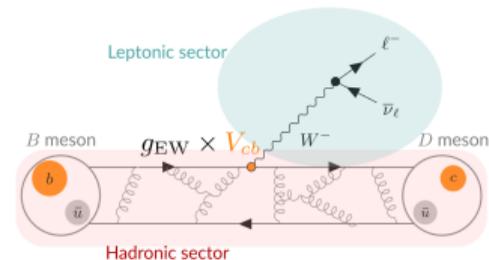# Full Event Interpretation at Belle II

Characterization and Comparison of ML-Based Semileptonic B Tagging

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Department of Physics and Astronomy
University of Victoria | Belle II Experiment

SuperKEKB Accelerator

- e^+e^- collider in Tsukuba, Japan
- Operates at $\Upsilon(4S)$ (10.58 GeV)
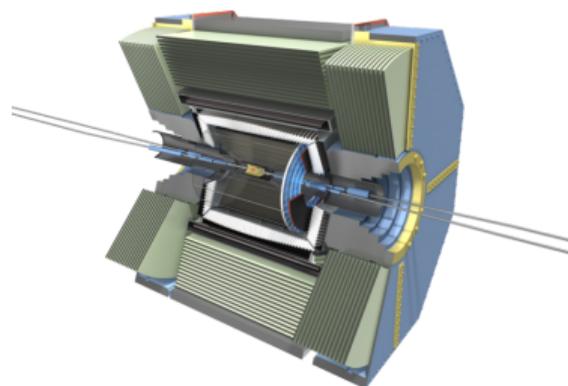- Produces 2 B mesons pairs nearly at rest

Belle II Experiment

- General-purpose flavor physics detector
- Precision studies of B, D, and τ decays
- Clean $B\bar{B}$ factory: full reconstruction

| Process	σ [nb]
$B\bar{B}$	1.1
$q\bar{q}(u,d,s,c)$	4.7
$\tau^+\tau^-$	0.92
Total Hadronic	5.8

Cross sections

The Challenge: Invisible Neutrinos

- Many interesting B decays have neutrinos in the final state. ($B \to K \nu \bar{\nu}$, $B \to D^{(*)} \ell \bar{\nu}$, etc.)

- Initial state precisely known

- No other particles in the event apart from the two B mesons

- Directly detected particles from both B decays overlap in the detector
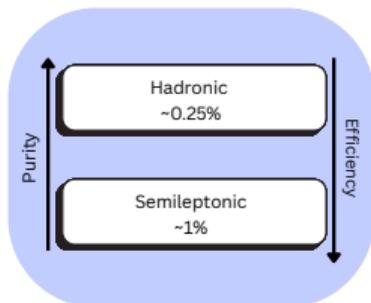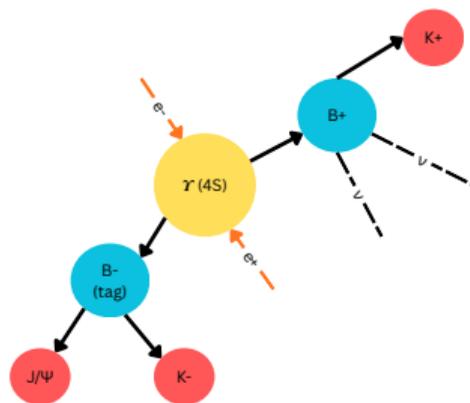
- **Solution**: Use B_{tag} to constrain the B_{sig}.
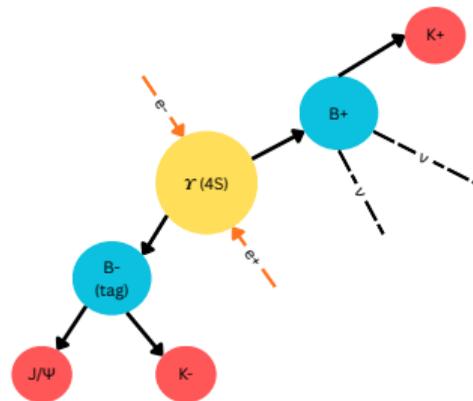
4-momentum Conservation

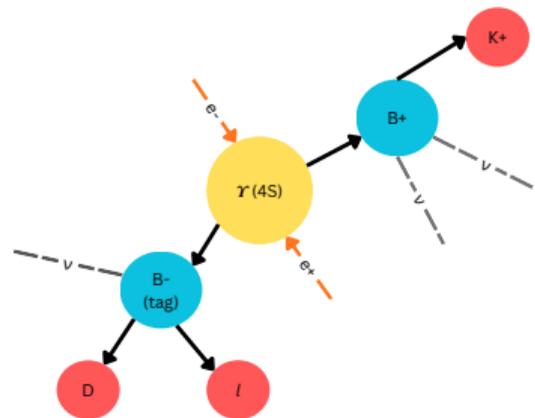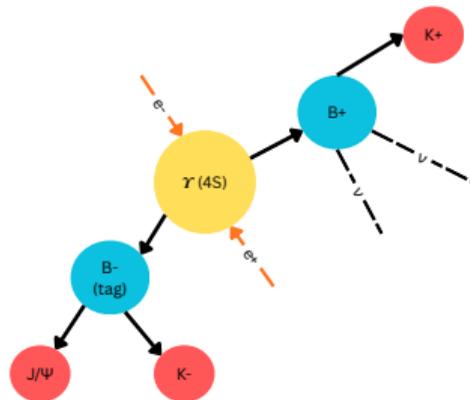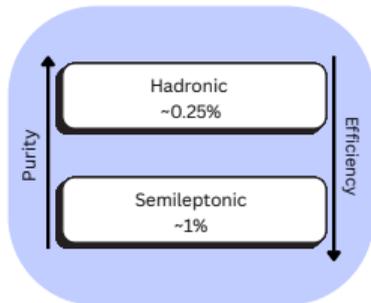$$P_{miss} = P_{e^+e^-} - P_{B_{tag}} - P_{visible}$$

B-Tagging for Missing Energy

- **Hadronic Tagging**
  - $B_{tag} \rightarrow$ hadrons (fully reconstructed)
  - **Pro:** Full constraint of B_{sig} kinematics

- **Hadronic Tagging**
  - $B_{tag} \to$ hadrons (fully reconstructed)
  - **Pro:** Full constraint of B_{sig} kinematics
- **Semileptonic Tagging**
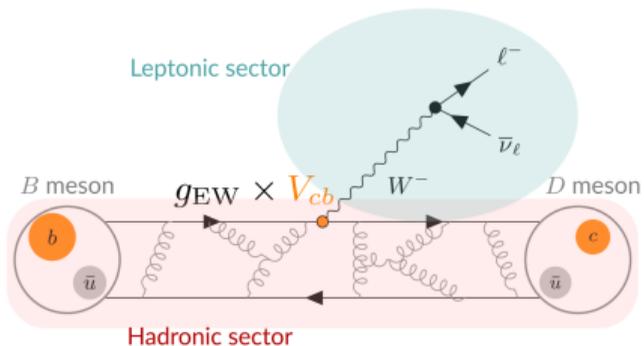 - $B_{tag} \to D^{(*)}\ell\nu$ (missing neutrino, like nuclear beta decay!)

Full Event Interpretation (FEI)

Full Event
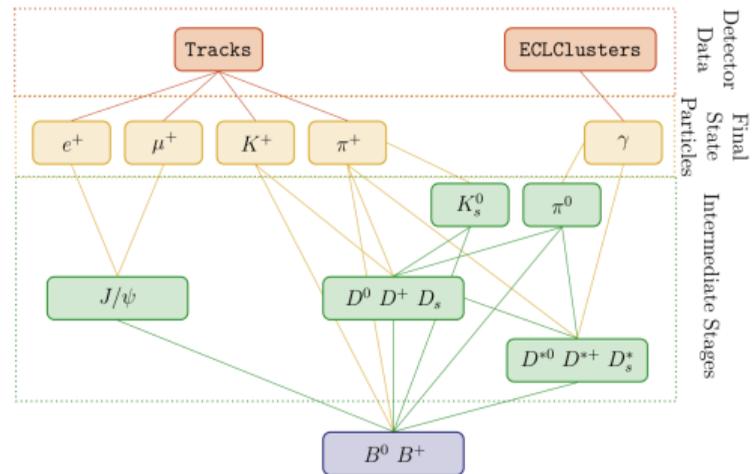Reconstructs $\Upsilon(4S)$ event using a bottom up approach.

ML-Based (FEI)
Hierarchical `FastBDT` trained on $> 10,000$ decay chains; generates $\mathrm{SigProb}$ to give likelihood of correct reconstruction

Statistical Gain
Increase in sample size since no hard selection cuts applied but may require calibration

Semileptonic Decay

BDT Training Levels
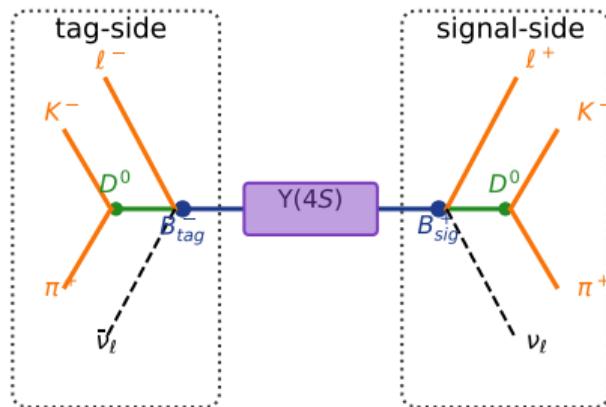
- High-level features such as BDTs have to be well understood in simulation

- FEI requires careful calibration

- Excited $D^* \to D\pi^0/\gamma$ has low mass difference

- Low energy neutrals are often missed in the detector

BDT Training Levels
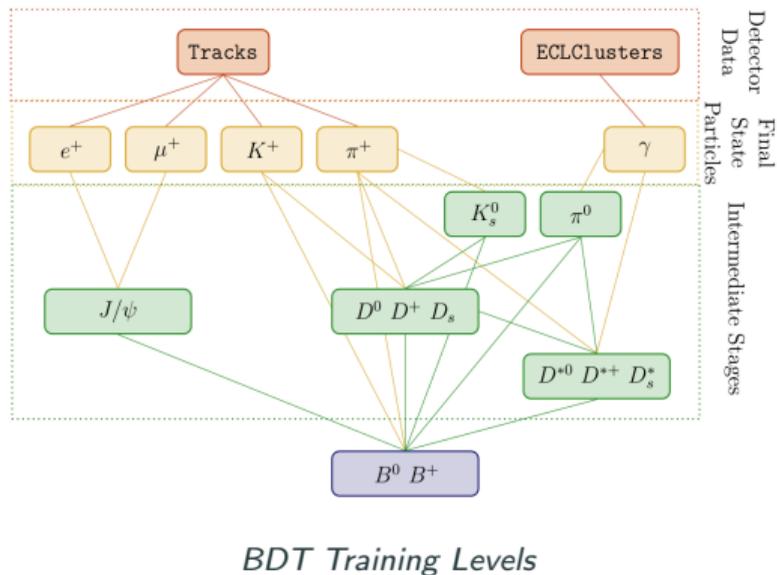
- **Hard cuts** on kinematics and PID (e.g. $\cos\theta_{BY}$)
- Apply a D^0 constraint $m_{D^0} = 1.86 \text{GeV}/c^2$
- Allows for events from $D^* \to D\pi^0/\gamma$ but does not explicitly reconstruct the π^0/γ
- **Why Simple?** No multivariate classifier; relies on cuts and vertex fitting
- Ideally should not require corrections and calibration like FEI
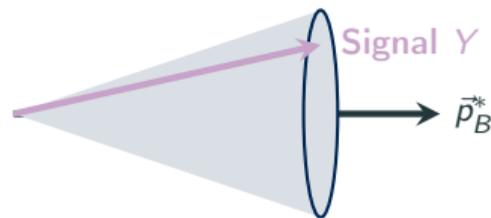
Angular Variables for Semileptonic Tagging

FEI B$^+$ Tag:

Legend:
- q$\bar{\text{q}}$ (11,442)
- B$^0\bar{\text{B}}^0$ (22,034)
- B$^\pm$B$^\mp$ (232,889)
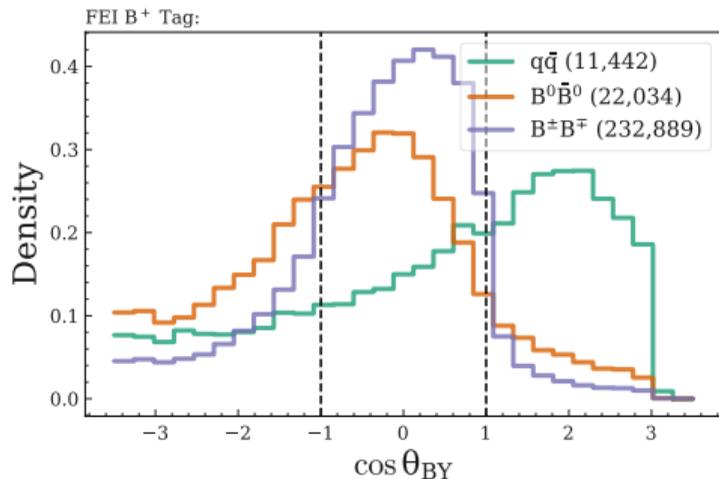
$$\boxed{\begin{array}{c} \cos\theta_{BY} \\ \\ B \to Y\nu \text{ where } Y = D^{(*)}\ell \\ \\ \cos\theta_{BY} = \dfrac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|\vec{p}_B^*||\vec{p}_Y^*|} \\ \\ \textbf{Signal: } -1 \leq \cos\theta_{BY} \leq 1 \end{array}}$$
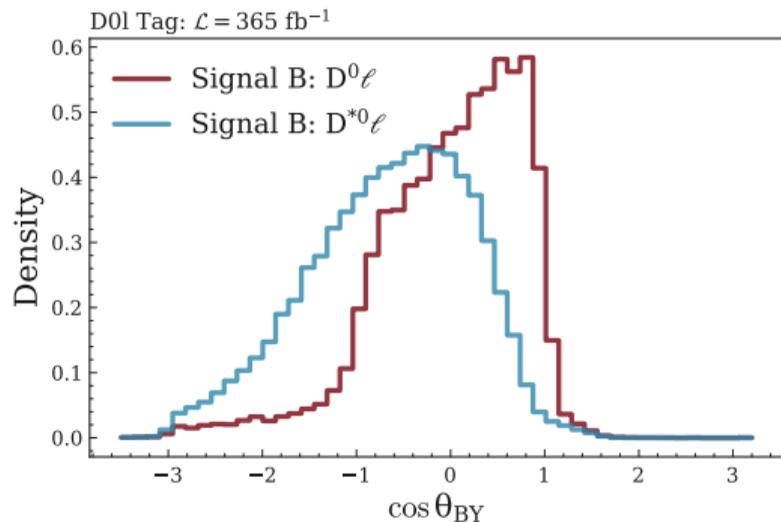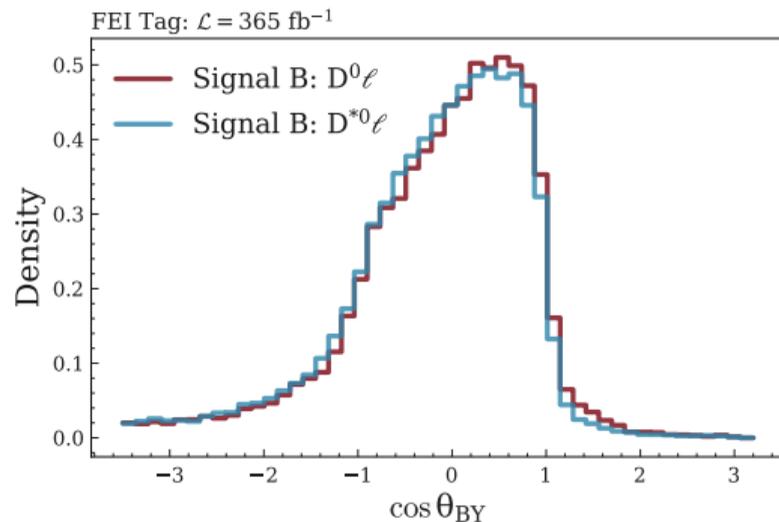

Signal Y

$\vec{p}_B^*$

- **Inside Cone:** Kinematically allowed.

- **Low Tail:** m_Y underestimated due to missing low energy π^0/γ. (Unphysical $\angle$)

- **High Tail:** E_Y overestimated via incorrect association of particles. (Unphysical $\angle$)

FEI vs. Simple Tagging: Decay Topology

- **Simple Tag:** Unreconstructed π^0/γ from $D^{*0} \to D^0(\pi^0/\gamma)$ shifts the $D^{*0}\ell$ component toward negative $\cos\theta_{BY}$ (blue hist).

- **FEI:** Fully reconstructs the decay chain, centering both $D^0\ell$ and $D^{*0}\ell$ distributions at zero.
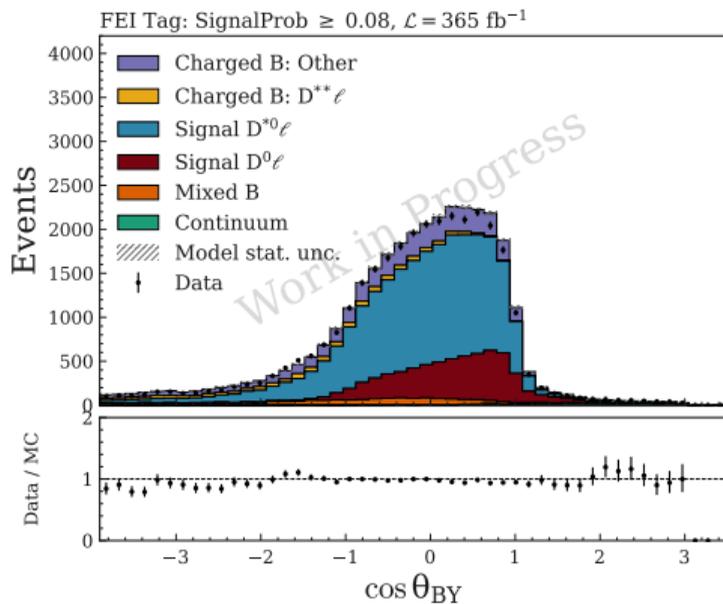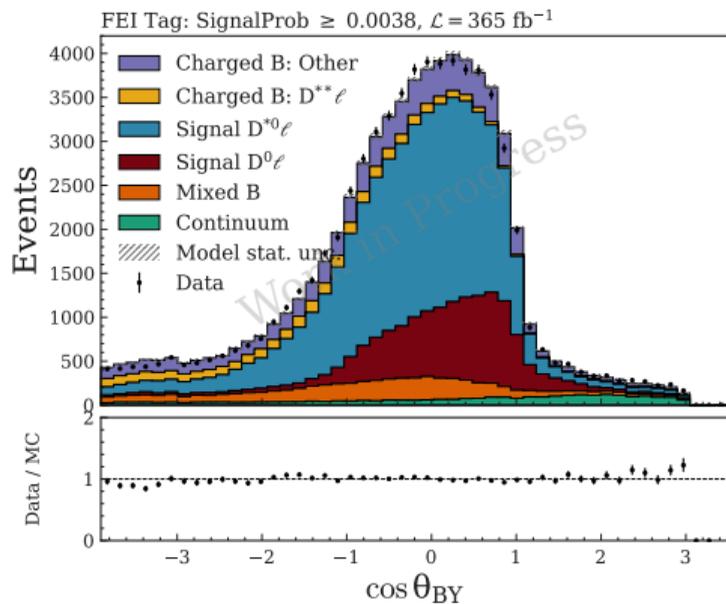

Simple Tag: Shifted $D^{*0}\ell$ component



FEI Tag: Centered signal peaks

(FEI) Tagging- Using Signal Probability

- **Signal Probability:** Multivariate classifier output to select high-purity B_{tag} candidates. (NOT A TRUE PROBABILITY*)
- **Selection Tuning:** Tighter cut → higher purity, lower efficiency (High Tail reduced)

Looser Cut: SigProb > 0.0038   **Tighter Cut: SigProb > 0.08**

FEI vs. Simple Tagging — $\cos\theta_{BY}$

- **Data–MC:** Out-of-the-box agreement in $\cos\theta_{BY}$ comparable
- **Background:** ~20% fewer continuum events (at matched efficiency)
- **Higher Efficiency:** Small increase in background (mostly $B^0\bar{B}^0$) at ×2 efficiency

Simple Tag

FEI (Matched $\mathrm{SigProb} \geq 0.08$)

FEI (Loose $\mathrm{SigProb} \geq 0.0038$)
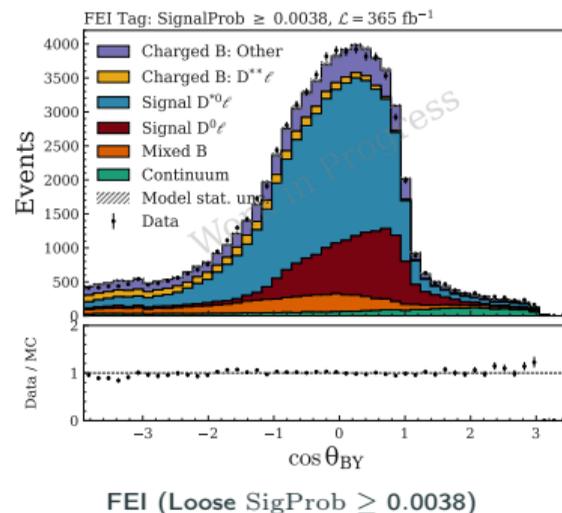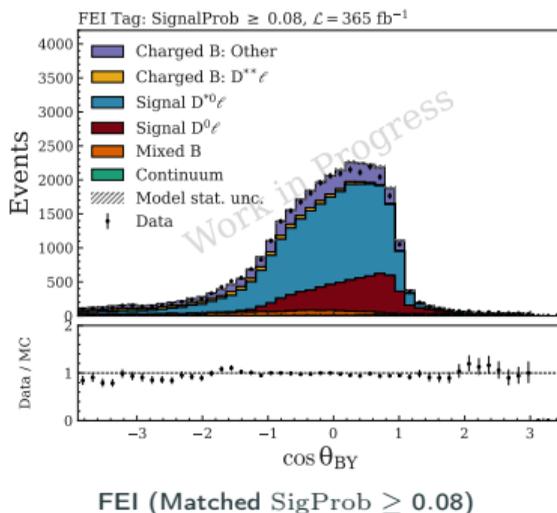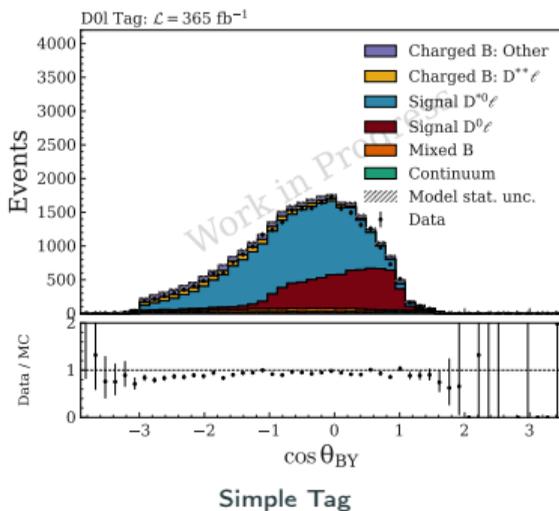
Future Studies

- **BDT Optimization:** Replace hard cuts with BDTs does maximize efficiency
- **Recovery:** FEI recovers $> 80\%$ of events found via Simple tagging
- **Missing events:** Study non-reconstructed events to identify FEI limitations
- **Hybrid Development:** Co-develop Simple and FEI tags to further improve SL tagging performance
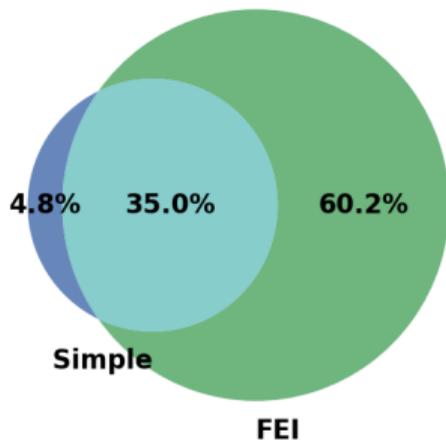
Event overlap (Loose $\mathrm{SigProb}$ cut)

$\cos\theta_{BY}$ distribution (Loose cut)

Conclusion
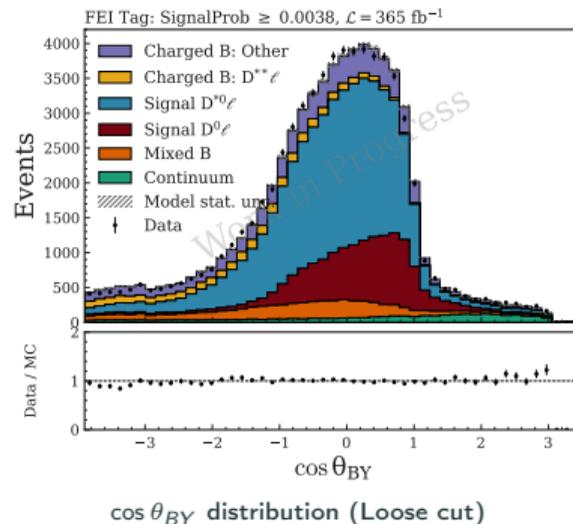
- **Performance:** FEI achieves efficiency gains at comparable purity relative to Simple Tag. ($\sim 0.9\%$ overall tagging efficiency)
- **Data–MC Agreement:** FEI shows improved Data–MC agreement in $\cos\theta_{BY}$
- **Observation:** Level of agreement is notable, FEI's multivariate structure was expected to require larger corrections and calibration
- **Applications:** Results applicable to all Belle II analyses using semileptonic B tagging
- **Future Work:** Further optimization and hybrid approaches could yield better performance

Thank you for listening!

Thanks to my supervisors, Prof. Bob Kowalewski and Dr. Philipp Horak, and the UVic Belle II group for their support.

Backup

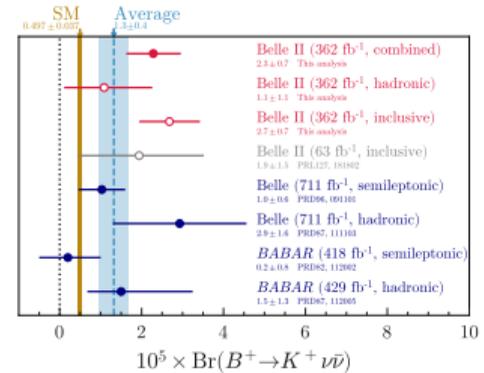**The Challenge: Invisible Neutrinos**

- $\Upsilon(4S) \to B\bar{B}$ kinematics are precisely known.

- B_{sig} with ν's cannot be directly reconstructed.

- **Solution**: Reconstruct B_{tag} to fully constrain event.

Key Measurements

- $B \to K\nu\bar{\nu}$: Rare SM process; requires tagging to constrain B_{sig} kinematics (only 1 track).

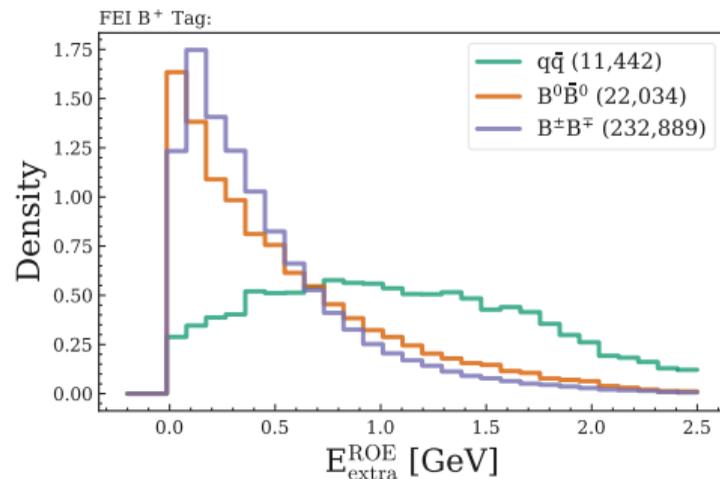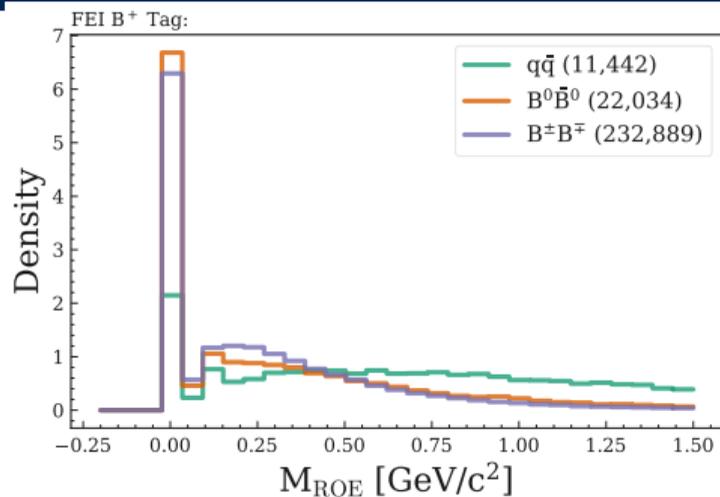- $B \to \tau\nu$: V_{ub} measurement; requires tagging for improved efficiency.

$B \to K\nu\bar{\nu}$ Measurements

4-momentum Conservation

$$P_{miss} = P_{e^+e^-} - P_{B_{tag}} - P_{visible}$$

ROE Variables: M_{ROE} and E_{extra}

M_{ROE}

Invariant mass of the Rest of Event.

Used to identify background leakage or missing neutrals.

Target Signal: $\approx 0\,\mathrm{GeV}/c^2$

E_{extra}^{ROE}

Calorimeter energy not associated with B_{sig} or B_{tag}.

Ensures all energy is accounted for (no "hidden" particles).

Target Signal: $\approx 0\,\mathrm{GeV}$

FEI vs. Simple Tag: Rest of Event (ROE)

- **Better Resolution:** FEI reduces events with large missing energy ($> 500\,\mathrm{MeV}$) by **25%** relative to Simple tagging.
- **Consistency:** Comparable Data–MC agreement maintained across all tags. (Hard to model MC due to beam background and detector effects)

Simple Tag

FEI (Matched $\mathrm{SigProb} \geq 0.08$)

FEI (Loose $\mathrm{SigProb} \geq 0.0038$)
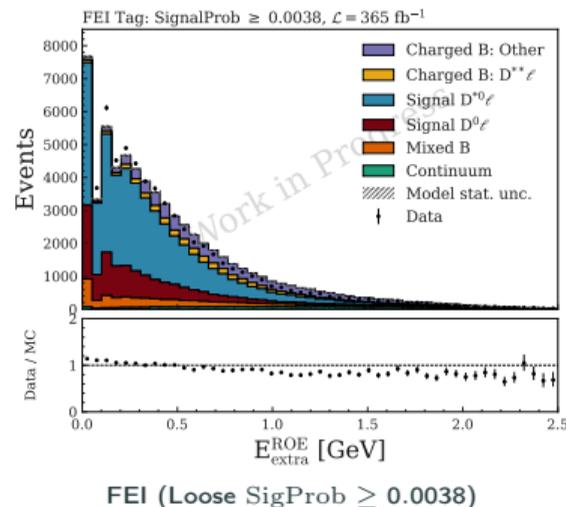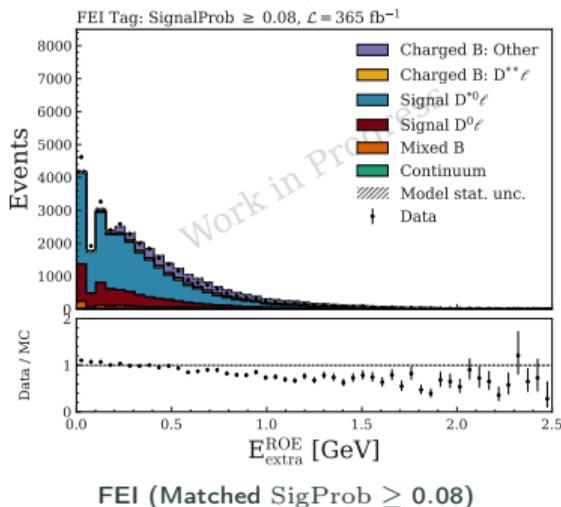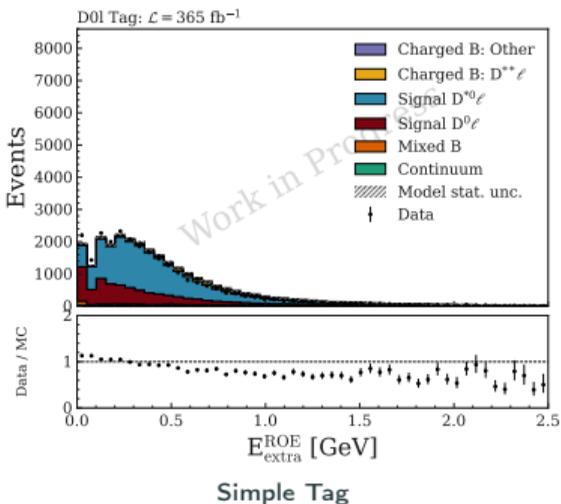
- **Data–MC**: Comparable agreement in M_{ROE} distribution.

- **Peak at** $135\,\mathrm{MeV}$: From missing π^0 in the events possibly from $B \to D\pi\ell\nu$

Simple Tag

FEI at a Matched Efficiency ($\mathrm{SigProb} \geq 0.08$)
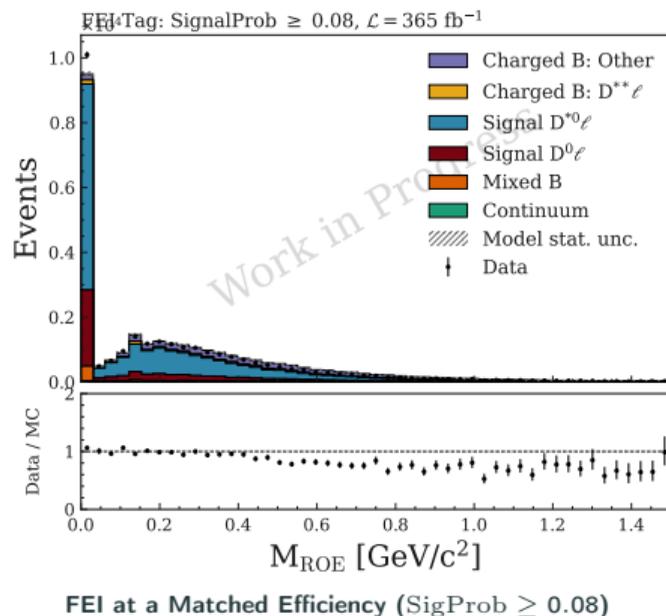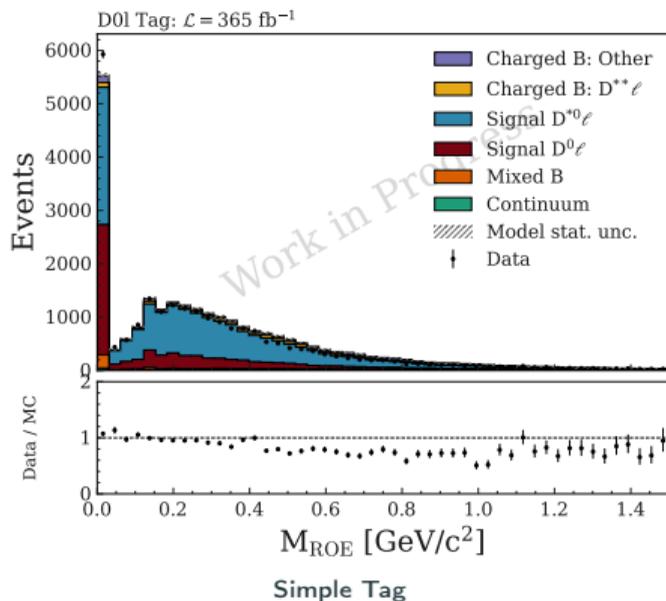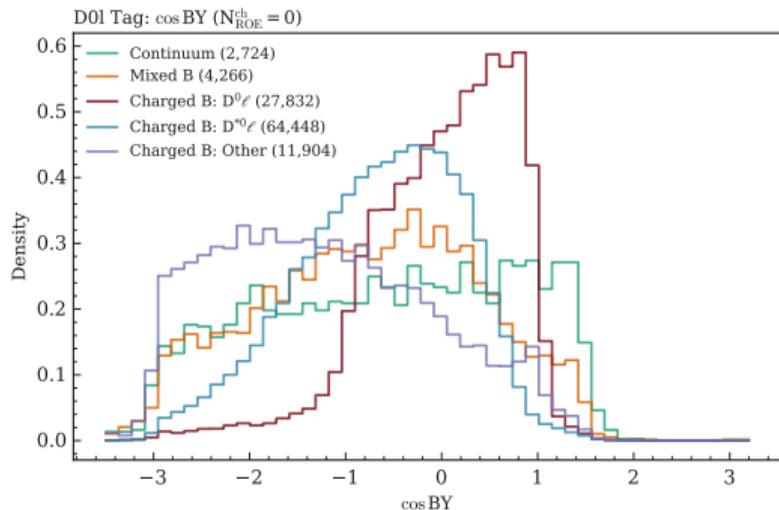
Selection Cuts

FEI Selection

- **ROE & Reco**

  - No charged tracks in ROE
  - Only 6 D Common decays used from the FEI (14 in FEI total)

- **Singal Prob**

  - Set to 0.1 to match efficiency of $D^0\ell$

- **Best Candidate**

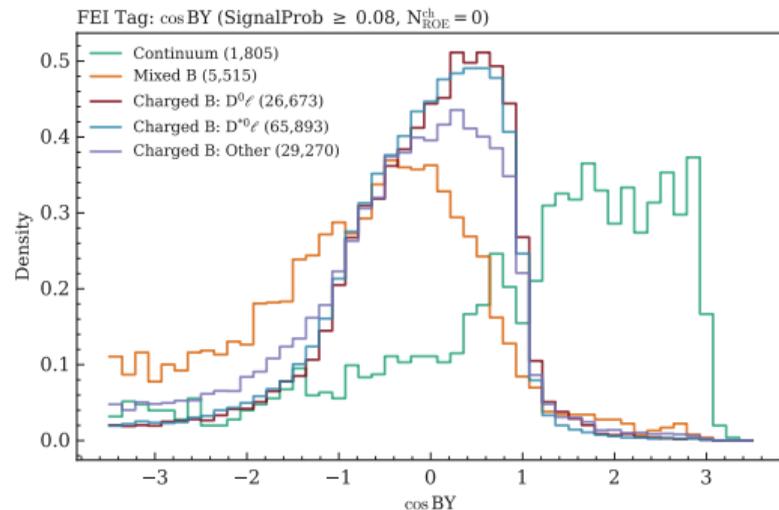 - B SigProb Used for candidate selection

$D^0\ell$ Selection

- **ROE & Reco**

  - No charged track in ROE
  - 6 D Decay Modes

- **Kinematic Cuts**

  - InvM > 2.5 and $-3.0 < \cos BY < 1.5$ at steering level

- **Best Candidate**

  - B χProb vertex fit

FEI vs. Simple Tagging: Decay Topology

- **Simple Tag:** Unreconstructed π^0/γ from $D^{*0} \to D^0(\pi^0/\gamma)$ shifts the $D^{*0}\ell$ component toward negative $\cos\theta_{BY}$ (blue hist).
- **FEI:** Fully reconstructs the decay chain, centering both $D^0\ell$ and $D^{*0}\ell$ distributions at zero.
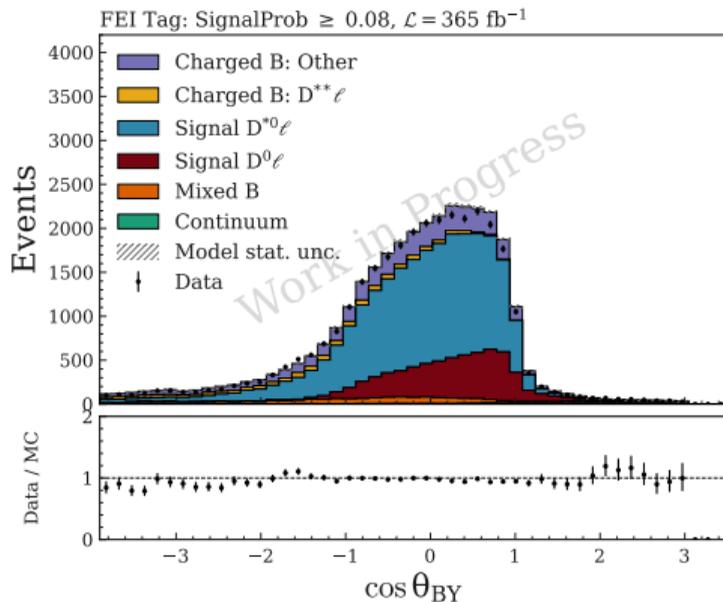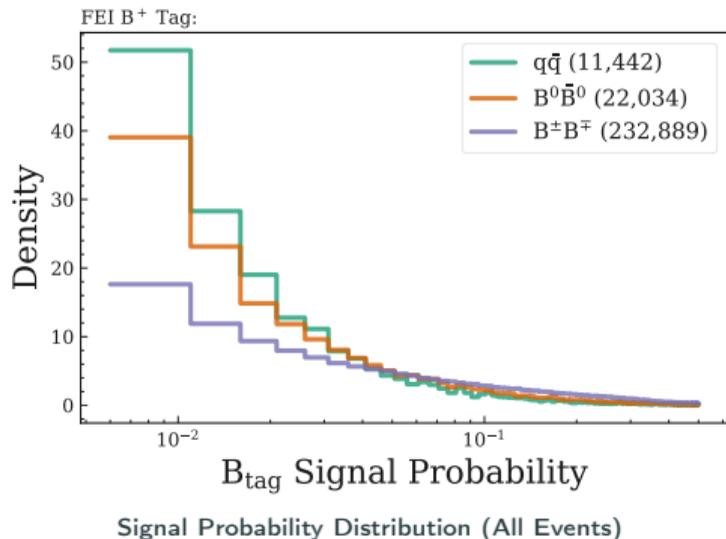

Simple Tag: Shifted $D^{*0}\ell$ component

FEI Tag: Centered signal peaks

(FEI) Tagging- Using Signal Probability

- **Signal Probability:** Multivariate classifier output to select high-purity B_{tag} candidates. (NOT A TRUE PROBABILITY*)
- **Selection Tuning:** Tighter cut → higher purity, lower efficiency

Signal Probability Distribution (All Events)

Tighter Cut: SigProb > 0.08