Measuring $B(B^- \to D^{**0}\pi^-)$ using FEI Hadronic Tagging

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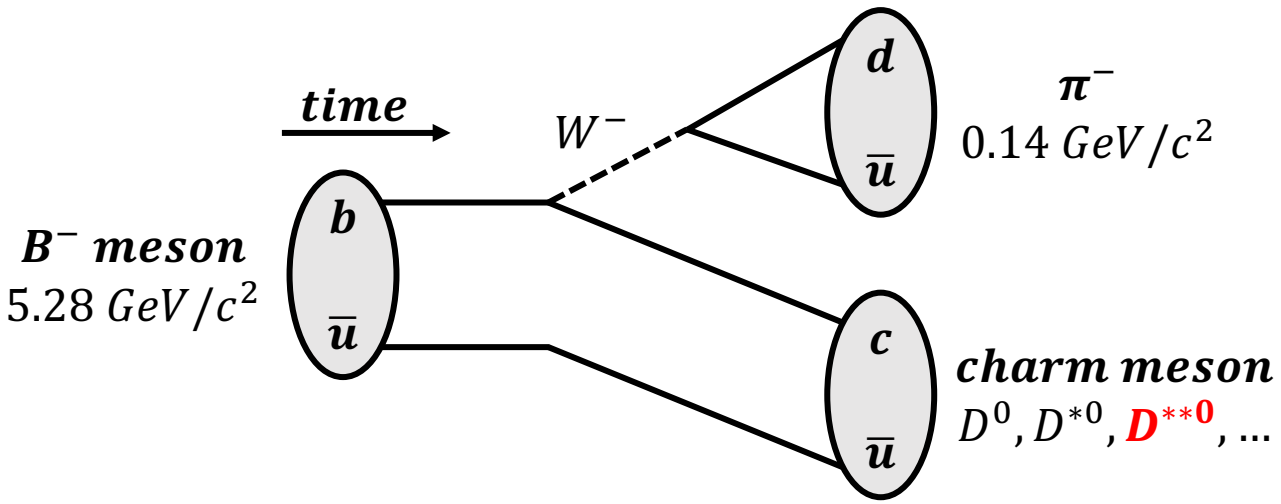
Belle 2 Summer Workshop at Virginia Tech

June 26, 2025

University of Cincinnati

Decay Process



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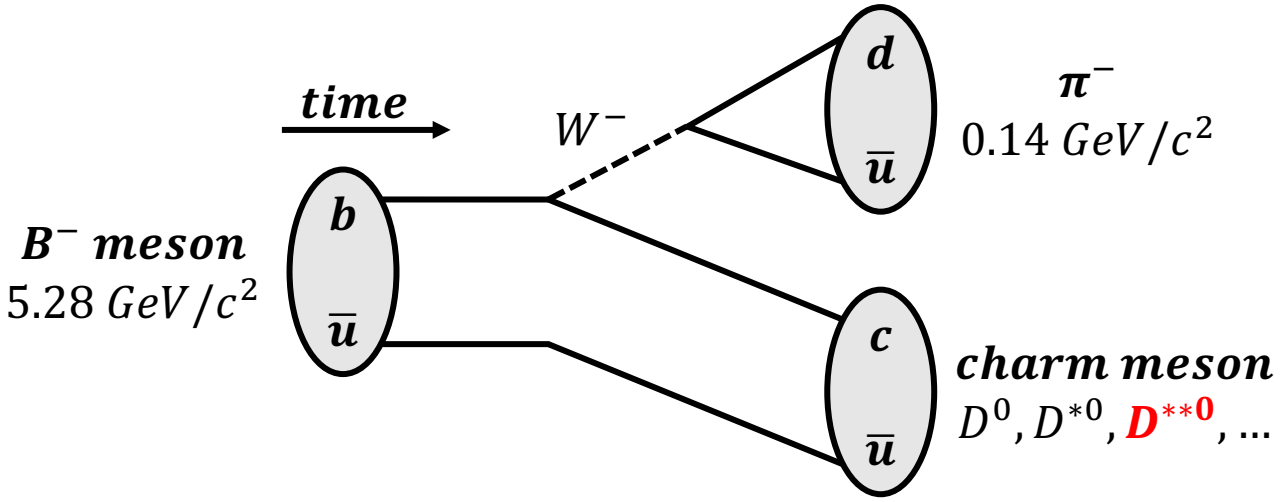

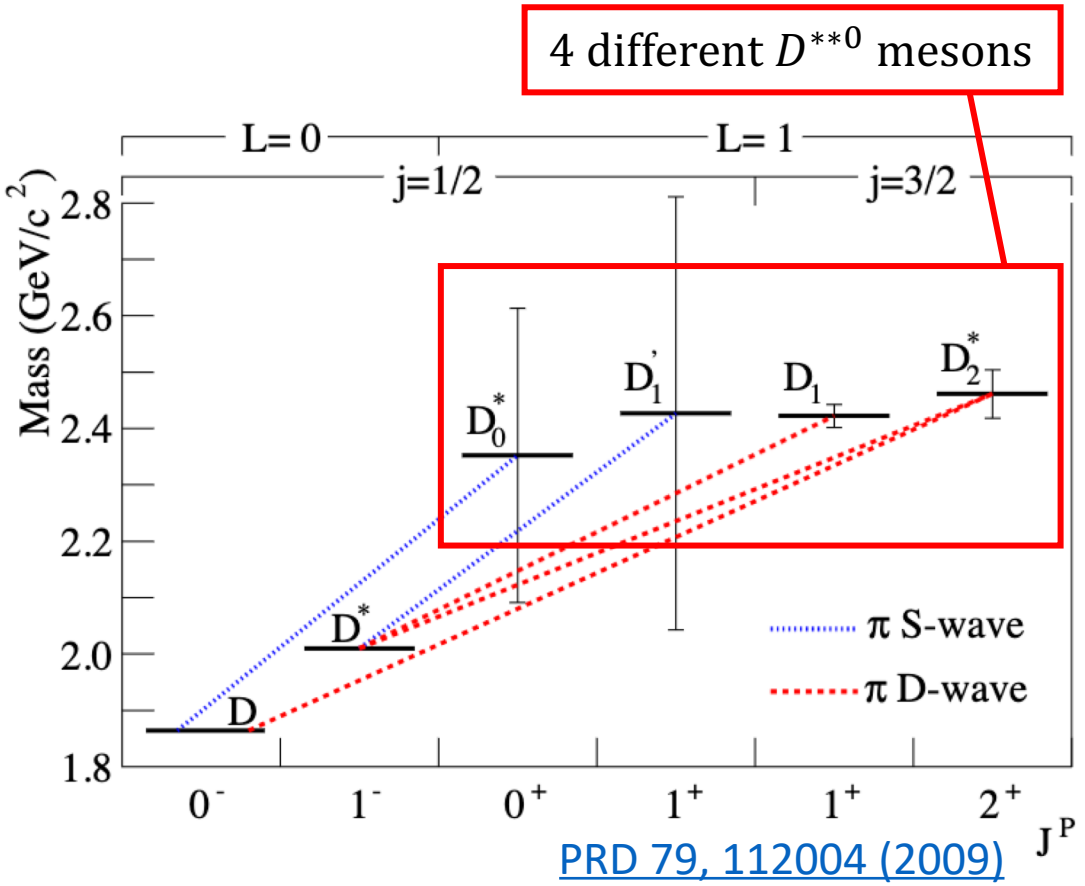

PRD 79, 112004 (2009)

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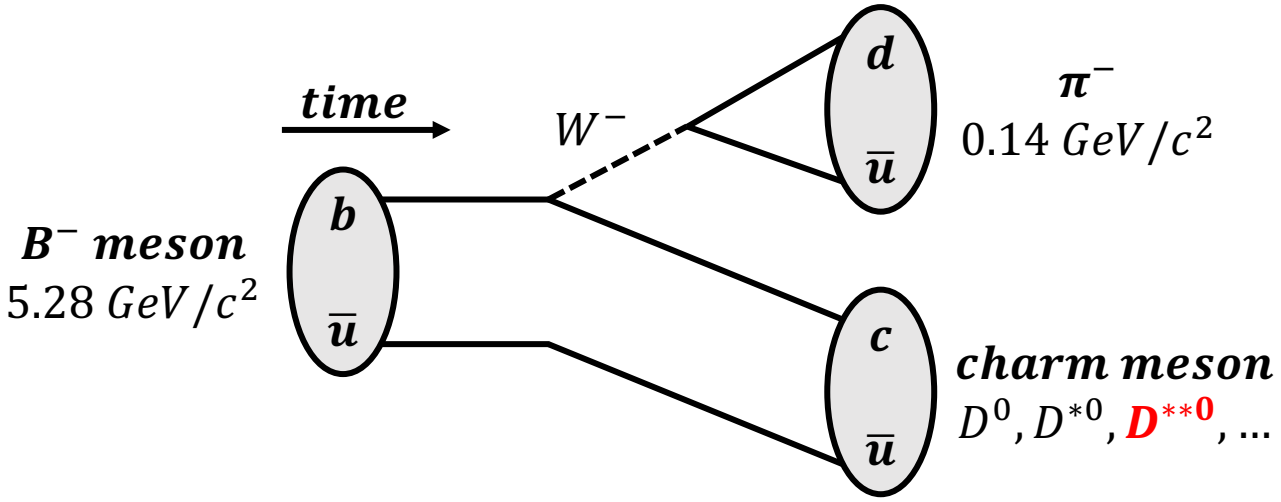
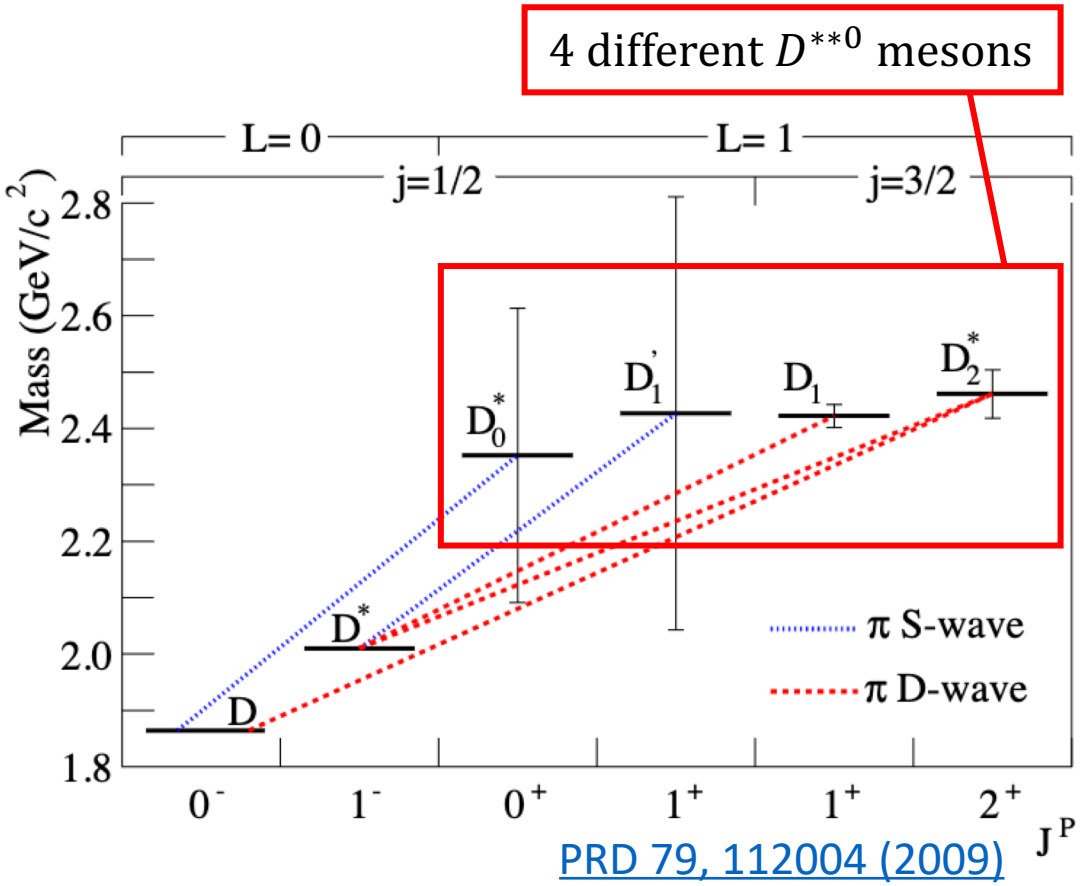


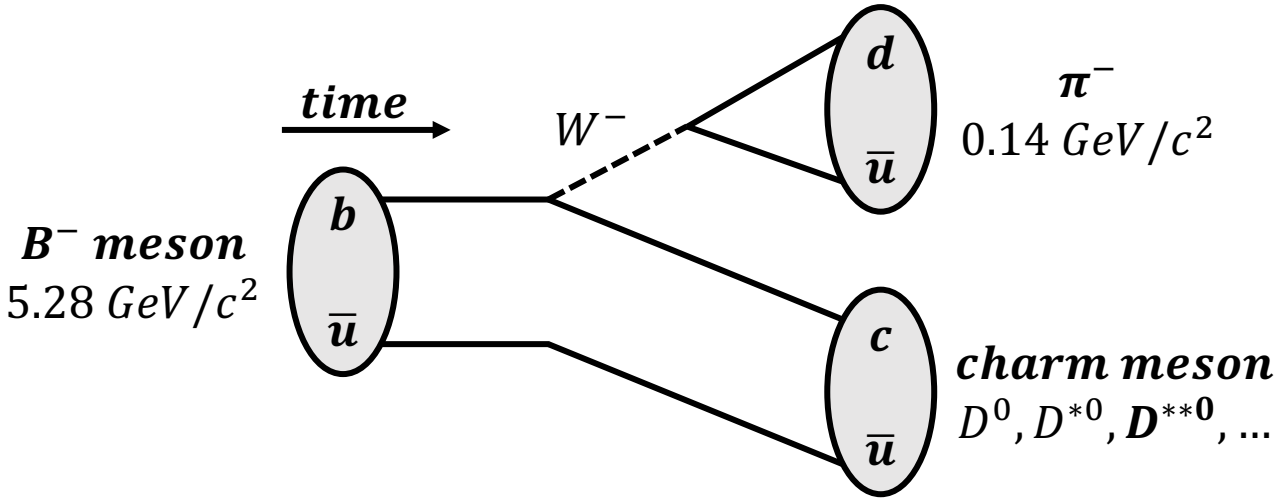


PRD 79, 112004 (2009)

Decay Mode		Branching Fraction
Γ_{54}	$D^0\pi^-$	$(4.61 \pm 0.10)\times10^{-3}$
Γ_{131}	$D^{*0}\pi^-$	$(5.17 \pm 0.15)\times10^{-3}$
Γ_{151}	Combined $D^{**0}\pi^-$	$(5.6 \pm 1.2)\times10^{-3}$
		Particle Data Group

We want to measure four $D^{**0}\pi^-$ branching fractions individually!

Motivation



Exclusive $|V_{cb}| = (39.10 \pm 0.50) \times 10^{-3}$
PRD 107, 052008 (2023)
Inclusive $|V_{cb}| = (41.97 \pm 0.48) \times 10^{-3}$
JHEP 02 (2024) 206

- $|V_{cb}|$ is determined through semileptonic decays
- Tension between inclusive and exclusive $|V_{cb}|$

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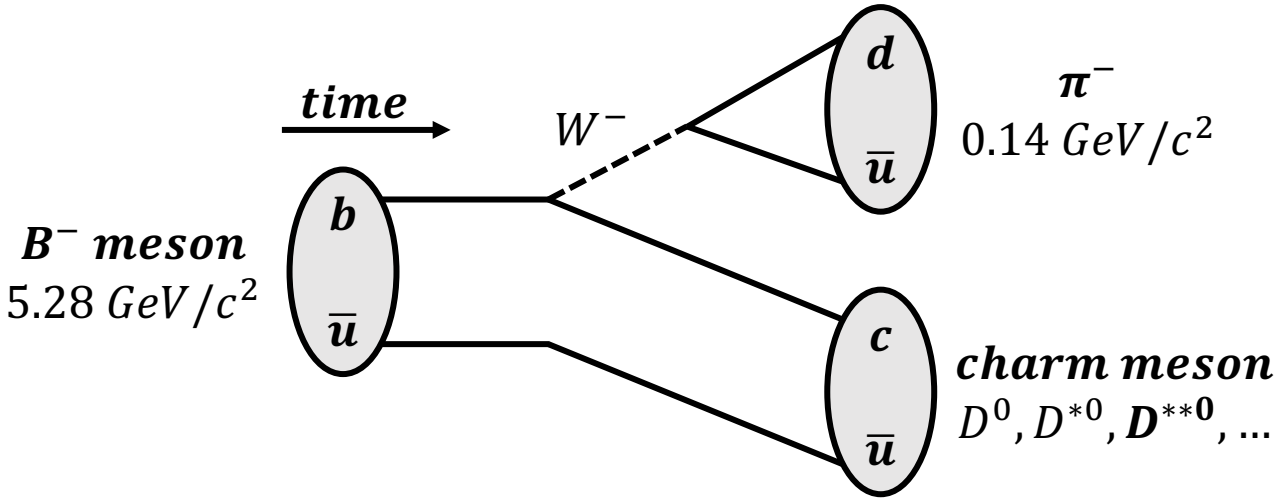

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  - $B \to D^{**} l\, nu$ not well known

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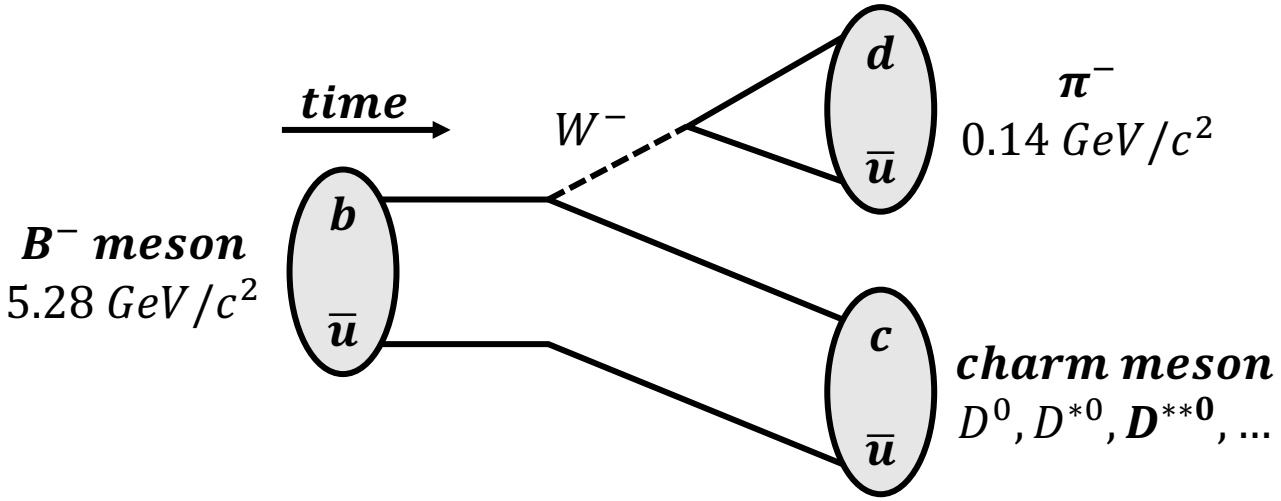

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- Tension between inclusive and exclusive $|V_{cb}|$
- Possibly from poor modeling of higher excited charm states
  - $B \to D^{**} l\, nu$ not well known
- $B \to D^{**}\pi$ can help understand $B \to D^{**} l\, nu$ at corresponding kinematic point

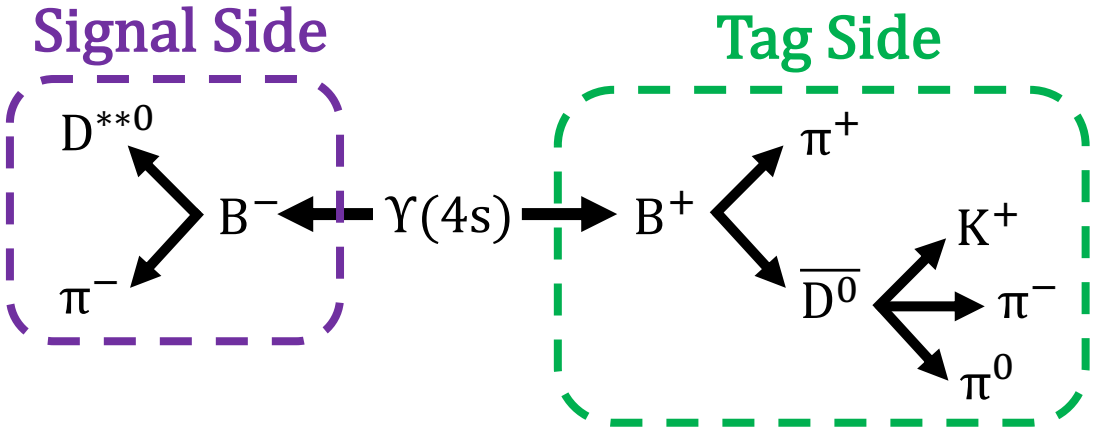
Analysis Strategy

- Use Full Event Interpretation (FEI) to hadronically tag charged B mesons
- Train Continuum Suppression and optimize with FEI
- Fit a distribution such as Mbc to extract tag B number

- Use tag B and pion from signal B decay to calculate missing mass
- Fit missing mass distribution for each D^{**} peak
  - Extract currently unknown absolute branching fractions

B Meson Tagging

- Full Event Interpretation (FEI)
  - Hadronic tagging
  - Kinematic constraint on signal B



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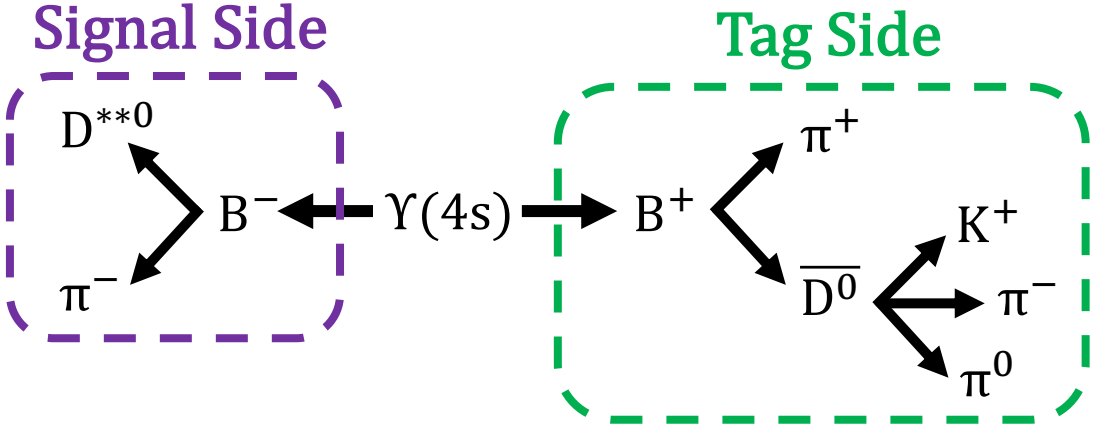

***tag B* selection**

$5.27 < \mathrm{Mbc} < 5.29\ GeV/c^2$

$-0.1 < \Delta E < 0.05\ GeV$

FEI MVA output > 0.001

FEI MVA Rank $= 1$

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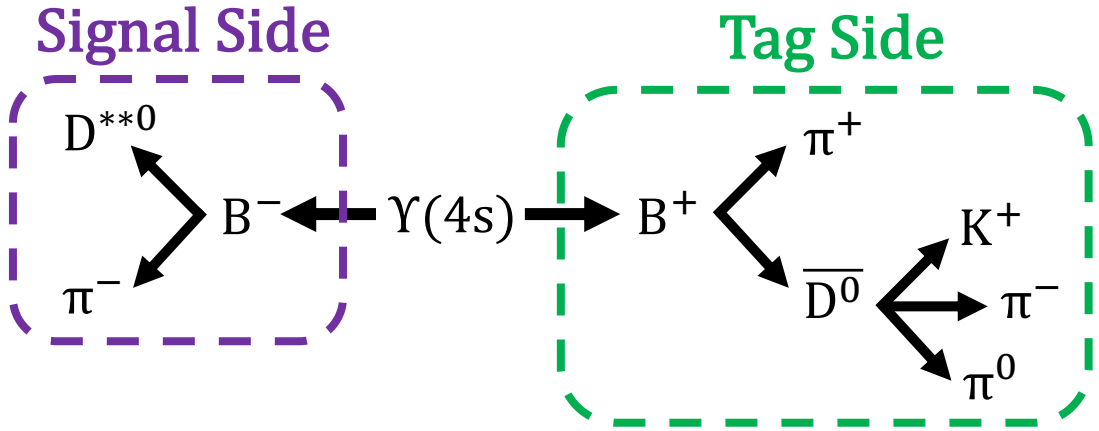

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$$M_{bc} = \sqrt{{E_{beam}}^2 - \left|\overrightarrow{p_{tag}}\right|^2}$$

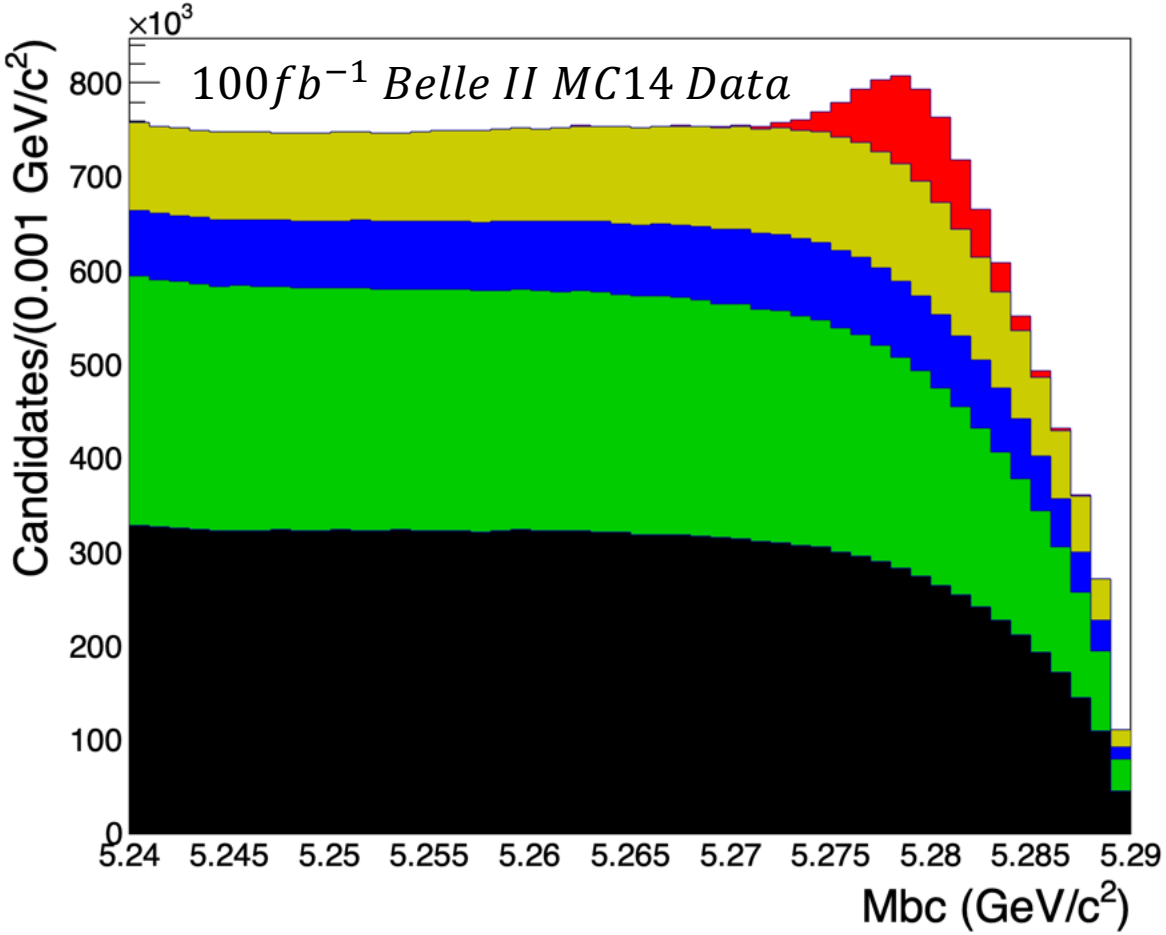
True B^+B^- tags

Fake B^+B^- tags

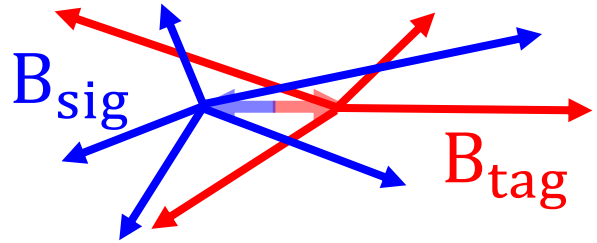
Fake $B^0\overline{B^0}$ tags

$c\bar{c}$ background

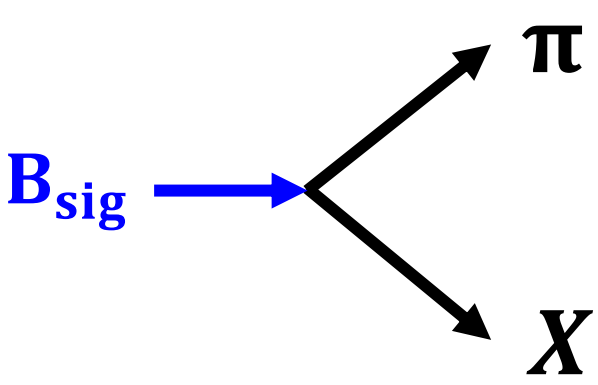
uds background



Missing Mass

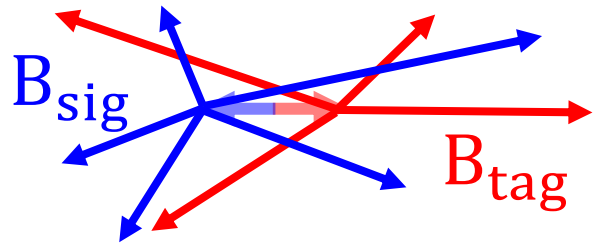


- With best candidate tag B
  - Particles not combined to make tag B → from signal B
  - Look for $D^{**0}\pi^-$ in signal B decay



Find π on signal side
Measure E_π and $\overrightarrow{p_\pi}$
Cuts: pionID > 0.6 , $p_{\pi^-} > 1.5 GeV/c$,
dr $< 0.5 cm$, |dz| $< 2 cm$, $17° < \theta < 150°$

Missing Mass



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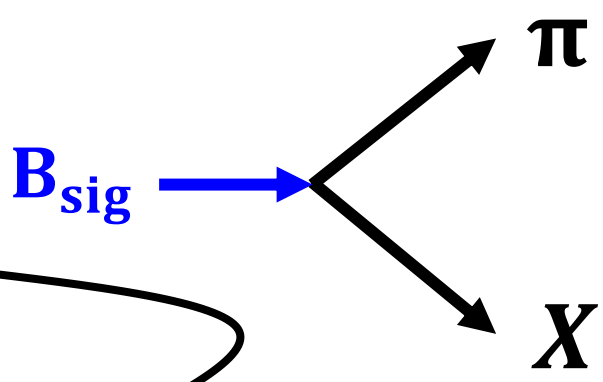
In Y(4s) center of mass frame:

$$\overrightarrow{p_{sig}} = -\overrightarrow{p_{tag}}$$
$$E_{sig} = E_{beam}$$



$$\overrightarrow{p_X} = \overrightarrow{p_{sig}} - \overrightarrow{p_\pi}$$
$$E_X = E_{sig} - E_\pi$$

$$M^2 = E^2 - |\vec{p}|^2$$

$$\boldsymbol{M_{missing} = \sqrt{(E_{beam} - E_\pi)^2 - \left|-\overrightarrow{p_{tag}} - \overrightarrow{p_\pi}\right|^2}}$$

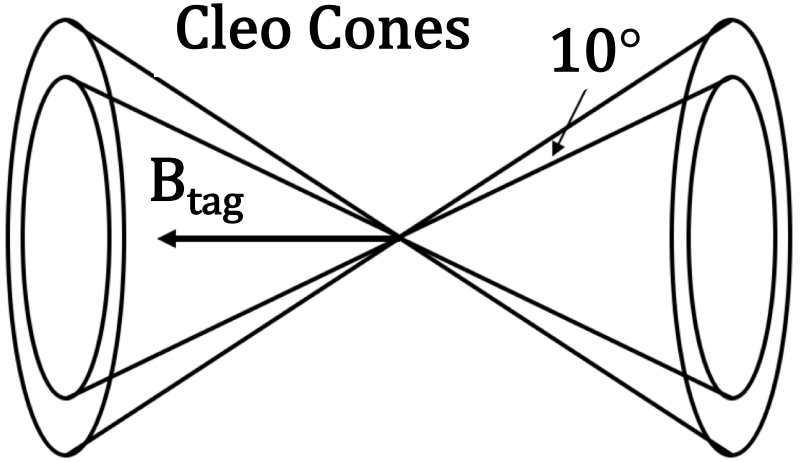
Continuum Suppression (CS) with FastBDT

- 50fb^{-1} for training and 50fb^{-1} for validation

$$R_l = \frac{H_l}{H_0} \qquad H_l = \sum_{i,j} \frac{|\vec{p_i}||\vec{p_j}|}{s} P_l(cos\theta_{ij})$$

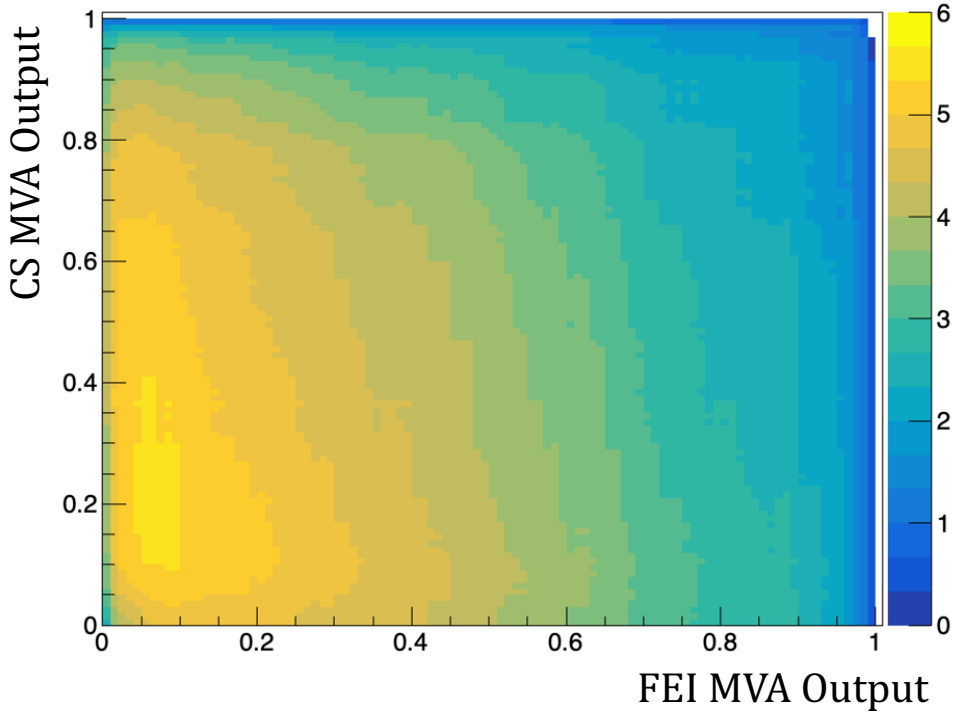
Variables

- R2 is the second Fox Wolfram moment
- 16 Kakuno Super Fox Wolfram (KSFW) moments
- KSFW(mm2) is the missing mass squared (missing from tag B and Rest of Event)
- KSFW(et) is transverse energy
- Cleo Cones, a set of 9 cones summing particle energy in 10° sections
  - Runs from 0° (aligned with the B_{tag}) and 90° (transverse to the B_{tag})
  - Sums the forward and backward direction
- cosTBz angle between B_{tag} thrust and the z-axis
- cosTBTO angle between the B_{tag} thrust and ROE thrust
- thrustBm B_{tag} thrust magnitude
- thrustOm ROE thrust magnitude



Significance Optimization

- Estimated significance of $D^{**0}\pi^{-}$ signal vs cuts in FEI MVA output and CS MVA output
- Significance $= \frac{N_{sig}}{\sqrt{N_{sig}+N_{bkg}}}$ in signal box:
  $5.27 < M_{bc} < 5.29$ GeV/c^2 and $2.2 <$ Missing Mass < 2.8 GeV/c^2
- 2D figure of merit optimizes significance to find best cuts in the FEI MVA output and CS MVA output



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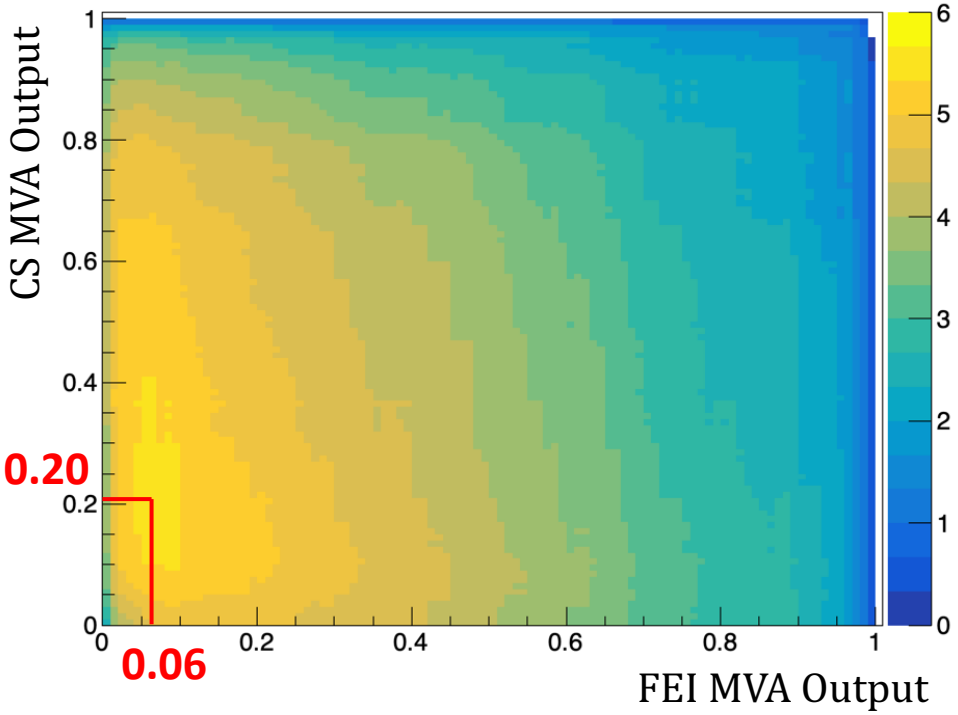
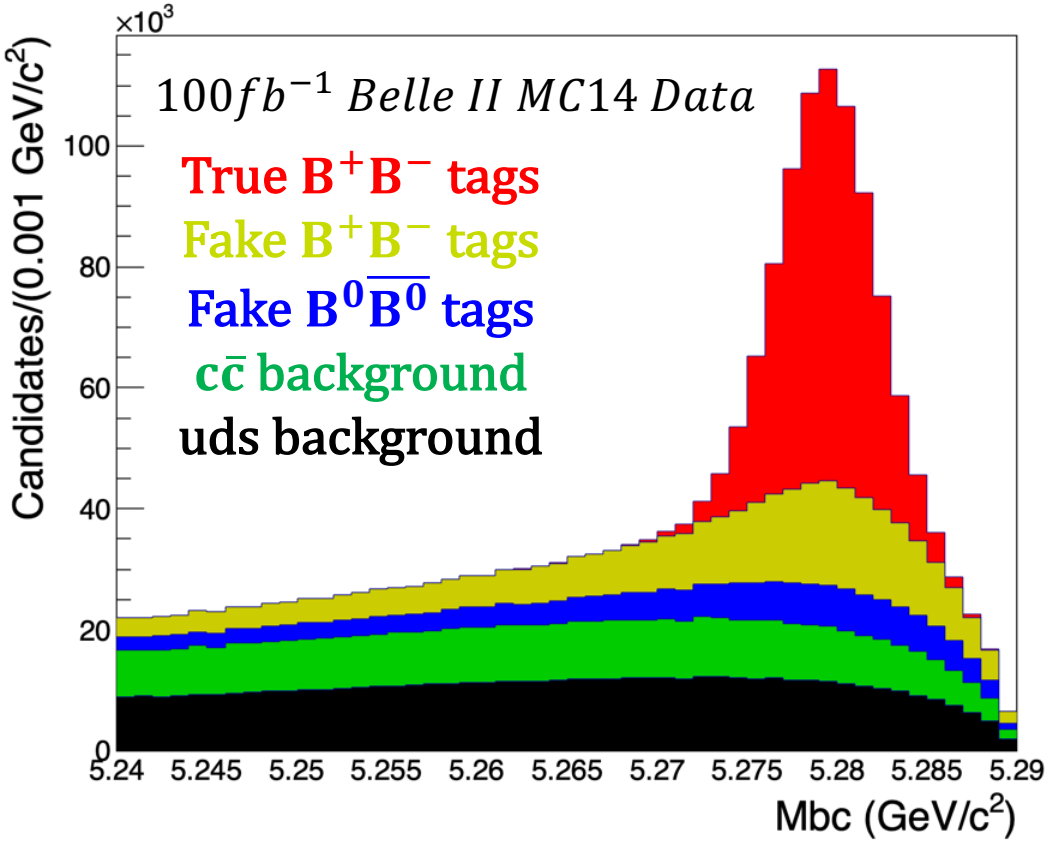
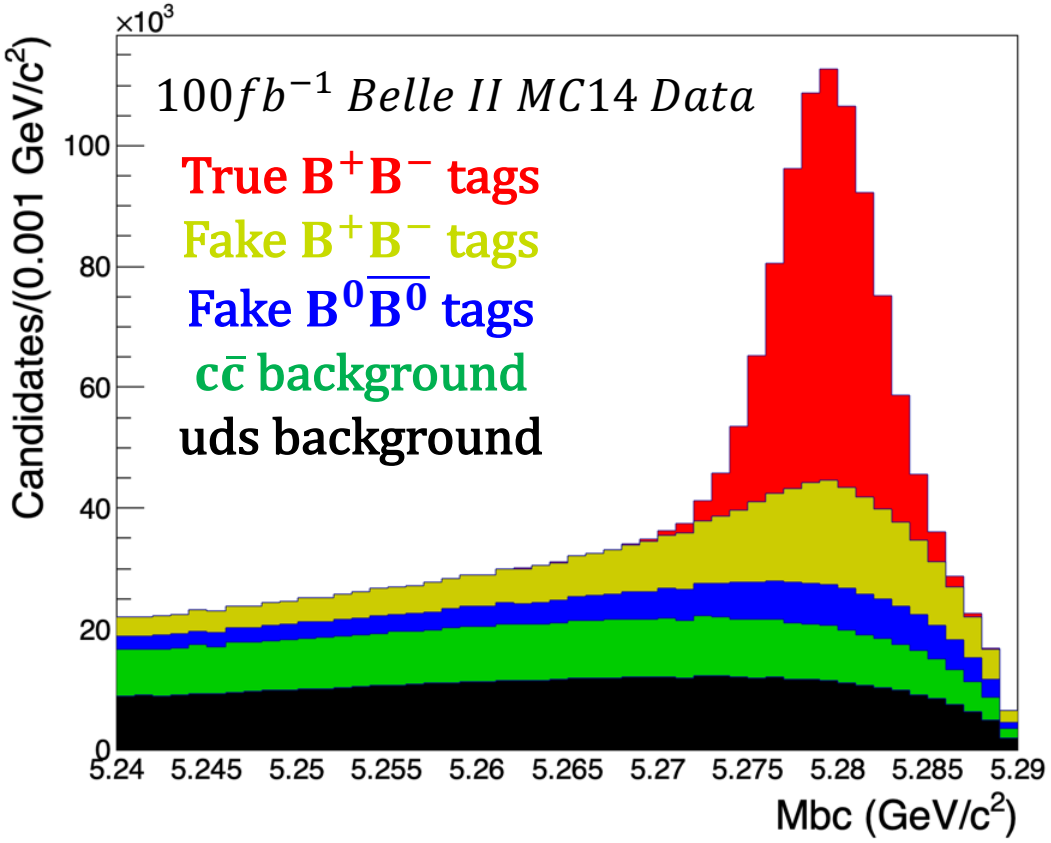




Issues with Standard FEI Trainings

- isSignal misses good FEI tags using standard FEI training (well known issue)
- Special variables exist to help… but don't recover all good tags



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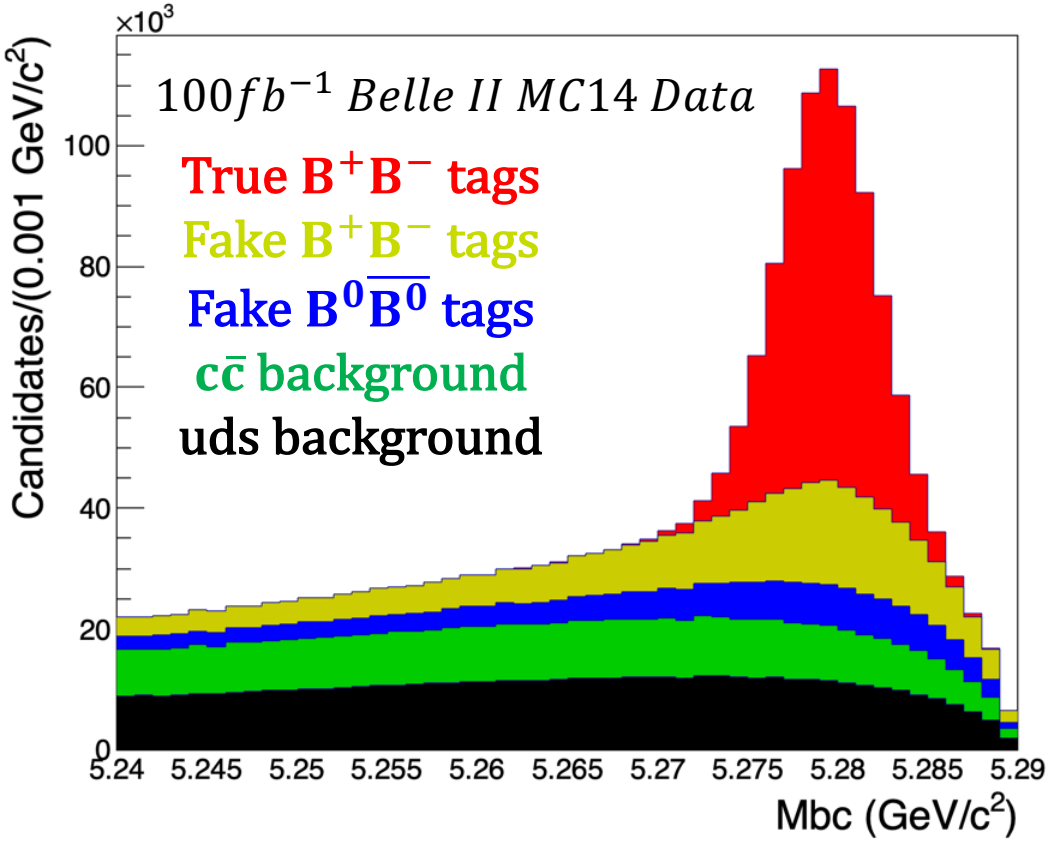

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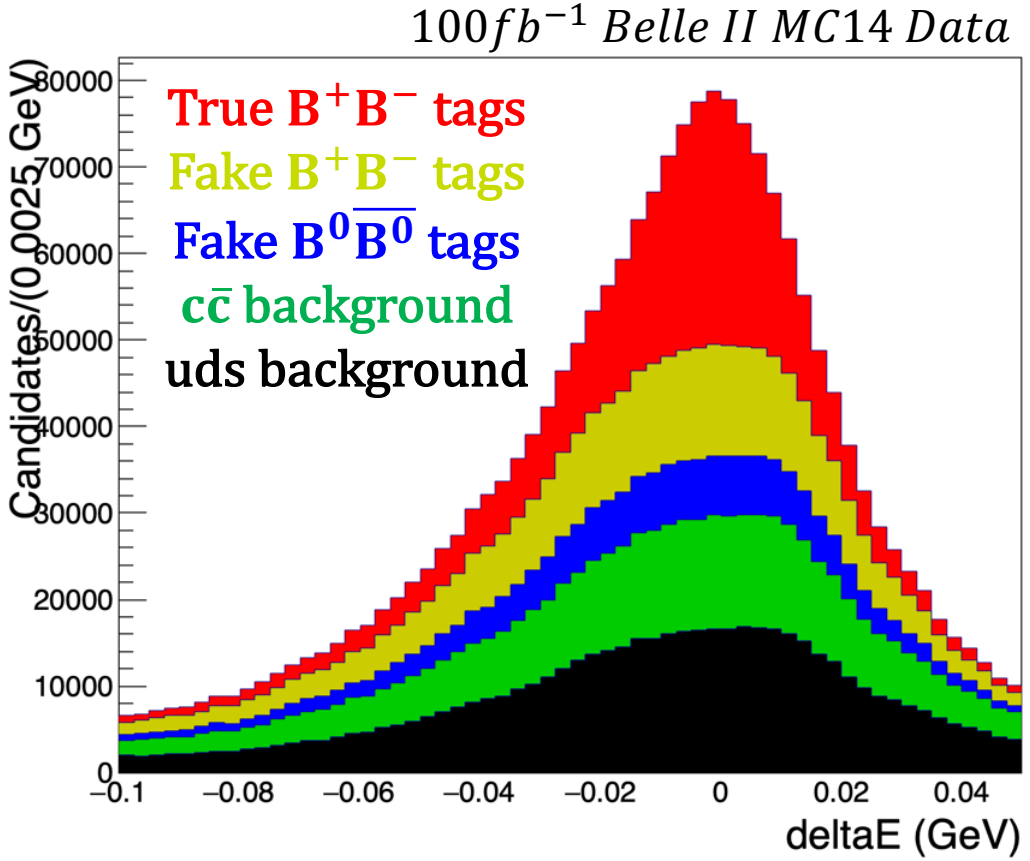

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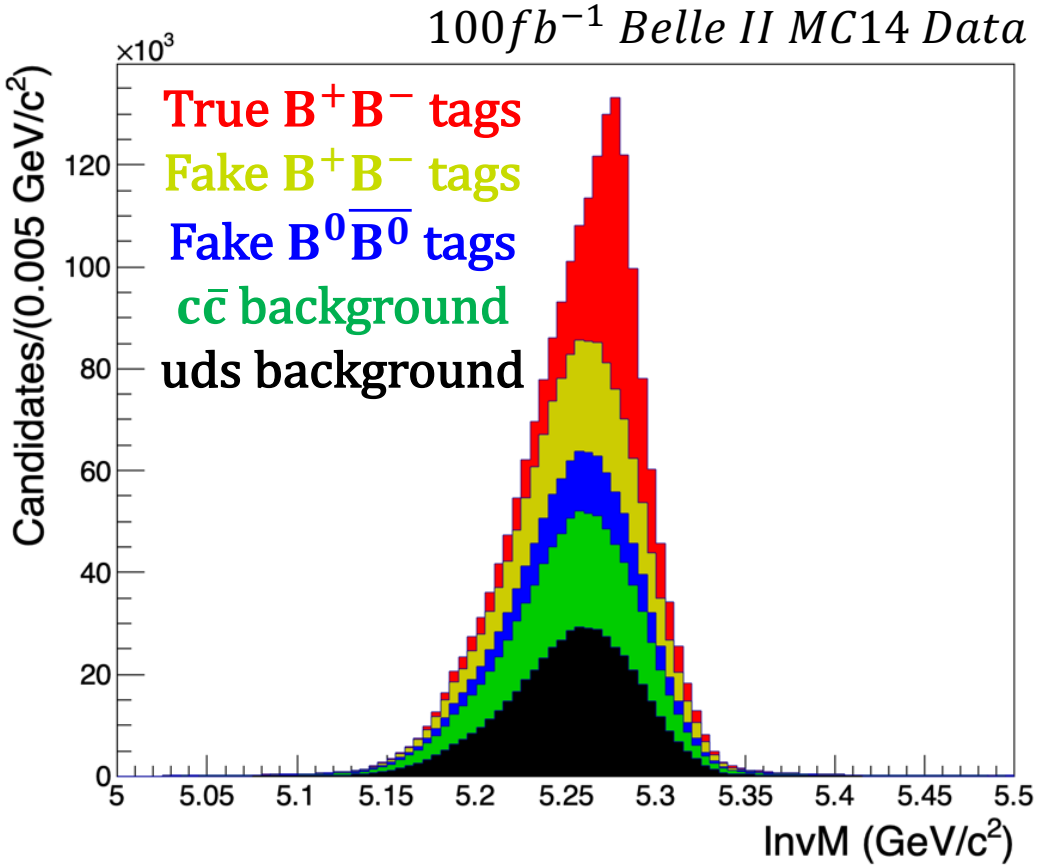

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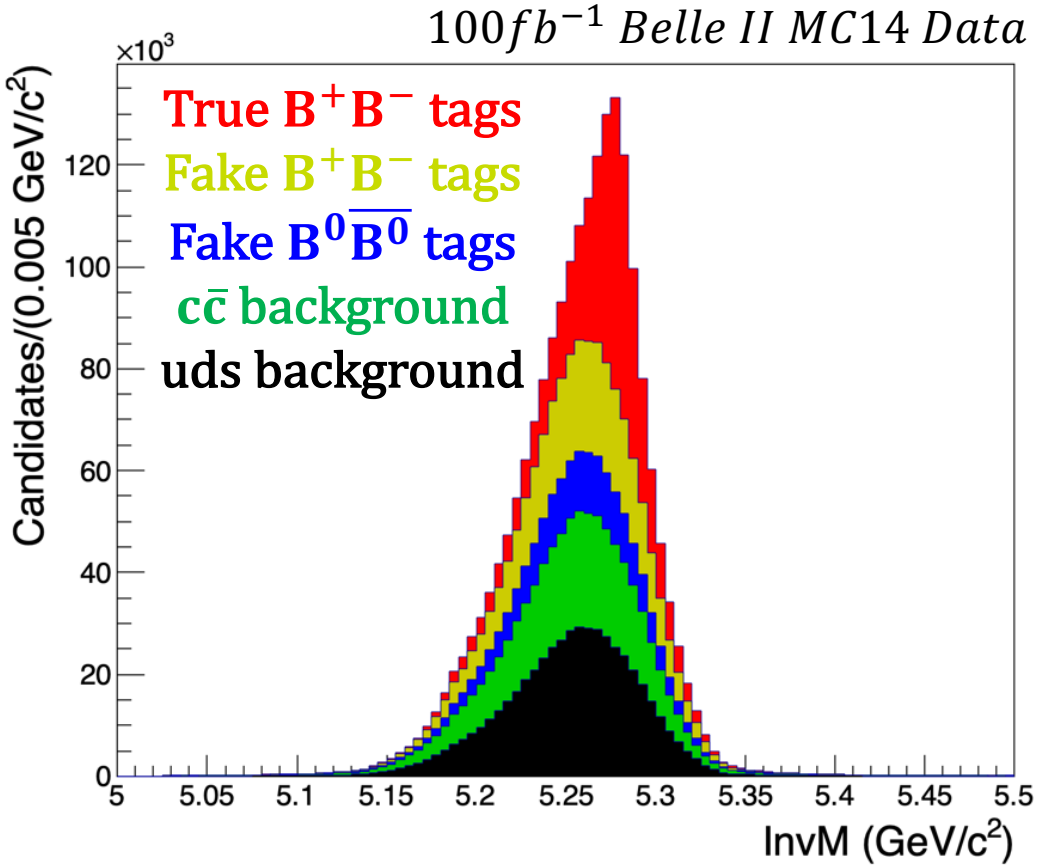
- FEI group recently completed MC16 FEI training without deltaE!



BABAR Measurement

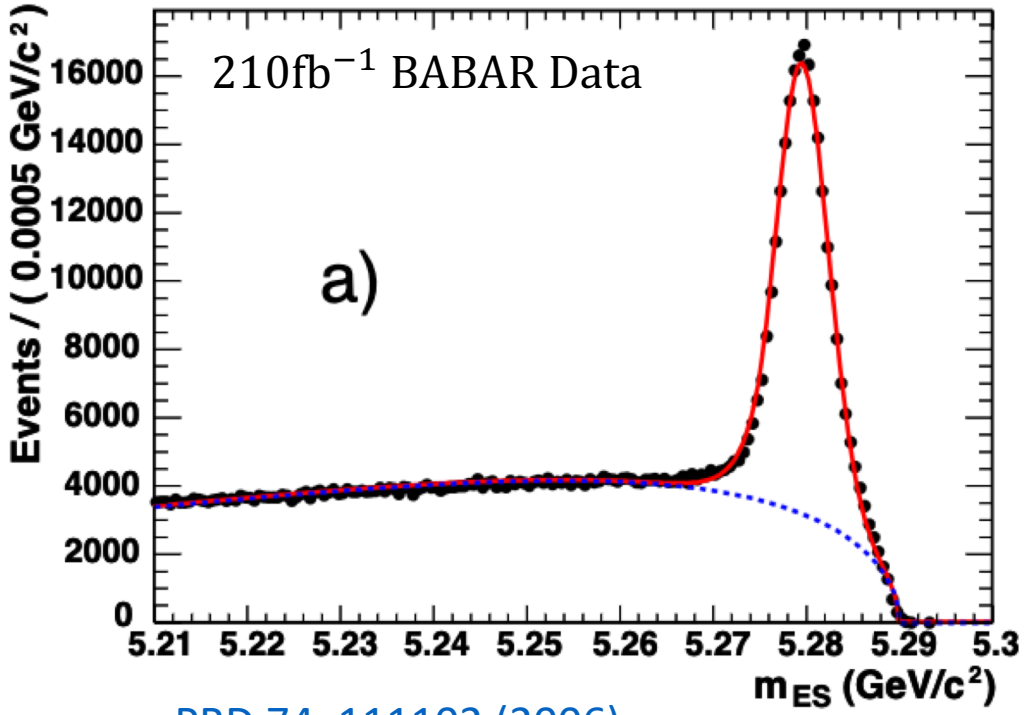
- Measured branching fraction to four D^{**0} states combined
- Full reconstruction tagging

$B^- \to D^{(*)0}\pi^-, D^{(*)0}\rho^-, D^{(*)0}a_1^-$

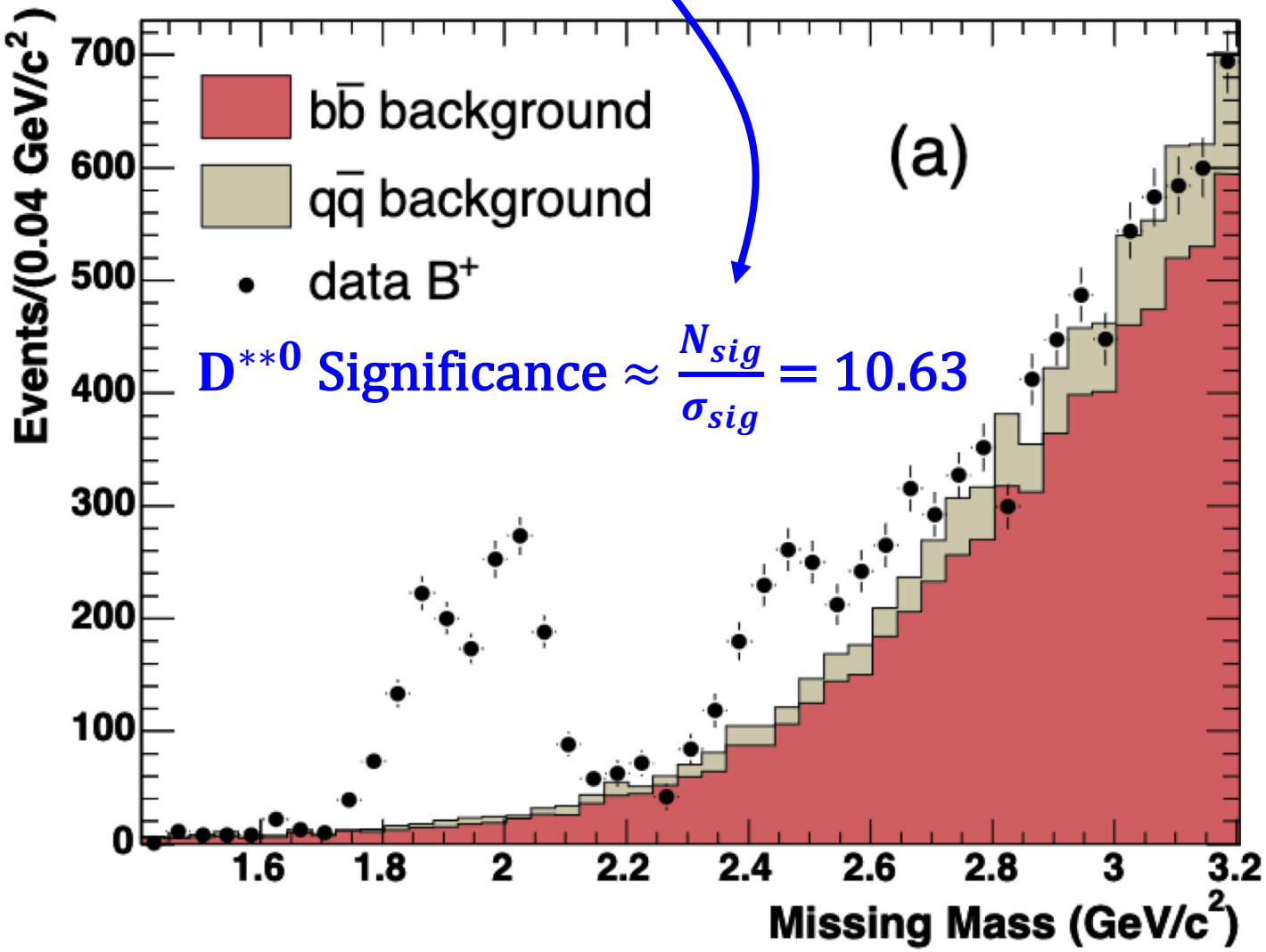
$D^{*0} \to D^0\pi^-$

$D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+, K_s\pi^-\pi^+$

Decay mode	Yield	Efficiency	$\mathcal{B}(10^{-3})$
$B^- \to D^0\pi^-$	677 ± 32		$4.49 \pm 0.21 \pm 0.23$
$B^- \to D^{*0}\pi^-$	774 ± 33	0.796 ± 0.007	$5.13 \pm 0.22 \pm 0.28$
$B^- \to D^{**0}\pi^-$	829 ± 78		$5.50 \pm 0.52 \pm 1.04$



PRD 74, 111102 (2006)



Missing Mass and Significance

$tag\ B$ selection

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$-0.1 < \Delta E < 0.05\ GeV$

FEI MVA output > 0.06

CS MVA output > 0.20

FEI MVA Rank $= 1$

π^- selection

$p_{\pi^-} > 1.5 GeV/c$,

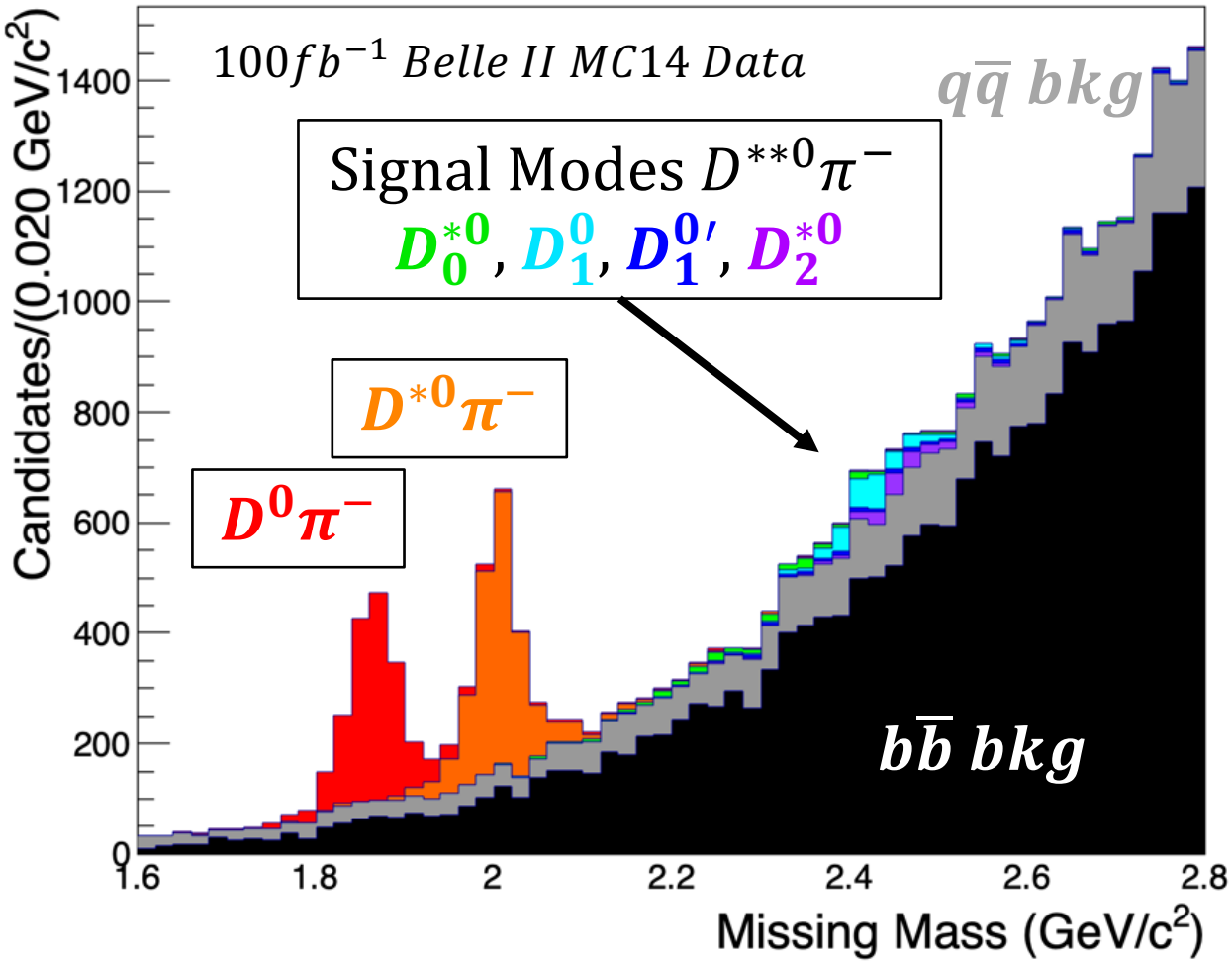
$\mathrm{dr} < 0.5\,cm$

$|\mathrm{dz}| < 2\,cm$

$17° < \theta < 150°$

pionID > 0.6

$$M_{missing} = \sqrt{(E_{beam} - E_{\pi^-})^2 - |-\overrightarrow{p_{cand}} - \overrightarrow{p_{\pi^-}}|^2}$$



Missing Mass and Significance

	Estimated Significance	
Mode	BABAR scaled to 100fb^{-1}	100fb^{-1} Belle II MC
$D^0\pi^-$	14.60	30.11
$D^{*0}\pi^-$	16.19	29.05
$D^{**0}\pi^-$	7.33	11.19

$$N_{D^{**0}} \approx N_{D^{*0}} \frac{N_{D^{**0}(BABAR)}}{N_{D^{*0}(BABAR)}}$$

- Belle II MC14 observed D^{**0} does not match BABAR data
- MC16 decay file and evt.pdl match better

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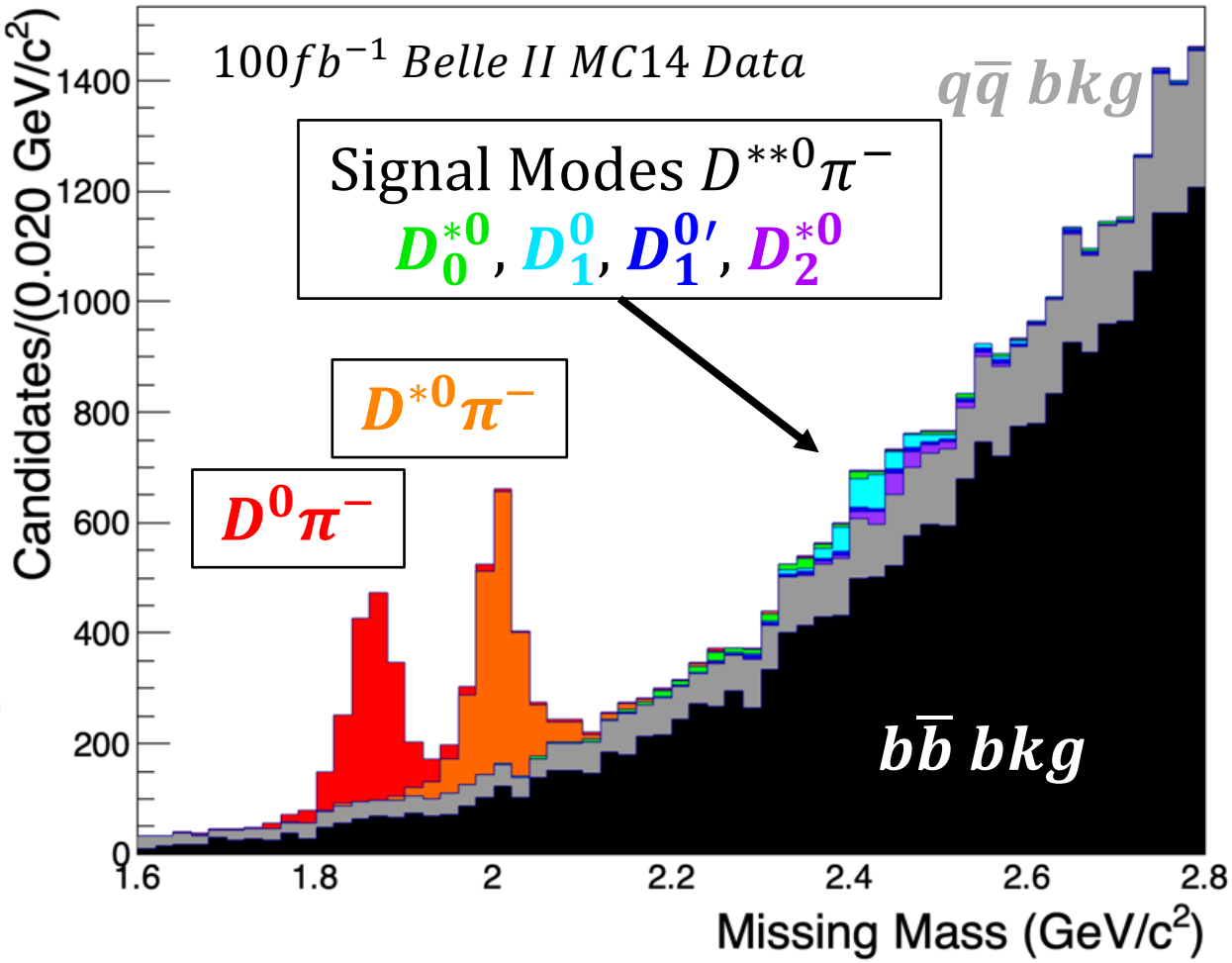

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- Belle II MC14 observed D^{**0} does not match BABAR data
- MC16 decay file and evt.pdl match better
- Fitting $D^{**0}s$ is difficult
  - Need to get shape parameters before fitting missing mass

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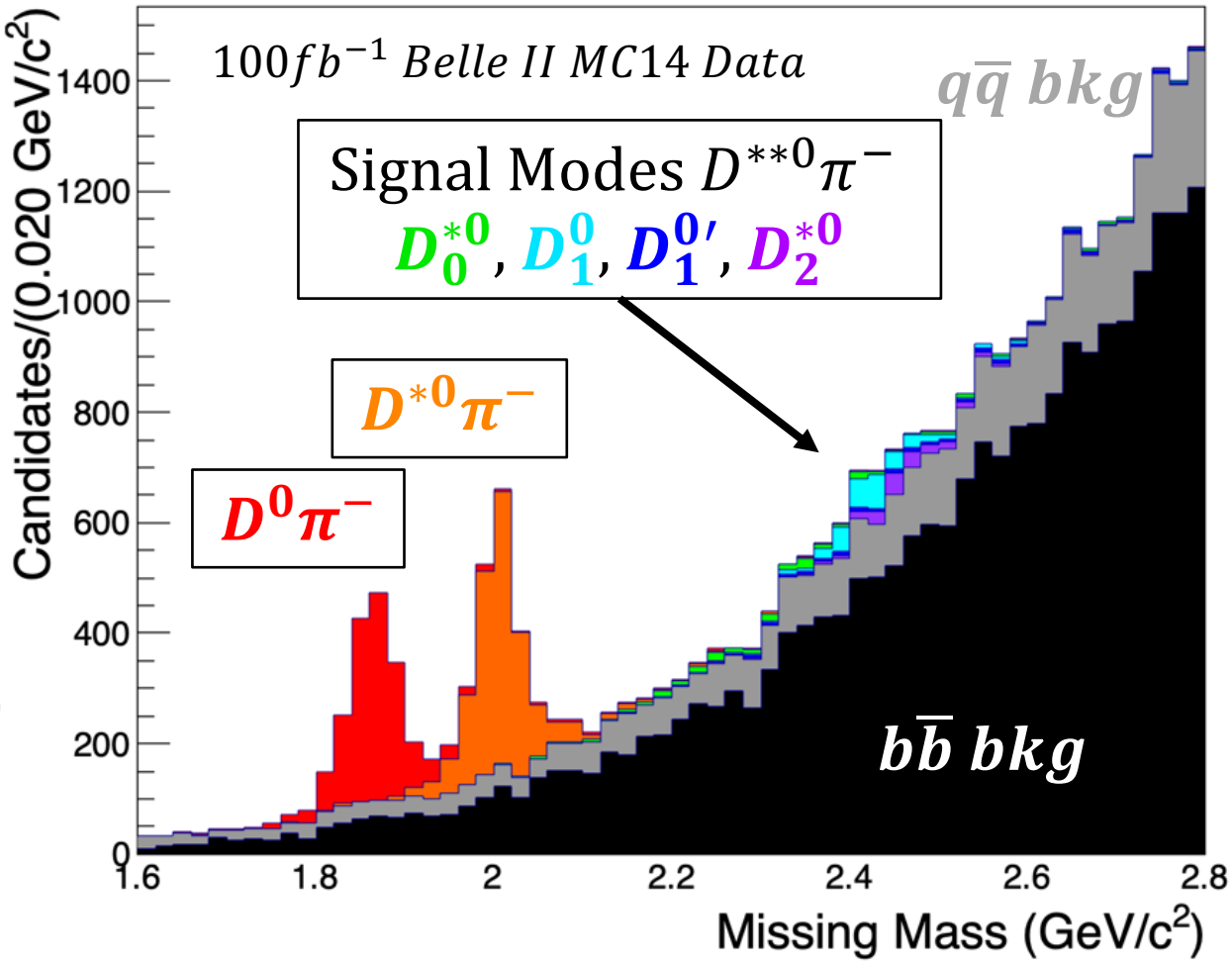
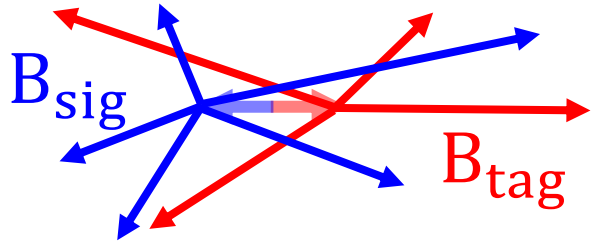
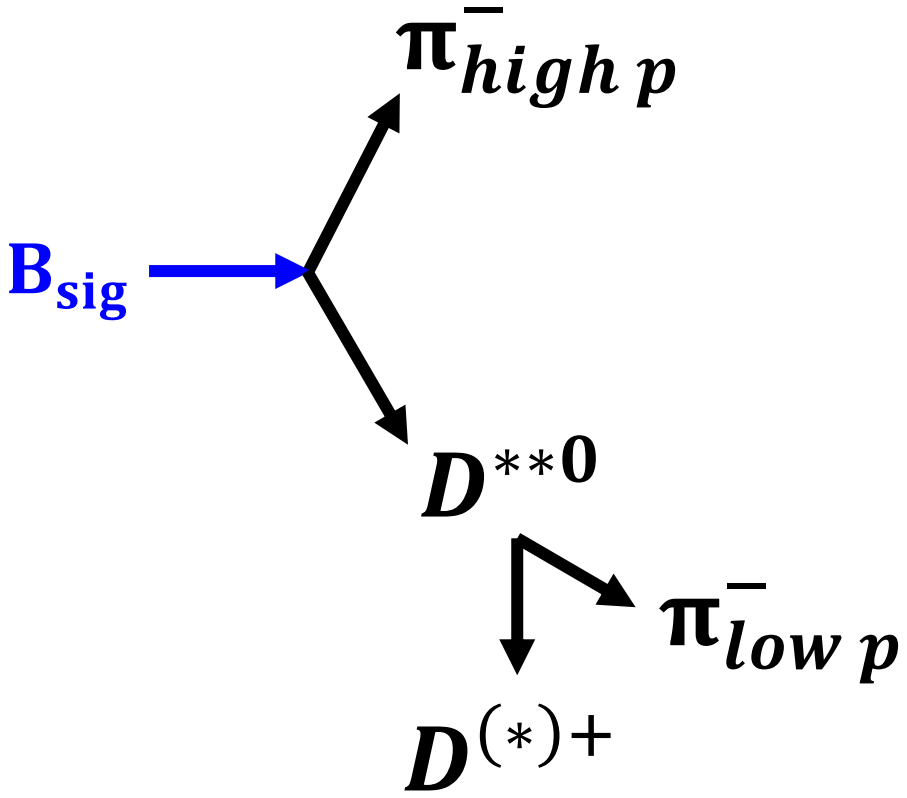


Missing Mass with Two Pions



- D^{**0} can decay to $D^{(*)+}\pi^-$
- D^+ or D^{*+} depends on the D^{**0}



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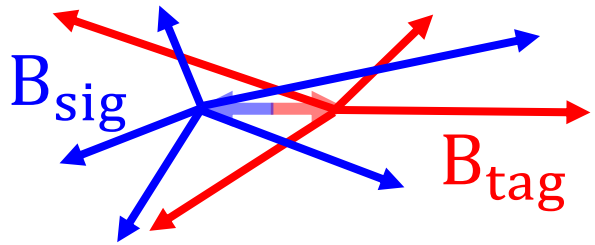

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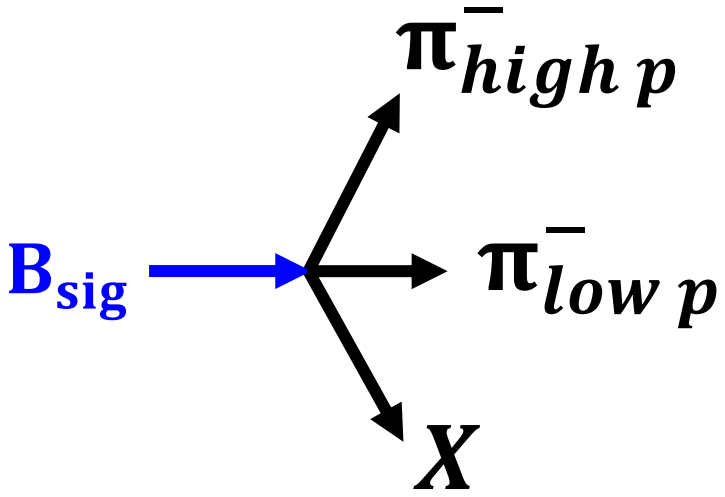

High momentum pion $\pi^-_{high\ p}$ Cuts: pionID > 0.6 , $p_{\pi^-} > 1.5 GeV/c$, dr $< 0.5 cm$, $\lvert dz \rvert < 2 cm$, $17° < \theta < 150°$
Low momentum pion $\pi^-_{low\ p}$ Cuts: pionID > 0.6 , $p_{\pi^-} < 1.5 GeV/c$, dr $< 0.5 cm$, $\lvert dz \rvert < 2 cm$, $17° < \theta < 150°$

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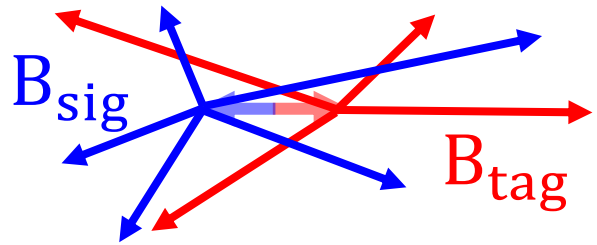

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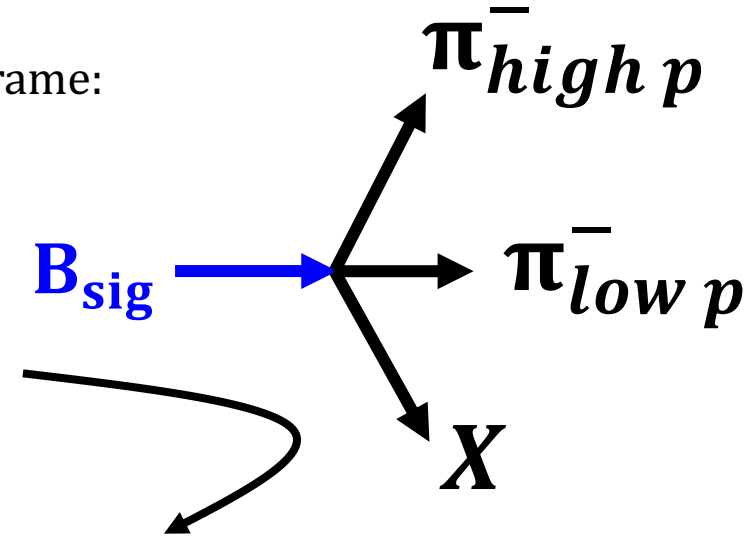
In Y(4s) center of mass frame:

$$\overrightarrow{p_{sig}} = -\overrightarrow{p_{tag}}$$
$$E_{sig} = E_{beam}$$



High momentum pion $\boldsymbol{\pi^-_{high\ p}}$
Cuts: pionID > 0.6 , $p_{\pi^-} > 1.5 GeV/c$,
dr $< 0.5 cm$, |dz| $< 2 cm$, $17° < \theta < 150°$

Low momentum pion $\boldsymbol{\pi^-_{low\ p}}$
Cuts: pionID > 0.6 , $p_{\pi^-} < 1.5 GeV/c$,
dr $< 0.5 cm$, |dz| $< 2 cm$, $17° < \theta < 150°$

$$M^2 = E^2 - |\vec{p}|^2$$

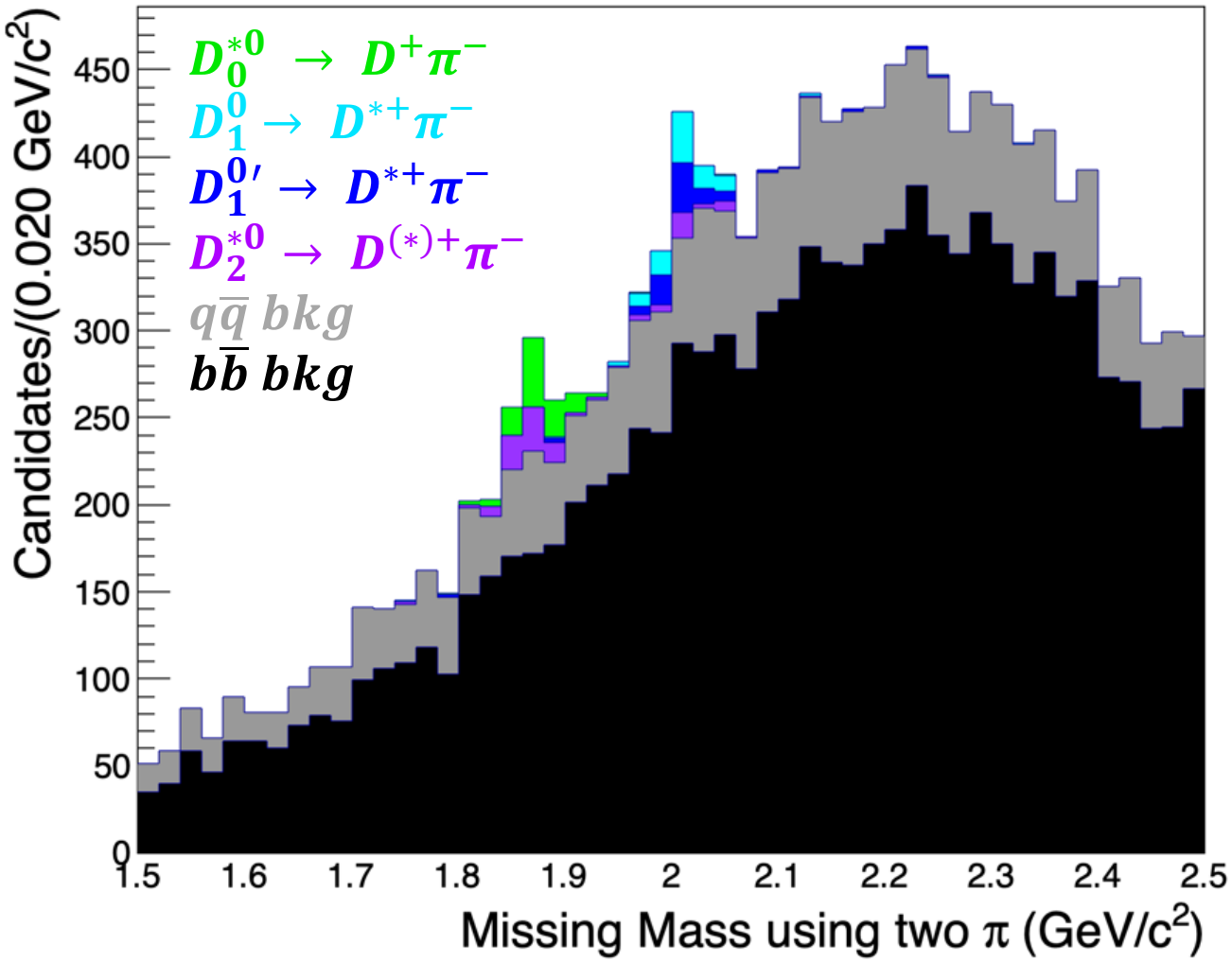
$$\overrightarrow{p_X} = \overrightarrow{p_{sig}} - \overrightarrow{p_{\pi^-_{high\ p}}} - \overrightarrow{p_{\pi^-_{low\ p}}}$$
$$E_X = E_{sig} - E_{\pi^-_{high\ p}} - E_{\pi^-_{low\ p}}$$

$$\boldsymbol{M_{missing\ 2\pi} = \sqrt{\left(E_{beam} - E_{\pi^-_{high\ p}} - E_{\pi^-_{low\ p}}\right)^2 - \left|-\overrightarrow{p_{tag}} - \overrightarrow{p_{\pi^-_{high\ p}}} - \overrightarrow{p_{\pi^-_{low\ p}}}\right|^2}}$$

Missing Mass with Two Pions

- Use different D^{**0} decay modes to begin separating D^{**0}s

$100 fb^{-1}$ *Belle II MC14 Data*

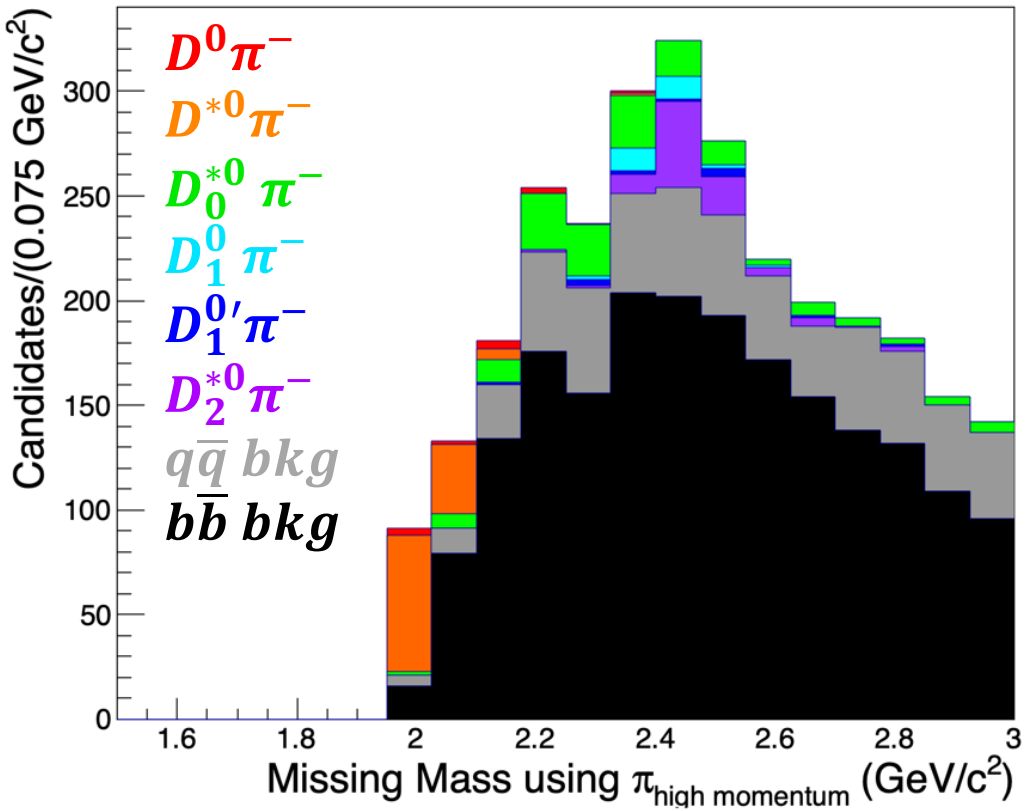


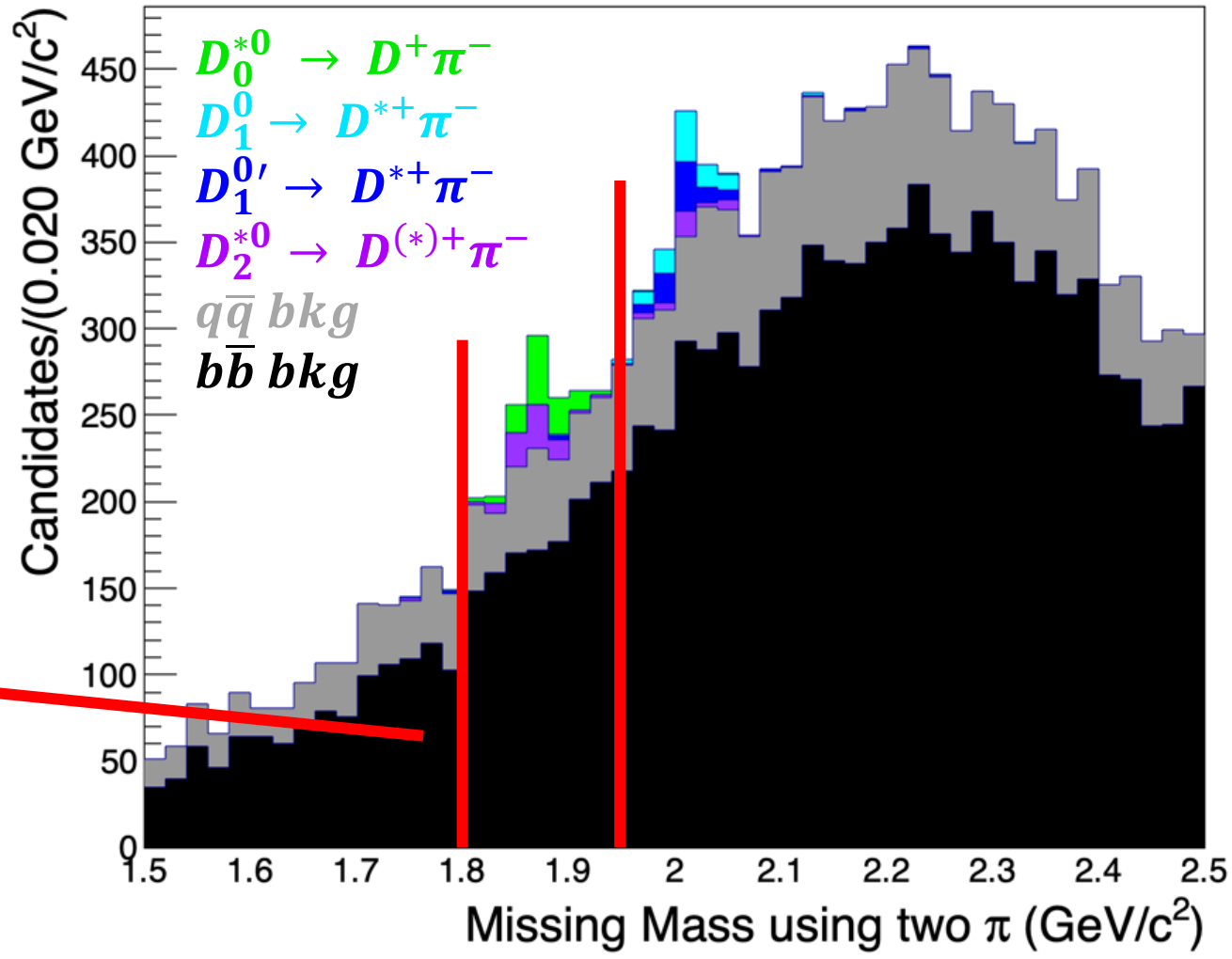
$$M_{missing\ 2\pi} = \sqrt{\left(E_{beam} - E_{\pi^-_{high\ p}} - E_{\pi^-_{low\ p}}\right)^2 - \left|-\overrightarrow{p_{cand}} - \overrightarrow{p_{\pi^-_{high\ p}}} - \overrightarrow{p_{\pi^-_{low\ p}}}\right|^2}$$

Missing Mass with Two Pions

$100 fb^{-1}$ *Belle II MC14 Data*

- Use different D^{**0} decay modes to begin separating D^{**0}s





$$M_{missing\ 2\pi} = \sqrt{\left(E_{beam} - E_{\pi^-_{high\ p}} - E_{\pi^-_{low\ p}}\right)^2 - \left|-\overrightarrow{p_{cand}} - \overrightarrow{p_{\pi^-_{high\ p}}} - \overrightarrow{p_{\pi^-_{low\ p}}}\right|^2}$$

Summary

- Reconstruct hadronic tag B with FEI
- Optimize $D^{**0}\pi^-$ significance with CS and FEI MVA outputs in a 2D FOM
- Fitting missing mass D^{**0} peaks difficult
- Missing mass with 2^{nd} π^- helps separate D^{**0}s
  - Help determine fit shapes before fitting D^{**0}s for branching fractions

- Switching to MC16
  - Much better D^{**0} modeling
  - No deltaE in FEI training

Thank you!