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# Characterization of Hadronic Showers in the Belle II Electromagnetic Calorimeter

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# Outline

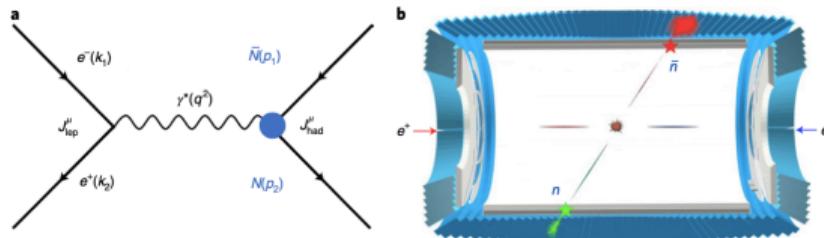


- 1. Anti-neutrons in physics experiments**
- 2. Preliminary study via signal Monte Carlo sample**
- 3. Study of Monte Carlo cocktail**
- 4. Outlook**

# Anti-neutron in HEP experiments

The  $\bar{n}$  plays a key role in several physics measurements, such as:

- The neutron e.m. form factor studies in  $e^+ + e^- \rightarrow n + \bar{n}$  process



- Some decay channels studied at B-factories which involve  $\bar{n}$ 
  1. The hyperons decay channel:
$$\bar{\Lambda}^0 \rightarrow \pi^0 + \bar{n}, \quad \bar{\Sigma}^- \rightarrow \pi^- + \bar{n}, \quad \bar{\Lambda}_c \rightarrow K_s^0 + \pi^0 + \bar{n}$$
- Discrimination between other neutral particles ( $\gamma$ ) and  $\bar{n}$

# Anti-neutrons in astrophysics

The  $\bar{n}$  also plays a key role in several astrophysics measurements, such as:

- Studying  $\bar{n}$  - anti-hyperon potential to improve the understanding of the equation of state of the neutron stars
- Investigating dark matter through anti-deuterons ( $\bar{D}$ ) in cosmic rays, produced by dark matter annihilation or decay

$A_{d.m.} + B_{d.m.} \rightarrow \text{hadrons } (n, \bar{n}, p, \bar{p} \text{ etc...})$

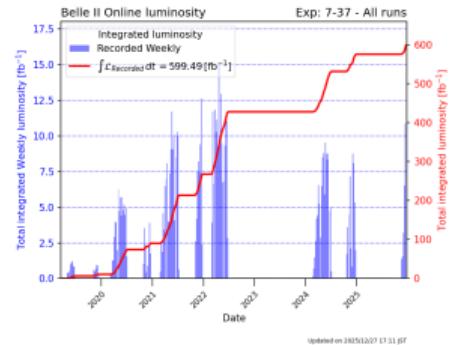
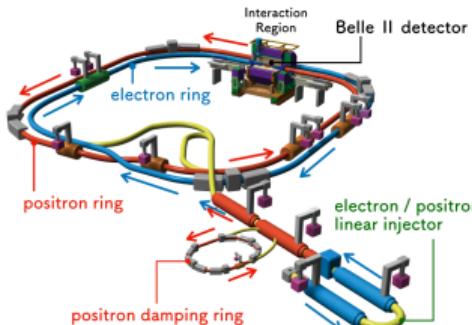
$X_{d.m.} \rightarrow \text{hadrons } (n, \bar{n}, p, \bar{p} \text{ etc...})$

$\bar{D}$  is mainly produced through a coalescence mechanism  $\bar{n} + \bar{p} \rightarrow \bar{D}$ , where  $\bar{p}$  and  $\bar{n}$  are nearby in the phase-space

# The Belle II experiment

SuperKEKB is an asymmetric  $e^+ e^-$  collider (Tsukuba, Japan)

- 7 GeV electron beam (HER)
- 4 GeV positron beam (LER)
- Peak Luminosity  $\sim 5.1 \times 10^{34} cm^{-2}s^{-1}$
- Design Luminosity  $\sim 8 \times 10^{35} cm^{-2}s^{-1}$   
→ x40 the Belle's one



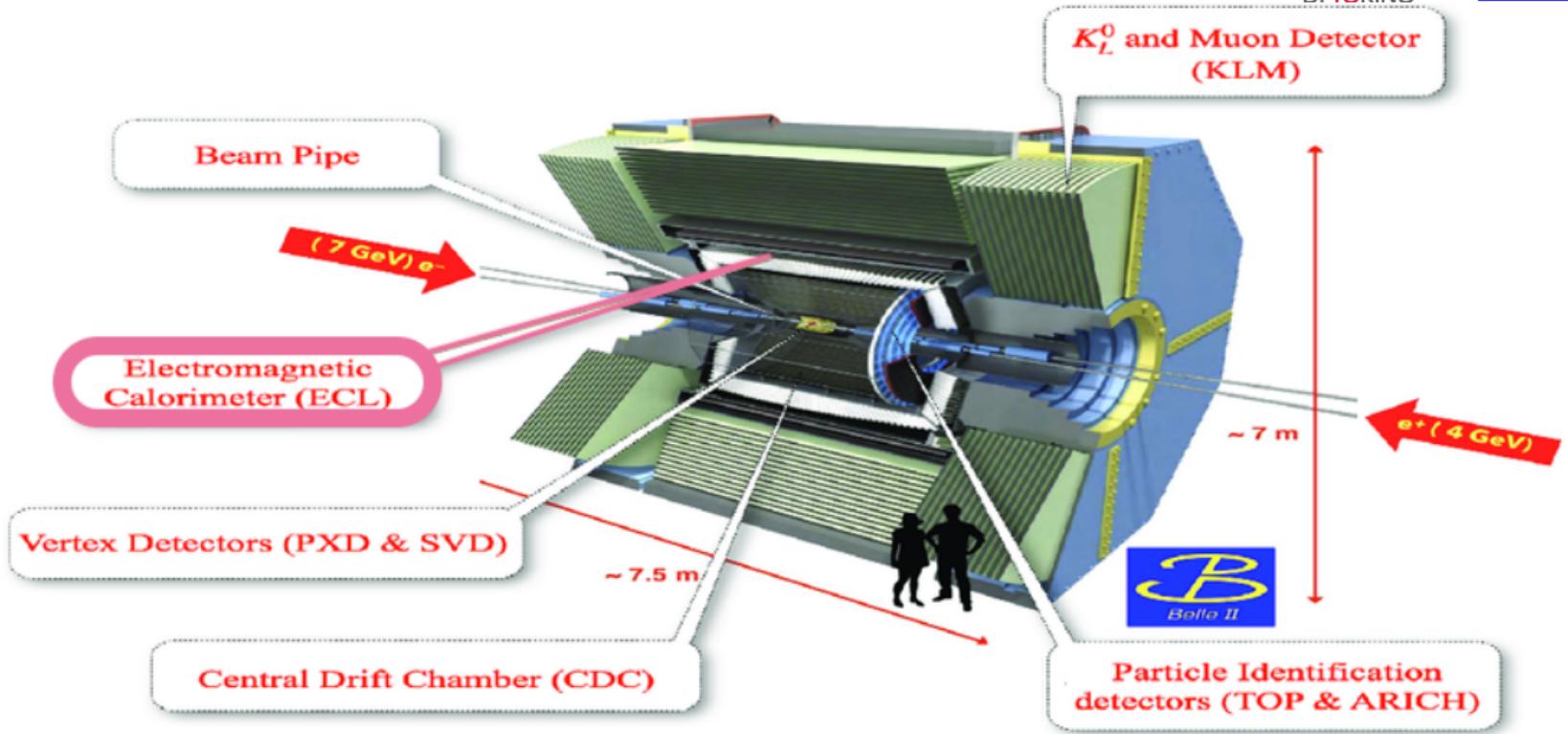
It operates mainly around  $\Upsilon(4S)$  resonance ( $\sim 10.58$  GeV):

- This resonance decays almost exclusively into entangled couples of  $B\bar{B} \rightarrow B$ -factory
- Several goals: flavour physics, BSM physics, heavy hadrons spectroscopy etc...

# The Belle II experiment



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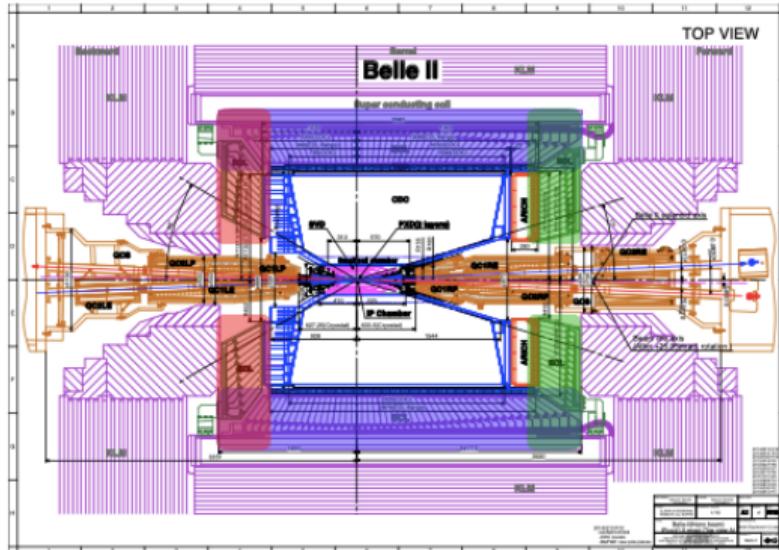


# The Electromagnetic Calorimeter

The ECL plays a central role in this thesis

- Array of **CsI(Tl)** crystals (8376  $6 \times 6 \times 30 \text{ cm}^3$  crystals in total)
- It covers barrel and end-cap regions ( $12^\circ \leq \theta \leq 155^\circ$ )
- Energy resolution of 4% @100 MeV and 1.6% @8 GeV

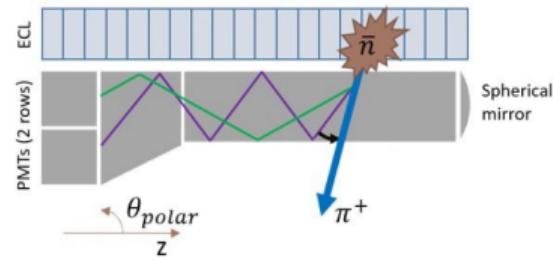
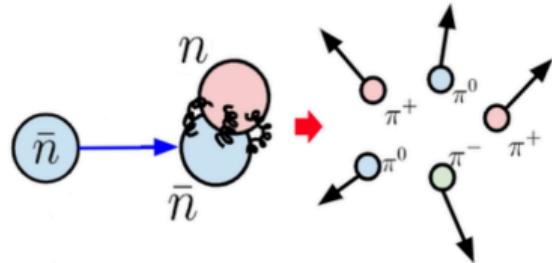
Barrel  
FWD endcap  
BWD endcap



# Anti-neutron interactions in physics

The  $\bar{n}$  interacts primarily via strong nuclear force, producing hadronic showers  
It can annihilate with nucleons in the ECL, producing light mesons (mainly pions)

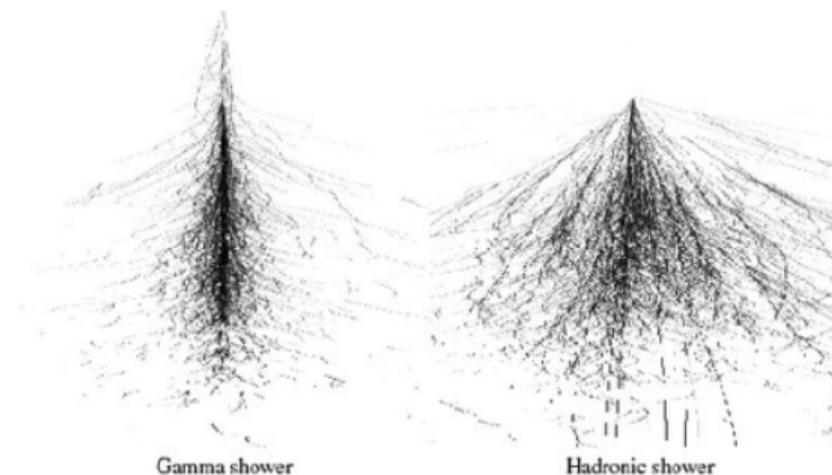
- $\pi^0$  decays into  $\gamma\gamma$ , producing electromagnetic showers that are fully contained in the ECL
- $\pi^\pm$  undergo hadronic interactions, which are not fully contained in the ECL → both the forward (KLM) and backward (TOP) directions are involved



# Electromagnetic and hadronic showers

Different processes occur for electromagnetic and hadronic showers:

1. Bremsstrahlung and pair production process ( $e^+, e^-, \gamma$ ) and  $\pi^0 \rightarrow \gamma\gamma$
  2. Strong interactions of hadrons with the material ( $p, n, pions, kaons...$ )
- 
- About the 95% of the hadronic shower is contained within a cylinder of radius  $\lambda_{had}$  ( $\sim 44.12$  cm in CsI(Tl))
  - About the 90% of the e.m. shower is contained within a cylinder of radius  $R_M$  ( $\sim 3.6$  cm in CsI(Tl))



# The MANTRA project (PRIN2022)

Measuring Anti-Neutron: Tagging and Reconstruction Algorithm



- A general method to measure the  $E_{\bar{n}}$  up to 10 GeV, by combining information from:
  1. A detector with high time resolution (TOP)
  2. An electromagnetic calorimeter (**ECL**)
  3. A muon system (KLM)
- These features are common in modern general-purpose collider experiments such as **Belle II** and BESIII, which do not have a dedicated calorimeter
- For MANTRA project, only signals from ECL and TOP are taken into account. In this thesis only ECL signals are studied

**Are  $\bar{n}$  hadronic showers correctly simulated in the Belle II software?**

# The MANTRA project

Anti-neutrons cannot be reconstructed by sub-detectors.

The measurement of the energy is a two-step process:

1.  $\bar{n}$  identification via its induced ECL clusters (study of the shower shape)
2. Combine the signals from TOP and ECL to reconstruct the  $\bar{n}$  energy, in cases of backscattering or pre-showering
  - If only  $\pi^0$  ( $\sim 5\%$ ) are produced energy is all contained in the calorimeter, the shower is fully reconstructed
  - Otherwise ( $\sim 95\%$ ): the products may escape the crystals  
→ the goal is to complement the calorimeter information with that from the adjacent detectors

# Preliminary concept

Several channels can be selected to look at  $\bar{n}$  annihilations, such as:

- $e^+ + e^- \rightarrow p + \bar{n} + \pi^- + (\gamma_{ISR})$  (Mine)
- $\bar{\Lambda}_c \rightarrow K_s^0 + \pi^0 + \bar{n}$
- $\Lambda(\rightarrow p + \pi^-) + \bar{\Lambda}(\rightarrow \bar{n} + \pi^0)$

Several variables can be used to validate the showers shape for  $\bar{n}$  identification, such as:

- **Zernike Moments** (backup)
- **Lateral momentum** defined as:  $C_{LM} = \frac{\sum_{i=2}^n \omega_i E_i r_i^2}{\omega_0 E_0 r_0^2 + \omega_1 E_1 r_1^2 + \sum_{i=2}^n \omega_i E_i r_i^2}$
- **Second moment** defined as:  $C_{SM} = \frac{\sum_{i=0}^n \omega_i E_i r_i^2}{\sum_{i=0}^n \omega_i E_i}$

# Analysis outline

1. Study of the selected signal channel  $e^+ + e^- \rightarrow p + \bar{n} + \pi^- + (\gamma_{ISR})$ 
  - (a) Recoil identification from the system  $p + \pi^-$  (with and without ISR)
  - (b) Study of the kinematic recoil variables (momentum, angles, energy, etc...)
  - (c) Study of the effect of 1C kinematic fit over the recoil mass
  - (d) Study of ECL shower shape variables
2. Study of MC cocktail sample:
  - (a) Recoil identification from the system  $p + \pi^-$  (with and without ISR)
  - (b) Study of the kinematic recoil variables (momentum, angles, energy, etc...)
3. Study of real data sample:
  - (a) Recoil identification from the system  $p + \pi^-$  (with and without ISR)
  - (b) Constraint with 1C kinematic fit over the recoil mass
  - (c) Examine Data/MC agreement in ECL cluster shapes from  $\bar{n}$  channel

# Analysis outline (1)

- The analyzed channel is:

$$e^+ + e^- \rightarrow p + \bar{n} + \pi^- + (\gamma_{ISR})$$

The reconstructed particles are (cuts and selections in the next slide):

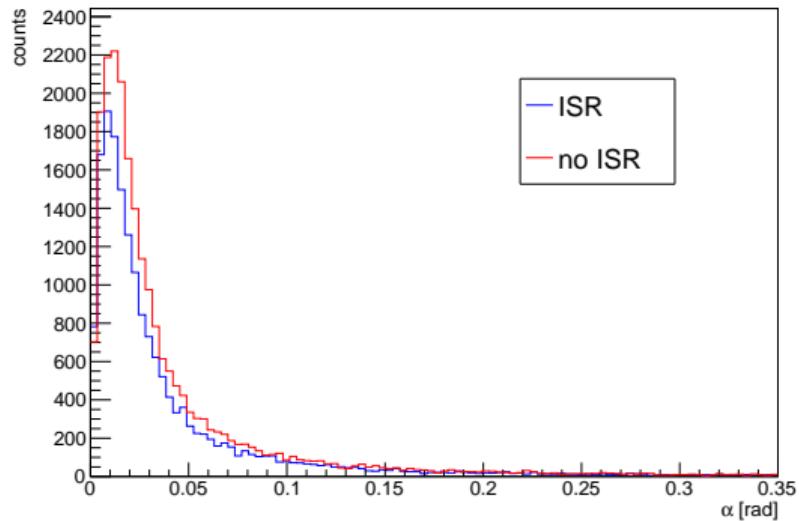
- (a)  $p + \pi^- + (\gamma_{ISR})$  which compose the recoil system
- (b) Neutral clusters associated to  $\bar{n}$  candidates list used to compare its variables with those of the recoil

- 100k events.** The reconstruction efficiency is:

$$\epsilon = \frac{n^{\circ} \text{ of reconstructed candidates}}{n^{\circ} \text{ of generated events}} \sim 22\% (18\%)$$

# Applied selections and cuts

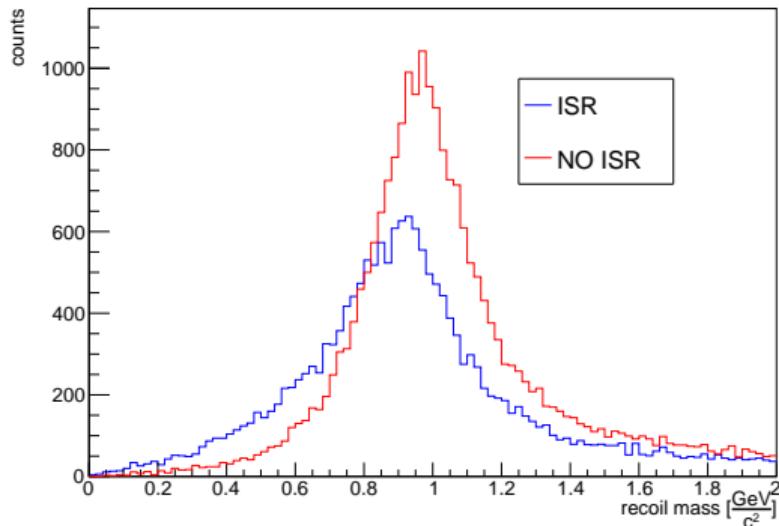
- (a) **proton**: standard PID selection, with tracks required to originate from the IP
- (b) **pion**: standard PID selection
- (c) **anti-neutron**: neutral clusters from ECL
- (d)  $0 \text{ GeV} < \text{recoil mass} < 2 \text{ GeV}$
- (e)  $\alpha < 0.35 \text{ rad} (\sim 20 \text{ deg})$



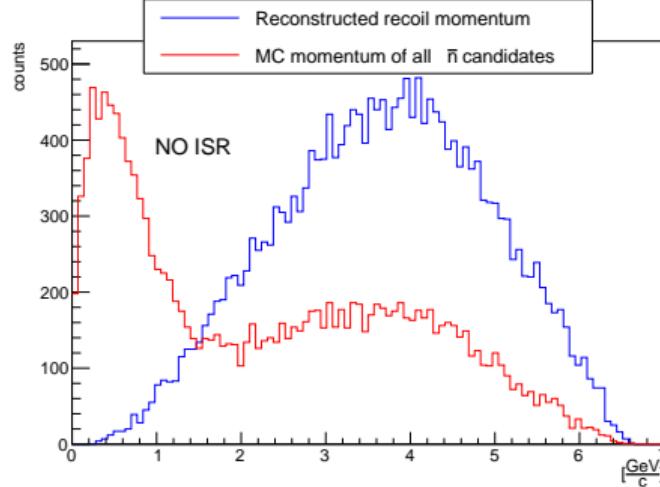
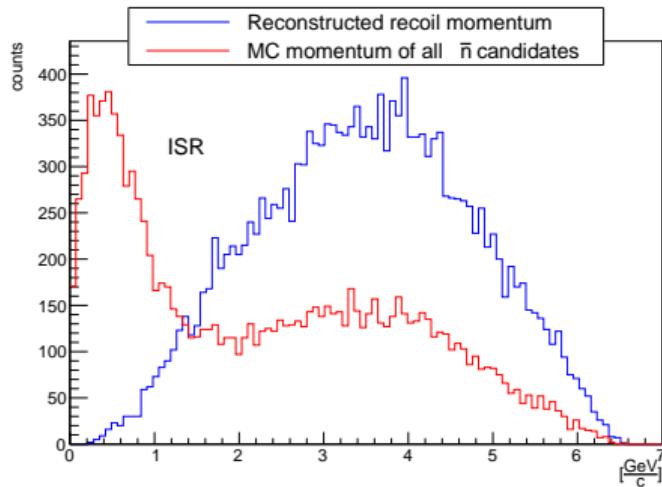
Where  $\alpha$  is the angle between the recoil vector direction and the closest  $\bar{n}$  cluster

# The recoil mass

- The recoil mass is well reconstructed in both ISR ( $p, \pi^-, \gamma_{ISR}$ ) and no ISR ( $p, \pi^-$ ) cases
  - Variables associated with the  $\bar{n}$  candidate clusters can be compared with the reconstructed recoil variables ( $p, \theta$ )
- Since there is more than one  $\gamma_{ISR}$  per event, the  distribution shows a higher number of entries in the left tail



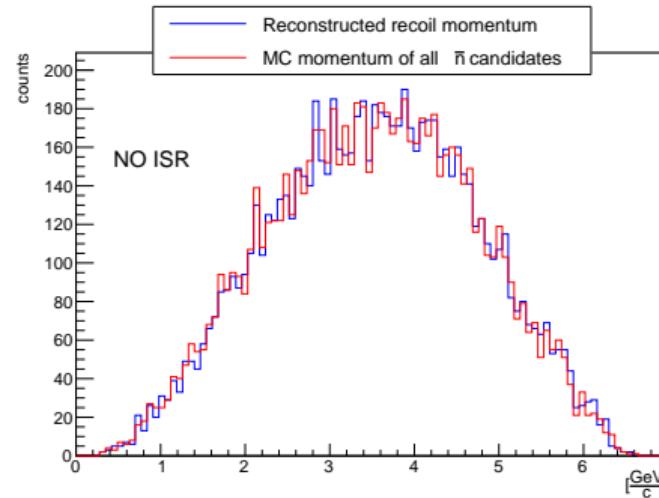
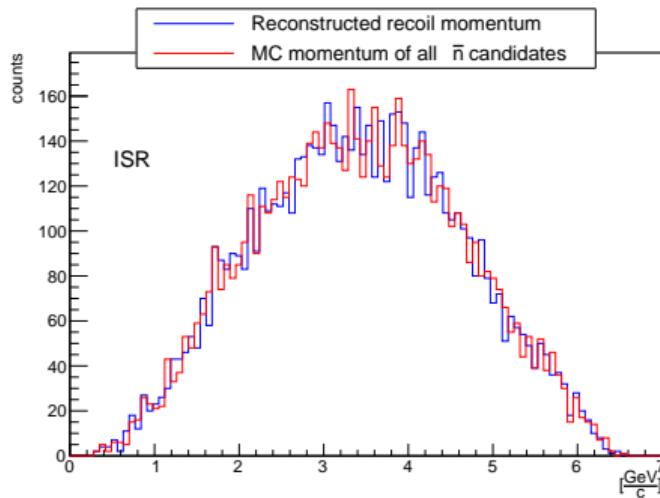
# The recoil and the $\bar{n}$ momentum



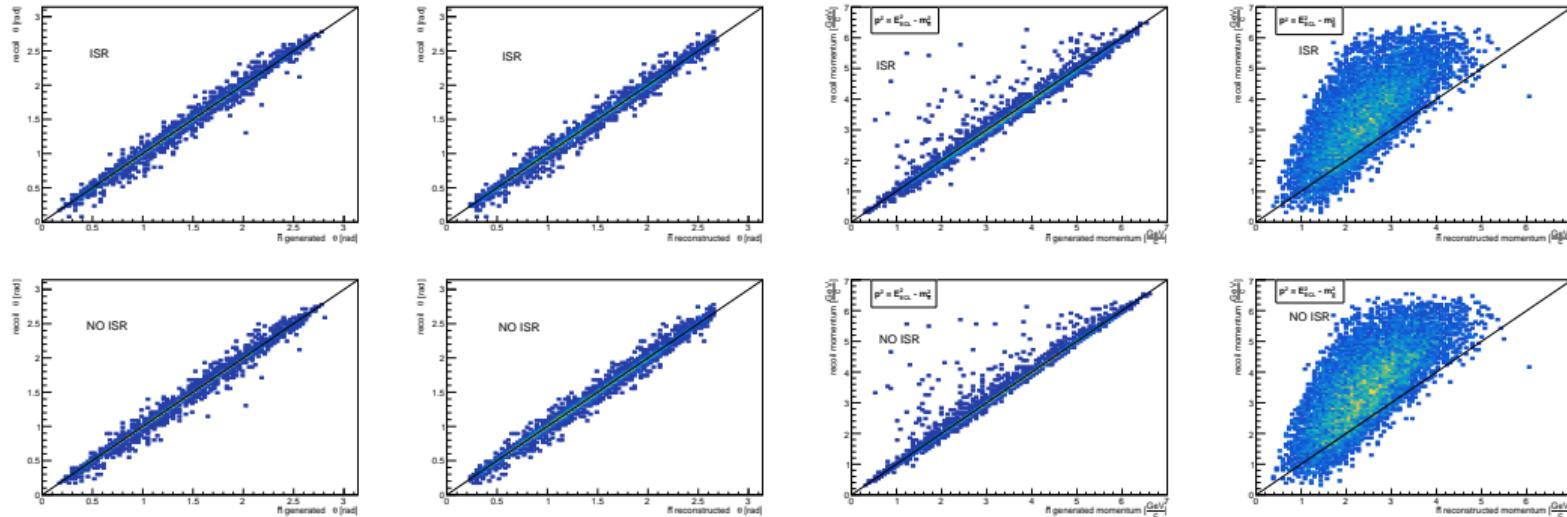
- The  $\bar{n}$  candidate list shows a discrepancy with the recoil momentum
  - (a) Could **cluster split-off** and/or **pre-showering** introduce the left peak?
  - (b) **Do they affect MC association too?**

# The recoil and the $\bar{n}$ momentum

- MC truth can be imposed by selecting only correctly reconstructed  $\bar{n}$  candidates from the  $\bar{n}$  list
- A good correspondence can be observed between the two distributions, in both the ISR and NO ISR cases



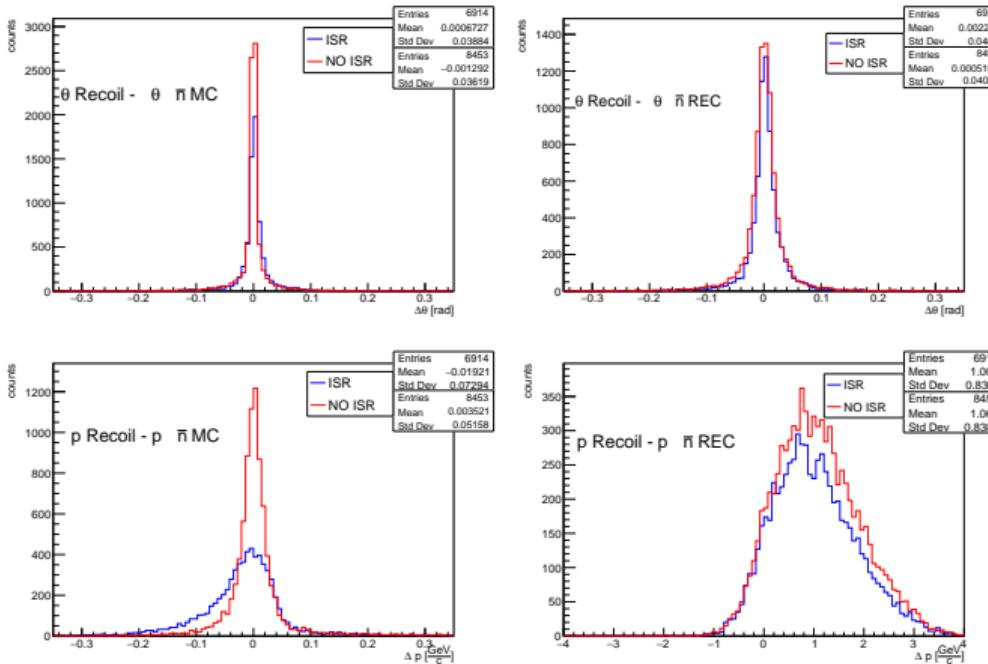
# $\bar{n}$ vs recoil vector correlation



- Poor resolution is observed in reconstructed  $\bar{n}$  momentum ( $p_{rec}^2 = E_{ECL}^2 - m_{\bar{n}}^2$ ), in both the ISR and NO ISR cases

# $\bar{n}$ vs recoil vector residuals

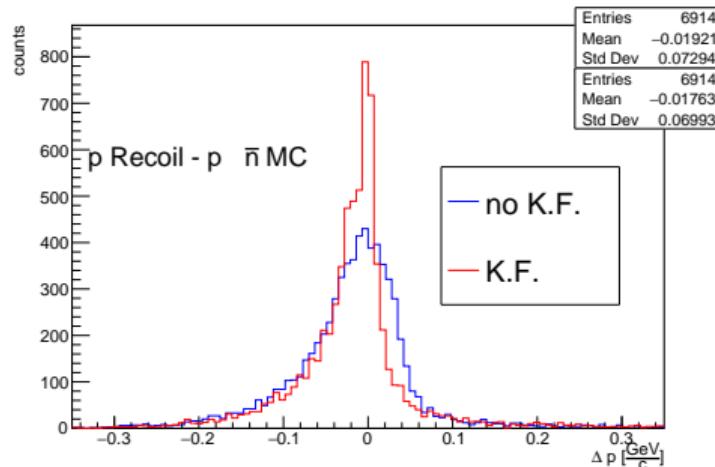
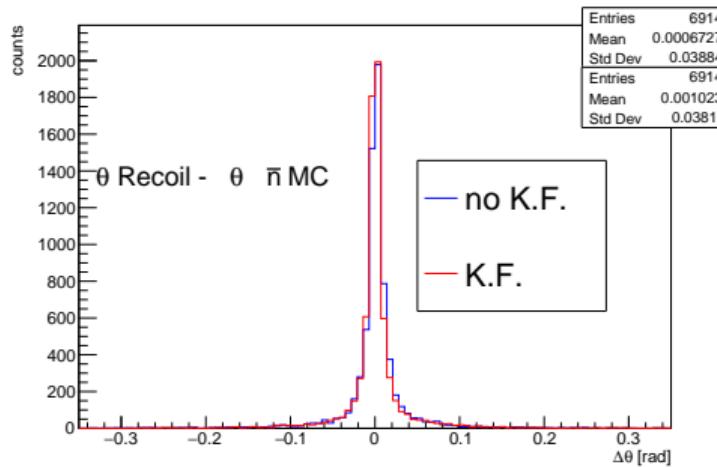
- Good correlation is observed at the generator level in both the momentum and  $\theta$  distributions
- Besides exhibiting poor resolution, the reconstructed momentum of the  $\bar{n}$  is underestimated  
→ missing energy in the shower



# Kinematic Fit over the recoil mass

A 1C kinematic fit can possibly be used to add a constraint and improve the recoil resolution:

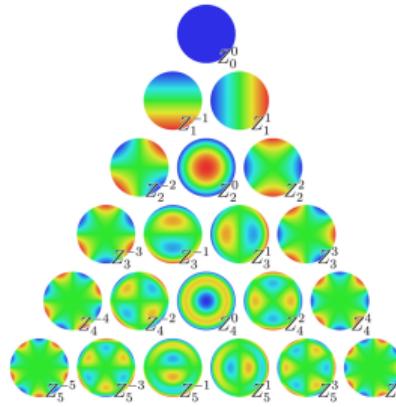
- No significant differences can be seen in  $\theta_{recoil}$  vs MC  $\theta_{\bar{n}}$
- An improvement can be observed in  $p_{recoil}$  vs MC  $p_{\bar{n}}$



# $\bar{n}$ ECL cluster variables

The aim is to validate several  $\bar{n}$  shower shapes variables, such as:

- **Energy** of the cluster
- **E1E9** and **E9E21**
- **Zernike Moments**



10	11	12	13	14
25	2	3	4	15
24	9	1	5	16
23	8	7	6	17
22	21	20	19	18

- **Lateral momentum** and **Second moment** defined as:

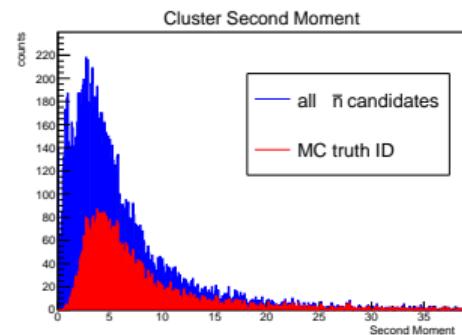
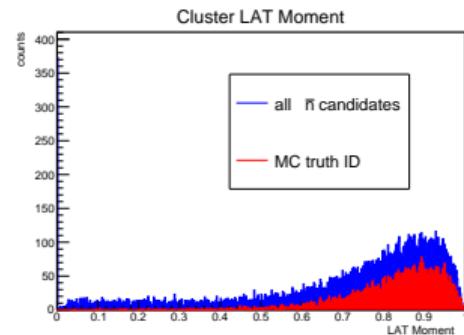
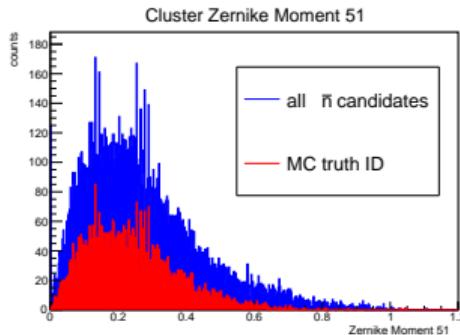
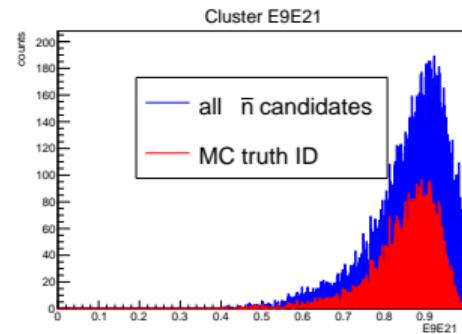
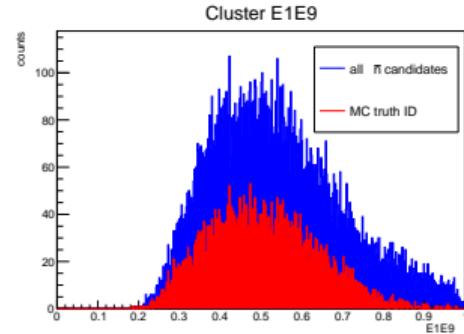
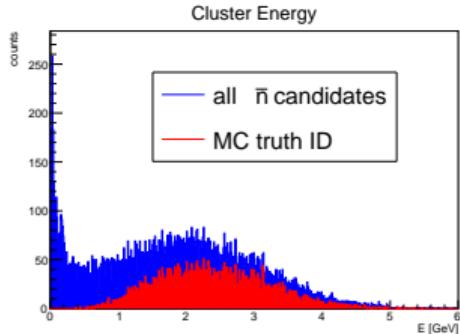
$$C_{LM} = \frac{\sum_{i=2}^n \omega_i E_i r_i^2}{\omega_0 E_0 r_0^2 + \omega_1 E_1 r_1^2 + \sum_{i=2}^n \omega_i E_i r_i^2}$$

$$C_{SM} = \frac{\sum_{i=0}^n \omega_i E_i r_i^2}{\sum_{i=0}^n \omega_i E_i}$$

# $\bar{n}$ ECL cluster variables

all  $\bar{n}$  candidates

$\bar{n}$  MC truth ID

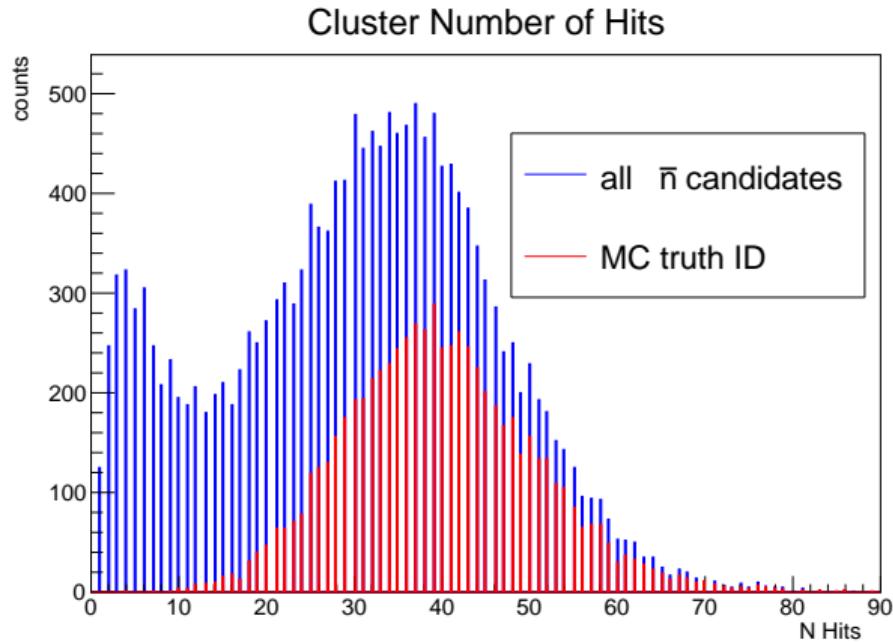


# $\bar{n}$ ECL cluster variables

1. Could several cluster (split-off) be mis-identified as  $\bar{n}$  primary cluster during reconstruction?
2. Could it be a wrong association due to pre-showering in the TOP detector?

→ further studies can be addressed with a particle gun generator

$\bar{n}$  clusters mainly involve 15 or more crystals



# Summary (1)

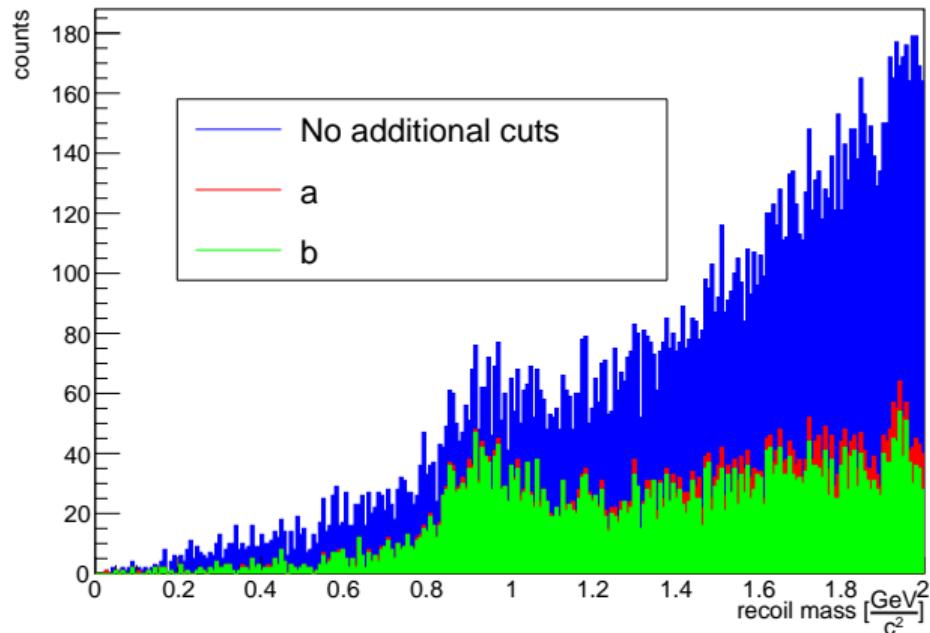
- Channel  $e^+ + e^- \rightarrow p + \bar{n} + \pi^- + (\gamma_{ISR})$  has been studied and recoil system is correctly reconstructed from the secondary background
- Reconstructed  $\bar{n}$  variables, such as momentum and shower-shape variables, should be further investigated. This could be due to:
  - (a) MC association affected by pre-showering within the TOP (?)
  - (b) Secondary cluster (split-off) mis-identified in the best candidate (?)  
→ This could be addressed by testing the ECL response with a  $\bar{n}$  particle gun generator
- 1C kinematic fit can be possibly adopted during MC/Data comparison, in order to improve the recoil resolution

# Analysis outline (2)

- Study of cocktail using the following MC sample:  
 $q\bar{q}$  cocktail with 341  $M$  events (Luminosity:  $215 \text{ fb}^{-1}$ )
- Only the  $p$  and  $\pi^-$  are used to build the recoil vector (NO ISR for the moment) →  
**Can the signal be correctly reconstructed among the other cocktail channels?**
- Following selections have been applied:
  1. Real particles ID selection on  $p$  and  $p\pi^-$  from the MC truth
  2.  $0 \text{ GeV} < \text{recoil mass} < 2 \text{ GeV}$
  3. The best candidate is selected via  $\alpha$  (closest candidate)
- Same strategy as before:
  - (a) Identify the signal peak near the  $\bar{n}$  mass ( $\sim 0.939 \text{ GeV}$ ) adding further cuts
  - (b) Study the shower shape variables in a selected recoil mass region, replacing the MC truth selections with data driven ones
  - (c) Compare it with data (Data/MC agreement)

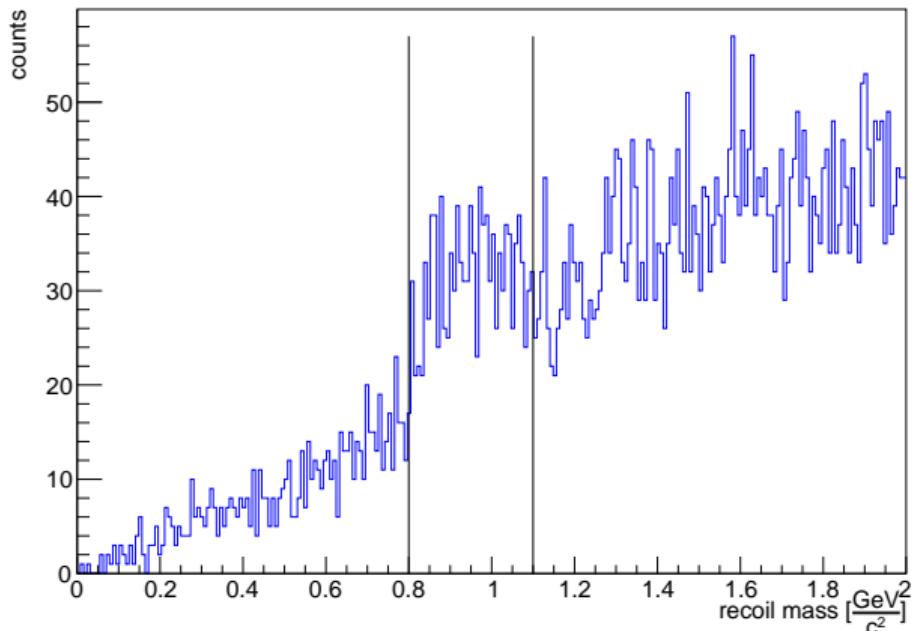
# Recoil mass distribution - MC selections

- The following cuts are applied to enhance the signal:
  - No additional charged tracks in the event 
  - No additional charged tracks in the event and  $\alpha < 0.35$  (additional angular cut on the closest candidate) 
- A peak can be observed above the  $\bar{n}$  mass → **the signal is correctly selected in the MC cocktail**

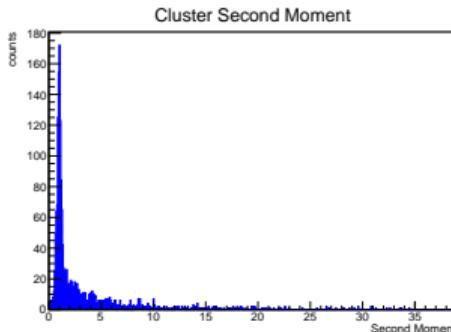
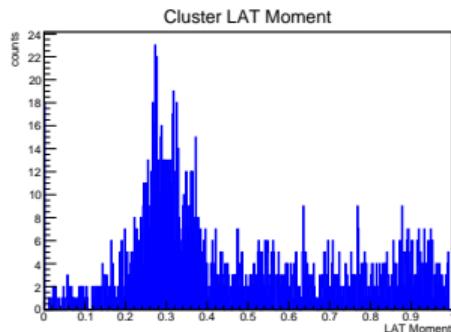
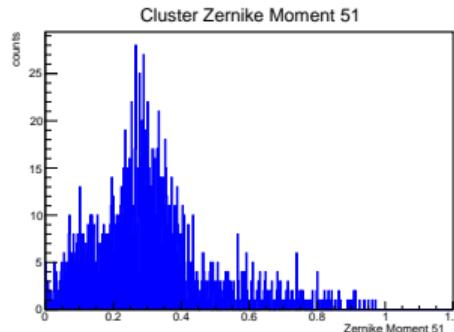
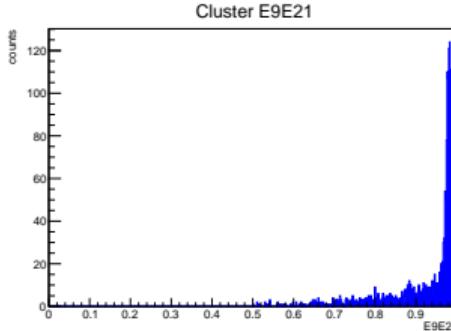
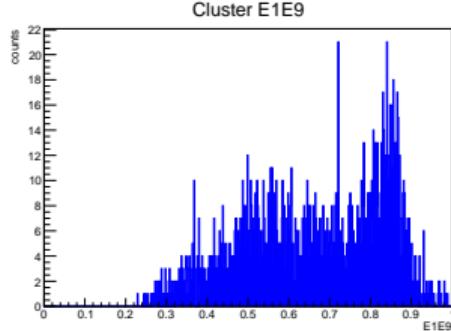
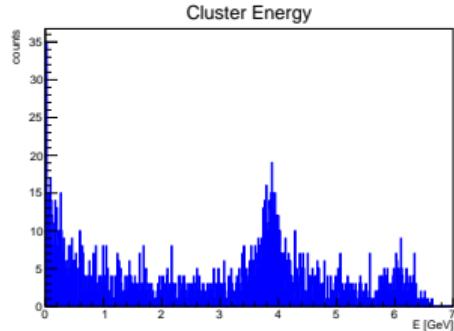


# Recoil mass distribution - Real cuts

- "Real cuts" can be applied instead of MC truth selections, such as:
  - (a) **proton**: standard PID selection, with tracks required to originate from the IP
  - (b) **pion**: standard PID selection
- To select the signal, a recoil mass cut in the range (0.8-1.2) GeV can be applied to study the shower shapes variables



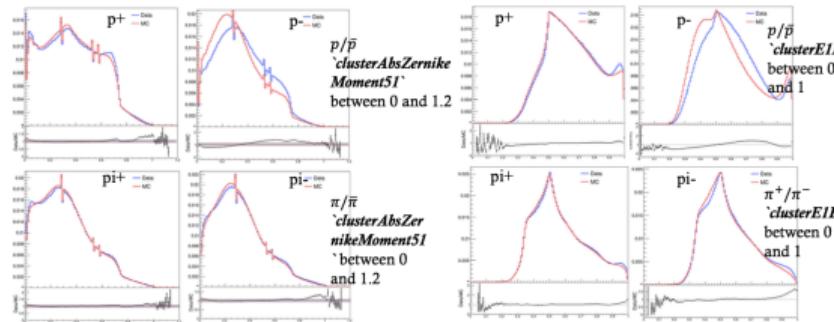
# $\bar{n}$ ECL cluster variables



# Summary (2)

- Study of  $q\bar{q}$  cocktail has been performed
- The recoil mass is correctly reconstructed using both Monte Carlo based selections and data-driven cuts, in the presence of other cocktail channels
- A further selection on the recoil mass has been applied in order to study the shower shape variables and then validate it in a Data/MC agreement

Analysis of a  $\Lambda \rightarrow p + \pi^-$  ( $\bar{\Lambda} \rightarrow \bar{p} + \pi^+$ ) sample shows that:



Poor Data/MC agreement in  $\bar{p} \rightarrow$  will it be the same for  $\bar{n}$ ?

# Outlook

The following topics will be faced from today:

1. Study of the Monte Carlo software association and of cluster split-off effects in the ECL using a particle gun
2. Study the entire cocktail production, adding further collections
3. Study of the Data/MC agreement of the shower-shape variables using the evaluated real selections



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# Thank you for your attention

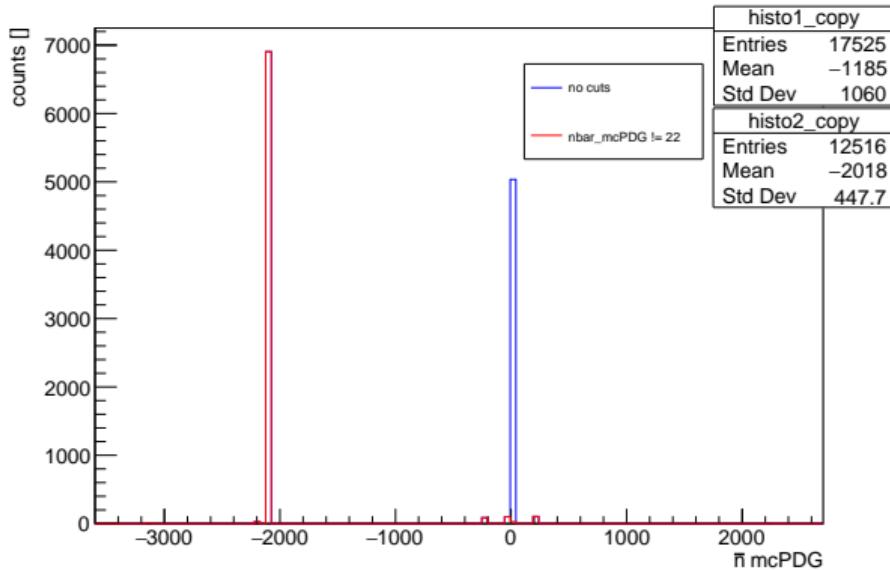
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# $\bar{n}$ mcPDG I

$\gamma$ 's are mis-identified as  $\bar{n}$  in reconstruction:



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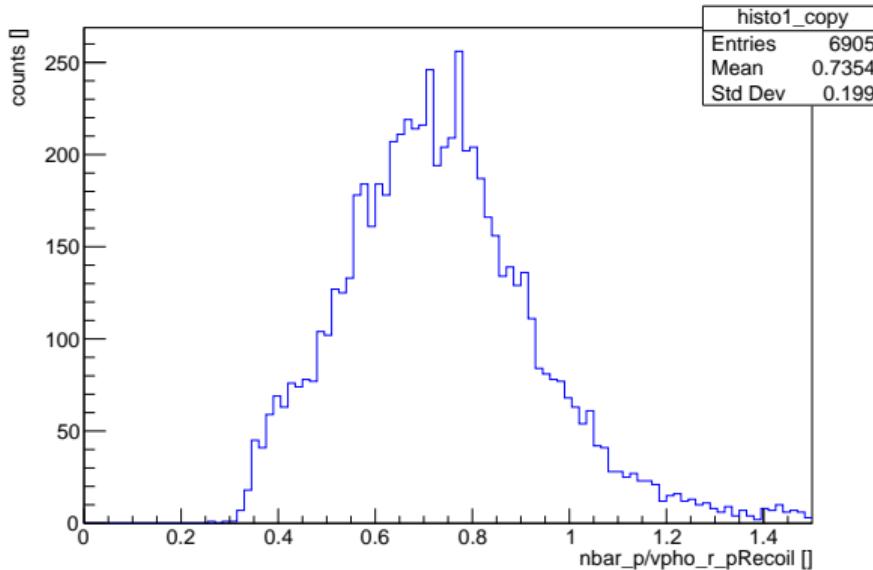


# $p_{\bar{n}}/\text{pRecoil}$ |

$\bar{n}$  is underrated in the most of cases (annihilation process + loss of energy)



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# Recommended PID selections I

PID probability defined as:

## protonID

[\[source\]](#)

proton identification probability defined as  $\mathcal{L}_p / (\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p + \mathcal{L}_d)$ , using info from all available detectors

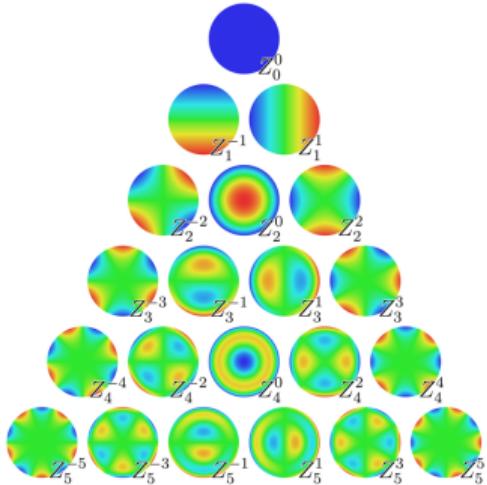
## pionID

[\[source\]](#)

pion identification probability defined as  $\mathcal{L}_\pi / (\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p + \mathcal{L}_d)$ , using info from all available detectors

# Zernike Moments I

- Zernike polynomials are widely used as basis functions of image moments



Ci sono polinomi di Zernike [pari e dispari](#). Quelli pari sono definiti come:

$$Z_n^m(\rho, \varphi) = R_n^m(\rho) \cos(m\varphi)$$

e quelli dispari come:

$$Z_n^{-m}(\rho, \varphi) = R_n^m(\rho) \sin(m\varphi)$$

dove  $m$  e  $n$  sono [numeri interi non negativi](#) con  $n \geq m$ ,  $\phi$  è l'[angolo azimutale](#),  $\rho$  è la distanza radiale  $0 \leq \rho \leq 1$  e  $R_n^m$  sono i polinomi radiali definiti di seguito. I polinomi di Zernike hanno la proprietà di essere limitati a un intervallo da -1 a +1, cioè  $|Z_n^m(\rho, \varphi)| \leq 1$ . I polinomi radiali  $R_n^m$  sono definiti come:

$$R_n^m(\rho) = \sum_{k=0}^{\frac{n-m}{2}} \frac{(-1)^k (n-k)!}{k! (\frac{n+m}{2} - k)! (\frac{n-m}{2} - k)!} \rho^{n-2k}$$

per  $n - m$  pari e sono identicamente zero per  $n - m$  dispari.