Measuring $B(B^- \to D^{**0}\pi^-)$ using the Missing Mass Method
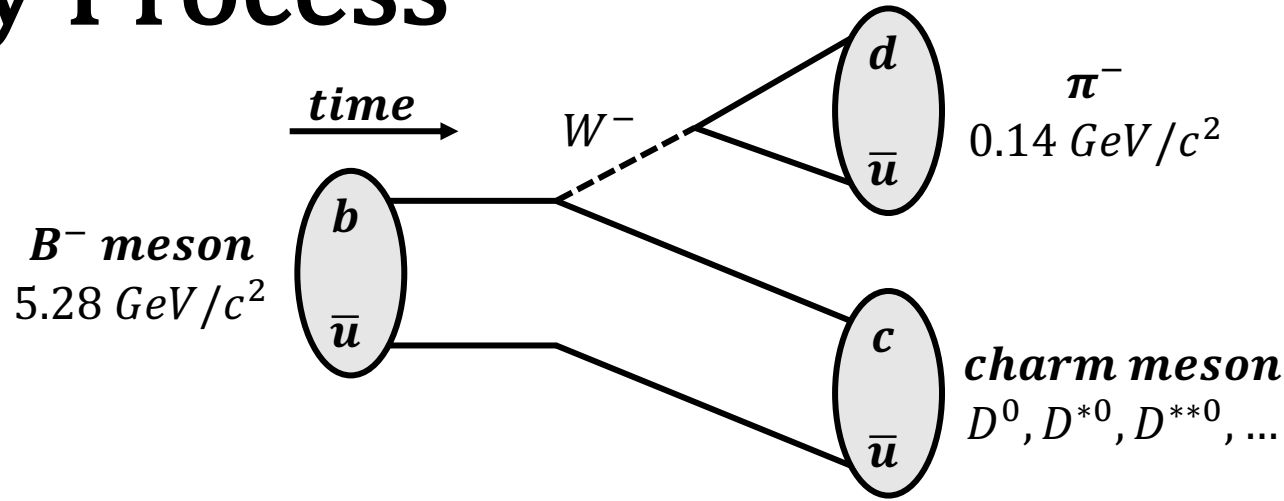
Alex Gale

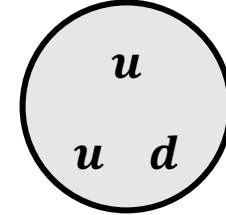University of Cincinnati

June 21, 2024

Decay Process
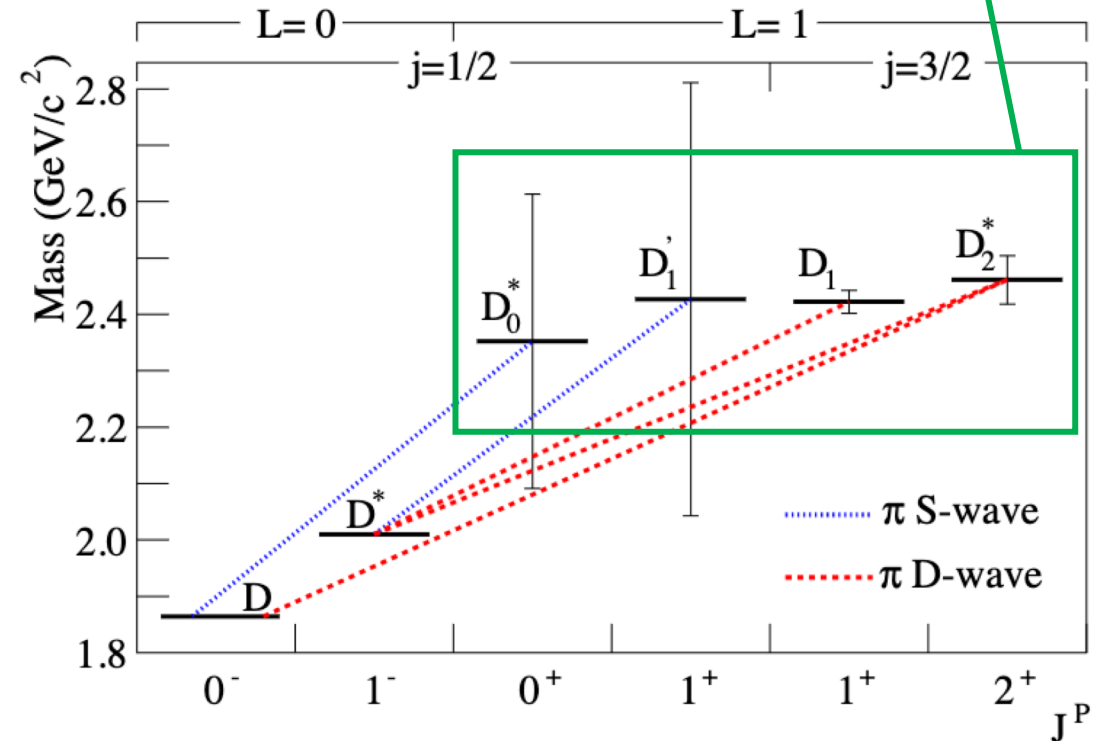
time →

W^-

b
$\bar{u}$

B^- meson
$5.28 \ GeV/c^2$

d
$\bar{u}$

π^-
$0.14 \ GeV/c^2$

c
$\bar{u}$

charm meson
$D^0, D^{*0}, D^{**0}, \dots$

For reference:
Proton mass $\approx 0.94 \ GeV/c^2$

u
$u \quad d$

4 different D^{**0} mesons

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 $D^{**0}\pi^-$	$(5.6 \pm 1.2)\times10^{-3}$
		From the Particle Data Group

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

L=0   L=1

j=1/2   j=3/2

Mass (GeV/c^2)

D_0^* D_1' D_1 D_2^*

D^*

D

0^- 1^- 0^+ 1^+ 1^+ 2^+
J^P

$\cdots\cdots$ π S-wave
$----$ π D-wave

Motivation
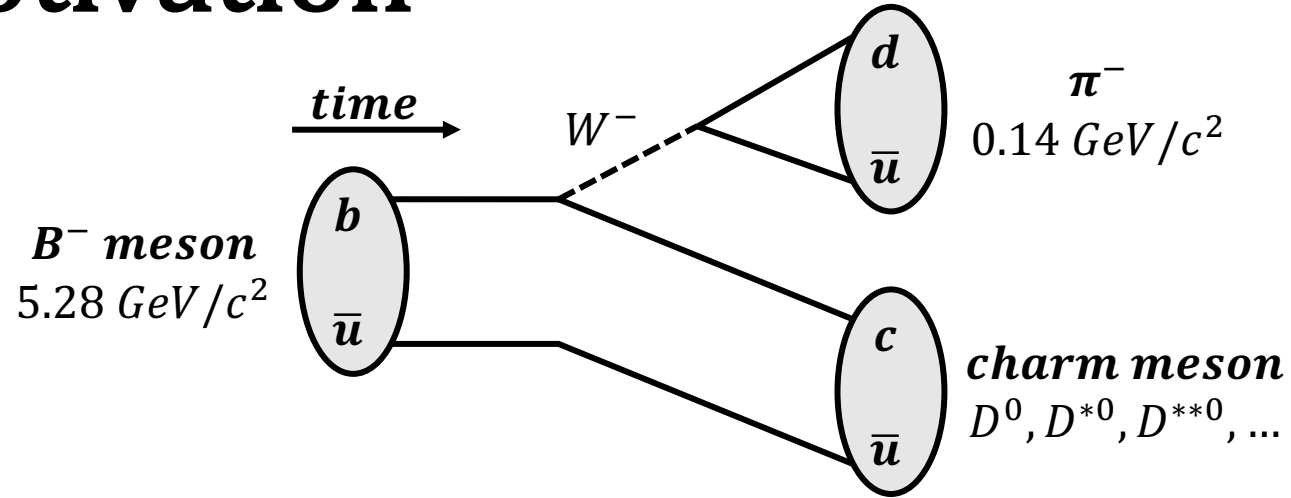
Exclusive $|V_{cb}| = (39.10 \pm 0.50) \times 10^{-3}$
PRD 107, 052008 (2023)

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 $|V_{cb}|$
- Possibly from poor modeling of higher excited charm states
  - $B \to D^{**} l\, nu$ not well known
- $B \to D^{**} \pi$ can help understand D** (form factor at $|V_{cb}|$ kinematic point)

B Meson Tagging

- Full Event Interpretation (FEI)
  - Hadronic tagging
  - Select B candidate (tag B)
    - $-0.1 < \Delta E < 0.05$
    - FEI MVA output (signalProbability) > 0.001
    - Candidate with highest signalProbability
  - Kinematic constraint on other B (signal B)
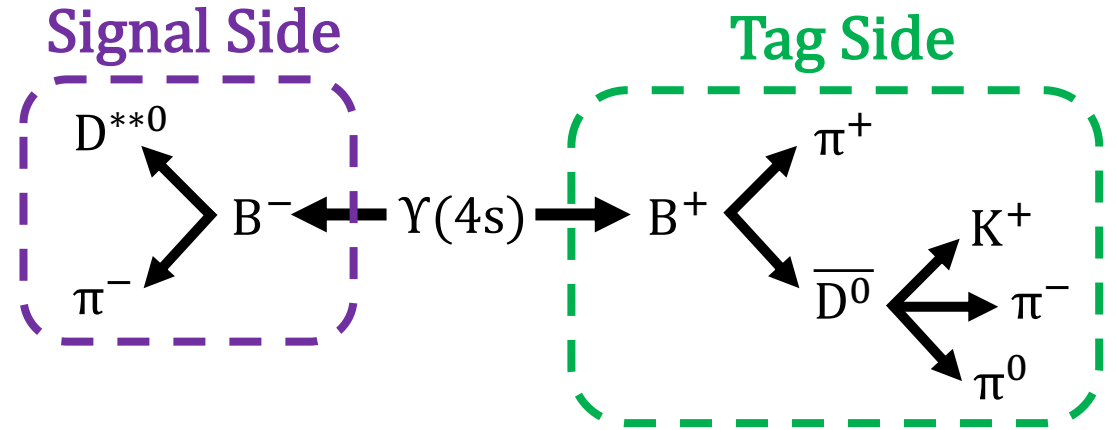
- Beam constrained mass

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

Signal Side

Tag Side

D^{**0}

B^- ← $\Upsilon(4s)$ → B^+

π^-

π^+

$\overline{D^0}$

K^+

π^-

π^0

Tag Tree - Mbc

True $B^+ B^-$ tags
Fake $B^+ B^-$ tags
Fake $B^0 \overline{B^0}$ tags
$c\bar{c}$ background
uds background
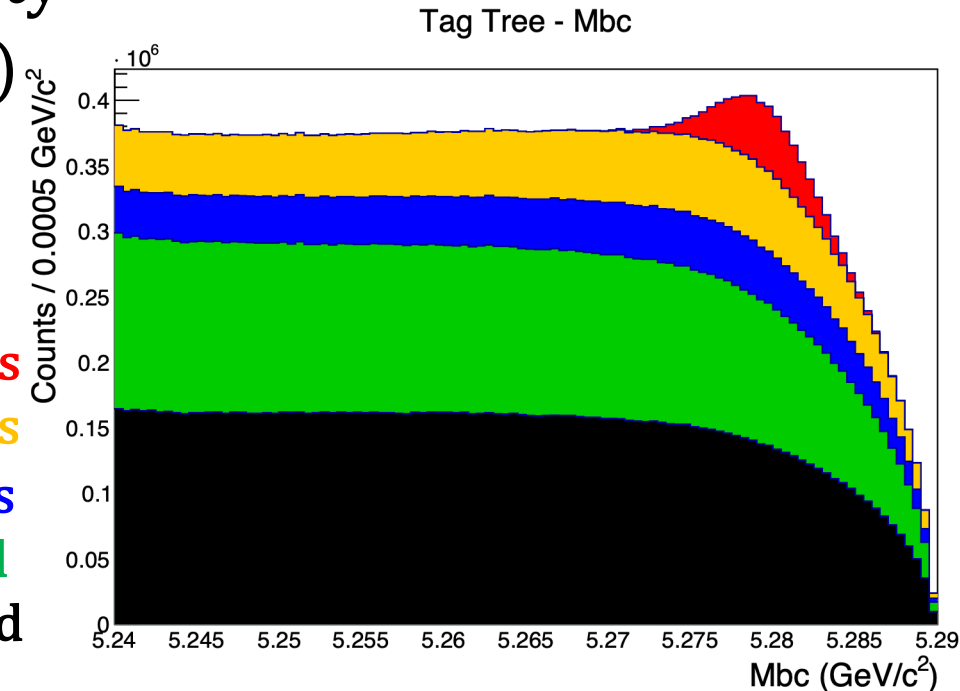
Continuum Suppression with FastBDT

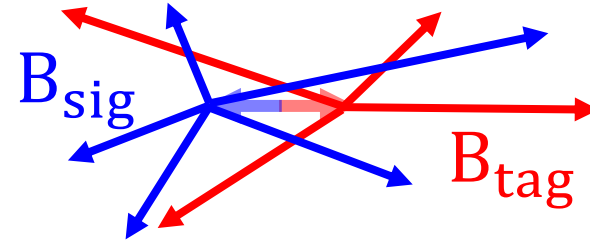- 50fb^{-1} for training and 50fb^{-1} for validation

Variables

- R2 is the second Fox Wolfram moment
- There is a set of KSFW moments

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

- KSFW(mm2) is the missing mass squared
- 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

Cleo Cones **10°**

B_{tag}

Missing Mass

B$_{sig}$ B$_{tag}$
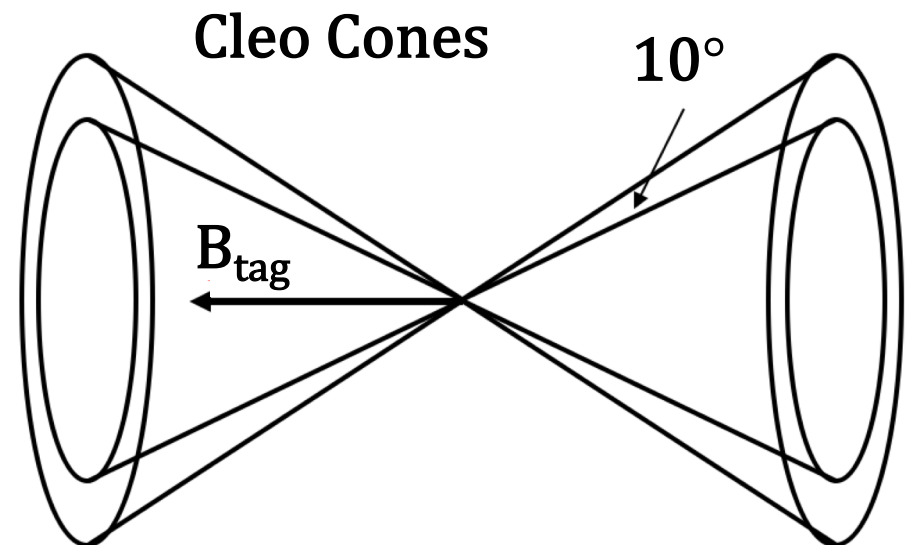
- Say we have a tag B
  - Particles not combined to make tag B → from signal B
  - Look for D**π in signal B decay

In center of mass frame:

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

$$E_{sig} = E_{beam}$$

B$_{sig}$ → π

X $\overrightarrow{p_X} = \overrightarrow{p_{sig}} - \overrightarrow{p_\pi}$

$E_X = E_{sig} - E_\pi$

Find π on signal side
Measure E_π and $\overrightarrow{p_\pi}$
Cuts: pionID > 0.6 , $p_{\pi^-} > 1.5$,
dr < 0.5 , |dz| < 2 , 17° < θ < 150°
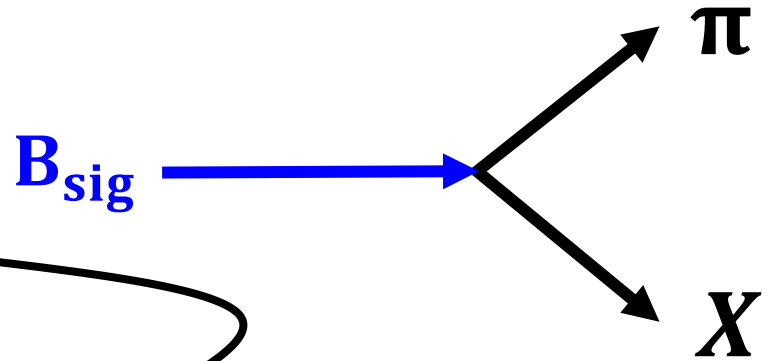
$$M^2 c^4 = E^2 - |\vec{p}|^2 c^2$$

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

Significance Optimization

- Estimated significance of $D^{**0}\pi^-$ signal vs cuts in signalProbability and Continuum Suppression MVA output

- Significance $= \dfrac{N_{sig}}{\sqrt{N_{sig}+N_{bkg}}}$ in signal box: $5.27 < M_{bc} < 5.29$ and $2.2 <$ Missing Mass < 2.8

- 2D figure of merit optimizes significance to find best cuts in signalProbability and Continuum Suppression MVA outputs
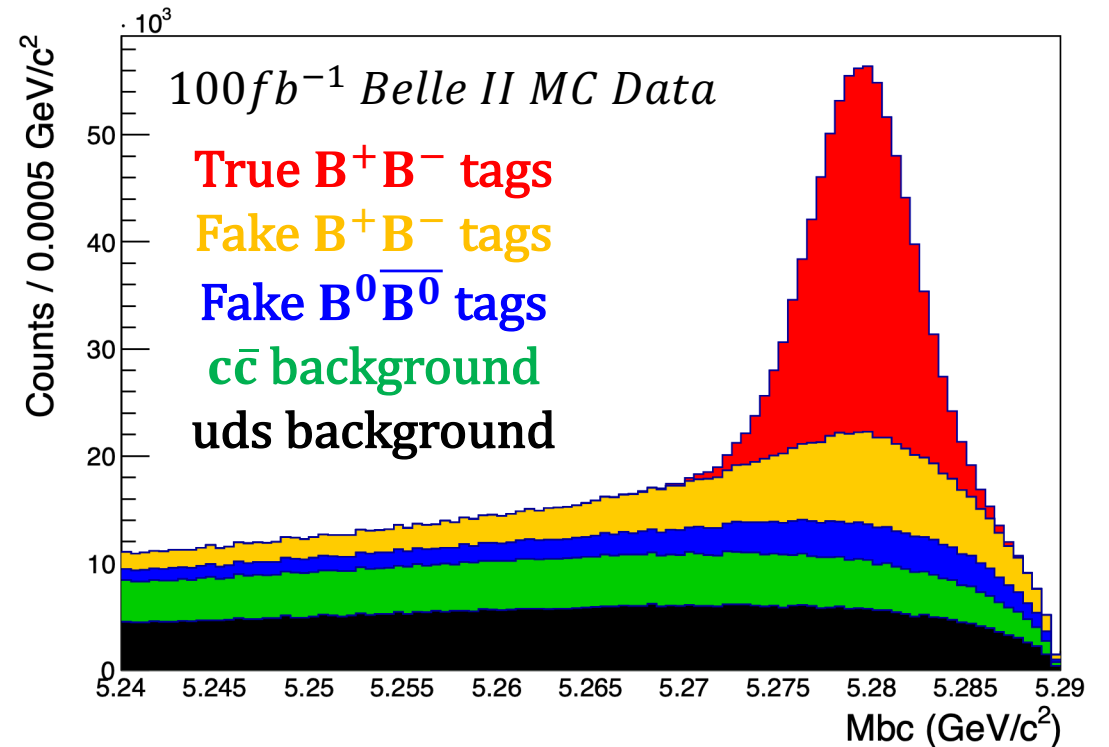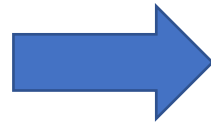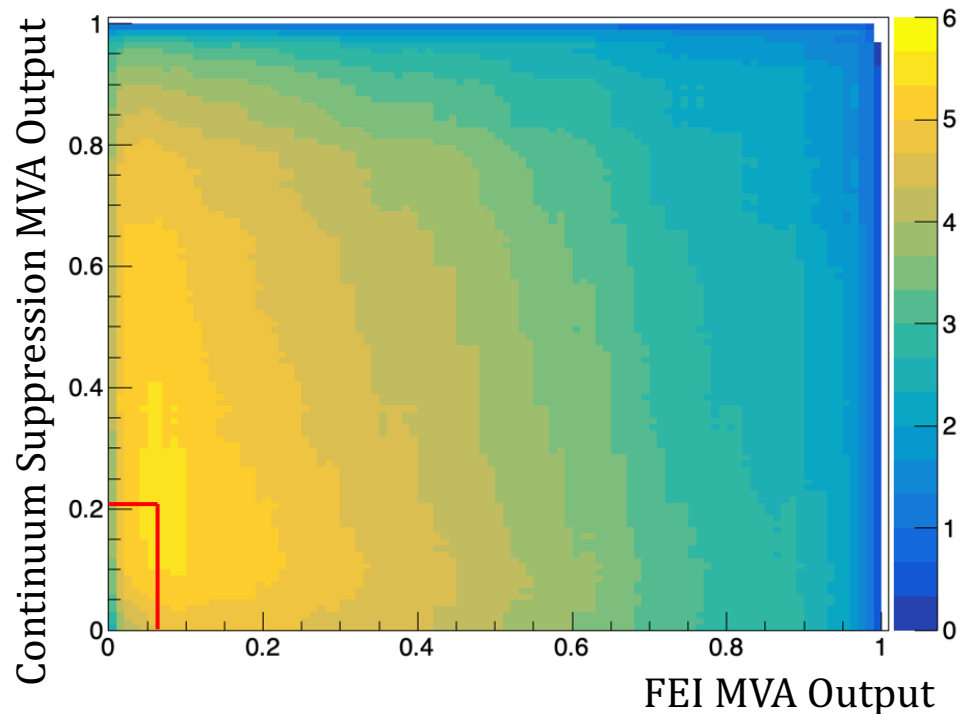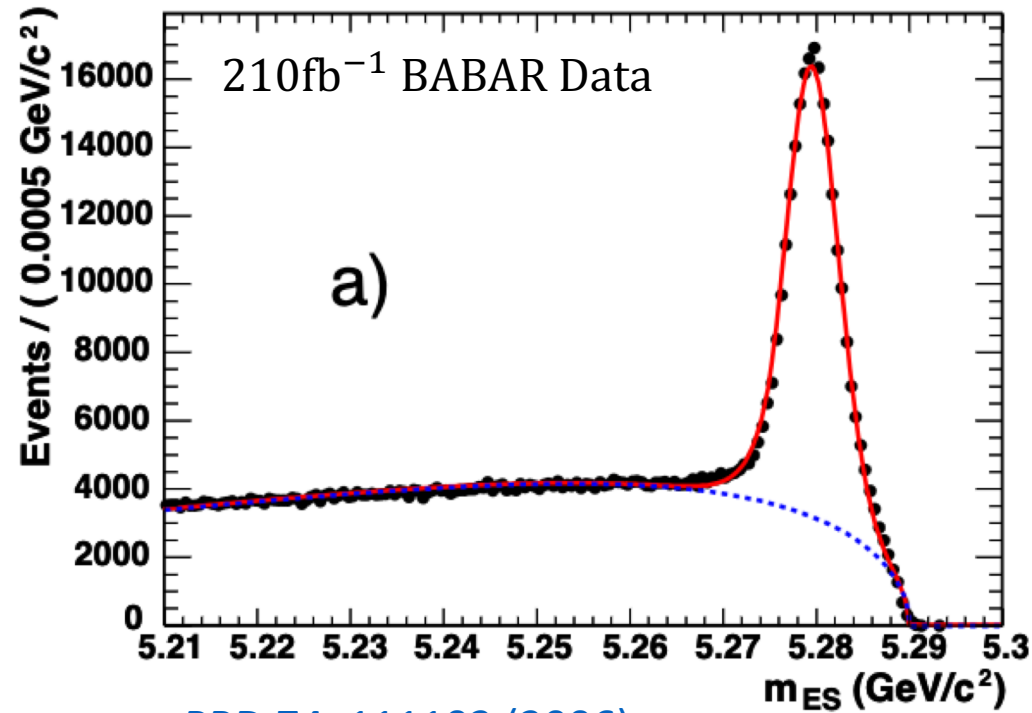
BABAR Measurement

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

- Full reconstruction tagging
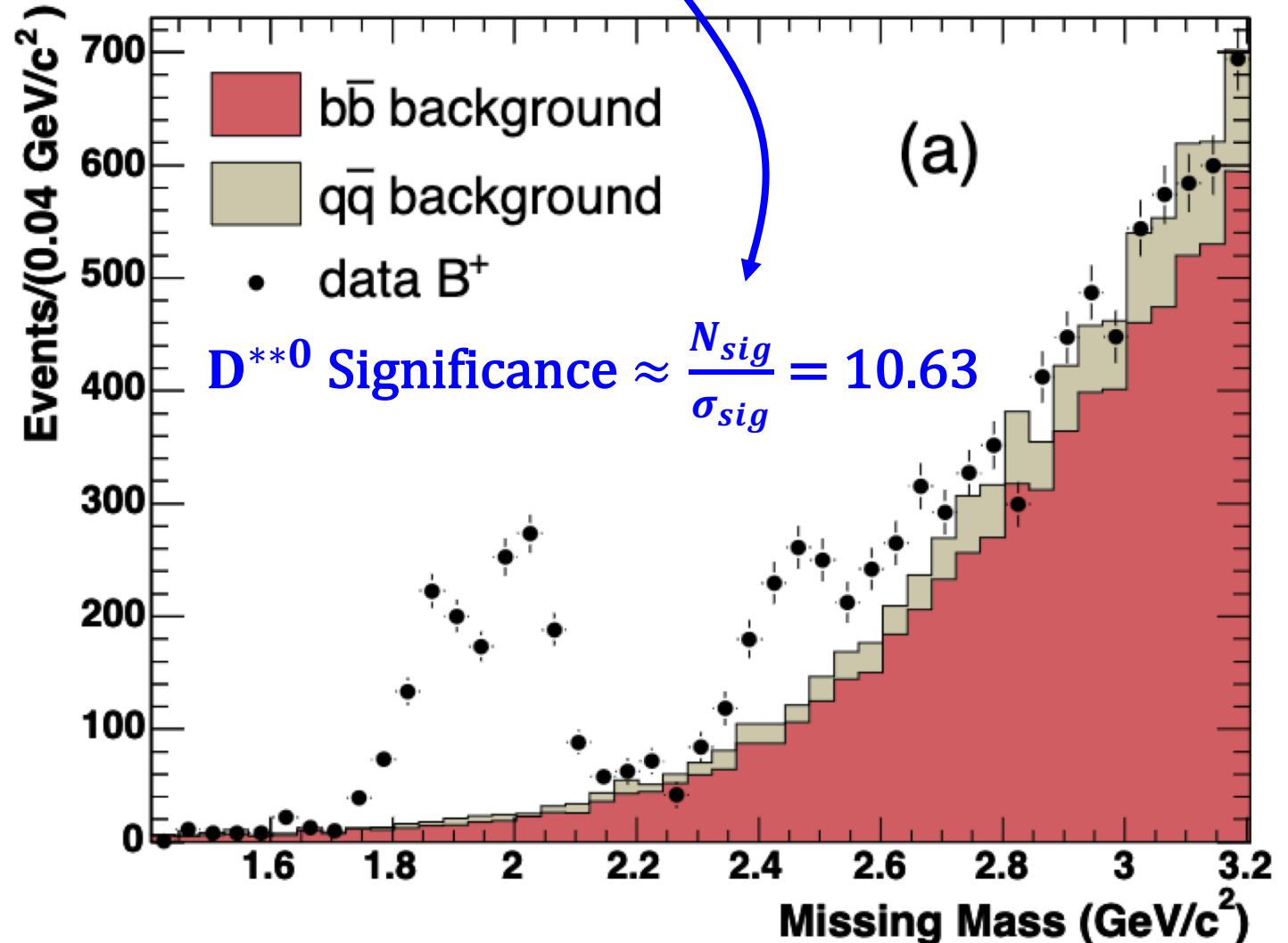
$B^- \to D^{(*)0}\pi^-, D^{(*)0}\rho^-, D^{(*)0}a_1^-$
$D^{*0} \to D^0\pi^-$
$D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+, K_s\pi^-\pi^+$

Decay mode	Yield	Efficiency	$\mathcal{B}(10^{-3})$
$B^- \to D^0\pi^-$	677 ± 32		$4.49\pm0.21\pm0.23$
$B^- \to D^{*0}\pi^-$	774 ± 33	0.796 ± 0.007	$5.13\pm0.22\pm0.28$
$B^- \to D^{**0}\pi^-$	829 ± 78		$5.50\pm0.52\pm1.04$

210fb^{-1} BABAR Data

a)

PRD 74, 111102 (2006)

$b\bar{b}$ background

$q\bar{q}$ background

data B$^+$

(a)

D^{**0} Significance $\approx \dfrac{N_{sig}}{\sigma_{sig}} = 10.63$

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

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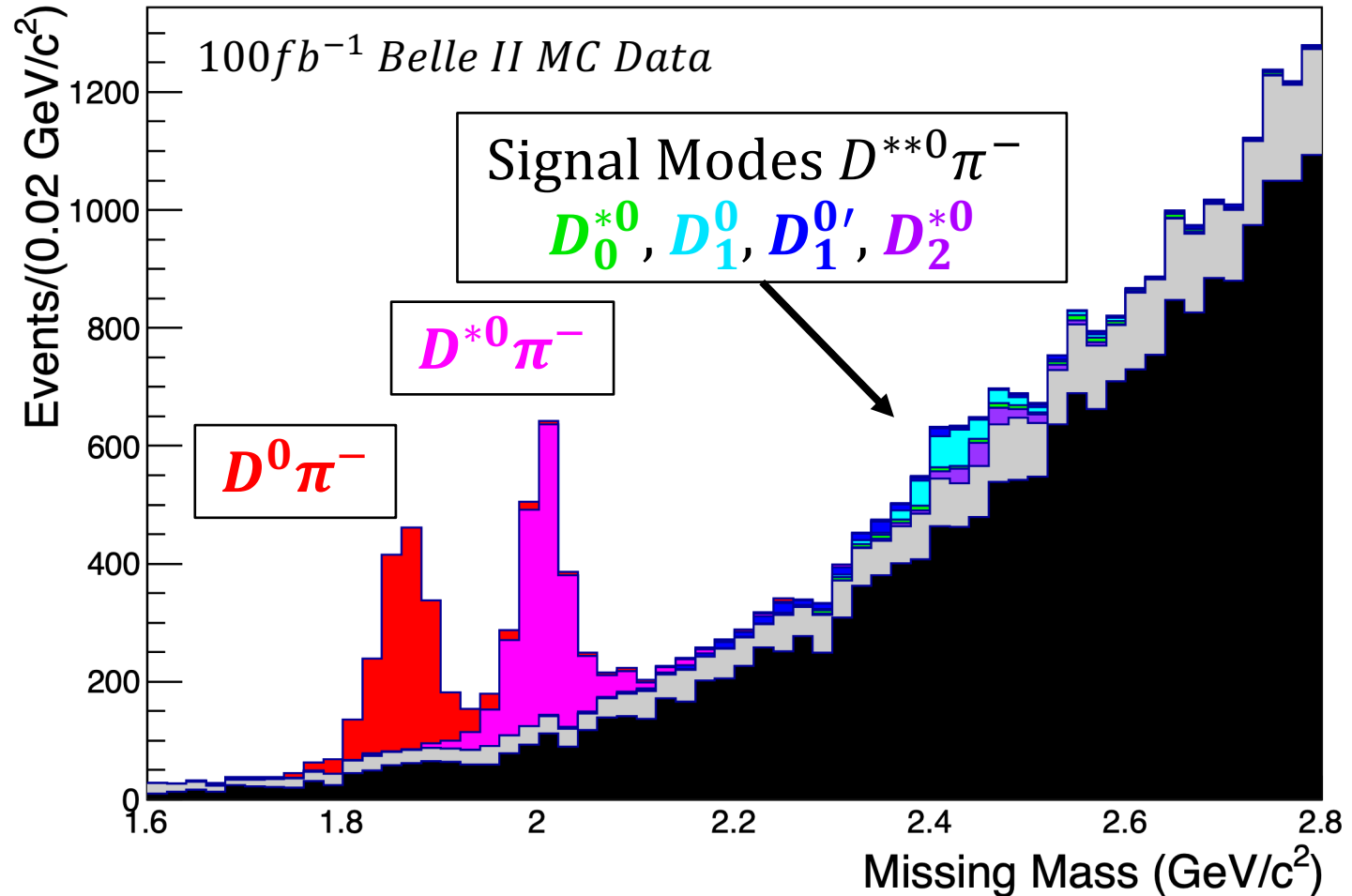
Summary

- Full Event Interpretation hadronically reconstructs tag-side B mesons
- Continuum Suppression applied on the tag-side

- Optimize $D^{**0}\pi^-$ significance FEI and Continuum Suppression MVA outputs

	BABAR scaled to 100fb^{-1}	100fb^{-1} Belle II MC
$\boldsymbol{D^{**0}\pi^-}$ Counts	395	1683
Significance	7.33	11.19

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

Thank you!