Weak mixing angle measurement and RICH testbeams

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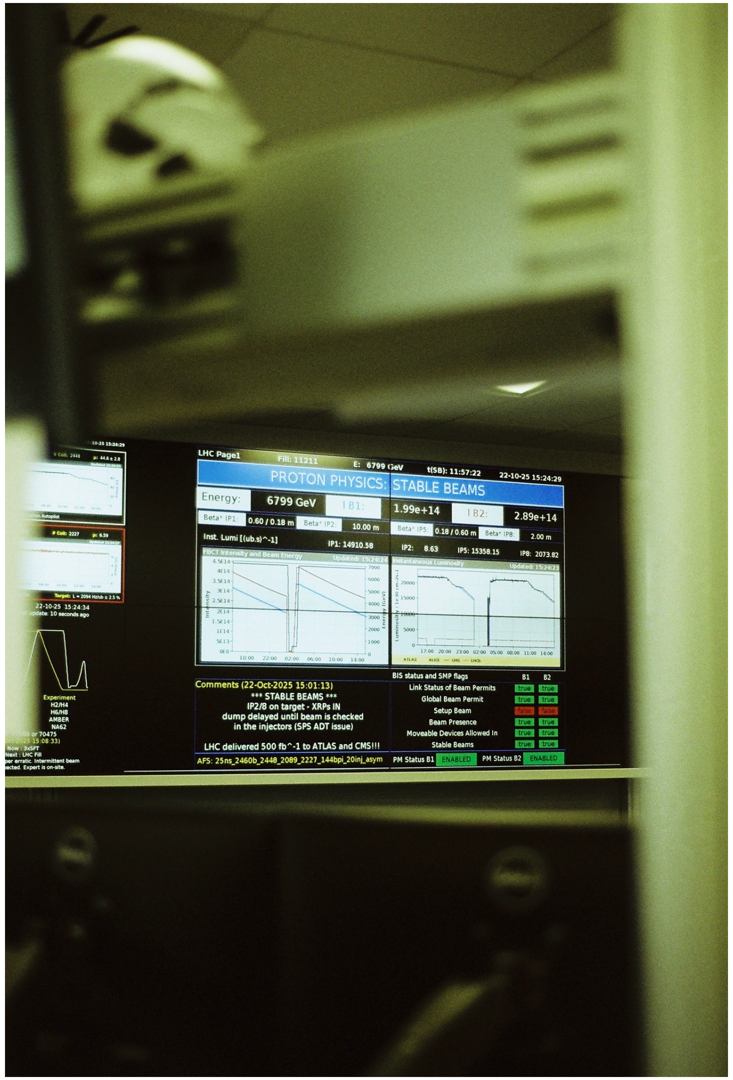
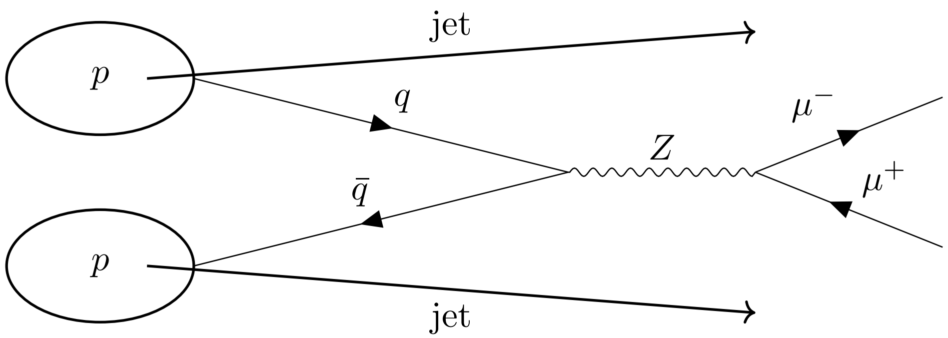
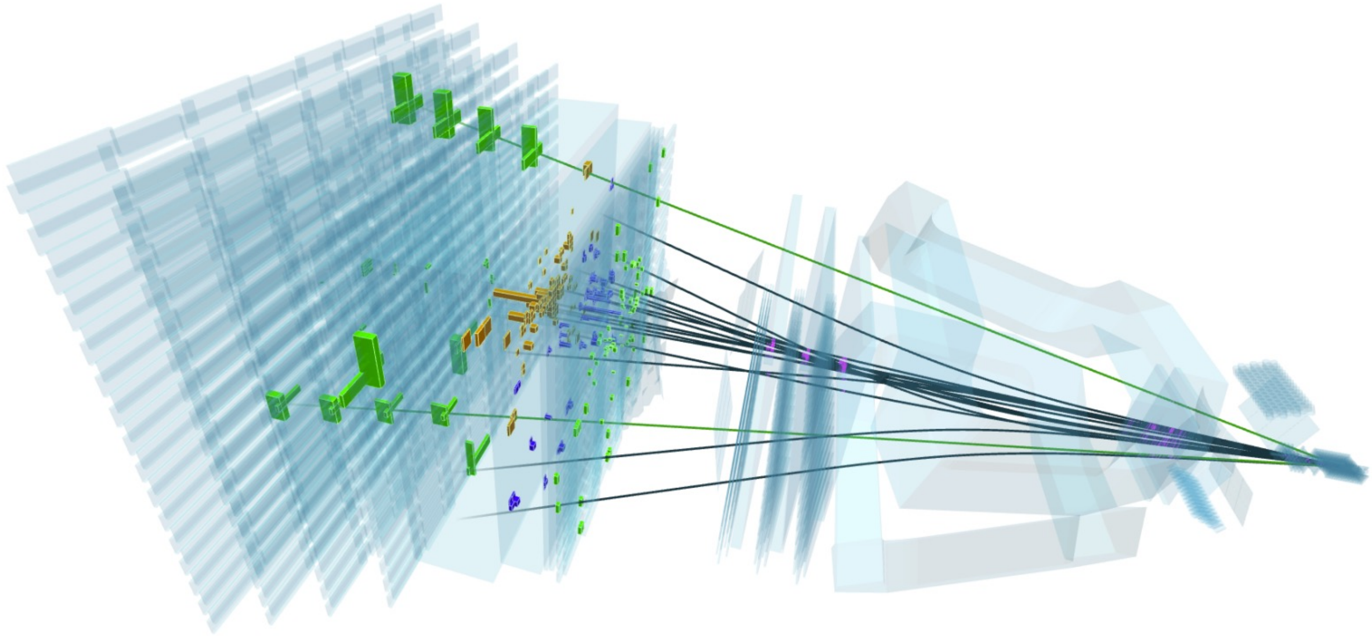
CERN Oct-Dec 2025



Analysis



‘Born Level’ diagram: $pp \to Z \to \mu^+\mu^-$



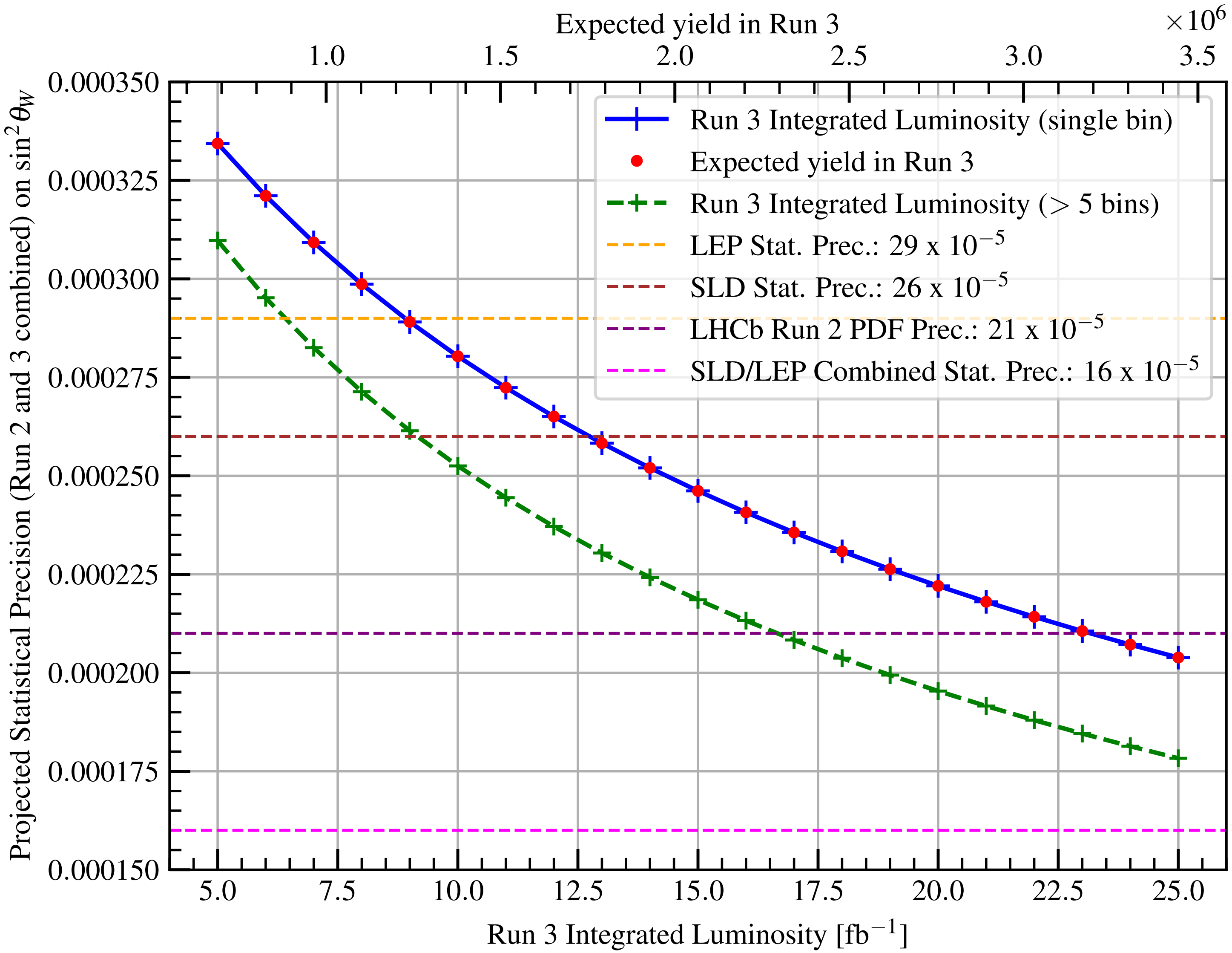
$Z \to \mu^+\mu^-$ event in LHCb, from Will

$$A_{FB} \Leftrightarrow \sin^2(\theta_w)$$

POWHEG Simulation and Statistical Precision

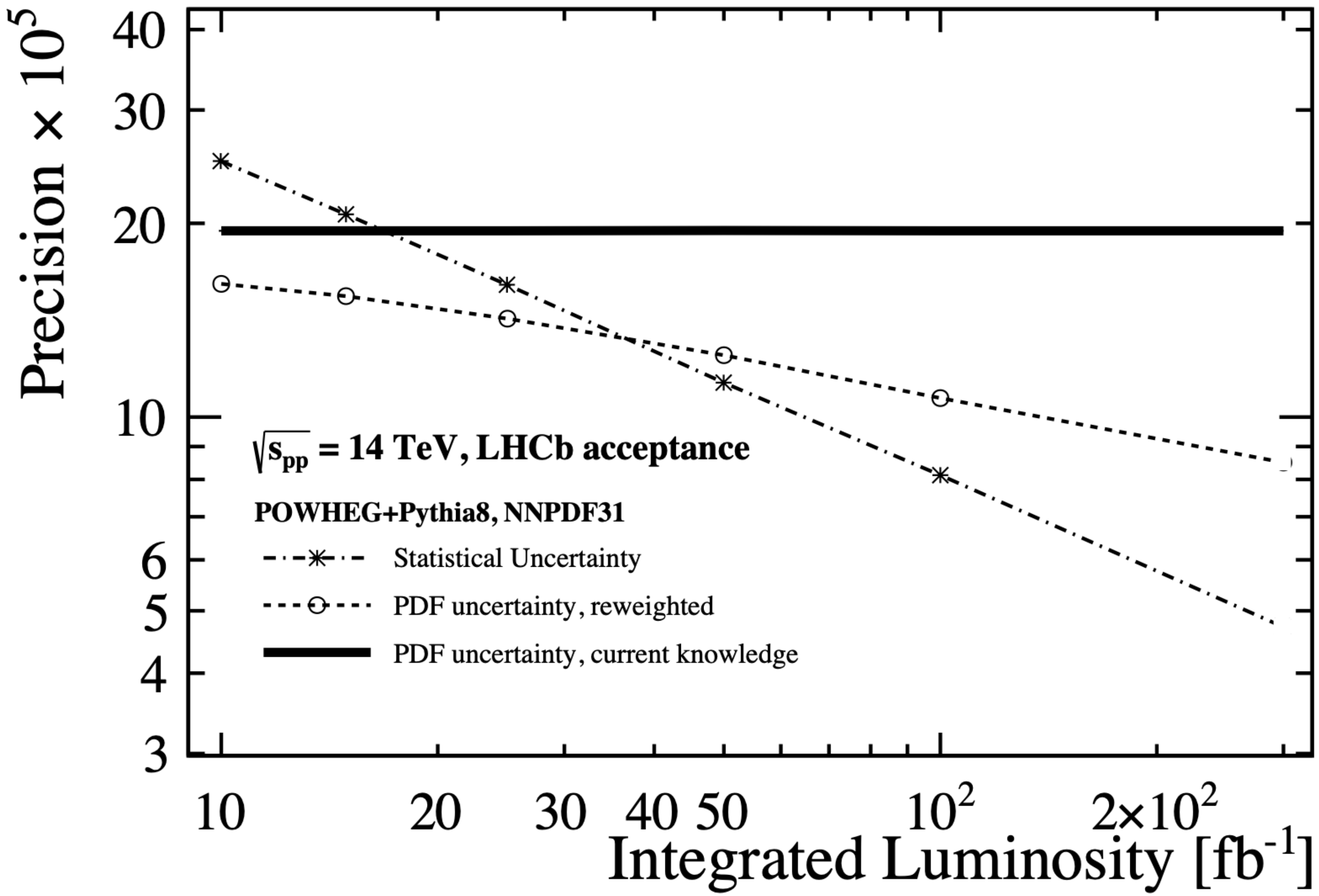
- POWHEG $\mathrm{pp} \rightarrow Z \rightarrow \mu^+\mu^-$ simulations with different values of $\sin^2(\theta_w)$
- LHCb acceptance cuts applied
- Expected events in LHCb then scaled using expected LHCb Run 3 integrated luminosity
- A_{FB} calculated as function of $|\Delta\eta|$ - binning in $|\Delta\eta|$ improves precision by around 15%
- Final expected Run 2+3 statistical precision from LHCb: 19×10^{-5}
- Combined with profiling, aim to achieve precision $< 30\times10^{-5}$, equivalent to best LEP/SLD measurements

Statistical Precision on $\sin^2\theta_W$, comparison



- Baseline statistical precision more powerful than, LHCb Run 2, LEP, and just less than SLD; roughly $\sqrt{21^2 + 19^2} * 10^{-5} = 0.00028$
- Potential to be a 'world best' measurement ***if***: PDF uncertainty reduced by profiling the PDFs
- Unlikely to beat SLD/LEP combination

Profiling improvement



Precision plot, from Figure 5 of [3]

- Might expect improvement from expected baseline precision of ~0.00028 to ~0.00023 if we assume profiling to reduce PDF uncertainty to ~0.00012 from [3]
- Further experimental uncertainties expected too, assume ~0.00005 from [2]

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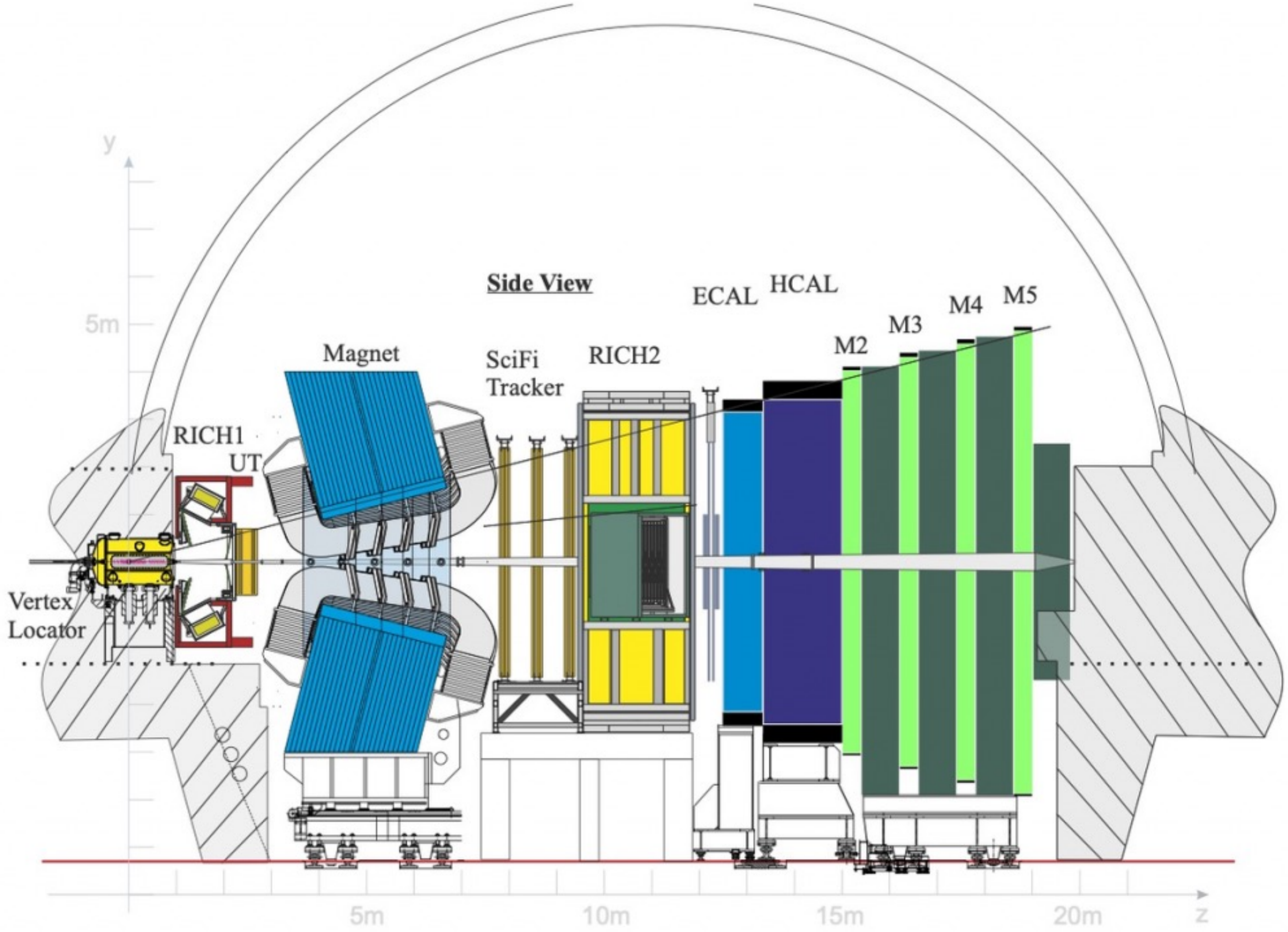
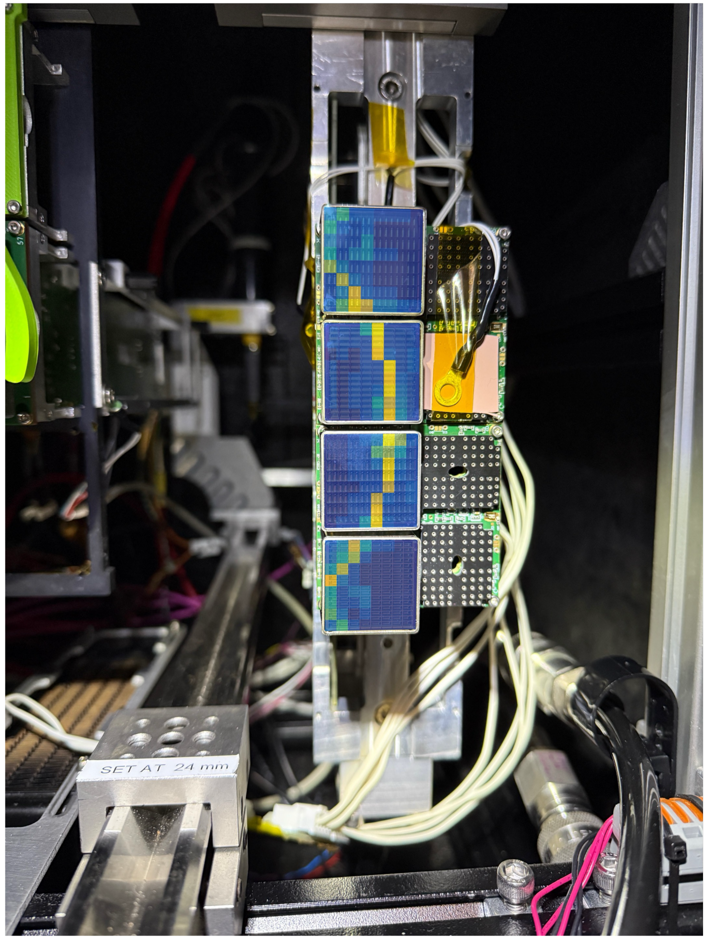
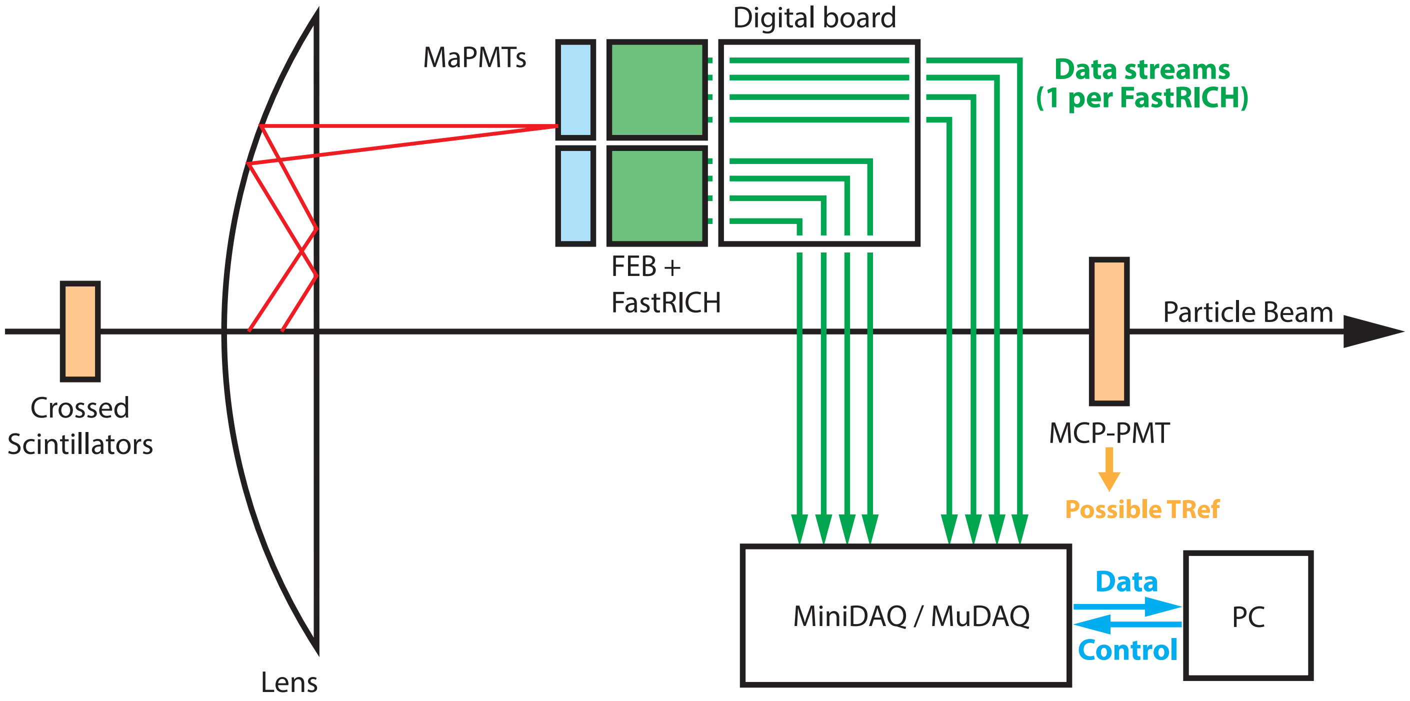
Hardware



Side View
y
5m
Magnet
SciFi
Tracker
RICH2
ECAL
HCAL
M2
M3
M4
M5
RICH1
UT
Vertex
Locator
5m
10m
15m
20m
z

Hardware

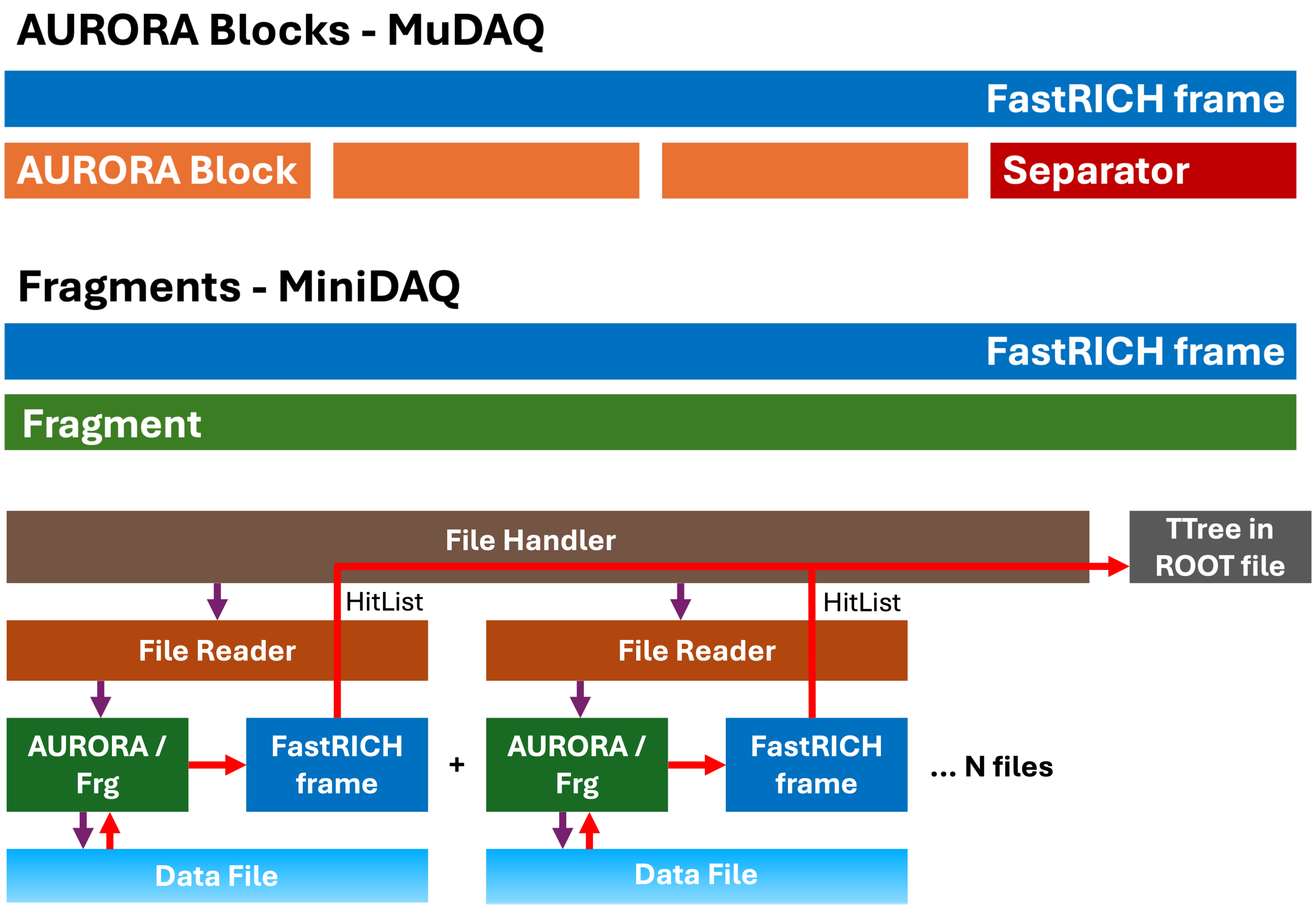




Superimposed ring and testbeam Diagrams, courtesy of Dan

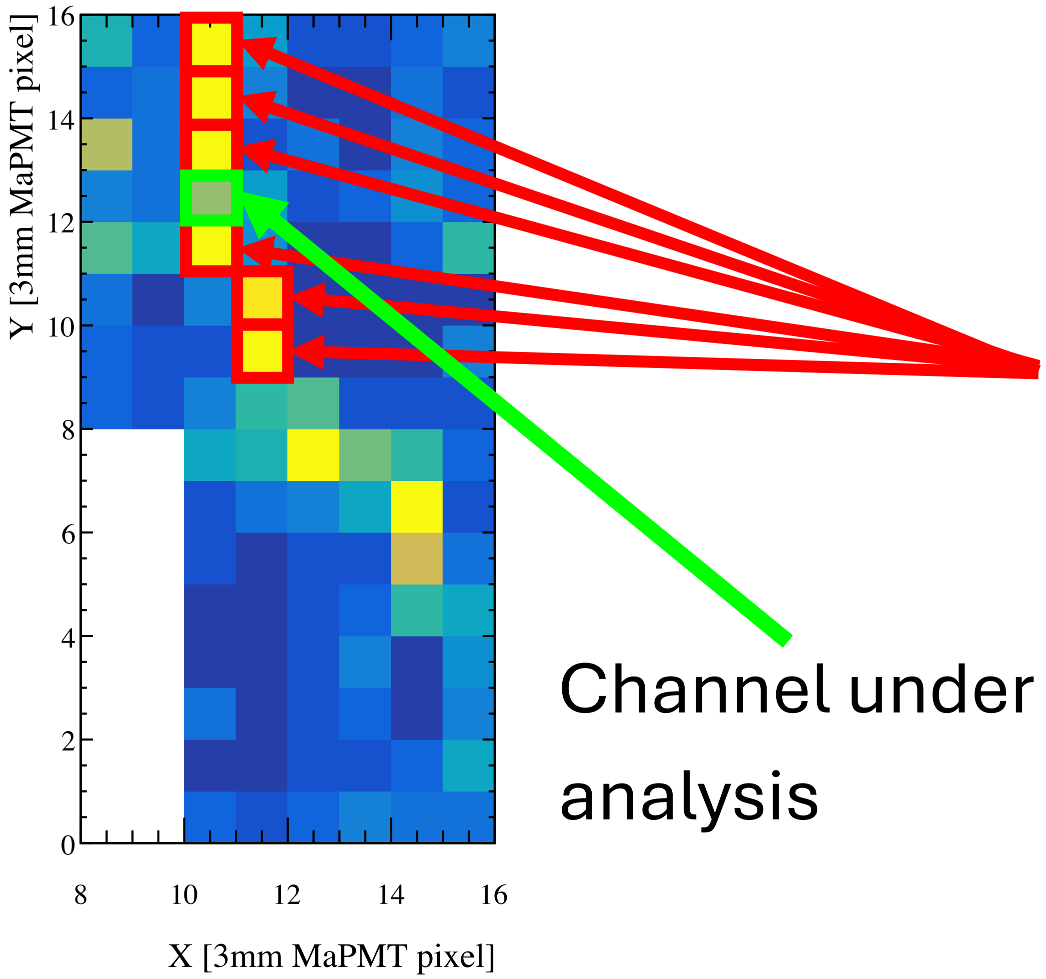
Decoding

- See oct-25-decoding branch of the GitLab repository
- Includes decoding of multiple FastRICHs in parallel for muDAQ and FastRICH and picoTDC data in parallel for miniDAQ into an intuitive Tree structure
- Includes a now widely used analysis class and event building based on BXID/trgNo
- Intricate structure to handle, also copes with data corruptions to help understand the full readout chain, and corrects BXID rollovers from FastRICH



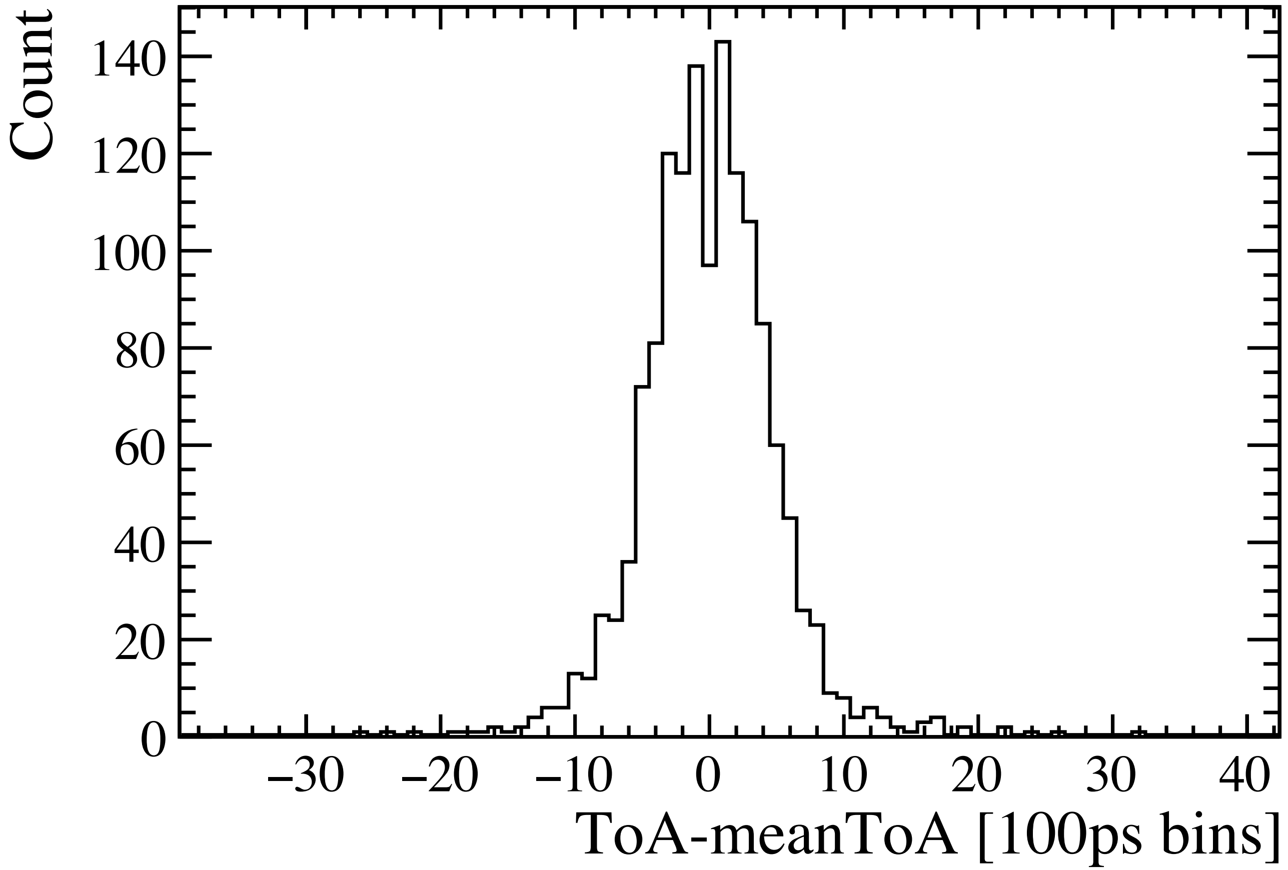
Decoding Structure, courtesy of Dan

Cherenkov ring as a time reference - muDAQ



- Without synchronized picoTDC data there is no external time reference available
- Time reference constructed from the mean time of arrival of all other photons in an event
- ToA is then measured with respect to this time reference

Relative timing

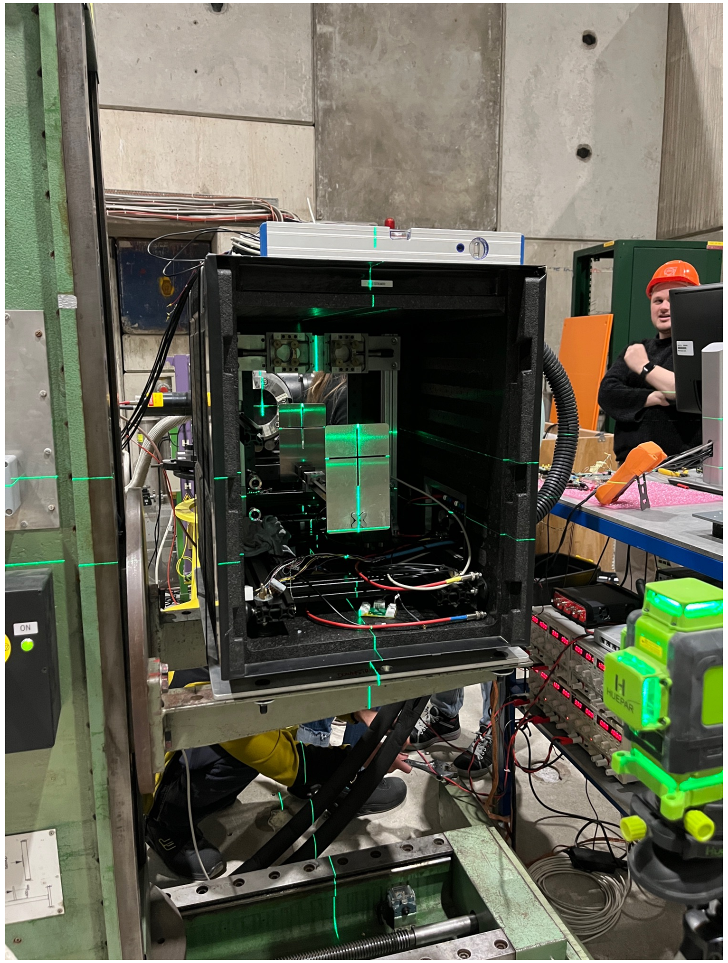


- When combining ToAs measured with respect to time references constructed from all event sizes, a lower bound for the time resolution, can be extracted from the fit:

$$\sigma_{MaPMT} \geq \frac{1}{\sqrt{2}} \sigma_{Fit}$$

- Selecting only one channel as a reference allows for more accurate measurement whilst sacrificing statistics

SPS installation

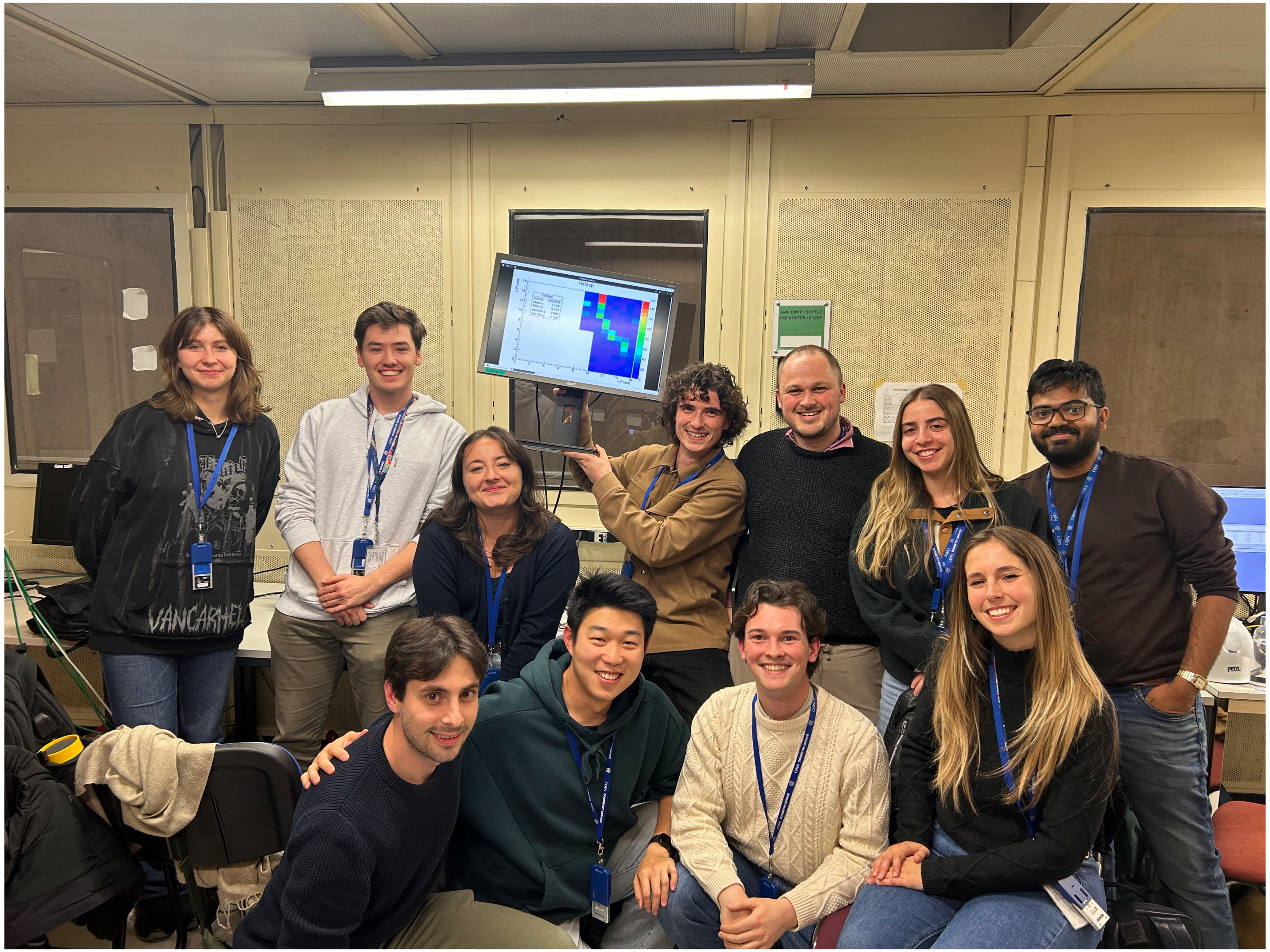


PS installation

Next Steps

- Short term:
  - Getting Run 3 analysis without profiling up and running
  - Analysing LAPPD timing data
  - Maintaining decoding and analysis repository for (4!) testbeams next year
  - Helping with LAPPD paper being prepared now
- Longer term:
  - FastRICH and HRPPD papers are anticipated
  - Work for RICH TDR
  - Incorporate profiling into Run 3 analysis

First FastRICH readout Ring at the SPS



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References

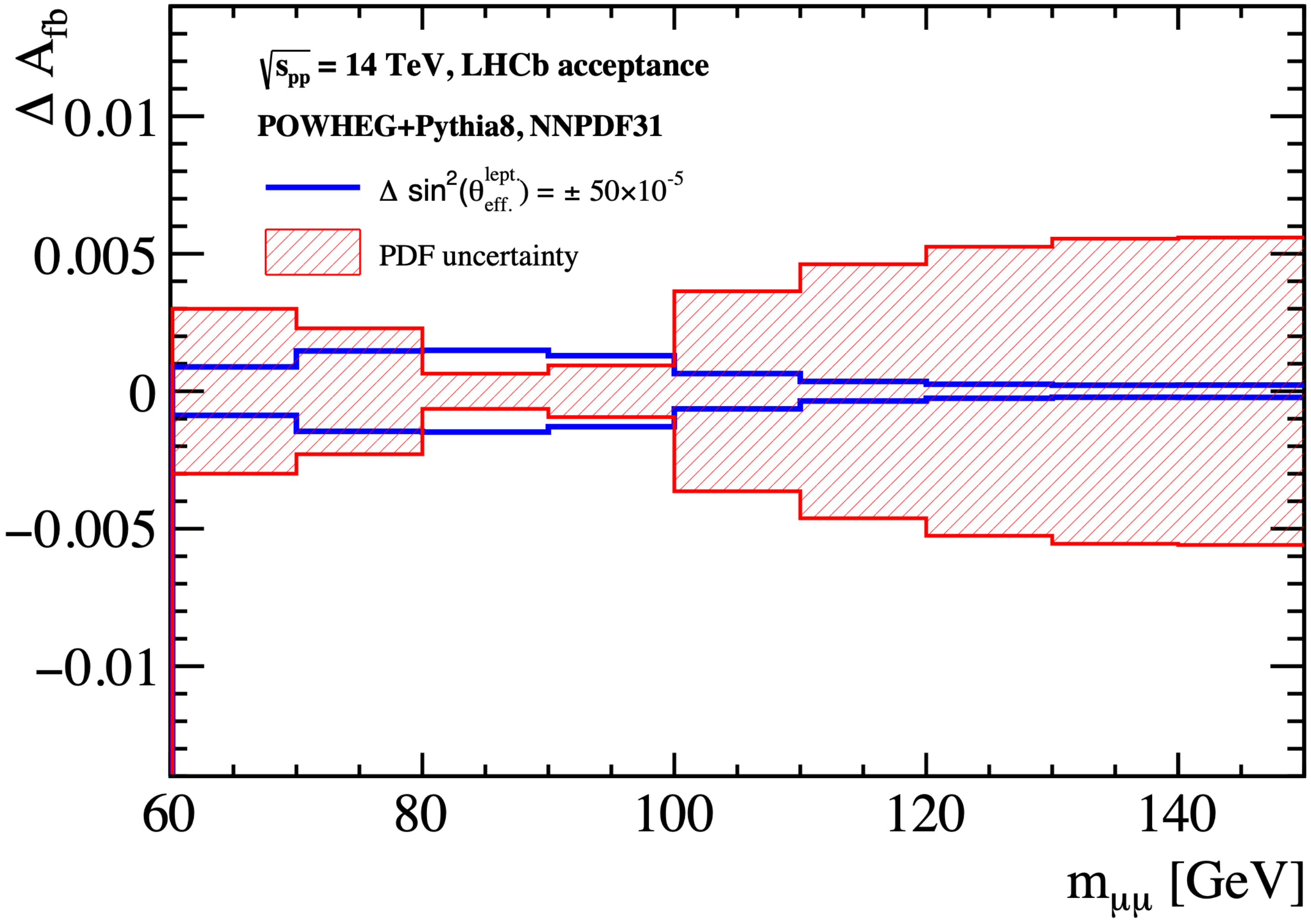
- [1]: Measurement of vector boson production cross sections and their ratios using pp collisions at $\sqrt{s}=13.6$ TeV with the ATLAS detector, https://arxiv.org/abs/2403.12902
- [2]: Measurement of the effective leptonic weak mixing angle, https://arxiv.org/abs/2410.02502
- [3]: Prospects for measurement of the weak mixing angle at LHCb, https://cds.cern.ch/record/2647836/files/LHCb-PUB-2018-013.pdf
- [4]: https://lblogbook.cern.ch/RICH+Testbeam/

Conclusions - Backup

New VELO acceptance change: $2 < \eta < 4.3$

- Run 3 simulated $\sin^2(\theta_w)$ expected statistical precisions:
  - 'Worst case', Run 3 single bin and binned Run 2 statistical precision: ~ 0.00023
  - 'Baseline', Run 3 binned and binned Run 2 statistical precision: ~ 0.00021
- Baseline projected precision with unprofiled PDFs: $\sim 0.00029 \ \rightarrow$ beats Run 2, similar to LEP
- Projected precision with profiling: $\sim 0.00024 \ \rightarrow$ Potential 'world best' measurement
- Next step is to implement the Run 3 baseline analysis

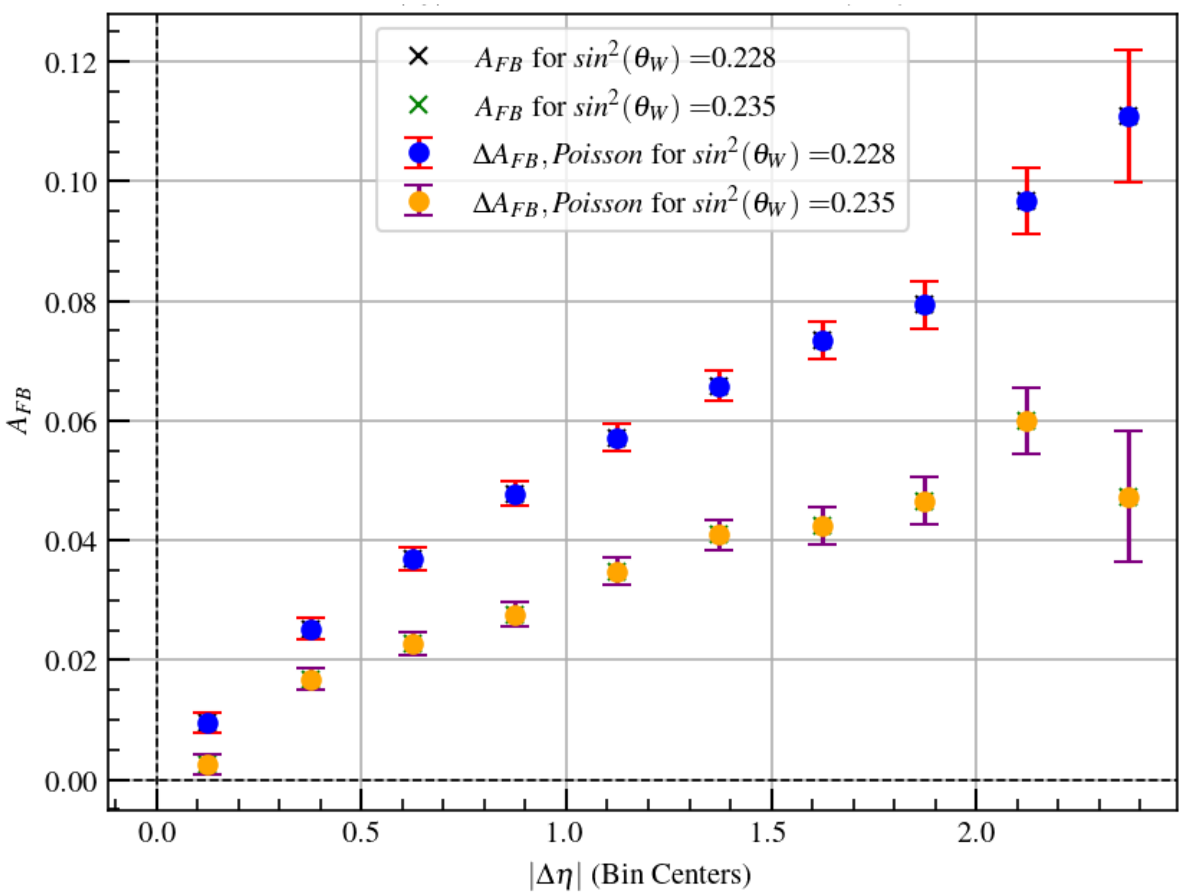
Profiling - Backup

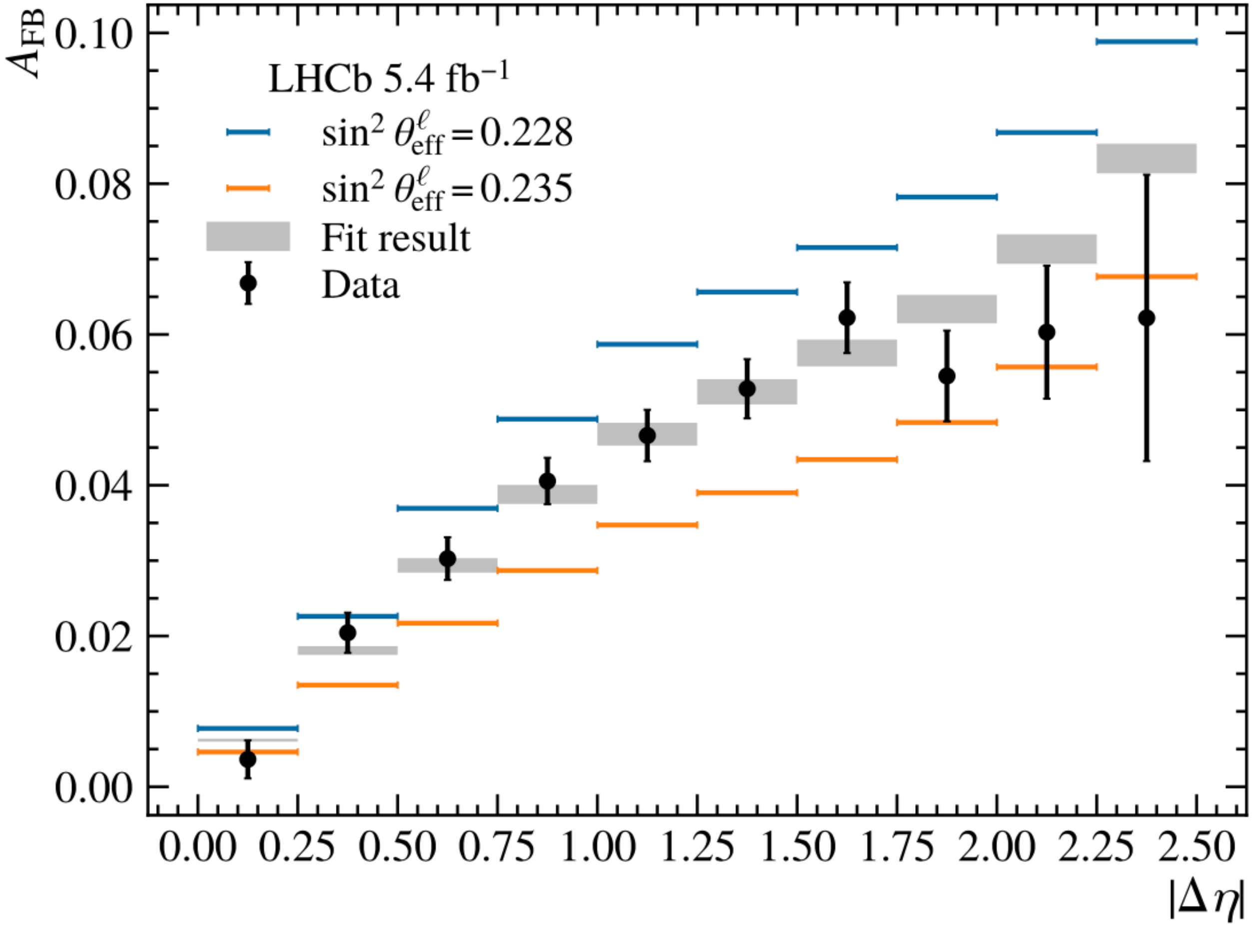


PDF Uncertainty plot, from Figure 4 of [3]

- Profiling allows us to "downweight" PDFs that don't describe the data well, reducing the PDF uncertainty
- Parts of the distribution that weakly constrain $\sin^2(\theta_w)$ can be used to constrain the PDFs

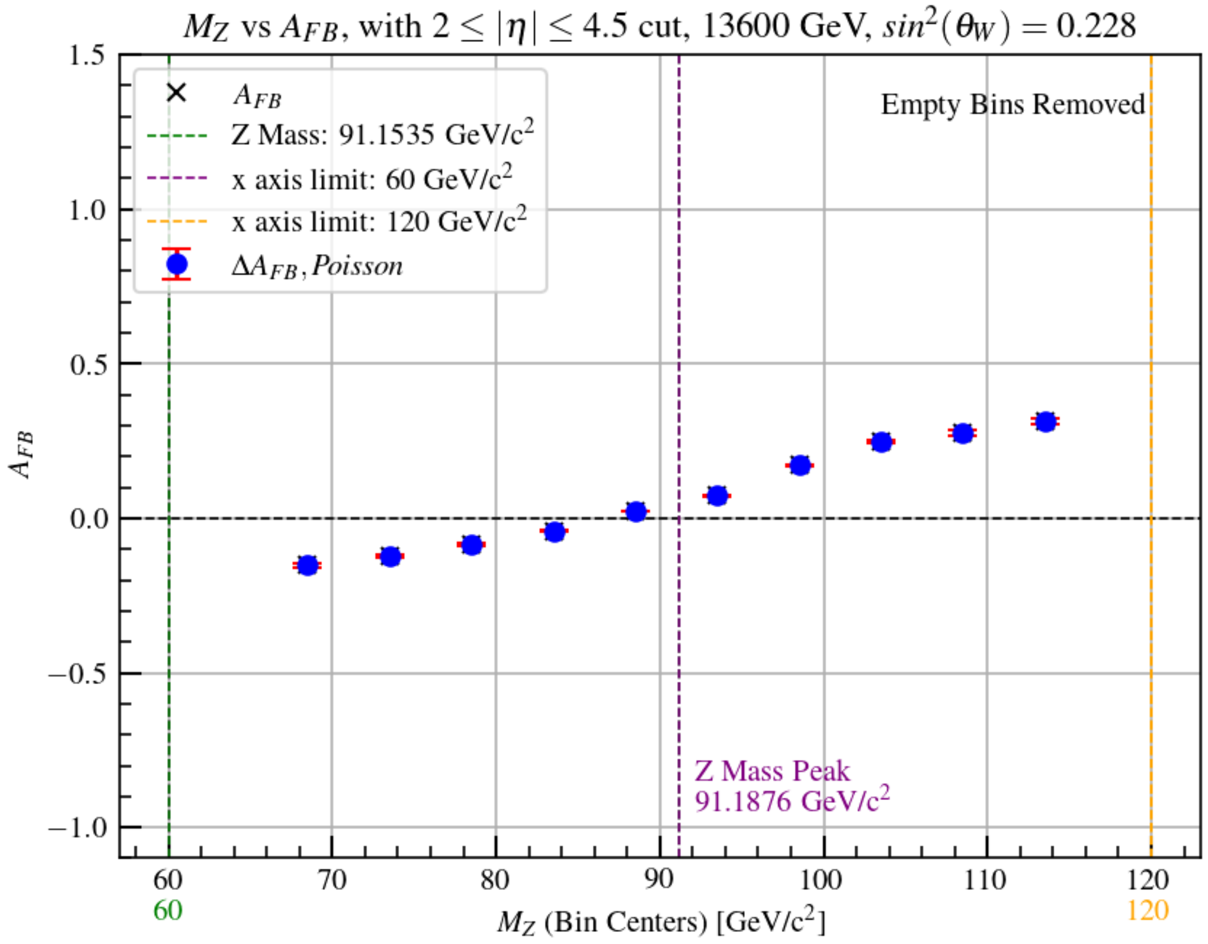
ΔA_{FB} 13Tev - Backup

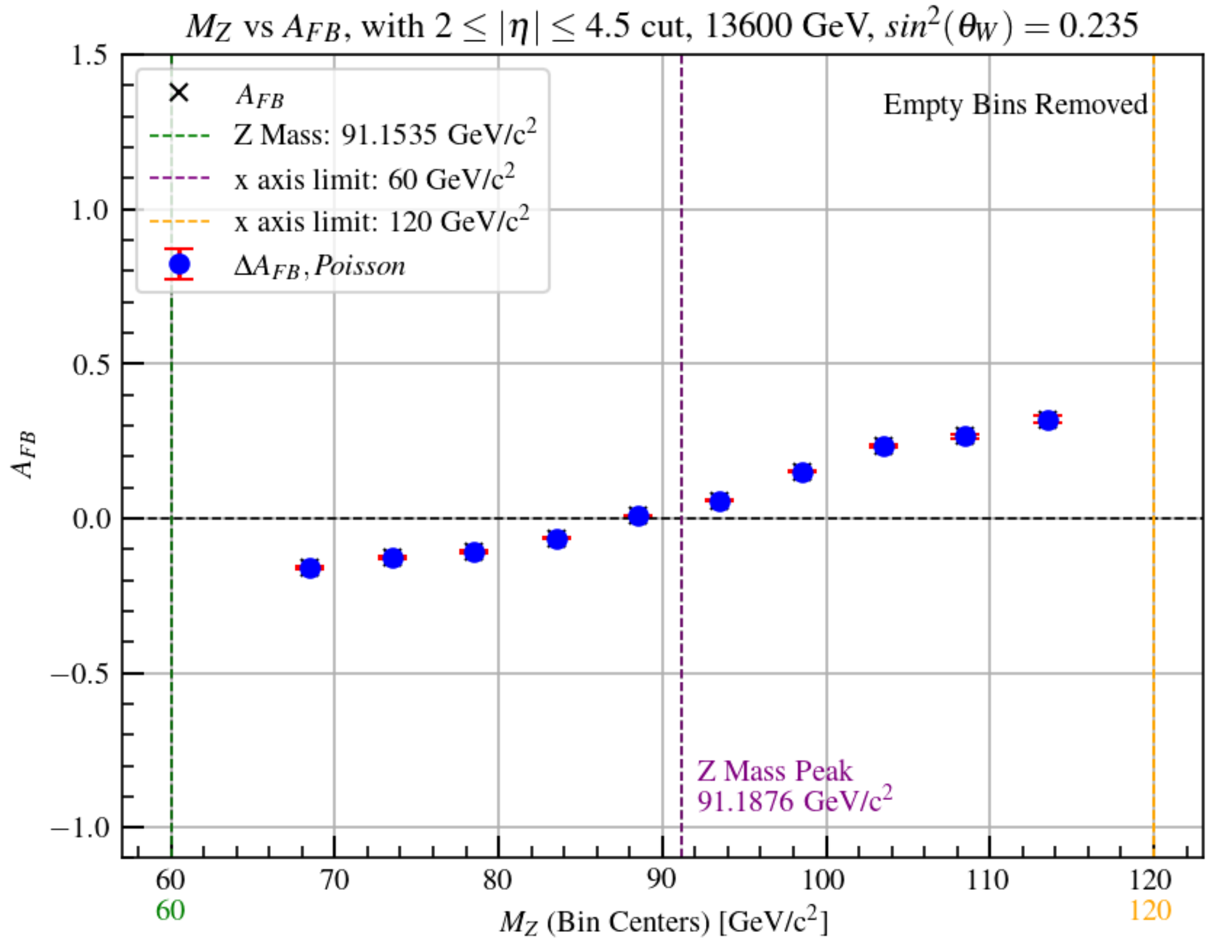




A_{FB} plot, from Figure 4 of [2]

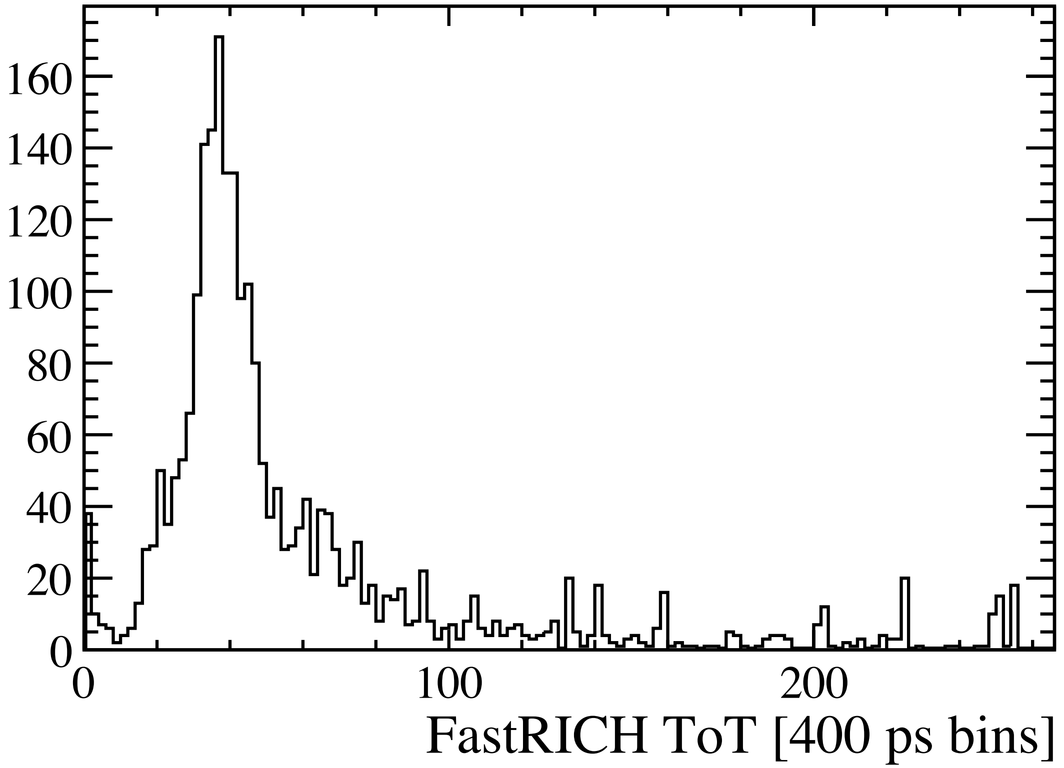
V_M vs A_{FB} simulation examples - Backup

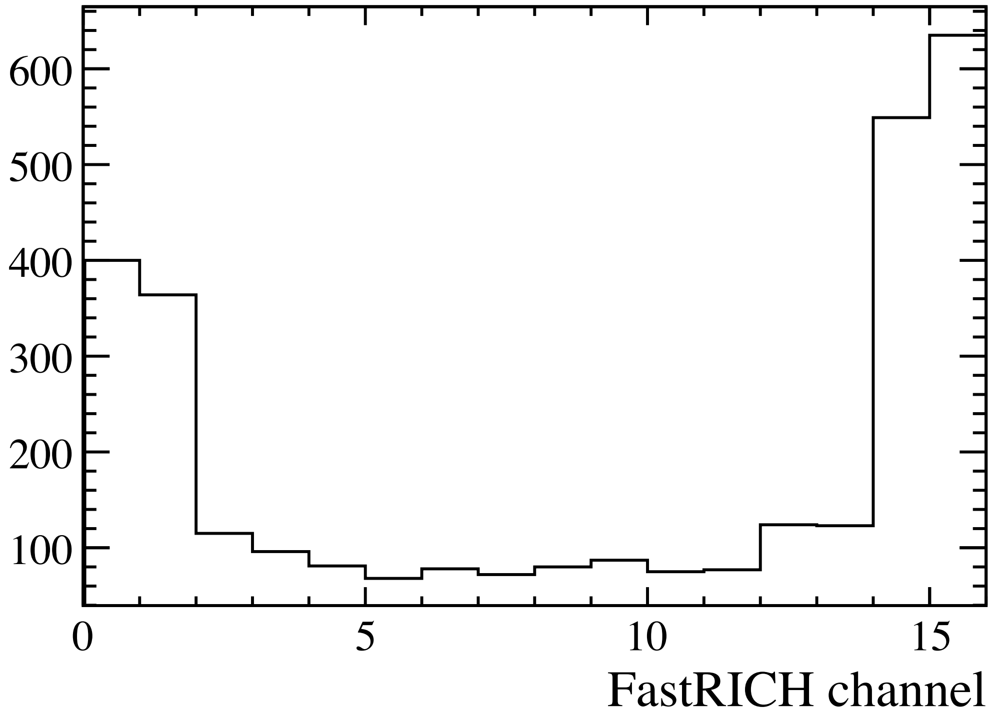




First decoding of muDAQ FastRICH Data - Backup

- First decoded FastRICH data with muDAQ using two ECR's with two FEBs! First data taking with photon detector; laser illumination at low repetition rate (20kHz).
- LHS, ToT plot shown; seem consistent across streams. Threshold P+9
- RHS, Channel occupancy plot showing we can read across all channels

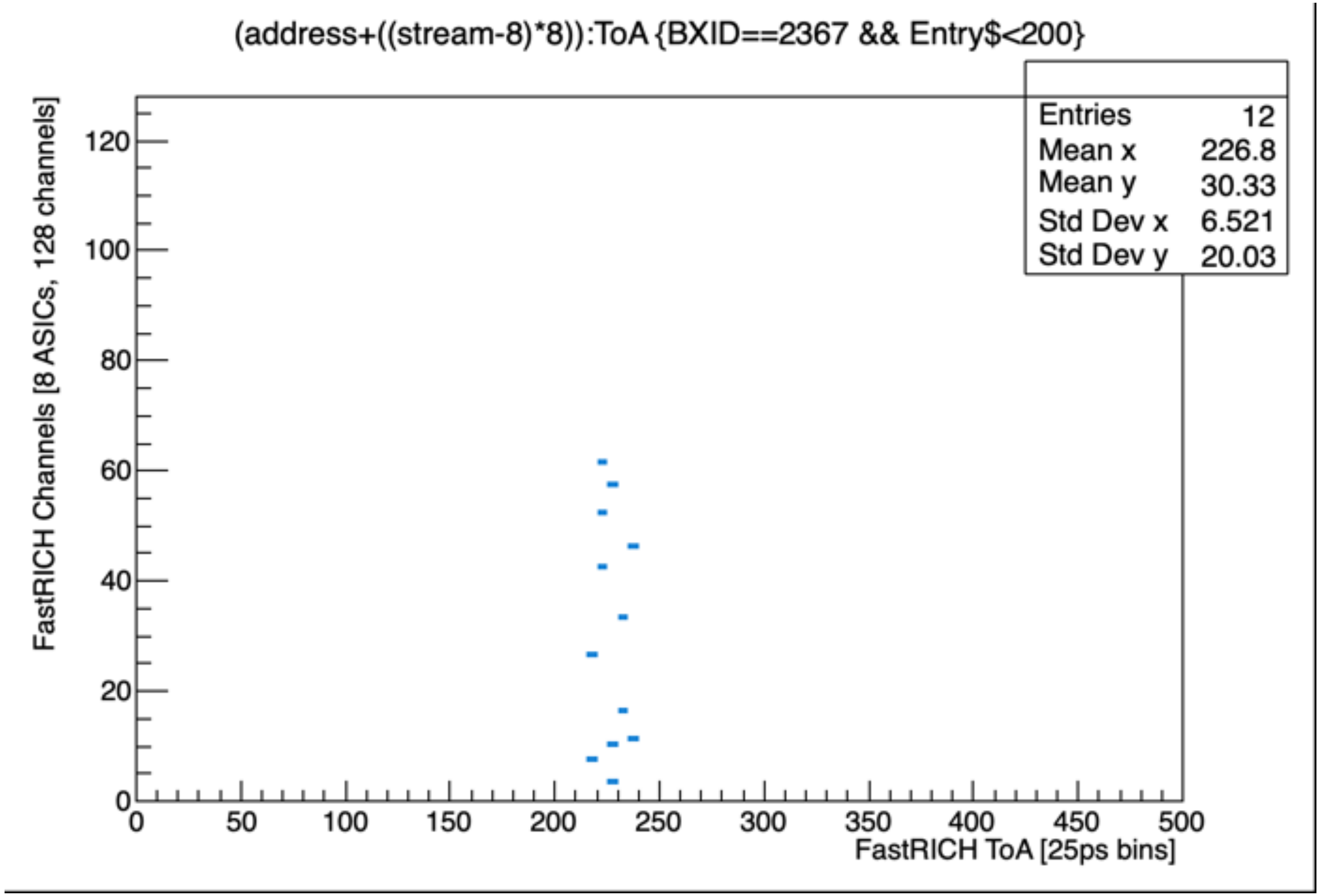




https://lblogbook.cern.ch/RICH+Testbeam/1018

First decoding of multiple muDAQ FastRICH Streams

- First full decoding script that loops through multiple MuDAQ FastRICH streams.
- ToA plot for multiple FastRICH hits with the same BXID correlated across multiple ASICs. Note: FastRICH channels -> FastRICH channel IDs (across 8 FastRICHs). Also in this mode the FastRICH bin width is 100ps NOT 25ps. As it is in LED threshold mode, stdDevX includes time walk.
- Most importantly this earned us all croissants from Carmelo



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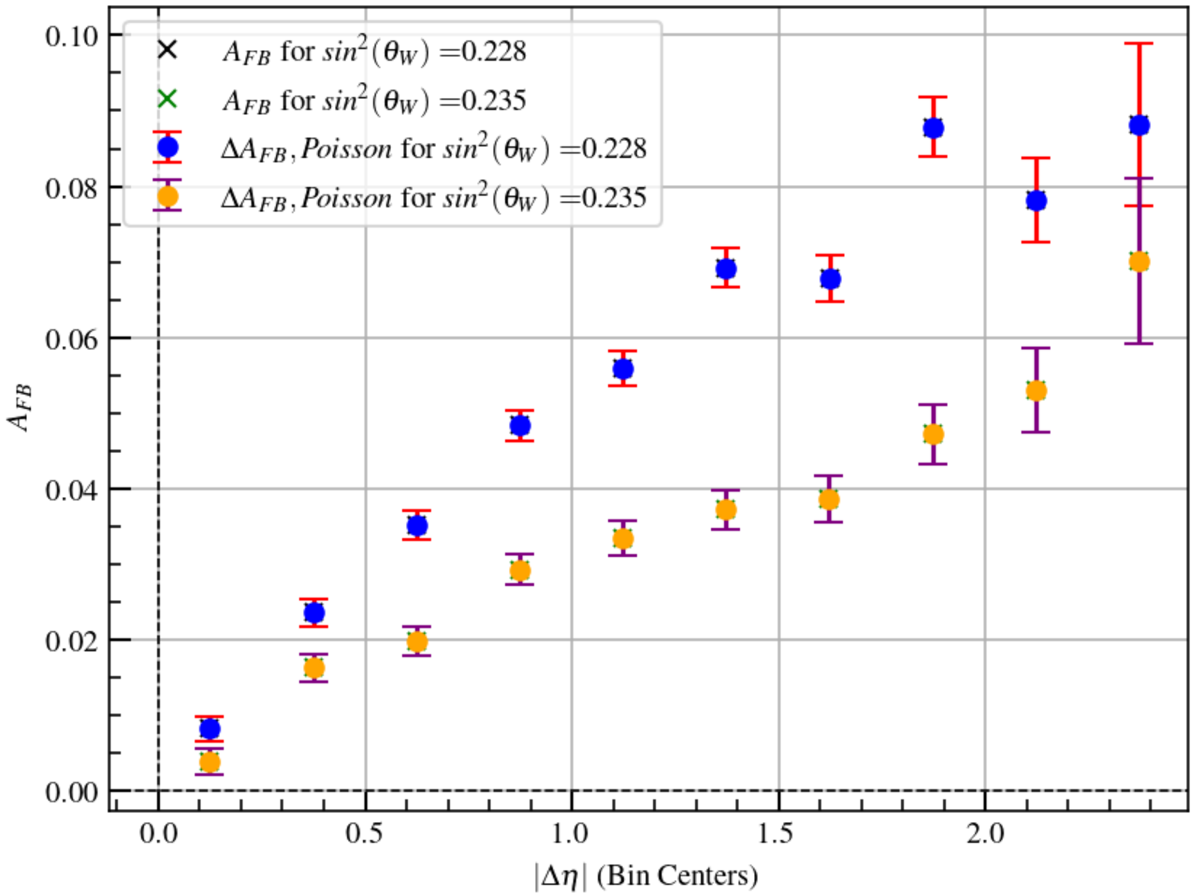
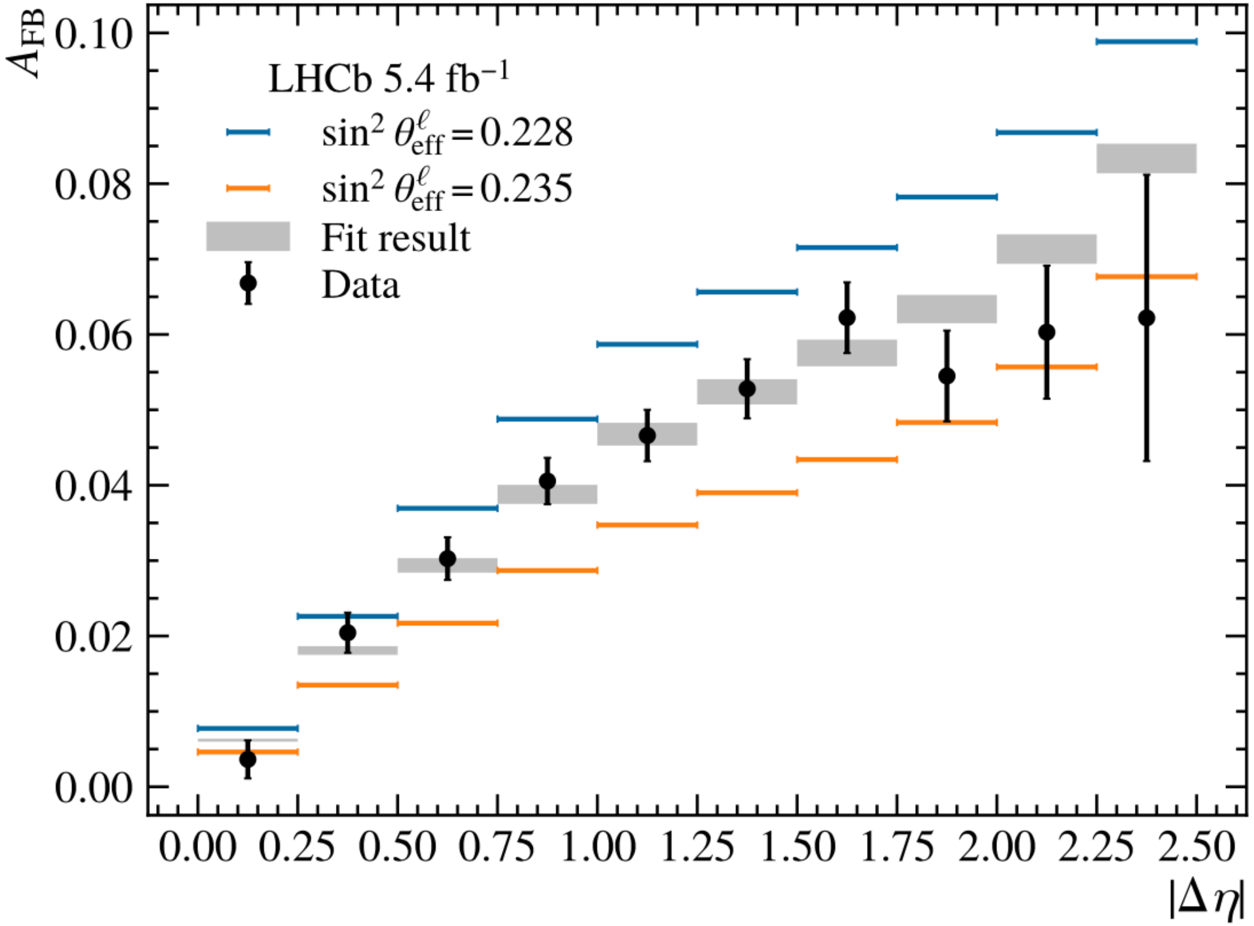
Timing without external reference – Backup

- The average time resolution of hits in an event of N channels, $\sigma_{Average}$ is the quadrature sum of the true FastRICH resolution, σ_{MaPMT} and the fit resolution, σ_{Fit}. Hence:
- $(\sigma_{MaPMT})^2 = (\sigma_{Fit})^2 - (\sigma_{Average})^2$
- For a channel wrt. to the average of all other channels: $(\sigma_{Average})^2 = \frac{(\sigma_{MaPMT})^2}{N-1}$
- $(\sigma_{MaPMT})^2 = (\sigma_{Fit})^2 - \frac{(\sigma_{MaPMT})^2}{N-1}$
- $(\sigma_{MaPMT})^2(N-1) = (N-1)(\sigma_{Fit})^2 - (\sigma_{MaPMT})^2$
- $\sigma_{MaPMT} = \sqrt{\frac{(N-1)(\sigma_{Fit})^2}{N}} = \sqrt{\frac{(N-1)}{N}}\sigma_{Fit}$
- This is the best possible resolution with this time reference, so a lower bound, necessarily excluding events with less than $N = 2$:

$$\sigma_{MaPMT} \geq \sqrt{\frac{1}{2}}\sigma_{Fit}$$

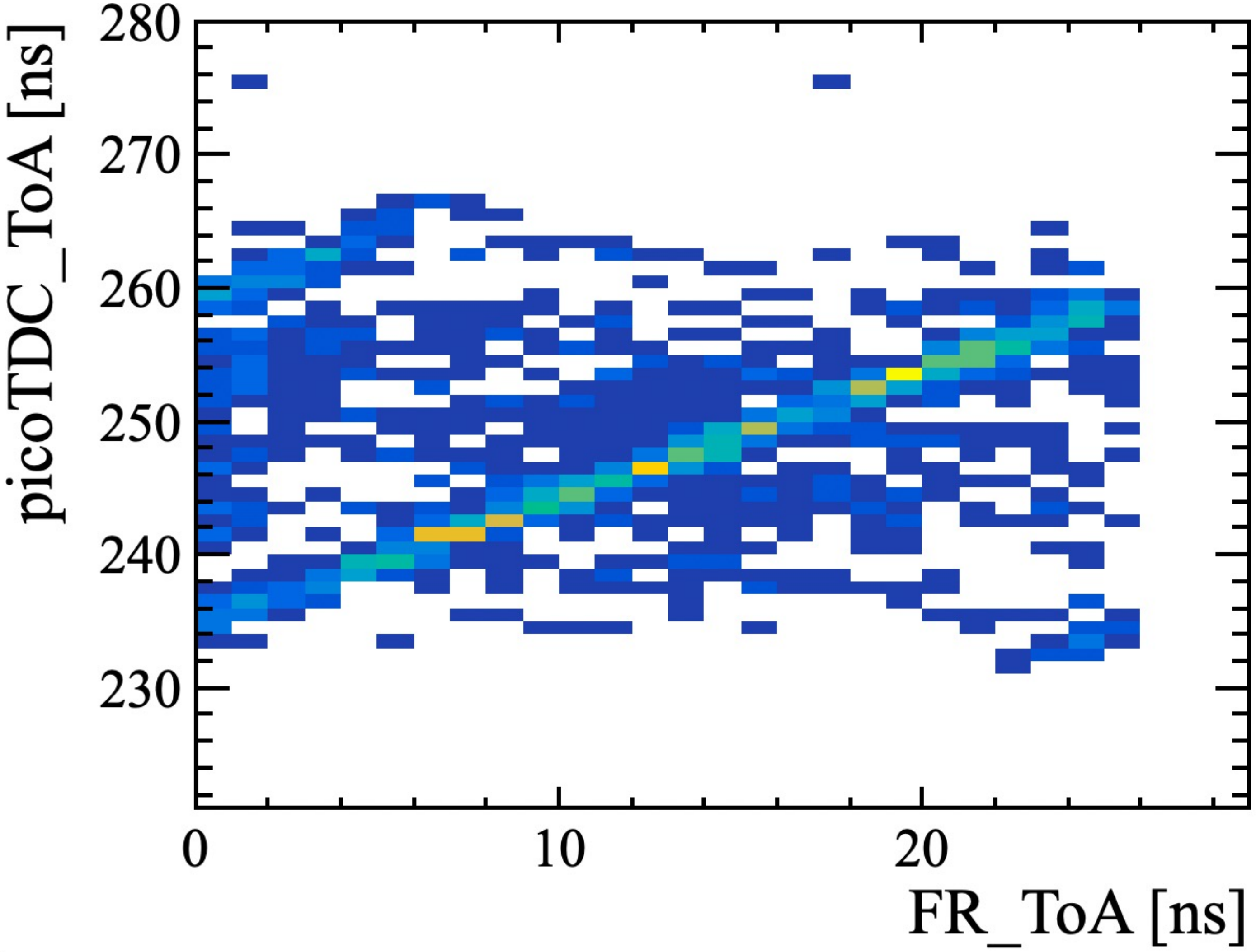
ΔA_{FB} for $\sin^2\theta_W = 0.228, 0.235$ - Backup





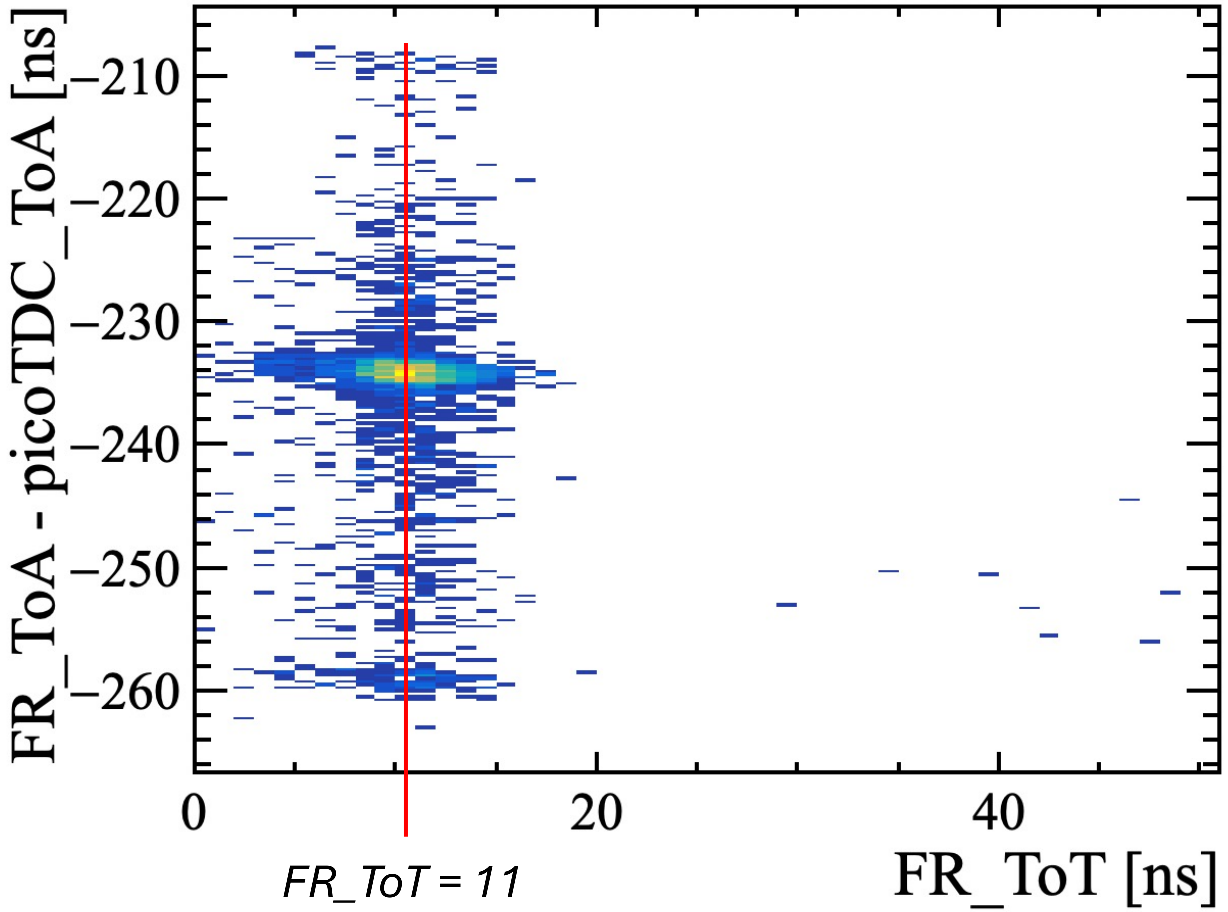
A_{FB} plot, from Figure 4 of [2]

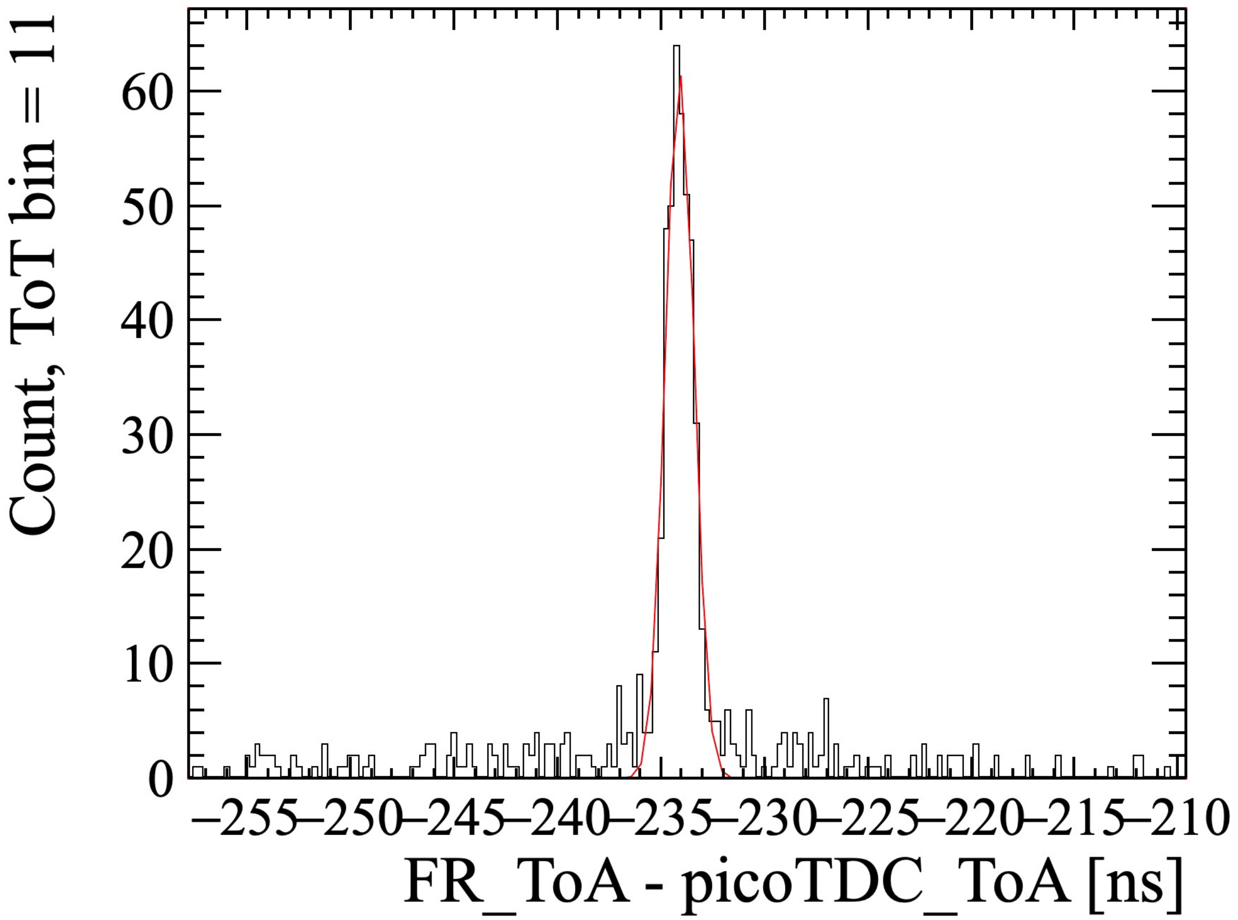
Preliminary time resolution MiniDAQ - Backup



- Events across FastRICH and picoTDC are correlated and aligned via the trgNo
- Timing analysis for picoTDC done in: *fastrich_analysis/src/**picoTDCreference.cxx***
- New Event Building with trgNo rather than BXID – ELOG 1159
- Time reference takes the mean ToA for a FastRICH event (multiple hits average), and subtracts the ToA from picoTDC ToA
- Run 2981: 9870 triggers, LED p+90, ToT enabled, Gating disabled, Some FastRICHes missing

Preliminary time resolution MiniDAQ - Backup

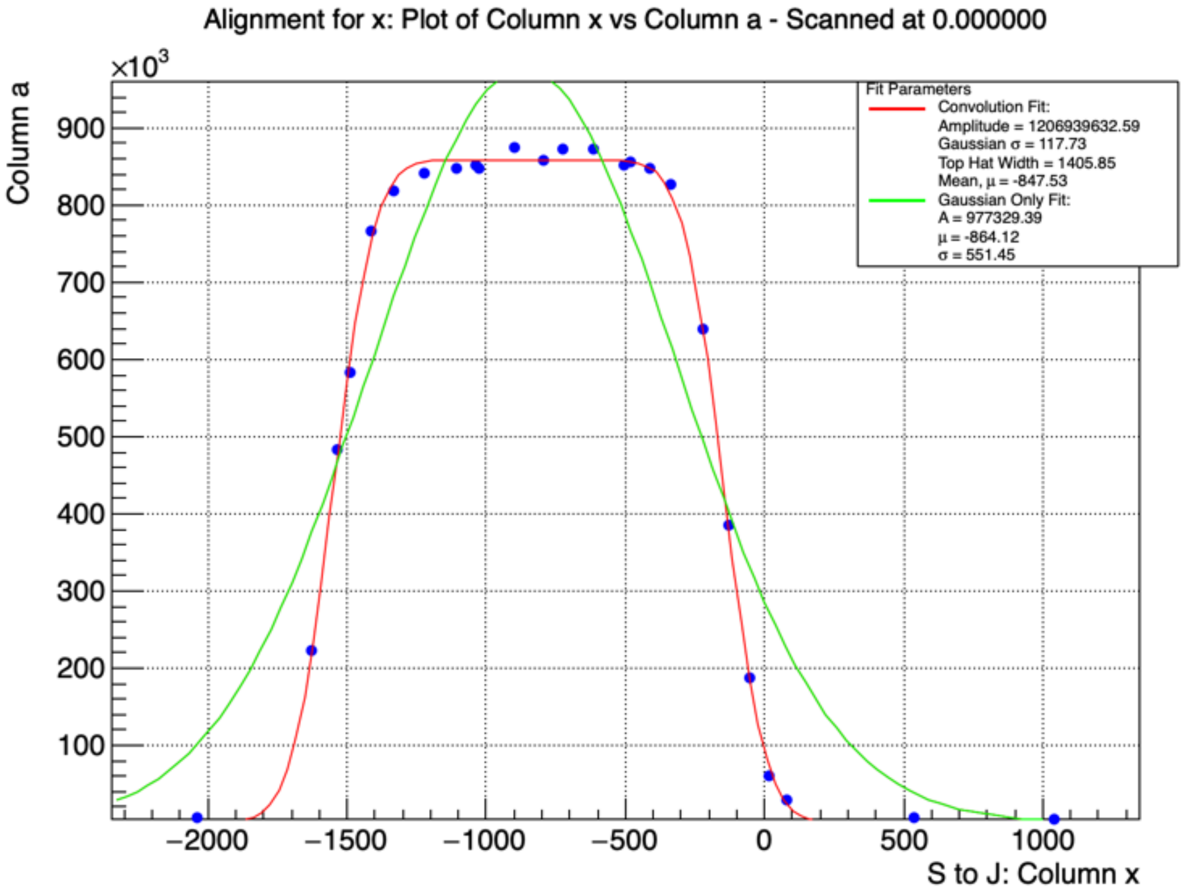


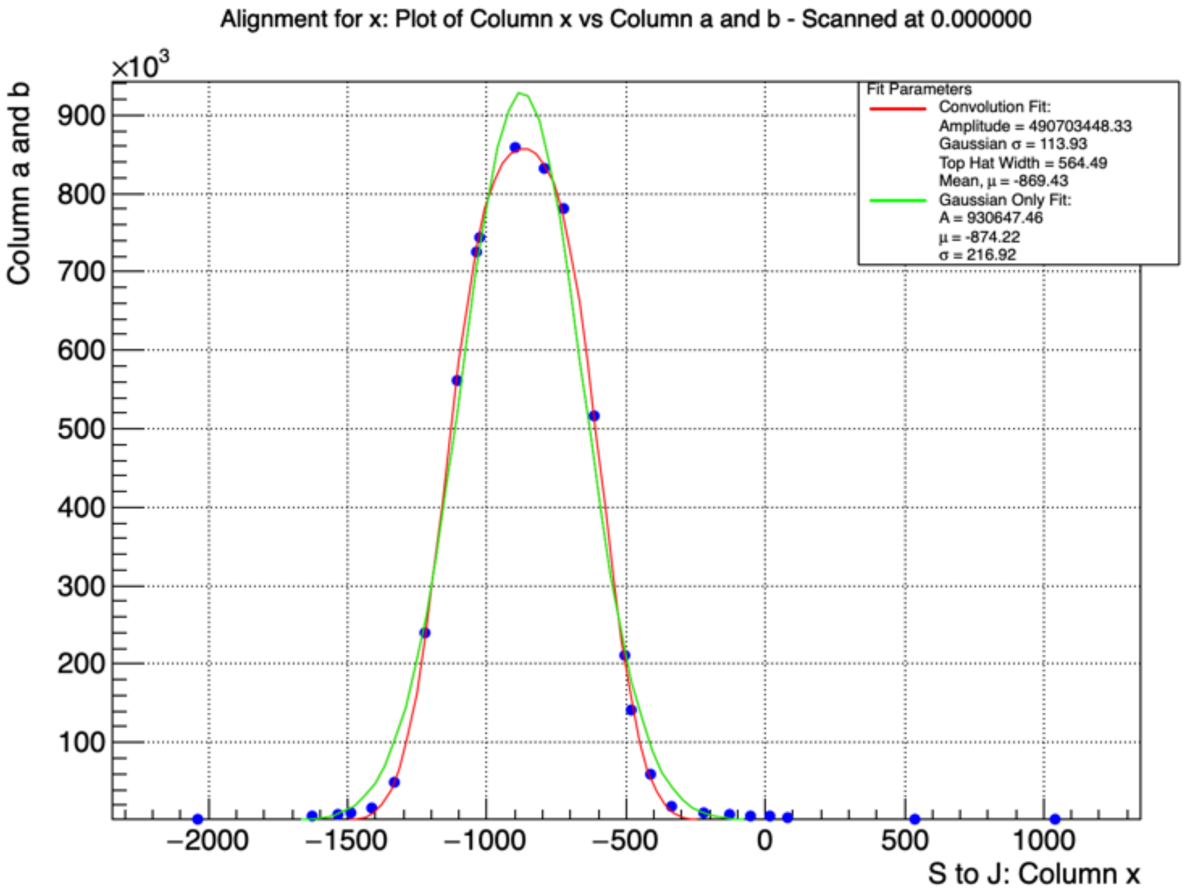


- Preliminary picoTDC triggered Timing resolution: $\sigma = 660 \pm 28$ ps
- All channels on FastIC 5

Improved beam alignment fits - Backup

- Now incorporates top hat for 5mm scintillator finger widths used for alignment





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