MANTRA - Measuring Anti-Neutron: Tagging and Reconstruction Algorithm for frontier experiments

Description of the project

With this project we plan to develop a general method to measure the energy of anti-neutrons combining the informations collected by an electromagnetic calorimeter (of crystal structure in our case), a detector providing a high-resolution time response (such as a time-of-flight or a fast cherenkov counter with resolution below 100 ps) located in front of it, and a muon system comprising active layers interleaved with a high Z absorber located behind it, also capable of good time resolution (below 500 ps). This detector structure is common in modern, general-purpose collider spectrometers like Belle II and BESIII. Starting from MonteCarlo (MC) simulations, we plan to verify and test the procedure using experimental data collected by BESIII and Belle II, providing a general usage algorithm suitable also for other different particle detectors with a similar structure.

Since anti-neutrons do not lose energy in tracking systems through subsequent inelastic collisions, our method relies on the detection of their annihilation on the nucleons of either the calorimeter or the timing system material. Such annihilations produce mostly high-energy pions and soft nuclear fragments. The charged pions can themselves undergo inelastic interactions with the calorimeter material, initiating a so-called hadronic shower, or leave the detector losing only energy by ionization. Neutral pions, on the other hand, decay immediately into two photons which produce electromagnetic showers in the calorimeter volume, and may be completely contained within it. If the annihilation takes place before or inside the calorimeter we expect several crystals will be interested in the shower development, which will form an asymmetric cluster with extended dimensions: typically, the 95% of the hadronic shower is contained in a cylinder with radius equal to the interaction length (the pion interaction length in CsI is about 44 cm).
Similarly, photons produce an electromagnetic shower, a cyclic process of pair production and bremsstrahlung which invest a few crystals forming a mostly symmetrical and contained cluster: in the electromagnetic shower, the 90% of the energy is contained in a cylinder with a radius equal to the Moliere radius (Rm), which corresponds to 3.5 cm for CsI scintillators.
For our project we don't consider the case in which the n-bar annihilation takes place in the muon system, but only the ones that left a signal in at least both the calorimeter and the timing detector.
The measurement of the energy of the anti-neutrons is a two-step process.
First, the n-bar annihilation must be identified. We plan to use all the available detectors to perform this task, but the electromagnetic calorimeter will be the most contributing one, discriminating the n-bar-induced shower from the one produced by photons or other hadrons.
Our aim is to study the shape of the clusters induced by n-bar's and by photons (and other possible background sources including neutrons, nearby photon pairs producing merged clusters and K^0_L), in order to exploit the full information by the calorimeter to distinguish between the two kinds of particles. This involves several variables commonly used for photon identification, such as total deposited energy, fraction of energy around the central crystal, lateral momentum, 2^{nd} momentum, dispersion, Zernike polynomials, etc.. The timing of the calorimeter signals could also be included in the list, but since inorganic scintillators are slow detectors with poor time resolution we don't expect this to be a discriminant variable. Because of the huge number of parameters, we plan to use the Machine-Learning algorithms commonly adopted by the HEP community, exploring different architectures (such as GAN, CNN, etc.) to find the most effective one for the identification.
A typical design for an electromagnetic calorimeter could be represented by the BESIII setup, composed of 6240 CsI(Tl) crystals, arranged in one barrel and two end caps, and each crystal being 28 cm long (corresponding to about 15 radiation lenghts) and with a cross section of about 6 x 6 cm^2, or by the Belle II one (ECL), which deploys a total of 8736 CsI(Tl) crystals with a typical dimension of 6 x 6 x 30 cm^3.

Once the anti-neutron has been identified, its energy can be measured combining again the signals of all available detectors. We plan to distinguish several cases. If the n-bar annihilates only in neutral pions, either inside or in front of the calorimeter, the total shower would be contained in the electromagnetic calorimeter and the total deposited energy can be used to determine its energy. However, this occurs only in a tiny fraction of cases (about 5%), while usually, charged pions and nucleons are produced. In this case we can assume safely that part of the energy is lost because the n-bar annihilation products can escape the crystals. In these cases, our goal is to complement the calorimeter information with the time information from detectors close to the calorimeter and hit by a charged pion produced in the annihilation.
In the BESIII apparatus, a time-of-flight (TOF) system consisting of plastic scintillator bars is placed around the interaction point at a distance of about 90 cm, just before the EMC, to measure the flight time of charged particles in combination with the accelerator radio-frequency clock which provides the start time, with a resolution around 100 ps. In Belle II, a time-of-propagation (TOP) counter made of bars of fused silica covers the barrel region just before the ECL. The TOP is a novel detector concept that, measuring the timing of the Cherenkov photons with a resolution of 100 ps per photon, provides a simultaneous measurement of the Cherenkov angle and the time-of-flight of a charged particle crossing it. We plan to modify its reconstruction algorithm to provide a timing of the hadronic annihilations or backsplash events.
In case of a n-bar event, the two detectors can provide a signal when hit by a backsplash following annihilation in the calorimeter, or when the n-bar directly annihilates in their material just before the calorimeter; in the first case, the time measurement depends also on the position inside the crystal where the shower initiated, while in the second case the time signal will be prompt and more precise. In both cases, the presence of a signal by these detectors will also assist in the n-bar identification, since a photon travels much faster than a n-bar, and their component may be singled out.
If the shower develops in the forward region the charged pions escape towards the outer region, and they can be detected by the outermost detectors, i.e. the BESIII muon counter (MUC) or the Belle II K_L and muon (KLM) detection system, which can also provide time measurements with a very good resolution. In this case, the time information must be elaborated taking into account the additional flight-time of the charged pions over a distance of tens of centimeters.

Of course the detection efficiency will depend on the nucleon-anti-nucleon cross sessions. These measurements both in the low (<500 MeV/c) and higher momentum region (>500 MeV/c) were challenged by several experiments in the past years. A complete review on n-bar physics can be found in [18]. The annihilation cross section from n-bar-proton and antiproton-neutron in the momentum range from 50 MeV/c up to 700 MeV/c were investigated by several experiments and collaborations [19 - 23] and their comparison shows a good agreement in the same momentum range (even if the relative uncertainties are high, due to the small collected statistics) as expected by isospin symmetry. Concerning the comparison of proton-antiproton and anti-neutron-proton cross sections, their ratio is close to one in the low momentum range between (300-500) MeV/c, while it becomes larger with, however, huge fluctuations both for lower and higher momenta. The measurements of n-bar nucleon annihilation cross sections is consistent with a scaling law of A^(2/3), where A is the mass number of the material, and a n-bar momentum dependence proportional to 1/p. The neutron-n-bar annihilation can lead to the production of between two and six intermediate particles. Using isospin symmetry relations the corresponding probability [24] for n-bar-neutron annihilation into neutral final states is close to 5%.
We plan to develop the project along two main directions:

- n-bar identification via electromagnetic signatures based on an independent study of a clusterization algorithm
- n-bar energy measurement via the combination of time-of-flight and calorimeter deposit information, using the Belle II and BESIII data as benchmark.

To develop these research lines we have defined five different working packages (WPs), each of which may be divided into several sub-tasks necessary to achieve the final goal. The methodologies, objectives and expected deliverables for each WP are summarized below.

WP1 is focused on the study of the electromagnetic response. The features of all the observables needed to identify and reconstruct the energy and momentum distributions from the shower induced by n-bar's could be optimized based on Machine Learning technique. The results will be then compared with experimental data from BESIII and Belle II. When the clusterization algorithm is ready, it could be expanded including the information from other detectors, as investigated in WP2 and WP3. The WP1 will be coordinated by the Torino Unit (UNITO): the expertise on n-bar physics from S. Marcello (expert of n-bar physics at PS178 and PS201 at LEAR - CERN and at FENICE - ADONE, member of the team for the construction of a neutron tagging detector based on plastic scintillators, expert of Antinucleon-Nucleon and Nuclei Interaction Dynamics at LEAR) and S. Spataro (software expert for tracking and particle identification for several collaborations, expert of multivariate analysis and machine learning techniques), along with the involvement in both Belle II and BESIII Collaborations make the UNITO unit the ideal candidate to coordinate this WP.

WP2 and WP3 share common activities but are based on two different experimental setups and software frameworks. Starting from simulated and real data from Belle II and BESIII, the backsplash and n-bar annihilation in Belle II TOP (WP2) and BESIII TOF (WP3) will be studied in detail. In addition, the possibility to include, respectively, the KLM and MUC detectors should be investigated to improve the quality of the time information. The WP2 will be coordinated by the INFN unit which could profit from the great experience of A. Filippi on n-bar physics (main author of the n-bar review "Antineutron physics" [18] and author of all the meson spectroscopy papers on anti-neutron induced reactions as well as of the studies of annihilation dynamics of antineutron-protons reactions, with the data collected by the PS201 experiment at CERN) and the expertise of U. Tamponi (member of Belle II collaboration and expert of particle identification and TOP detector operations, as well as expert of analysis techniques for quarkonia and di-baryon studies at Belle II). The WP3 will be coordinated by the Ferrara unit (UNIFE) thanks to the expertises achieved by I. Garzia (member of BESIII collaboration with wide experience on particle identification and tracking software, expert of physics analysis in BESIII and BaBar collaborations).

WP4: this WP requires the synergy of all the three units. The clusterization algorithm together with all the studies and results pursued in WP2 and WP3 will be merged in a general-purpose technique aimed to identify and measure the energy of n-bar in modern spectrometers. First, this technique will be validated using ad-hoc benchmark channels identified in the Belle II and BESIII experiments. This WP will be supervised by the INFN unit which will profit from the knowledge of Belle II group experts on developing NN-based clustering algorithms. Its main task is the coordination of all the efforts and skills (including also the experience of F. De Mori, expert analyst and member of BESIII collaboration) for the finalization of this WP.

WP5: dissemination of the results to dedicated conferences and outreach events, such as the International Conference on Computing in High-Energy and Nuclear Physics (CHEP), the International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT), the International Workshop on Ring Imaging Cherenkov Detectors (RICH), and "Notte dei Ricercatori" at Torino and Ferrara towns. The deliverables will be distributed to the HEP community for validation and test by other experiments, reaching a large and qualified audience. These reasons make both CHEP and ACAT the best choices. The coordination of this WP will be covered by the UNIFE unit taking advantage of the experiences achieved in outreach event organization and dissemination.

A detailed description of each working package is given in section B.3

Several physics channels have been identified to test the n-bar identification procedure and the energy reconstruction technique, as well as to check all the intermediate stages from the different WPs.

Thanks to the 10 billion J/psi events collected by the BESIII experiments, a high purity n-bar sample could be selected searching for the e+e- → J/psi → proton n-bar pi- decay channel, whose

branching fraction is (2.12 $\pm$ 0.09) *10^(-3) [12, 24]. This means that approximately we can count on a sample of about 2*10^7 n-bar's.
The typical n-bar momentum range for this decay goes up to 1.2 GeV/c, with n-bar's emitted in the full 4pi solid angle, and the n-bar's kinematics can be determined with very high precision from the reconstruction of the four-momenta of proton and pion together with the constraint on the initial four-momentum of the J/psi, with a very low background level.
In the BESIII experiment the n-bar candidate is usually reconstructed by looking at the invariant mass of the system recoiling against the reconstructed charged tracks (proton and pion in this case) [24 - 26] . This means that the momentum may be calculated, as well as its direction with a precision, respectively, of few MeV and few mrad. The results from the missing mass approach can therefore be compared with those from the new developed technique.
In addition, there are a lot of different ongoing BESIII analysis on J/psi → hyperon anti-hyperon decays in which the n-bar is reconstructed by looking at the missing mass distributions of the system recoiling against the reconstructed charged tracks. A tool for n-bar energy reconstruction could provide not only a complementary analysis technique, but it could also allow more complex final states to be investigated.

As for the BESIII case, Belle II experiment offers an unique n-bar's data set useful for testing the developed technique. Anti-neutron can be tagged by charmed baryon decays: lambda_c → n-bar K^0_S pi (with a branching fraction of 1.82%) and lambda→n-bar pi0 (with a branching fraction of about 39%). In addition, using initial-state-radiation (ISR) J/psi events (about 40 events/fb-1 with tagged ISR photon) the technique could also be tested in the J/psi → proton n-bar pi- decay channel, allowing a direct comparison of the proposed methods using the same analysis channel from two different experimental setups and different center of mass energies.

WPs:
The project is scheduled to complete in two years. As mentioned in section B.2 we foresee five working packages, namely:

- WP1: Calorimetric signature
- WP2: Time-of flight signature in cherenkov detectors
- WP3: Time-of-flight signature in scintillators
- WP4: Development of the global reconstruction algorithm
- WP5: Dissemination

The project will articulate over two phases: the first one encompasses the activities of WP1, WP2 and WP3. Its goal is to provide the foundations on detector response which will be used as input to the second phase. The core of phase 2 will be WP4, which is intended to gather all the information from the preliminary studies and deliver the tools to identify the n-bar and measure its energy. All the available workforce already committed to WP1-3 will contribute to WP4. WP5 will start close to the end of phase 2, when preliminary results will be available for presentation at conferences and outreach activities. A detailed description of the human resources needed for each WP will be described later in this section.

We list in the following the sub-structure of each working package. As several people will be working together on the same WP, some tasks can be completed in parallel.

WP1 timeline:

- 1.1: implementation of GEANT4 calorimeter model.
- 1.2: study of the n-bar, photons and hadrons shower features and identification of the variables needed for n-bar discrimation.
- 1.3: comparison of the simulation with real data from BESIII and Belle II using dedicated control channels with n-bar's and anti-protons from anti-Lambda decays.

WP2 timeline:

- 2.1: Study of the timing signature of n-bar annihilation and backsplash events in the TOP active volume and identification of the relevant variables for its measurement.
- 2.2: Development of a reconstruction algorithm to measure the timing of the interactions studied in 2.1.
- 2.3: Study the timing signature of n-bar interactions in the innermost layers of the muon identification system. This step is expected to be quicker as the default muon system reconstruction is already designed to identify n-bar interactions.
- 2.4: comparison of the simulation results with real data from Belle II using control channels with n-bar's and anti-protons from anti-Lambda decays.

WP3 timeline:

- 3.1: Study the timing signature of n-bar annihilation and backsplash events in the BESIII ToF volume and identify the relevant variables for its measurement.
- 3.2: Development of a reconstruction algorithm to measure the timing of the interactions studied in 2.1.
- 3.3: Study the timing signature of n-bar interactions in the innermost layers of the BESIII muon identification system.
- 3.4: comparison of the simulation results with real data from BESIII using control channels with n-bar's and anti-protons from anti-Lambda and J/psi decays.

WP4 timeline:

- 4.1: Determination of the NN design for the identification of the n-bar interaction and training on MC simulation.
- 4.2: Determination of the NN design for the measurement of the energy on the n-bar and training on a MC simulation.
- 4.3: Application of the method to a simplified detector geometry modeled with GEANT4 to prepare general usage publication.
- 4.4: Application on the existing dataset by BESIII and Belle II.