Search for the unobserved $B^0 \to K_s^- \rho^+$ decay and π^0 investigation of the reconstruction Performance at LHCb during Run 3

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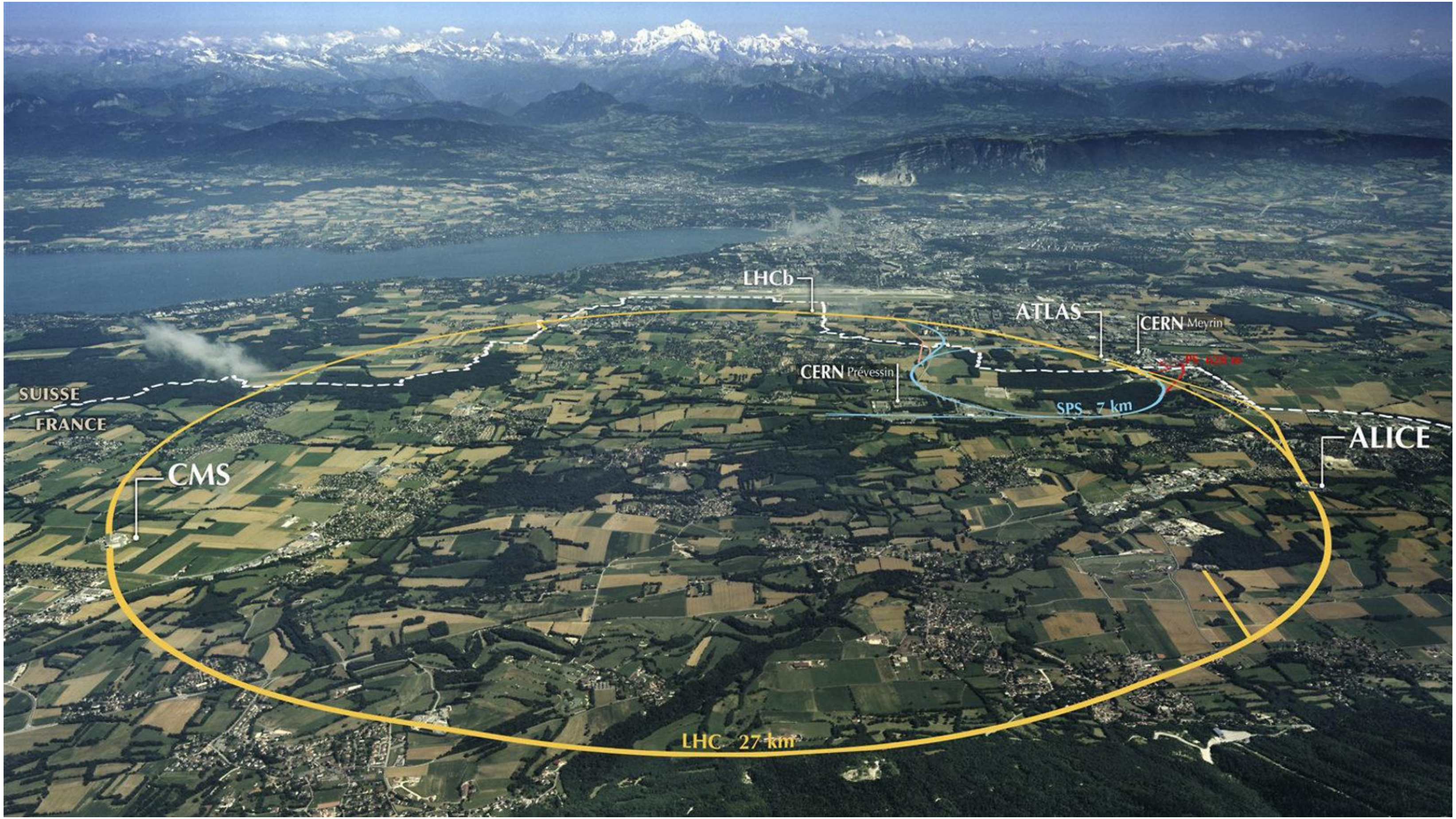
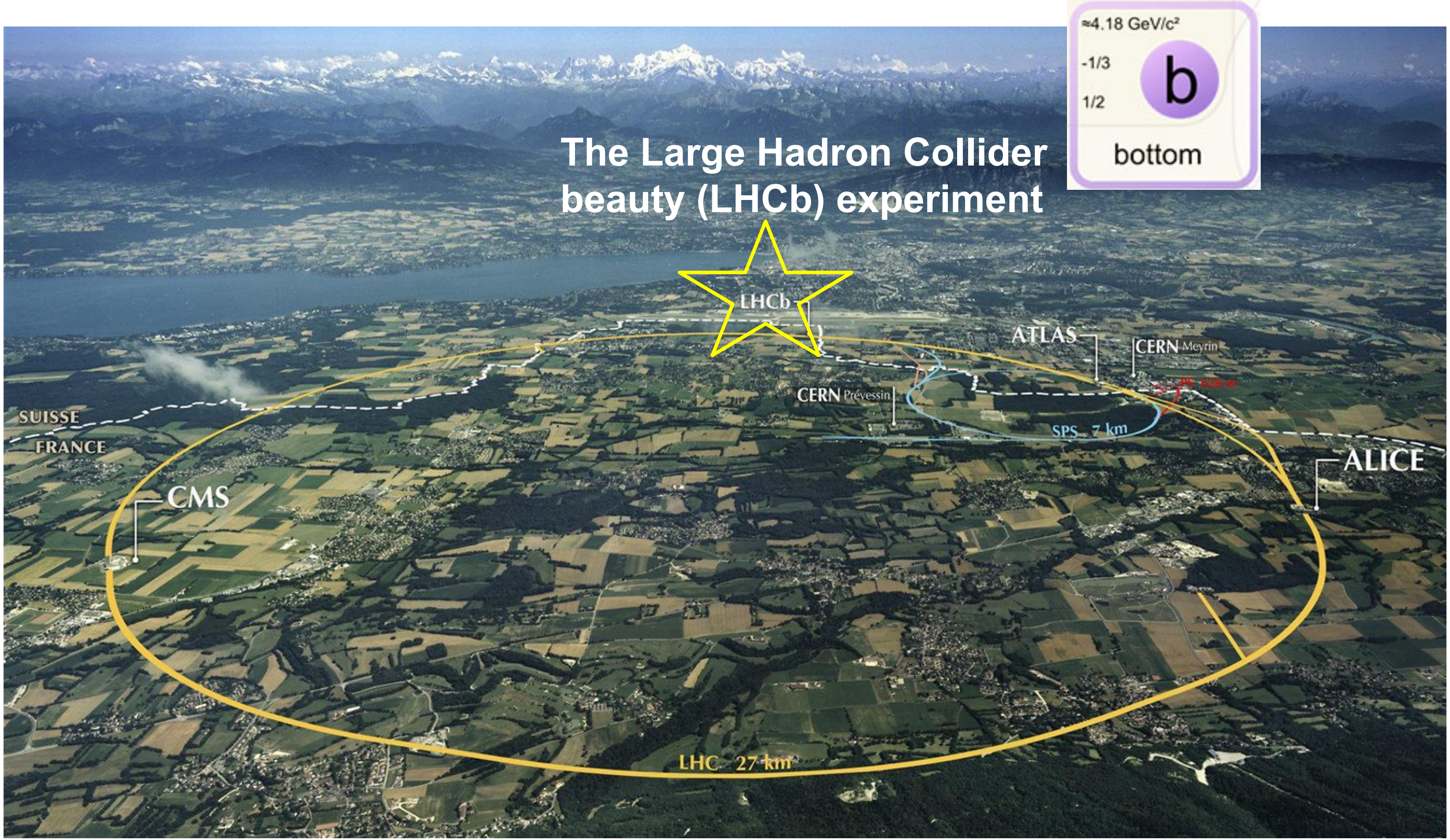
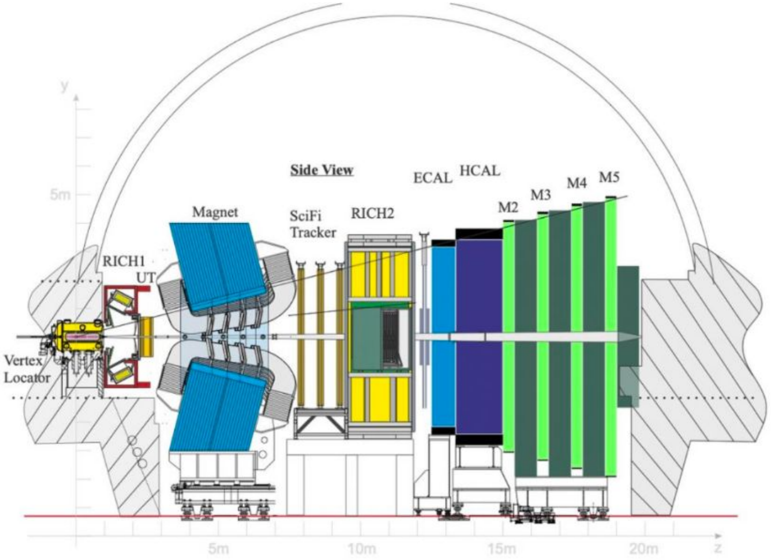

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SUISSE
FRANCE
SPS 7 km
ALICE
CMS
LHC 27 km

The Large Hadron Collider beauty (LHCb) experiment



Large Hadron Collider beauty experiment

LHCb detector

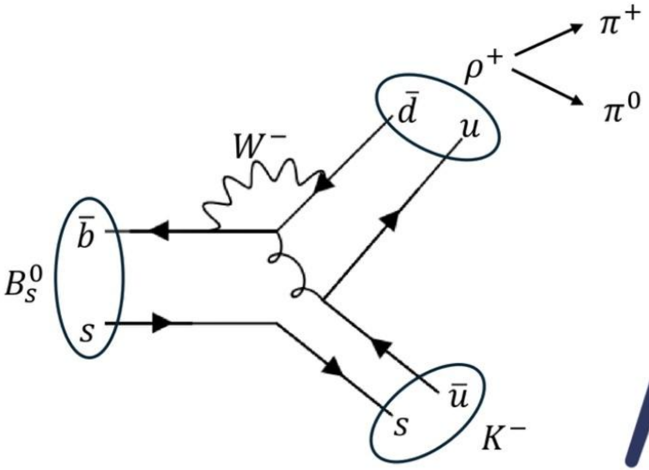


specializes in investigating the slight differences between matter and antimatter by studying a type of particle called the "**beauty quark**", or "**b quark**".

- **Vertex Locator (VELO):** pinpoints the origin of particles to identify decay vertices
- **Tracking detectors (UT & SciFi):** reconstruct the paths of charged particles like $K^{\pm}$, $\pi^{\pm}$
- **Magnet:** bends charged particles to measure their momentum
- **RICH detectors:** identify particle types (e.g. kaons vs pions) using Cherenkov radiation
- **ECAL (Electromagnetic Calorimeter):** detects photons from $\pi^0 \to \gamma\gamma$, essential for neutral pion reconstruction
- **HCAL (Hadronic Calorimeter):** measures hadronic energy (less relevant for this decay)
- **Muon system (M2–M5):** identifies muons (not used directly in this analysis)

Why π^0 Reconstruction ?

$$B_s^0 \rightarrow K^-\rho^+ \quad \text{where} \quad \rho^+ \rightarrow \pi^+\pi^0 \text{ and } \pi^0 \rightarrow \gamma\gamma$$



- The decay $B_s^0 \rightarrow K^-\rho^+$ includes a neutral pion π^0, which decays promptly into two photons ($\gamma\gamma$)
- Accurate π^0 reconstruction is essential for:
  - Reconstructing the full decay chain
  - Improving mass resolution
  - Enhancing signal-to-background separation

A key challenge :

- reconstruction π^0 relies entirely on ECAL, with limited resolution and high background rates
- $B^0 \rightarrow K^+\rho^-$ have a higher yield, it would be very challenging to directly see the Bs peak as it may hide in the B^0 tail.

Electromagnetic CALorimeter (ECAL)

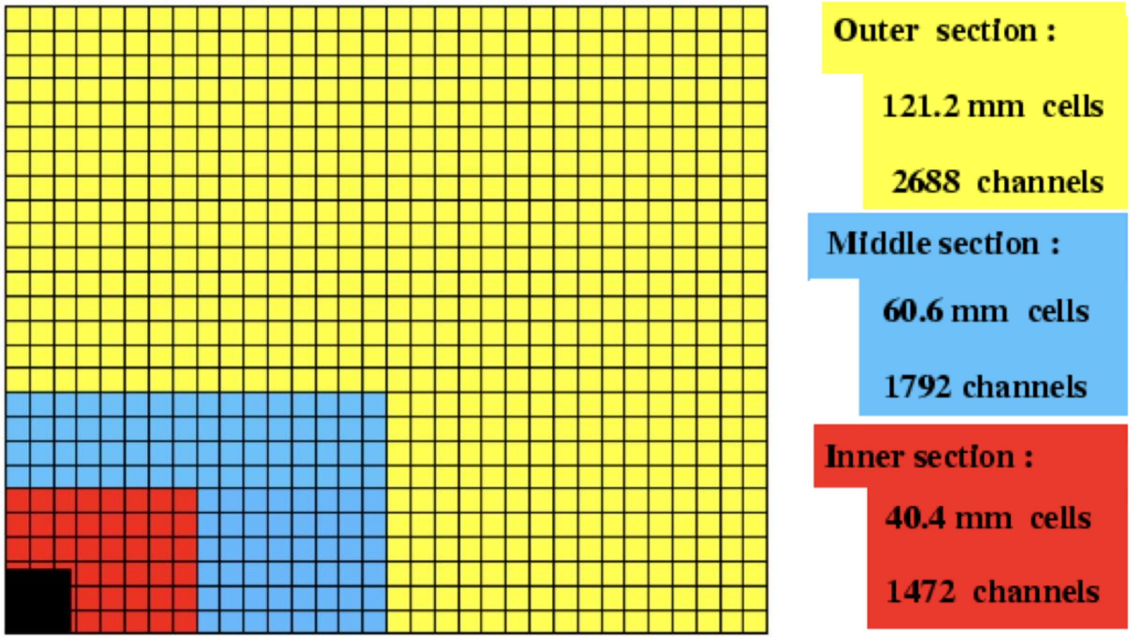
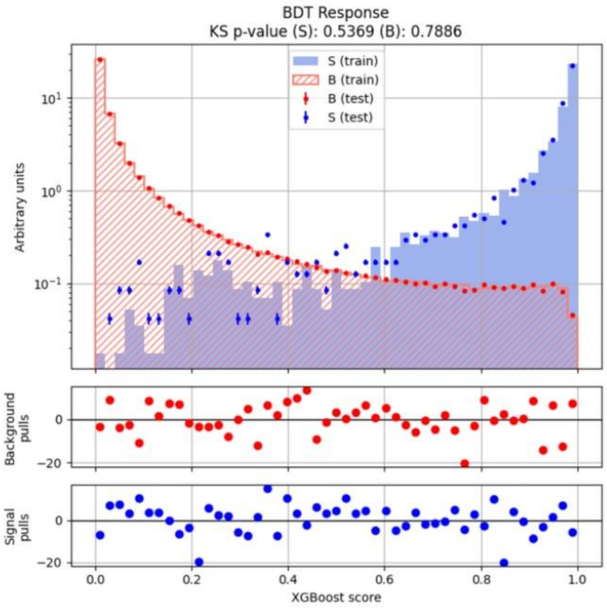


Fig 1 : Calorimeter cells segmentation of the ECAL (LHCb Calorimeter group, 2020, p.3)

Using Machine Learning to Help

- The goal is to reduce **combinatorial background** (random combinations of particles that mimic real decays)
- Machine learning is applied to improve signal-background separation, specifically using a **Boosted Decision Tree (BDT)**
- The BDT is trained using:
  - **Simulated signal** (where we know the particles really come from the decay)
  - **Background from data** in sideband regions (where we expect only random combinations)
- It uses many input variables (features) like particle energy, position, and angles to learn the difference
- This helps **separate true signal from background**, improving our ability to search for the decay



Truth matching (Run 2)

Data
h1_ID = 321
h2_ID = -211
Pi0_ID = 111
Pi0_gam1_ID = 22
Pi0_gam2_ID = 22

MC	
h1_ID = 321	h2_TRUEID = - 211
h2_ID = -211 Pi0_ID = 111 Pi0_gam1_ID = 22 Pi0_gam2_ID = 22 h1_TRUEID = 321	hB_BKGCAT = 0 | (hB_BKGCAT = 50 & Pi0_gam1_TRUEID = 22 & Pi0_gam2_TRUEID = 22 & Pi0_TRUEID = 111 & (Pi0_MC_MOTHER_ID = -511 | Pi0_MC_MOTHER_ID = 511))

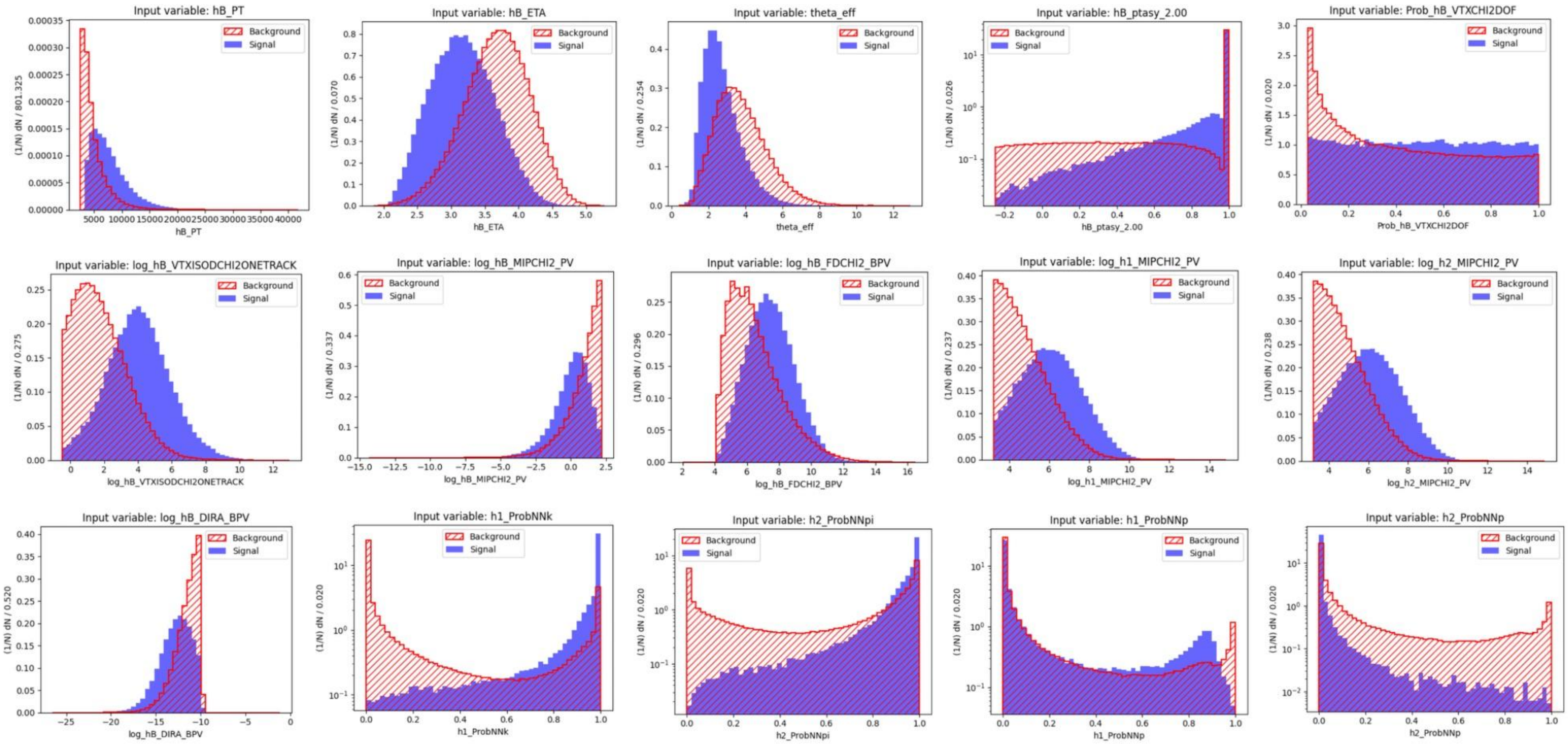
Particle ID	Particle
321	K^+
211	π^+
111	π^0
22	γ
511	B^0

Preselection and Veto cut (Run2)

Preselection
Prob(hB_VTXCHI2DOF) > 0.03
hB_ptasy_2.00 > - 0.25
Pi0_CL > 0.20
Tot_IsNotE > 0.10
IsMuon != 1
Log(hB_VTXISODCHI2ONETRACK) > - 0.5
hB_MIPCHI2_PV < 9
hasRich != 0
2590 MeV/c^2 ≤ h_P ≤ 100000 MeV/c^2

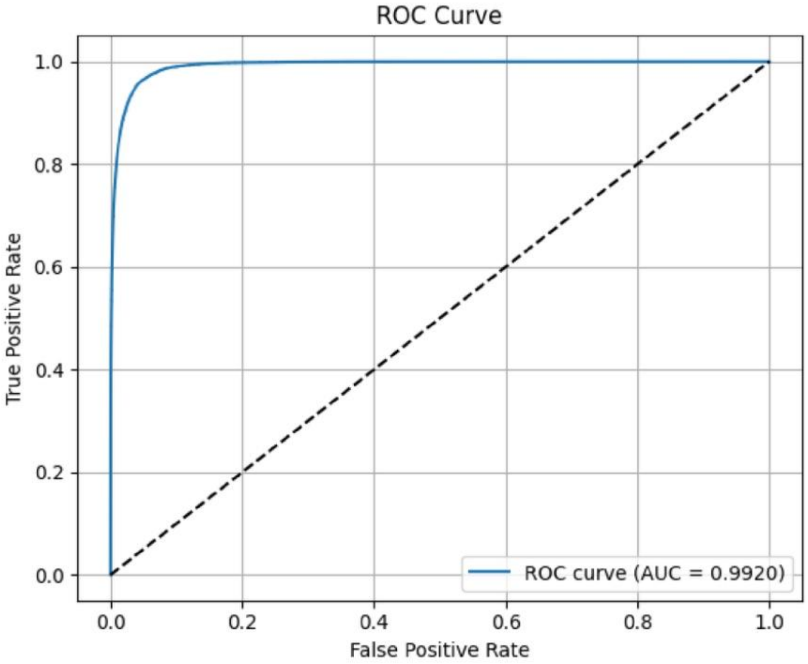
Veto cut
$\left\|m_{K^\pm\pi^\mp} - m_{D^0}\right\| > 30\ \mathrm{MeV}/c^2$
$\left\|m_{K^\pm\pi^\mp} - m_{B^0}\right\| > 50\ \mathrm{MeV}/c^2$
$\left\|m_{\pi^\pm\pi^0} - m_{D^\pm}\right\| > 60\ \mathrm{MeV}/c^2$
$\left\|m_{K^\pm\pi^0} - m_{D_S^\pm}\right\| > 60\ \mathrm{MeV}/c^2$
$\left\|m_{K^\pm\pi^0} - m_{B^\pm}\right\| > 102\ \mathrm{MeV}/c^2$

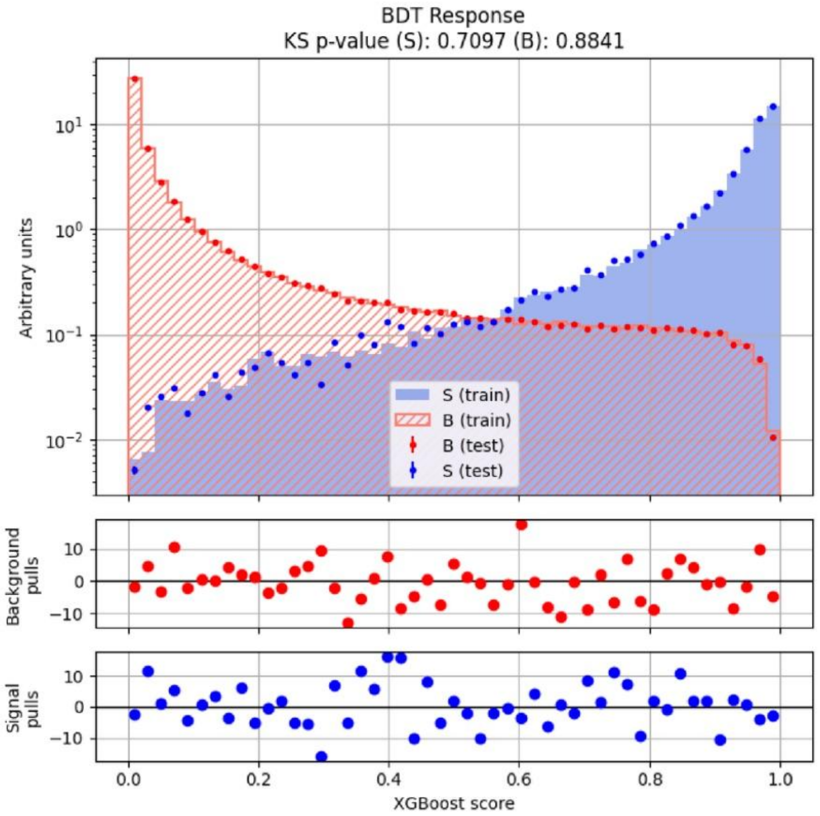
Training variables (Run 2)



ROC Curve & BDT response (Run 2)

sideband :
hB_pi0constPVconst_M > 5600 MeV





Truth matching (Run 3)

Data and simulation are only from <u>block7 and block8 from run 3</u>

Data
|hp_ID| = 321
|hm_ID| = 211
pi0_ID = 111
g1_ID = 22
g2_ID = 22

MC	
|hp_ID| = 321	|hm_TRUEID| = 221
|hm_ID| = 211 pi0_ID = 111 g1_ID = 22 g2_ID = 22 |hp_TRUEID| = 321	B_BKGCAT = 0 | (B_BKGCAT = 50 & g1_TRUEID = 22 & g2_TRUEID = 22 & pi0_TRUEID = 111 & (pi0_MC_MOTHER_ID = -511 | pi0_MC_MOTHER_ID = 511))

Particle ID	**Particle**
321	K^+
211	π^+
111	π^0
22	γ
511	B^0

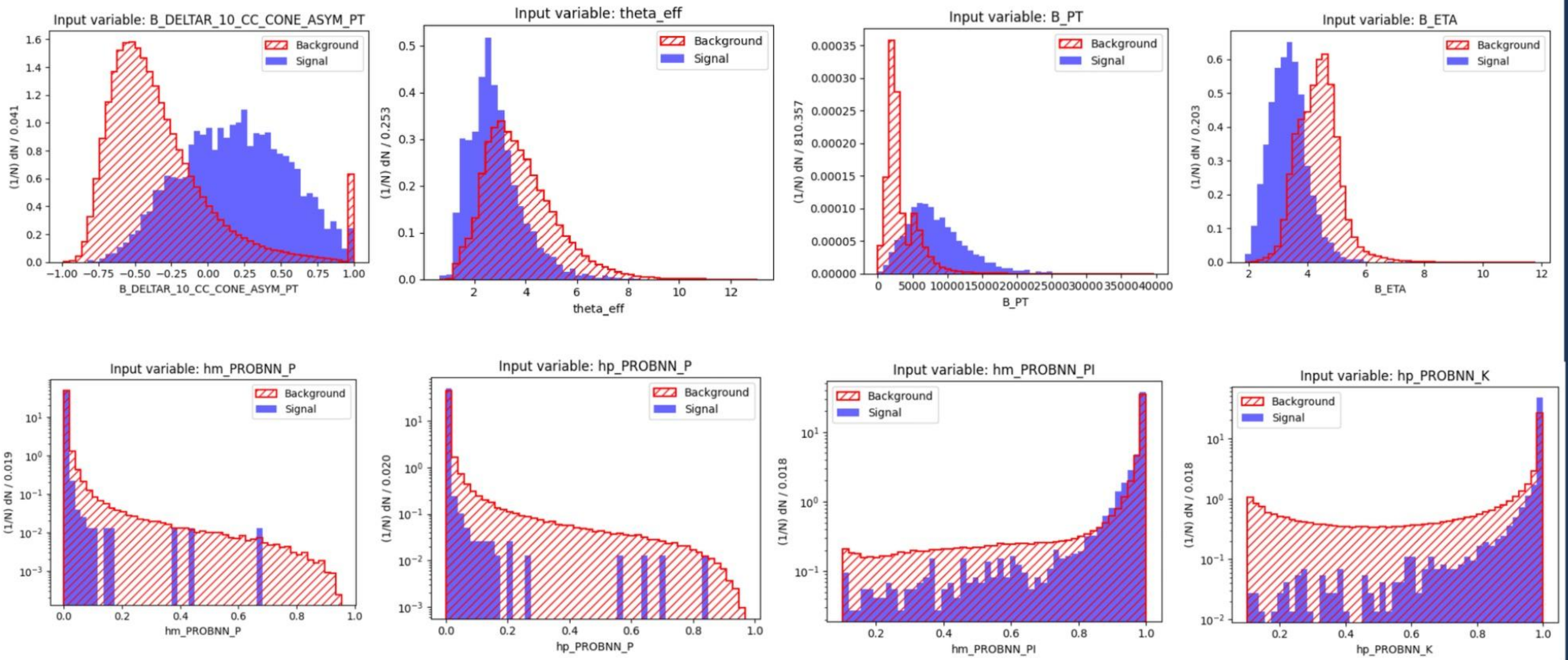
Preselection and Veto cut (Run3)

Preselection
Prob(B_VTXCHI2DOF) > 0.03
B_DELTAR_004_CC_CONE_ASYM_PT > - 0.25
Pi0_CL > 0.20
0 < B_MIN_BPVIPCHI2 < 40000
ISMuon != 1
OWNPVIPCHI2 > 0
B_OWNPVIPCHI2 < 10
PPHASRICH != 0
2590 MeV/c^2 ≤ h_P ≤ 100000 MeV/c^2
hp_PROBNN_K > 0.1
hm_PROBNN_PI > 0.1

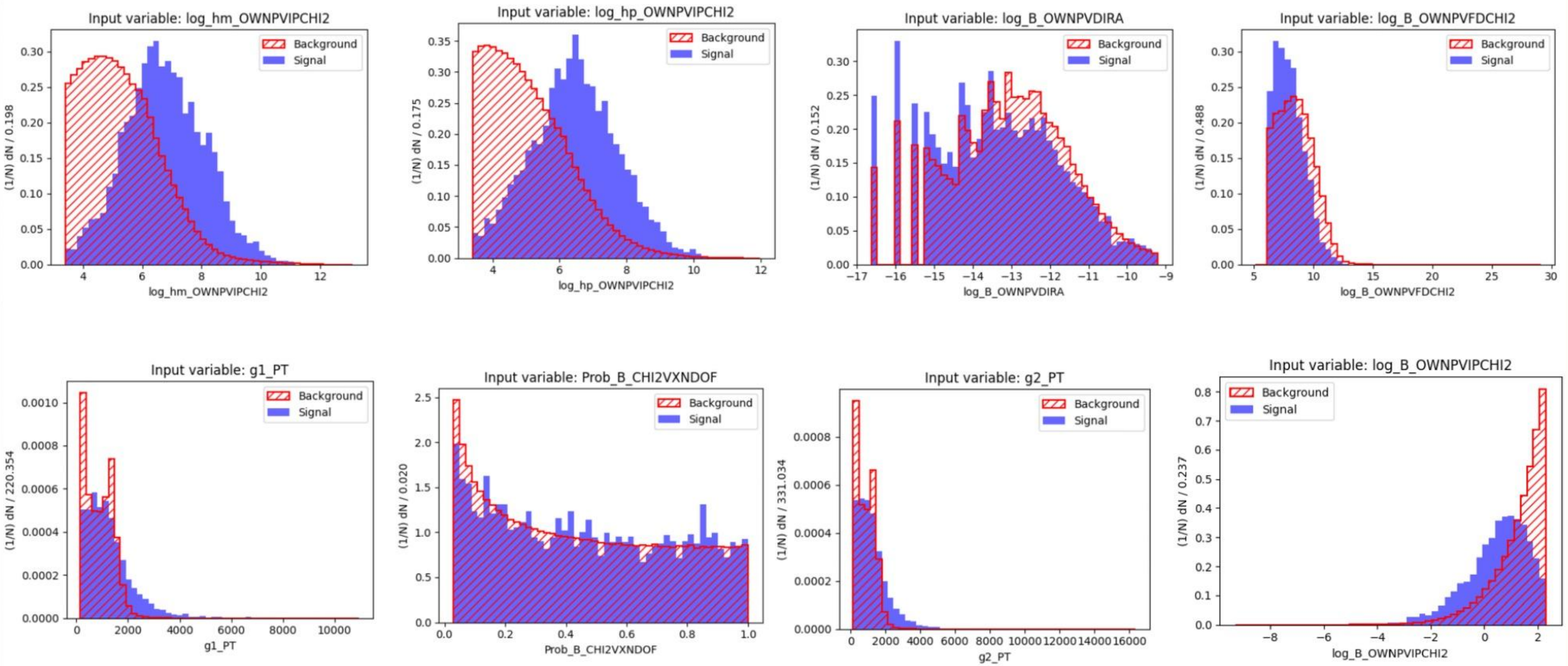
Preselection
nPVs ≤ 4
IS_NOT_H > 0.4
hp_PROBNN_K > 0.1
hm_PROBNN_PI > 0.1

Veto cut
$\left\|m_{K^\pm\pi^\mp} - m_{D^0}\right\| > 30\ \mathrm{MeV}/c^2$
$\left\|m_{K^\pm\pi^\mp} - m_{B^0}\right\| > 50\ \mathrm{MeV}/c^2$
$\left\|m_{\pi^\pm\pi^0} - m_{D^\pm}\right\| > 60\ \mathrm{MeV}/c^2$
$\left\|m_{K^\pm\pi^0} - m_{D_s^\pm}\right\| > 60\ \mathrm{MeV}/c^2$
$\left\|m_{K^\pm\pi^0} - m_{B^\pm}\right\| > 102\ \mathrm{MeV}/c^2$

Training variables (Run 3)



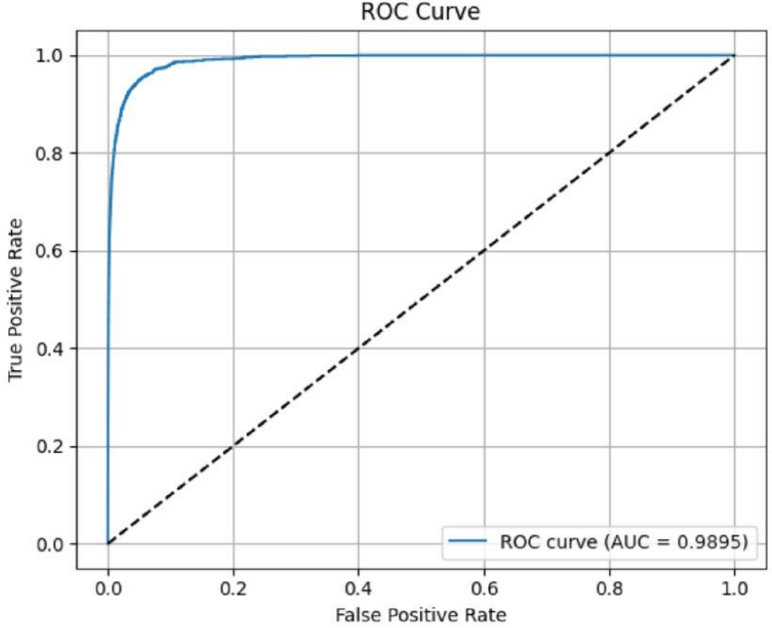
Training variables (Run 3)

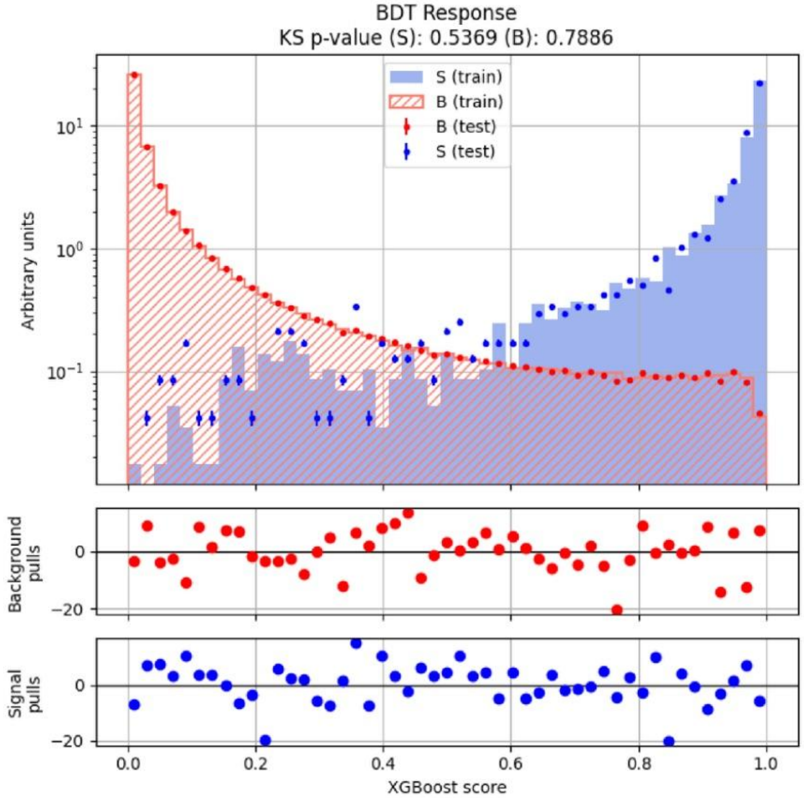


ROC Curve & BDT response (Run 3)

sideband :

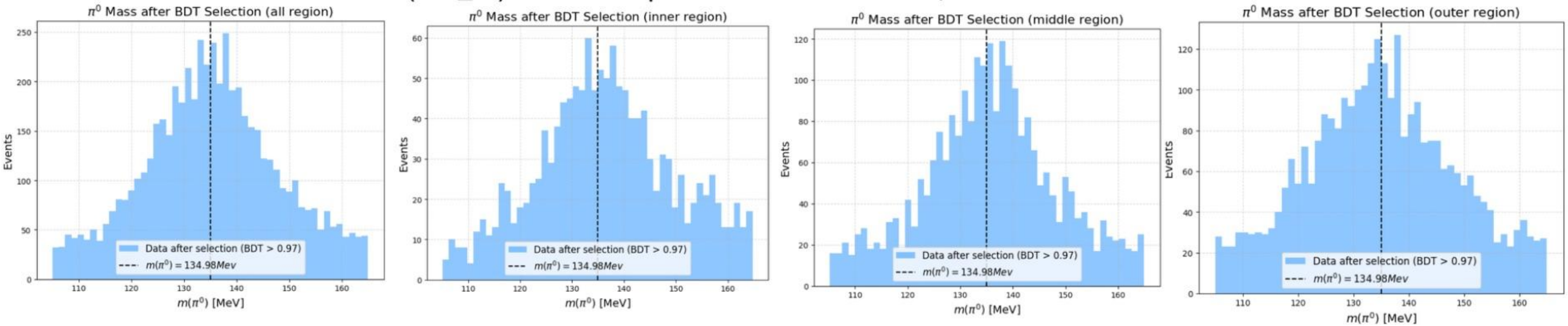
B_OwnPV_MASS > 5600 MeV



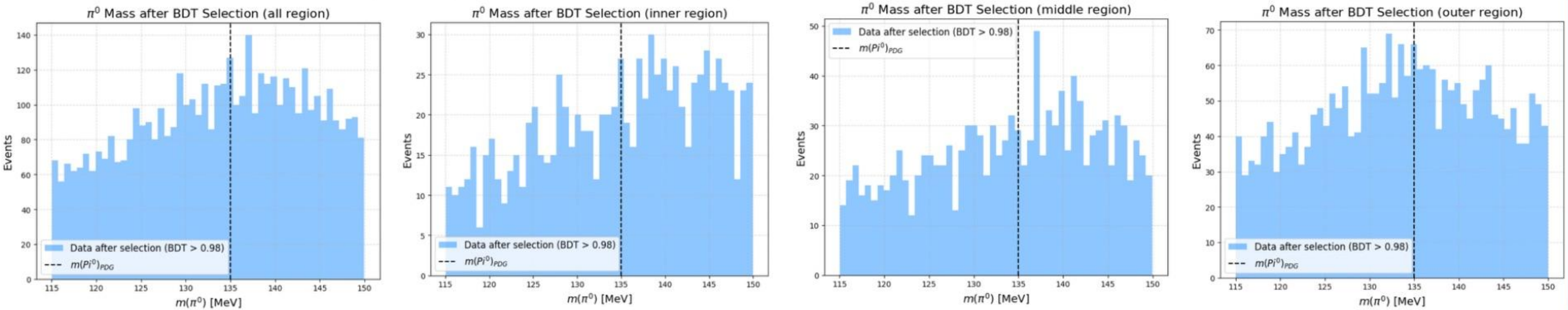


π^0 mass distribution

Run2 (Pi0_M) : clear π^0 peak around 135 MeV, consistent with PDG

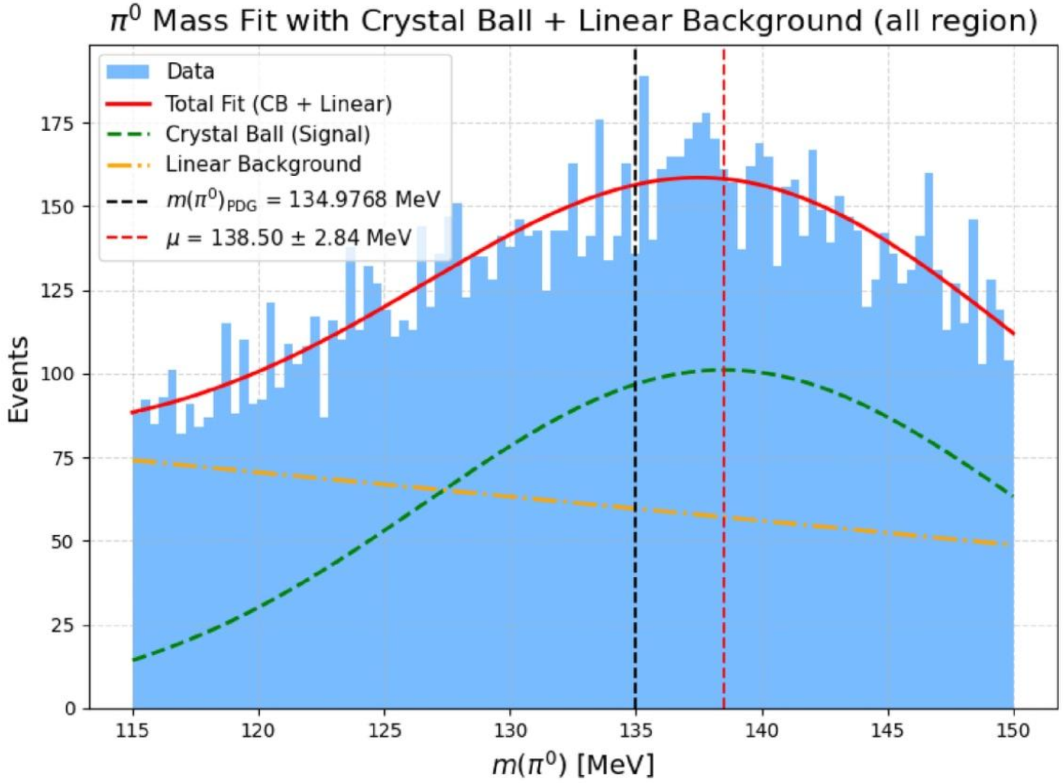


Run3 (pi0_M) : Mass peak shifts upward, especially in all/inner regions.



Key point: Reconstruction quality differs between runs → possible calibration/cluster effects in ECAL.

π^0 mass distribution fit (Run 3)



The fit provides only an approximate estimate of the mean due to the limited π^0 mass window, therefore, the result should not be interpreted as a precise determination.

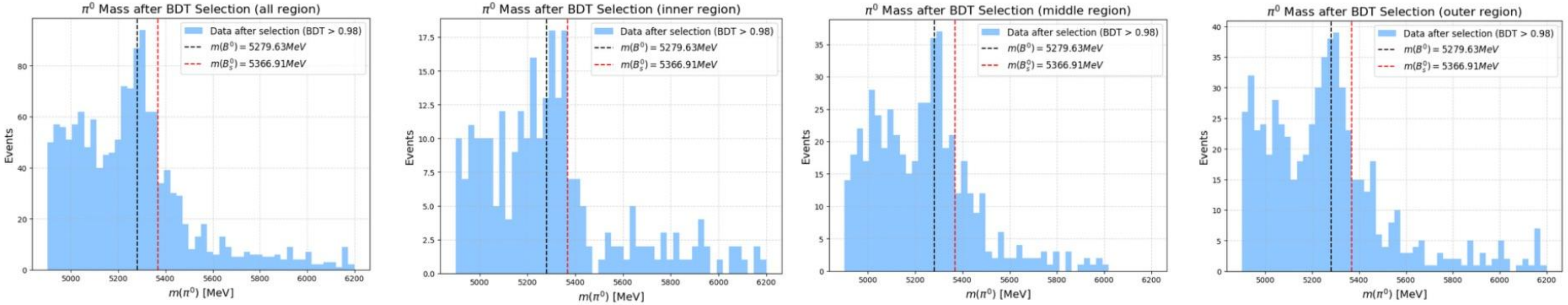
Peak measured at **138.5 ± 2.8 MeV**

higher than PDG 134.9768 MeV

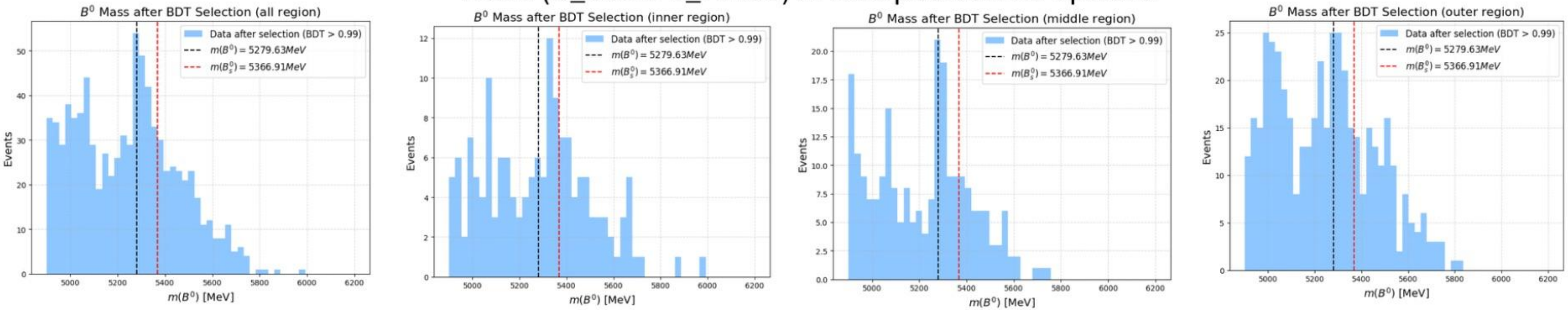
systematic **bias** in Run 3 π^0 reconstruction

B^0 mass distribution

Run2 (hB_M) : Peak close to B^0 mass (5279 MeV).



Run3 (B_OwnPV_MASS) : Mass peak shifts upward



Key point: B^0 mass shift follows π^0 bias → confirms π^0 reconstruction impacts final B mass.

Conclusion

- **Run 2** : π^0 mass peaks sharply at PDG value,
  B^0 peak visible but shifted in different directions relies on region.
- **Run 3** : π^0 distributions broader and slightly shifted upward,
  B^0 peak is weaker and less separated from the background.
- **Comparison**: Both runs recover the expected mass features.
  Run 2 achieves good π^0 resolution, while Run 3 shows a decrease in reconstruction quality.

Thank you