# New measurements of $|V_{cb}|$ and $|V_{ub}|$ at Belle and Belle II

## 17th International Conference on Heavy Quarks and Leptons

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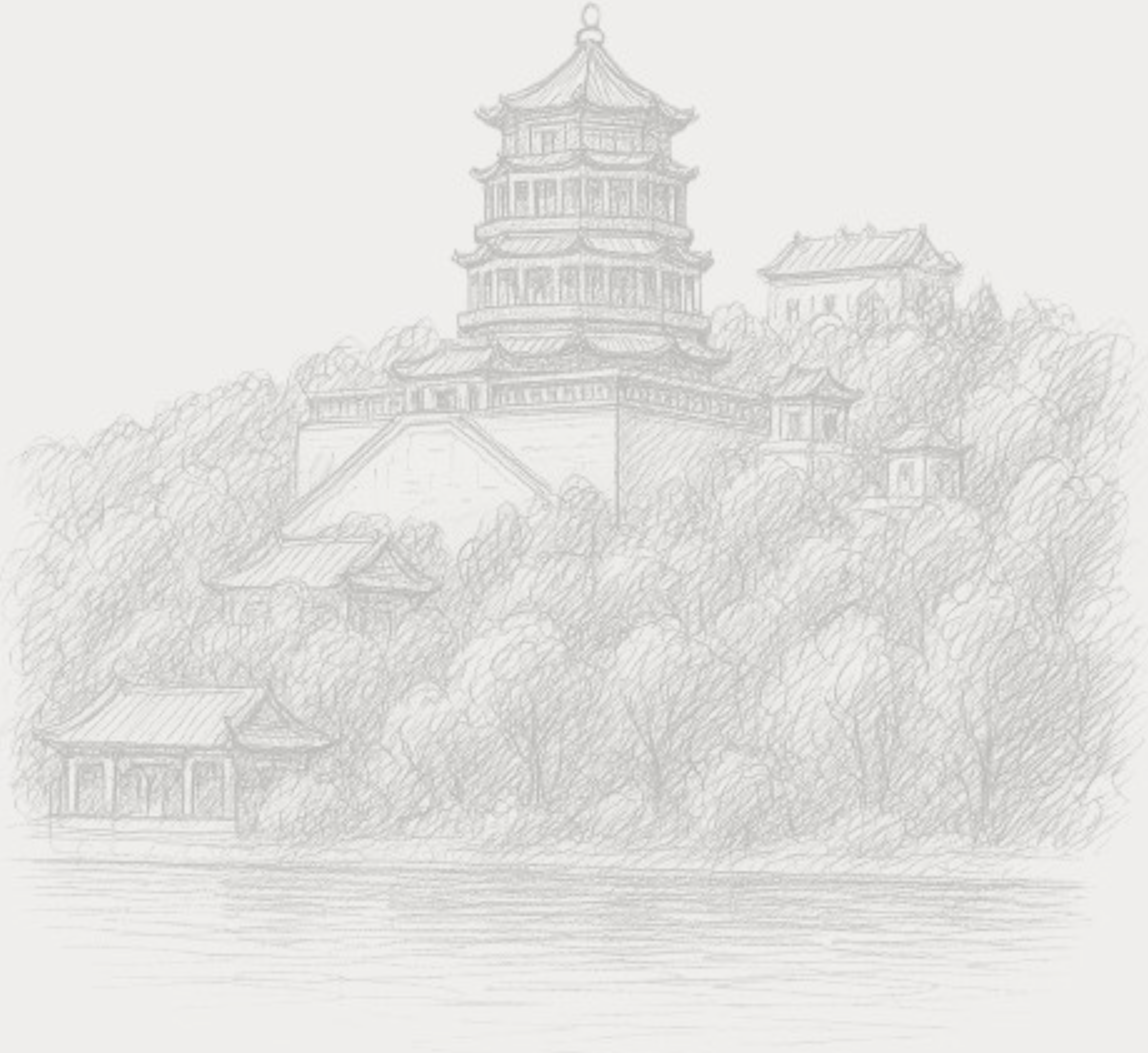
# Introduction



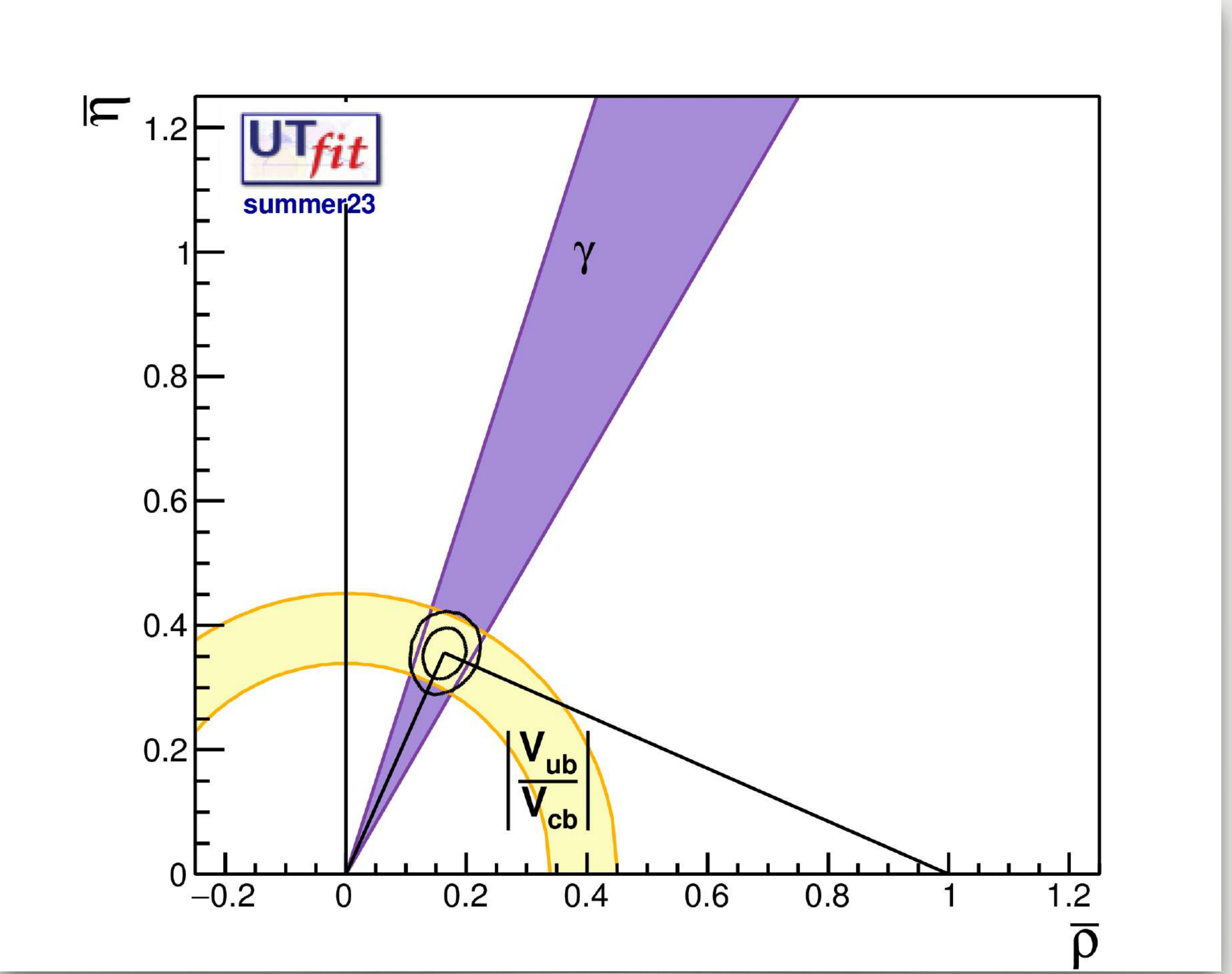
- Motivation
- $|V_{cb}|$ and $|V_{ub}|$ puzzle
- Belle (II) experiment
- Tagging strategies

# $|V_{cb}|$ and $|V_{ub}|$ why?

- $|V_{ub}|$ and $|V_{cb}|$ important to constrain CKM unitarity triangle.

$$\mathbf{V}_{\text{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

- Important inputs to the Standard Model (SM) predictions.
- Most precise determination from semileptonic $B$ decays:
  - Theoretically clean prediction.
  - Experimentally accessible at $B$-factories.




UTfit, Summer 2023

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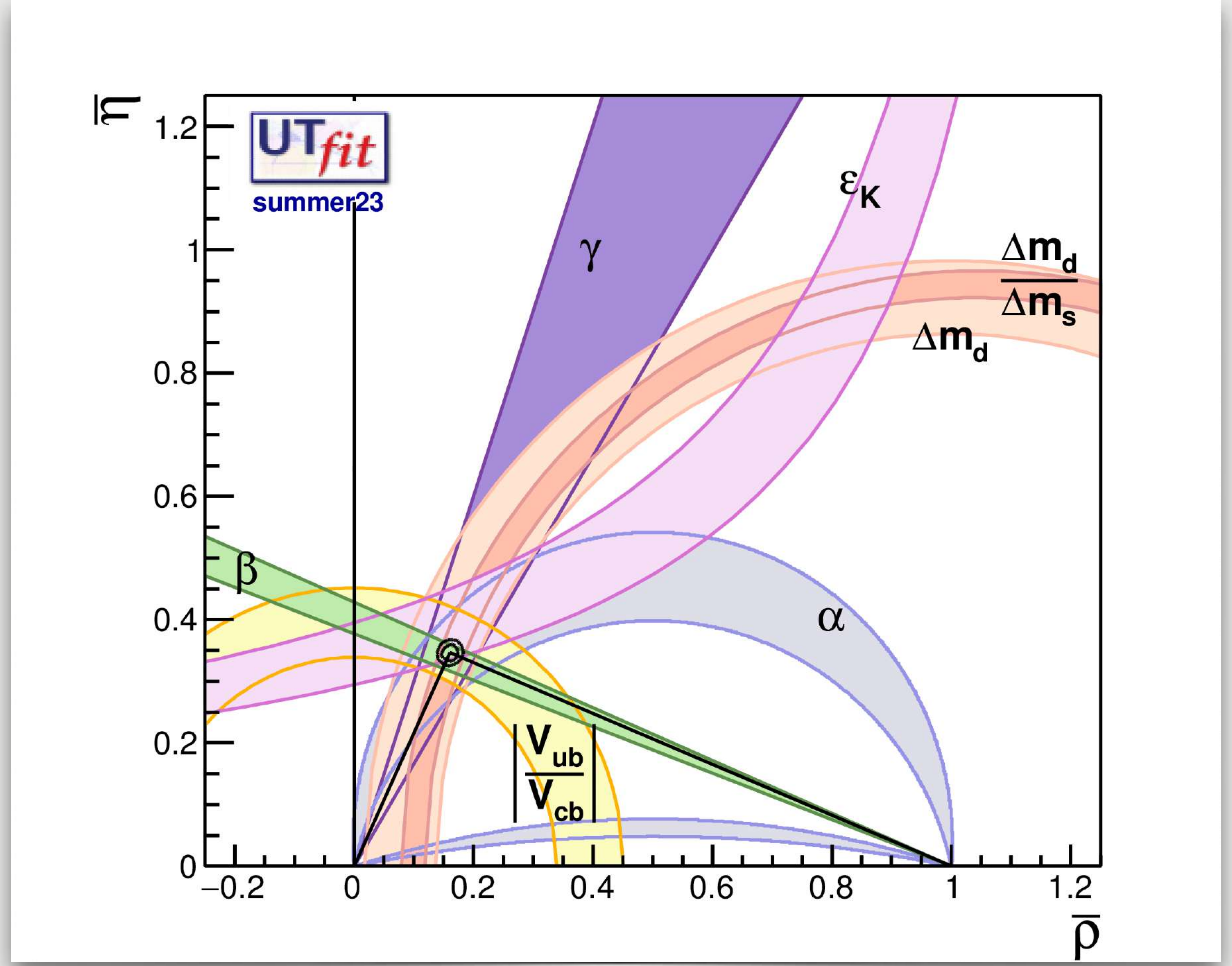
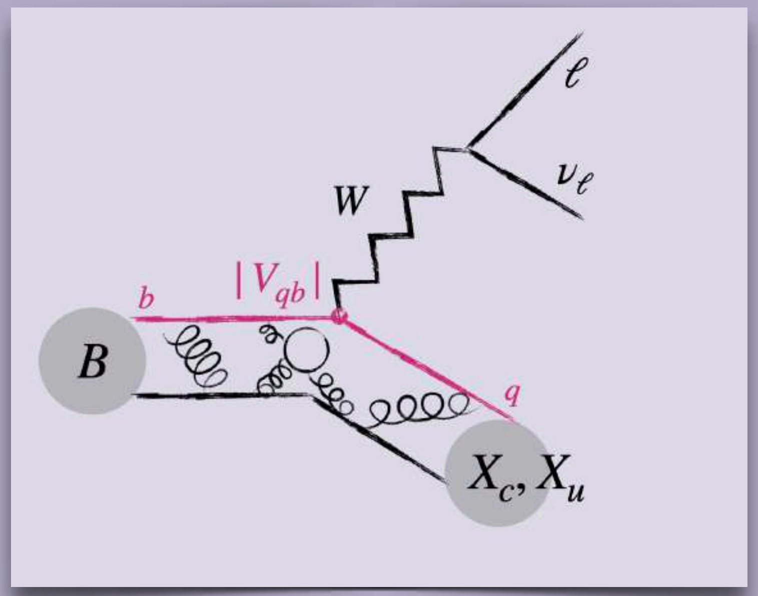



UTfit, Summer 2023

# $|V_{cb}|$ and $|V_{ub}|$ where?

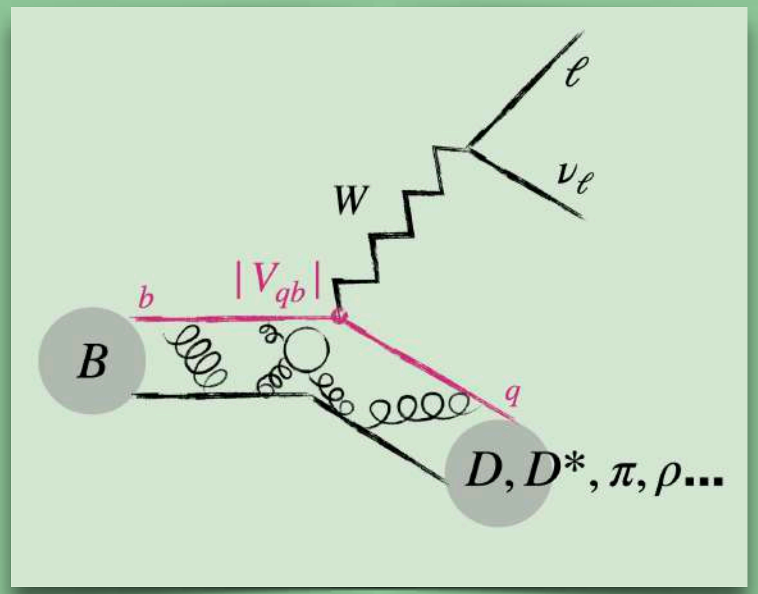
## Inclusive




- Sensitive to all semileptonic final states
- $\mathscr{B} \sim |V_{qb}|^2 \left[\Gamma(b \to q\ell\bar{\nu}_\ell) + 1/m_b^2 + \alpha_s + \ldots\right]$
- Theoretical input: Heavy Quark Expansion Theory

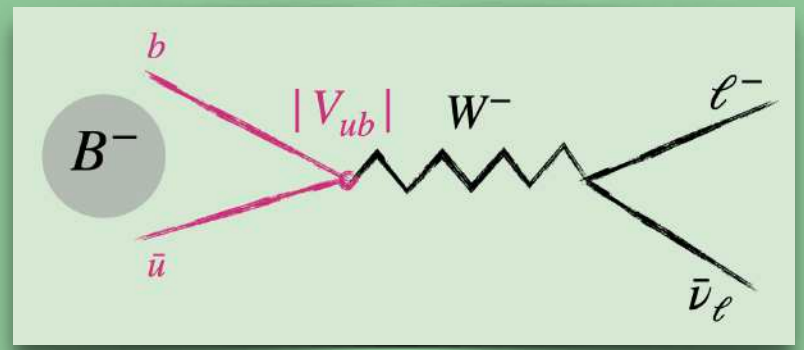
- For $|V_{ub}|$ also include non-perturbative shape functions:
  - **BLNP**; Phys. Rev. D 72, 073006 (2005)
  - **GGOU**; JHEP 10, 058 (2007)
  - **DGE**; JHEP 01, 097 (2006)

## Exclusive




- Reconstruct specific final state: $D, D^*$ for $|V_{cb}|$ or $\pi, \rho$ for $|V_{ub}|$
- $\mathscr{B} \sim |V_{qb}|^2 f^2$
- Theoretical input: Form factors from Lattice QCD or LCSR

## Leptonic

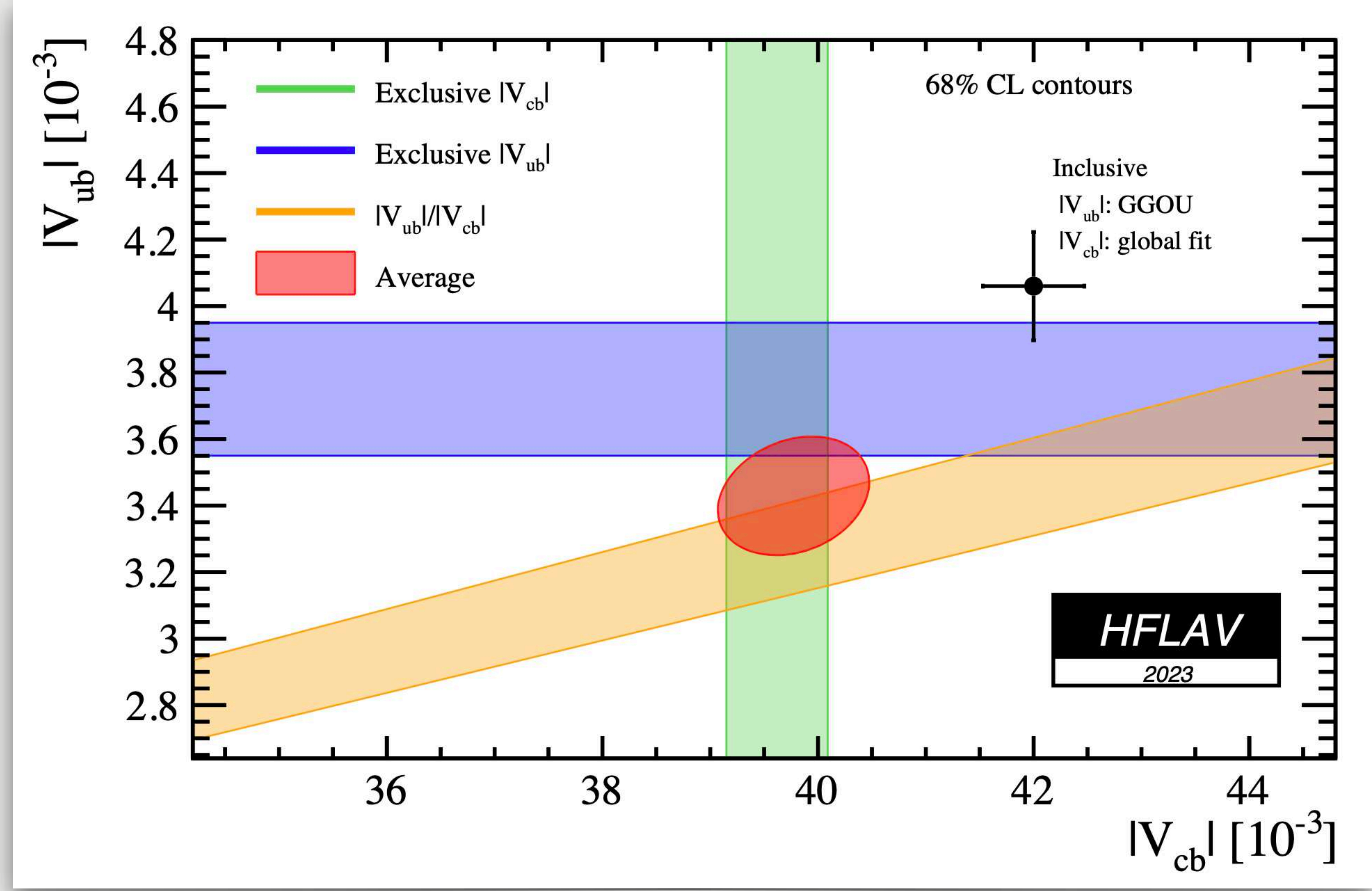



- $\mathscr{B} \sim |V_{ub}|^2 f_B^2 m_\ell^2$

- Leptonic decay of $B^- \to \ell^- \bar{\nu}_\ell$ to determine $|V_{ub}|$
- Theoretical input: $B$ meson decay constant from Lattice QCD

# $|V_{cb}|$ and $|V_{ub}|$ puzzle?

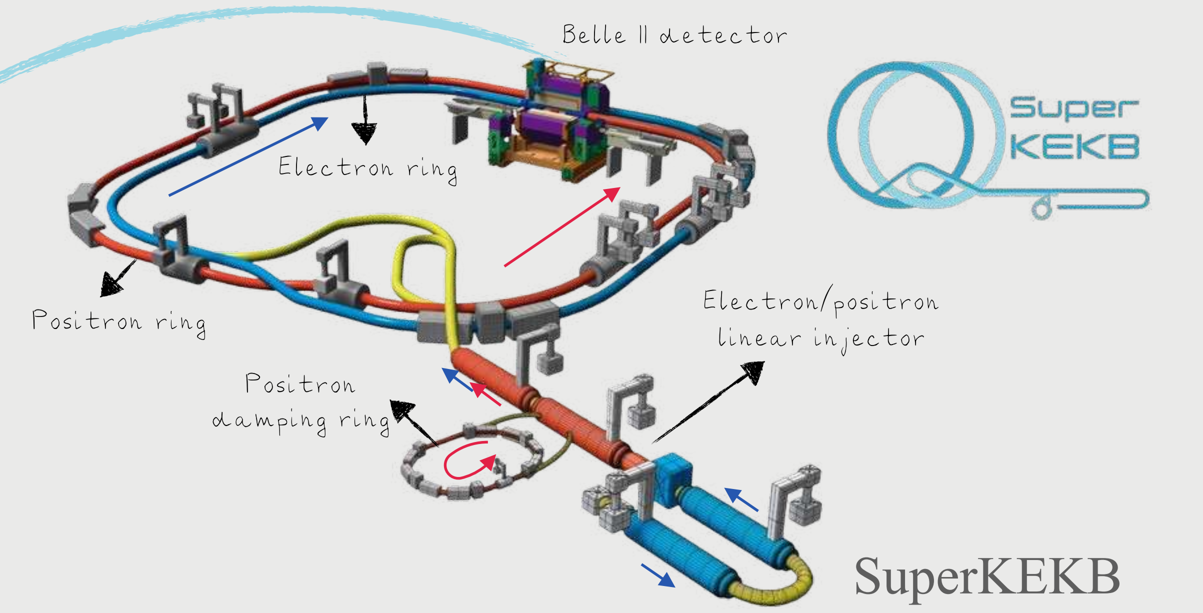
- A longstanding tension between exclusive and inclusive measurements of $|V_{ub}|$ and $|V_{cb}|$.
- $\sim 3\sigma$ difference between exclusive and inclusive (GGOU) measurement of $|V_{ub}|$:
  $|V_{ub}|^{\text{excl.}} = (3.75 \pm 0.20) \times 10^{-3}$
  $|V_{ub}|^{\text{incl.}} = (4.06 \pm 0.12 \pm 0.11) \times 10^{-3}$
- More than $3\sigma$ difference in $|V_{cb}|$:
  $|V_{cb}|^{\text{excl.}} = (39.62 \pm 0.47) \times 10^{-3}$
  $|V_{cb}|^{\text{incl.}} = (41.97 \pm 0.48) \times 10^{-3}$
- Combined fit:
  $|V_{ub}| = (3.43 \pm 0.12) \times 10^{-3}$
  $|V_{cb}| = (39.77 \pm 0.46) \times 10^{-3}$



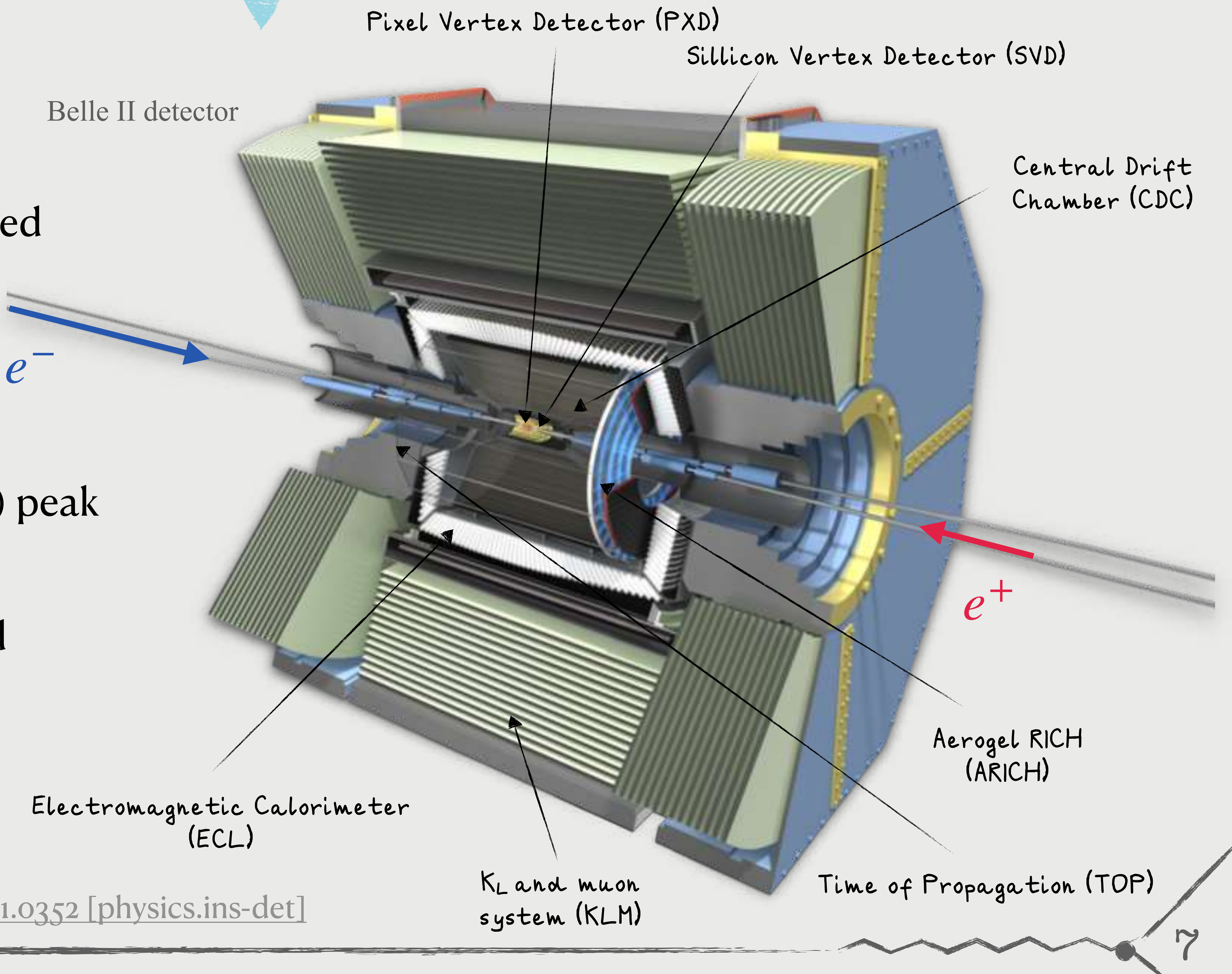

HFLAV 2023, arXiv:2411.18639 [hep-ex]

# Belle (II) experiment

- B-factory experiments at KEK in Tsukuba, Japan
  - Asymmetric $e^+e^-$ colliders (KEKB, SuperKEKB) operating at or near $\Upsilon(4S)$ resonance.
  - Well known initial state enables precise measurements with missing energy.



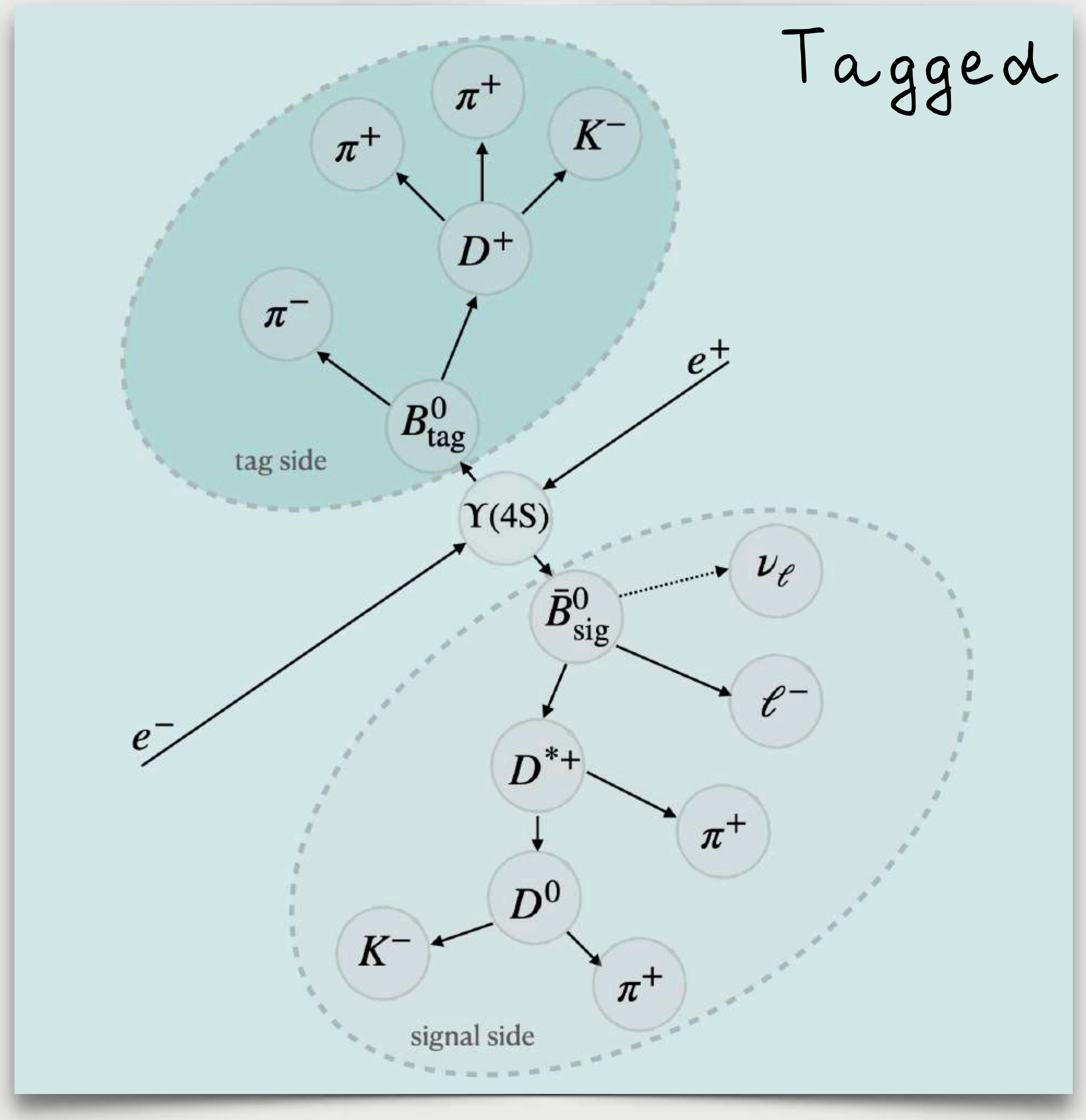

- **Belle (1999 - 2010)**
  - KEKB achieved peak luminosity: $\mathscr{L} = 2.1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Belle detector: general-purpose spectrometer designed for precise vertexing, charged particle tracking, neutral particle detection, and particle identification
  - Collected 1 $\mathrm{ab}^{-1}$ of data → $711\,\mathrm{fb}^{-1}$ at $\Upsilon(4S)$
- **Belle II (2019 - )**
  - SuperKEKB with nano-beam optics and higher beam currents achieved (**RECORD**) peak luminosity in December 2024: $\mathscr{L} = 5.1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Belle II detector: upgraded Belle spectrometer with most components replaced and improved.
    - **Run 1 (2019 - 2022)**: collected 424 $\mathrm{fb}^{-1}$ of data → $365\,\mathrm{fb}^{-1}$ at $\Upsilon(4S)$
    - **Run 2 (2024 - )**: collected $\sim 150\,\mathrm{fb}^{-1}$ of data



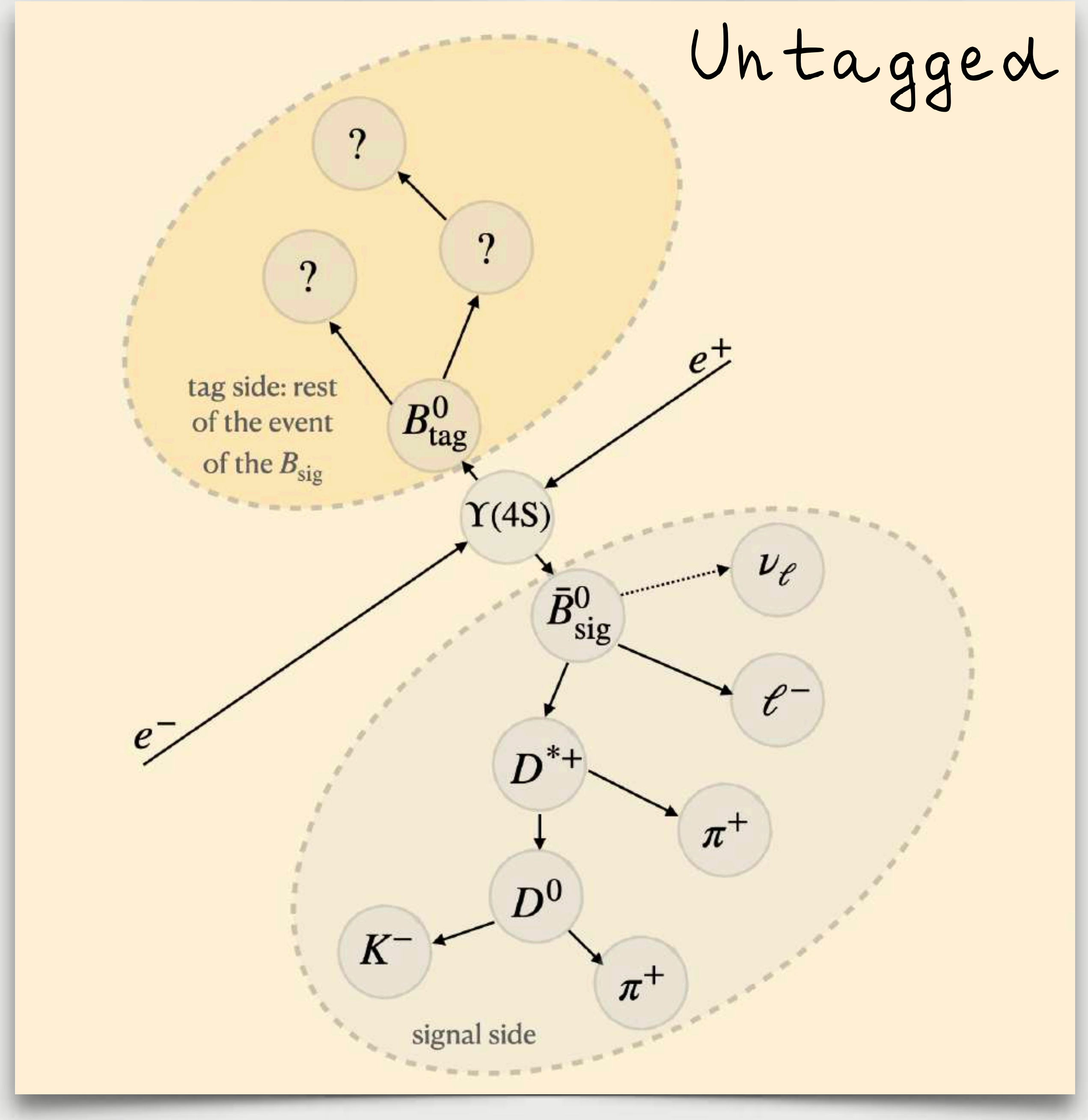

arXiv:1011.0352 [physics.ins-det]

# Tagging strategies

- In semileptonic decays we have undetected neutrino(s) in final state.
- By reconstructing one $B$ in the event - $B_{tag}$, the information about the other $B$ - $B_{sig}$ can be recovered - clean initial state $\Upsilon(4S)$
- 3 distinct tag-side reconstruction methods:
  - *Hadronic* - reconstruct $B_{tag}$ with hadronic decay modes
  - *Semileptonic* - reconstruct $B_{tag}$ with semileptonic decay modes
  - *Inclusive* - reconstruct only $B_{sig}$




+ high purity (especially hadronic tag),
+ good neutrino reconstruction,
+ low backgrounds,
- low efficiency,
- tag callibration.

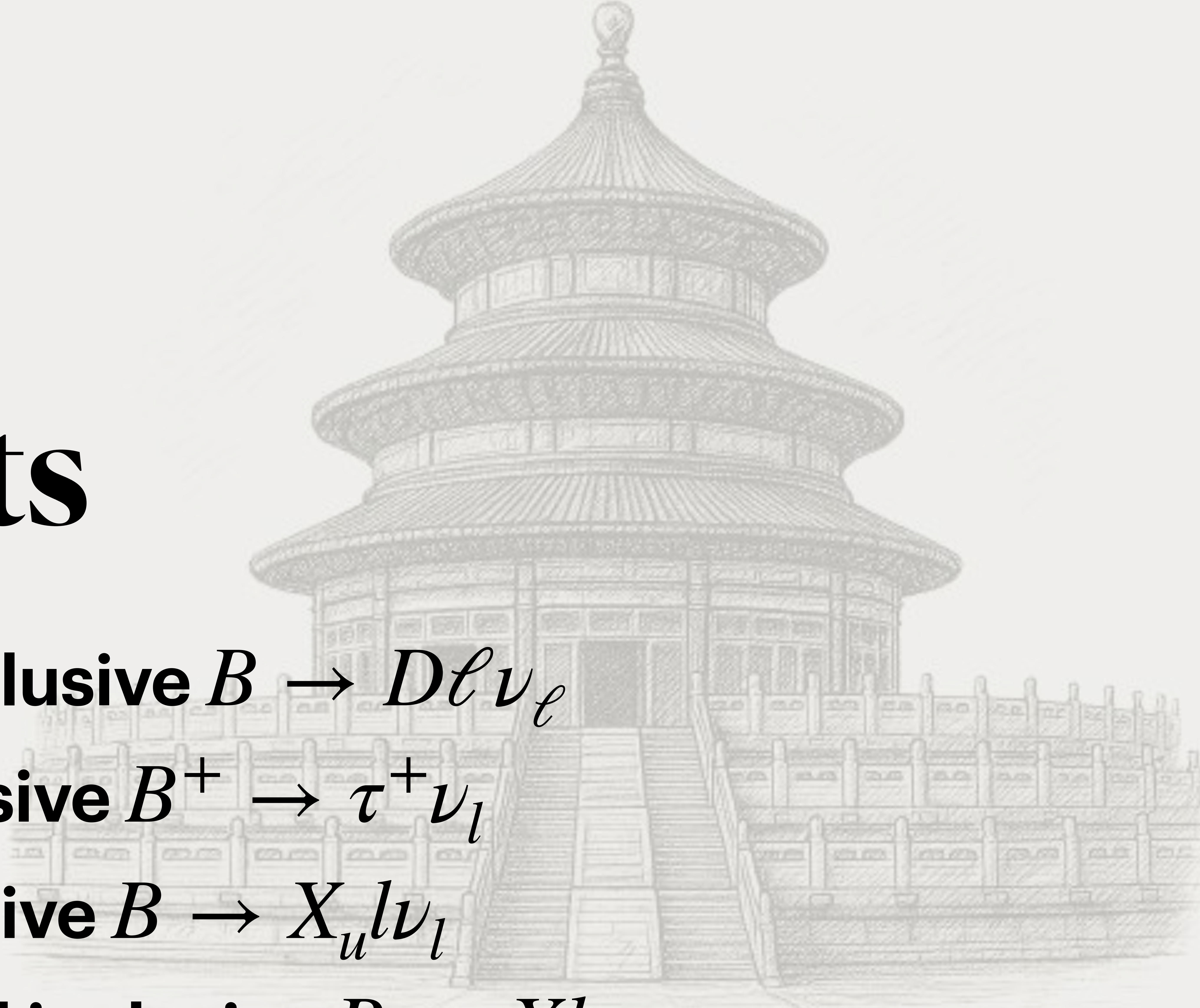



+ high efficiency,
- high backgrounds,
- poor neutrino reconstruction.

Comput Softw Big Sci 3, 6 (2019)

**Full Event Interpretation (FEI)** algorithm at Belle II: hierarchical approach of reconstructing $B_{tag}$ decay chains using multivariate technique.

# Measurements



$|V_{cb}|$ **from untagged exclusive** $B \to D\ell\nu_\ell$

$|V_{ub}|$ **from tagged exclusive** $B^+ \to \tau^+\nu_l$

$|V_{ub}|$ **from tagged inclusive** $B \to X_u l\nu_l$

$|V_{ub}|/|V_{cb}|$ **from tagged inclusive** $B \to Xl\nu_l$

# Measurements

$|V_{cb}|$ from untagged exclusive $B \to D\ell\nu_\ell$

$|V_{ub}|$ from tagged exclusive $B^+ \to \tau^+\nu_l$

$|V_{ub}|$ from tagged inclusive $B \to X_u l\nu_l$

$|V_{ub}|/|V_{cb}|$ from tagged inclusive $B \to X l\nu_l$

# $|V_{cb}|$ from untagged exclusive $B \to D\ell\nu_\ell$

Submitted to PRD
arXiv:2506.15256

- Differential decay rate as function of the recoil variable $w$:

$$\frac{\Delta\Gamma(B \to D\ell\nu_\ell)}{\Delta w} \sim (w^2-1)^{3/2}\eta_{\mathrm{EW}}^2(1+\delta_{\mathrm{C}}^{+,0})\mathcal{G}^2(w)|V_{cb}|^2 \qquad w = \frac{m_B^2+m_D^2-q^2}{2m_Bm_D}$$

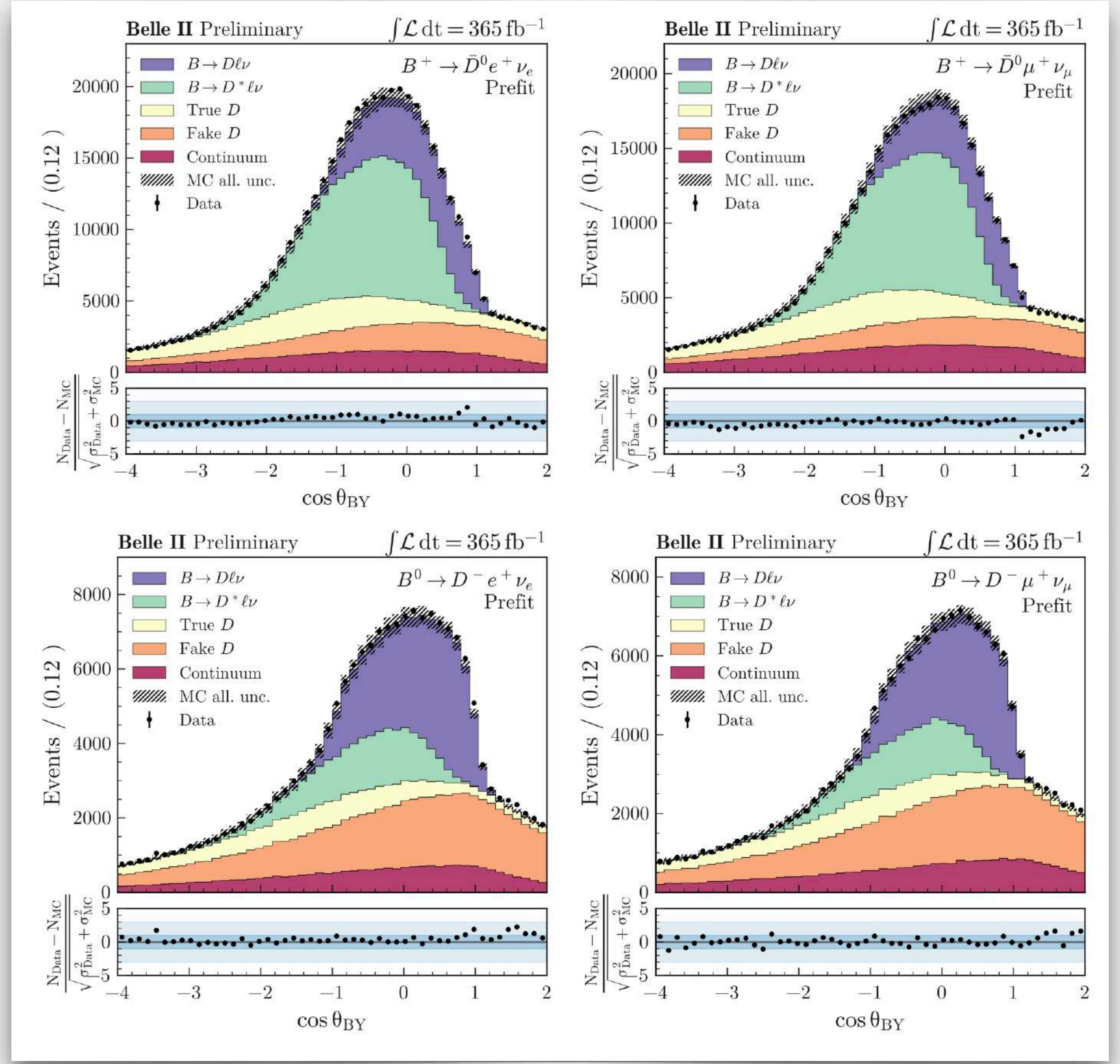
$\mathcal{G}(w)$ contains the vector form factor function $f_+(w)$

- $B$ meson candidates ($B^+$ or $B^0$) are formed from reconstructed $D^0 \to K^-\pi^+$ or $D^+ \to K^-\pi^+\pi^-$ and combined with charged lepton $\ell = e, \mu$

- Reconstruct the angle between the signal $B$ and $Y = D\ell$ system:

$$\cos\theta_{BY} = \frac{2E_{\mathrm{beam}}E_Y - m_B^2 - m_Y^2}{2|\vec{p}_B||\vec{p}_Y|}$$

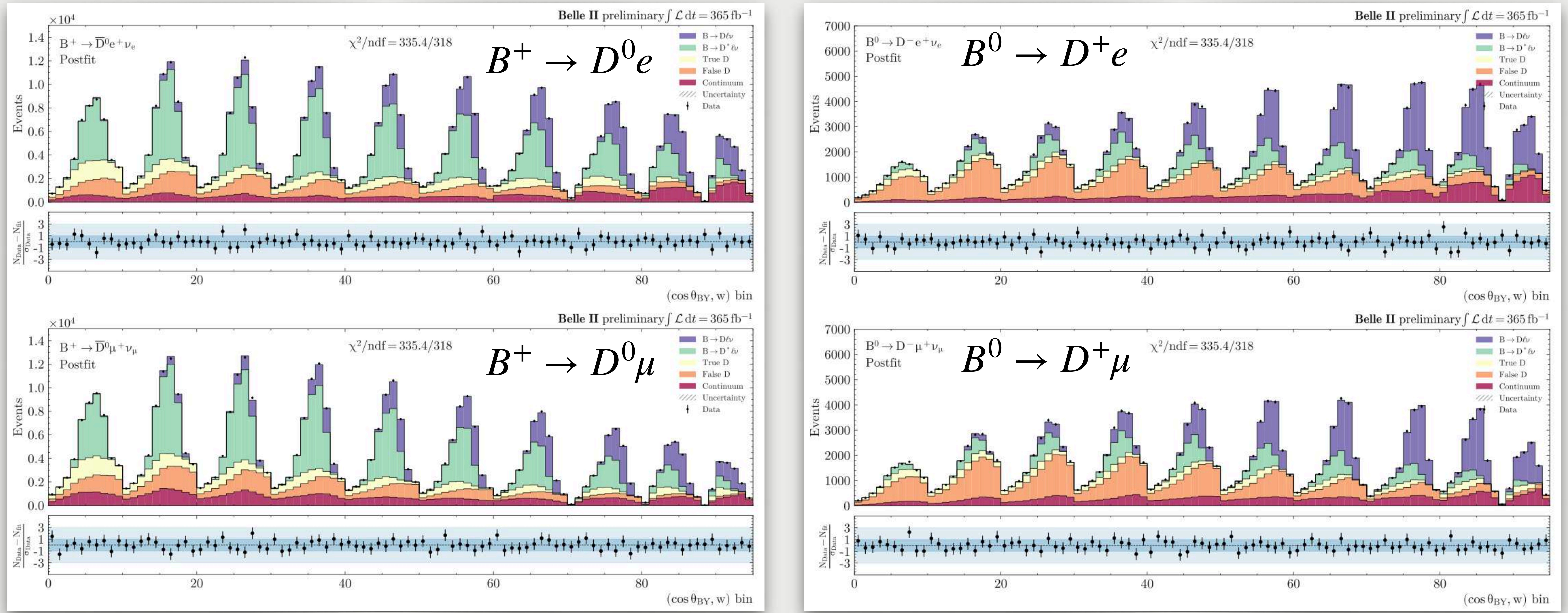
- Main backgrounds:
  - Continuum events ($e^+e^- \to q\bar{q}$) are suppressed with set of selection on various variables exploiting the event topology
  - Feed-down from $B \to D^*\ell\nu_\ell$ events: significant despite active $D^*$ veto




Distribution of $\cos\theta_{BY}$ separately for the charged and neutral modes and electron and muon channels.

# $|V_{cb}|$ from untagged exclusive $B \to D\ell\nu_\ell$ - Signal extraction

- Signal yields are extacted in 10 bins of $w$ by fitting the $\cos\theta_{BY}$ simultaneously in the electron and muon channels and for the charged and neutral modes




Fitted distributions of $\cos\theta_{\rm BY}$ in bins of $w$ in the $D^0 e$, $D^0\mu$, $D^+e$ and $D^+\mu$ samples.

# $|V_{cb}|$ from untagged exclusive $B \to D\ell\nu_\ell$ - Results

- The signal branching fractions from sum over $w$ bins, multiplied by the bin widths and the corresponding $B$ meson lifetime. After averaging over lepton flavours:

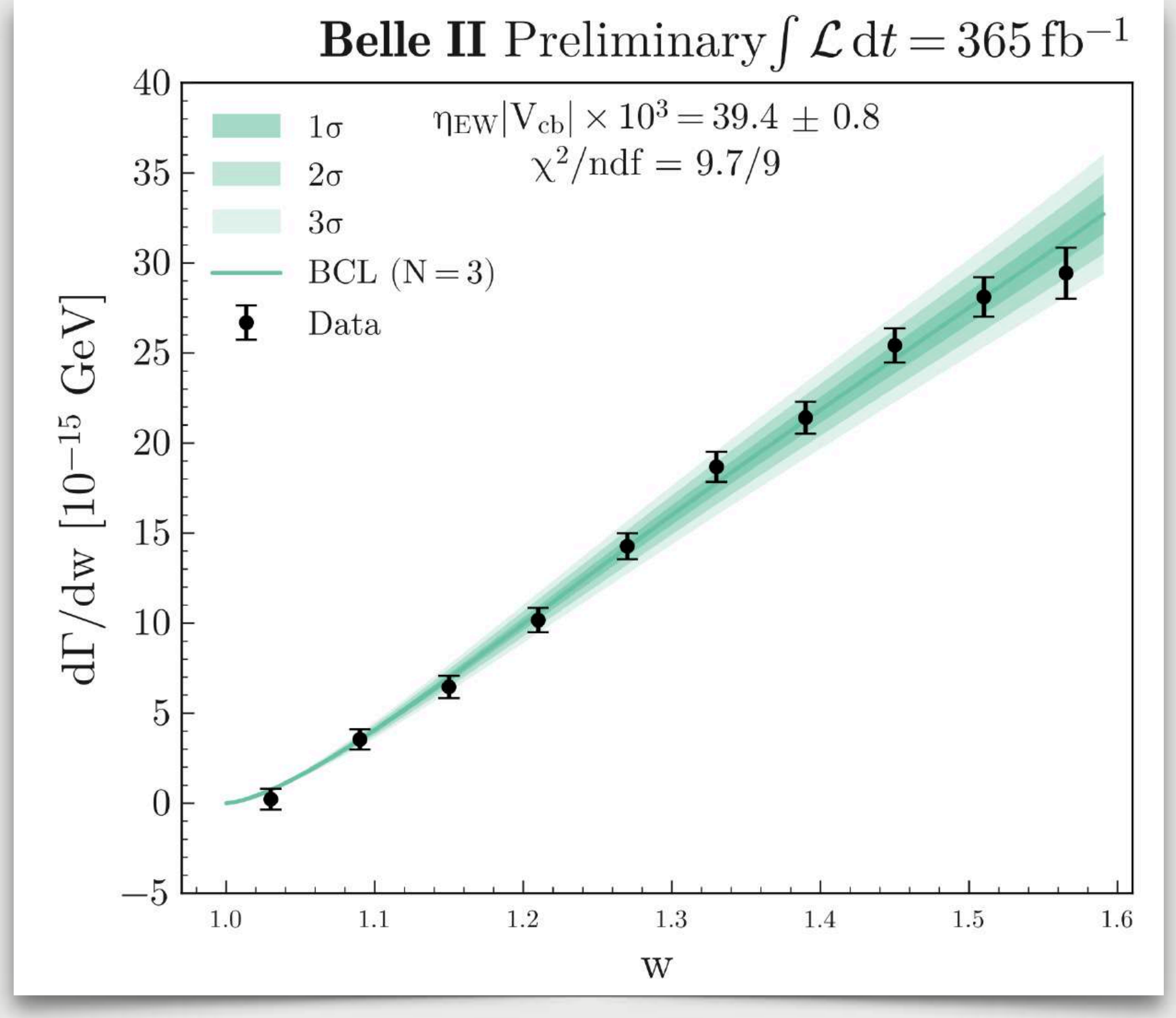
$$\mathcal{B}(B^0 \to D^-\ell^+\nu_\ell) = (2.06 \pm 0.05(\text{stat.}) \pm 0.10(\text{syst.}))\,\%$$

$$\mathcal{B}(B^+ \to \bar{D}^0\ell^+\nu_\ell) = (2.31 \pm 0.04(\text{stat.}) \pm 0.09(\text{syst.}))\,\%$$

- Extract $|V_{cb}|$ by fitting values of $\Delta\Gamma/\Delta w$ using BCL (Phys. Rev. D 82, 099902 (2010)) form factor parametrisation.

$$|V_{cb}| = (39.2 \pm 0.4(\text{stat.}) \pm 0.6(\text{syst.}) \pm 0.5(\text{th.})) \times 10^{-3}$$

  - Result in agreement with exclusive HFLAV average
  - **Most precise** measurement using $B \to D\ell\nu_\ell$ decays




Form factor resulting from the fit compared to the measurement of $\Delta\Gamma/\Delta w$.

# $|V_{ub}|$ from tagged exclusive $B^+ \to \tau^+ \nu_\tau$

Accepted to PRD
arXiv:2502.04885

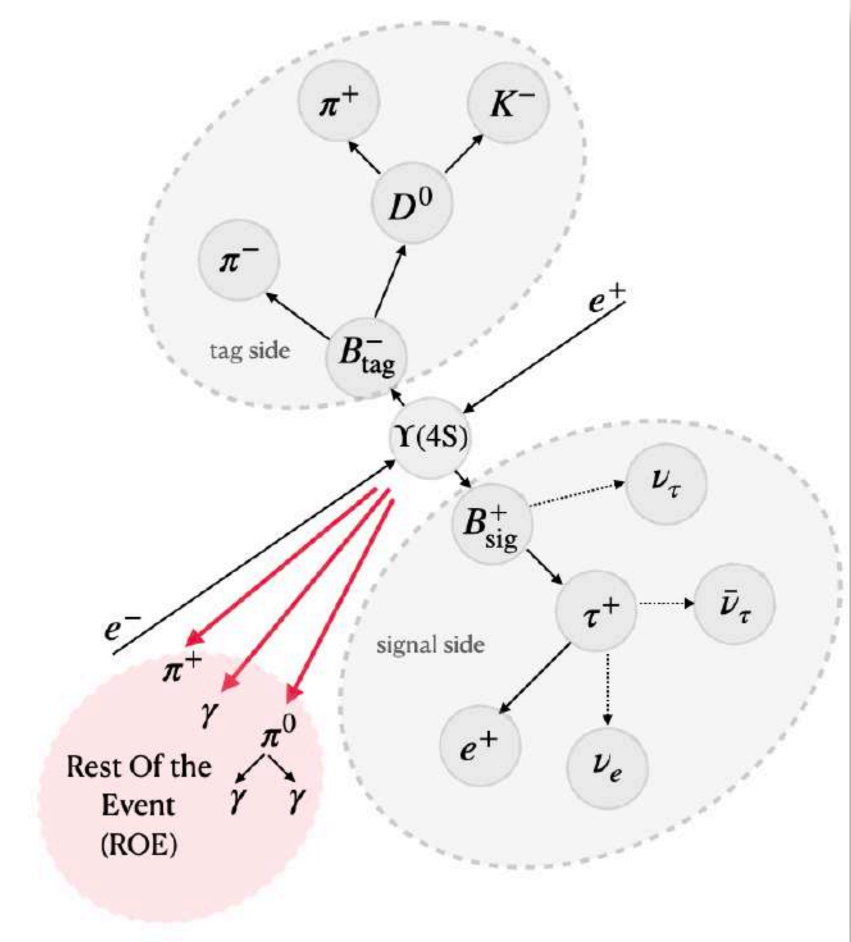
- In the SM:

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

- Use FEI with hadronic tagging to reconstruct $B_{\text{tag}}$
- $\tau$ is reconstructed using 1 prong decays channels:
  - $\tau \to e\nu\bar{\nu}$
  - $\tau \to \mu\nu\bar{\nu}$
  - $\tau \to \pi\bar{\nu}$
  - $\tau \to \rho\bar{\nu}$, where $\rho \to \pi^0\pi^+$

  covering ~72% of all $\tau$ decays.
- Build Rest of the Event (ROE):
  - Sum of the cleaned-up energy in the calorimeter - $E_{\text{ECL}}^{\text{extra}}$
  - Missing mass squared of undetected particles:

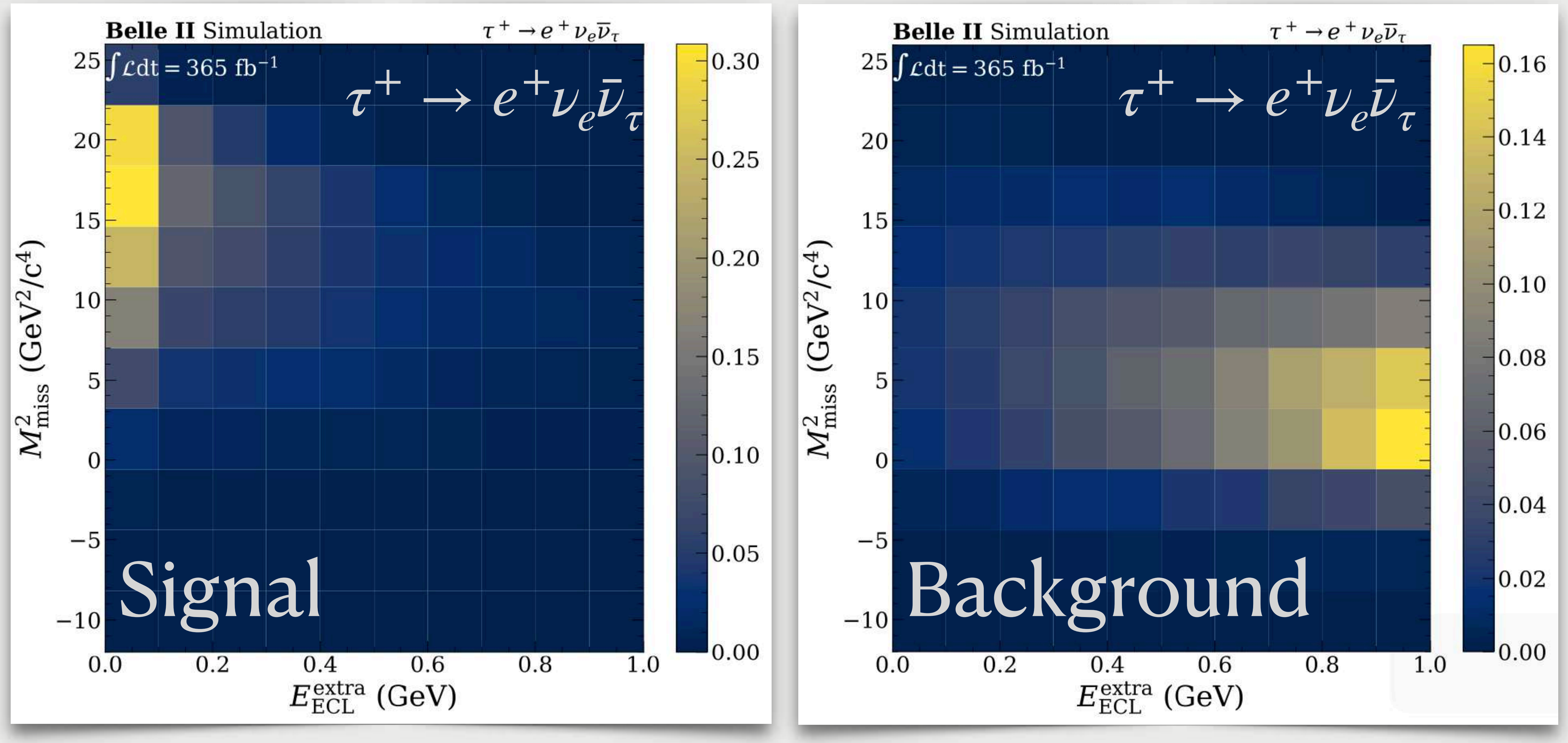
$$M_{\text{miss}}^2 = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_{\text{track}} - p_{\text{ROE}})^2$$




ROE - unassigned neutral clusters and charged tracks

Adding extra clusters due to:
- wrongly reconstructed/matched clustering algorithm
- beam background

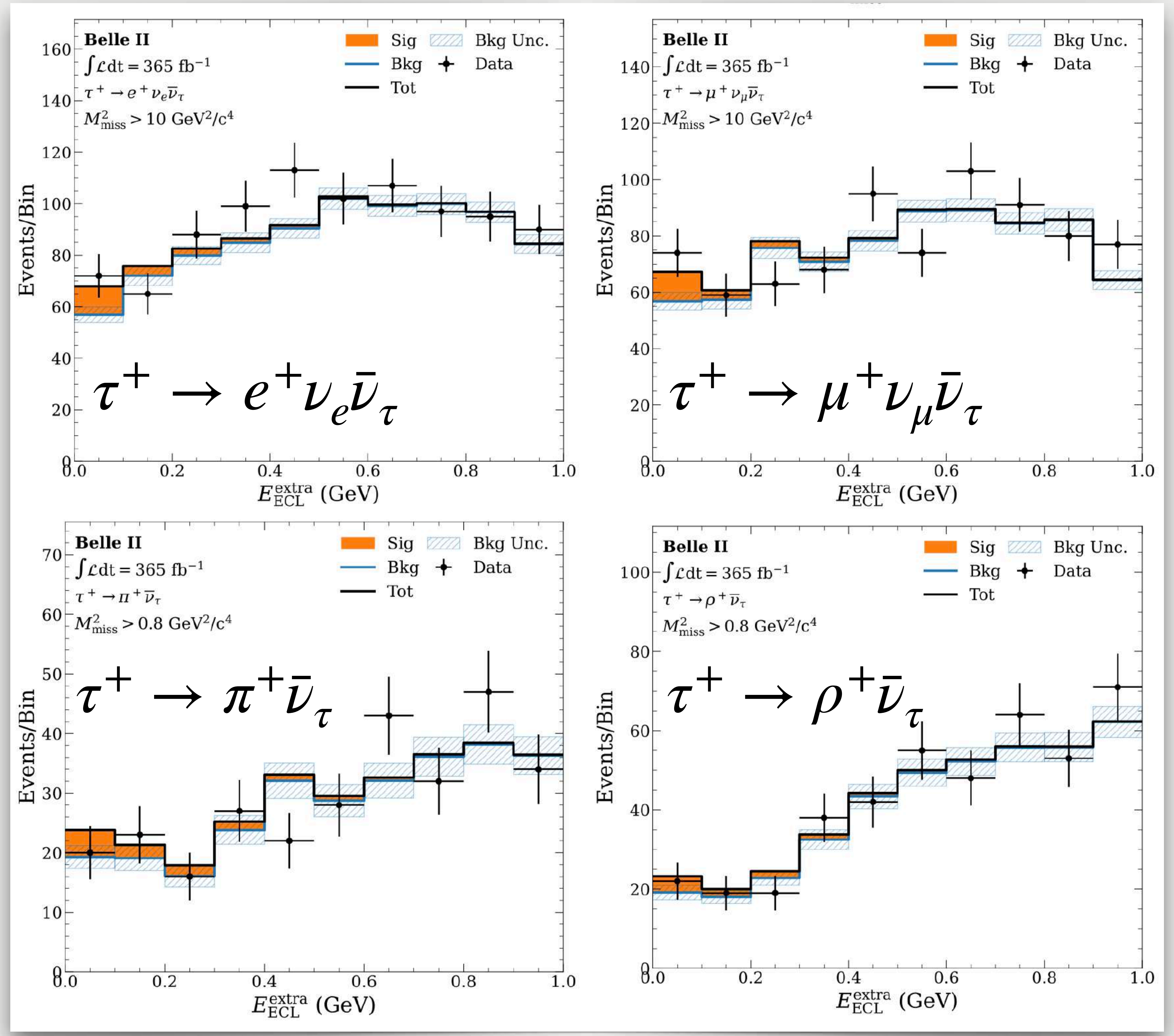
It is crucial to reject fake photons in the ECL from background - ECL clean-up.




2D PDFs of $E_{\text{ECL}}^{\text{extra}}$ and $M_{\text{miss}}^2$ from simulation for signal and background in the $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ channel.

# $|V_{ub}|$ from tagged exclusive $B^+ \to \tau^+ \nu_\tau$ - Signal extraction

- To suppress the continuum background, two separate BDTs are trained—one for the leptonic mode and one for the hadronic mode—using event shape variables as inputs
- Important variables to enhance the signal:
  - the output of the FEI algorithm - $\mathcal{O}_{\text{FEI}}$
  - the output of the continuum suppression BDT - $\mathcal{O}_{\text{CS}}$
  - the momentum of the reconstructed daughter of the $\tau^+$ - $p_{\text{cand.}}$
- Signal yield is extracted from a simultaneous 2D binned likelihood fit on $E_{\text{ECL}}^{\text{extra}}$ and $M_{\text{miss}}^2$ to all four $\tau^+$ channels




Distributions of $E_{\text{ECL}}^{\text{extra}}$ with the fit results superimposed for all four considered $\tau^+$ decay channels.

# $|V_{ub}|$ from tagged exclusive $B^+ \to \tau^+\nu_\tau$ - Result

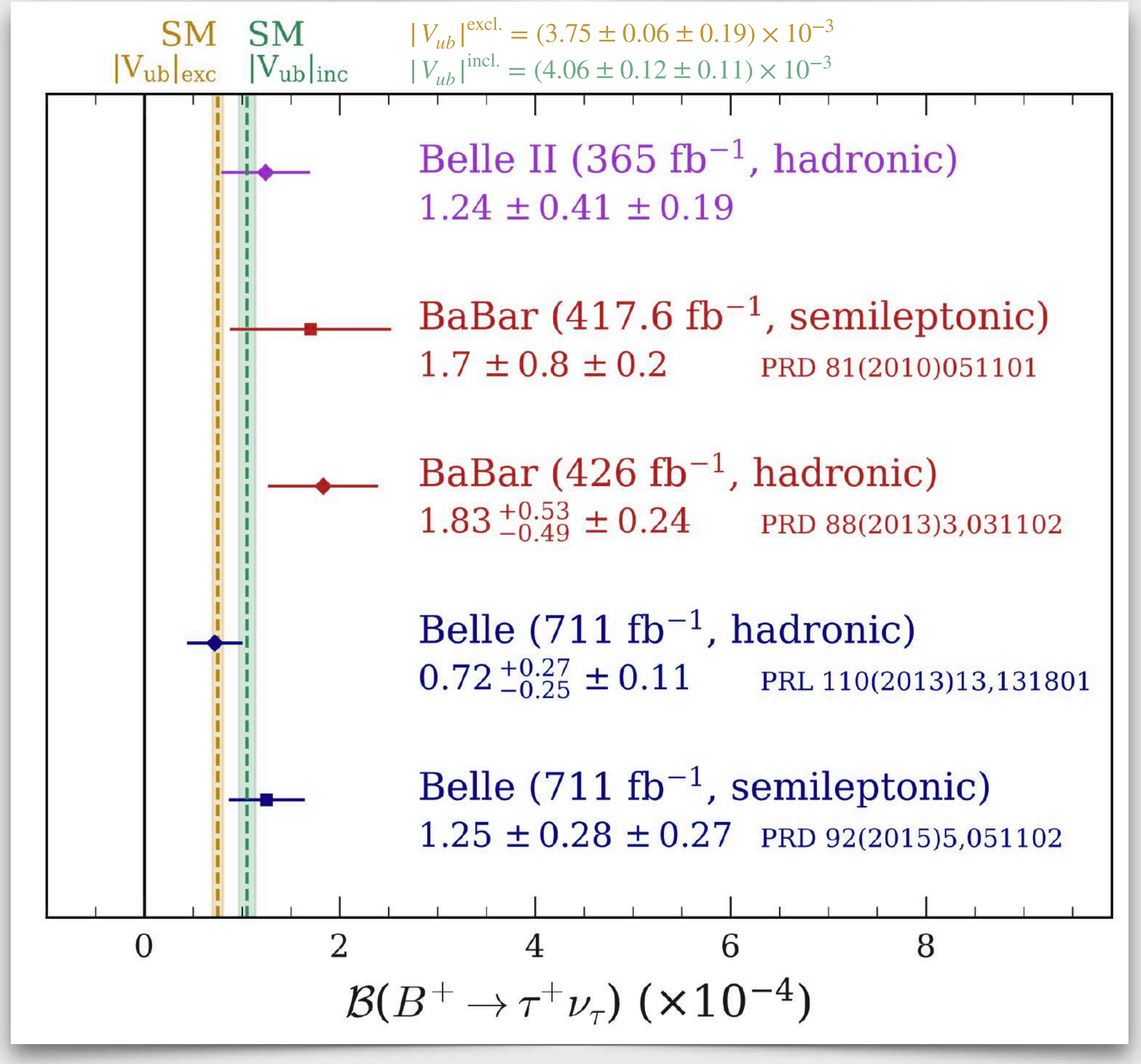
- Branching fraction is measured with $3\sigma$ significance

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.24 \pm 0.41(\text{stat.}) \pm 0.19(\text{syst.})) \times 10^{-4}$$

  - Result is consistent with the current world average and with the SM prediction.
- Extract $|V_{ub}|$ assuming the SM and using $f_B = 190.0 \pm 1.3$ MeV (FLAG Review 2024, arXiv:2411.04268 [hep-lat] ) from Lattice QCD:

$$|V_{ub}| = (4.41^{+0.74}_{-0.89}) \times 10^{-3}$$

  - Uncertainty is comparable with previous hadronically tagged measurements from BaBar and Belle despite smaller data sample used
  - Improved sensitivity due to FEI tagging algorithm and an optimised selection




Comparison of $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ measurements and the two SM expectation values - using $|V_{ub}|$ from exclusive determination (yellow) and from inclusive determination (green).

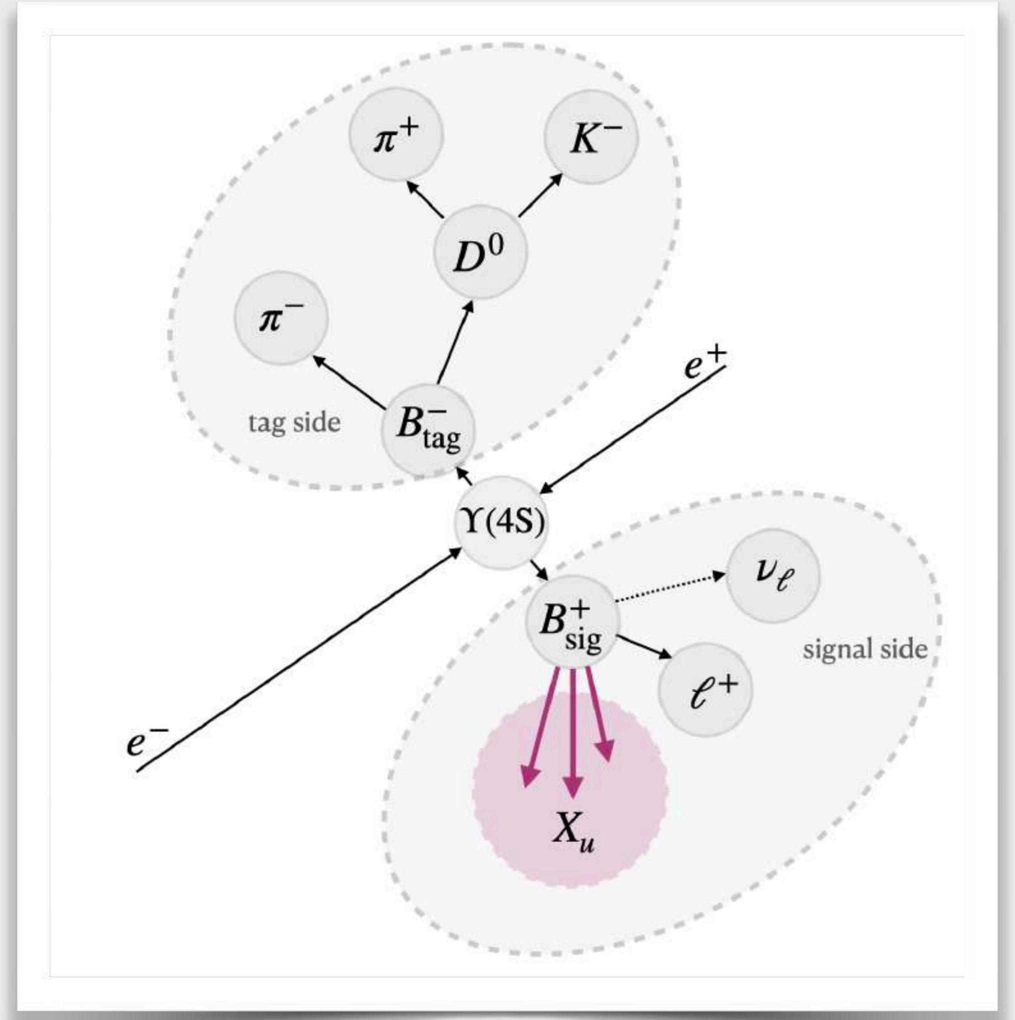
# $|V_{ub}|$ from tagged inclusive $B \to X_u \ell \nu_\ell$

To be submitted to PRD

- $|V_{ub}|$ is extracted from inclusive partial branching fractions in various phase-space regions.

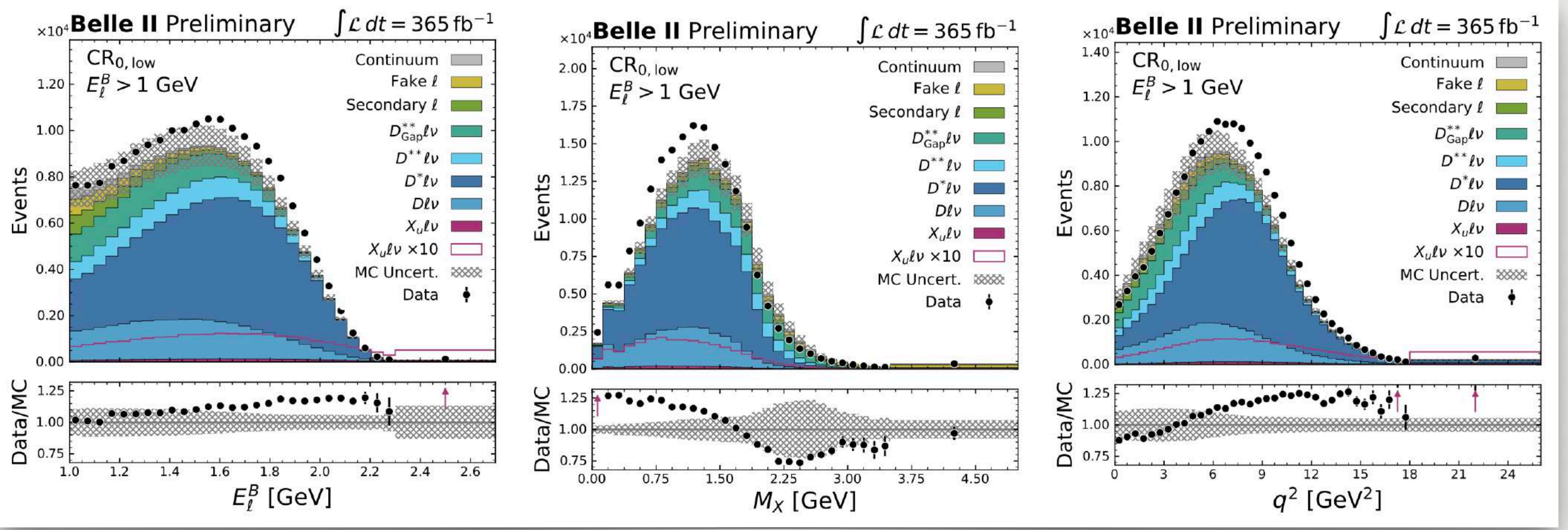
$$|V_{ub}| = \sqrt{\frac{\Delta\mathscr{B}(B \to X_u \ell \nu_\ell)}{\tau_B \Delta\Gamma(B \to X_u \ell \nu_\ell)}}$$

- 3 main kinematic variables:
  - lepton energy (in $B_{\text{sig}}$ rest frame) - $E_\ell^{(B)}$,
  - mass of hadronic system - $M_X$
  - squared momentum transfer - $q^2 = (p_\ell + p_\nu)^2$
- Train 2 separate MVA classifiers to suppress main backgrounds - continuum ($e^+e^- \to q\bar{q}$) and $B \to X_c \ell \nu_\ell$




- Event reconstruction:
  - $B_{\text{tag}}$ reconstructed using FEI with hadronic tagging
  - Reconstructed lepton - $\ell = e$ or $\mu$
  - Hadronic system $X$ characterised from ROE
  - Neutrino caracterised as missing energy:

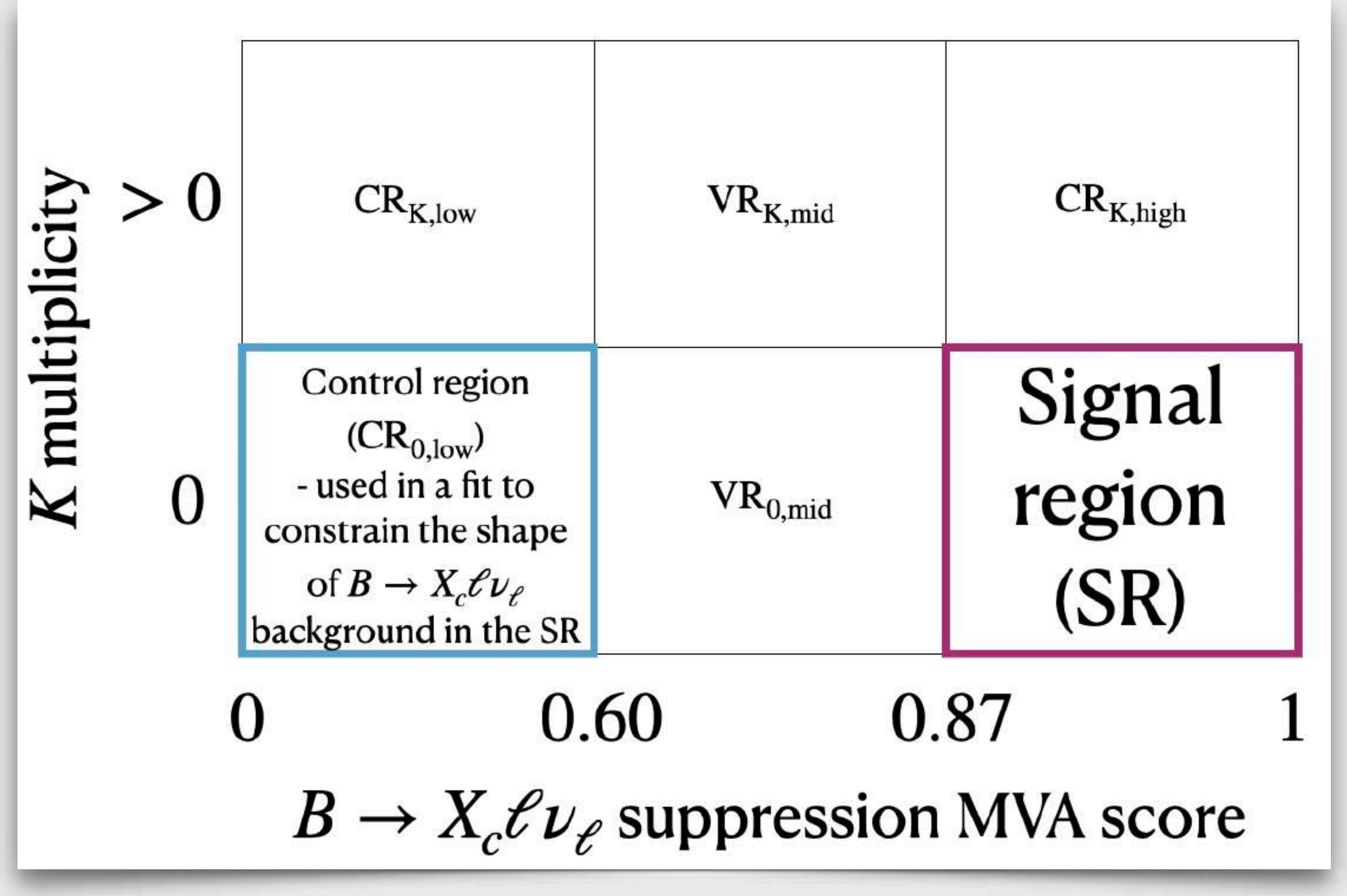
$$p_{\text{miss}} = p_{e^+e^-} - p_{B_{\text{tag}}} - p_\ell - p_X$$



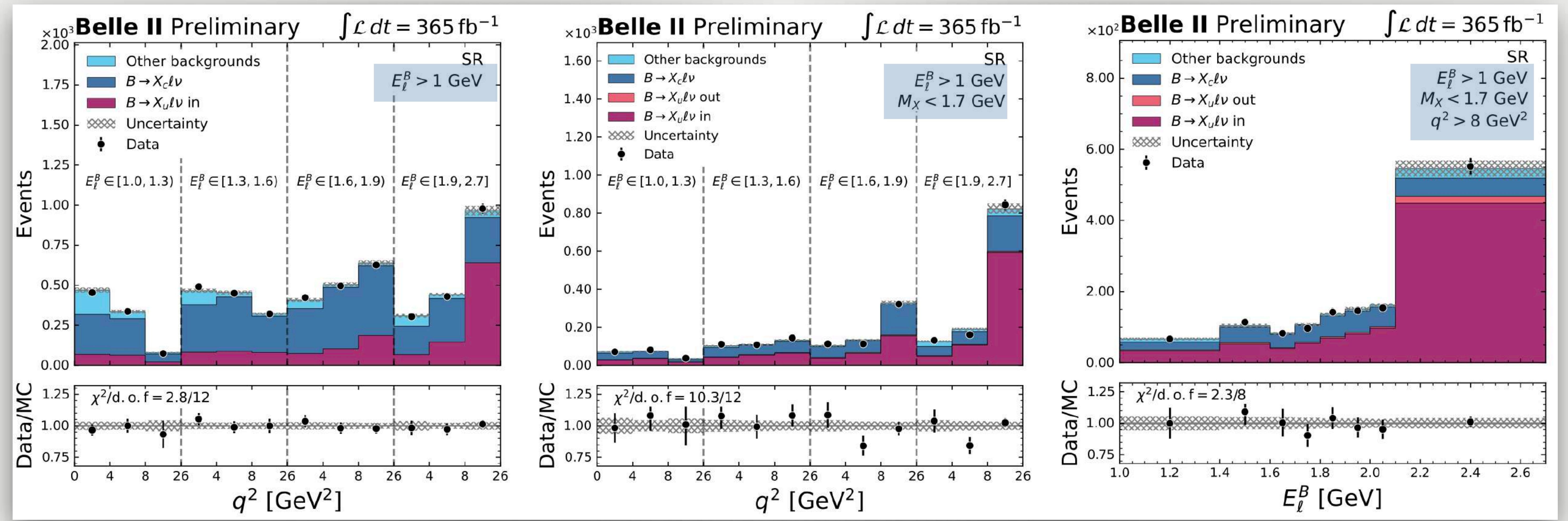

$E_\ell^B$, $M_X$ and $q^2$ distributions in data and simulated data.

# $|V_{ub}|$ from tagged inclusive $B \to X_u \ell \nu_\ell$ - Signal extraction

- Extract branching fraction from template fit in bins of $E_\ell^B$ and $q^2$
- Define control regions based on kaon multiplicity and $B \to X_c \ell \nu_\ell$ suppression classifier score - fit validation and biases estimation due to mismodelling of $B \to X_c \ell \nu_\ell$




- Fit is performed in three different phase space regions:
  - $E_\ell^B > 1$ GeV
  - and $M_X < 1.7$ GeV
  - and $q^2 > 8$ GeV$^2$




Post-fit signal region distributinos for 3 different phase space regions.

# $|V_{ub}|$ from tagged inclusive $B \to X_u \ell \nu_\ell$ - Result

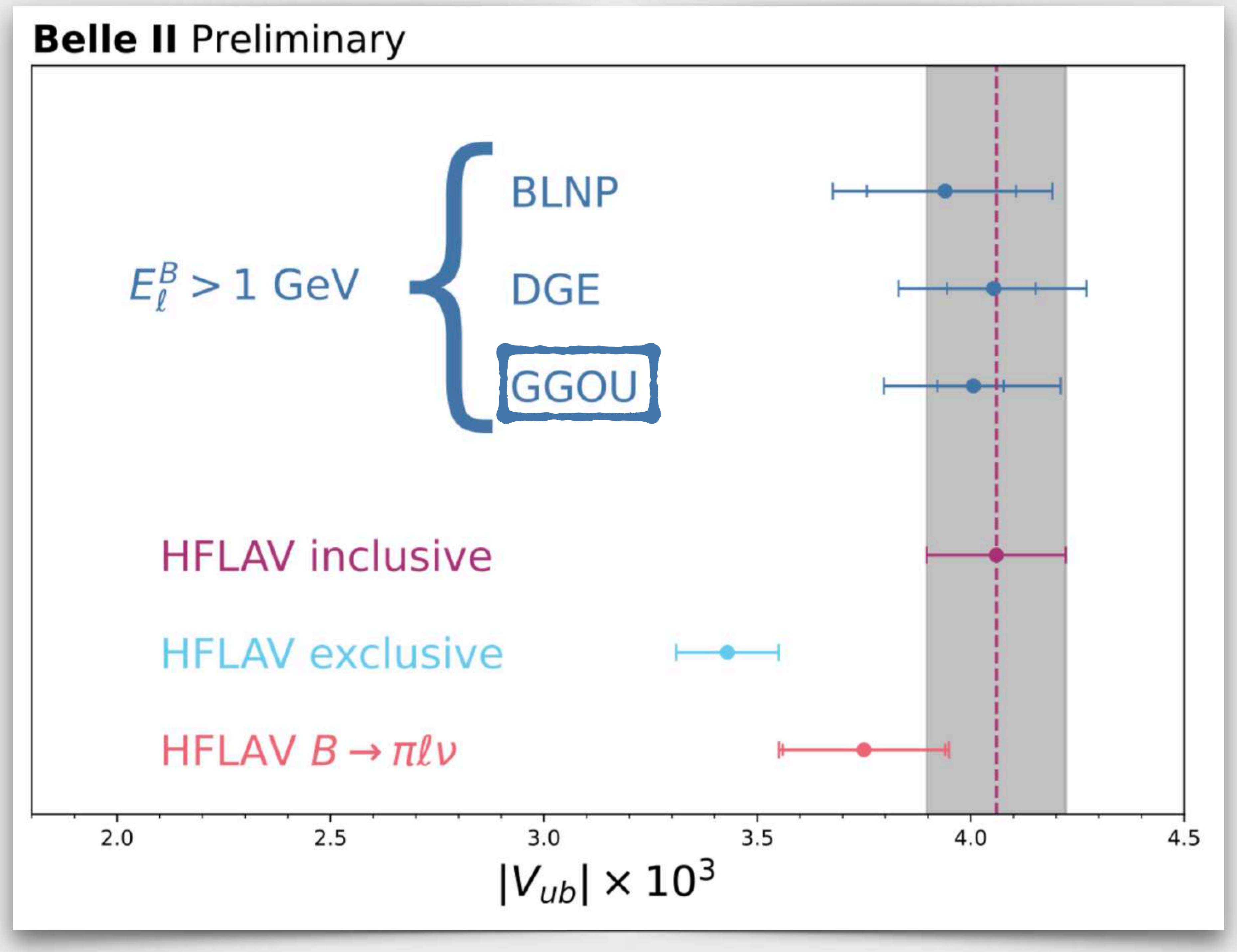
- In the broadest phase-space region - cut only on $E_\ell^B > 1$ GeV, where inclusive $B \to X_u \ell \nu_\ell$ theoretical predictions are most reliable, the measured partial branching fraction is:

$$\Delta\mathcal{B}(B \to X_u \ell \nu_\ell) = (1.54 \pm 0.08(\text{stat.}) \pm 0.12(\text{syst.})) \times 10^{-3}$$

- Extract $|V_{ub}|$ using averaged $B^+$ and $B^0$ lifetimes as $\tau_B = 1.578 \pm 0.003$ and GGOU framework to obtain $\Delta\Gamma$:

$$|V_{ub}| = (4.01 \pm 0.11(\text{stat.}) \pm 0.16(\text{syst.})^{+0.09}_{-0.07}(\text{th.})) \times 10^{-3}$$

  - Measurement is systematically limited due to $B \to X \ell \nu_\ell$ modeling
  - Result in agreement with inclusive HFLAV average and in exceedes exclusive HFLAV average
  - Competitive result with half the dataset of Belle due to better tagging algoritm and more modern background suppression methods




Comparison between the three values of $|V_{ub}|$ (obtained from the fit in a phase space region defined by $E_\ell^B > 1$ GeV and using three different theoretical frameworks), the inclusive, the exclusive and $B \to \pi \ell \nu_\ell$ averages from HFLAV.

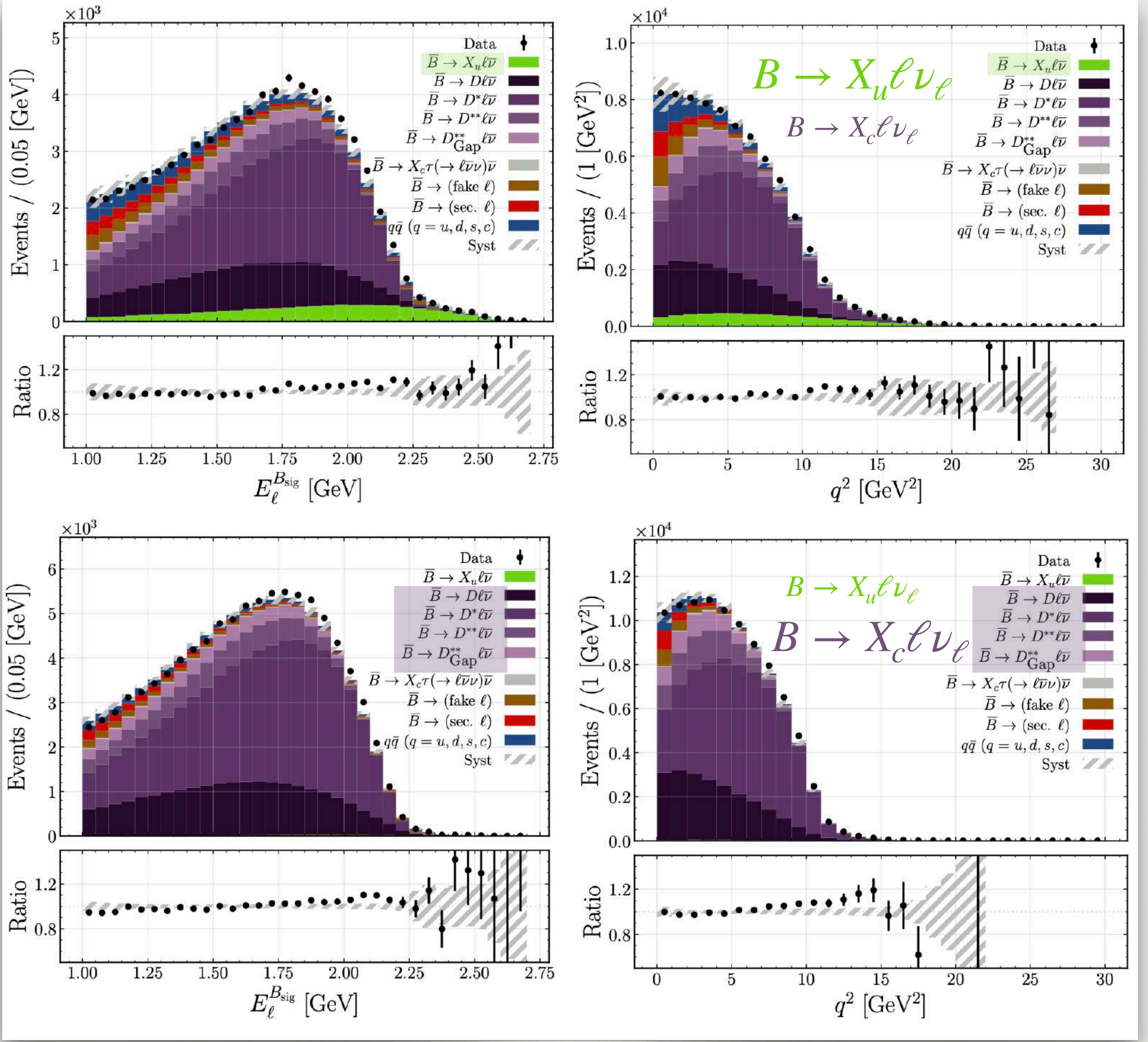
# $|V_{ub}|/|V_{cb}|$ from tagged inclusive $B \to X\ell\nu_\ell$

Published
PRD 111, 092016 (2025)

- Exract the ratio of $|V_{ub}|/|V_{cb}|$ as:

$$\frac{|V_{ub}|}{|V_{cb}|} = \sqrt{\frac{\Delta\mathscr{B}(B \to X_u\ell\nu_\ell)\Delta\Gamma(B \to X_c\ell\nu_\ell)}{\Delta\mathscr{B}(B \to X_c\ell\nu_\ell)\Delta\Gamma(B \to X_u\ell\nu_\ell)}}$$

- Use full Belle data sample of 771 $\text{fb}^{-1}$ and apply Belle II hadronic tagging algorithm
- After event selection separate the sample into $B \to X_u\ell\nu_\ell$ enhanced and depleted subsamples based on $N(K^\pm, K_S^0)$ in $X$ system
- Region of interest: $E_\ell^B > 1$ GeV
- Simple cut-based selection to suppress $B \to X_c\ell\nu_\ell$ background:
  - $M^2_{\text{miss}} < 0.43\ \text{GeV}^2$
  - Veto $D^*$ to suppress $B \to D^*\ell\nu_\ell$ events



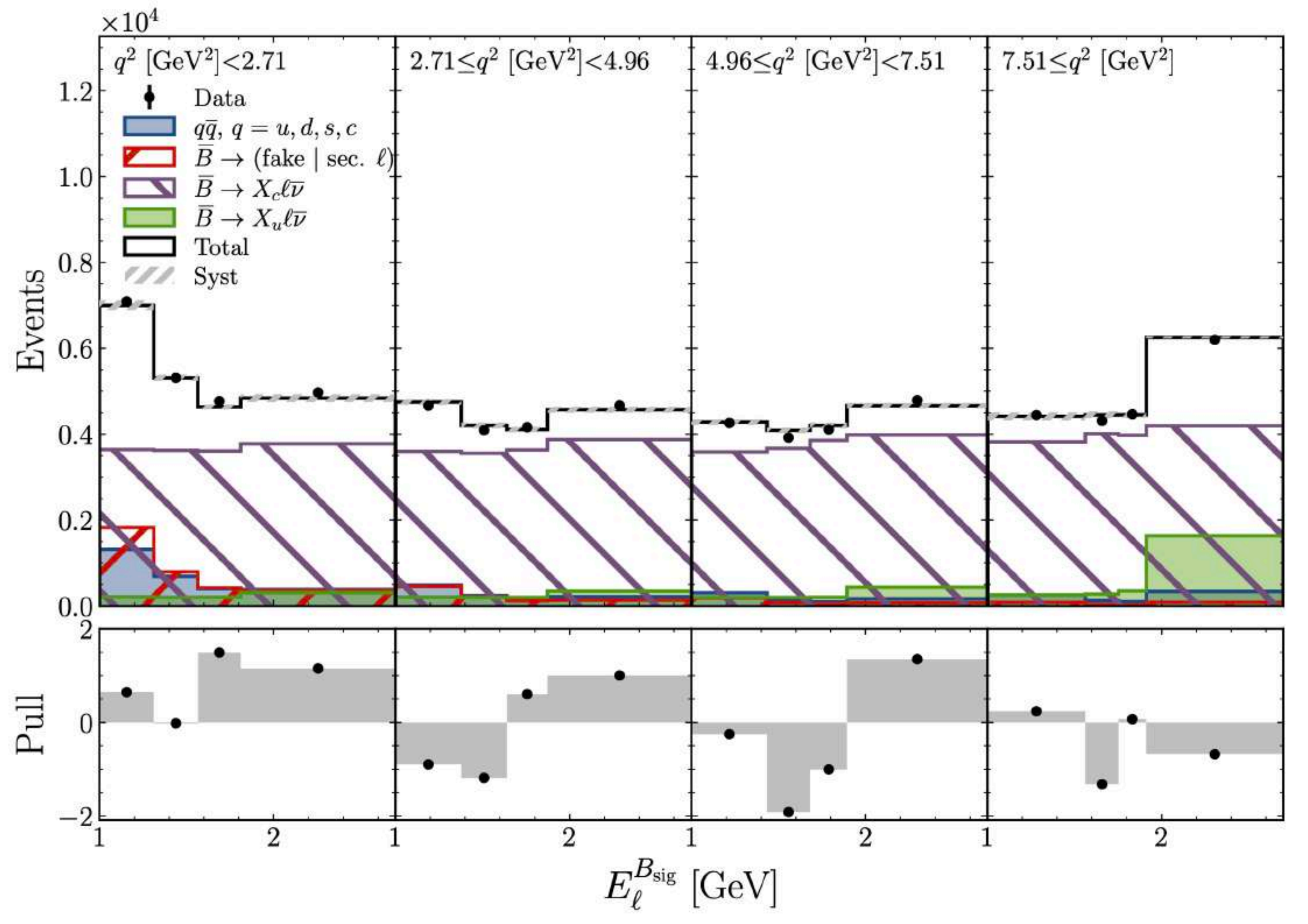

$E_\ell^B$ and $q^2$ distributions in data and simulated data for the $B \to X_u\ell\nu_\ell$ enhanced (top) and depleted (bottom) subsamples.

# $|V_{ub}|/|V_{cb}|$ from tagged inclusive $B \to X\ell\nu_\ell$ - Signal extraction

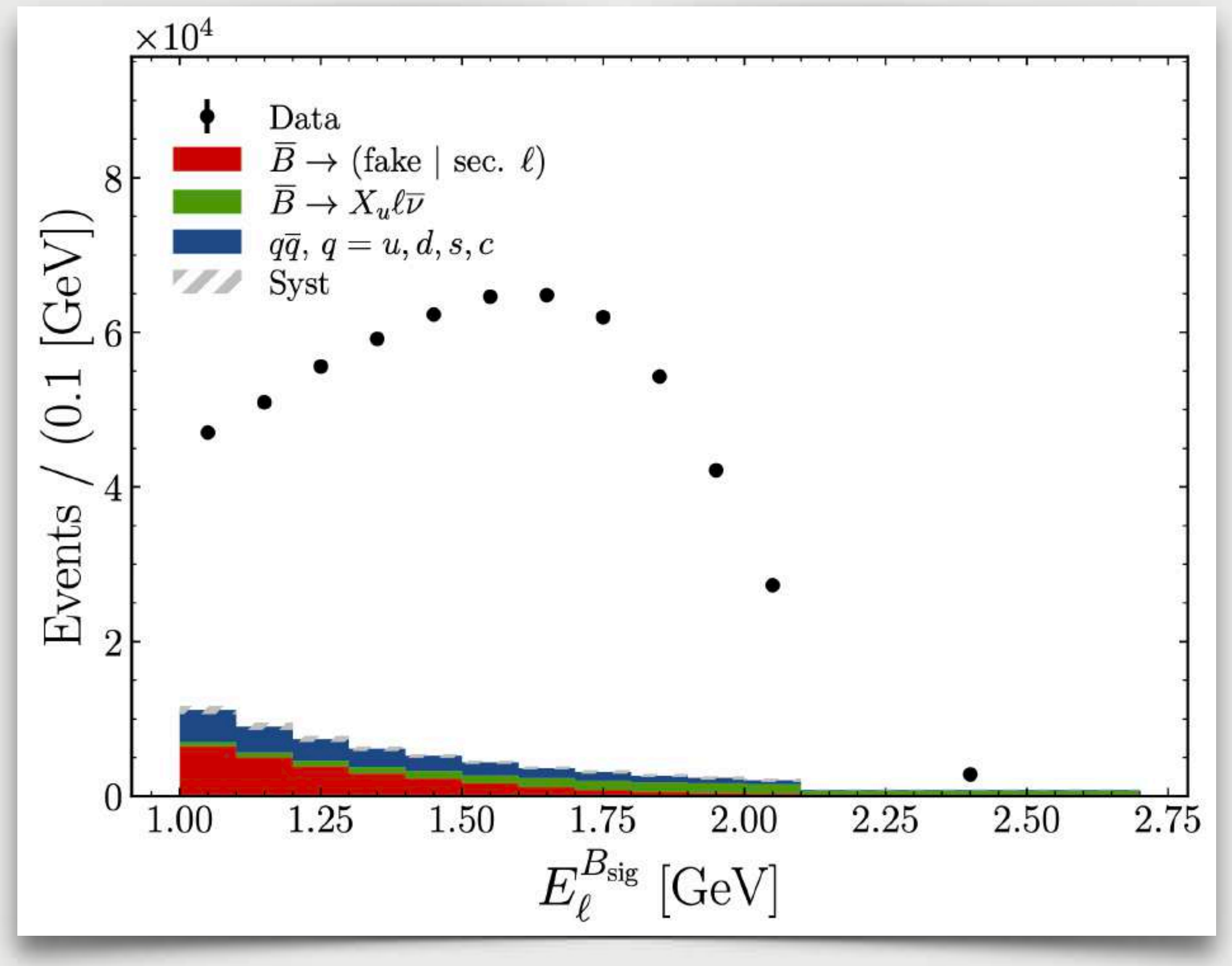
- Extract $B \to X_u\ell\nu_\ell$ yield from 2D fit to $q^2 : E_\ell^B$ in the enhanced sample using 4 templates:
  - Signal component: $B \to X_u\ell\nu_\ell$
  - Continuum events ($e^+e^- \to q\bar{q}$) - calibrated to off-resonance sample
  - Secondary ($\ell$ from a secondary $c \to s\ell\nu_\ell$ decay) and fake (hadron misidentified as $\ell$) lepton - calibrated from high $M_X$ and low $E_\ell^B$ control region
  - $B \to X_c\ell\nu_\ell$ template $T_i = \tau_i(N_{i,D}^{\text{Data}} - \eta_{i,D}^{B\to X_u\ell\nu_\ell} - \eta_{i,D}^{q\bar{q}} - \eta_{i,D}^{\text{S+F}})$

$\tau$ - transfer factor from $X_u\ell\nu_\ell$ depleted to enhanced subsample derived from the simulaton
D - $X_u\ell\nu_\ell$ depleted sample
$N_i^{\text{Data}}$ - data yield in the i-th bin
$\eta$ - yields for each component from the simulation

- Extract $B \to X_c\ell\nu_\ell$ yield via simple background subtraction in total $B \to X\ell\nu_\ell$ sample (remove $D^*$ veto and $M_{\text{miss}}^2$ cut):
  - $N^{X_c\to\ell\nu_\ell} = N^{\text{Data}} - \eta^{q\bar{q}} - a\eta^{X_u\ell\nu_\ell} - \eta^{\text{S+F}}$, where $a$ is obtained from the previous fit




Fit to the $q^2 : E_\ell^B$ distribution.




Determined background compared with all events in the $B \to X\ell\nu_\ell$ sample.

# $|V_{ub}|/|V_{cb}|$ from tagged inclusive $B \to X\ell\nu_\ell$ - Result

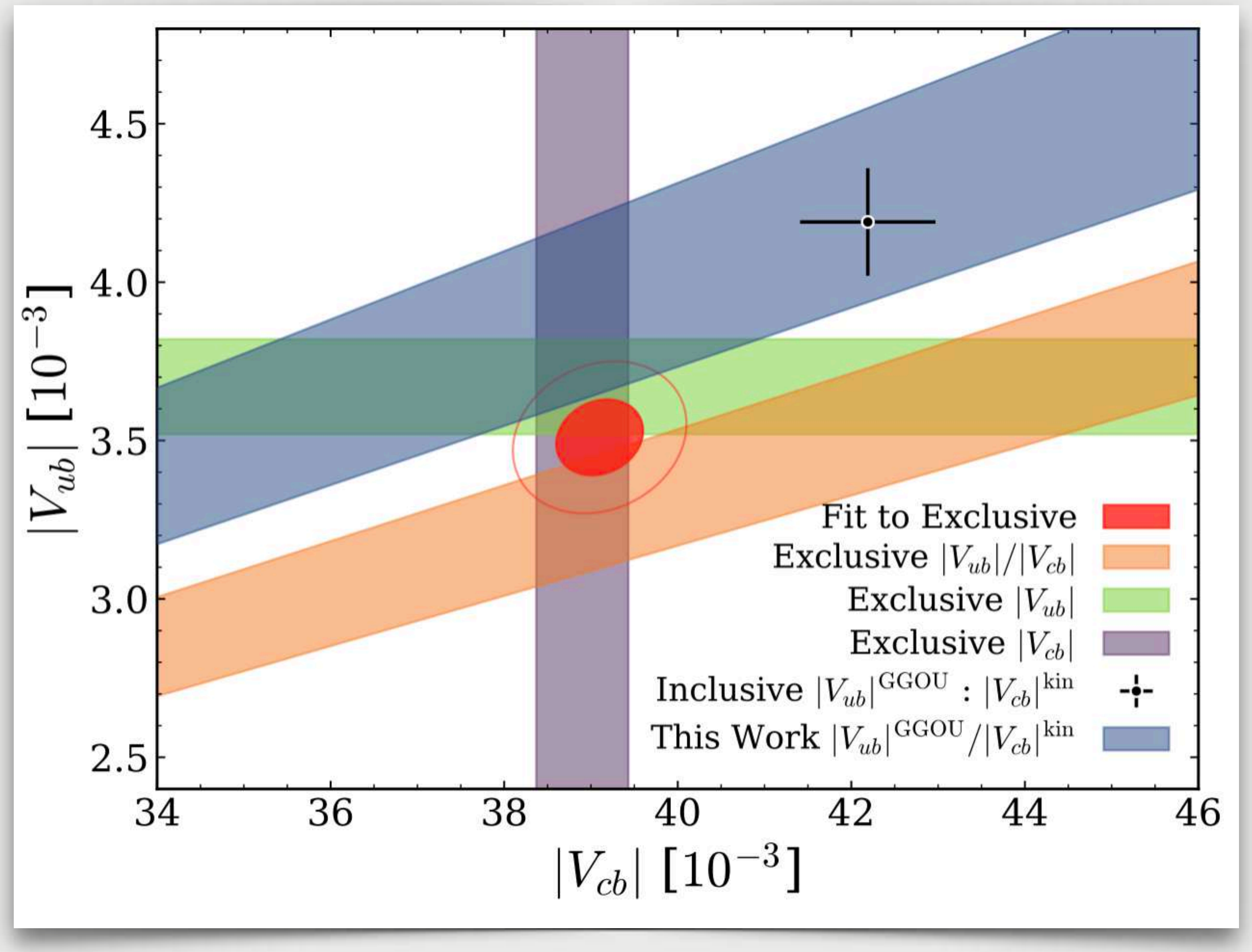
- The measured ratio of partial branching fraction for $E_\ell^B > 1$ GeV is:

$$\frac{\Delta\mathscr{B}(B \to X_u\ell\nu_\ell)}{\Delta\mathscr{B}(B \to X_c\ell\nu_\ell)} = (1.99 \pm 0.17(\text{stat.}) \pm 0.16(\text{syst.})) \times 10^{-2}$$

- Extract $|V_{ub}|/|V_{cb}|$ using $\Delta\Gamma^{\text{GGOU}}(B \to X_u\ell\nu_\ell) = 58.5^{+2.7}_{-2.3}\ \text{ps}^{-1}$ and $\Delta\Gamma^{\text{kin}}(B \to X_c\ell\nu_\ell) = 29.7 \pm 1.2\ \text{ps}^{-1}$ (Eur. Phys. J. C 81, 226 (2021)):

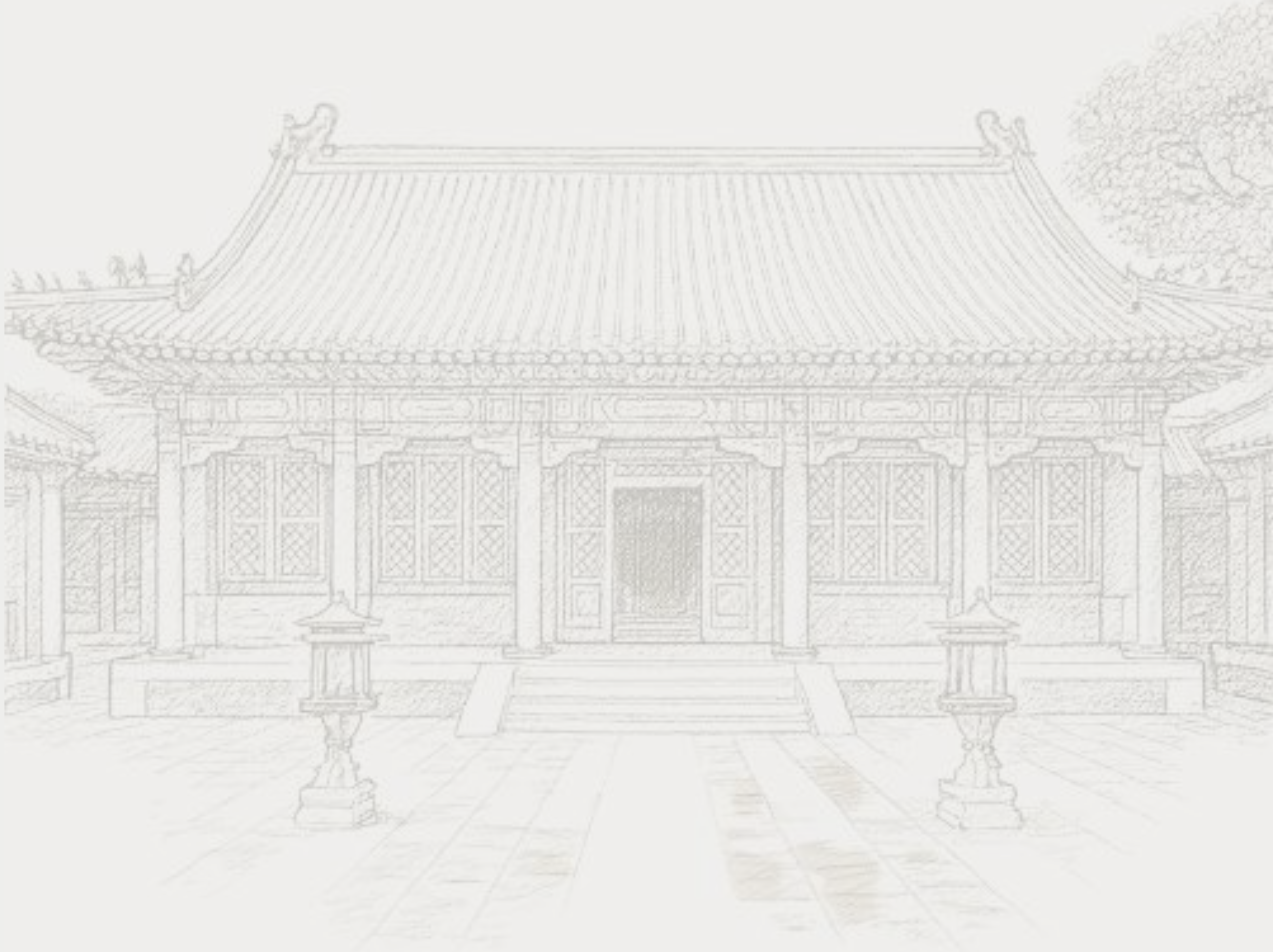
$$\frac{|V_{ub}|}{|V_{cb}|} = \big(10.06 \pm 0.43(\text{stat.}) \pm 0.39(\text{syst.}) \pm 0.23(\Delta\Gamma(B \to X_u\ell\nu_\ell)) \pm 0.20(\Delta\Gamma(B \to X_c\ell\nu_\ell))\big) \times 10^{-2}$$

  - Compatible with both inclusive and exclusive determinations of $|V_{ub}|$ and $|V_{cb}|$
  - Most important sources of systematic uncertainties: modeling of the $B \to X_u\ell\nu_\ell$ component; composition of the secondary and fake lepton component




Different measures of $|V_{ub}|$ and $|V_{cb}|$ compared to the result from tagged inclusive $B^0 \to X\ell\nu_\ell$. (Image by M. Hohmann)

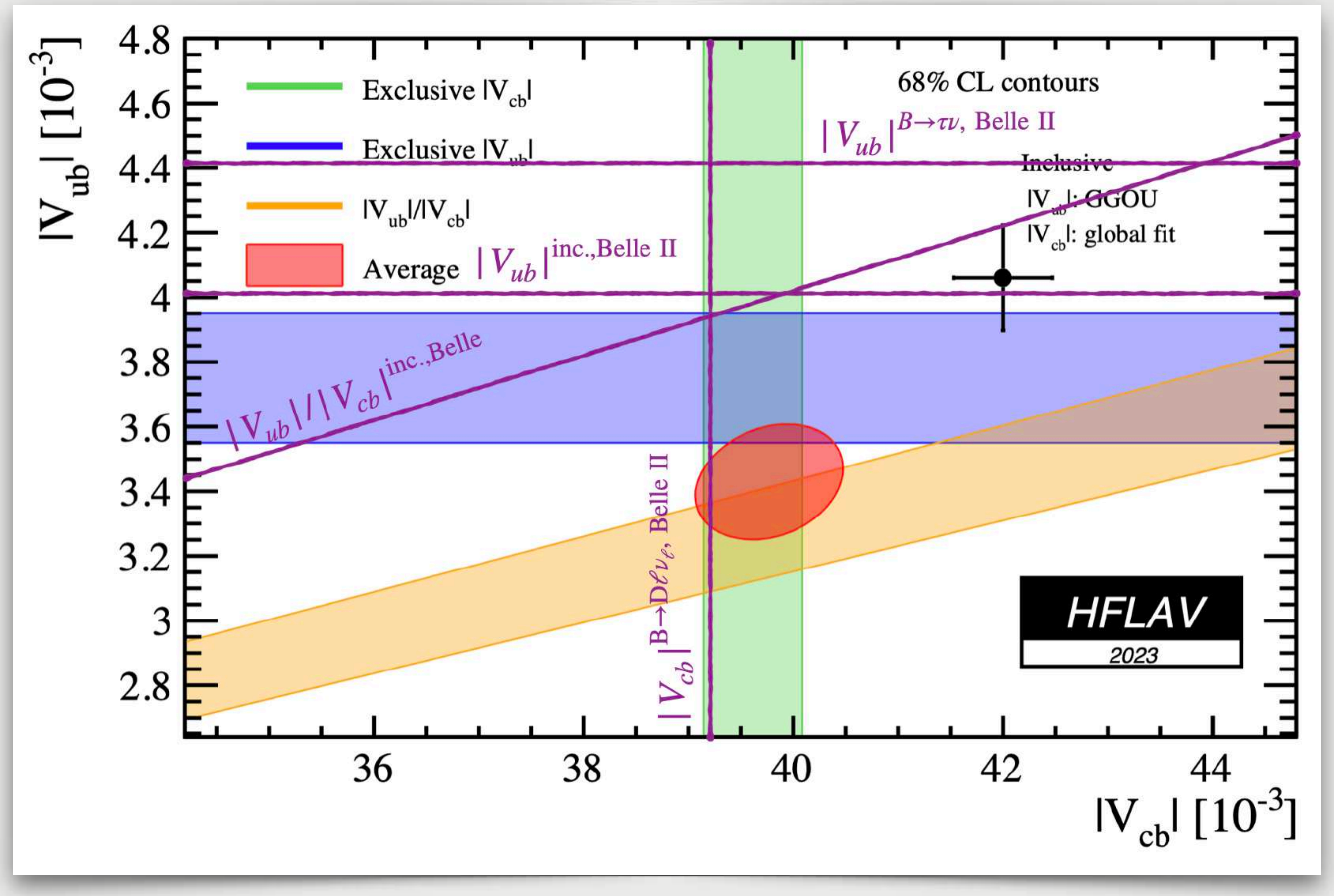
# Conclusion



# Summary

- Studying semileptonic and leptonic $B$ decays at Belle II provide key tests of the Standard Model and are sensitive to New Physics.

- Measurements presented in this talk:
  - $|V_{cb}| = (39.2 \pm 0.4(\text{stat.}) \pm 0.6(\text{syst.}) \pm 0.5(\text{th.})) \times 10^{-3}$
  - $|V_{ub}| = (4.41^{+0.74}_{-0.89}) \times 10^{-3}$
  - $|V_{ub}| = (4.01 \pm 0.11(\text{stat.}) \pm 0.16(\text{syst.})^{+0.09}_{-0.07}(\text{th.})) \times 10^{-3}$
  - $\frac{|V_{ub}|}{|V_{cb}|} = \big(10.06 \pm 0.43(\text{stat.}) \pm 0.39(\text{syst.}) \pm 0.23(\Delta\Gamma(B \to X_u \ell \nu_\ell)) \pm 0.20(\Delta\Gamma(B \to X_c \ell \nu_\ell))\big) \times 10^{-2}$



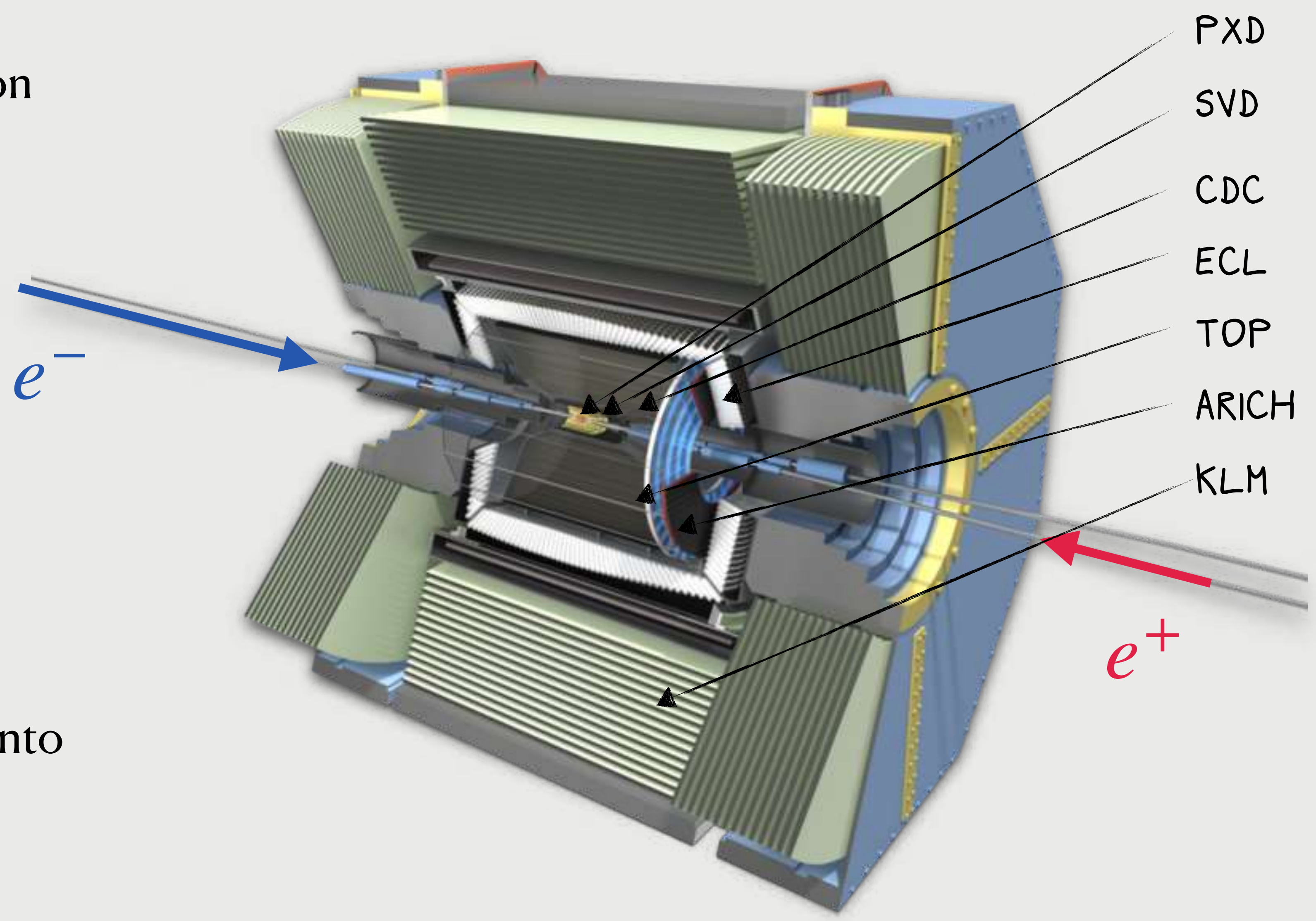

*Stay tuned for more interesting measurements from Belle II.*

Thank you

# Backup

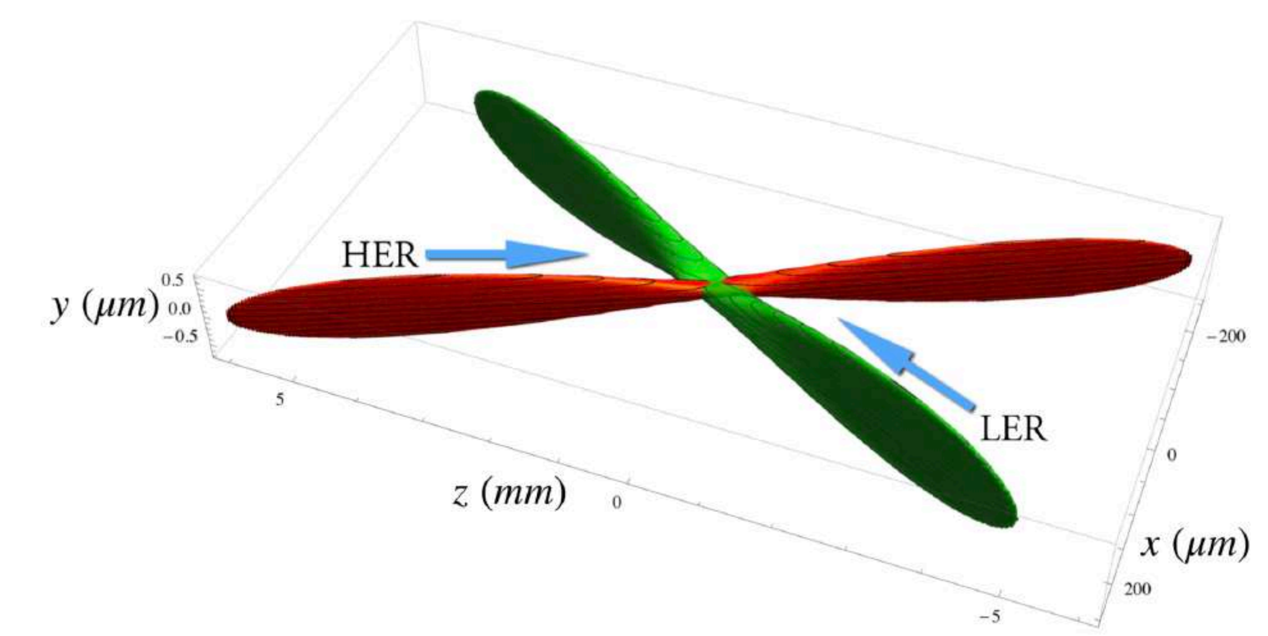
# More about Belle II: detector + accelerator

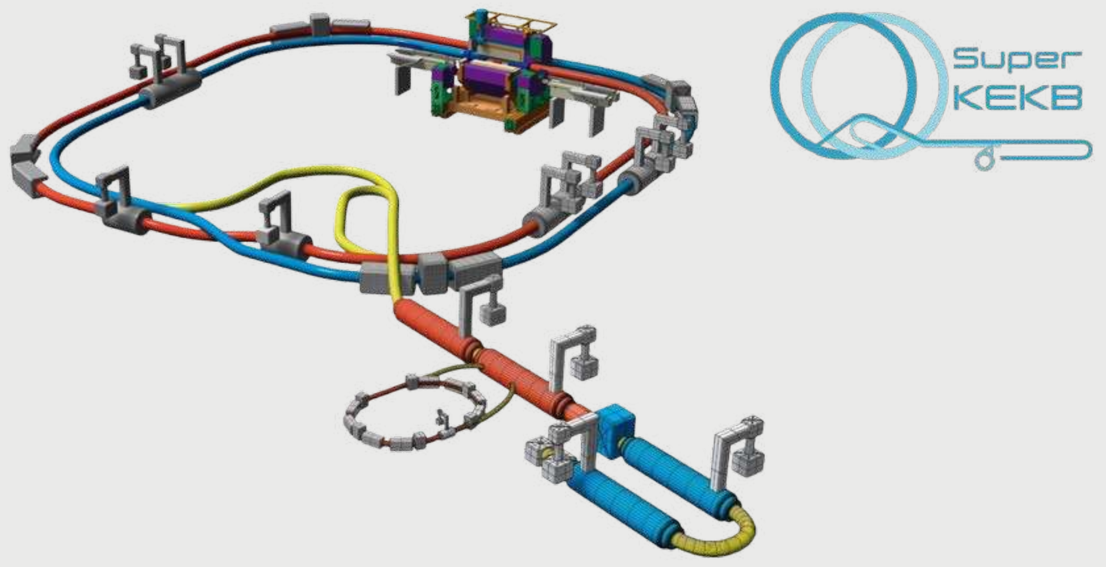
- Belle II: general purpose spectrometer: $4\pi$ coverage; clean $e^+e^-$ environment with known initial state; good charged track reconstruction efficiency, excellent particle identification, $(\gamma, \pi^0)$ reconstruction; excellent vertexing ($\sigma \sim 60\mu$m for $B, D$ vertices)
- Sub-systems:
  - VerteX Detector (**VXD**) = PXD + SVD: $\sigma$(Track impact parameter) $\sim$ 15 $\mu$m
    - PiXel Detector (**PXD**): inner vertex detector, 2 layer pixel detector, DEPFET technology
    - Silicon Vertex Detector (**SVD**): outer part of the vertex detector, 4 layer double-sided strips
  - Central Drift Chamber (**CDC**): main tracking system, 56 layers of longitudinal and stereo wires, He(50%):$C_2H_6$(50%), 91% of solid angle coverage, $dE/dx$ resolution 5% (low-p PID)
  - Electromagnetic CaLorimeter (**ECL**): consists of over 8000 CsI(T) crystsals which create scintillalation light when a particle flies into them, waveform sampling, 94% of solid angle coverage, $e$ID eff. 90% at <0.1% fake, energy resolution 1.6-4%
  - Particle identification: $K/\pi$: $K$ eff. 90% at 1.8% $\pi$ fake rate
    - Time Of Propagation (**TOP**): PID in barrel region, 16 quartz bars, utilises the Cherenkov effect
    - Aerogel Ring-Imaging CHerenkov (**ARICH**): PID in forward region, aerogel as a radiator medium, utilises the Cherenkov effect
  - KLong and Muon (**KLM**) system: Alternating iron and detector plates, scintillator / resistive plate chamber, $\mu$ eff. 90% at 2% fake rate.



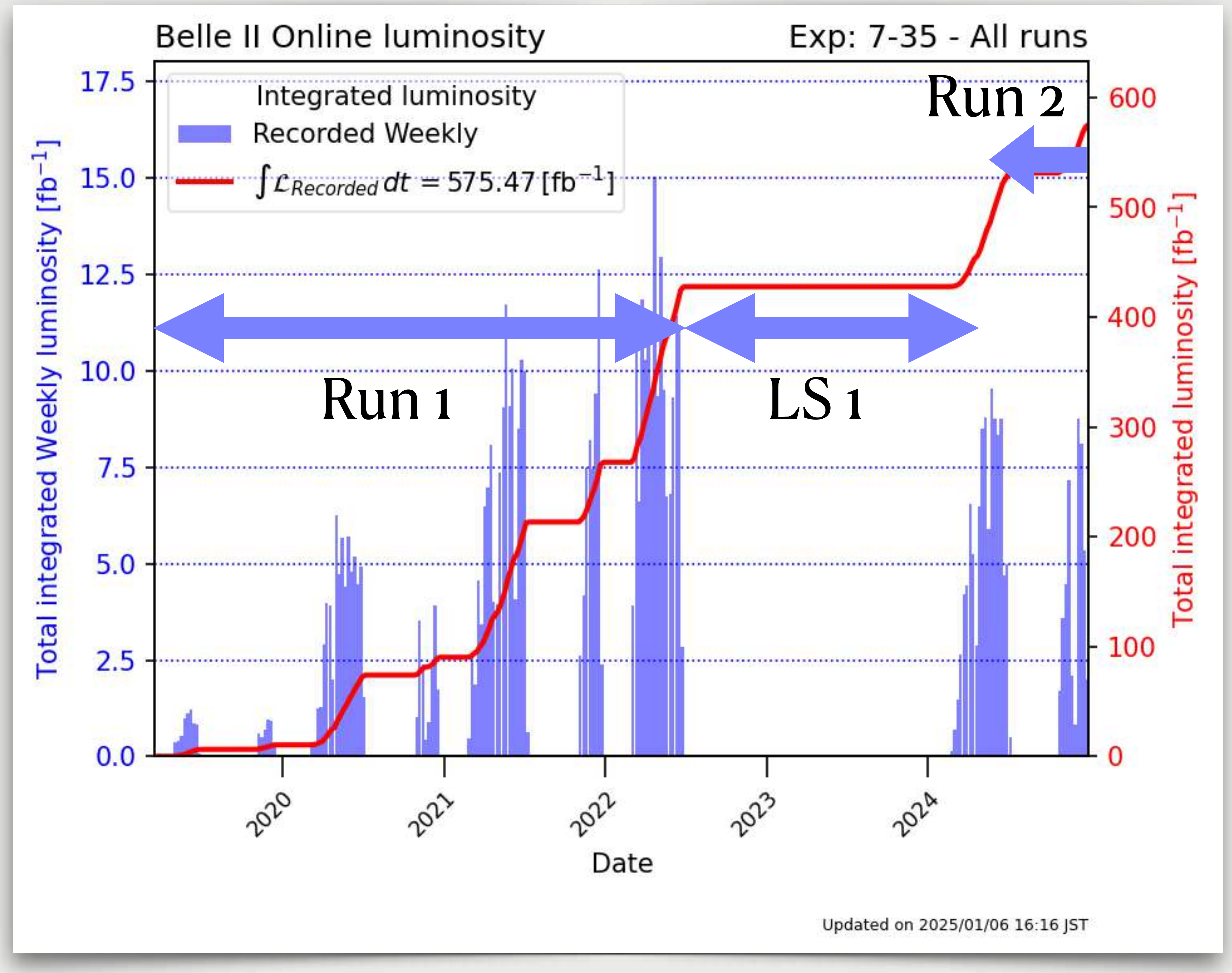

The Belle II Physics Book, arXiv:1808.10567 (hep-ex)

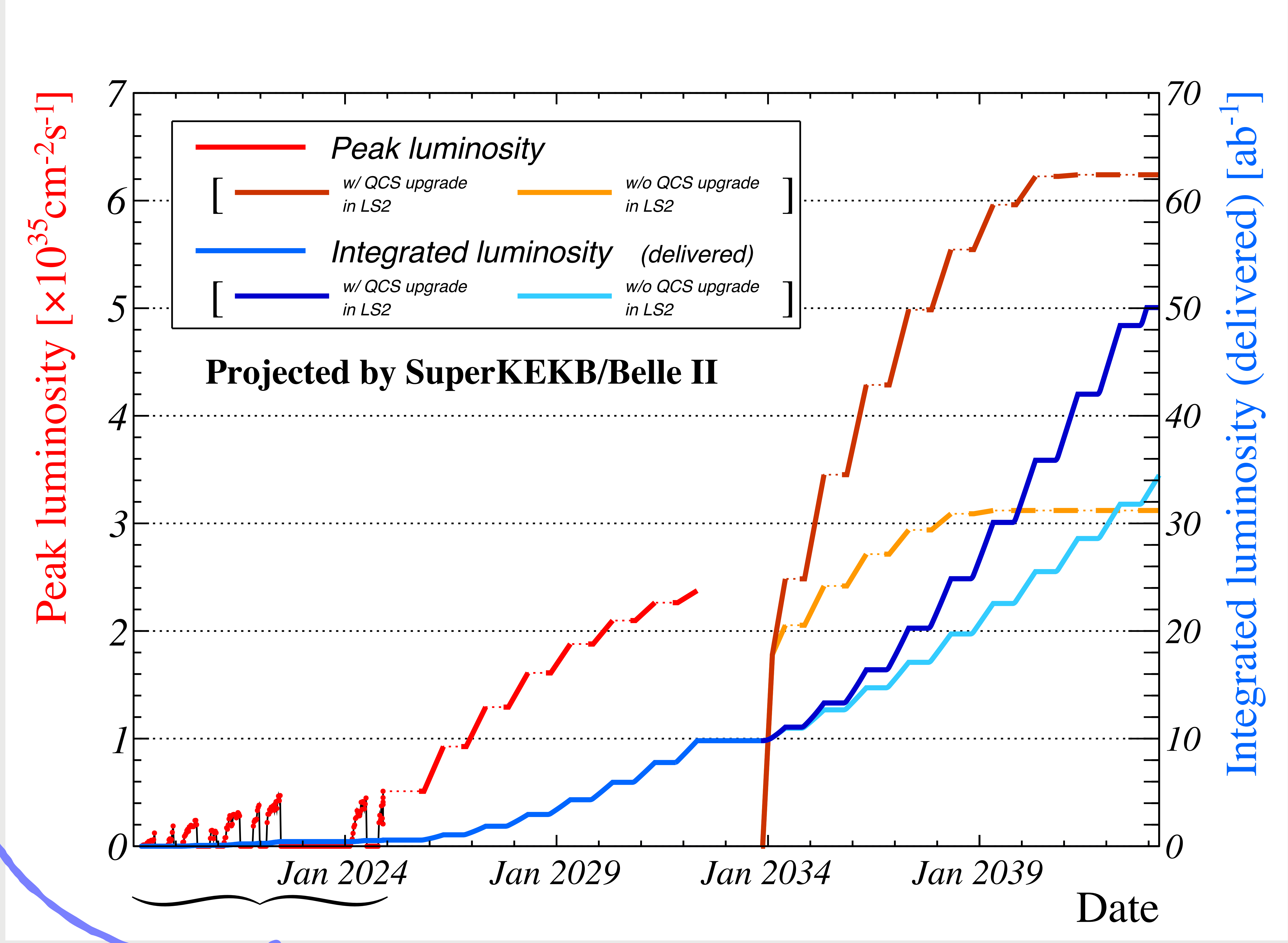
- SuperKEKB collider:
  - Asymetric $e^+e^-$ collider
  - Nano-beam scheme
  - Target peak luminosity: $6 \times 10^{35}$ cm$^{-2}$s$^{-1}$



# More about Belle II: Luminosity



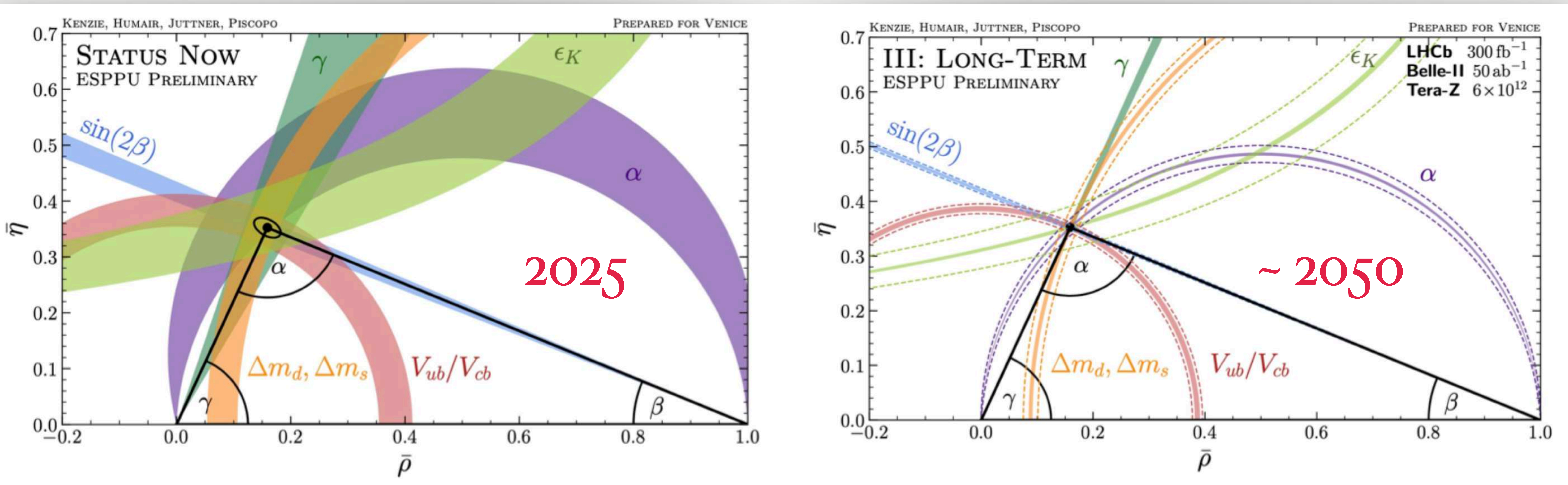




Belle II Luminosity Status

- Final goal: collect 50 $ab^{-1}$ data in the experiment lifetime.

# Prospects

- Major improvements with the  full exploitation of the available facilities up to ~2040: importance of LHCb-UII (300 $fb^{-1}$) and Belle II (50 $ab^{-1}$)
- ~2050 perspective: FCCee at $Z^0$ pole: 6 TeraZ:  $6x10^{12}$ $Z^0$ would have a major impact
- Support needed for theory: precision on SM predictions should also be improved to match the expected experimental precisions



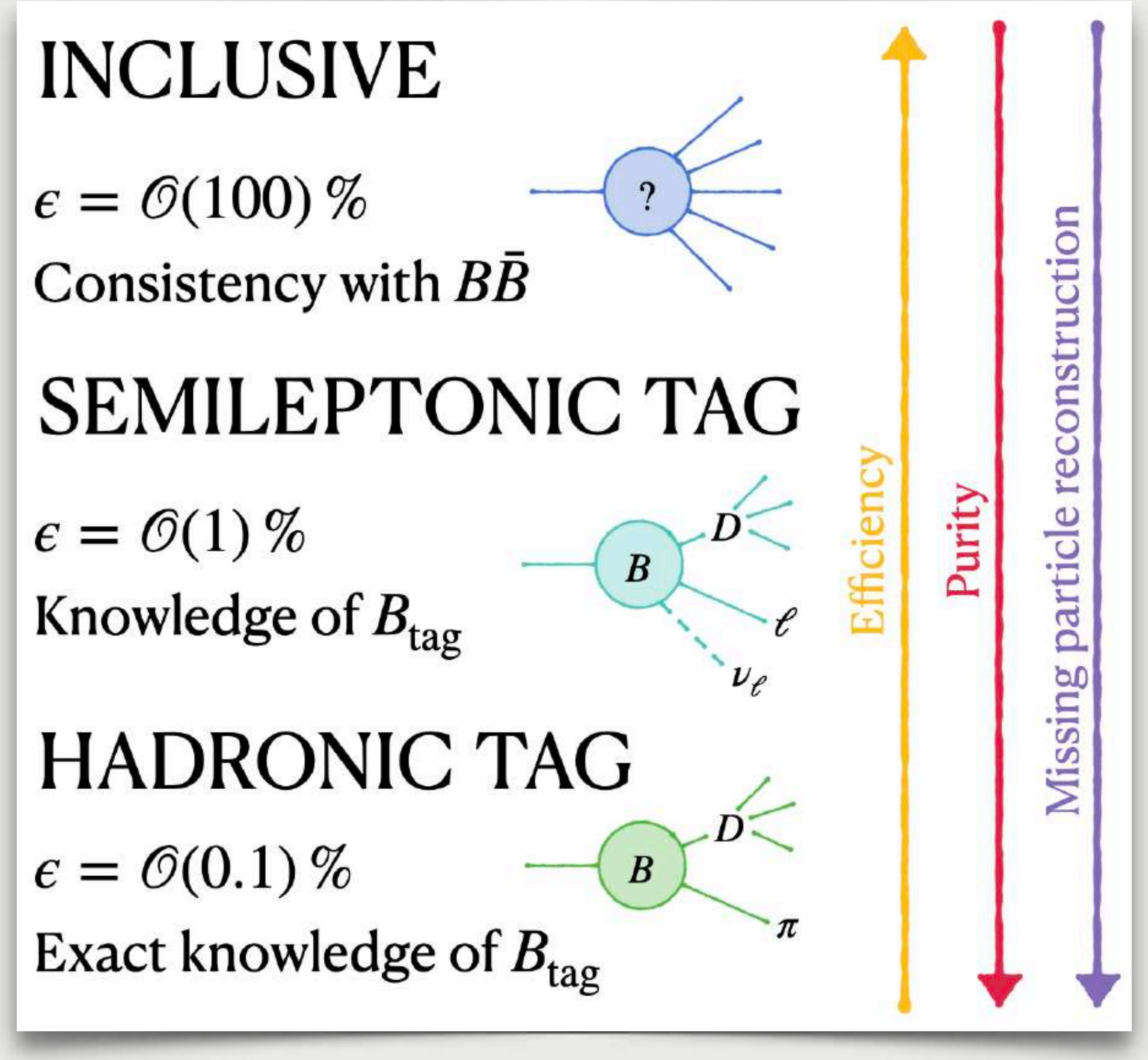

European Strategy for Particle Physics, 2025

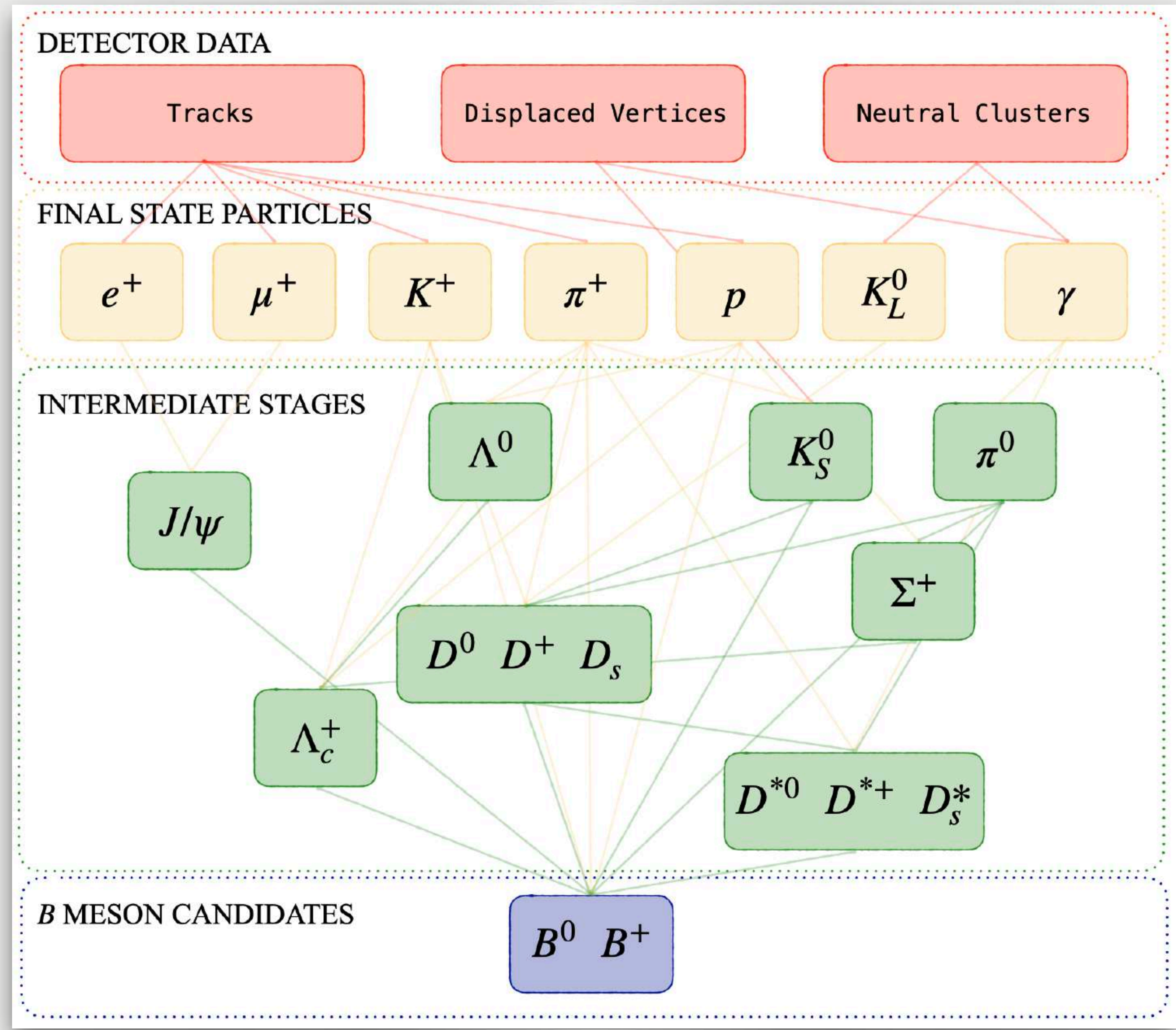
# More about FEI

Comput Softw Big Sci 3, 6 (2019)

- Full Event Interpretation (FEI) algorithm: tagging tool used at Belle II
- Especially useful when studying modes with missing energy - modes with one or more $\nu$ or specific dark matter searches
- Employs over 200 BDTs to reconstruct over $\mathcal{O}(10^4)$ $B$ decay chains
- Training output: list of $B$ tag candidates and a probability to have a correct reconstruction
- Tagging techinques include reconstruction of the $B$ meson candidate with:
  - Inclusive tagging
  - Semileptonic tagging
  - Hadronic tagging

  } FEI
- Trade-off between:
  - High efficiency: fraction of events that are identified as tag
  - High purity: fraction of identified tags that are correct
  - Good kinematics information: minimise missing/fake



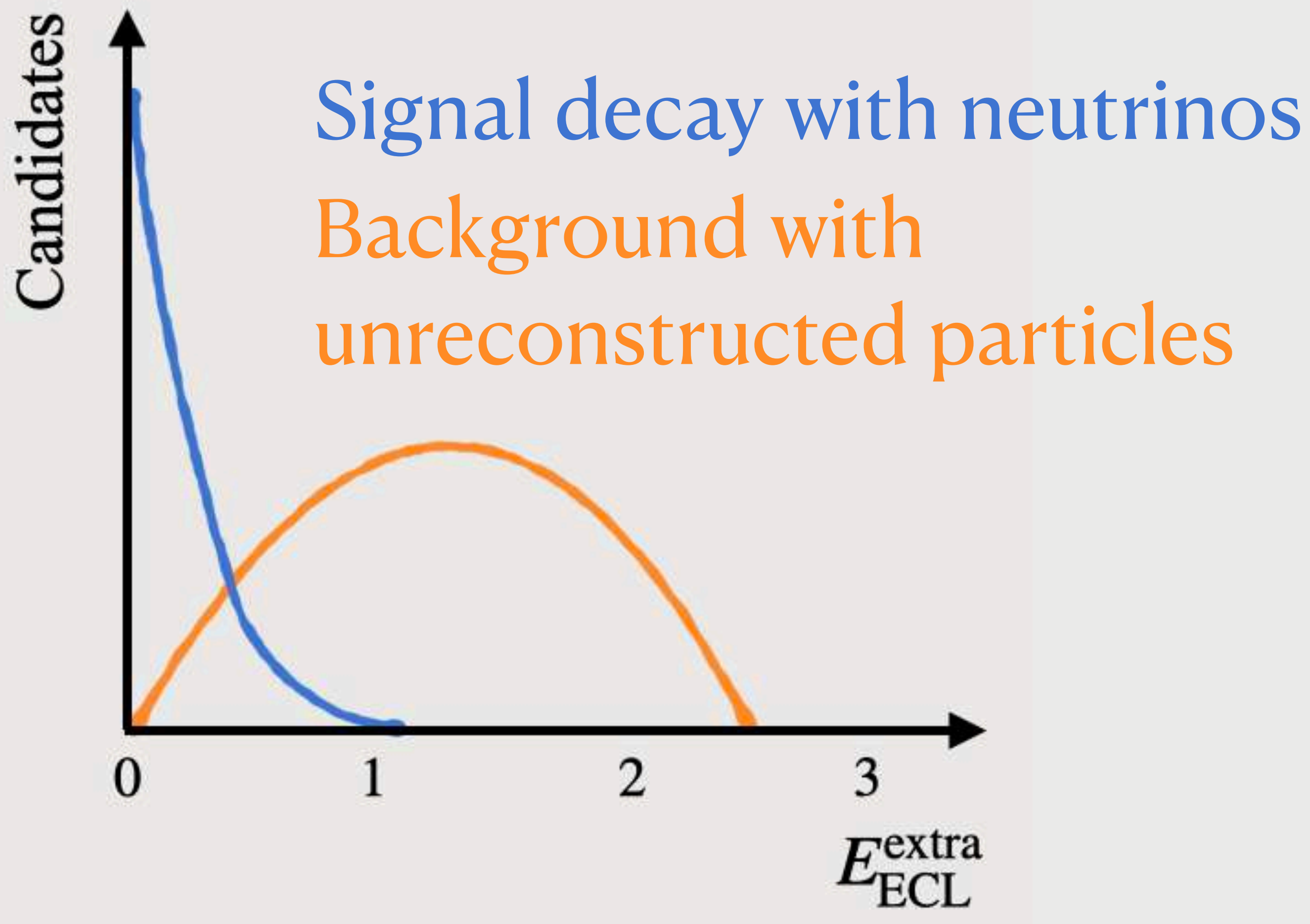

Hierarchical reconstruction applied by the FEI, which starting from charged tracks, neutral clusters and displaced vertices. These basic objects are interprated as final-state particles ($e^+, \mu^+, K^+, \pi^+, p, K_L^0$ and $\gamma$) combined to reconstructs intermediate particles ($J/\psi, \pi^0, K_S^0, \Lambda_c, D, D^*$) and finally candidate $B$ tags.

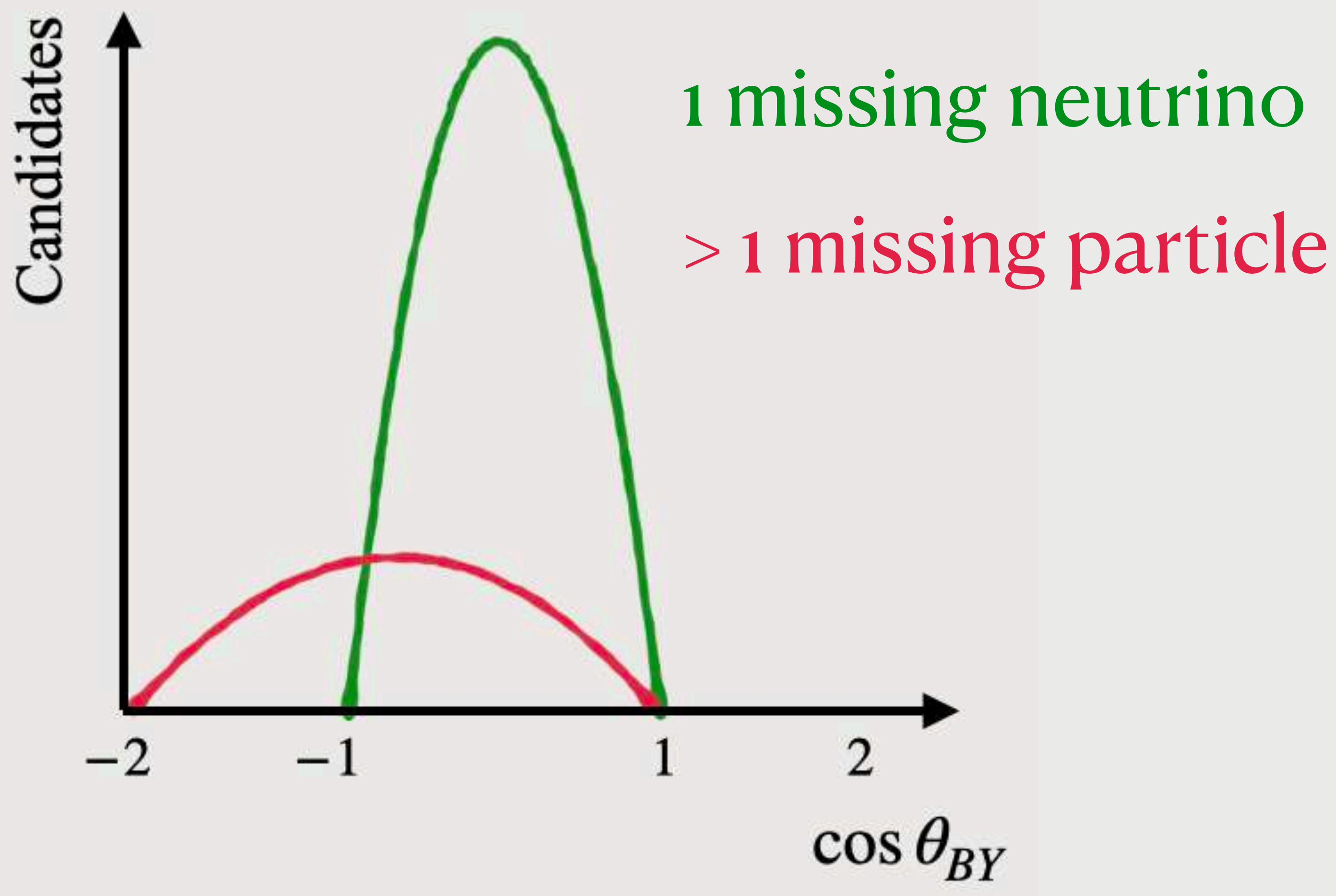
# Missing energy in the event

In semileptonic decays of $B$ meson we have at least one $\nu$ in the final state. To partially recover missing kinematic information we use tagging technique by reconstructing one of the $B$ mesons in hadronic/semileptonic decasys. Then the signal $B$ is constructed from the remaining particles in the event.

Powerful variables to suppress background or to identify signal decays are:

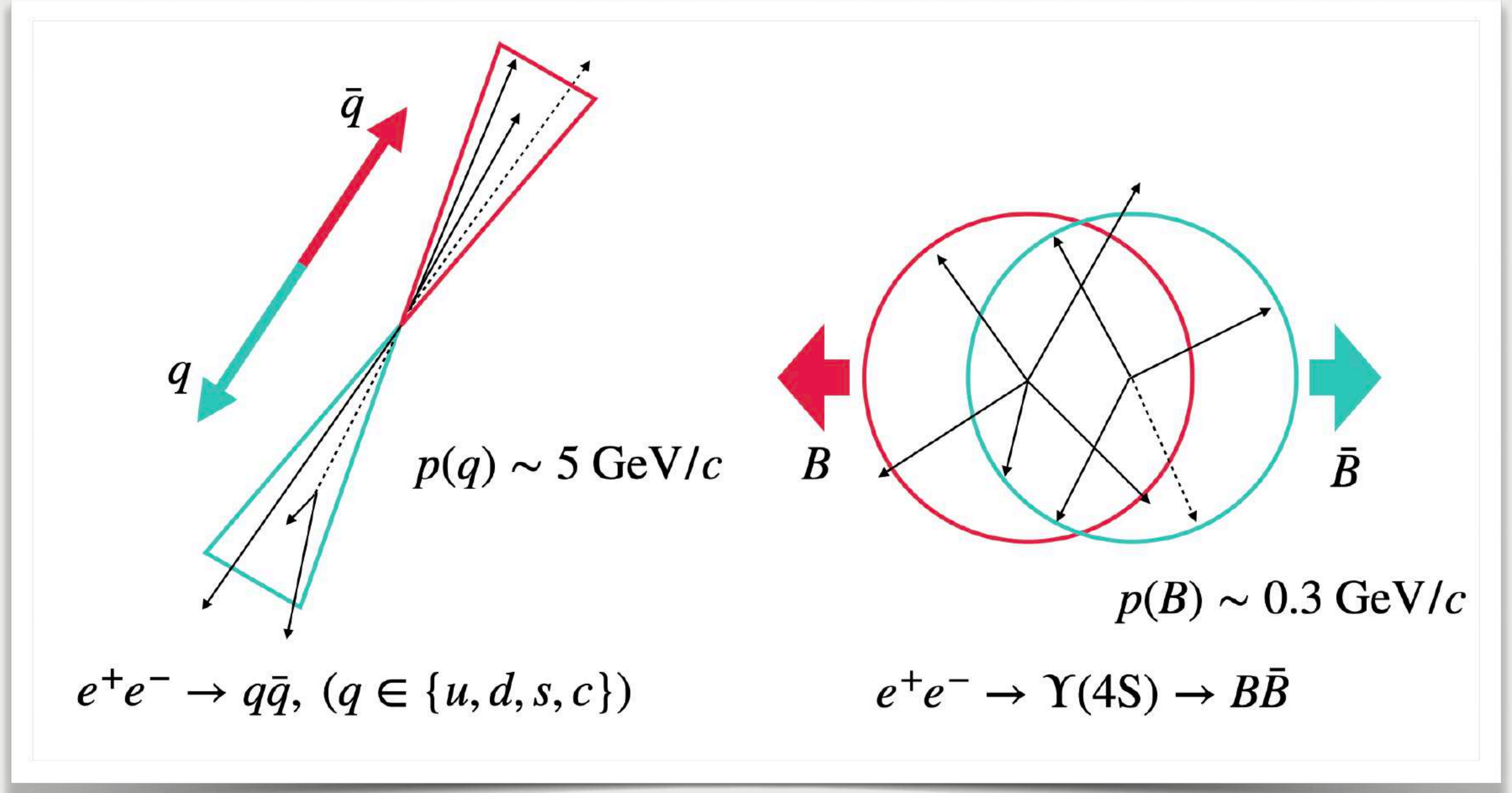
- Missing mass of undetected particles $M^2_{\text{miss}} = (p_{e^+e^-} - p_{\text{visible}})^2$
- Residual energy in the calorimeter $E^{\text{extra}}_{\text{ECL}}$
- Use available kinematic constraint $\cos\theta_{BY} = \dfrac{2E^*_B E^*_Y - m^2_B - m^2_Y}{2|\vec{p}^*_B||\vec{p}^*_Y|}$, where $Y$ is a meson-charged lepton system.

# Continuum suppression

- Total cross section of $e^+e^- \to q\bar{q}\ (q \in \{u, d, s, c\})$ is $\sim 3 \times$ larger than the process of $e^+e^- \to \Upsilon(4S)$. The pairs of quarks created in the $e^+e^-$ annihilation hadronise into light hadrons that can be a large source of background - continuum background.
- These two types of events can be separated using variables describing the event topologies. While in continuum events the initial pairs of light quarks are produces back-to-back in the CMS and the hadrons produced in the fragmentation are spatially confined into a jet-like structure, in $B\bar{B}$ events, produced $B$ mesons are almost at rest in the CMS and by having spin 0, the momenta of their daughter particles have mo directional preference and are distributed isotripically - resulting in a spherical shape of $B\bar{B}$ events.



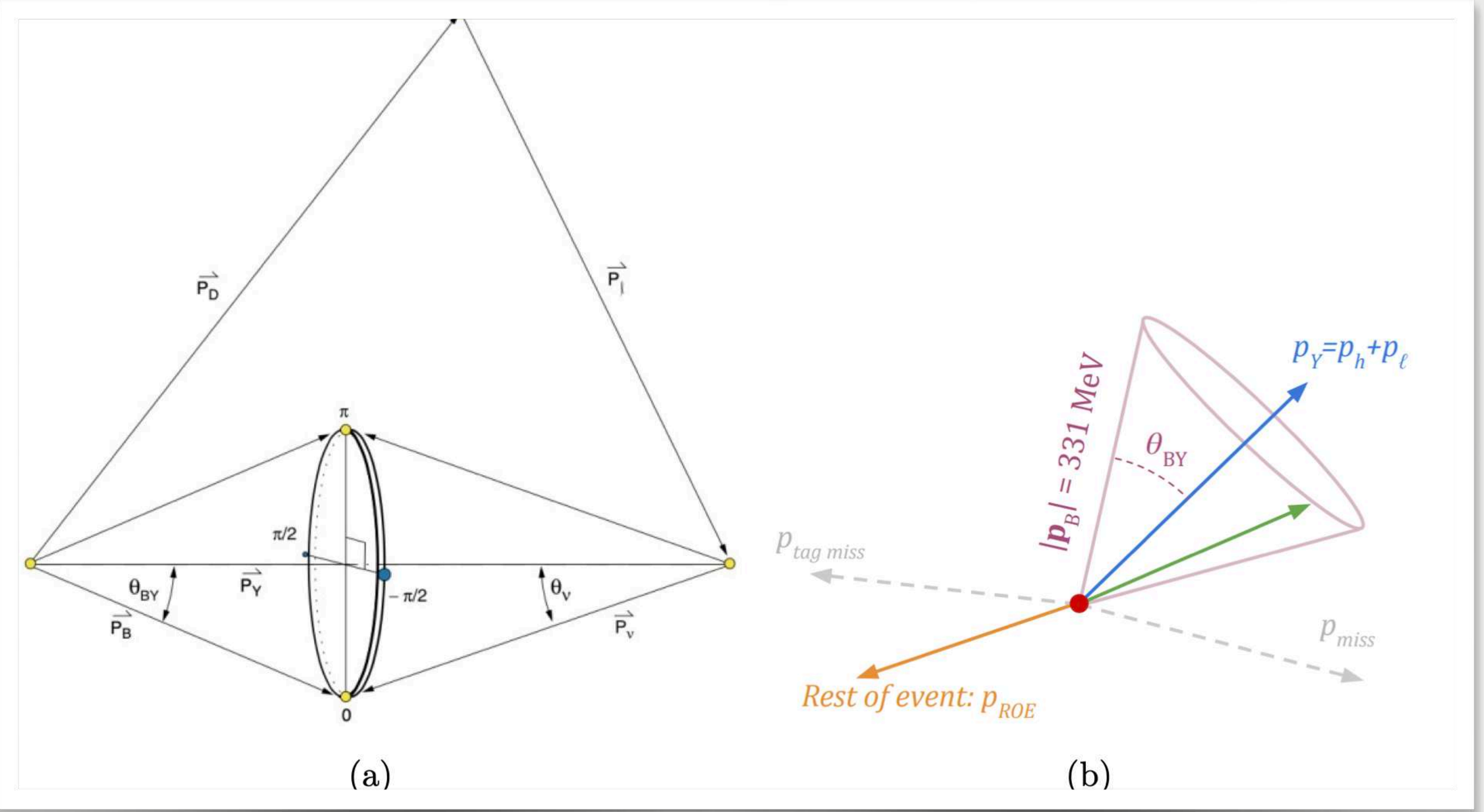

A schematic illustration of the geometrical event shape difference between continuum and $B\bar{B}$ events

PhD, M. Röhrken

# $|V_{cb}|$ from untagged exclusive $B \to Dl\nu_l$

The precision of determining $w$ relies on knowing the $B$ meson direction - cannot be measured directly (missing $\nu$). To access $B$ meson direction in untagged analyses different techniques are used:

- *diamond frame* approach: We know that the $B$ meson 3 momentum must lie on a cone around $Dl$ system, but the flight direction of the signal $B$ meson on the cone is unknown. The diamond frame technique assumes an arbitrary flight direction by choosing an azimuthal angle on the cone and computing the kinematic variables – i.e. $w$ or $q^2$– under that assumption. By repeating the procedure for multiple directions on the cone and assigning a weight for each, the parameters are obtained in a weighted average over the directions. Here, the weight is a $\sin^2\theta_B^*$ since $Y(4S)$ is produced in $e^+e^-$ annihilation.
- *Use the information from the ROE* to constrain the $B$ meson direction. Constructing $\vec{p}^*_{\text{ROE}}$ by summing up all unused tracks and clusters then place the $B$ meson on the direction on the cone that is most back-to-back with $\vec{p}^*_{\text{ROE}}$.
- Combining the two: in the diamond frame approach, a weighted average is computed over arbitrarily chosen cone direction, but now the weight, $\alpha = \frac{1}{2}(1 - \vec{p}^*_B\vec{p}^*_{\text{ROE}})\sin^2\theta^*_B$, takes into account how back-to-back the $B$ meson lies with the ROE and the angular distribution in $\Upsilon(4S)$ decays.




(a) Shematic of the diamond frame method, averaging over 4 direction.
(b) Schematic of the ROE method, placing the $B$ meson direction back-to-back with $\vec{p}^*_{\text{ROE}}$.

PhD, P. Horak

# $|V_{cb}|$ from untagged exclusive $B \to D\ell\nu_\ell$

- Other results:
  - To test lepton flavour universality

$$R^{e/\mu} = \mathscr{B}(B \to De\nu_e)/\mathscr{B}(B \to D\mu\nu_\mu)$$

$$R^{e/\mu} = 1.020 \pm 0.020(\text{stat.}) \pm 0.022(\text{sys.})$$

    - Consistent with the SM expectation
  - Determine $|V_{cb}|$ using CLN (Nucl.Phys. B530 (1998) 153-181) form factor fit

$$|V_{cb}|^{\text{CLN}} = (38.5 \pm 1.3) \times 10^{-3}$$

    - Consistent with previous measurements by BaBar and Belle
    - Due to limited precision of the CLN form factor, the $|V_{cb}|$ value obtained using BCL form fator is selected as the central value

| Source | Uncertainty [%] |
|---|---|
| Statistical | 0.9 |
| Systematic | 1.5 |
| $B^{0/+}$ lifetime | 0.1 |
| Signal form factor | 0.1 |
| $B \to D^*\ell\nu$ form factor | 0.1 |
| $\mathcal{B}(B \to X_c\ell\nu)$ | 0.3 |
| $\mathcal{B}(D \to K\pi(\pi))$ | 0.5 |
| Tracking efficiency | 0.5 |
| $N_{\Upsilon(4S)}$ | 0.7 |
| $f_{00}/f_{+-}$ | 0.1 |
| $f_{\not{B}}$ | 0.4 |
| Background $w$ modelling | 0.3 |
| $(E^*_Y, m_Y)$ reweighing | 0.3 |
| Lepton identification | 0.3 |
| Kaon identification | 0.6 |
| Vertex fit $\chi^2$ correction | 0.3 |
| Simulation sample size | 0.5 |
| Theoretical | 1.3 |
| Lattice QCD inputs | 1.2 |
| Long-distance QED | 0.5 |
| Total | 2.1 |

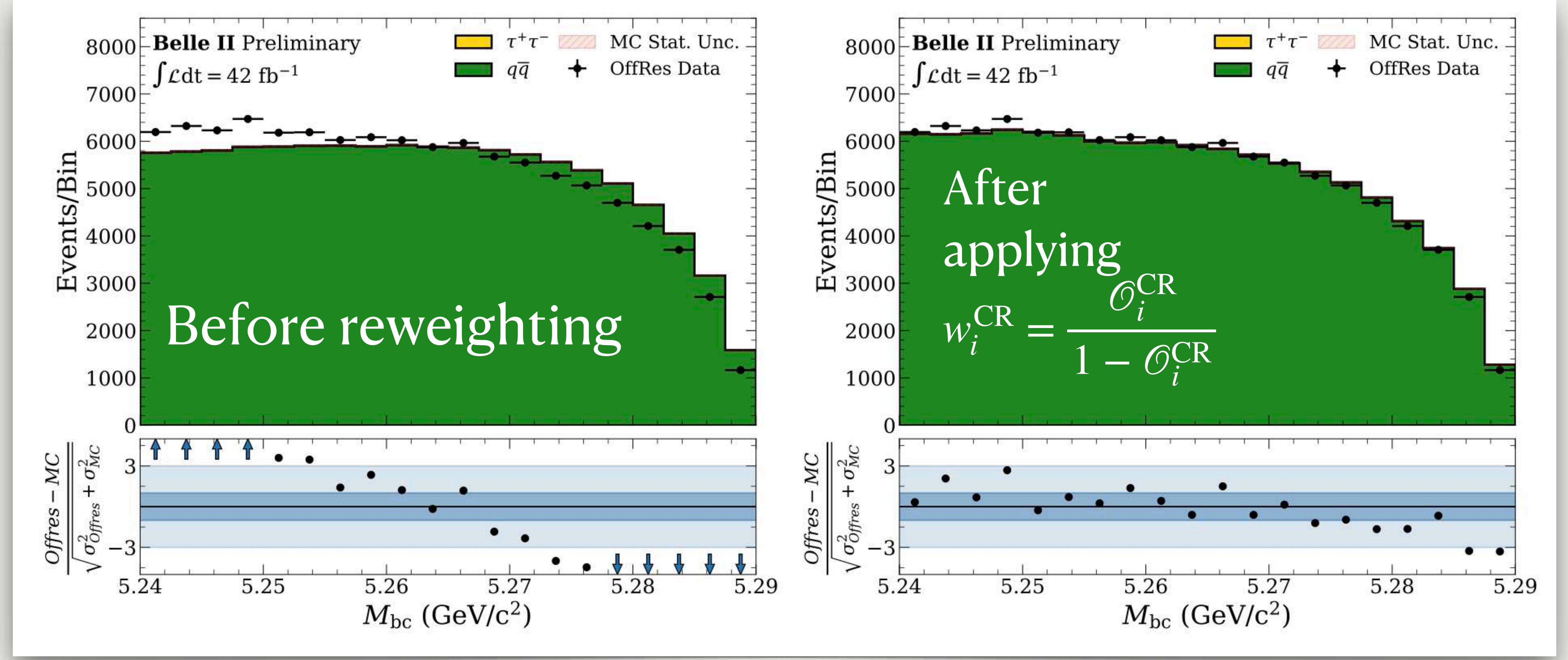
Fractional contributions to the total uncertainty on the extracted value of $|V_{cb}|$. The sizes of the contributions are given relative to the central value.

# $|V_{ub}|$ from tagged exclusive $B^+ \to \tau^+ \nu_l$

- Continuum reweighting to correct the mis-modeling between simulation and data using MVA classifier to obtain weights.

$$w_i^{CR} = \frac{\mathcal{O}_i^{CR}}{1 - \mathcal{O}_i^{CR}}$$

$\mathcal{O}_i$ - output of the classifier for event $i$



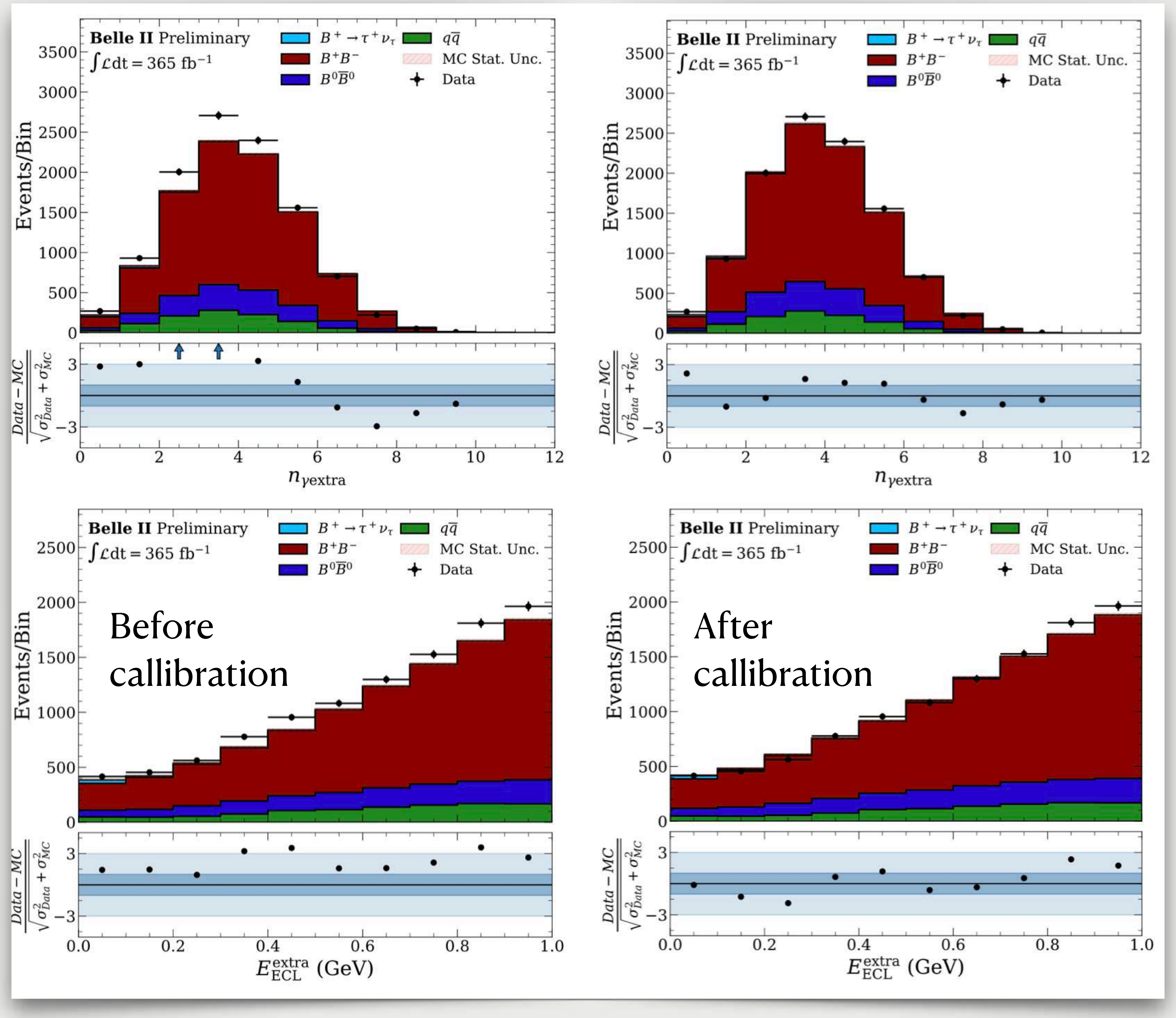

$M_{bc} = \sqrt{(E^*_{beam})^2 - |\vec{p}^*_{tag}|}$ in off-resonance data and continuum simulation before (left) and after (right) the continuum MC reweighting.

| Source | Syst. |
|---|---|
| Simulation statistics | 13.3% |
| Fit variables PDF corrections | 5.5% |
| Decay branching fractions in MC | 4.1% |
| Tag $B^-$ reconstruction efficiency | 2.2% |
| Continuum reweighting | 1.9% |
| $\pi^0$ reconstruction efficiency | 0.9% |
| Continuum normalization | 0.7% |
| Particle identification | 0.6% |
| Number of produced $\Upsilon(4S)$ | 1.5% |
| Fraction of $B^+B^-$ pairs | 2.1% |
| Tracking efficiency | 0.2% |
| Total | 15.5% |

Summary of systematic uncertainties (syst.) on the fitted branching fraction presented as relative uncertainties. The effect of each source is evaluated in the simultaneous fit of the four signal modes. The last three sources do not affect the signal yields. The sizes of the contributions are given relative to the central value.

# $|V_{ub}|$ from tagged exclusive $B^+ \to \tau^+\nu_l$

- To calibrate $E_{\mathrm{ECL}}^{\mathrm{extra}}$ use bin-by-bin correction of $n_{\gamma_{\mathrm{extra}}}$ (multiplicity of extra neutral clusters) from several control samples:
  - Extra-Tracks sample (>2 tracks in ROE ): reweight $B\bar{B}$ simulation
  - Reconstruct $B^+ \to D^{*0}\ell^+\nu_\ell$: reweight the signal simulation for leptonic modes
  - Reconstruct two non-overlapping hadronic tag $B$ mesons with opposite charges in the event: reweight the signal simulation for hadronic modes




Distributions of $n_{\gamma_{\mathrm{extra}}}$ (top) and $E_{\mathrm{ECL}}^{\mathrm{extra}}$ (bottom) before (left) and after (right) applying the $n_{\gamma_{\mathrm{extra}}}$ calibration.

# $|V_{ub}|$ from tagged inclusive $B \to X_u l \nu_l$

- The measured partial branching fractions are in three separate phase space regions - **Fit 1** ($E_\ell^B > 1$ GeV), **Fit 2** ($E_\ell^B > 1$ GeV & $M_X < 1.7$ GeV) and **Fit 3** ($E_\ell^B > 1$ GeV & $M_X < 1.7$ GeV & $q^2 > 8$ GeV$^2$):

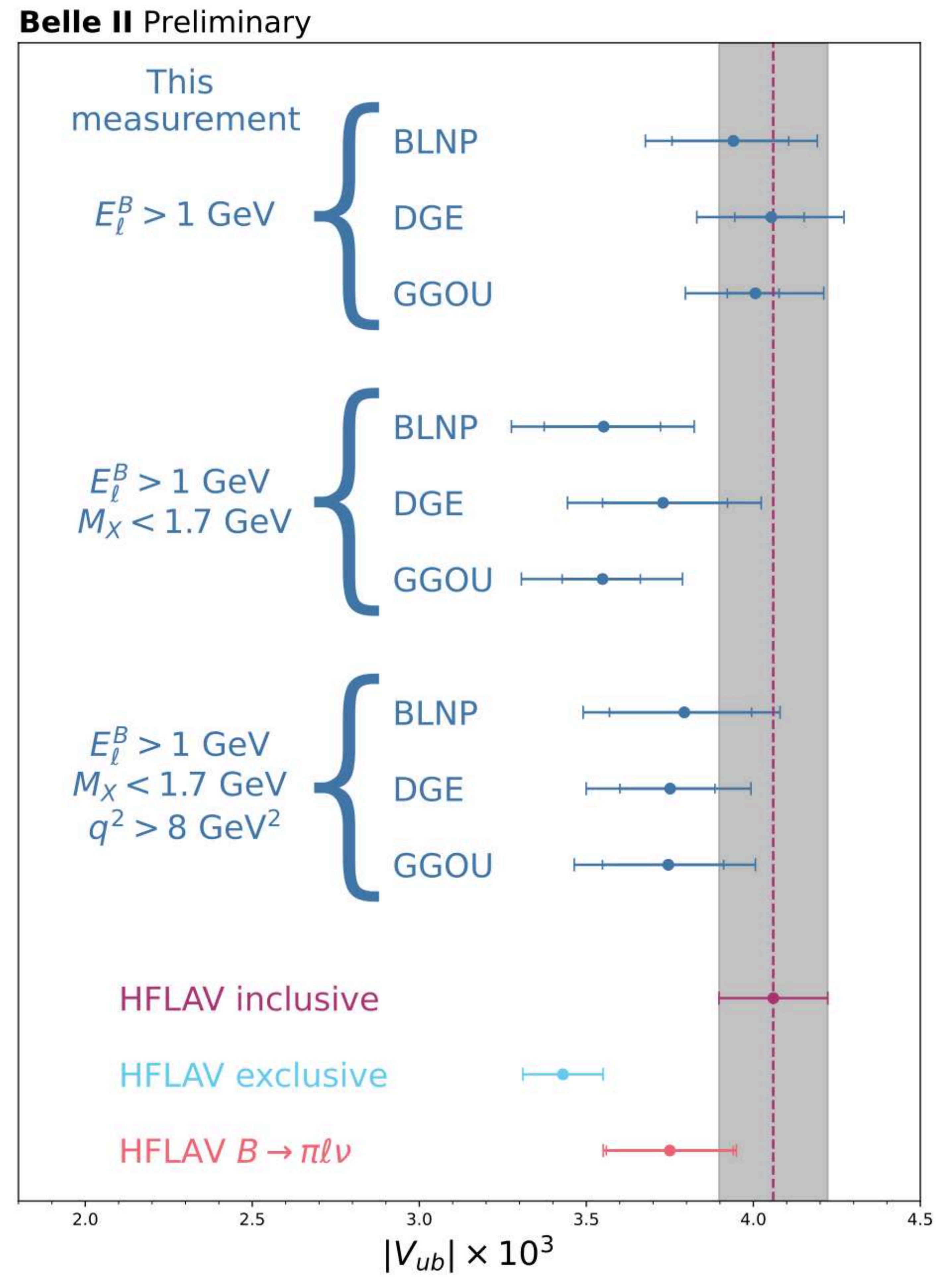
$$\Delta\mathcal{B}(B \to X_u \ell \nu_\ell)^{\text{Fit 1}} = (1.54 \pm 0.08(\text{stat.}) \pm 0.12(\text{sys.}))$$

$$\Delta\mathcal{B}(B \to X_u \ell \nu_\ell)^{\text{Fit 2}} = (0.95 \pm 0.05(\text{stat.}) \pm 0.10(\text{sys.}))$$

$$\Delta\mathcal{B}(B \to X_u \ell \nu_\ell)^{\text{Fit 3}} = (0.55 \pm 0.03(\text{stat.}) \pm 0.05(\text{sys.}))$$

| | Inclusive $B \to X_u \ell \nu$ model | Fit 1 | Fit 2 | Fit 3 |
|---|---|---|---|---|
| $\Delta\Gamma[\text{ps}^{-1}]$ | BLNP | $62.9^{+5.3}_{-5.9}$ | $47.5^{+4.5}_{-4.8}$ | $24.4^{+2.6}_{-2.9}$ |
| | DGE | $59.4^{+2.9}_{-3.2}$ | $43.1^{+4.5}_{-4.2}$ | $25.0^{+1.8}_{-2.0}$ |
| | GGOU | $60.8^{+2.2}_{-2.6}$ | $47.6^{+3.0}_{-3.2}$ | $25.0^{+2.2}_{-2.6}$ |
| $\vert V_{ub}\vert \times 10^3$ | BLNP | $3.94 \pm 0.11 \pm 0.16^{+0.17}_{-0.18}$ | $3.55 \pm 0.10 \pm 0.19^{+0.17}_{-0.18}$ | $3.79 \pm 0.09 \pm 0.18^{+0.20}_{-0.22}$ |
| | DGE | $4.05 \pm 0.11 \pm 0.16^{+0.10}_{-0.11}$ | $3.73 \pm 0.10 \pm 0.20^{+0.19}_{-0.18}$ | $3.75 \pm 0.08 \pm 0.18^{+0.13}_{-0.15}$ |
| | GGOU | $4.01 \pm 0.11 \pm 0.16^{+0.07}_{-0.08}$ | $3.55 \pm 0.10 \pm 0.19^{+0.11}_{-0.12}$ | $3.75 \pm 0.08 \pm 0.18^{+0.17}_{-0.20}$ |

Theoretical $B \to X_u \ell \nu_\ell$ decay rates $\Delta\Gamma$ (excluding the $|V_{ub}^2|$ term) and $|V_{ub}|$ obtained from three different theoretical predictions in three separate phase space regions. The values of $\Delta\Gamma$ are used to compute $|V_{ub}|$. The uncertainties are (stat.), (sys.), (th.).




Comparison between the three values of $|V_{ub}|$ (obtained from the fits in different phase space regions and using three different theoretical frameworks), the inclusive, the exclusive and $B \to \pi \ell \nu_\ell$ averages from HFLAV.

# $|V_{ub}|$ from tagged inclusive $B \to X_u l \nu_l$

Non-resonant $B \to X_u \ell \nu_\ell$ decays are simulated using the model of De-Fazio and Neubert (DFN)

Breakdown of systematic uncertainties of the partial branching fraction obtained from each fit.

| Uncertainty source | Relative uncertainty (%) Fit 1 | Fit 2 | Fit 3 |
|---|---|---|---|
| DFN parameters | 4.4 | 4.5 | 5.7 |
| DFN → BLNP | 0.2 | 0.8 | 1.3 |
| $\gamma_S$ | 1.7 | 2.1 | 2.1 |
| $B \to \pi \ell \nu$ form factors | 0.3 | 0.3 | 0.3 |
| $B \to \rho \ell \nu$ form factors | 0.3 | 0.3 | 0.2 |
| $B \to \omega \ell \nu$ form factors | 0.1 | 0.1 | 0.1 |
| $B \to \eta/\eta' \ell \nu$ form factors | < 0.1 | < 0.1 | < 0.1 |
| $B^\pm \to X_u \ell \nu$ branching fractions | 0.9 | 0.6 | 0.5 |
| $B^0 \to X_u \ell \nu$ branching fractions | 0.6 | 0.5 | 0.5 |
| $B \to D^{**}_{\mathrm{Broad}}$ form factors | 0.5 | 0.1 | 0.2 |
| $B \to D^{**}_{\mathrm{Narrow}}$ form factors | 0.1 | < 0.1 | < 0.1 |
| $B \to D/D^* \ell \nu$ form factors | < 0.1 | < 0.1 | < 0.1 |
| $B^\pm \to X_c \ell \nu$ branching fractions | 0.7 | 0.5 | 0.2 |
| $B^0 \to X_c \ell \nu$ branching fractions | 0.6 | 0.2 | 0.1 |
| $D$ decay branching fractions | 0.1 | 0.3 | 0.1 |
| SR $X_c \ell \nu$ normalisation | 1.6 | 3.5 | 3.4 |
| CR $X_c \ell \nu$ normalisation | 0.9 | 1.1 | 0.4 |
| *Other backgrounds* normalisation | 0.3 | N/A | N/A |
| $X_u$ fragmentation | 0.3 | 4.4 | 3.9 |
| $N_{\Upsilon(4S)}$ | 1.4 | 1.4 | 1.4 |
| FEI | 1.3 | 1.3 | 1.4 |
| Slow pion efficiency | 0.4 | 0.2 | 0.3 |
| $\ell$ identification | 0.7 | 0.7 | 0.6 |
| $f^{\pm/00}$ | 0.6 | 0.7 | 0.6 |
| Continuum calibration | 0.2 | 0.2 | 0.2 |
| Tracking | 0.3 | 0.3 | 0.3 |
| $K^0_S$ efficiency | 0.1 | 0.1 | < 0.1 |
| $K^\pm$ ID | < 0.1 | < 0.1 | < 0.1 |
| Simulated data statistics | 1.1 | 1.1 | 0.8 |

Breakdown of uncertainties added following the bias corrections. All systematic, statistical and total uncertainties of the corrected branching fractions are listed.

| | Relative uncertainty (%) | | |
|---|---|---|---|
| Fit bias | 2.6 | 2.3 | 1.8 |
| Composition uncertainty | 1.3 | 5.7 | 0.2 |
| $B \to X_c \ell \nu$ overestimation correction | 2.6 | 0.4 | 1.3 |
| Total systematic | 7.9 | 10.5 | 9.7 |
| Statistical | 5.4 | 5.6 | 4.5 |
| Total | 9.6 | 11.9 | 10.7 |

Fit test:

- Invert $K$ veto and fit $CR_{K,\mathrm{low}} - CR_{K,\mathrm{high}}$
- Take signal MC template from SR and inject it in MC and data
- Can choose the normalisation of the signal injected in data

Two sources of bias were identified in a fit test:

- Small shape and mismodelling differences between CR and SR
- $B \to X_c \ell \nu_\ell$ correction factor is overestimated

# $|V_{ub}|/|V_{cb}|$ from tagged inclusive $B \to X\ell\nu_\ell$

- Other results:
  - Lepton flavour universality

$$\frac{\Delta\mathcal{B}(B \to X_u e\nu_e)}{\Delta\mathcal{B}(B \to X_u \mu\nu_\mu)} = 0.79 \pm 0.13(\text{stat.}) \pm 0.07(\text{sys.})$$

$$\frac{\Delta\mathcal{B}(B \to X_c e\nu_e)}{\Delta\mathcal{B}(B \to X_c \mu\nu_\mu)} = 1.002 \pm 0.005(\text{stat.}) \pm 0.024(\text{sys.})$$

$$\frac{\mathcal{B}(B \to X_c e\nu_e)}{\mathcal{B}(B \to X_c \mu\nu_\mu)} = 1.007 \pm 0.005(\text{stat.}) \pm 0.025(\text{sys.})$$

Non-resonant $B \to X_u\ell\nu_\ell$decays are simulated using the model of De-Fazio and Neubert (DFN)

  - Isospin breaking effects: measuring the ratio of partial branching

$$R_{\text{iso}} = \frac{\tau_{B^0}}{\tau_{B^+}} \frac{\Delta\mathcal{B}(B^+ \to X_u^0 \ell^+\nu_\ell)}{\Delta\mathcal{B}(B^0 \to X_u^- \ell^+\nu_\ell)}$$

$$R_{\text{iso}} = 0.70 \pm 0.13(\text{stat.}) \pm 0.07(\text{syst.})$$

$R_{\text{iso}}$ is 2.0$\sigma$ apart from the expectation of equal semileptonic rates for both isospin rates.

  - $|V_{ub}|/|V_{cb}|$ using BLNP prediction of the partial rate

$$\frac{|V_{ub}|}{|V_{cb}|} = \left(9.81 \pm 0.42(\text{stat.}) \pm 0.38(\text{syst.}) \pm 0.51(\Delta\Gamma(B \to X_u\ell\nu_\ell)) \pm 0.20(\Delta\Gamma(B \to X_c\ell\nu_\ell))\right) \times 10^{-2}$$

| | |
|---|---|
| $R \times 100$ | 1.99 |
| Stat. Error (Data) | 8.5 |
| $\mathcal{B}(\bar{B} \to \pi/\eta/\rho/\omega/\eta'\ell\bar{\nu})$ | 0.2 |
| $\mathcal{FF}(\bar{B} \to \pi/\eta/\rho/\omega/\eta'\ell\bar{\nu})$ | 0.3 |
| $\mathcal{B}(\bar{B} \to x_u\ell\bar{\nu})$ | 0.8 |
| Hybrid Model (BLNP) | 1.0 |
| DFN $(m_b^{\text{KN}}, a^{\text{KN}})$ | 5.1 |
| $N_{g\to s\bar{s}}$ | 0.4 |
| $\mathcal{B}(\bar{B} \to D\ell\bar{\nu})$ | 0.1 |
| $\mathcal{B}(\bar{B} \to D^*\ell\bar{\nu})$ | 0.8 |
| $\mathcal{B}(\bar{B} \to D^{**}\ell\bar{\nu})$ | 0.3 |
| $\mathcal{B}(\bar{B} \to D^{(*)}\eta\ell\bar{\nu})$ | 0.2 |
| $\mathcal{B}(\bar{B} \to D^{(*)}\pi\pi\ell\bar{\nu})$ | 0.2 |
| $\mathcal{FF}(\bar{B} \to D\ell\bar{\nu})$ | 0.2 |
| $\mathcal{FF}(\bar{B} \to D^*\ell\bar{\nu})$ | 0.9 |
| $\mathcal{FF}(\bar{B} \to D^{**}\ell\bar{\nu})$ | 0.4 |
| Sec.Fakes. Composition | 3.8 |
| In-situ $q^2$ Calibration | 2.8 |
| $\ell$ID Efficiency | 0.1 |
| $\ell$ID Fake Rate | 0.3 |
| $K\pi$ID Efficiency | 1.0 |
| $K\pi$ID Fake Rate | 0.6 |
| $K_S^0$ Efficiency | 0.2 |
| $\pi_{\text{slow}}$ Efficiency | $< 0.1$ |
| Tracking | 0.1 |
| Continuum Calibration | 0.4 |
| $N_{BB}$ | $< 0.1$ |
| $f_{+/0}$ | $< 0.1$ |
| Stat. Error (MC) | 2.6 |
| Total Syst. | 7.8 |

Summary of the central value ($R$), statistical and systematic uncertainties for the ratio of partial branching fractions. The uncertainties are given as relative values on the central value in percent.