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# Characterization of Hadronic Showers in the Belle II Electromagnetic Calorimeter

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# Outline

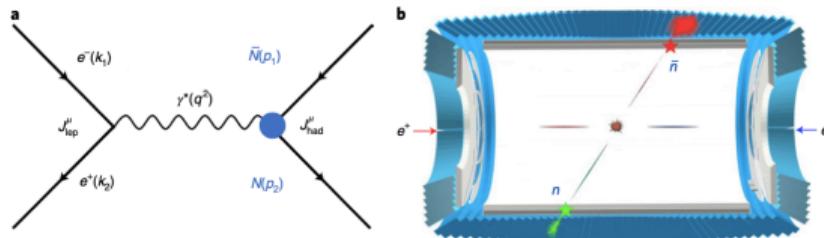


- 1. Anti-neutrons in physics experiments**
- 2. Preliminary study via signal Monte Carlo sample**
- 3. Study of Monte Carlo cocktail**
- 4. Outlook**

# 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

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

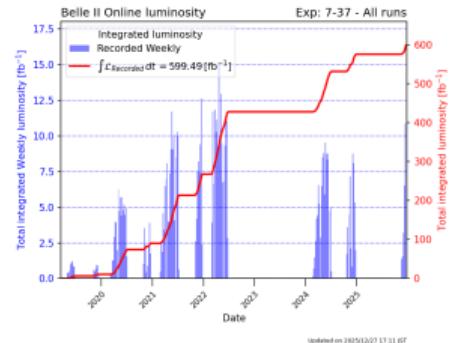
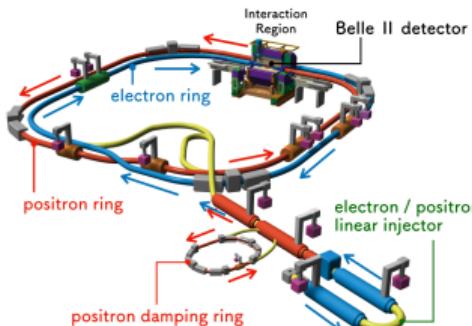
$X_{d.m.} \rightarrow \text{hadrons } (n, \bar{n}, p, \bar{p} \text{ etc...})$

$\bar{D}$  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)

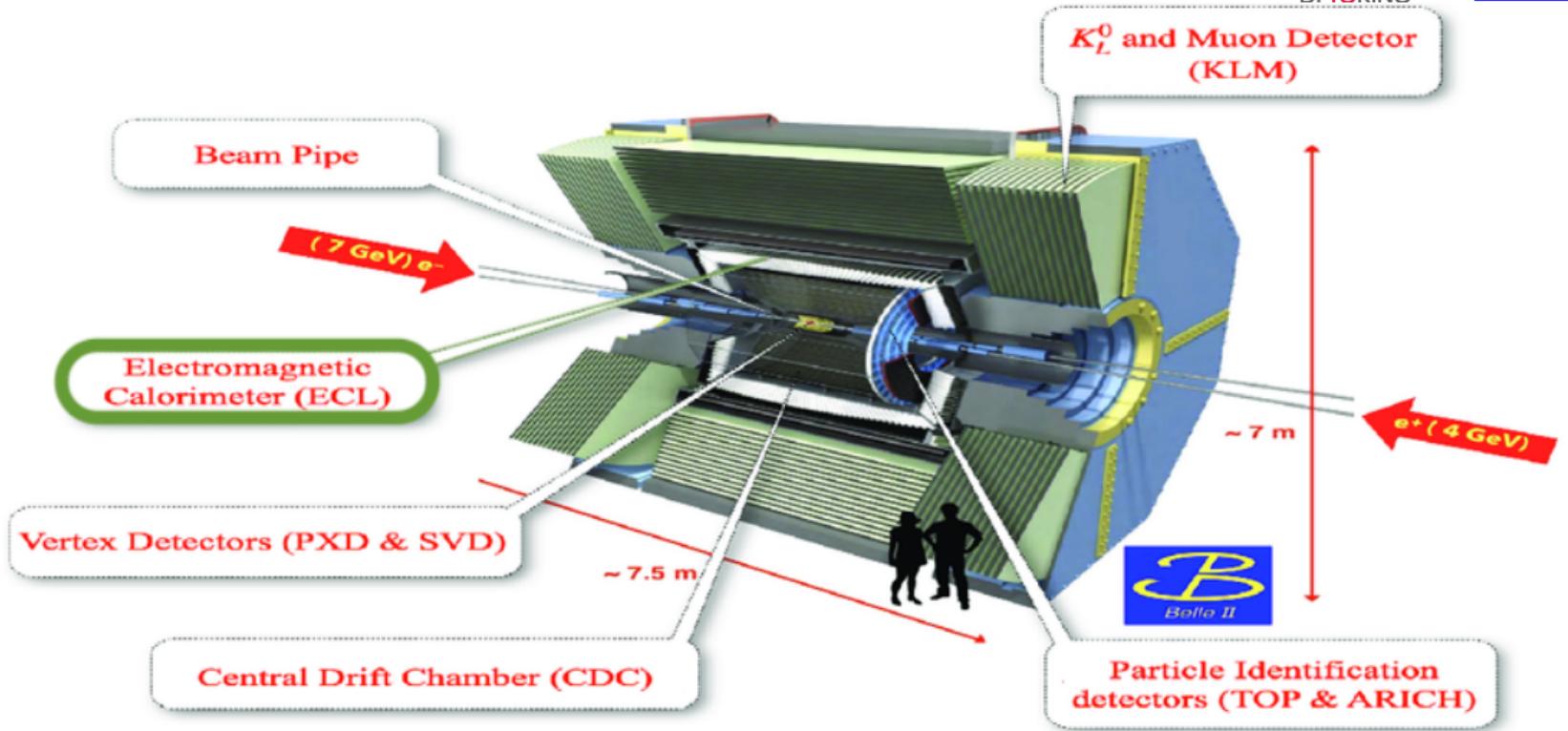
- 7 GeV electron beam (HER)
- 4 GeV positron beam (LER)
- Peak Luminosity  $\sim 5.1 \times 10^{34} cm^{-2}s^{-1}$
- Design Luminosity  $\sim 8 \times 10^{35} cm^{-2}s^{-1}$   
→ x40 the Belle's one



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

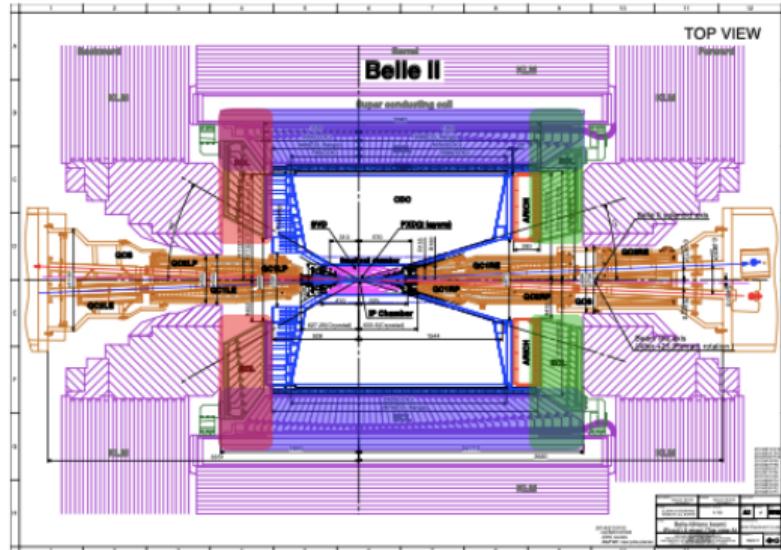


# The Electromagnetic Calorimeter

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

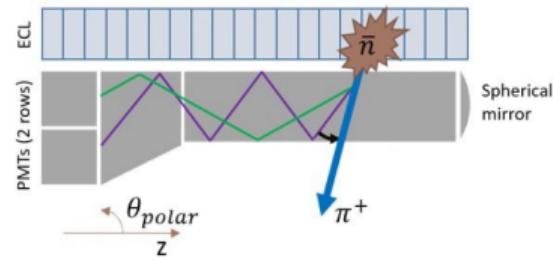
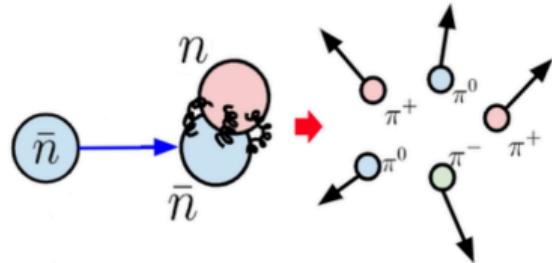
Barrel  
FWD endcap  
BWD endcap



# 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



# 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

LA LEVO????? 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  $\pi^0$  ( $\sim 5\%$ ): energy is all contained in the calorimeter, the shower is fully reconstructed
  - If  $\pi^\pm$  ( $\sim 95\%$ ): their 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,  $\bar{n}$  identification via its induced ECL clusters (study of the shower shape) such as:

- **Zernike Moments**, which describe cluster shape (backup)

$$\bullet \text{ **Lateral momentum** defined as: } C_{LM} = \frac{\sum_{i=2}^n \omega_i E_i r_i^2}{\omega_0 E_0 r_0^2 + \omega_1 E_1 r_1^2 + \sum_{i=2}^n \omega_i E_i r_i^2}$$

$$\bullet \text{ **Second moment** defined as: } C_{SM} = \frac{\sum_{i=0}^n \omega_i E_i r_i^2}{\sum_{i=0}^n \omega_i E_i}$$

# 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

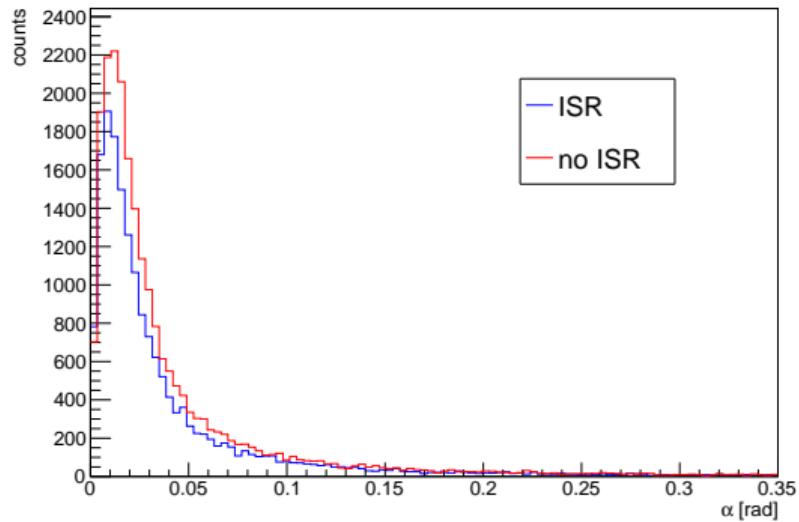
rowNo	decay tree	decay final state	iDcyTr	nEtr	nCEtr
1	$vpho \rightarrow \pi^- \bar{n} p$	$\pi^- \bar{n} p$	0	35291	35291
2	$e^+ e^- \rightarrow vpho \gamma^I \gamma^J, vpho \rightarrow \pi^- \bar{n} p$	$\pi^- \bar{n} p \gamma^I \gamma^J$	2	22971	58262
3	$e^+ e^- \rightarrow vpho \gamma^I, vpho \rightarrow \pi^- \bar{n} p$	$\pi^- \bar{n} p \gamma^I$	1	18735	76997
4	$vpho \rightarrow \pi^- \bar{n} p \gamma^F$	$\pi^- \bar{n} p \gamma^F$	3	10005	87002
5	$e^+ e^- \rightarrow vpho \gamma^I \gamma^J, vpho \rightarrow \pi^- \bar{n} p \gamma^P$	$\pi^- \bar{n} p \gamma^I \gamma^J \gamma^P$	6	5274	92276
6	$e^+ e^- \rightarrow vpho \gamma^I, vpho \rightarrow \pi^- \bar{n} p \gamma^P$	$\pi^- \bar{n} p \gamma^I \gamma^P$	4	4621	96897
7	$vpho \rightarrow \pi^- \bar{n} p \gamma^F \gamma^P$	$\pi^- \bar{n} p \gamma^F \gamma^P$	7	1503	98400
8	$e^+ e^- \rightarrow vpho \gamma^I \gamma^J, vpho \rightarrow \pi^- \bar{n} p \gamma^P \gamma^F$	$\pi^- \bar{n} p \gamma^I \gamma^J \gamma^P \gamma^F$	8	700	99100
9	$e^+ e^- \rightarrow vpho \gamma^I, vpho \rightarrow \pi^- \bar{n} p \gamma^F \gamma^P$	$\pi^- \bar{n} p \gamma^I \gamma^F \gamma^P$	5	597	99697
10	$vpho \rightarrow \pi^- \bar{n} p \gamma^F \gamma^P \gamma^F$	$\pi^- \bar{n} p \gamma^F \gamma^P \gamma^F$	9	167	99864
11	$e^+ e^- \rightarrow vpho \gamma^I, vpho \rightarrow \pi^- \bar{n} p \gamma^F \gamma^F \gamma^F$	$\pi^- \bar{n} p \gamma^I \gamma^F \gamma^F \gamma^F$	12	63	99927
12	$e^+ e^- \rightarrow vpho \gamma^I \gamma^J, vpho \rightarrow \pi^- \bar{n} p \gamma^F \gamma^F \gamma^P$	$\pi^- \bar{n} p \gamma^I \gamma^J \gamma^F \gamma^F \gamma^P$	10	61	99988
13	$e^+ e^- \rightarrow vpho \gamma^I, vpho \rightarrow \pi^- \bar{n} p \gamma^F \gamma^F \gamma^F \gamma^P$	$\pi^- \bar{n} p \gamma^I \gamma^F \gamma^F \gamma^F \gamma^P$	11	4	99992
14	$e^+ e^- \rightarrow vpho \gamma^I \gamma^J, vpho \rightarrow \pi^- \bar{n} p \gamma^F \gamma^F \gamma^F \gamma^F$	$\pi^- \bar{n} p \gamma^I \gamma^J \gamma^F \gamma^F \gamma^F \gamma^F$	15	4	99996
15	$vpho \rightarrow \pi^- \bar{n} p \gamma^F \gamma^F \gamma^F \gamma^P$	$\pi^- \bar{n} p \gamma^F \gamma^F \gamma^F \gamma^P$	14	2	99998
16	$vpho \rightarrow \pi^- \bar{n} p \gamma^F \gamma^F \gamma^F \gamma^F \gamma^P$	$\pi^- \bar{n} p \gamma^F \gamma^F \gamma^F \gamma^F \gamma^P$	13	1	99999
17	$e^+ e^- \rightarrow vpho \gamma^I \gamma^J, vpho \rightarrow \pi^- \bar{n} p \gamma^F \gamma^F \gamma^F \gamma^F \gamma^P$	$\pi^- \bar{n} p \gamma^I \gamma^J \gamma^F \gamma^F \gamma^F \gamma^P$	16	1	100000

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

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

# Applied selections and cuts

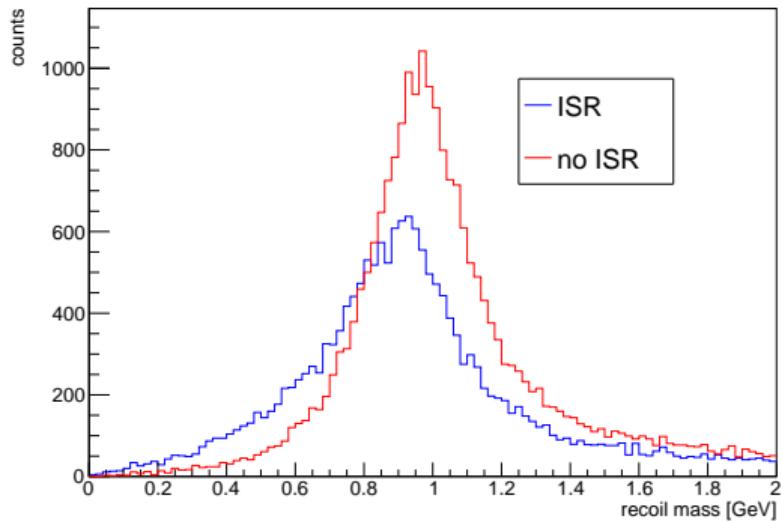
- (a) **proton**: standard PID selection, with tracks required to originate from the IP
- (b) **pion**: standard PID selection
- (c) **anti-neutron**: neutral clusters from ECL
- (d)  $0 \text{ GeV} < \text{recoil mass} < 2 \text{ GeV}$
- (e)  $\alpha < 0.35 \text{ rad} (\sim 20 \text{ deg})$



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

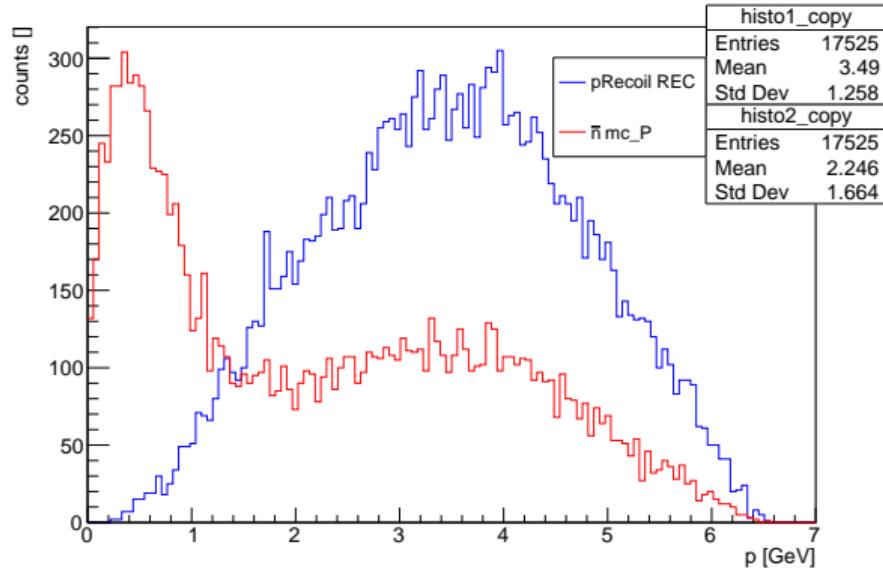
# The recoil mass (1a)

- 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



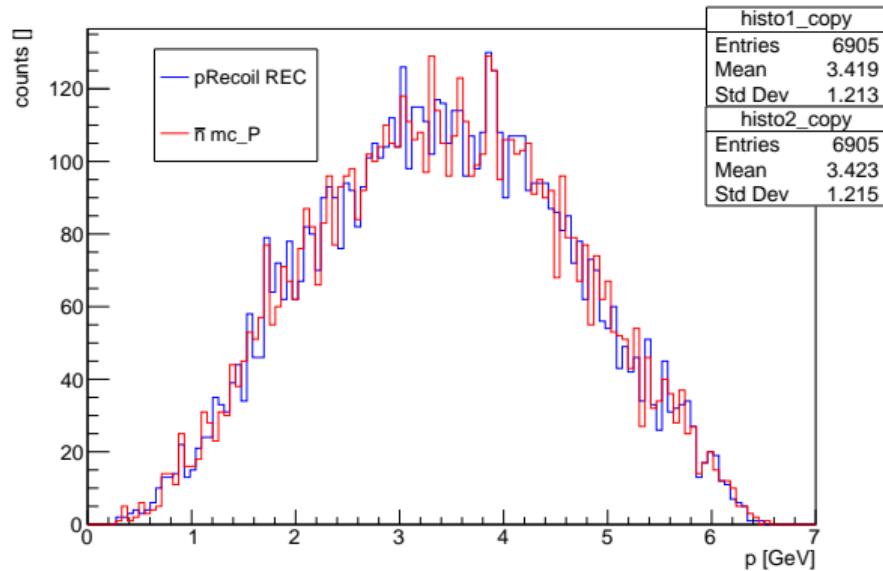
# The recoil and the $\bar{n}$ momentum (1b)

- The reconstructed  $\bar{n}$  candidate list shows a discrepancy with the recoil momentum  $\rightarrow$  several  $\gamma$  are mis-identified as  $\bar{n}$  in reconstruction
- MC selection  $\bar{n}_{mcPDG} = -2112$  is applied in order to directly compare the recoil kinematic variables with the  $\bar{n}$  from MC truth (next slide)



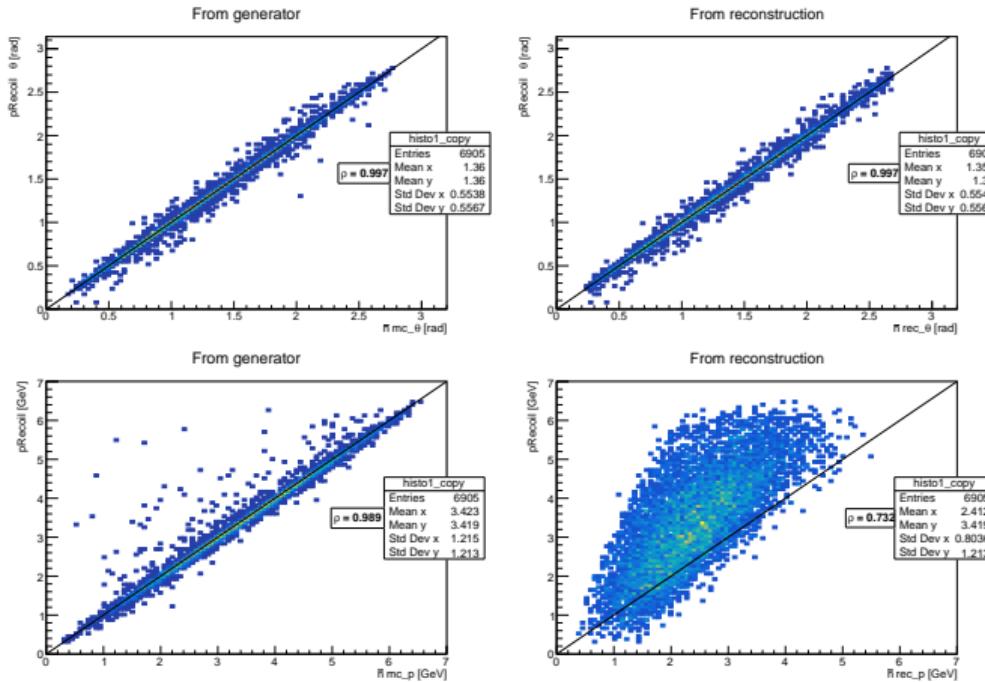
# The recoil and the $\bar{n}$ momentum (1b)

- Among the 17525 reconstructed candidates, 6905 correspond to real  $\bar{n}$ .
  - 100000 generated events
  - 17525 reconstructed events ( $\sim 18\%$ )
  - 6905 real  $\bar{n}$  in candidates list ( $\sim 7\%$ )
- For a ( $LUMI$ ) real data, ( $TOTevents$ ) are expected



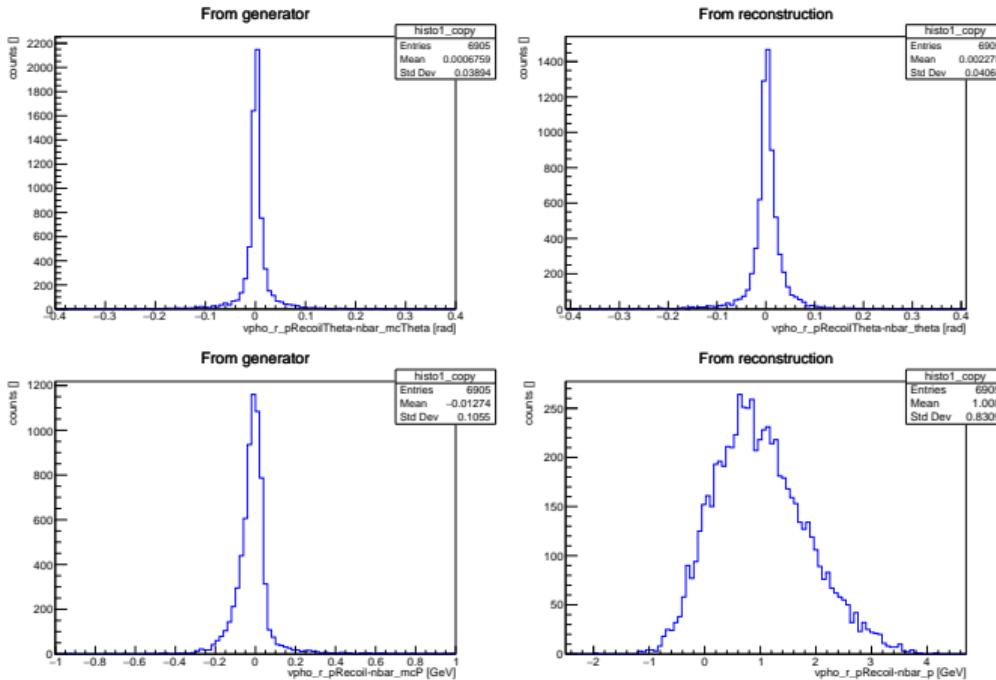
# $\bar{n}$ vs recoil vector correlation (1b)

- Good correlation is observed at the generator level in both the momentum and  $\theta$  distributions
- The reconstructed  $\bar{n}$  momentum in the ECL is not a reliable variable, since no high correlation is observed (annihilation and energy loss)



# $\bar{n}$ vs recoil vector residuals (1b)

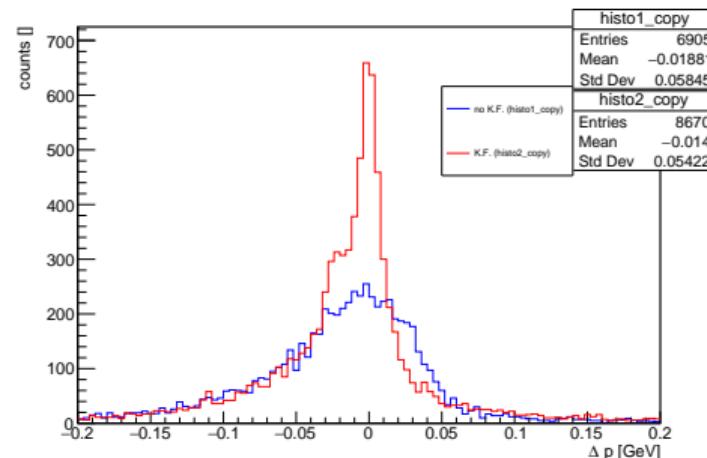
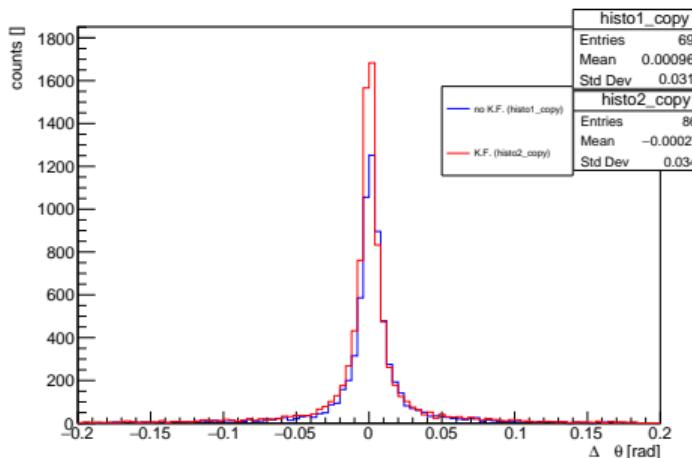
- Good correlation is observed at the generator level in both the momentum and  $\theta$  distributions
- The reconstructed  $\bar{n}$  momentum in the ECL is not a reliable variable, since no high correlation is observed (annihilation and energy loss)



# Kinematic Fit over the recoil mass (1c)

A 1C kinematic fit can possibly be used to add a constraint and improve the agreement in  $p$  and  $\theta$

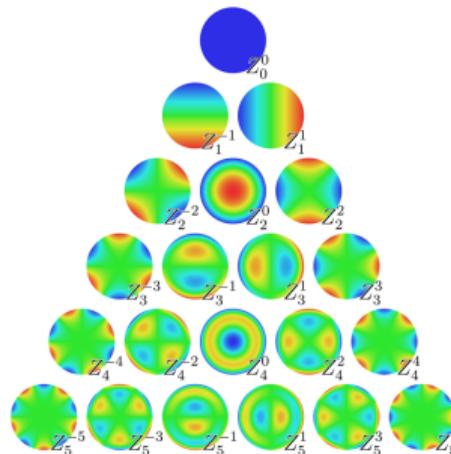
- Highest amount of reconstructed candidates ( $\sim 24\%$ ) and of real  $\bar{n}$  ( $\sim 9\%$ )
- No significant differences can be seen in  $\theta_{recoil}$  vs MC  $\theta_{\bar{n}}$
- An improvement can be observed in  $p_{recoil}$  vs MC  $p_{\bar{n}}$



# $\bar{n}$ ECL cluster variables (1d)

Shower shapes variables can be studied to distinguish  $\bar{n}$  from other neutral particles:

- **E, E1E9 and E9E21**  
 $(E_{min} = 20 \text{ GeV})$
- **ZernikeMoment51:**  $|Z_{51}|$



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

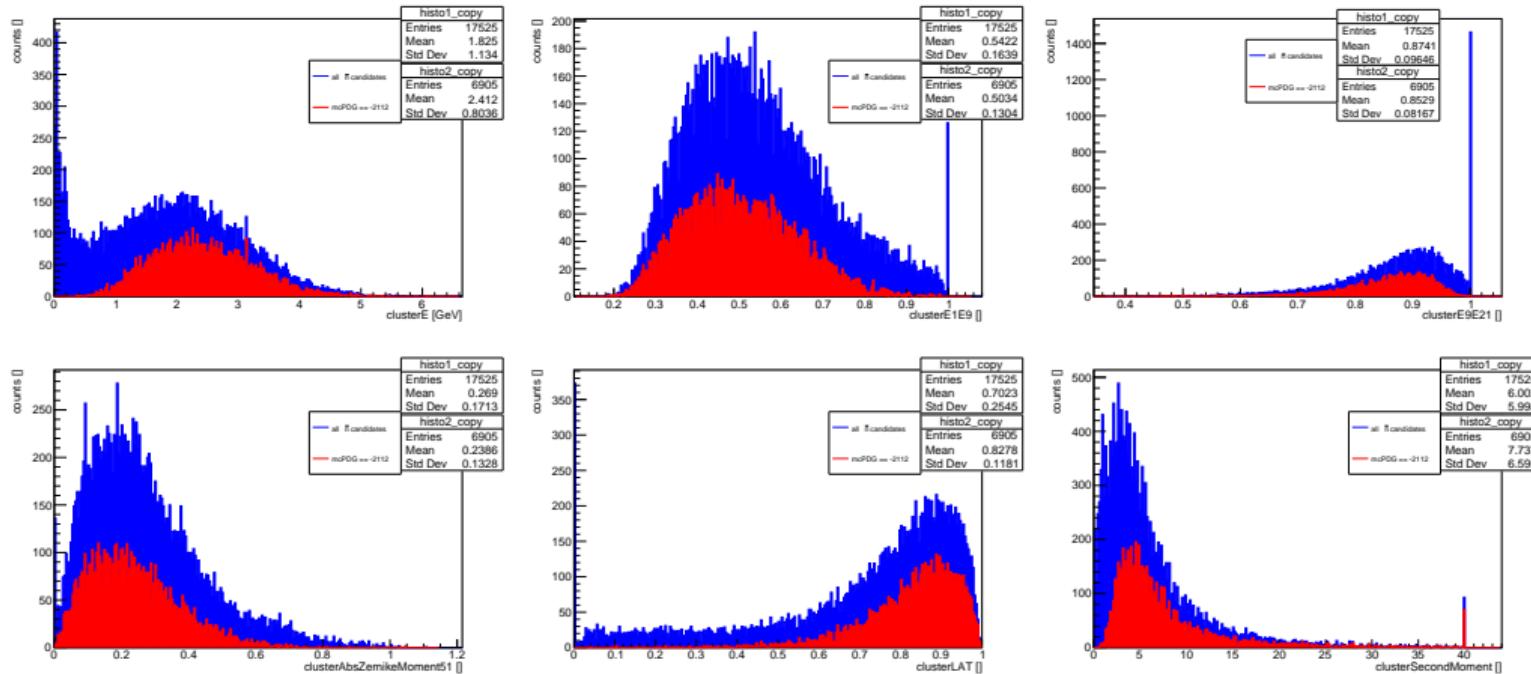
- **Lateral momentum:** lateral energy distribution, defined as:

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

# $\bar{n}$ ECL cluster variables (1d)



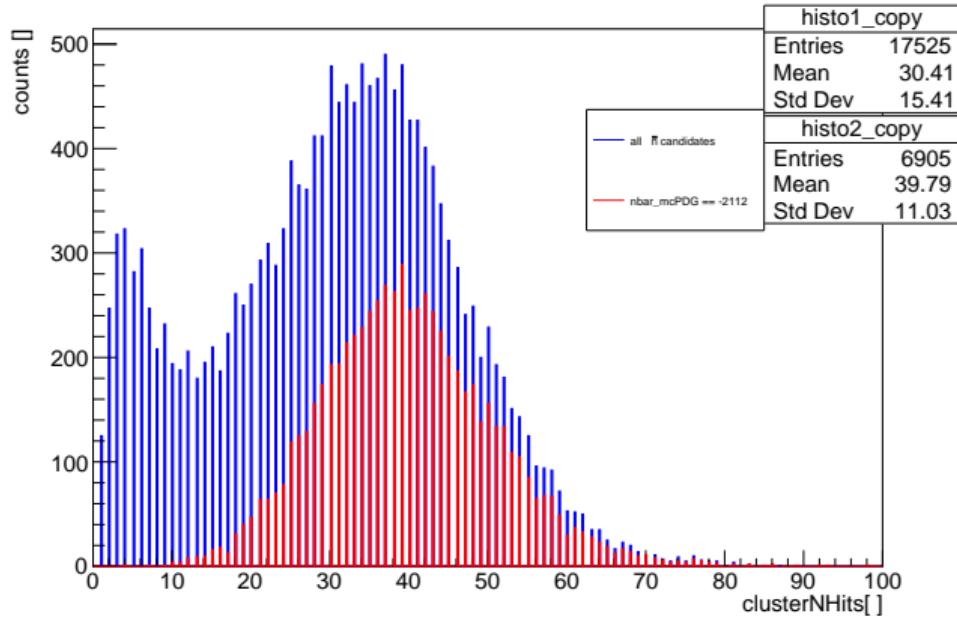
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# $\bar{n}$ ECL cluster variables (1d)

- $\bar{n}$  clusters mainly involve 15 or more crystals
- Several photons are mis-identified as  $\bar{n}$  during reconstruction (backup) → further selection can be studied such as:

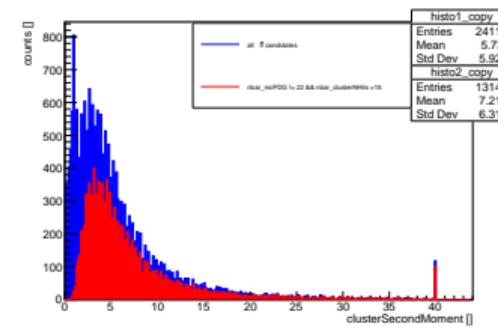
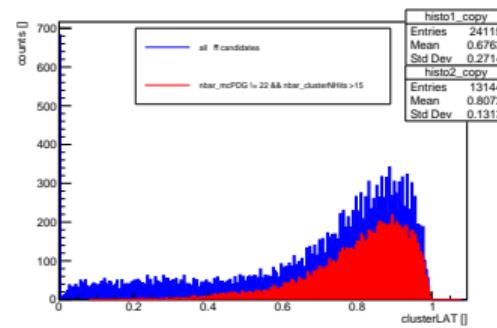
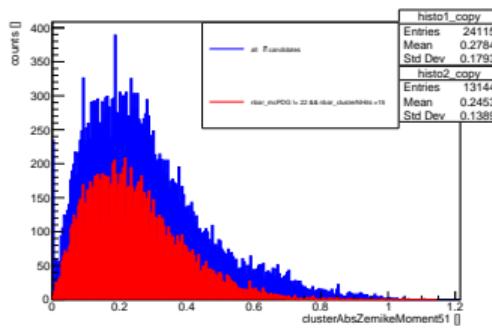
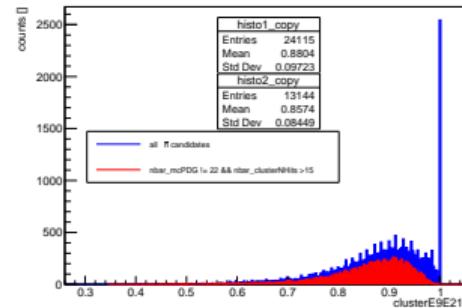
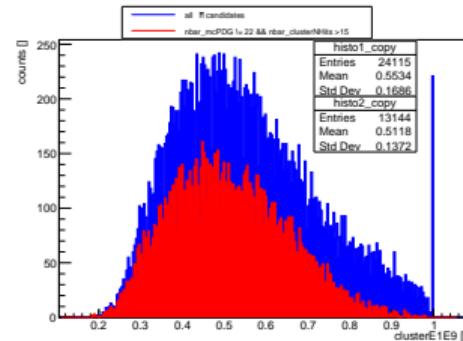
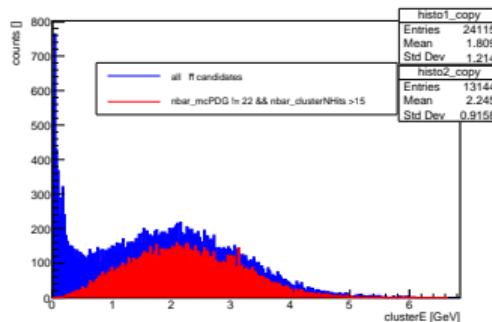
$\bar{n}_{mcPDG} \neq 22$   
  &&  
 $\bar{n}_{clusterNHits} > 15$



# $\bar{n}$ ECL cluster variables (1d)



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# Summary (1)

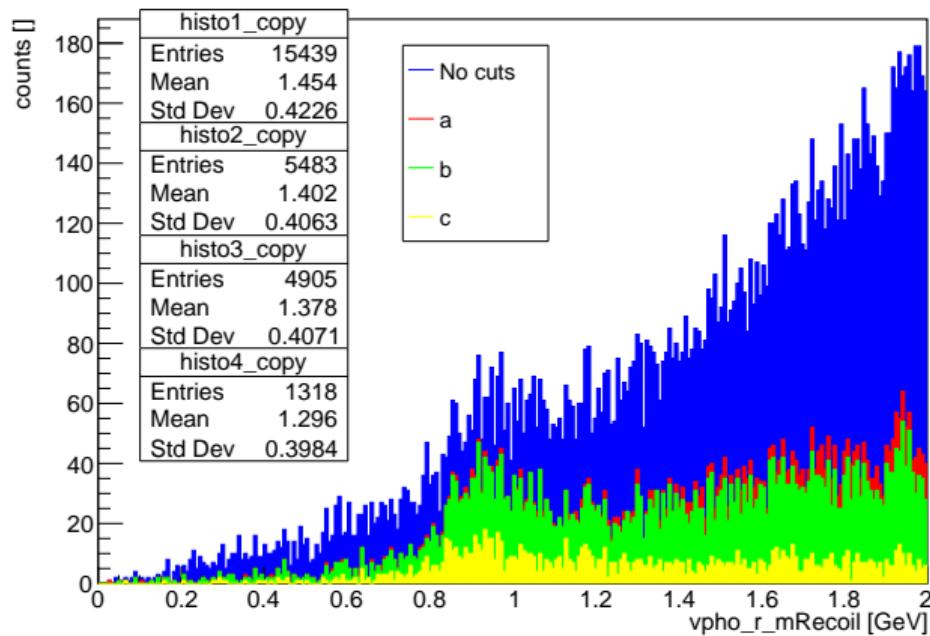
- Channel  $e^+ + e^- + \gamma_{ISR} \rightarrow X \rightarrow p + \bar{n} + \pi^-$  has been studied
- The recoil three body system ( $p + \pi^- + \gamma_{ISR}$ ) is correctly reconstructed from the secondary background, ISR/FSR photons
- The  $\bar{n}$  kinematic is properly described by the three body system  $p, \pi^-, \gamma$  recoil vector
- Reconstructed  $\bar{n}$  variables are mainly affected by mis-identified photons, which can be partially cleaned by cluster size cuts (*clusterNHits*)
- 1C kinematic fit can be possibly adopted during MC/Data comparison, in order to improve the recoil on the recoil momentum

# Analysis outline (2)

- Study of cocktail from MC16rd\_proc16 using the following MC sample:
  - (a)  $q\bar{q}$  cocktail powered by Pythia
  - (b) Number of Events:  $341 M$
  - (c) Luminosity:  $215 fb^{-1}$
- To obtain a first attempt, only the  $p$  and  $\pi^-$  are used to build the recoil vector (ISR neglected for the moment)
- 2345 jobs have been submitted to the grid, with the following online cuts:
  1.  $p\_mcPDG == 2212$  and  $pi\_mcPDG == -211$  and  $0 \text{ GeV} < m\text{Recoil} < 2 \text{ GeV}$
  2. The best candidate is selected with RankByLowest method on  $\alpha$  (backup)
- Same strategy as before:
  - (a) Identify the signal peak near the  $\bar{n}$  mass ( $\sim 0.939 \text{ GeV}$ ) adding offline cuts
  - (b) Study the previous variables (recoil and cluster) in a  $m\text{Recoil}$  zoomed region
  - (c) (3) Compare it with data (Data/MC agreement)

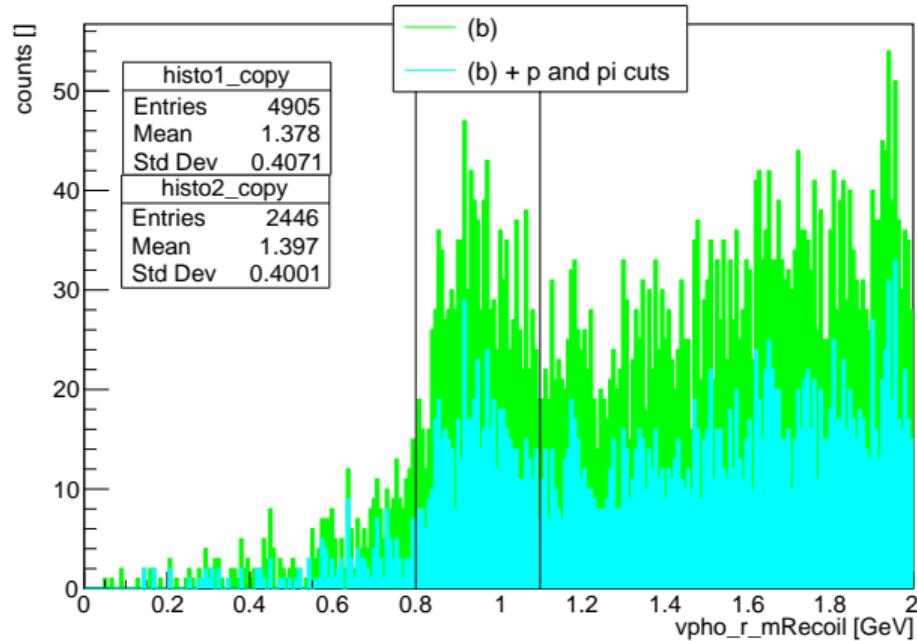
# mRecoil distribution

- The following cuts are applied to enhance the signal:
  - $nRoeCharged == 0$  (no additional charged particles in the Rest Of Event) 
  - $nRoeCharged == 0$  and  $\alpha < 0.35$  (additional angular cut on the closest candidate) 
  - $nRoeCharged == 0$  and  $\alpha < 0.35$  and  $nbar_mcPDG == -2112$  (MC truth selection) 



# mRecoil distribution

- “Real selections” can be applied as well, with (b), such as: [longo2025]  
 $\text{protonID} > 0.9$  and  $\text{pionID} > 0.1$  and  $\text{dr} < 1$  and  $\text{abs(dz)} < 3$  (from IP) ■■■
- To maximize purity, a recoil mass selection in the range (0.8-1.1) GeV can be applied to study the recoil variables
- This set of selections will be applied in the following sections



# Variables



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# Summary (2)

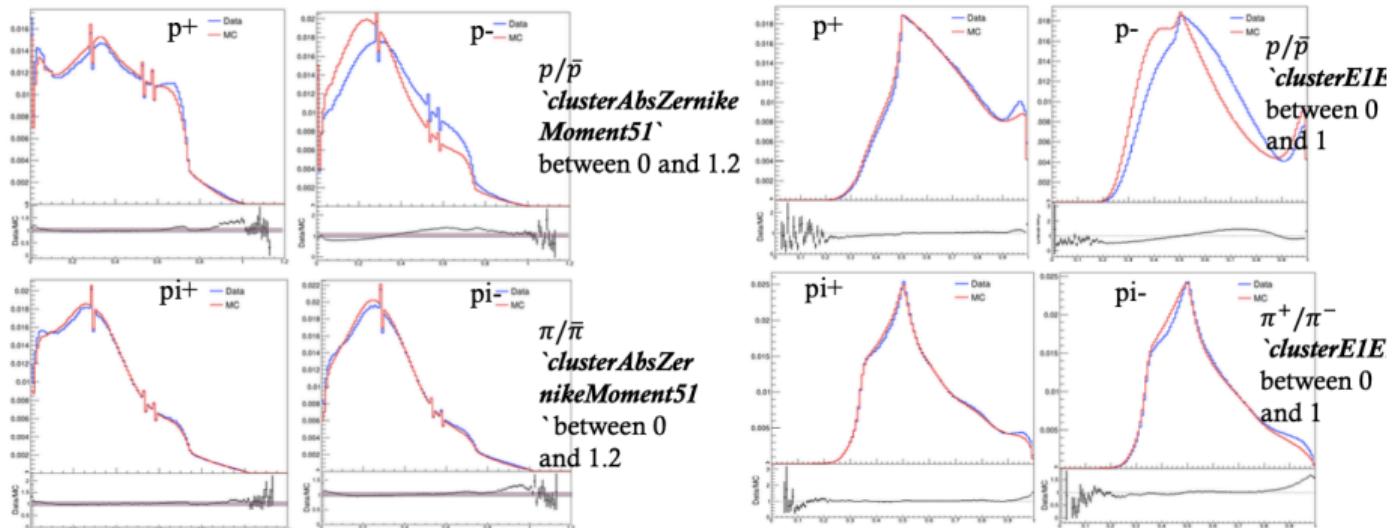


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# Data/MC agreement $\bar{n}$ case

Analysis of a  $\Lambda \rightarrow p + \pi^-$  ( $\bar{\Lambda} \rightarrow \bar{p} + \pi^+$ ) sample shows that [shanette2025]:



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

# Outlook Until Graduation





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# Thank you for your attention

**Emanuele Zanuso**

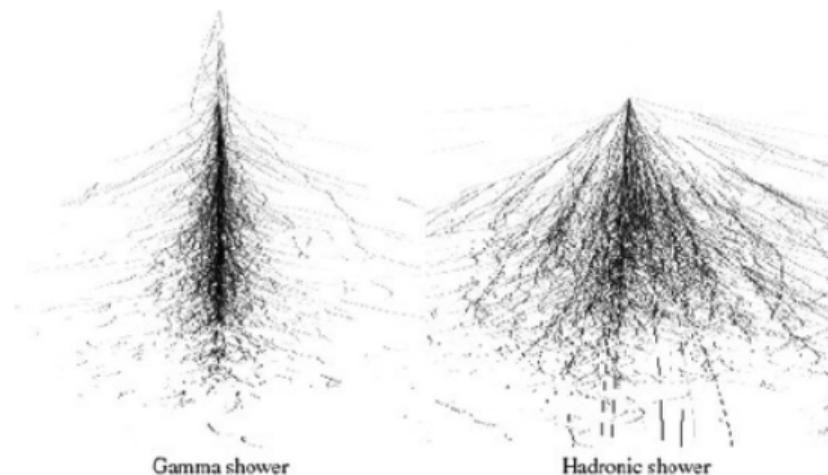
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January 14, 2026

# Electromagnetic and hadronic showers

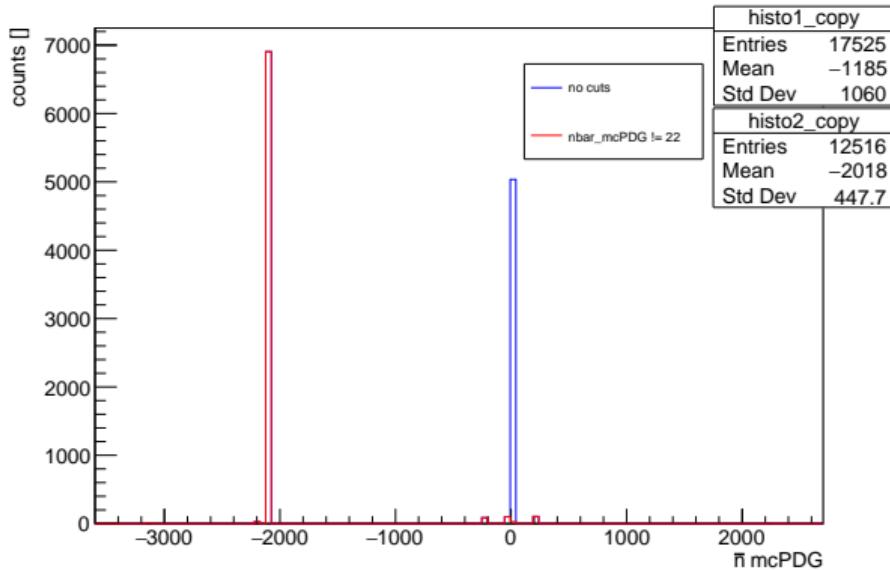
Different processes occur for e.m. (1) and hadronic (2) showers:

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))



# $\bar{n}$ mcPDG I

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



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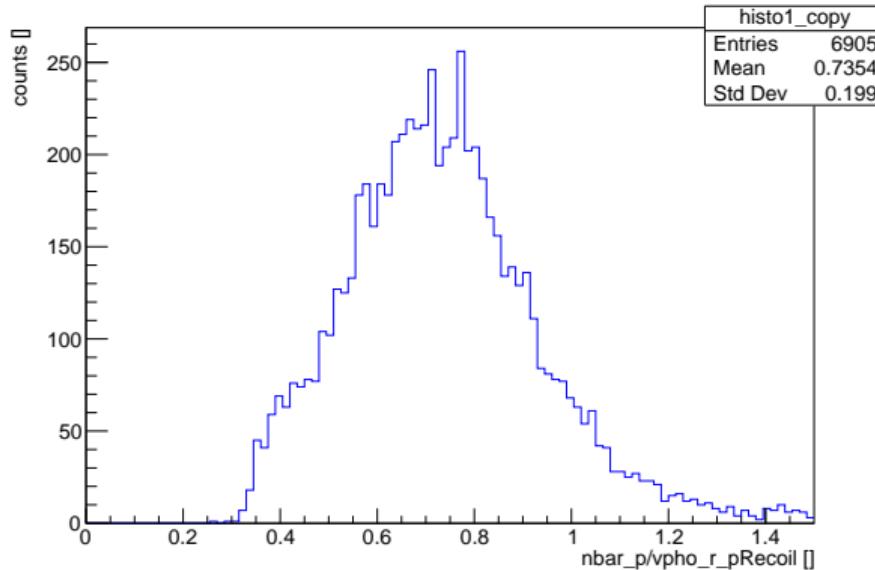


# $p_{\bar{n}}/\text{pRecoil}$ |

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



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# References I

