SemiLeptonic and Missing Energy B decays at Belle II

Giovanni Gaudino on behalf of Belle II collaboration

ICNFP Kolymbari – 2024, 28th August

Semileptonic B decays

Motivations of Semileptonic B decays

Lepton–Flavor Universality tests | SM Precision Measurements | Electroweak Penguins

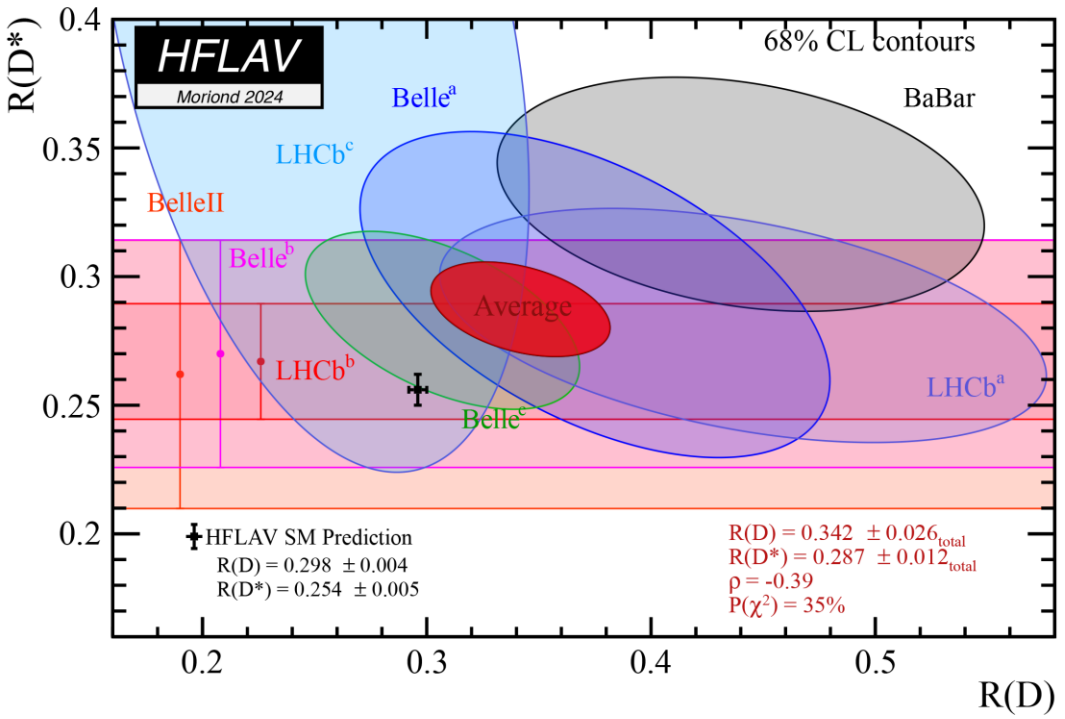
- In SM, the W boson couples equally to τ, μ, e → Lepton–Flavor Universality (LFU)
- Semileptonic B decays are sensitive to new physics beyond SM
- Ratio measurements provide stringent LFU tests: branching fractions, angular asymmetry, etc.
  - ✓ Normalization ($|V_{xb}|$) cancels
  - ✓ Part of theoretical, experimental uncertainties cancels

$$R\left(H_{\tau/\ell}\right) = \frac{B(B \to H\tau\nu)}{B(B \to H\ell\nu)}$$

$H = D^{(*)}, X, \pi, \ldots$

$\ell = e, \mu$

Tension of $R\left(D^{(*)}_{\tau/\ell}\right)$ with SM ~3σ



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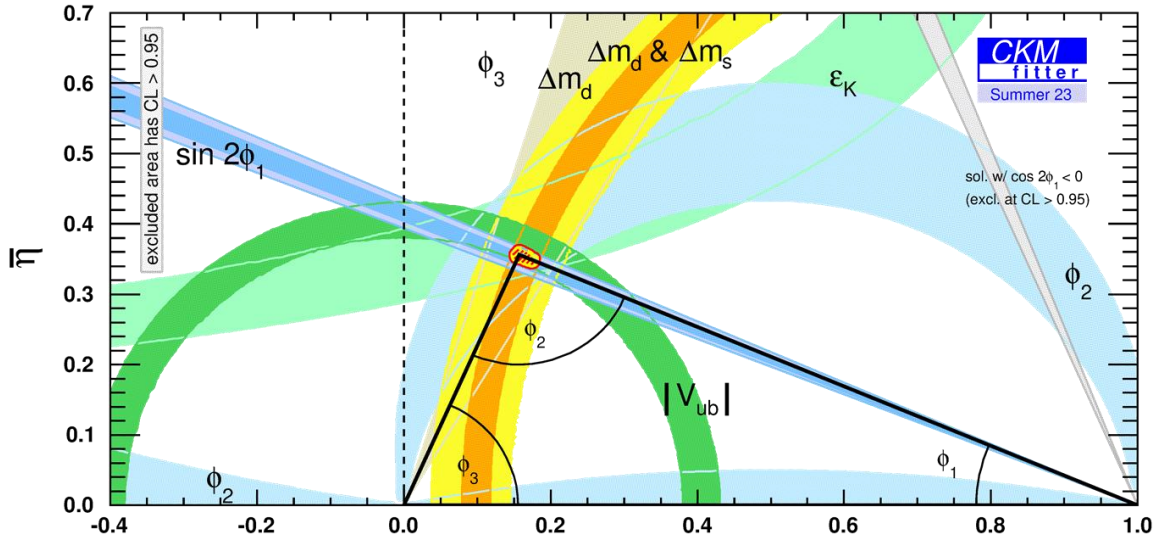
Motivations of Semileptonic B decays

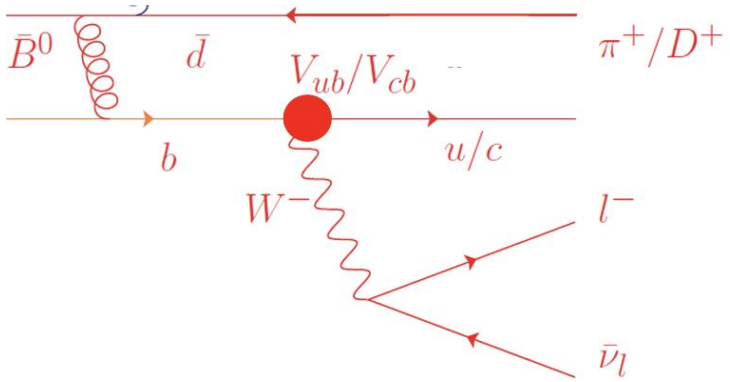
Lepton–Flavor Universality tests | **SM Precision Measurements** | Electroweak Penguins

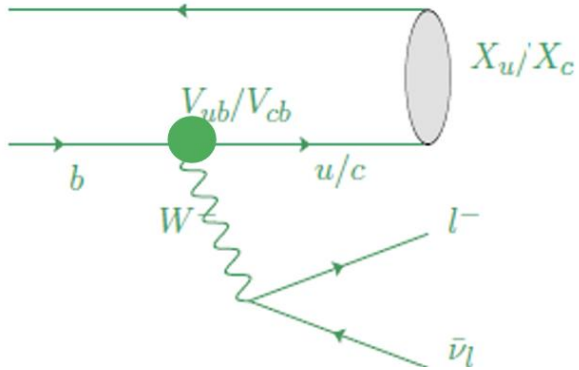
- $|V_{ub}|$ and $|V_{cb}|$ important to **constrain** CKM Unitarity
- **Precisely** measured with semileptonic B decays

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



Longstanding **tension** between exclusive and inclusive determinations

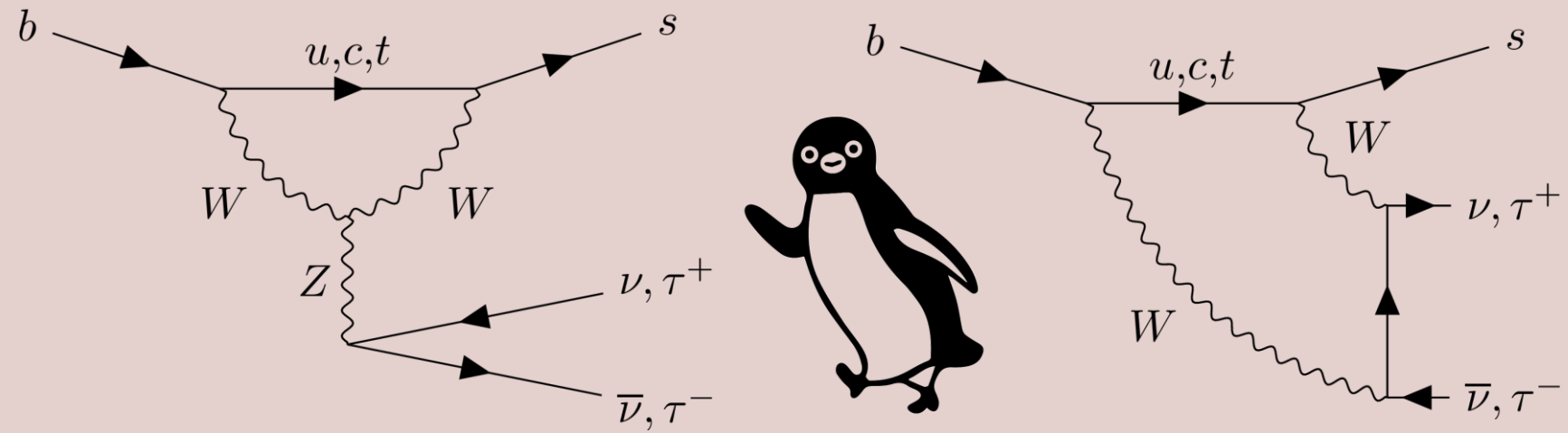




Motivations of Semileptonic B decays

Lepton–Flavor Universality tests | SM Precision Measurements | **Electroweak Penguins**

- Flavor–changing neutral currents are not possible at tree level in the **Standard Model (SM)**
- Branching fractions predicted in the range 10^{-7}–10^{-4} with 5–30% uncertainties (dominated by soft QCD effects).
- Highly sensitive to potential **non–SM contributions.**



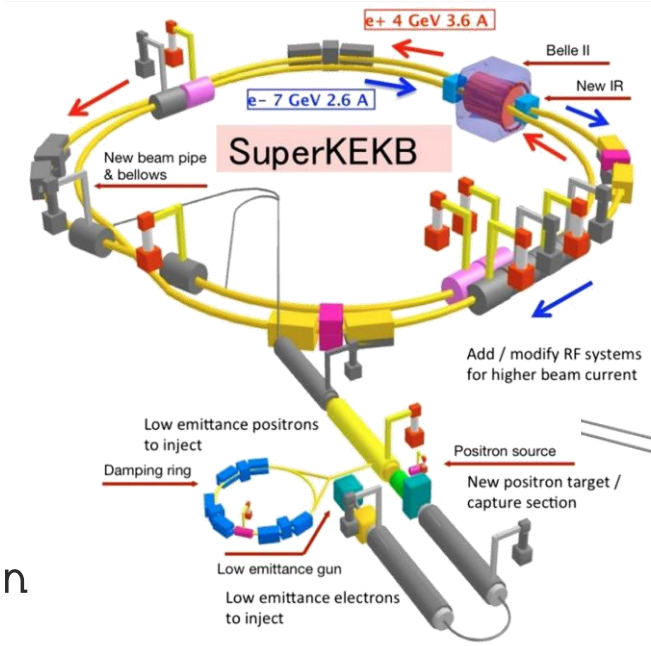
Standard Model Feynman diagram of Penguins with missing energy

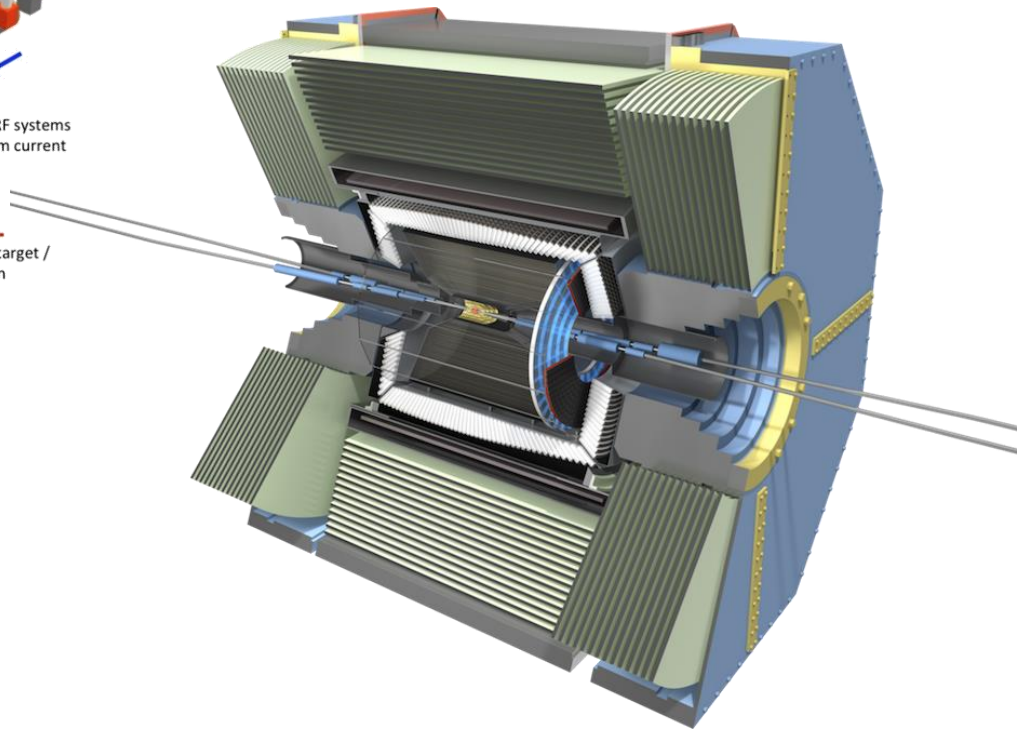
Belle II and SuperKEKB

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 $L = 4.7 \times 10^{34} cm^{-2} s^{-1}$





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

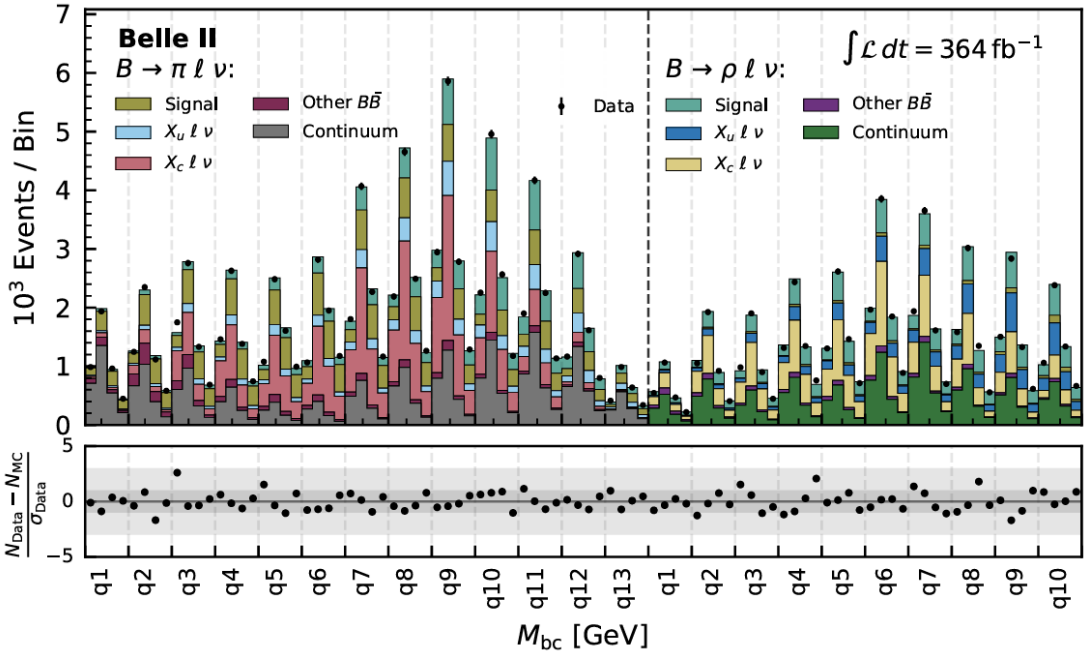
SM Precision Measurements

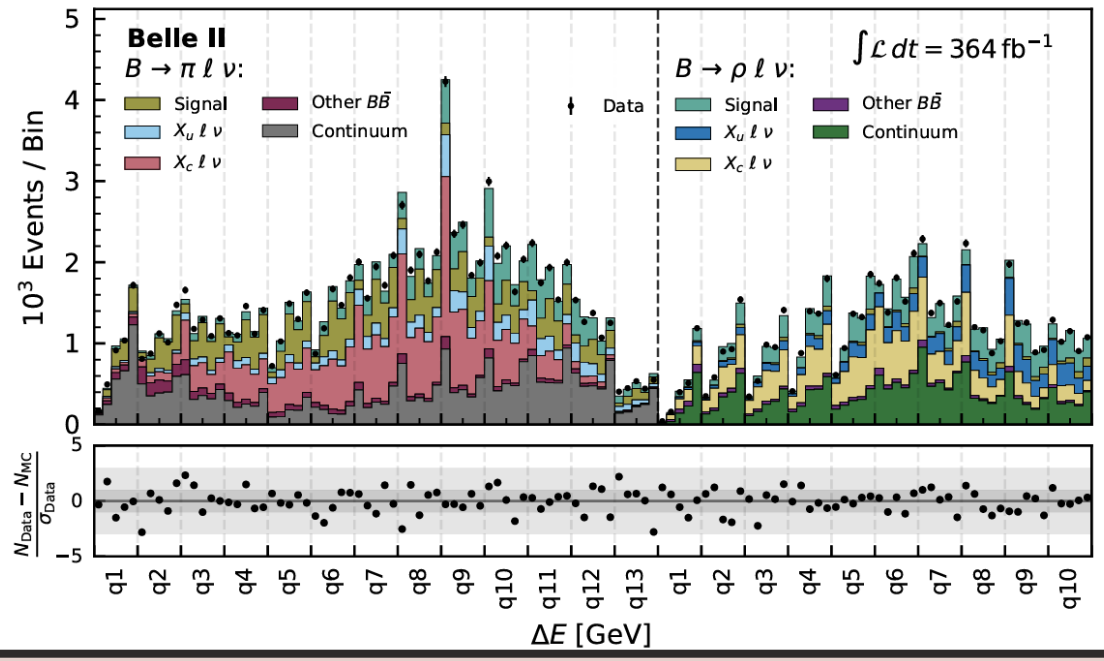
$|V_{ub}|$ from $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \rho^0 \ell^+ \nu$

- Full Belle II Run1 dataset of 364 fb^{-1}, untagged
- Non-resonant e^+e^- interactions and B background suppressed using BDTs
- Signal yields extracted from 2 kinematic variables in bins of q^2 simultaneously for $\pi l \nu$ and $\rho l \nu$ mode $\to (13 + 10) \times 4 \times 5$ bins

$$M_{bc}c^2 = \sqrt{E^{*2}_{beam} - c^2 \left|\overrightarrow{p^*_B}\right|^2}$$

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





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

Consistent with PDG

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

$|V_{ub}|$ extracted separately from $\pi l \nu$ and $\rho l \nu$ mode using χ^2 fits to the measured q^2 spectra

$$\chi^2 = \sum_{i,j=1}^{N} (\Delta B_i - \Delta\Gamma_i \tau) C_{ij}^{-1} (\Delta B_j - \Delta\Gamma_j \tau) + \sum_m \chi^2_{Theory,m}$$

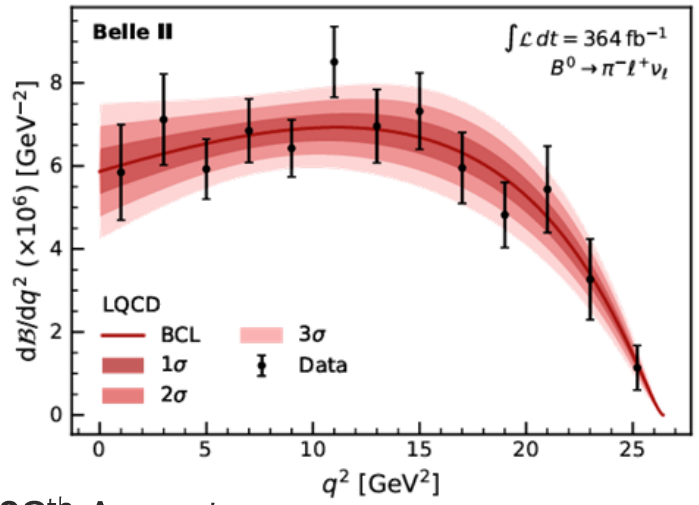
Belle II Preliminary

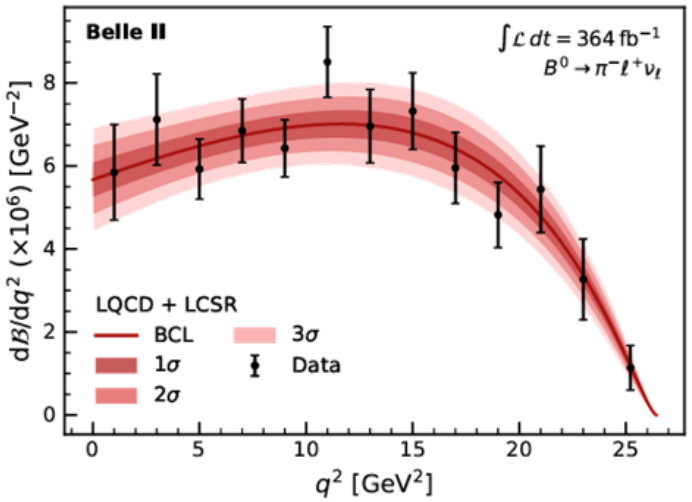
Form-factor coefficients:
BCL for $B^0 \to \pi^- l^+ \nu_l$
BSZ for $B^+ \to \rho^0 l^+ \nu_l$

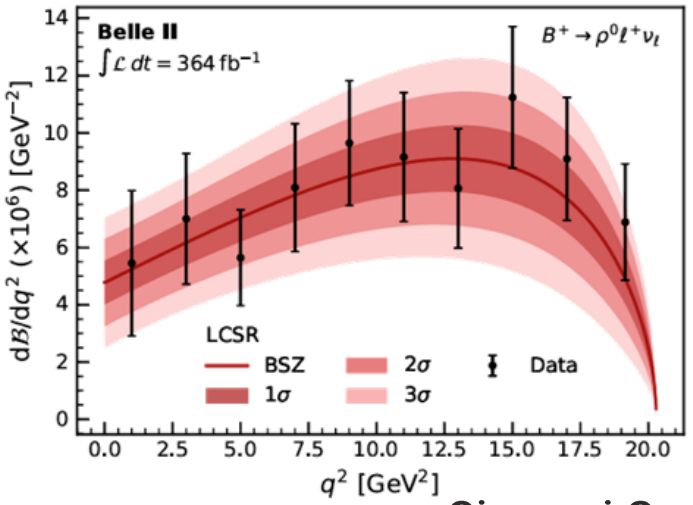
$B^0 \to \pi^- l^+ \nu_l$: $|V_{ub}| = (3.93 \pm 0.09(stat) \pm 0.13(sys) \pm 0.19(theo)) \times 10^{-3}$ **LQCD constraints**

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



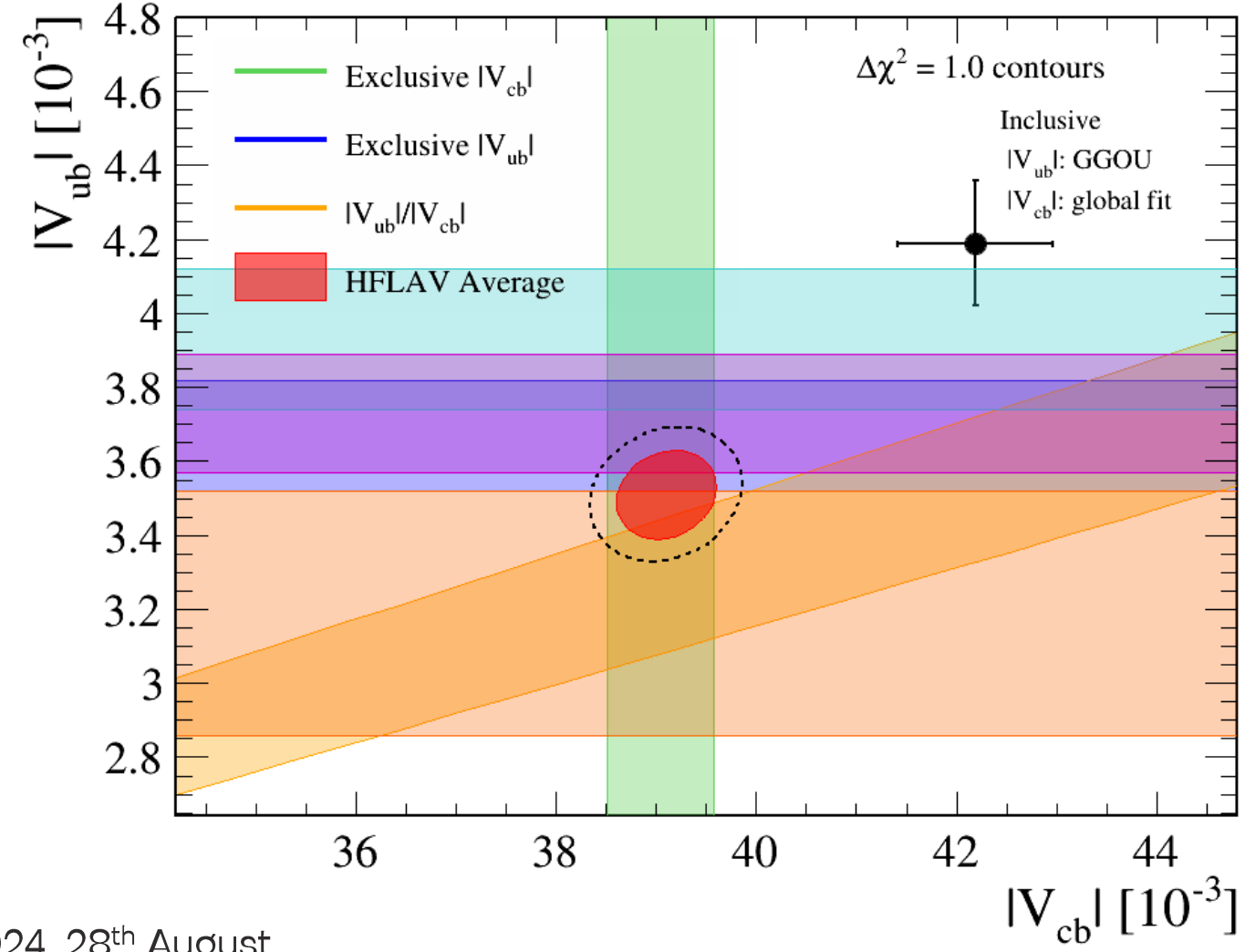




Comparison with HFLAV averages

arxiv:2407.17403

Last **HFLAV** averages with the **BelleII measurements**



- **Reducing the tension** with $|V_{ub}|$ inclusive
- Still **large** uncertainty

$B^0 \to \pi^- l^+ \nu_l$:

$(3.93 \pm 0.19) \times 10^{-3}$

$(3.73 \pm 0.16) \times 10^{-3}$

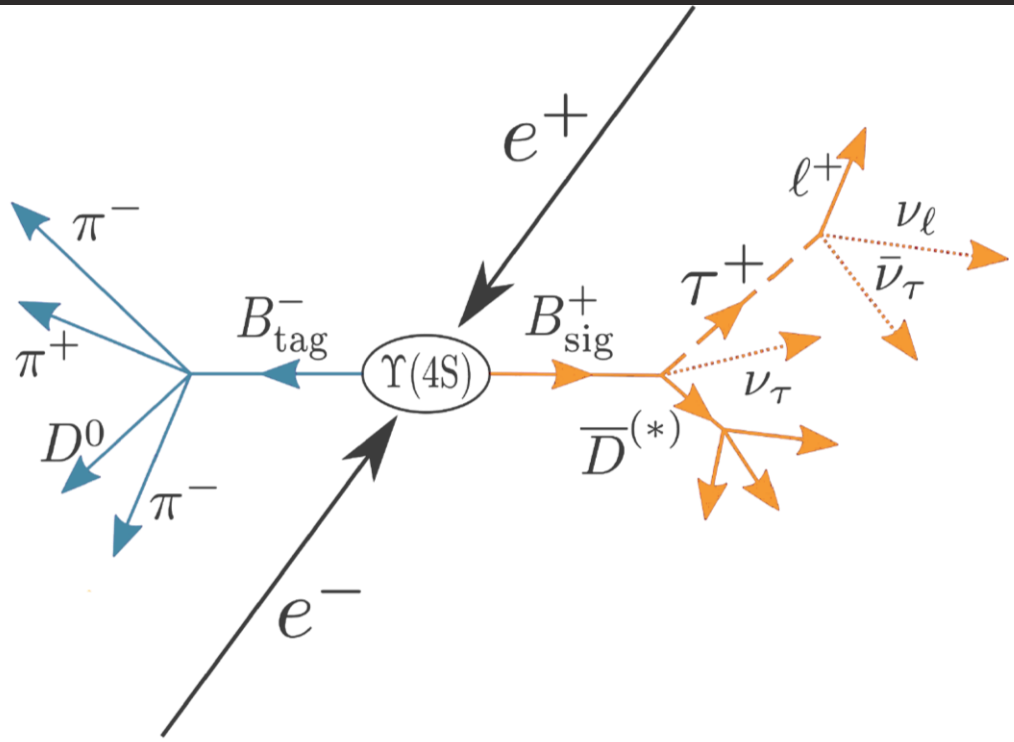
$B^+ \to \rho^0 l^+ \nu_l$:

$(3.19 \pm 0.33) \times 10^{-3}$

Lepton Flavor Universality tests

Measurement of $R(D^*_{\tau/\ell})$

- Dataset Luminosity: $L = 189/fb$
- 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 poorly understood $B \to D^{**}\ell\nu$ backgrounds.



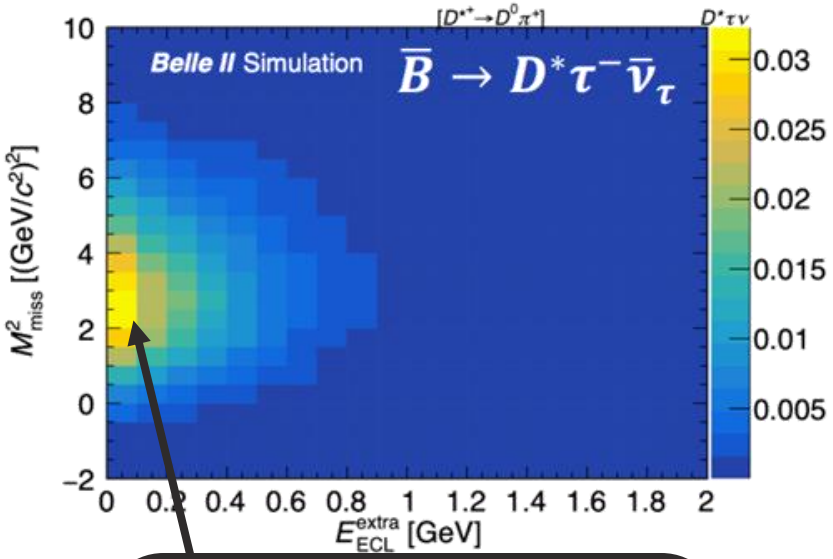
$$R(D^*_{\tau/\ell}) = \frac{B(B \to D^*\tau\nu)}{B(B \to D^*\ell\nu)}$$

Signal extraction

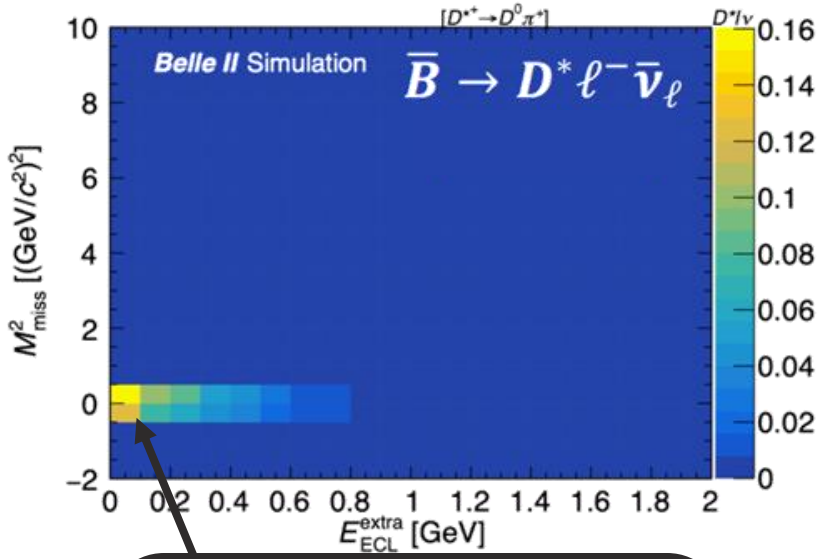
Two-dimensional binned likelihood fit to

- 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

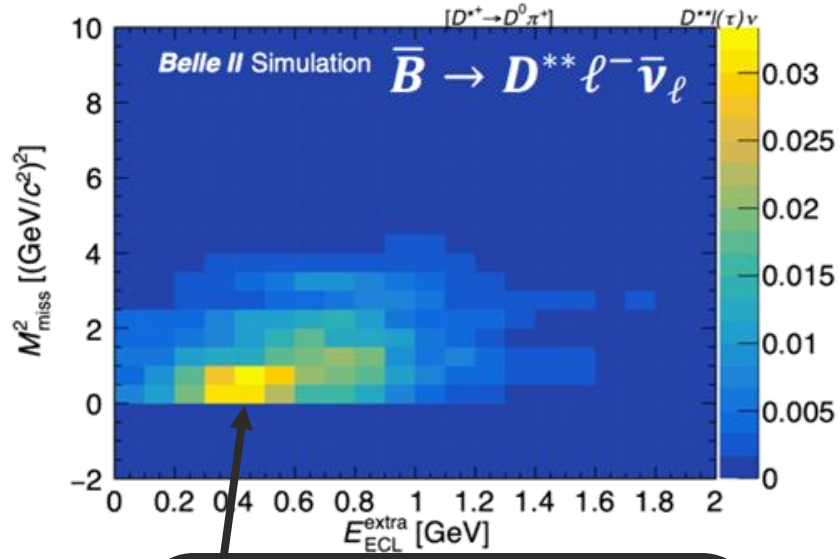
Comparable sensitivities between B^+ and B^0



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^{**}

Results

arXiv:2401.02840

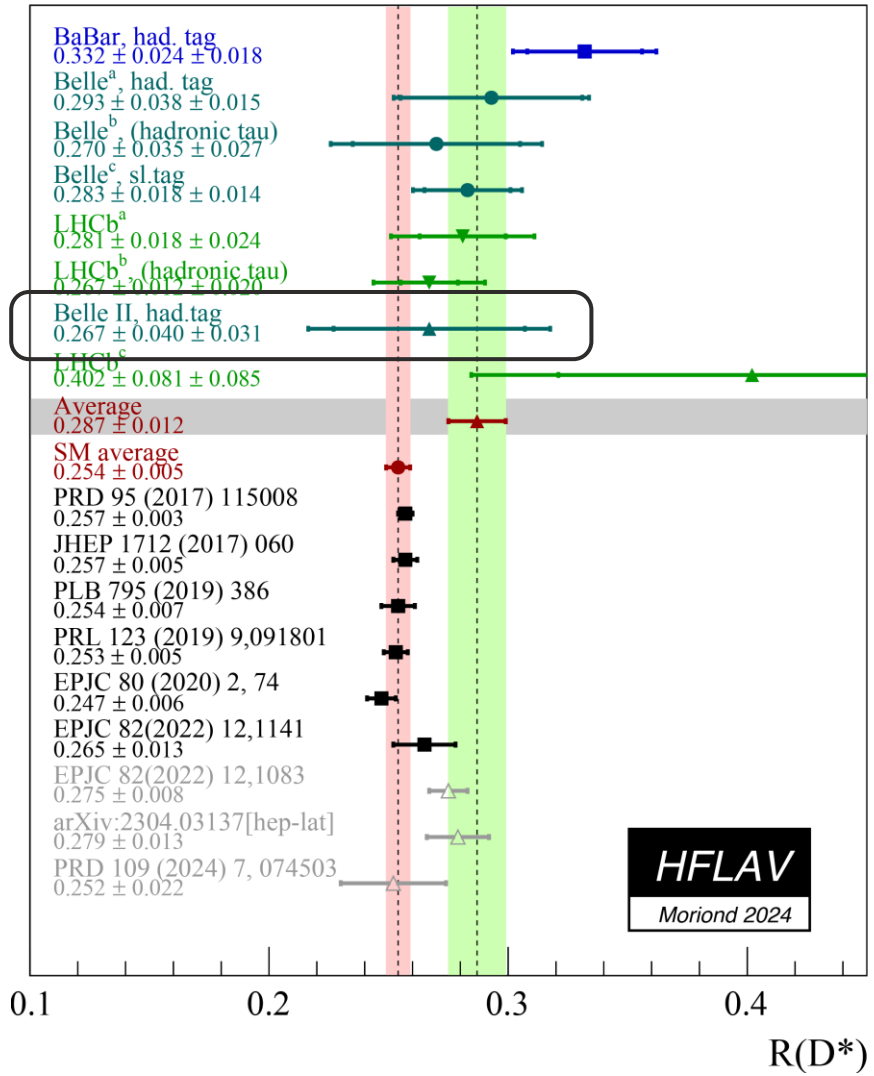
Belle II preliminary result

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

- Main systematics: MC statistics, shape of E_{ECL}
- Consistent with SM and HFLAV
- Previous version presented at Lepton Photon 2023
- Minor updates applied

In the future:

- Update of the measurement with 364/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]



Electroweak Penguins

Measurement of $B^+ \to K^+ \nu\bar{\nu}$

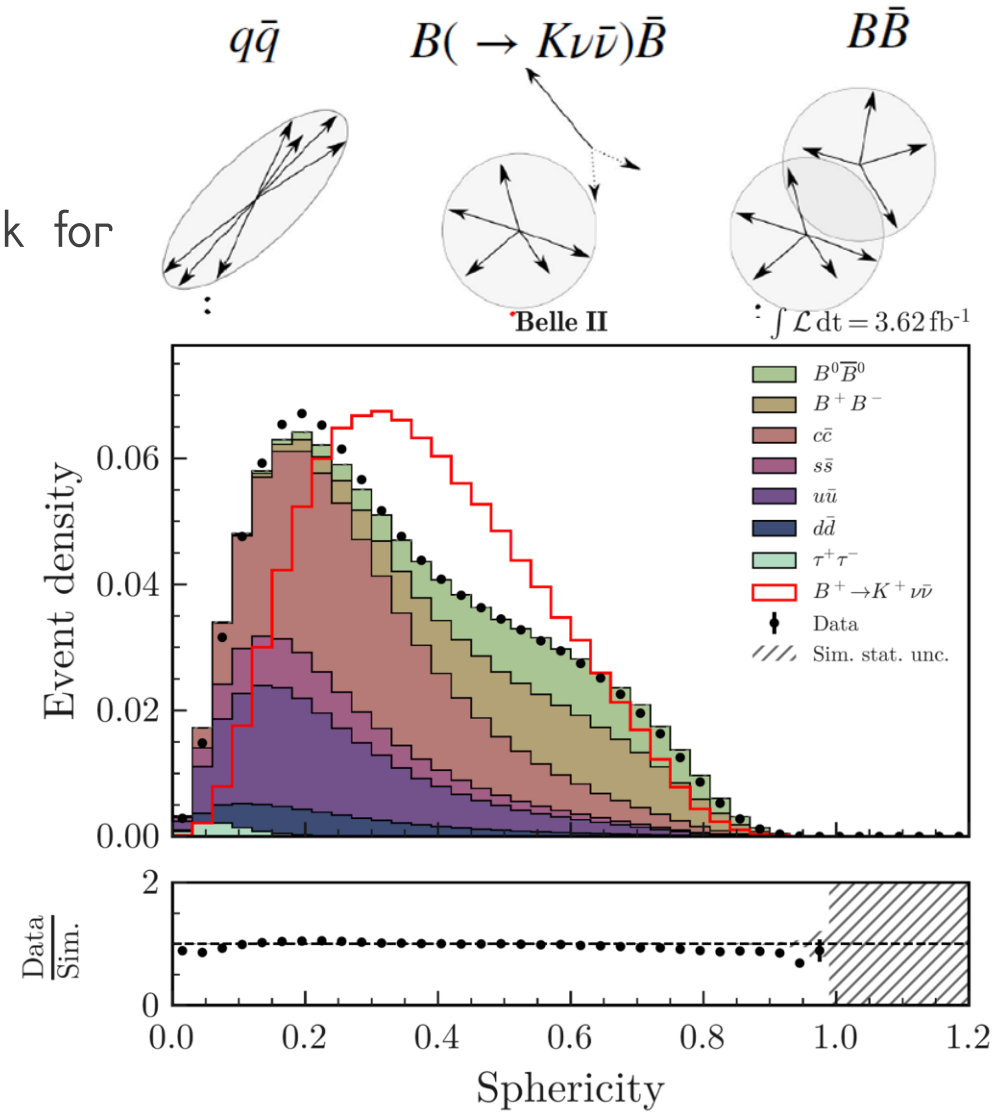
- Dataset Luminosity: $L = 362/fb$
- The final analysis is the combination of 2 measurements:
  1. **ITA:** Innovative Method, more sensitive.
  2. **HTA:** Hadronic Tag Analysis (Conventional way, cross check for the inclusive analysis)

Focus on the Inclusive Tag: Two consecutive classifiers with signal kaon (the one with the lowest q^2), event shape and Rest of Event information

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

$$q^2 = \frac{s}{4c^4} + \mathrm{M}_\mathrm{K}^2 - \frac{\sqrt{s}E_K^*}{c^4}$$

ITA: Inclusive Tag Analysis (Untagged analysis)



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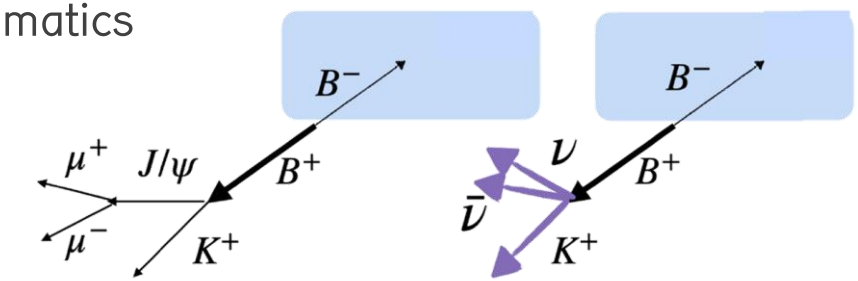
Control Sample studies

Signal Efficiency Validation: $B \to J/\psi \mathrm{K}$ sample, removing J/ψ and correcting K^+ kinematics



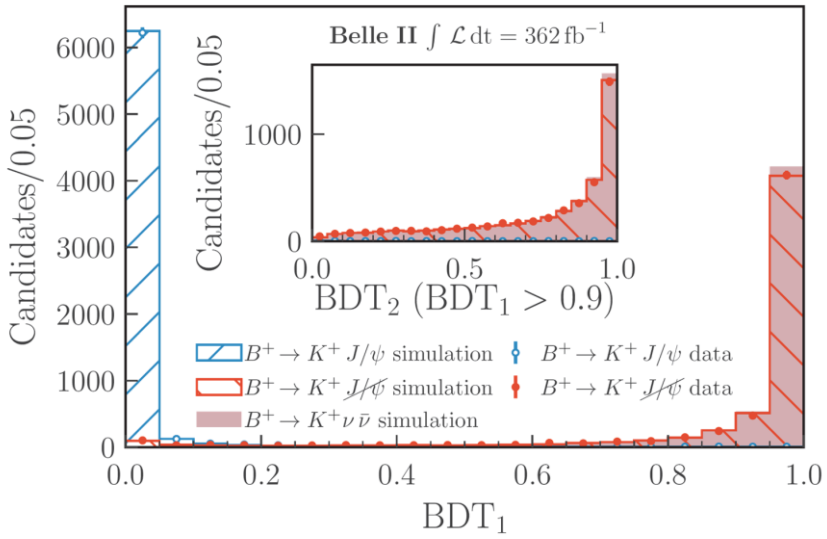
Background Validation:

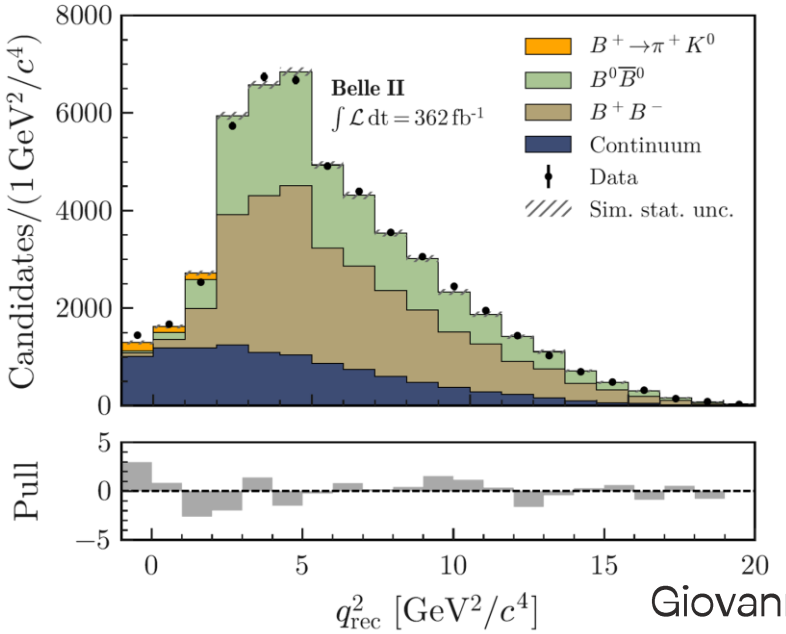
- $q\bar{q}$: off-resonance data
- Undetected K_L in ECL can mimic neutrinos:
  - K_L efficiency: $e^+e^- \to \gamma\phi(\to K_L K_S)$
  - Corrections for $B^+ \to K^+K_LK_L$ background from $B^+ \to K^+K_SK_S$
  - $B \to X_c(K_LX)K$ corrected using a pion enriched sample

Closure validation measuring:

$B\ (B^+ \to \pi^+K^0) = (2.5 \pm 0.5) \times 10^{-5}$

Compatible with PDG $(2.38 \pm 0.08) \times 10^{-5}$





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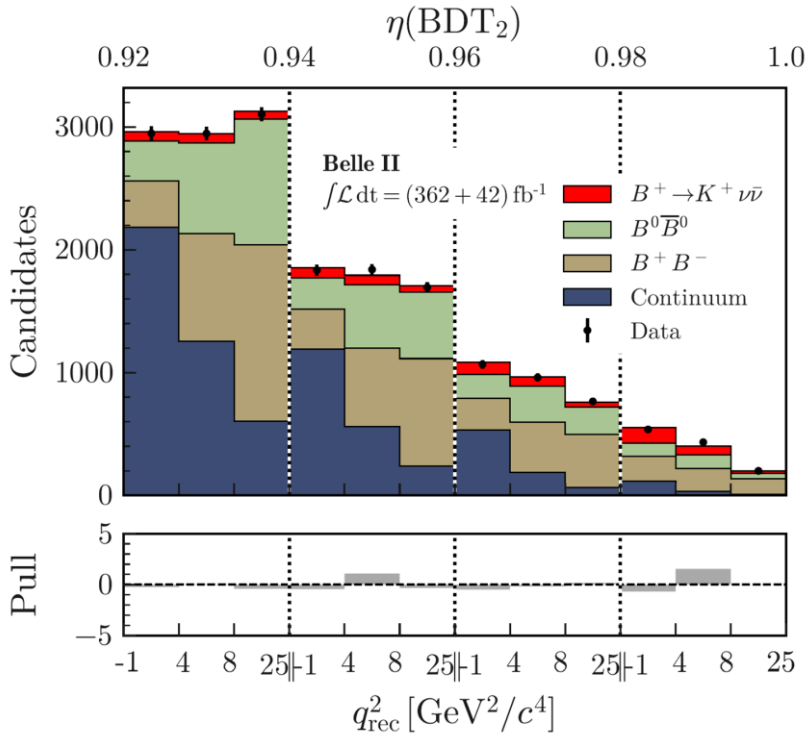
Evidence for $B^+ \to K^+ \nu\bar{\nu}$

PhysRevD.109.112006



ITA

$BR = [2.4 \pm 0.5 \pm 0.5] \times 10^{-5}$

Excess Significance: 3.5σ

2.9σ SM deviation

HTA

$BR = \left[1.1^{+0.9+0.8}_{-0.8-0.5}\right] \times 10^{-5}$

Excess Significance: 1.1σ

0.6σ SM deviation

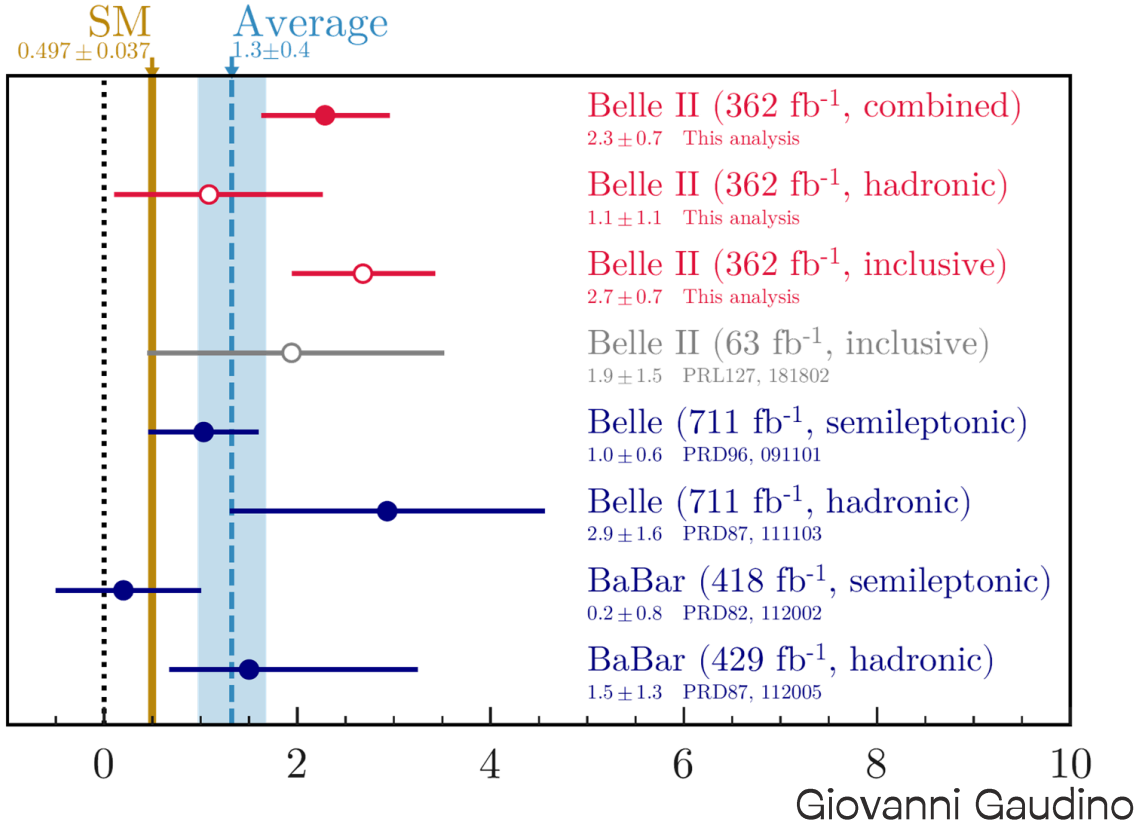
Combination

ITA and **HTA** compatibility: 1.2σ

$BR(B^+ \to K^+ \nu\bar{\nu}) = \left[2.3 \pm 0.5(stat)^{+0.5}_{-0.4}(sys)\right] \times 10^{-5}$

Excess Significance: 3.5σ

SM Deviation: 2.7σ



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Conclusions

Belle II at SuperKEKB: rich and diversified physics program to probe new physics in an indirect way

Few highlights presented today, using full or partial dataset

- First evidence of $B^+ \to K^+ \nu\bar{\nu}$, 2.7σ above the SM prediction
- New Exclusive $|V_{ub}|$ measurement from untagged $B \to \pi/\rho \ell \nu$
- New measurement of $R\left(D^*_{\tau/\ell}\right)$

More and more results to discuss (2 other important results in the backup)

More and more data to analyze

Belle II General Meeting, KEK, June 2024

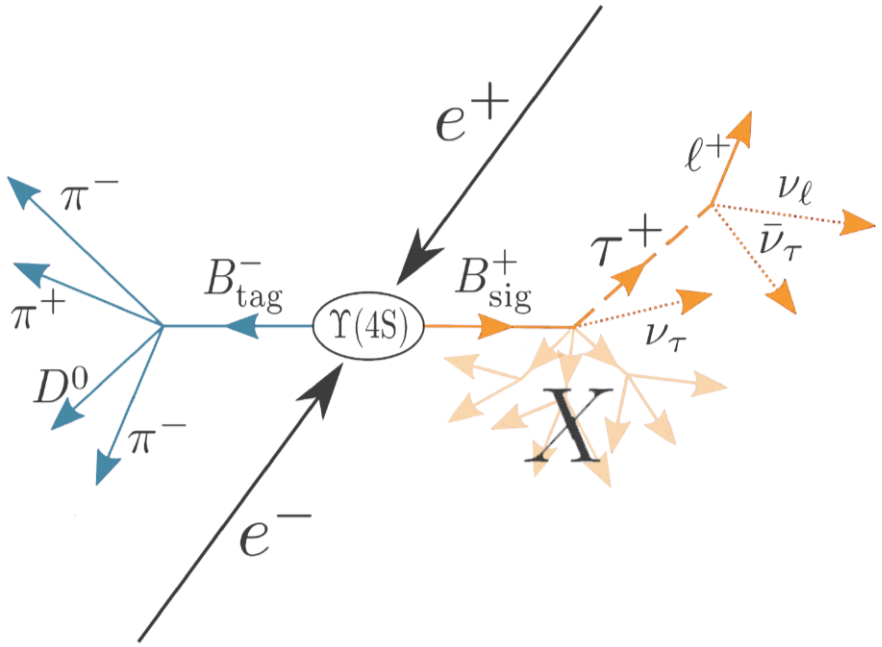
Thanks for the attention

and for the wonderful location!

Images and colors from visitgreece.gr

Backup

Measurement of $R(X_{\tau/\ell})$



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

- Dataset Luminosity: $L = 189/fb$
- 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.

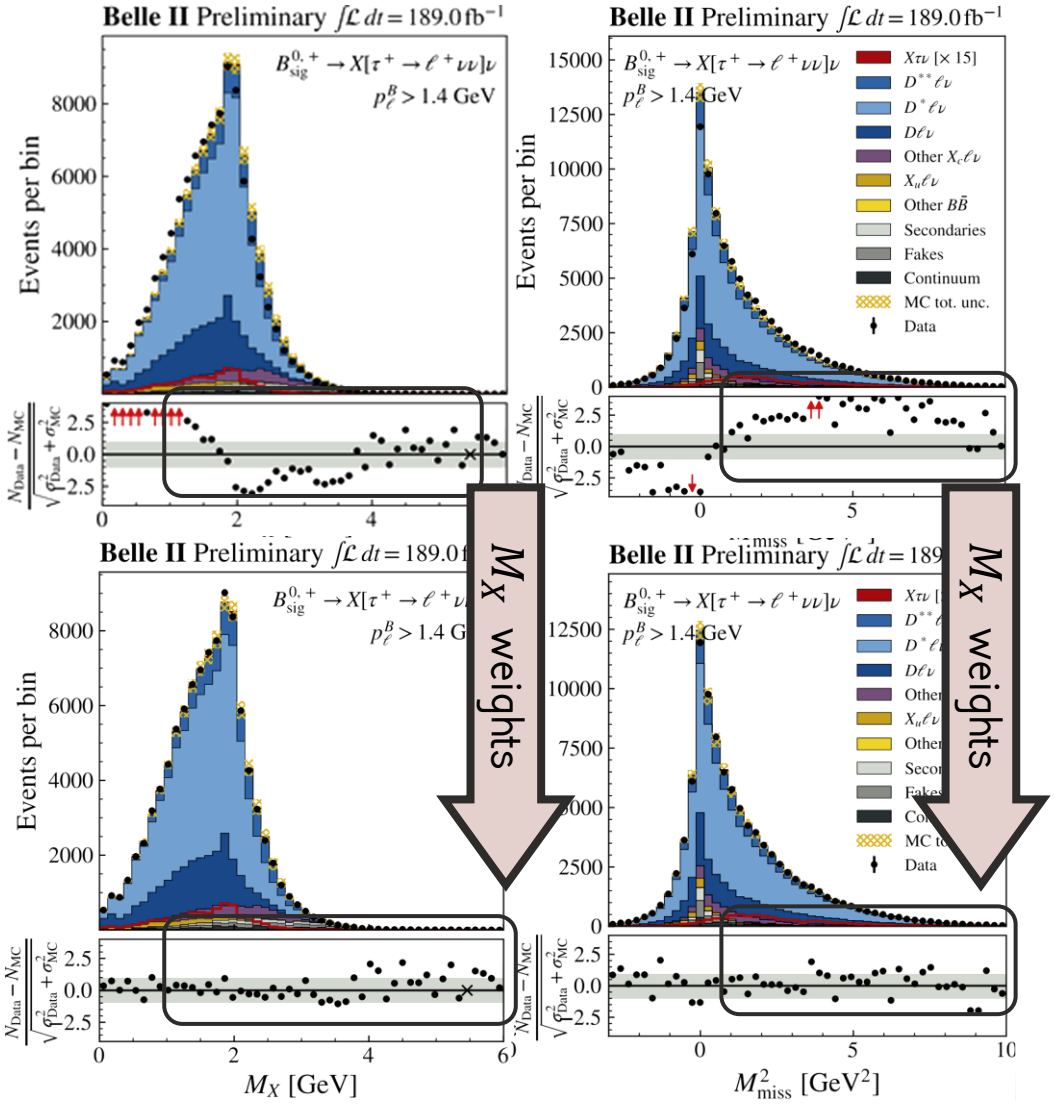
Data driven MC Corrections and Fit

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

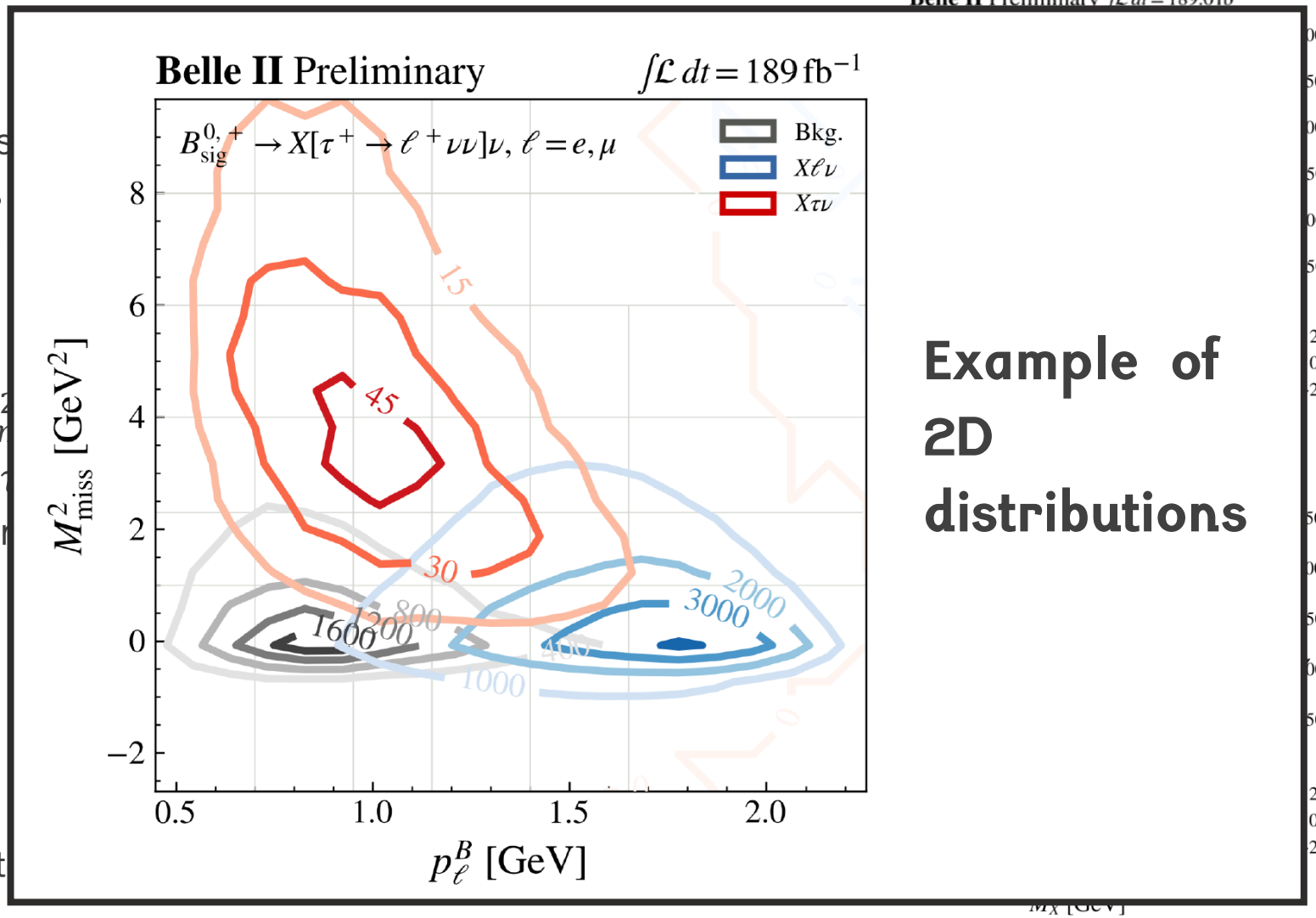
MC corrections:

- Detailed adjustments
- Detailed corrections
  control regions: low

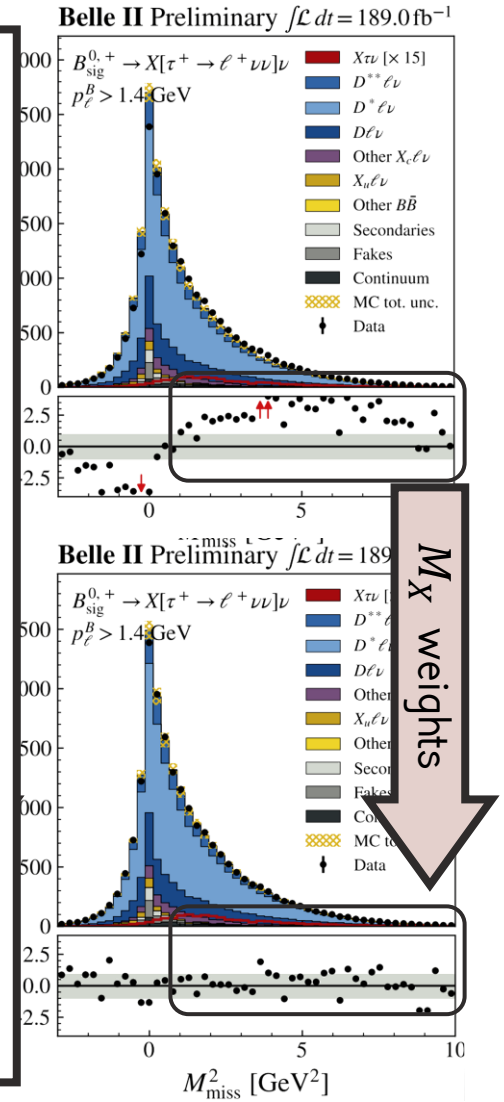
Final Fit:

- 34 bins in p_ℓ vs M_{ν}^2
- Fit components: $X\tau$
  secondaries) and cor

*Off resonance data: dat



Example of 2D distributions



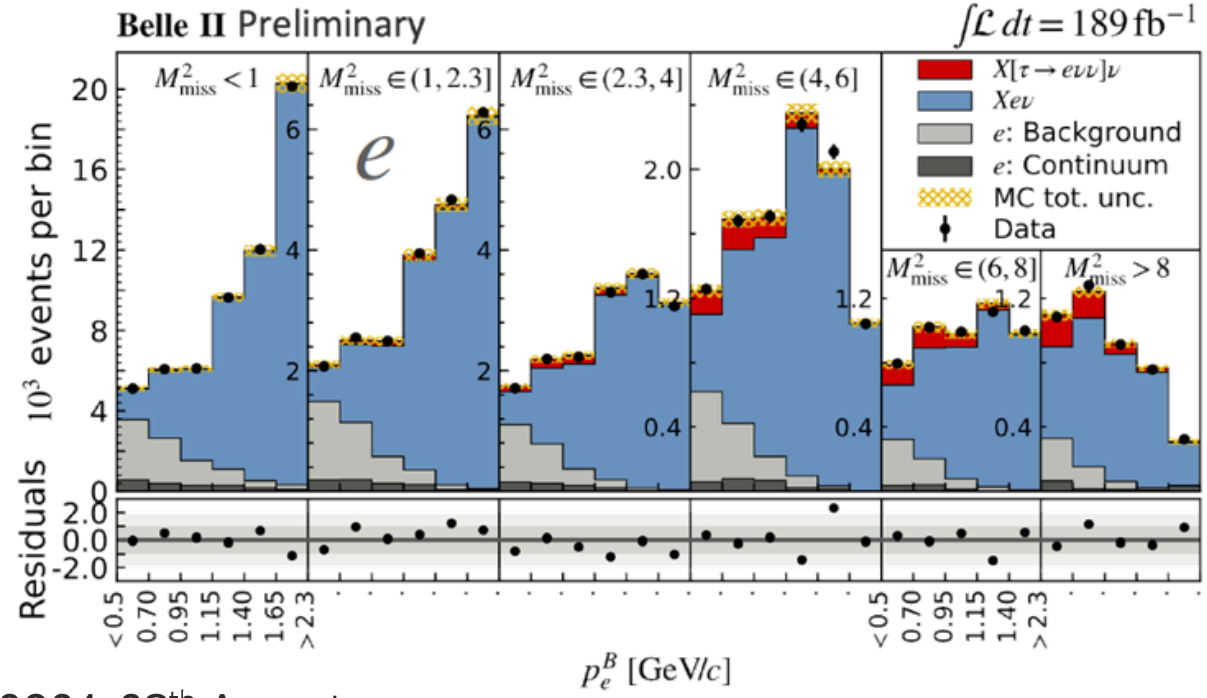
Results

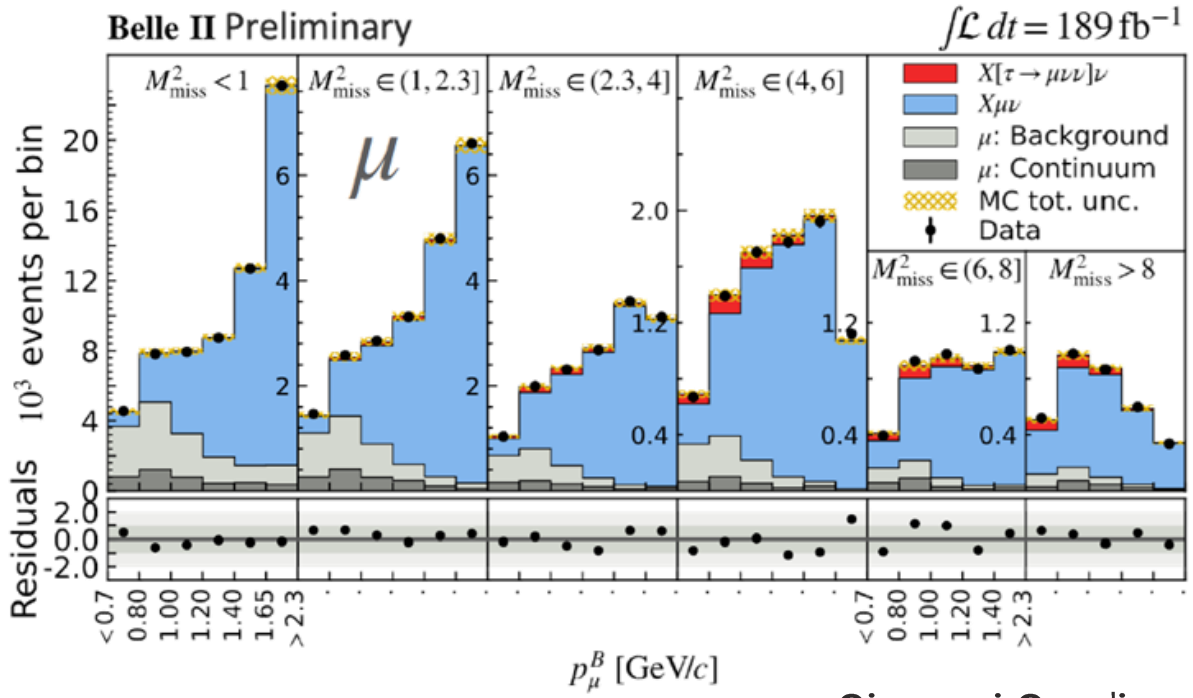
Belle II preliminary result

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

dominated by gap modes branching fraction, $B \to D^*$ form factors, background shape

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





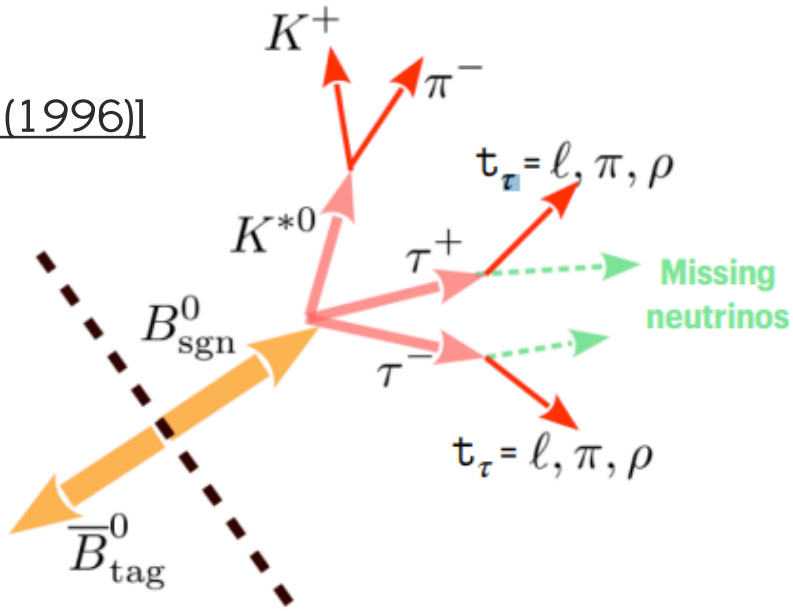
Measurement of $B^0 \to K^{*0}\tau^+\tau^-$

- Dataset Luminosity: $L = 364/fb$

- **Hadronic Tag** Analysis

Challenges

- Low Branching Fraction: $BR_{SM} = (0.98 \pm 0.10) \times 10^{-7}$ [PRD 53, 4964 (1996)]
- No signal peaking kinematic observable
- Large backgrounds+more than 3 prompt track
- Up to 4 neutrinos orignating from the 2 τ
- K^{*0} has low momentum due to the phase space

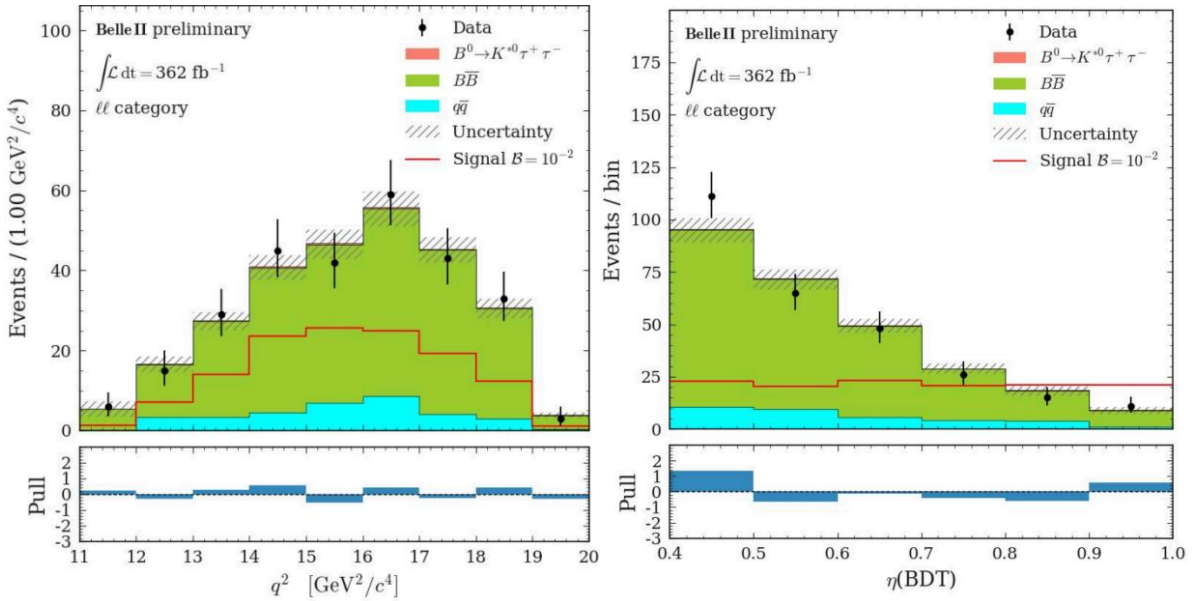


Status of the Art:

Belle $(L = 711\ /fb)$: $BR < 3.1 \times 10^{-3}$ at 90% CL
[PRD 108 L011102 (2023)]

Strategy and Results

- Combinations of sub-track from τ lead to 4 categories: $\ell\ell, \ell\pi, \pi\pi, \rho X$
- **BDT** is trained using missing energy, extra cluster energy in EM calorimeter, q^2, etc.
- BDT output $\boldsymbol{\eta(BDT)}$ is used to extract the signal yield with simultaneous fit to 4 categories



Validation:

- Total efficiency and Peaking $B\overline{B}$: $B^0 \to K^{*0}J/\psi$ sample, replace $K^{*0}J/\psi$ with $K^{*0}\tau^+\tau^-$ (14% uncertainty)
- Non-peaking $B\overline{B}$: sample with B_{sig} and B_{tag} and having same flavor
- $q\overline{q}$ background is scaled by off-resonance data

Belle II Preliminary Result

$BR < 1.8 \times 10^{-3}$ at 90% CL

Twice better with only half sample wrt Belle!

Better tagging + more categories + BDT classifer

Missing Energy decays at Belle II

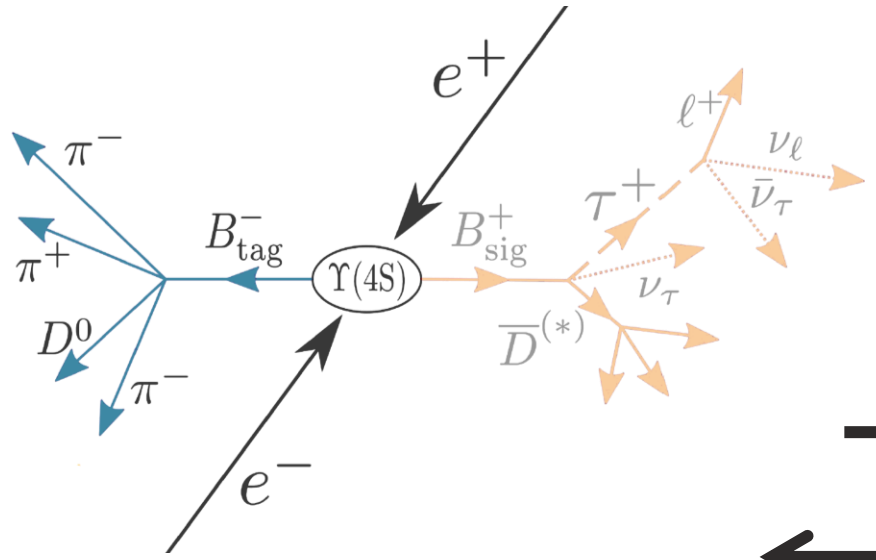
Backup

Reconstruction tecnique

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

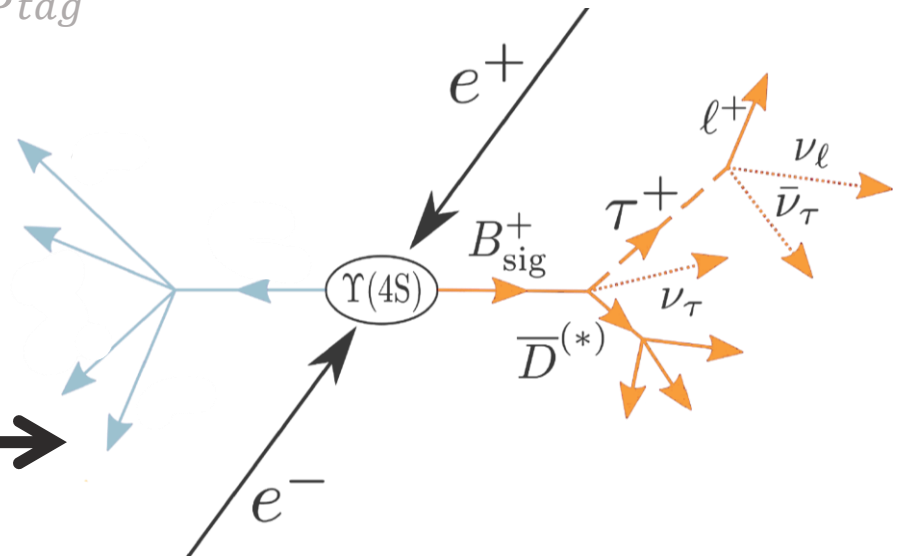
Full Event Interpretation (FEI):

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 or Untagged:

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



Efficiency

Purity

Reconstruction tecnique

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

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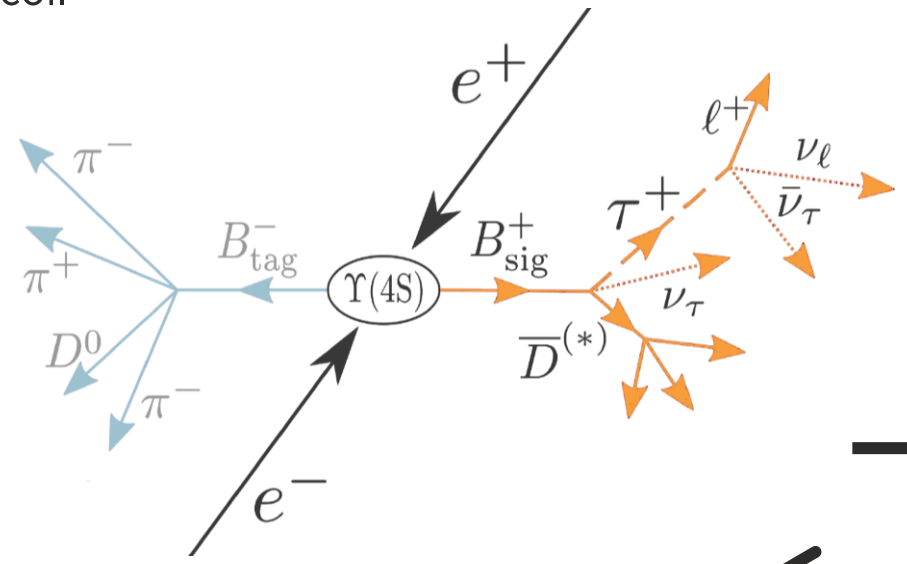

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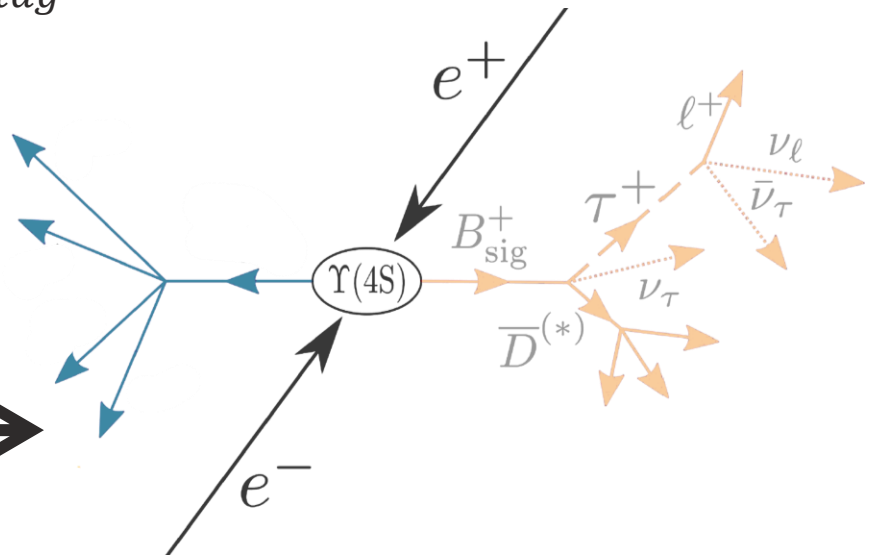


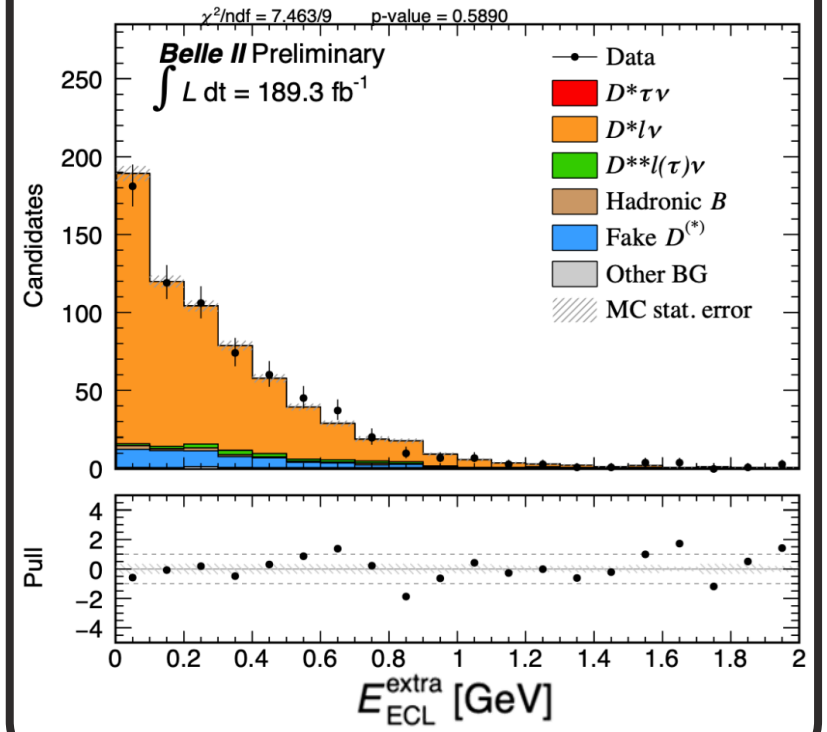
Efficiency →

← Purity

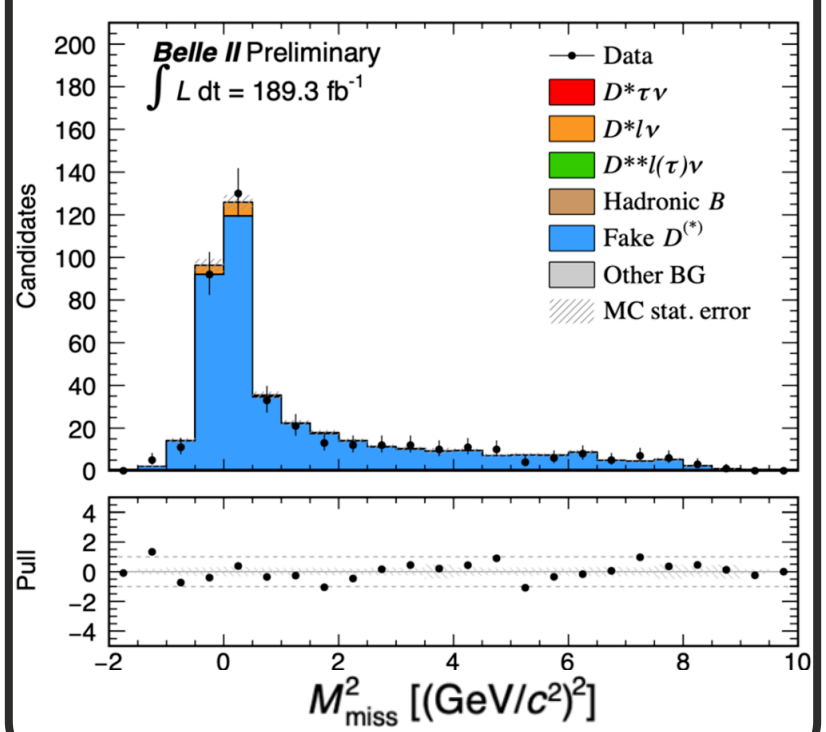
Control Samples Background Validation

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



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