Measurements of inclusive $B \to X_u \, l \, \nu$ decays with hadronic tagging

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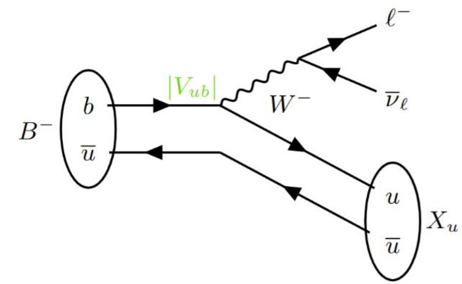
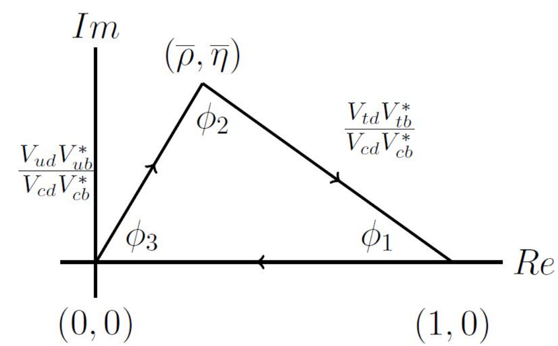
DESY.

Inclusive $B \to X_u\, l\, \nu$ measurement

Introduction

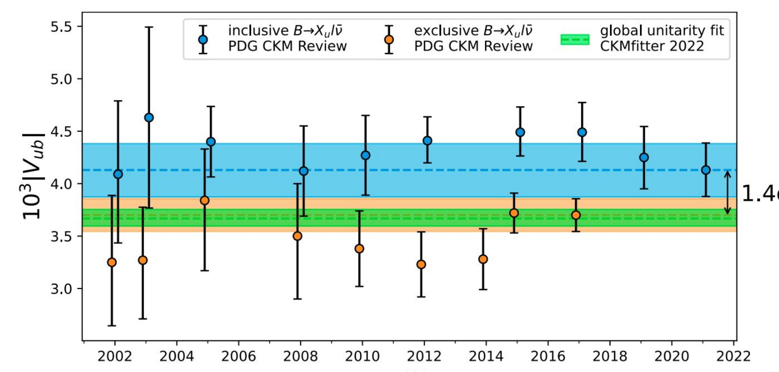


- **Semi-leptonic** decays to constrain the CKM unitarity triangle
  - $B \to X_u\, l\, \nu$ to measure $|V_{ub}|$
  - $B \to X_c\, l\, \nu$ to measure $|V_{cb}|$
- **Two ways** to measure $|V_{ub}|$
  - **Exclusive** decays
    - $B \to \pi\, l\, \nu,\ B \to \rho\, l\, \nu \ldots$
  - **Inclusive** decays



$$|V_{ub}| = (4.13 \pm 0.12^{+0.13}_{-0.14} \pm 0.18) \times 10^{-3} \quad \text{PDG incl.}$$

$$|V_{ub}| = (3.70 \pm 0.10 \pm 0.12) \times 10^{-3} \quad \text{PDG excl.}$$



Inclusive $B \to X_u \, l \, \nu$ measurement

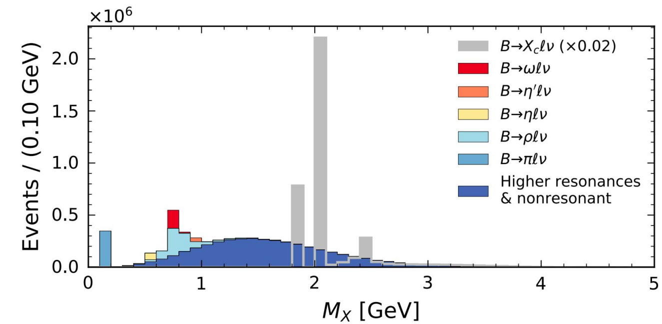
Theory

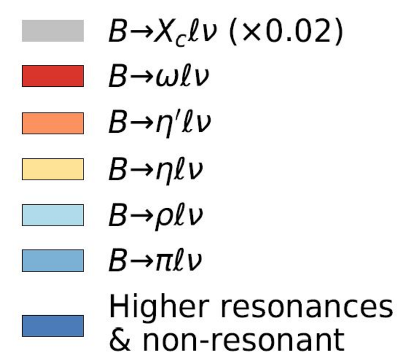
$B \to \pi \, l \, \nu$

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |p_\pi|^3 |f_+(q^2)|^2$$

- Resonant decays depend on form factors

- **Non-resonant** decays
  - Based on **Heavy Quark Expansion**
  - Large $\boldsymbol{B \to X_c \, l \, \nu}$ **background** ($|V_{cb}|^2 / |V_{ub}|^2 \sim 100$)
  - → **cuts** in phase space (ex: $M_X < 1.7$ GeV)
  - → **HQE breaks down**
  - Sensitivity on **Shape Function**(s)
    - Leading-order SF extracted from $B \to X_s \, \gamma$
  - **Different models**: BLNP, DFN, GGOU…
  - What about weak annihilation effects ?





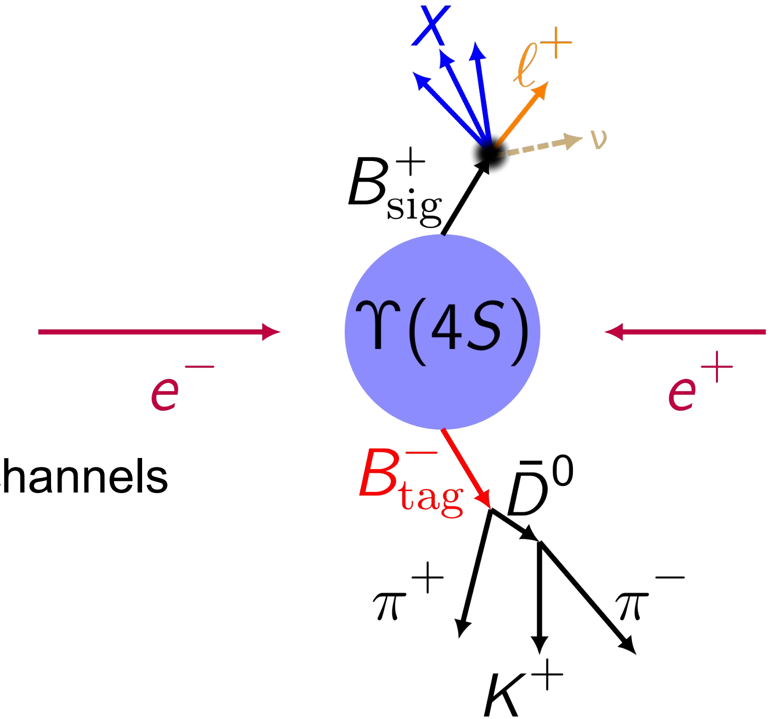
Outline

- **Inclusive $B \to X_u\, l\, \nu$ partial Branching Ratio measurement and extraction of $|V_{ub}|$**
- **Inclusive $B \to X_u\, l\, \nu$ differential Branching Ratio measurement**
- **Inclusive Weak Annihilation $B \to X_u\, l\, \nu$ measurement**
- All 3 analyses are performed with the Full Event Interpretation hadronic tag

Event reconstruction

Full Event Interpretation

- 3 types of tagging
  - Inclusive (untagged)
  - Semi-leptonic
  - **Hadronic**

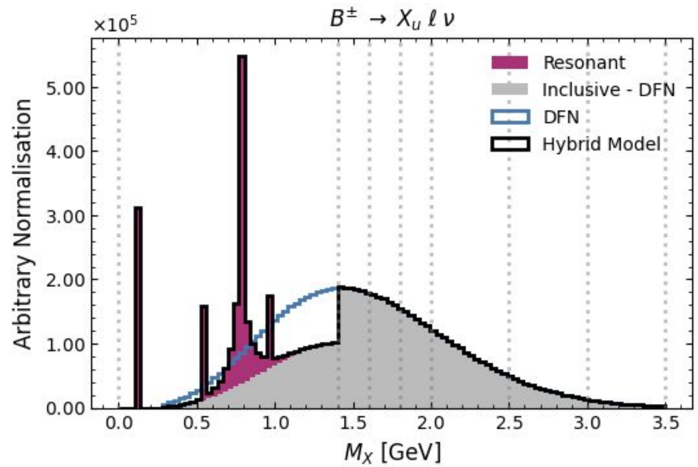


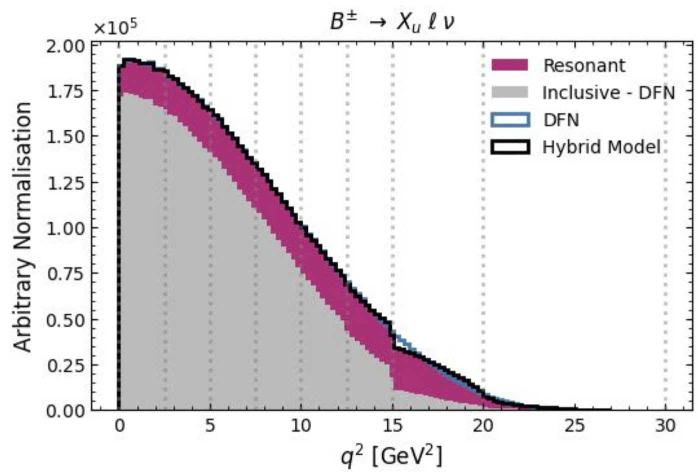
- ***B_{tag}* reconstructed** in its hadronic decay channels
  - Accurate information about the event
  - Background suppression
- **Lepton reconstructed**
- **Neutrino** → missing energy
- **Hadronic system *X*** → rest-of-event
- 3 important variables: M_X, q^2, E_l

Modelling

$$\Delta\mathcal{B}^{\text{incl}}_{ijk} = \Delta\mathcal{B}^{\text{excl}}_{ijk} + w_{ijk} \times \Delta\mathcal{B}^{\text{incl}}_{ijk}$$

- Inclusive $\boldsymbol{B \to X_u\, l\, v}$: signal
  - **Hybrid model:** combine **resonant** (*π, ρ, ω, η, η'*) and **non-resonant** contribution (DFN)
- Inclusive $\boldsymbol{B \to X_c\, l\, v}$: main background
  - No model for non-resonant contribution
  - → Sum of resonant modes (*D, D*, D***) and "gap" modes
- **Other backgrounds**
  - $Y(4S) \to q\bar{q}$ (continuum)
  - Fake/secondary leptons
- Weak Annihilation contribution
  - Dedicated measurement

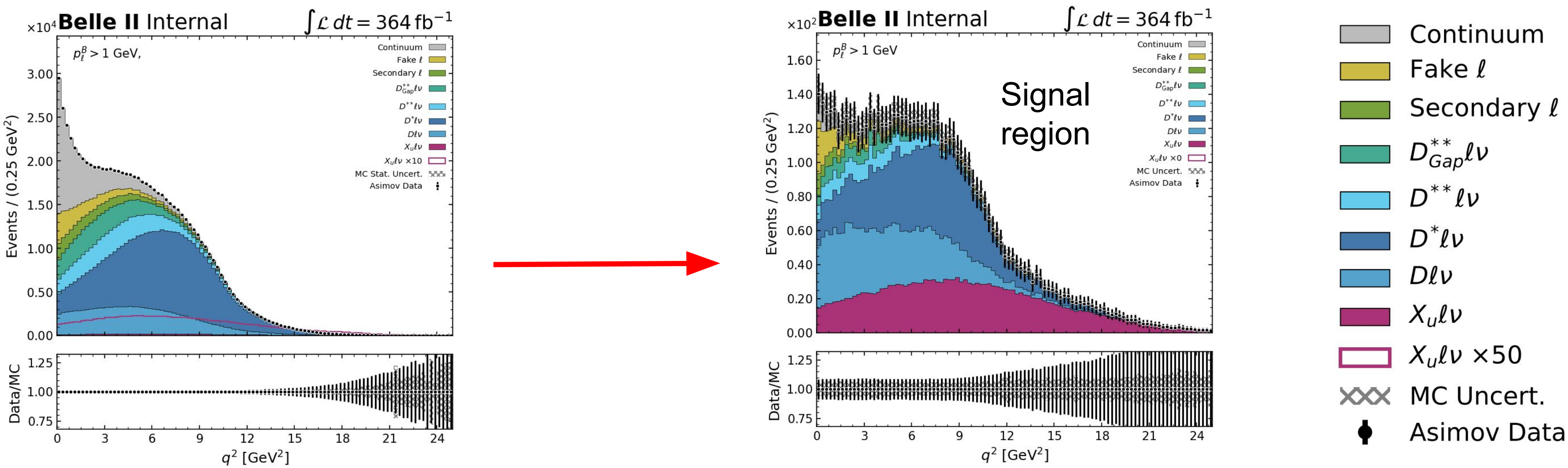




$B \rightarrow X_u \, l \, \nu$ partial Branching Ratio

Inclusive $B \rightarrow X_u\, l\, \nu$ measurement

Background suppression, Example: q^2



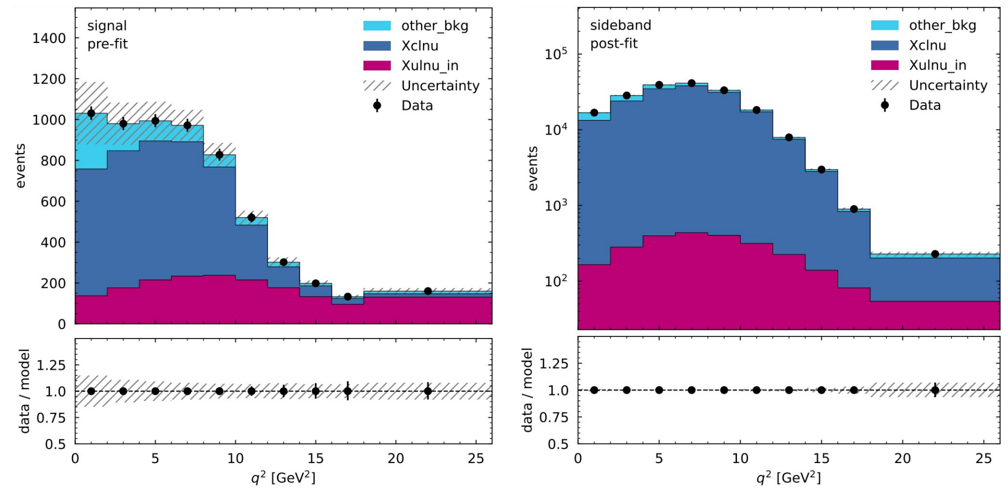
Before selections **After selections**

- **Two multivariate classifiers (Neural Networks)**
  - One to suppress $e^+e^- \rightarrow Y(4S) \rightarrow q\bar{q}$ (continuum) events
  - One to suppress $B \rightarrow X_c\, l\, \nu$ events
- **Events where a kaon (K^+, K^0_S) is found are rejected**

Partial branching fraction extraction

Asimov data

- Extract **partial Branching Fraction**
- **Simultaneous fit** of signal region and background-enriched control region in order to correct any potential $B \to X_c\, l\, \nu$ mismodelling
- **Binned template fit** with pyhf
  - Constrained source-wise nuisance parameters: ~150 NPs
  - 3 templates
  - Parameter of interest (POI): signal strength
- **3 templates**
  - **Signal:** $B \to X_u\, l\, \nu$
  - **Main background**: $B \to X_c\, l\, \nu$
  - **Other backgrounds**: fake/secondary leptons and continuum
- **Fitted variables**
  - Main kinematic variables: q^2, E_l^B, M_X
  - 2D combinations of these: e.g. M_X:q^2



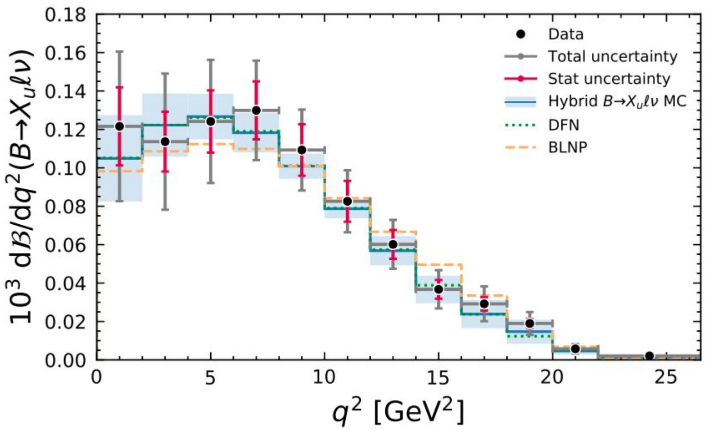
Phase space cuts	Acceptance $\varepsilon_{\Delta\mathcal{B}}$
$p_\ell^B > 1.0$ GeV	86.7%
$p_\ell^B > 1.0$ GeV $M_X < 1.7$ GeV	56.5%
$p_\ell^B > 1.0$ GeV $M_X < 1.7$ GeV $q^2 > 8$ GeV^2	31.5%
$p_\ell^B > 2.1$ GeV	19.0%

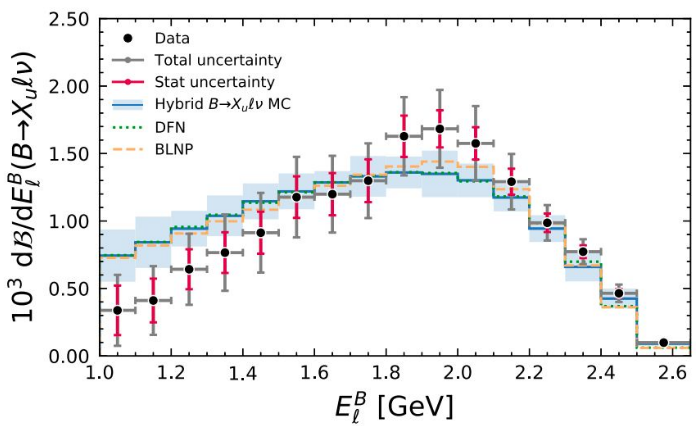
$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}}{\tau_B \Delta\Gamma_{\text{th}}}}$$

$B \to X_u \, l \, \nu$ differential Branching Ratio

Differential $B \rightarrow X_u \, l \, \nu$ measurement

Taken from Belle measurement



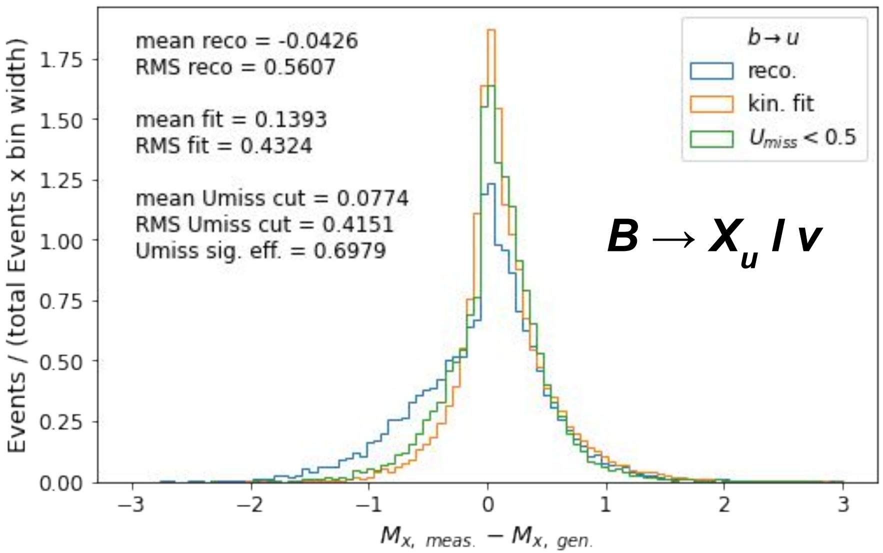


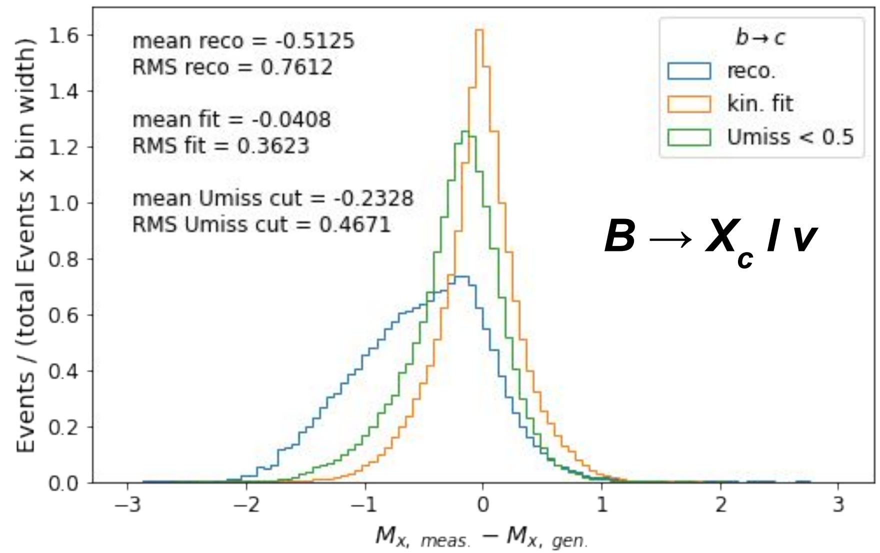
- **Shape information** on kinematic variables → crucial to evaluate models and extract HQE parameters
- **Subtract background** using fitting procedure
    - Resolution is key (see next slide)
- **Unfold signal yields**
    - Next step, work in progress

Differential $B \rightarrow X_u \, l \, \nu$ measurement

Resolution

- Cut $U_{miss} = |E_{miss} - P_{miss}| < 0.5$ GeV improves resolution but reduces efficiency
- New strategy at Belle II: apply the **kinematic fit**
  - Use kinematic constraints from known initial state to recalculate kinematic variables
  - **Improve resolution without reducing efficiency**

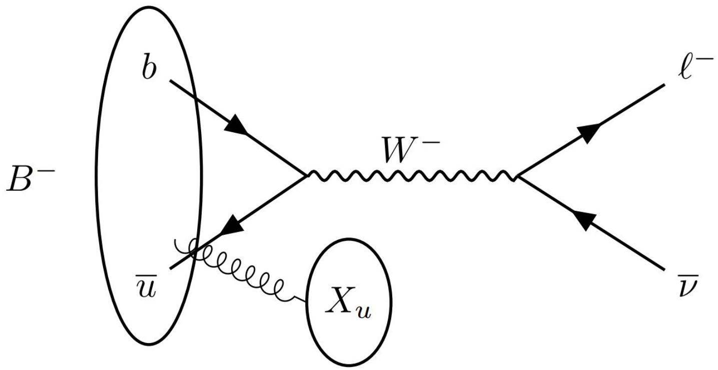


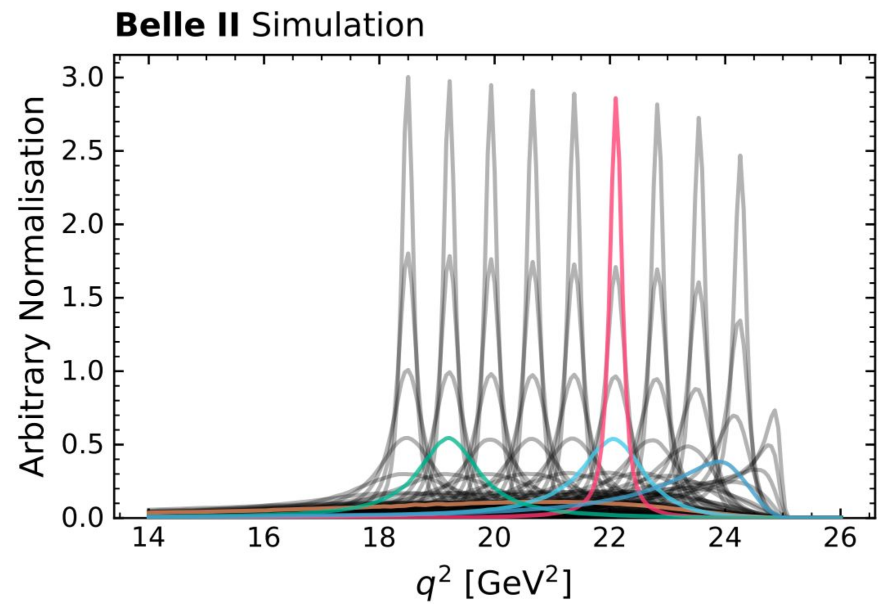


$B \to X_u\, l\, \nu$ via Weak Annihilation

Weak Annihilation

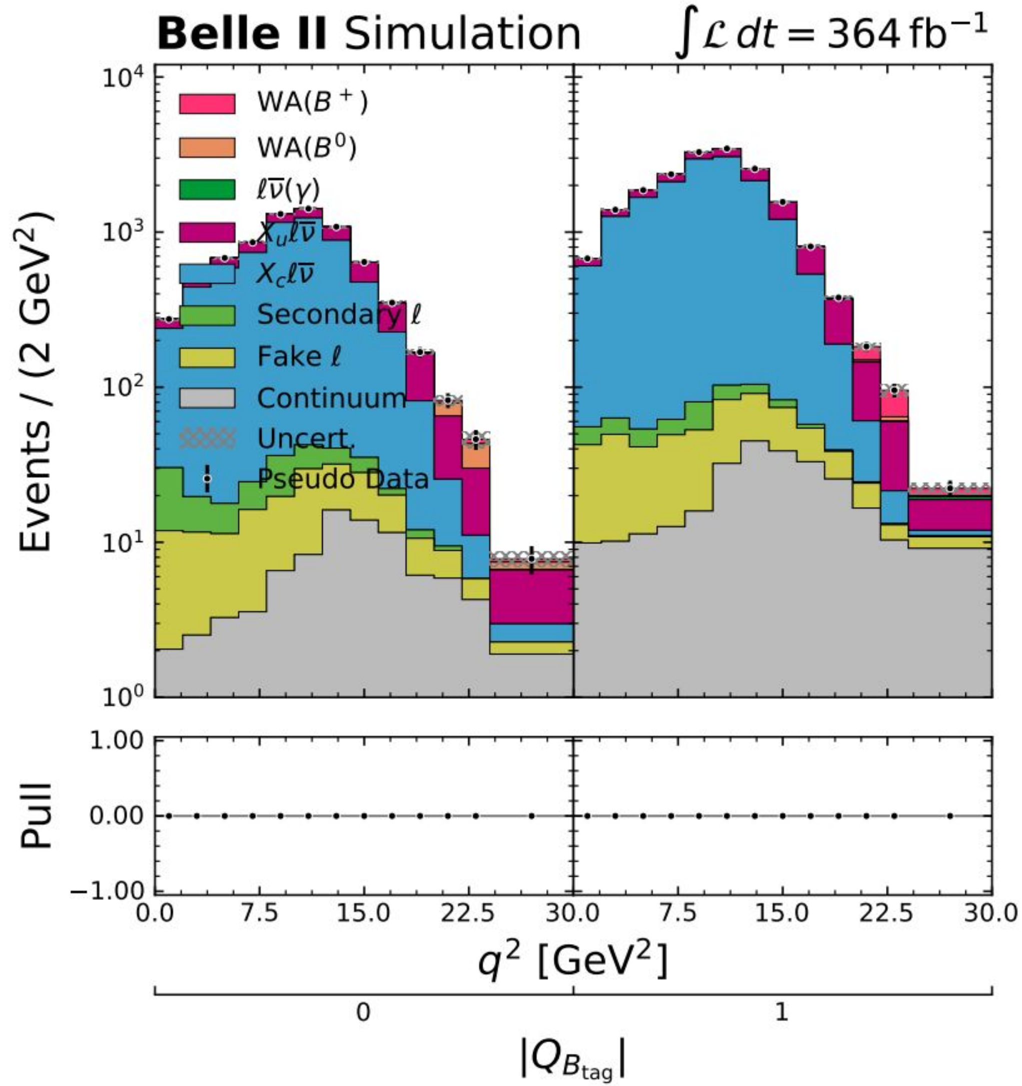
- Weak Annihilation contribution enters inclusive $\boldsymbol{B \to X_u \, l \, \nu}$ **modelling at** $\boldsymbol{O(1/m_b^3)}$
  - **Not included** in most available $B \to X_u \, l \, \nu$ models
  - **Poorly understood theoretically**
  - Sub-leading but **sizeable uncertainty** in inclusive $|V_{ub}|$ extraction
  - Expected to become **more important** as experimental uncertainty and other modelling **uncertainties shrink**
- One attempt at a direct measurement at CLEO
  - $\Gamma_{\mathrm{WA}} / \Gamma_{b \to u} < 7.4\%$ at 90% C.L.
- **Soft hadronic system**
- $\to$ Weak Annihilation visible at high q^2/E_l





Weak Annihilation

- **Shape of peak is poorly known**
  - → scan a range of models built from off-shell W
  - Peaks in q^2 distribution of different widths around $m_B{}^2$
- Goal is to **extract a limit on WA** contribution
- **Fitting procedure**
  - 2D fit of B^+/B^0 channels
  - Extract WA limits for different W width and mass hypotheses



OUTLOOK AND CONCLUSIONS

Summary

- **Status of analyses**
  - Most of the technology in place
  - Branching fraction measurement currently moving to RC
    - Expected uncertainty from nominal fit with Asimov data ~20% lower than Belle measurement despite smaller dataset
  - Two other measurements are work-in-progress
- **Outlook**
  - Sensitivity projections for inclusive $|V_{ub}|$

	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\|V_{ub}\|$ inclusive					
5 ab^{-1}	1.1	(1.3, 1.6)	2.3	2.5–4.5	3.4–5.1
50 ab^{-1}	0.4	(0.4, 1.6)	1.7	2.5–4.5	3.0–4.8

THANK YOU FOR YOUR ATTENTION !