Recent Belle II results on semitauonic decays and tests of lepton-flavor universality

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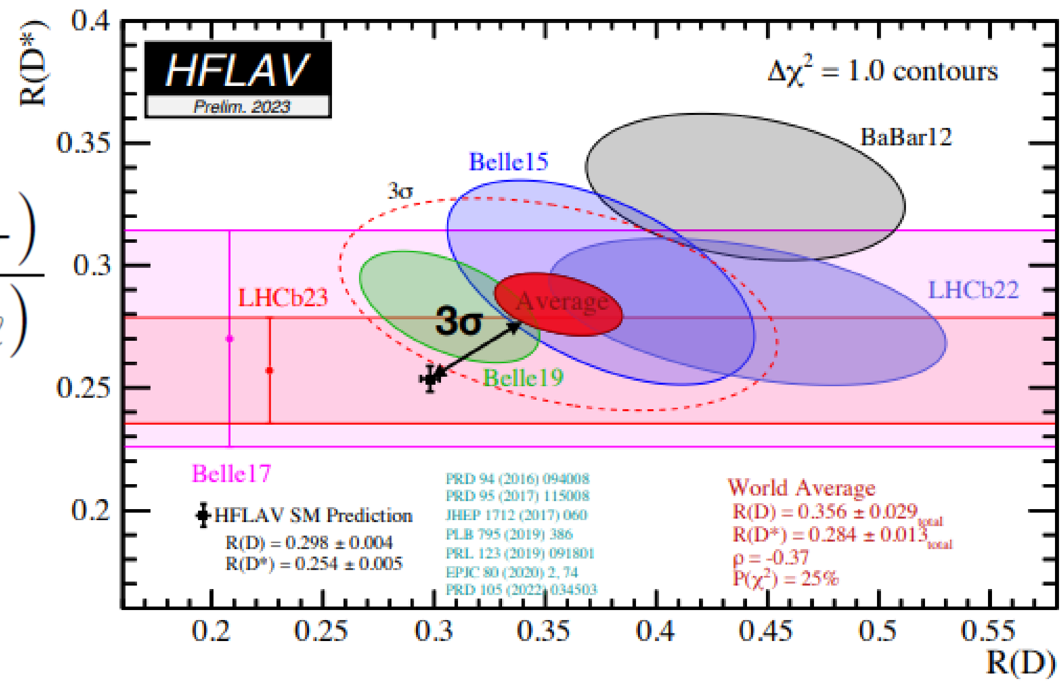
Lepton Flavor Universality (LFU) anomaly in B decays

-SM expects lepton coupling to EW gauge bosons to be flavor-universal, but tension exists

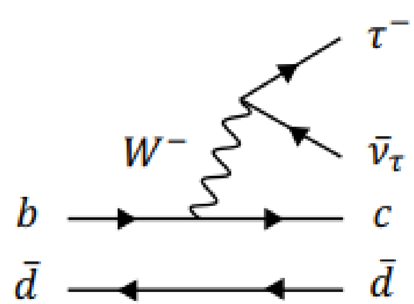
PRD 107,052008 (2023)

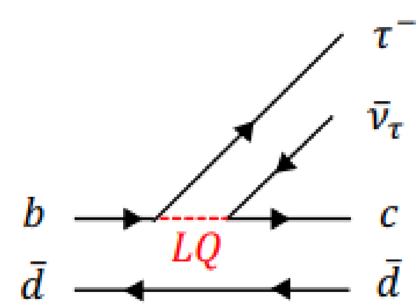
$$R(D^{(*)}) = \frac{\mathcal{B}\left(B \to D^{(*)}\tau\nu_\tau\right)}{\mathcal{B}\left(B \to D^{(*)}\ell\nu_\ell\right)}$$

(ℓ=e or μ)



-Tests of LFU are important to search for new physics



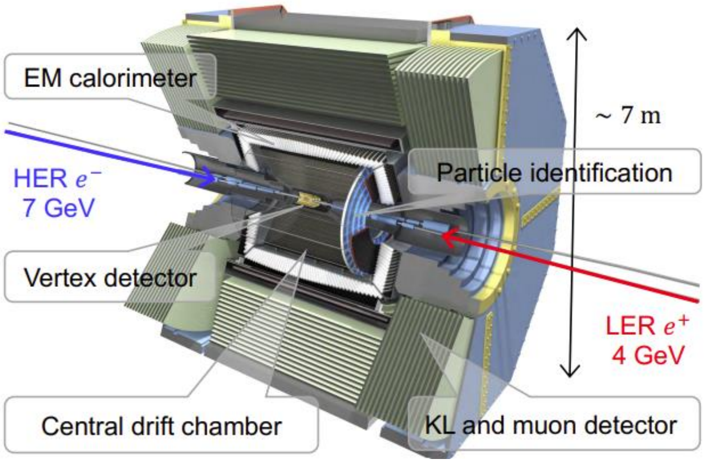


Test of LFU with semitauonic B decay

-Belle II at SuperKEKB: on-threshold $B\bar{B}$ production from $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$, reconstructed with hermetic detector

-Advantage to measure semileptoinc decays:

- -clean background environment
- -known initial beam state
- -achieved luminosity of $4.7 \times 10^{34}\,\mathrm{cm}^2\mathrm{s}^{-1}$
- -total integrated luminosity at $\Upsilon(4S)$ energy: $363\mathrm{fb}^{-1}$



-Four LFU tests by BelleII with $189\mathrm{fb}^{-1}$ (198×10^6 $B\bar{B}$ events):

X:any decays

-τ and ℓ (ℓ=e or μ):

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

$$R(X) = \frac{\mathcal{B}(B \to X \tau \nu_\tau)}{\mathcal{B}(B \to X \ell \nu_\ell)}$$

-μ and e:

Angular asymmetries

$$\Delta A_{\mathrm{FB}} = A^{\mu}_{\mathrm{FB}} - A^{e}_{\mathrm{FB}}$$

$$R(X_{e/\mu}) = \frac{\mathcal{B}(B \to X e \nu_e)}{\mathcal{B}(B \to X \mu \nu_\mu)}$$

R(D*) Measurement

-The first measurement of $R(D^*) = \frac{\mathcal{B}(B \to D^*\tau\nu_\tau)}{\mathcal{B}(B \to D^*\ell\nu_\ell)}$ at BelleII, 189fb^{-1}

-Reconstruct $B \to D^*\tau\nu_\tau$, $B \to D^*\ell\nu_\ell$

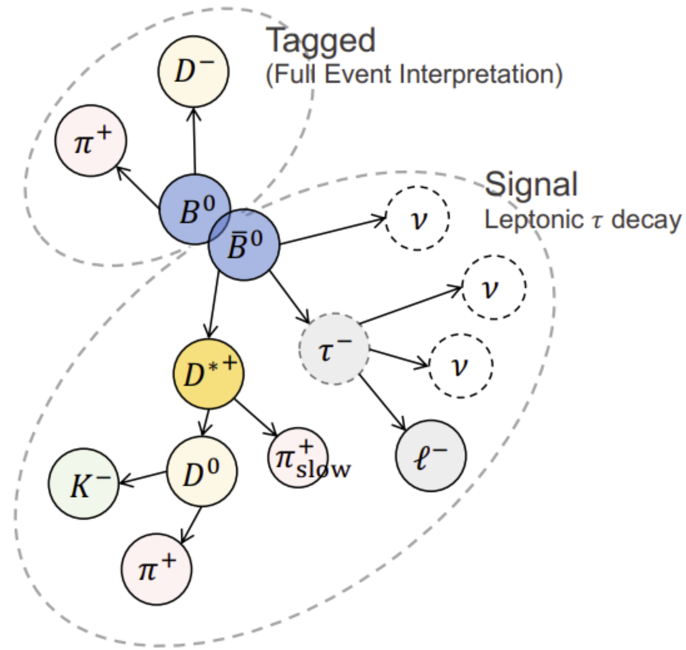
-B_{tag}: Fully reconstructed hadronic decay with machine learning method(hadronic tag)

-B_{sig}: Leptonic τ decays of $\tau \to e\bar{\nu}_e\nu_\tau / \mu\bar{\nu}_\mu\nu_\tau$

Three D* decay channels

$D^{*+} \to D^0\pi^+/D^+\pi^0,\ D^{*0} \to D^0\pi^0$

-Rest of events: No charged tracks, No π^0 candidates



-Challenge: Multiple neutrinos in final state

-Identification of D*τν, D*ℓν, D**ℓν

-Low statistics due to hadronic tag

-Advantage:

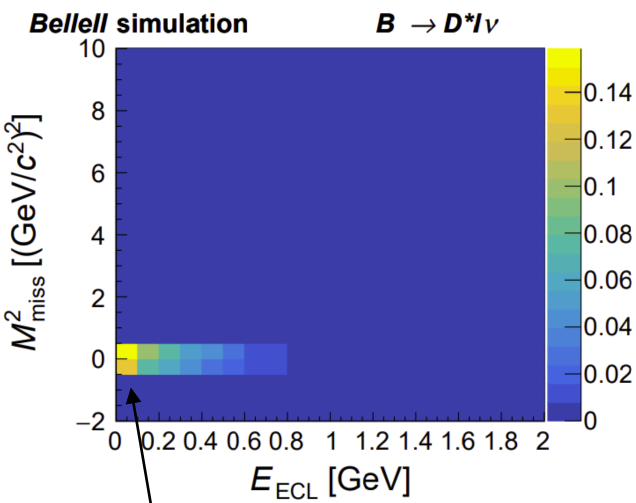
-Cancel many systematics by taking ratio with the same final state particles

R(D*) signal extraction

-Two-dimensional binned likelihood is used to extract $N_{B\to D^*\tau\nu}$, $N_{B\to D^*\ell\nu}$

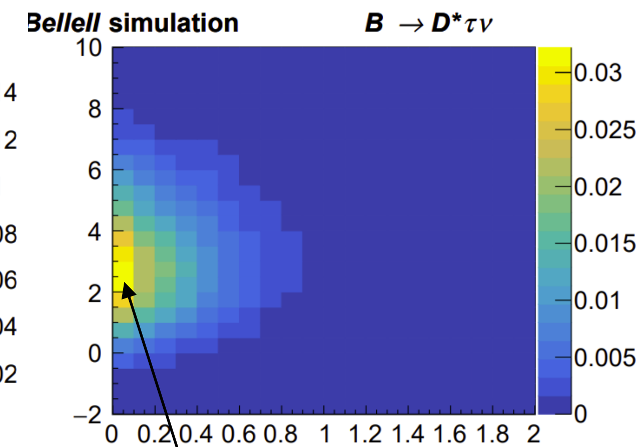
- E_{ECL} : sum of energy in calorimeter not used for $B\bar{B}$ reconstruction
- $M^2_{\mathrm{miss}} \equiv \left(p_{e^+e^-} - p_{B_{\mathrm{tag}}} - p_{D^*} - p_\ell\right)^2$: missing mass of un-detected particles

B→D*ℓν



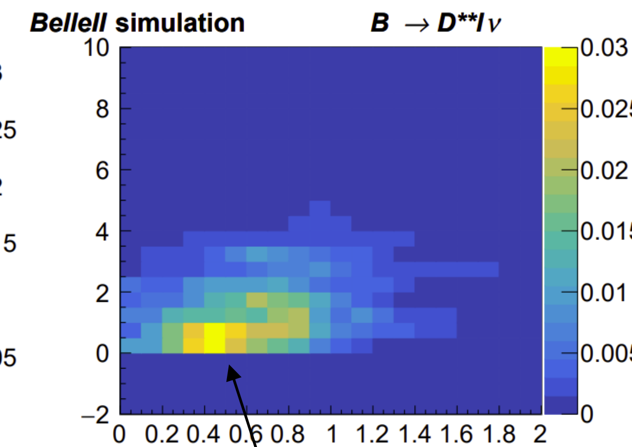
Peaked around E_{ECL}=0, M^2_{miss}=0 with a neutrino

B→D*τν



Peaked around E_{ECL}=0, Higher M^2_{miss} with multiple neutrinos

B→ D**ℓν



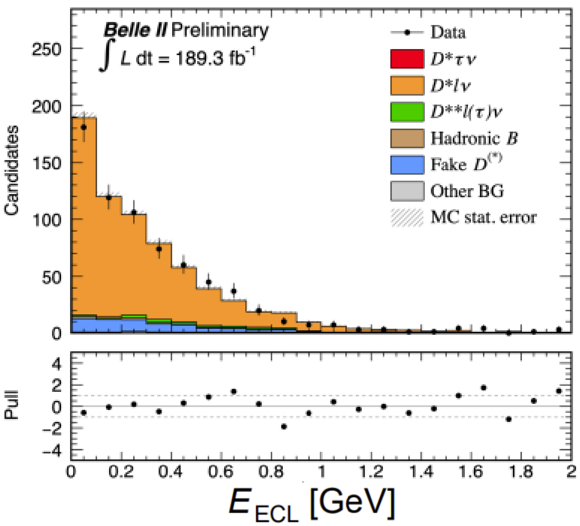
Higher E_{ECL} and M^2_{miss} with daughters of D** decays

Data-driven validation at side-band

-Signal and background PDF are validated at side-band regions:

q^2 side band for $\bar{B} \to D^* \ell^- \bar{\nu}_\ell$

$q^2 \equiv (p_\ell + p_\nu)^2 < 3.5\ \mathrm{GeV}/c$ below m_τ^2 threshold

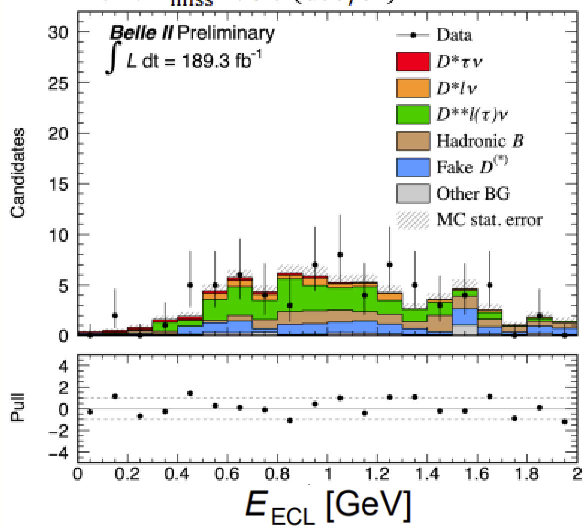


$\bar{B} \to D^{**} \ell^- \bar{\nu}_\ell$-enhanced side band

An additional π^0 is require to $B\bar{B}$.

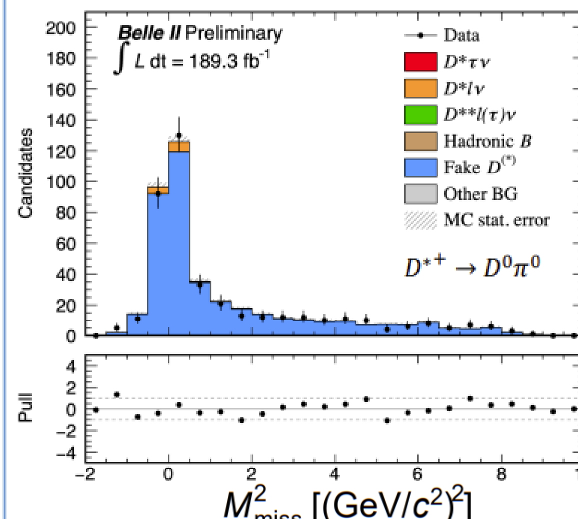
$\bar{B} \to D^{**} \ell^- \bar{\nu}_\ell$ have unknown rates and can mimic $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$.

$1.0 < M_{\mathrm{miss}}^2 < 5.0\ (\mathrm{GeV}/c^2)^2$



$\Delta M_{D^*} (\equiv M_{D^*} - M_D)$ side bands for fake D^*

Constrain the fake D^* yields in the signal regions with calibration factors at the ΔM_{D^*} side bands.



-Data agree with simulation at all side-band regions

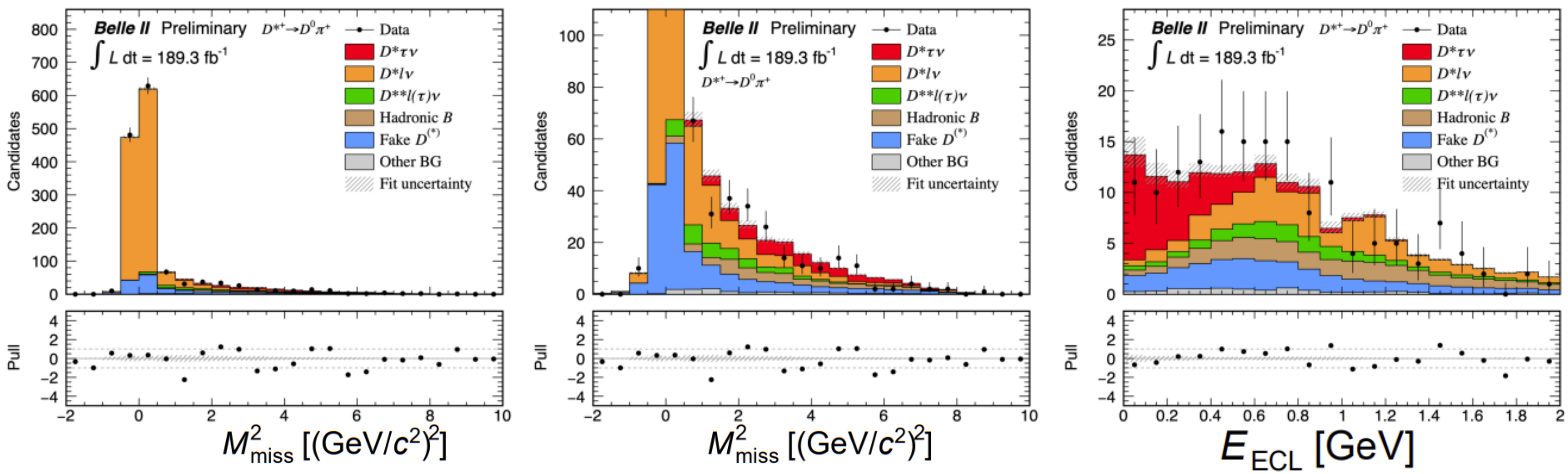
R(D*) Result

-Post fit distributions with good data/MC agreement:

zoomed

D*τν enhanced

$1.5 < M^2_{\rm miss} < 6.0\ ({\rm GeV}/c^2)^2$

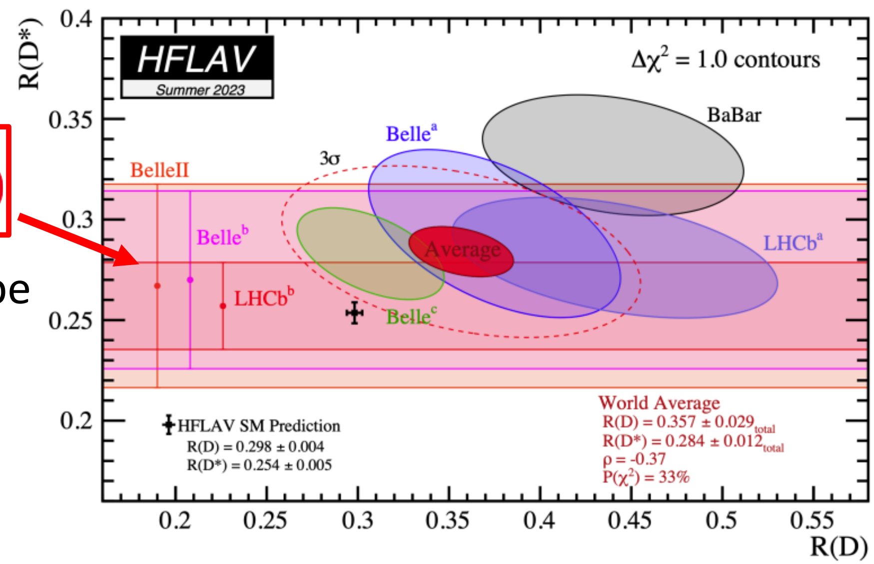


-The first R(D*) results from BelleII:

$$R(D^*) = 0.267\ ^{+0.041}_{-0.039}\,(\text{stat.})\ ^{+0.028}_{-0.033}\,(\text{syst.})$$

Major systematics: MC statistics, E_{ECL} PDF shape

-Consistent with both SM and past measurements



Inclusive measurement of R(X)

New EPSHEP 2023

-The first measurement of $R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$ at B factory, 189fb^{-1}

-inclusive: complementary to exclusive analyses of R(D*)

-one of unique and high-profile goals of BelleII

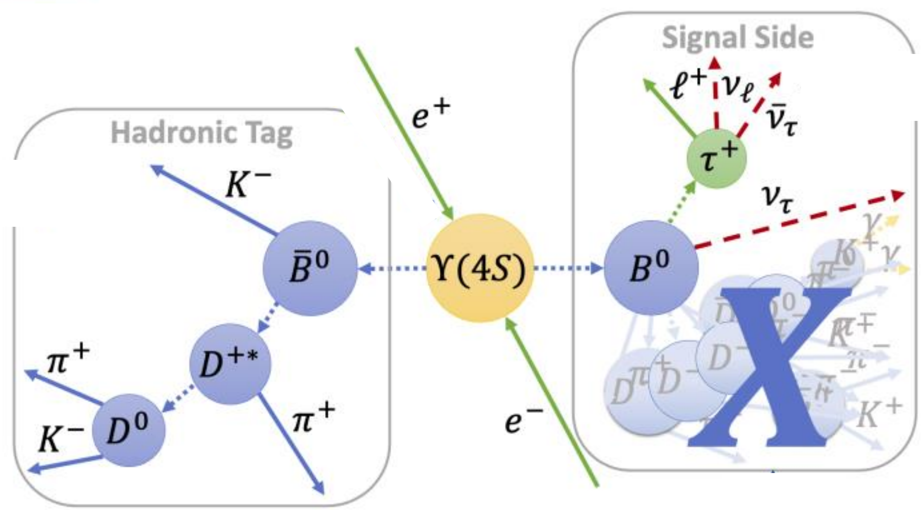
-Reconstruct $B \to X\tau\nu_\tau$, $B \to X\ell\nu_\ell$

-B_{tag}: Hadronic tag

-B_{sig}: Leptonic τ decays of $\tau \to e\bar{\nu}_e\nu_\tau / \mu\bar{\nu}_\mu\nu_\tau$

e(μ) momentum^{lab} > 0.5(0.7) GeV

Any other particles in final state (X)



-Challenge: contamination and modeling of many decay channels

-correct understanding of PDF shapes and background yields:

PDF shapes are calibrated in side-band by using X mass distribution

R(X) signal extraction

New EPSHEP 2023

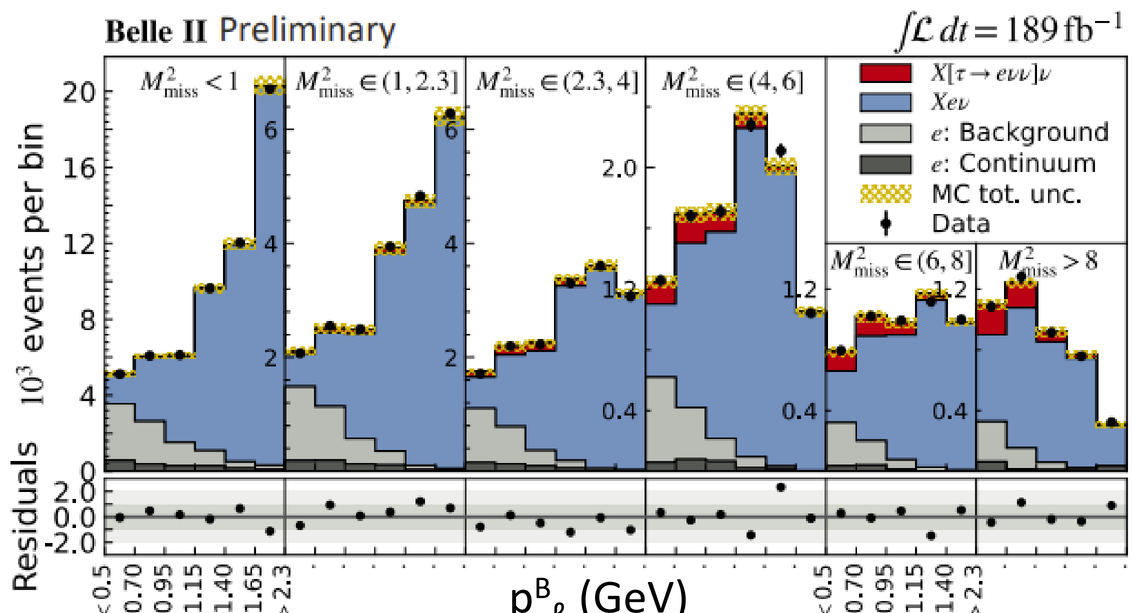
-Two-dimensional binned likelihood is used to extract $N_{B\to X\tau\nu}$, $N_{B\to X\ell\nu}$

- p^B_ℓ : lepton momentum in B rest frame
- $M^2_{\rm miss}$: missing mass of un-detected particles

-Templates for fitting

- -Xτν, Xℓν
- -Continuum with off-resonant data constraint
- -Background from fake and secondaries leptons

-Post fit distributions show good data/MC agreement, including BG dominant bin:



R(X) Result

New EPSHEP 2023

-The first results of $R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$ at B factory:

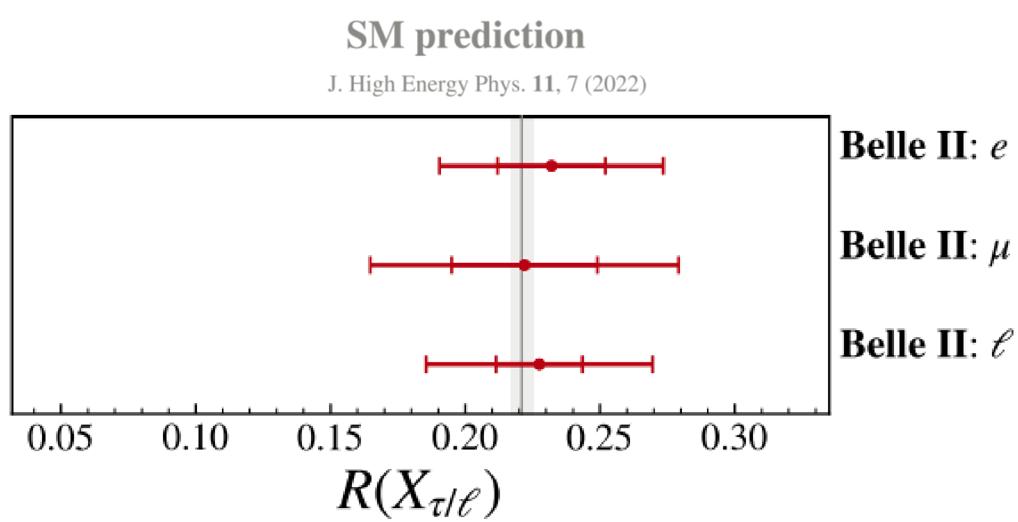
$R(X_{\tau/\ell}) = 0.228 \pm 0.016(\text{stat.}) \pm 0.036(\text{syst.})$

-e only: $R(X_{\tau/\mu}) = 0.232 \pm 0.020(\text{stat.}) \pm 0.037(\text{syst.})$

-μ only: $R(X_{\tau/e}) = 0.228 \pm 0.027(\text{stat.}) \pm 0.050(\text{syst.})$

Major systematics: MC statistics, PDF shape, BR of B→D**ℓν

-Consistent with SM prediction



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

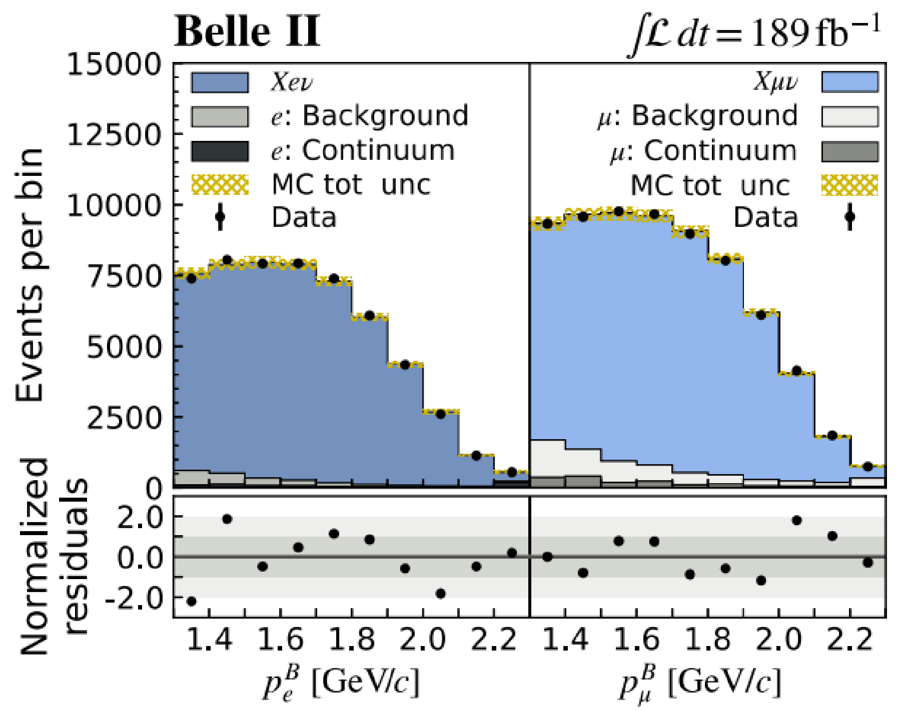
[PhysRevLett.131.051804]

-The first measurement of $R(X_{e/\mu}) = \frac{\mathcal{B}(B \to Xe\nu_e)}{\mathcal{B}(B \to X\mu\nu_\mu)}$ at BelleII

- -test LFU of light leptons, e and μ
- -unique measurement at BelleII with inclusive analysis

-Common analysis technique to R(X)

- -hadronic tag with a signal lepton
- -extract signal from high lepton momentum
- -constraint continuum BG by using beam energy shifted (off-resonance) data



-Result:

$$R(X_{e/\mu}) = 1.007 \pm 0.009(\mathrm{stat}) \pm 0.019(\mathrm{syst})$$

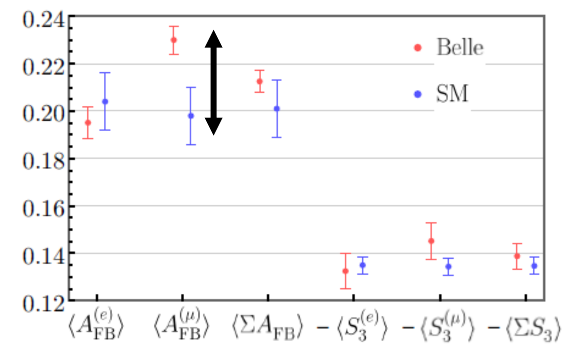
major systematics: lepton identification

-Most precise measurement in the world, in agreement w/SM.

B→D*ℓν angular asymmetries

-Measurement of angular asymmetries of B→D*eν and B→D*μν

- -independent LFU test of light leptons, e and mu
- -tension was reported by [Eur. Phys. J. C 81, 984 (2021)]



-Forward-backward asymmetry:

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

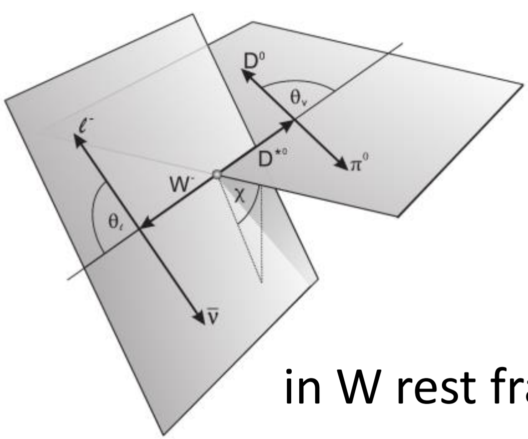
N_F= number of events with cos(θ) > 0

N_B = number of events with cos(θ) < 0

$$\Delta A_{FB} = A^{\mu}_{FB} - A^{e}_{FB}$$

-Measure asymmetries with several angles at the first time by BelleII:

- A_{FB}: $\cos\theta_\ell$
- S_3: $\cos 2\chi$
- S_5: $\cos\chi\cos\theta_{l\ell}$
- S_7: $\cos\chi\cos\theta_v$
- S_9: $\sin\chi \cos\theta_v$



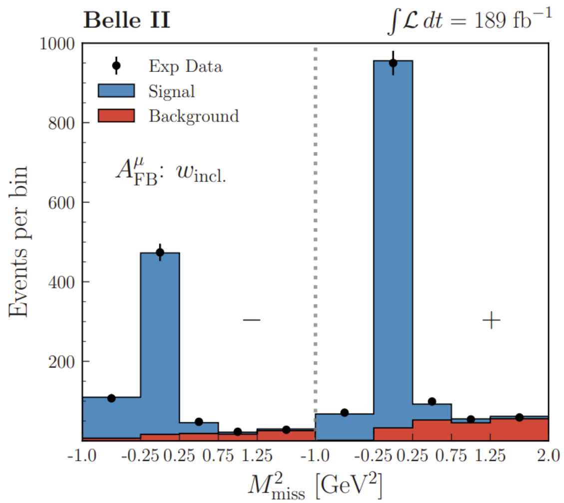
in W rest frame

-Challenge: precise lepton identification

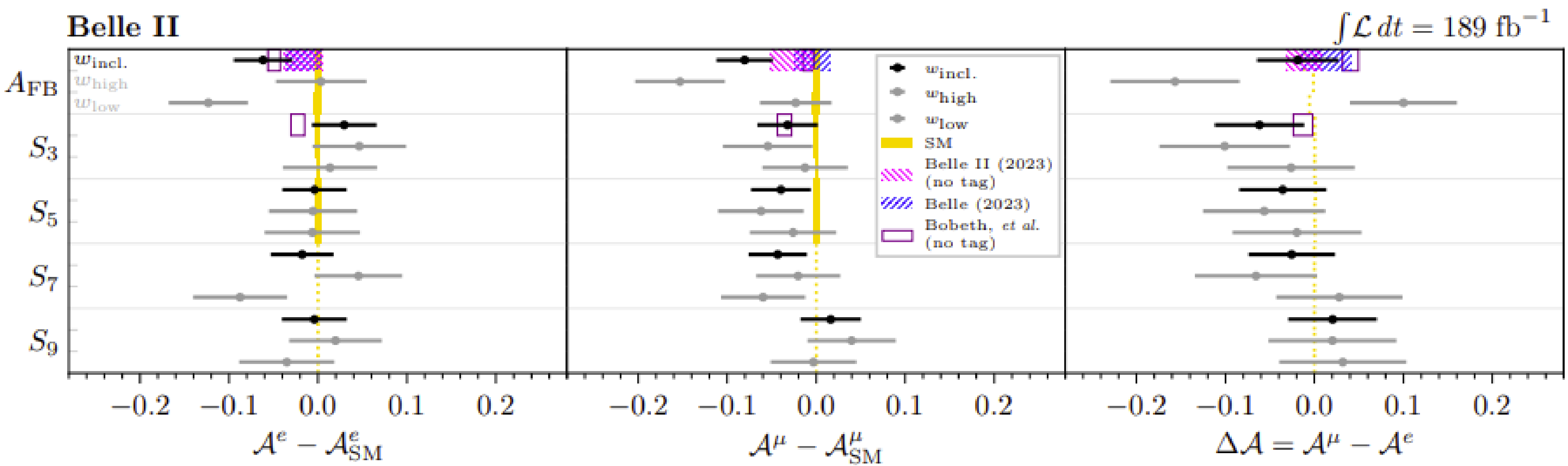
B→D*ℓν angular asymmetries: Result

- B→D*ℓν reconstructed with hadronic tag

- N_F, N_B are extracted from missing mass of un-detected particles in each angular and energy transfer regions



- Results:



statistical errors are dominant

- Most precise measurements in agreement with SM.

Summary

-Tests of LFU are important to search for new physics

-BelleII performed unique LFU tests of semileptonic B decays
with clean environment and known initial beam energy of e^+e^- collision

-LFU of τ and ℓ

- -R(D*): first result at BelleII
- -R(X): first result at B factory

-LFU of μ and e

- -R($X_{e/\mu}$): most precise result in the world
- -Angular asymmetries of B→D*ℓν: most precise results in the world

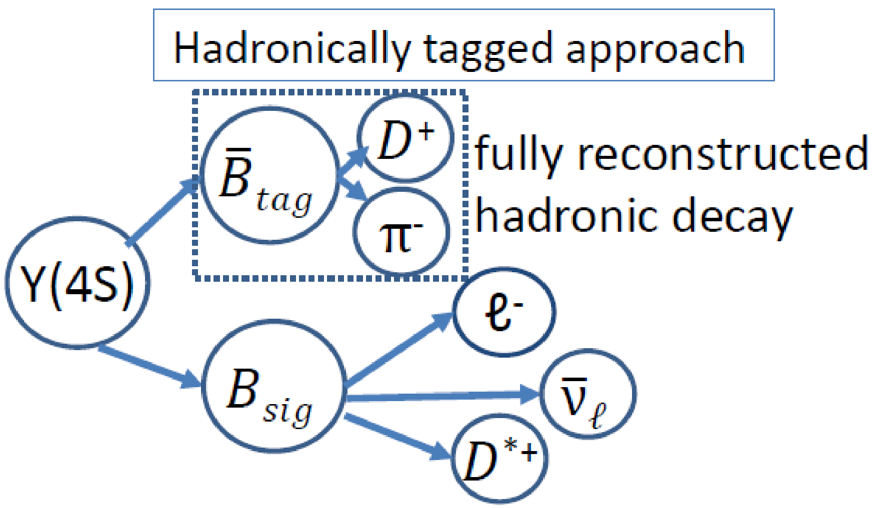
backup

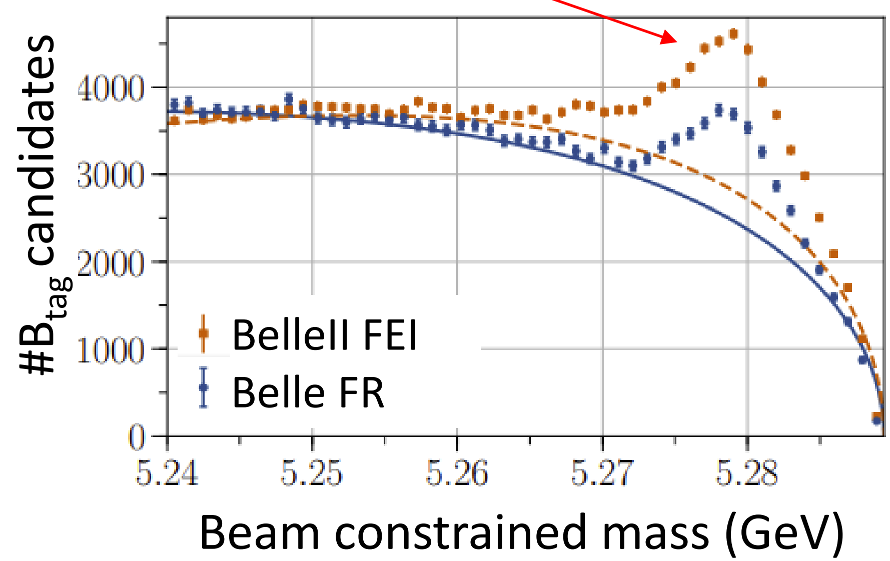
Reconstruction of semileptonic B decays

-The kinematics of a B decay with neutrinos can be known through the full reconstruction of partner B (B_{tag}) with initial beam energy

-Machine learning based algorithm (FEI) is developed for the tagging

- -~30 kind of hadronic decays (hadronic tag)
- -~0.45%(0.30%) B^0(B^+) efficiency: ~twice higher than Belle's method (FR)





(*Comput Softw Big Sci* **3,** 6 (2019))