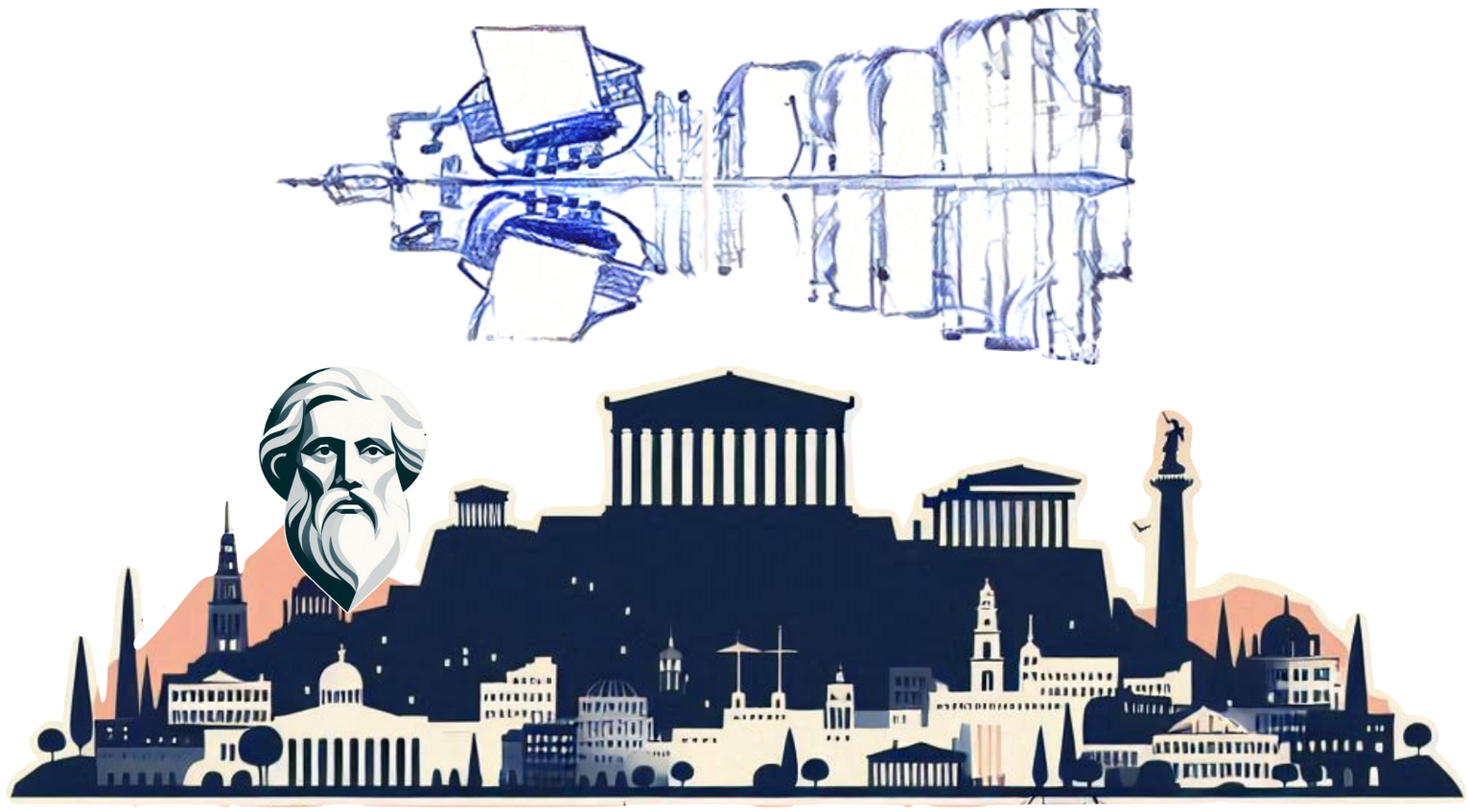
Analysis of Local and Non-local Amplitudes of $B^0 \to K^{*0}\mu^+\mu^-$



PIC 2024, ATHENS

LEVERHULME TRUST

University of BRISTOL

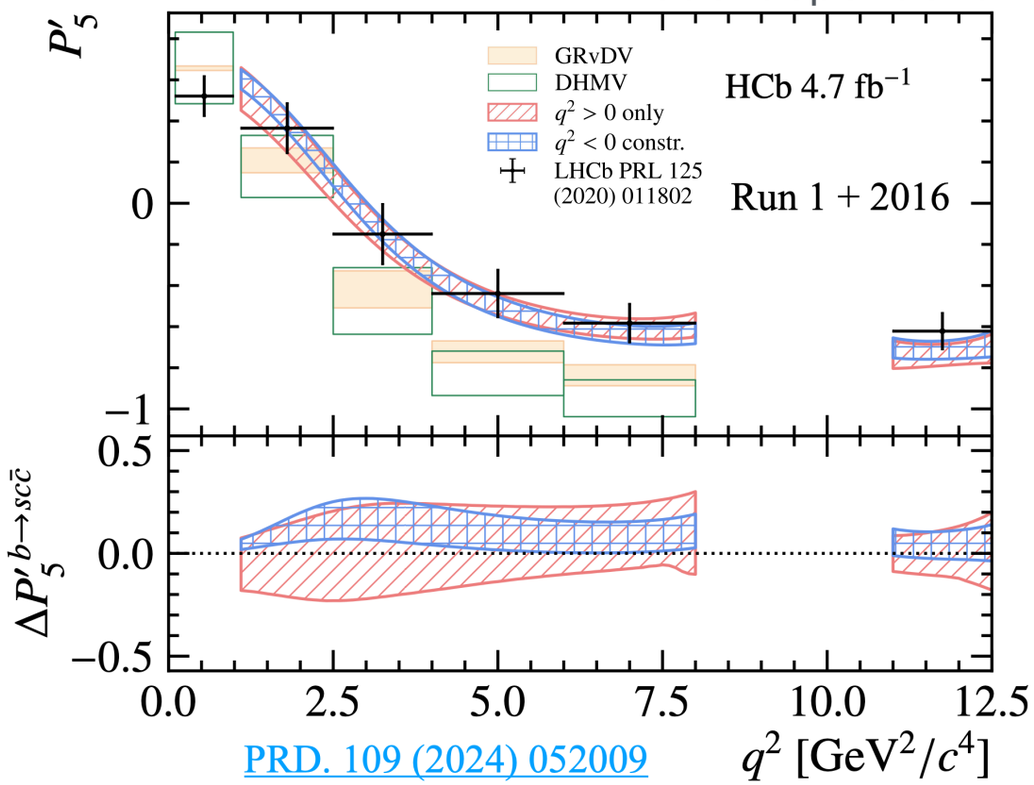
Zahra Gh.Moghaddam

On behalf of LHCb collaboration

Motivation

- **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

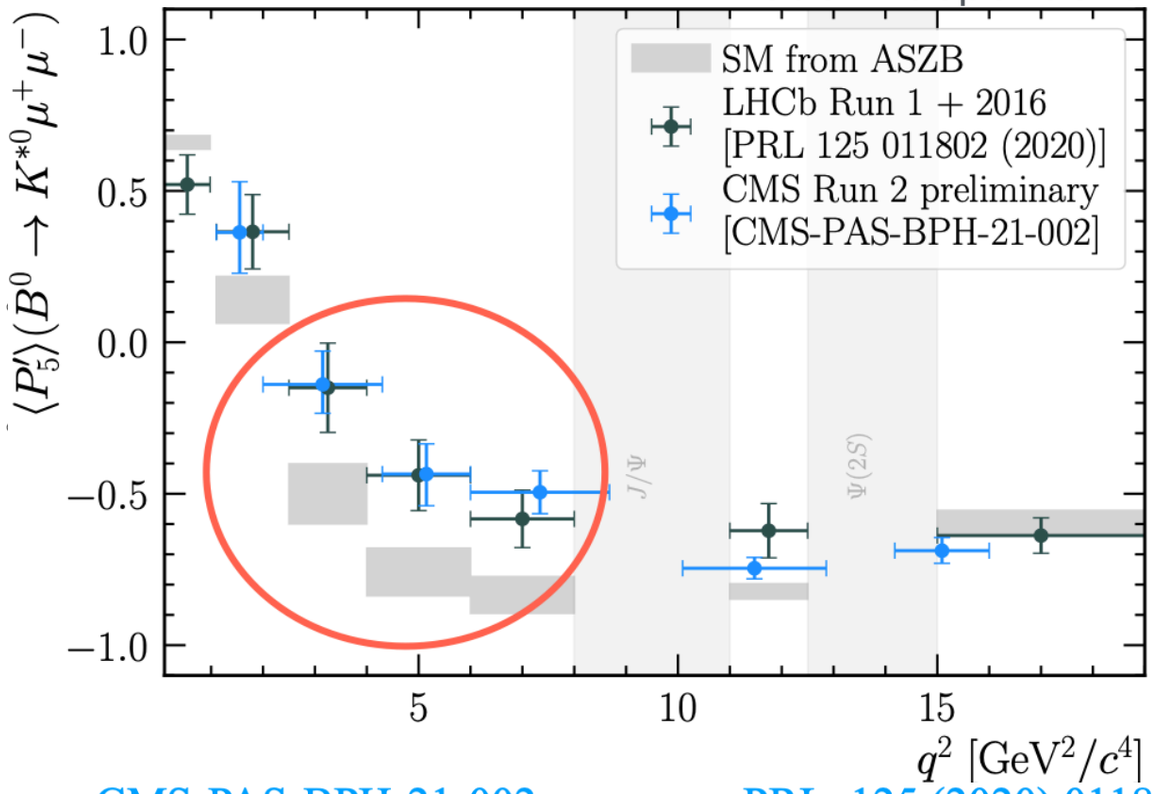
Model dependent



PRD. 109 (2024) 052009

https://arxiv.org/abs/2304.07330

Model Independent

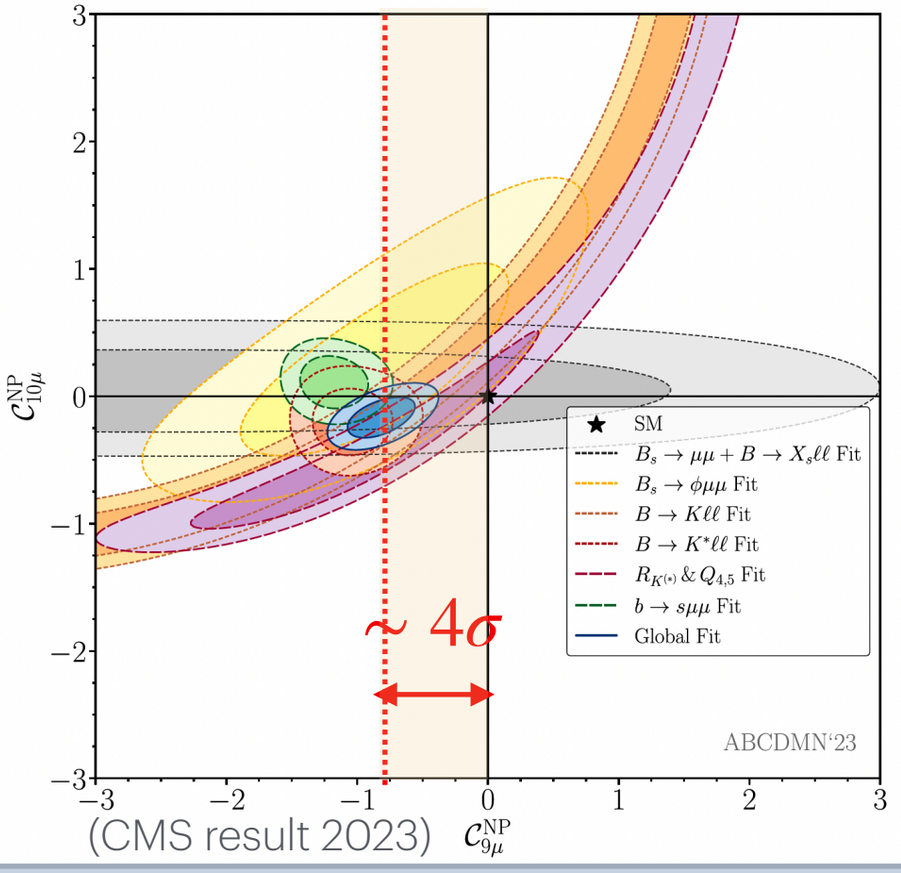


CMS-PAS-BPH-21-002

PRL. 125 (2020) 011802

C_9 **shift**

$\sim 4\sigma$

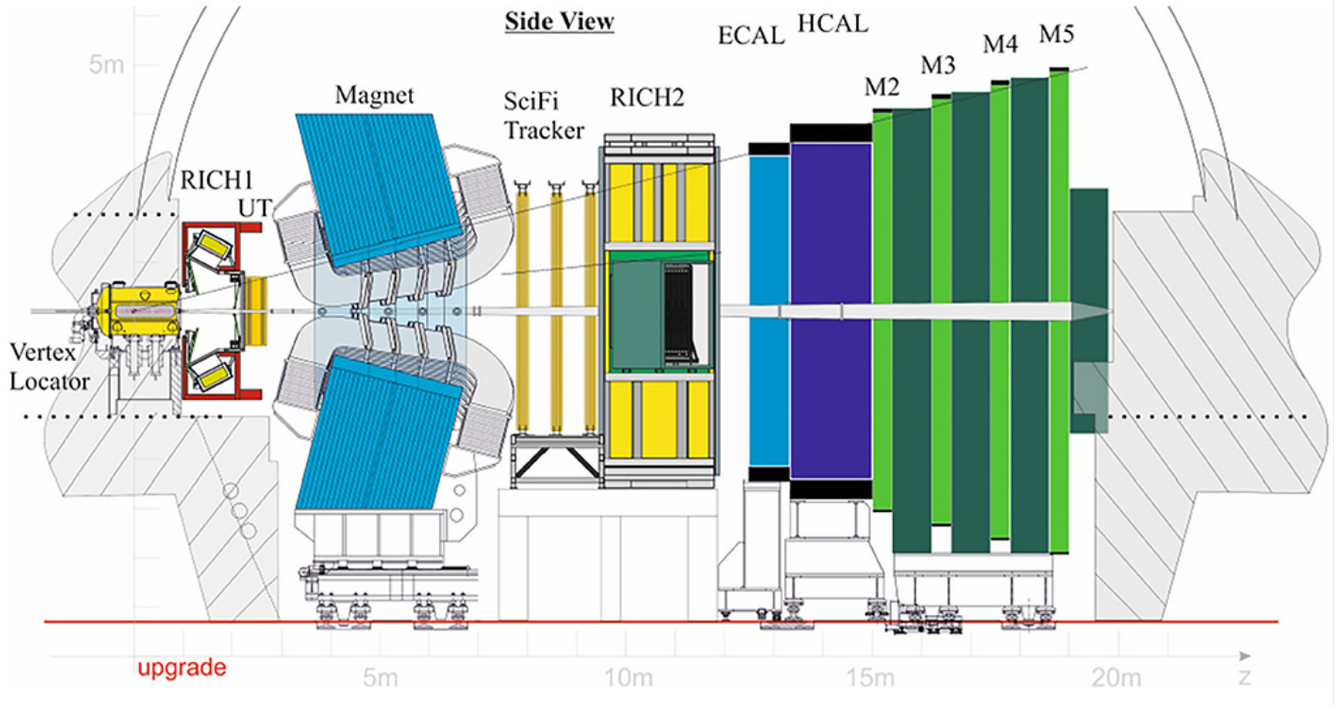


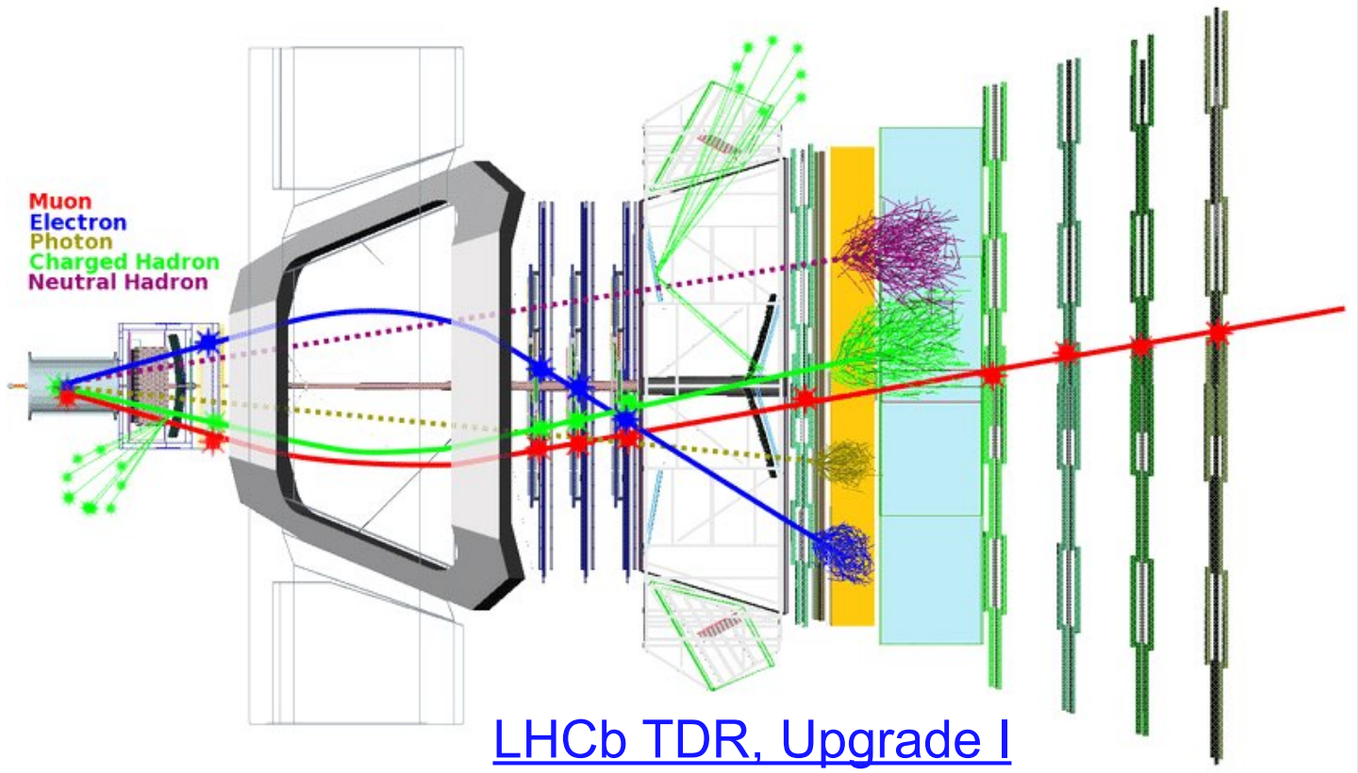
(CMS result 2023)

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:

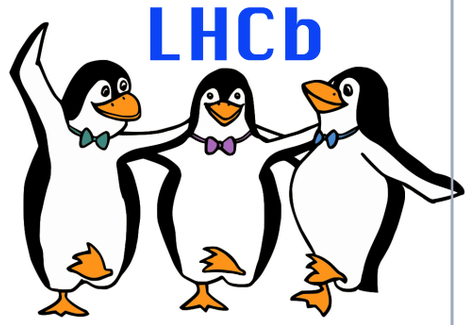
$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$



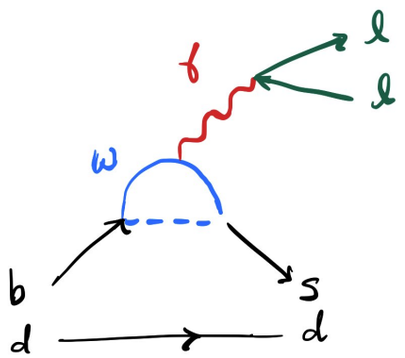


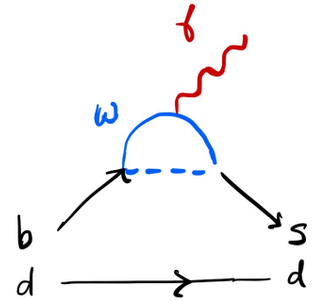
LHCb TDR, Upgrade I

Vertex Contributions

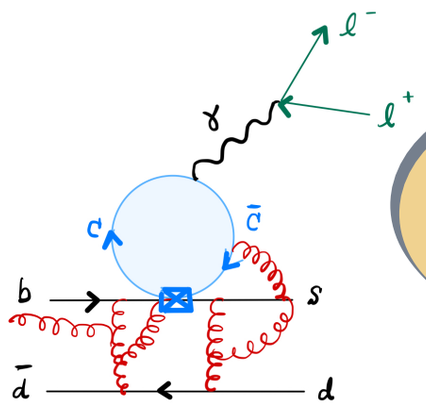


$$\mathscr{H}_{WET} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i (C_i^{SM} + \Delta C_i^{NP})\mathcal{O}_i$$

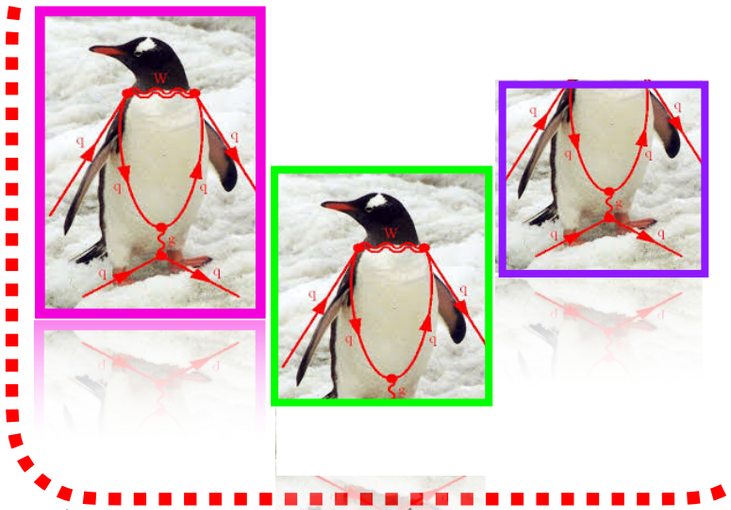




B



O_{9V} O_{10A} $O_{7\gamma}$ $O_{1,2}$



O'_{9V} O'_{10A} $O'_{7\gamma}$

S

μ^+

μ^-

$$\mathcal{O}_{9V} = \frac{1}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\alpha \bar{\ell}\gamma_\mu \ell\,, \qquad \textit{vector}$$

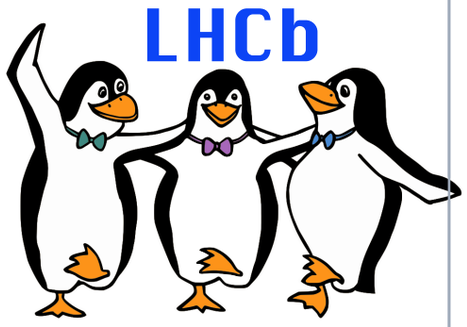
$$\mathcal{O}_{10A} = \frac{1}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\alpha \bar{\ell}\gamma_\mu\gamma_5 \ell\,, \qquad \textit{axial-vector}$$

$$\mathcal{O}_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{b}_R^\alpha \sigma^{\mu\nu} F_{\mu\nu} s_L^\alpha\,, \qquad \textit{photon}$$

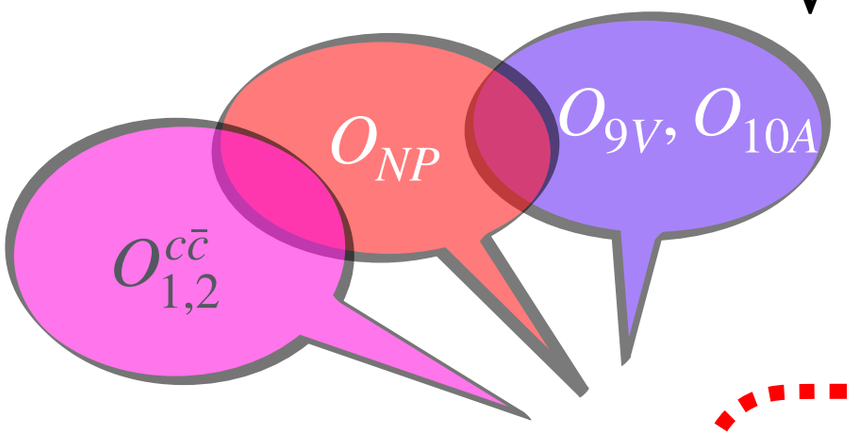
JHEP 01 (2009) 019

JHEP 01 (2009) 019

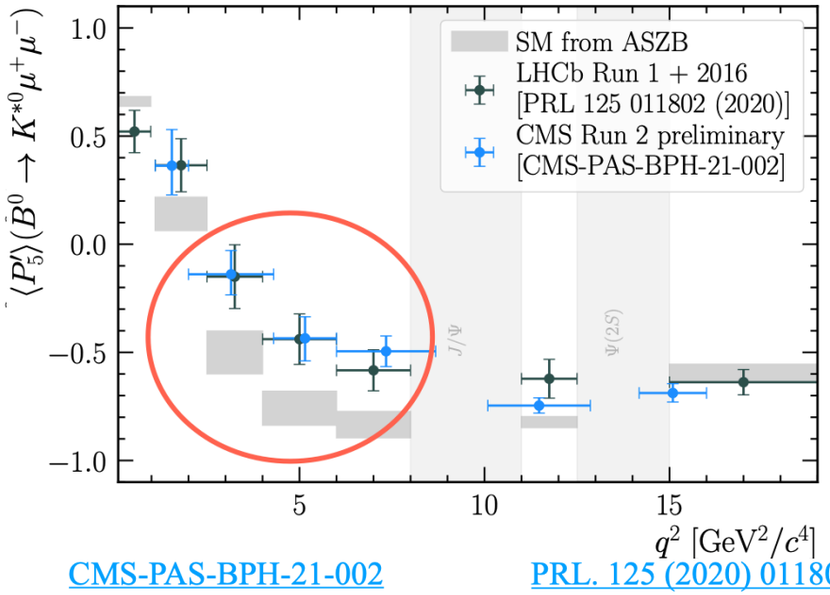
Charm Loop or New Physics?



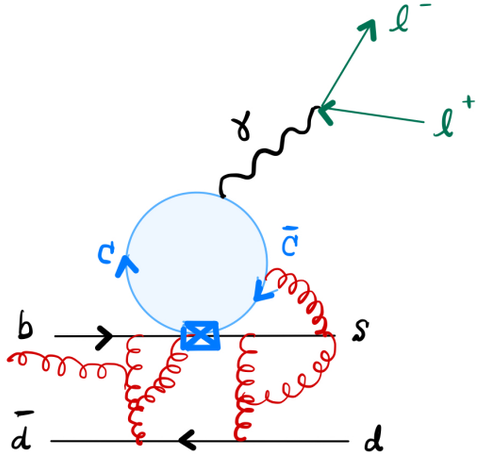
$$\mathscr{H}_{WET} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i (C_i^{SM} + \Delta C_i^{NP}) \mathcal{O}_i$$

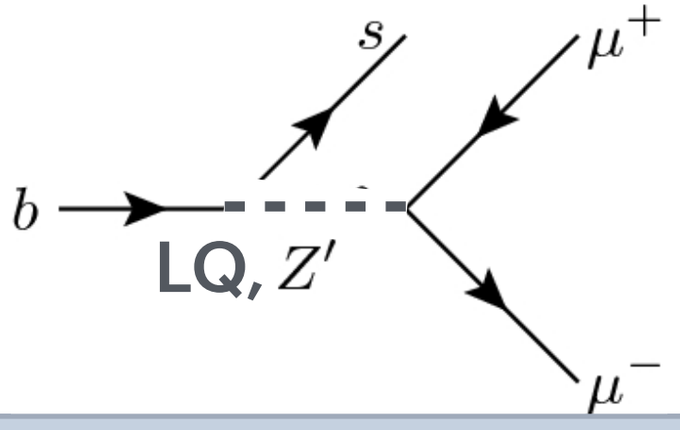


$$C_{9,7}^{eff} = C_{9,7}^{SM} + C_{9,7}^{c\bar{c}} + C_{NP}$$



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





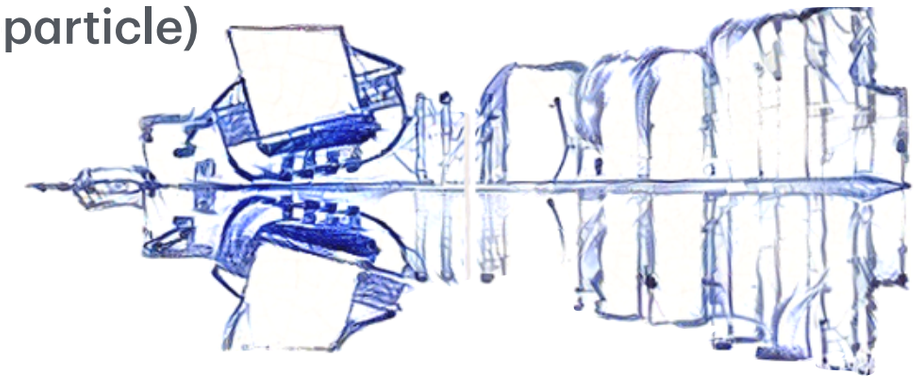
JHEP09(2024)026

Analysis Strategy

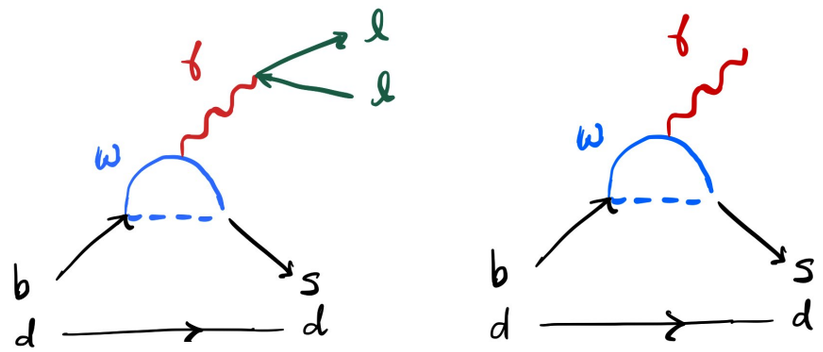
- PP collision data RUN I and RUN II , $8.4[fb^{-1}]$ luminosity
- LHCb data is fitted with a model combines local and non-local amplitudes in $0.1 < q^2 < 18[GeV^2/c^4]$

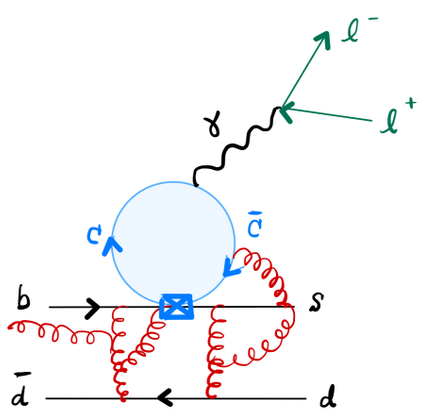
Non-local

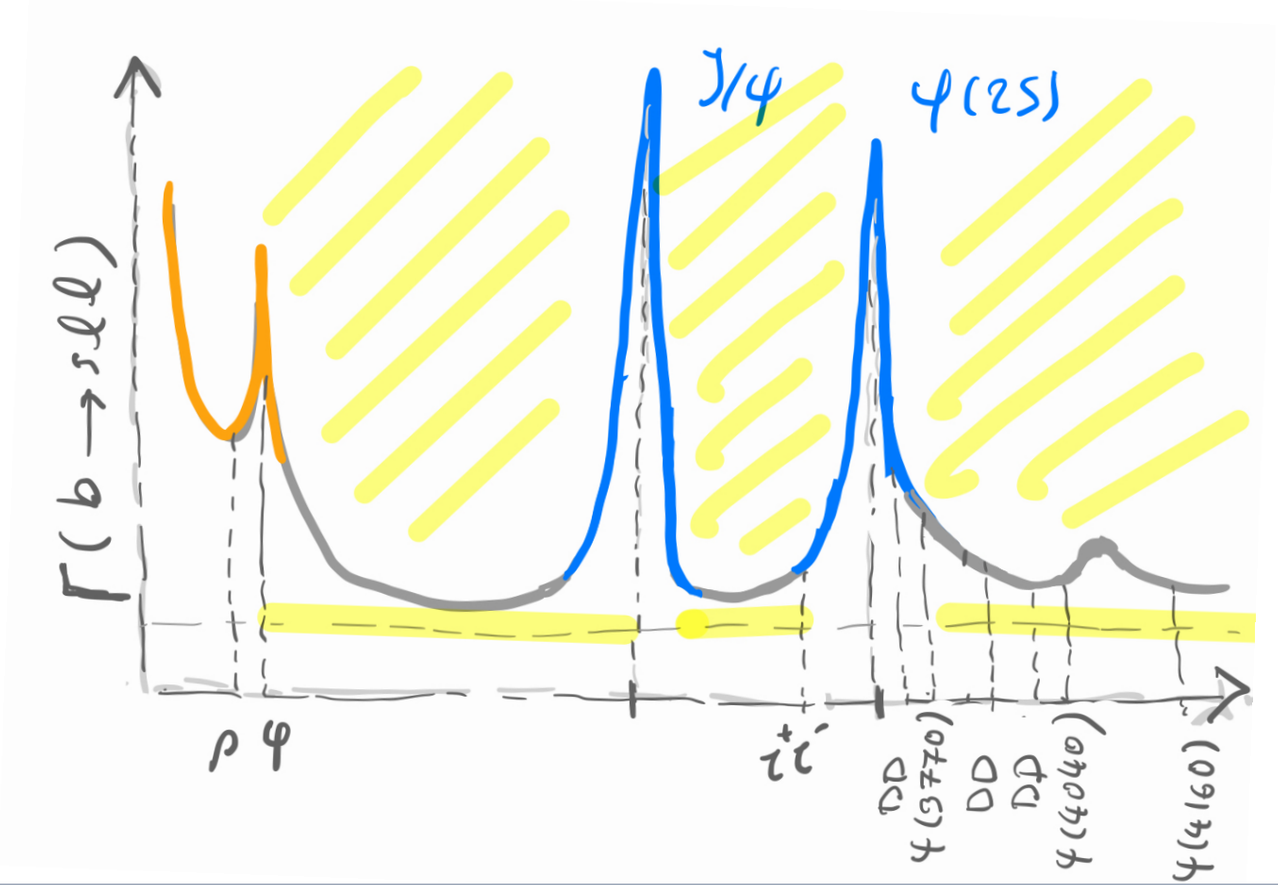
- All vector Resonances coupling to muons (1-particle)
- 2-particle $D^{(*)}\bar{D}^{(*)}$, $\tau^+\tau^-$
- $\mathscr{C}_9$, $\mathscr{C}_{10}$, $\mathscr{C}_7$,$\mathscr{C}'_9$, $\mathscr{C}'_{10}$,$\mathscr{C}'_7$ and $\mathscr{C}_{9\tau}$
- Angular Observables



- Non-locals impact the rare mode regions







Analysis Strategy

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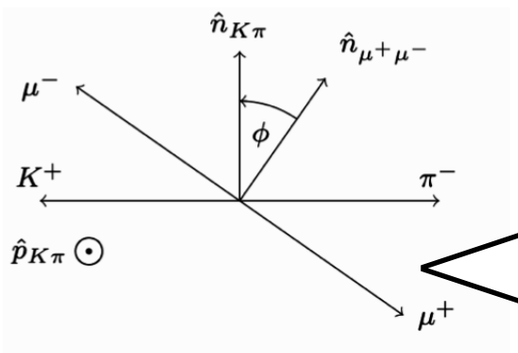
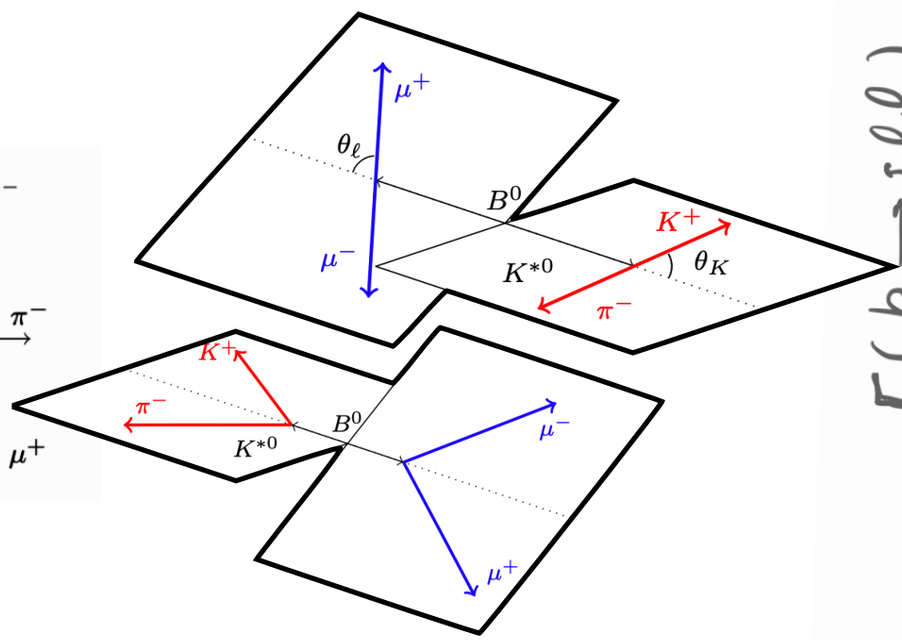
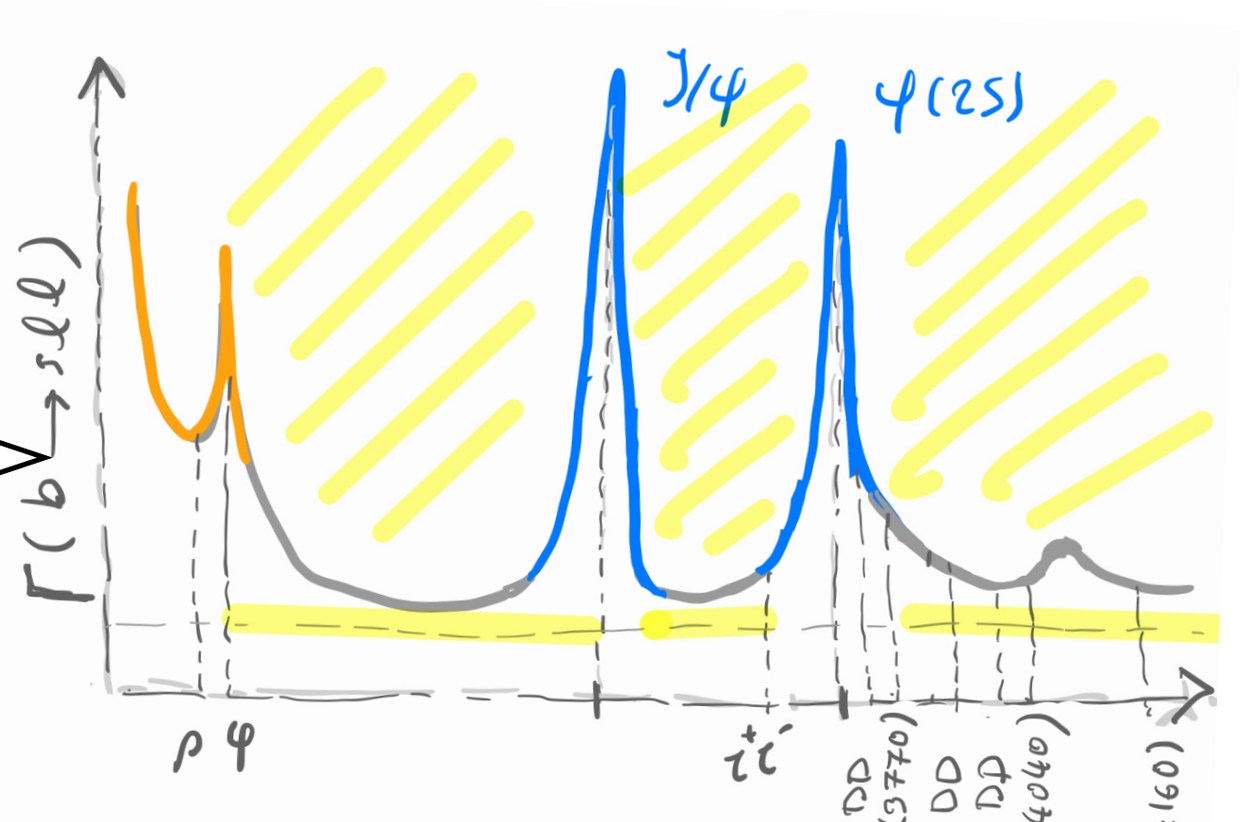
$$\frac{d^5\bar{\Gamma}(B^0 \to K^+\pi^-\mu^+\mu^-)}{dq^2 d\vec{\Omega} dm^2_{K\pi}} = \frac{9}{32\pi}\sum_i \bar{J}_i(q^2) f_i(cos\theta_l, cos\theta_K, \phi) g_i(m^2_{K\pi})$$

- **J(q2) + Angular Coefficient +** $0.796 < m_{K^*(K\pi)} < 0.996[GeV/c^2]$
  - P-wave line shape: RBW
  - S-Wave line shape:LASS PhysRevD.109.052009
  - P-wave and S-wave amplitude contributions
  - Local and non-local form factors:
    - Local FF :
      - 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 FF: Absorbed into $\mathcal{C}_{7,9}^{eff}$







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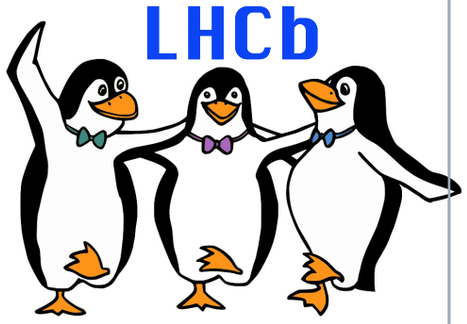
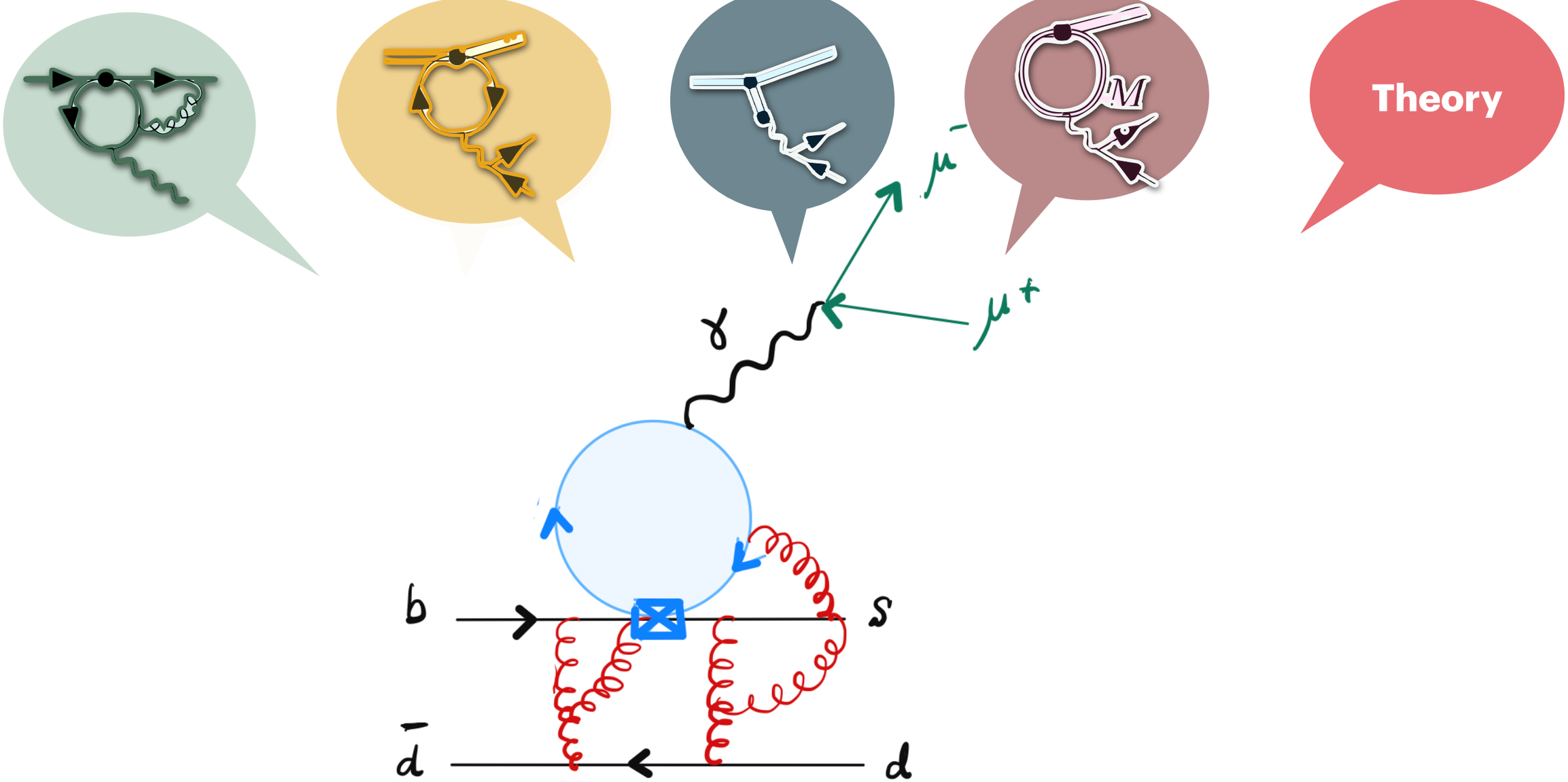
Non-Locals, Dispersion Model



$$Y_{q\bar{q},\lambda}(q^2) = Y_{q\bar{q}\,\lambda}(q_0^2) + \frac{(q^2 - q_0^2)}{\pi} \int_{4m_\mu^2}^{\infty} \frac{\rho_{q\bar{q},\lambda}(s)}{(s - q_0^2)(s - q^2 - i\epsilon)} \mathrm{d}s$$

$\xi^\lambda e^{i\omega^\lambda}$ $Y_{\tau\bar{\tau}}(q^2)$ $Y^{1P,\lambda}_{c\bar{c}}(q^2)$ $Y^{2P,\lambda}_{c\bar{c}}(q^2)$ $Y^{0}_{c\bar{c}}(q_0^2)$



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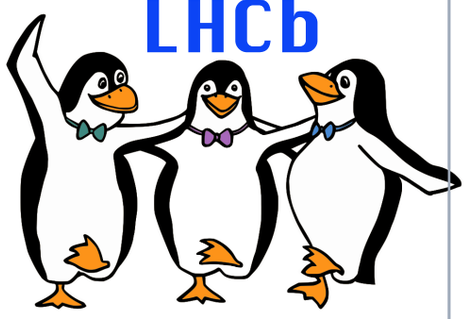
Non-Locals, Dispersion Model



$$C_7^{eff,\lambda} = C_7 + \xi^\lambda e^{i\omega^\lambda} \qquad C_9^{eff,\lambda} = C_9^\mu + \sum_{n=0}^{2} Y_{c\bar{c}}^{n,\lambda}(q^2) + Y_{\tau\bar{\tau}}(q^2)$$

$\xi^\lambda e^{i\omega^\lambda}$ | $Y_{\tau\bar{\tau}}(q^2)$ | $Y_{c\bar{c}}^{1P,\lambda}(q^2)$ | $Y_{c\bar{c}}^{2P,\lambda}(q^2)$ | $Y_{c\bar{c}}^{0}(q_0^2)$

$\mathscr{C}_7$ vertex correction

Polarisation dependent shift

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

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

1-Particle

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

$\phi(1020), J/\psi$

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

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

2-Particle

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

Constant

$q^2 < 0$

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

Analysis Strategy

JHEP09(2024)026

Total PDF in q^2 regions(i)

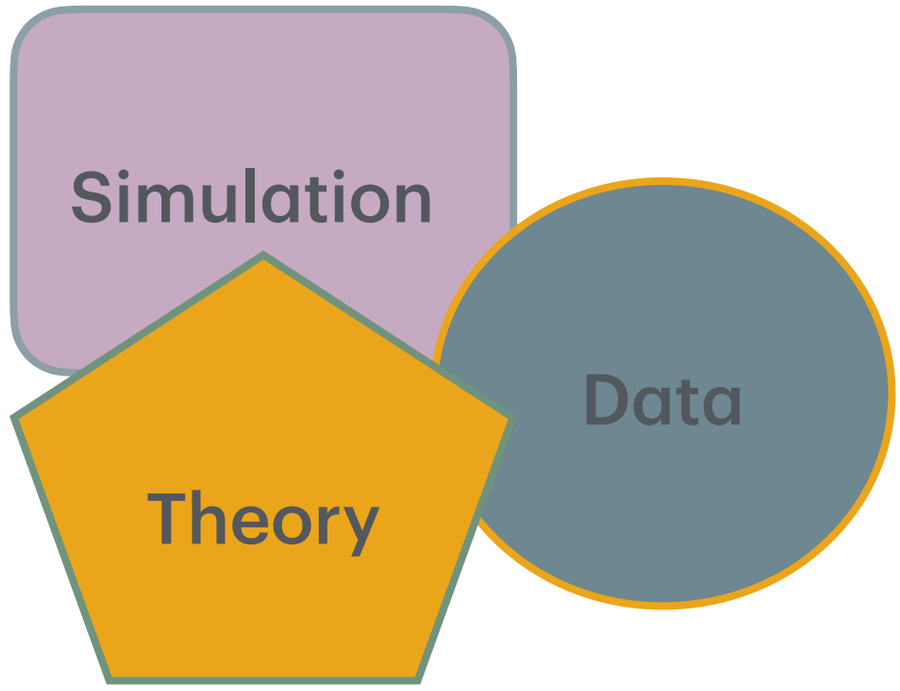
Diff decay rate Acceptance Resolution

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

Signal fr

bkg

- **Signal**
  - Signal candidate selection
  - Signal Shape in $M_{K\pi}$ mass is integrated out
  - Signal decay rate is modelled 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)**
  - Acceptance
  - Resolution
  - Form Factors, JHEP 09, 133 (2022)
  - Wilson Coeff
  - 1P, 2P parameters

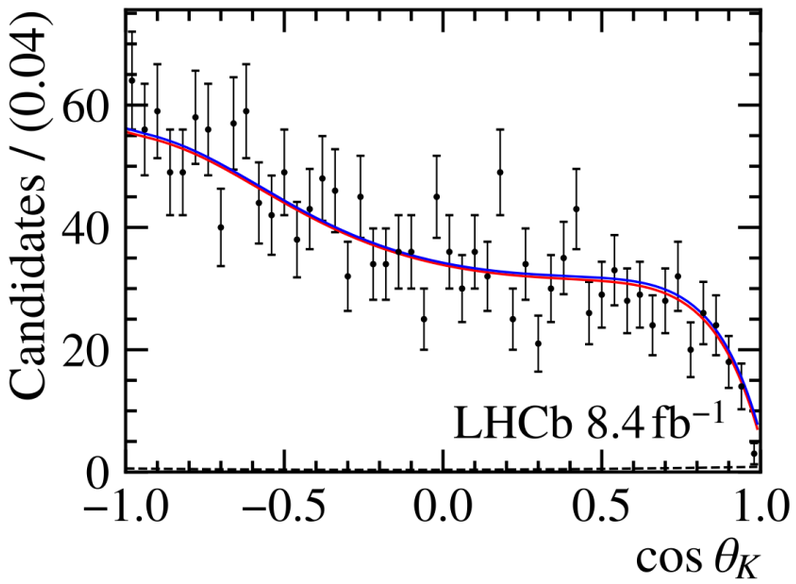


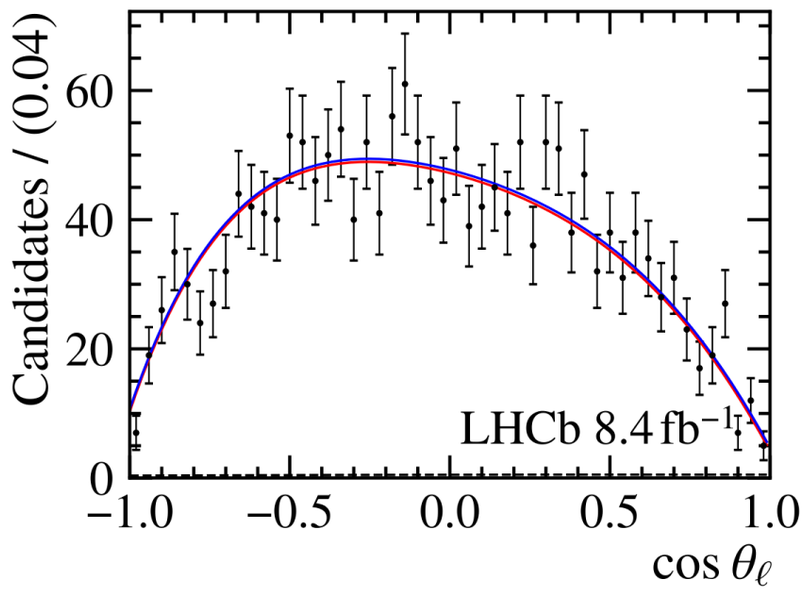
Category	q^2 region [GeV^2/c^4]	Signal fraction ($f^{\mathrm{full}}_{\mathrm{Sig},i}$)
Low-q^2	$[0.10, 3.24]$	0.9196 ± 0.0088
Fully combinatorial mid-q^2	$[3.24, 8.20] \cup [10.6, 11.56]$	0.8045 ± 0.0093
Resonant mid-q^2	$[8.20, 10.6]$	0.9934 ± 0.0002
Fully combinatorial high-q^2	$[11.56, 12.40] \cup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

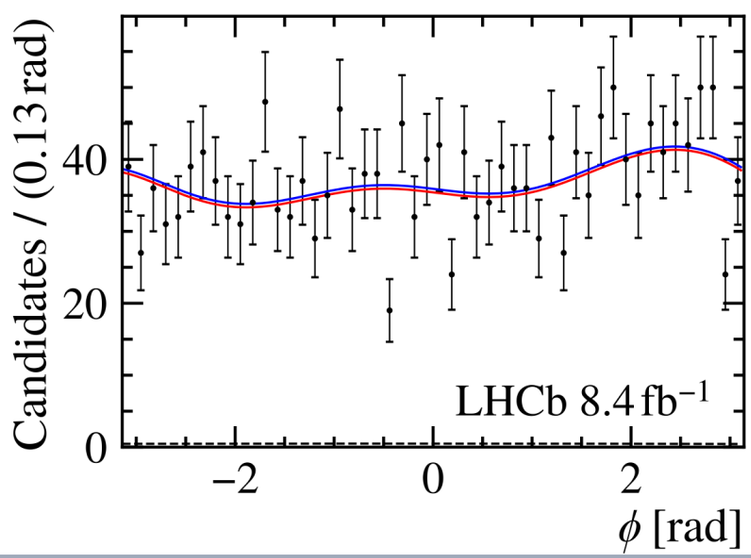
- **Systematic uncertainty dominated -> $\mathscr{B}(B^0 \to K^{*0}J/\psi)$,**
  Phys. Rev. D 90 (2014), 112009

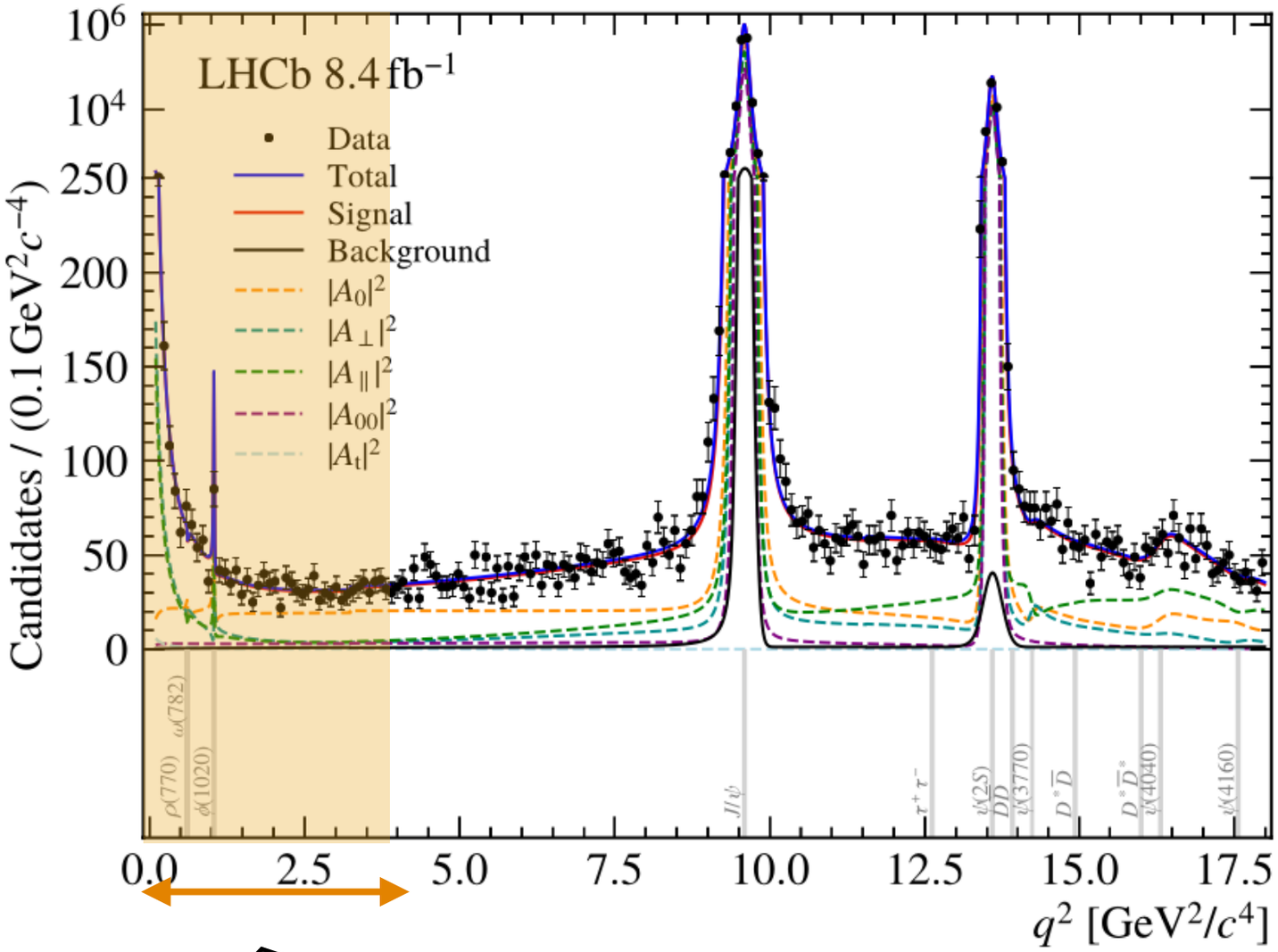
Results

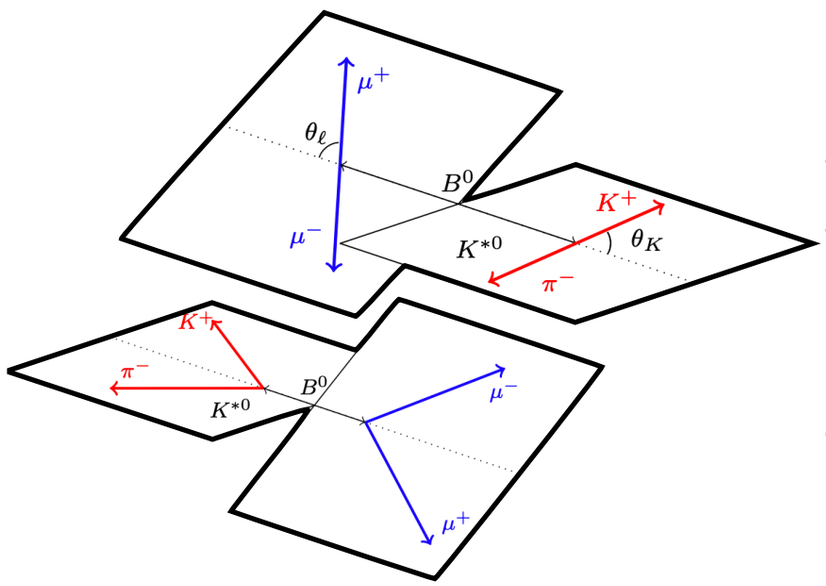
JHEP09(2024)026









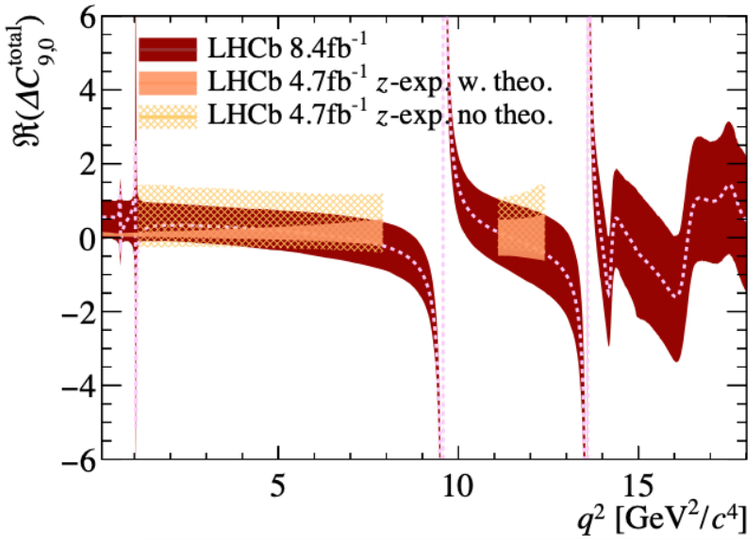


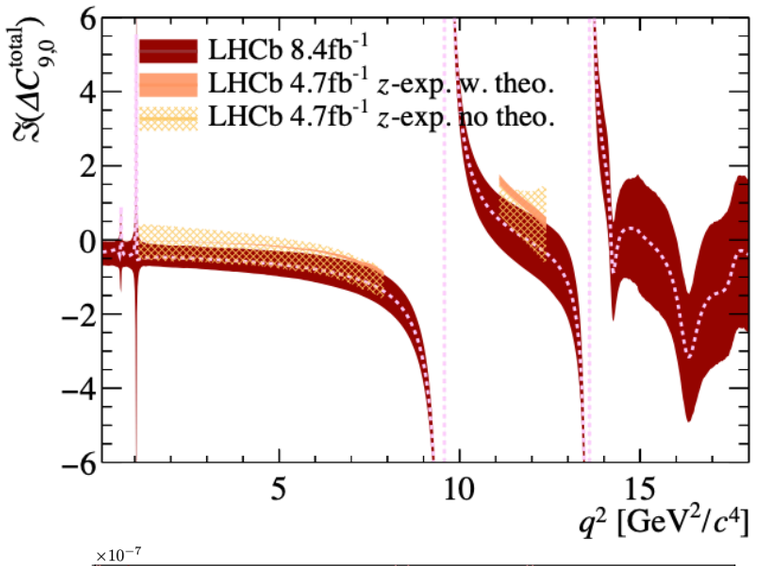
Category	Region
Low-q^2	$0.10 \leq q^2 < 3.24\,\text{GeV}^2/c^4$
Mid-q^2	$3.24 \leq q^2 < 11.56\,\text{GeV}^2/c^4$
High-q^2	$11.56 \leq q^2 \leq 18.00\,\text{GeV}^2/c^4$

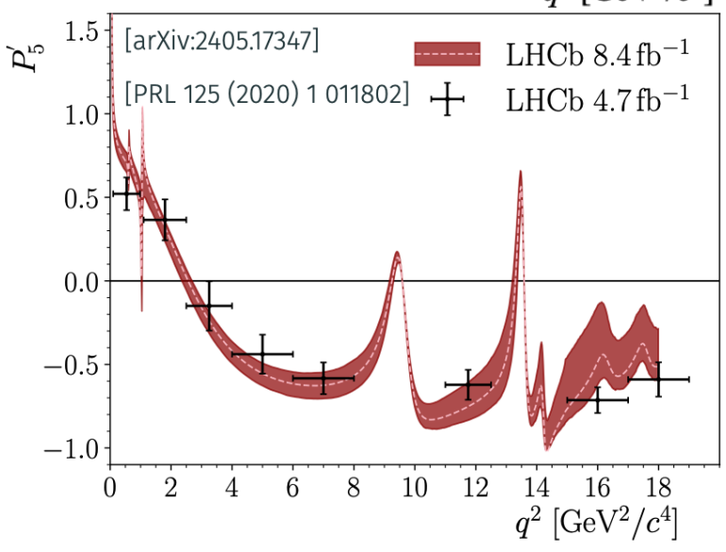
Results

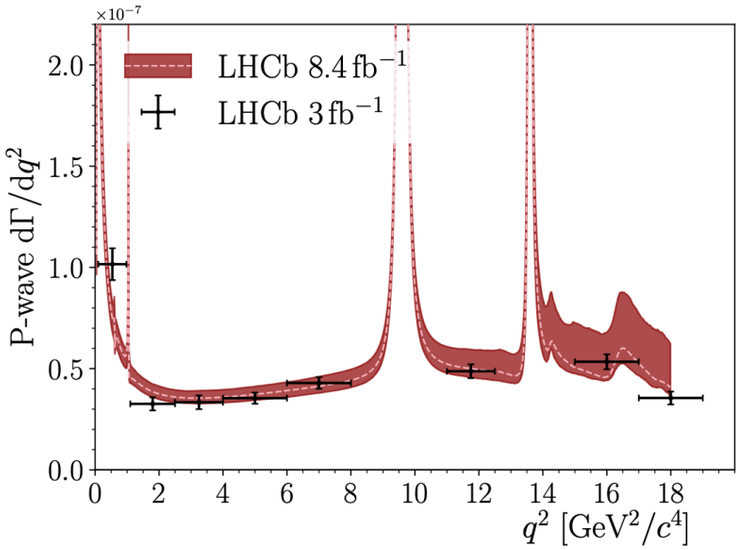
JHEP09(2024)026

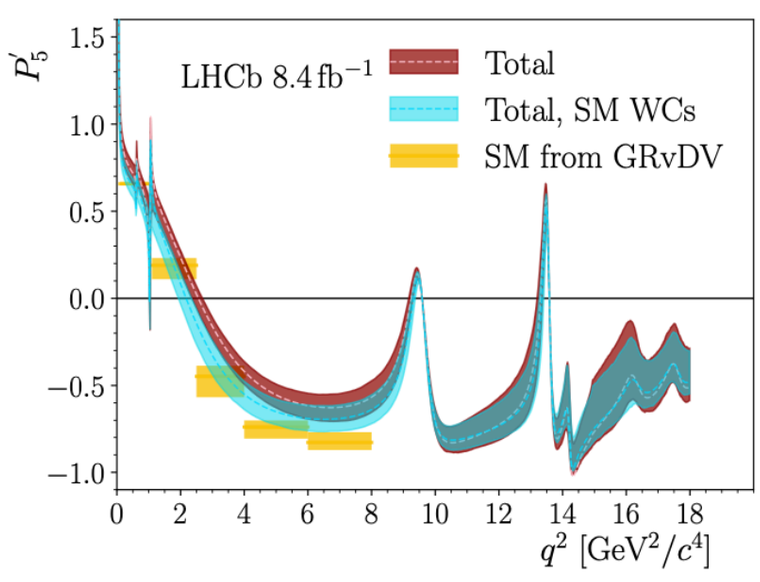
- **Impact from nonlocal contributions on WCs (per helicity)**
- **Good agreement with:**
  - Previous Unbinned LHCb measurement(black points)
  - Run 1+ 2016 ($4.7[fb]^{-1}$), which models non-locals with polynomial expansion in limited q^2 range, PRD. 109 (2024) 052009
  - **non-local contributions:**
    - Data prefers larger
    - Not enough to explain $\mathscr{C}_9$ shift
- **Tensions in Observables persist**

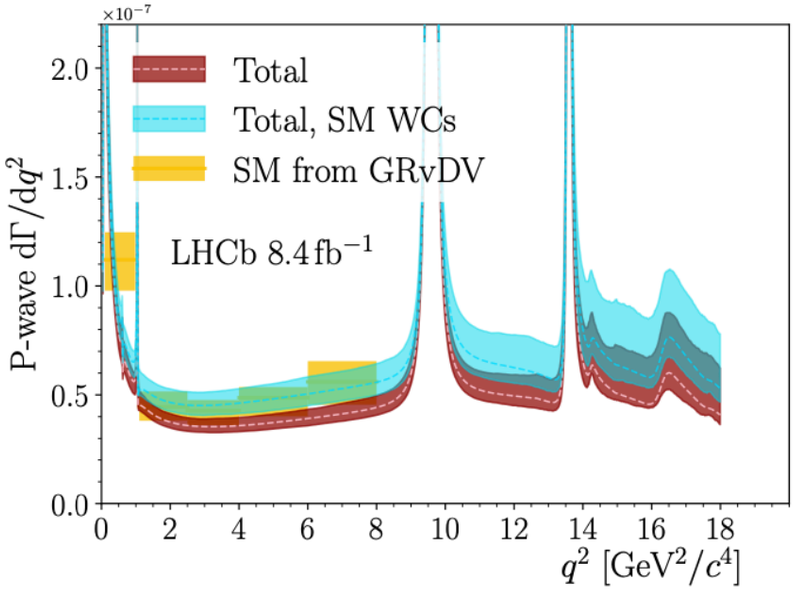






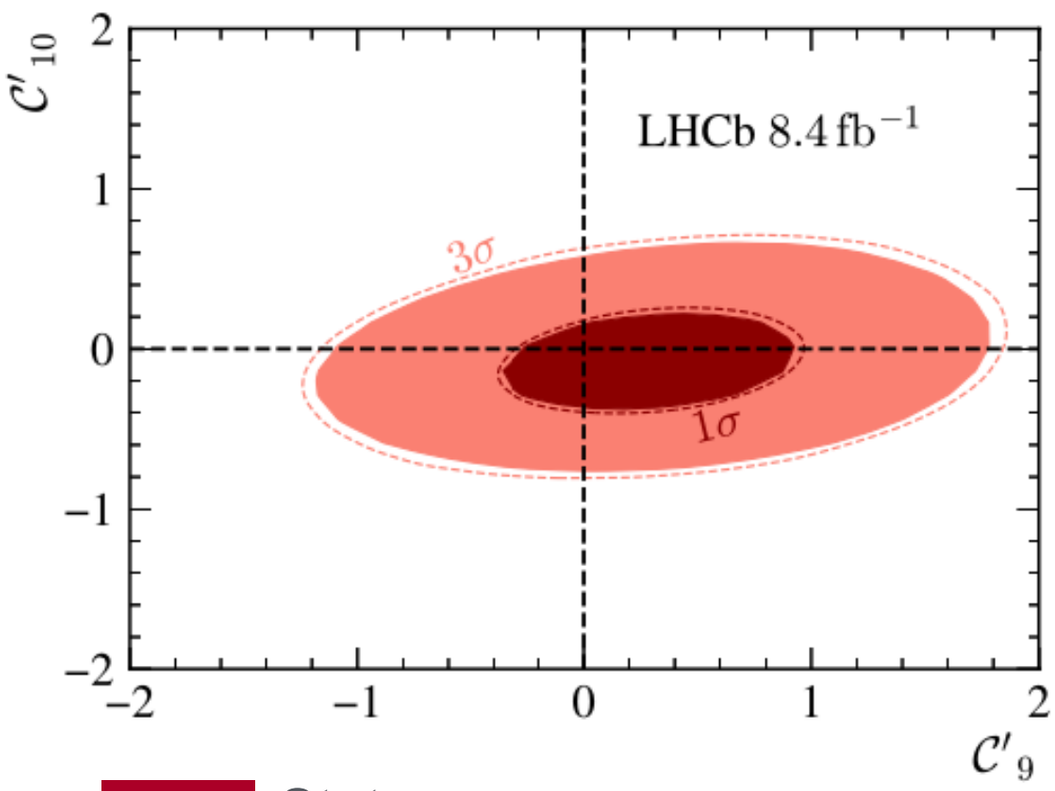


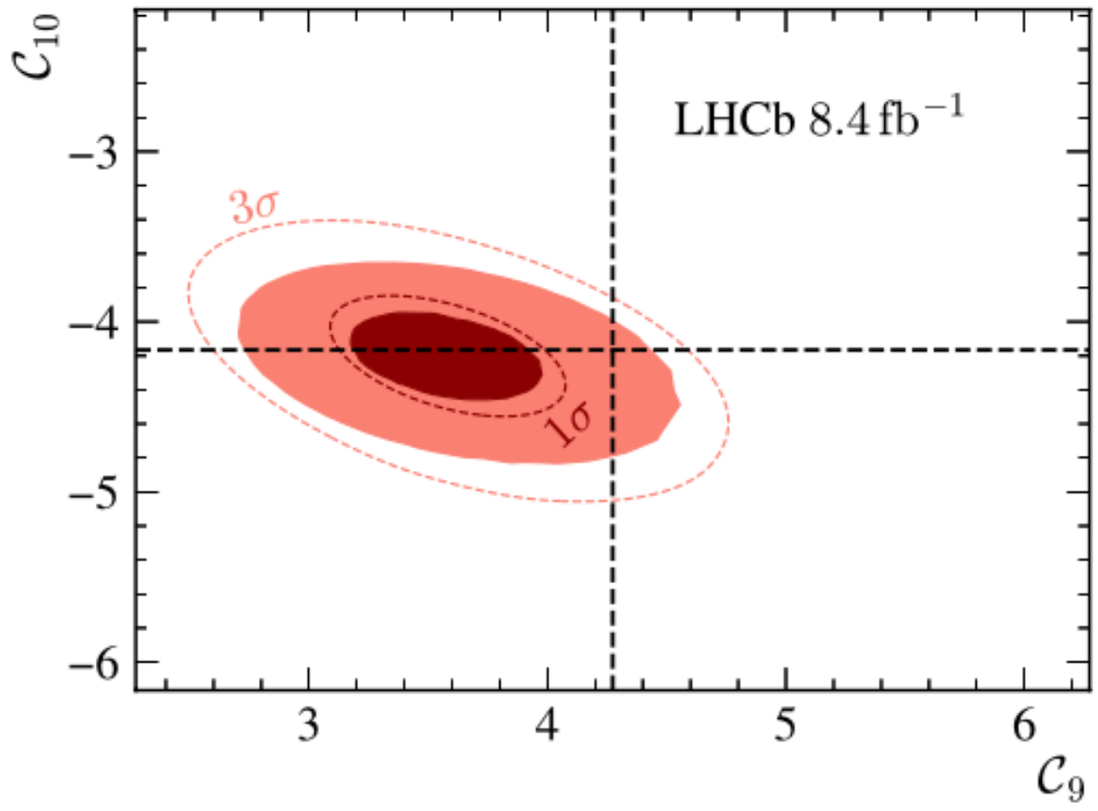




Results

JHEP09(2024)026

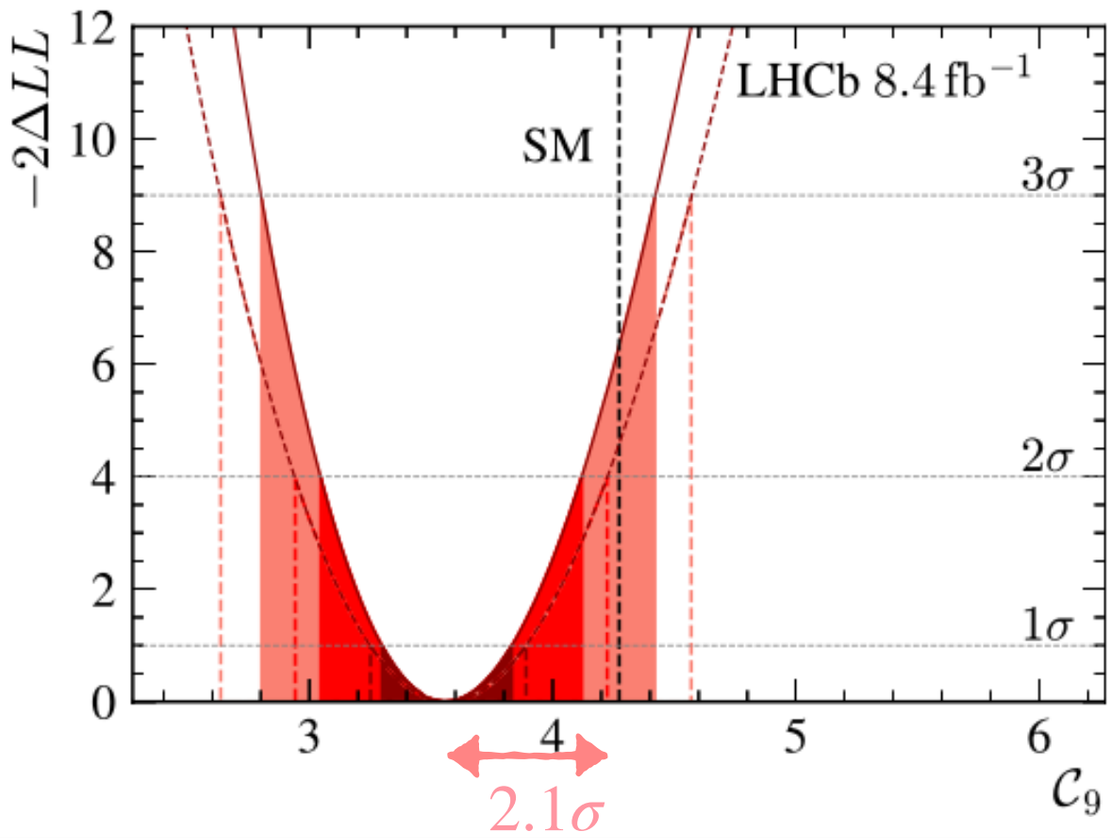




Stat

Stat+Syst

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



Using Likelihood profile method

Results

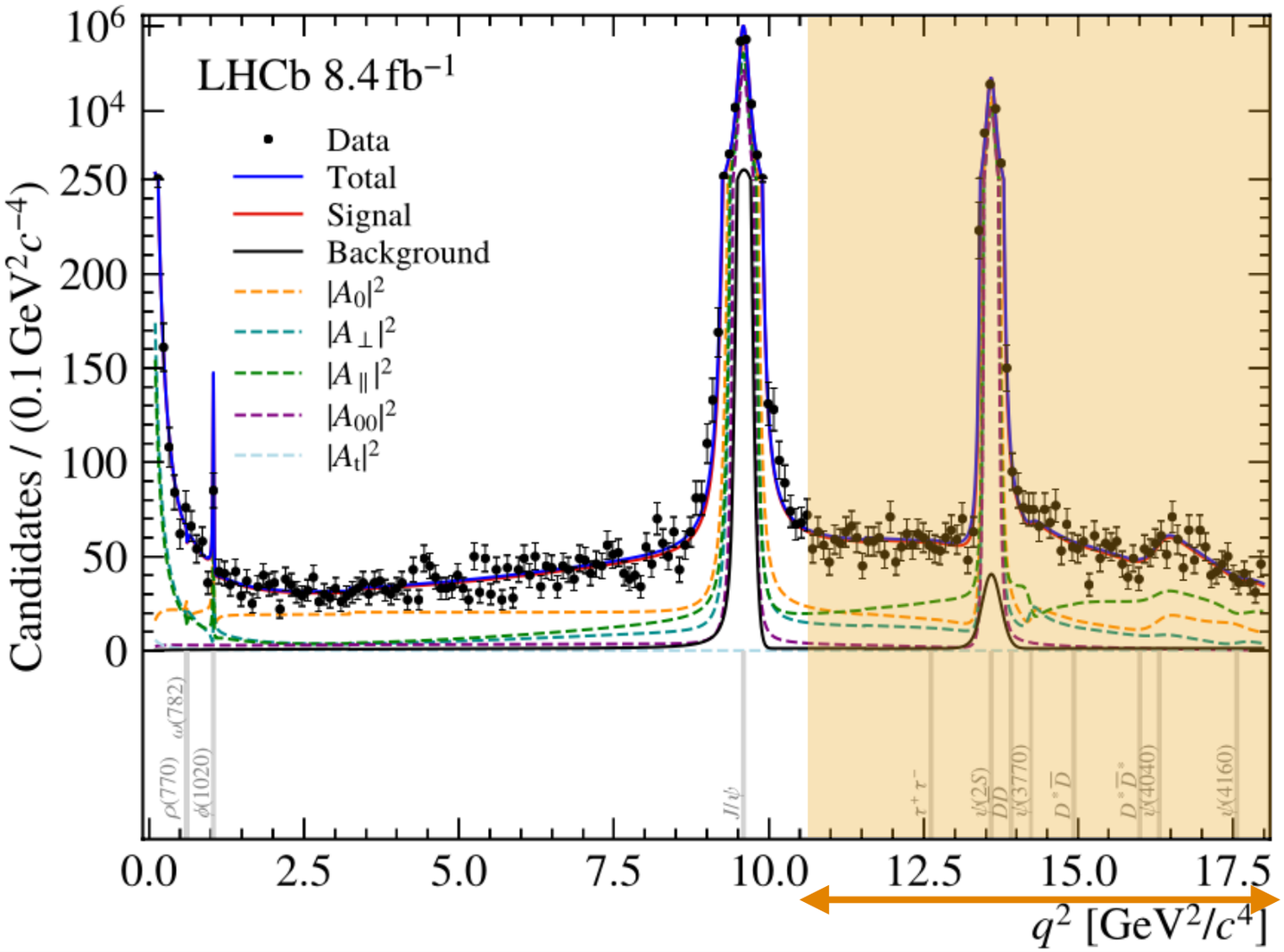
JHEP09(2024)026

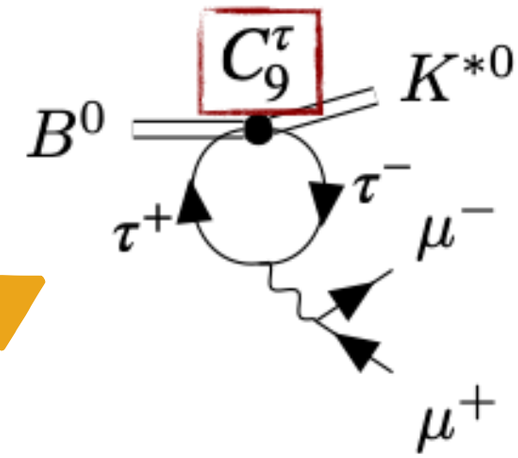
Wilson Coefficient results	
$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$
$\mathcal{C}_{10}$	$-4.02 \pm 0.18 \pm 0.16$
$\mathcal{C}'_9$	$0.28 \pm 0.41 \pm 0.12$
$\mathcal{C}'_{10}$	$-0.09 \pm 0.21 \pm 0.06$
$\mathcal{C}_{9\tau}$	$(-1.0 \pm 2.6 \pm 1.0) \times 10^2$

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

Belle, Phys. Rev. D108 (2023) L011102

ICHEP_EWPLFV_BELLEBELLEII_0719.pdf

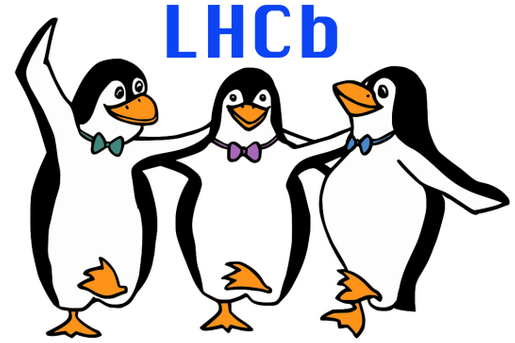




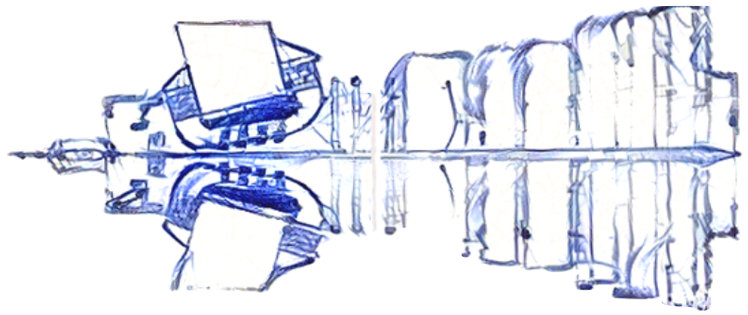
Third Generation enhancement expected in many NP models

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

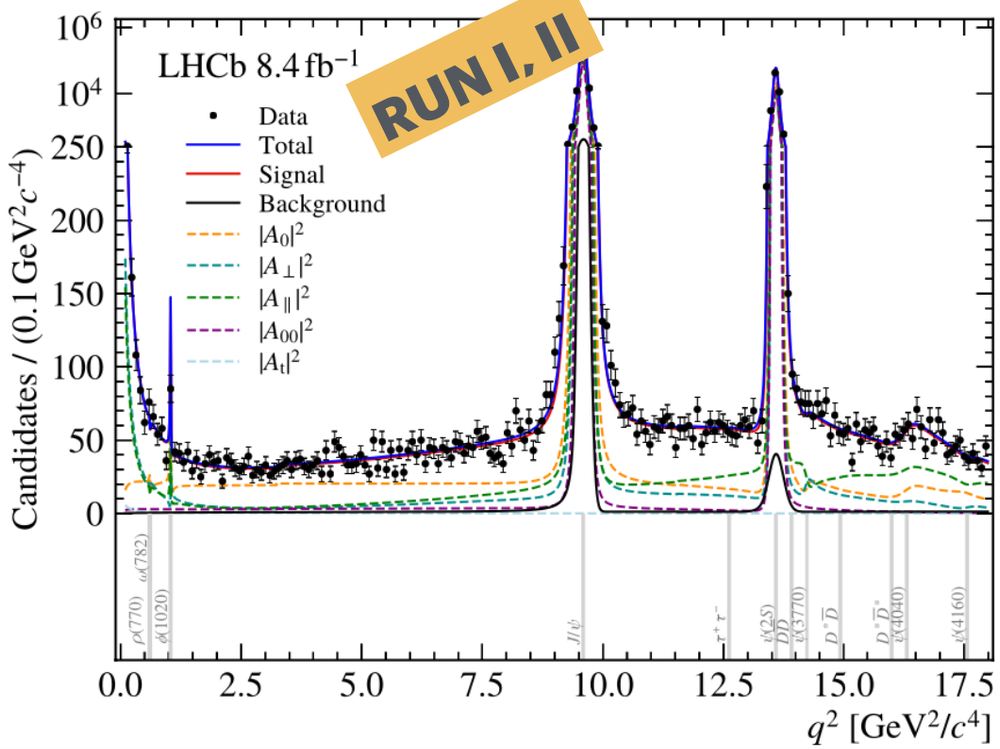
Summary



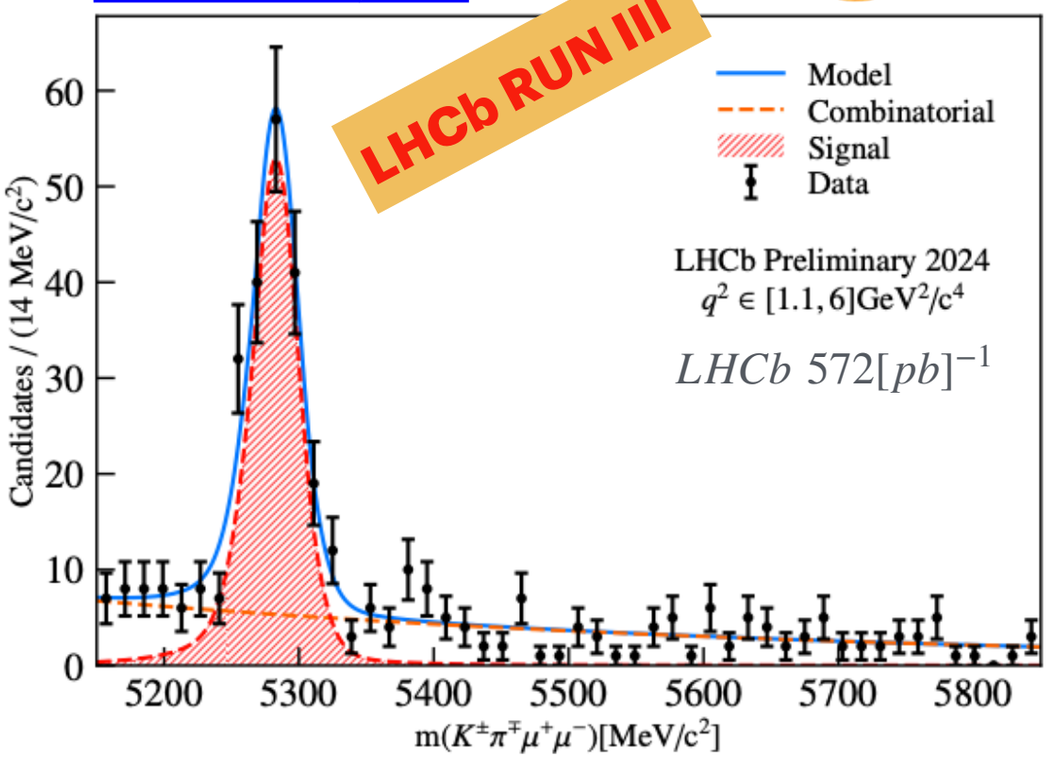
- **Rare decays are promising probe to search for NP**
  - $b \to s l^+ l^-$ global fit, shows $\sim 4\sigma$ from SM
- **Model independent/dependent measurements of various observables in $B^0 \to K^{*0}\mu^+\mu^-$ show tension wrt SM (**Br fr , Angular Observables **)**
- **Latest unbinned results -> $\mathscr{C}_9$ 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, [Belle, Oct 2021]
  - Run III LHCb data will help [JHEP09(2024)026]



[LHCb RUN III, CDS]

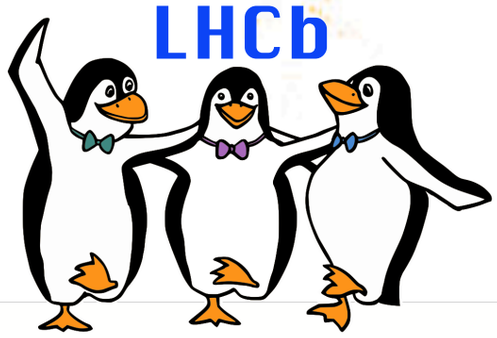


University of BRISTOL

LHCb

Thanks!

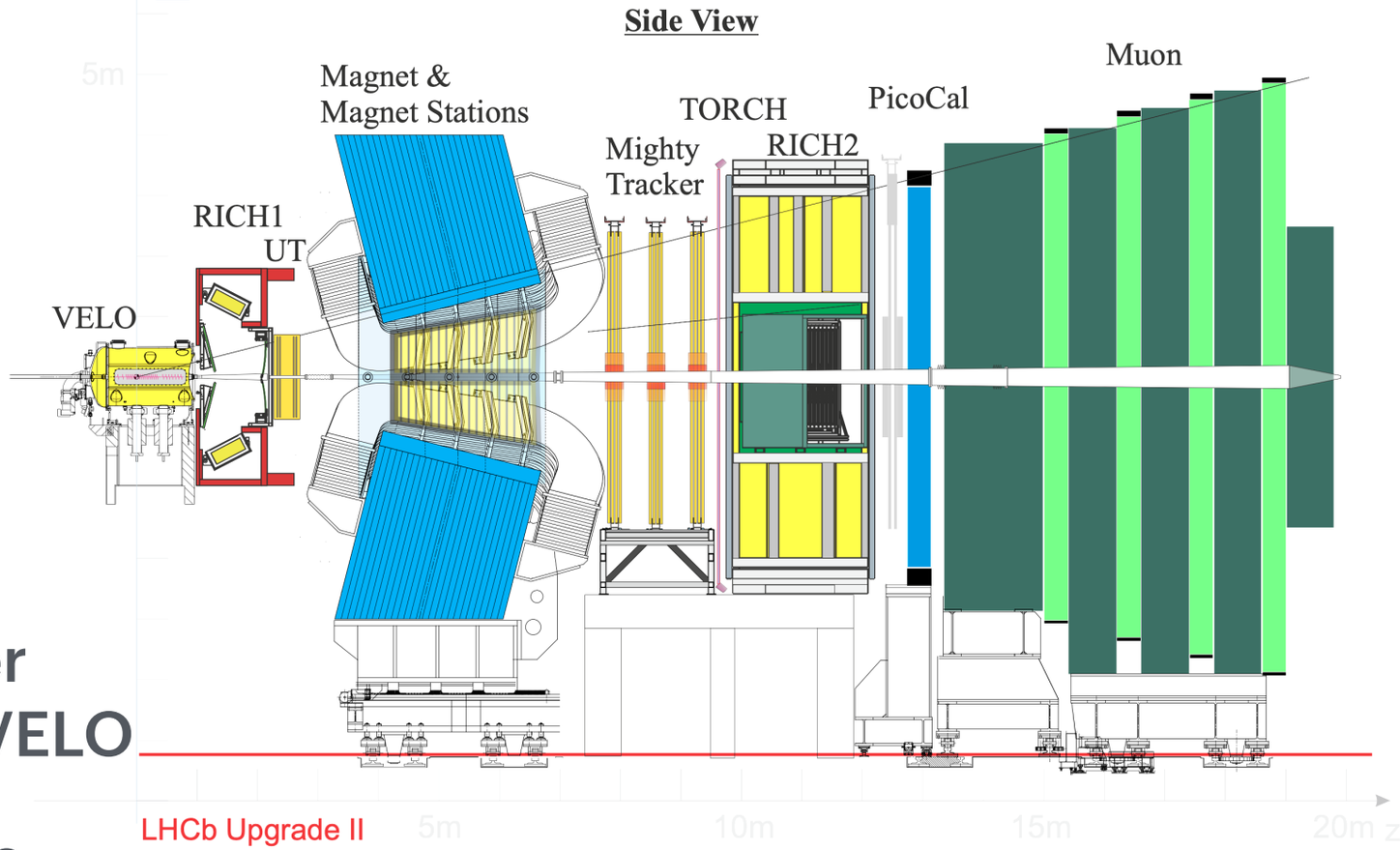
PIC 2024, ATHENS

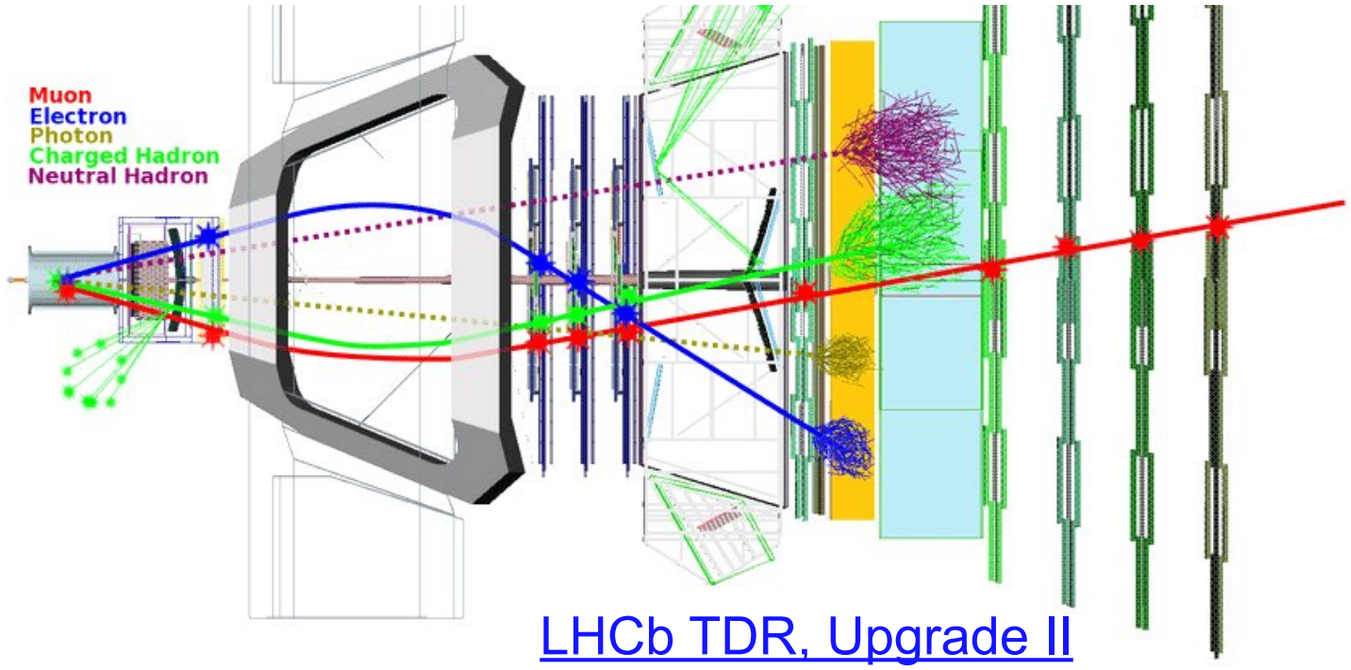


Backup Slides

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

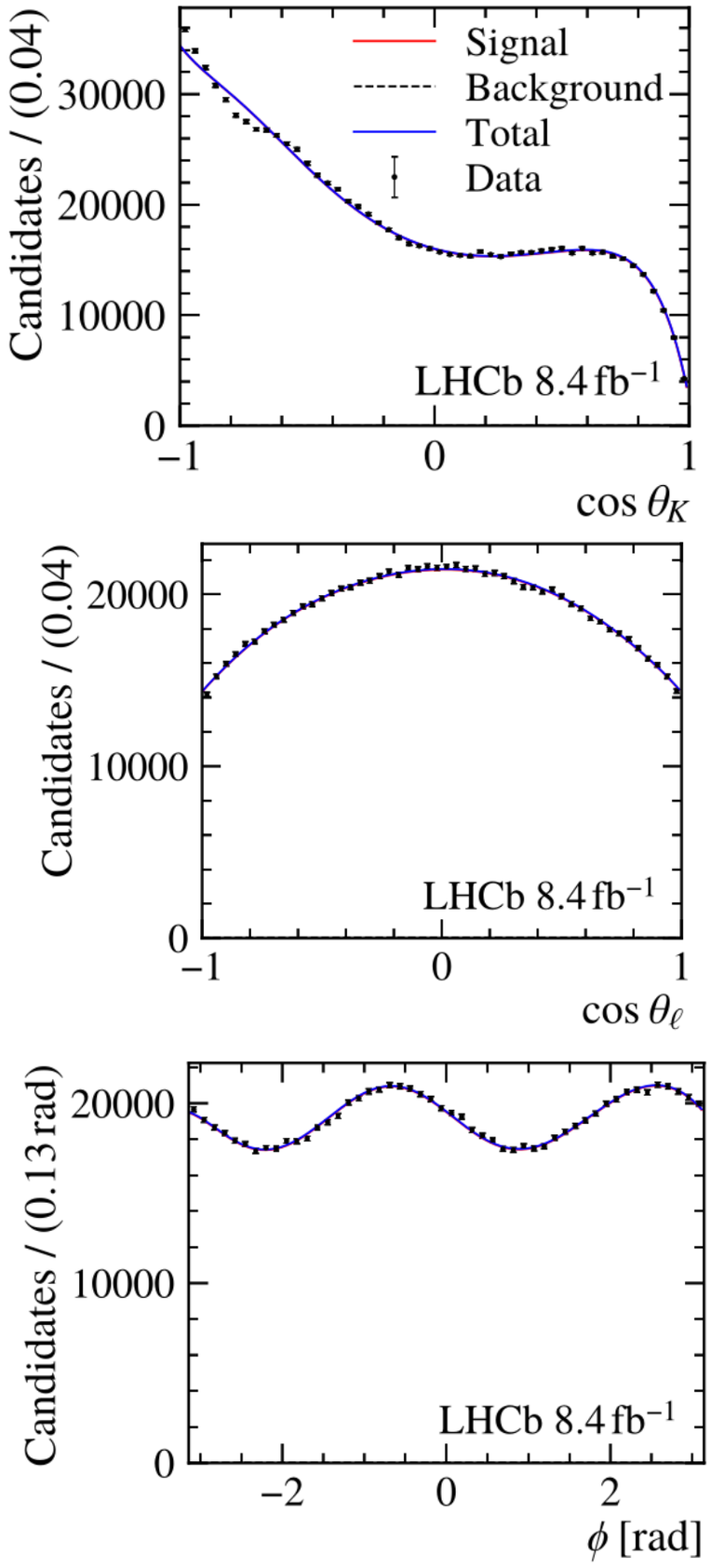


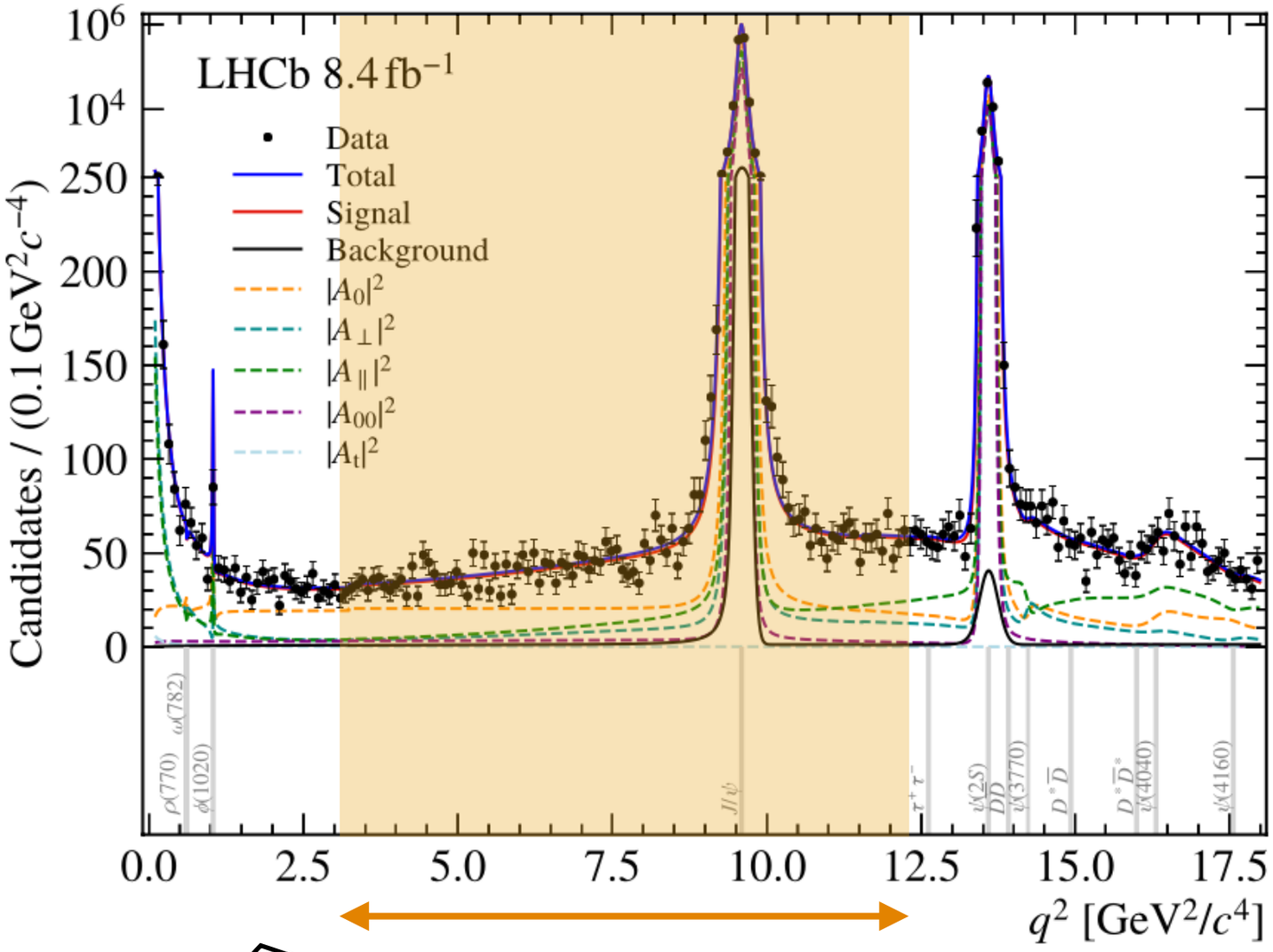


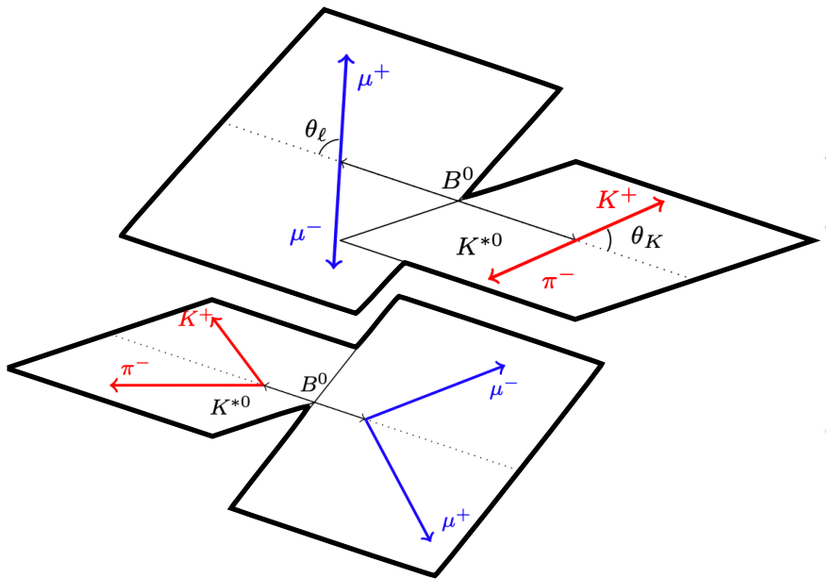
LHCb TDR, Upgrade II

Results

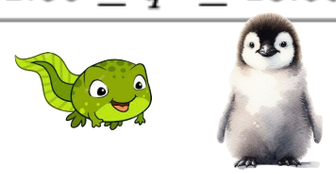
JHEP09(2024)026



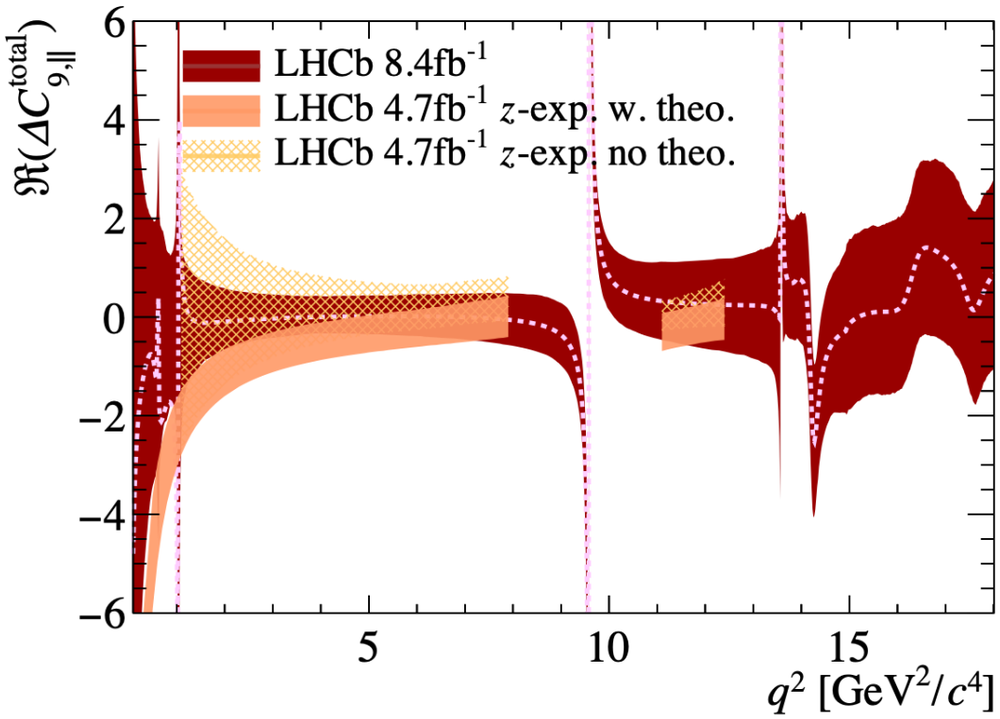


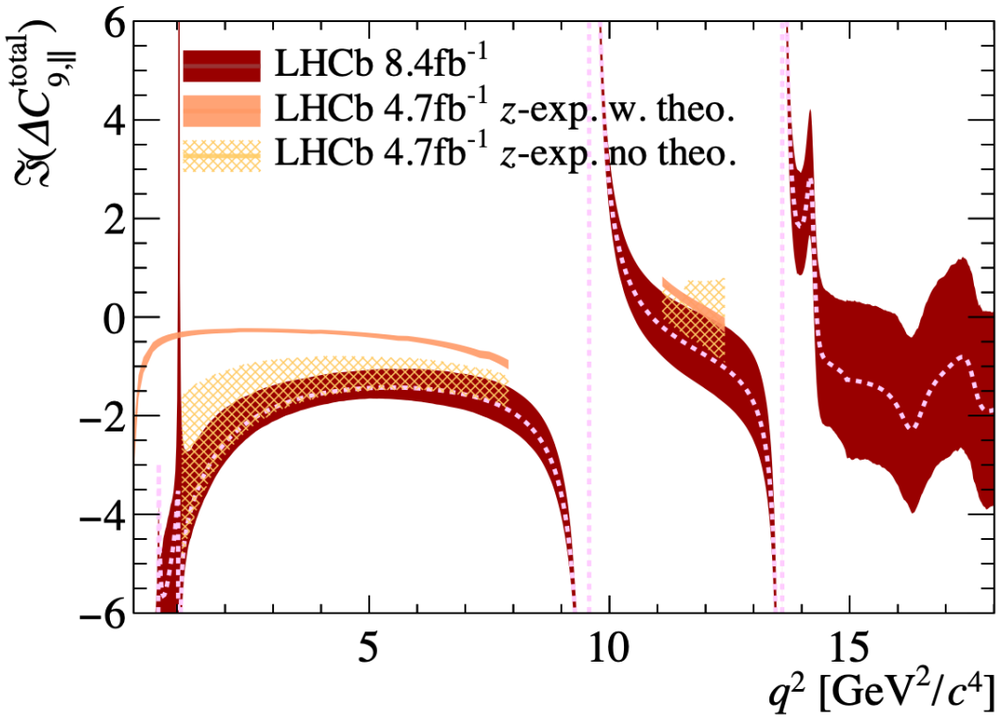


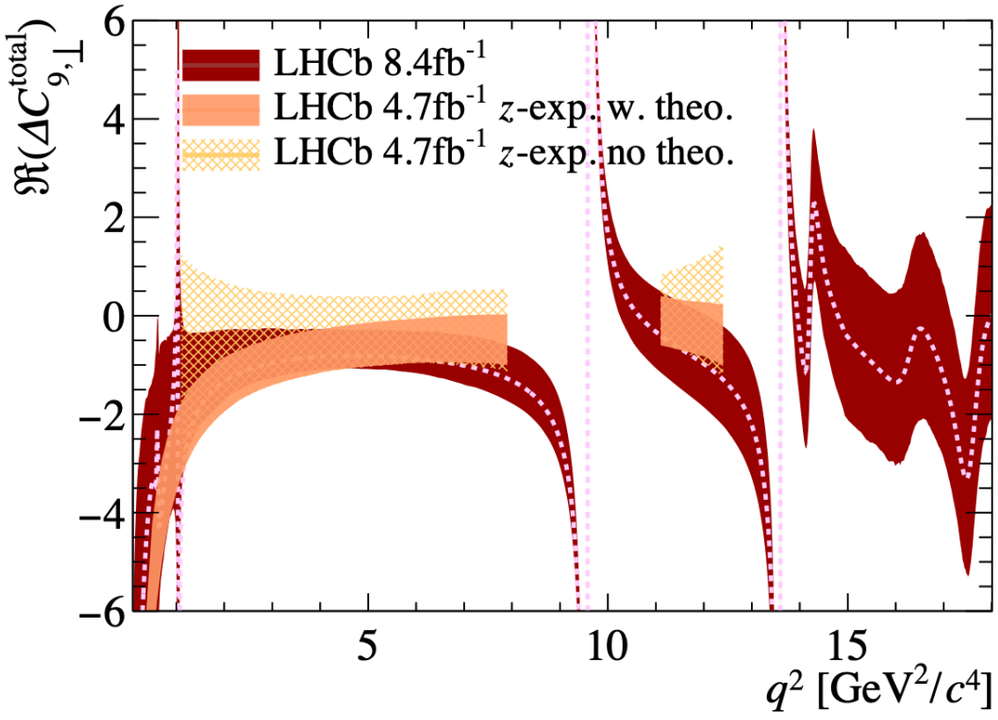
Category	Region
Low-q^2	$0.10 \leq q^2 < 3.24\,\text{GeV}^2/c^4$
Mid-q^2	$3.24 \leq q^2 < 11.56\,\text{GeV}^2/c^4$
High-q^2	$11.56 \leq q^2 \leq 18.00\,\text{GeV}^2/c^4$

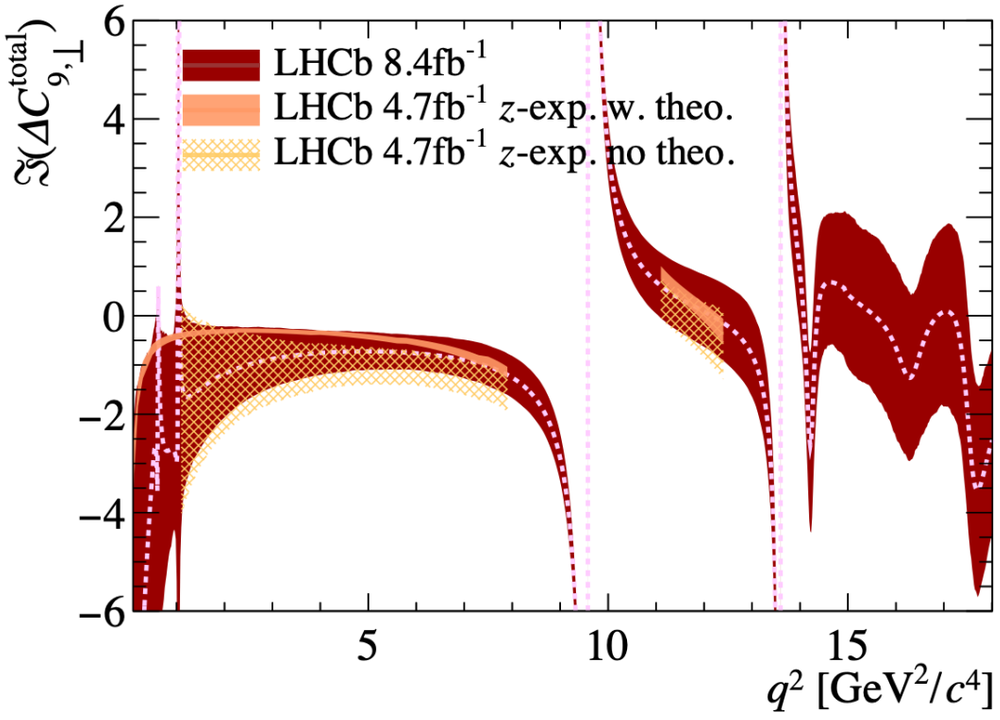


Results


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


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


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


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