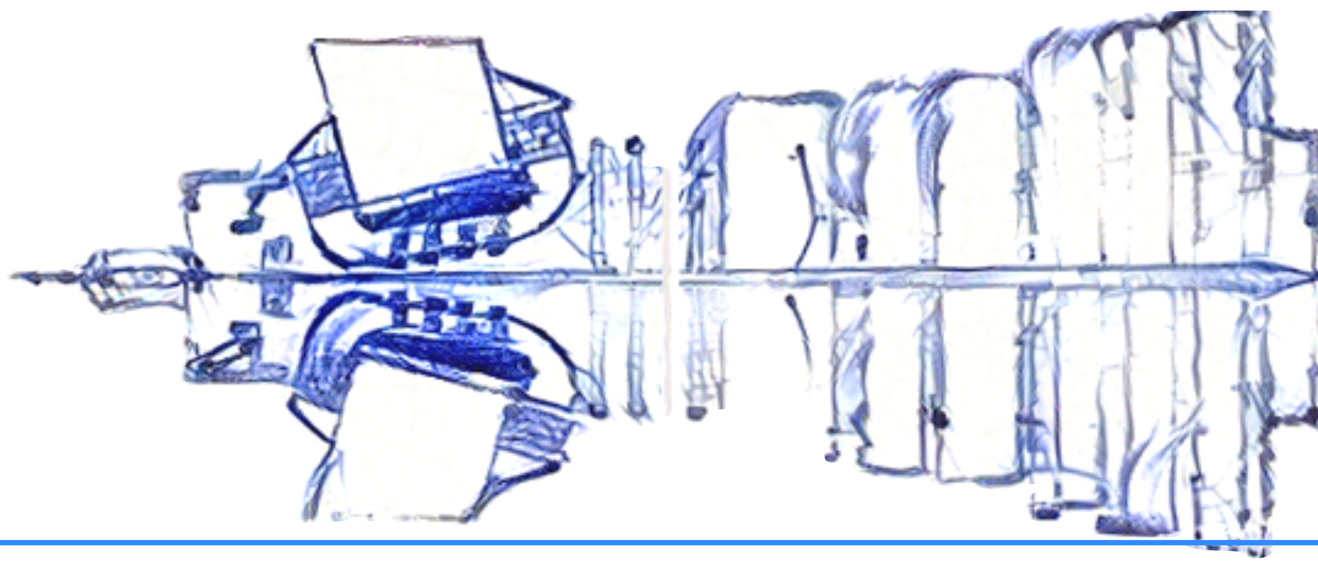
Flavour physics EFT highlights

$(B^0 \to K^{*0}\mu^+\mu^-)$

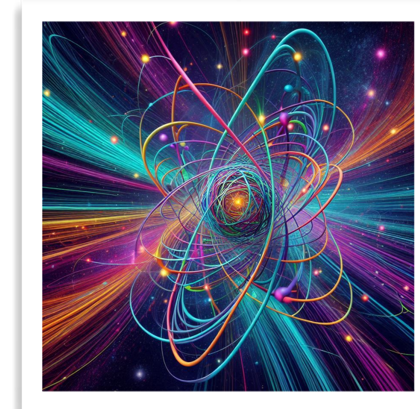


8th General Meeting of the LHC EFT Working Group

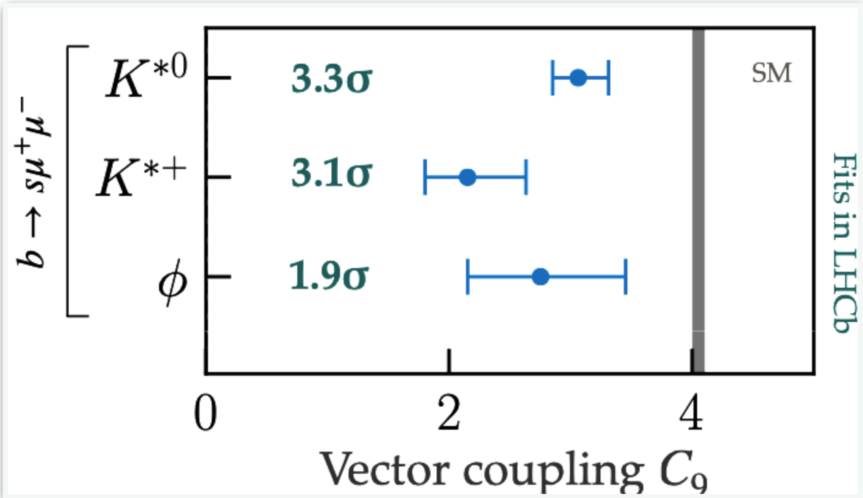
(December 2nd 2024)

Zahra Gh.Moghaddam
On behalf of LHCb collaboration

Introduction



- **Motivation:**
  - FCNCs ($b \to sll$) are good candidates to probe new physics (NP)
  - FCNC is suppressed in SM (Loop level, CKM, GIM)
  - NP processes compete with SM in tree level and can modify the effective couplings
- **Experimental evidence:**
  - Discrepancies in model dependent/independent measurements of different observables from SM in several B decays:
    - Branching fraction
    - Angular Observable
- **$b \to s\mu\mu$:**
  - ➡ $B^+ \to K^+\mu^+\mu^-$
  - ➡ $B^0 \to K^{*0}\mu^+\mu^-$
  - ➡ $B_s \to \phi\mu^+\mu^-$
  - ➡ $\Lambda_b \to \Lambda l^+ l^-$ ...

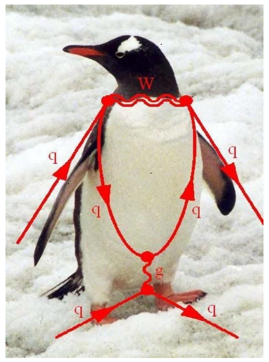


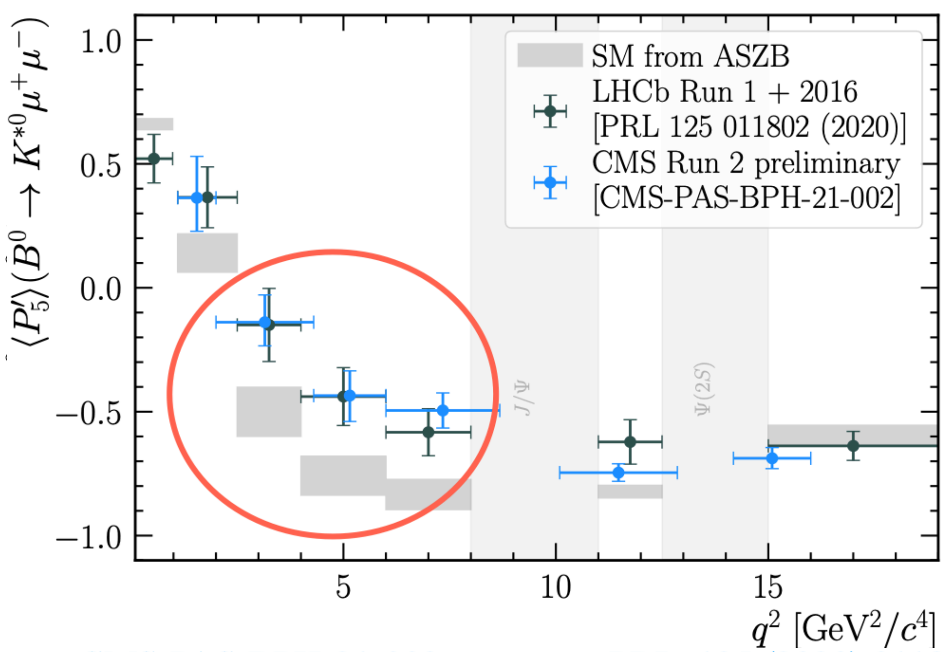
PRL 125(2020)011802

PRL 126(2021)161802

JHEP11(2021)043

- **Challenges:**
  - Theoretical: Estimating non-perturbative contributions (four quark interactions)
  - Experimental: Precision measurement
- **Goal:**
  - Precision measurement
  - Better understanding of SD/LD physics



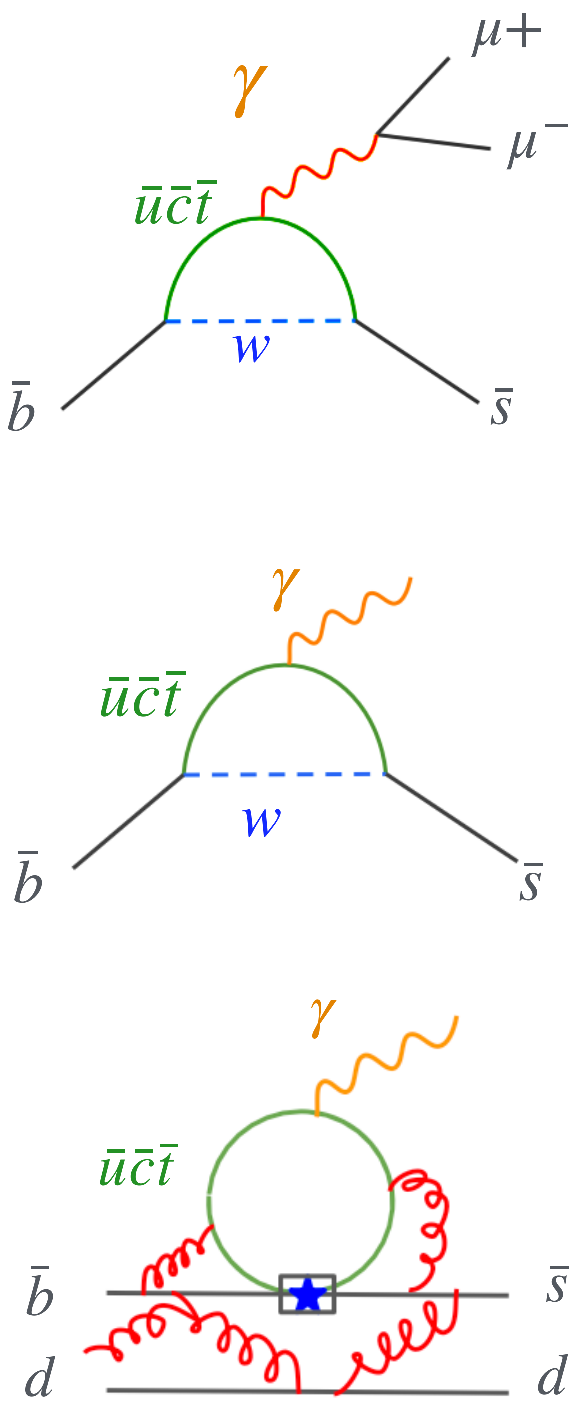


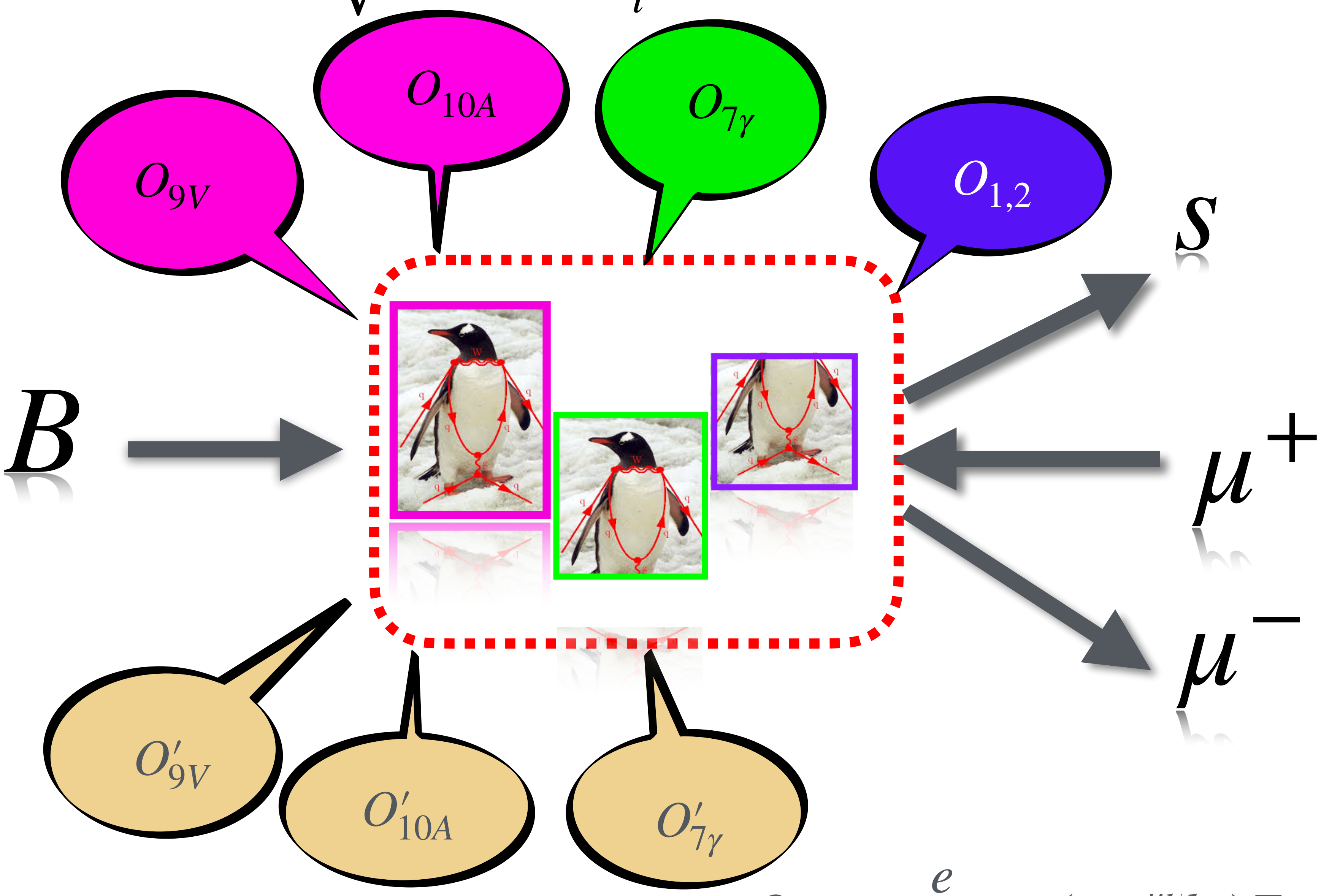
CMS-PAS-BPH-21-002 PRL. 125 (2020) 011802

Rare Decays

LHCb

$$\mathcal{H}_{WET} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_i (C_i^{SM} + \Delta C_i^{NP}) \mathcal{O}_i$$





$$O_1 = (\bar{s}^{\alpha}_L \gamma_\mu c^{\beta}_L)(\bar{c}^{\alpha}_L \gamma^\mu \bar{b}^{\beta}_L)$$

$$O_2 = (\bar{s}^{\alpha}_L \gamma_\mu c^{\alpha}_L)(\bar{c}^{\beta}_L \gamma^\mu \bar{b}^{\beta}_L)$$

$$O_{7\gamma} = \frac{e}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}$$

$$O_{9V} = \frac{e}{16\pi^2} (\bar{s}_L \gamma_\mu b_L)(\bar{l} \gamma^\mu l)$$

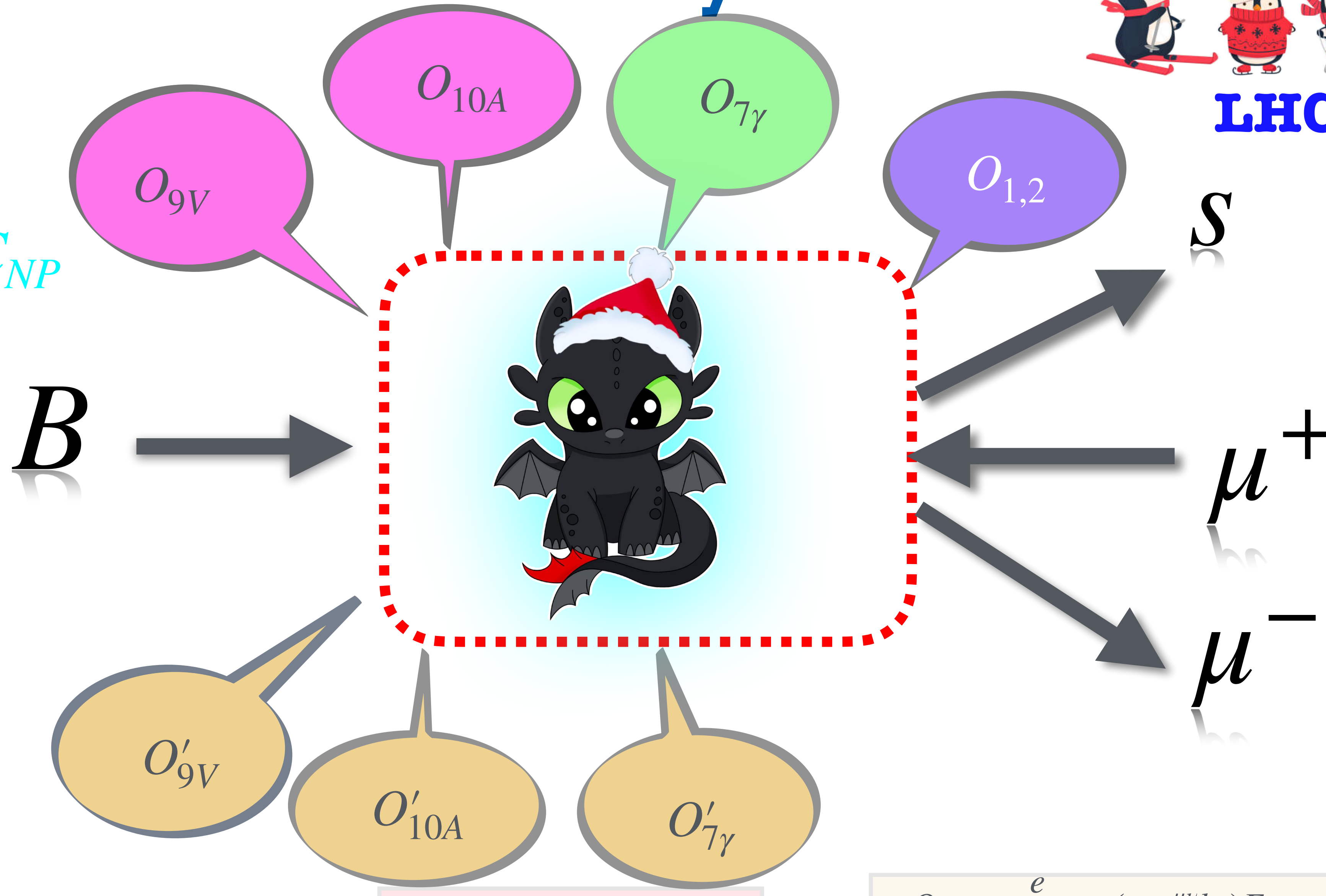
$$O_{10A} = \frac{e}{16\pi^2} (\bar{s}_L \gamma_\mu b_L)(\bar{l} \gamma^\mu \gamma_5 l)$$

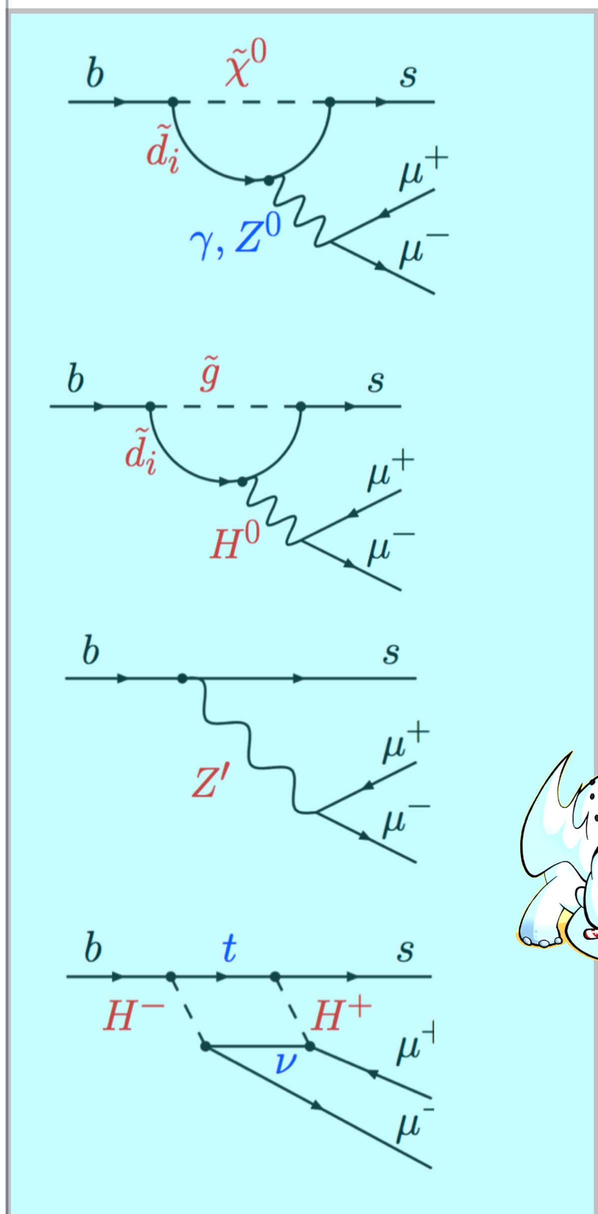
[JHEP 01 (2009) 019]

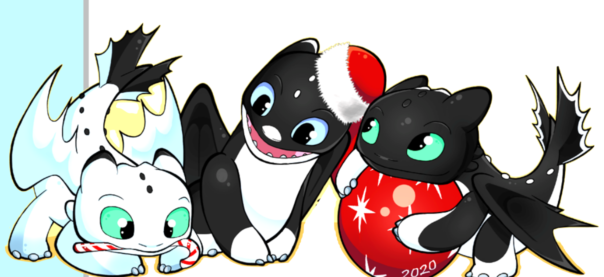
Rare Decays

LHCb

$$C^{eff}_{9,7} = C^{SM}_{9,7} + C^{c\bar{c}}_{9,7} + C_{NP}$$







?

$$O_1 = (\bar{s}^\alpha_L \gamma_\mu c^\beta_L)(\bar{c}^\alpha_L \gamma^\mu \bar{b}^\beta_L)$$

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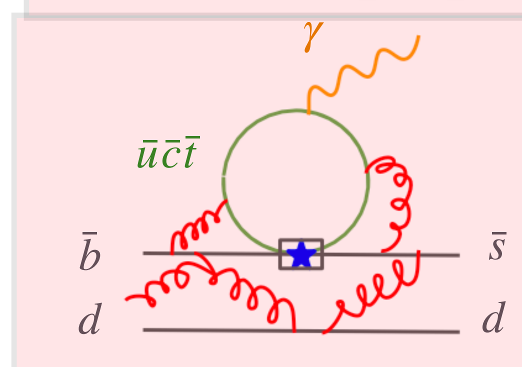
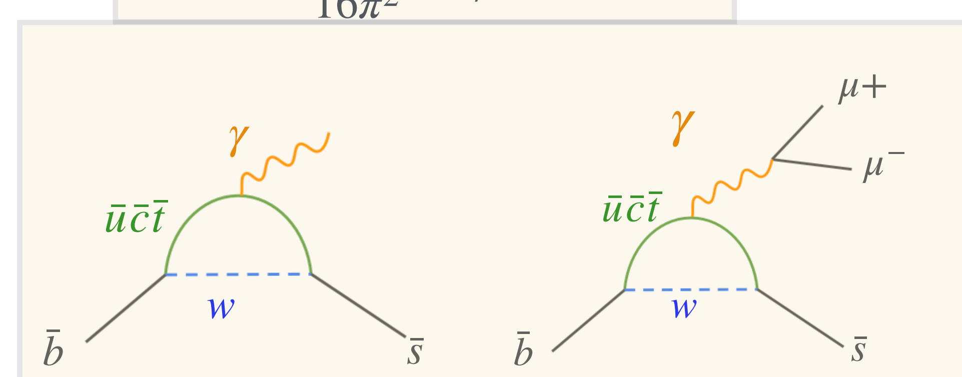
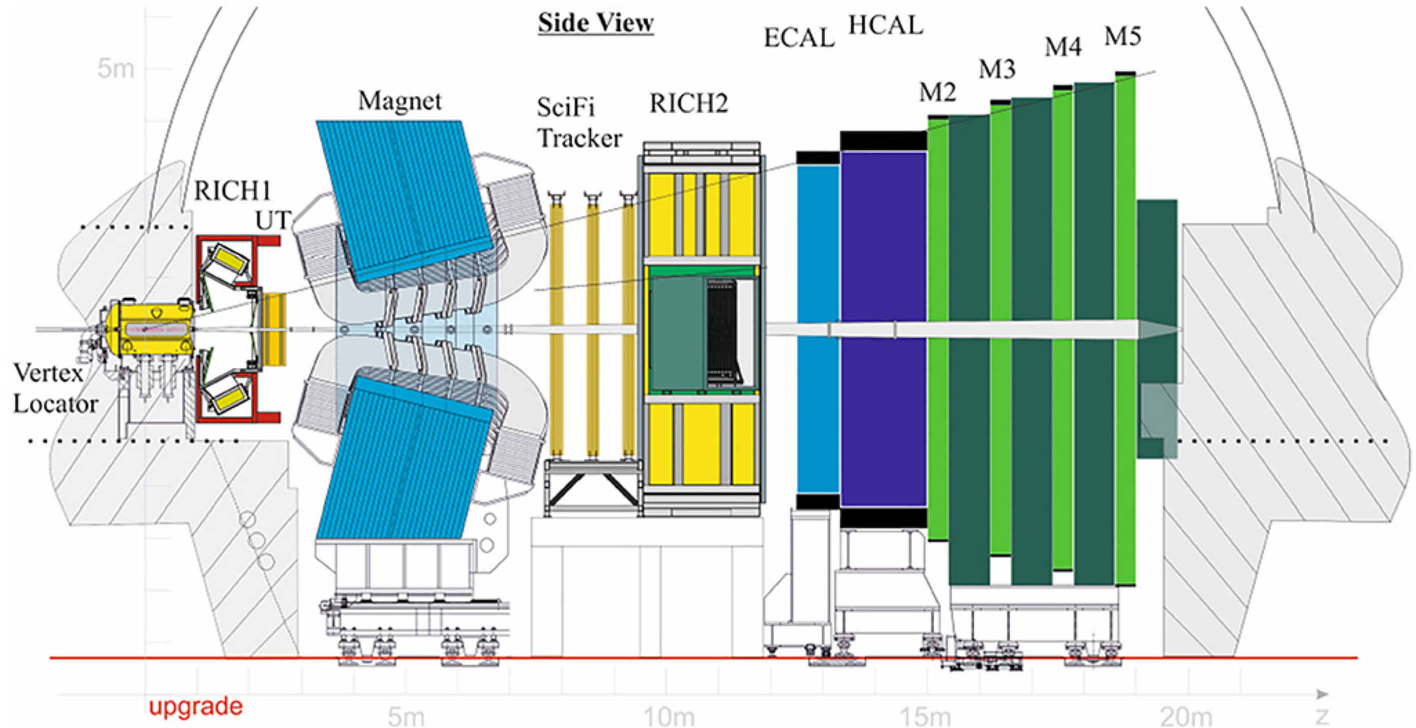


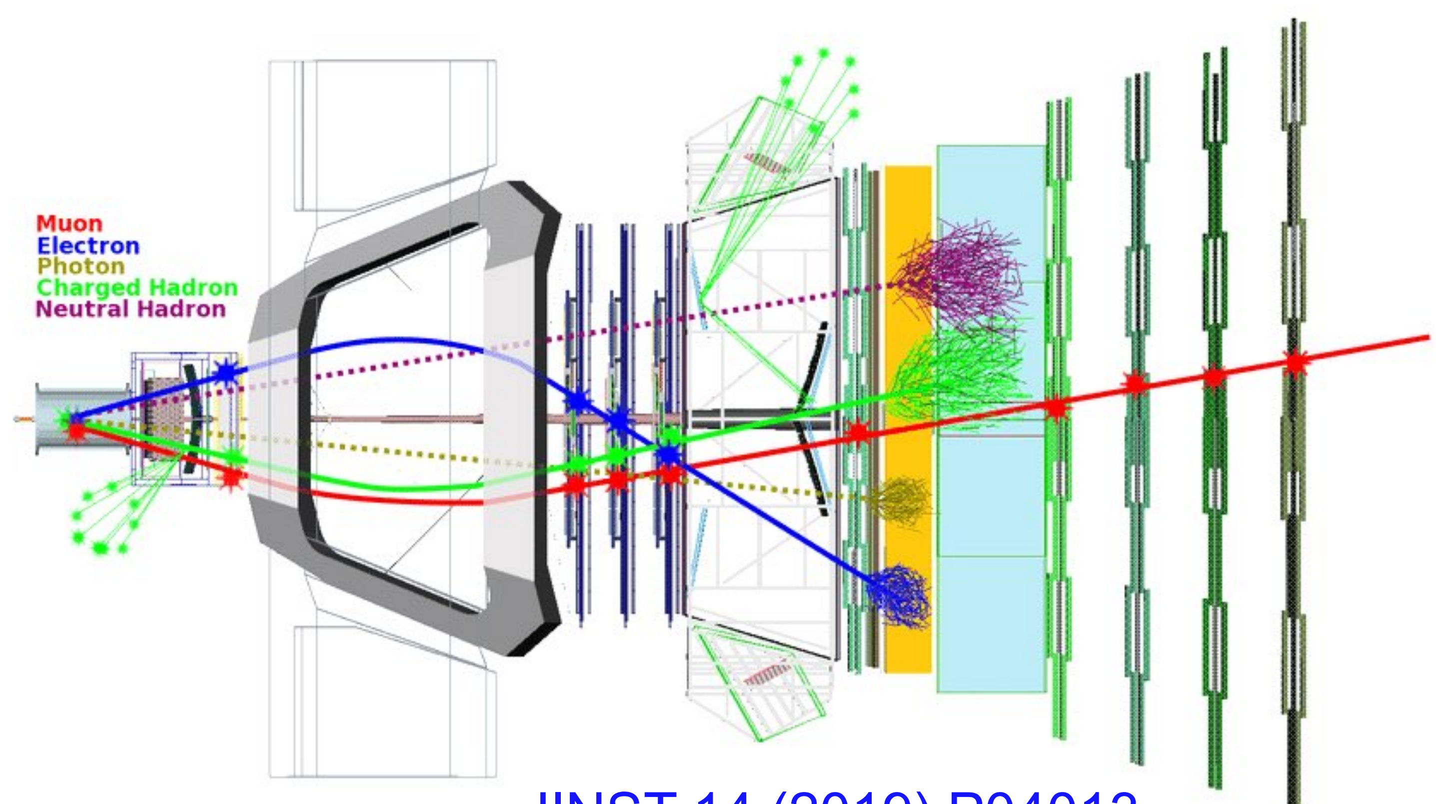


LHCb Experiment

- LHCb is single-arm forward spectrometer
- B hadrons typically decay after traveling ~ 1 [cm], vertex measured by VELO
- Large fraction of B hadrons are produced in forward direction in LHC
- Excellent PID System:

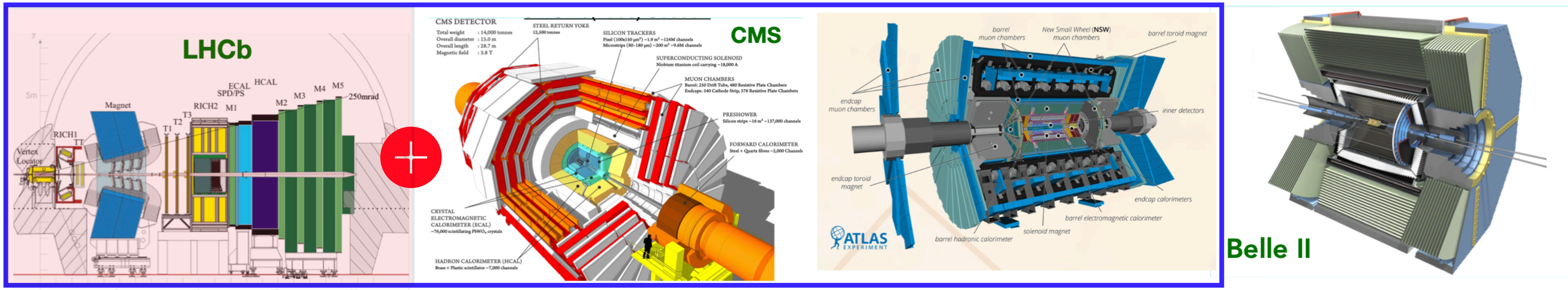
$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$





JINST 14 (2019) P04013

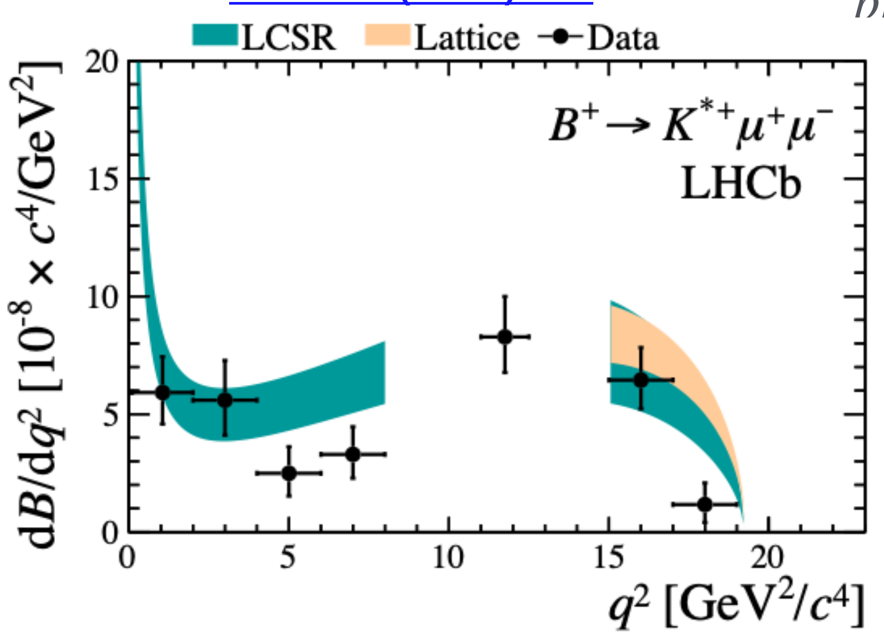
Rare Decays, Branching Ratio

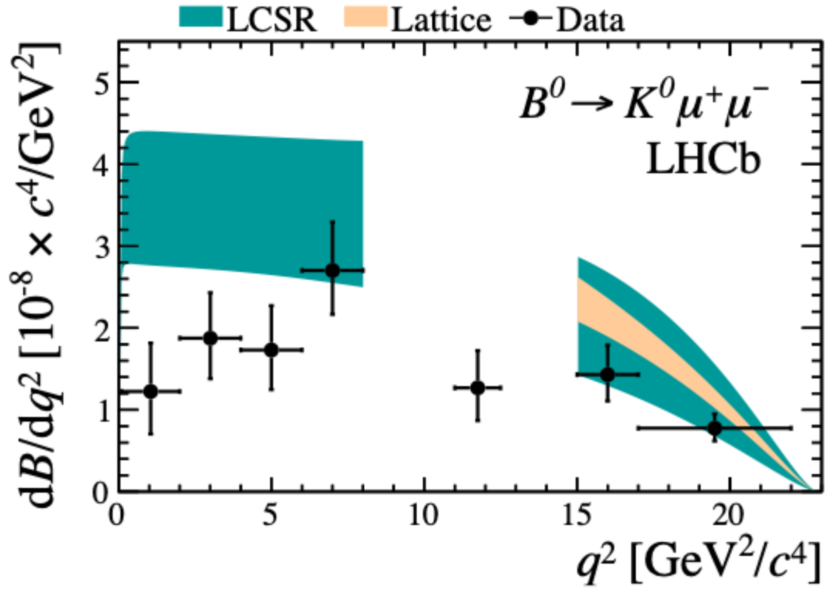


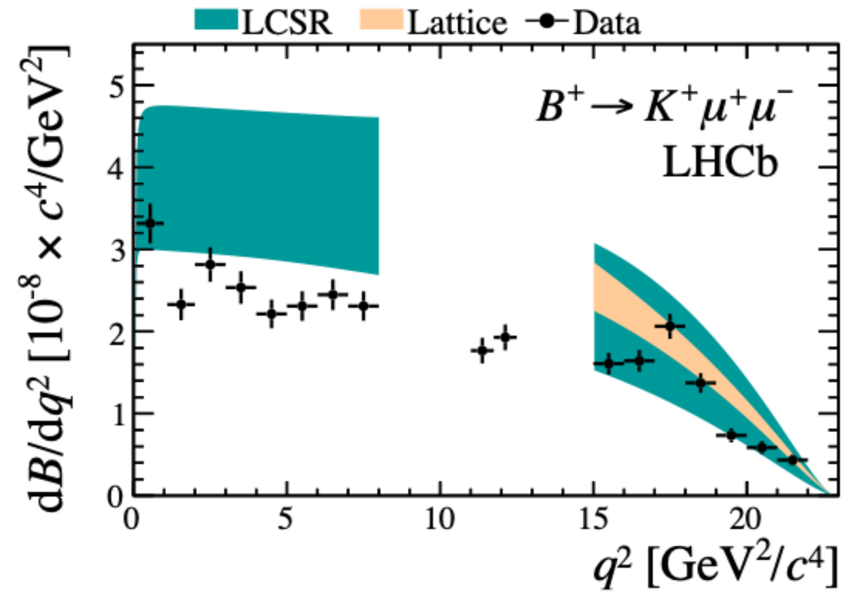
[JHEP 06 (2014) 133](#)

$pp, \sqrt{s} = 7{,}8{,}13[\text{TeV}]$

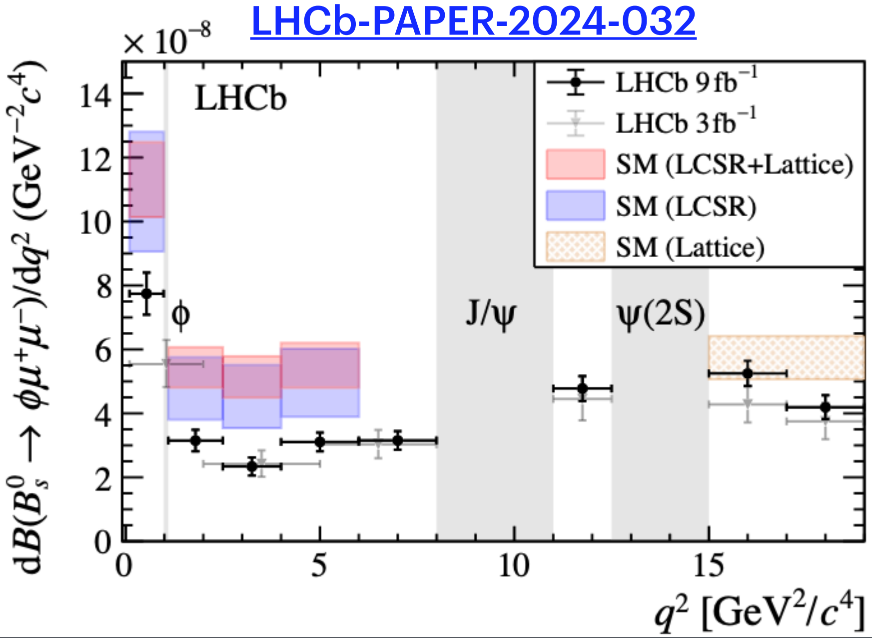
$e^+e^- \sqrt{s} = 10.58[\text{GeV}]$



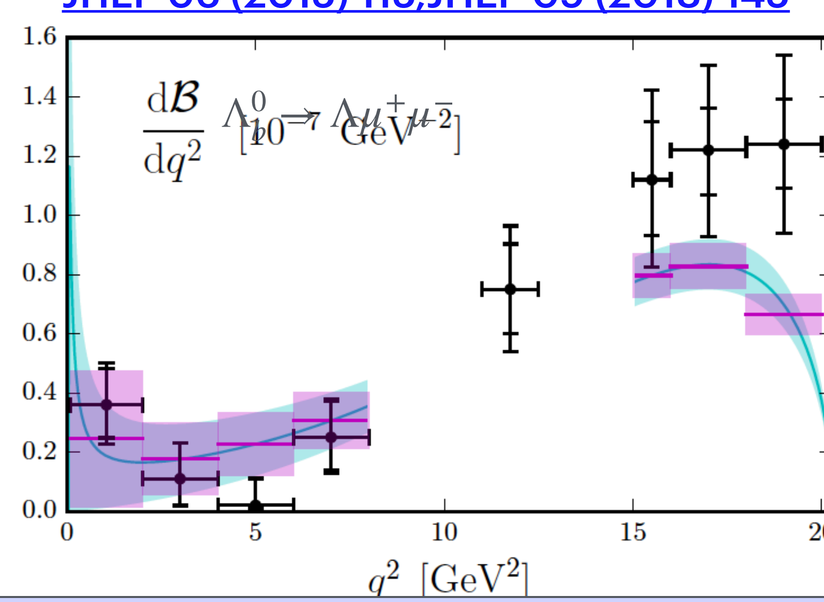




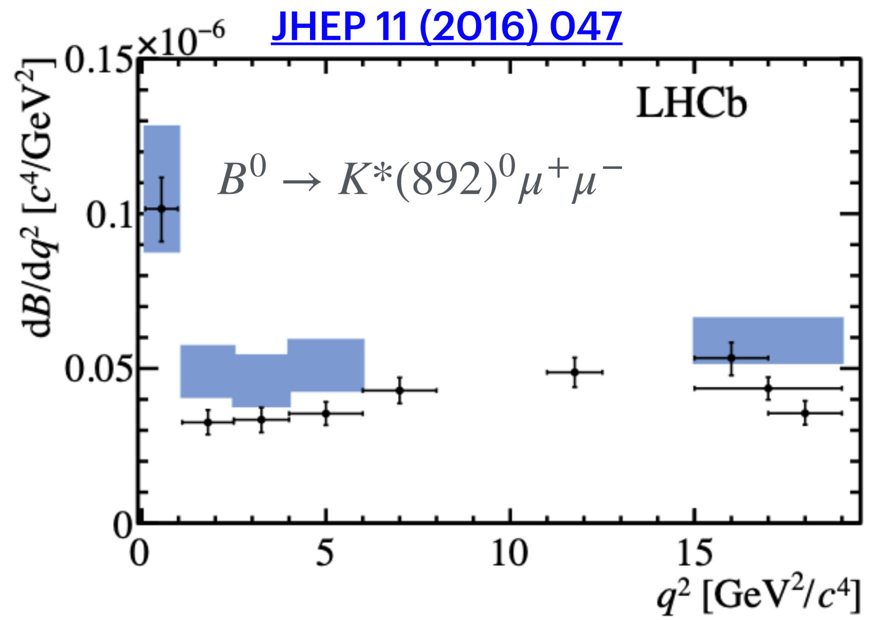
[LHCb-PAPER-2024-032](#)



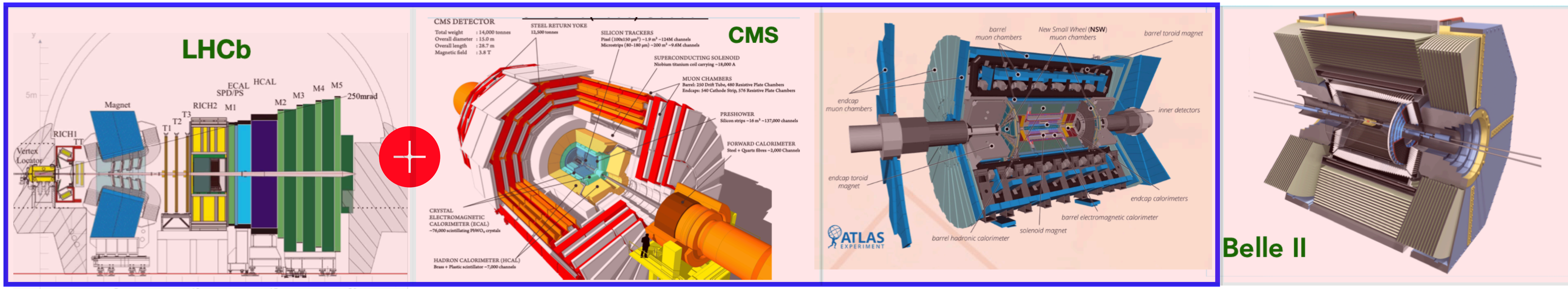
[JHEP 06 (2015) 115](#), [JHEP 09 (2018) 145](#)



[JHEP 11 (2016) 047](#)



Rare Decays,Global Fit



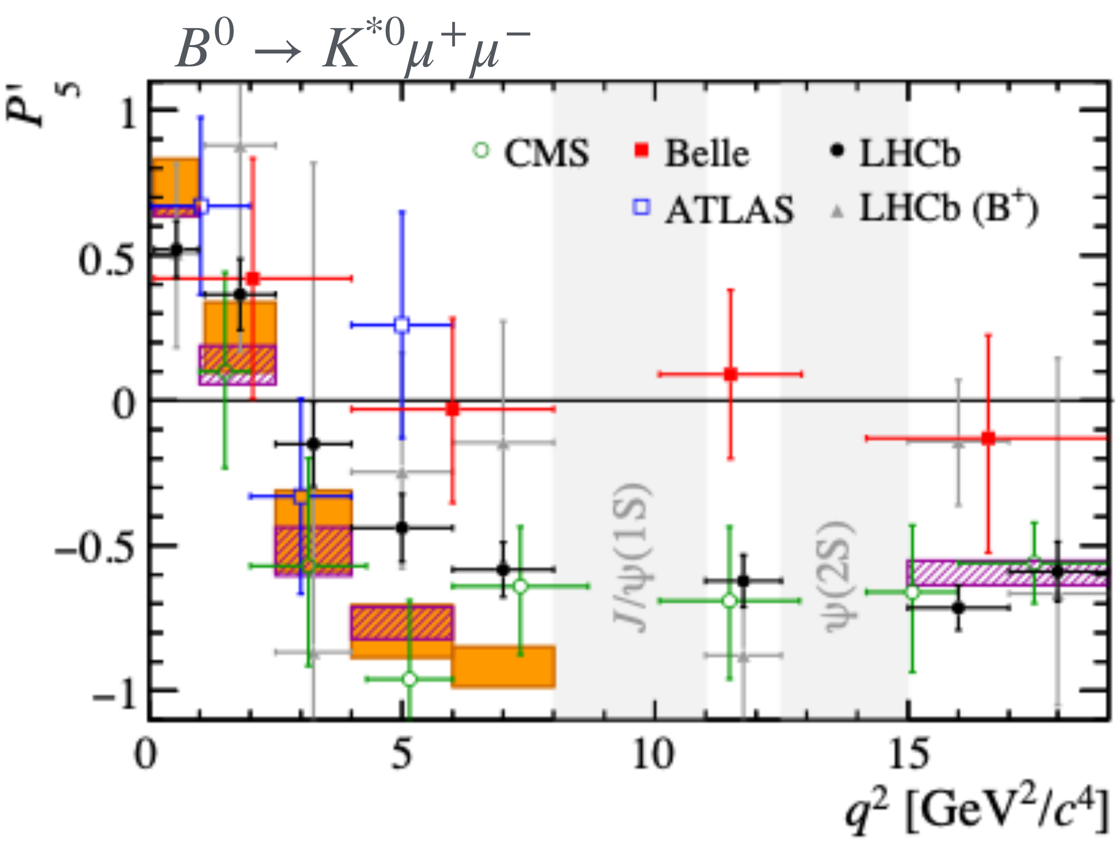
$pp, \sqrt{s} = 7{,}8{,}13[\mathrm{TeV}]$ $e^+e^- \sqrt{s} = 10.58[\mathrm{GeV}]$

PRL 126 (2021) 161802, PRL 125(2020) 1 011802)

JHEP 11 (2021) 043, JHEP 12 (2016) 065, JHEP 09 (2018) 146

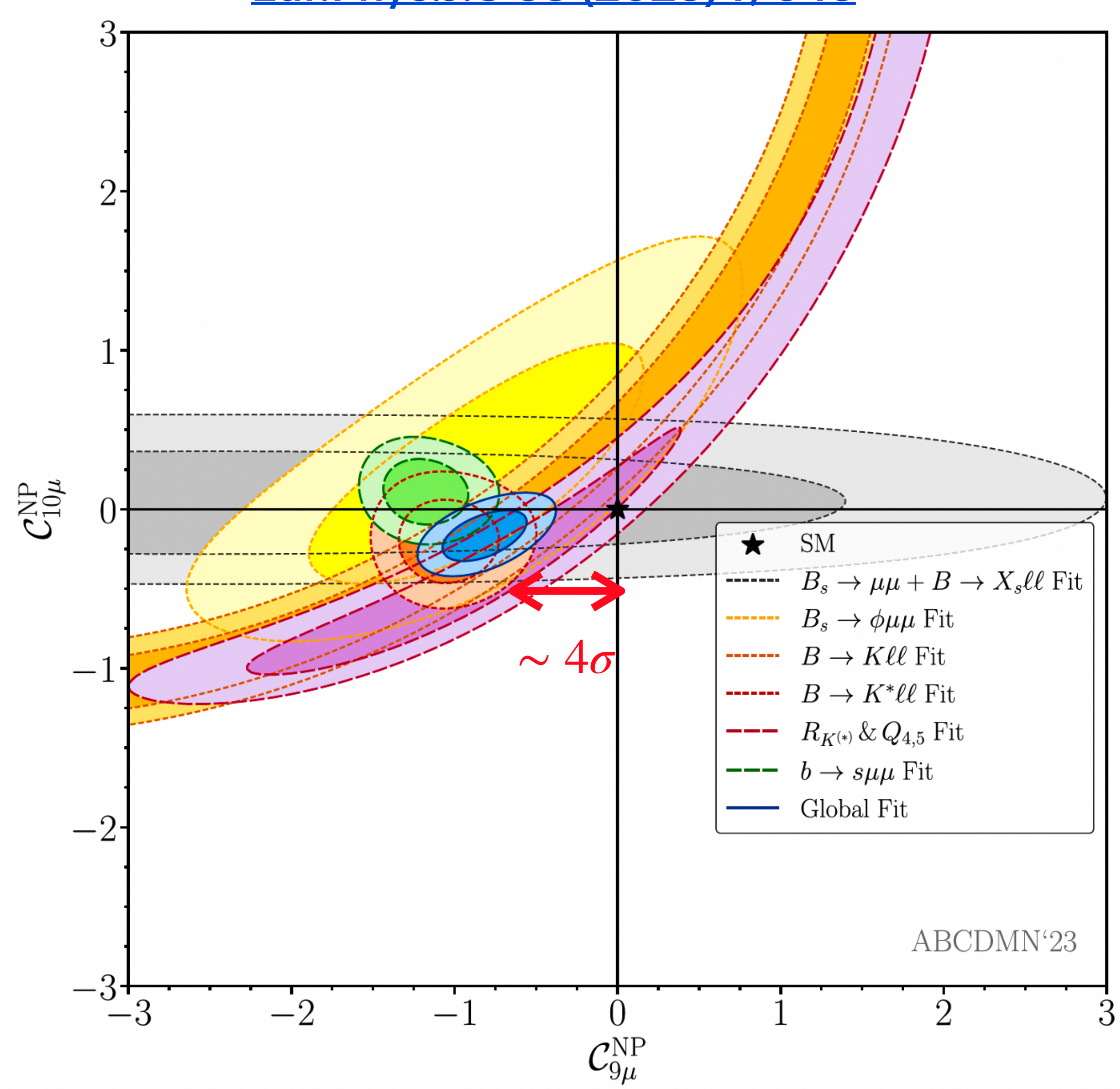
CMS-PAS-BPH-21-002

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

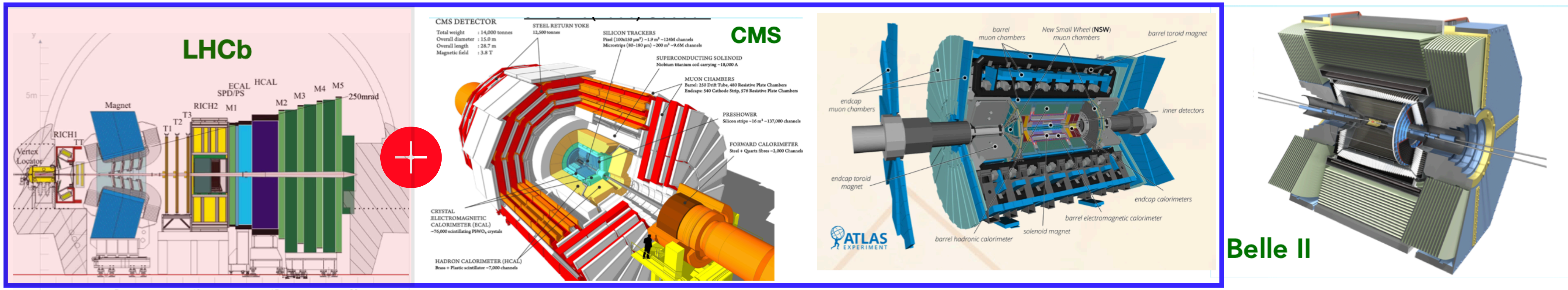


C_9 **shift**

Eur.Phys.J.C 83 (2023) 7, 648



LFU Test

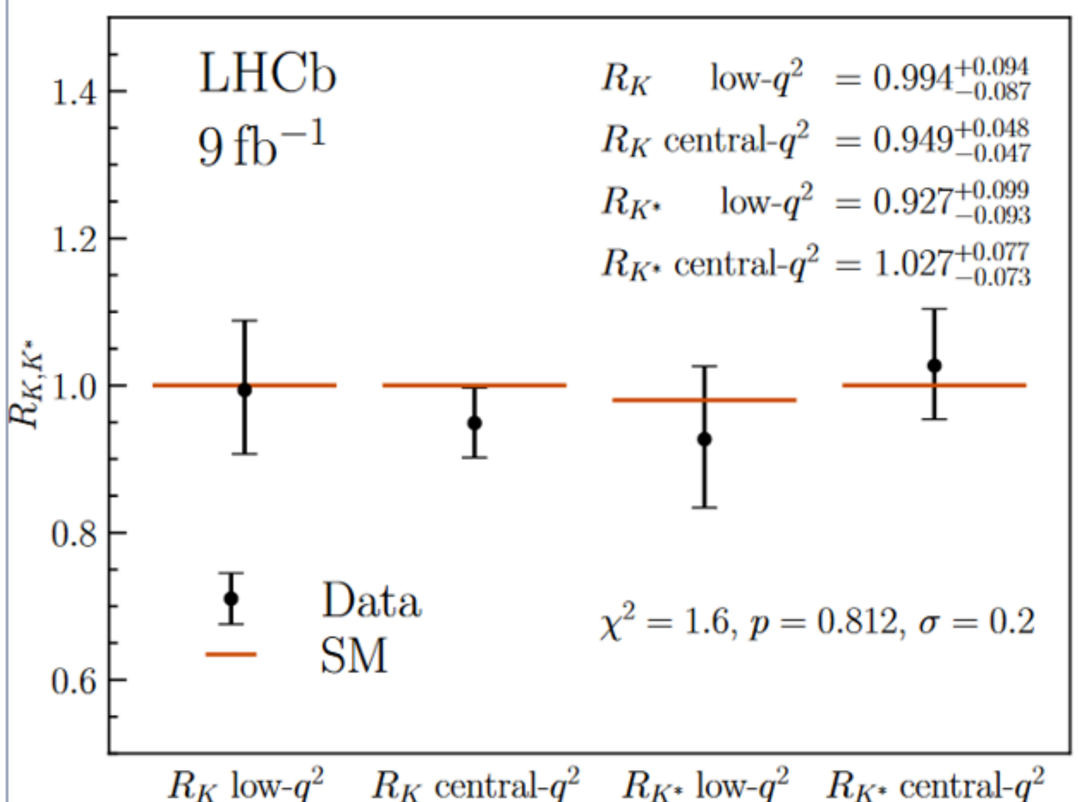


$pp, \sqrt{s} = 7{,}8{,}13[\text{TeV}]$

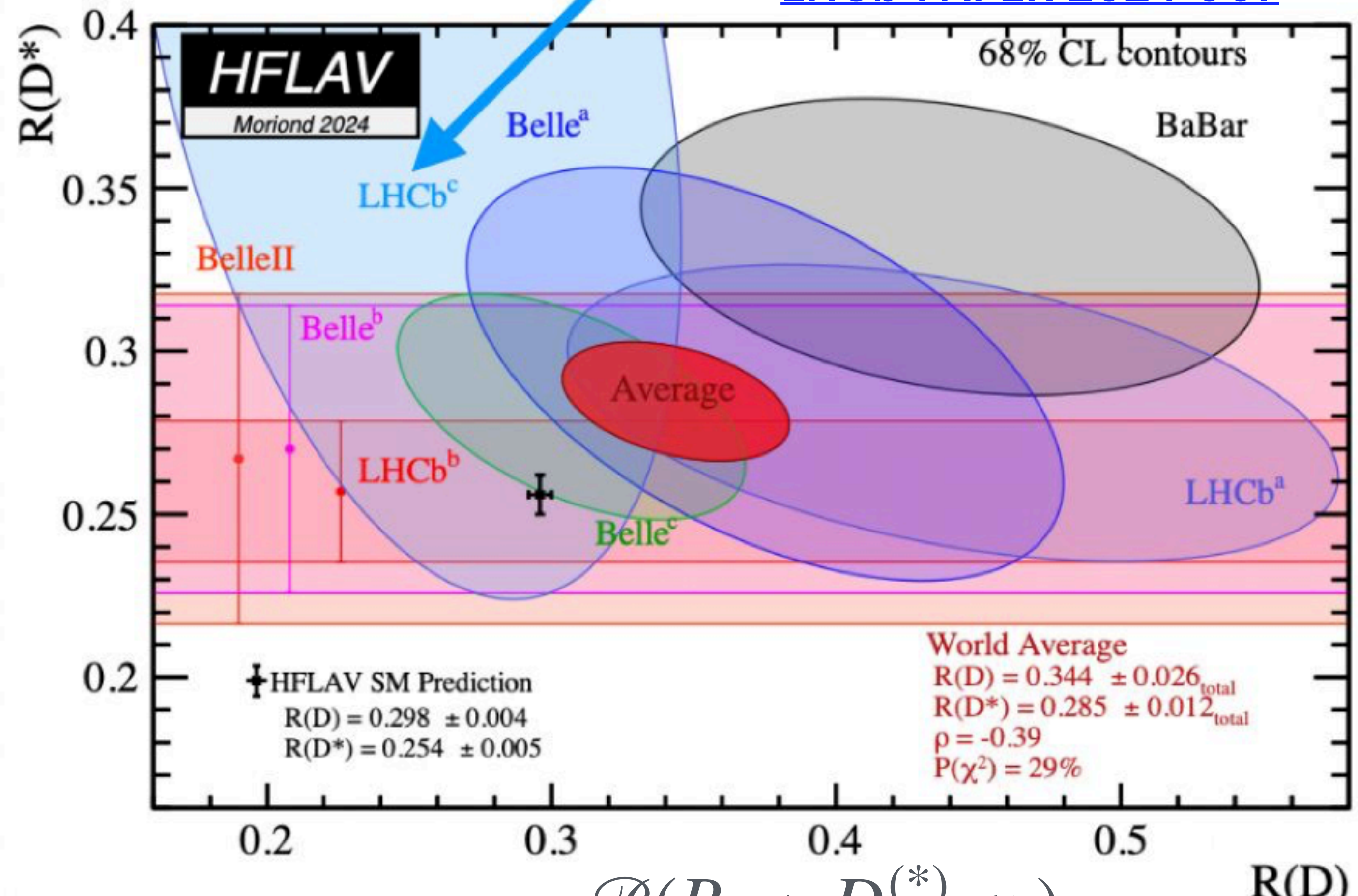
This result

$e^+e^- \sqrt{s} = 10.58[\text{GeV}]$

Phys. Rev. Lett. 131 (2023) 051803



LHCb-PAPER-2024-007



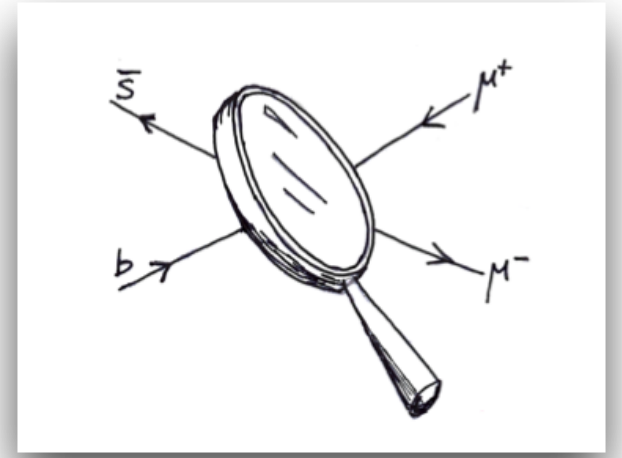
$$R_{K^{(*)}} = \frac{\mathcal{B}(B^{+(0)} \to K^{+(0^*)}\mu^+\mu^-)}{\mathcal{B}(B^{+(0)} \to K^{+(0^*)}e^+e^-)}$$

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu\nu_\mu)}$$

See the talk by **Abhijit Mathad**

Unbinned Analysis $B^0 \to K^{*0}\mu^+\mu^-$

- **Motivation:**
  - Maximising statistical Power
  - No Loss of information
  - Enhanced sensitivity to New Physics due to its higher precision
- **Challenges:**
  - Computationally heavy
  - Sensitive to statistical fluctuations
  - Challenging systematics uncertainty



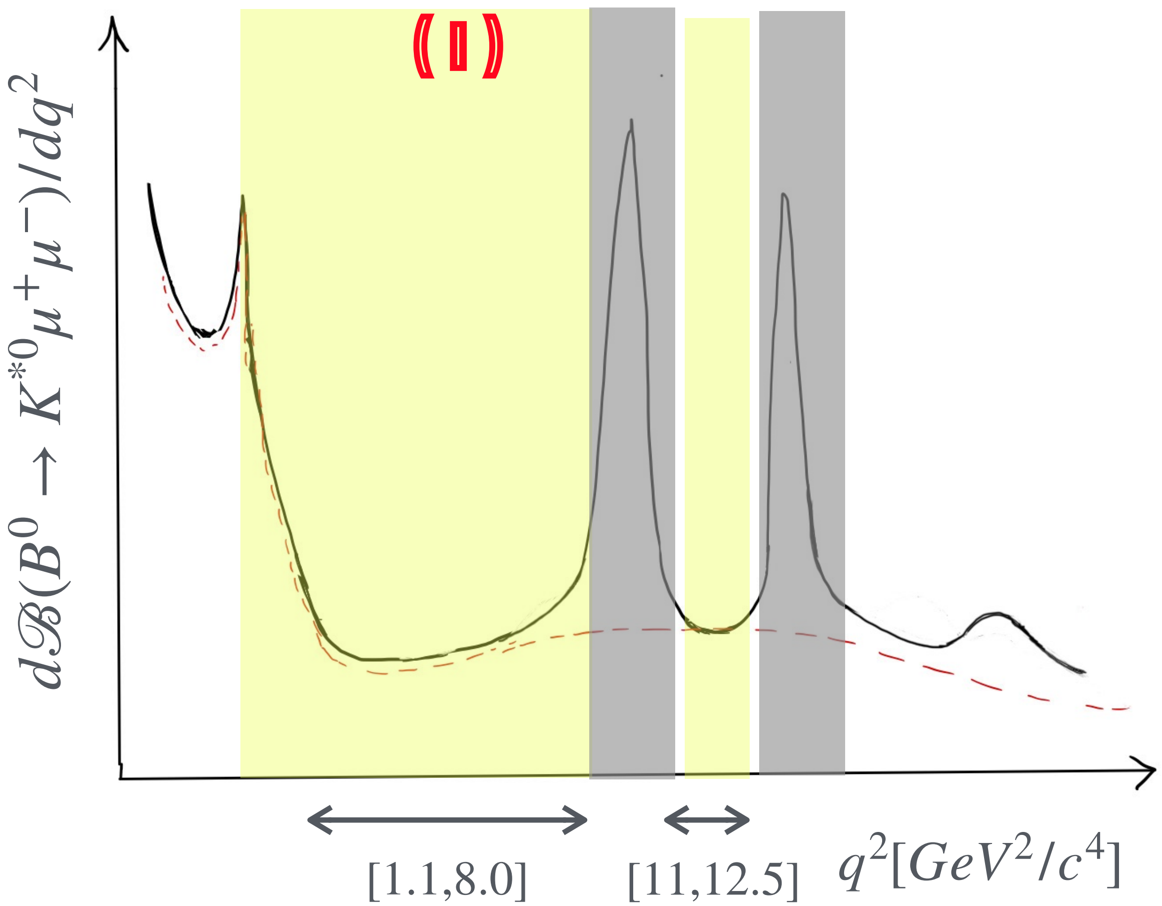
- **LHCb Analysis Recent Unbinned Analysis :**

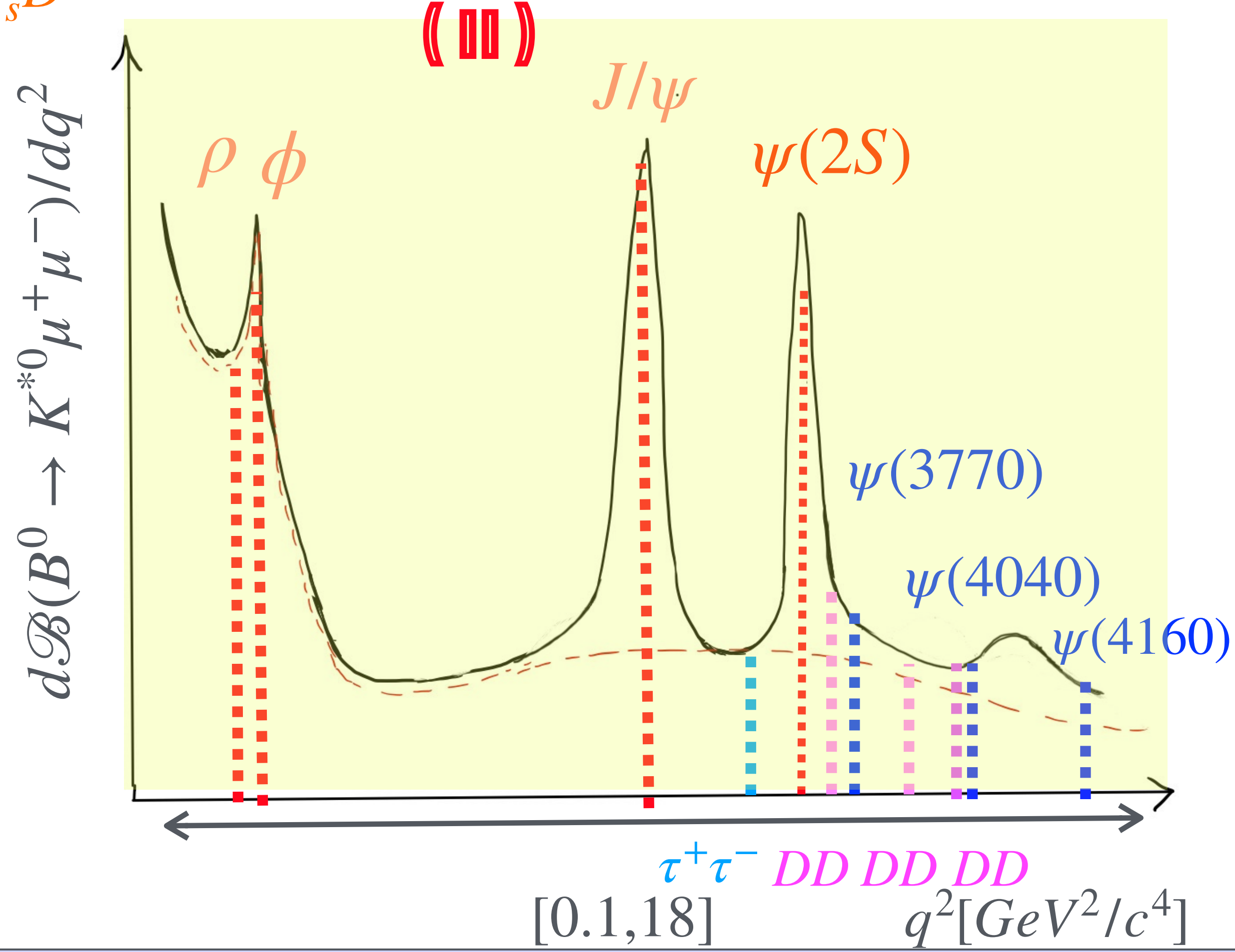
  I. Z-expansion:

  II.Dispersion Model:
  - 1-particle (Vector Resonances coupling to muons)
  - 2-particle $D^{(*)}\bar{D}^{(*)}$, $\tau^+\tau^-$ Eur.Phys.J.C 80 (2020) 12, 1095
  - Not including re-scattering $D_s D^*$

PRD. 109 (2024) 052009

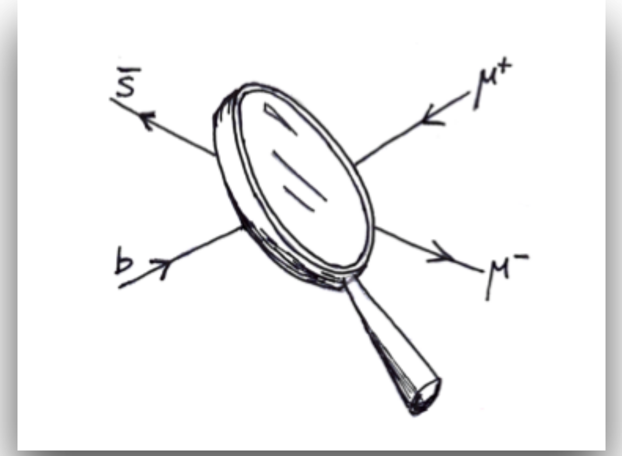
JHEP 09 (2024) 026





Unbinned Analysis $B^0 \to K^{*0}\mu^+\mu^-$

- **Differences:**
  - q^2 region: Limited Vs Broad
  - Non-local treatment: z-expansion, dispersion relation
  - Luminosity (PP collision data) : Run 1+ 2016, $4.7[fb^{-1}]$ Vs RUN I+II , $8.4[fb^{-1}]$
- **Similarities:**
  - Local FFs, Asatrian, Greub, Virto [JHEP 04 (2020) 012]:
    - LQSR
    - LQCD



Eur.Phys.J.C 80 (2020) 12, 1095

$$A_{L,R} = \frac{\alpha}{\pi}\Big[(C_9 \pm C_9')\ (C_{10} \pm C_{10}')\Big]F(q^2) + \frac{2m_b M_B}{q^2}\Big[(C_7 \pm C_7')\,F_\lambda^T(q^2) - \frac{16\pi^2 M_B}{m_b}\mathcal{H}_\lambda(q^2)\Big]$$

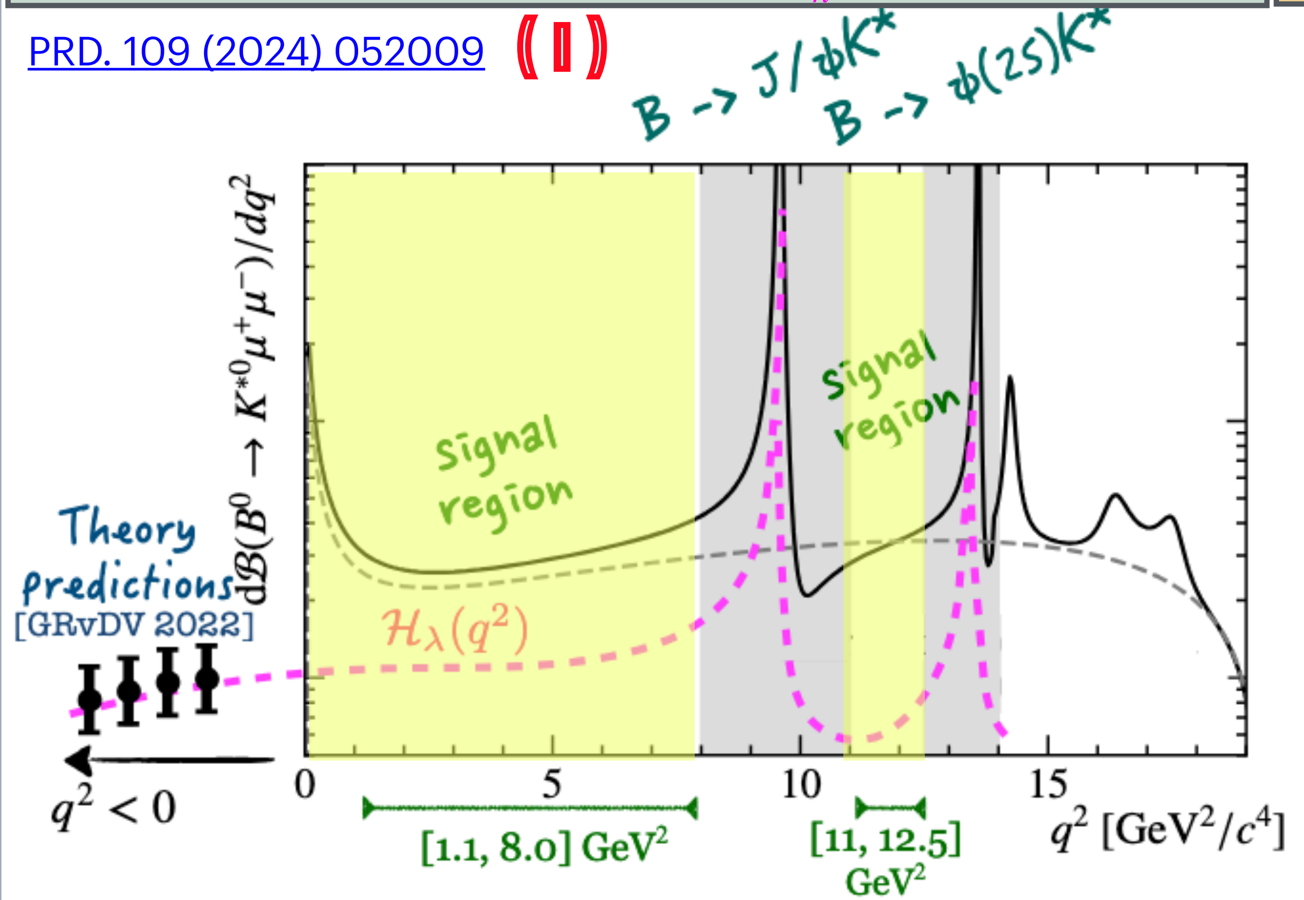
$$\mathcal{H}_\lambda(z) = \frac{1 - zz^*_{J/\psi}}{z - z_{J/\psi}}\frac{1 - zz^*_{\psi(2S)}}{z - z_{\psi(2S)}} \times \ldots \times \sum_n \alpha_{\lambda,n} z^n$$

$$Y^{q\bar{q},\lambda}(q^2) = Y^{q\bar{q}}(q_0^2) + \frac{q^2 - q_0^2}{\pi}\int_{q^2_{min}}^{\infty} ds \frac{\rho^{q\bar{q},\lambda}(s)}{(s - q_0^2)(s - q^2 - i\varepsilon)}$$

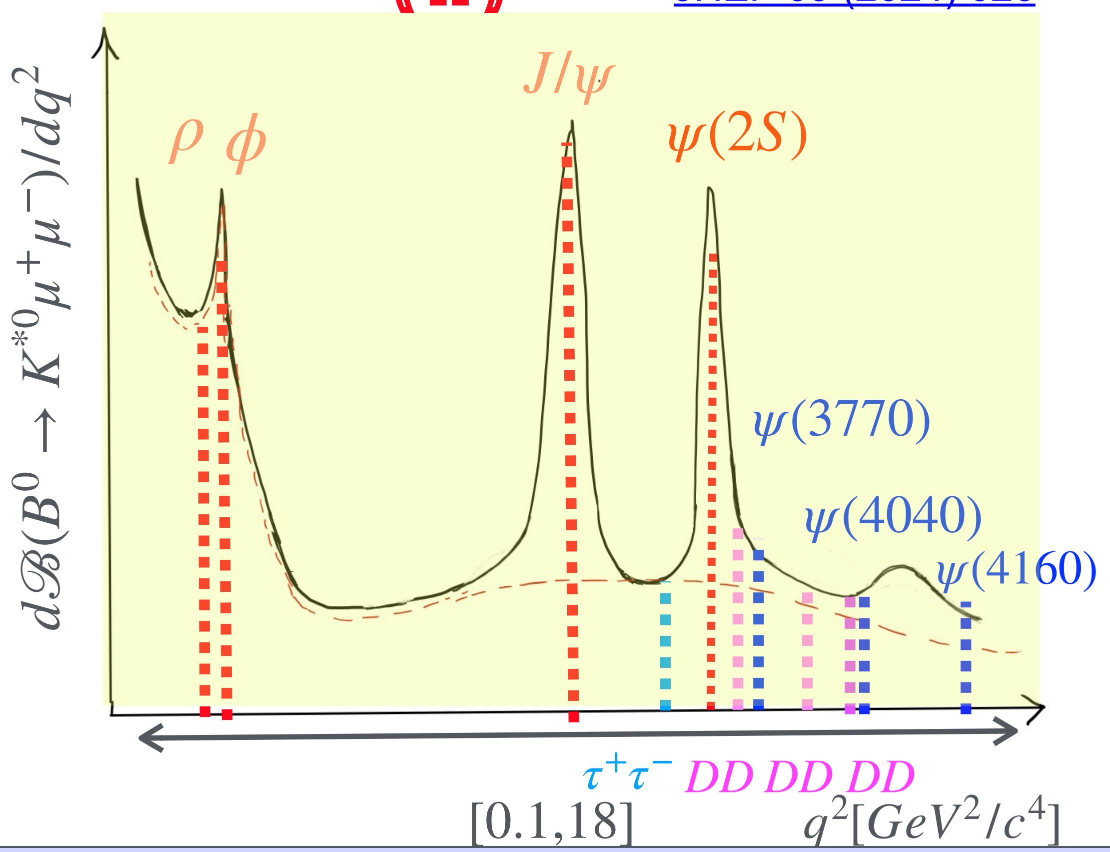
$$C_9^{eff,\lambda} = C_9 + Y^{q\bar{q},\lambda}(q^2)$$

$$C_7^{eff,\lambda} = C_7 + \zeta^\lambda e^{i\omega^\lambda}$$

PRD. 109 (2024) 052009 (I)



(II) JHEP 09 (2024) 026



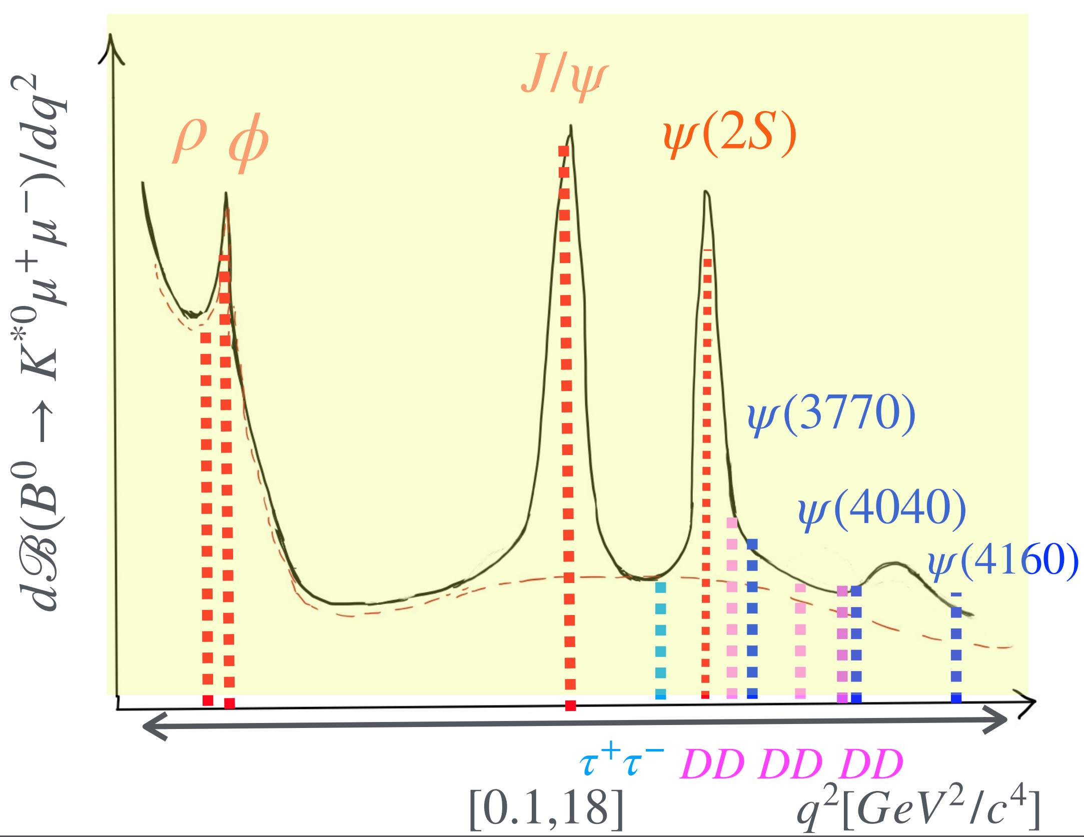
Dispersion Model

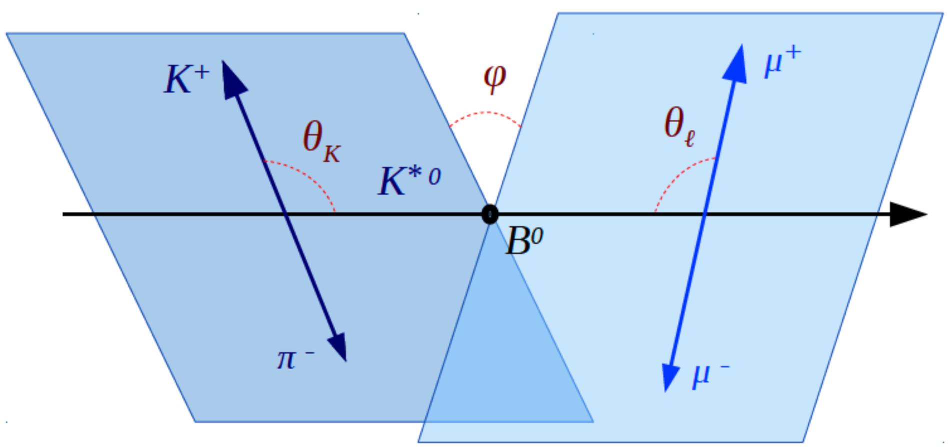
$$\frac{d^5\overset{(-)}{\Gamma}(B^0 \to K^+\pi^-\mu^+\mu^-)}{dq^2 d\overrightarrow{\Omega} dm^2_{K\pi}} = \frac{9}{32\pi}\sum_i \overset{(-)}{\bar{J}}_i(q^2) f_i(cos\theta_l, cos\theta_K, \phi) g_i(m^2_{K\pi})$$

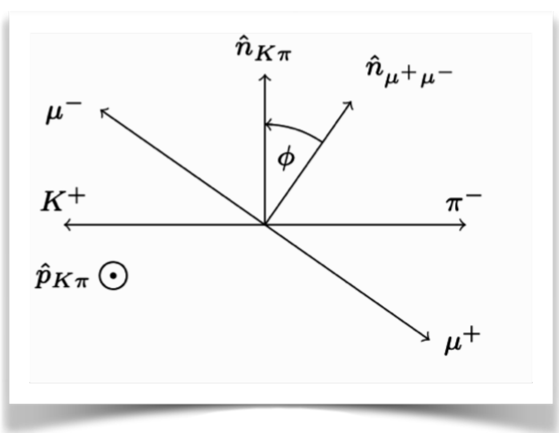
- Angular Observable(F_L, S_i, A_{FB}) + Angular Functions + $0.796 < m_{K^*(K\pi)} < 0.996[GeV/c^2]$
  - **P-wave and S-wave amplitude contribution**
  - **Local and non-local form factors:**
    - Local :
      - P-wave->LCSR + LQCD [Asatrian, Greub, Virto [JHEP 04 (2020) 012]]
      - S-wave->Data Driven method (S-wave amplitude treated as nuance parameter)
    - Non-local : Absorbed into $\mathscr{C}^{eff}_{7,9}$ [JHEP09(2024)02]

- P-Wave line shape: RBW
- S-Wave line shape:LASS

[Phys RevD 109.052009]







JHEP09(2024)026

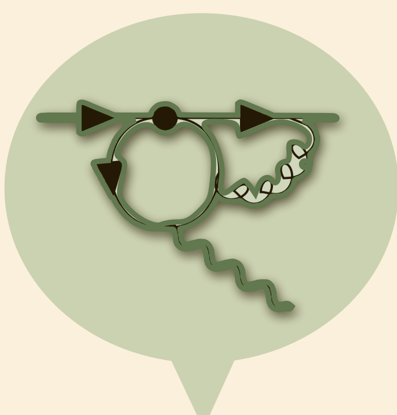
Non-Locals

$$Y^{q\bar{q},\lambda}(q^2) = Y^{q\bar{q}}(q_0^2) + \frac{q^2 - q_0^2}{\pi} \int_{q^2_{min}}^{\infty} ds \frac{\rho^{q\bar{q},\lambda}(s)}{(s - q_0^2)(s - q^2 - i\varepsilon)}$$

$$C_7^{eff,\lambda} = C_7 + \xi^\lambda e^{i\omega^\lambda}$$

$$C_9^{eff,\lambda} = C_9 + Y^{1P}_{light}(q^2) + \sum_{n=1P}^{2P} Y^{n,\lambda}_{c\bar{c}}(q^2) + Y_{\tau\bar{\tau}}(q^2)$$

$\xi^\lambda e^{i\omega^\lambda}$

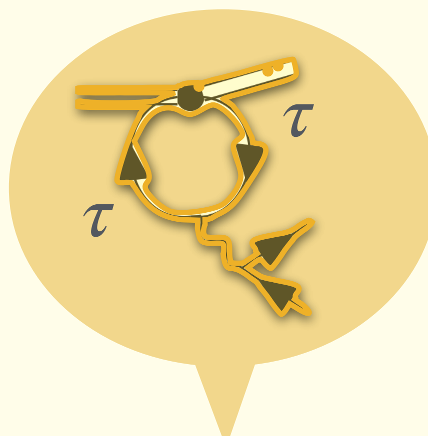


$\mathscr{C}_7$ **vertex correction**

Polarisation dependent shift

Eur.Phys.J.C 80 (2020) 12, 1095

$Y_{\tau\bar{\tau}}(q^2)$



$\mathscr{C}_9^\tau$ **Contribution**

$B^0 \to K^{*0}\tau^+\tau^-$

$Y^{1P,\lambda}_{c\bar{c}}(q^2) + Y^{1P,\lambda}_{light}(q^2)$

$\mathscr{C}_9$ **1-Particle**

$J/\psi, \psi(2S), \psi(3770)$

$\psi(4040), \psi(4160)$

$\rho(770), \omega(782), \phi(1020)$

$Y^{2P,\lambda}_{c\bar{c}}(q^2)$

$\mathscr{C}_9$ **2-Particle**

$D\bar{D}, D^*\bar{D}, D^*\bar{D}^*$

$Y^0_{c\bar{c}}(q_0^2)$

$\mathscr{C}_9$ **Constant**

$q^2 < 0$

[Asatrian, Greub, Virto [JHEP 04 (2020) 012]](Asatrian, Greub, Virto [JHEP 04 (2020) 012])

Analysis Strategy

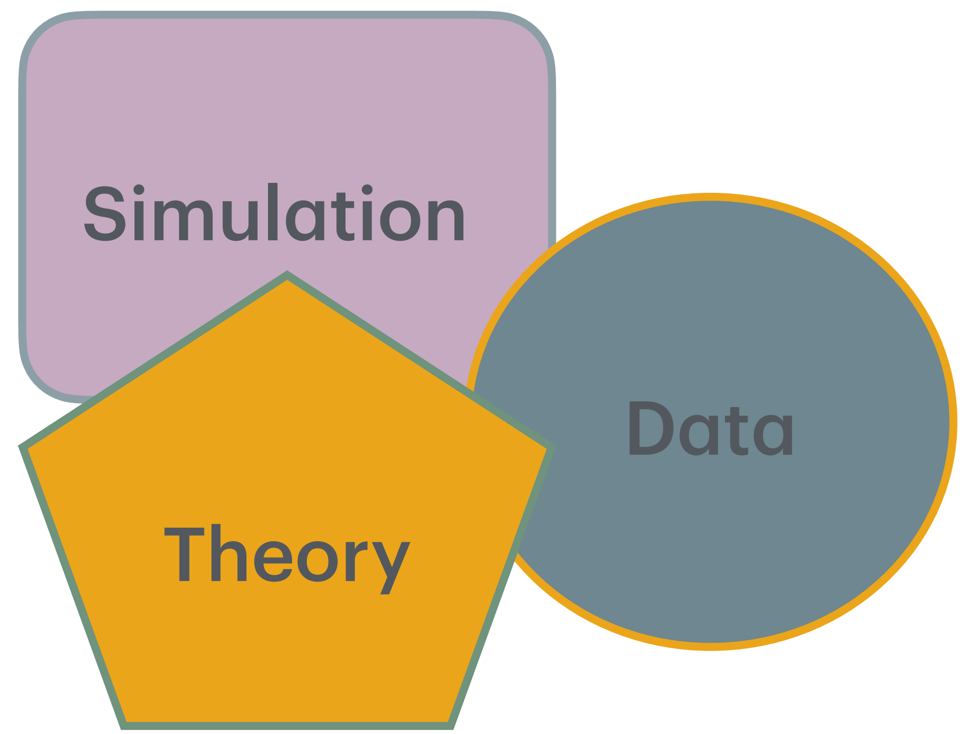
JHEP09(2024)026

Total PDF in q^2 regions(i) — **Diff decay rate** — **Acceptance** — **Resolution**

$$\mathscr{P}^i_{tot}(\bar{\Omega}, q^2) = f^i_{sig}[(\Gamma_{sig}(\bar{\Omega}, q^2) \times \epsilon(\bar{\Omega}, q^2)) \otimes R^i(q^2)] + (1 - f^i_{sig})\mathscr{P}_{bkg}(\bar{\Omega}, q^2)$$

Signal fr — $\underbrace{\qquad}_{\mathscr{P}^i_{sig}(\bar{\Omega}, q^2)}$ — **bkg**

- **Signal**
  - Signal Shape in $M_{K\pi}$ mass is integrated out
  - Signal decay rate is modeled in 4-D
- **Background**
  - Combinatorial
    - Resonant (e.g. J/ψ prompt combined with random $K^+\pi^-$)
    - Fully combinatorial (Fully random $K^+\pi^-\mu^+\mu^-$)
- **Unbinned maximum likelihood fit in 4-D (150 par)**
  - $Re(C_9), Re(C_{10}), Re(C'_9), Re(C'_{10}), Re(C^\tau_9)$
  - ΔC_7 per helicity
  - Mag. and phase 1P
  - Re. and Im. Of open charm 2P
  - Acceptance
  - Form Factors, JHEP 09, 133 (2022)

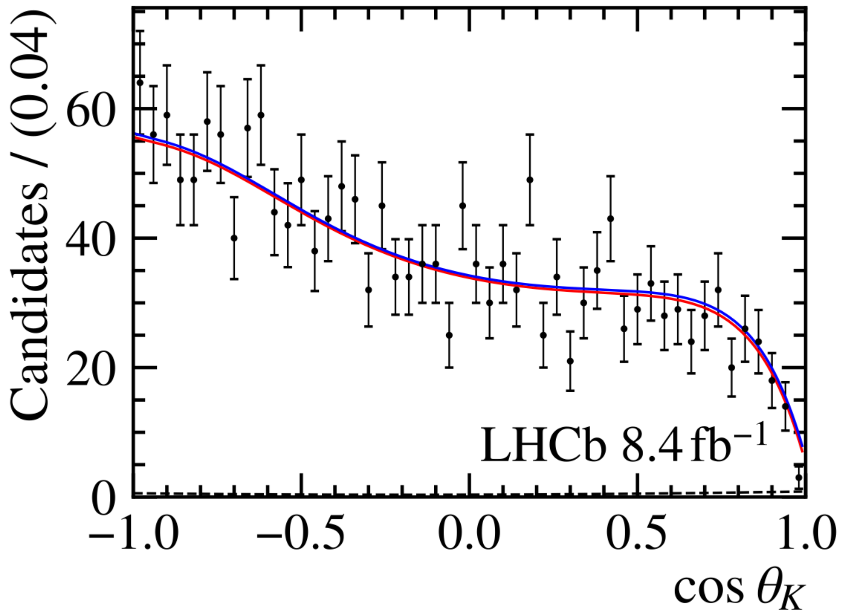


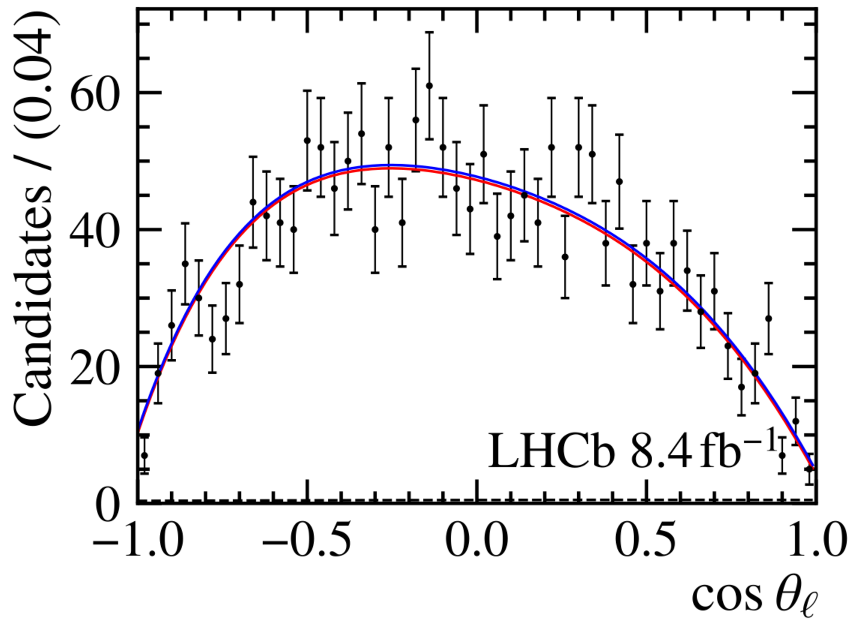
Category	q^2 region [GeV^2/c^4]	Signal fraction ($f^{\mathrm{full}}_{\mathrm{Sig},i}$)
Low-q^2	[0.10, 3.24]	0.9196 ± 0.0088
Fully combinatorial mid-q^2	$[3.24, 8.20] \cup [10.6, 11.56]$	0.8045 ± 0.0093
Resonant mid-q^2	[8.20, 10.6]	0.9934 ± 0.0002
Fully combinatorial high-q^2	$[11.56, 12.40] \cup [14.40, 18.00]$	0.8656 ± 0.0088
Resonant high-q^2	[12.40, 14.40]	0.9862 ± 0.0010

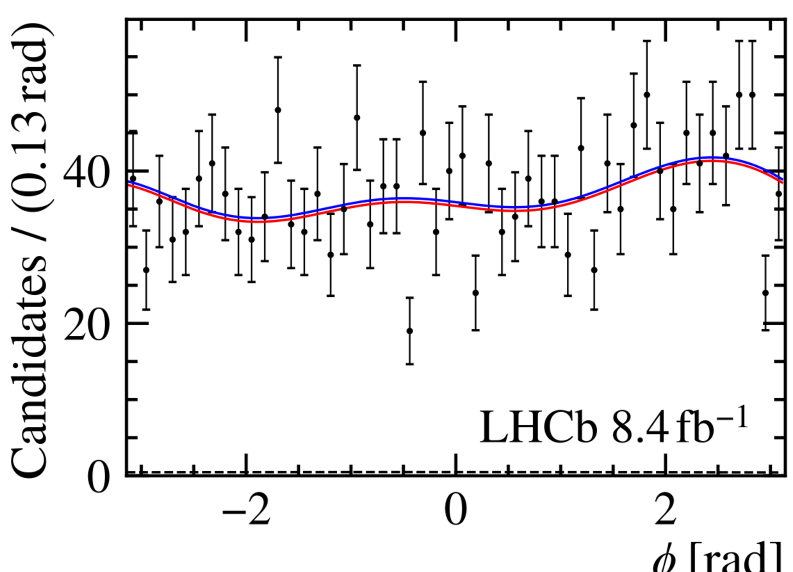
- **Systematic uncertainty dominated ->** $\mathscr{B}(B^0 \to K^{*0}J/\psi)$, Phys. RevD 90 (2014) 112009

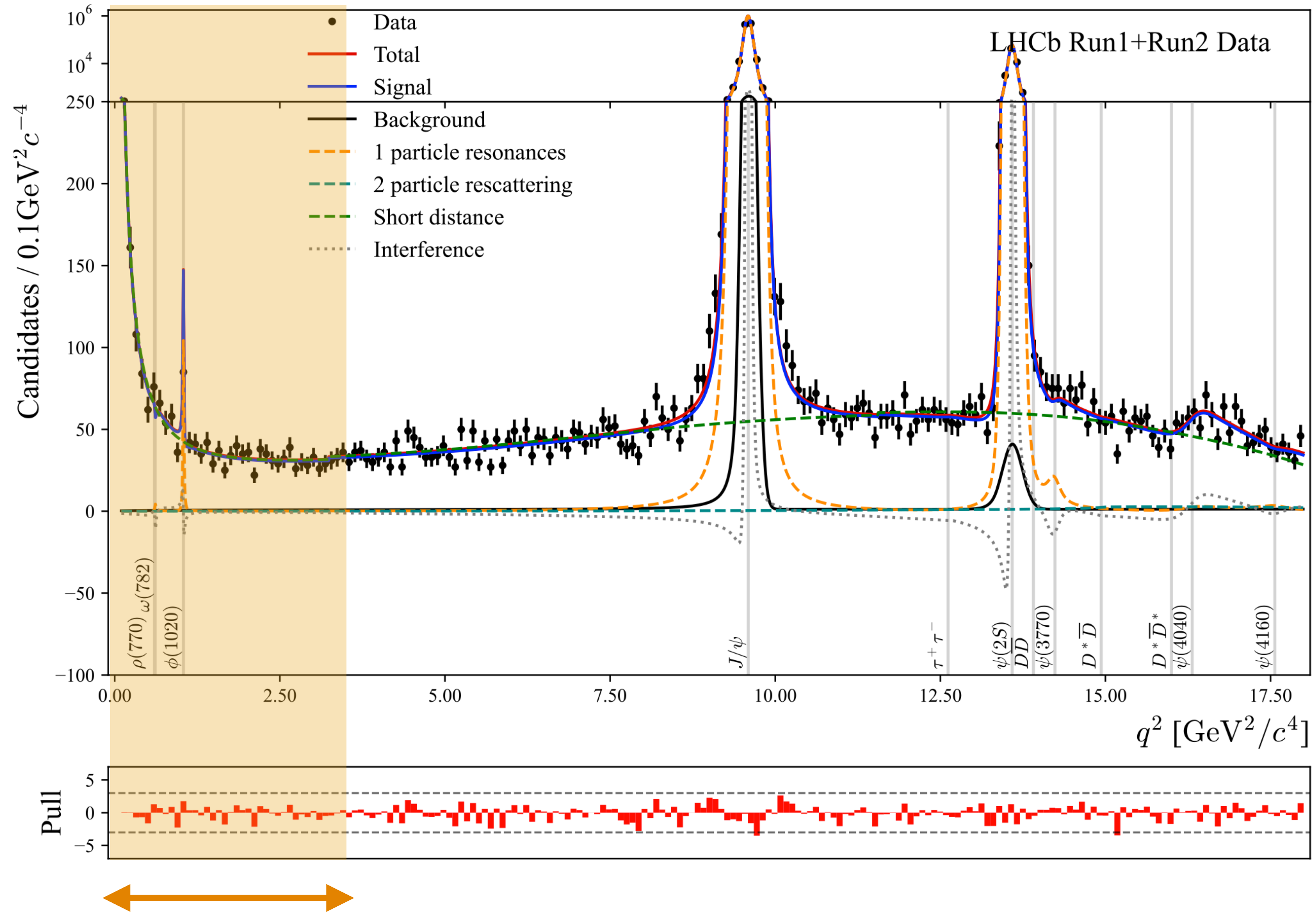
Results

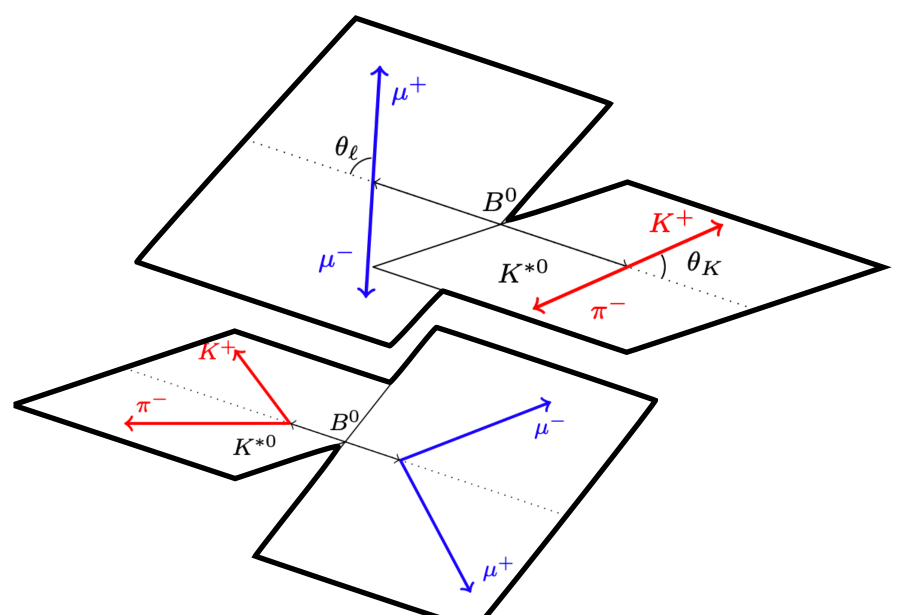
JHEP09(2024)026











Category	Region
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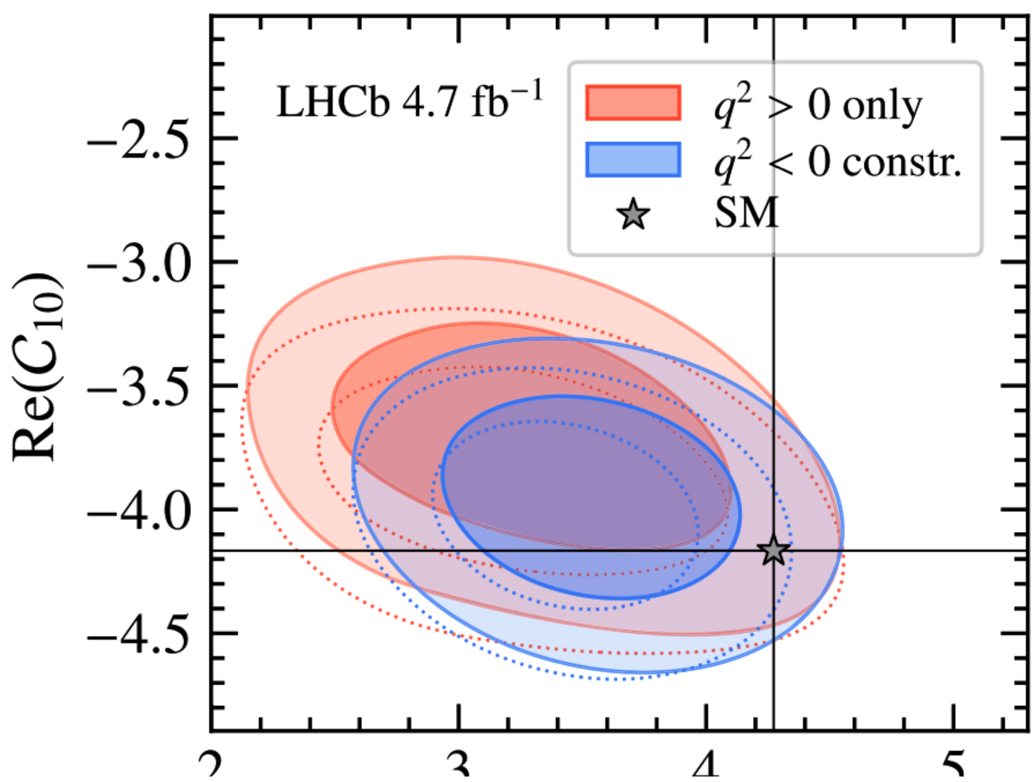
Results

PRD 109 (2024) 052009



$\mathcal{C}_9$ $3.34^{+0.53}_{-0.57}$ ($3.59^{+0.33}_{-0.46}$) 1.9 (1.8) σ

Wilson Coefficient results		
$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$	2.1σ
$\mathcal{C}_{10}$	$-4.02 \pm 0.18 \pm 0.16$	0.6σ
$\mathcal{C}_9'$	$0.28 \pm 0.41 \pm 0.12$	0.7σ
$\mathcal{C}_{10}'$	$-0.09 \pm 0.21 \pm 0.06$	0.4σ
$\mathcal{C}_{9\tau}$	$(-1.0 \pm 2.6 \pm 1.0) \times 10^2$	0.4σ

Using Likelihood profile method

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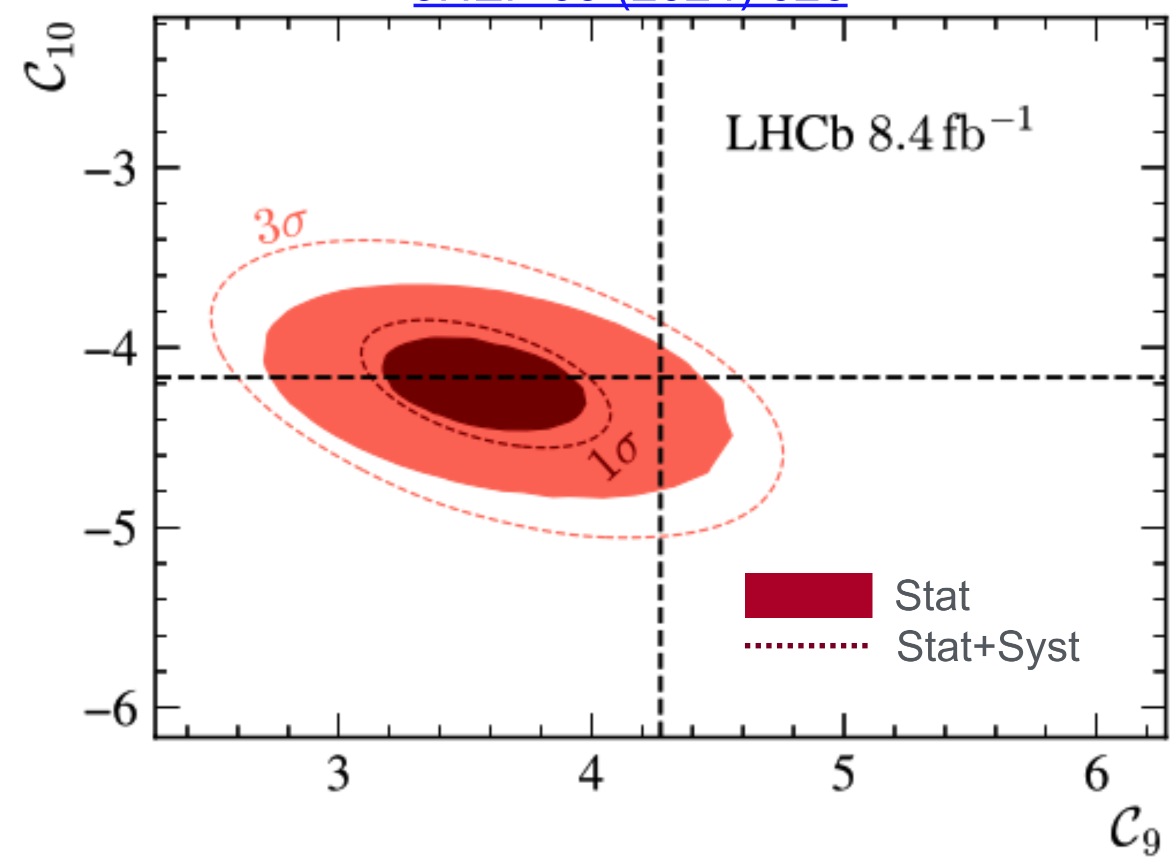
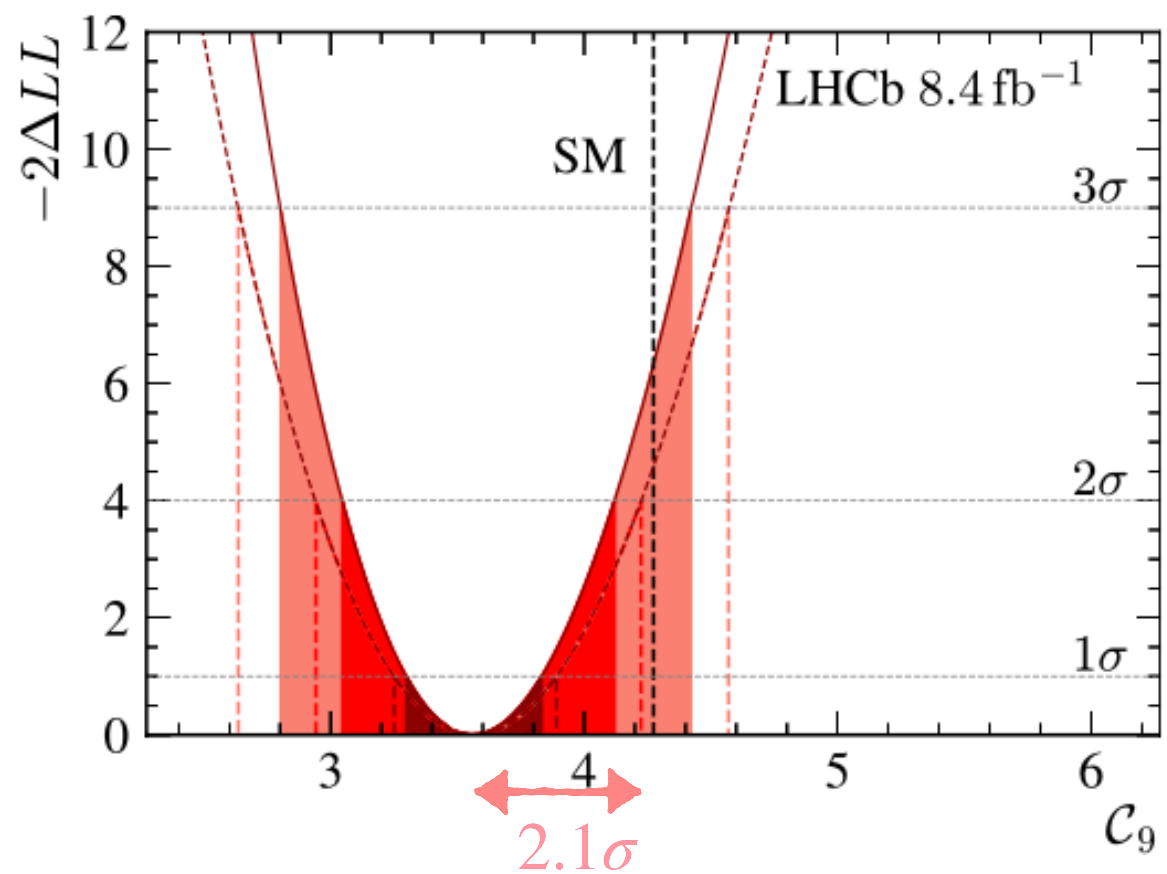
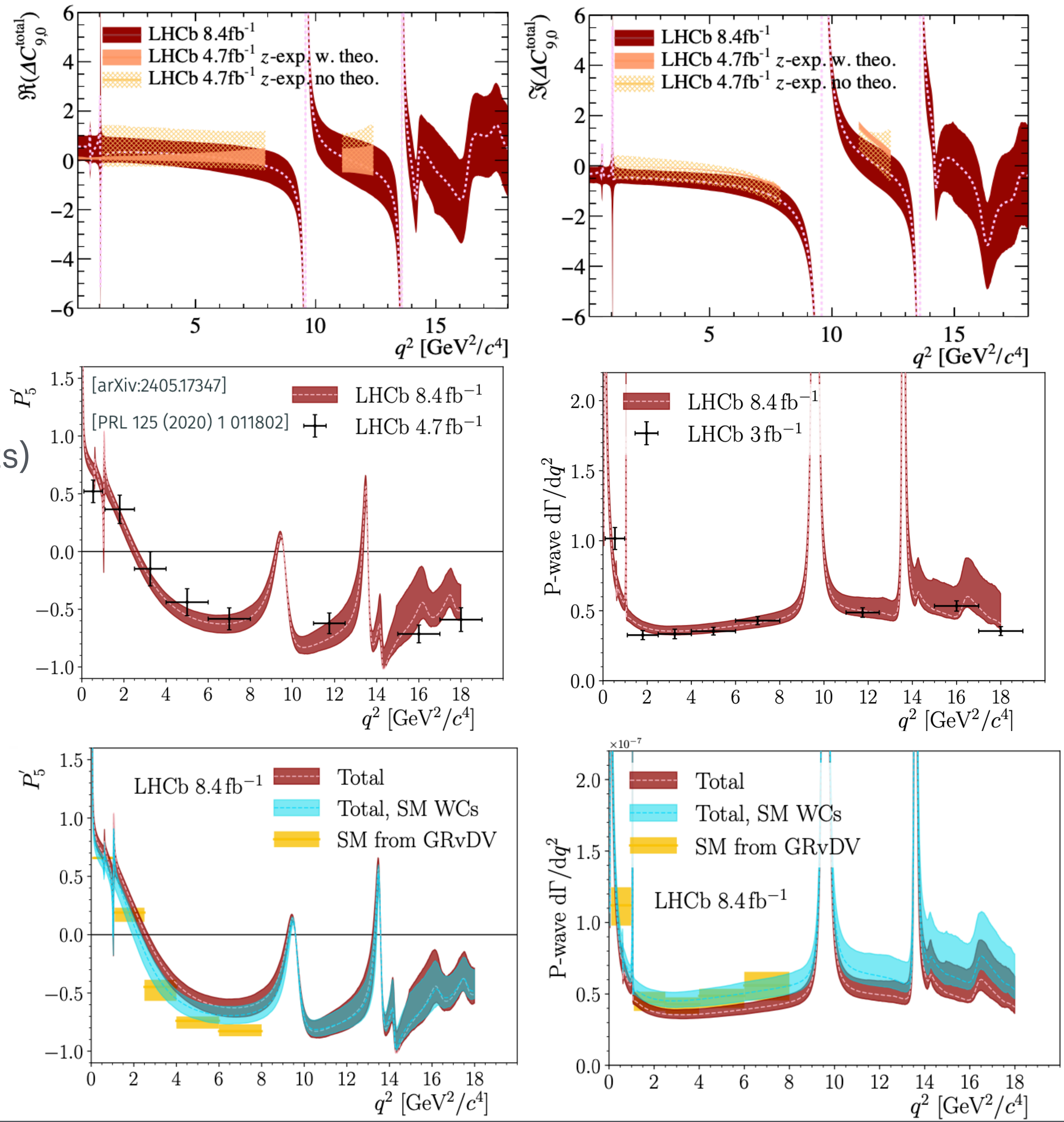




Results

JHEP09(2024)026

- **Impact from nonlocal contributions on WCs (per helicity)**
- **Good agreement with:**
  - Previous Unbinned LHCb measurement (black points)
  - Z-expansion Analysis
- **Non-local contributions:**
  - Data prefers larger
  - Not enough to explain $\mathscr{C}_9$ shift
- **Tensions in Observables persist**



Results

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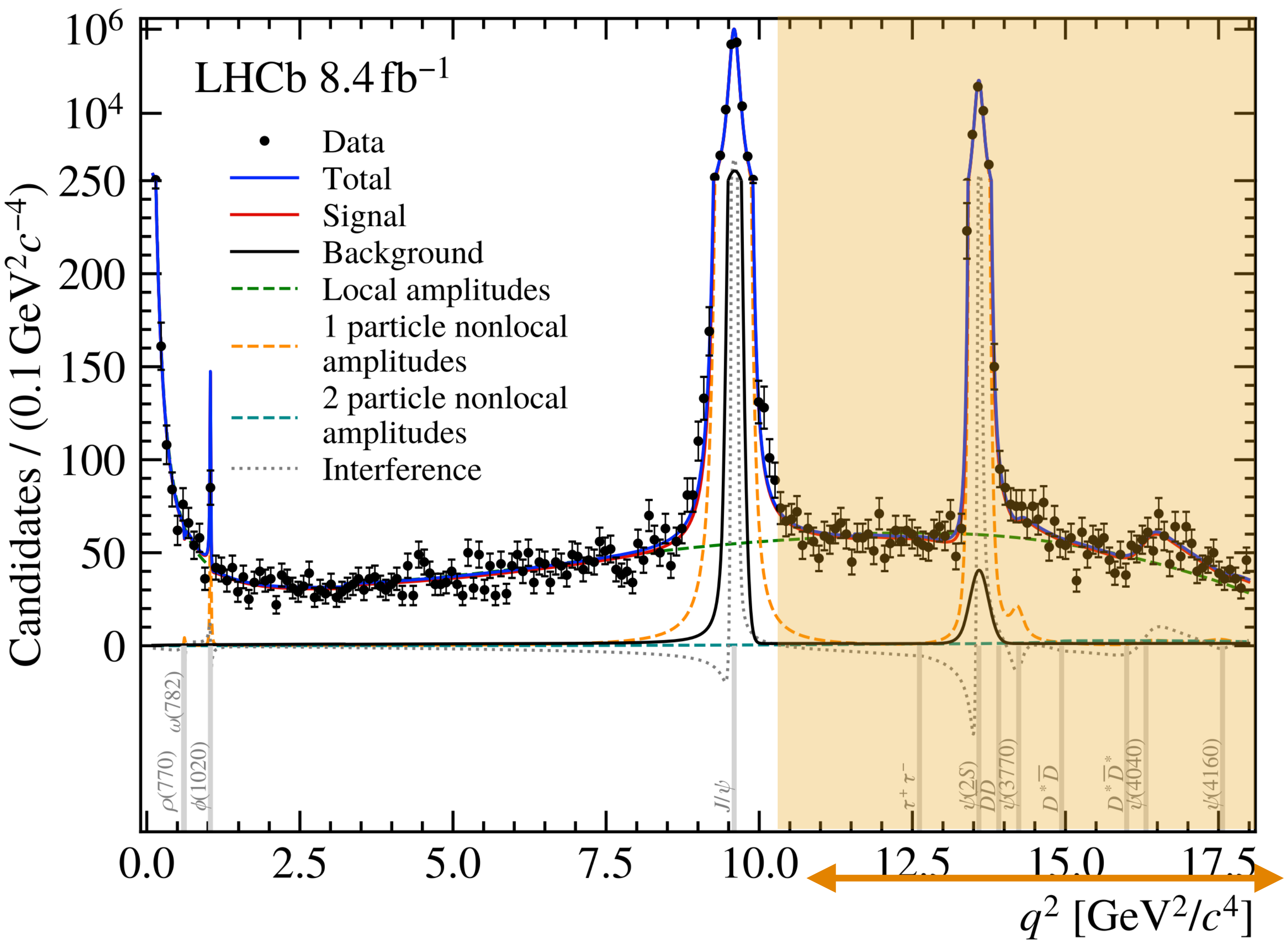
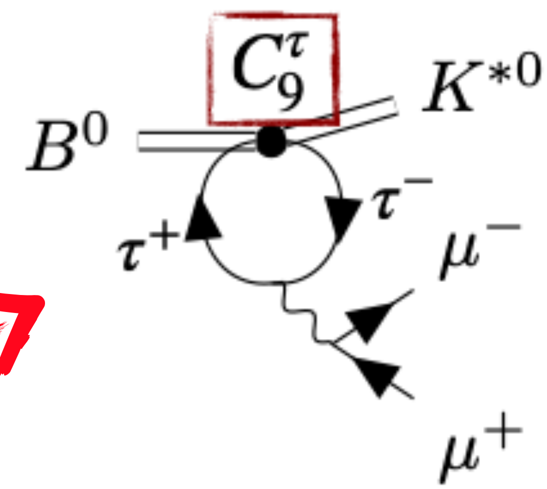
Wilson Coefficient results	
$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$
$\mathcal{C}_{10}$	$-4.02 \pm 0.18 \pm 0.16$
$\mathcal{C}_9'$	$0.28 \pm 0.41 \pm 0.12$
$\mathcal{C}_{10}'$	$-0.09 \pm 0.21 \pm 0.06$
$\mathcal{C}_{9\tau}$	$(-1.0 \pm 2.6 \pm 1.0) \times 10^2$

- **90% CL:**
  - $|\mathscr{C}_{9\tau}| < 500$
- **Best 90% CL:** $\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) \sim 3.1 \times 10^{-3}$ (**Belle II in prep paper** $\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) \sim 1.8 \times 10^{-3}$)
  - $|\mathscr{C}_{9\tau}| < 680$ **(Belle result)**

Belle, Phys. Rev. D108 (2023) L011102

ICHEP_EWPLFV_BELLEBELLEII_0719.pdf





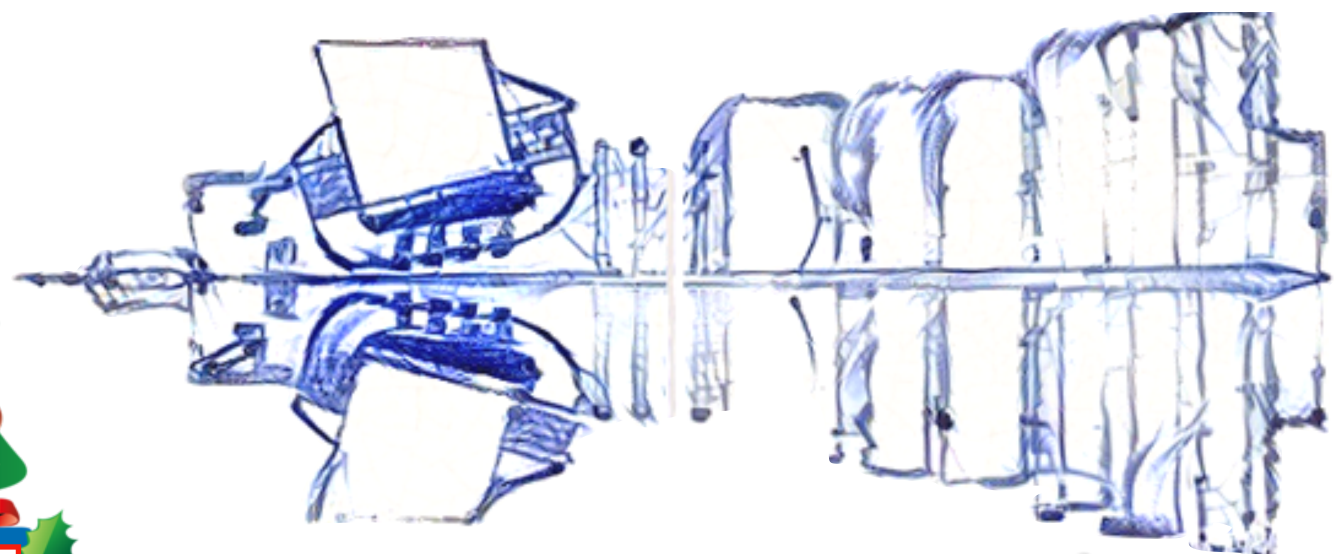
Third Generation enhancement expected in many NP models

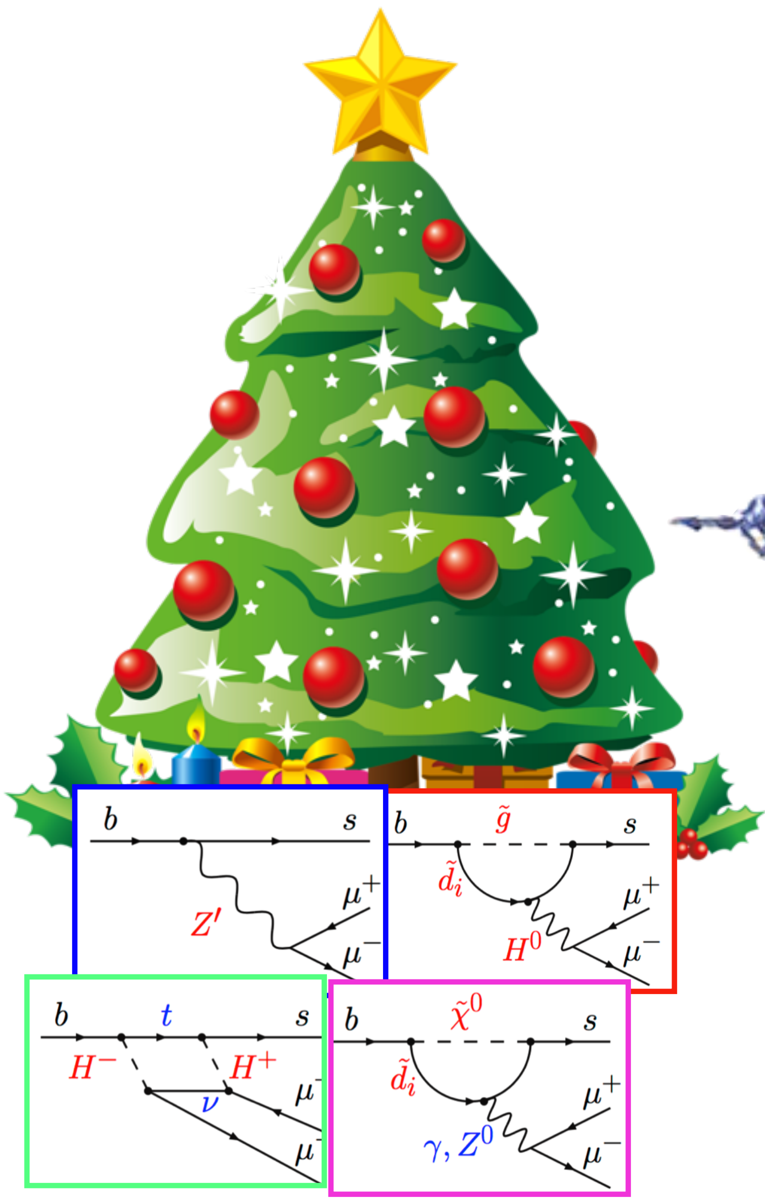
New Physics in 3red gen, JHEP03(2024)049

Summary

- **Rare decays are promising probe to search for NP**
  - $b \to sl^+l^-$ global fit, shows $\sim 4\sigma$ from SM
- **Model independent/dependent measurements of various observables in $B^0 \to K^{*0}\mu^+\mu^-$ show tension wrt SM (** Br fr , Angular Observables **)**
- **Latest unbinned results compatible with one another -> $\mathscr{C}_9$ still shifted from SM expectation:**
  - Non-Local contributions are more important than SM expected
  - $\mathscr{C}_9^{NP} = -0.71 \pm 0.33$ corresponding to 2.1σ deviation from $\mathscr{C}_9^{SM} = 4.27$
- **First direct measurement of $\mathscr{C}_9^{\tau} = (-1.0 \pm 2.6 \pm 1.0) \times 10^2$**
  - Competitive sensitivity to direct measurements, Phys. Rev. D 108, L011102
  - Run III LHCb data, $9.6[fb]^{-1}$, will help

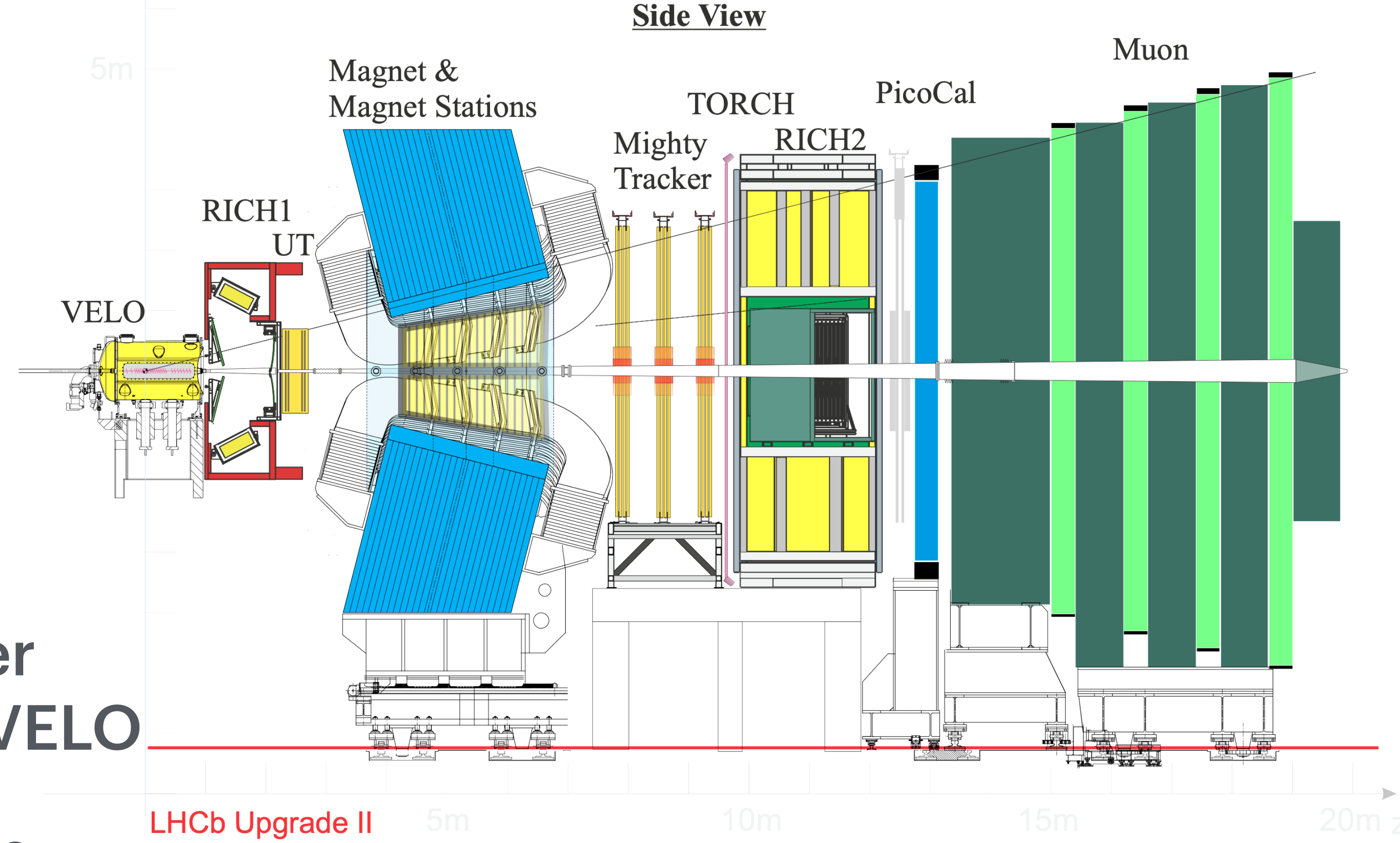
Thanks!



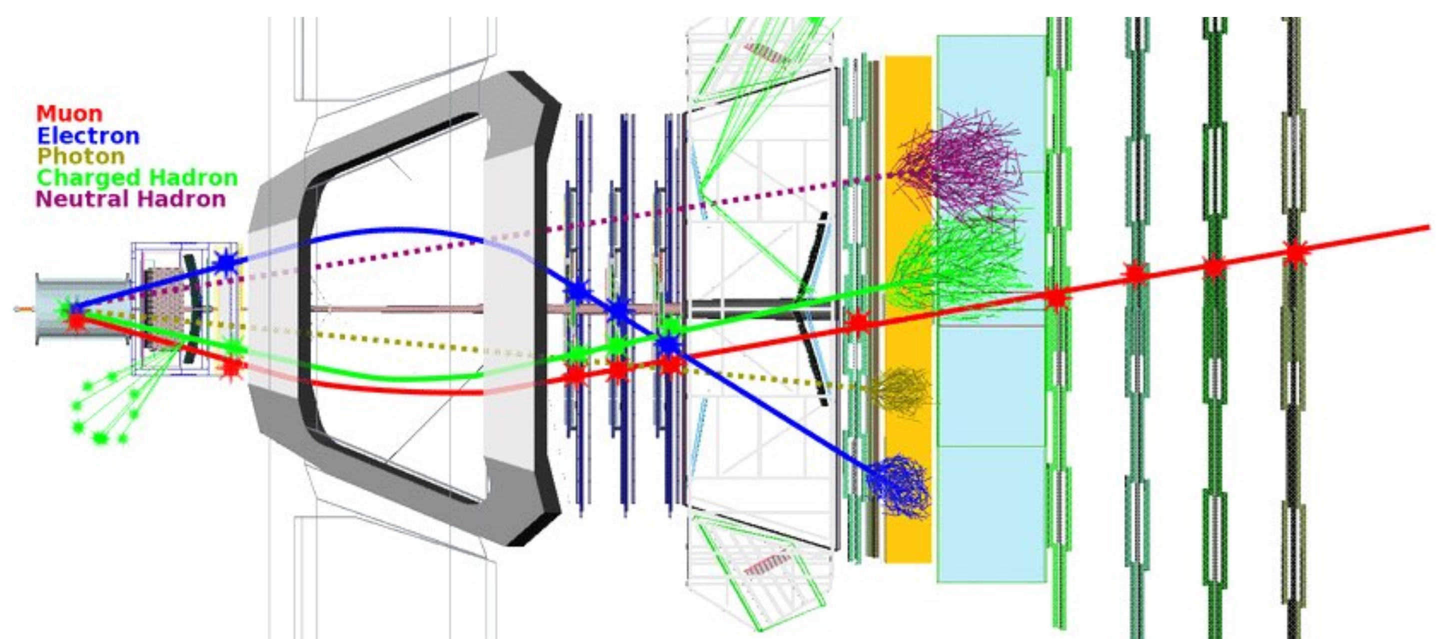


Back up

LHCb Experiment



- LHCb is single-arm forward spectrometer
- B hadrons typically decay after traveling ~ 1 cm measured by VELO
- Large fraction of B hadrons are produced in forward direction in LHC
- Excellent PID System:
  $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$



[LHCb TDR, Upgrade II]

Results

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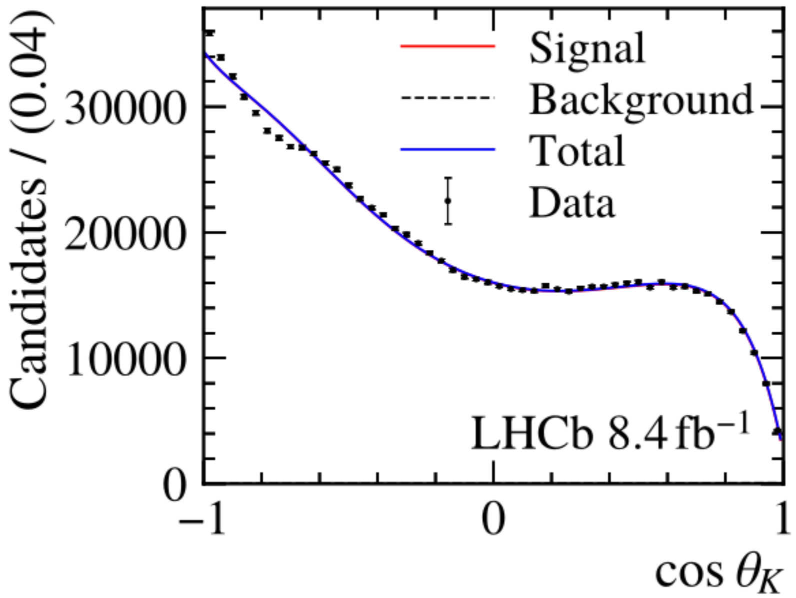

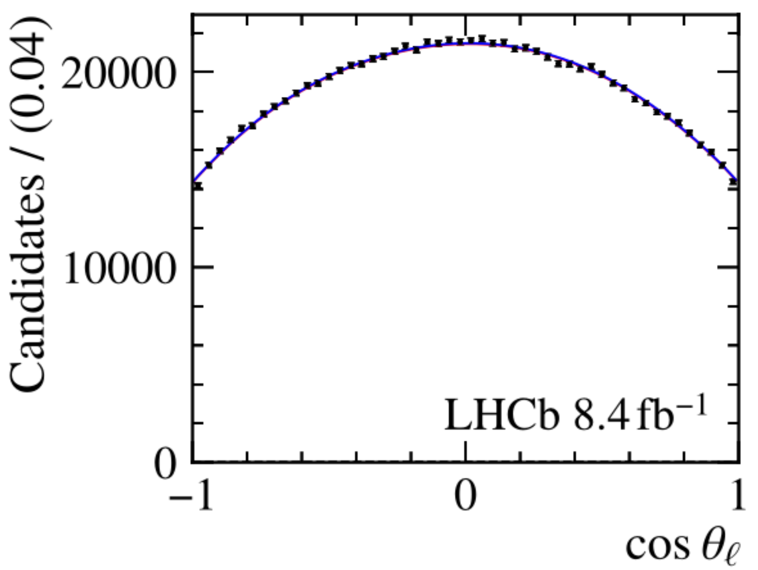

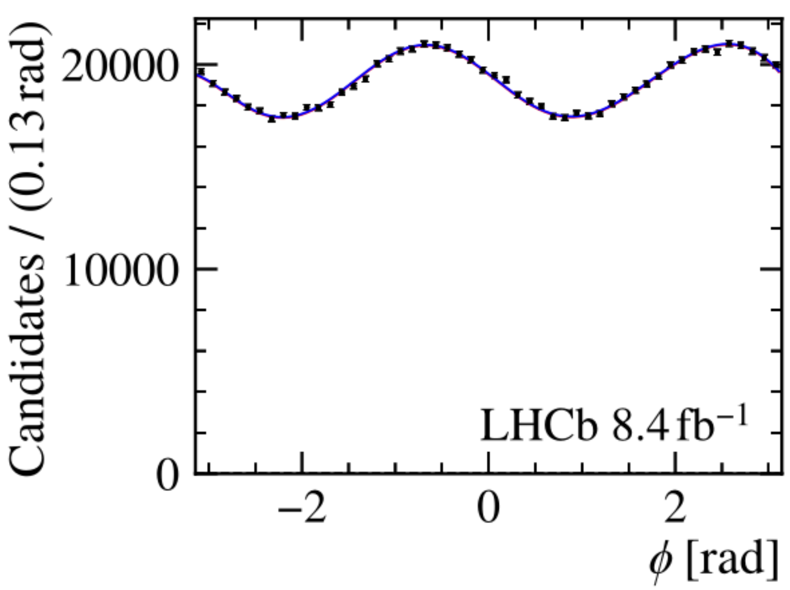

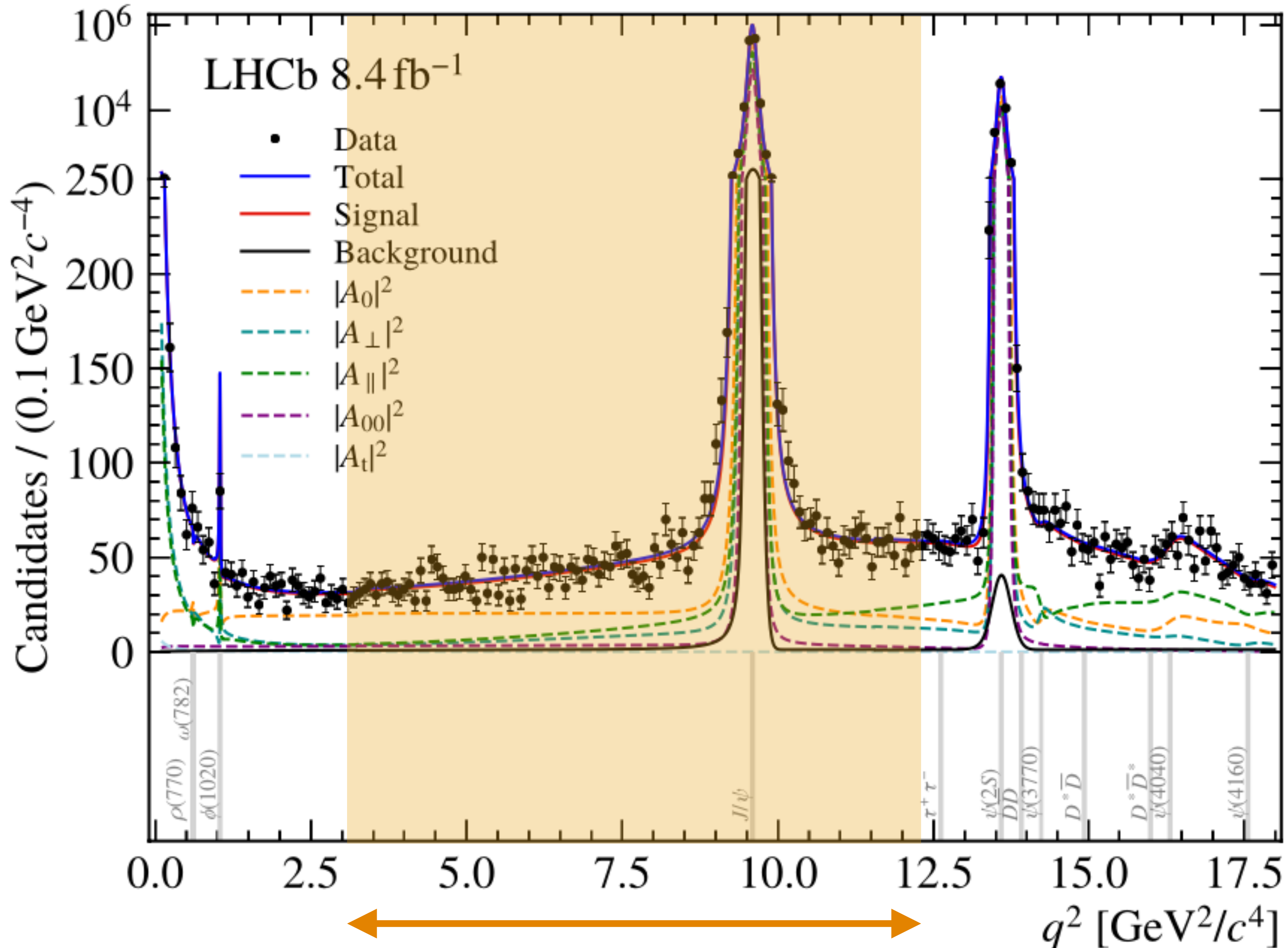

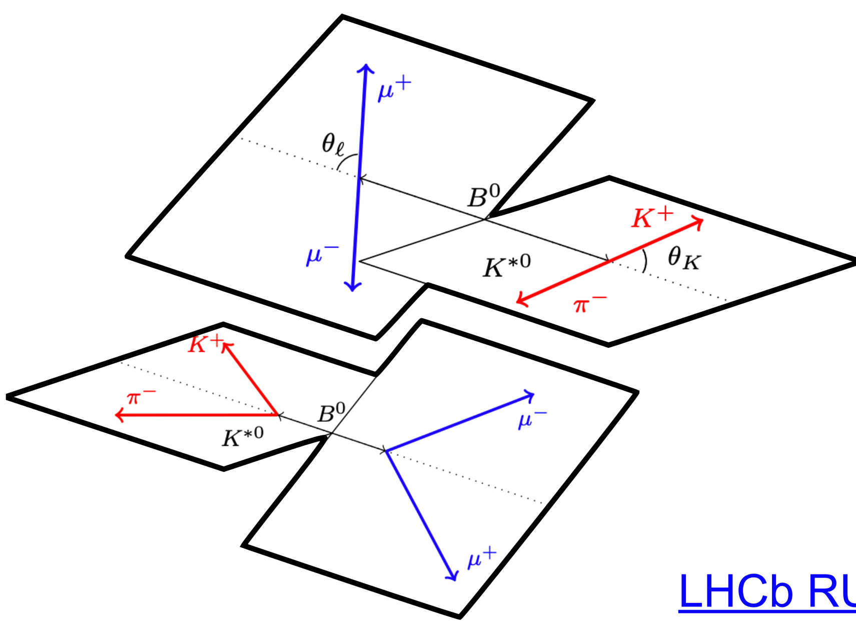

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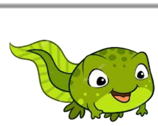
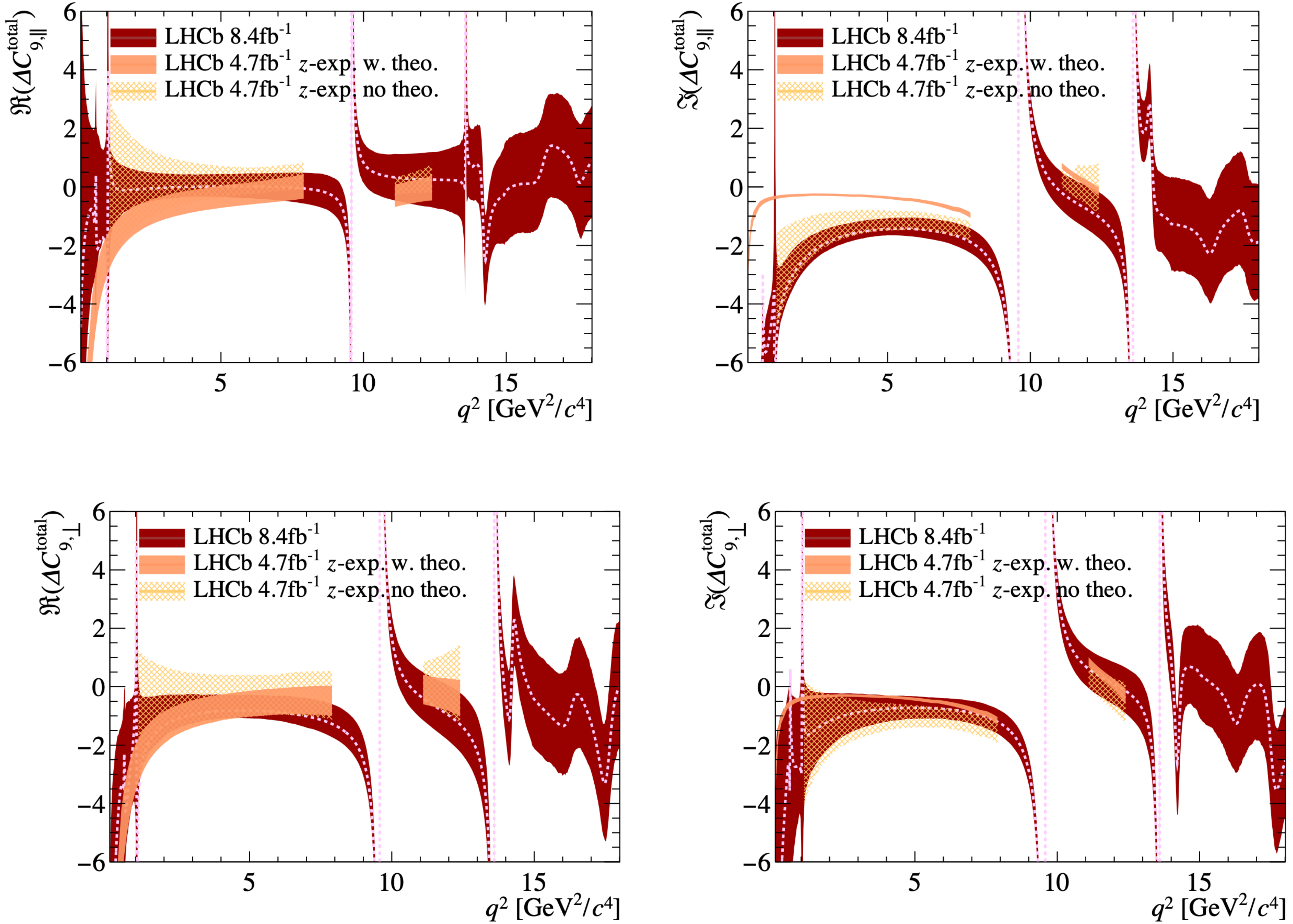


LHCb RUN III, CDS

Results



$\Re(\Delta C^{\text{total}}_{9,\parallel})$
$\Im(\Delta C^{\text{total}}_{9,\parallel})$
$\Re(\Delta C^{\text{total}}_{9,\perp})$
$\Im(\Delta C^{\text{total}}_{9,\perp})$
LHCb 8.4fb^{-1}
LHCb 4.7fb^{-1} z-exp. w. theo.
LHCb 4.7fb^{-1} z-exp. no theo.
q^2 [GeV^2/c^4]