# ANTI-NEUTRON MEASUREMENT WITH THE TOP SUBDETECTOR AT BELLE II

*Putting a pin in deriving characteristic TOP timing, moving to data-MC agreement of $\bar{n}$ TOP signal*


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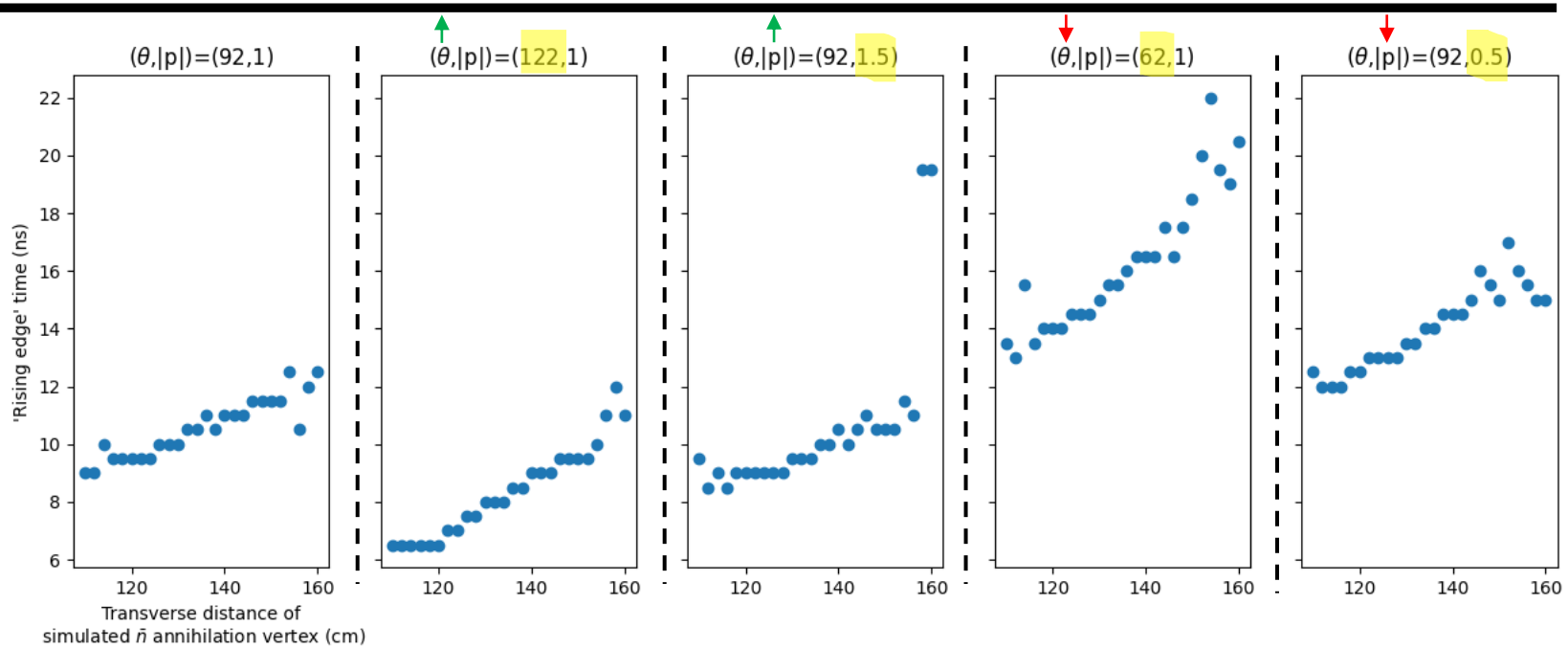
KEK, October 2023

# 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)
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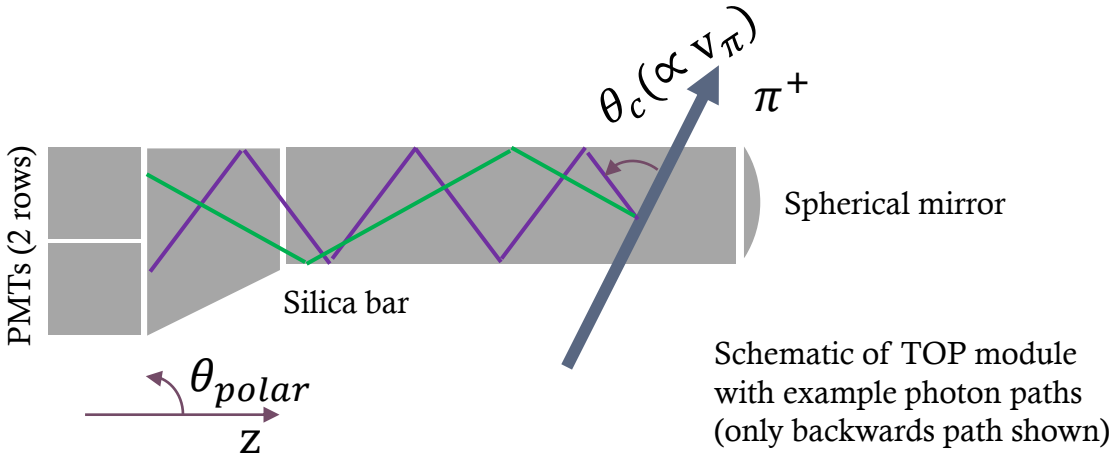
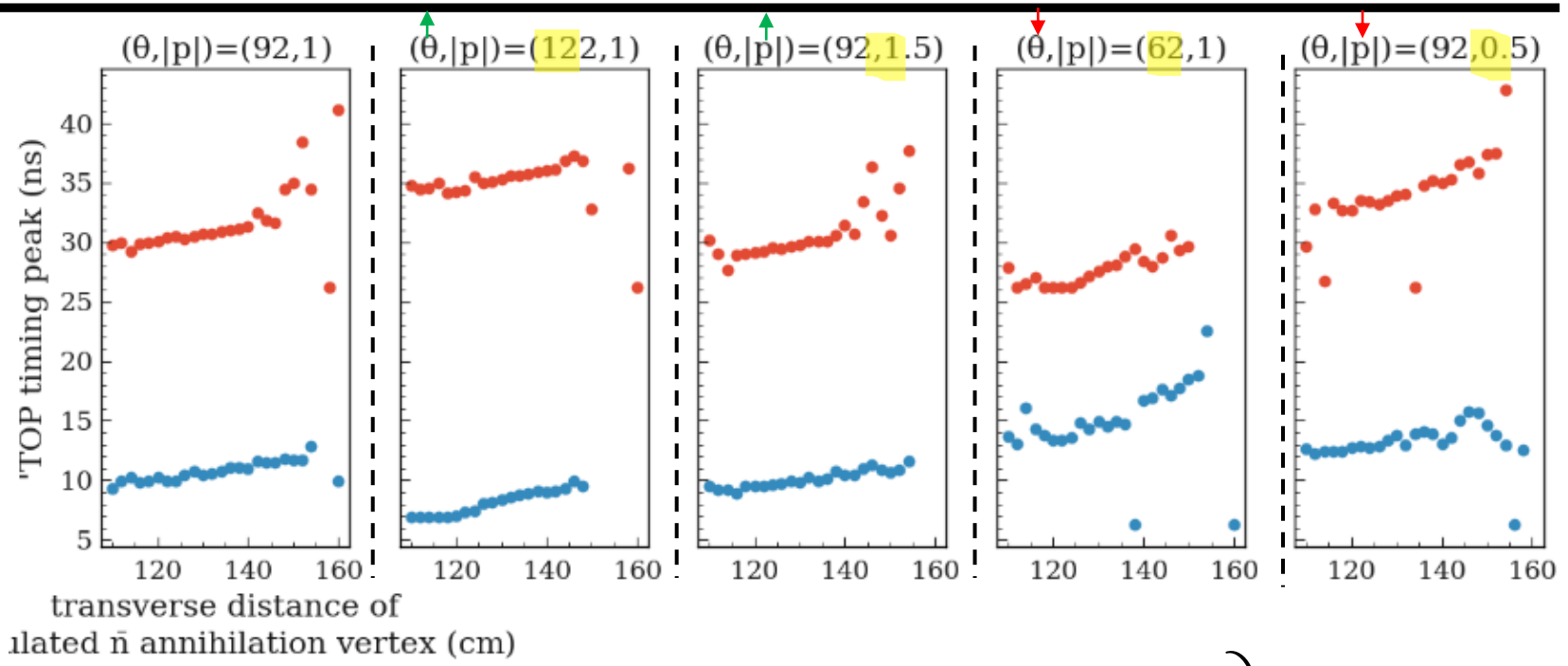


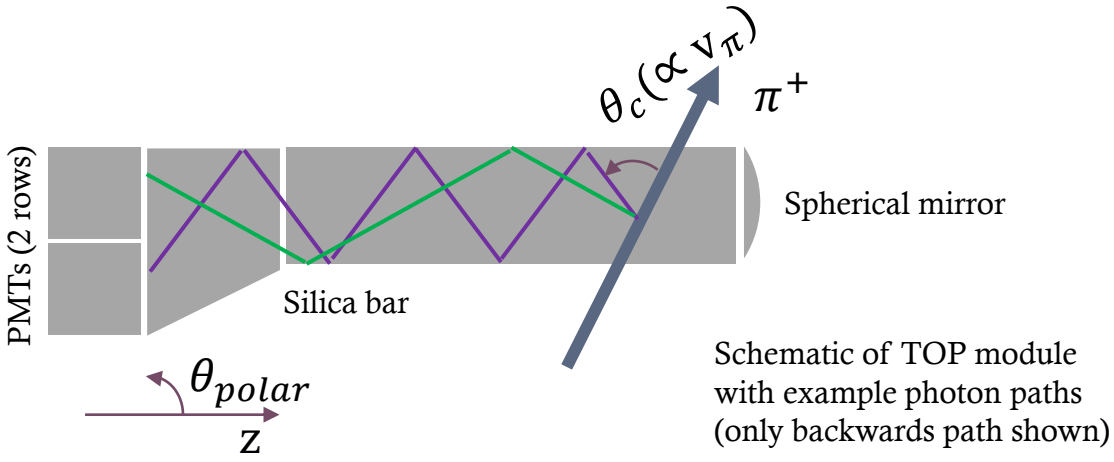

Schematic of TOP module with example photon paths (only backwards path shown)

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.

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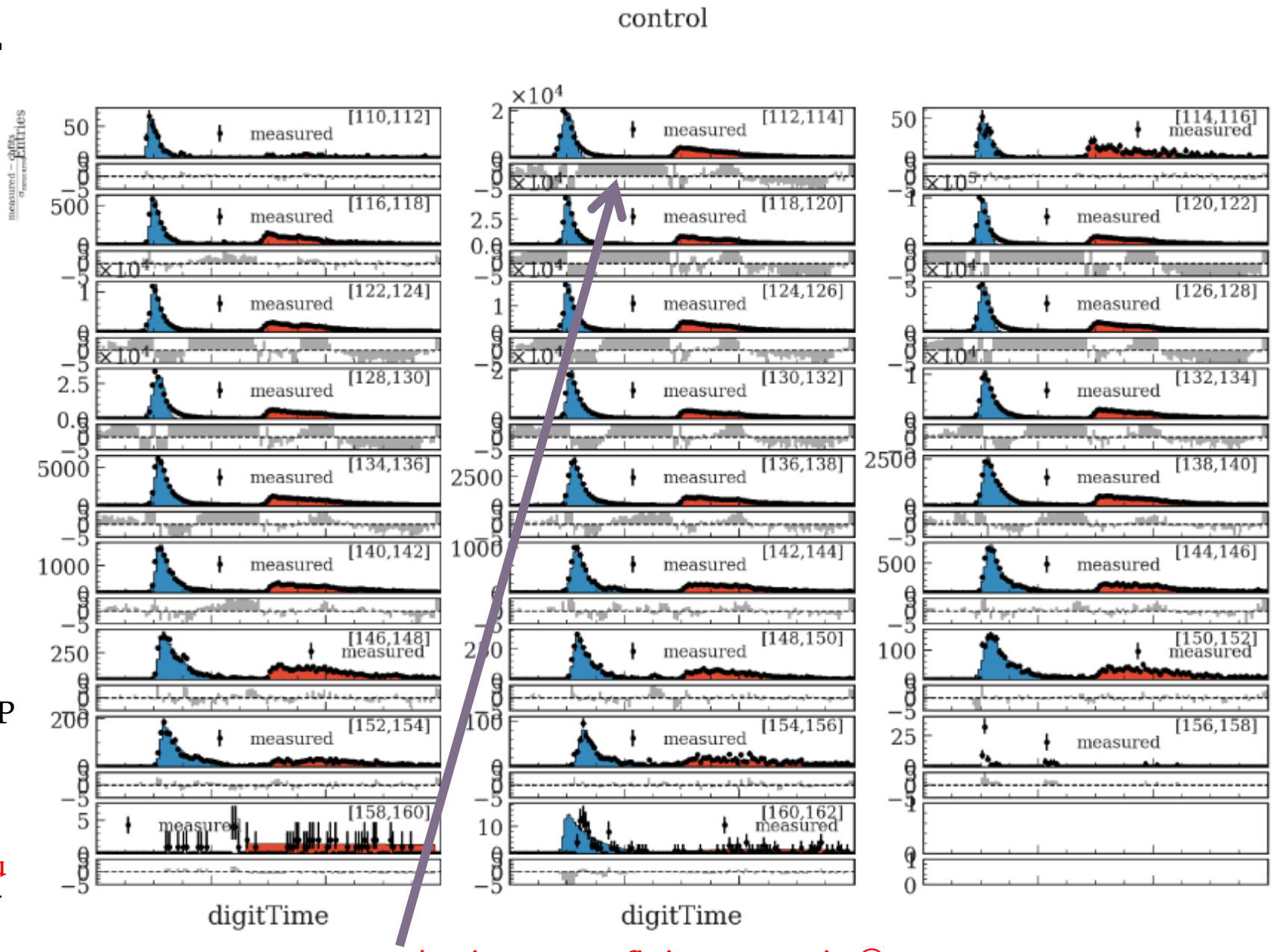
# ANTI-NEUTRON TIMING VIA TOP VS PENETRATION DEPTH OF $\bar{n}$ *CRYSTAL BALL FITS*

- 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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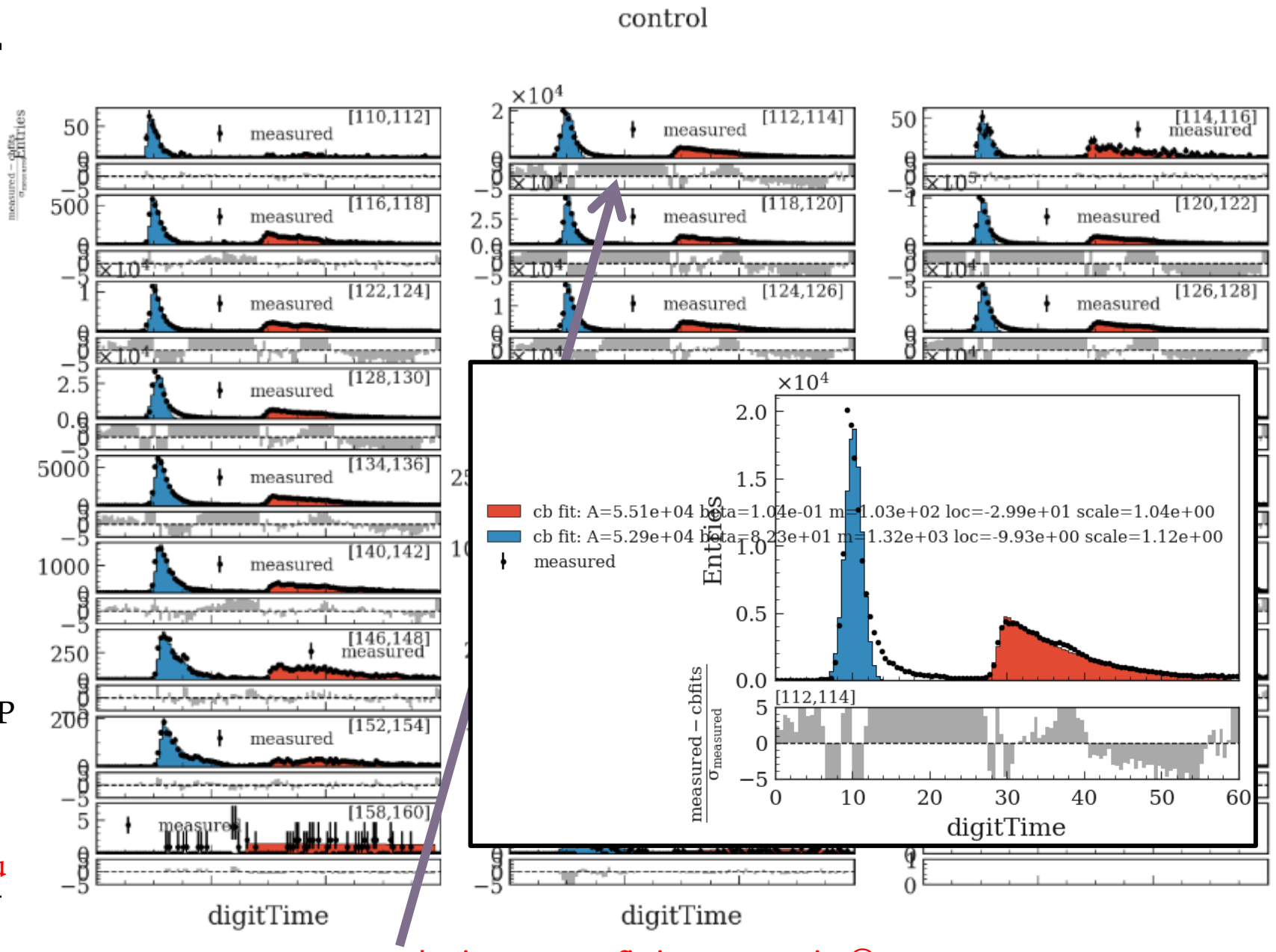


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# CHANGING FOCUS: DATA/MC AGREEMENT OF TOP SIGNAL

- TO DO: Reconstruct a physics process involving $\bar{n}$, remove all other contributions to look at potential $\bar{n}$ annihilations' in TOP
- First: Generate MC16ri of Savino's key $\bar{n}$ modes, and follow his reconstruction (See BELLE2-NOTE-TE-2025-012)
- Then: Once reconstruction method and TOP signal is validated in signal modes, extend to general proc16/MC16 data
- Develop a skim to condense the dataset??

$$\mathrm{p3\pi} \equiv \mathrm{e^+e^-} \to \mathrm{p\bar{n}\pi^-\pi^+\pi^-}$$

$$\mathrm{p5\pi} \equiv \mathrm{e^+e^-} \to \mathrm{p\bar{n}\pi^-\pi^+\pi^-\pi^+\pi^-}$$

$$\mathrm{p7\pi} \equiv \mathrm{e^+e^-} \to \mathrm{p\bar{n}\pi^-\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-}$$

$$\mathrm{p3\pi 2K} \equiv \mathrm{e^+e^-} \to \mathrm{p\bar{n}\pi^-\pi^+\pi^-K^+K^-}$$

$$\mathrm{p5\pi 2K} \equiv \mathrm{e^+e^-} \to \mathrm{p\bar{n}\pi^-\pi^+\pi^-\pi^+\pi^-K^+K^-}$$

**Need to `dumpOtherSlots` for multiple tracks??
Reco a pseudoparticle and pass to `TOPRingPlotter`?

```
1 Decay vpho
2 1.0 p+ anti-n0 pi- pi+ pi- PHSP;
3 Enddecay
4
5 End
```

**Sufficient decfile?

“Japanese flowering cherry”
Collegno (Torino),
April 2025

# TO DO

- Generate MC16ri $\bar{n}$ modes
- Factorise Savino’s reconstruction script and add `TOPRingPlotter` module.
- Validate reconstruction and `TOPRingPlotter` signal in signal sample.
- Extend to data/MC
- Come back to fitting TOP digitTime pulse (later)


# Cheers!
# Ciao!

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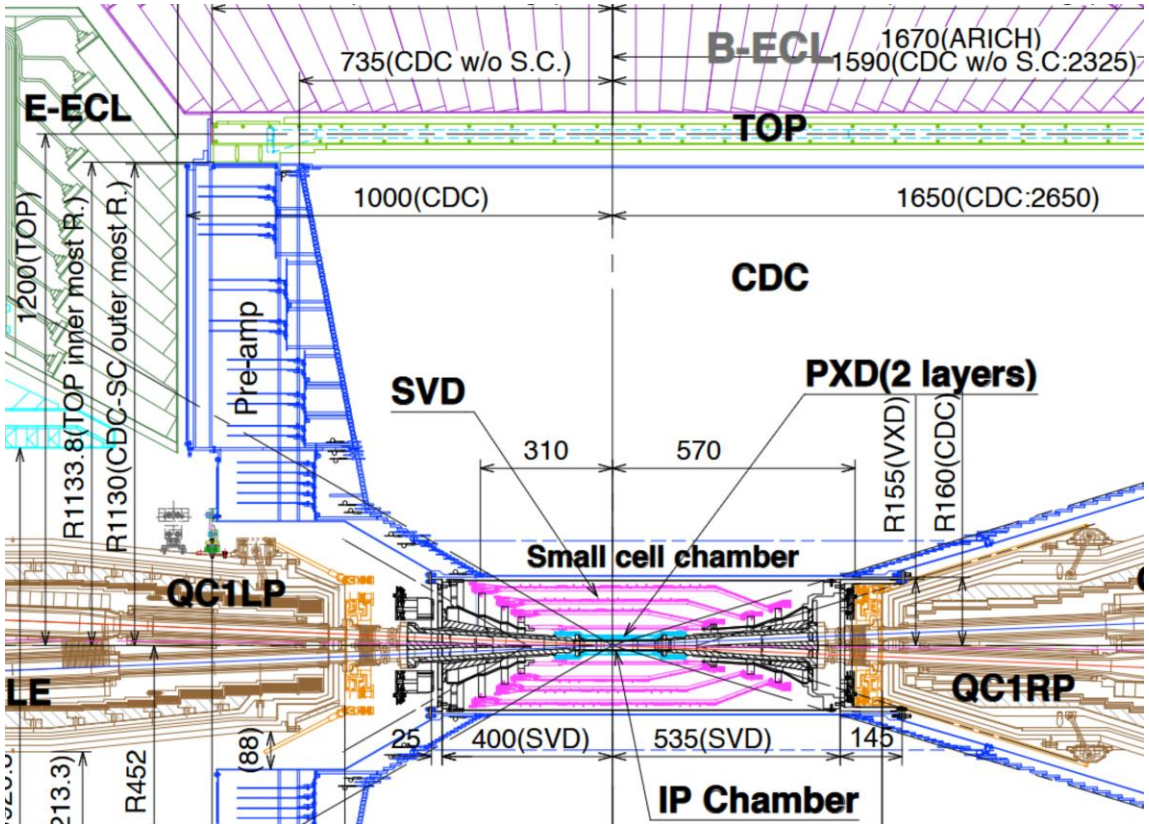
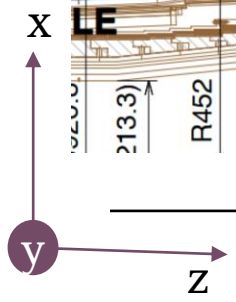
(Back-up slides following)

# 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.

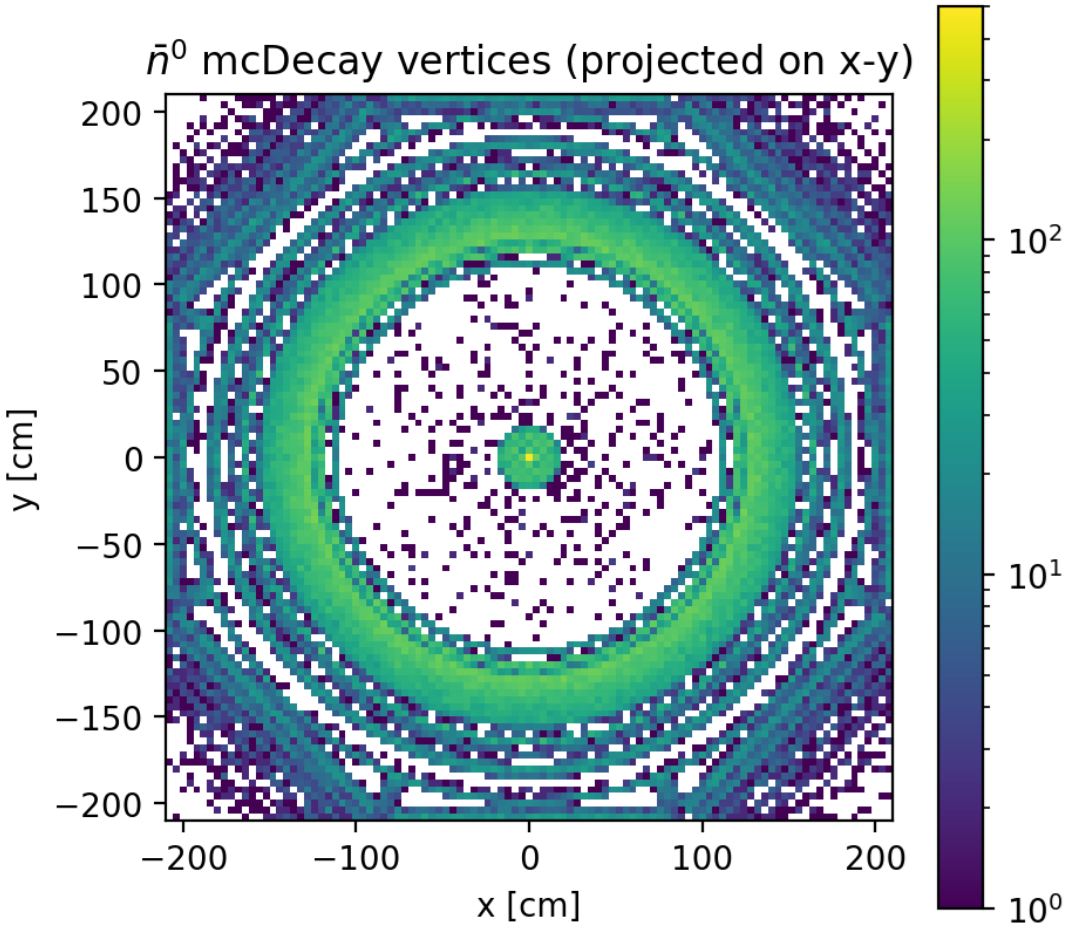
*Generated using “main” (last commit: Sat Nov 2 18:37:56 2024 +0100, globaltag: main_2024-07-19),
Default run-independent phase III conditions (i.e. expNum is 0)

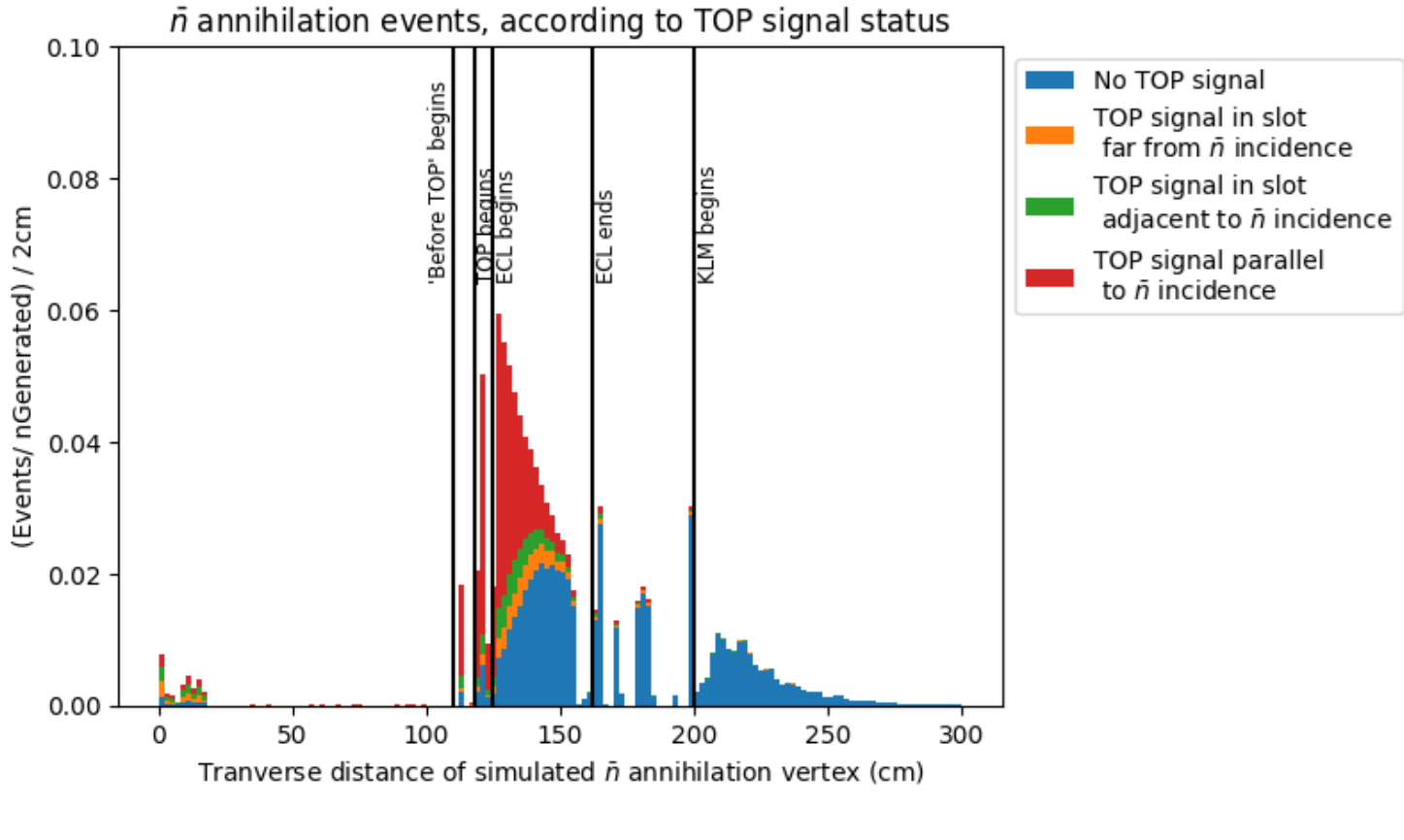
# DESIGN OF MC STUDY

- 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, $\theta$=92 and uniformly distributed $\phi \in [-\pi, \pi]$
  - **Also** place $\mu^+$ at origin with same dynamics (i.e. also $\theta$=92 with random $\phi$ ), 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%** |

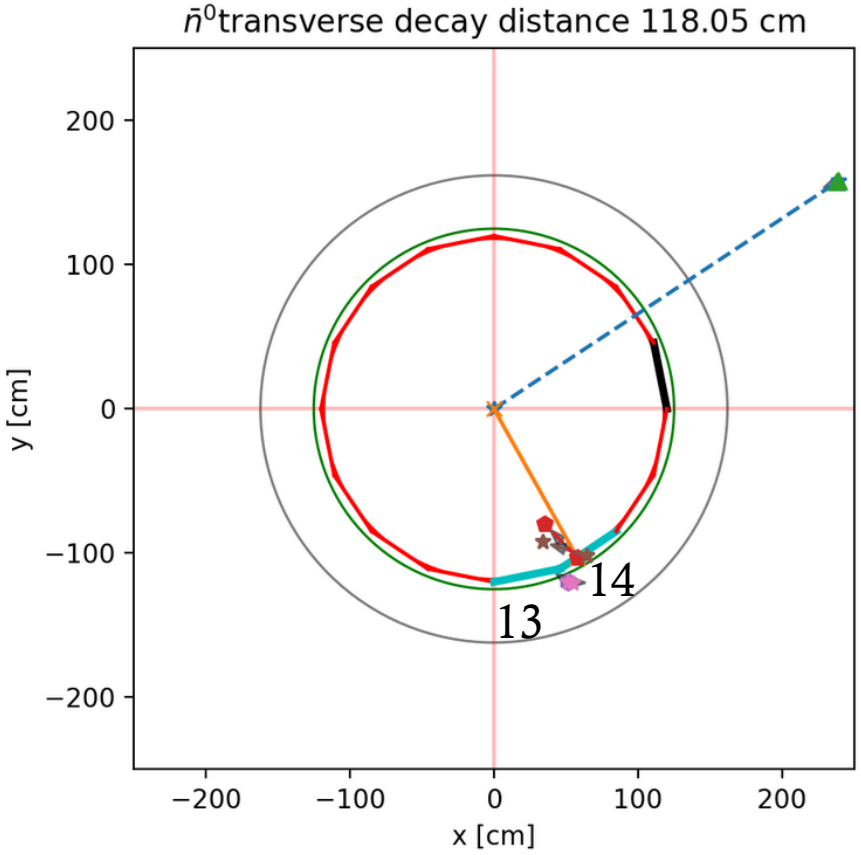
# WHERE ARE OUR ANTI-NEUTRONS ANNIHILATING?

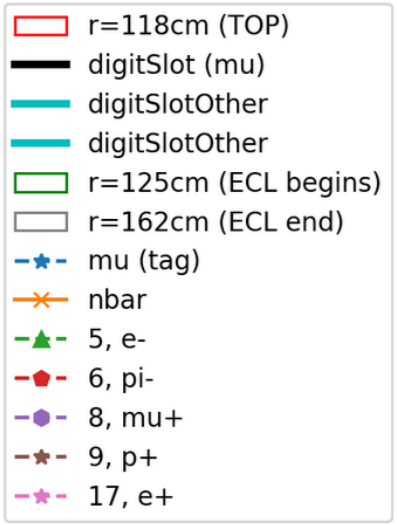


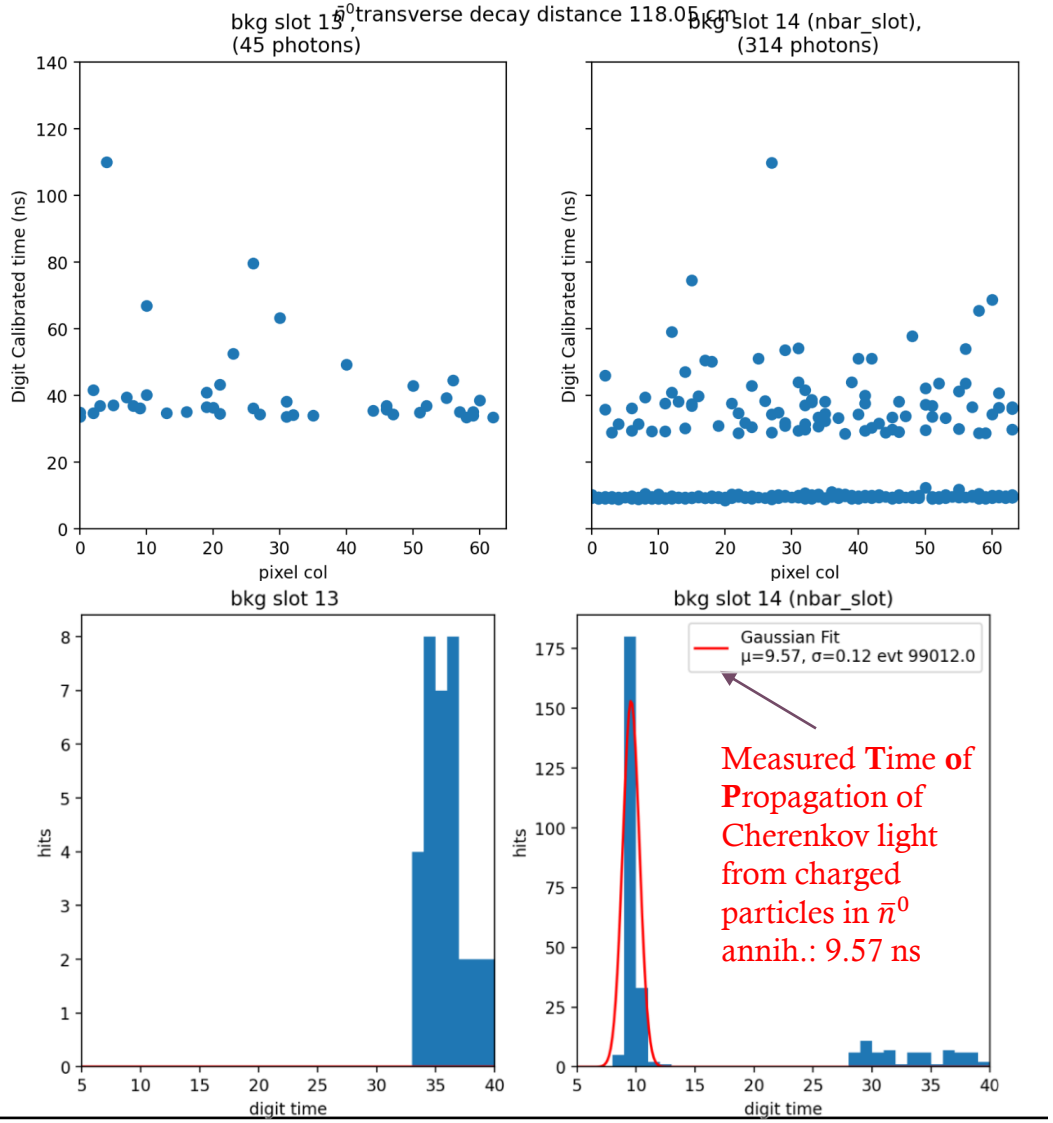



**TOP facts!** 16 TOP modules in Belle II. Each module has two rows of 16 PMTs, and each PMT has 4x4 channels → each module has 8 rows of 64 columns of channels (digits)

# 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?

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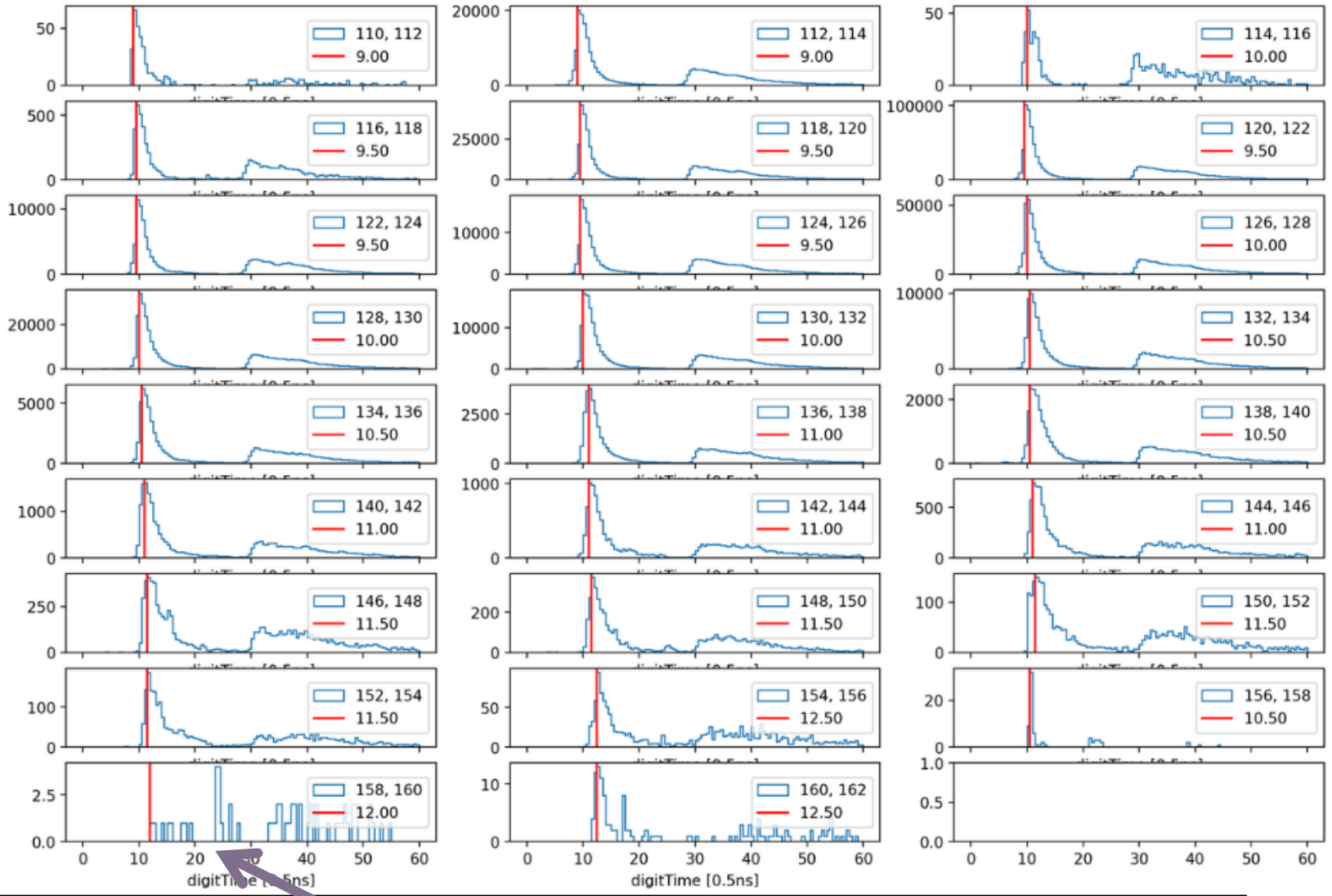


*TODO: improve peak finding algorithm!

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

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

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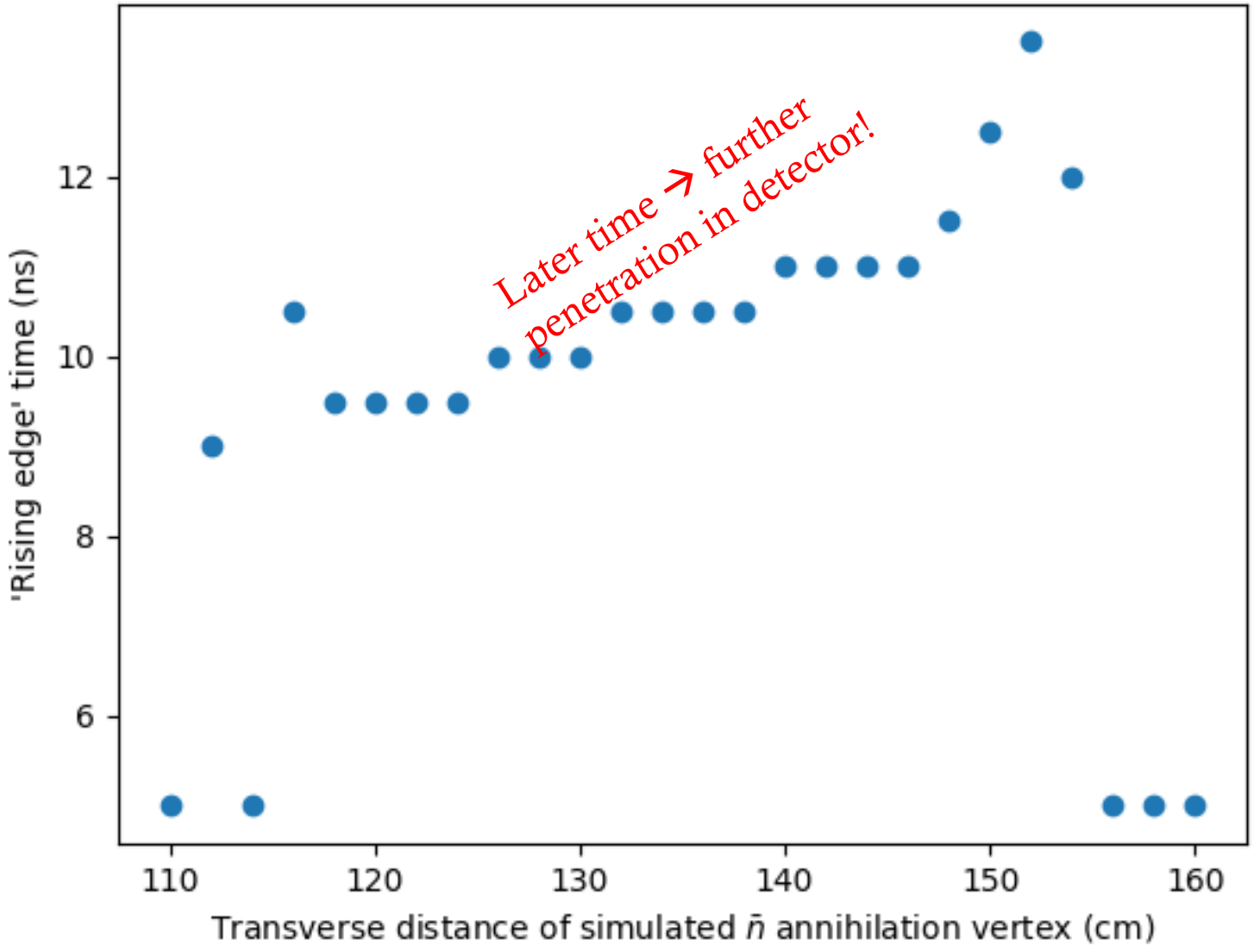

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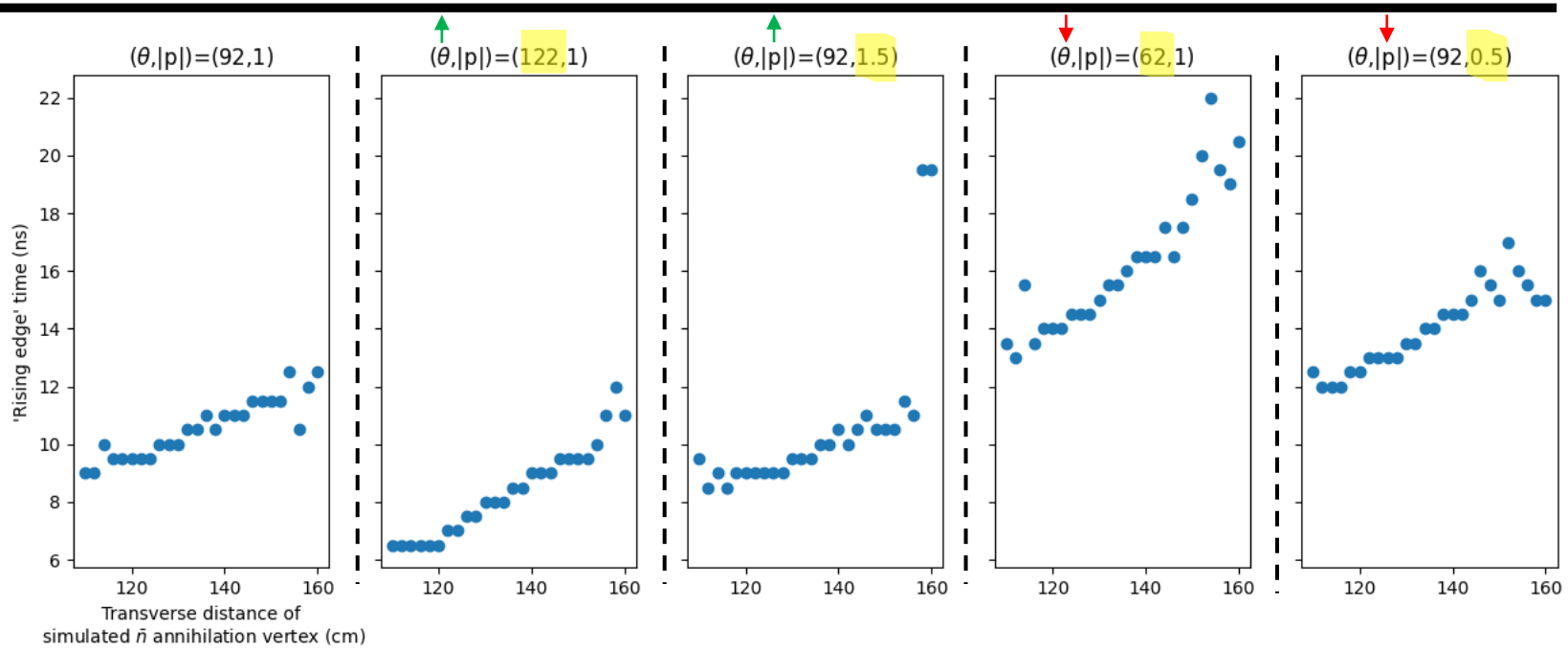


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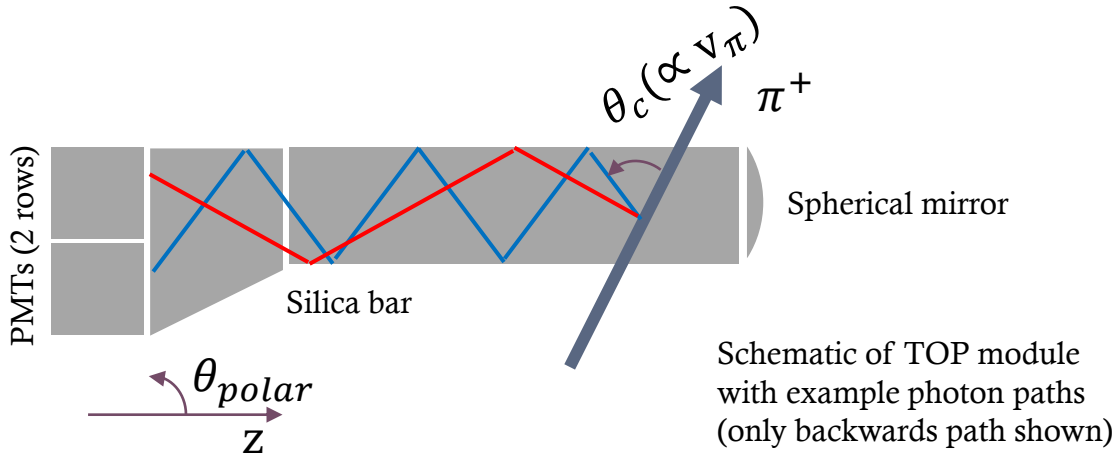


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