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

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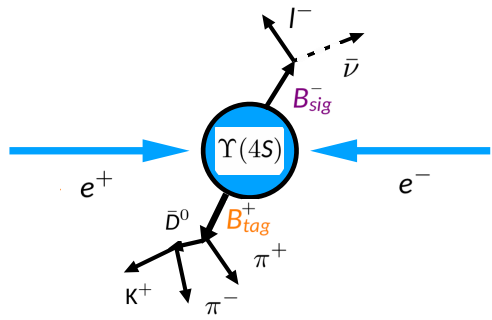
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Event in Belle II

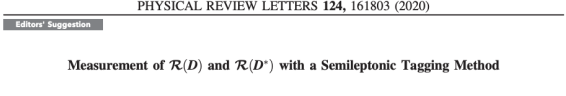
- $e^+ e^-$ collision at $\Upsilon(4S)$ resonance
- $\Upsilon(4S) \to B^+B^-, B^0\bar{B}^0$ with $\mathcal{B} > 96\%$
- If possible, reconstructs one of the B meson in either semileptonic or hadronic decay chains (B_{tag})
- Properties of the other B can be studied (B_{sig})
- Flavour constraint: $B^+_{tag} \to B^-_{sig}$
- 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)?

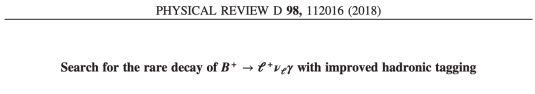
- Flexible multivariate tagging algorithm developed for *B*-meson reconstruction in Belle II
  Keck, T. et al. Comput. Softw. Big. Sci. (2019) 3: 6
- **Task**: Correctly identifying one *B* decay (B_{tag}) allowing for detailed investigation of the other *B* (B_{sig})
- **Use in *B*-physics**: Especially 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

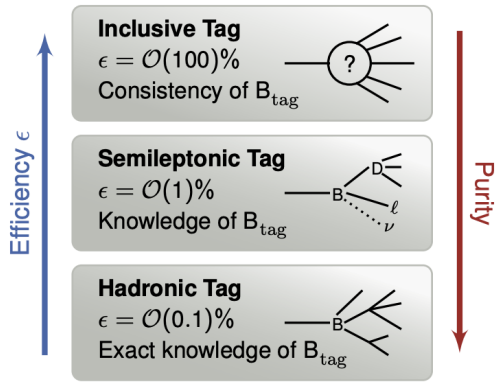

PHYSICAL REVIEW D **98,** 112016 (2018)

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

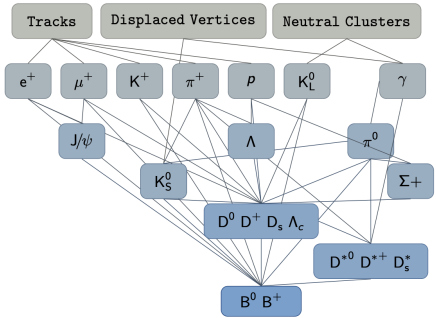
- Generic FEI techniques include reconstruction of the *B*-meson candidate with
  - Semileptonic Tagging
  - Hadronic Tagging
- Trade-off between efficiency, purity, and knowledge of missing kinematics
- Another possibility: dedicated signal-specific FEI



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...

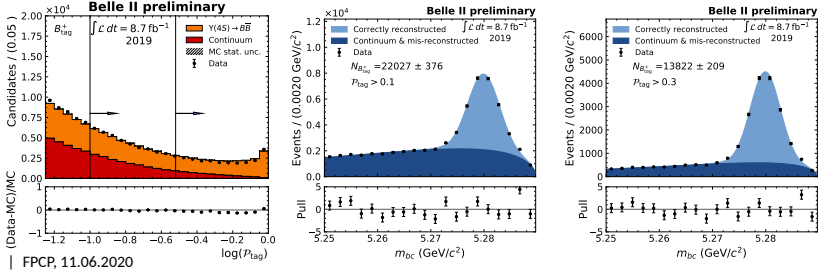
Schematic view



- Usually only one *B*-meson candidate with the highest probability is kept
- **Recent development:** Inclusion of baryonic modes

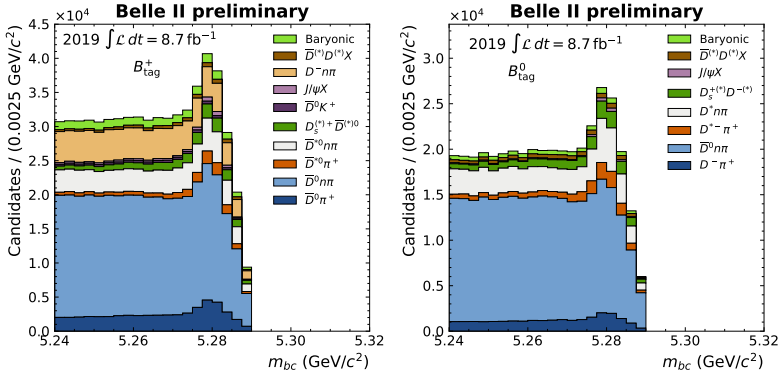
Hadronic FEI Performance in Early Belle II Data

- 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**

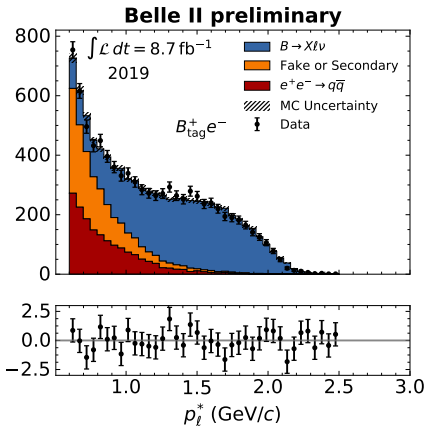
@10% Purity	Had. B^+/B^0 [%]	SL. B^+/B^0 [%]
Full Reconstruction Belle	0.28/0.18	0.67/0.63
FEI Belle	0.76/0.46	1.80/2.04
FEI Belle II **preliminary**	**0.58/0.37**	-
corresponding to 8.7 fb^{-1}		
N of correct B_{tag} per 1 fb^{-1} in Belle II	6380/4070	-

- FEI outperforms Full Reconstruction
- Lower efficiency of FEI Belle II compared to Belle due to lower reconstruction efficiency

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** $\epsilon_{(DATA/MC)}(B^+_{tag}e^-) = 0.61 \pm 0.02$
- 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/ψ 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, exploration of graph convolutions

Used B_s^0 channels

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

Conclusion

- Generic FEI algorithm now includes baryonic modes
- FEI performance with early Belle II data corresponding to $\mathcal{L} = 8.7$ 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 are under-way
- New developments of FEI algorithm can open door to B_s^0 physics in Belle II

Backup