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# Characterization of hadronic showers in the Belle II Electromagnetic Calorimeter

Metatesi Seminar

Emanuele Zanuso

Dipartimento di Fisica  
Università degli Studi di Torino

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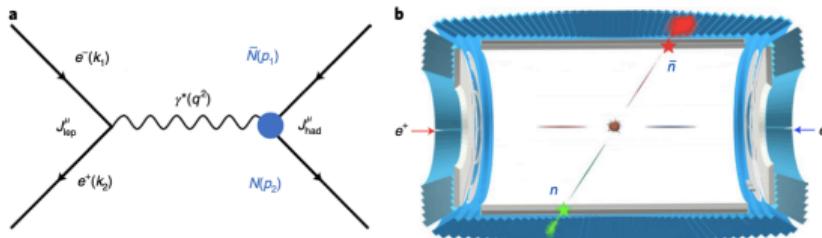
# Outline

- 1. Anti-neutrons in physics experiments**
- 2. Preliminary study via signal MC 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 [1]



- Some decay channels studied at B-factories which involve  $\bar{n}$ , such as:

1. The hyperons decay channel:

$$\bar{\Lambda}^0 \rightarrow \pi^0 + \bar{n}, \quad \bar{\Sigma}^- \rightarrow \pi^- + \bar{n}, \quad \bar{\Lambda}_c \rightarrow K_s^0 + \pi^0 + \bar{n}$$

2. Other typical B-factories processes:

$$e^+ + e^- \rightarrow p + \bar{n} + X^- \quad (X^-: \text{combination of charged pions and kaons})$$

# Anti-neutron in astrophysical experiments

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

- Studying  $\bar{n}$  - anti-hyperon potential to improve the understanding of the equation of state of the neutron star [2]
- Investigating dark matter through anti-deuterons ( $\bar{D}$ ) in cosmic rays, produced by dark matter annihilation or decay [3]:  
 $A_{d.m.} + B_{d.m.} \rightarrow \text{hadrons } (\bar{n}, \bar{p}, \bar{p} \text{ etc...})$   
 $X_{d.m.} \rightarrow \text{hadrons } (\bar{n}, \bar{p}, \bar{p} \text{ etc...})$
- $\bar{D}$  is mainly produced through a coalescence mechanism:

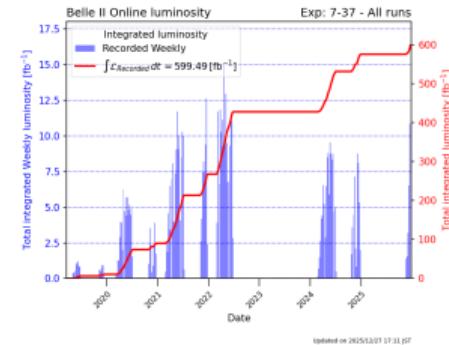
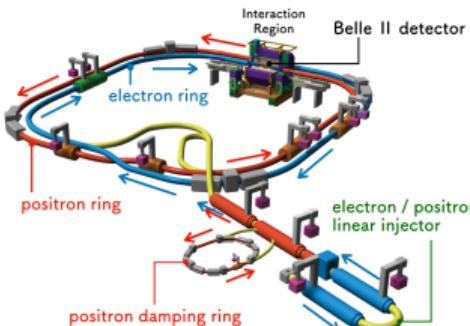
$$\bar{n} + \bar{p} \rightarrow \bar{D}$$

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 electrons beam (HER)
- 4 GeV positrons beam (LER)
- Peak Lumi  $\sim 5.1 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
- Design Lumi  $\sim 8 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1}$   
 $\rightarrow$  x40 the Belle's one



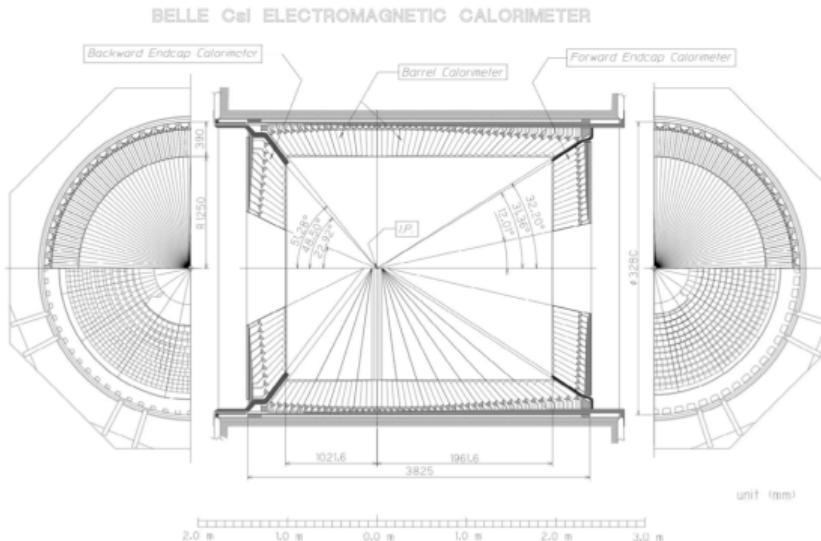
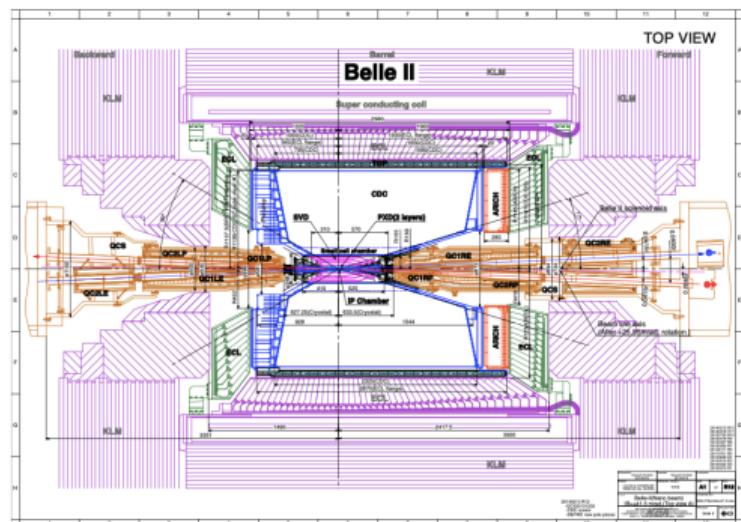
It operates mainly around  $\Upsilon(4S)$  resonance ( $\sim 10.58$  GeV):

- It decays almost exclusively into entangled couple of  $B\bar{B} \rightarrow B$ -factory
- Several goals: flavour physics, BSM, B and charm mesons etc...

# The Electromagnetic Calorimeter

The ECL plays a central role in this thesis

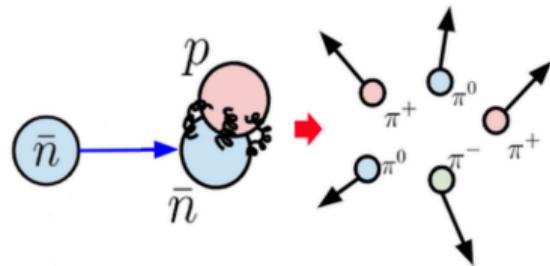
- Array of **CsI(Tl)** crystals (8376 6x6x30cm<sup>3</sup> crystals in total)
- It covers barrel and end-caps regions ( $12^\circ \leq \theta \leq 155^\circ$ )
- Energy resolution of 4% @100 MeV and 1.6% @8 GeV



# Anti-neutron interactions in physics

The  $\bar{n}$  interacts with matter primarily via strong nuclear force

- It can annihilate with nucleons in the material, producing light mesons (mainly pions)
- Hadronic ( $\pi^+$ ,  $\pi^-$ ) and electromagnetic ( $\pi^0$ ) showers are generated within the ECL
- Since annihilation stars are produced, both backward (TOP) and forward (KLM) directions are involved



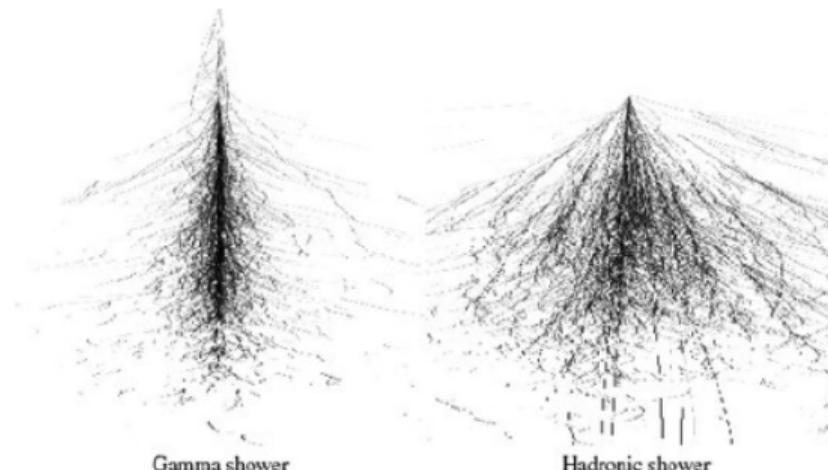
# Electromagnetic and hadronic showers

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

1. Brems. and p.p. process ( $e^+, e^-, \gamma$ ) and  $\pi^0 \rightarrow \gamma\gamma$
2. Strong interactions of hadrons with the material ( $p, n, \text{pions}, \text{kaons}...$ )

After  $\bar{n}$  annihilation, the produced pions can be detected via their showers:

- 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

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 (< 100ps), like a T.O.F. detector (TOP)
  2. An electromagnetic calorimeter (**ECL**)
  3. A muon system (alternating layers of active material and high-Z absorber) (KLM)
- These features are common in modern general-purpose collider experiments such as **Belle II** and BESIII
- For MANTRA project, only signals from ECL and TOP are taken into account. In this thesis only ECL signals are studied

# The MANTRA project

Anti-neutrons do not interact with tracking sub-detector. The measurement of the energy is a two-step process:

1.  $\bar{n}$  identification via its induced ECL clusters and correlation to the initial energy
2. Combine the signals from (1) and (2) to reconstruct the  $\bar{n}$  energy, in cases of backscatter or pre-annihilation
  - 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

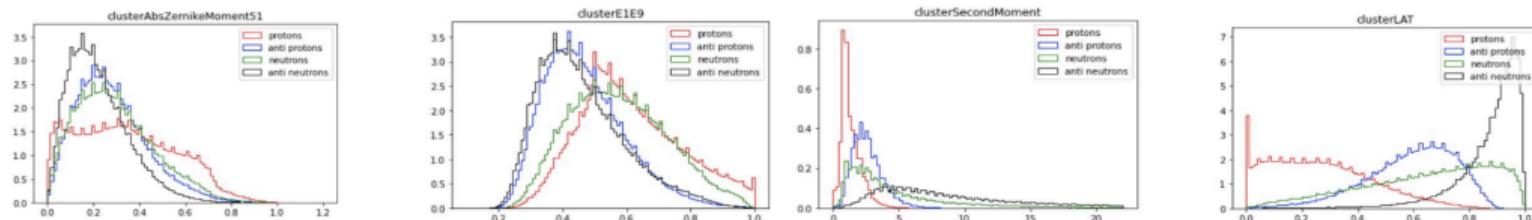
# Preliminary concept

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

- $e^+ + e^- \rightarrow X \rightarrow p + \bar{n} + \pi^-$  (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 distinguish their clusters, such as:

- clusterZernikeMoment, clusterSecondMoment, clusterLAT etc...



The distributions for ECL variables for  $\bar{p}$  and  $\bar{n}$  do not agree [4]  $\rightarrow \bar{p}$  cannot be used as proxy for  $\bar{n}$

# Analysis outline

1. Preliminary study of a clean selected channel via generators
  - (a) Recoil identification from the three-body system  $p + \gamma_{ISR} + \pi^-$
  - (b) Study of the kinematic recoil variables (momentum, angles, energy, etc...)
  - (c) Study of the effect of 1C kinematic fit over the  $p + \gamma_{ISR} + \pi^-$  recoil mass
  - (d) Study of ECL clusters
2. Study of MC cocktail events sample:
  - (a) Recoil identification from the two-body system  $p + \pi^-$  (cleaner channel)
  - (b) Study of the kinematic recoil variables (momentum, angles, energy, etc...)
3. Study of real data events sample:
  - (a) Recoil identification from the three-body system  $p + \gamma_{ISR} + \pi^-$
  - (b) Constraint with 1C kinematic fit over the  $p + \gamma_{ISR} + \pi^-$  recoil mass
  - (c) Examine Data/MC agreement in ECL cluster shapes from  $\bar{n}$  channel

# Analysis outline (1)

- The analyzed channel is:

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

The reconstructed particles are (cuts and selections in backup):

- (a)  $vpho \rightarrow p + \gamma_{ISR} + \pi^-$ , where  $vpho$  is a fake particle, mimicking the recoil system
- (b)  $\bar{n}$  candidates list used to compare its variables with those of the recoil

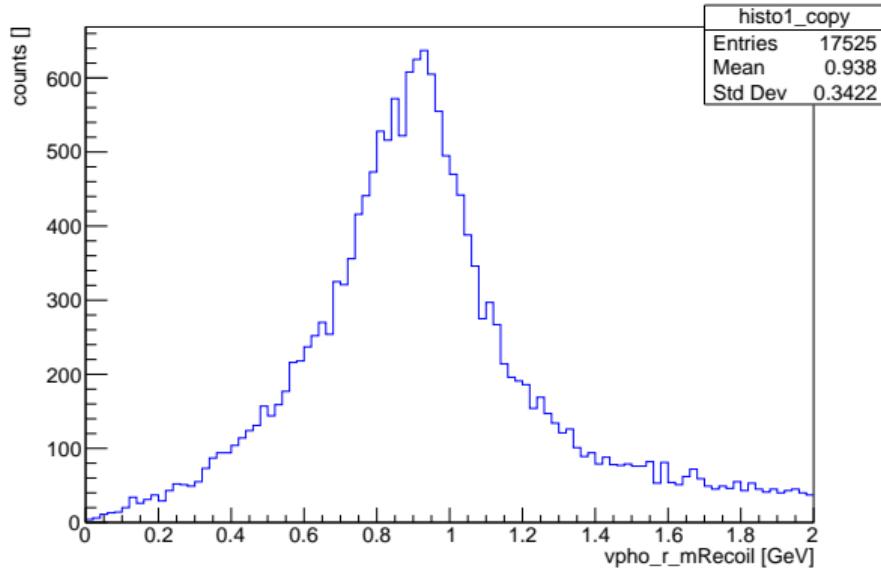
- 100k events** were generated, **17525** candidates have been reconstructed  
→ reconstruction efficiency:

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

# The recoil mass (1a)

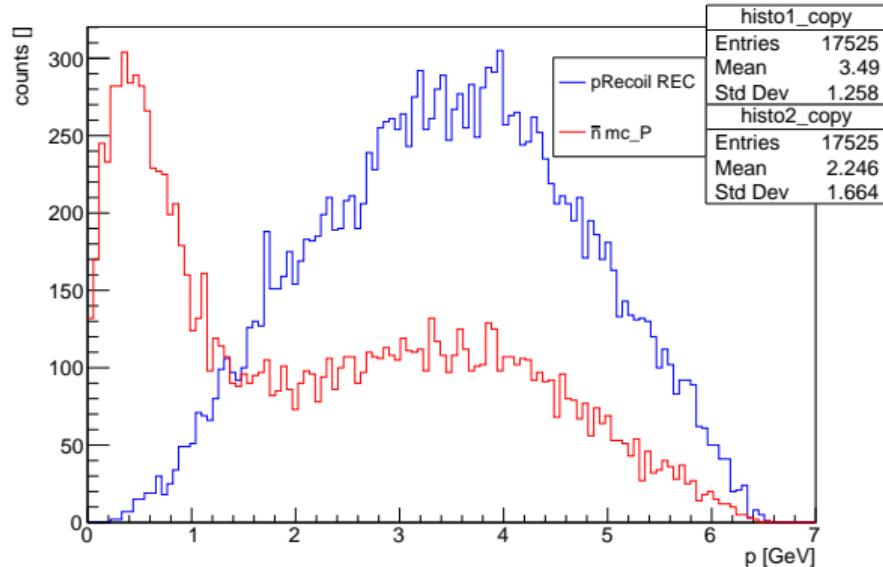
- The recoil three body system is well reconstructed as shown in the recoil mass distribution, where a peak emerges above the  $\bar{n}$  mass.

→ reconstructed  $\bar{n}$  variables can be compared with the reconstructed recoil variables ( $p$ ,  $\theta$ )



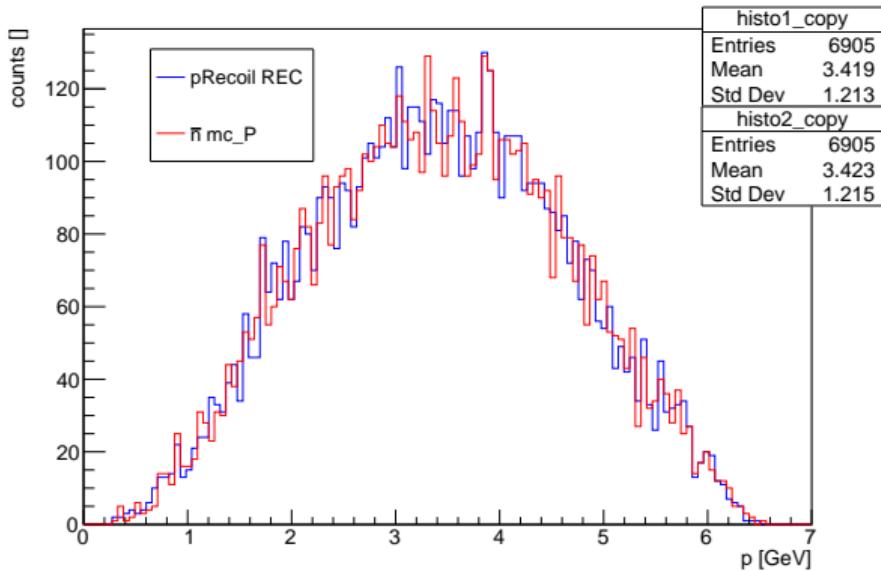
# The recoil and the $\bar{n}$ momentum (1b)

- 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)



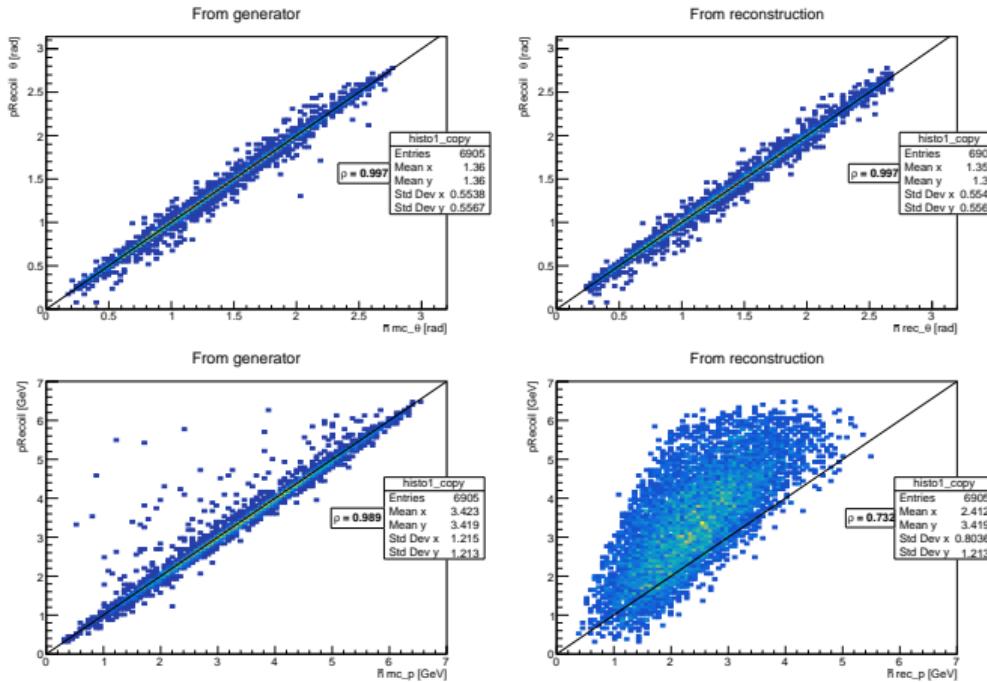
# The recoil and the $\bar{n}$ momentum (1b)

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



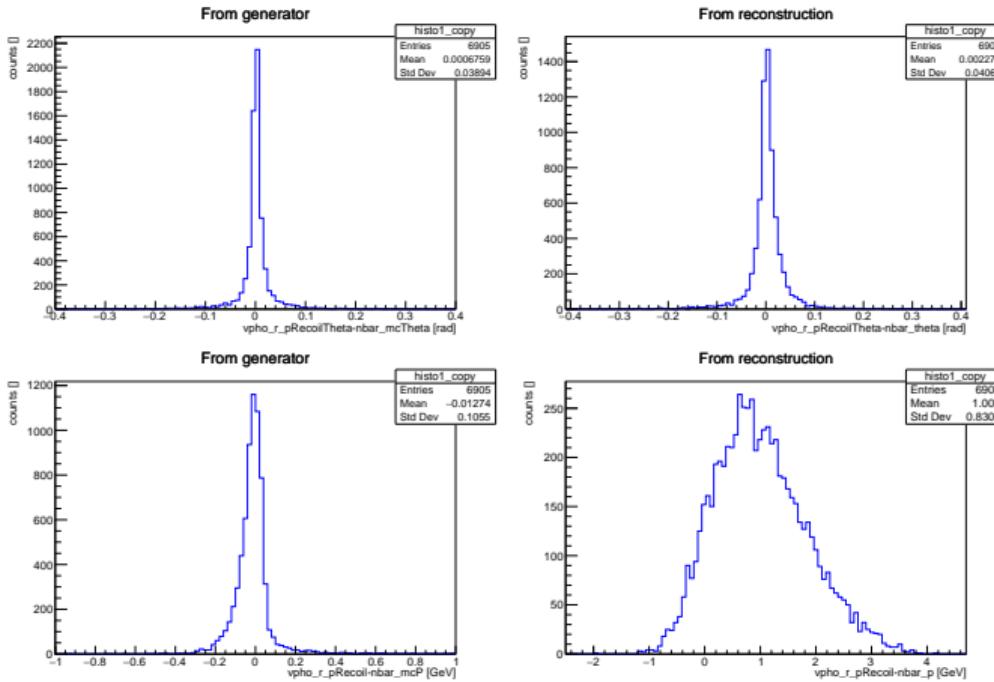
# $\bar{n}$ vs recoil vector correlation (1b)

- 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)

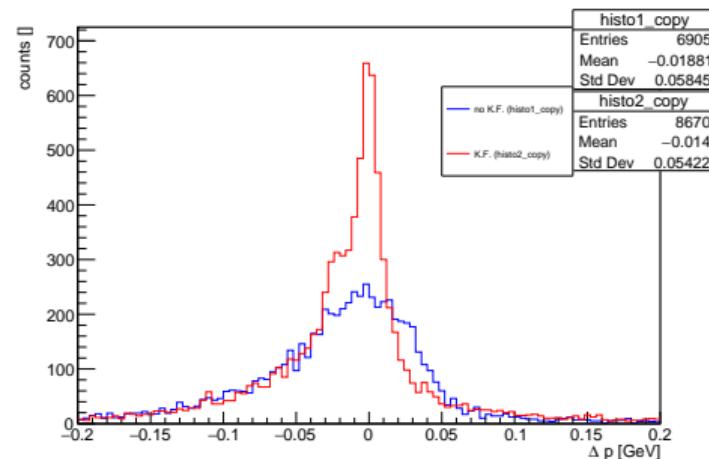
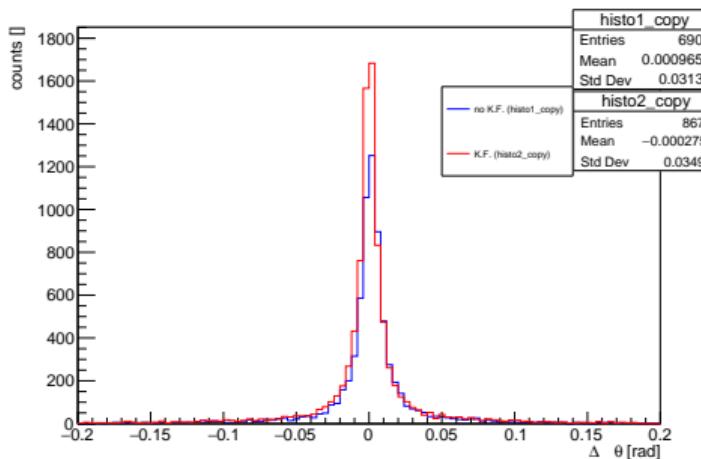
- Good correlation is observed at the generator level in both the momentum and  $\theta$  distributions
- The reconstructed  $\bar{n}$  momentum in the ECL is not a reliable variable, since no high correlation is observed (annihilation and energy loss)



# 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  $\theta$

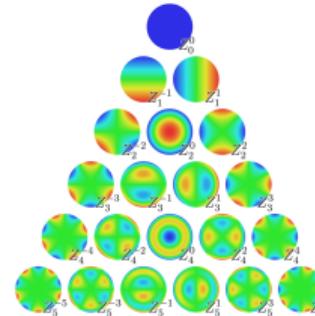
- Highest amount of reconstructed candidates ( $\sim 24\%$ ) and of real  $\bar{n}$  ( $\sim 9\%$ )
- No significant differences can be seen in  $\theta_{recoil}$  vs MC  $\theta_{\bar{n}}$
- A slightly improvement can be observed in  $p_{recoil}$  vs MC  $p_{\bar{n}}$



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

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

- **clusterE**, **clusterE1E9** and **clusterE9E21**  
( $E_{min} = 20$  GeV)
- **clusterAbsZernikeMoment51**:  $|Z_{51}|$



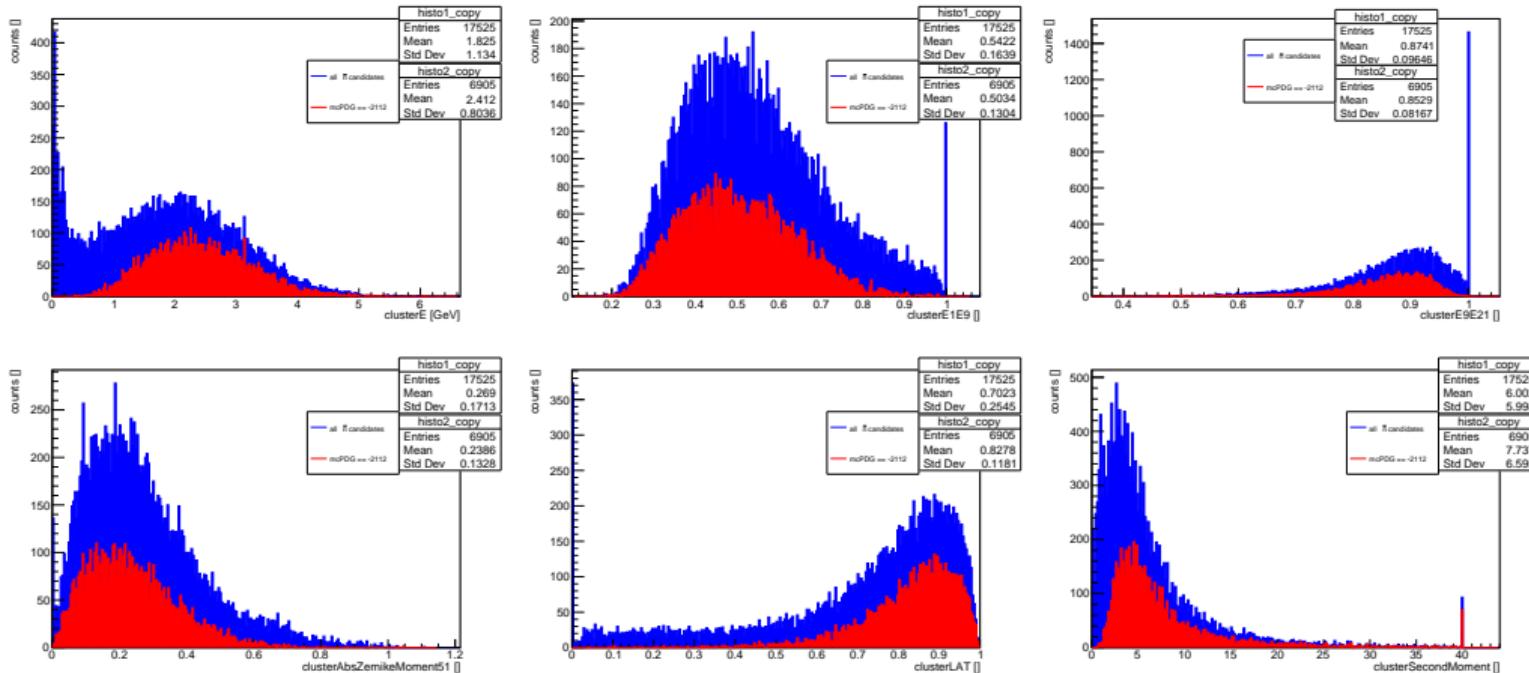
10	11	12	13	14
25	2	3	4	15
24	9	1	5	16
23	8	7	6	17
22	21	20	19	18

- **clusterLAT**: lateral energy distribution, defined as:  $S = \frac{\sum_{i=2}^n \omega_i E_i r_i^2}{\omega_0 E_0 r_0^2 + \omega_1 E_1 r_1^2 + \sum_{i=2}^n \omega_i E_i r_i^2}$
- **clusterSecondMoment**: second moment S, defined as:  $S = \frac{\sum_{i=0}^n \omega_i E_i r_i^2}{\sum_{i=0}^n \omega_i E_i}$

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



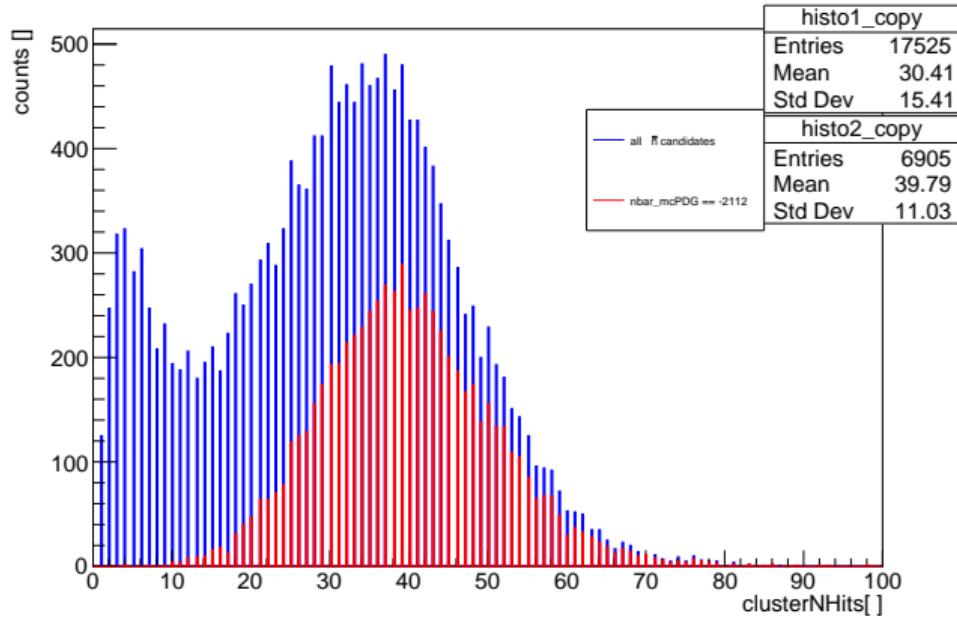
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# $\bar{n}$ ECL cluster variables (1d)

- $\bar{n}$  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:

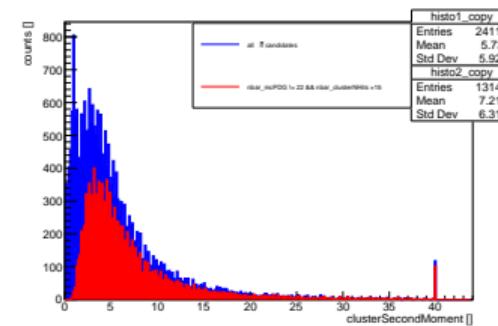
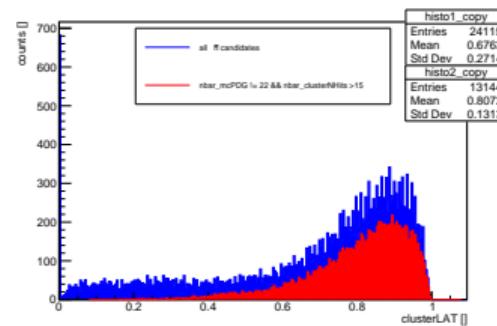
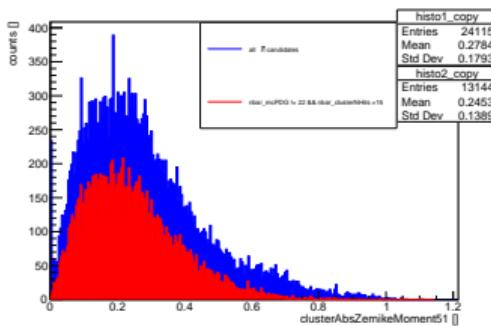
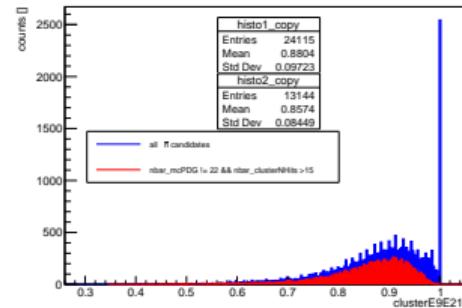
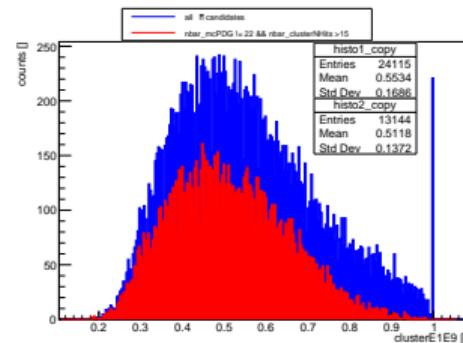
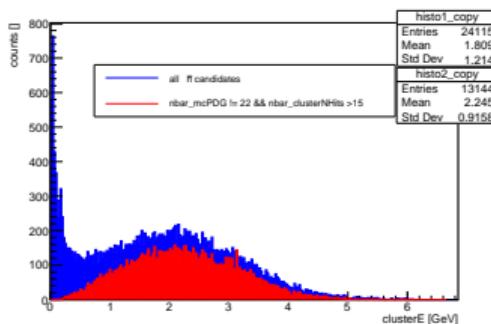
$\bar{n}_{mcPDG} \neq 22$   
  &&  
 $\bar{n}_{clusterNHits} > 15$



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



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# Summary (1)

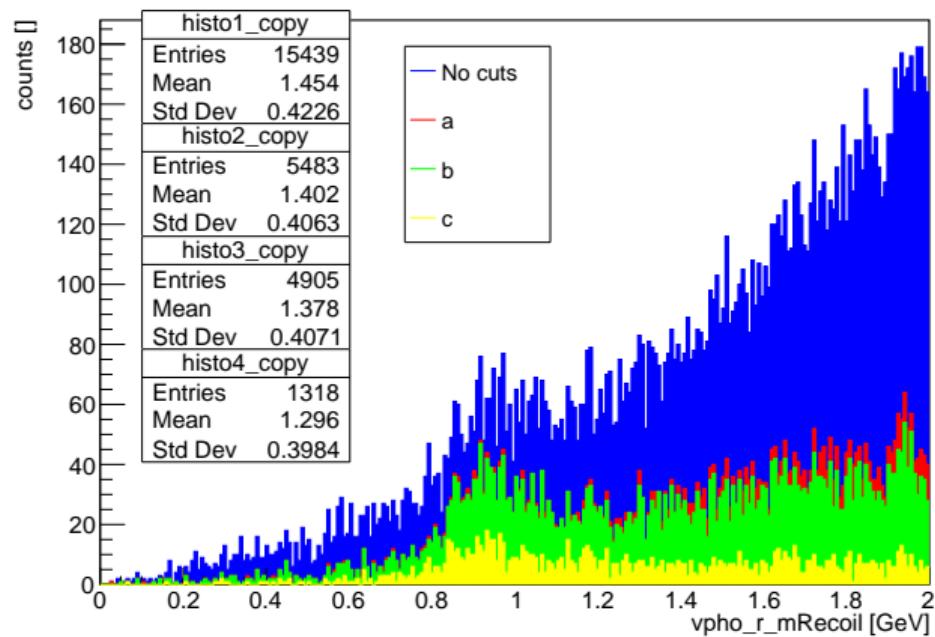
- Channel  $e^+ + e^- + \gamma_{ISR} \rightarrow X \rightarrow p + \bar{n} + \pi^-$  has been studied
- The recoil three body system ( $p + \pi^- + \gamma_{ISR}$ ) is correctly reconstructed from the secondary background, ISR/FSR photons
- The  $\bar{n}$  kinematic is properly described by the three 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 reduce the uncertainty on the recoil momentum

## Analysis outline (2)

- Study of uubar continuum using the following MC cocktail sample:  
*/belle/collection/MC/MC16rd\_proc16\_chunk1\_uubar\_4S\_v1*
- To obtain a cleaner channel, 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)

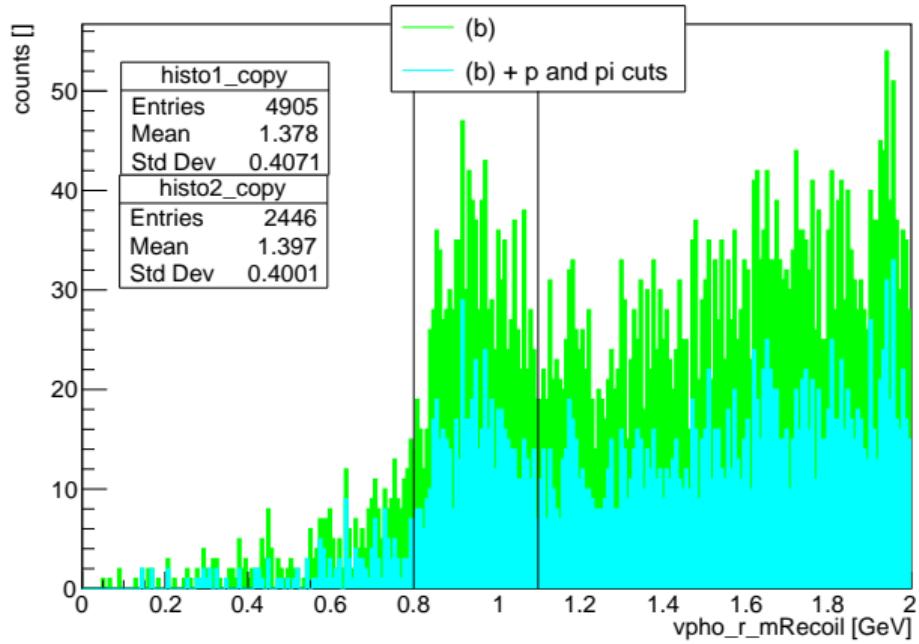
# mRecoil distribution

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



# mRecoil distribution

- Other "Real selections" can be applied as well, with (b), such as: [5]  
 $\text{protonID} > 0.9$  and  $\text{pionID} > 0.1$  and  $\text{dr} < 1$  and  $\text{abs(dz)} < 3$  (from IP) ■■■
- To maximize purity, a recoil mass zoom 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)

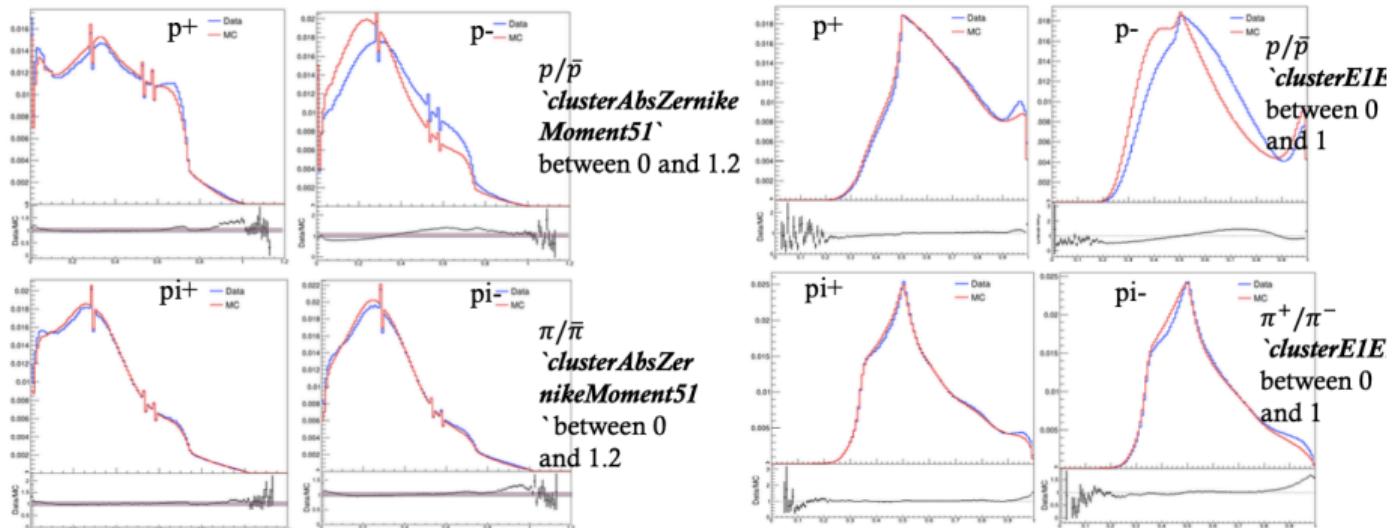


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# Data/MC agreement $\bar{n}$ case

Analysis of a  $\Lambda \rightarrow p + \pi^-$  ( $\bar{\Lambda} \rightarrow \bar{p} + \pi^+$ ) sample shows that [6]:



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

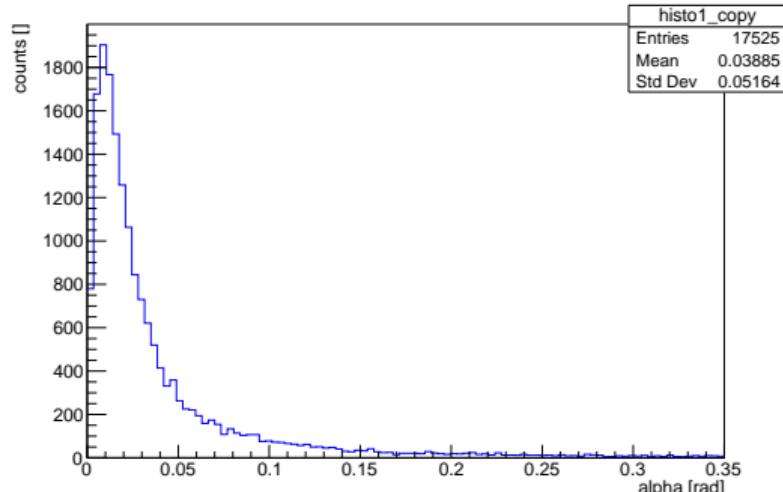
**Emanuele Zanuso**

Dipartimento di Fisica  
Università degli Studi di Torino

January 14, 2026

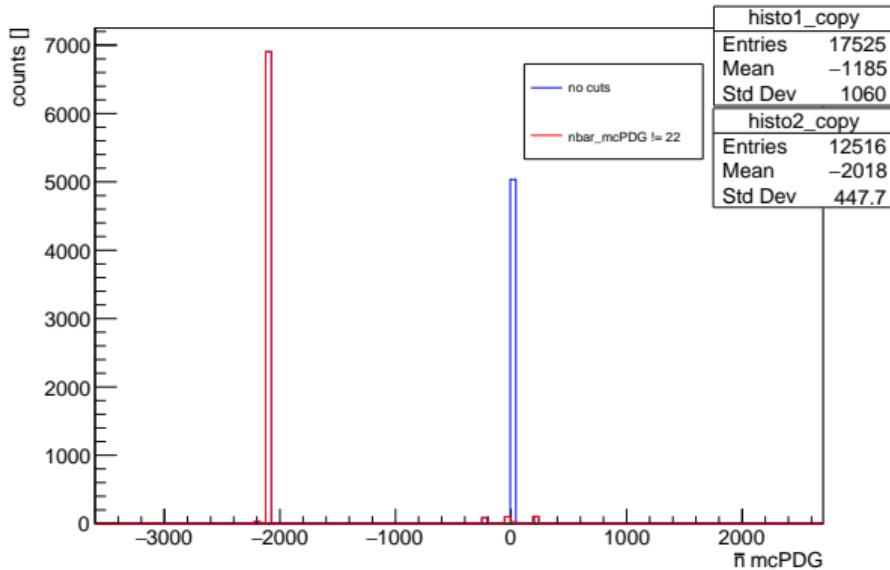
# Selections/cuts on clean MC sample I

- (a)  $protonID > 0.9$  and  $dr < 1$  and  $abs(dz) < 3$  and  $pionID > 0.1$  (From IP?)
- (b)  $p\_mcPDG == 2212$  and  $pi\_mcPDG == -211$  and  $gamma\_mcPDG == 22$
- (c) Rec.  $\bar{n}$  in theta ECL Acceptance and From ECL
- (d)  $mRecoil > 0\text{GeV}$  and  $mRecoil < 2\text{GeV}$
- (e)  $\alpha < 0.35 \text{ rad} (\sim 20 \text{ deg})$ , where  $\alpha$  is the 3D angle between the recoil vector and the closest reconstructed  $\bar{n}$  candidate (rankByLowest)



# $\bar{n}$ mcPDG I

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



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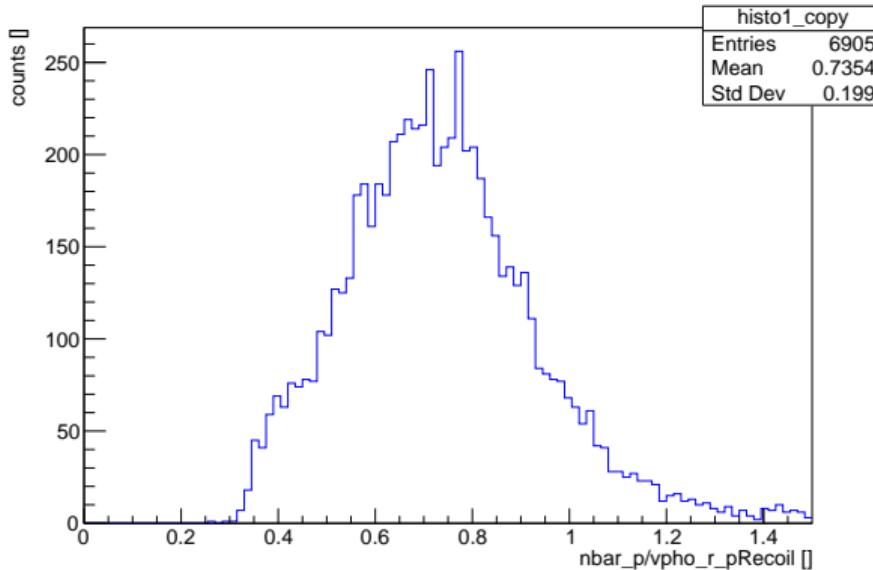


# $p_{\bar{n}}/\text{pRecoil}$ |

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



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- [1] M. Ablikim et al. In: *Nature Physics* 17 (2021).
- [2] G.F. Burgio et al. In: *Prog. Part. Nucl. Phys.* 10389 (2021), p. 120.
- [3] F. Donato, N. Fornengo, and P. Salati. In: *Phys. Rev. D* 62 (2000), p. 043003.
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- [6] Shanette De La Motte. In: *Belle II Italy December* (2025).

