$B^0 \to \pi^- \ell^+ \nu_\ell$ with Hadronic Tagging at the Belle II Experiment

Nadia Toutounji

The University of Sydney

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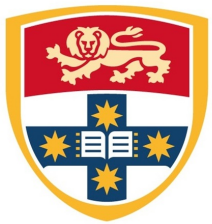

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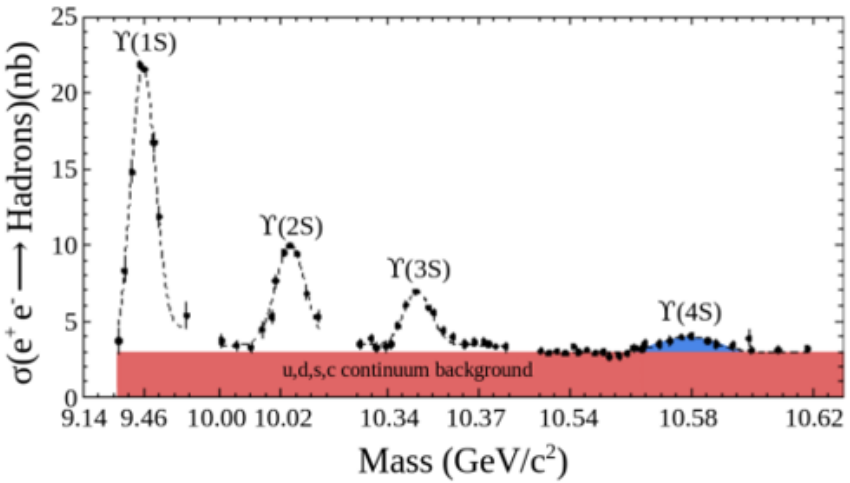
Overview

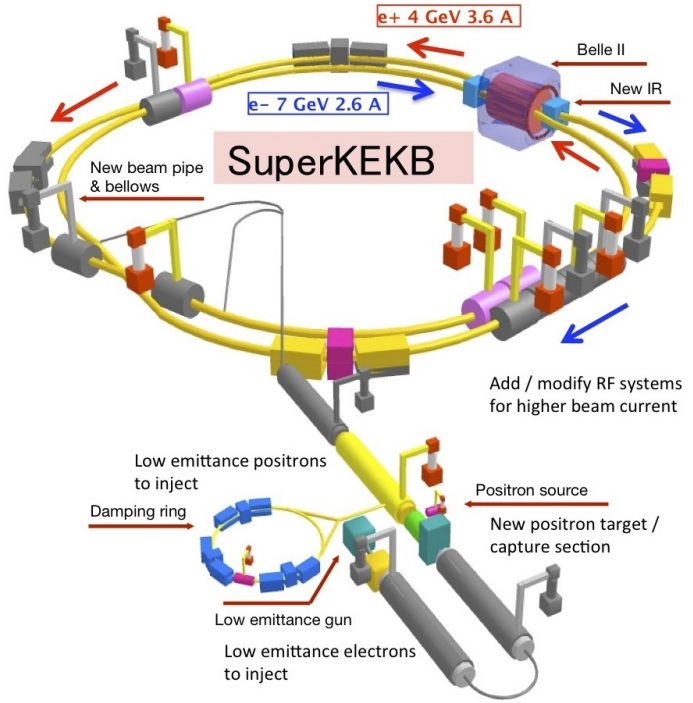
- The Belle II Experiment
- Why $B \to \pi \ell \nu$?
- Tagged analyis techniques
- Results from early Belle II data

The Belle II Experiment

- Successor to the Belle Experiment, one of two experiments to first observe CP-violation in neutral B-mesons *arXiv:hep-ex/0107061*
- SuperKEKB accelerator collides asymmetric e^+e^- beams at the $\Upsilon(4S)$ ($b\bar{b}$) resonance, producing pairs of B-mesons

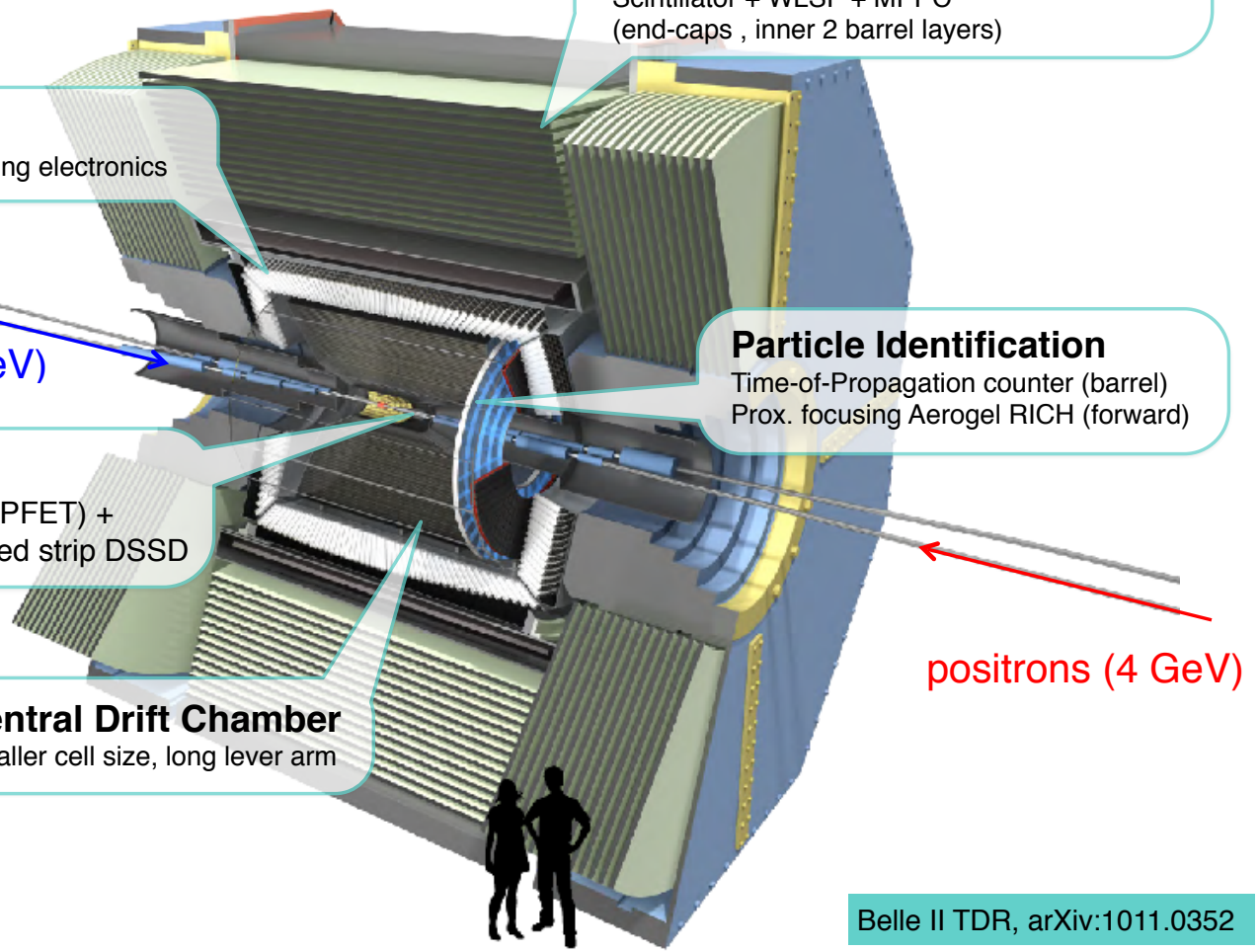


arXiv:0901.1443 [hep-ex]



- Primary aim is to study rare decays in the search for new physics, with an expected data-set of 50× that of Belle
- 90 fb^{-1} of data recorded so far (over 80 million collisions!)

The Belle II Detector



KL and muon detector
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC
(end-caps , inner 2 barrel layers)

EM Calorimeter
CsI(Tl), waveform sampling electronics

electrons (7 GeV)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

Vertex Detector
2 layers Si Pixels (DEPFET) +
4 layers Si double sided strip DSSD

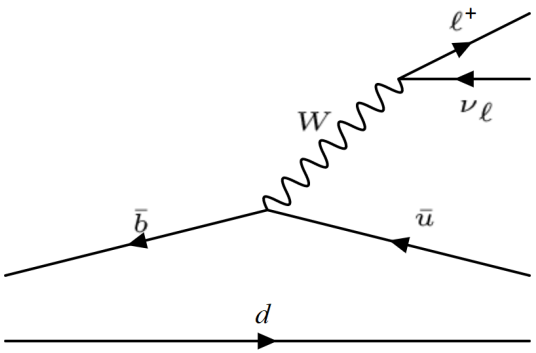
positrons (4 GeV)

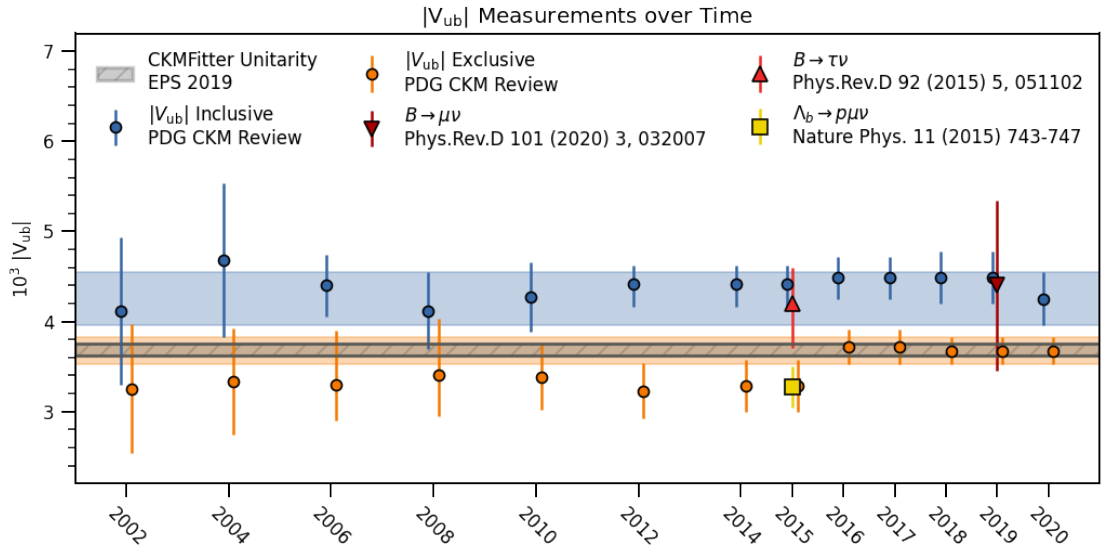
Central Drift Chamber
Smaller cell size, long lever arm

Belle II TDR, arXiv:1011.0352

$B^0 \to \pi^- \ell^+ \nu_\ell$: Motivation

- $B^0 \to \pi^- \ell^+ \nu_\ell$ decay involves a $b \to u$ quark transition, characterised by CKM matrix element $|V_{ub}|$
- With expected size of Belle II data-set, aim to improve the precision of $|V_{ub}|$ measurements from rare decays including $B^0 \to \pi^- \ell^+ \nu_\ell$
- Investigate the current tension between inclusive and exclusive measurements of $|V_{ub}|$



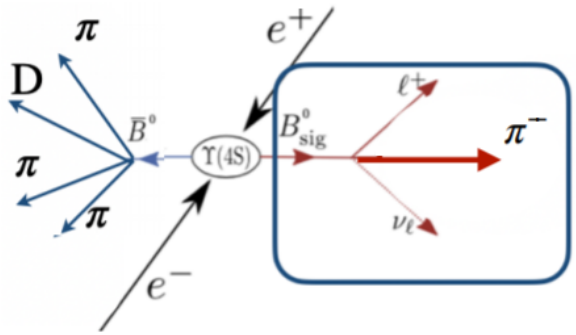


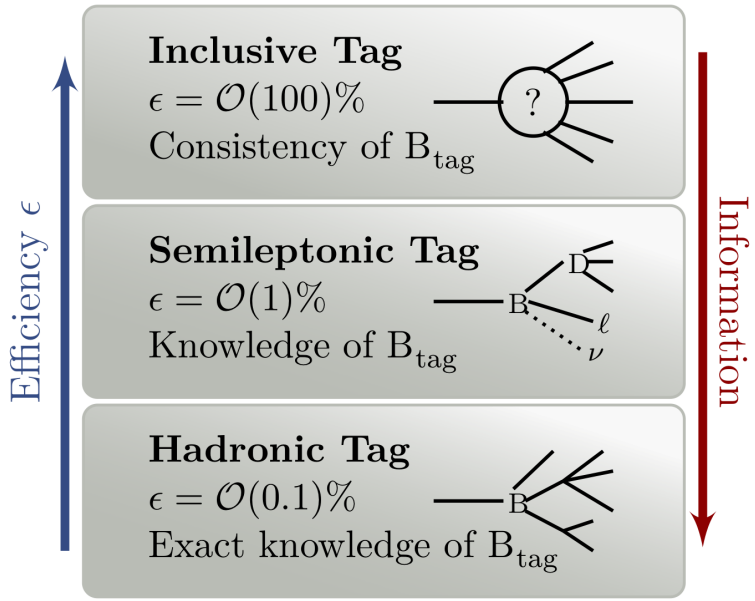
$B^0 \to \pi^- \ell^+ \nu_\ell$ where $\ell = e, \mu$

Credit: Markus Prim

Reconstructing B-mesons - Tagged Analysis

- One B-meson from an $\Upsilon(4S)$ decay acts as a tag, can be reconstructed in multiple decay channels
- Select a signal B-meson, B_{sig}, with required decay mode for analysis. e.g. $B^0 \to \pi^- \ell^+ \nu_\ell$
- Since the initial state of the $\Upsilon(4S)$ is well-known, the reconstruction of B_{tag} provides kinematic information for B_{sig}



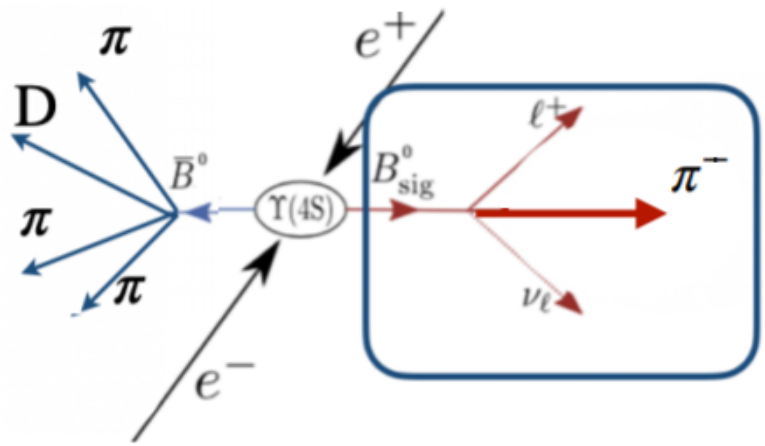


$$\Upsilon(4S) \to \bar{B}^0_{tag} B^0_{sig}$$

Credit: Markus Prim

Hadronic Tagging

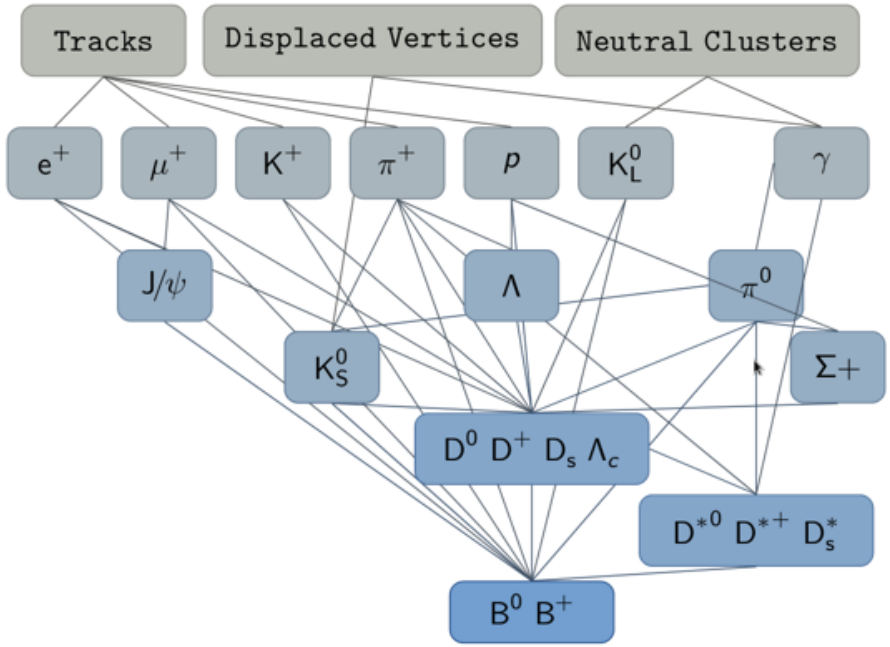
- B_{tag} decay is purely hadronic. Can completely reconstruct tag-side with high purity
- Neutrinos are not detected by Belle II $\rightarrow$ can determine 4-momentum of a neutrino present on signal side through momentum conservation



$$M^2_{\text{miss}} = |p_{B\text{sig}} - p_\pi - p_\ell|^2$$

Full Event Interpretation (FEI)

- Machine learning algorithm that reconstructs over 4000 B-meson decay chains for tagging, training a multi-variate classifier for each
- Each B_{tag} built has an associated classifier output, the `SignalProbability`, which lies between 0 (background-like) and 1 (signal-like)

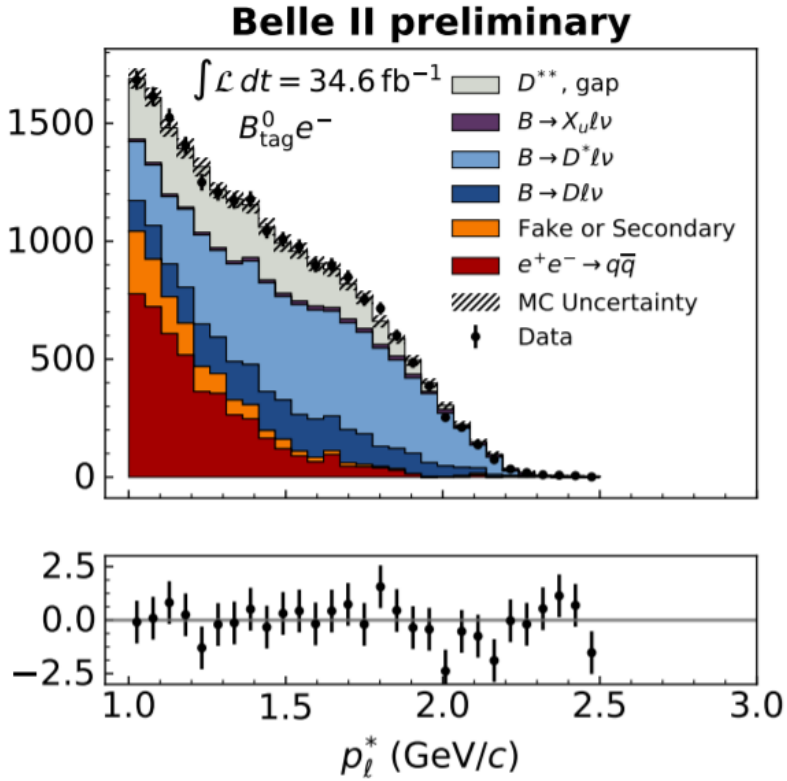


Credit: Thomas Keck, William Sutcliffe

- Hierarchical approach that builds B-mesons from final-state particles

Full Event Interpretation (FEI)

- Reconstruction efficiency of the FEI is higher for simulated data (Monte Carlo) than real data
- Algorithm can be calibrated by comparing the relative number of correctly reconstructed events in data and MC for a specific signal mode
- Choose signal mode with high branching fraction, $B^0 \to X\ell\nu$, where X is any hadronic system



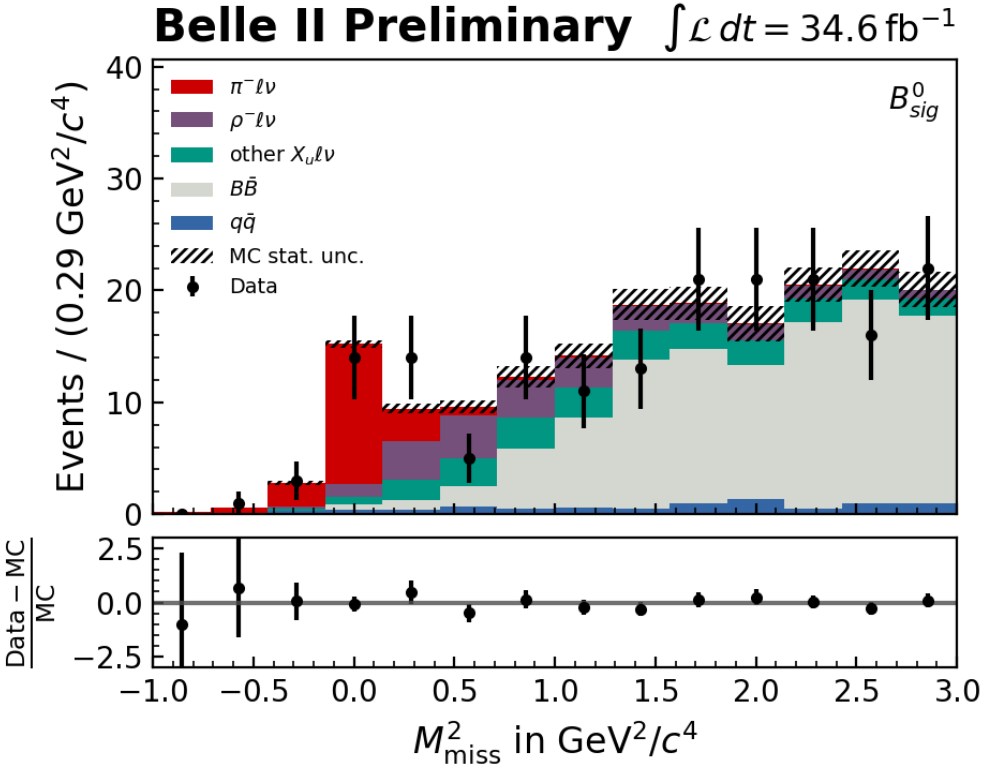
$$\epsilon_{\mathrm{cal}} = N^{X\ell\nu}_{\mathrm{data}} / N^{X\ell\nu}_{\mathrm{MC}}$$

$$\epsilon_{\mathrm{cal}} = 0.83 \text{ for } B^0 \text{ tags}$$

arXiv:2008.06096 [hep-ex]

$B^0 \to \pi^- \ell^+ \nu_\ell$ in Early Belle II Data

- Looked at M^2_{miss} comparison between data and MC after selections (back-up)
- MC has been scaled down by the hadronic FEI calibration factor, 0.83



Cut on FEI classifier to reduce background:

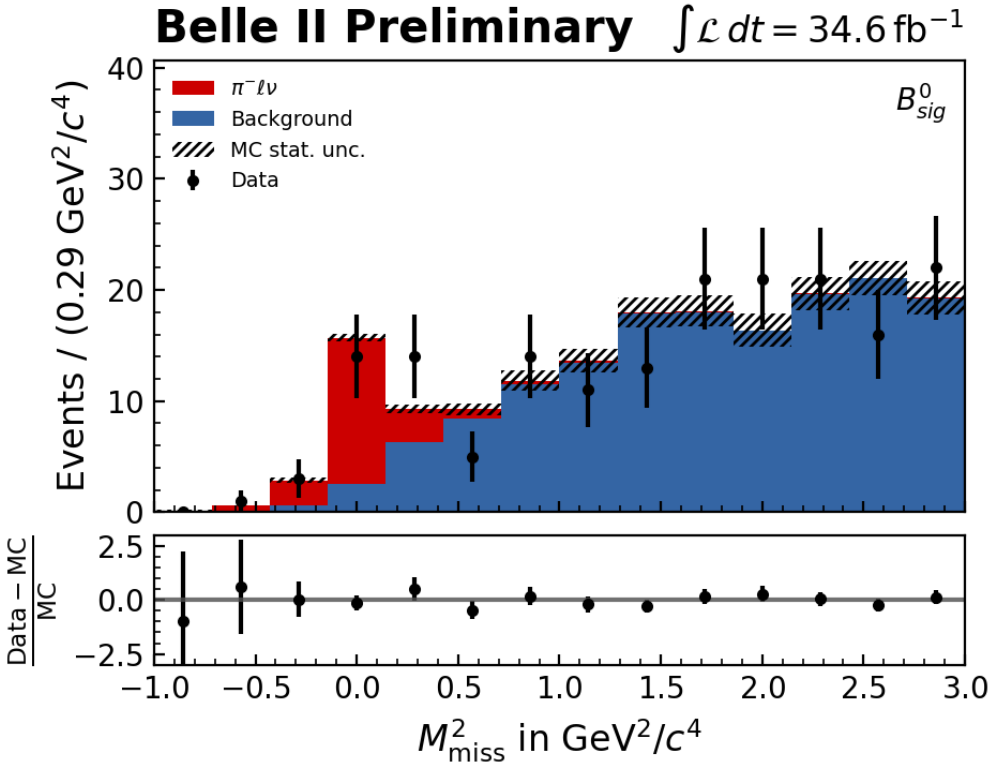
`SignalProbability > 0.001`

Various backgrounds involved: *arXiv:2008.08819 [hep-ex]*

- Cross-feed from other semi-leptonic decays to a hadronic system containing a u quark, $B \to X_u \ell \nu$
- Other $B\bar{B}$ decays
- Continuum events, where $e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}$ or $c\bar{c}$

$B^0 \to \pi^- \ell^+ \nu_\ell$ in Early Belle II Data

- Performed a 2-dimensional fit to the M^2_{miss} distribution to extract the yield of our signal $B^0 \to \pi^- \ell^+ \nu_\ell$ events
- Signal and background MC distributions are used as templates to fit the data to, and fit is performed by maximising the likelihood



- We see 20.79 $\pm$ 5.68 $B^0 \to \pi^- \ell^+ \nu_\ell$ events in 34.6 fb^{-1} of Belle II data with a 5.69σ significance!

arXiv:2008.08819 [hep-ex]

Branching Fraction Measurement, $B^0 \to \pi^- \ell^+ \nu_\ell$

- Branching fraction measurement based on 34.6 fb^{-1}:

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = \frac{N_{\rm sig}^{\rm data}(1 + f_{+0})}{4 \times {\rm CF}_{\rm FEI} \times N_{B\bar{B}} \times \epsilon} \ ,$$

$N_{\rm sig}^{\rm data}$: Fitted signal yield from data
f_{+0}: Ratio of BFs for $\Upsilon(4S) \to B^+B^-$ / $B^0\bar{B}^0$
${\rm CF}_{\rm FEI}$: FEI calibration factor
$N_{B\bar{B}}$: Number of total $B\bar{B}$ pairs in data-set
ϵ: Signal reconstruction efficiency

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

- In agreement with current world average: $(1.50 \pm 0.06) \times 10^{-4}$

Summary

- Belle II aims to search for new physics, particularly through the study of rare decays
- One specific goal is improving our precision on measurements of CKM matrix elements e.g. $|V_{ub}|$
- Improved software for performing tagged analyses at Belle II $\rightarrow$ the Full Event Interpretation
- Using hadronic tagging via the FEI, we were able to re-discover the decay $B^0 \rightarrow \pi^- \ell^+ \nu_\ell$ in early Belle II data (with a $> 5\sigma$ significance!)
- As more data is recorded, we will improve the precision on the branching fraction measurement and extract $|V_{ub}|$

Analysis Selections

Event	visibleEnergyOfEventCMS $>$ 4 GeV, foxWolframR2 $<$ 0.4 2 GeV $<$ E$_{ECL}$ $<$ 7 GeV, $E_{miss} > 0.3$ GeV nCleanedTracks($\|z0\| < 2.0$ cm, $\|d0\| < 0.5$ cm, $p_t > 0.1$ GeV) ≥ 3 nCleanedECLClusters($0.296706 < \theta < 2.61799$, E > 0.1 GeV) ≥ 3 No additional tracks in event
B_{tag}	`SignalProbability` > 0.001 or dmID $= 23(25)$ for $B^0(B^+)$ $M_{bc} > 5.27$ GeV, $\|\Delta E\| < 0.2$ GeV One B_{tag} per event with highest `SignalProbability`
e (μ)	$\|dr\| < 2$ cm, $\|dz\| < 5$ cm, $0.297 < \theta < 2.618$ `electronID`(`muonID`) > 0.9 $p_{lab} > 0.3$ GeV ($p_{lab} > 0.6$ GeV) One lepton per event with highest `leptonID`
$\pi^{\pm}$	$\|dr\| < 2$ cm, $\|dz\| < 4$ cm, `pionID` > 0.5, `nCDCHits` > 20 and $0.297 < \theta < 2.618$
π^0	May 2020 stdPi0s *eff40* list
B^0_{sig}	$-3 < cos\theta_{BY} < 3$, $E_{residual} < 1.0$ GeV, $\|z_\ell - z_\pi\| < 1$ mm
B^+_{sig}	$-3 < cos\theta_{BY} < 3$, $E_{residual} < 0.6$ GeV, $cos\psi_{\gamma\gamma} > 0.25$
$\Upsilon(4S)$	One $\Upsilon(4S)$ per event with lowest M^2_{miss}

Systematics, $B^0 \to \pi^- \ell^+ \nu_\ell$, 34.6 fb^{-1}

Source of systematic uncertainty	% of $\mathcal{B}$
f_{+0}	1.70
FEI calibration	3.45
$N_{B\bar{B}}$	1.60
Reconstruction efficiency ϵ	0.46
Tracking	1.60
Lepton ID	1.05
Total	4.61

- Dominant systematic uncertainty from FEI calibration