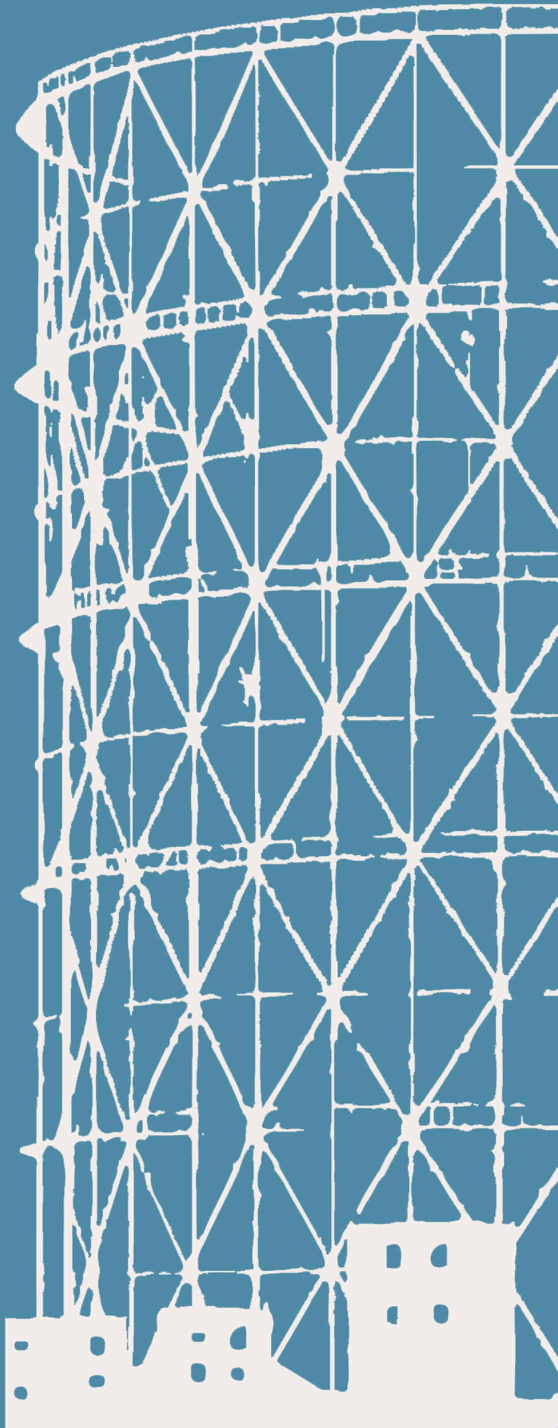
Lepton Flavour Universality tests at Belle II

Giovanni Gaudino on behalf of Belle II Collaboration
Scuola Superiore Meridionale – INFN Napoli

WiFai 2023 – Roma – November 10th 23



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Belle II

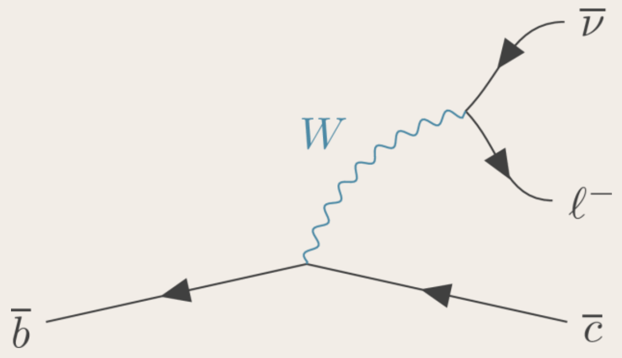
Lepton Flavour Universality

Why Lepton Flavour Universality is tested?

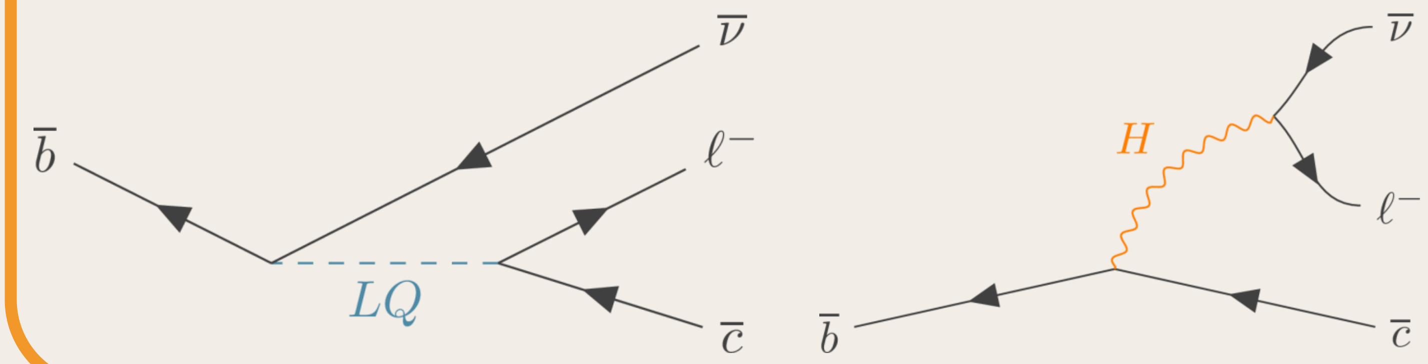
Universality of W Boson Interaction: LFU investigates whether the W boson interacts equally with different lepton flavors, which is a fundamental concept in the Standard Model of particle physics.

Detecting Non-Standard Model Physics: LFU research is about identifying deviations from this universality, which could suggest the existence of particles or interactions beyond what the Standard Model predicts, such as Leptoquarks or charged Higgs bosons.

SM Diagram



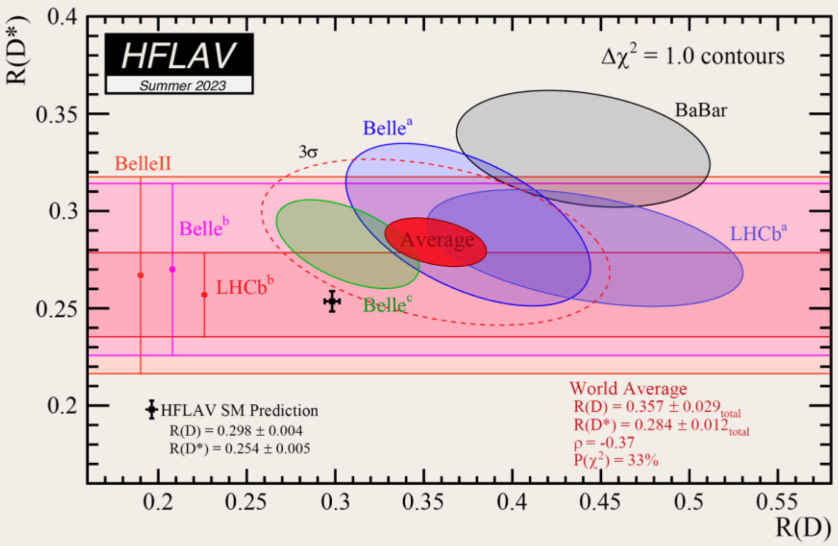
Possible Non SM Feynman Diagrams



Lepton Flavour Universality

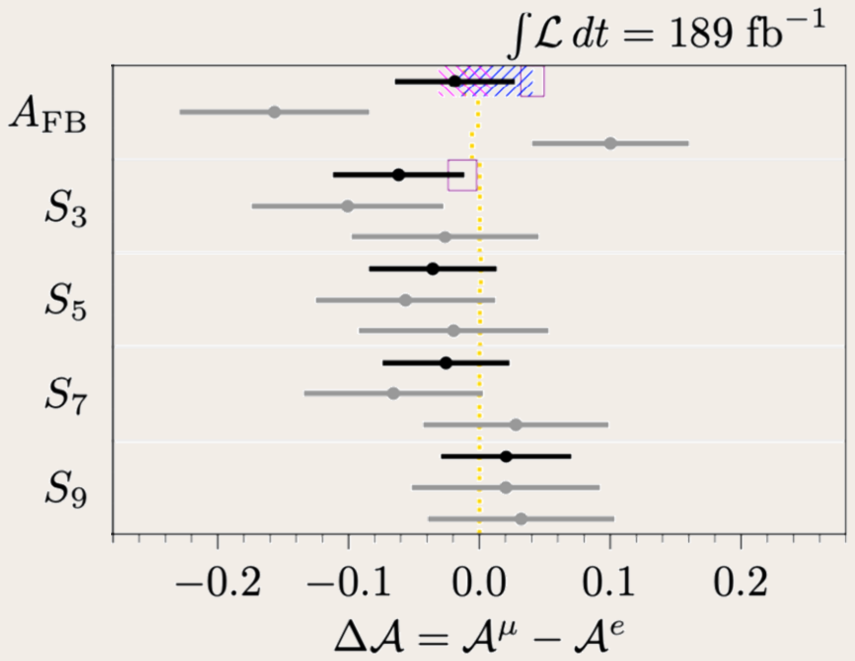
How Lepton Flavour Universality is tested?

Semileptonic decays:
they are nearly free from contamination; **Form Factors** (FFs) and experimental uncertainties partially cancel in the ratios of R for $b \to q\{\tau/\mu/e\}\nu$ decay rates.



There is a long-standing tension between the LFU sensitive quantities $R_{D^{(*)}}$ and SM predictions:

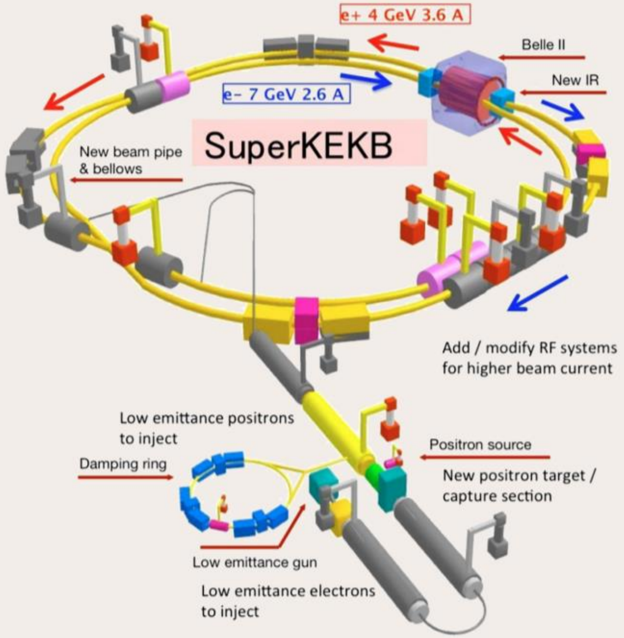
Differences in angular asymmetries:
for different lepton flavors they are also responsive to Beyond the Standard Model (BSM) physics and exhibit small systematic uncertainties.

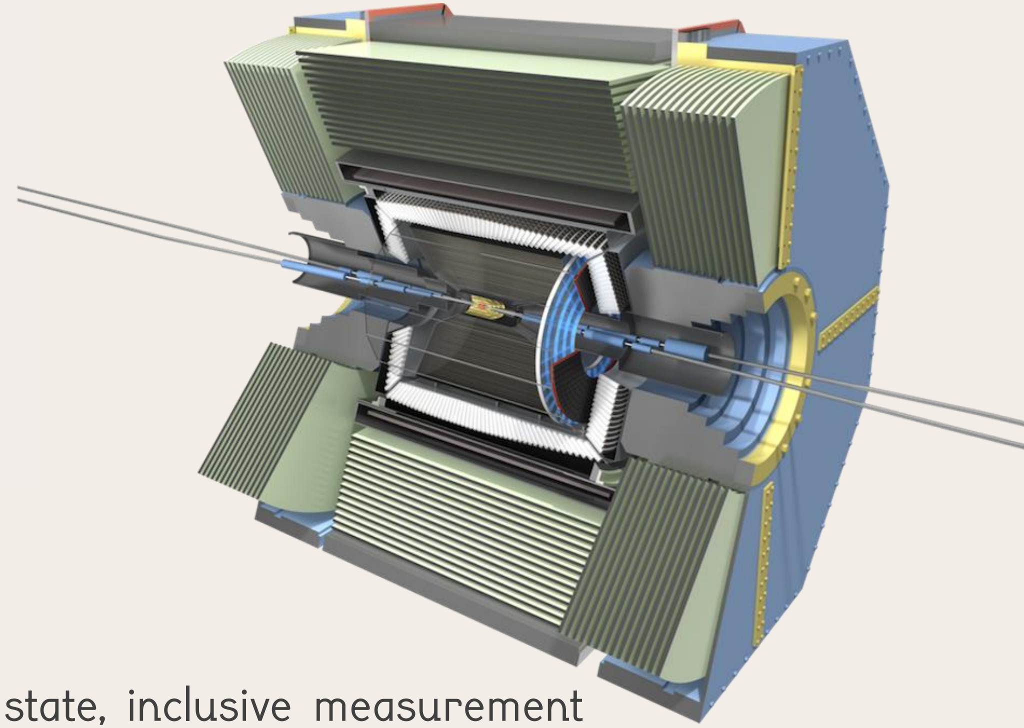


Belle II and SuperKEKB

SuperKEKB:

- e^+e^- collider with energies 4 GeV and 7 GeV operating around $\Upsilon(4S)$ resonance.
- Achieved world-record peak Luminosity of $L = 4.7 \times 10^{34} cm^{-2} s^{-1}$
- Based in Tsukuba, Japan





Belle II:

- Nearly 4π detector coverage
- Tracking, PID and photon reconstruction capabilities
- Similar performance for electrons and muons
- Well-suited to measure decays with missing energy, π^0 in the final state, inclusive measurement

Collected at $\Upsilon(4S)$: 362 fb^{-1}, about $\mathbf{4 \times 10^8}\ \boldsymbol{B\overline{B}}$
in total: 424 fb^{-1}

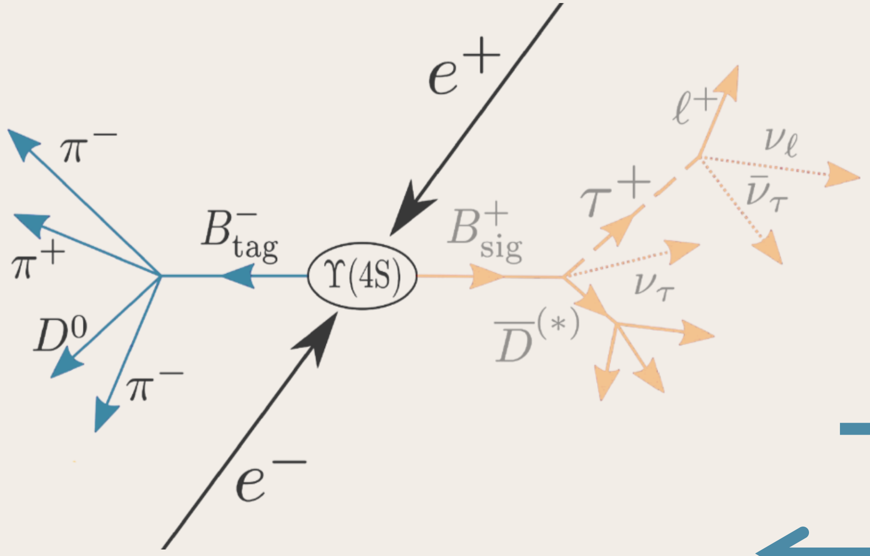
Missing energy decays at Belle II

Reconstruction tecnique

Two different algorithms to reconstruct events with at least one neutrino in the final state

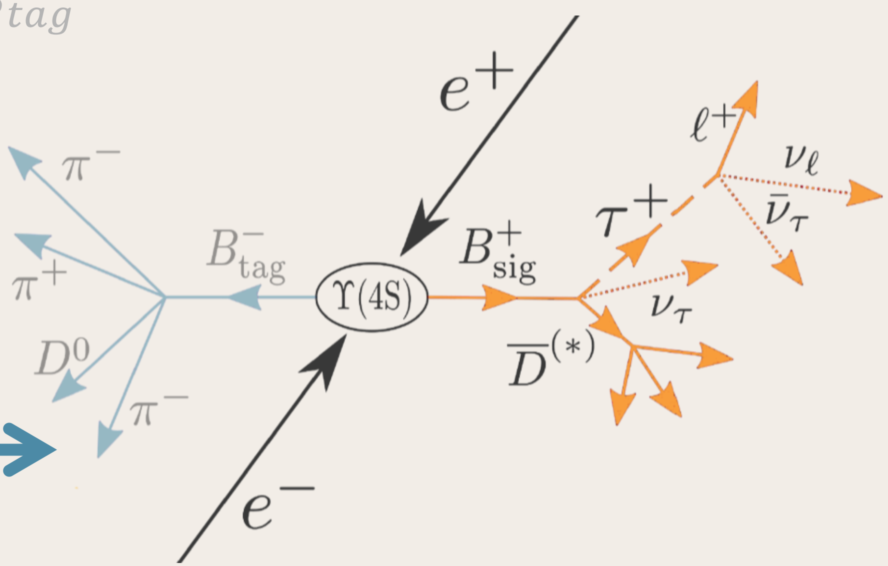
Full Event Interpretation (FEI):

1. Reconstruct all the decay chain of a B meson (both hadronic and semileptonic ways)
2. Search for the signal signature in the B_{tag} recoil



Inclusive Tag:

1. Reconstruct the signal signature, identifying the B_{sig}
2. All the remaining tracks and clusters represent the B_{tag}



Efficiency →

← Purity

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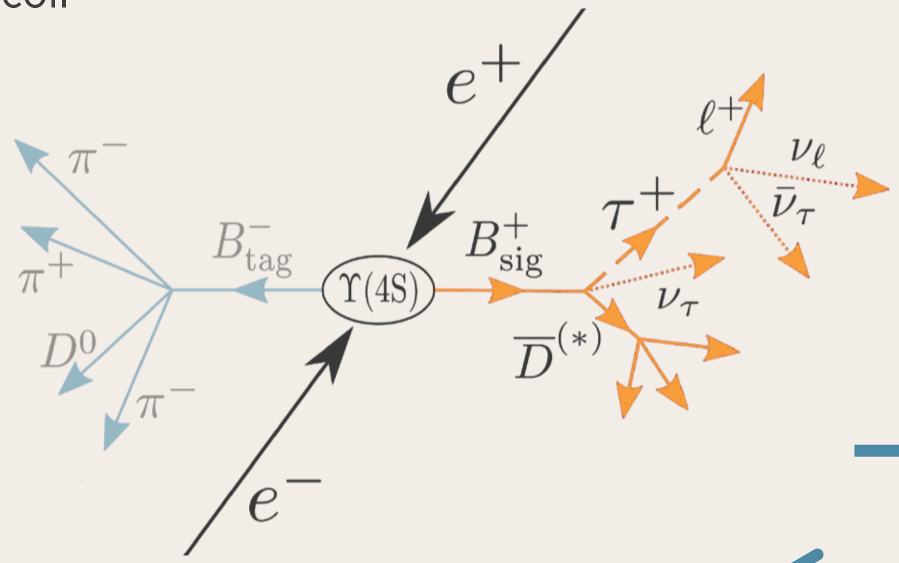

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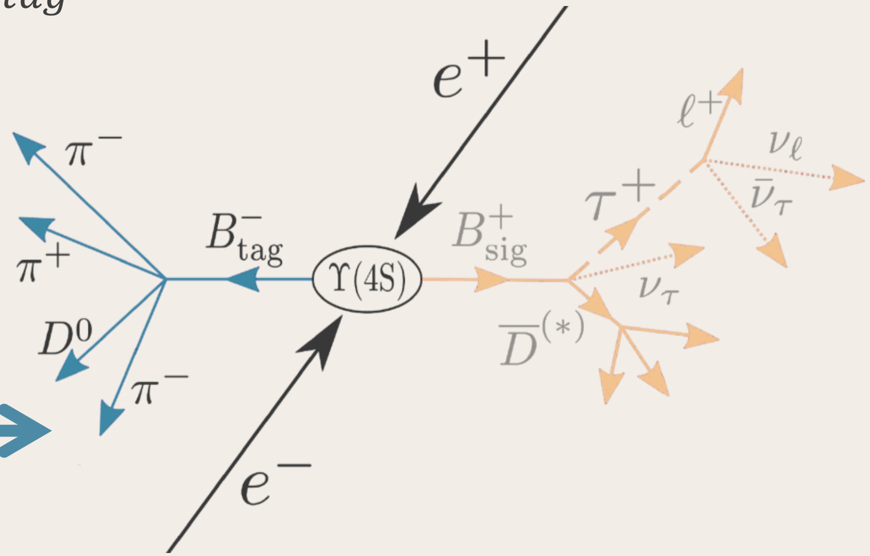

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Reconstruction tecnique

Two different algorithms to reconstruct events with at least one neutrino in the final state

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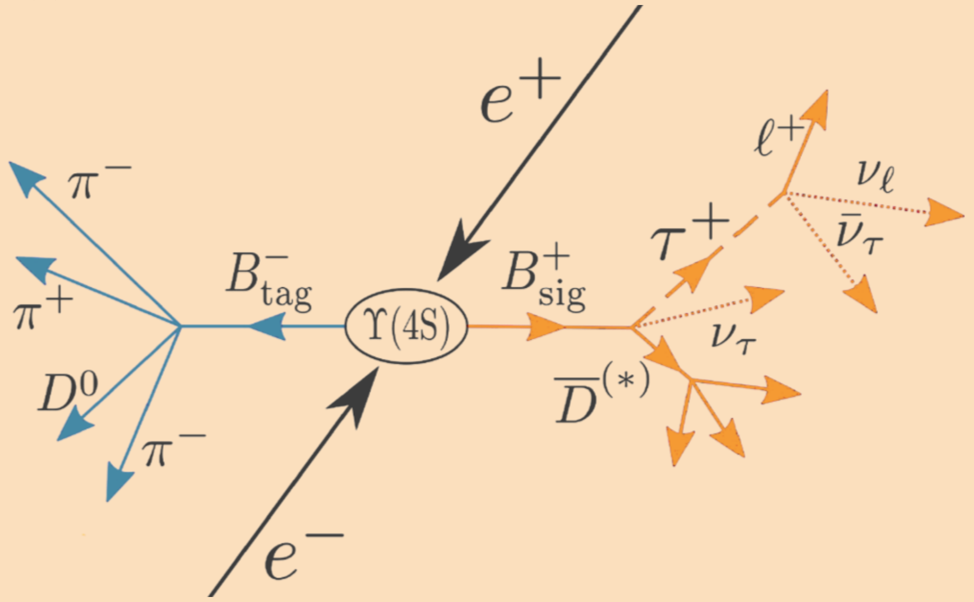


Only **Hadronic Tag** analyses are presented in this talk.

- Hadronic Tag **FEI** select *good* B_{tag} candidates with an efficiency $\approx 0.4\%$;
- Reduces $e^+e^- \to q\overline{q}$ **continuum** and $B \leftrightarrow B$ **combinatorial** background;
- Can determine $\boldsymbol{p_{miss}}$ since full initial state is known;
- **Completeness** of the signal event: only low energy neutral clusters in the extra event.

Table of Contents

Belle II analysis for Lepton Flavour tests

- $R_{\tau/\ell}(D^*)$ from Belle II (189 /fb), preliminary (Lepton-Photon 2023)
- $R_{\tau/\ell}(X)$ from Belle II (189 /fb), preliminary (EPS-HEP 2023)
- $R_{\mu/e}(X)$ from Belle II (189 /fb) PhysRevLett.131.051804
- Tests of light-lepton universality in angular asymmetries of $B \to D^* \ell \nu$ from Belle II (189 /fb), PhysRevLett.131.181801

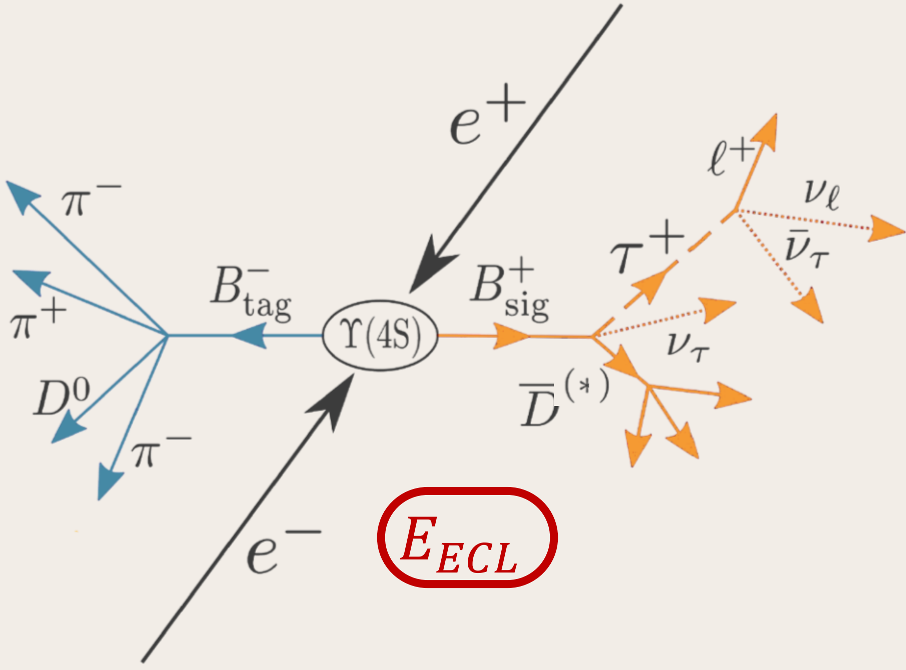
Definition

$$R_{\ell_1/\ell_2}(M) = \frac{\mathcal{BR}(B \to M \ell_1 \nu_1)}{\mathcal{BR}(B \to M \ell_2 \nu_2)}$$

$$R_{\tau/\ell}(D^*)$$

Reconstruction

- Hadronic decay of the B_{tag}.
- Reconstruct τ and light lepton decays into the same final state particles to cancel many systematic uncertainties.
- Reconstruct the D^* in the following channels: $D^* \to D^0\pi/D\pi^0$ – $D^{*0} \to D^0\pi^0$.
- Rest of the event: no good quality tracks, no π^0 candidates. The sum of all the neutral extra clusters energy is called E_{ECL}.
- The main challenges are the separation between the $\tau(3\nu)$ and $\ell(1\nu)$ final states and the poor understood $B \to D^{**}\ell\nu$ backgrounds.



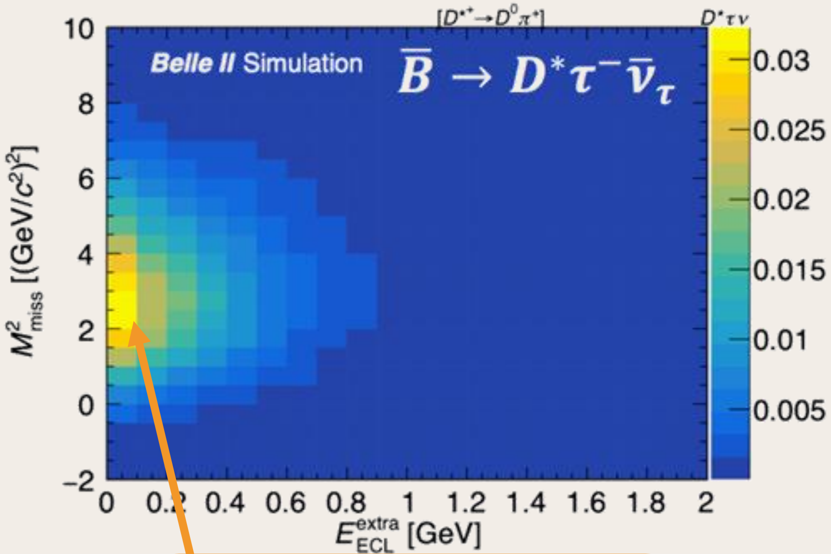
$$R_{\tau/\ell}(D^*) = \frac{\mathcal{BR}(B \to D^*\tau\nu)}{\mathcal{BR}(B \to D^*\ell\nu)}$$

Signal extraction

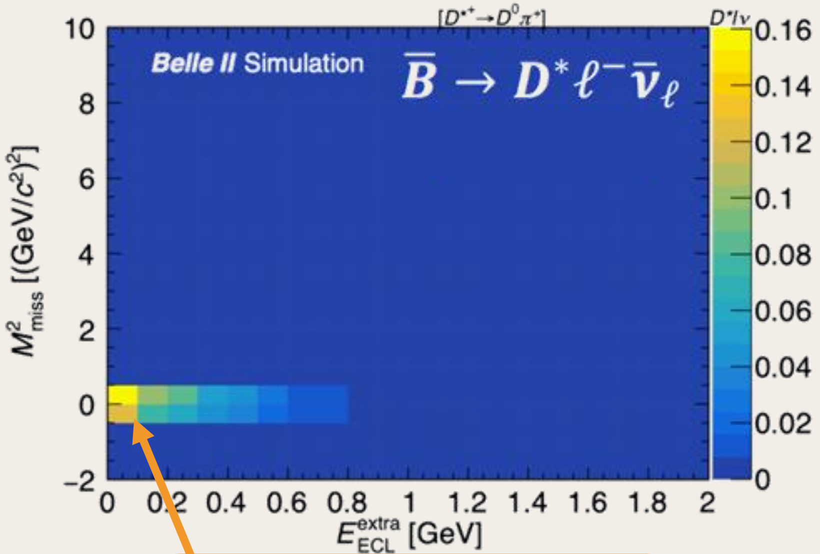
Two-dimensional binned likelihood fit to

- E_{ECL}: energy from neutral clusters remaining in the calorimeter after removing all reconstructed particles
- $M^2_{\text{miss}} = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^*} - p_\ell)^2$ missing mass of the event

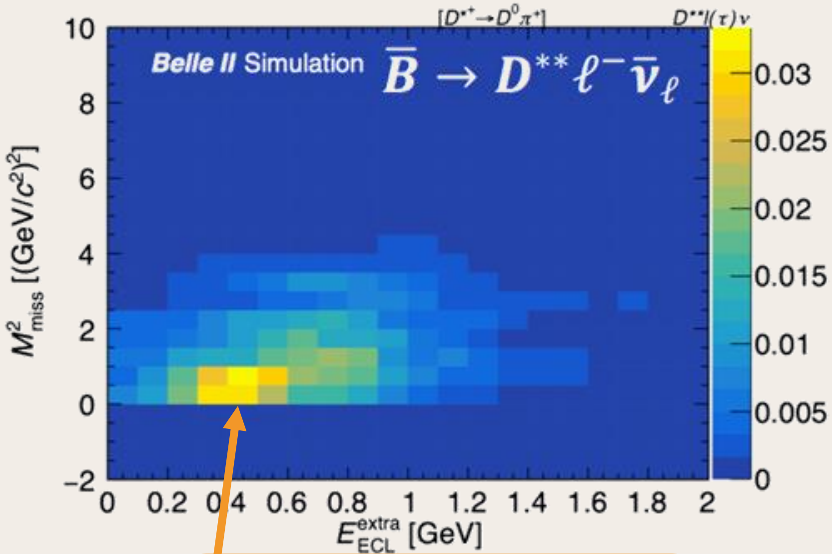
Comparable sensitivities between B^+ and B^0



Peaked around $E_{ECL} = 0$ and $M^2_{miss} \approx 3\ GeV^2$



Peaked around $E_{ECL} = 0$ and $M^2_{miss} = 0$

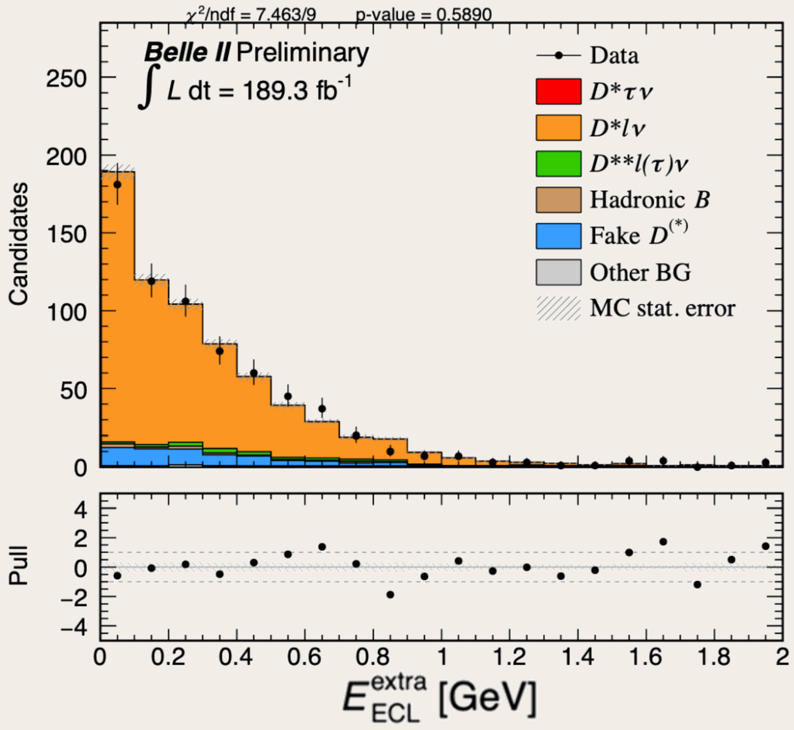


Higher E_{ECL} and M^2_{miss}: daughters of D^{**}

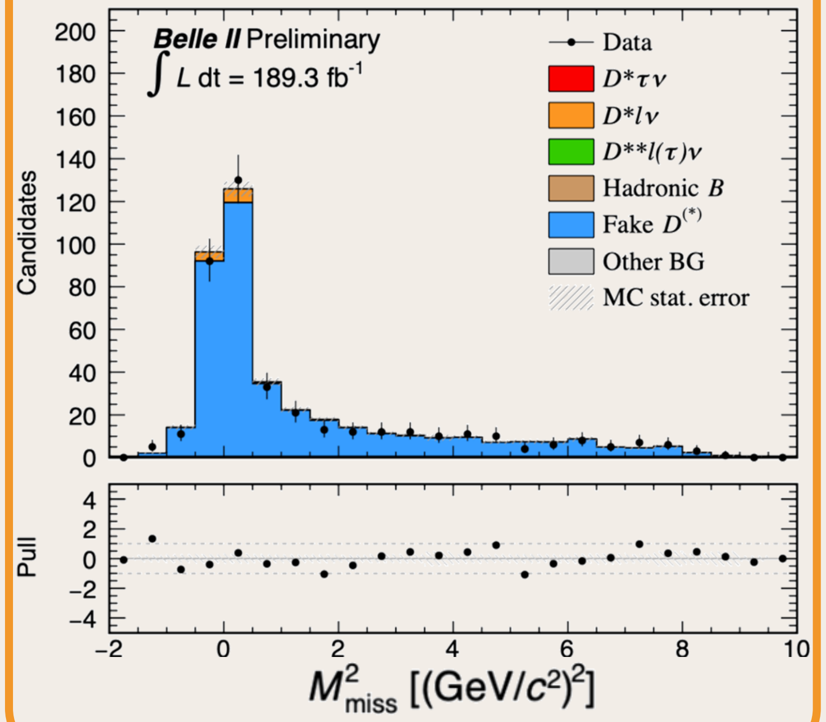
Control Samples Background Validation

The final result is extracted using a MonteCarlo template fit. To validate/correct the shape and the normalization three different control samples:

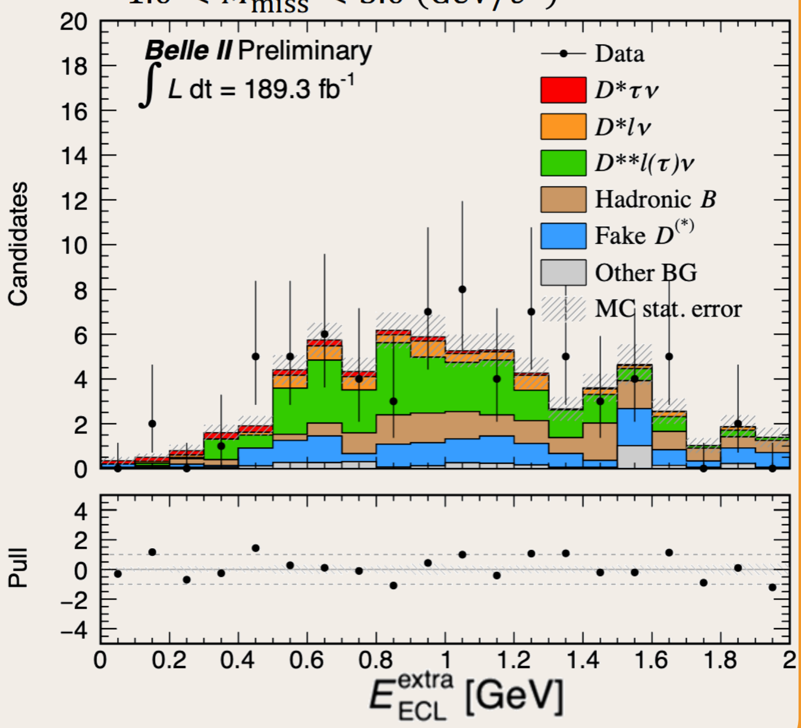
$q^2 = (p_\nu + p_e)^2 < 3.5\ \mathrm{GeV}^2$



$\Delta M_{D^*} = M_{D^*} - M_D$ Sideband



$B \to D^*\pi^0\ell\nu$



Results

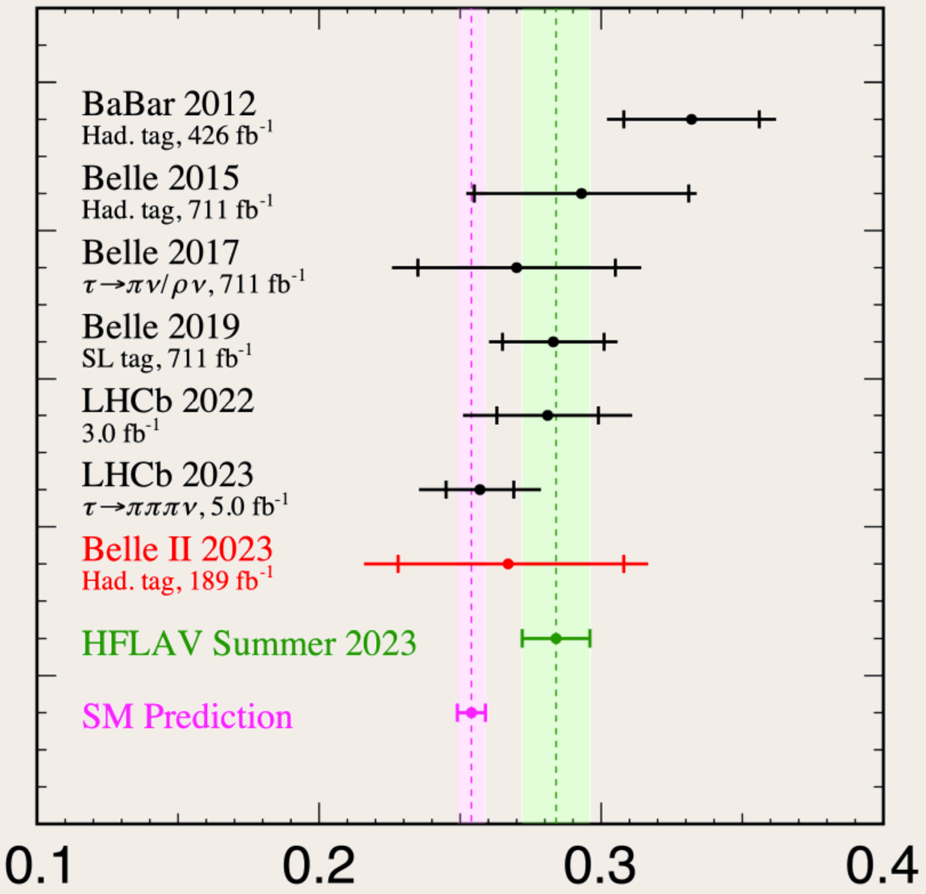
Belle II preliminary result

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

- First result from Belle II data
- Main systematics: MC statistics, shape of E_{ECL}
- Consistent with SM and HFLAV

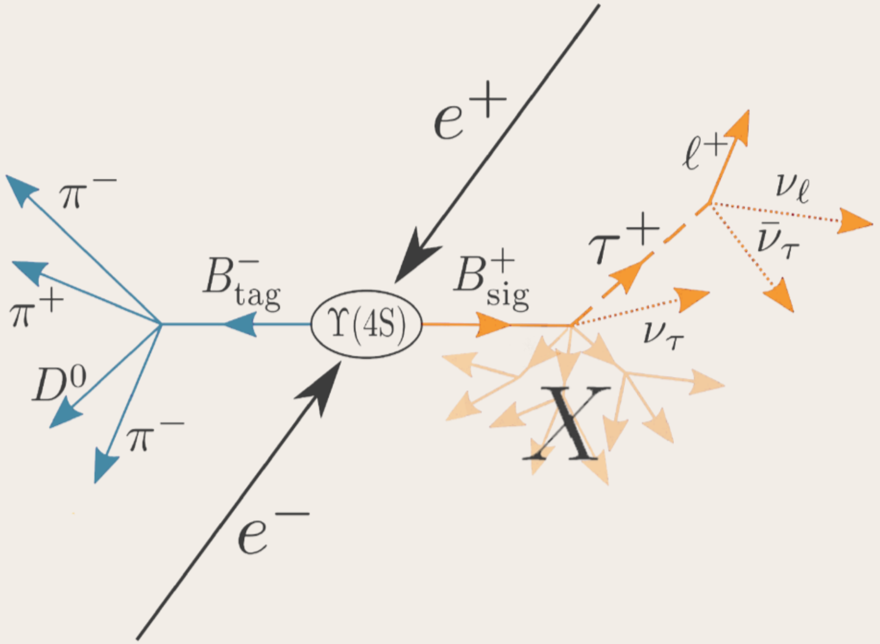
In the future:

- Update of the measurement with 362/fb in progress
- Belle II will provide the most precise experimental information to resolve the $R(D)$ and $R(D^*)$ anomalies [Snowmass White Paper: 2207.06307]



$$R_{\tau/\ell}(X)$$

Reconstruction



$$R_{\tau/\ell}(X) = \frac{\mathcal{BR}(B \to X\tau\nu)}{\mathcal{BR}(B \to X\ell\nu)}$$

- Hadronic decay of the B_{tag}.
- Reconstruct τ and light lepton decays into the same final state particles to cancel many systematic uncertainties. p_e > 0.3 (0.5) GeV and p_μ > 0.4 (0.7) GeV in CMS (lab)
- The remaining particles on the signal side are collectively referred to as X
- Main challenge: correct model of backgrounds.

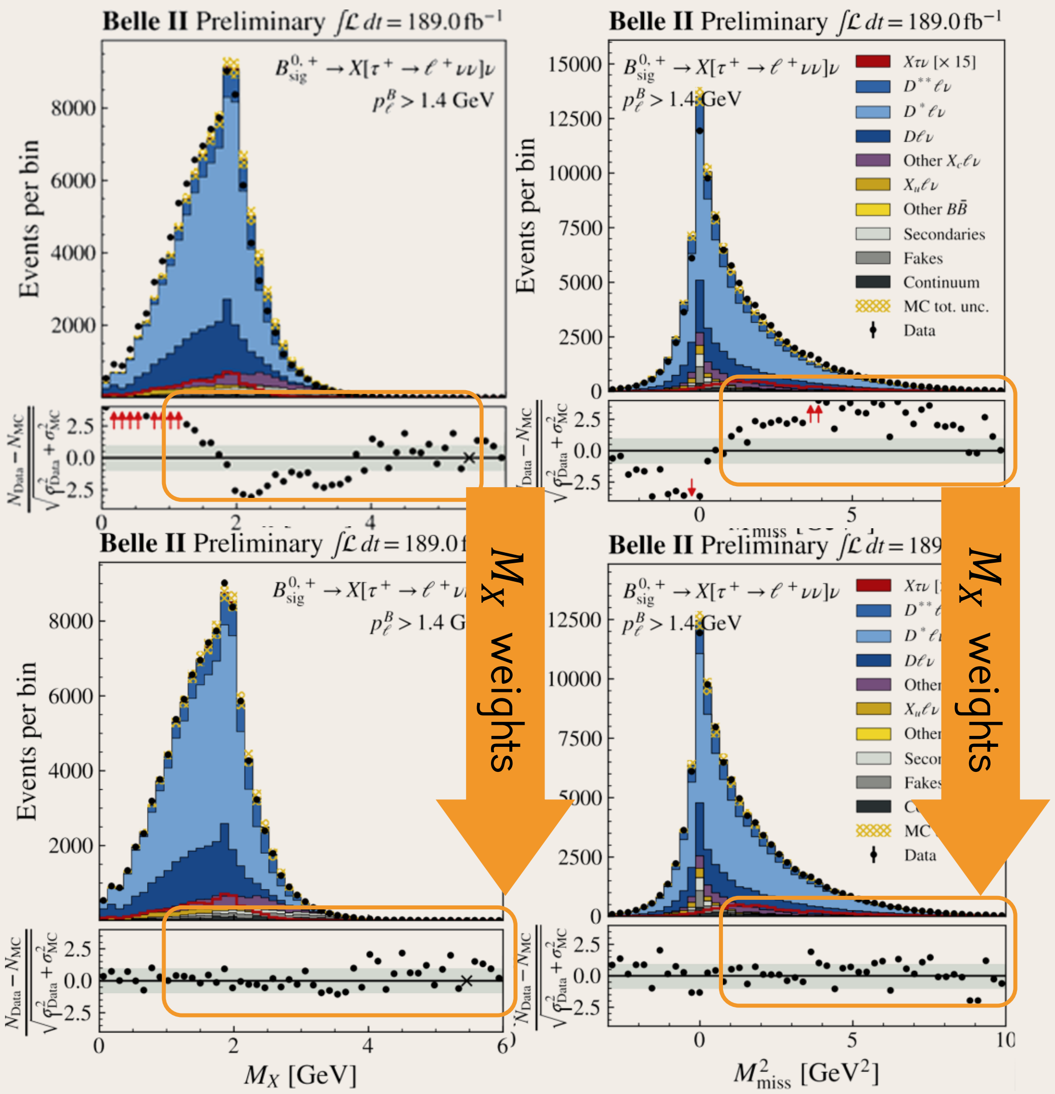
Data-driven MC Corrections and Fit

MC corrections:

- Detailed adjustments to MC (FFs, B and D BFs)
- Detailed corrections based on comparisons of simulation with control regions: low q^2, low M^2_{miss}, high M_X.

Final Fit:

- 34 bins in p_ℓ vs M^2_{miss}
- Fit components: $X\tau\nu$, $X\ell\nu$, $B\overline{B}$ background (fakes and secondaries) and continuum (off resonance data*)



*Off resonance data: data taken under 60 MeV the Y(4S) threshold

Data-driven MC Corrections and Fit

MC corrections:

- Detailed adjustments t
- Detailed corrections simulation with contro high M_X.

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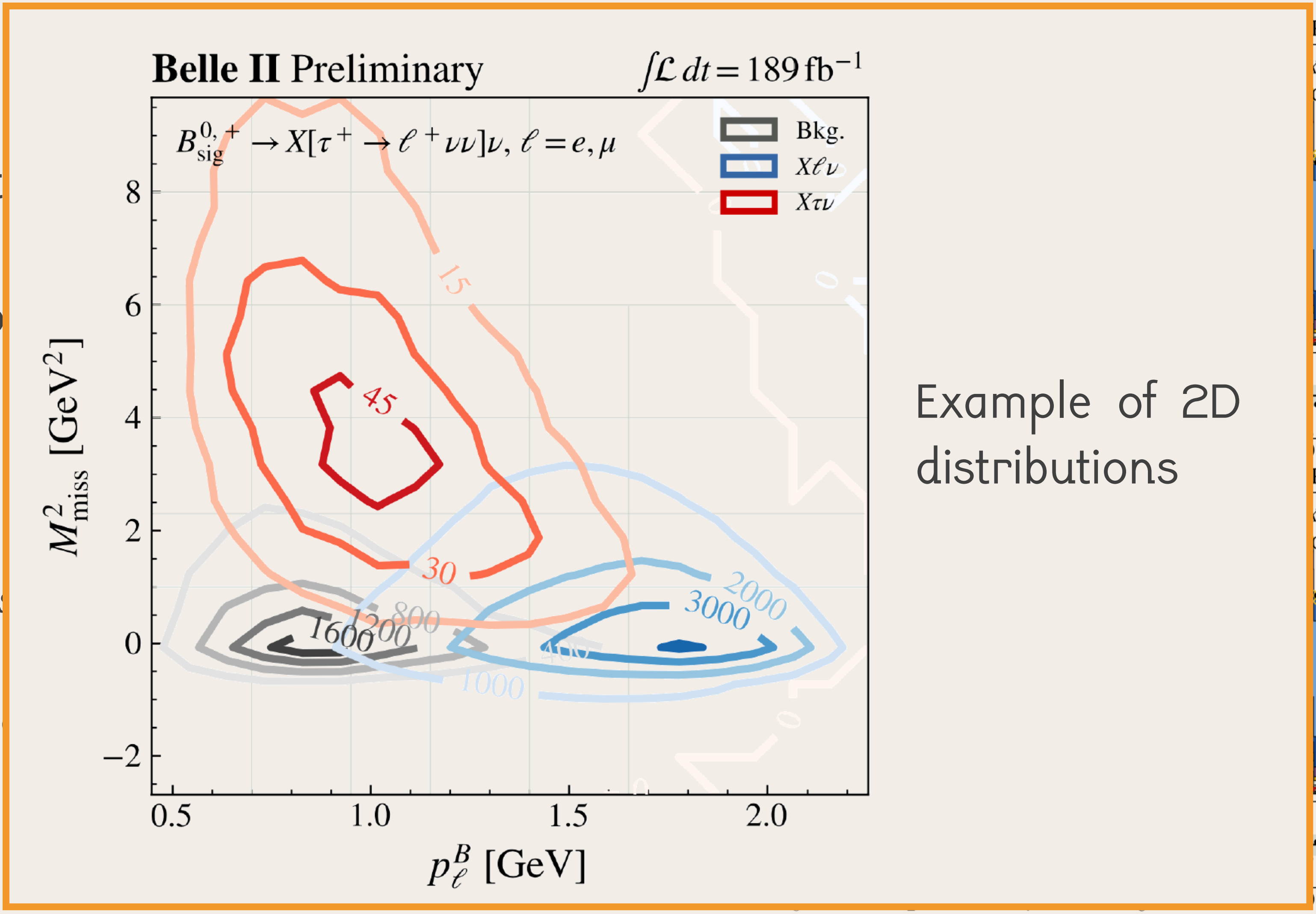
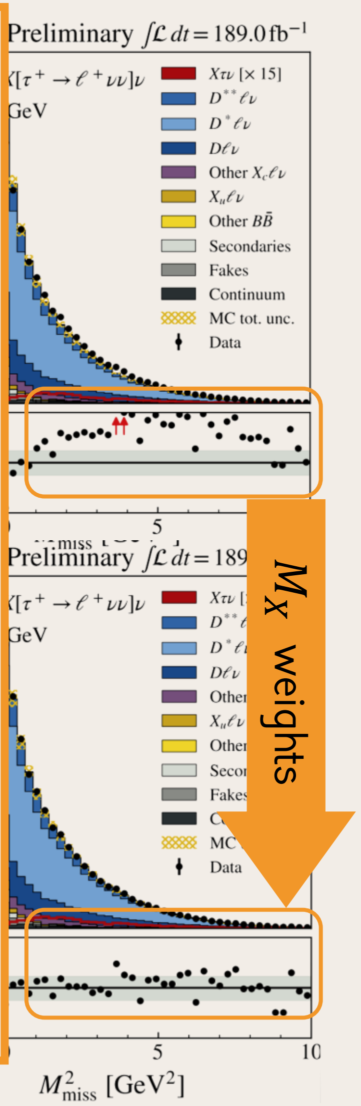


Example of 2D distributions



*Off resonance data: data taken under 60 MeV the Υ(4S) threshold

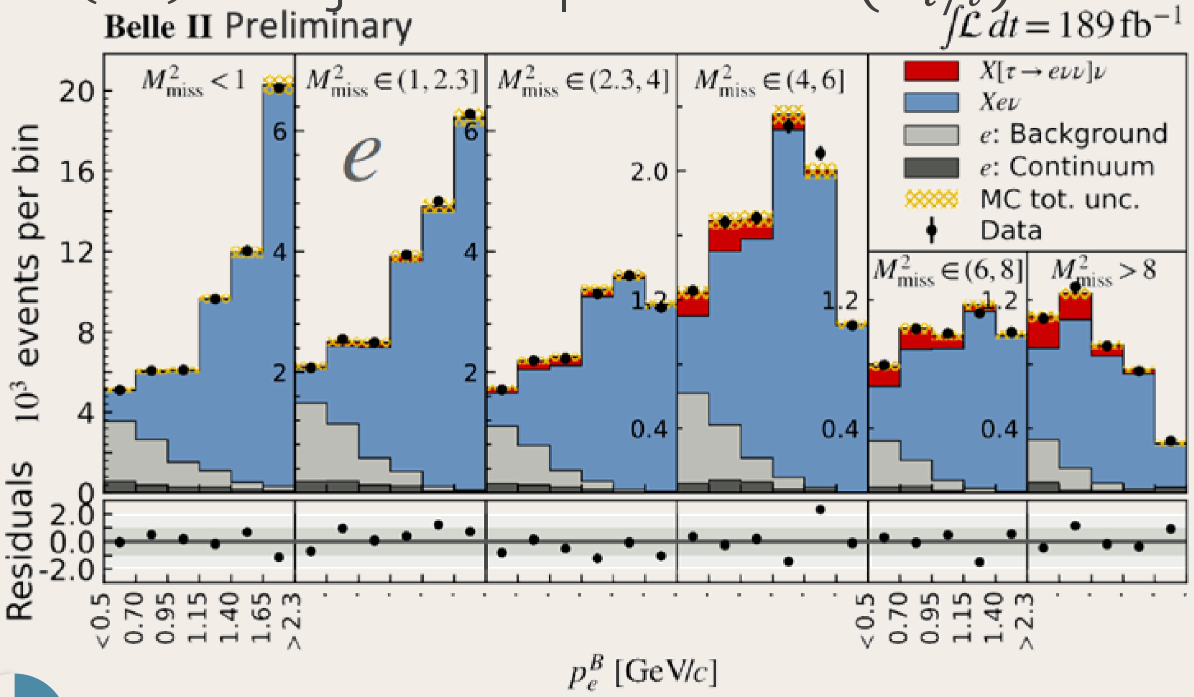
Results

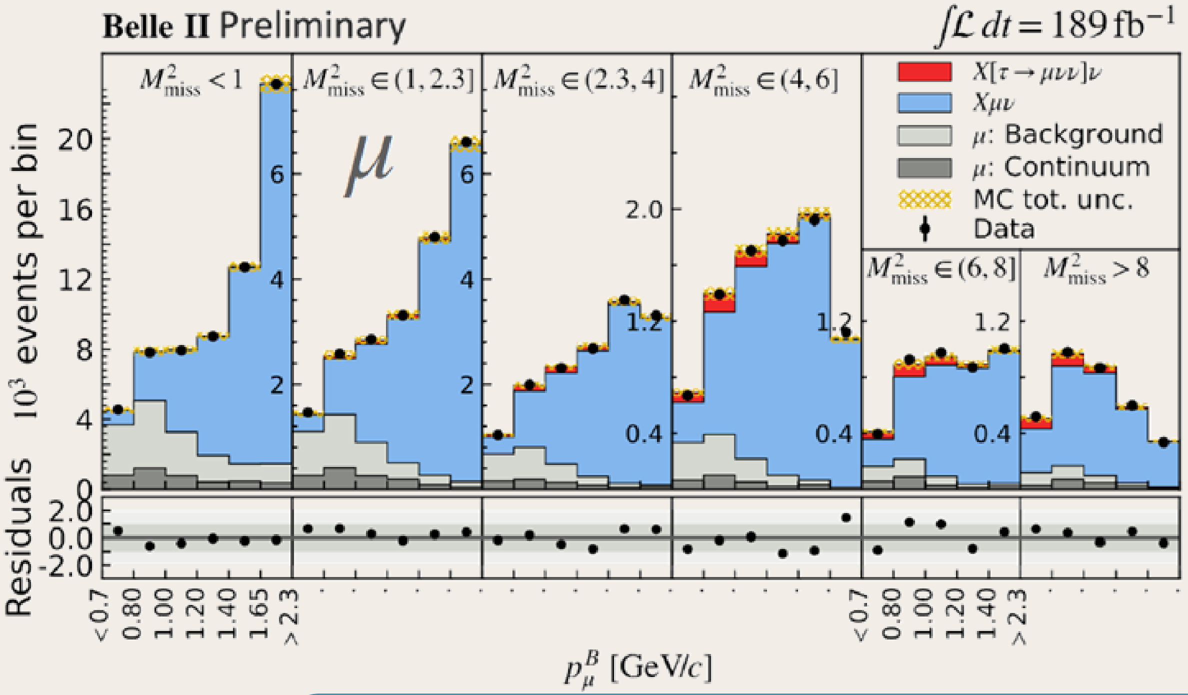
Belle II preliminary result

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

First measurement coming from the B factories

- Largest systematics: signal and background model
- Consistent with previous measurements from LEP, the SM expectation and constraints from $R(D^*)$. Rough SM expectation: $R(X_{\tau/\ell}) \approx 0.222$

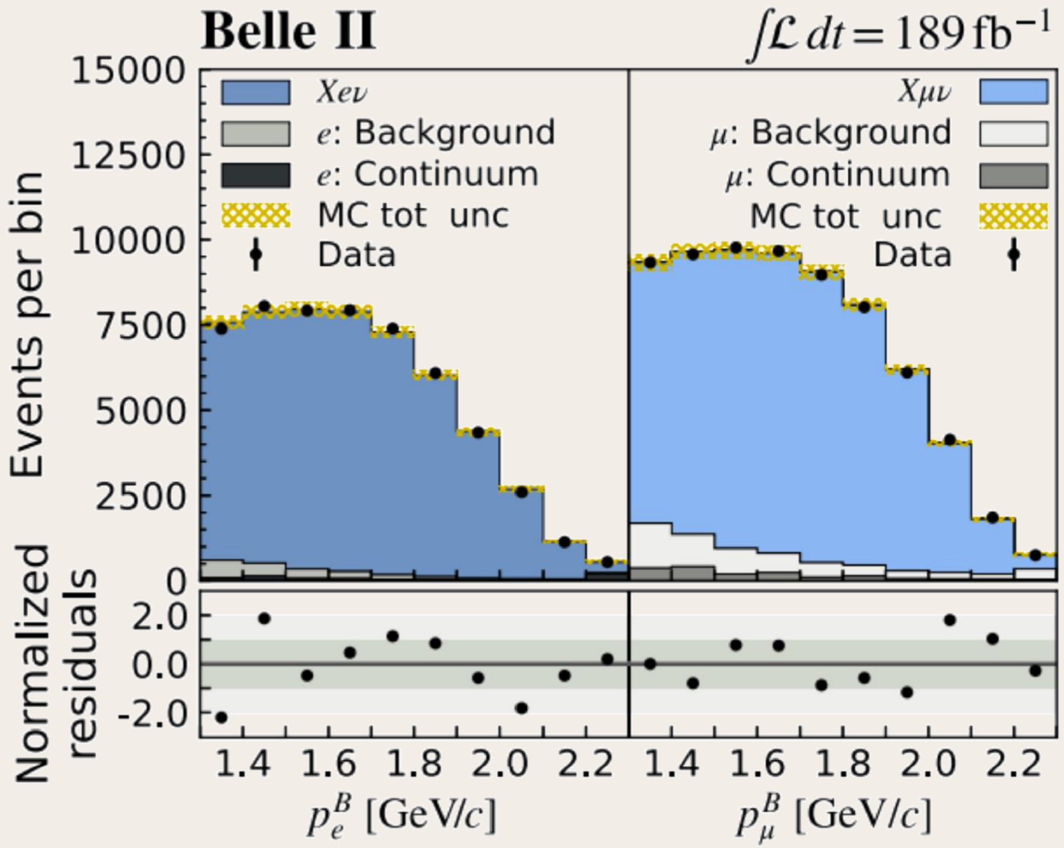




$$R_{e/\mu}(X)$$

Workflow and result

- Analysis and background correction technique is shared with the $R_{\tau/\ell}(X)$ measurement
- The ratio of inclusive semileptonic decays to e and to μ is obtained in the region $p > 1.3\ GeV$



Belle II result

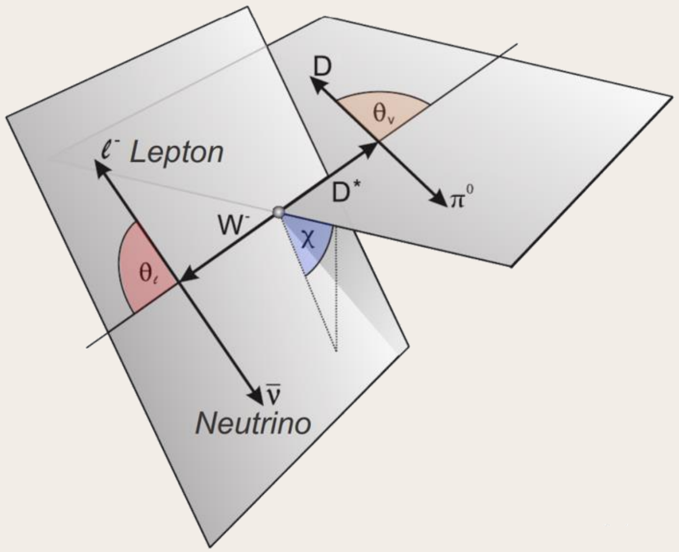
$$R(X_{e/\mu}) = 1.007 \pm 0.009(\text{stat}) \pm 0.019(\text{sys})$$

PhysRevLett.131.051804

Angular Asymmetries

Definition of angular variables in $B \to D^*\ell\nu$

We tested lepton universality by comparing five angular asymmetries of e and μ, ΔA using exclusive decays $B^0 \to D^*\ell\nu$



$$\Delta A_x(w) \equiv A_x^{\mu}(w) - A_x^{e}(w)$$

$$A_x(w) \equiv \left(\frac{d\Gamma}{dw}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right] dx \frac{\partial^2\Gamma}{\partial w \partial x}$$

$$A_x(w) = \frac{N_x^+(w) - N_x^-(w)}{N_x^+(w) + N_x^-(w)}$$

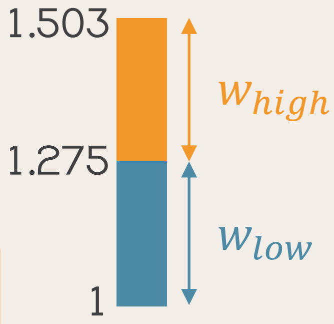
$$x = \begin{cases} \cos\theta_\ell & \text{for } A_{FB} \\ \cos 2\chi & \text{for } S_3 \\ \cos\chi\cos\theta_V & \text{for } S_5 \\ \sin\chi\cos\theta_V & \text{for } S_7 \\ \sin 2\chi & \text{for } S_9 \end{cases}$$

$$w \equiv \frac{m_{B^0}^2 + m_{D^*}^2 - q^2}{2 m_{B^0} m_{D^*}} = \frac{E_{D^*}^*}{m_{D^*}} = \gamma_{D^*}^*$$

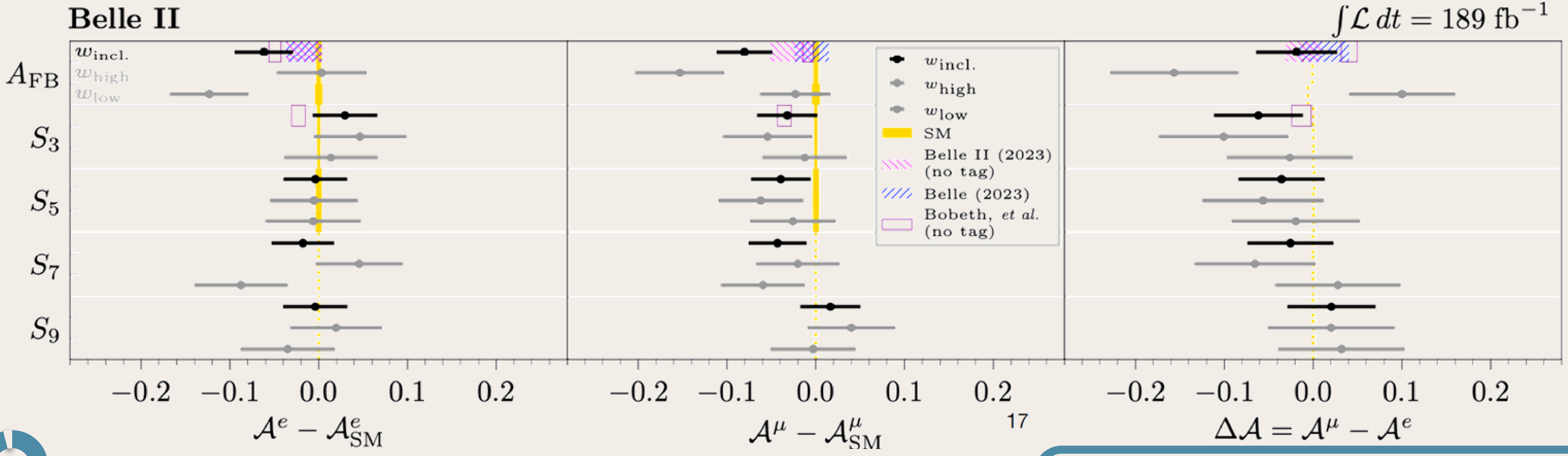
$* \equiv B$ rest frame

Results

$B^0 \to D^* \ell \nu$ decays are reconstructed in hadronically tagged $\Upsilon(4S)$ events.
Signal is extracted from the M^2_{miss} distributions.
The simultaneous determination of all asymmetries is performed in different w ranges



Our results agree well with the SM expectations and provide no evidence for LUV.



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Summary of recent LFU tests at Belle II

New tests of LFU in measured ratios of decay rates at Belle II (189/fb):

$R(X_{e/\mu}) = 1.007 \pm 0.009(\mathrm{stat}) \pm 0.019(\mathrm{sys})$ PhysRevLett.131.051804

$R(D^*) = 0.267^{+0.041}_{-0.039}(\mathrm{stat})^{+0.028}_{-0.033}(\mathrm{sys})$

$R(X_{\tau/e}) = 0.232 \pm 0.020(\mathrm{stat}) \pm 0.037(\mathrm{sys})$

$R(X_{\tau/\mu}) = 0.222 \pm 0.027(\mathrm{stat}) \pm 0.050(\mathrm{sys})$

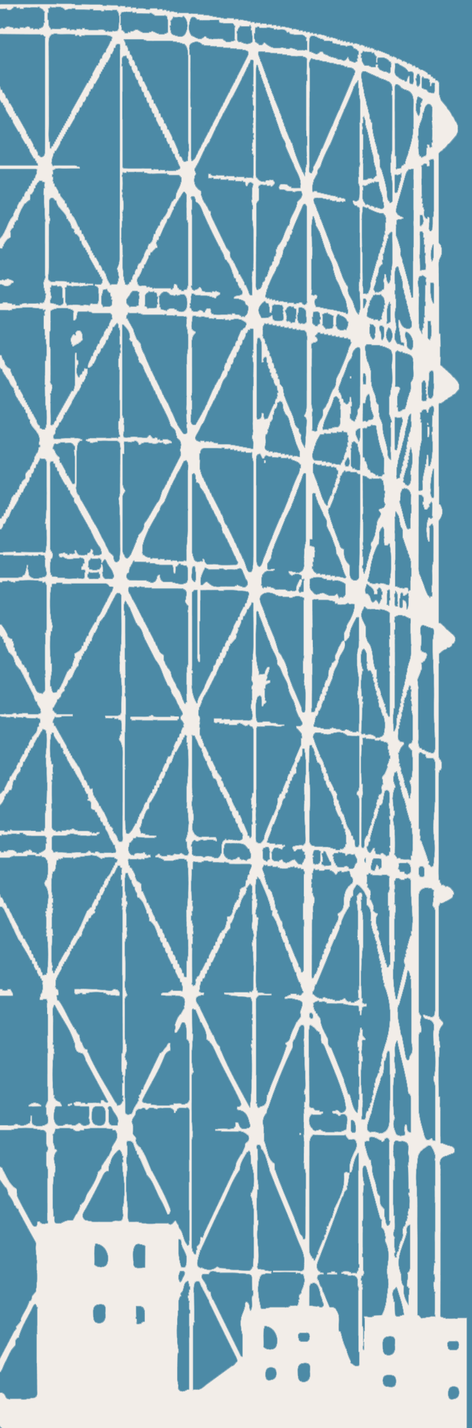
$R(X_{\tau/\ell}) = 0.228 \pm 0.016(\mathrm{stat}) \pm 0.036(\mathrm{sys})$

Preliminary

All measurements presented here are consistent with SM and with previous measurements where available

Forward–Backward asymmetry (and other variables) in $B \to D^* \ell \nu$
PhysRevLett.131.181801

Belle II has already collected a bigger data sample analyzed here and also, more data to come.



That's all!

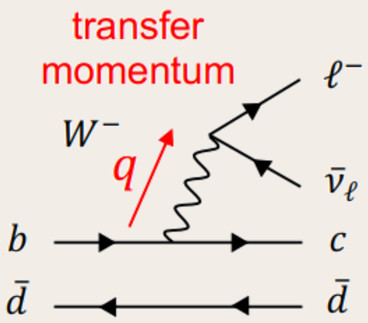
Thanks for the attention

Backup Slides

Control Samples

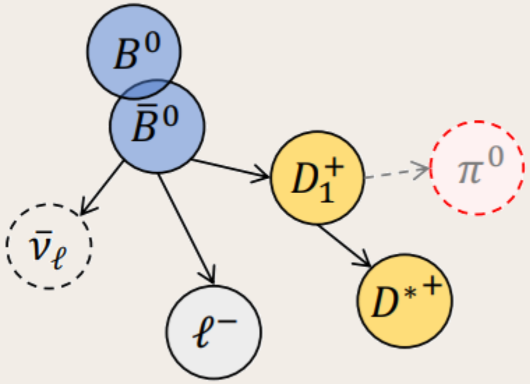
q^2 side band for $\bar{B} \to D^* \ell^- \bar{\nu}_\ell$

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



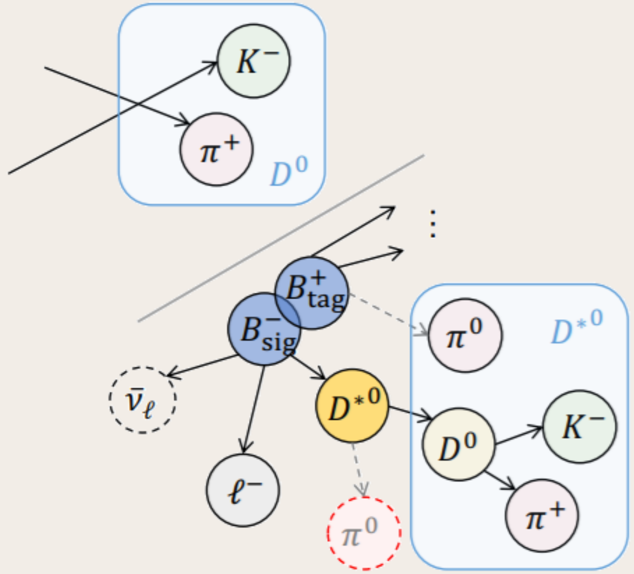
$\bar{B} \to D^{**} \ell^- \bar{\nu}_\ell$-enhanced side band

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



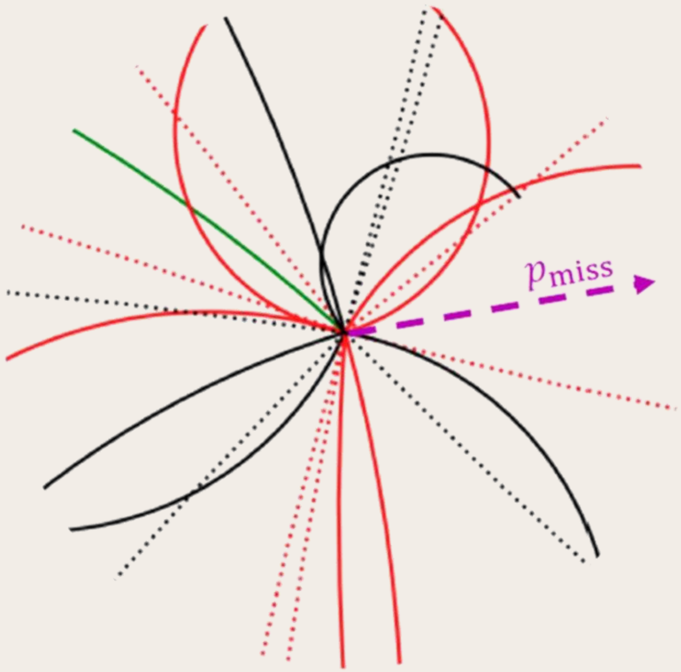
$\bar{B} \to D^{**} \ell^- \bar{\nu}_\ell$ have unknown rates and can mimic $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$.

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



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

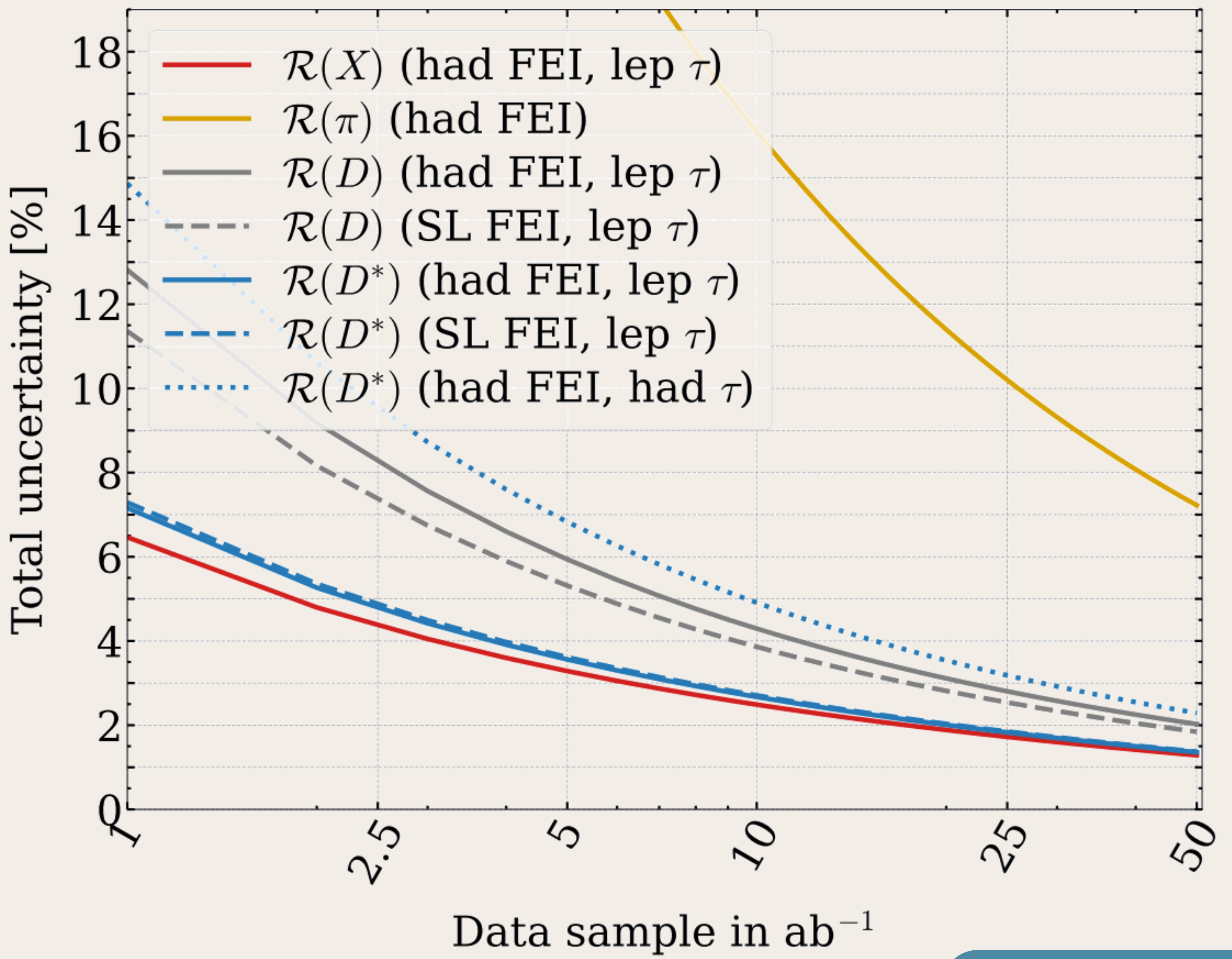
FEI Hadronic Tag: Pros and Cons



Hadronic FEI (Full Event Interpretation):

- Fully reconstructs one B in a hadronic decay mode, e.g. $B \to D^* n\pi\, m\pi^0$; require $n \leq 3$ and $m \leq 1$ in most modes (trade-off between efficiency and purity)
- Demand remaining particles match desired signal decay up to soft neutral activity (completeness)
- Reduces $e^+e^- \to q\overline{q}$ continuum background, $B \leftrightarrow B$ combinatorial background
- Can determine p_{miss} since full initial state is knows
- Makes B_{tag} efficiency $< 1\%$

Expected sensitivity of at Belle II



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