Characterization of hadronic showers in the Belle II Electromagnetic Calorimeter

Metatesi exam

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Talk Outline

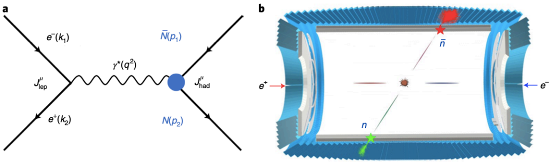
1. **Anti-neutron in physics experiment**

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 $e^+ + e^- \to n + \bar{n}$ process [1]



- The decay channels studied at B-factories which involved $\bar{n}$, such as:
  1. The hyperons decay channel:
  $$\bar{\Lambda}^0 \to \pi^0 + \bar{n}, \qquad \bar{\Sigma}^- \to \pi^- + \bar{n}, \qquad \bar{\Lambda}_c \to K_s^0 + \pi^0 + \bar{n}$$
  2. Other typical B-factories processes:
  $$e^+ + e^- \to p + \bar{n} + X^- \quad (X^-\text{: combination of charged pions and kaons})$$

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]:
  $A_{d.m.} + B_{d.m.} \rightarrow hadrons$ ($n, \bar{n}, p, \bar{p}$ etc...)
  $X_{d.m.} \rightarrow$ hadrons ($n, \bar{n}, p, \bar{p}$ etc...)
- $\bar{D}$ is mainly produced through a coalescence mechanism:

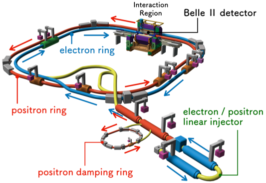
$$\bar{n} + \bar{p} \rightarrow \bar{D}$$

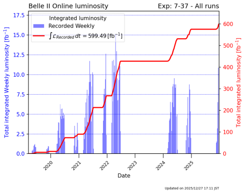
  Where $\bar{p}$ and $\bar{n}$ are nearby in the phase-space

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 $\sim 5.1 \times 10^{34} cm^{-2} s^{-1}$ 🏆
- Design Lumi $\sim 6.5 \times 10^{35} cm^{-2} s^{-1}$ $\rightarrow$ x40 the Belle's one





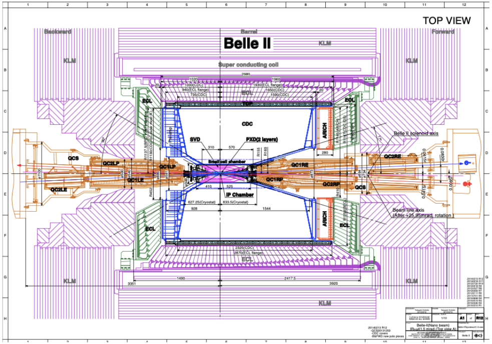
It operates mainly around $\Upsilon(4S)$ resonance ($\sim 10.58 GeV$):

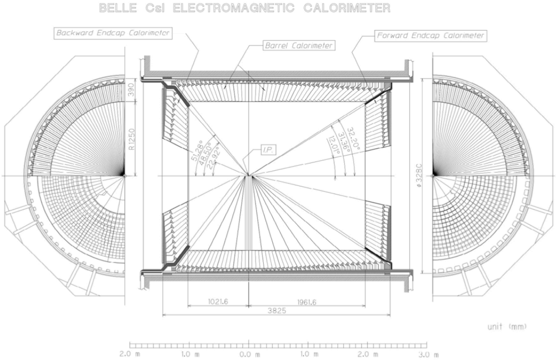
- It decays almost exclusively into entangled couple of $B\,\bar{B} \rightarrow$ B-factory
- Several goals: flavour physics, BSM, B and charm mesons etc...

The Electromagnetic CaLorimeter

The ECL plays a central role in this thesis

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

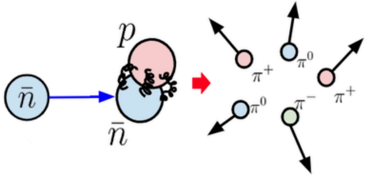




Anti-neutron interactions in physics

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 (π^+, π^-) and electromagnetic (π^0) showers are generated within the ECL
- Since annihilation stars are produced, both backward (TOP) and forward (KLM) directions are involved



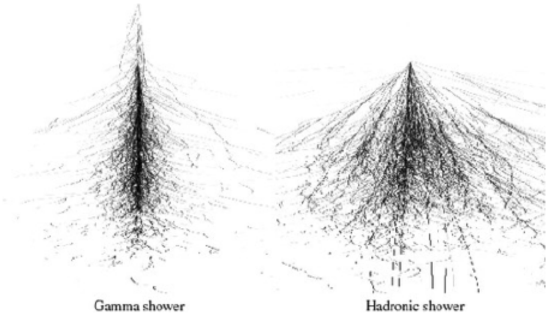
Electromagnetic and hadronic showers

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

1. Brems. and p.p. process (e^+, e^-, γ) and $\pi^0 \to \gamma\gamma$
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 λ_{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))



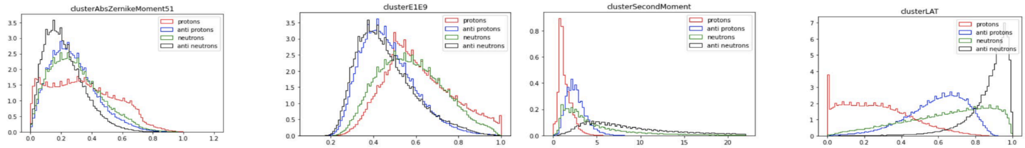
Anti-neutron interactions in physics

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

- $e^+ + e^- \to X \to p + \bar{n} + \pi^-$ (Mine)
- $\bar{\Lambda}_c \to K^0_s + \pi^0 + \bar{n}$
- $\Lambda(\to\ p + \pi^-) + \bar{\Lambda}(\to \bar{n} + \pi^0)$

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 in agree [4] $\to$ $\bar{p}$ cannot be used as proxy for $\bar{n}$

The MANTRA project

Measuring **A**nti-**N**eutron: **T**agging and **R**econstruction **A**lgorithm:

- 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 hey 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 π^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
     $\rightarrow$ 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

- The analyzed channel 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

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

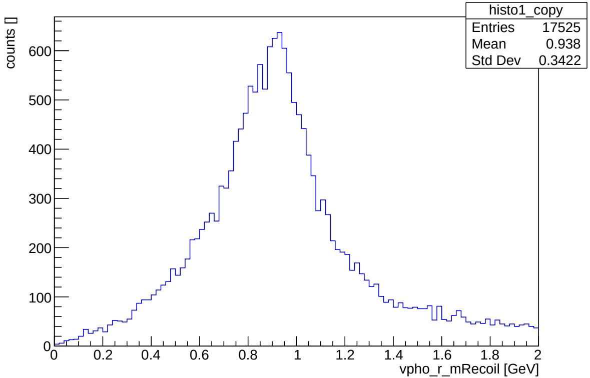
- **100k events** were generated, **17525** candidates have been reconstructed $\rightarrow$ reconstruction efficiency:

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

The recoil mass (1a)

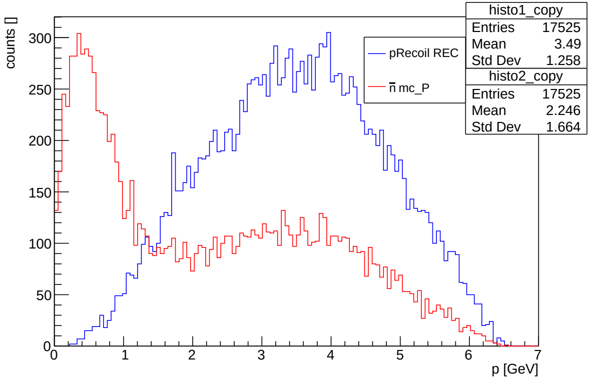
- The recoil three body system is well reconstructed as shown in the recoil mass distribution, where a peak emerges above the $\bar{n}$ mass.

  $\rightarrow$ reconstructed $\bar{n}$ variables can be compared with the reconstructed recoil variables (p, θ, ϕ)



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

- 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



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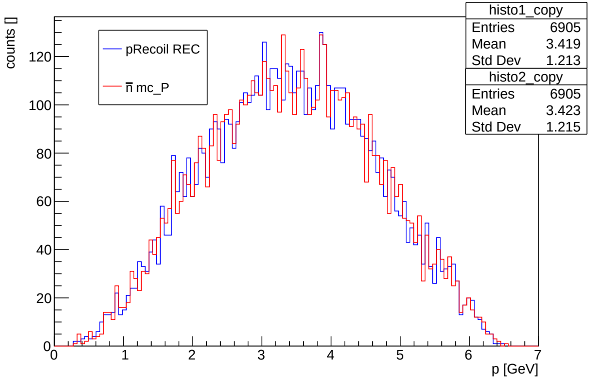
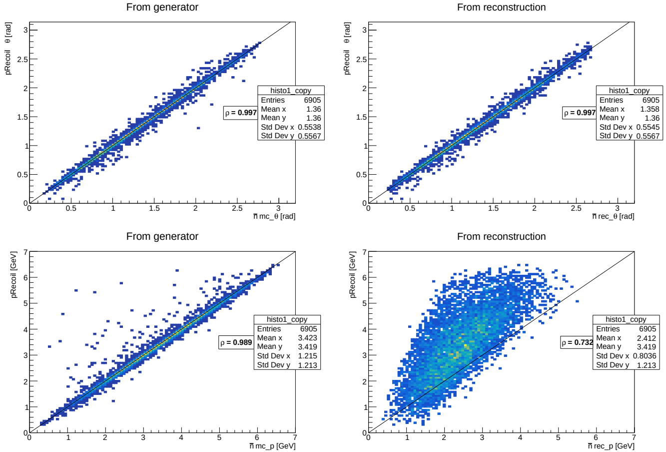


$\bar{n}$ vs recoil vector correlation (1b)

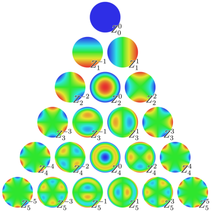
- Good correlation is observed at the generator level in both the momentum and θ distributions
- The reconstructed $\bar{n}$ momentum in the ECL is not a reliable variable, since no high correlation is observed (energy loss)



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

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

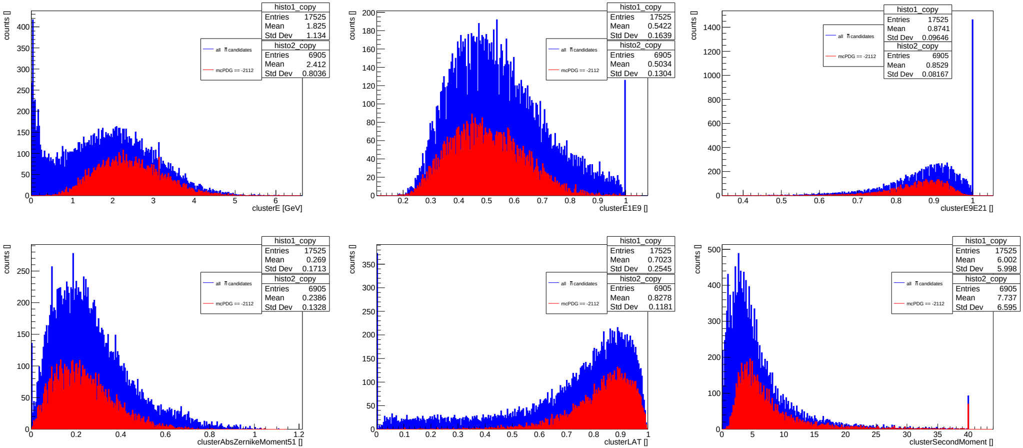
- **clusterE**, **clusterE1E9** and **clusterE9E21** ($E_{min} = 20$ GeV)
- **clusterAbsZernikeMoment51**: $|Z_{51}|$



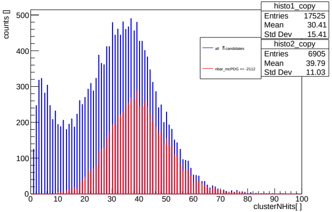
10	11	12	13	14
25	2	3	4	15
24	9	1	5	16
23	8	7	6	17
22	21	20	19	18

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

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

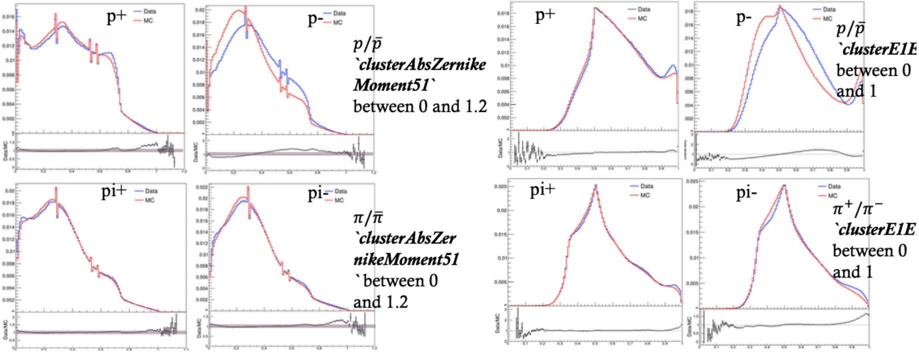


$\bar{n}$ ECL cluster variables (1c)



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

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Applied selections and cuts on clean MC sample

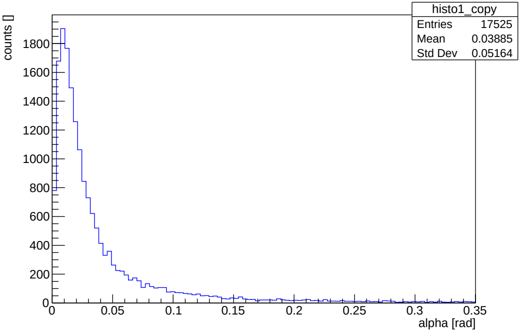
(a) *protonID* > 0.9 and *dr* < 1 and *abs*$($*dz*$) < 3$ and *pionID* > 0.1 (From IP?)

(b) *p_PDG* $== 2212$ and *pi_PDG* $== -211$ and *gamma_PDG* $== 22$

(c) Rec. $\bar{n}$ in theta ECL Acceptance and From ECL

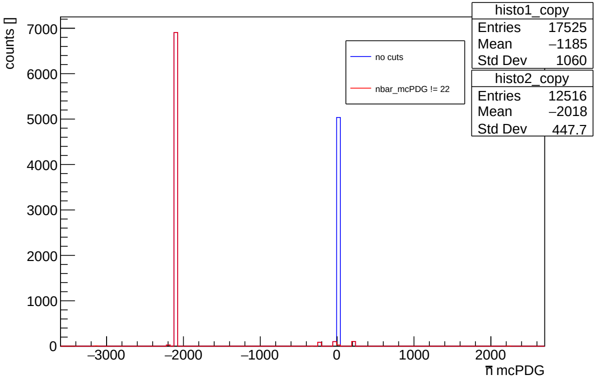
(d) *mRecoil* > 0*GeV* and *mRecoil* < 2*GeV*

(e) α < 0.35 rad (~ 20 deg), where α is the 3D angle between the recoil vector and the closest reconstructed $\bar{n}$ candidate (rankByLowest)



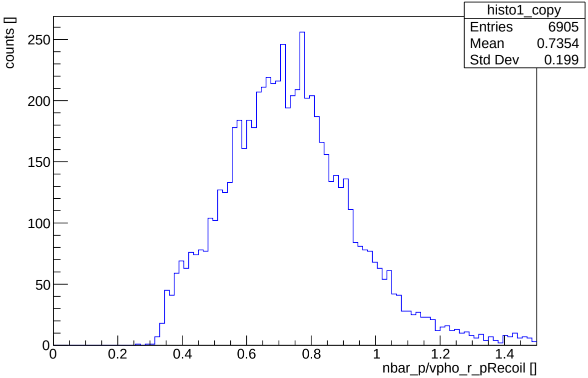
$\bar{n}$ mcPDG I

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



$p_{\bar{n}}$/pRecoil I

$\bar{n}$ 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).

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[3] F. Donato, N. Fornengo, and P. Salati. In: *Phys. Rev. D* 62 (2000), p. 043003.

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