Experimental Status of Semi-Leptonic B-decays

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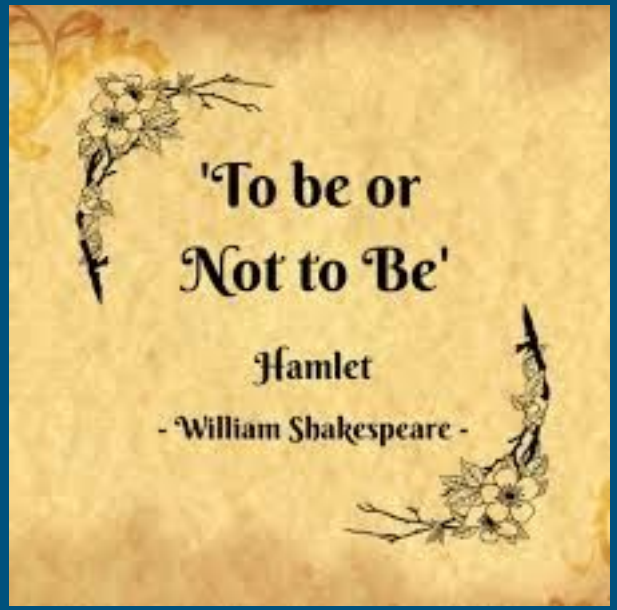
Talk Outline

- Introduction
- Tagging methods
- $|V_{ub}|$ from $B^0 \rightarrow \pi^- l^+ \nu$ and $B^+ \rightarrow \rho^0 l^+ \nu$
- Lepton Flavor Violation (LFV):
  Measurement of $R(D^*)$
  Measurement of $R(X)$
- Measurement of BR ($B \rightarrow K \nu \bar{\nu}$)
- Conclusions

Selected modes using Belle II results shown

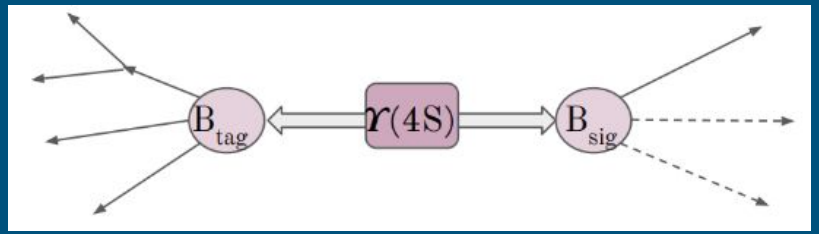


Introduction

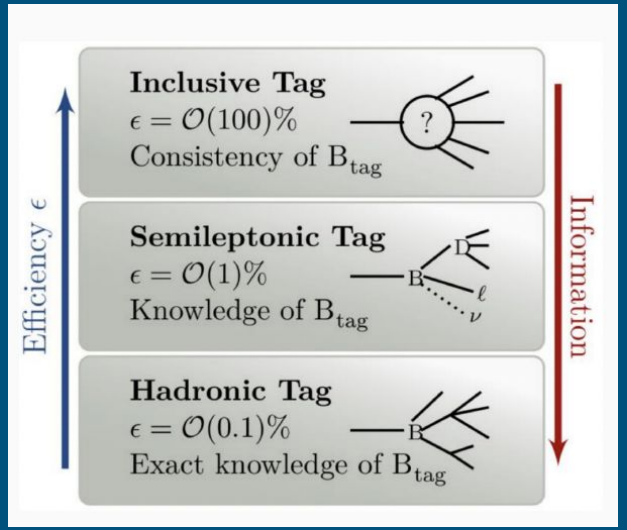
- Unitarity of CKM matrix imposes constraints to test Standard Model.
- Belle II provides a unique testbed for SM tests in the B-sector as it is primarily a B-factory ($e^+ e^- \rightarrow \Psi(4S) \rightarrow$ BB-bar)

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

Tagging Methods



Both B_{tag} and B_{sig} are reconstructed.

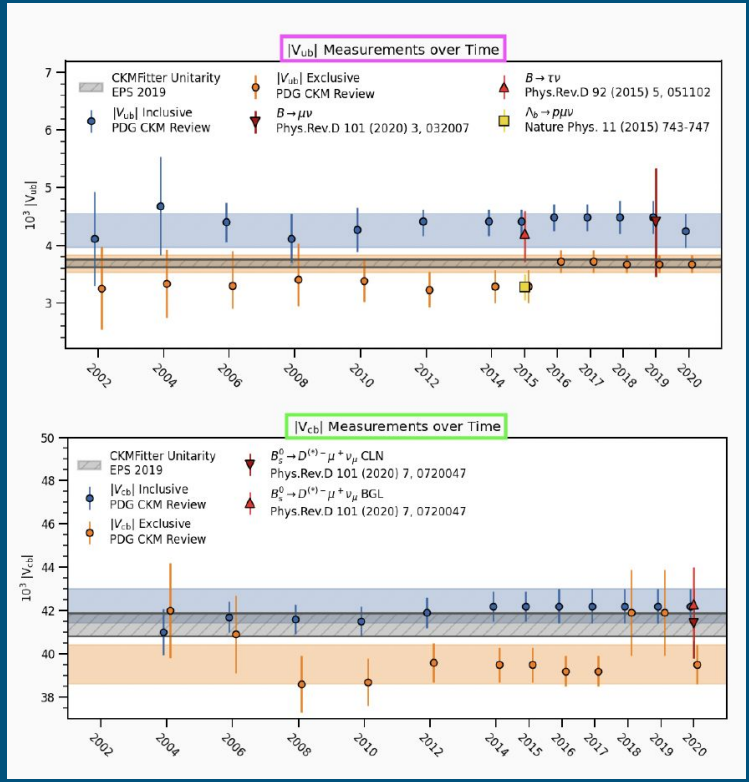


Exclusive vs. Inclusive: depends on reconstruction of B_{sig}

- Exclusive: B_{sig} is reconstructed in a specific decay mode.
- Inclusive: B_{sig} reconstructed as many modes, e.g., $B_{sig} \rightarrow X\ell\nu$.

$|V_{ub}|$ from $B^0 \rightarrow \pi^- l^+ \nu$ and $B^+ \rightarrow \rho^0 l^+ \nu$

- Tension between exclusive (orange band) and inclusive (blue band)
- Precision measurements of the CKM parameters $|V_{ub}|$ and $|V_{cb}|$ can be done using semi-leptonic B decays
- $|V_{ub}|$: b → u transitions (B → X_u lν)
  $|V_{cb}|$: b → c transitions (B → X_c lν)



$|V_{ub}|$

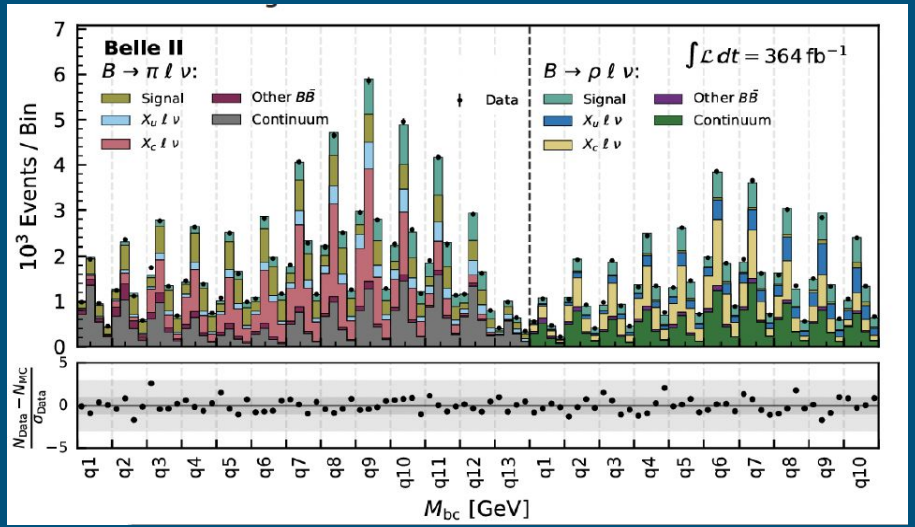
$|V_{cb}|$

$|V_{ub}|$ from $B^0 \to \pi^- l^+ \nu$ and $B^+ \to \rho^0 l^+ \nu$ arXiv:2407.17403

- Belle II, Run 1 data (364 fb^{-1}) untagged
- Background suppression done using BDTs
- Kinematic variables used are ΔE and M_{bc}
- Signal yields are extracted from these 2 kinematic variables in bins of q^2 simultaneously. For $B \to X l \nu$, $\mathbf{q^2 = (p_B - p_X)^2}$

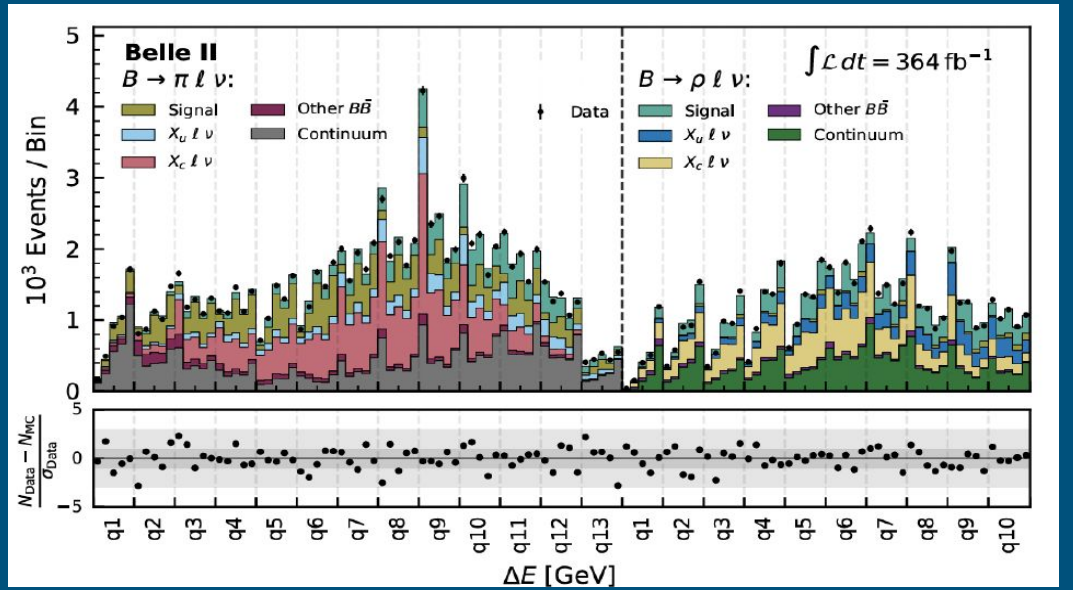
$M_{bc}c^2 = \sqrt{(E^{*2}_{beam} - |p^*_B|^2)}$

$\Delta E = E^*_B - E^*_{beam}$



$|V_{ub}|$ from $B^0 \rightarrow \pi^- l^+ \nu$ and $B^+ \rightarrow \rho^0 l^+ \nu$

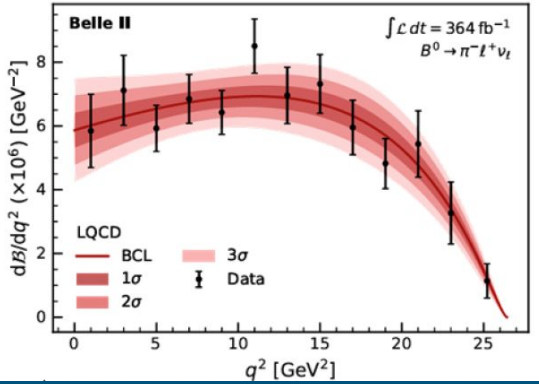
- $|V_{ub}|$ is extracted separately from $B^0 \rightarrow \pi^- l^+ \nu$ and $B^+ \rightarrow \rho^0 l^+ \nu$ modes using chi^2 fits to the measurement q^2 spectra.

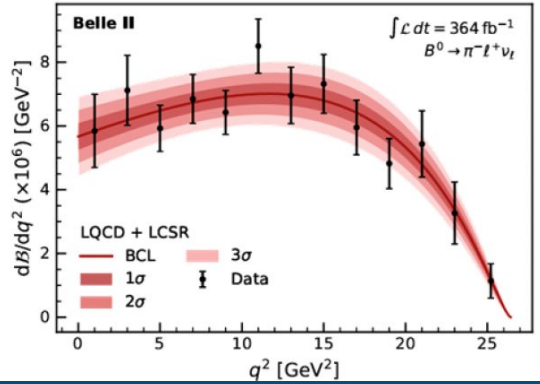


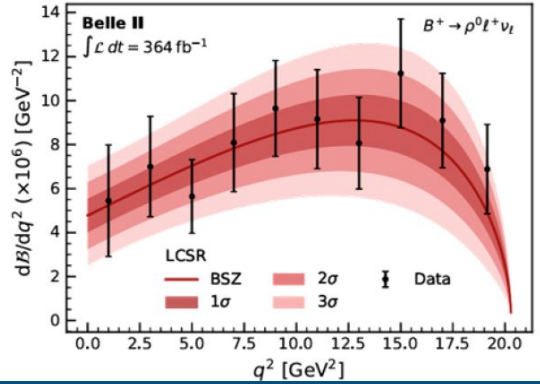
$|V_{ub}|$ from $B^0 \to \pi^- l^+ \nu$ and $B^+ \to \rho^0 l^+ \nu$

$$\mathcal{B}(B^0 \to \pi^- l^+ \nu_l) = \left(1.516 \pm 0.042(stat) \pm 0.059(sys)\right) \times 10^{-4}$$
$$\mathcal{B}(B^+ \to \rho^0 l^+ \nu_l) = \left(1.625 \pm 0.079(stat) \pm 0.180(sys)\right) \times 10^{-4}$$

Consistent with PDG







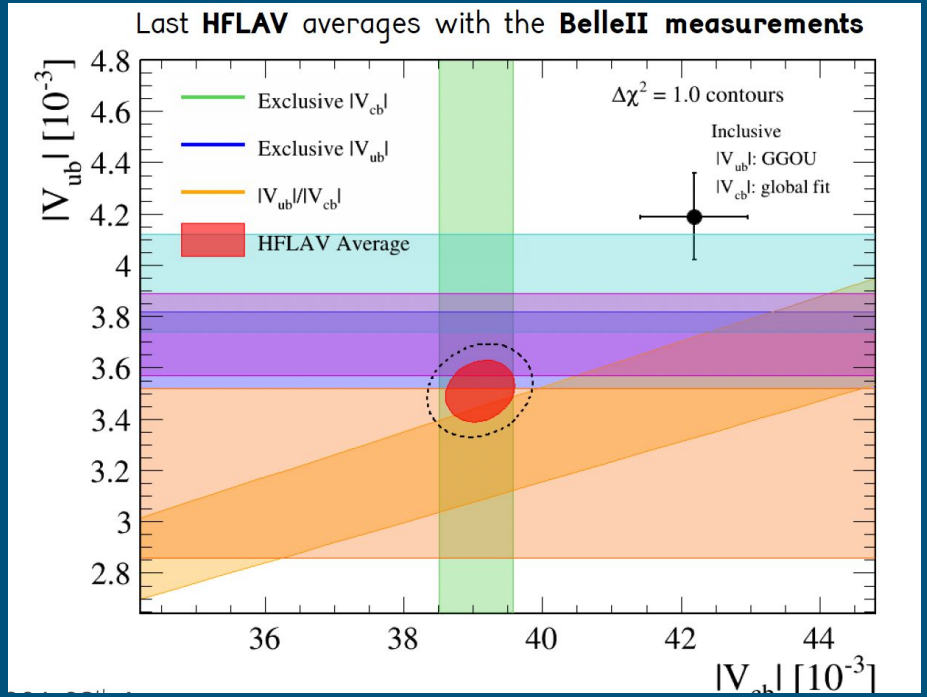
$B^0 \to \pi^- l^+ \nu_l$: $|V_{ub}| = (3.93 \pm 0.09(stat) \pm 0.13(sys) \pm 0.19(theo)) \times 10^{-3}$ LQCD constraints

$|V_{ub}| = (3.73 \pm 0.07(stat) \pm 0.07(sys) \pm 0.16(theo)) \times 10^{-3}$ LQCD+LCSR constraints

$B^+ \to \rho^0 l^+ \nu_l$: $|V_{ub}| = (3.19 \pm 0.12(stat) \pm 0.17(sys) \pm 0.26(theo)) \times 10^{-3}$ LCSR constraints

$|V_{ub}|$ from $B^0 \rightarrow \pi^- l^+ \nu$ and $B^+ \rightarrow \rho^0 l^+ \nu$

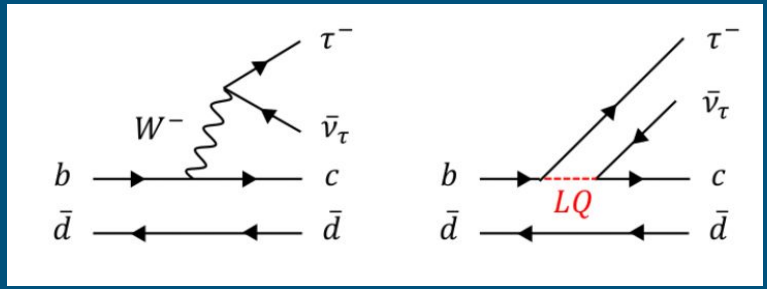
- Large uncertainty on the $|V_{ub}|$ values
- Tension with inclusive measurement is reduced.



LFV: Measurement of R(D*)

- Test of LFU

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)} \quad (\ell = e \text{ or } \mu)$$

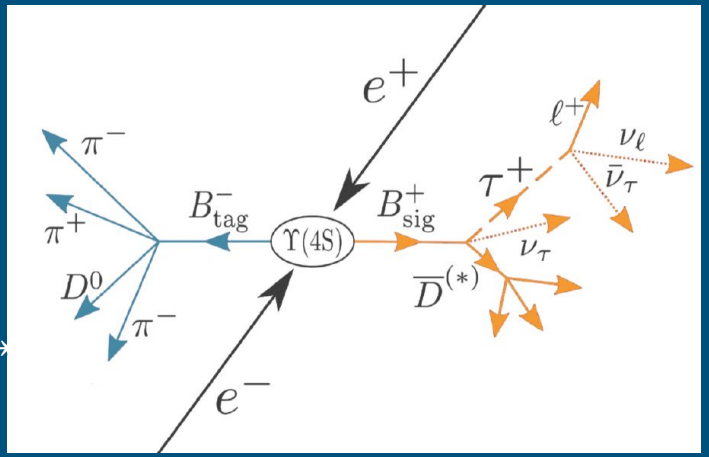


- Semileptonic B decays involving a τ lepton are sensitive to physics beyond the SM (BSM).
- Coupling to all lepton flavors is the same in the SM, but the large value of the τ mass results in a reduced phase space factor, and hence R(D) and R(D*) are expected to be 0.298 +/- 0.004 and 0.254 +/- 0.005, respectively in SM.

LFV: Measurement of R(D*)

arXiv:2401.02840

- Belle II, Run 1 data (189 fb^{-1})
- Btag decays hadronically
- Reconstruct τ and light lepton decays into the same final state particles to cancel many systematic uncertainties
- Reconstruct the D^* in the following channels: $D^* \rightarrow D^0\pi+$, $D+\pi^0$ and $D^0\pi^0$.
- Rest of the event: no good quality tracks, no π^0 candidates. Sum of all the neutral extra clusters energy is called E_{ECL} .
- Poorly understood $B \rightarrow D^{**}\ell\nu$ backgrounds is one of the major background

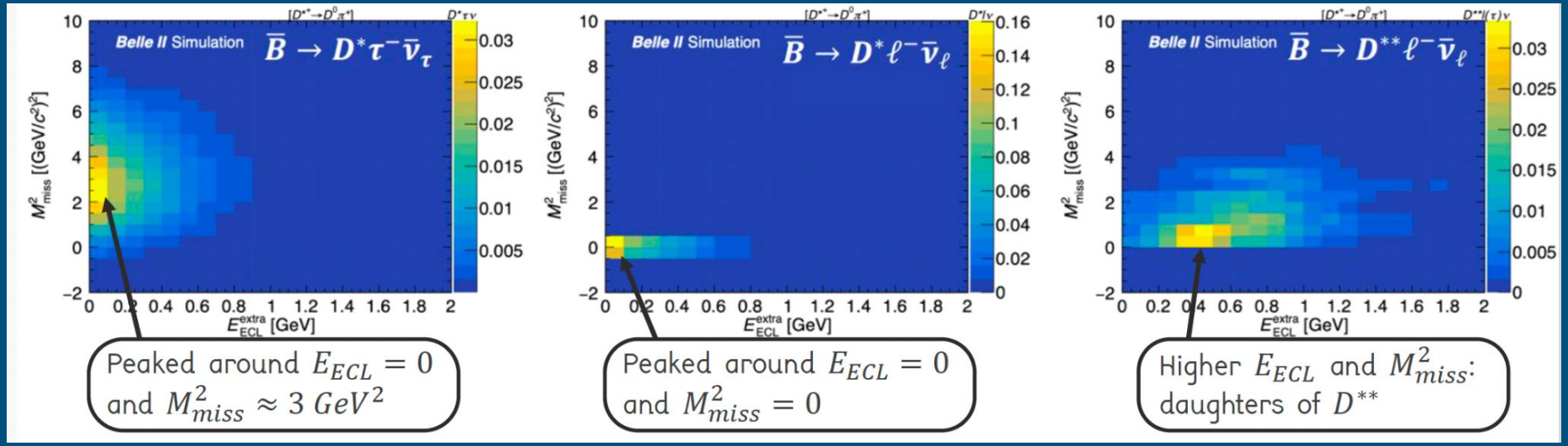


$$R\left(D^*_{\tau/\ell}\right) = \frac{B(B \rightarrow D^*\tau\nu)}{B(B \rightarrow D^*\ell\nu)}$$

LFV: Measurement of R(D*)

2D fit to E_{ECL} and missing mass of the event (M^2_{miss})

$$M^2_{\text{miss}} = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^*} - p_\ell)^2$$

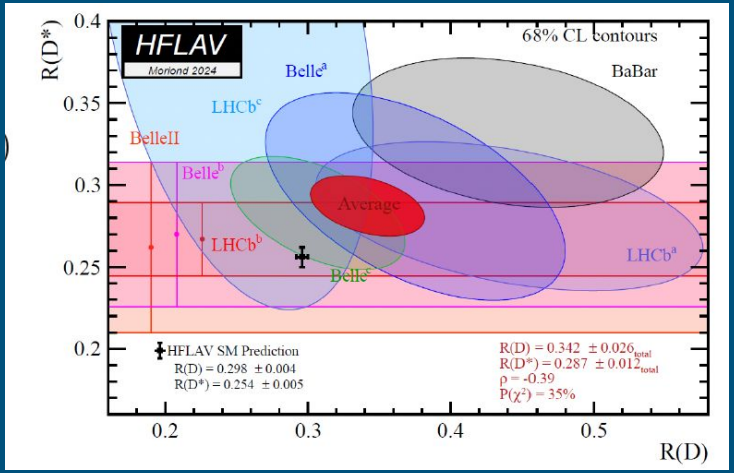


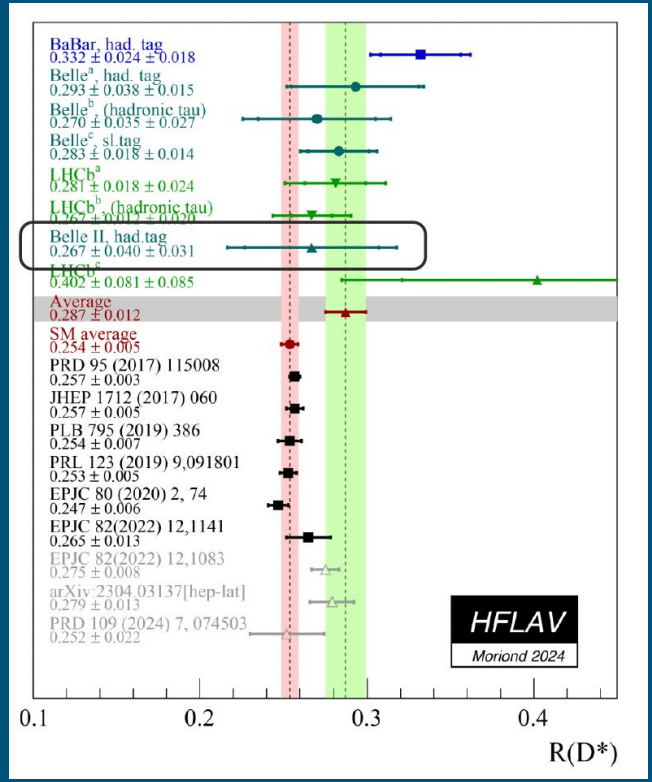
LFV: Measurement of $R(D^*)$

Belle II preliminary result

$$R\left(D^*_{\tau/\ell}\right) = 0.262^{+0.041}_{-0.039}(stat)^{+0.035}_{-0.032}(sys)$$

- Consistent with SM and HFLAV
- Update using 364 fb^{-1} in progress



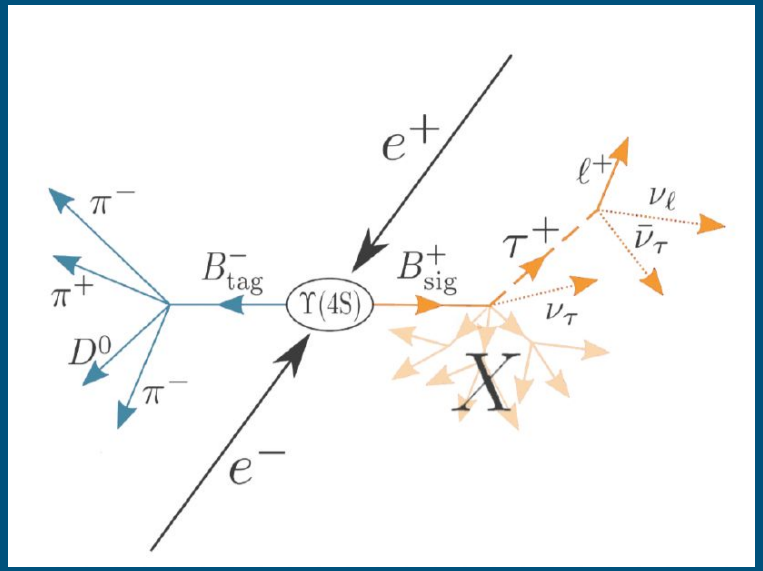


SM prediction: 0223 +/- 0.005

Measurement of R(X)

Phys. Rev. Lett. 132.211804 (2024)

- Belle II, Run 1 data (189 fb^{-1})
- 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



$$R(X_{\tau/\ell}) = \frac{B(B \to X\tau\nu)}{B(B \to X\ell\nu)}$$

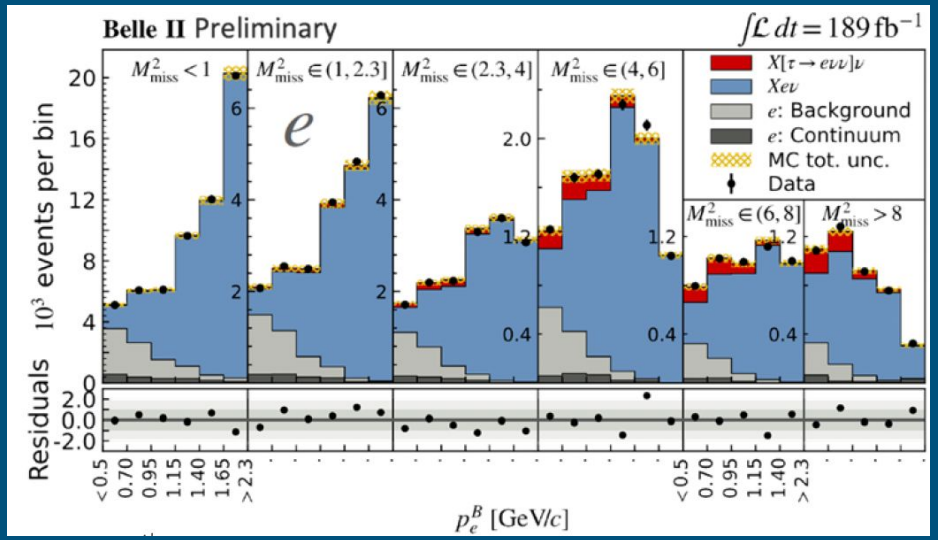
Measurement of R(X)

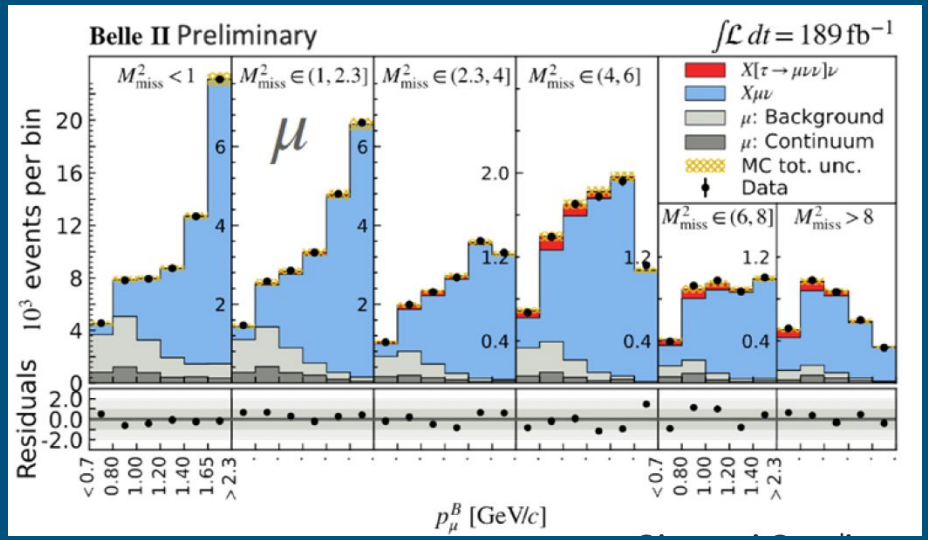
- **MC corrections are applied**

- **Final Fit:** We extract the signal and normalization yields for the electron and muon modes from a simultaneous maximum-likelihood fit to the binned two-dimensional distributions of p_ℓ and M^2_{miss}

  Fit components: $X\tau\nu$, $X\ell\nu$, BB background (fakes and secondaries) and continuum (off resonance data)

Measurement of R(X)





First measurement of the tau-to-light-lepton ratio of inclusive semileptonic B-meson branching fractions [complementary probe of LUV to the exclusive D* decays]

Measurement of R(X)

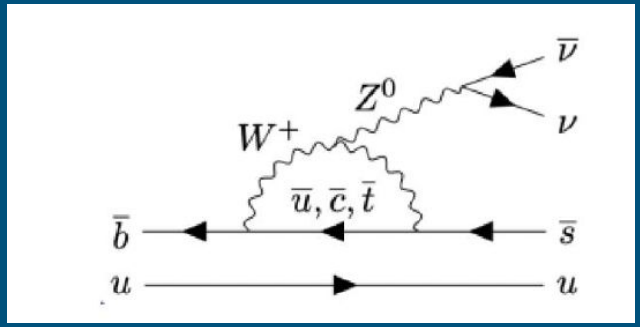
$$R(X_{\tau/e}) = 0.232 \pm 0.020(\text{stat}) \pm 0.037(\text{syst}),$$
$$R(X_{\tau/\mu}) = 0.222 \pm 0.027(\text{stat}) \pm 0.050(\text{syst}),$$

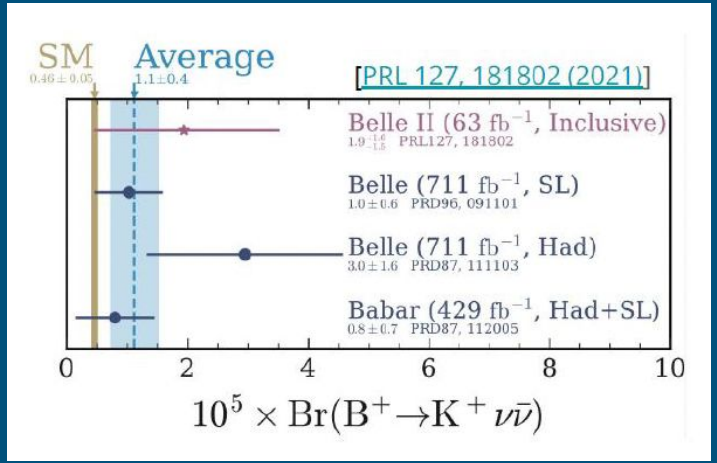
$$R(X_{\tau/\ell}) = 0.228 \pm 0.016(\text{stat}) \pm 0.036(\text{syst})$$

- Largest systematics: signal and background model
- Consistent with previous measurements from LEP, SM expectation, and constraints from $R\,(D^*)$.
- **SM expectation: $R\,(X_{\tau/\ell}) \approx 0.223$** [JHEP11(2022)007]

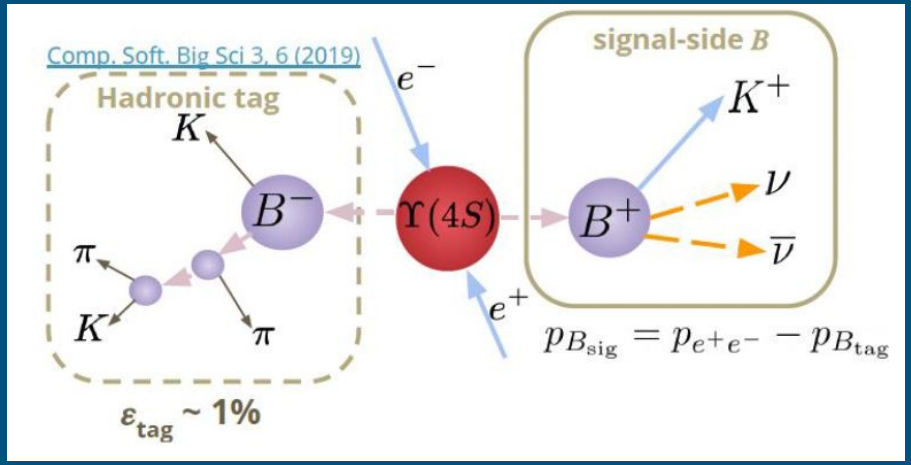
Measurement of BR (B → K ν ν-bar)

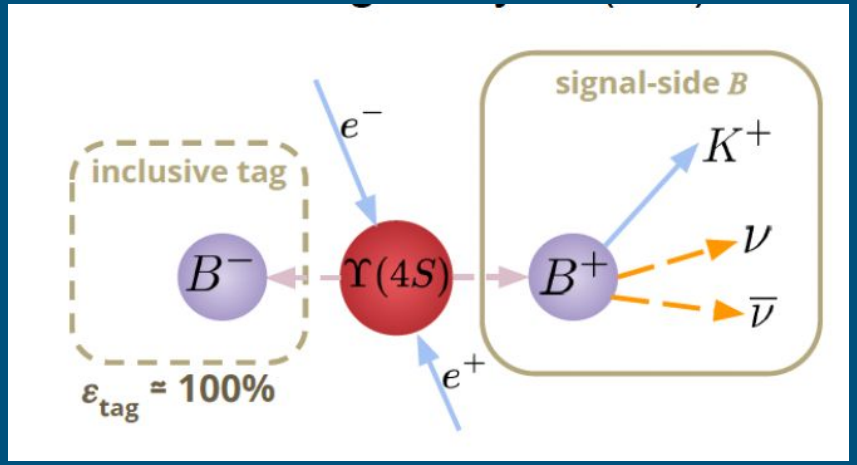
- FCNC process
- SM prediction: Small BF
  BR ($B^+ \rightarrow K^+ \nu\,\bar{\nu}$) = (0.56 ± 0.04) 10^{-5}
  [PRD 107, 014511 (2023)]
- EW penguin, sensitive to NP
- Mode unique to $e^+ e^-$ colliders





Measurement of BR (B → K ν ν-bar)





- Hadronic Tag (HT): Conventional method
- Reconstruct tag-side B with hadronic mode
- Lesser background

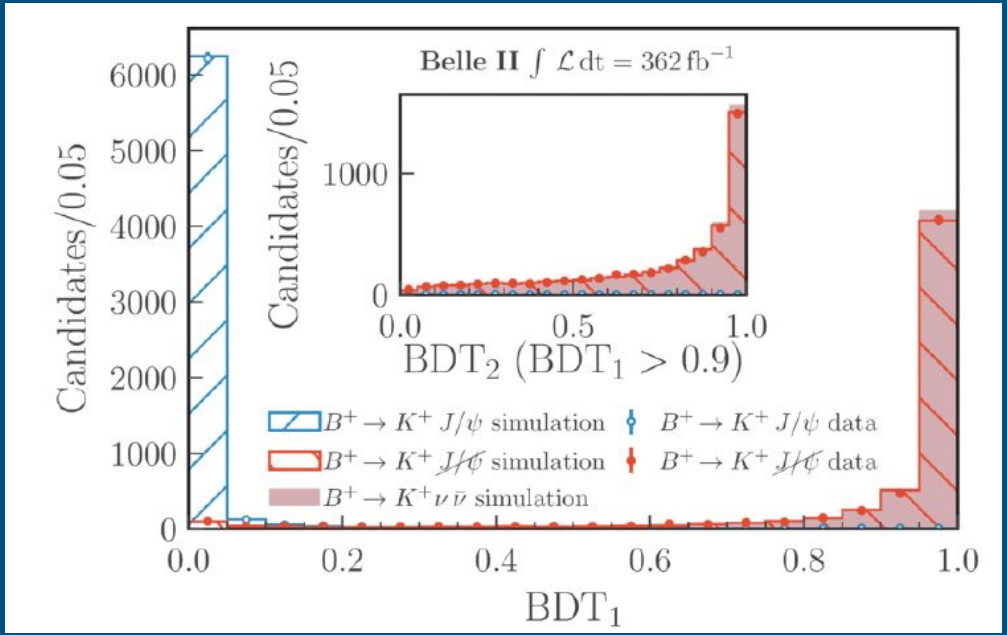
- Inclusive Tag (IT): Novel technique at Belle II— more sensitive than HT
- Reconstruct signal B (pick up K^+) only exploit the rest of the event (ROE) to suppress backgrounds.

Measurement of BR (B → K ν ν-bar)

Phys. Rev. D. 109.112006 (2024)

- Belle II, Run 1 data (362 fb^{-1})
- Analysis used 2 different tagging methods: IT (innovative) and HT (conventional).
- Inclusive tag (IT): uses 2 consecutive classifiers with single kaon (one with the lowest q^2), event shape, and rest of the event information—2 BDTs

q^2: mass squared of the neutrino pair



Measurement of BR (B → K ν ν-bar)

Phys. Rev. D. 109.112006 (2024)

- **Signal Efficiency Validation done with control channel,** $B \to J/\psi$K sample, removing J/ψ and correcting K^+ kinematics

- **Background Validation: Detailed studies of other B decay modes especially with K_L in the final states**
  - Undetected K_L in ECL can mimic neutrinos
  - K_L efficiency: $e^+e^- \to \gamma\phi \to K_L K_S$
  - Corrections for $B^+ \to K^+ K_L K_L$ background from $B^+ \to K^+ K_S K_S$
  - $B \to X_c$ ($\to K_L$) validated using a pion enriched sample

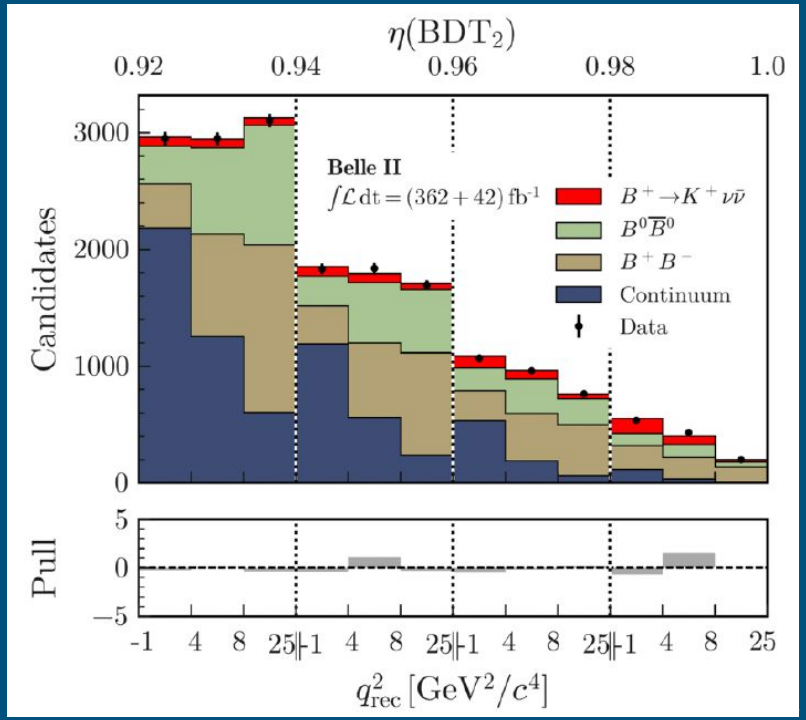
Measurement of BR (B → K ν ν-bar)

Phys. Rev. D. 109.112006 (2024)

Binned maximum likelihood fit done to extract signal:

- HT fit: uses Classifier output
- IT fit: uses Classifier output and mass squared of neutrino pair

Final observables: q_{rec}^2 in bins of the second classifier (BDT)



Phys. Rev. D. 109.112006 (2024)

Measurement of BR (B → K ν ν-bar)

Inclusive Tag:

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

3.5σ significance wrt bkg only hypothesis

2.9σ deviation from SM

Hadronic Tag:

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

1.1σ significance wrt bkg only

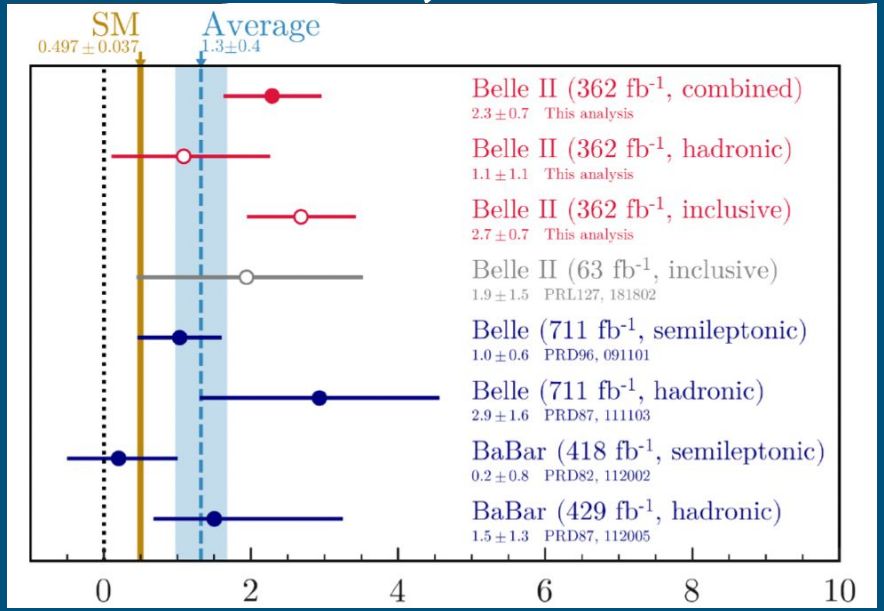
0.6σ deviation from SM

Combination:

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

3.5σ significance wrt bkg only

2.7σ deviation from SM



First evidence for B → K ν ν-bar

Conclusions

- New Exclusive V_{ub} measurement from untagged $B \to \pi/\rho \ell \nu$: Key to understanding exclusive-inclusive tension and important in testing CKM parameters in the context of SM predictions

- New measurement of R (D*)
  Important test for SM and probe beyond the SM physics

- Measurement of R (X)
  Important test for SM and probe beyond the SM physics

- First evidence of $B^+ \to K^+ \nu\nu$-bar, 2.7σ above the SM prediction
  Important test for SM and probe beyond the SM physics

$|V_{ub}|$ from $B^0 \to \pi^- l^+ \nu$ and $B^+ \to \rho^0 l^+ \nu$

$$\frac{\mathrm{d}\Gamma(B \to \pi \ell \nu_\ell)}{\mathrm{d}q^2 \mathrm{d}\cos\theta_{W\ell}} = |V_{ub}|^2 \frac{G_F^2 |\vec{p}_\pi|^3}{32\pi^3} \sin^2\theta_{W\ell} |f_+(q^2)|^2$$

$$\frac{\mathrm{d}\Gamma(B \to \rho \ell \nu_\ell)}{\mathrm{d}q^2 \mathrm{d}\cos\theta_{W\ell}} = |V_{ub}|^2 \frac{G_F^2 |\vec{p}_\rho| q^2}{128\pi^3 m_B^2}$$
$$\times \left[\sin^2\theta_{W\ell} |H_0(q^2)|^2 + (1-\cos\theta_{W\ell})^2 \frac{|H_+(q^2)|^2}{2} \right.$$
$$\left. + (1+\cos\theta_{W\ell})^2 \frac{|H_-(q^2)|^2}{2} \right],$$

Measurement of R(X)

- **MC corrections are applied:**

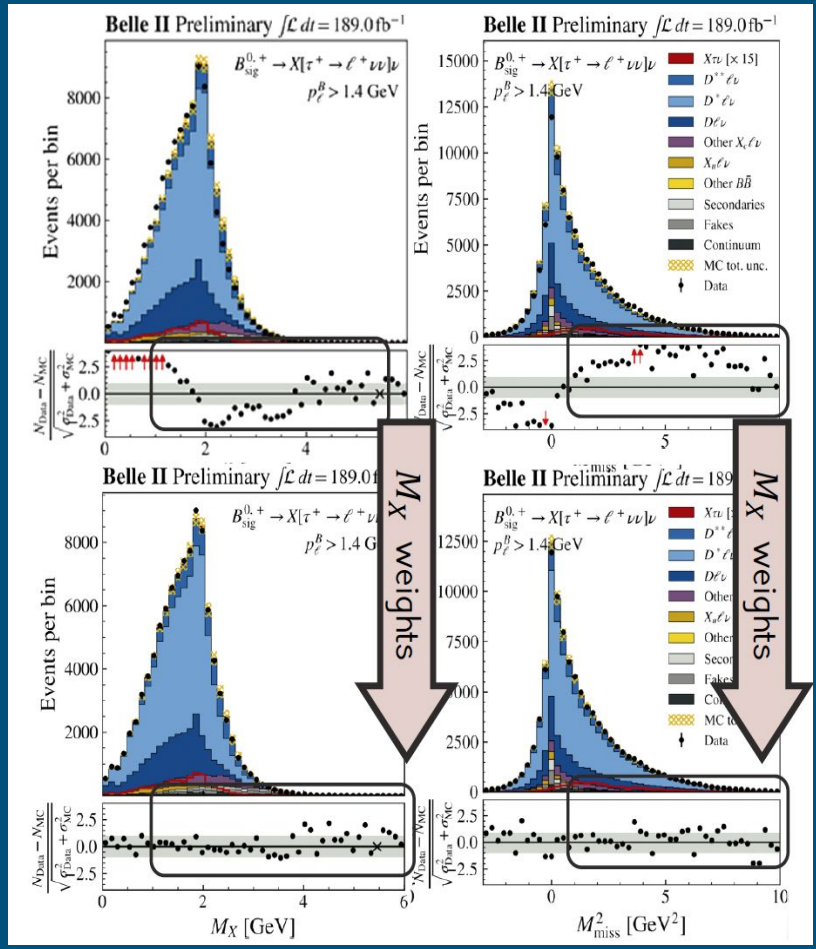
  Detailed adjustments to MC (FFs, B and D BFs)

  Detailed corrections based on comparisons of simulation with control regions: low q^2, low M^2_{miss}, high M_X.

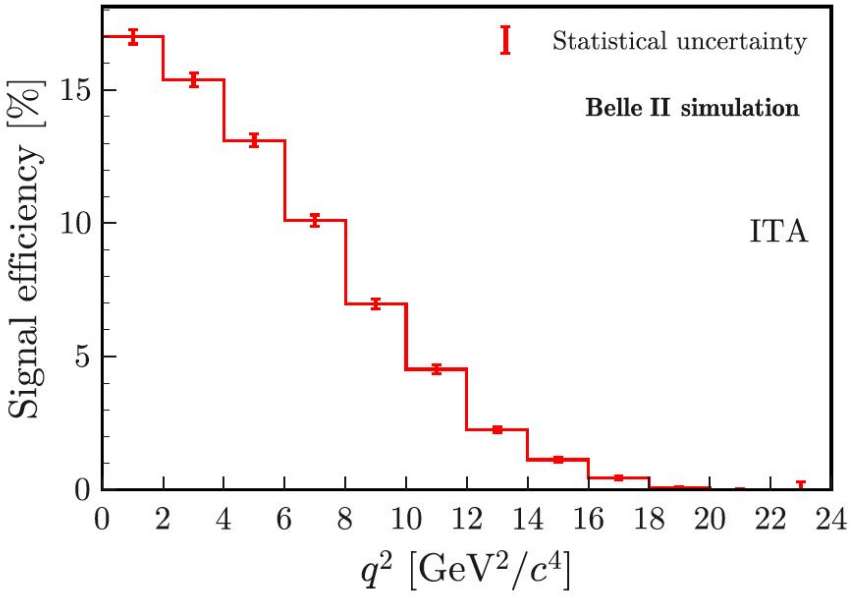
- **Final Fit:** We extract the signal and normalization yields for the electron and muon modes from a simultaneous maximum-likelihood fit to the binned two-dimensional distributions of p_ℓ and M^2_{miss}

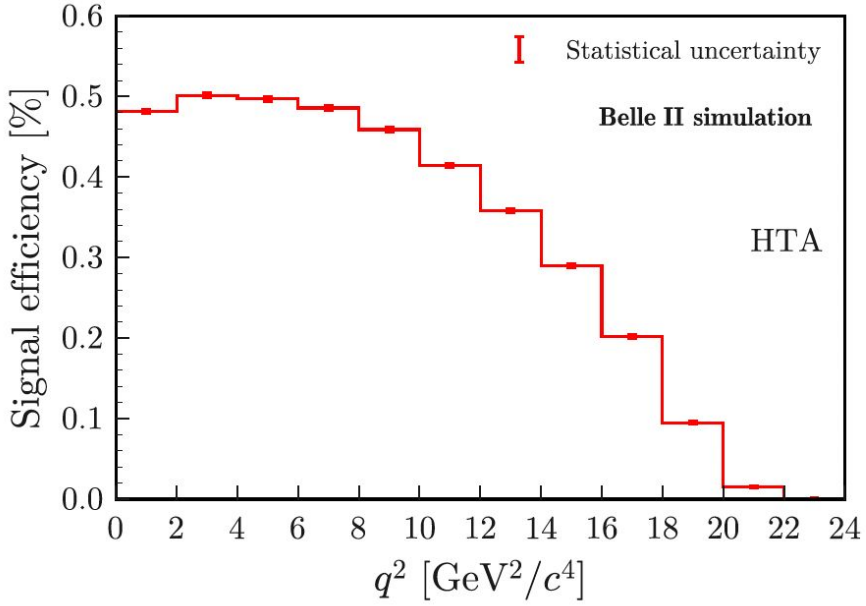
  Fit components: $X\tau\nu$, $X\ell\nu$, BB background (fakes and secondaries) and continuum (off resonance data)

Measurement of R(X)



Measurement of BR (B → K ν ν-bar)





q^2: di-neutrino mass-squared

$$q^2_{\text{rec}} = s/(4c^4) + M_K^2 - \sqrt{s}E_K^*/c^4$$