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# Characterization of hadronic showers in the Belle II Electromagnetic Calorimeter

Metatesi exam

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# Talk Outline



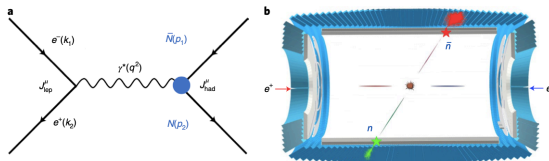
**1. Anti-neutron in physics experiment**

**2. Preliminary study via clean MC sample**

# 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]



- The decay channels studied at B-factories which involved  $\bar{n}$ , such as:
  - The hyperons decay channel:

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

- 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

$\bar{n}$  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]:

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

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

- $\bar{D}$  is mainly produced through a coalescence mechanism:

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

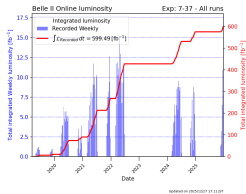
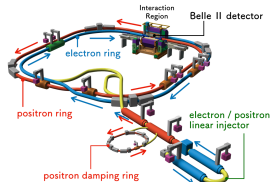
Where  $\bar{p}$  and  $\bar{n}$  are nearby in the phase-space

# The Belle II experiment



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

- 7 GeV electrons beam (HER)
- 4 GeV positrons beam (LER)
- Peak Lumi  $\sim 5.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  🏆
- Design Lumi  $\sim 6.5 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$   
→ x40 the Belle's one



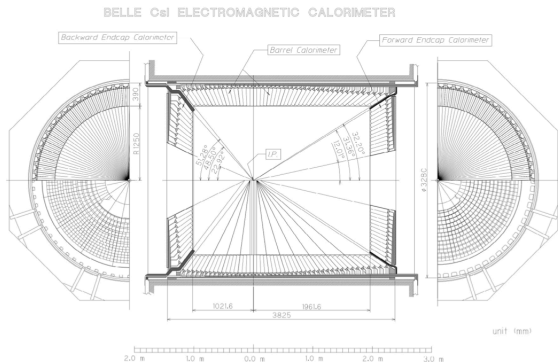
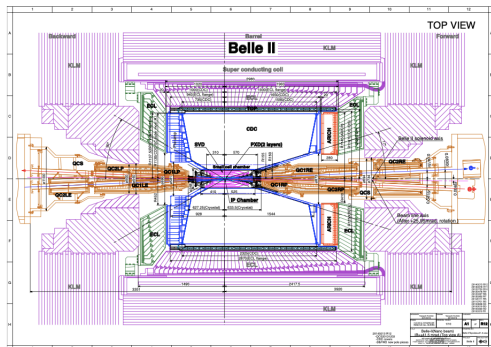
It operates mainly around  $\Upsilon(4S)$  resonance ( $\sim 10.58 \text{ GeV}$ ):

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

# The Electromagnetic CaLorimeter

The ECL plays a central role in this thesis

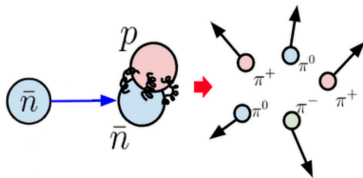
- Array of **CsI(Tl)** crystals (8376  $6\times6\times30\text{cm}^3$  crystals in total)
- It covers barrel and end-caps regions ( $12^\circ \leq \theta \leq 155^\circ$ )
- Energy resolution of 4% @100 MeV and 1.6% @8 GeV



# 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



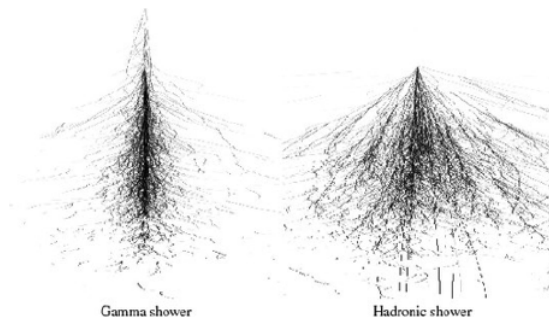
# Electromagnetic and hadronic showers

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 ( $p$ ,  $n$ , *pions*, *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 Csl(Tl))
- About the 90% of the e.m. shower is contained within a cylinder of radius  $R_M$  ( $\sim 3.6$  cm in Csl(Tl))





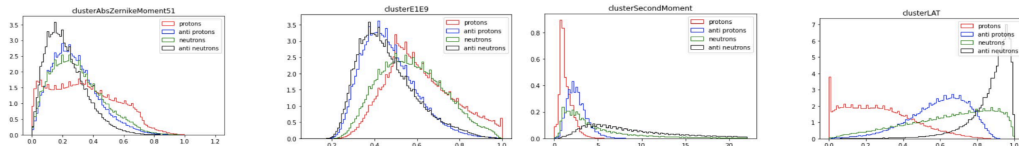
# Anti-neutron interactions in physics

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  $\bar{n}$

# 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 how they correlate to the initial energy
2. Combine the signals from (1) and (2) to reconstruct the  $\bar{n}$ 's 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

# 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 ECL clusters
  - (d) Study of the effect of 1C kinematic fit over the  $p + \gamma_{ISR} + \pi^-$  recoil mass
2. Study of MC cocktail events sample:
  - (a) Recoil identification from the three-body system  $p + \gamma_{ISR} + \pi^-$
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

- Several channels can be selected to study  $\bar{n}$  at Belle II experiment. The chosen one is:

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

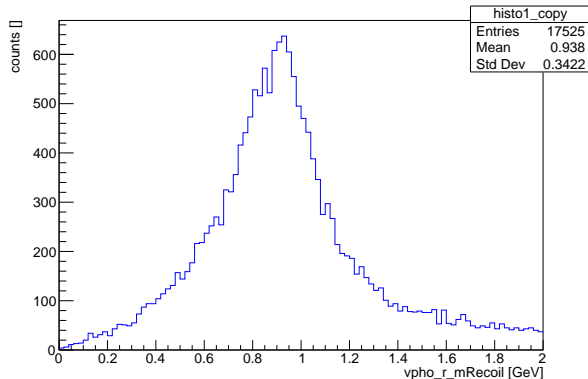
- The reconstructed particles are (cuts and selections in backup)
  - (a)  $vpho \rightarrow p + \gamma_{ISR} + \pi^-$ , where  $vpho$  is a fake particle, mimicking the recoil system
  - (b)  $\bar{n}$  candidate list, used to compare its variables with those of the recoil
- **100k events** were generated, **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)

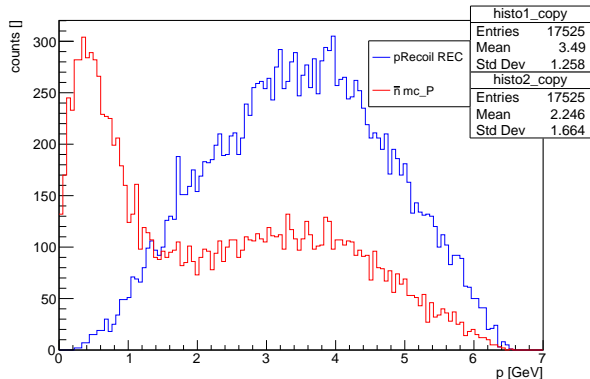
- The recoil three body system is well reconstructed as shown in the recoil mass distribution, where a peak emerges above the  $\bar{n}$  mass.

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



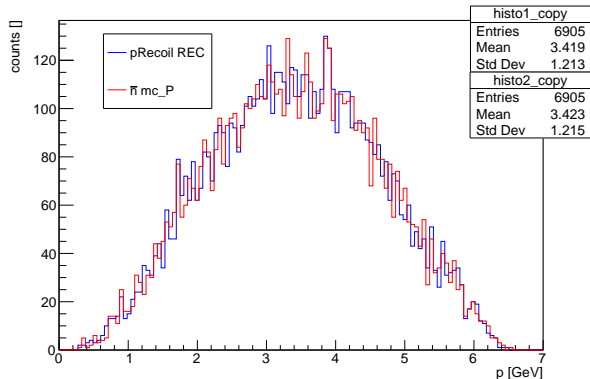
# The recoil and the $\bar{n}$ momentum

- The reconstructed  $\bar{n}$  candidate list shows a discrepancy with the recoil momentum  $\rightarrow \gamma$ 's are mis-identified as  $\bar{n}$  in reconstruction
- MC selection  $\bar{n}_{mcPDG!} = 22$  is applied in order to directly compare the recoil kinematic variables with the  $\bar{n}$  from MC truth



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

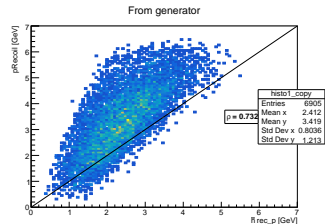
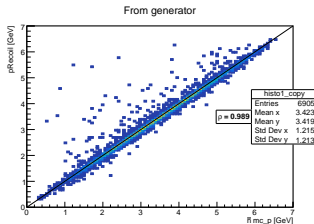
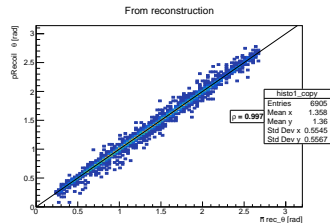
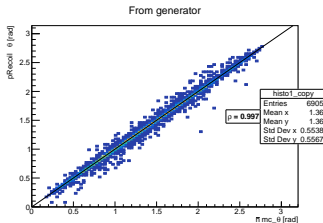
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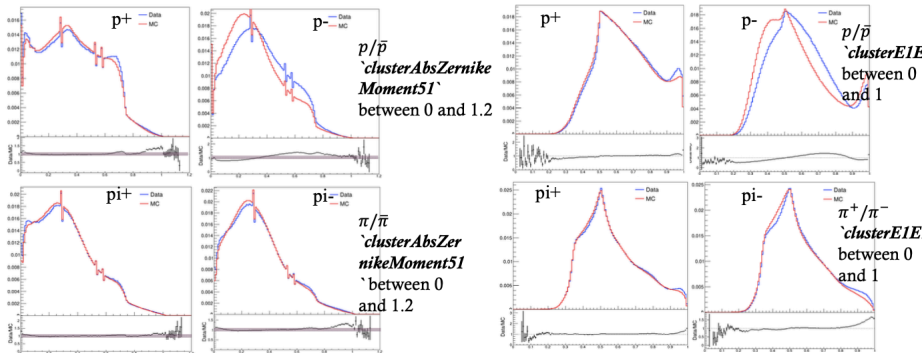
# $\bar{n}$ vs recoil vector correlation

- 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 (energy loss)



# Analysis outline

Analysis of a  $\Lambda \rightarrow p + \pi^-$  ( $\bar{\Lambda} \rightarrow \bar{p} + \pi^+$ ) sample shows that [5]:



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



# Thank you for your attention

**Emanuele Zanusso**

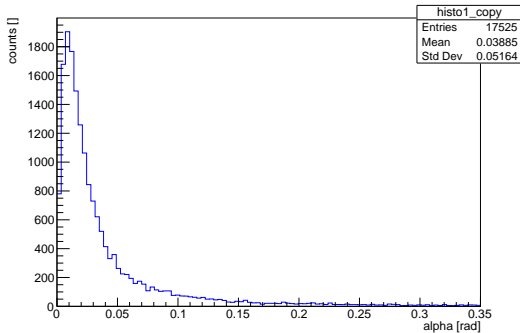
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# Applied selections and cuts on clean MC sample

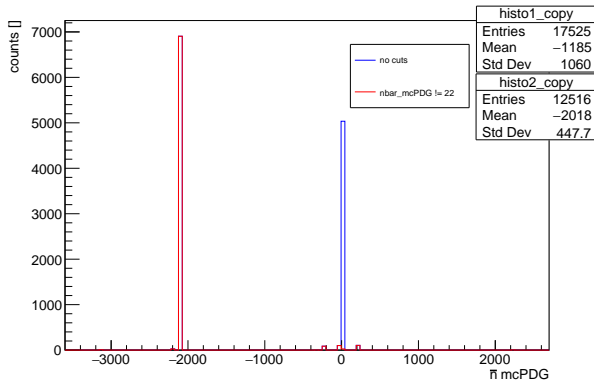


- (a)  $protonID > 0.9$  and  $dr < 1$  and  $abs(dz) < 3$  and  $pionID > 0.1$  (From IP?)
- (b)  $p\_PDG == 2212$  and  $pi\_PDG == -211$  and  $gamma\_PDG == 22$
- (c) Rec.  $\bar{n}$  in theta ECL Acceptance and From ECL
- (d)  $mRecoil > 0GeV$  and  $mRecoil < 2GeV$
- (e)  $\alpha < 0.35$  rad (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



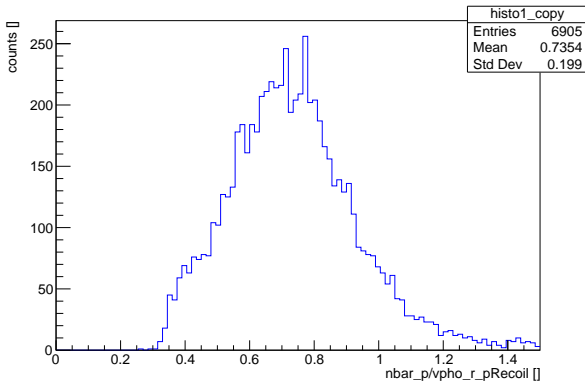
# $\bar{n}$ mcPDG I

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



# $p_{\bar{n}}/p_{\text{Recoil}}$ I

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



# References I

- [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.
- [4] Sanjeeda Das. In: *Belle II Italy May* (2025).
- [5] Shanette De La Motte. In: *Belle II Italy December* (2025).