GPU-based Online Track Reconstruction in LHC Run 3 for the ALICE TPC with Continous Read Out

David Rohr for the ALICE Collaboration
drohr@cern.ch, CERN

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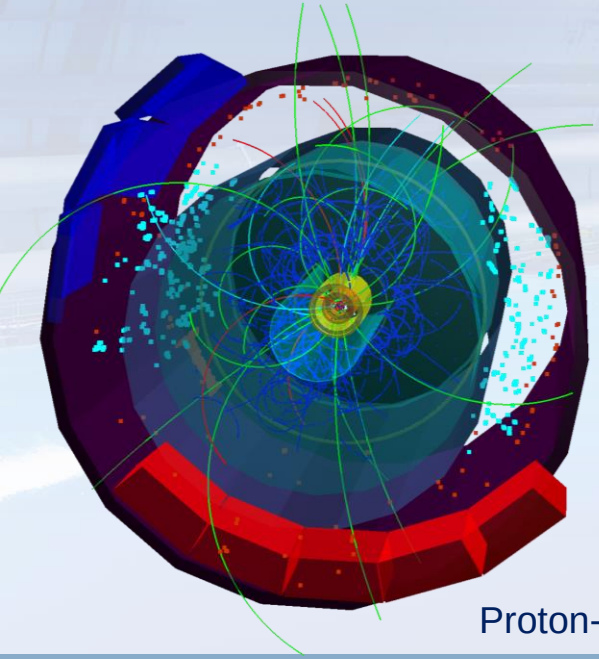
10.7.2018

Run 2: O(1) kHz single events…

- **What data will we see with the ALICE Upgrade…?**



Proton-Proton

David Rohr, drohr@cern.ch

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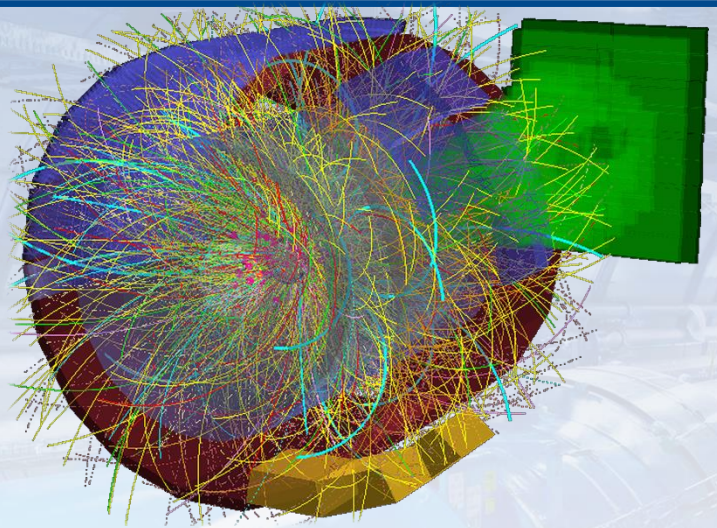
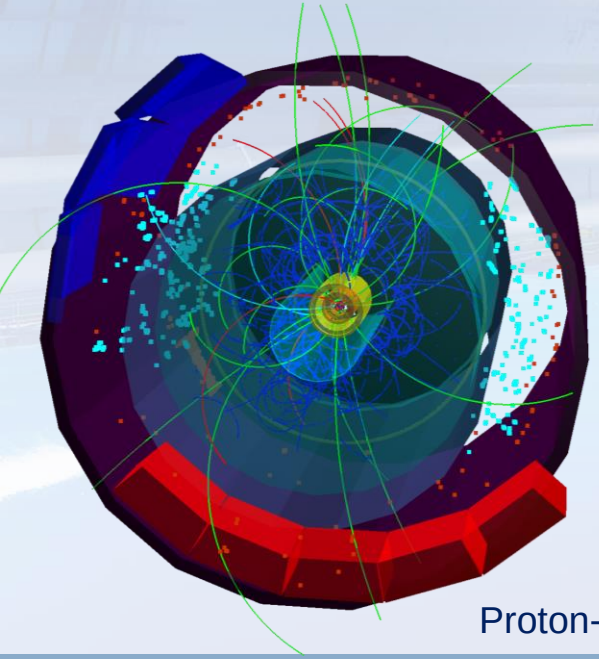


Proton-Lead



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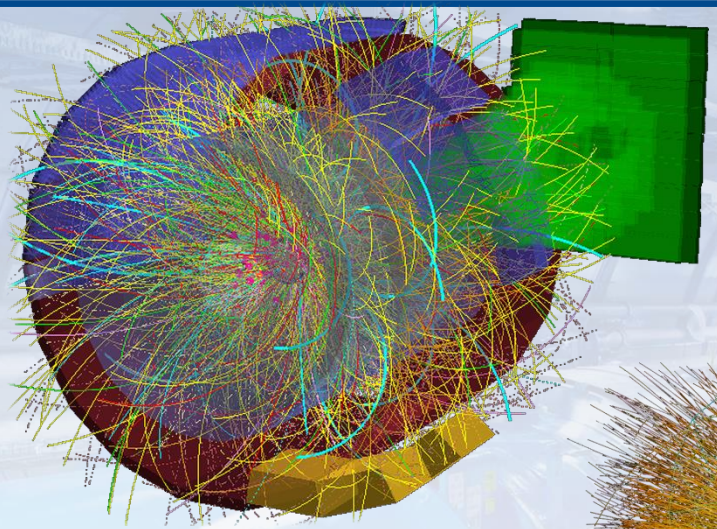

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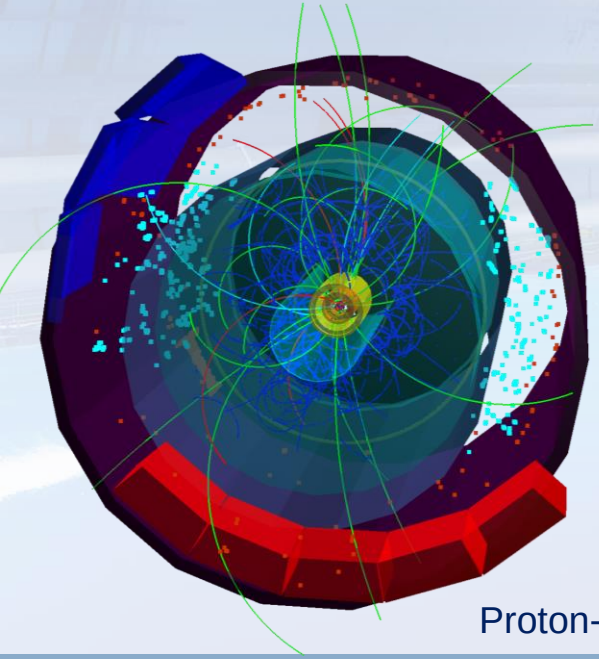

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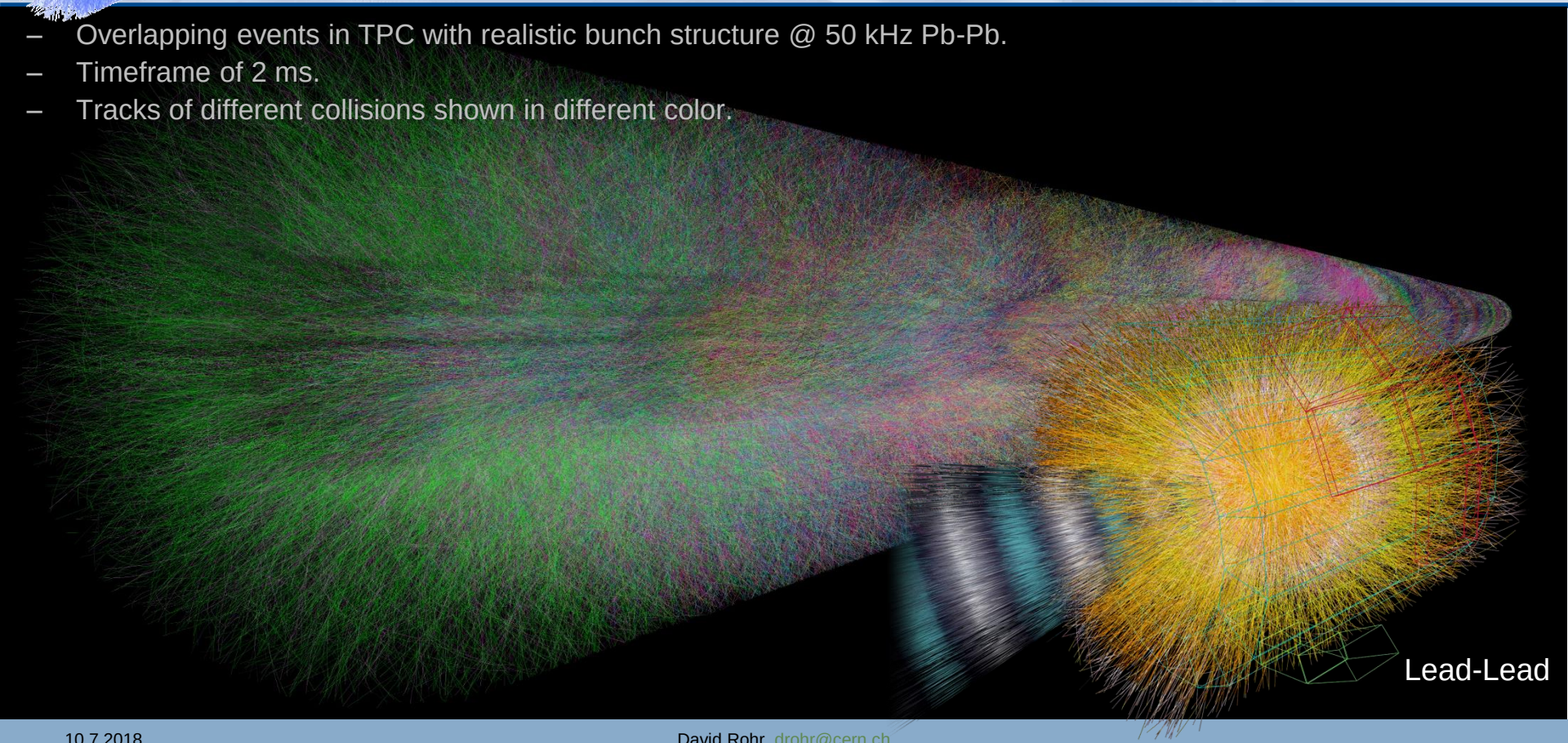
Run 2: O(1) kHz single events → Run 3: 50 kHz continuous data

- Overlapping events in TPC with realistic bunch structure @ 50 kHz Pb-Pb.
- Timeframe of 2 ms.
- Tracks of different collisions shown in different color.



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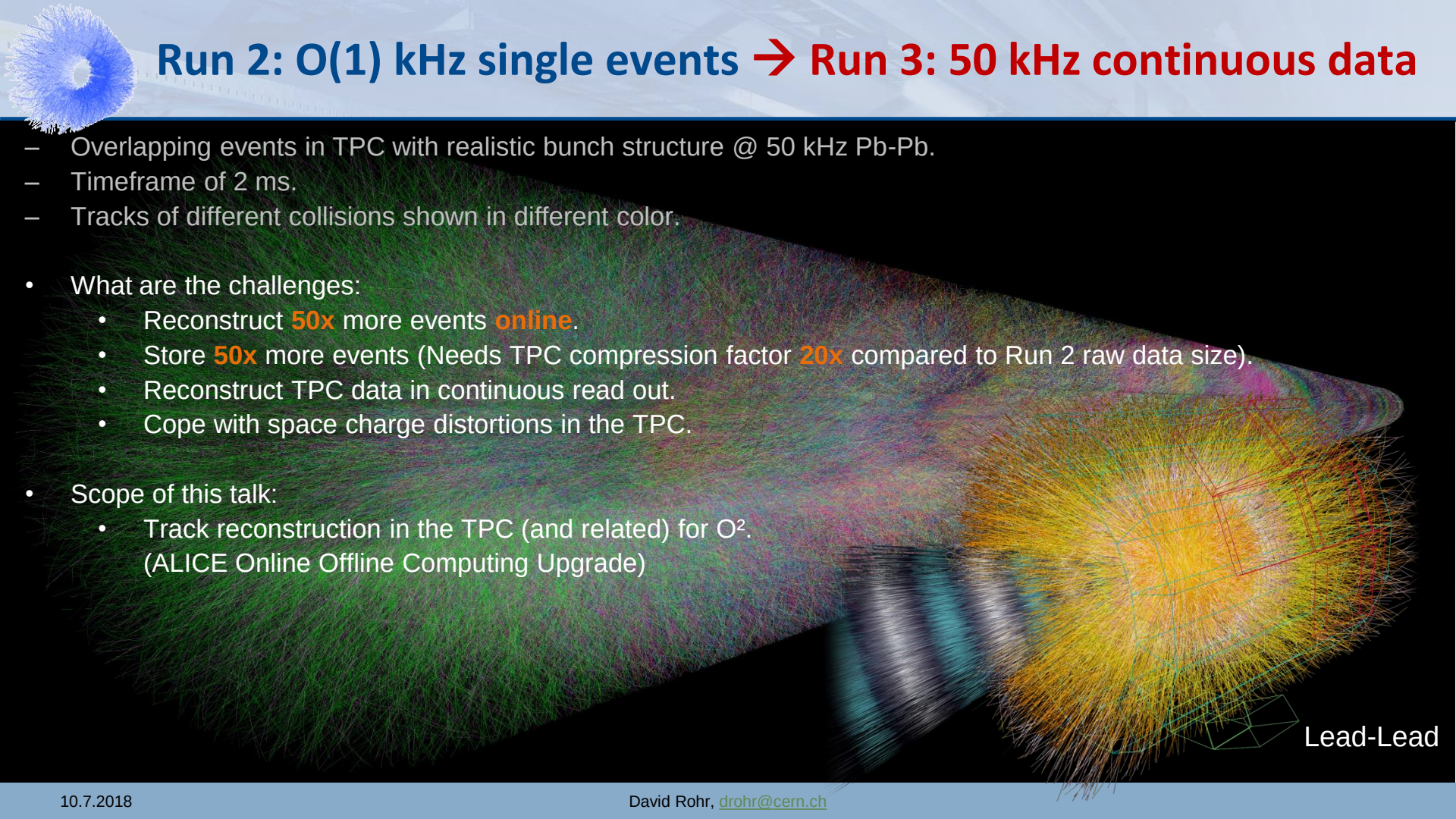
Run 2: O(1) kHz single events → Run 3: 50 kHz continuous data

- Overlapping events in TPC with realistic bunch structure @ 50 kHz Pb-Pb.
- Timeframe of 2 ms.
- Tracks of different collisions shown in different color.

- What are the challenges:
  - Reconstruct **50x** more events **online**.
  - Store **50x** more events (Needs TPC compression factor **20x** compared to Run 2 raw data size).
  - Reconstruct TPC data in continuous read out.
  - Cope with space charge distortions in the TPC.

- Scope of this talk:
  - Track reconstruction in the TPC (and related) for O^2.
    (ALICE Online Offline Computing Upgrade)



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Tracking in ALICE in Run 3

- **ALICE uses mainly 3 detectors for tracking: ITS, TPC, TRD** ***+ (TOF)***
  - **7 layers ITS** (Inner Tracking System – Silicon Tracker)
  - **152 pad rows** TPC (Time Projection Chamber)
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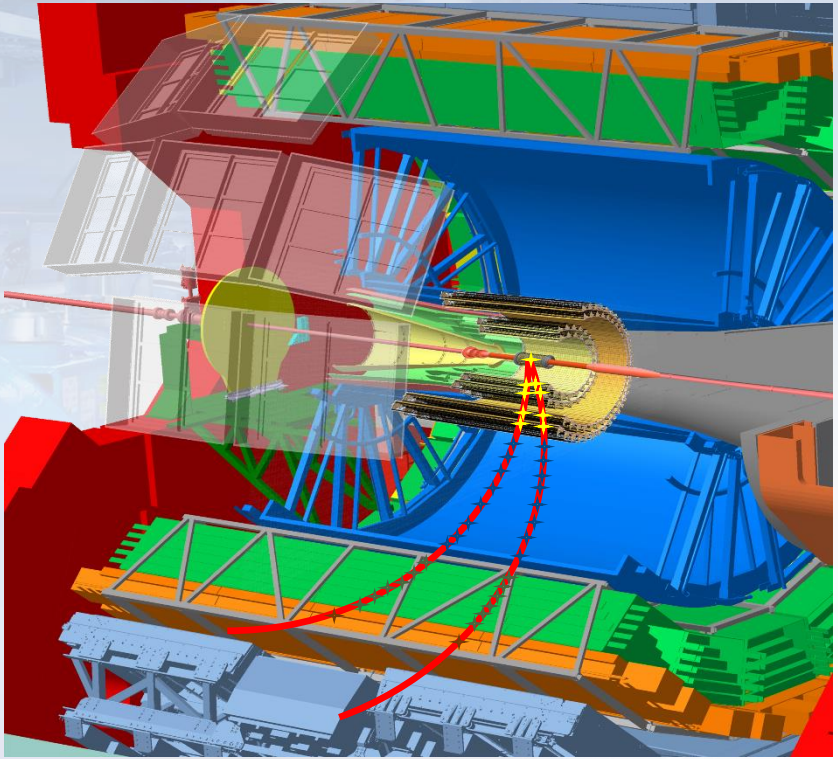

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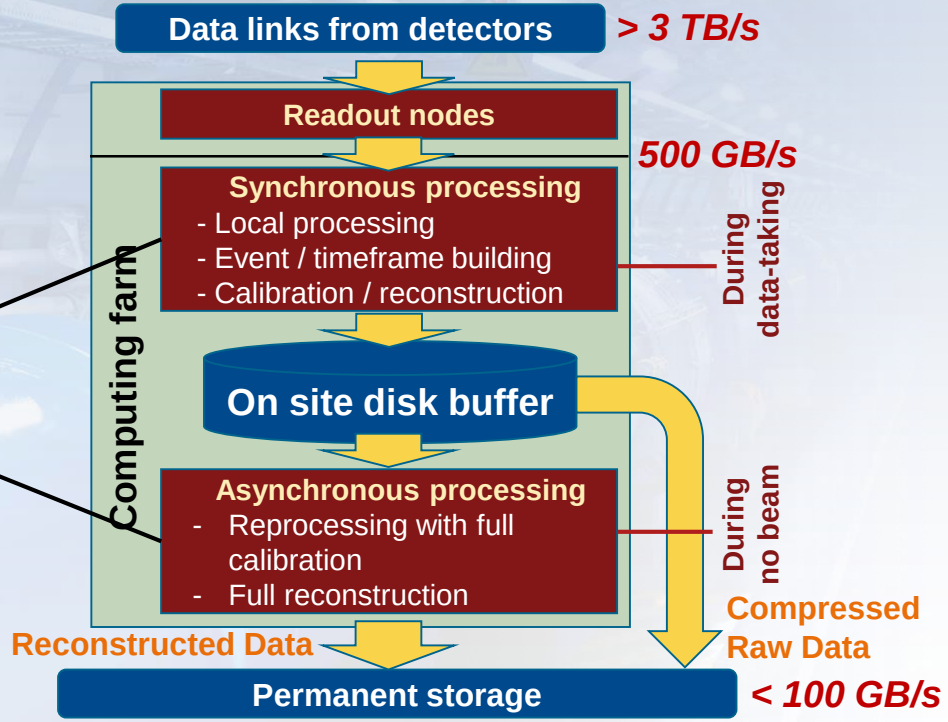
- **Two reconstruction phases in Run 3:**
  - Synchronous reconstruction (during data taking):
    - **Calibration**
    - **Data compression**
  - Asynchronous reconstruction (when no beam):
    - **Full reconstruction with final calibration**



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Partial ITS + TPC + TRD tracking
- ***reduced statistics sufficient***

(calibration based on matching of TPC / ITS / TRD tracks and TPC residuals v.s. TRD-ITS refit: see arXiv:1709.00618)

Full TPC tracking
- ***cluster to track residuals → better entopy coding***

(needs track refit in distorted coordinates: see TODO)
- ***removal of tracks not used for physics***

Second tracking pass with final calibration

- **This means:**
  - **Full TPC online tracking @50 kHz Pb-Pb**
  - **Reduced ITS + TRD online tracking (ITS standalone tracking, matching to TPC, extrapolation to TRD)**
  - **Reprocessing of all detectors when no beam (including full ITS + TRD tracking)**

→ **Full online TPC tracking defines peak compute load, ITS + TRD must be fast enough at reduced statistics.**

→ **Developing new track reconstruction derived from ALICE Run 2 HLT TPC tracking, heavy usage of GPUs.**

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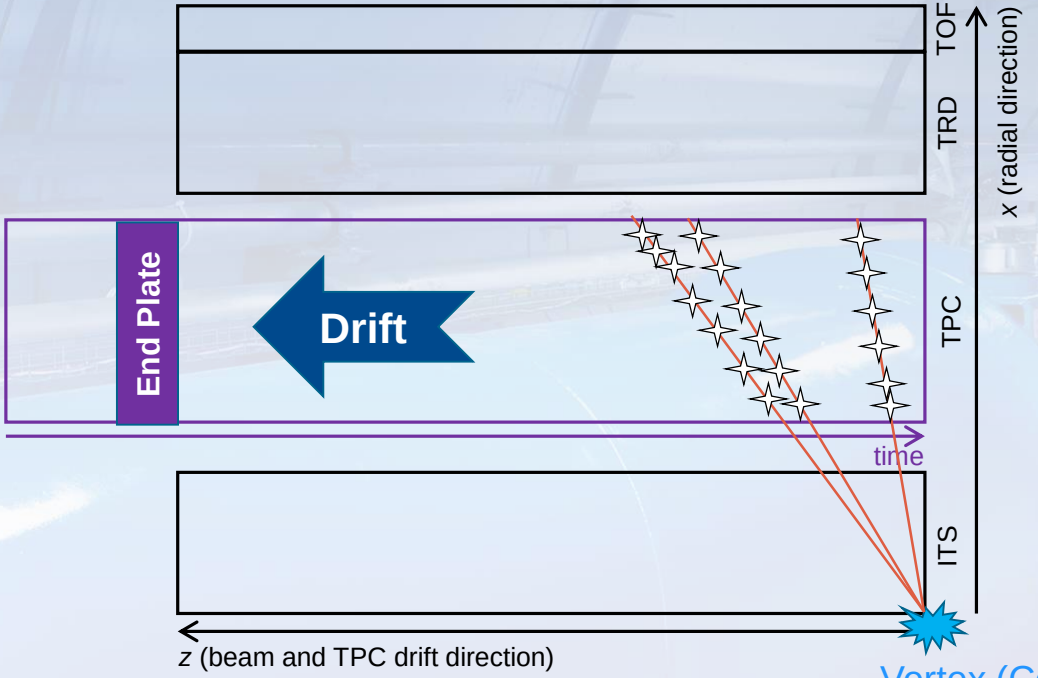
The tracking challenge

- **Tracking continuous data…**
  - The TPC sees **multiple overlapped collisions** (shifted in time).
  - Other detectors know the (rough) time of the collision.



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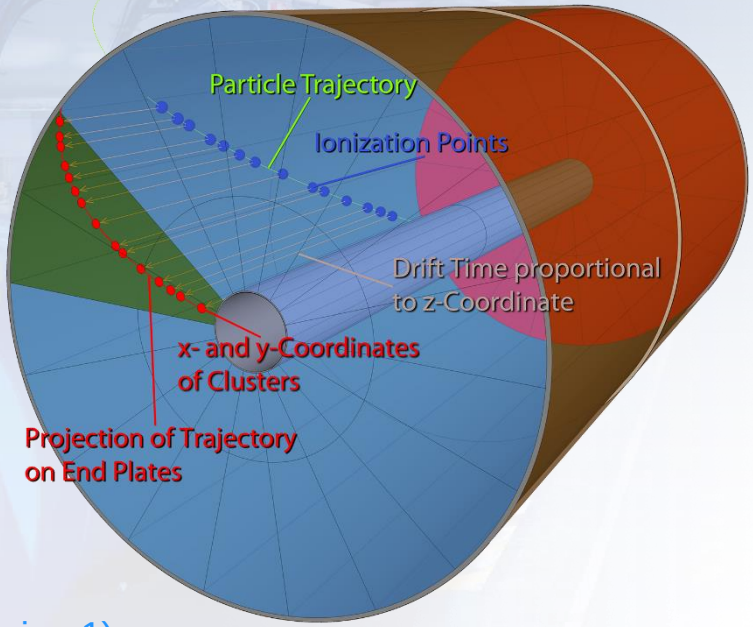

Vertex (Collision 1)

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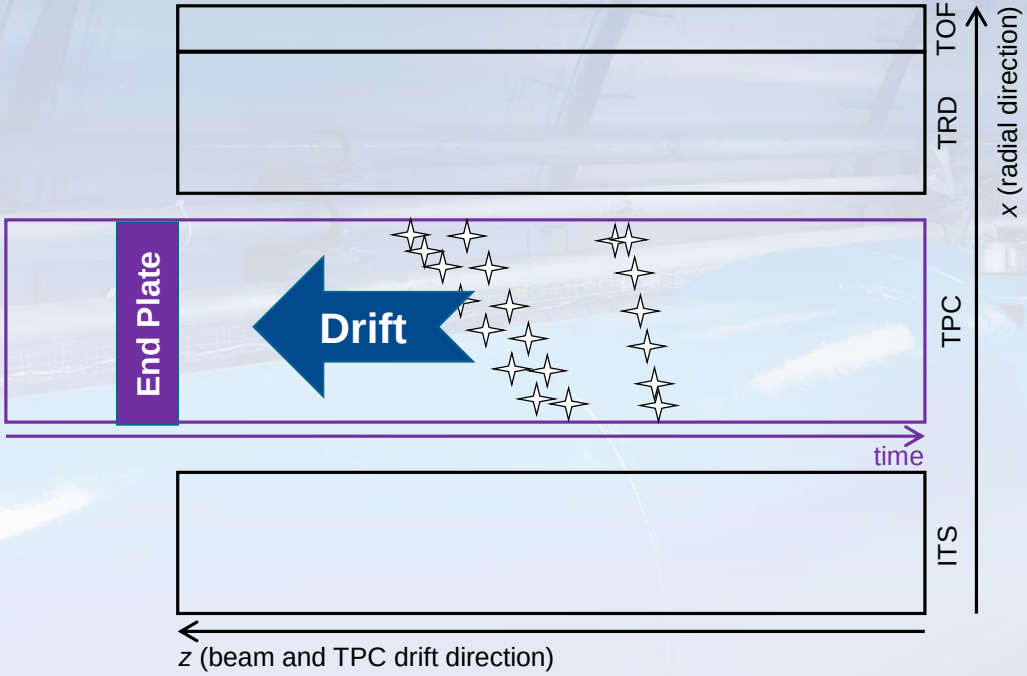

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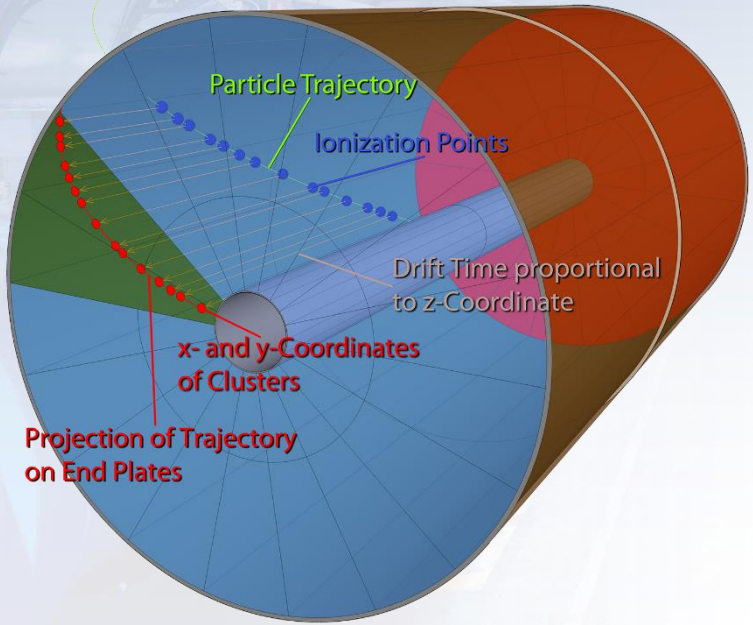

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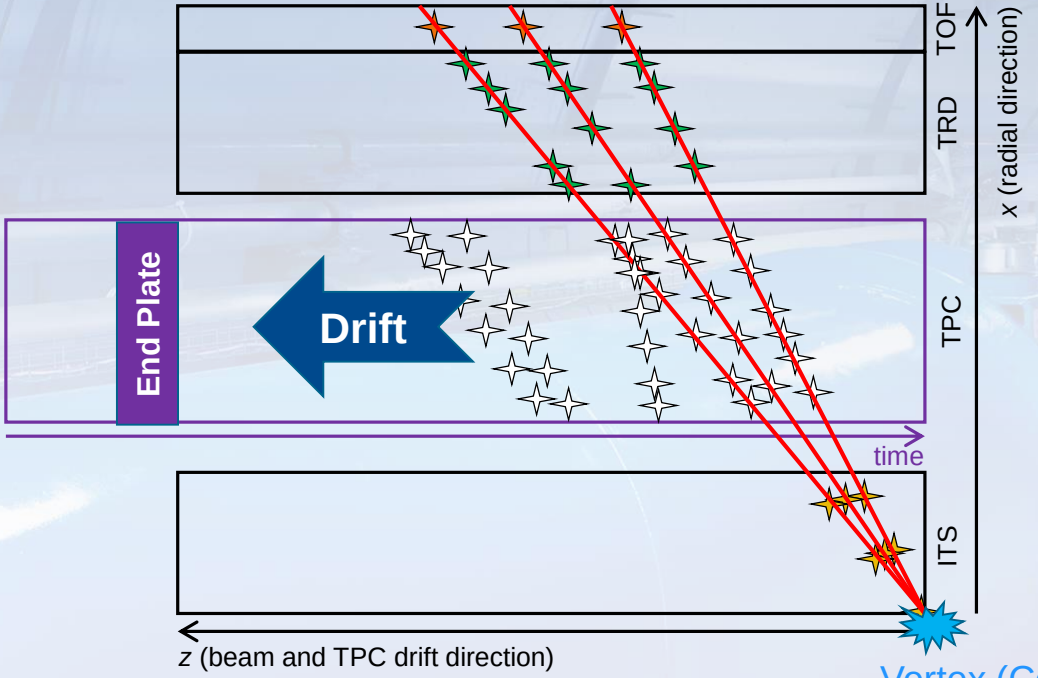

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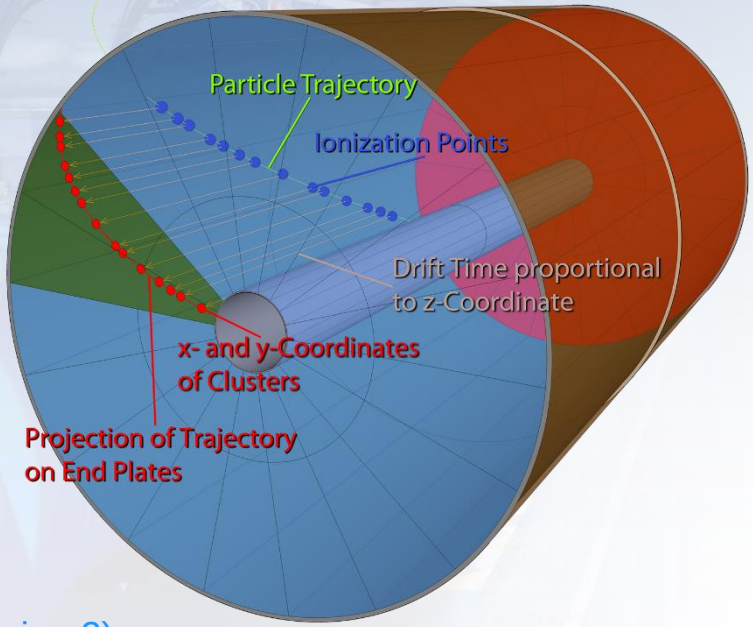

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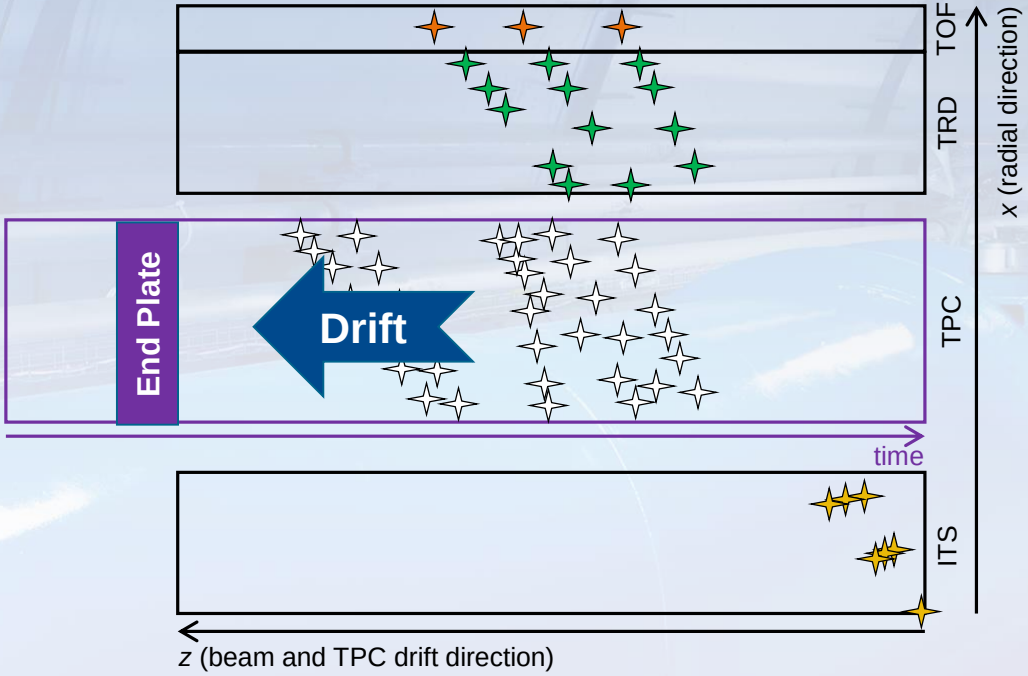

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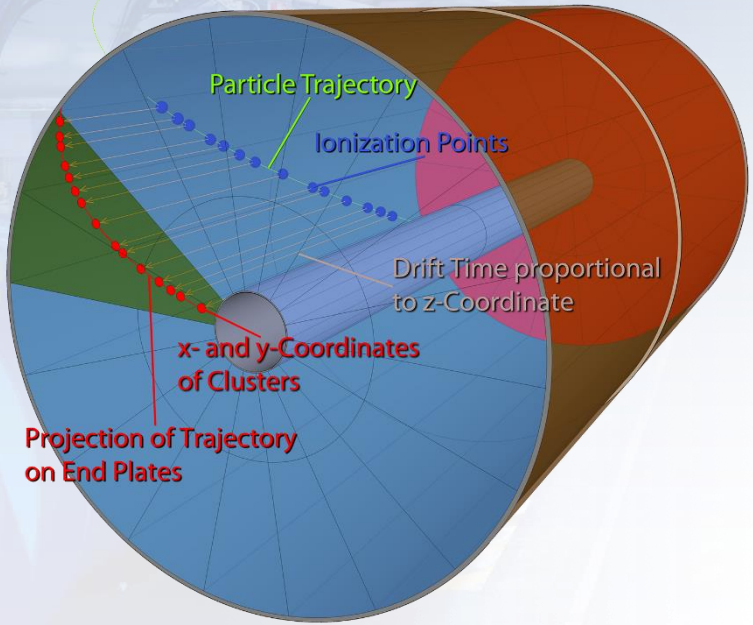

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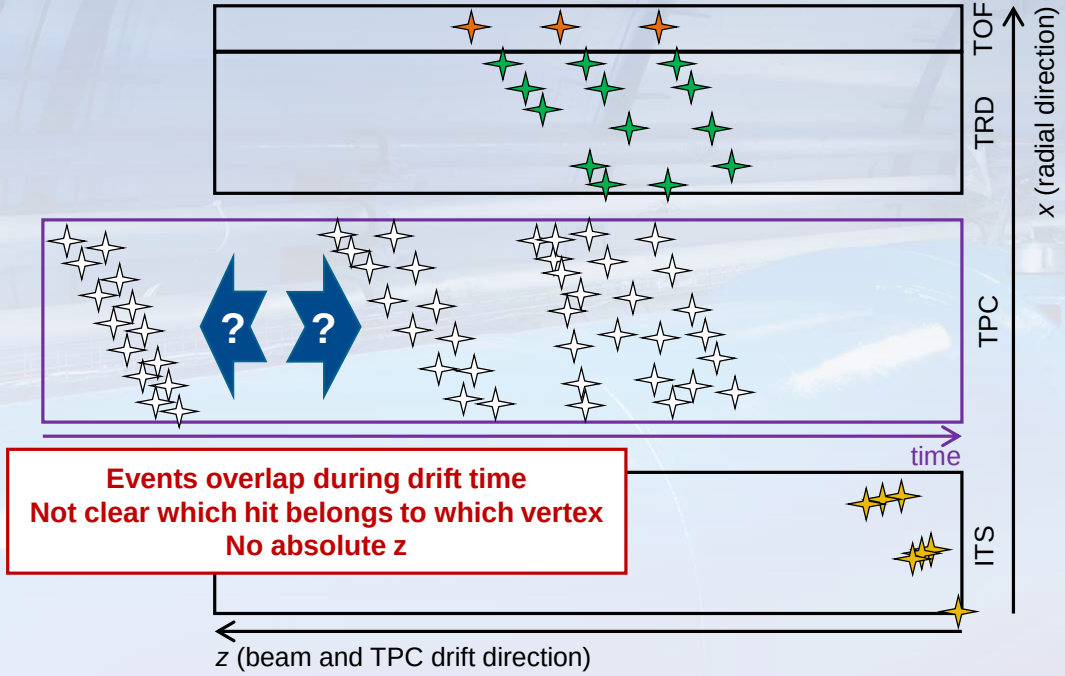

Events overlap during drift time
Not clear which hit belongs to which vertex
No absolute z

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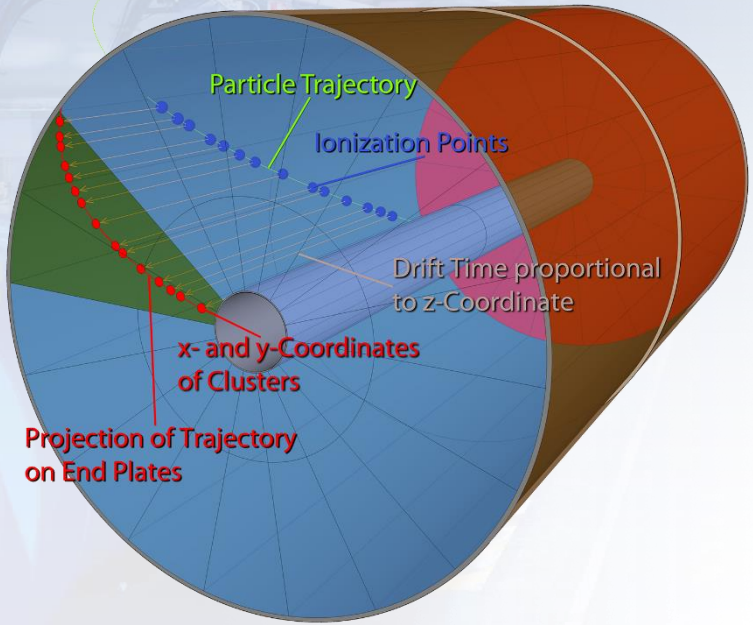

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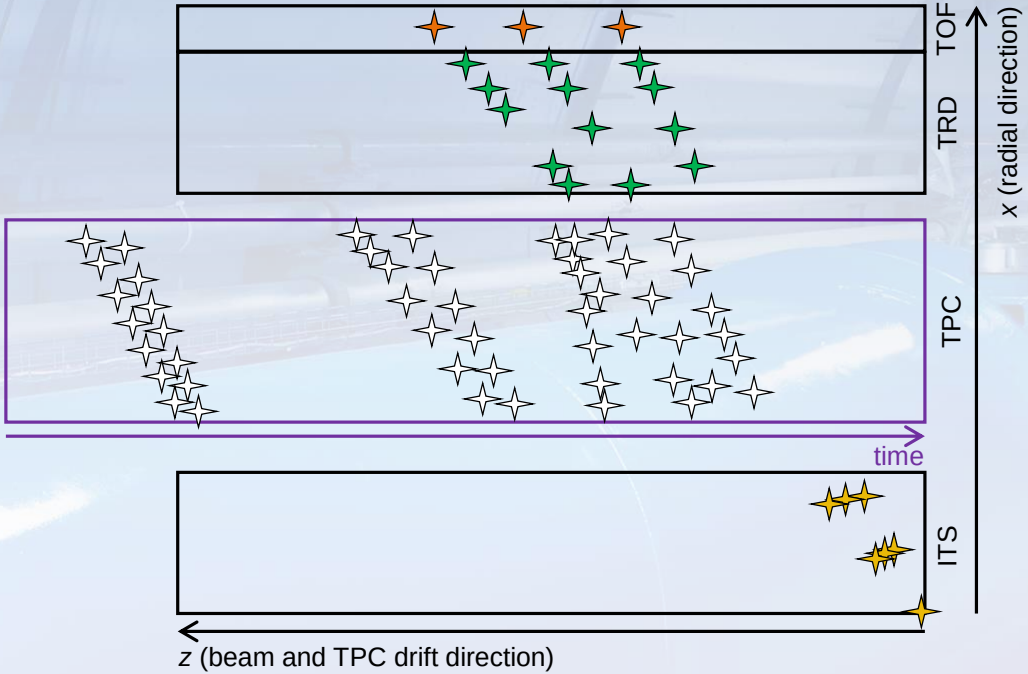

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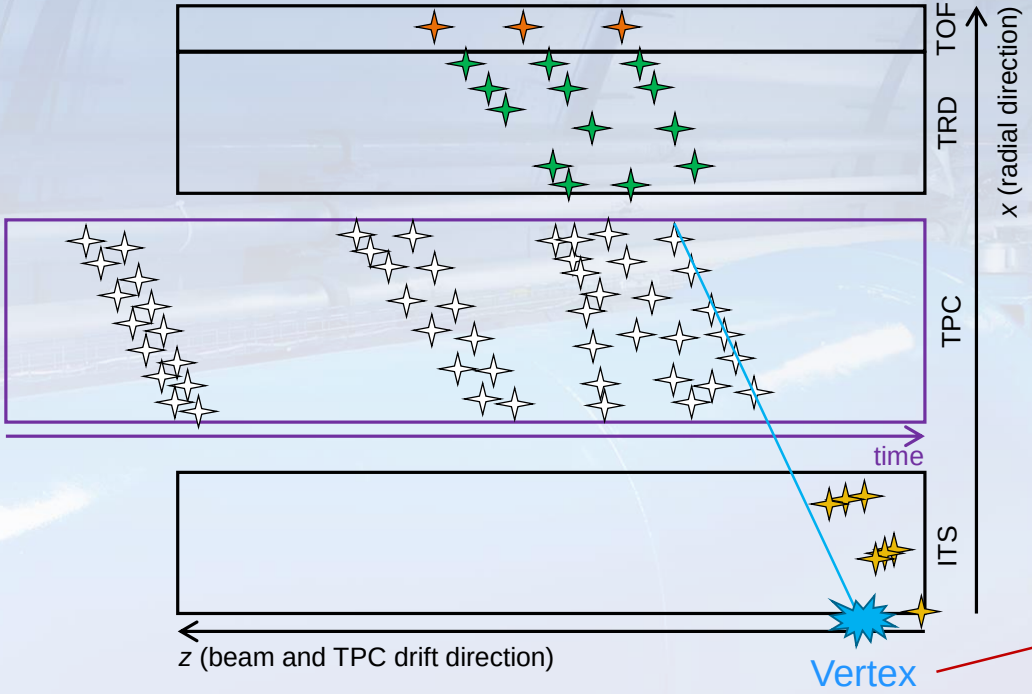

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$z \sim t - t_{Vertex}$

→ Need to identify the primary vertex, before assigning final *z* to cluster.

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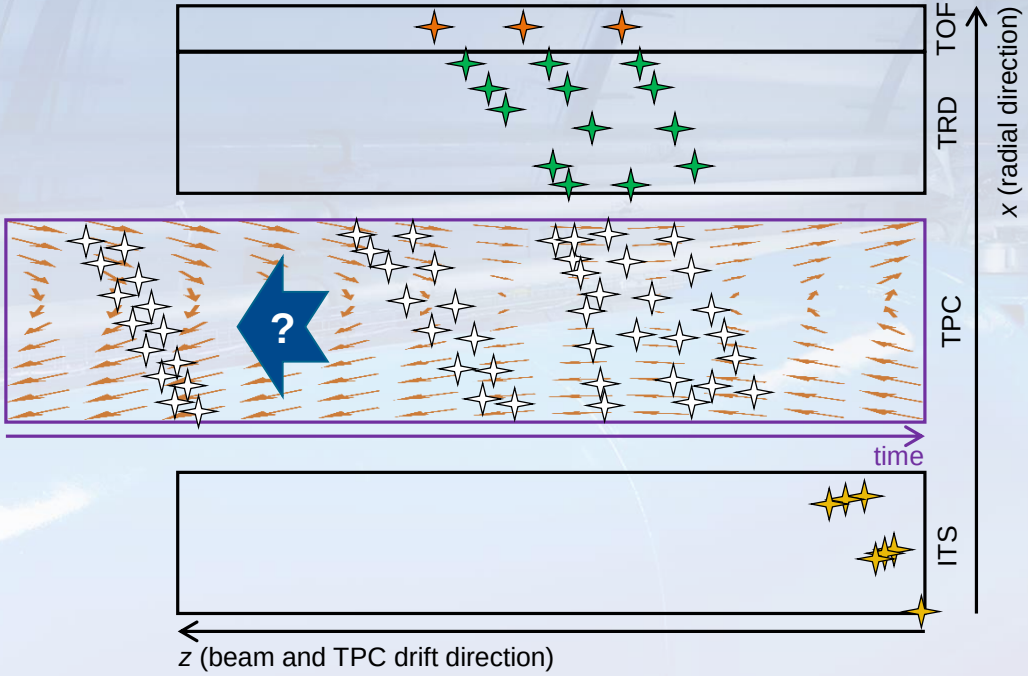

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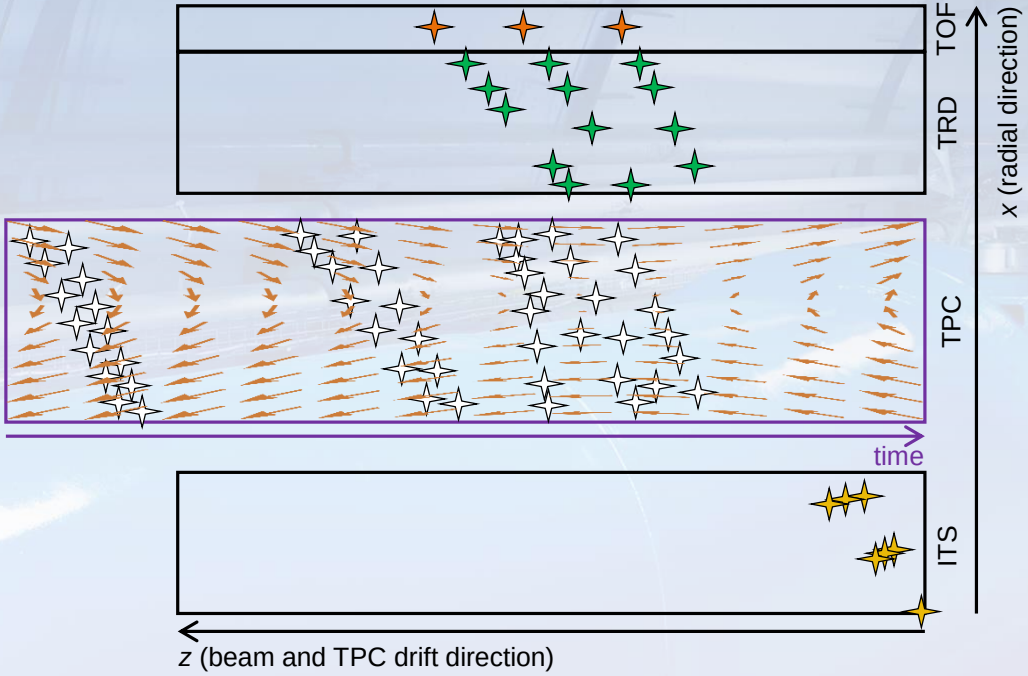

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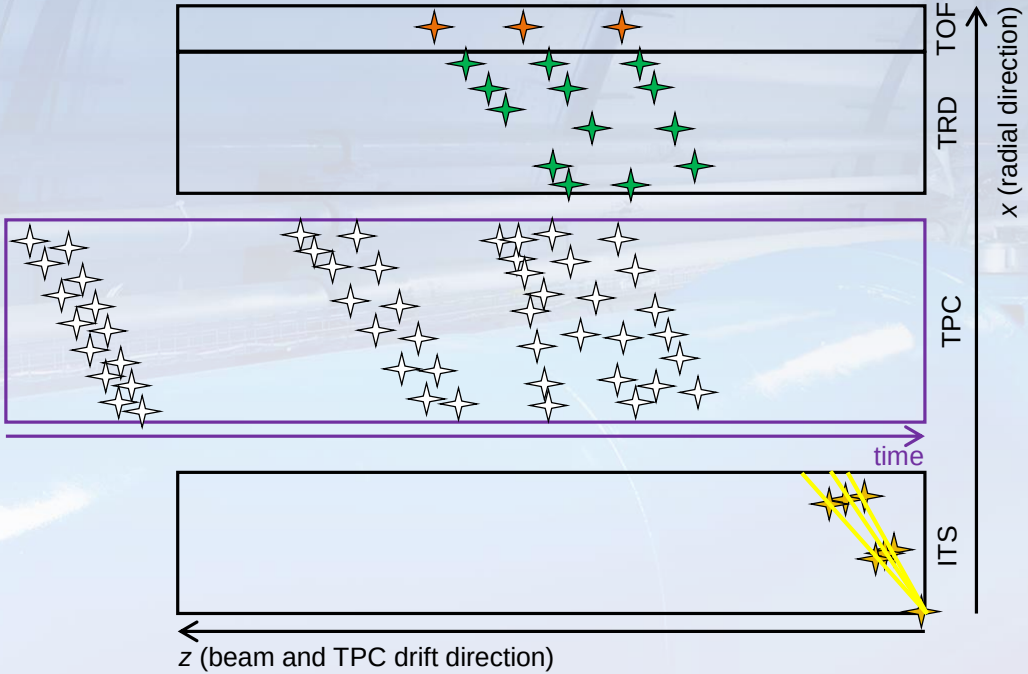

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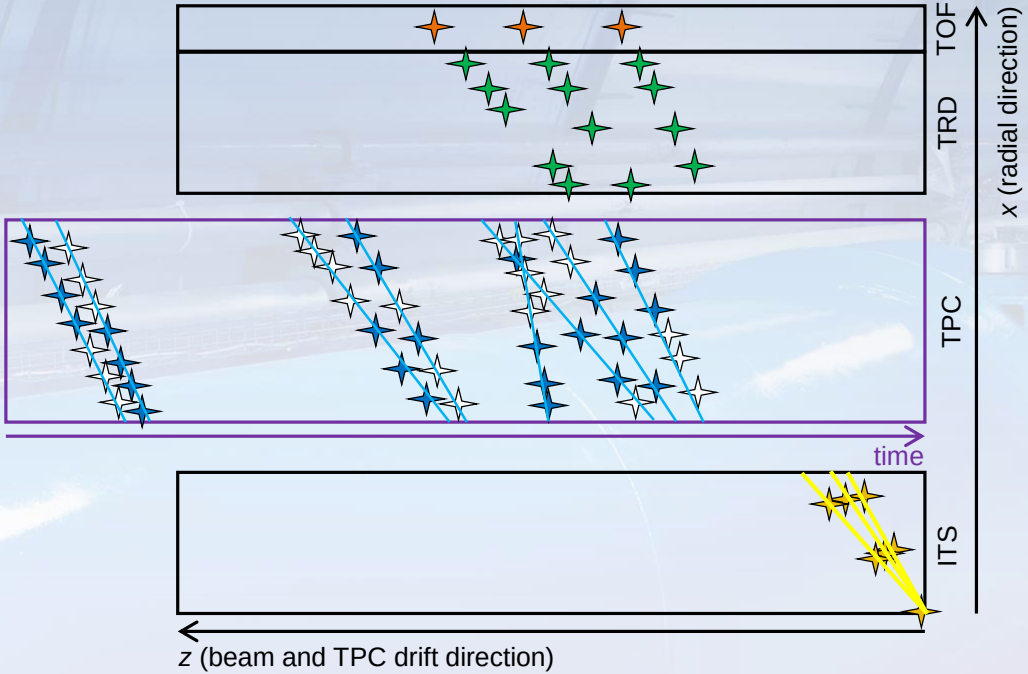

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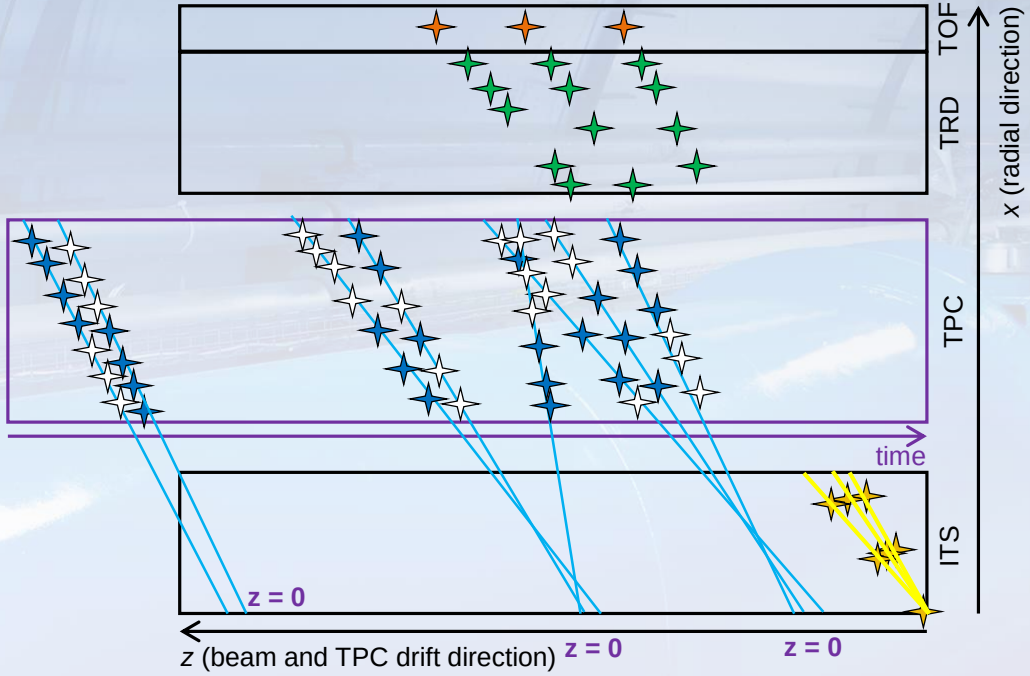

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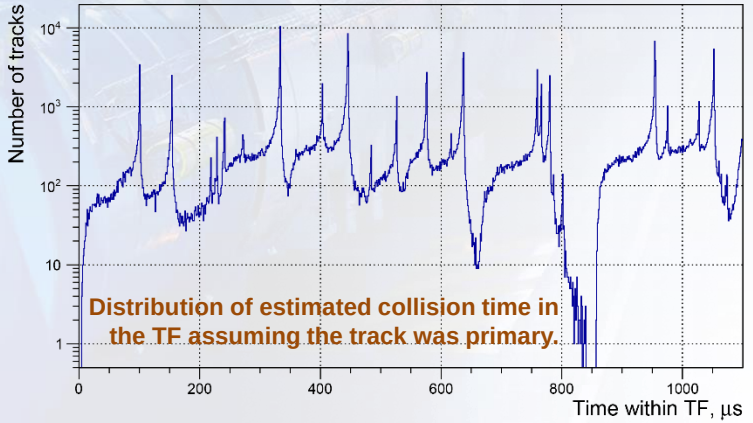

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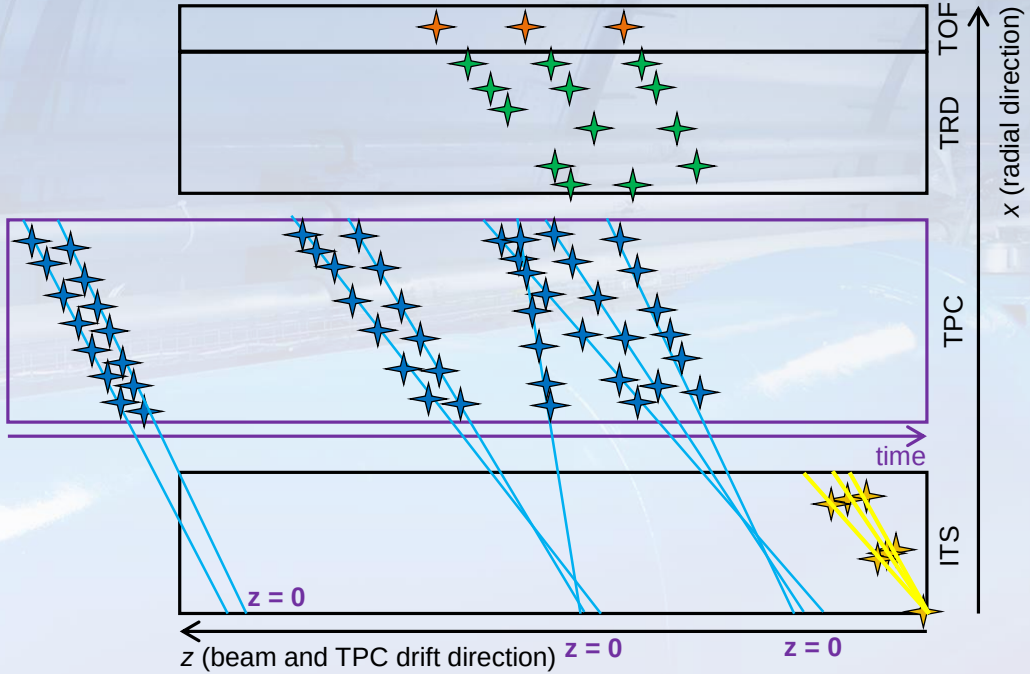

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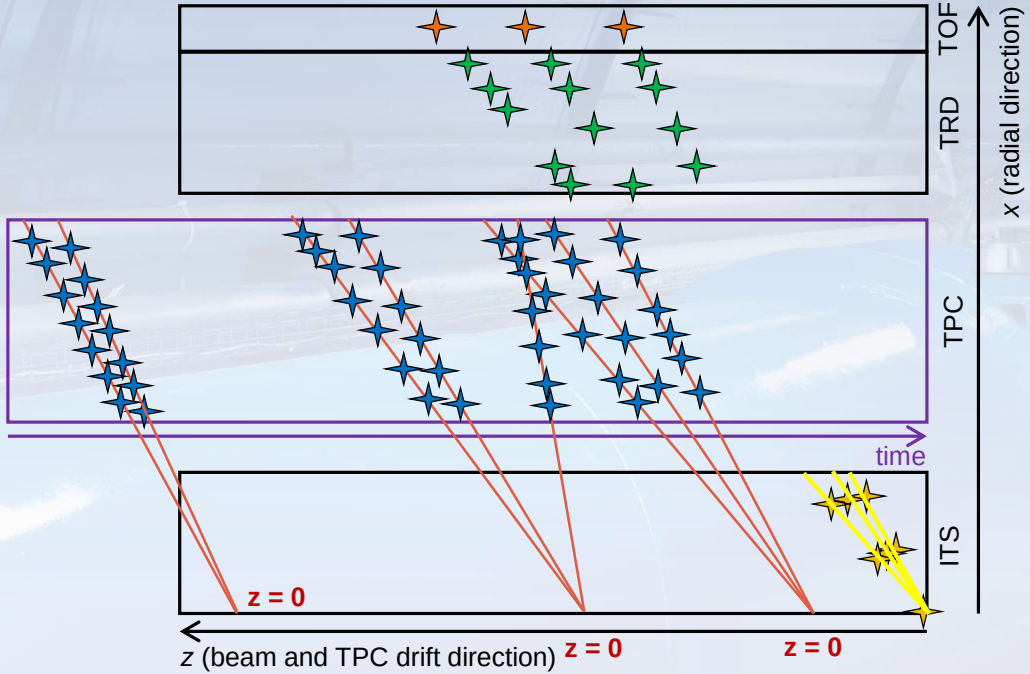

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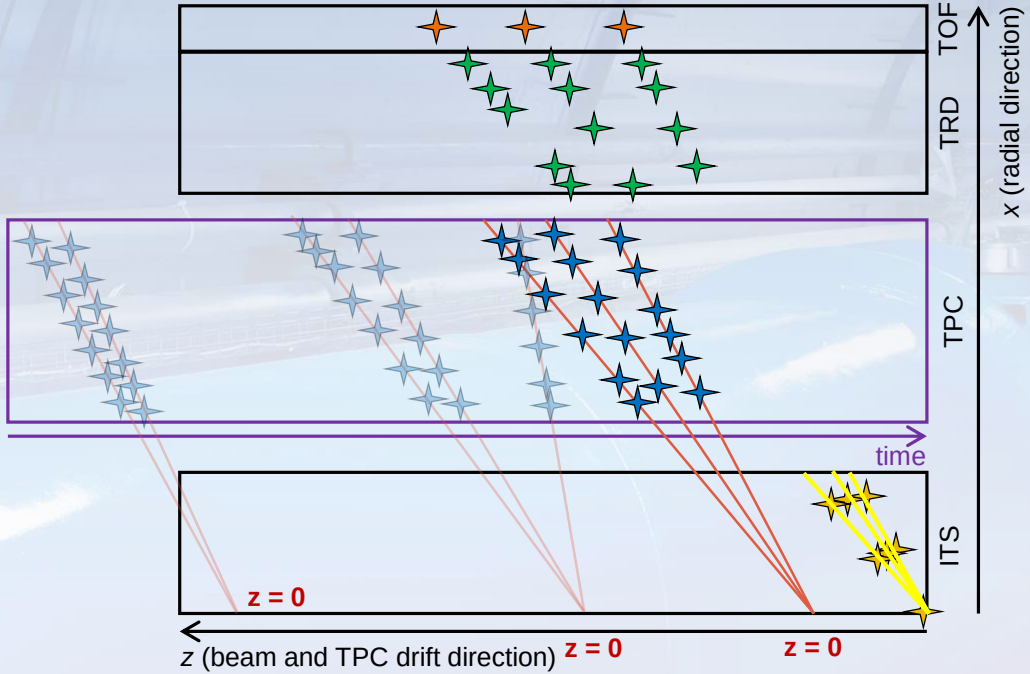

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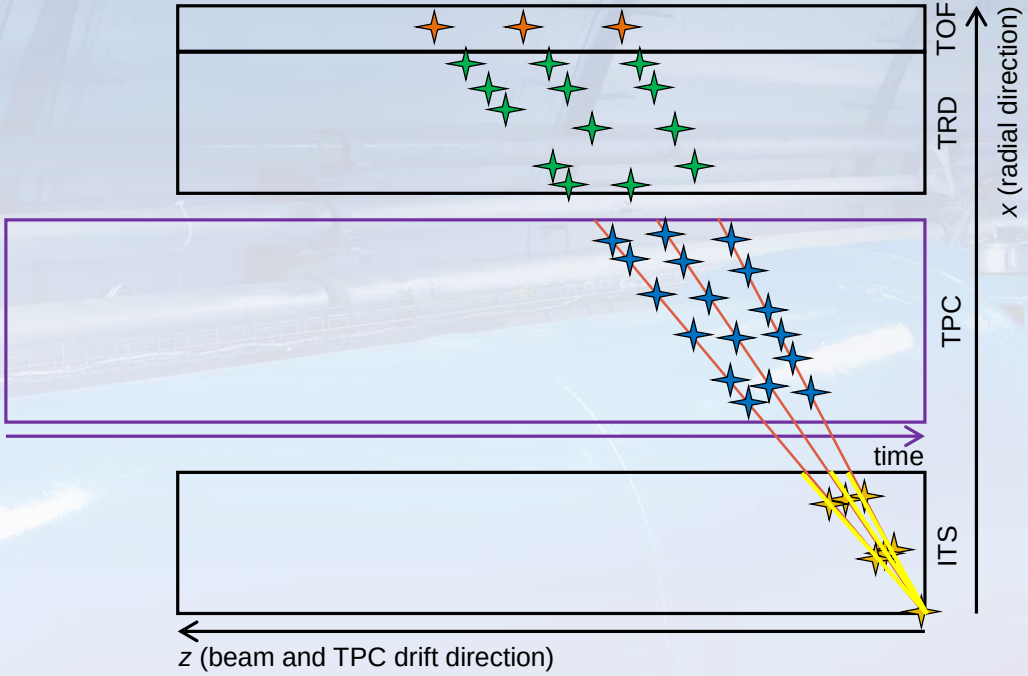

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- For the tracks seen in one ITS read out frame, select all TPC events with a matching time (from z = 0 estimate).
- Match TPC track to ITS track, fixing the time and thus the z position of the TPC track.

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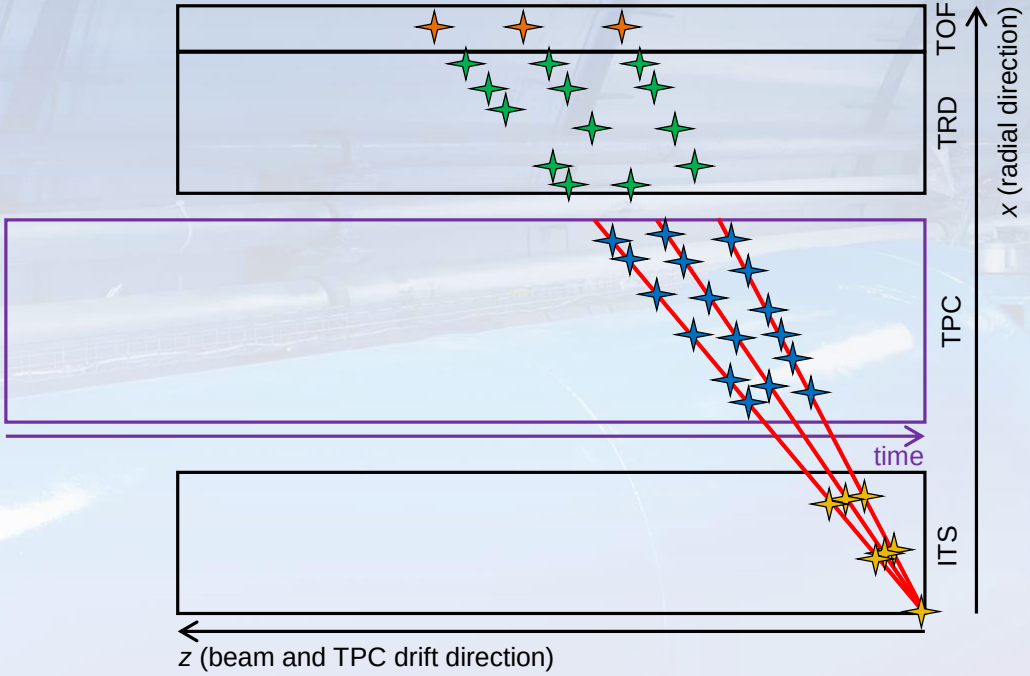

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- Refit ITS + TPC track outwards.

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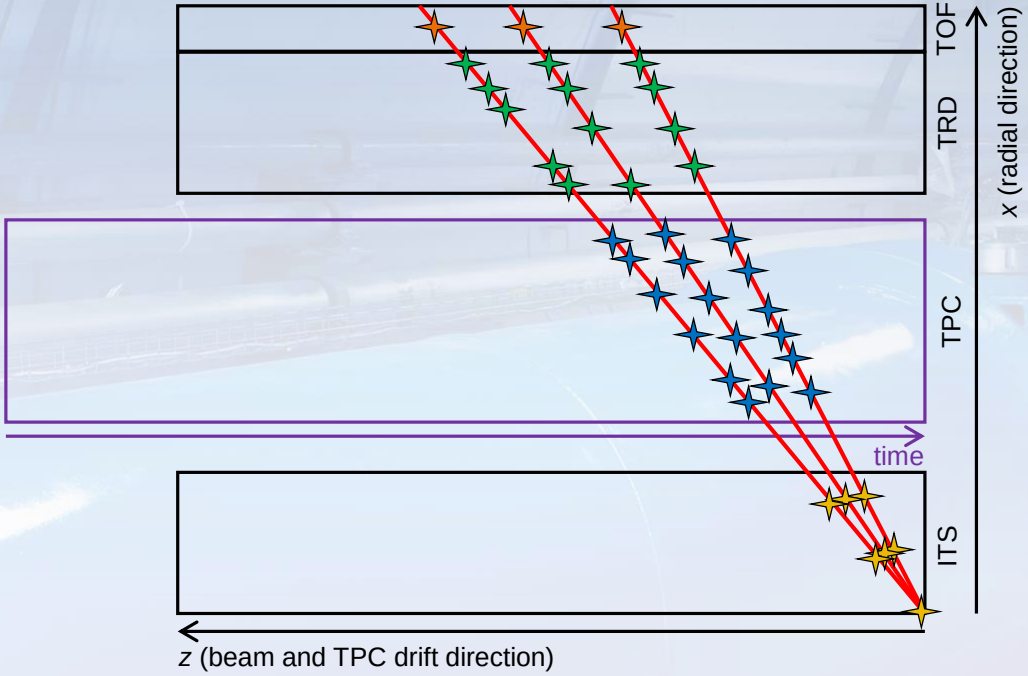

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- **GEM amplifications produces ions that deflect the electrons during the drift. The correction of these space-charge distortions requires the absolute z position.**

- Standalone ITS tracking.
- Standalone TPC tracking, scaling t linearly to an arbitrary z.
- Extrapolate to x = 0, define z = 0 as if the track was primary.
- Track following to find missing clusters. For cluster error parameterization, distortions, and B-field, shift the track such that z = 0 at x = 0.
- Refine z = 0 estimate, refit track with best precision
- For the tracks seen in one ITS read out frame, select all TPC events with a matching time (from z = 0 estimate).
- Match TPC track to ITS track, fixing the time and thus the z position of the TPC track.
- Refit ITS + TPC track outwards.
- Prolong into TRD / TOF.

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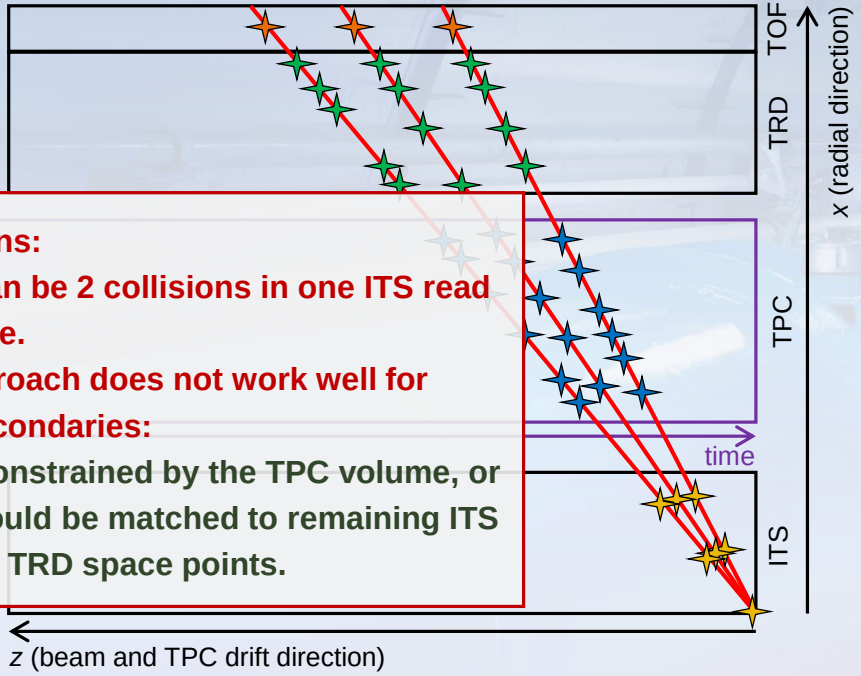
The tracking challenge – How the tracking will work

- **Tracking continuous data…**
  - The TPC sees **multiple overlapped collisions** (shifted in time).
  - Other detectors know the (rough) time of the collision.



Complications:

- **There can be 2 collisions in one ITS read out frame.**
- **The approach does not work well for deep secondaries:**
  - **Constrained by the TPC volume, or could be matched to remaining ITS or TRD space points.**

- **Problem: TPC clusters have no defined z-position but only a time. They can be shifted in z arbitrarily.**
- **GEM amplifications produces ions that deflect the electrons during the drift. The correction of these space-charge distortions requires the absolute z position.**

- Standalone ITS tracking.
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ALICE TPC Tracking Status

- **ALICE TPC tracking for O² developed.**
  - Derived from Run 2 HLT tracking (See https://indico.physics.lbl.gov/indico/event/149/contributions/222/attachments/216/230/berkeley-tracker.pdf).
    - Can track 40.000.000 tracks / second in the ALICE HLT.
  - Based on Cellular Automaton and Kalman Filter.
  - Uses GPU-acceleration to meet compute constraints.
    - Generic source code that run on CPU (with OpenMP) and GPU (CUDA and OpenCL)
    - Identical results from GPU and CPU version.
  - Adapted for ALICE O² software, available in standard software installation since 2018.
    - Improved efficiency and resolution compared to Run 2 in order to match offline quality.
    - Added low-p_T tracking to enable cluster rejection needed for Run 3 data reduction.

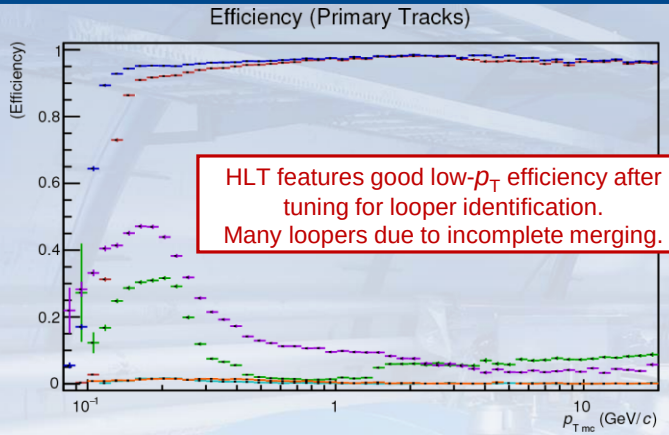
- **TODO: Make slide nice!**

Tracking efficiency (Run 2, O²/HLT v.s. Offline – Pb-Pb)

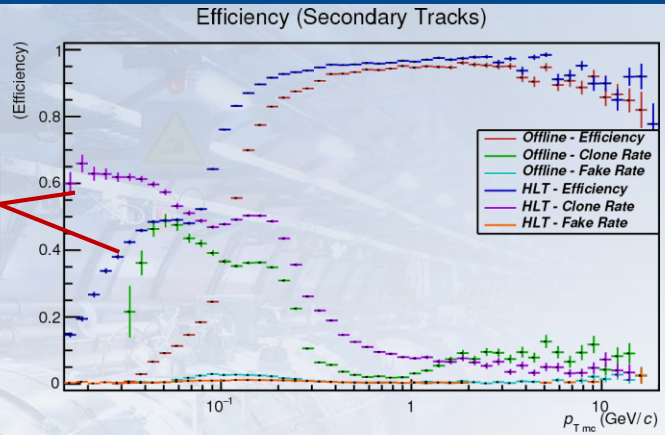
- New HLT / O² tracking shows comparable efficiency to Run 2 offline tracking.
- In certain situations the new tracking is already superior thanks to tuning for Run 3 conditions.

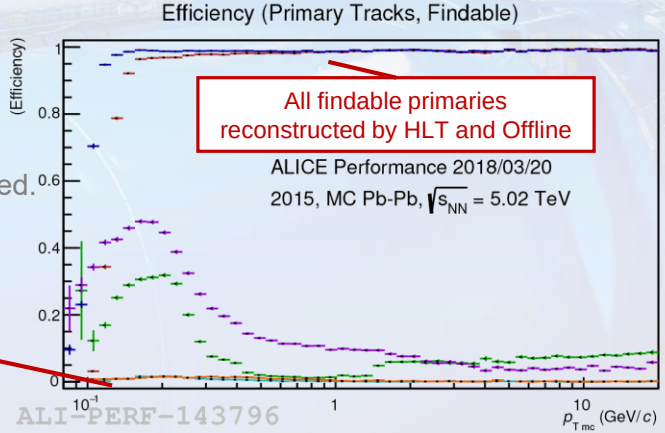
- All plots are Monte Carlo.
- All plots are TPC only.
- Resolutions at inner end of TPC.
- Findable tracks: min 70 TPC hits.
- Others: min 1 TPC hit.
- Other offline features (dE/dx, …) disabled.
- Same calibration for offline / HLT.
- Same cluster error parameterization.

(See backup for proton-proton plot.)



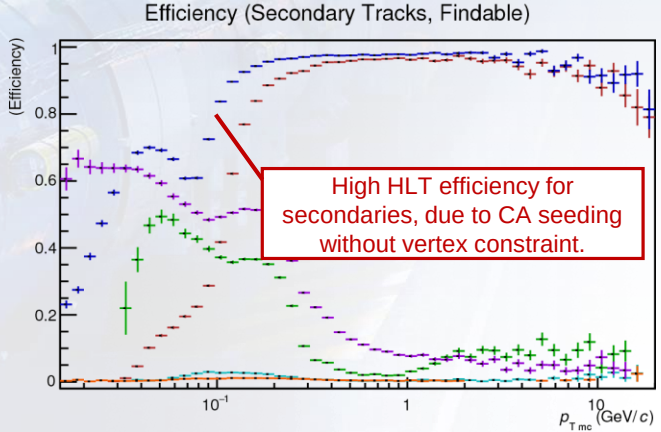
HLT features good low-p_T efficiency after tuning for looper identification.
Many loopers due to incomplete merging.





All findable primaries reconstructed by HLT and Offline

Practically zero fake rate for both trackers



High HLT efficiency for secondaries, due to CA seeding without vertex constraint.

ALI-PERF-143796

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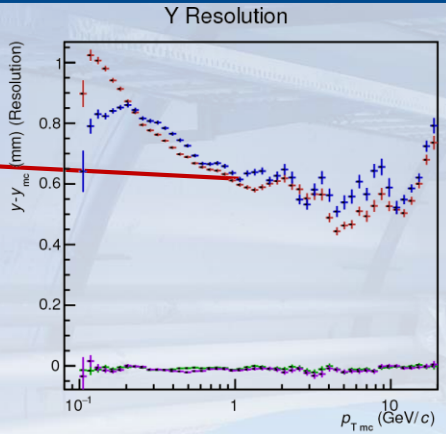
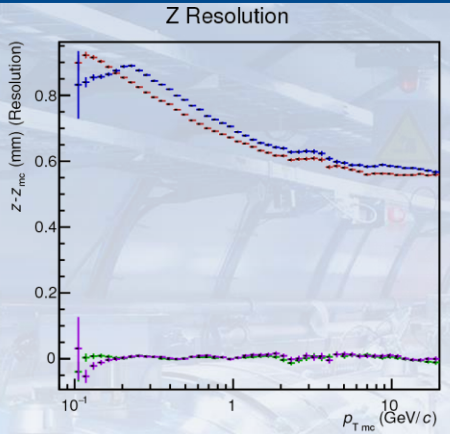
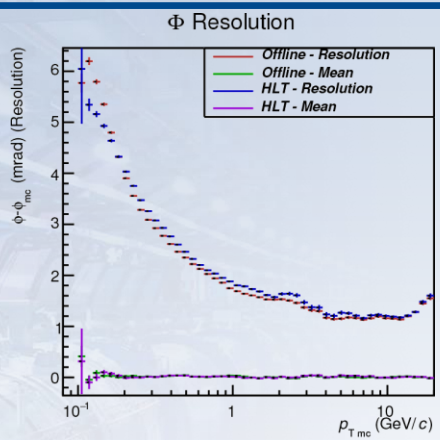
Track resolution (Run 2, Pb-Pb, with space-charge distortions)

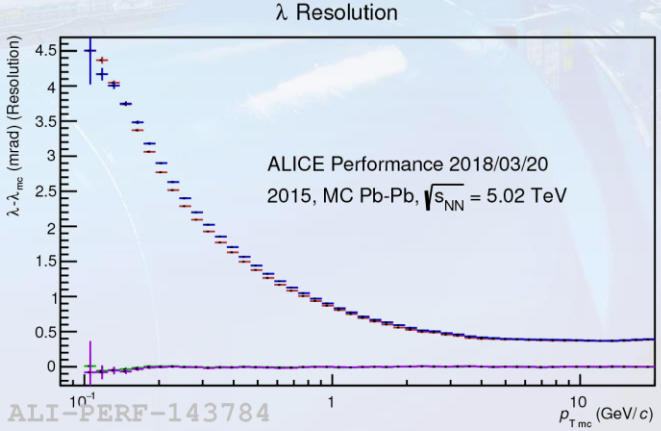
- Small differences with space-charge distortions.
- Similar structure in y-resolution.

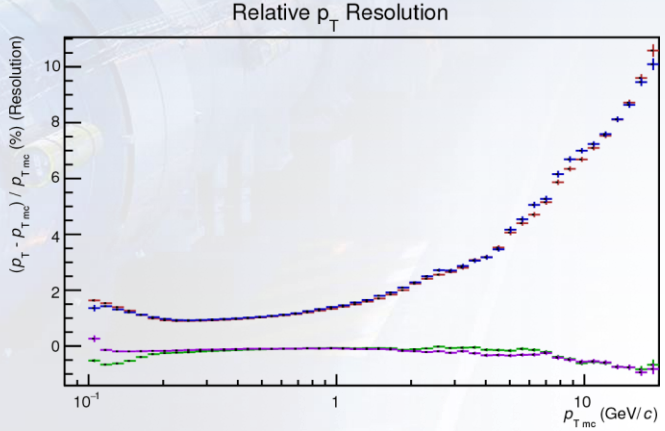
- HLT/O² has not been tuned for distortions so far.
- Only using systematic cluster error parameterization obtained from offline distortion map residuals.











(See poster of S. Gorbunov.)

(See backup for without distortions.)

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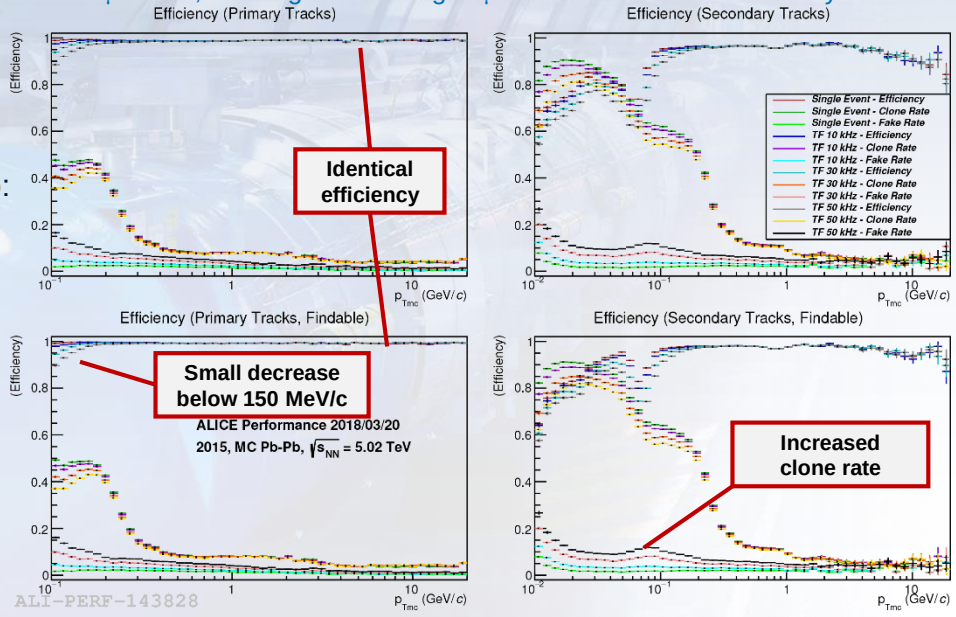
Track fit / finding stability

- Various benchmarks ensure same results in O2 scenario as during Run 2:
  - z-independent tracking: Take “normal” Run 2 event, forget about absolute z an process like O2 time frame:
    - Identical efficiency, negligible resolution decrease for secondaries.
  - In bunch pile up: μ = 100 to 1000 in proton-proton:
    - No change up to μ = 300, minor efficiency decrease for secondaries above μ = 300, tracking still working at μ = 1000 at reduced efficiency.
    - No effect on resolution.
  - Length of time frame (100 μs to 20 ms):
    - No difference (with fix for limited single precision float accuracy).
  - **TPC occupancy: Single event to 50 kHz time frame Pb-Pb**: *(see figure on the right)*
    - Resolution identical.
    - Small efficiency decrease below 150 MeV/c.
    - Clone rate of short low-p_T tracks increases with occupancy.



(See backup for respective figures)

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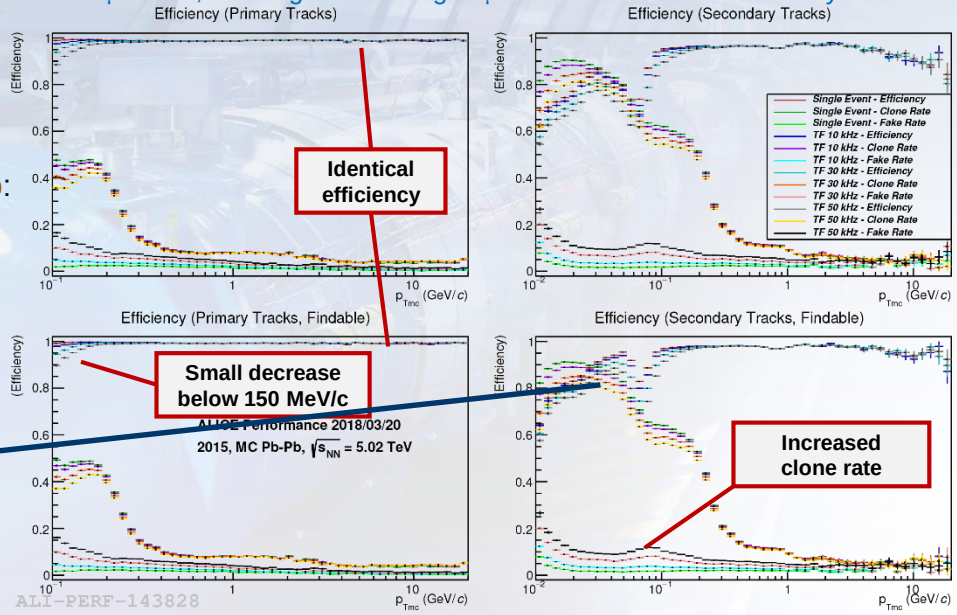
    - Small efficiency decrease below 150 MeV/c
    - Clone rate of short low-p_T tracks increases with occupancy.

Good efficiency for low-p_T looping secondaries.

- Absolutely crucial for rejecting tracks not used for physics.
- High clone rate due to incomplete implementation of low-p_T merging.

(See backup for respective figures)



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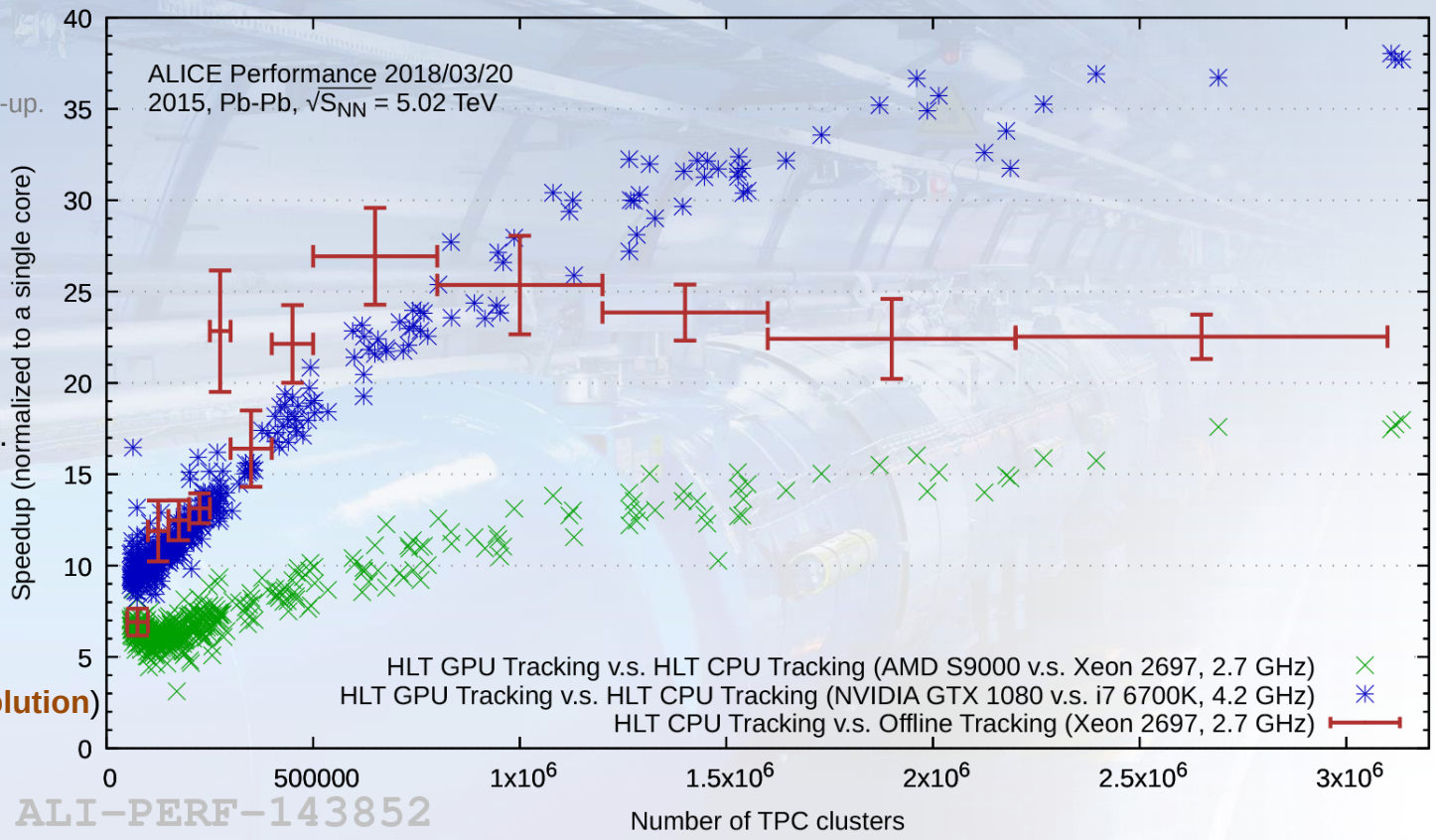
Tracking time

Speed-up normalized to single core.

- Red curve: exactly the speed-up.
- Other curves: corrected for required CPU resources.
  - How many cores does the GPU replace.

- Significant (**>20x**) **speed-up** compared to offline.
- A modern GPU replaces about **40 cores @4.2 GHz**.
- Significant gain with new GPU models.
- One GPU replaces **>800 CPU cores** running Run 2 Offline tracking. (**at same efficiency / resolution**)



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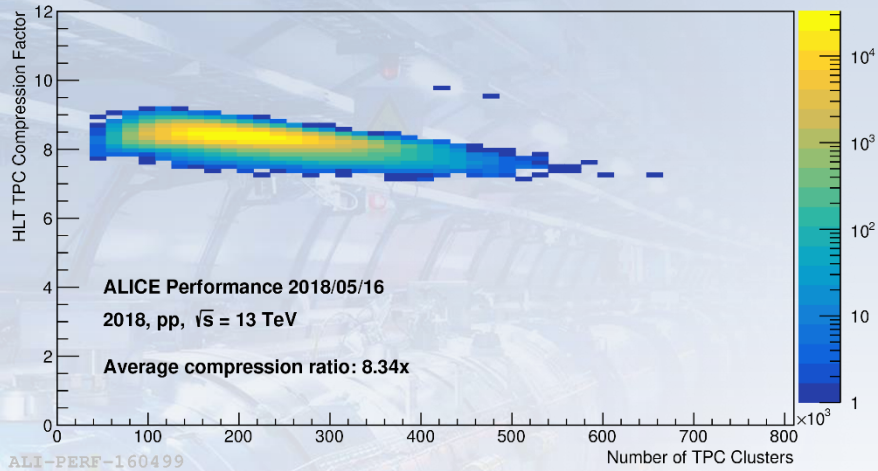
TPC Data Compression

- TPC Data compression involves 3 steps:
  1. Entropy reduction (Track model, logarithmic precision, etc.)
  2. Entropy encoding
  3. Removal of tracks not used for physics.

- Steps 1 + 2 implemented for Run 2.
  - Current compression factor **8.3x**.
  - Prototype for Run 3 achieves factor 9.1x.

- Missing factor ~2 to reach total reduction factor 20x for Run 3.



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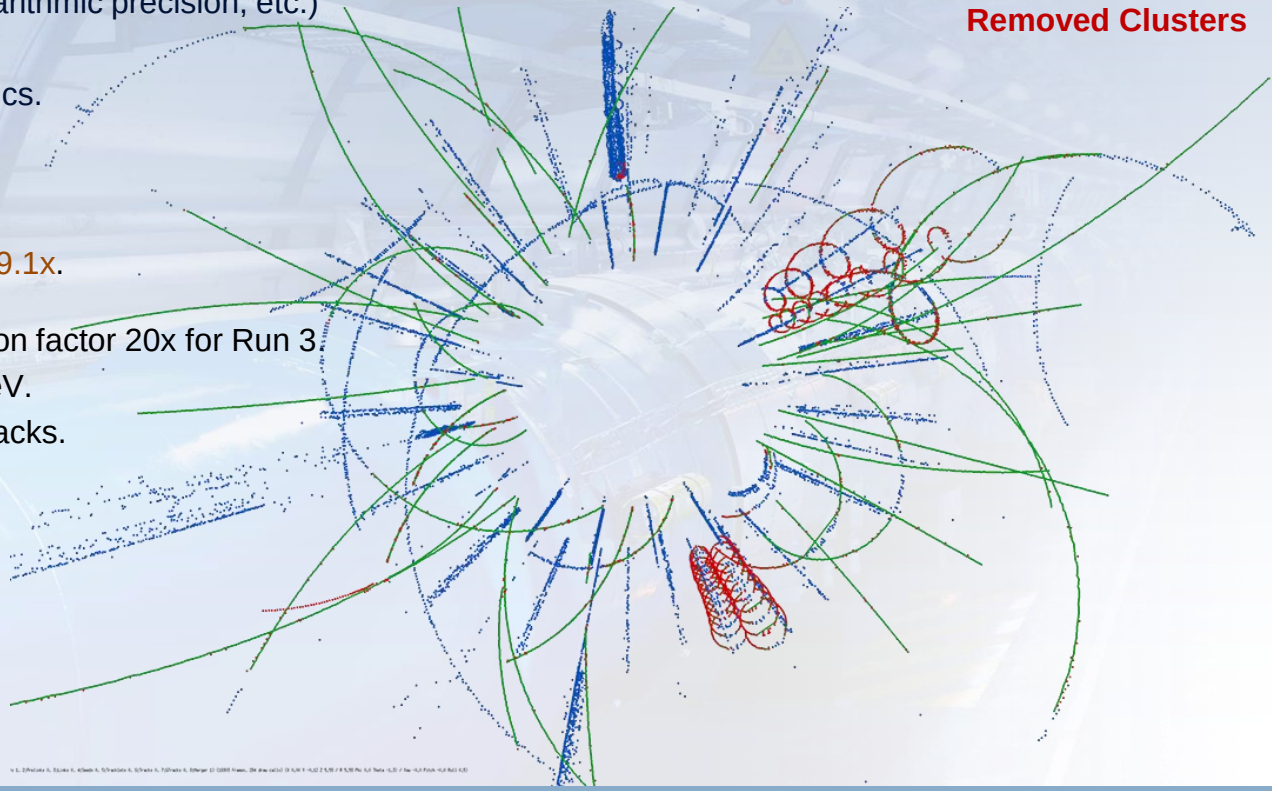
- Steps 1 + 2 implemented for Run 2.
  - Current compression factor **8.3x**.
  - Prototype for Run 3 achieves factor 9.1x.

- Missing factor ~2 to reach total reduction factor 20x for Run 3.
  - Remove non-physics tracks < 50 MeV.
  - Remove additional legs of looping tracks.
  - Remove track segments with high inclination angle.

- **TODO: Better event display!**



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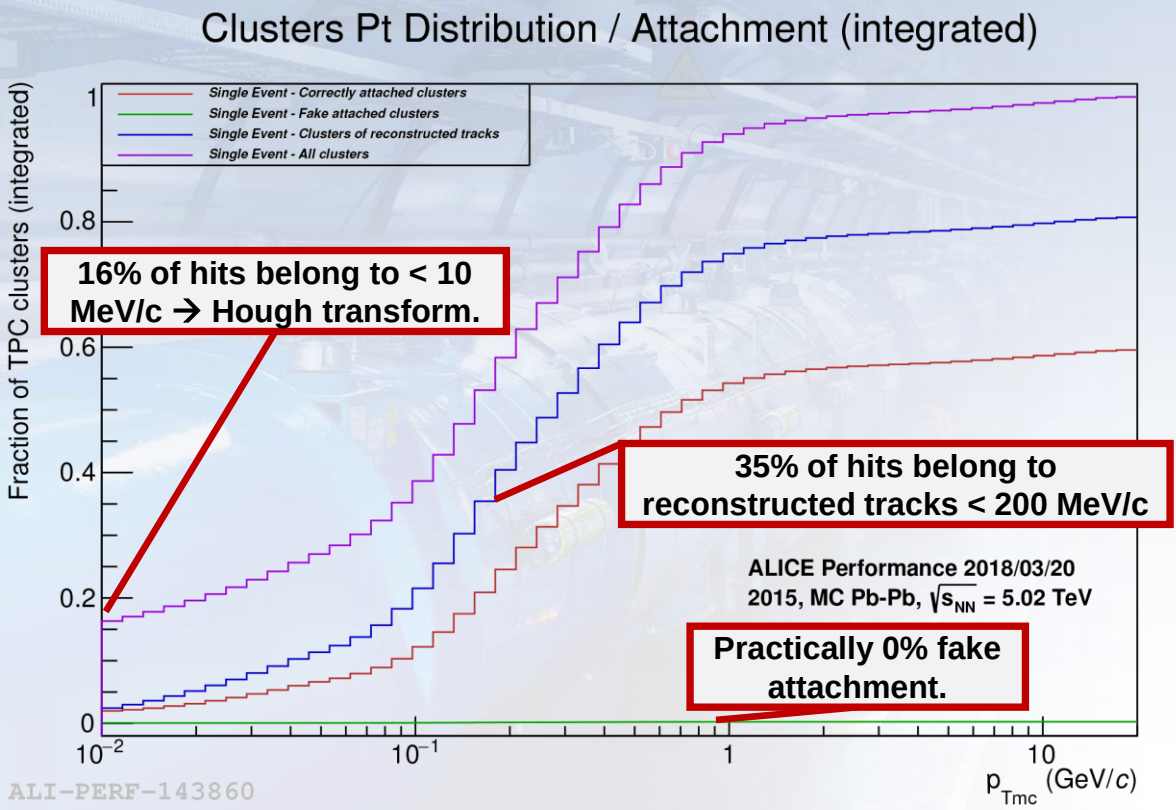
Cluster removal for O²

- Integrated plot:
  - Purple: all clusters
  - Red: clusters attached to the correct track.
  - Green: clusters attached to wrong track.
  - Blue: All clusters (if attached or not) of a reconstructed track.

  - **TODO: Outdated plot, update, add text.**



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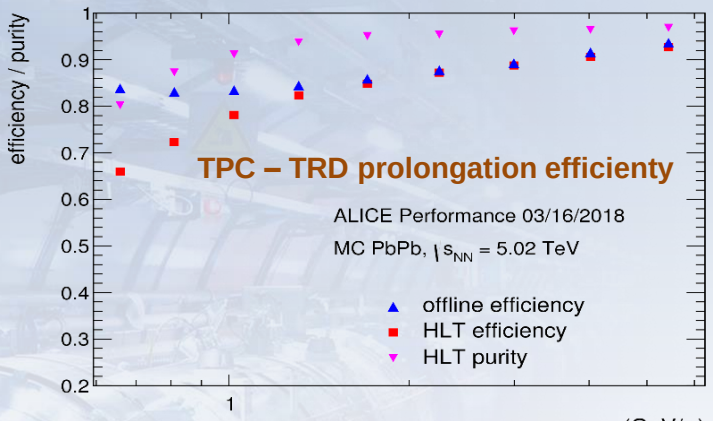
Global Tracking (TPC + ITS + TRD)

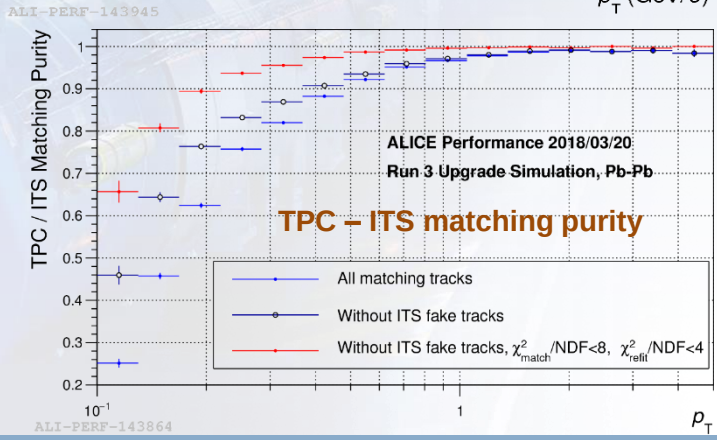
(R. Shahoyan, M. Puccio, O. Schmidt)

- **TPC-TRD Prolongation TRD developed within HLT framework.**
  - Good efficiency so far, comparable to offline.
  - Online version uses only TRD tracklets.
  - Decrease for low-p_T due to absence of TRD hits in Run 3.
  - Reduced purity in Pb-Pb due to large amount of TRD fake tracklets.
  - See: TODO

- **Status of TRD and ITS tracking**:
  - GPU-accelerated ITS standalone tracking under development. (first version available)
  - TPC to ITS track matching available (comparable purity as in Run 2).
  - See poster of M. Concas!

- **Next steps**:
  - Work on combined TPC + ITS + TRD tracking and fit on GPU without intermediate data transfer.
  - Test TPC calibration procedure using TPC + ITS + TRD tracking.





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Summary

- TODO

BACKUP

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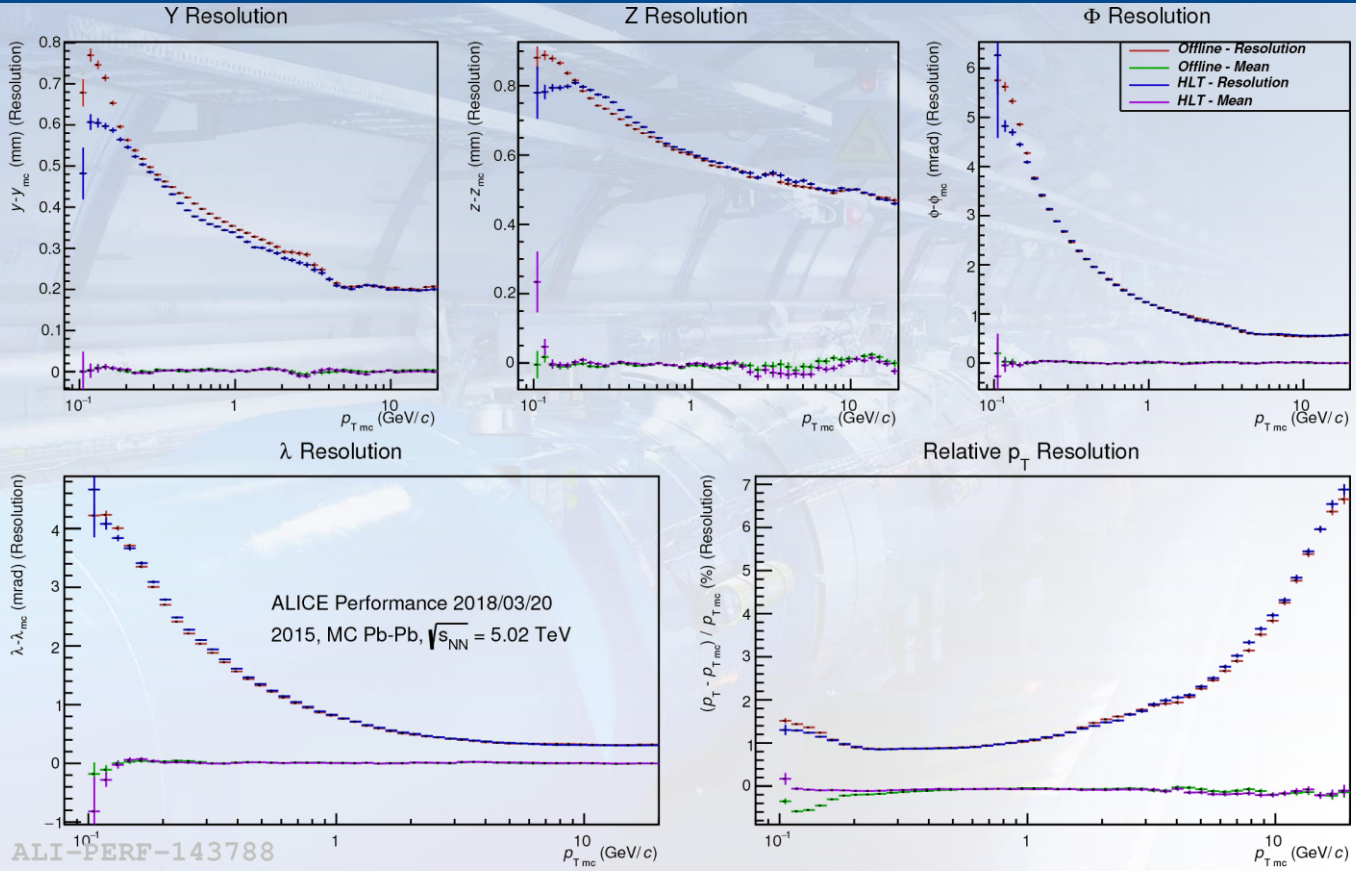
Track resolution (Run 2, Pb-Pb, no space-charge distortions)

- HLT / Offline resolution practically identical (no space-charge distortions).

- Improvements in HLT tracking:
  - Propagation using polynomial approximation of 3D B-field.
  - Outlier cluster rejection during refit.
  - Improved cluster error parameterization, depending on flags set by clusterizer. (edge, deconvoluted, …)
  - 3-way fit. (inward, outward, inward)



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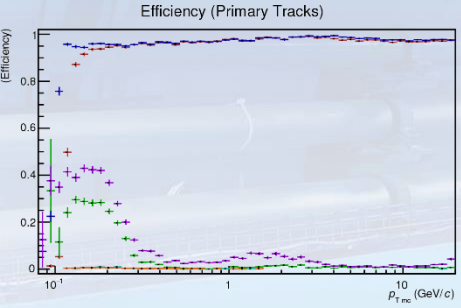
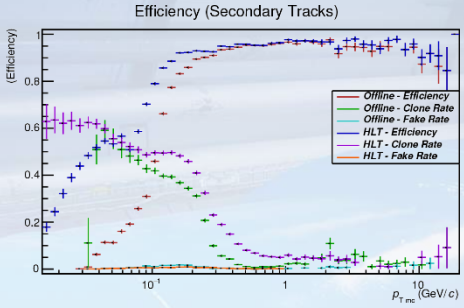
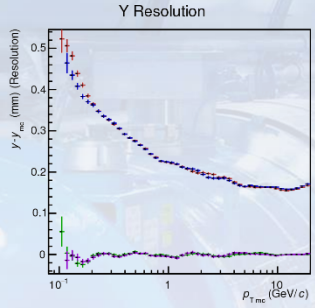
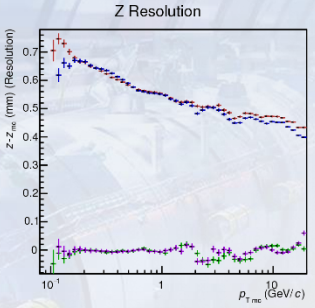
Tracking efficiency / resolution (Run 2, HLT v.s. Offline – pp)

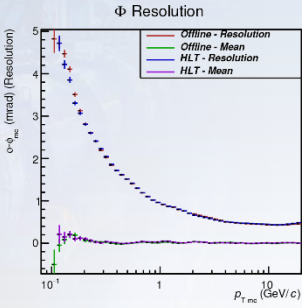
- **For reference (same situation for pp).**
  - Identical resolution.
  - Same efficiency for primaries.
  - Better efficiency for secondaries / low p_T.

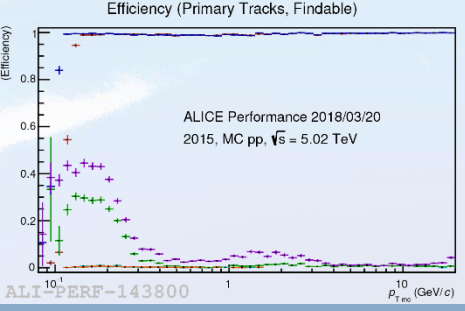


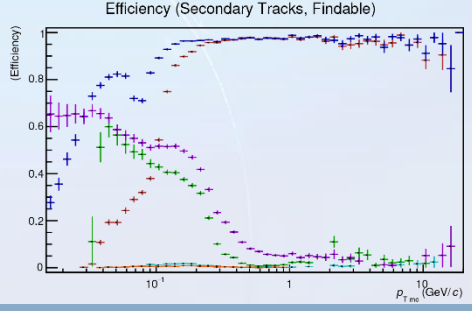


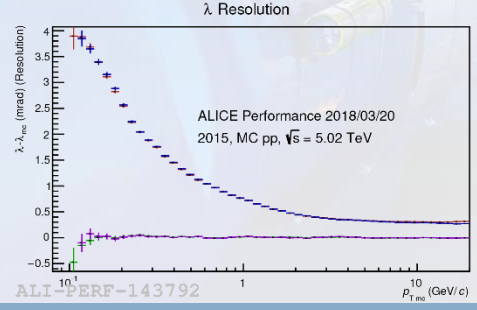


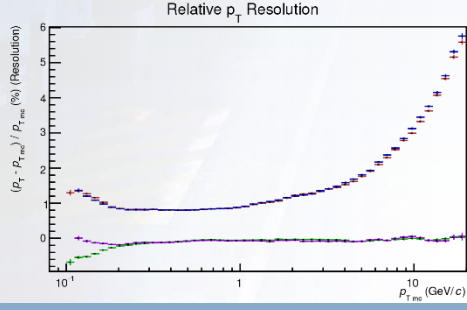












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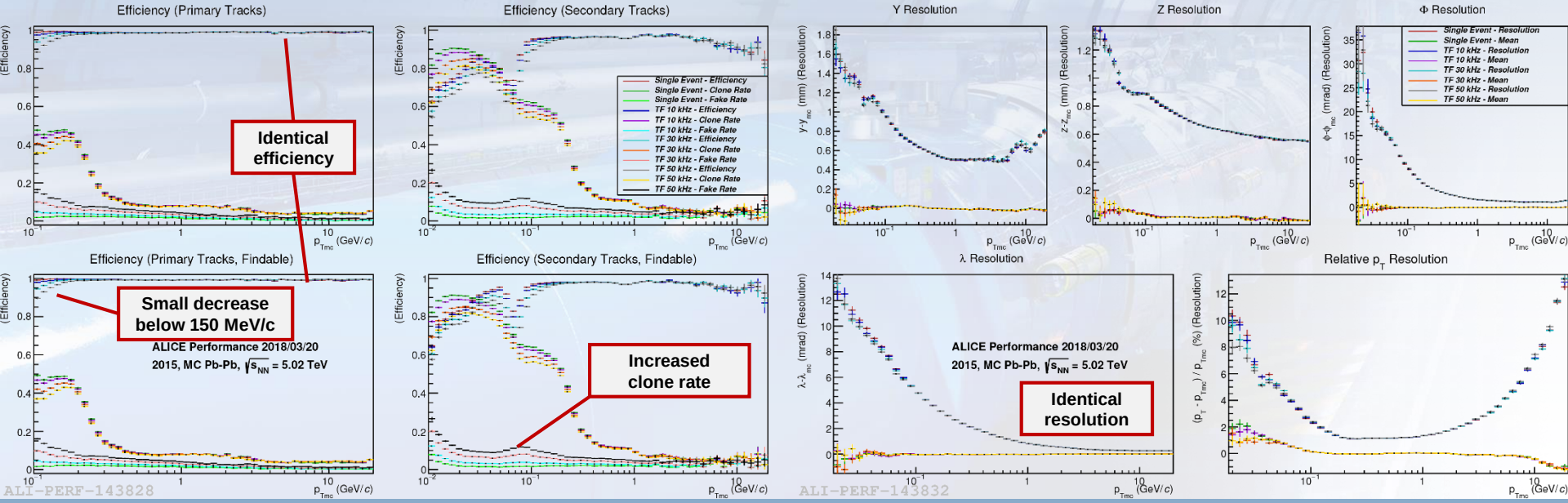
Tracking time frames at different interaction rates

- Simulation uses correct bunch structure as expected for Run 3 Pb-Pb(from ALICE TPC upgrade TDR).
- Practically no deterioration of resolution, even at 50 kHz.
- Minor efficiency decrease below 150 MeV/c.
- Still, fake rate increases with interaction rate (in particular for low p_T) – Should improve with better merging.



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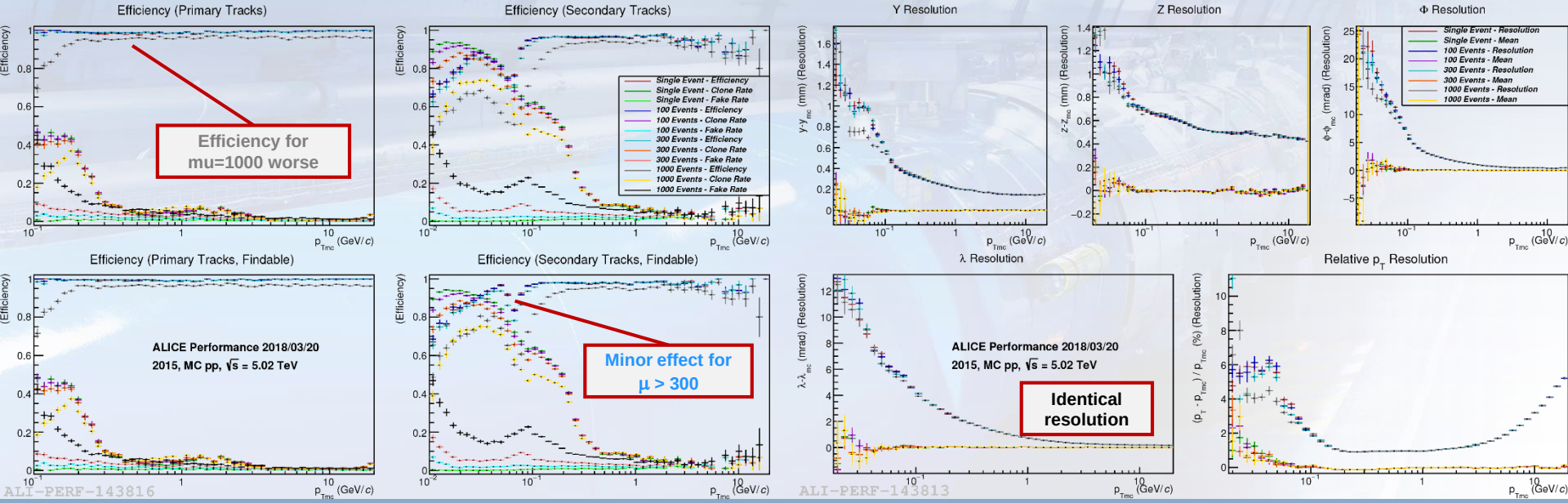
Multiplicity / event pile-up (pp)

- Overlaying up to μ = 100 pp TPC events (in-bunch pile-up) has absolutely no impact on efficiency, minimal impact on fake rate.
- At 300 overlaid pp events, one starts to see a small deterioration in the efficiency below 120 MeV/c.
- Above (at μ = 1000), there is a significant effect, but the tracking still works.
- Pile-up has does not affect resolution at all.



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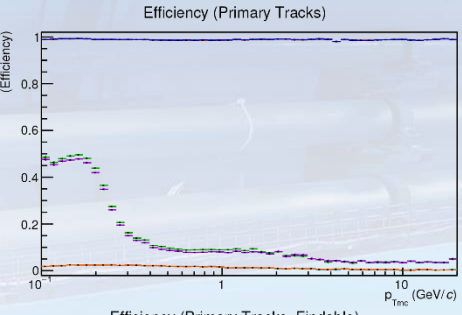
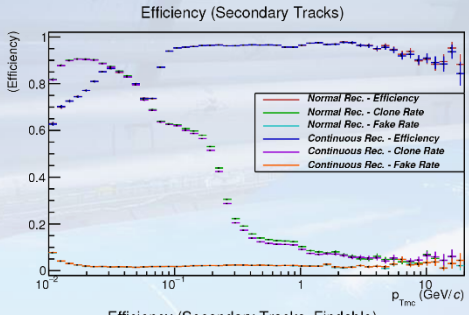
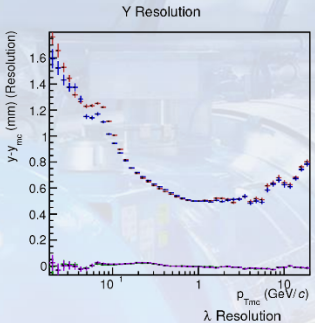
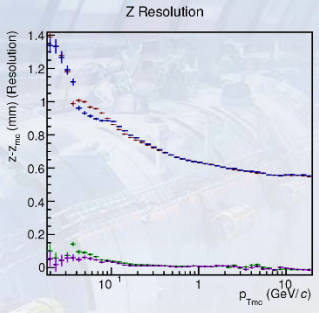
Normal tracking / z-independent tracking

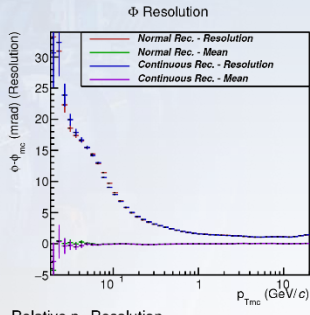
- In continuous tracking, the absolute z-position of the track is not known, but estimated from the assumption that the track is primarily pointing towards the origin (B-field and cluster errors are computed under this assumption).
- Naturally, secondary tracks suffer a bit, while primaries are mostly unaffected.
- **No significant difference between Run 2 tracking and z-independent Run 3 tracking.**
  - Due to slightly larger errors, more tracks are merged.

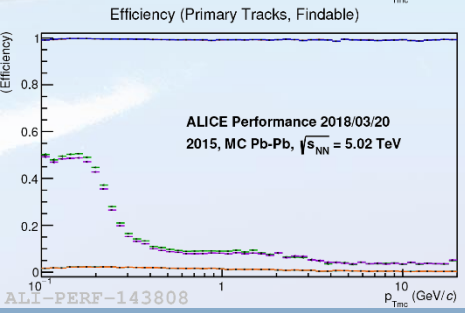


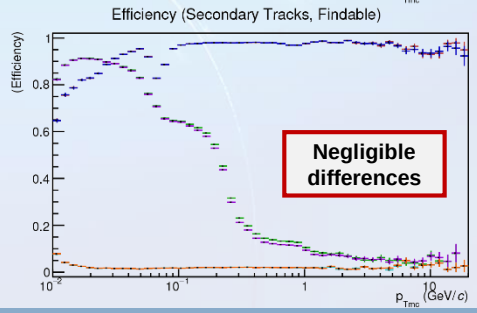


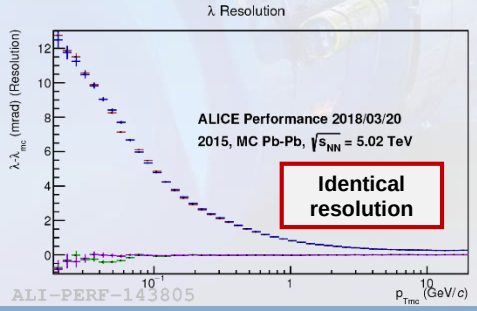


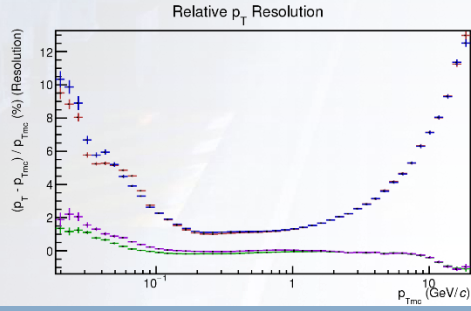












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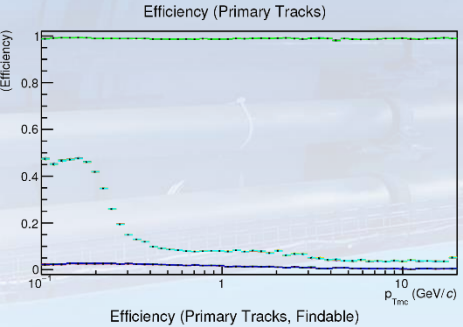
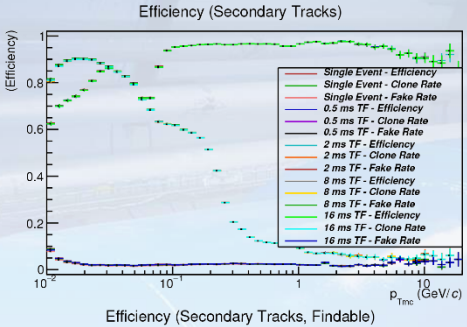
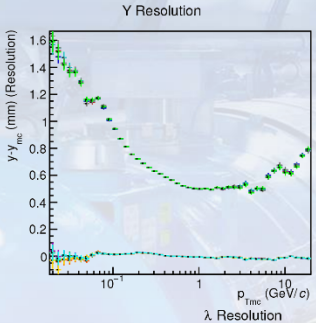
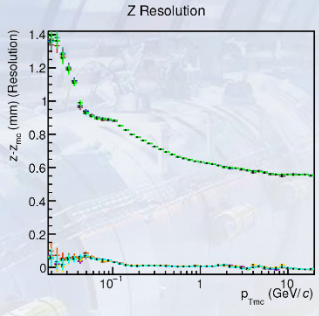
Length of time frame

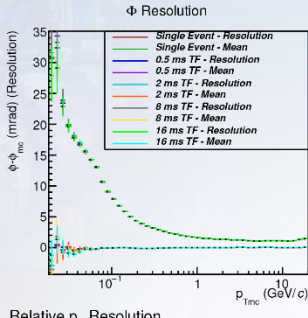
- **Identical result independent of length of time frame.**
- Before, efficiency / resolution decreased with long time frames.
  - Completely fixed.
  - Floating point problems avoided by z-independent tracking (track fit happens in |z| < 250 cm).
  - Fixed precision for storing clusters (16 bits as used in the HLT insufficient for full TF).
  - Some other minor problems solved.

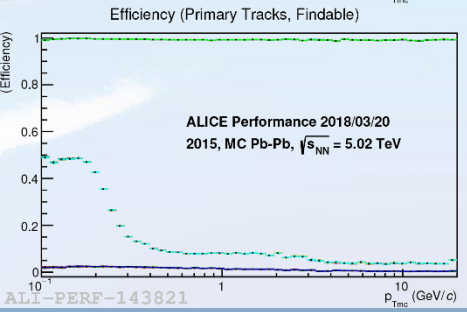


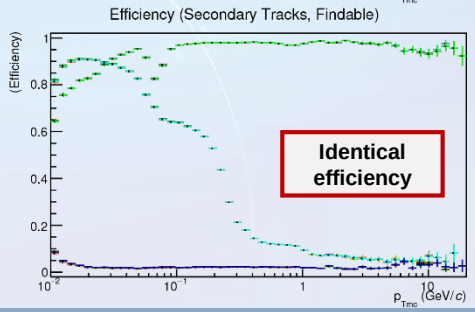


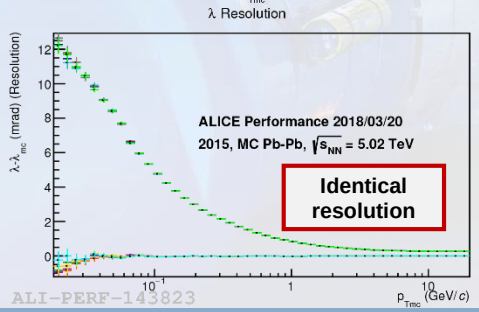


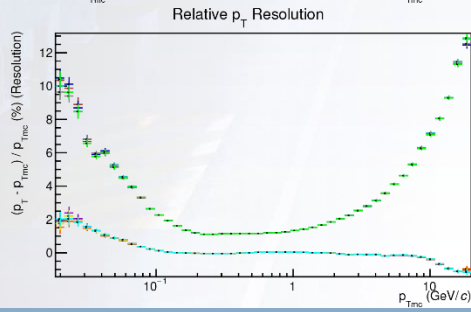












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