Rare B decays

On behalf of Belle, Belle II, CMS and LHCb collaborations

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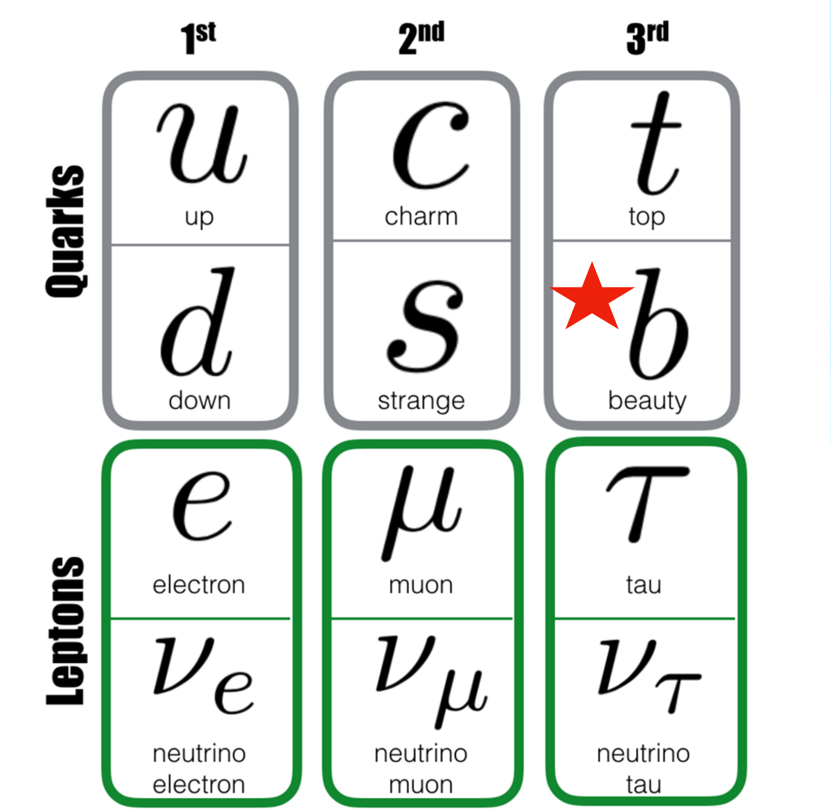
B physics

- B-hadrons decays:
  - Light enough to be produced abundantly, but heavy (~ps) enough to have many decays
  - Predictions for SM observables are well-known



- One of the main missions of B-factories and LHCb is to perform searches for new physics (NP) in rare decays

- Rare decays searches can allow to access the particle of higher energy than direct searches

- Rare B decays: branching fraction $\mathscr{B}(B \to \text{decay products}) < 10^{-5}$

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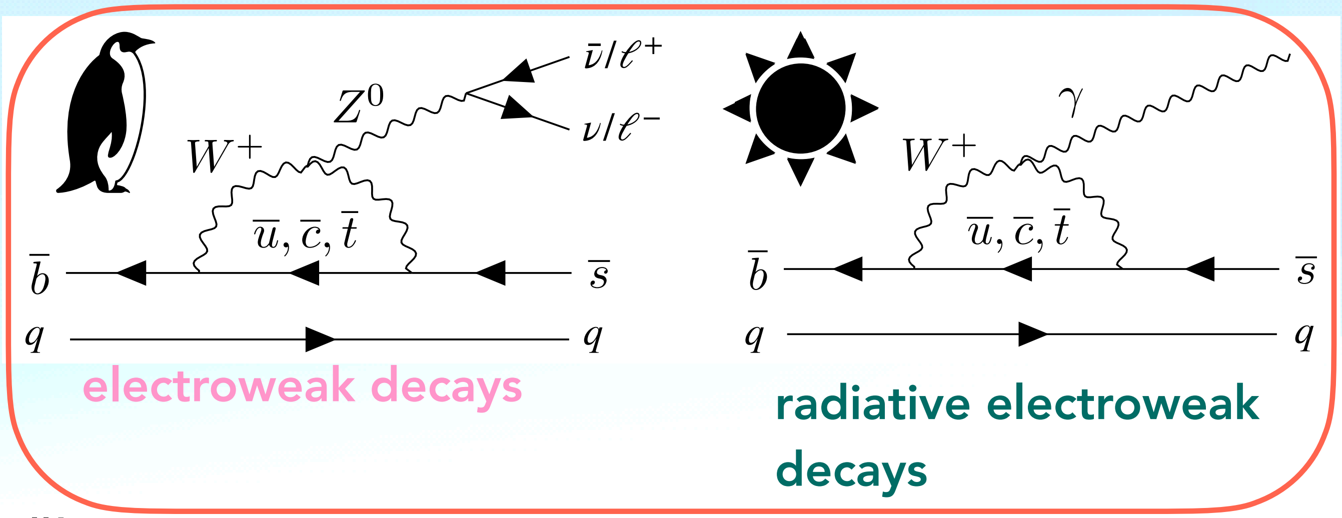
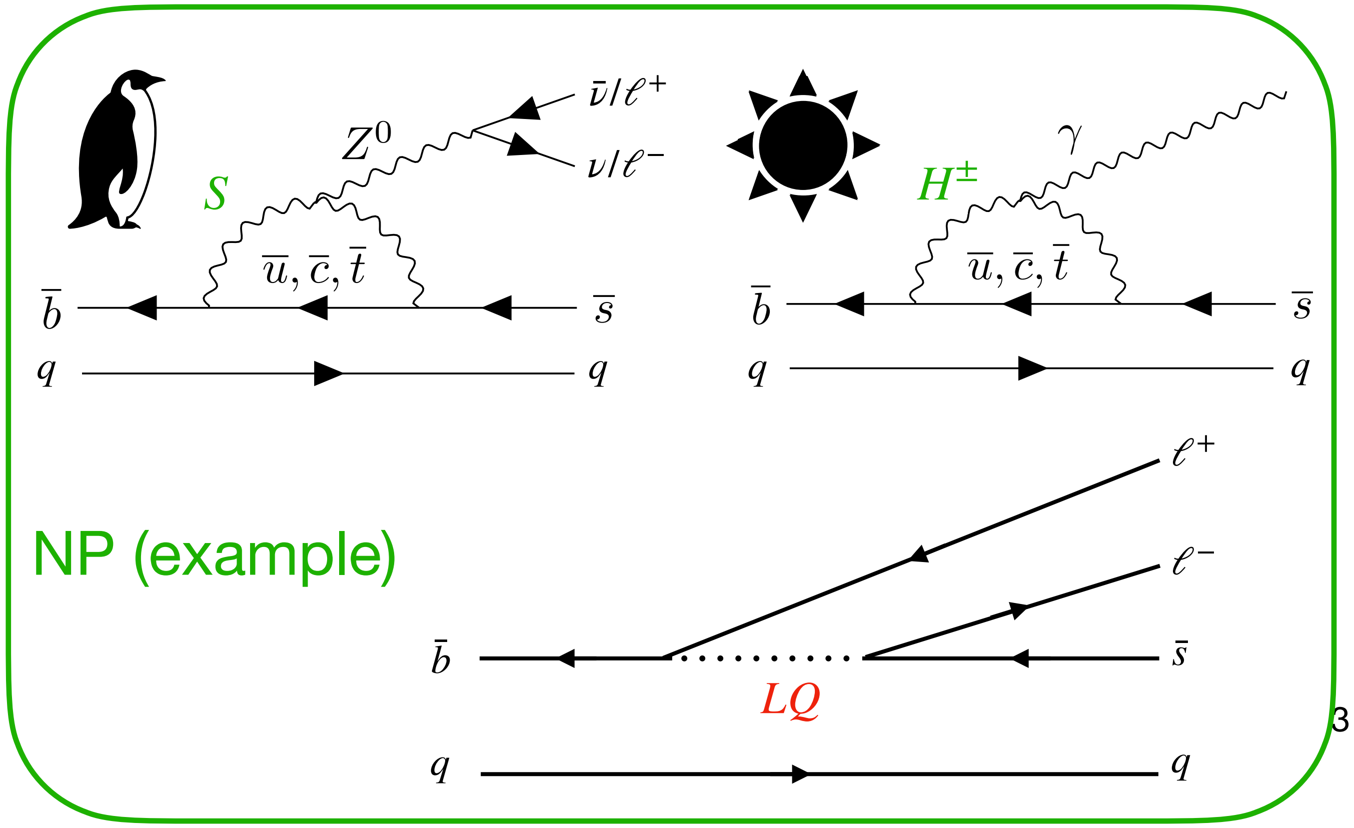
Rare B decays

- Rare B-decays:
  - Flavour Changing Neutral Currents (FCNC): $q \rightarrow q^{'}\gamma$ and $q \rightarrow q^{'}\ell^{+}\ell^{-}$
    - Proceed at the loop-level → very suppressed in the SM
    - Low BF's due to CKM and GIM suppression
    - m_{ν}^{2}/m_{W}^{2} suppressed lepton flavour violating decays
  - Helicity suppressed in purely leptonic decays



  - Very sensitive to NP since SM contribution is small!



Rare B decays

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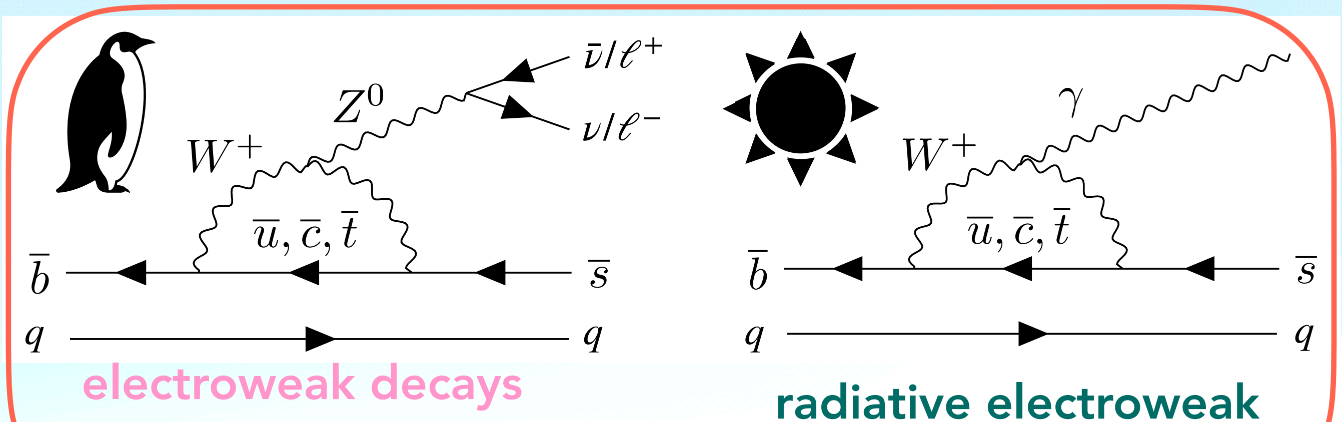


  - Very sensitive to NP since SM contribution is small!

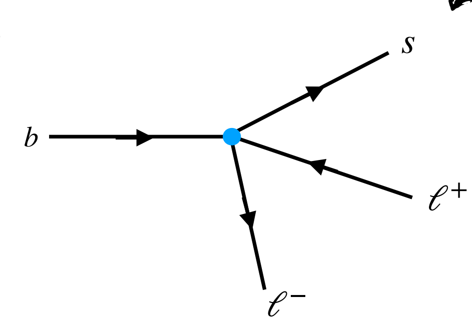
Effective hamiltonian described as operator product expansion, C_i being the Wilson coefficients, that encode the short-distance physics, and $\mathcal{O}_i$ the corresponding operators

$$\mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i (C_i\mathcal{O}_i + C_i^{'}\mathcal{O}_i^{'})$$

Left handed part

Right handed part

$$C_i^{(')} = C_i^{SM} + C_i^{NP}$$



NP (example)

Coupling	Radiative $b \to s\gamma$	Leptonic $B \to \mu\mu$	Semileptonic $b \to s\ell\ell$
$C_7^{(\prime)}$	✓		✓
$C_9^{(\prime)}$			✓
$C_{10}^{(\prime)}$		✓	✓
$C_S^{(\prime)}$		✓	
$C_P^{(\prime)}$		✓	

Experimental observables

Branching fractions:

Experimental: simple extraction, good control of efficiencies through control modes

Theory: affected by hadronic uncertainties

Angular observables

Experimental: complex extraction, need to control acceptance, many parameters of interests

Theory: first order cancellation of form-factors

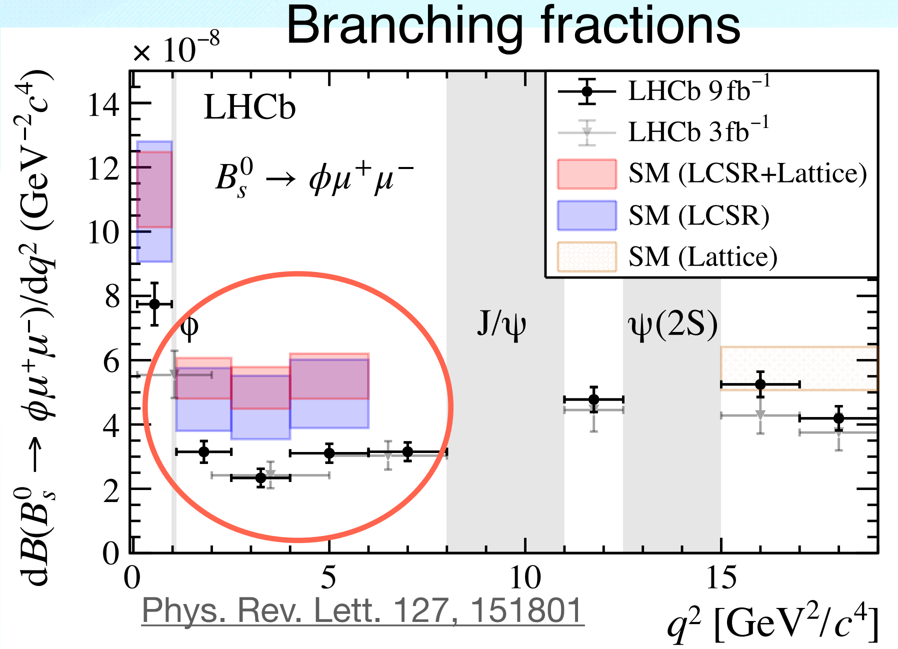
Universality tests

Experimental: need to control $e^{\pm}$ vs $\mu^{\pm}$ efficiencies, very challenging

Theory: full cancellations in the SM

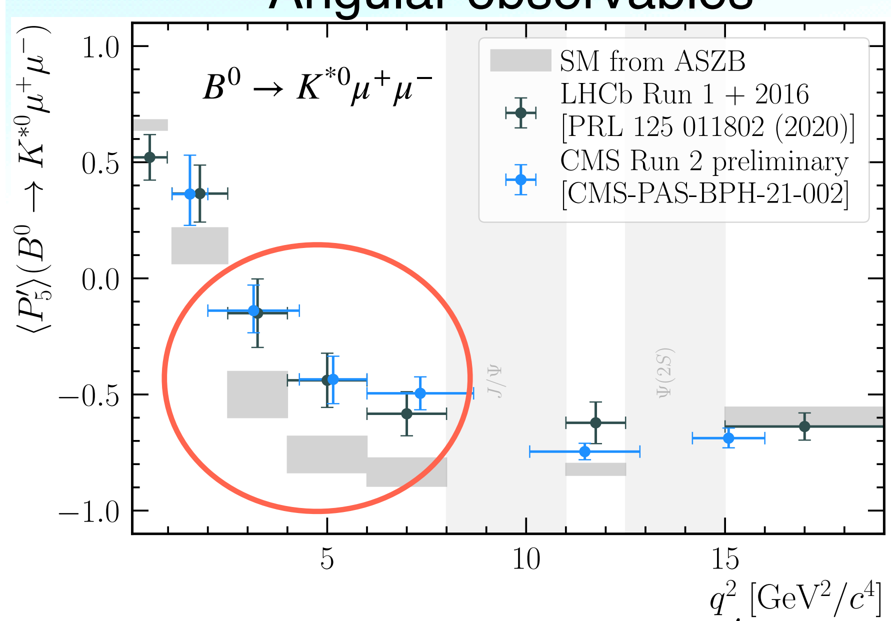
Increasing precision of the SM prediction

Branching fractions



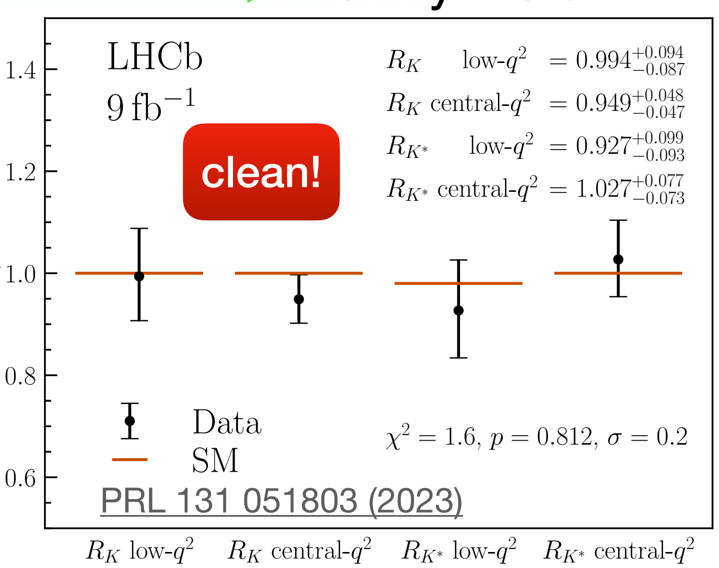
Lower than SM predictions

Angular observables



Local tension in the P_5'

Universality tests



- Several anomalies or common issue related to form factors/$c\bar{c}$ loop are seen in $b \to s\ell^+\ell^-$
- Explore new final states of $b \to s\ell^+\ell^-$, new radiative modes, or search for forbidden decays

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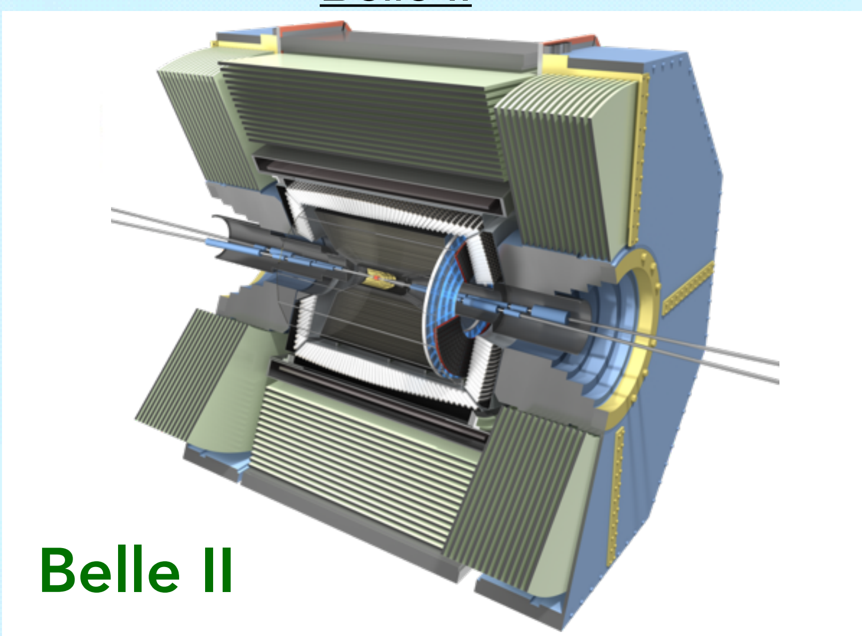
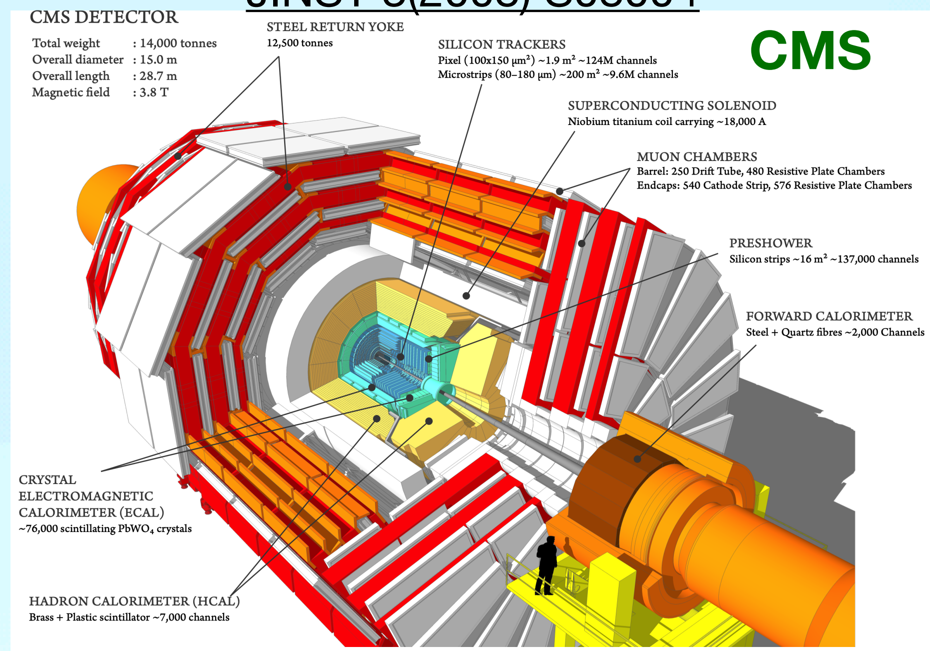
Experiments:

Belle II



JINST 3(2008) S08004



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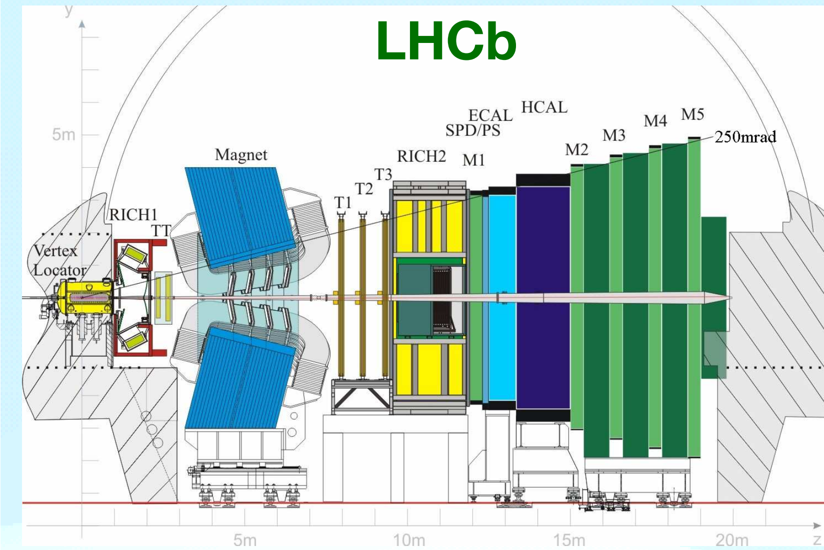

e^+e^- energy-asymmetric collisions at $\sqrt{s}$ = 10.58 GeV

- Accelerator: KEKB (Belle) and SuperKEKB (Belle II)
- General purpose detectors
- Period: 1999-2010 (Belle) / 2019-now (Belle II)
- 711 fb^{-1} (Belle): 770 mil. $B\bar{B}$ pairs
- 362 fb^{-1} (Belle II): 370 mil. $B\bar{B}$ pairs
- Plan: 50 ab^{-1}

- Very clean environment
- Higher trigger efficiency
- Excellent charged ID
- Better with neutrals, similar sensitivity for e and μ

pp collisions at 7, 8, 13 TeV

CMS:

- Accelerator: LHC
- General purpose detectors
- Period: 2011-now
- Collected 165 fb^{-1} (Run-1+2) data
- All species of B hadrons
- Plan: 3000 fb^{-1}

- Very busy environment
- Low trigger efficiency
- Better with muons
- No charged ID

LHCb:

- Accelerator: LHC
- Forward-looking spectrometer for b and c meson studies
- Period: 2011-now
- Collected 9 fb^{-1} (Run-1+2) data
- All species of B hadrons
- Plan: 300 fb^{-1}

- Busy environment (but smaller than CMS)
- Low trigger efficiency
- Excellent charged ID
- Better with tracks

Very selected results from rare B decays

- New • Test for LFU with $B_s^0 \to \phi \ell^+ \ell^-$ decays [LHCb-PAPER-2024-032, in preparation]
- LFU test with $B_c^+ \to J/\psi \ell^+ \nu$ decays [CMS PAS BPH-23-001]
- New • Constraints on the photon polarisation in $b \to s\gamma$ transitions using $B_s^0 \to \phi e^+ e^-$ decays [LHCb-PAPER-2024-030, in preparation]
- Angular analysis of $B^0 \to K^{*0} e^+ e^-$ decays [LHCb-PAPER-2024-022, submitted to JHEP]
- Analysis of $\Lambda_b^0 \to p K^- \mu^+ \mu^-$ decays [LHCb-PAPER-2024-024, submitted to JHEP]
- Evidence for $B^+ \to K^+ \nu \bar{\nu}$ decays [Phys. Rev. D. 109,112006]
- Search for the decay $B^0 \to \gamma\gamma$ using Belle and Belle II data [Phys. Rev. D 110, L031106]
- Search for $B^0 \to K^* \tau\tau$ decays using Belle II data [In preparation]
- Search for $B^0 \to K_S^0 \tau^\pm \ell^\mp$ decays using Belle + Belle II data [In preparation]
- Search for $B_s^0 \to \phi \mu^\pm \tau^\mp$ decays using LHCb data [Submitted to PRD, 2405.13103]

Other recent results not covered in this talk

- Analysis of local and nonlocal amplitudes in the $B^0 \to K^{*0} \mu^+ \mu^-$ [Submitted to JHEP, arXiv:2405.17347] [see talk by Zahra]
- Amplitude analysis of the radiative decay $B_s^0 \to K^+ K^- \gamma$ [JHEP08(2024)093]
- Search for $B_{(s)}^{*0} \to \mu^+ \mu^-$ decays using LHCb data [Submitted to EPJC, 2409.17209]
- Test of lepton flavour universality with $B^+ \to K^+ \pi^+ \pi^- \ell^+ \ell^-$decays [LHCb-PAPER-2024-046, in preparation]

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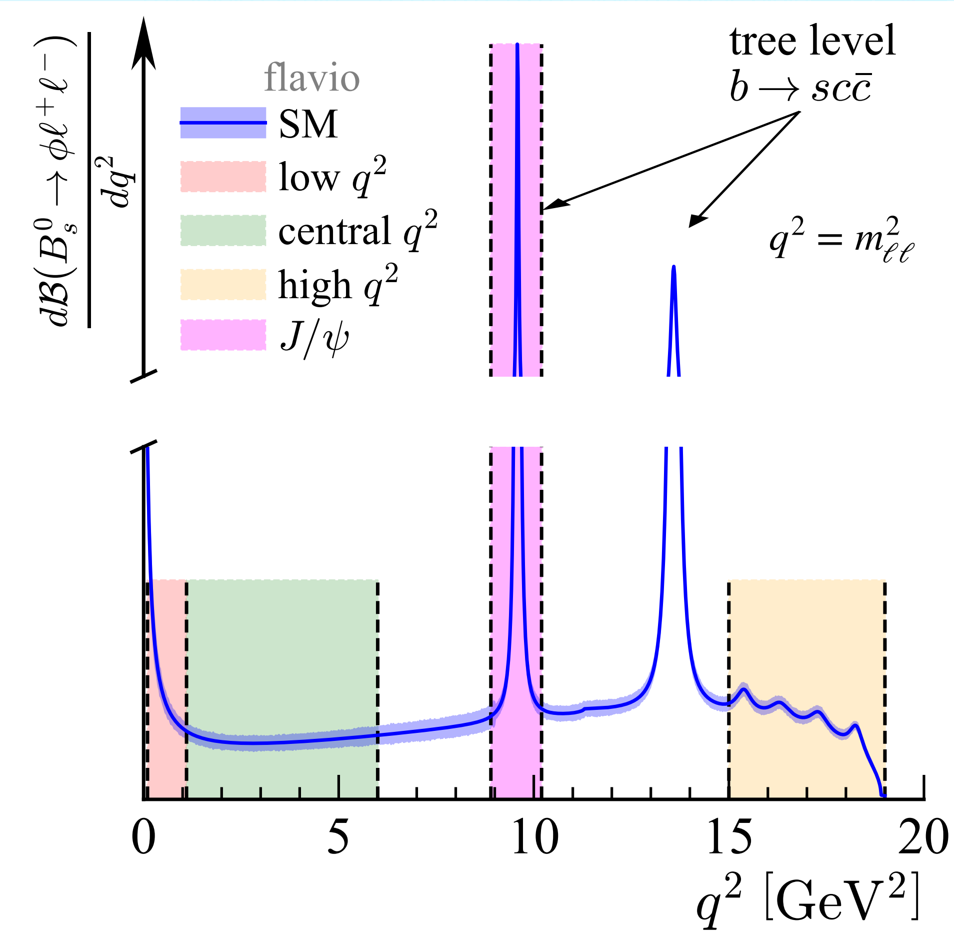
LFU test with $B_s^0 \to \phi\ell^+\ell^-$ decays

LHCb-PAPER-2024-032
arXiv: 2410.13748
Submitted to PRL

New



- FCNC $b \to s$ transition
- **First LFU test with $B_s^0 \to \phi\ell^+\ell^-$ decays at LHCb using Run 1+2 (9 fb^{-1}) data**
- Measure

$$\mathcal{R}_\phi^{-1} = \frac{\mathcal{B}(B_s^0 \to \phi e^+e^-)}{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)} \Big/ \frac{\mathcal{B}(B_s^0 \to J/\psi(e^+e^-)\phi)}{\mathcal{B}(B_s^0 \to J/\psi(\mu^+\mu^-)\phi)}$$

- Most efficiency-related **systematic** uncertainties cancel in double ratio
- Experimentally

$$\mathcal{R}_\phi^{-1} = \boxed{\frac{N(\phi e^+e^-)}{N(J/\psi(e^+e^-)\phi)} \cdot \frac{N(J/\psi(\mu^+\mu^-)\phi)}{N(\phi\mu^+\mu^-)}} \cdot \boxed{\frac{\epsilon(J/\psi(e^+e^-)\phi)}{\epsilon(\phi e^+e^-)} \cdot \frac{\epsilon(\phi\mu^+\mu^-)}{\epsilon(J/\psi(\mu^+\mu^-)\phi)}}$$

Extended maximum likelihood fit — Simulated samples

- Narrow ϕ resonances from K^+K^- and displaced secondary vertex
- Combinatorial and semi-leptonic backgrounds are suppressed by multivariate classifier

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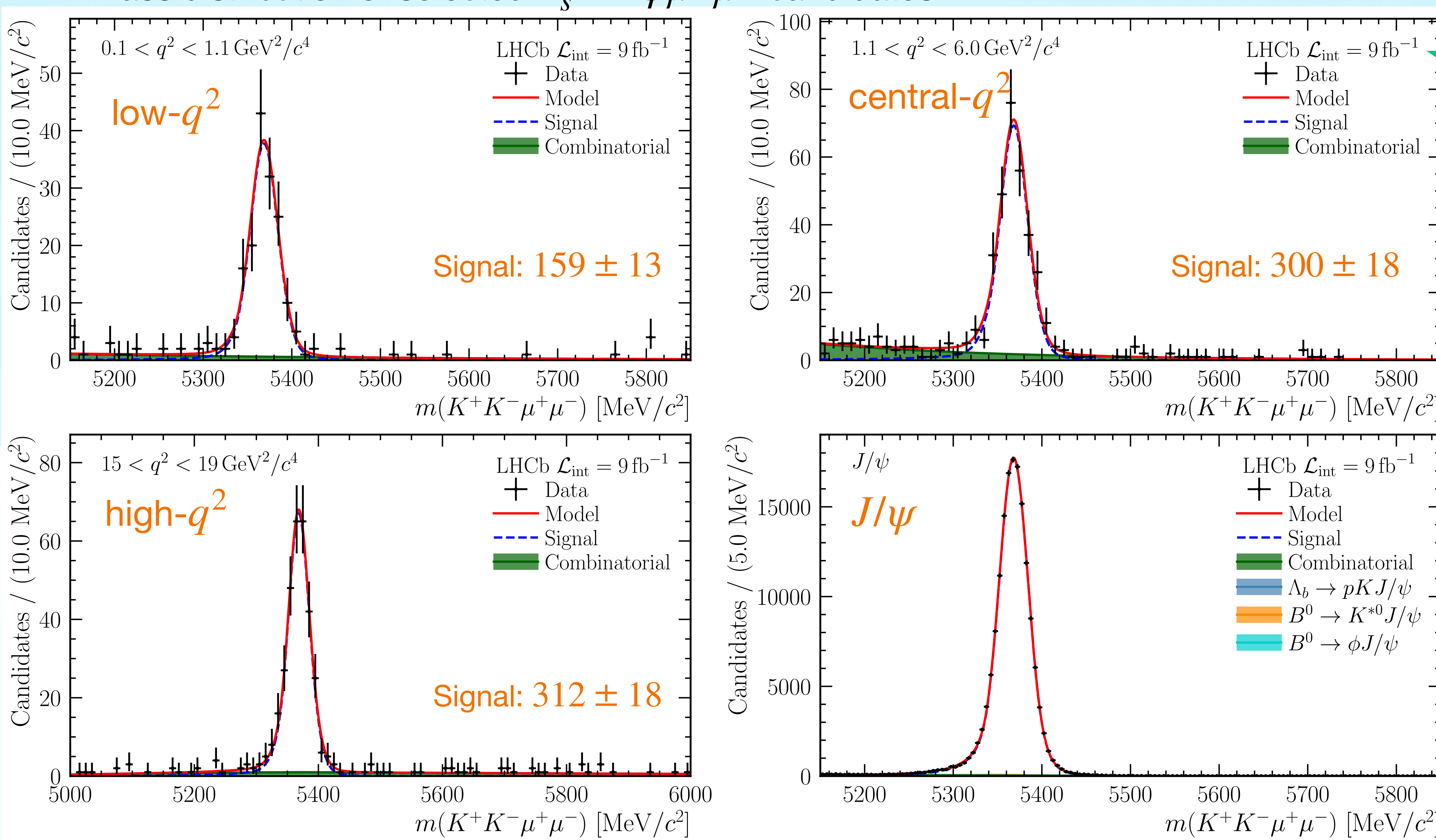
LFU test with $B_s^0 \to \phi\ell^+\ell^-$ decays

LHCb-PAPER-2024-032
arXiv: 2410.13748
Submitted to PRL

New

Mass distribution of selected $B_s^0 \to \phi\mu^+\mu^-$ candidates



Signal, combinatorial and mis ID backgrounds morphed by phase space for high-q^2

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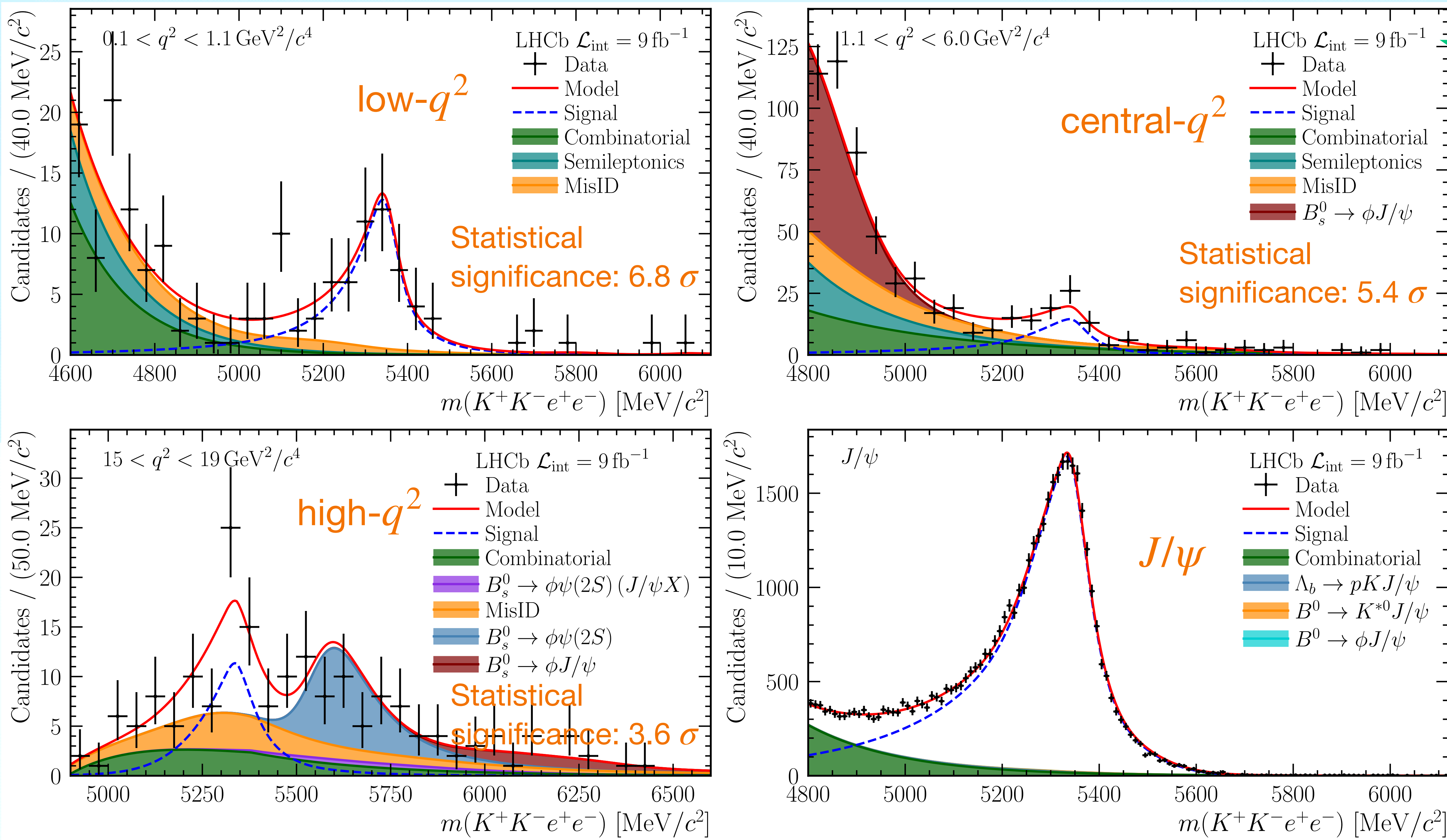
LFU test with $B_s^0 \to \phi \ell^+ \ell^-$ decays

LHCb-PAPER-2024-032
arXiv: 2410.13748
Submitted to PRL

Mass distribution of selected $B_s^0 \to \phi e^+ e^-$ candidates



- Signal, combinatorial and mis ID backgrounds morphed by phase space for high-q^2
- Different from $B_s^0 \to \phi \mu^+ \mu^-$ modes, due to bremsstrahlung from $e^\pm$ and imperfect nature of the brem. recovery.

LFU test with $B_s^0 \to \phi \ell^+ \ell^-$ decays

LHCb-PAPER-2024-032
arXiv: 2410.13748
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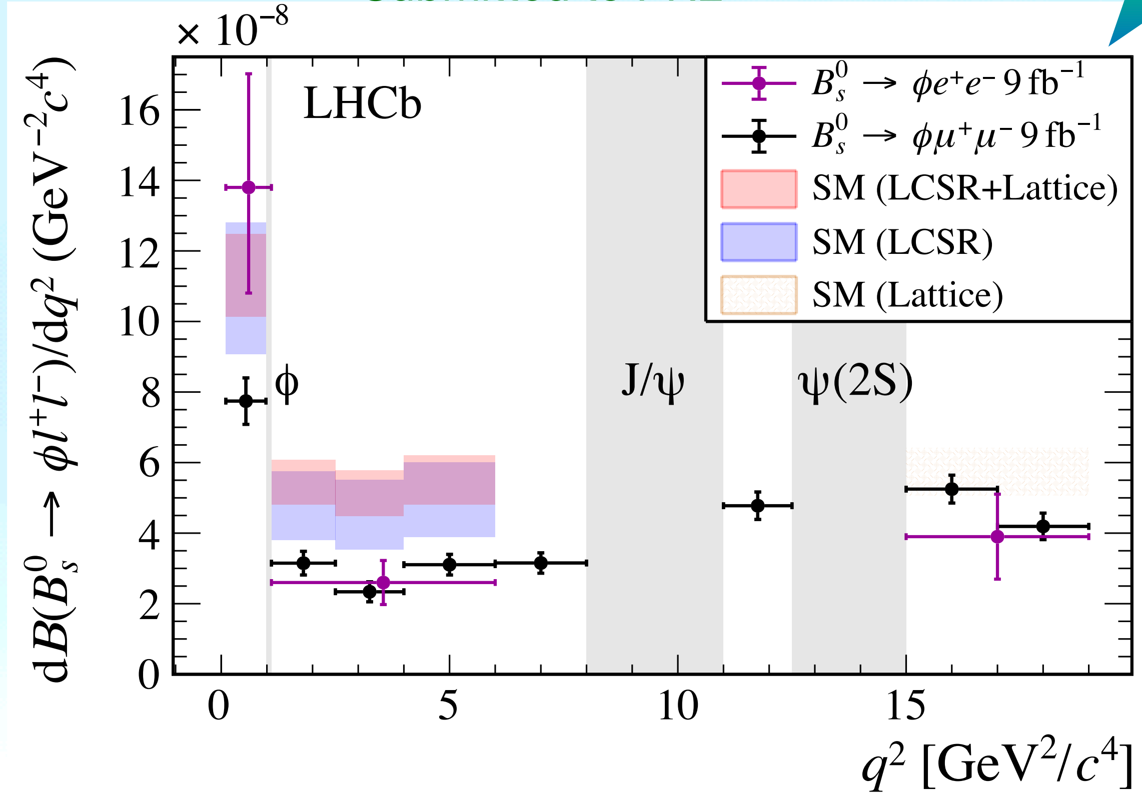
New



- $\mathcal{B}(B_s^0 \to \phi e^+ e^-)$ agrees with the SM and the measured $\mathcal{B}(B_s^0 \to \phi \mu^+ \mu^-)$
- Upward fluctuation in the low-q^2
- Similar deviation in central-q^2 for both modes

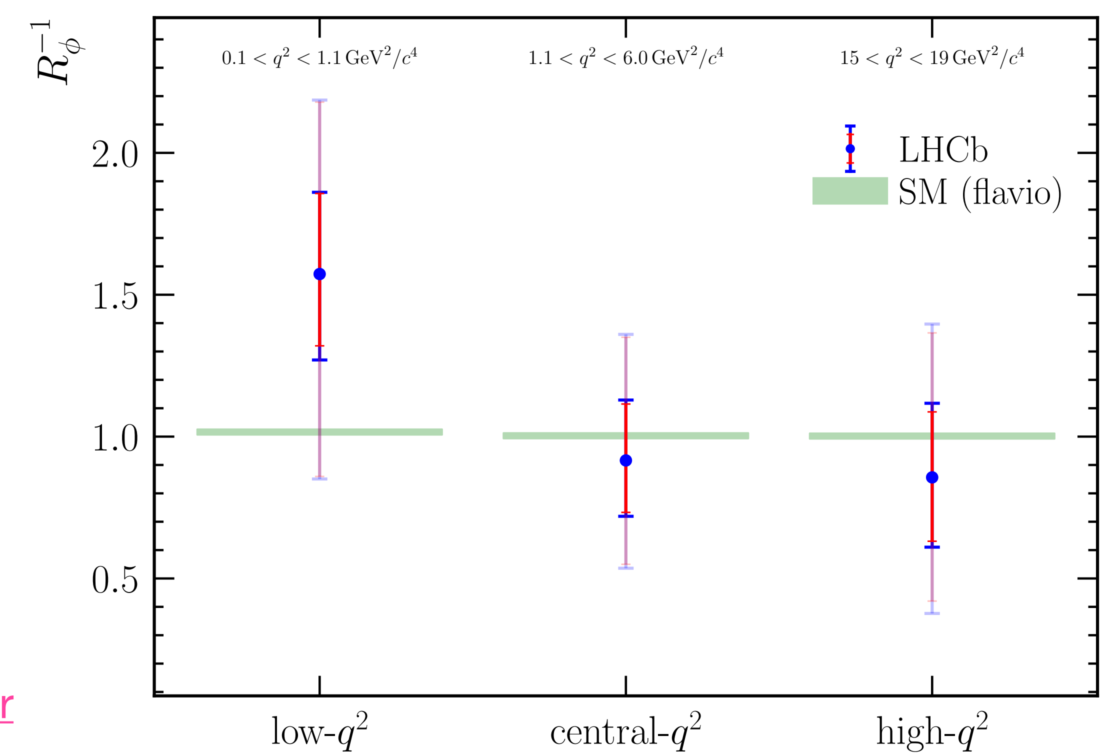
- Crosschecks

$$r_{J/\psi} = \frac{\mathcal{B}(B_s^0 \to J/\psi(\mu^+\mu^-)\phi)}{\mathcal{B}(B_s^0 \to J/\psi(e^+e^-)\phi)} = 0.997 \pm 0.013$$

- And

$$R_\psi = \frac{\mathcal{B}(B_s^0 \to \psi(2S)(\mu^+\mu^-)\phi)}{\mathcal{B}(B_s^0 \to \psi(2S)(e^+e^-)\phi)} \times r_{J/\psi}^{-1} = 1.010 \pm 0.026$$

- Consistent with SM predictions in all q^2 bins
- First and most precise LFU test in high-q^2 for LHCb



CERN seminar

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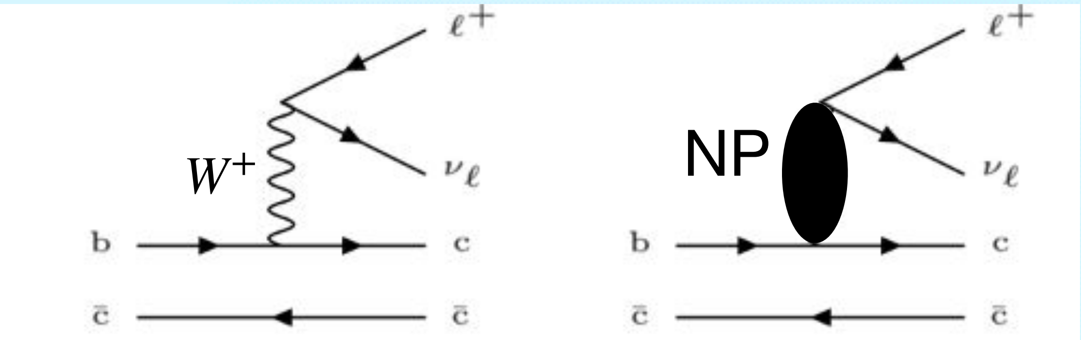
LFU test with $B_c^+ \to J/\psi \ell^+ \nu$ decays

- $b \to c$ transition at tree level

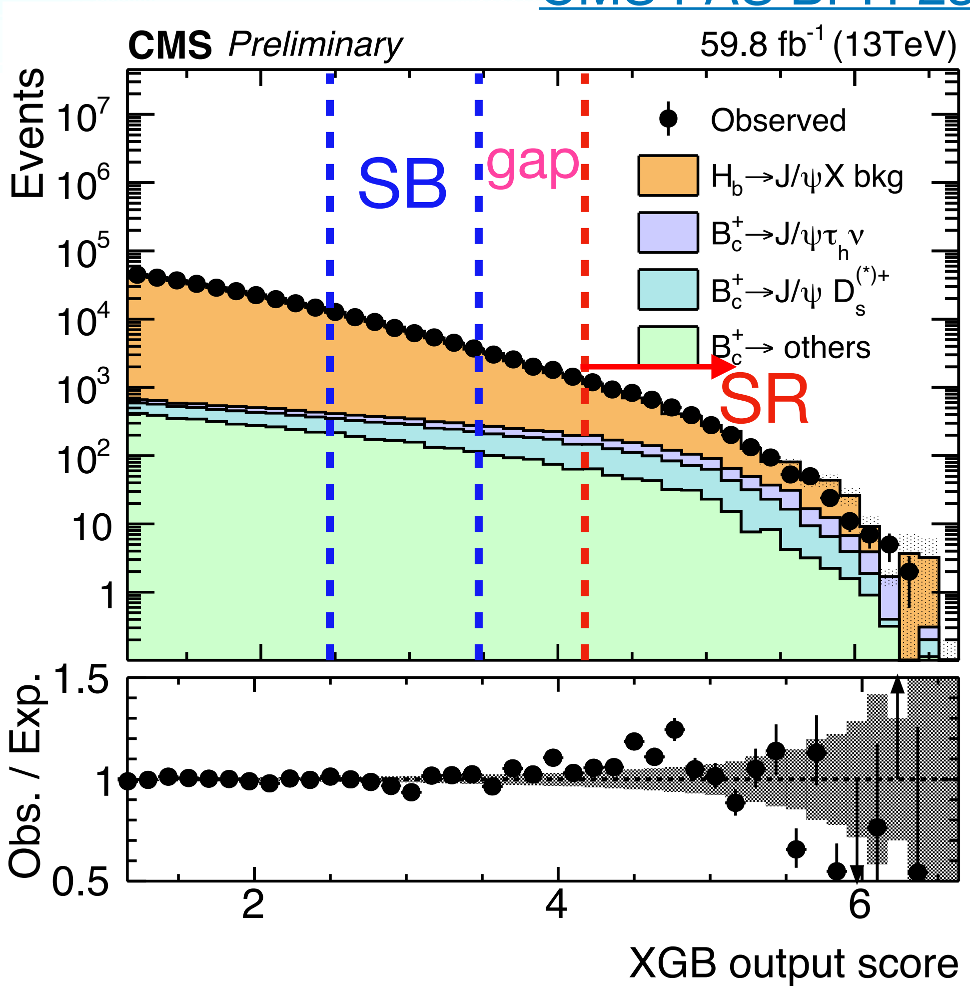
$$R_{J/\psi} = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$$



- 3-prong decay modes, $\tau \to \pi^+\pi^-\pi^+(+\pi^0)\bar{\nu}_\tau$
- SM prediction $R_{J/\psi} = 0.2582 \pm 0.0038$ [PRL 125 222003]
- Previously measured by LHCb using 3 fb^{-1}[PRL 120(2018)121801] and CMS [2408.00678] using muonic modes
- CMS Run 2 data 138 fb^{-1}

- BDT was trained to maximize the background rejection
- Sideband background-enriched region (SB) used to predict the background events in signal region (SR)
- Background prediction is validated in "gap" region
- Ratio between the data and the expected sum of signal and background contributions are consistent

CMS PAS BPH-23-001



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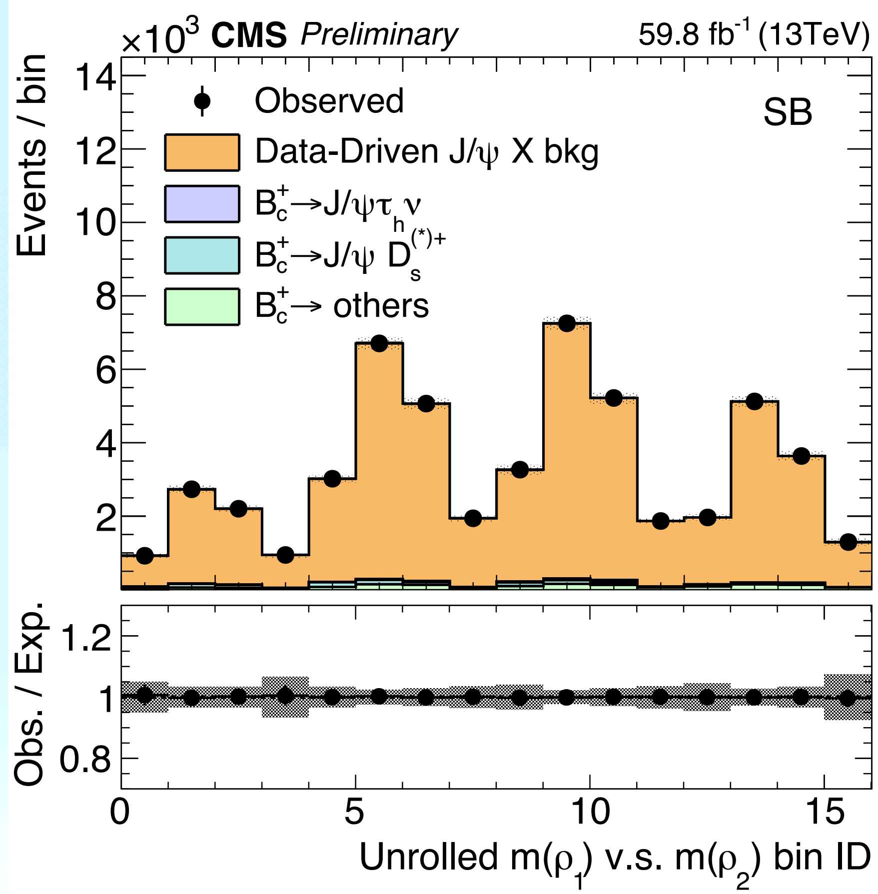
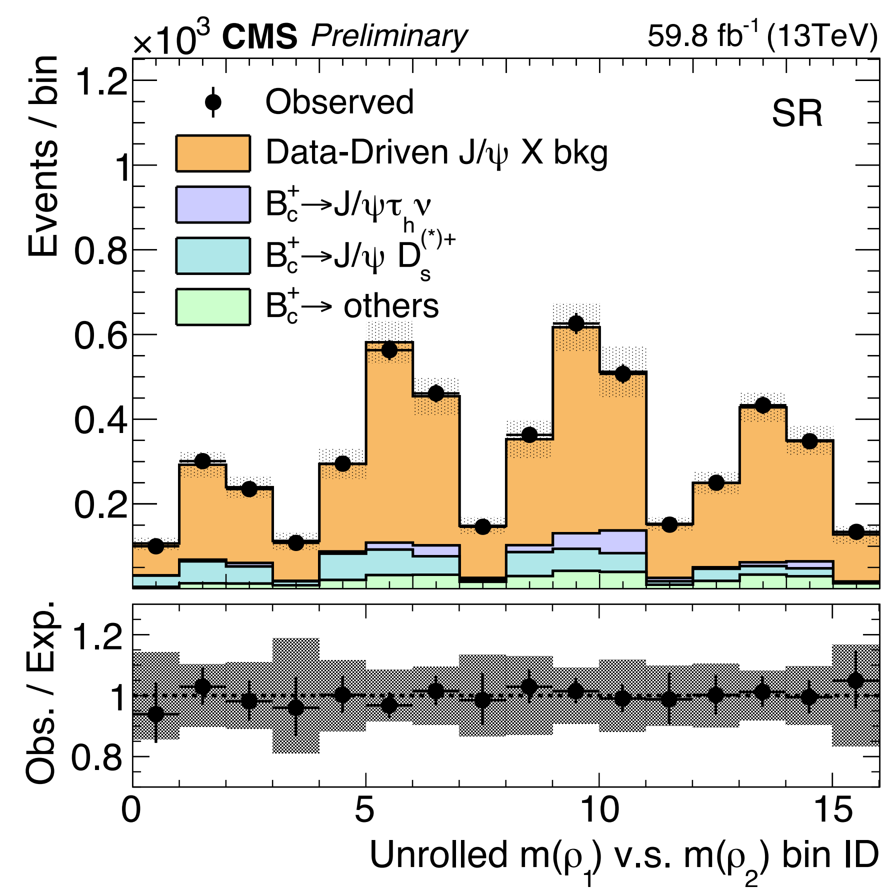
LFU test with $B_c^+ \to J/\psi \ell^+ \nu$ decays

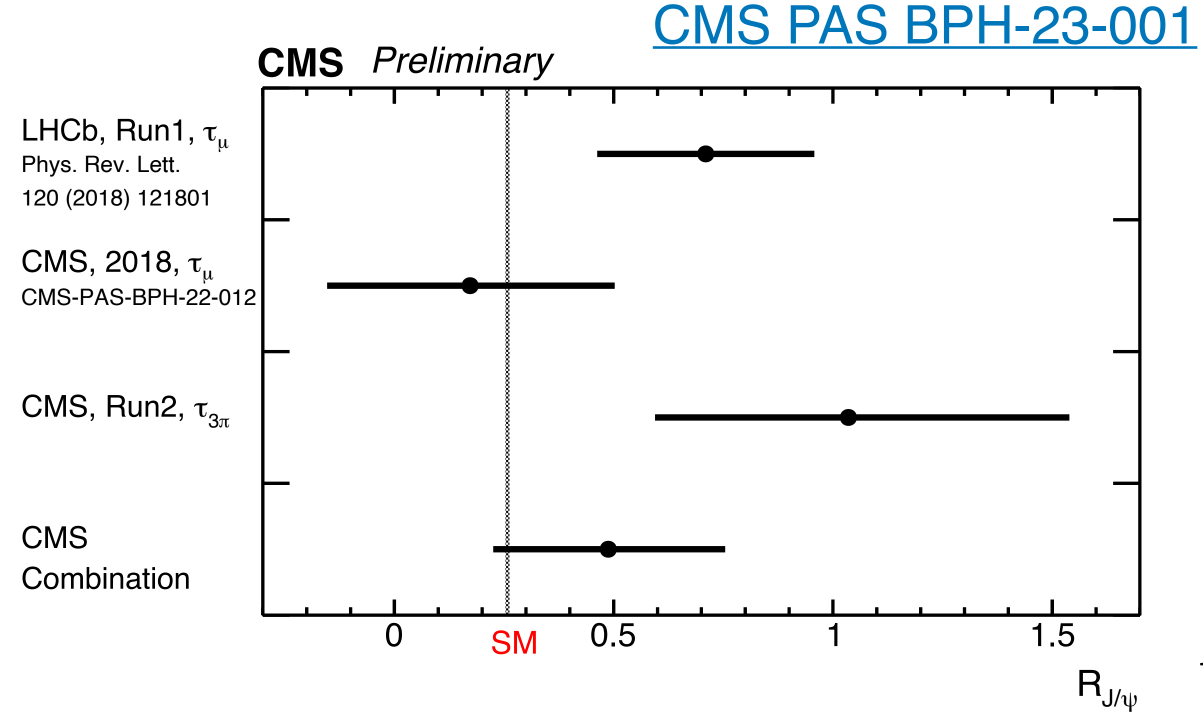
- $\rho_1 = (\pi_1^+, \pi_2^-)$, $\rho_2 = (\pi_3^+, \pi_2^-)$
- Simultaneous fit of SB and SR to extract $R_{J/\psi}$
- Data/expected background are in agreement for all bins





[CMS PAS BPH-23-001]

- Using Run-2 data measured $R_{J/\psi} = 1.04^{+0.50}_{-0.44}$
- Combined with leptonic decay of tau lepton results $R_{J/\psi} = 0.49 \pm 0.25$ (stat) ± 0.09 (syst)
- Consistent with SM prediction



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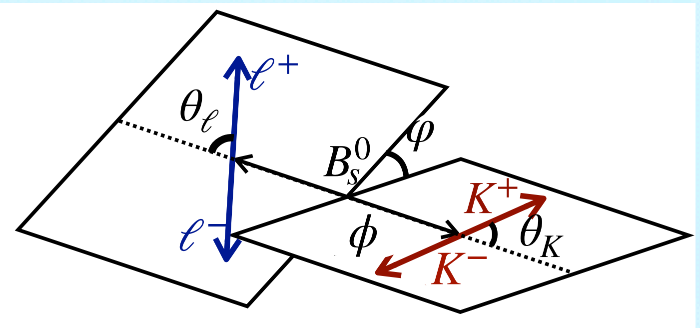
Angular analysis of $B_s^0 \to \phi e^+ e^-$ decays

LHCb-PAPER-2024-030
In preparation

New

- First angular analysis at LHCb: low q^2 region [0.0009, 0.2615] GeV^2/c^4
- Full Run 1+ 2 LHCb statistics (9 fb^{-1})
- Decay rate is described as follows



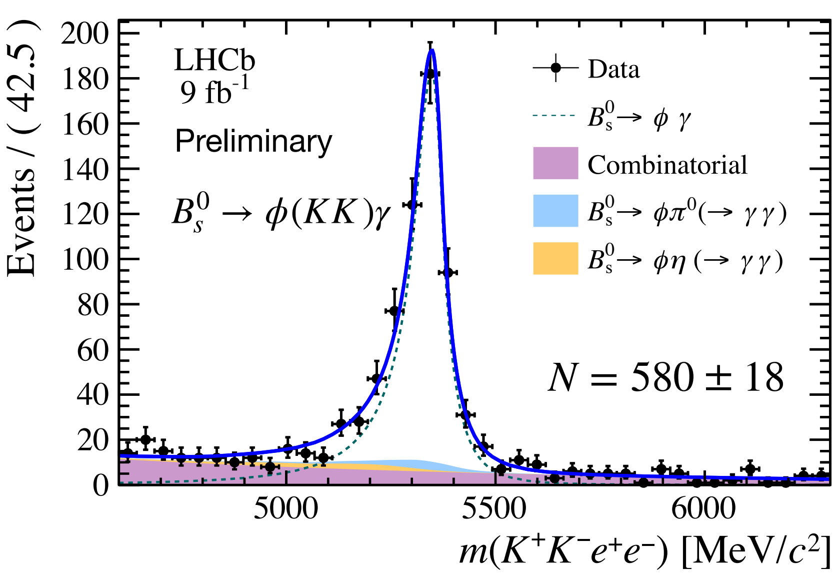
$$\frac{1}{\mathrm{d}(\Gamma+\bar\Gamma)/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar\Gamma)}{\mathrm{d}\cos\theta_L \mathrm{d}\cos\theta_K \mathrm{d}\tilde\varphi} = \frac{9}{32\pi}\left\{\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K \right.$$
$$+\left[\frac{1}{4}(1-F_L)\sin^2\theta_K - F_L\cos^2\theta_K\right]\cos 2\theta_L$$
$$+\frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_L\cos 2\tilde\varphi$$
$$+(1-F_L)A_T^{\mathcal{R}eCP}\sin^2\theta_K\cos\theta_L$$
$$\left.+\frac{1}{2}(1-F_L)A_T^{\mathcal{I}mCP}\sin^2\theta_K\sin^2\theta_L\sin 2\tilde\varphi\right\}.$$

F_L : Longitudinal polarisation of ϕ meson
A_T^{ReCP}: related to the forward-backward asymmetry
$A_T^{(2)}$ and A_T^{ImCP} are sensitive to photon polarisation

$$A_T^{(2)}(q^2\to 0) = \frac{2Re(C_7 C_7^{\prime *})}{|C_7|^2+|C_7^\prime|^2} + \Delta_1^2,$$
$$A_T^{ImCP}(q^2\to 0) = \frac{2Im(C_7 C_7^{\prime *})}{|C_7|^2+|C_7^\prime|^2} + \Delta_2^2,$$

Δ_i due to Δm_s and $\Delta\Gamma_s$

- Background mostly dominated with combinatorial, suppressed by BDT
- The radiative $B_s^0 \to \phi(KK)\gamma$ decay with converted photon used as control channel with m_{ee}< 10 MeV/c²



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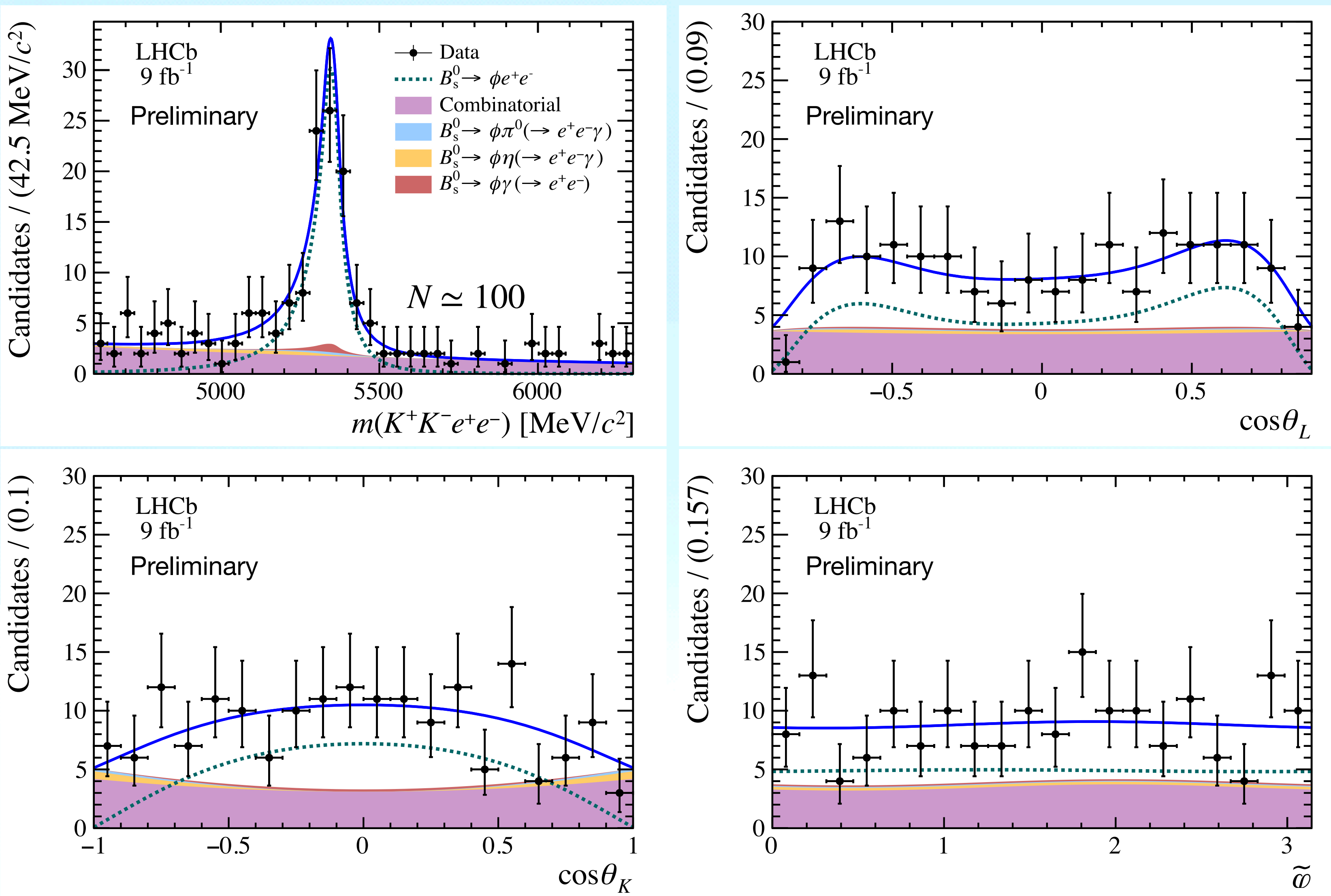
Angular analysis of $B_s^0 \to \phi e^+ e^-$ decays

LHCb-PAPER-2024-030
In preparation

New

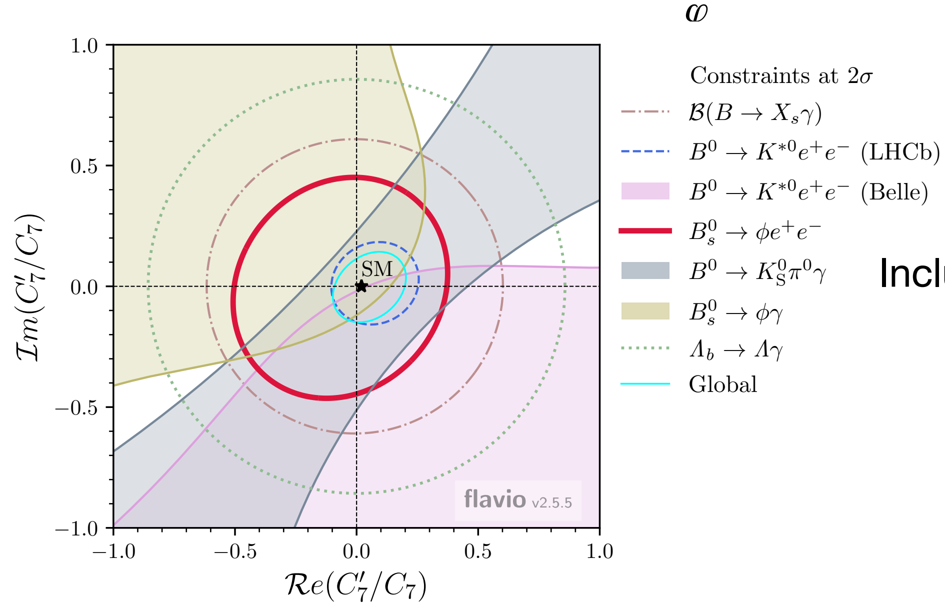
4D unbinned maximum likelihood fit to mass and angular variables



$$A_{\rm T}^{(2)} = -0.045 \pm 0.235 \pm 0.014\,,$$
$$A_{\rm T}^{\mathcal{I}mCP} = 0.002 \pm 0.247 \pm 0.016\,,$$
$$A_{\rm T}^{\mathcal{R}eCP} = 0.116 \pm 0.155 \pm 0.006\,,$$
$$F_{\rm L} < 11.5\% \text{ at } 90\% \text{ CL}$$

SM predictions	
F_L	0.068
$A_T^{(2)}$	0.094
A_T^{ImCP}	0.000
A_T^{ReCP}	0.000

Results are consistent with the SM predictions



10 < M(ee) <500 MeV

M(ee) < 1058 MeV, [arXiV: 2404.00201]

Including the Belle II result, [arXiV: 2407.09139]

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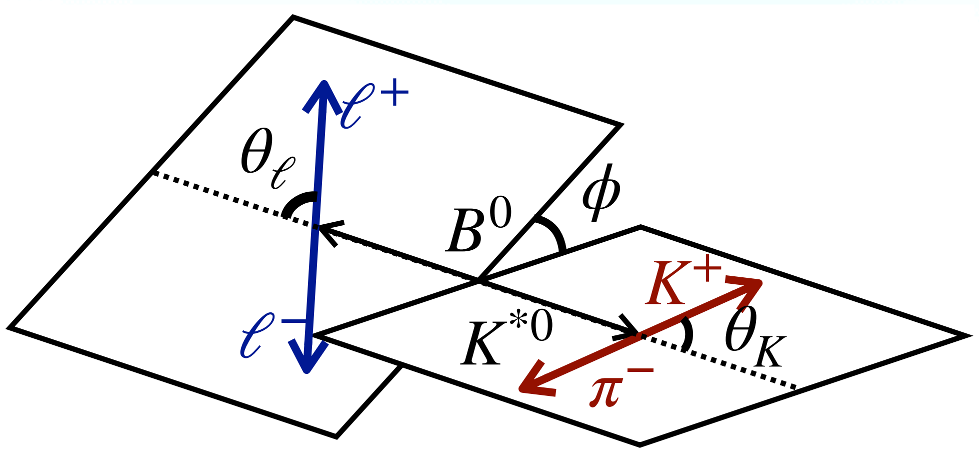
Angular analysis of $B^0 \to K^{*0}e^+e^-$ decays

LHCb-PAPER-2024-022
In preparation

- First angular analysis at LHCb: central q^2 region [1.1, 6.0] GeV$^2/c^4$
- Full Run 1+ 2 LHCb statistics (9 fb^{-1})
- Differential decay rate is described by $q^2(=m_{ee}^2)$ and angular variables $(\theta_l, \theta_K, \phi)$

$$\frac{d^4\Gamma[B^0 \to K^{*0}e^+e^-]}{dq^2 dcos\theta_K dcos\theta_l d\phi} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\theta_K, \theta_l, \phi)$$



angular observables

- F_L — Fraction of longitudinal polarization of K^{*0}
- S_i — CP-averaged
- A_{FB} — Forward-backward asymmetry of the dielectric system

F_L, A_{FB}, and S_i are sensitive to Wilson coefficient ($C_{7,9,10}^{(')}$) and form factors

Perform ratio of observables $(e.g.P_5')$ where form factors cancels

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

JHEP, 05 (2013) 137

See talk by Alice Biolchini

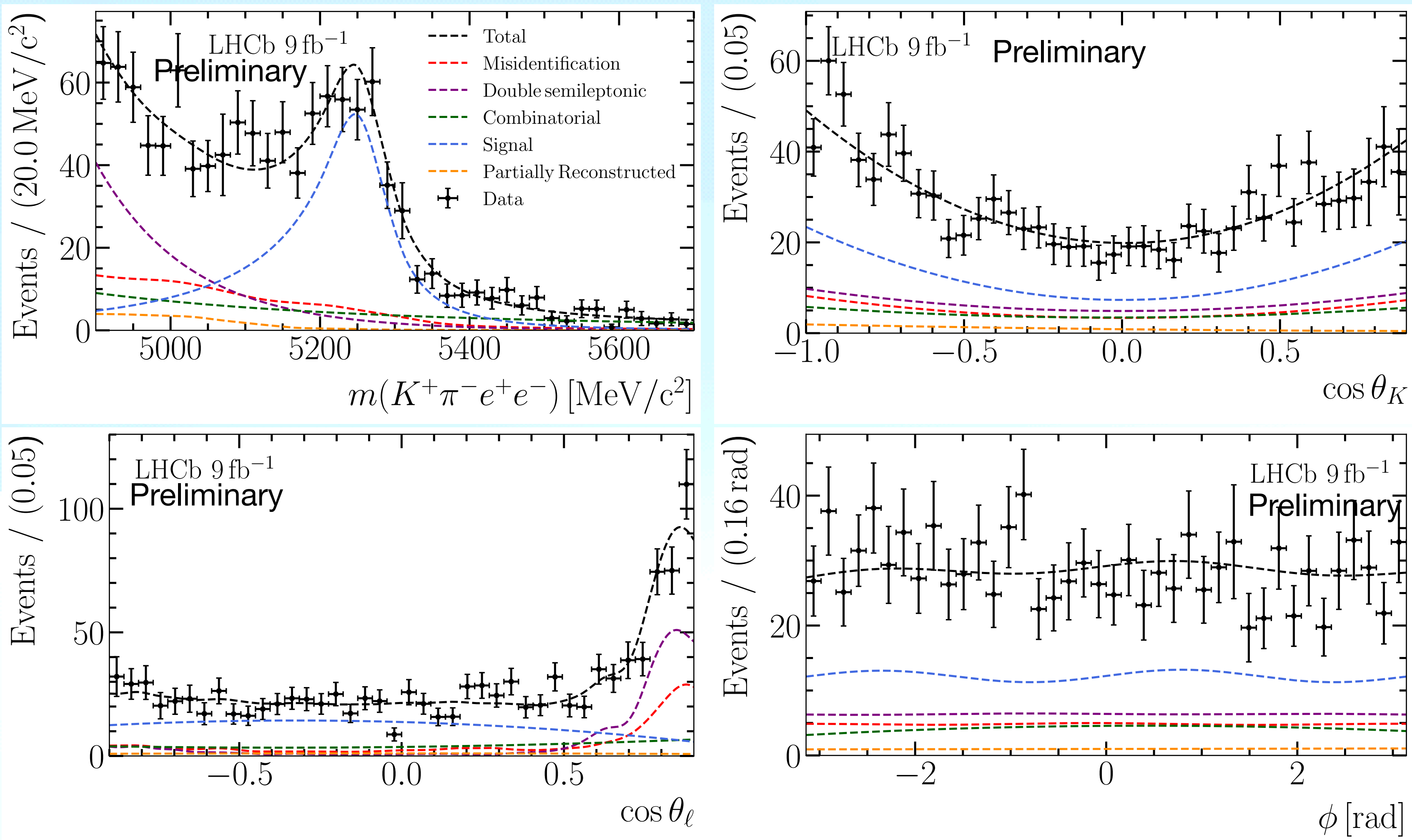
Angular analysis of $B^0 \to K^{*0}e^+e^-$ decays

Detailed talk by Alice Biolchini

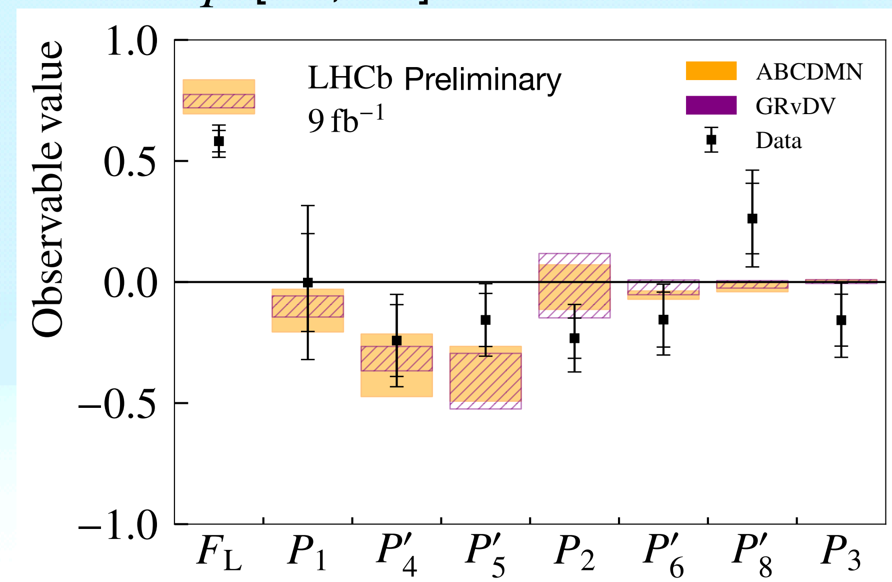
LHCb-PAPER-2024-022

In preparation

4D unbinned weighted fit to the mass and angular distributions

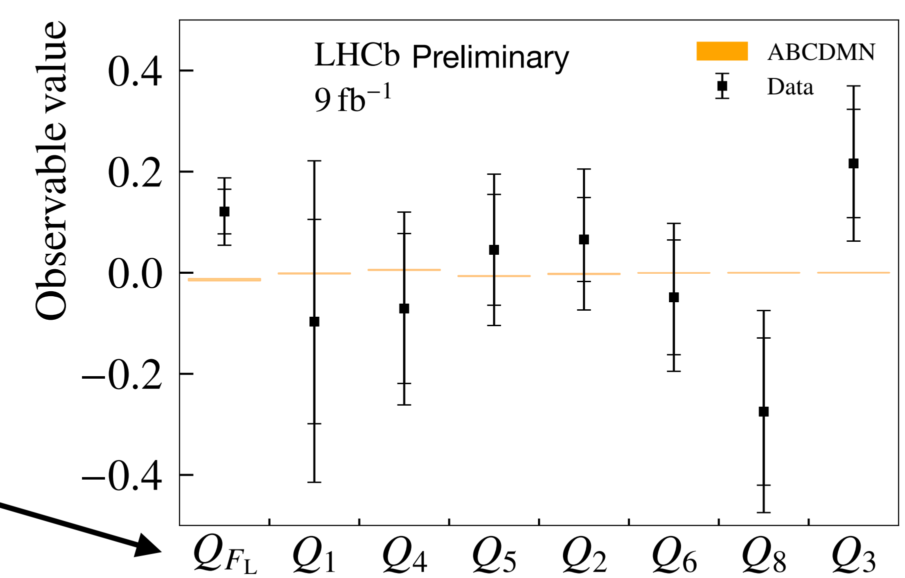


Angular observables measured in q^2 [1.1, 6.0] GeV$^2/c^4$



Overall good agreement with SM predictions

Lepton Flavour Universality observables are derived using $Q_i = P_i^{(\mu)} - P_i^{(e)}$



Results are consistent with the LFU hypothesis

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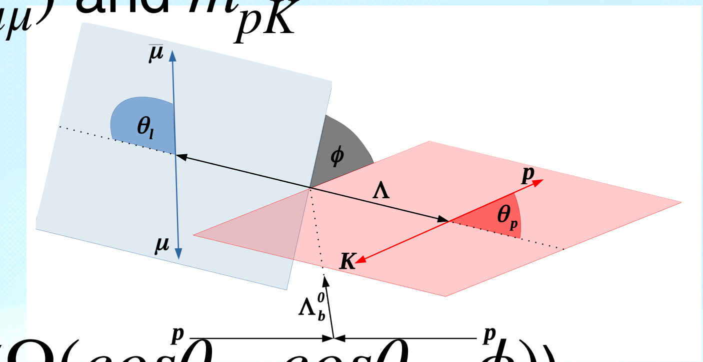
Analysis of $\Lambda_b^0 \to pK^-\mu^+\mu^-$ decays

LHCb-PAPER-2024-024
arXiv: 2409.12629
Submitted to JHEP

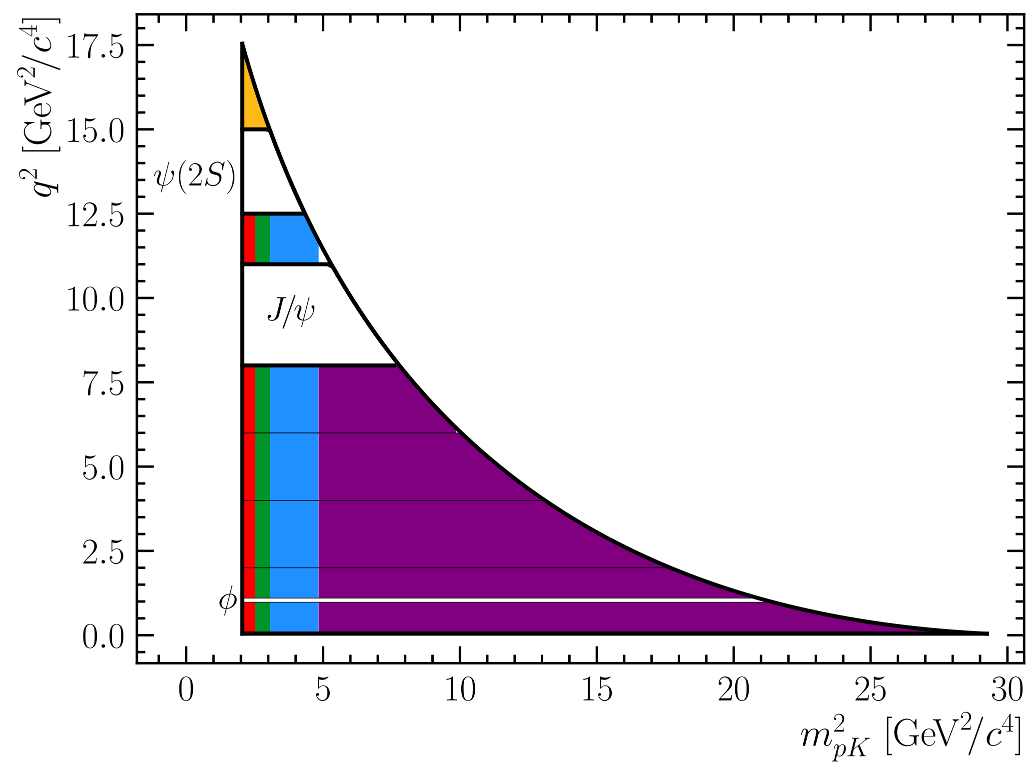
- FCNC $b \to sll$ transition
- The decay was previously observed in LHCb using 3 fb^{-1} data JHEP 06 (2017) 108
- Measure branching fraction and angular moments in bins of $q^2(=m^2_{\mu\mu})$ and m^2_{pK}
  - BF measured relative to that of the $\Lambda_b^0 \to J/\psi pK^-$ decay



- Full Run 1+ 2 LHCb statistics (9 fb^{-1})
- Differential decay rate is described by q^2, m^2_{pK} and angular variables ($\Omega(cos\theta_\mu,\ cos\theta_p,\ \phi)$)

$$\frac{d^4\Gamma}{d\Phi} = \frac{3}{8\pi}\sum_{i=1}^{46} K_i(q^2, m^2_{pK}) f_i(cos\theta_\mu, cos\theta_p, \phi)$$

JHEP02(2023)189



- Using sPlot weighted data and applying efficiency corrections gives pure weighted signal events $\omega(\Phi)$ in the 3D angular distribution
- Moments determined from weighted sum over basis functions

$$N = \sum_{\text{event } n} w(\vec{\Phi}_n) \qquad \overline{K}_i = \frac{1}{N}\sum_{\text{event } n} w(\vec{\Phi}_n) f_i(\vec{\Omega}_n)$$

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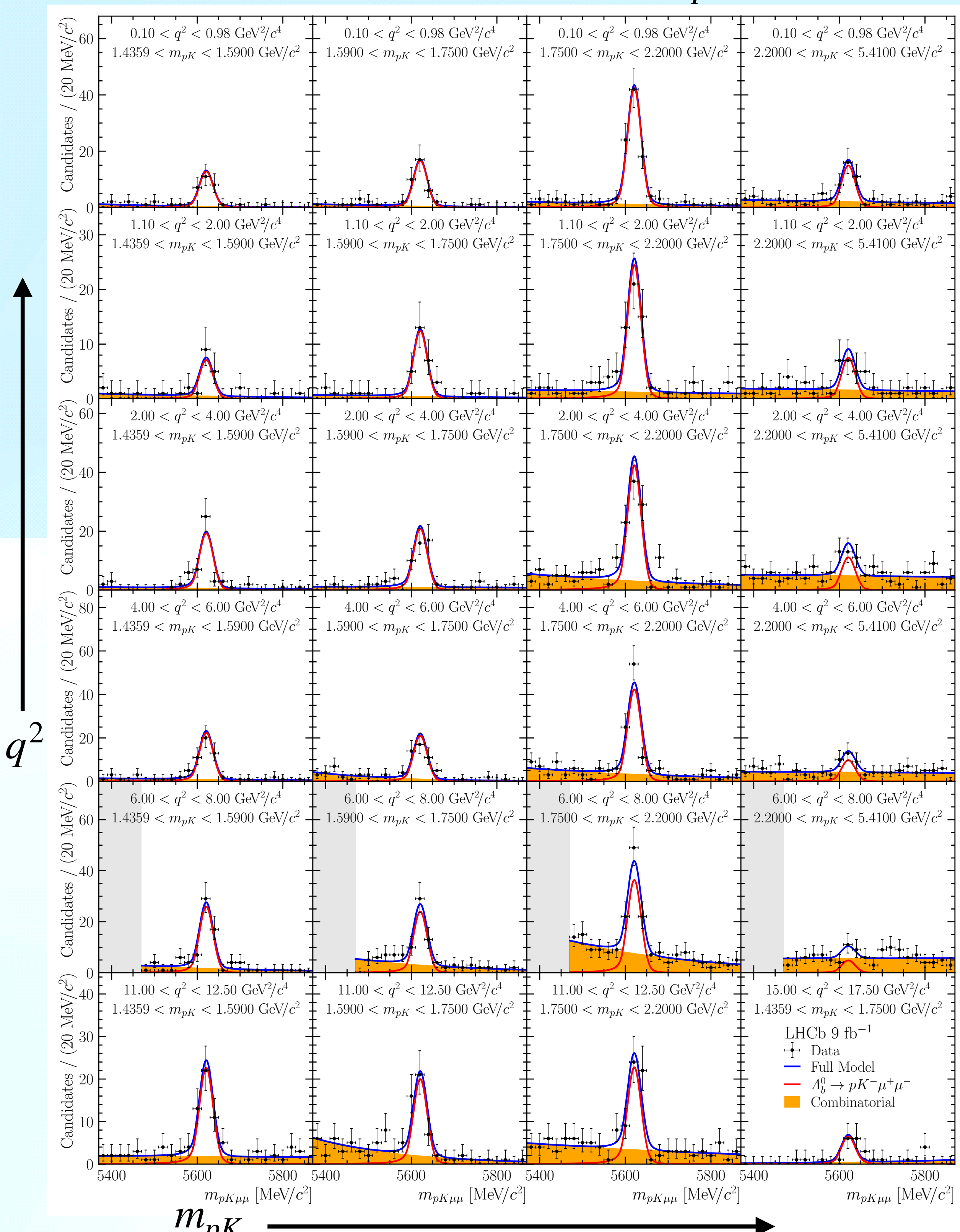
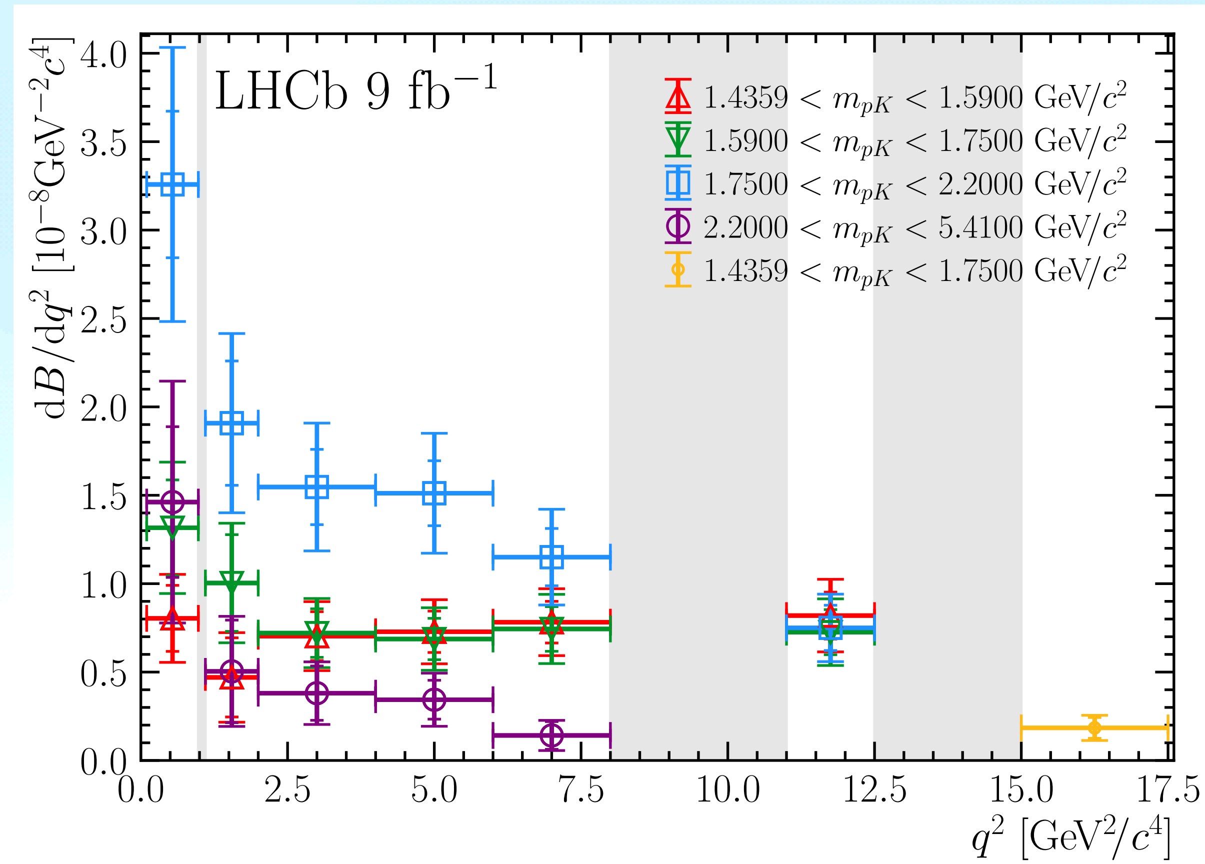
Analysis of $\Lambda_b^0 \to pK^-\mu^+\mu^-$ decays

LHCb-PAPER-2024-024
arXiv: 2409.12629
Submitted to JHEP

Mass distributions in bins of m_{pK} and q^2



Differential branching fraction as a function of q^2



- Results in first m_{pK} bin are compatible with the results of $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ [arXiv: 2302.08262]
- Precision limited by the knowledge of $\Lambda_b^0 \to J/\psi pK^-$ BF
- Variation do not match with the predictions from Quark model [arXiv:1108.6129]

Analysis of $\Lambda_b^0 \to pK^-\mu^+\mu^-$ decays

LHCb-PAPER-2024-024
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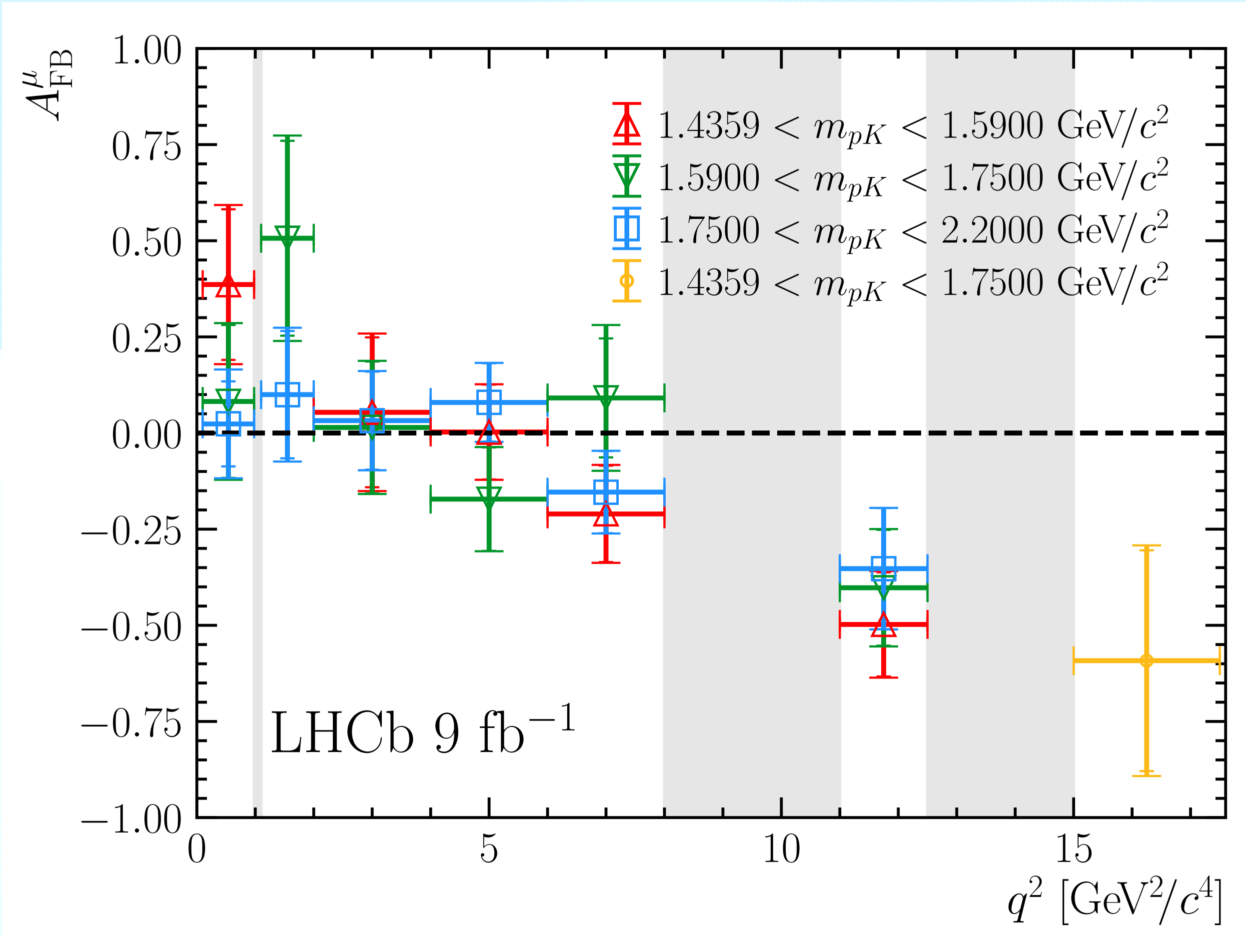
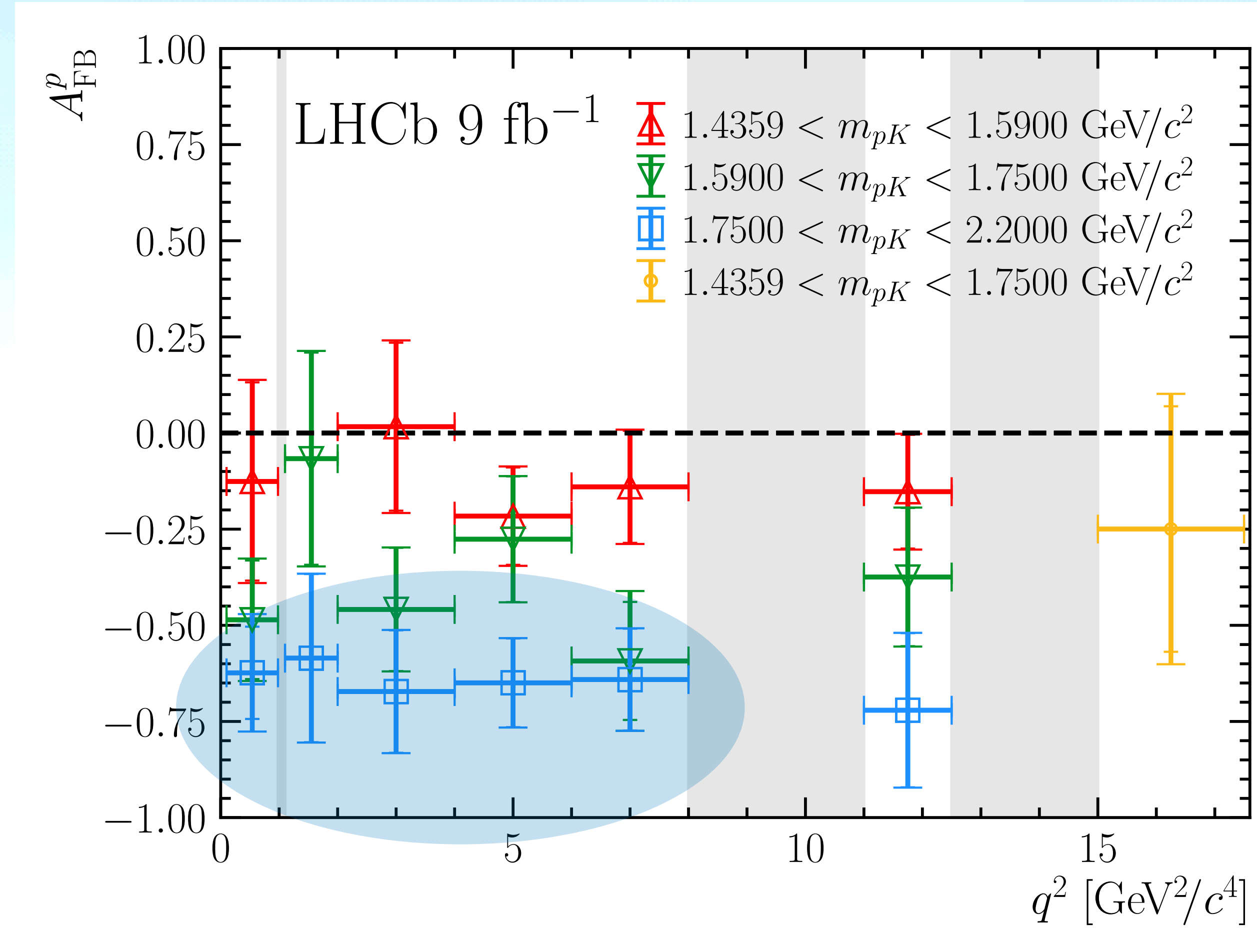
Forward-backward asymmetry of the leptons, which are sensitive to Wilson coefficient C_9 and C_{10}

$$A^{\mu}_{FB} = \frac{3}{2}\bar{K}_2$$

Forward-backward asymmetry of the hadron

$$A^{p}_{FB} = \frac{3}{2}\bar{K}_4 - \frac{\sqrt{21}}{8}\bar{K}_{10} + \frac{\sqrt{33}}{16}\bar{K}_{16}$$





Same patterns as observed in $B^0 \to K^{*0}\mu\mu$ decays but sign-flipped between low and high q^2

Large asymmetry is the effect of interference of resonances with different parity

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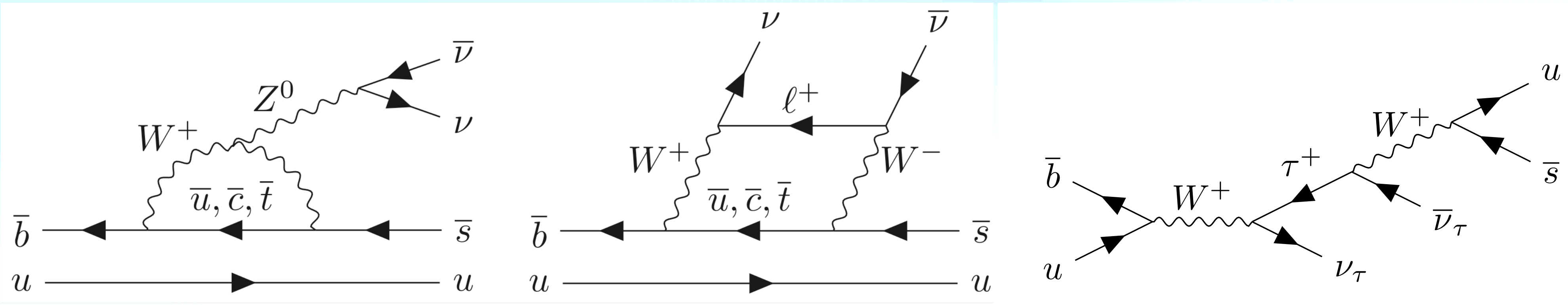
Evidence of $B \to K\nu\bar{\nu}$ decays

PRD 109 112006 2024

- FCNC $b \to s$ transition
  - very precise SM prediction $\mathscr{B} = (5.58 \pm 0.37) \times 10^{-6}$
    - Dominated by form factor uncertainties
- NP scenario:
  - Light: axions [PRD 102, 015023 (2020)], dark scalars [PRD 101, 095006 (2020)],
  - Heavy: Leptoquark [PRD 98, 055003 (2018)], Z' [PLB 821 (2021) 136607]



- Experimentally challenging
  - Large backgrounds+one prompt track
  - Missing energy from undetected neutrinos
- Experimentally status
  - Suitable for experiments at e^+e^- collider

Exp	U.L. (90% CL)	Tag Method	Stat (fb^{-1})
BaBar	1.6 x 10^{-5}	SL+HAD	429
Belle	5.5 x 10^{-5}	HAD	711
Belle	1.9 x 10^{-5}	SL	711

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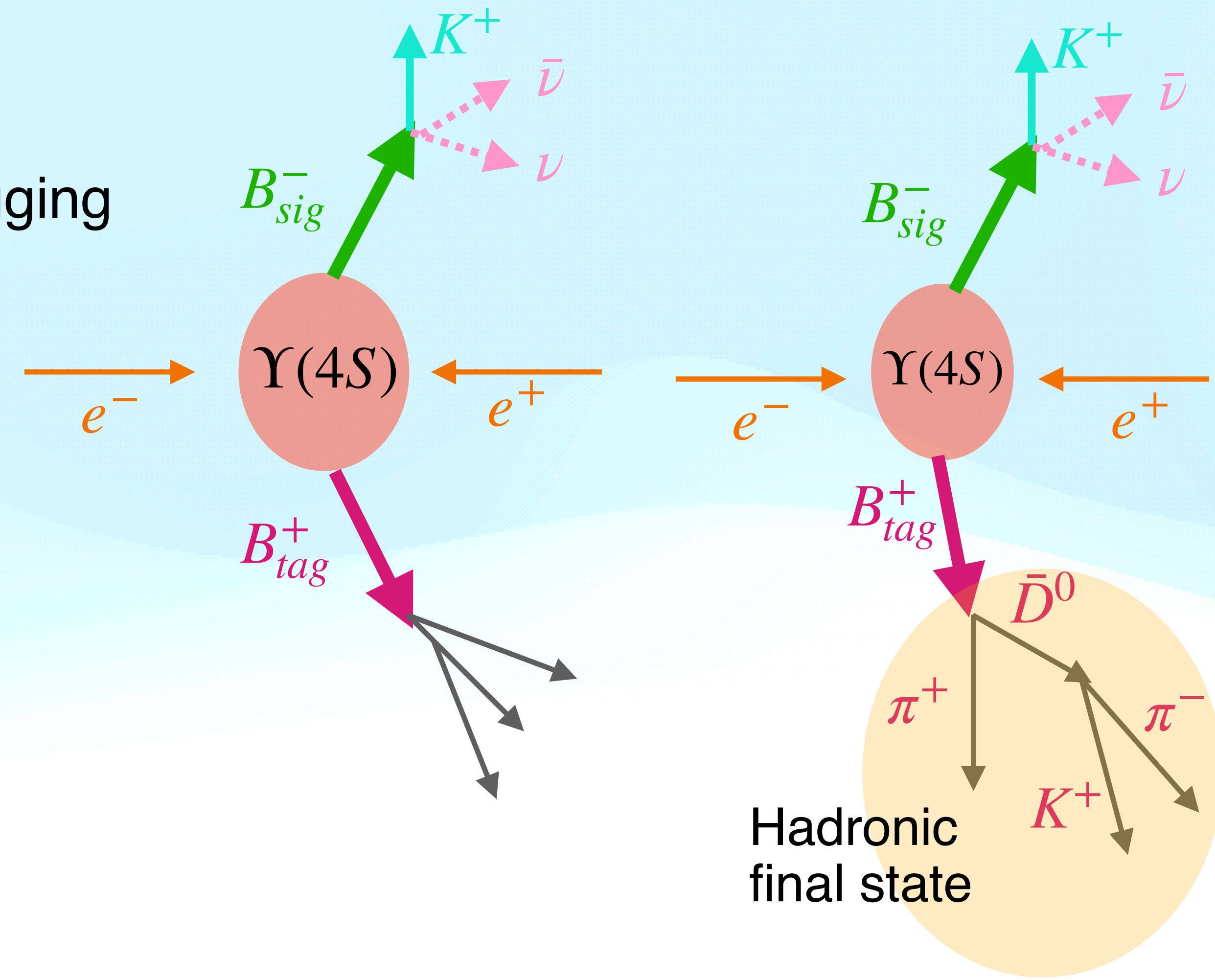
Evidence of $B \to K\nu\bar{\nu}$ decays

PRD 109 112006 2024

- Use Run 1 Belle II (362 fb^{-1}) data
- Use inclusive tagging in addition to hadronic tagging
  - Inclusive tagging: Reconstruct signal kaon, Identify rest-of-event object (ROE)
    - Nested BDT to suppress background
      - Efficiency = 8%, purity = 0.9%
  - Hadronic tagging: Reconstruct hadronic tag, Reconstruct signal kaon
    - One BDT to suppress background
      - Efficiency = 0.4%, purity = 3.5%



- Validations:
  - Signal efficiency validation with $B^+ \to J/\psi K^+$sample, remove J/ψ and correct K^+ kinematics to match $K^+\nu\bar{\nu}$
  - Continuum validated with off-resonance
  - $B \to X_c(\to K_L^0)$ validated from pion enriched sideband
  - Modelling the signal-like $B^+ \to K^+K_L^0K_L^0$ decays checked with $B^+ \to K^+K_S^0K_S^0$ decays

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Evidence of $B \to K\nu\bar{\nu}$ decays

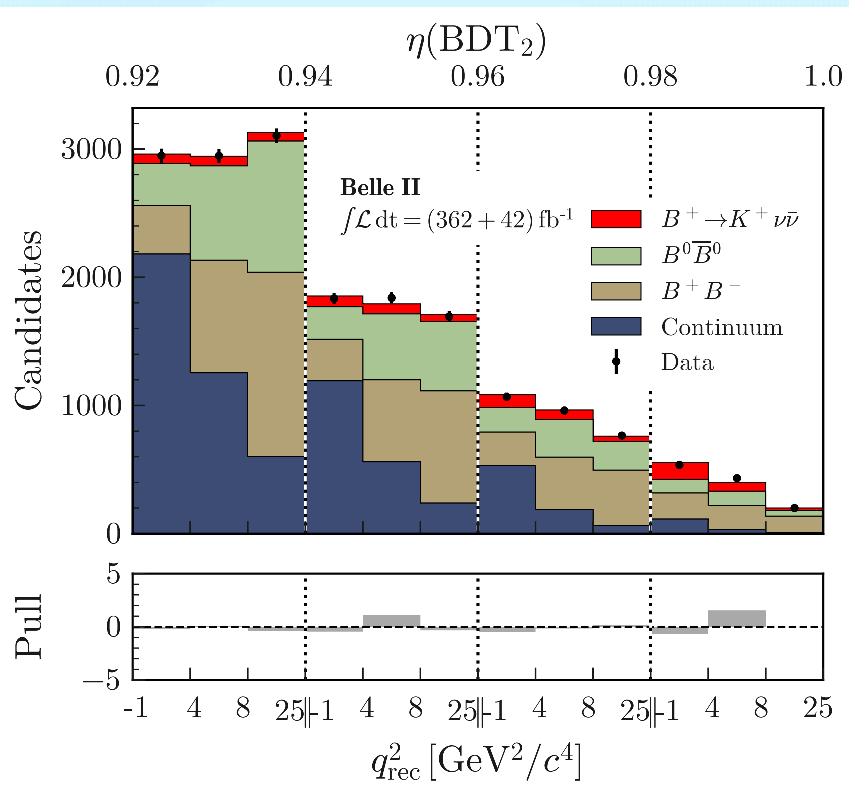
[PRD 109 112006 2024](PRD 109 112006 2024)

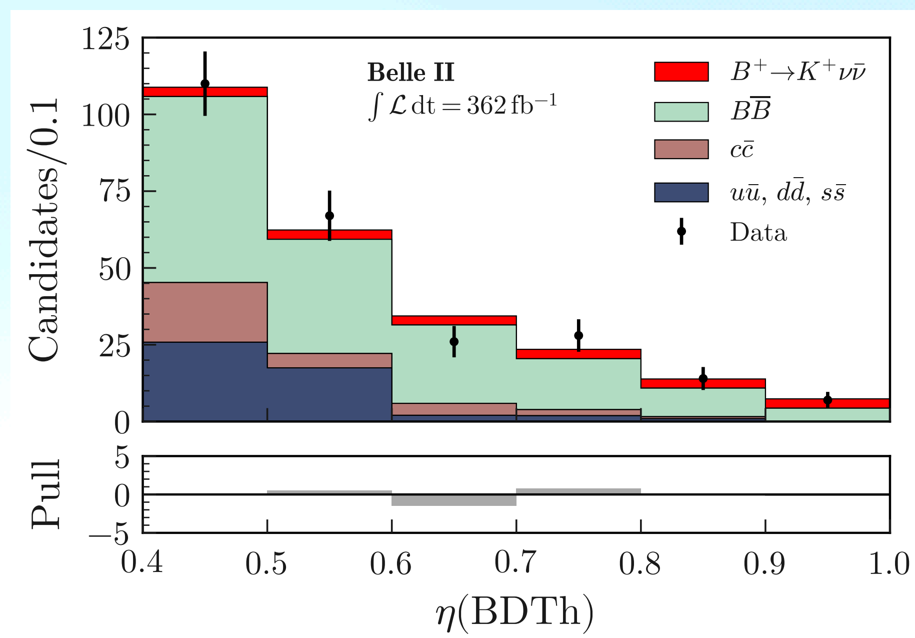
- Fit strategy:
  - Binned maximum likelihood fit to extract parameter of interest signal strength μ

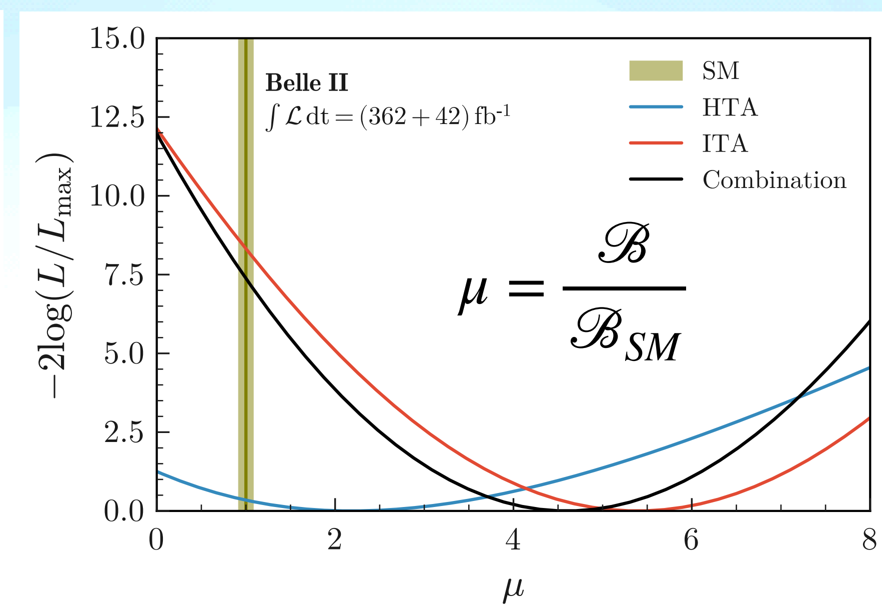
$$\mu = \frac{\mathscr{B}}{\mathscr{B}_{SM}}, \text{ where } \mathscr{B}_{SM} = 4.97 \times 10^{-6}$$

Inclusive tag fit: Classifier output and mass square of neutrino pair

Hadronic tag fit: Classifier output







Inclusive tag:

$\mathscr{B} = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$

$3.5\ \sigma$ significance wrt bkg only hypothesis

$2.9\ \sigma$ deviation from SM

Hadronic tag:

$\mathscr{B} = (1.1^{+0.9}_{-0.8}{}^{+0.8}_{-0.5}) \times 10^{-5}$

$1.1\ \sigma$ significance wrt bkg only

$0.6\ \sigma$ deviation from SM

Combination:

$\mathscr{B} = (2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$

$3.5\ \sigma$ significance wrt bkg only

$2.7\ \sigma$ deviation from SM

- First evidence of the $B \to K\nu\bar{\nu}$ process

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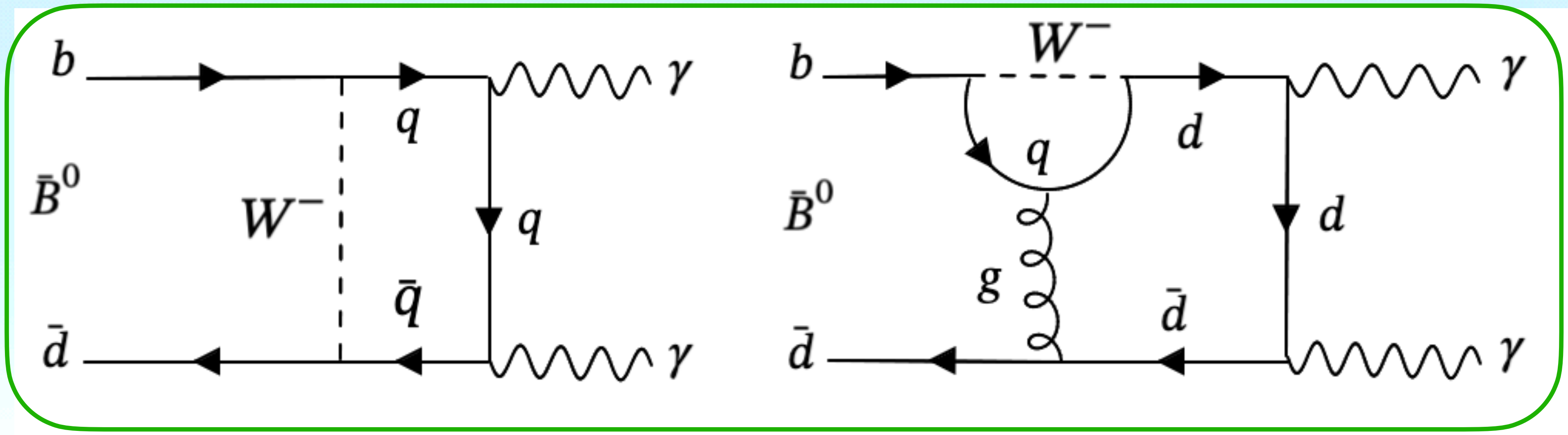
$B^0 \to \gamma\gamma$ decays

PRD 110, L031106 (2024)

- Very rare decay with expected $\mathscr{B}$ to be $(1.4^{+1.4}_{-0.8}) \times 10^{-8}$
  - Uncertainty dominated by the uncertainty on λ_b [JHEP 12, 169 (2020)]



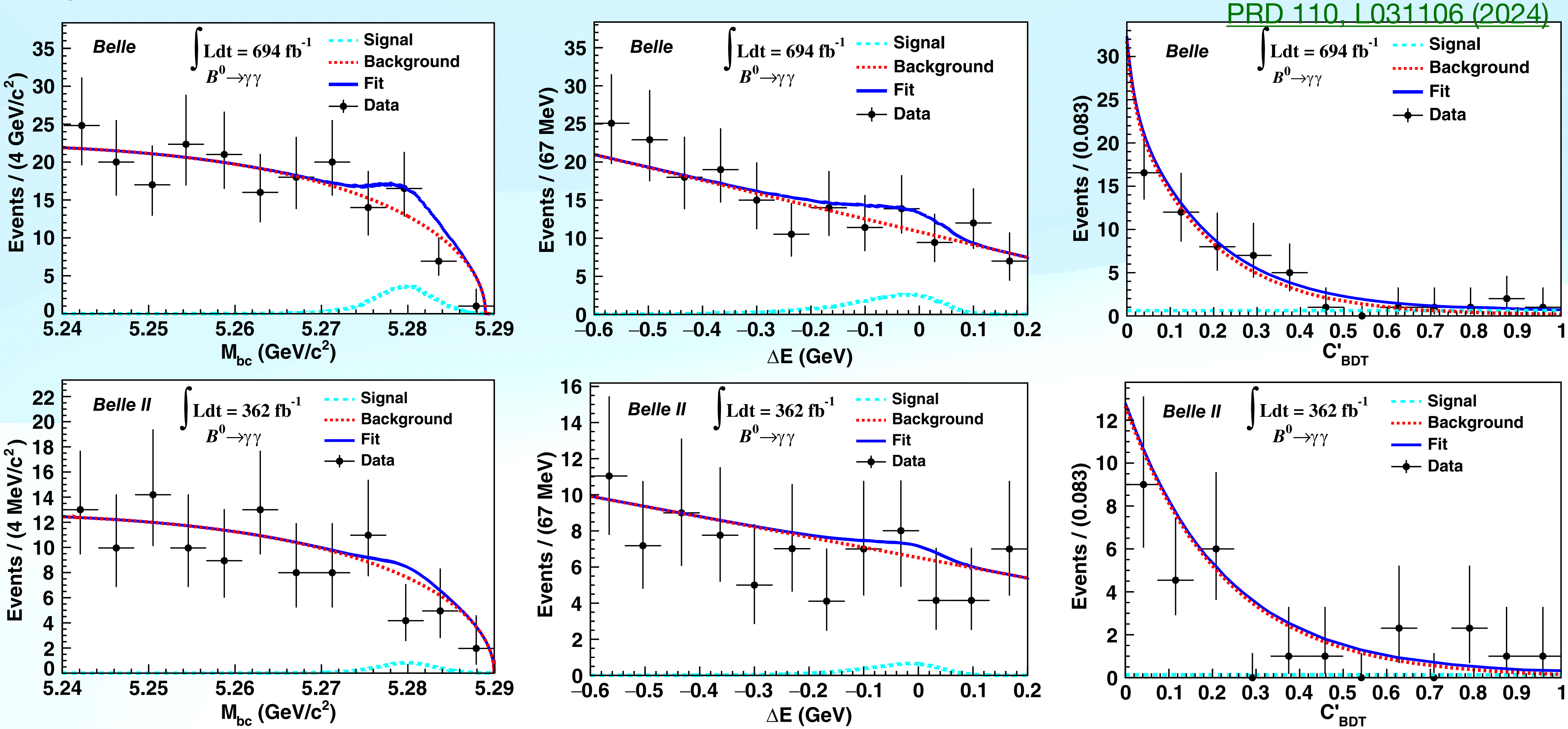
  - Experimentally challenging due to presence of two photons; large backgrounds

- First studied at L3 (PLB 363 (1995) 137-144) and the most stringent limit is by Babar (PRD 83, 032006 (2011))
- Combined Belle (694 fb^{-1}) + Belle II (362 fb^{-1}) data
- Signal reconstruction using two photons, where $E_\gamma \in (1.4,\ 3.4)$ GeV
- Use timing cuts to remove peaking back-to-back off-time photons, and separate BDT to veto $\pi^0/\eta \to \gamma\gamma$
- Use $B^0 \to K^{*0}(892)\gamma$ as control sample

$B^0 \to \gamma\gamma$ decays

- Simultaneous 3D fit to M_{bc}, ΔE and C'_{BDT} (transformed BDT to suppress continuum ($q\bar{q}$) background)

PRD 110, L031106 (2024)



- $11.0^{+6.5}_{-5.5}$ signal events corresponding to a significance of $2.5\ \sigma$
- Combined upper limit on $\mathcal{B}(B^0 \to \gamma\gamma) < 6.4 \times 10^{-8}$ (expected $\mathcal{B}_{SM}(B^0 \to \gamma\gamma) < 4.4 \times 10^{-8}$) at 90% CL
  - $5 \times$ **improvement** in limit wrt previous best result from Babar

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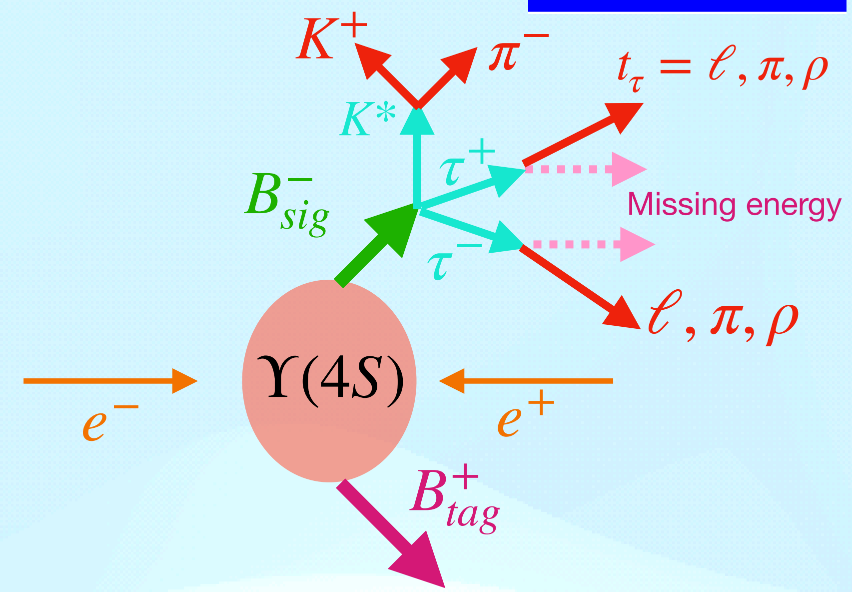
Search for $B^0 \to K^{*0}\tau^+\tau^-$ decays

Results are preliminary; Paper in preparation

- FCNC $b \to s$ transition
  - SM prediction $\mathscr{B} = (0.98 \pm 0.10) \times 10^{-7}$
- NP models which accommodate $b \to c\tau l$ anomalies predict an **enhancement of several order magnitude with $\tau\tau$ pairs in the final state**
- Experimentally challenging: small BF, Large background, upto 4 neutrinos in the final state
- BDT is trained using missing energy, extra cluster energy in EM calorimeter, $M(K^{*0}t_\tau)$, q^2 etc
- BDT output to extract signal yield with simultaneous fit to four ($\ell\ell$, $\ell\pi$, $\pi\pi$, ρX) categories

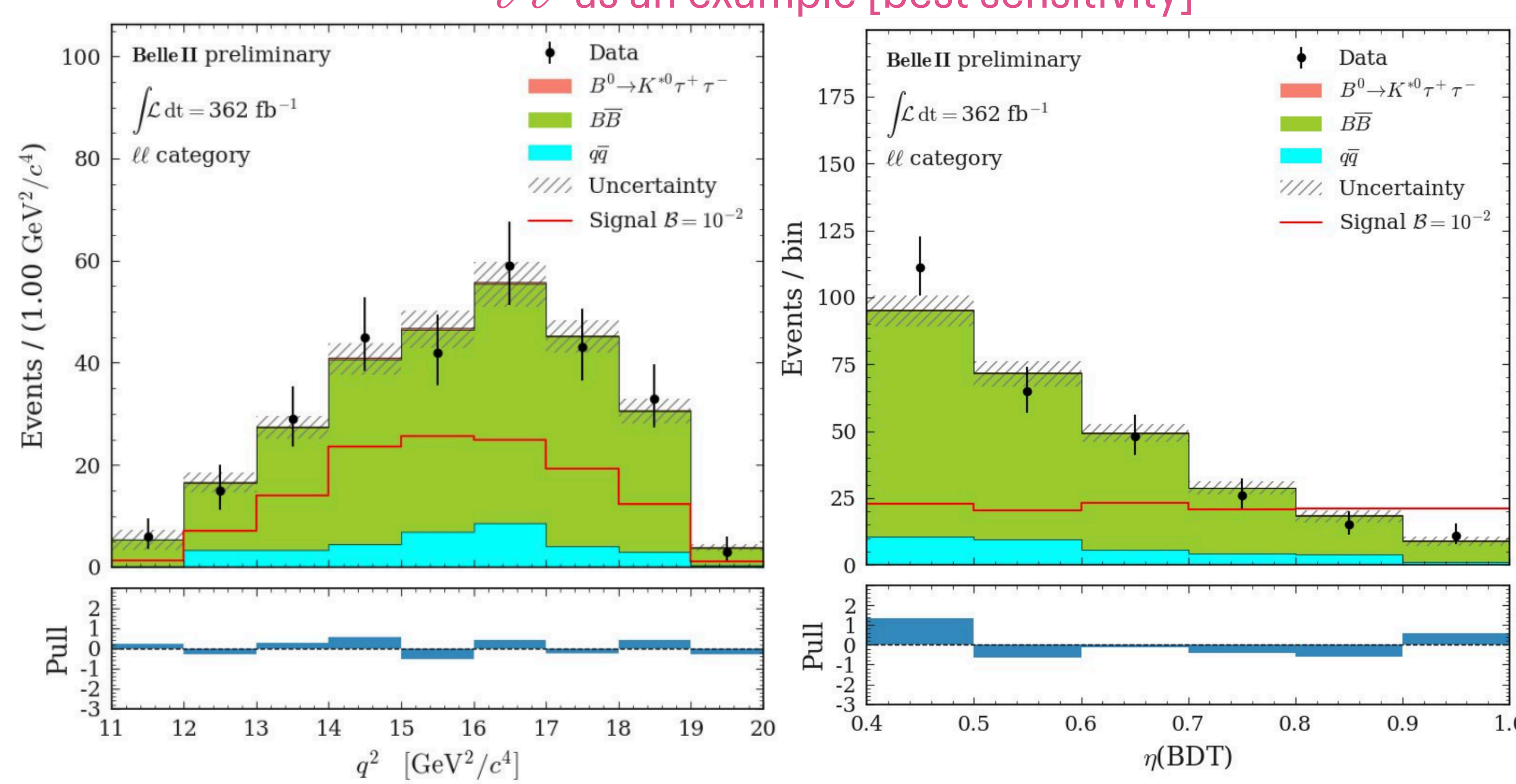


$\ell\ell$ as an example [best sensitivity]

- Belle II 362 fb^{-1} data
- No excess signal is observed $\to$ upper limit

$\mathscr{B}^{UL} < 1.8 \times 10^{-3}$ @ 90 % CL

Most stringent limit so far



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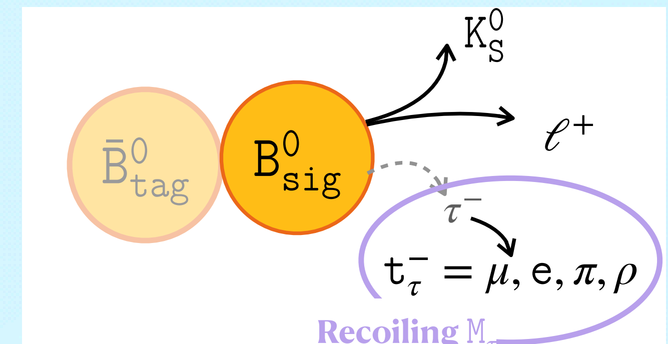
Search for $B^0 \to K_S^0 \tau^\pm \ell^\mp (\ell = e, \mu)$ decays

- NP coupling preferentially to 2nd and 3rd generation leptons could result decay to LFV $b \to s\tau\ell$

First search for the decay $B^0 \to K_S^0 \tau^\pm \ell^\mp$

- Has neutrinos only from one $\tau \Rightarrow$ can compute the recoil mass (M_τ)
- K_S^0 reconstructed from pair of charged pions ⇒ 98% purity
- BDT is trained to suppress the remaining bkg

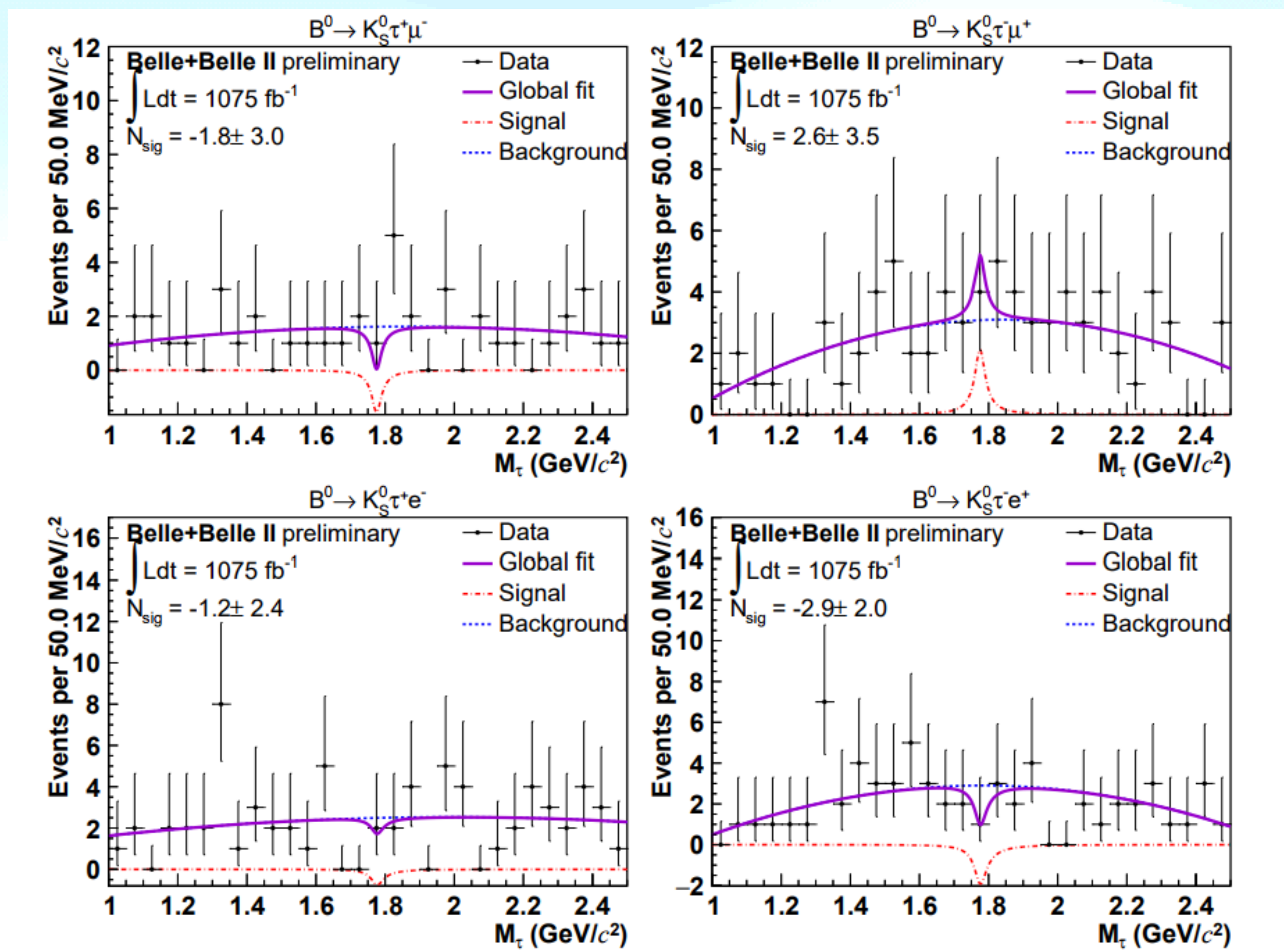


$$M_\tau^2 = (p_{e^+e^-} - p_K - p_\ell - p_{B_{tag}})^2$$

- Belle + Belle II (711 + 364 fb^{-1})
- No excess signal is observed → upper limit at 90% CL

$\mathcal{B}(B^0 \to K_S^0 \tau^+ \mu^-) < 1.1 \times 10^{-5}$
$\mathcal{B}(B^0 \to K_S^0 \tau^- \mu^+) < 3.6 \times 10^{-5}$
$\mathcal{B}(B^0 \to K_S^0 \tau^+ e^-) < 1.5 \times 10^{-5}$
$\mathcal{B}(B^0 \to K_S^0 \tau^- e^+) < 0.8 \times 10^{-5}$

Most stringent limit so far



Results are preliminary;
Paper in preparation

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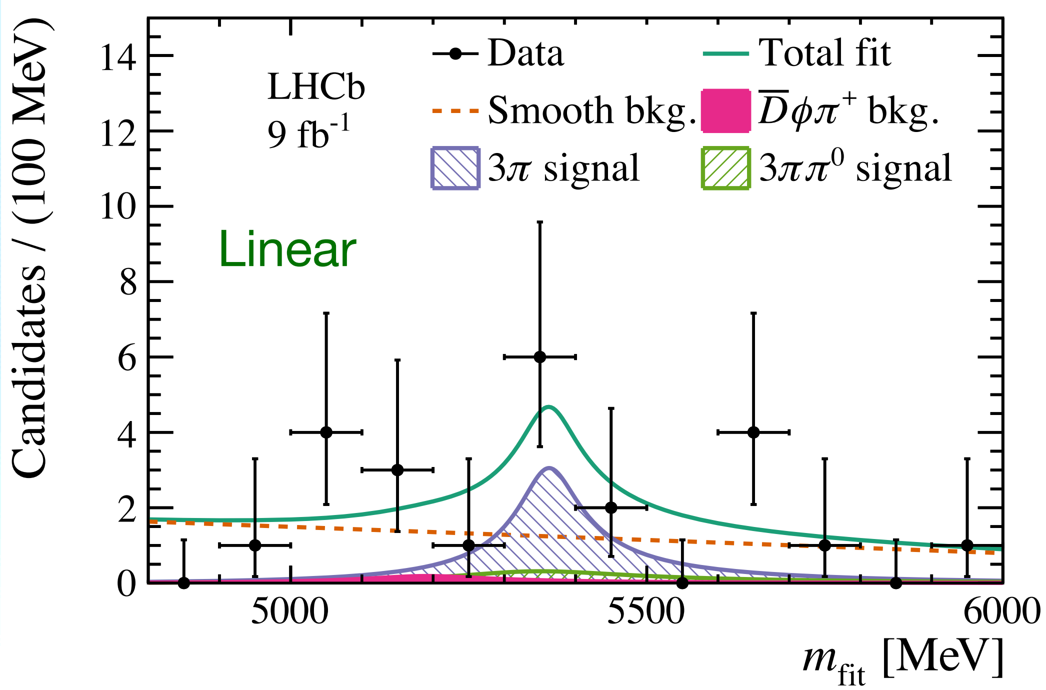
Search for $B_s^0 \to \phi\mu^{\pm}\tau^{\mp}$ decay

First search for the decay $B_s^0 \to \phi\mu^{\pm}\tau^{\mp}$

- 9 fb^{-1} from Run 1+ Run 2 dataset

- B_s^0 is produced at low rate but low background
- Signal reconstruction with $\phi \to K^+K^-$ and $\tau \to 3\pi$ (including $\tau \to 3\pi\pi^0$)
- Missing neutrino: reconstruct B_s^0 mass using vertex and kinematic constraints

Submitted to PRD. arXiv: 2405.13103



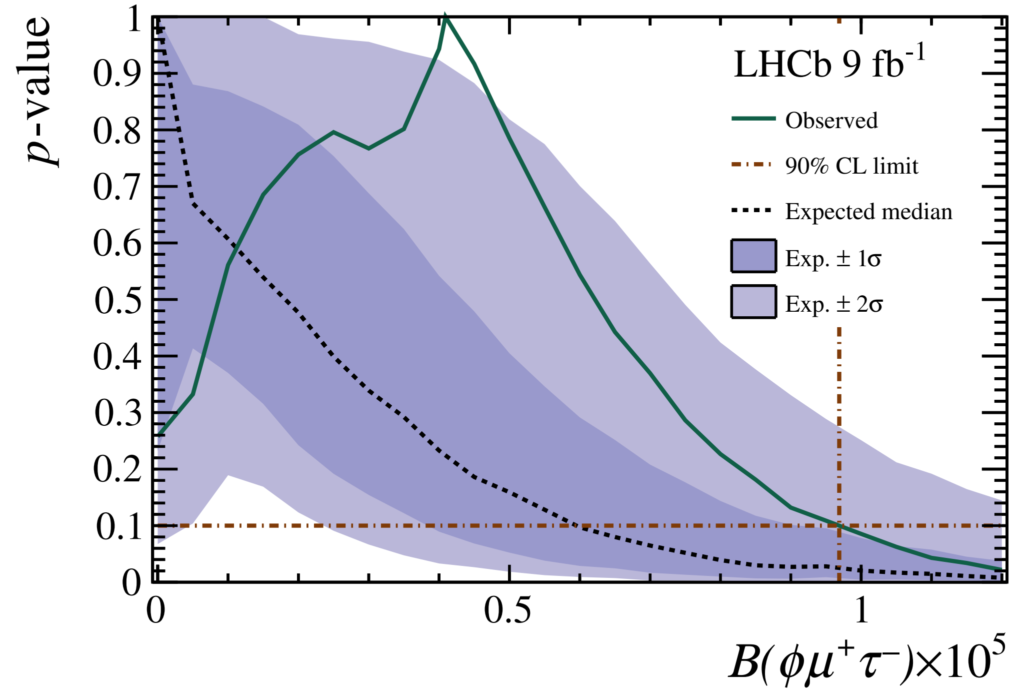
- No significant signal observed over background-only hypothesis
- Best fit used the linear background model, extracted BF is 4.1×10^{-6}

$\mathscr{B}(B_s^0 \to \phi\mu^{\pm}\tau^{\mp}) < 1.0 \times 10^{-5}$ at 90% CL

$\mathscr{B}(B_s^0 \to \phi\mu^{\pm}\tau^{\mp}) < 1.1 \times 10^{-5}$ at 95% CL

- First upper limit on this decay mode→ competitive with other $b \to s\mu\tau$ searches

[JHEP 06 (2020) 129
JHEP 06 (2023) 143]



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Conclusion

- In the search for physics beyond the Standard Model, rare B decays are one of the key tools

- Belle, Belle II, CMS and LHCb are producing world-leading results in rare B decays:
  - Results:
    - First LFU test in high-q^2 at LHCb with B_s^0 decay mode: most precise to date (new)
    - First LFU test in B_s^0 decays and first observation of $B_s^0 \to \phi e^+ e^-$
    - First angular analysis $B_s^0 \to \phi e^+ e^-$ at low q^2 region
    - Angular analysis of $B^0 \to K^{*0} e^+ e^-$ and $\Lambda_b^0 \to p K^- \mu^+ \mu^-$
    - Evidence of $B^+ \to K^+ \nu \bar{\nu}$ by Belle II
    - Best upper limit on $B^0 \to \gamma\gamma$ by Belle II
    - Several searches of $b \to s \tau \ell$ decays in LHCb and Belle II

  - All the analysis presented today are in agreement with the SM predictions

- Most of the measurements are statistically limited → bigger datasets are of particular interest!

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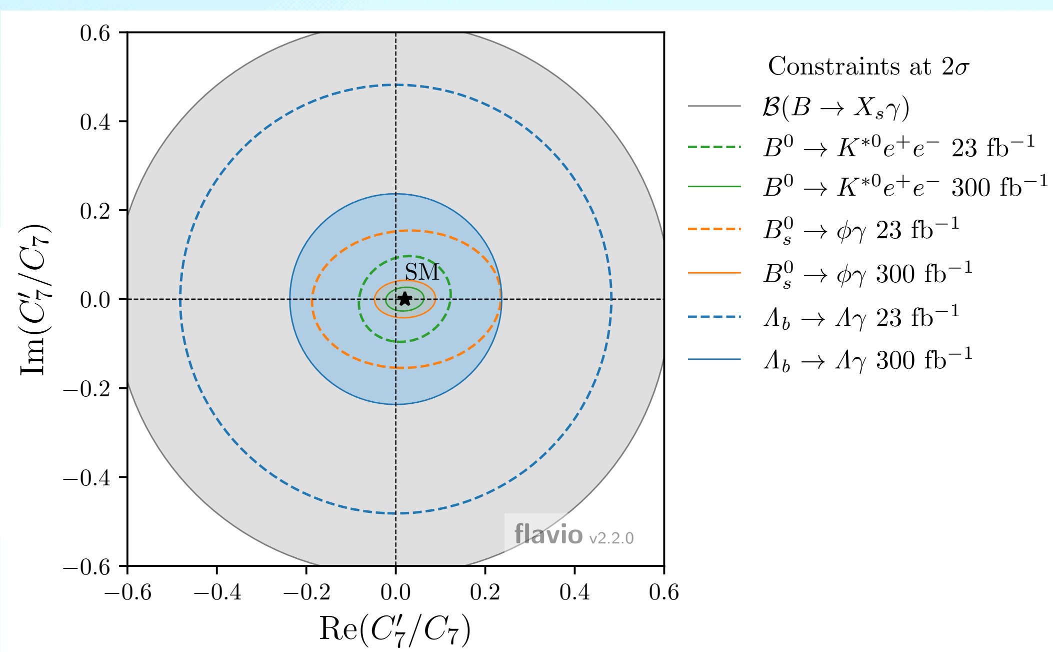
Prospects

- LHCb Run 3 and 4 data will increase the number of recorded B decays by a several factors which will improve the measurements
  - Data collected in 2024 is 9.6 fb^{-1}



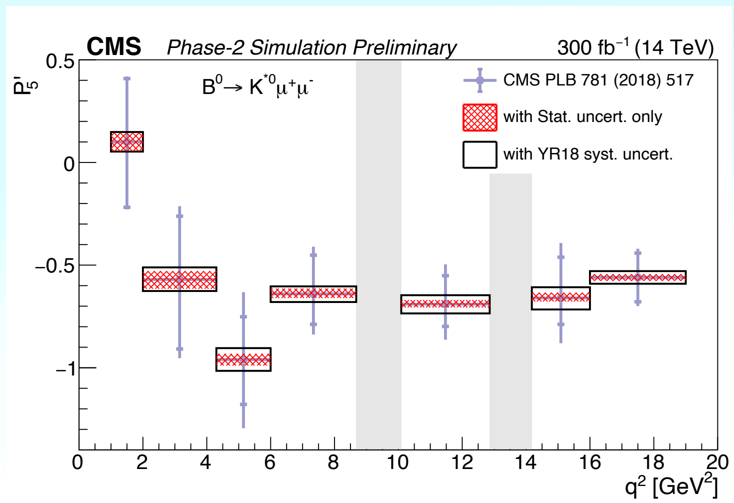
LHCb_TDR_023

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	$4°$	[9, 10]	$1.5°$	$1°$	$0.35°$
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\mathrm{T}}^{\mathrm{Im}}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002

Prospects

- CMS upgrade, planned for 2026-2027, aims to cope up with harsher environment and increase the data rate which will improve the overall detector performance.

$\mathcal{L}$ (fb^{-1})	$N(B_s)$	$N(B^0)$	$\delta\mathcal{B}(B_s \to \mu\mu)$	$\delta\mathcal{B}(B^0 \to \mu\mu)$	$\sigma(B^0 \to \mu\mu)$	$\delta[\tau(B_s)]$(stat-only)
300	205	21	12%	46%	$1.4 - 3.5\sigma$	0.15 ps
3000	2048	215	7%	16%	$6.3 - 8.3\sigma$	0.05 ps



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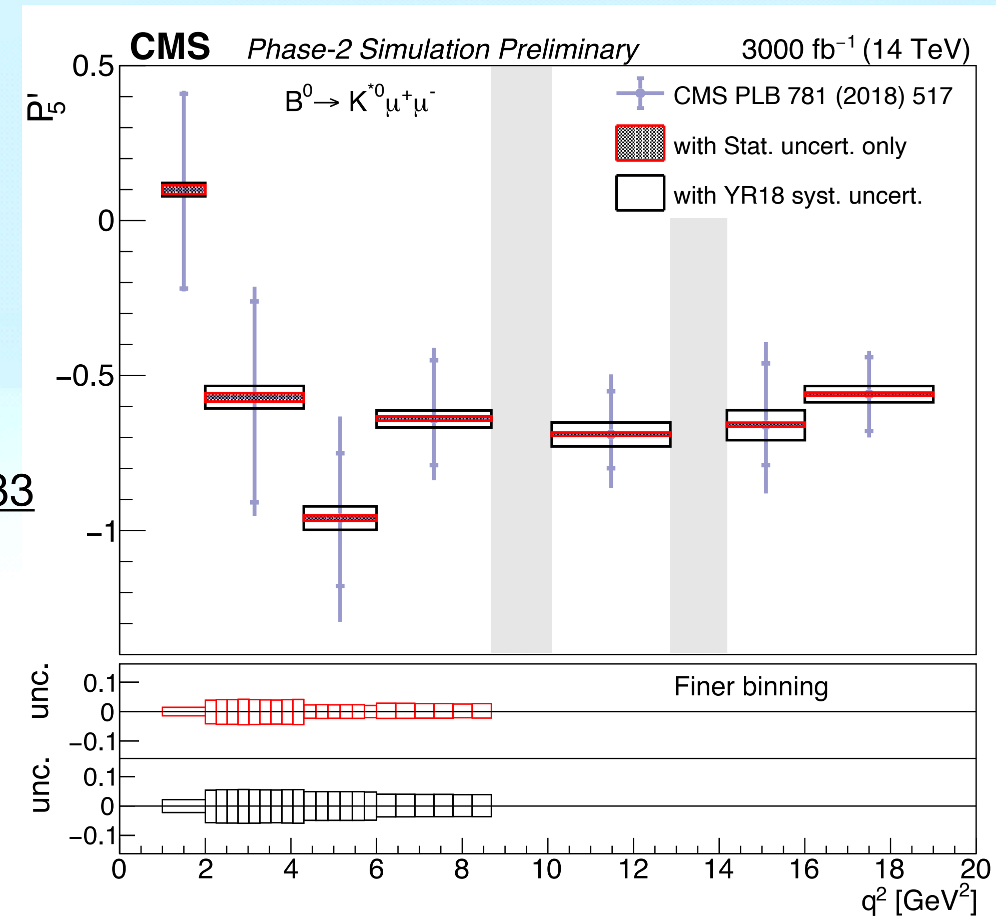

- Belle-II projections

$B \to \gamma\gamma$ — Belle II physics book

Observables	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B_d \to \gamma\gamma)$	30%	9.6%
$A_{CP}(B_d \to \gamma\gamma)$	78%	25%
$\mathrm{Br}(B_s \to \gamma\gamma)$	23%	–

$B^+ \to K^+\nu\bar{\nu}$ — Belle II snowmass white paper

Decay	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)

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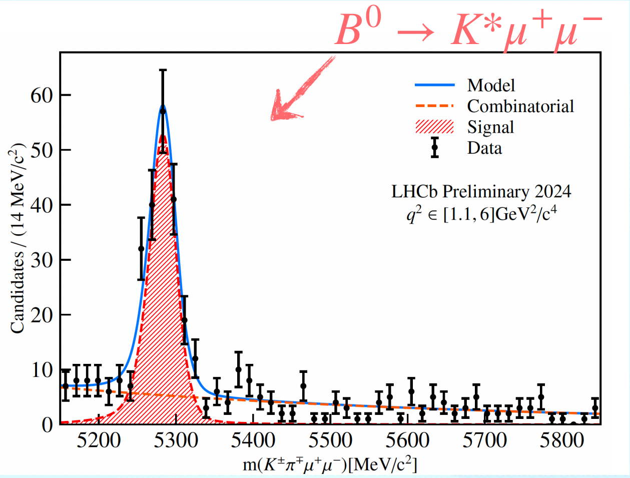
Thank you for your attention

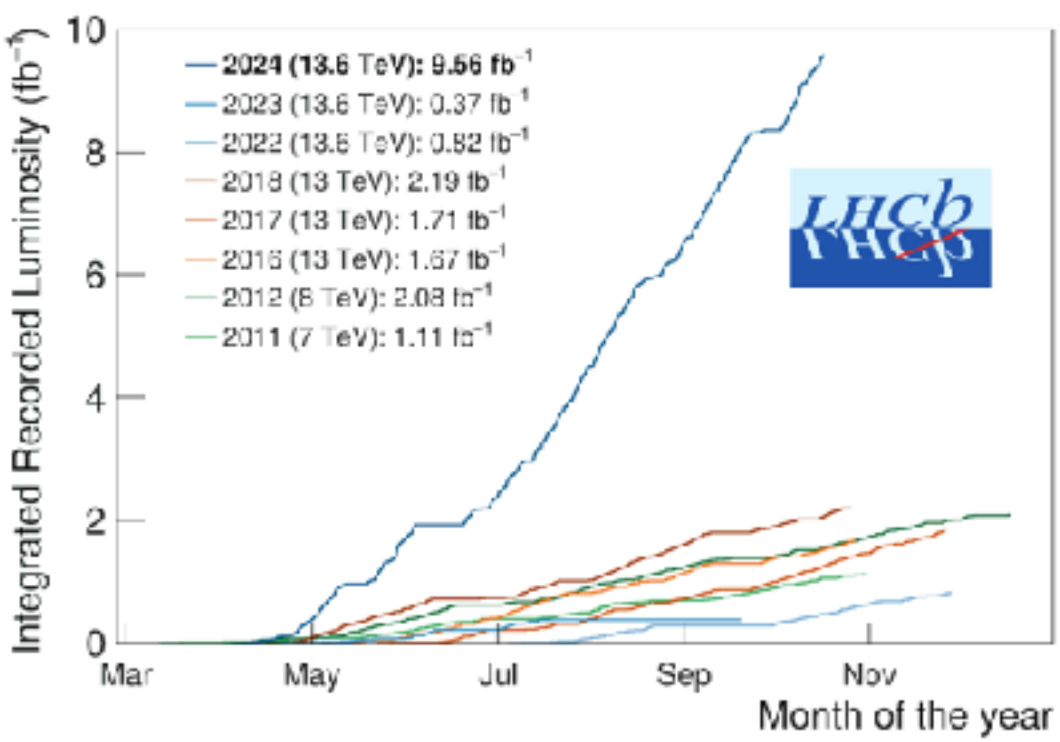
Backup

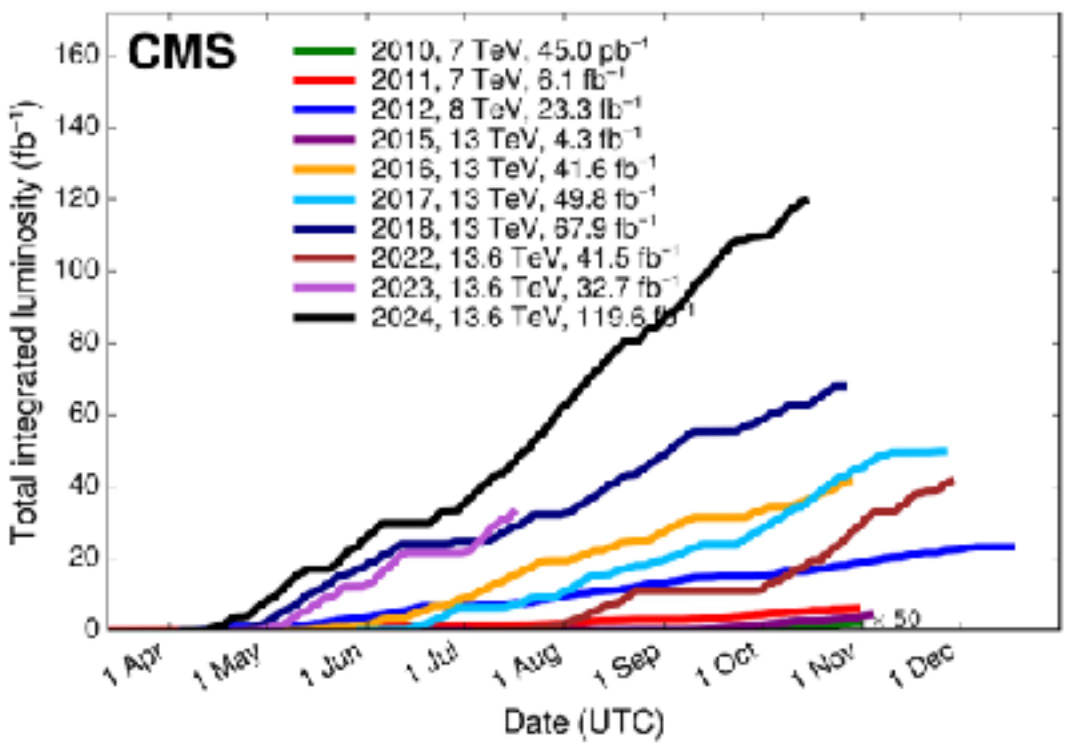
Current status

- LHCb Run 3 and 4 data will increase the number of recorded B_s^0 decays by a factor of about 5
  - Already seen visible improvement in 2024 data taking



- CMS upgrade is foreseen in 2026-2027 to cope up with harsh environment and increase the data rate which will improve the overall detector performance.





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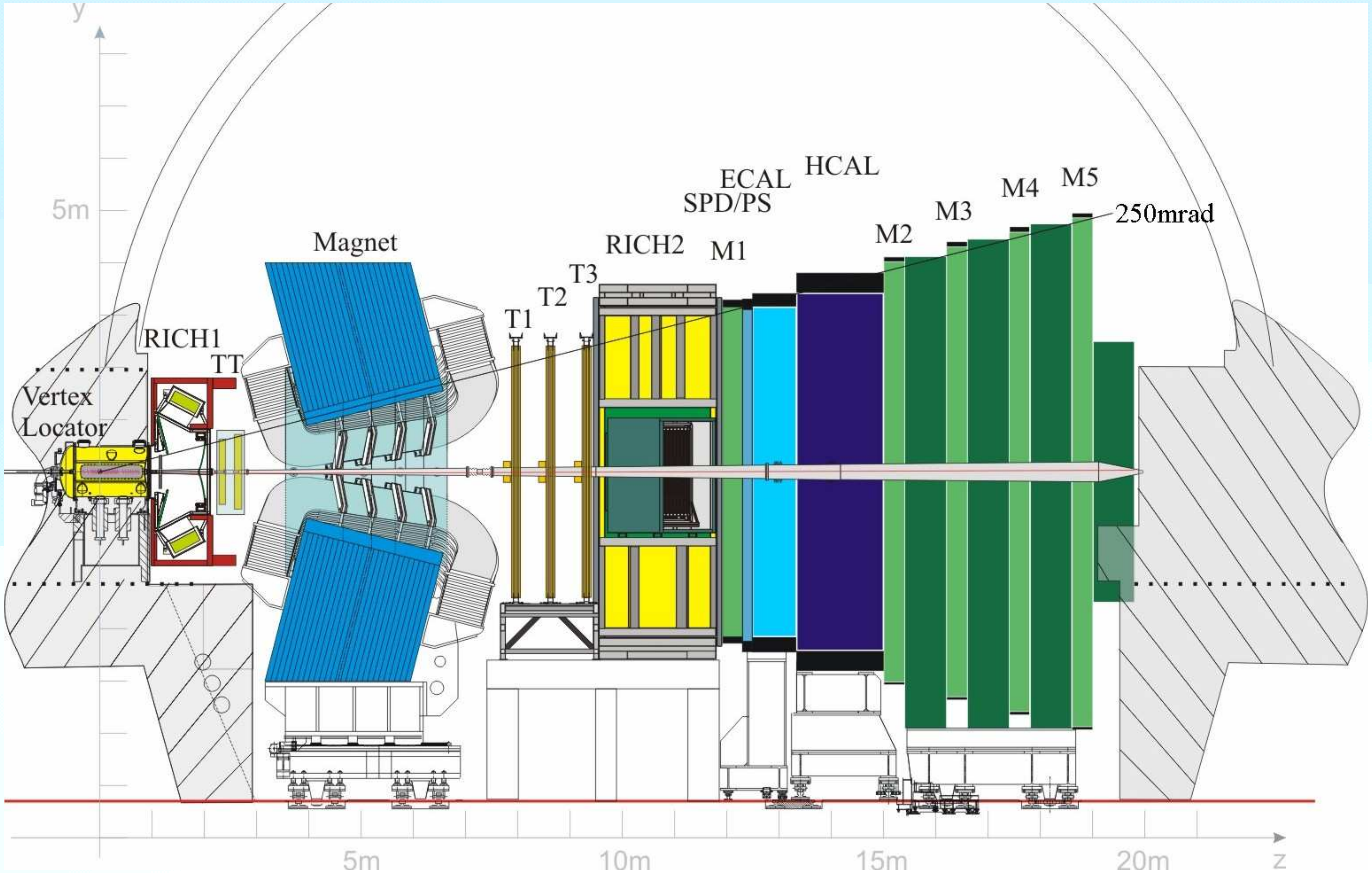
LHCb detector



- Impact parameter resolution: (15+29/p_T) μm
- Momentum resolution: $\Delta p/p \approx$ 0.5-1 %
- Energy resolution: $\Delta E/E =$ 1% +10%/$\sqrt{E}$
- Belle : $\Delta E/E =$ 1% +2.2%/$\sqrt{E}$

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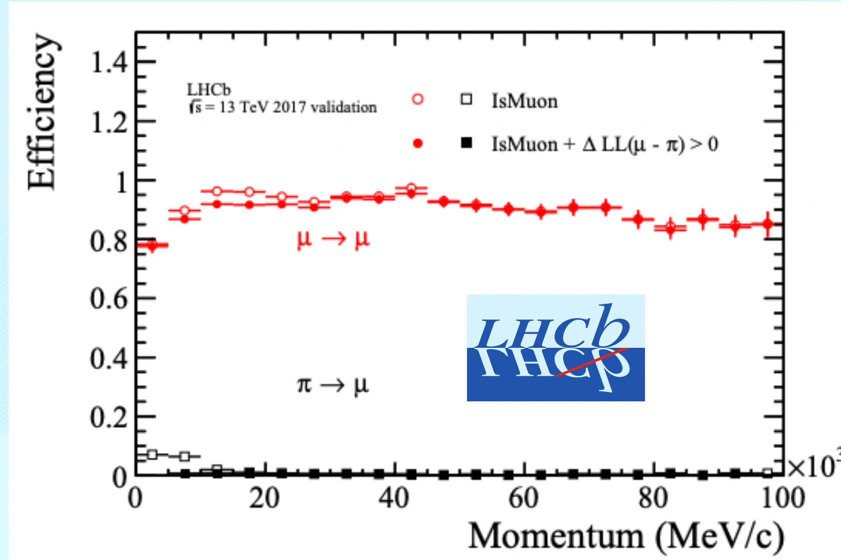
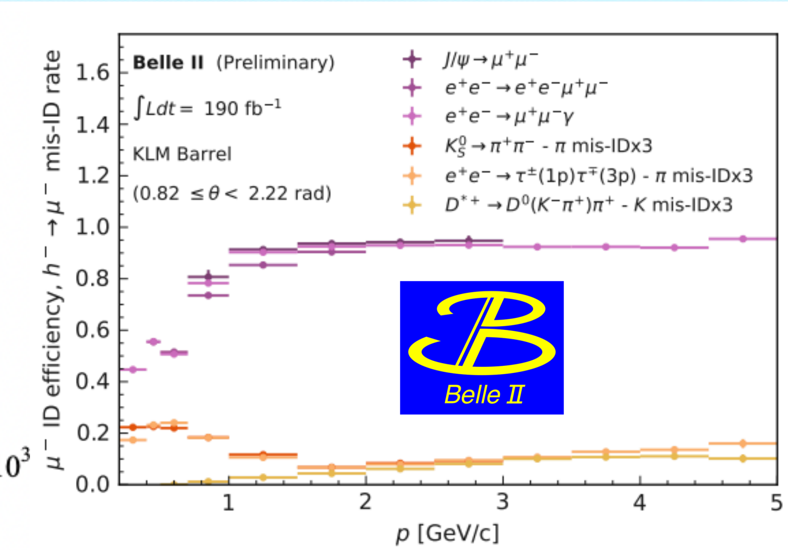
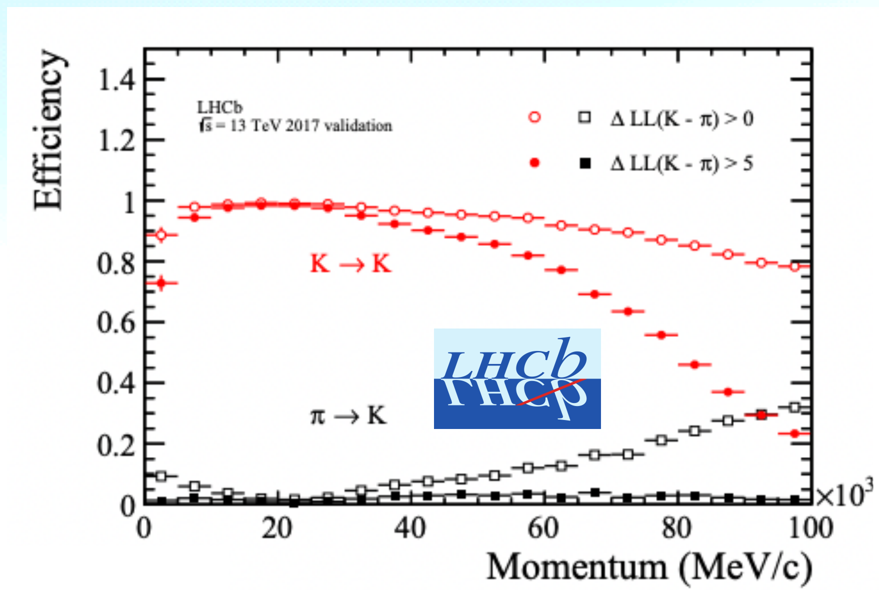
Charge Track Performance

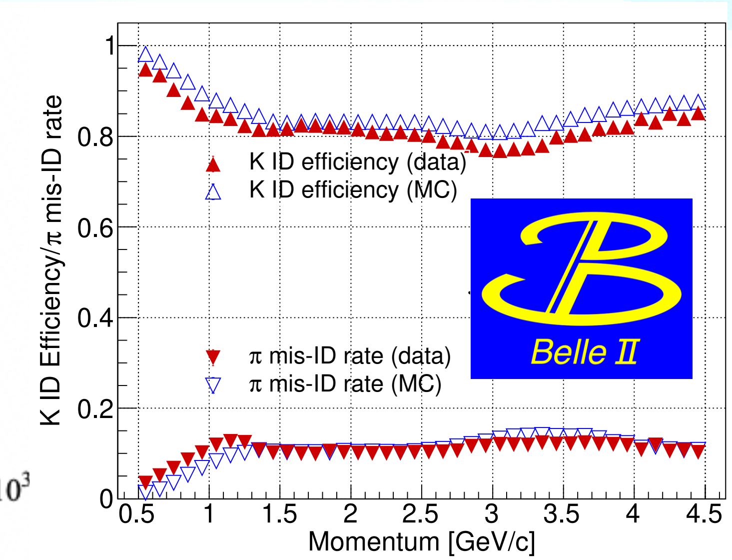
	Belle II	LHCb
Muon trigger efficiency	100 %	90 %
Muon ID efficiency	95 %	97 %
$\pi \rightarrow \mu$ misID	7 %	1-3%

	Belle II	LHCb
Kaon ID efficiency	90 %	95 %
$K \rightarrow \pi$ misID	5 %	5 %









- In CMS, Muon reconstruction and identification efficiency > 96 %
  - $\pi \rightarrow \mu, K \rightarrow \mu$ misidentification efficiency < 0.5% 1804.04528

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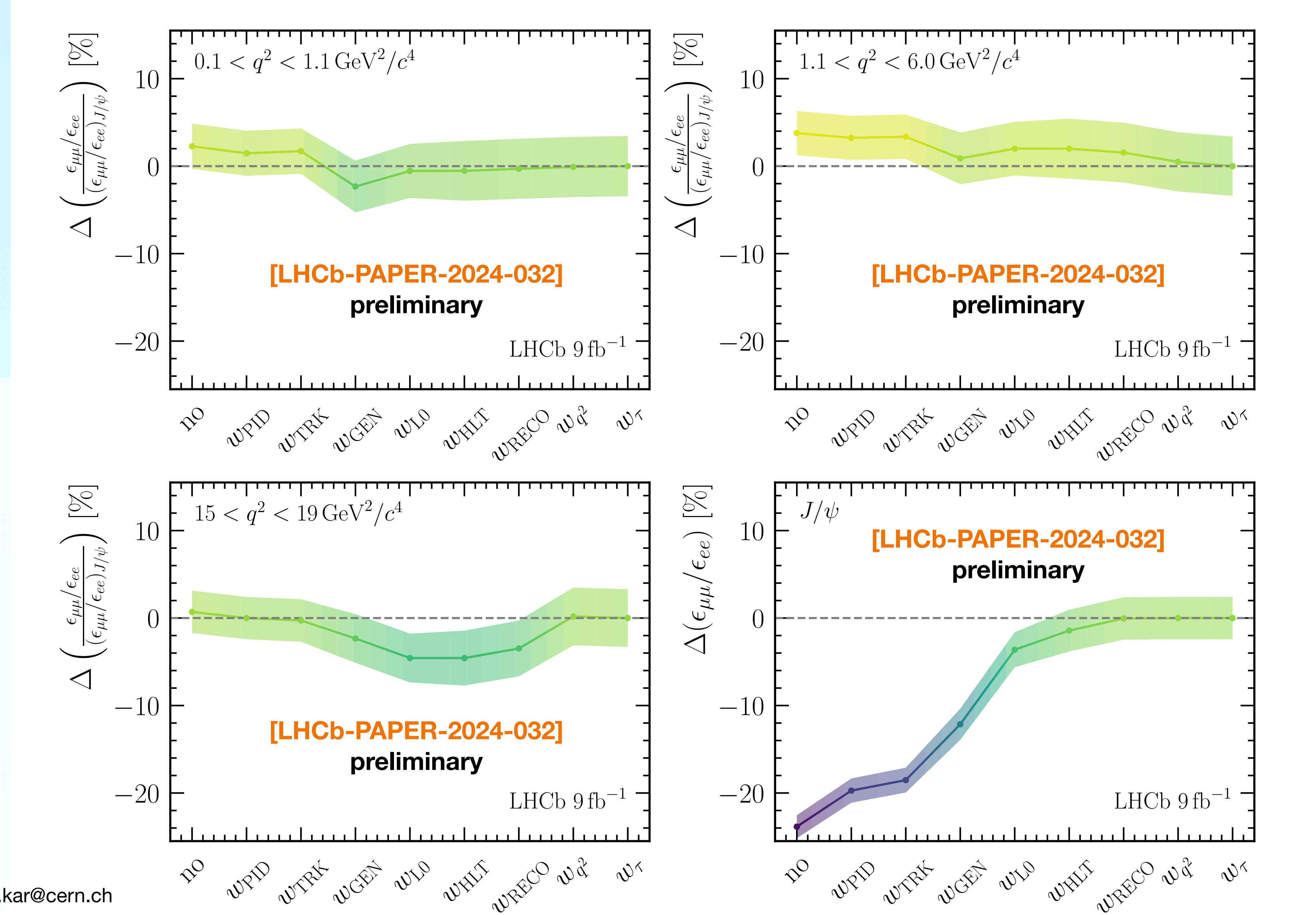
LFU test with $B_s^0 \to \phi l^+ l^-$ decays

- Single ratio $r_{J/\psi}$ changes about 25% after all simulation corrections applied
- Double ratio R_ϕ changes by 1%



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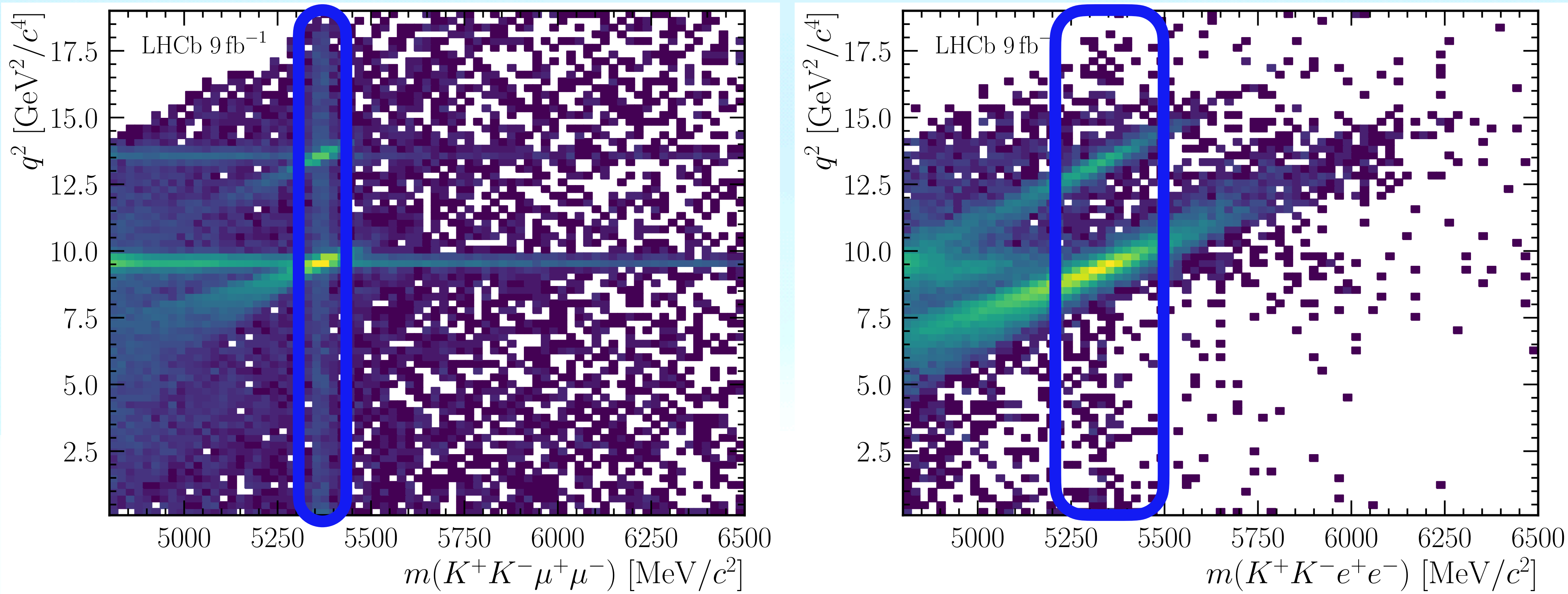
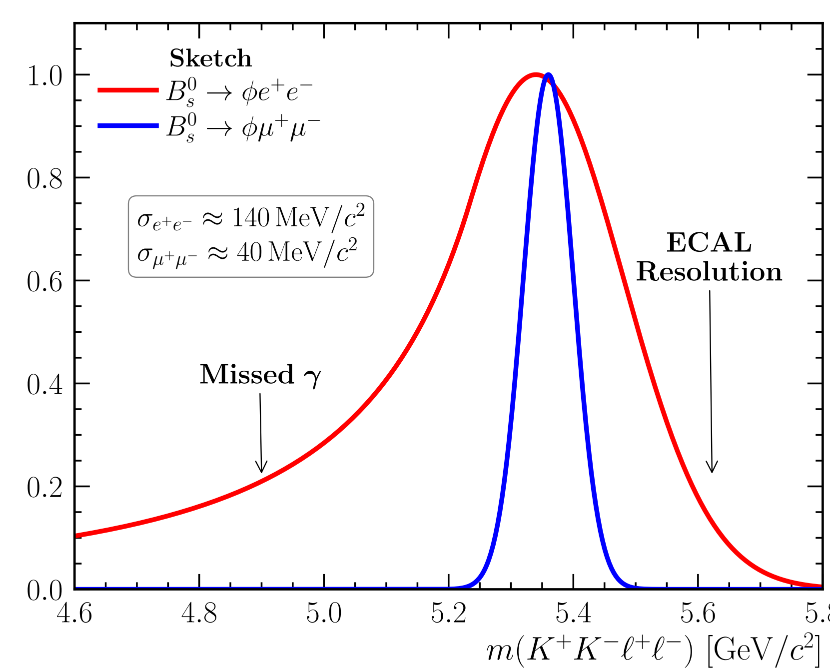
LFU test with $B_s^0 \to \phi l^+ l^-$ decays

- Effect of Bremsstrahlung in electron making the resolution wider



- Corrected using bremsstrahlung recovery
  - $\mathcal{O}$(50)% efficient and **well modelled** in simulation



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LFU test with $B_s^0 \to \phi l^+ l^-$: Systematic summary

- Systematic uncertainties are dominated by the model used to describe the signal and background shapes
- Total uncertainties are dominated by statistical components (21.8 % (low-q^2), 17.2 % (central-q^2), 28.8 % (high-q^2)

Source	low	central	high
Fit bias	0.0%	0.9%	1.4%
Normalisation	0.2%	0.2%	0.2%
$r_{J/\psi}$ variation	1.3%	0.6%	0.9%
Efficiency calibration	0.7%	0.5%	1.2%
q^2 smearing	0.6%	0.5%	0.3%
Decay model	0.1%	0.3%	0.1%
Signal lineshape	1.7%	1.5%	3.7%
Hadronic bkg.	4.1%	4.3%	7.4%
Combinatorial bkg.	–	–	3.9%
Leakage bkg.	–	0.9%	2.1%
Semileptonic bkg.	1.3%	1.2%	–
Total	4.9%	4.9%	9.6%

Systematics

Angular analysis of $B_s^0 \to \phi e^+ e^-$ decays

- Systematic uncertainties are dominated by the background contaminations but smaller compared to statistical uncertainty

Source of systematic	$A_{\rm T}^{(2)}$	$A_{\rm T}^{\mathcal{I}mCP}$	$A_{\rm T}^{\mathcal{R}eCP}$	$F_{\rm L}$
$\Delta\Gamma_s/\Gamma_s$	0.008	<0.001	<0.001	<0.001
Corrections to simulation	0.002	<0.001	<0.001	0.010
Acceptance function modelling	<0.001	<0.001	0.001	0.002
Simulation sample size for acceptance	0.006	0.008	0.005	0.002
Background contamination	0.009	0.014	0.004	0.006
Angles resolution	-0.005	<0.001	-	-
Total systematic uncertainty	0.014	0.016	0.006	0.012
Statistical uncertainty	0.235	0.247	0.155	+0.056

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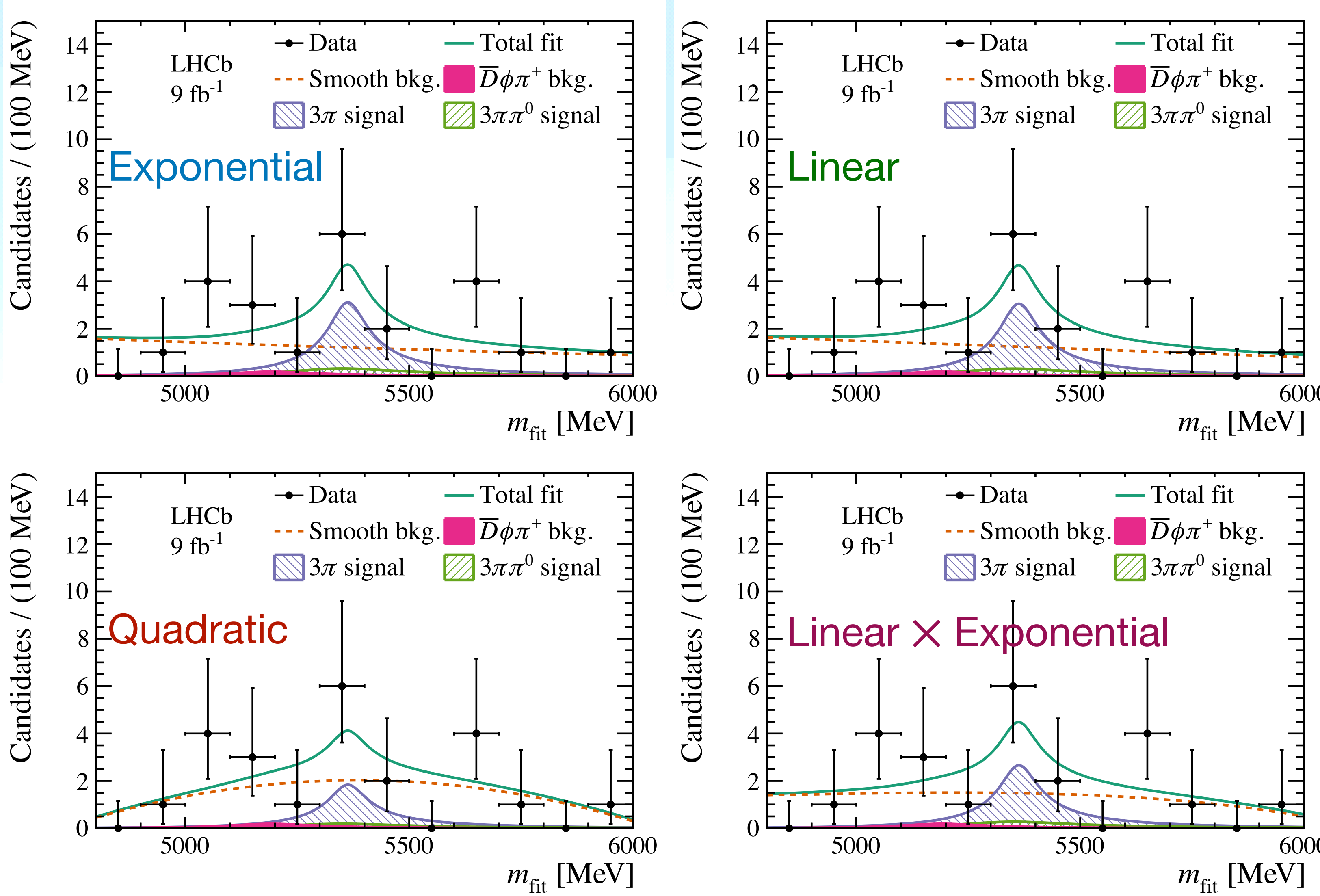
Search for cLFV decay $B_s^0 \to \phi\mu^\pm\tau^\mp$

- Possible in SM with neutrino oscillation ($\mathscr{B} < 10^{-50}$), NP scenarios $\mathscr{B} < 10^{-11}$
- NP models predict deviations especially involving the 3rd family

First search for the decay $B_s^0 \to \phi\mu^\pm\tau^\mp$

- $9\ \text{fb}^{-1}$ from Run 1+ Run 2 dataset
- B_s^0 is produced at low rate but low background
- Signal reconstruction with $\phi \to K^+K^-$ and $\tau \to 3\pi$ (including $\tau \to 3\pi\pi^0$)
- Missing neutrino: reconstruct B_s^0 mass using vertex and kinematic constraints

Mass fit with 4 different background shapes



Submitted to Phys. Rev. D. arXiv: 2405.13103

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Search for cLFV decay $B_s^0 \to \phi\mu^{\pm}\tau^{\mp}$

- No significant signal observed over background-only hypothesis
- First upper limit on this decay mode→ competitive with other $b \to s\mu\tau$ searches

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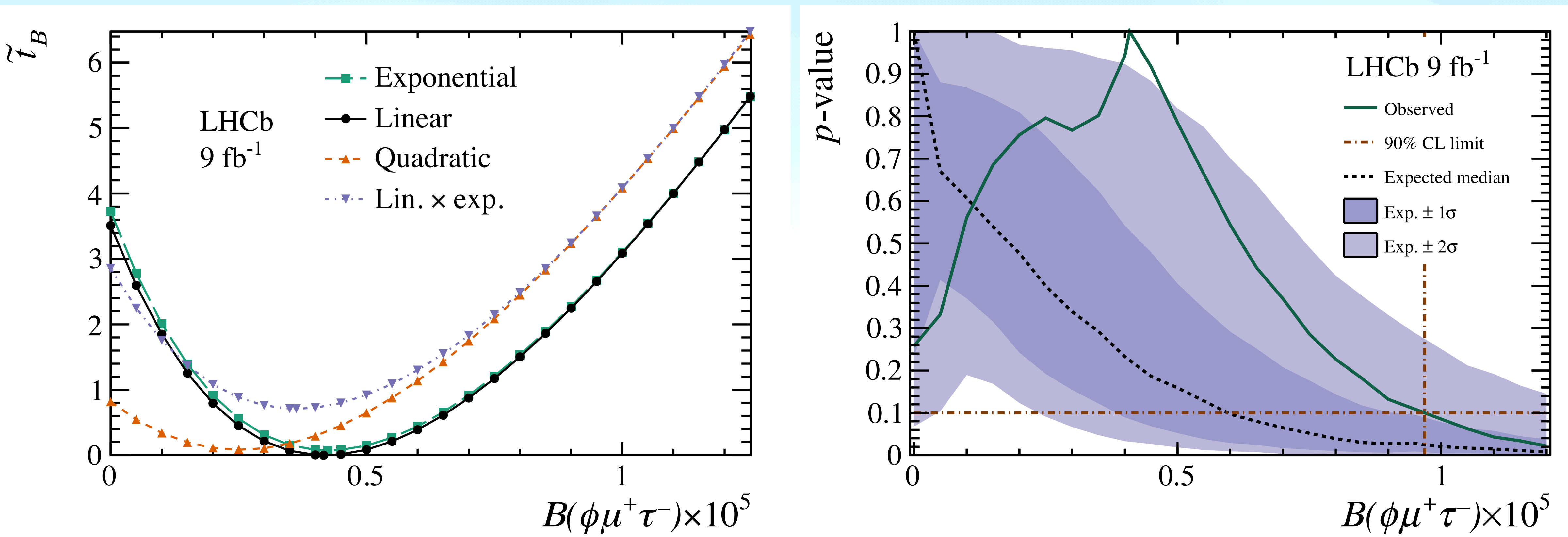
- Best fit used the linear background model, extracted BF is 4.1×10^{-6} with a local significance below 1.5σ



$$\mathscr{B}(B_s^0 \to \phi\mu^+\tau^-) < 1.0 \times 10^{-5} \text{ at 90\% CL}$$

$$\mathscr{B}(B_s^0 \to \phi\mu^+\tau^-) < 1.1 \times 10^{-5} \text{ at 95\% CL}$$

Submitted to Phys. Rev. D. arXiv: 2405.13103

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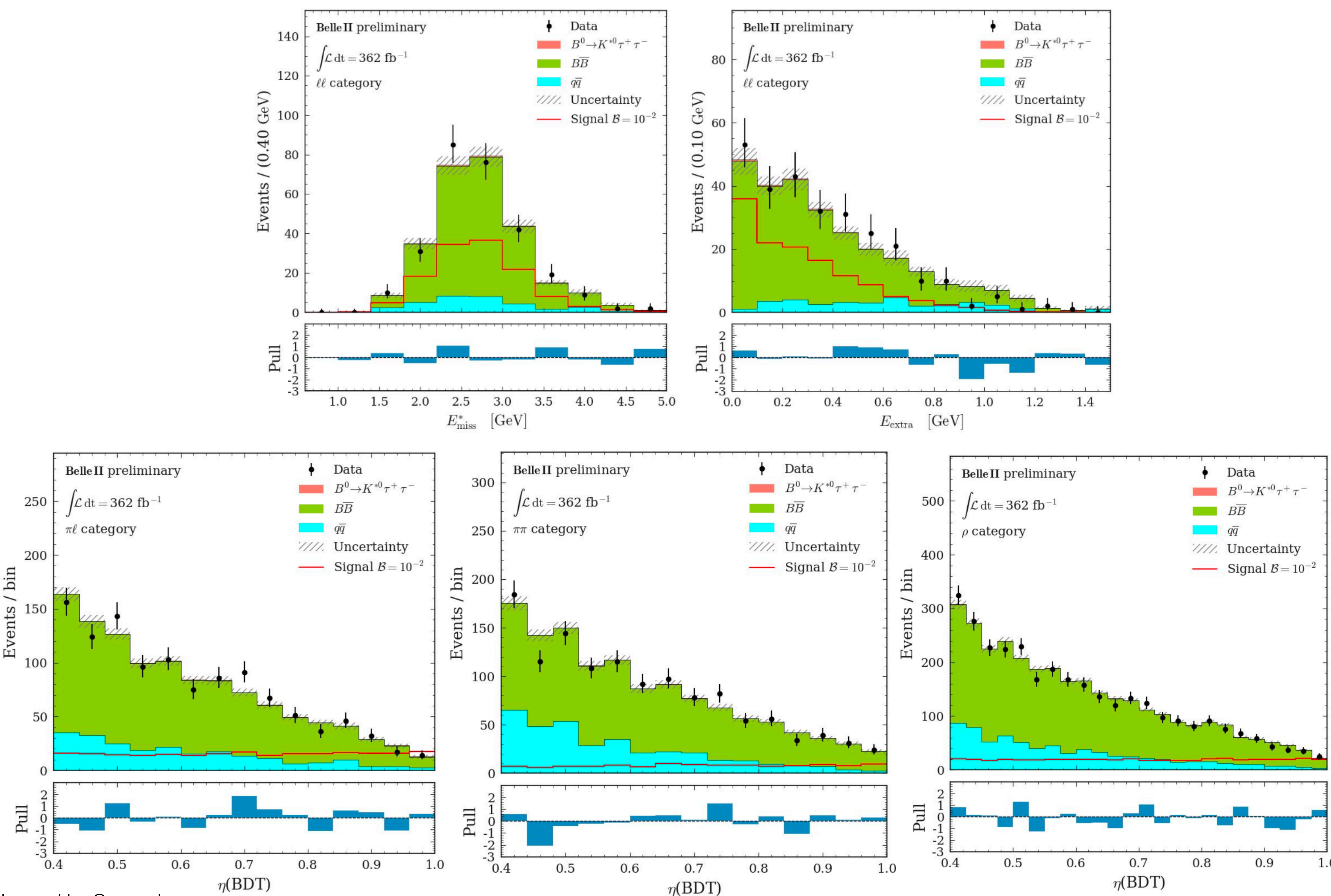
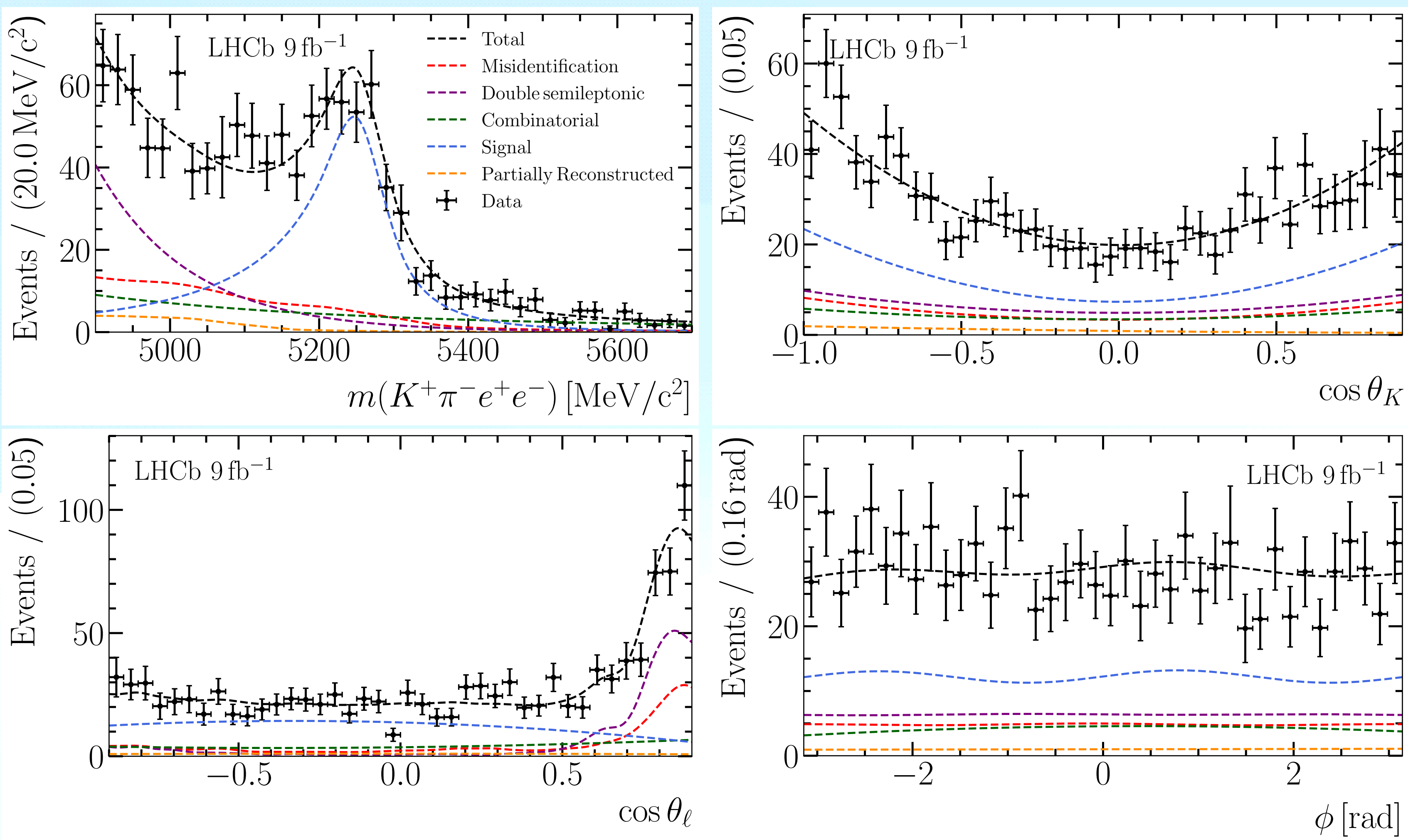
Search for $B^0 \to K^*\tau^+\tau^-$: BDT features and output

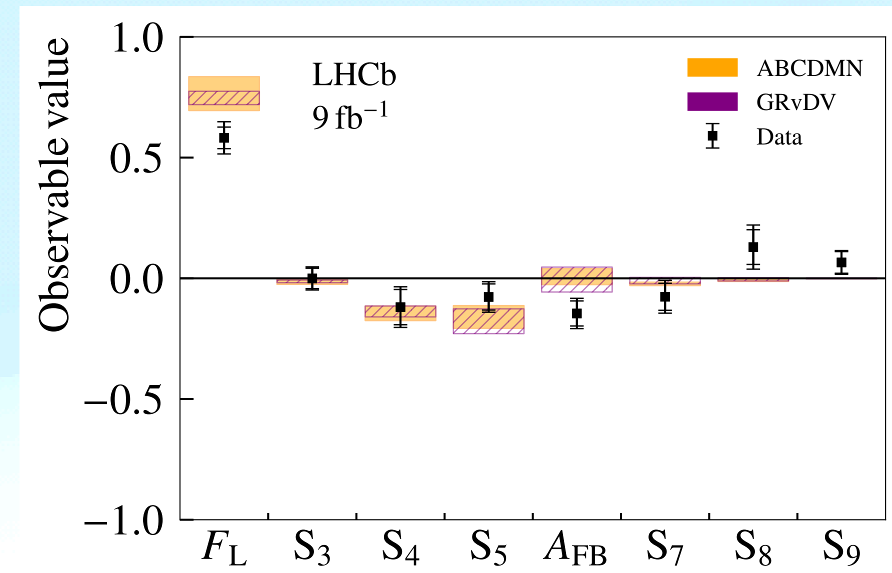


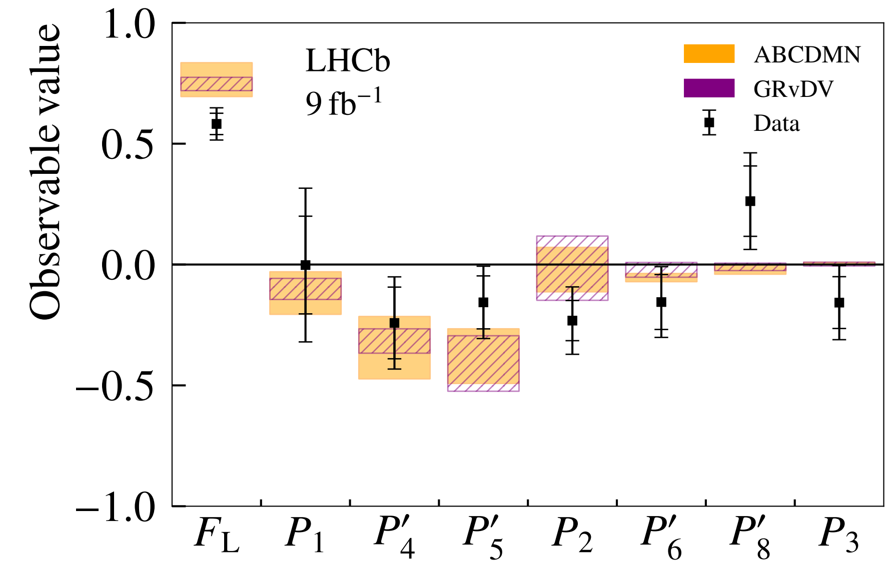
Angular analysis of $B^0 \to K^{*0}e^+e^-$ decays

4D unbinned weighted fit to the mass and angular distributions



Angular observables measured in q^2 [1.1, 6.0] GeV$^2/c^4$





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Overall good agreement with SM predictions

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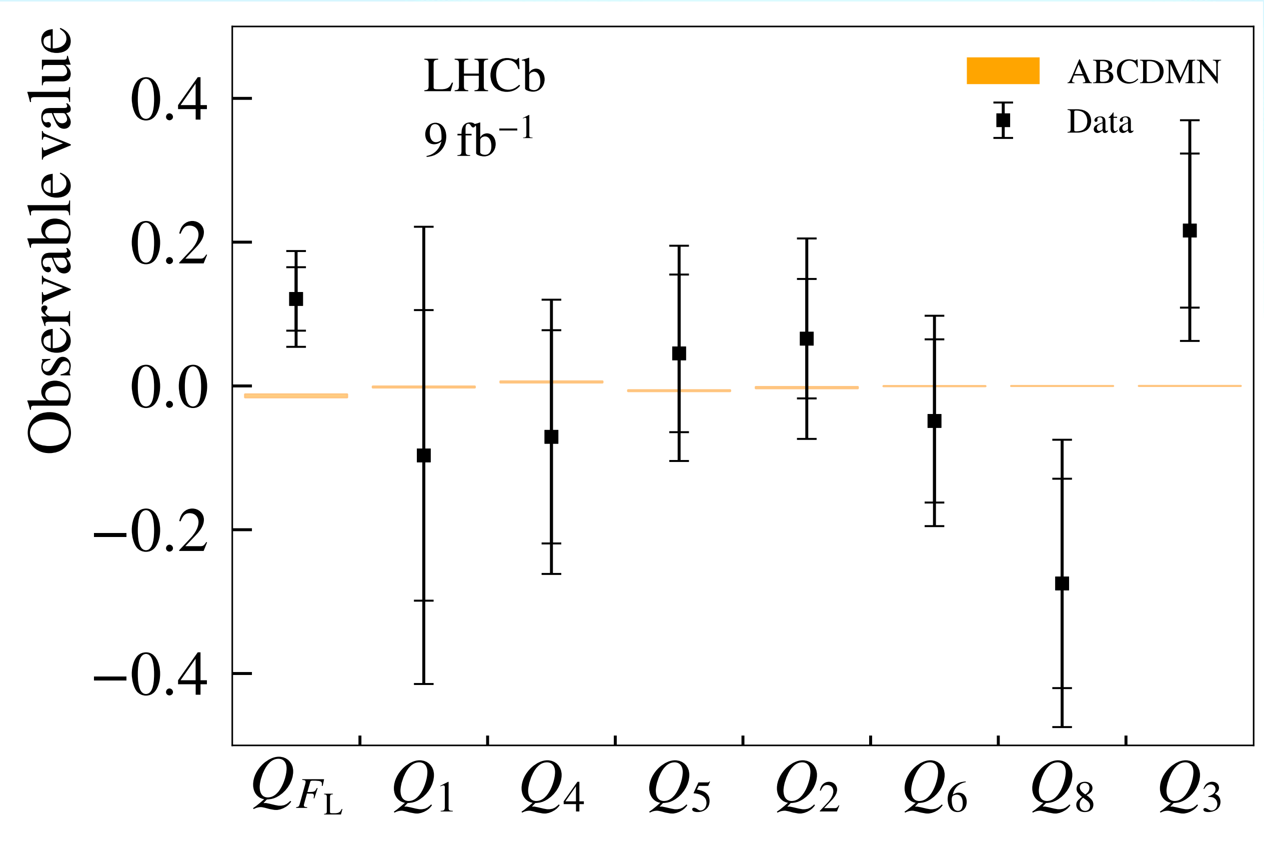
Angular analysis of $B^0 \to K^{*0} e^+ e^-$ decays

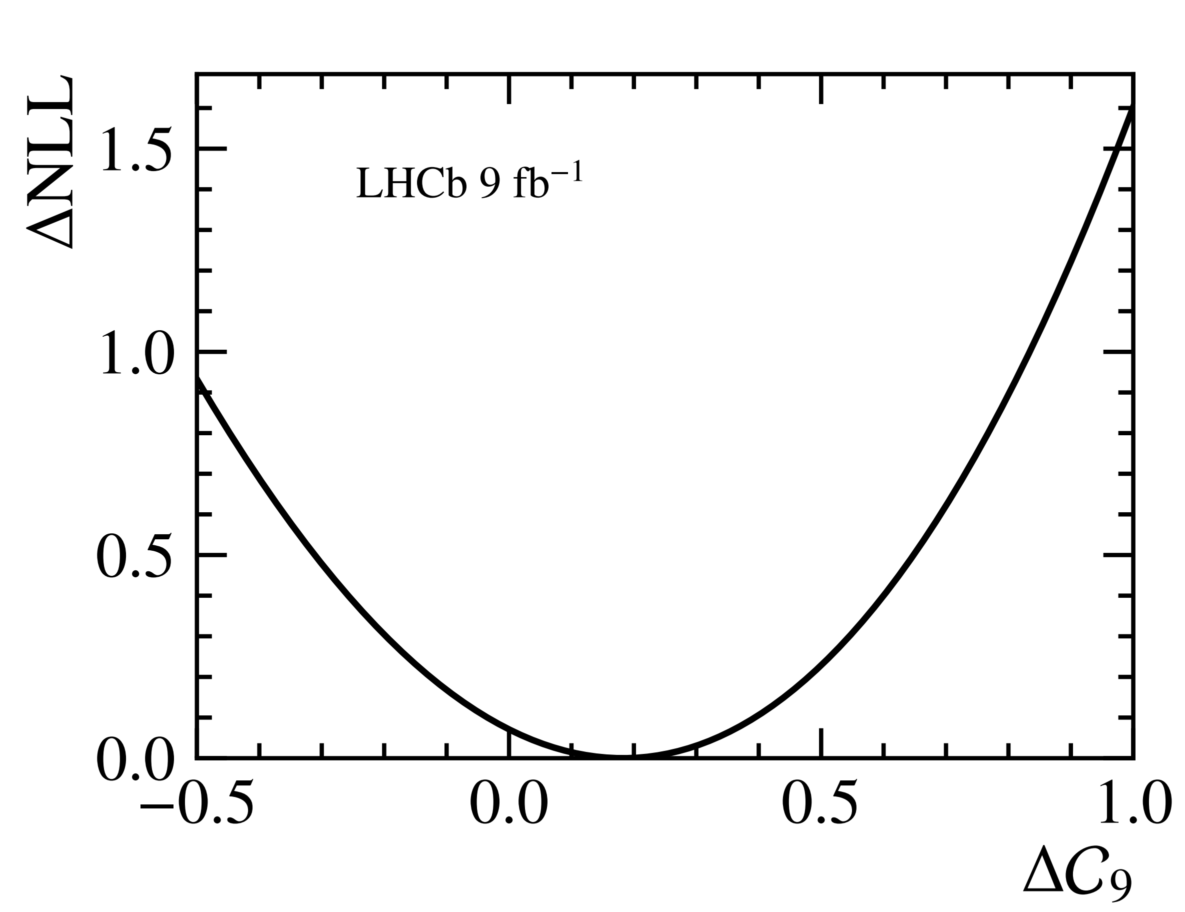
Lepton Flavour Universality observables are derived using $Q_i = P_i^{(\mu)} - P_i^{(e)}$



A global fit with all angular observables is performed varying $Re(C_9)$

$$\Delta C_9 = C_9^{(\mu)} - C_9^{(e)}$$

Local and non-local hadronic contributions are shared



Results are consistent with the LFU hypothesis

ΔC_9 consistent with zero

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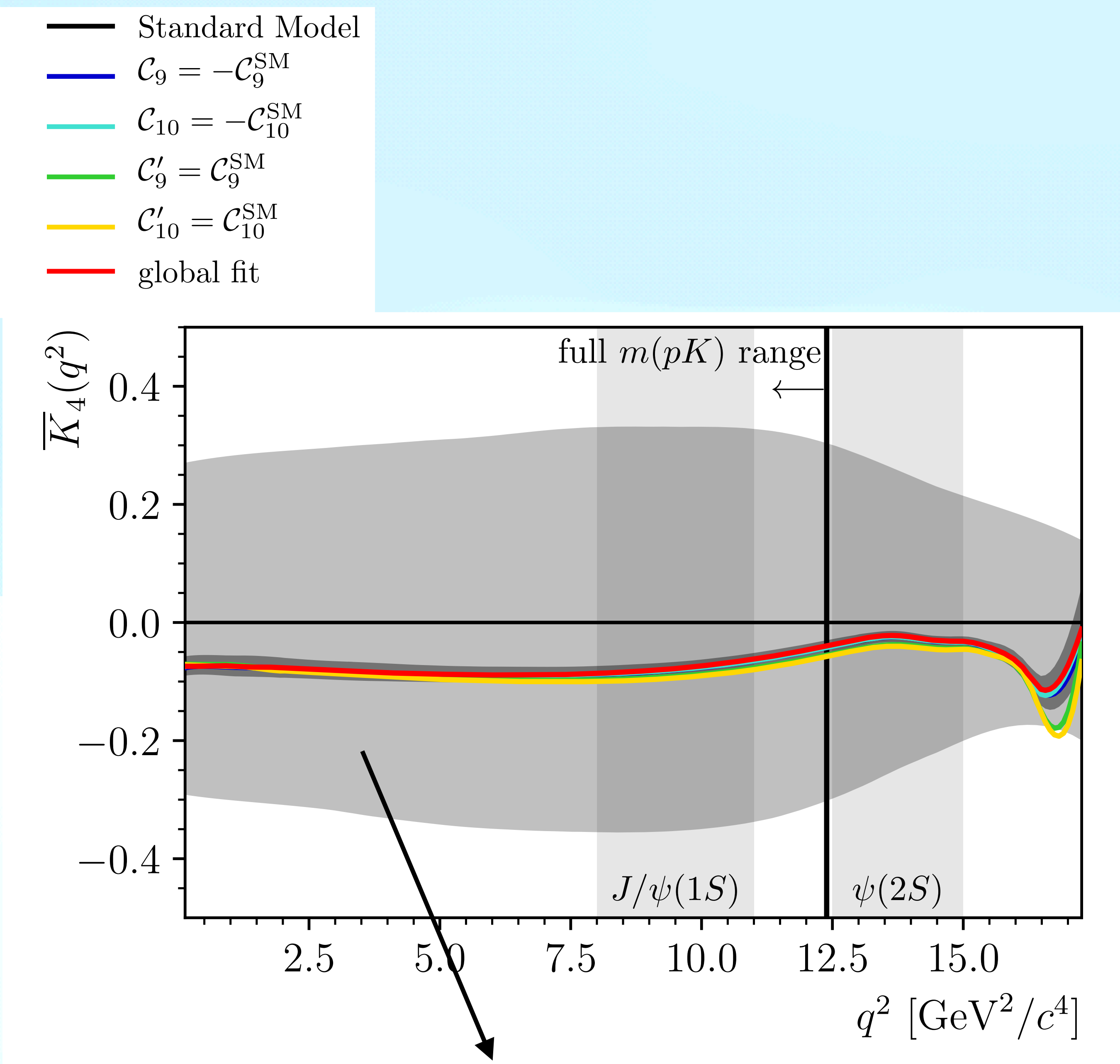
Angular analysis of $B^0 \to K^{*0}e^+e^-$ decays

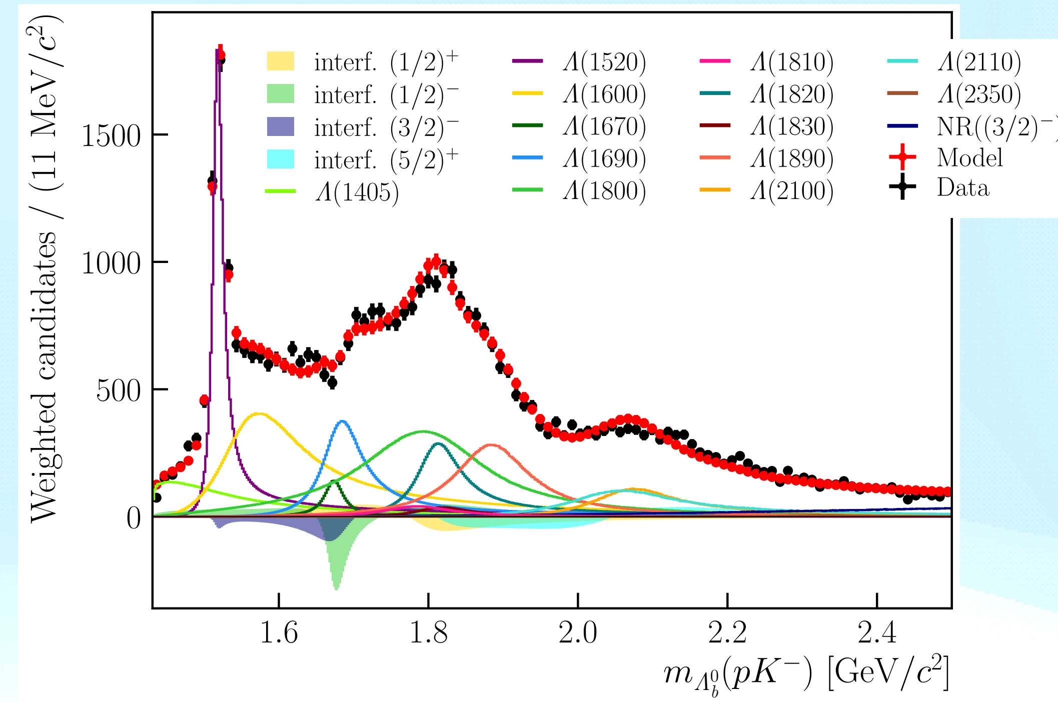
- Systematics
  - Large source is due to modelling the DSL (double semi-leptonic bkg.) and combinatorial background shape

	F_L	P_1	P_4'	P_5'	P_2	P_6'	P_8'	P_3
DSL and comb.	0.690	0.865	0.488	0.611	0.952	0.244	0.813	0.715
Part. reco.	0.153	0.218	0.086	0.152	0.145	0.049	0.055	0.111
Had. misid.	0.378	0.574	0.182	0.264	0.342	0.408	0.168	0.358
Effective acceptance	0.400	0.413	0.469	0.462	0.463	0.576	0.447	0.332
Signal mass modelling	0.255	0.159	0.136	0.169	0.310	0.061	0.064	0.152
Residual backgrounds	0.180	0.133	0.066	0.117	0.288	0.041	0.042	0.119
S-wave component	0.352	0.098	0.176	0.110	0.285	0.207	0.012	0.201
B^+ veto	0.501	0.408	0.278	0.373	0.516	0.217	0.207	0.373
Fit bias	0.001	0.009	0.043	0.027	0.069	0.013	0.015	0.027
Total	1.129	1.231	0.795	0.935	1.338	0.810	0.970	0.989

Analysis of $\Lambda_b^0 \to pK^-\mu^+\mu^-$ decays



Possible values obtained from the varying the phase, given the unknown phase of Λ from QCD, is represented by the lighter gray band



- A more complete understanding of the different contributing states needed.

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