Characterization of hadronic showers in the Belle II Electromagnetic Calorimeter

Metatesi exam

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January 14 2026

Summary

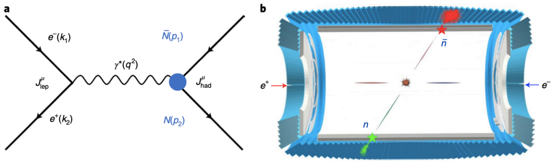
1. **Anti-neutron in physics experiment**

2. **Cluster variables**

Anti-neutron in HEP experiments

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

- The neutron e.m. form factor study in $e^+ + e^- \to n + \bar{n}$ annihilation [1]



- The hyperon decay channels which involved $\bar{n}$, such as:

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

- Other typical B-factories decay channels which involved $\bar{n}$, such as:

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

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:

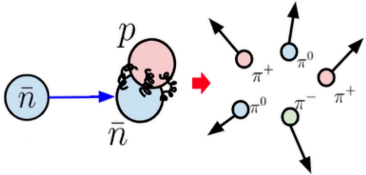
$$\bar{n} + \bar{p} \rightarrow \bar{D}$$

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

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 detectors
- Since annihilation stars are produced, both forward and backward directions are involved



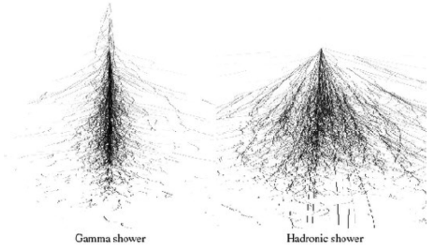
Electromagnetic and hadronic showers

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

1. $\pi^0 \to \gamma\gamma$ and bremsstrahlung process (e^+, e^-, γ)
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)
- About the 90% of the e.m. shower is contained within a cylinder of radius R_M ($\sim$ 3.6 cm in CsI)



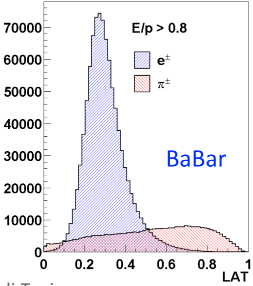
Anti-neutron interactions in physics

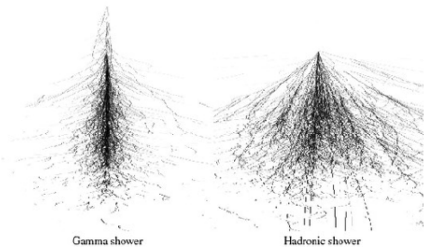
Several channels can be selected to look at $\bar{n}$ annihilation, such as:

- $e^+ + e^- \to J/\Psi \to p + \bar{n} + \pi^-$ (BESIII)
- $e^+ + e^- + \gamma_{ISR} \to X \to p + \bar{n} + \pi^-$ (Belle II)
- $\bar{\Lambda}_c \to K_s^0 + \pi^0 + \bar{n}$

Several variables can be used to distinguish their clusters, such as:

- clusterLAT, clusterSecondMoment, clusterZernikeMoment, clusterNHits...





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
  2. An electromagnetic calorimeter
  3. A muon system (alternating layers of active material and high-Z absorber)
- These features are common in modern general-purpose collider experiments such as **Belle II** and BESIII
- For MANTRA project, only signals from (1) and/or (2) are taken into account. In this thesis only (2) signals are studied

The MANTRA project

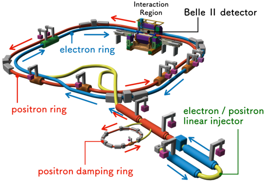
The measurement of the energy of the anti-neutrons is a two-step process:

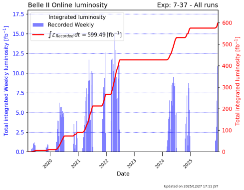
1. $\bar{n}$ identification via its induced shower vs ones from by photons or other hadrons
2. Combine the signals from (1) and (2) to reconstruct the $\bar{n}$'s energy
    - If π^0 ($\sim 5\%$): energy is all contained in the calorimeter, the shower is fully reconstructed
    - If $\pi^\pm$ ($\sim 95\%$): their products may escape the crystals
      $\rightarrow$ the goal is to complement the calorimeter information with that from the adjacent detectors

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 $\sim 5.1 \times 10^{34} cm^{-2} s^{-1}$ (Dec 2024)





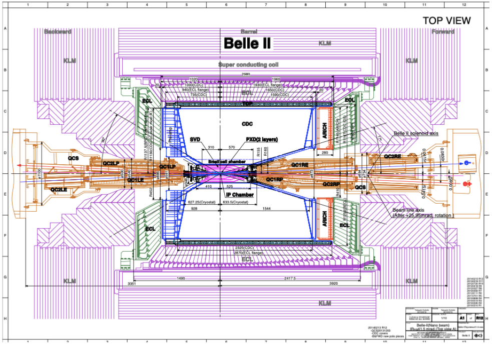
It operates mainly around $\Upsilon(4S)$ resonance ($\sim 10.58 GeV$):

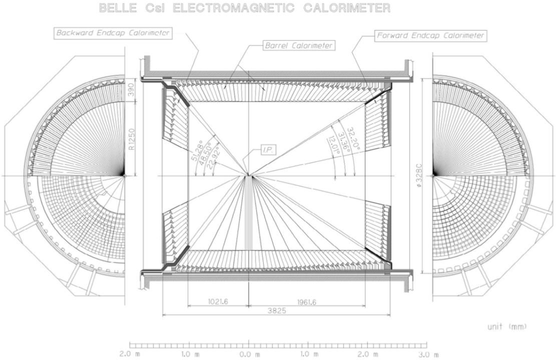
- It decays almost exclusively into entangled couple of $B\,\bar{B} \rightarrow B - factory$
- Several goals: flavour physics, BSM, B and charm mesons etc...

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





n vs gamma list in cluster variables

Thank you for your attention

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References I

- M. Ablikim et al.
  Nature Physics, 17, 2021.
- G.F. Burgio et al.
  Prog. Part. Nucl. Phys., 10389:120, 2021.
- F. Donato, N. Fornengo, and P. Salati.
  Phys. Rev. D, 62:043003, 2000.