ANTI-NEUTRON MEASUREMENT WITH THE TOP SUBDETECTOR AT BELLE II

Towards data-MC agreement of reconstructed $\bar{n}$ TOP signal

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KEK, October 2023

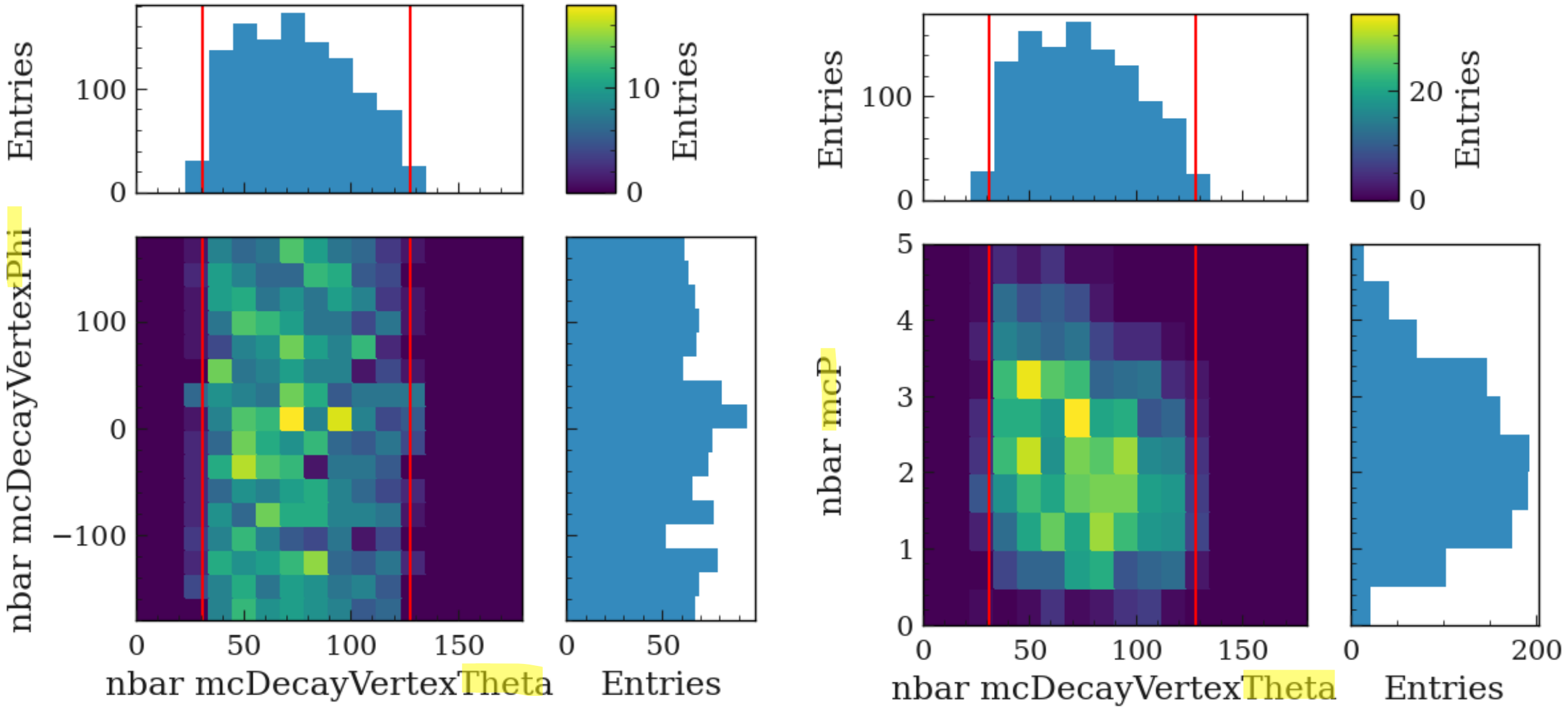
EXPERIMENTAL DESIGN

- Generate **10k** cdst events $e^+e^- \rightarrow p\bar{n}\pi^-\pi^+\pi^-$. *No restrictions to* $\bar{n}$ kinematics.
- Follow Savino's reconstruction method:
  - Tracks: $|dz| < 3$, $dr < 1$, exactly 4 tracks in evt
  - p: *protonID* > 0.9, no other protons in event.
  - Pions: *pionID* > 0.9
  - Reconstruct $vpho \rightarrow p\bar{n}\pi^-\pi^+\pi^-$, with $0.5 <$ *mRecoil* < 1.5, *pRecoil* > 0.1 and $0.25 <$ *pRecoilTheta* < 2.5
  - Perform tree fit, require $\chi^2 < 20$
  - Perform recoil mass fit to $\bar{n}$ mass, require $\chi^2 < 100$
  - Save three ECL clusters within 0.2 radians of *pRecoil*
- Add *TOPRingPlotter*, save TOP signal from all modules **not** matched to the reco proton.

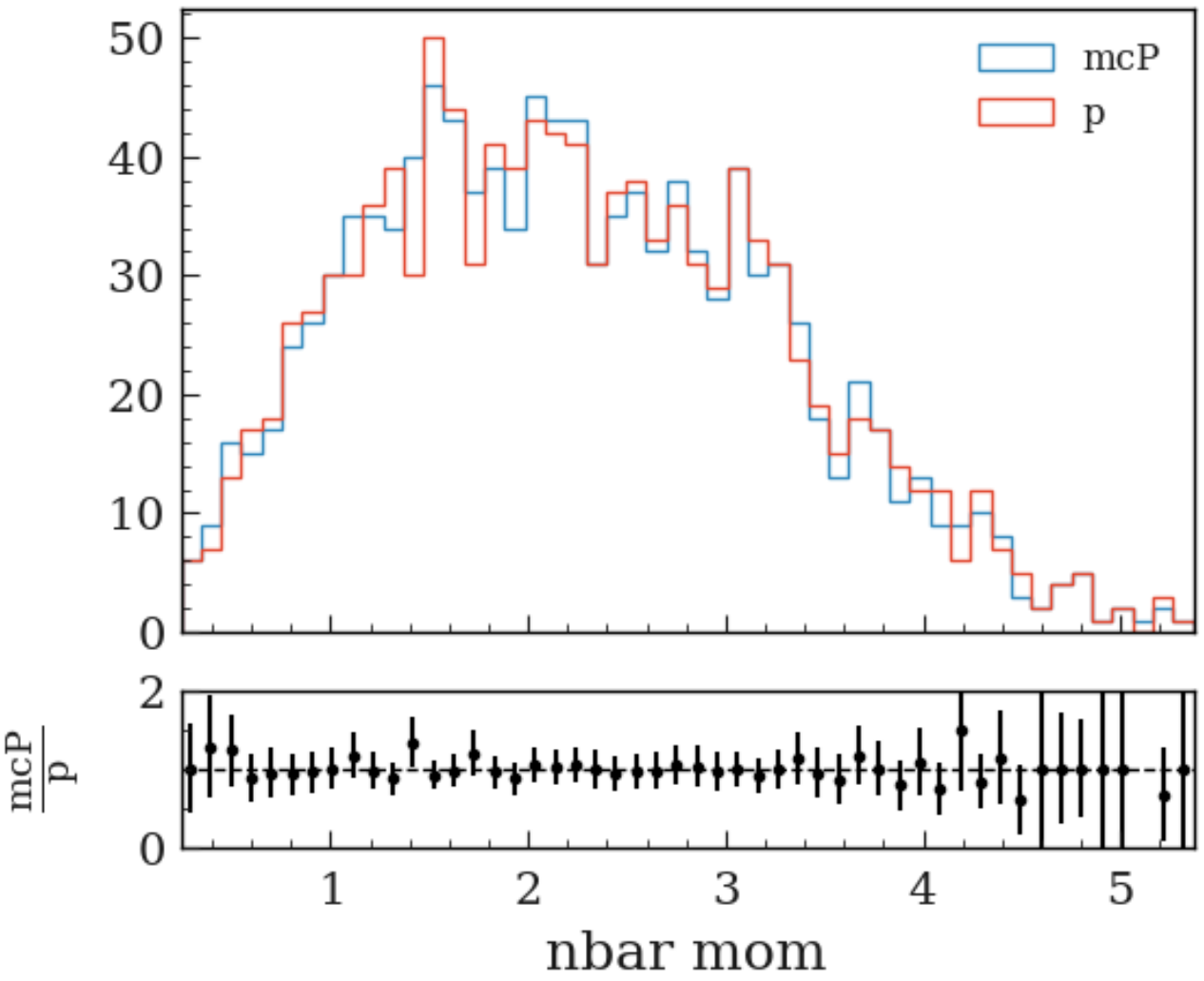
Condition	$\bar{n}$ annihi. before TOP *(+ in TOP angular acceptance)*	$\bar{n}$ annihi. in TOP *(+ in TOP angular acceptance)*	$\bar{n}$ annihi. in ECL *(+ in TOP angular acceptance)*	$\bar{n}$ annihi. in all ROI *(+ in TOP angular acceptance)*
TOP signal seen *not* associated with p	66 *(37)*	162 *(141)*	987 *(948)*	1215 *(1126)*
TOP signal seen in slot parallel to $\bar{n}$	61 *(35)*	153 *(135)*	906 *(869)*	1120 *(1039)*

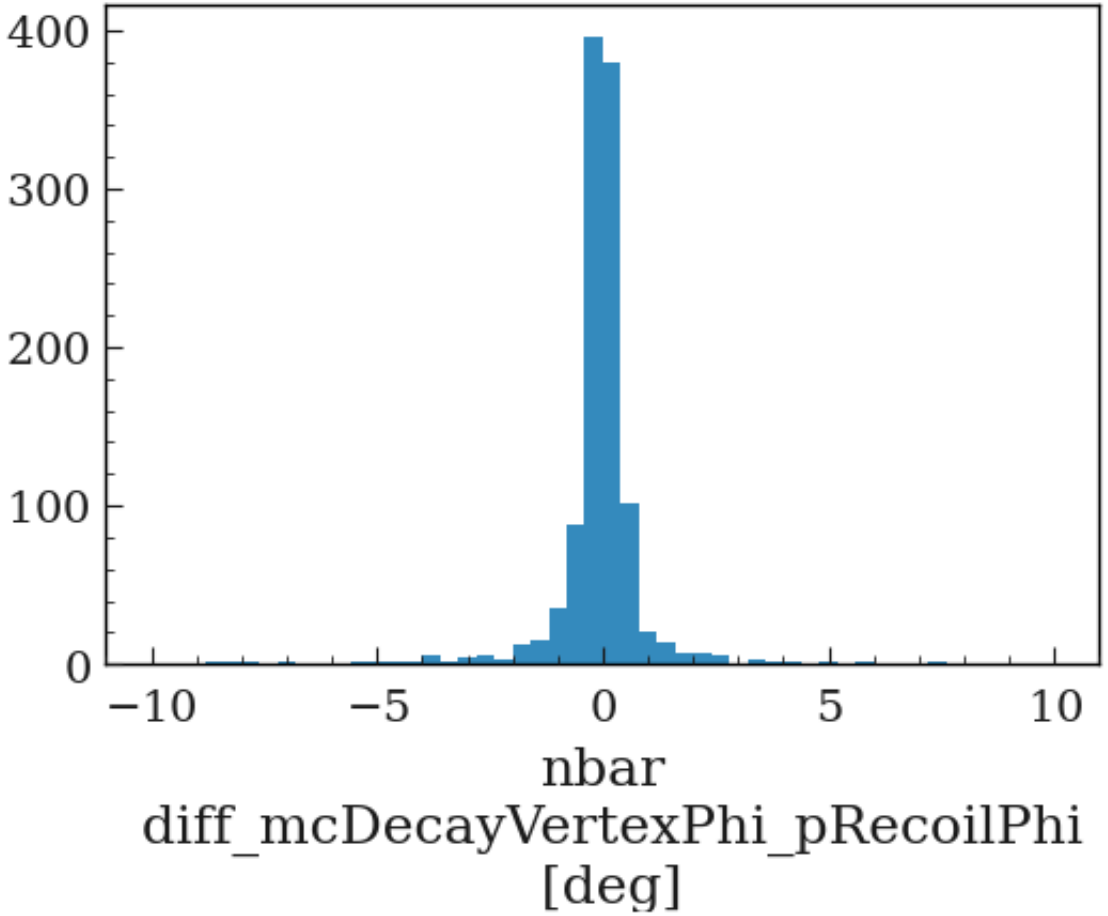
c.f. 200k control sample (p=1, θ = 92) ≈14.72%

Kinematics of $\bar{n}$



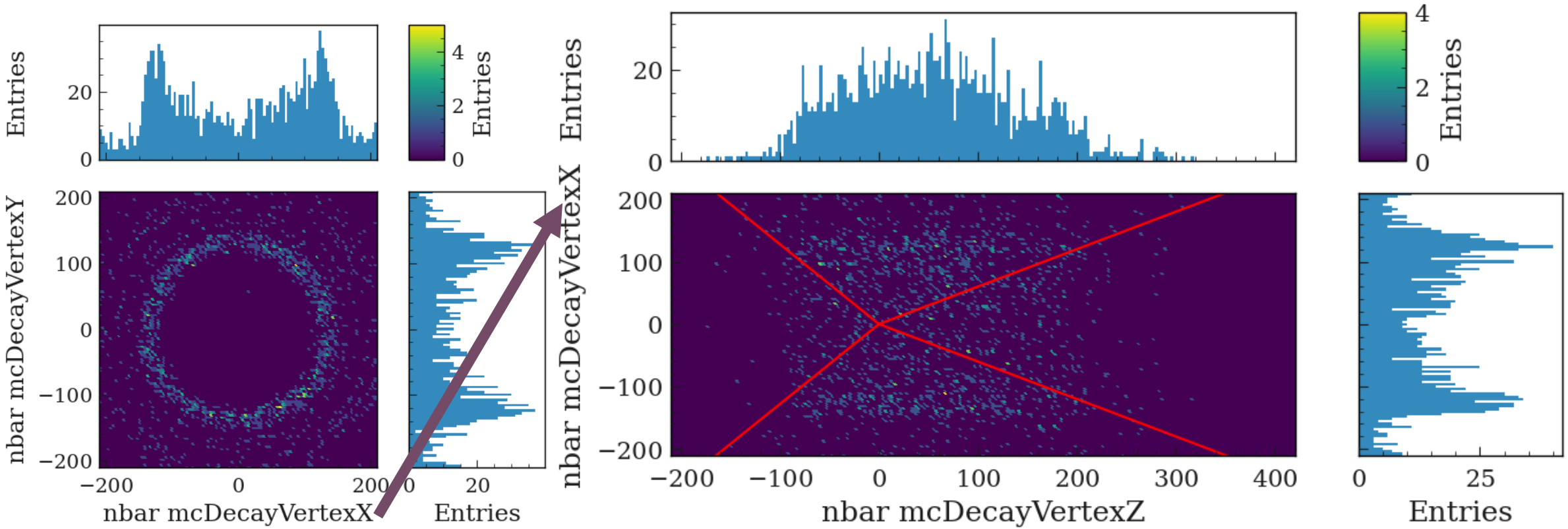
Kinematics $\bar{n}$: generated vs recoil



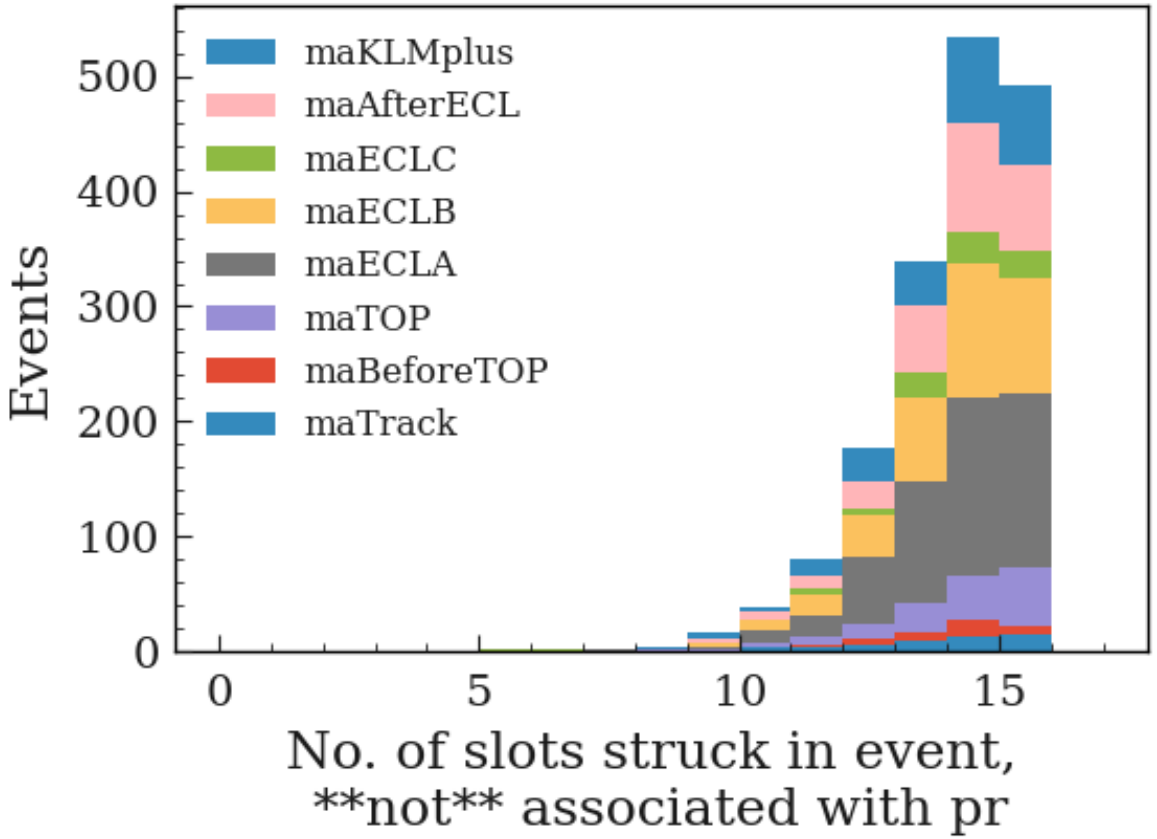


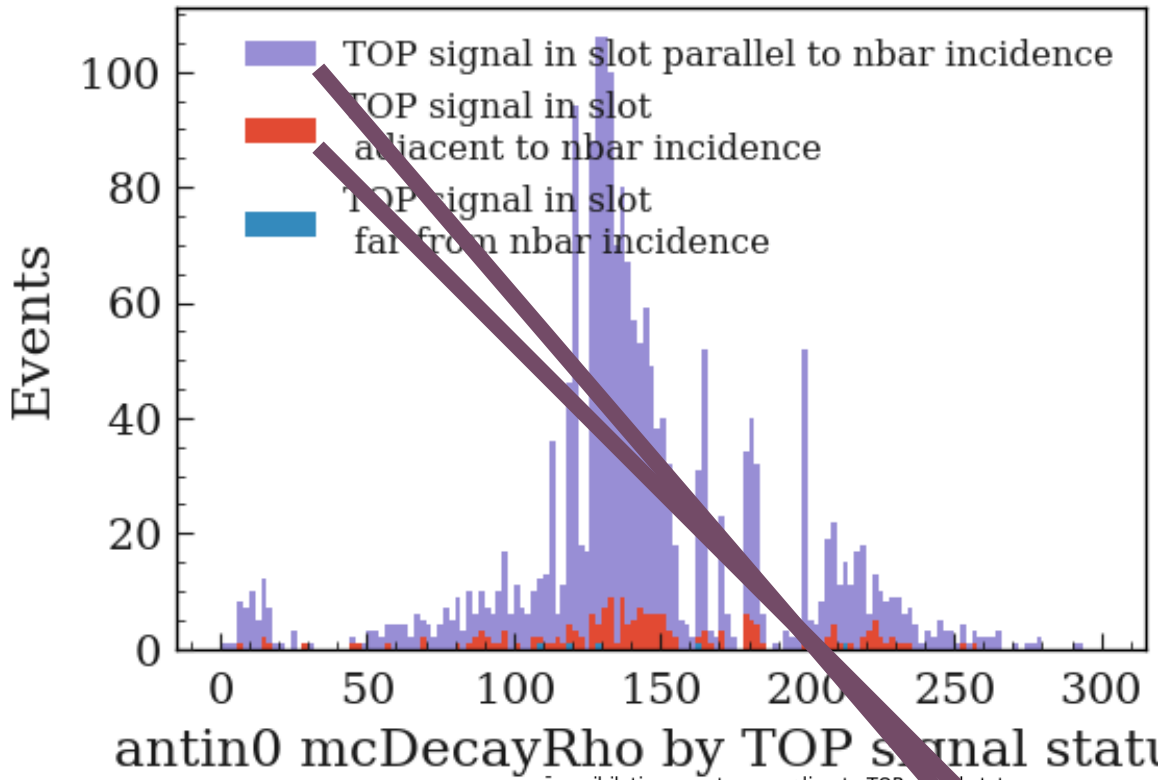
* Each TOP module covers ~ 20 deg
→ Recoil angle can point towards TOP signal/ECL cluster!

Annih. of $\bar{n}$ in the detector

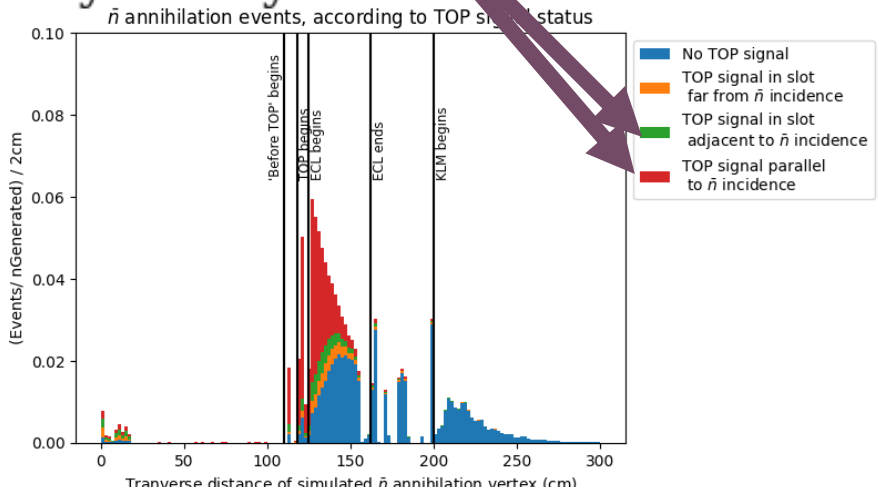


TOP modules

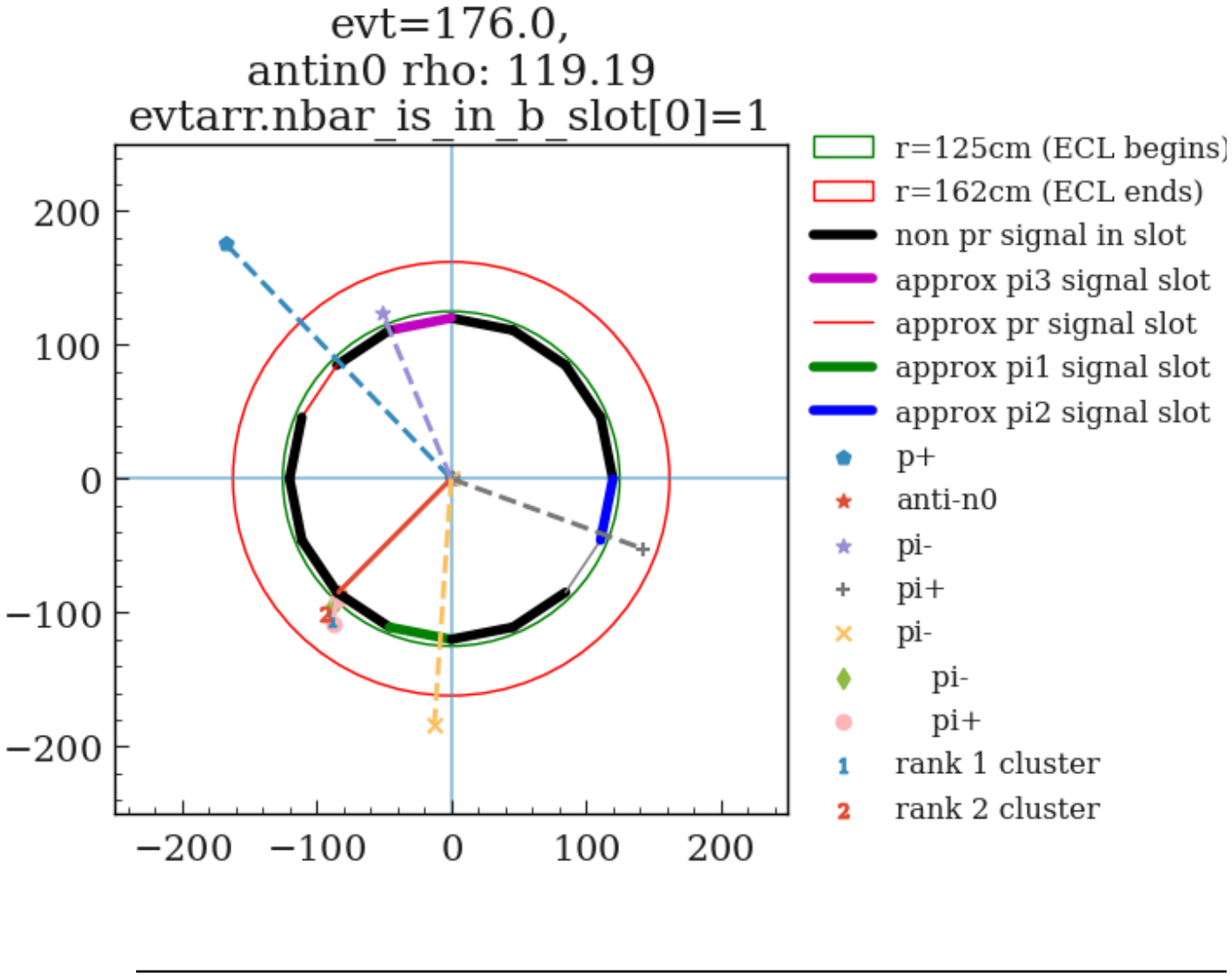


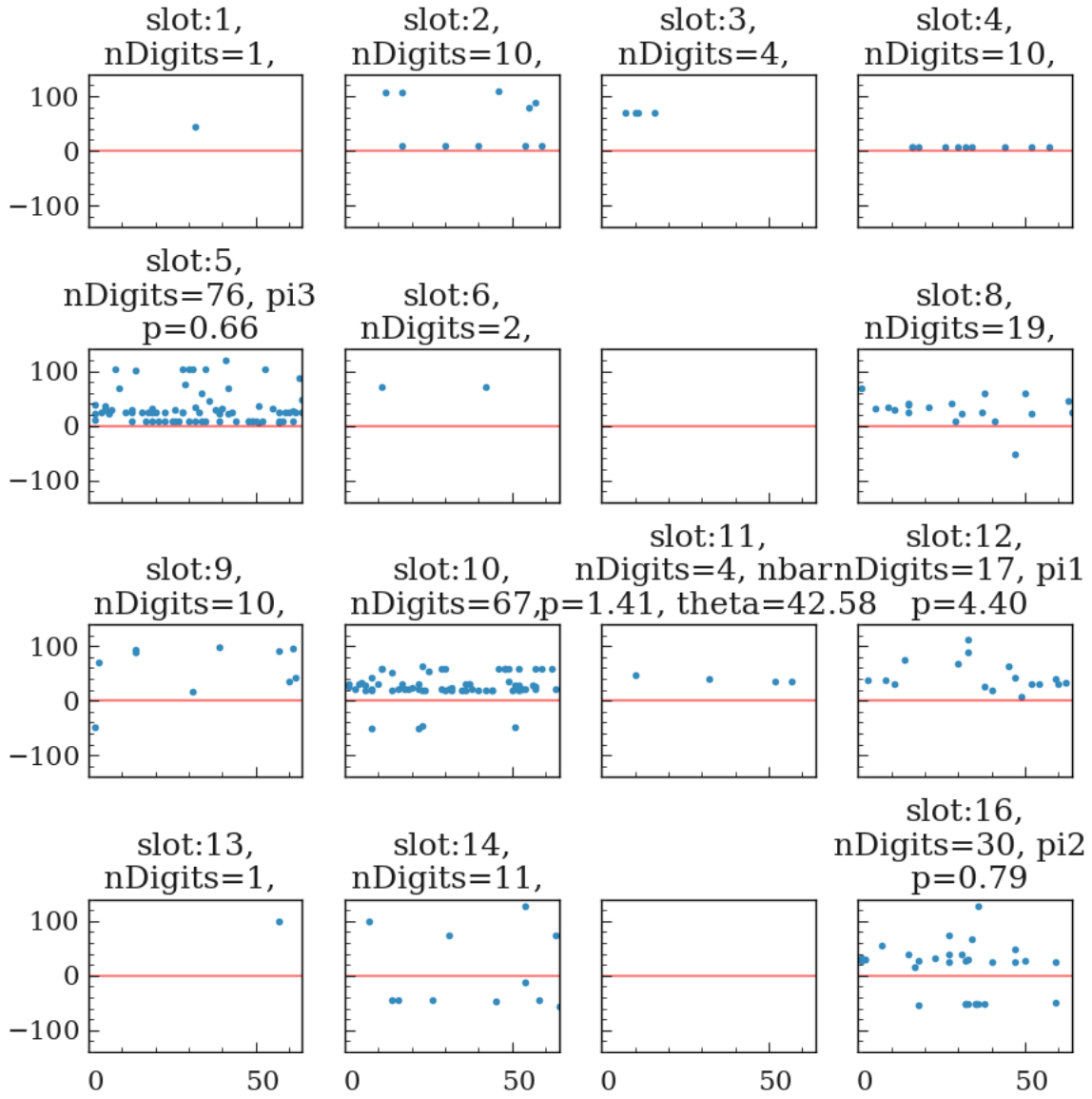


Not pr, but could be other tracks from $e^+e^- \to p\bar{n}\pi^-\pi^+\pi^-$!!
Isolating $\bar{n}$ needs more thought (i.e. match ECL cluster/recoil)

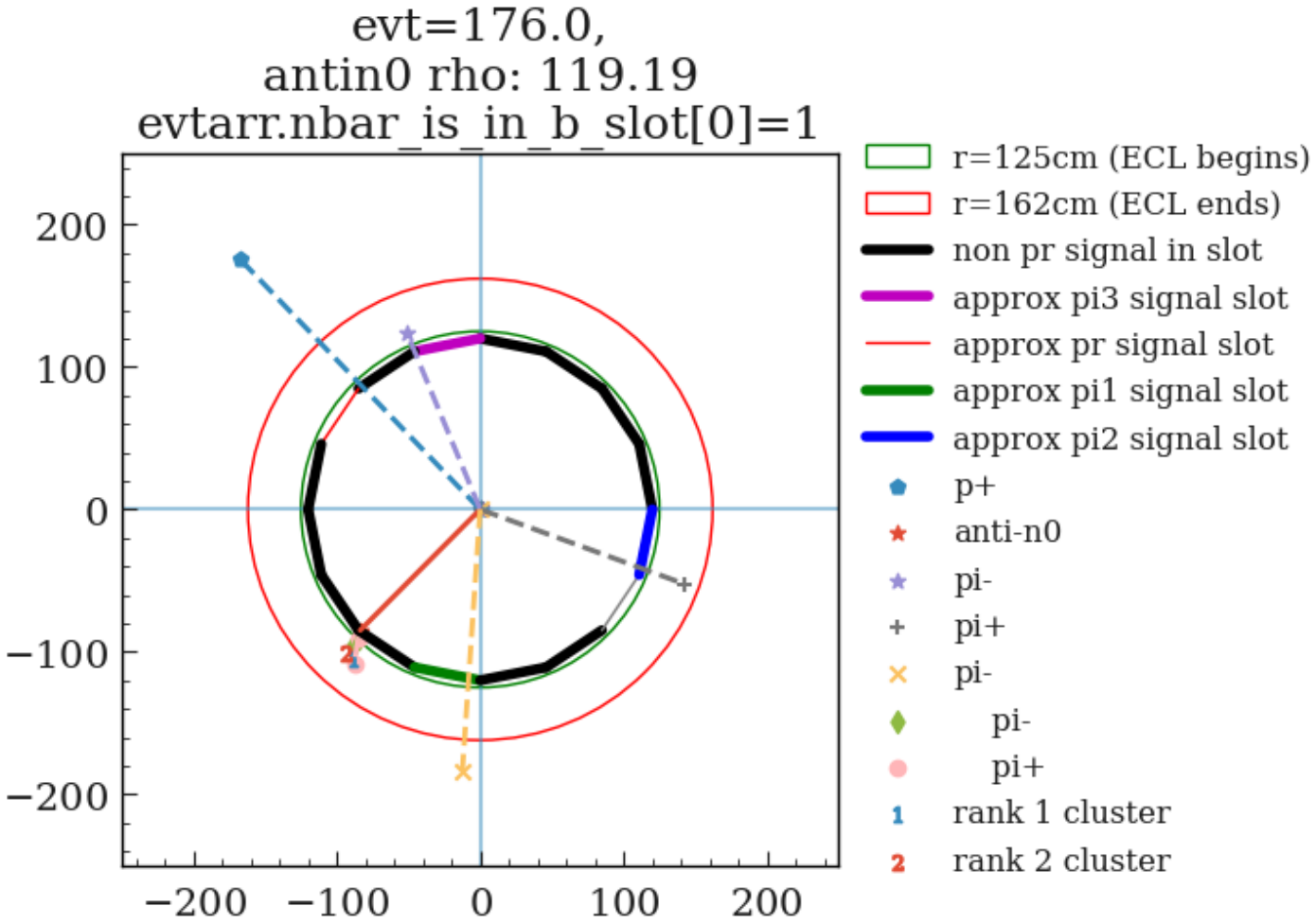


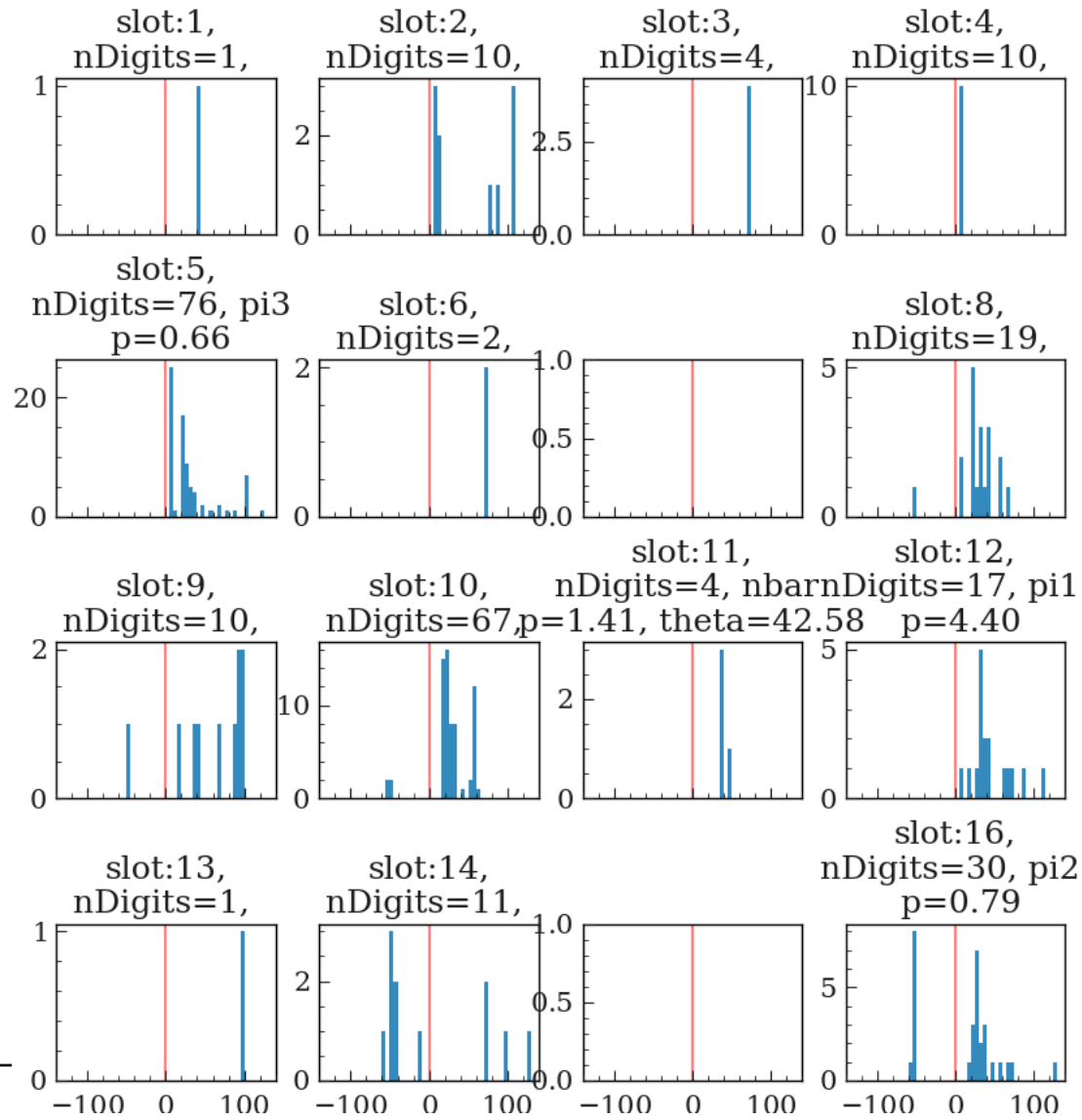
TOP signal: timing v pixel col (64)



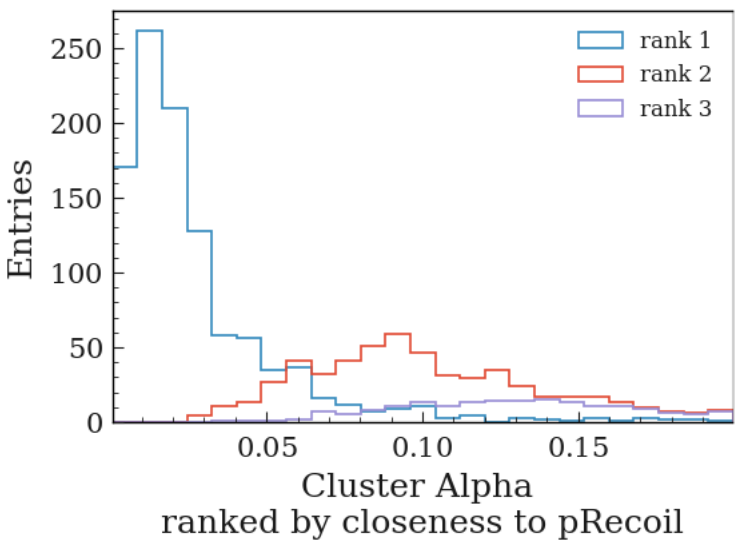


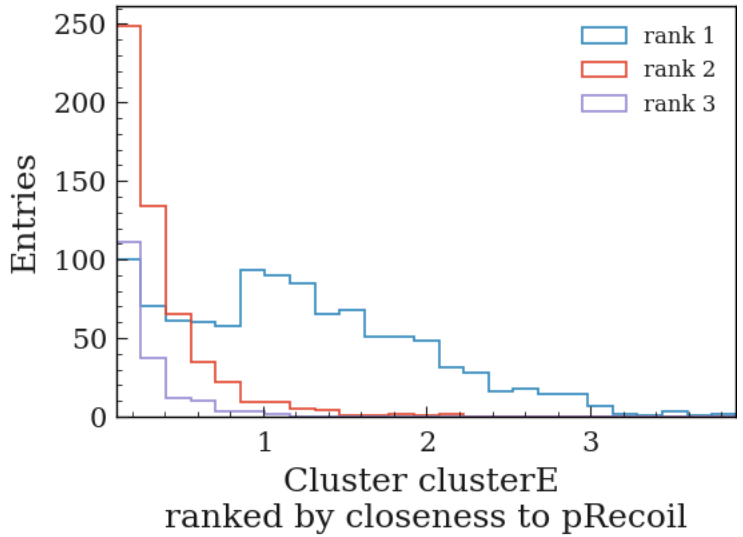
TOP signal: timing histogram

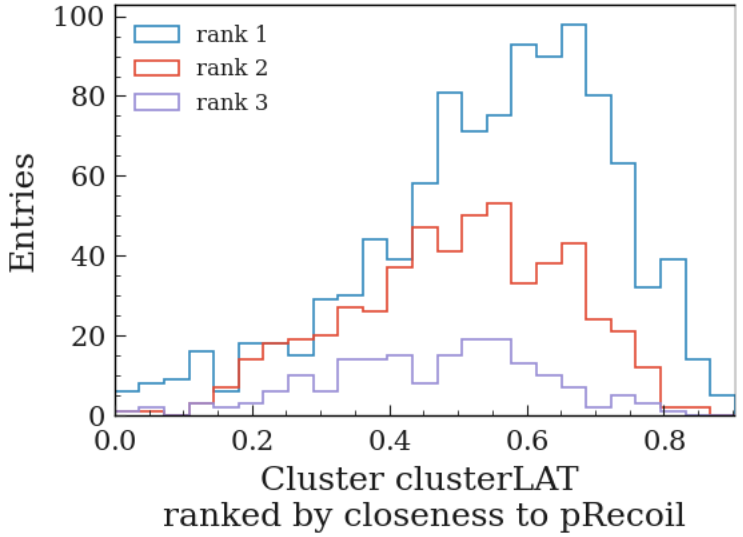


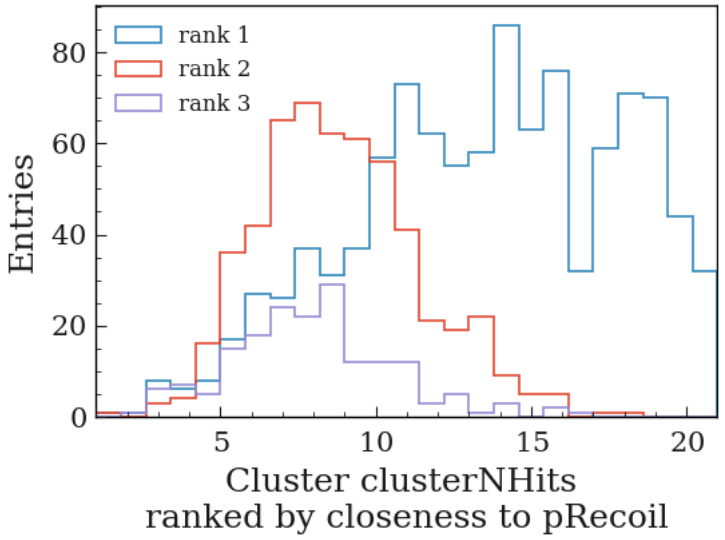


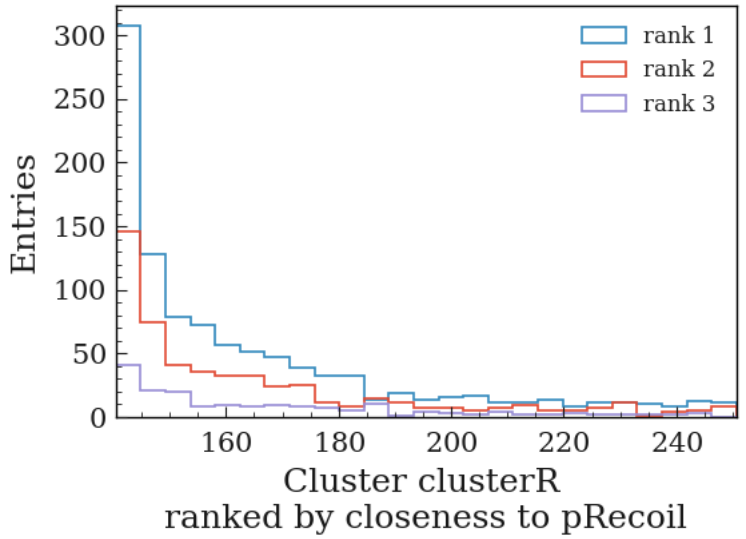
Cluster variables matched via recoil

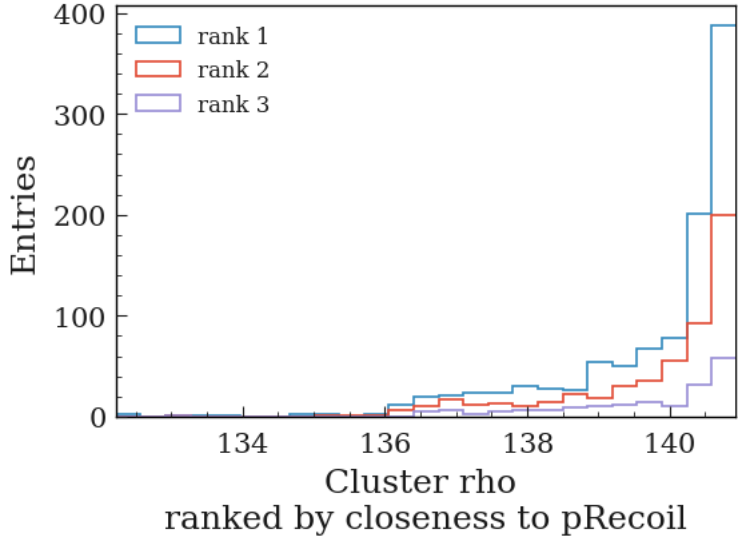








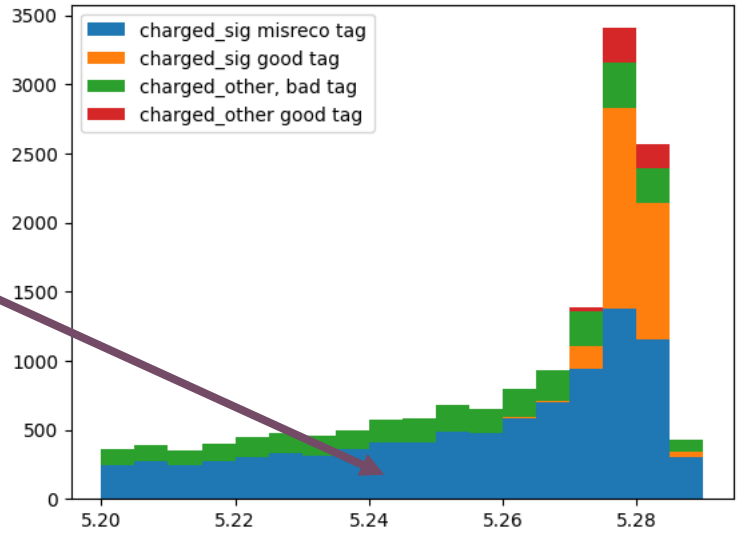




AN ASIDE ON B→PROTON INCLUSIVE…

- **Some concerns from B2GM presentation:**

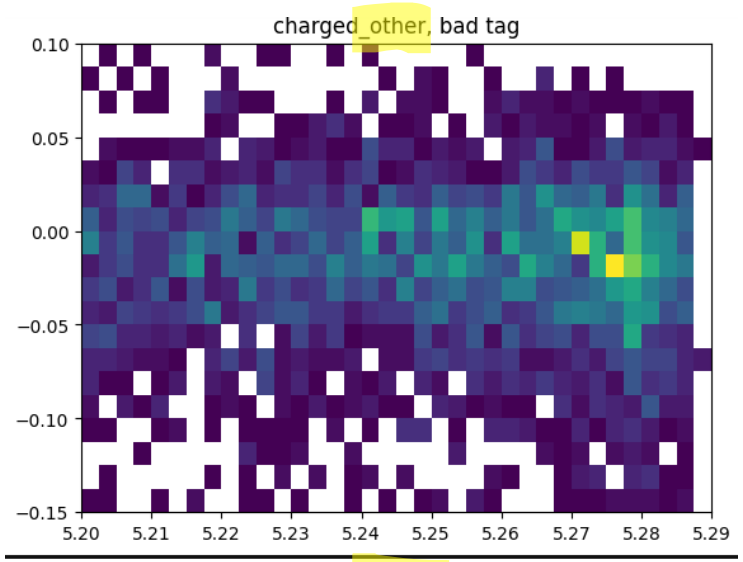
1. Mbc < 5.27 tail in signal component → misreco Btags in signal? Signal definition broken?

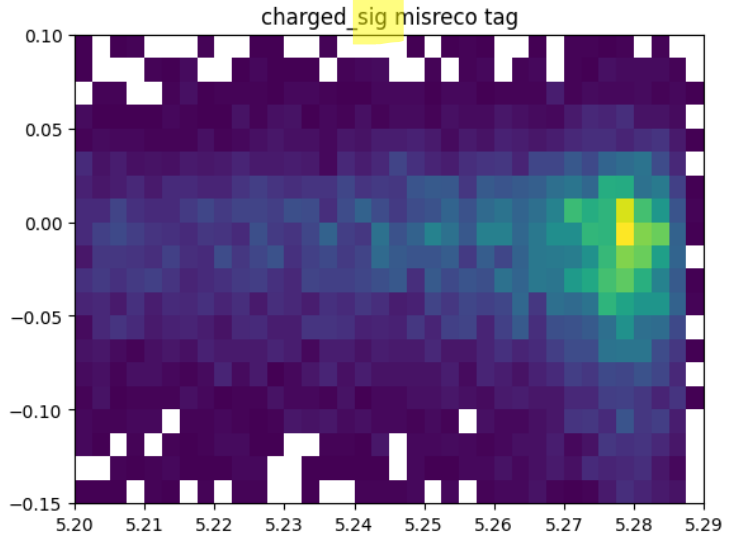


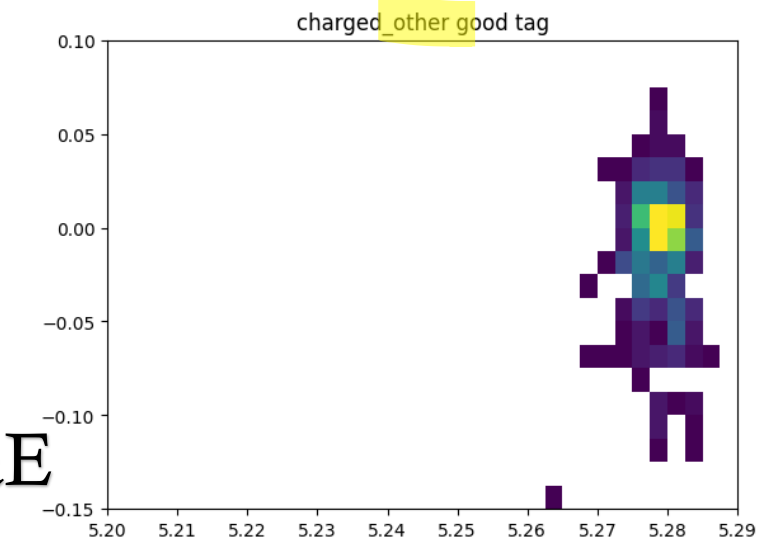
Sample: 4 streams of charged MC from proc16 (exp24)

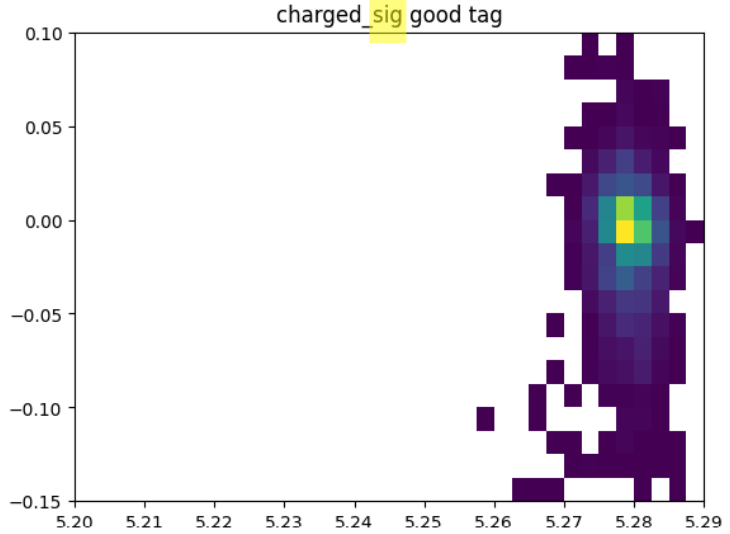
Signal defn: charged MC & proton is mcPrimary & reconstructed from MC proton of same charge.

- **Some concerns from B2GM presentation:**
  Redefine sig? 2D fit?
  Work in progress…









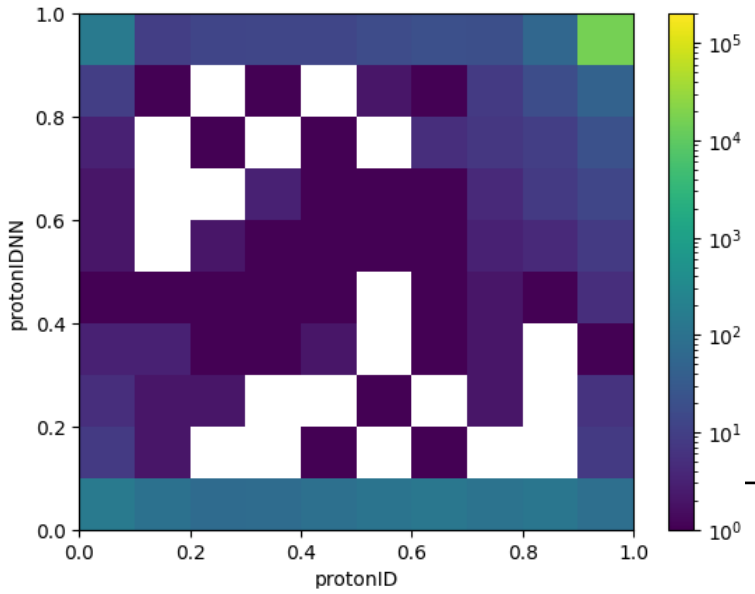
deltaE

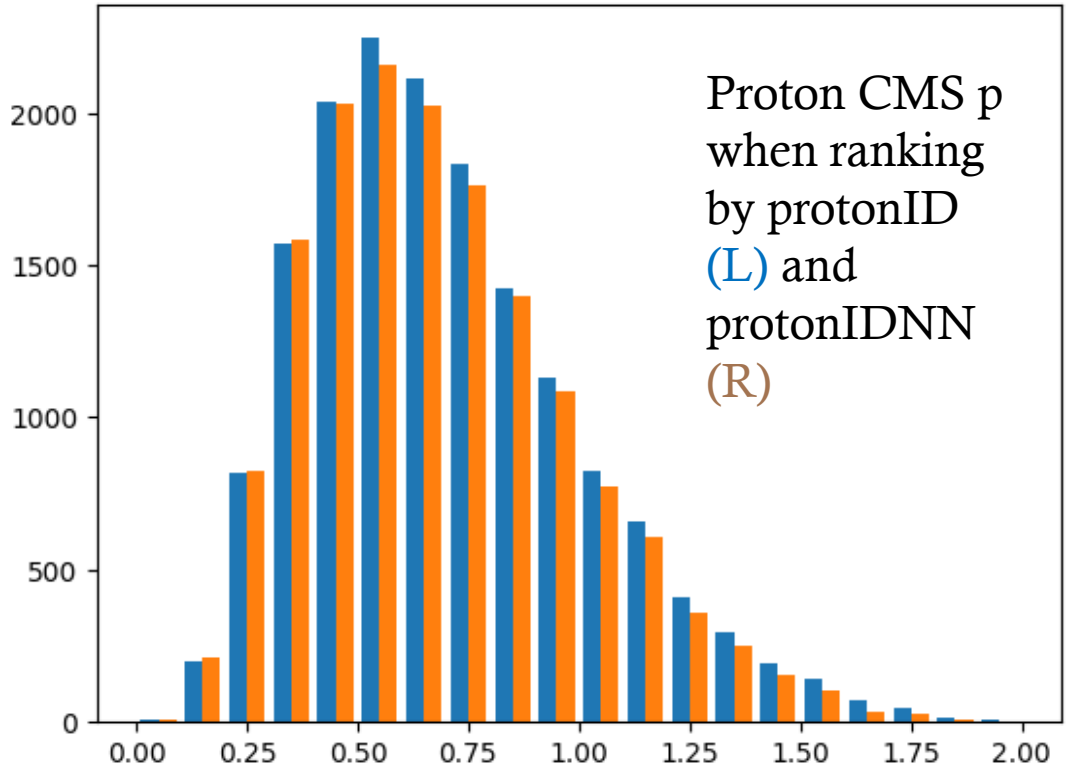
Mbc

AN ASIDE ON B→PROTON INCLUSIVE…

- **Some concerns from B2GM presentation:**

2. Need (?) to update to MC16 PID variables i.e. protonID > 0.99 (likelihood-based) vs protonIDNN > 0.99



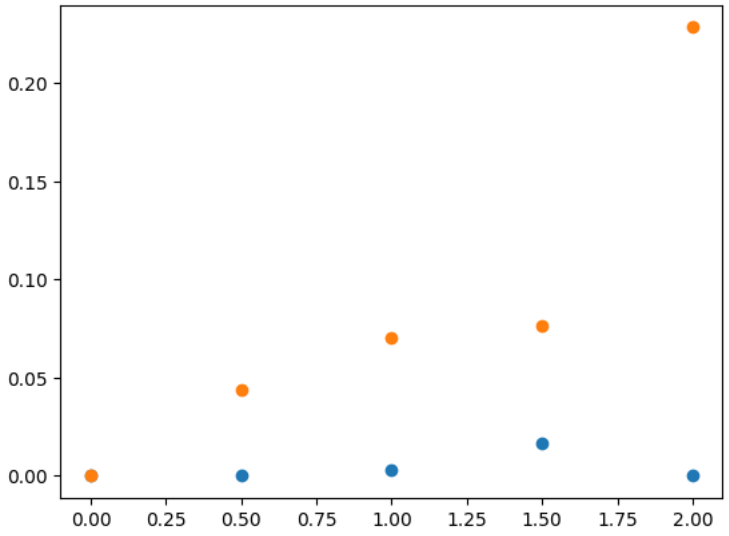


Proton CMS p when ranking by protonID (L) and protonIDNN (R)

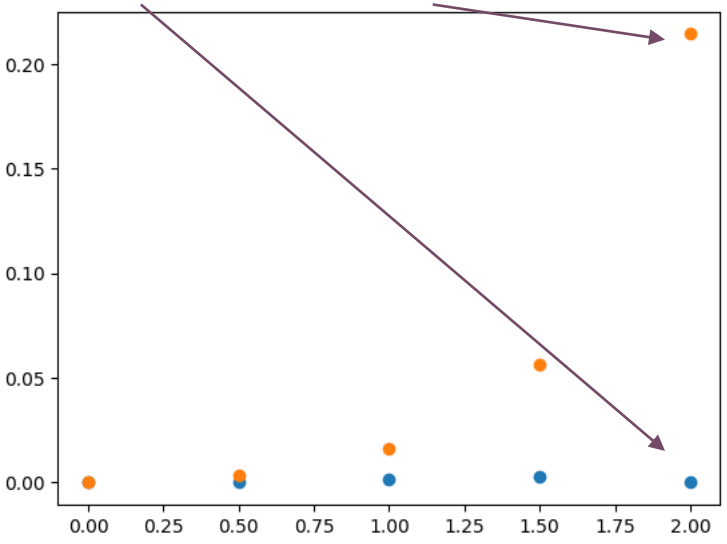
Protons with mcPDG==PDG

AN ASIDE ON B→PROTON INCLUSIVE…

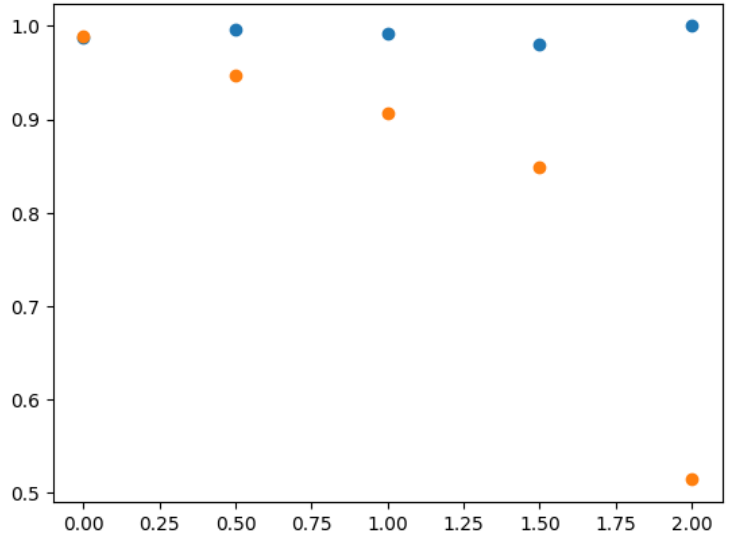
when ranking by protonID and protonIDNN



Proton-kaon fake rate in bins of proton lab momentum…



Proton-pion fake rate in bins of proton lab momentum…



Purity in bins of proton lab momentum…

"Japanese flowering cherry"
Collegno (Torino),
April 2025

TO DO

TOP

- More statistics? 10k →100k?
- Continue to validate reconstruction and then extend to data/MC
- Extracting digitTime pulse TOP signal (later)

B→pX

- Verify purity and fake rates to help decide on hadronID
- Sig defn? Further Btag cuts?

Cheers!
Ciao!

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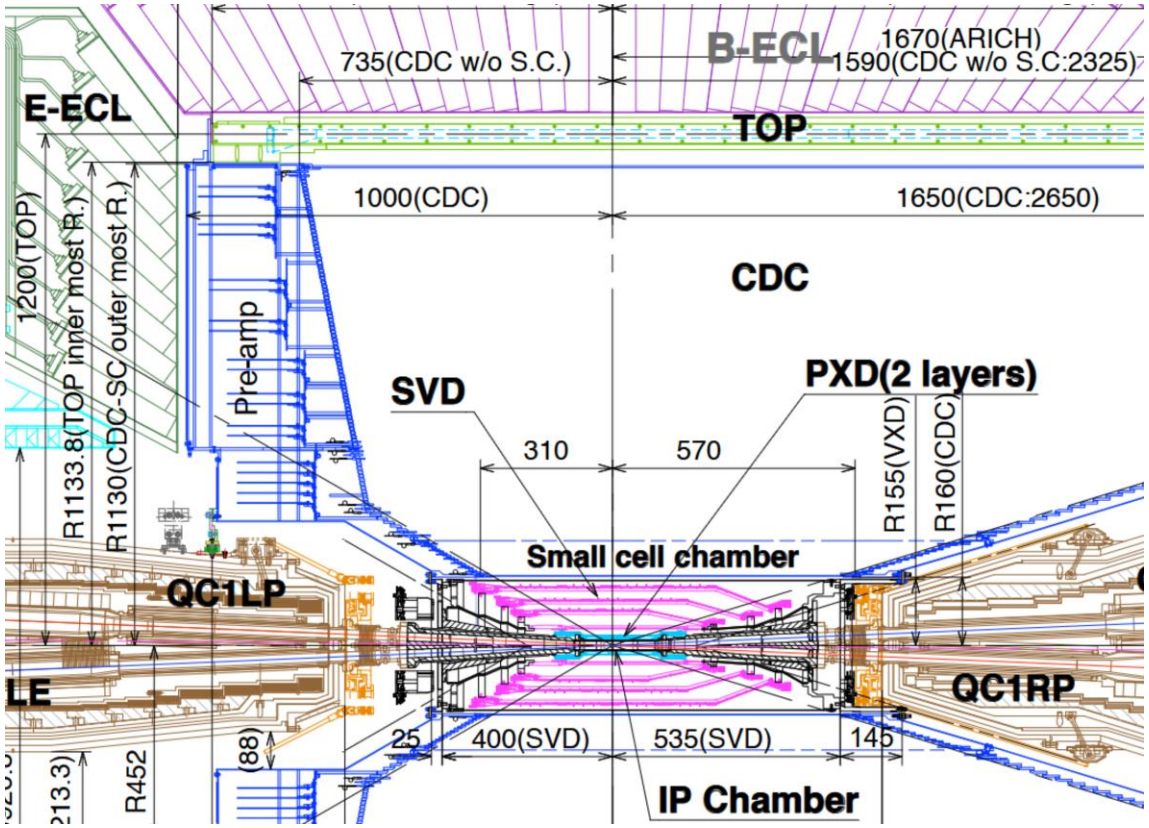
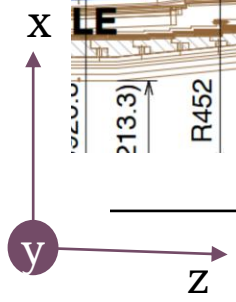
(Back-up slides following)

OUR GOAL:

Determine a method of measuring the properties of anti-neutrons ($\bar{n}^0$ or "n-bar"), via the timing signatures of their annihilation in detector volumes.





- Our case-study: the **TOP sub-detector** of the Belle II experiment.
- Anti-neutron identification differs from standard neutrons, in that they can be **identified via annihilation** events within detector volumes.
- **IF** anti-neutron annihilation induces an **electromagnetic shower in the ECL**, the full $\bar{n}^0$ energy can be measured.
- **IF** anti-neutron annihilation instead induces a **hadronic shower where charged products escape the ECL**, measurements can be incomplete.
- Can improve $\bar{n}^0$ measurement by studying **cases where annihilation products back-scatter** into the Time-of-Propagation (TOP) subdetector, a timing-based Cherenkov radiation detector.
- Additionally, can look at cases where anti-neutron annihilation **occurs slightly before or within the TOP**, where products can be detected before **further measurement when entering the ECL.**

GOALS

1. MOTIVATE THAT EVENTS WITH $\bar{n}$-ANNIHILATIONS AROUND TOP ***THAT ALSO LEAVE SIGNAL*** ARE NOT AN UNCOMMON OCCURRENCE

2. SHOW THAT 'BACKGROUND' TOP TIMING DISTRIBUTIONS, LIKE $\bar{n}$-ANNIHILATIONS, HAVE STRUCTURE AND ARE NON-NEGLIGIBLE (I.E. NOT FLAT)

3. DEMONSTRATE THAT THERE IS CORRELATION IN MEASURED TOP TIMING AGAINST THE SIMULATED PENETRATION DEPTH OF $\bar{n}$

HOW CAN THE TOP COUNTER BE USED TO COMPLEMENT MEASUREMENTS OF ANTI-NEUTRON SHOWERING IN THE ECL?

- Measurement of the anti-neutron annihilation within ECL depend heavily shower containment:
  - **If** annihilation particles produces an **electromagnetic shower**, the full $\bar{n}^0$ energy can be measured.
  - **Else if** the annihilation particles produces a **hadronic shower where charged products escape the ECL**, energy measurements is incomplete.
- TOP measurements can complement ECL information in situations where charged products transverse the TOP and scatter in ECL, such as when $\bar{n}^0$ annihilates…
  - … in material slightly ***before TOP*** (110 cm – 118 cm away from IP), and charged products transverse the TOP **before** entering ECL.
  - … ***within TOP*** active volume or shielding (118 cm – 125cm), and charged products transverse the TOP before entering ECL.
  - …in ***ECL*** (125 cm – 162 cm), where the charged products back-scatter through the ECL and then transverse the TOP.

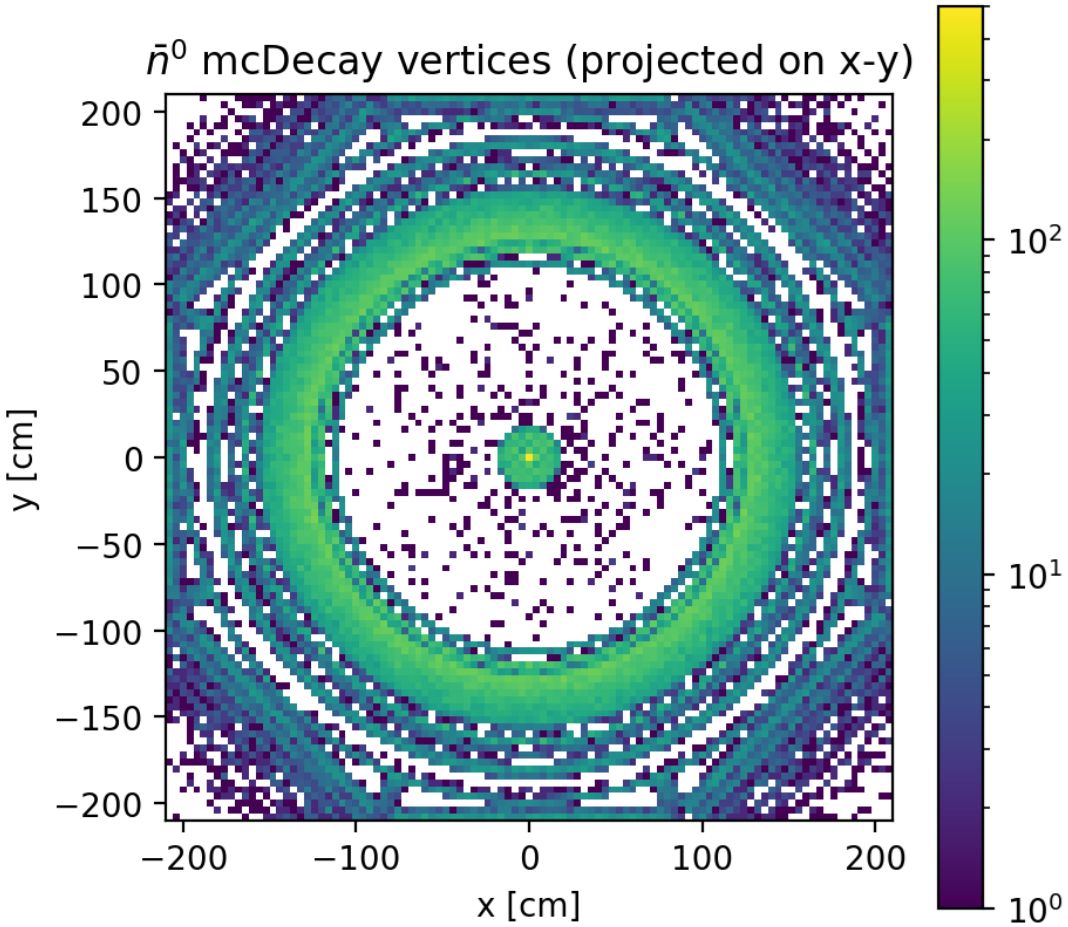
*Generated using “main” (last commit: Sat Nov 2 18:37:56 2024 +0100, globaltag: main_2024-07-19),
Default run-independent phase III conditions (i.e. expNum is 0)

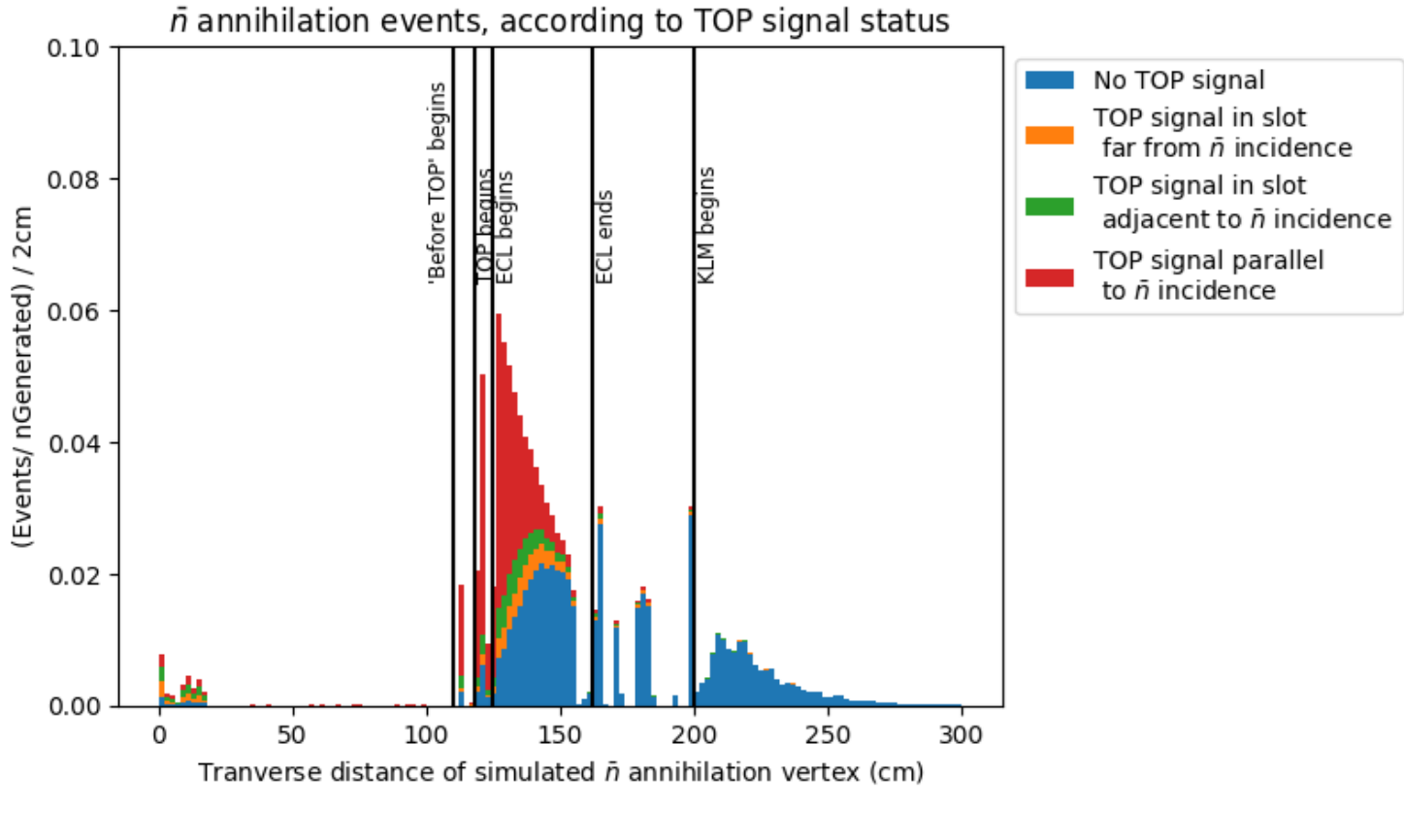
DESIGN OF MC STUDY

- Studying simulated **TOP response to 200 000 MC events** generated (via Particle Gun/EvtGen packages)
  - $\bar{n}^0$ begin at origin and travelling radially outwards with $|p|$=1 GeV, θ=92 and uniformly distributed $\phi \in [-\pi, \pi]$
  - **Also** place μ^+ at origin with same dynamics (i.e. also θ=92 with random ϕ), to “tag” the event start time for the TOP.
- Use `*TOPRingPlotter*` module to save MC TOP digits attributed to “tagging” muon, as well as other event info.
  - *Then* use new `*dumpOtherSlots*` option with `*TOPRingPlotter*` to access **all TOP signal **not** associated with the tagging muon i.e. from the annihilation**
  - Useful as charged particles produced in $\bar{n}^0$ event might not reach tracking detectors!

Statistics
200 000 events generated
89 751 events contain a TOP signal *not* associated with tagging muon (i.e. from $\bar{n}$ annihilation)
82 154 of $\bar{n}$ annihilations occur “just before” TOP, in TOP, or in ECL (i.e. in region of interest, between 110cm and 162cm)
Proportion of generated events with TOP signal and in region of interest ≈ **31.34%**

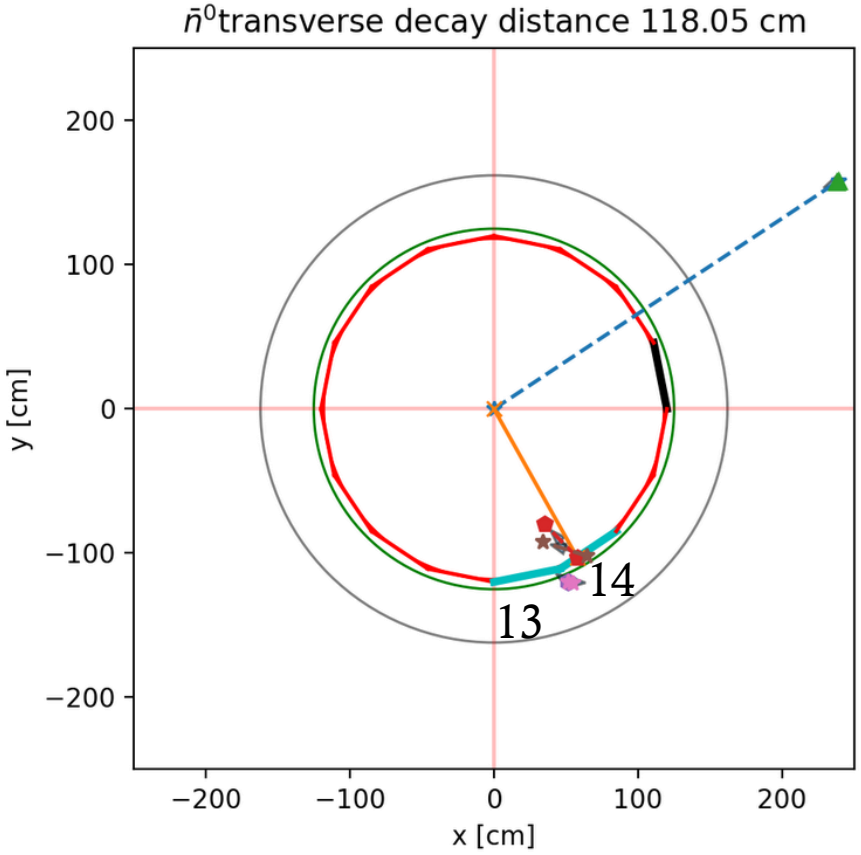
WHERE ARE OUR ANTI-NEUTRONS ANNIHILATING?

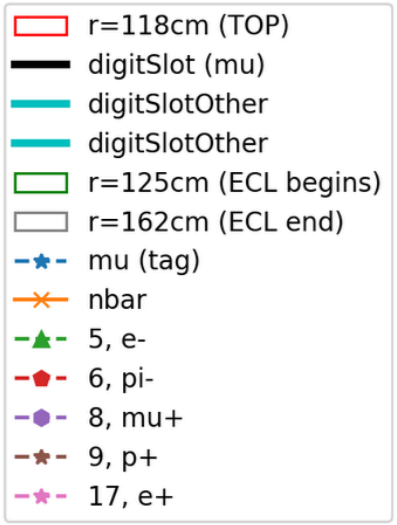


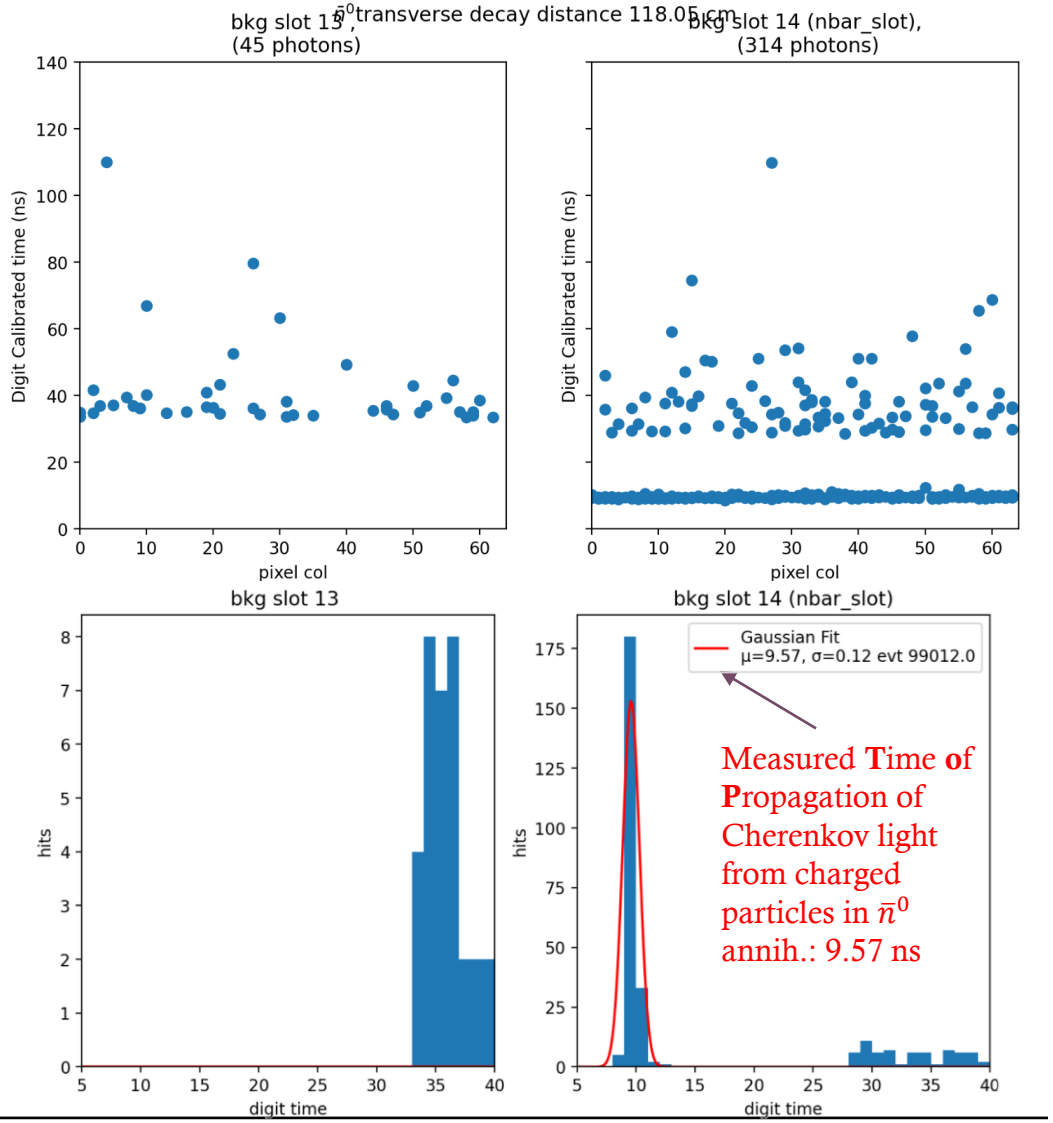


TOP facts! 16 TOP modules in Belle II. Each module has two rows of 16 PMTs, and each PMT has 4x4 channels → each module has 8 rows of 64 columns of channels (digits)

AN EXAMPLE EVENT



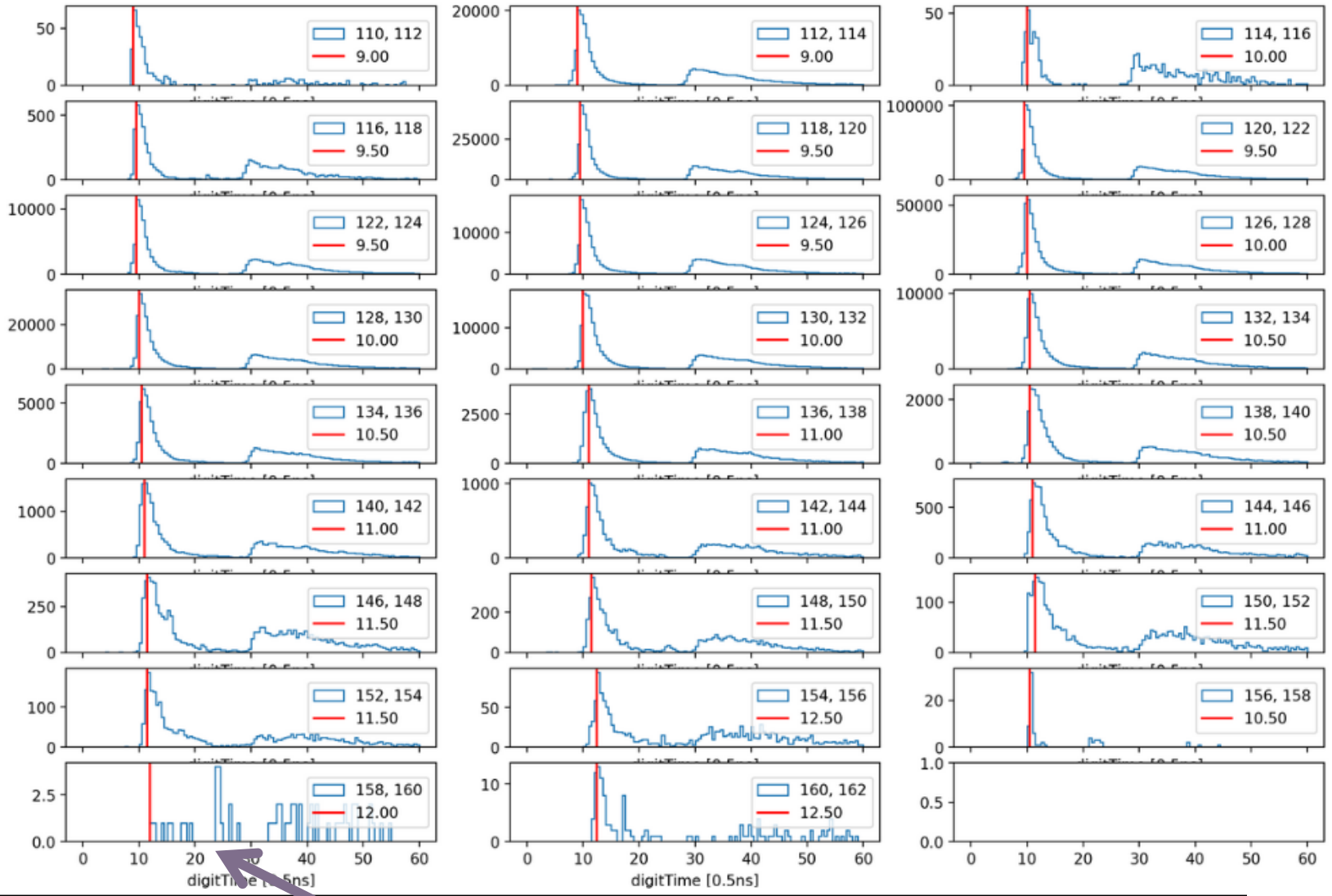




*TODO: Fit to "rising edge" of each $\bar{n}^0$ event, examine as a function of transverse distance
→ can we extract $\bar{n}^0$ transverse vertex from TOP timing alone?

ANTI-NEUTRON TIMING VIA TOP VS PENETRATION DEPTH OF $\bar{n}$

- Look at **29 432** events which have TOP signal in the direction of $\bar{n}$, and are in regions of interest (110,162)cm
- Create *digitTime* histograms in 2cm bins of $\bar{n}$ transverse distance. ** in lieu of fitting to individual events
- Measure "rising-edge" i.e. timing from maximum bin, limited by resolution



*TODO: improve peak finding algorithm!

*0.5 ns steps due to binning, to be improved with fitting

CORRELATION IN TOP TIMING WITH PENETRATION DEPTH OF $\bar{n}$

- Look at **29 432** events which have TOP signal in the direction of $\bar{n}$, and are in regions of interest (110,162)cm
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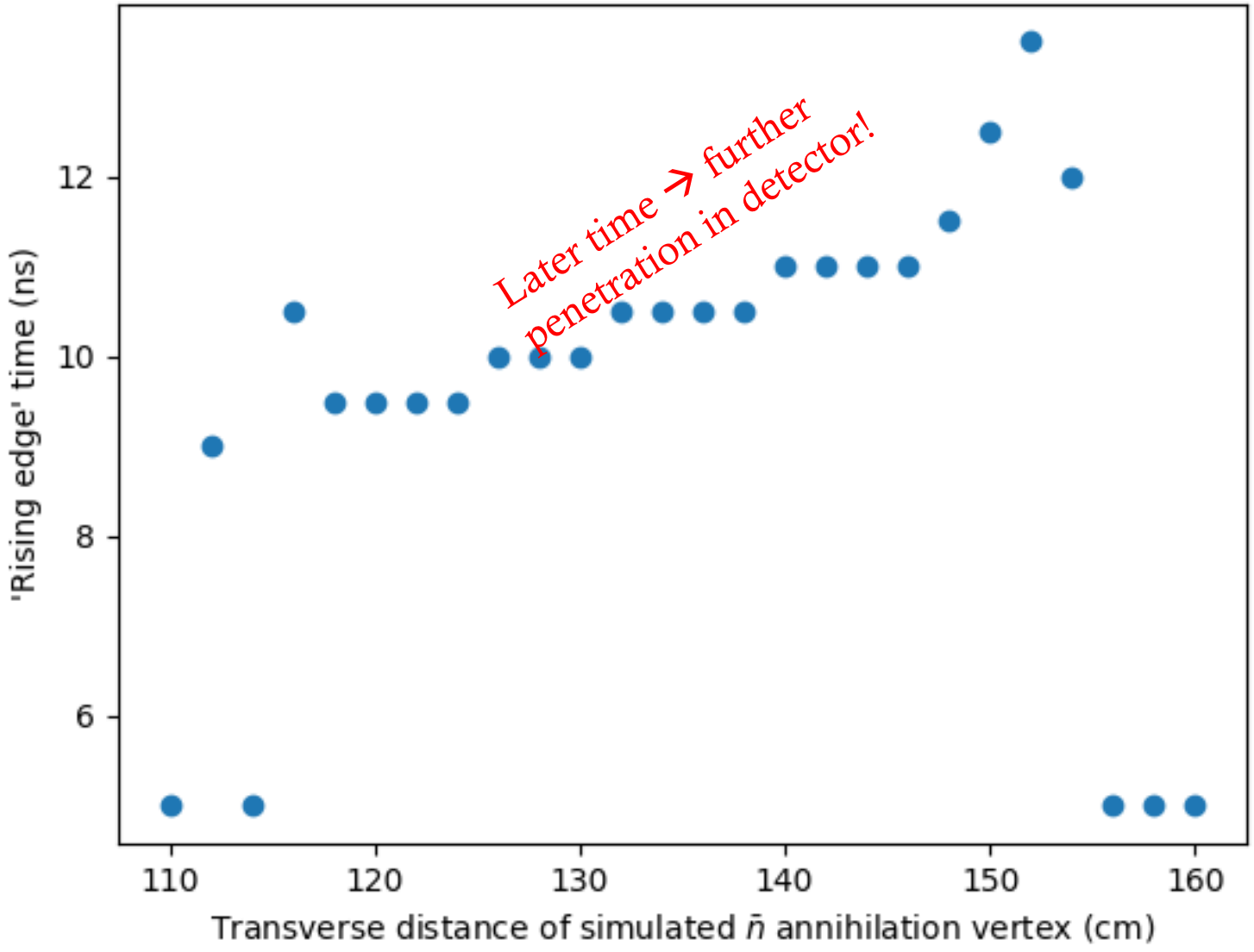
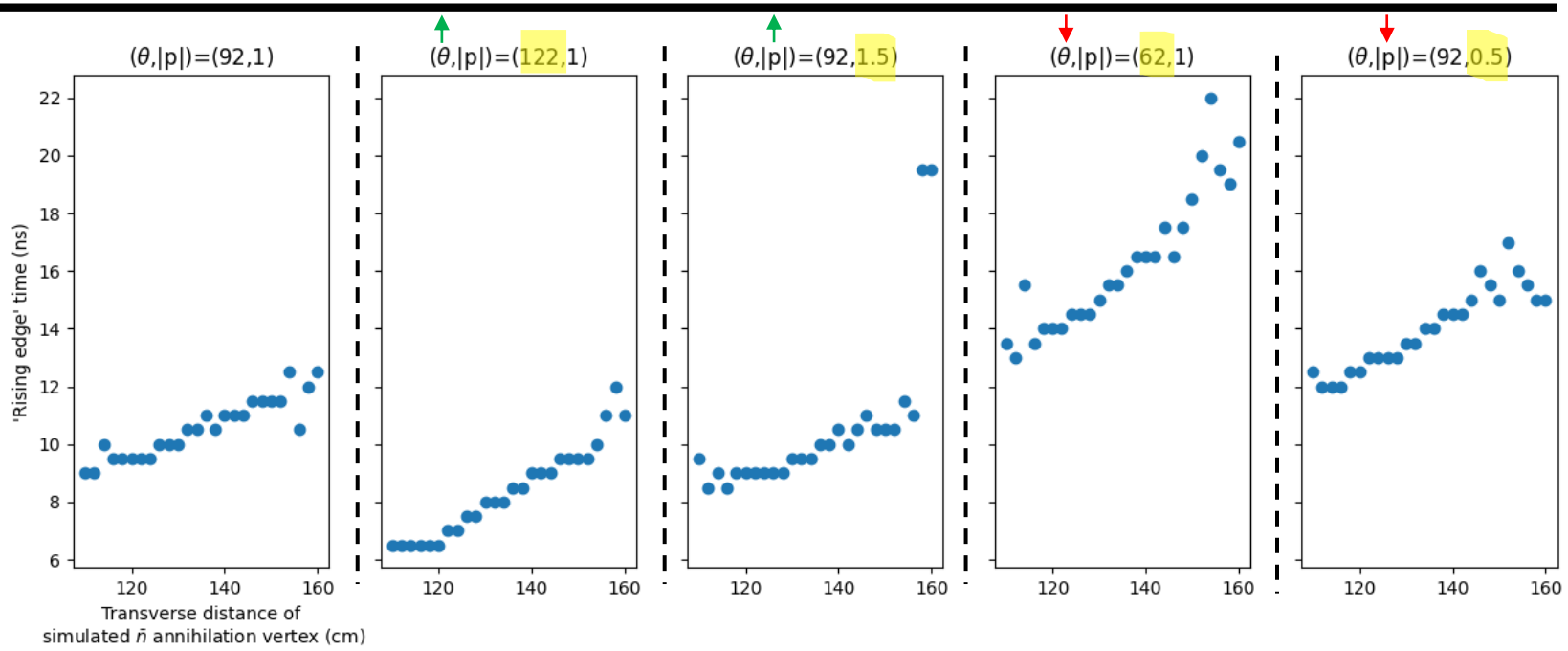
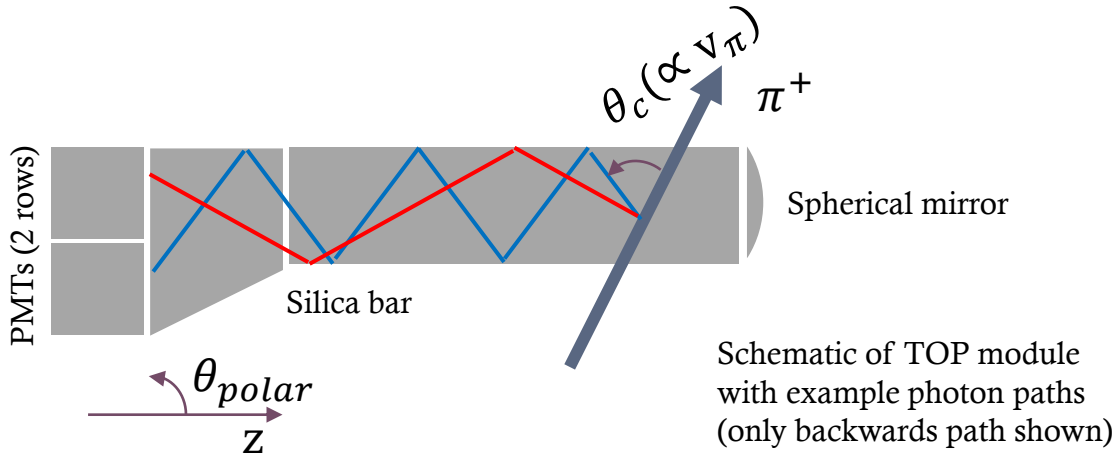


TOP TIMING AND PENETRATION DEPTH, WHEN VARYING $\bar{n}$ KINEMATICS



- Smaller time of propagation measured when $\bar{n}^0$/annihilation event is at larger polar angle (i.e. closer to the TOP readout electronics)

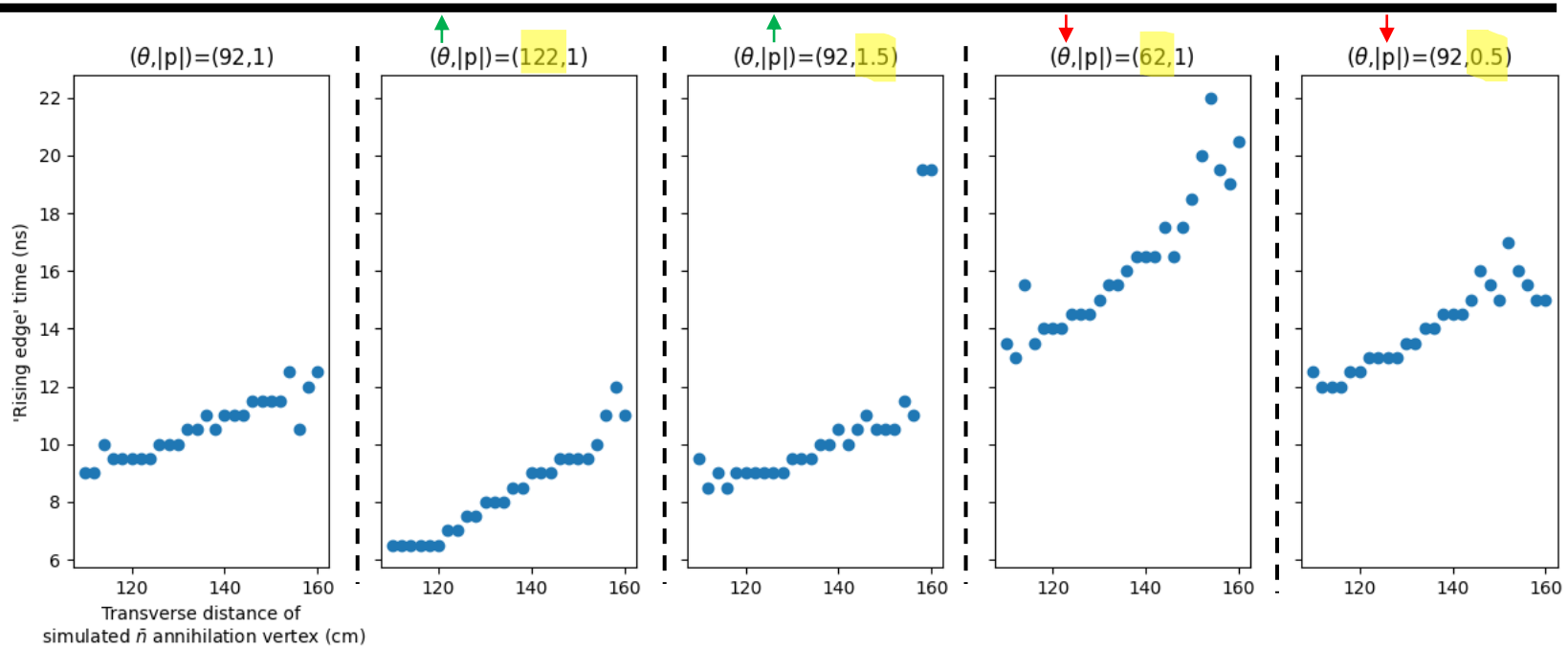
- Larger time of propagation measured when $\bar{n}^0$/annihilation has less energy (i.e. lower momentum annihilation particles leads to smaller Cherenkov angle θ_c, longer Cherenkov photon path.)



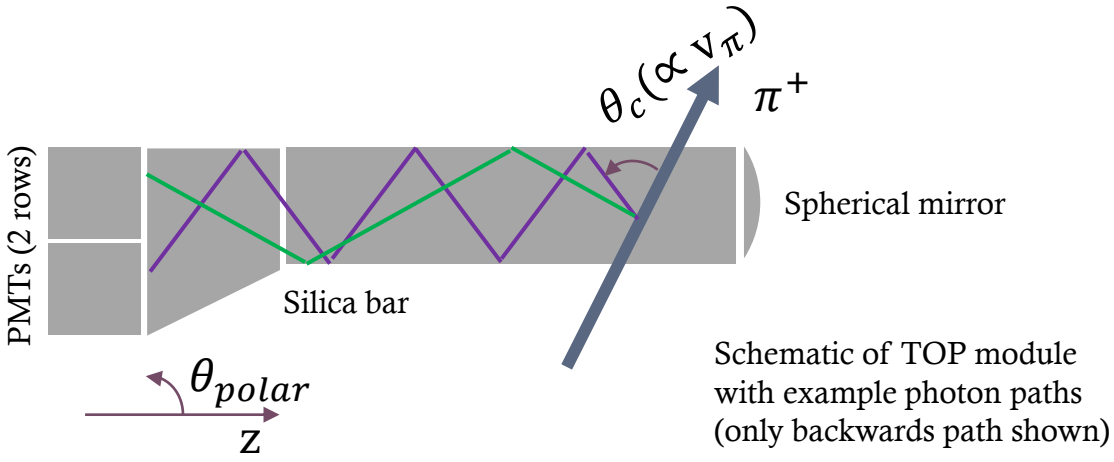
Schematic of TOP module with example photon paths (only backwards path shown)

Last time!

TOP TIMING AND PENETRATION DEPTH, WHEN VARYING $\bar{n}$ KINEMATICS



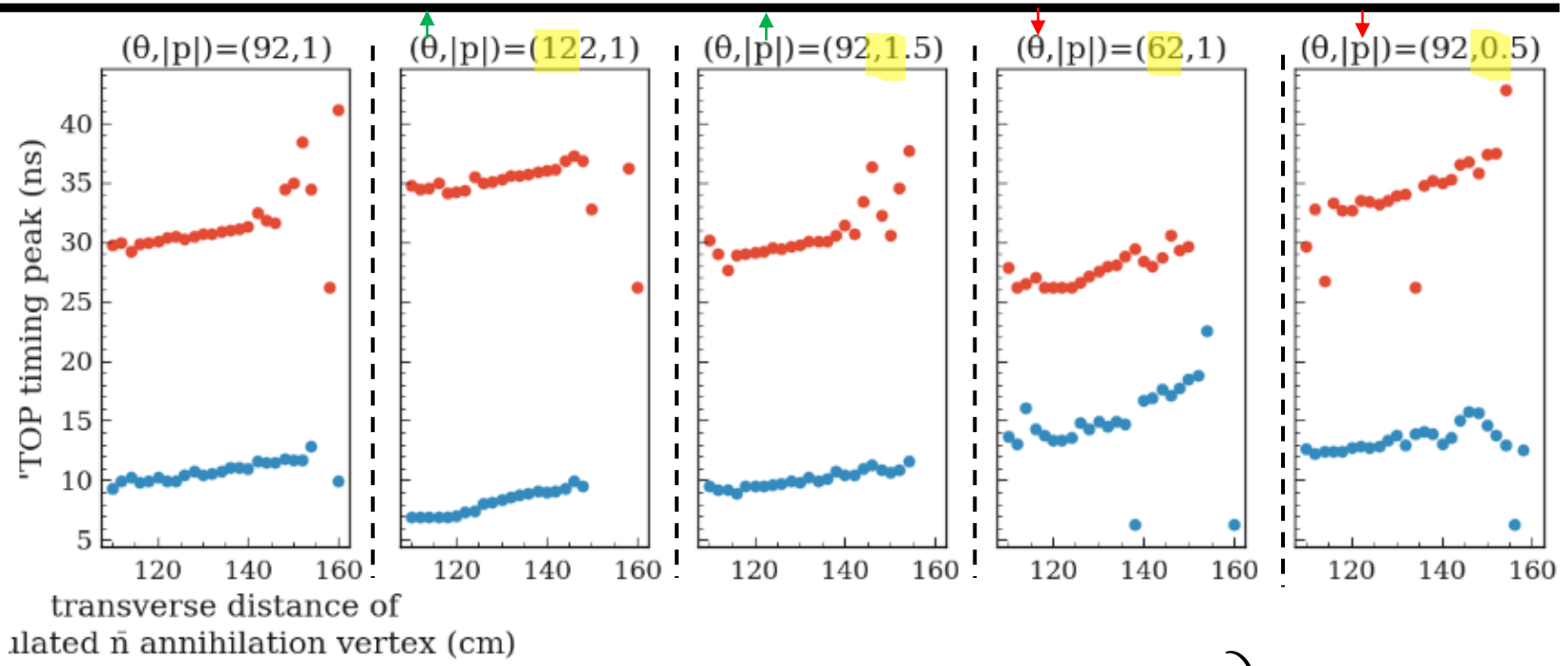
- **Measure "rising-edge" i.e. timing from maximum bin, limited by resolution**
- Smaller time of propagation measured when $\bar{n}^0$/annihilation event is at larger polar angle (i.e. closer to the TOP readout electronics)
- Larger time of propagation measured when $\bar{n}^0$/annihilation has less energy (i.e. lower momentum annihilation particles leads to smaller Cherenkov angle θ_c, longer Cherenkov photon path.)



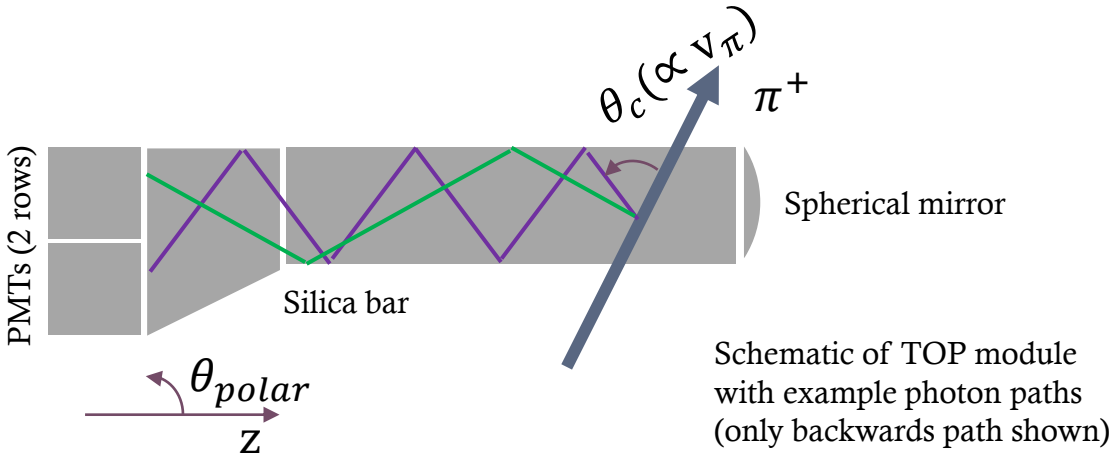
Schematic of TOP module with example photon paths (only backwards path shown)

Now!

TOP TIMING AND PENETRATION DEPTH, WHEN VARYING $\bar{n}$ KINEMATICS: *CRYSTAL BALL FIT*



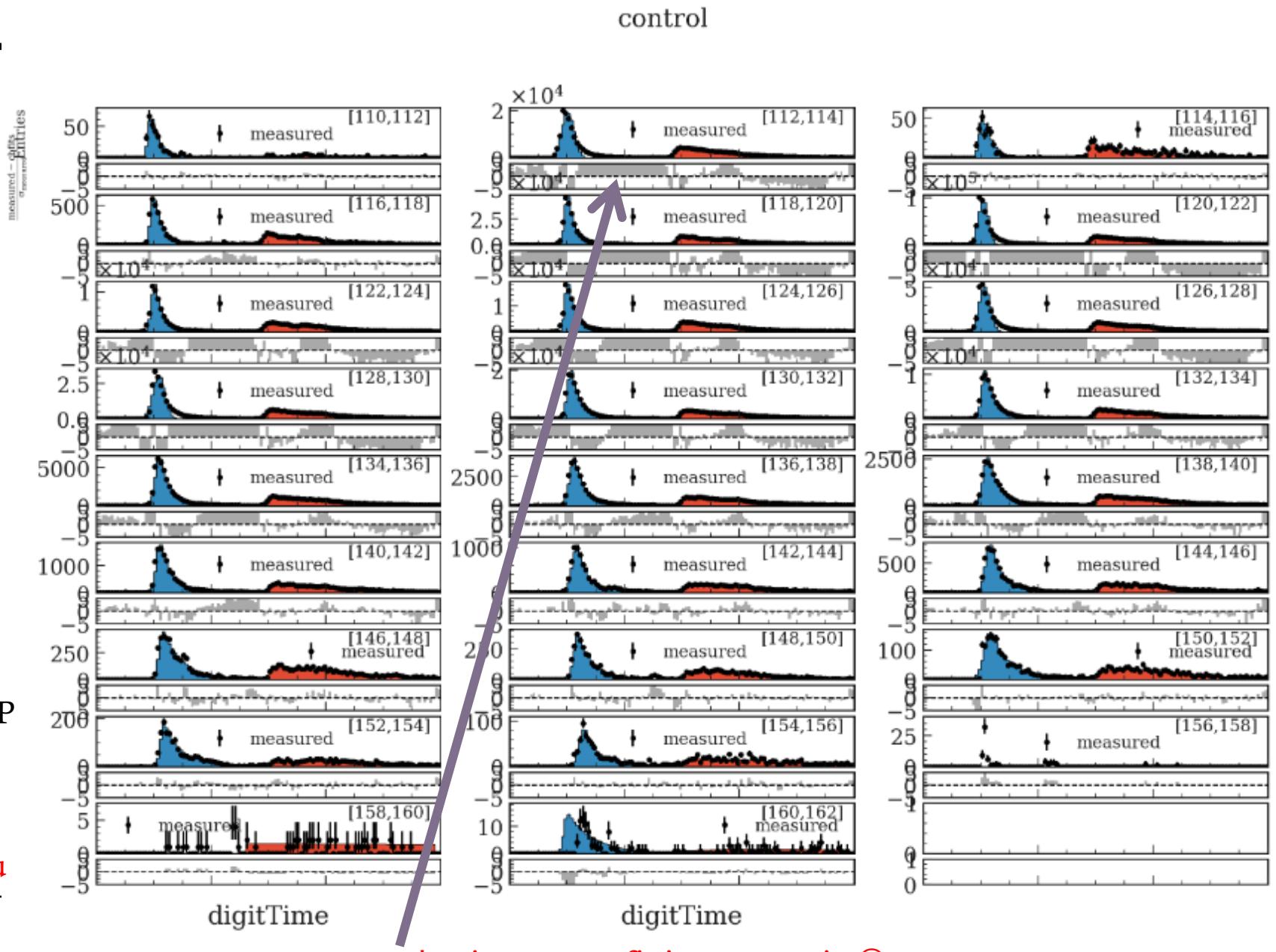
- For higher timing precision, perform binned fit using $scipy.stats.crystallball.pdf(-1 * x, beta, m, loc, scale)$ (two separate fits for forward and backwards to pulse)
- Plot **maximum of timing peak** as estimate of rising edge for now.



Schematic of TOP module with example photon paths (only backwards path shown)

ANTI-NEUTRON TIMING VIA TOP VS PENETRATION DEPTH OF $\bar{n}$ *CRYSTAL BALL FITS*

- Look at **29 432** events which have TOP signal in the direction of $\bar{n}$, and are in regions of interest (110,162)cm
- Create *digitTime* histograms in 2cm bins of $\bar{n}$ transverse distance. ** in lieu of fitting to individual events



* scipy.curve_fit is not magic ☹

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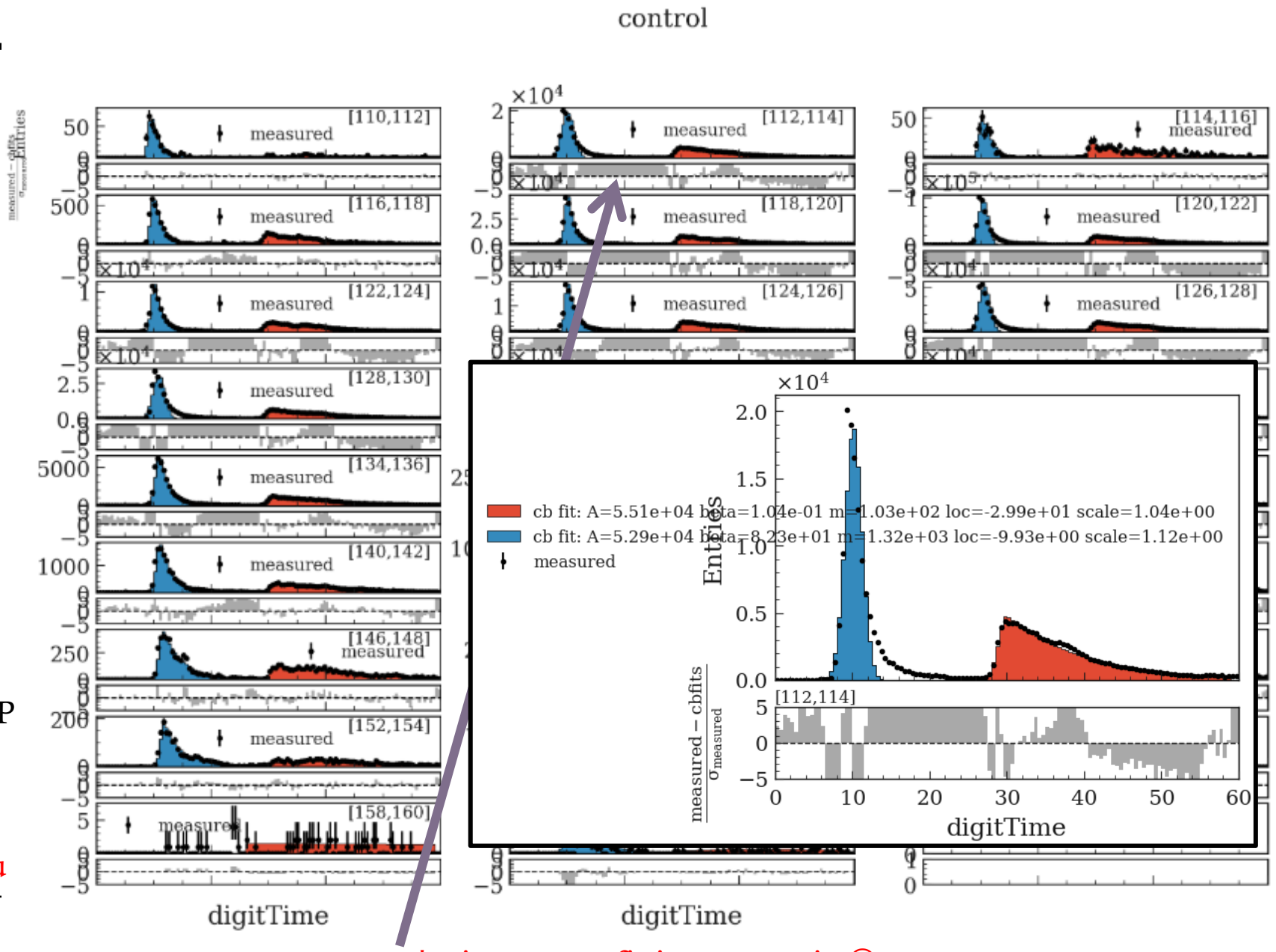

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