

The ALICE Time Projection Chamber

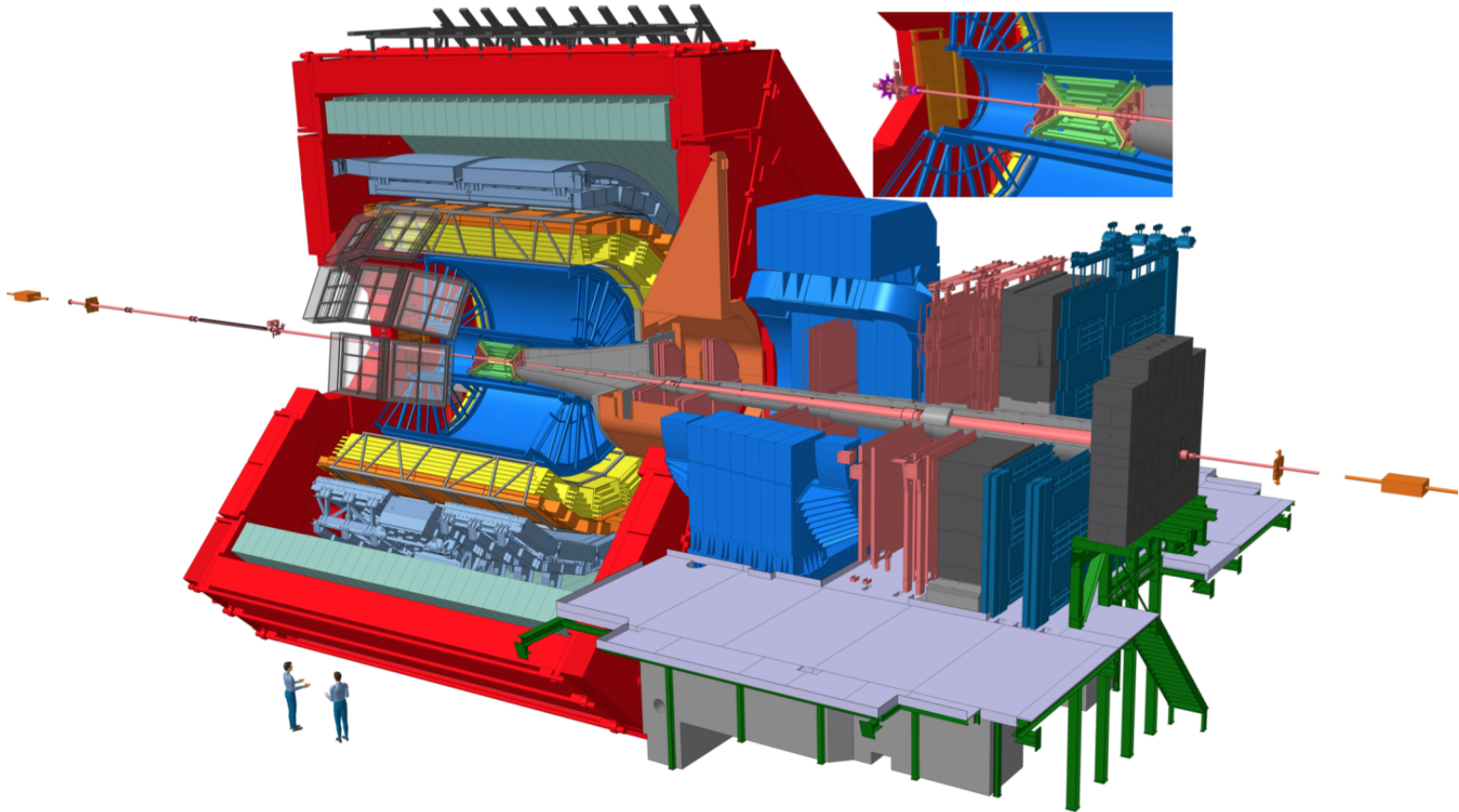


Alexander Schmäh for the TPC Group

05.11.2025

TPC Overview

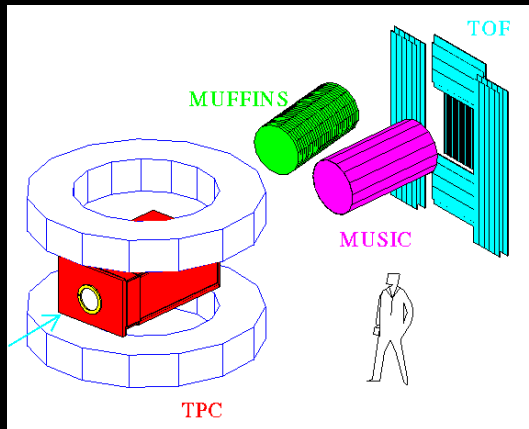
ALICE at CERN/LHC



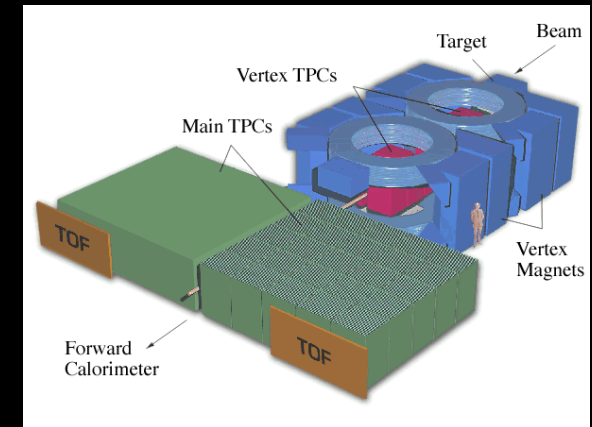
- Dedicated heavy-ion experiment.
- TPC is the central tracking and particle identification detector of ALICE.
- Upgraded for Run3: continuous readout + GEMs.

Short History of TPC based Experiments

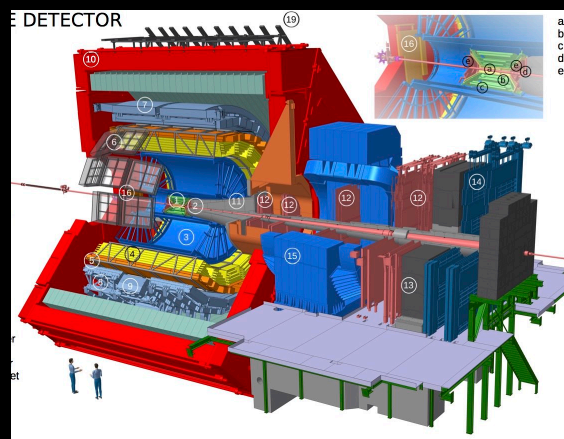
EOS: 1992-1997



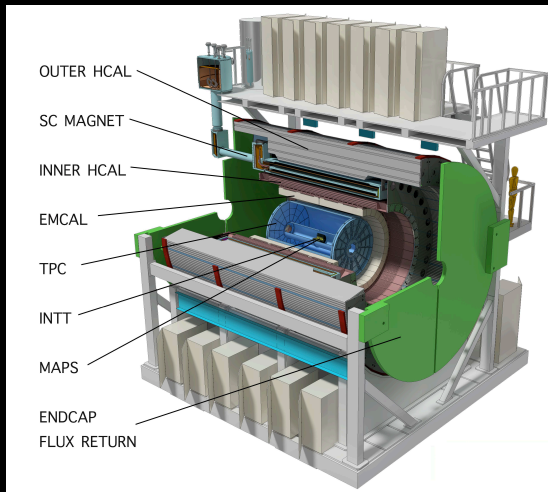
NA49: 1994-2002



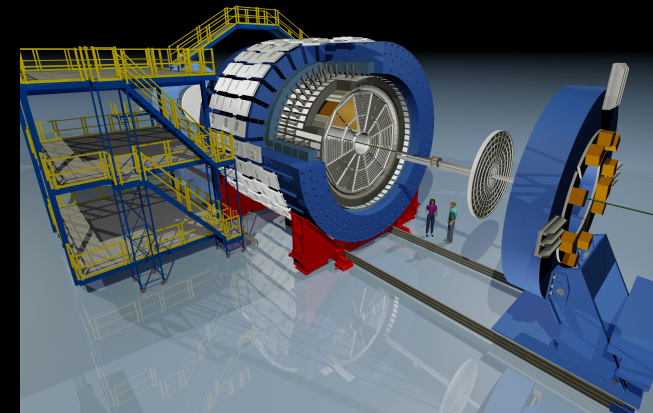
ALICE: 2008-now



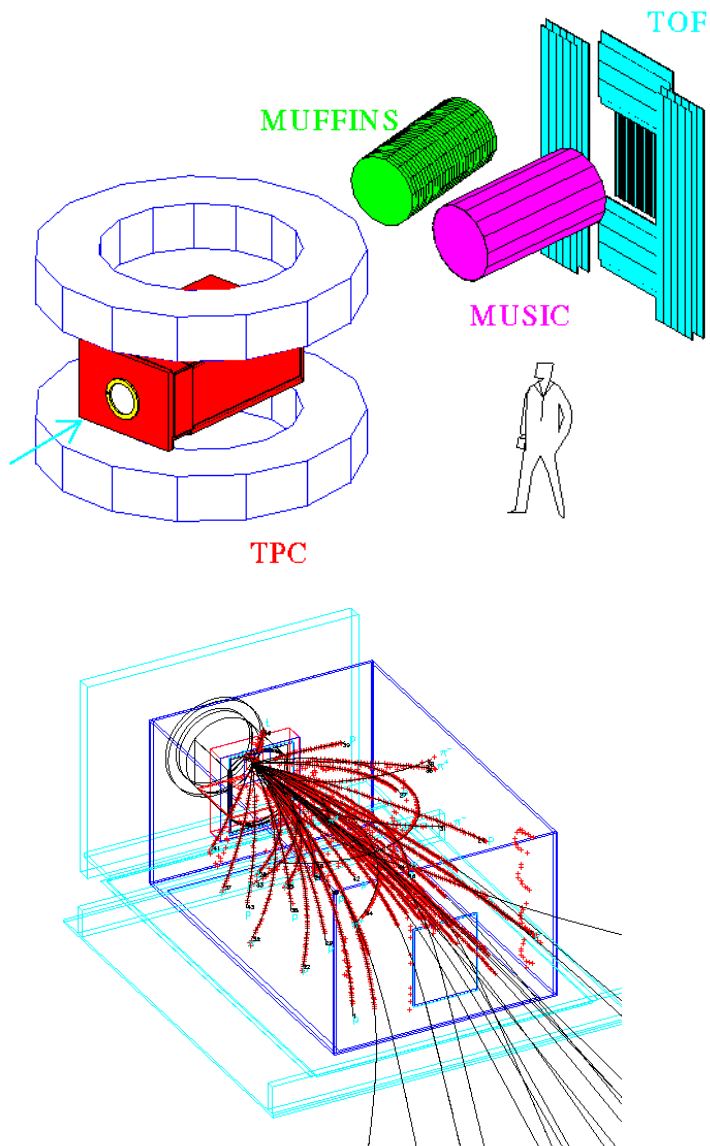
sPHENIX: 2023-2026



STAR: 2000-2026



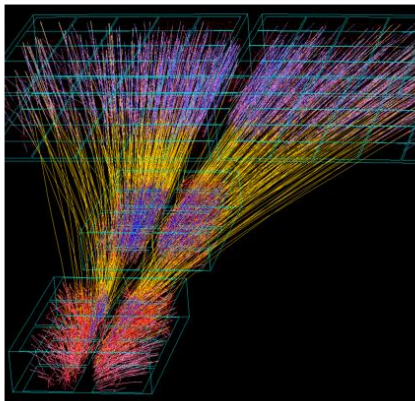
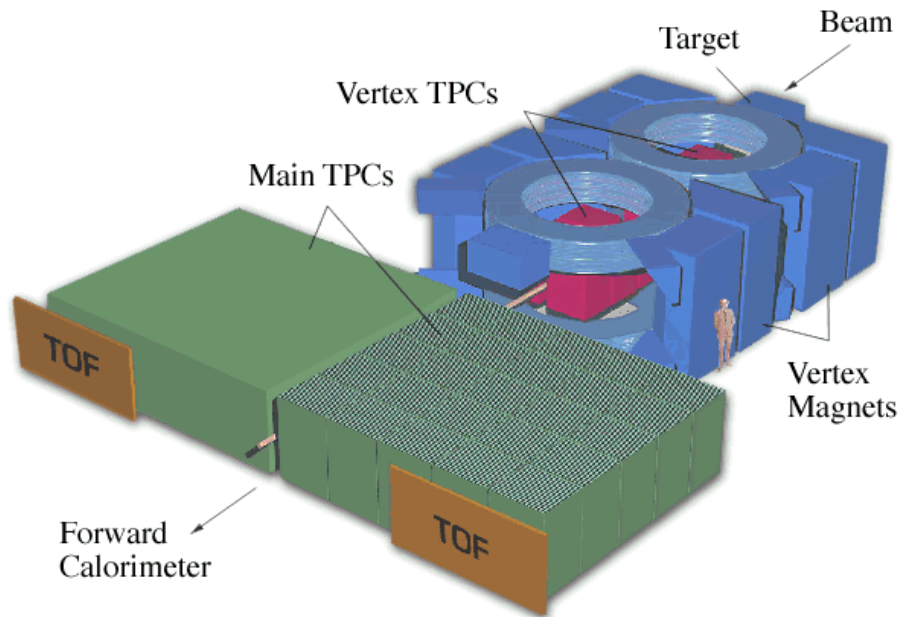
EOS @ BEVALAC



- 1992-1997
- **First TPC for heavy ions**
- Large acceptance, good PID
- ~ 2 AGeV fixed target
- ~ 1 -10 events/second
- ~ 1 MB/second data rate
- 15360 pads
- 1.5x1.0 m pad plane
- Mult. limit ~ 200 tracks
- $\sim 10^5$ events in total

NA49 (NA61) @ SPS

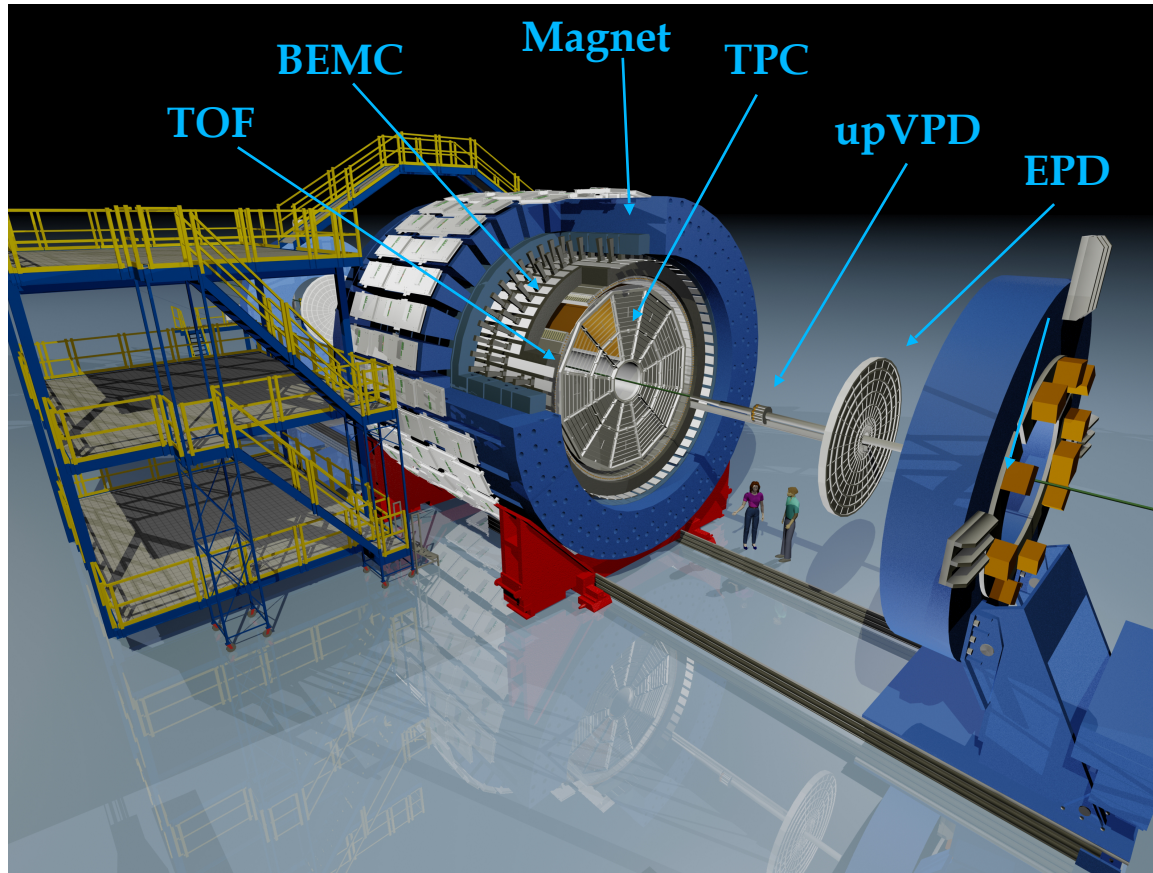
North Area 49



- 1994-2002 (NA49)
- **Setup of multiple TPCs** for tracking and vertexing
- PID for charged particles
- **For the first time the energy density for the QGP was reached at the NA-series experiments**

STAR @ RHIC

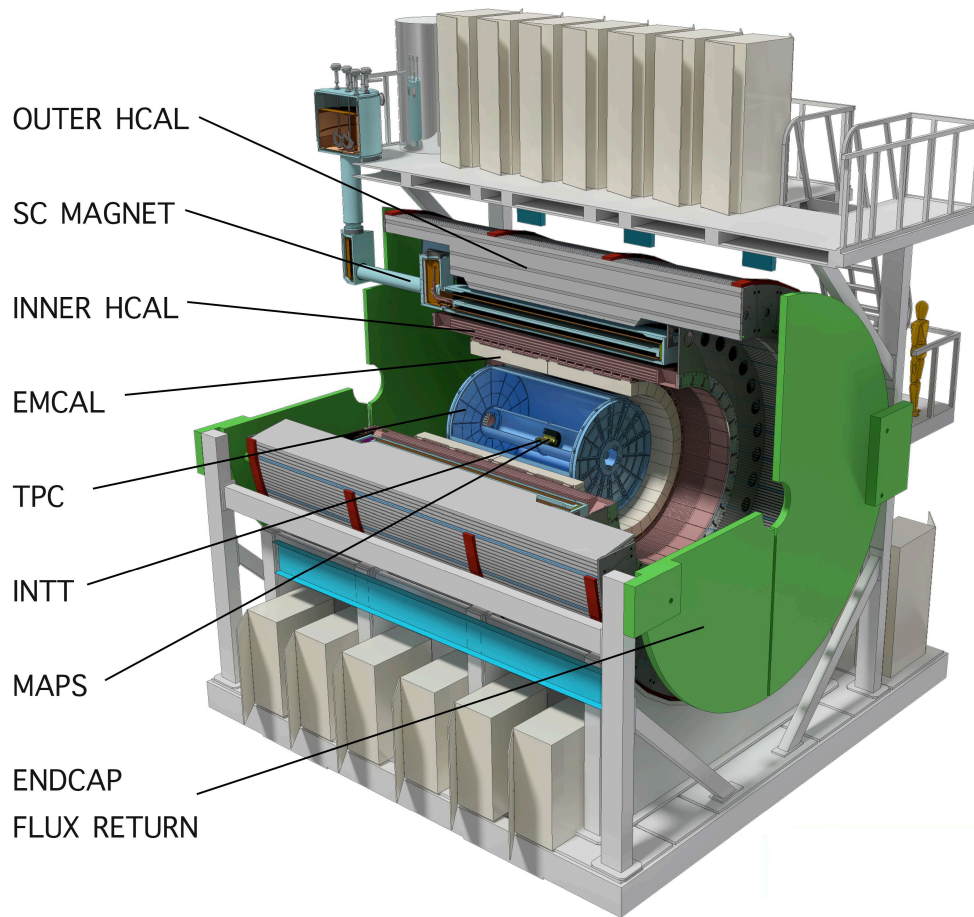
Solenoidal Tracker At RHIC



- **Large TPC for tracking and PID with full azimuthal coverage**
- Time-of-flight system
- Calorimetry
- Forward-backward detectors for event plane
- **First MAPS based silicon pixel vertexer for HI**
- 7.7 GeV - 200 GeV + fixed target
- 1 Hz - ~4.5 kHz for Au+Au

sPHENIX @ RHIC

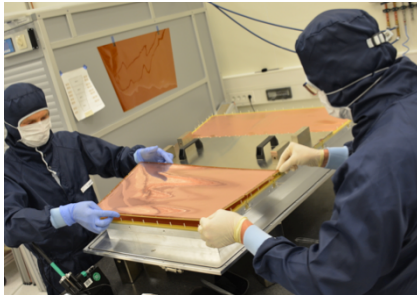
super PHENIX 2023-2026? (end date depends on EIC start at BNL)



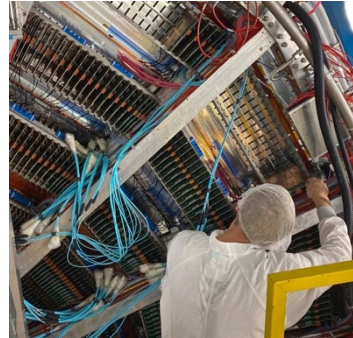
- Full azimuthal coverage, $|\eta| < 1.1$
- Full calorimetry (EMCAL + HCAL)
- MAPS based vertexer
- TPC with GEM based **continuous readout**
- **~ 15 kHz trigger rate**
→ > 10 GB/s DAQ
- Focus on hard probes: jets, Υ , open heavy flavor, photons etc.

The ALICE TPC

ALICE TPC Upgrade Timeline



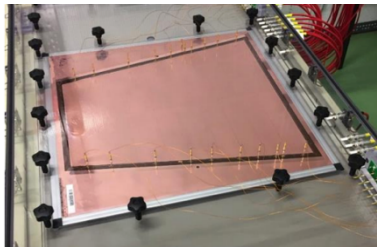
Start GEM ROC production



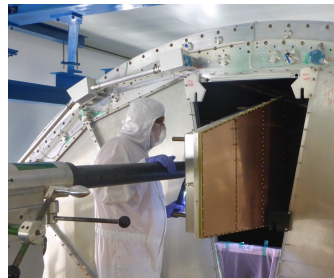
Start installation FEE and services



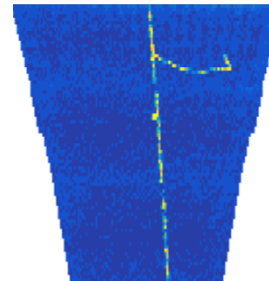
Transportation to LHC P2



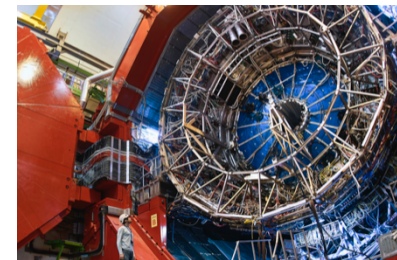
Start GEM production



Start GEM ROC installation



Start pre-commissioning



Start connection and commissioning

Aug 2016

March 2017

May 2019

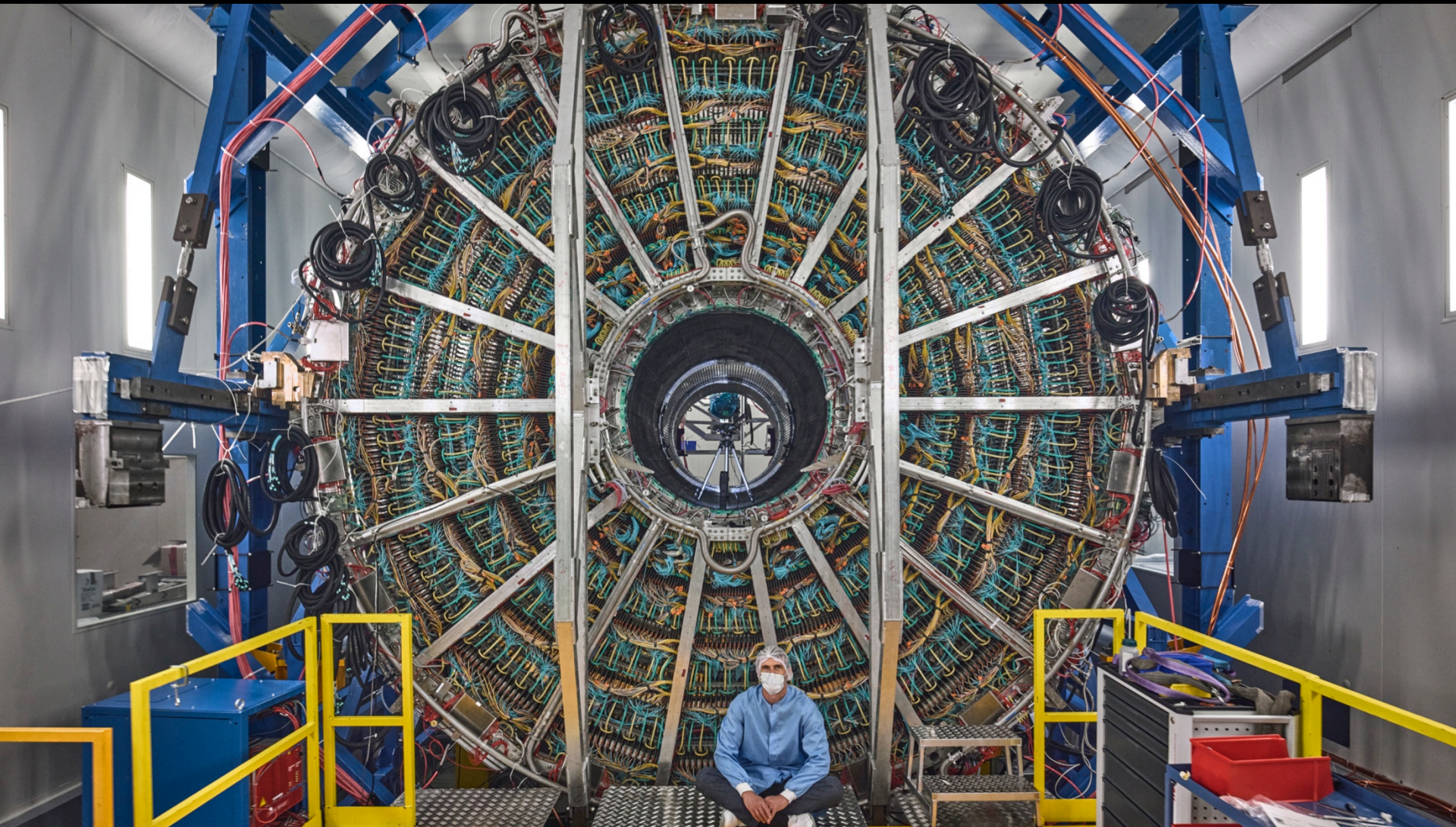
Sep 2019

Nov 2019

Aug 2020

Dec 2020

Backside of the TPC

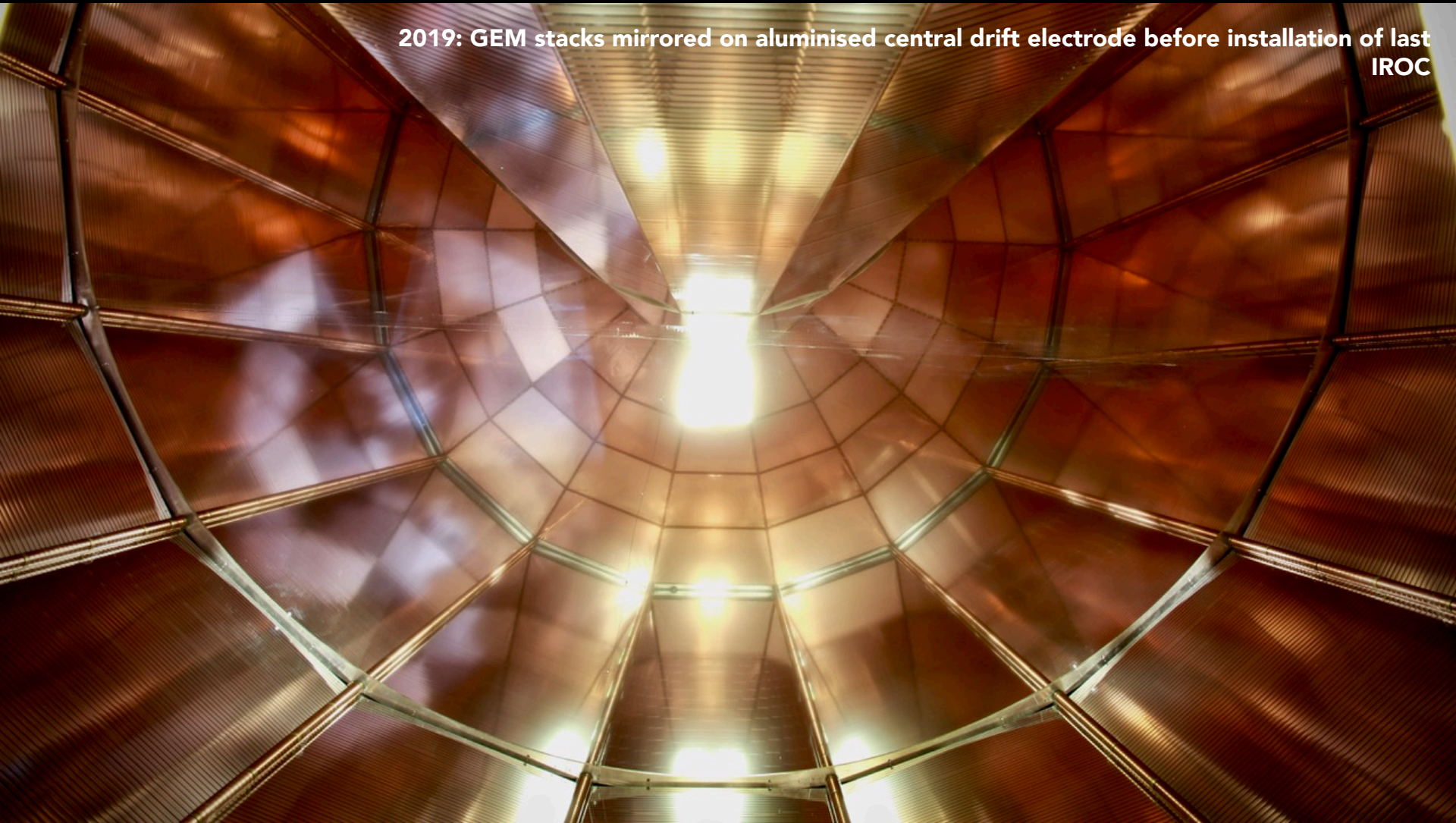


Insertion of a TPC Sector

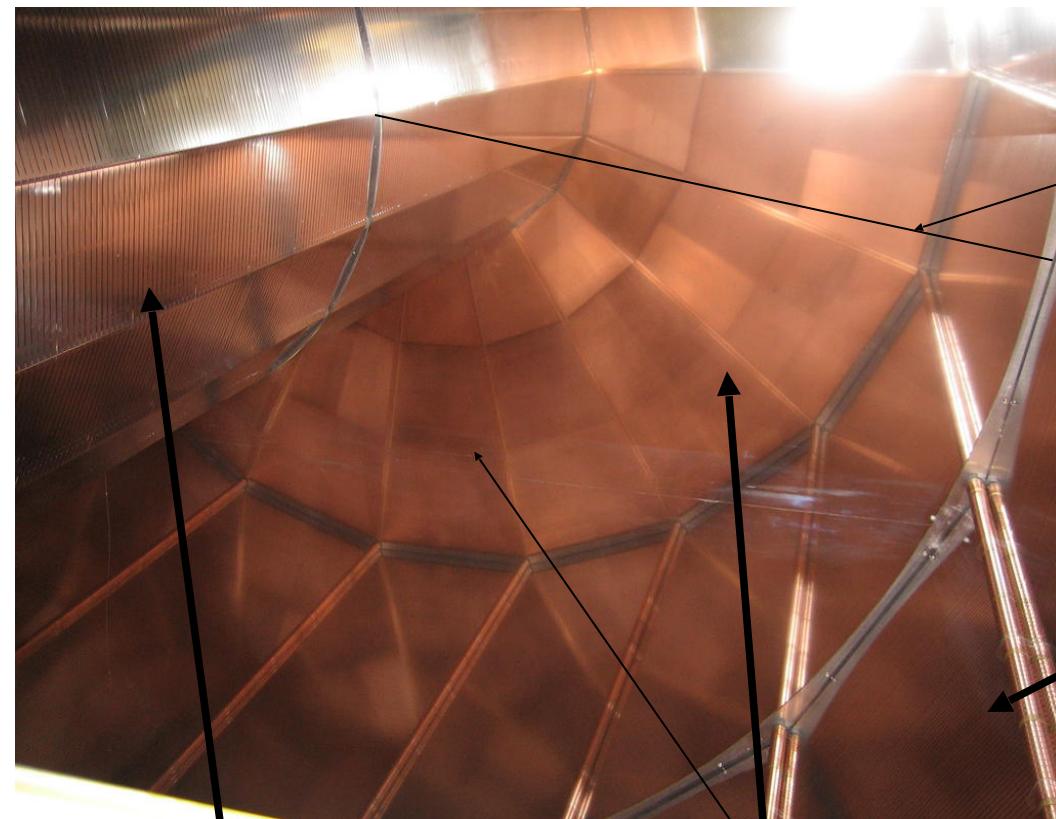


Inside of the TPC

2019: GEM stacks mirrored on aluminised central drift electrode before installation of last IROC



Central Electrode and Field Cage

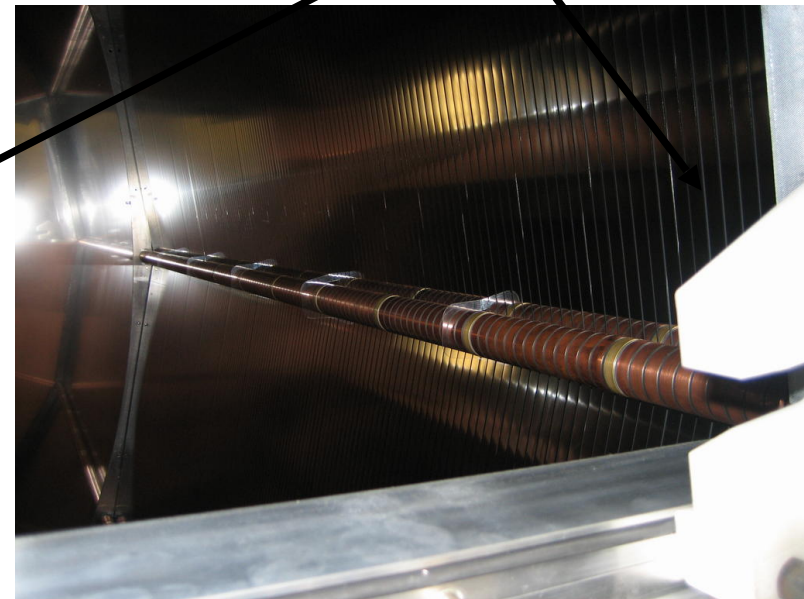


Central electrode

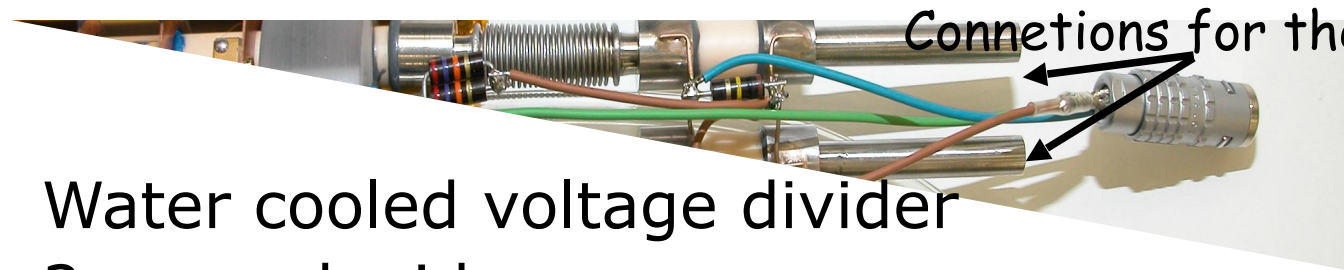
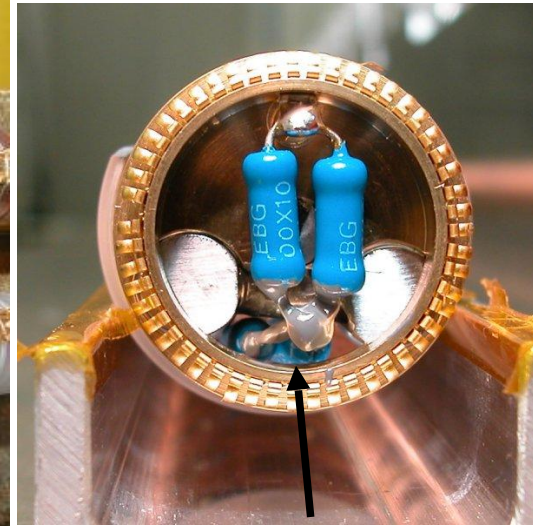
Outer part of the field cage

Inner part of the field cage

Reflection of the pad-plane, mirrored on the CE



Voltage Dividers

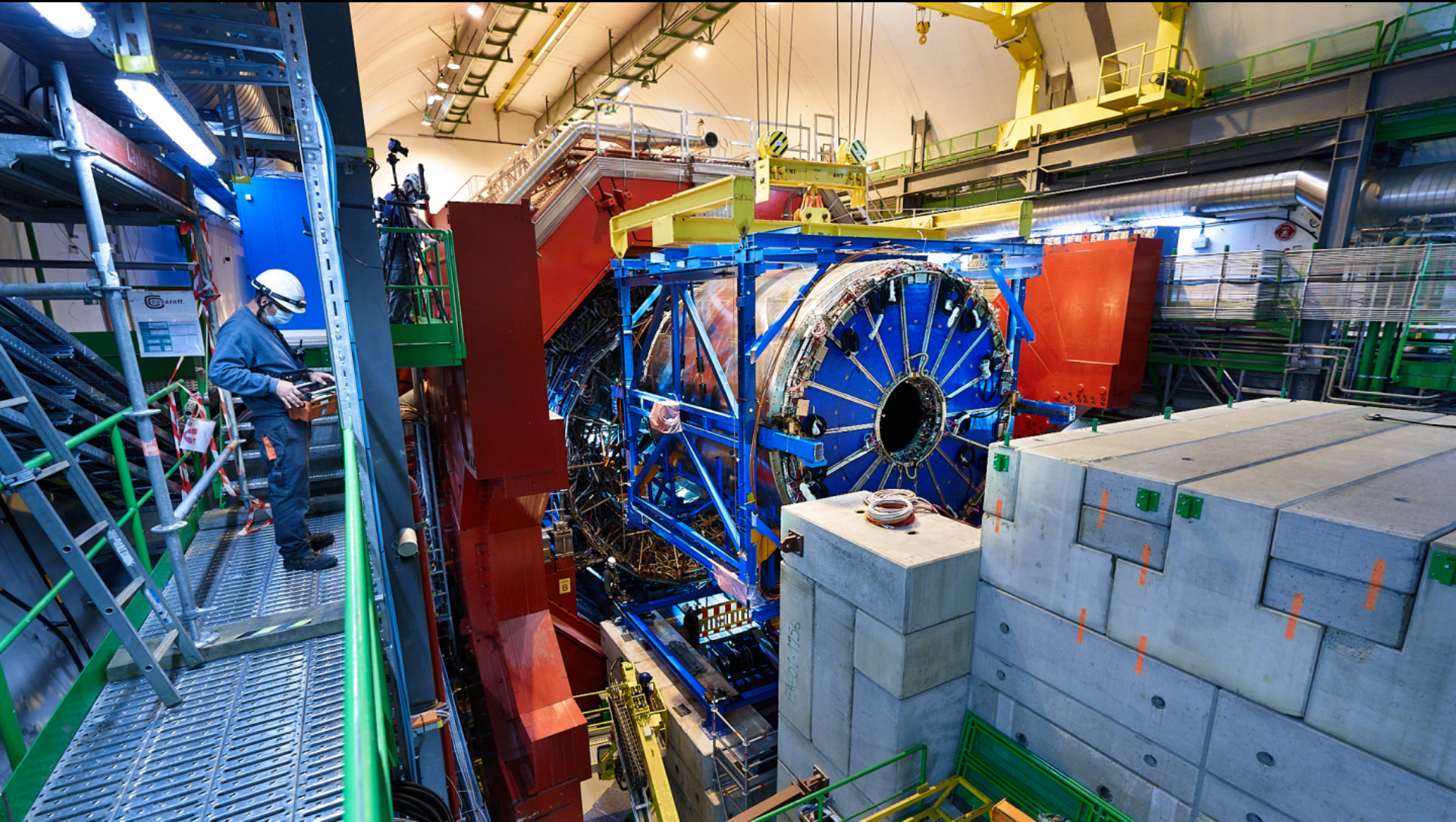


Water cooled voltage divider
2 on each side (1 inner, 1 outer)

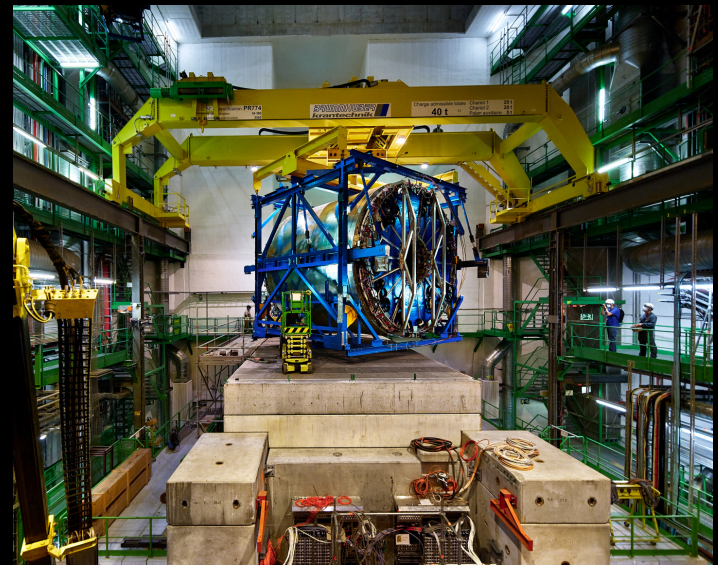
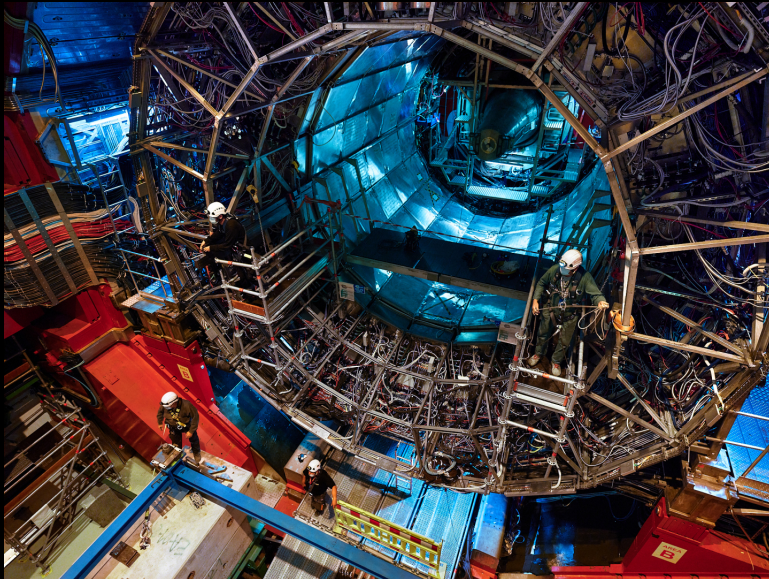
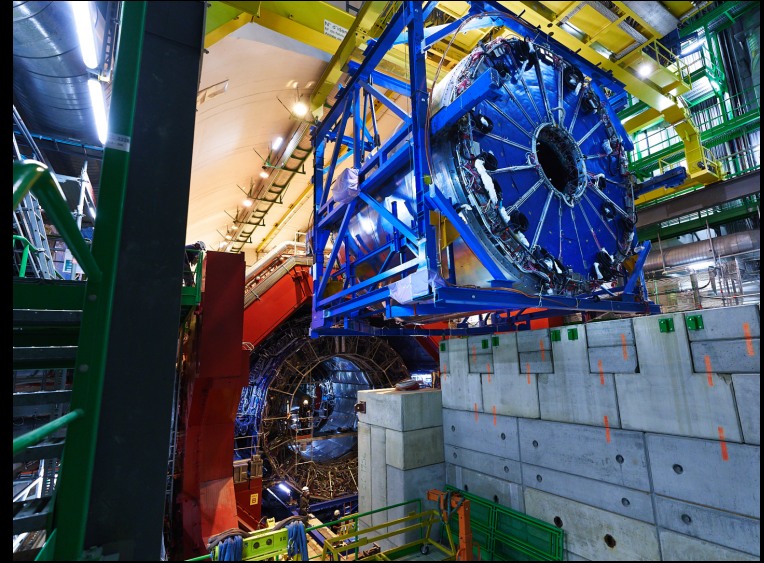
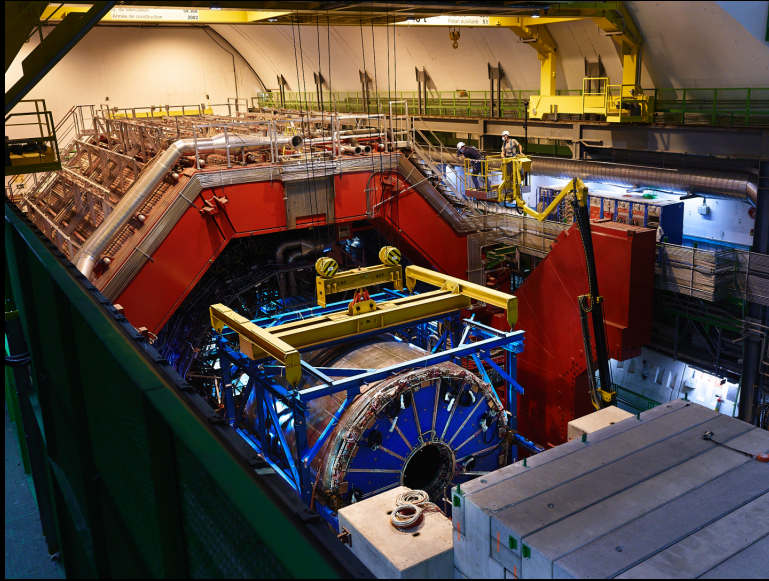
Power dissipation $\approx 4 \times 8W$ ($\approx 40\text{min}$ to heat the gas by 1K, planned T stability 0.1K)



TPC is inserted into the L3 Magnet

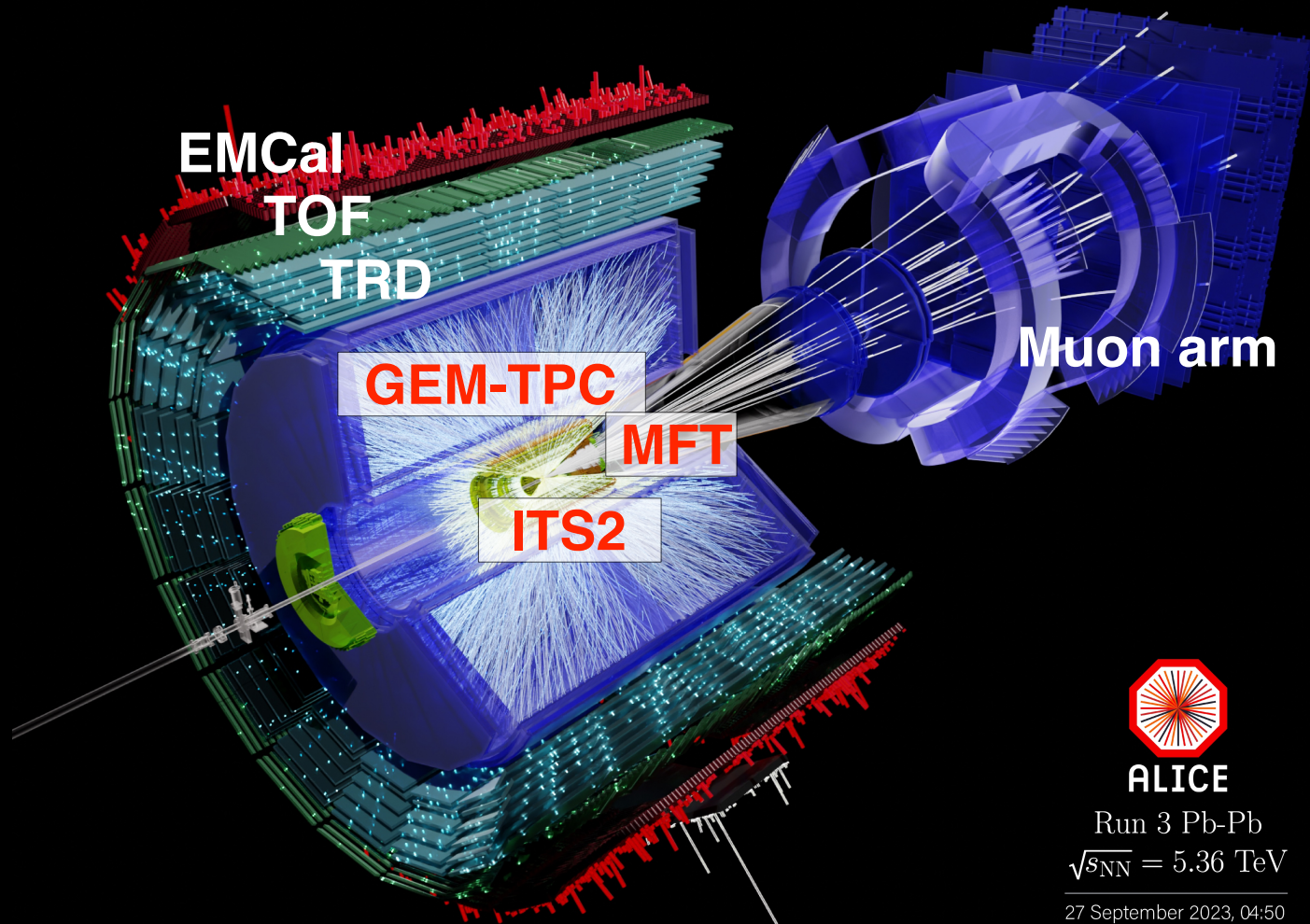


More Impressions



Move Upgraded TPC into the Cave

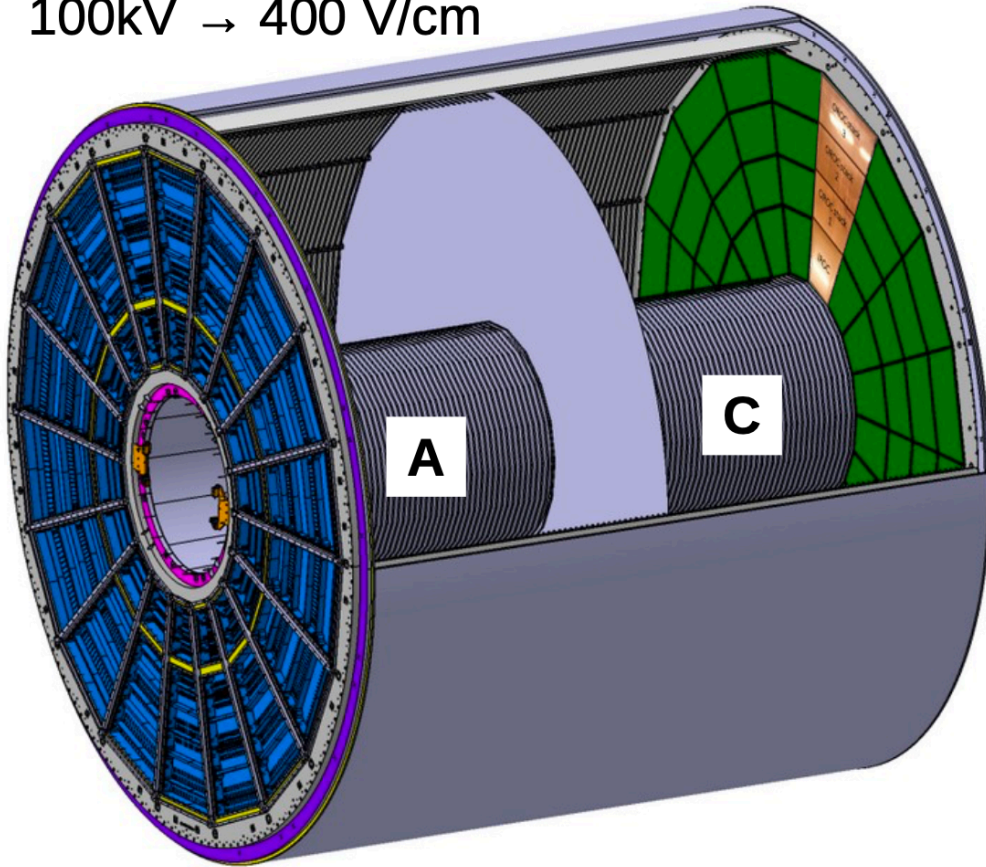
Setup in Run 3 (2022-2026)



- ~5000 charged particles per central collision.
- TPC is in between ITS2 and TRD/TOF for tracking.

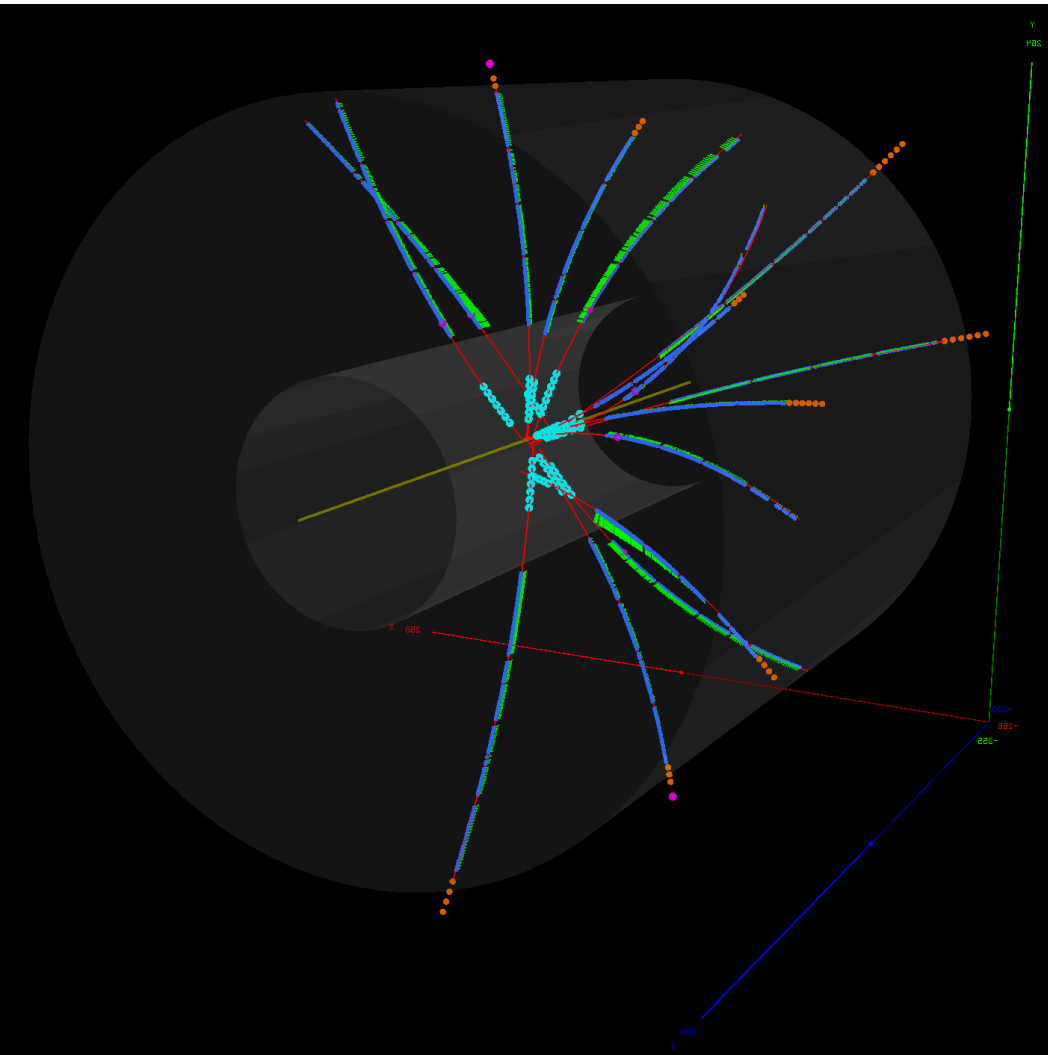
The ALICE TPC

Central HV electrode (CE)
100kV $\rightarrow$ 400 V/cm



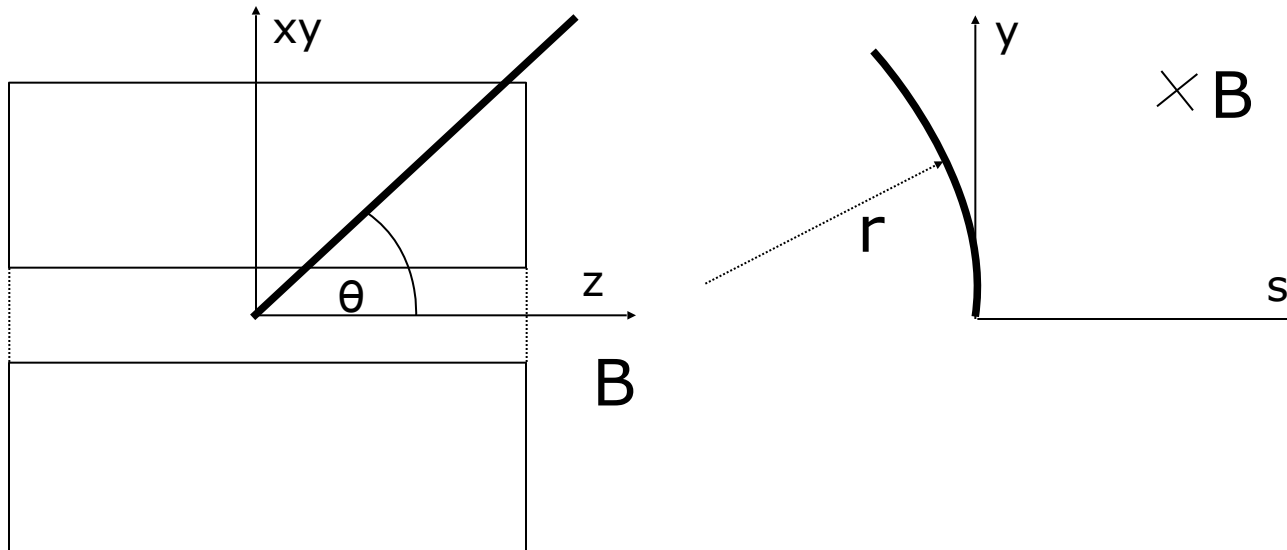
- 5 m diameter.
- 5 m length.
- 18 sectors, each subdivided into 4 sections.
- Two sides (A,C) separated by the central electrode (CE).
- Gas mixture: Ne-CO₂-N₂ (90-10-5).
- Main task: 3D particle track imaging.
- Drift time electrons: $\sim 100 \mu\text{s}$.
- Drift time ions: $\sim 200 \text{ ms}$.
- Interaction rate: $\sim 50 \text{ kHz}$ for Pb-Pb, $\sim 500 \text{ kHz}$ for p-p but up to $\sim 2 \text{ MHz}$ for p-p possible.

3D Track Imaging



- Charged particle tracks from the collision ionise the gas.
- The electrons are drifting away from the central electrode towards the end caps.
- At the end caps the charge is amplified and measured on the pads $\rightarrow (x,y)$ information.
- The arrival time t_1 is measured and together with the start time t_0 the z -component can be calculated: $z = v_D \cdot (t_1 - t_0)$.
- v_D is the electron drift velocity.

Momentum Measurement



longitudinal:

$$\tan \theta = \frac{p_T}{p_z}$$

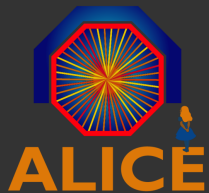
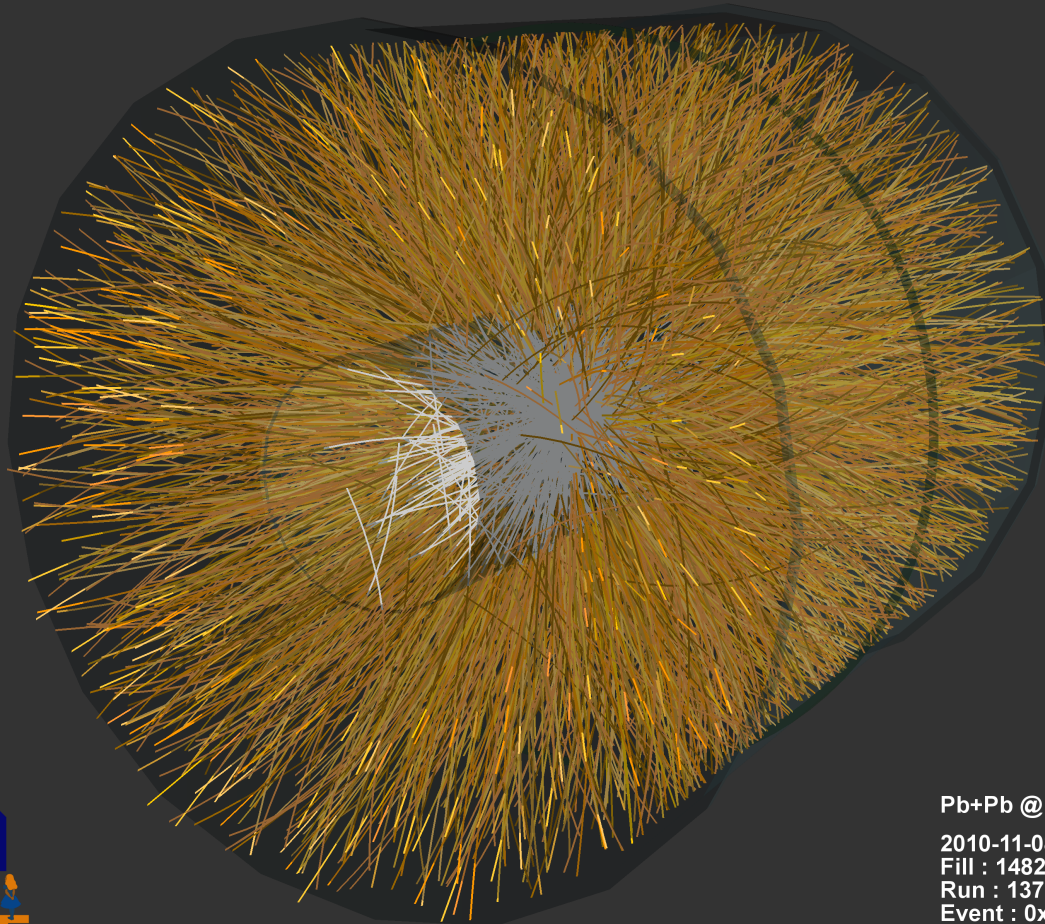
transverse:

$$\begin{aligned} \omega &= q \cdot B / m; \quad v_T = \omega \cdot r \rightarrow \\ p_T &= m v_T = q B r \\ p_T [\text{GeV}] &= 0.3 B r [\text{T} \cdot \text{m}] \end{aligned}$$

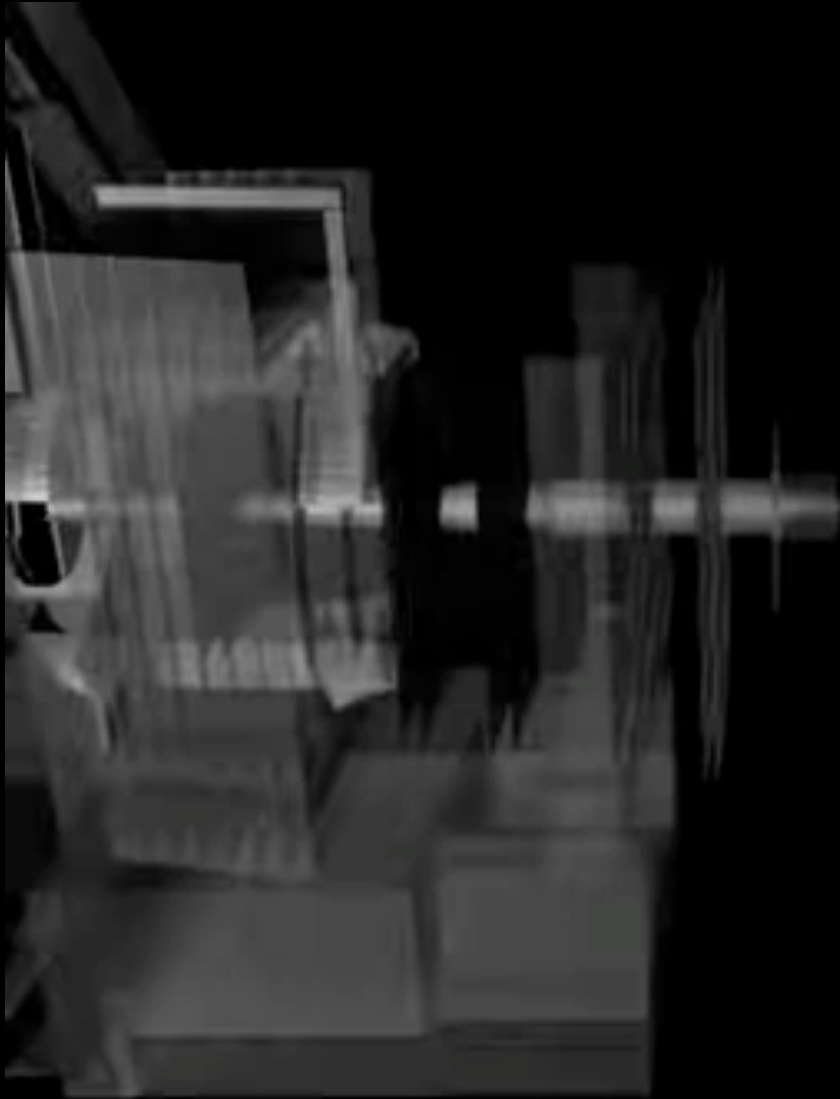
equation of motion:

$$\begin{aligned} \vec{F} &= q \cdot \vec{v} \times \vec{B} \quad (\vec{B} = B \cdot \vec{e}_z) \\ \vec{F} &= m \cdot \dot{\vec{v}} \rightarrow \text{Helix} \end{aligned}$$

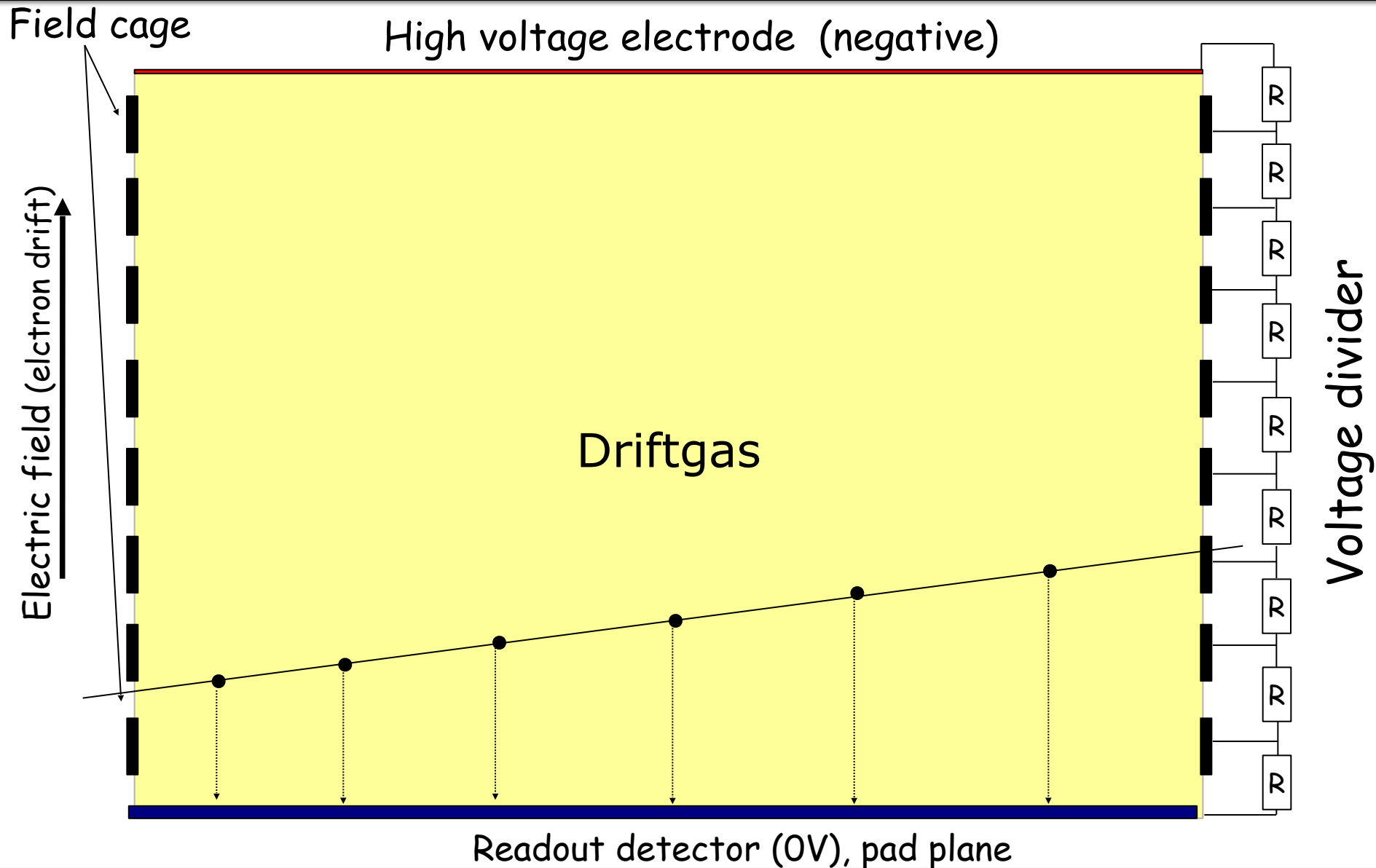
Pb-Pb collision



Pb+Pb @ $\sqrt{s} = 2.76$ ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693



Structure of a TPC



Gas mixture - Considerations

- Primary ionisation
 - Gas amplification (High voltage) → stability of detector
 - Production of space charge → distortions of the drift field
- Multiple scattering
 - Momentum resolution
- Drift velocity
 - Sensitivity on environment
 - Readout time of the detector
- Diffusion
 - Widening of the signal → two track resolution
 - Signal loss for long drift → signal resolution
 - Gas amplification → detector stability
- Ageing
 - Deterioration of performance over time
 - Risk of breakdown
 - Important is also the choice of ALL materials which are in contact with the gas (outgassing)

ALICE Gas Mixture

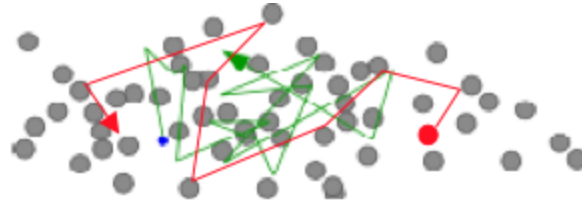
- Carrier Gas Ne
 - Low $Z \rightarrow$ low multiple scattering $\rightarrow$ high momentum resolution
 - Low primary Ionisation $\rightarrow$ low space charge $\rightarrow$ small distortions
- Quench Gas CO_2 (+ N_2)
 - low diffusion $\rightarrow$ good resolution for long drift
 - No ageing expected $\rightarrow$ no deterioration of detector performance
 - (quenching of photons with different energies $\rightarrow$ more stable operation)
- Disadvantage:
 - Very sensitive to gas density changes (drift velocity)
 - Large gain ($\sim 10^4$) needed $\rightarrow$ high voltages $\rightarrow$ might lead to stability problems

Ionisation, clusters,
drifting,...

Diffusion

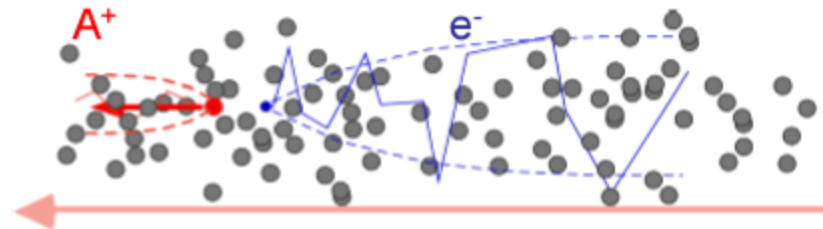
$E=0$ thermal diffusion

$$\langle \mathbf{v} \rangle_t = 0$$

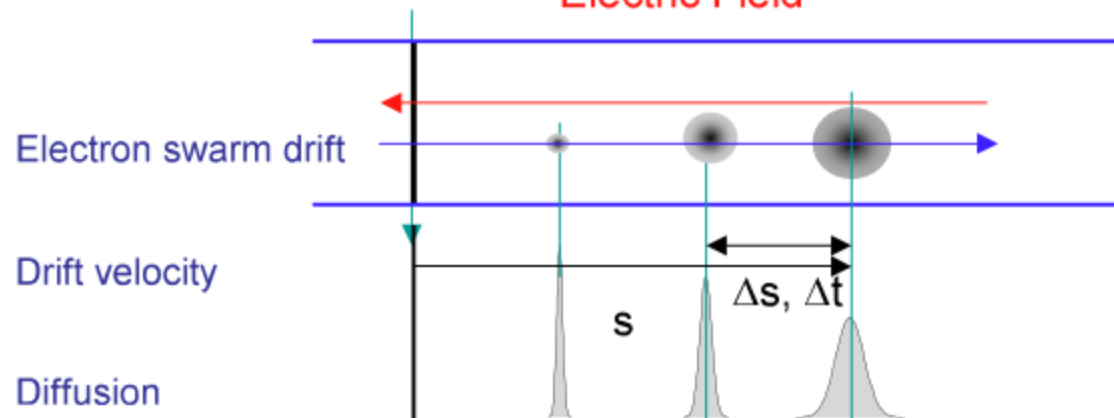


$E > 0$ transport and diffusion

$$\langle \mathbf{v} \rangle_t = \mathbf{v}_D$$

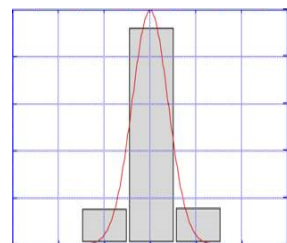
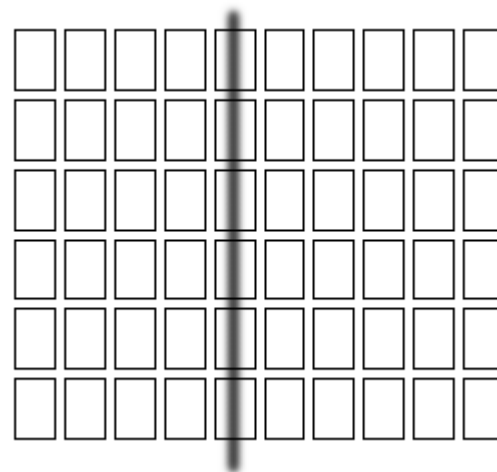


Electric Field



Diffusion

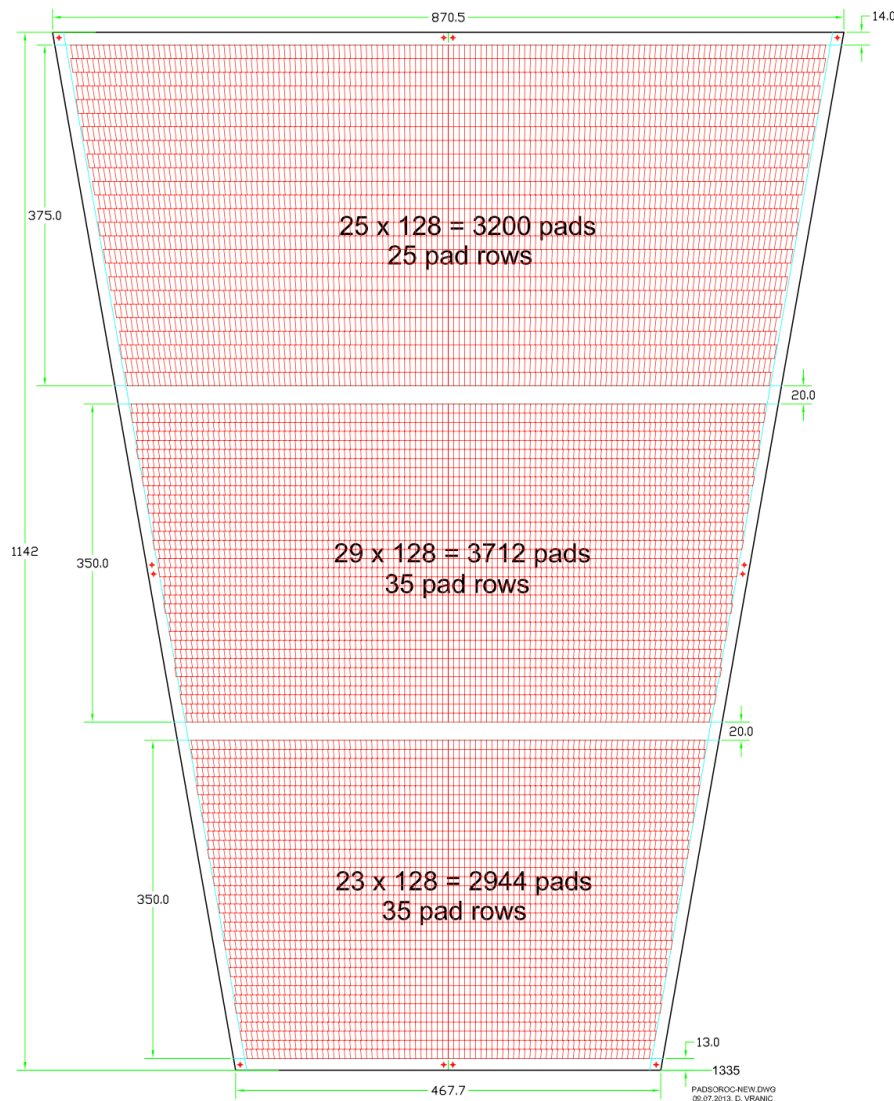
The diffusion constant is one of the **essential parameters for choosing the gas mixture**. To get the desired **two track separation and position resolution** the diffusion constant has to be chosen very carefully.



pick-up pads

How good can you separate two close tracks?

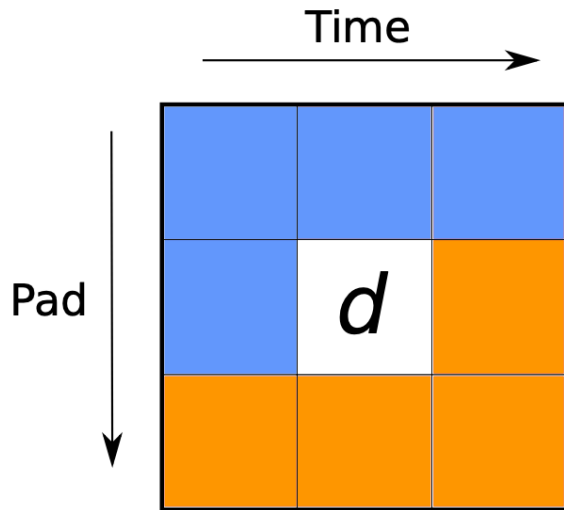
The Pad Plane



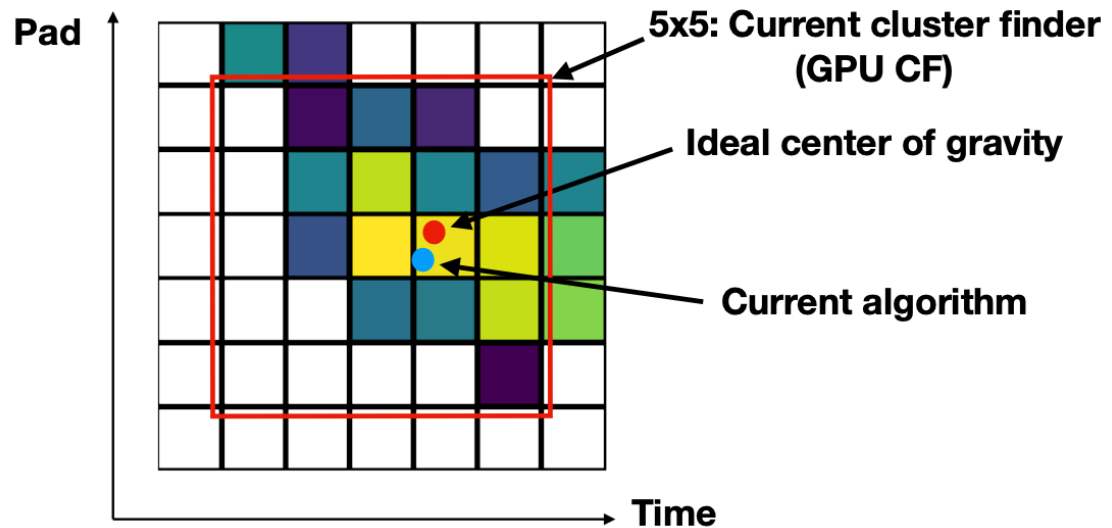
- 152 pad rows.
- 552 960 pads in total over 18*2 sectors.
- 4-6 mm*7-15 mm pad size.
- Intrinsic resolution of clusters $O(< 1 \text{ mm})$.
- Pad plane geometry (pad sizes) fit to the gas mixture and the corresponding diffusion.

TPC Clusterizer

Finding peaks per pad row
and 3 time bins

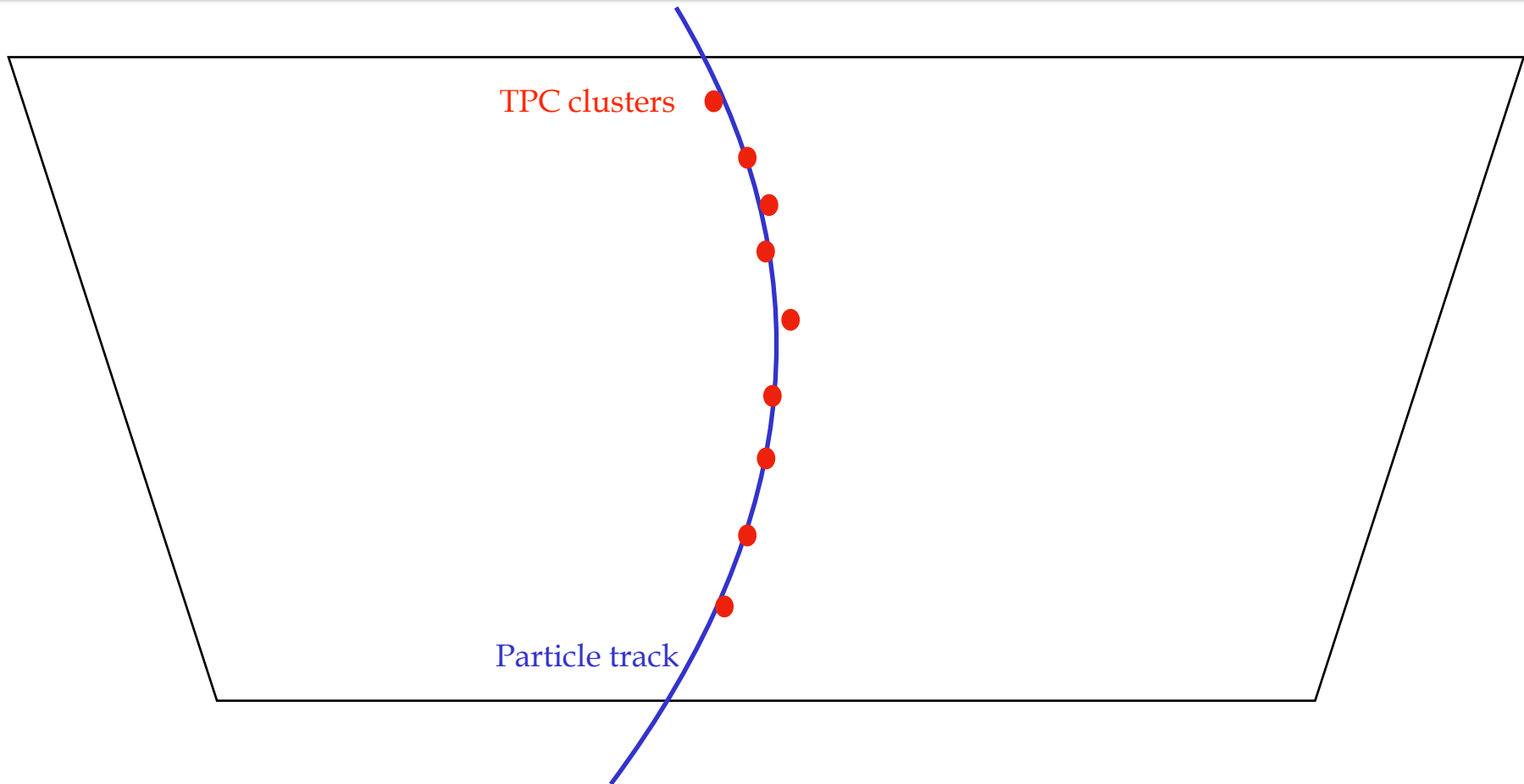


Under development: neural
network cluster finder



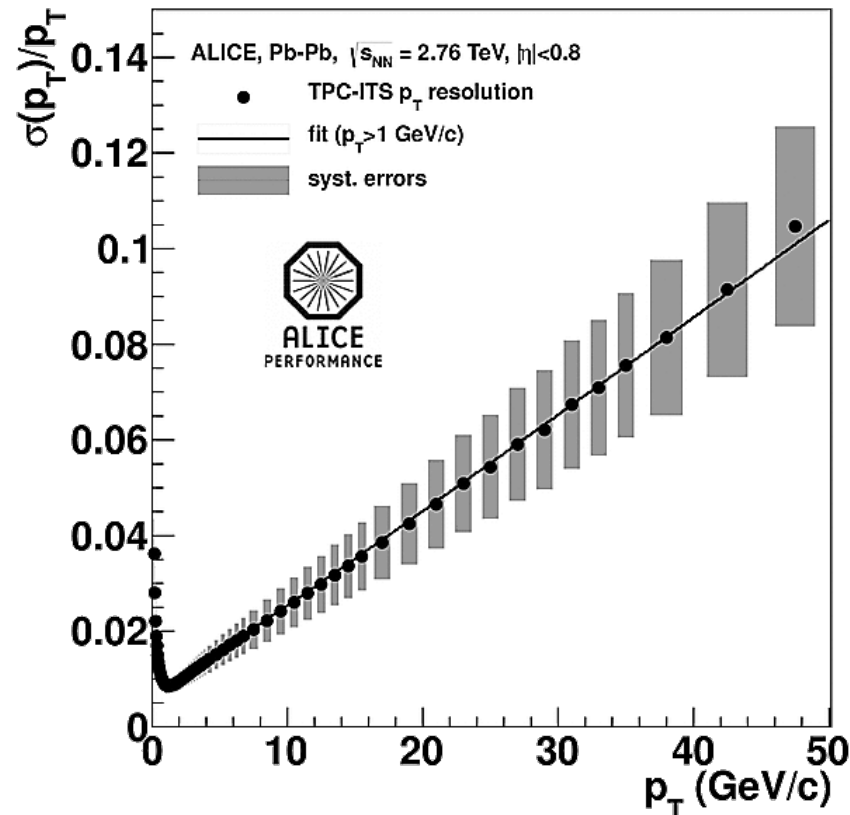
- 10 MHz sampling for clusterization = 100 ns.
- Digits as input (ADC value per pad = dE/dx).
- Creates most of the data in ALICE.
- Done on GPUs during data taking.
- Peak finding in 2D per pad row.

Tracking



- TPC clusters as input.
- Kalman based particle tracking.
→ curvature of tracks → transverse momentum.

Run 2 Momentum Resolution



Combined tracking TPC-ITS
**momentum resolution $\sim 10\%$ at
50 GeV/c**

(Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV from
2010).

For latest Run 2 productions, the
momentum resolution **improved to
 $\sim 5\%$ at 50 GeV/c**, as a result of
improved TPC-ITS matching.

ALI-PERF-16396

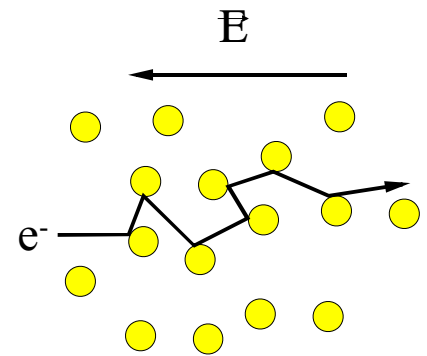
Drift of Electrons in an Electric Field

Electrons in a gas drift with a constant drift velocity u_{Drift} in an external electric field:

Mechanism:

Due to its small mass the electron scatters isotropically at the (heavy) gas molecules and loses its initial direction. In between the collisions (mean time between collisions τ) the electrons are accelerated to the velocity u_{Drift} in the electric Field:

$$u_{\text{Drift}} = a \cdot \tau = \frac{F}{m} \cdot \tau = \frac{e}{m} \cdot \tau \cdot E = \mu \cdot E$$



In the next collisions this additional energy is lost, so that there is an **equilibrium between the gained energy and the scattering loss**; therefore a **constant macroscopic drift velocity u_{Drift}** is observed.

Z-Position: How to Extract the Values

- $z = v_D \cdot (t_1 - t_0)$.
- Calibration based on matching between ITS and TPC.

$$\Delta z = \underbrace{\left(\frac{v_D^{CCDB}}{v_D^{calib}} - 1 \right)}_{\mathbf{m}} \cdot z + \underbrace{\Delta t \cdot v_D^{CCDB} - 250.0 \cdot \left(\frac{v_D^{CCDB}}{v_D^{calib}} - 1 \right)}_{\mathbf{B}}$$

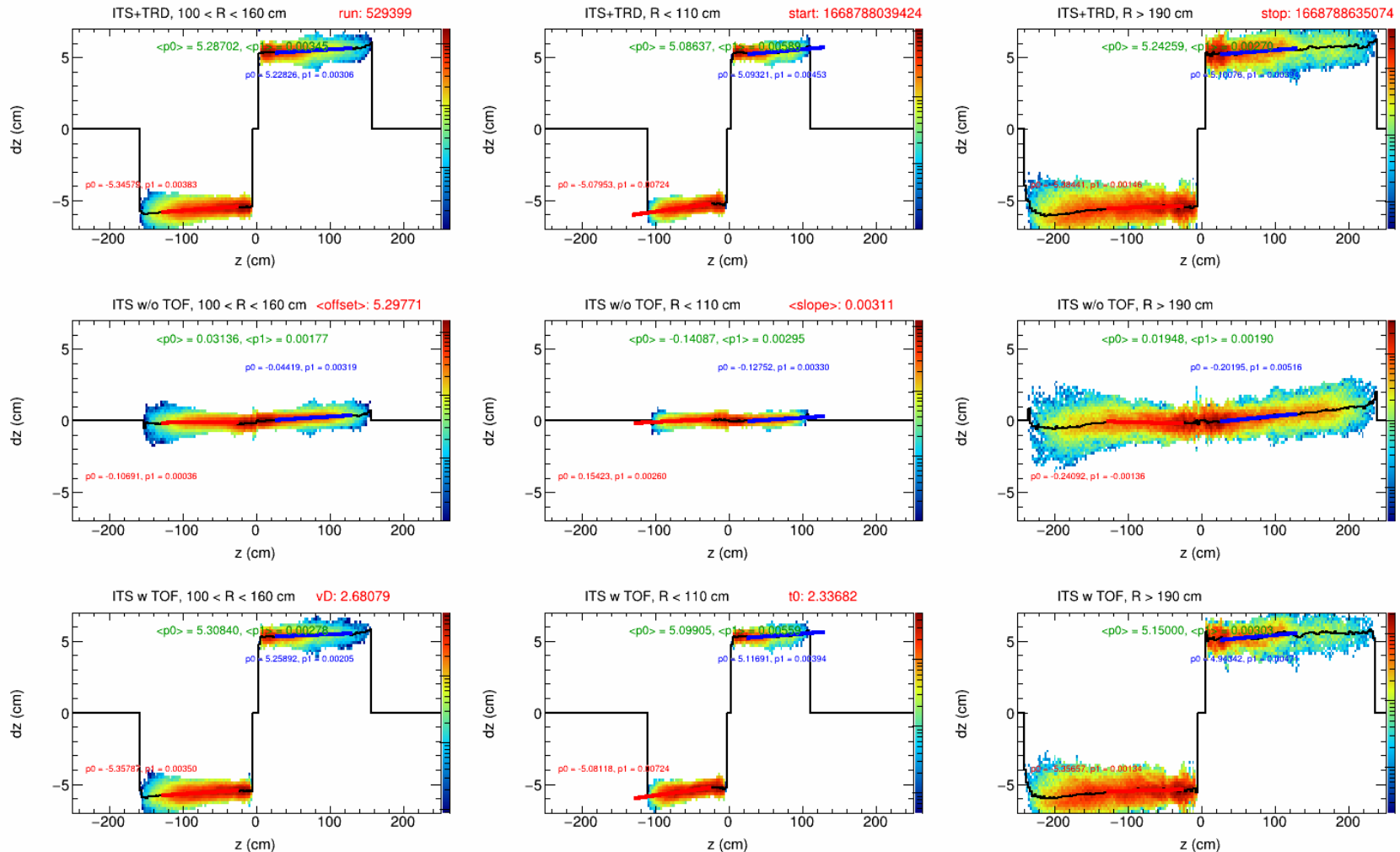
$$v_D^{calib} = \frac{v_D^{CCDB}}{m + 1} \qquad \Delta t = \frac{b + 250 \cdot \left(\frac{v_D^{CCDB}}{v_D^{calib}} \right)}{v_D^{CCDB}}$$

$$t_0^{used} = t_0^{BC} \cdot LHCbunchSpacingNS \cdot 1E^{-3} + t_0^{CCDB}$$

$$t_0^{calib} = t_0^{used} - \Delta t$$

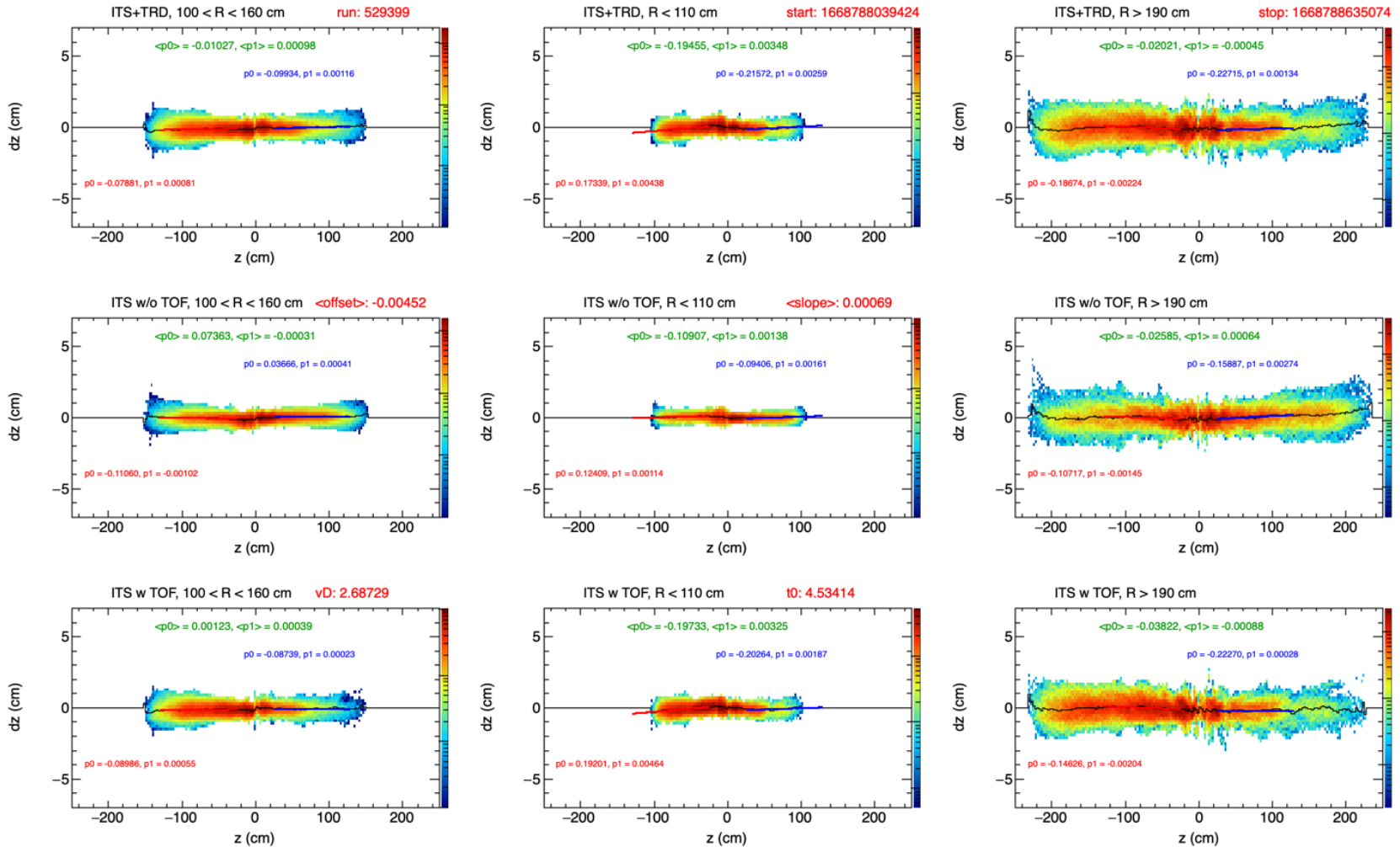
TPC Drift Velocity Calibration: Before

- Difference between ITS track and TPC cluster in z before calibration.

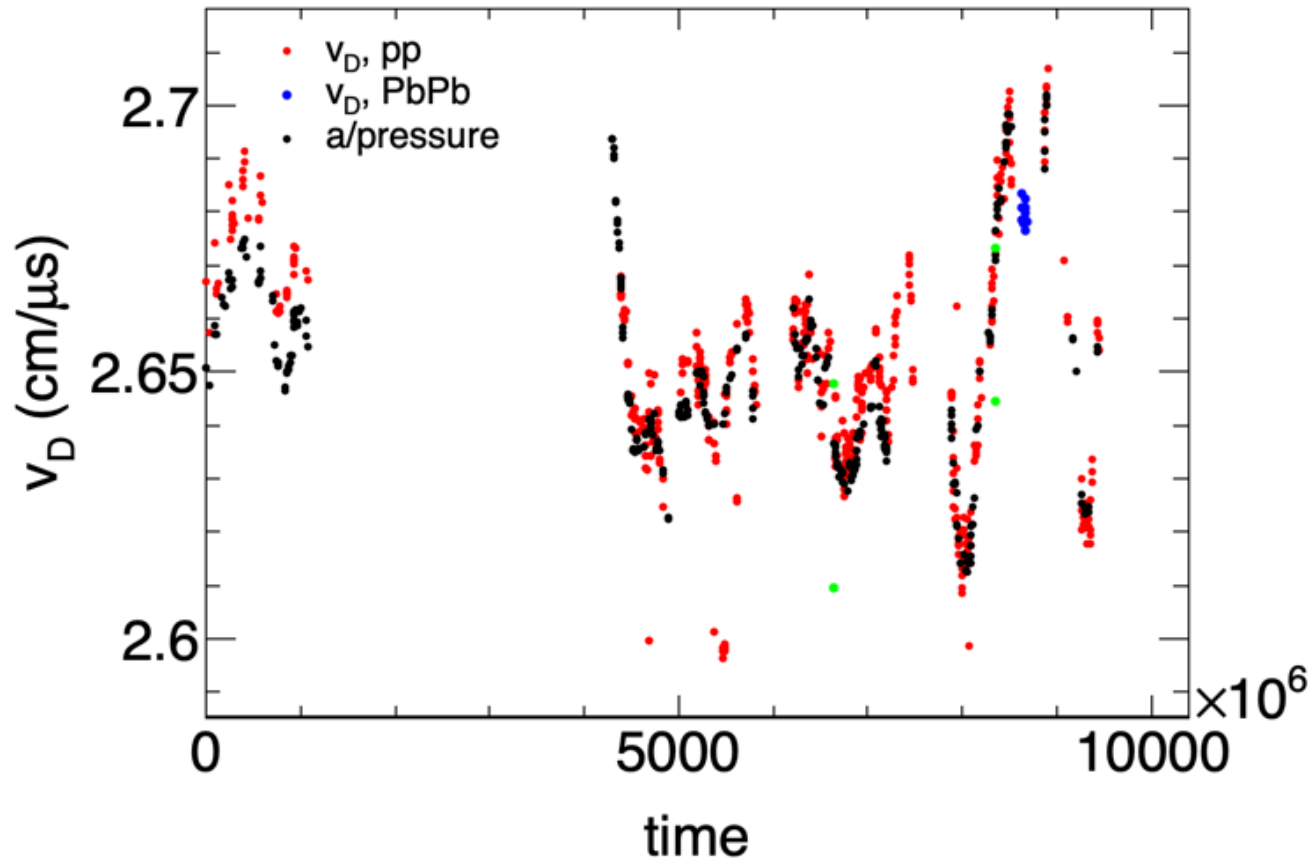


TPC Drift Velocity Calibration: After

- Difference between ITS track and TPC cluster in z after calibration.

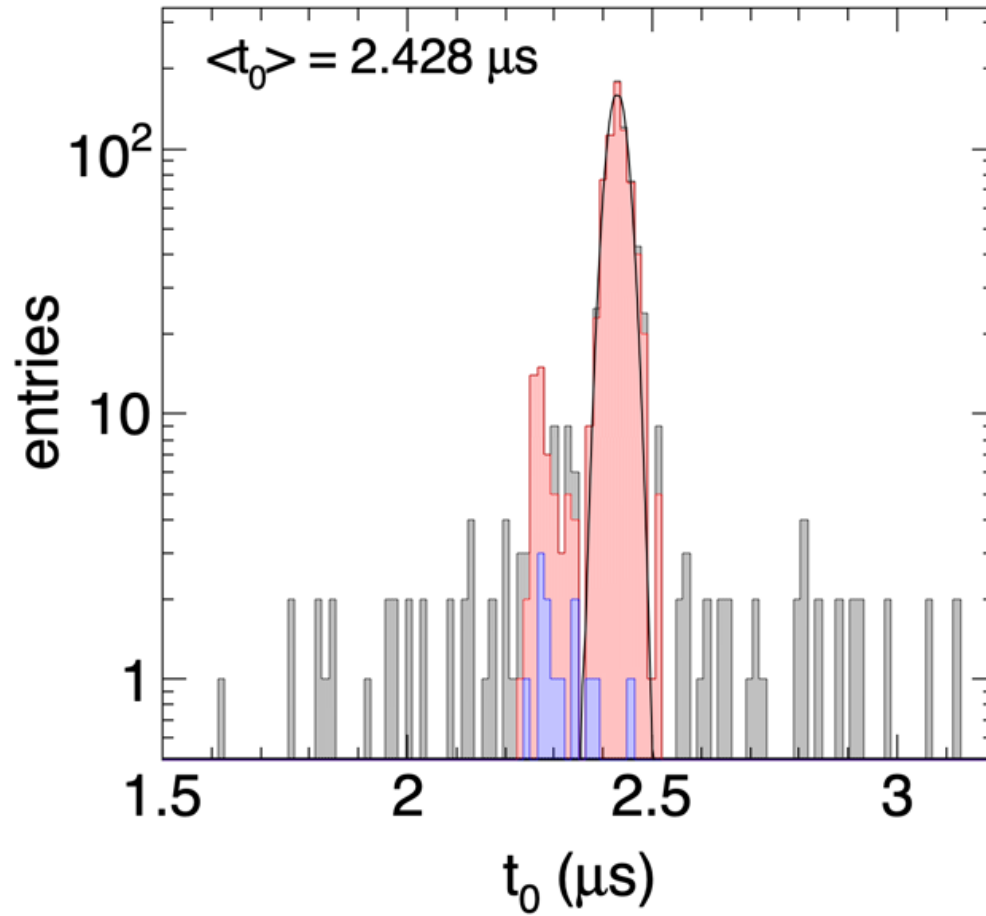


Drift Velocity vs. Time



- Trend follow the inverse pressure except a few outliers.

t_0

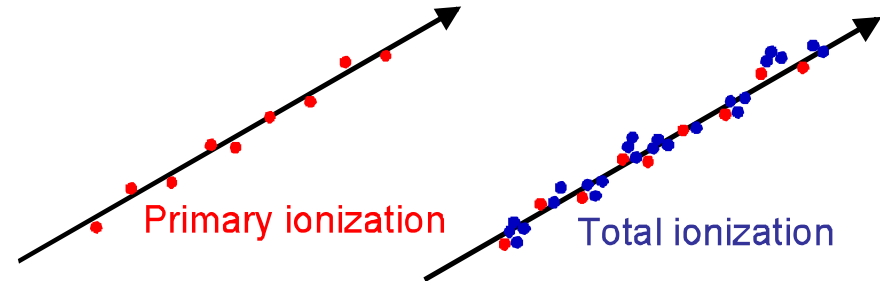


- t_0 almost stable, some dependency on interaction rate.

Ionisation

Distinguish between **primary** and **secondary** ionisation:

Atoms become excited or suffer **primary ionisation**, electrons with energies above 100 eV can make **secondary ionisation**.



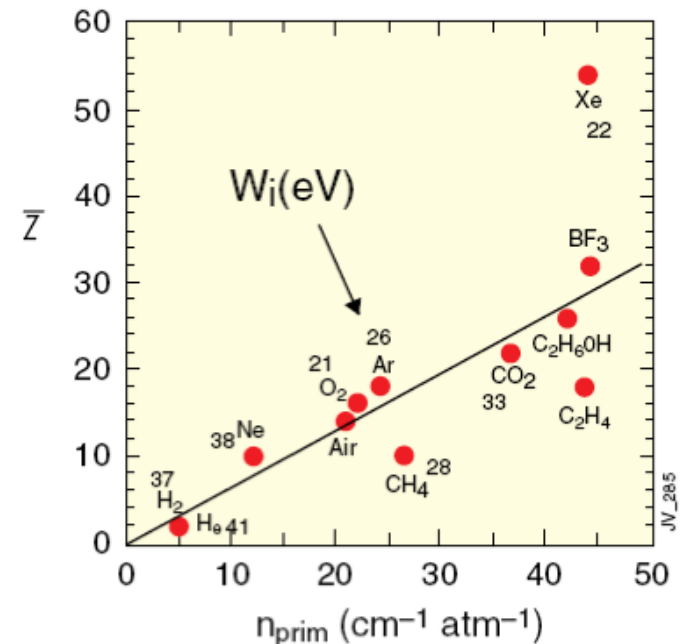
Lohse and Witzeling, Instrumentation In High Energy Physics, World Scientific, 1992

$$n_{total} = n_{primary} + n_{secondary} = \frac{\Delta E}{W_i} = \frac{\frac{dE}{dx} \Delta x}{W_i}$$

$$n_{total} \approx 3 \dots 4 \cdot n_{primary}$$

W_i = mean energy loss per produced ion pair ≈ 30 eV

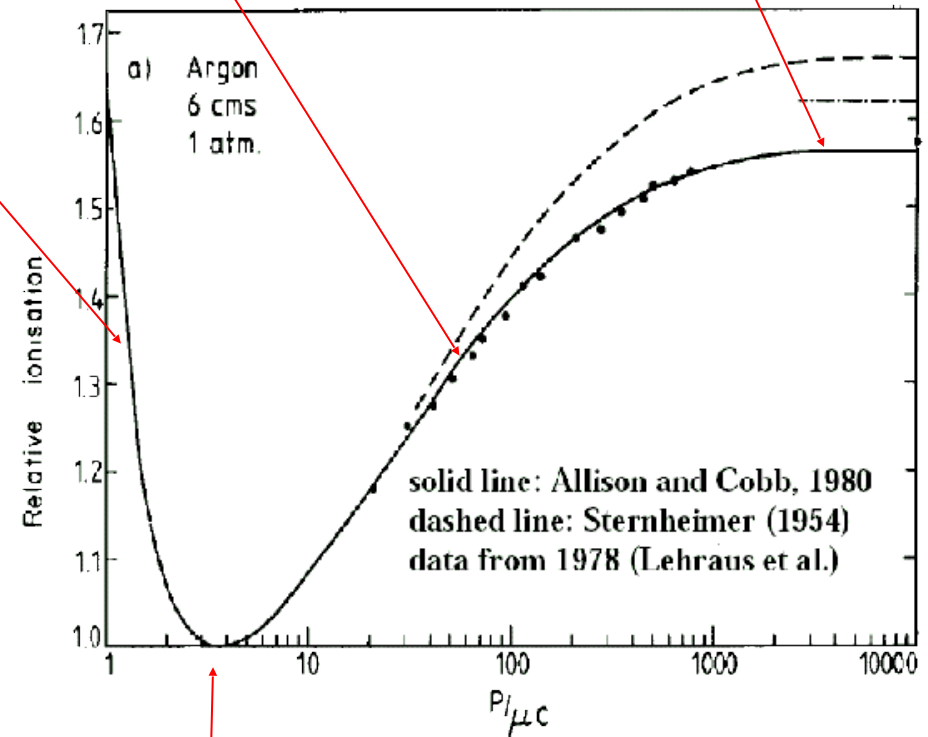
ΔE = total energy loss



The Bethe-Bloch Formula

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

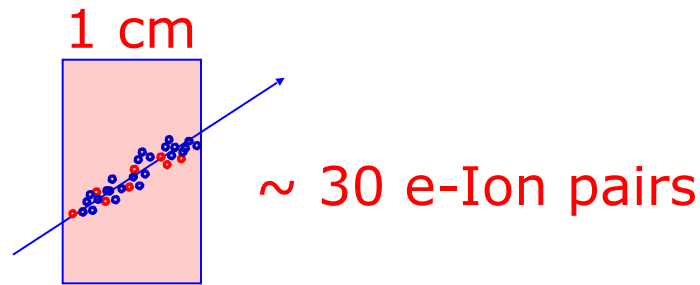
- dE/dx first falls $\propto 1/\beta^2$ (kinematic factor)
- a minimum is reached at $\beta\gamma \approx 4$ (**Minimum Ionising Particle** - MIP)
- then again rising due to the $\ln \gamma^2$ term (**relativistic rise**: contributions of more distant particles due to the relativistic expansion of the transverse E-Field)
- at high γ the relativistic rise is cancelled by the “density effect” (**fermi plateau**: polarisation of medium screens more distant atoms; described by the δ parameter)



Minimum Ionising Particle (MIP)

Measurement of Ionisation

Example: 1 cm gas counter, filled with Neon;
 $n_{\text{prim}} \approx 10 / (\text{cm atm})$, $n_{\text{total}} \approx 30$



≈ 30 Electron-ion-pairs are hard to detect!

Amplifier noise is typically ≈ 1000 e^- !

⇒ Number of electrons has to be increased noiseless

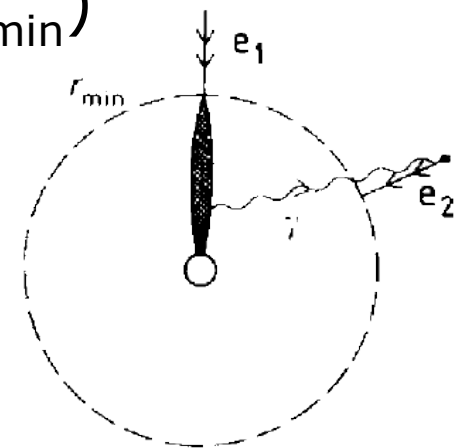
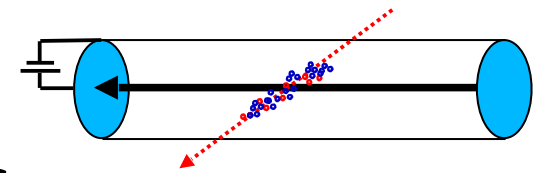
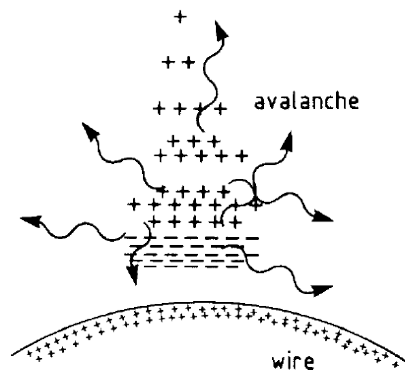
⇒ Gas amplification

Gas Amplification - Wires

- Development started already in 1948
- Simple concept
- Allows for detection of single electrons
- Electrons see increasingly larger fields

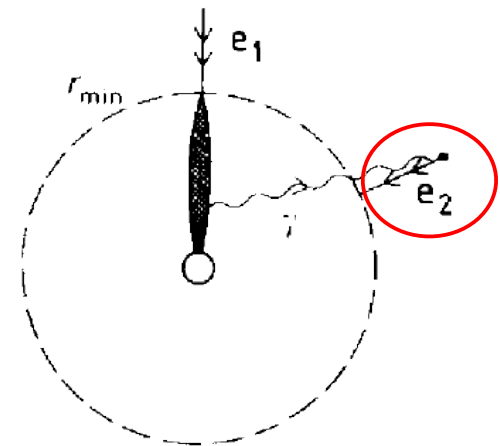
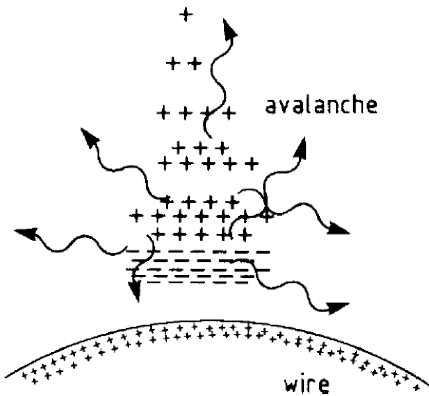
$$E = \frac{\lambda}{2\pi\epsilon_0} \frac{1}{r}$$

- If picked up energy between incidents with gas molecules is large enough for ionisation and avalanche starts (distance to wire: $r_{\min}$)



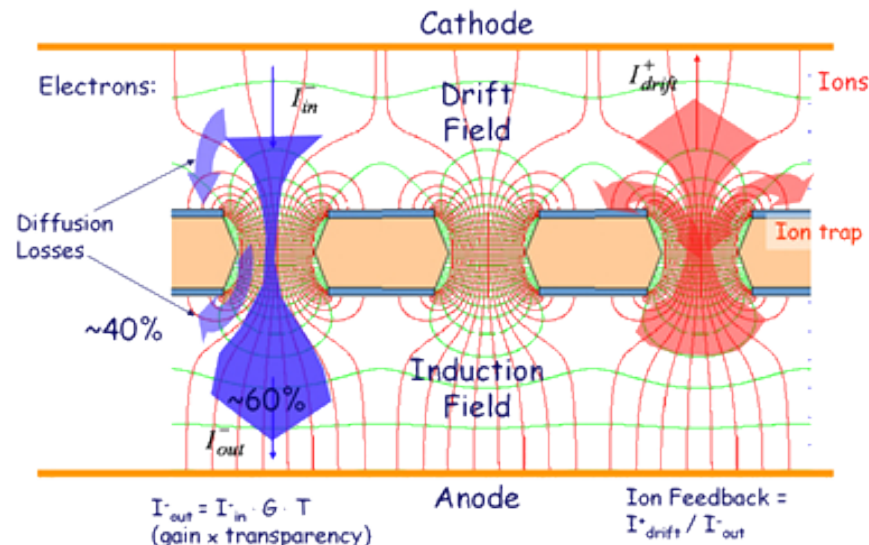
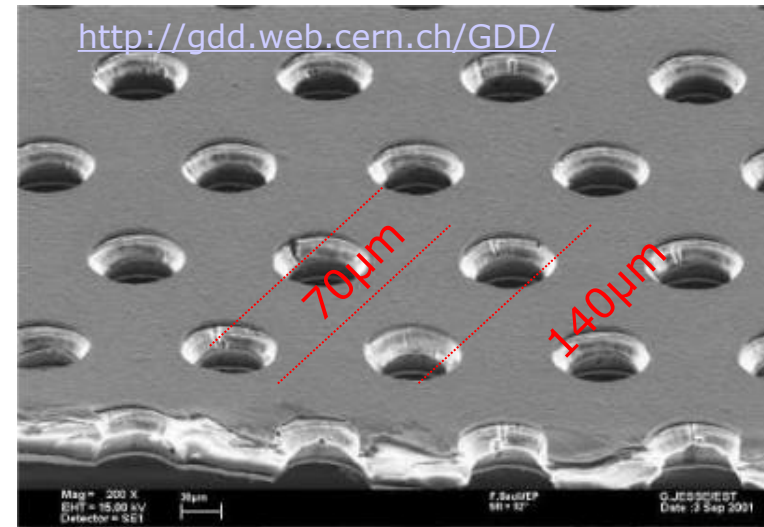
Need for a Quench Gas

- Cross-sections of photon-production is of same order as ionisation
- No influence by electrostatic force of the wire
- Photons may be energetic enough to make ionisation
- **If energy lost outside of $r_{\min}$ (where avalanche starts) self induced ionisation happens $\rightarrow$ break down of detector**
- Process needed to absorb photons inside $r_{\min} \rightarrow$
Quench gas (organic molecule with many degrees of freedom)
 - Examples: CH_4 , C_2H_6 , ... , CO_2 , CF_4



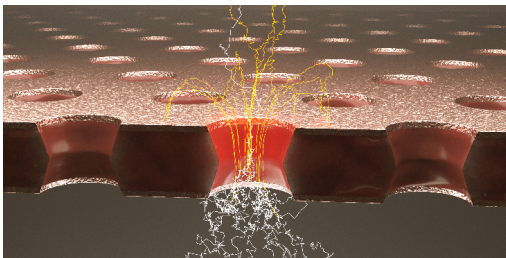
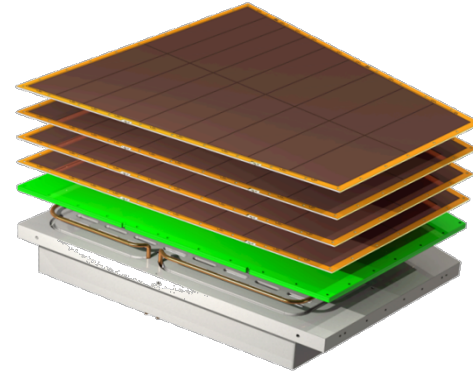
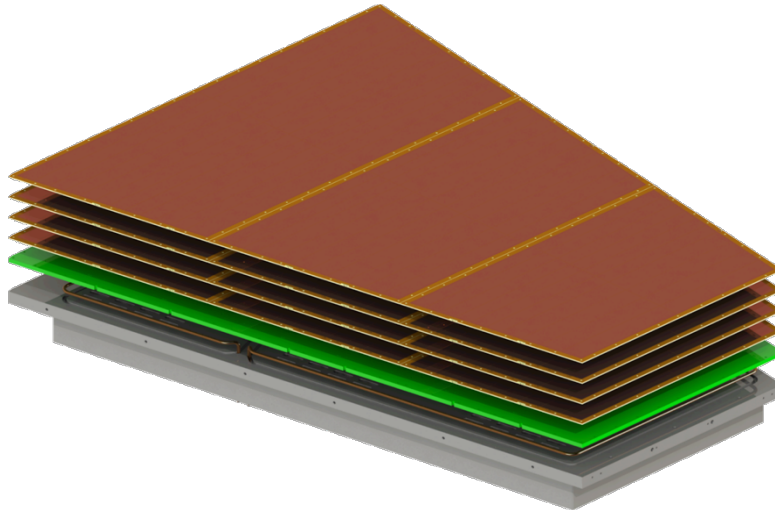
Gas Amplification - GEMs

- Copper coated kapton foils (50 μm)
- Holes etched into the foil
- Size $\sim 70\mu\text{m}$
- Distance $\sim 140\mu\text{m}$
- Apply voltage on copper coating
 - Up to $\Delta U \approx 500\text{V}$
 - Fields up to $\sim 100\text{kV/cm}$
- Holes act as multiplication channels
- Natural Ion Back-Flow (IBF) suppression



<http://www.infn.it/csn5/joomla/GEMINI/>

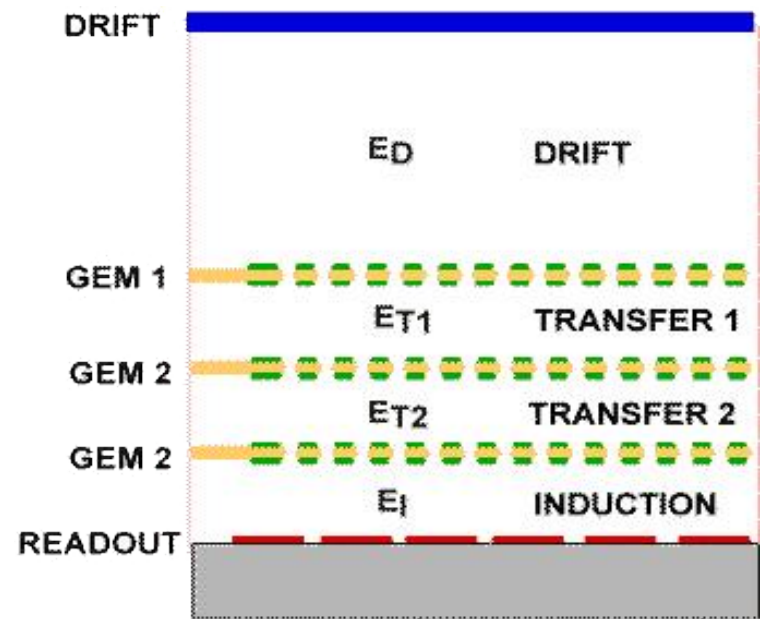
Readout Chambers: GEMs



- GEM = Gas Electron Multiplier
- Stacks of 4 GEM foils
- 3 stacks for the large Outer ReadOut Chambers (OROC)
- 1 stack for the smaller Inner ReadOut Chambers (IROC)

GEM Stacks

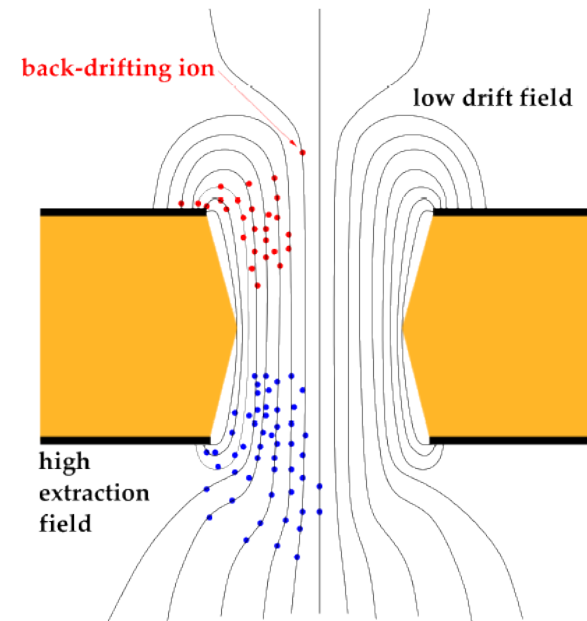
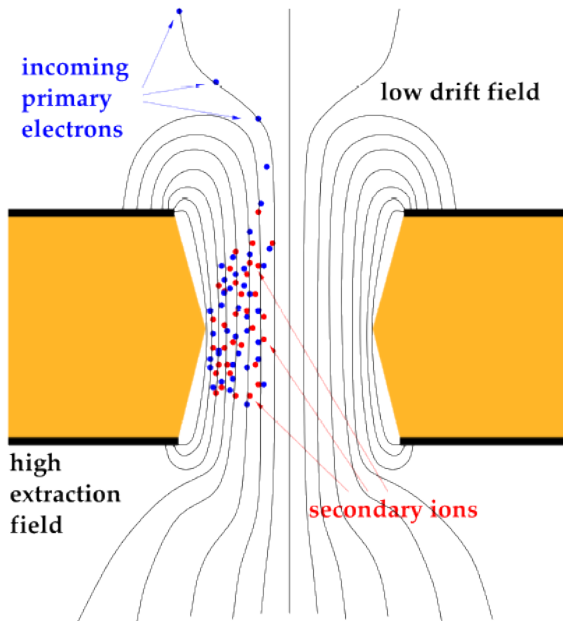
- Usually more than 1 GEM foil used (often 3)
- Many advantages
 - Larger gain at lower $\Delta U \rightarrow$ higher stability
 - Allows for higher total gain (cascaded amplification)
 - Large parameter space $\rightarrow$ tuning of voltages to obtain low IBF



GEMs: Ion Backflow

Natural IBF suppression:

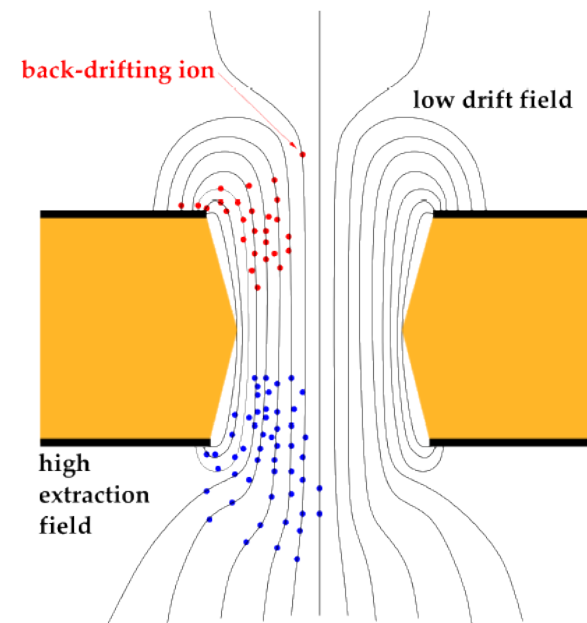
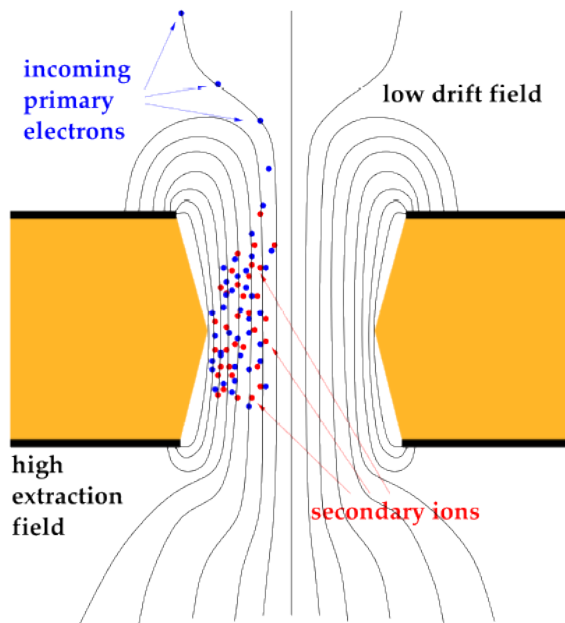
- Asymmetric mobility [low for ions – high for electrons]
 - Electrons move to larger fields in the amplification channel
 - More ions are produced at the edges → trajectory ends on top electrode
- Asymmetric field [drift – induction]
 - Many field lines end on top electrode (ion capture)
 - Transfer region allows for good electron extraction



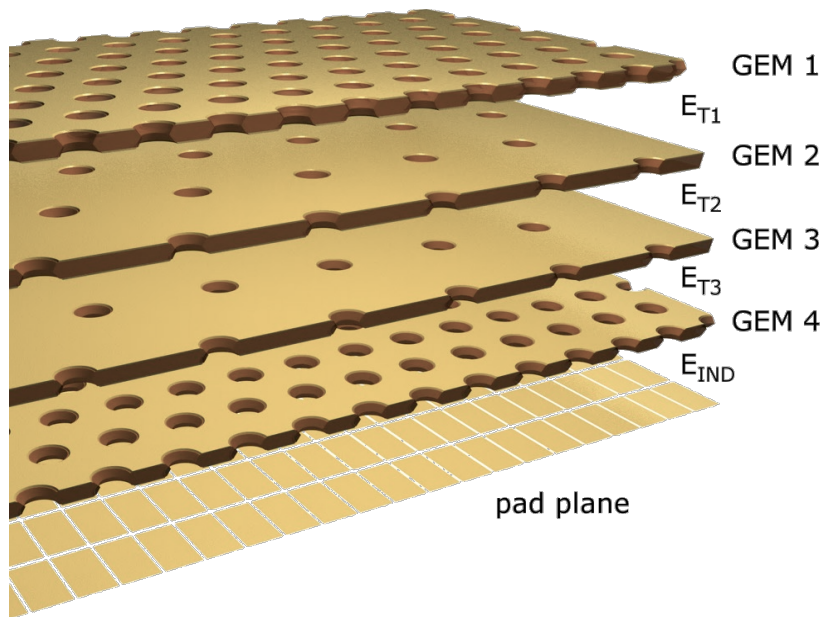
GEMs: Ion Backflow Optimization

- Challenge: Minimize IBF – space charge in drift region!
- Low ion density in drift region requires
 - low primary ionization n_{ion}
 - low gain G_{eff}
 - low ion backflow IBF

$$n_{\text{tot}} = n_{\text{ion}} \times \text{IBF} \times G_{\text{eff}}$$

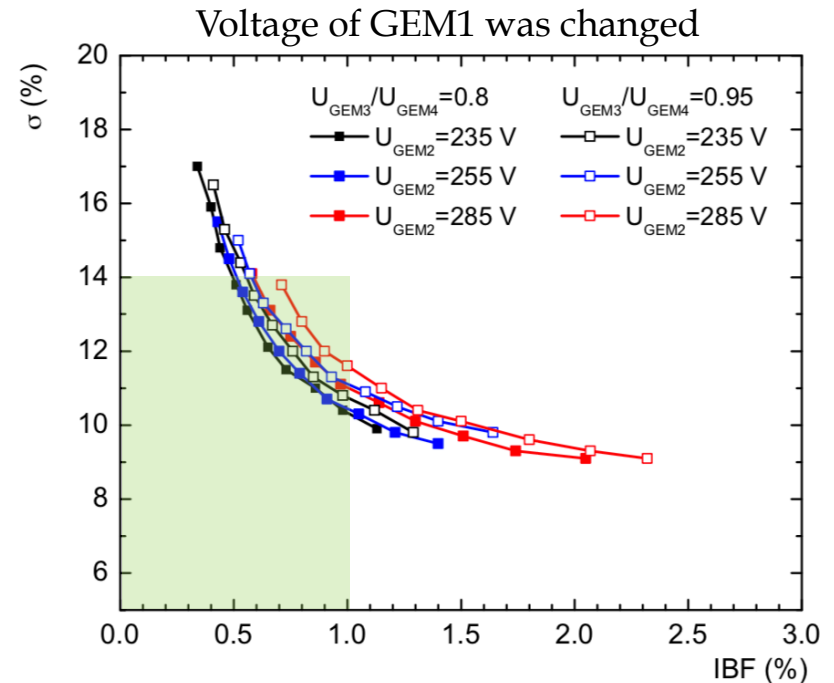


GEM Stacks



Schematic view of pad plane and 4-GEM stack
 GEMs 1 and 4: Standard large-area single-mask GEM foils
 GEMs 2 and 3: Large-pitch GEM foils

Highly optimized HV settings



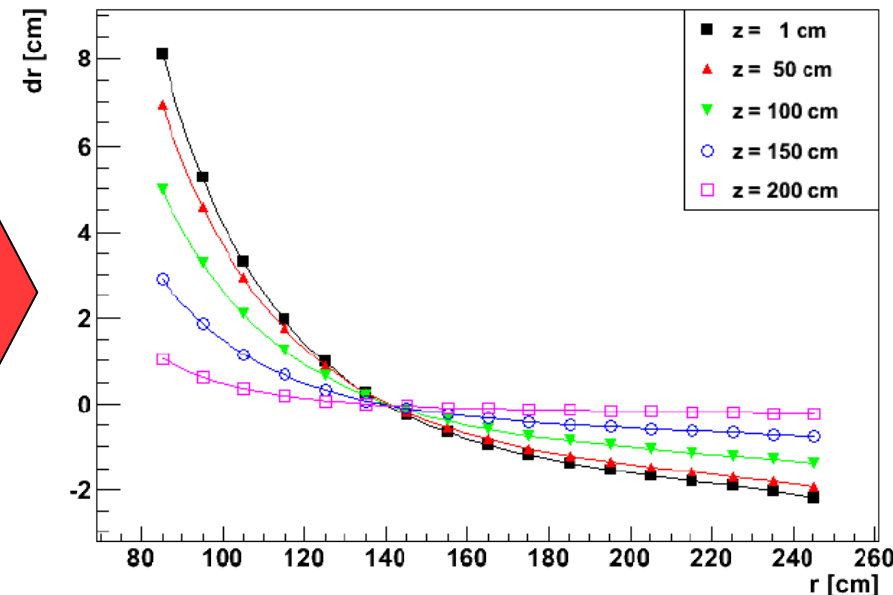
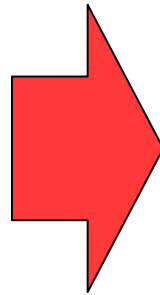
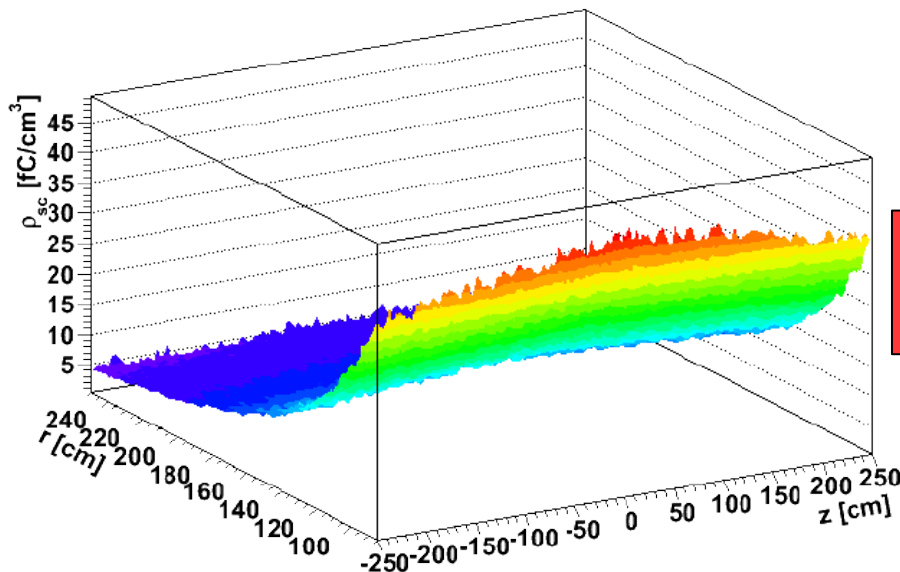
Performance with optimised HV configuration

IBF = Ion BackFlow

σ = energy resolution for ^{55}Fe

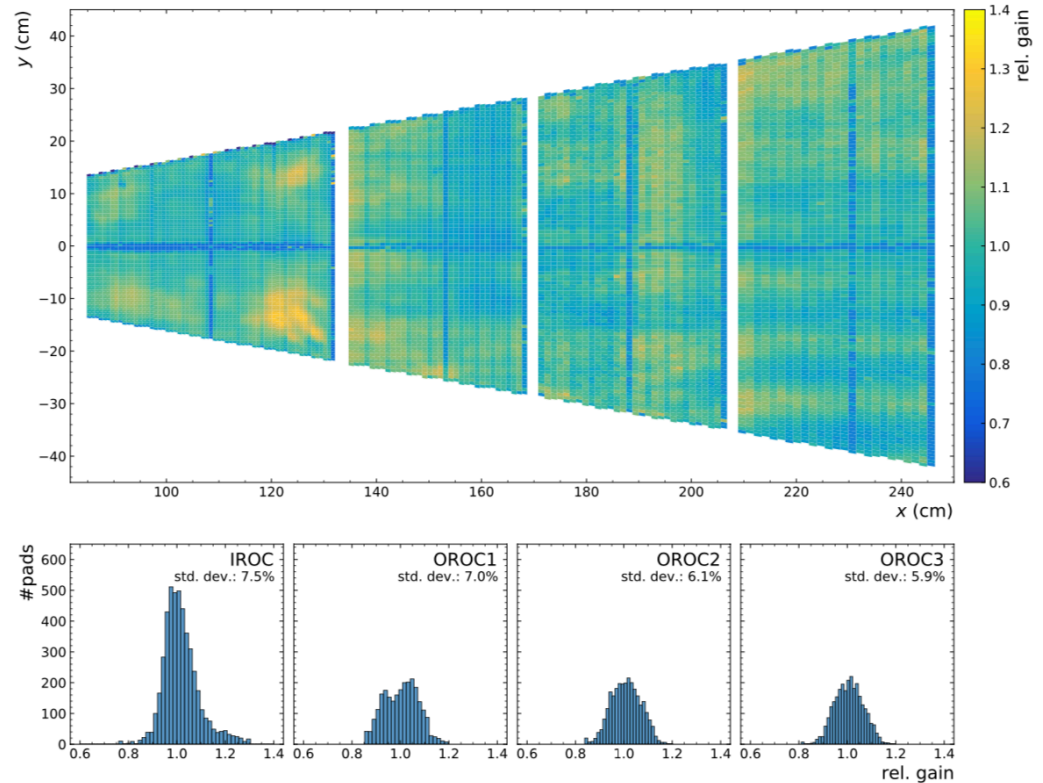
GEMs: Ion Backflow Optimization

- Challenge: Minimize IBF - space charge in drift region!
 - Goal: $IB = 0.5\%$, at $G_{\text{eff}} = 2000$
- ⇒ Resulting distortions [$O(\text{cm})$] **can be corrected**
- Optimisation of IBF:
 - Measurements and simulations
 - Direction of studies: Different gas mixtures, Voltage settings, 4-GEM configuration



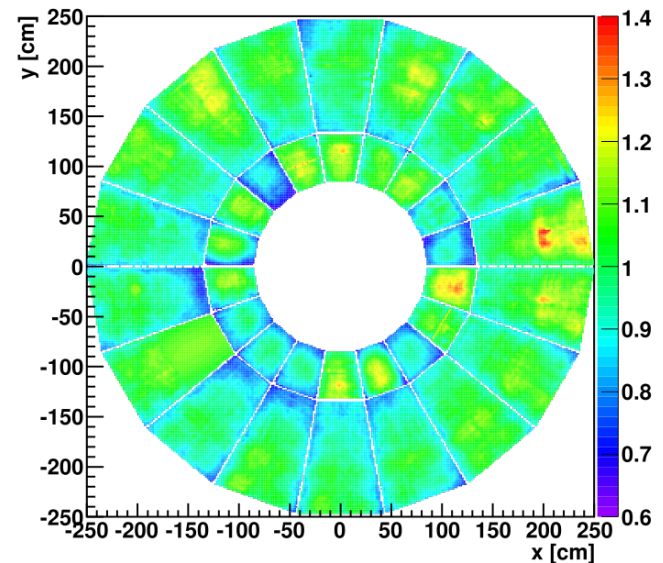
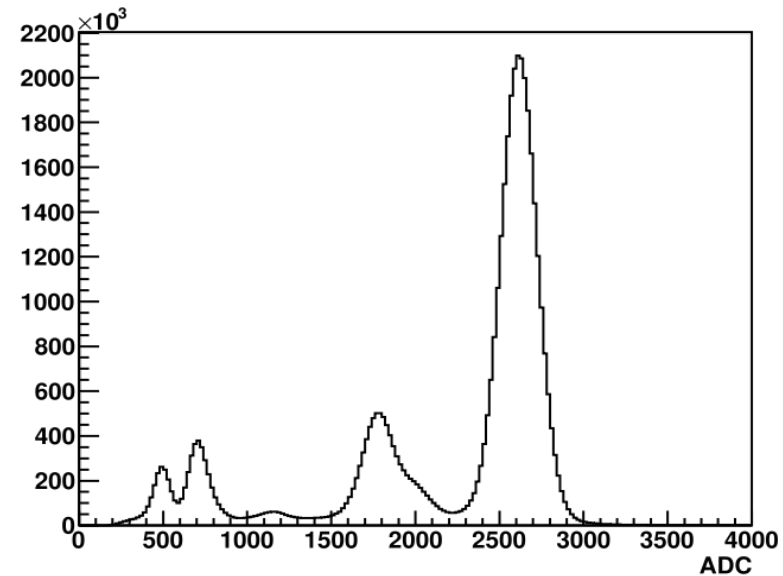
Gain Calibration

- **Krypton gain calibration**
 - Well known technique for TPCs
 - ^{83}Rb (half life 86 days) decays into $^{83\text{m}}\text{Kr}$
 - Radioactive $^{83\text{m}}\text{Kr}$ isotopes decay in TPC volume
 - Spectrum for each GEM stack or for each pad
- **Stack-by-stack HV adjustment**
- **Spectrum for each pad $\rightarrow$ gain calibration (using main peak of spectrum)**
- **Some remarkable structures**
 - foil sagging,
 - wrinkles,
 - GEM hole size distribution



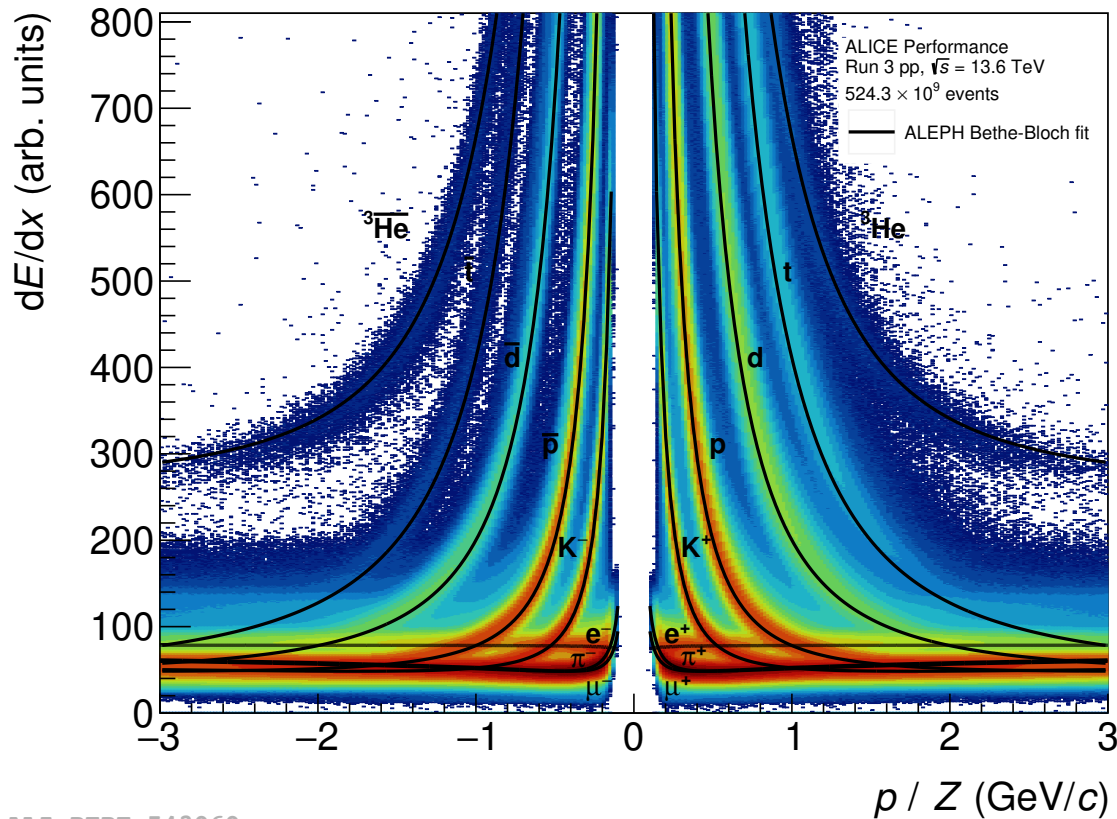
dE/dx Calibration

- Gain variations expected due to manufacturing tolerances (readout chips, chambers)
- **Calibration**
 - Release radioactive ^{83}Kr into the TPC gas
 - Record decay spectrum for each single pad
 - Create gain map on single pad level
 - Repeat $\sim$ yearly
- Now also done with integrated digital currents.



Energy loss Measurement

Run 3 PID with the GEM-TPC



ALI-PERF-543060

- Use ADC values of all (up to) 152 clusters.

Data taking, infrastructure

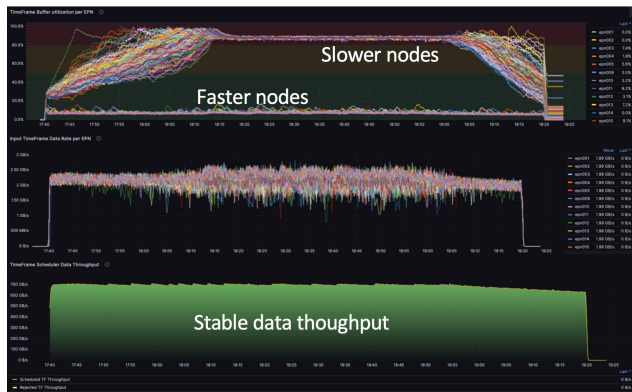
ALICE Computing



3.6 TBytes/s raw data

→ up to 170 GBytes/s to disk

- 50k CPUs, 2700 GPUs, 130 PBytes disk
- New online/offline system (O²)
- Online reconstruction of all events.
- Offline reconstruction with improved calibration.

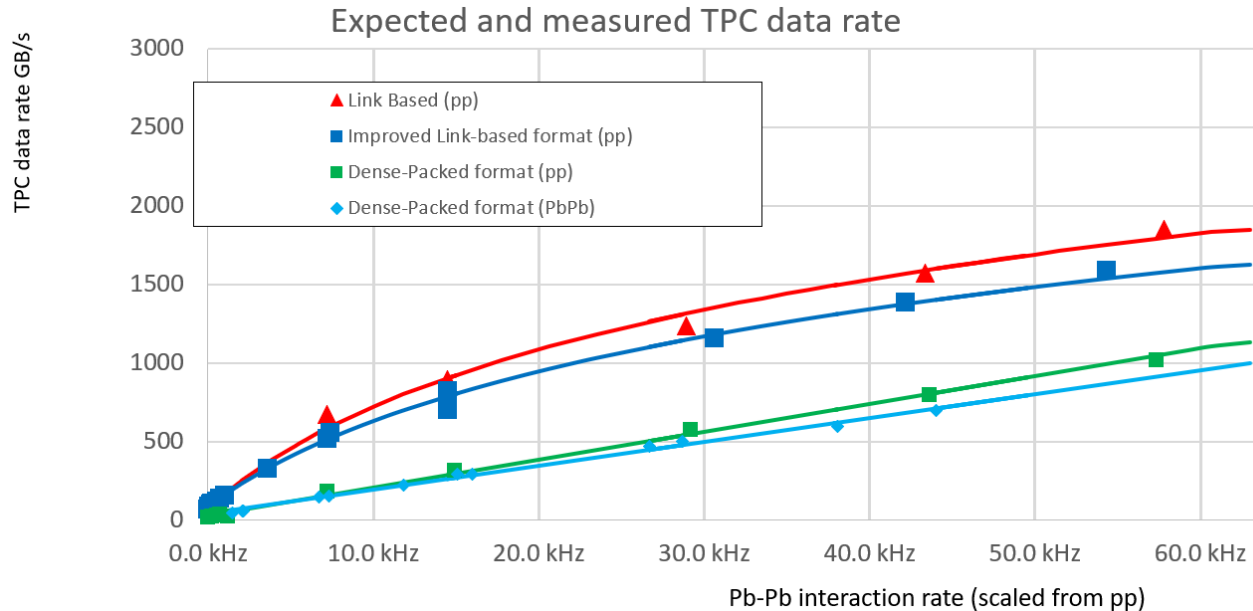


TDR (O²): CERN-LHCC-2015-006



- **pp data:** software skimming based on physics triggers
- **Pb-Pb data:** all data is kept (minimum bias)

TPC data rates in Run 3



Dense packed format

~50 kHz Pb-Pb: 800 GBytes/s (CRU - Common Readout Unit)

→ still about 20% margin to readout limit

Auxiliary Systems: Gas System

Control Backup Mixer Purifier CO2 Distr Analys Pump



- Recirculating gas system -> recover Ne
- Purifier (removal of H_2O and O_2)

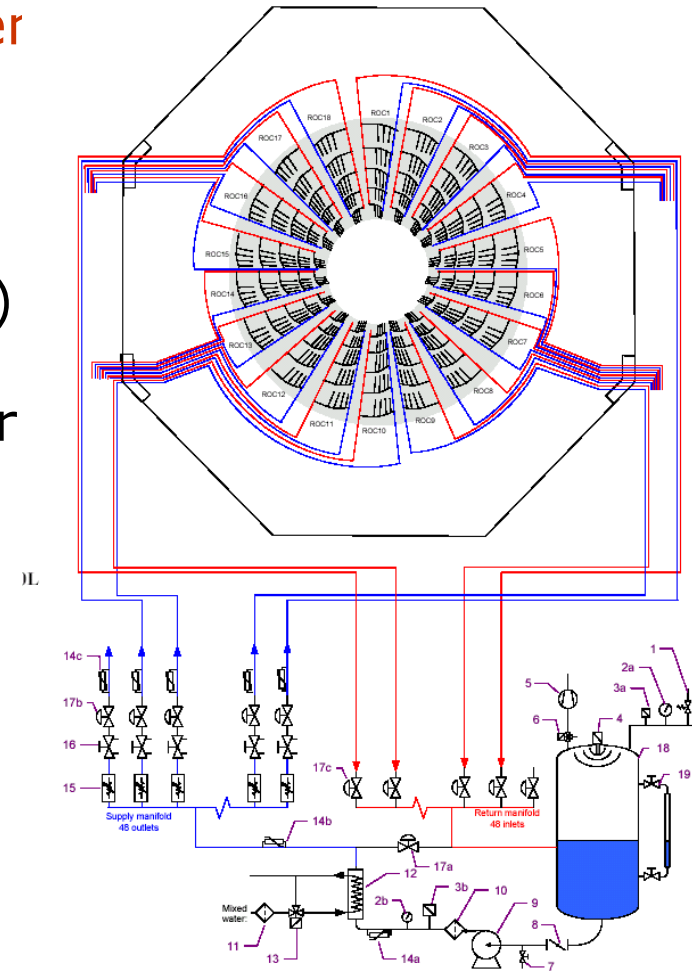
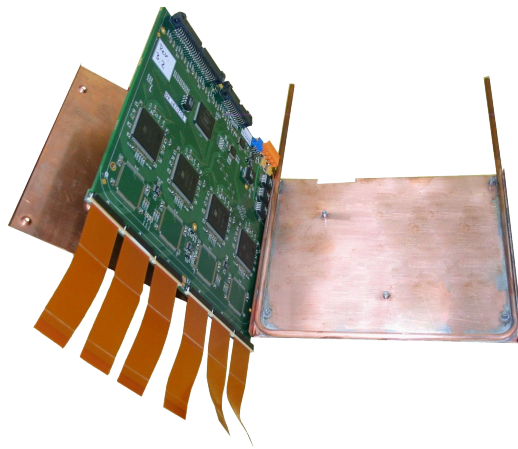
TPC Gas System at SLXL2

Auxiliary Systems: Cooling

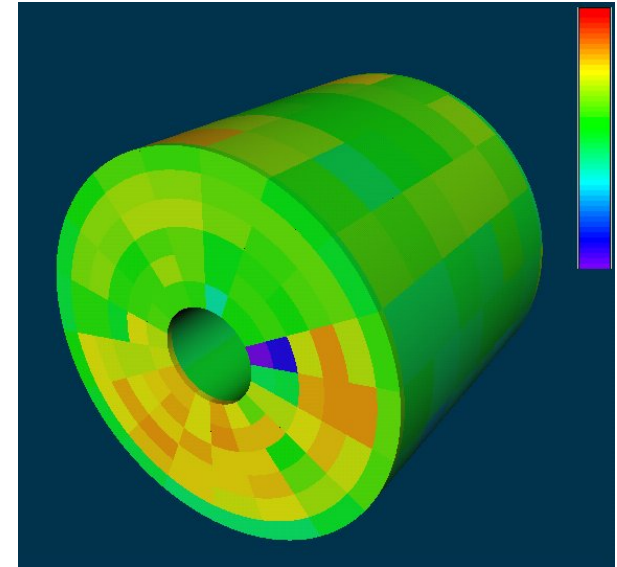
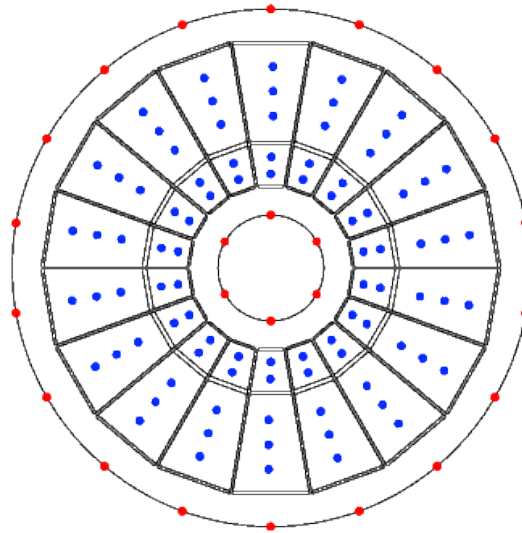
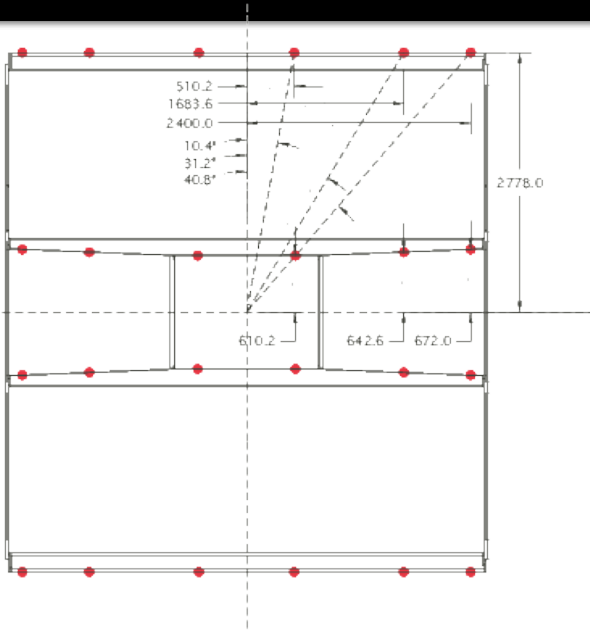
Complex cooling system to equalise TPC ter

About 60 adjustable cooling circuits:

- leakless underpressure system
- cooling of ROC bodies
- FEE enveloped in copper plates ($\approx 27\text{kW}$)
- thermal screens towards ITS and TRD
- service Support Wheel closed with copper shields

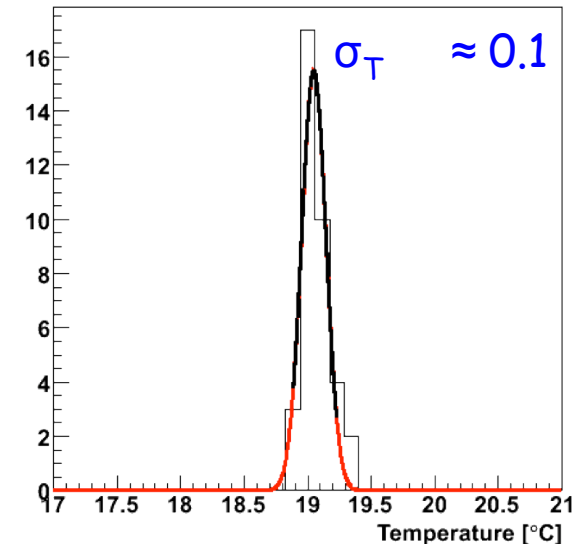


Auxiliary Systems: Temperature



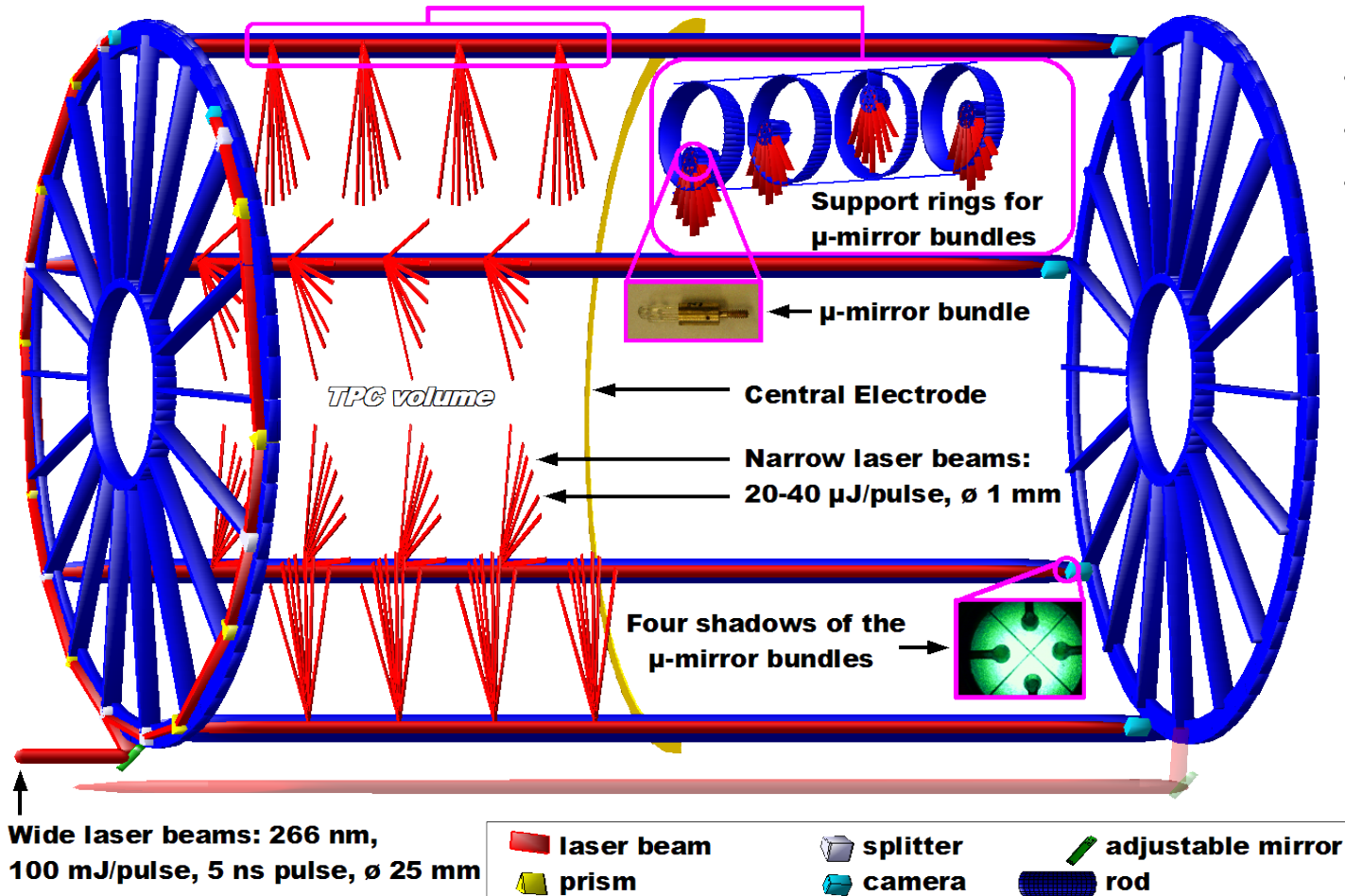
About 500 sensors distributed all over the TPC
calibrated within $\sim 100\text{mK}$

Successful calibration of the cooling system to
design specifications



Auxiliary Systems: LASER

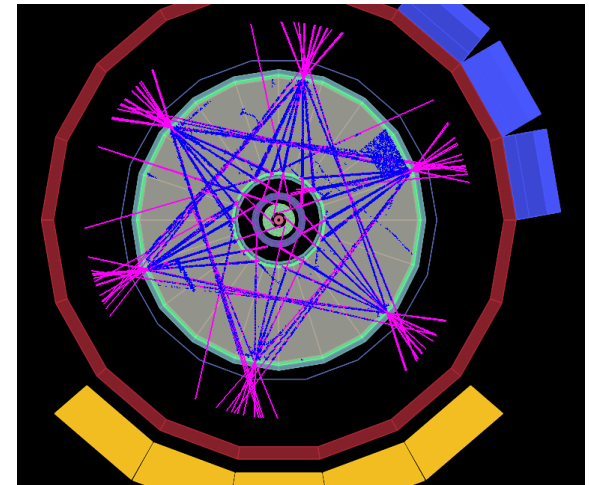
The principle of the laser system for the TPC



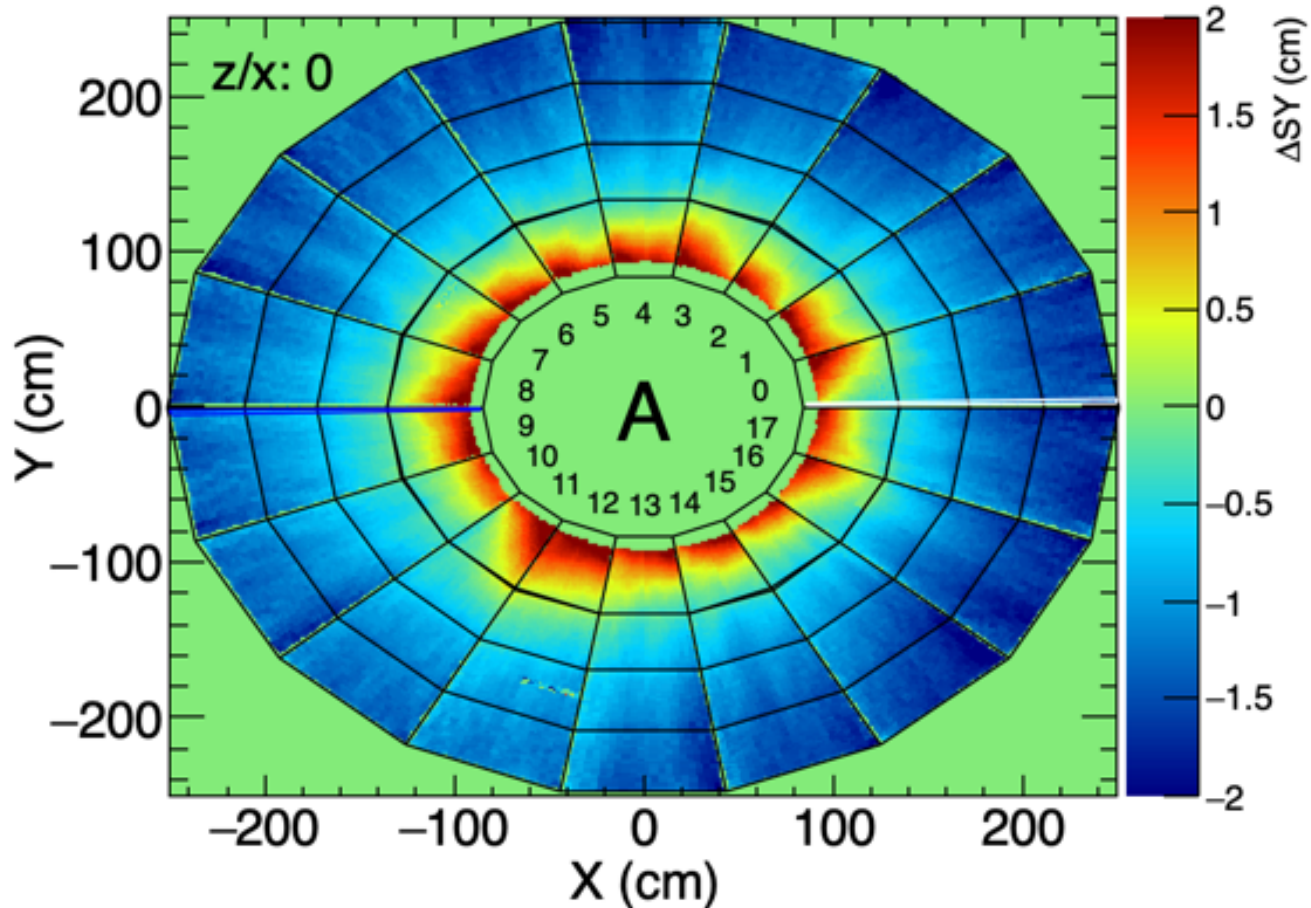
- Drift velocity
- Alignment
- Space charge effects

LASERs to measure ExB Effects

- ExB distortions arise from **nonparallel E and B fields**.
- It is difficult to build a very big detector ($\sim 5\text{m}$) such that E and B fields are always perfectly parallel.
- Remaining effects must be corrected for in data.
- In ALICE we use a Laser system to calibrate ExB distortions.



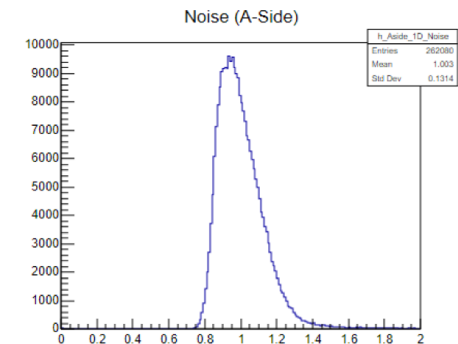
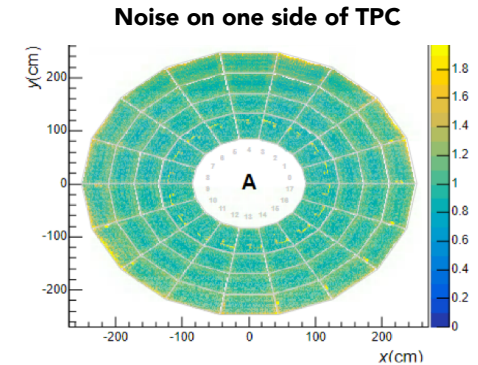
ExB Effects in Data



- Image shows the y-component (in azimuthal direction) of the space charge distortions at high interaction rates.
- Asymmetry at low radii is due to ExB (from SCD).

TPC Readout Electronics

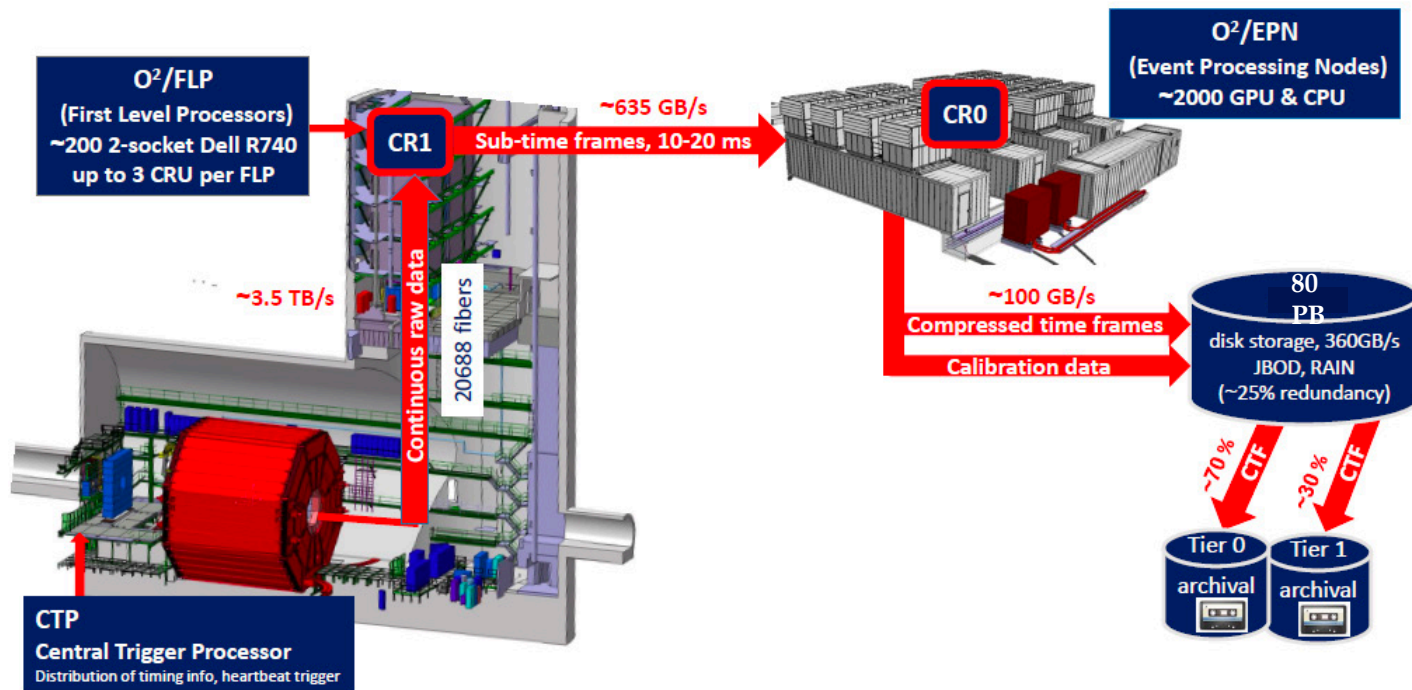
- **SAMPA ASIC**
 - 130 nm TSMC CMOS
 - 32 channels with preamplifier, shaper, 10 bit ADC and digital filters
 - Continuous or triggered readout
- **Front-End Cards (FECs)**
 - 5 SAMPA chips per FEC (3276 FECs in total)
 - Continuous sampling at 5 MHz
 - All ADC values read out: 3.3 TB/s total
 - Readout link: CERN GBT / Versatile link system
- **FPGA-based readout cards** receive the data through 6552 optical links



Excellent mean noise: 670 e⁻ @18 pF

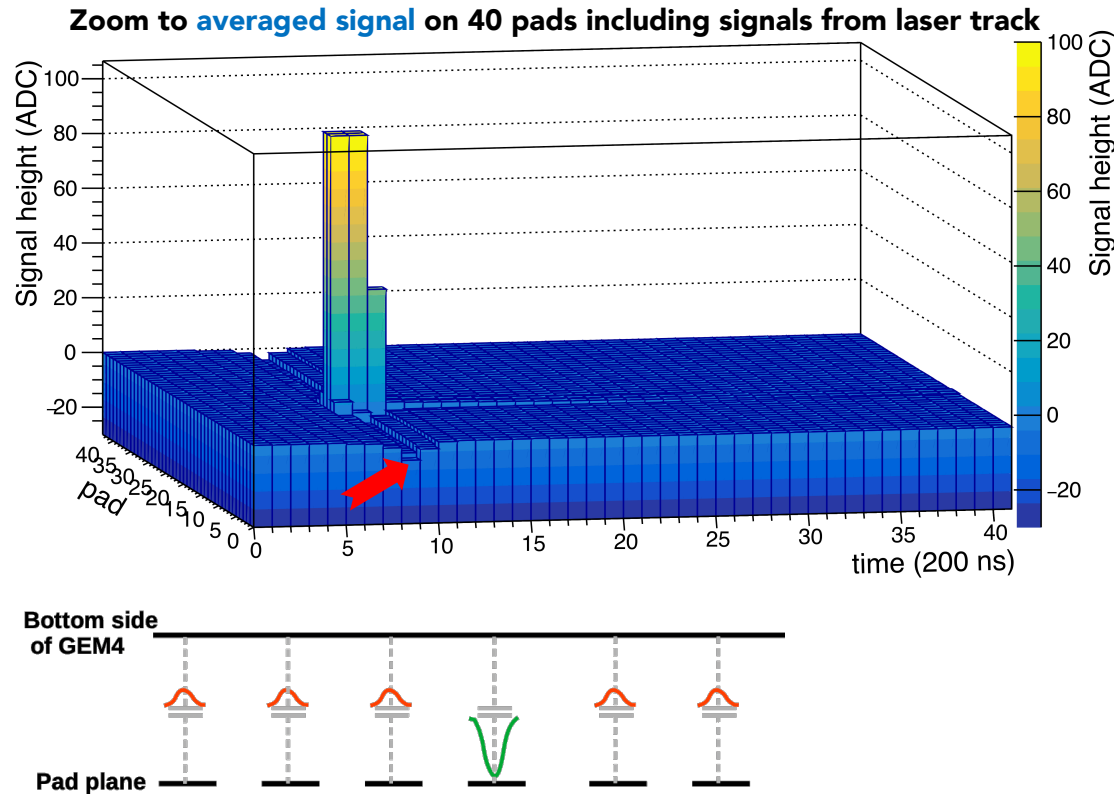
TPC Readout System: O2

- O² = Online × offline (the new ALICE data processing cluster)
- 3.5 TB/s continuous raw data flow (all ALICE detectors)
- **Continuous data flow is chopped into (sub-)time frames** on the FLPs
- Data volume reduction in two steps: On FPGA readout cards and after tracking



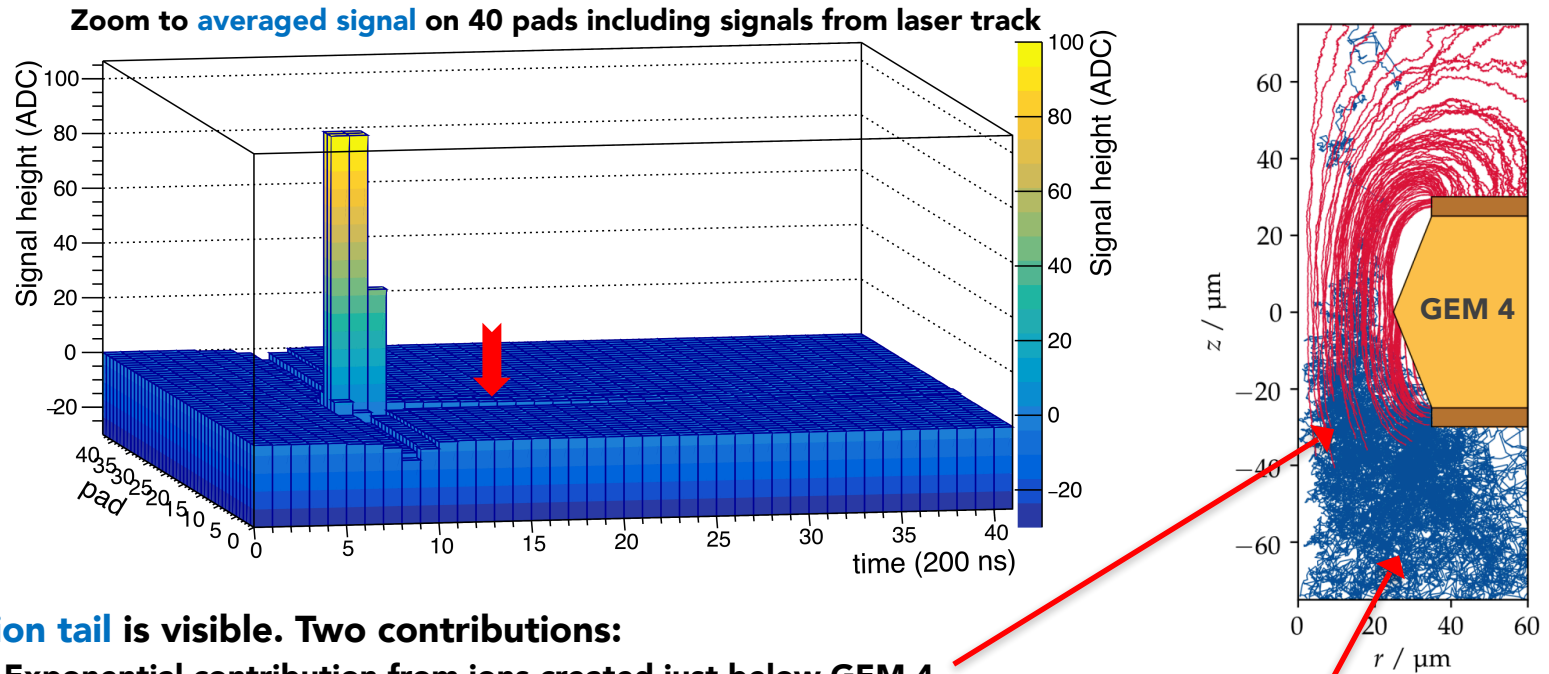
Common Mode and Ion Tails

Common Mode Effect

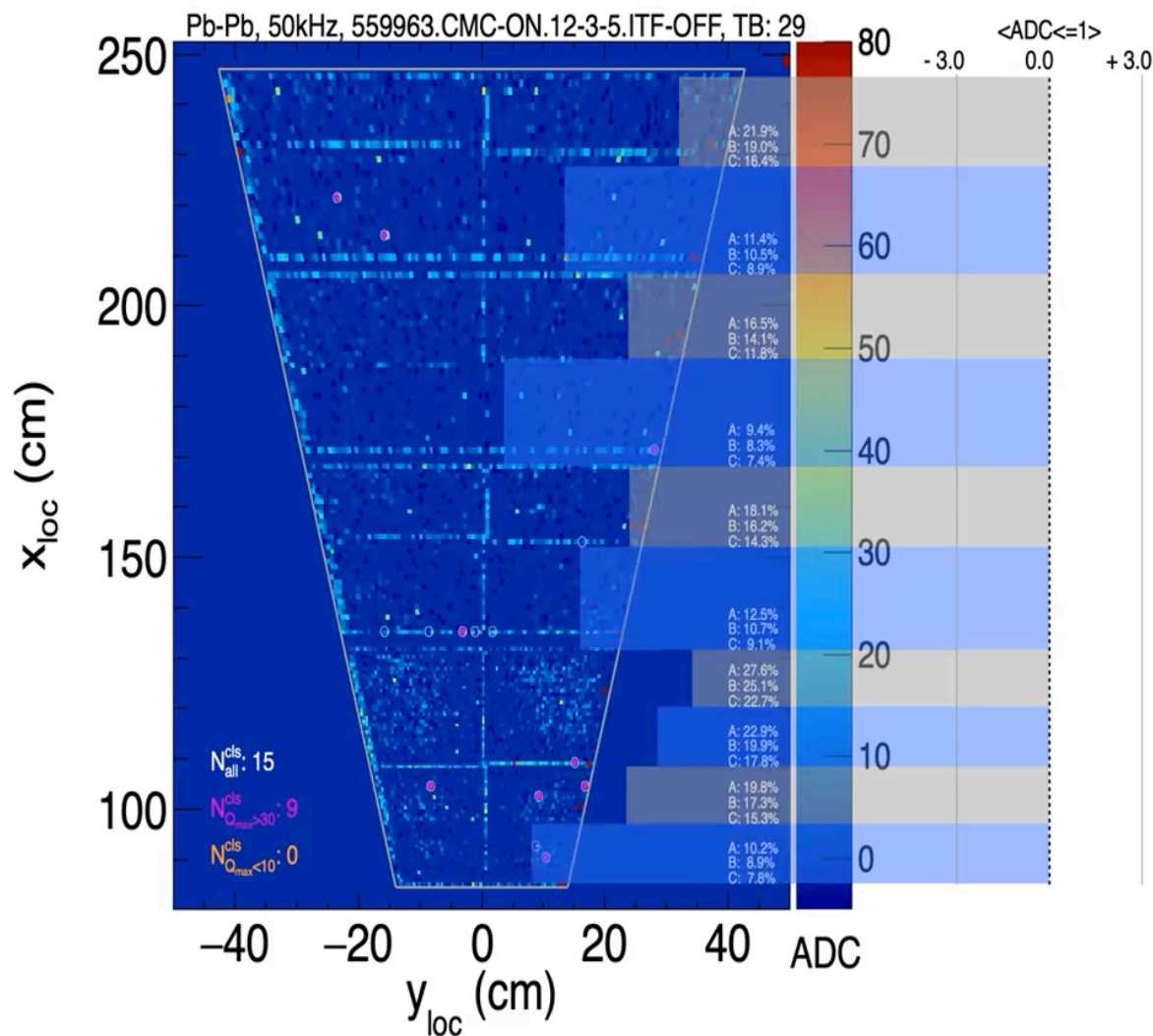


- Capacitors in HV distribution often used to reduce CM effect
- But such capacitors would lead to potential problems with discharges
- At high occupancy the CM signals from many tracks will superimpose and lead to a **baseline shift**
- This baseline shift is measured in the readout system (CRU FPGA) and **removed online**

Ion Tail



- An **ion tail** is visible. Two contributions:
 - Exponential contribution from ions created just below GEM 4
 - Linear component from ions produced in induction gap (particular to our HV settings)
- **Online ion tail correction** also in CRU FPGA

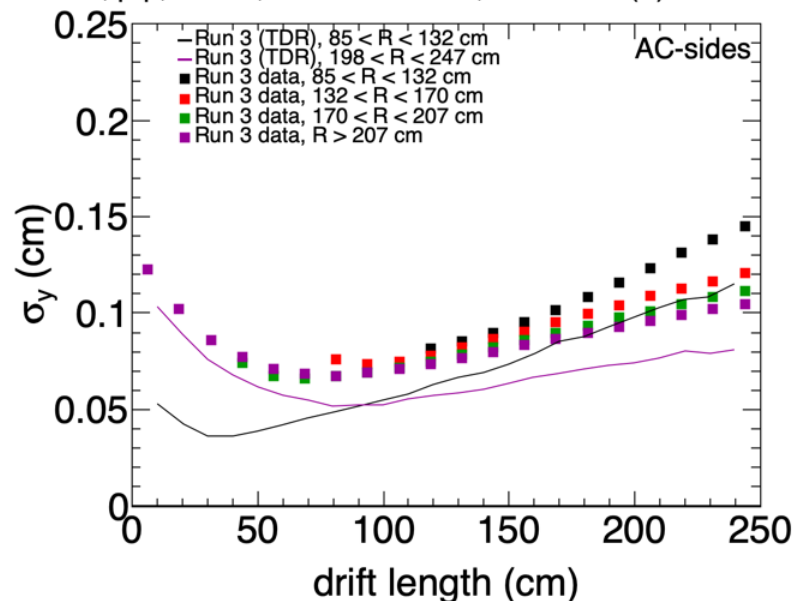


- 50kHz Pb-Pb, Run3, 2024
- Raw data, with common mode correction activated.
- Circles show reconstructed TPC clusters.
- Every image corresponds to 200 ns.

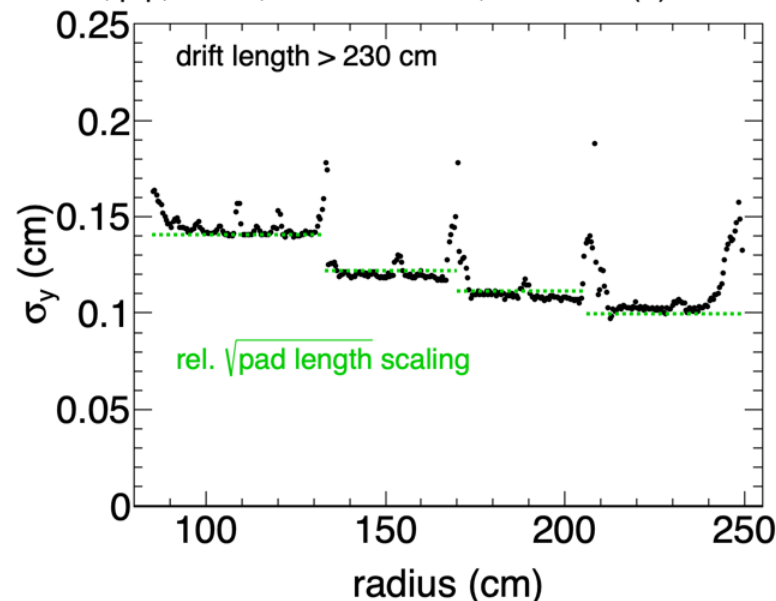
TPC Intrinsic Resolution

Intrinsic TPC Resolution

549597, p-p, 13kHz, $0 < dE/dx < 100$, $0.000 < |\tan(\alpha)| < 0.115$



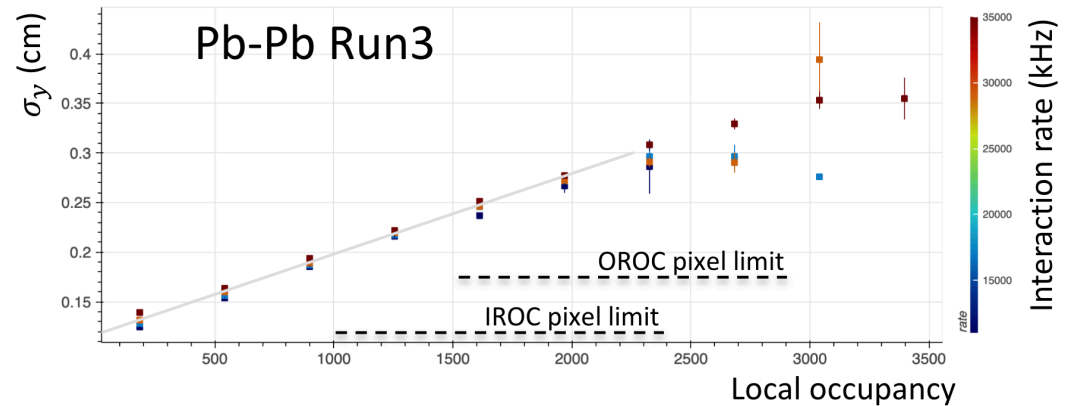
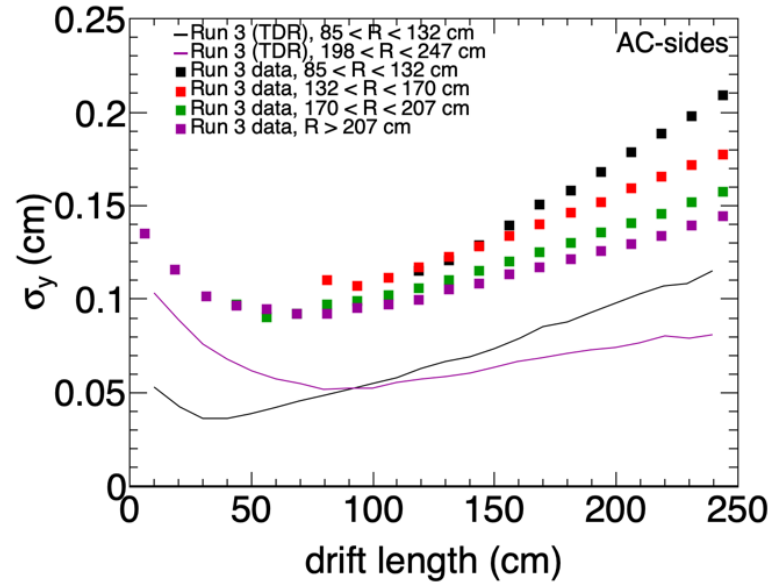
549597, p-p, 13kHz, $0 < dE/dx < 100$, $0.000 < |\tan(\alpha)| < 0.115$



- Very low IR p-p $\rightarrow$ low occupancy $\rightarrow$ mainly TPC intrinsic effects.
- At low drift length we have a significant fraction of one pad clusters.
- At larger drift length multi-pad clusters dominate.
- **Data is in agreement with TDR calculations** (modulo known factor $\sqrt{2}$ due to lower electron transparency).

Pb-Pb Space Point Resolution

544121, Pb-Pb, 22kHz, $0 < dE/dx < 100$, $0.000 < |\tan(\alpha)| < 0.115$



- Does not depend on IR $\rightarrow$ no space charge distortion effect!
- Dominated by local occupancy effects.

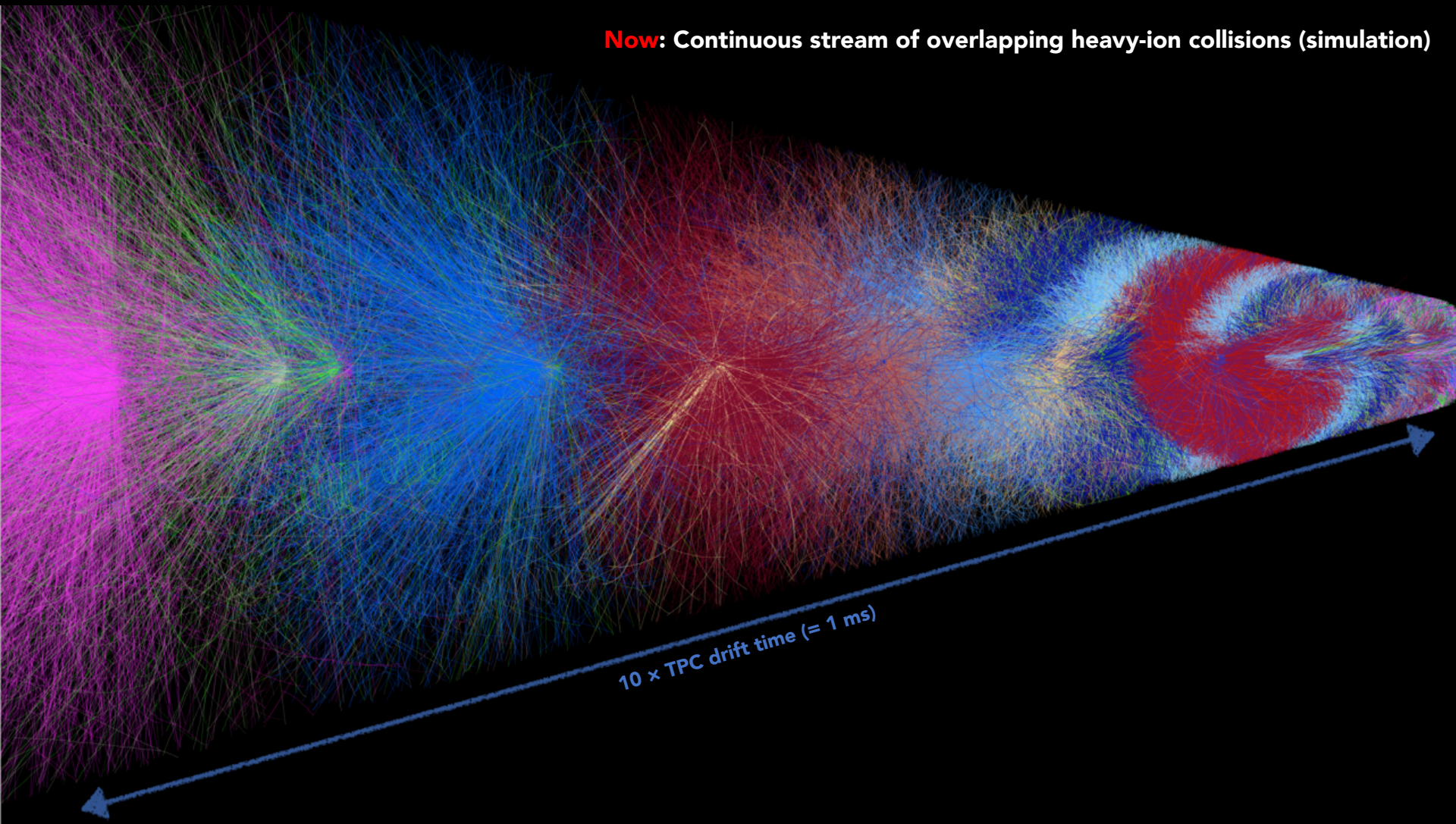
Summary

Summary:

- Space charge distortions are as expected in terms of magnitude and fluctuations.
- Space charge distortion calibration is right now limited by precisions of external detectors.
- TPC intrinsic resolution as expected! Occupancy dependence is dominating the resolution (clusterization + tracking).

Space Charge Distortion Corrections

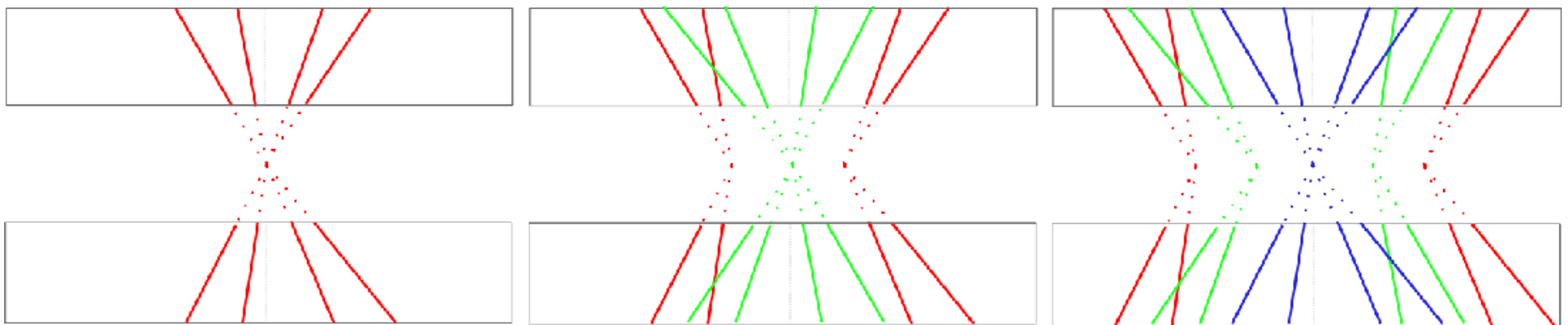
Now: Continuous stream of overlapping heavy-ion collisions (simulation)



10 x TPC drift time (= 1 ms)

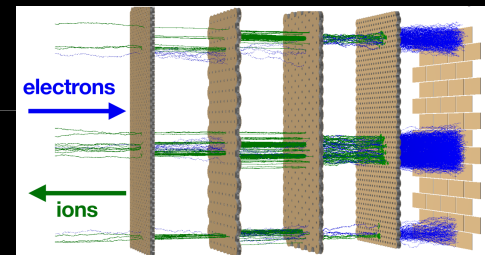
Continuous Readout: Challenges

- Goal: Operate TPC at high luminosity
 - Luminosity for lead collisions: 6×10^{27} Hz/cm²
 - Up to 50 kHz interaction rate
 - Up to 5 events overlapping (current gas, shown below)
 - Inspect all minimum bias events
- ⇒ No gating
- ⇒ Continuous readout (no triggers)



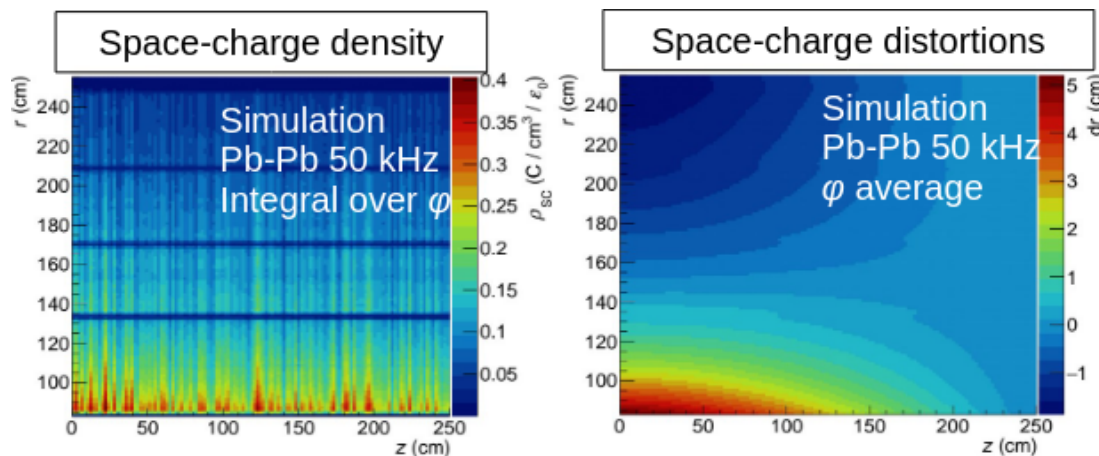
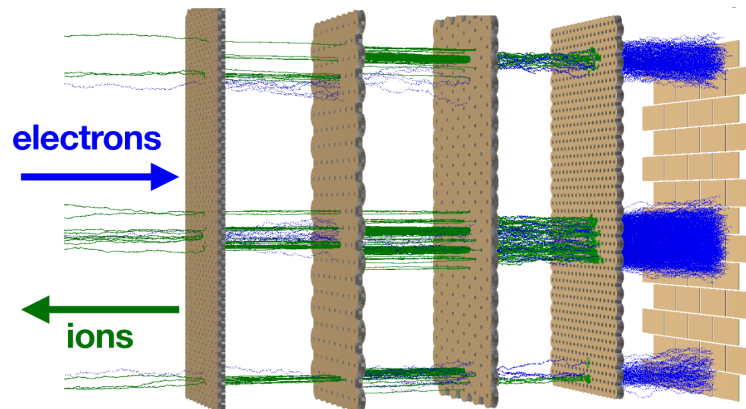


- At 50 kHz Pb-Pb about 10.000 ion discs pile up in the TPC
 - Space charge in the TPC volume created
 - Distortion of the drifting electron clusters



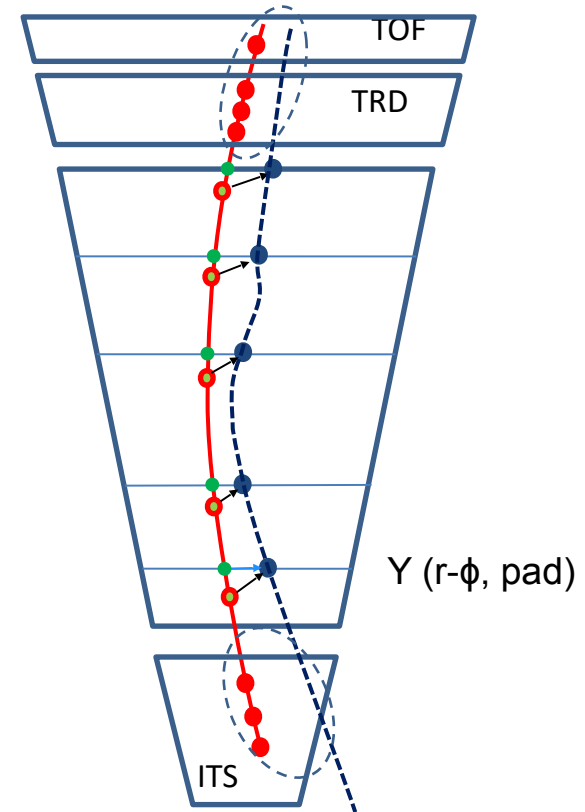
Space Charge Distortions

- Ions from the amplification stage move back into the drift volume
- Ions are slow (~ 200 ms for full drift)
 - Ions from large number of events pile up (~ 10 k events @ 50 kHz IR)
 - Significant **space-charge density** (SCD) in drift volume
 - Large average **distortions** ($O(5-10$ cm))
 - Intrinsic TPC resolution: ~ 200 μ m
 - $\rho_{SC} \sim I_{prim} \cdot gain \cdot IBF$

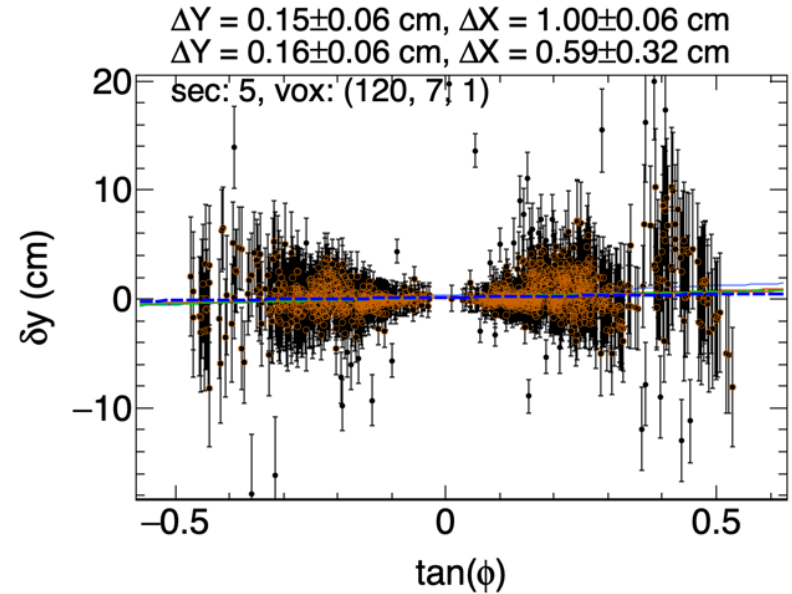
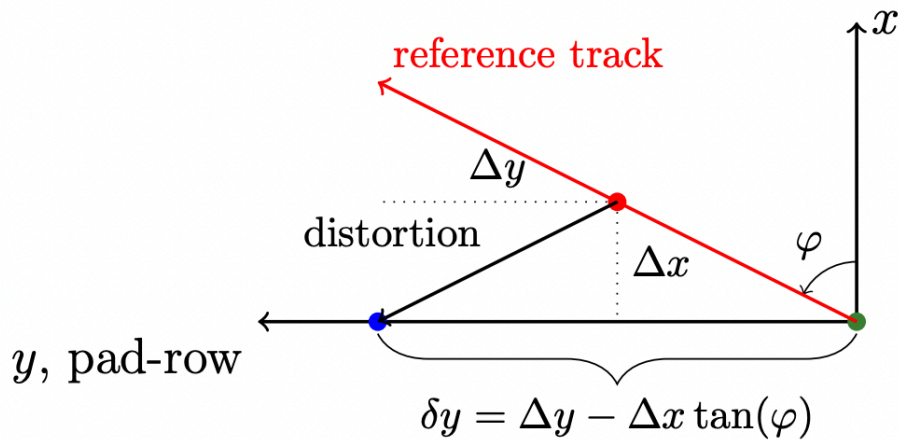


Extracting the Residuals

- Define **reference track** position in TPC from ITS extrapolation (or ITS-TRD-TOF interpolation)
- Collect δy and δz **differences between distorted clusters and reference points** in TPC sub-volumes (2.7M voxels)
- Output: *unbinned residuals*
- Build voxel maps from unbinned residuals to extract real distortions ΔX , ΔY , ΔZ

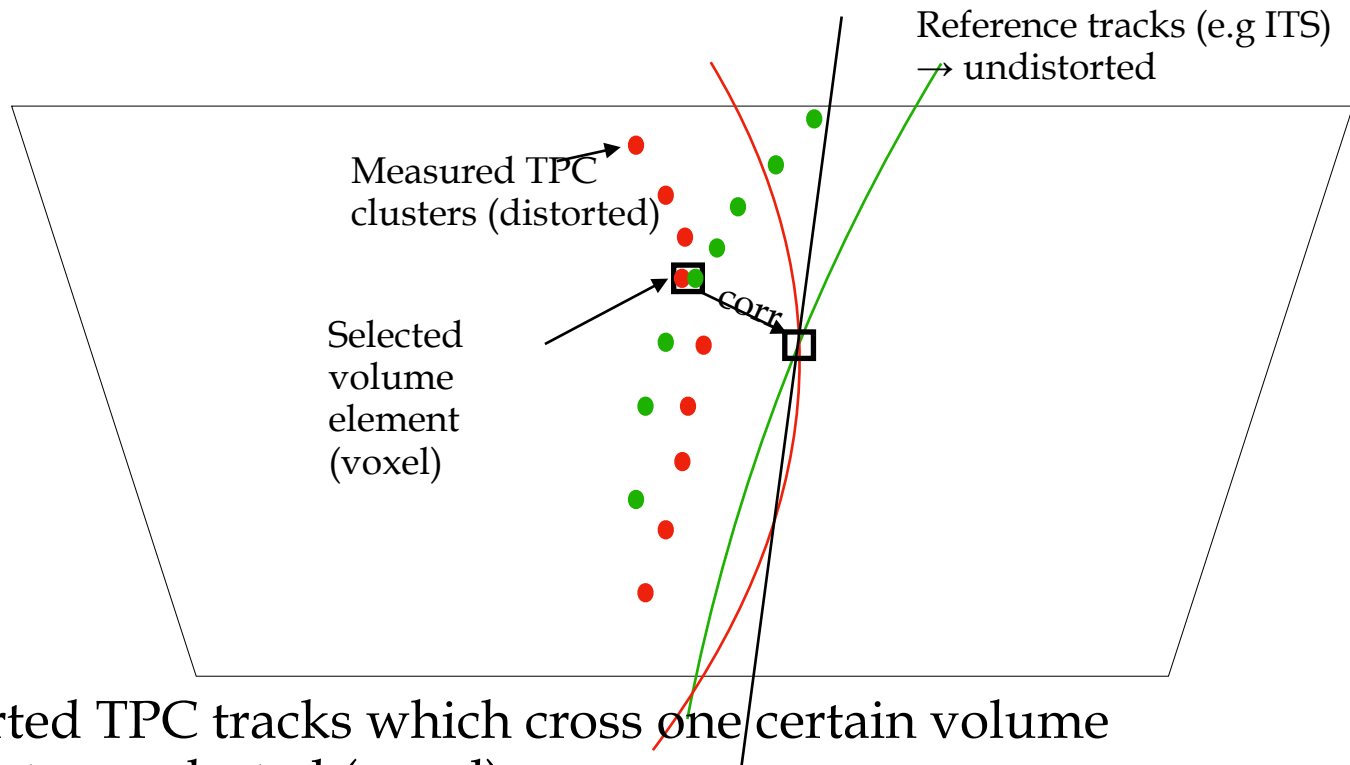


Disentangle the Residuals



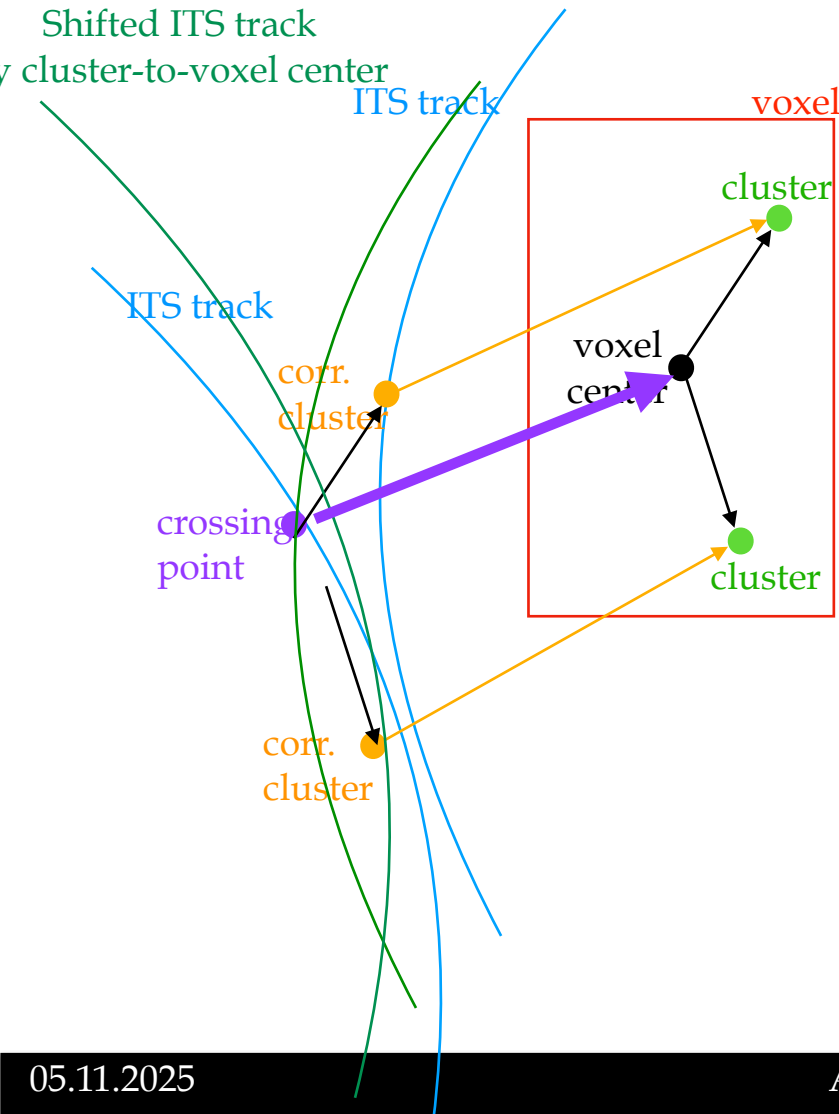
- Residuals are always measured at row position.
- The true distortions need to be extracted for each voxel using fits to δy vs $\tan(\varphi)$.

Crossing Point Method



- Distorted TPC tracks which cross one/certain volume element are selected (voxel).
 - The corresponding matched ITS tracks will cross in the respective undistorted frame (every point in the distorted frame has exactly one corresponding point in the undistorted frame - basis of SCD correction).
 - The vector between the crossing points in the two frames directly gives the correction.

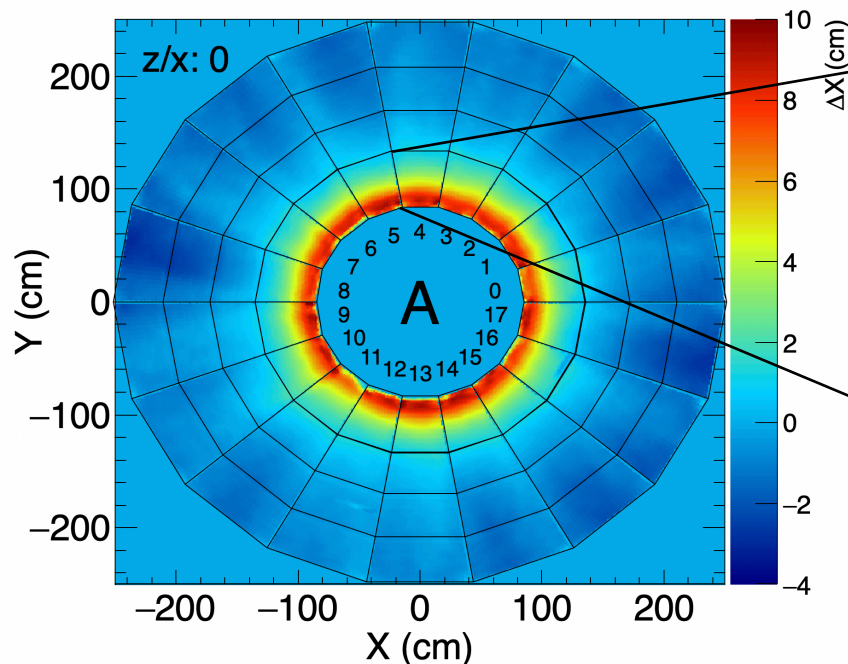
Details of the CPM Method



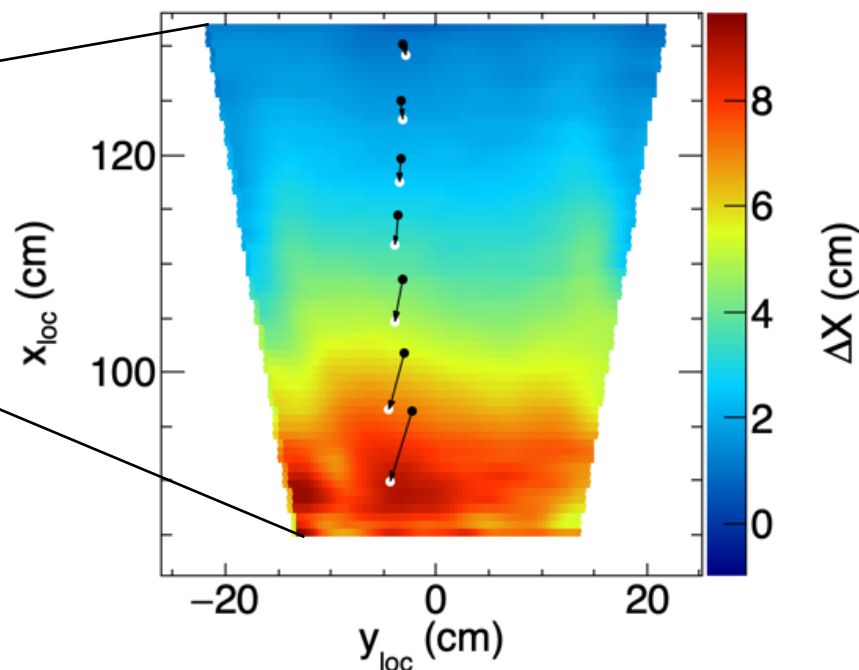
- For each voxel the ITS tracks are stored as circles nearby the voxel position.
- Once 10 positive charged or 10 negative charged tracks per voxel are there then crossing points are calculated.
- The circle centres are first shifted by the vector (cluster-voxel center) to adjust for the voxel size.
- A running average is calculated per voxel.

Space Charge Distortion Correction (SCD)

SCD correction map @ 47 kHz Pb-Pb

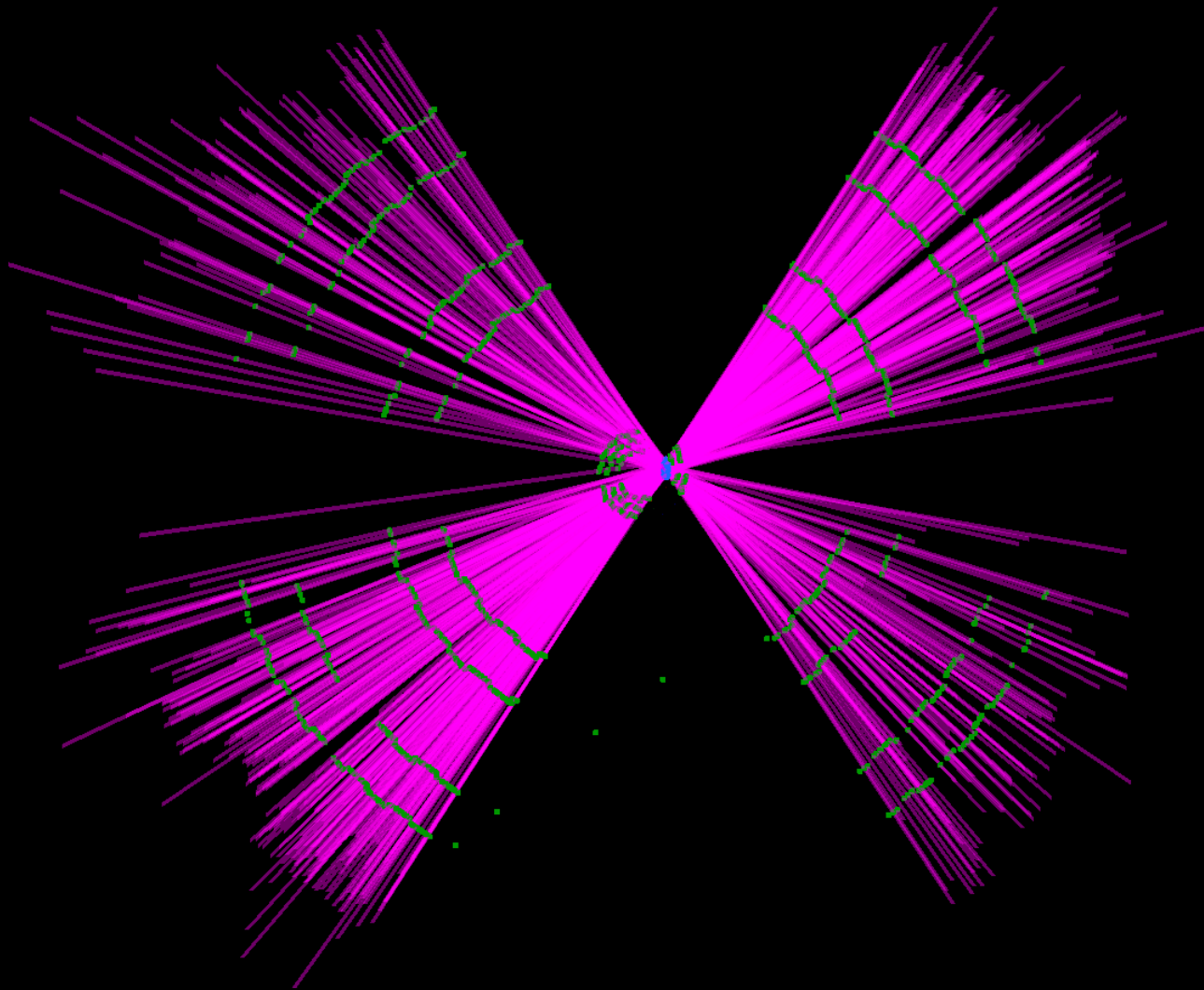


Corrected/uncorrected clusters

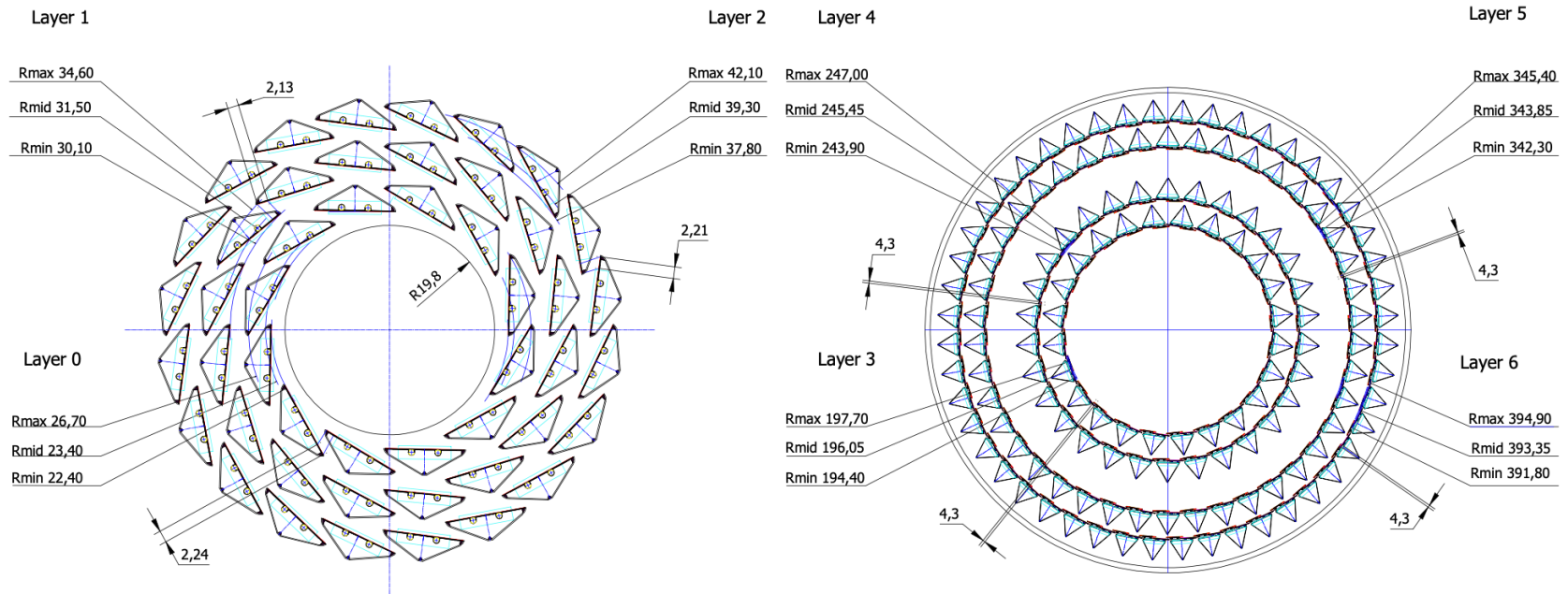


- SCD correction maps correct distortions from ~ 10 cm down to < 1 mm.
- Fluctuations are measured and corrected every millisecond.
- We are now close to Run 2 performance in terms of SCD corrections!

ITS Alignment

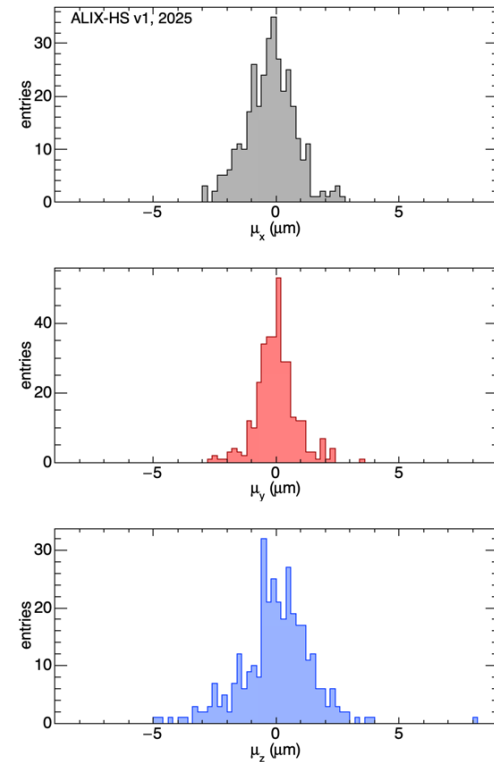
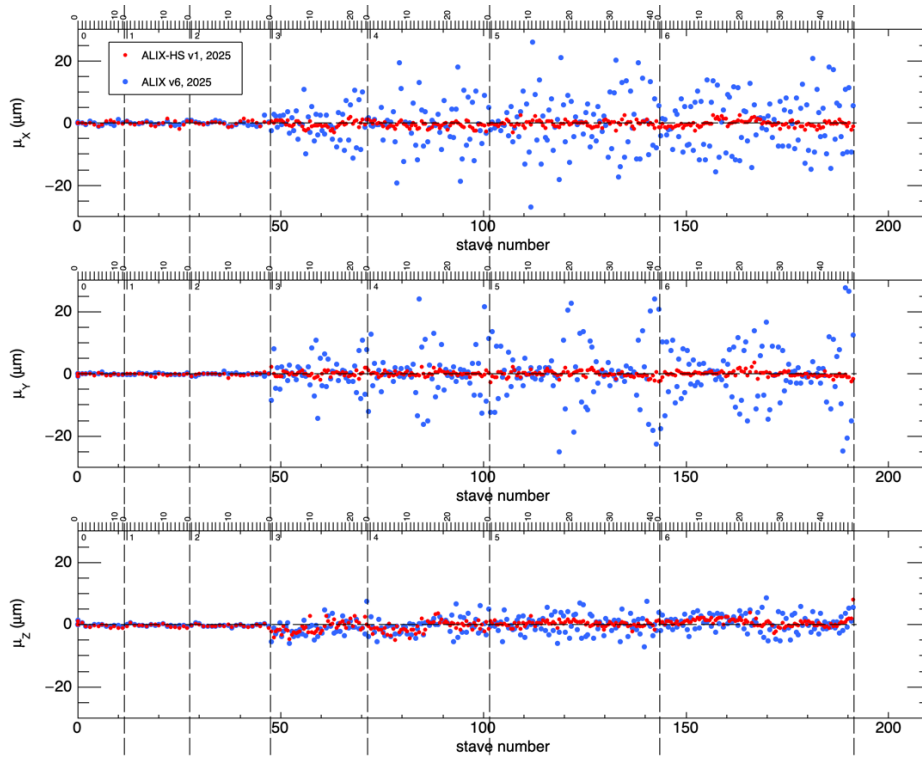


ITS Alignment Status



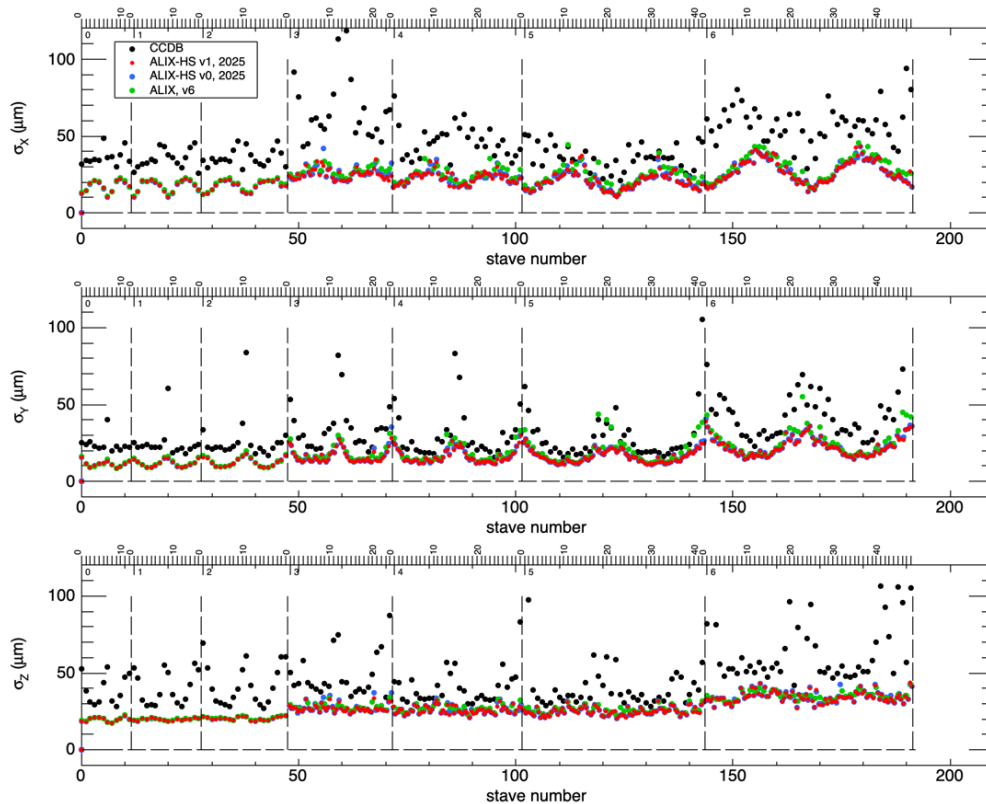
- 192 staves. All need to be aligned with a precision of about 5 μm .
- Important for SCD maps extraction!

Means after ITS alignment



- Means are below 2.5 μm .

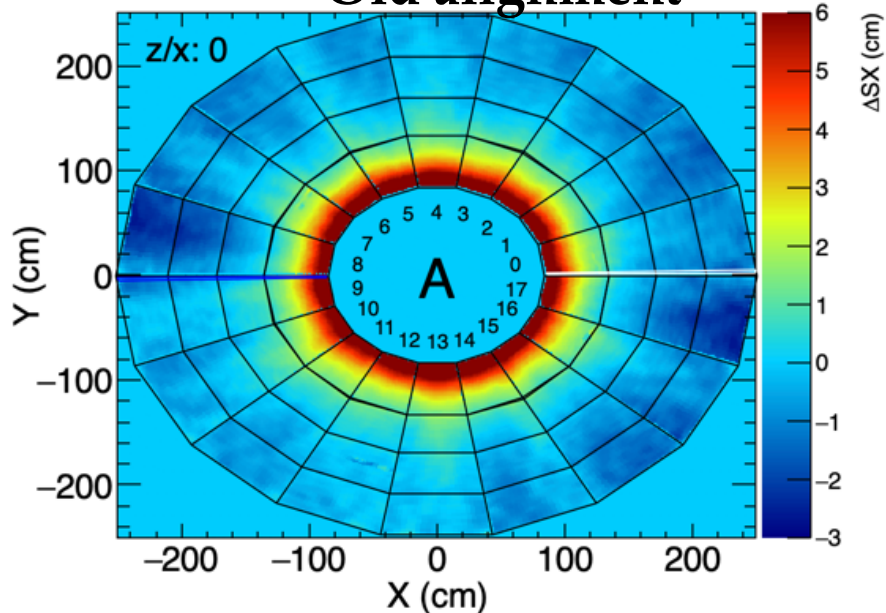
Width after ITS alignment



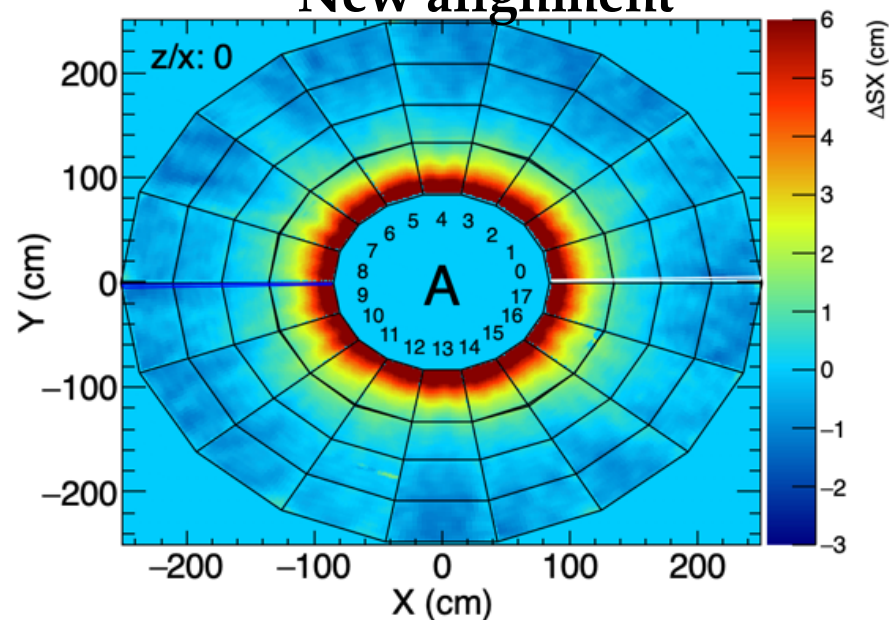
- Significant improvement compared to previous alignment.

Old vs New Alignment

Old alignment

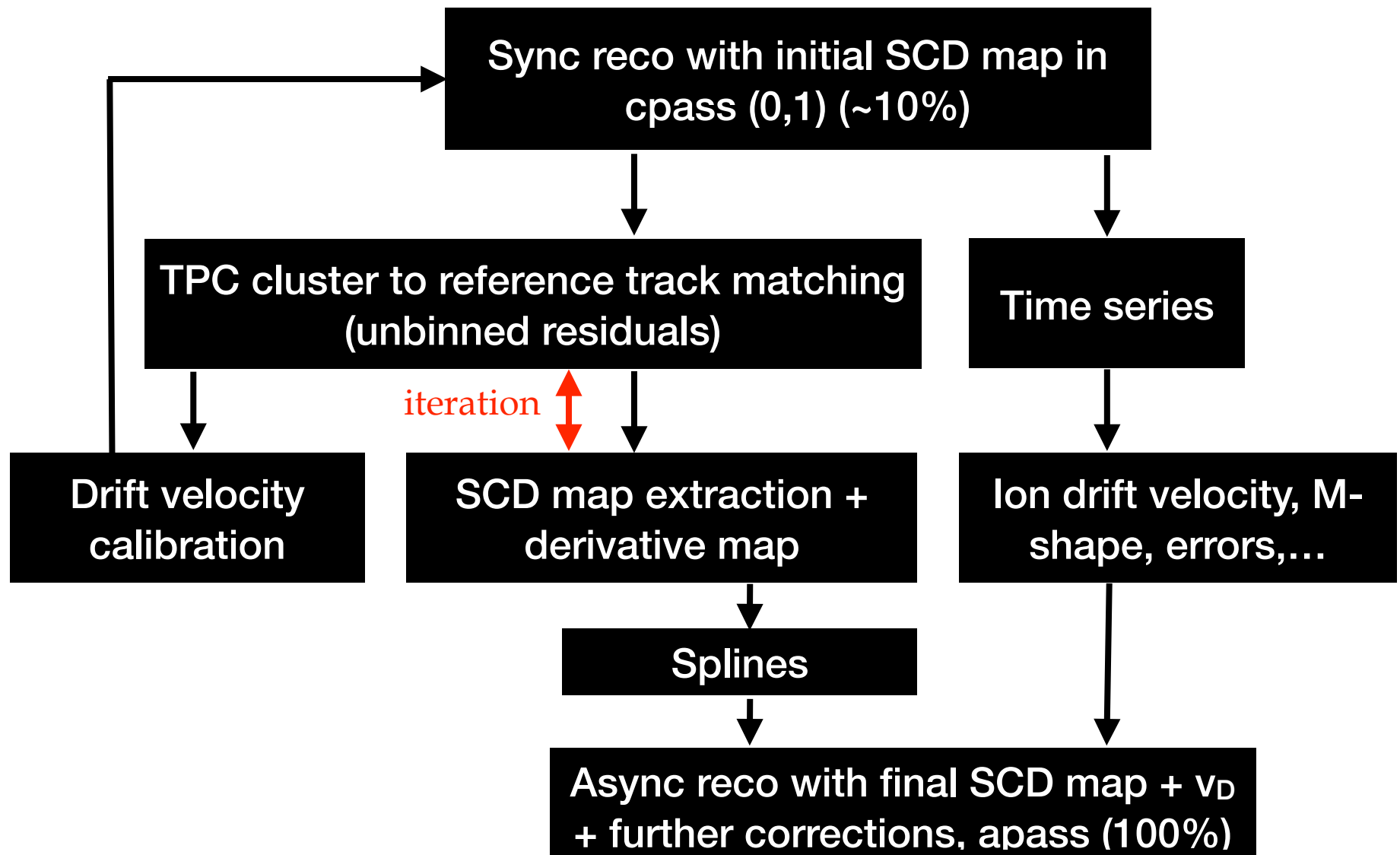


New alignment

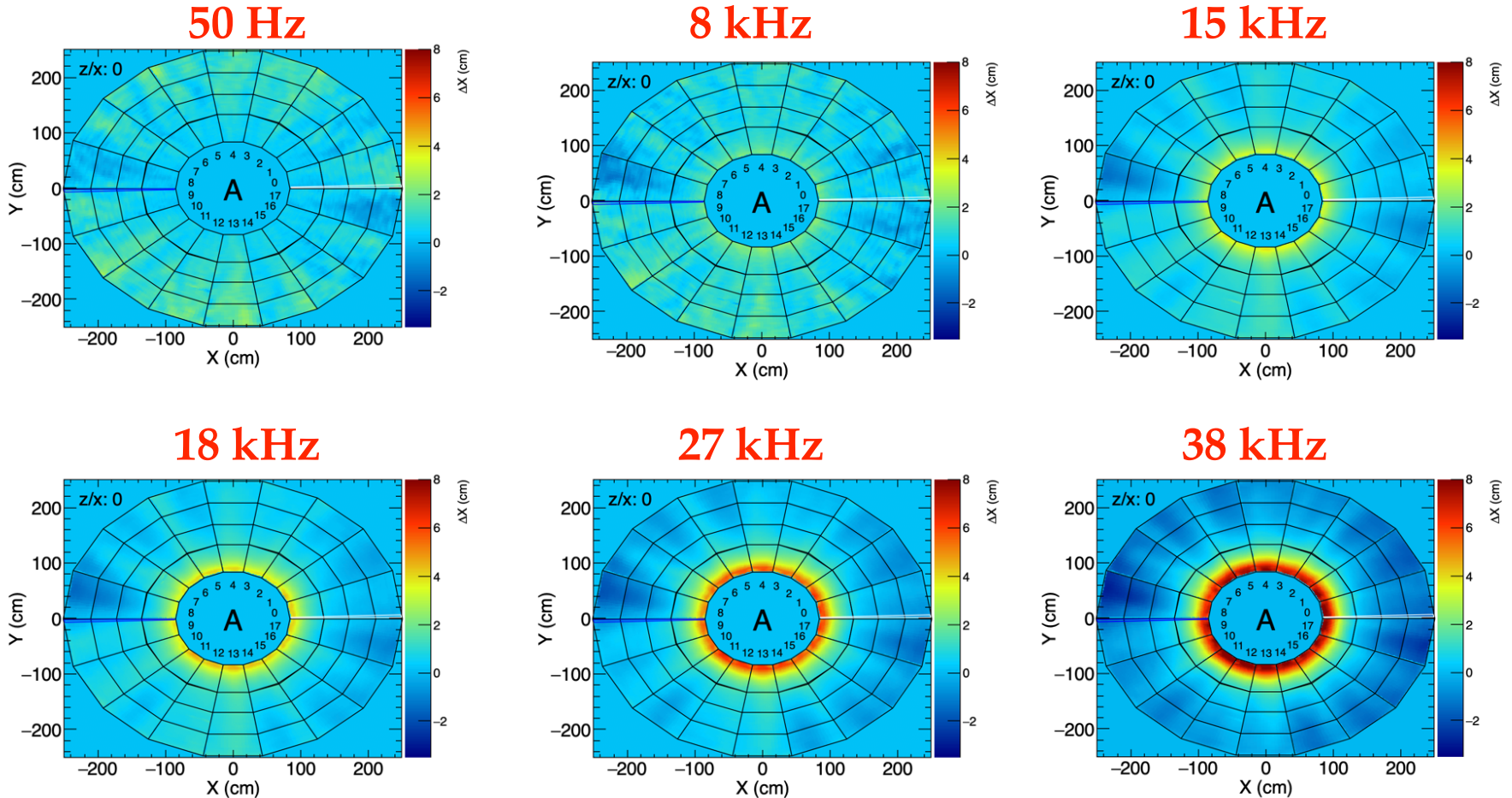


- New alignment removes the structures from sectors 8 and 17.
- Overall very smooth map.

Correction Workflow

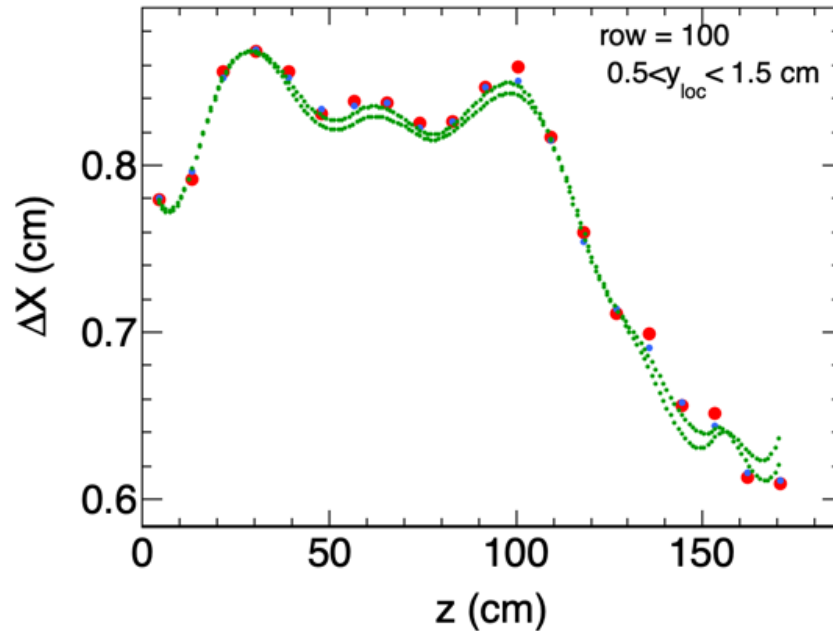


Space Charge Distortion Maps



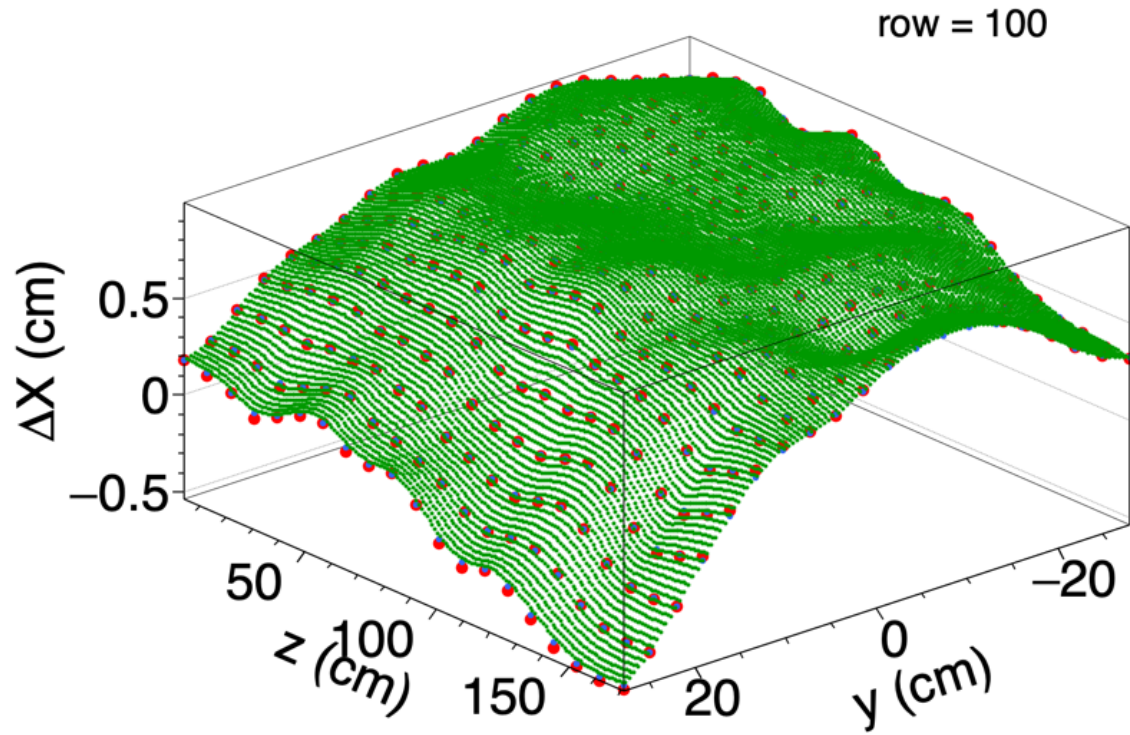
- Average maps. Fluctuations and IR dependence are treated on top.
- Distortions up to ~ 8 cm in radial direction!

Splines



- Splines: analytical representation of the binned maps.
- Used during GPU reconstruction.

Splines in 2D

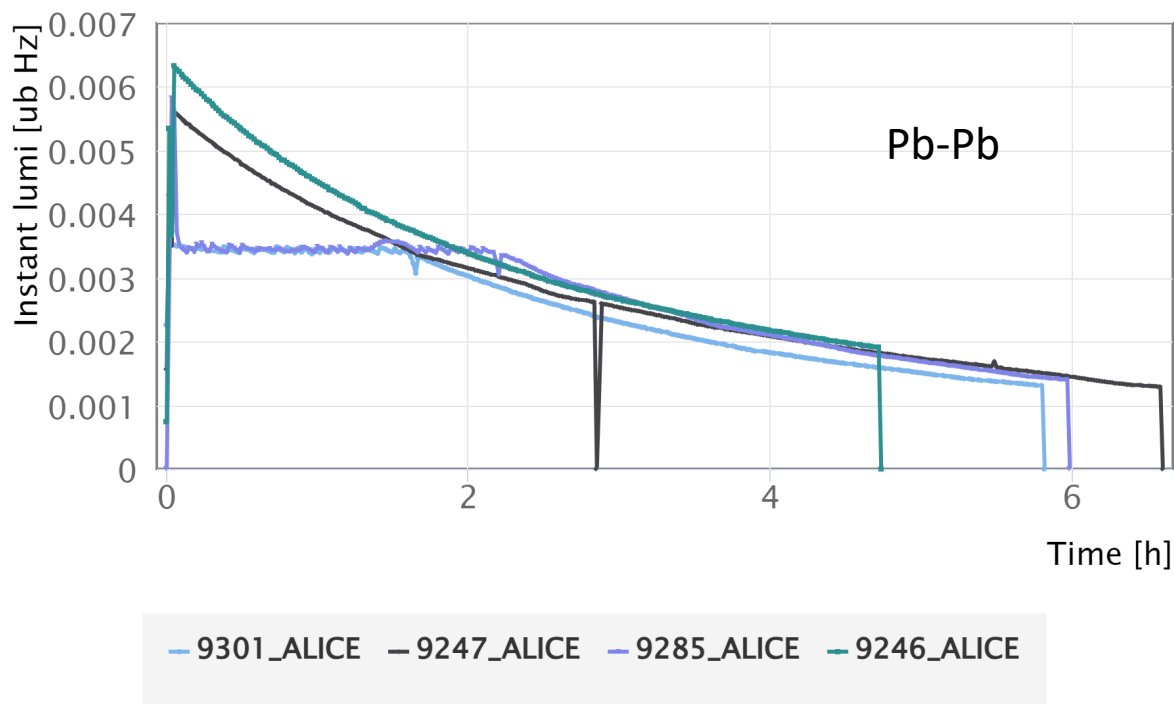


- Example of a 2D spline for pad row 100.

Interaction Rate Dependence

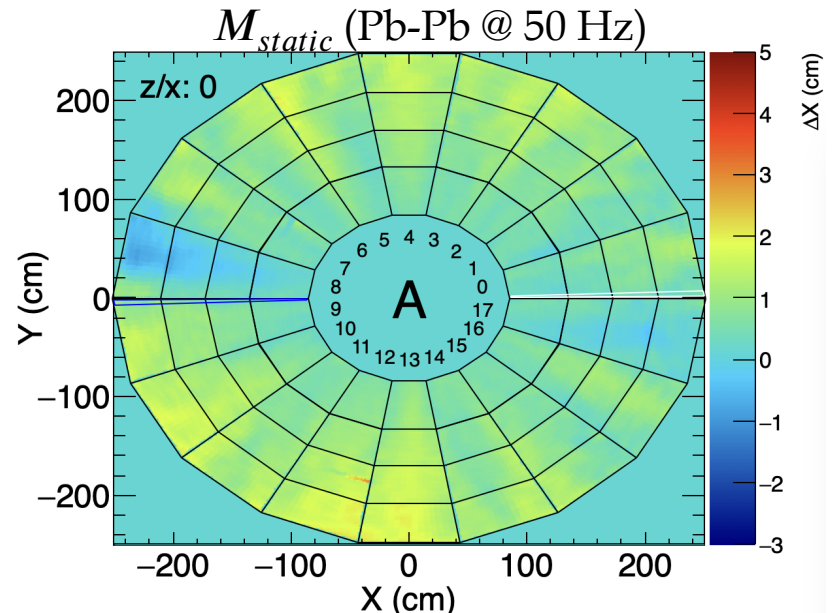
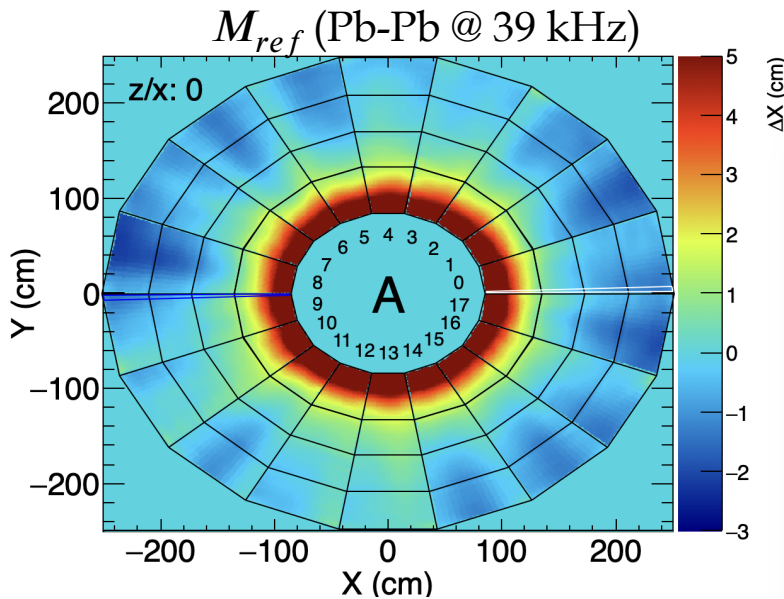
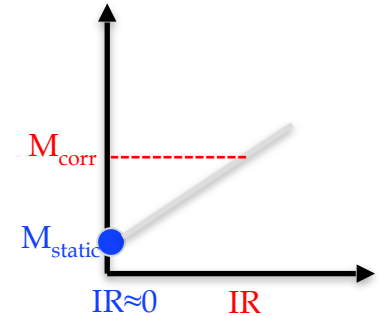
- In Pb-Pb interaction rate **drops rapidly** within a fill
 - Additional complication for SCD calibration – expected leveling at least for major part of the fill
- SCD correction must account for IR changes

Instantaneous Fill Lumi



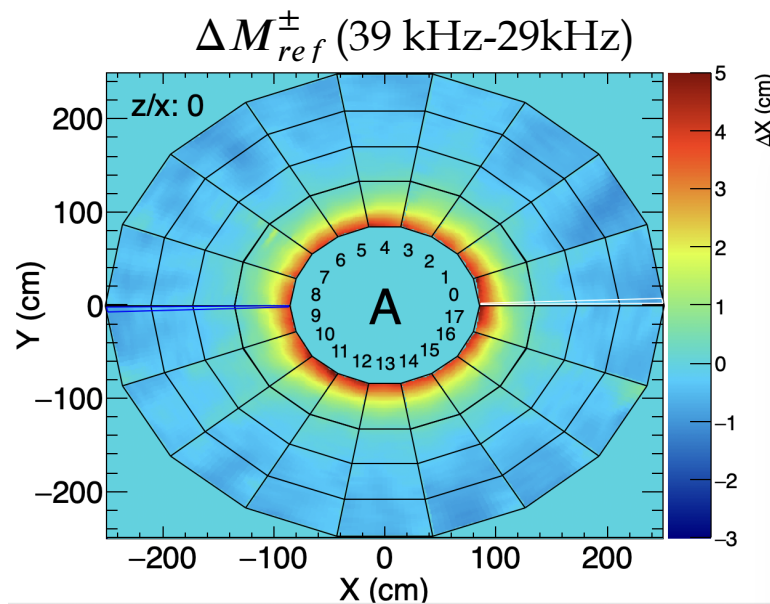
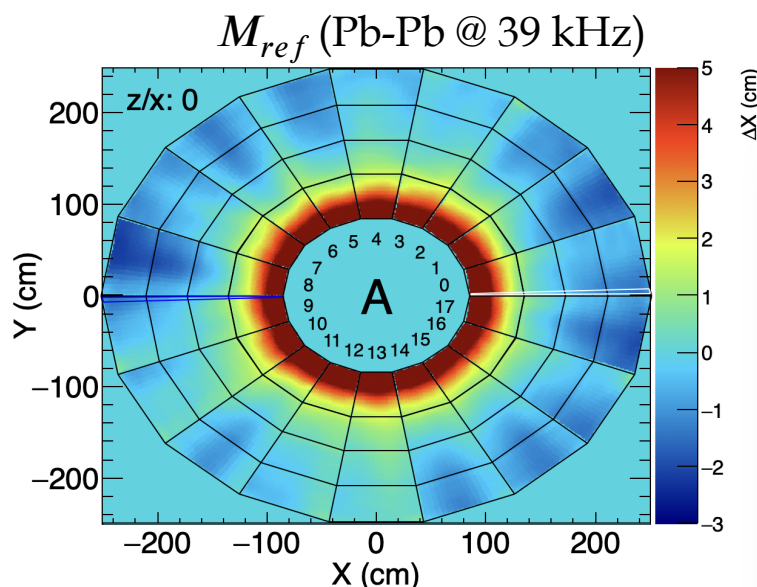
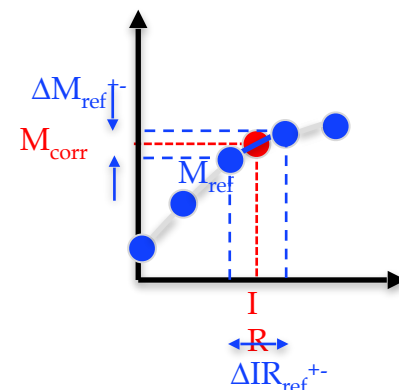
IR Dependence, Linear Scaling

- $M_{corr}(IR) = (M_{ref}(IR_{ref}) - M_{static}) \cdot IR/IR_{ref} + M_{static}$
- M_{static} : long-term-average map at *low* IR ($IR \approx 0$)
- M_{ref} : long-term-average reference map at *high* IR (IR_{ref})
- Caveat: distortions do *not* scale exactly linearly with IR



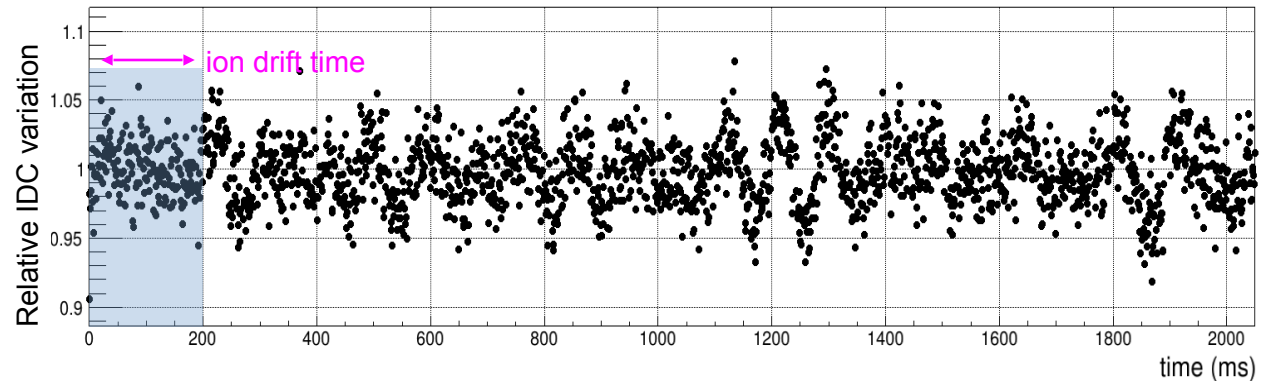
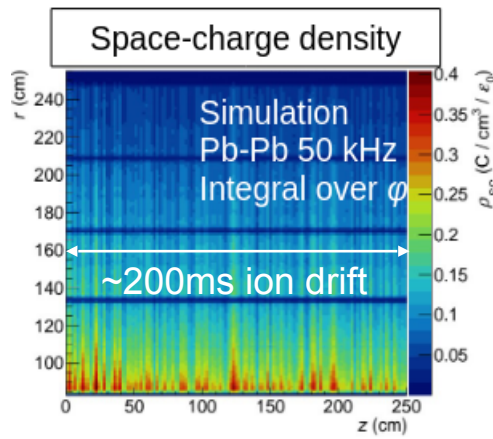
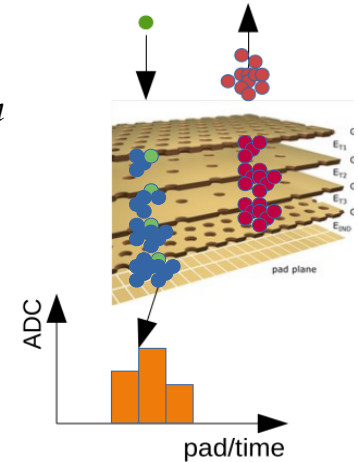
IR Dependence, Differential Scaling

- $M_{corr}(IR) = M_{ref}(IR_{ref}) + \Delta M_{ref}^{\pm} / \Delta IR_{ref}^{\pm} \cdot (IR - IR_{ref})$
- M_{ref} : long-term-average reference map at *high* IR L_{ref}
- $\Delta M_{ref}^{\pm}$: *derivative map*, difference between two maps at slightly different interaction rates around IR
- Improved scaling behaviour
- IR variations from ZDC or *Integrated Digital Currents* (IDCs)

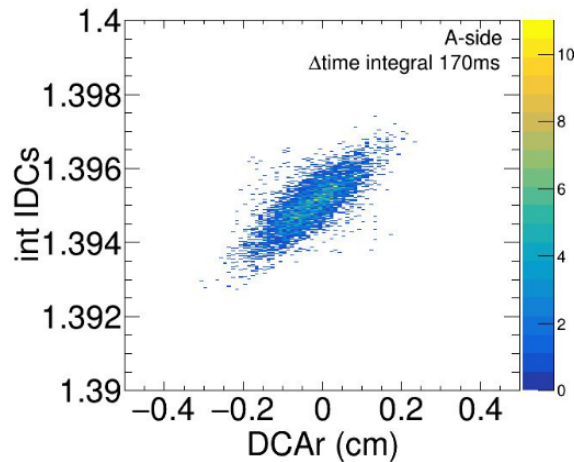


Integrated Digital Currents

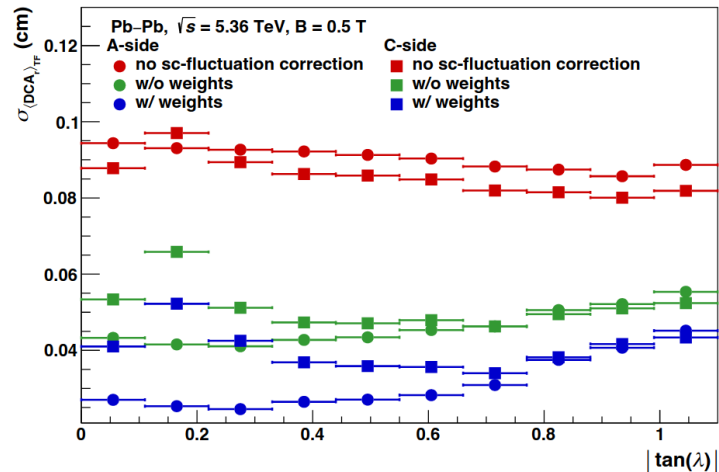
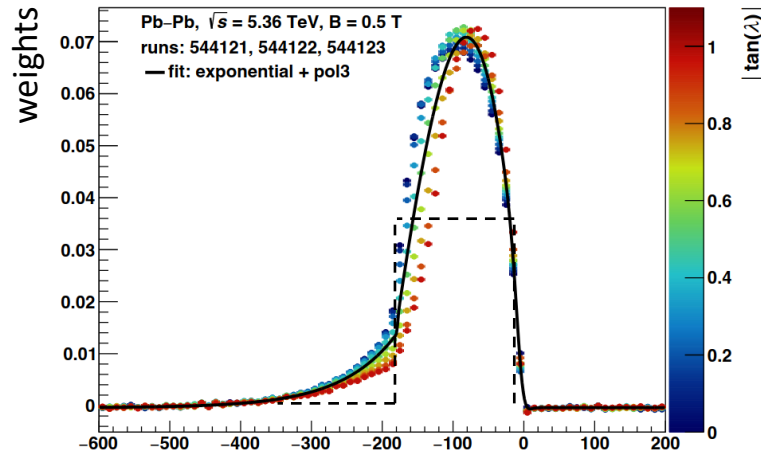
- *IDCs* – the ultimate measure for SC variations and fluctuations:
 - *Pad-by-pad ADC values integrated over 1 ms inside the CRU, injected in data stream*
- SC density related to IDC via IBF
 - $\rho_{SC} \sim I_{prim} \cdot gain \cdot IBF$
 - $IDC \sim I_{prim} \cdot gain$
- Relevant for ρ_{SC} fluctuations: *IDC history over typical ion drift time (200ms)*



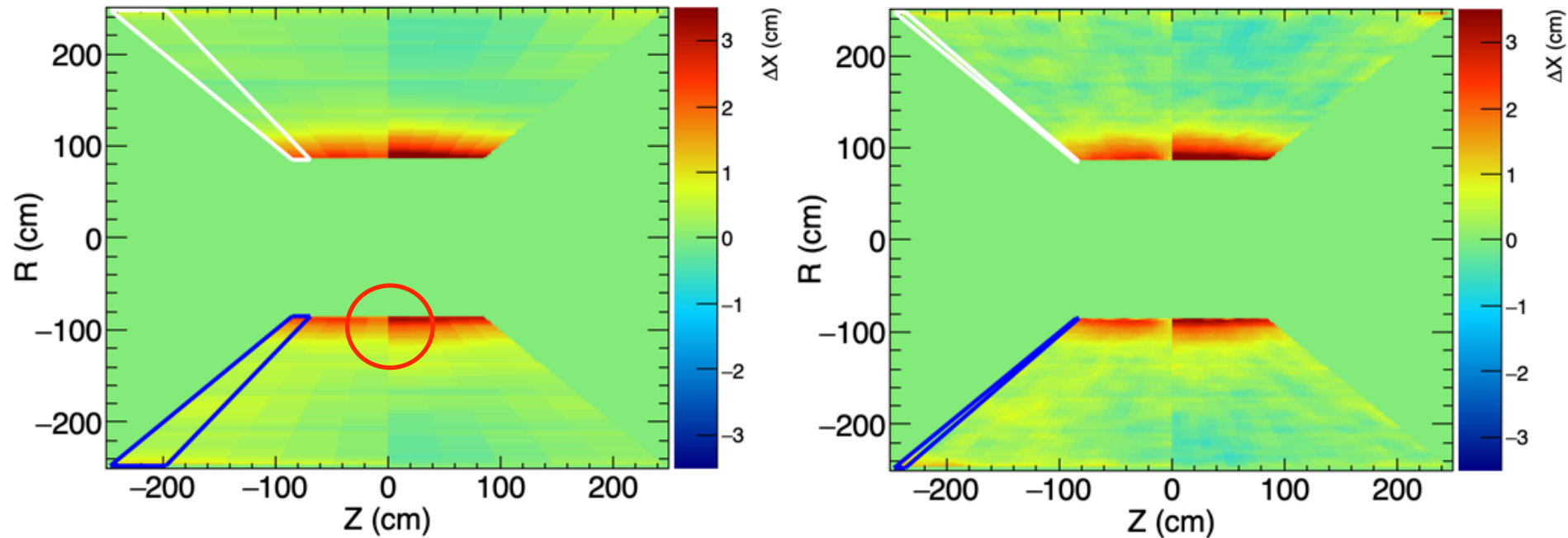
Effective Ion Drift Time



- Not all ions from the past 200 ms contribute equally to the distortions
- Δt - dependent weights developed based on correlation with observed distortions (DCA_r)
- Significant improvement compared to flat weight

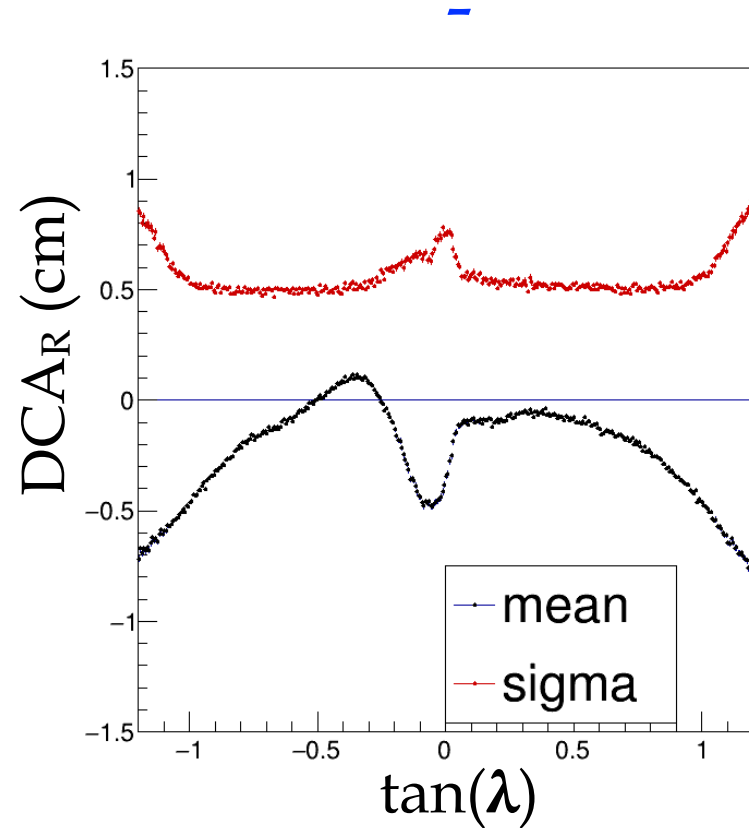
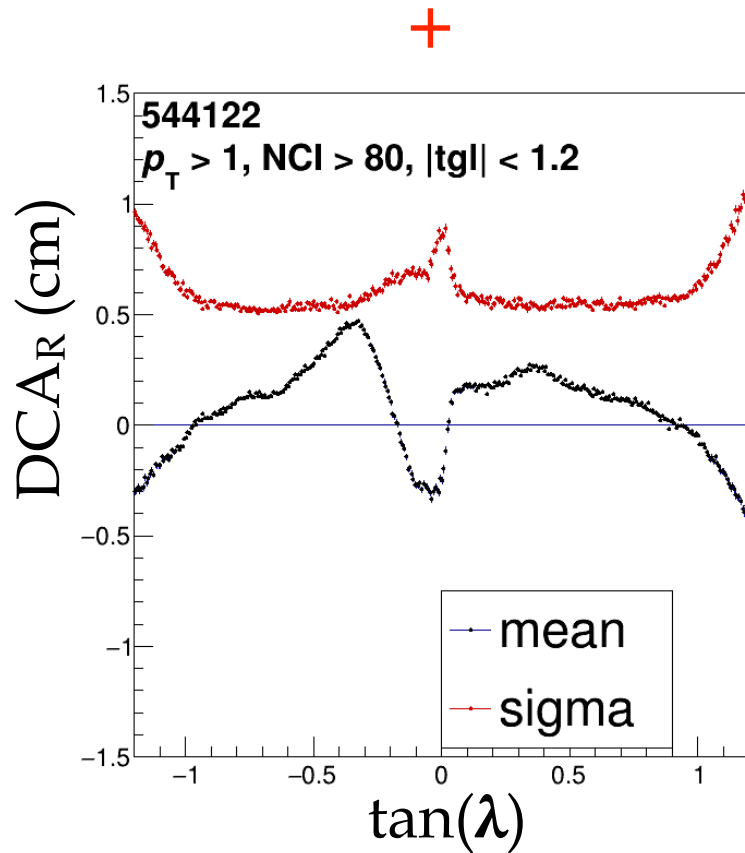


Map Granularity



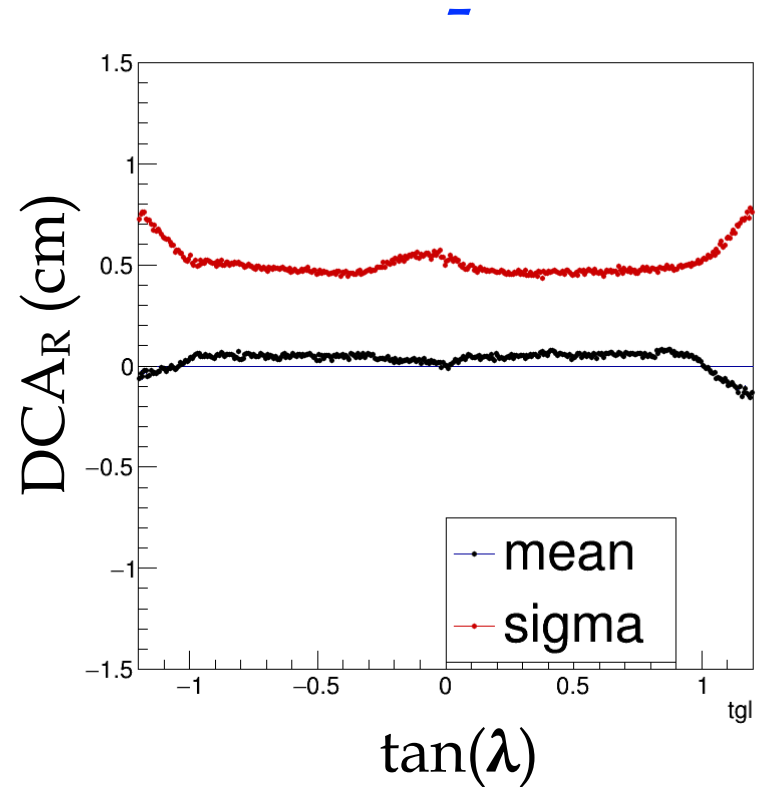
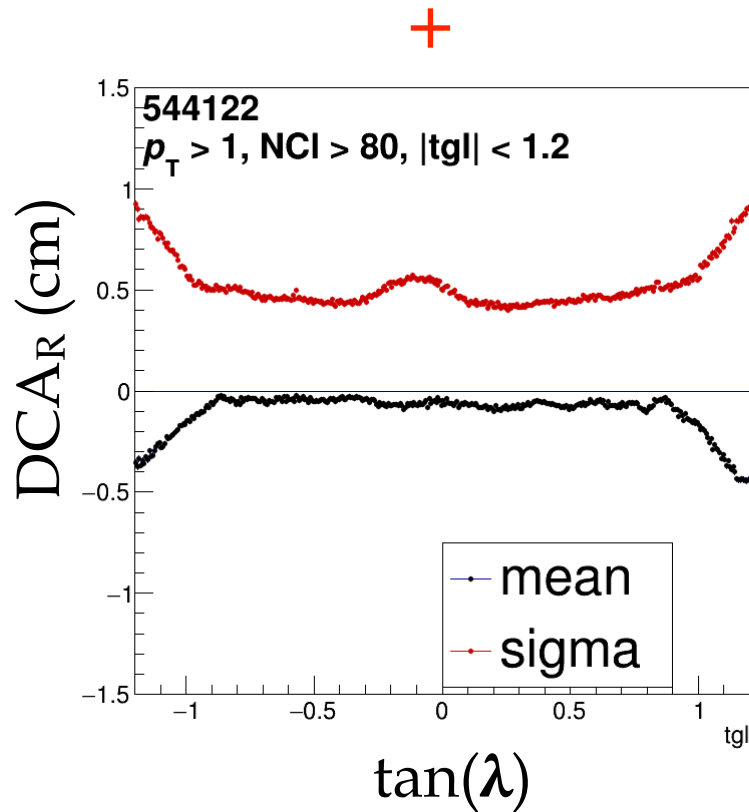
- Standard setting so far: 36 sectors, 15 bins in Y, 152 in X, 5 in Z: 410400 voxels
- Now: Increase in Z from 5 to 20 (tested up to 25), 20 in Y (tested up to 30)
- Especially at the central electrode we need a higher granularity to follow the gradients.
- Future: Non-equidistant binning!

544122, NY=15, NZ=5



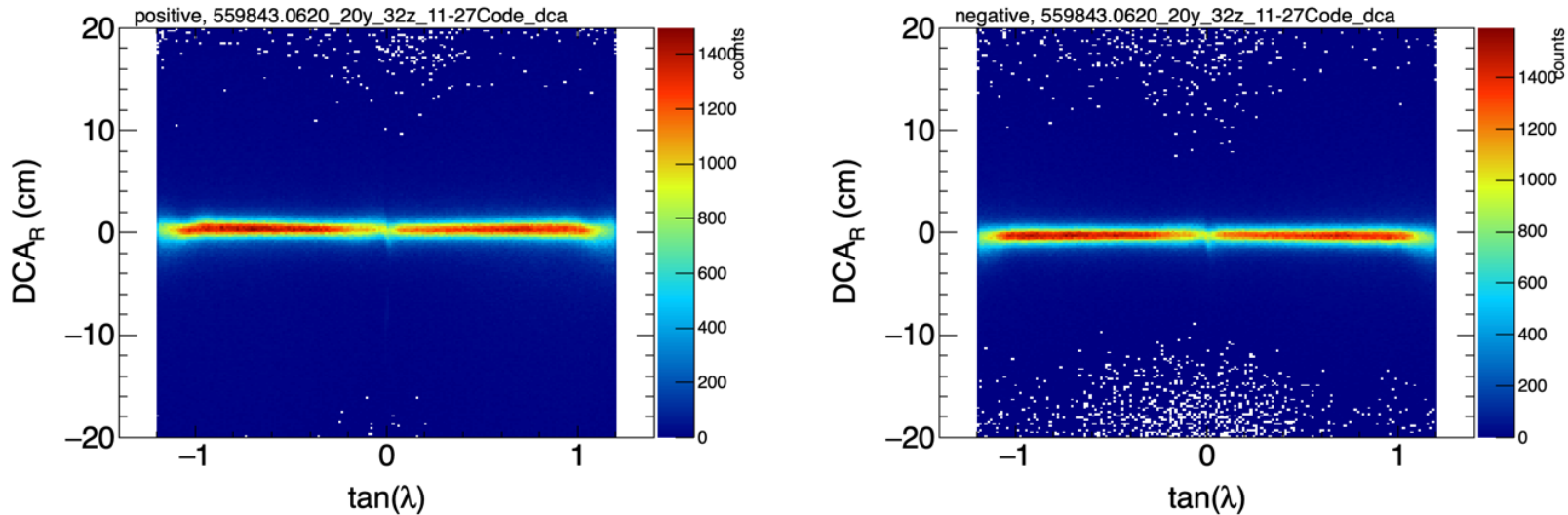
- DCA = distance of closest approach to primary vertex.
- 15kHz Pb-Pb
- Standard binning for voxel map
- TPC only tracks!

544122, NY=20, NZ=30



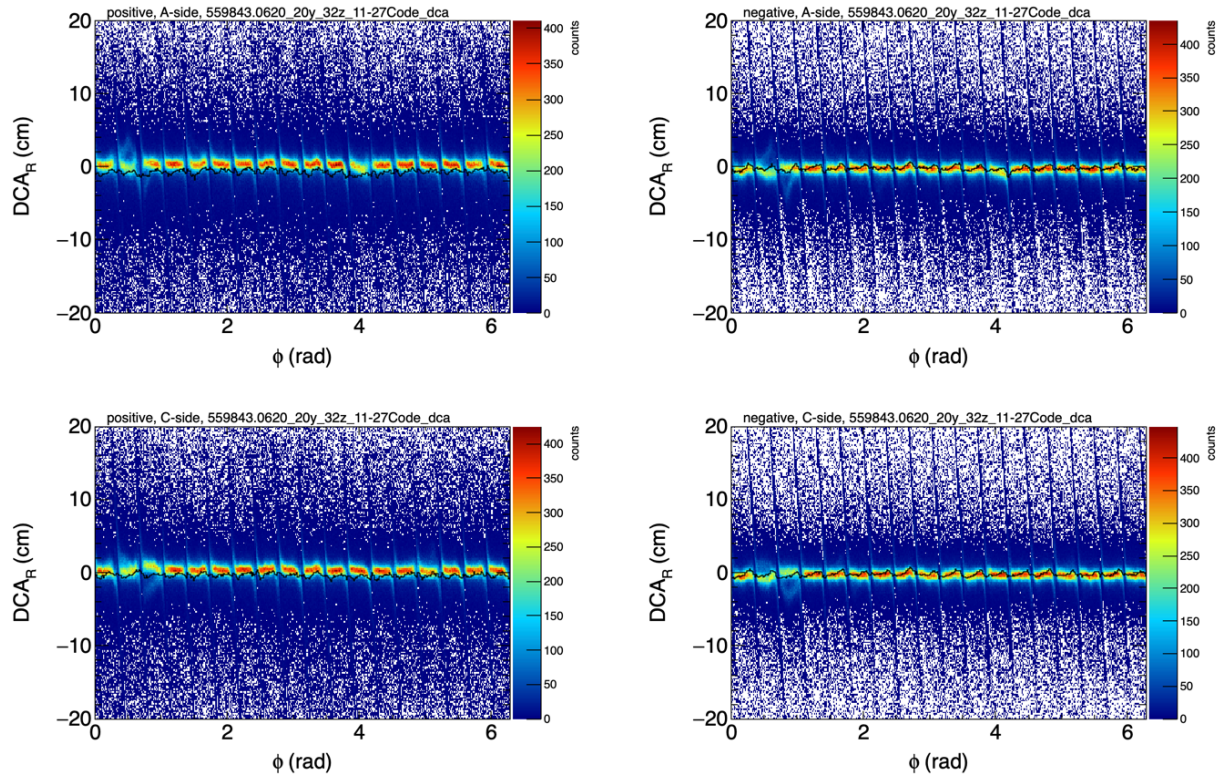
- 15kHz Pb-Pb.
- 30 bins in y, 20 bins in z.
- Much better DCAs.

Closure Test for $Z/X = 1.4$ Map



- Typical plots to check the quality of a calibration.
- DCA_R is flat over full acceptance.

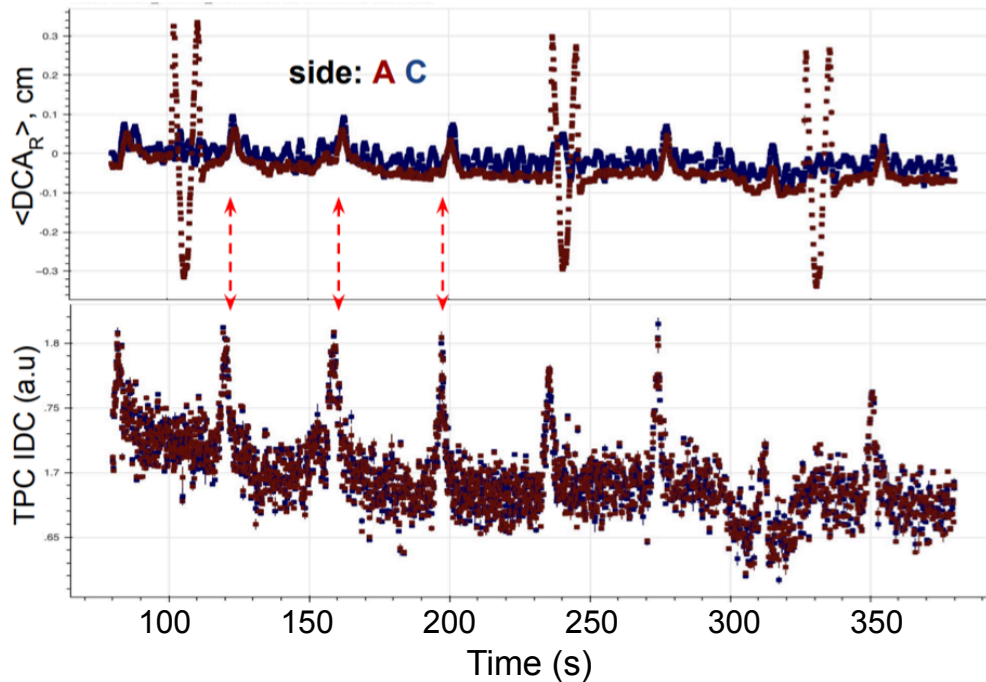
Closure Test for $Z/X = 1.4$ Map



- Typical plots to check the quality of a calibration.
- DCA_R is flat over full acceptance.

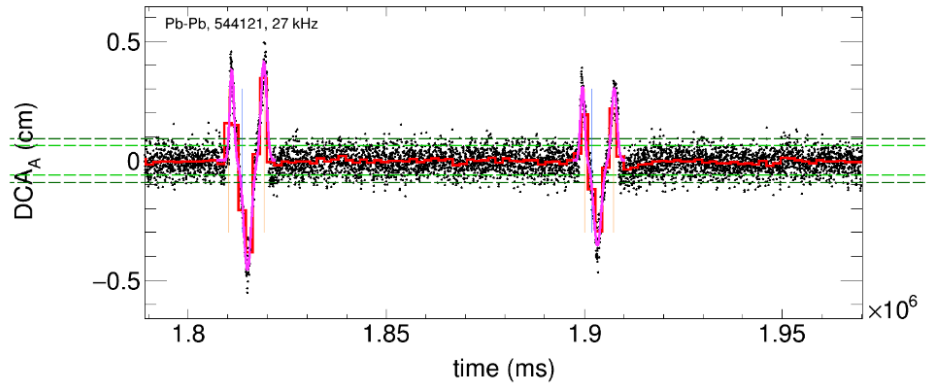
Hardware Related Effects

M-Shape Distortions

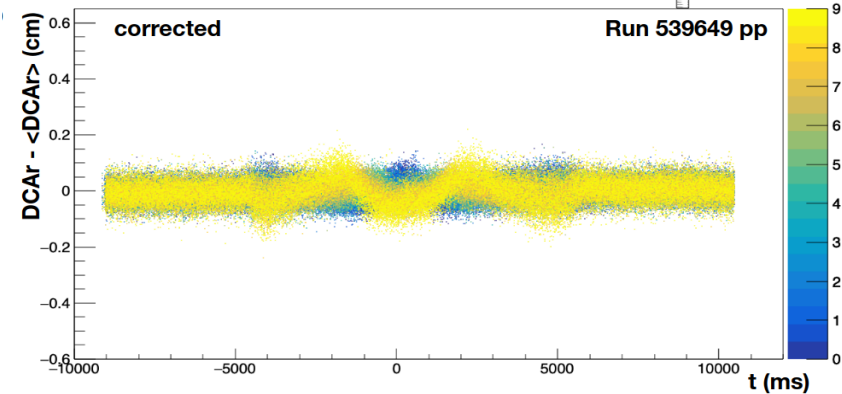
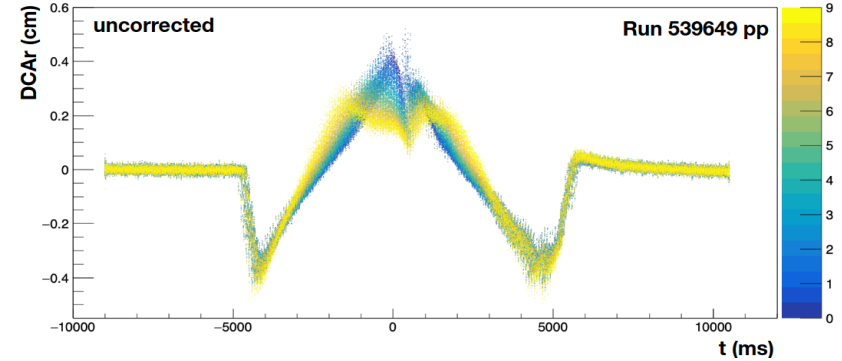


- In general, very good correspondence between observed distortions and IDCs
 - Ideal tool to correct for SC fluctuations
- Additional M-shaped distortion patterns observed with **no correspondence to IDCs**
 - Origin is **not space charge**
 - Magnitude larger than typical SCD
 - Duration O(10s)
 - Only on the A-side
 - Frequency changes but not related to IR
 - Air bubble in the water cooling system cause the effect!
 - Solved now.

M-Shape Correction

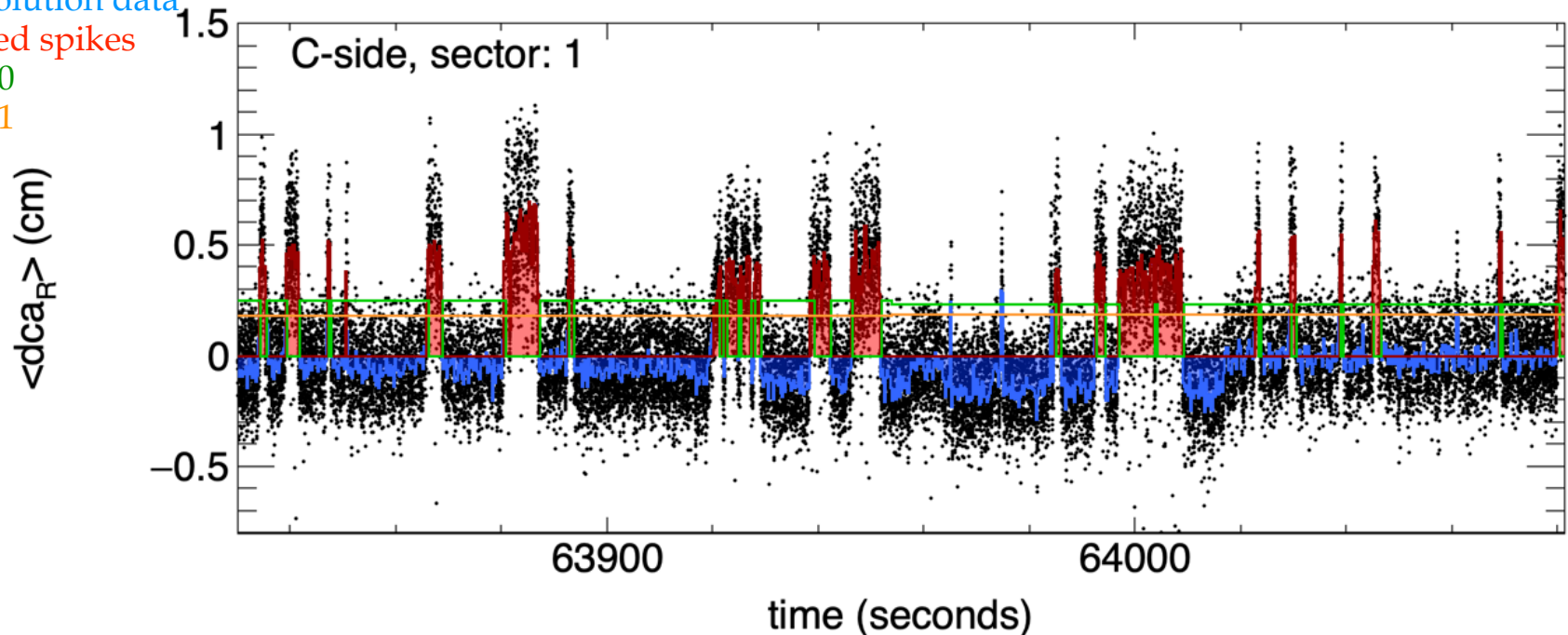


- M-shaped excursions detected in **full data set**
- Correction implemented based on parametric model of **field cage boundary condition variations**
- Added to SCD maps.
- Origin is a **leak in one of the field cage resistor rod cooling circuits**
- Cooling water removed during YETS – solved



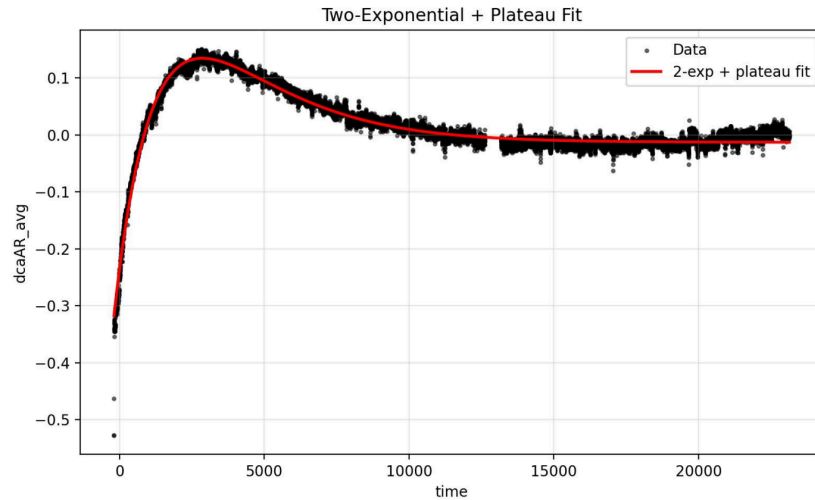
Sector Edge Fluctuations

0.1 second data
low resolution data
identified spikes
RMS itt0
RMS itt1

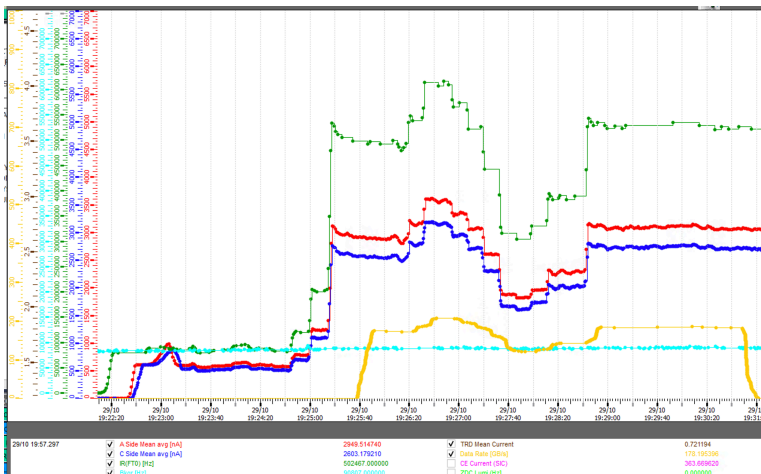


- Large spikes from sector edge fluctuations.
- Only for a few sectors.
- Hardware related effect.
- Special calibration needed.

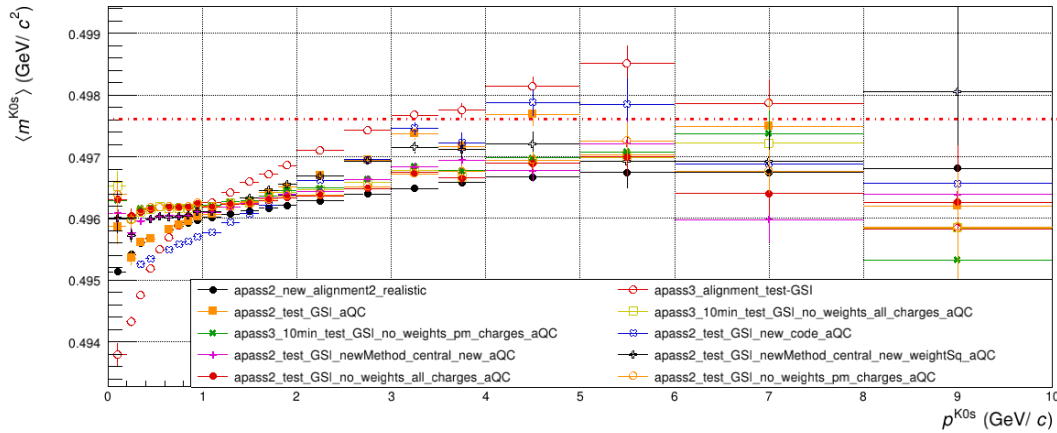
Charge up of the Inner Field Cage



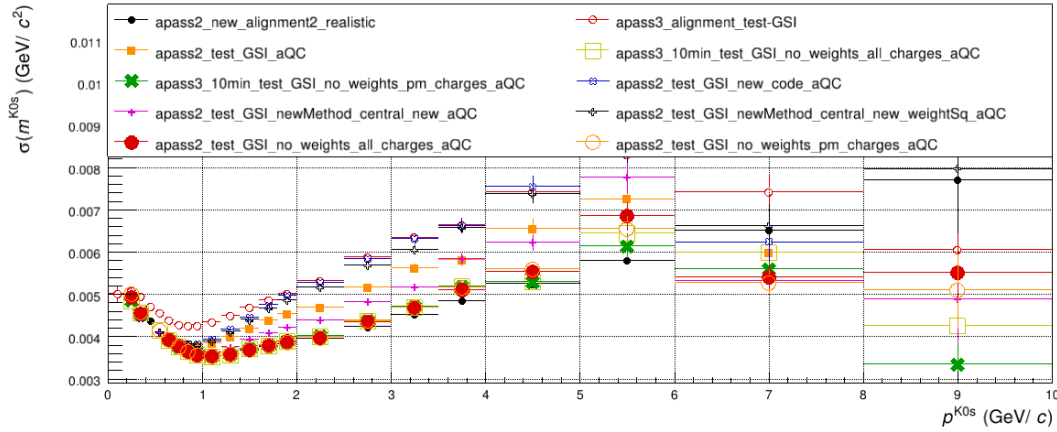
- We observe a charge up mainly on the A-side which takes $O(10 \text{ min})$.
- No dedicated calibration for this period at the moment.
- To decompose several effects we requested two special calibration runs with various steps in IR at the beginning (charge up) and at the end.



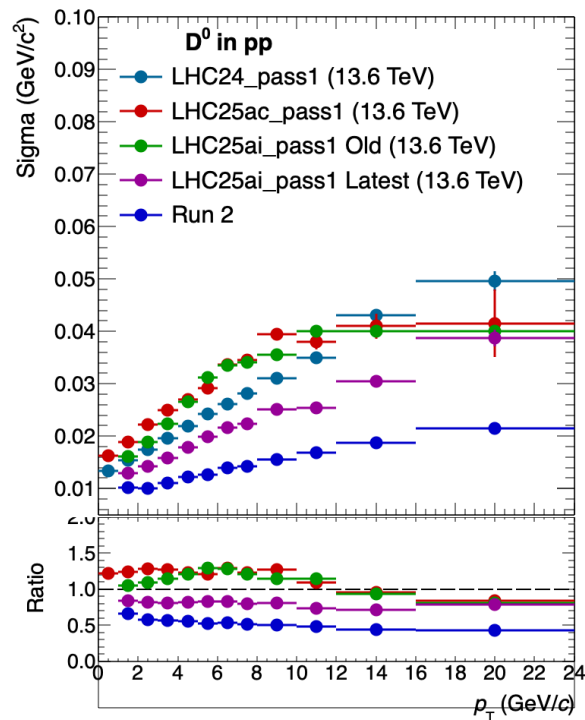
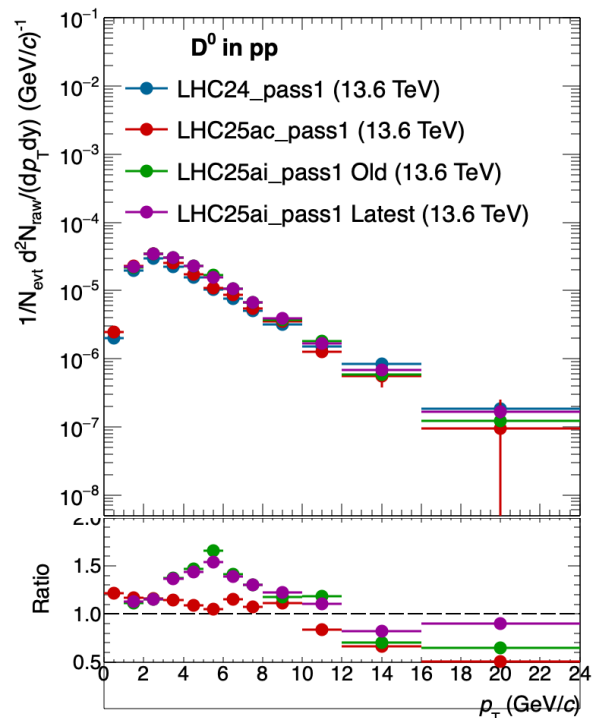
Performance K0s



- Significant improvements over time, close to Run2 performance for K0s.



D⁰ performance



- Significant improvements over time, also includes new alignment.
- Still a difference to Run 2 performance.

Calibrators within the ALICE TPC



Yuanjing



Yongzhen



Pengzhong

- More people are very much welcome.
- Join the ALICE TPC team now!