Existing Cherenkov detectors for ***charged particle ID*** can also be used to ***measure energy*** of ***neutral hadrons,*** like ***anti-neutrons***

Measuring anti-neutron energy with the TOP counter of Belle II

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- Energy of anti-neutrons ($\bar{n}$) produced in e^+e^- collisions at Belle II experiment are measured by a CsI electromagnetic calorimeter (ECL).
- Accuracy of energy measurement relies on the containment of the shower induced $\bar{n}$.
- ***Goal***: Improve energy measurements by combining ECL information with $\bar{n}$ timing.
- Use timing from charged particle identification detector placed in front of ECL – the Time of Propagation (TOP) counter.
- Fused silica light guide of TOP traps Cherenkov photons emitted by incident charged particles - particle ID is performed by measuring characteristic photon flight time.

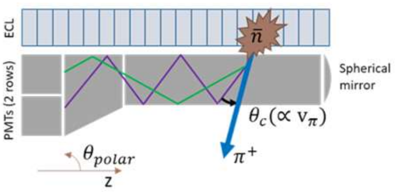

Fig 1: *Schematic of a back-scattering event in one of the 16 TOP modules placed azimuthally within the Belle II detector (only forward rays shown). Particle momentum can be determined via Cherenkov angle, derived from the time of propagation and geometry of the bar.*

- TOP is designed for charged hadrons, but signal from neutral ones can be measured if:
  - They annihilate close to, or within the TOP
  - or, ECL shower of neutral hadron "splashes back" towards TOP.
- Show that TOP timing signature of $\bar{n}$ annihilation events correlate with $\bar{n}$ momentum, polar angle and annihilation vertex, i.e. more kinematic information than from ECL alone.

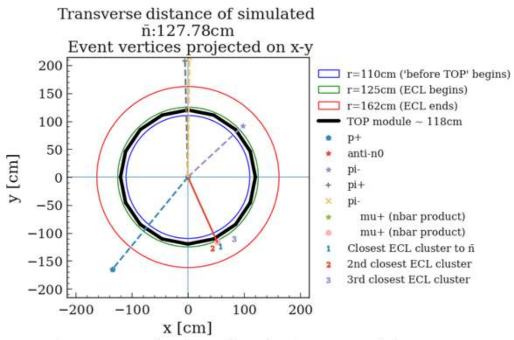

Fig 2: *Event display of $\bar{n}$ physics event ($e^+e^- \rightarrow p\bar{n}\pi^-\pi^+\pi^-$), showing key subdetector boundaries. Dotted lines are displacement vectors, not charged tracks.*

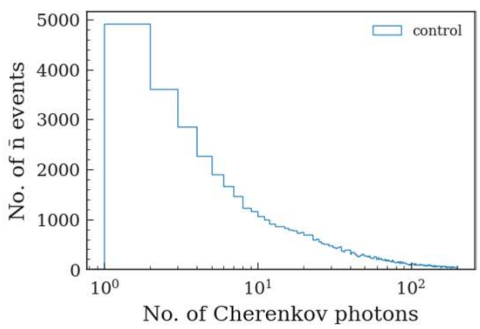

Fig 3: *Histogram of the number of events according to number of Cherenkov photons recorded by the TOP. Signal is taken from TOP module closest to $\bar{n}$ annihilation. Searching for $\bar{n}$ ECL clusters can help to guide which TOP module to locate $\bar{n}$ signal in real collisions*

Table 1: *200k $\bar{n}$ events with $|p|$ = 1 GeV/c θ= 92° are generated using Particle Gun and the simulated response of the Belle II detector is measured.*

Statistics of $\bar{n}$-only MC with control kinematics
135 801 $\bar{n}$ (~68%) annihilate within our region of interest (i.e. within TOP angular acceptance and either in/before TOP or within ECL)
Of these events, **73 136** events have TOP signal parallel to $\bar{n}$ (~54%)
Proportion of generated events with TOP signal and in region of interest $\approx$ **36.57%**

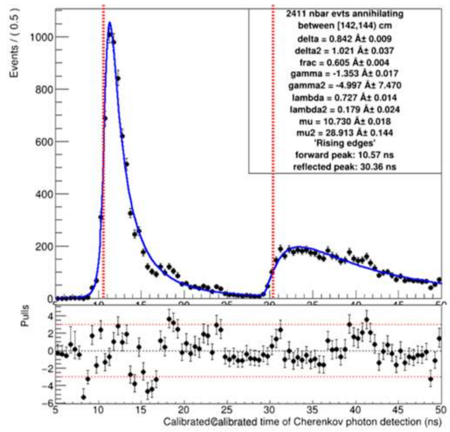

Fig 4 *Histogram of MC Cherenkov photon timings associated to $\bar{n}$ shower. Average timing of forward and reflected Cherenkov pulses are extracted as the 'rising edge' (x at half-maximum) to Johnson S_U fitted data.*

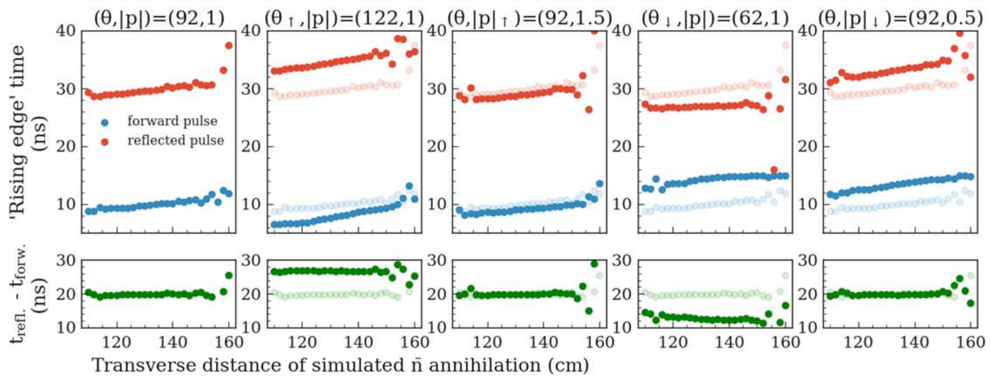

Fig 4: *Simulated timing measured by TOP, of $\bar{n}$ annihilations with varying kinematics, as a function of where in the Belle II detector the $\bar{n}$ annihilation takes place The control dataset described in Table 1 is compared with four additional sets of 200k events, where either $|p|$ or θ are varied. Timing is correlated with $\bar{n}$ depth, as well as increased angle or decreased momentum. Additionally, the difference in average timing between pulses correlates with $\bar{n}$ angle. These correlations can thus be used to determine $\bar{n}$ momentum in real collisions.*

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