ICHEP CONFERENCE: JULY 8, 2022

NEW TEST OF LEPTON FLAVOR UNIVERSALITY IN INCLUSIVE SEMILEPTONIC B DECAYS

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On behalf of the Belle II collaboration

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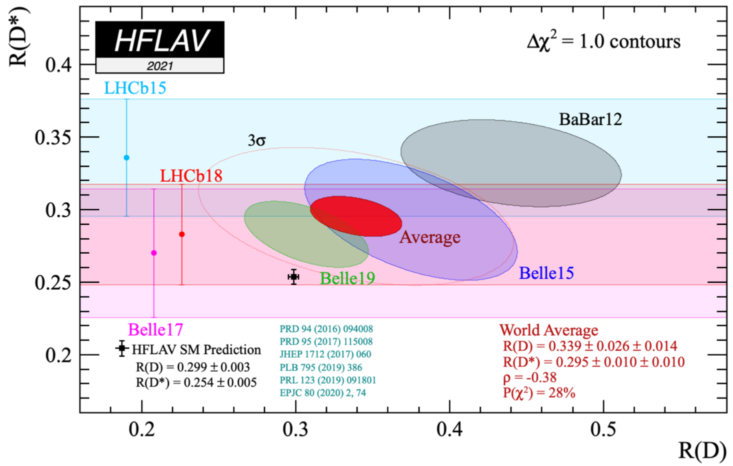
MOTIVATION

- **Several measurements challenge lepton flavor universality** showing tension with the SM
- $R\left(D^{(*)}\right) = \frac{\mathcal{B}\,(B \to D^{(*)}\tau\nu)}{\mathcal{B}\,(B \to D^{(*)}\ell\nu)}, \ell = e, \mu$



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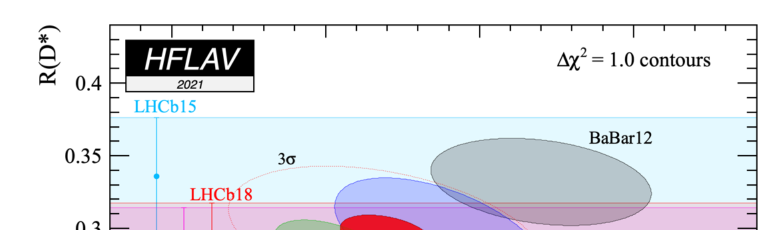
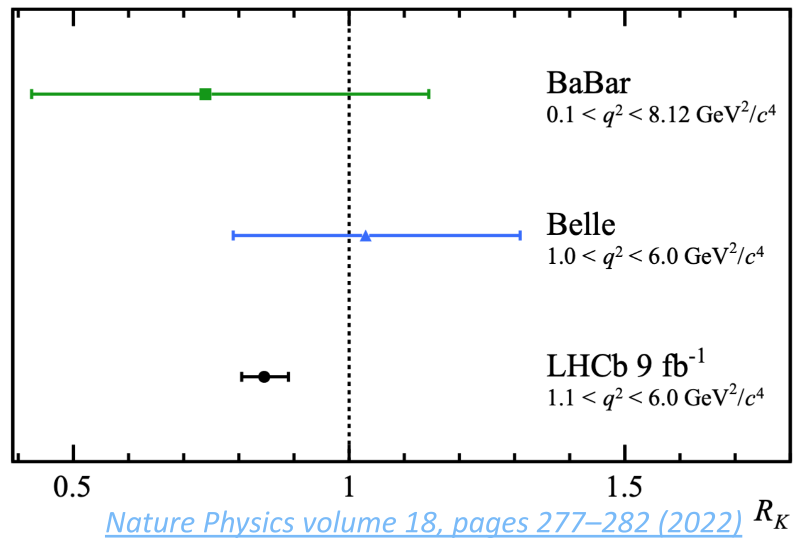
- $\mathrm{R_K} = \frac{\mathscr{B}\,(B\to K\mu^+\mu^-)}{\mathscr{B}\,(B\to K e^+ e^-)}$





Nature Physics volume 18, pages 277–282 (2022)

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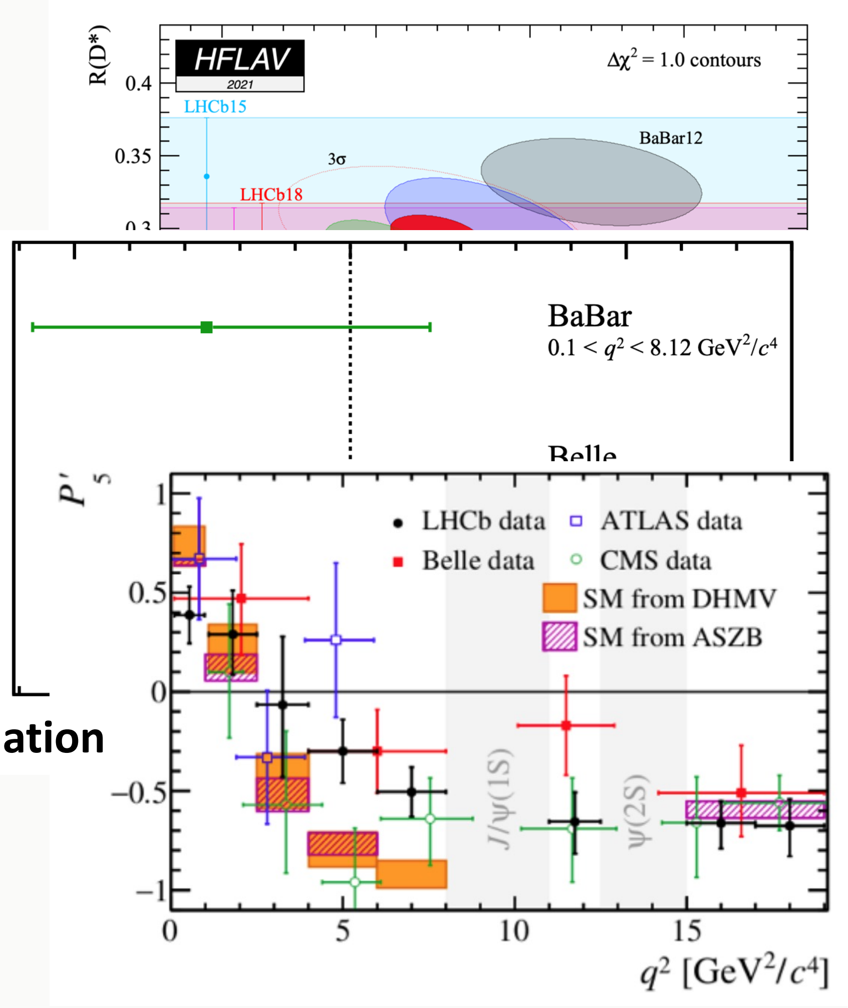
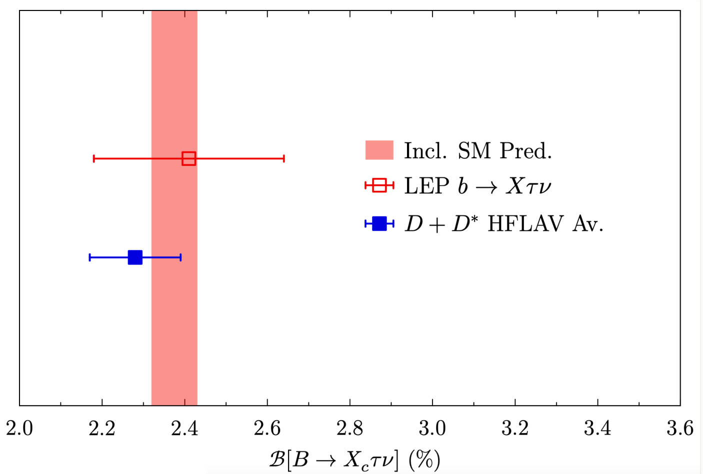
- $R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)} \tau \nu)}{\mathcal{B}(B \to D^{(*)} \ell \nu)}, \ell = e, \mu$
- $R_K = \frac{\mathcal{B}(B \to K \mu^+ \mu^-)}{\mathcal{B}(B \to K e^+ e^-)}$
- $b \to s\ell\ell$ anomalies in angular observables.
  Global discrepancy strongly unlikely to be a fluctuation

➢ All “anomalies“ observed in **direct** (not secondary) ***B*** **decays**



ANALYSIS GOAL



Complementary tests of LFU via inclusive B decays:

- $R(X_{\tau/\ell}) = \frac{\mathcal{B}(B\to X\tau\nu)}{\mathcal{B}(B\to X\ell\nu)}$
- one of the unique and high profile goals of Belle II
- Last measurements at LEP
- Challenging due to larger background from less constrained X system
- **Critically relying on precise modeling of $B \to X\ell\nu$, $X \to \cdots$ processes**

- $R(X_{c,\tau/\ell})_{SM} = 0.223 \pm 0.004$

  Phys. Rev. D 92, 054018 (2015)

- $R(X_{e/\mu})_{SM} = 1.006 \pm 0.001$

  K. Vos, M. Rahimi, in progress

  Published exclusive predictions:

  Eur. Phys. J. C 81, 984 (2021)

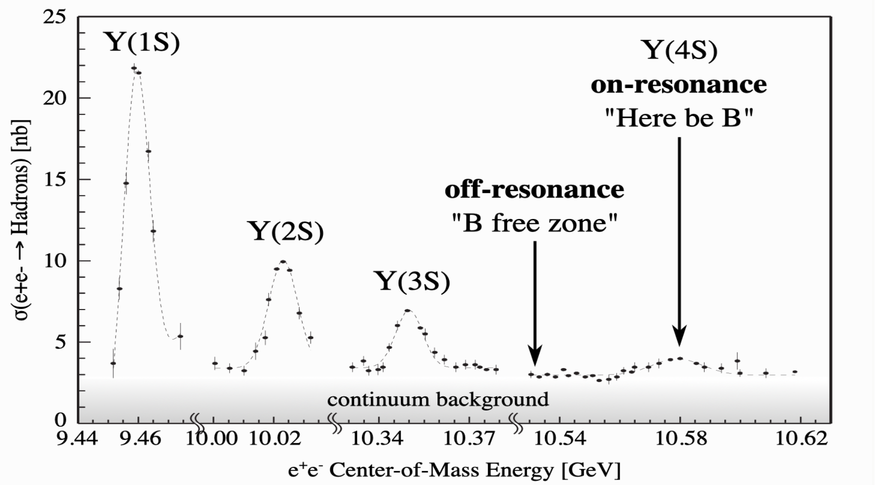
  arXiv:2206.11281

TODAY:

- Probe inclusive $B \to X\ell\nu$ modeling in a data-driven way
- **test LFU for light leptons: $R(X_{e/\mu}) = \frac{\mathcal{B}(B\to Xe\nu)}{\mathcal{B}(B\to X\mu\nu)}$**

SUPERKEKB

- Asymmetric e^+e^- collider at (and near) $E_{CM} = 10.58$ GeV (resonant $\Upsilon(4S)$ production)
- **World record instantaneous luminosity more than doubled to $4.7 \cdot 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$**
- $\int L\, dt = 424\ \mathrm{fb}^{-1}$ on tape (BaBar @ $\Upsilon(4S)$: ≈ $425\ \mathrm{fb}^{-1}$, Belle @ $\Upsilon(4S)$: $711\ \mathrm{fb}^{-1}$)



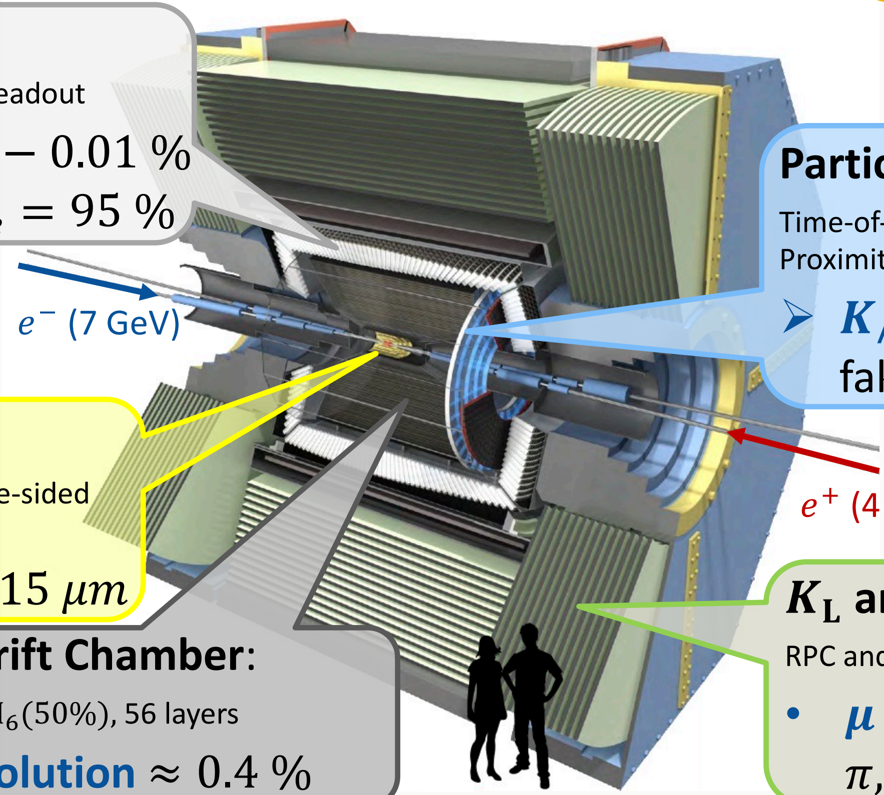
BELLE II DETECTOR

Nearly **4π coverage** to reconstruct inclusive states with many neutrinos

EM Calorimeter:

8k CsI Crystals, 16 X_0PMT/APD readout

- **e identification:** $1 - 0.01\ \%$ π, K fake rate at $\epsilon_e = 95\ \%$



Particle Identification:

Time-of-propagation counter (barrel), Proximity focusing Aerogel RICH (forward)

➢ **K/π identification** ($1.8\ \%\ \pi$ fake rate at $\epsilon_K = 90\ \%$)

Vertex detectors:

2 layers of pixels + 4 layers of double-sided microstrips

➢ **Vertex resolution** $\approx 15\ \mu m$

Central Drift Chamber:

$\mathrm{He}(50\%){:}\,\mathrm{C_2H_6}(50\%)$, 56 layers

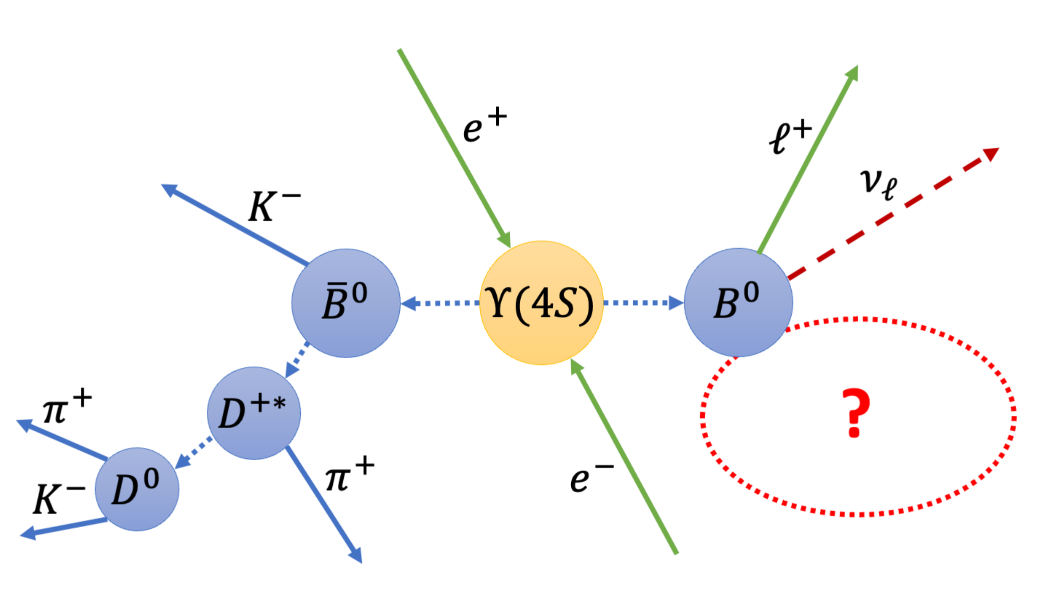
➢ **p_T resolution** $\approx 0.4\ \%$

K_L and μ detector:

RPC and scintillator + SiPM b/w iron plates

- **μ identification:** $2 - 1\ \%$ π, K fake rate at $\epsilon_\mu = 95\ \%$

EVENT SELECTION



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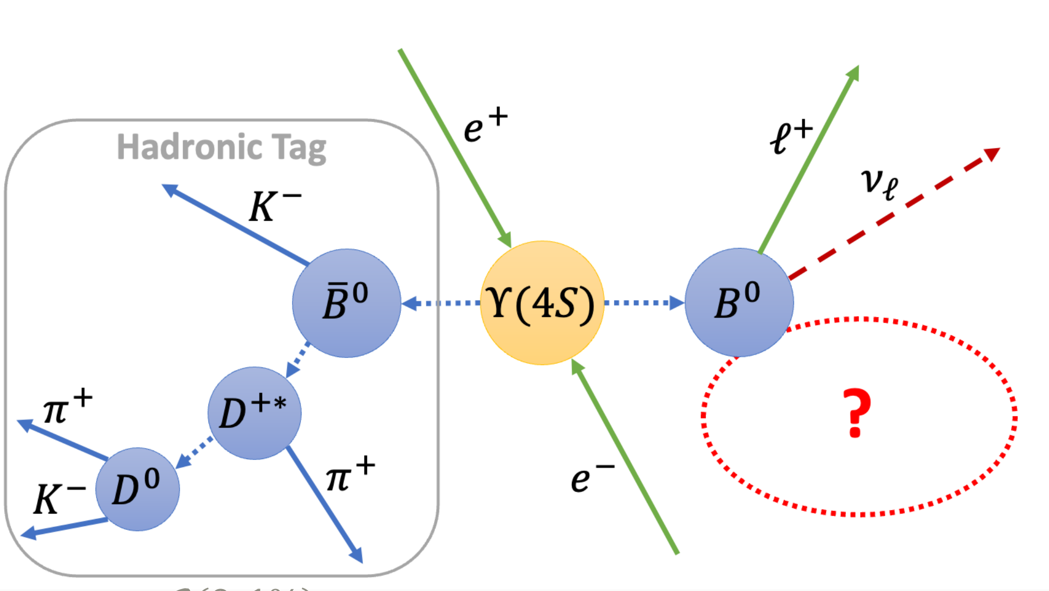
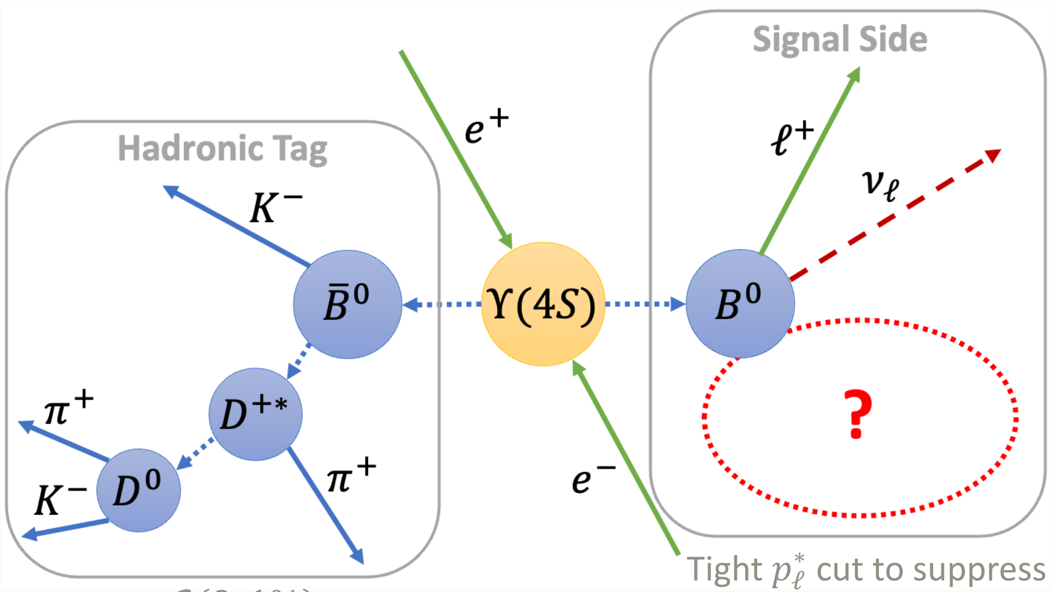


$\epsilon = \mathcal{O}(0.1\%)$

Precise knowledge of B_{tag} kinematics

- **Reconstruct** $\Upsilon(4S) \to B^-_{\text{tag}}$ $\Upsilon(4S) \to \bar{B}^0_{\text{tag}}$

EVENT SELECTION



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Precise knowledge of B_{tag} kinematics

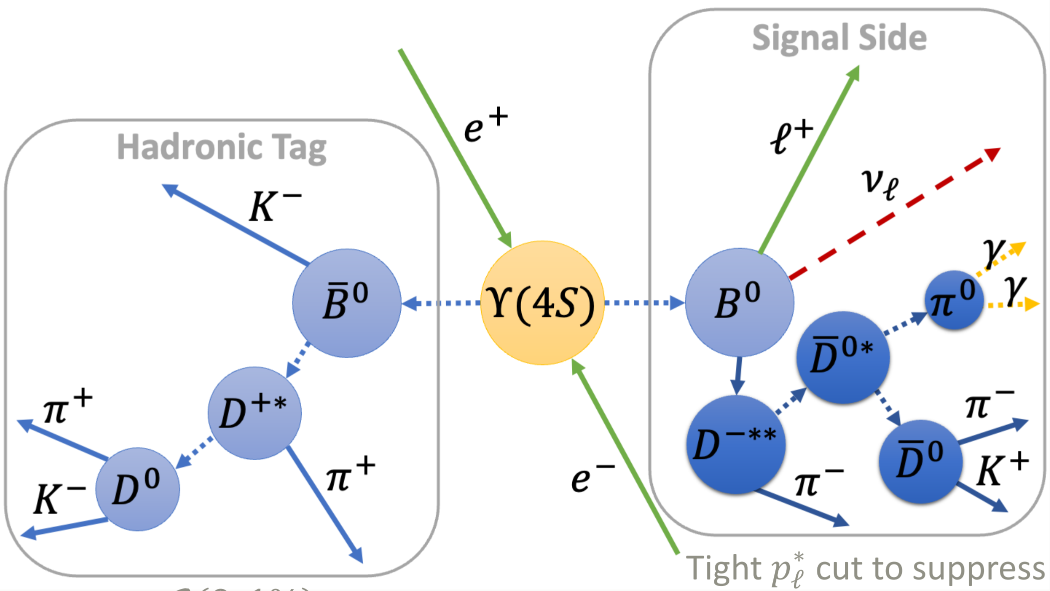
Tight p_ℓ^* cut to suppress

- hadrons faking leptons ("**fakes**")
- secondary leptons from $b \to c \to (\ell, s)$ cascades ("**secondaries**")
- $B \to X\tau\nu$

[53% (e) / 66% (μ) of selected $\mathrm{B} \to X\ell\nu$ is retained]

- **Reconstruct**
  $\Upsilon(4S) \to B_{\text{tag}}^- \ell^+$
  $\Upsilon(4S) \to \bar{B}_{\text{tag}}^0 \ell^+$
- $p_\ell^* > 1.3$ **GeV**

EVENT SELECTION



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- **Only basic quality cuts on tracks and calorimeter signals**
- **Tight constraints on tag quality**

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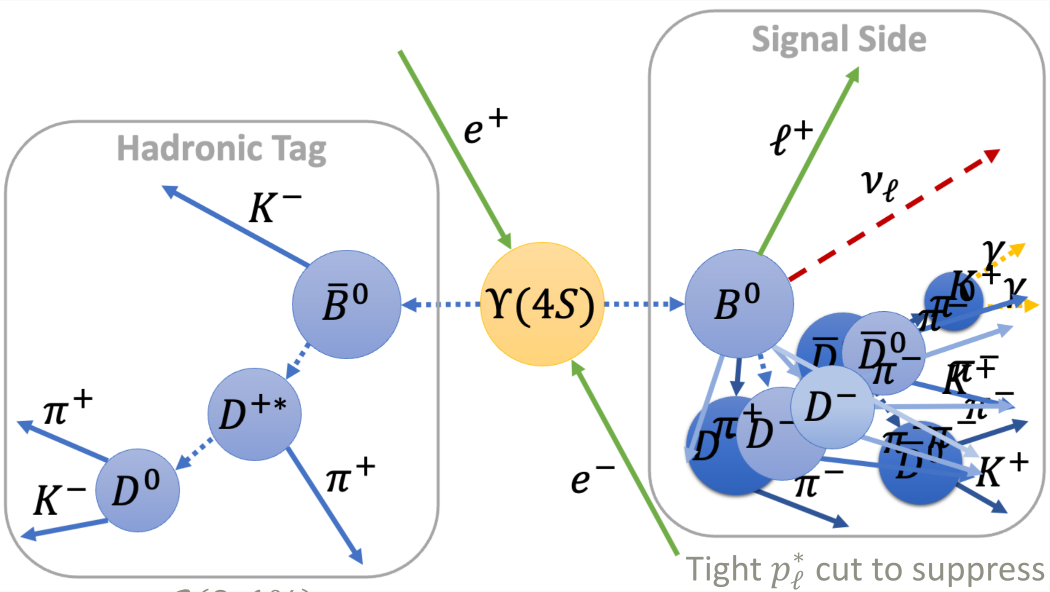

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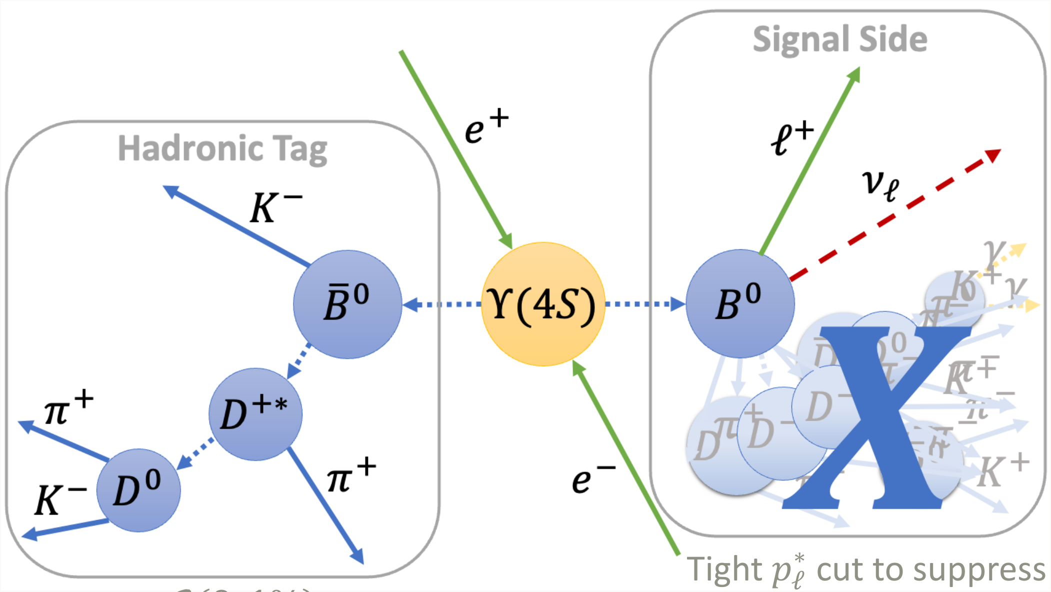

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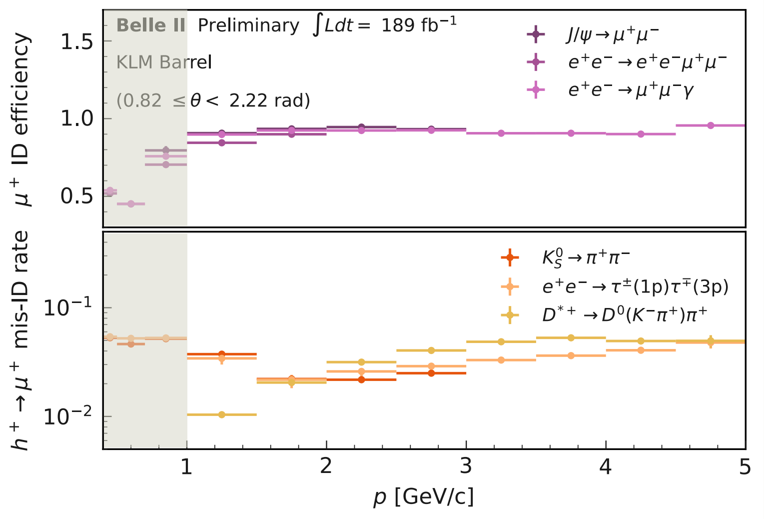
LEPTON IDENTIFICATION

Control of lepton identification performance is crucial as **efficiencies** and **fake rates** directly bias $R(X_{e/\mu})$.

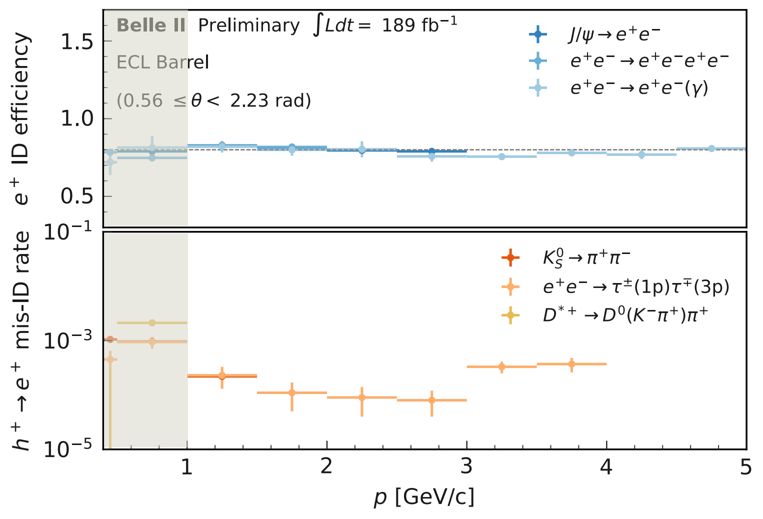
Muon channel:

ID via likelihood ratio using all subdetector information



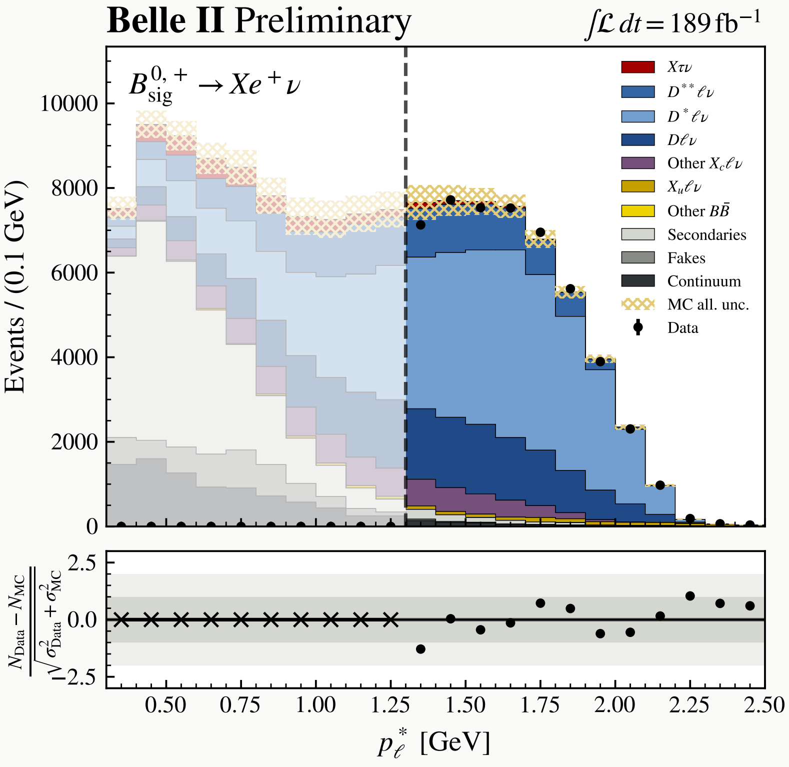
Electron channel:

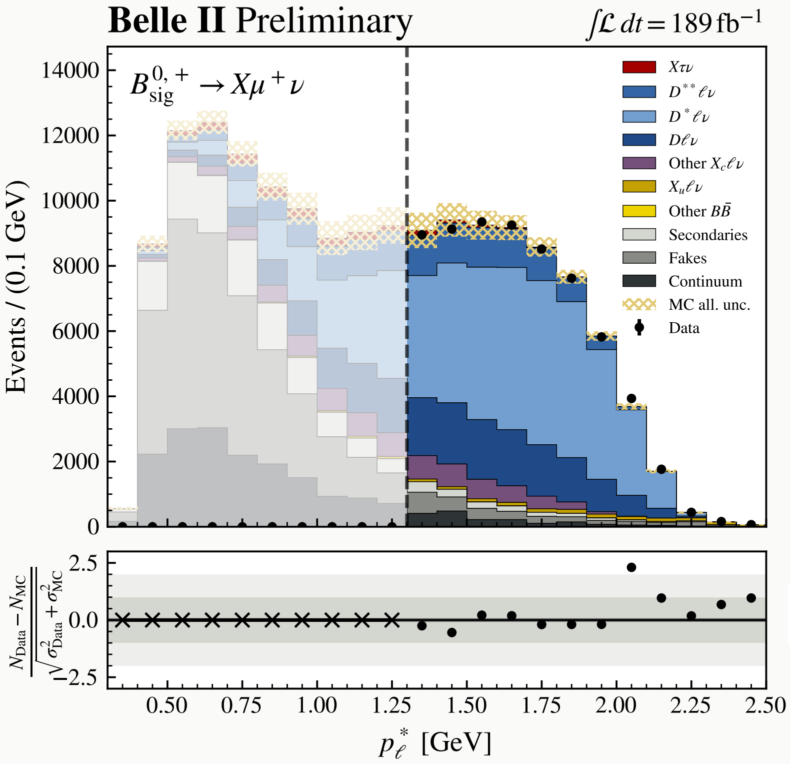
ID via BDT utilizing calorimetric shower shapes

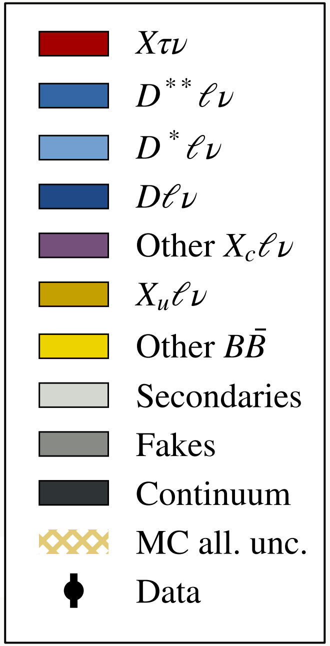


- calibrated in well controlled, **data-driven channels**
- Most corrections are close to 1.0, efficiencies are measured to a precision of $\mathcal{O}(0.1 - 2\%)$

SAMPLE COMPOSITION



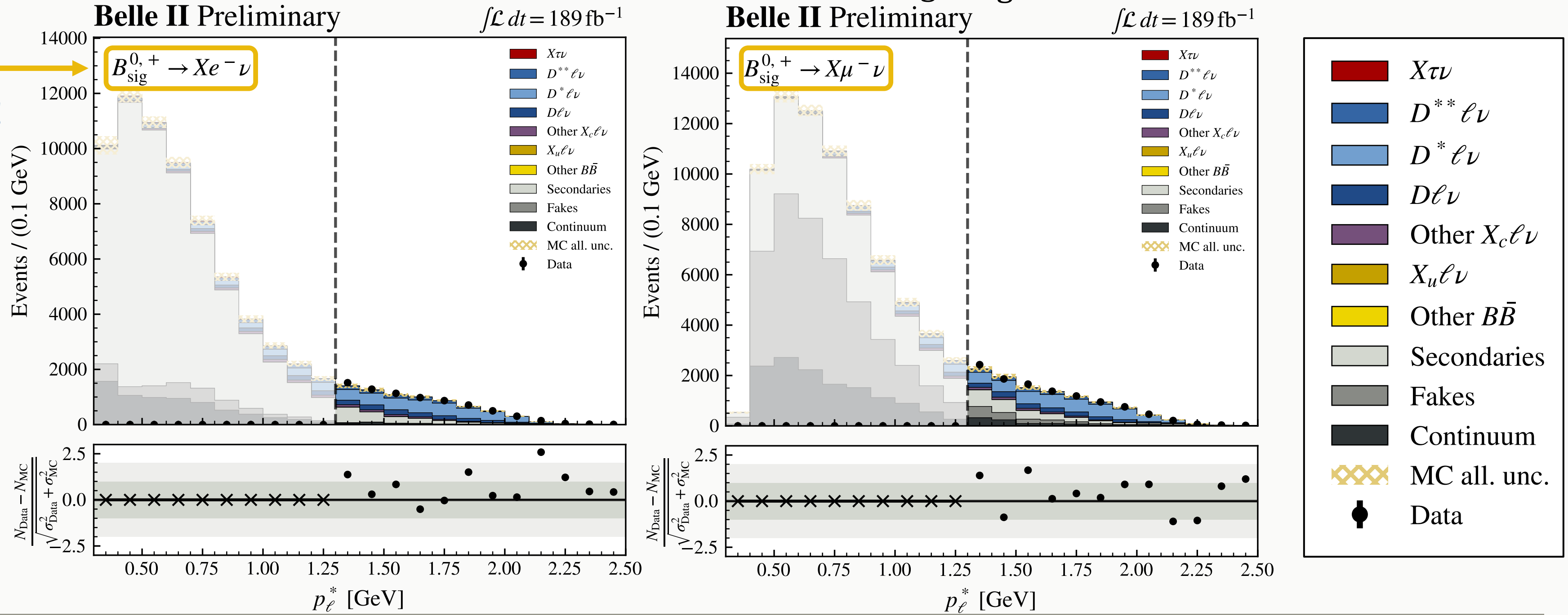




BACKGROUNDS CONSTRAINED BY INCORRECT CHARGE SIDEBAND

- **Fakes + secondaries** are normalized to data with correction factors derived from fits in the **“incorrect lepton charge“** control region: $\Upsilon(4S) \rightarrow B^{0,-}_{\text{tag}} B^{0,+}_{\text{sig}} (\rightarrow X \ell^- \nu) + \text{c.c.}$

Incorrect charge sideband!



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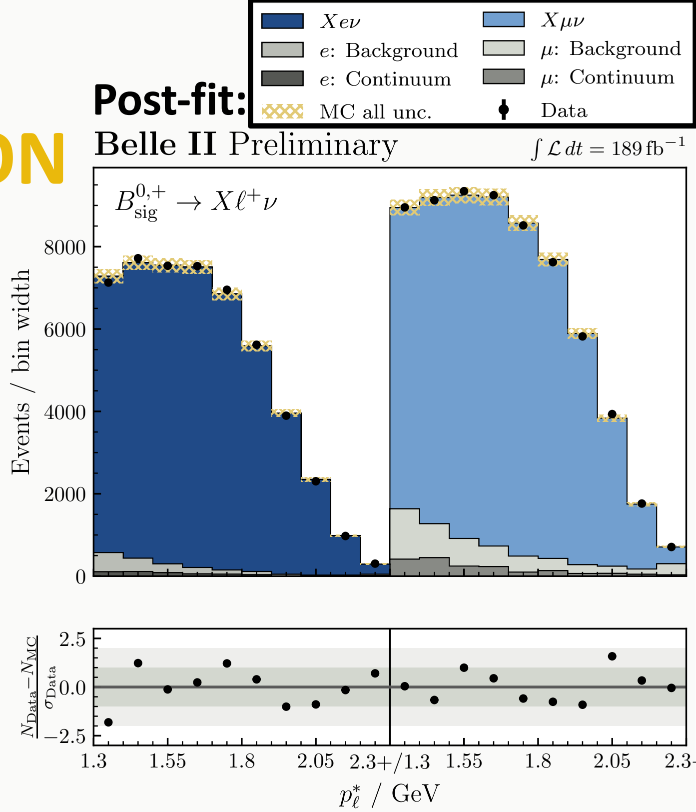
SIGNAL EXTRACTION

- 3 · 2 model templates: **"continuum"**, **"background"**, $\boldsymbol{X\ell\nu}$
- e and μ templates are fitted simultaneously in **10 p_ℓ^* bins** each in a binned **likelihood fit**
- Continuum (offresonant data) and background (incorrect charge sideband) yields constrained, **$X\ell\nu$ yields float freely**
- **Systematic uncertainties** are included as **nuisance parameters (one per bin and template),** including:
  - ➢ MC statistics
  - ➢ Lepton efficiency & fake rate corrections
  - ➢ $X_c\ell\nu$ branching fractions
  - ➢ $X_c\ell\nu$ form factors
  - ➢ Track reconstruction efficiency

Post-fit:



$$R(X_{e/\mu}) = \frac{N_{Xe\nu}\cdot\epsilon_{X\mu\nu}}{N_{X\mu\nu}\cdot\epsilon_{Xe\nu}} \quad \text{with}$$

$$\epsilon_{X\ell\nu} = \frac{N_{sel}^{\ell}\cdot(\epsilon_{B_{tag}}^{data}/\epsilon_{B_{tag}}^{MC})}{2\cdot N_{BB}\cdot BR(B\to X\ell\nu)}$$

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$R(X_{e/\mu})$ EXTRACTION

NEW FOR ICHEP

$$R(X_{e/\mu})^{p_\ell^*>1.3\,\mathrm{GeV}} = \mathbf{1.033 \pm 0.010^{stat} \pm 0.020^{syst}}$$

- Most precise BF based LFU test with semileptonic B decays to date!
- In agreement with Standard Model value of 1.006 ± 0.001 within 1.2σ
  K. Vos, M. Rahimi, in progress
- Compatible within 0.6σ with exclusive Belle measurement:
  $R(D^*_{e/\mu}) = 1.01 \pm 0.01^{\mathrm{stat}} \pm 0.03^{\mathrm{syst}}$
  Phys. Rev. D 100, 052007 (2019)

Also see q^2 LFU shape test:
Phys. Rev. D 104, 112011 (2021)

Source of uncertainty	Lepton ID	$X_c\ell\nu$ BFs	$X_c\ell\nu$ FFs	Statistical	Total
Rel. unc. of $R(X_{e/\mu})$	1.8%	0.1%	0.2%	1.0%	2.2%

(from Asimov fits)

SUMMARY AND OUTLOOK

- First **inclusive measurement of** $\boldsymbol{R(X_{e/\mu})^{p_\ell^*>1.3\mathrm{GeV}}}$ with 2.2% combined precision

➢ **World-leading BF based LFU test with semileptonic $\boldsymbol{B}$ decays**

- Path is paved to extend the lepton momentum range to low momenta

➢ This enables the possibility to **inclusively measure** $\boldsymbol{R(X_{\tau/\ell}) = \frac{\mathcal{B}(B\to X\tau\nu)}{\mathcal{B}(B\to X\ell\nu)}}$ (relative uncertainty expected to be within $10-20$ %)

BACKUP

$X_c \ell \nu$ MODELING

1: Eur. Phys. J. C 81, 226 (2021)
2: Phys. Rev. Lett. 74, 4603 (1995)
3: Phys. Rev. D 93, 032006 (2016)
4: Phys. Rev. D 103, 073005 (2021)
5: Prog. Theor. Exp. Phys. 2020, 083C01 (2020)
6: Phys. Rev. D 95, 014022 (2017)
7: Phys. Rev. D 97, 075011 (2018)
8: Phys. Rev. Lett. 116, 041801 (2016)

Resonant decays:

- $\boldsymbol{B \to D^{(*)} \ell \nu}$: BFs taken from latest HFLAV [1] averages. Charged and neutral channels are combined assuming isospin symmetry. Form factors are modelled using BGL [2 – 4]
- $\boldsymbol{B \to D^{**} \ell \nu}$: BFs extrapolated from existing final state measurements to full D^{**} $(D_1, D_0^*, D_1', D_2^*)$ width [5] assuming isospin symmetry. Heavy flavor quark theory based BLR used for form factors [6-7]

Non-resonant decays:

- $\boldsymbol{B \to D^{(*)} \pi\pi \ell \nu}$: BFs extrapolated to all charge configurations from [8]
- $\boldsymbol{B \to D^{(*)} \eta \ell \nu}$: Not measured yet. Used to fill the gap between exclusive and inclusive measurements. 100% uncertainty on BF
- Non-resonant modes simulated via broad intermediate D_0^*/D_1' mesons. BLR used for form factors

LEPTON IDENTIFICATION: EFFICIENCY AND FAKE RATE CORRECTIONS

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Electron channel

1. **Efficiency:** $J/\Psi \to e^+e^-$, $e^+e^- \to e^+e^-(\gamma)$, $e^+e^- \to (e^+e^-)e^+e^-$
   factors $\in [0.96, 1.01]$,
   uncertainties $\in [0.1, 2]$%, dominated by differences b/w calibration channels

2. ***π* → *e* fake rate:** $K_S^0 \to \pi^+\pi^-$, $e^+e^- \to \tau^\pm(1P)\tau^\mp(3P)$
   factors $\in [2, 8]$,
   uncertainties $\in [20, 70]$%, stat. limited

3. ***K* → *e* fake rate:** $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$
   factors $\in [0, 10]$,
   high uncertainties up to 200% due to very low statistics

Muon channel

1. **Efficiency:** $J/\Psi \to \mu^+\mu^-$, $e^+e^- \to \mu^+\mu^-\gamma$, $e^+e^- \to (e^+e^-)\mu^+\mu^-$
   factors $\in [0.9, 1.02]$,
   precision similar to electron case

2. ***π* → *μ* fake rate:** $K_S^0 \to \pi^+\pi^-$, $e^+e^- \to \tau^\pm(1P)\tau^\mp(3P)$
   factors $\in [0.5, 1.5]$,
   uncertainties $\in [5, 20]$%, stat. limited

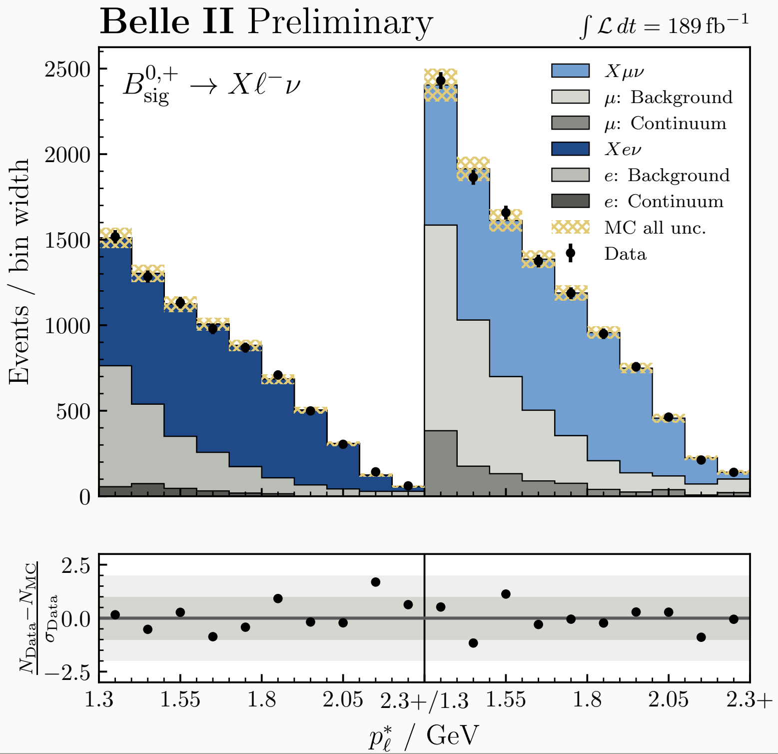
3. ***K* → *μ* fake rate:** $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$
   factors $\in [0.9, 2]$,
   uncertainties $\in [20, 30]$%, stat. limited

BACKGROUND CONSTRAINT IN INCORRECT CHARGE SIDEBAND

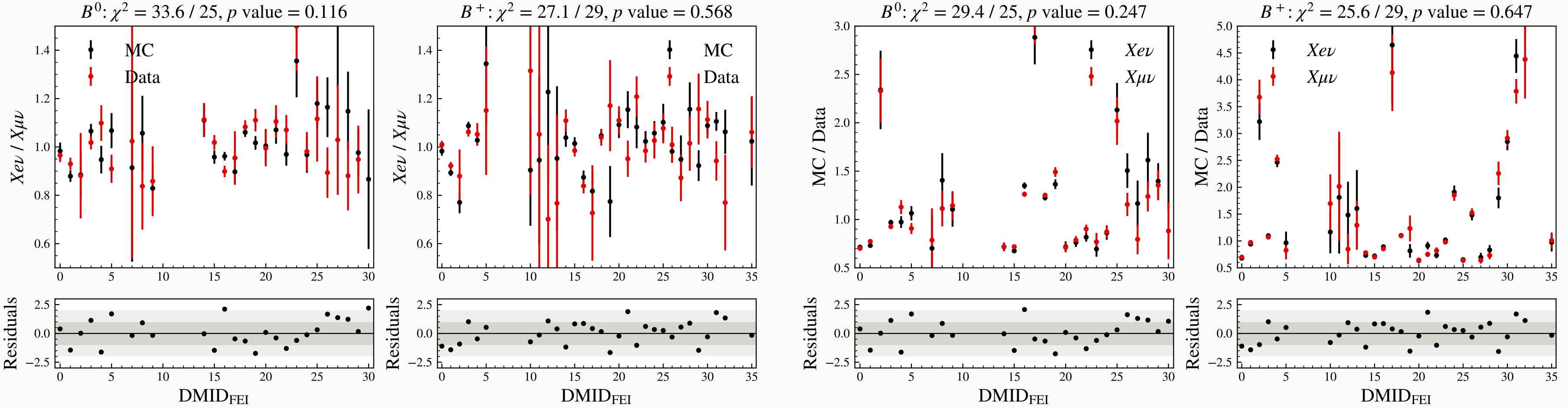
- $X\ell\nu$ yields are unchanged within errors in the control region fit
- ➢ The background scaling factors are reliable and are used to constrain their templates in the signal region fit

	Electron channel			Muon channel		
Template	Pre-fit yield	Post-fit yield	rel. factor	Pre-fit yield	Post-fit yield	rel. factor
Continuum	251	240 ± 51	0.95 ± 0.21	962	987 ± 100	1.03 ± 0.11
Background	1736	2115 ± 238	1.22 ± 0.14	3567	3823 ± 343	1.07 ± 0.10
$X\ell\nu$	5235	5143 ± 242	0.98 ± 0.05	6201	6224 ± 326	1.00 ± 0.06

Post-fit:



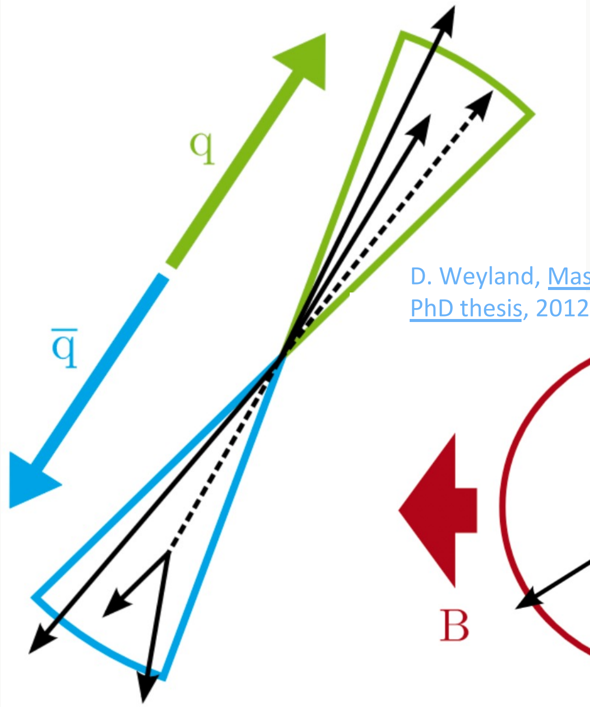
TAG EFFICIENCY MODELLING e VS μ

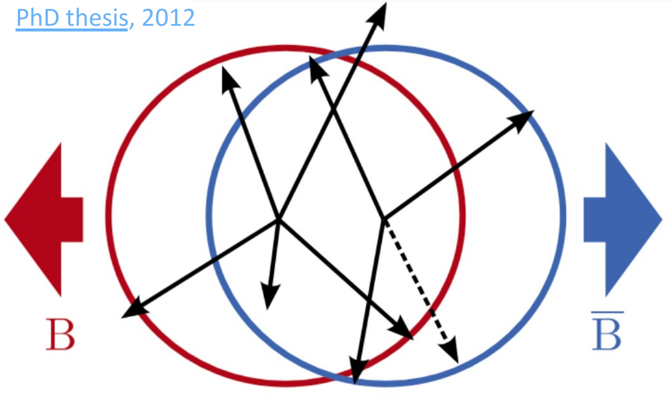


- The $Xe\nu/X\mu\nu$ ratio is consistent in data and MC within statistical uncertainties.
- ➢ Thus, the excess of electrons/muons is correctly modeled in each tag-side decay mode ID ($\mathrm{DMID_{FEI}}$)
- The MC/data ratios of each DMID for the electron and muon channel also agree with each other within statistical uncertainties
- ➢ $\epsilon_{B_{\mathrm{tag}}}^{\mathrm{data}}/\epsilon_{B_{\mathrm{tag}}}^{\mathrm{MC}}(e) = \epsilon_{B_{\mathrm{tag}}}^{\mathrm{data}}/\epsilon_{B_{\mathrm{tag}}}^{\mathrm{MC}}(\mu)$, cancels in $R(X_{e/\mu})$ calculation

CONTINUUM SUPPRESSION

Continuum suppression BDT trained on well-modeled event-shape quantities





D. Weyland, Master thesis, 2017, inspired from M. Röhrken, PhD thesis, 2012