The ATLAS Forward Proton Time-of-Flight Detector System

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Theory and Experiment in High Energy Physics

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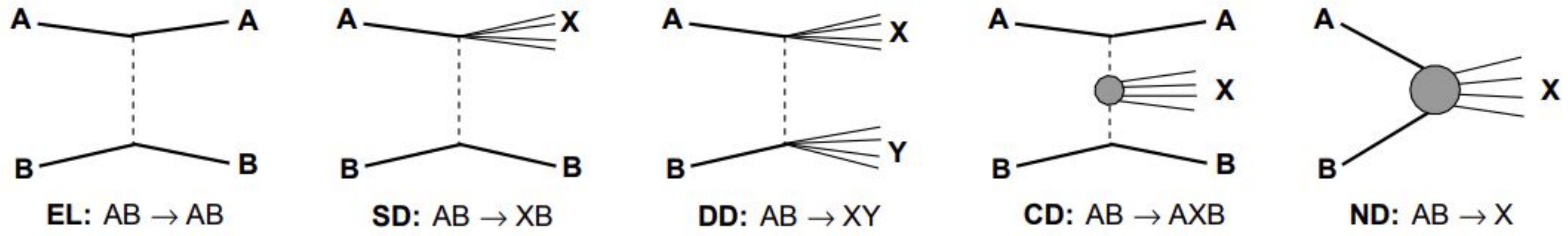
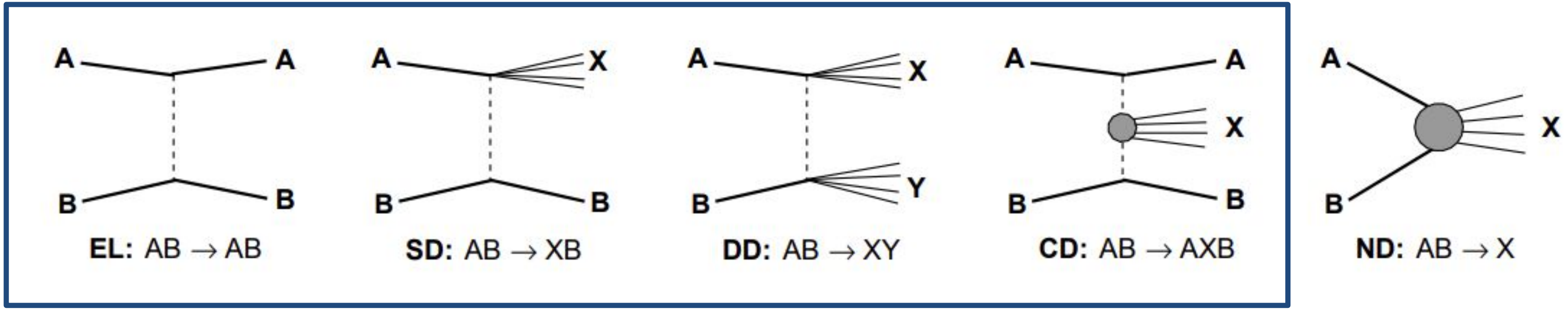
https://indico.cern.ch/event/1454114/

Event topologies at the LHC



Event topologies at the LHC

this is what forward community likes



Event topologies at the LHC

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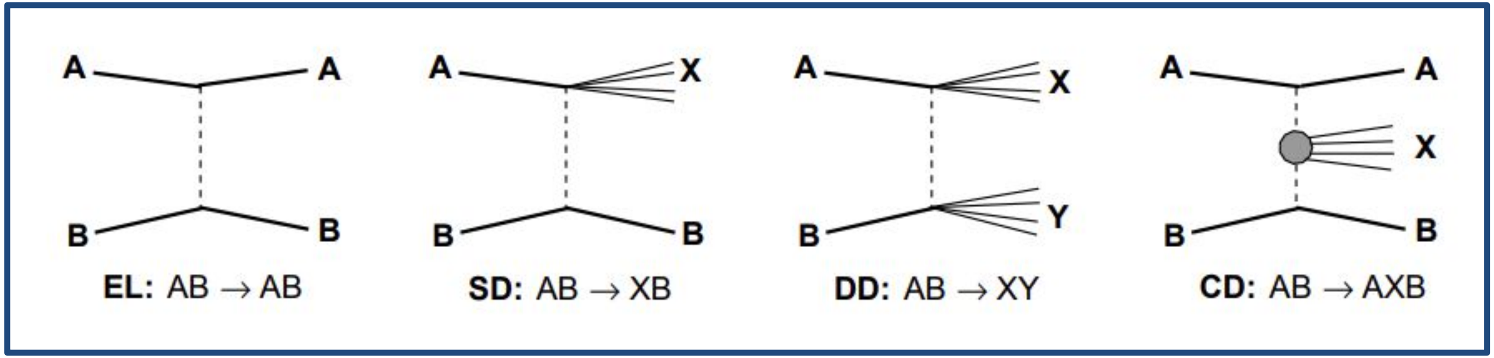
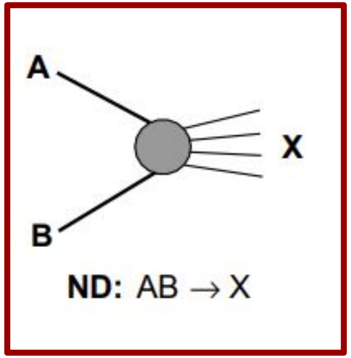




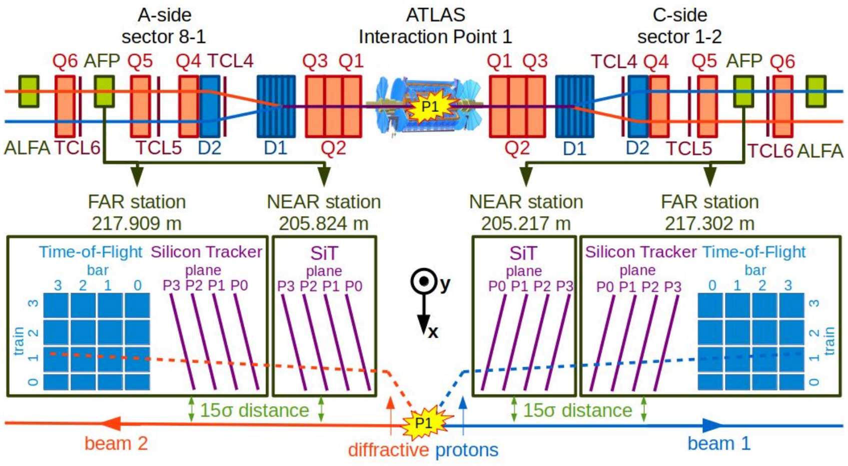
most of LHC physics

The ATLAS Forward Proton detector (AFP)

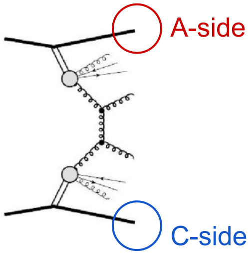
Designed to detect **protons** produced in **diffractive processes** at high rapidities not covered by the central detectors.

The protons are transported via the accelerator optics to the detectors' locations.

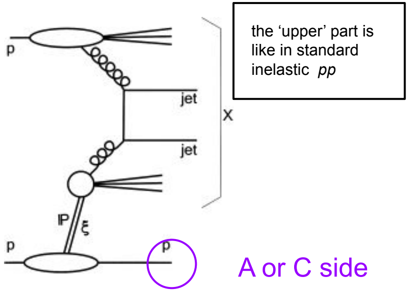
Forward detectors is the only option to identify diffraction when there is pile-up at LHC.



Examples of diffractive production of two jets.



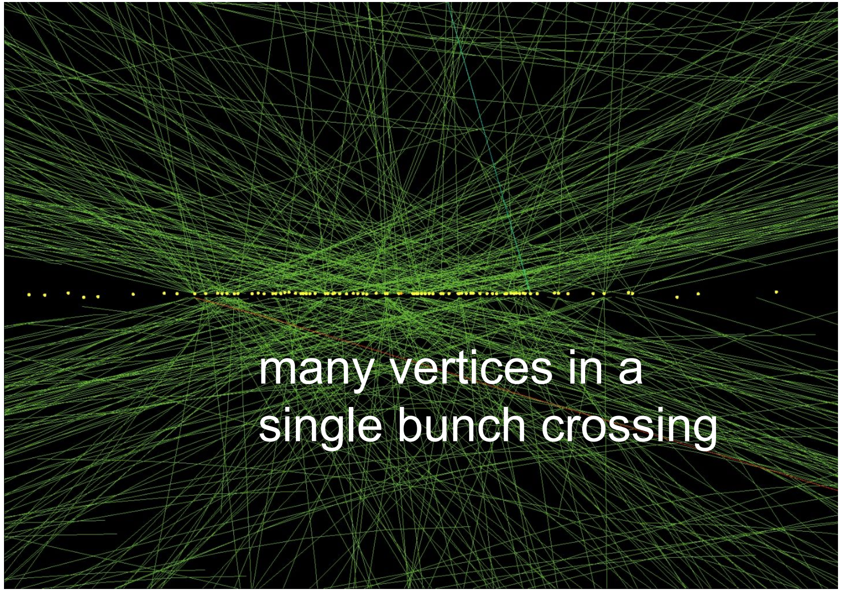
Central diffraction (CD) or sometimes central diffractive dissociation.
Double Pomeron exchange (DPE).
double tag = proton on both sides



Single diffraction (SD).
single tag = proton on one sides

Central diffraction & pile-up ✘ → ⊕Time-of-Flight ✔

Pile-up causes troubles to detect central diffraction.



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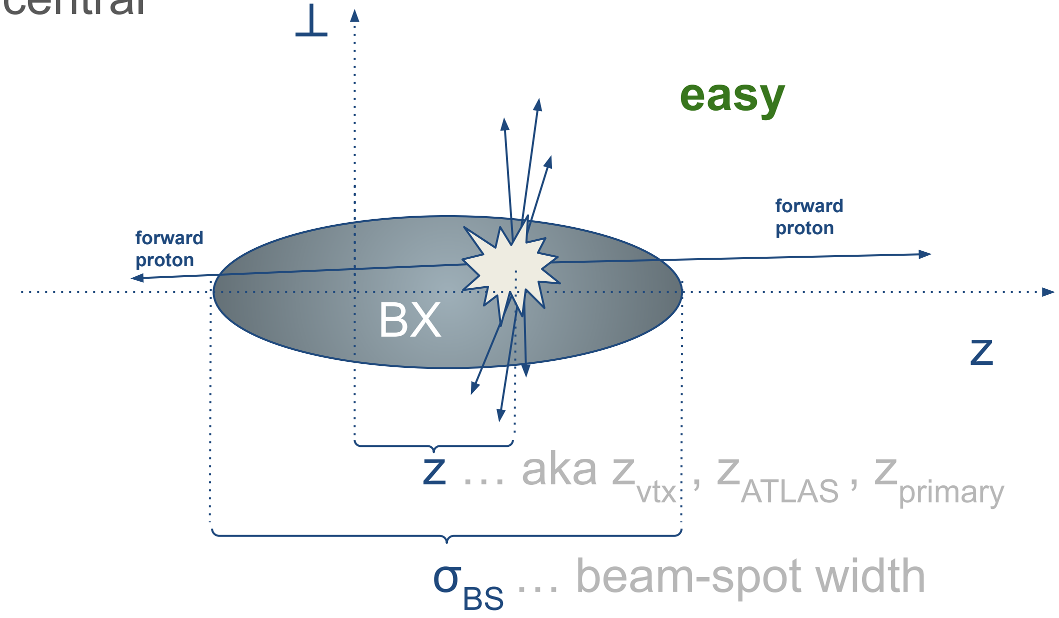
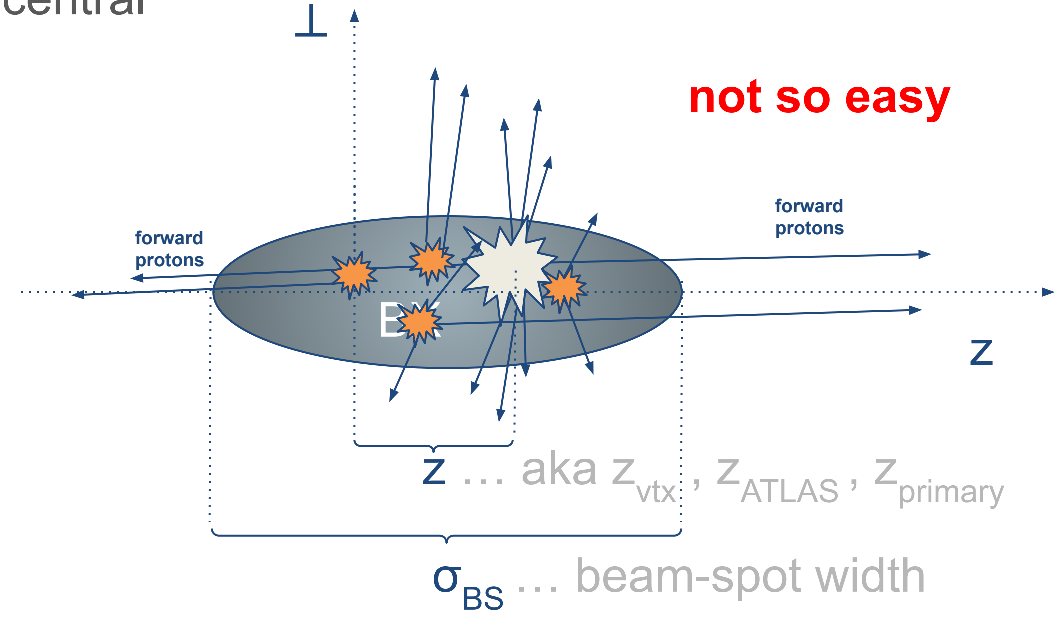


Central diffraction & pile-up ✘ → ⊕Time-of-Flight ✔

Pile-up causes troubles to detect central diffraction.

not so easy

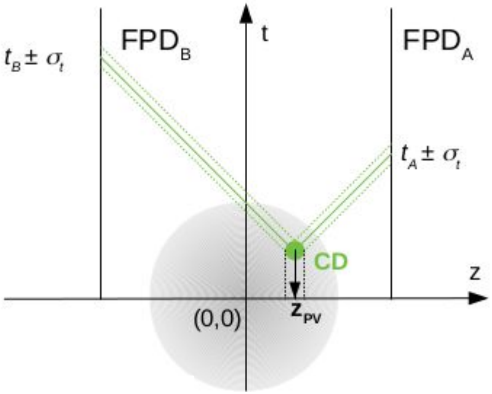


let's use only z-coord and time

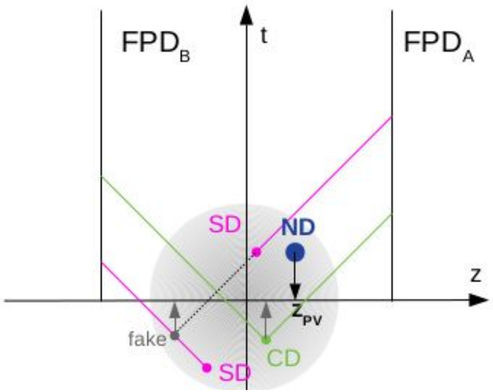
Central diffraction & pile-up ✘ → ⊕Time-of-Flight ✔

Pile-up causes troubles to detect central diffraction.

Independent SD events create spurious double tags.



no pile-up



non-diff signal and 3 PUs

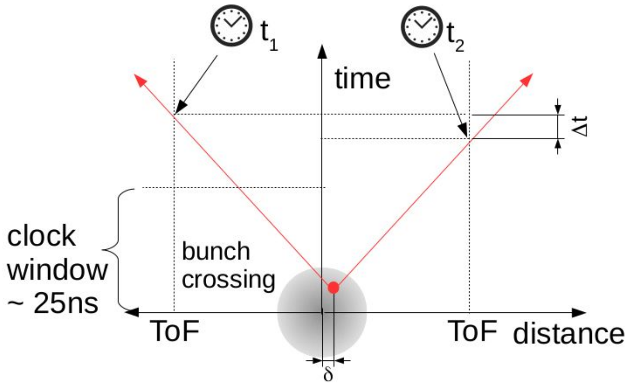
Central diffraction & pile-up ✘ → ⊕Time-of-Flight ✔

Pile-up causes troubles to detect central diffraction.

Independent SD events create spurious double tags.

Difference between times the two protons from CD process arrive to AFP stations on the opposite sides gives information about the **production vertex** in the central detector.

ToF housed in AFP's FAR stations.



$$\delta = \frac{c}{2}(t_C - t_A)$$

or better $\mathbf{z_{ToF}}$ … longitudinal position of interaction

The Time-of-Flight method for vertex reconstruction

Proposed in 2000 by M. Albrow & A. Rostovtsev arXiv:hep-ph/0009336

Exists in several experiments already

- ATLAS **σ ~ 6 mm** & ε ~ O(1%) in Run 2, see Viktoriia's talk for Run 3
- CMS σ ~ 27 mm (Run 2) and σ ~ 19 mm (Run 3) CERN-CMS-DP-2024-009
- STAR σ ~ 100 mm JHEP 07 (2020) 178, [arXiv:2004.11078]

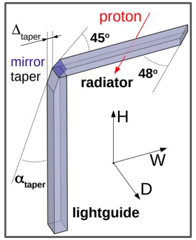
ToF elements

Mechanical

- Roman pot

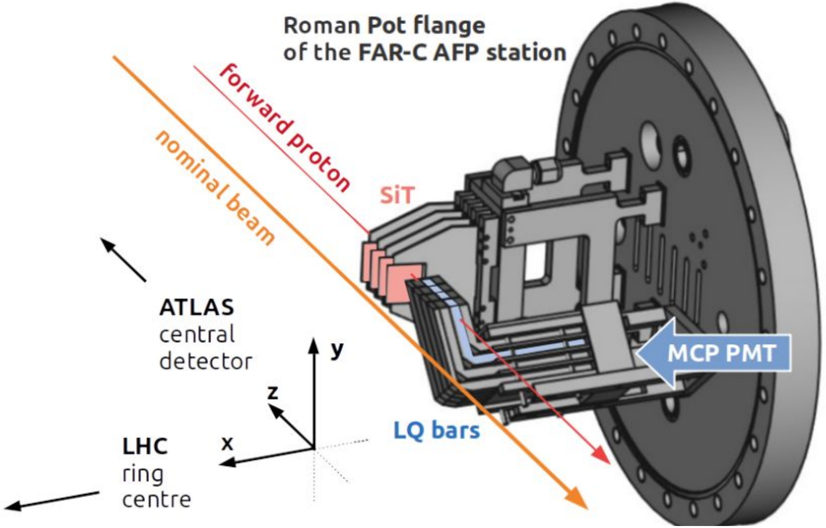
Optical part

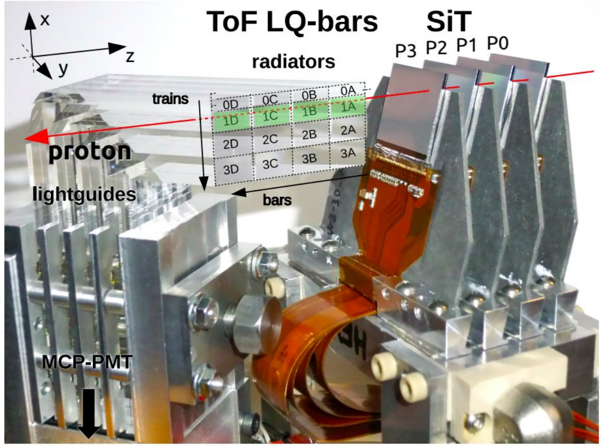
- Cherenkov light from Quartz bars
  - 16 bars on each side
  - mounted to MCP-PMT



Electronics

- MCP-PMT
- amplifiers (2 stages)
- CFD (signal rising edge identification)
- HPTDC (high performance TDC)





Analysis of the 2017 data

2017 was first year with two operating ToF detectors.

Since August 2017 the stations were synchronised.

The goals were to measure

- detection efficiency
- timing resolutions
- consistency of z_{ToF} with ATLAS primary vertex

Along the way

- estimate backgrounds and systematic uncertainties
- optimise data and event selections
- calibrate TDCs
- calibrate system to ATLAS coordinates along z (via channel delays)

Data and event selection

Data

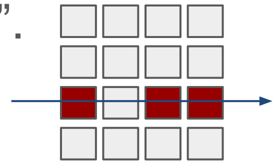
- Only **runs at low and moderate μ** (~2) analysed in the paper.

Noise and background sources discussed

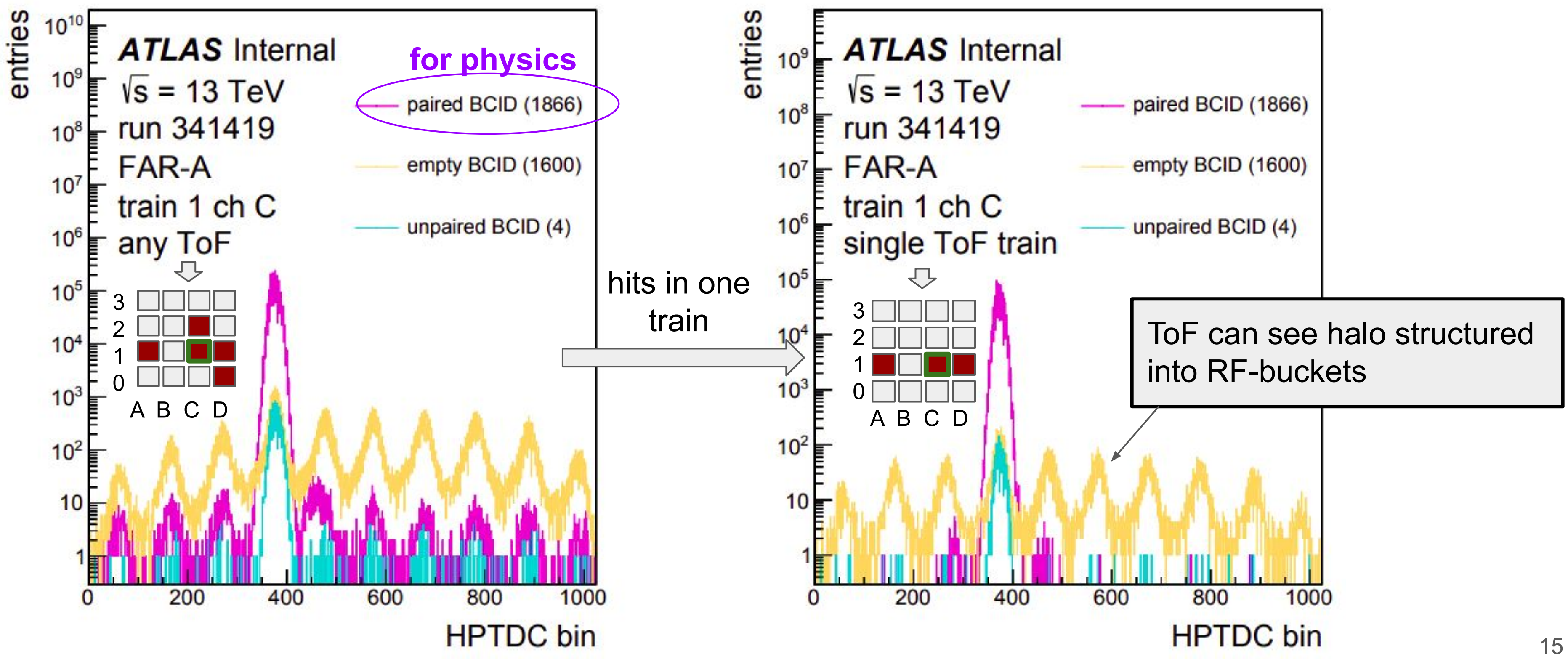
- Random noise not observed (dark counts etc.)
- Non-collision background present.

Selections

- Practical observation: ToF hits in **one train only** behave “better”.
  - (-) tolerable loss of statistics
  - (+) signals in the expected time ranges
  - (+) better timing, presumably less secondaries from showers



Raw time from an ‘example’ channel



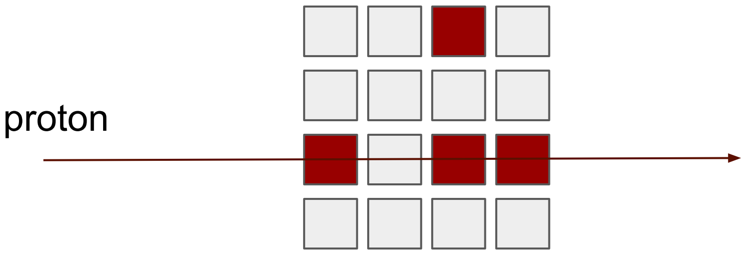
Efficiencies

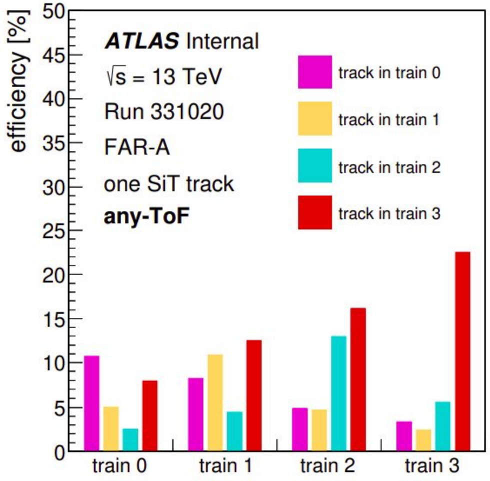
Probing ToF channels in events with exactly **one track**.

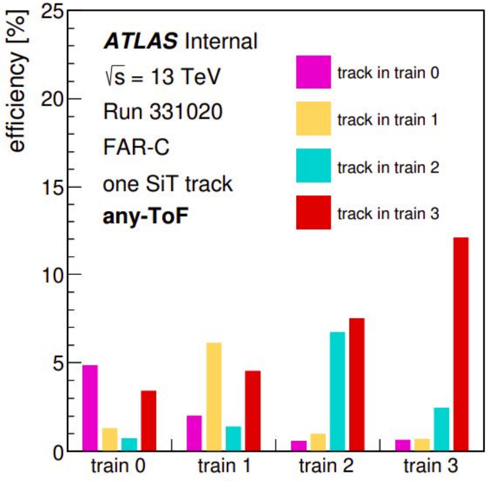
If ToF channel measures any time, it is called a hit … no hit = no time info.

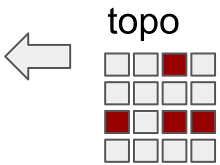
Channel efficiency:

$$\varepsilon_{ijk} = \frac{N(\text{bar-ij} \;\cap\; \text{track-k})}{N(\text{track-k})}$$



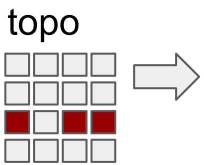


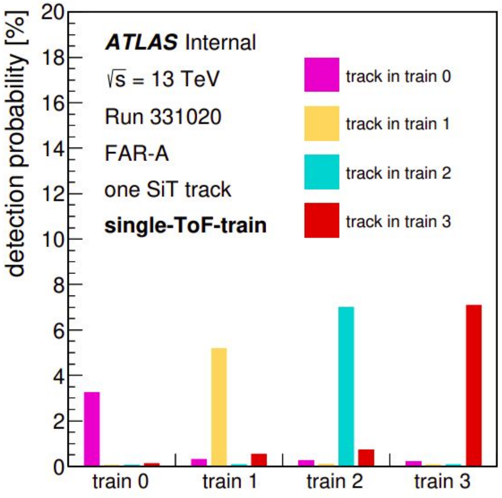


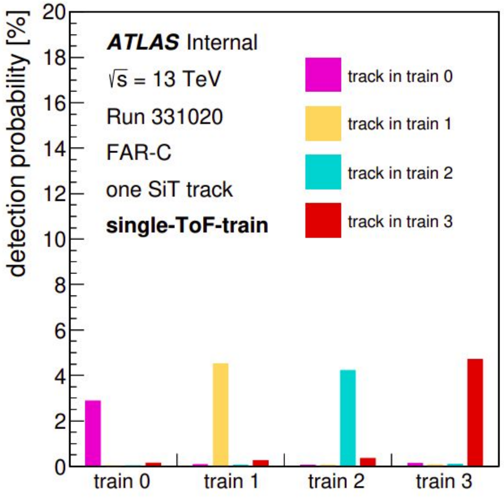


Results for only one (first) run shown.

Efficiencies are low and do not improve any further later in 2017.



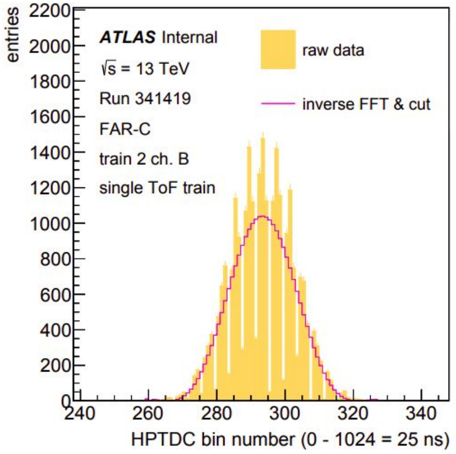


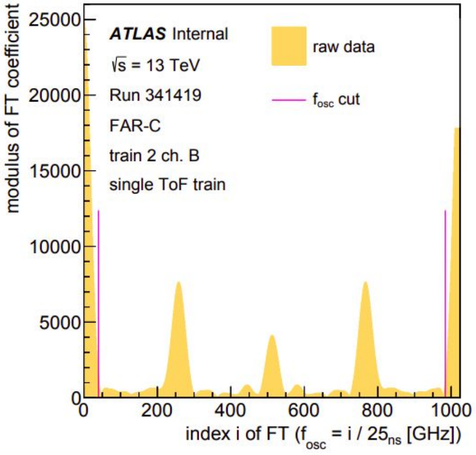


Effect of adding an extra criterion on hit topology.

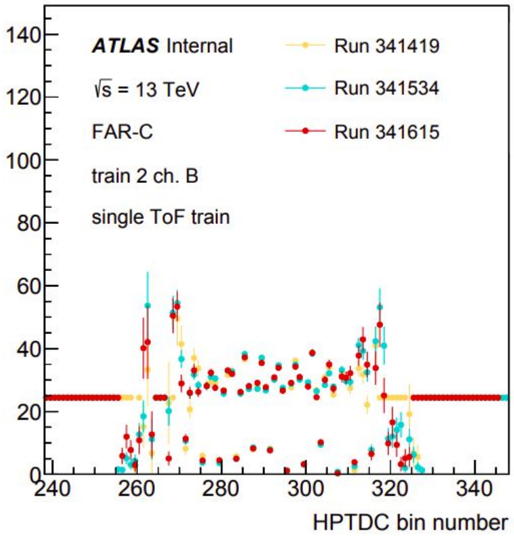
HPTDC calibration

Rapid bin content variations in raw time distributions removed with FFT. Bin centers adjusted accordingly.





example channel in run 341419

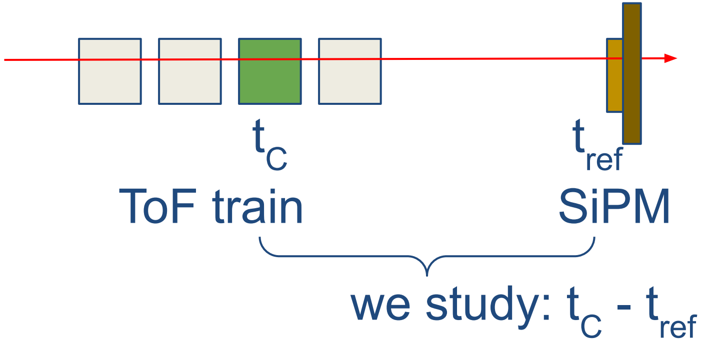


bin widths in runs 341(419|534|615)

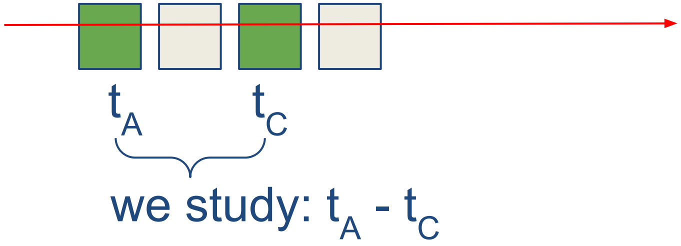
Resolutions

No external time measurement, then channels of a train must be used as a reference to other channels of the train.

Test beam situation



Real situation in the tunnel



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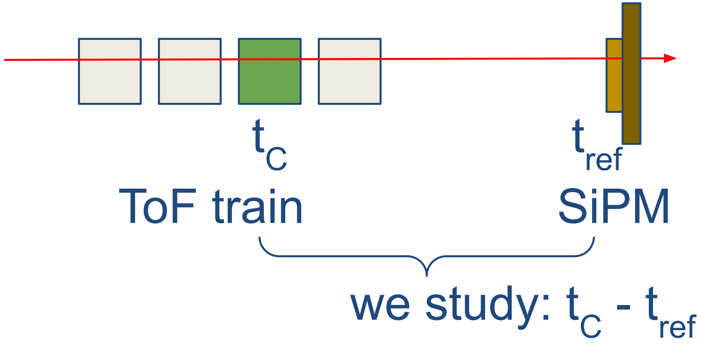

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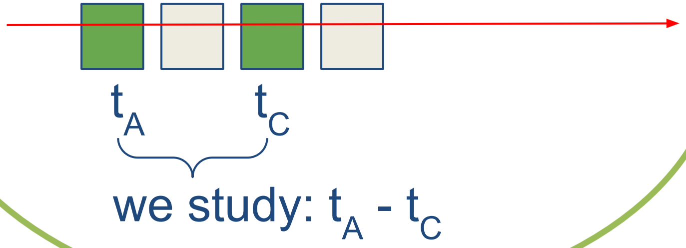


Resolutions

No external time measurement, then channels of a train must be used as a reference to other channels of the train.

Four channels produce six time difference observables measured on event-by-event basis, what’s left is only the term responsible for resolution and constant channel delays.

$$t_i = t_{\text{proton}} + t_{i,\text{delay}} + t_{i,\text{smear}} - t_{\text{clock}}$$

$$\Delta t_{ij} = t_i - t_j = t_{i,\text{delay}} - t_{j,\text{delay}} + t_{i,\text{smear}} - t_{j,\text{smear}}$$

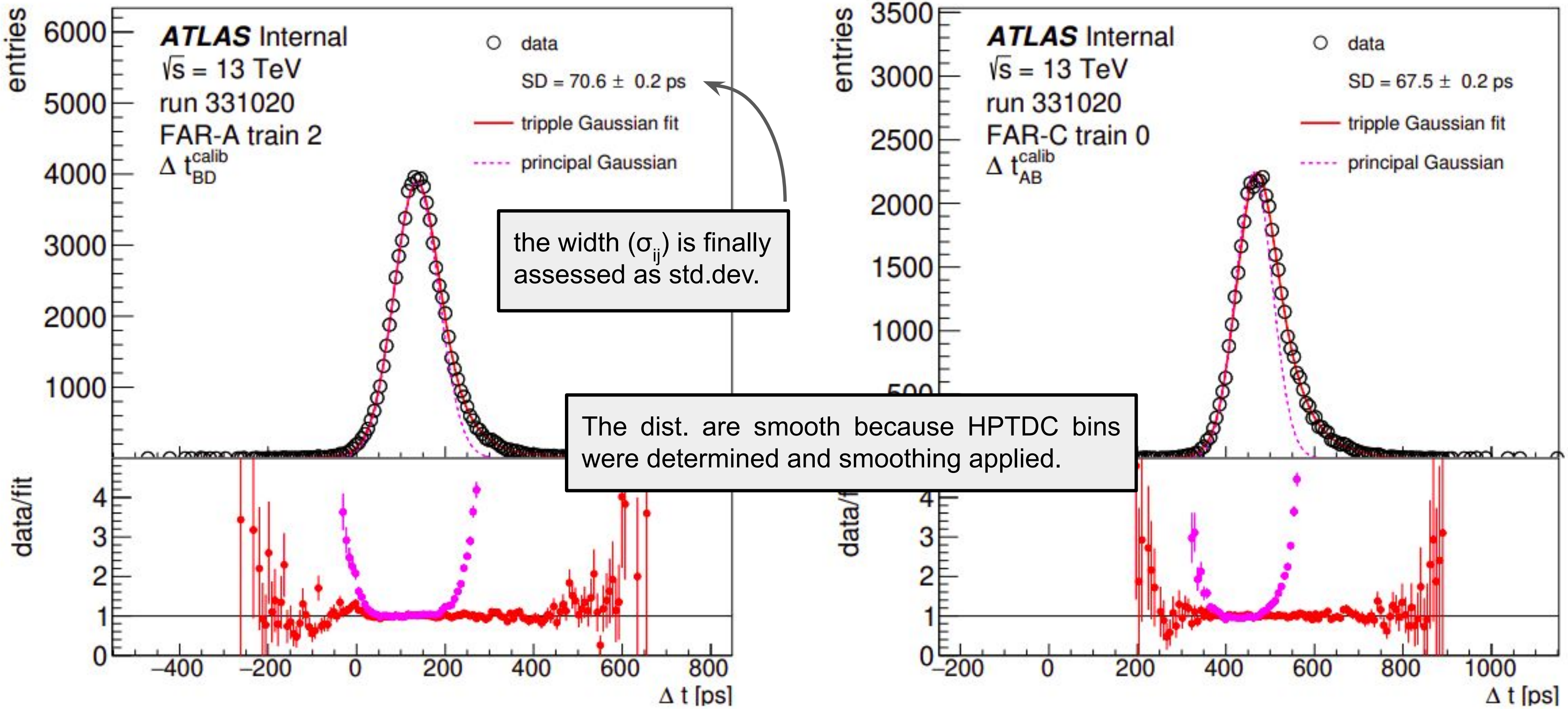
width

Assuming $\sigma_i = \sqrt{\text{Var}(t_{i,\text{ smear}})}$ and $\sigma_{ij} = \sqrt{\sigma_i^2 + \sigma_j^2 - 2\rho_{ij}\sigma_i\sigma_j}$

Individual channels’ σ are obtained by minimising the expression:

$$\chi^2 = \Sigma_{ij} \frac{\left(\sigma_{ij} - \sqrt{\sigma_i^2 + \sigma_j^2 - 2\rho_{ij}\sigma_i\sigma_j}\right)^2}{\left(\delta_{\text{stat}}(\sigma_{ij})\right)^2}$$

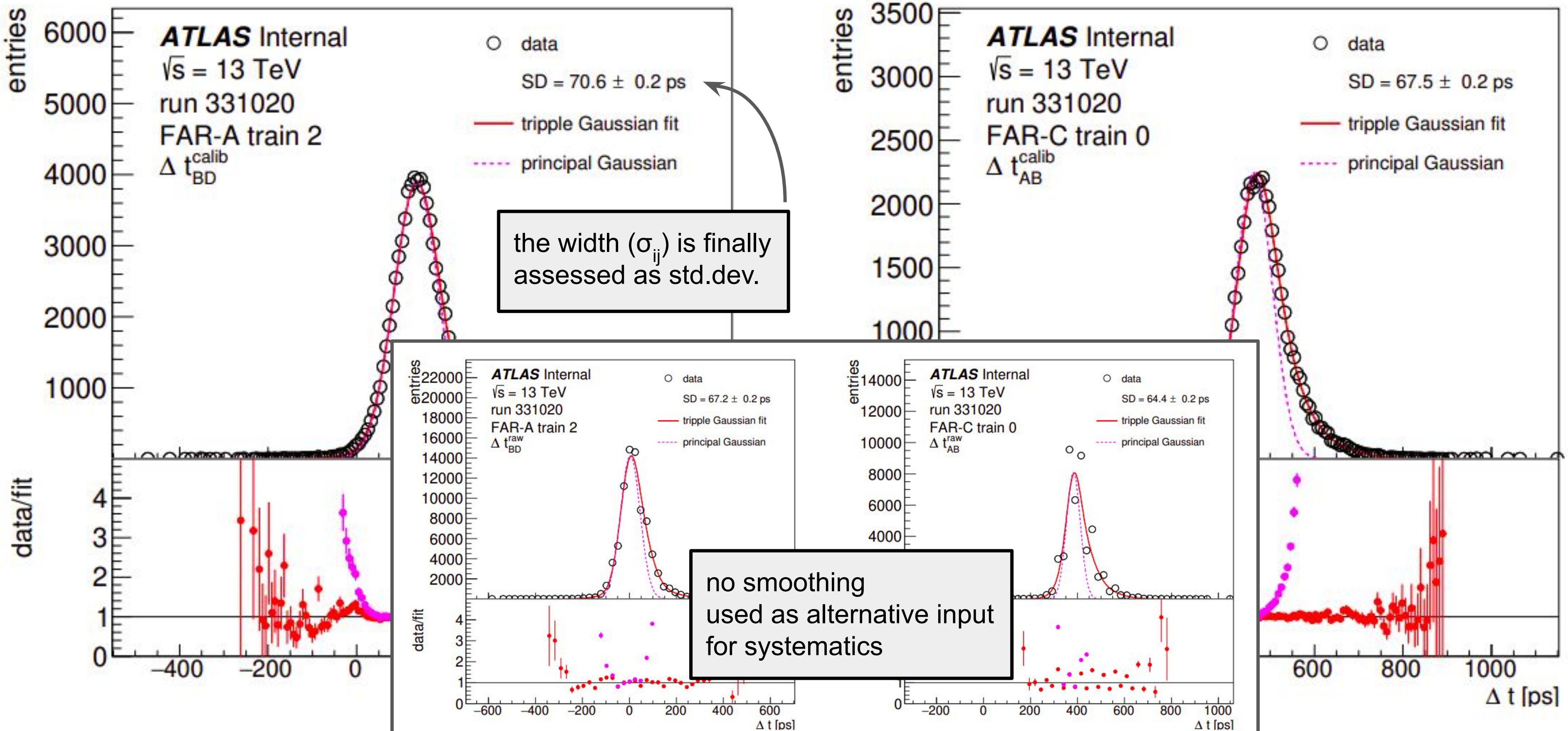
Two examples of Δt distributions



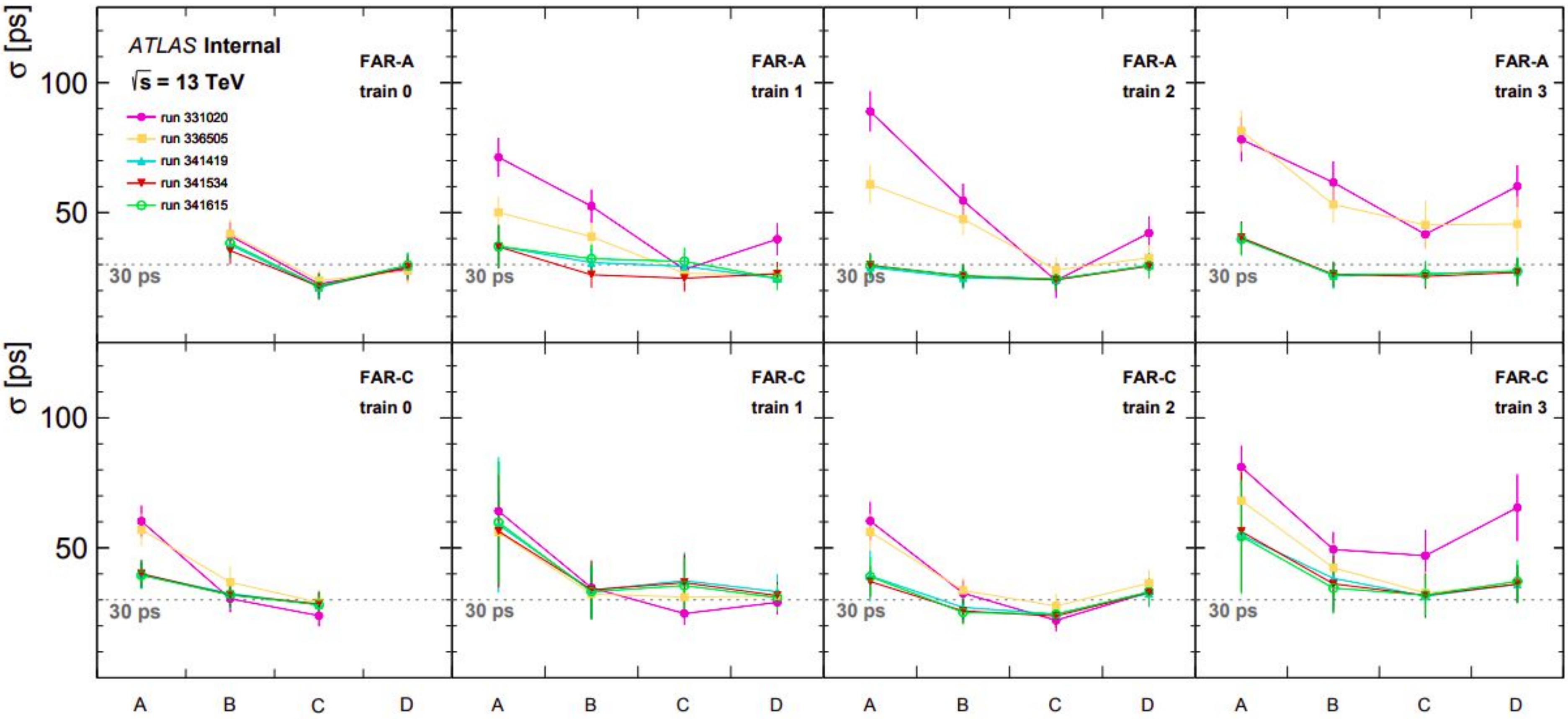
the width (σ_{ij}) is finally assessed as std.dev.

The dist. are smooth because HPTDC bins were determined and smoothing applied.

Two examples of Δt distributions



Extracted channel resolutions



Vertex matching analysis

The primary vertex, z_{ATLAS} , is compared with z_{ToF} by as: $\mathbf{z_{ATLAS} - z_{ToF}}$

Only **single-ToF-train used** & no AFP tracker (SiT) info used to keep statistics.

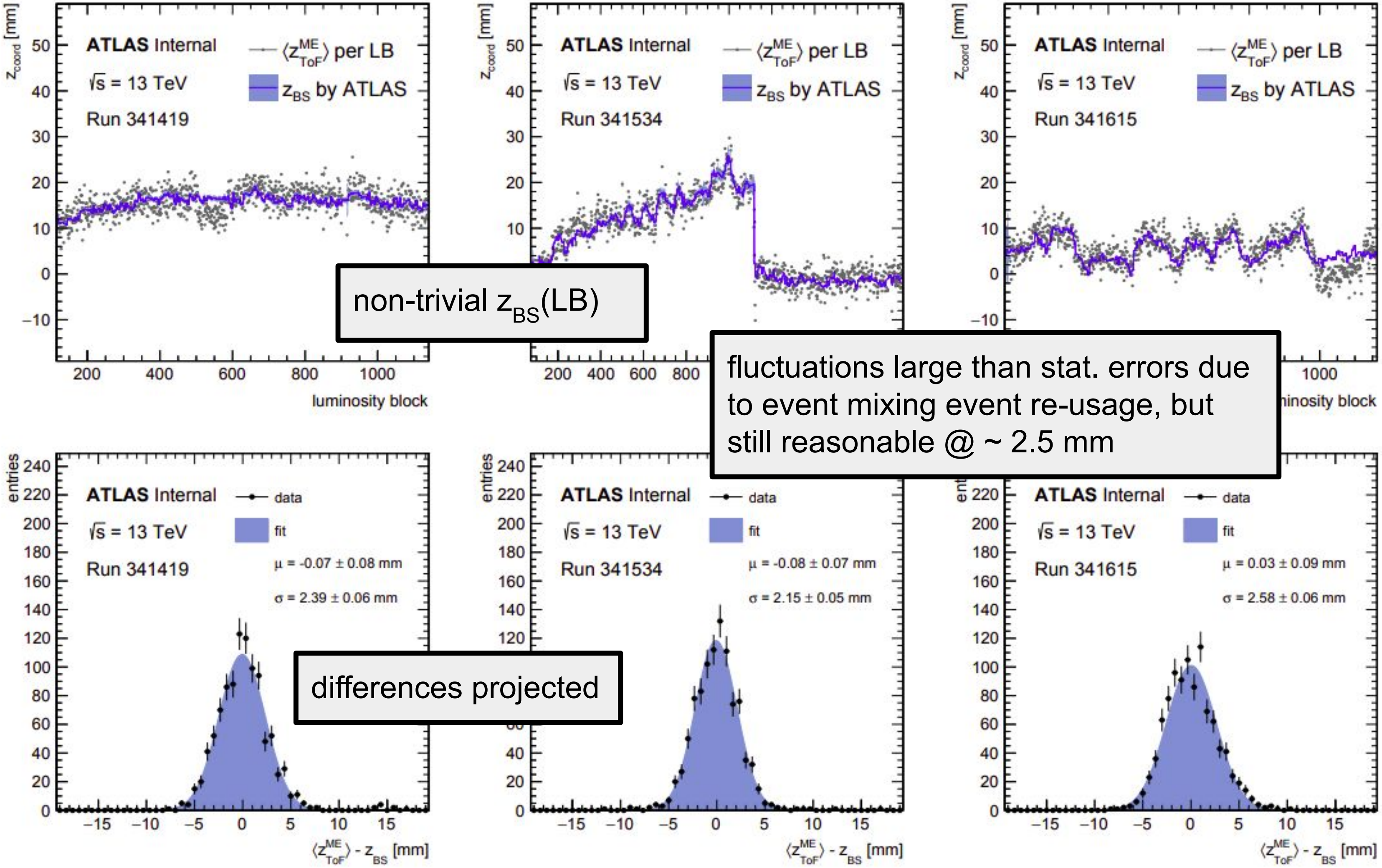
ATLAS 2017 runs with μ~2 used.

$z_{ToF} = c/2\ (t_C - t_A)$ … where side times t_A and t_C are be averaged

The averaging makes sense if delays are known in all channels.

Calibration to a beamspot z-position (z_{BS}) is performed.

- using data driven technique of event mixing
- each ~1 min of data ATLAS reco tracks provide z_{BS}
- 31 channel delays are found such that they optimise z_{BS} description
- closure plots using ev.mixing compare z_{BS} from ToF and from ATLAS



non-trivial z_{BS}(LB)

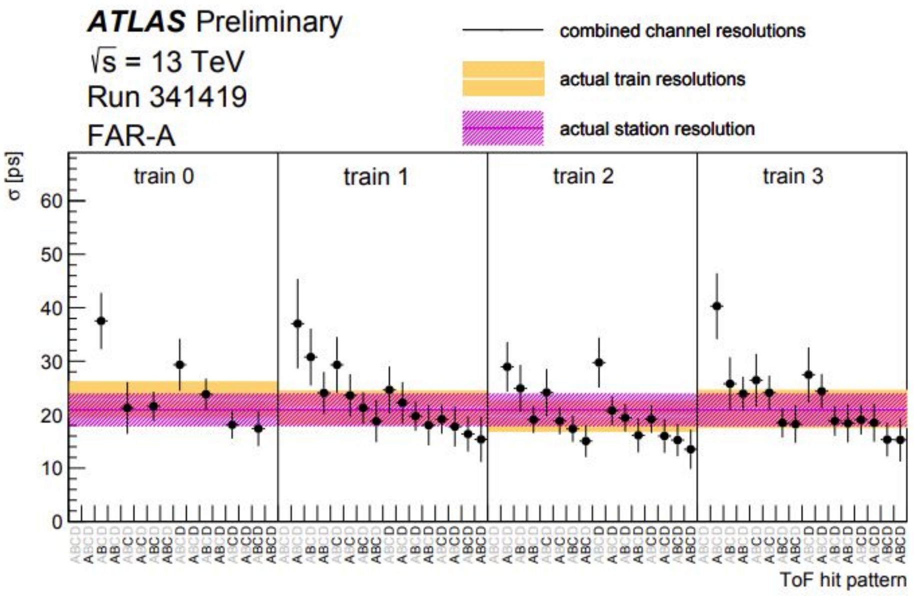
fluctuations large than stat. errors due to event mixing event re-usage, but still reasonable @ ~ 2.5 mm

differences projected

Expected resolutions

In each train

- Use channel resolutions from the first part of the analysis.
- Average for every possible choice of contributing channels.
- Weight the averaged resolutions proportionally to the number cases observed in the data.
- The outcome: train resolutions.



For each station

- Average the train resolutions to station resolutions.

Run	FAR-A resolution [ps]	FAR-C resolution [ps]	combined resolution [mm]
341419	21 ± 3 (stat ⊕ syst)	28 ± 4 (stat ⊕ syst)	5.3 ± 0.6 (stat ⊕ syst)
341534	20 ± 3 (stat ⊕ syst)	28 ± 4 (stat ⊕ syst)	5.2 ± 0.6 (stat ⊕ syst)
341615	22 ± 3 (stat ⊕ syst)	28 ± 4 (stat ⊕ syst)	5.3 ± 0.6 (stat ⊕ syst)

$$z_{ToF} = \frac{c}{2}(t_C - t_A) \qquad \sigma(z_{ToF}) = \frac{c}{2}\sqrt{\sigma^2_{t_C} + \sigma^2_{t_A}}$$

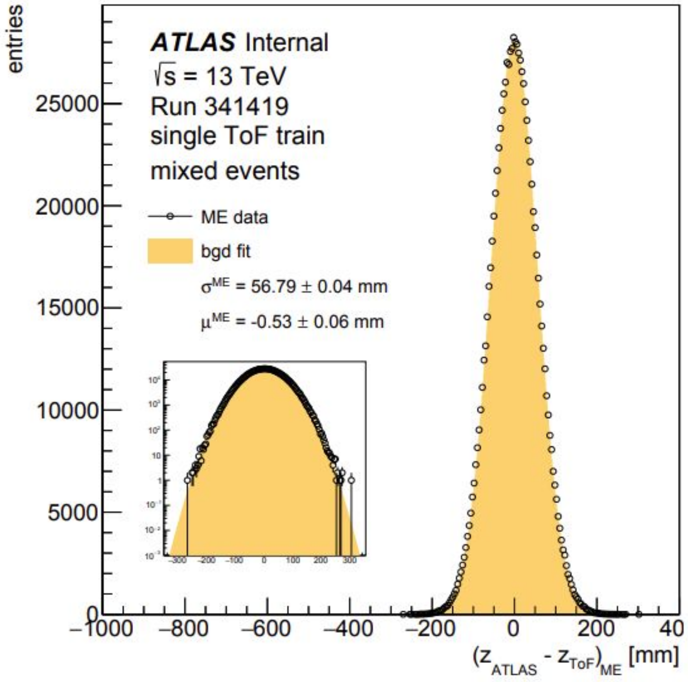
Event-by-event z_{vtx} comparison

First, the **shape of background** is modeled by using **event mixing**.

The shape described by a following fcn:

$$n_1\, g(\mu, \sigma) + n_2\, g(\mu, \frac{\sigma}{\sqrt{2}})$$

Shape parameters of the background the **μ and σ are kept fixed** in the subsequent fits of the data.



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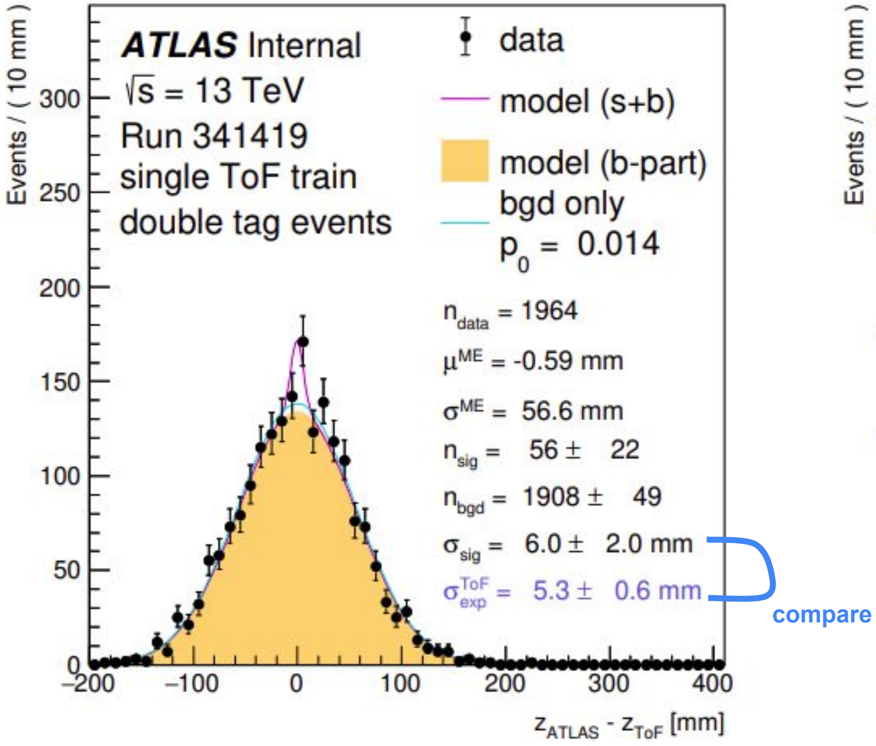
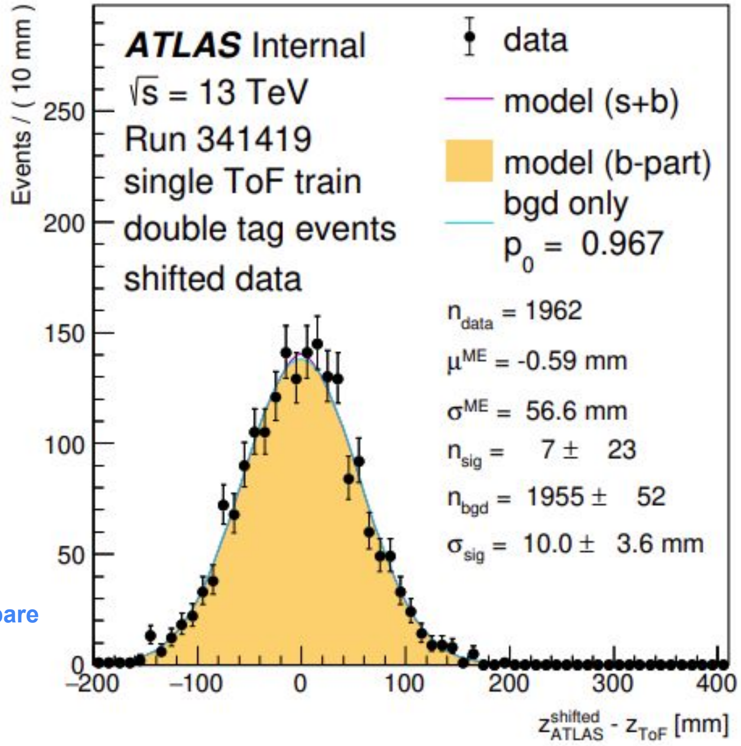


nominal event combinations



event combinations w/o signal

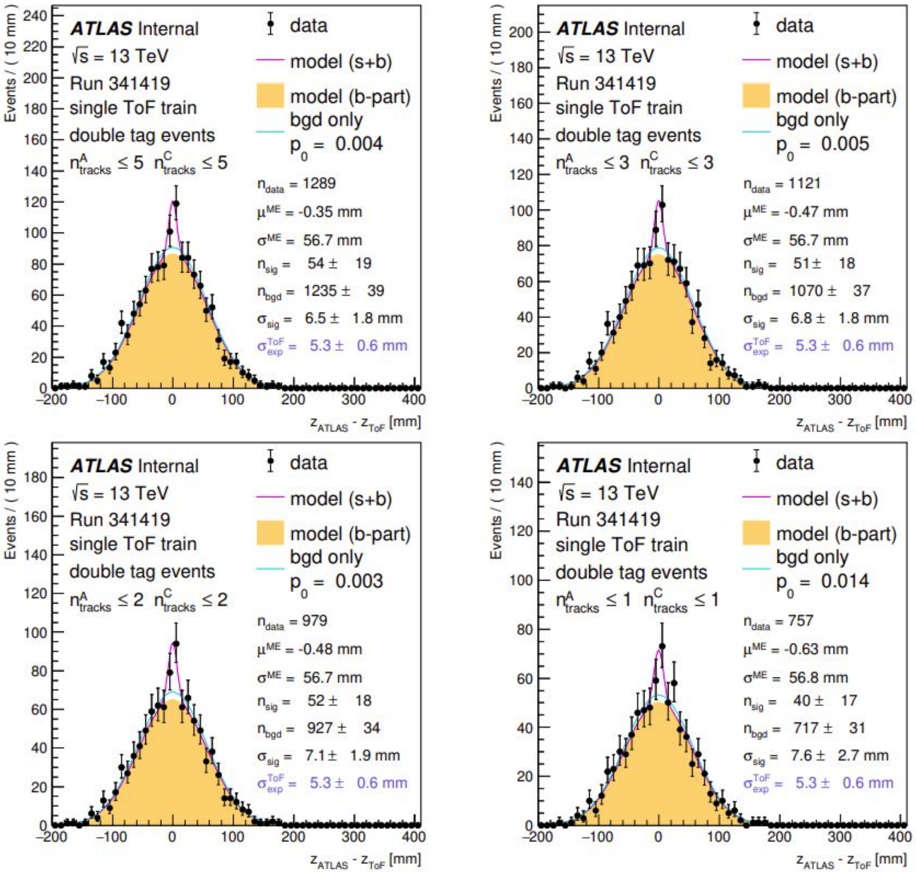
Suppressing non-collision background

For statistics reasons no explicit selections in the AFP tracker (SiT) done.

Events with higher number of tracks are likely to contain non-collision background.

Results for cuts on n_{tracks} on the sides are made.

Increased signal significance with rather stable signal yield (with large errors).



Conclusions summarised in an ATLAS paper JINST 19 (2024) P05054

Efficiencies low

- The lifetime of MCP-PMTs exceeded.
- In accordance with expected rapid degradation at high gains, which was identified as a source of problems already back then in 2017 and 2018.

Very good timing resolutions

- Best technology so far for timing in this harsh radiation environment.

Vertex matching

- Independent x-check of the resolutions.
- Proof of concept of the method (although the delay closure plots might serve a purpose too)
- Little signal studied with fits to the data.
- Signal width consistent with expected resolutions obtained from previous measurement.

Future plans

No proton tagging for ATLAS in Run 4 (neither ToF)

Considerations for Run 5

- new Roman Pots
- new technique for ToF
  - Cherenkov
  - LGAD
  - ???
- must be
  - rad-hard
  - handle high-rates
  - as good resolution as possible
    - timing
    - space (i.e. granularity)