Characterization of hadronic showers in the Belle II Electromagnetic Calorimeter

Metatesi Seminar

Emanuele Zanusso

Dipartimento di Fisica
Università degli Studi di Torino

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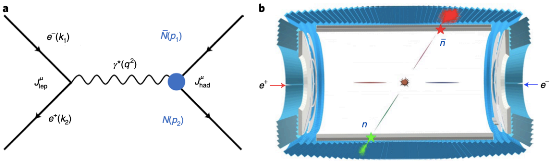
Outline

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



- Some decay channels studied at B-factories which involve $\bar{n}$
  1. The hyperons decay channel:

$$\bar{\Lambda}^0 \to \pi^0 + \bar{n}, \qquad \bar{\Sigma}^- \to \pi^- + \bar{n}, \qquad \bar{\Lambda}_c \to K^0_s + \pi^0 + \bar{n}$$

  2. Other typical B-factories processes:

(Altro canale di fisca)

Anti-neutrons 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 stars [2]
- Investigating dark matter through anti-deuterons ($\bar{D}$) in cosmic rays, produced by dark matter annihilation or decay [3]:

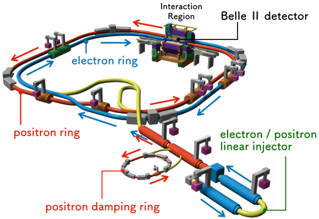
$$A_{d.m.} + B_{d.m.} \rightarrow hadrons\ (n, \bar{n}, p, \bar{p} \text{ etc... })$$
$$X_{d.m.} \rightarrow \text{hadrons}\ (n, \bar{n}, p, \bar{p} \text{ etc... })$$

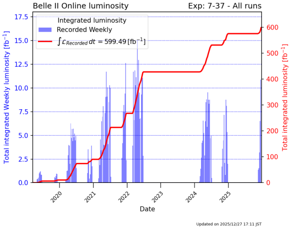
$\bar{D}$ is mainly produced through a coalescence mechanism $\bar{n} + \bar{p} \rightarrow \bar{D}$, where $\bar{p}$ and $\bar{n}$ are nearby in the phase-space

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





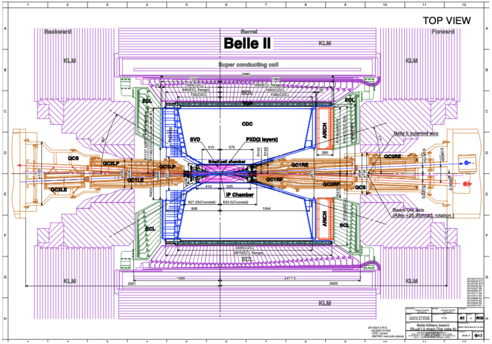
It operates mainly around $\Upsilon(4S)$ resonance (~ 10.58 GeV):

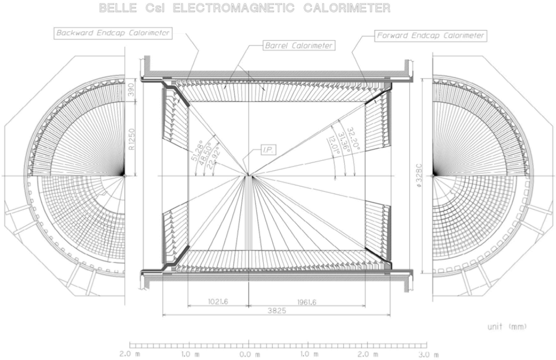
- This latter decays almost exclusively into entangled couples of $B\,\bar{B} \rightarrow$ B-factory
- Several goals: flavour physics, BSM, B and charm mesons spectroscopy etc...

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-cap regions ($12° \leq \theta \leq 155°$)
- Energy resolution of 4% @100 MeV and 1.6% @8 GeV

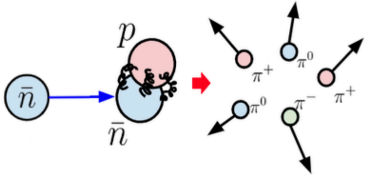




Anti-neutron interactions in physics

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 and electromagnetic showers are produced by $\pi^{\pm}$ interactions and $\pi^0 \to \gamma\gamma$ decays, respectively, within the ECL
- Since "Annihilation stars" are produced, showers develop in both forward and backward directions

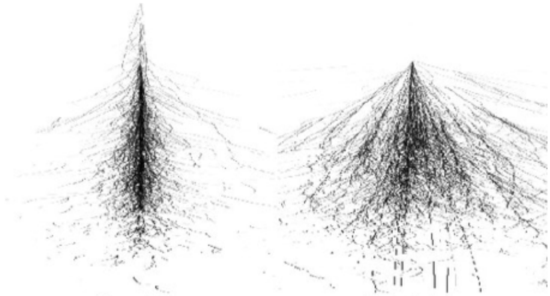


Electromagnetic and hadronic showers

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

1. Bremsstrahlung and pair production process (e^+, e^-, γ) and $\pi^0 \to \gamma\gamma$
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 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))



Gamma shower Hadronic shower

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 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 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

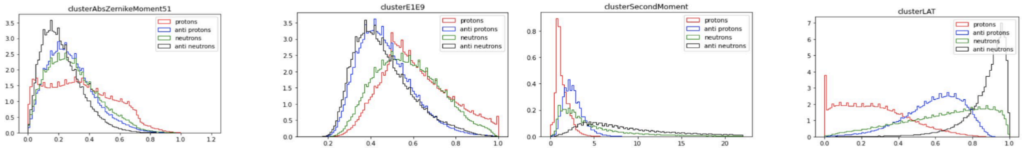
Preliminary concept

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 in 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:

$$e^+ + e^- + \gamma_{ISR} \to p + \bar{n} + \pi^- \text{ (Phokhara+evt\_gen generator)}$$

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

(a) $vpho \to p + \gamma_{ISR} + \pi^-$, 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

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

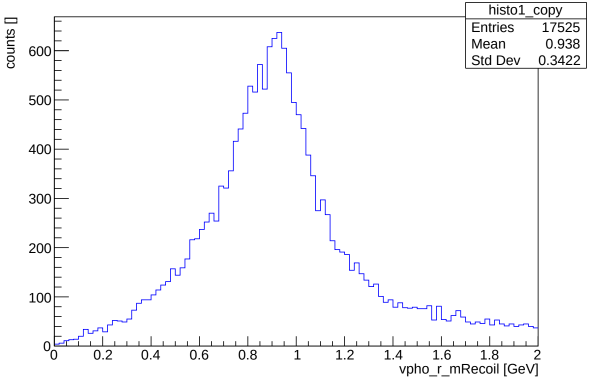
- **100k events** were generated, **17525** candidates have been reconstructed $\to$ reconstruction efficiency:

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

The recoil mass (1a)

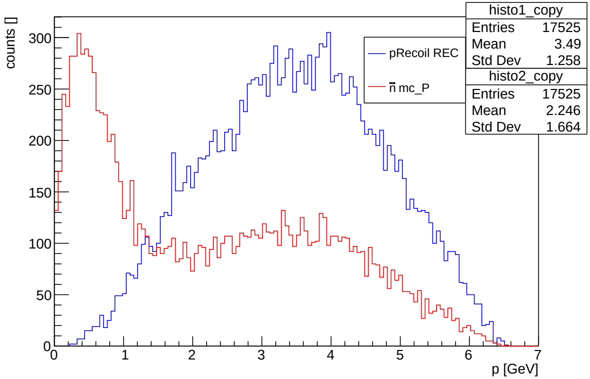
- The recoil three body system is well reconstructed as shown in the recoil mass distribution, where a peak emerges above the $\bar{n}$ mass.

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



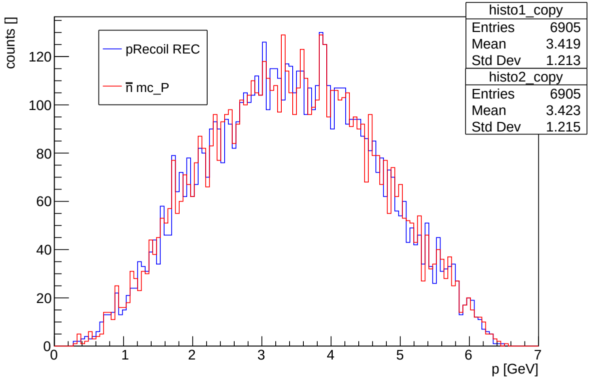
The recoil and the $\bar{n}$ momentum (1b)

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



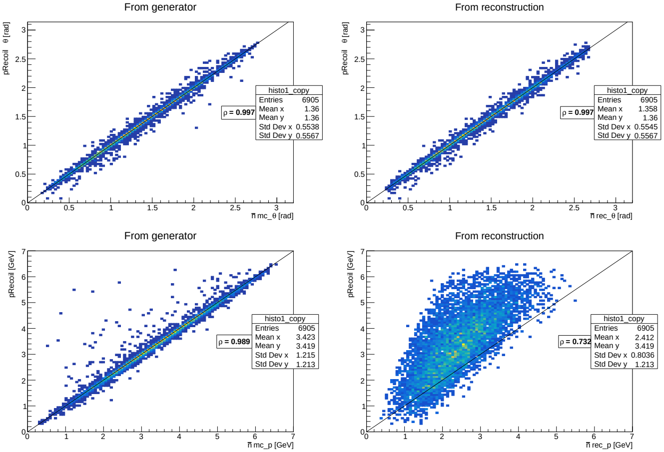
The recoil and the $\bar{n}$ momentum (1b)

- 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



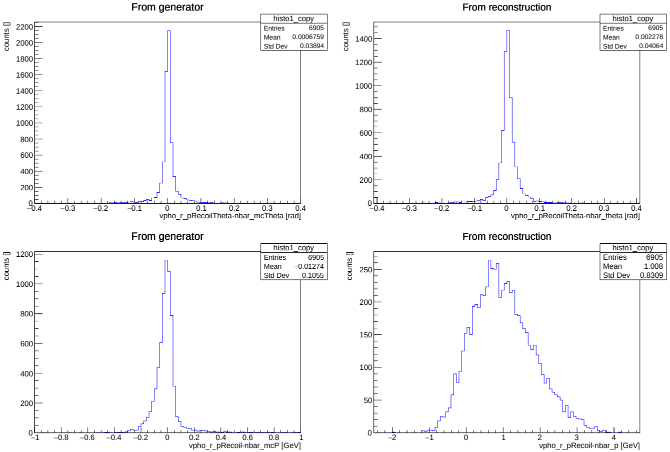
$\bar{n}$ vs recoil vector correlation (1b)

- Good correlation is observed at the generator level in both the momentum and 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)

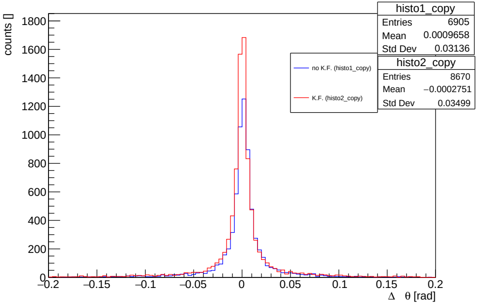
- Good correlation is observed at the generator level in both the momentum and θ distributions
- The reconstructed $\bar{n}$ momentum in the ECL is not a reliable variable, since no high correlation is observed (annihilation and energy loss)

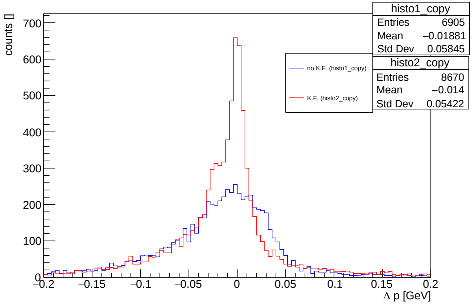


KInematic Fit over the recoil mass (1c)

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

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

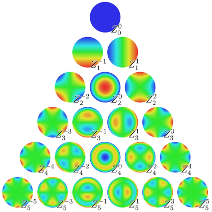




$\bar{n}$ ECL cluster variables (1d)

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

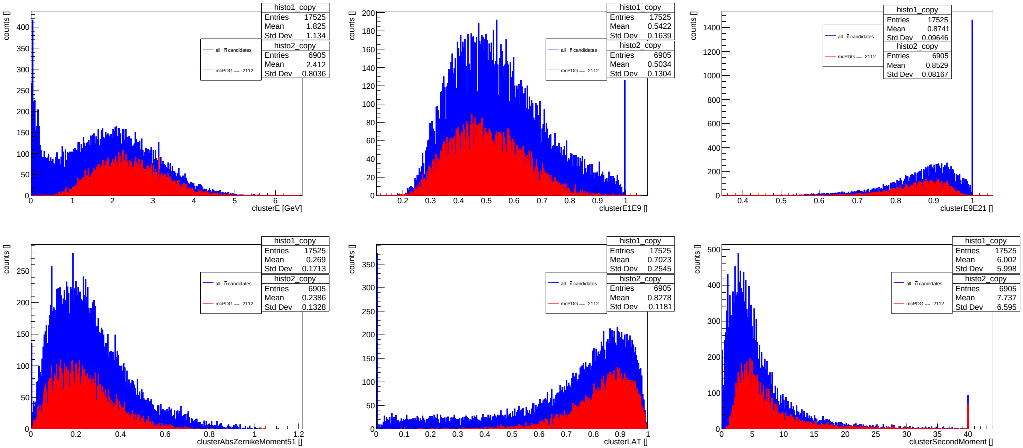
- **clusterE**, **clusterE1E9** and **clusterE9E21** ($E_{min} = 20$ GeV)
- **clusterAbsZernikeMoment51**: $|Z_{51}|$



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

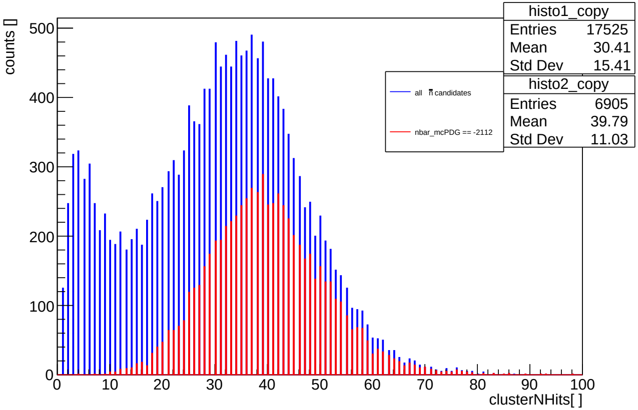
$\bar{n}$ ECL cluster variables (1d)



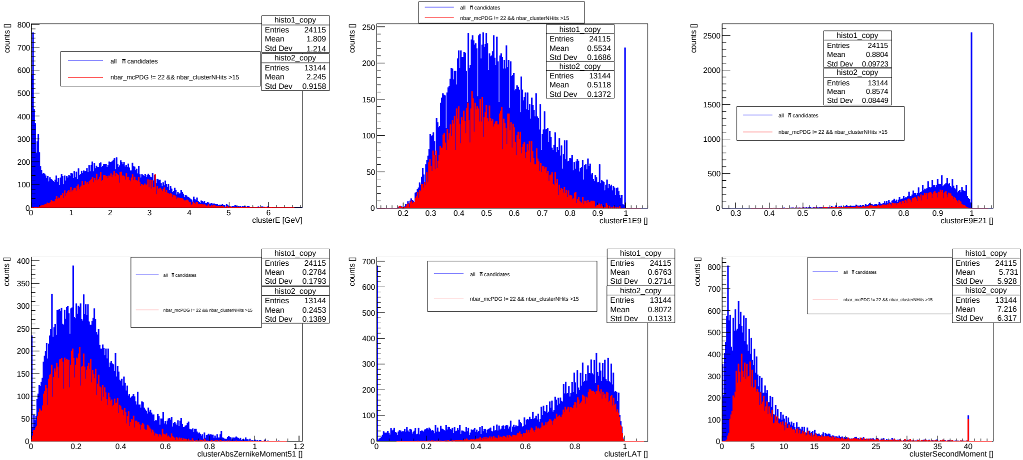
$\bar{n}$ ECL cluster variables (1d)

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

$$\bar{n}\_mcPDG \neq 22$$
$$\&\&$$
$$\bar{n}\_clusterNHits > 15$$



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



Summary (1)

- Channel $e^+ + e^- + \gamma_{ISR} \to X \to p + \bar{n} + \pi^-$ 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, π^-, γ 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)

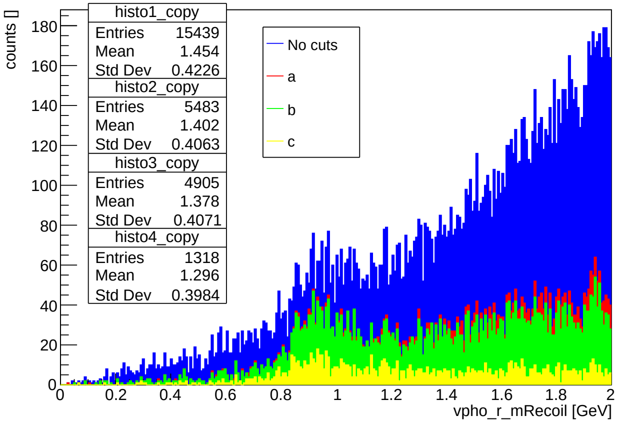
- Study of uubar continuum using the following MC cocktail sample:

$$/belle/collection/MC/MC16rd\_proc16\_chunk1\_uubar\_4S\_v1$$

- To obtain a cleaner channel, only the *p* and π^- 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 GeV < mRecoil < 2 GeV
  2. The best candidate is selected with RankByLowest method on α (backup)
- Same strategy as before:
  (a) Identify the signal peak near the $\bar{n}$ mass (~ 0.939 GeV) adding offline cuts
  (b) Study the previous variables (recoil and cluster) in a mRecoil zoomed region
  (c) (3) Compare it with data (Data/MC agreement)

mRecoil distribution

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

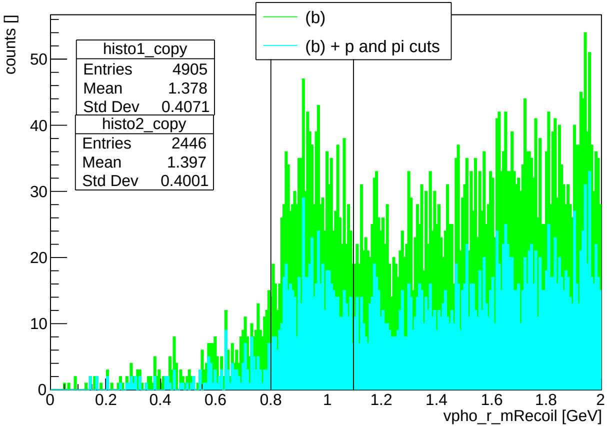


mRecoil distribution

- Other ”Real selections” can be applied as well, with (b), such as: [5]

  protonID > 0.9 and pionID > 0.1 and dr < 1 and 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

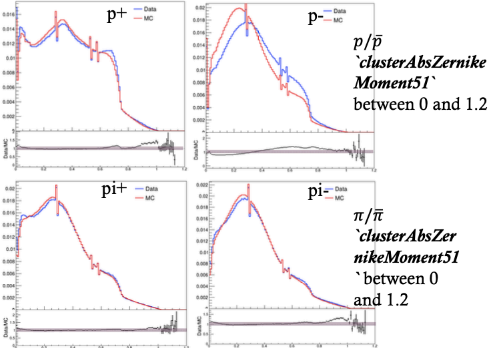


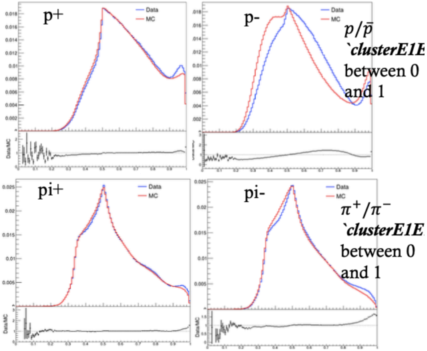
Variables

Summary (2)

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

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





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

Outlook Until Graduation

Thank you for your attention

Emanuele Zanusso

Dipartimento di Fisica
Università degli Studi di Torino

January 14, 2026

Selections/cuts on clean MC sample I

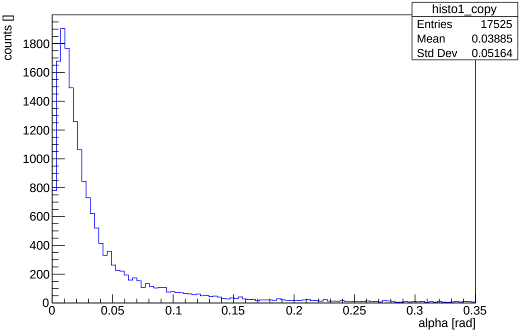
(a) $protonID > 0.9$ and $dr < 1$ and $abs(dz) < 3$ and $pionID > 0.1$ (From IP?)

(b) $p\_mcPDG == 2212$ and $pi\_mcPDG == -211$ and $gamma\_mcPDG == 22$

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

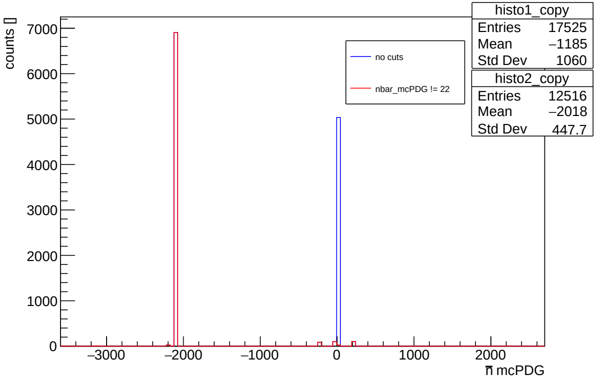
(d) $mRecoil > 0GeV$ and $mRecoil < 2GeV$

(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)



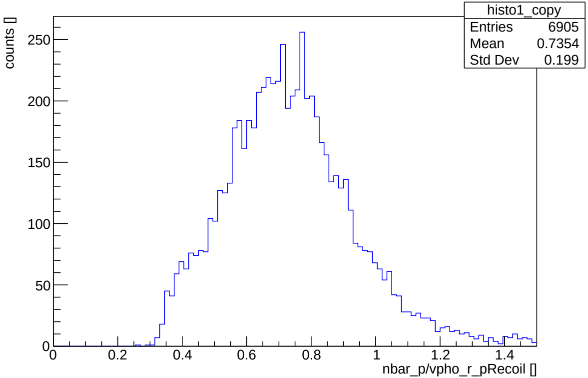
$\bar{n}$ mcPDG I

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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