

Measurement of $b \rightarrow u \ell \nu_\ell$ at Belle II

Andrea Fodor
McGill University

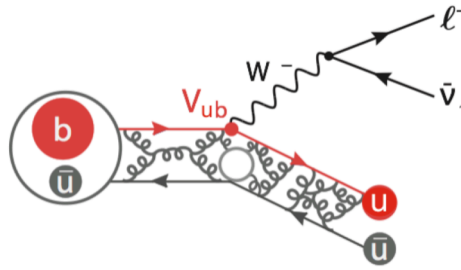
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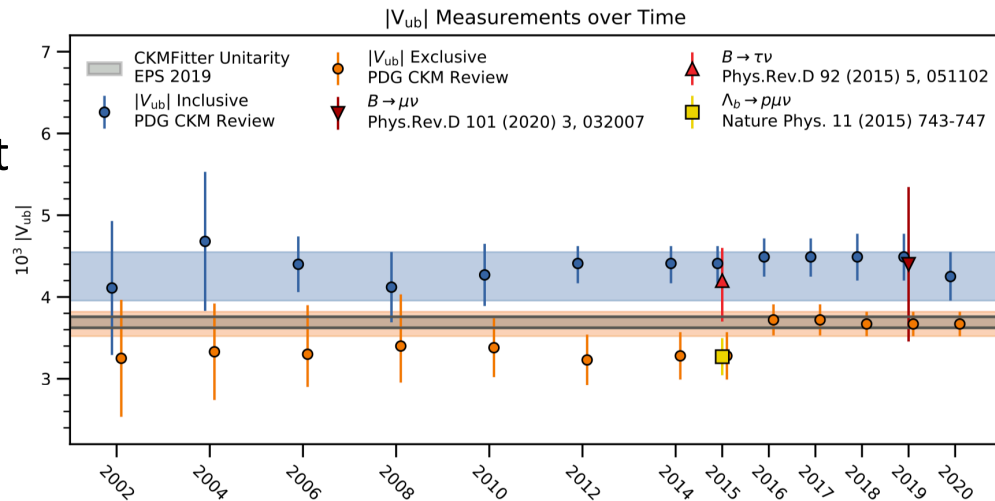
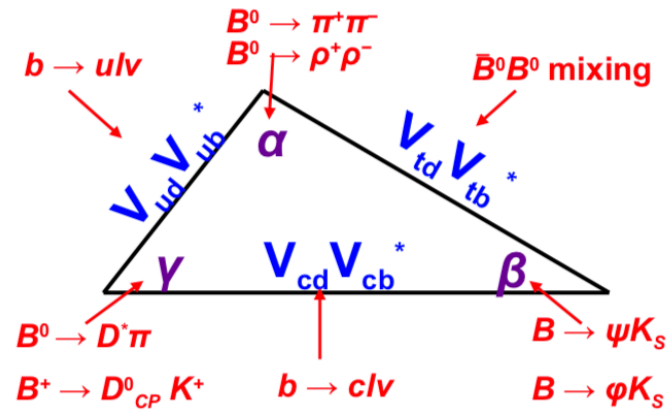


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Introduction



- Precision measurement of Cabbibo-Kobayashi-Maskawa (CKM) matrix elements is at the core of the Belle II physics program.
- Semileptonic decays of B mesons play a critical role in the determination of the CKM quark-mixing matrix elements $|V_{cb}|$ and $|V_{ub}|$
- $b \rightarrow u \ell \nu$ measurements important for measuring CKM matrix element V_{ub}
- Previous results show tension between inclusive and exclusive measurement of V_{ub} matrix element
- Challenging measurements because of the missing neutrino and dominant $b \rightarrow c \ell \nu$ background



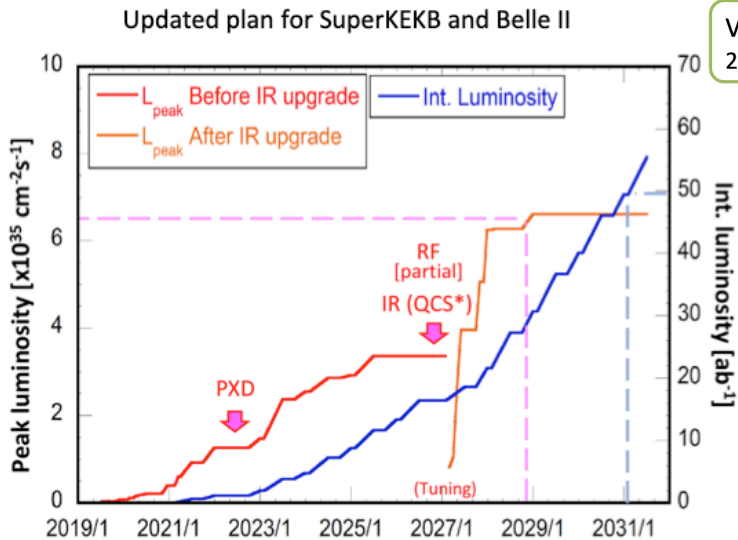
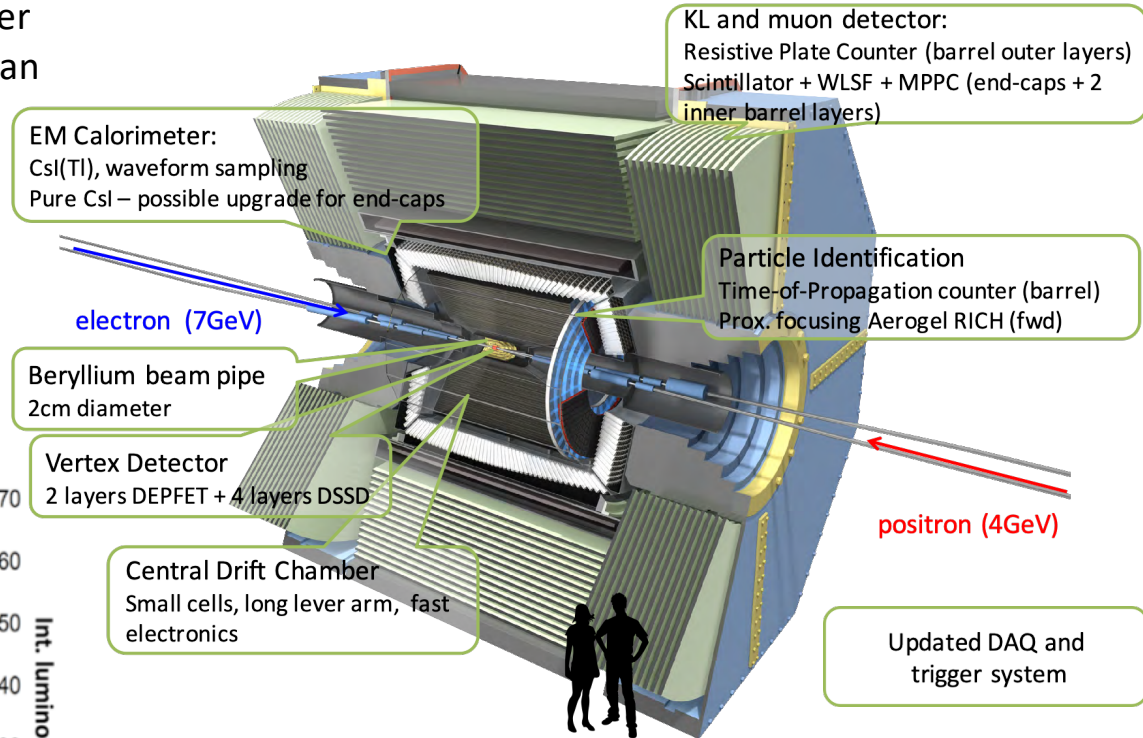
Overview

- Belle II experiment
- Tagged vs untagged analysis
- Untagged inclusive $B \rightarrow X_u e \nu_e$
- Tagged exclusive $B \rightarrow \pi \ell \nu_\ell$
- Prospects for $b \rightarrow u$ measurements at Belle II

Belle II experiment and SuperKEKB

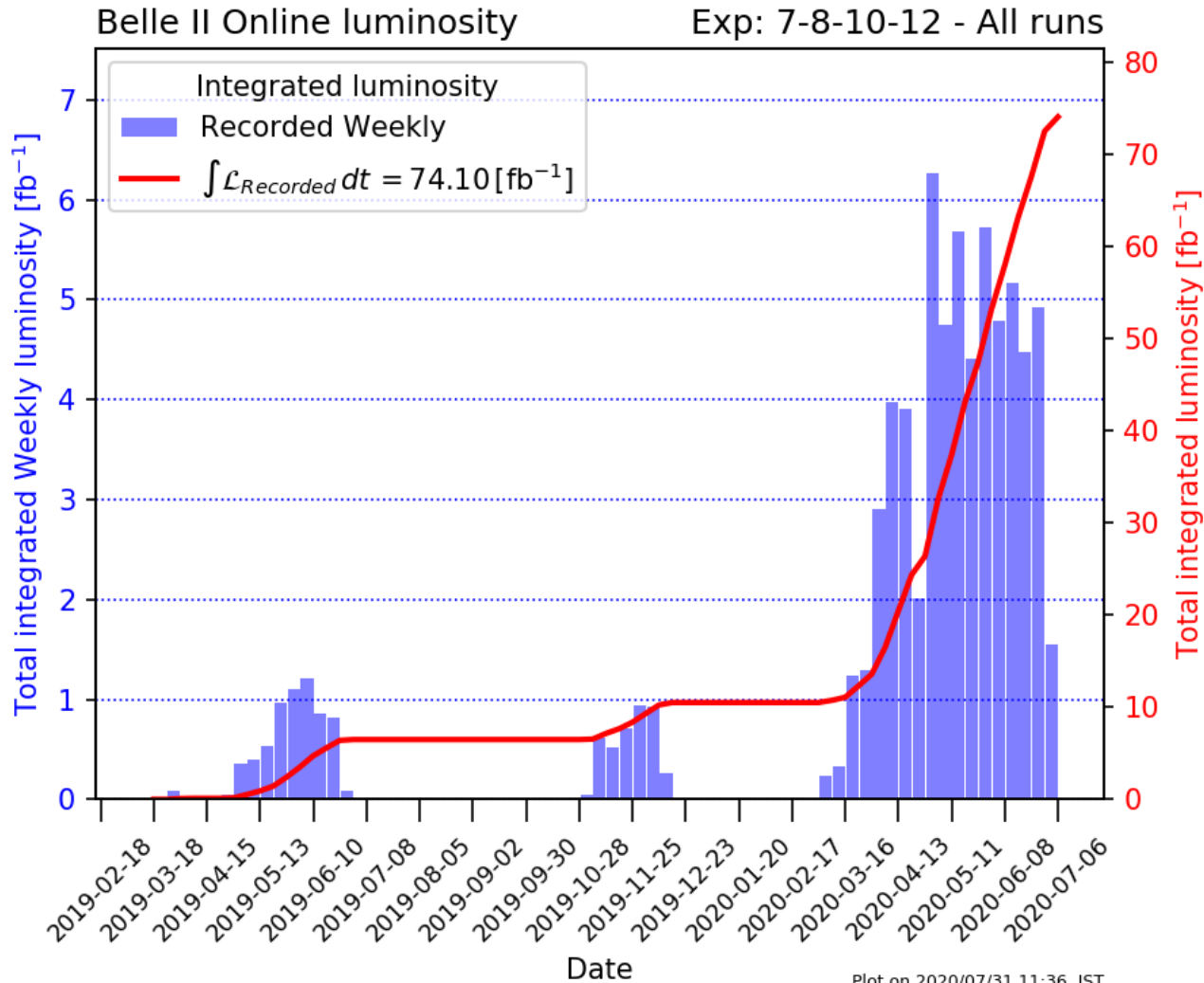


- Belle II is a B meson factory ($\sim 1.1 \cdot 10^9 \bar{B}B$ pairs per ab^{-1})
- SuperKEKB is an electron - positron collider located at KEK Laboratory in Tsukuba, Japan
 - High Energy electron ring - **7 GeV**
 - Low Energy positron ring - **4 GeV**
 - **$\Upsilon(4S)$ resonance**



Four steps: *Intermediate luminosity* ($1\text{-}2 \times 10^{35} / \text{cm}^2/\text{sec}$, 5ab^{-1});
High Luminosity ($6.5 \times 10^{35} / \text{cm}^2/\text{sec}$, 50ab^{-1}) with a detector upgrade
 Polarization Upgrade, Advanced R&D
 Ultra high luminosity ($4 \times 10^{36} / \text{cm}^2/\text{sec}$, 250ab^{-1}), R&D Project

Belle II Luminosity

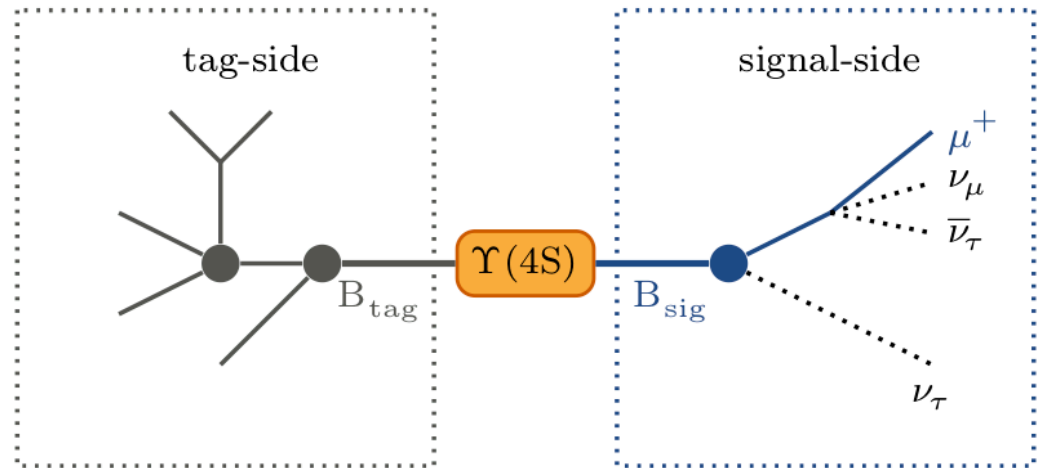


- World record luminosity (June 2020) $\approx 2.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

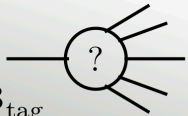
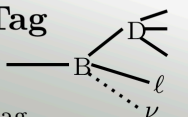

Results presented here use 34.6 fb⁻¹ of reprocessed data

Tagged vs untagged analysis

- B mesons produced almost at **rest in the CoM frame**
- Several approaches in the analysis depending on the treatment of the companion B meson, B_{tag}



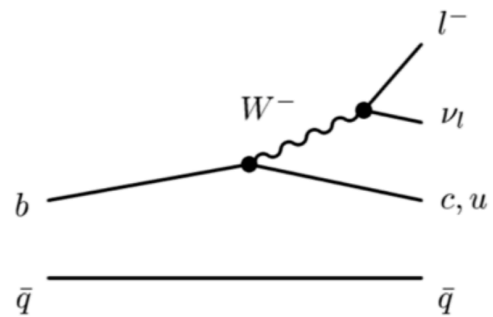
Efficiency ϵ

<p>Inclusive Tag $\epsilon = \mathcal{O}(100)\%$ Consistency of B_{tag}</p> 
<p>Semileptonic Tag $\epsilon = \mathcal{O}(1)\%$ Knowledge of B_{tag}</p> 
<p>Hadronic Tag $\epsilon = \mathcal{O}(0.1)\%$ Exact knowledge of B_{tag}</p> 

Information

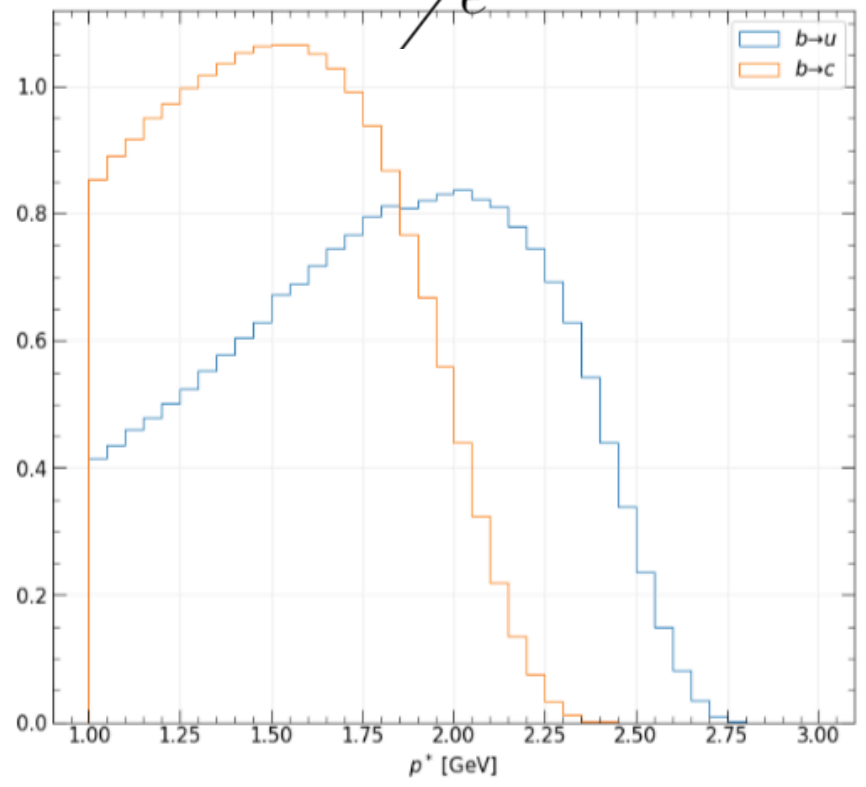
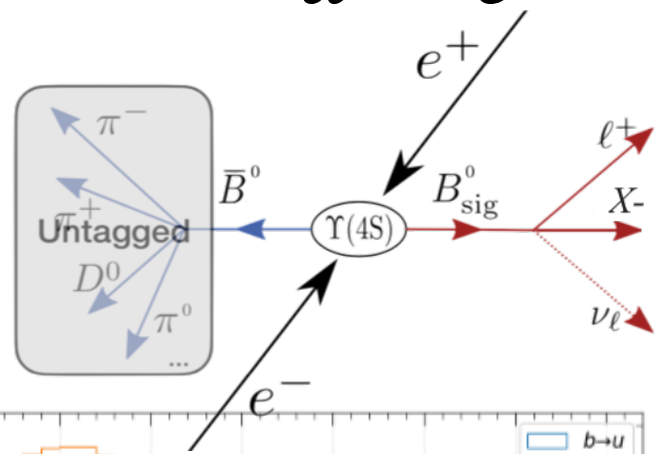
- **Untagged reconstruction** – signal reconstruction without full B_{tag} reconstruction
- **Tagged approach** – reconstruction of the B_{tag} first using semileptonic or hadronic decay modes and attributing the remaining detected depositions to the B_{sig}
- **Full Event Interpretation**
 - implemented by Belle II
 - uses Machine Learning and reconstructs B_{tag} from more than 200 different decay modes, improving the B_{tag} reconstruction efficiency;
 - enables precise determination of the energy carried by undetected neutrinos

Untagged inclusive $B \rightarrow X_u e \nu_e$



Untagged inclusive $B \rightarrow X_u e \nu_e$

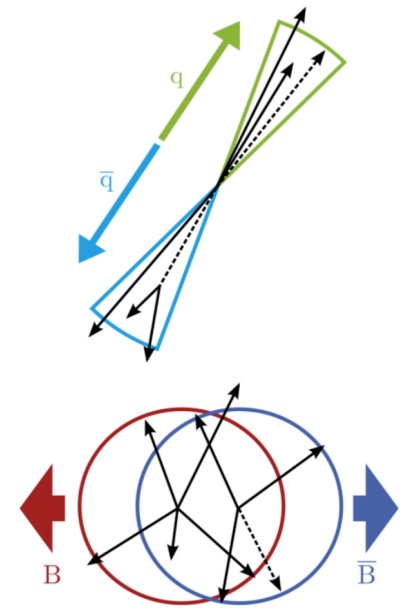
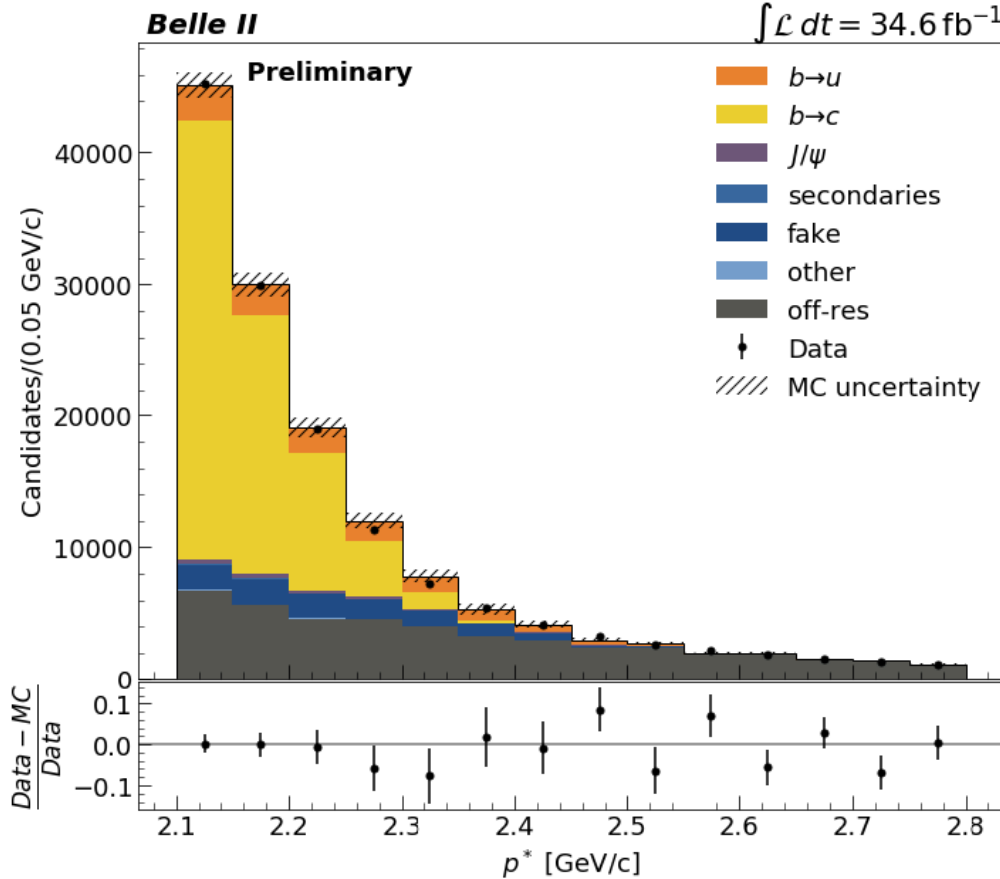
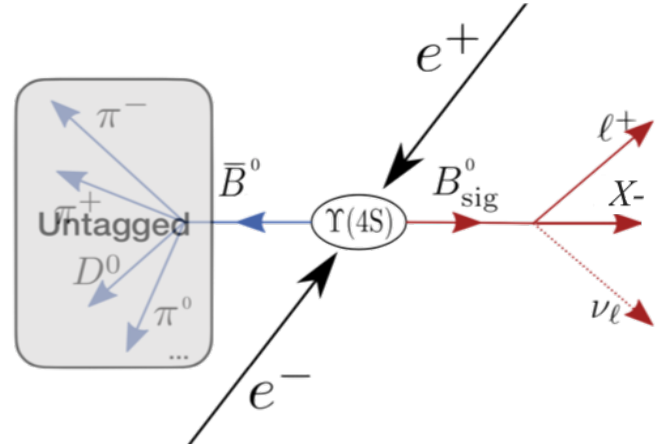
- The aim is to **'rediscover'** $B \rightarrow X_u \ell \nu$ decays via an **inclusive** analysis approach: *only the outgoing lepton is selected*
- Using the **untagged** analysis approach, the companion B meson is not reconstructed
- Looking in the **endpoint region of the lepton momentum** in the CM frame to avoid the dominant background from the decay $B \rightarrow X_c \ell \nu$



$B \rightarrow X_u \ell \nu$ and $B \rightarrow X_c \ell \nu$ electron momentum endpoints, truth MC

Inclusive $B \rightarrow X_u e \nu_e$

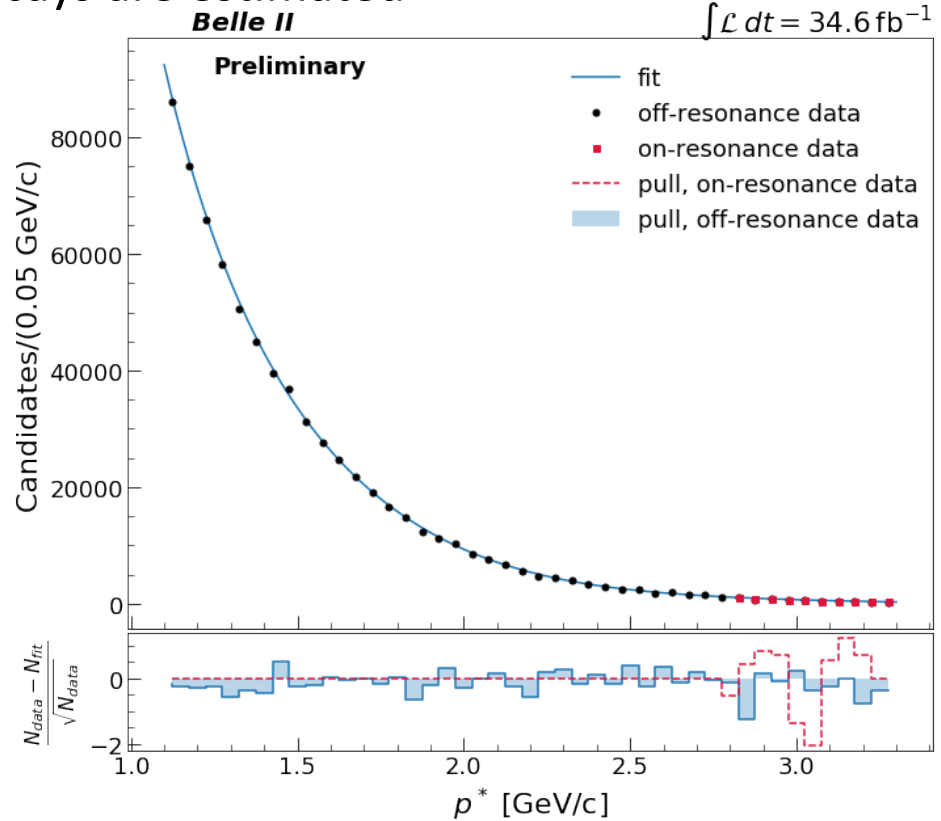
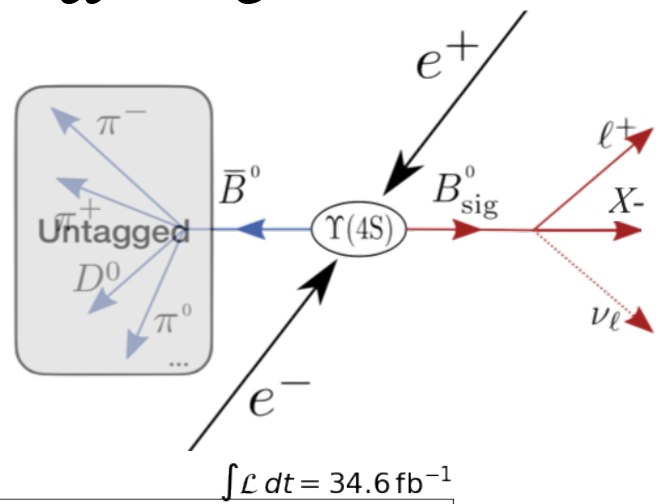
- Analysis approach:
 - One electron is identified using PID algorithms
 - Continuum backgrounds are suppressed using MVA trained with event shape variables



$B\bar{B}$ events are more spherical,
 $q\bar{q}$ events are more jet-like

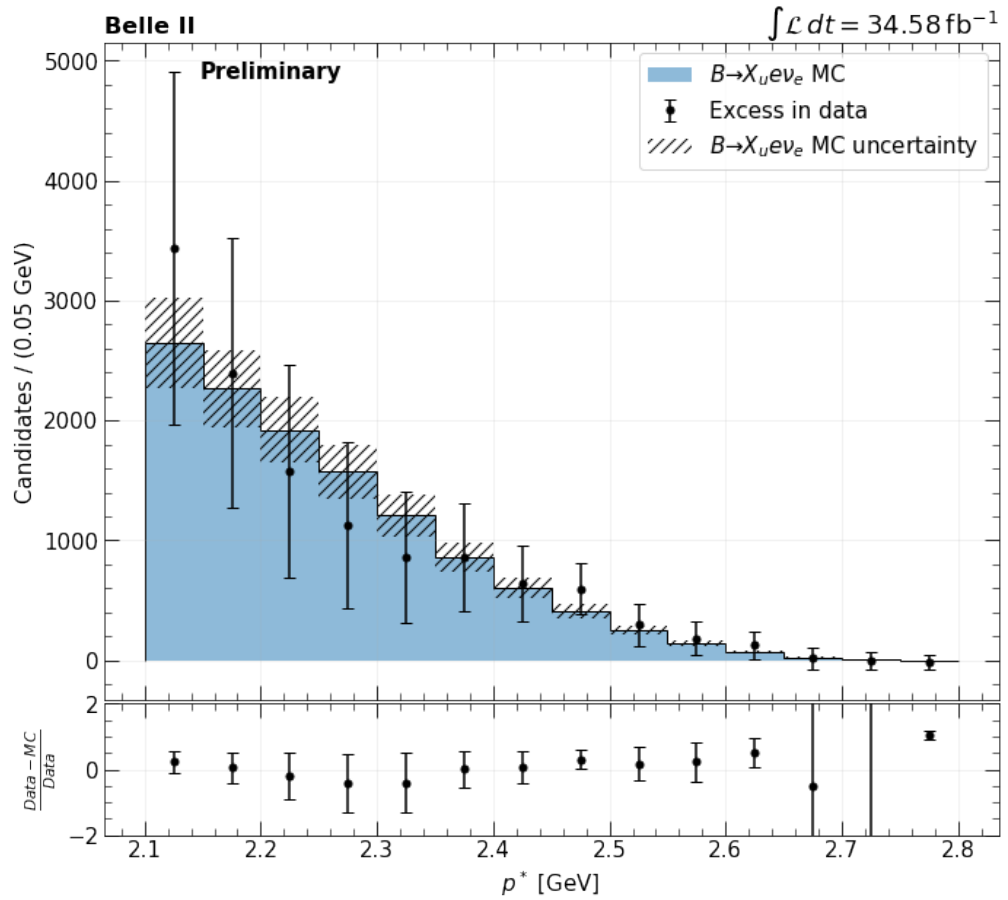
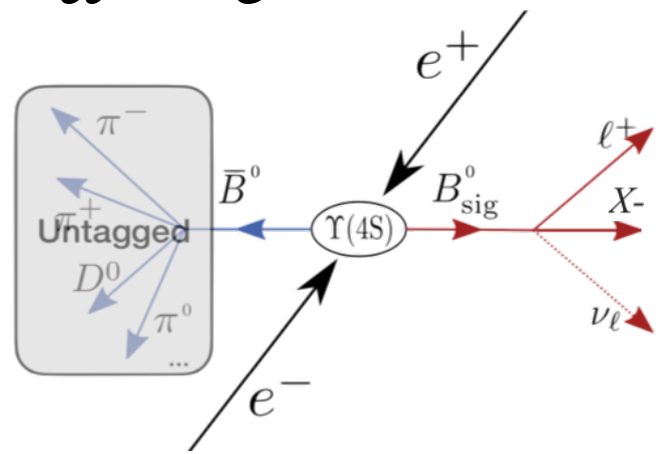
Inclusive $B \rightarrow X_u e \nu_e$

- Analysis approach:
 - One electron is identified using PID algorithms
 - Continuum backgrounds are suppressed using MVA trained with event shape variables
 - Fit was performed on off-resonance data to estimate continuum contributions
 - Backgrounds from $B\bar{B}$ decays are estimated using a MC template fit

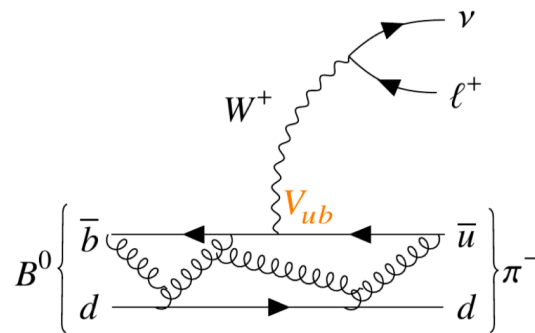


Inclusive $B \rightarrow X_u e \nu_e$

- Continuum and other $B\bar{B}$ contributions are subtracted in the endpoint region of the electron momentum [2.1, 2.8] GeV
- Observed $B \rightarrow X_u e \nu_e$ excess in data ($> 3\sigma$)
- Systematics from electron PID, fitting, $B \rightarrow X_c e \nu_e$ BF



Tagged exclusive $B^0 \rightarrow \pi^- \ell^+ \nu_\ell$



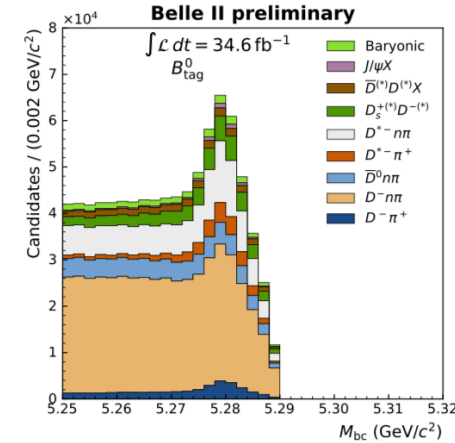
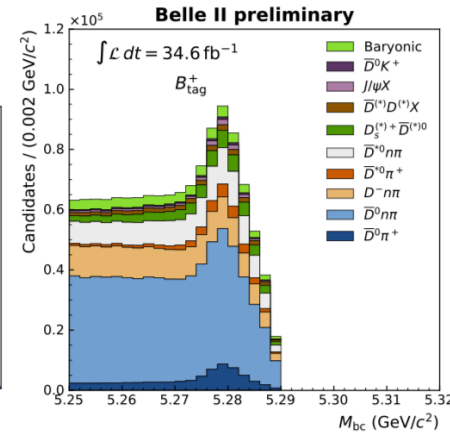
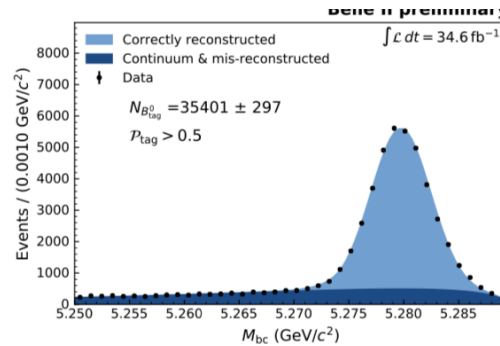
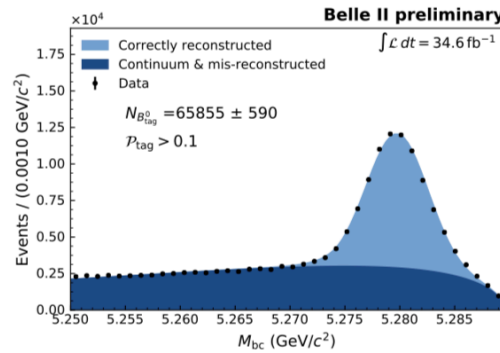
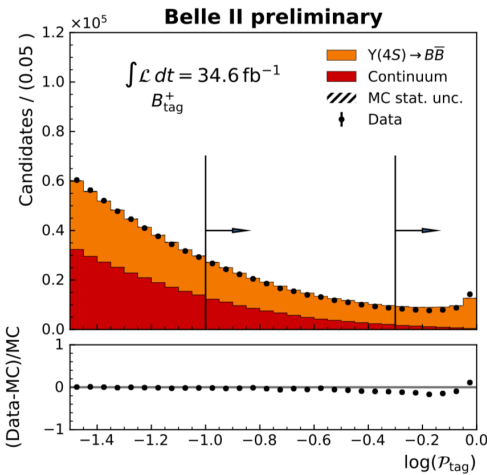
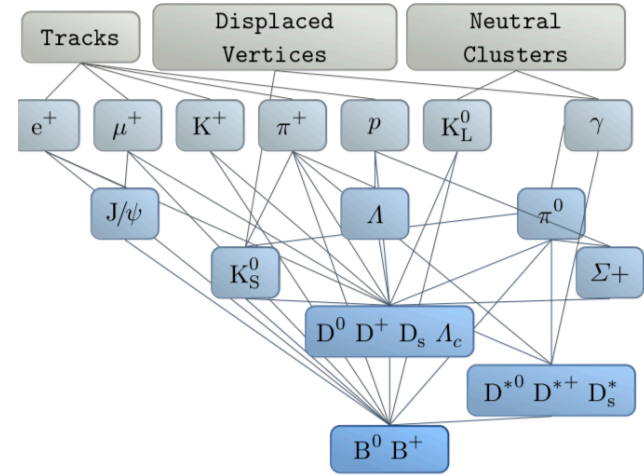
Full Event Interpretation (FEI)

Keck, T. et al. *Comput Softw Big Sci* (2019) 3: 6.

- Exclusive reconstruction of B meson in hadronic and semileptonic decay modes
- Multivariate algorithm with a hierarchical approach
- Classifier value, p_{tag} , discriminates correctly reconstructed tag-sides from background
- Infer momentum and direction of signal B candidate:

$$p_{sig} \equiv (E_{B_{sig}}, \vec{p}_{B_{sig}}) = \left(\frac{m(Y(4S))}{2}, -\vec{p}_{B_{tag}} \right)$$

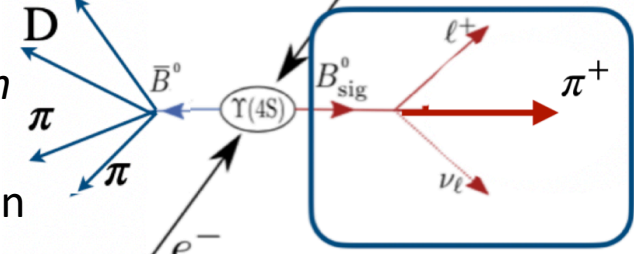
- Ideal for decays with neutrinos, missing energy signatures



$$M_{bc} = \sqrt{E_{beam}^2/4 - (p_{B_{tag}}^{cm})^2}$$

Tagged exclusive $B^0 \rightarrow \pi^- \ell^+ \nu_\ell$

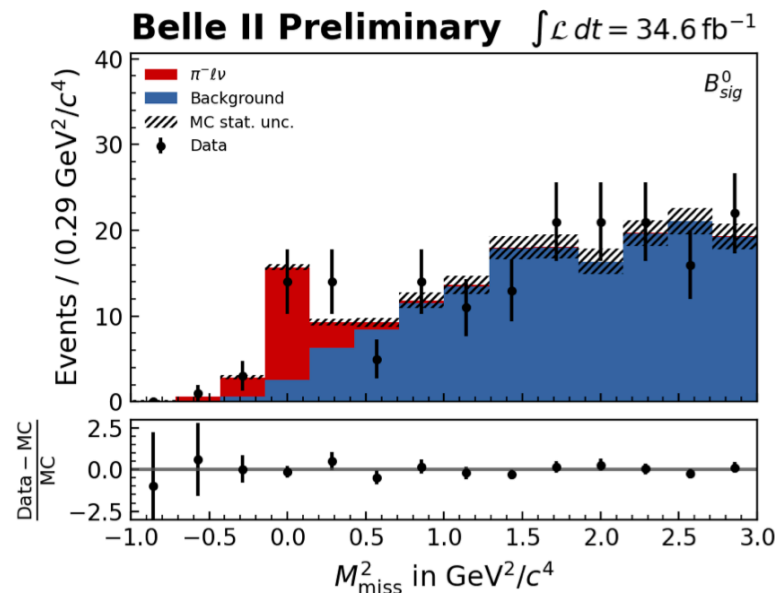
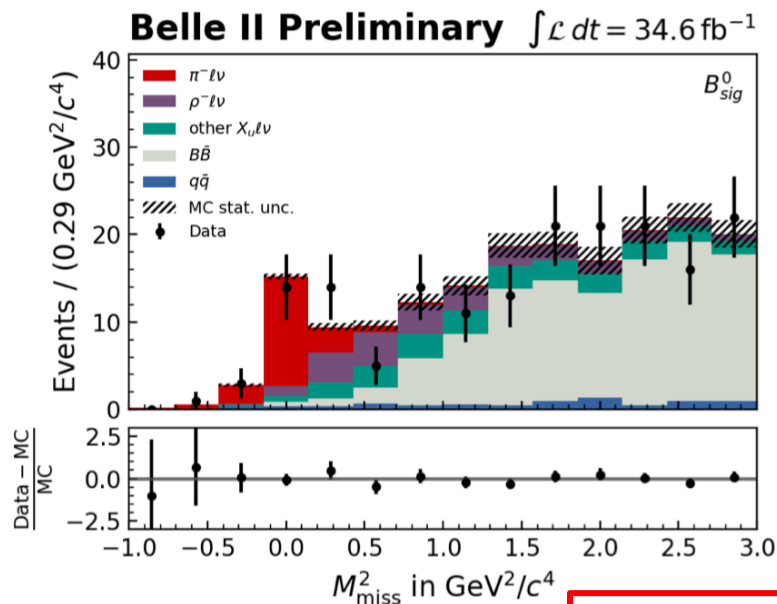
- **FEI hadronic tagging** used to identify B_{tag}
- Oppositely charged *muon* or *electron* candidate, and a *pion* candidate are identified using PID algorithms
- Fox-Wolfram R2 moment is used for continuum suppression
- Yield is extracted using the distribution of the square of the missing mass:



$$M_{\text{miss}}^2 \equiv p_{\text{miss}}^2$$

$$p_{\text{miss}} \equiv (E_{\text{miss}}, \vec{p}_{\text{miss}}) = p_{B_{\text{sig}}} - p_Y$$

- Analysis was performed blinded in the signal region $M_{\text{miss}}^2 < 1 \text{ GeV}^2/c^4$
- Result in agreement with world average; observed **signal significance 5.69σ**



$$\mathcal{B}(B^0 \rightarrow \pi^- \ell^+ \nu_\ell) = (1.58 \pm 0.43_{\text{stat}} \pm 0.07_{\text{sys}}) \times 10^{-4}$$

Prospects for $b \rightarrow u$ measurements at Belle II

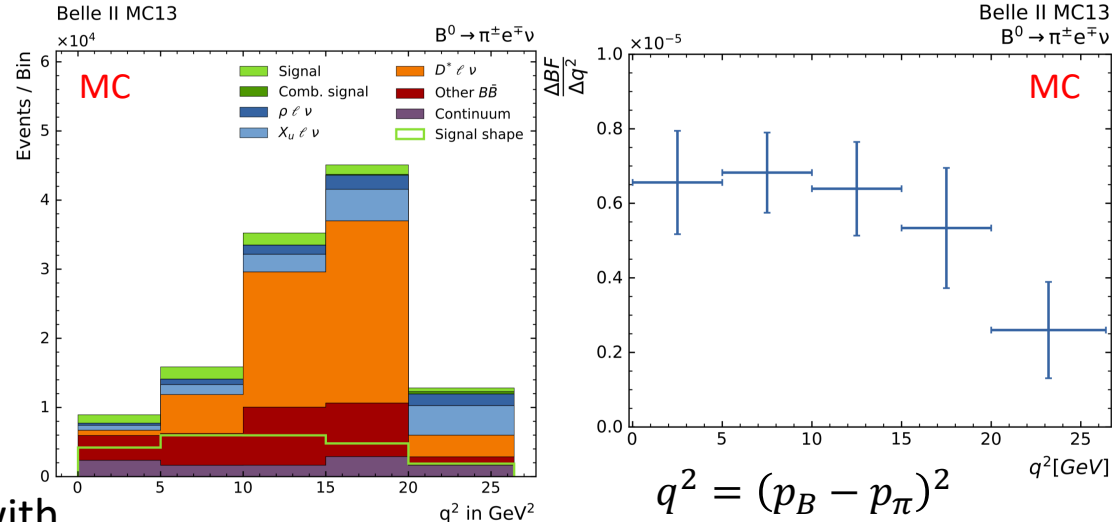
Prospects for $b \rightarrow u$ measurements at Belle II



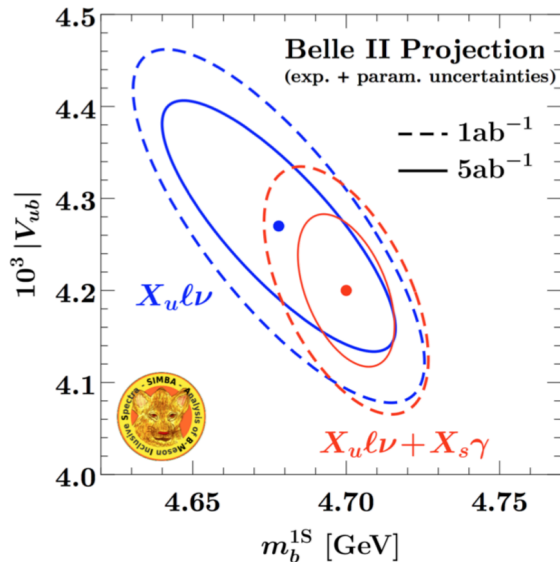
Significant improvement is expected with higher luminosities and better understanding of the detector's performance.

• $B \rightarrow \pi \ell \nu$ untagged measurement

- $\text{BF} \propto |V_{ub}|^2 f(q^2)$
- Extract ΔBF in five q^2 bins
- Extract $|V_{ub}|$ from a form factor fit to the partial branching fraction spectrum



• V_{ub} precision to be improved to 3% with the full 50 ab^{-1} dataset



	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$ V_{ub} $ exclusive (had. tagged)					
711 fb^{-1}	3.0	(2.3, 1.0)	3.8	7.0	8.0
5 ab^{-1}	1.1	(0.9, 1.0)	1.8	1.7	3.2
50 ab^{-1}	0.4	(0.3, 1.0)	1.2	0.9	1.7
$ V_{ub} $ exclusive (untagged)					
605 fb^{-1}	1.4	(2.1, 0.8)	2.7	7.0	7.5
5 ab^{-1}	1.0	(0.8, 0.8)	1.2	1.7	2.1
50 ab^{-1}	0.3	(0.3, 0.8)	0.9	0.9	1.3
$ V_{ub} $ inclusive					
605 fb^{-1} (old B tag)	4.5	(3.7, 1.6)	6.0	2.5–4.5	6.5–7.5
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

Summary

- Belle II has an ideal environment for semileptonic B meson decays
- $B \rightarrow X_u e \nu_e$ mode was rediscovered, showing evidence of non-zero V_{ub} in the electron momentum endpoint; muon mode under study
- $B^0 \rightarrow \pi^+ \ell \nu$ mode was rediscovered with measured $\mathcal{B} = (1.58 \pm 0.43_{stat} \pm 0.07_{sys}) \times 10^{-4}$, in agreement with previous measurements
- More $b \rightarrow u$ measurements to come with increased luminosity



@belle2collab