Status and Future Development of the Full Event Interpretation Algorithm at Belle II

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Belle II

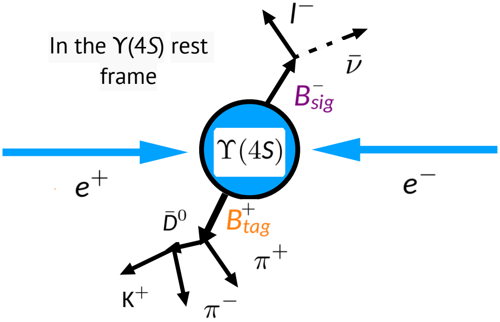
18th FPCP 2020 A TOXA JUNE 8-12

DESY.

Event in Belle II

- Asymmetric $e^+ e^-$ collision at $\Upsilon(4S)$ resonance
- $\Upsilon(4S) \to B^+B^-, B^0\bar{B}^0$ with $\mathcal{B} > 96\%$
- If possible, reconstructs one of the B-mesons in either semileptonic or hadronic decay chains (B_{tag})
- Properties of the other B can be studied (B_{sig})
- Flavour constraint: $B^+_{tag} \to B^-_{sig}$
- Kinematically constrained system with hadronically tagged event: $\vec{p}_\nu + \vec{p}_l = \vec{p}_{e^+e^-} - \vec{p}_{B_{tag}}$

Example of mode with hadronic B_{tag}



What is Full Event Interpretation (FEI)?

- Flexible multivariate tagging algorithm developed for *B*-meson reconstruction in Belle II
  [*Keck, T. et al. Comput. Softw. Big. Sci. (2019) 3: 6*]
- **Task**: Correctly identifying one *B* decay (B_{tag}) allowing for detailed investigation of the other *B* (B_{sig})
- **Use in *B*-physics**: Especially useful when studying modes with missing energy (modes with one or more neutrinos, specific dark matter searches)
- Successor of the Belle Full Reconstruction [*Feindt, M. et al. Nucl.Instrum.Meth.A 654 (2011) 432-440*]
- Can be used on Belle data set

PHYSICAL REVIEW LETTERS **124,** 161803 (2020)

Editors' Suggestion

Measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with a Semileptonic Tagging Method

The Belle Collaboration, Phys. Rev. Lett. 124, 161803

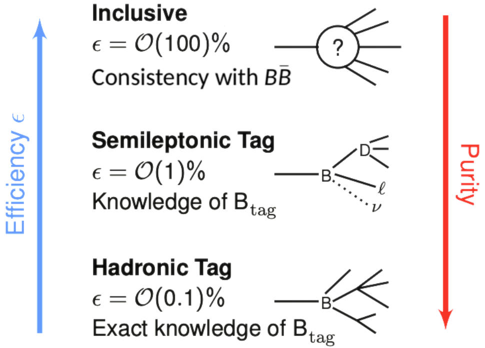
PHYSICAL REVIEW D **98,** 112016 (2018)

Search for the rare decay of $B^+ \to \ell^+ \nu_\ell \gamma$ with improved hadronic tagging

The Belle Collaboration, Phys. Rev. D 98, 112016

Tagging Techniques in Belle II

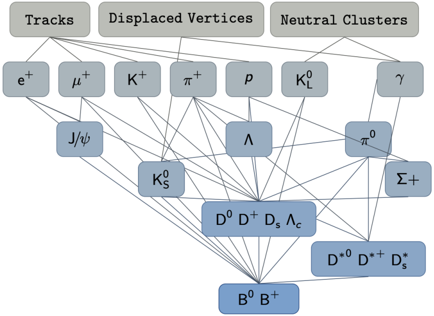
- Generic FEI techniques include reconstruction of the B-meson candidate with
  - Semileptonic Tagging
    $\mathcal{B}(B^+ \to \text{SL decays}) \approx 20\%$
  - Hadronic Tagging
    $\mathcal{B}(B^+ \to \text{Had decays}) \approx 15\%$
- Trade-off between efficiency, purity, and knowledge of missing kinematics
- Another possibility: dedicated signal-specific FEI



How Does FEI Work?

- FEI uses hierarchical approach to reconstruct $\mathcal{O}(200)$ decay channels via $\mathcal{O}(10^4)$ decay chains
- Firstly tracks, neutral clusters and displaced vertices are interpreted as final state particles (FSPs) e.g $e^{\pm}$, $\mu^{\pm}$, $K^{\pm}$, ...
- FSPs are then combined into intermediate particles until *B* candidates are formed
- Each unique particle has its own multivariate classifier which quantifies the correctness of reconstruction based on input features such as four-momentum, vertexing information...

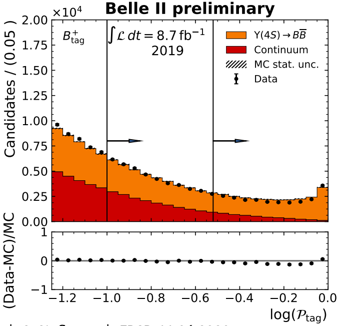
Schematic view

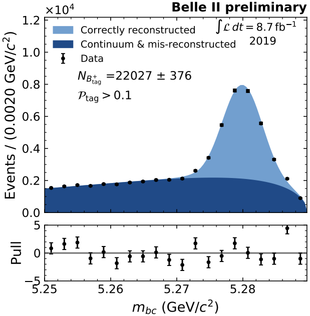


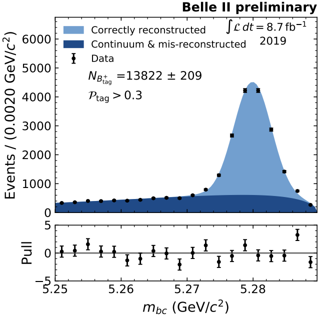
- Usually only one *B*-meson candidate (the highest probability) is kept
- **Recent development:** Inclusion of baryonic modes $[\mathcal{B}(B^+/B^0 \to \text{baryons}) \approx 5.3/2.4 \times 10^{-3}]$

Hadronic FEI Performance in Early Belle II Data

- Evaluated with efficiency-purity scan
- **Tag-side efficiency**: *N* of correct B_{tag} candidates / *N* of $\Upsilon(4S)$
- **Purity**: *N* of correct B_{tag} candidates / *N* of B_{tag} candidates
- **Correct B_{tag} yield**: Fit to $m_{bc} = \sqrt{\frac{s}{4} - p^{*2}_{B_{tag}}}$
- $p^{*2}_{B_{tag}} :=$ three-momentum of B_{tag} candidate, $\sqrt{s} :=$ beam energy (Υ(4S) frame)
- *N* of correct B_{tag} candidates can be controlled with *B* classifier value: $\mathcal{P}_{B_{tag}}$

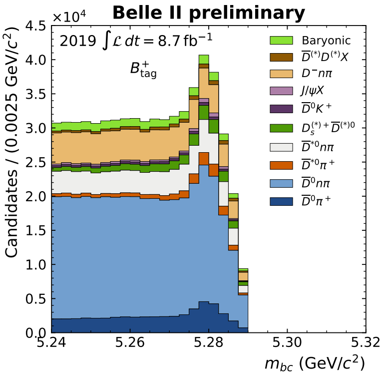


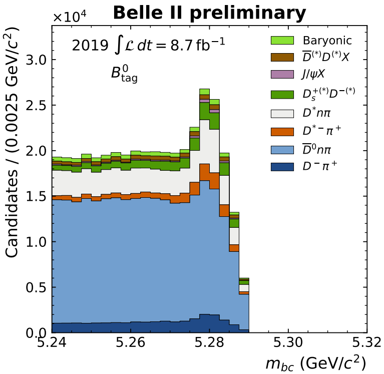




Effect of Baryonic Modes on Hadronic FEI Performance

- Inclusion of baryonic modes improves hadronic tag-side efficiency by 3% (2%) for $B^+ (B^0)$
- Below m_{bc} distribution highlighting contributions from several decay modes for B^+ and B^0 in early Belle II Data

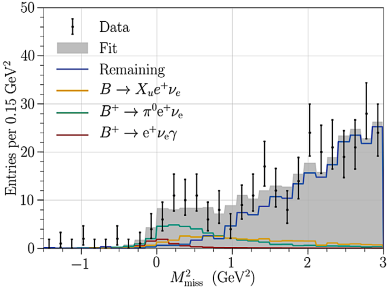




Generic FEI Performance Comparison

MC tag-side efficiency @10% purity	Had. B^+/B^0 [%]	SL. B^+/B^0 [%]
Full Reconstruction Belle	0.28/0.18	0.67/0.63
FEI Belle	0.76/0.46	1.80/2.04
N of correct B_{tag} per 1 fb^{-1} in Belle (FEI)	8350/5060	19800/22440

- FEI **outperforms** Full Reconstruction
- Search for $B \to l\nu\gamma$:
  - Analyses with both Belle algorithms
  - FEI improved sensitivity



The Belle Collaboration, Phys. Rev. D 98, 112016

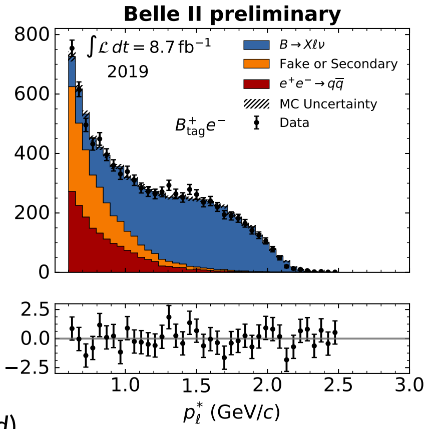
Hadronic FEI Calibration in Early Belle II Data

Calibration: difference in tagging efficiency between data and MC

- Sources: hadronic branching fraction ratios, simulation of detector, dynamics of the hadronic decays...
- Calibration Strategy: measure signal-side yield in well-known, high $\mathcal{B}$ channel

Steps:

- Reconstruct $B_{sig} := B \to Xl\nu$ with specific selection
- Extract the number of signal events: Fit to p_l^*
- Derive calibration factors: $\epsilon_{(DATA/MC)}$
- **Preliminary** $\epsilon_{(DATA/MC)}(B^+_{tag}e^-) \approx 0.60$ (*to be improved*)
- Calibration factors used to correct the tag-side efficiency in physics measurements



Upcoming FEI-related Work

Calibration plans:

- Hadronic FEI calibration with $B \to D^{(*)} l\nu$
- Semileptonic FEI calibration

Expected physics results with FEI:

- Observation of $B \to D^{(*)} l\nu$, $J/\psi\, X$, $B \to \pi l\nu$
- $B \to l\nu$, $B \to X_u l\nu$, $B \to h\nu\nu$

Future FEI Developments:

- FEI for $\Upsilon(5S)$ resonance
  - $\Upsilon(5S) \to B^{(*)} = 76.2\%$, $\Upsilon(5S) \to B_s^{(*)} = 20.1\%$
  - Physics target: $B_s^0 \to \tau\tau$, $B_s^0 \to l\tau$, $B_s^0 \to \phi\nu\nu$
- Deep classifiers in FEI instead of FastBDTs [*Keck T., Comput. Softw. Big. Sci. 1, 2 (2017)*], exploration of graph convolutional networks [*Kipf N. T, Welling M. 2016*]

Used B_s^0 channels

$B_s^0 \to D_s^- D_s^+$
$B_s^0 \to D_s^{*+} D_s^-$
$B_s^0 \to D_s^{*-} D_s^{*+}$
$B_s^0 \to D_s^+ D^-$
$B_s^0 \to D^{*-} D_s^+$
$B_s^0 \to D_s^{*+} D^-$
$B_s^0 \to D_s^- K^+$
$B_s^0 \to D_s^- \pi^+$
$B_s^0 \to D_s^{*-} \pi^+$
$B_s^0 \to D_s^- \pi^+ \pi^+ \pi^-$
$B_s^0 \to D_s^- D^0 K^+$
$B_s^0 \to D_s^- \pi^+ \pi^0$
$B_s^0 \to D_s^- D^0 K^+ \pi^0$
$B_s^0 \to D_s^- D^{*0} K^+$
$B_s^0 \to D_s^{*-} D^0 K^+$
$B_s^0 \to D_s^{*-} D^{*0} K^+$
$B_s^0 \to D_s^{*-} \pi^+ \pi^+ \pi^-$
$B_s^0 \to D_s^{*-} \pi^+ \pi^0$
$B_s^0 \to D_s^{*-} D^0 K^+ \pi^0$

Conclusion

- Generic FEI algorithm now includes baryonic modes
- FEI performance with early Belle II data corresponding to $\mathcal{L} = 8.7\ \text{fb}^{-1}$ was presented
- FEI performs significantly better than its Belle predecessor
- Calibration with hadronic tag in early Belle II data is being performed
- Exciting physics analyses utilising FEI algorithm such as $B \to K^{(*)}\nu\nu$ are under-way
- New developments of FEI algorithm can open door to B_s^0 physics in Belle II

Backup