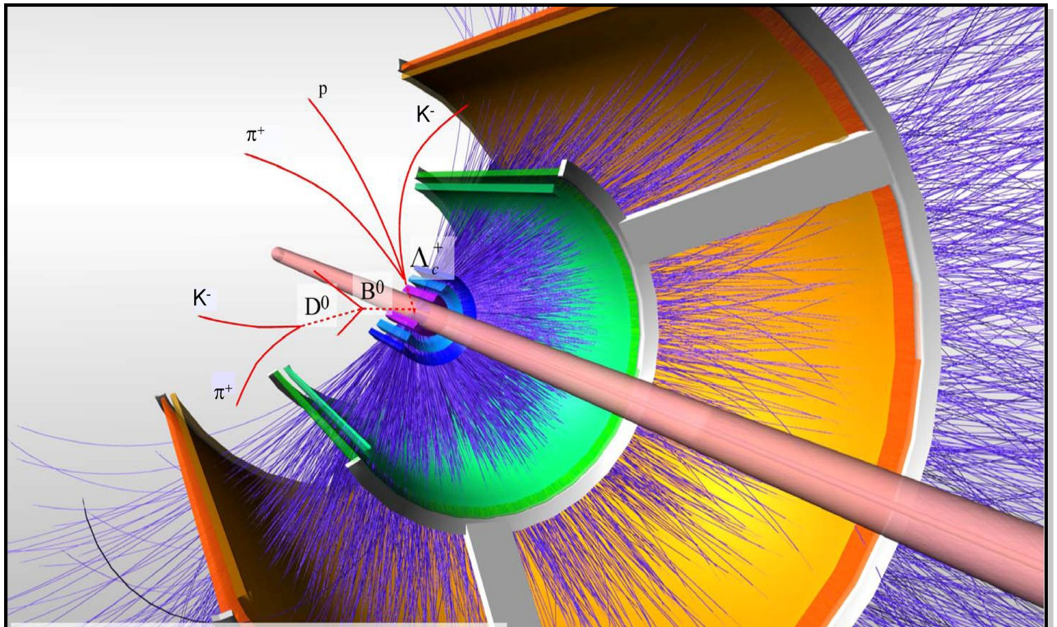
A Large Ion Collider Experiment

Tracking and vertexing in ALICE

(Iouri Belikov for the ALICE Collaboration)

- **ALICE experiment at the LHC**
  - Physics goals
  - Detector layout
- **ALICE reconstruction so far (Run 1 and 2)**
  - Triggered readout
  - Offline
  - Primary vertex
  - Tracks from one detector to another
  - Secondary vertices
- **ALICE reconstruction upgraded (Run 3)**
  - Continuous readout
  - (Quasi)online
  - New challenges and strategies



Sketch of the ITS upgrade with half a Pb-Pb event superimposed

A Large Ion Collider Experiment

http://alice-collaboration.web.cern.ch/

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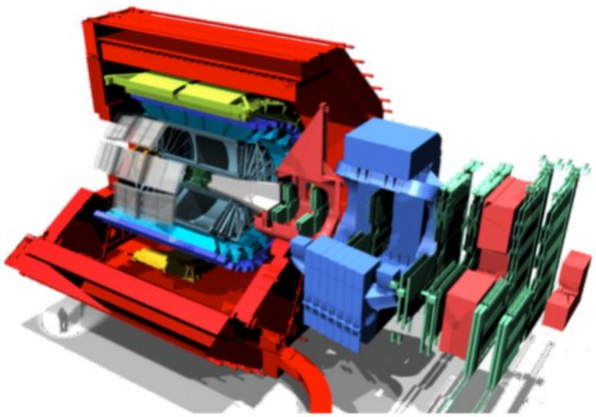
CALENDAR TODAY

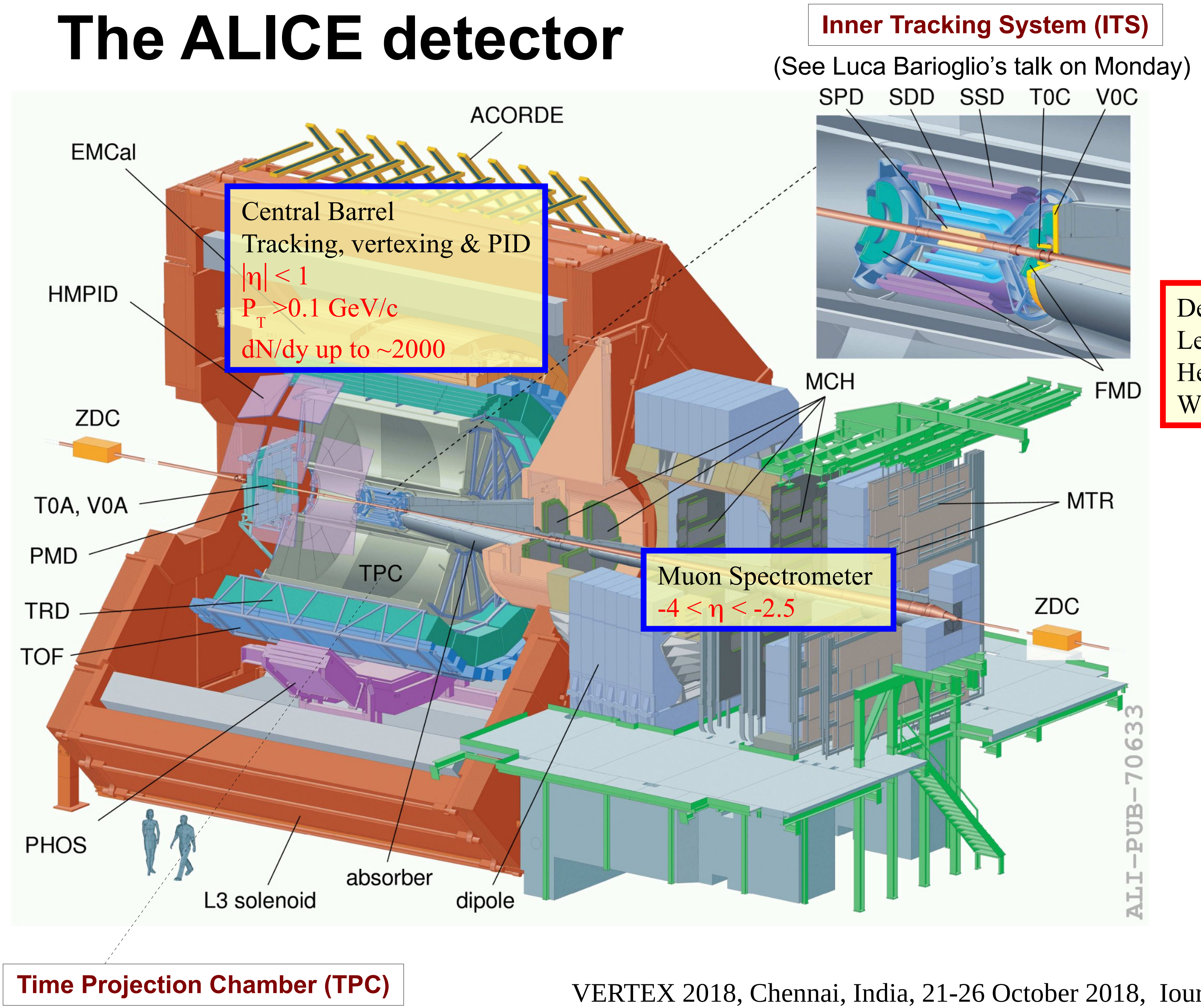
Welcome to the ALICE collaboration

Our mission

The ALICE Collaboration has built a dedicated heavy-ion detector to exploit the unique physics potential of nucleus-nucleus interactions at LHC energies. Our aim is to study the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma, is expected. The existence of such a phase and its properties are key issues in QCD for the understanding of confinement and of chiral-symmetry restoration. For this purpose, we are carrying out a comprehensive study of the hadrons, electrons, muons and photons produced in the collision of heavy nuclei. Alice is also studying proton-proton collisions both as a comparison with lead-lead collisions and in physics areas where ALICE is competitive with other LHC experiments.



The ALICE detector

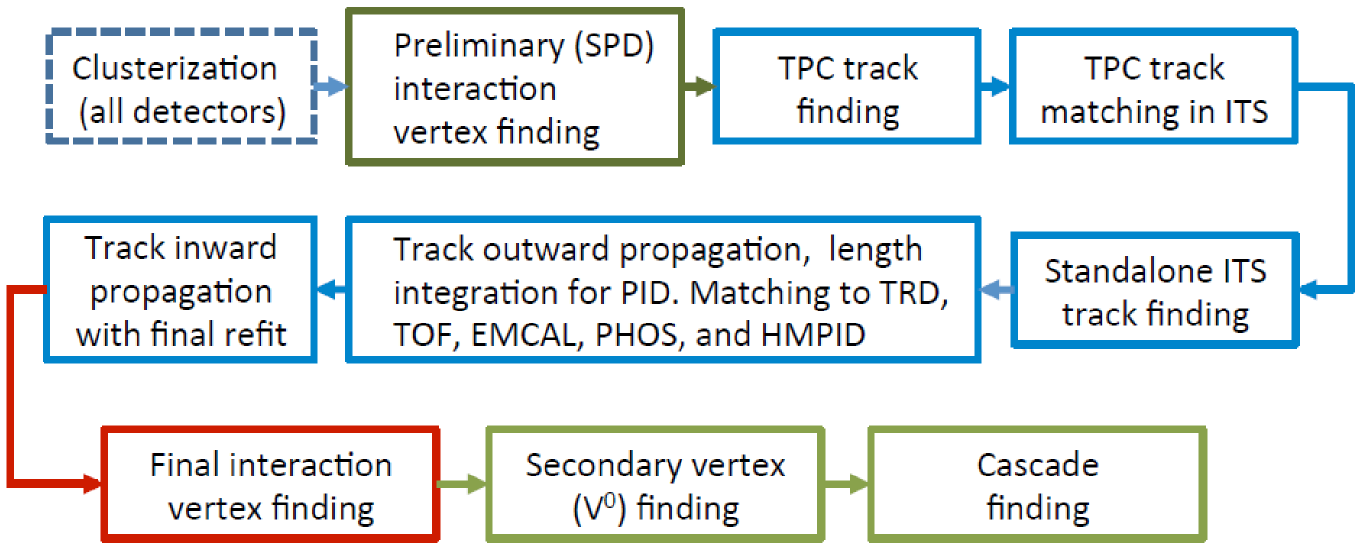


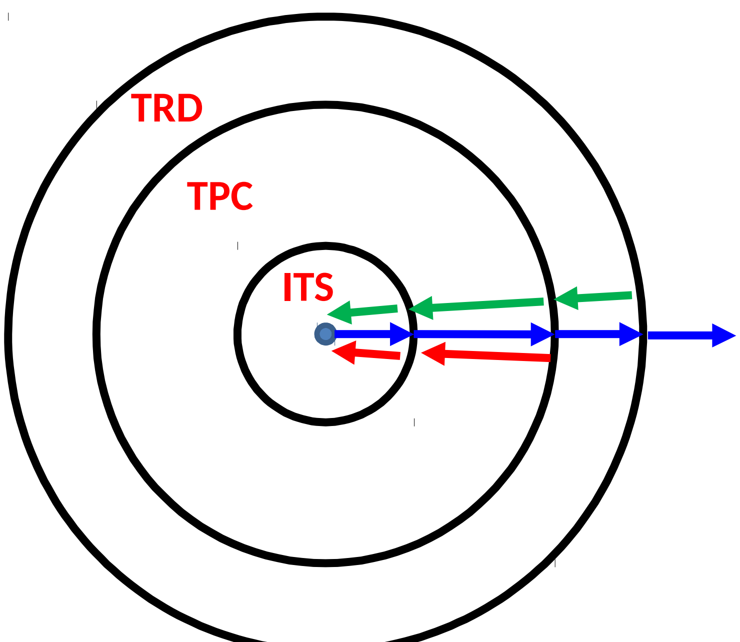
Collaboration:
- 1800 members
- 177 institutes
- 41 countries

Detector:
- Length: 26 meters
- Height: 16 meters
- Weight: 10,000 tons

Part I: Run 1 and 2

Central reconstruction strategy (Run 1 and 2)

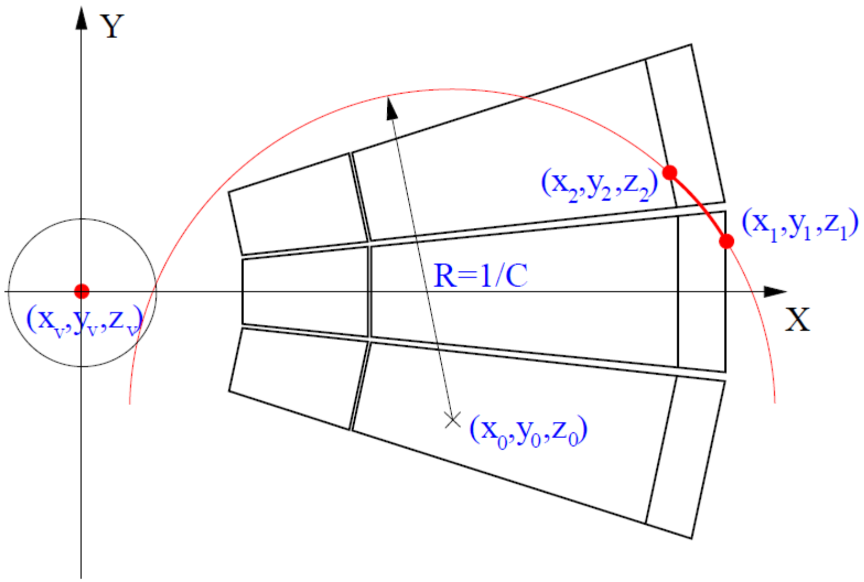


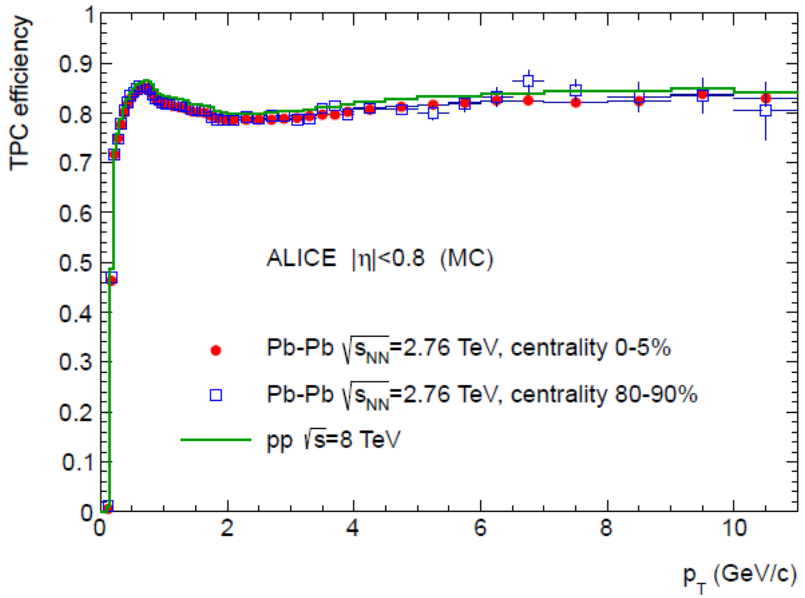


- **Kalman filter** both for track finding and fitting
- Track "seeding" in the TPC
- **Three tracking passes**, all detectors one after the other
  - Inward: track params at the primary vertex, no PID from outer detectors
  - Outward: extrapolation to outer detectors, full PID information
  - Refit: full PID info and optimal track parameters at the primary vertex

TPC tracking

- Seeding for Kalman filter:
  - SPDvertex + 2 clusters for primaries
  - 3 clusters for secondaries
- Inward extrapolation to next pad-row with update of best matching cluster
- Seeding repeated in different regions starting from 159-th to 64-th pad row
- After each tracking step best track is validated among tracks with large amount of shared clusters

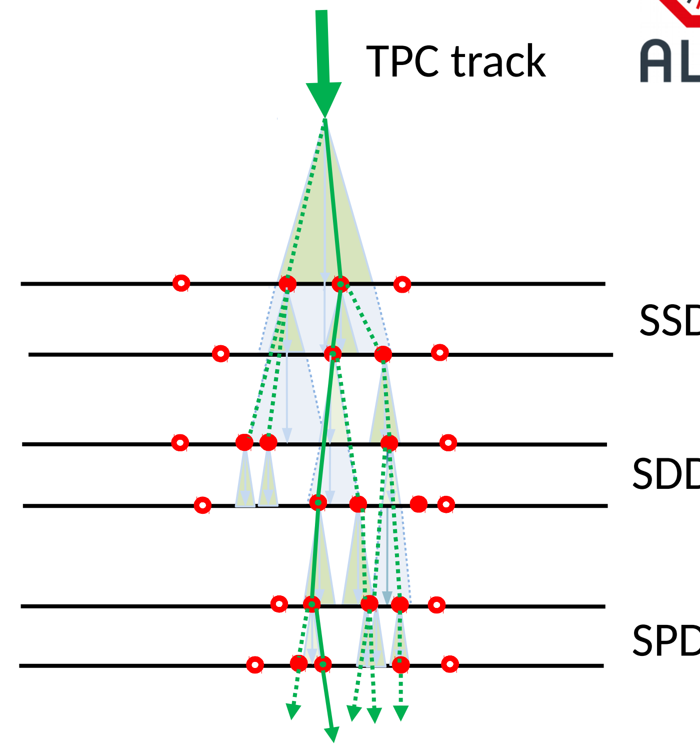


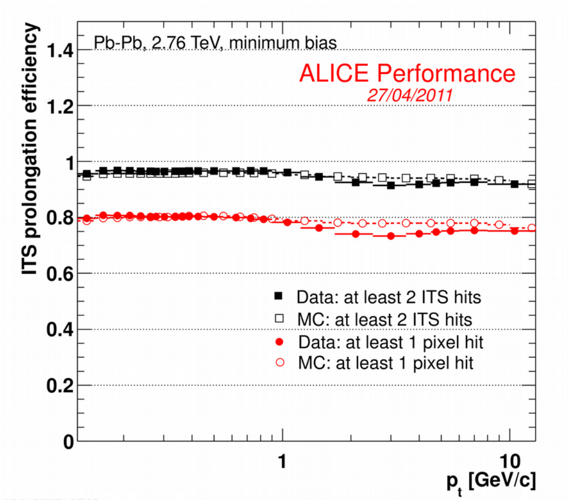


Min number of crossed pad rows: 140
Min crossed pad rows/clusters: 0.8
Max chi2/cluster: 4
Max Distance of Closest Approach (DCA) to the primary vertex: 3 cm
Max fraction of shared clusters: 0.5

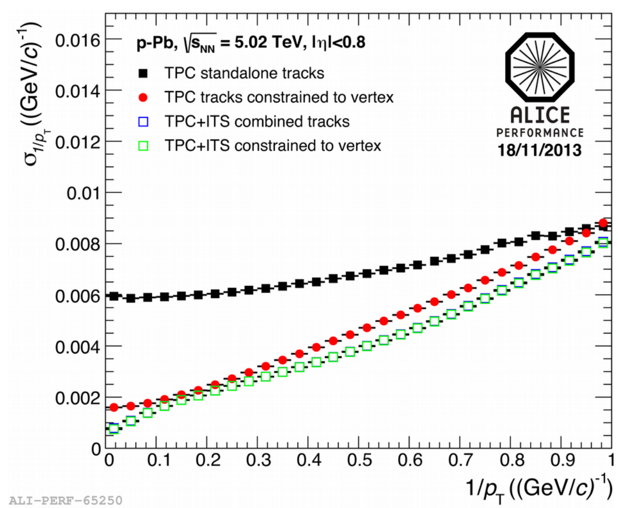
TPC-ITS “global” tracking

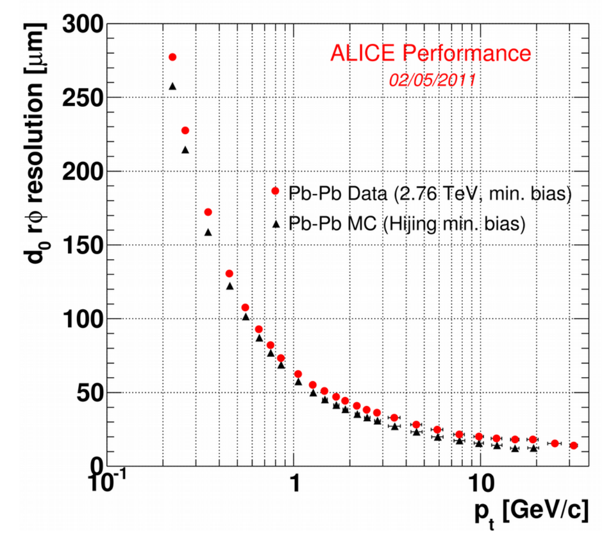
- TPC tracks used as seeds for Kalman filter
- 2 iterations of inward layer to layer propagation: with and without SPD vertex constraint
- Hypotheses tree: at each layer the seed may be branched if multiple clusters match to seed extrapolation
- The seed may jump over layer without attaching the cluster (with certain constraints), but χ^2 is penalized if a hit was expected
- Final selection of winning candidate after simplified Kalman smoothing (inward-backward filters) according to length, χ^2 of track and its matching to TPC
- Optionally, cluster sharing can be allowed
- “On-the-fly” V0-decay reconstruction





Efficiency for the tracks requiring SPD hits is reduced because of the presence of dead staves





ITS standalone tracking

- Useful for recovering :
  - Low-p_T tracks (below ~150 MeV/c for π's, below ~400 MeV/c for protons)
  - High-p_T track (above a few GeV/c) lost in the dead zones between TPC sectors

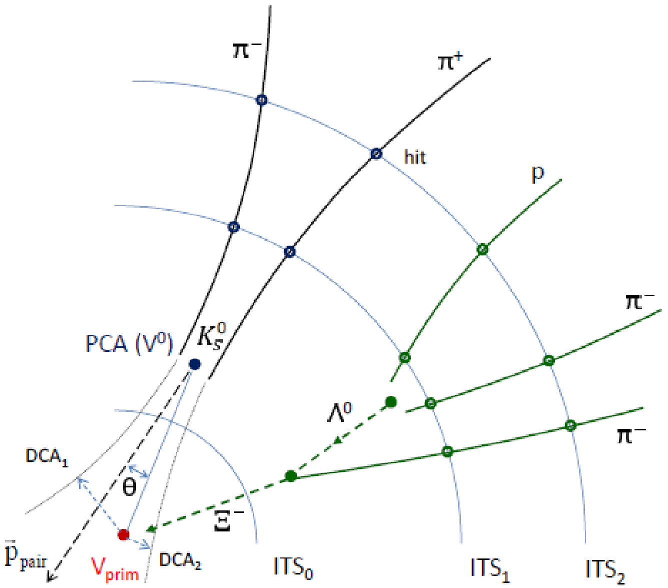
- The procedure :
  - Seeds defined by SPDvertex + 2 clusters at the 2 innermost layers
  - Matching clusters are found on all layers within a "search road"
  - All combinations are fitted by Kalman filter and the best candidate is retained
  - Procedure repeated multiple times increasing road widths, trying to get low p_T's and secondaries
  - Cluster sharing is not allowed

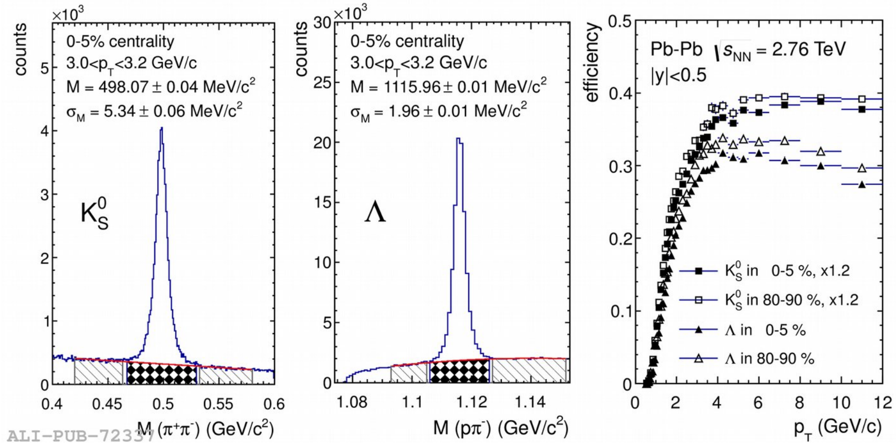
- Two modes of running :
  - Complementary to the global tracking: using only the clusters left after the global TPC-ITS tracking
  - Completely standalone: all clusters are used (pp and p-A only)
    - Serves also for a data-driven evaluation of tracking efficiency and associated systematics

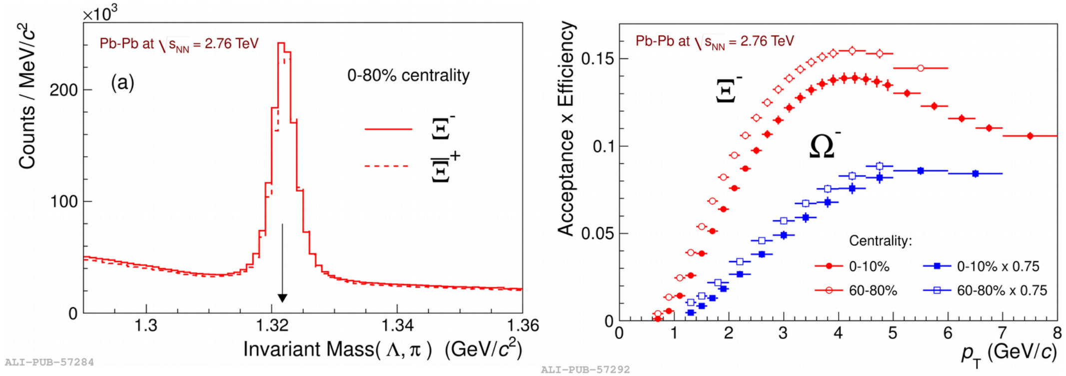
ALICE

Strange particle decays

- **V_0 candidates** :
  - pairs of unlike-sign with DCA>0.5 (1.0) mm in pp (Pb-Pb)
  - distance at Points of Closest Approach (PCA) between tracks < 1.5 σ
  - cos(θ)>0.9 between pair momentum and vector connecting primary vertex and PCA
- **Cascade candidates** :
  - V_0 candidates with the mass matched to ~M_Λ
  - bachelors satisfying their cuts on the DCA, PCA and pointing angle cos(θ)
- The decay vertex is put on the line connecting the PCAs, taking into account the reconstruction precision for the daughter tracks.
  - Optionally, a vertex can be fitted using full track covariance matrices

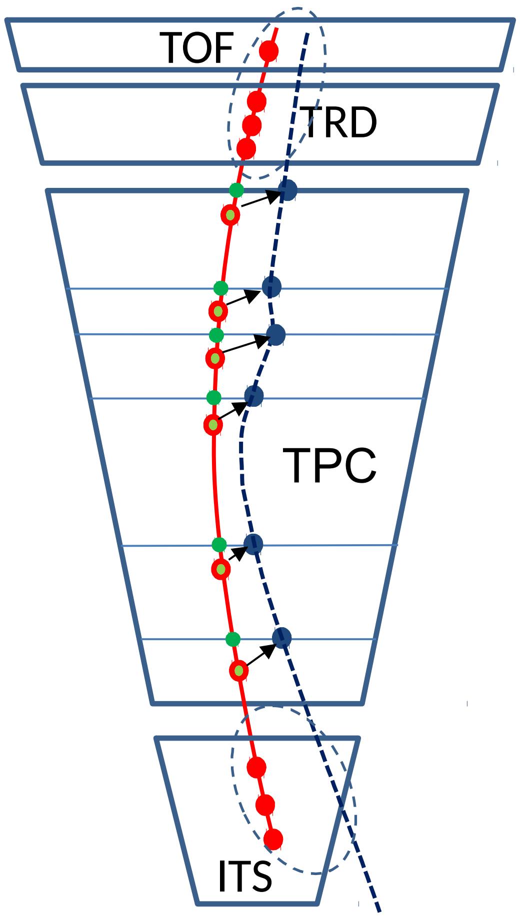






Calibration and Alignment

Space-charge corrections in TPC



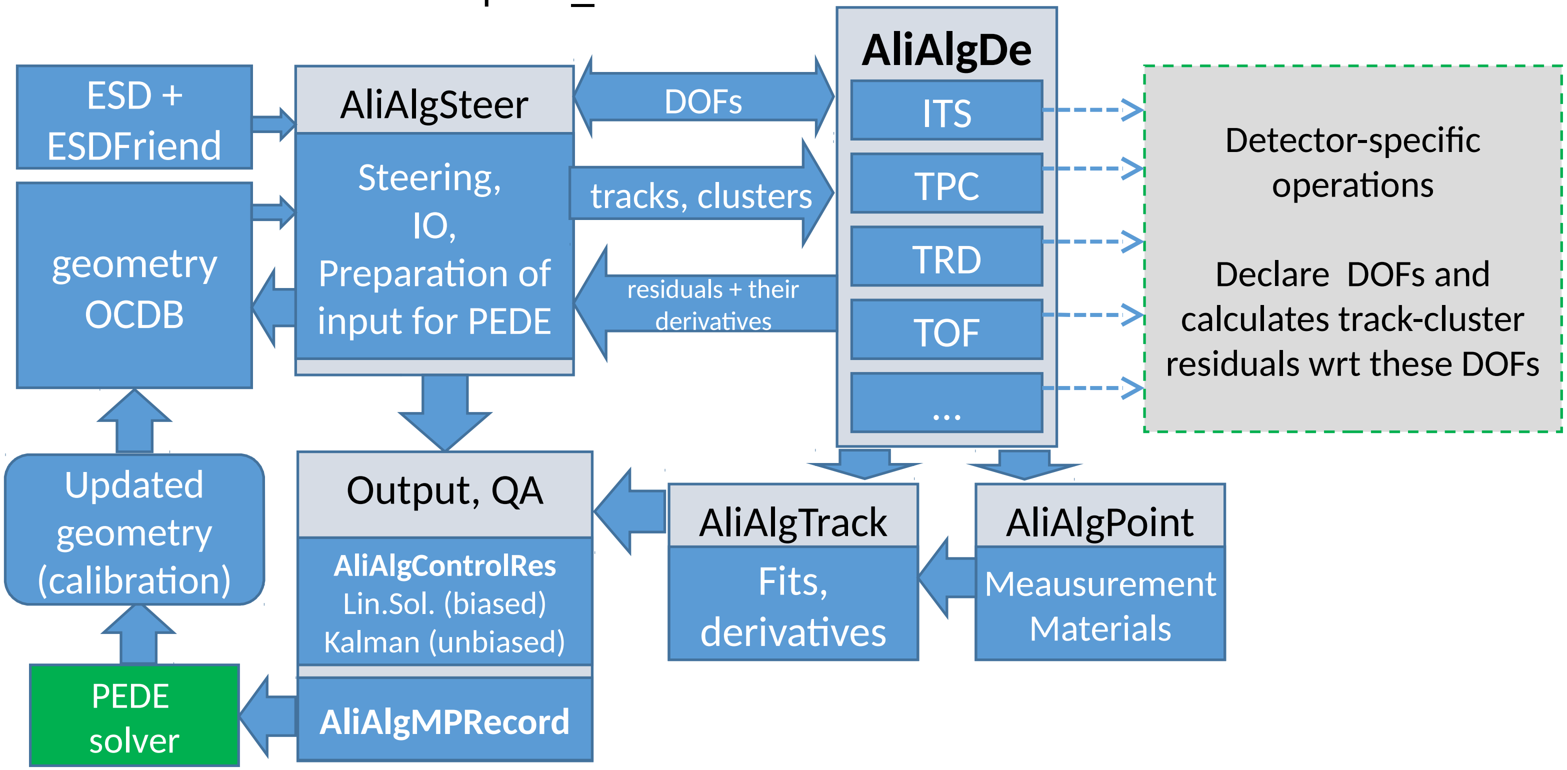
- Up to a few cm distortions changing with time

  A new **correction map** is provided every **~30 min**

- Reconstruct TPC tracks with relaxed tolerances (applying "default distortion maps" if available)
- Match to ITS and TRD/TOF with relaxed tolerances
- Refit ITS-TRD-TOF part and interpolate to TPC as a **reference** of the **true track position** at every pad-row
- Collect Y, Z differences between **distorted clusters** and **reference** points in sub-volumes (voxels) of TPC
- Extract 3D vector of distortion in every voxel
- Create smooth parameterization (fast interpolation by Chebyshev polynomials) to use for corrections during the reconstruction

Global alignment with Millipede II

https://www.terascale.de/wiki/millepede_ii/



Blue: preparation of input data for PEDE II, processing of its output, utilities for OCDB and geometry manipulation

Green: external PEDE II solver (Fortran 90 + OpenMP) supported by DESY

Minimize track residuals : $z_i = y_i - f(x_i, \boldsymbol{q}, \boldsymbol{p}) = \sum_{j=1}^{\nu} \left(\frac{\partial f}{\partial q_j}\right) \Delta q_j + \sum_{\ell \in \Omega} \left(\frac{\partial f}{\partial p_\ell}\right) \Delta p_\ell \, .$

The track model depends on global (detector DOF's) and local (per a track) parameters

ALICE central barrel case: up to ~27k DOFs

Part II: Run 3, ...

ALICE upgraded reconstruction
(Run 3)

- Readout rate in Pb-Pb : 0.5 kHz → **50 kHz**
  - Low cross-section processes → large statistics required
- High comb. background → triggering is inefficient
- TPC drift time **~100 μs**
  - ~5 Pb-Pb events in the drift volume
- ITS strobe length **~10 μs**
  - Still, a few events per a "RO frame" in pp

Detector	Event Size After Zero Suppression (MByte)	Bandwidth @50 kHz Pb-Pb (GByte/s)
TPC	20.0	1000
TRD	1.6	81.5
ITS	0.8	40
Others	0.5	25
Total	**22.9**	**1146.5**

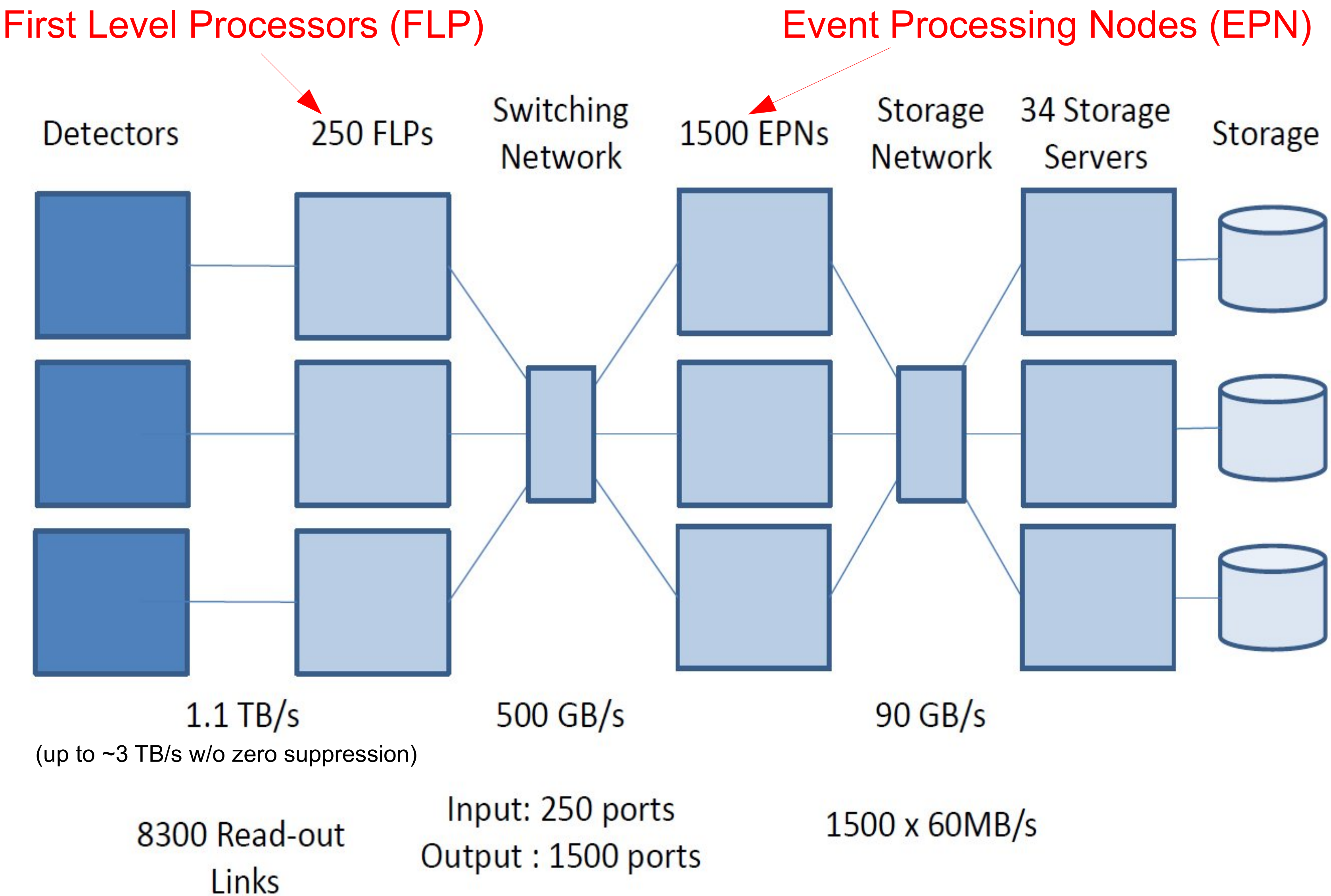
Continuous readout for upgraded TPC and ITS
(See Serhiy Senyukov's talk on Tuesday)

(Quasi)online reconstruction

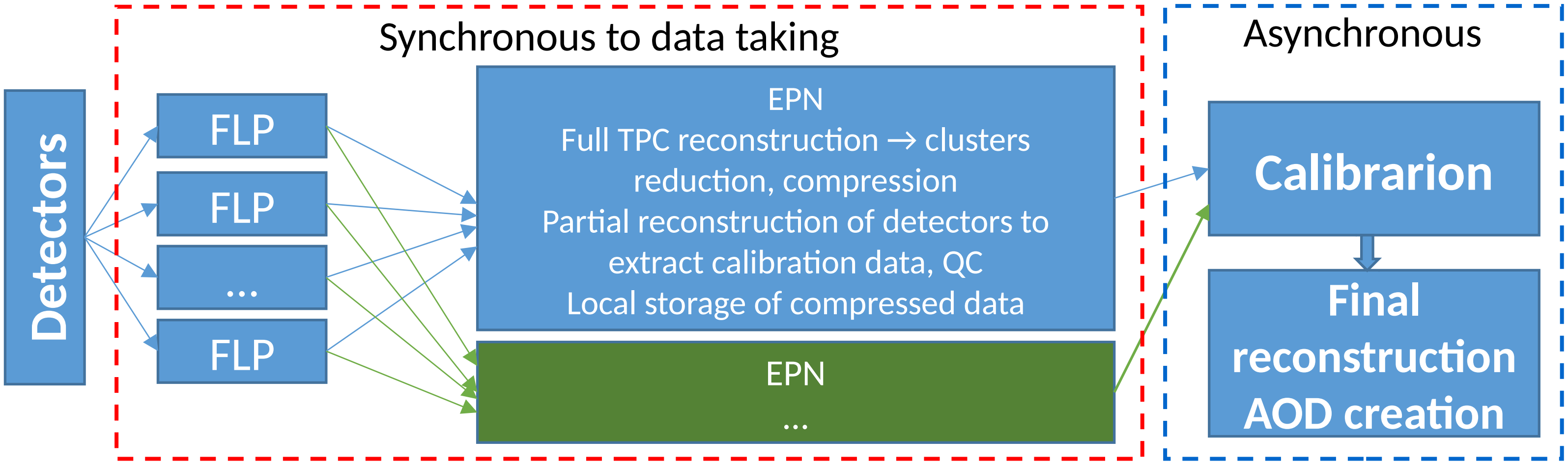
New challenges and strategies

(Quasi)online reco. using the Online-Offline (O^2) farm

(CERN-LHCC-2015-006)



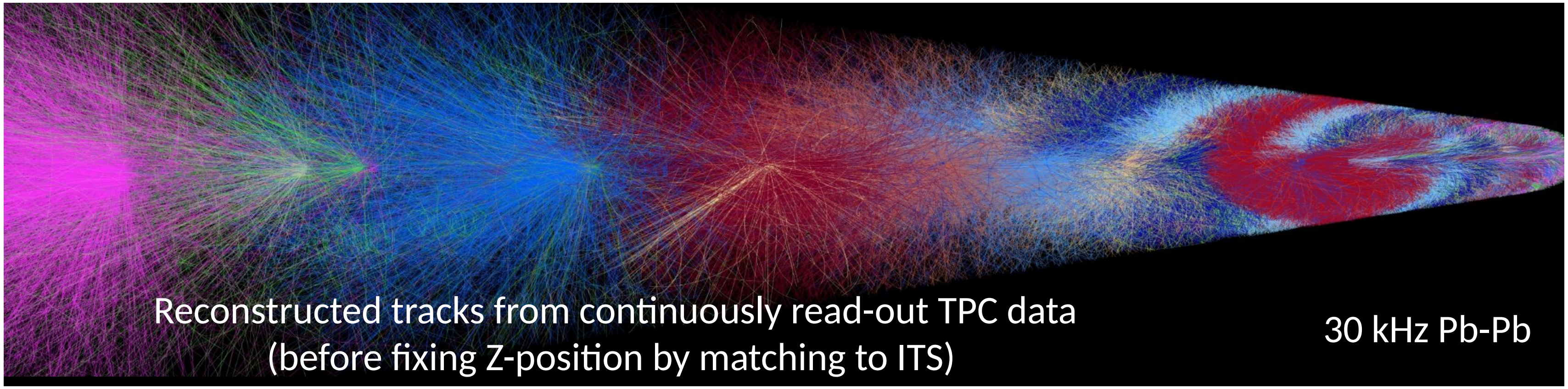
Reconstruction workflow in Run 3



- **First Level Processors** (FLP) receive continuous data from parts of detectors and perform local tasks like cluster-finding, mask creations etc.
- Each FLP chops the output data to SubTimeFrames (~20 ms long) and dispatches STF of the same time stamp to one of the **Event Processing Nodes** (EPN)
- EPN performs **full TPC reconstruction** to compress the data and **partial (a few % only) reconstruction of other detectors** to produce enough calibration data.
  Aggregates STF to single TimeFrame (TF).
  1500 EPNs → ~30 s of real time to process TF

- **Calibration data** of different EPNs aggregated, CCDB populated with calibration objects
- **Final reconstruction** in all detectors, matching, vertexing performed for each TF
- **Compact AODs** written per TF (up 1000 consecutive events in Pb-Pb @ 50kHz)
- AOD design will be aimed at storage minimization

Central reconstruction strategy in Run 3

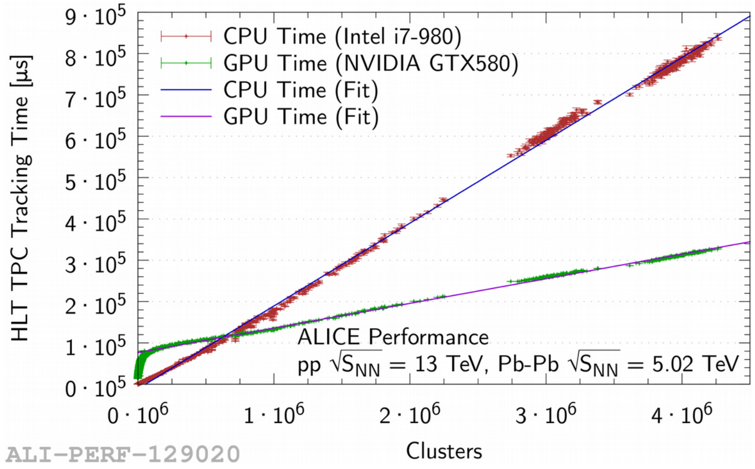


- **The Run 1 and 2 (slide #5) strategy will not be possible anymore**
  - Z position of tracks in TPC is not fixed (continuous readout)
  - Non-negligible residual TPC mis-calibration (large space-charge distortions)
- **Instead, we will perform:**
  - Preliminary primary vertex reconstruction using ITS
  - Standalone tracking separately for TPC and ITS (sufficiently good, for the upgraded ITS)
  - TPCtrack – to – ITStrack matching (not using the Z coordinate)
  - TPC-seeded ITS tracking with unmatched TPC tracks and unused ITS clusters (secondaries)
  - Reconstruction of the primary vertices using global tracks
  - Secondary vertices and their association with the primary vertices ...

Standalone TPC tracking in Run 3

- Derived form the Run 2 High Level Trigger
  - 36 TPC sectors (159 padrows/sector) processed independently
    - Track seeding with **Cellular Automaton**
    - Track following with a simplified **Kalman Filter** within a sector
  - Track merging between sectors
    - Prolongation towards adjacent sectors, finding matching segments
    - Picking up additional clusters
    - Final refit with **Kalman Filter**

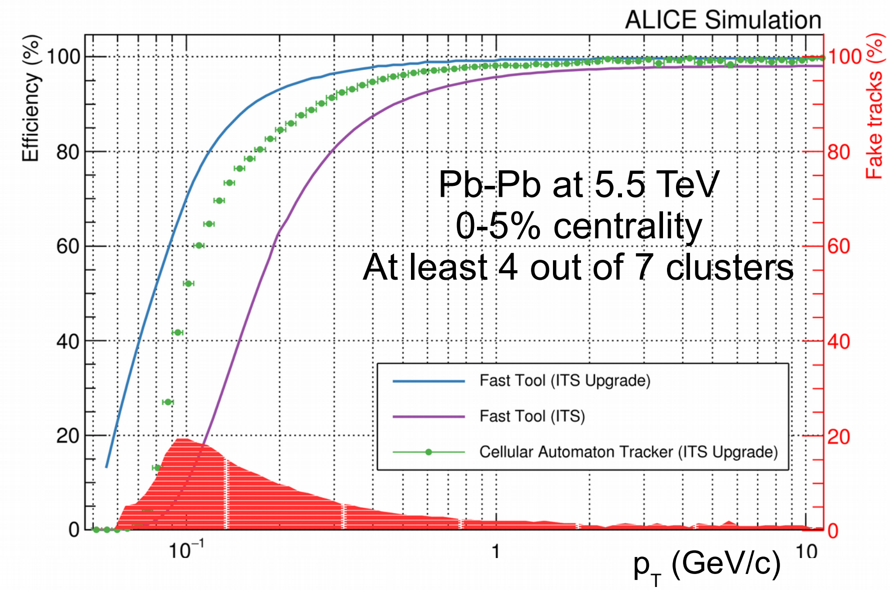
- Runs on **GPU**s (can be compiled for CPU as well)
  - **Common** for CPU and GPU source code in OpenMP / CUDA / OpenCL
  - **1 GPU** replaces **~40 CPU** cores @4.2 GHz (GTX 1080 *vs* Core i7 6700K)
  - **Linear** dependence of the processing time on cluster multiplicity
  - Processes **23 ms** TimeFrames **in ~20 s** (O^2 farm has 1500 EPNs)



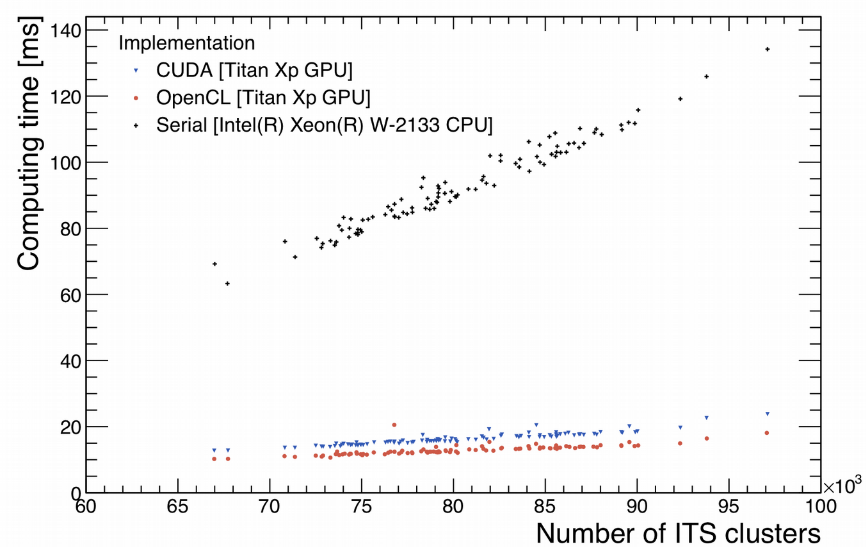
- Does not rely on the absolute Z-coordinate of clusters
  - Yet, **the same** efficiency and resolutions as the offline (primary tracks)
  - A little less efficiency for short low-p_T secondaries
- Provides a considerable data-compression factor
  - **~9.1x** – noise removal, bits per charge and size, residuals, arithmetic coding
  - Additional rejection due to looper and highly-inclined track-segment removal

Standalone ITS tracking in Run 3

- Work-in-progress new development
  - Traditional Kalman Filter tracker
    - CPU, multi-threaded
    - Used for initial efficiency and resolution studies
  - Cellular Automaton tracker
    - Pattern recognition with **Cellular Automaton (CPU & GPU)**
    - Track fitting with **Kalman Filter (CPU)**
    - The main production tracker



- Both versions show similar efficiencies and resolutions
- Main problem : wrong cluster-to-track association at low p_T
  - Multiple scattering, fluctuations of energy losses...



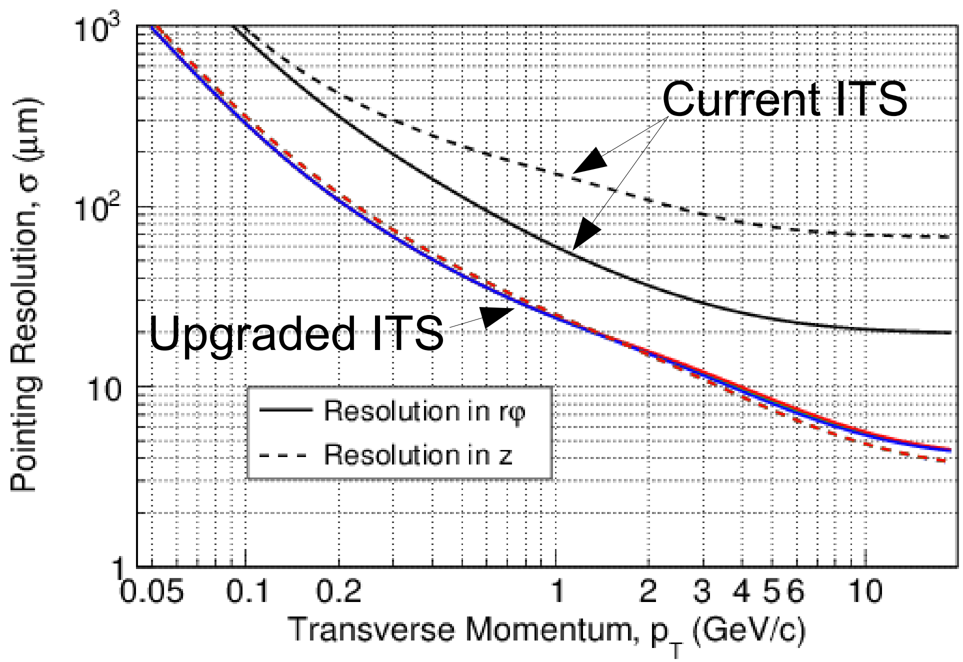
- The **GPU** version is **2.5x – 5x** faster
  - The gain factor increases with the number of pileup vertices
- The CA tracker can be used for the on-line TPC calibration
  - Parameters tuned for high-p_T tracks

The challenge of track-to-vertex association

- Preliminary primary vertex positions with the Inner Barrel of ITS
  - About 1 mm separation between vertices
  - Enough to initiate the standalone ITS tracking

- The vertex-fitting algorithms are the same as for Run 1 and 2

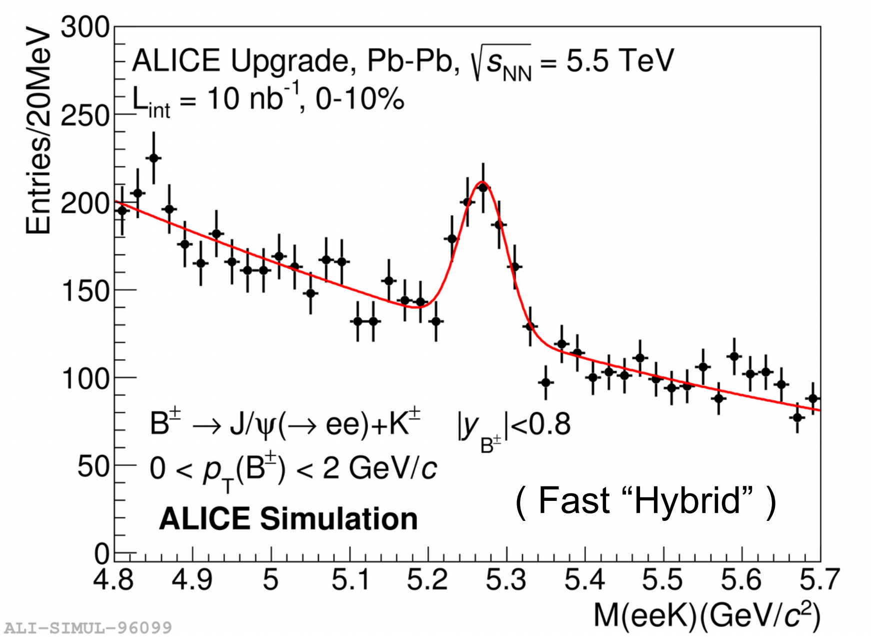
- The tracks to be associated are now of quite different quality :
  - **Unmatched TPC tracks** **(σt~100 μs, σz~10 cm)**
    - The time resolution comes from the TPC drift time
    - The "Z resolution" is just the size of the beam-beam interaction region
  - **Unmatched ITS tracks** **(σt~10 μs, σz~10 μm)**
    - The time resolution is defined by the strobe length
    - OK for vertexing in Pb-Pb
  - **Matched ITS-TPC tracks** **(σt~100 ns, σz~10 μm)**
    - The time resolution is given by (matching resolution in Z)/Vdrift
    - OK for vertexing in both Pb-Pb and pp
  - **Matched ITS-TPC-TOF tracks** **(σt~1 ns, σz~10 μm)**
    - Best for all collision systems and kinds of physics analysis
    - Relies on the PID information from TPC
    - Only ~60% of such tracks



- All primary vertices will be reconstructed (at least, those having a couple of tracks above ~1 GeV/c)
- The charm and beauty vertexing capability will drastically improve
  - A factor 3 (5) better pointing resolution in XY (Z) at ~1 GeV/c
- **More background for strange-particle decays**
  - Track impact parameters much larger than an average separation between primary vertices
  - The TPC-only tracks will require checking of multiple interaction-time hypotheses (needed for calibrations)
- **A certain fraction of tracks will remain un-associated (low p_T , secondary)**

Conclusions

- The successful operation in Runs 1 and 2 has demonstrated ALICE’s excellent tracking and vertexing capabilities
- From Run 3 on: **A totally new computing model and reconstruction strategy**
- Coming soon: completion of the new reconstruction software and detailed physics performance studies

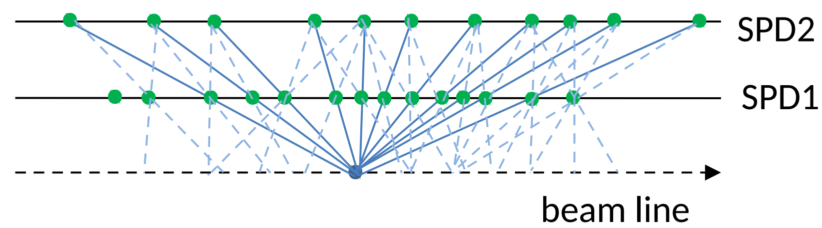


Backup slides

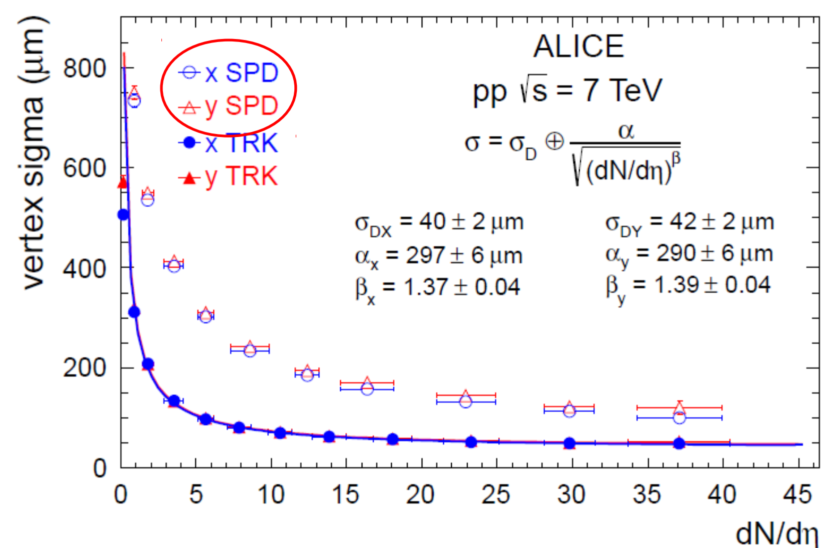
Primary vertex estimation

Silicon Pixel Detector (SPD, two innermost layers of the ITS)

- Point of attraction for maximum number of tracklets (vectors defined by 2 SPD clusters)
- Track bending in the B field neglected



- Two algorithms
  - Vertexer3D : search in 3D fiducial envelope around luminous region)
  - VertexerZ : 1D search of attraction point along Z axis with subsequent fit of 3D coordinate (a fall-back if Vertexer3D failed)

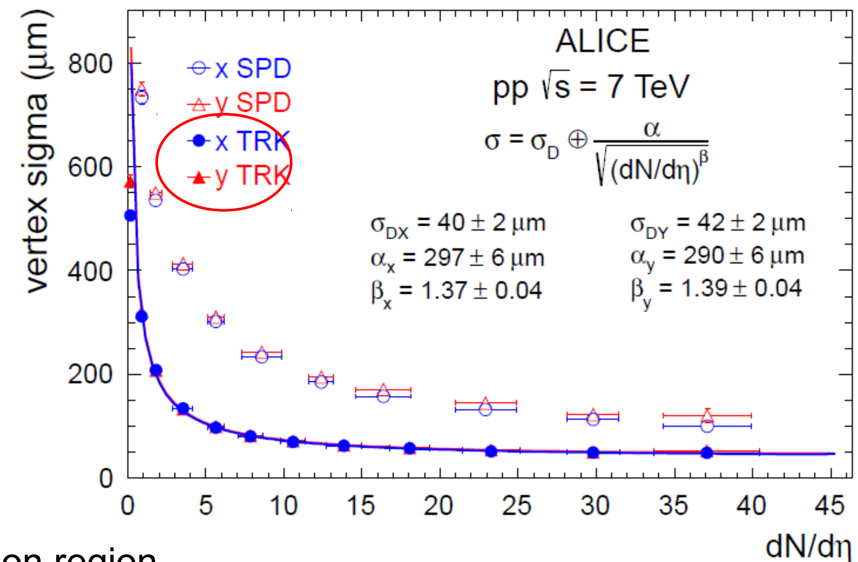


  - Used as a constraint to reduce combinatorics in subsequent track finding
  - Tag pile-up repeating iteratively, each time removing clusters attributed to found vertices
  - The first vertex (max. number of trackelts) is used as a measure of event multiplicity

Final primary vertex reconstruction

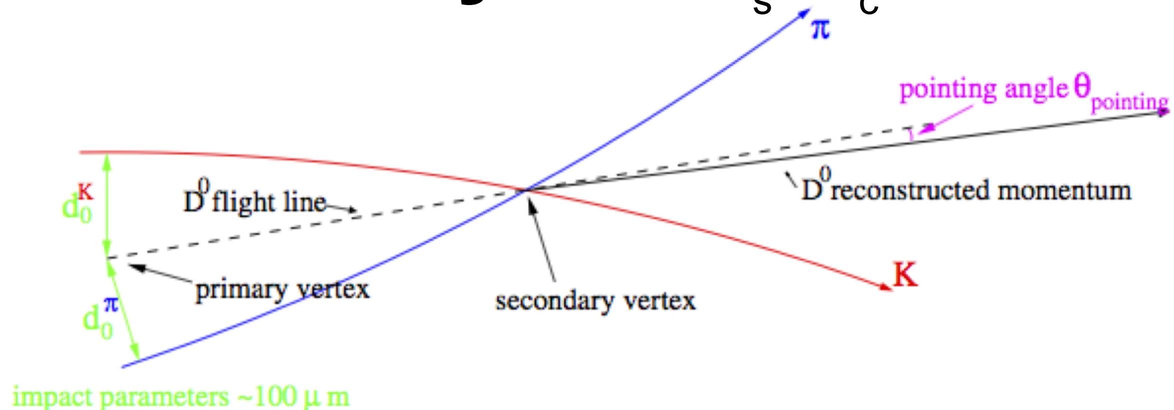
ALICE

- Use global ITS+TPC and complementary ITS standalone tracks with at least 3 ITS hits
- Two alternative approaches sharing the same vertex fitter
  - For **Pb-Pb** (no pile-up in ITS), only **one vertex** is reconstructed
    - "outliers" removed by a cut on the DCA to the beam line
  - For **pp** and **p-A**, **multiple vertices** search
    - suppressing outliers by Tukey bi-weights
    - each vertex is found in iterative fit
    - tracks contributing to found vertex are removed and next vertex is searched
    - optionally, only tracks within the same Bunch Crossing (as measured by the TOF) can contribute to a given vertex
    - optionally, a constraint by the size of the beam-beam interaction region

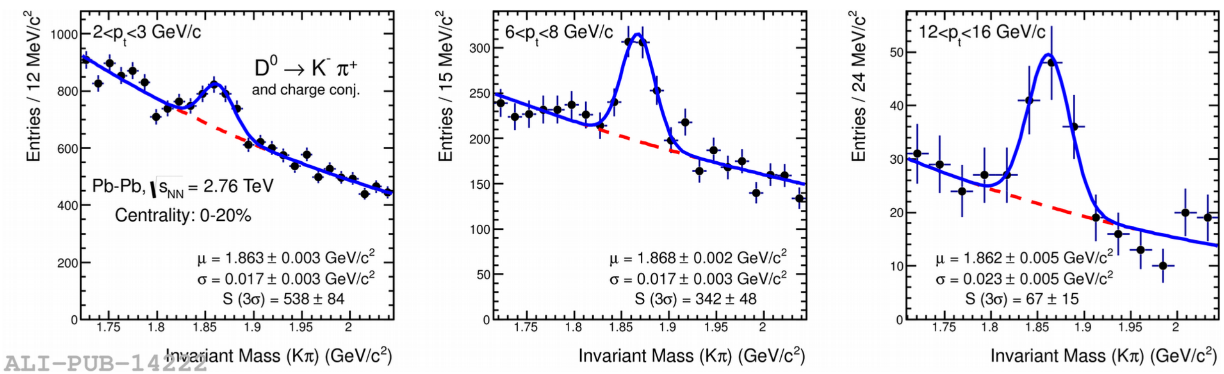


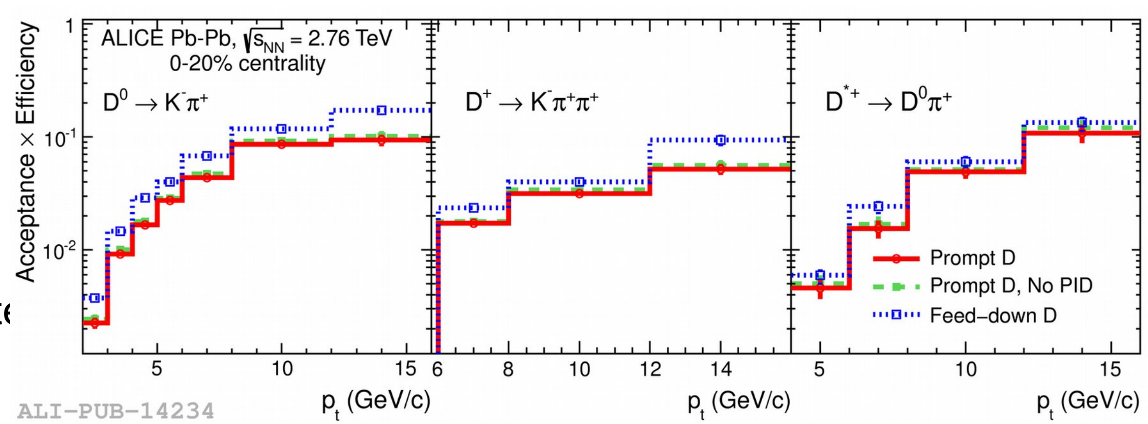
- χ^2 fit performed using inverse track covariance matrices as weights

Open charm decays (D, D_s, Λ_c ...)



- Done at the **physics analysis** step
- Cuts similar to strange particle decays
  - DCA wrt the primary vertex
  - PCA between the daughter tracks
  - cos(θ) (pointing angle)
- Charm-specific cuts
  - d0k x d0π <~ -45000 µm
  - |cos(θ*)| <~ 0.8 (decay angle in the rest frame)
  - Transverse projections of θ and decay length
- The same fit procedure as for the primary verte





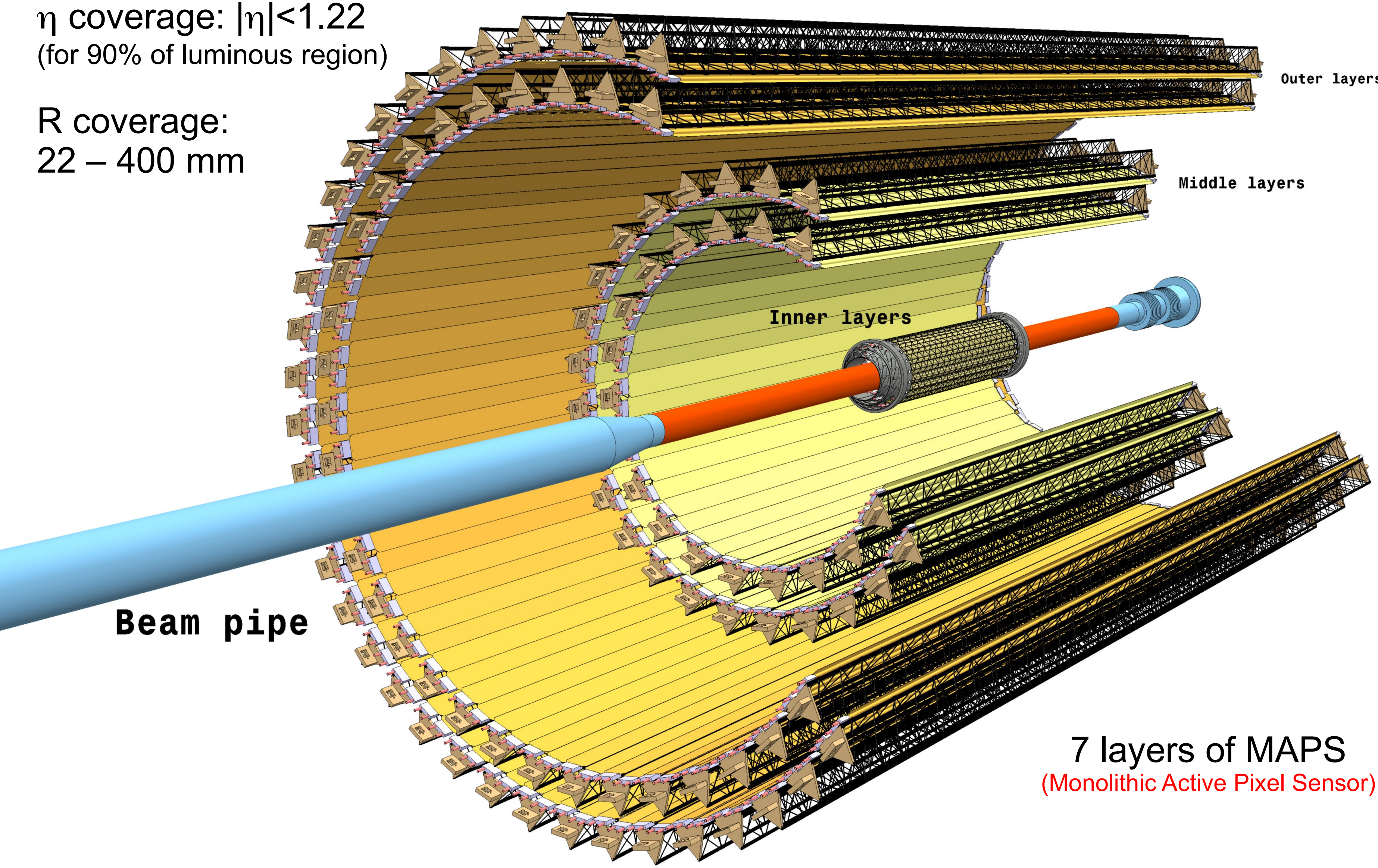
Layout of the upgraded ITS

12.6 G-pixel camera
(~10 m^2 of Si, ~13.6M CHF)

ALICE

η coverage: |η|<1.22
(for 90% of luminous region)

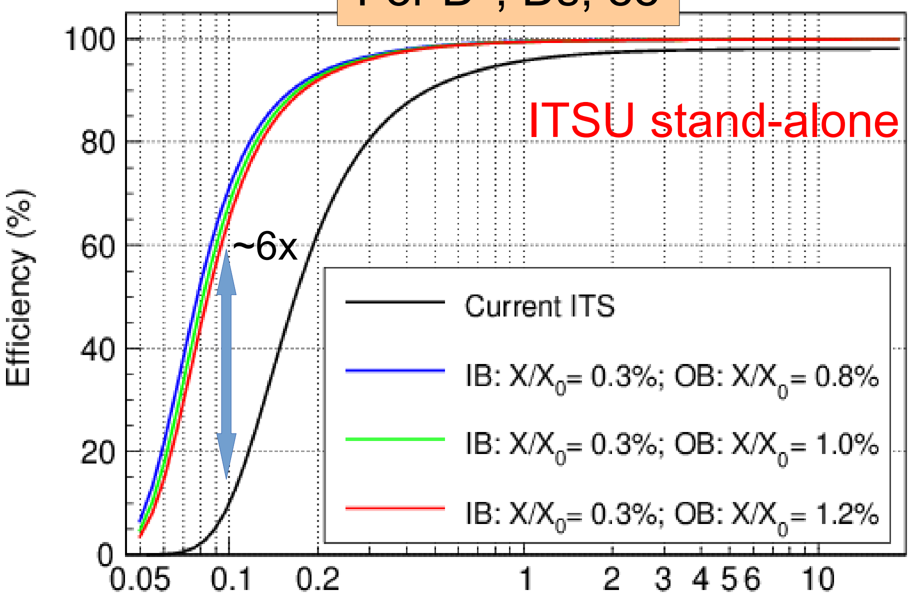
R coverage:
22 – 400 mm



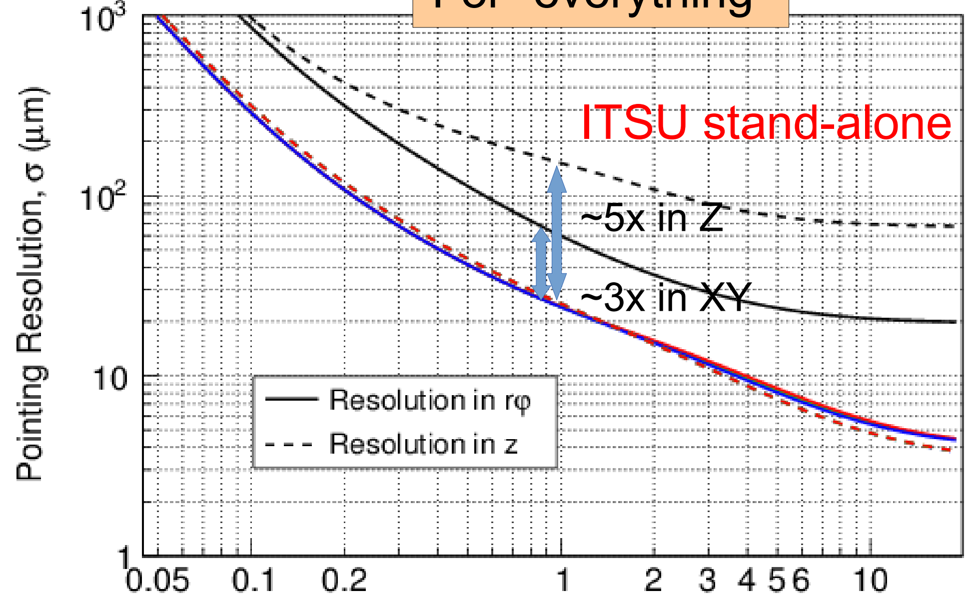
7 layers of MAPS
(Monolithic Active Pixel Sensor)

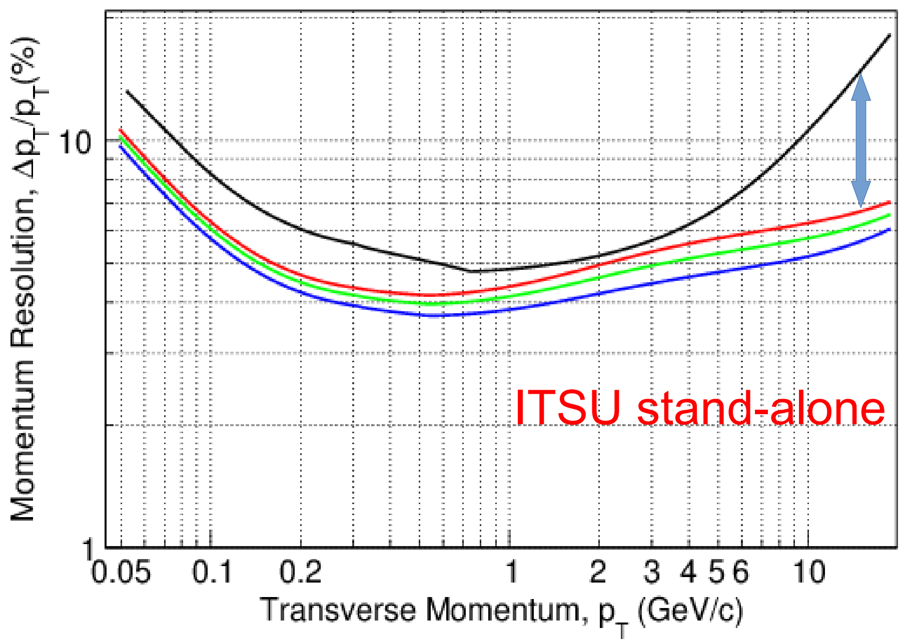
Detector performance (CERN-LHCC-2013-024, fast simulations)

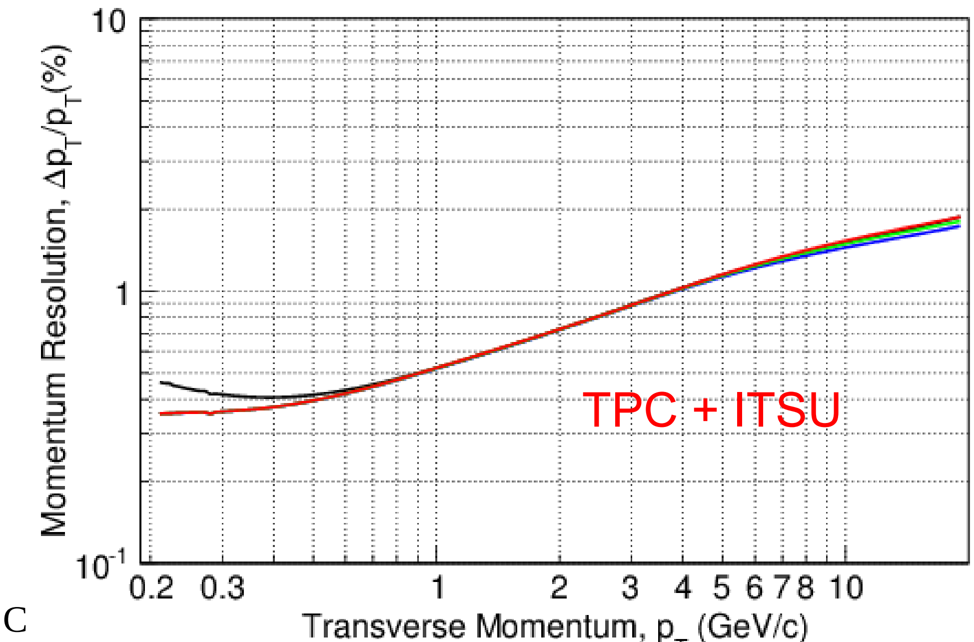
For D*, Ds, ee



For “everything”



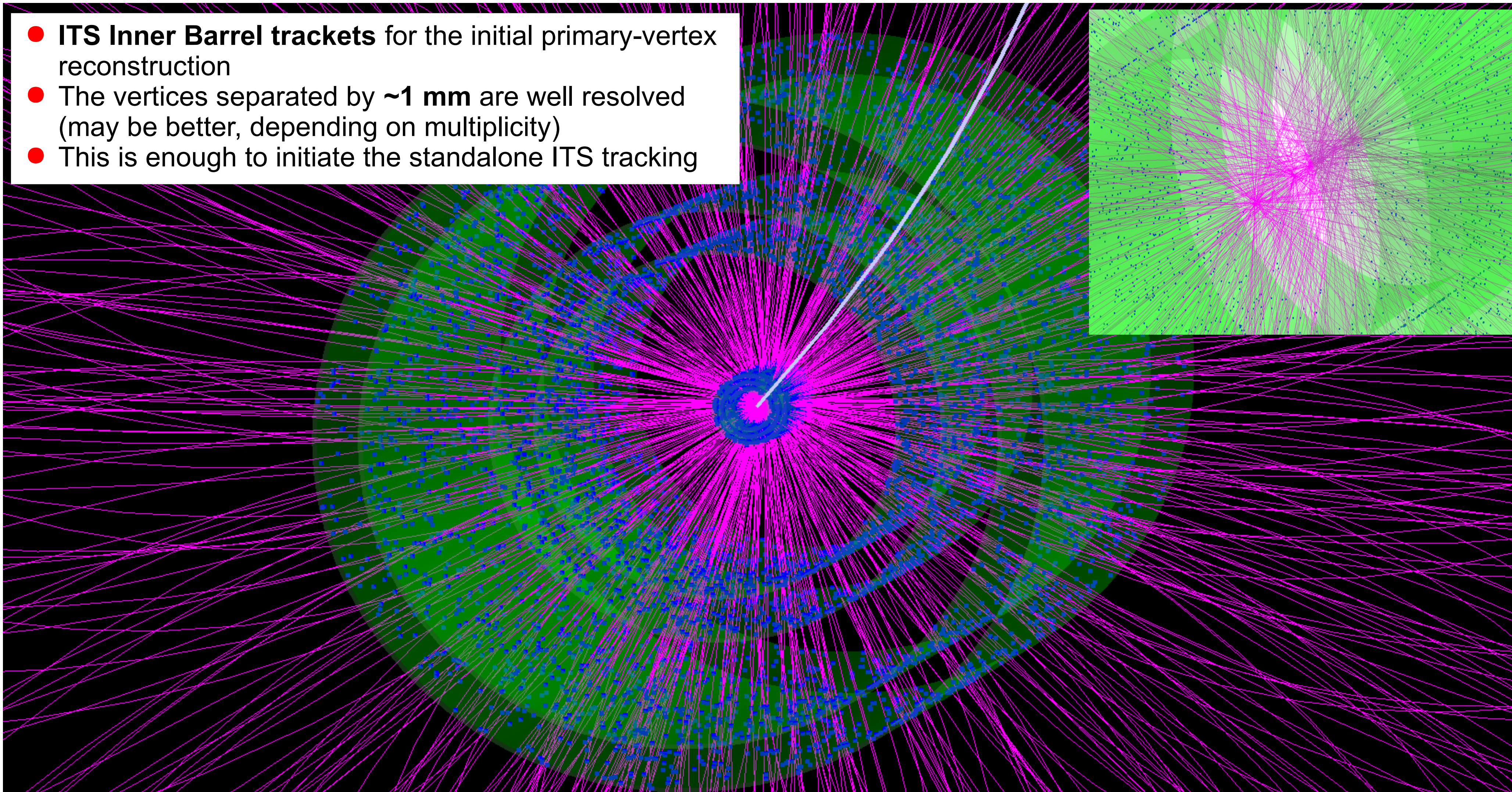




The challenge of track-to-vertex association

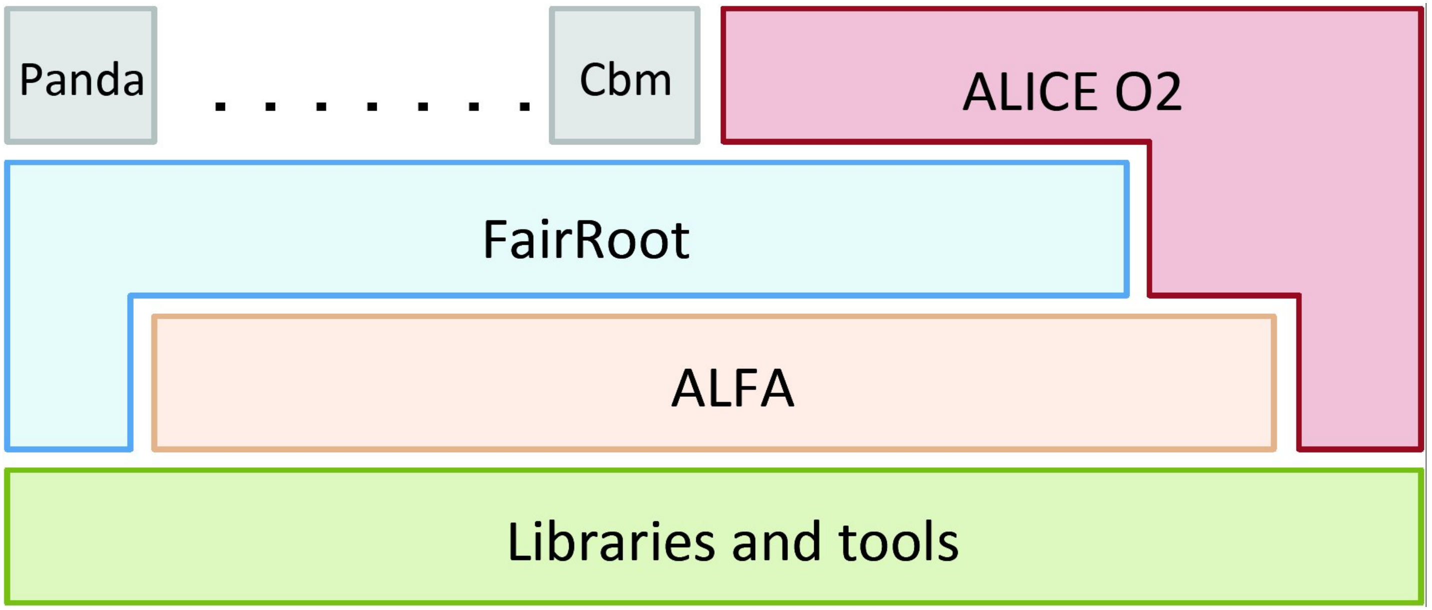
An event with 35 MC and 29+4 reconstructed vertices (ITSU standalone, Pythia6 @ 14 TeV)

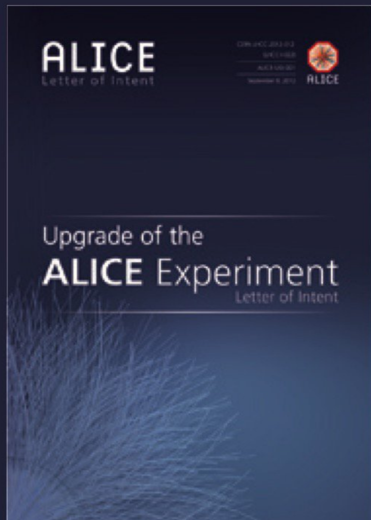
- **ITS Inner Barrel trackets** for the initial primary-vertex reconstruction
- The vertices separated by **~1 mm** are well resolved (may be better, depending on multiplicity)
- This is enough to initiate the standalone ITS tracking



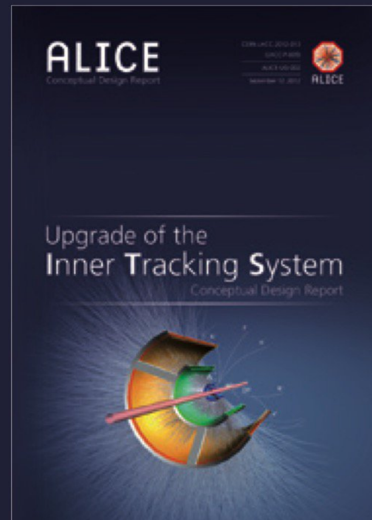
ALICE O² and ALFA framework

CERN-LHCC-2015-006, p. 75:
As shown in Fig. 7.1, the O2 software not only relies on general libraries and tools such as Boost [1], ROOT [2] or CMake [3], but also on 2 other frameworks called ALFA and FairRoot. ALFA is the result of a common effort of the ALICE and FAIR experiments to provide the underlying communication layer as well as the common parts for a multi-process system. The multi-process approach, rather than a purely multi-threaded one, is justified by the need for high-throughput parallelisation and the necessity to have a flexible and easy-to-use software framework. At the same time the system is fully capable of multi-threading within processes when required.





CERN-LHCC-2012-012



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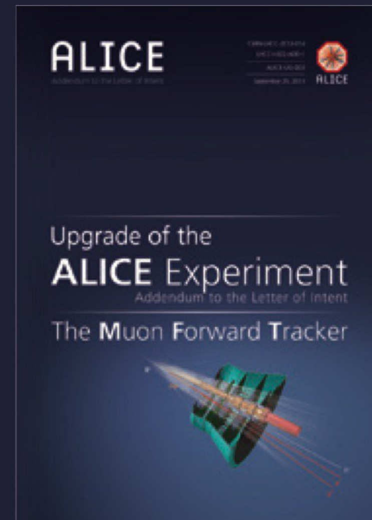

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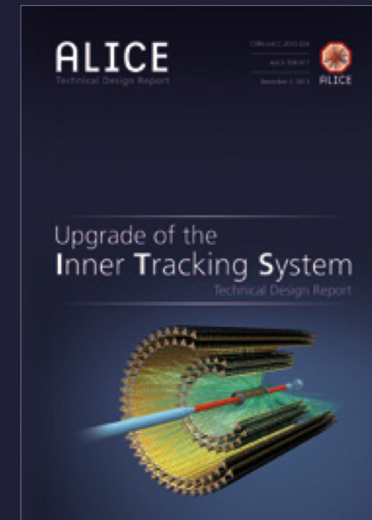
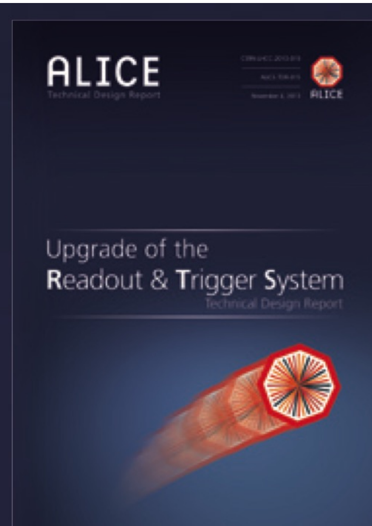


CERN-LHCC-2013-024

CERN-LHCC-2015-006



CERN-LHCC-2013-019

CERN-LHCC-2013-020

CERN-LHCC-2015-001