Lepton Flavour Universality and Beyond at CMS

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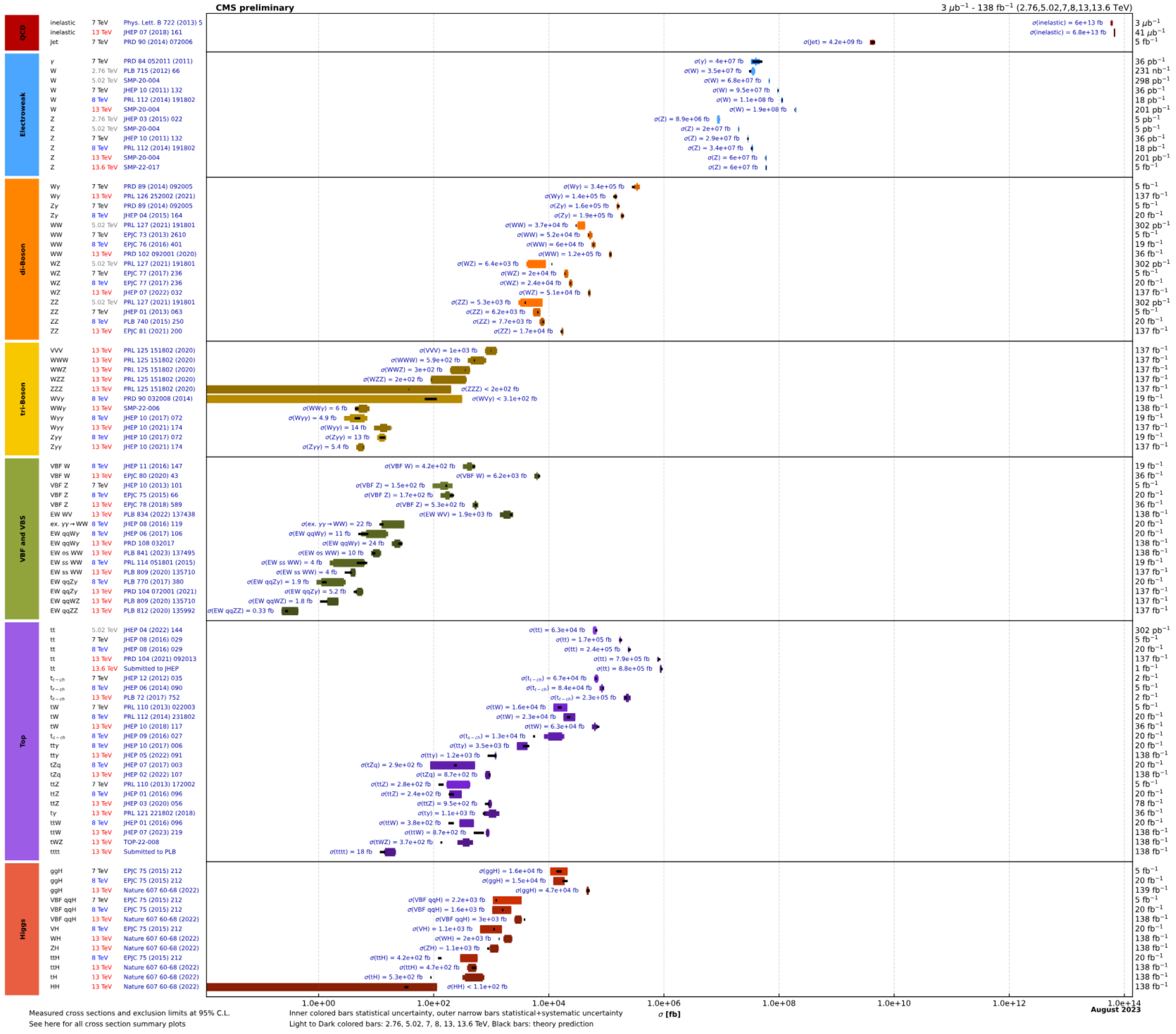
The Standard Model

- The Standard Model (SM) describes three fundamental forces of nature, and the particles connected to them.
  - **Successfully validated by experiments**

Overview of CMS cross section results [CMS Public]



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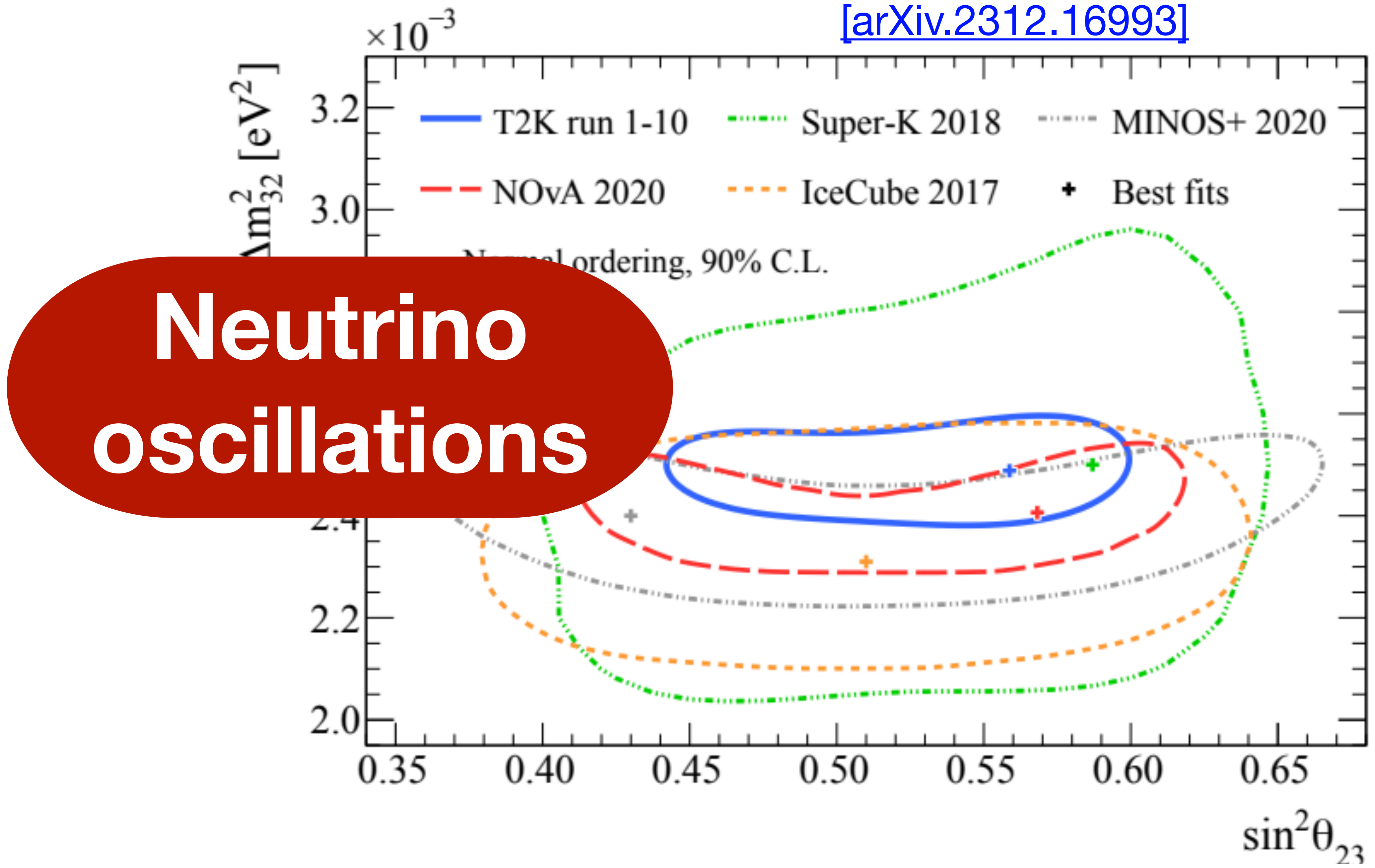
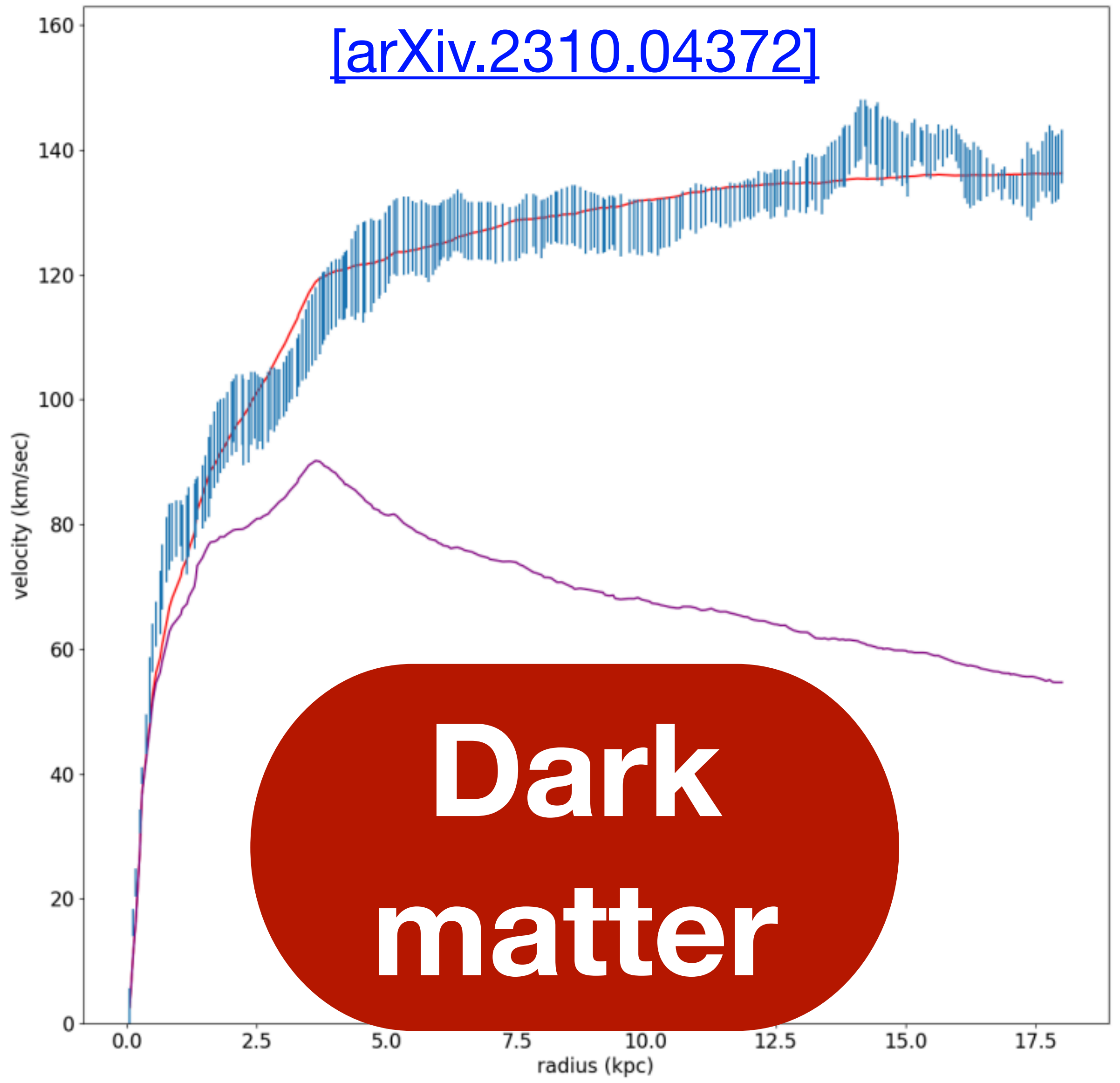
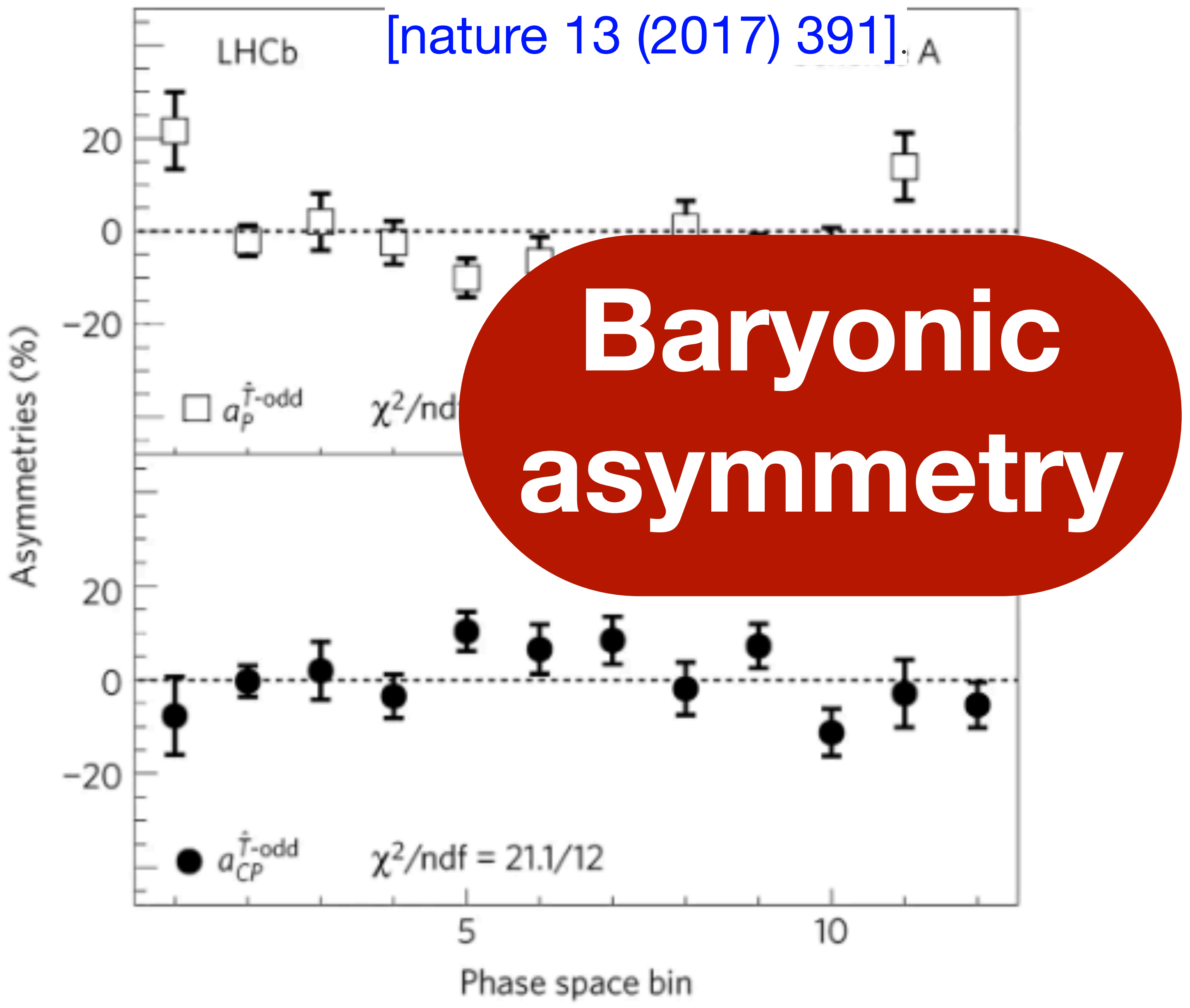
[arXiv.2312.16993]



[arXiv.2310.04372]

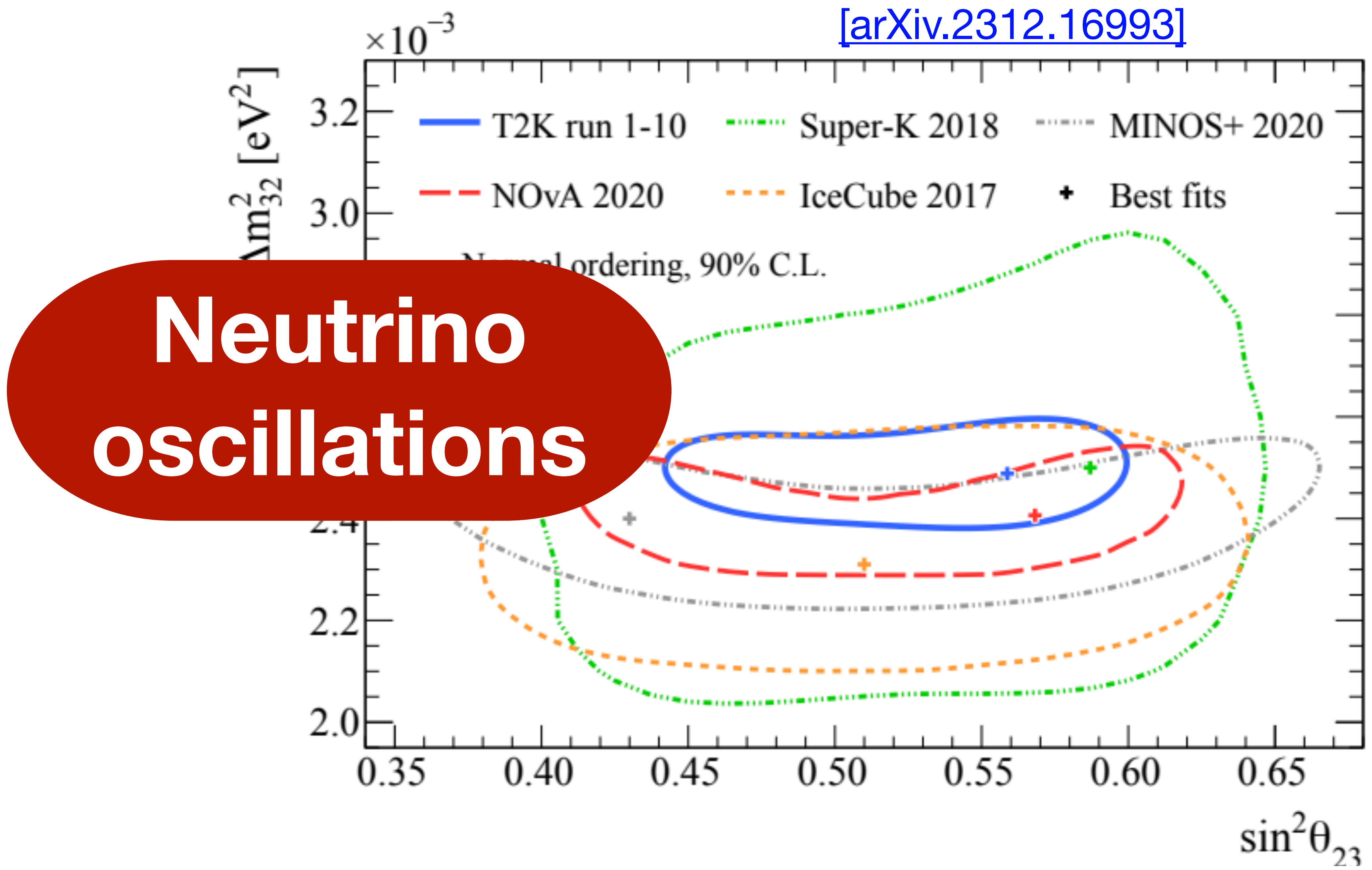


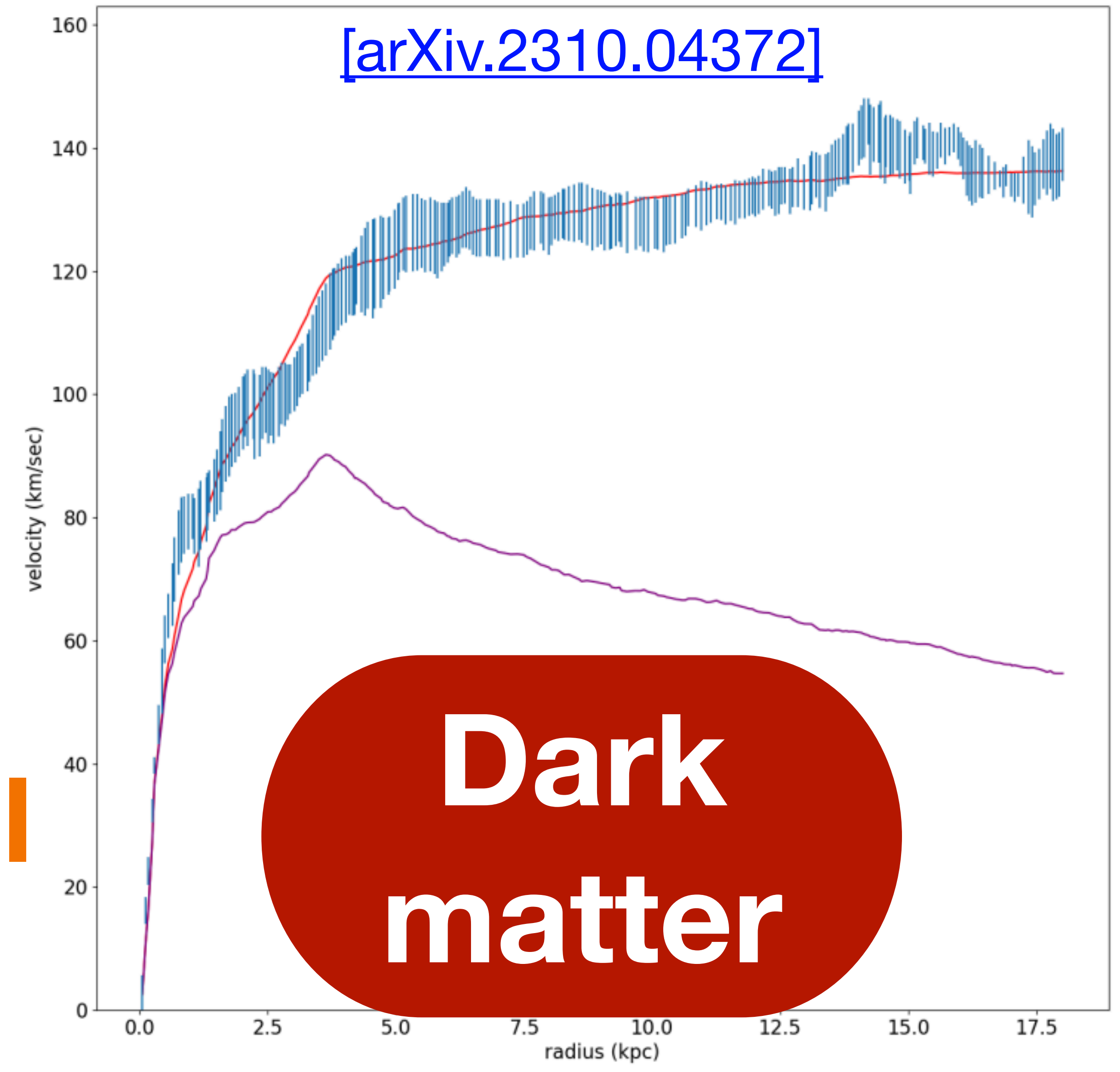
[nature 13 (2017) 391]

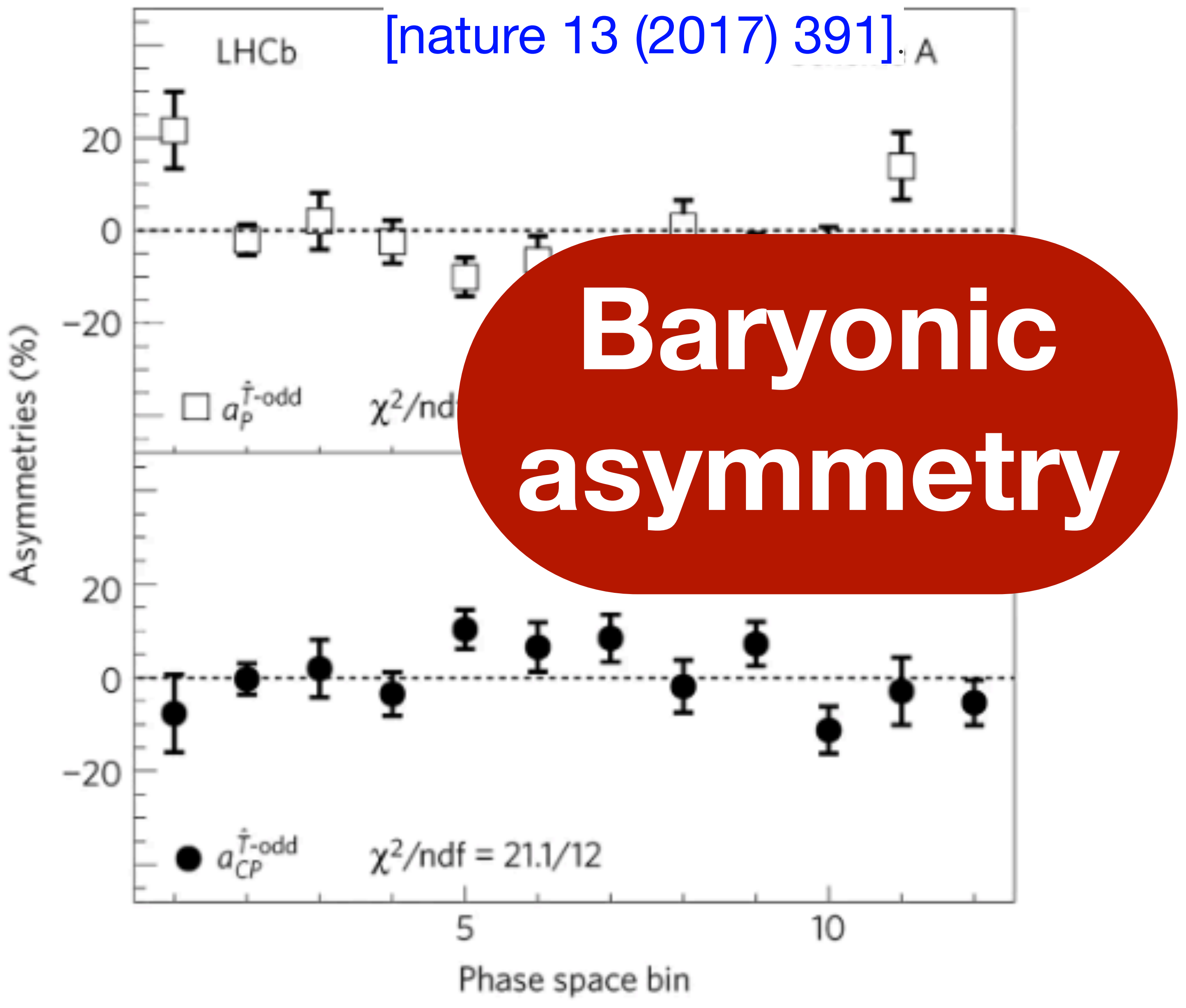


The Standard Model

- The Standard Model (SM) describes three fundamental forces of nature, and the particles connected to them.
  - Successfully validated by experiments
  - **Fails to account for several phenomena**
    - **Efforts are ongoing to test SM predictions to identify potential deviations**

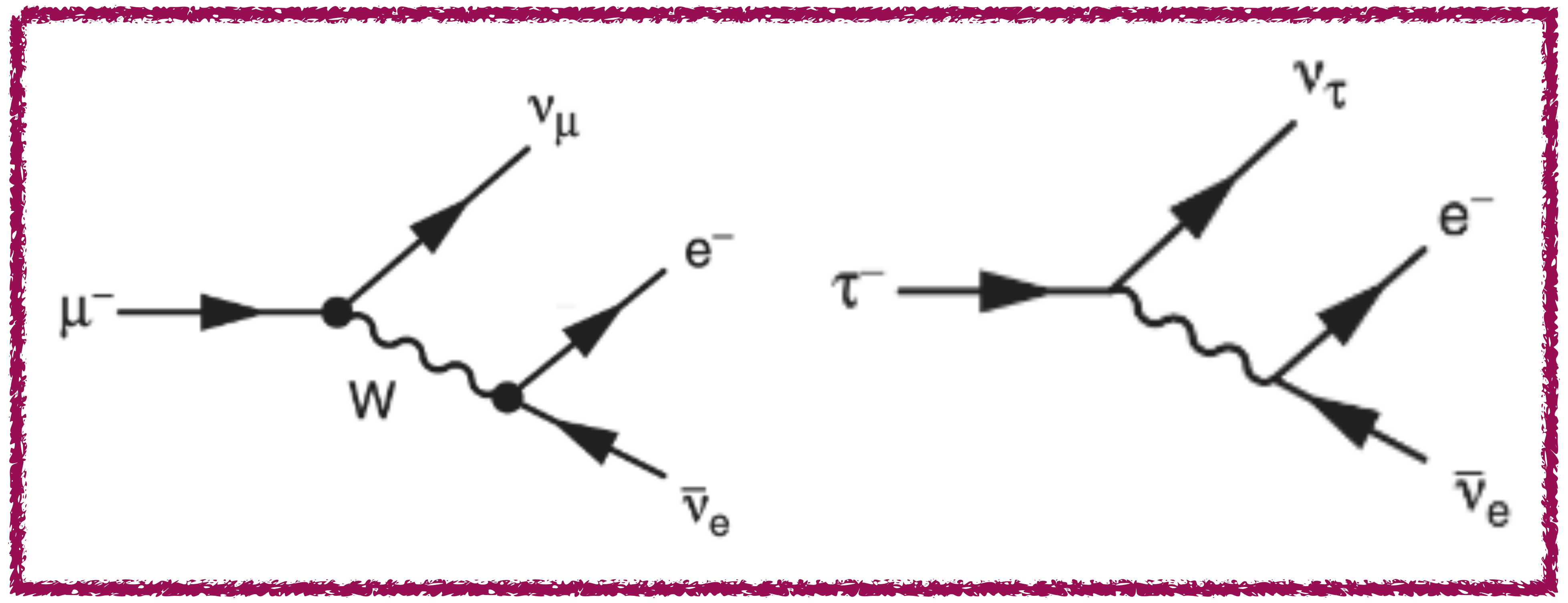






Lepton Flavour Universality

- Lepton Flavour Universality (LFU): the mediators of EW interactions (γ, W, Z) exhibit the same couplings to the three lepton families (e, μ, τ)
  - **Accidental symmetry** of the SM:
    - *Not protected by any conservation law but successfully tested in several classes of decays*
      - **Purely leptonic decays**



$$\frac{G_F^{(\tau)}}{G_F^{(\mu)}} = \frac{m_\mu^5 \tau_\mu}{m_\tau^5 \tau_\tau} \mathscr{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$$

Using measured values for [PPNP 11 (2013) 002] $\mathscr{B}, m, \tau$:

$$\frac{G_F^{(\tau)}}{G_F^{(\mu)}} = 1.0011 \pm 0.0015$$

$$\frac{G_F^{(e)}}{G_F^{(\mu)}} = 1.000 \pm 0.004$$

Lepton Flavour Universality

- Lepton Flavour Universality (LFU): the mediators of EW interactions (γ, W, Z) exhibit the same couplings to the three lepton families (e, μ, τ)
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    - *Not protected by any conservation law but successfully tested in several classes of decays*
      - Purely leptonic decays
      - **Z and W boson decays**

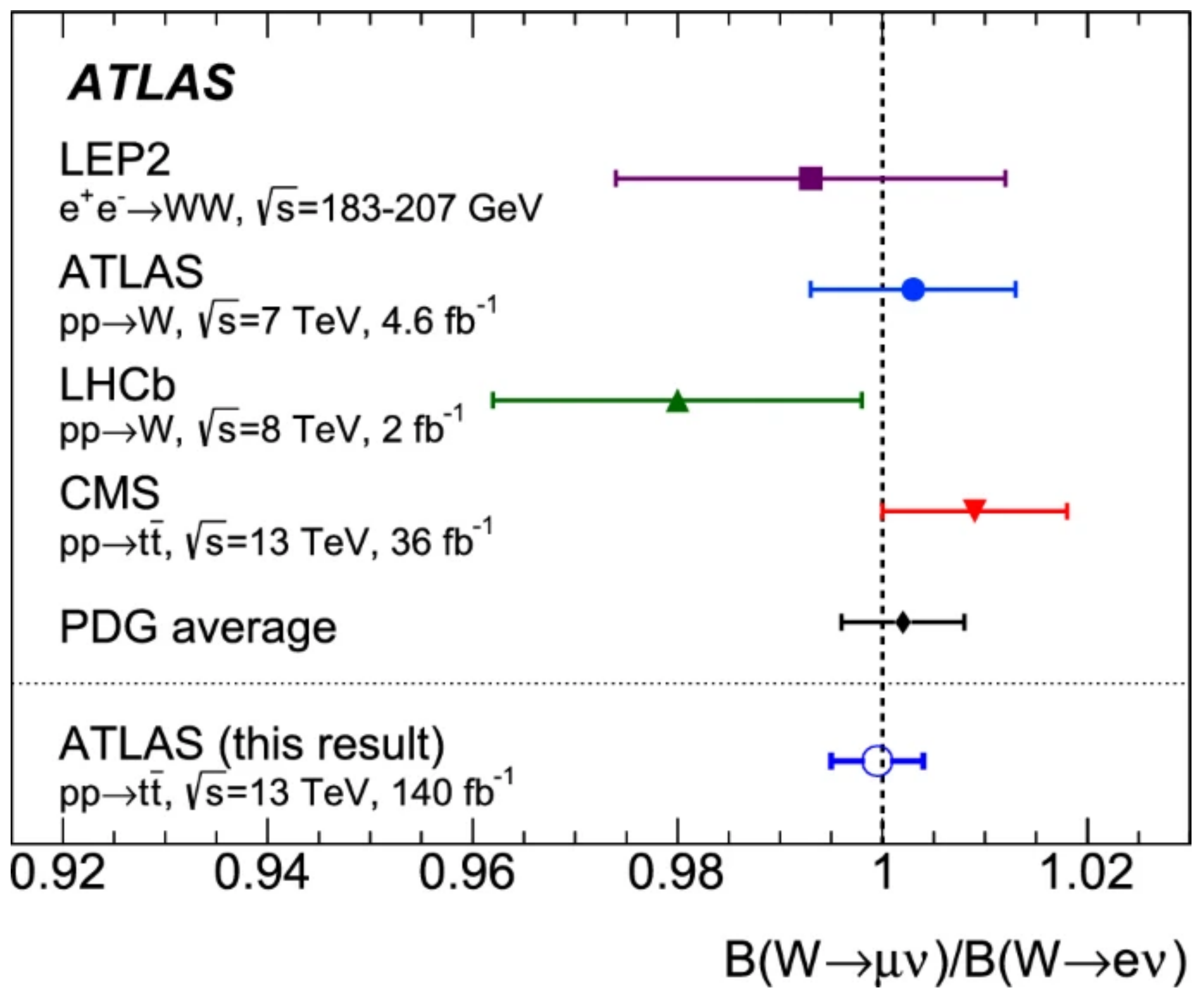
Agreement at per-mille level

$$\frac{\Gamma_{\mu\mu}}{\Gamma_{ee}} = \frac{B(Z \to \mu^+\mu^-)}{B(Z \to e^+e^-)} = 1.0009 \pm 0.0028$$

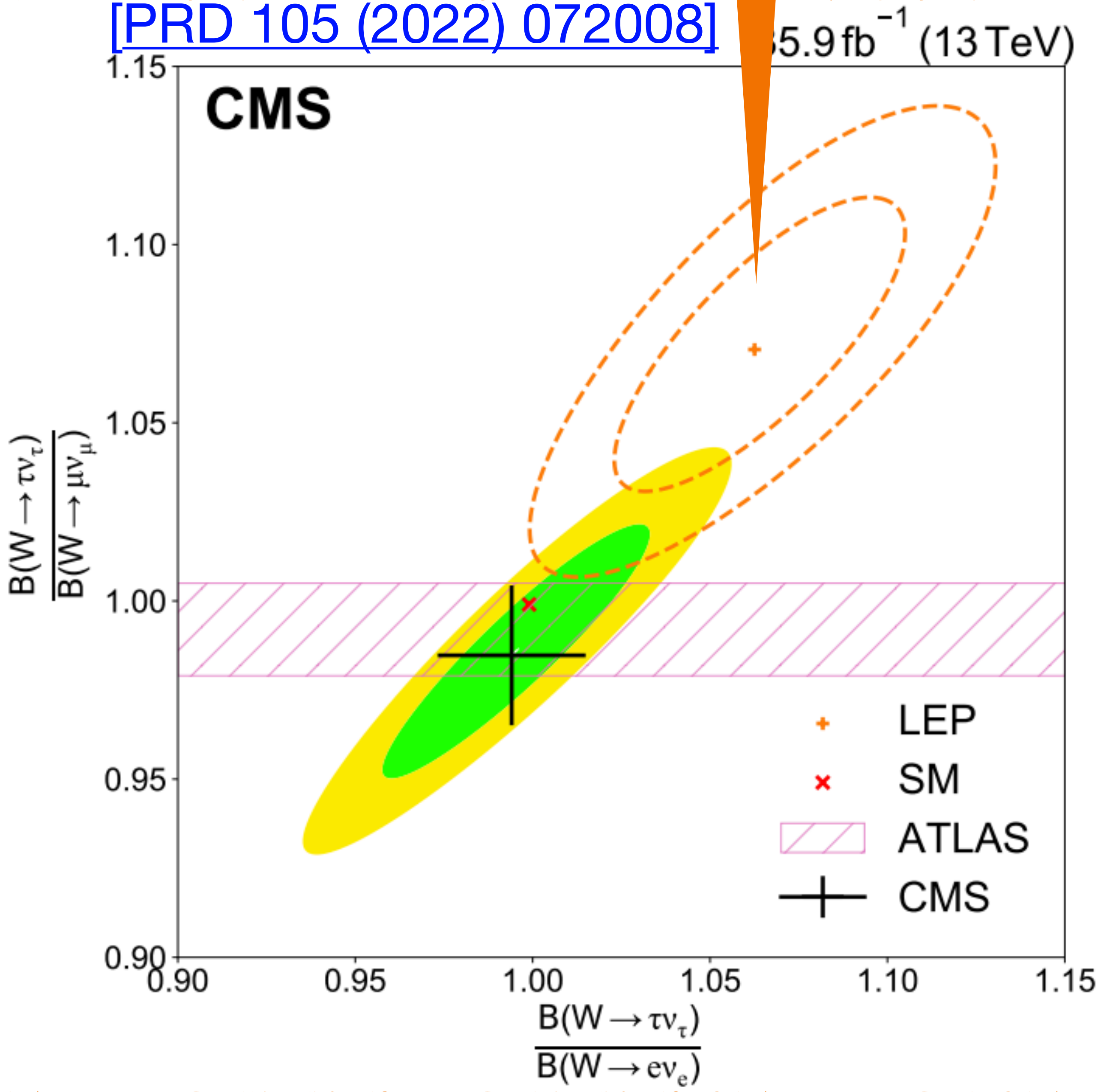
$$\frac{\Gamma_{\tau\tau}}{\Gamma_{ee}} = \frac{B(Z \to \tau^+\tau^-)}{B(Z \to e^+e^-)} = 1.0019 \pm 0.0032$$

[PR 12 (2005) 006]

[EPJC 84 (2024) 993]



[PRD 105 (2022) 072008]



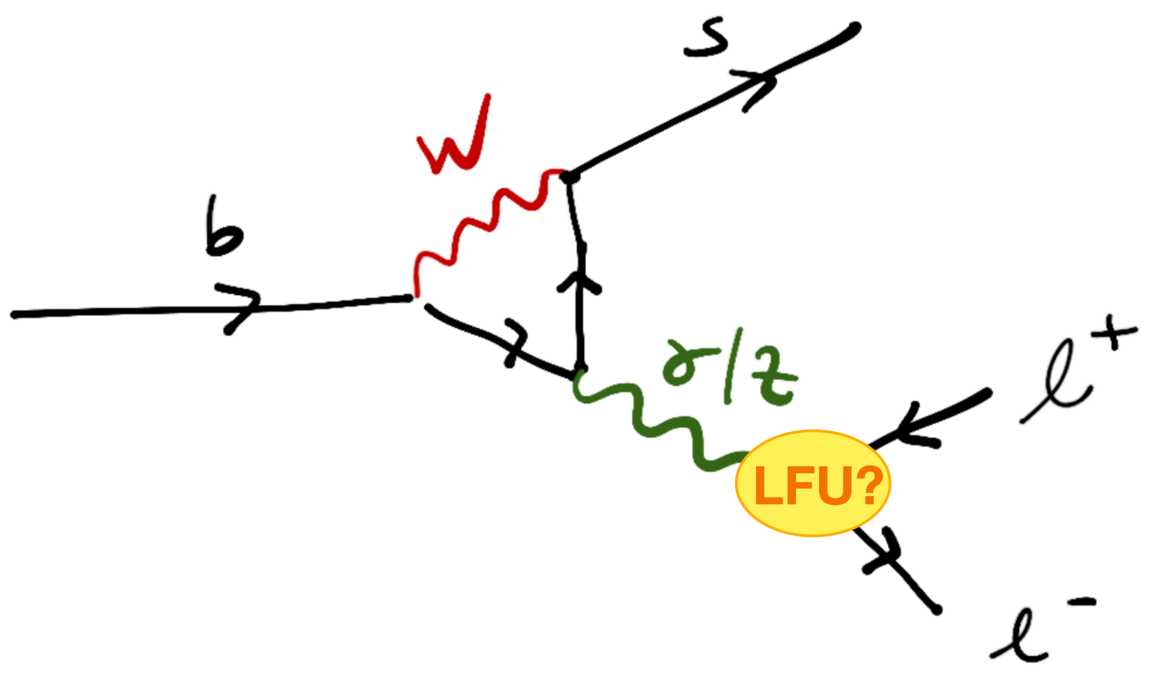
LEP $2\,\sigma$ tension solved by ATLAS and CMS

LFU in the b-sector

Therefore LFU is assumed as a symmetry in the SM

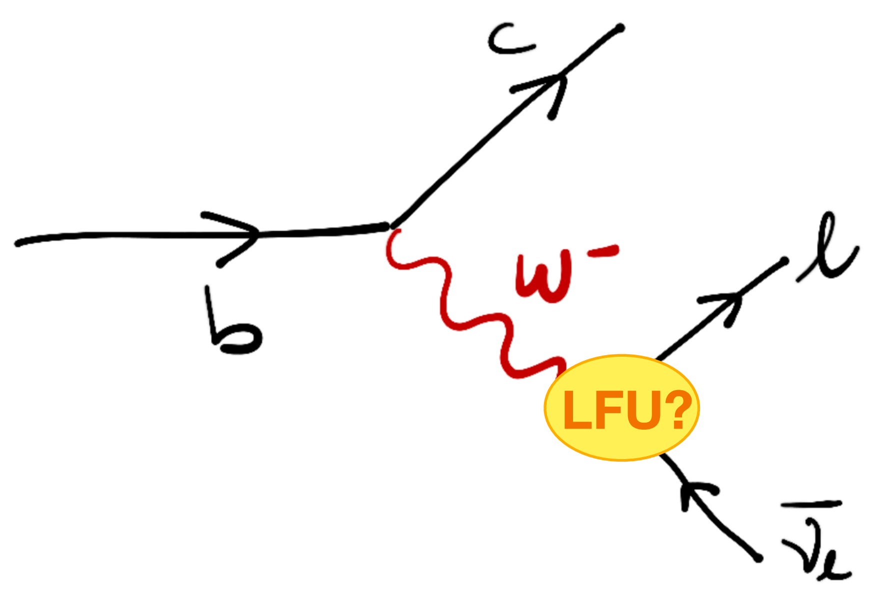
But is LFU also valid in semi-leptonic b-decays?

FCNC: $b \to s l^+ l^-$



- Loop-level → smaller BR
- ν-less

FCCC: $b \to c l^- \bar{\nu}_l$



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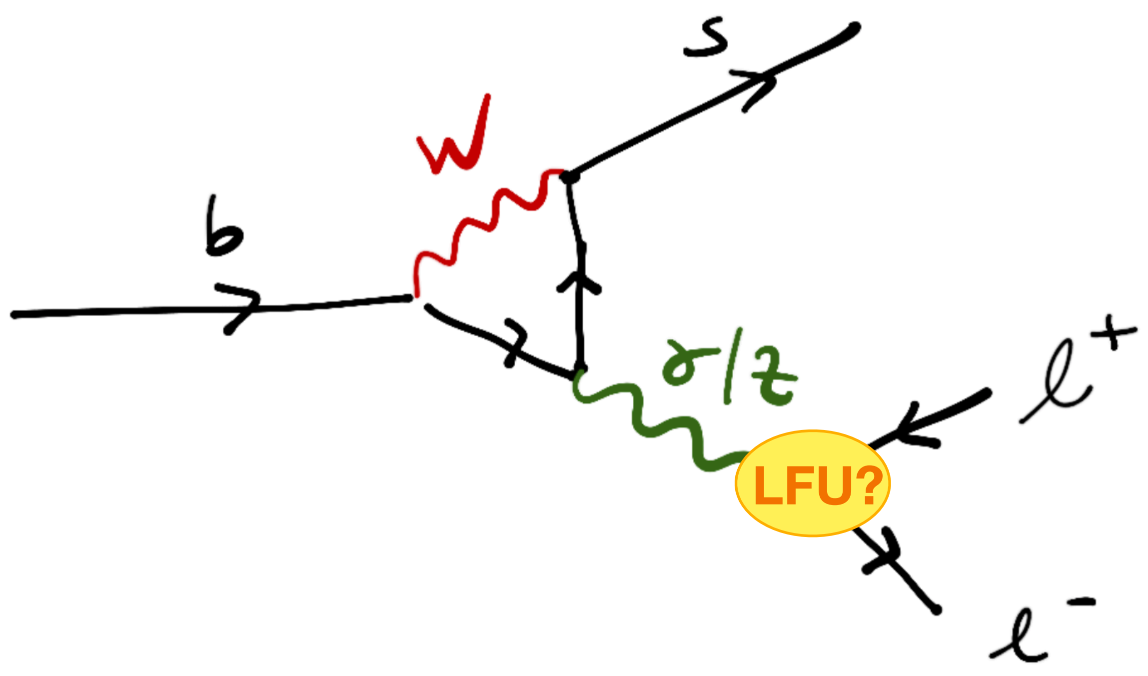

- Loop-level → smaller BR
- ν-less

$$R_{H_s} = \frac{\mathcal{B}(h_b \to h_s \mu^+ \mu^-)}{\mathcal{B}(h_b \to h_s e^+ e^-)}$$

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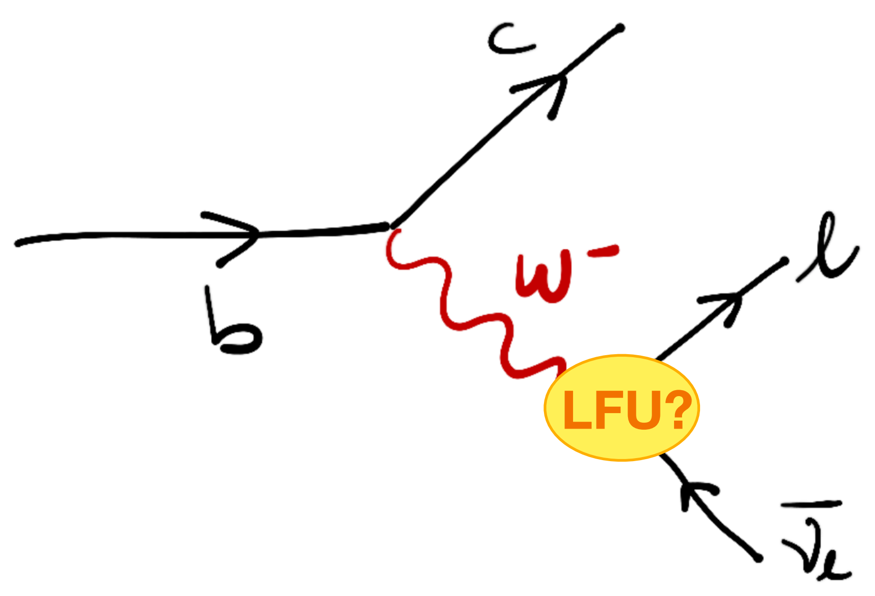

- Tree-level → large BR
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$$R_{H_c} = \frac{\mathcal{B}(h_b \to h_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(h_b \to h_c \mu^- \bar{\nu}_\mu)}$$

Ratio based observables are the best for LFU tests:

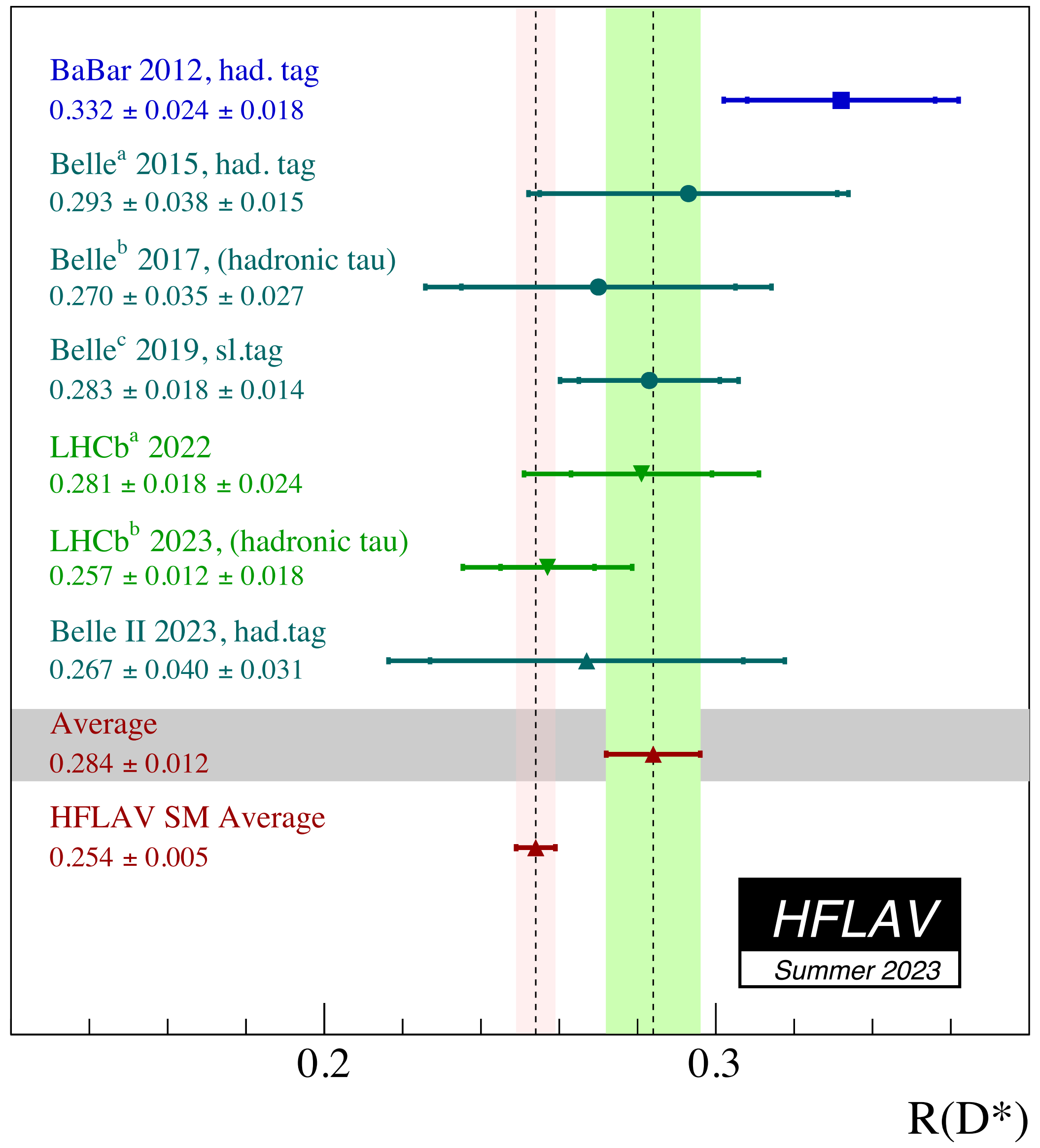
- Cancellation of form factors (partial) and CKM matrix elements
- Reduced dependency on efficiencies and systematic uncertainties

Experimental status of LFU tests

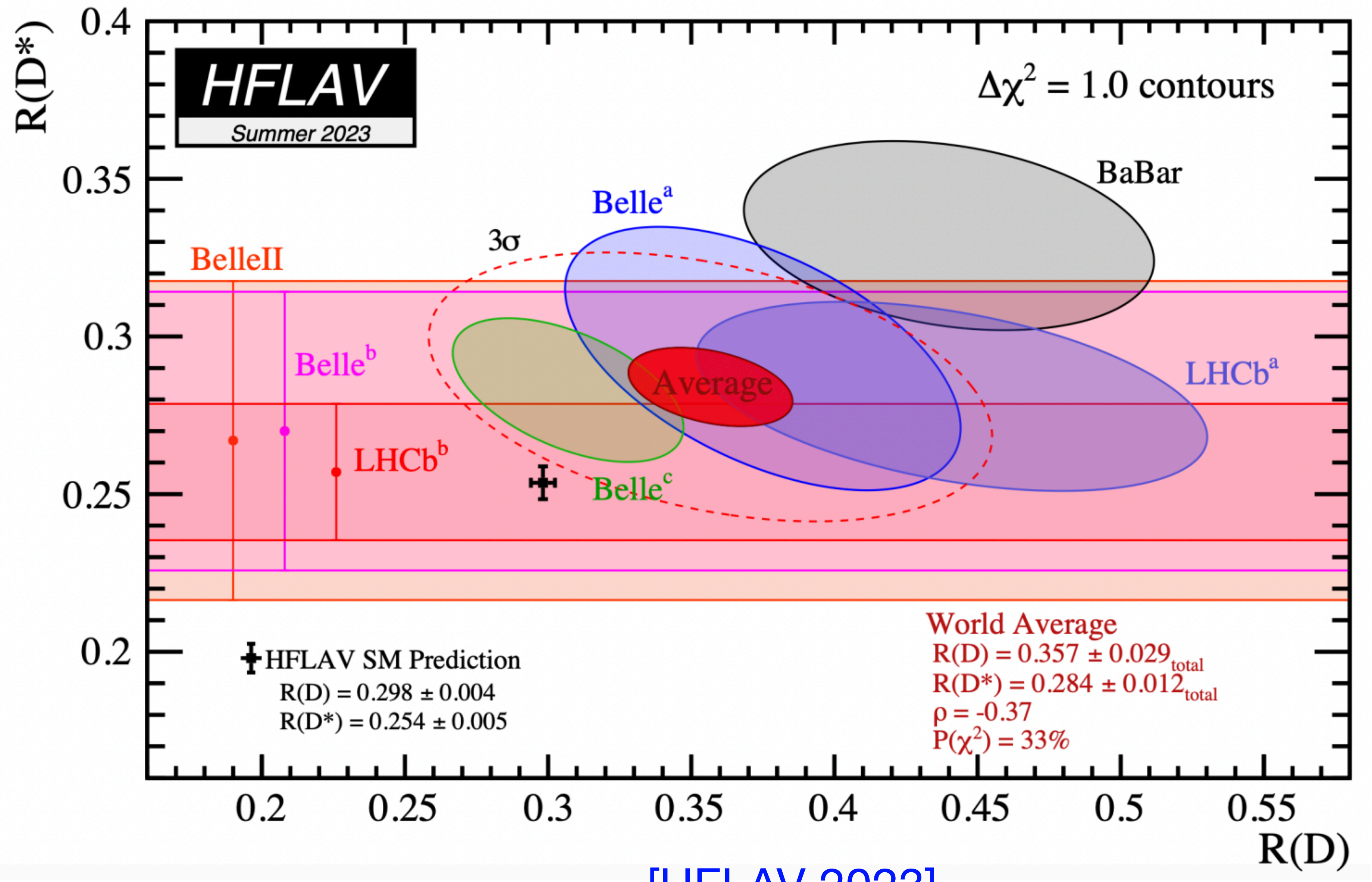
- LFU in b-physics is a very active field.

Recent results in the **FCCC** channel : $b \to cl\nu$

$$R(D^{(*)}) = \frac{\mathscr{B}(B \to D^{(*)}\tau^+\nu)}{\mathscr{B}(B \to D^{(*)}\mu^+\nu)}$$



[HFLAV 2023]



[HFLAV 2023]

$3\,\sigma$ deviation from the SM prediction!

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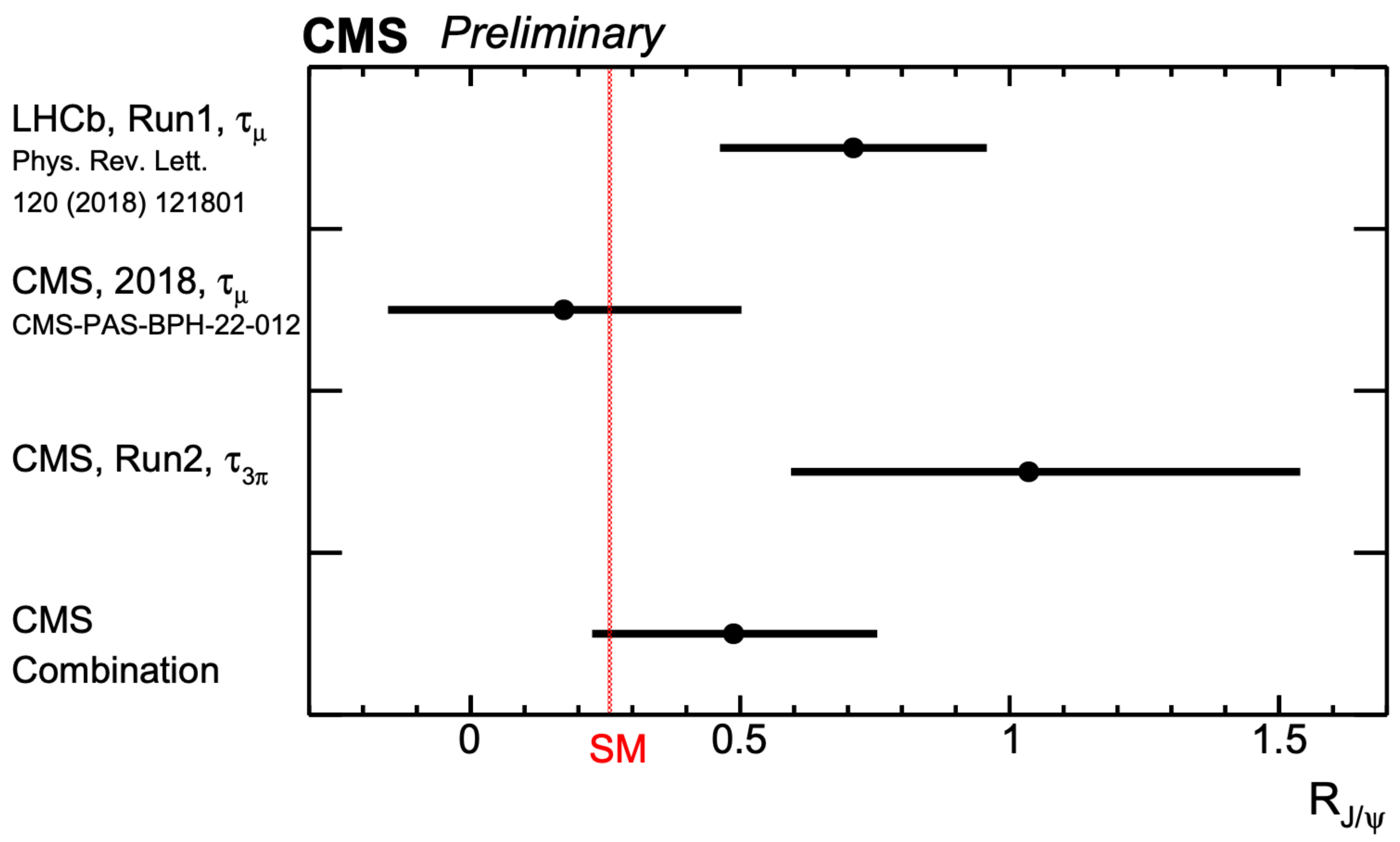
$$R(J/\psi) = \frac{\mathscr{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathscr{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$



[PRD 111 (2025) L051102] [CMS-PAS-BPH-23-001]

Compatible with SM predictions

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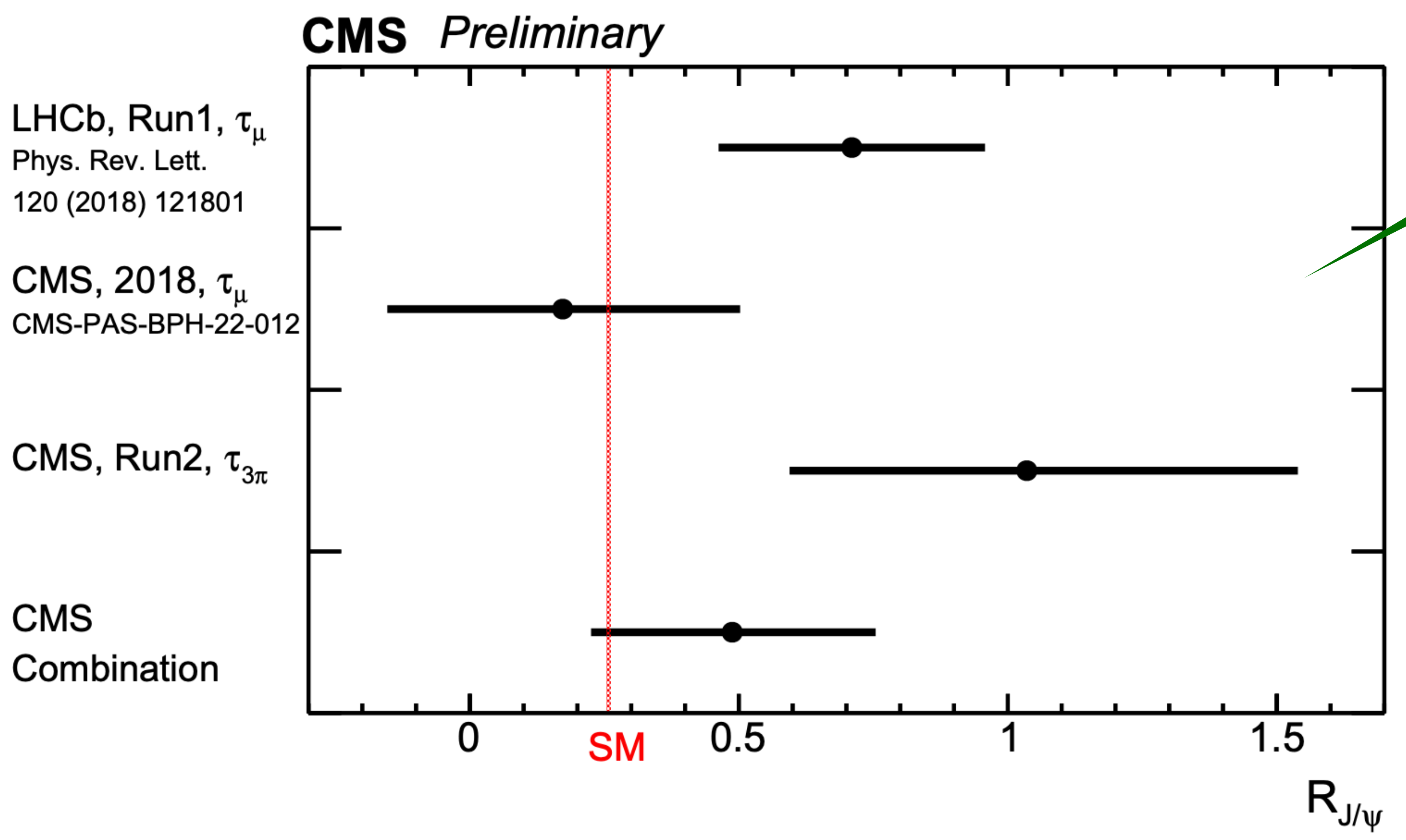

[PRD 111 (2025) L051102] [CMS-PAS-BPH-23-001]

More details about this analysis later!!

Compatible with SM predictions

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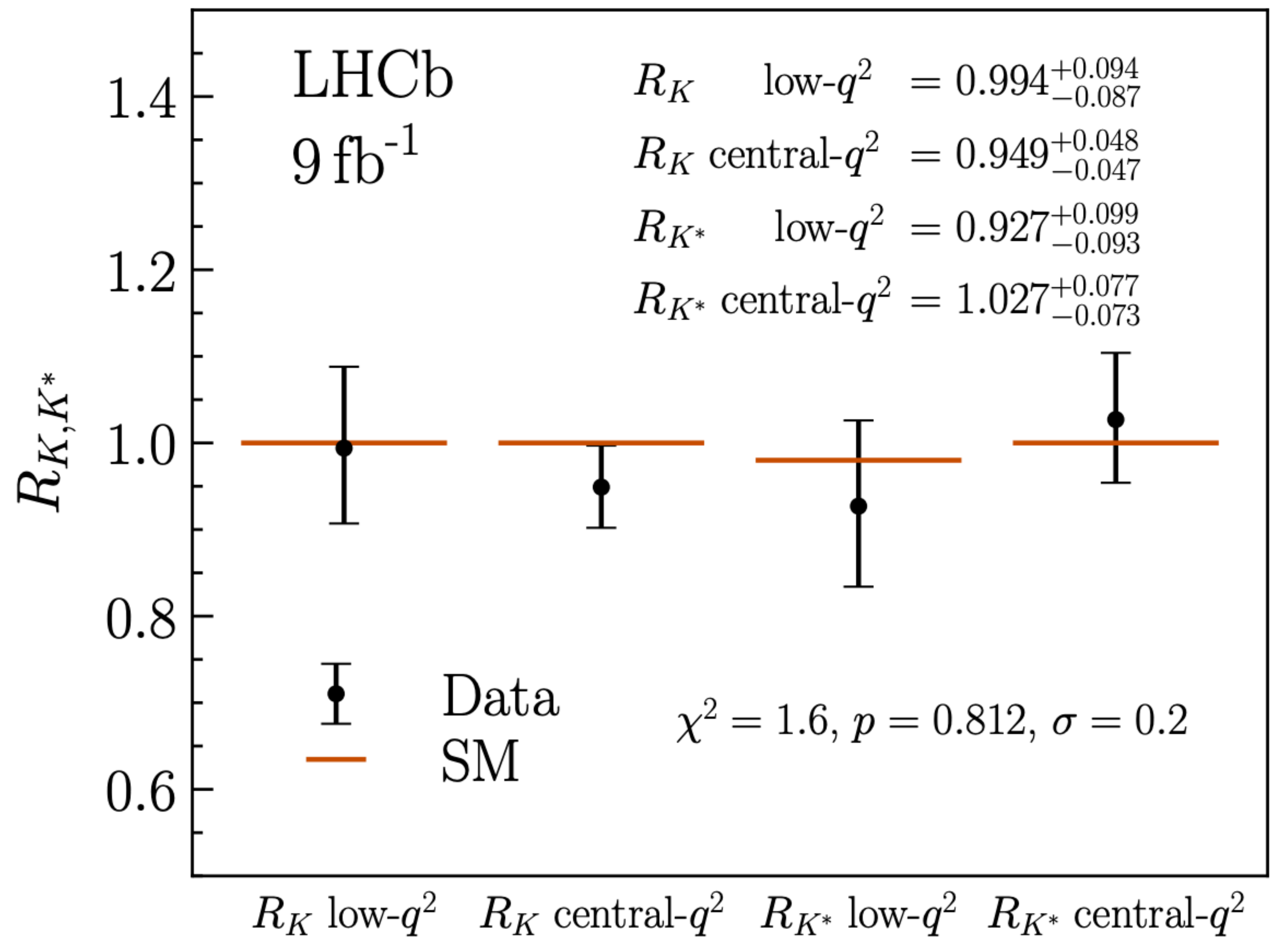
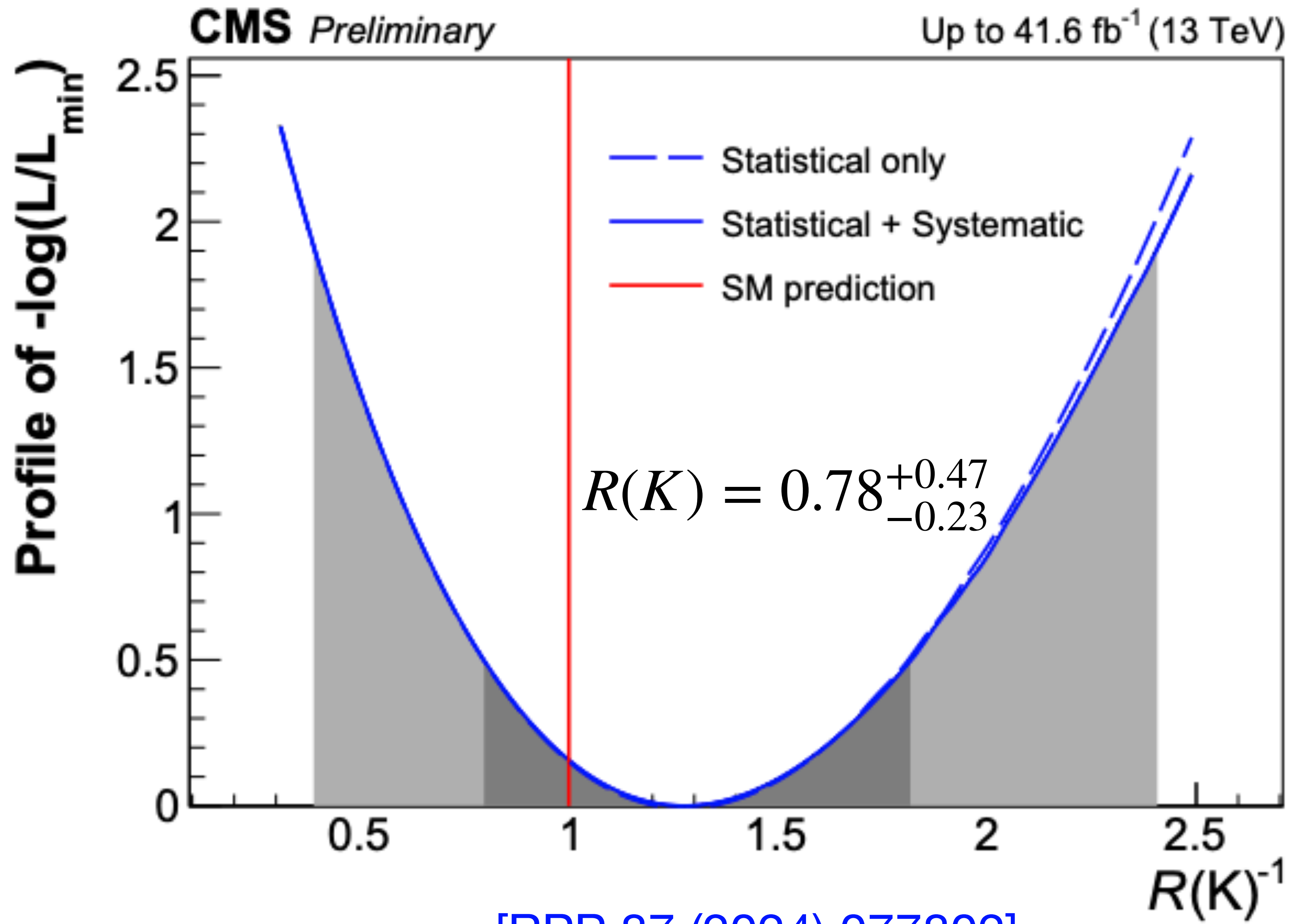
Recent results in the **FCNC** channel : $b \to sl^+l^-$

$$R(K) = \frac{\mathscr{B}(B^+ \to K^+\mu^+\mu^-)}{\mathscr{B}(B^+ \to K^+e^+e^-)}$$



[PRD 108 (2023) 032002] [PRL 131 (2023) 051803]



[RPP 87 (2024) 077802]

Compatible with SM predictions

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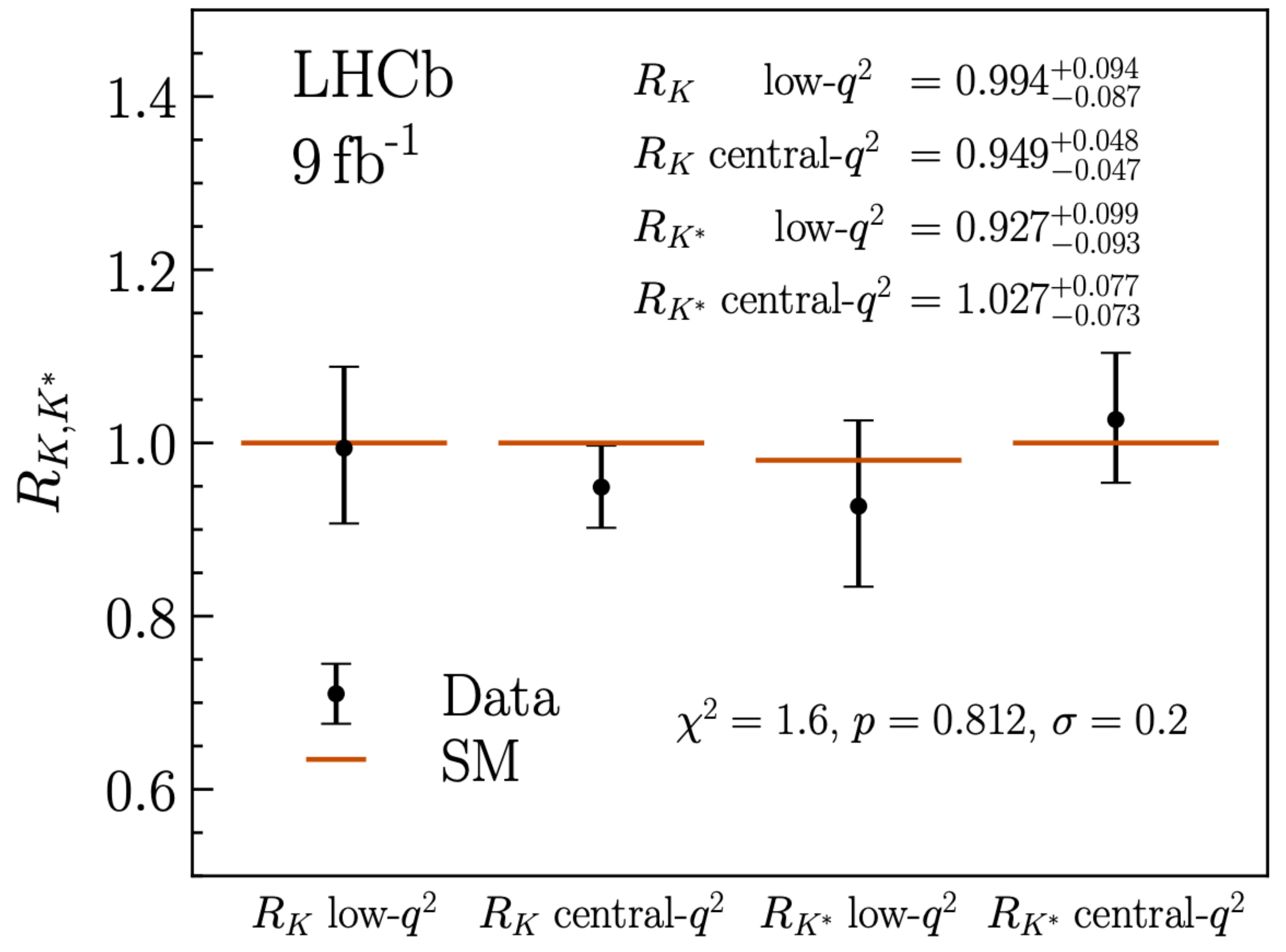
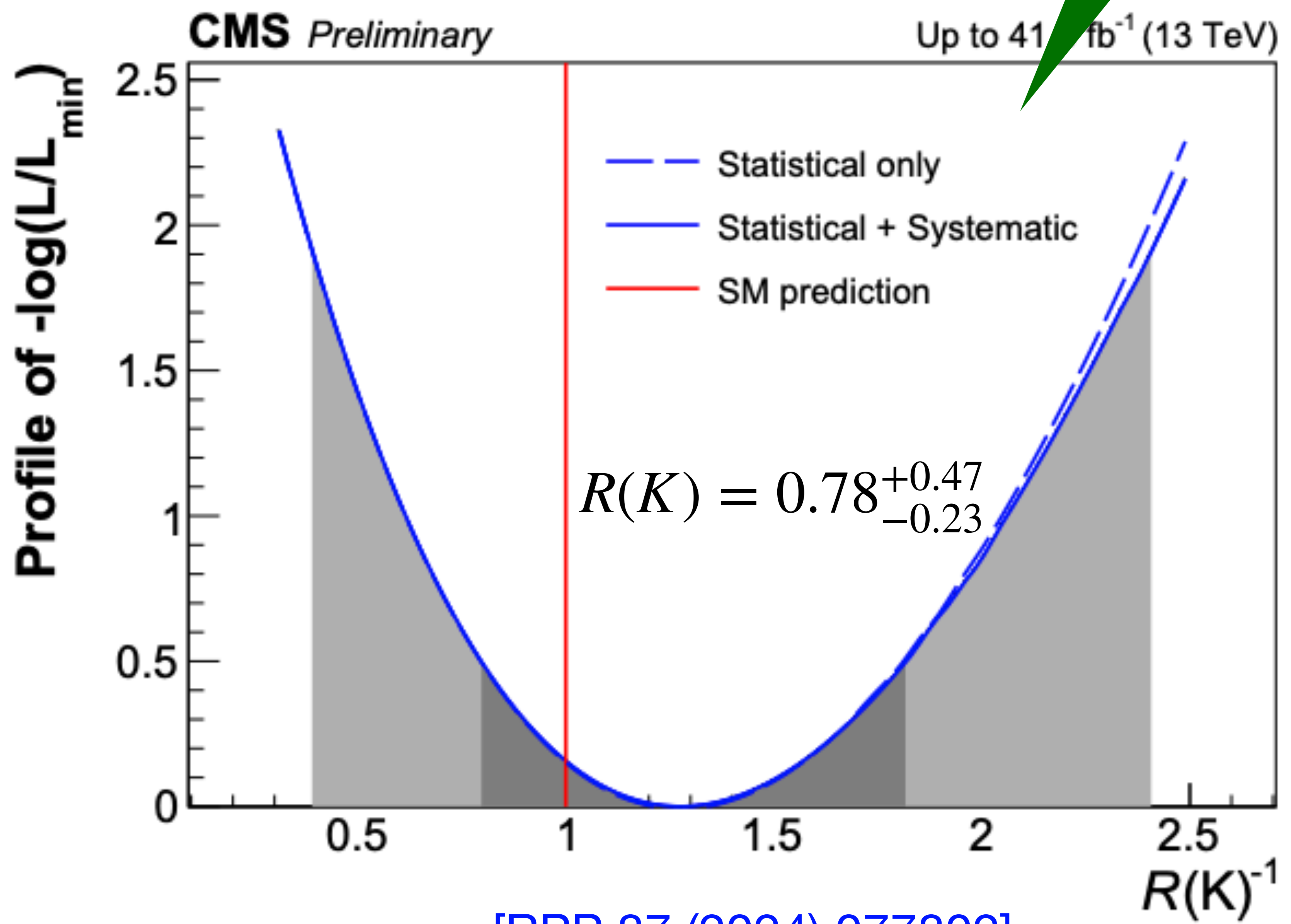


[PRD 108 (2023) 032002] [PRL 131 (2023) 051803]

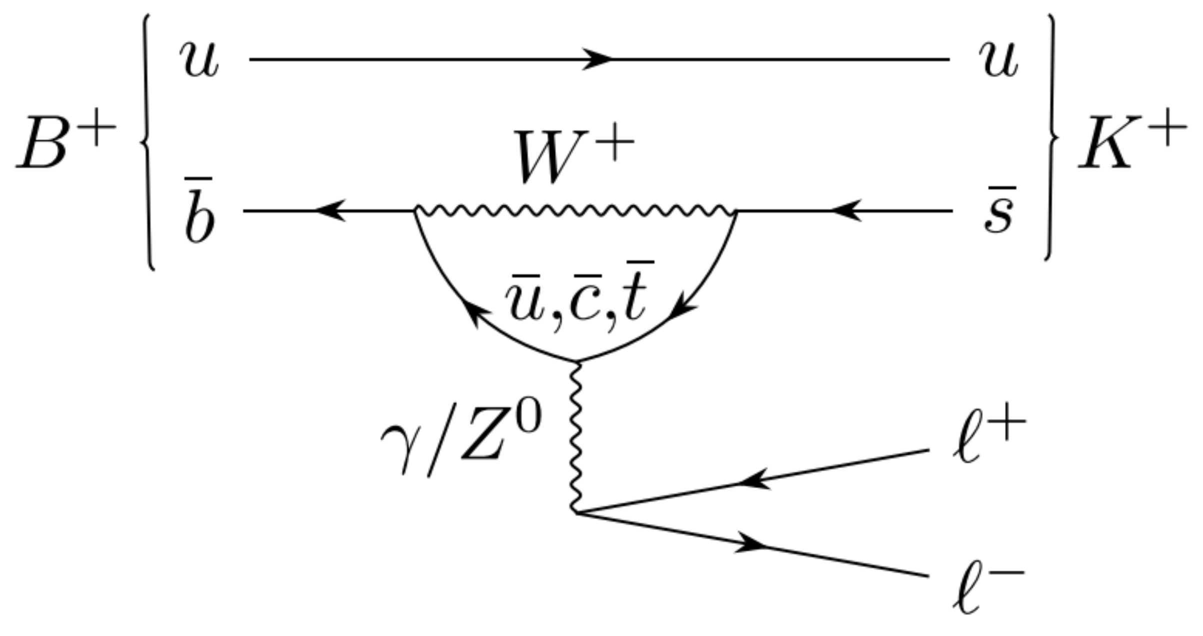


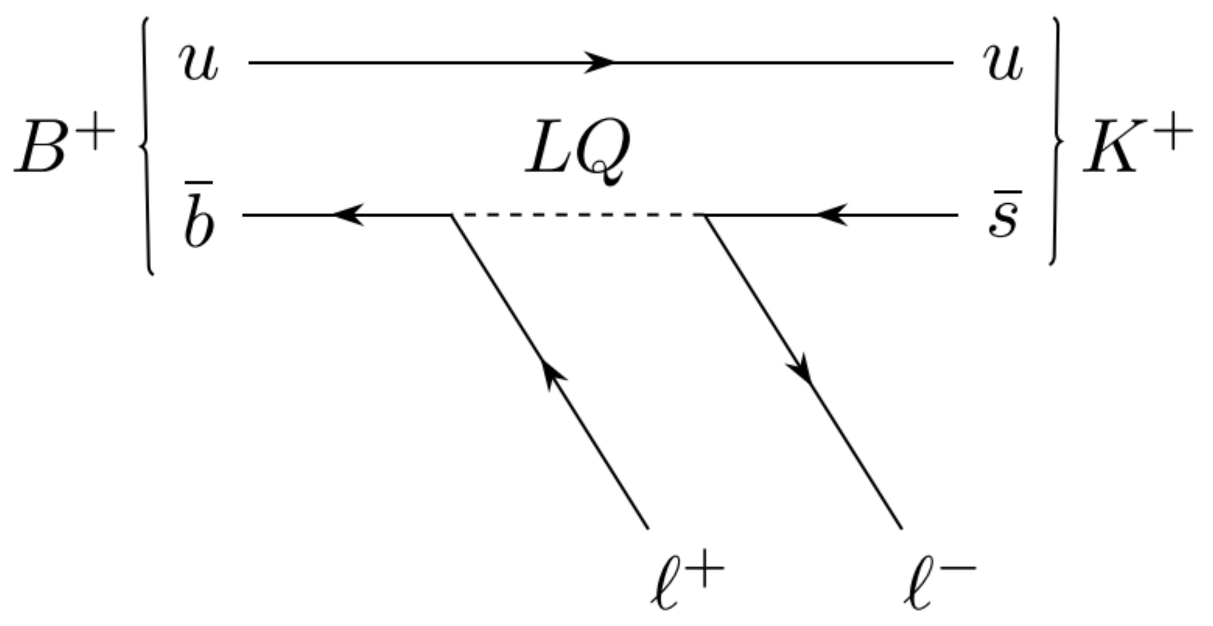
[RPP 87 (2024) 077802]

Compatible with SM predictions

Beyond LFU Tests

- The FCNC $b \to s l^+ l^-$ **rare** decay is a powerful probe for New Physics (NP)
  - Not only tests LFU via ratios like $R(K)$
  - Sensitive to virtual contributions from heavy new particles, like Z′, leptoquarks (LQ)…
  - **Complement LFU tests with independent, theoretically clean probes of the same NP**





Branching Ratios

- (Some) Interesting experimental observables:
  - **Branching Ratios / Lifetimes**

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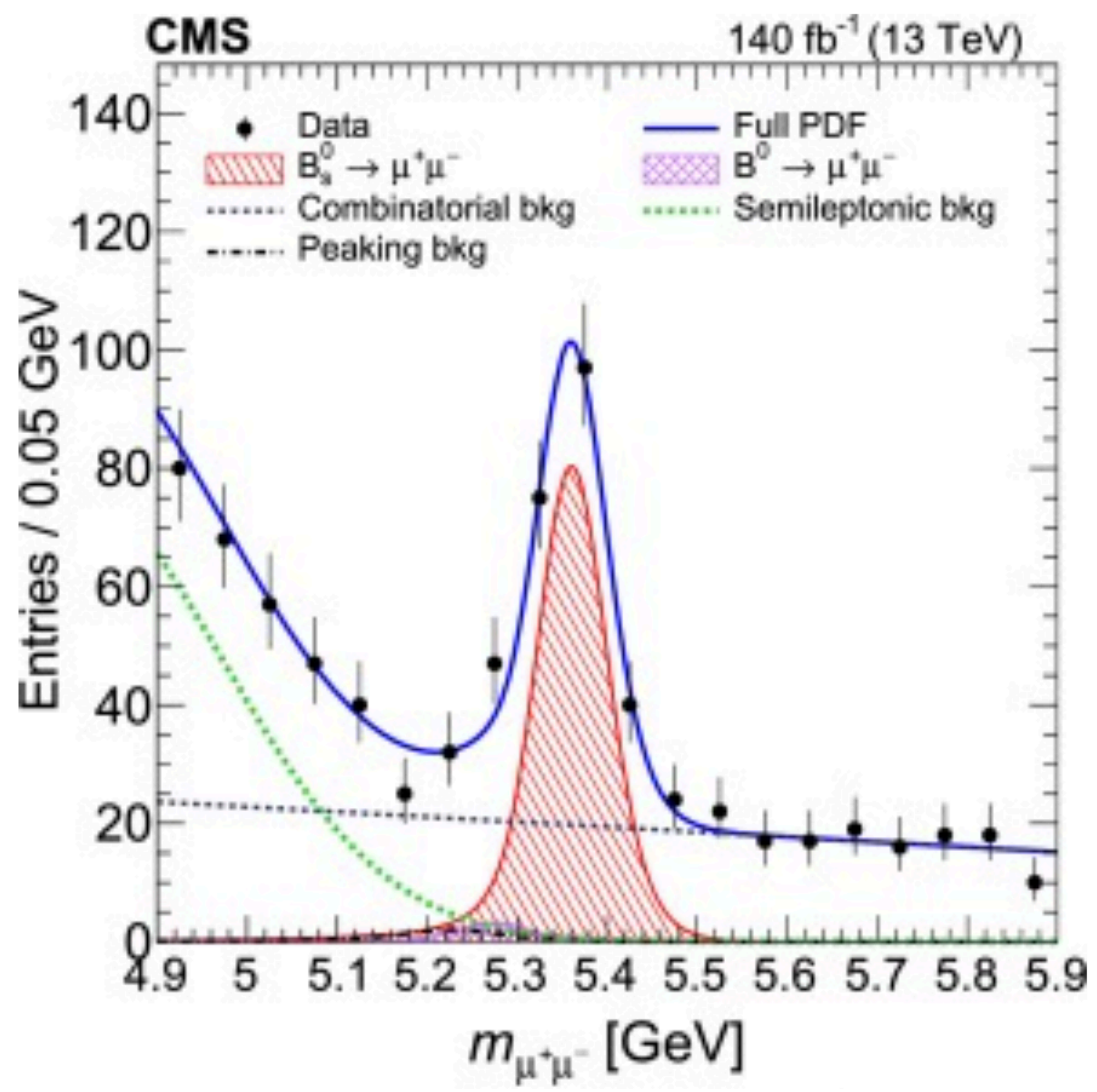
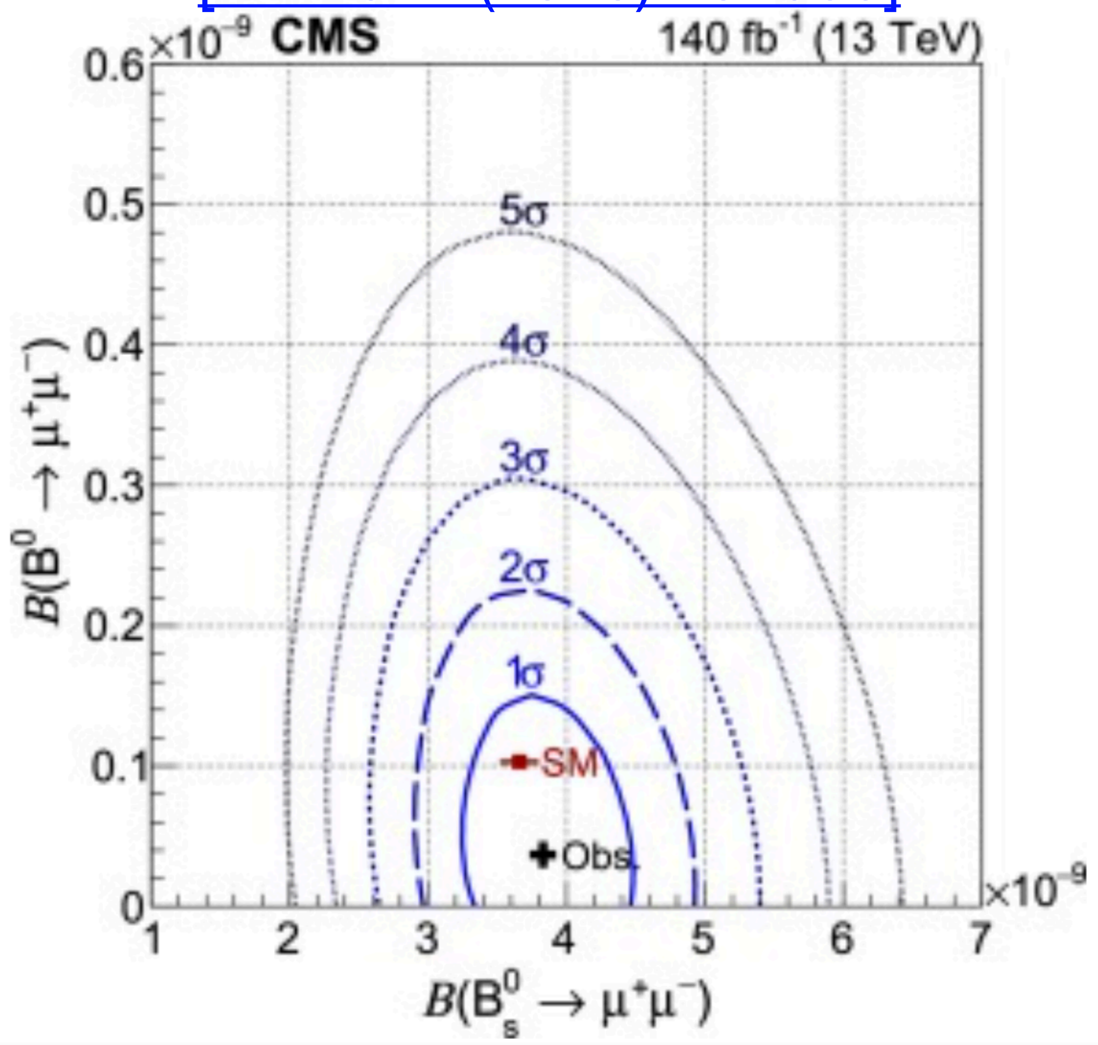
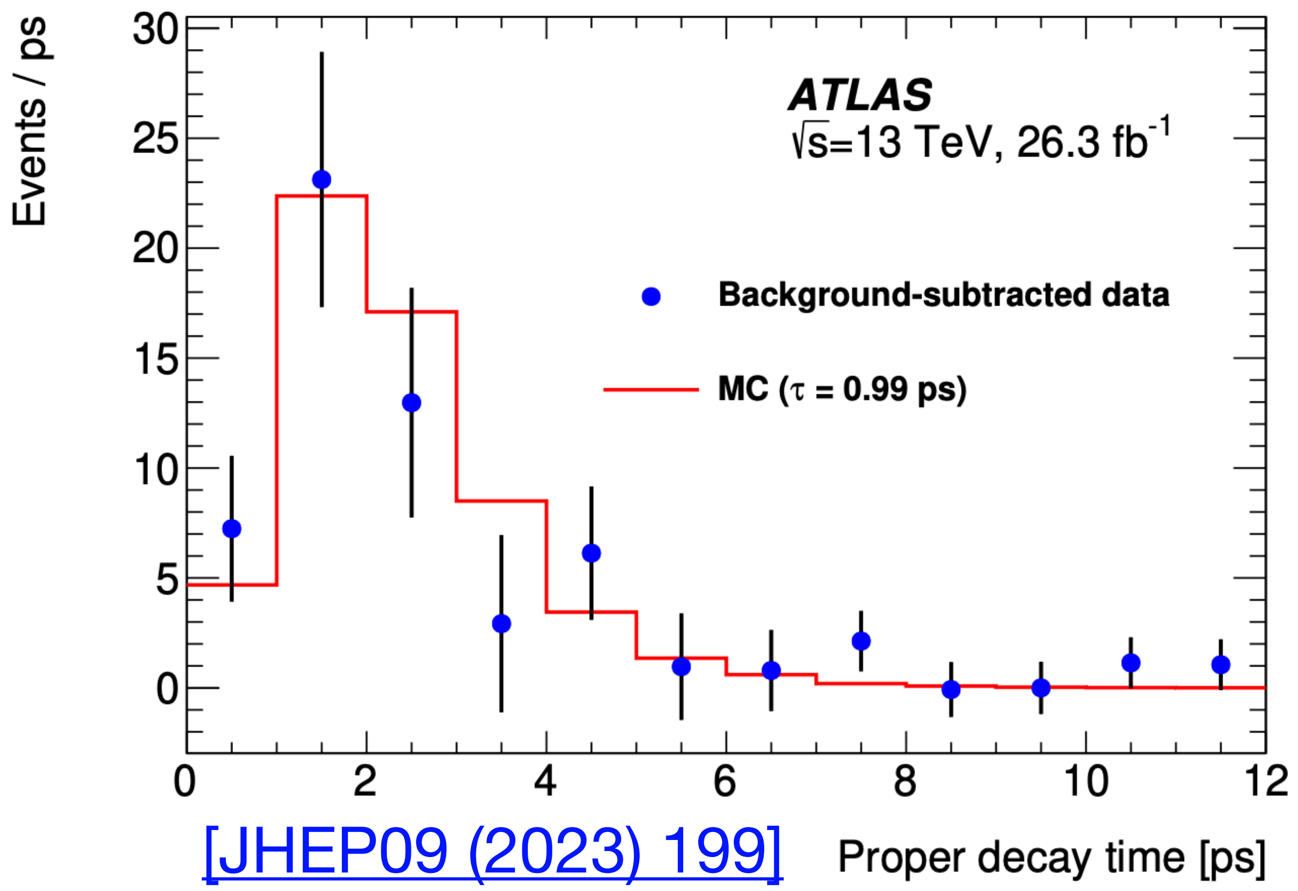
- $B^0_{(s)} \to \mu^+\mu^-$ decay:
  - Precise SM expectation and clear experimental signature
  - Recent measurements of branching ratio and lifetime by CMS, ATLAS and LHCb
    [PRL 128 (2022) 041801]
  - **Excellent agreement between experiments and SM**

[PLB 842 (2023) 137955]



[PLB 842 (2023) 137955]





[JHEP09 (2023) 199]

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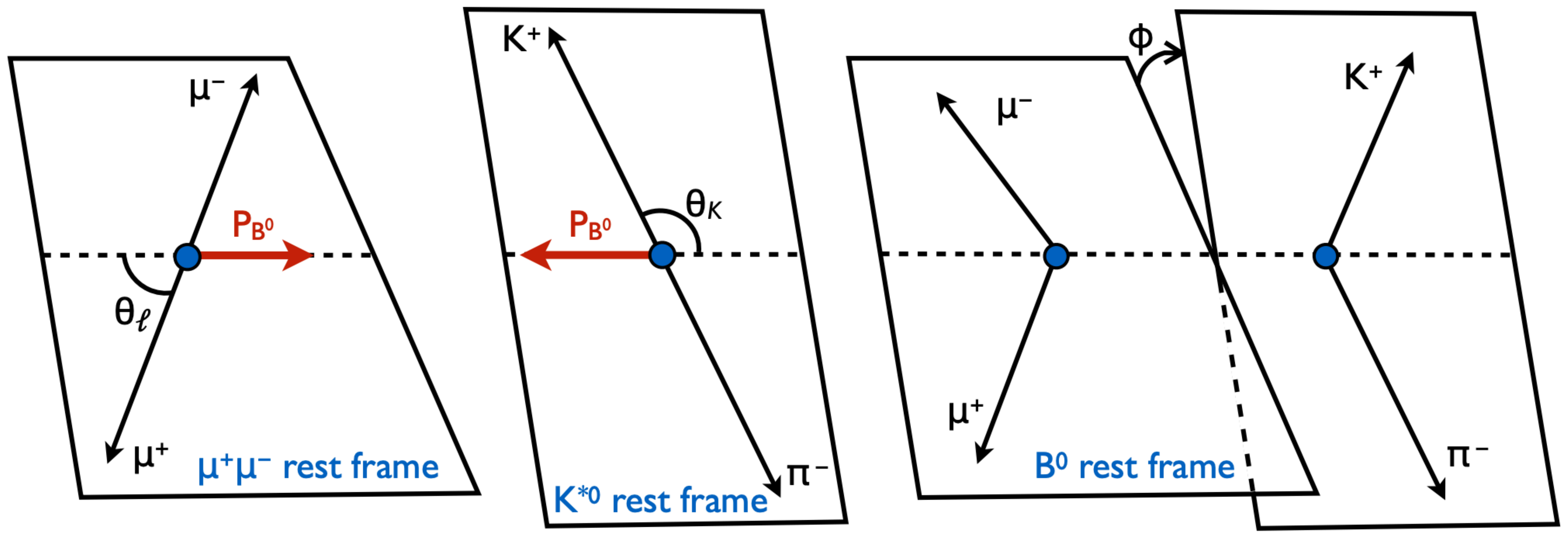
- Angular analysis of the rare decay $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$
  - Amongst the $\bar{b} \to \bar{s}l^+l^-$ measurements (as $R(K)$)
  - Rate can be written as function of angular variables: θ_l, θ_K and ϕ



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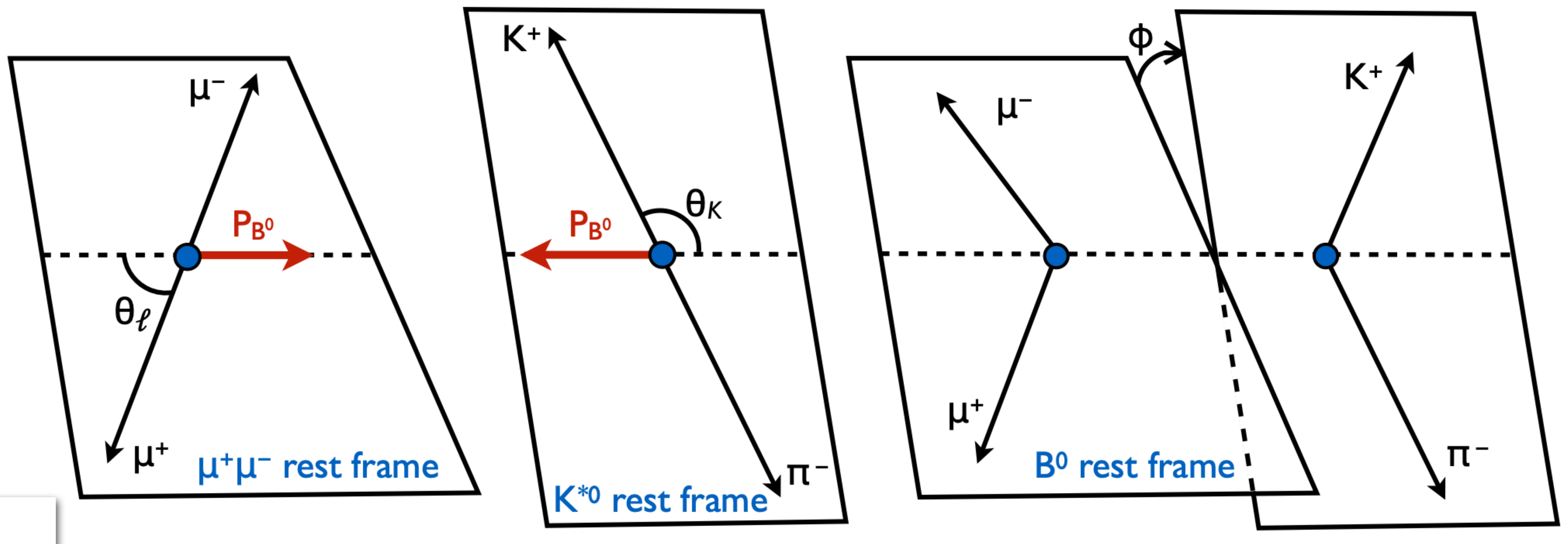

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$$\Gamma_P \equiv \frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{dcos}\theta_l\mathrm{dcos}\theta_K\mathrm{d}\phi} = \frac{9}{32\pi}\Bigg[\frac{3}{4}(1-\boxed{F_L})\sin^2\theta_K + \boxed{F_L}\cos^2\theta_K$$
$$+\left(\frac{1}{4}(1-F_L)\sin^2\theta_K - F_L\cos^2\theta_K\right)\cos 2\theta_l$$
$$+\frac{1}{2}\boxed{P_1}(1-F_L)\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+\sqrt{(1-F_L)F_L}\left(\frac{1}{2}\boxed{P_4'}\sin 2\theta_K\sin 2\theta_l\cos\phi + \boxed{P_5'}\sin 2\theta_K\sin\theta_l\cos\phi\right)$$
$$-\sqrt{(1-F_L)F_L}\left(P_6'\sin 2\theta_K\sin\theta_l\sin\phi + \frac{1}{2}P_8'\sin 2\theta_K\sin 2\theta_l\sin\phi\right)$$
$$+2P_2(1-F_L)\sin^2\theta_K\cos\theta_l - P_3(1-F_L)\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Bigg],$$

- Set of clean observables related to Wilson coefficients
  - $\boxed{F_L}$ is the fraction of longitudinal polarisation of the K^{*0} meson
  - $\boxed{P_i^{(\prime)}}$ base of the optimised clean observables

Angular Observables

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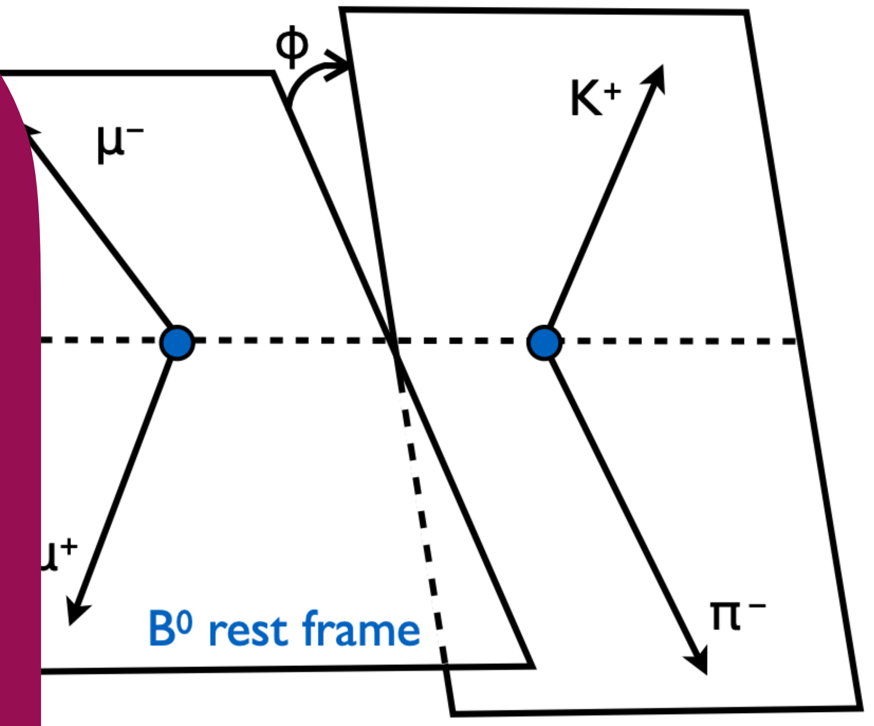

...bles related to

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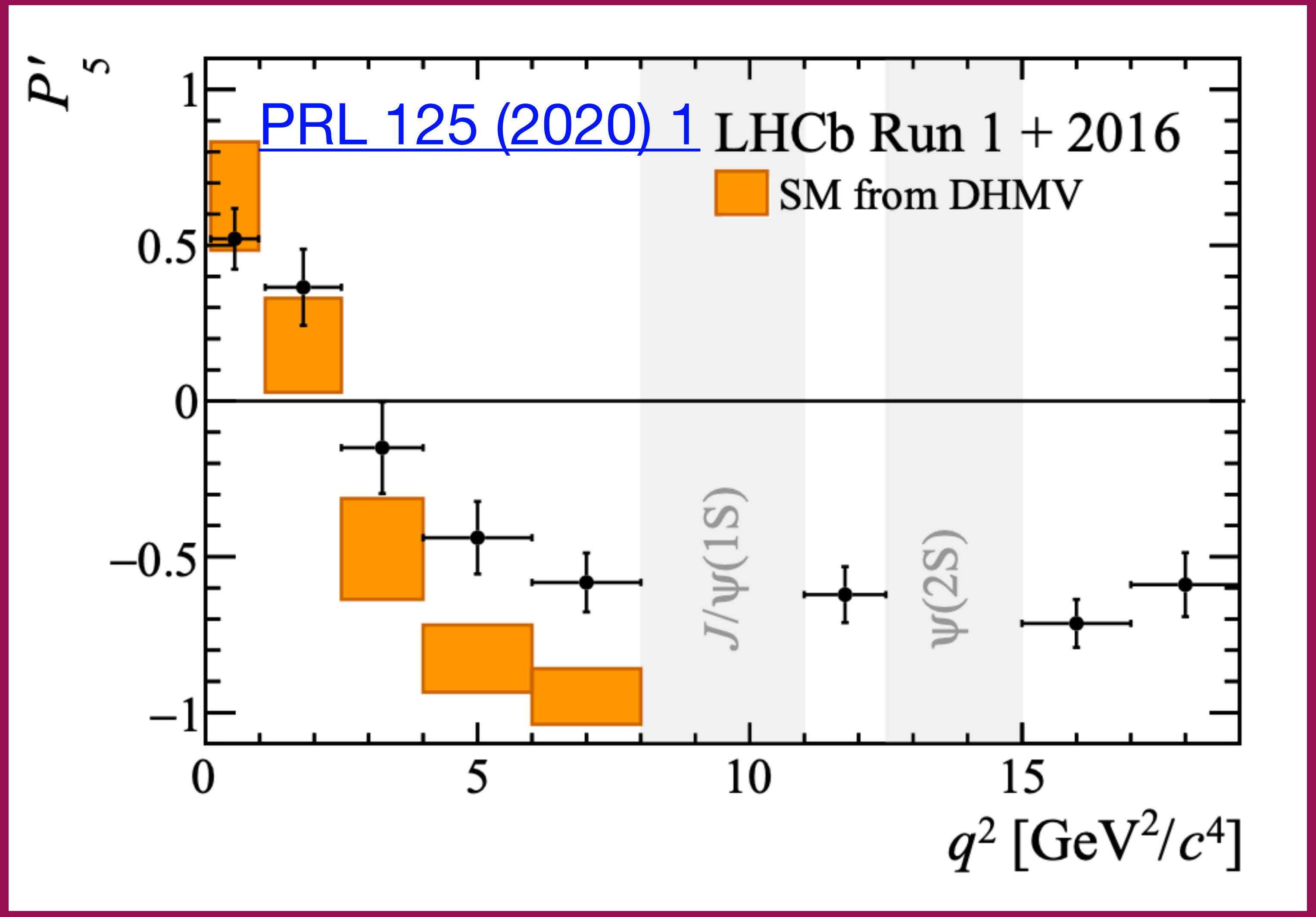
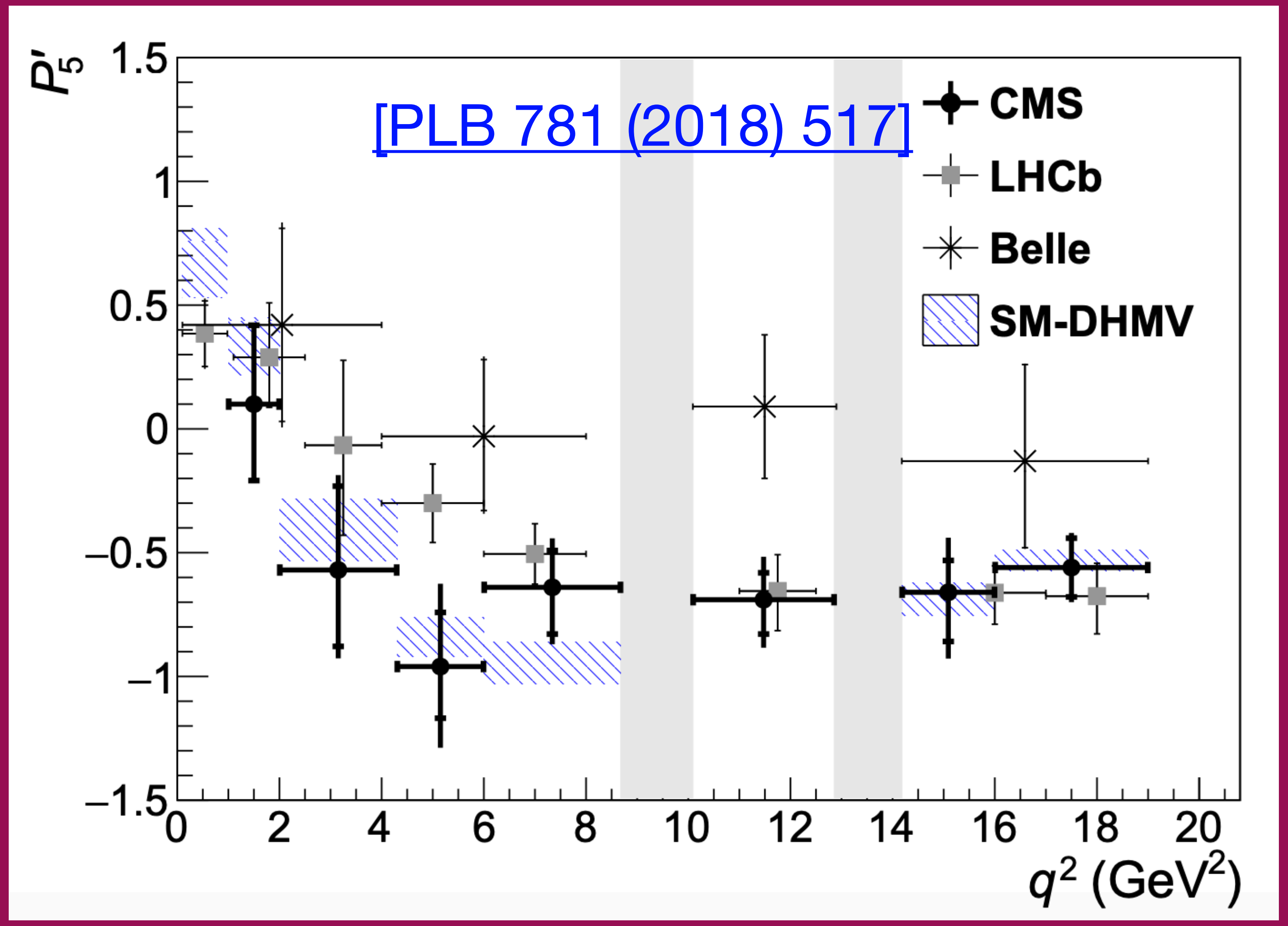
$$\Gamma_P \equiv \frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\,\frac{}{\mathrm{d}q^2\mathrm{d}}$$

$$+2P_2(1-F_{\mathrm{L}})\sin^2\theta_{\mathrm{K}}\cos\theta_l - P_3(1-F_{\mathrm{L}})\sin^2\theta_{\mathrm{K}}\sin^2\theta_l\sin 2\phi\Big],$$

- **Deviations for the P_5' observable from the SM prediction for two q^2 bins**





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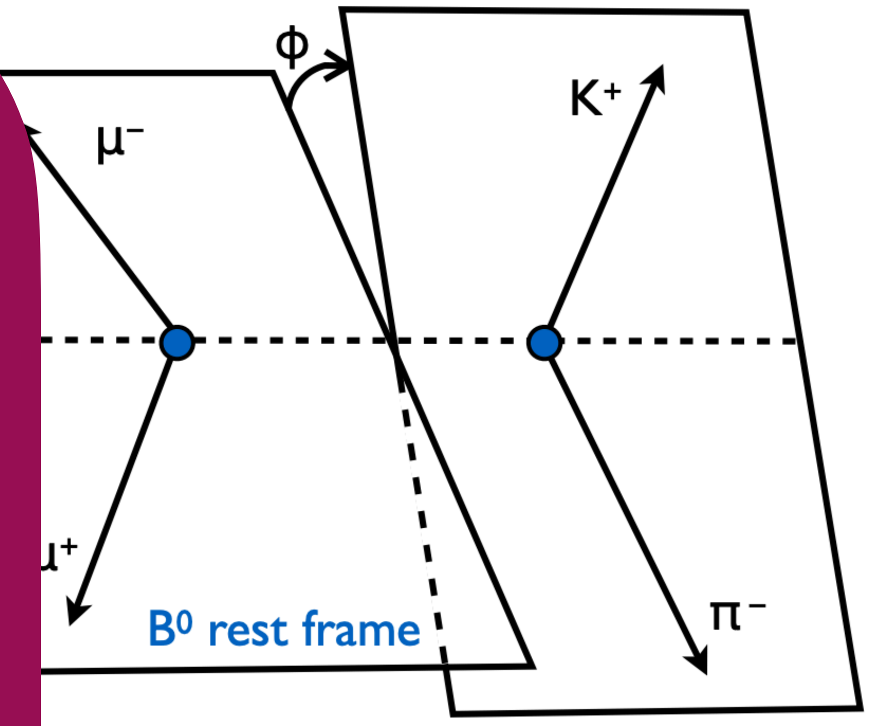

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$$\Gamma_P \equiv \frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\,\mathrm{d}q^2\mathrm{d}$$

$+$

$+\frac{1}{2}$

$+\sqrt{}$

$-\sqrt{(}$

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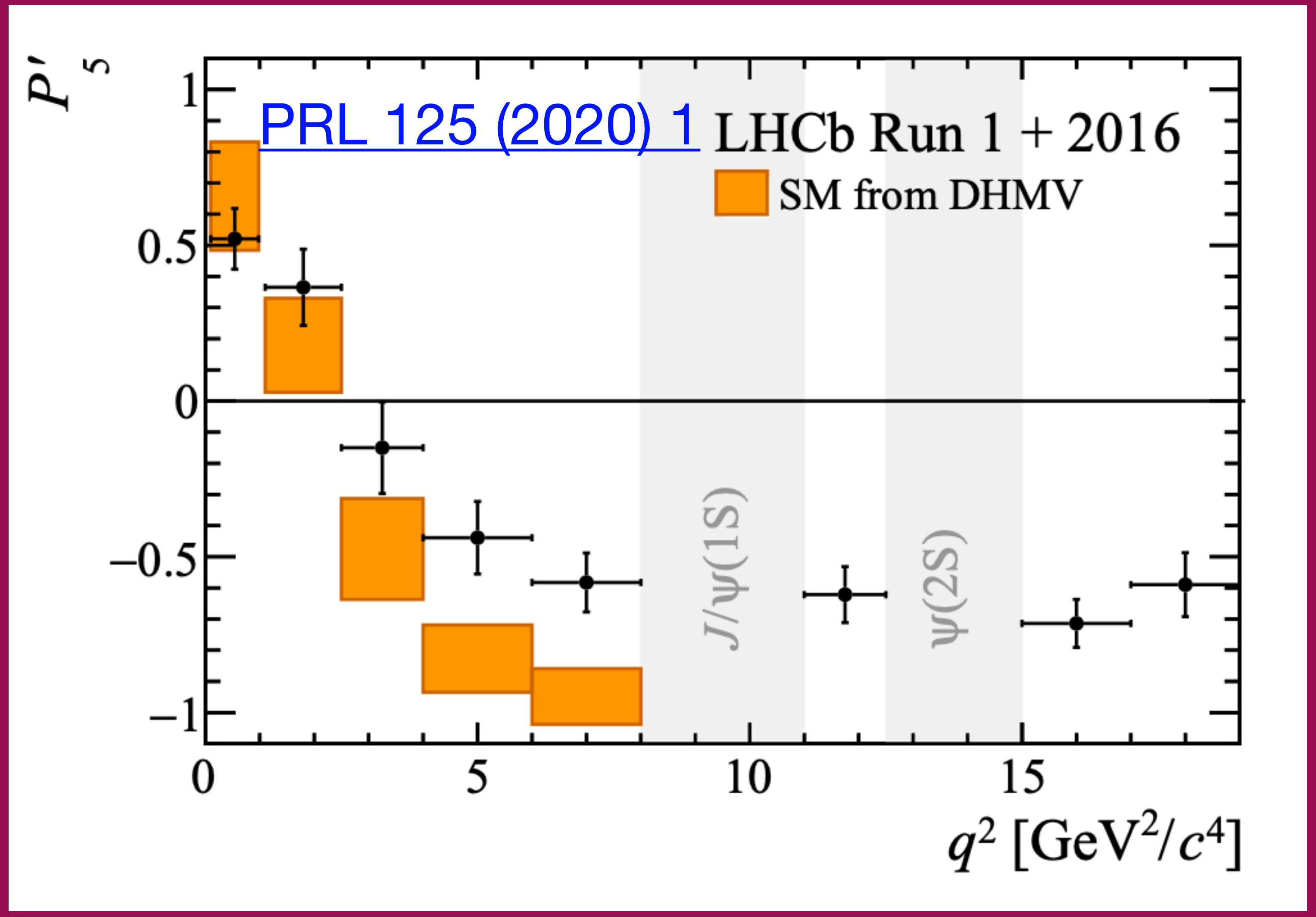
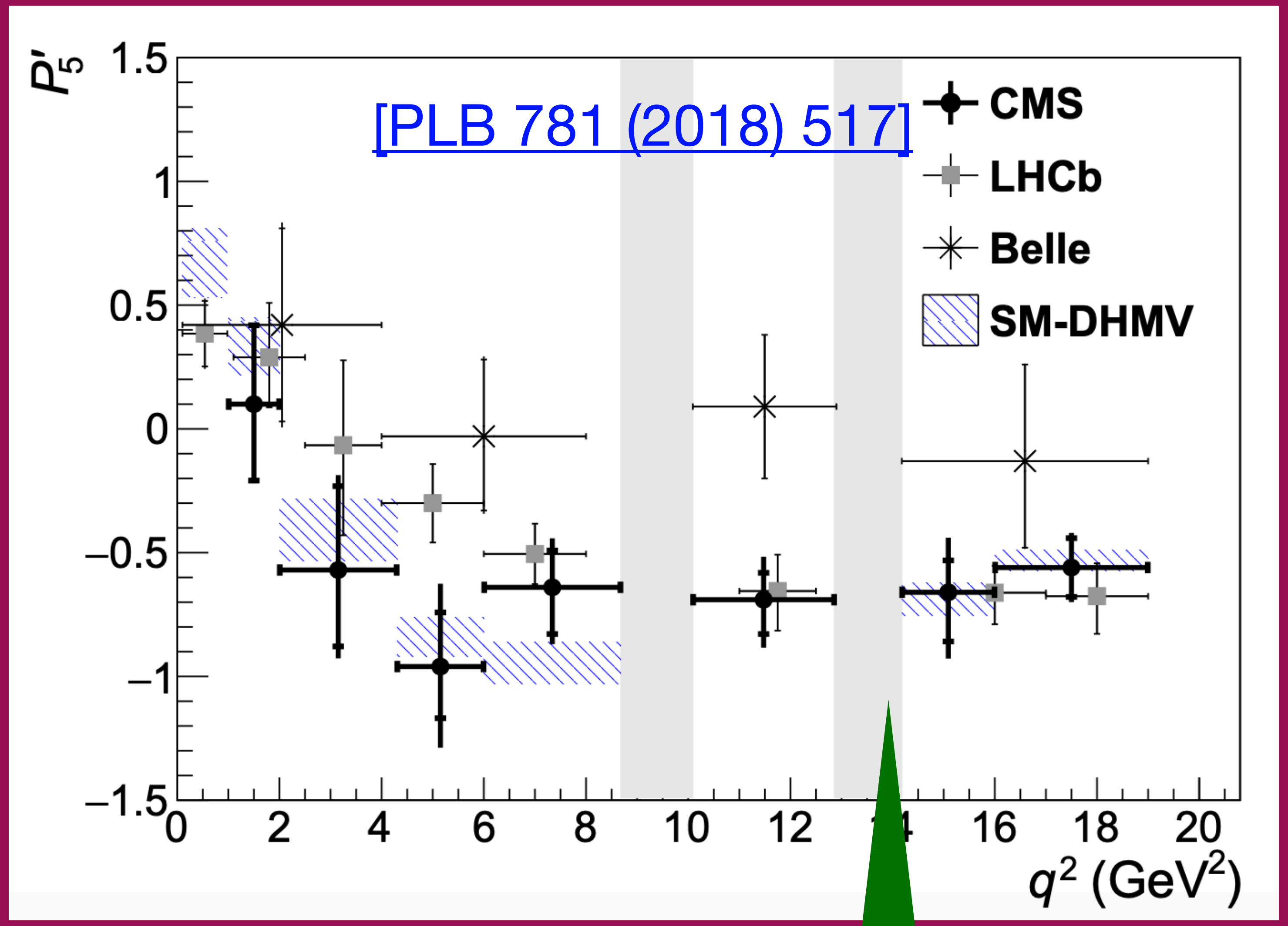




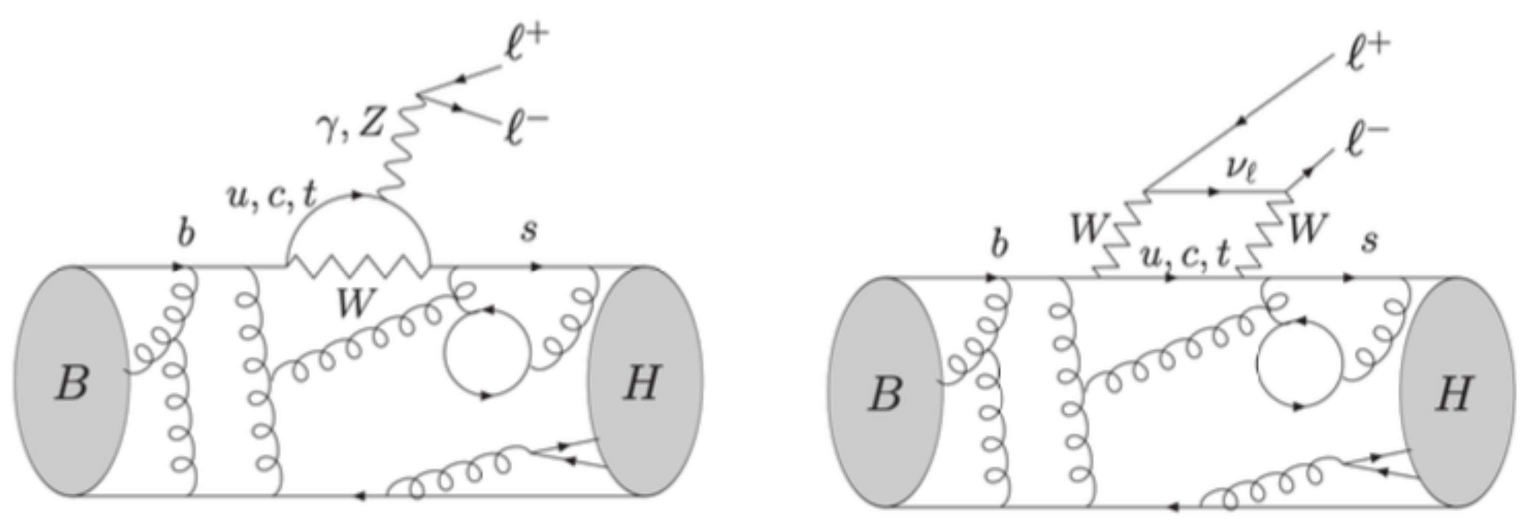
More details about most recent CMS analysis later!!

Effective Field Theory

How can the anomalies be explained?

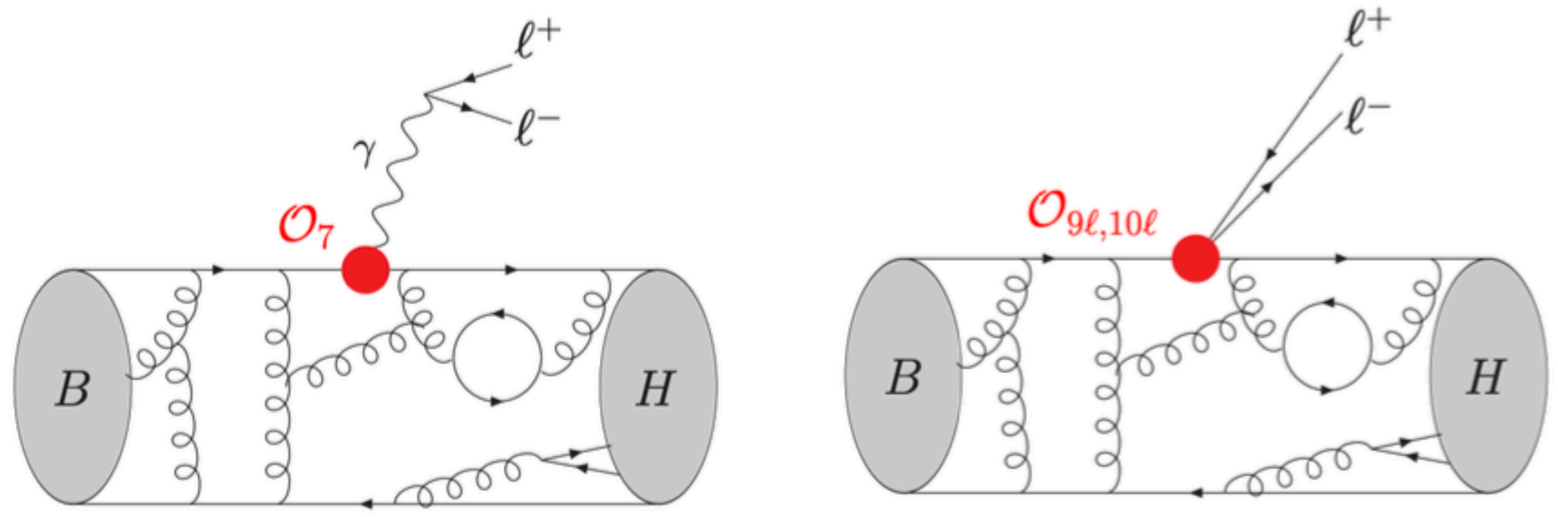
- To separate the effects from different energy scales, a EFT approach is employed
  - Heavy particles are incapsulated in Wilson coefficients
  - Light particles are the operators
- **Easily adaptable framework to include NP effects**

FCNC: $b \to s l^+ l^-$

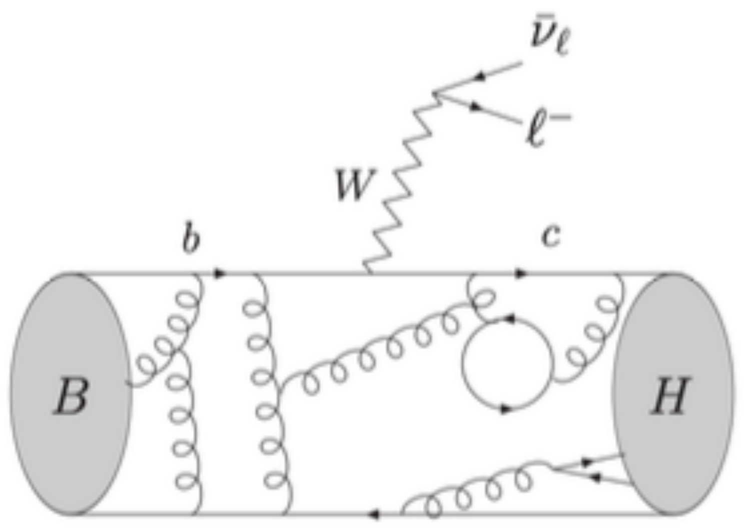


$$\mathcal{H}_{eff}(b \to s l^- l^+) = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

Dominant operators:

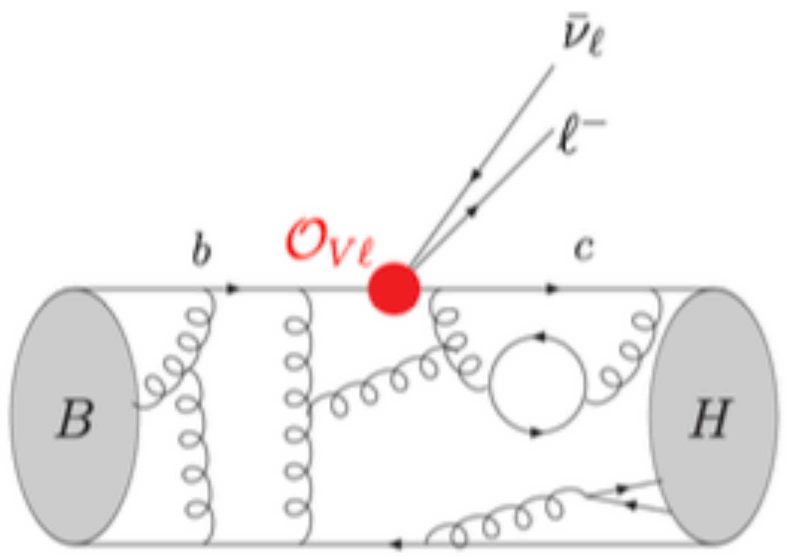


FCCC: $b \to c l^- \bar{\nu}_l$



$$\mathcal{H}_{eff}(b \to c l^- \bar{\nu}_l) = \frac{4G_F}{\sqrt{2}} V_{cb} \sum_i \mathcal{C}_i \mathcal{O}_i$$

Dominant operator:

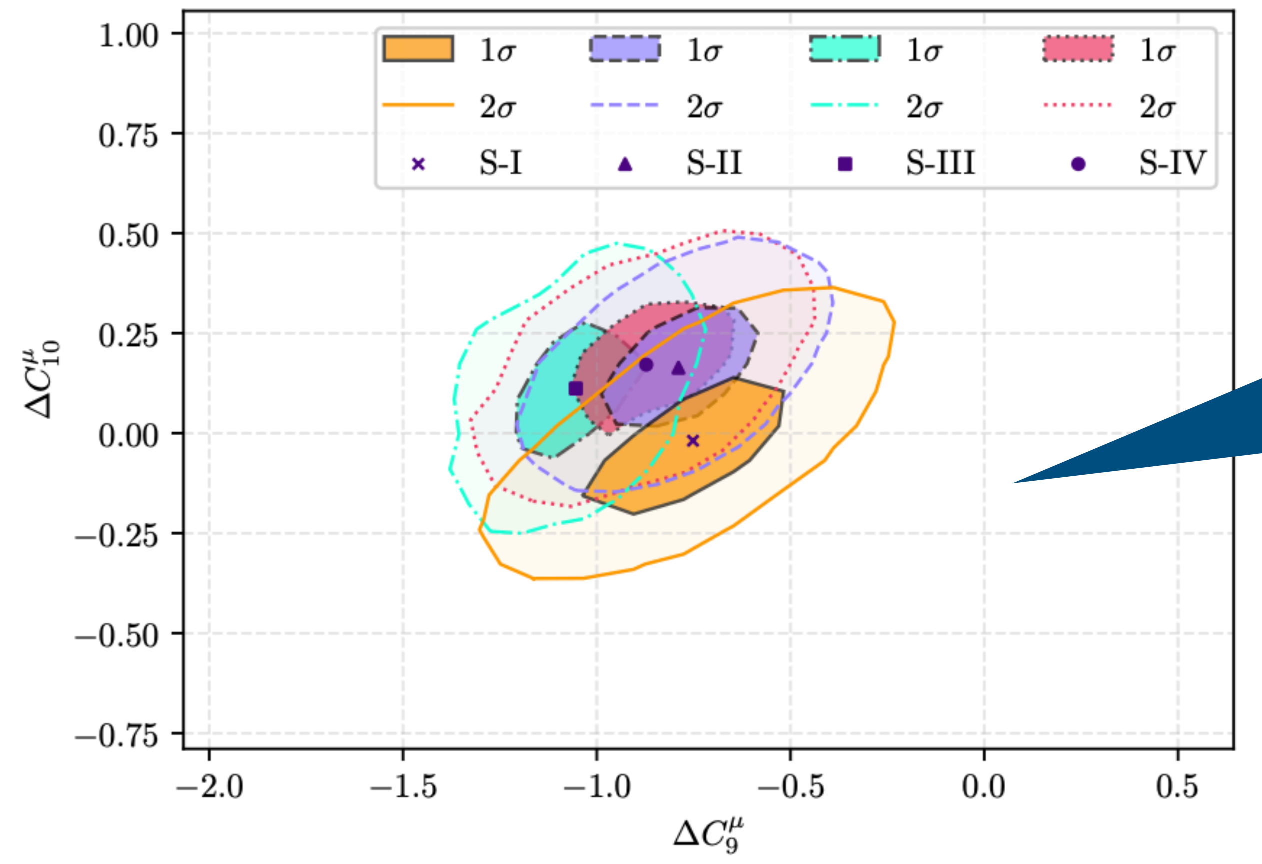


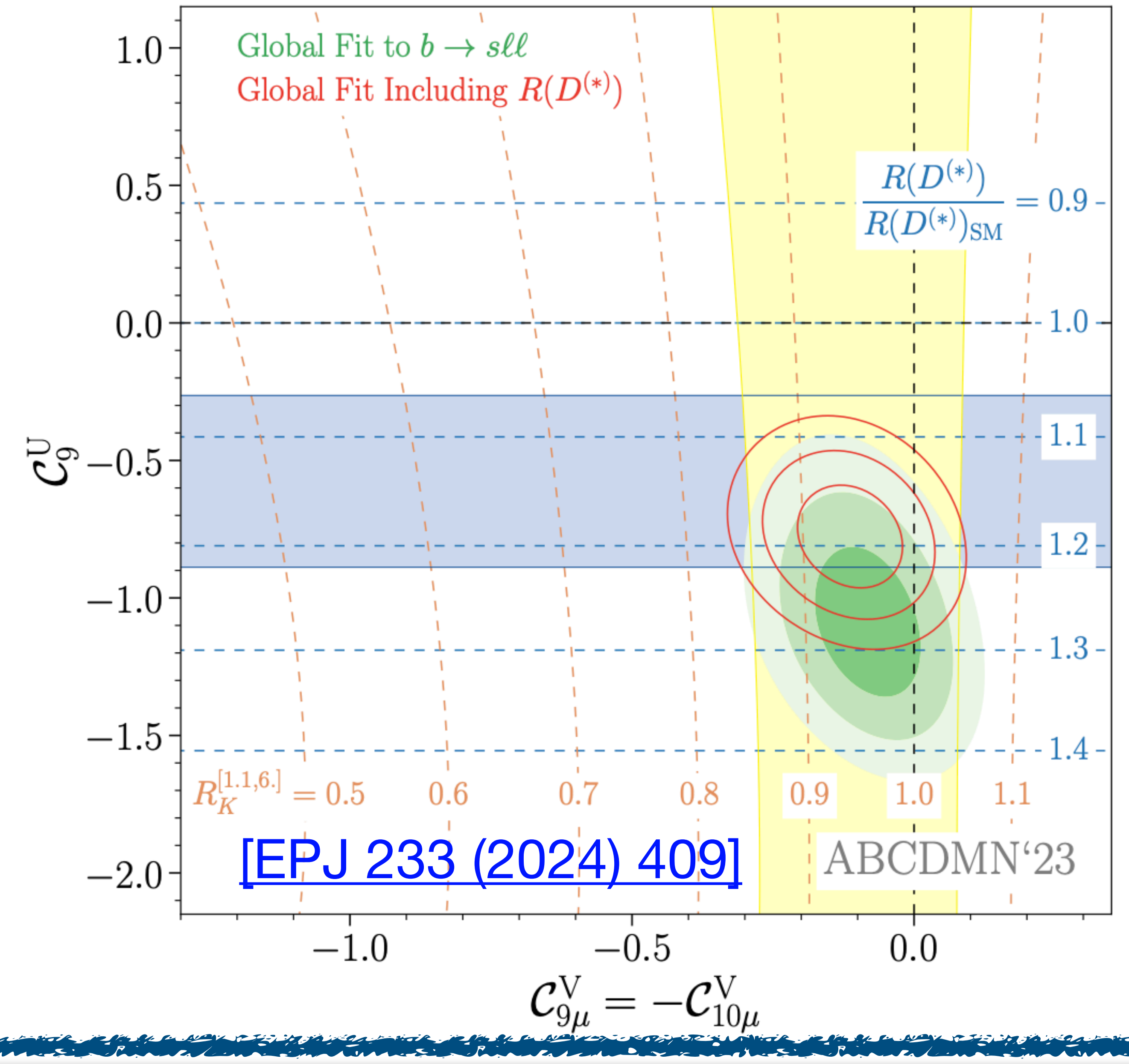
Global Model-Independent Fits

Example of global-fit to FCNC NP Wilson coefficients, considering different NP scenario. Clear deviations for $\Delta\mathscr{C}_9^\mu$

- **Model-independent analyses**: addition of NP contributions to Wilson coefficients
  - Global fits to relevant observables

[PRD 108 (2023) 095038]





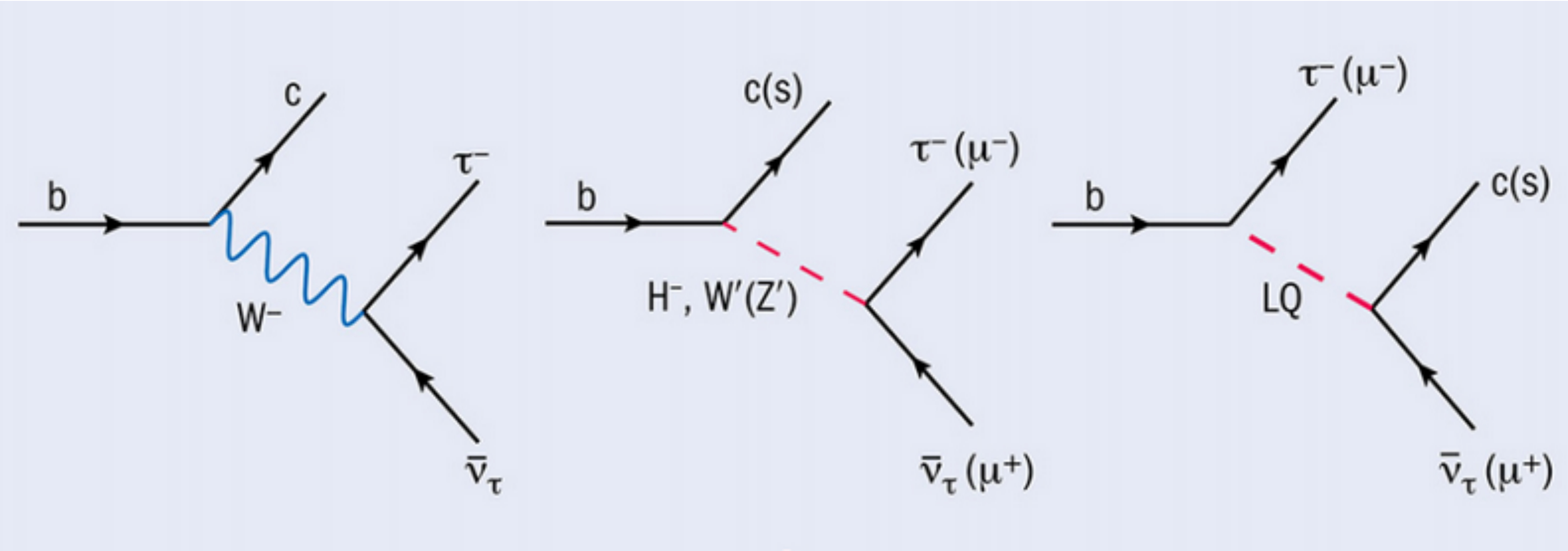
[EPJ 233 (2024) 409]

- Wilson coefficients can contain two types of NP contributions:
  - $\mathcal{C}_{i\ell}^{\rm NP} = \mathcal{C}_{i\ell}^{\rm V} + \mathcal{C}_{i}^{\rm U}$: one violating and one not violating LFU
- **An example** is shown in the figure, a specific NP scenario, one of the best from a quality-of-fit prospective
  - Model-independent connection between charged and neutral anomalies

Interpretations

Other than global fits, there are simpler models that could explain the anomalies.

- **Introduction of new particles** as:
  - Charged Higgs boson [EPJC 81 (2021) 723] [PRD 102 (2020) 072001] [JHEP 07 (2020) 126] [JHEP 01 (2020) 096]
  - Leptoquarks (LQ) [JHEP 05 (2024) 311] [PRL 132 (2024) 061801] [PRL 132 (2024) 061801]
  - New vector bosons [Summary plots EXO]



Interpretations

Other than global fits, there are simpler models that could explain the anomalies.

- **Introdu**
  - Charg
  - Lepto
  - New v

- After this introductory overview, we will study in more detail three interesting and recent CMS analyses
  - Test of LFU through the $R(J/\psi)$ measurement [CMS-PAS-BPH-23-001] [PRD 111 (2025) L051102]
  - Test of LFU through the $R(K)$ measurement [RPP 87 (2024) 077802]
  - $B^0 \to K^*(892)^0\mu^+\mu^-$ Angular Analysis [PLB 864 (2025) 139406]

$R(J/\psi)$ Measurement

Leptonic and Hadronic Channels

- **SM prediction**: $R(J/\psi) = 0.2582 \pm 0.0038$
  [PhysRevLett.125.222003]

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

- Only one previous result:
  - **LHCb experiment** (Run I: $3\ fb^{-1}$)
    $R(J/\psi) = 0.71 \pm 0.17(stat) \pm 0.18(syst) = 0.71 \pm 0.25$
    [PhysRevLett.120.121801]
    - $\sim 2\sigma$ from SM prediction (enhanced τ couplings)

Decay mode	Resonance	$\mathcal{B}$ (%)
Leptonic decays		35.2
$\tau^- \to e^- \overline{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$		17.4
Hadronic decays		64.8
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	25.9
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other		3.3

- Two measurements performed in CMS
  - **Fully leptonic analysis**: [PRD 111 (2025) L051102]
    - Same final state (3μ + νs) for both num. and den.
    - 2018 data (59.7 fb^{-1})
  - **Hadronic Analysis**: [CMS-PAS-BPH-23-001]
    - $\tau \to \pi\pi\pi(+\pi^0)$
    - Num. with full Run-2
    - Den. from leptonic channel analysis

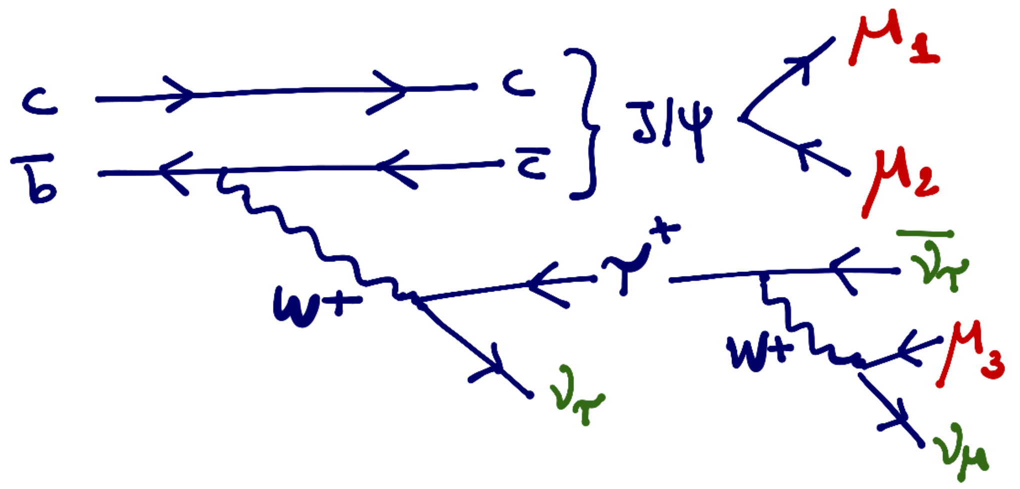
$J/\psi \to \mu^+\mu^-$ in both channels

R(J/ψ) Leptonic Channel

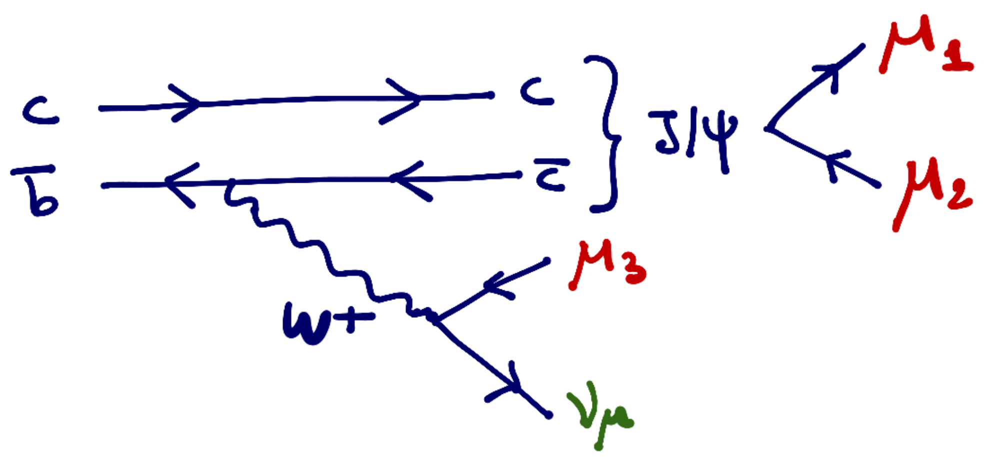
- **Leptonic channel :** $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$
- **Muonic decay of** $J/\psi \to \mu^+ \mu^-$
- Similar final state ($3\mu + \nu s$), → same reconstruction and simultaneously fit

$$R(J/\psi) = \frac{\mathscr{B}(B_c^+ \to J/\psi(\to \mu^+\mu^-)\tau^+(\to \mu^+\nu_\mu\bar{\nu}_\tau)\nu_\tau)}{\mathscr{B}(B_c^+ \to J/\psi(\to \mu^+\mu^-)\mu^+\nu_\mu)}$$

Num: $B_c^+ \to J/\psi \tau^+ \nu$



Den: $B_c^+ \to J/\psi \mu^+ \nu$



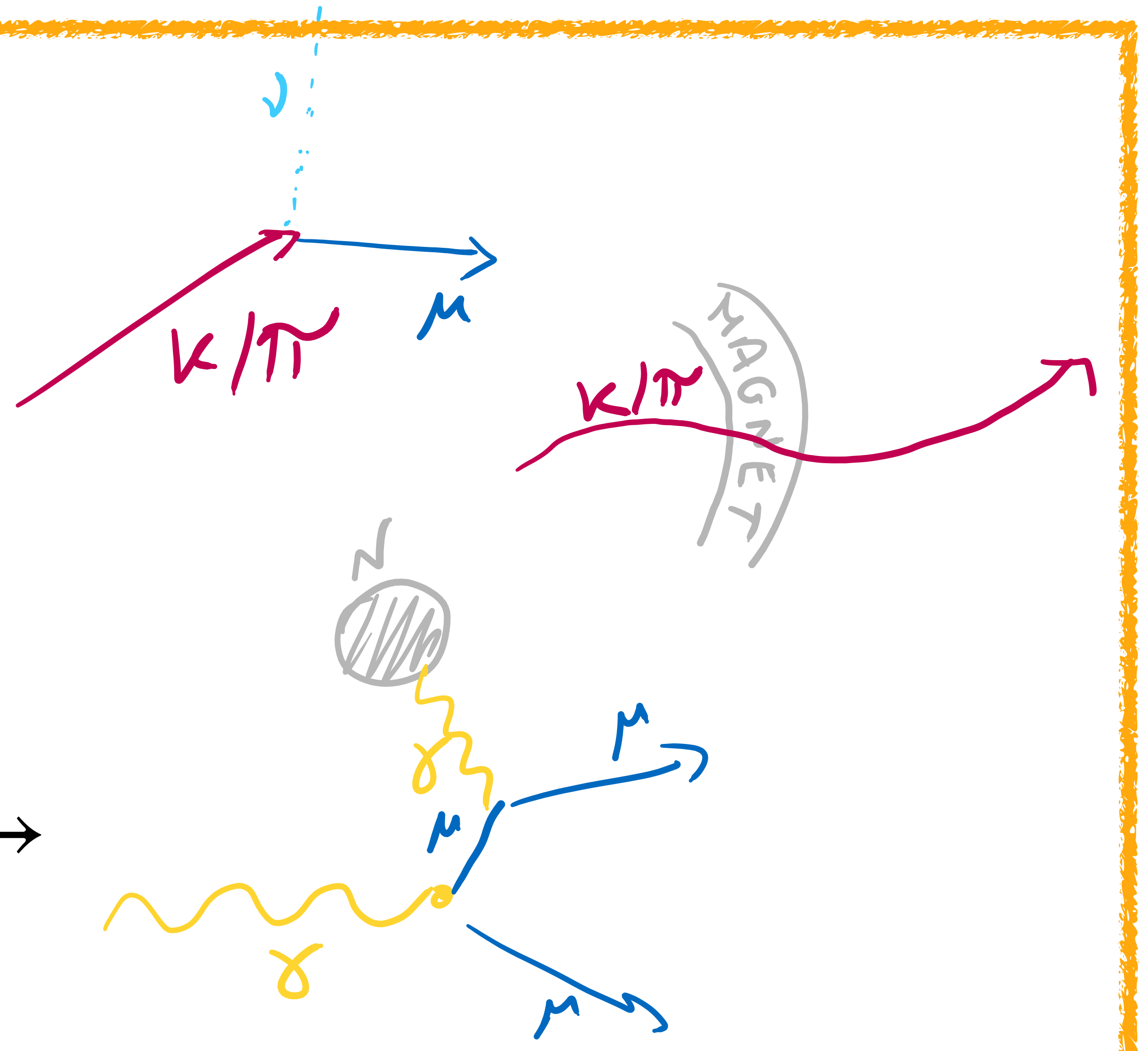
Signal and Bkg Contributions

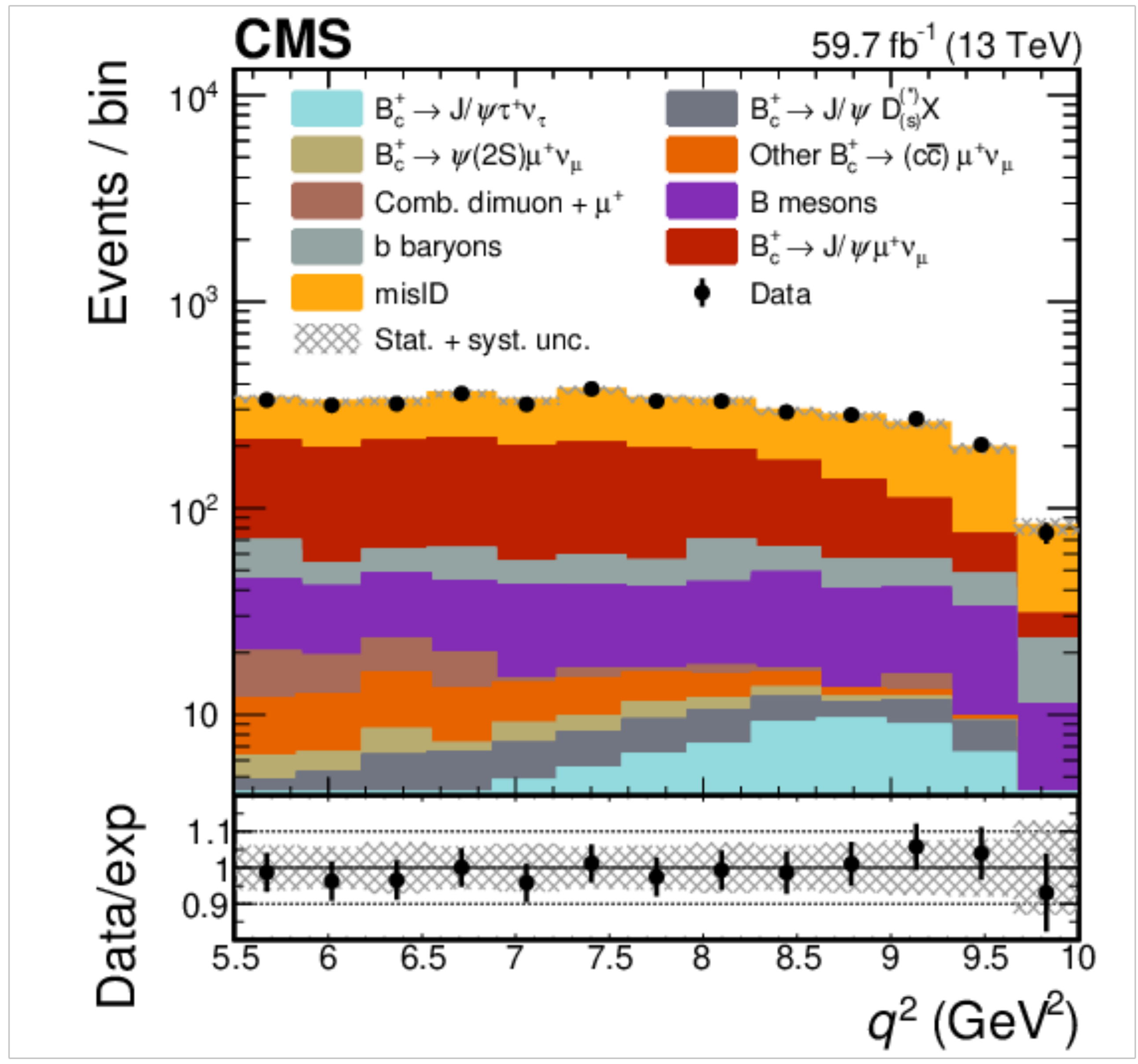
- **Signal τ: $B_c \to J/\psi\tau\nu_\tau$**
- **Signal μ: $B_c \to J/\psi\mu\nu_\mu$**
- **misID bkg**: J/ψ + misidentified hadron (**mostly decay in flight $K \to \mu\nu$**)

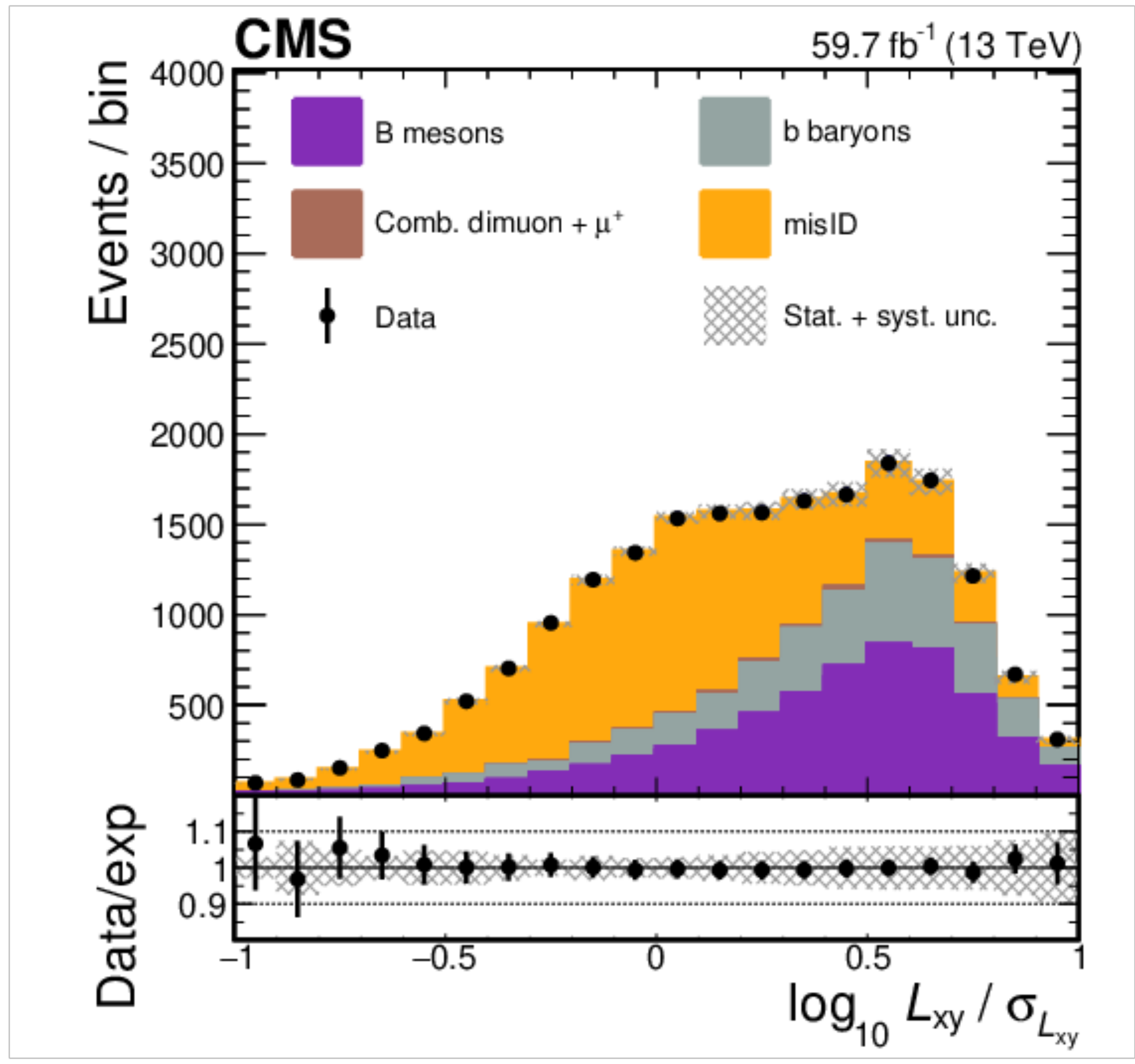
data-driven

In the detector there are events where a J/ψ meson is coupled with objects coming from:
- Decay in flight ($K \to \mu\nu$)
- Punch-through (hadrons that pass the magnet)
- Photon conversion ($\gamma \to \mu\mu$)
- Actual fakes coming from accidental reconstruction

Some of these object could be misidentified as muons → *muon misID*.







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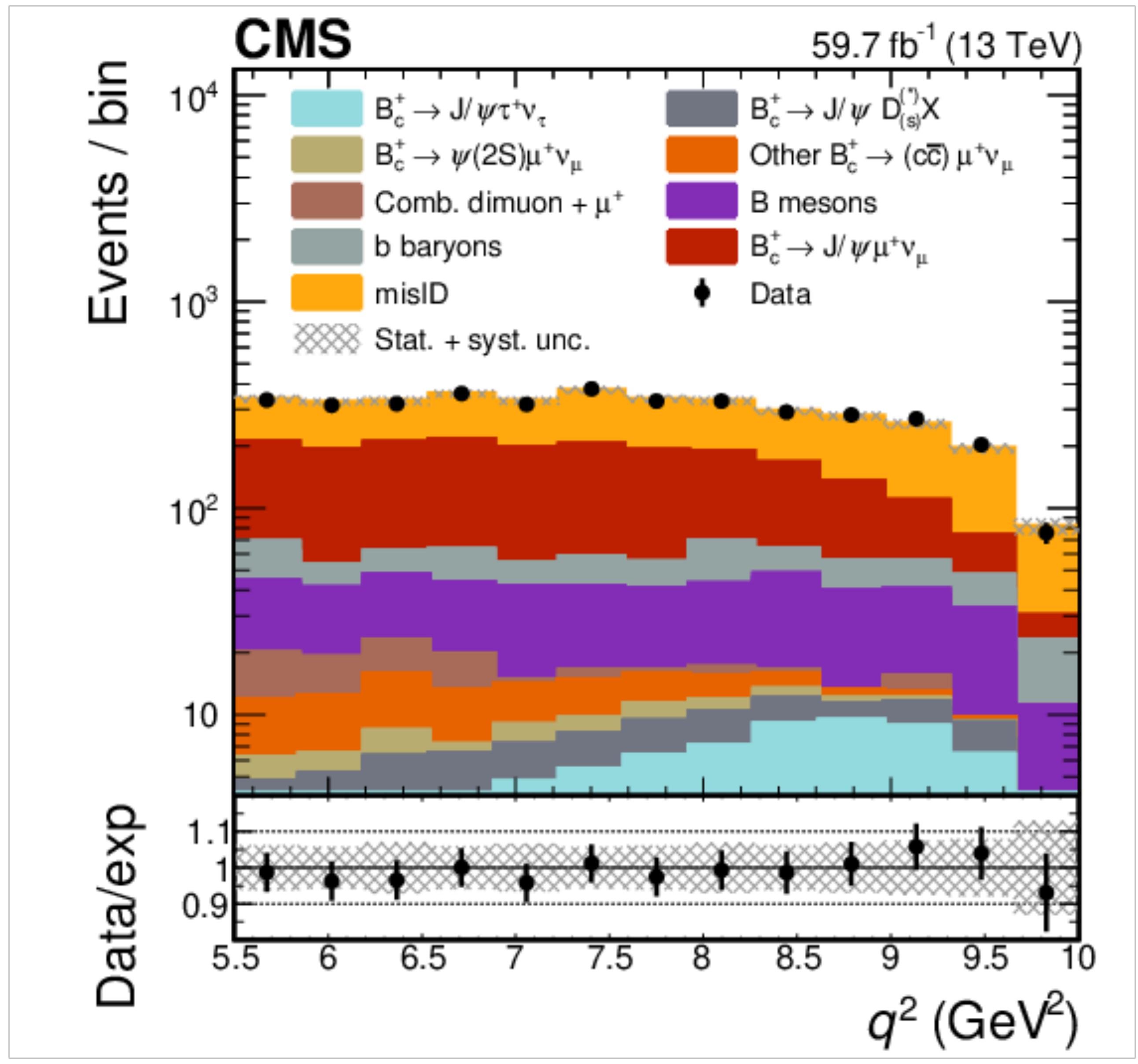
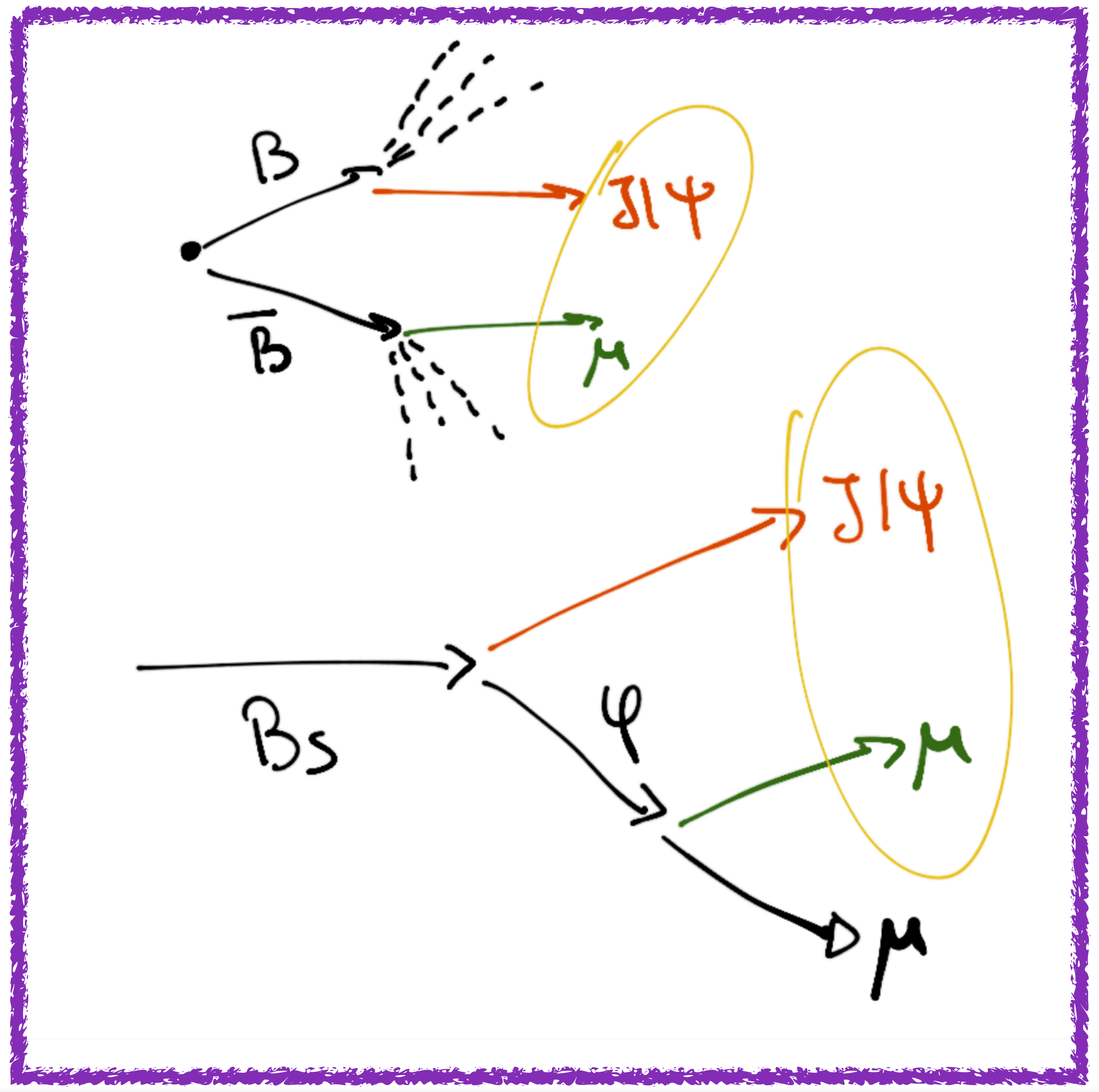
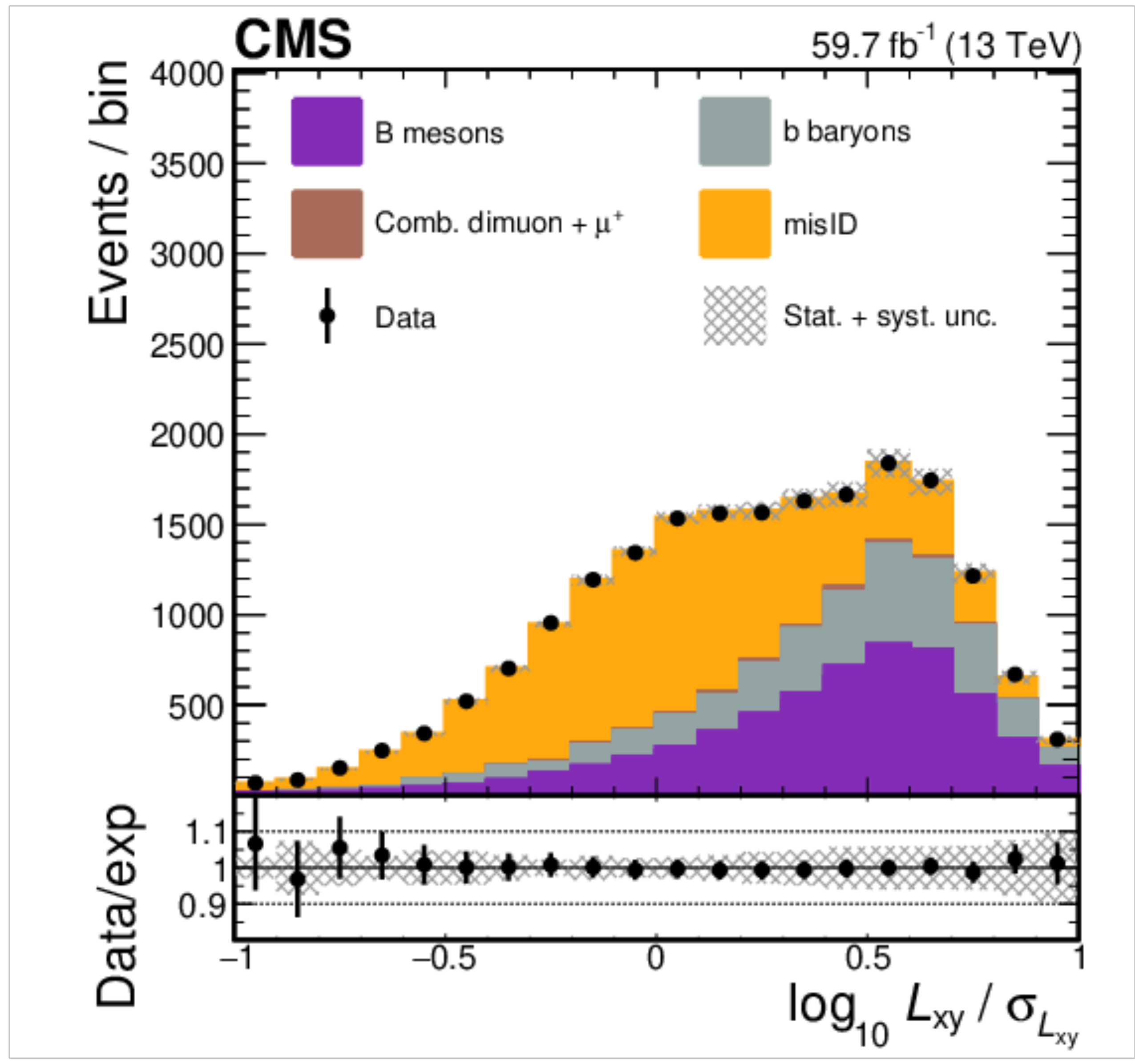
- **H_B bkg**: combinatorial $J/\psi + \mu$ *from simulation*







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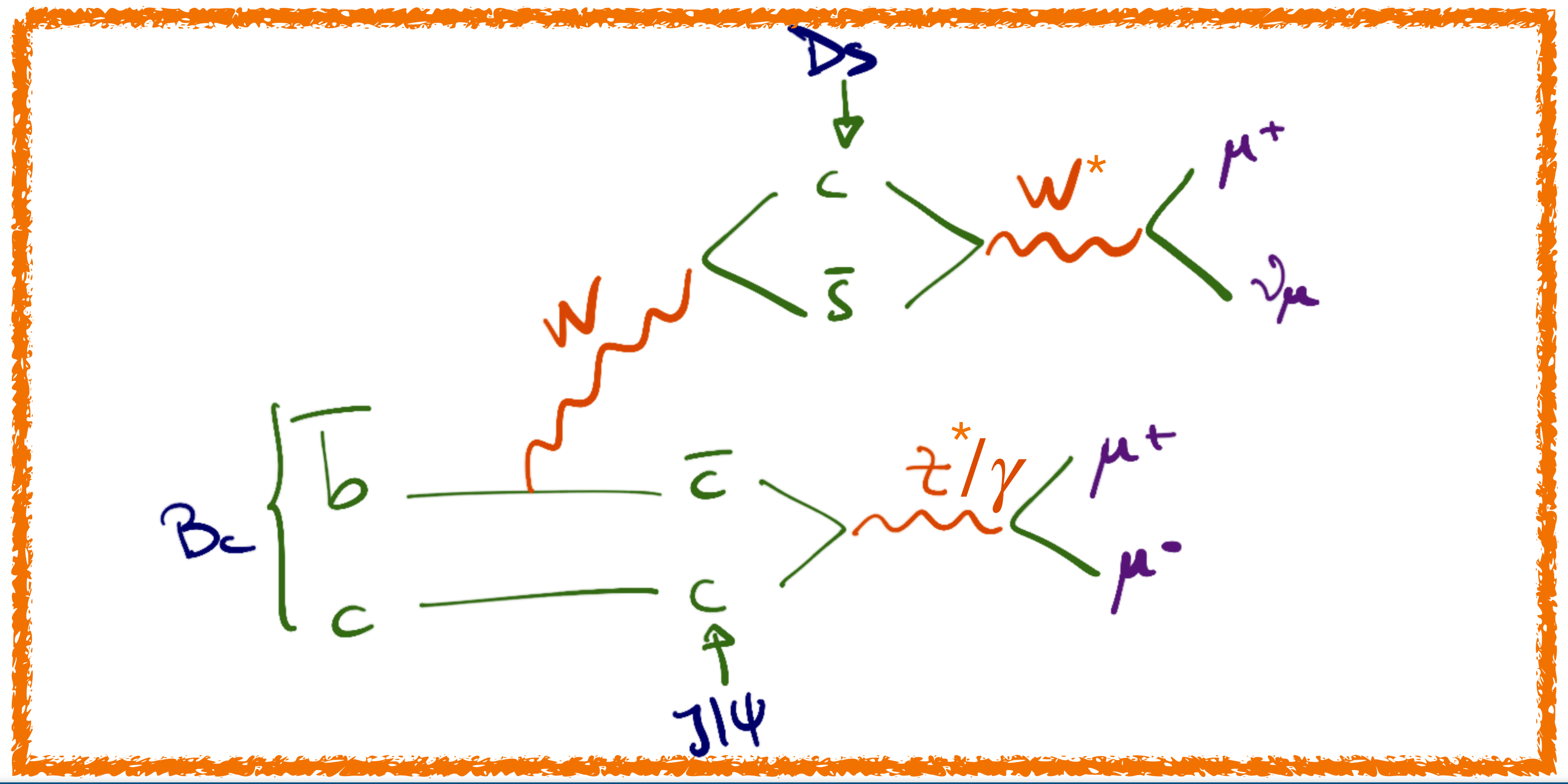
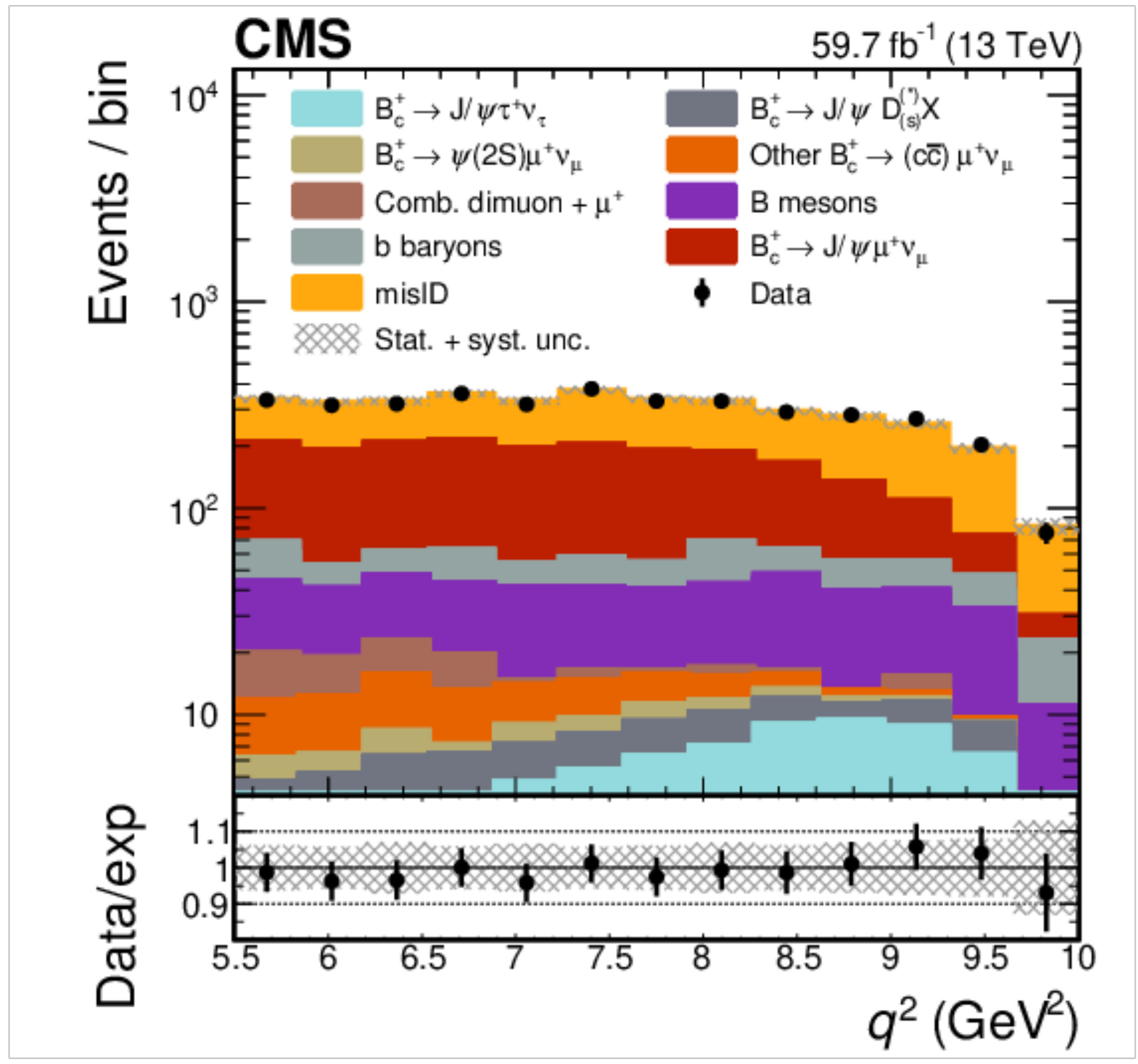
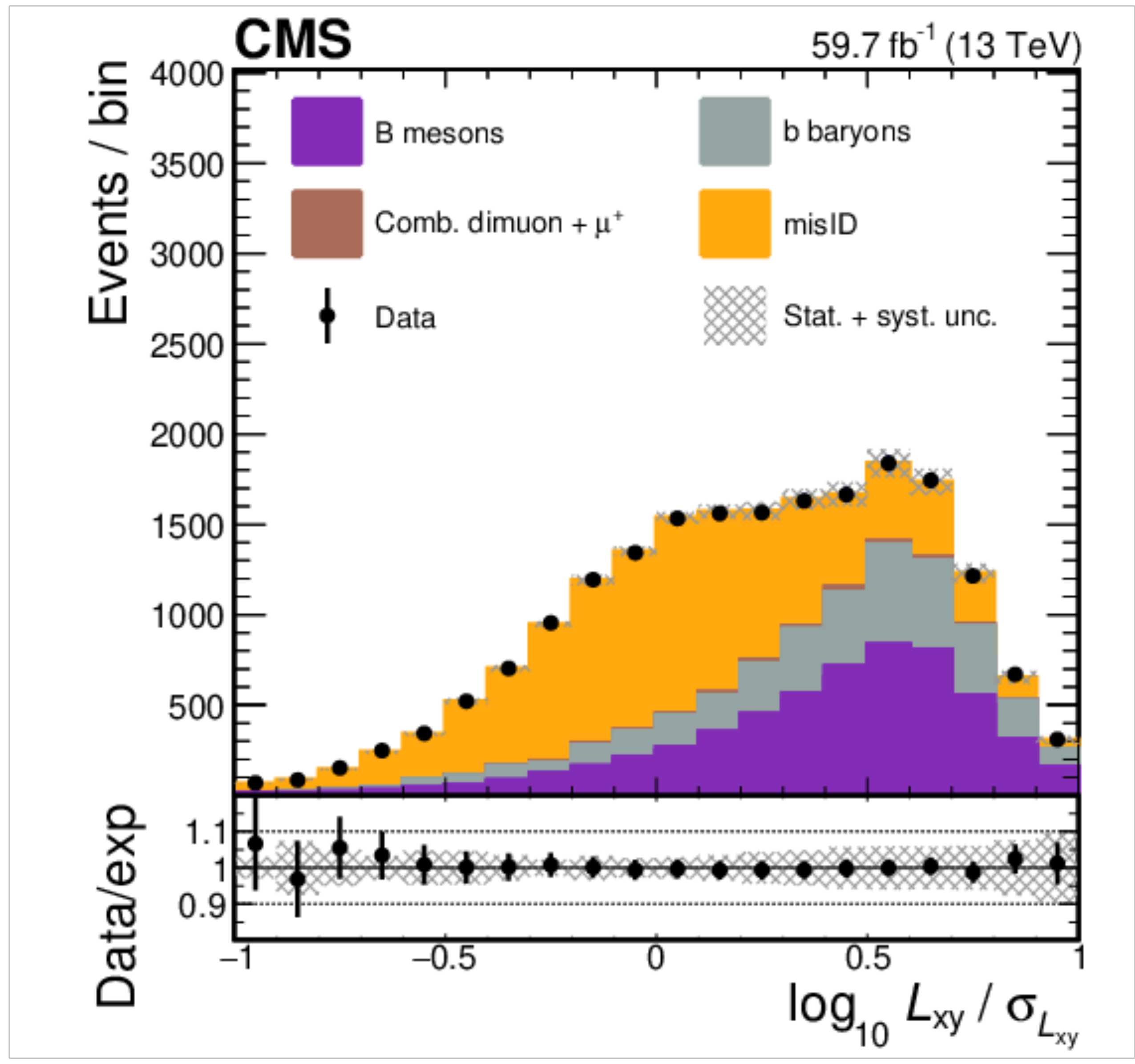
data-driven

from simulation







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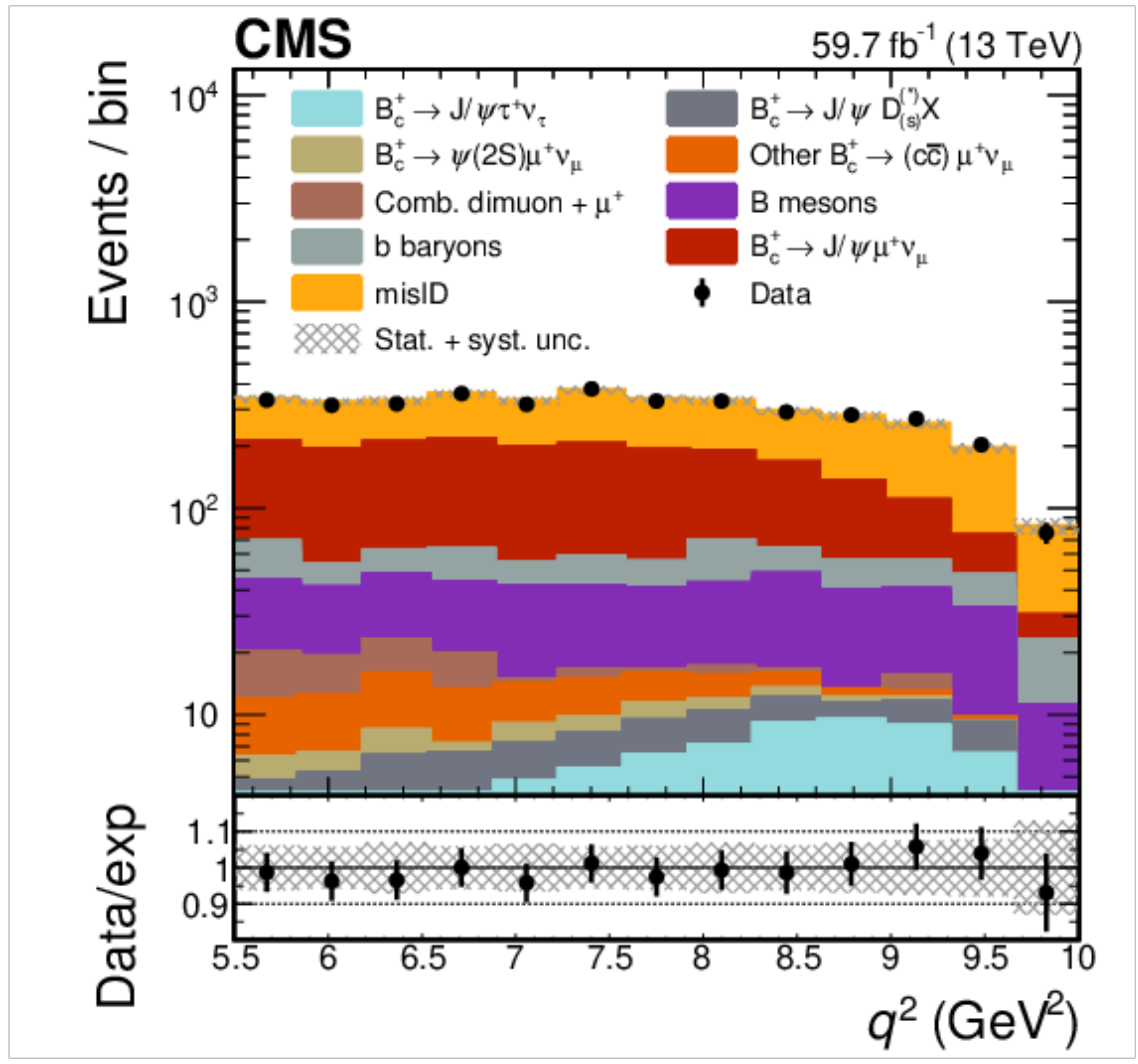
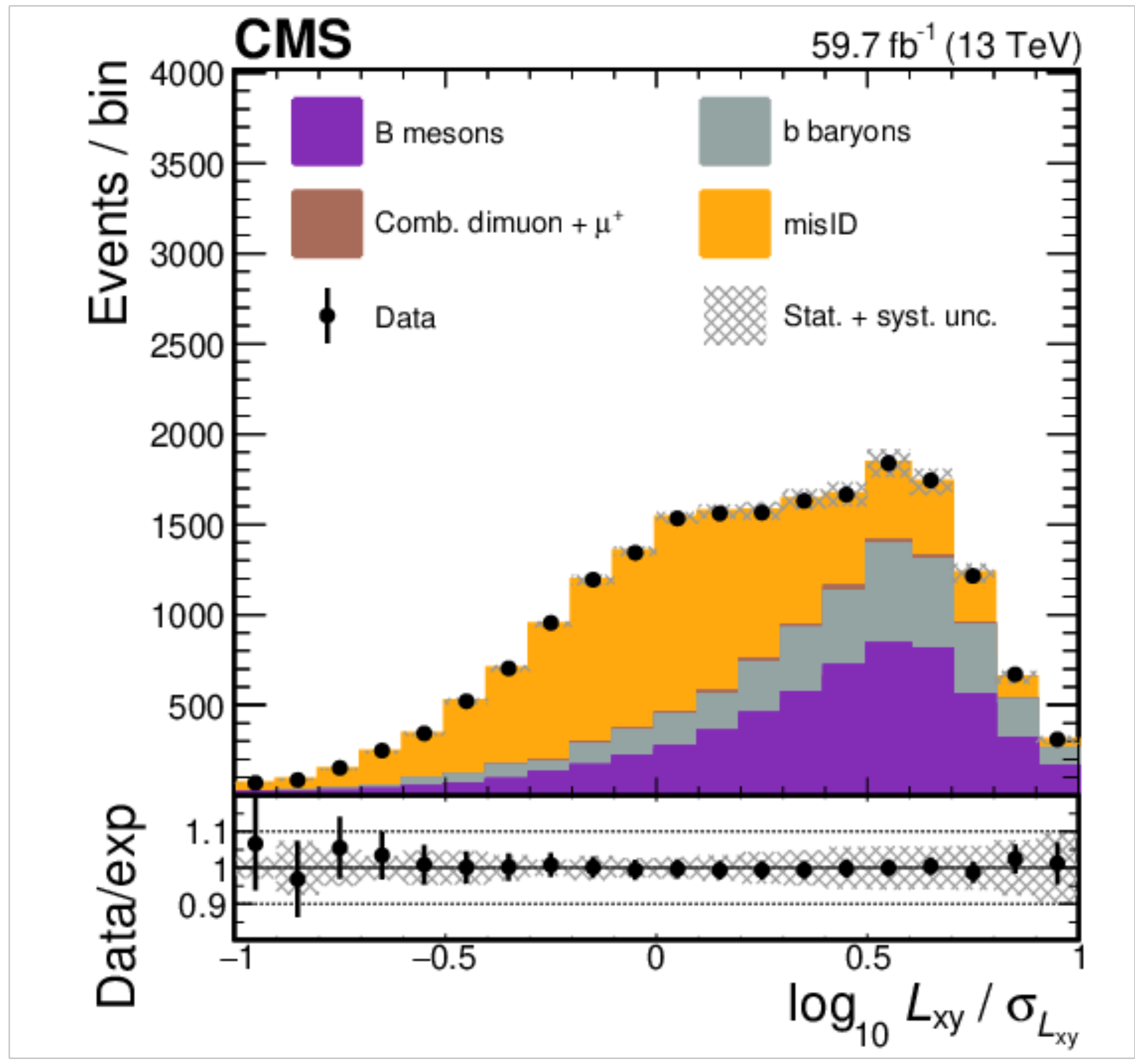
from simulation

- **Combinatorial dimuon $+\mu^+$**: unrelated muons with $m(\mu\mu)$ close to that of the J/ψ *data-driven*

total contribution





Signal and Bkg Contributions

fake μ_3

- **Signal τ:** $B_c \to J/\psi\tau\nu_\tau$
- **Signal μ:** $B_c \to J/\psi\mu\nu_\mu$

data-driven

- **misID bkg**: J/ψ + misidentified hadron (**mostly decay in flight $K \to \mu\nu$**)

total contribution

- H_B **bkg**: combinatorial $J/\psi + \mu$
- B_c **bkg**:
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from simulation

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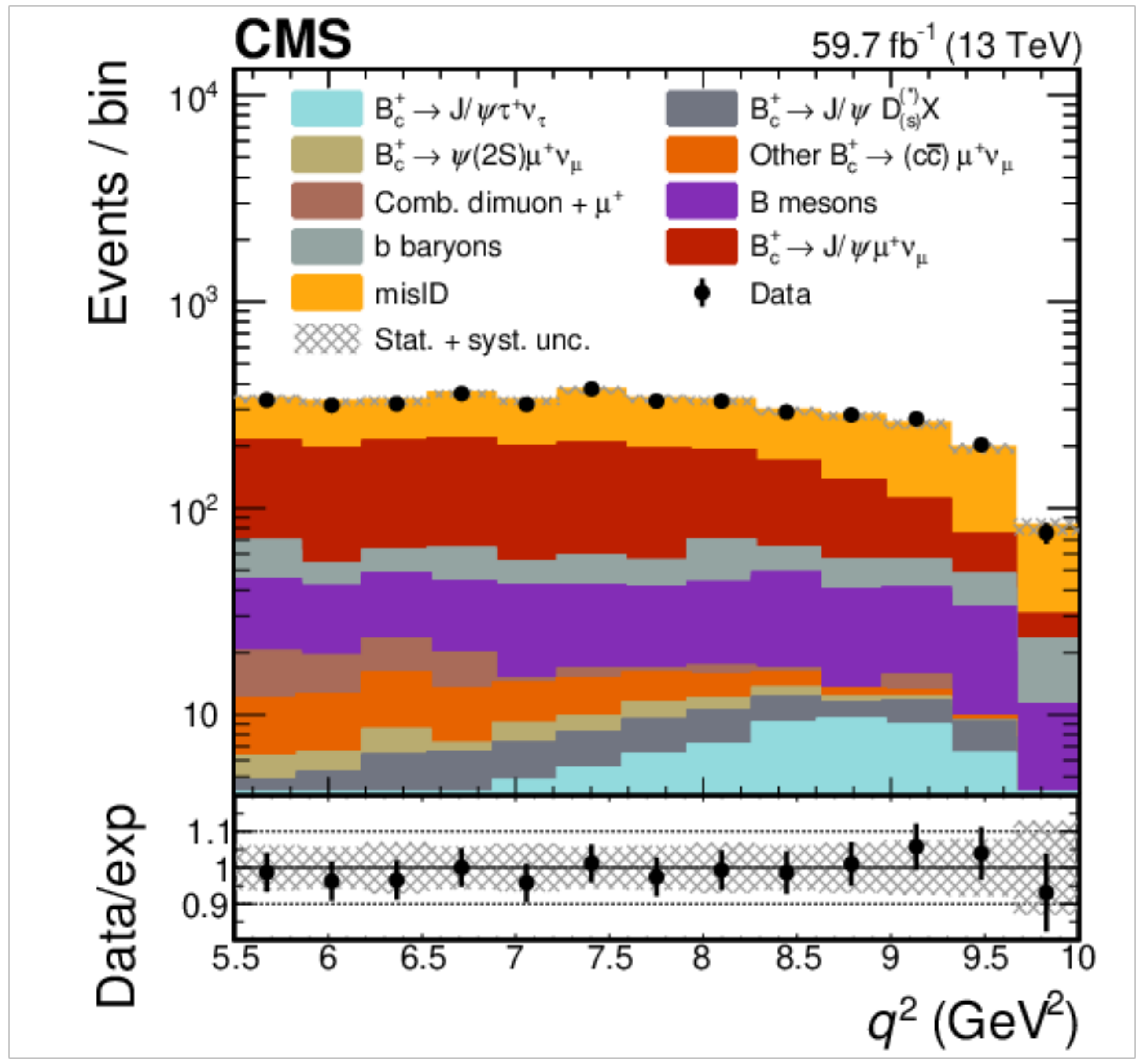
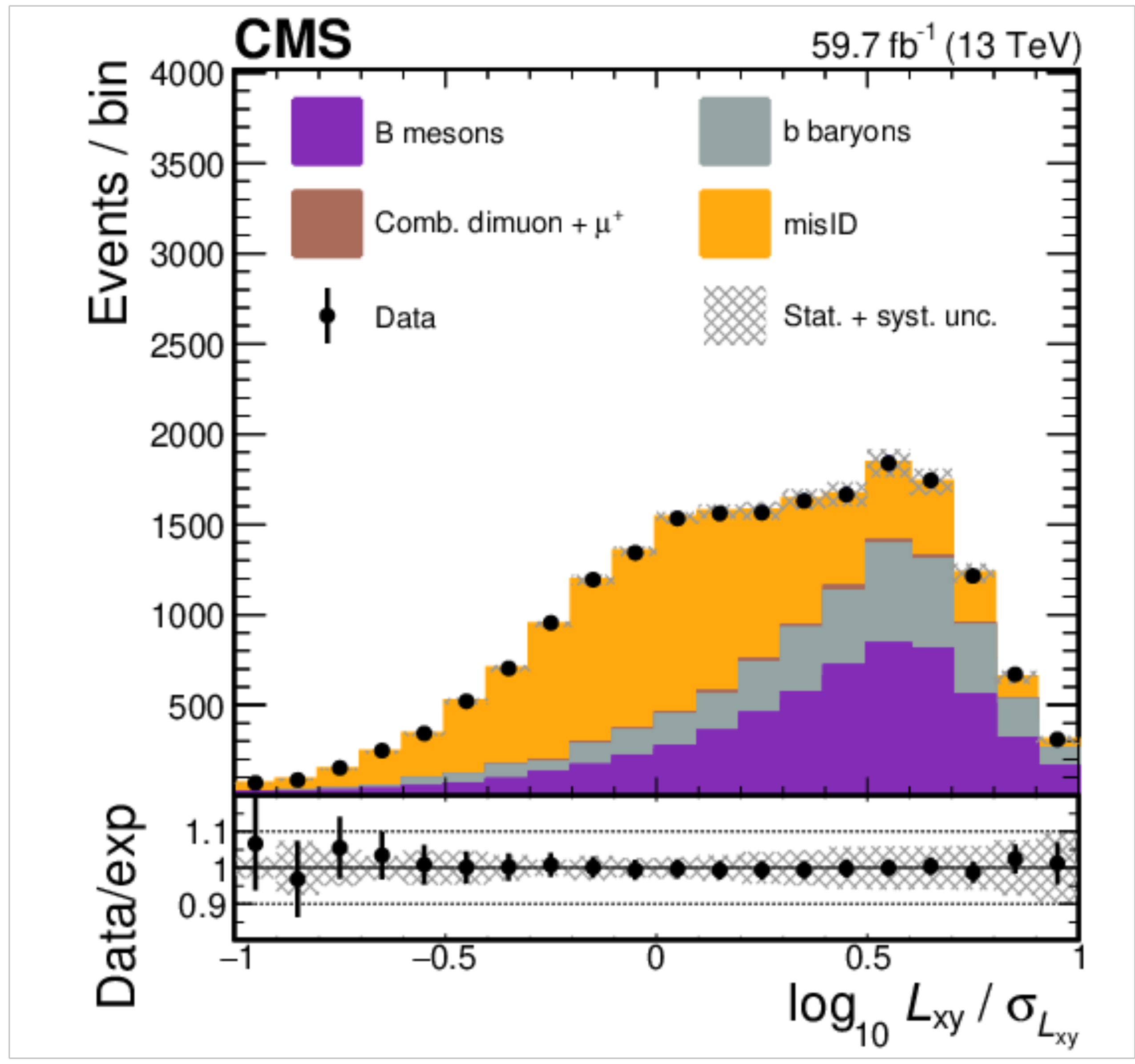
data-driven

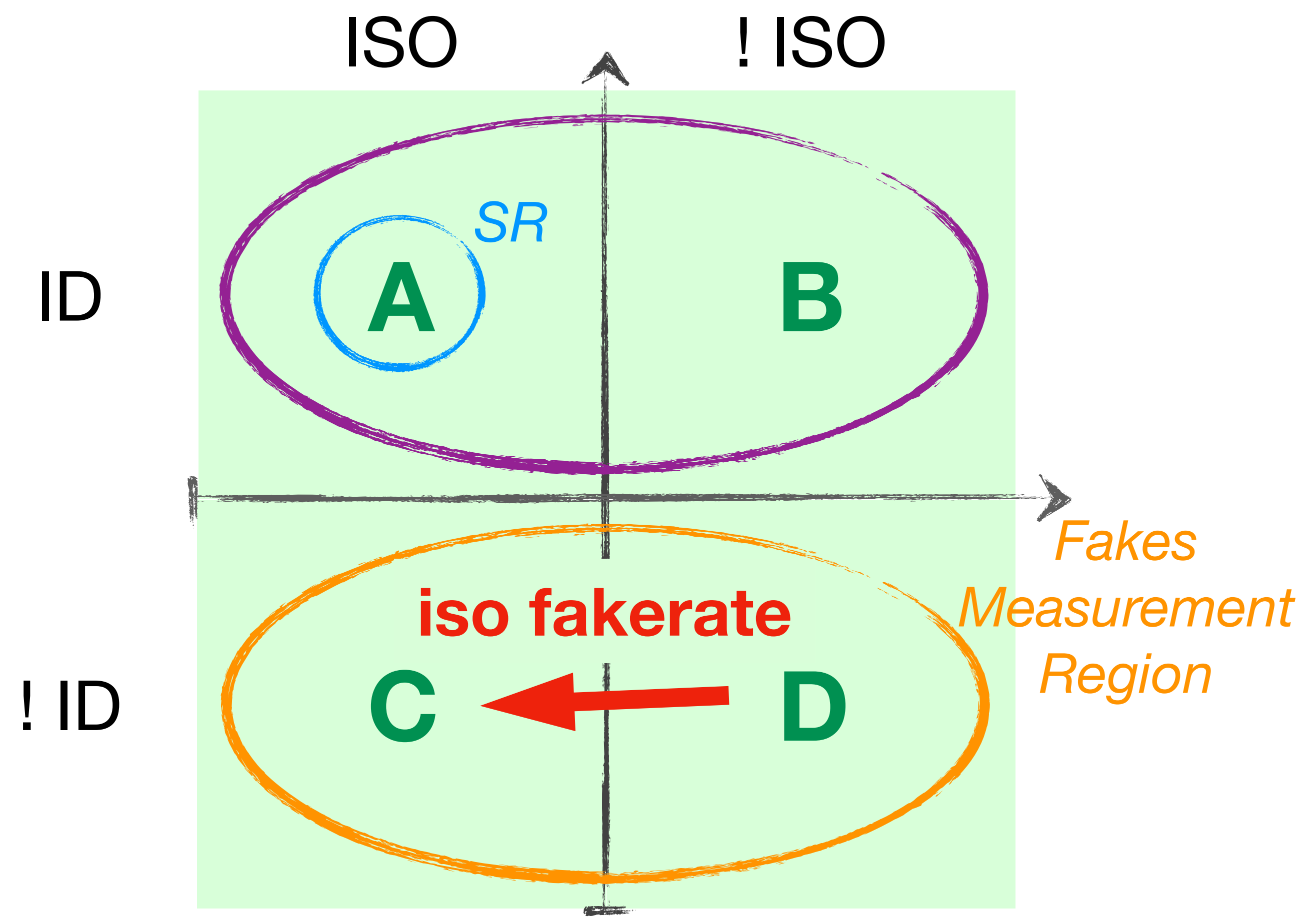
real μ_3





MisID Background

- Four regions defined on μ_3 features: μ_3 ISO and ID
- **measurement of *iso fakerate*** (fr_{ISO}) ***in !ID***: fit in multiple dimensions using **NN classifiers;** outputs interpreted as event-by-event weights



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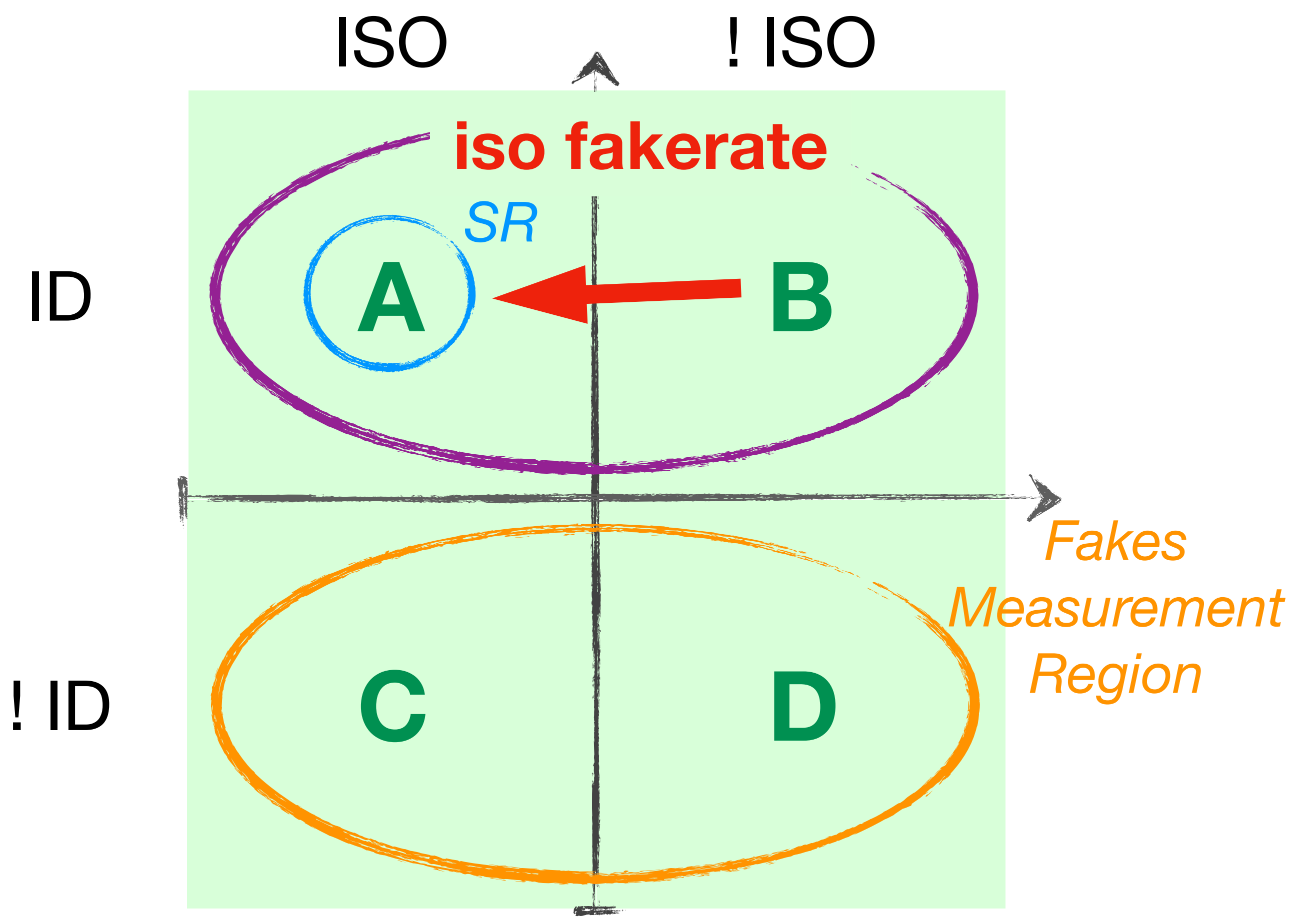
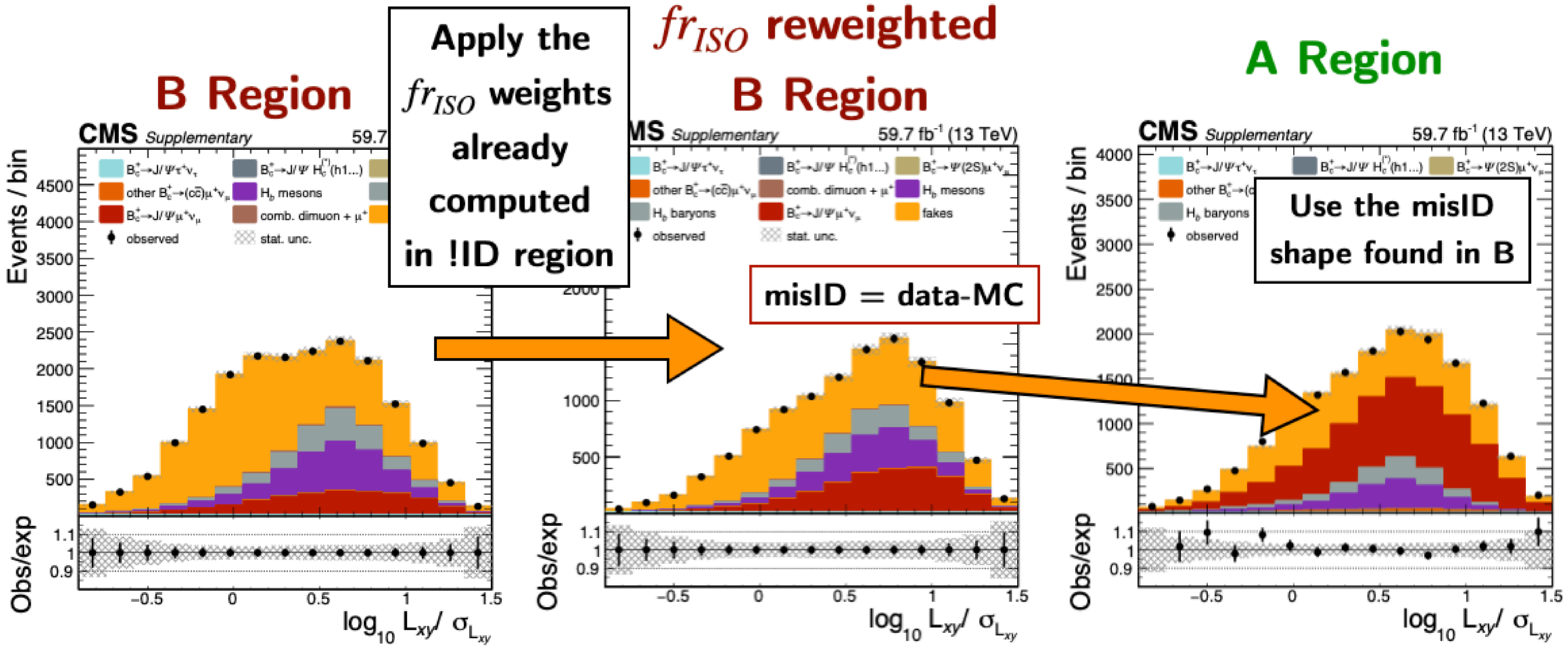


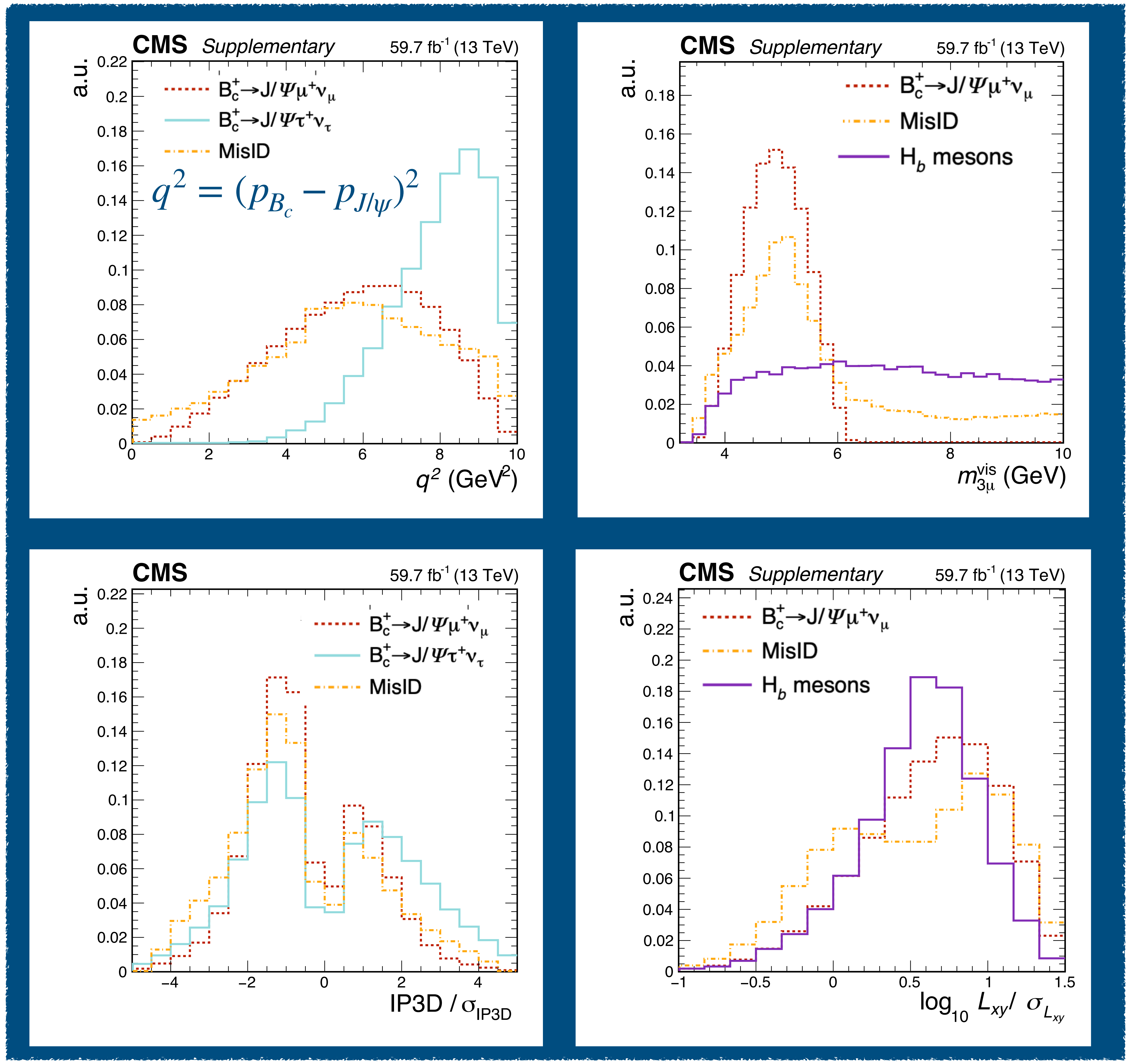
- **application in B:** ISO fakerate weights applied to events in B to find misID in A

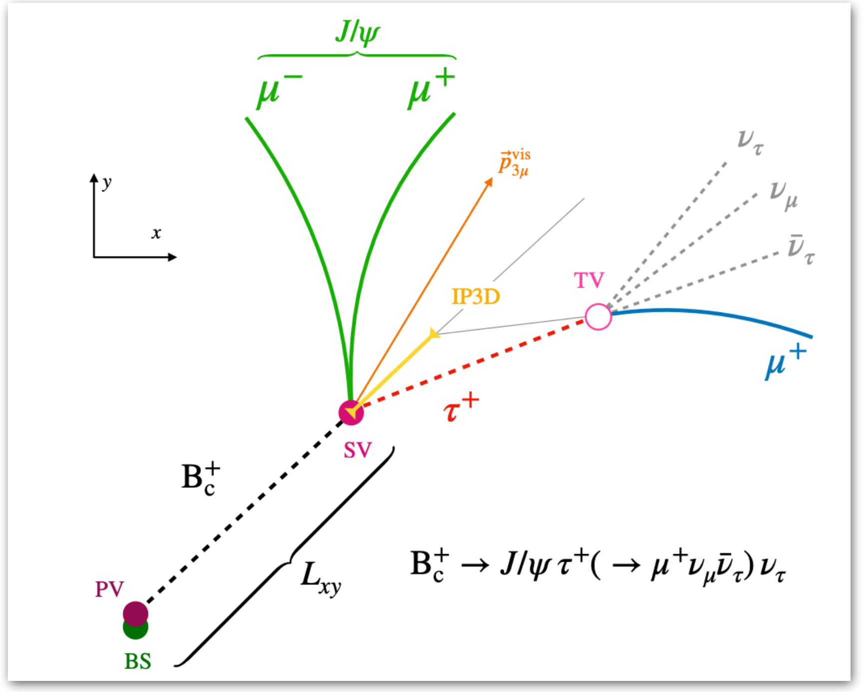
$$misID(SR) = fr_{ISO}(x_i) \cdot data(B) - fr_{ISO}(x_i) \cdot MC(B)$$



[PRD 111 (2025) L051102]

Observables and categories





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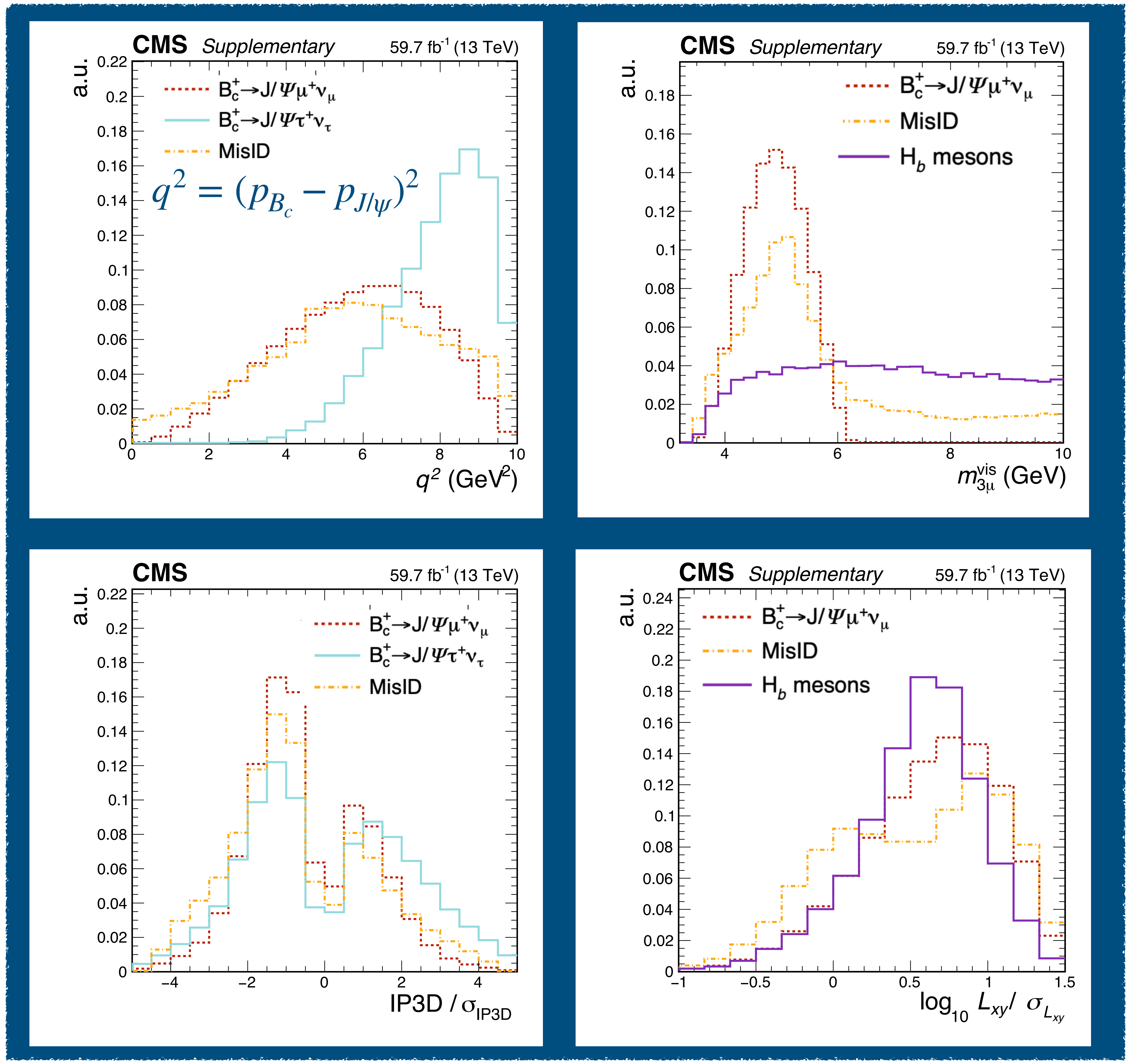
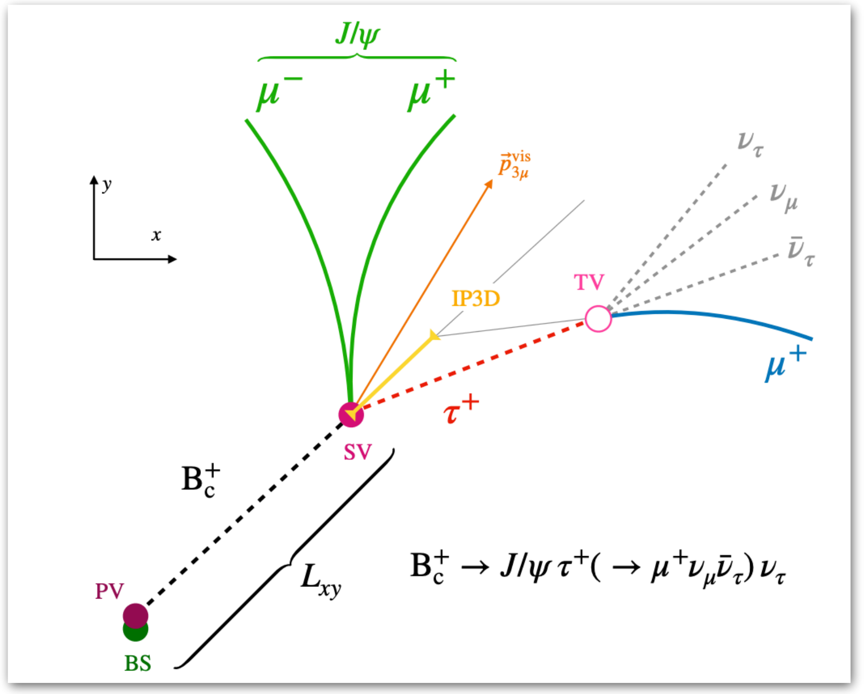
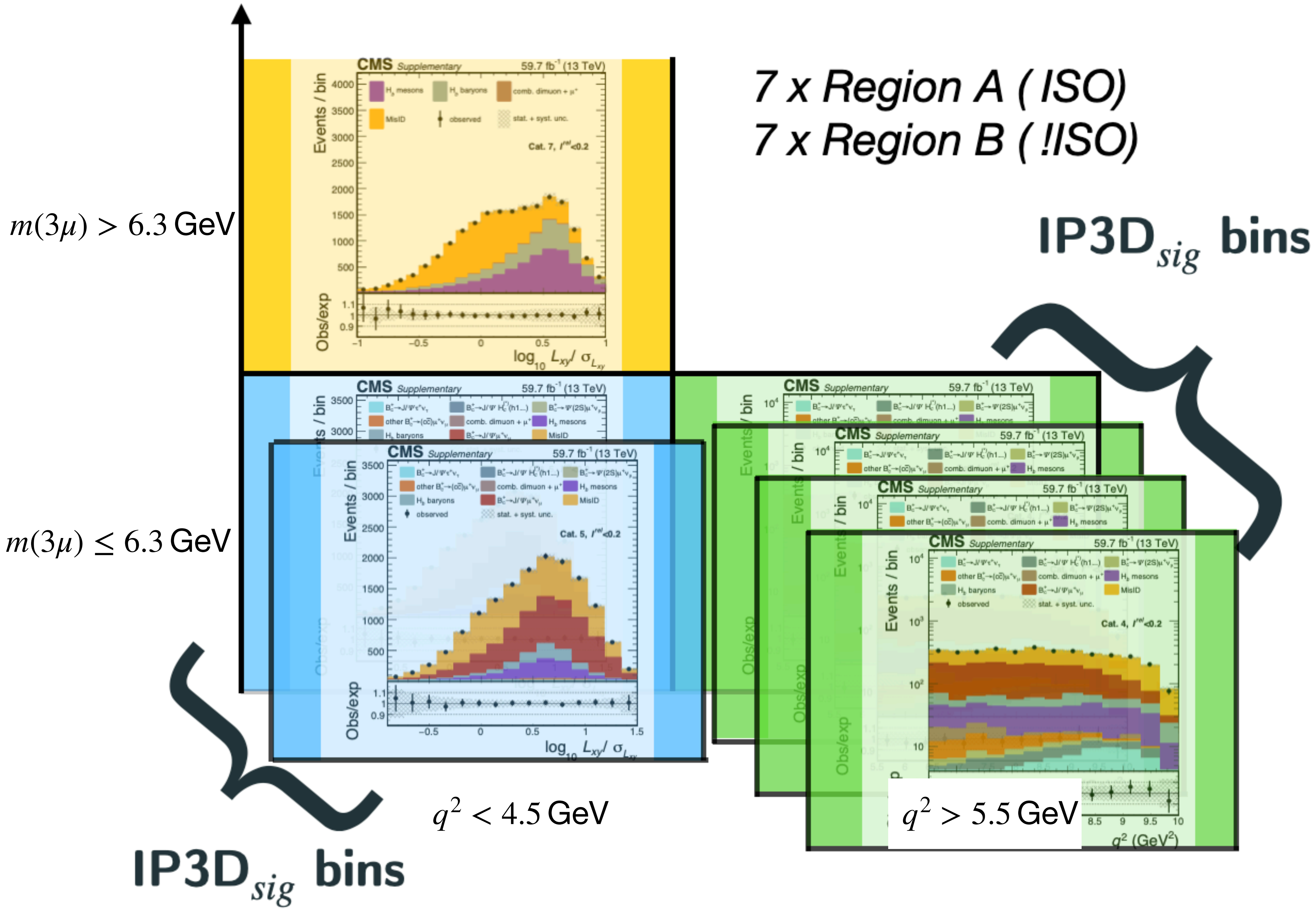






Fit Model

Parameters of interest

Signal and background pdfs

$$\mathscr{L}(\text{data} \mid \vec{\alpha}, \vec{\theta}) = \prod_i \text{Poisson}(n_i \mid s_i(\vec{\alpha}, \vec{\theta}) + b_i(\vec{\theta}))p(\vec{\tilde{\theta}} \mid \vec{\theta})$$

Nuisance parameters

prior nuisance pdfs

- **Binned maximum likelihood fit**
- Uncertainties are integrated into the fit as nuisance parameters
- Normalisation of B_c is a free floating parameter
  - Correlation between the 2 signals and the B_c bkg
  - Additional independent normalisation for τ-signal treated as POI → **result of the $R(J/\psi)$ measurement**
- Normalisation of H_b bkg is a free floating parameter
  - Correlation among different H_b contributions
- **MisID background is estimated in the fit.**

R(J/ψ) Leptonic Result

$$R(J/\psi) = 0.17^{+0.33}_{-0.33}$$

$$R(J/\psi) = 0.17^{+0.21}_{-0.22}(Syst.)^{+0.19}_{-0.18}(Theo.)^{+0.18}_{-0.17}(Stat.)$$

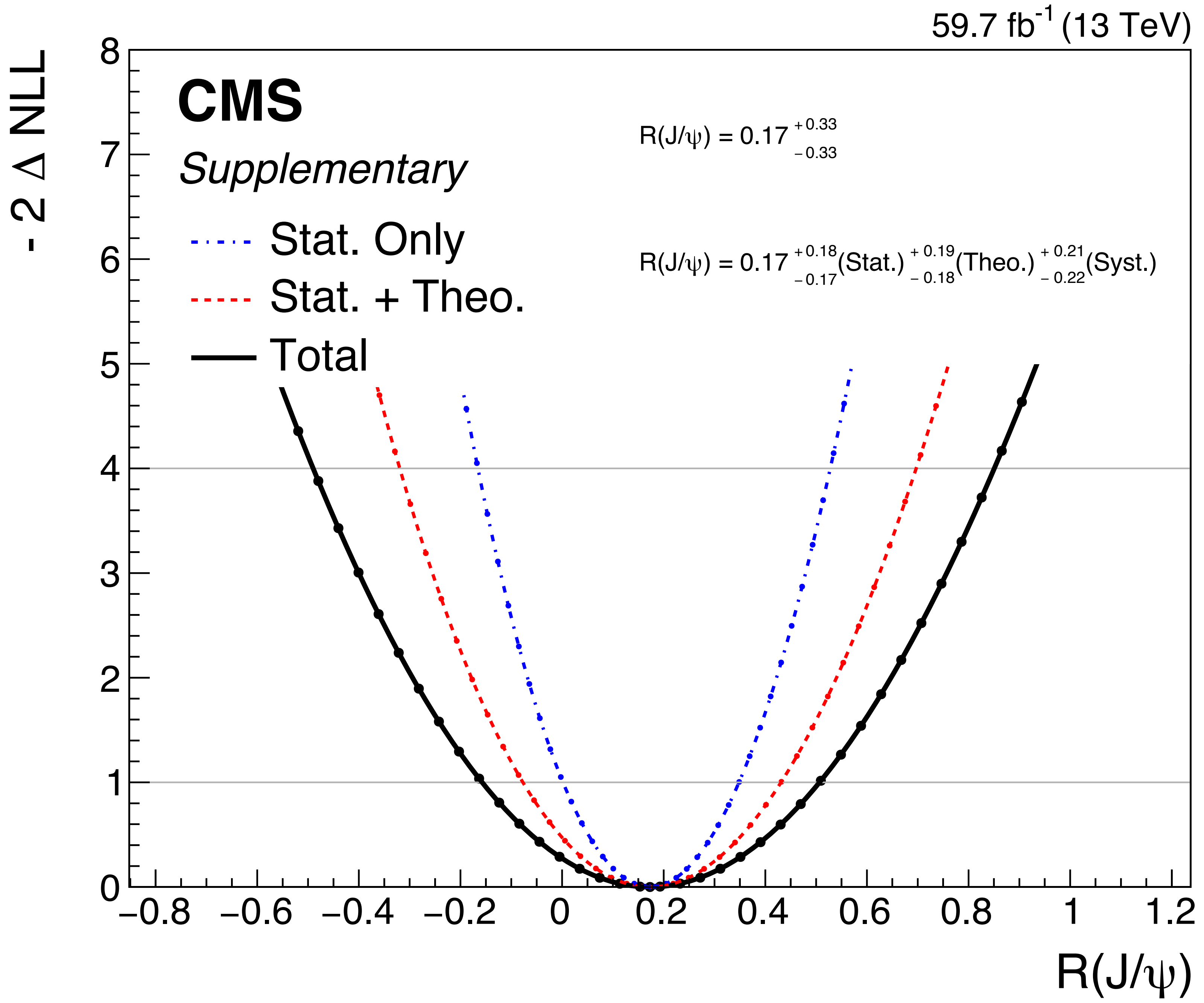
Compatible with SM prediction within 0.3 σ

with LHCb result within 1.3 σ

- **The first LFU result in $b \to c l^{-} \bar{\nu}_l$ in CMS**, on limited part of the statistics (only 2018 data)

Total of 435 systematic uncertainties in the fit

Contribution	Type	Uncertainty (10^{-2})
Form factor (theory)	S	19
misID statistical	S (bin by bin)	13
misID systematic	N, S	8, 0.7
Finite MC size	S (bin by bin)	9
Topological	S	9
Efficiencies	N	6
Total systematic uncertainty		28



R(J/ψ) Hadronic Channel

- **Hadronic channel :** $\tau_{had} \to \pi\pi\pi(\pi^0)$
- **Muonic decay of** $J/\psi \to \mu^+\mu^-$
- Different final state in numerator and denominator
  - Denominator from leptonic channel analysis, including only 2018 dataset (59.7 fb^{-1})
  - Numerator includes full Run 2 ($138\ fb^{-1}$)

$$R(J/\psi) = \frac{\mathscr{B}(B_c^+ \to J/\psi(\to \mu^+\mu^-)\tau^+(\to \pi\pi\pi(+\pi^0))\nu_\tau)}{\mathscr{B}(B_c^+ \to J/\psi(\to \mu^+\mu^-)\mu^+\nu_\mu)}$$

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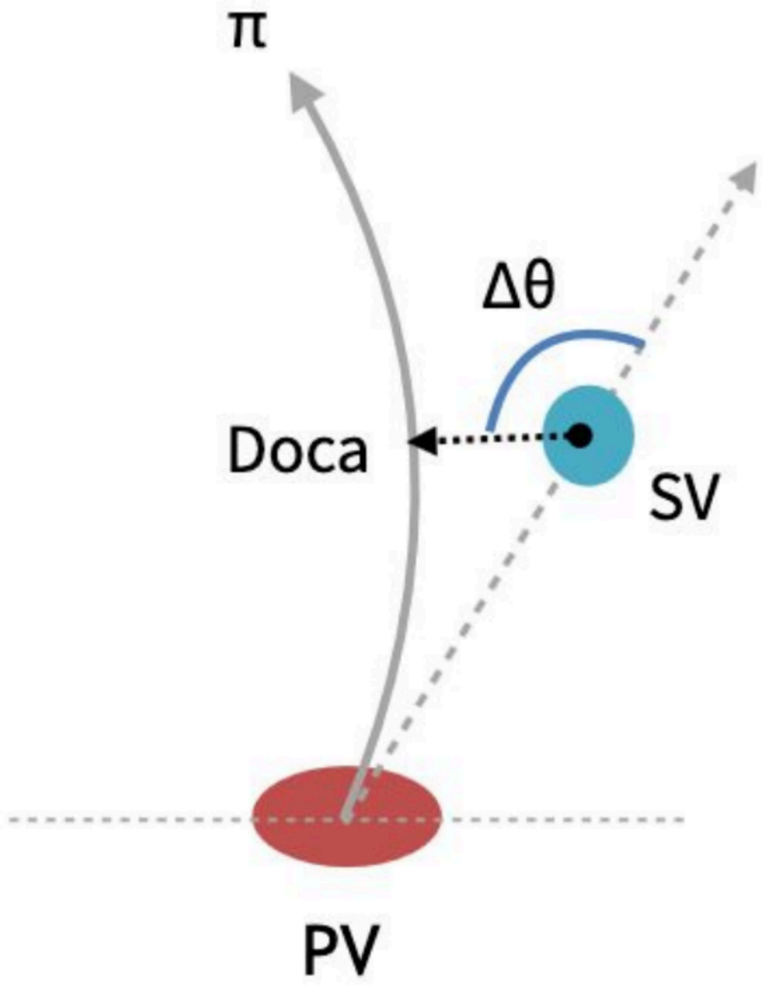
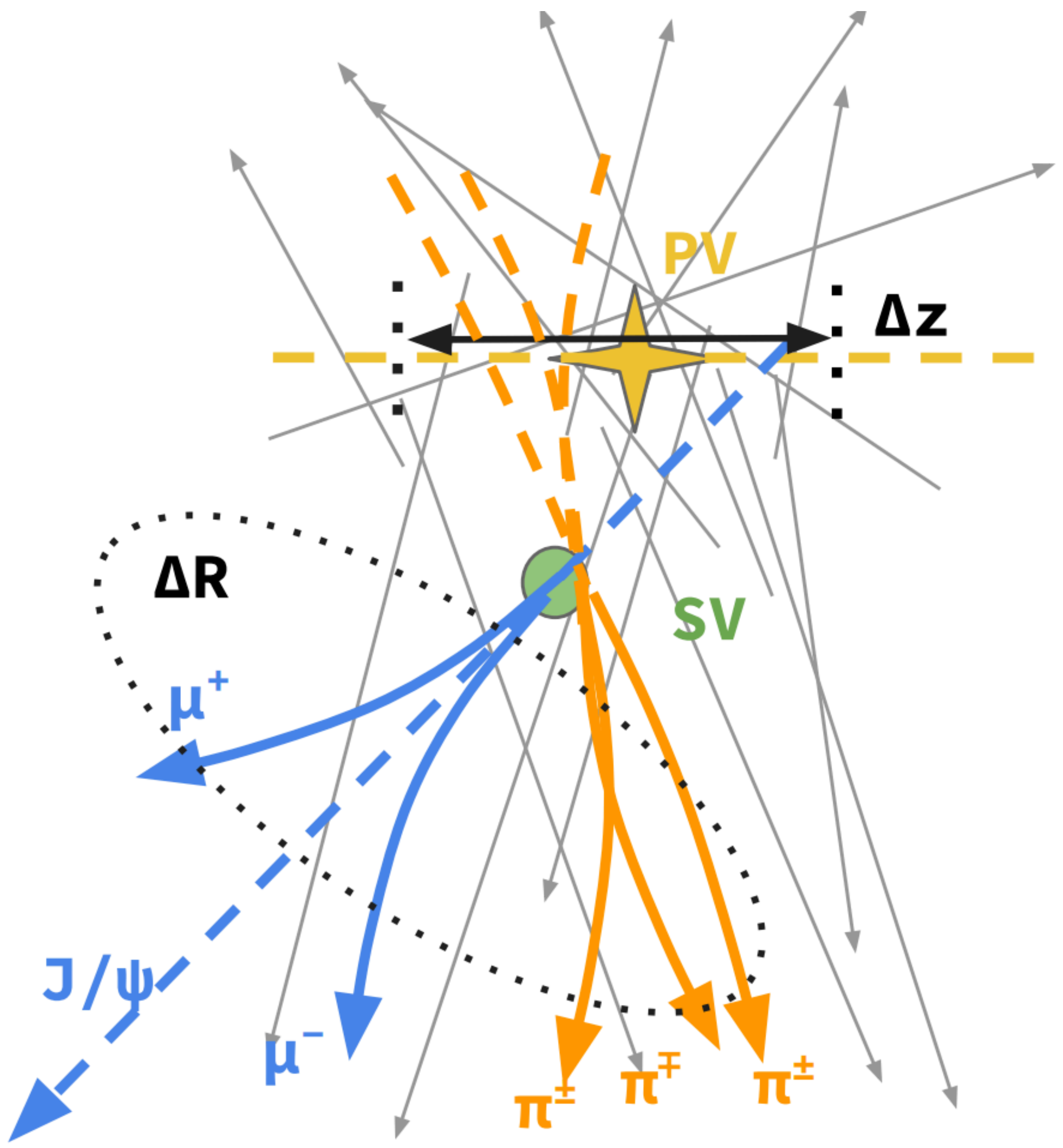
- Different final state in numerator and denominator
  - Denominator from leptonic channel analysis, including only 2018 dataset (59.7 fb^{-1})
  - Numerator includes full Run 2 ($138\ fb^{-1}$)

- Pre-fit B_c normalisation derived from the leptonic analysis for 2018
  - Relative corrections for possible $\epsilon \cdot A$ differences due to year of data taking are computed by fitting $B_c \to J/\psi\pi\pi\pi$ mass peak
  - Uncertainty computed with validation study on $B_c \to J/\psi\pi$ mass peak

Low pT τ Reconstruction

1. **Pre-filtering of charged pions**
   - Close to PV: $\Delta z(PV, \pi) < 0.12\ cm$
   - Close to the J/ψ: $\Delta R(J/\psi, \pi) < 1$
   - Close to the SV: distance of closest approach -0.4 mm < DOCA(SV,π) < 0.6 mm
2. **Build all possible triplets**
   - Trigger matching for one track required
3. **If multiple triplets, pick the highest in p_T**
   - Good vertex: vtx prob > 10%
   - Flight significance > 3 σ
   - Compatible with a τ: invariant mass < 1.7 GeV



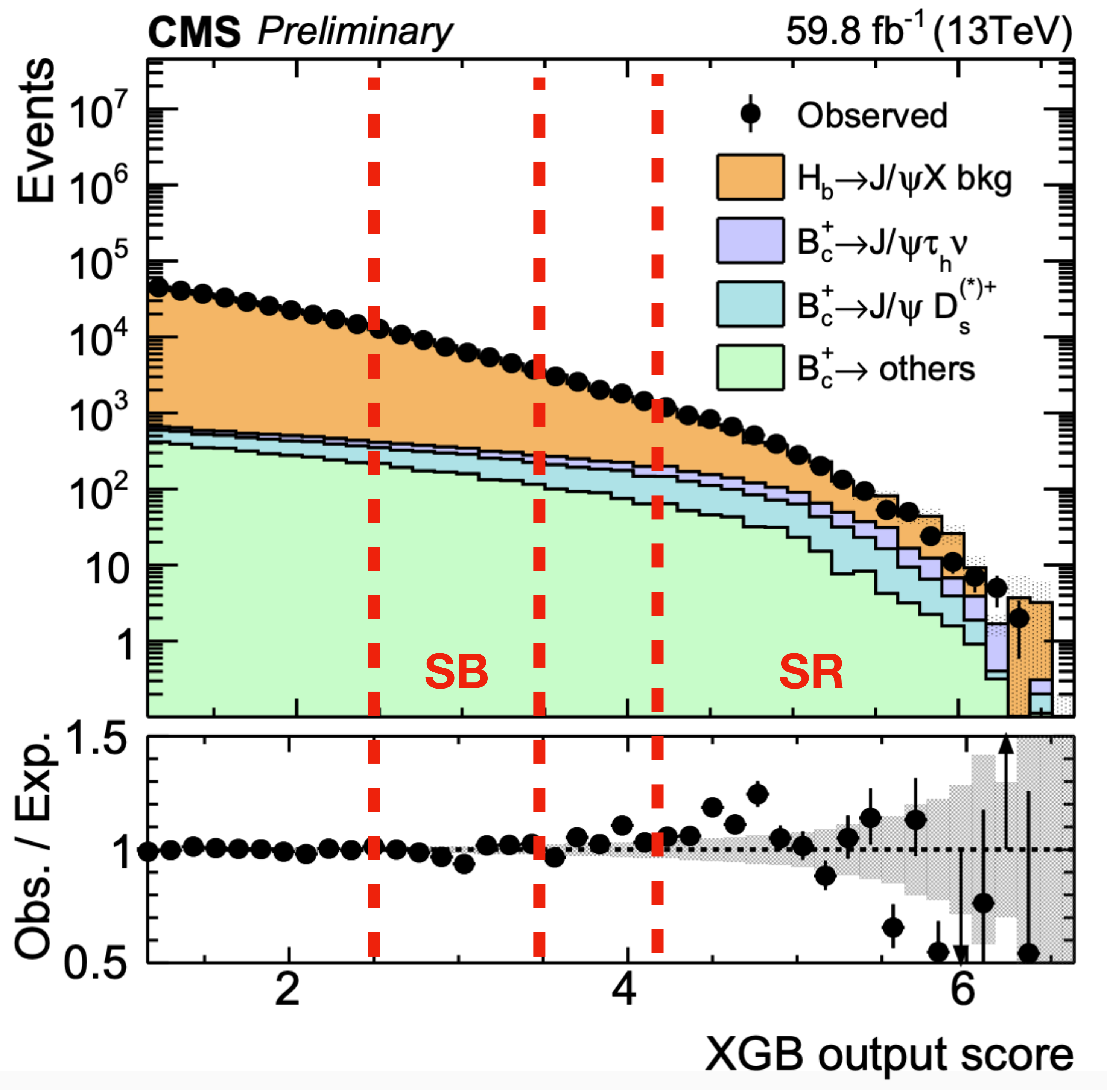


Background Suppression

total contribution

- **Main backgrounds:**
  - $H_b \to J/\psi + X$ bkg
    - B-hadrons that are not B_c
    - Dominant background by orders of magnitude
    - Estimated directly in data
  - $B_c \to J/\psi D_s^{(*)}$
  - Other B_c decays
    - e.g. $B_c \to J/\psi D^{+(*)}$, $B_c \to J/\psi D^+ K_0^{(*)}$,$B_c \to J/\psi D^{0(*)} K^+$

- **BDT to maximise background rejection**
  - Variables: τ flight length significance, particles multiplicity, vertices quality, isolation, ID…
  - Main goal: maximise signal vs H_b bkg separation

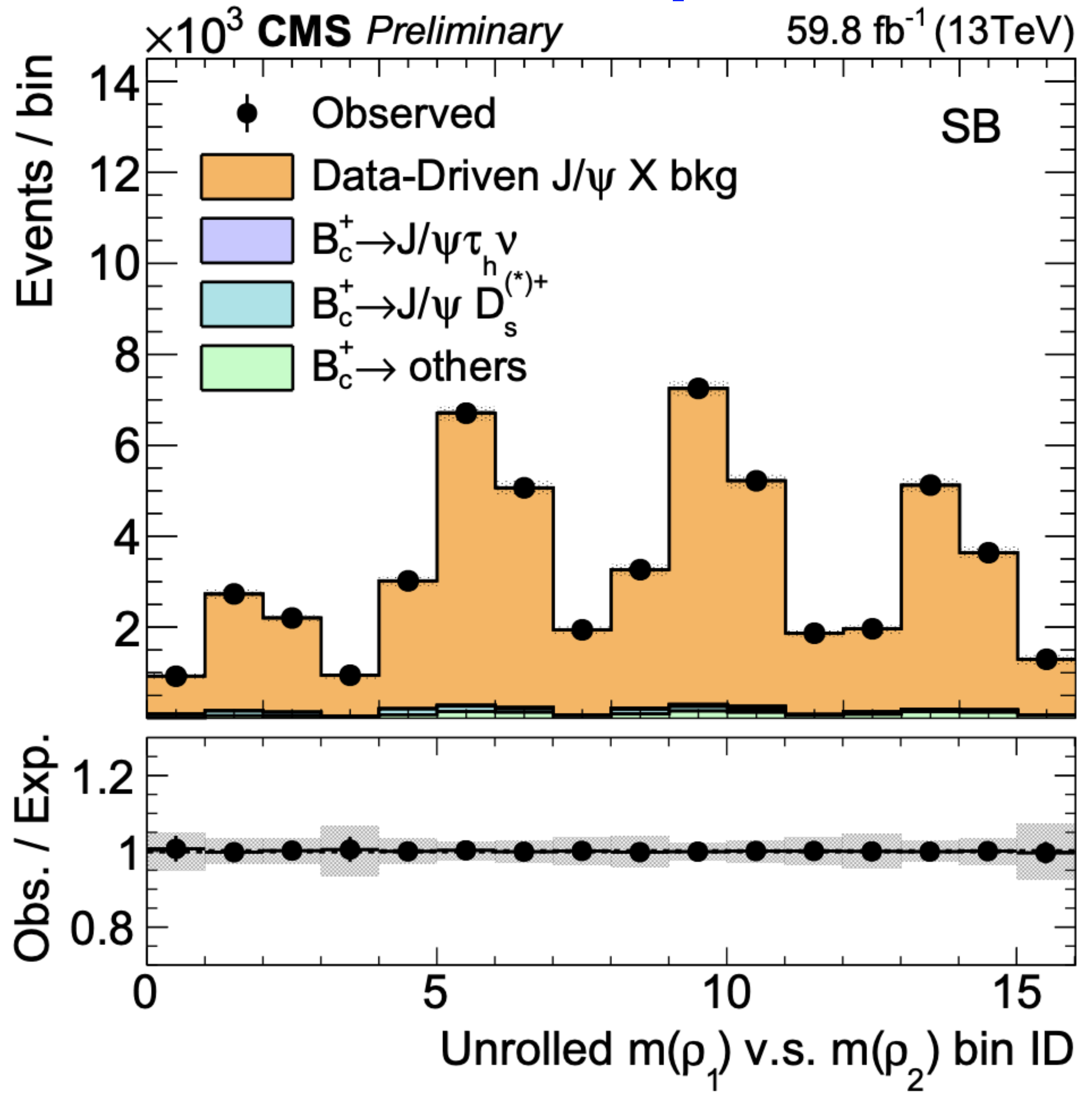


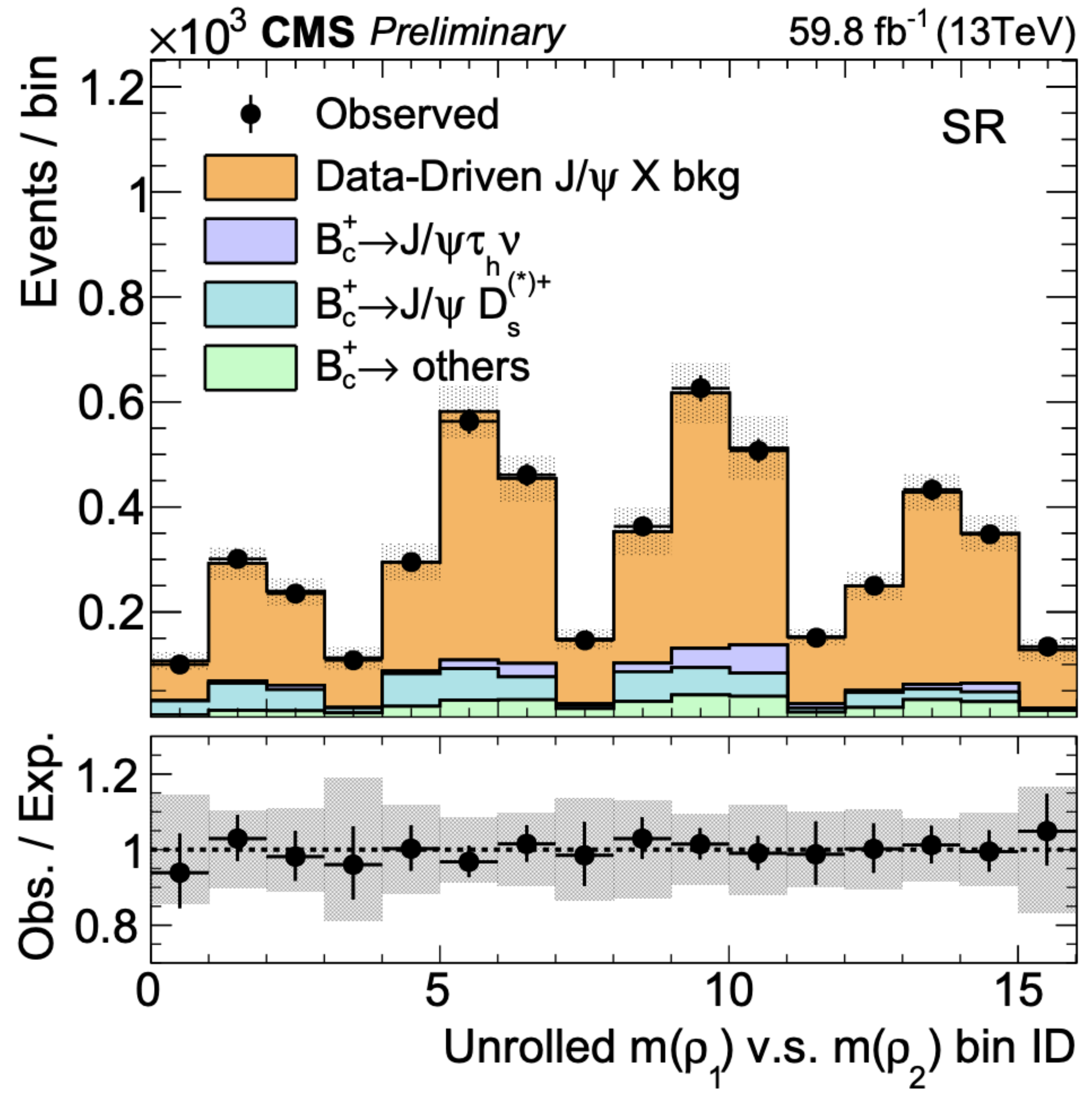
- BDT score used to define SR and SB
  - SB used to derive the data-driven $H_b \to J/\psi + X$ bkg

[CMS-PAS-BPH-23-001]

Signal Extraction

- The possible hadronic τ leptons 3-prong decay through $\tau^+ \to a_1 \nu_\tau$, with $a_1 \to \rho^0(\to \pi^+\pi^-)\pi^+$ is exploited for signal extraction
- **Maximum likelihood fit** of 1D unrolled distribution of the 2D distribution ($m(\rho_1)$,$m(\rho_2)$)
    1. Pions ordered by pT
    2. OS pairs combined as possible ρ: $\pi_1 + \pi_2;\ \ \pi_2 + \pi_3;\ \ \pi_2 + \pi_3$
    3. The **unrolled** $m(\rho_1)$,$m(\rho_2)$ distribution used as discriminating variable in the fit





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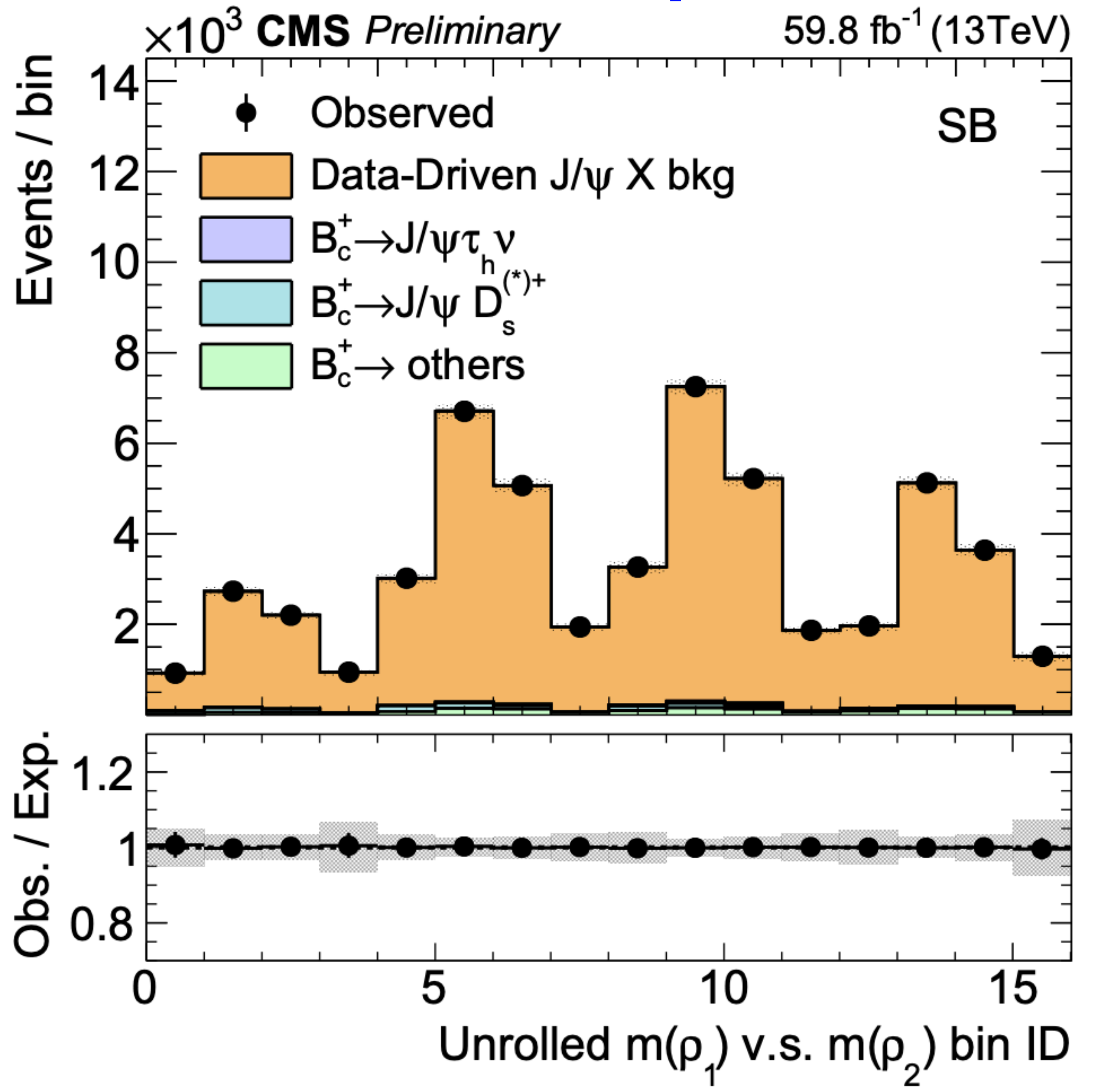
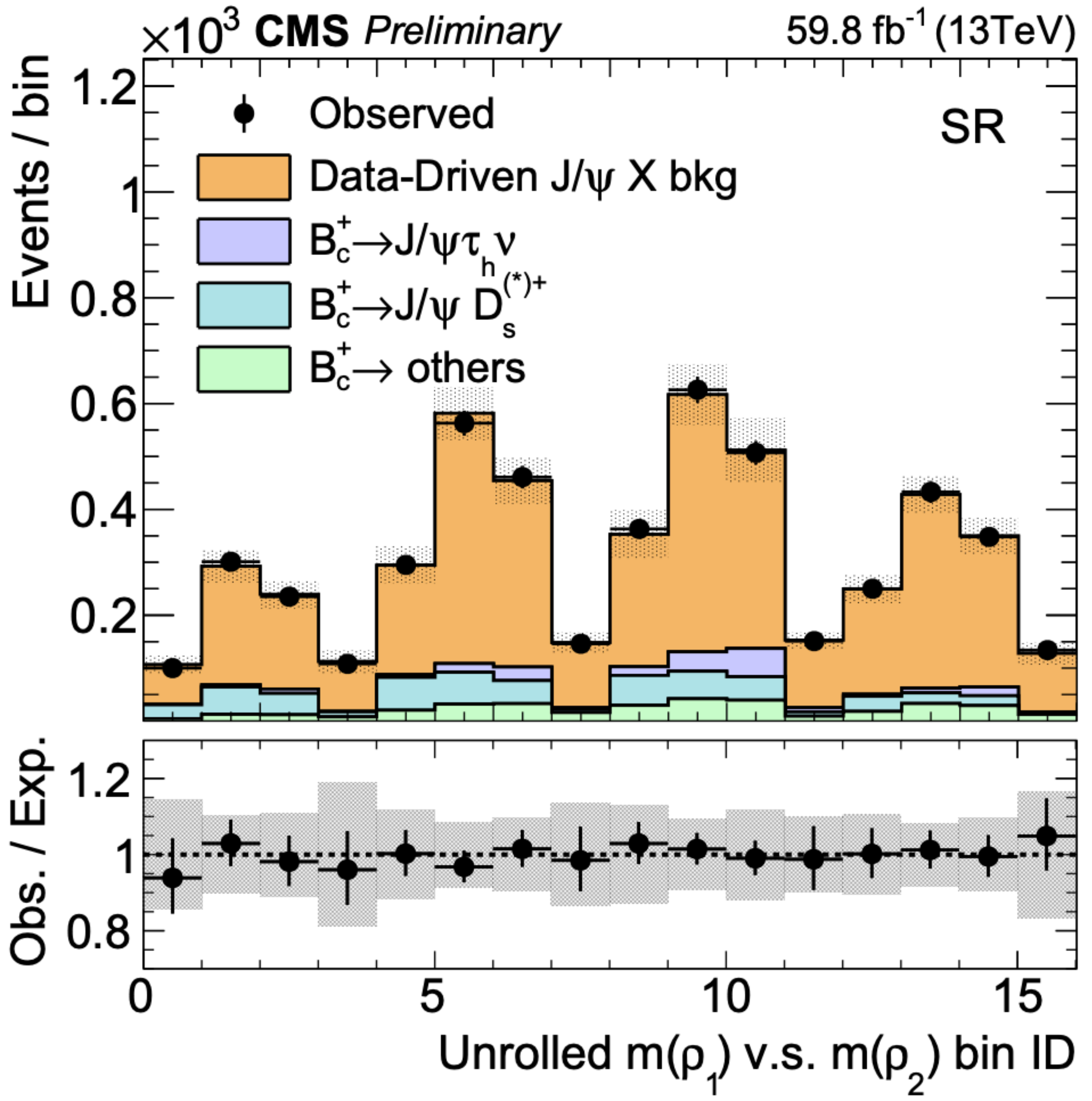
- **Simultaneous fit of SR and SB**
    - SB used to derive H_b bkg

Several studies performed to validate the bkg extrapolation method

$$N_{J/\psi,bkg}(SR, bin = i) = f_{ext}(i) \times \left(N_{data}(SB,i) - r_{B_c^+} \times N_{B_c^+,bkg}(SB,i) - r_{B_c^+} \times r \times N_{B_c^+,sig}(SB,i)\right)$$

f_{ext}: factor that extrapolates from SB to SR, derived from simulation





[CMS-PAS-BPH-23-001]

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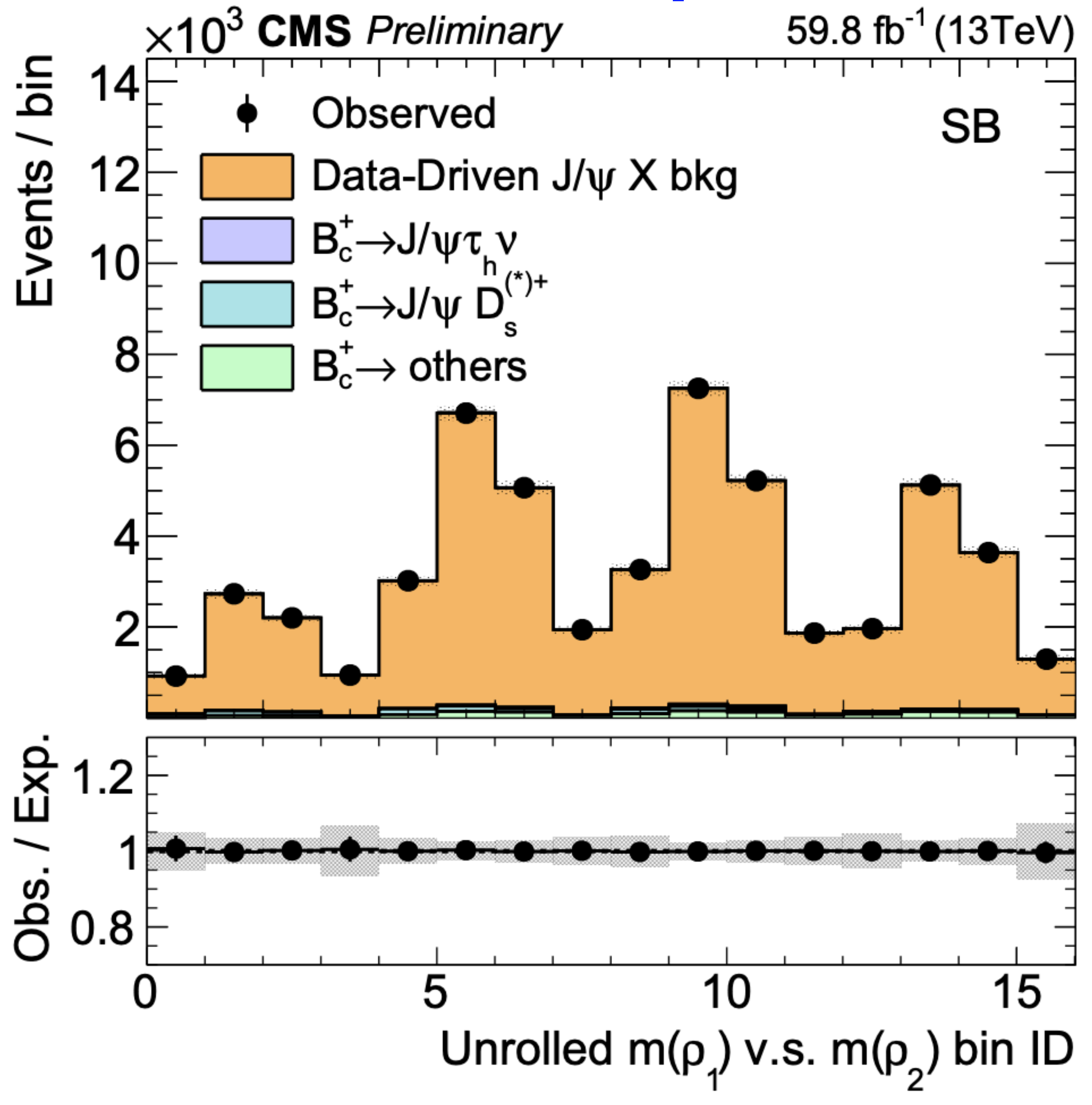

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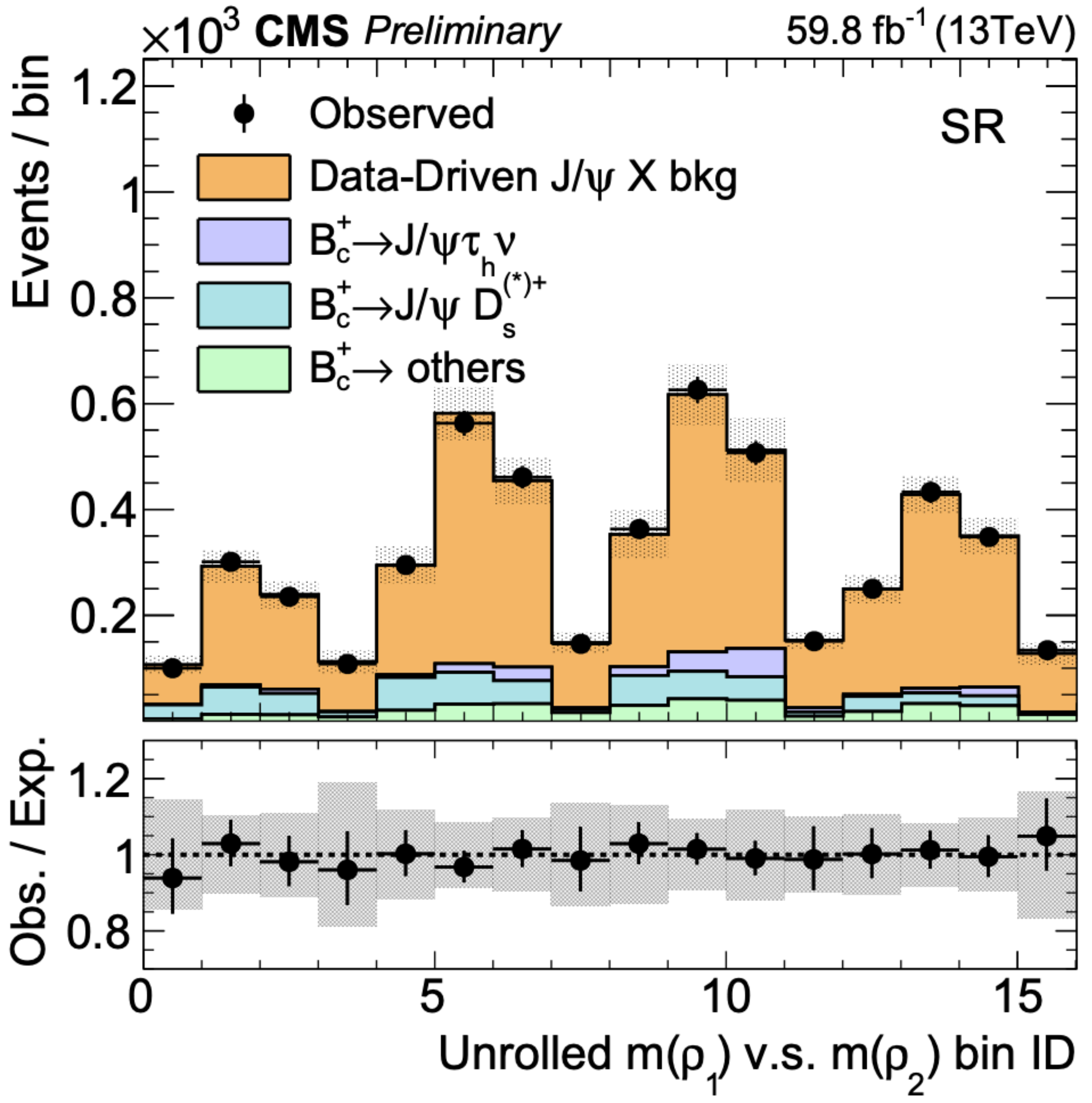

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f_{ext}: factor that extrapolates from SB to SR, derived from simulation

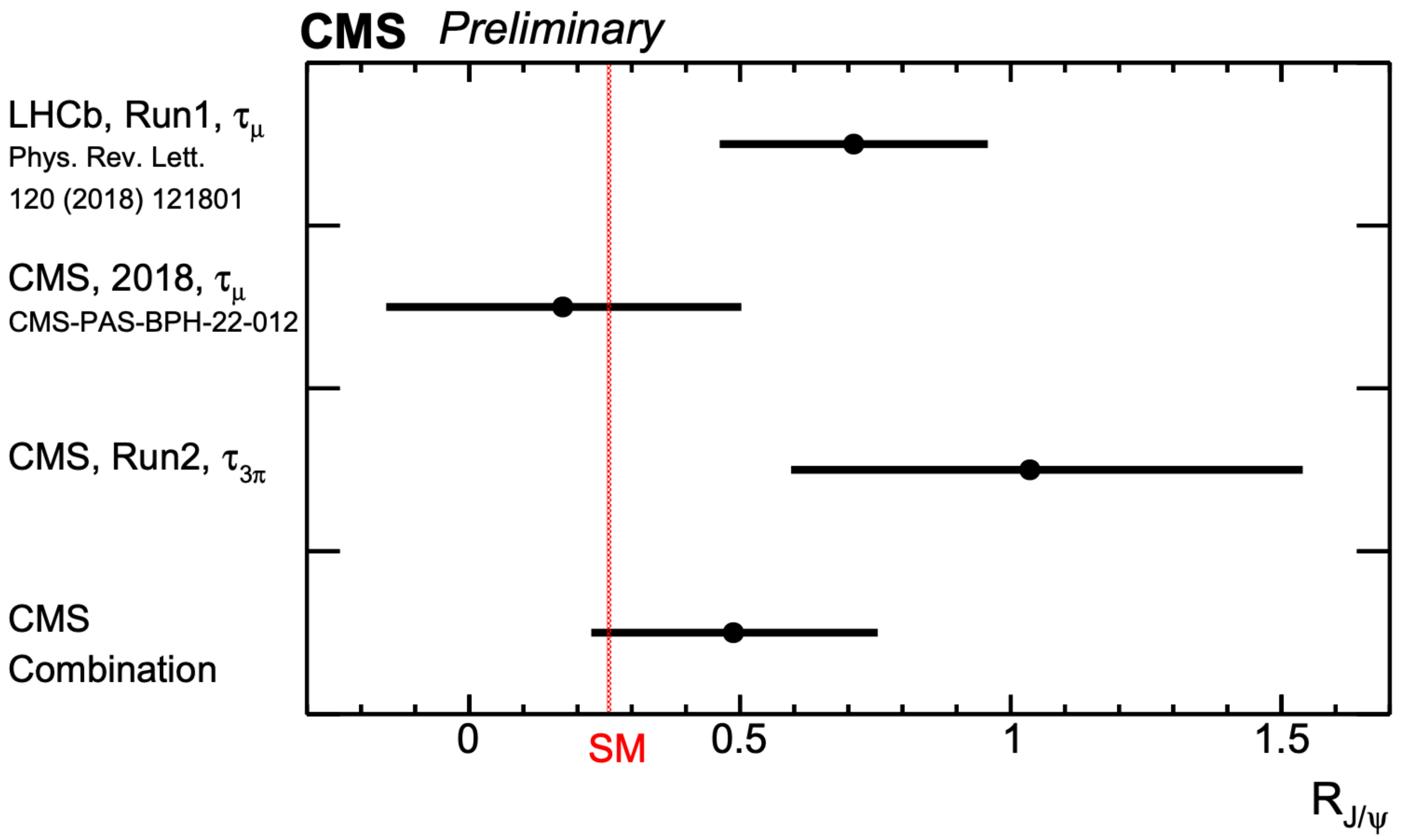
$$R(J/\psi)_{had} = 1.04^{+0.50}_{-0.44}$$

assuming denominator from leptonic channel result

$R(J/\psi)$ Combination

- Leptonic analysis provides both numerator and denominator for 2018
- Hadronic analysis provides numerator for 2016, 2017, 2018
- **Simultaneous fit of leptonic and hadronic channels**
    - Signal POI and free floating parameters correlated between the two channels
    - Treatment of systematic uncertainties

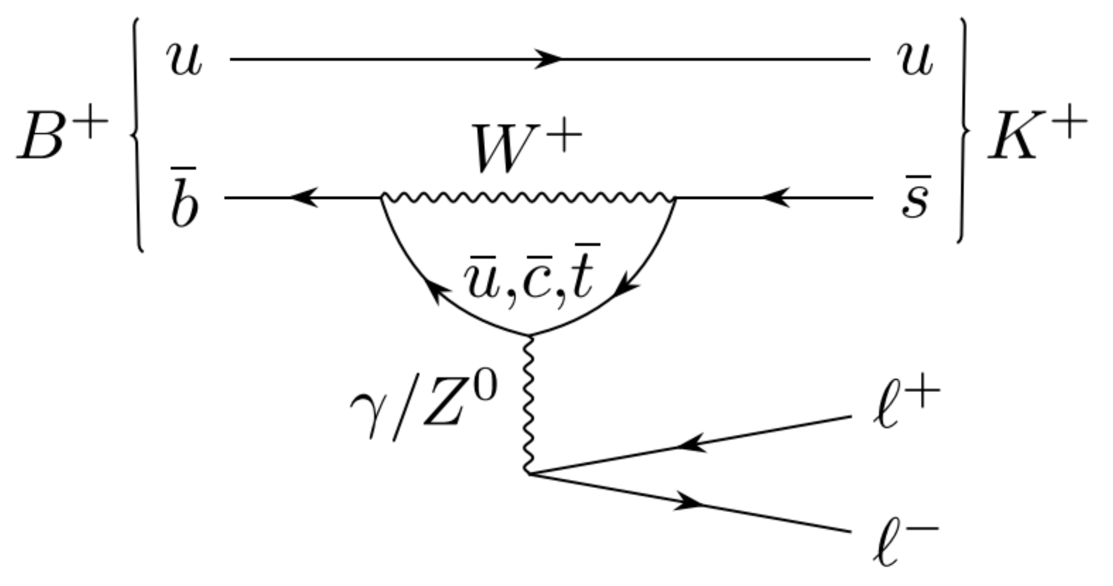
Systematic source	Type	Affected proc.	channel			
			τ_μ 2018	τ_h 2018	τ_h 2017	τ_h 2016
Form factor	shape	$B_c^+ \to J/\psi \ell \nu_\ell$	✓	✓	✓	✓
Tauola modeling	shape	$B_c^+ \to J/\psi \tau^+ \nu_\tau$		✓	✓	✓
B_c^+ decay lifetime	shape	All B_c^+ procs.	✓	✓	✓	✓
$H_b \to J/\psi X$ shape	shape	DD bkg.		✓	✓	✓
Pileup weight	shape	All MC	✓	✓	✓	✓
Missing B_c^+ bkg.	shape	other B_c^+		✓	✓	✓
Bin-by-bin uncertainties	shape	All	✓	✓	✓	✓
Triplet reco. eff.	norm.	$B_c^+ \to J/\psi \tau^+ \nu_\tau$		6.9% (✓)	6.9% (✓)	6.9% (✓)
$B_c^+ \to J/\psi D_s^{(*)+}$ normalisation	norm.	$B_c^+ \to J/\psi D_s^{(*)+}$	38% (✓)	38% (✓)	38% (✓)	38% (✓)
Other minor B_c^+ normalisation	norm.	other B_c^+		50% (✓)	50% (✓)	50% (✓)
Trigger ($\mu^+\mu^-$)	norm.	All MC	10% (✓)	10% (✓) $\oplus$ 5%	10%	10%
Trigger (track)	norm.	All MC		10%	10%	10%
Trigger (J/ψ)	norm.	All MC		10%	10%	10%
Muon ID	norm.	All MC	4%	4%	4%	4%
Muon Reco	norm.	All MC	4% (✓)	4% (✓)	4%	4%
Bkg. norm.	norm.	DD bkg.		30%	30%	30%
B_c^+ MC norm.	norm.	All B_c^+		5%	30%	30%
Displaced track reco eff.	norm.	All B_c^+		5% (✓)	5% (✓)	5% (✓)



$$R(J/\psi) = 0.49 \pm 0.09\ (stat) \pm 0.25\ (syst)$$

$R(K)$ Measurement

$R(K)$ Analysis Overview



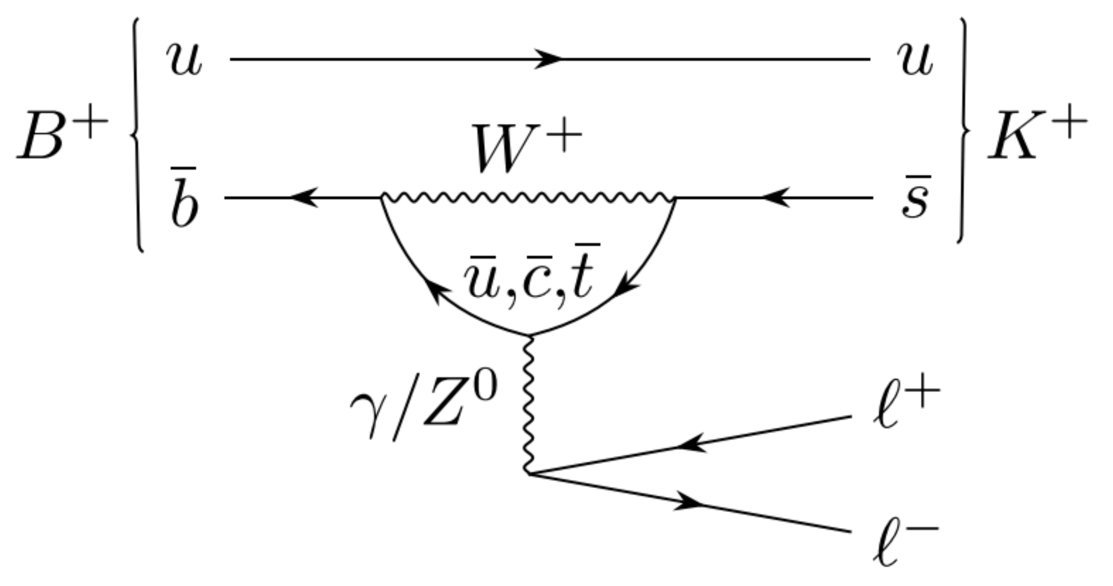
- Rare decay $\bar{b} \to \bar{s}l^+l^-$
- Test LFU measuring $R(K)$

$$R(K) = \frac{\mathscr{B}(B \to \mu\mu K)}{\mathscr{B}(B \to eeK)}$$

- To reduce experimental uncertainties, $R(K)$ measured as a double ratio normalised to $\mathscr{B}(B^+ \to J/\psi K^+)$

$$\boxed{R(K) = \frac{\mathscr{B}(B \to \mu\mu K)}{\mathscr{B}(B \to J/\psi(\to \mu\mu)K)} / \frac{\mathscr{B}(B \to eeK)}{\mathscr{B}(B \to J/\psi(\to ee)K)}}$$

$R(K)$ Analysis Overview



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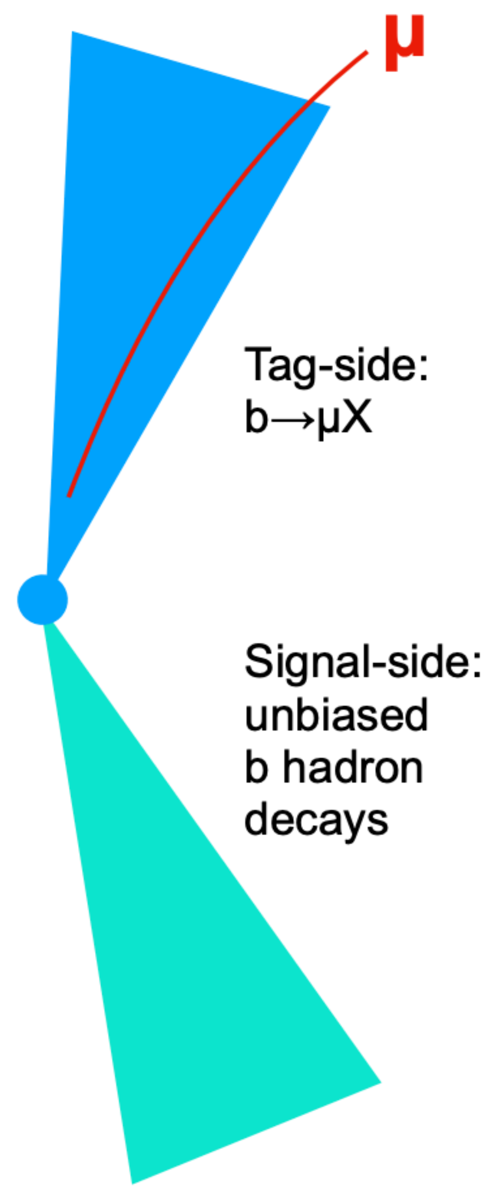
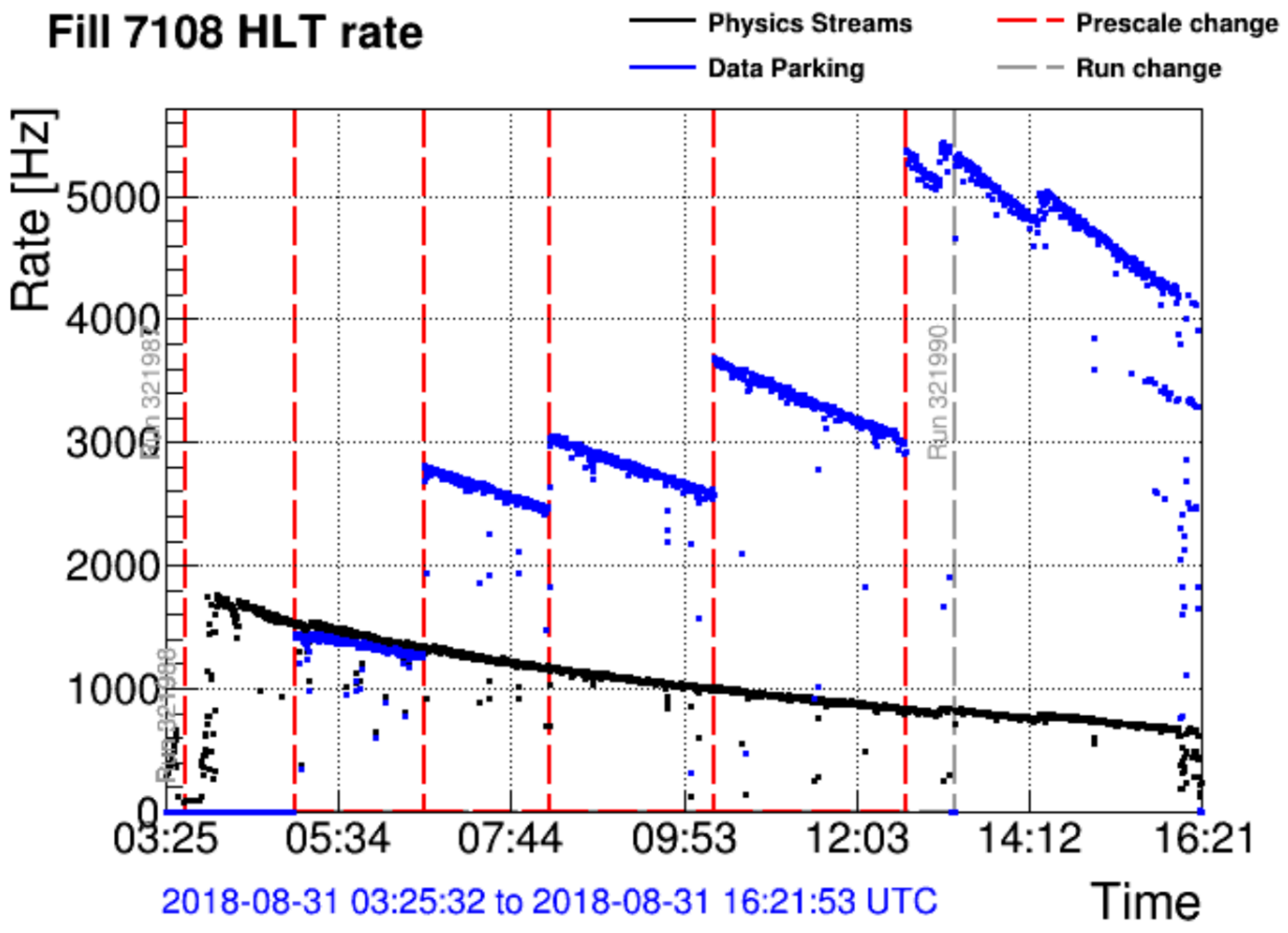
$$\boxed{R(K) = \frac{\mathscr{B}(B \to \mu\mu K)}{\mathscr{B}(B \to J/\psi(\to \mu\mu)K)} \Big/ \frac{\mathscr{B}(B \to eeK)}{\mathscr{B}(B \to J/\psi(\to ee)K)}}$$

- Innovative technique to collect data:
  - 2018 B-parking CMS-DP-2019/043
- $R(K)$ ratio measured in the q^2 of di-lepton system $1.1 < q^2 < 6.0\ GeV^2$ "low-q^2" region
  - CR: $8.41 < q^2 < 10.24\ GeV^2$ for normalisation channel $B^+ \to J/\psi(l^+l^-)K^+$
- Dedicated low p_T electron reconstruction and ID
- $R(K)$ measured through Kll mass fit

CMS B-Parking Data

- For this analysis, CMS developed new trigger and data processing strategy for 2018 → B Parking
  - B Parking dataset still in use for BPH and other analyses
- Events recorded with a trigger logic that requires the presence of a single displaced muon
- $b\bar{b}$ events with high purity
  - The μ candidate responsible for the trigger comes from the ”tag-side” b hadron that undergoes a $b \to \mu + X$ decay.
  - The ”signal-side” b hadron decays naturally as it is not biased by the trigger requirements.



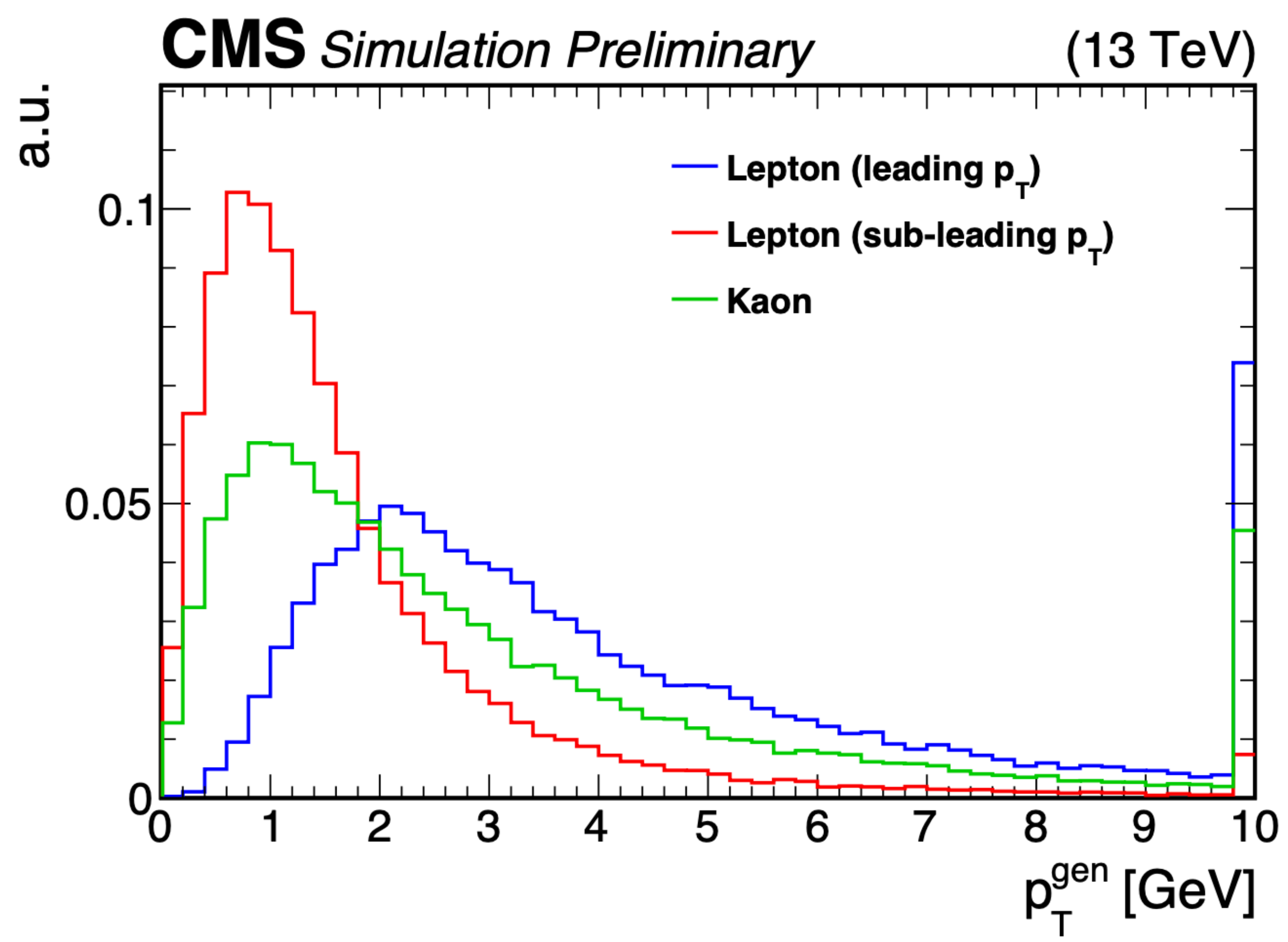


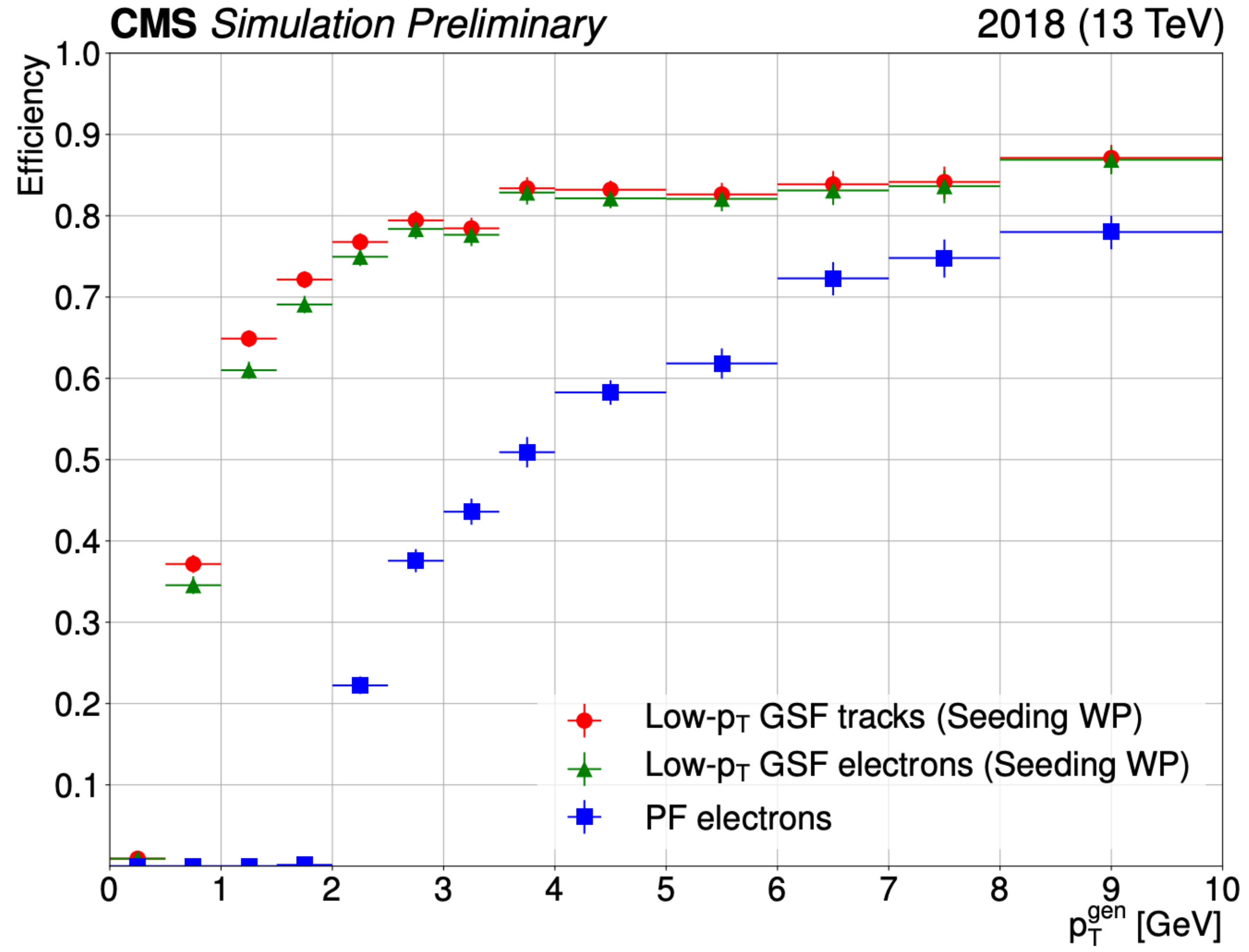
- B-Parking trigger threshold depends on instantaneous luminosity:
  - when it decreases, together with the other physics triggers, B-parking trigger requirements are loosened (lower pT seed enabled) to exploit spare bandwidth.

12 Billion events recorded in 2018 with $b\bar{b}$ purity of 75 %

Low pT e reconstruction and ID

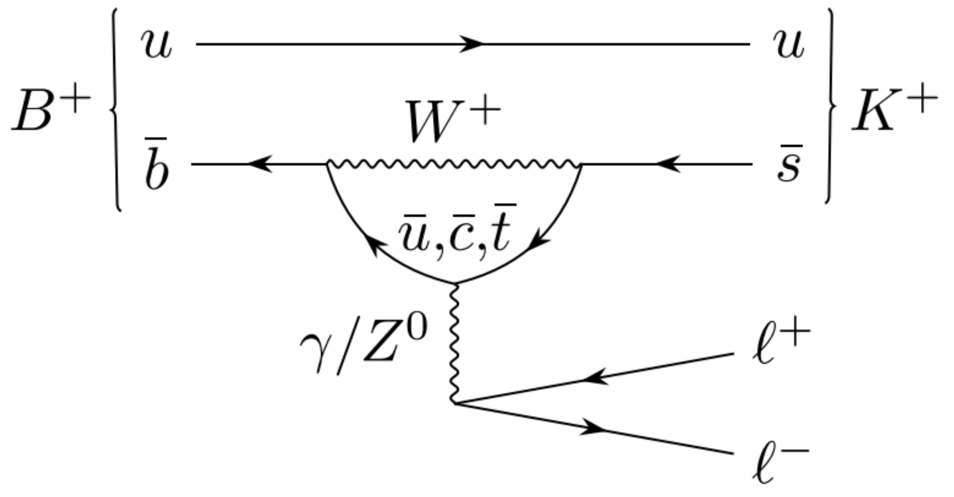
- Leptons from B decays are soft
- Standard reco efficiency (PF) for electrons with $p_T < 5\ GeV$ is very low
  - New type of e introduced: **LP electron**
    - Reconstruction made with a combination of 2 BDTs trained on tracker (mostly) and ECAL inputs
- Also electron ID optimised
  - Two different BDTs for PF and LP electrons
    - Input variables: track related quantities; ECAL shower shapes; matching…

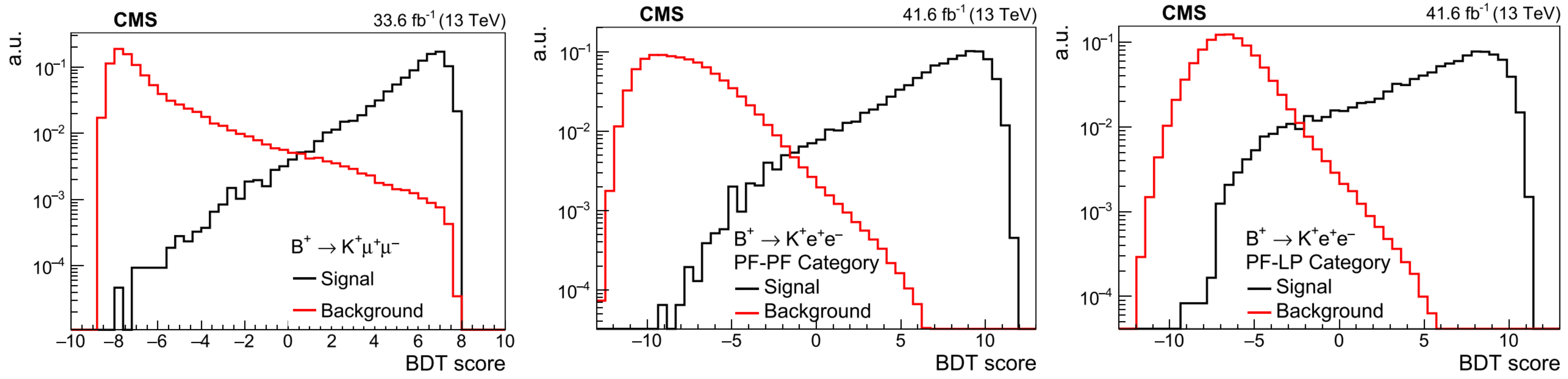




B candidate selection

- To maximise sensitivity: $B^+ \to K^+\mu^+\mu^-$ selected from the tag side and $B^+ \to K^+e^+e^-$ from the probe side
- B candidates reconstructed combining leptons with OS and same flavor + track
  - In the $B^+ \to K^+e^+e^-$ channel, two regions defined: PF-PF and PF-LP
  - Several quality criteria to leptons and track
  - Final selection based with MVA
    - Three BDTs (one for μ channel, and two for e channel) trained with signal MC and data from the SBs (outside m_{K^+ll} peak)
    - BDTs tested to ensure they don't introduce mass sculpting



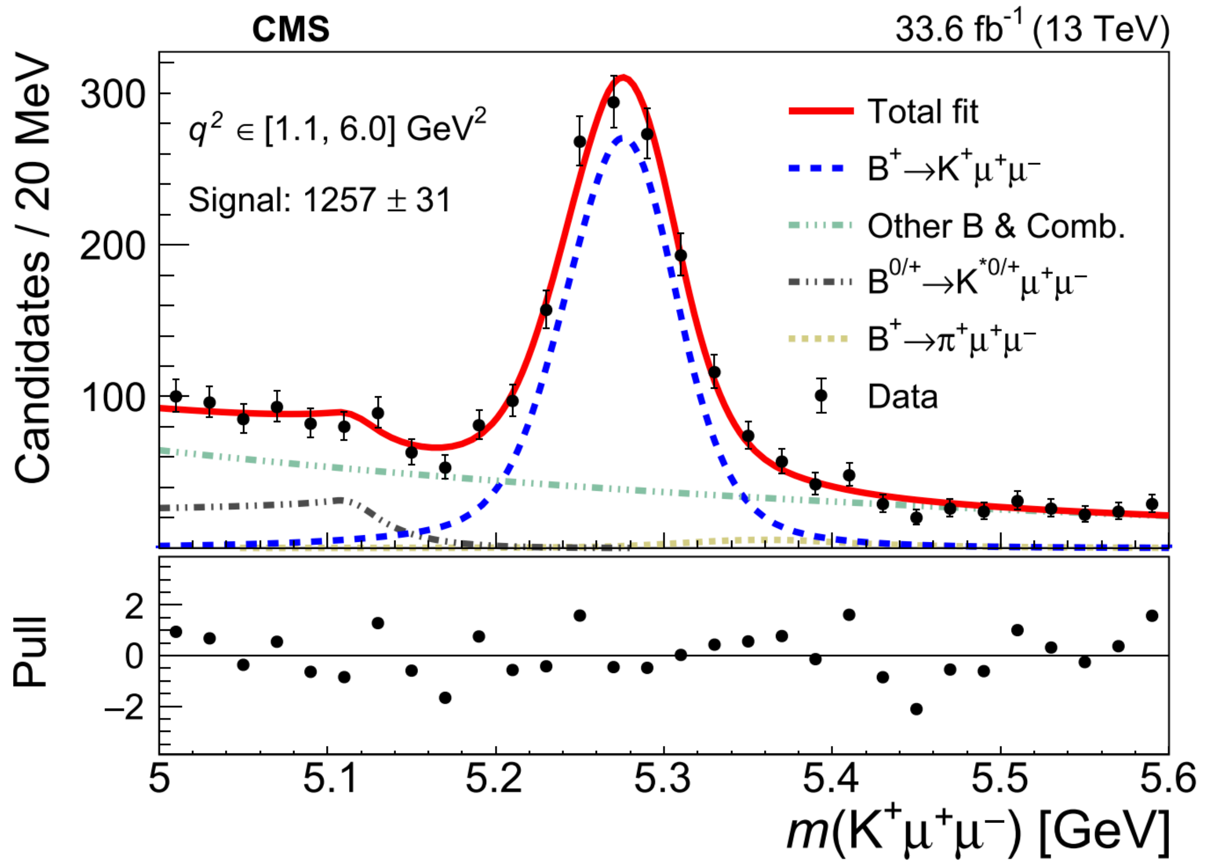


Background in plots: data in SR with inverted OS requirement

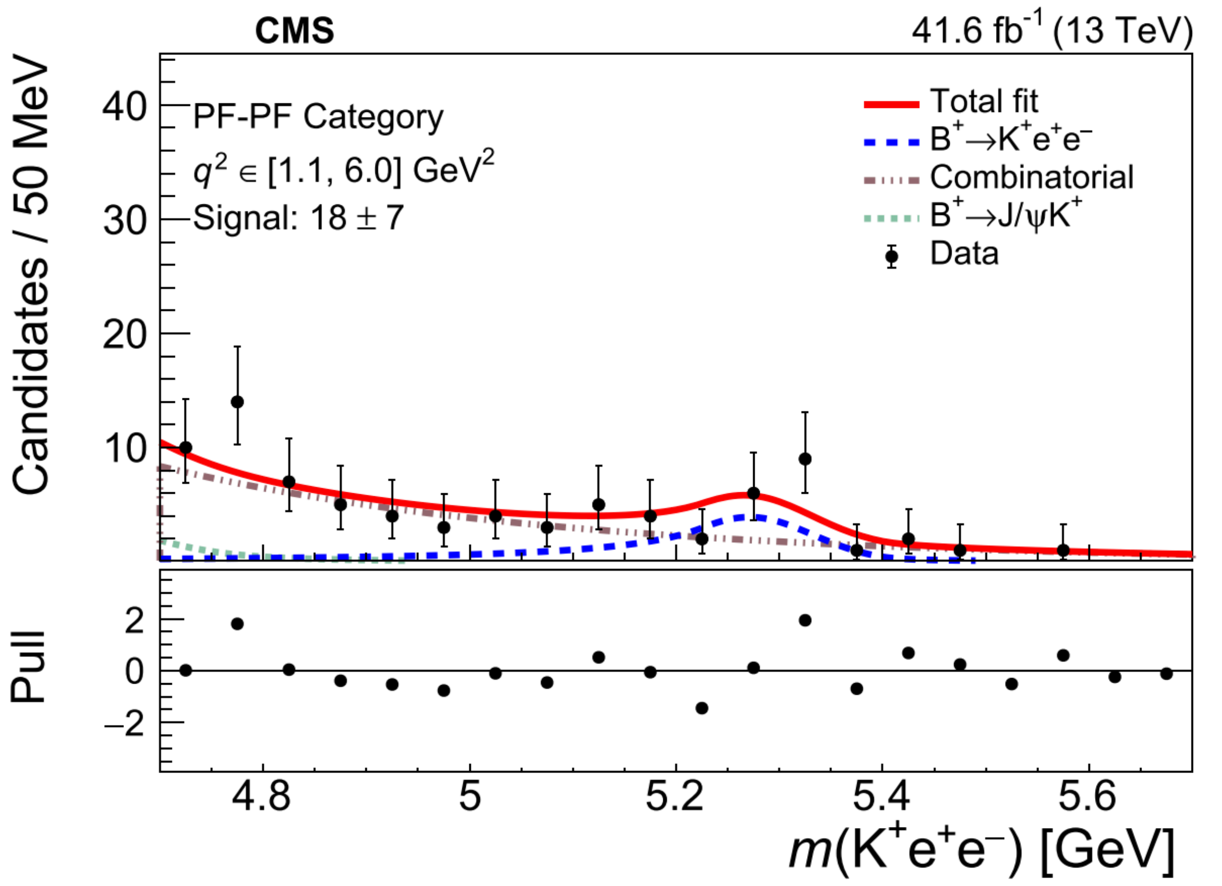
Mass Fit

- Unbinned Maximum likelihood fit to invariant mass to extract $B^+ \to K^+ l^+ l^-$signal yield
- Signal and background shapes described by analytical functions or templates
- **Bkg composition** differs from channel to channel
    - $B \to K^* ll$: partially reconstructed background
    - Combinatorial: random combination of objects from different b hadron decays
    - $J/\psi K$ leakage: leptons produced in the normalisation decays can radiate photons. Relevant in eeK channel
    - Other B: Any other B decay
    - Misidentified hadron bkg: negligible

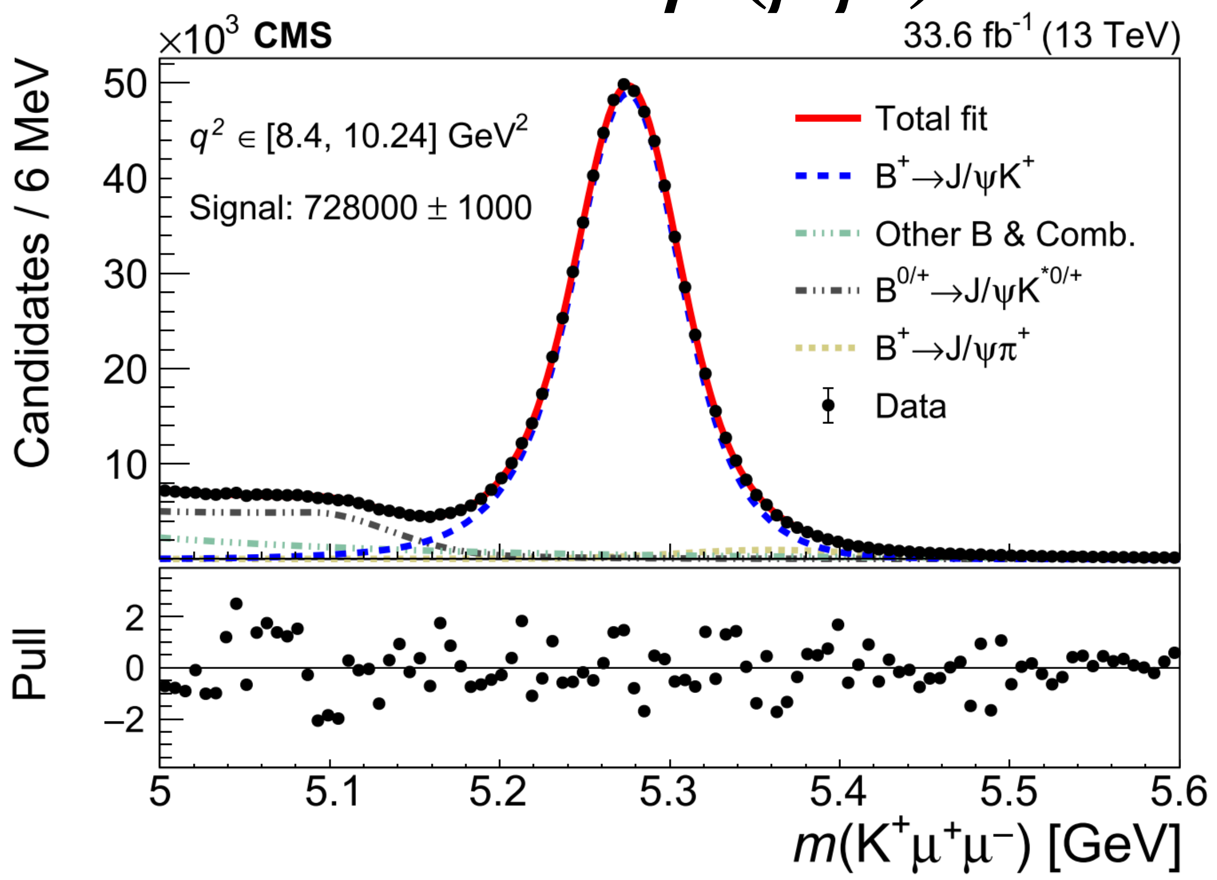
$B^+ \to K^+ \mu^+ \mu^-$



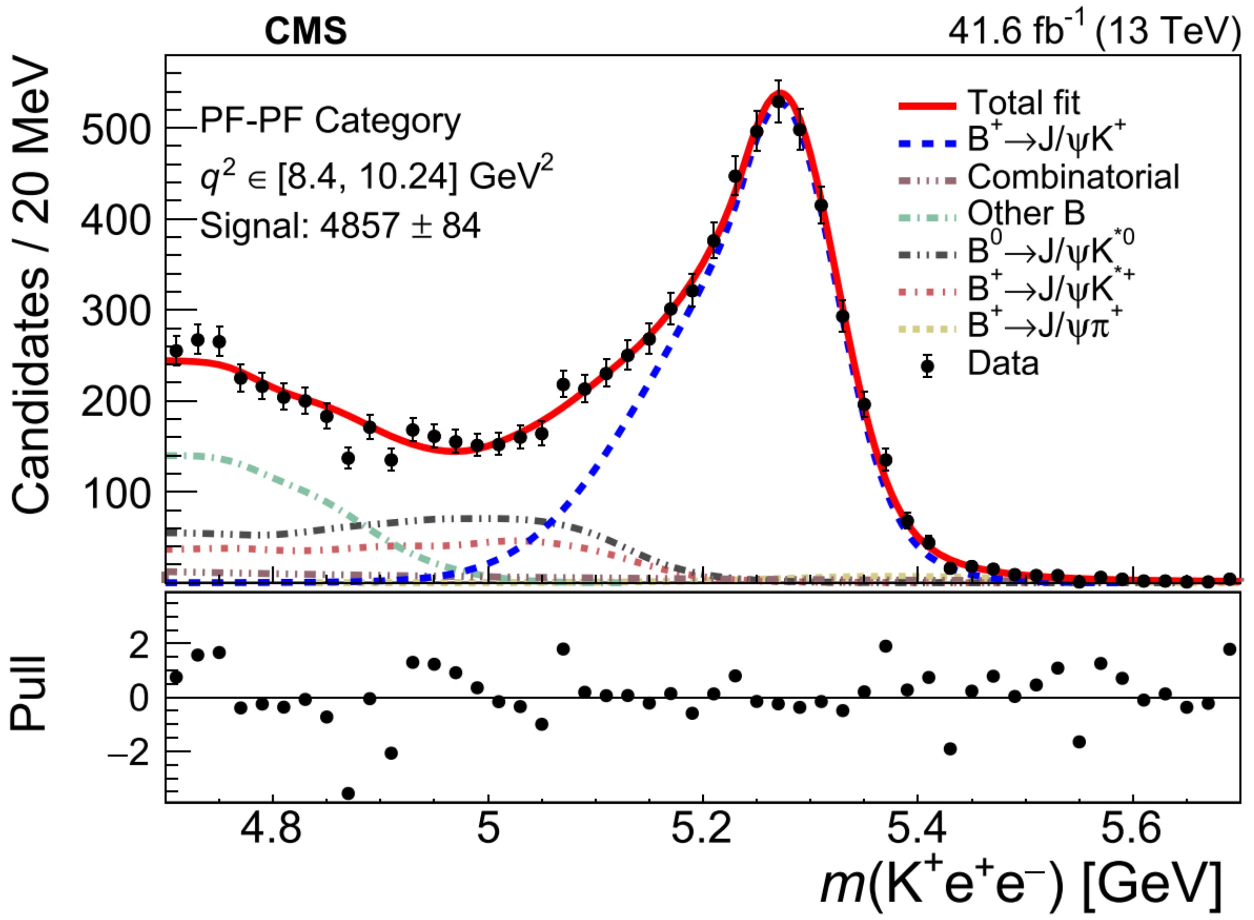
$B^+ \to K^+ e^+ e^-$



$B^+ \to J/\psi(\mu\mu) K^+$



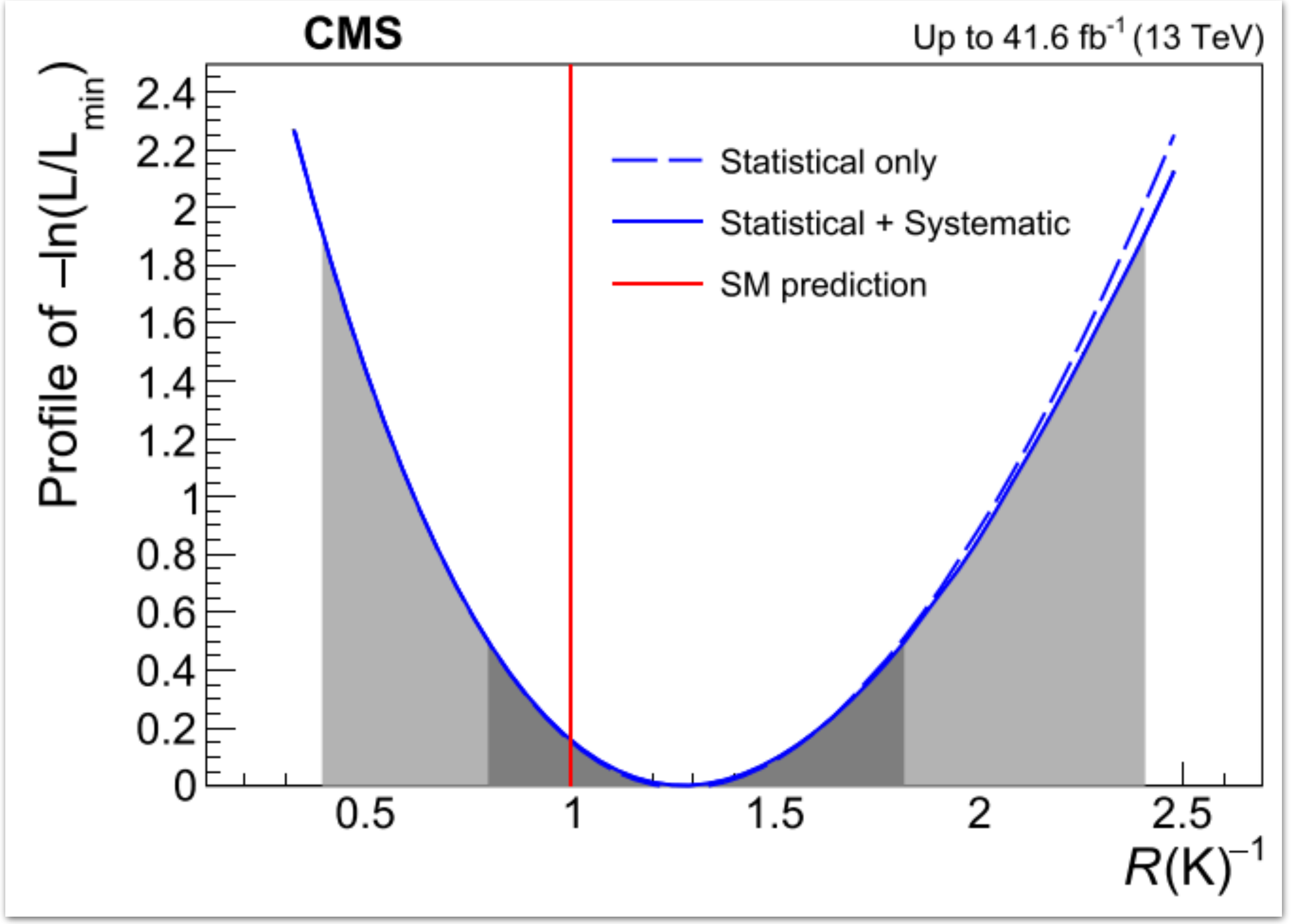
$B^+ \to J/\psi(ee) K^+$



R(K) Results

$$R(K) = 0.78^{+0.46}_{-0.23}(stat)^{+0.09}_{-0.05}(syst) = 0.78^{+0.47}_{-0.23}$$

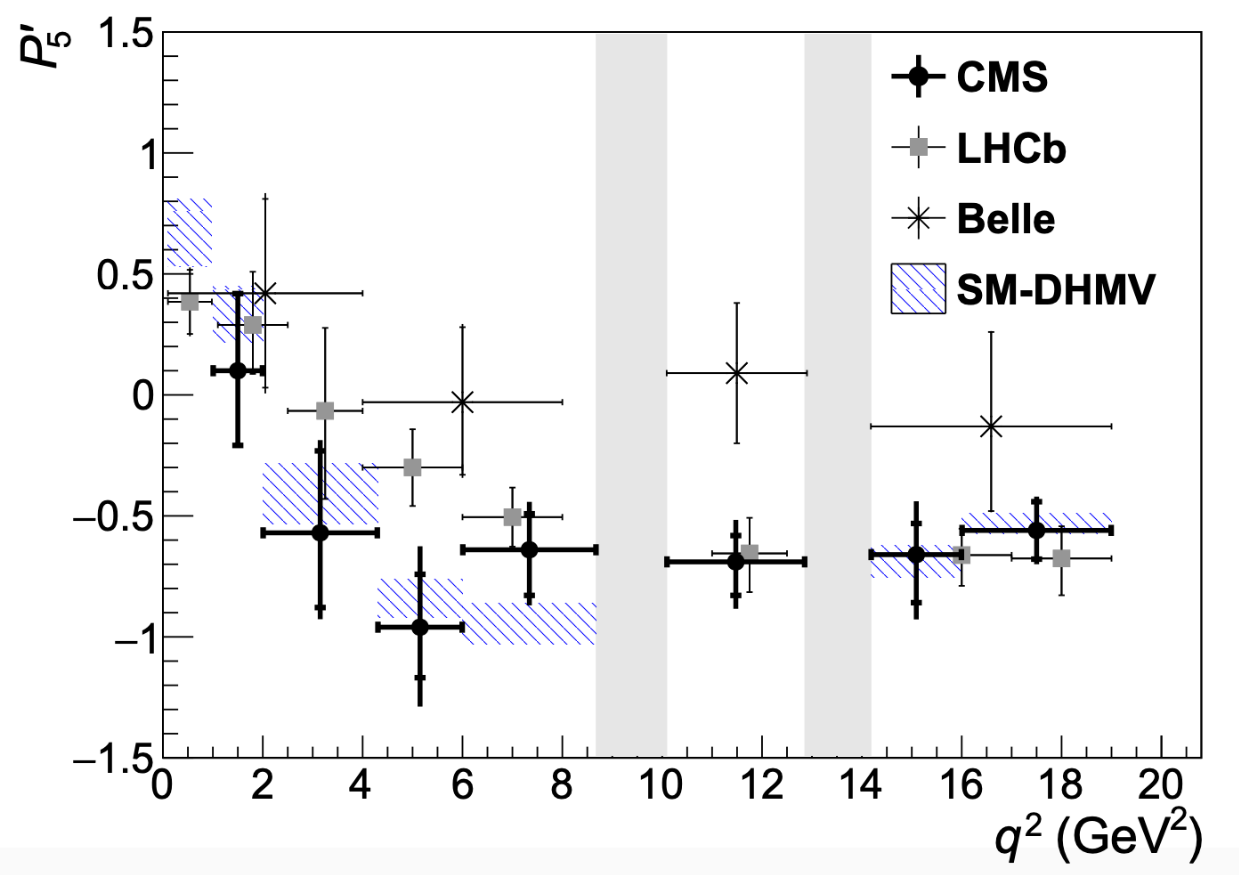
- In agreement with SM expectations of ~1
- Measurement limited by the low statistics of $B \to eeK$ channel
    - Improvements foreseen in Run3
- **The first LFU result in $b \to sll$ in CMS**



$B^0 \to K^*(892)^0\mu^+\mu^-$ Angular Analysis

Angular Analysis

[PLB 781 (2018) 517]



- Angular analysis of the rare decay $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$
- Already a **CMS analysis available, but only** Run-1(20 fb^{-1}) and partial angular observables measured [PLB 753 (2016) 424] [PLB 781 (2018) 517]
  - **This analysis: CMS Full Run-2 (140 fb^{-1})**

- **Selection:**
  - Two OS good muons + two OS tracks coming from a common displaced vertex
    - Tracks fitted to common vertex to form K^{*0} candidate
      - K^{*0} invariant mass computed for both $K^+\pi^-$ and $K^-\pi^+$, the closer to $m_{PDG}(K^*)$ assigned (~12% of wrong assignment)
- **MVA analysis** to optimise background rejection
  - BDT trained on data events from mass sidebands and signal events from MC, separately for each year of data-taking
  - *Input features: decay-vertex quality and displacement, isolation, mass of $K\pi$ system*
- Veto on invariant mass of possible $K\mu\mu$ combinations to reduce $B^+ \to K^+\mu^+\mu^-$ contamination,

Fit Procedure

- Angular observables measured in q^2 bins of di-muon system [1.1,16] GeV^2
- 4D unbinned maximum likelihood fit

$$P(m,\cos\theta_K,\cos\theta_l,\phi) = \underbrace{Y_S}_{\text{Signal Yield}}\Big[S^C(m)\,S^a(\cos\theta_K,\cos\theta_l,\phi)\,\epsilon^C(\cos\theta_K,\cos\theta_l,\phi)$$
$$+R\,S^M(m)\,S^a(-\cos\theta_K,-\cos\theta_l,-\phi)\,\epsilon^M(\cos\theta_K,\cos\theta_l,\phi)\Big]$$
$$+\underbrace{Y_B}_{\text{Background Yield}}\,B^m(m)\,B^a(\cos\theta_K,\cos\theta_l,\phi),$$

Signal Component

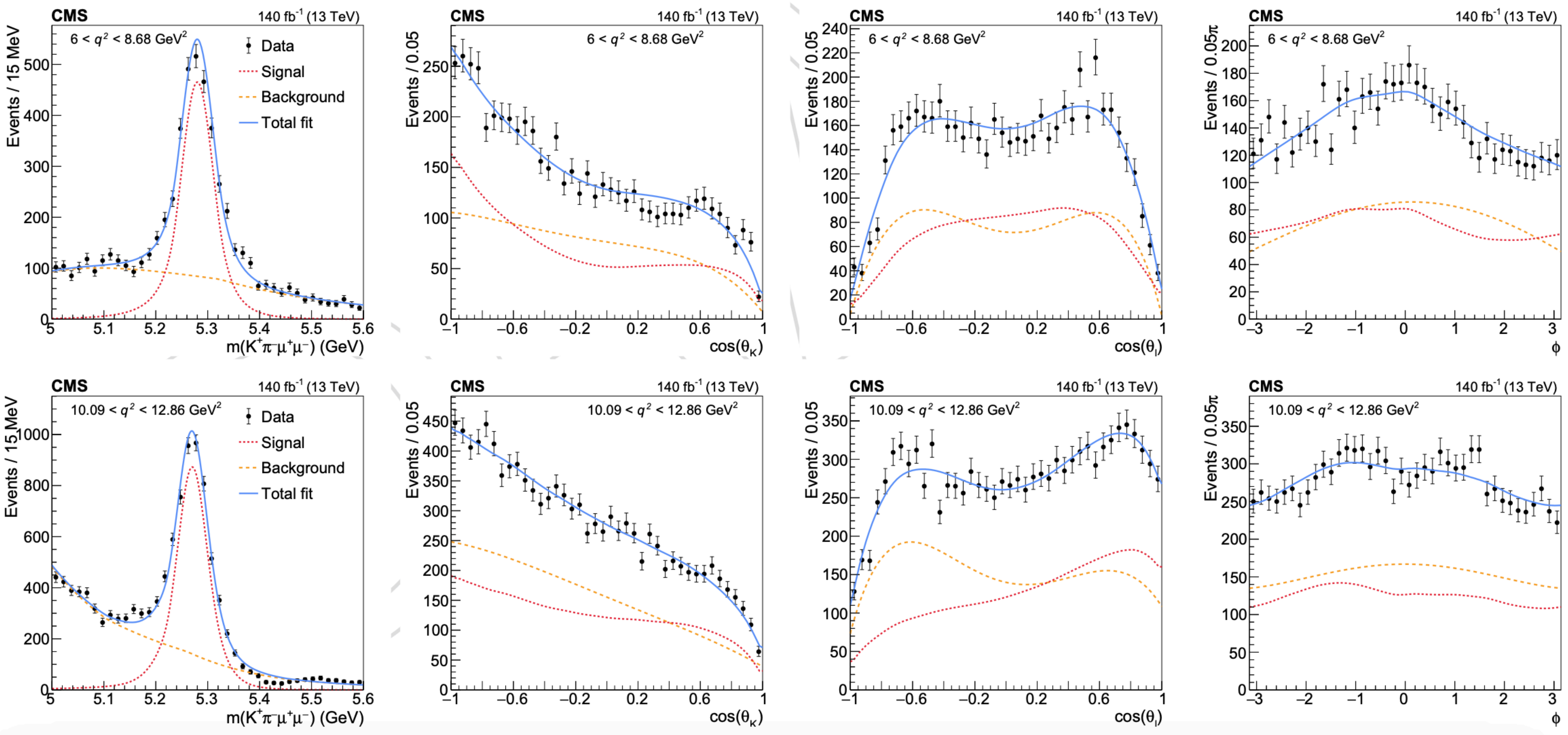
Background Component

- S^C, S^M : mass distributions of correctly and misidentified signal candidates
- ϵ^C, ϵ^M : efficiency for correctly and misidentified events
- R : ratio of mistag fraction in data and MC
- B^m : distribution of the combinatorial bkg events
- B^a : angular distribution of background (determined using sidebands)

Fit Projections

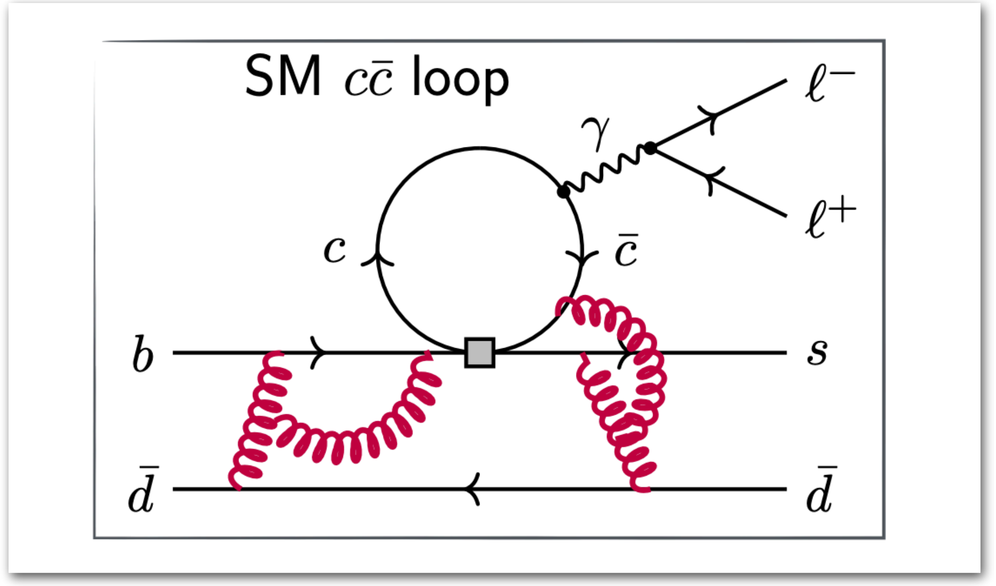
- Fit performed simultaneously on each year of data taking
- Projections on invariant mass and three angles
- Good agreement between data and PDF

Example of two q^2 bins

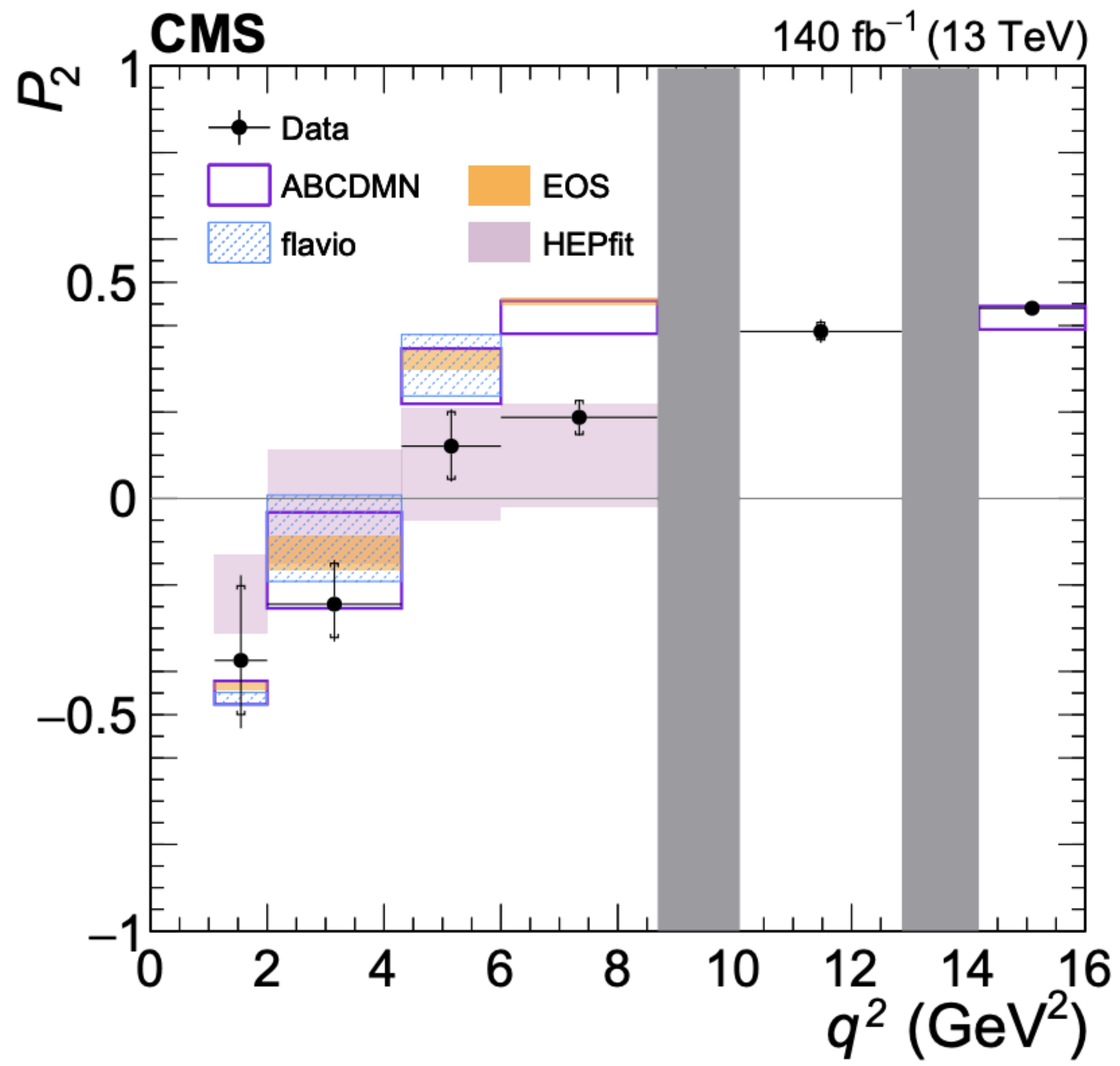


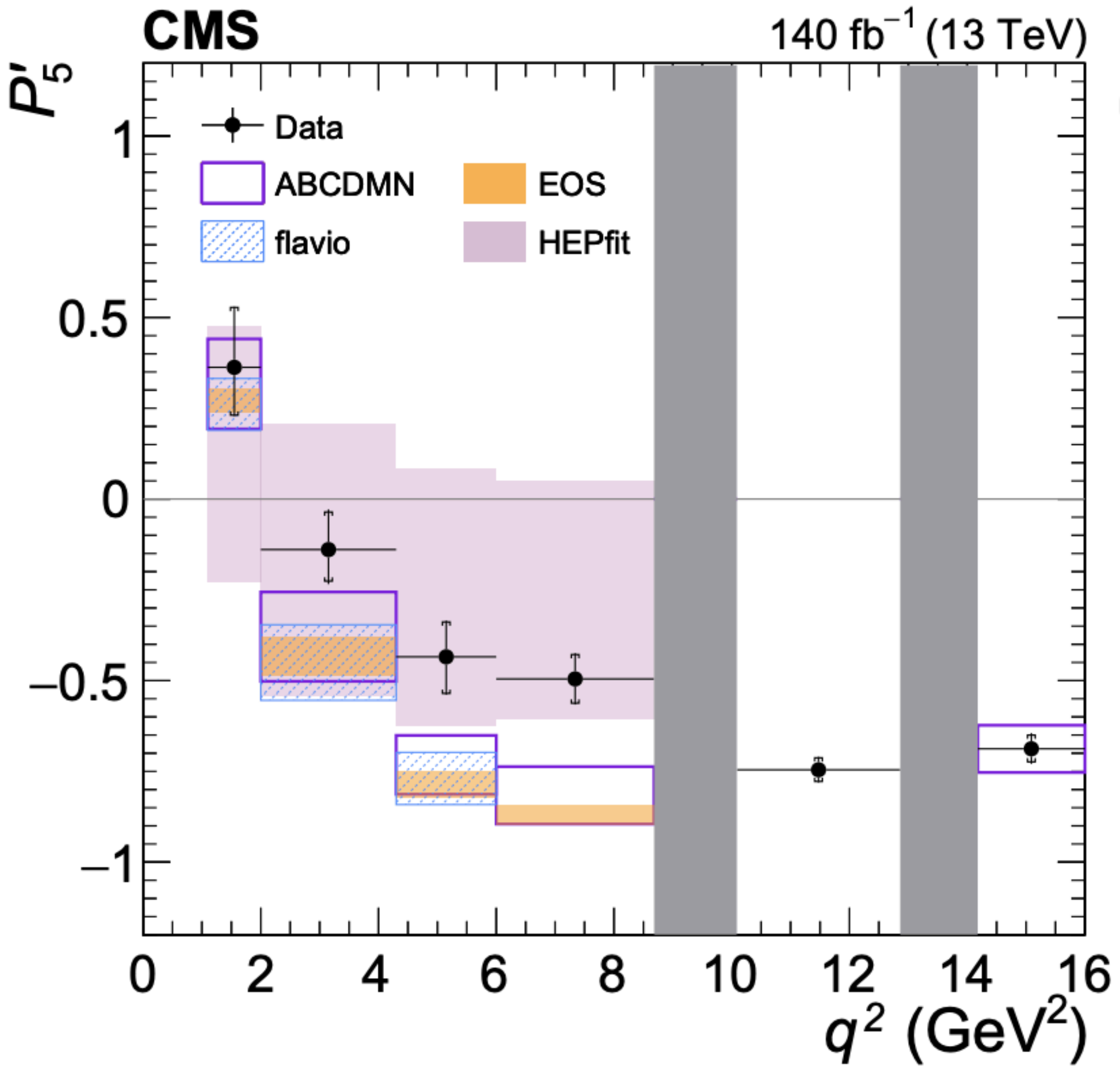
Results

[CKM Workshop]



[PLB 864 (2025) 139406]

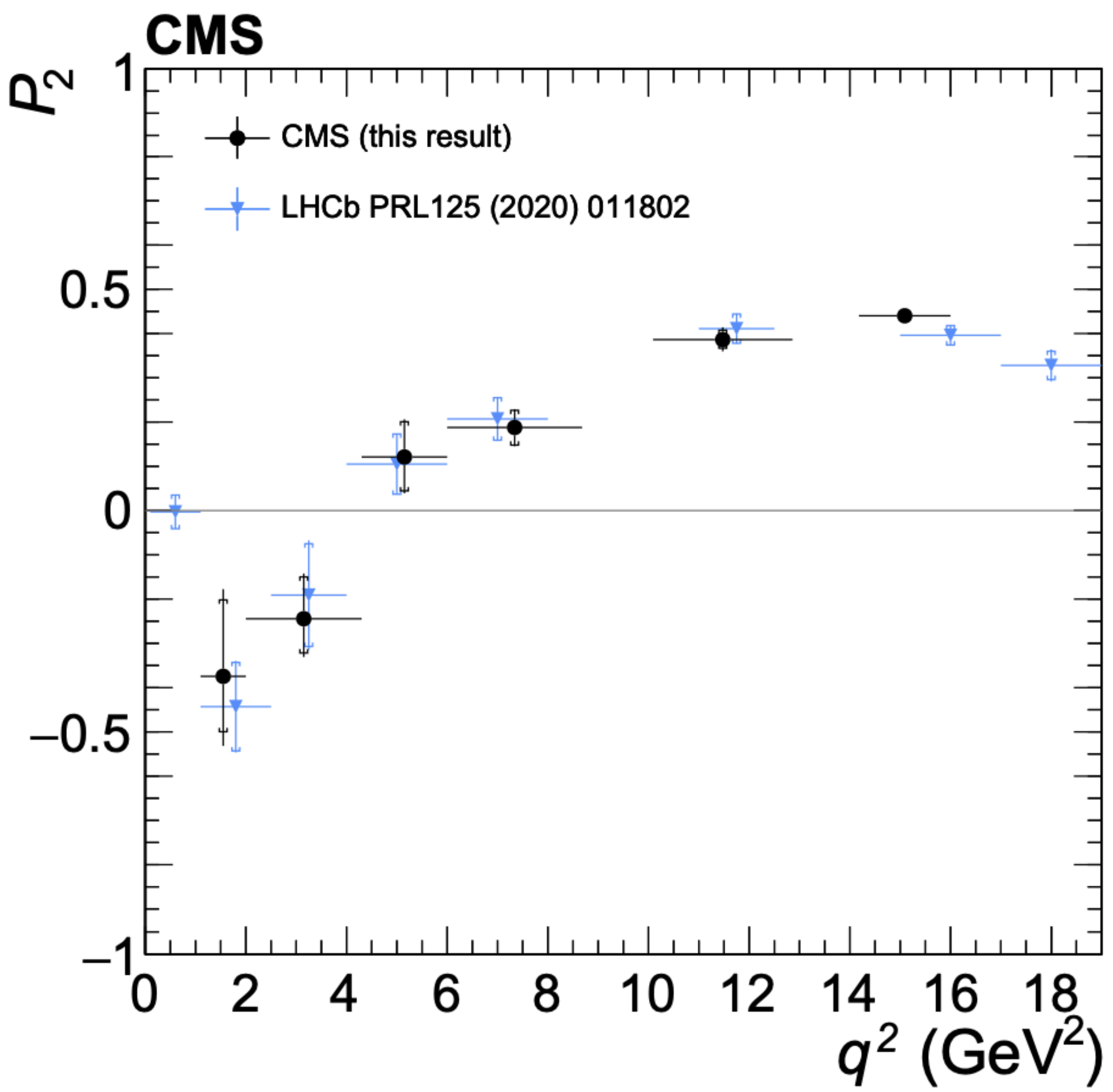


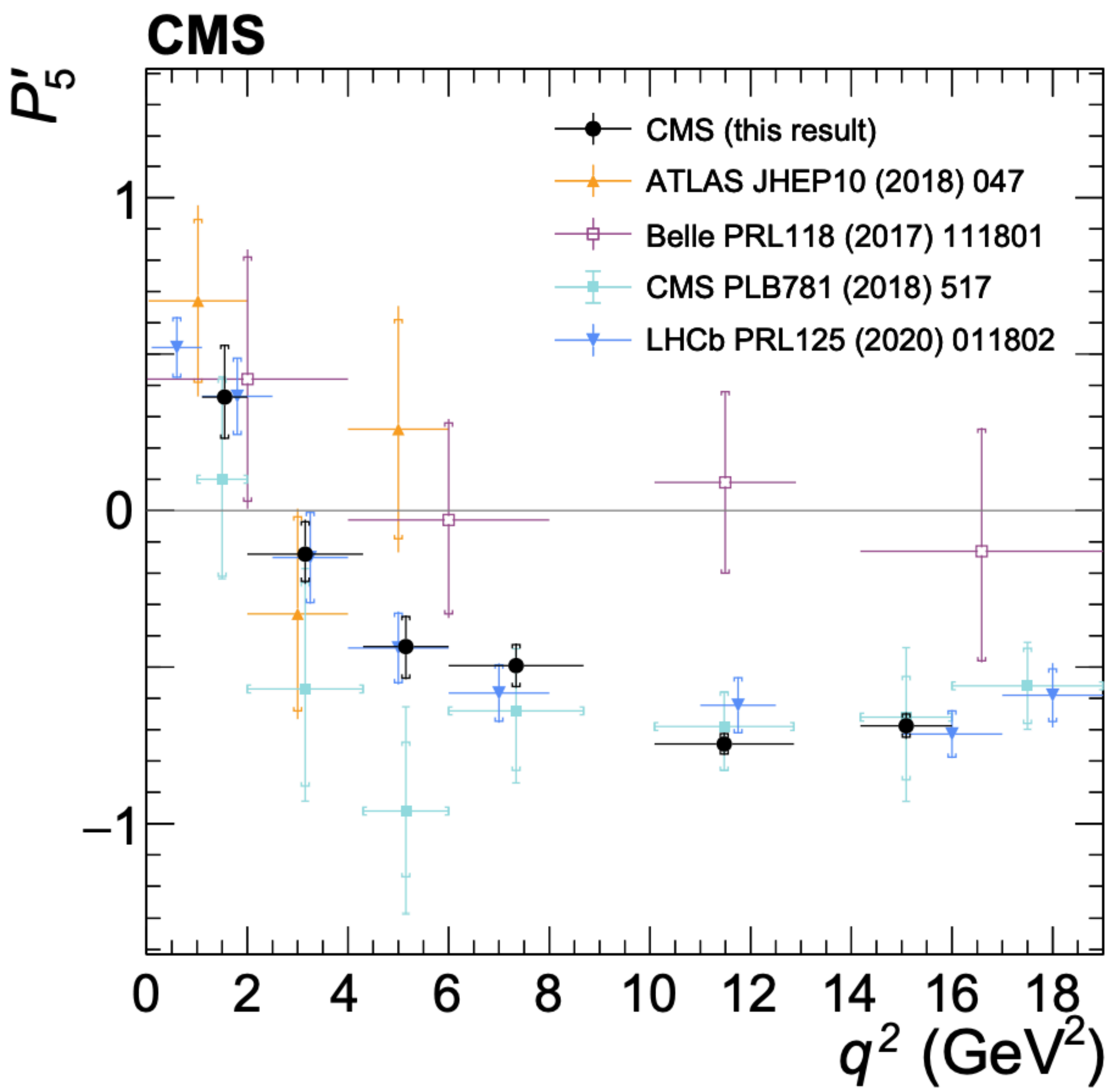


- Various sets of predictions compared with measurements:
  - ABCDMN: local form-factors (LQCD and Light-Cone Sum Rule) + non-local form-factors from [JHEP 02(2021)088]
  - flavio: local form-factors (LQCD and Light-Cone Sum Rule) + non-local form-factors (QCDF)
  - EOS: local form-factors (LQCD and LCSR), novel parametrisation of non-local form-factors
  - HEPfit: more conservative estimation of non-local hadronic matrix elements to account for possible large impact from charm-loop penguin diagrams
- HEPfit compatible with data, due to high uncertainties
- Tensions for P_5' and P_2 parameters for EOS and ABCDMN predictions

Comparison

- Comparison between CMS and other experiments measurements
- Good agreement with previous CMS measurement and LHCb most recent result
  - N.B. Bin choice slightly different





Conclusions

Conclusions

- Comprehensive overview of **LFU tests and beyond in the b-sector**
- Discussed the **motivation** behind these measurements and their potential to reveal physics beyond the Standard Model.
- Reviewed the current experimental status of key observables.
- Took a closer look at three (four) recent analyses in CMS: $R(J/\psi)$, $R(K)$ and $B^0 \to K*(892)^0\mu^+\mu^-$ Angular Analysis
- The **B-physics sector** remains a highly dynamic and exciting area, rich with discovery potential.
- I am looking forward to the **next developments** in this field!

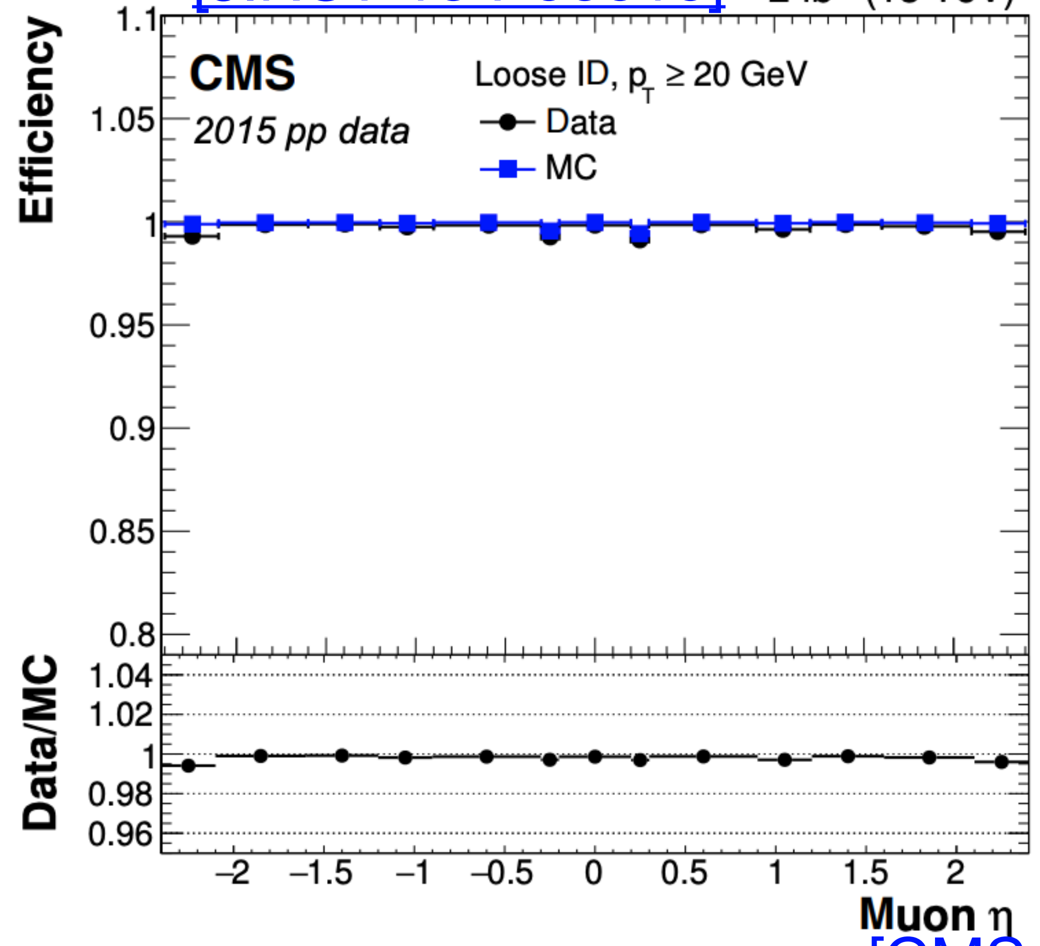
Backup

$R(J/\psi)$ Measurement - Leptonic Channel

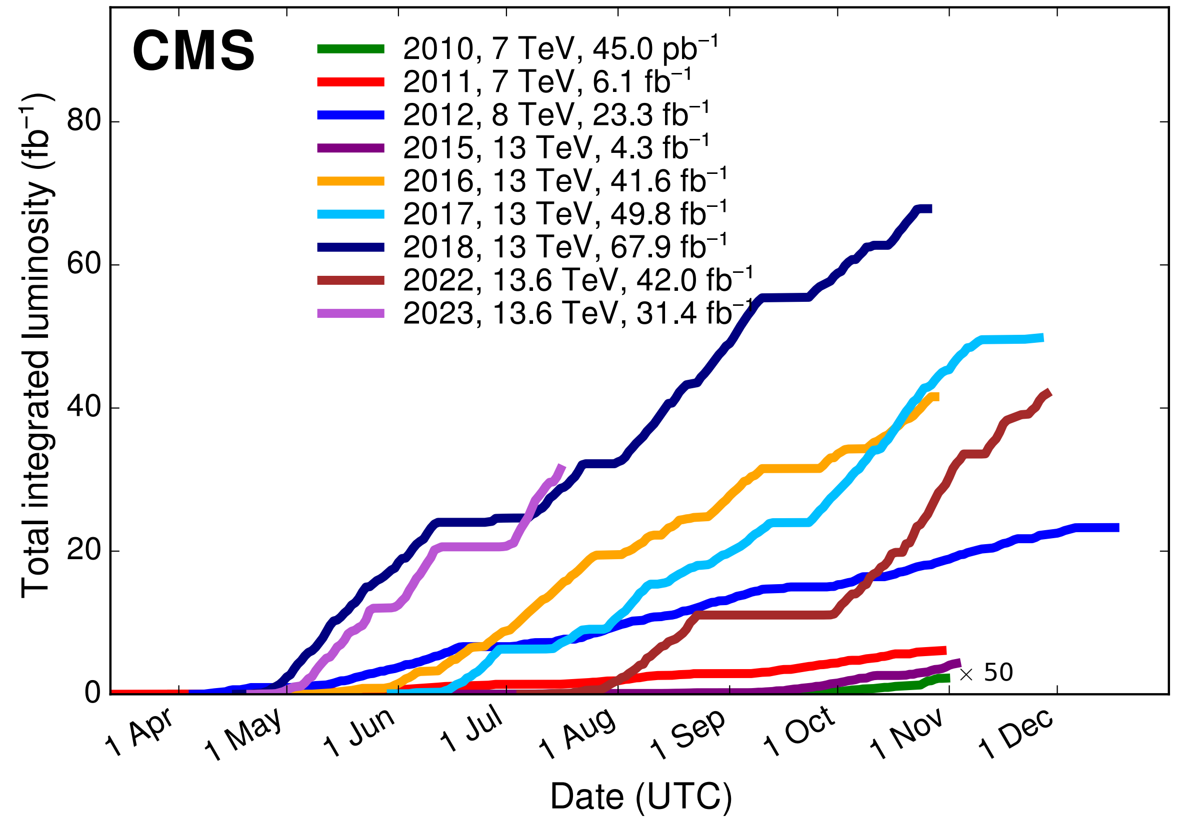
Why $R(J/\psi)$ at CMS?

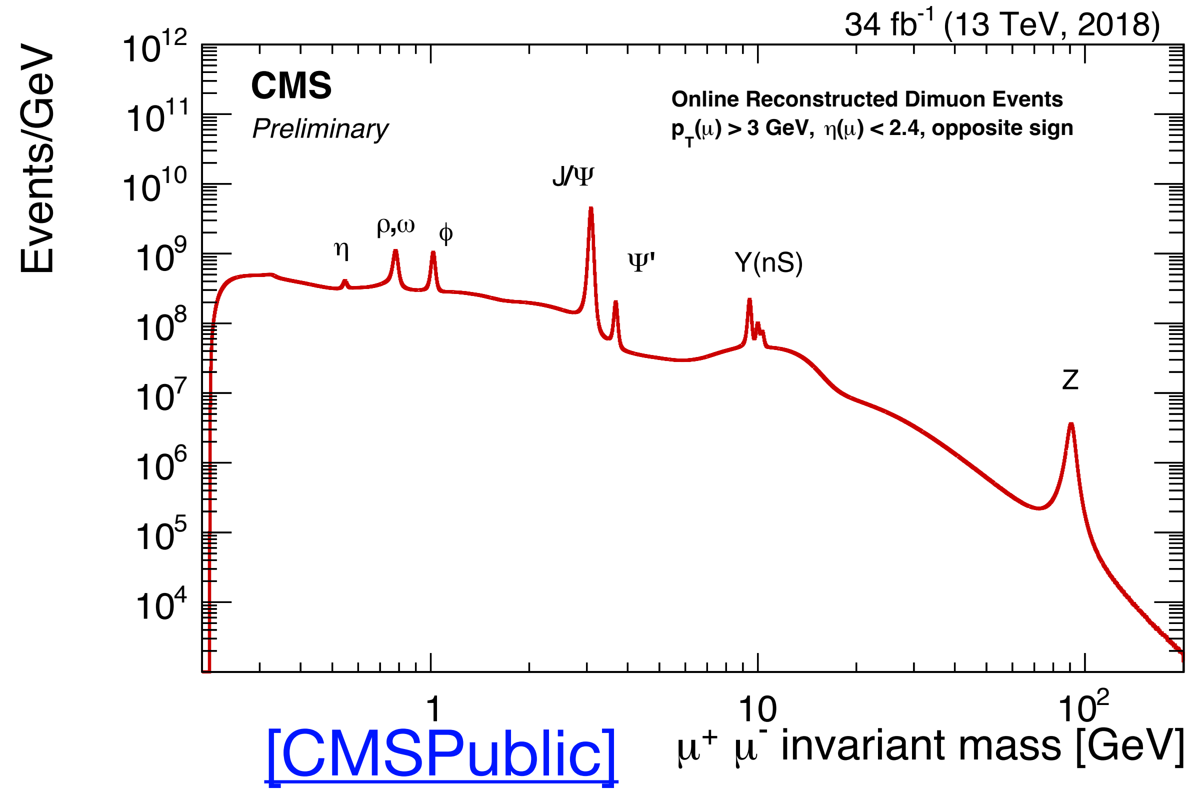
- B_c meson cannot be produced at B-factories (Belle, BaBar, BelleII): e^+e^-at c.o.m energies around $Y(4S)$ peak
    - B_c **can only be produced at hadron colliders** -> in fact previous measurement from LHCb
- **In CMS we can perform measurement of $R(J/\psi)$:**
    - **Excellent muon reconstruction and identification performances**
        - Efficient $J/\psi \to \mu\mu$ triggers
        - No need of particle ID detectors (only muons in the final state)
    - **Higher luminosity and solid-angle acceptance than LHCb, which compensate for CMS lower acceptance in soft muon p_T**
        - $\mathscr{L} = 59.7\ fb^{-1}$ for CMS 2018 data vs $\mathscr{L} = 3\ fb^{-1}$ for the full LHCb Run 1;
        - Almost 4π acceptance for CMS vs about 0.16π for LHCb
        - CMS muon p_T as low as 3 GeV vs LHCb that reaches 0.8 GeV

[JINST 13 P06015]



[CMS Public]





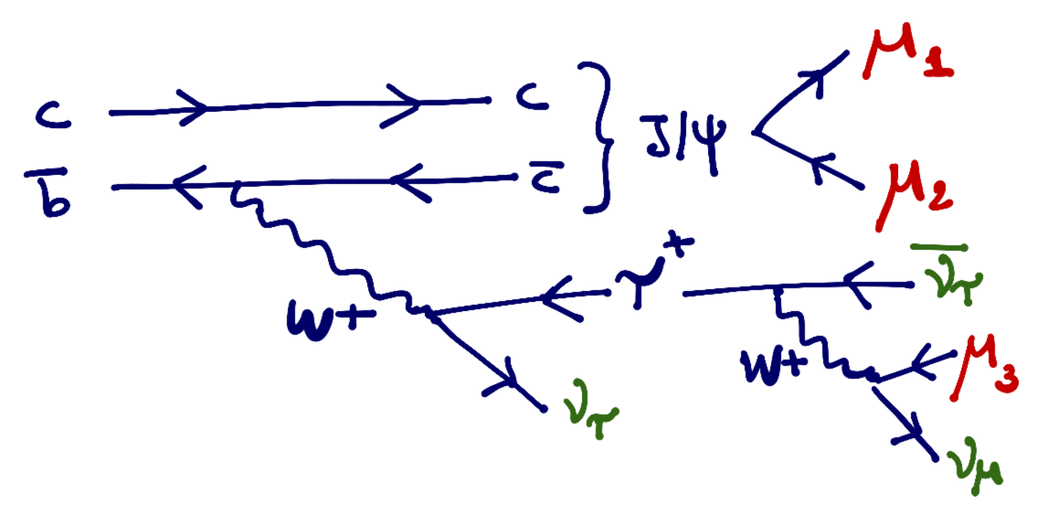
[CMSPublic]

R(J/ψ) Leptonic Channel

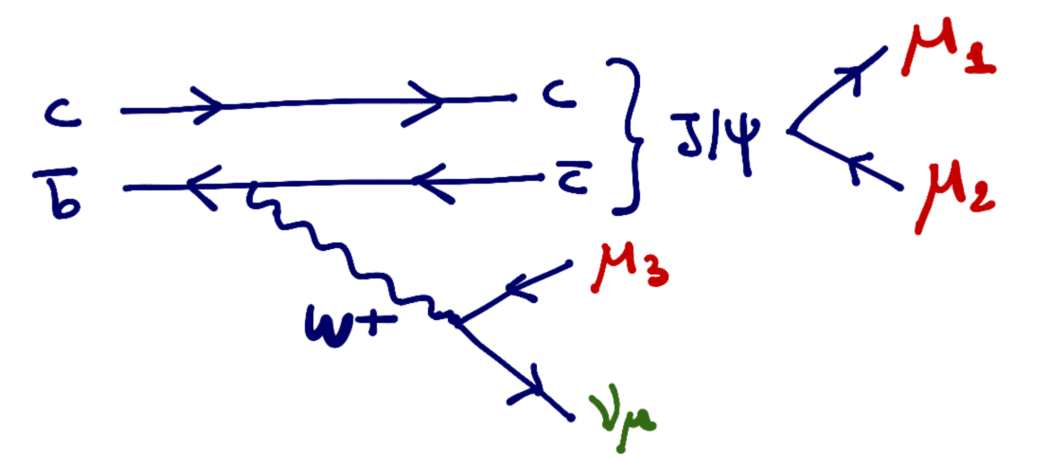
- **Leptonic channel :** $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$
- **Muonic decay of** $J/\psi \to \mu^+ \mu^-$
- Similar final state ($3\mu + \nu s$), → same reconstruction and simultaneously fit

$$R(J/\psi) = \frac{\mathscr{B}(B_c^+ \to J/\psi(\to \mu^+\mu^-)\tau^+(\to \mu^+\nu_\mu\bar{\nu}_\tau)\nu_\tau)}{\mathscr{B}(B_c^+ \to J/\psi(\to \mu^+\mu^-)\mu^+\nu_\mu)}$$

Num: $B_c^+ \to J/\psi\tau^+\nu$



Den: $B_c^+ \to J/\psi\mu^+\nu$



The B_c^+ 4-momentum useful to build kinematic observables to distinguish between τ and μ signals

	B_c direction	p reweighing
collinear approximation	3μ direction	$p^{B_c} = \frac{m_{B_c}}{m_{3\mu}} p_{3\mu}^{B_c}$

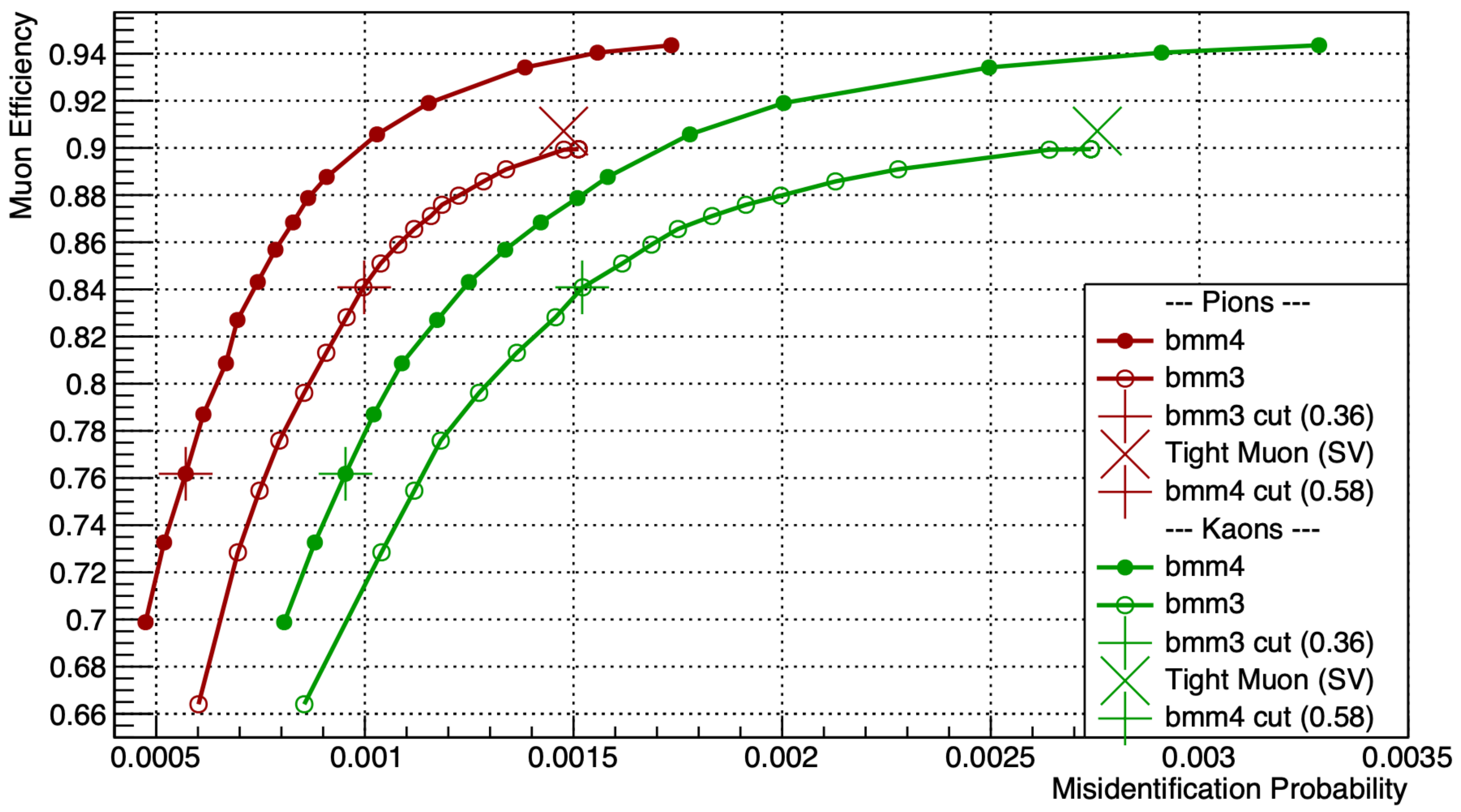
B_c Form Factors

- B_c form factors (FF) are very relevant in this analysis
  - They parametrise the internal structure of hadrons
- B_c MC samples are generated using 20-year old FF model "Kiselev" [arXiv.hep-ph/0211021]
  - **A correction to the FFs has to be applied**, to update them to the "*Boyd, Grinstein, and Lebed*" (BGL) parametrisation [PhysRevD.100.094503]
- **Uncertainties are added to this correction**
  - Total of 10 shape uncertainties for each signal
  - **They impact the sensitivity of the analysis**

Observables for misID bkg measurement

Identification (ID) on μ_3: softMva ID

[JHEP04(2020)188]



Isolation (ISO) on μ_3: $\Delta\beta_{corr} iso$

Charged hadrons from the PV

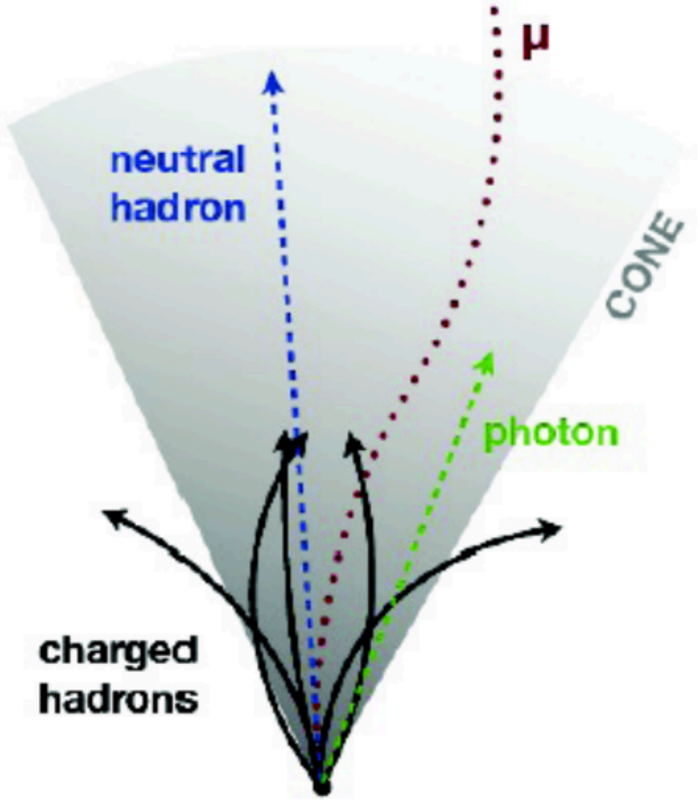
Photons

Pileup charged hadrons

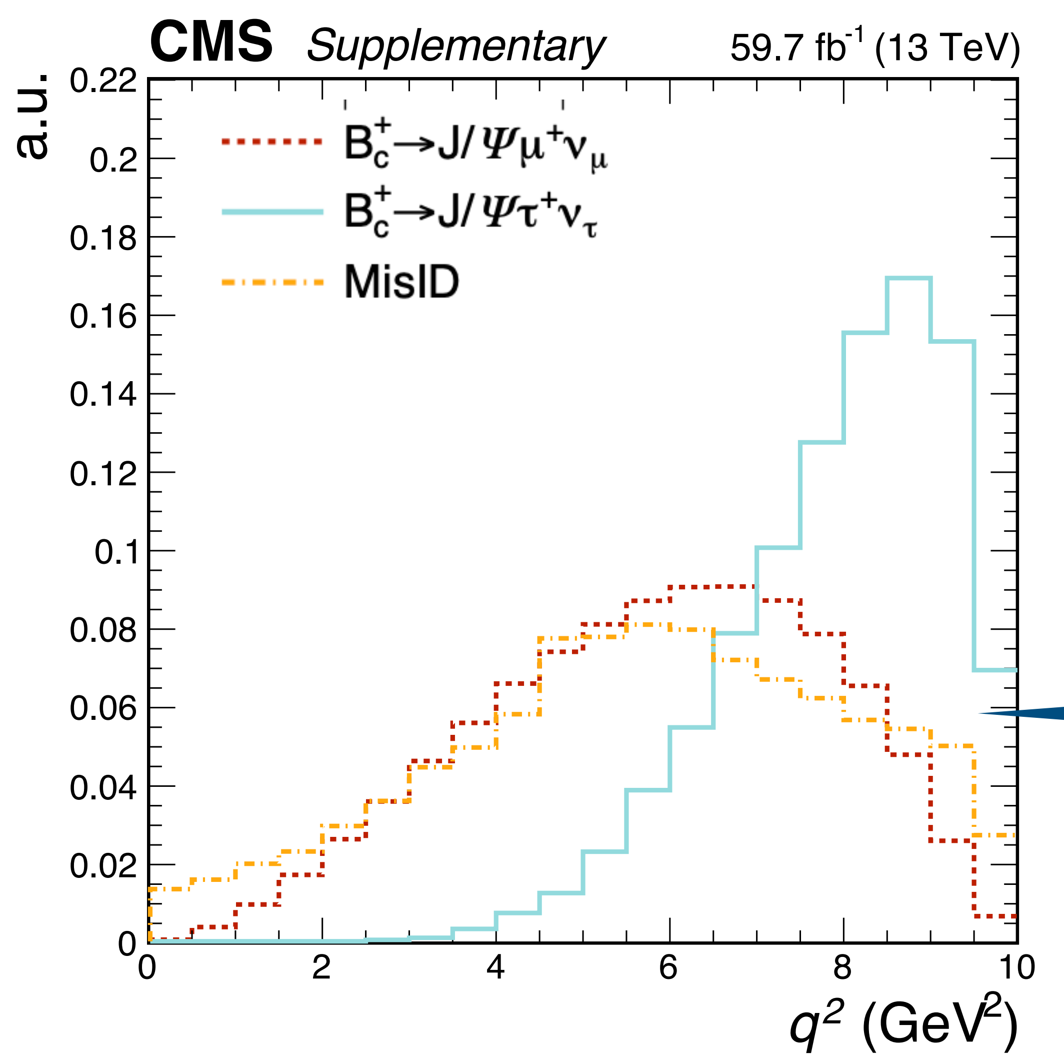
$$\Delta\beta_{corr} iso = \frac{I^{ch} + max(I^{n} + I^{pho} - \Delta\beta I^{pu}, 0)}{p_T}$$

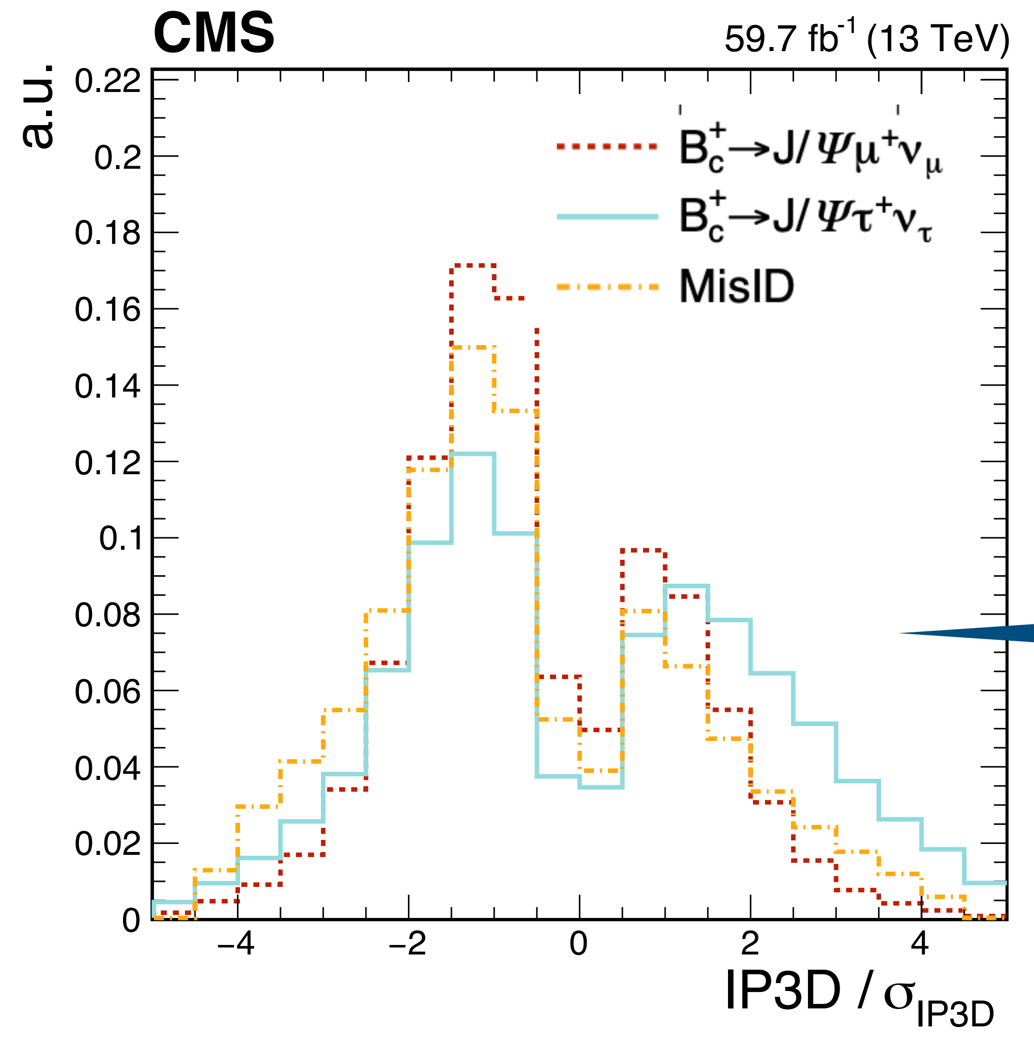
Neutral hadrons

0.5 tuned on data



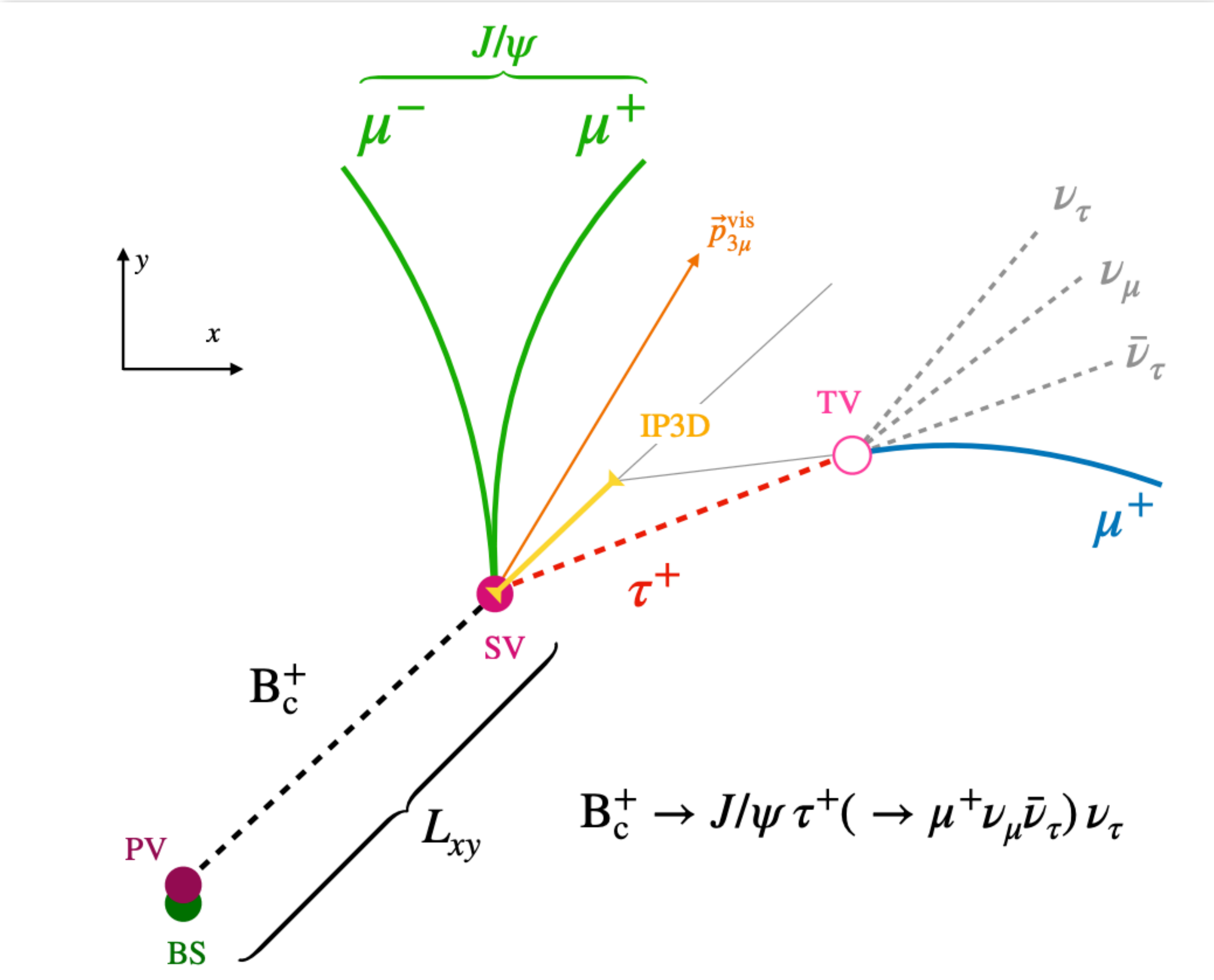
Observables for τ/μ separation



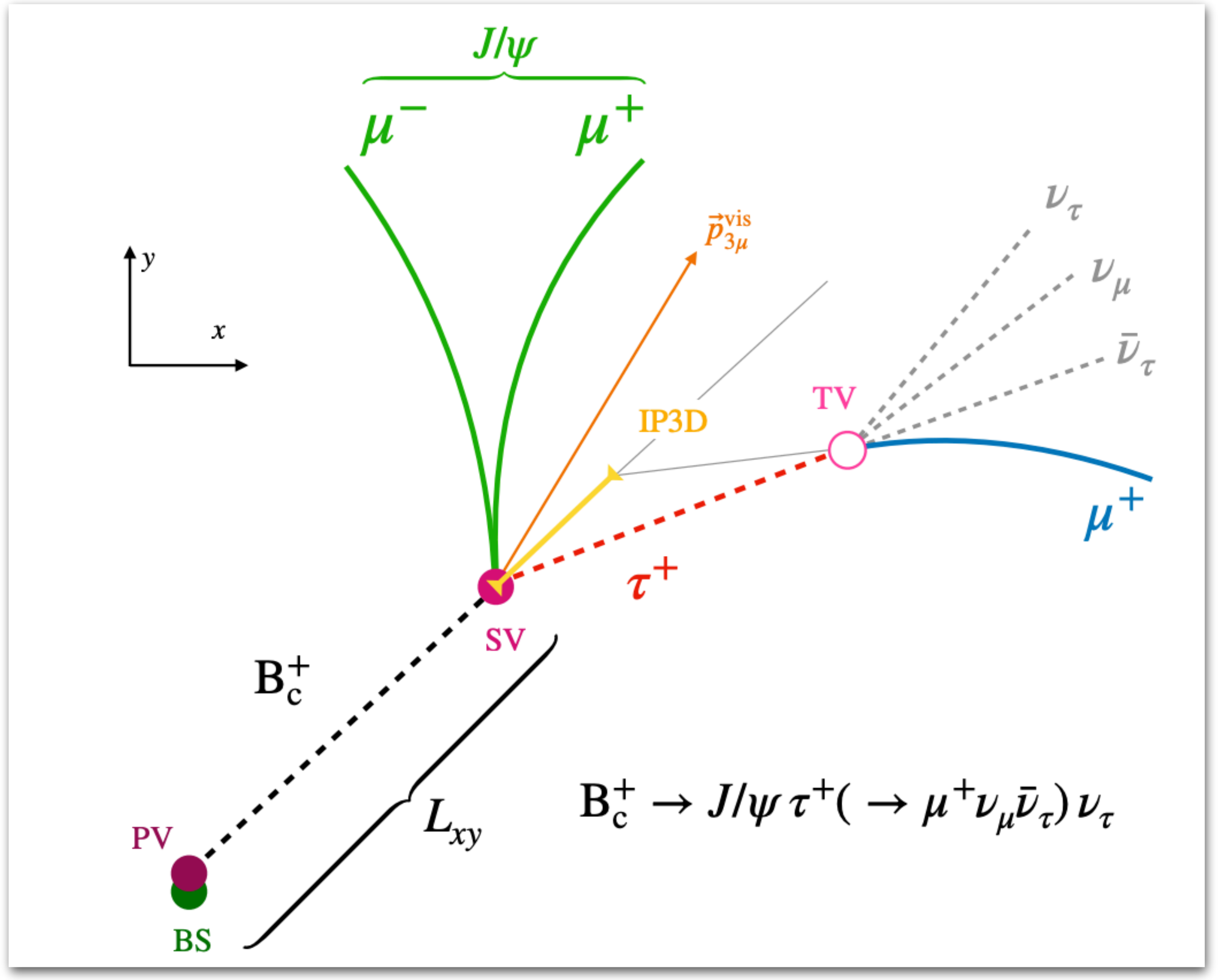


Kinematic variable $q^2 = (p_{B_c} - p_{J/\psi})^2$ useful to distinguish between τ and μ signals

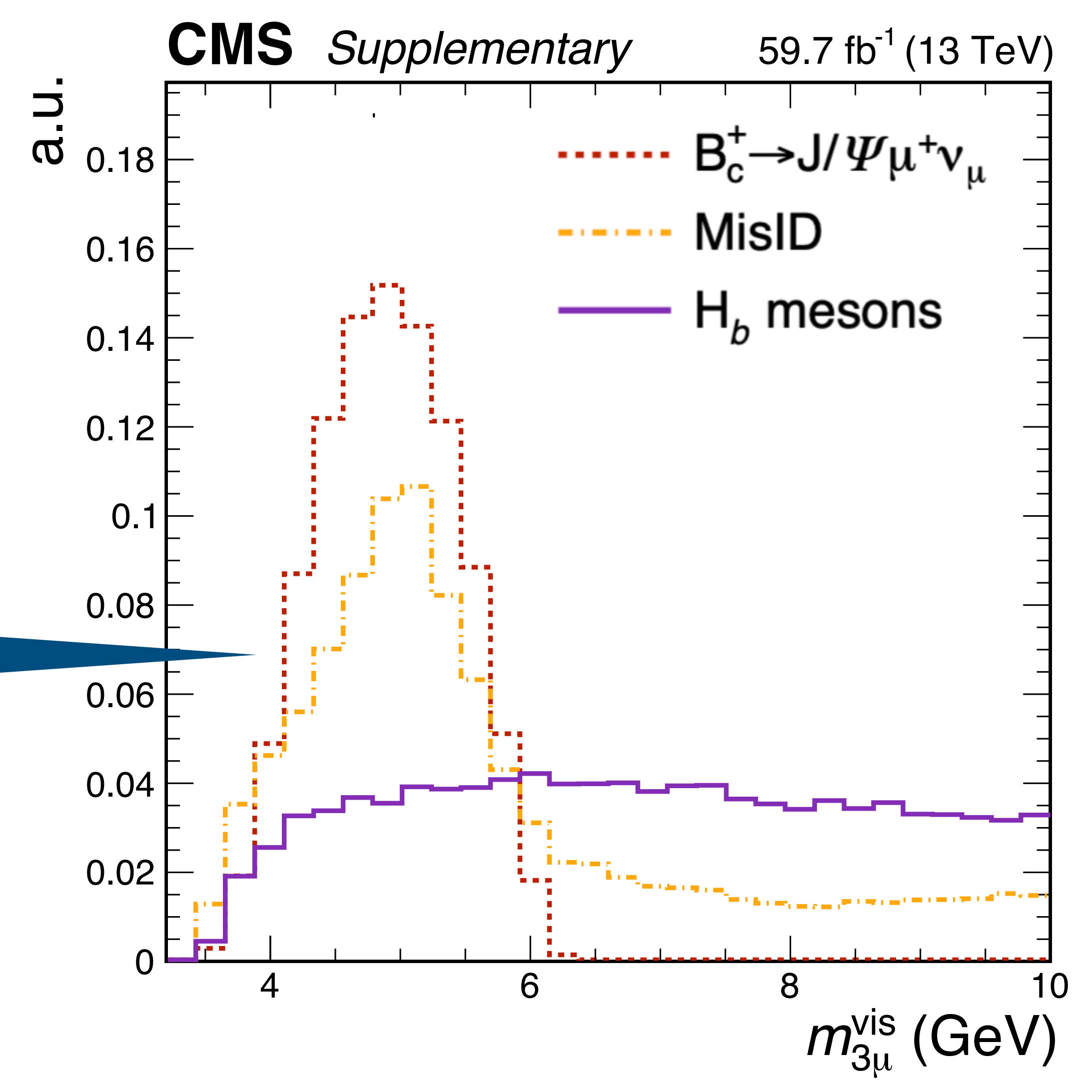
The IP3D significance of μ_3 helps in increasing the significance of the analysis

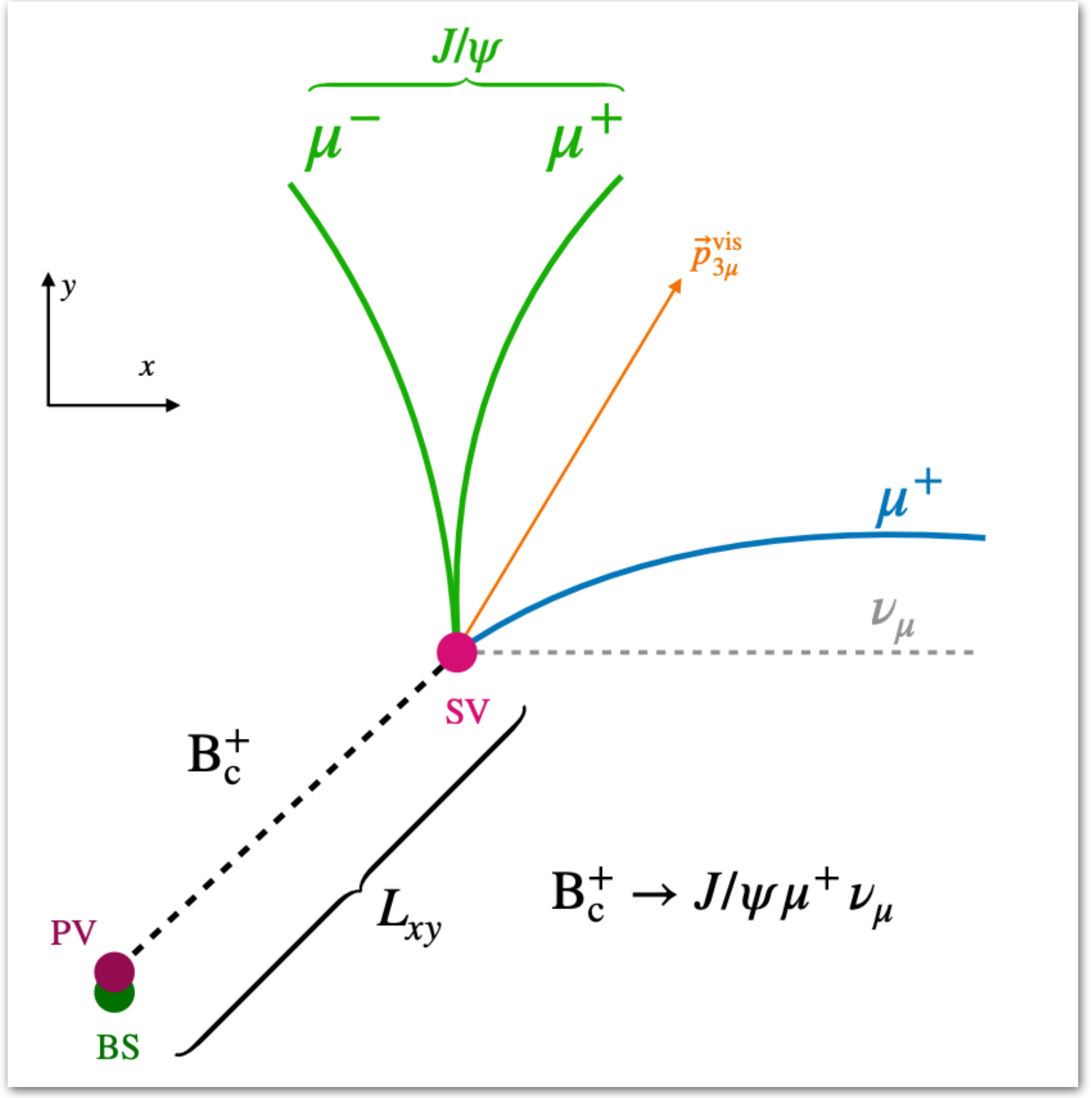


Observables for bkg control

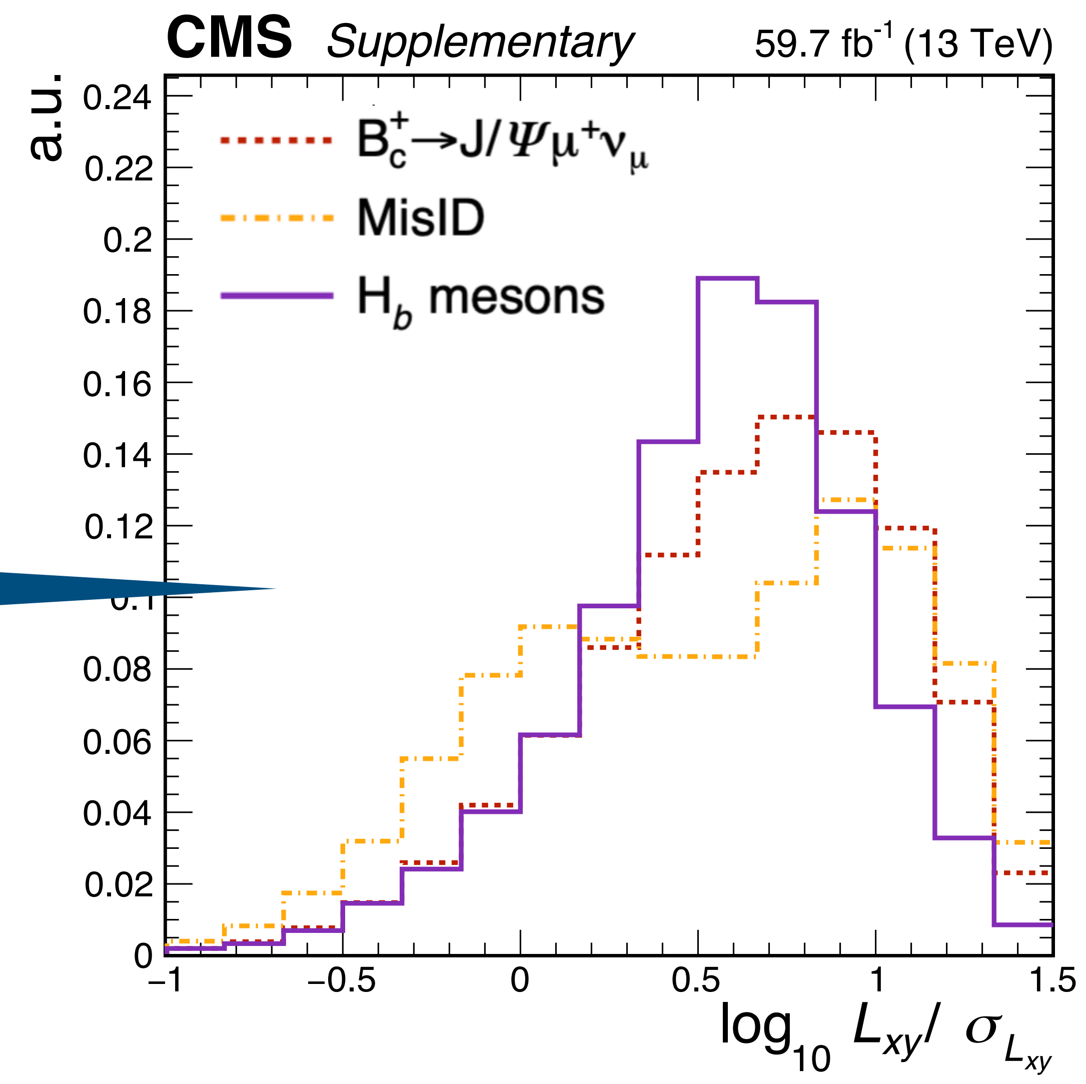


Invariant mass of the 3μ useful to constrain H_b bkg: $m(3\mu) > m_{B_c} = 6.3\,GeV$ sideband





B_c meson decay length significance useful to distinguish between misID background and other contributions



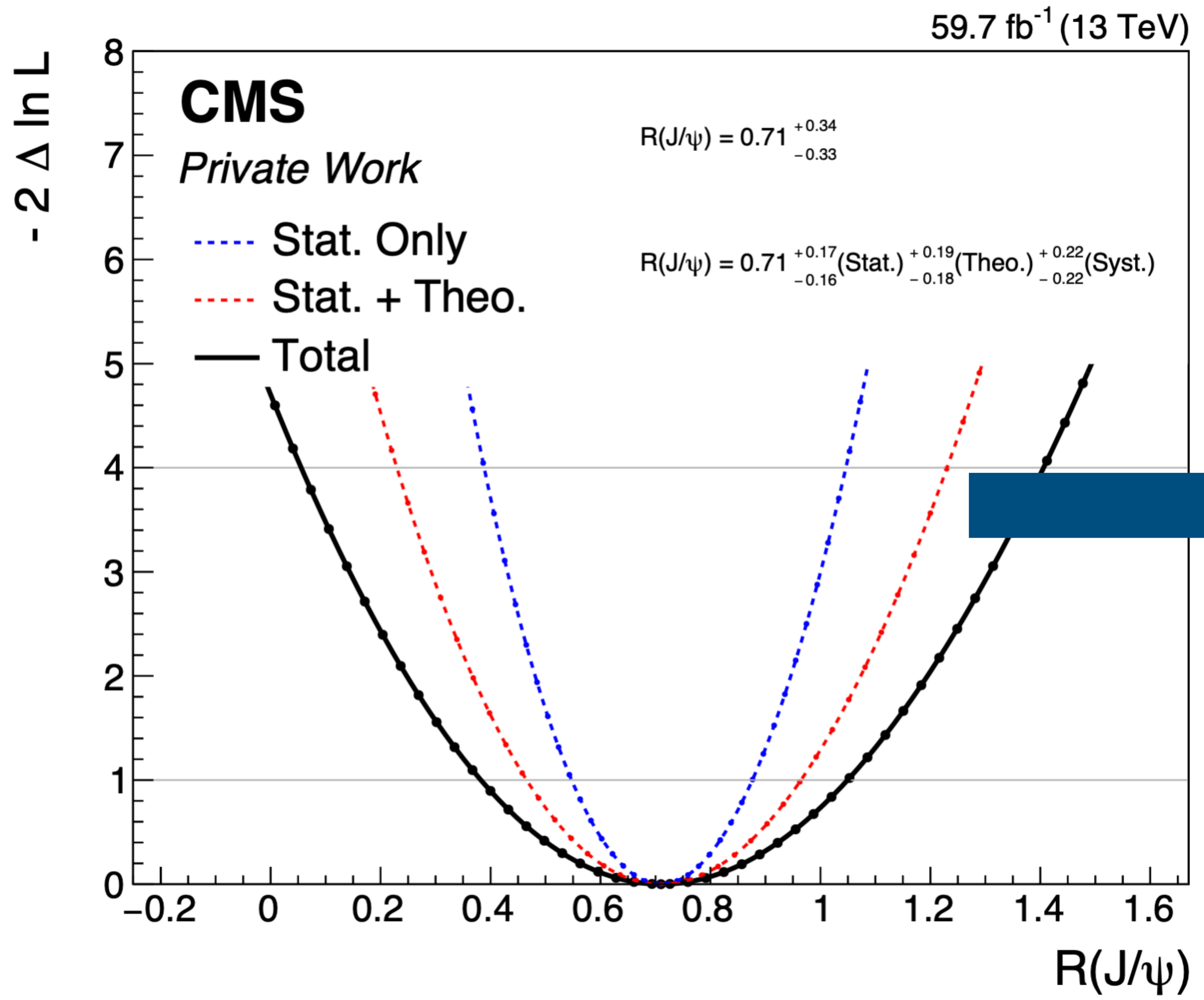
Outlook

Stat reduced of $1/\sqrt{3}$

- **Add more data**: Run 2 (tot $137\,fb^{-1}$) and Run 3 ($67.37\,fb^{-1}$ when paper was published)

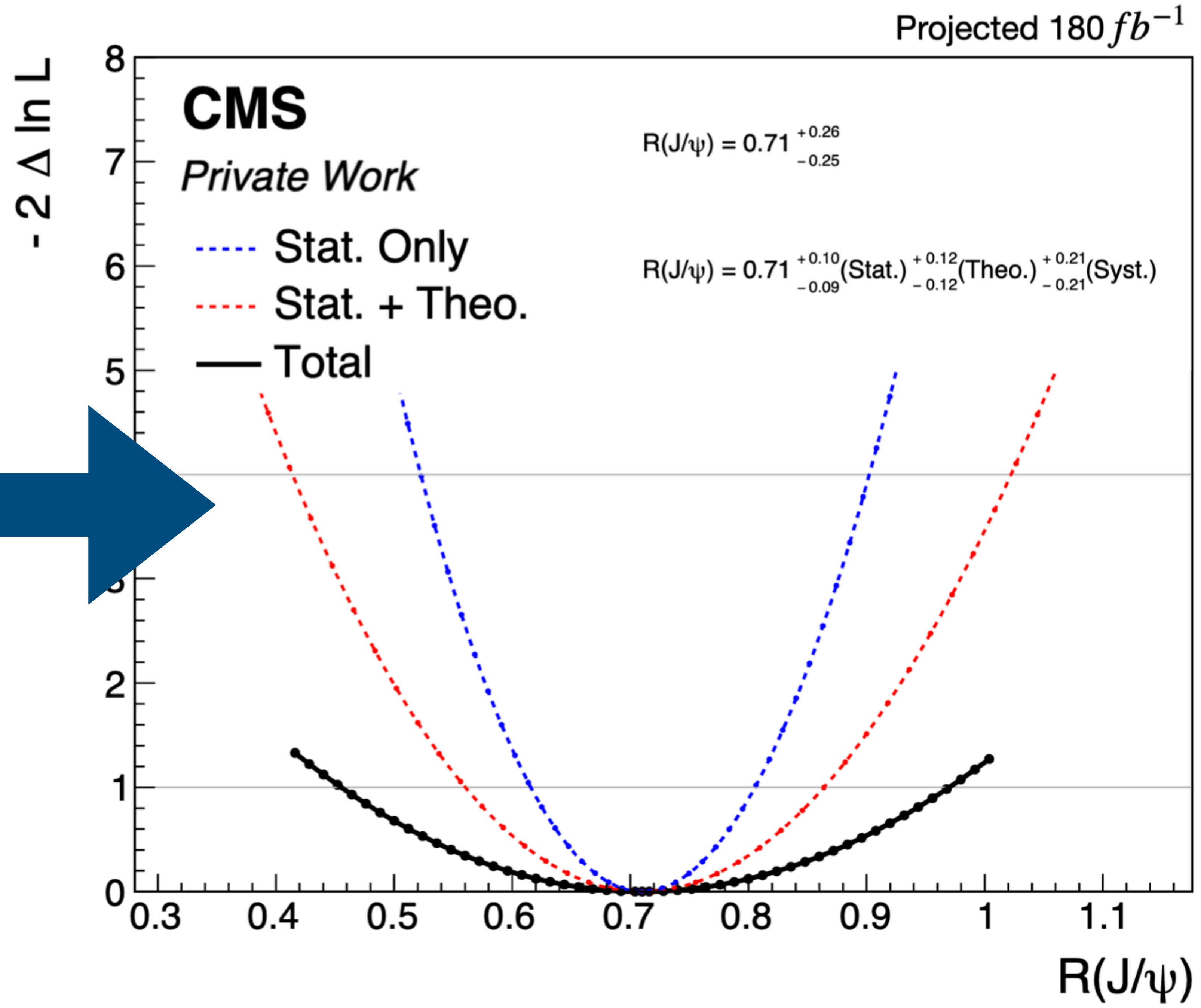
Current Asimov fit

$R(J/\psi) = 0.71\,^{+0.17}_{-0.16}(\text{Stat.})\,^{+0.19}_{-0.18}(\text{Theo.})\,^{+0.22}_{-0.22}(\text{Syst.})$

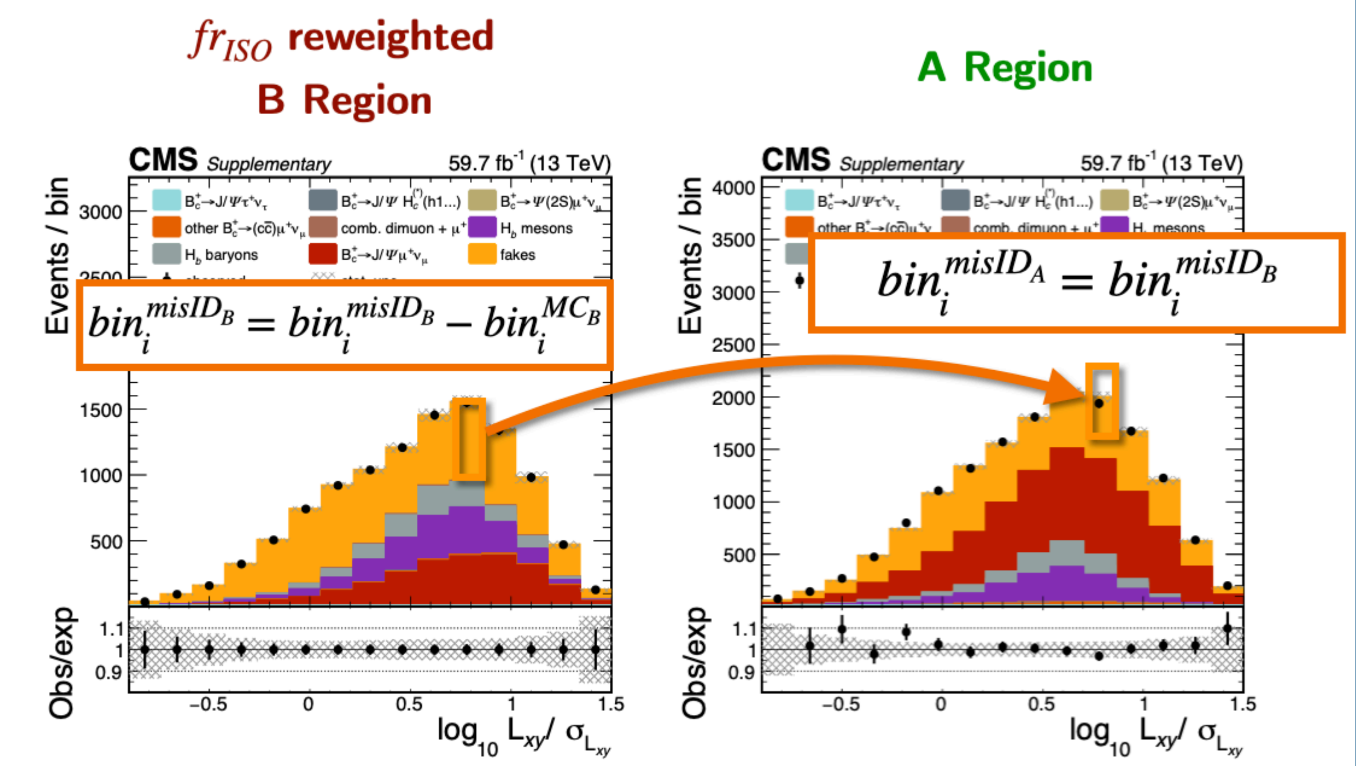


Lumi. projection: 3xlumi

$R(J/\psi) = 0.71\,^{+0.10}_{-0.09}(\text{Stat.})\,^{+0.12}_{-0.12}(\text{Theo.})\,^{+0.21}_{-0.21}(\text{Syst.})$



Fakes bkg has a statistical part of its uncertainty (from data in B), and a systematic part (from MC in B, subtracted from data). These two are correlated, and when stat increases in B, also correlations diminish



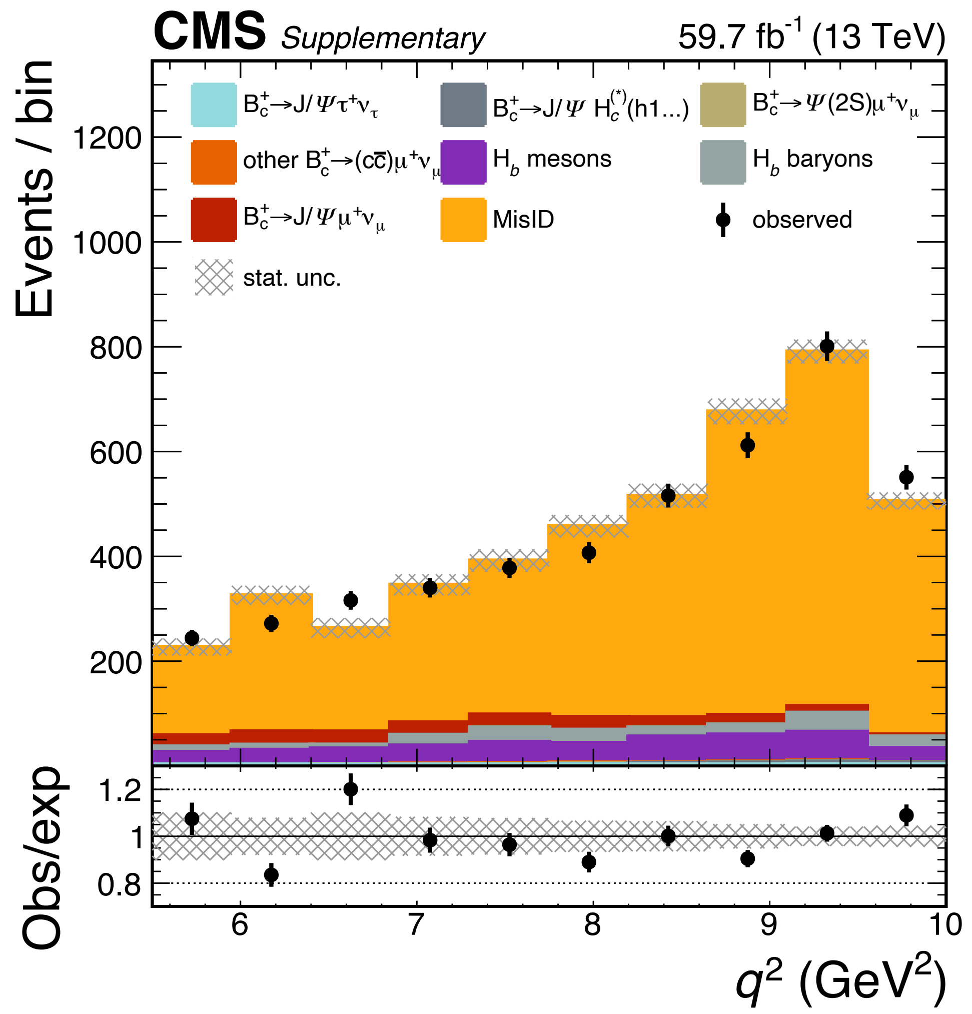
Outlook

- **Add more data**: Run 2 (tot $137 fb^{-1}$) and Run 3 ($67.37 fb^{-1}$ to date)

- Would reduce uncertainties of statistical nature associated to fakes background **estimation** and **validation**

Bin-by-bin unc. from limited statistics of the NNs training region

Bin-by-bin unc. from limited statistics of the validation region



Systematics

	Systematic	name in combine	type	$J/\psi\mu$	$J/\psi\tau$	$\chi c,0\mu$	$\chi c,1\mu$	$\chi c,2\mu$	$hc\mu$	$J/\psi hc$	$\psi(2S)\mu$	$\psi(2S)\tau$	B^0	B^+	B^0_s	$\Sigma_b^{-/0}$	Ξ_b^-	Λ_b^0	fakes	comb J/ψ	A	B	corr
1	form factor (10 systematics)	bglvar_e(#syst)	shape	X	X																X	X	yes
2	fakes normalisation	fake_rate	lnN																13%		X		
3	fakes bins (one for each bin)	fakes_bin#	rateParam																X		X		
4	fakes method	fakesmethod	shape																X		X		
5	fakes shape	fakesshape	shape																X		X		
6	fakes stat (one for each bin)	fakes_stat_bin#ch#	shape																X		X		
7	pileup weights	puWeight	shape	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	yes
8	B_c MC correction	bccorr	shape	X	X	X	X	X	X	X	X	X									X	X	yes
9	B_c decay time	ctau	shape	X	X	X	X	X	X	X	X	X									X	X	yes
10	IP3D$_{sig}$ correction	ip3d_corr_unc	shape	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	yes
11	$L_{xy,sig}$ correction	jpsivtx_corr_unc	shape	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	yes
12	SF Reco A	sfReco	lnN	3.1%	3.0%	2.7%	2.9%	3.0%	4.1%	3.2%	2.8%	2.2%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%			X		yes
13	SF Reco B	sfReco	lnN	2.6%	2.6%	2.6%	2.7%	2.6%	2.9%	2.8%	2.6%	3.0%	2.8%	2.8%	2.8%	2.8%	2.8%	2.8%				X	yes
14	SF MediumID A	sfIdjpsi	lnN	2.7%	2.7%	2.6%	2.6%	2.7%	4.1%	2.9%	2.6%	2.4%	2.8%	2.8%	2.8%	2.8%	2.8%	2.8%			X		yes
15	SF MediumID B	sfIdjpsi	lnN	2.6%	2.6%	2.6%	2.6%	2.5%	2.9%	2.6%	2.5%	2.8%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%				X	yes
16	SF SoftMvaID	sfIdk	lnN	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%			X	X	yes
17	SF iso	sfiso	lnN	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%			X	X	no
18	SF trigger	trigger	lnN	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%			X	X	yes
19	BR $\chi_{c,0}\mu$	br_chic0_over_mu	lnN			16%															X	X	yes
20	BR $\chi_{c,1}\mu$	br_chic1_over_mu	lnN				10%														X	X	yes
21	BR $\chi_{c,2}\mu$	br_chic2_over_mu	lnN					22%													X	X	yes
22	BR $hc\mu$	br_hc_over_mu	lnN						15%												X	X	yes
23	BR $J/\psi hc$	br_jpsi_hc_over_mu	lnN							38%											X	X	yes
24	BR $\psi(2S)\mu$	br_psi2s_mu_over_mu	lnN								13%										X	X	yes
25	BR $\psi(2S)\tau$	br_psi2s_tau_over_mu	lnN									15%									X	X	yes
26	B_c not-yet measured decays	missing_mc	shape							X											X		yes
27	norm B^0 (H_b bkg)	jpsimother_bzero	lnN										10%								X	X	yes
28	norm B^+ (H_b bkg)	jpsimother_bplus	lnN											10%							X	X	yes
29	norm B^0_s (H_b bkg)	jpsimother_bzero_s	lnN												10%						X	X	yes
30	norm $\Sigma_b^{-/0}$ (H_b bkg)	jpsimother_sigma	lnN													10%					X	X	yes
31	norm $\Xi_b^{-/0}$ (H_b bkg)	jpsimother_xi	lnN														10%				X	X	yes
32	norm Λ_b^0 (H_b bkg)	jpsimother_lambdazero_b	lnN															10%			X	X	yes
33	Comb J/ψ dimuon norm	dimuon_norm	lnN																	20%	X	X	yes
34	MC stat fail (one for each bin)	bbb(#bin)fail	shape													X	X	X				X	
35	MC stat pass (one for each bin)	bbb(#bin)pass	shape													X	X	X			X		

Systematics

	Systematic	name in combine	type	$J/\psi\mu$	$J/\psi\tau$	$\chi c,0\mu$	$\chi c,1\mu$	$\chi c,2\mu$	$hc\mu$	$J/\psi hc$	$\psi(2S)\mu$	$\psi(2S)\tau$	B^0	B^+	B^0_s	$\Sigma_b^{-/0}$	Ξ_b^-	Λ_b^0	fakes	comb J/ψ	A	B	corr
1	form factor (10 systematics)	bglvar_e(#syst)	shape	X	X																X	X	yes
2	fakes normalisation	fake_rate	lnN																13%		X		
3	fakes bins (one fo[illegible]in)	fakes_bin#	rateParam																X		X		
4	fakes method	fakesmethod	shape																X		X		
5	fakes shape	fakesshape	shape																X		X		
6	[illegible]	[illegible]	[illegible]																X		X		
7	[illegible]	[illegible]	[illegible]																		[illegible]	X	yes
8	[illegible]	[illegible]	[illegible]																		[illegible]	X	yes
9	[illegible]	[illegible]	[illegible]																		[illegible]	X	yes
10	[illegible]	[illegible]	[illegible]																		[illegible]	X	yes
11	[illegible]	[illegible]	[illegible]																		[illegible]	X	yes
12	[illegible]	[illegible]	[illegible]																		[illegible]		yes
13	SF Reco B	sfReco	lnN	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				X	yes
14	SF MediumID A	sfIdjpsi	lnN	2.7%	2.7%	2.6%	2.6%	2.7%	4.1%	2.9%	2.6%	2.4%	2.8%	2.8%	2.8%	2.8%	2.8%	2.8%			X		yes
15	SF MediumID B	sfIdjpsi	lnN	2.6%	2.6%	2.6%	2.6%	2.5%	2.9%	2.6%	2.5%	2.8%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%				X	yes
16	SF SoftMvaID	sfIdk	lnN	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%			X	X	yes
17	SF iso	sfiso	lnN	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%			X	X	no
18	SF trigger	trigger	lnN	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%			X	X	yes
19	BR $\chi_{c,0}\mu$	br_chic0_over_mu	lnN			16%															X	X	yes
20	BR $\chi_{c,1}\mu$	br_chic1_over_mu	lnN				10%														X	X	yes
21	BR $\chi_{c,2}\mu$	br_chic2_over_mu	lnN					22%													X	X	yes
22	BR $hc\mu$	br_hc_over_mu	lnN						15%												X	X	yes
23	BR $J/\psi hc$	br_jpsi_hc_over_mu	lnN							38%											X	X	yes
24	BR $\psi(2S)\mu$	br_psi2s_mu_over_mu	lnN								13%										X	X	yes
25	BR $\psi(2S)\tau$	br_psi2s_tau_over_mu	lnN									15%									X	X	yes
26	B_c not-yet measured decays	missing_mc	shape							X											X		yes
27	norm B^0 (H_b bkg)	jpsimother_bzero	lnN										10%								X	X	yes
28	norm B^+ (H_b bkg)	jpsimother_bplus	lnN											10%							X	X	yes
29	norm B^0_s (H_b bkg)	jpsimother_bzero_s	lnN												10%						X	X	yes
30	norm $\Sigma_b^{-/0}$ (H_b bkg)	jpsimother_sigma	lnN													10%					X	X	yes
31	norm $\Xi_b^{-/0}$ (H_b bkg)	jpsimother_xi	lnN														10%				X	X	yes
32	norm Λ_b^0 (H_b bkg)	jpsimother_lambdazero_b	lnN															10%			X	X	yes
33	Comb J/ψ dimuon norm	dimuon_norm	lnN																	20%	X	X	yes
34	MC stat fail (one for each bin)	bbb(#bin)fail	shape													X	X	X				X	
35	MC stat pass (one for each bin)	bbb(#bin)pass	shape													X	X	X			X		

Most impacting form factors #1

Systematics

	Systematic	name in combine	type	$J/\psi\mu$	$J/\psi\tau$	$\chi c, 0\mu$	$\chi c, 1\mu$	$\chi c, 2\mu$	$hc\mu$	$J/\psi hc$	$\psi(2S)\mu$	$\psi(2S)\tau$	B^0	B^+	B^0_s	$\Sigma_b^{-/0}$	Ξ_b^-	Λ_b^0	fakes	comb J/ψ	A	B	corr
1	form factor (10 systematics)	bglvar_e(#syst)	shape	X	X																X	X	yes
2	fakes normalisation	fake_rate	lnN																13%		X		
3	fakes bins (one for each bin)	fakes_bin#	rateParam																X		X		
4	fakes method	fakesmethod	shape																X		X		
5	fakes shape	fakesshape	shape																X		X		
6	fakes stat (one for each bin)	fakes_stat_bin#ch#	shape																X		X		
7	pileup wei	puWeight	shape	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	yes
8	B_c MC n	bccorr	shape	X	X	X	X	X	X	X	X	X									X	X	yes
9	B_c de	ctau	shape	X	X	X	X	X	X	X	X	X									X	X	yes
1													X	X	X	X	X	X			X	X	yes
													X	X	X	X	X	X			X	X	yes
												%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%			X		yes
												%	2.8%	2.8%	2.8%	2.8%	2.8%	2.8%				X	yes
												%	2.8%	2.8%	2.8%	2.8%	2.8%	2.8%			X		yes
												%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%				X	yes
													3%	3%	3%	3%	3%	3%			X	X	yes
													3%	3%	3%	3%	3%	3%			X	X	no
1													5%	5%	5%	5%	5%	5%			X	X	yes
19	BR $\chi_{c,0}\mu$	br_chic0_over_mu	lnN			16%															X	X	yes
20	BR $\chi_{c,1}\mu$	br_chic1_over_mu	lnN				10%														X	X	yes
21	BR $\chi_{c,2}\mu$	br_chic2_over_mu	lnN					22%													X	X	yes
22	BR $hc\mu$	br_hc_over_mu	lnN						15%												X	X	yes
23	BR $J/\psi hc$	br_jpsi_hc_over_mu	lnN							38%											X	X	yes
24	BR $\psi(2S)\mu$	br_psi2s_mu_over_mu	lnN								13%										X	X	yes
25	BR $\psi(2S)\tau$	br_psi2s_tau_over_mu	lnN									15%									X	X	yes
26	B_c not-yet measured decays	missing_mc	shape							X											X		yes
27	norm B^0 (H_b bkg)	jpsimother_bzero	lnN										10%								X	X	yes
28	norm B^+ (H_b bkg)	jpsimother_bplus	lnN											10%							X	X	yes
29	norm B^0_s (H_b bkg)	jpsimother_bzero_s	lnN												10%						X	X	yes
30	norm $\Sigma_b^{-/0}$ (H_b bkg)	jpsimother_sigma	lnN													10%					X	X	yes
31	norm $\Xi_b^{-/0}$ (H_b bkg)	jpsimother_xi	lnN														10%				X	X	yes
32	norm Λ_b^0 (H_b bkg)	jpsimother_lambdazero_b	lnN															10%			X	X	yes
33	Comb J/ψ dimuon norm	dimuon_norm	lnN																	20%	X	X	yes
34	MC stat fail (one for each bin)	bbb(#bin)fail	shape													X	X	X				X	
35	MC stat pass (one for each bin)	bbb(#bin)pass	shape													X	X	X			X		

Fakes uncertainties

Systematics

	Systematic	name in combine	type	$J/\psi\mu$	$J/\psi\tau$	$\chi c,0\mu$	$\chi c,1\mu$	$\chi c,2\mu$	$hc\mu$	$J/\psi hc$	$\psi(2S)\mu$	$\psi(2S)\tau$	B^0	B^+	B^0_s	$\Sigma_b^{-/0}$	Ξ_b^-	Λ_b^0	fakes	comb J/ψ	A	B	corr
1	form factor (10 systematics)	bglvar_e(#syst)	shape	X	X																X	X	yes
2	fakes normalisation	fake_rate	lnN																13%		X		
3	fakes bins (one for each bin)	fakes_bin#	rateParam																X		X		
4	fakes method	fakesmethod	shape																X		X		
5	fakes shape	fakesshape	shape																X		X		
6	fakes stat (one for each bin)	fakes_stat_bin#ch#	shape																X		X		
7	pileup weights	puWeight	shape	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	yes
8	B_c MC correction	bccorr	shape	X	X	X	X	X	X	X	X	X									X	X	yes
9	B_c decay time	ctau	shape	X	X	X	X	X	X	X	X	X									X	X	yes
10	IP3D$_{sig}$ correction	ip3d_corr_unc	shape	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	yes
11	$L_{xy,sig}$ correction	jpsivtx_corr_unc	shape	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	yes
12	SF Reco A	sfReco	lnN	3.1%	3.0%	2.7%	2.9%	3.0%	4.1%	3.2%	2.8%	2.2%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%			X		yes
13	SF Reco B	sfReco	lnN	2.6%	2.6%	2.6%	2.7%	2.6%	2.9%	2.8%	2.6%	3.0%	2.8%	2.8%	2.8%	2.8%	2.8%	2.8%				X	yes
14	SF MediumID A	sfIdjpsi	lnN	2.7%	2.7%	2.6%	2.6%	2.7%	4.1%	2.9%	2.6%	2.4%	2.8%	2.8%	2.8%	2.8%	2.8%	2.8%			X		yes
15	SF MediumID B	sfIdjpsi	lnN	2.6%	2.6%	2.6%	2.6%	2.5%	2.9%	2.6%	2.5%	2.8%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%				X	yes
16	SF SoftMvaID	sfIdk	lnN	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%			X	X	yes
17	SF iso	sfiso	lnN	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%			X	X	no
18	SF trigger	trigger	lnN	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%			X	X	yes
19	BR $\chi_{c,0}\mu$	br_chic0_c[illegible]r_mu	lnN			16%															X	X	yes
20	BR $\chi_{c,1}\mu$	br_chic[illegible]u	lnN				10%														X	X	yes
21	BR $\chi_{c,2}\mu$	br_c[illegible]	lnN					22%													X	X	yes
22	BR $hc\mu$	[illegible]	[illegible]																		X	X	yes
23	BR $J/\psi hc$	[illegible]	[illegible]																		X	X	yes
24	BR $\psi(2S)\mu$	[illegible]	[illegible]																		X	X	yes
25	BR $\psi(2S)\tau$	[illegible]	[illegible]																		X	X	yes
26	B_c not-yet measured decays	[illegible]	[illegible]																		X		yes
27	norm B^0 (H_b bkg)	[illegible]	[illegible]																		X	X	yes
28	norm B^+ (H_b bkg)	[illegible]	[illegible]																		X	X	yes
29	norm B^0_s (H_b bkg)	[illegible]	[illegible]																		X	X	yes
30	norm $\Sigma_b^{-/0}$ (H_b bkg)	[illegible]	[illegible]																		X	X	yes
31	norm $\Xi_b^{-/0}$ (H_b bkg)	jpsimother_xi	lnN														10%				X	X	yes
32	norm Λ_b^0 (H_b bkg)	jpsimother_lambdazero_b	lnN															10%			X	X	yes
33	Comb J/ψ dimuon norm	dimuon_norm	lnN																	20%	X	X	yes
34	MC stat fail (one for each bin)	bbb(#bin)fail	shape													X	X	X				X	
35	MC stat pass (one for each bin)	bbb(#bin)pass	shape													X	X	X			X		

Uncertainties on the corrections

(IP3D$_{sig}$ corr. most impacting one)

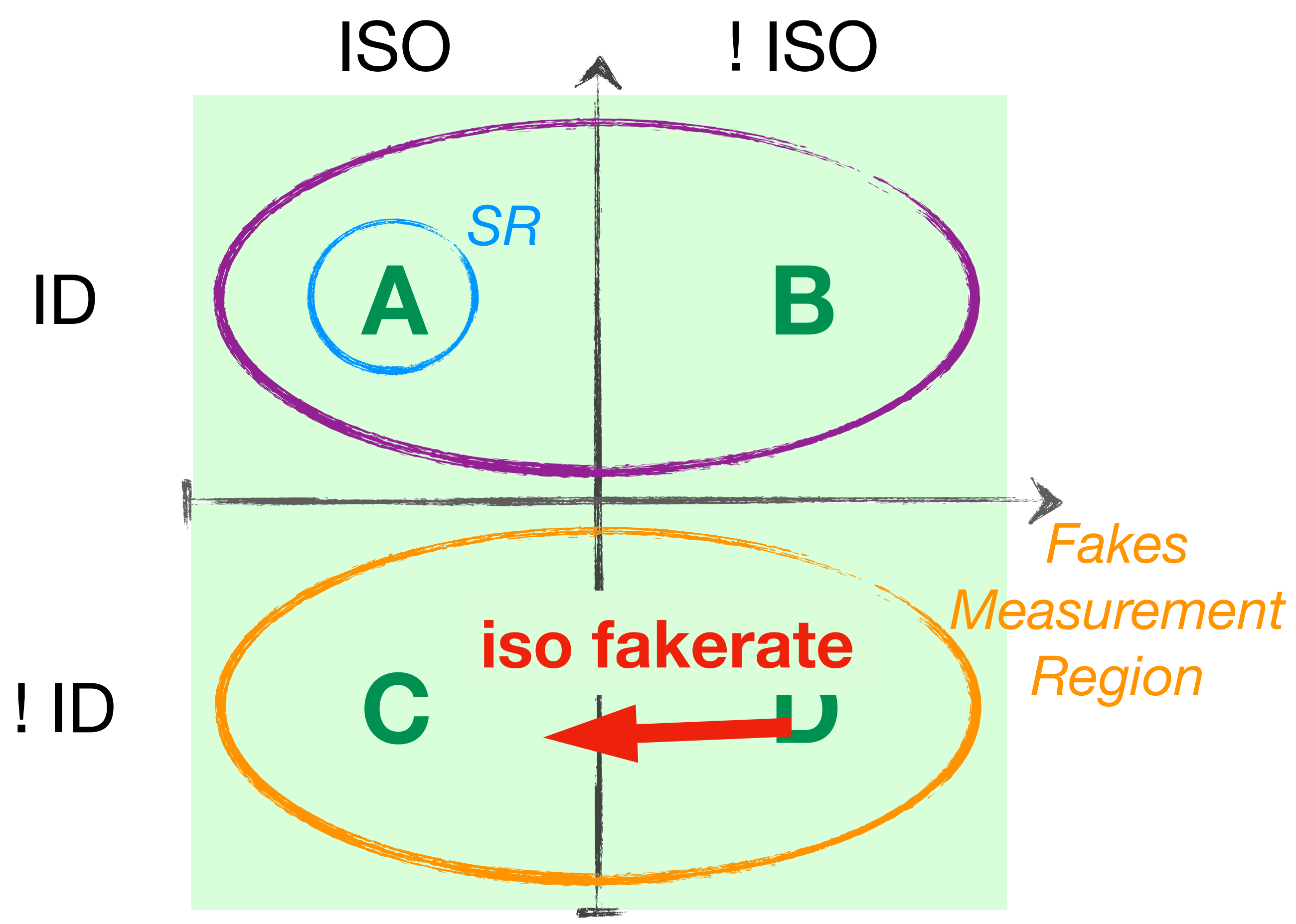
Systematics

Uncertainties on

- B_c BRs
- B_c not-yet measured decays
- H_b norm. uncertainties
- Comb. J/ψ bkg
- MC stat

												$(2S)\mu$	$\psi(2S)\tau$	B^0	B^+	B^0_s	$\Sigma_b^{-/0}$	Ξ_b^-	Λ_b^0	fakes	comb J/ψ	A	B	corr
1																						X	X	yes
2																				13%		X		
3																				X		X		
4																				X		X		
5																				X		X		
6																				X		X		
7												X	X	X	X	X	X	X	X			X	X	yes
8												X	X									X	X	yes
9												X	X									X	X	yes
10												X	X	X	X	X	X	X	X			X	X	yes
11												X	X	X	X	X	X	X	X			X	X	yes
12												8%	2.2%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%			X		yes
13												6%	3.0%	2.8%	2.8%	2.8%	2.8%	2.8%	2.8%				X	yes
14												6%	2.4%	2.8%	2.8%	2.8%	2.8%	2.8%	2.8%			X		yes
15												5%	2.8%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%				X	yes
16												3%	3%	3%	3%	3%	3%	3%	3%			X	X	yes
17												3%	3%	3%	3%	3%	3%	3%	3%			X	X	no
18												5%	5%	5%	5%	5%	5%	5%	5%			X	X	yes
19	BR $\chi_{c,0}\mu$	br_chic0_over_mu	lnN			16%																X	X	yes
20	BR $\chi_{c,1}\mu$	br_chic1_over_mu	lnN				10%															X	X	yes
21	BR $\chi_{c,2}\mu$	br_chic2_over_mu	lnN					22%														X	X	yes
22	BR $hc\mu$	br_hc_over_mu	lnN						15%													X	X	yes
23	BR $J/\psi hc$	br_jpsi_hc_over_mu	lnN							38%												X	X	yes
24	BR $\psi(2S)\mu$	br_psi2s_mu_over_mu	lnN								13%											X	X	yes
25	BR $\psi(2S)\tau$	br_psi2s_tau_over_mu	lnN									15%										X	X	yes
26	B_c not-yet measured decays	missing_mc	shape							X												X		yes
27	norm B^0 (H_b bkg)	jpsimother_bzero	lnN										10%									X	X	yes
28	norm B^+ (H_b bkg)	jpsimother_bplus	lnN											10%								X	X	yes
29	norm B^0_s (H_b bkg)	jpsimother_bzero_s	lnN												10%							X	X	yes
30	norm $\Sigma_b^{-/0}$ (H_b bkg)	jpsimother_sigma	lnN													10%						X	X	yes
31	norm $\Xi_b^{-/0}$ (H_b bkg)	jpsimother_xi	lnN														10%					X	X	yes
32	norm Λ_b^0 (H_b bkg)	jpsimother_lambdazero_b	lnN															10%				X	X	yes
33	Comb J/ψ dimuon norm	dimuon_norm	lnN																		20%	X	X	yes
34	MC stat fail (one for each bin)	bbb(#bin)fail	shape													X	X	X					X	
35	MC stat pass (one for each bin)	bbb(#bin)pass	shape													X	X	X				X		

misID bkg - fr_{ISO} measurement



$$data(C) = MC(C) + fakes(C)$$

$$\frac{data(C)}{data(D)} \cdot data(D) = \frac{MC(C)}{MC(D)} \cdot MC(D) + \frac{fakes(C)}{fakes(D)} \cdot fakes(D)$$

$$\frac{data(C)}{data(D)} = TF_{data};\ \frac{MC(C)}{MC(D)} = TF_{MC};\ \frac{fakes(C)}{fakes(D)} = fr_{ISO};\ \frac{MC(D)}{data(D)} = \alpha$$

$$TF = p/(1-p)$$

$$TF_{data} \cdot data(D) = TF_{MC} \cdot MC(D) + fr_{ISO} \cdot fakes(D)$$

$$TF_{data} = TF_{MC} \cdot \alpha + fr_{ISO} \cdot (1-\alpha)$$

$$fr_{ISO}(x_i) = \frac{TF_{data}(x_i) - TF_{MC}(x_i) \cdot \alpha(x_i)}{1-\alpha(x_i)}$$

$$fakes(C) = \left(\frac{TF_{data}(x_i) - TF_{MC}(x_i) \cdot \alpha(x_i)}{1-\alpha(x_i)}\right) \cdot data(D) - \left(\frac{TF_{data}(x_i) - TF_{MC}(x_i) \cdot \alpha(x_i)}{1-\alpha(x_i)}\right) \cdot MC(D)$$

misID bkg - fr_{ISO} measurement

- TF_{data}, TF_{MC} and α are transfer functions between two different regions
  - They are fitted in many dimensions using classification NNs
  - **For the Universal Approximation Theorem, A Neural Network (NN) can approximate any arbitrary complex f(x)**
- Three classification NNs are trained to distinguish between 2 classes
  - Provide the probability for each event to belong to either class p
  - The weights for the transfer functions are computed as $w = \dfrac{p}{1-p}$
- TF_{data} : data(C) vs data(D)
- TF_{MC}: MC(C) vs MC(D)
- α : data(D) vs MC(D)

Input features

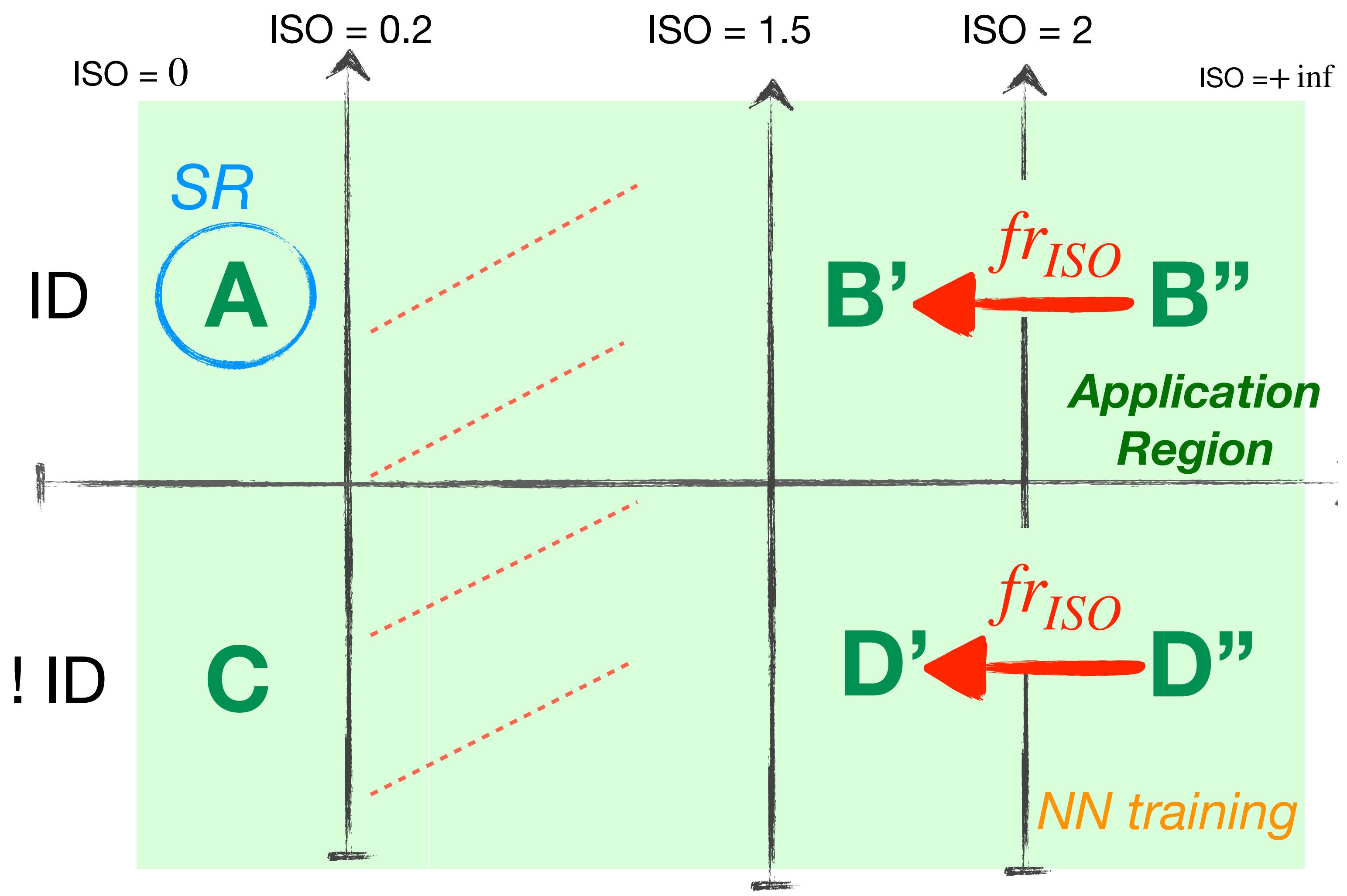
- q^2
- $|\eta_B|$
- p_T^B
- m^2_{miss}
- $log_{10} vtx(\mu_1, \mu_2) L_{xy}/\sigma_{L_{xy}}$
- $vtx(\mu_1, \mu_2, \mu_3)$ prob
- $(\mu_1, \mu_2, \mu_3) 2Dcos\alpha$
- $\mu_3 IP3D(vtx_{J/\Psi})$ sig
- $\mu_3 |d_{xy}|/\sigma_{d_{xy}}$
- $\mu_3 |d_z|/\sigma_{d_z}$

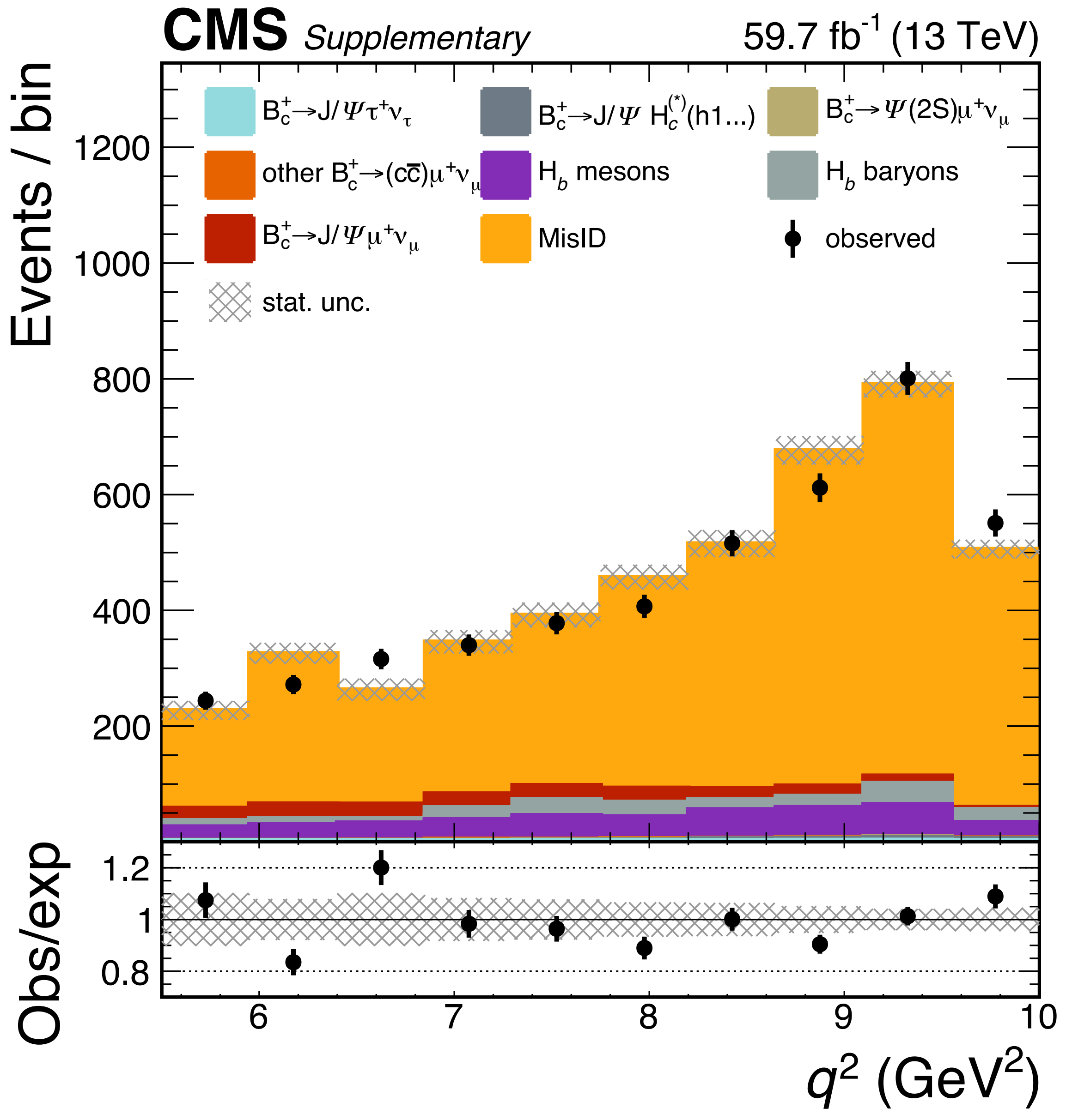
misID bkg - fr_{ISO} measurement

- It is important that the NNs learn to discern the observables and correlations on which the fake rates depend
  - This guarantees the applicability of the fake rate to different phase space regions
- **Check the NNs ability to generalise properly → done**
- **Check closure in the C region → it closes by design**

misID Background Data Validation

- **Validation on data control regions**
  - ISO>1.5 → fakes enriched
  - Same strategy of analysis: train NN in !ID; apply weights in B” to find fakes in B’

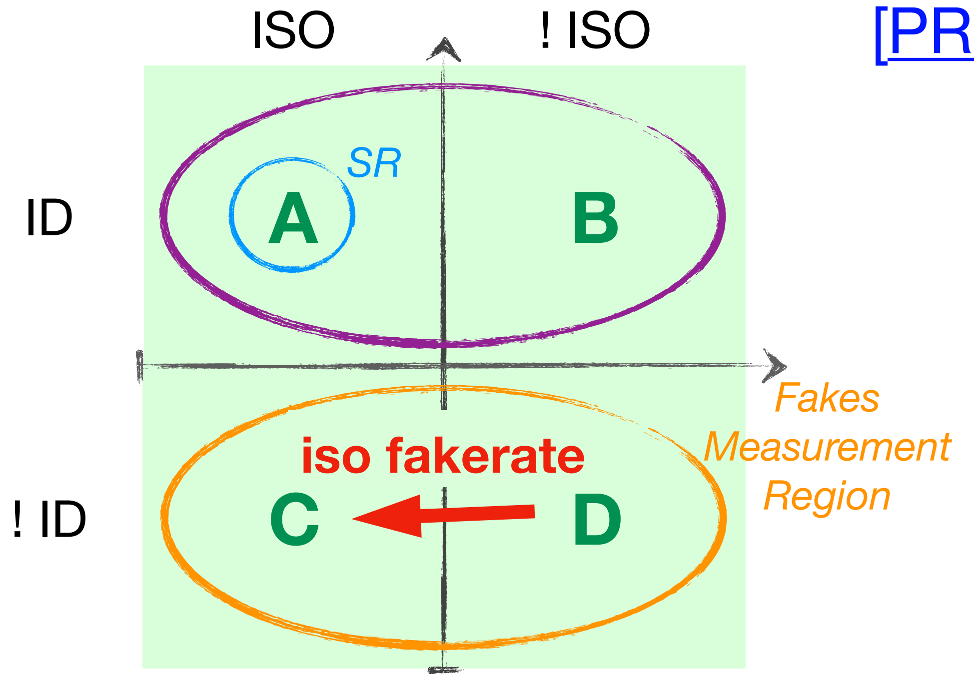




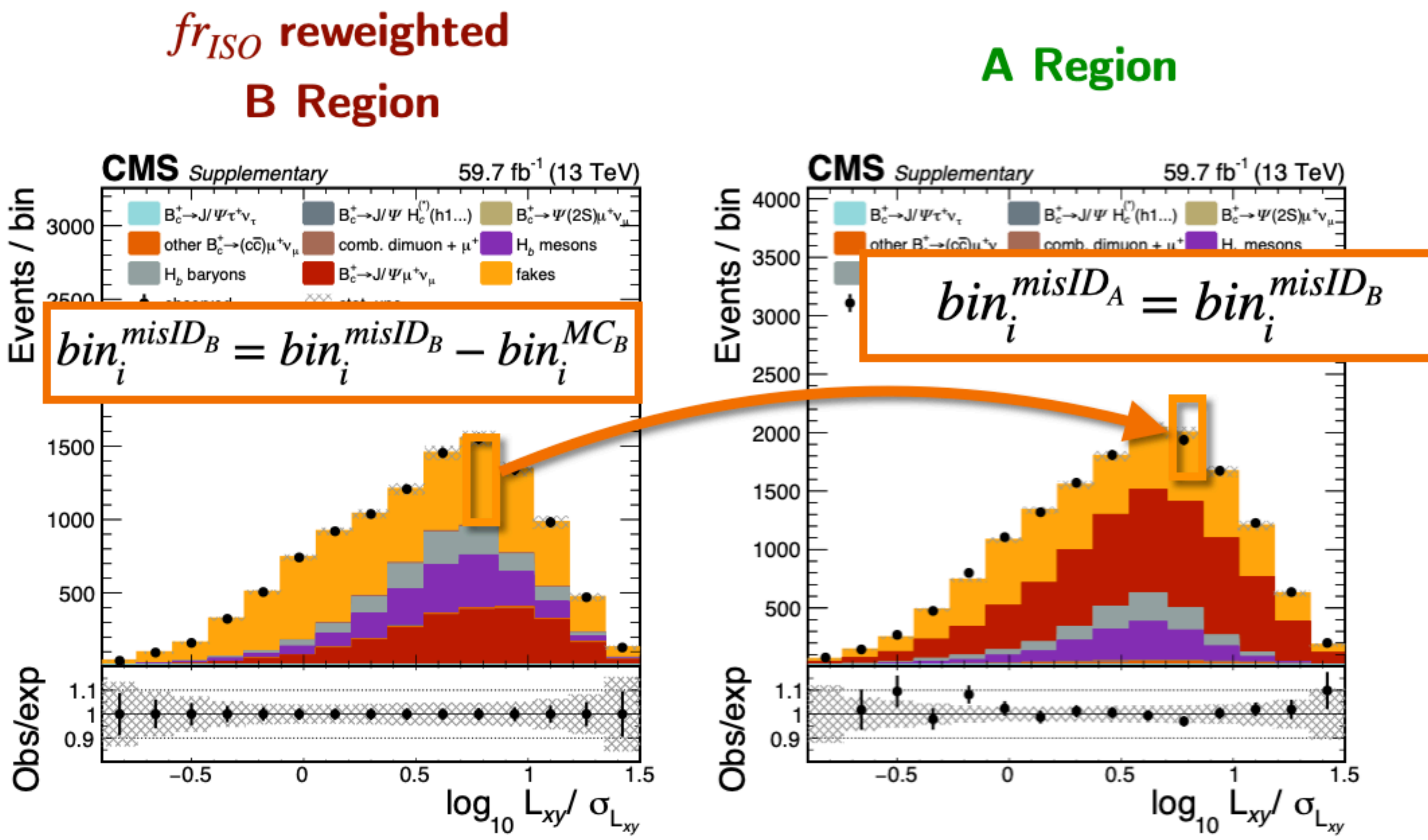
- **Closure in B’ → good agreement data-fakes**
- Conservative uncertainties added to account for limited statistics of the test
- **Several other uncertainties added to this data-driven bkg**

[PRD 111 (2025) L051102]

MisID estimation in the fit



- Each one of the 7 categories is split into two further categories for the **estimation of the fakes background during the fit**.
  - reweighted-B Region *with* fr_{ISO}, already measured in the !ID categories.
  - Region A
- B_c and H_b bkg shapes and norm. could change during the fit because of their syst. unc.
  - Hence each fakes bin is defined as a free **floating parameter**, which compensates the difference between data and MC in reweighted-B region during the fit

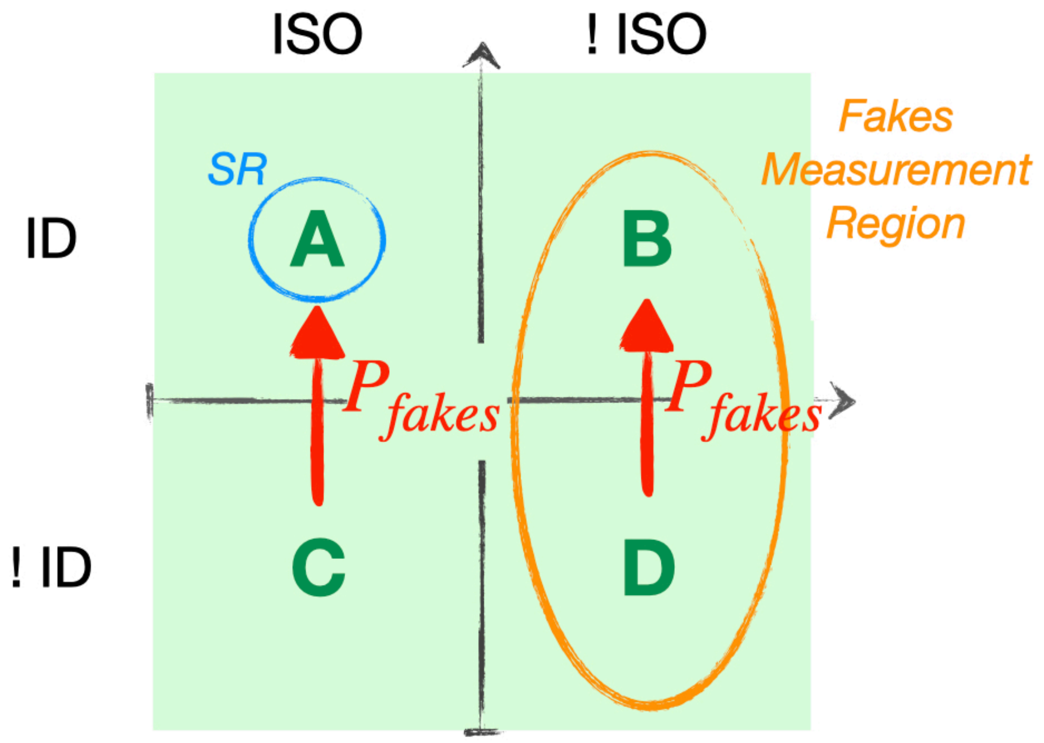


7x2 total categories

Overview on misID background uncertainties

Uncertainty on the method

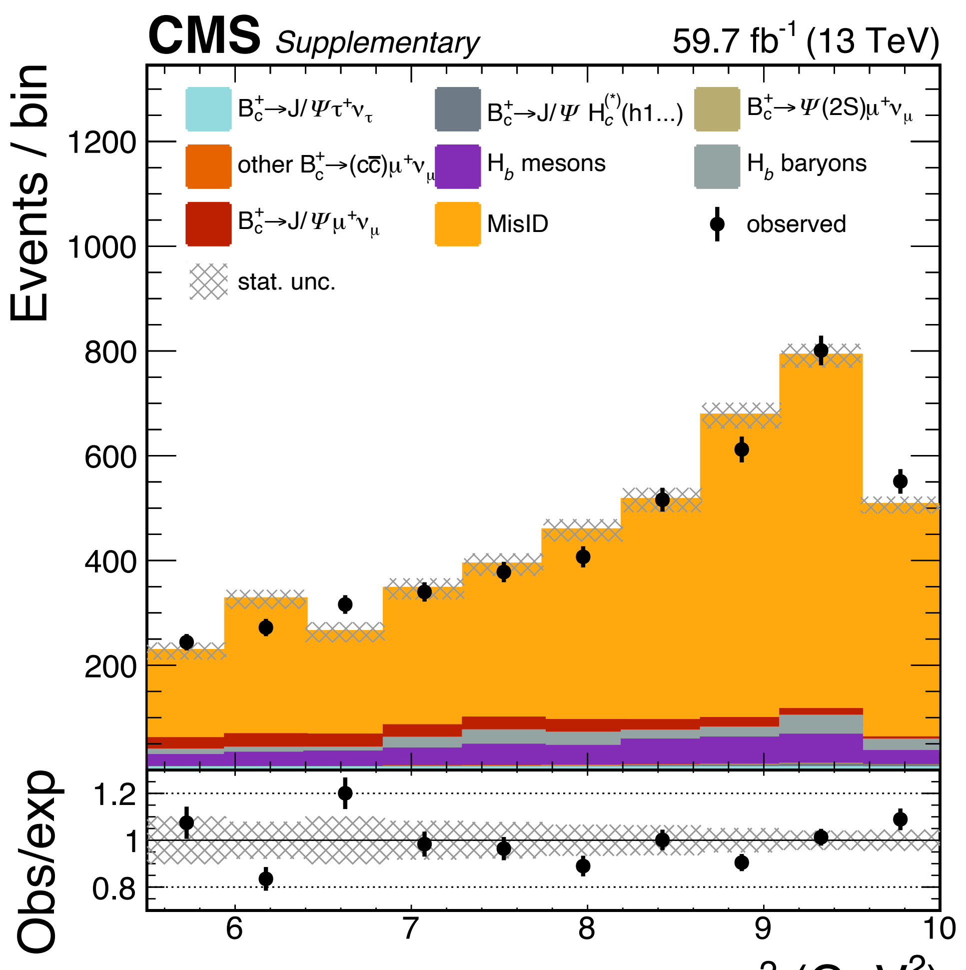
- Instead of measuring fr_{ISO} we measure fr_{ID} and rotate the scheme
- The difference between misID shape from nominal method to rotated one is added as single unc. in the fit



Stat. uncertainty on validation

- Validation on data stat. limited: bin-by-bin uncertainties on misID shape

$$\sqrt{(\text{stat}^i_{\text{data}})^2 + (\text{stat}^i_{\text{fakes}})^2} \leq 10\,\%$$



Stat. uncertainty on NN training

- The NN is trained 5 times, each on a statistically independent training sample
- MisID shape derived for each NN
- Std dev derived for each bin and applied bin-by-bin as uncertainty on misID shape

Combinatorial J/ψ dimuon background

- Two unrelated muons can accidentally return invariant mass within the analysis J/ψ window
- Data driven background

Normalisation

- Fit to the J/ψ invariant-mass in Loose SR
  - Signal shape: Crystal Ball + gaussian
  - Bkg: exponential fixed from sideband
- Result: 2-3 % contribution in the SR

Sidebands cut at trigger level, therefore another dataset, including dimuon enriched sideband, is considered

Combinatorial J/ψ dimuon background

- Two unrelated muons can accidentally return invariant mass within the analysis J/ψ window
- Data driven background

Shape

- q^2 shape from sideband $3\,\sigma$ from the J/ψ peak

$q^2 \propto m^2_{J/\psi}$

- Extrapolated to the SR by scaling the J/ψ four-momentum by the ratio $< m^{PDG}_{J/\psi} > / < m_{SB} >$

Successful closure test of the method extrapolating the q^2 shape from a left sideband to a right sideband

For $l_{xy,sig}$ no shape shift

Event Selection

Final State particles:

- μ_1: *mediumID*, $p_T^{\mu_1} > 6$, $|\eta^{\mu_1}| < 2.5$, $|d_{xy}^{\mu_1}| < 0.05$ cm
- μ_2: *mediumID*, $p_T^{\mu_2} > 4$, $|\eta^{\mu_2}| < 2.5$, $|d_{xy}^{\mu_2}| < 0.05$ cm
- μ_3: $p_T^{\mu_3} > 4$, $|\eta^{\mu_3}| < 2.5$, $|d_{xy}^{\mu_3}| < 0.05$ cm
- $|d_z^{\mu_1} - d_z^{\mu_2}| < 0.2$ cm, $|d_z^{\mu_1} - d_z^{\mu_3}| < 0.2$ cm, $|d_z^{\mu_2} - d_z^{\mu_3}| < 0.2$ cm
- $\Delta R_{12} > 0.01, \Delta R_{13} > 0.01, \Delta R_{23} > 0.01$
- *ID on μ_3 is discussed later*

J/ψ and B_c vertices properties:

- $prob_{J/\psi} > 0.01$
- $prob_{B_c} > 10^{-4}$
- A η dependent $m^{J/\psi}$ cut

PV defined as the closest in z-direction to the J/ψ.
Transverse displacement L_{xy} computed wrt the beamspot.

Trigger selection

- The trigger paths used are HLT_Dimuon0_Jpsi3p5_Muon2_v5 and HLT_Dimuon0_Jpsi3p5_Muon2_v6, from Charmonium dataset
- The seeds are L1_TripleMu_5SQ_3SQ_0OQ_DoubleMu_5_3_SQ_OS_Mass_Max9 OR L1_TripleMu_5SQ_3SQ_0_DoubleMu_5_3_SQ_OS_Mass_Max9
- The two muons coming from the J/ψ are matched with the filter label hltVertexmumuFilterJpsiMuon3p5
- μ_3 is matched with the filter label hltTripleMuL3PreFiltered222

The trigger requires :

- 3 muons;
- The probability of the $\mu\mu$ vertex fit better than 0.5 %;
- $p_T^{\mu_{1/2}} > 3.5$ GeV;
- $2.95 < m(\mu_1\mu_2) < 3.25$ GeV;
- $p_T^{\mu} > 2$ GeV.

$R(J/\psi)$ Measurement - Hadronic Channel

Event Selection

- **Trigger Selection**: HLT_DoubleMu4_JpsiTrk_Displaced_v*
  - 2 OS muons with pT> 4 GeV
  - m(μμ) in [2.9, 3.3] GeV
  - pT (μμ) > 6.9 GeV
  - Vertex prob. > 10%
  - Flight sig. > 3σ
  - Additional track with pT>1.2 GeV
  - chi2/ndof < 10

- **J/ψ candidate**:
  - OS muons (pT > 4 GeV, |η| < 2.4, loose ID, trigger matched within ΔR < 0.1)
  - 2.95 < m(μμ) < 3.25 GeV
  - If multiple, choose the highest pT(J/ψ) cand.

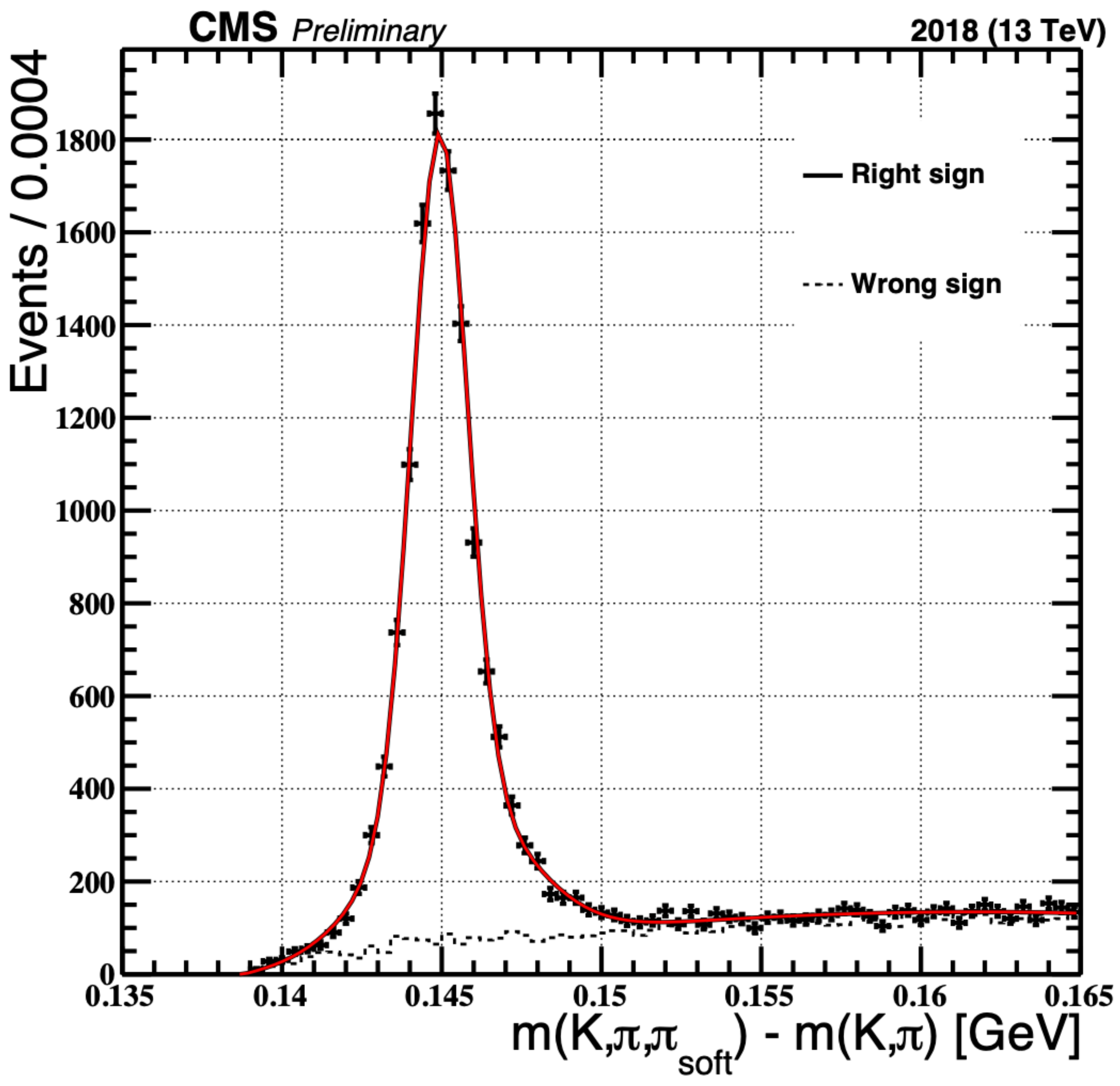
- **Vertex Selection**:
  - minΔz (extr. J/ψ to the beam axis)

- **Tau Reconstruction**:
  - In main presentation…

$R(K)$ Measurement

B-Parking Trigger Purity

- 12 Billion events recorded in 2018 with $b\bar{b}$ purity of 75 %
- Purity determination relies on decay $B^0 \rightarrow D^{*+}\mu\nu \rightarrow (D^0\pi_{soft})\mu\nu \rightarrow (K\pi\pi_{soft})\mu\nu$
- In the plot: difference for D^{*+} and D^0 masses
  - D^0 built combining opposite charged tracks
  - $D*$ built by combining D^0 with a soft track
  - μ required to pass the trigger
- The product of K and μ is required to be +1 (right sign), or -1 (wrong sign)
- Plot shows clear peak for the right sign curve

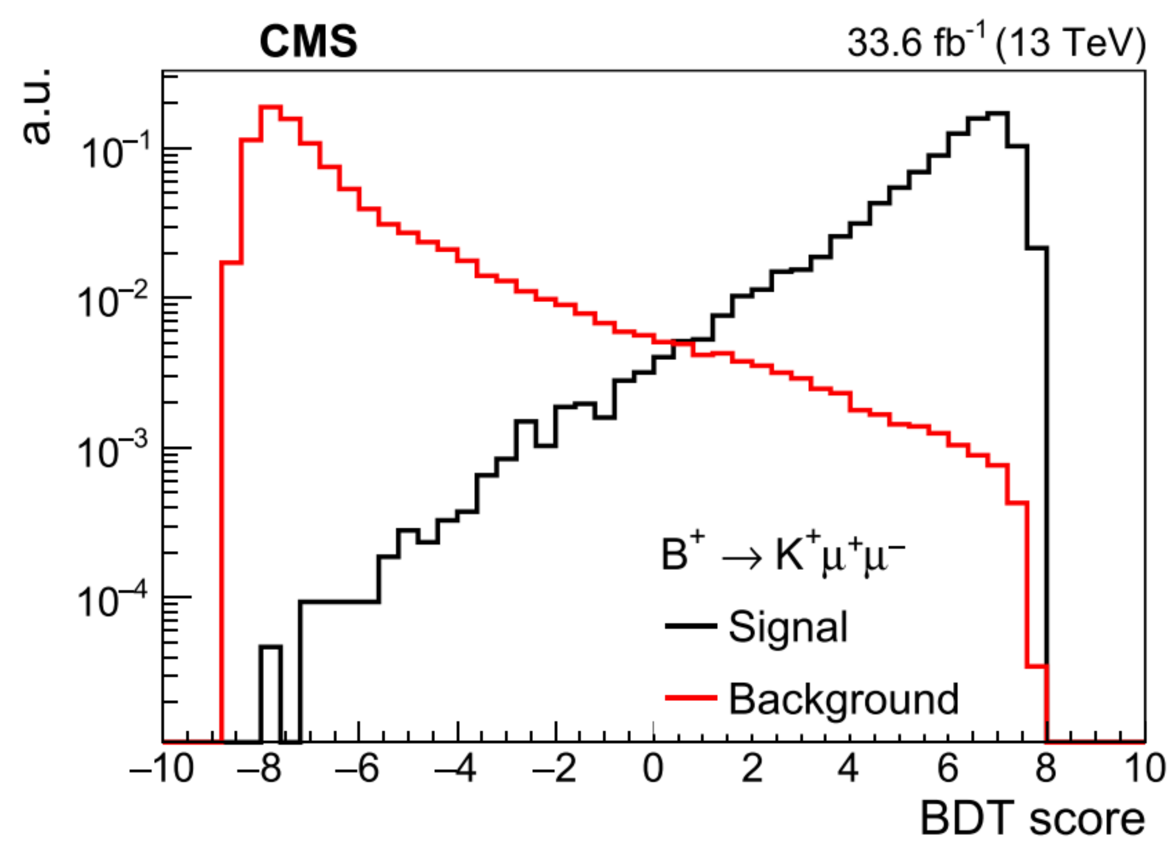


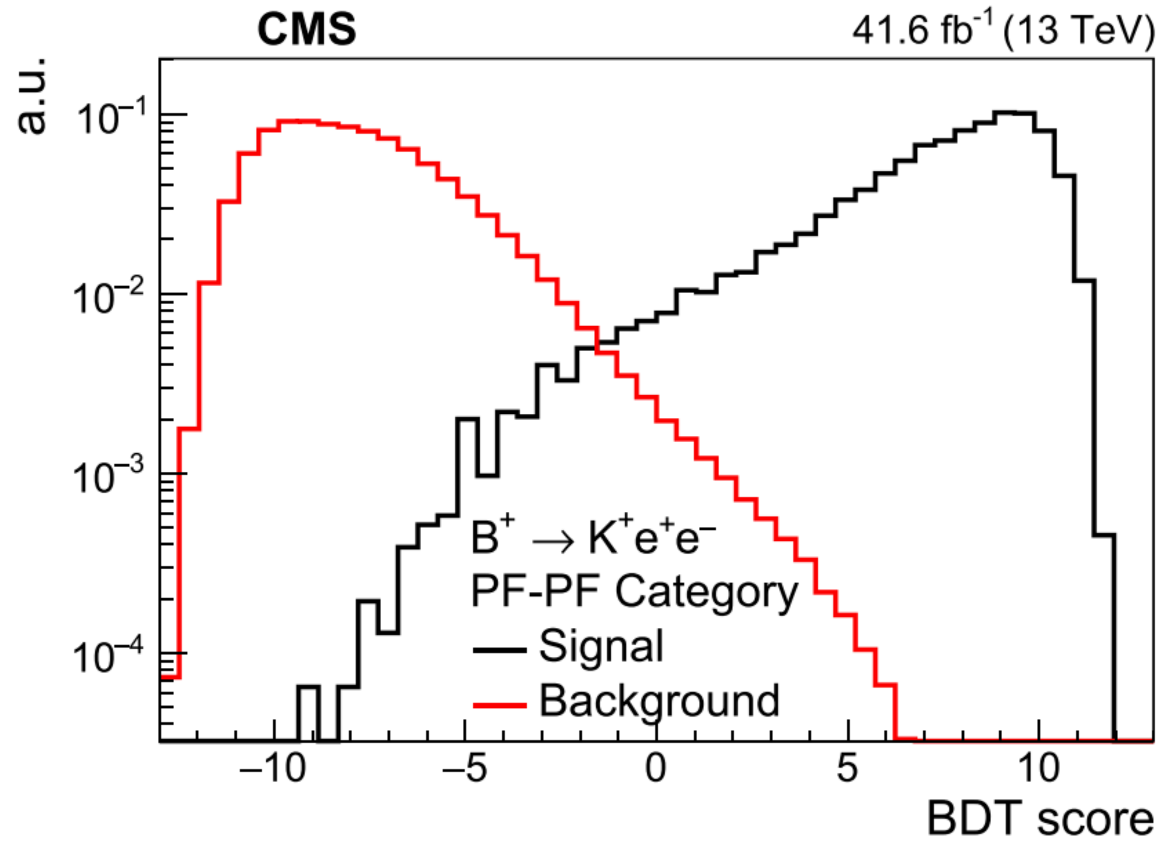
$$P_b = \frac{N(b \rightarrow \mu X)}{N(\mu)}$$

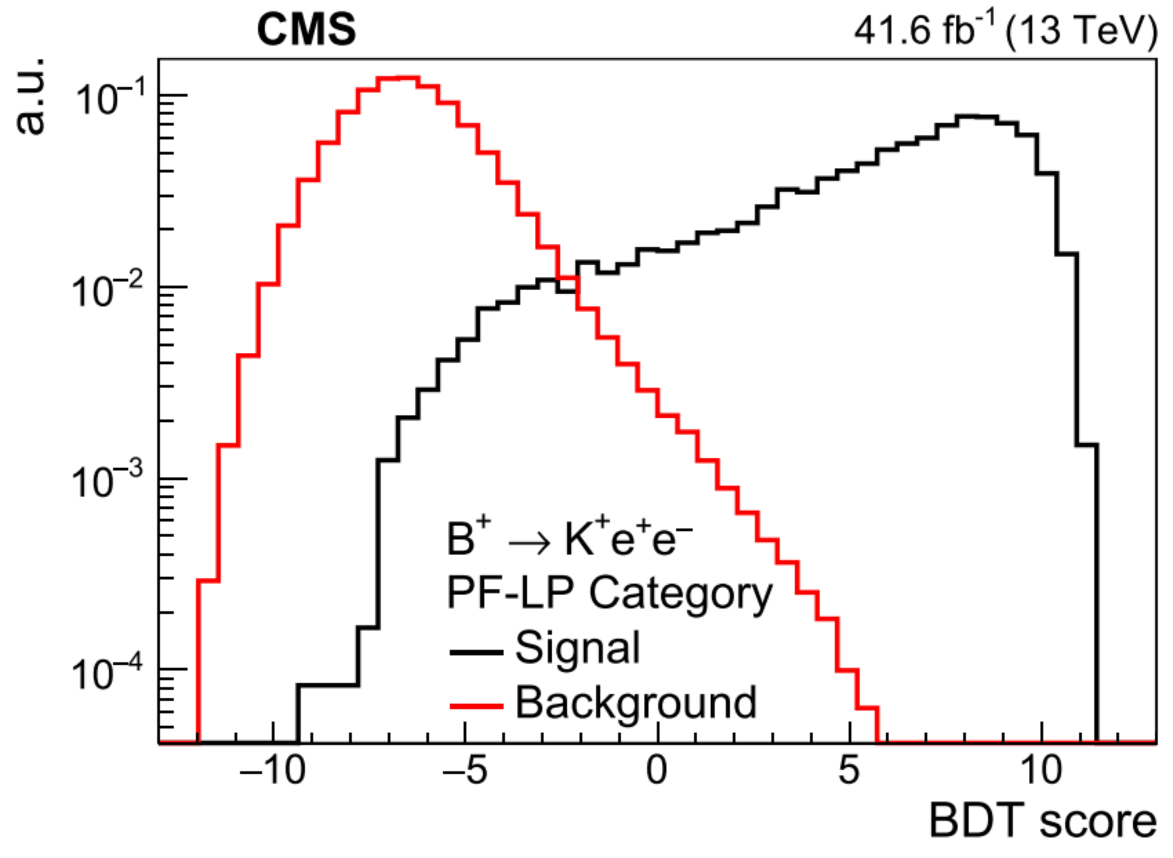
Pre-selection

- Preselection for μμK:
  - pT(B) > 3 GeV
  - Δz(trg μ, track/μ2) < 1.0 cm
  - pT(track) > 1 GeV
  - Lxy/σ > 1
  - cos (α) > 0.90
  - Prob > 10-5
  - m(K,μ) > 2 GeV [anti-D0]
- Preselection for eeK:
  - Δz(trg μ, track/e) < 1.0 cm
  - pT(e2) > 1.0 GeV
  - cos (α) > 0.95
  - Prob > 10-5
  - m(K,e) > 2 GeV [anti-D0]
  - d3d < 0.06 - ID (e1) > -2
  - ID (e2) > 0

BDT Working Points







- Working point definition
  - As final selection, cut on the BDT score to maximize $S/\sqrt{(S+B)}$:
    - For muon channels: BDT>4
    - For electron (2PF) channels: BDT>8.6
    - For electron (1PF & 1 low pT) channels: BDT>8.3

Cross Checks

- Several cross checks performed, the two most important are:
  - Measurement of $R_{\psi(2S)}$, exchanging the $B \to Kll$ with $B \to \psi(2S)K$ in the double ratio
  - Measurement of $R_{J/\psi}$, ratio of $B \to J/\psi(\mu\mu)K$ and $B \to J/\psi(ee)K$
- They are both expected to be flavour universal ~1
  - The measured ratios agree with the expectations <1 σ
- These cross checks also demonstrate that the efficiencies that cancel out in the R(K) ratio are well estimated

Fit Functions and Yields

- Muon channel

Process	$B^+ \to K^+\mu^+\mu^-$	$B^+ \to J/\psi(\mu^+\mu^-)K^+$	$B^+ \to \psi(2S)(\mu^+\mu^-)K^+$
Signal	DCB + Gaussian	Sum of 3 Gaussians	DCB + Gaussian
Comb. & other b bkg.	Exponential[a]	Exponential	Exponential
$B^+ \to K^*(892)^{0/+}X$	DCB (+ expon.)	DCB + exponential	DCB + exponential
$B^+ \to \pi^+X$	DCB	DCB	DCB
$B^+ \to J/\psi(\mu^+\mu^-)K^+$	DCB (nearby q^2)	—	—
$B^+ \to \psi(2S)(\mu^+\mu^-)K^+$	DCB (nearby q^2)	—	—

Channel	q^2 range [GeV^2]	Yield
$B^+ \to K^+\mu^+\mu^-$	1.1–6.0	1267 ± 55
$B^+ \to J/\psi(\mu^+\mu^-)K^+$	8.41–10.24	$728\,000 \pm 1000$
$B^+ \to \psi(2S)(\mu^+\mu^-)K^+$	12.60–14.44	$68\,300 \pm 500$

- Electron channel

Process	$B^+ \to K^+e^+e^-$	$B^+ \to J/\psi(e^+e^-)K^+$	$B^+ \to \psi(2S)(e^+e^-)K^+$
Signal	DCB function	CB + Gaussian	CB + Gaussian
Comb. background	Exponential	Exponential	Exponential
$B^+ \to K^*(892)^{0/+}X$	—	KDE template	KDE template
$B^+ \to \pi^+X$	—	CB function	—
$B^+ \to J/\psi(e^+e^-)K^+$	KDE template	—	—
Other b decays	—	KDE template	KDE template

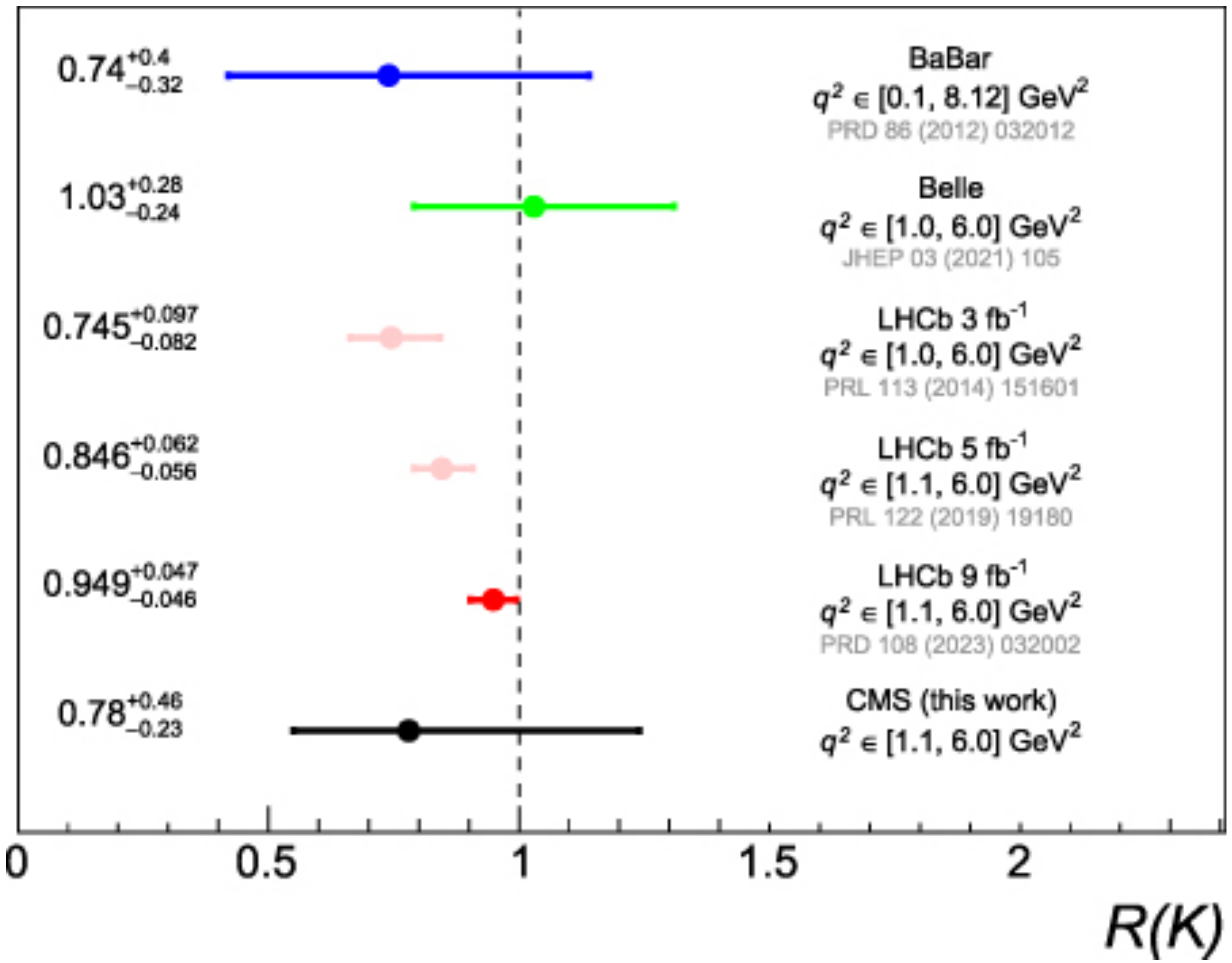
Channel	q^2 range [GeV^2]	PF-PF yield	PF-LP yield
$B^+ \to K^+e^+e^-$	1.1–6.0	17.9 ± 7.2	3.0 ± 5.9
$B^+ \to J/\psi(e^+e^-)K^+$	8.41–10.24	4857 ± 84	2098 ± 58
$B^+ \to \psi(2S)(e^+e^-)K^+$	12.60–14.44	320 ± 20	94 ± 11

Systematic Uncertainties

Source	Impact on the $R(\mathrm{K})$ ratio (%)
Background description, low-q^2 bin	1.8
Trigger turn-on	1.3
Reweighting in p_{T} and rapidity	0.9
Background description, J/ψ CR	0.6
J/ψ meson radiative tail description	0.5
Pileup	0.4
Signal shape description	0.3
Trigger efficiency	0.2
J/ψ resonance shape description	0.1
Nonresonant contribution to the J/ψ CR	0.1
Total systematic uncertainty	2.6
Statistical uncertainty in MC samples	1.7
Statistical uncertainty in data	7.5
Total uncertainty	8.1

	Impact on the $R(\mathrm{K})$ ratio (%)	
Source	PF-PF	PF-LP
Signal and background description	5	5
J/ψ event leakage to the low-q^2 bin	4	9
BDT efficiency stability	2	5
BDT cross validation	2	3
Trigger efficiency	1	4
BDT data/simulation difference	1	2
J/ψ meson radiative tail description	1	1
Total systematic uncertainty	7	13
Statistical and total uncertainty	40	200

Measurements Comparison

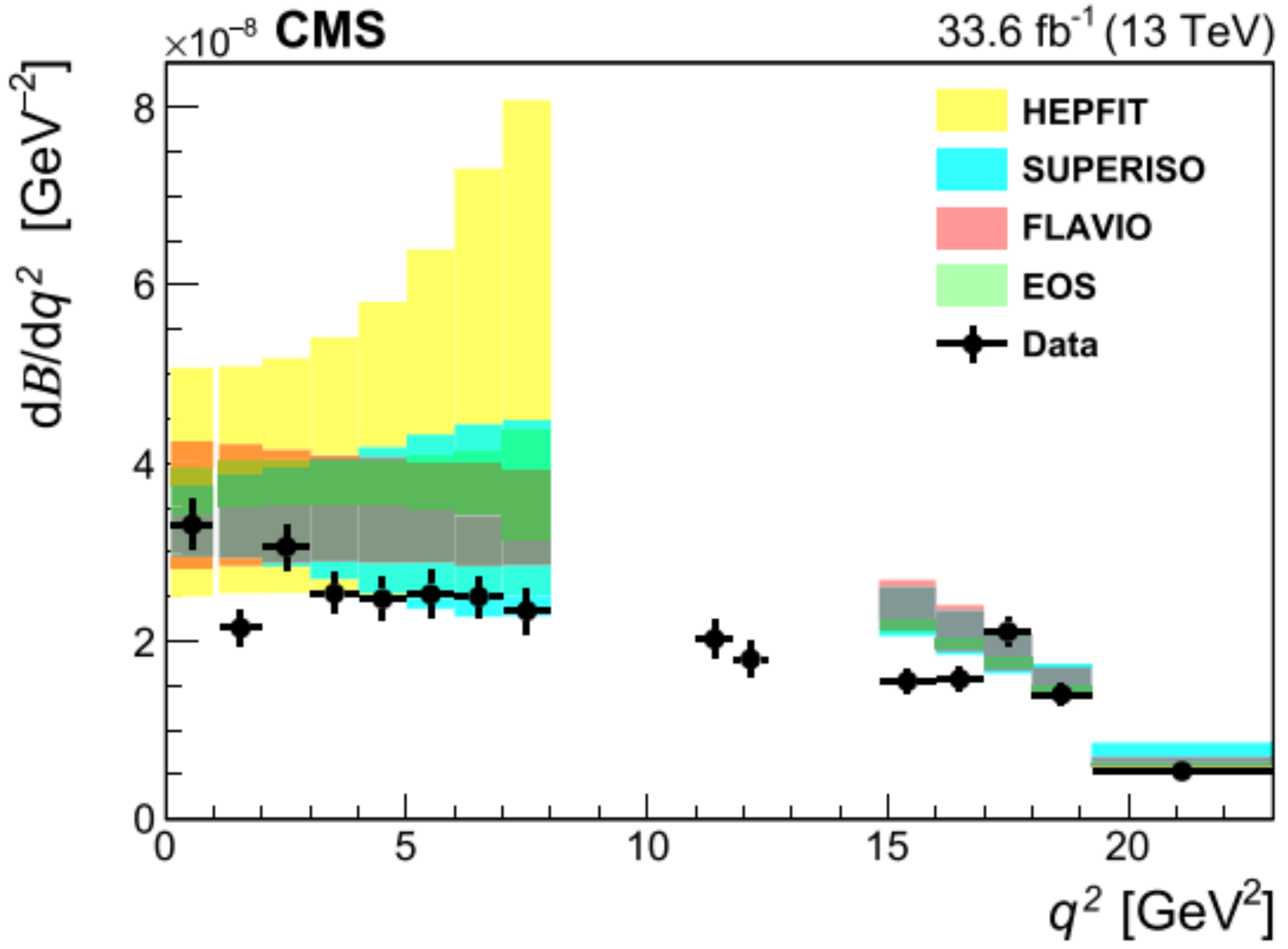


Measurement of BR

- Measurement of the differential branching fraction of the $B^+ \rightarrow K^+\mu^+\mu^-$ decay in the full q^2 range, excluding the J/ψ and ψ(2S) resonances
  - From the simultaneous fit in all the q^2 bins
  - To reduce uncertainties, it is normalised with the J/ψ channel

$$\mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\mu^+\mu^-)\,[q^2_{\min}, q^2_{\max}] = \frac{N_{\mathrm{B}^+\to\mathrm{K}^+\mu^+\mu^-}\,[q^2_{\min}, q^2_{\max}]}{N_{\mathrm{B}^+\to\mathrm{J}/\psi(\mu^+\mu^-)\mathrm{K}^+}\,[8.41, 10.24]\ \mathrm{GeV}^2} \times \frac{(\mathcal{A}\epsilon\epsilon_{\mathrm{trig}})_{\mathrm{B}^+\to\mathrm{J}/\psi(\mu^+\mu^-)\mathrm{K}^+}\,[8.41, 10.24]\ \mathrm{GeV}^2}{(\mathcal{A}\epsilon\epsilon_{\mathrm{trig}})_{\mathrm{B}^+\to\mathrm{K}^+\mu^+\mu^-}\,[q^2_{\min}, q^2_{\max}]} \times \mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+)\,\mathcal{B}(\mathrm{J}/\psi \to \mu^+\mu^-),$$

q^2 range (GeV^2)	Signal yield	Branching fraction (10^{-8})
0.1–0.98	260 ± 20	2.91 ± 0.24
1.1–2.0	197 ± 19	1.93 ± 0.20
2.0–3.0	306 ± 23	3.06 ± 0.25
3.0–4.0	260 ± 21	2.54 ± 0.23
4.0–5.0	251 ± 23	2.47 ± 0.24
5.0–6.0	264 ± 27	2.53 ± 0.27
6.0–7.0	267 ± 21	2.50 ± 0.23
7.0–8.0	256 ± 23	2.34 ± 0.25
11.0–11.8	207 ± 19	1.62 ± 0.18
11.8–12.5	172 ± 16	1.26 ± 0.14
14.82–16.0	272 ± 20	1.83 ± 0.17
16.0–17.0	246 ± 17	1.57 ± 0.15
17.0–18.0	317 ± 19	2.11 ± 0.16
18.0–19.24	242 ± 19	1.74 ± 0.15
19.24–22.9	158 ± 19	2.02 ± 0.30



Integrated BR in low-q^2

Source	$\mathcal{B}(\mathrm{B}^+ \to \mathrm{K}^+\mu^+\mu^-)[1.1, 6.0]\,\mathrm{GeV}^2$ (10^{-8})
Measurement	12.42 ± 0.68
EOS	18.9 ± 1.3
FLAVIO	17.1 ± 2.7
SUPERISO	16.5 ± 3.4
HEPFIT	19.8 ± 7.3

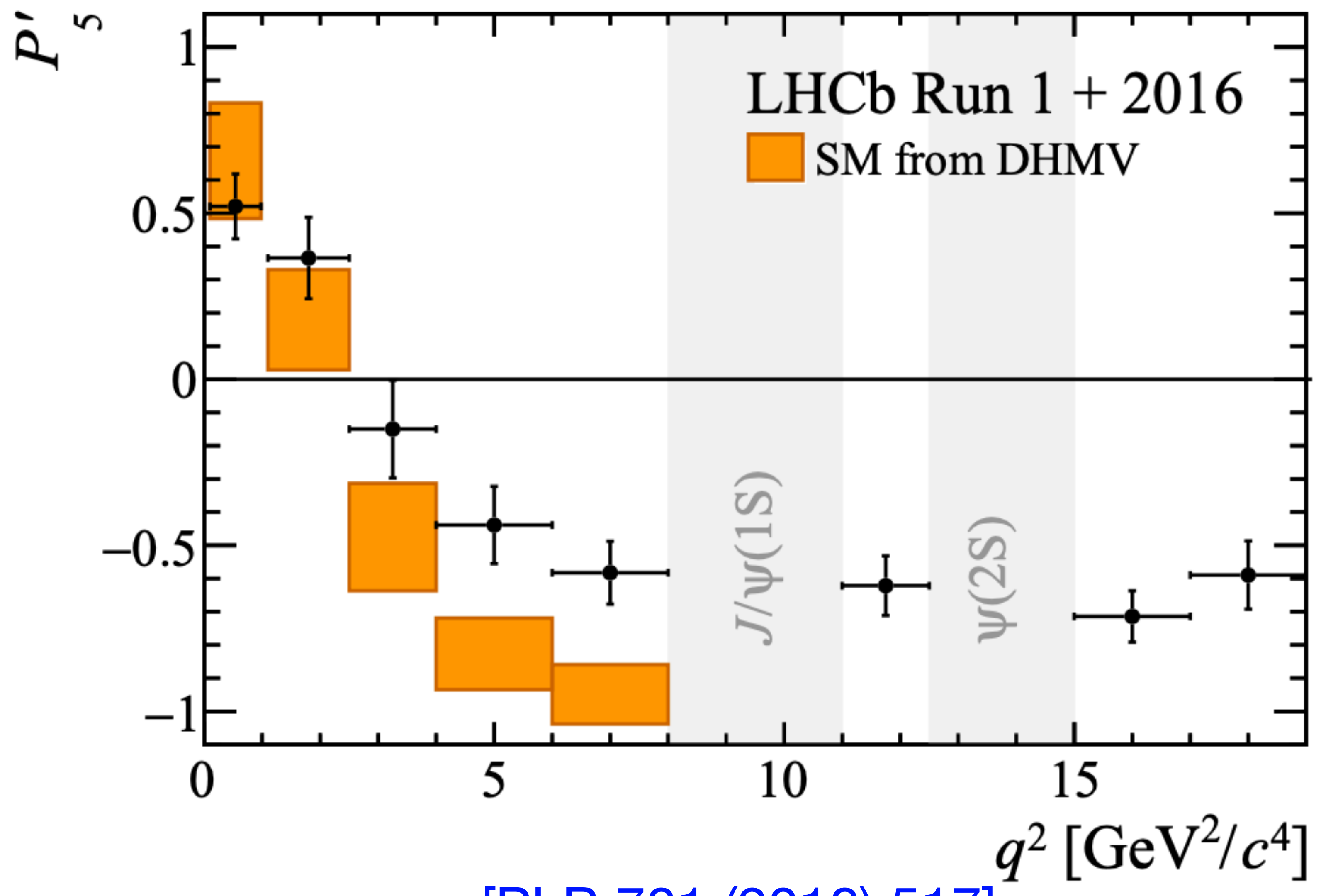
$B^0 \to K^*(892)^0\mu^+\mu^-$ Angular Analysis

Angular Analysis Previous Results

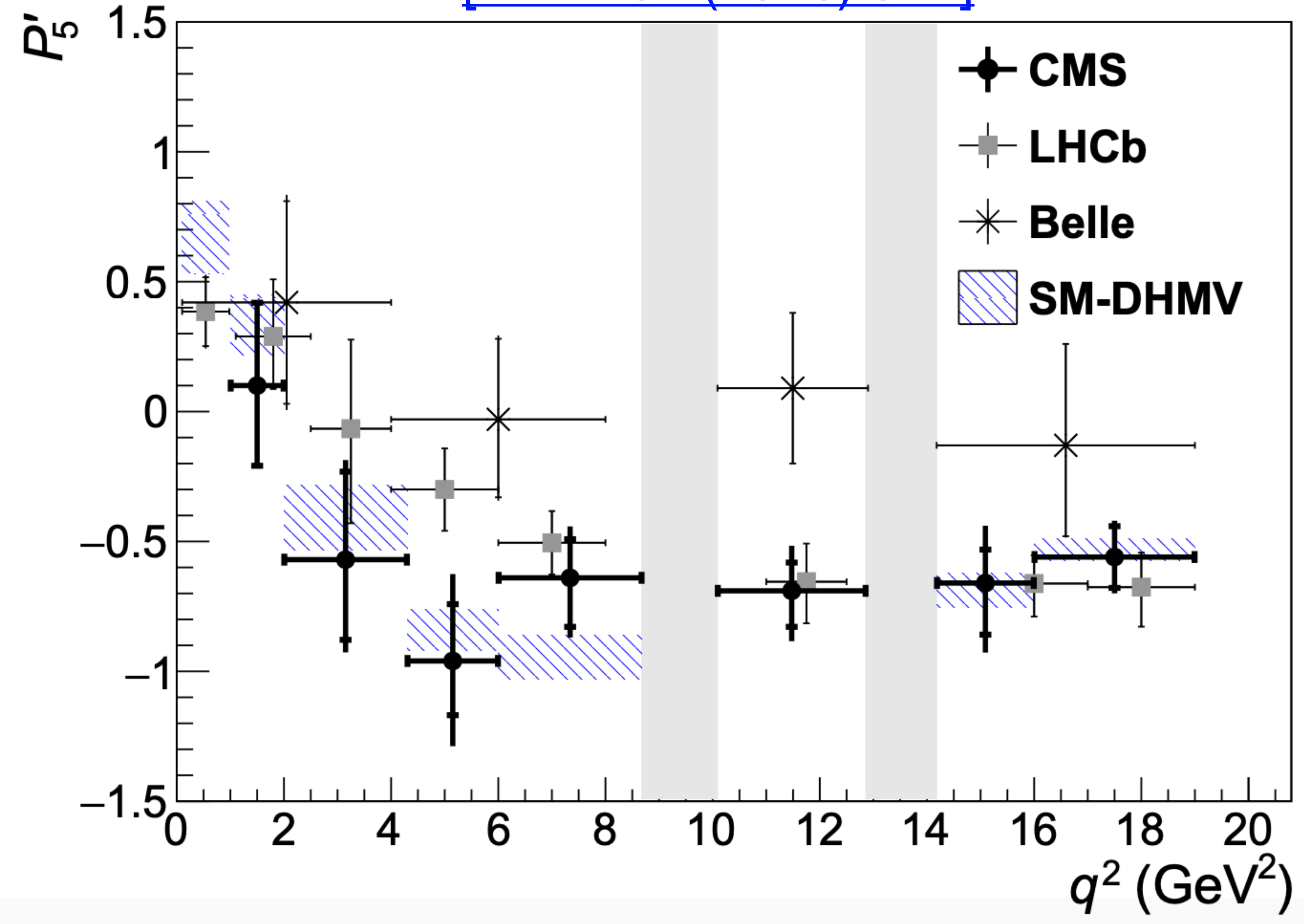
- **CMS** Run-1(20 fb^{-1}) ~1400 signal events [PLB 753 (2016) 424] [PLB 781 (2018) 517]
  - Measure of partial angular observables, including P'_5, consistent with SM
- **Atlas** Run-1 (20.3 fb^{-1}) JHEP 10 (2018) 047
  - Foldings used to measure various parameters
- **LHCb**, Run-1 + 2016 (4.7 fb^{-1}) PRL 125 (2020) 1
  - Full angular analysis, discrepancy found in both Run1 and 2016 data

This analysis: CMS Full Run-2 (140 fb^{-1})

PRL 125 (2020) 1



[PLB 781 (2018) 517]



Rejection of Specific Backgrounds

- $B^+ \to K^+\mu\mu$ (plus combinatorial track)
  - additional veto on mass of two h+μμ systems
- $B_s \to \phi(\to KK)\mu\mu$
  - veto at preselection level on KK mass hypothesis
  - residual contribution negligible wrt signal (<1%)
- $B^+ \to K^+\psi(2S)$, with ψ(2S)→J/ψππ (partially reconstructed, a π track is lost)
  - only affects J/ψ control region
  - combination of cuts on intermediate masses
- $B_s \to KK\mu\mu$ contribution (4%) treated as combinatorial bkg
- Negligible contribution from $B_s \to K^*\mu\mu$ (< 1%), no evidence of Λb → pKμ+μ−

Systematic Uncertainties

Table 1
The uncertainties considered in the analysis on the various angular observables. For each source of uncertainty, the range covers the absolute variation observed across the q^2 bins.

Source	F_L ($\times10^{-3}$)	P_1 ($\times10^{-3}$)	P_2 ($\times10^{-3}$)	P_3 ($\times10^{-3}$)
Efficiency modeling	1–9	7–44	3–11	0–46
Fit bias	1–2	0–6	2–62	1–12
Misidentification fraction	0–2	1–4	1–3	0–14
Signal mass resolution	1–10	1–12	2–11	1–21
Signal mass shape	0–9	1–22	0–10	3–70
Background mass shape	0–5	1–16	1–13	0–8
Efficiency (statistical)	1–10	5–31	1–64	4–45
Background (statistical)	2–6	4–20	1–21	2–16
Data/simulation differences	8	0–23	0–16	0–13
Partially reco background	1	1	0	1
Resonant background	0–1	0–6	0–5	0–2

Source	P'_4 ($\times10^{-3}$)	P'_5 ($\times10^{-3}$)	P'_6 ($\times10^{-3}$)	P'_8 ($\times10^{-3}$)
Efficiency modeling	3–87	2–13	5–16	6–28
Fit bias	9–54	0–8	0–3	0–24
Misidentification fraction	1–5	1–10	0–4	0–12
Signal mass resolution	4–23	0–12	0–5	0–16
Signal mass shape	2–16	1–15	0–7	0–91
Background mass shape	6–30	1–13	0–7	1–10
Efficiency (statistical)	5–47	4–22	4–13	10–59
Background (statistical)	6–37	4–24	3–9	5–23
Data/simulation differences	0–11	0–13	0–3	0–30
Partially reco background	25	0	0	2
Resonant background	0–30	0–11	0–5	0–12

Results

Table 2
The measured CP-averaged angular observables, in the corresponding q^2 bins. The first uncertainty is statistical and the second is systematic.

	$1.1 < q^2 < 2\,\mathrm{GeV}^2$	$2 < q^2 < 4.3\,\mathrm{GeV}^2$	$4.3 < q^2 < 6\,\mathrm{GeV}^2$
F_L	$0.709\,^{+0.073}_{-0.054} \pm 0.021$	$0.810\,^{+0.036}_{-0.030} \pm 0.016$	$0.714\,^{+0.032}_{-0.030} \pm 0.012$
P_1	$0.09\,^{+0.23}_{-0.20} \pm 0.04$	$-0.29\,^{+0.19}_{-0.21} \pm 0.05$	$-0.30\,^{+0.15}_{-0.17} \pm 0.04$
P_2	$-0.37\,^{+0.17}_{-0.13} \pm 0.10$	$-0.244\,^{+0.094}_{-0.077} \pm 0.039$	$0.121\,^{+0.080}_{-0.076} \pm 0.030$
P_3	$-0.05\,^{+0.21}_{-0.22} \pm 0.04$	$-0.19\,^{+0.20}_{-0.22} \pm 0.09$	$-0.03 \pm 0.14 \pm 0.08$
P_4'	$-0.44\,^{+0.29}_{-0.32} \pm 0.11$	$-0.43\,^{+0.16}_{-0.19} \pm 0.08$	$-0.72\,^{+0.15}_{-0.16} \pm 0.07$
P_5'	$0.36\,^{+0.17}_{-0.13} \pm 0.03$	$-0.14\,^{+0.10}_{-0.09} \pm 0.04$	$-0.44 \pm 0.10 \pm 0.03$
P_6'	$0.000\,^{+0.094}_{-0.097} \pm 0.021$	$0.108\,^{+0.075}_{-0.071} \pm 0.018$	$0.129\,^{+0.074}_{-0.071} \pm 0.011$
P_8'	$0.16 \pm 0.37 \pm 0.11$	$0.73\,^{+0.18}_{-0.19} \pm 0.06$	$-0.01 \pm 0.22 \pm 0.04$

	$6 < q^2 < 8.68\,\mathrm{GeV}^2$	$10.09 < q^2 < 12.86\,\mathrm{GeV}^2$	$14.18 < q^2 < 16\,\mathrm{GeV}^2$
F_L	$0.627 \pm 0.016 \pm 0.011$	$0.474\,^{+0.011}_{-0.013} \pm 0.009$	$0.394 \pm 0.012 \pm 0.009$
P_1	$-0.06 \pm 0.10 \pm 0.05$	$-0.439\,^{+0.051}_{-0.047} \pm 0.030$	$-0.465 \pm 0.037 \pm 0.025$
P_2	$0.188\,^{+0.039}_{-0.040} \pm 0.014$	$0.386\,^{+0.021}_{-0.019} \pm 0.018$	$0.440\,^{+0.008}_{-0.010} \pm 0.008$
P_3	$0.099\,^{+0.092}_{-0.090} \pm 0.014$	$0.013\,^{+0.041}_{-0.043} \pm 0.007$	$-0.034\,^{+0.037}_{-0.038} \pm 0.010$
P_4'	$-0.95 \pm 0.10 \pm 0.06$	$-1.025\,^{+0.064}_{-0.066} \pm 0.059$	$-1.159\,^{+0.042}_{-0.038} \pm 0.041$
P_5'	$-0.495 \pm 0.067 \pm 0.023$	$-0.746\,^{+0.033}_{-0.032} \pm 0.014$	$-0.688\,^{+0.038}_{-0.036} \pm 0.021$
P_6'	$0.010 \pm 0.052 \pm 0.016$	$0.080\,^{+0.037}_{-0.041} \pm 0.011$	$0.121\,^{+0.040}_{-0.039} \pm 0.011$
P_8'	$0.06 \pm 0.14 \pm 0.04$	$0.09\,^{+0.09}_{-0.10} \pm 0.03$	$0.011\,^{+0.089}_{-0.086} \pm 0.022$

Other

$R(\Lambda_c^+)$ Result

- In the $b \to cl\nu$ channel there is another result

$$R(\Lambda_c^+) = \frac{\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}$$

- LHCb result $R(\Lambda_c^+)$ = 0.242±0.075 = 0.242±0.026(stat.)±0.040(syst.)±0.059(BR)

[PhysRevLett.128.191803]

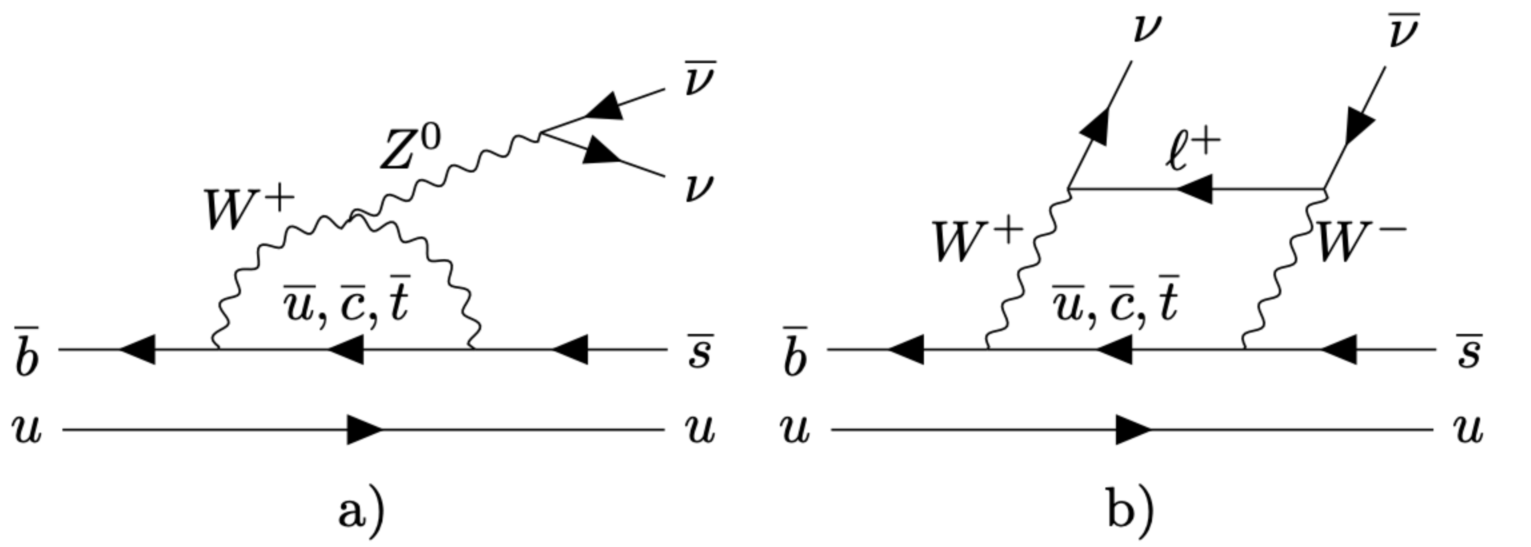
  - Last uncertainty term comes from external BR measurements

- SM prediction $R(\Lambda_c^+)$= 0.324 ± 0.004

[PhysRevD.107.L011502]

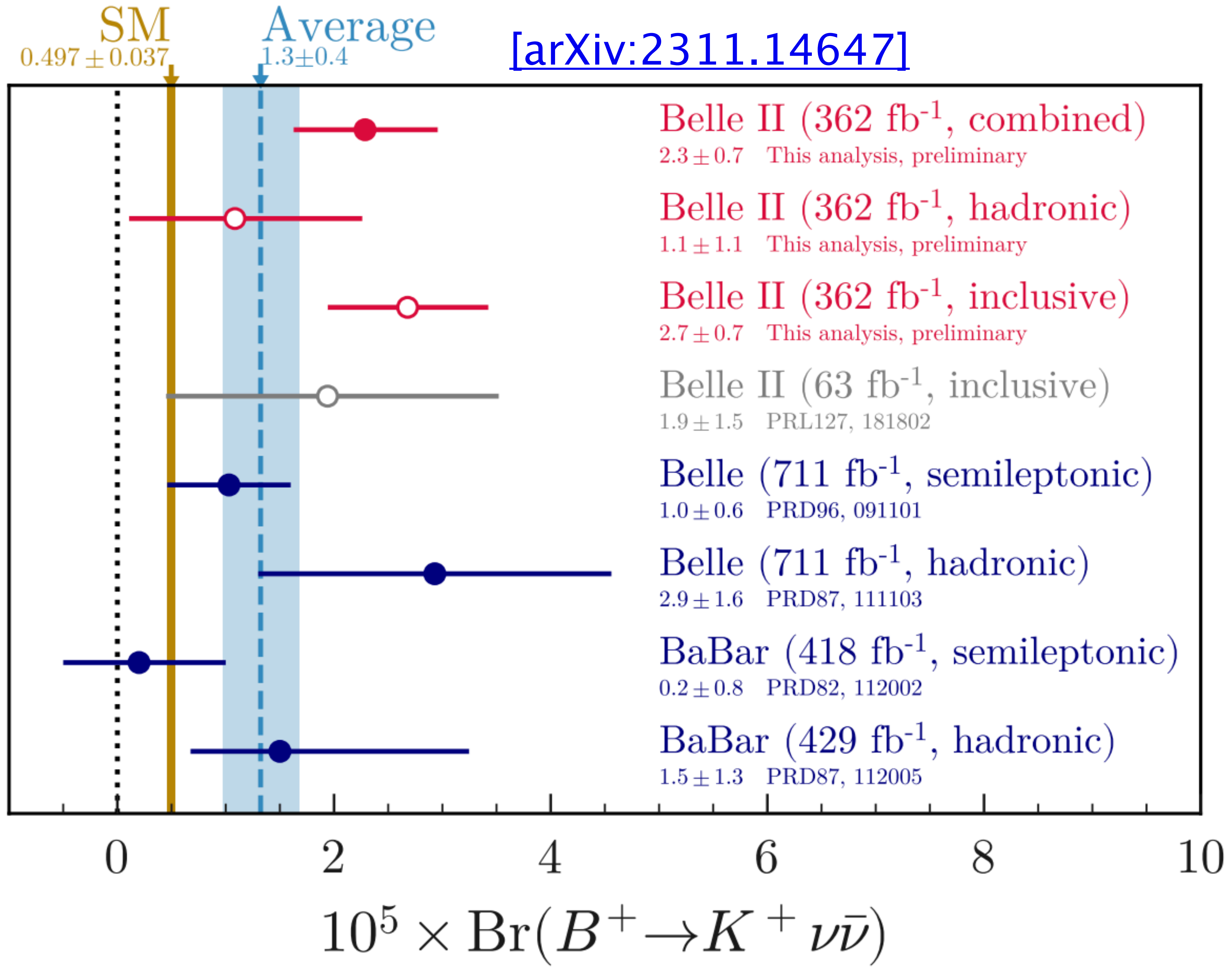
Compatible with SM predictions within 2 σ

Belle II $B^+ \to K^+ \nu\bar{\nu}$



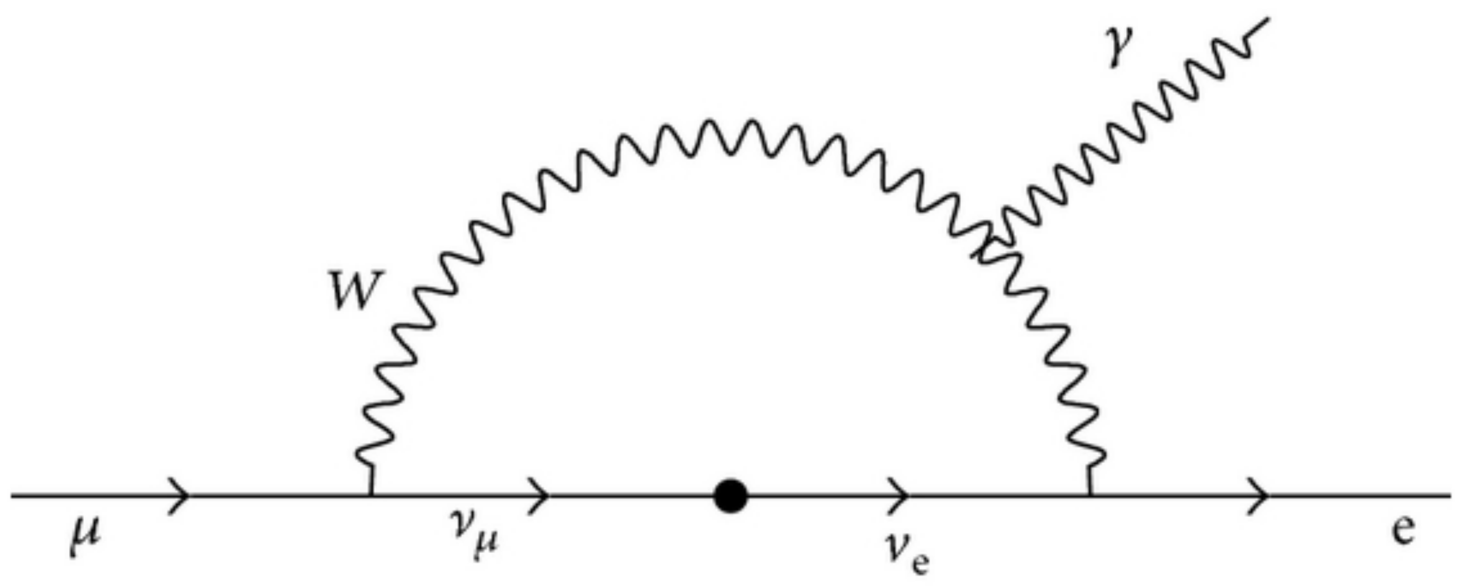
- FCNC transition $b \to s\nu\bar{\nu}$
- SM prediction: $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$
- Belle II measurement:
  $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (2.3 \pm 0.7) \times 10^{-5}$
  - **2.9 σ deviation from SM prediction**
  - It goes on the same direction of the other anomalies

[arXiv:2311.14647]



Lepton Flavour Violation

Other than LFU, there is another accidental symmetry of the SM, the Lepton Flavour



- **Lepton Flavour Violation (LFV)**
  - There is evidence of neutral LFV through neutrino oscillations
  - Charged LFV happens in loop diagrams with ν mixing, but strongly suppressed (rate $\sim 10^{-55}$) [NuclPhysB(2007)02.014]
    - SM extensions predict larger BR up to $10^{-10} - 10^{-8}$ [EPJC57(2008)13-182]