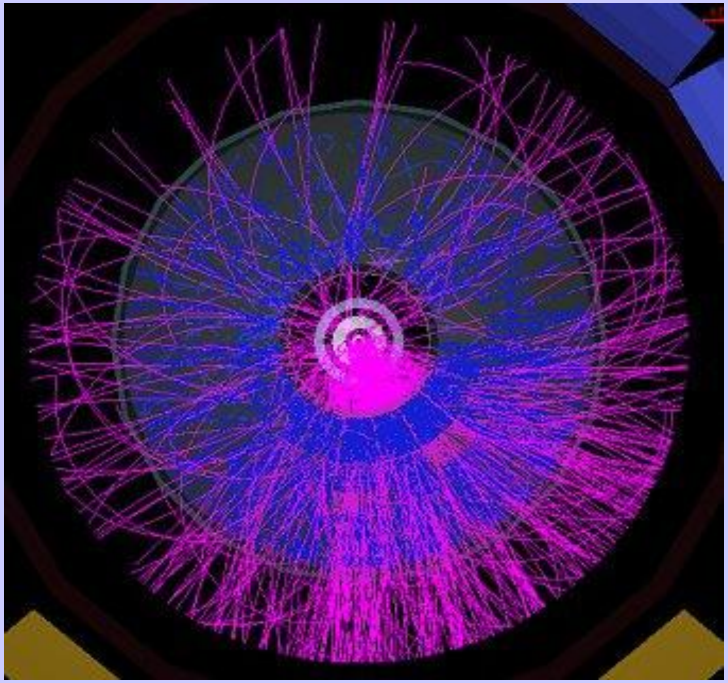
The ALICE Time Projection Chamber

... the World's largest Time Projection Chamber



Outline

- Time Projection Chambers
  - Introduction
  - Coordinate Measurement and Limitations
  - Particle Identification (d*E*/d*x*)
  - TPCs for Heavy Ion Experiments
- The ALICE TPC
  - ALICE Experiment
  - Construction
  - Gas Choice
  - Read Out Electronics
  - Calibration
  - Performance
- Summary

Detector Physics for TPCs

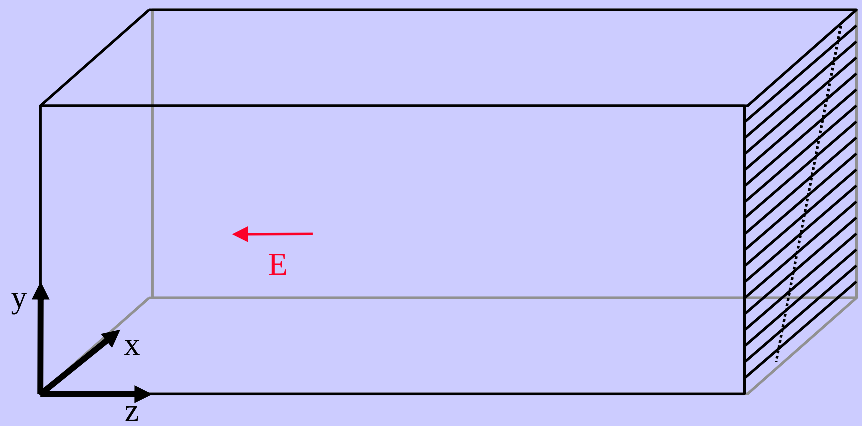
1) Gas **Ionisation** by Charged Particles,
2) Electron **Drift** and **Diffusion** in Gases,
3) Ionisation **Amplification** (at Anode Wires),
4) Signal Creation (**Induction**),
5) Signal Processing in Readout **Electronics**,
6) Coordinate Measurement,
7) Ion gates.

All points are described in great detail in e.g.
[Blum, Riegler, Rolandi, Particle Detection with Drift Chambers, Second Edition, Springer, 2008]

TPC – The Concept (1)

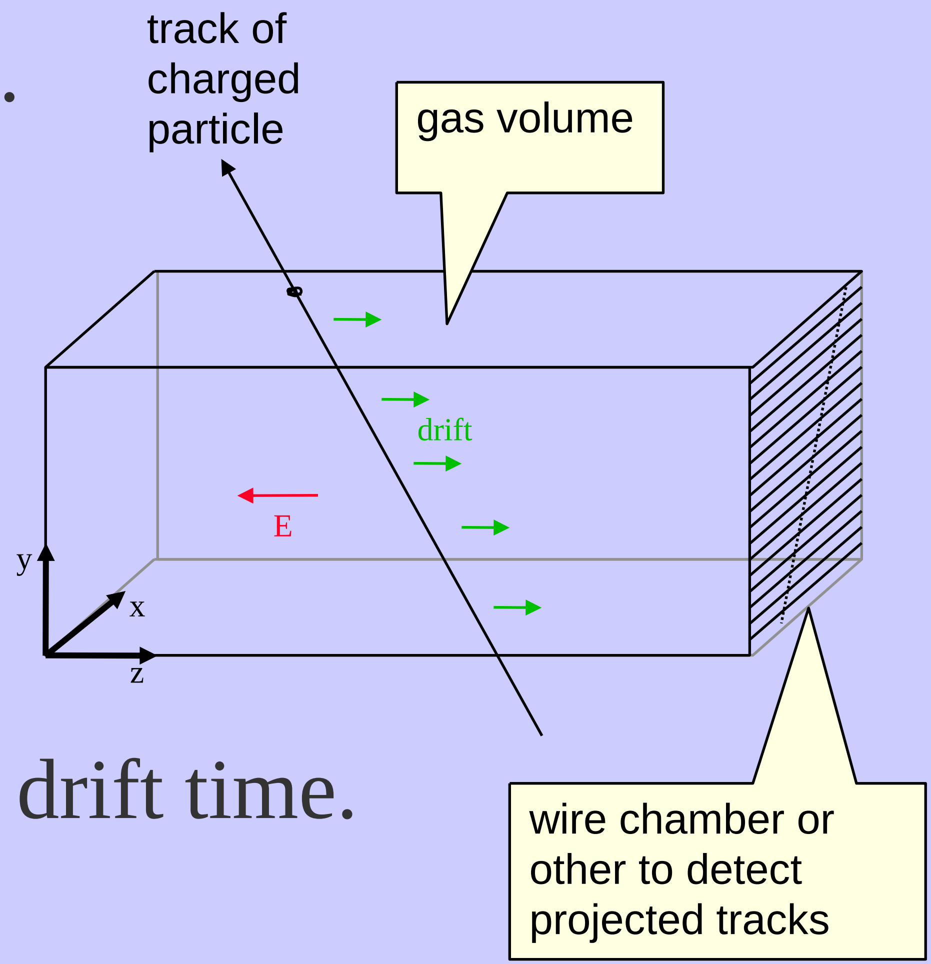
- Time Projection Chambers (TPCs) are simple but effective particle detectors.
- TPCs consist of:

1) A large volume filled with a **gas** (or liquid),
2) a **field cage** providing a uniform electric drift field and
3) at one or two surfaces of the volume **readout elements** (e.g. wire chambers, GEMs, ...).



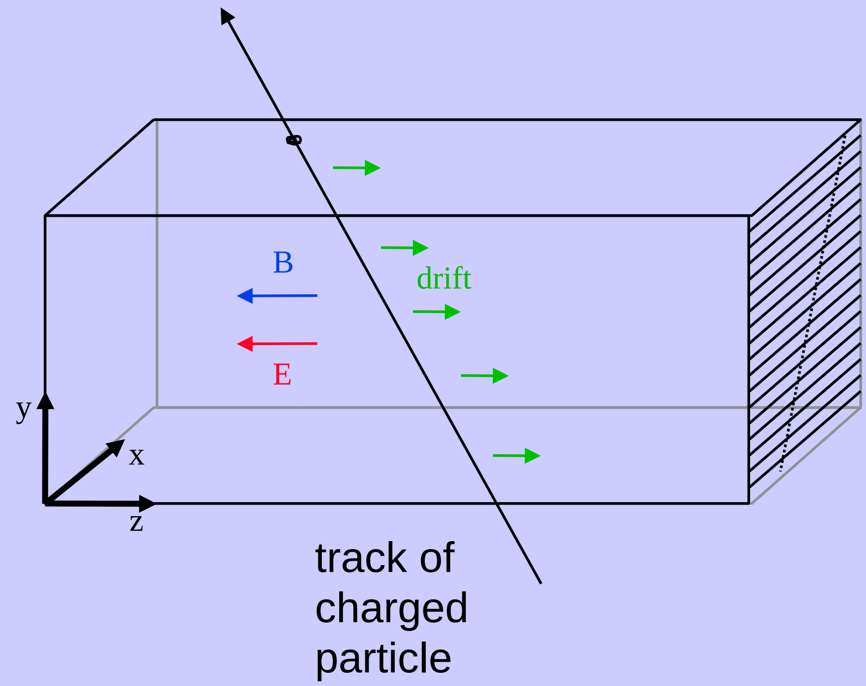
TPC – The Concept (2)

1) The track of a charged particle ionises the gas.
2) The electrons drift towards the readout elements.
3) The projected track is detected.
4) The third coordinate is reconstructed from the drift time.



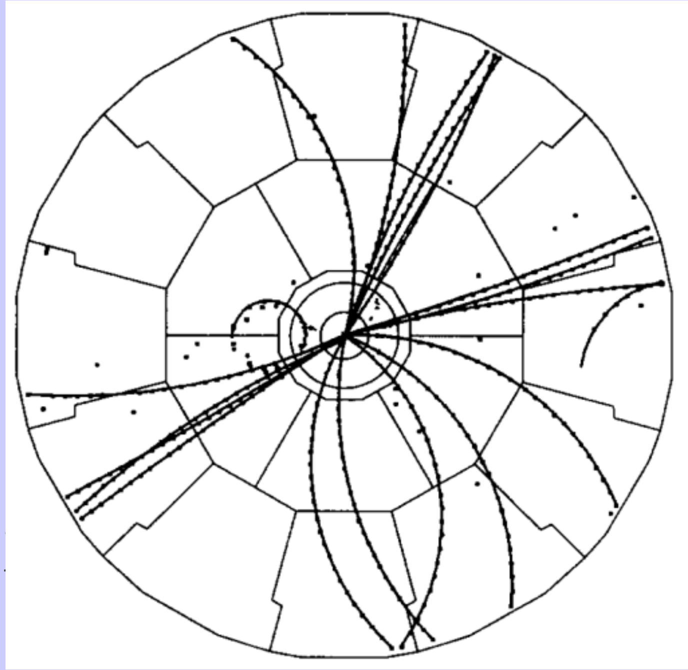
TPC – The Concept (3)

- A magnetic field is applied in order to measure the track curvature
  and thus the
  particle momenta.



TPC – The Concept (4)

- A magnetic field is applied in order to measure the track curvature
  and thus the
  particle momenta.
- A simple formula:
  $p_T = 0.3\ B\ R$, where
  B = magnetic field in
  Tesla;
  R = radius of particle track



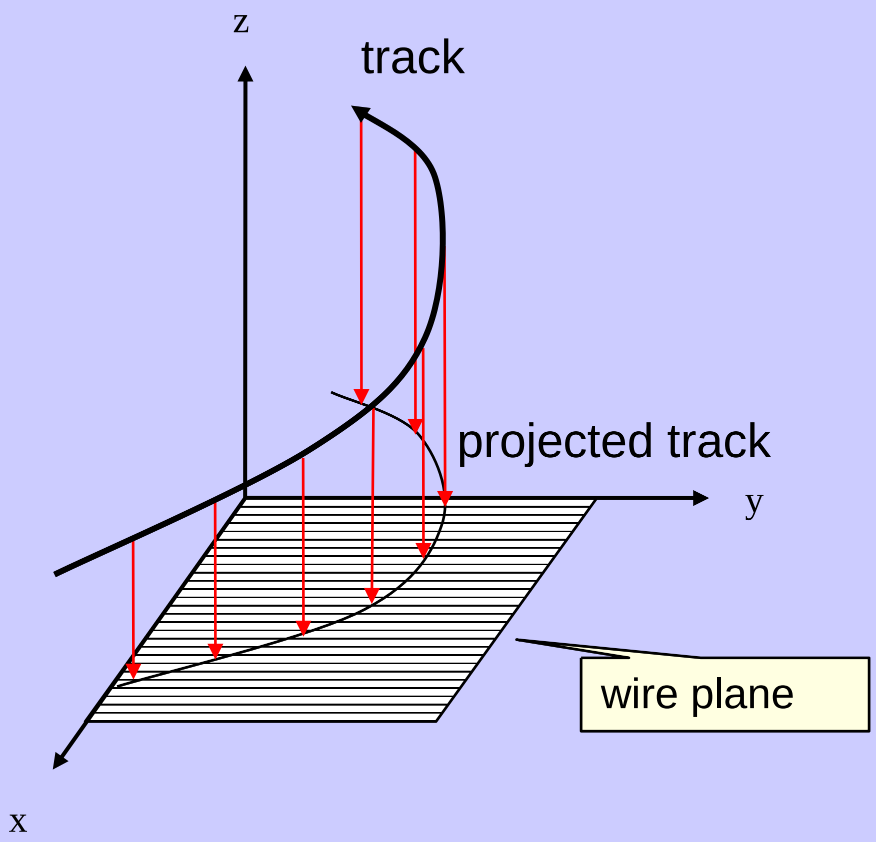
What is special about TPCs?

- Abilities:
  - **3D coordinate measurement:** Tracking of charged particles in high track density environments and
  - **PID: Particle Identification** through their ionisation energy loss (**d*E*/d*x***).
- Advantages:
  - Low amount of material leads to low **multiple scattering** of particles.
  - Easy **pattern recognition** (continuous tracks).

Coordinate Measurement with TPCs

TPC – 3D Coordinate Measurement

- *z* coordinate is calculated from **drift time** *t* and drift velocity v_{d}.



A General Equation of Motion (2)

- z *coordinate* is measured via the drift time.
- The drift of electrons in *E* and *B* fields:

$$\vec{v}_d = \frac{\mu}{1+(\omega\tau)^2}\left(\vec{E} + (\omega\tau)\frac{\vec{E}\times\vec{B}}{|\vec{B}|} + (\omega\tau)^2\frac{(\vec{E}\cdot\vec{B})\vec{B}}{|\vec{B}|^2}\right)$$

τ mean drift time between collisions

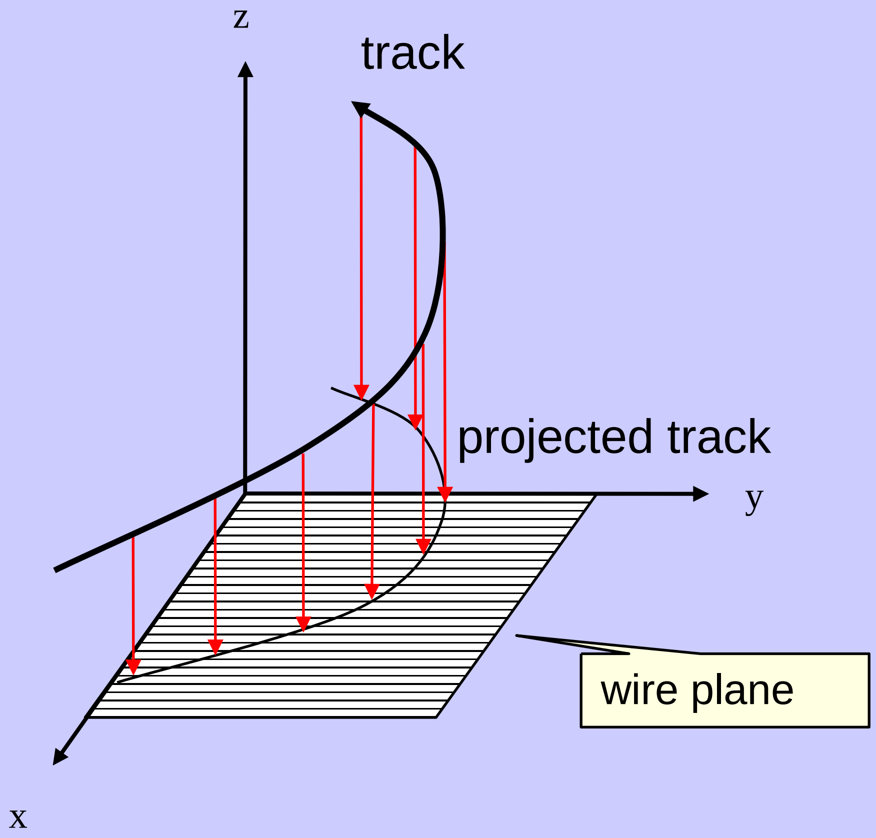
$$\mu = \frac{e\tau}{m}$$ particle mobility

$$\omega = \frac{eB}{mc}$$ cyclotron frequency

- $\omega\tau \ll 1$: Drift along *E* field lines.
- $\omega\tau \gg 1$: Drift along *B* field lines.

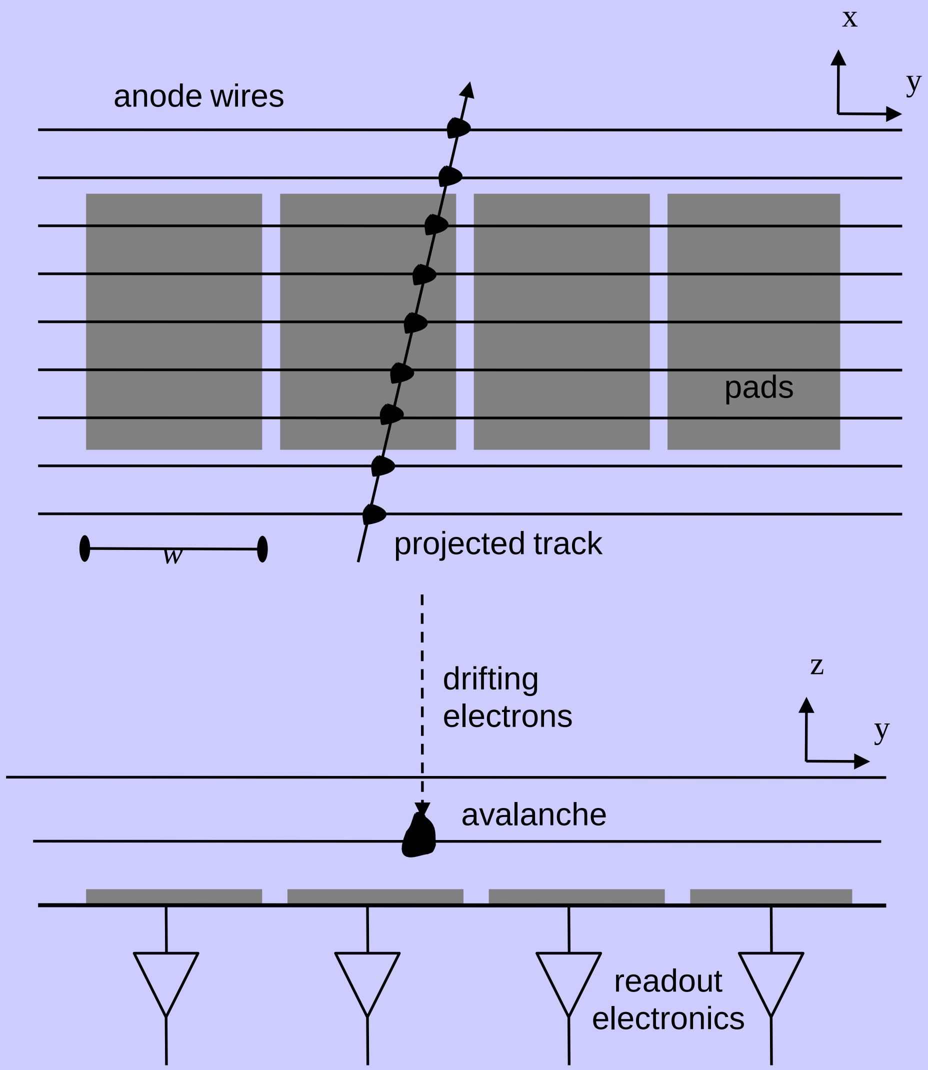
TPC – 3D Coordinate Measurement

- *z* coordinate is calculated from **drift time** *t* and drift velocity v_D;
- *x* and *y* coordinates are calculated using **cathode pads**.



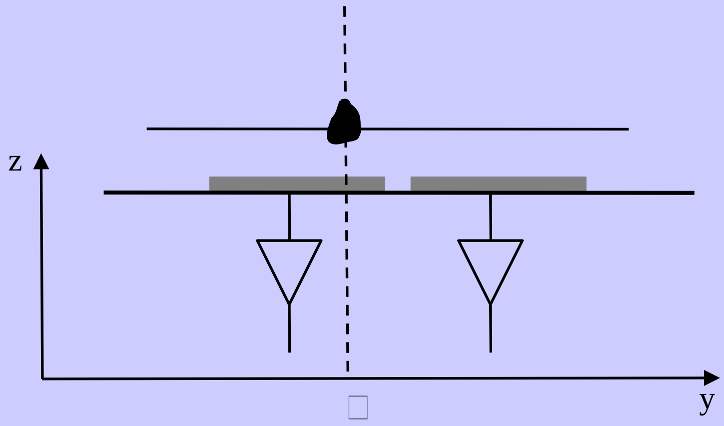
TPC – Cathode Pads (1)

- If the cathode pads are small, we measure signals on at least two adjacent pads in *y* direction (along wires).
- The pulse-height ratio can be used to determine the position of the avalanche with precision much smaller than the pad width *w*.

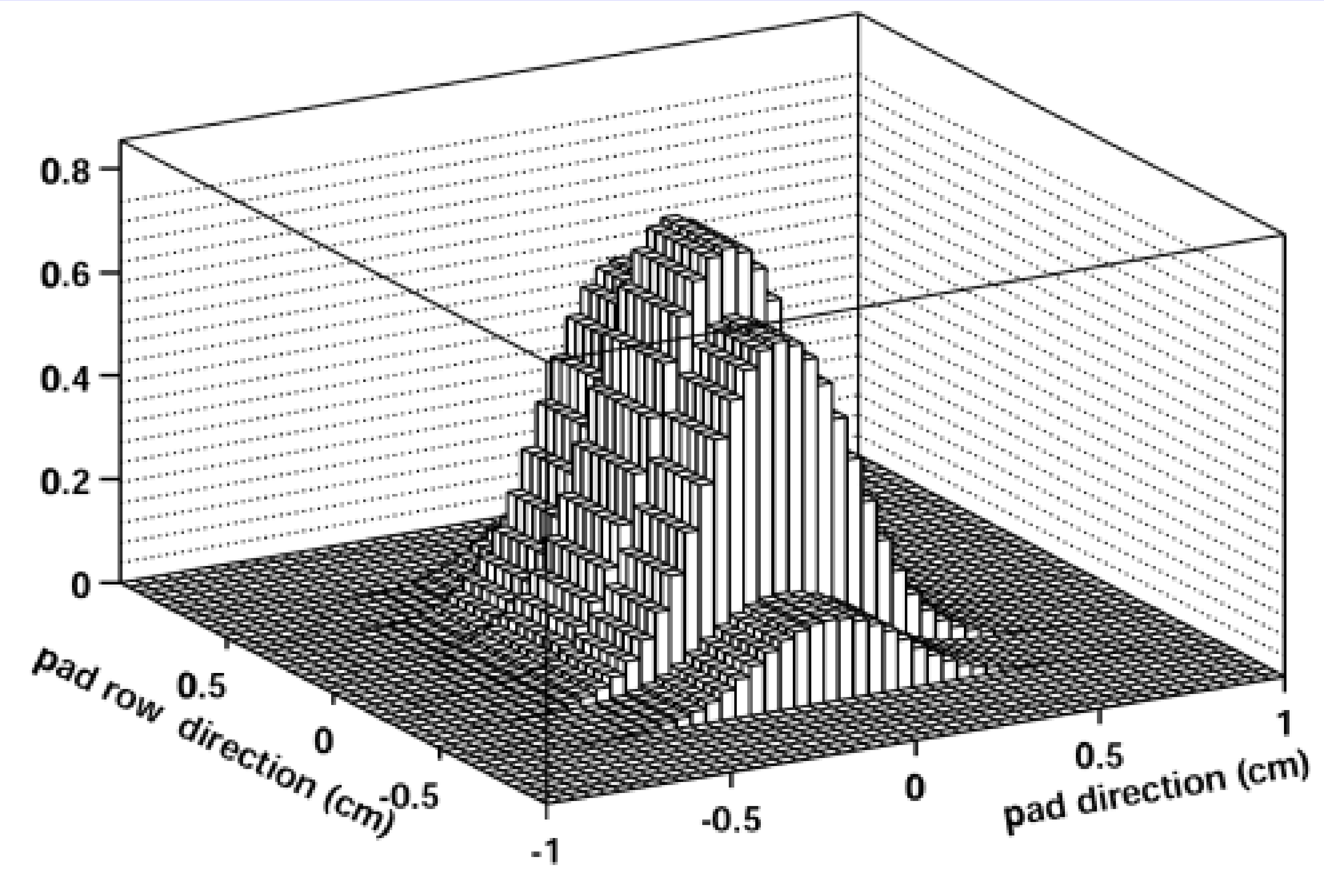


TPC – Cathode Pads (2)

- Assume an avalanche and the two signal amplitudes: A_1 and A_2.
- Width of pads: *w*.
- Then: $A_1 / A_2 = P_0(\lambda) / P_0(\lambda - w)$, which can be used to get the avalanche position λ.
- P_0 is called Pad Response Function and can be measured or calculated.



TPC – Pad Response Function



- Pad Response Function for the ALICE TPC (rectangular 4×7.5mm^2 pads).

Limitations for Coordinate Measurement

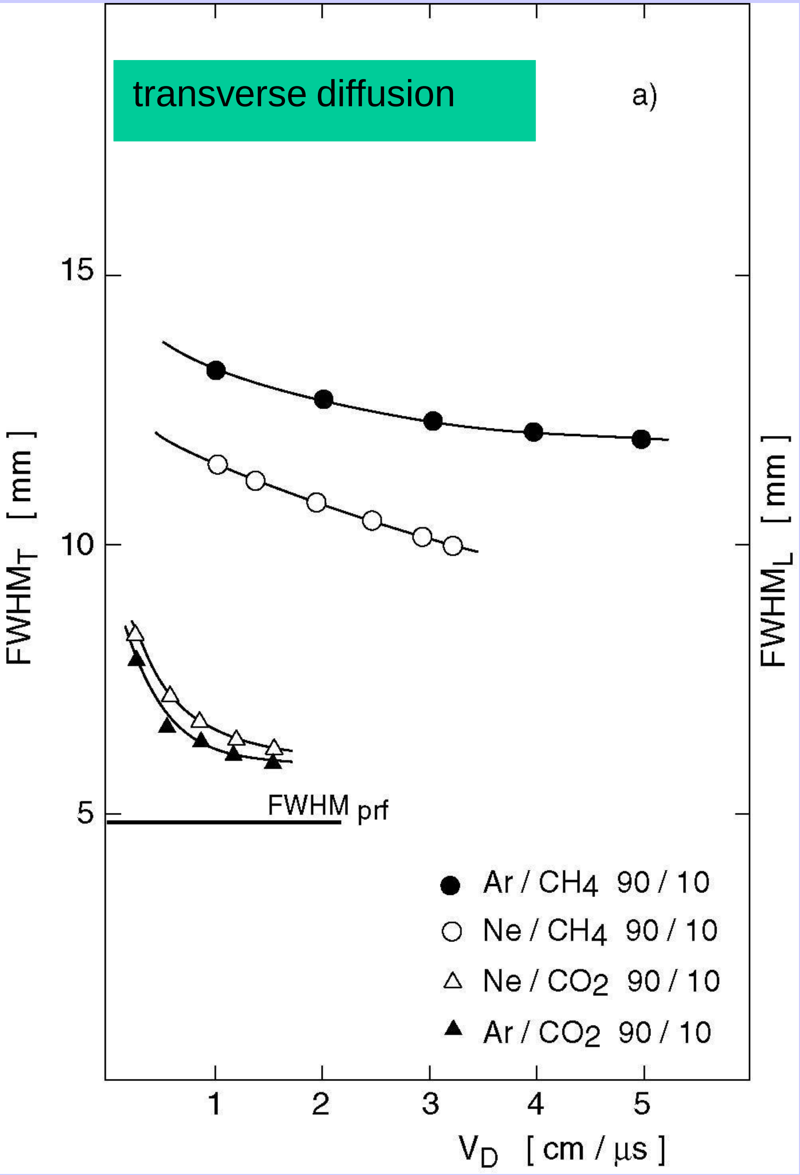
1) **Diffusion** displaces the charge clusters during the long drift.
2) **Attachment** of drifting electrons leads to loss of signal amplitude.
3) ***E*x*B* effects**: Small misalignment (*E* and *B* not perfectly parallel) displaces the charge clusters during the long drift.
4) **Field distortions** due to *space charge* in the drift volume.

Limitation 1: Diffusion (1)

- Electrons are drifting along z and scatter on gas molecules.
- As a consequence, their drift velocity deviates from the average due to the random nature of the collisions.
- The diffusion is Gaussian with $\sigma(z)=D\sqrt{z}$, where
  - z = drift length and
  - D = diffusion coefficient [$\mu m/\sqrt{cm}$].
- Longitudinal (in drift direction) and transverse diffusion can differ.

Limitation 1: Diffusion (2)

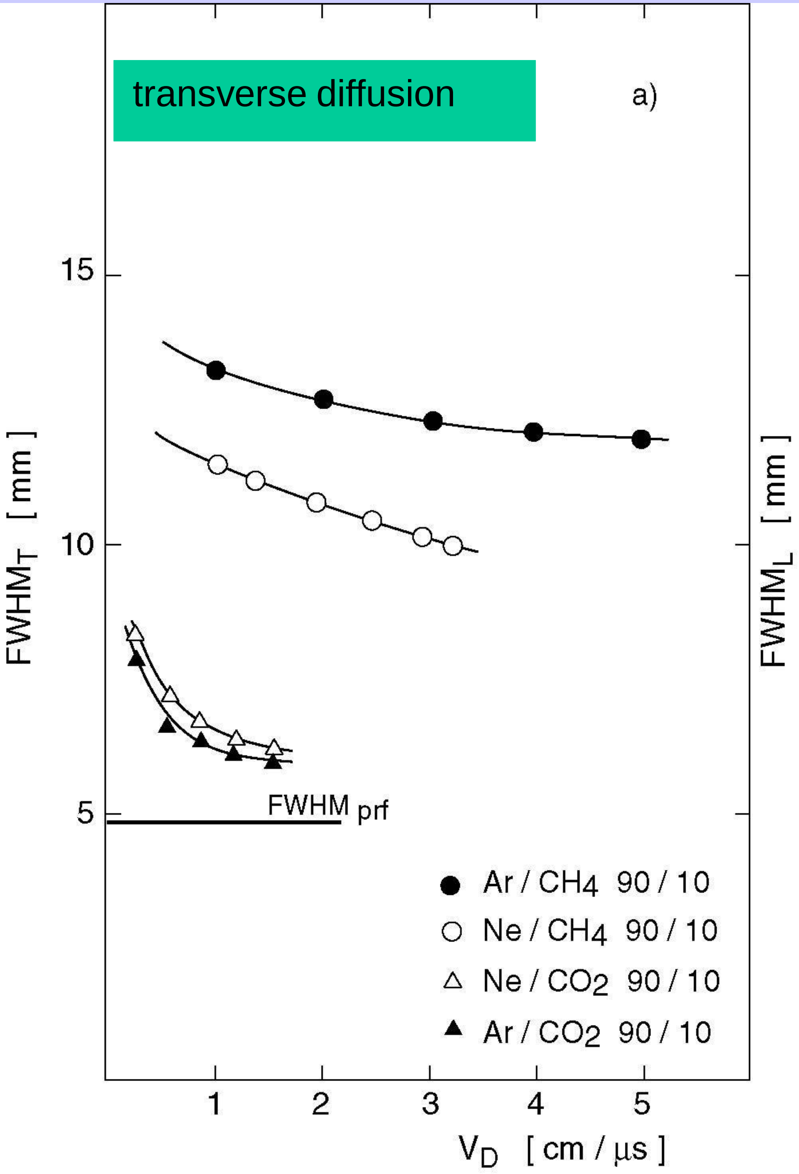
- How to reduce diffusion?
  1) Certain additions to the gas mixture (like e.g. CO_2) help reduce the diffusion.



Limitation 1: Diffusion (2)

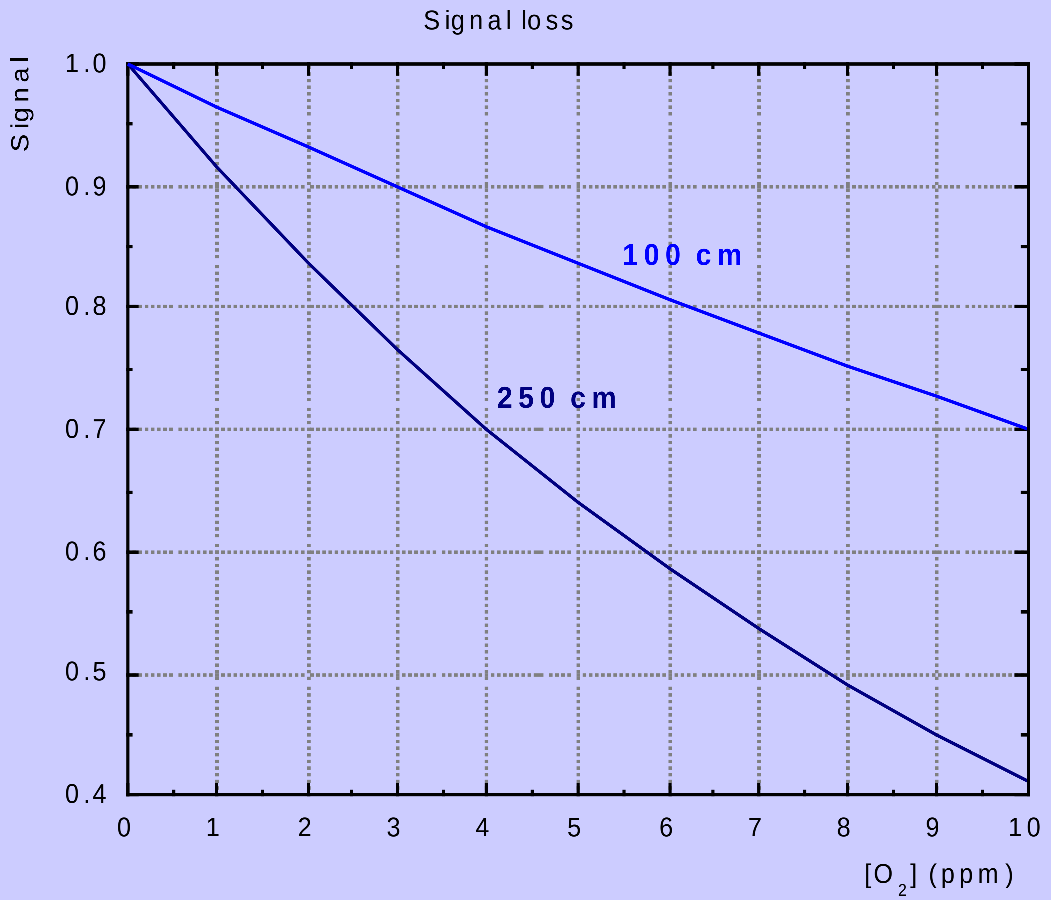
- How to reduce diffusion?
  1) Certain additions to the gas mixture (like e.g. CO_2) help reduce the diffusion.
  2) Assume *E||B and* $\omega\tau$ *>>1:* Transverse Diffusion is suppressed by a large factor:

$$D(B)/D(0) = \frac{1}{1+\omega^2\tau^2}$$



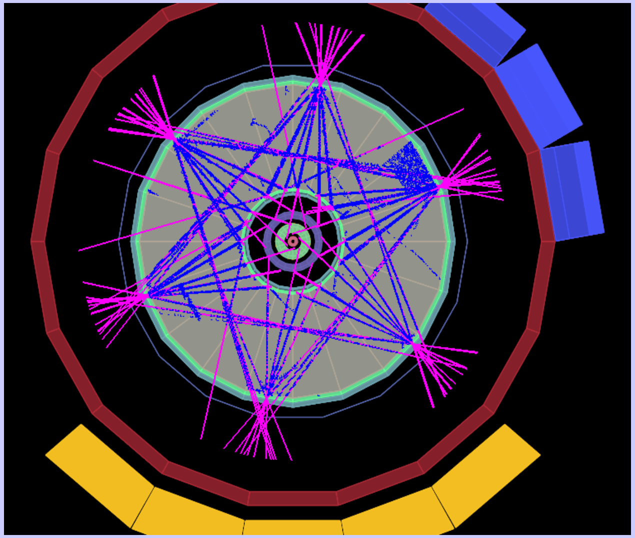
Limitation 2: Attachment

- The drifting electrons can be absorbed in the gas by the formation of negative ions.
- Need to keep O_2 content low!
- <1ppm of O_2 keeps signal loss below 10% for 250cm drift.



Limitation 3: ExB Effects

- *E*x*B* distortions arise from **nonparallel *E* and *B* fields**.
- It is difficult to build a very big detector (~5m) 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 *E*x*B* distortions.

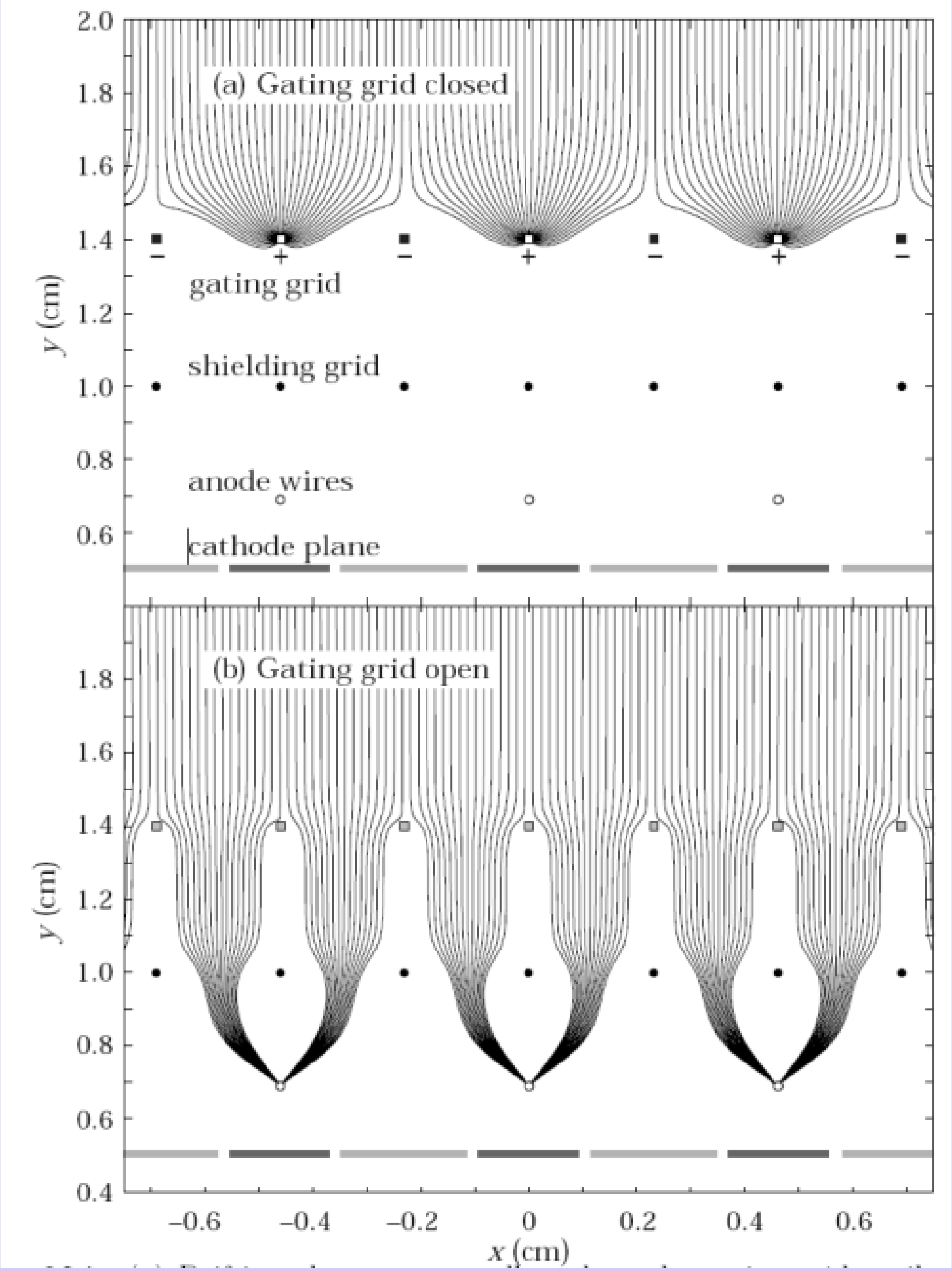


Limitation 4: Space Charge

- In high-rate environments charges distort the electric field.

Limitation 4: Space Charge

- In high-rate environments charges distort the electric drift field.
- The **gating grid**
  - allows electrons to enter anode region only for interesting events
  - and keeps ions produced in avalanches out of the drift region.



Particle Identification with TPCs

Particle Identification by dE/dx (1)

- Charged particles loose energy in the gas volume.

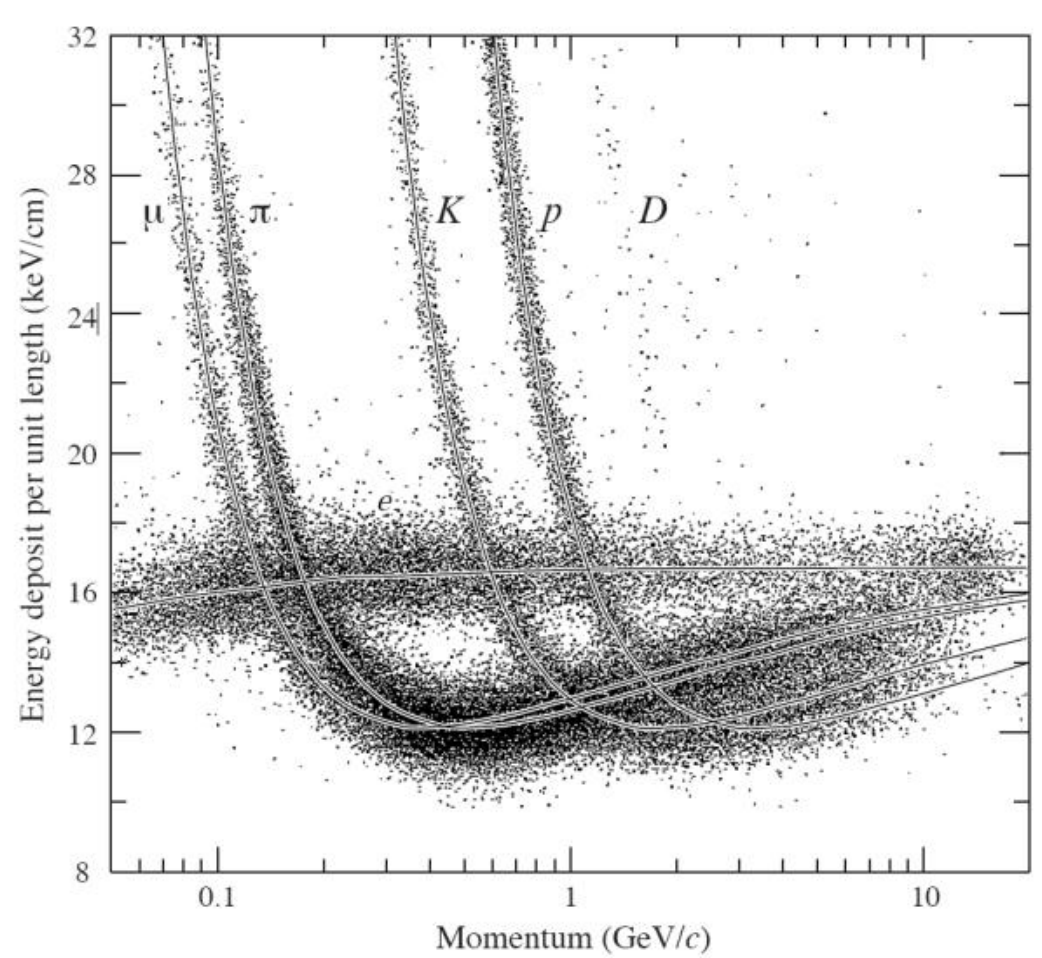
Energy loss (Bethe-Bloch)

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{2mv^2}{J(1-\beta^2)} - \beta^2 - \frac{\delta}{2} \right]$$

m	mass of electron
z, v	charge and velocity of incident particle
J	mean ionization energy
δ	density effect term

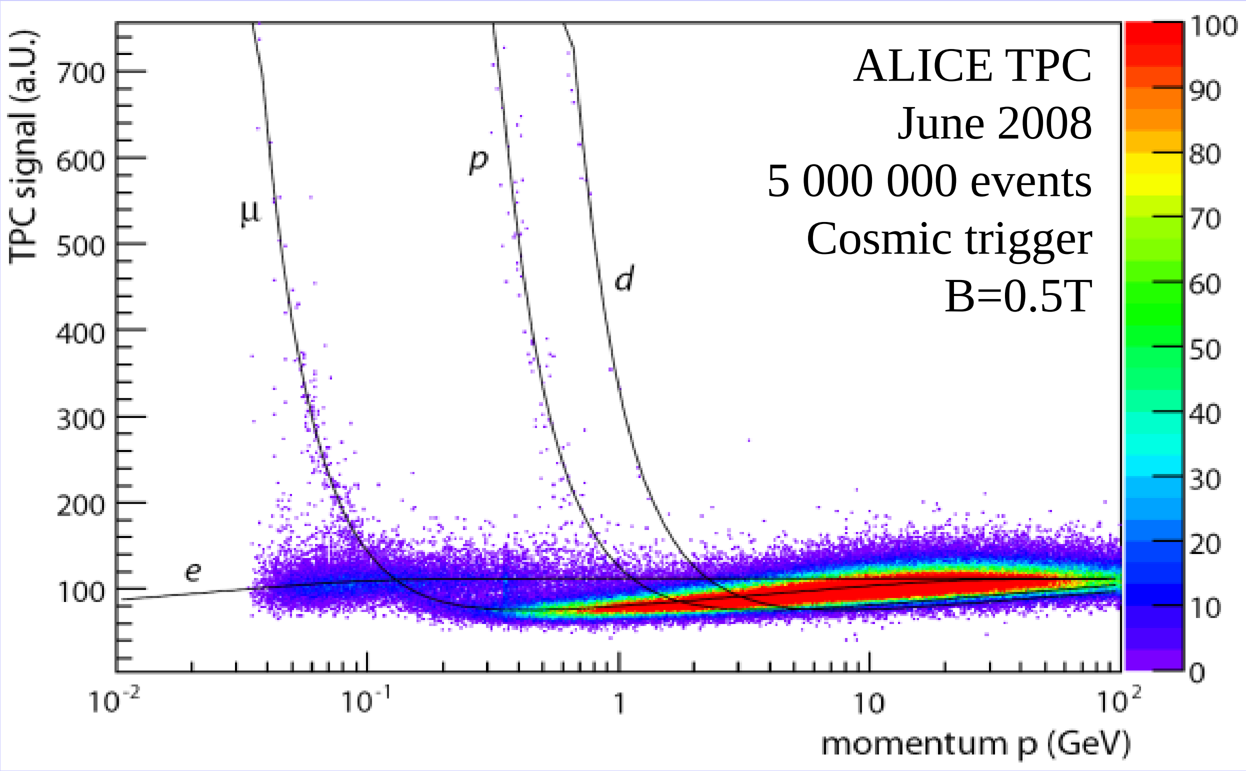
Particle Identification by dE/dx (2)

- Energy loss distributions as function of particle momentum.
- Different particle species can be identified in certain regions.
- Image: Measurements with PEP4 TPC.



Particle Identification by dE/dx (3)

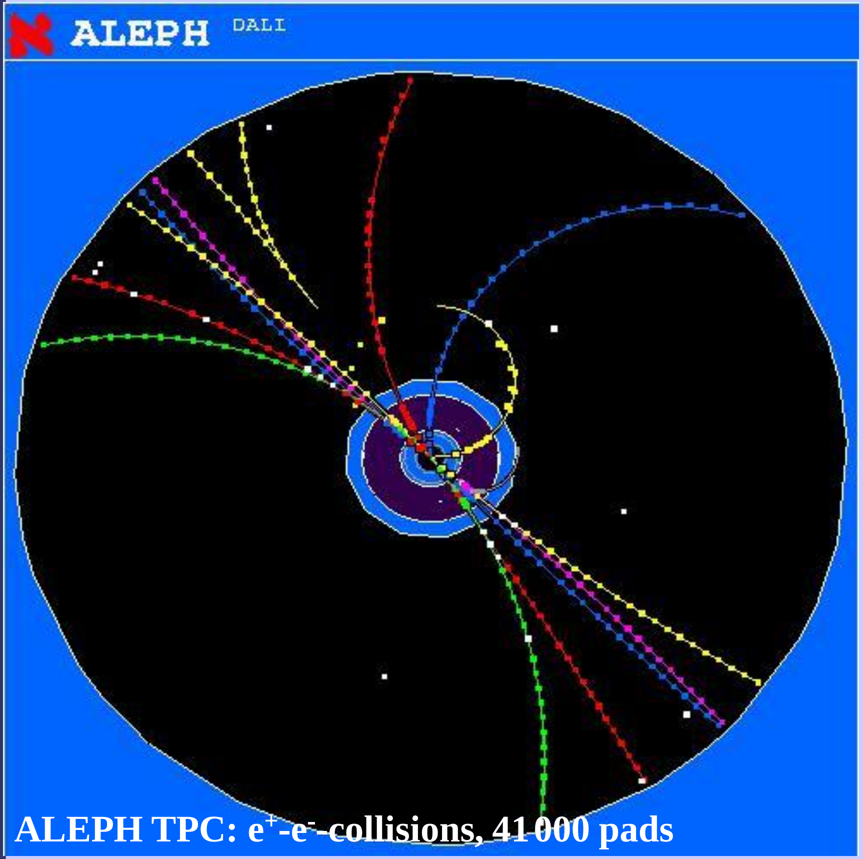
- Energy loss distributions as function of particle momentum.
- For ALICE TPC we have so far only cosmic particles that make it through ~50m of rock (muons) and some secondary electrons and protons.



TPCs for Heavy Ion Experiments

TPCs for Heavy Ion Experiments

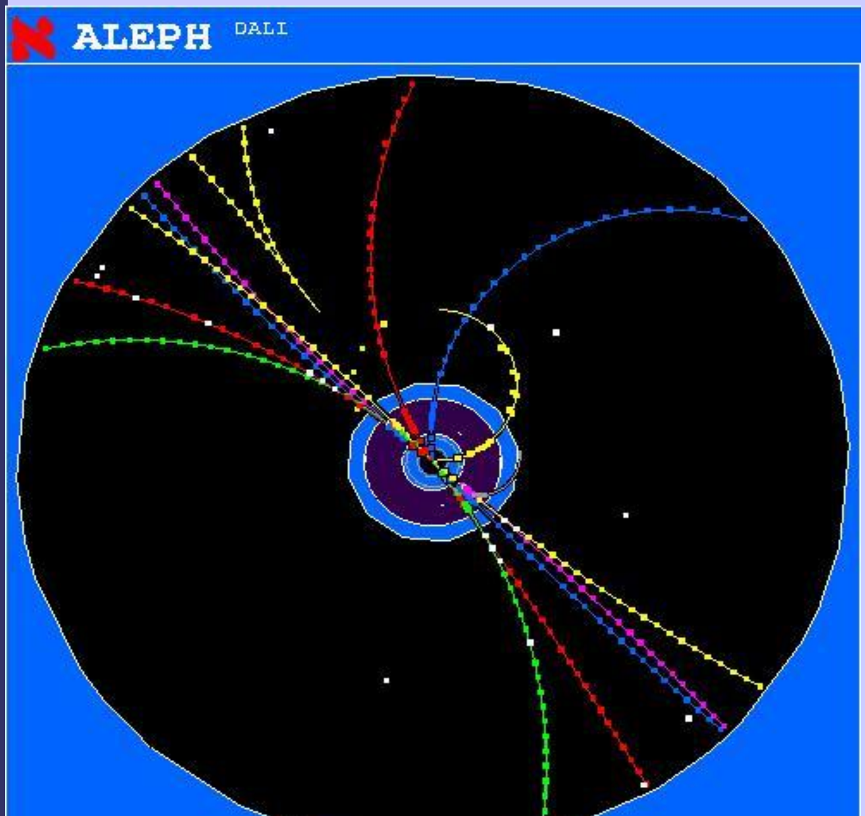
- Events in **e^+-e^-** collisions have rather low densities of charged tracks.



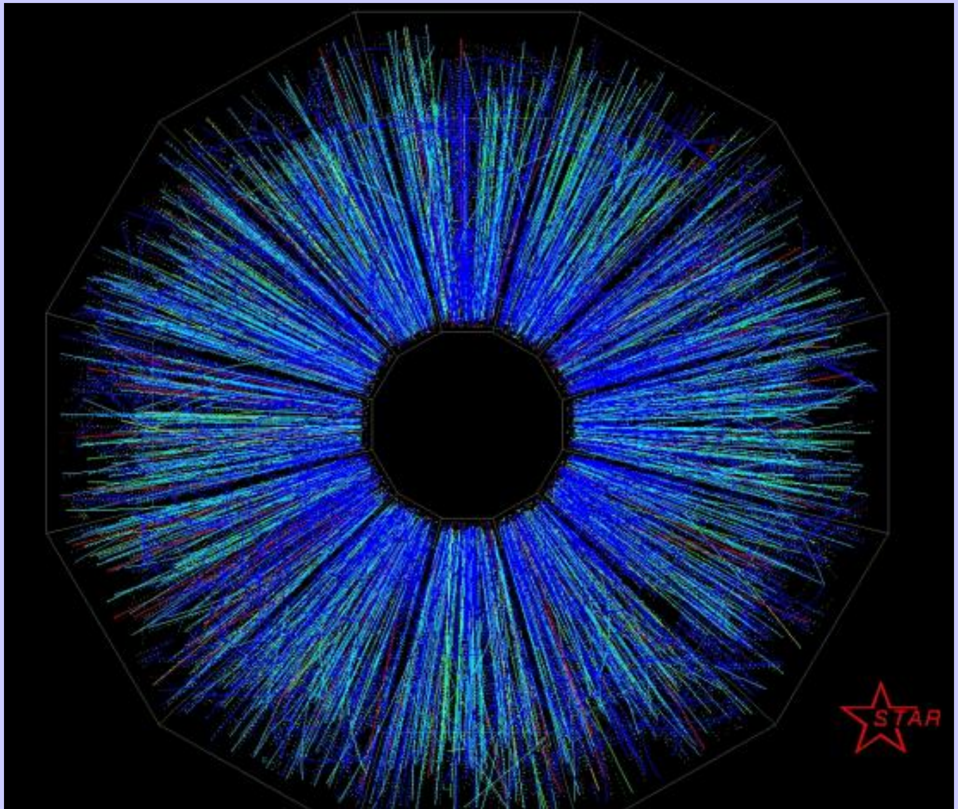
ALEPH TPC: e^+-e^--collisions, 41 000 pads

TPCs for Heavy Ion Experiments

- Events in **e^+-e^-** collisions have rather low densities of charged tracks.
- In heavy ion collisions we need much smaller pad sizes and a large number of pads (ALICE TPC: 570 000).



ALEPH TPC: e^+-e^--collisions, 41 000 pads

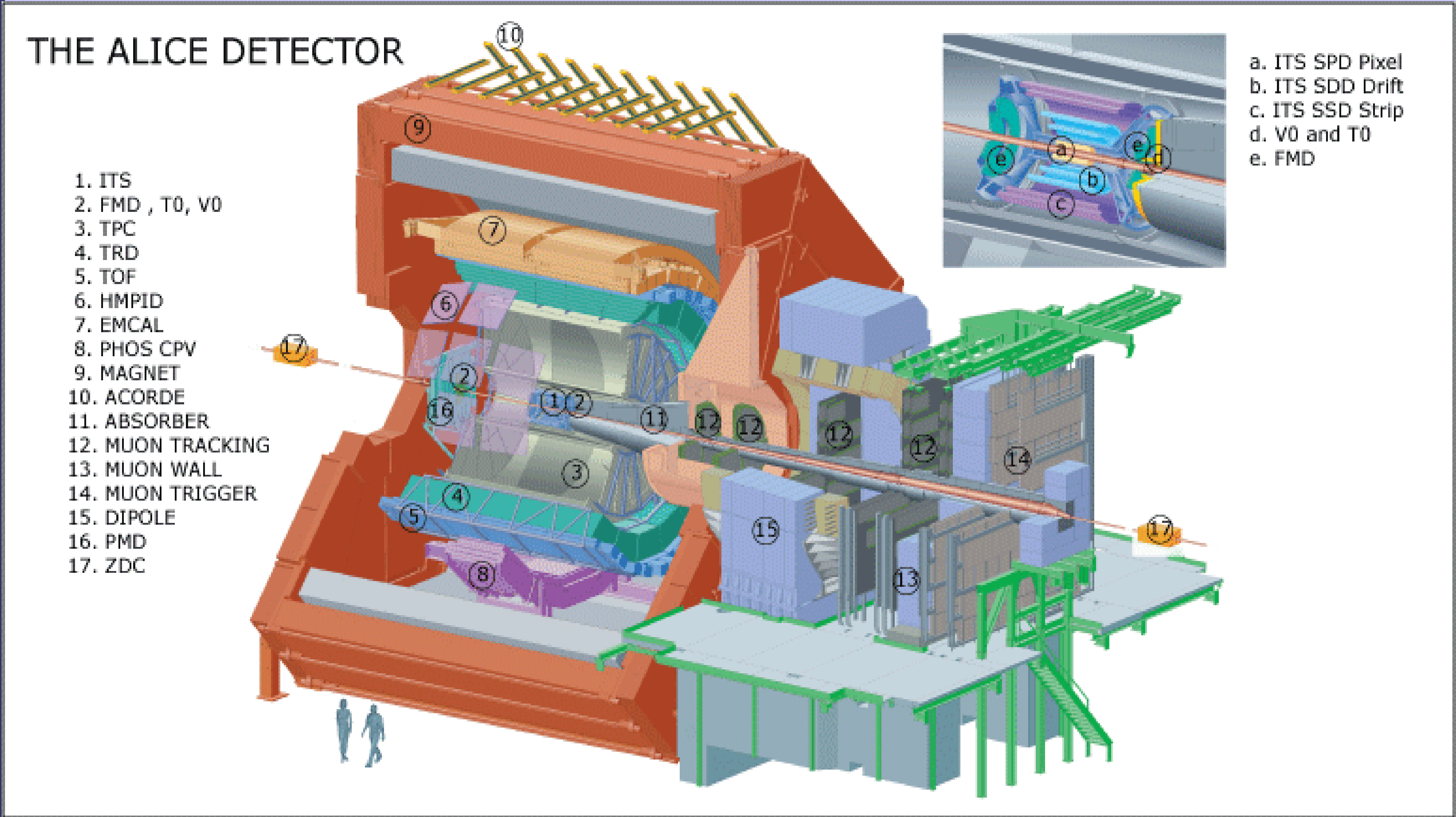


STAR TPC: Au-Au collisions, 137 000 pads

The ALICE TPC

A rapid 3-dimensional tracking device for ultra-high multiplicity events.

The ALICE Experiment

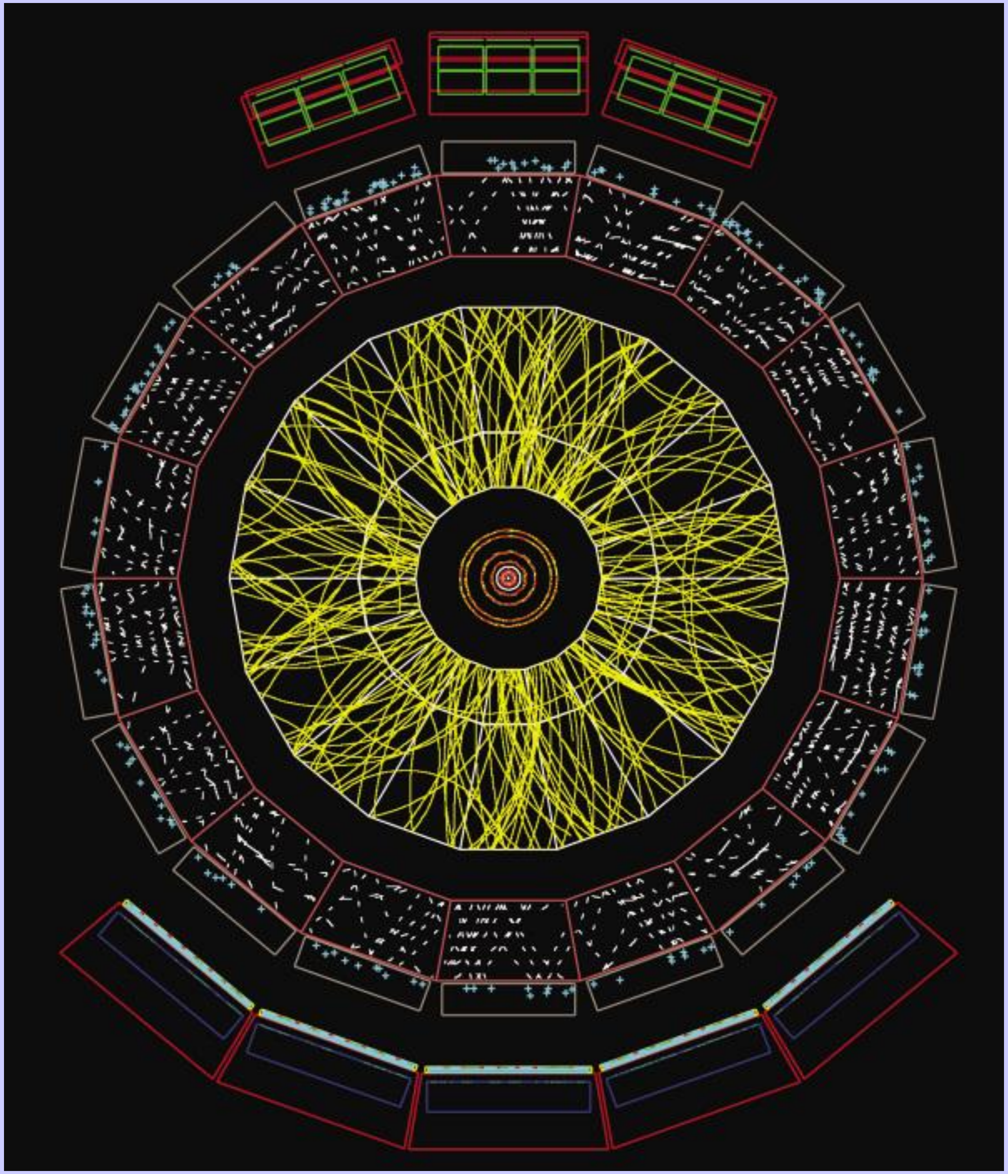


A Large Ion Collider Experiment

- Search for evidence of quark-gluon plasma in Pb-Pb collisions at the LHC (5.5 TeV per nucleon pair).
- Study properties of p-p collisions (14 TeV).

- Trajectories of thousands of particles (~20 000) produced in central collisions have to be measured and the particles have to be identified.
- To serve these tasks, the largest TPC in the world was built.

Pb-Pb collisions in ALICE



- Pb-Pb collisions at 5.5TeV per nucleon pair.
- Simulated event with **cut in theta** 60-62 deg.
- If all tracks would be shown, the image would be yellow ...

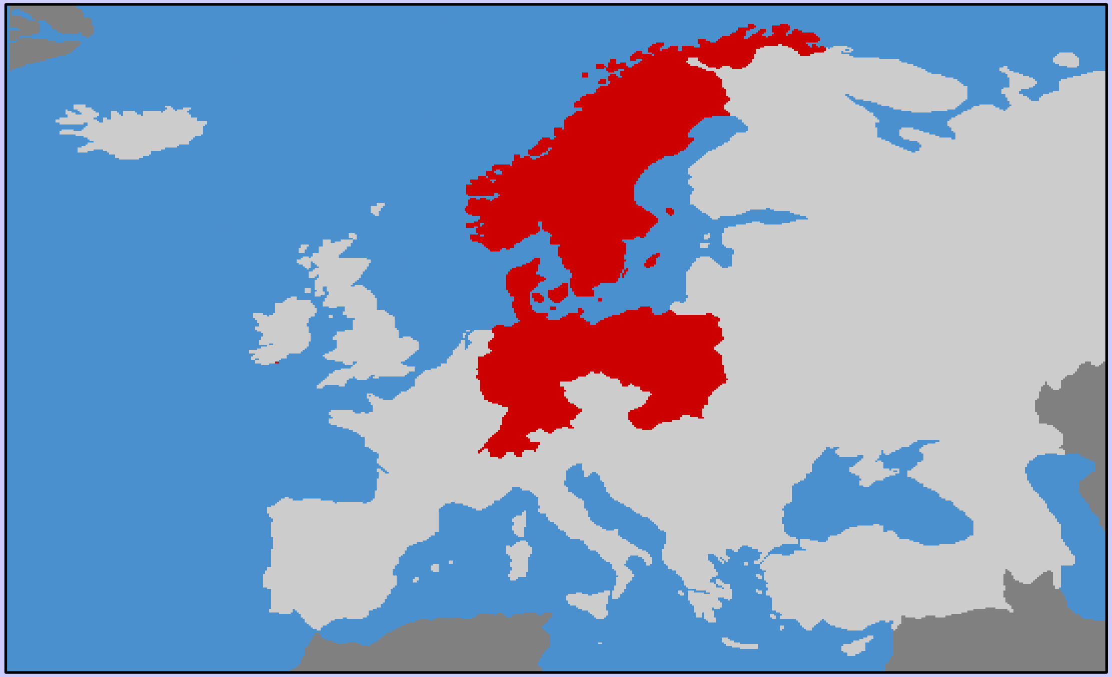
The ALICE TPC: Tasks

- Track finding,
- momentum measurement and
- particle identification

- at transverse momenta $0.1 < p_T < 100\,GeV/c$.

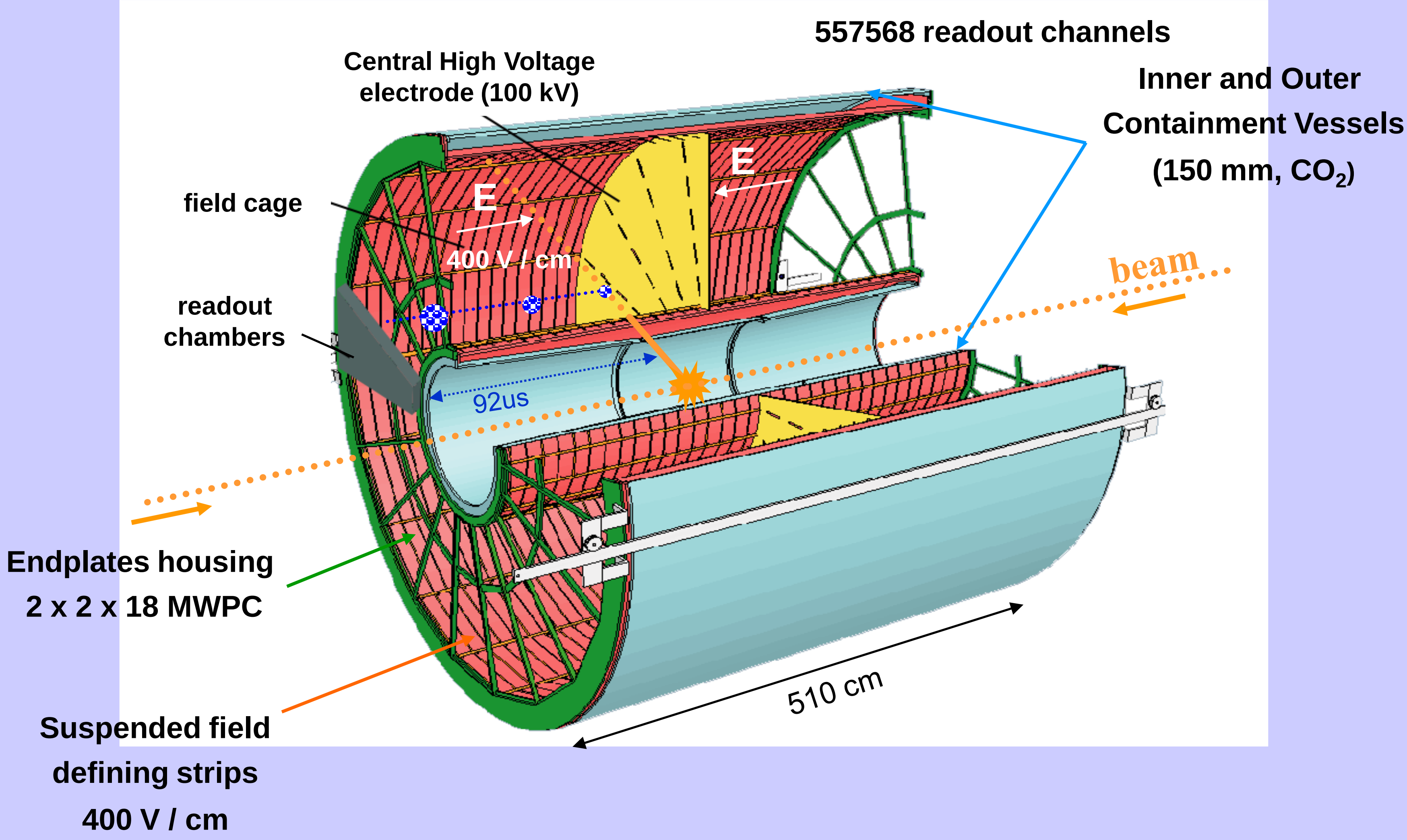
- Rate capability:
  - 200 Hz for central Pb-Pb collsions and
  - 1 kHz for p-p collisions.

The ALICE TPC Collaboration

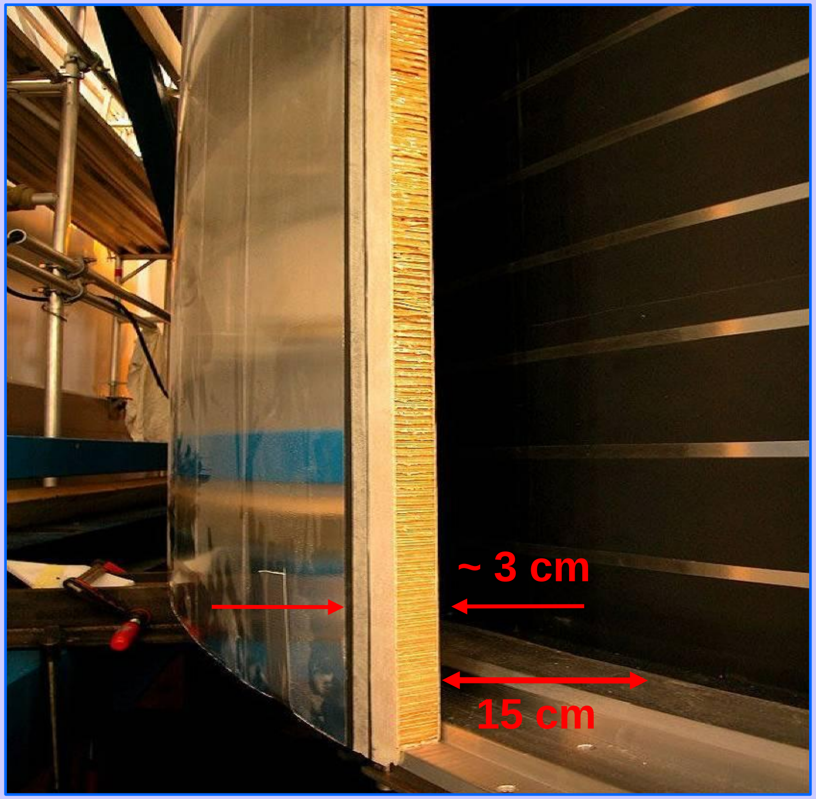


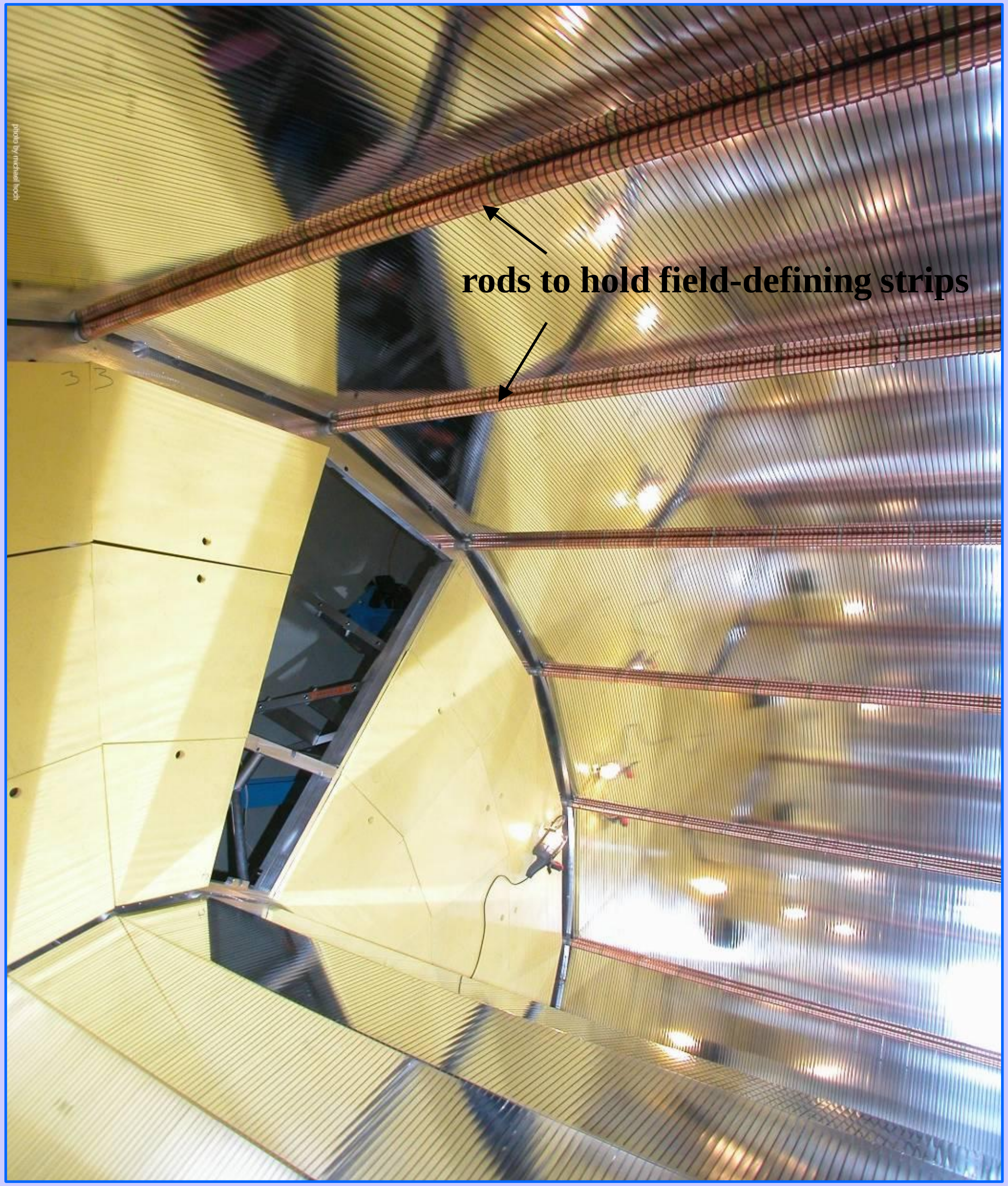
Bergen	**Bratislava**
CERN	**Copenhagen**
Darmstadt TU	**Frankfurt**
GSI Darmstadt	**Heidelberg KIP**
Heidelberg PI	**Krakow**
Lund	

ALICE TPC: Overview



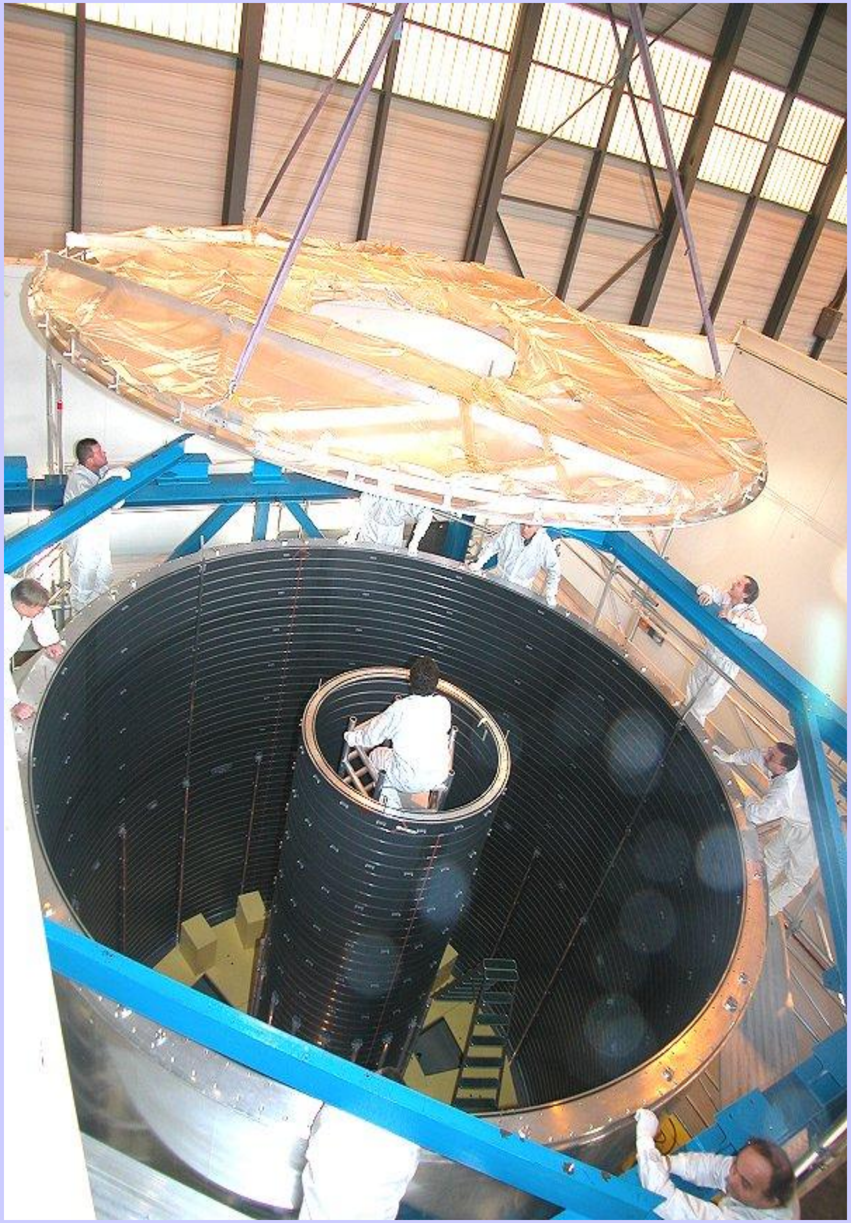
ALICE TPC: Low-Mass Field Cage

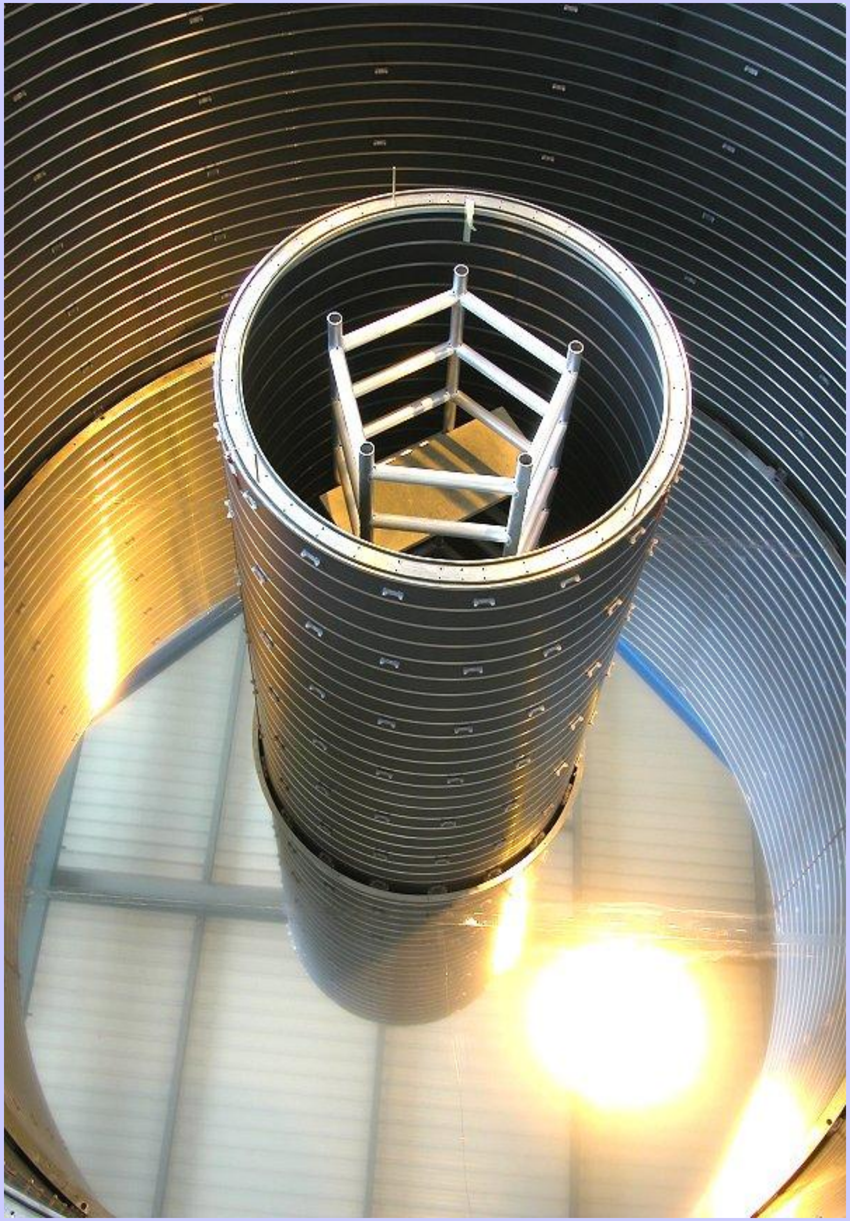




- Light composite materials for all four cylinders.

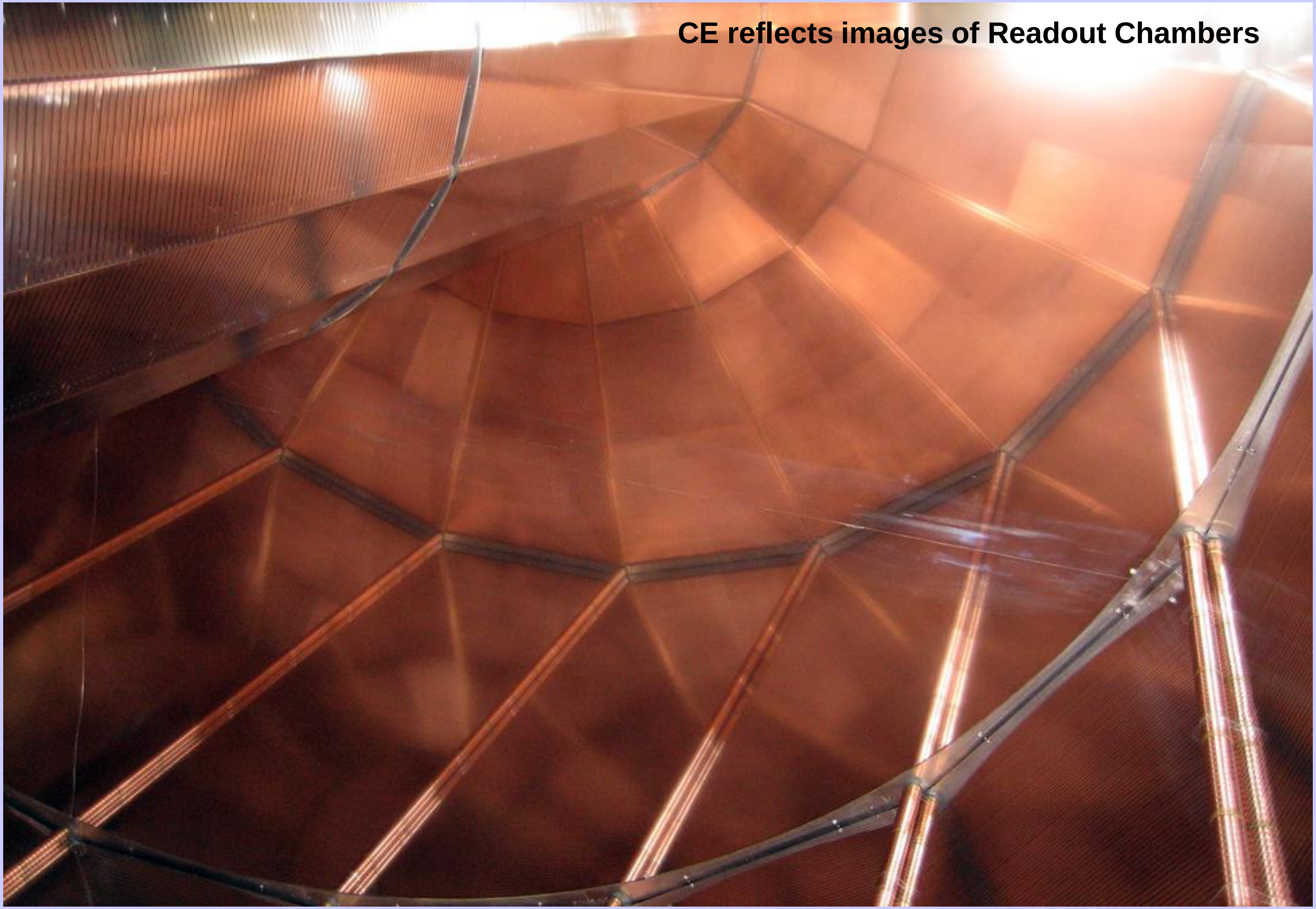
Field Cage Construction (2002-04)





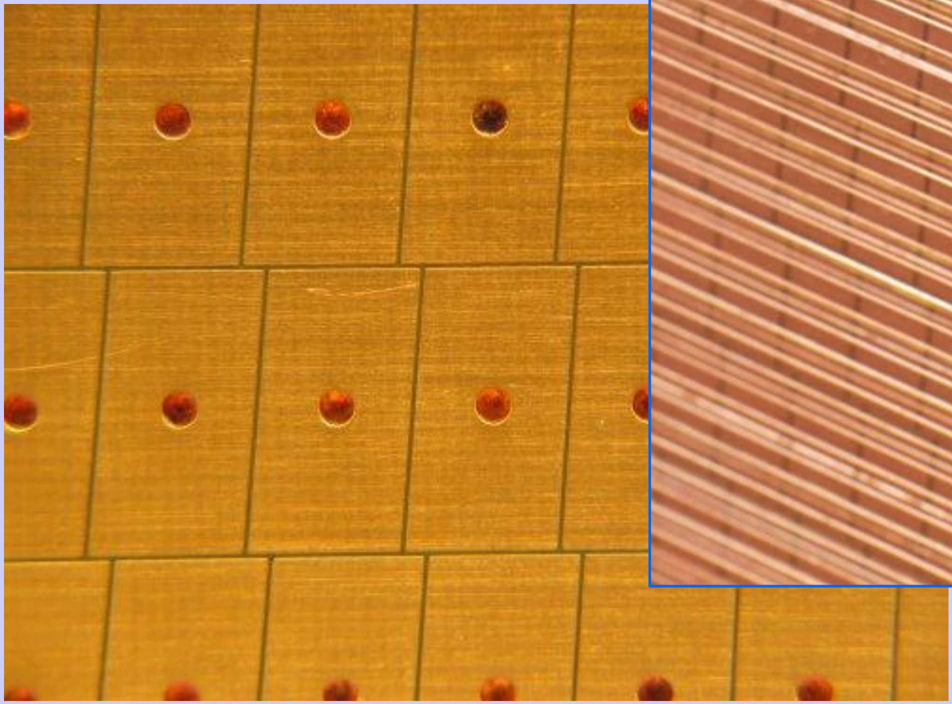
ALICE TPC: Central Drift Electrode

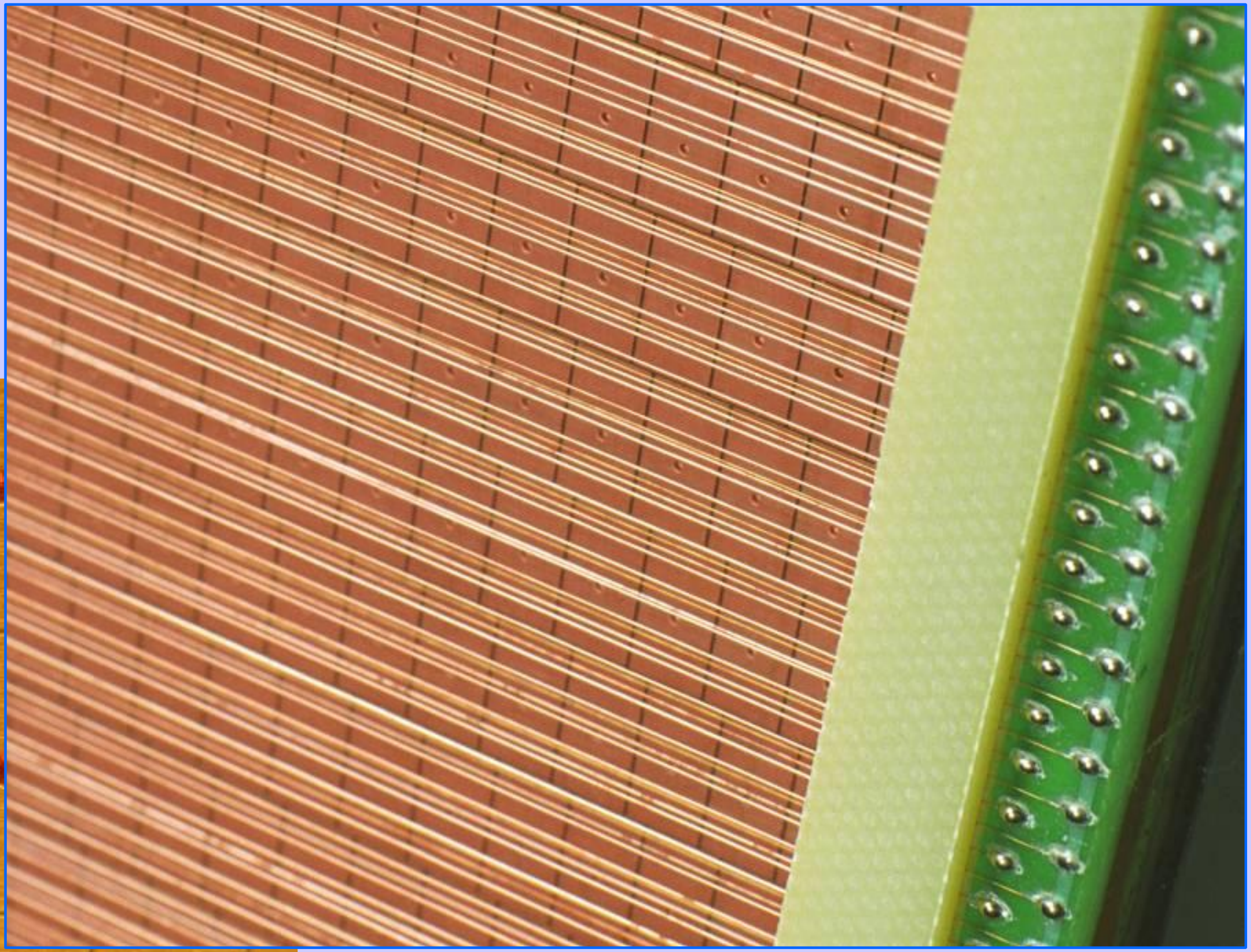
- Aluminized mylar on 100kV potential.



ALICE TPC: Read Out Chambers

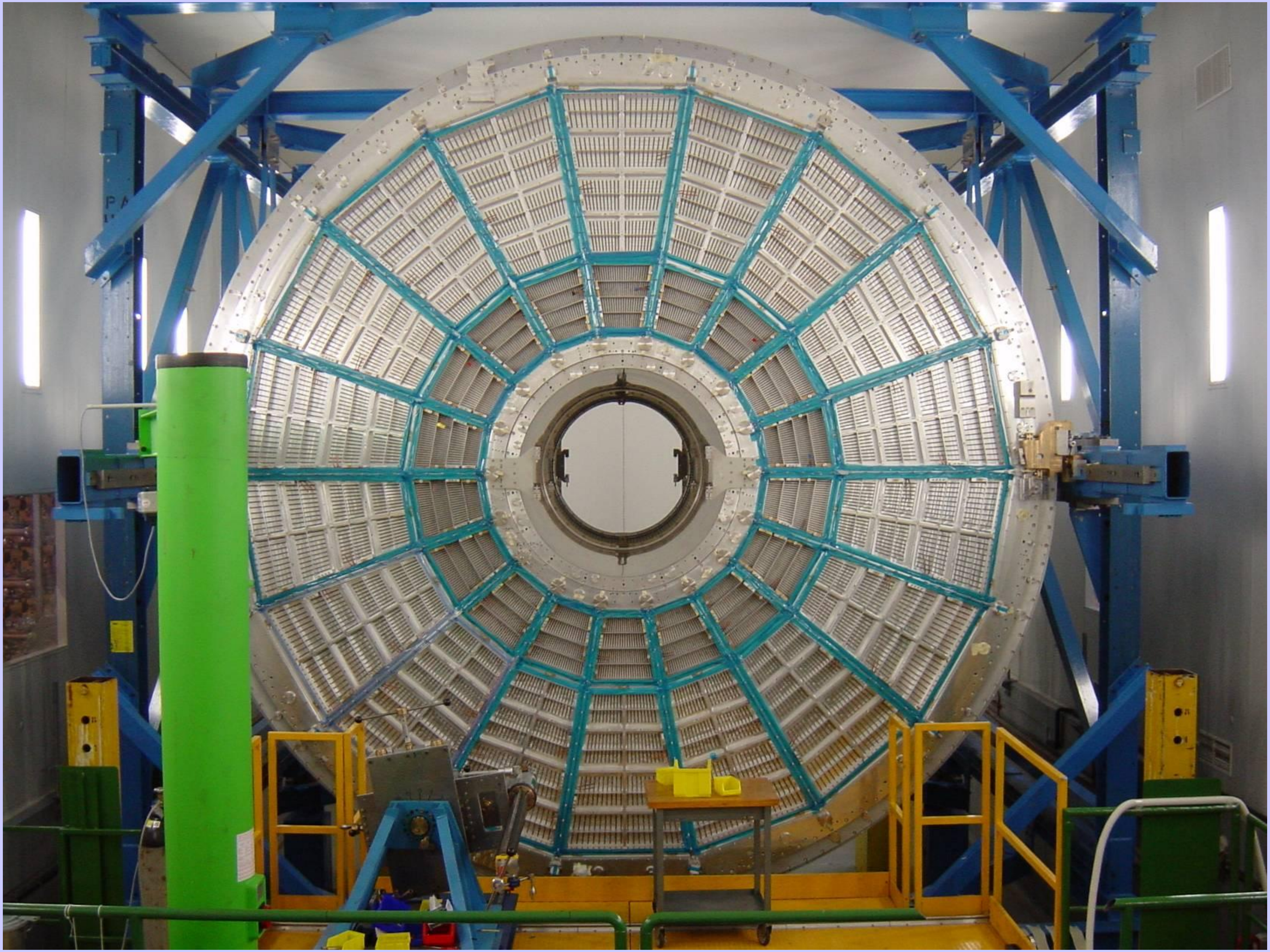
- MWPCs with 2 (3)mm wire spacing,
- 3 different pad sizes.





Read Out Chamber Installation (2005)

Completion ROC Installation (2005)



The gas mixture for the ALICE TPC

ALICE TPC - Choosing a Gas

- Basic components could be Ar, Ne, CO_2, CH_4, N_2.
- Different (competing) requirements:
  - Low **multiple scattering** ($\Rightarrow$ low Z),
  - Low **gas gain** ($\Rightarrow$ high primary ionisation $\Rightarrow$ high Z),
  - Low space charge distortions ($\Rightarrow$ low **primary ionisation** $\Rightarrow$ low Z),
  - Low event overlap ($\Rightarrow$ high **drift velocity**),
  - Low **sensitivity to variations** in gas composition or ambient conditions.

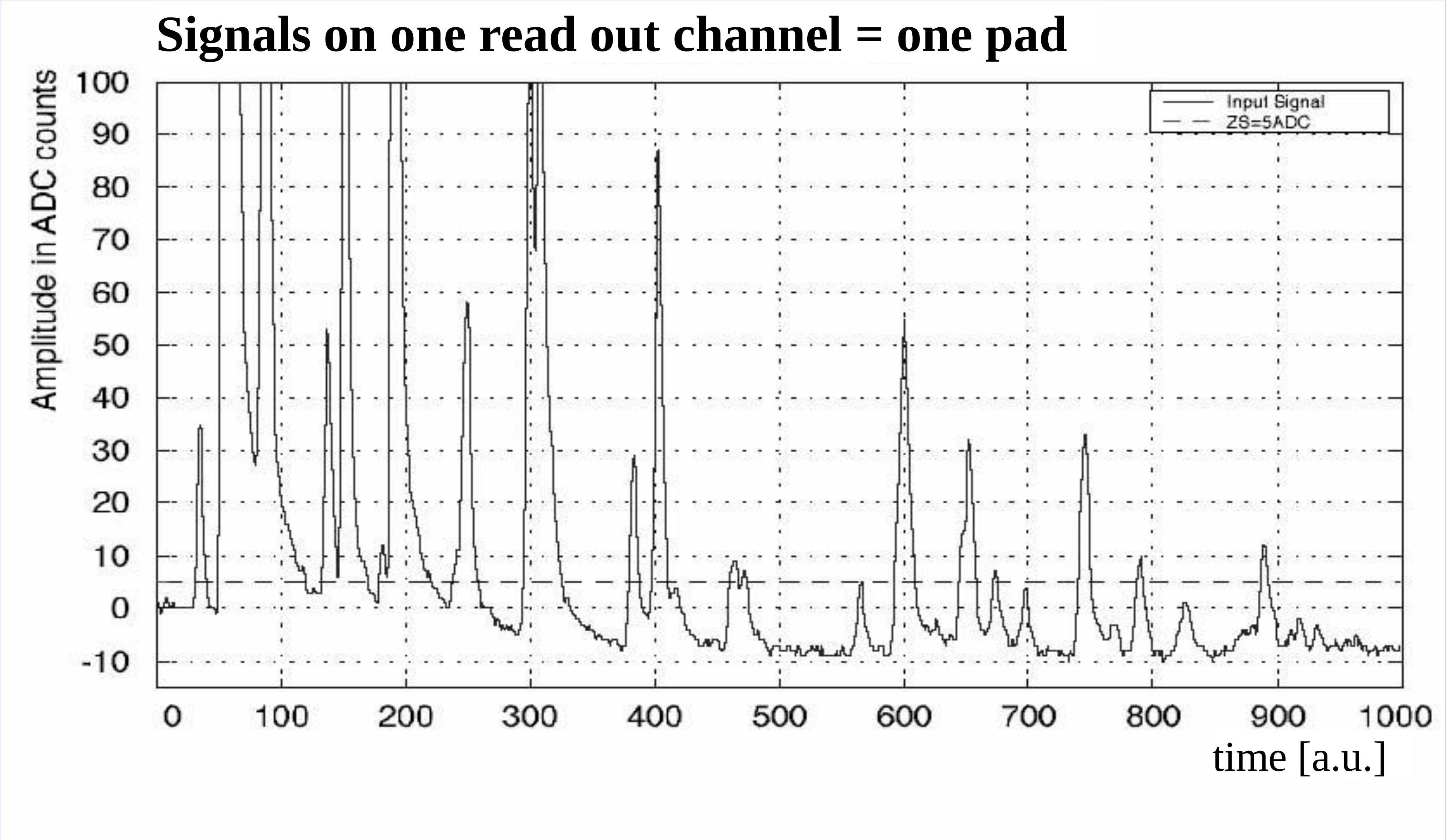
ALICE TPC Gas: Ne-CO_2-N_2

- ALICE TPC uses **Ne-CO_2-N_2** [90%-10%-5%].
- **Advantage**: Low diffusion, fast drift, low space charge by primary ionisation.
- **Drawback**: High gain needed, sensitive to variations of pressure, temperature and to exact composition;
- But: Addition of N_2 reduces this sensitivity.

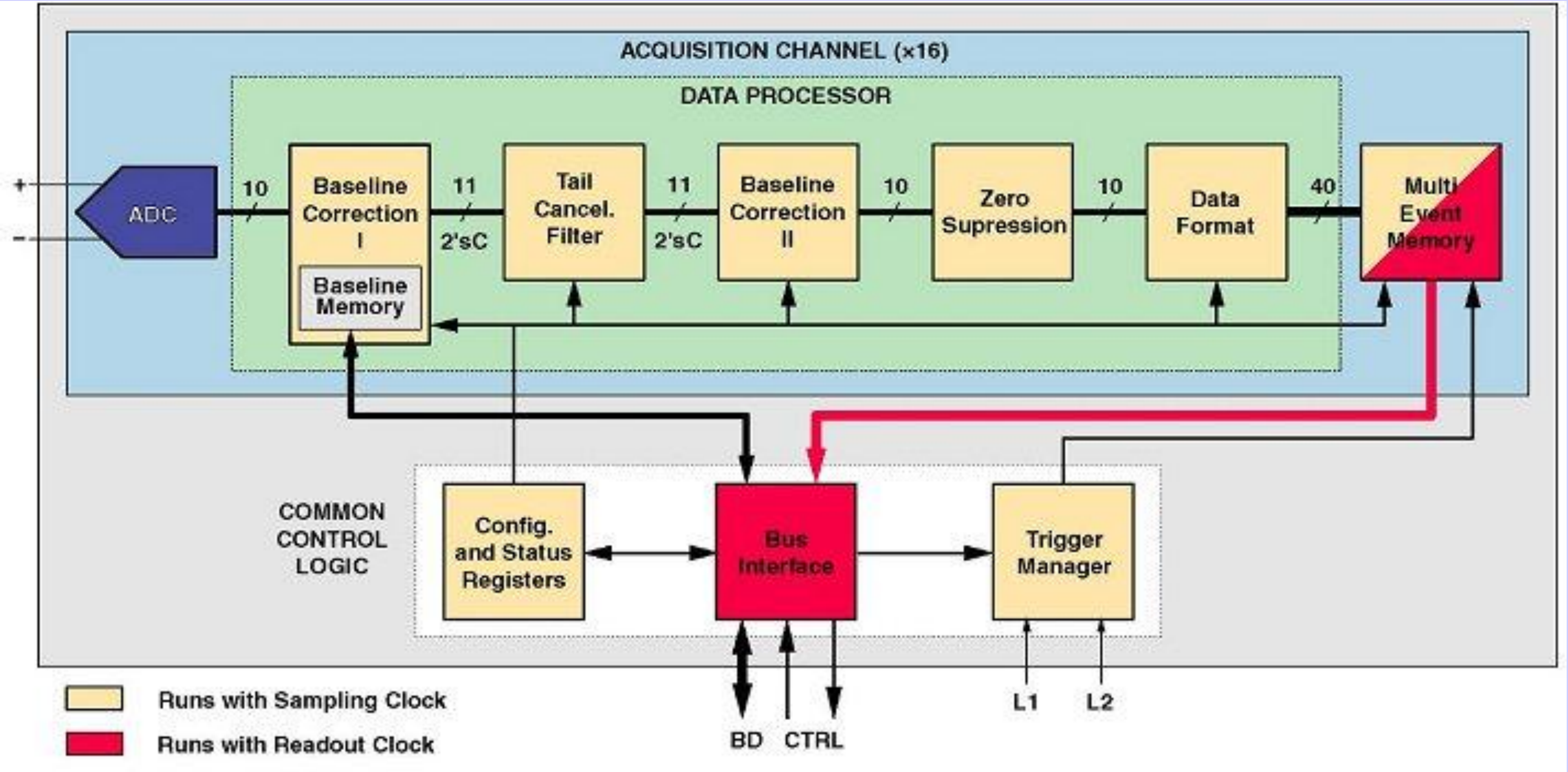
The ALICE TPC Read Out Electronics

ALICE TPC Electronics (1)

- In Pb-Pb collisions the high occupancy (many consecutive signals per read out pad) is challenging.



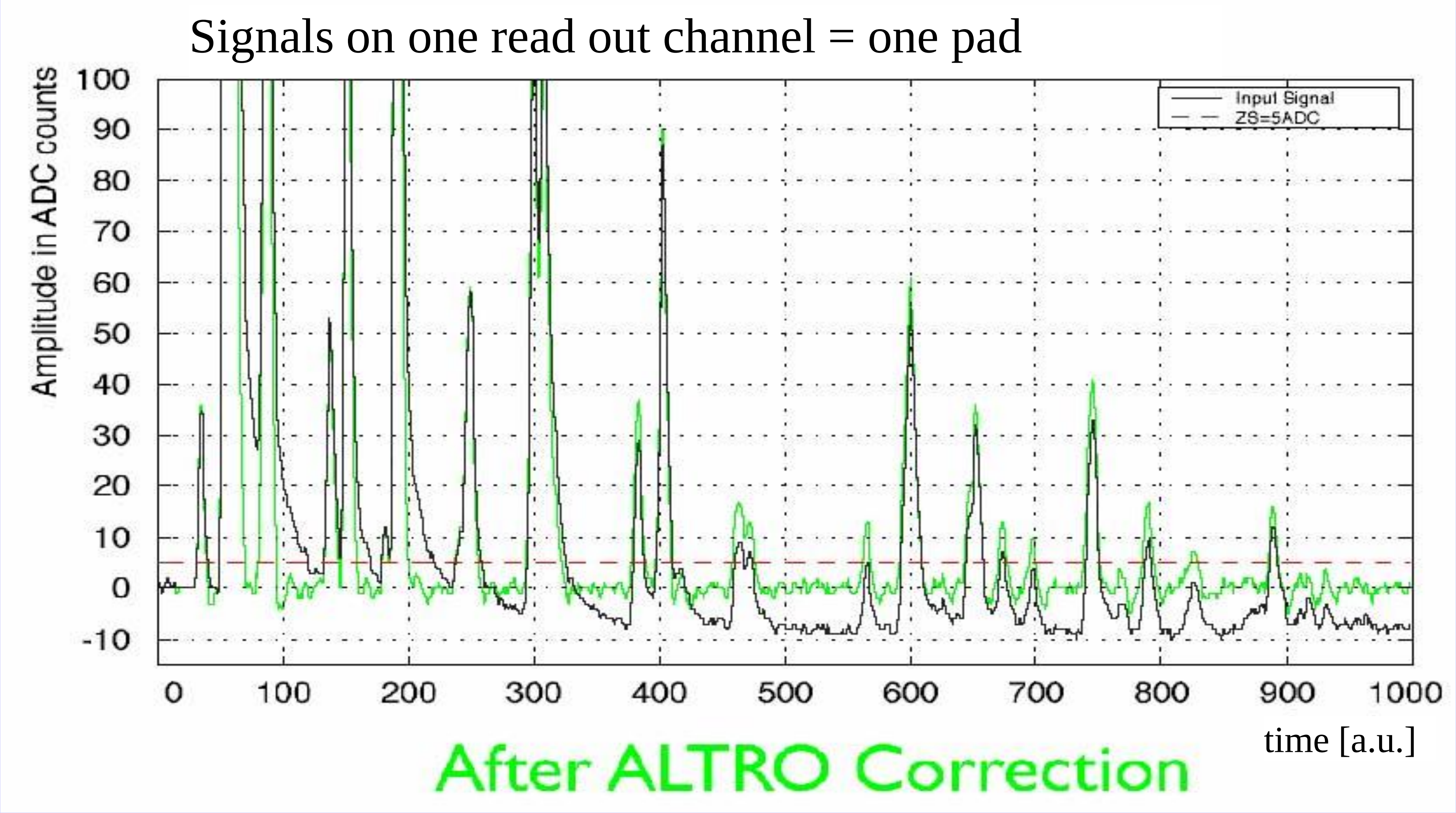
ALICE TPC Electronics (2)



- ALICE TPC **R**ead **O**ut Chip (**ALTRO**):
  - 2 baseline correction circuits, Signal tail cancellation and Zero Supression (to reduce data size save only interesting signals) for 16 channels.

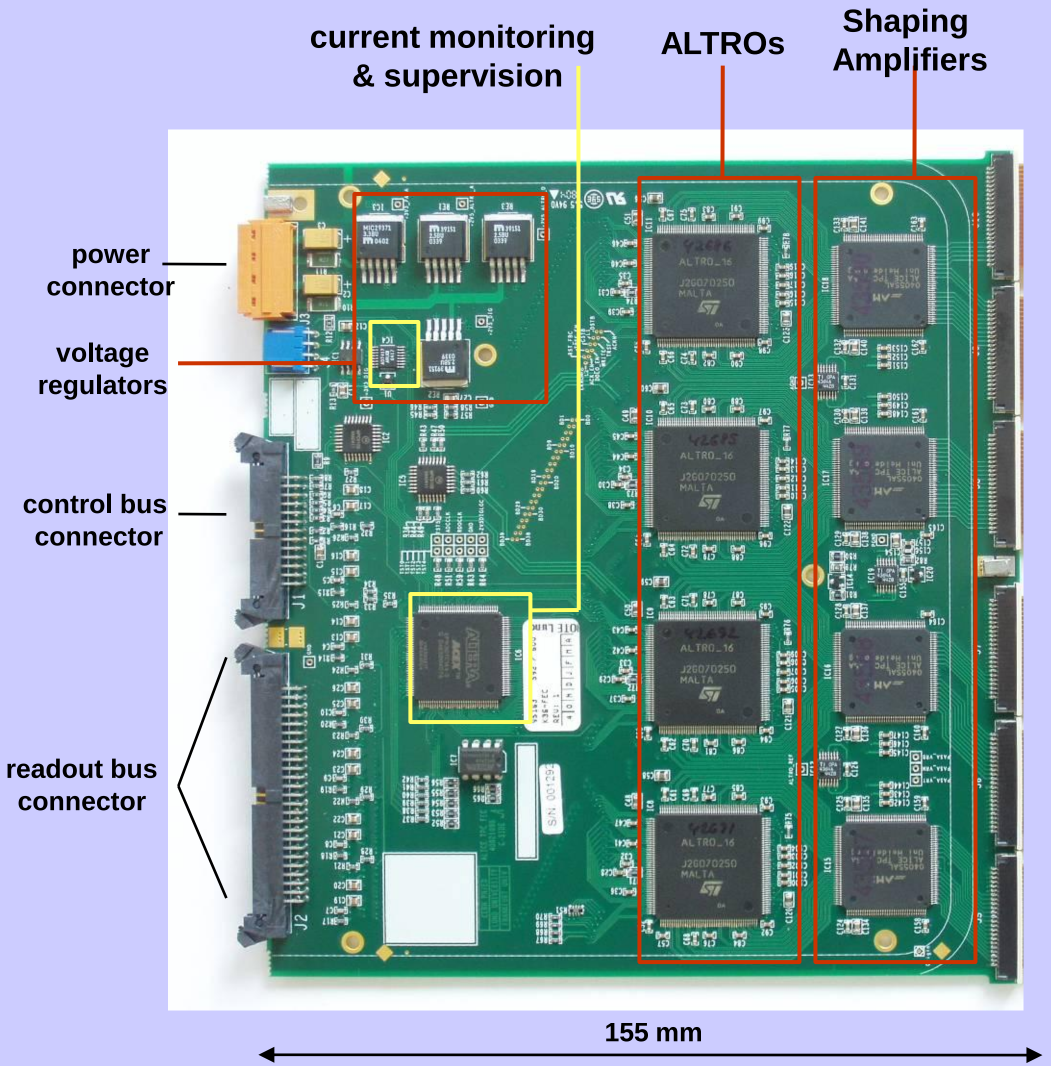
ALICE TPC Electronics (3)

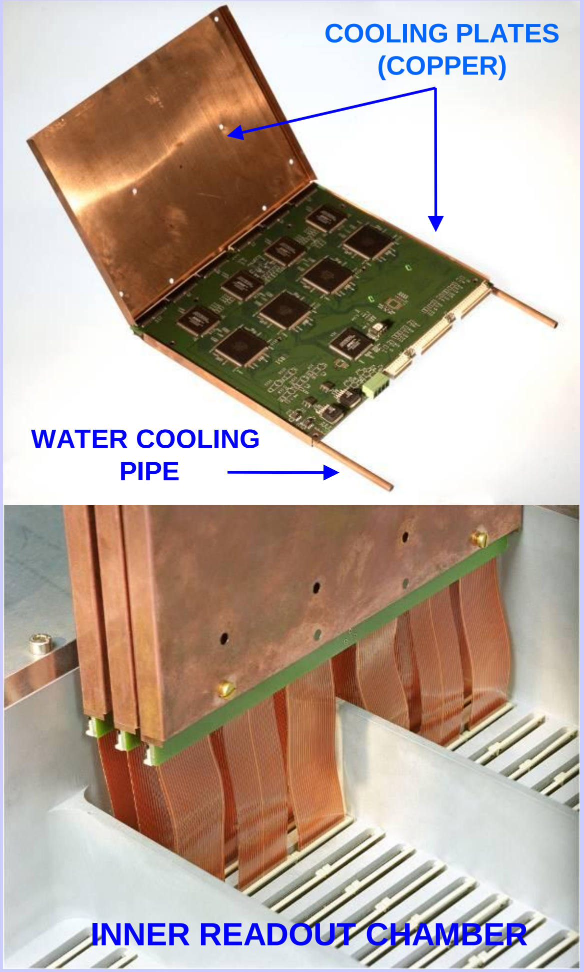
- After signal correction in the ALTRO the baseline is nicely restored.



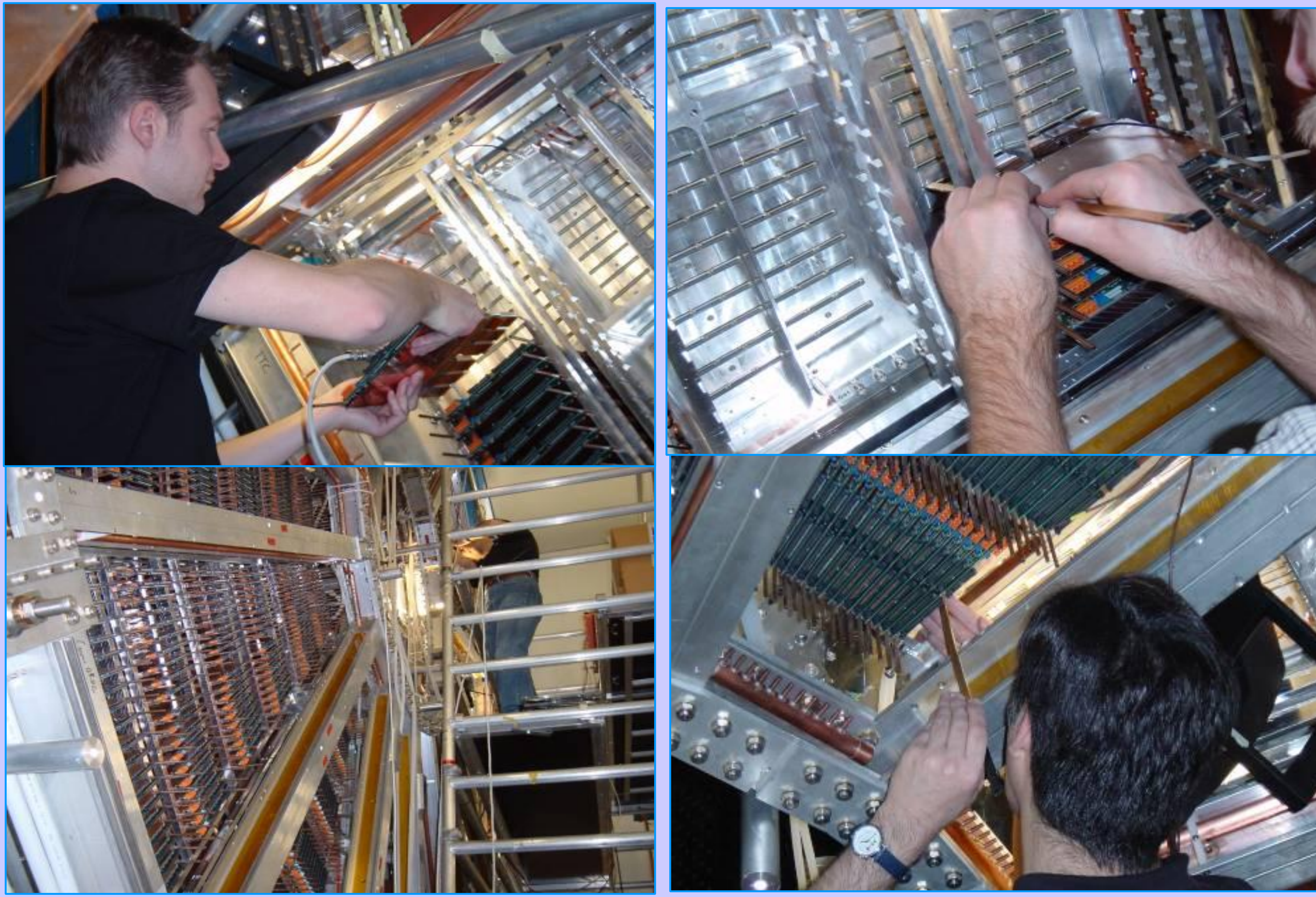
ALICE TPC Electronics (4)

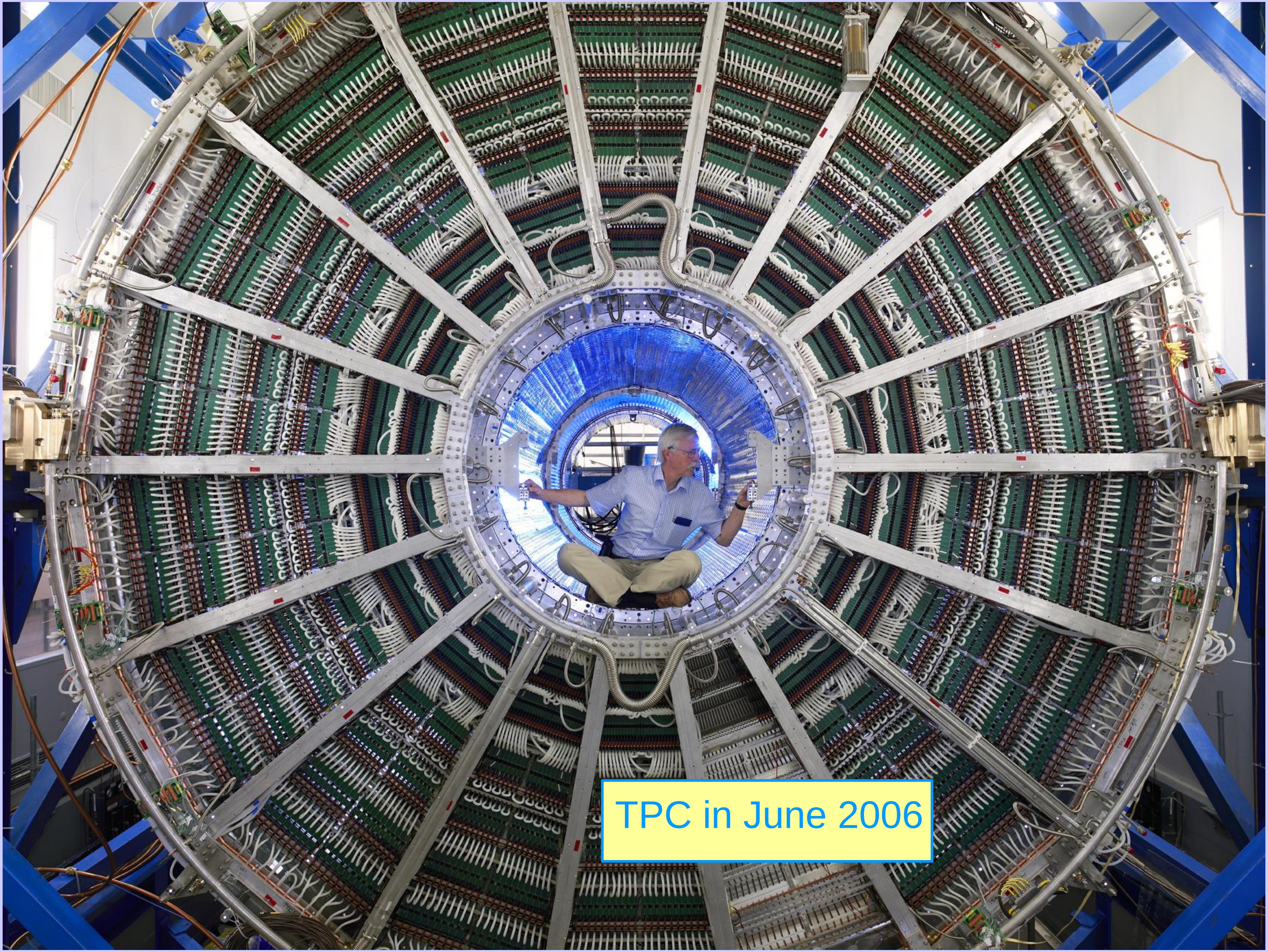
- Front End Cards hold 8 ALTRO chips each.
- 128 read out channels per FEC.





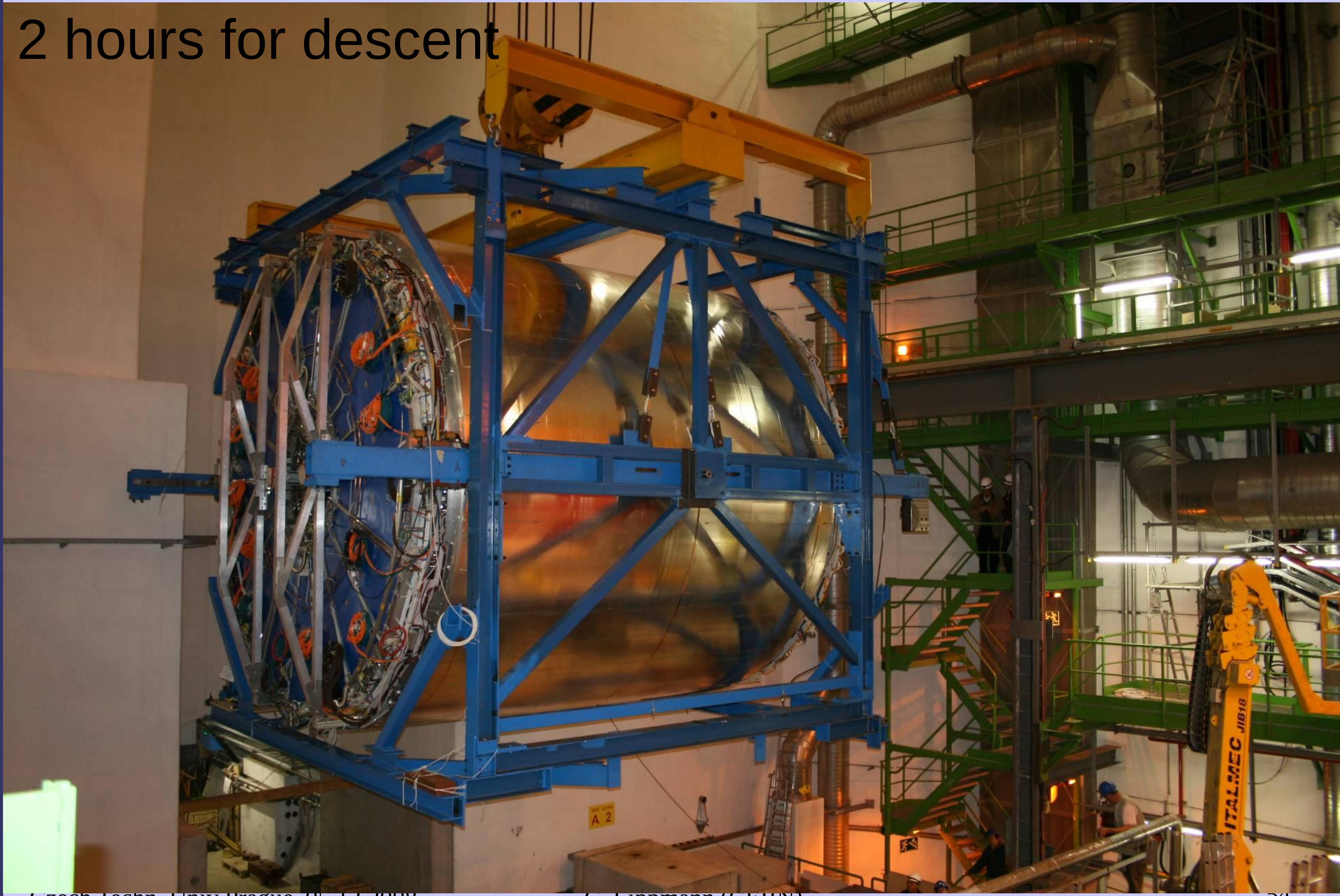
Install. of Read Out Electronics (2006)



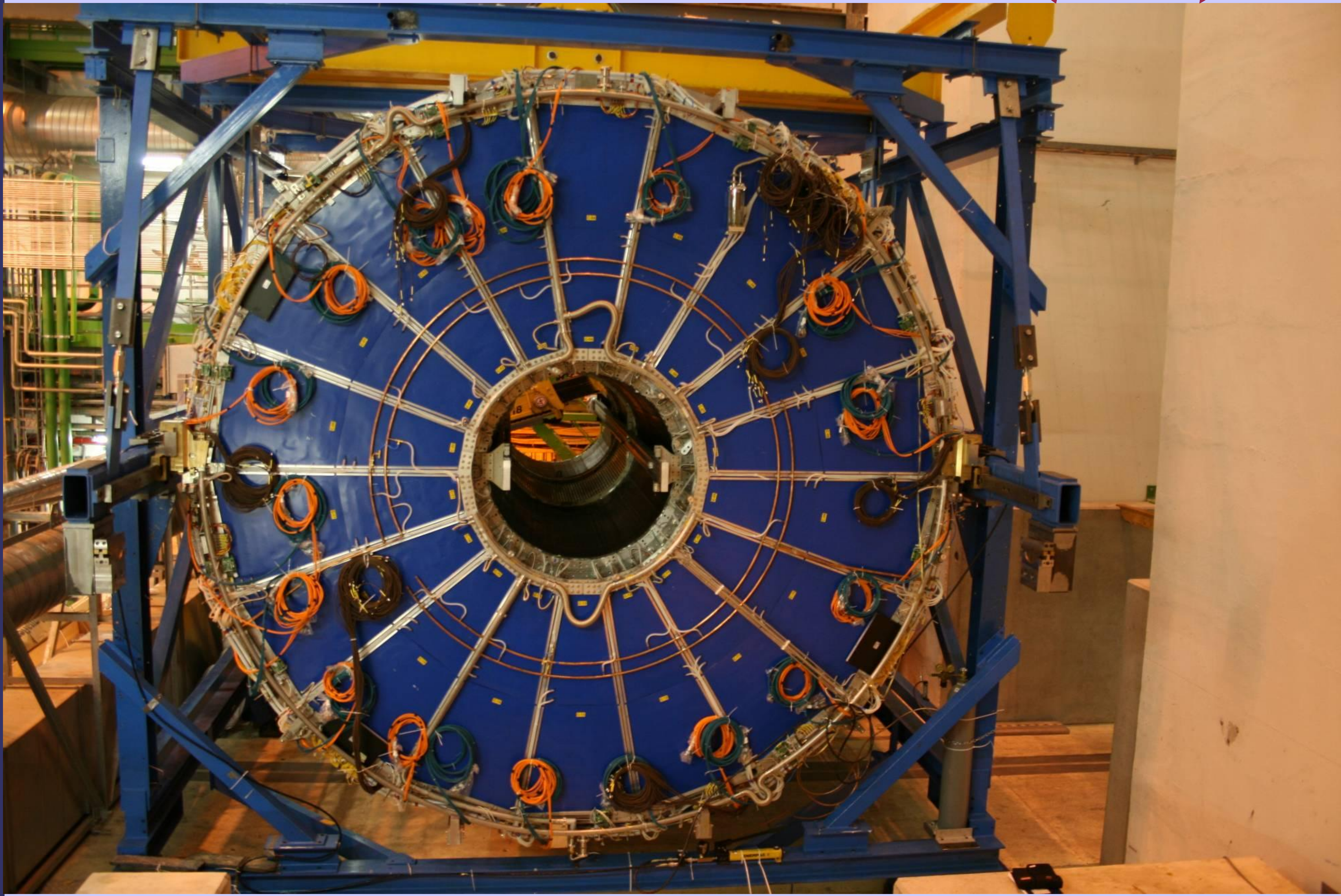

TPC in June 2006

Descent of the TPC into Cavern (2007)

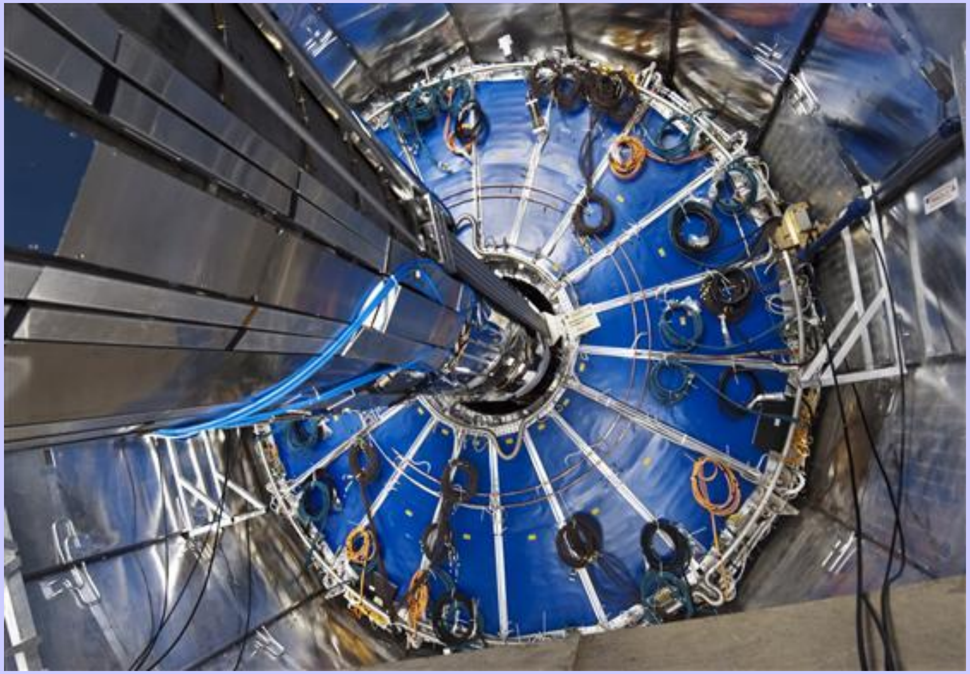
2 hours for descent

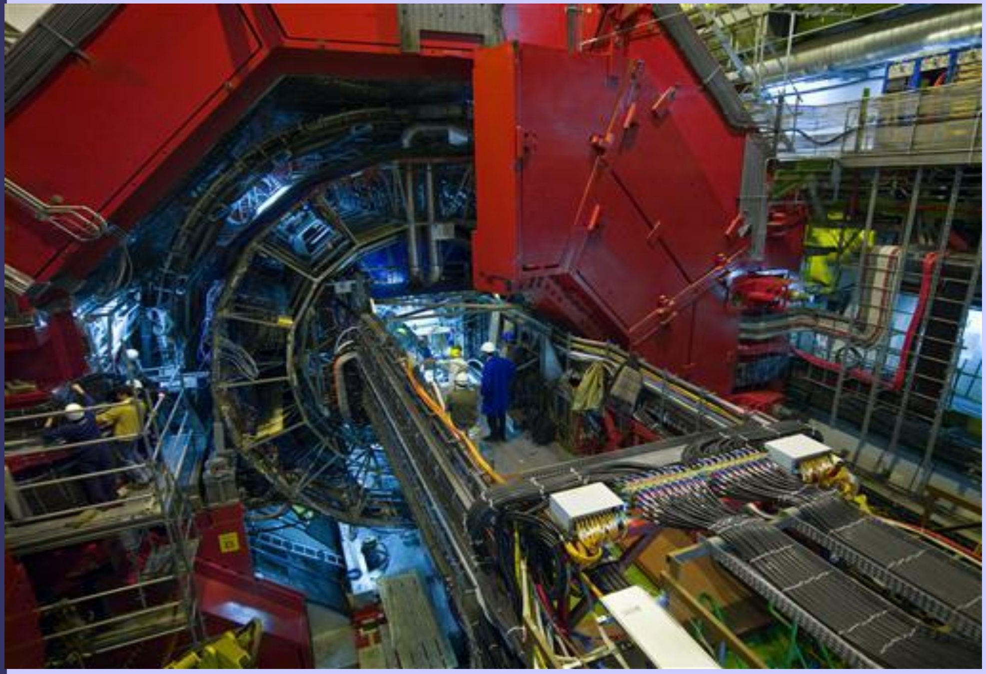


The TPC in the ALICE Cavern (2007)



TPC in ALICE (2007-08)

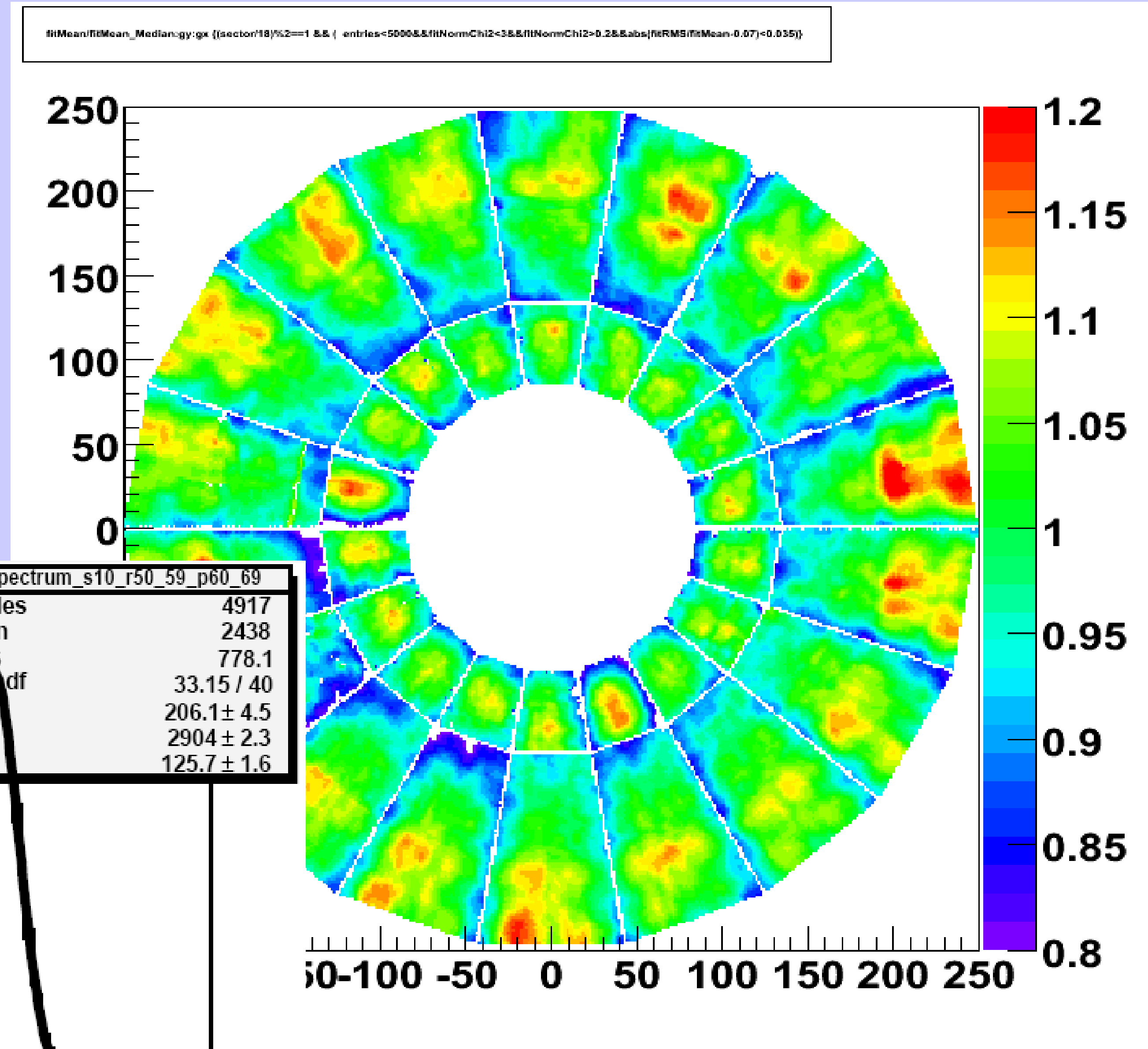


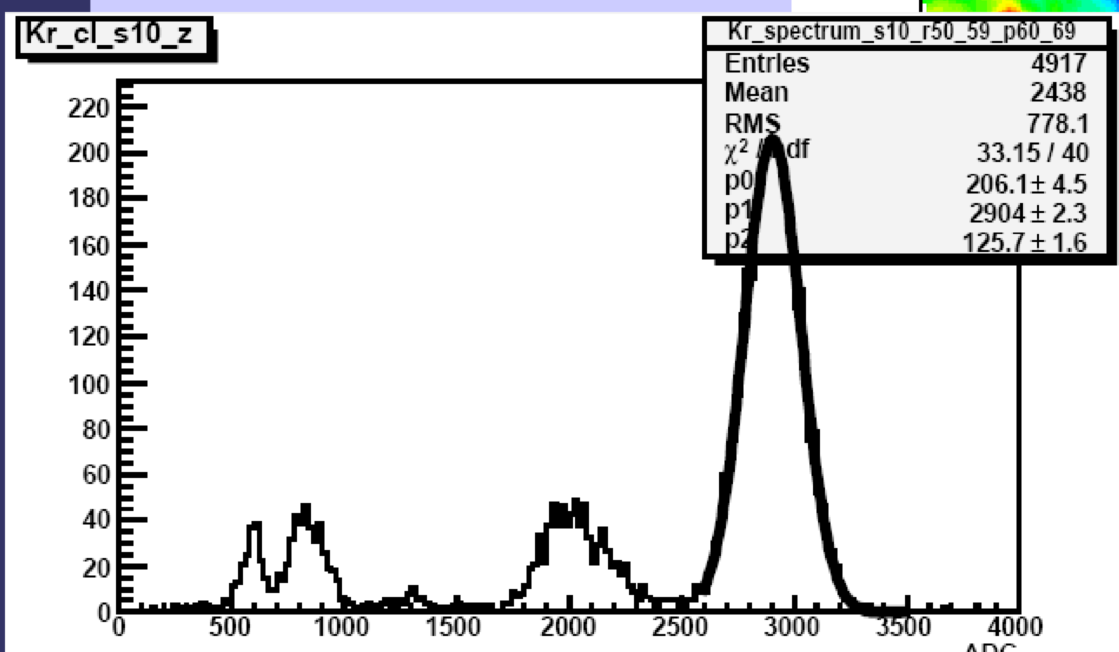



Calibration of the ALICE TPC

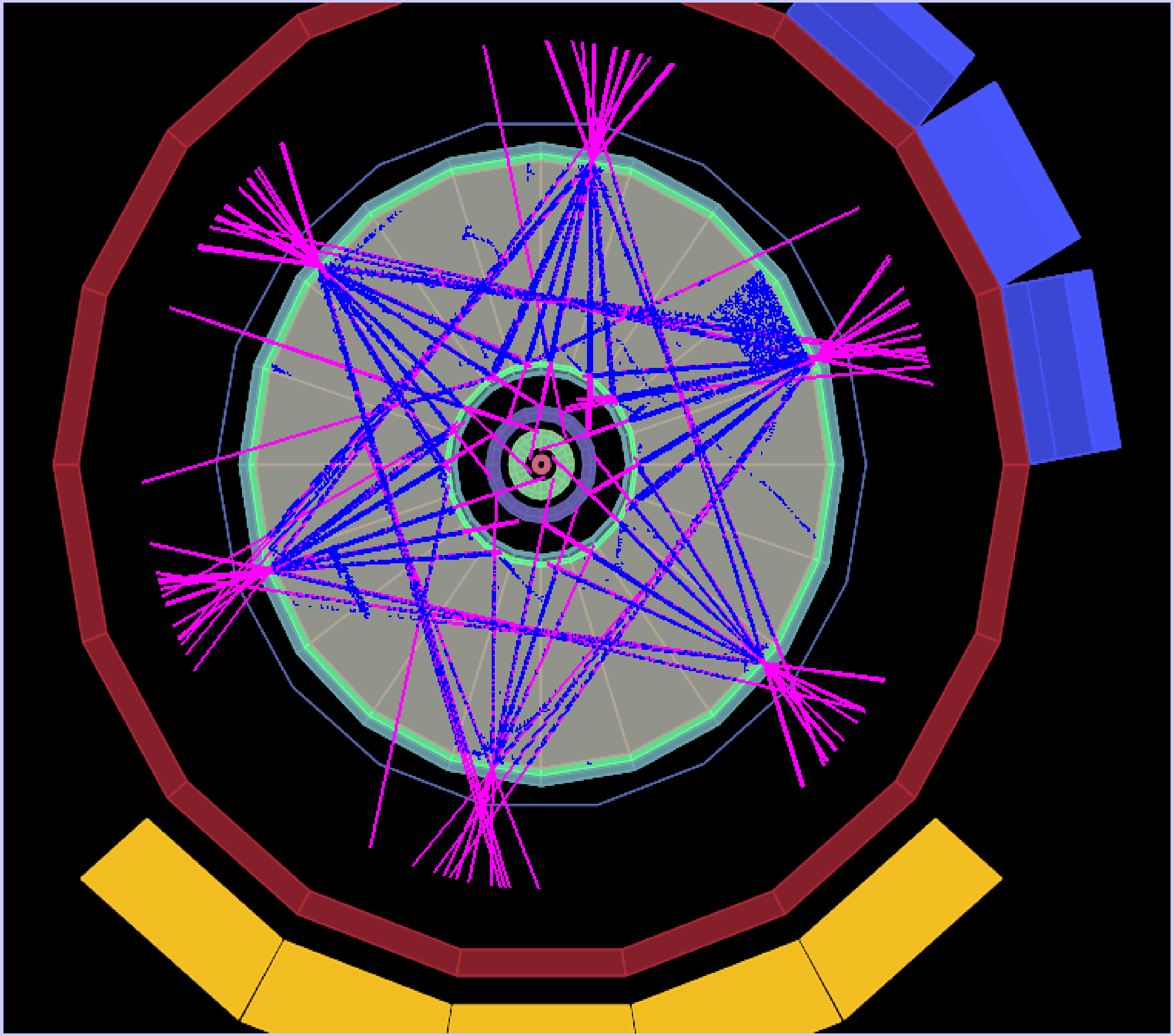
ALICE TPC - Gain Calibration

- **Gain**: How large are the signals on the pads for given charge?
- ^{83}Kr isotopes released into the gas.
- Relative resolution of main peak: ~5%.
- Pad to pad calibration.



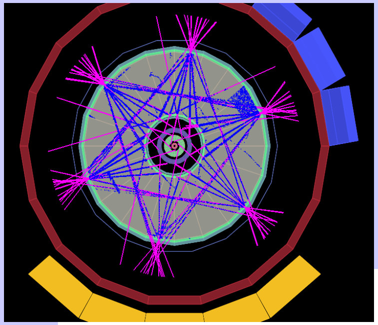


ALICE TPC - Laser Calibration (1)

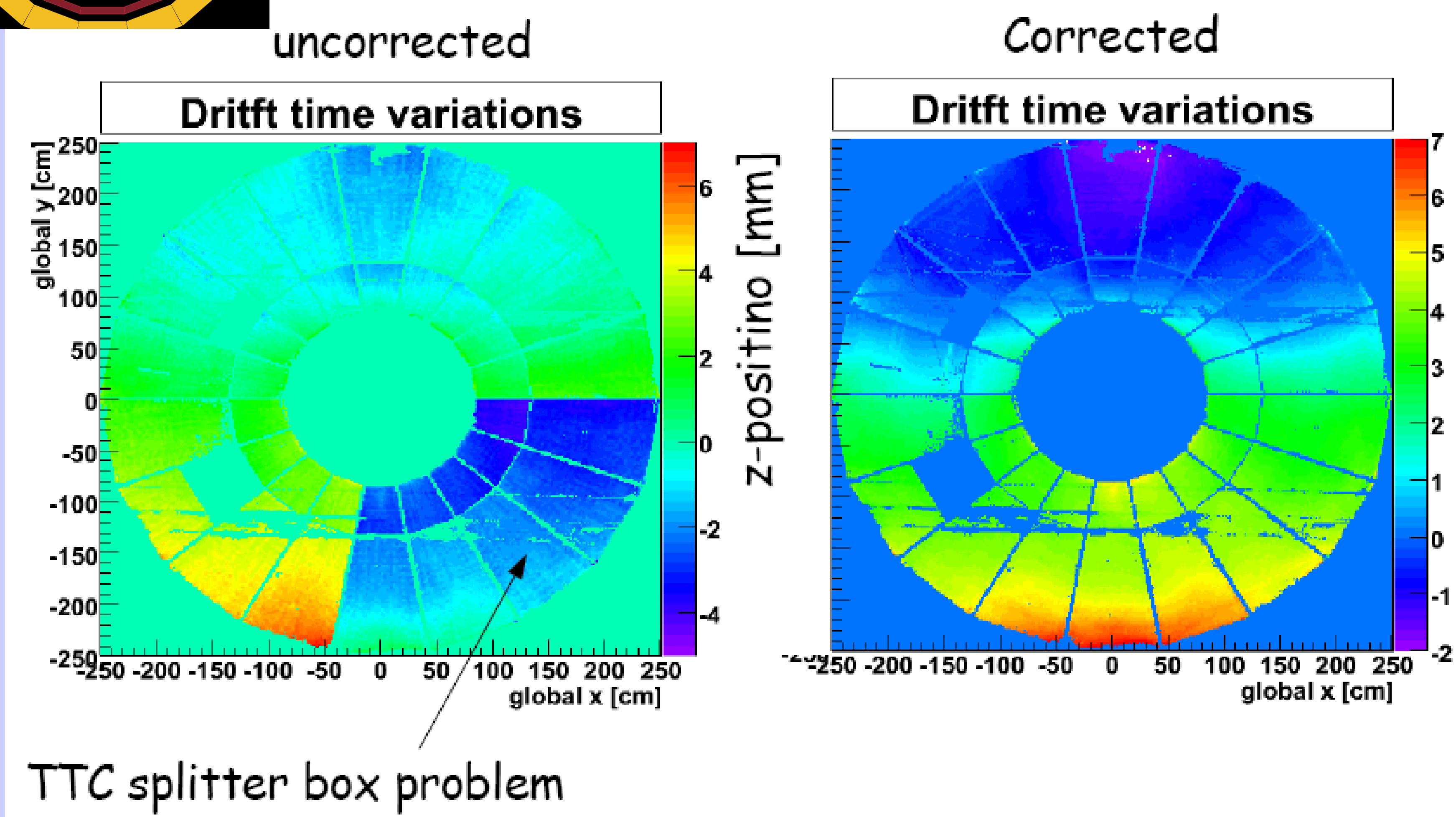


- Can inject 168 laser beams into the drift volume on both sides.
- Can calibrate distortions (*E*x*B*, Space Charge).

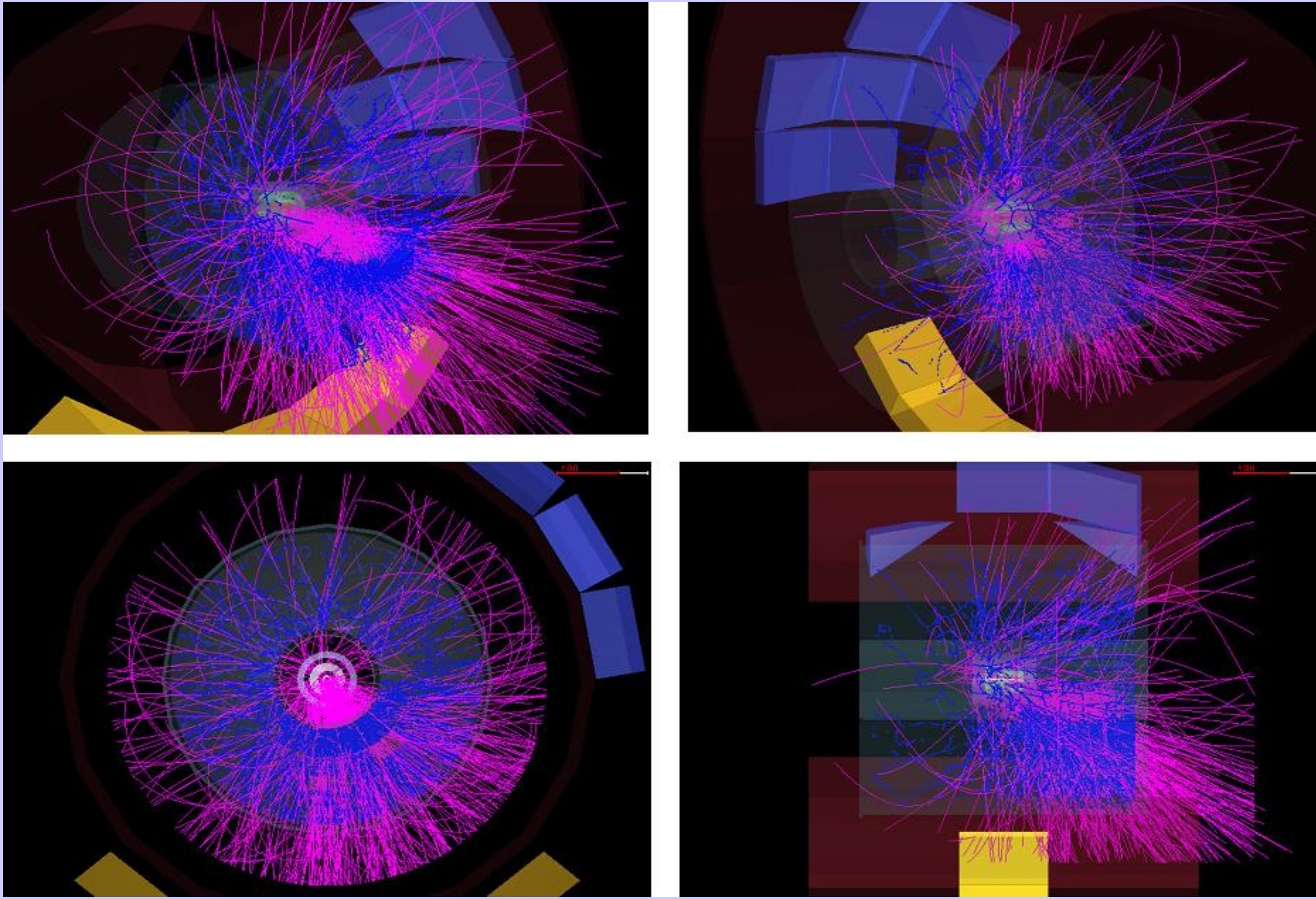
ALICE TPC - Laser Calibration (2)



- Stray laser light **extracts electrons from central electrode**.
- Used to calibrate v_d (~2.65cm/μs, pressure dependent, precision 10^{-4}) and analyse **pad-by-pad** variations.



ALICE TPC: Cosmics Event



Performance (Preliminary)

- Systematic effects on position resolution before (after) calibration:
  - ExB Effects: Δy<3mm (<0.3mm)
  - Drift velocity: Δz~50mm (1mm)
  - Alignment: $\sigma_y = \sigma_z$=0.15mm (0.1mm)
- Momentum resolution (from cosmic tracks):
  - $\sigma(p_T)$ = 3% at 2 GeV/c
  - $\sigma(p_T)$ = 10% at 10 GeV/c
- d*E*/d*x* Resolution (from cosmic tracks):
  - $\sigma(dE/dx)$ = 6%

Summary

- TPCs are quite simple constructions which allow to take “ 3D photographs” of particle tracks.
- It also allows particle identification via the characteristic energy loss.
- A strong magnetic field is used to bend the particle tracks (spectrometer) and on top reduces the diffusion over the long drift paths.
- The largest existing TPC is installed into the ALICE experiment.
- A lot of calibration data (Kryton, Laser, Cosmics) was taken in dedicated run periods in 2007 and 08.
- The start of LHC is now delayed until summer 2009.
- The ALICE TPC is ready for collisions.