LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Belle II

Bundesministerium für Forschung, Technologie und Raumfahrt

$B \to D^{**}\ell\nu$ Analysis at Belle II

57. Herbstschule HEP, Bad Honnef, 2026

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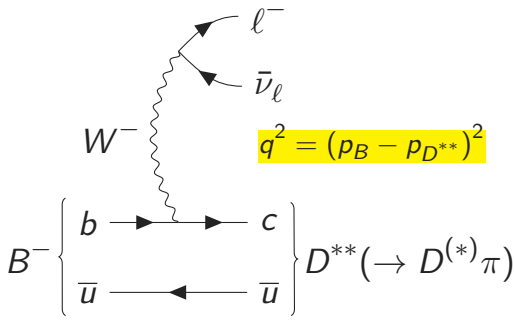
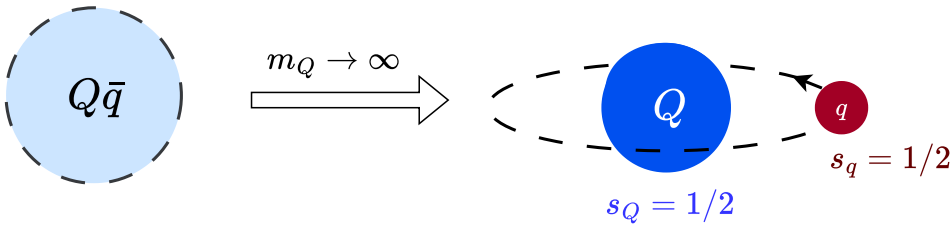
Introduction

- **Goal of the analysis:** Measure the product branching fraction: $\mathcal{B}(B \to D^{**}\ell\nu) \times \mathcal{B}(D^{**} \to D^{(*)}\pi)$
- Fit the q^2 distribution of the $B \to D^{**}\ell\nu$ decay ==> useful input for theory



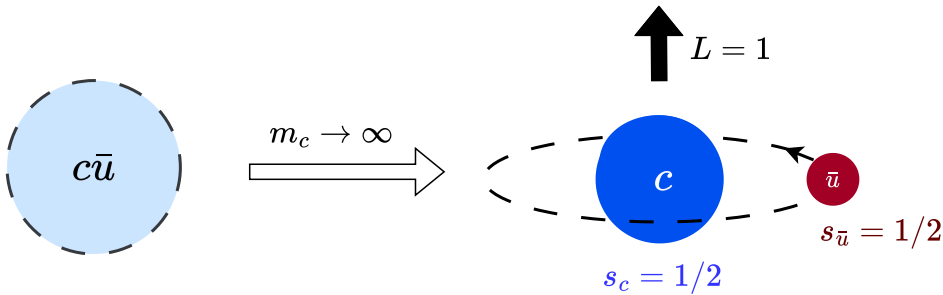
Introduction: The D^{**}s

The modelling of mesons with one light and one heavy quark (e.g. B,D) is simplified by taking the **heavy quark limit**.



Introduction: The D^{**}s

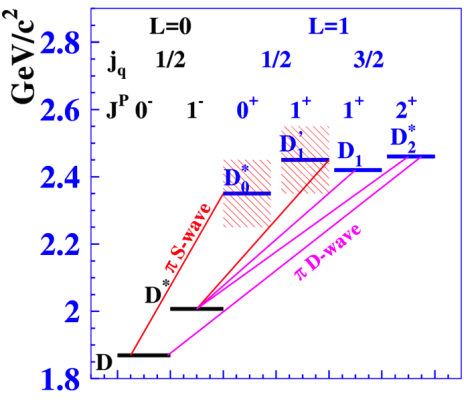
The D^{**}s are the **P-wave ($L = 1$)** excitations of the D meson.



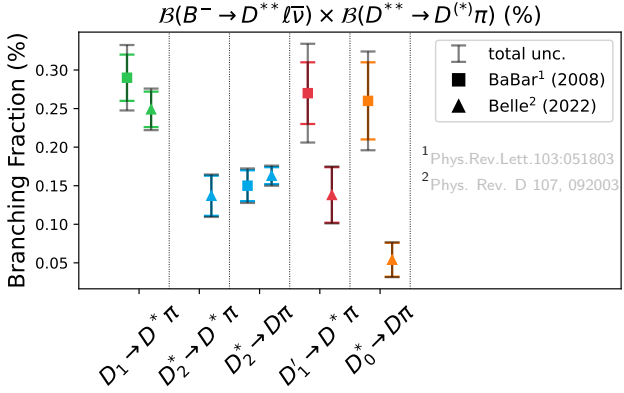
Introduction: The D^{**}s

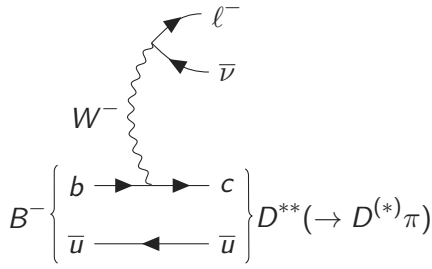
The D^{**}s form two doublets under the angular momentum of the lighter quark ($j_q = L + s_q$):

- $j_q = 3/2 : \{D_1(2420), D_2^*(2460)\}$
  $\Gamma = \mathcal{O}(10)$ MeV
- $j_q = 1/2 : \{D_1'(2430), D_0^*(2300)\}$
  $\Gamma = \mathcal{O}(100)$ MeV



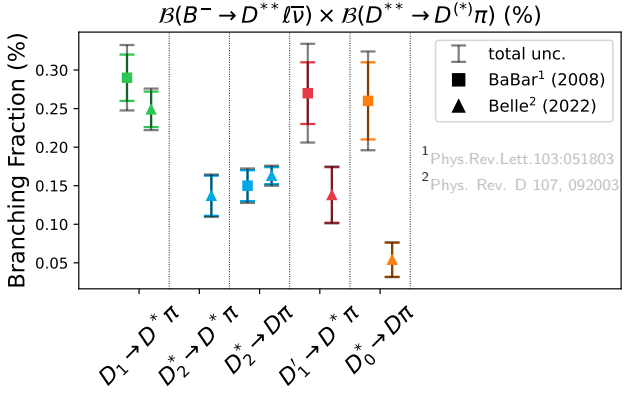
Motivation

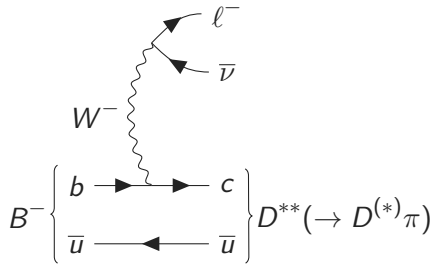




- Discrepancies between two previous measurements

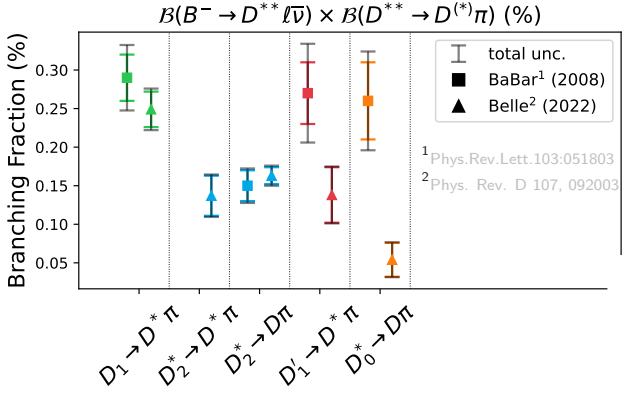
Motivation

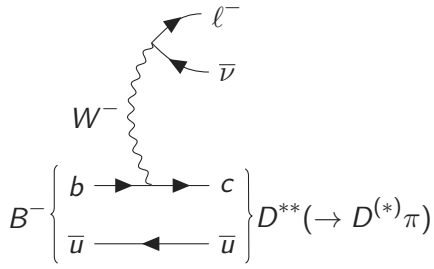


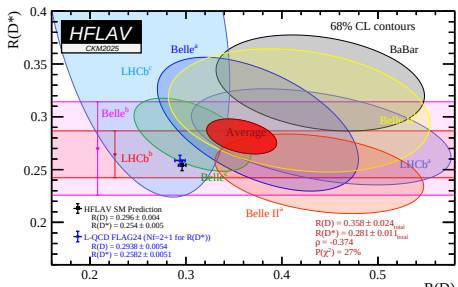


- Discrepancies between two previous measurements
- "The $1/2 - 3/2$ puzzle"

Motivation

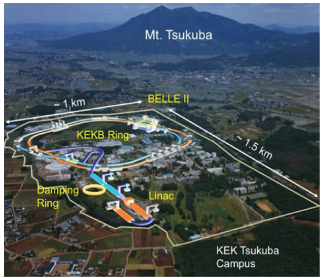


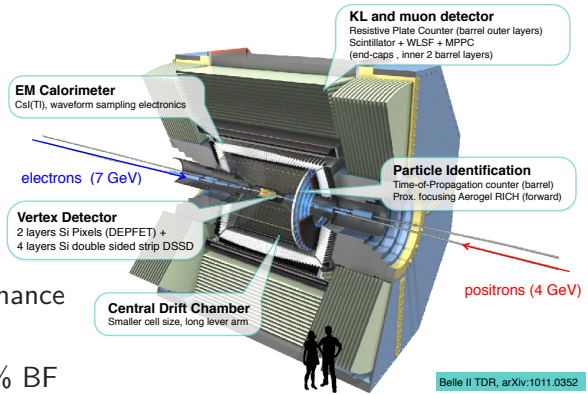




- Discrepancies between two previous measurements
- "The $1/2 - 3/2$ puzzle"
- Significant background to $R(D^*) = \frac{\mathcal{B}(B \to D^* \tau \nu)}{\mathcal{B}(B \to D^* \ell \nu)}$

Belle II Experiment





- Majority of data collected at $\Upsilon(4S)$ resonance energy (10.58 GeV)
- $\Upsilon(4S)$ decays into a $B\overline{B}$ pair with $> 96\%$ BF
- Very high instantaneous luminosity: $5.3 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Data collected so far is around $920\,\mathrm{fb}^{-1}$ (with $810\,\mathrm{fb}^{-1}$ at the $\Upsilon(4S)$ resonance)

Reconstruction Strategy

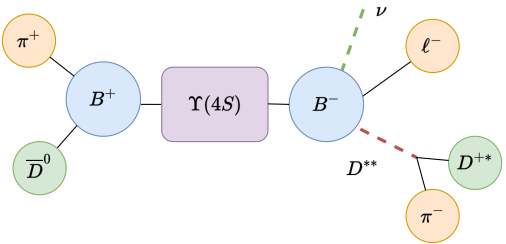
in CM Frame

$$E_\nu = E_{Tag} - (E_\ell + E_{D^*} + E_\pi)$$
$$\vec{p}_\nu = -\vec{p}_{Tag} - (\vec{p}_\ell + \vec{p}_{D^*} + \vec{p}_\pi)$$

$$B^- \to D^{**0}(\to D^{*+}\pi^-)\ell\nu$$
$$B^- \to D^{**0}(\to D^{+}\pi^-)\ell\nu$$
$$B^0 \to D^{**-}(\to D^{*0}\pi^-)\ell\nu$$
$$B^0 \to D^{**-}(\to D^{0}\pi^-)\ell\nu$$

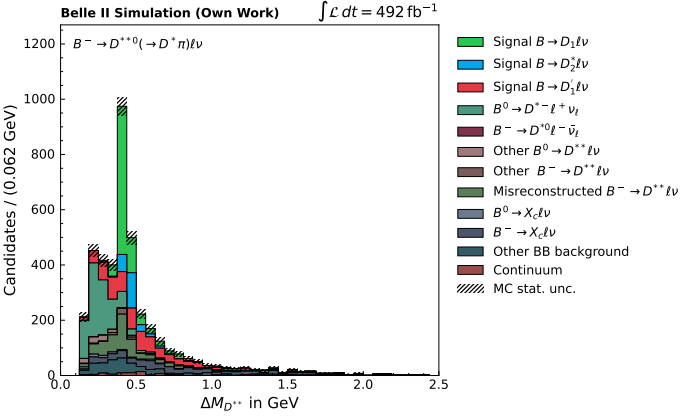
$$D^{*+} \to D^0\pi^+$$
$$D^{*0} \to D^0\pi^0$$

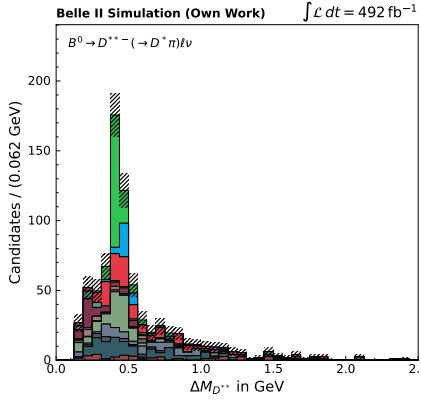
hadronic decay channels using FEI



FEI: **F**ull **E**vent **I**nterpretation $\quad \Delta M_{D^{**}} = (M_{D^{**}} - M_{D^*})$

$B \to D^* \pi \ell \nu$

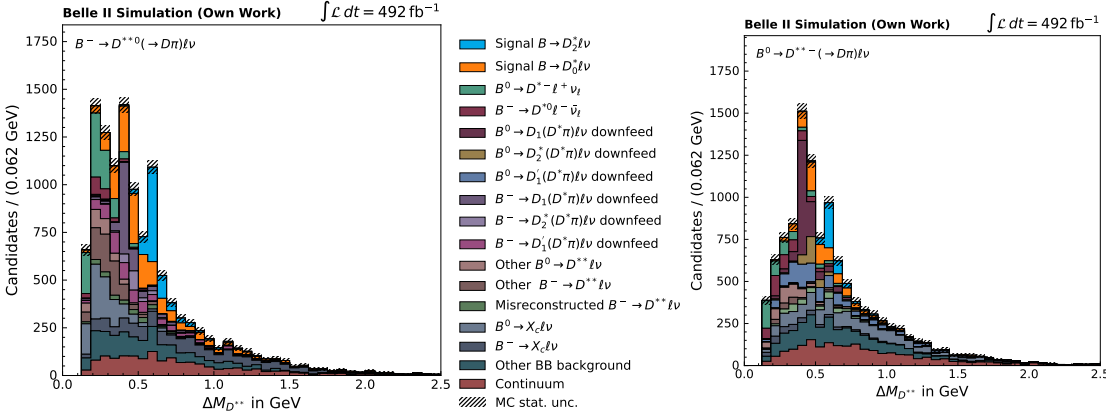




Dominant backgrounds

- Misreconstructed $B \to D^{**}(D^*\pi)\ell\nu$
- $B \to D^* \ell\nu$

$B \to D\pi\ell\nu$



Dominant backgrounds

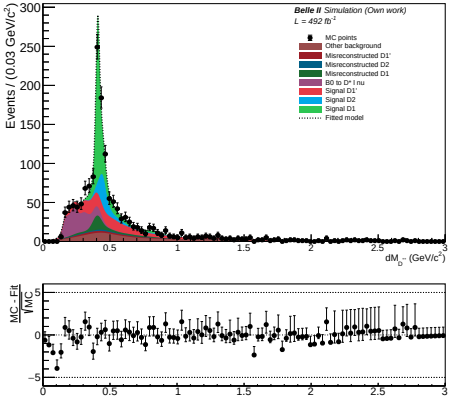
- $B \to D^{**}(D^*\pi)\ell\nu$ downfeed
- Other $B \to D^{**}\ell\nu$ downfeed, e.g. $D^{**} \to D\pi\pi$ or $D^{(*)}\pi^0$
- $B \to D^*\ell\nu$

$B^- \to D^{(*)}\pi\ell\nu$ simultaneous fit

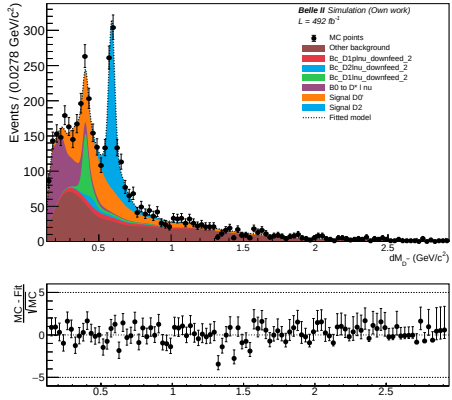
Downfeed/Signal rates obtained from $1.1\,\mathrm{ab}^{-1}$ *of Monte Carlo:*

D_1	D_2^*	D_1'
0.528	0.47	0.510

B- to D* pi l nu plot



B- to D pi l nu plot

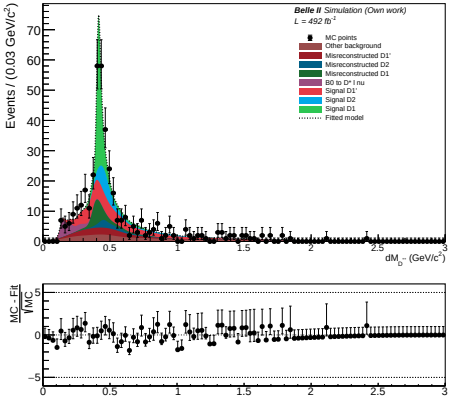


$\bar{B}^0 \to D^{(*)}\pi\ell\nu$ simultaneous fit

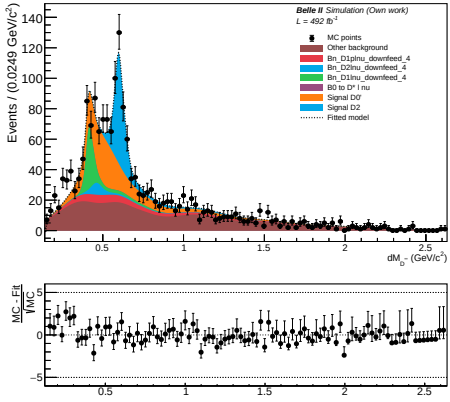
Downfeed/Signal rates obtained from $1.1\,\mathrm{ab}^{-1}$ *of Monte Carlo:*

D_1	D_2^*	D_1'
1.38	1.11	1.38

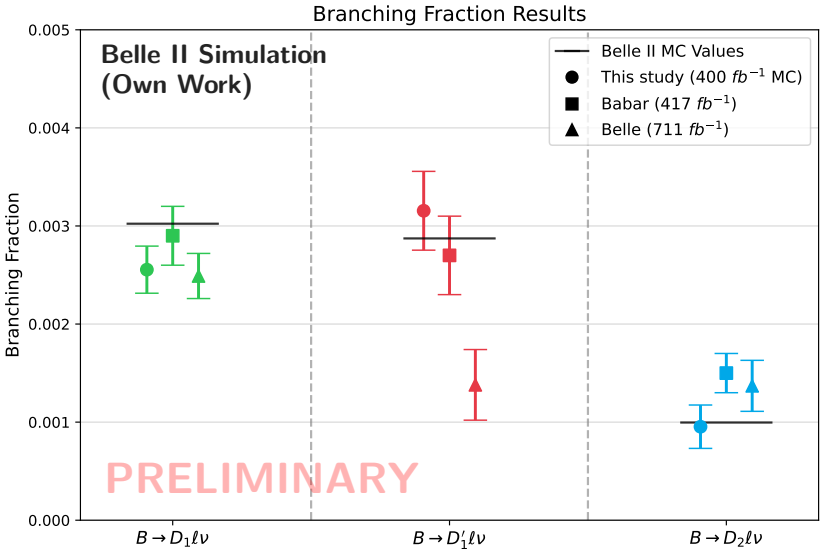
B0 to D* pi l nu plot



B0 to D pi l nu plot



Branching Fractions



Summary and Outlook

Summary

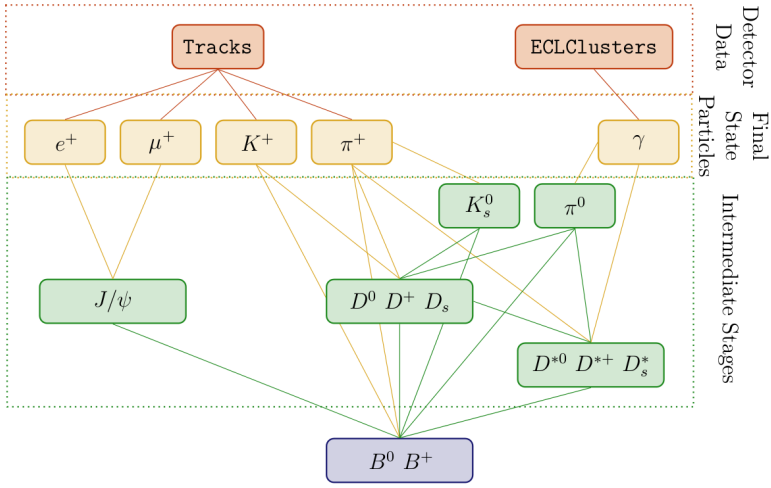
- **Goal:** Measure the product branching fraction: $\mathcal{B}(B \to D^{**}\ell\nu) \times \mathcal{B}(D^{**} \to D^{(*)}\pi)$
- **Motivation:** Improve precision of the result to resolve $1/2 - 3/2$ puzzle & constrain $R(D^*)$ backgrounds.
- **Method:** Unbinned ML fit to the $\Delta M_{D^{**}}$ variable across $D^{(*)}\pi$ modes.
- **Preliminary Result:** Optimized the measurement on simulation and obtained uncertainties comparable to previous experiments.

Outlook

- Validate Data-MC agreement in sideband regions.
- Finalize systematic uncertainties.
- Target finalization of the analysis by Summer 2027.

BACKUP

Full Event Interpretation



Online Selection: Reconstructed Modes

D^0 Modes ($\sim$ 27% BF)

1. $K^-\pi^+$
2. $K^-\pi^+\pi^0$
3. $K^-\pi^+\pi^+\pi^-$
4. $K^0_S\pi^+\pi^-$
5. K^-K^+
6. $\pi^+\pi^-$
7. $2K^0_S$
8. $K^0_S\pi^0$

D^+ Modes ($\sim$ 12% BF)

1. $K^-\pi^+\pi^+$
2. $K^0_S K^+$
3. $K^0_S\pi^+$
4. $K^-K^+\pi^+$

K^0_S and π^0 Reconstruction

- K^0_S using the `stdKshorts` list with significanceOfDistance < 3 and $dM < 15$ MeV
- $\pi^0 \to \gamma\gamma$ Reconstructed with 40% efficiency cuts

Online Selection: Kinematic & Quality Cuts

Track Quality & PID

- All tracks: $|dr| < 2\,\text{cm}$ and $|dz| < 4\,\text{cm}$
- Tracks within CDC Acceptance (`thetainCDCAcceptance`)
- Lepton PID: `leptonIDNN` > 0.9 for e^+ and μ^+
- Hadron PID: `hadronIDNN` > 0.3 for K^+ and π^+

Tag-Side B & ROE

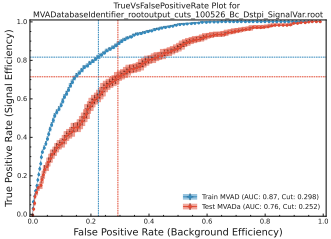
- B_{tag} selection taken from the recommendations for the hadronic FEI correction
- **Rest of Event (ROE):**
  $E_{extra} < 2.2\,\text{GeV}$
  $nCharged < 2$

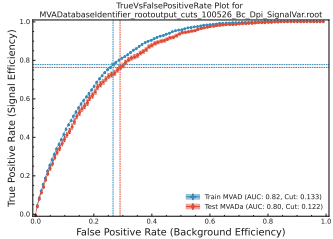
Signal Kinematics

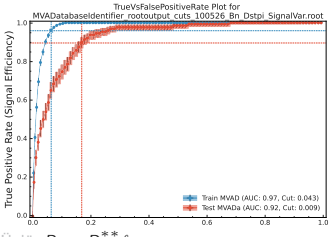
- M_D mass window at 3σ
- ΔM_{D^*} mass window at 3σ
- Soft π^- $p_{CMS} < 0.20\,\text{GeV}$
- Soft π^0 $p_{CMS} < 0.25\,\text{GeV}$
- Lepton $p_{lep}^{CMS} > 0.4\,\text{GeV}$
- cosThetaBY $\in [-5, 5]$

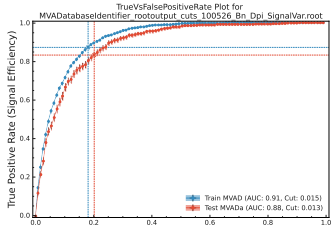
Background Suppression: BDT Training

Trained four separate BDTs for the different reconstruction channels. Below are the ROC curves for the training:









Key Input Variables:

- **Kinematics:**
  M_D, ΔM_{D^*}, p_ℓ^{CMS}
- **Tag-Side (B_{tag}):**
  M_{bc}, ΔE, Signal Prob.
- **B_{sig}**
  Vertex fit χ^2
- **Mode-Specifics:**
  Slow π momenta, D^* helicity, π^0 cluster variables

Background Suppression: Cut Optimization

Apply cut on the BDT output which maximizes significance $S/\sqrt{S+B}$: