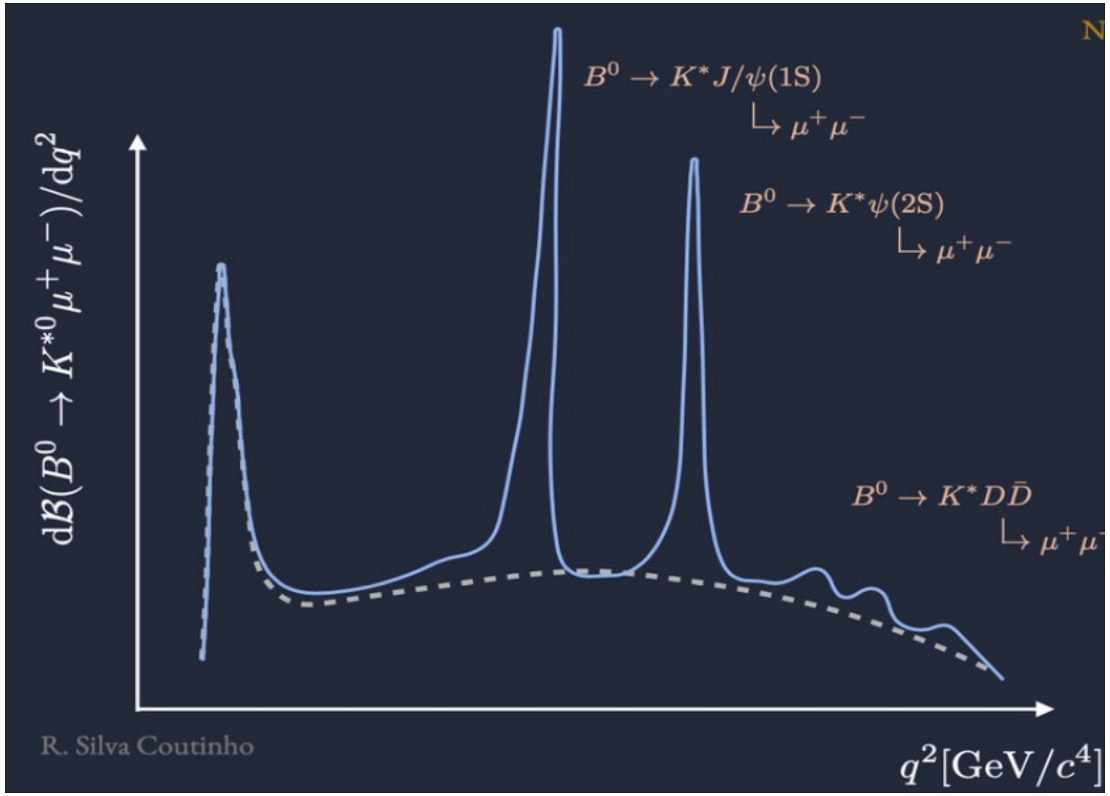
Contributions from $c\bar{c}$ resonances!



Charm loops!
Difficult to model theoretically

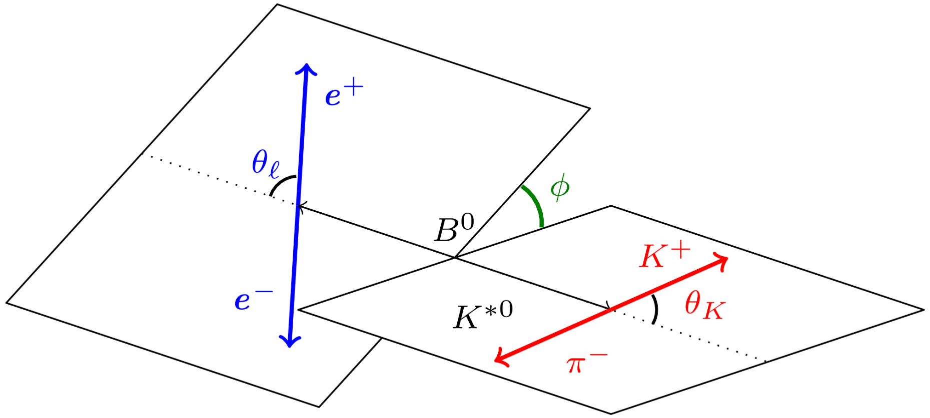
Dangerous ⚠️ They can enter the analysis region and mimic $\Delta C_i^{\text{NP}} \neq 0$
→ Need a complete simultaneous experimental modeling of local and nonlocal amplitudes!

Nonlocal amplitudes



$B^0 \to K^{*0}\mu^+\mu^-$: analysis strategy

- Unbinned measurement of **angular observables** through a parametrisation of q^2 and the 3 decay angles θ_l, θ_K and ϕ
- Dataset: Run 1 (2011-2012) + Run 2 (2016-2018): 8.4fb^{-1}
  → First analysis to use the full dataset!



Data
- Background modeling
- K^{*0} S-wave parameters

Simulation
- Selection + reconstruction + detection + resolution effects

Theory
- Local form factors [JHEP 09, 133 (2022)], gaussian constrained in the fit

↓

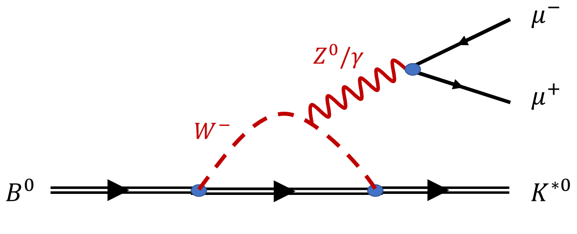
FINAL FIT of 150 parameters. Among which:
- $\mathcal{R}(C_9^{(\prime)}) + \mathcal{R}(C_{10}^{(\prime)})$
- Form factors parameters

Parametrisation of local and nonlocal contributions

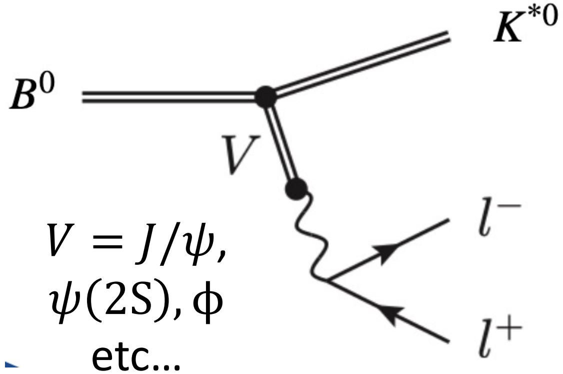
Angular observables → (Combinations of) → Decay amplitudes → (Depend on) → $C_i^{eff}(q^2)$

$$C_9^{eff}(q^2) = C_9^{\mu} + Y_{c\bar{c}+light}^{1P}(q^2) + Y_{c\bar{c}}^{2P}(q^2) + Y_{\tau\bar{\tau}}(q^2) + Y_{c\bar{c}}^{0}(q^2)$$

Penguin local term

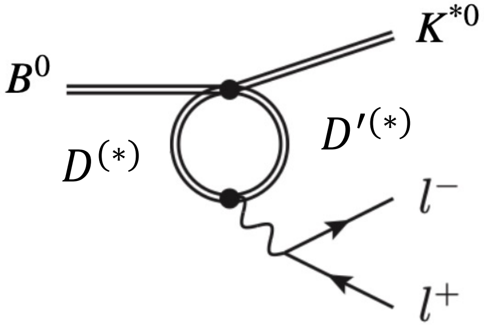


1-particle contributions

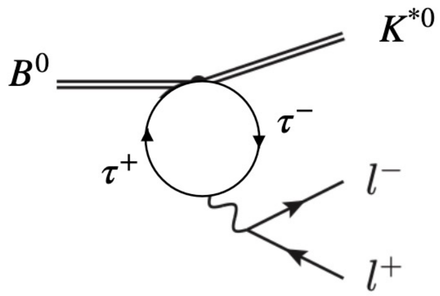


$V = J/\psi$, $\psi(2S), \phi$ etc…

2-particle contributions



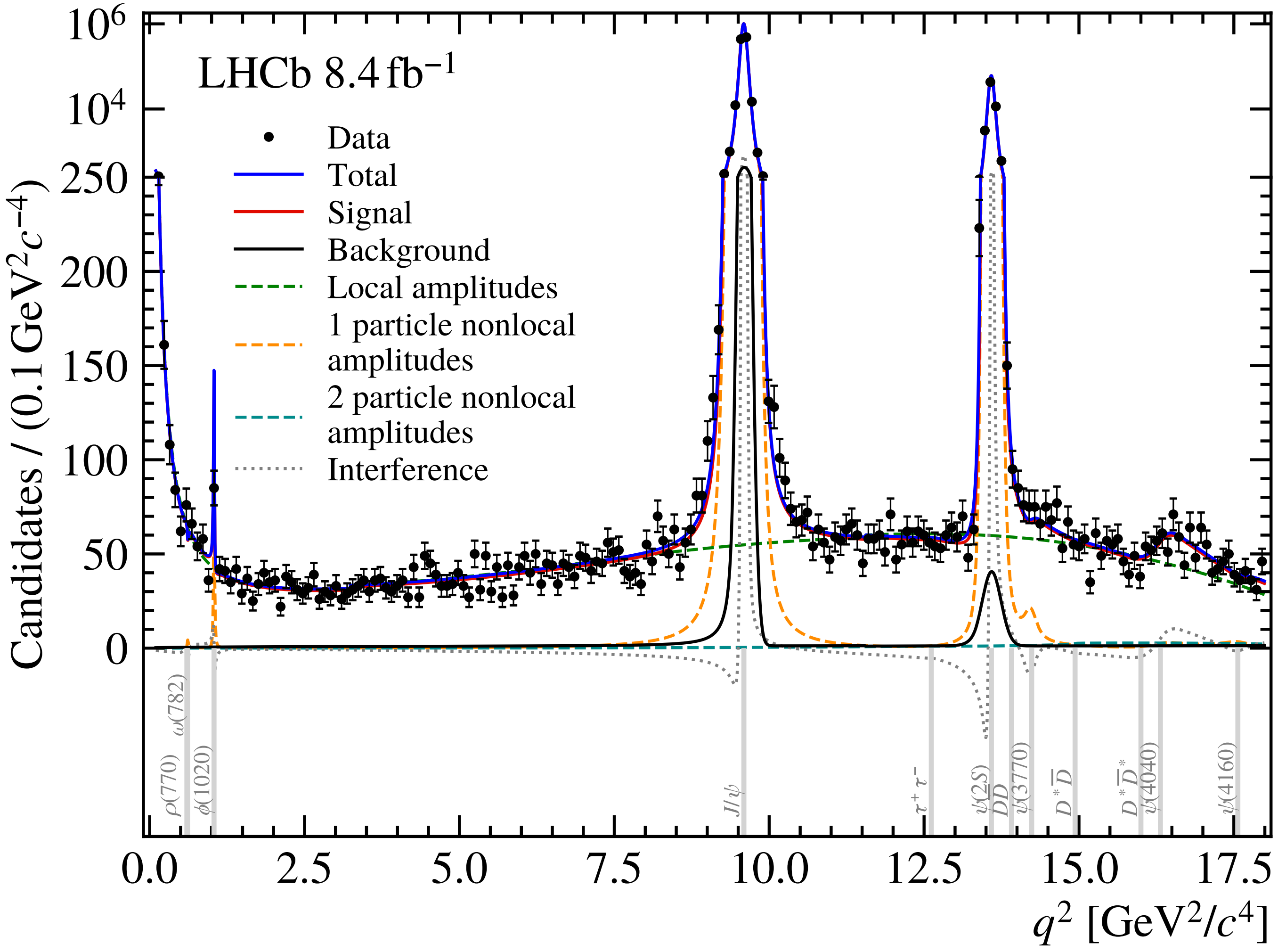
τ-loop contributions [Eur. Phys. J. C (2020) 80:1095]



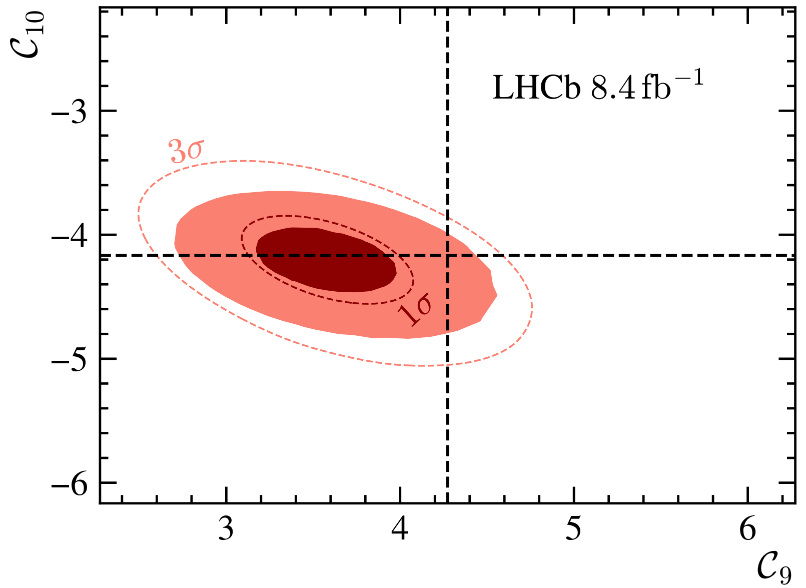
Subtraction term determined theoretically at $q^2 < 0$ [JHEP 04 (2020) 012]

Results

LHCb-PAPER-2024-011



LHCb-PAPER-2024-011



- Impressive modeling of the full q^2 spectrum!
- Results in agreement with previous LHCb analyses
- Biggest deviation is seen with:

$$\Delta C_9^{NP} = -0.71 \pm 0.33$$

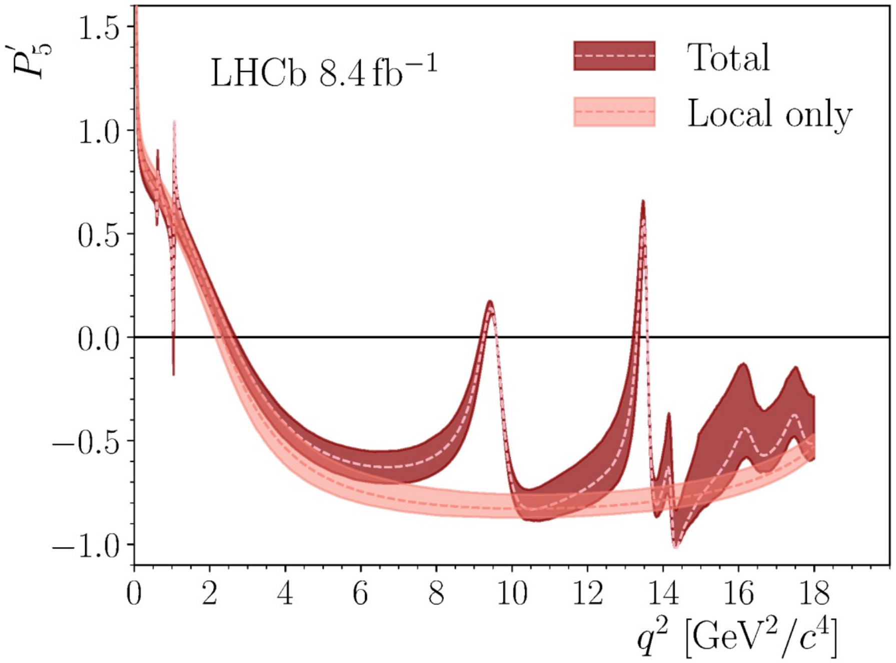
(2.1σ from zero!)

- Global significance: **1.5σ** from SM

Interpretation of the measurement

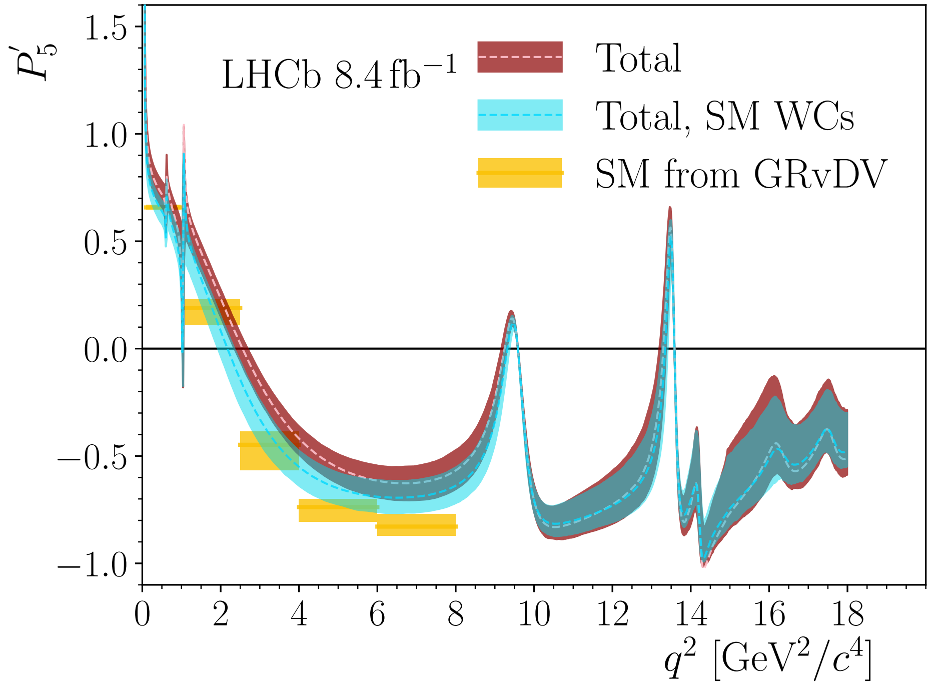
- Analysis makes it possible to separate local from non-local contributions!
- Non-local contributions do influence angular observables

LHCb-PAPER-2024-011



- Cyan: Fixing experimental local results to SM predictions:
  - Cyan and yellow: impact of non-local modelling
  - Cyan and red: impact of possible NP
- → P_5' tension cannot be fully described by non-local contributions!

LHCb-PAPER-2024-011

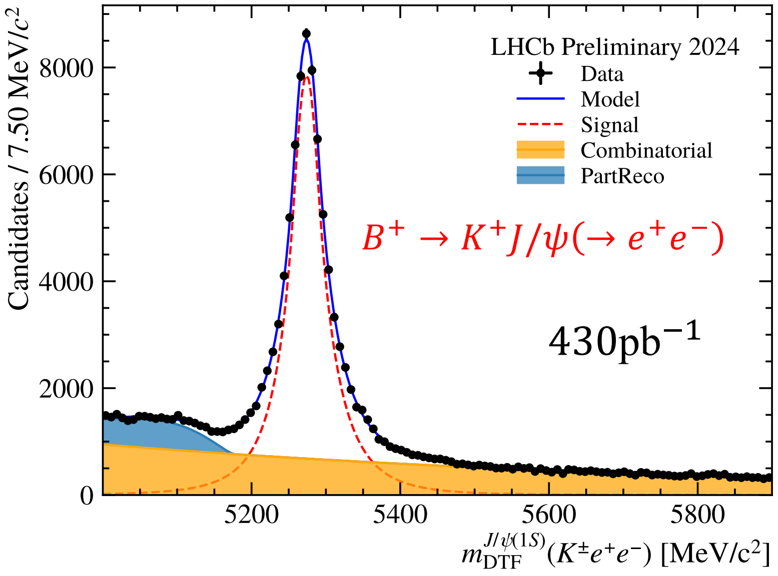


Towards Run 3 data

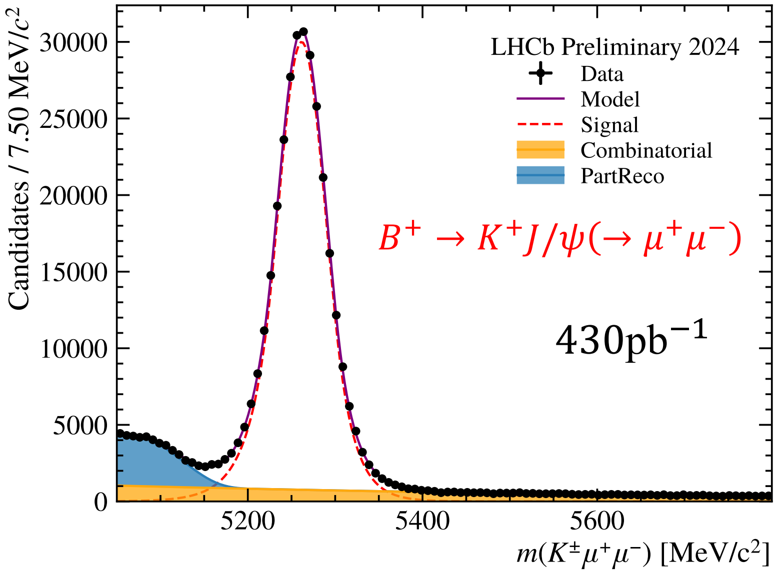
First B decays plots of 2024

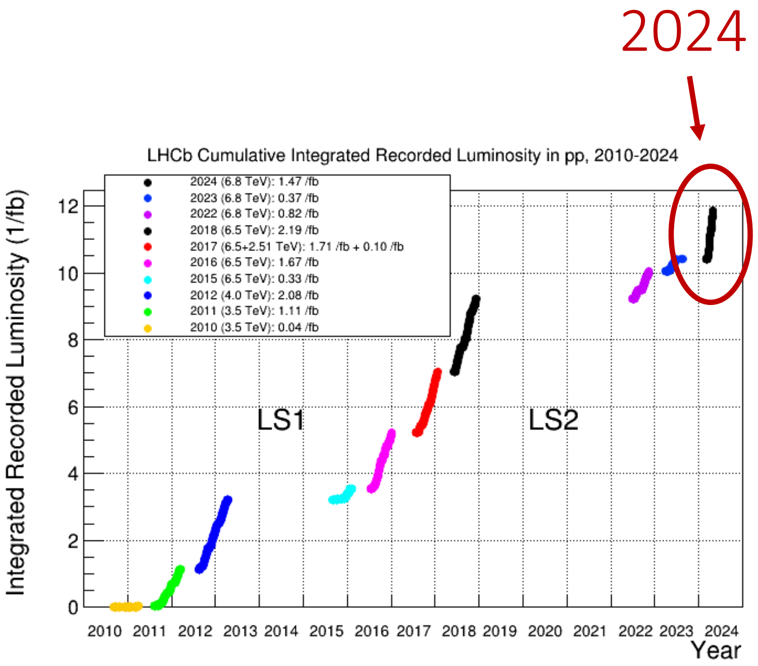
- LHCb is collecting copious data samples of B decays thanks to increased pile-up (from 1 to 5) and trigger efficiencies.
- Precision measurements expected with 2024 data!

LHCB-FIGURE-2024-007



LHCB-FIGURE-2024-007





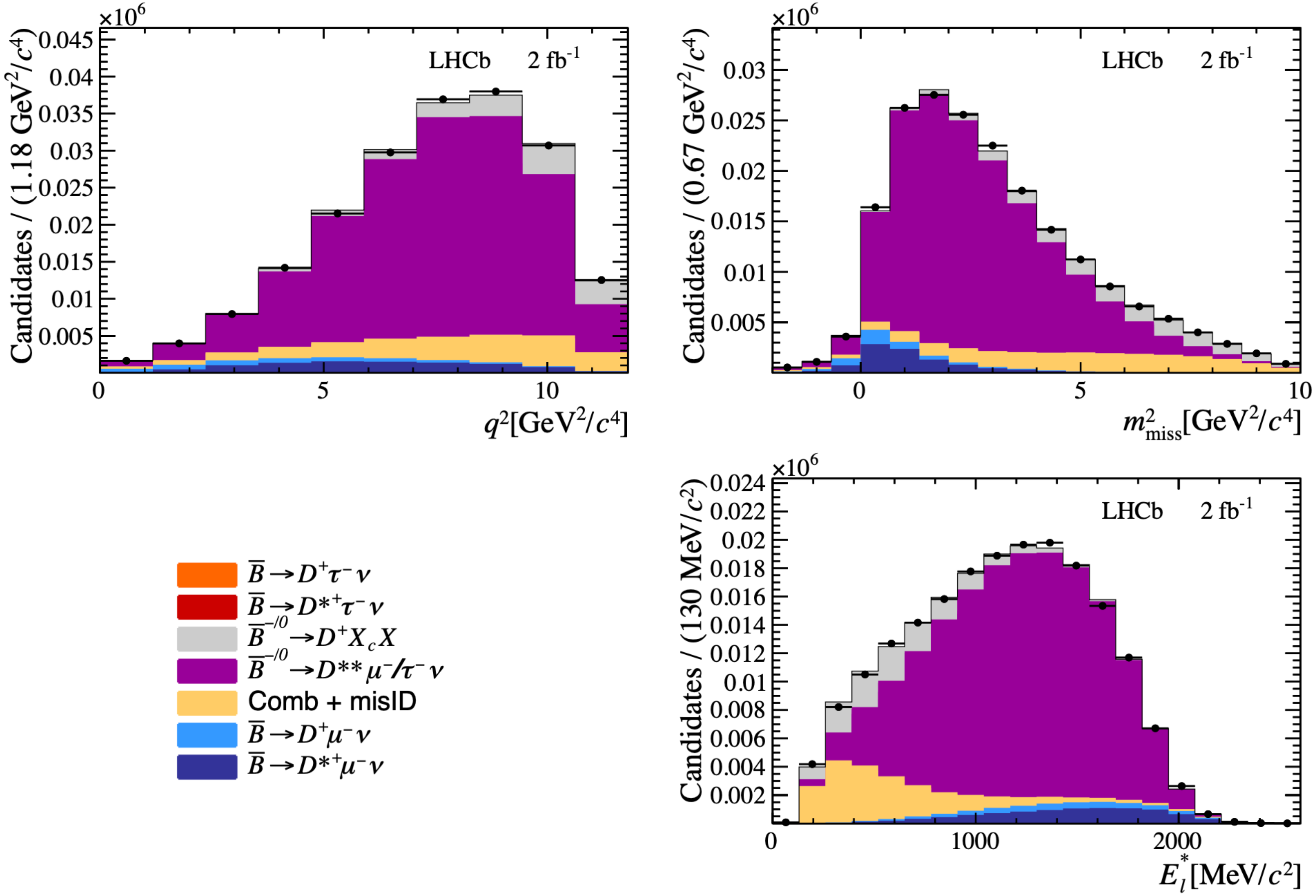
LHCb Operation Plots Webpage

Summary

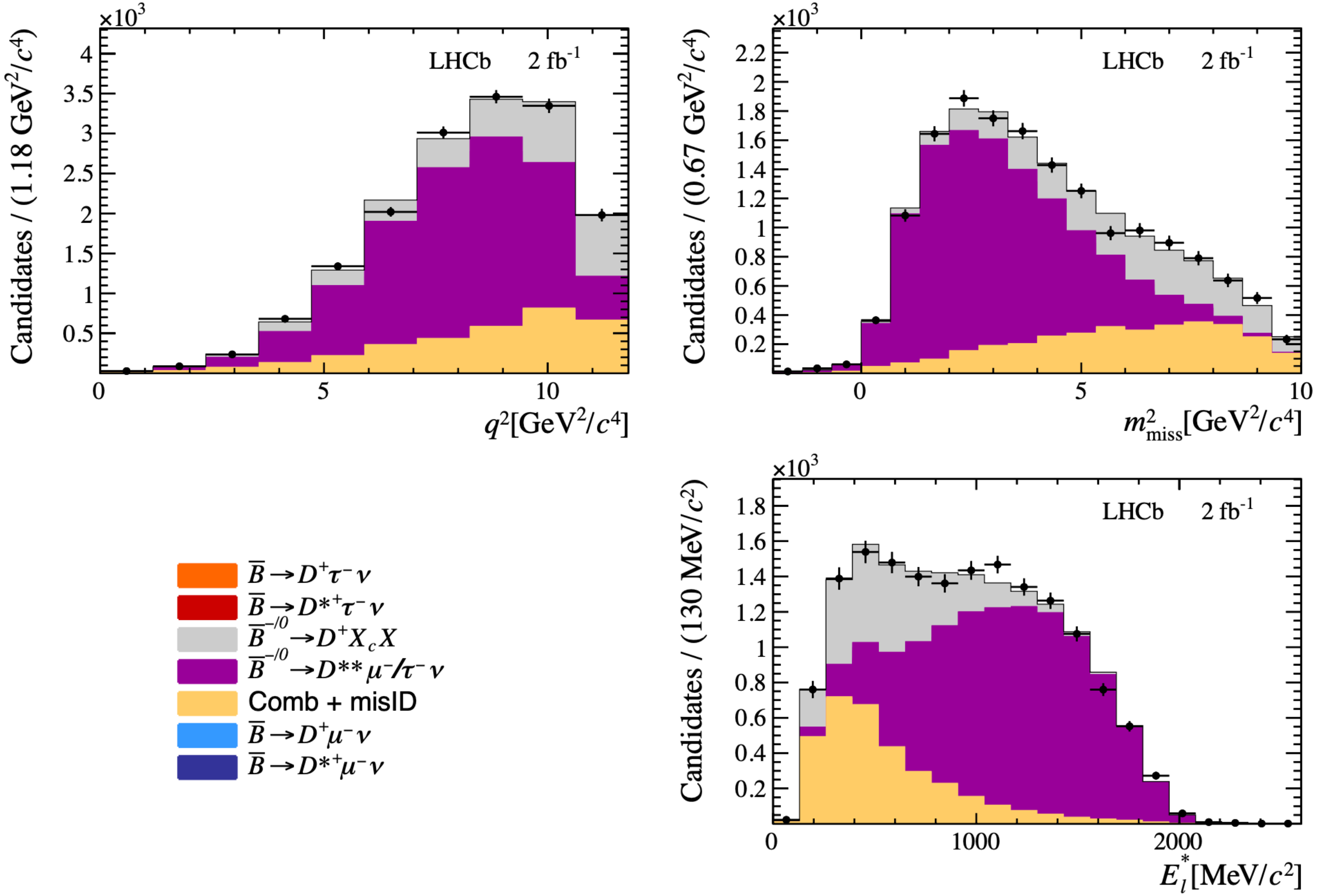
- New measurement of $R(D^{+})$ and $R(D^{*+})$ using muonic τ decays transitions compatible with world average and SM expectations:
  - $\sim 3\sigma$ tension remains
- Complex angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ allows to separate local from non-local effects:
  - Important input for theorists to improve our understanding of non-local effects
  - SM tensions not fully excluded
- LHCb is collecting high B-decays yields:
  - Expect precise updates on LFU and flavour anomalies measurements!

BACKUP

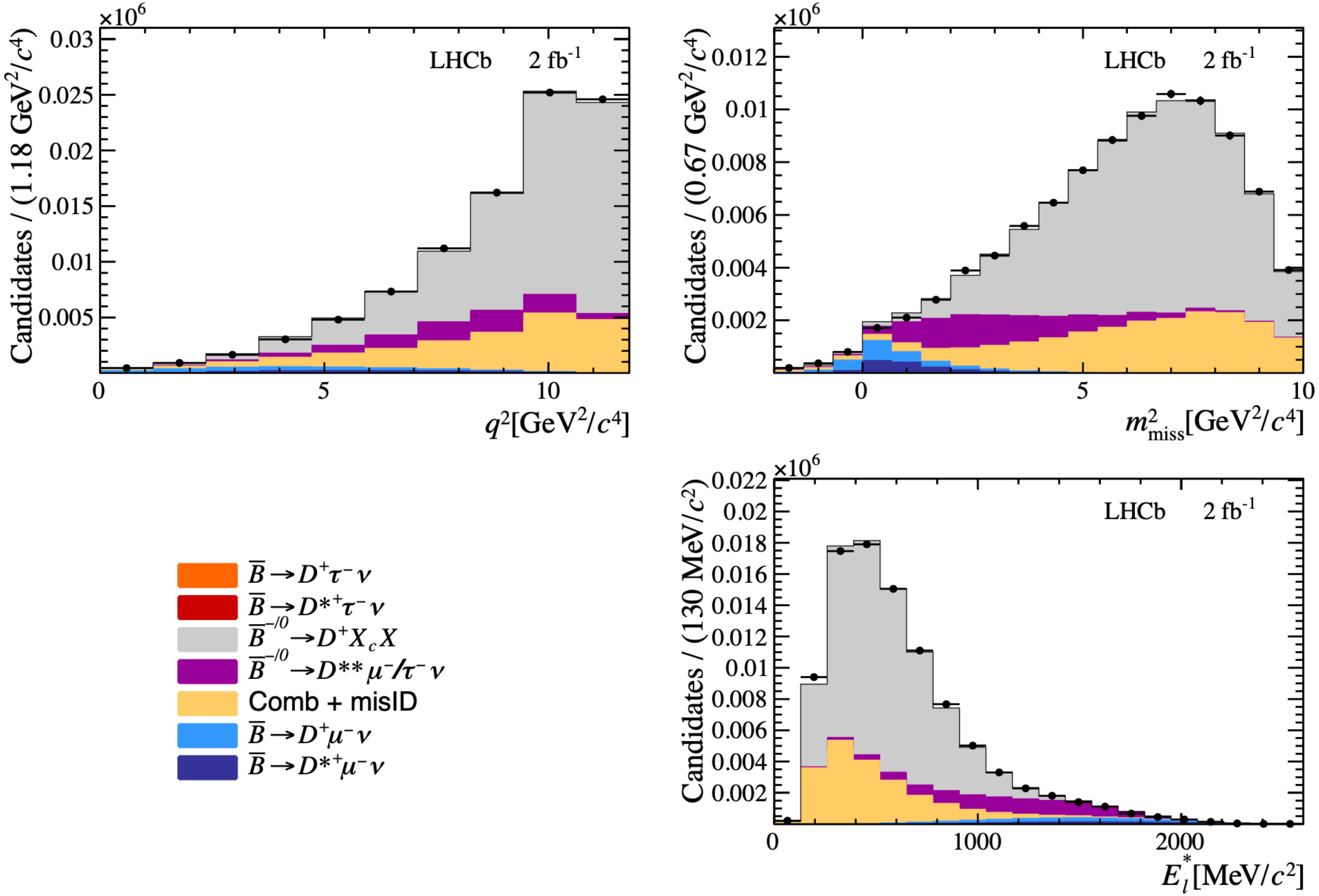
$R(D) - R(D^*)$ results in the 1π sample



$R(D) - R(D^*)$ results in the 2π sample



$R(D) - R(D^*)$ results in the $1K$ sample



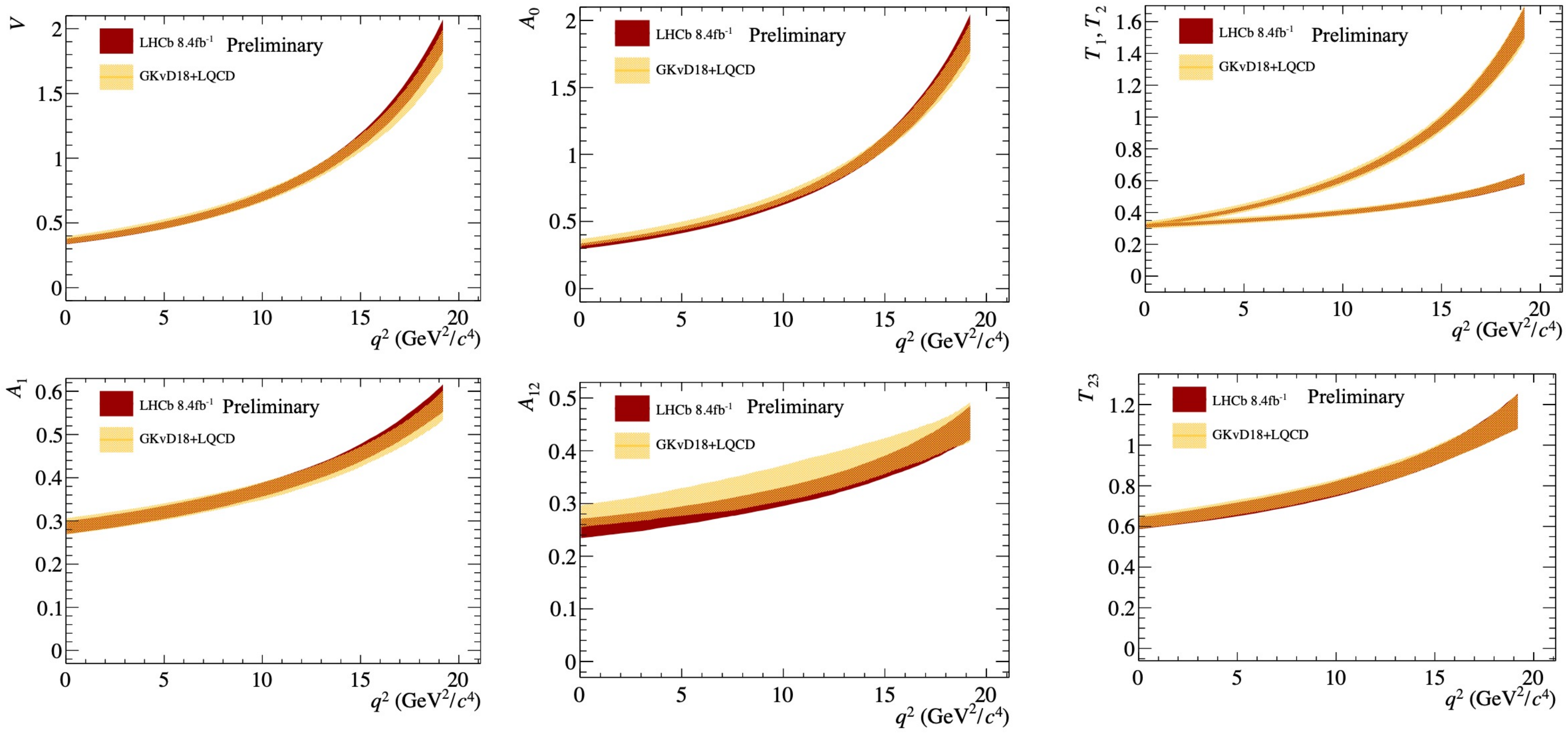
Neutrino Reconstruction

- For muonic decay:
  - $p_{B_Z} = \frac{m_B}{m_Y} p_{Y_Z}$
  - p_B direction aligns with the vector connecting B decay vertex and associated PV

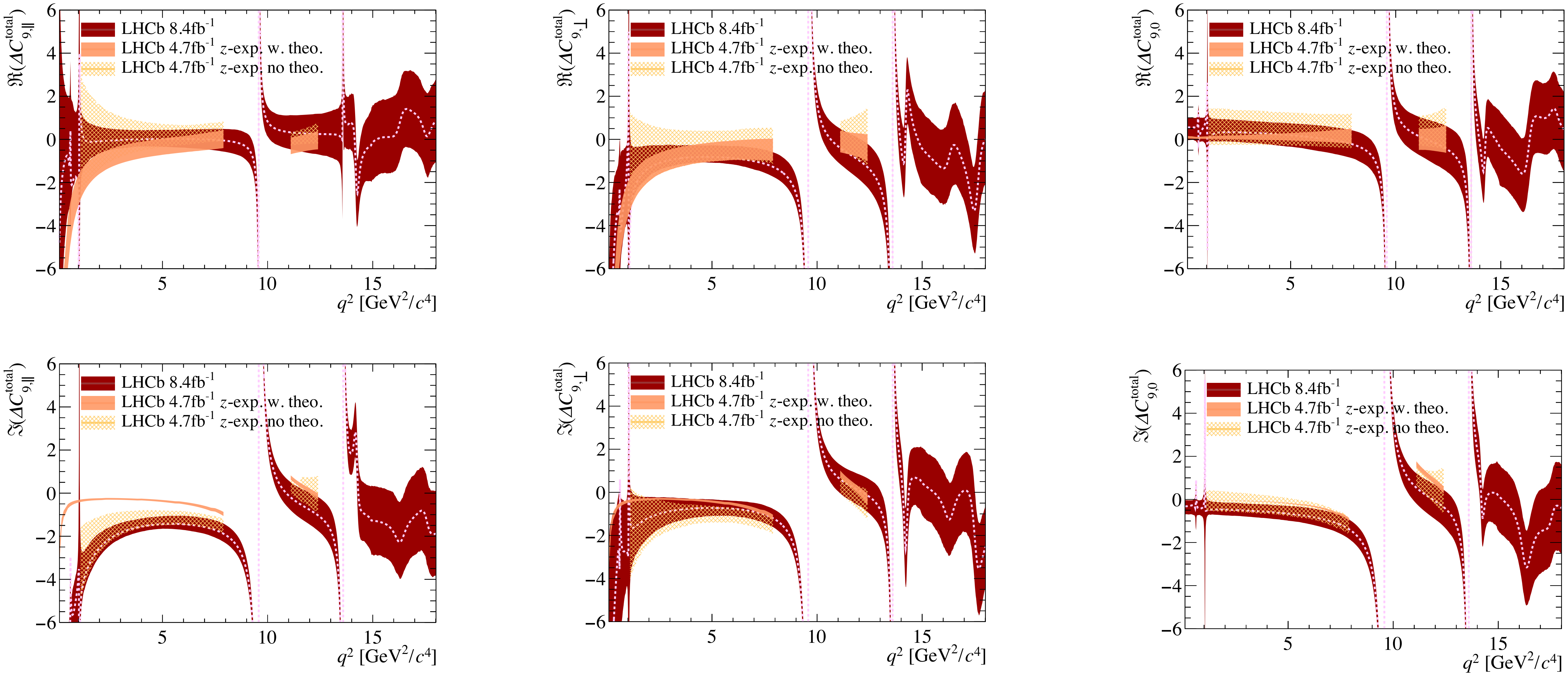
- For hadronic τ decay:
  - Four-momentum conservation
  - Constraints of τ and B known masses
  - p_B direction aligns with the vector connecting B vertex and associated PV
  - p_τ direction aligns with the vector connecting τ and B vertices
  - Solve equations to determine missing momentum with two-fold ambiguity

Local form factors interpolation

- Comparison between prior and posterior

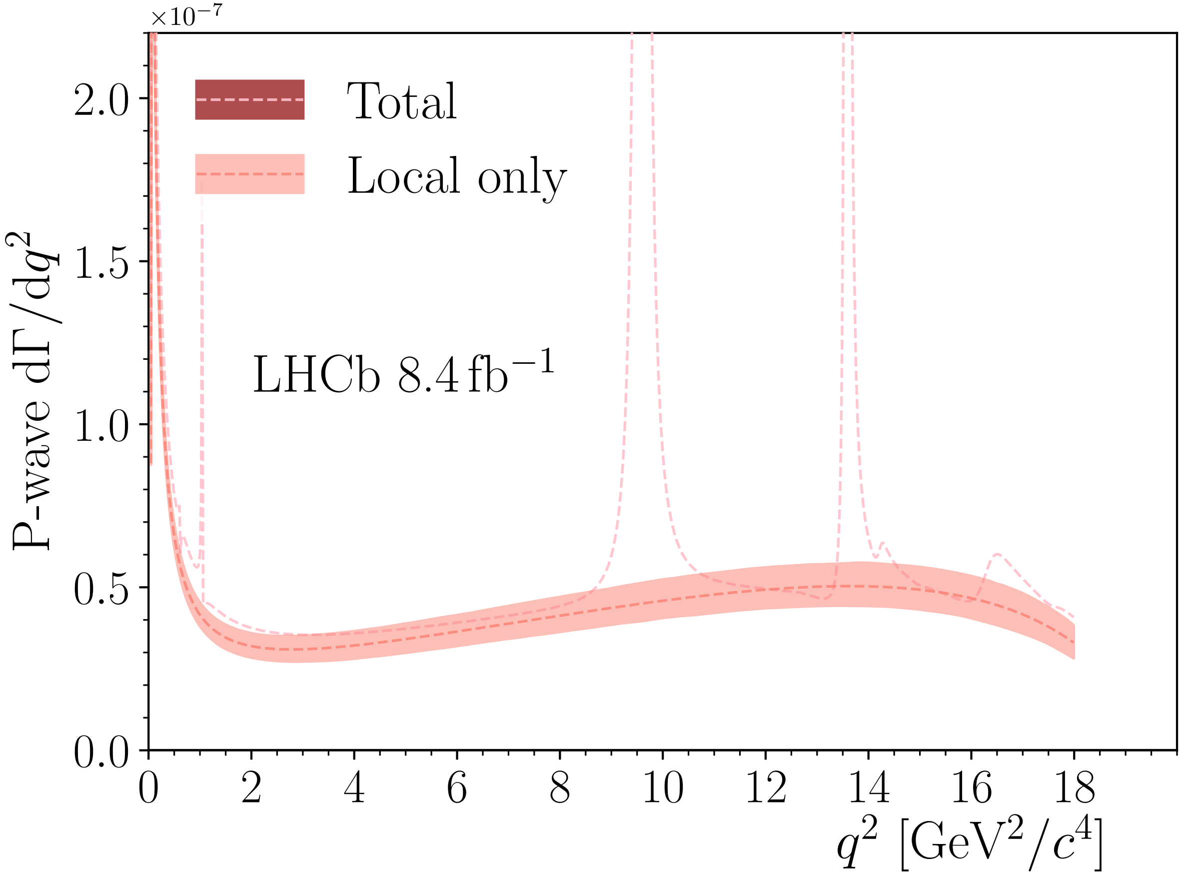


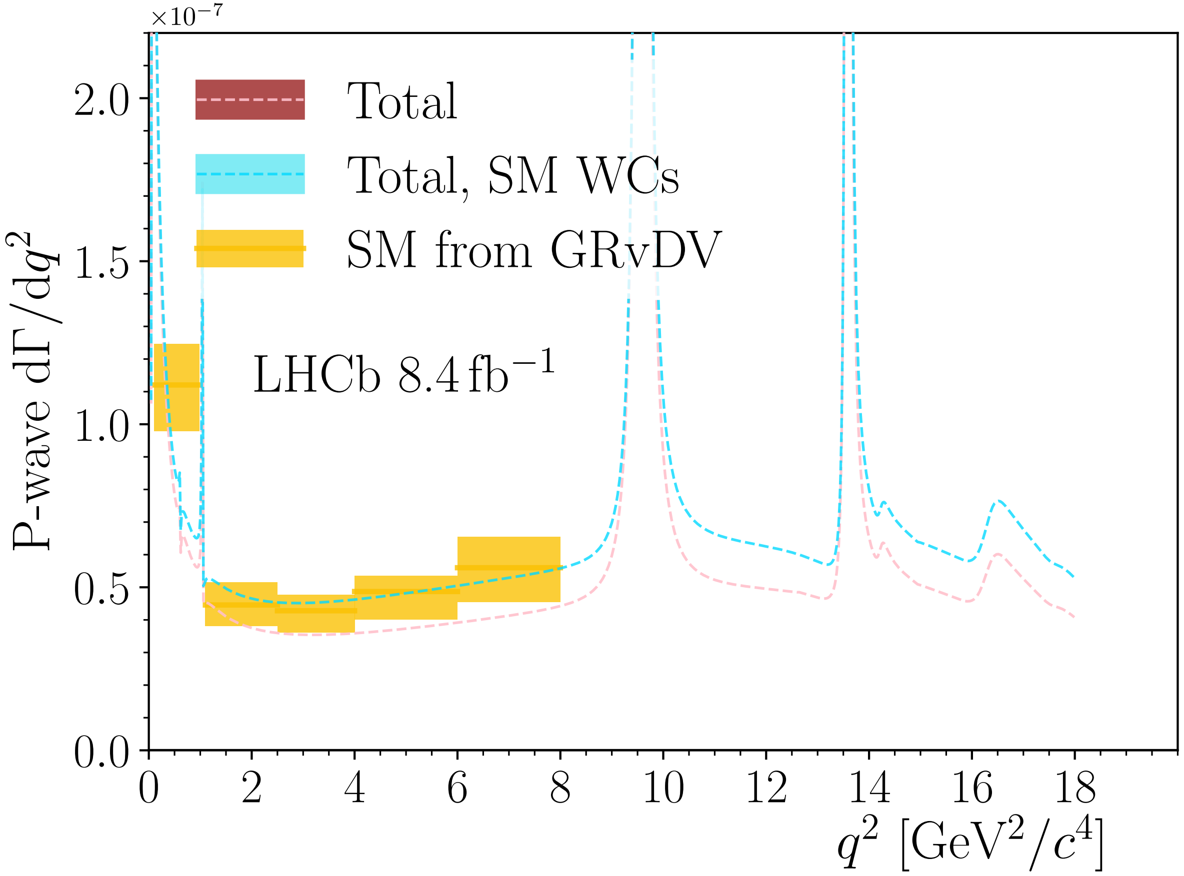
Impact of non-local amplitudes on the WCs, shown per helicity



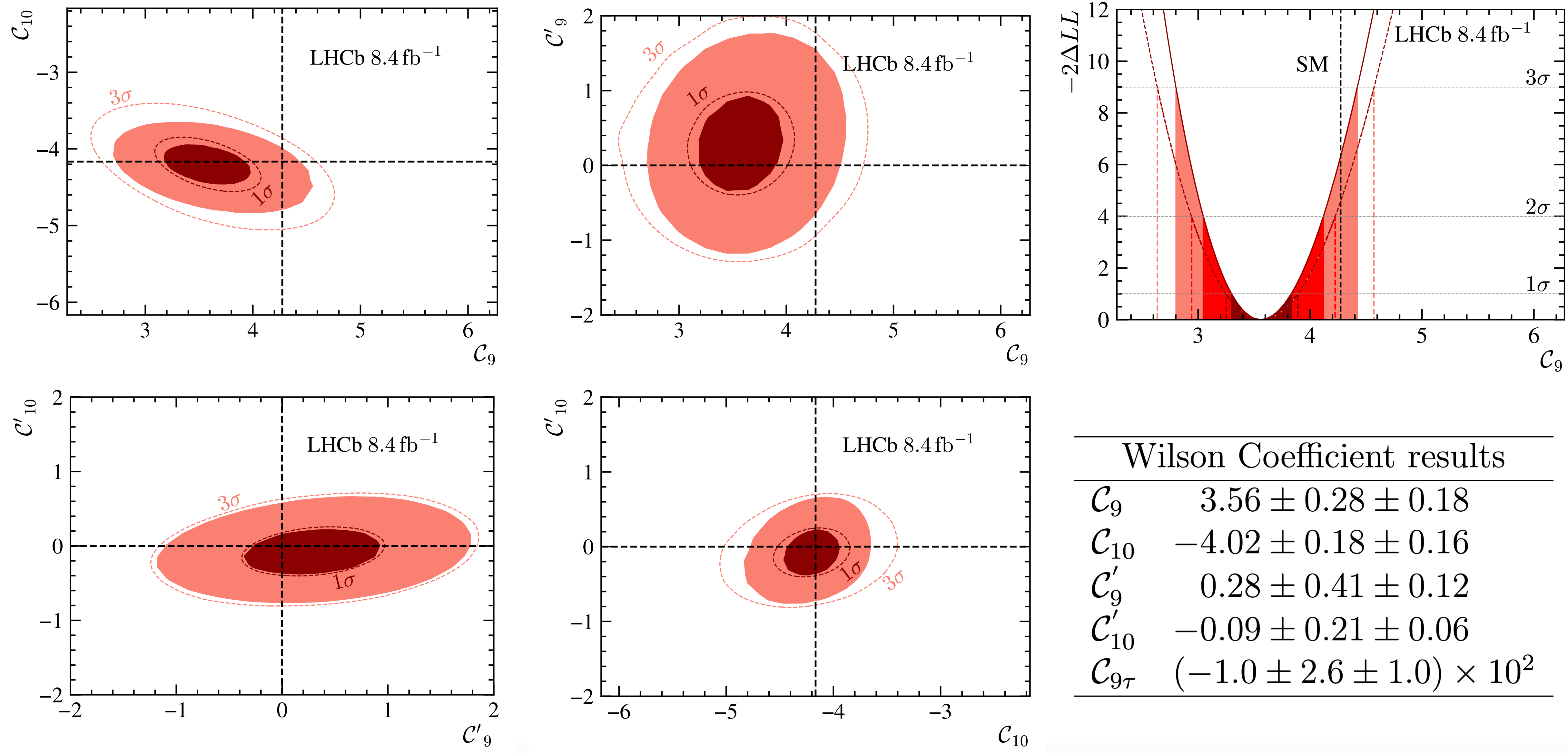
P-wave differential BF

- Cyan: Fixing experimental local results to SM predictions:
  - Cyan and yellow: impact of non-local modelling
  - Cyan and red: impact of possible NP



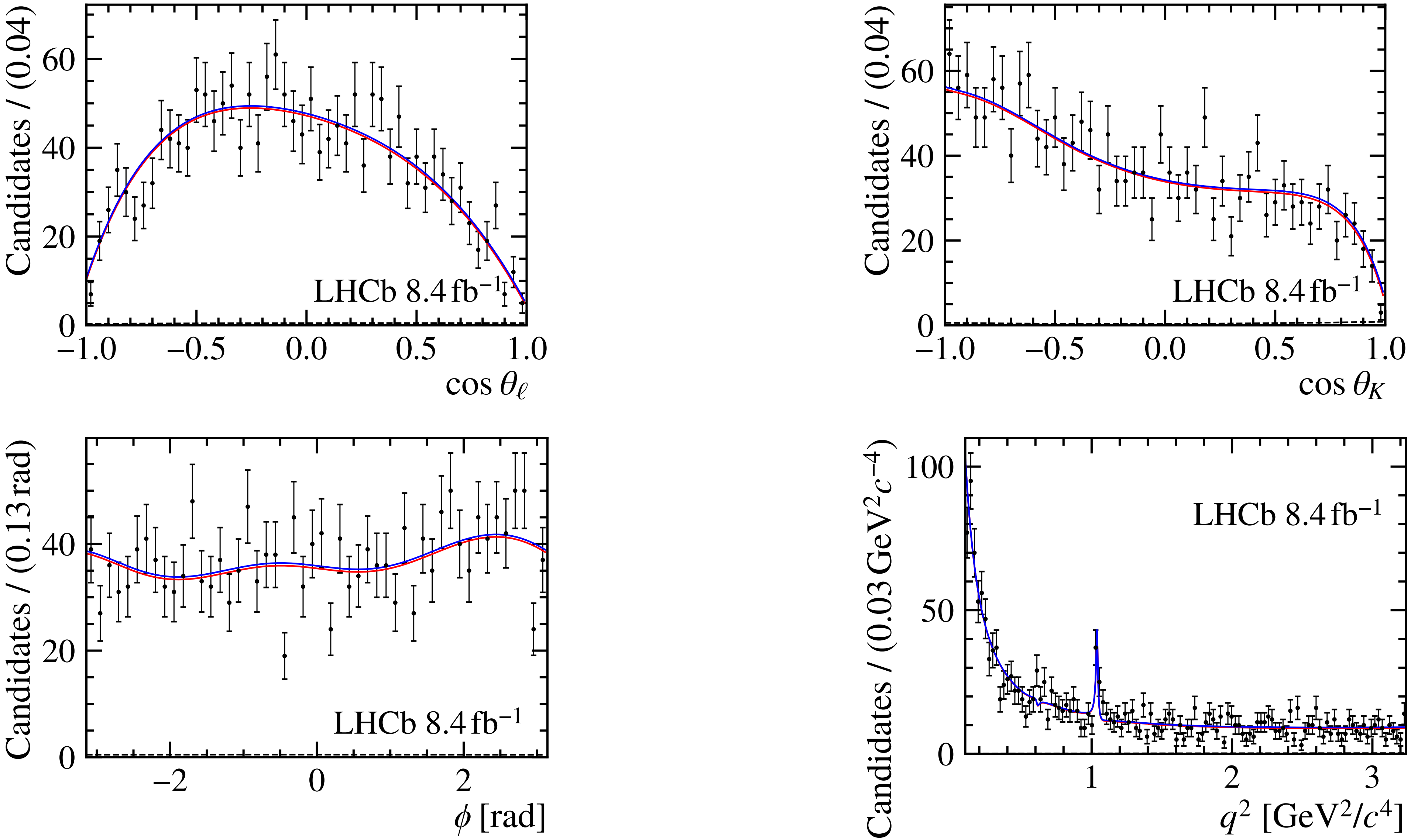


Wilson coefficients results

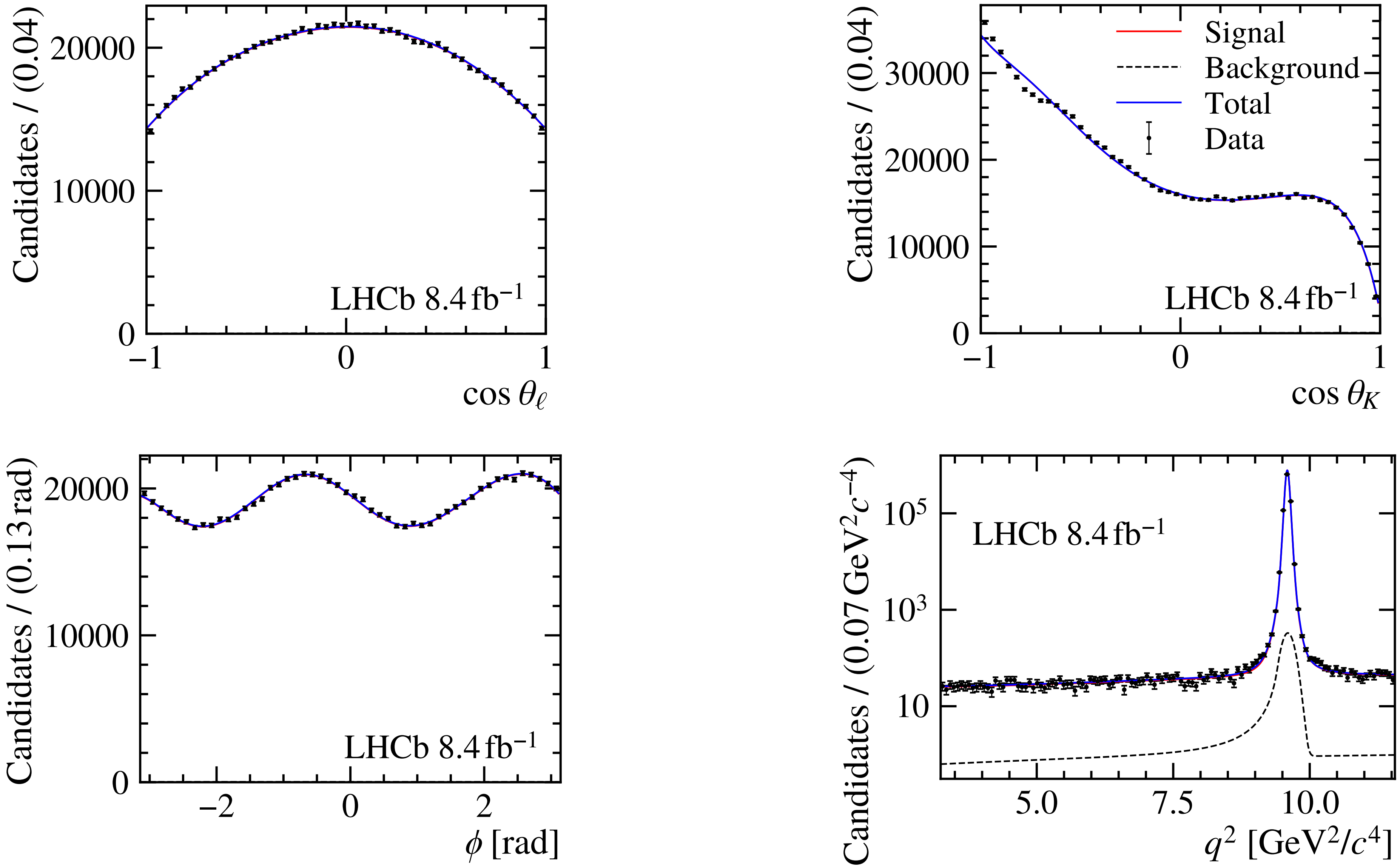


Wilson Coefficient results	
$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$
$\mathcal{C}_{10}$	$-4.02 \pm 0.18 \pm 0.16$
$\mathcal{C}'_9$	$0.28 \pm 0.41 \pm 0.12$
$\mathcal{C}'_{10}$	$-0.09 \pm 0.21 \pm 0.06$
$\mathcal{C}_{9\tau}$	$(-1.0 \pm 2.6 \pm 1.0) \times 10^2$

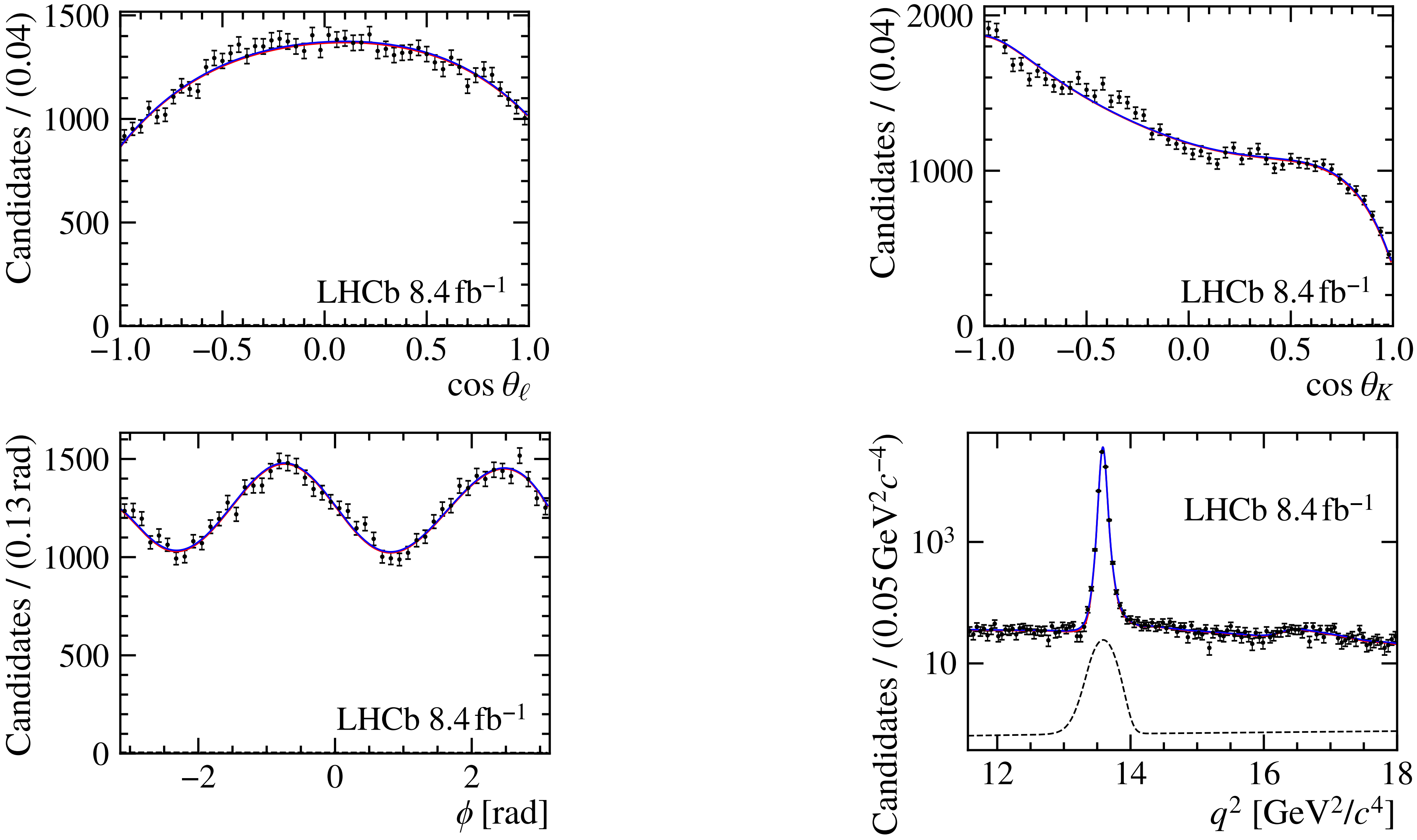
Angular fit: low-q^2



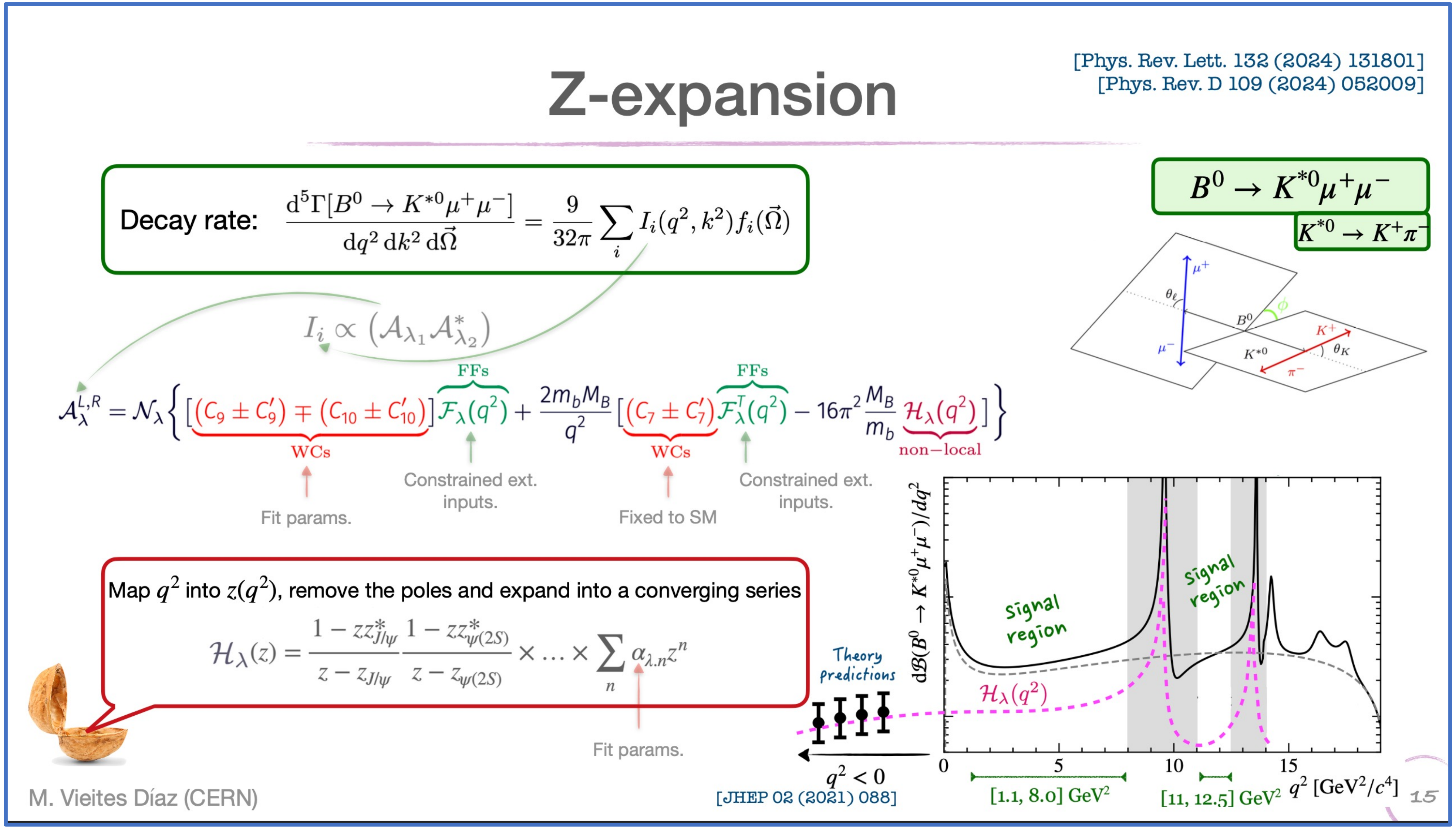
Angular fit: central-q^2



Angular fit: high-q^2



Z-expension: another cool method!



First B decays plots of 2024

LHCB-FIGURE-2024-007