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Characterization of hadronic showers in the Belle II Electromagnetic Calorimeter

Metatesi exam

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Talk Outline



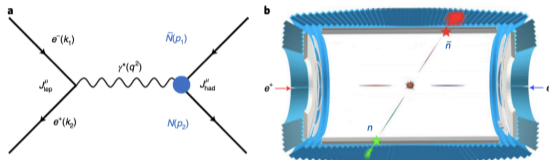
1. Anti-neutron in physics experiment

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:

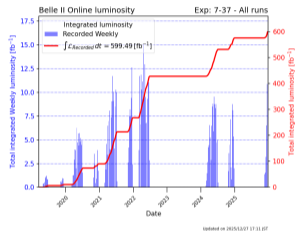
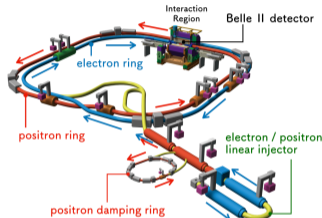
$$\bar{n} + \bar{p} \rightarrow \bar{D}$$

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 $\sim 8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
→ x40 the Belle's one



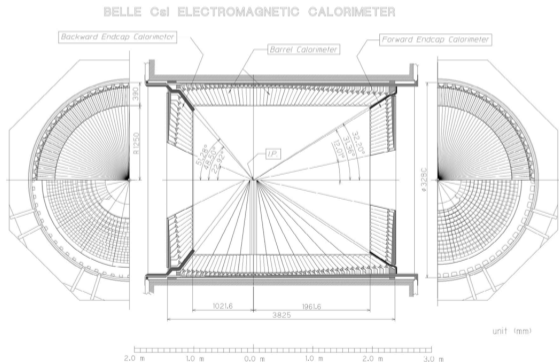
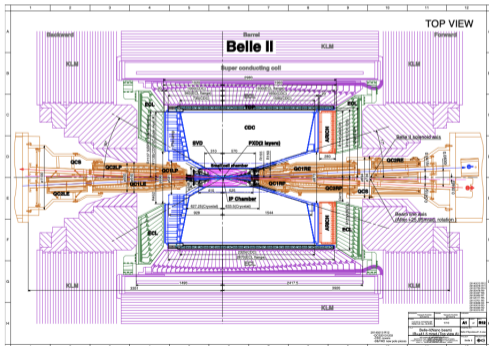
It operates mainly around $\Upsilon(4S)$ resonance ($\sim 10.58 \text{ GeV}$):

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

The Electromagnetic Calorimeter

The ECL plays a central role in this thesis

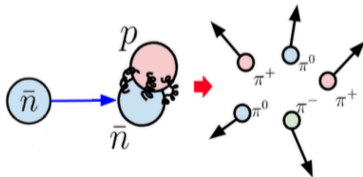
- Array of **CsI(Tl)** crystals ($8376\ 6\times6\times30\text{cm}^3$ crystals in total)
- It covers barrel and end-caps regions ($12^\circ \leq \theta \leq 155^\circ$)
- Energy resolution of 4% @100 Mev and 1.6% @8 GeV



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 (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



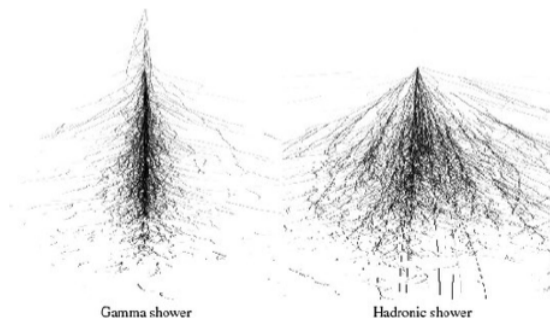
Electromagnetic and hadronic showers

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

1. Brems. and p.p. process (e^+ , e^- , γ) and $\pi^0 \rightarrow \gamma\gamma$
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 λ_{had} (~ 44.12 cm in Csl(Tl))
- About the 90% of the e.m. shower is contained within a cylinder of radius R_M (~ 3.6 cm in Csl(Tl))



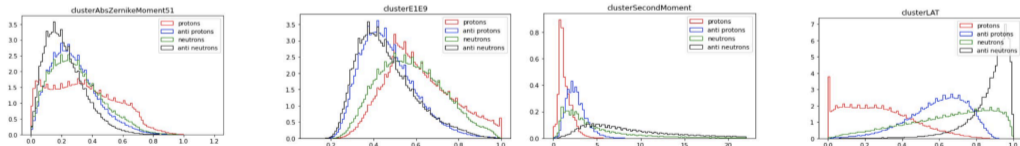
Anti-neutron interactions in physics

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 in 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 π^0 ($\sim 5\%$): energy is all contained in the calorimeter, the shower is fully reconstructed
 - If π^\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

- 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):

- $vpho \rightarrow p + \gamma_{ISR} + \pi^-$, where $vpho$ is a fake particle, mimicking the recoil system
- \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

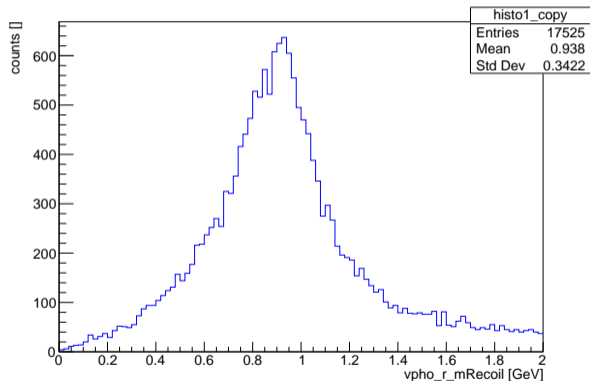
- 100k events** were generated, **17525** candidates have been reconstructed
→ reconstruction efficiency:

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

The recoil mass (1a)

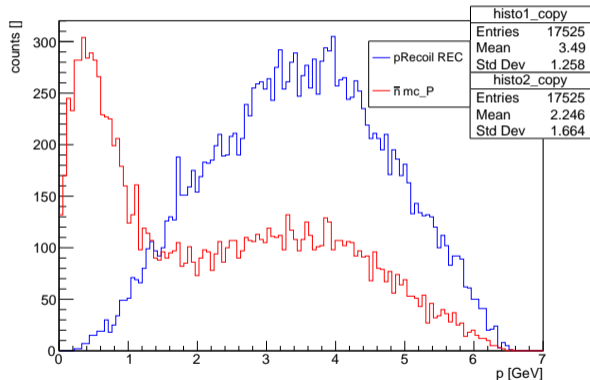
- The recoil three body system is well reconstructed as shown in the recoil mass distribution, where a peak emerges above the \bar{n} mass.

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



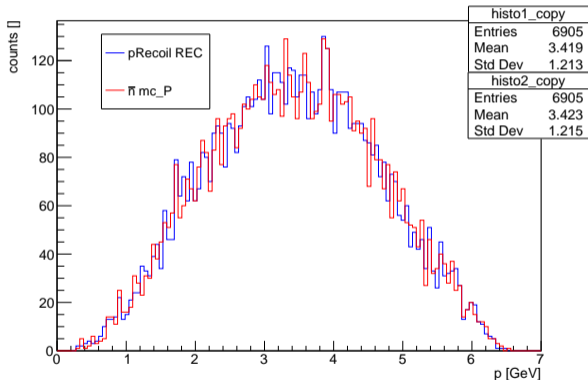
The recoil and the \bar{n} momentum (1b)

- The reconstructed \bar{n} candidate list shows a discrepancy with the recoil momentum \rightarrow several γ 's 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)



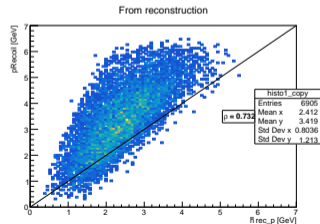
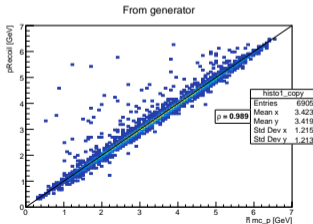
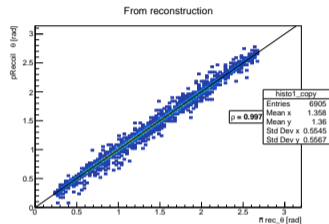
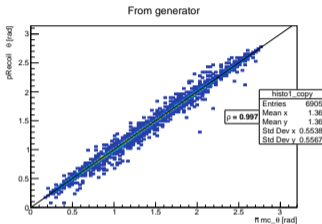
The recoil and the \bar{n} momentum (1b)

- 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
- For a ($LUMI$) real data, $t(TOTevents)$ are expected



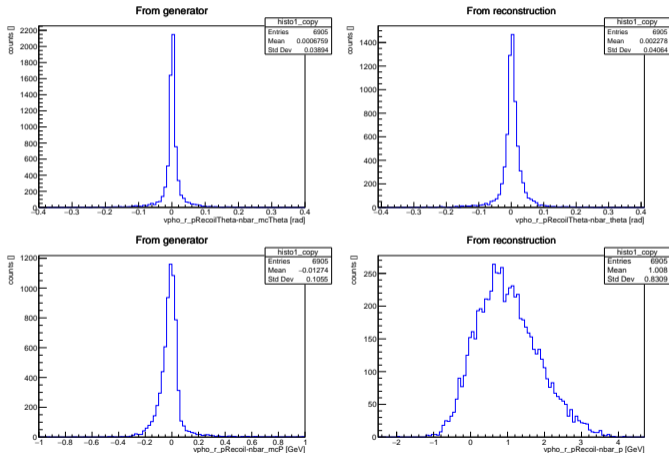
\bar{n} vs recoil vector correlation (1b)

- 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 (annihilation and energy loss)



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

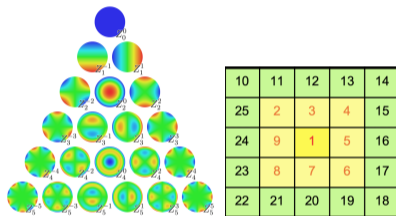
- Good correlation is observed at the generator level in both the momentum and θ distributions
- The reconstructed \bar{n} momentum in the ECL is not a reliable variable, since no high correlation is observed (annihilation and energy loss)



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

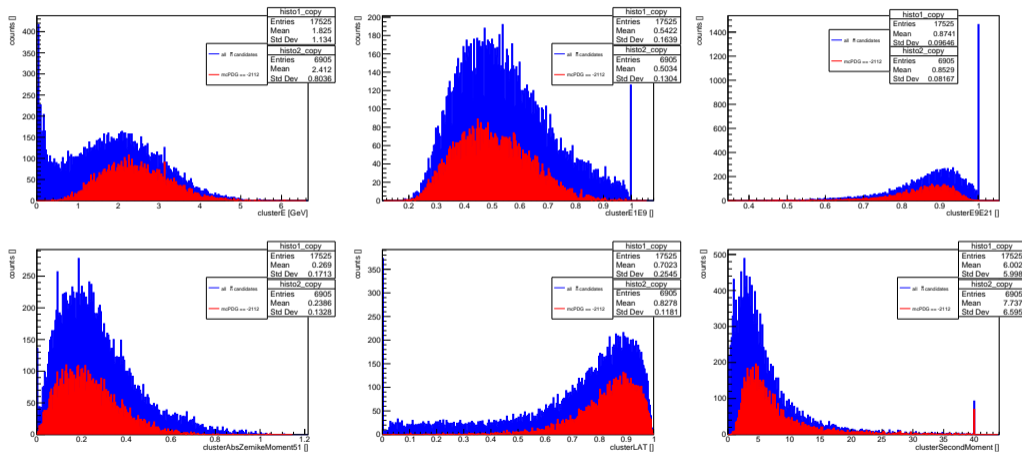
Cluster variables can be studied to distinguish \bar{n} from other neutral particles:

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

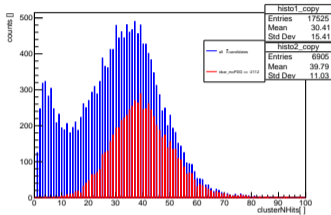


- **clusterLAT**: lateral energy distribution, defined as:
$$S = \frac{\sum_{i=2}^n \omega_i E_i r_i^2}{\omega_0 E_0 r_0^2 + \omega_1 E_1 r_1^2 + \sum_{i=2}^n \omega_i E_i r_i^2}$$
- **clusterSecondMoment**: second moment S , defined as:
$$S = \frac{\sum_{i=0}^n \omega_i E_i r_i^2}{\sum_{i=0}^n \omega_i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

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

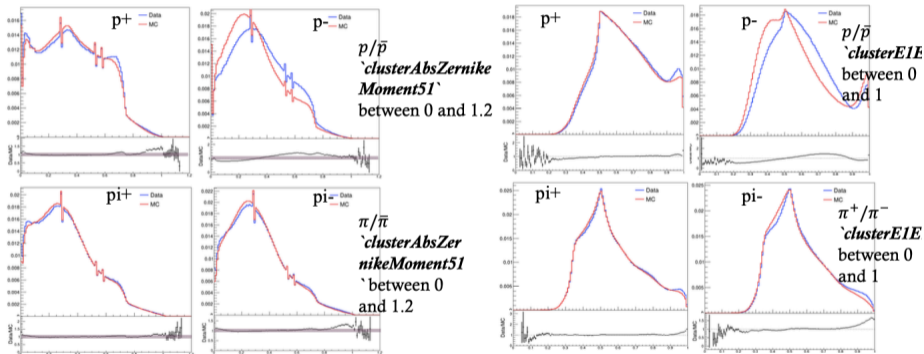


\bar{n} ECL cluster variables (1c)



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

Emanuele Zanusso

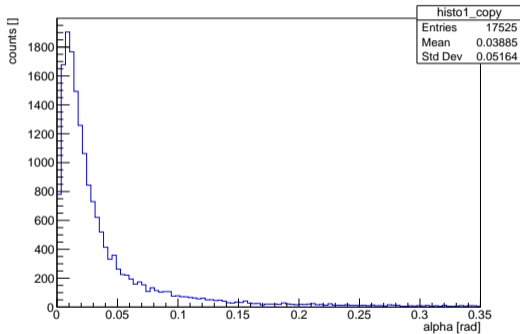
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Applied selections and cuts on clean MC sample

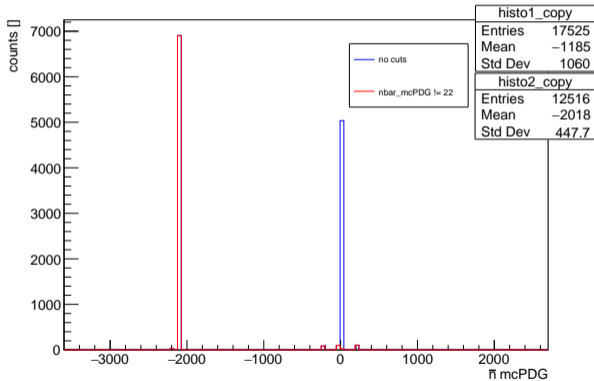


- (a) $protonID > 0.9$ and $dr < 1$ and $abs(dz) < 3$ and $pionID > 0.1$ (From IP?)
- (b) $p_PDG == 2212$ and $pi_PDG == -211$ and $gamma_PDG == 22$
- (c) Rec. \bar{n} in theta ECL Acceptance and From ECL
- (d) $mRecoil > 0GeV$ and $mRecoil < 2GeV$
- (e) $\alpha < 0.35$ rad (~ 20 deg), where α is the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



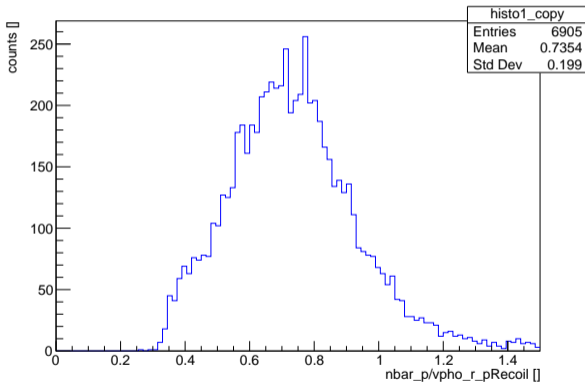
\bar{n} mcPDG I

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



$p_{\bar{n}}/p_{\text{Recoil}}$ 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).