Karlsruhe Institute of Technology

Belle II

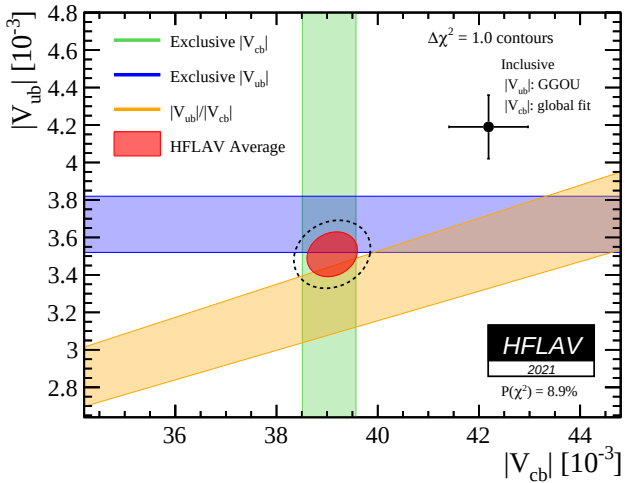
B $\rightarrow$ $\rho\ell\nu_\ell$ with Hadronic Full Event Interpretation Tag at Belle II

KSETA Plenary Workshop 2023

Moritz Bauer, Torben Ferber, Pablo Goldenzweig | 29. March 2023

B-Physics and Semileptonic Decays

- Many decay processes for B mesons $\rightarrow$ Many opportunities for SM tests and searches
- CKM Matrix $|V_{ub}|$and $|V_{cb}|$: Tension ($\approx 3.3\sigma$) between determination from
  - **inclusive (all B $\rightarrow$ X$\ell\bar{\nu}_\ell$)** and
  - **exclusive (one b $\rightarrow$ x process)**
- Differences both in theory and experiment

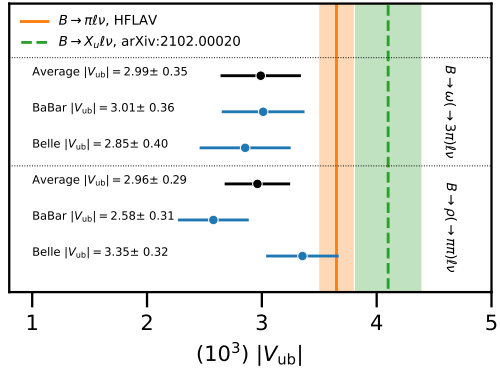


$B \to \rho \ell \nu_\ell$ decays

- CKM matrix element $|V_{ub}|$ from $B \to \rho \ell \nu_\ell$ shows tension with
  - $|V_{ub}|$ from $B \to \pi \ell \nu_\ell$
  - $|V_{ub}|$ from $B \to X_u \ell \nu_\ell$ (inclusive)
- Slight tension in last two published measurements of branching fraction of

  $\ldots B^+ \to \rho^0 \ell^+ \nu_\ell$:
  - Belle (2013): $1.83 \pm 0.10 \pm 0.10$
  - BaBar (2011): $0.94 \pm 0.08 \pm 0.14$

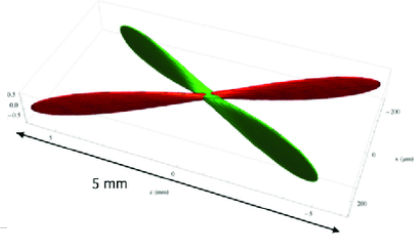
  $\ldots B^0 \to \rho^- \ell^+ \nu_\ell$:
  - Belle (2013): $3.22 \pm 0.27 \pm 0.24$
  - BaBar (2011): $1.75 \pm 0.15 \pm 0.27$

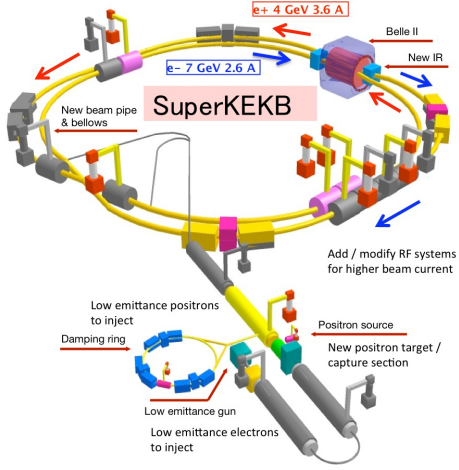


Determination by Bernlochner, Prim, and Robinson

World record luminosity: SuperKEKB accelerator

- Asymmetric e^+e^- collider with $\sqrt{s} \approx 10.6\,\text{GeV}$ ($\Upsilon(4S)$ resonance)
- Peak luminosity (June 22): $3.1 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$ (+50% vs. KEKB)
  - In part thanks to nano-beam scheme.





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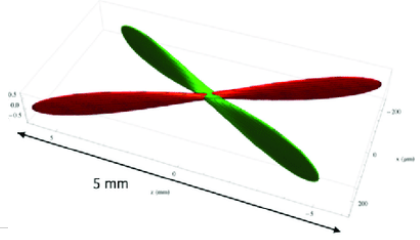
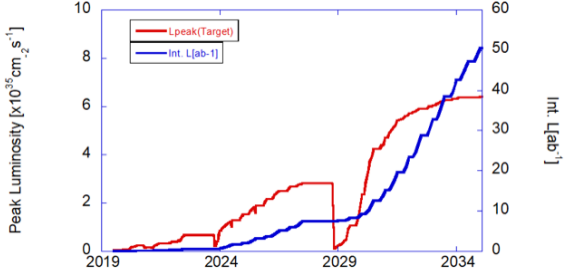
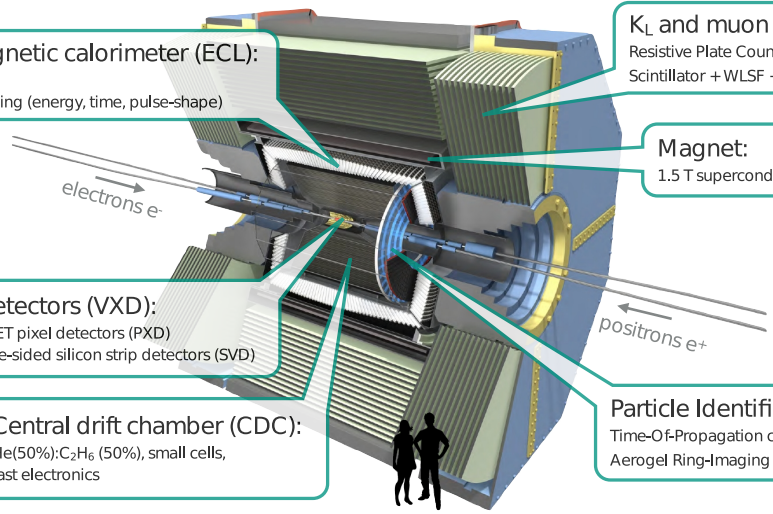
- Peak luminosity (June 22): $3.1 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$ (+50% vs. KEKB)
  - In part thanks to nano-beam scheme.
- Current recorded dataset: $\approx 428\,\text{fb}^{-1}$
  - $\approx 1/2$ Belle, $\approx$ BaBar
  - Aiming for 50x of Belle's dataset ($50\,\text{ab}^{-1}$)





The Belle II detector



Electromagnetic calorimeter (ECL):
CsI(Tl) crystals
waveform sampling (energy, time, pulse-shape)

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

Magnet:
1.5 T superconducting

Trigger:
Hardware: < 30 kHz
Software: < 10 kHz

Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detectors (SVD)

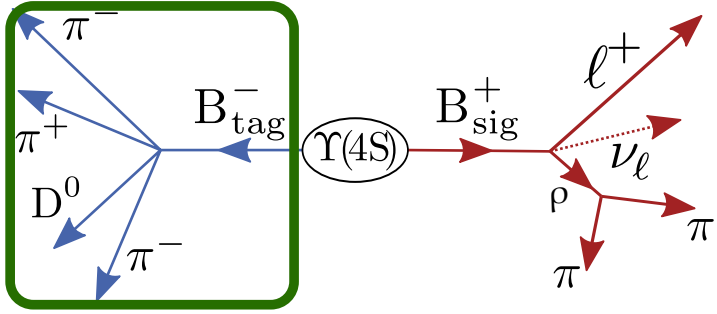
Central drift chamber (CDC):
He(50%):C_2H_6 (50%), small cells,
fast electronics

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

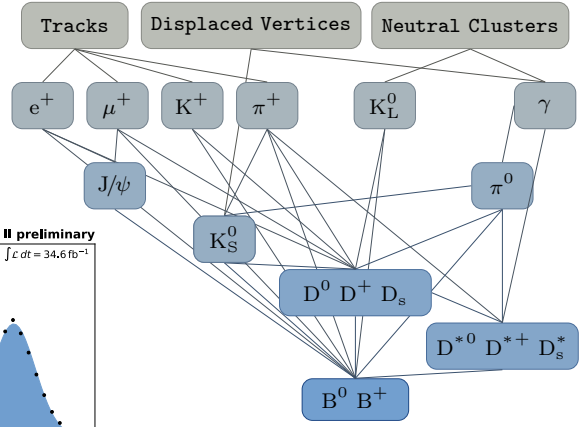
Experimental Techniques

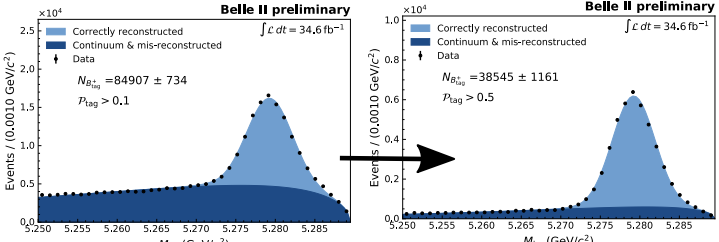
- $e^- e^+$ collisions “clean” compared to pp and initial state well known.
  - $\rightarrow$ knowing the second B gives you complete knowledge on kinematics
- Tagging: Reconstruct 2nd B (B_{tag}) e.g. with Full Event Interpretation (FEI). Keck, T. et al. Comput Softw Big Sci 3, 6



Experimental Techniques: FEI

- FEI: Use $\approx$ 200 BDT classifiers in 7 stages to reconstruct B mesons in $\mathcal{O}(10000)$ decay channels
- Cut on final classifier $\mathcal{P}_{tag}$ used to set working point



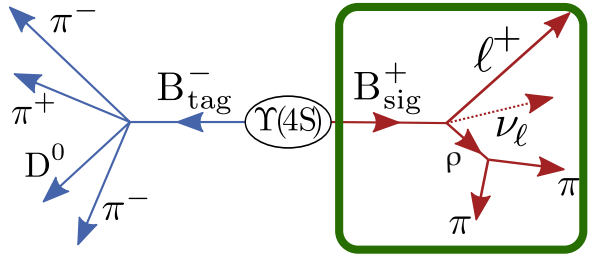


$\mathcal{P}_{tag} > 0.5$

arXiv:2008.06096

Event Reconstruction and Selection

- Use track & particle ID selections to determine track quality & particle species
- Create a ρ candidate from two pion-like tracks/clusters
- Combine ρ candidate with lepton-like track to B_{sig}
- Combine B_{sig} with B_{tag} from FEI to $\Upsilon(4S)$ candidate
- Enhance purity using remaining tracks & clusters



MVA Event Selection

Suppress $e^- e^+ \to q\bar{q}$ with BDT:

- Sphericity & thrust variables
- Only use most-discriminating variables as determined by re-training without each variable
- Cut at 0.8 rejects 95% of $q\bar{q}$ background and retains 93% of signal

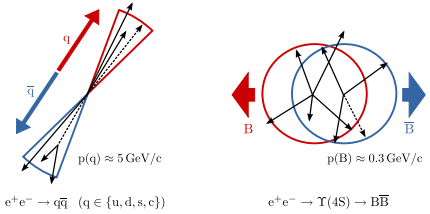
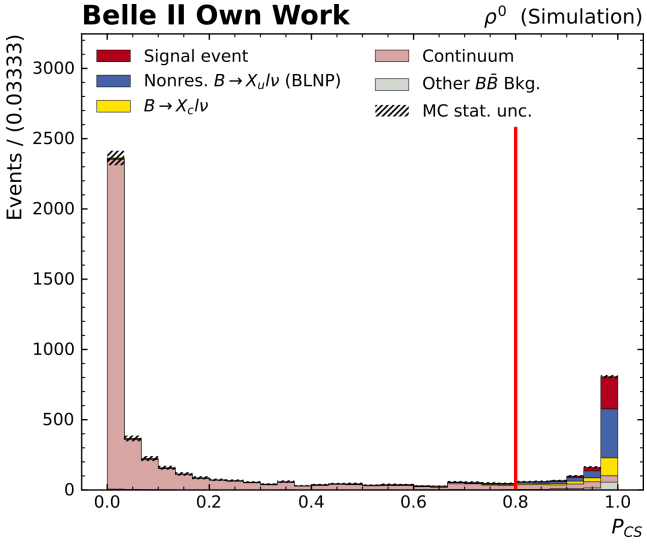


Illustration by M. Röhrken

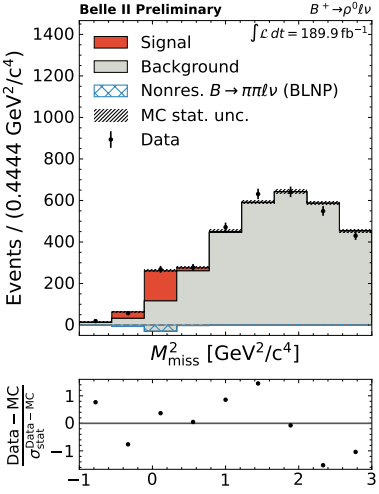


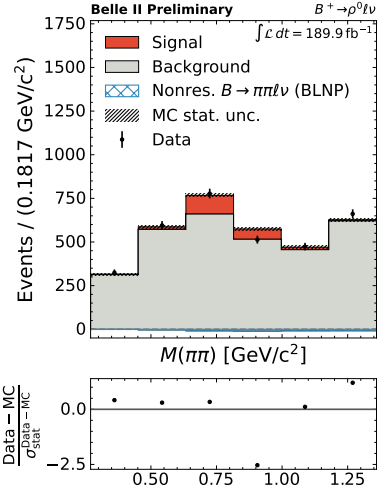
ICHEP 2022: Preliminary Result (arXiv:2211.15270)

- Signal extraction in di-pion mass $M_{\pi\pi}$ and missing mass

$$M^2_{\text{miss}} = (\mathbf{p_{CMS}} - \mathbf{p_{tag}} - \mathbf{p}_\rho - \mathbf{p}_\ell)^2$$

- Two-dimensional binned template fit with three components:
  - $B \to \rho \ell \nu_\ell$ signal
  - Non-resonant $B \to \pi\pi\ell\nu_\ell$
  - Other backgrounds (mostly $B \to X_c \ell \nu_\ell$)
- Large post-fit uncertainties from negative yield in non-resonant model





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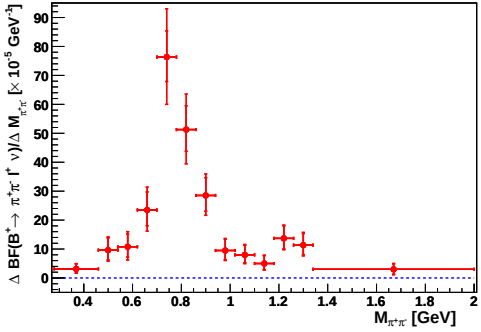
Source	% of $\mathcal{B}(B^0 \to \rho^- \ell^+ \nu_\ell)$	% of $\mathcal{B}(B^+ \to \rho^0 \ell^+ \nu_\ell)$
f_{+0}	1.2	1.2
FEI calibration	2.7	6.1
$N_{B\bar{B}}$	1.5	1.5
Reco. efficiency ϵ	0.5	0.3
Tracking	0.6	0.9
Lepton ID	0.7	0.5
Hadron ID	0.3	0.6
π^0 efficiency	4.4	—
$B \to f_2/f_0 \ell\nu_\ell$ BF	–	12.1
$B \to X_u \ell \nu_\ell$ BFs	2.8	4.8
$B \to X_c \ell \nu_\ell$ BFs	0.5	0.5
$B \to \rho \ell^+ \nu_\ell$ form factor	2.7	0.7
$B \to \pi\pi\ell\nu_\ell$ model	27.3	14.4
Total	28.2	20.5

Constraining the B $\to \pi\pi\ell\nu_\ell$ Background in $B^+ \to \rho^0\ell^+\nu_\ell$

- Complex backgrounds from other decays to two pions
  - $f_0(500)$, $f_0(980)$, $f_2(1270)$, $\rho^0(1450)$
  - Maybe non-resonant B $\to \pi\pi\ell\nu_\ell$
- These are not measured
  $\to$ extract in-situ using di-pion mass
- Constrain sum of all backgrounds and signal using input from Belle's 2021 inclusive measurement (`Belle 2021`) of B $\to \pi\pi\ell\nu_\ell$

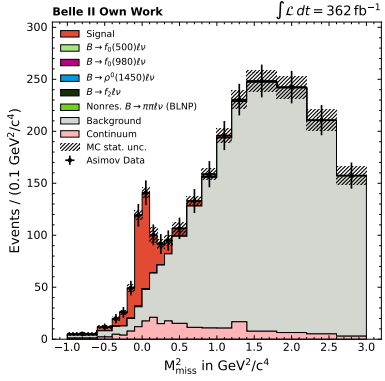
  Phys. Rev. D 103, 112001 (2021)

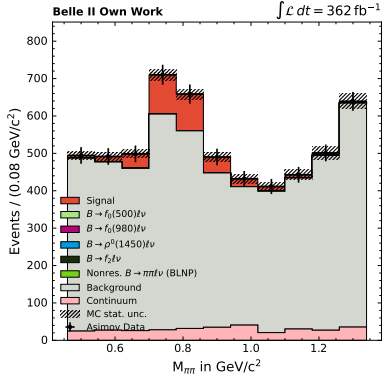


Di-pion mass in Belle's inclusive B $\to \pi\pi\ell\nu_\ell$

Fit Setup (Asimov Data)

- Two-dimensional fit with 8 templates:
  - 6 for resonant and non-resonant B $\to X_u \ell \nu_\ell$
  - 1 for all $B\overline{B}$ backgrounds (dominated by B $\to X_c \ell \nu_\ell$)
  - 1 for $q\bar{q}$ backgrounds (constrained from non-$\Upsilon(4S)$ data)
- Larger bins at edges of M^2_{miss}
- $M_{\pi\pi}$ bins matching `Belle 2021`





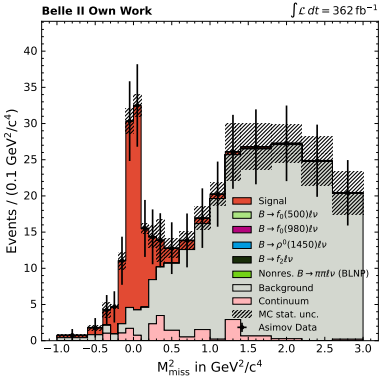
Fit Setup with Constraint (Asimov Data)

- Contributions from resonant, di-pion X_u backgrounds expected to be tiny but are unmeasured

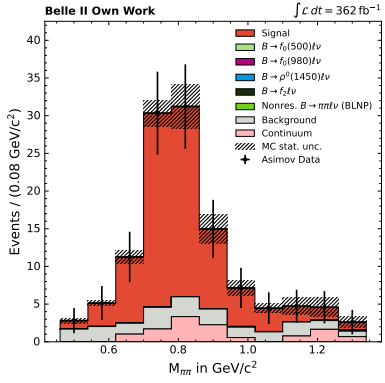
$\Rightarrow$ Float individual yields Y_i and constrain with `Belle 2021` by adding term to $-ln\mathcal{L}$:

$$\left(\frac{\mathcal{B}_{\texttt{Belle 2021}} - \sum_i^6 \epsilon_i \times \mathrm{Y}_i}{\sigma_{\mathcal{B}_{\texttt{Belle 2021}}}} \right)^2$$

- ϵ_i from simulation but allowed to vary within Gaussian prior



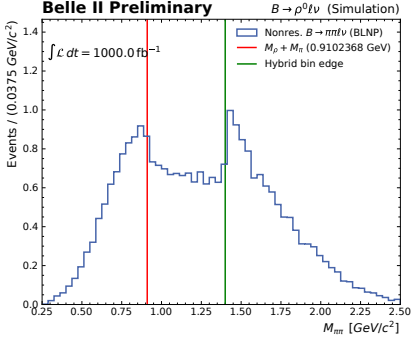
Bin 4: $0.7 < M_{\pi\pi} < 0.78\,\mathrm{GeV}$

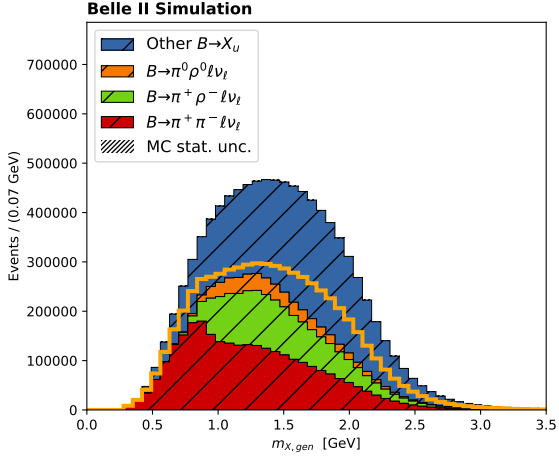


Bin 6: $-0.1 < M^2_{\mathrm{miss}} < 0.0\,\mathrm{GeV}^2$

Systematic Uncertainties: Non-resonant shape

- ICHEP2022: Uncertainty from fit with two model variants
- Now: Reweight distribution to halve the effect and allow fit to modify the shape



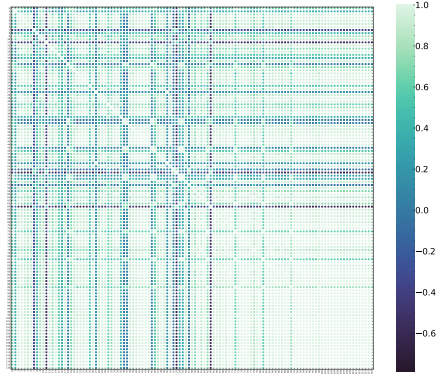


Non-resonant B $\to \pi\pi\ell\nu_\ell$ shape from PYTHIA

Systematic Uncertainties in the Fit

- Main sources:
  - MC sample statistics
  - Analysis methods: Particle ID and FEI
  - $B \to X\ell\nu_\ell$ branching fractions and form factors
  - Non-resonant $B \to \pi\pi\ell\nu_\ell$ decay model
- Procedure:
  - For each source, determine covariance matrix in bins of fit
  - In each template, sum covariance matrices assuming no correlation between sources

$\to$ $N_{bins} \times N_{template}$ nuisance parameters



Example: Correlation matrix for the background template

Up Next

$|V_{ub}|$ from B $\to \rho \ell \nu_\ell$

- BF in bins of momentum transfer + theory input gives access to $|V_{ub}|$
- At least three bins needed $\to$ challenging with Belle II's statistics

Average and fit by Bernlochner, Prim, Robinson $\to$