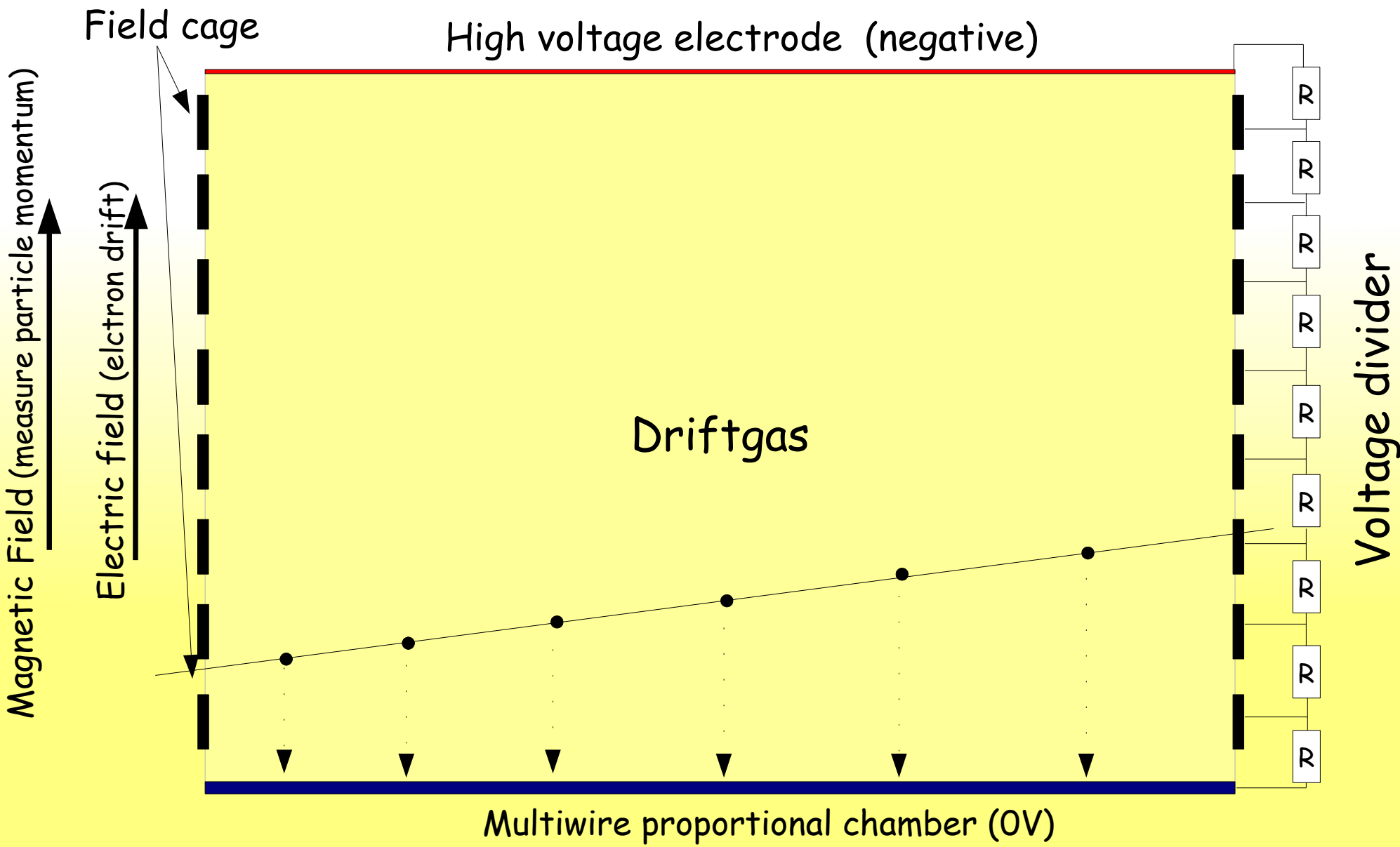
Everything you wanted to know about the TPC but were afraid to ask

Everything you were afraid to know about the TPC and never wanted to ask

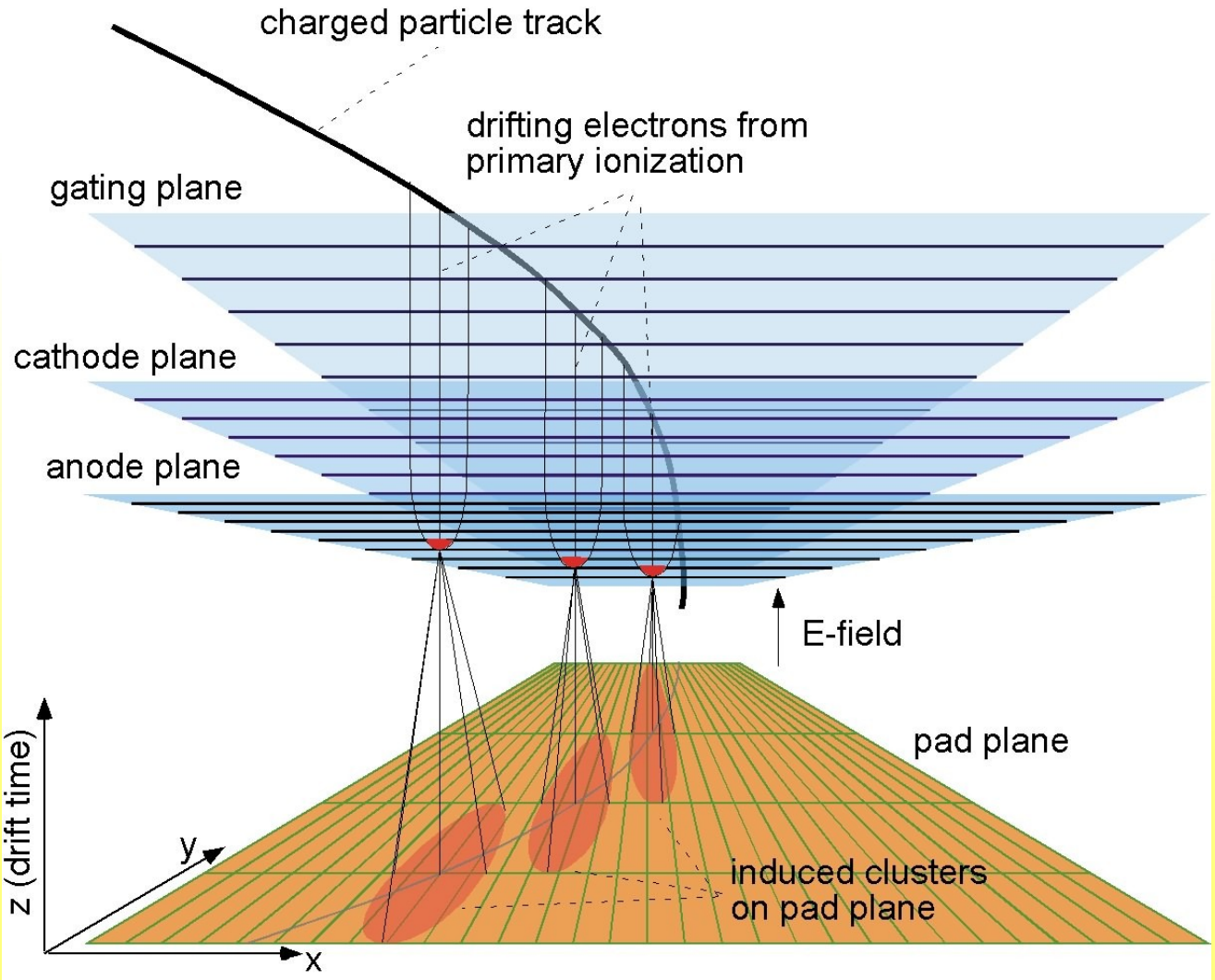
Outline

- Working principle of a Time Projection Chamber
- TPC basics
- Structure of the ALICE TPC + Auxiliary Systems
- Reconstruction & Calibration
- Performance
- Analysis

Structure of a TPC



Working principle of a TPC



- Two coordinates (x,y) given by the projection on the pad plane
- Third coordinate (z) given by the drift time and drift velocity ($z = v_{Drift} \times t_{Drift}$)
- Anode: 1400 - 1650 V
- Cathode: 0 V
- Gating: -100 ± 90 V
  open closed
- Gas gain ≈ $2 \cdot 10^4$

Why use a TPC

A TPC is the perfect detector for HI collisions …

- almost the whole volume is active
- minimal radiation length (field cage, gas)
- easy pattern recognition (continuous tracks)
- PID information from ionization measurements

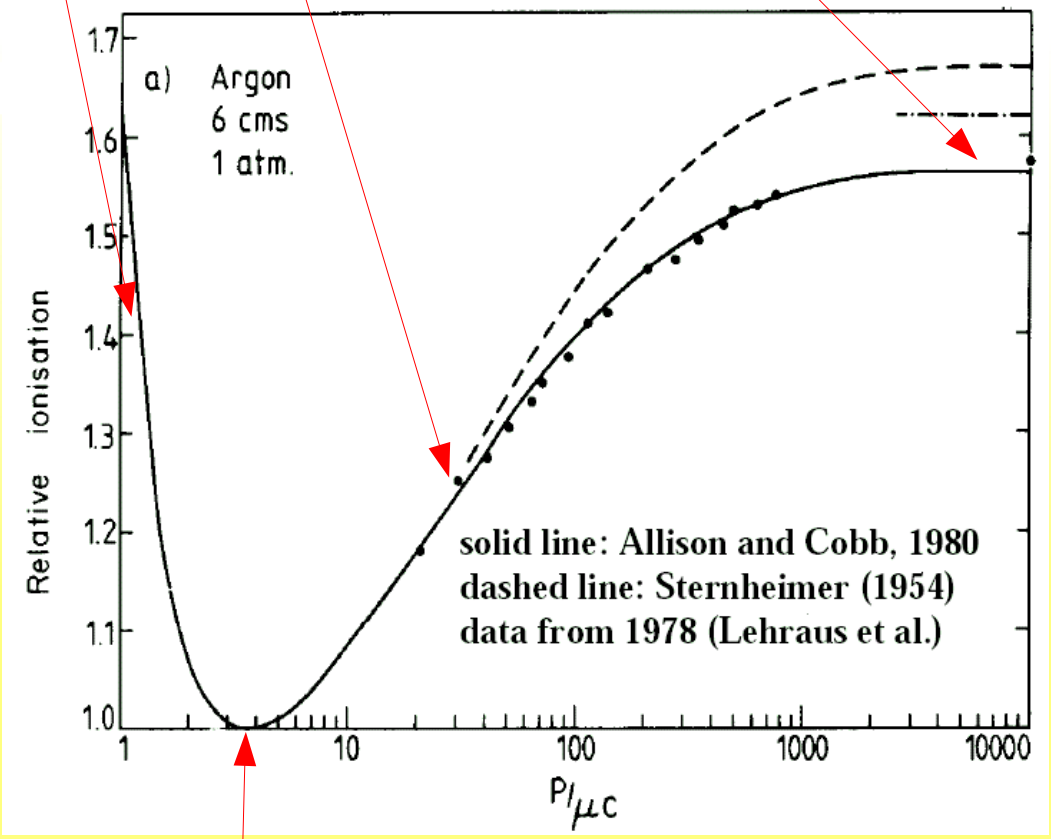
TPC basics

- Energy loss of charged particles
- Ionisation
- Gas amplification
- Drift velocity
- Diffusion

The Bethe-Bloch-Formula

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A \rho m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{2m_e c^2 \beta^2 \gamma^2}{I_0} - \beta^2 - \frac{\delta(\beta)}{2} \right]$$

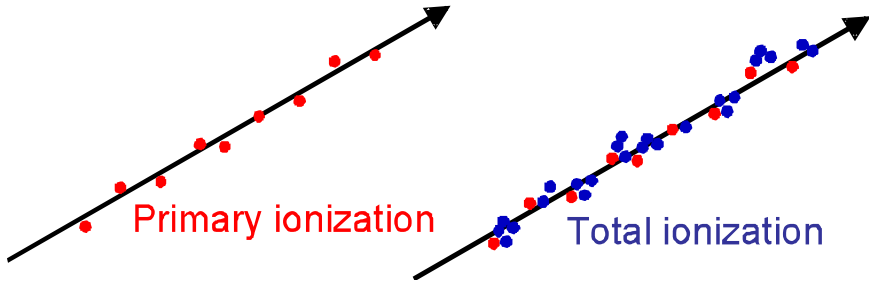
- dE/dx first falls ∝ $1/\beta^2$ (kinematic factor)
- a minimum is reached at $\beta\gamma \approx 4$ (Minimum Ionising Particle - MIP)
- then again rising due to the ln γ2 term (relativistic rise: contributions of more distant particles due to the relativistic expansion of the transverse E-Field)
- 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)

Ionisation

Distinguish between primary and secondary ionisation:
Atoms become excited or suffer primary ionisation , electrons with energies above 100 eV can make secondary ionisation.



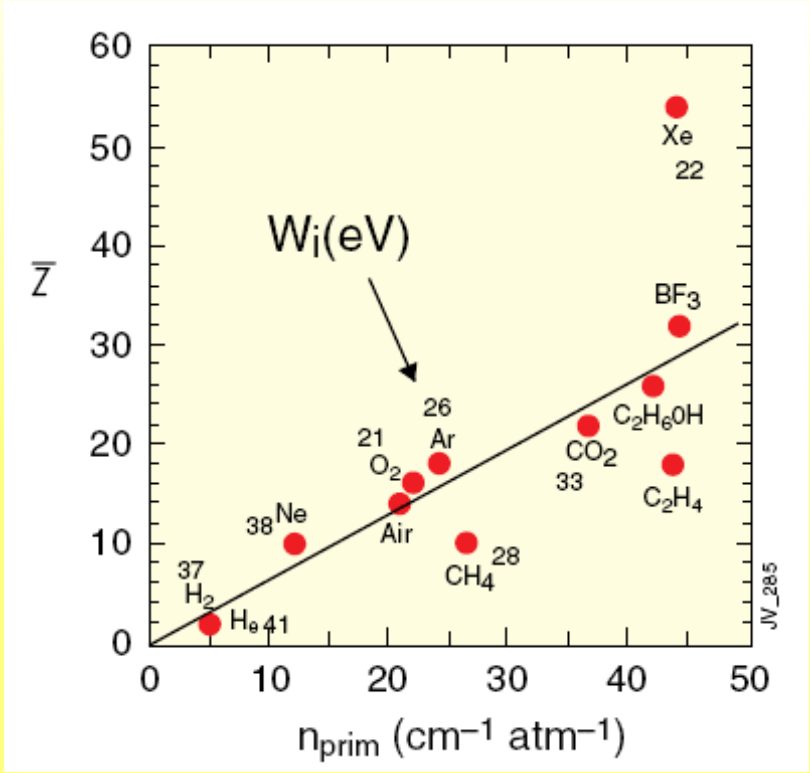
Lohse and Witzeling, Instrumentation In High Energy Physics, World Scientific,1992

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

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

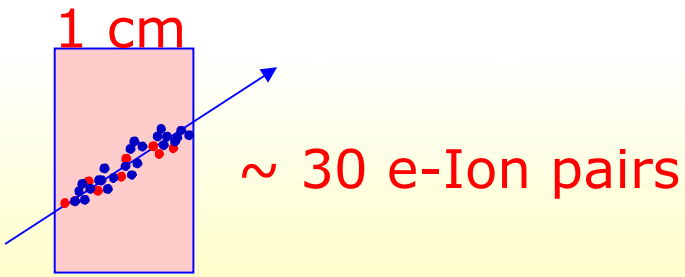
W_i = mean energy loss per produced ion pair ($W_i > I_0$) ≈ 30 eV

ΔE = total energy loss



Measurement of ionisation

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



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

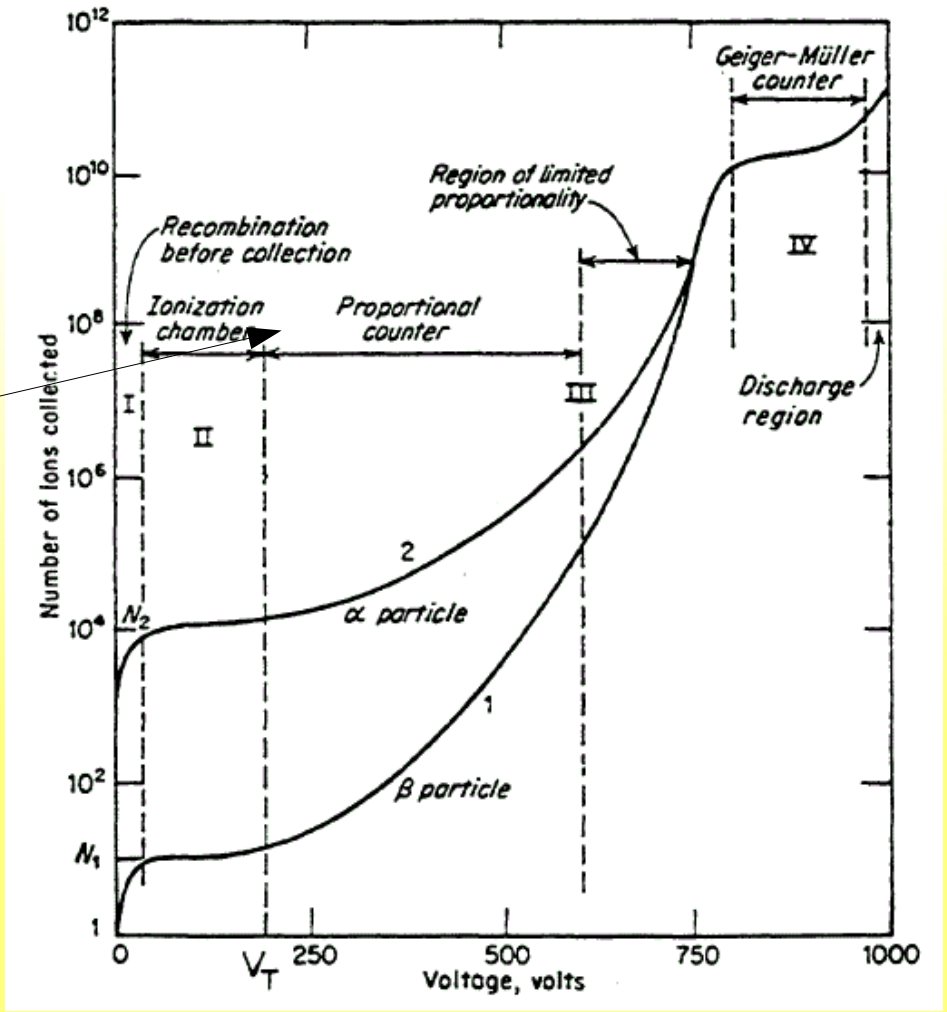
Amplifier noise is typically ≈1000 e^- (ENC) !

⇒ Number of electrons has to be increased noiselessly!

⇒ Gas amplification

Gas amplification

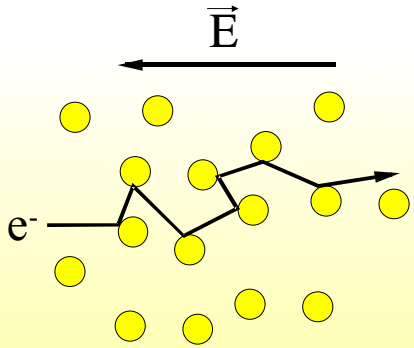
Proportional mode:
Detected signal is proportional to the original total ionisation → measurement of dE/dx! Gain ≈ 10^4 - 10^5



Drift of electrons 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 looses 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:



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

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.

Drift velocity

In the approximation that the energy from the electric field $\varepsilon_E >> \varepsilon_{therm}$ the thermal energy the drift velocity v_D can be written as

$$u_D = \frac{e}{\sqrt{2m}} \cdot \frac{E}{N} \frac{1}{\sigma(\epsilon)\sqrt{\epsilon}}$$

With e, m the electron charge and mass, E the electric field, N the density of the drift gas, σ(ε) the collision cross-section as a function of the electron energy.
Due to the trivial dependence on the gas density $N=1/k \cdot P/T$ the drift velocity is often plotted as a function of the reduced electric field E/P or E/N

Life gets more complicated with a B field ...

$$\vec{u} = \frac{\mu|\vec{E}|}{(1+\omega^2\tau^2)} \left[\hat{E} + \omega\tau \left(\hat{E} \times \hat{B}\right) + \omega^2\tau^2 \left(\hat{E} \cdot \hat{B}\right) \hat{B} \right]$$

Drift velocity measurements

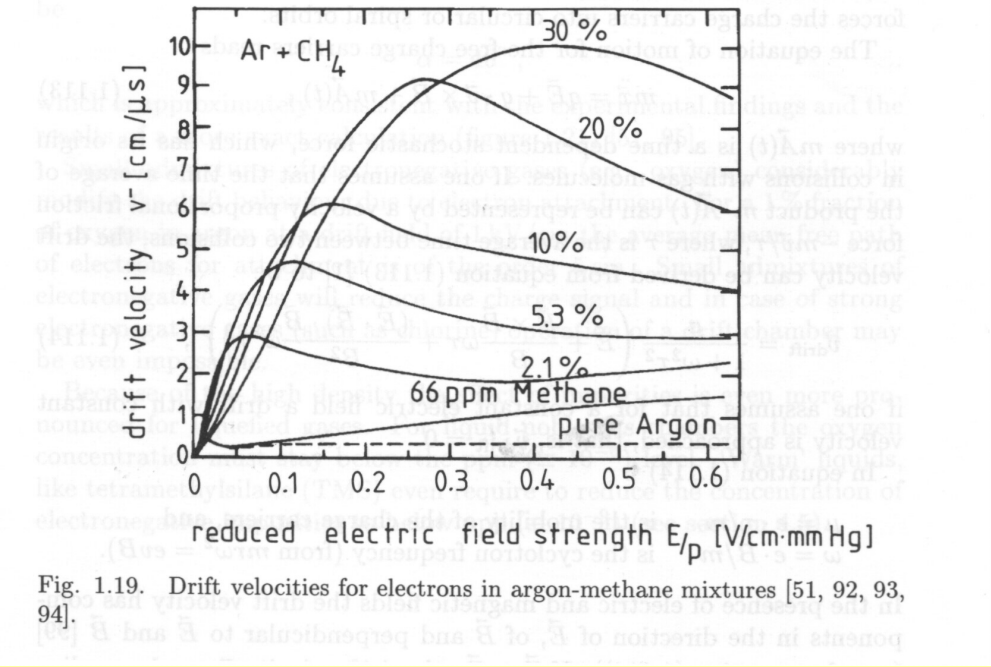
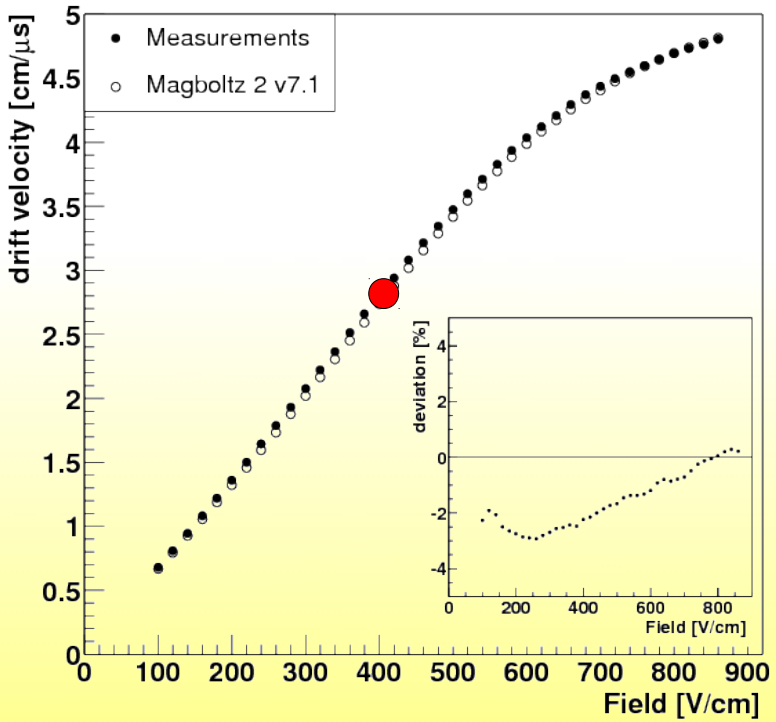


Fig. 1.19. Drift velocities for electrons in argon-methane mixtures [51, 92, 93, 94].

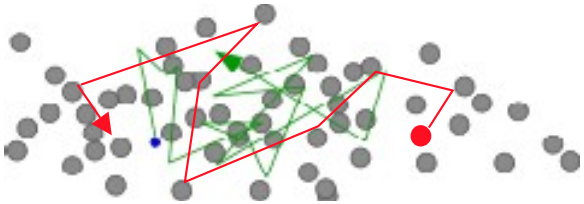
ALICE gas mixture: $NeCO_2$



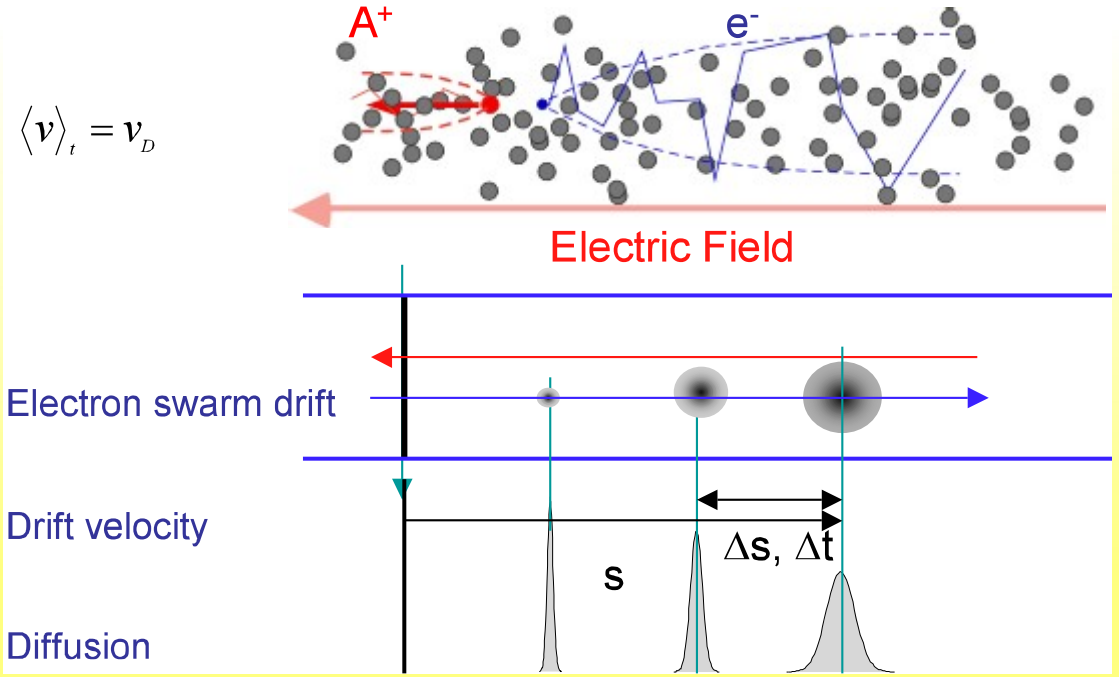
Non saturated drift velocity in ALICE
Challenging condition:
- sensitive to small variations in the gas density

Diffusion

E=0 thermal diffusion $\langle v \rangle_t = 0$

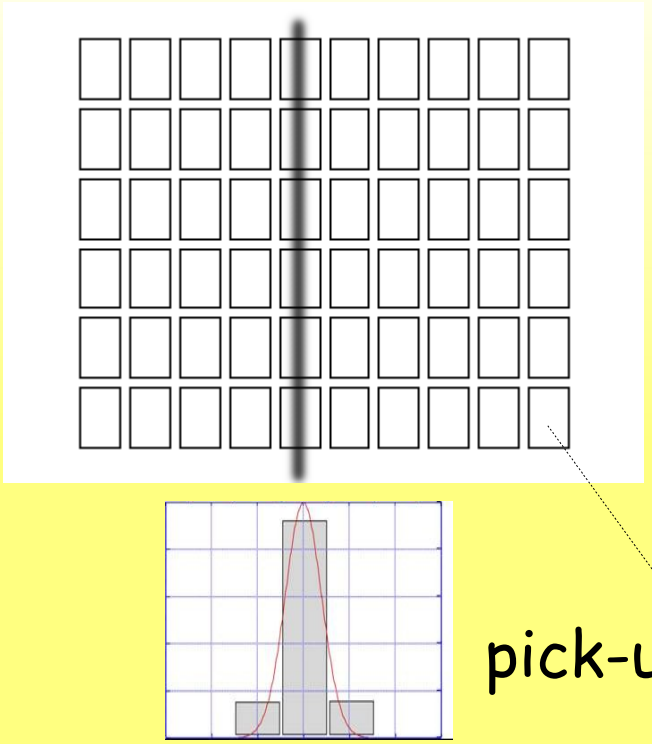


E>0 transport and diffusion $\langle v \rangle_t = v_D$



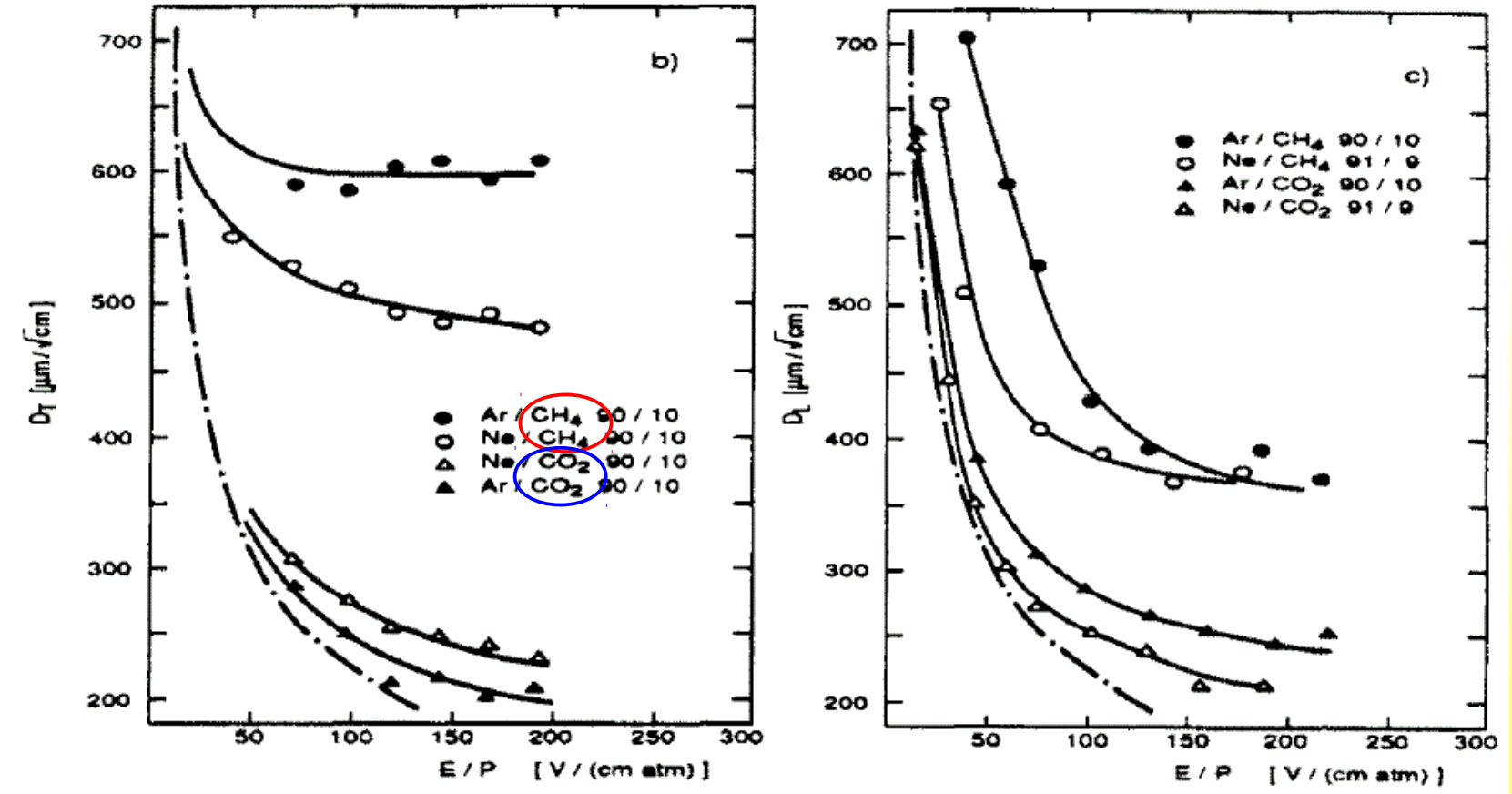
Diffusion

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.



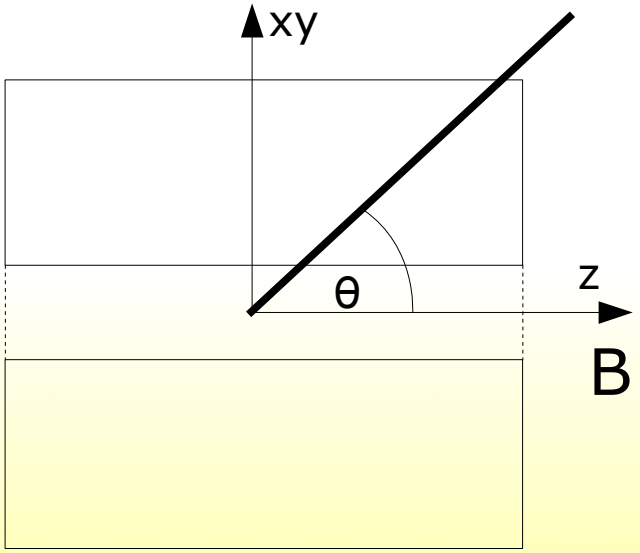
Diffusion measurements

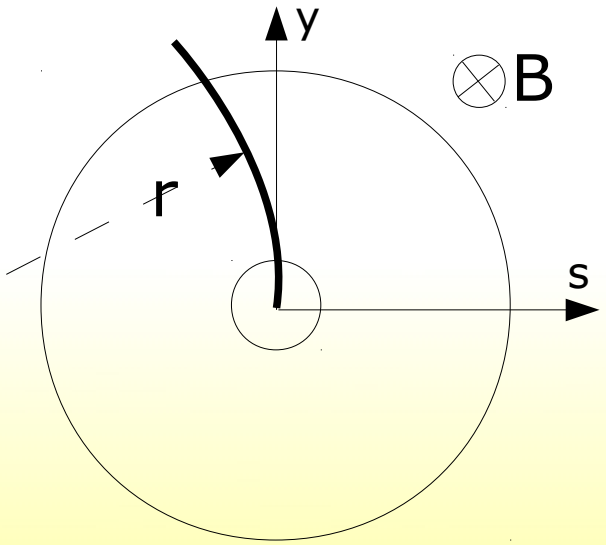
A. Kühmichel / Nucl. Instr. and Meth. in Phys. Res. A 360 (1995) 52–56



In rare gases the diffusion is high due to a small number of degrees of freedom for exitation. Molecular gases with a large number of excitation states have a small diffusion constant. Distinguish "hot" and "cold" gases.

Momentum measurement





equation of motion:

$\vec{F}=q\cdot\vec{v}\times\vec{B} \quad (\vec{B}=B\cdot\vec{e}_z)$

$\vec{F}=m\cdot\dot{\vec{v}} \quad \rightarrow \quad$ Helix

longitudinal

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

transverse

$\omega=q\cdot B/m; \quad v_T=\omega\cdot r \rightarrow$

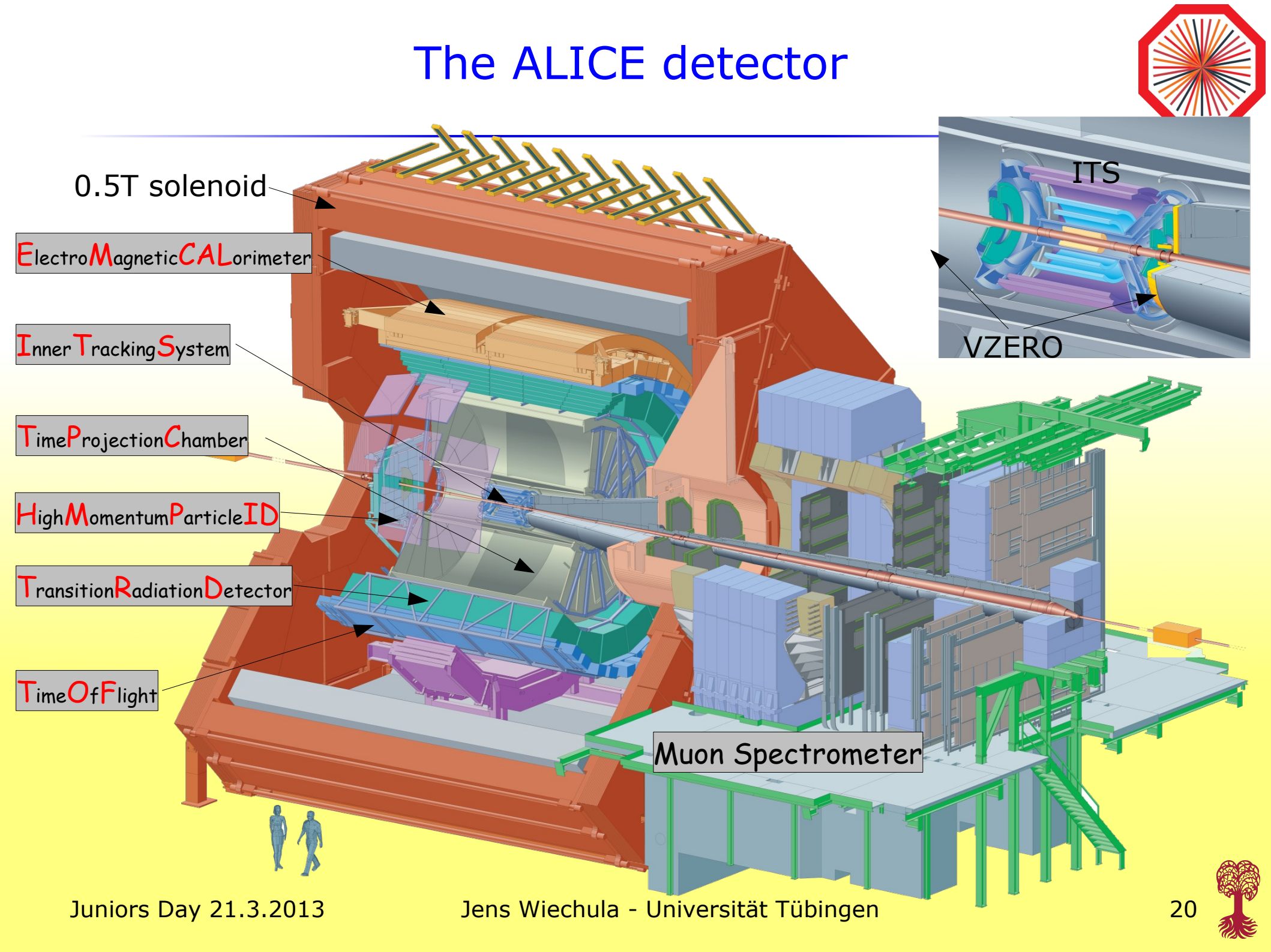
$p_T=mv_T=qBr$

$p_T[\mathrm{GeV}]=0.3Br[\mathrm{T\cdot m}]$

Structure of the ALICE TPC

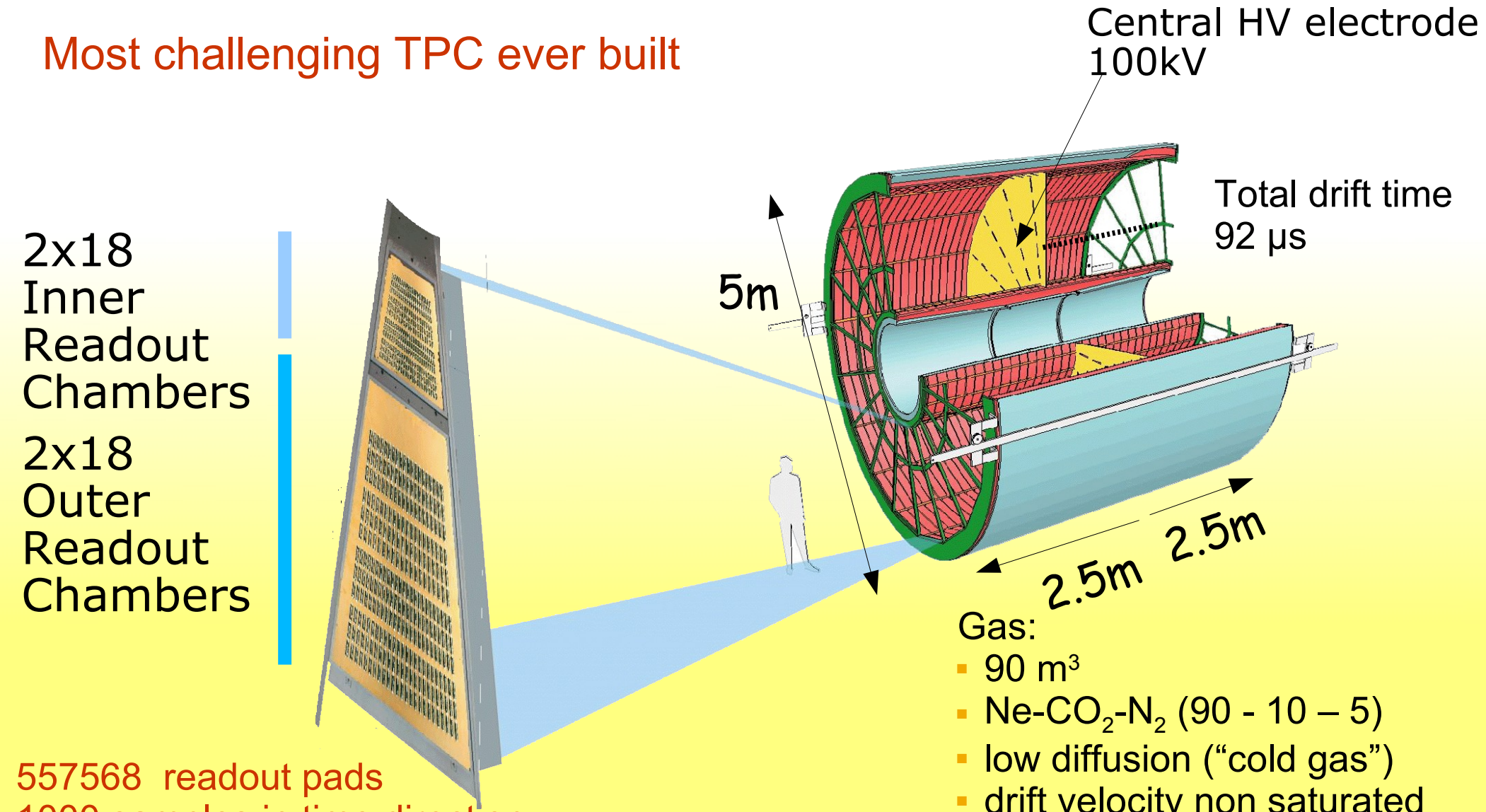
- The TPC in ALICE
- Gas volumes
- Central Electrode (CE), fiel cage, Endplates
- Voltage Divider, Resistor rod
- ReadOut Chambers (ROCs)
- Servie Support Wheel (SSW)
- FrontEnd Elektronics (FEE)

The ALICE detector



Overview

Most challenging TPC ever built

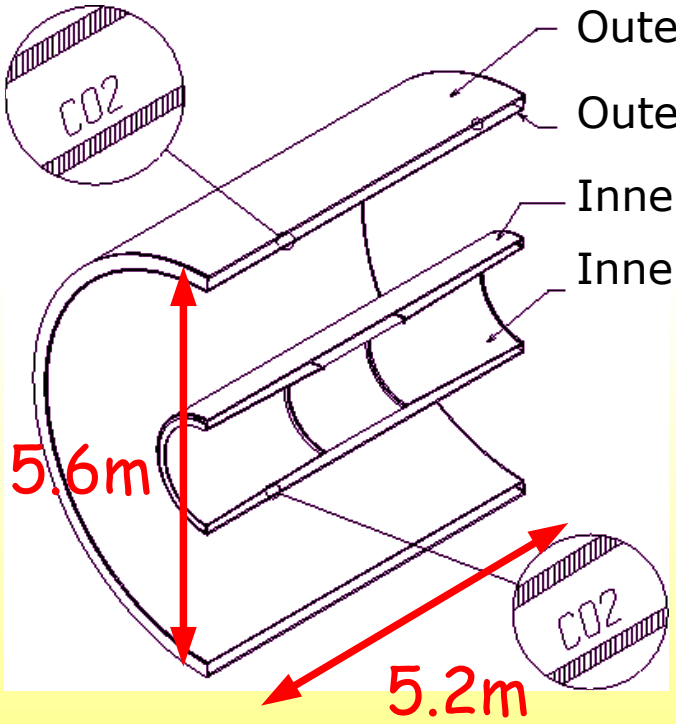


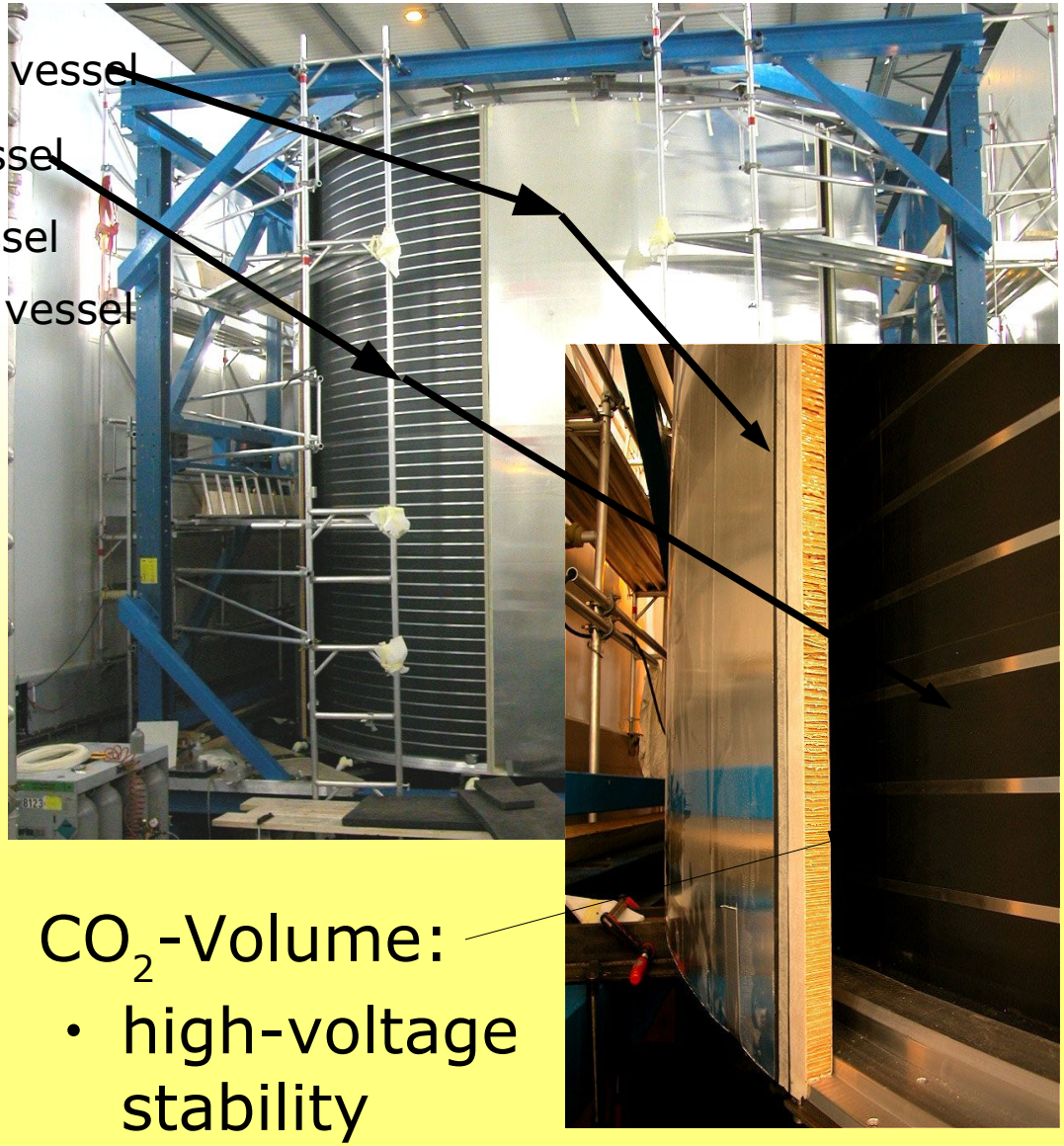
557568 readout pads
1000 samples in time direction

Gas:

- 90 m^3
- Ne-CO_2-N_2 (90 - 10 – 5)
- low diffusion (“cold gas”)
- drift velocity non saturated
  - temp. homogeneity and stability 0.1 K required

Gas Volumes





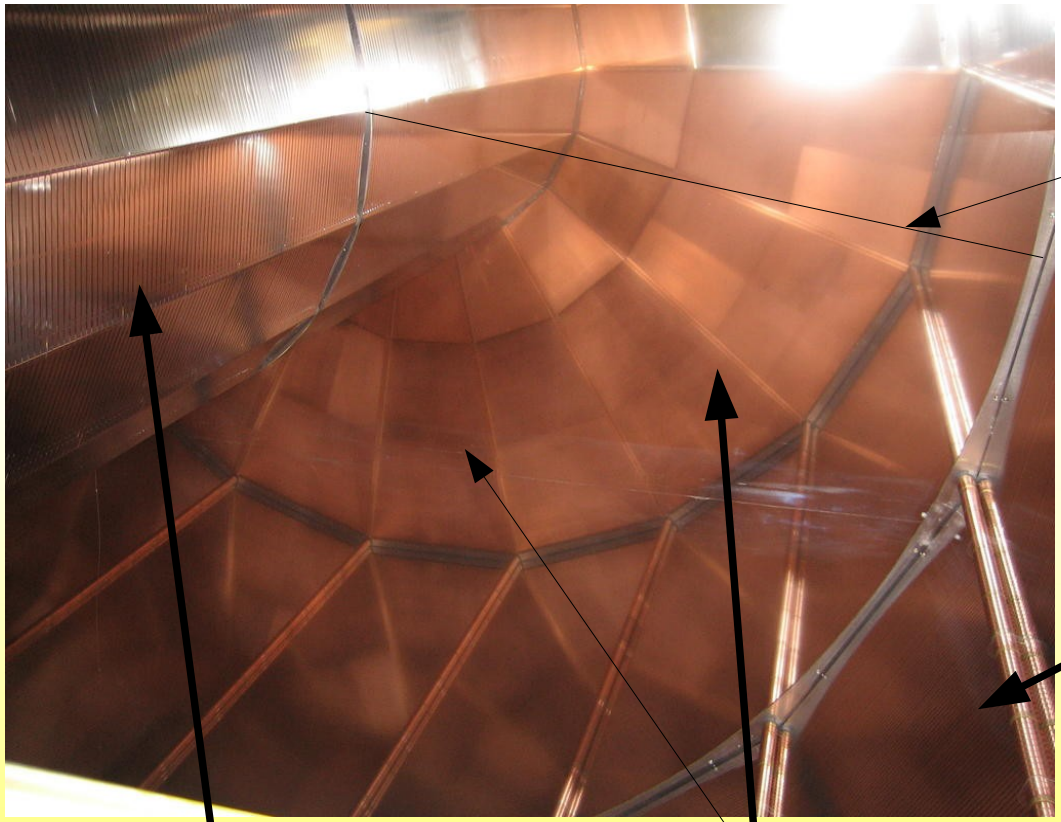
Drift gas Ne-CO_2(-N_2) [90-10(-5)]

- ≈ 90m^3
- Ionisation
- Drift
- Gas amplification

CO_2-Volume:

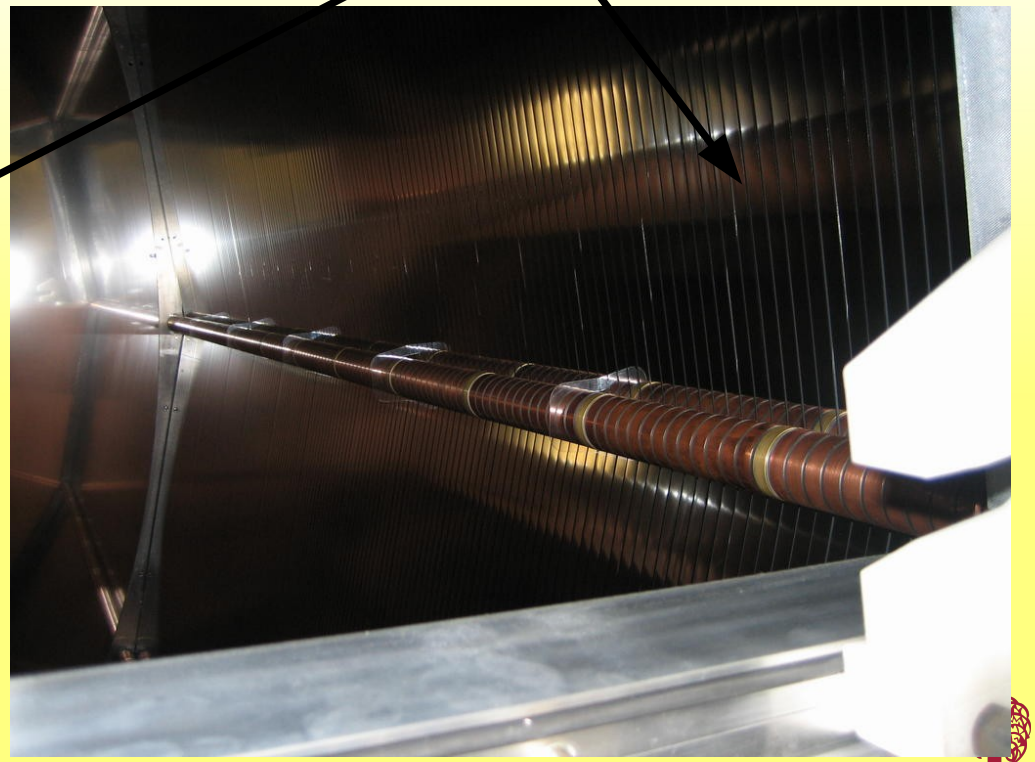
- high-voltage stability
- Gas tightness

Central Electrode and field cage



Central electrode

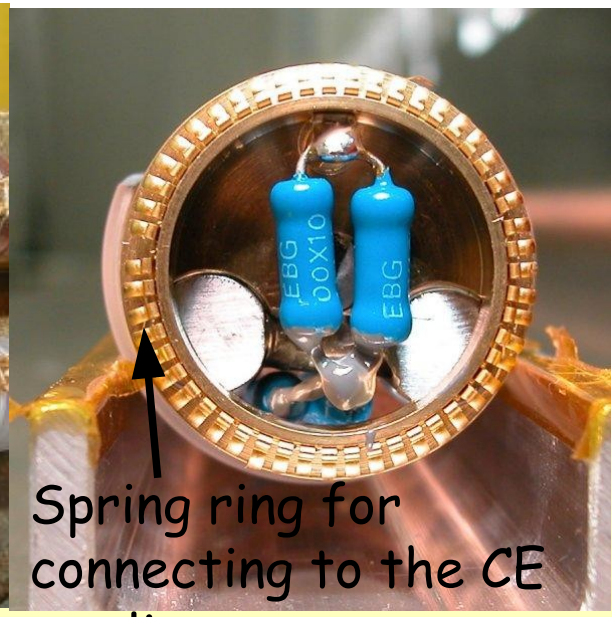
Outer part of the field cage



Inner part of the field cage

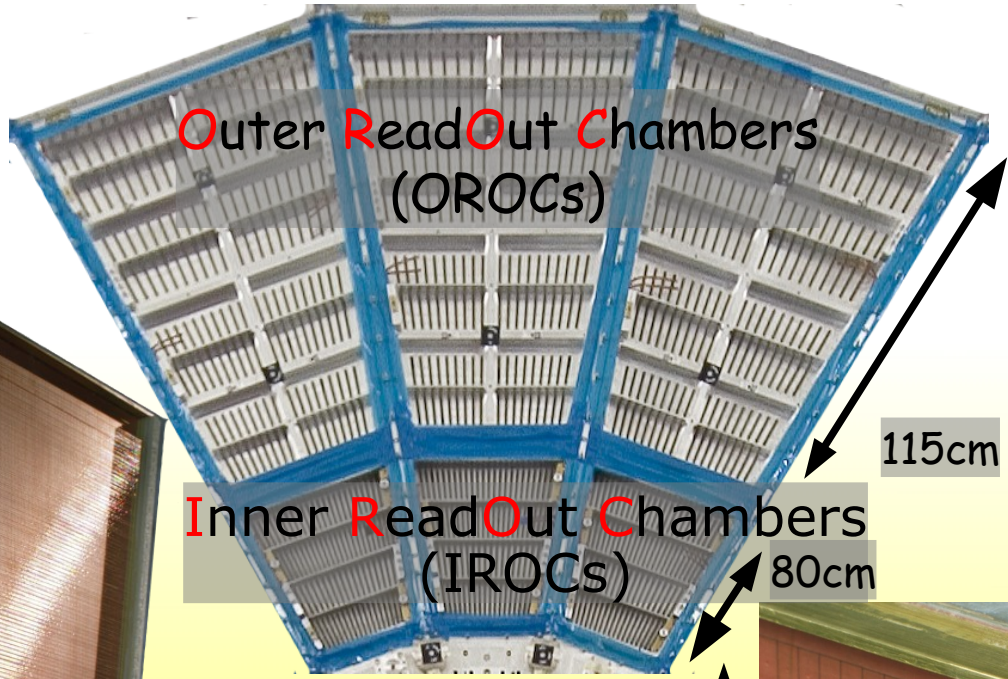
Refexion of the padplane. mirrord on the CE

Voltage divider (resistor rods)



- Water cooled voltage divider
- 2 on each side (1 inner, 1 outer)
- Power dissipation ≈ 4*8W (≈ 40min to heat the gas by 1K, planned T stability 0.1K)

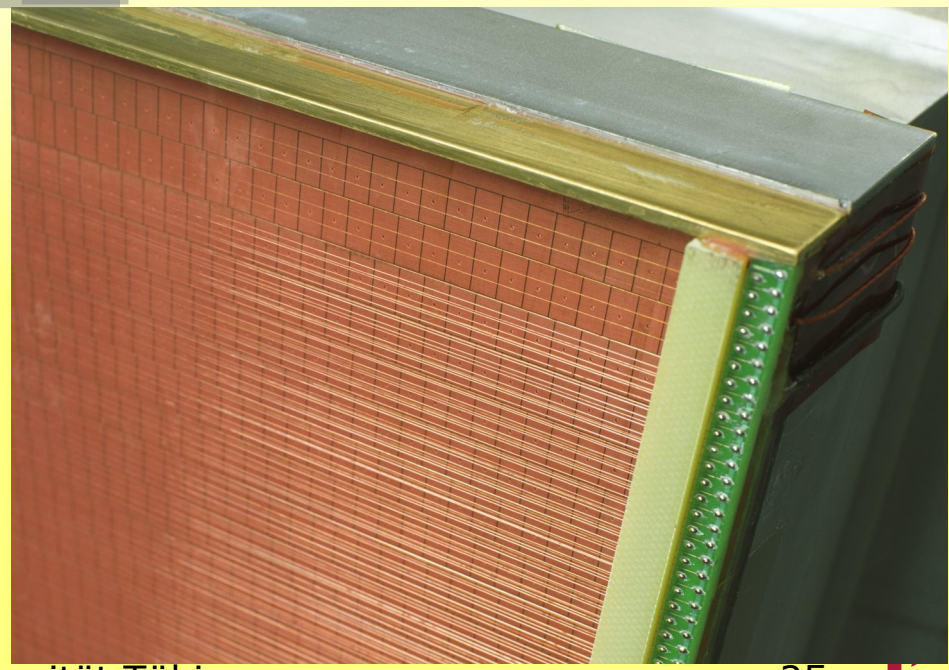
Readout chambers



On each side:

- 18 IROCs
- 18 OROCs

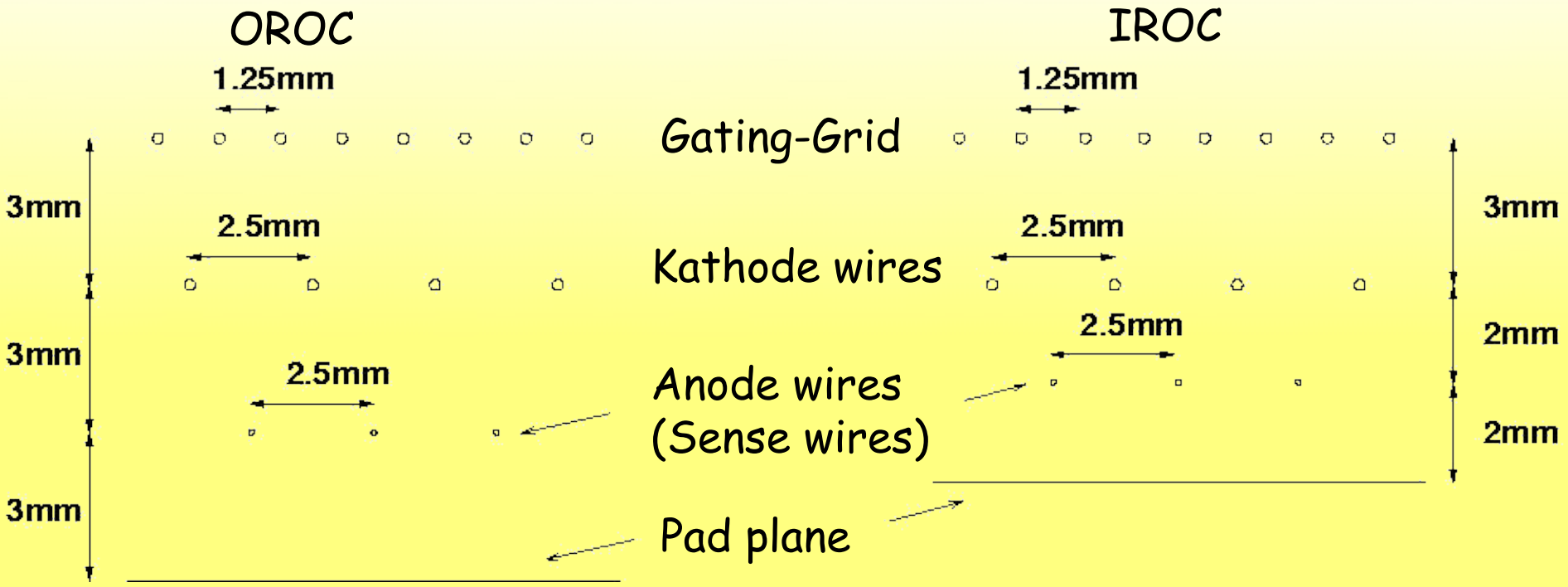
72 ROCs in total



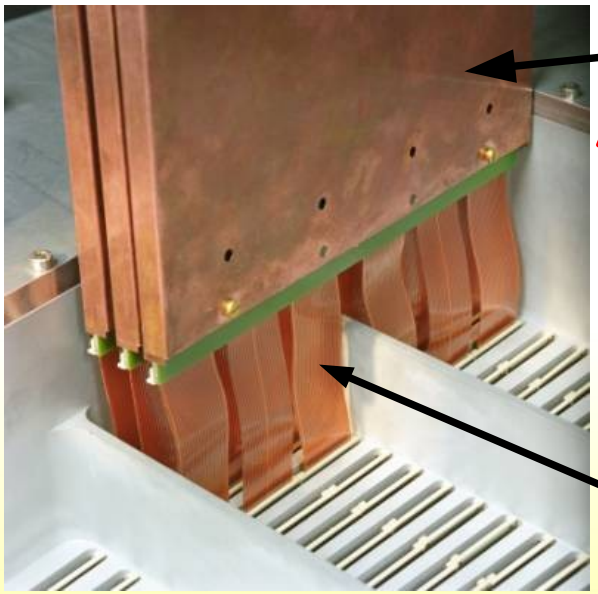
Readout chambers

	Pad Size [mm^2]	Number of pad rows	Number of pad
IROC (81.1 - 132.1 cm)	4 x 7.5	63	5504
OROC (134.6 - 198.6 cm)	6 x 10	64	5952
OROC (198.6 - 246.6 cm)	6 x 15	32	4032
TPC total		159	557 568

Pad size changes with track density



FrontEnd Cards

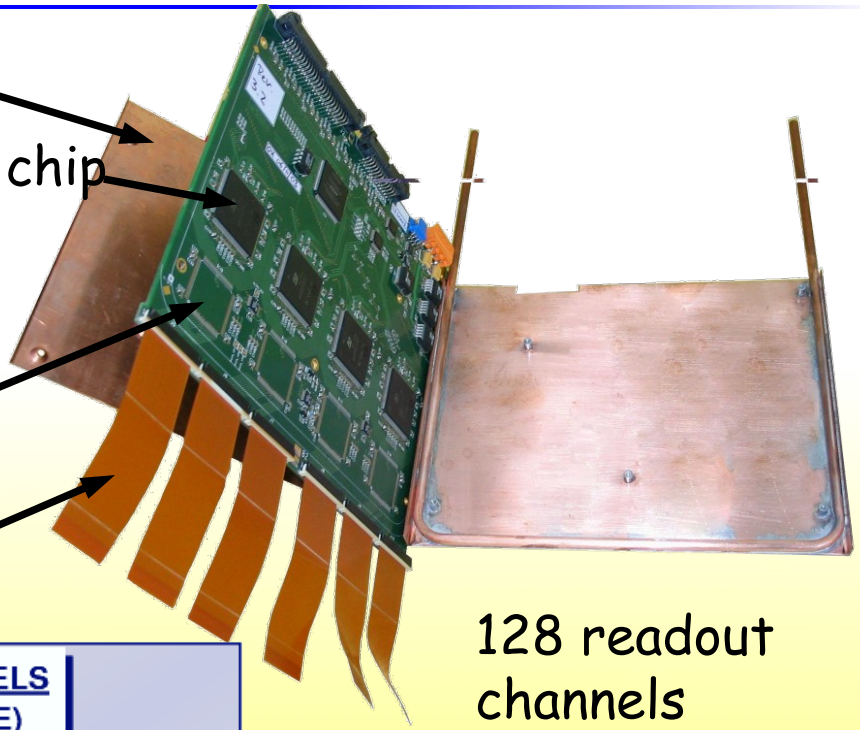


cooling plate

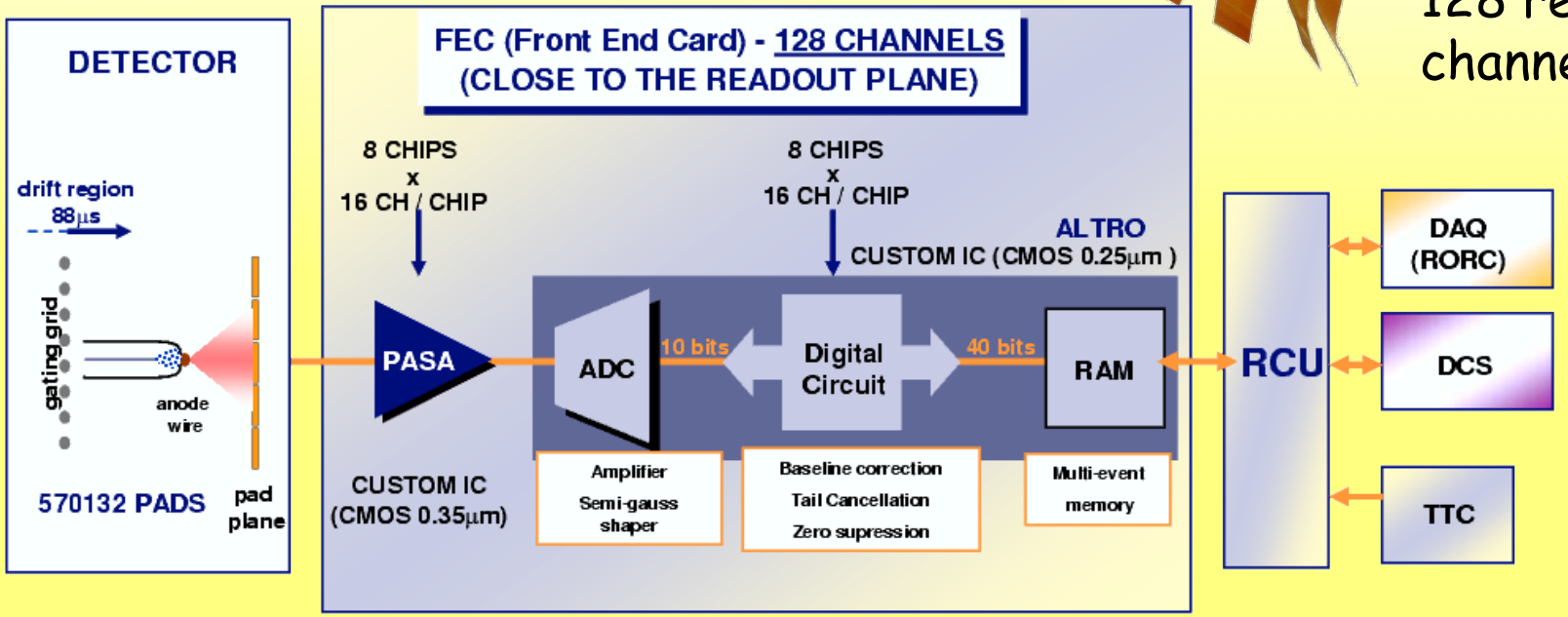
ALice TPC ReadOut chip

PreAmplifire-
ShAper

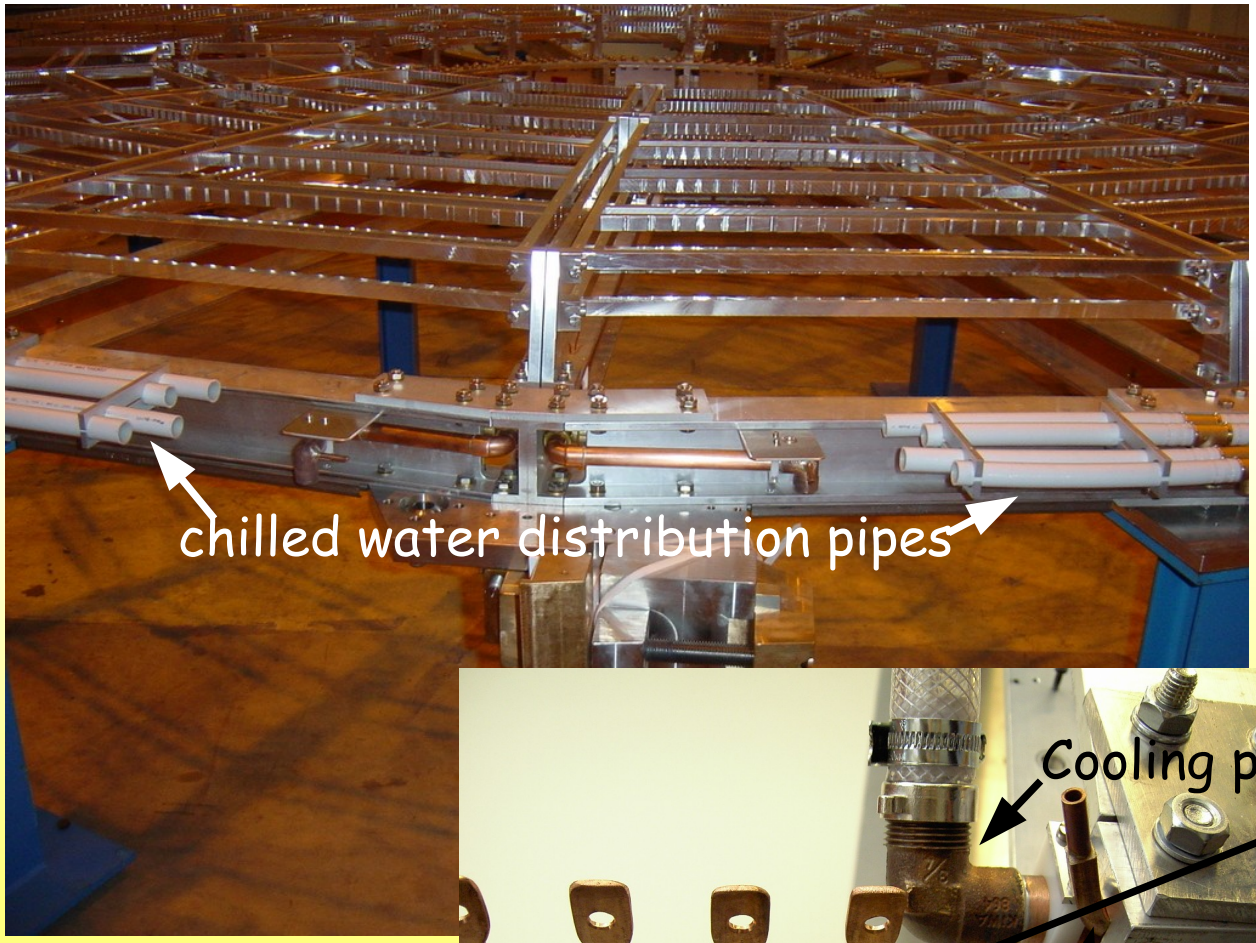
capton cables



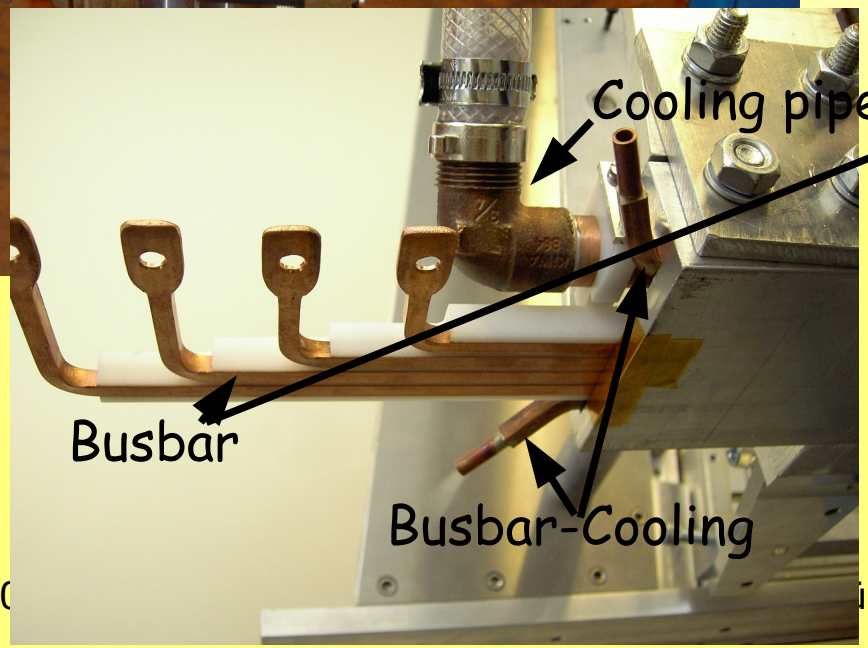
128 readout channels

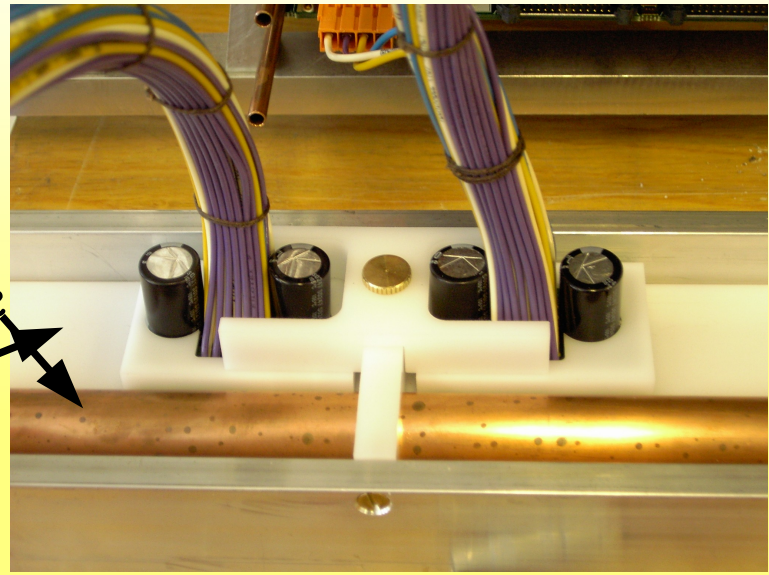


Service Support Wheel



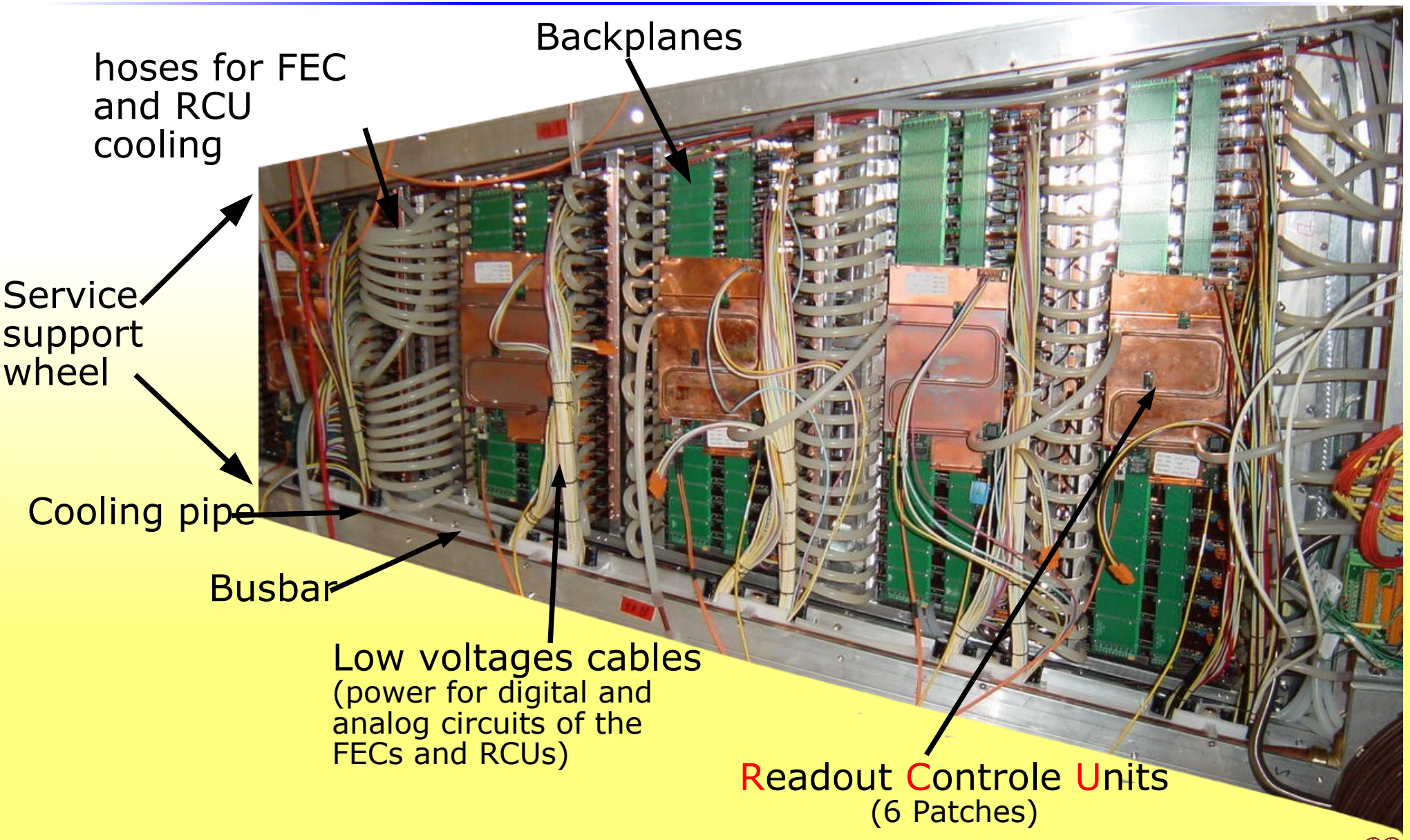
FEC mounting frames

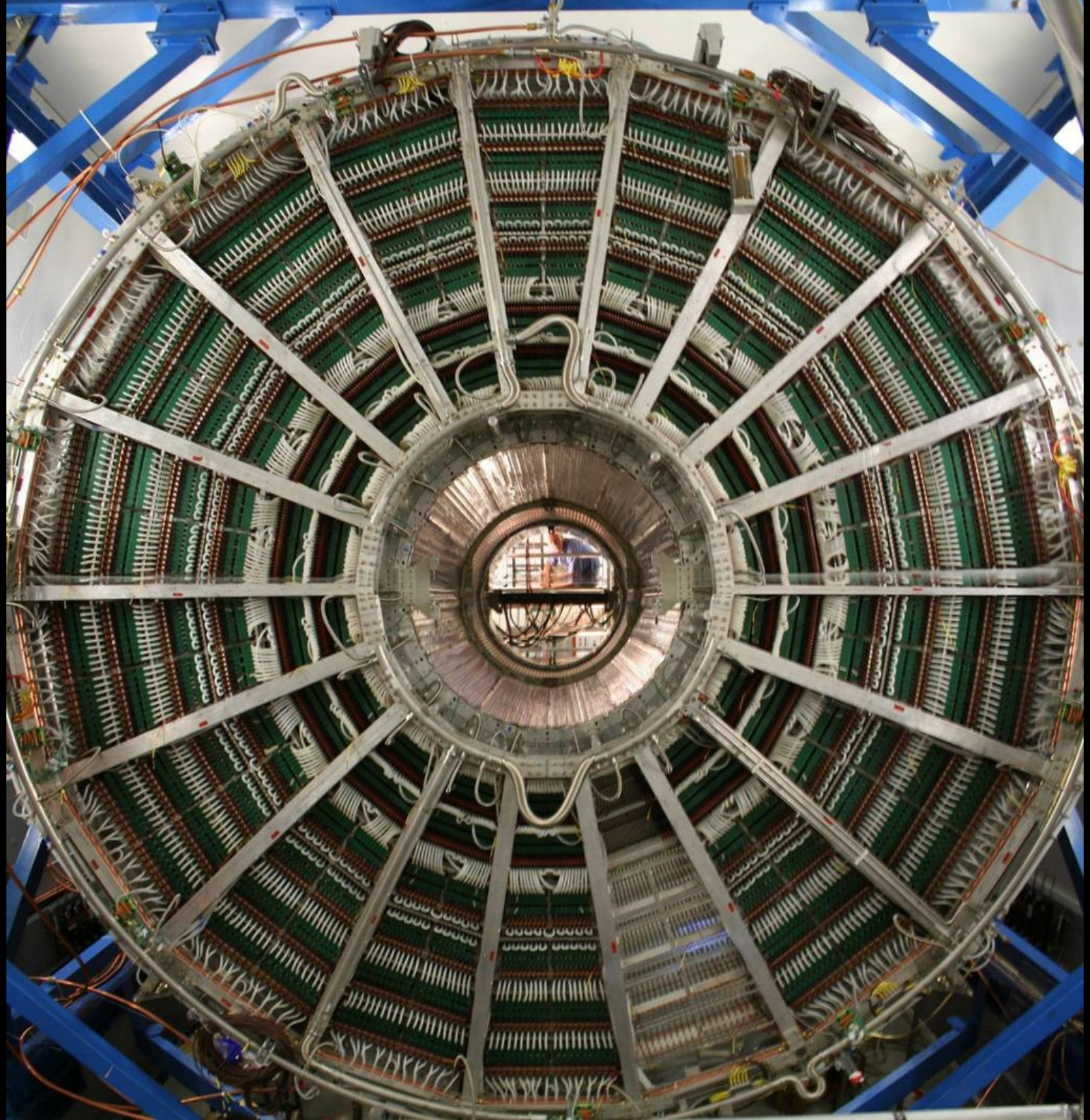


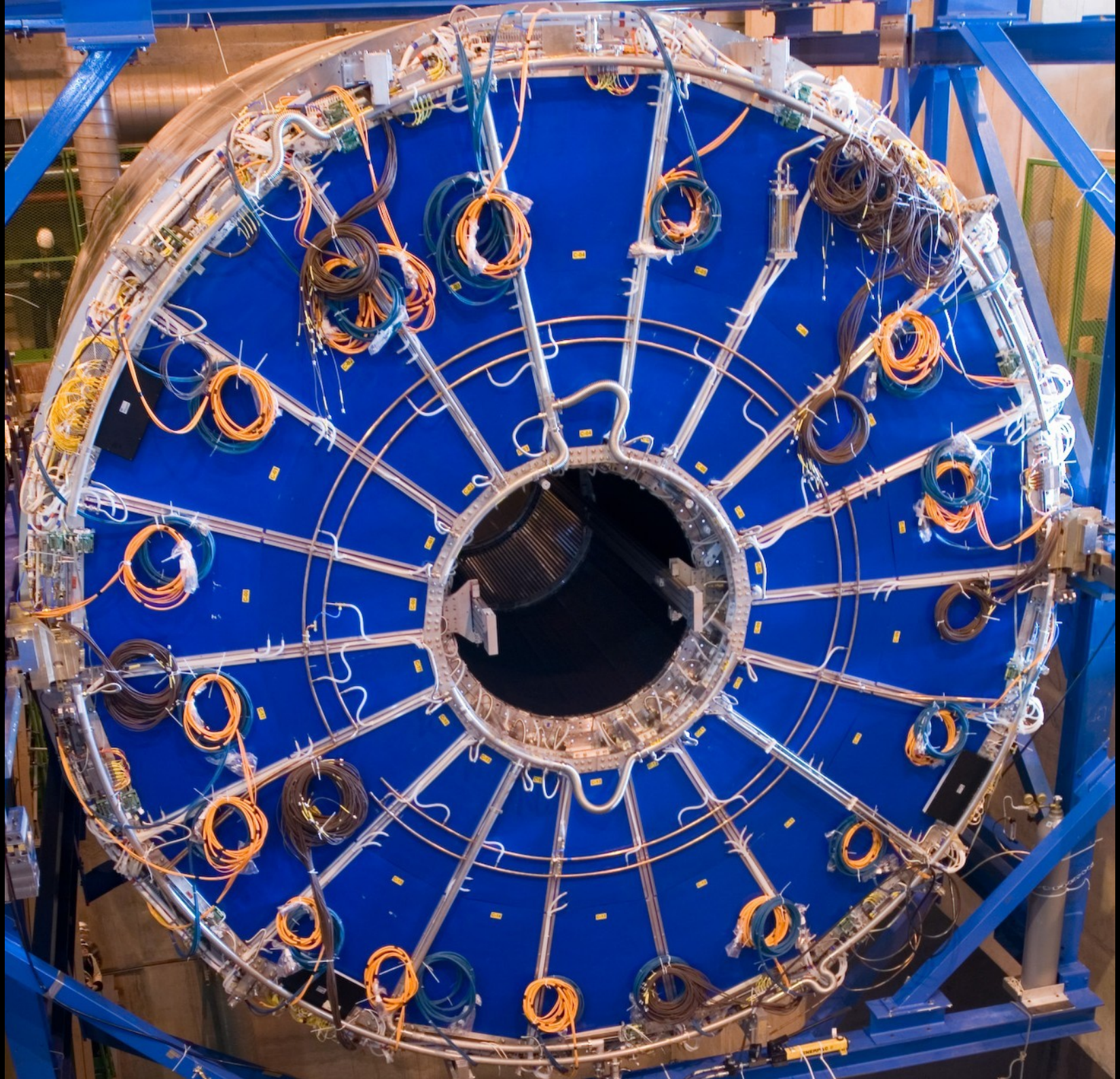


Low voltages cables

Fully assembled sector







Auxiliary systems

- Gas system
- Cooling system
- Temperature monitoring system
- Laser system

Gas system

TPC Gas System at SLXL2

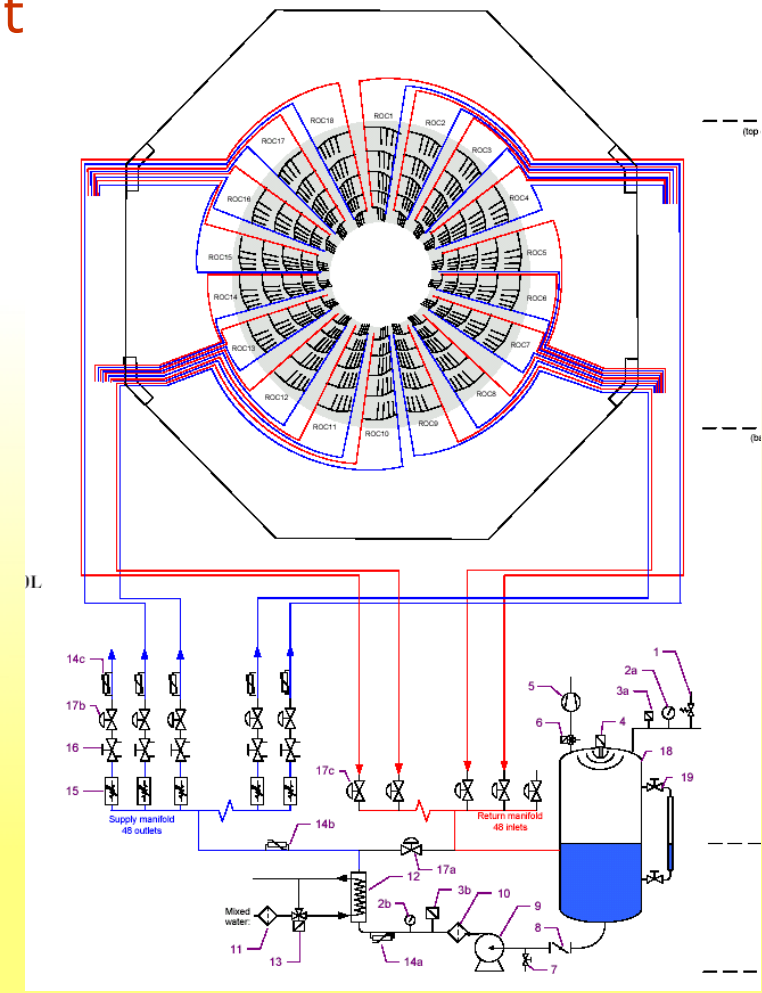
- Recirulating gas system -> recover Ne
- Purifier (removal of H_2O and O_2)

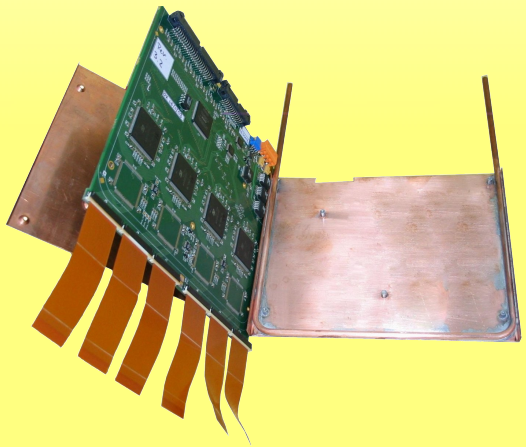
Cooling system

Complex cooling system to equalise TPC temperat

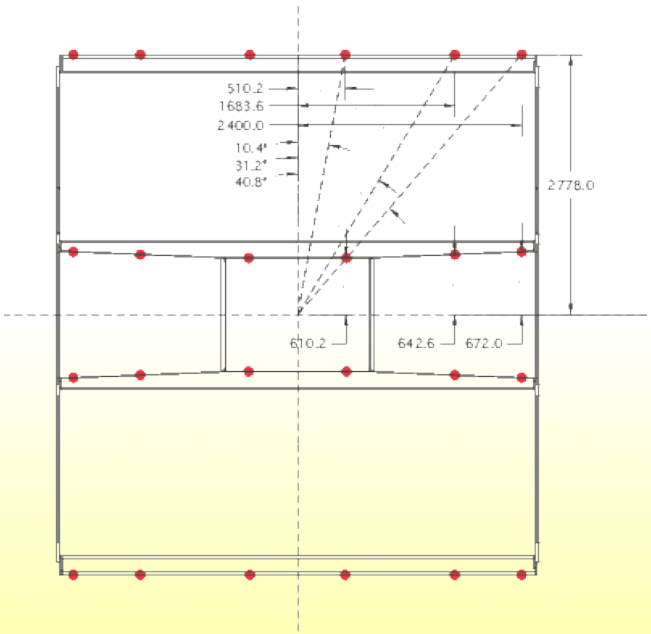
About 60 adjustable cooling circuits:

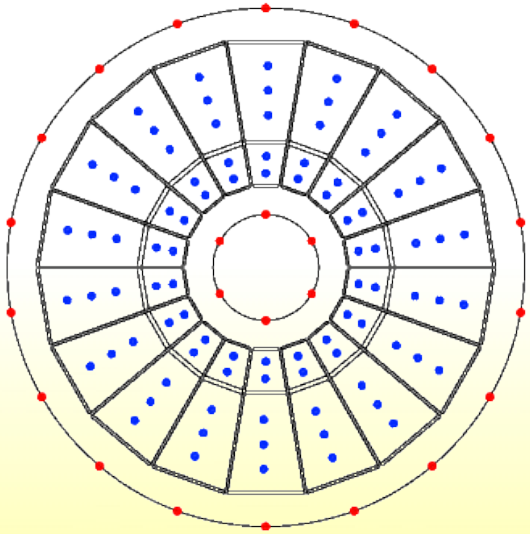
- leakless underpressure system
- cooling of ROC bodies
- FEE enveloped in copper plates (≈ 27kW)
- thermal screens towards ITS and TRD
- service Support Wheel closed with copper shields

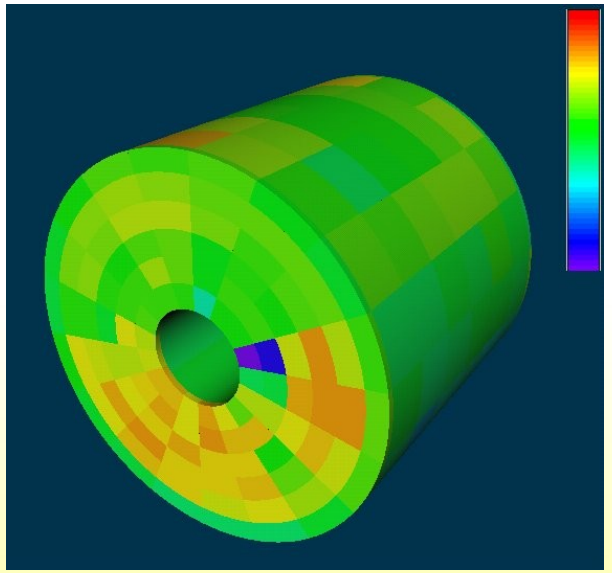




Temperature monitoring system

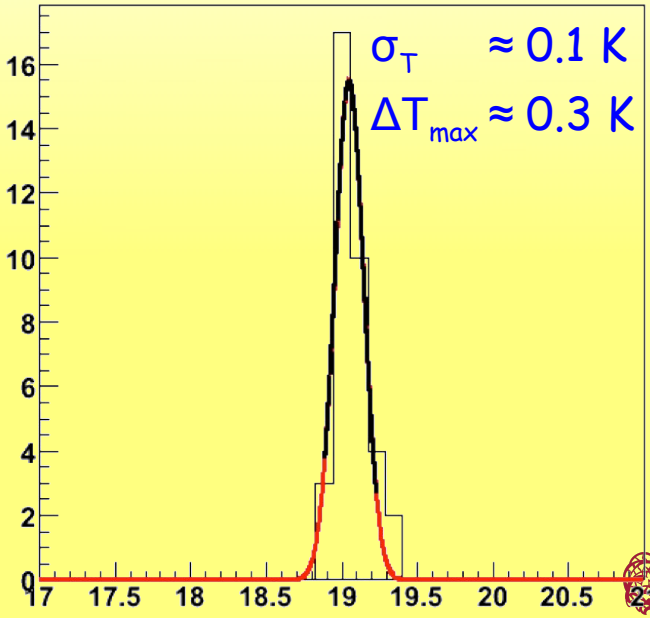




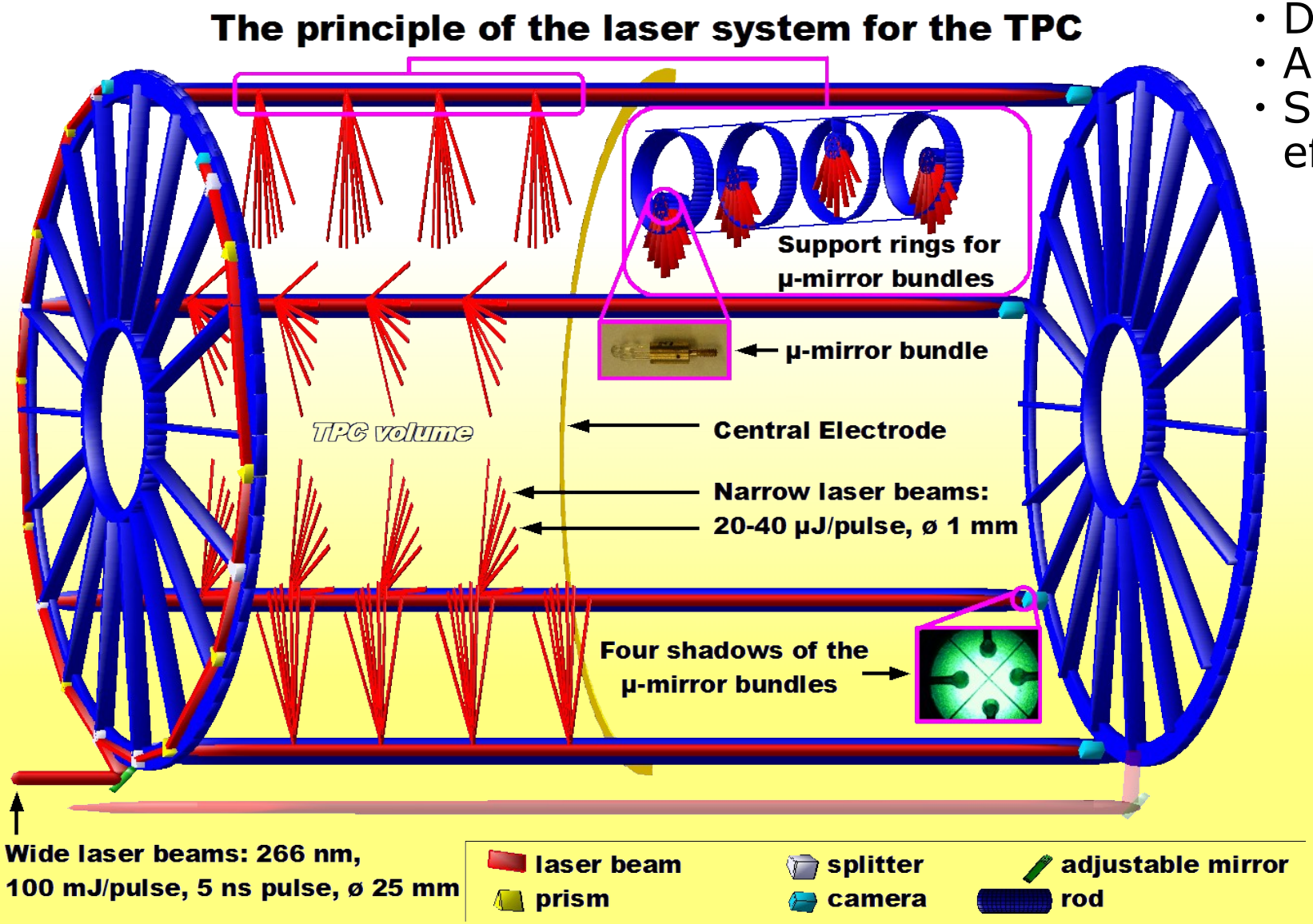


- About 500 sensors distributed all over the TPC
- calibrated within ~ 100mK

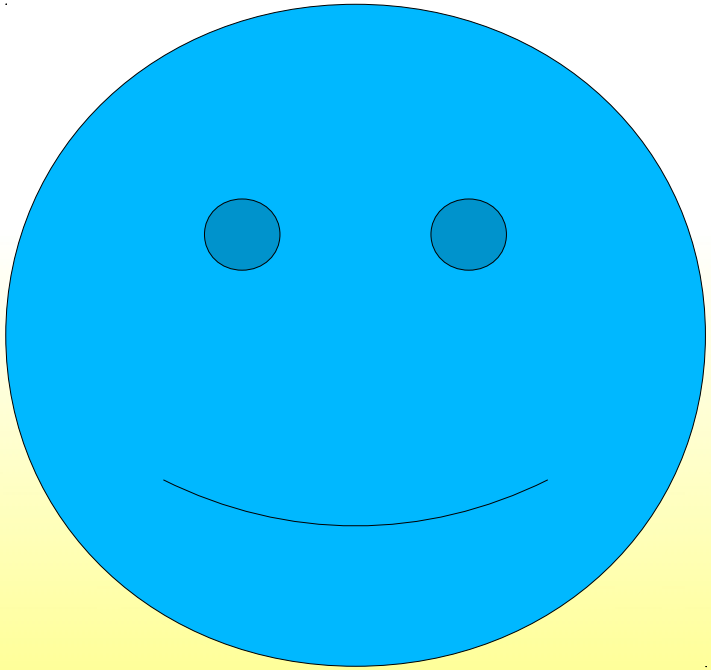
Successful calibration of the cooling system to design specifications



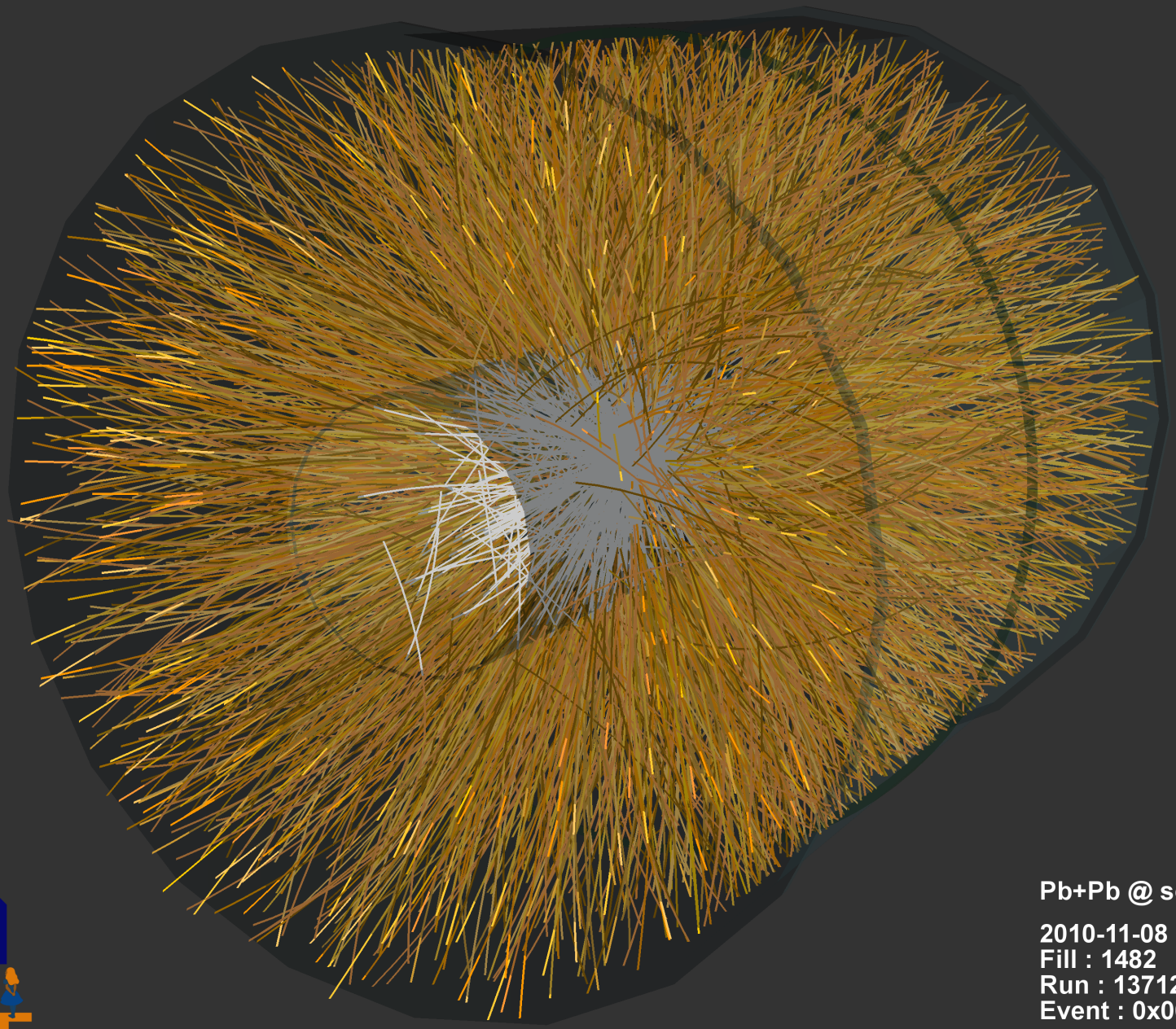
Laser calibration system



- Drift velocity
- Alignment
- Space charge effects



Lets breath for a moment, then the fun starts!



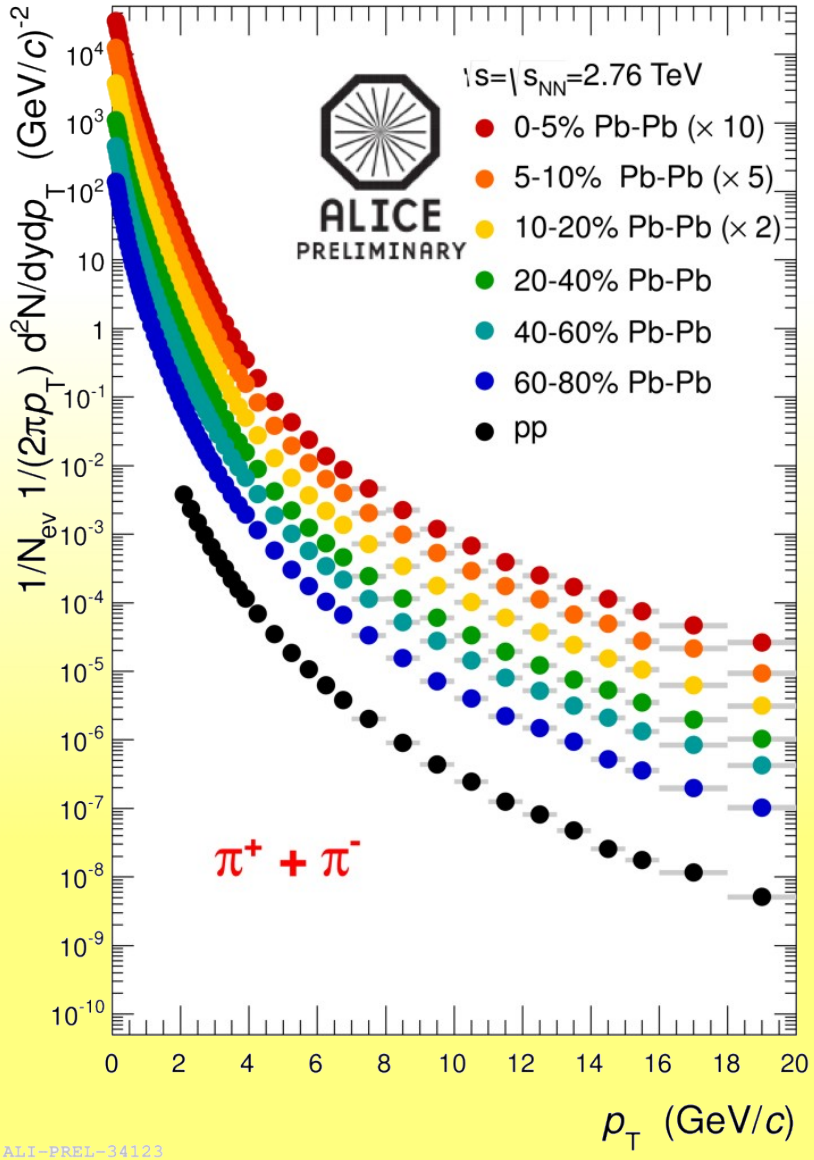
ALICE

Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

PHYSICS

AliAnalysisTaskGiveMeMy PiSpectraForAllMultiplicities



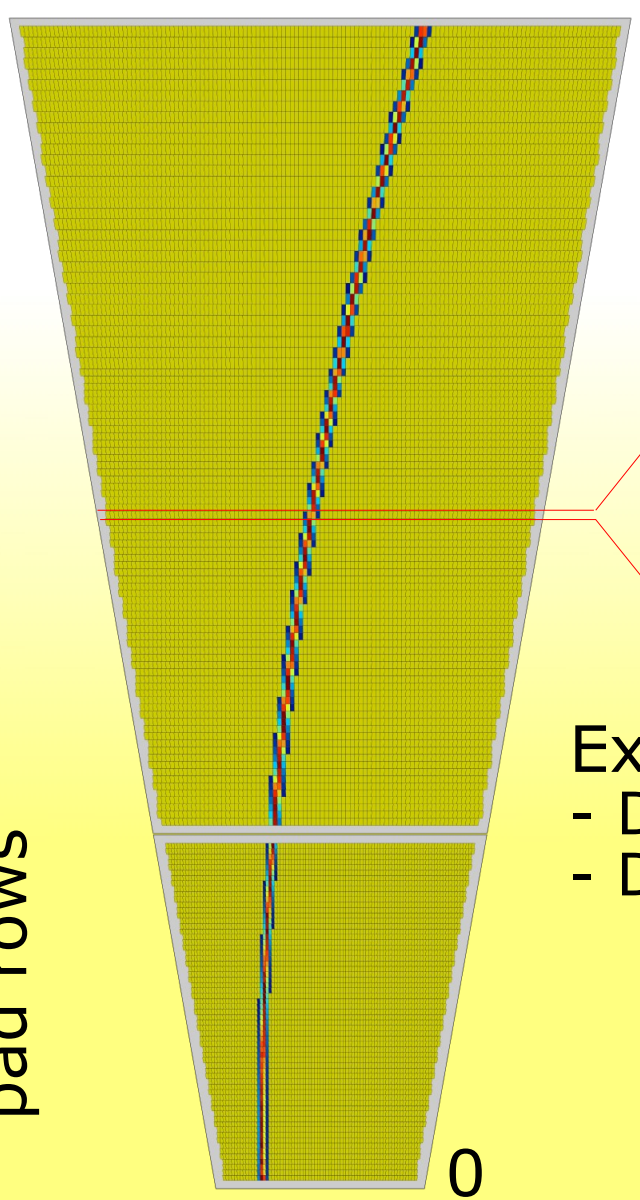
But ...

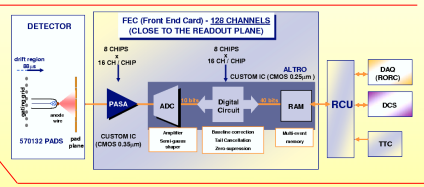
- How do I get those tracks out of my detector
- How do I know it's a pion

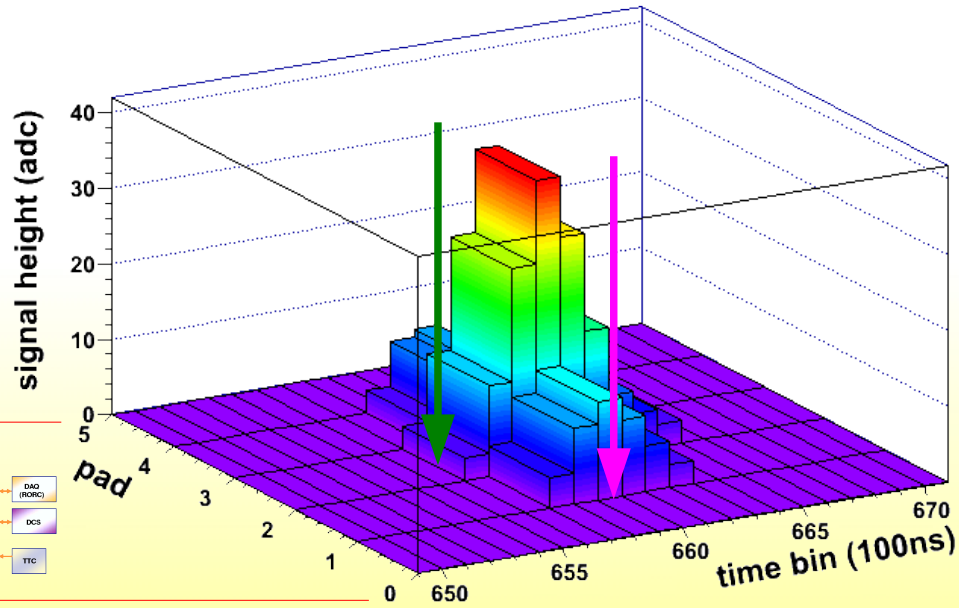
Reconstruction & Calibration

- Space points
- Track finding
- dE/dx calculation

Space point reconstruction



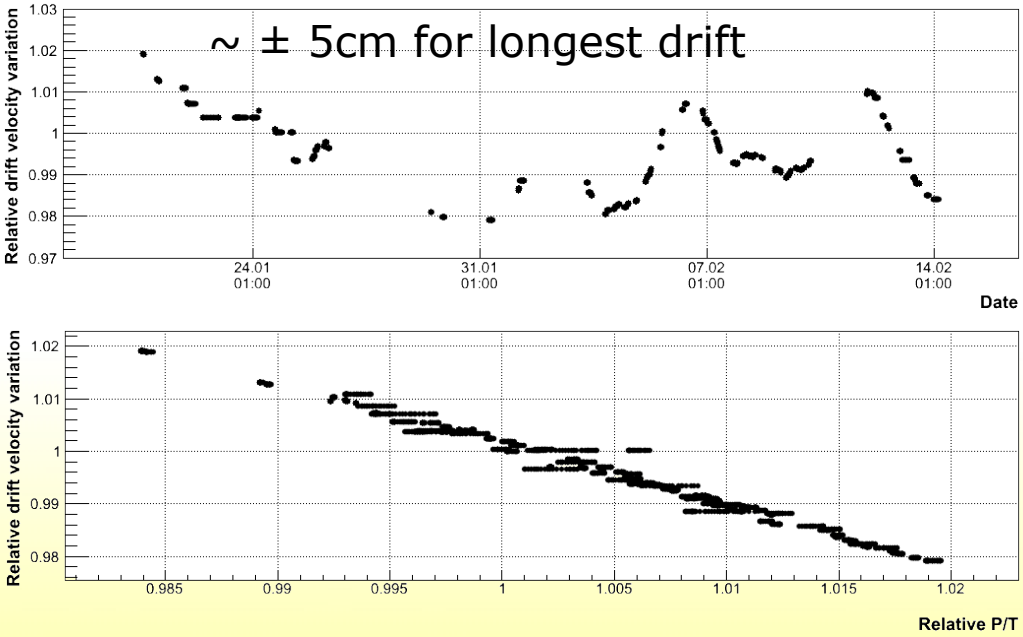


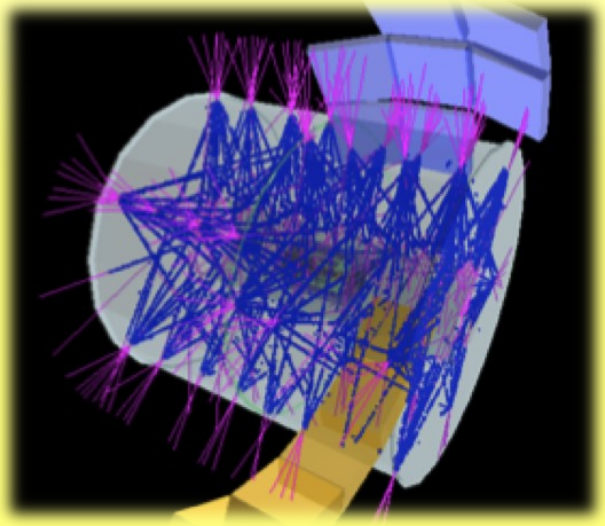


Extract space point for each pad row
- Determine centre of gravity in time direction
- Determine centre of gravity in pad direction

Space point calibration I

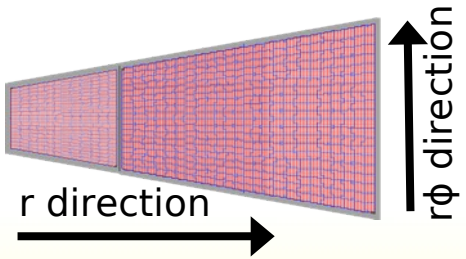
- z coordinate depends on the measured electron drift time and drift velocity
- Drift velocity changes over time
  - Variations in the gas density (P/T)
  - Changes in the gas composition
- Calibration
  - Use laser system for initial measurement (online)
  - User matching of TPC tracks with ITS

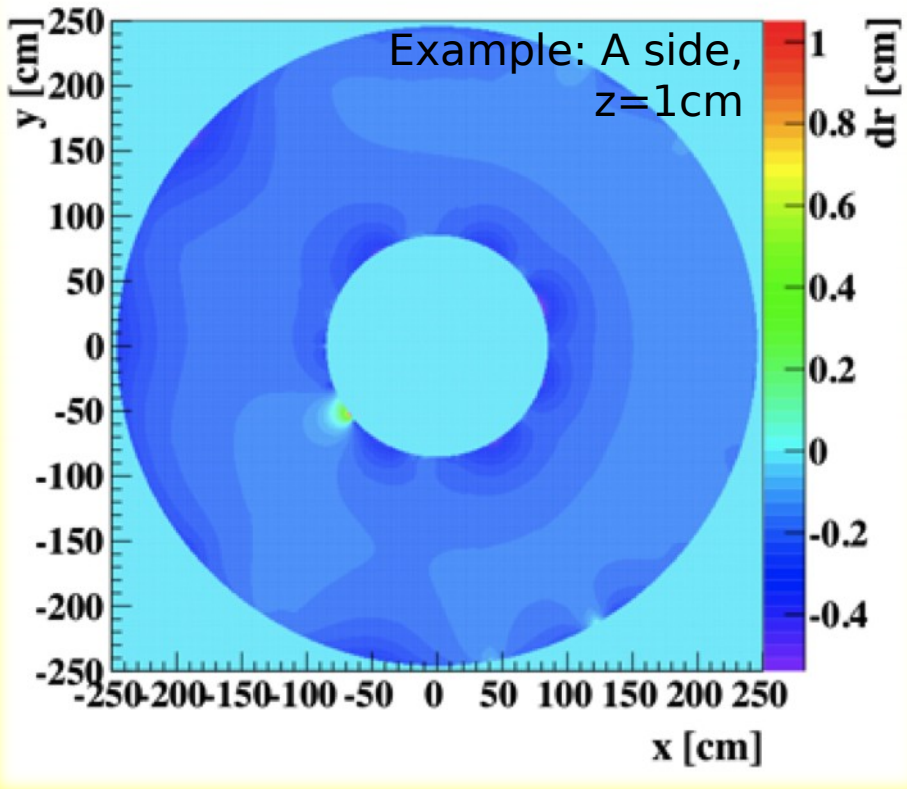


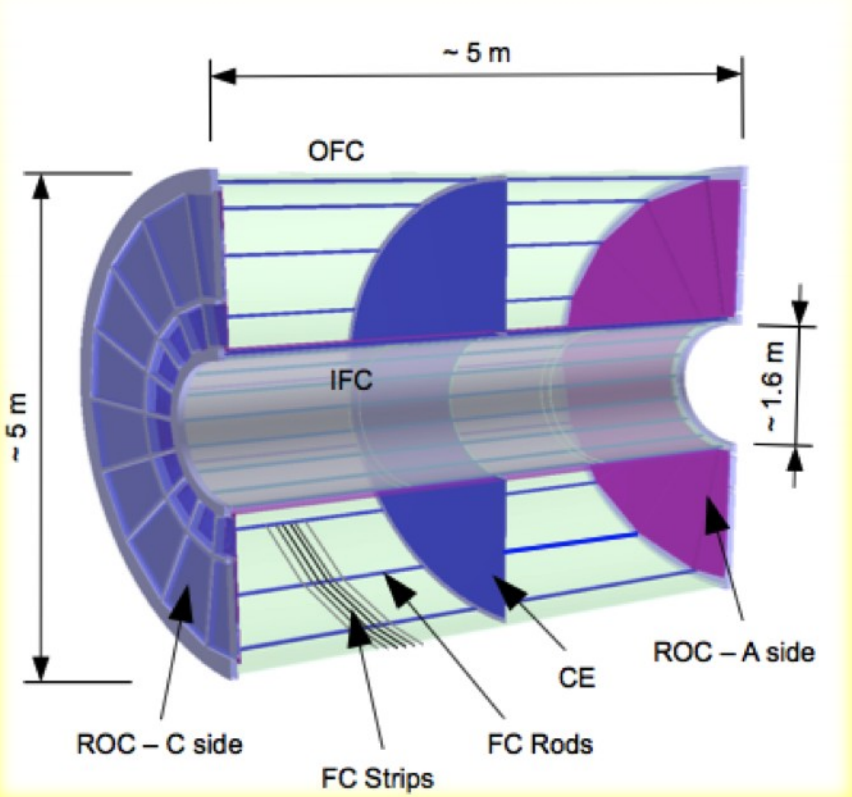


Space point calibration II

- Drifting electrons are deflected from ideal drift path
- Imperfections in the field cage
- Maximum (very local):
  - δr = 10 mm (shown here);
  - δrϕ = 0.8 mm

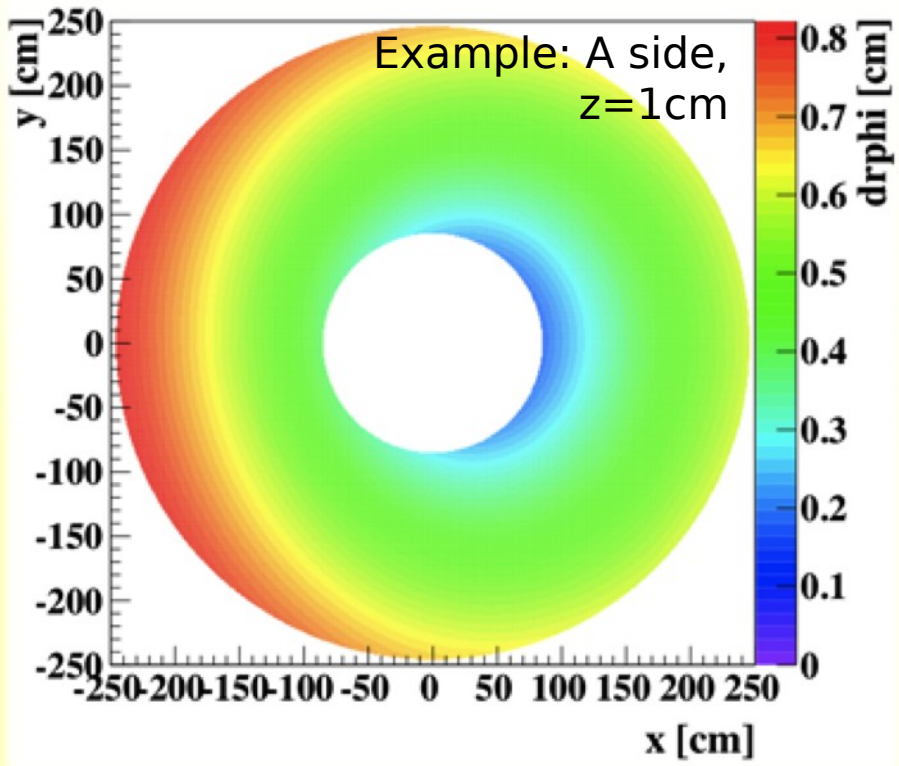


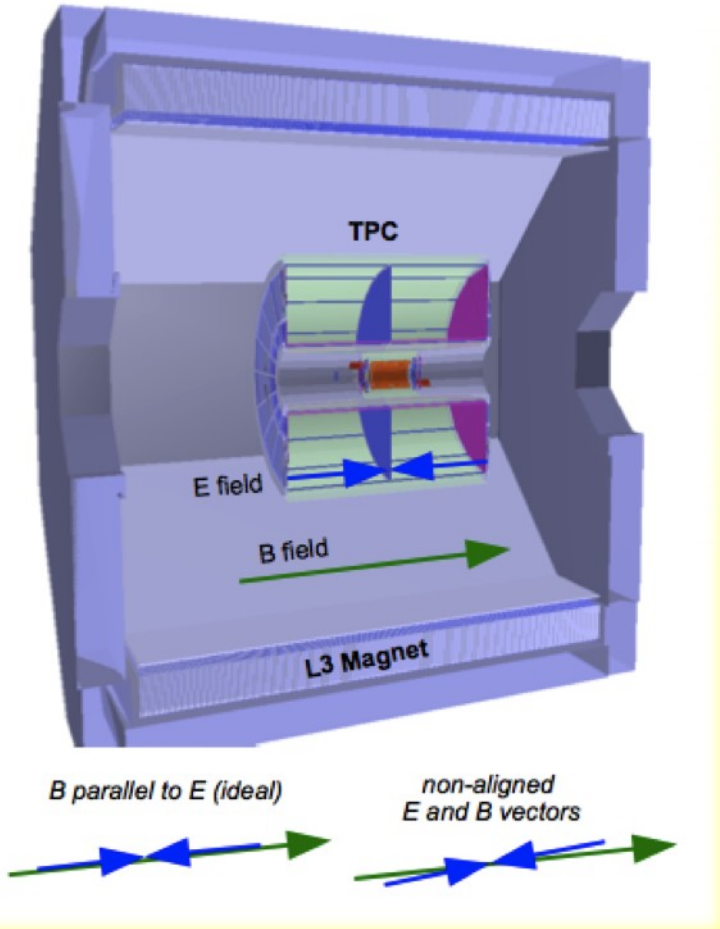




Space point calibration III

- Drifting electrons are deflected from ideal drift path
- B field shape (homogeneity) and alignment with E field
- Maximum
  - δr = 4 mm;
  - δrϕ = 8 mm (shown here)

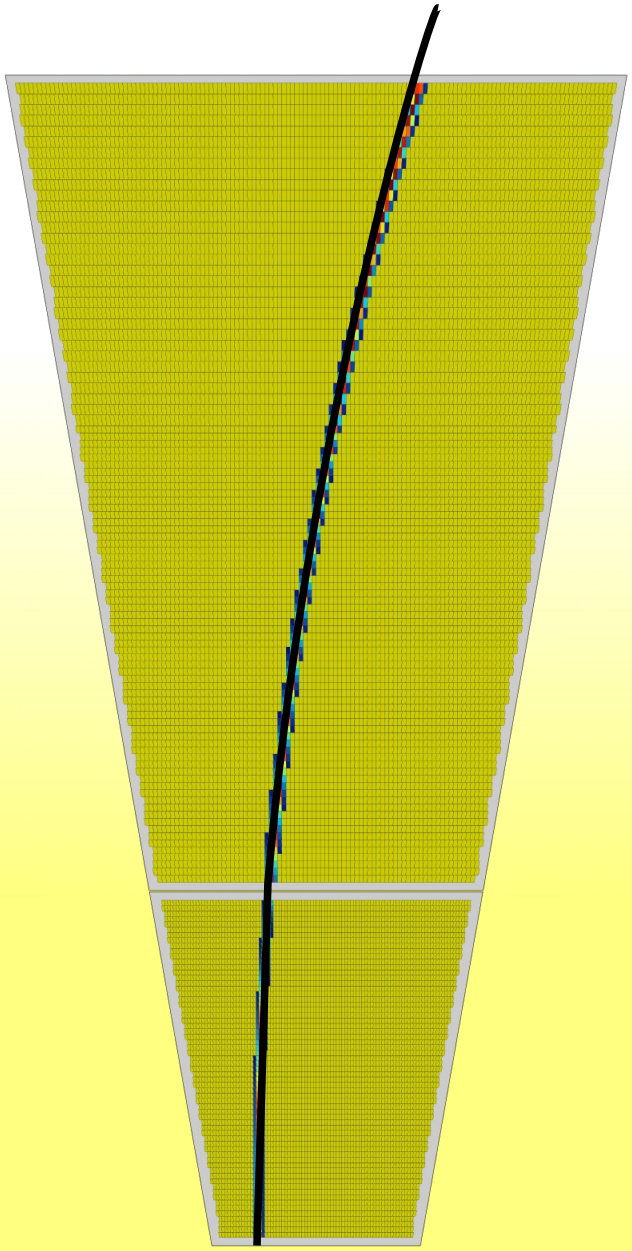




Space point calibration – even more

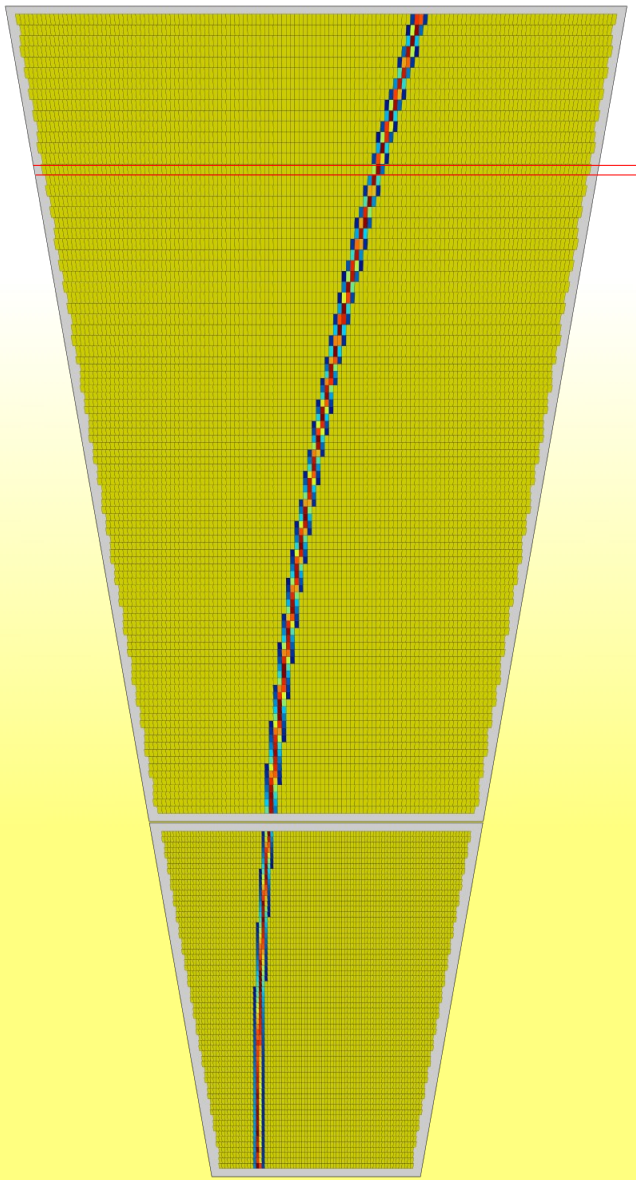
- Readout chamber alignment
- ...

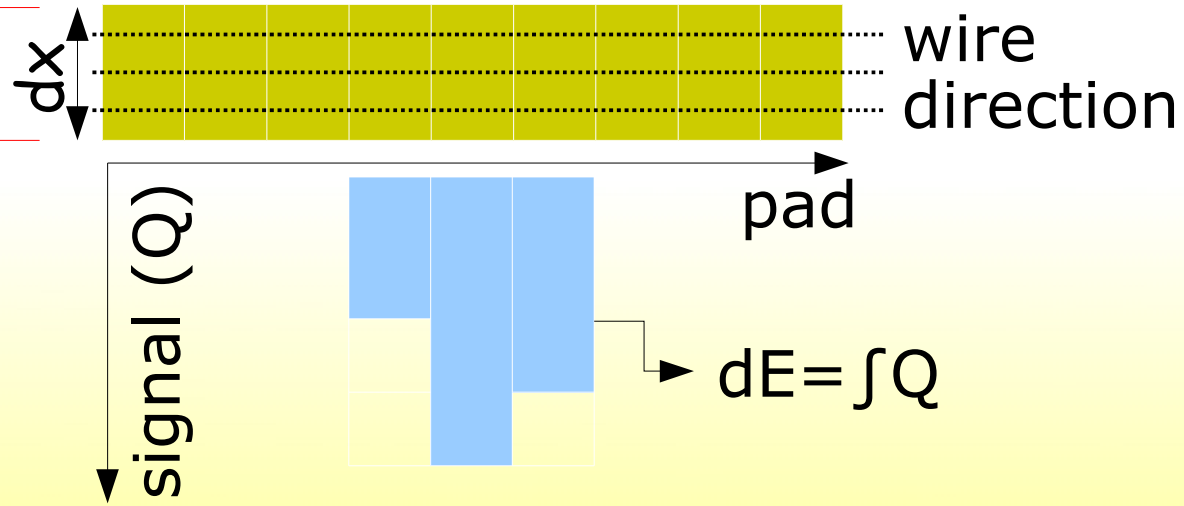
Track fitting

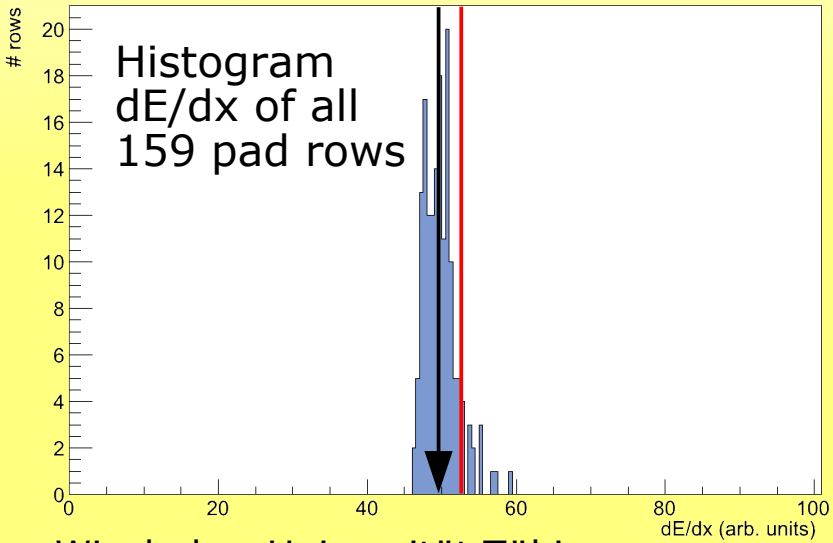


- Fit reconstructed space points with a helix parametrisation
- Procedure
  - Fit from larger to smaller radii
  - Start 'seeding' from outer most clusters (low occupancy)
  - Extrapolate to next row
  - Look for cluster close to extrapolation
  - Associate cluster to track & update parameters
- Kalman filter
  - Track parameters improve with added points
  - Provides error parametrisation of parameters & fit quality (e.g. X^2/cluster)

<dE/dx> measurement



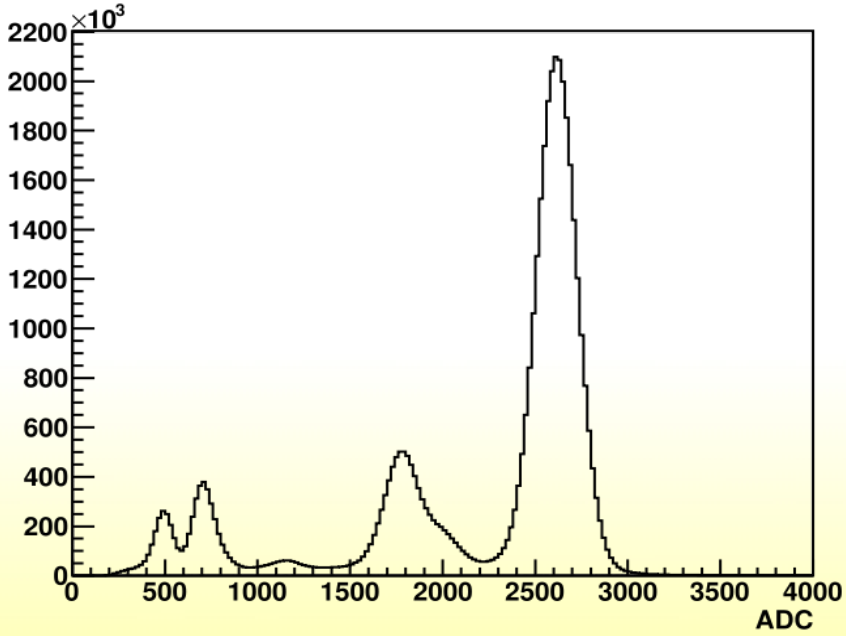


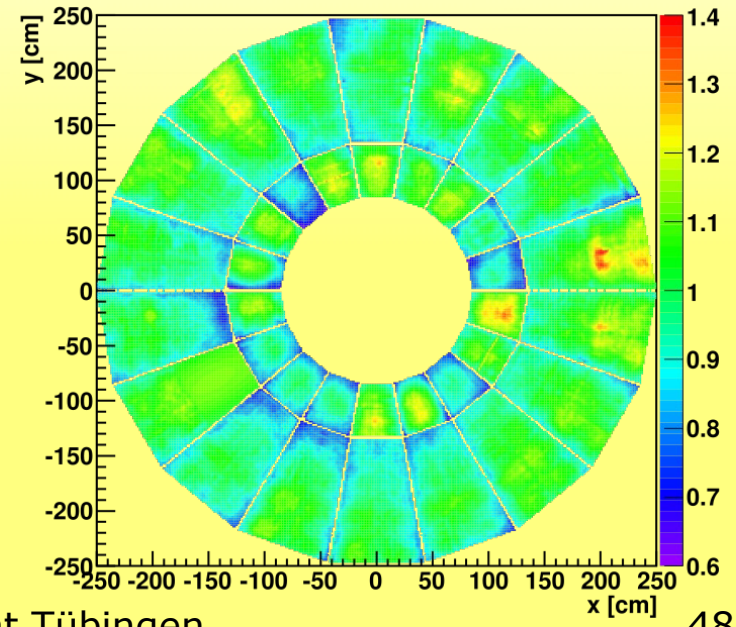


Truncated mean (<dE/dx>) cutting upper 40% of the charge distribution used as PID signal

<dE/dx> calibration I

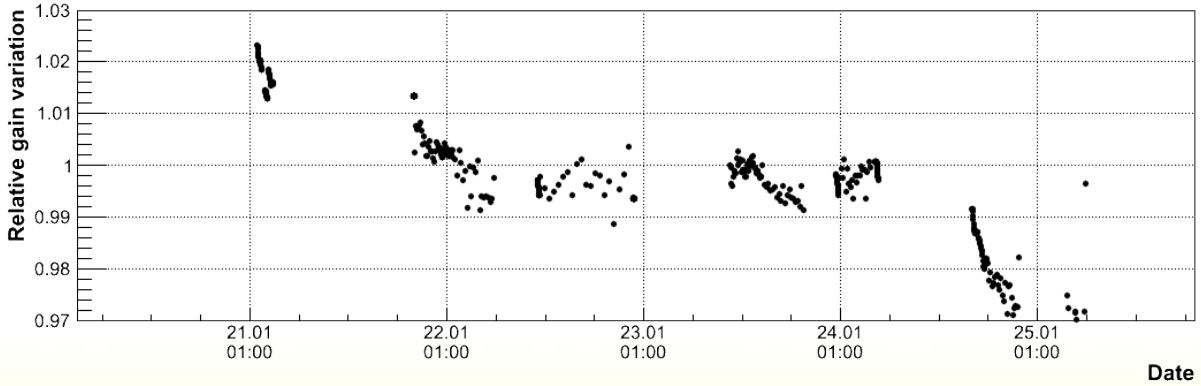
- Gain variations expected due to manufacturing tolerances (readout chips, chambers)
- Calibration
  - Release radioactive ^{83}Kr into the TPC gas
  - Record decay spectrum for each single pad
  - Create gain map on single pad level
  - Repeat ~ yearly

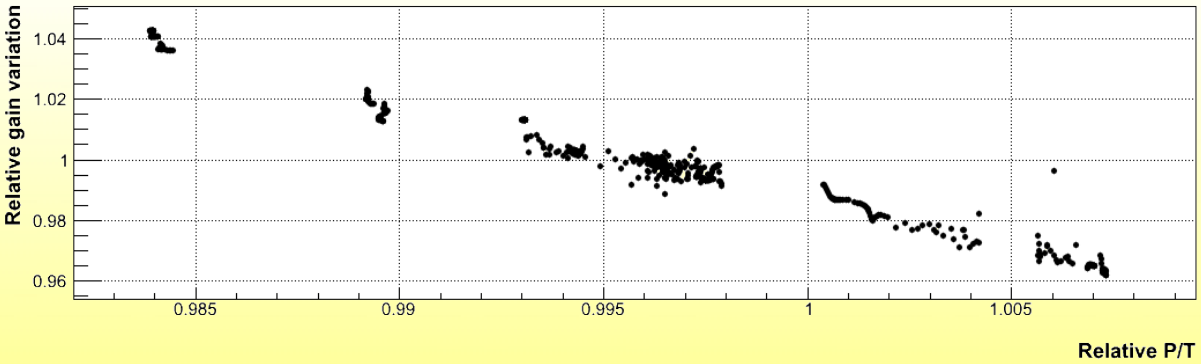




<dE/dx> calibration II

- Gain changes over time
  - Gas density (P/T)
  - Gas composition
  - HV on chambers
- Calibration
  - Monitor gain for each chamber





- Gain changes with drift distance
  - Electron attachment
  - Diffusion (cluster lost below threshold)
- Calibration
  - Monitor gain vs. drift time

<dE/dx> calibration – even more

- dx dependence on local inclination angles
- Correct for lost clusters (below electronics threshold)
- Ion tail corrections
- …

Performance

- Space point resolution
- Momentum resolution
- dE/dx resolution

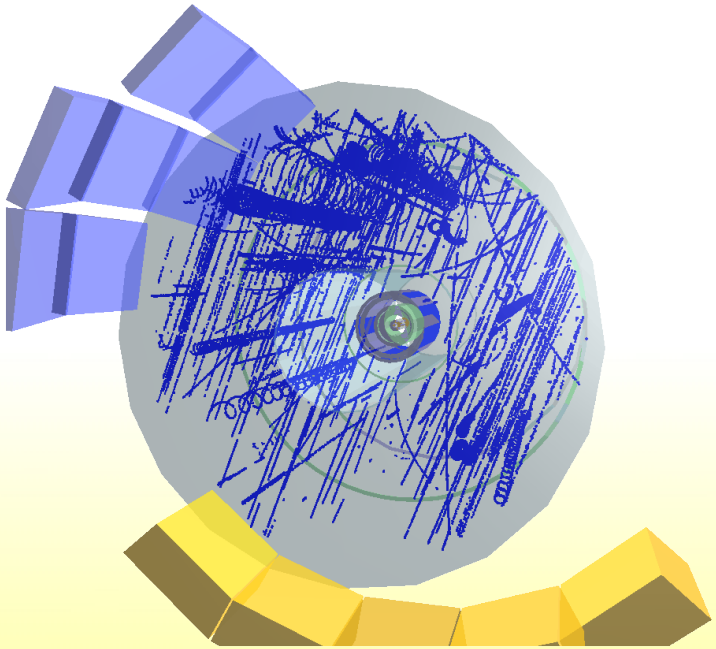
Space point resolution

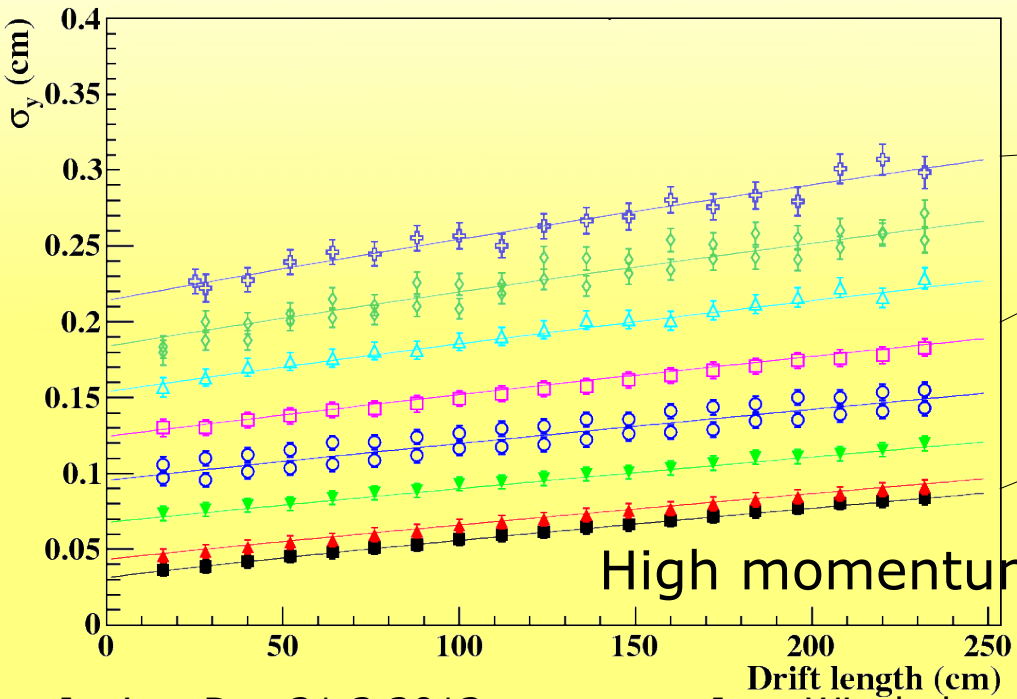
Space point resolution depending on

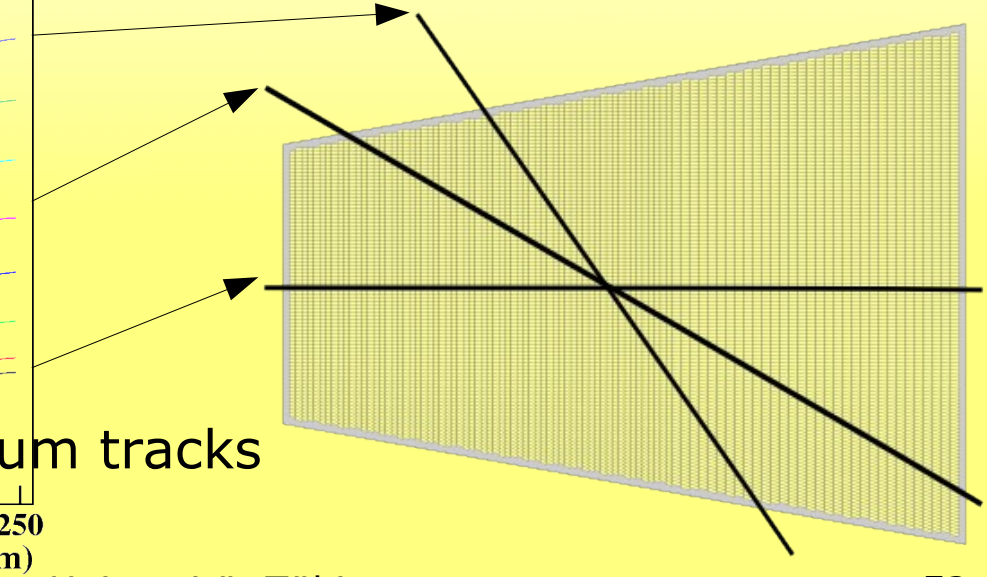
- drift length (diffusion)
- pad inclination angle (ideally close to zero)

Measurements in agreement with simulations:

space point resolution in rφ 300 – 800 µm
for small inclination angles
(high momentum tracks)

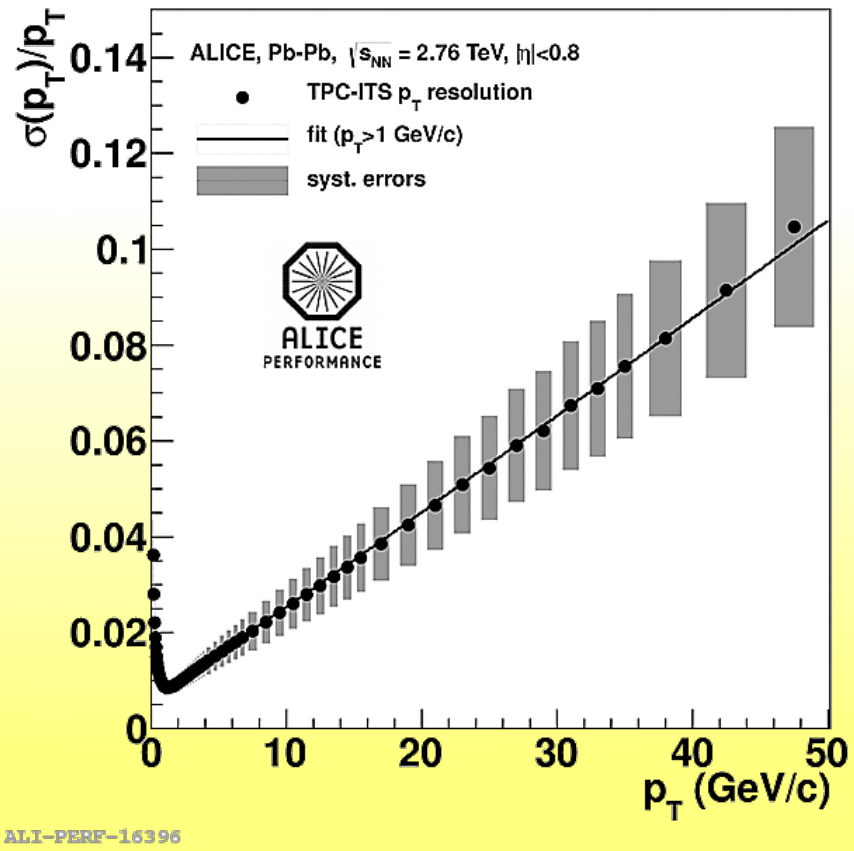






High momentum tracks

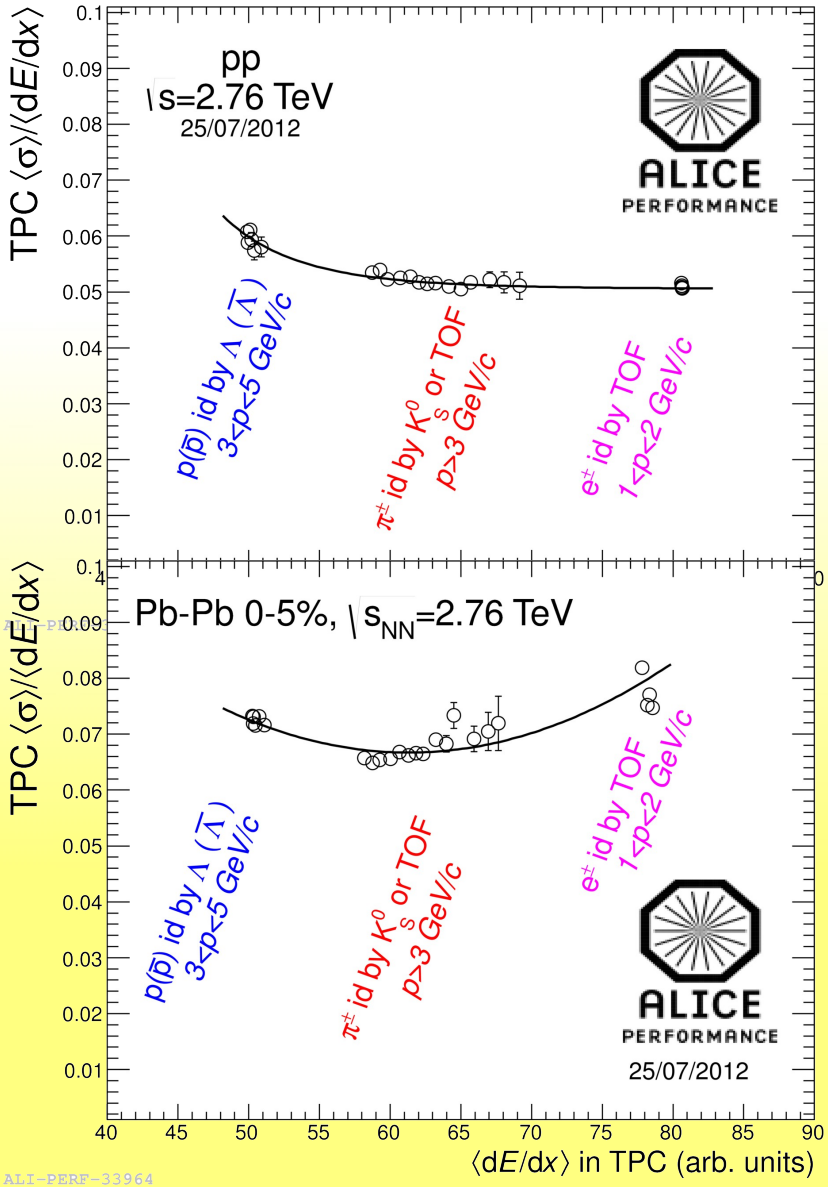
Momentum resolution



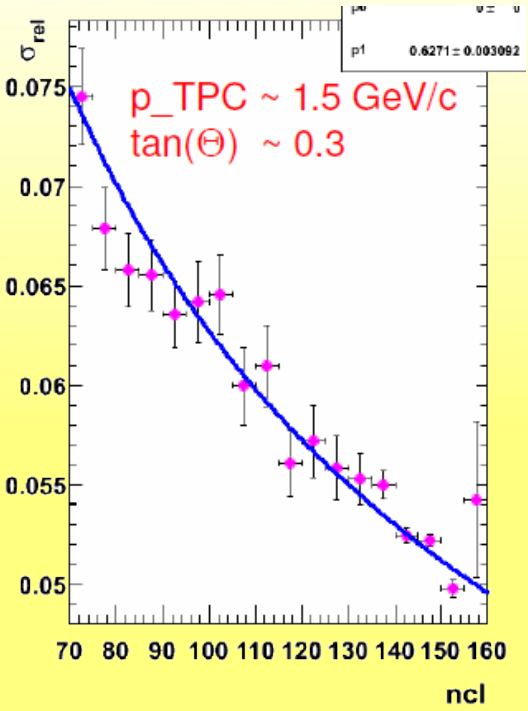
Combined tracking TPC-ITS **momentum resolution ~10% at 50 GeV/*c***
(Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV from 2010)

For new productions, the momentum resolution improved to ~ 5% at 50 GeV/*c*, as a result of improved TPC-ITS matching

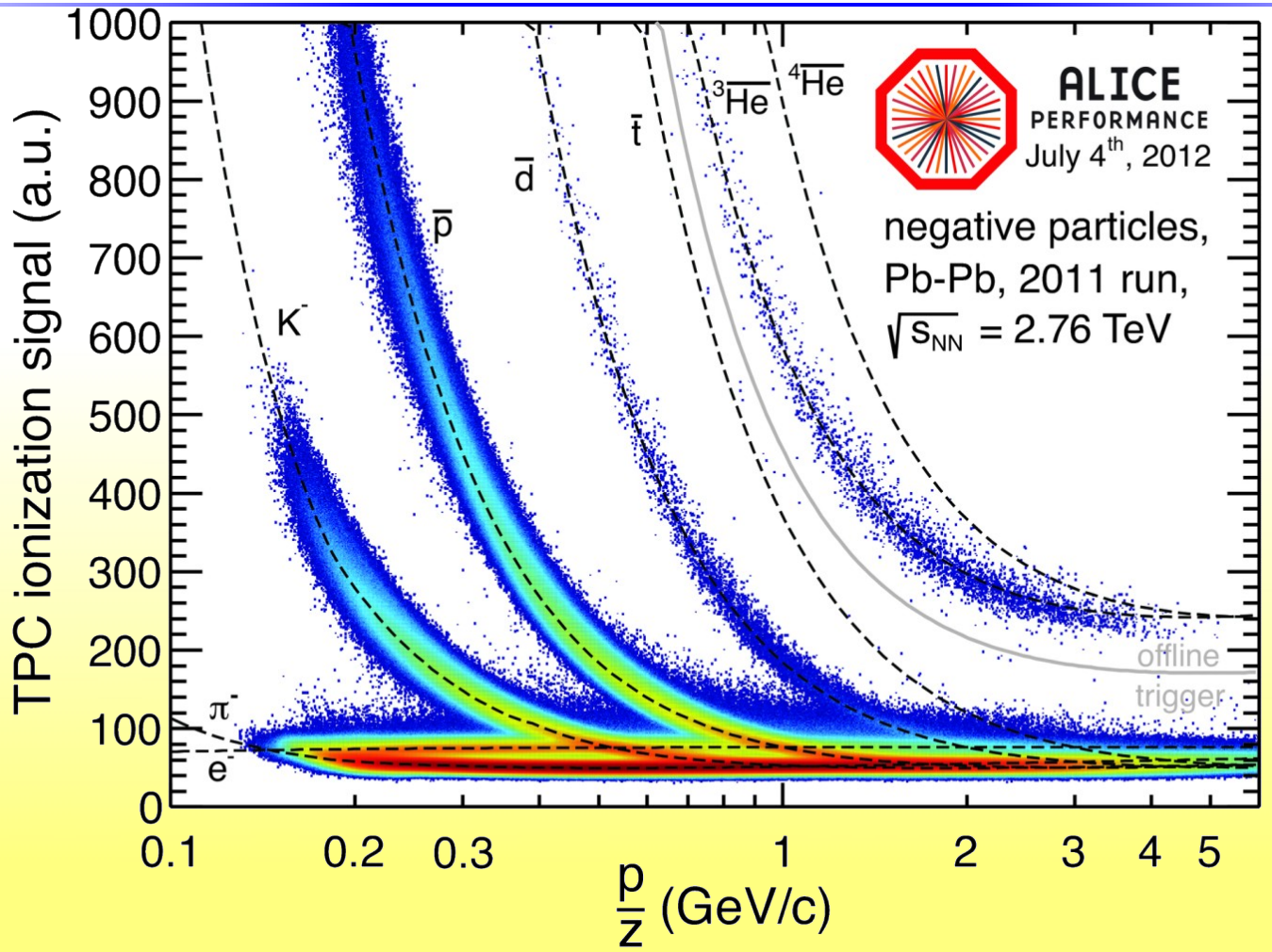
dE/dx resolution



- <dE/dx> resolution close to design values
  - 5.5% at low multiplicity
  - 6.8% at high multiplicity
- Depends on several parameters
  - <dE/dx> itself
  - # of used clusters
  - eta

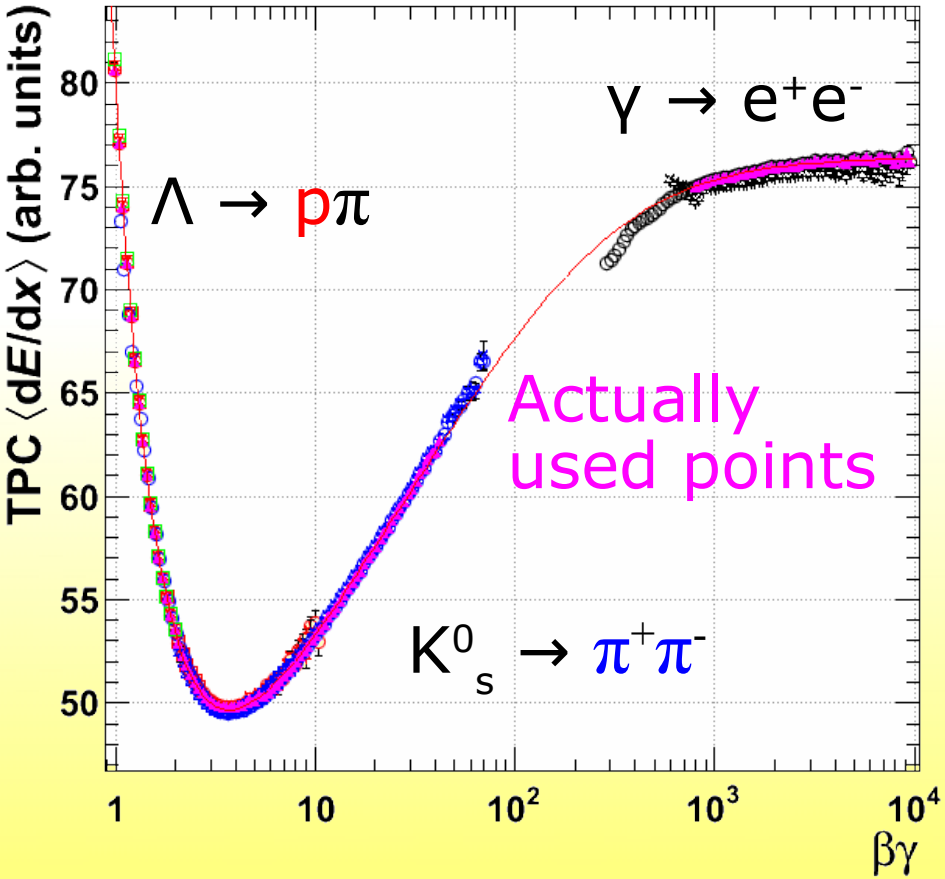


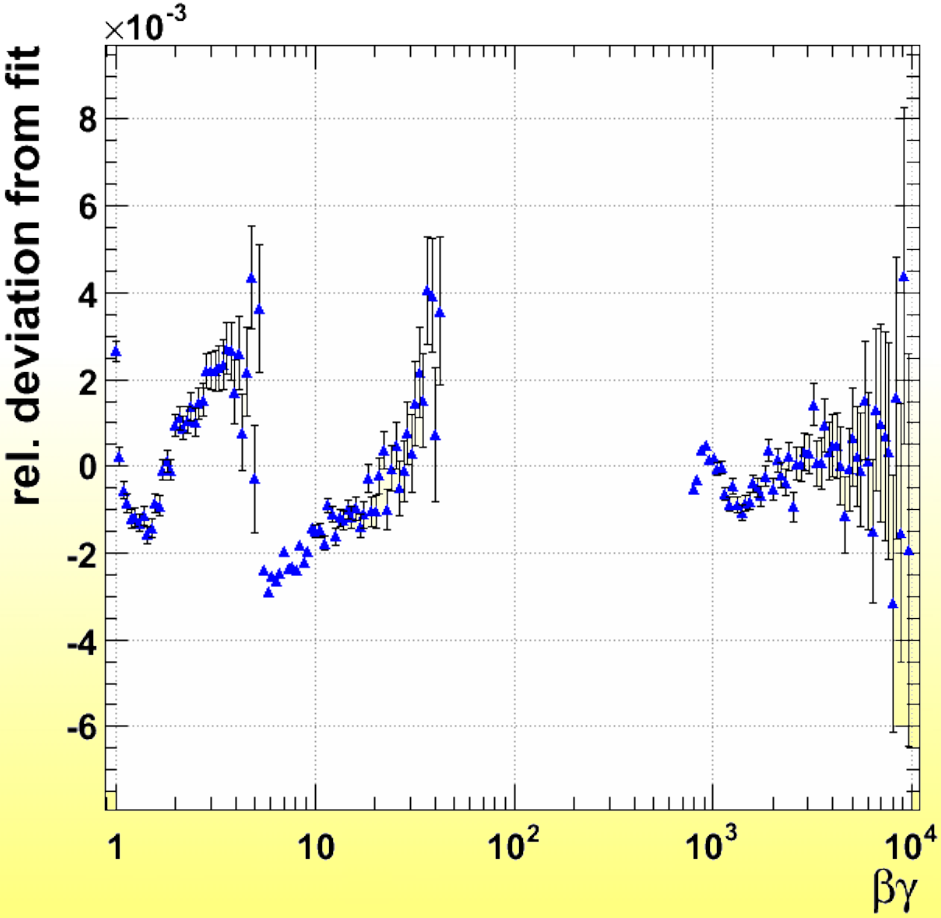
Particle identification with the TPC



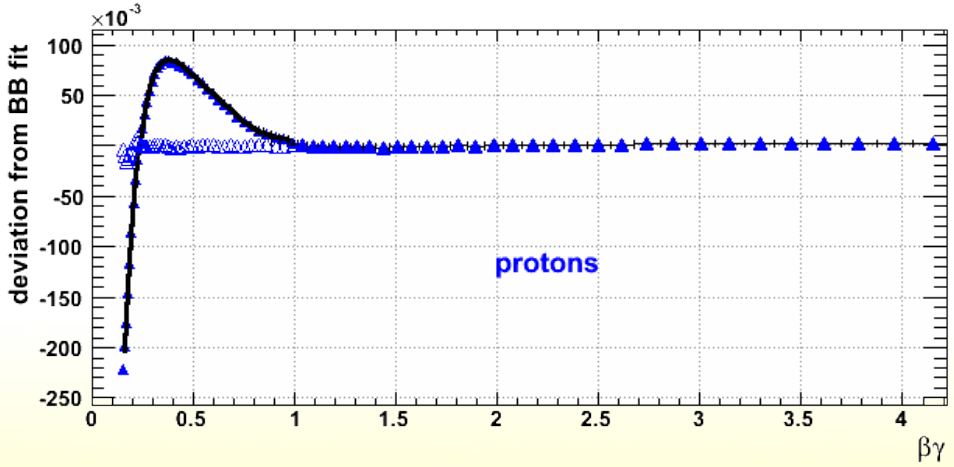
- Nicely calibrated TPC
- But how to identify particles → expected energy loss & resolution

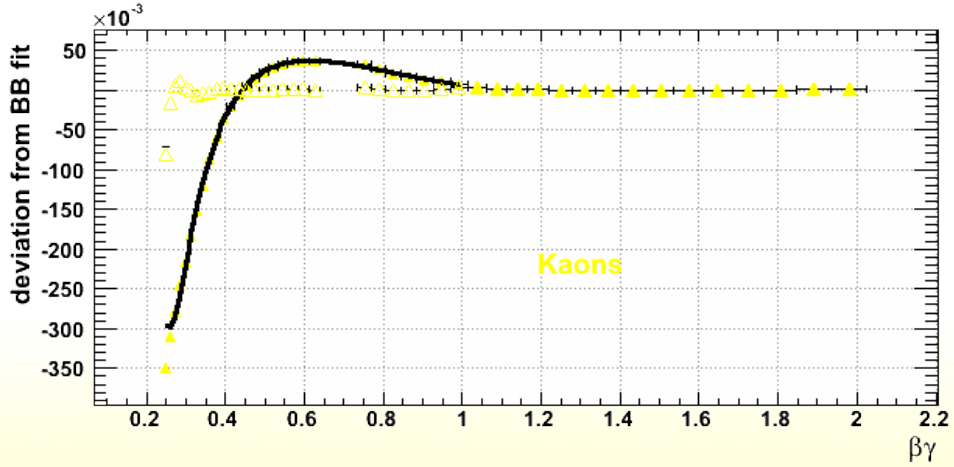
Fitting of the Bethe Bloch function

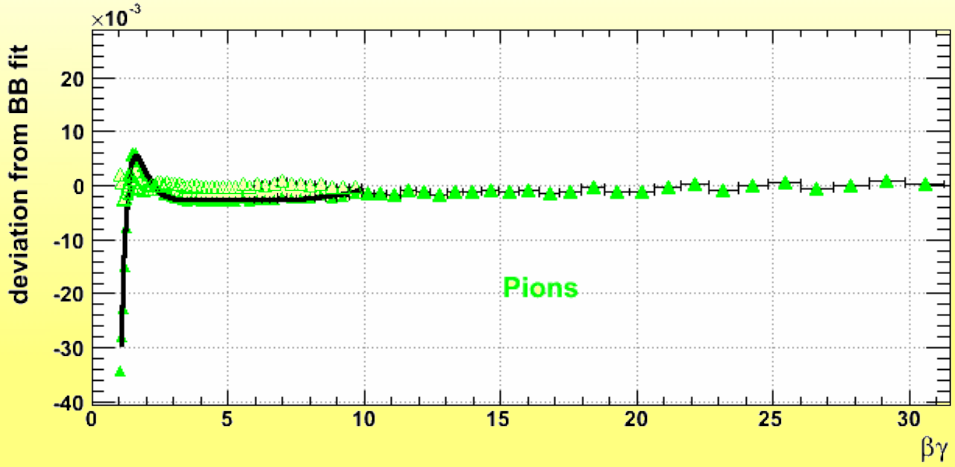


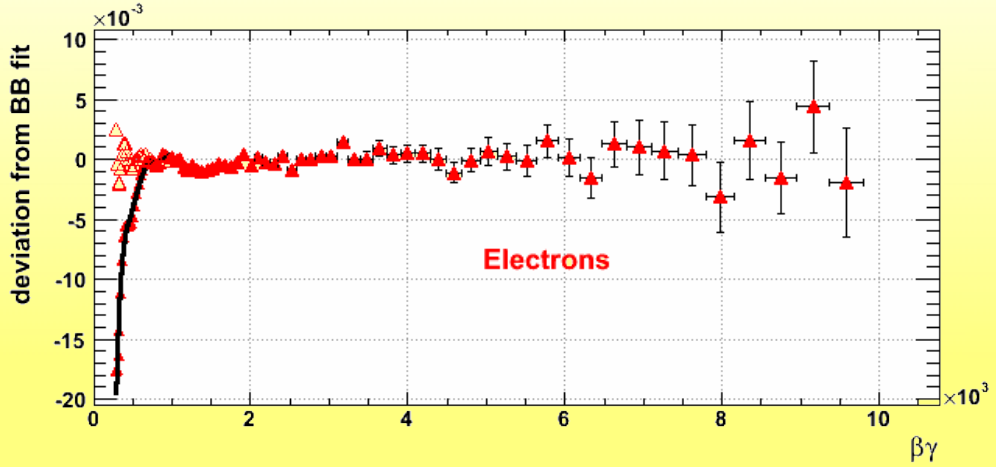


Residual calibration at low momentum



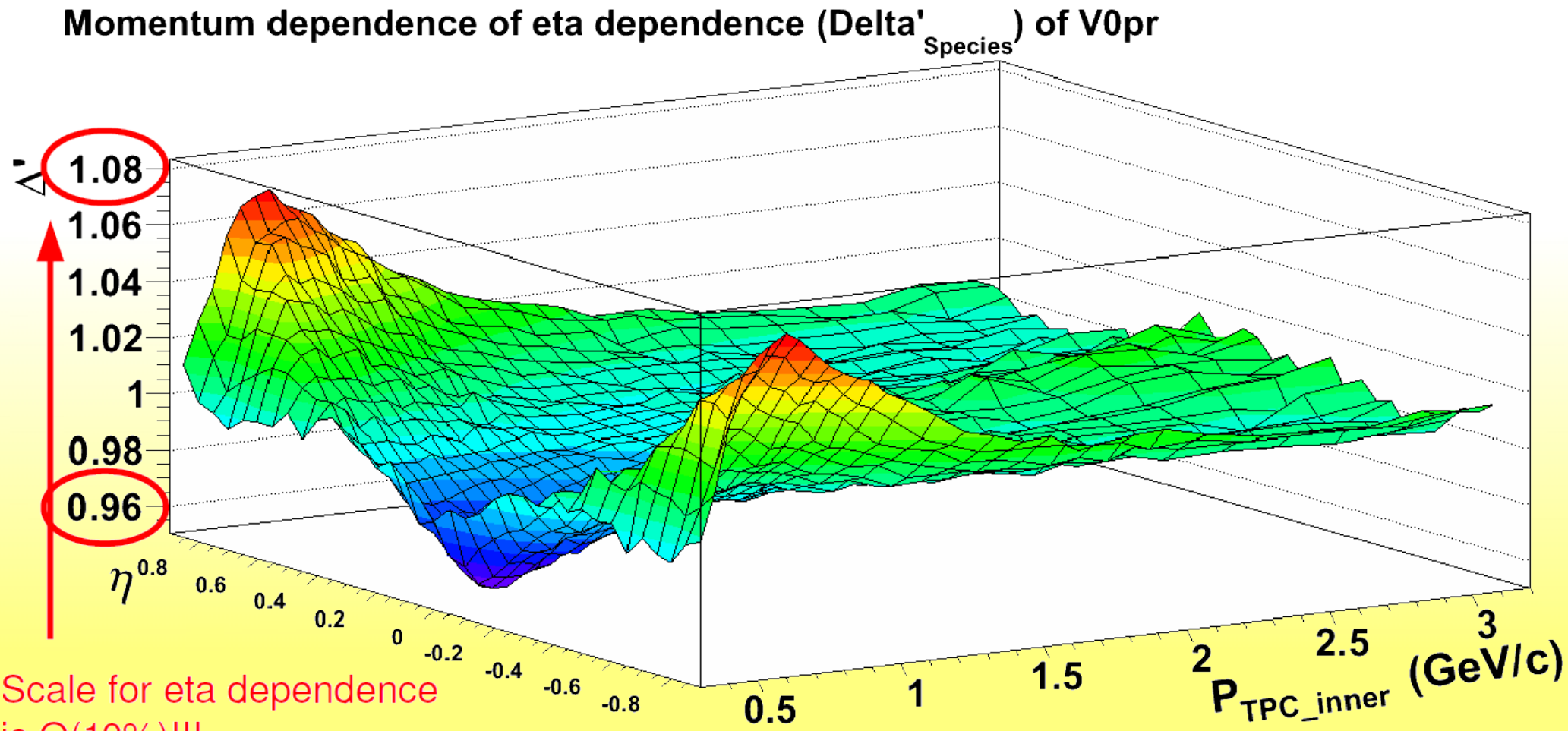






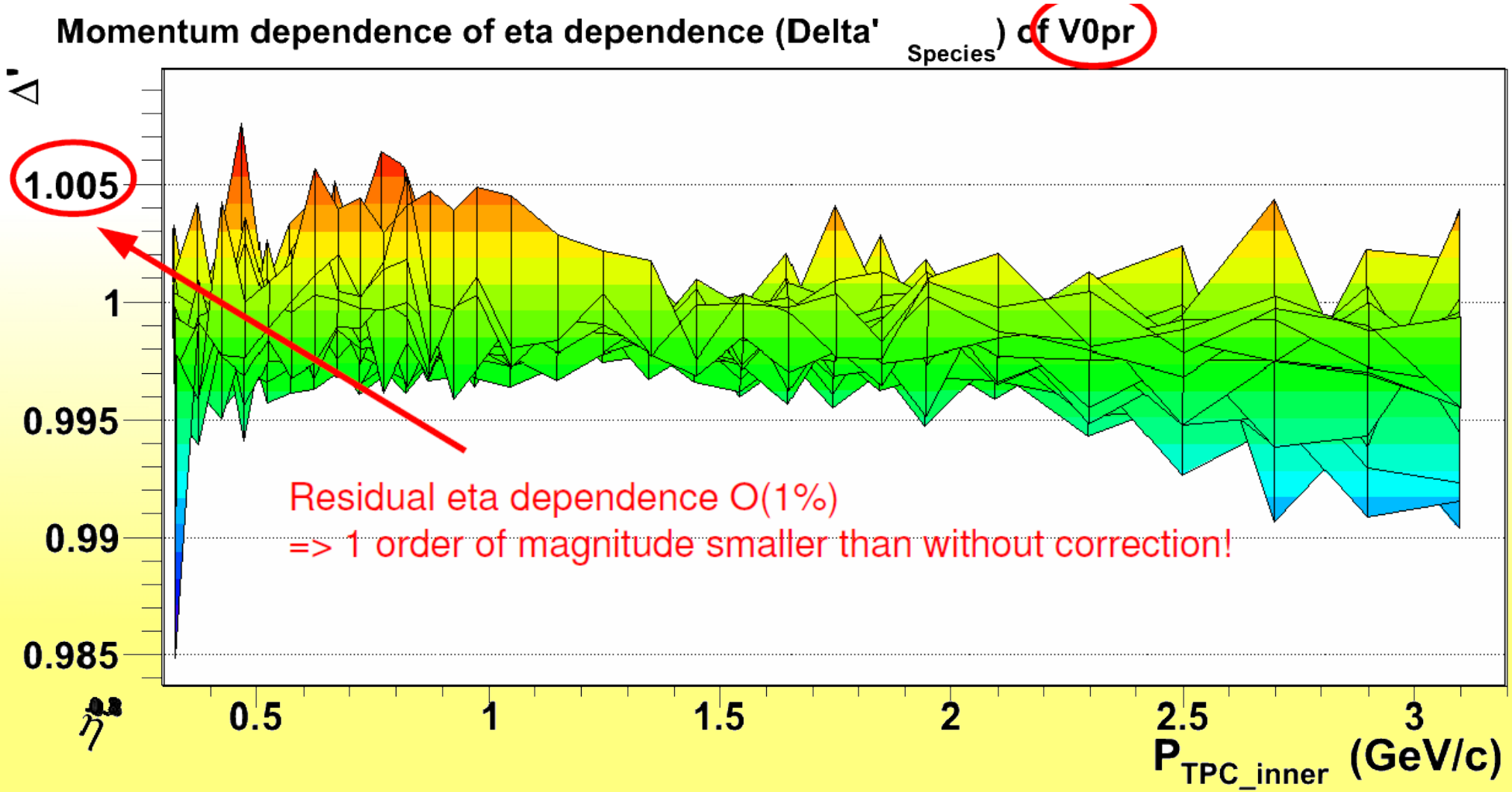
Small deviations at low momentum
The Bethe Bloch parametrisation, corrected for the low momentum effect is called spline

Residual calibration on eta



Scale for eta dependence is O(10%)!!!

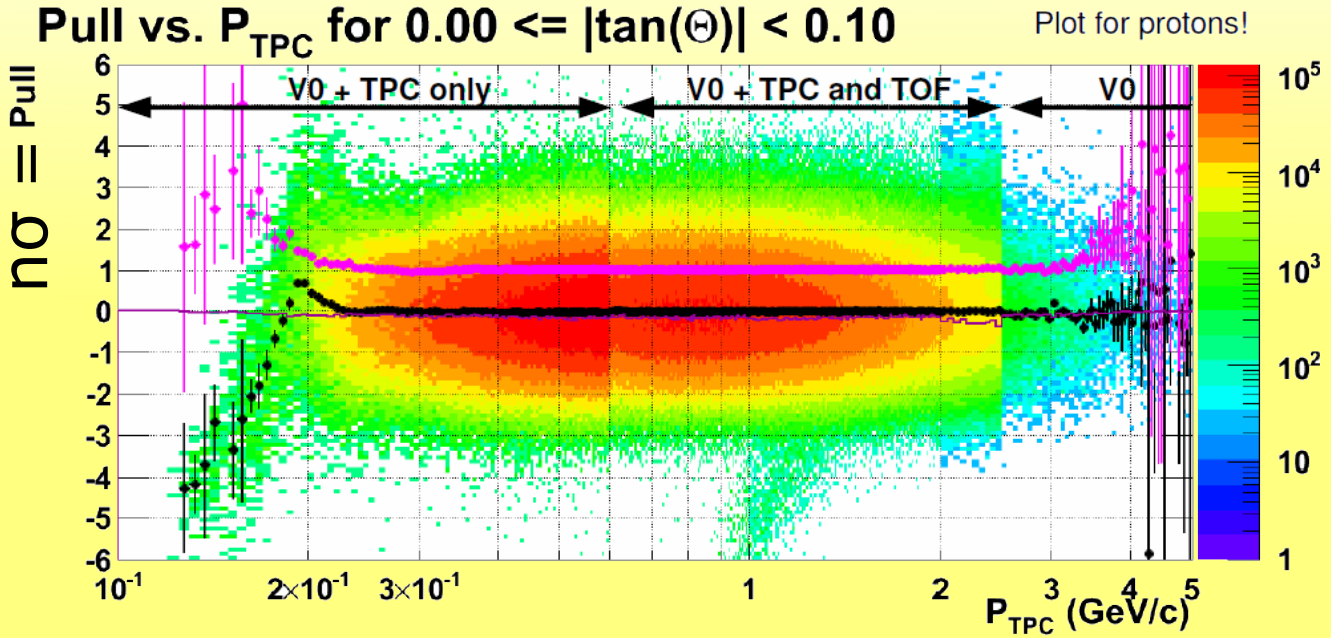
Residual variation after correction

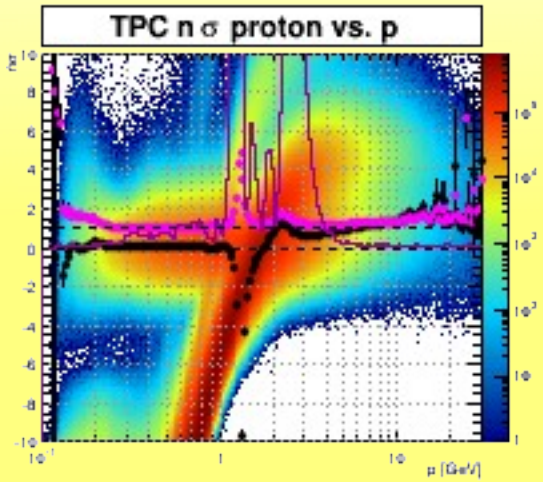


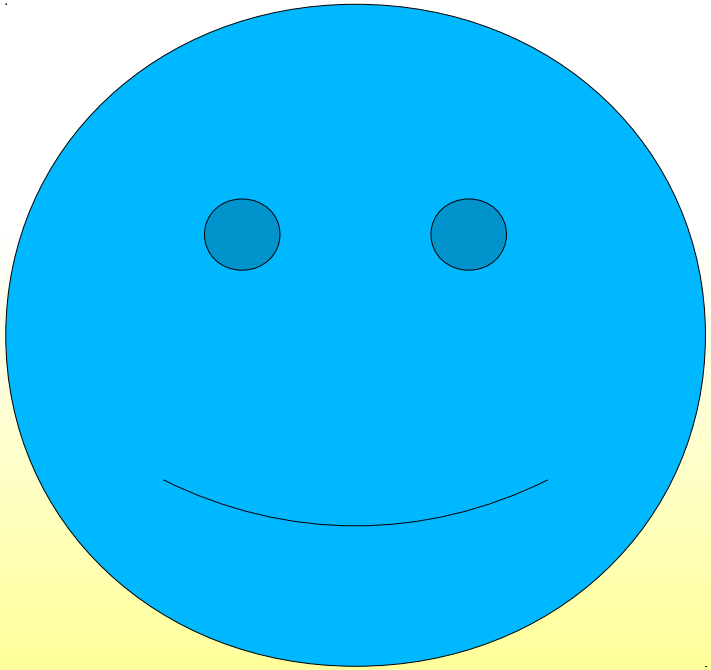
What is most commonly used - nσ

Number of sigmas:
"deviation of the measured energy loss to the expected energy loss of a certain particle expressed in terms of the detector resolution"

$$n\sigma^{particle} = \frac{\langle dE/dx \rangle^{measured} - \langle dE/dx \rangle^{spline,particle}}{\sigma(\langle dE/dx \rangle)(PID clusters, dE/dx, \eta)}$$







Ok, let's breath again!

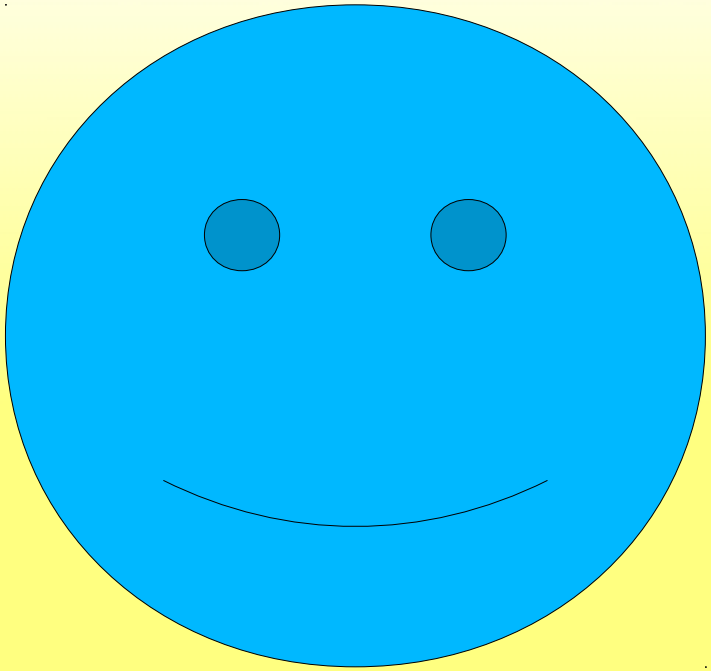
What you see from that

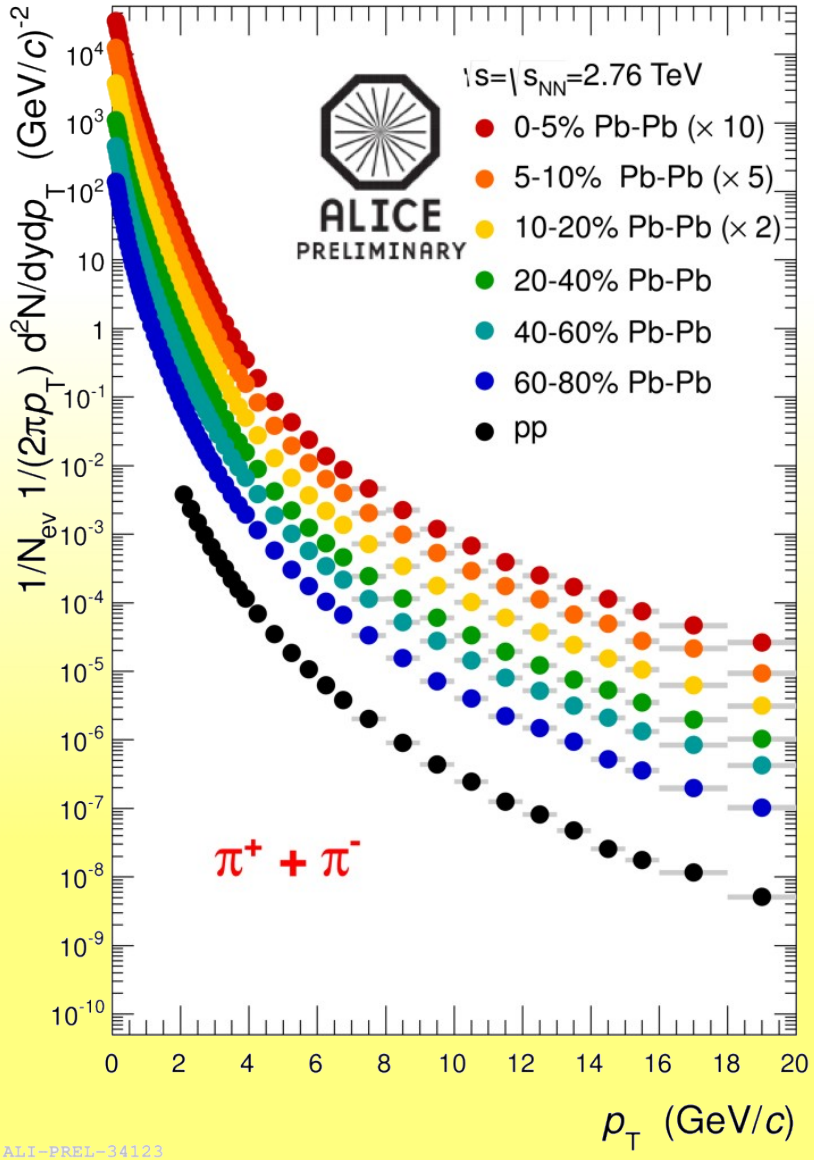
```
void AliAnalysisTaskGiveMeMyPiSpectraForAllMultiplicities::UserExec(Option_t *)
{
    AliVEvent *event=InputEvent();
    AliAnalysisManager *man=AliAnalysisManager::GetAnalysisManager();
    AliInputEventHandler* iH = (AliInputEventHandler*) (man->GetInputEventHandler());
    AliPIDResponse *pid=iH->GetPIDResponse();

    for (Int_t itrack=0; itrack<event->GetNumberOfTracks(); ++itrack) {
        AliVTrack track=(AliVTrack*)event->GetTrack(itrack);
        if (!passesMyCuts(track)) continue;
        Double_t nsigma=pid->NumberOfSigmasTPC(track,AliPID::kPion);
        if (abs(nsigma)>2) continue;
        myPionHist->Fill(track->Pt());
    }
}
```

… ok, also analysis is not THAT simple ;-)

Produce results

What's left?
- sweat lot
- work hard
- do some more magic
- get nice physics results





Summary

- The TPC is a very complex device
  - Most challenging TPC ever built
- It needs very sophisticated calibration in order to reach the desired physics performance
- Most of the time you don't see anything of this :-)

- Be patient if something doesn't work out of the box or may take some time

Summary

- The TPC is a very complex device
  - Most challenging TPC ever built
- It needs very sophisticated calibration in order to reach the desired physics performance
- Most of the time you don't see anything of this :-)

- Be patient if something doesn't work out of the box or may take some time

(Everything) you wanted to know about the TPC but were afraid to ask

?

Everything you were afraid to know about the TPC and never wanted to ask

Many people involved
Thanks to the TPC team

- Planning
- Design
- Construction
- Testing
- Calibration
- Operation
- ….

J. Alme[a], Y. Andres[d], H. Appelshäuser[g], S. Bablok[a], N. Bialas[g], R. Bolgen[a], U. Bonnes[f], R. Bramm[h], P. Braun-Munzinger[f,h,m,n], R. Campagnolo[d], P. Christiansen[j], A. Dobrin[j], C. Engster[d], D. Fehlker[a], P. Foka[h], U. Frankenfeld[h], J.J. Gaardhøje[e], C. Garabatos[h], P. Glässel[i], C. Gonzalez Gutierrez[d], P. Gros[j], H.-A. Gustafsson[j], H. Helstrup[b], M. Hoch[d], M. Ivanov[h], R. Janik[c], A. Junique[d], A. Kalweit[f], R. Keidel[o], S. Kniege[g], M. Kowalski[k], D.T. Larsen[a], Y. Lesenechal[d], P. Lenoir[d], N. Lindegaard[e], C. Lippmann[d], M. Mager[d], M. Mast[d], A. Matyja[k], M. Munkejord[a], L. Musa[d], B.S. Nielsen[e], V. Nikolic[l], H. Oeschler[f], E.K. Olsen[e], A. Oskarsson[j], L. Osterman[j], M. Pikna[c], A. Rehman[d], G. Renault[e], R. Renfordt[g], S. Rossegger[d], D. Röhrich[a], K. Røed[b], M. Richter[a], G. Rueshmann[g], A. Rybicki[k], H. Sann[†h], H.-R. Schmidt[h], M. Siska[c], B. Sitár[c], C. Soegaard[e], H.-K. Soltveit[i], D. Soyk[h], J. Stachel[i], H. Stelzer[h], E. Stenlund[j], R. Stock[g], P. Strmeň[c], I. Szarka[c], K. Ullaland[a], D. Vranic[h], R. Veenhof[d], J. Westergaard[e], J. Wiechula[i], B. Windelband[i]

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and a few more

Literatur

- ALICE Technical design report of the Time Projection Chamber, CERN/LHCC 2000-001
  https://edms.cern.ch/file/398930/1/ALICE-DOC-2003-011.pdf
- The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events, arXiv:1001.1950 [physics.ins-det]
  http://arxiv.org/pdf/1001.1950v1
- W. Blum, W. Riegler, L. Rolandi: Particle Detection with Drift Chambers
- F. Sauli: Principles of operation of multiwire proportional and drift chambers
  http://doc.cern.ch//archive/electronic/kek-scan//198908348.pdf

Backup

TPC related Abbreviations

ALTRO	ALice TPC ReadOut chip
DAQ	Data AcQuisition
DCS	Detectro Control System
DDL	Detector Data Link
FEC	FrontEnd Card
FEE	FrontEnd Electronics
HLT	High Level Trigger
HV	High Voltage
IROC	Inner ReadOut Chamber
LV	Low Voltage
MIP	Minimum Ionising Particle
OROC	Outer ReadOut Chamber
PASA	PreAmplifier ShAper
PID	Particle Identification
RCU	Readout Control Unit
RORC	ReadOut Receiver Card
SSW	Service Support Wheel
TPC	Time Projection Chamber
VHV	Very High Voltage

Energy loss of charged particles

The energy loss of "heavy" ($M >> m_e$) particles is described by the Bethe-Bloch-Formula and results in Ionisation

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A \rho m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{2m_e c^2 \beta^2 \gamma^2}{I_0} - \beta^2 - \frac{\delta(\beta)}{2} \right]$$

Absorber properties (Z,A, ρ, Ionisation potential I_0, Screening and density correction term δ)
Particle properties (β, z)

- <u>remarks</u>:
- dE/dx only depends on β, it is independent of m
- often dE/dx means $1/\rho \cdot dE/dx$; one defines $dx := \rho dx$
  ⇒dE/dx in [MeV g^{-1} cm^2]
- Electrons and positrons need special treatment ($m_{proj} = m_{target}$)
  ⇒$\langle dE/dx \rangle_{tot} = \langle dE/dx \rangle_{col} + \langle dE/dx \rangle_{rad}$ (energy loss because of bremsstrahlung)

Ionisation and energy loss of charged particles

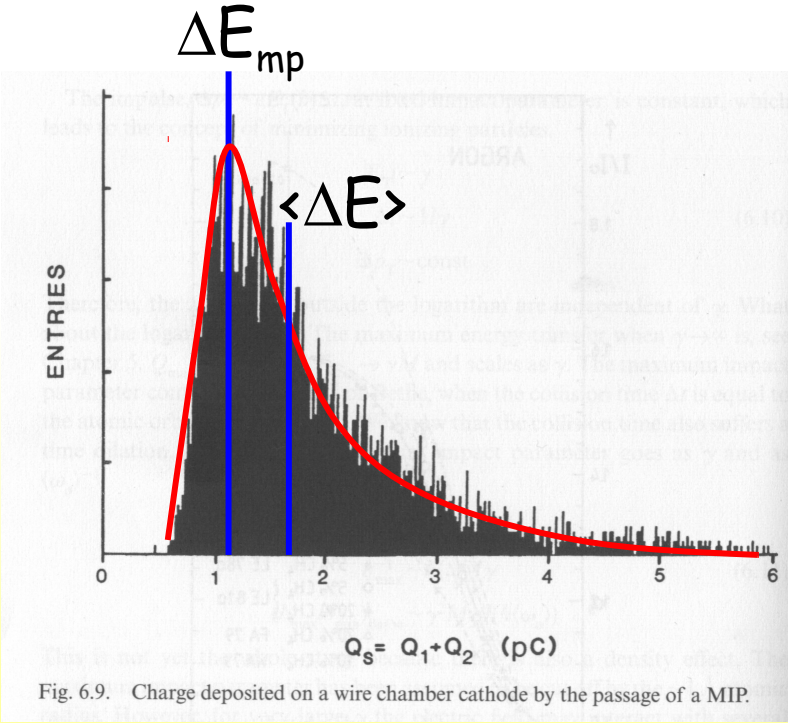


Fig. 6.9. Charge deposited on a wire chamber cathode by the passage of a MIP.

The distribution of the energy loss ΔE passing through a layer of thickness D is described by the Landau-Distribution:

$$\langle \Delta E \rangle \sim \langle dE/dx \rangle D$$

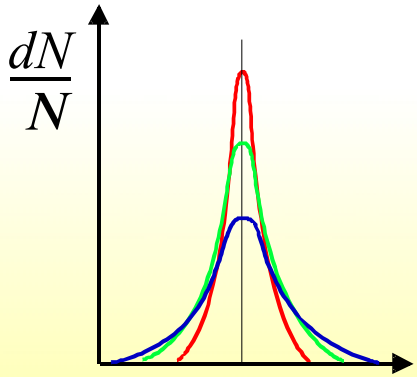
$$L(\lambda) = \frac{1}{\sqrt{2\pi}} e^{-1/2(\lambda + e^{-\lambda})}$$

$$\lambda \equiv \frac{(\Delta E - \langle \Delta E \rangle)}{\langle \Delta E \rangle}$$

Diffusion in a zero field environment

In the case of no external field the diffusion is isotropically and the densities follow a Gaussian distribution:

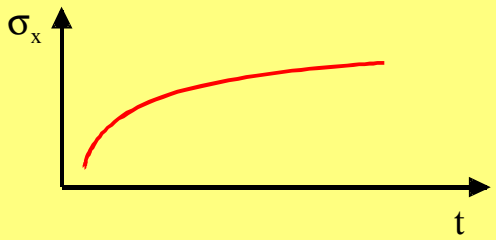
$$\frac{dN}{dx} = N \frac{1}{\sqrt{4\pi D_x t}} e^{\frac{-x^2}{4D_x}t}$$



It is assumed that all charge is located in (0,0,0) at t=0.
The equation describes which fraction (dN/N) of the charge is left in dx after the time t.

D is called the diffusion constant and is given by:

$$\sigma_x = \sqrt{2D_x t} \qquad \sigma_{vol} = \sqrt{3}\sigma_x = \sqrt{6D_x t}$$



Diffusion in an electric field

In an electric field the charge is transported over the distance L = $v_D \cdot t$ in the time t.

If we introduce the electron mobility μ ($v_D = \mu E$) we get $L = \mu E t$ and therefore:

$$\sigma_x = \sqrt{2D_{xt}} = \sqrt{\frac{2D_x L}{\mu E}}$$

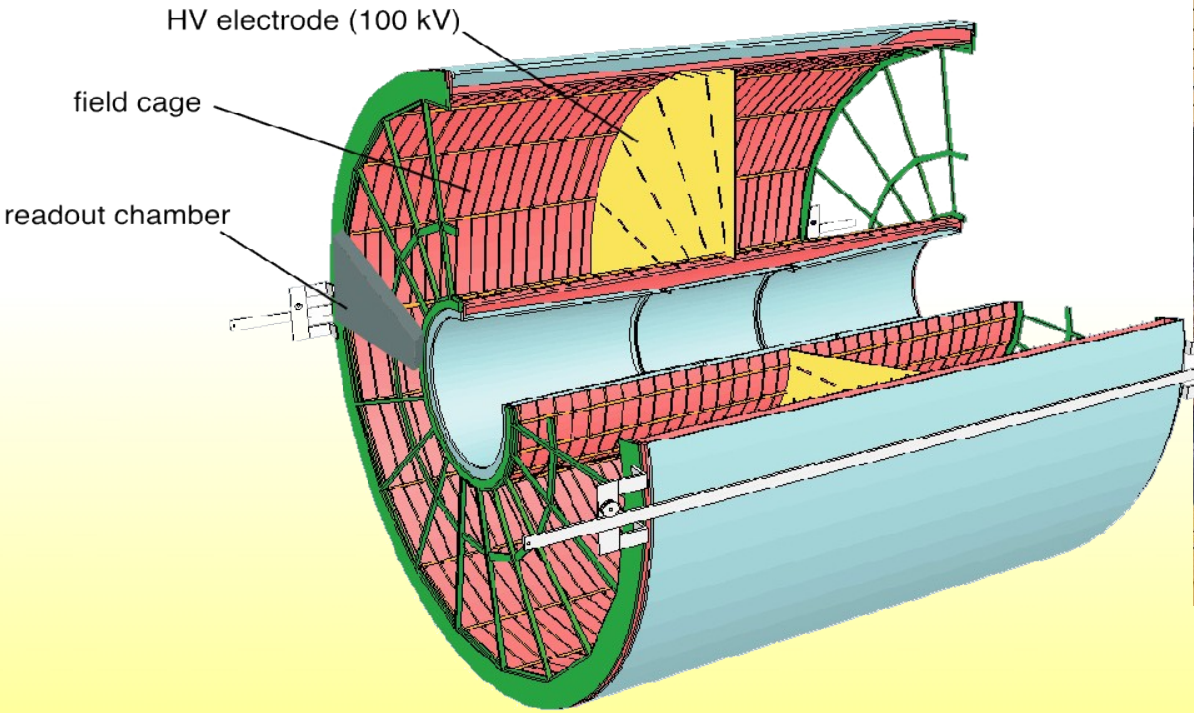
In literature the diffusion constant is often given by

$$D_X = \frac{\sigma_x}{\sqrt{L}} = \sqrt{\frac{2D_x}{\mu E}}$$

The minimum energy an electron can adopt is the mean thermal energy in of the gas. Therefore the diffusion must have a lower limit, which is described by the Nernst-Townsend-Formula:

$$\frac{D}{\mu} = \frac{kT}{e} \qquad D_X = \sqrt{\frac{2kT}{eE}}$$

Central Electrode, field cage, Endplates



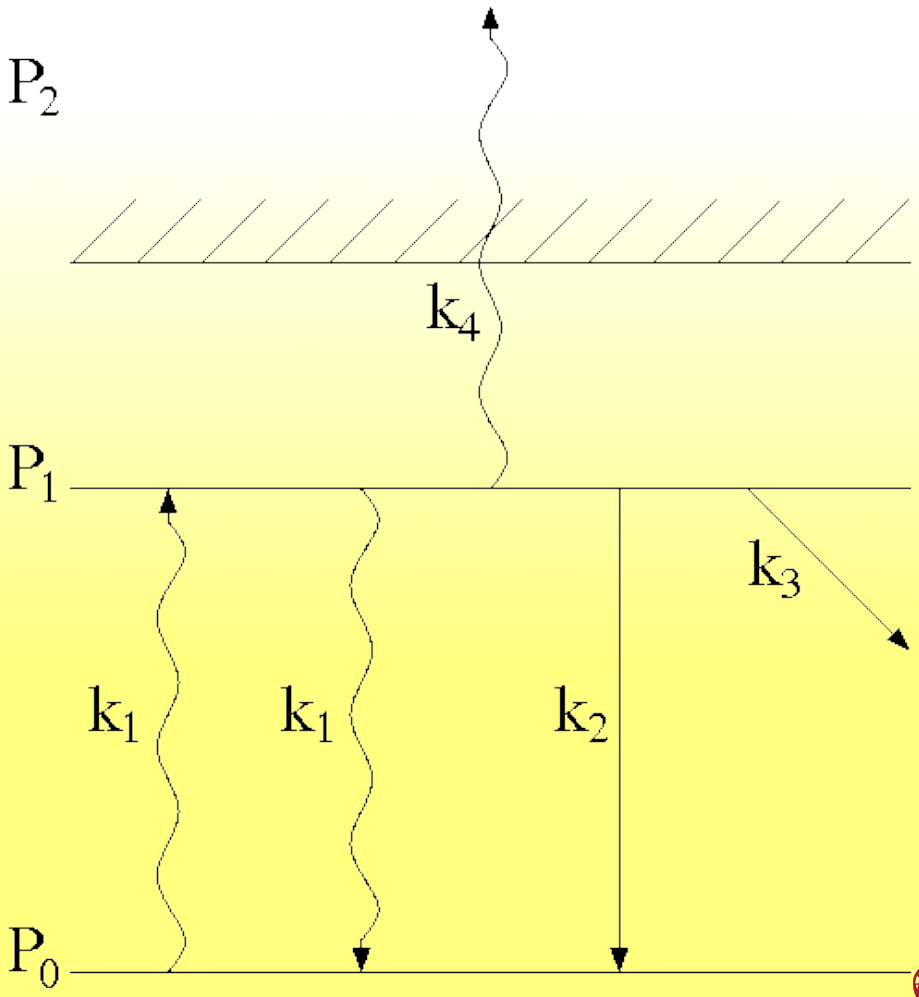
- TPC divided in two sides (A (Shaft), C (Muon))
- Field strength: 400V/cm, drift length 250cm -> 100kV
- ≈ 170 Field stripes on both sides
- End plates are segmented into 18 Sectors in phi
- Sectors are divided into an inner and outer part

Two photon ionisation (laser)

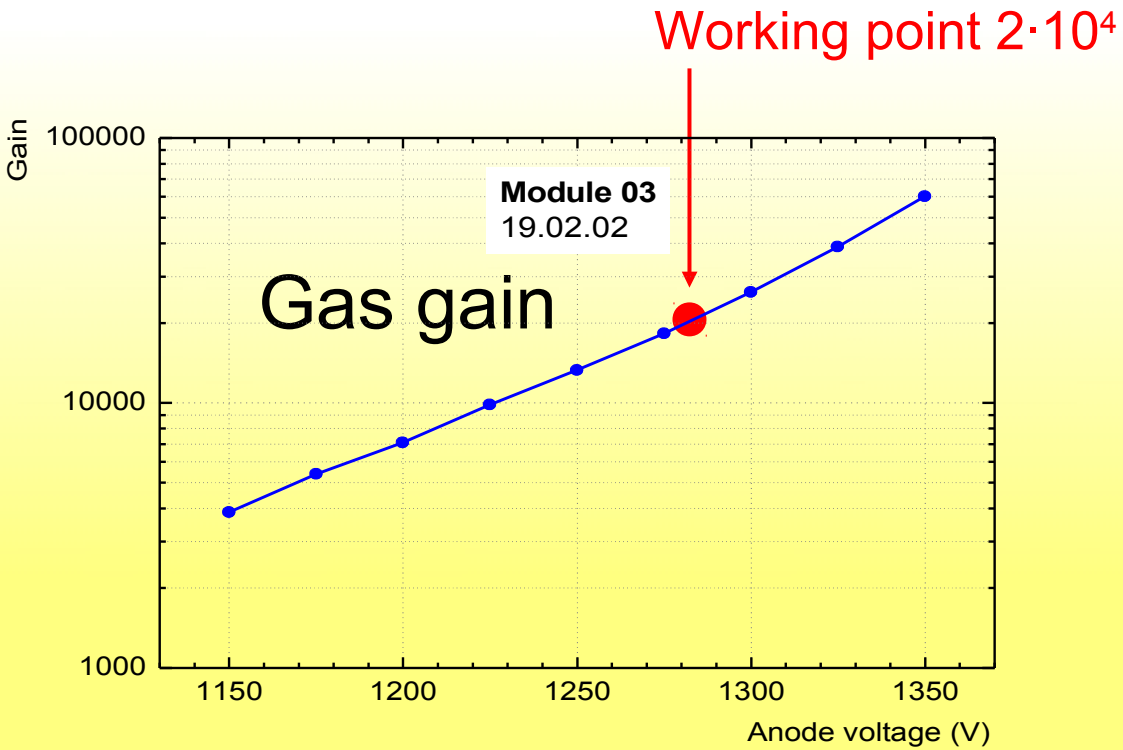
The typical lasers used have a wave length of 266nm (≈ 4.7 eV).
Ionisation energy of e.g. Ne ≈ 20eV.

What is ionized are impurities in the gas (long-chain hydrocarbons). A two photon process is needed to obtain a high enough energy.

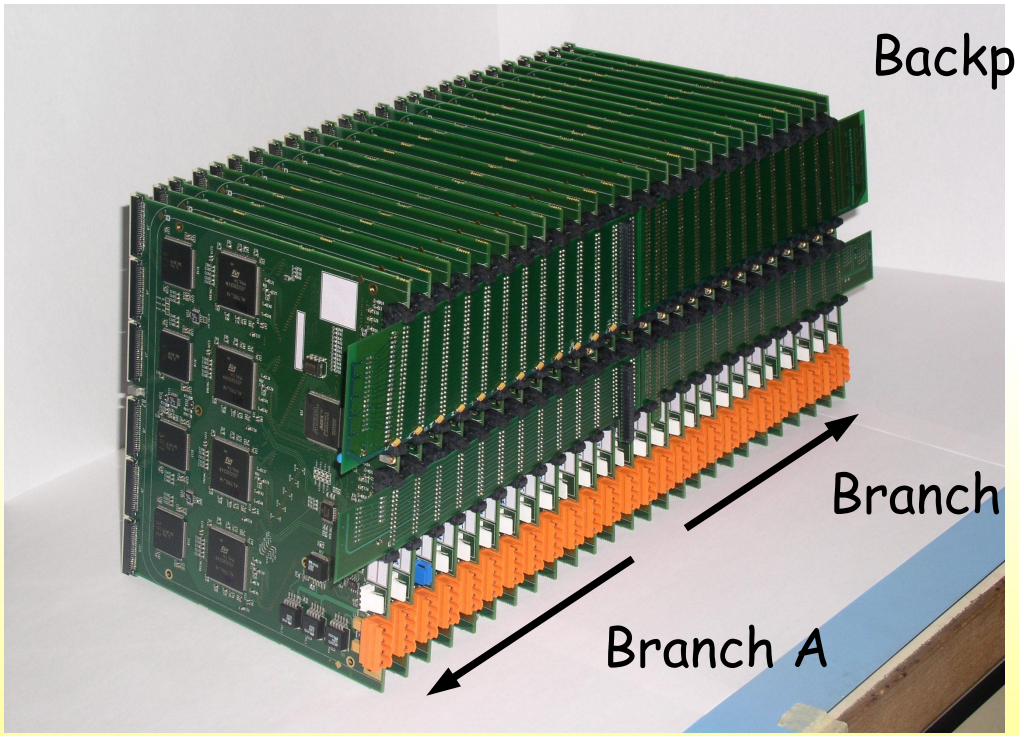
From the system of equations of the transition rates one obtains.
$P_2 \sim P_0 \Phi^2$

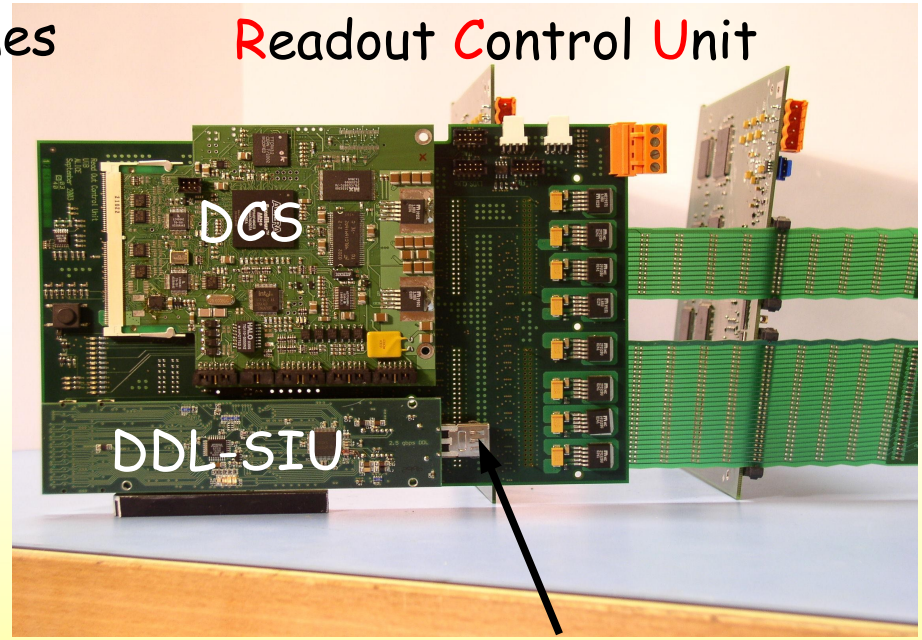


Gain curve


Working point 2·10⁴
Gain
100000
10000
1000
Module 03
19.02.02
Gas gain
1150
1200
1250
1300
1350
Anode voltage (V)

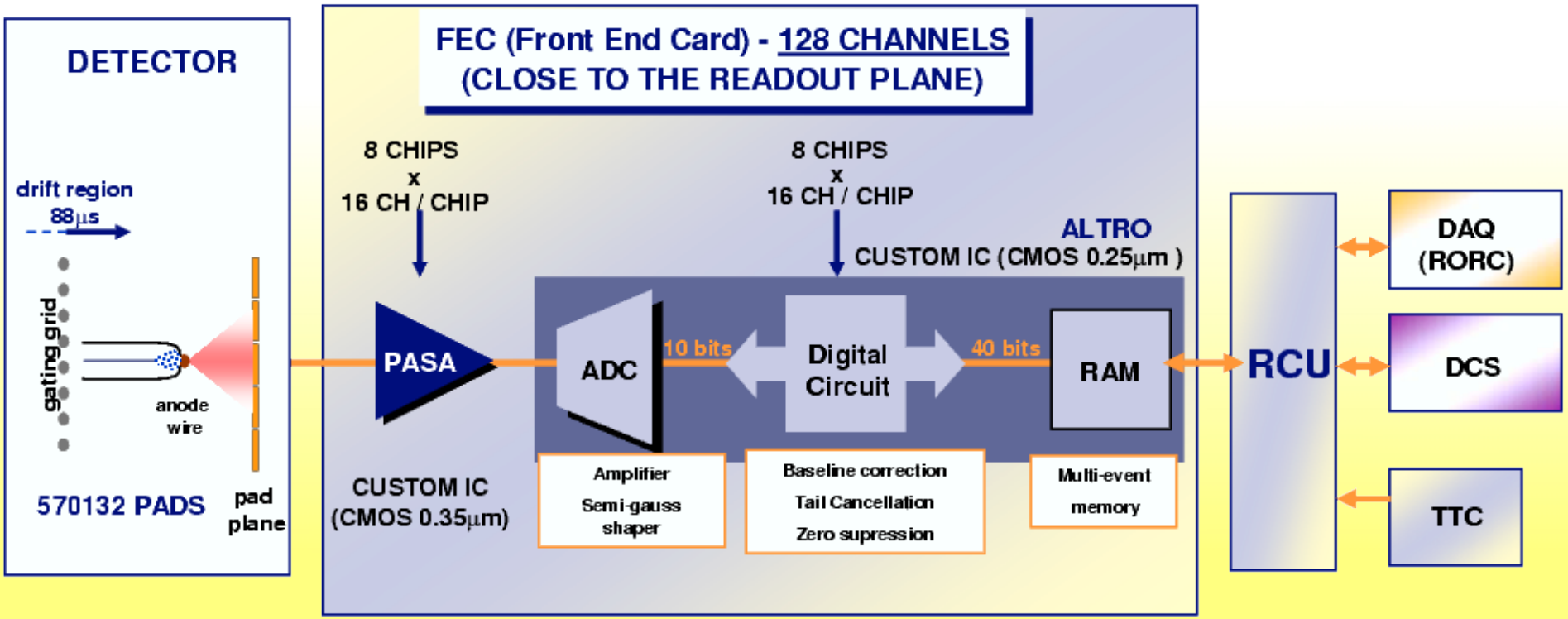
FrontEnd Electronics



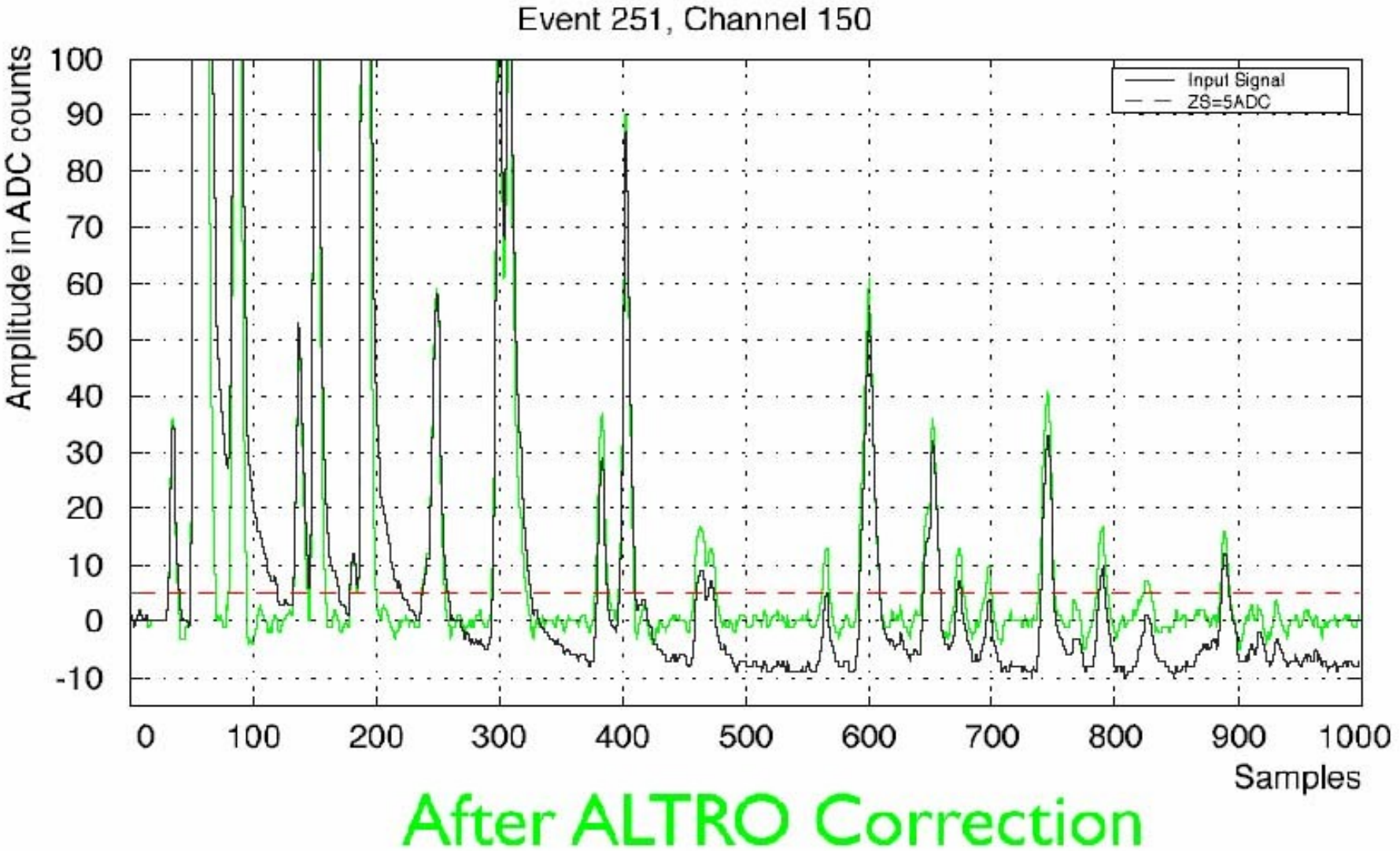


- 18 – 25 FECs (patch) per RCU
- 6 RCUs per sector (6patches)
- 6 x 36 = 216 RCUs in total

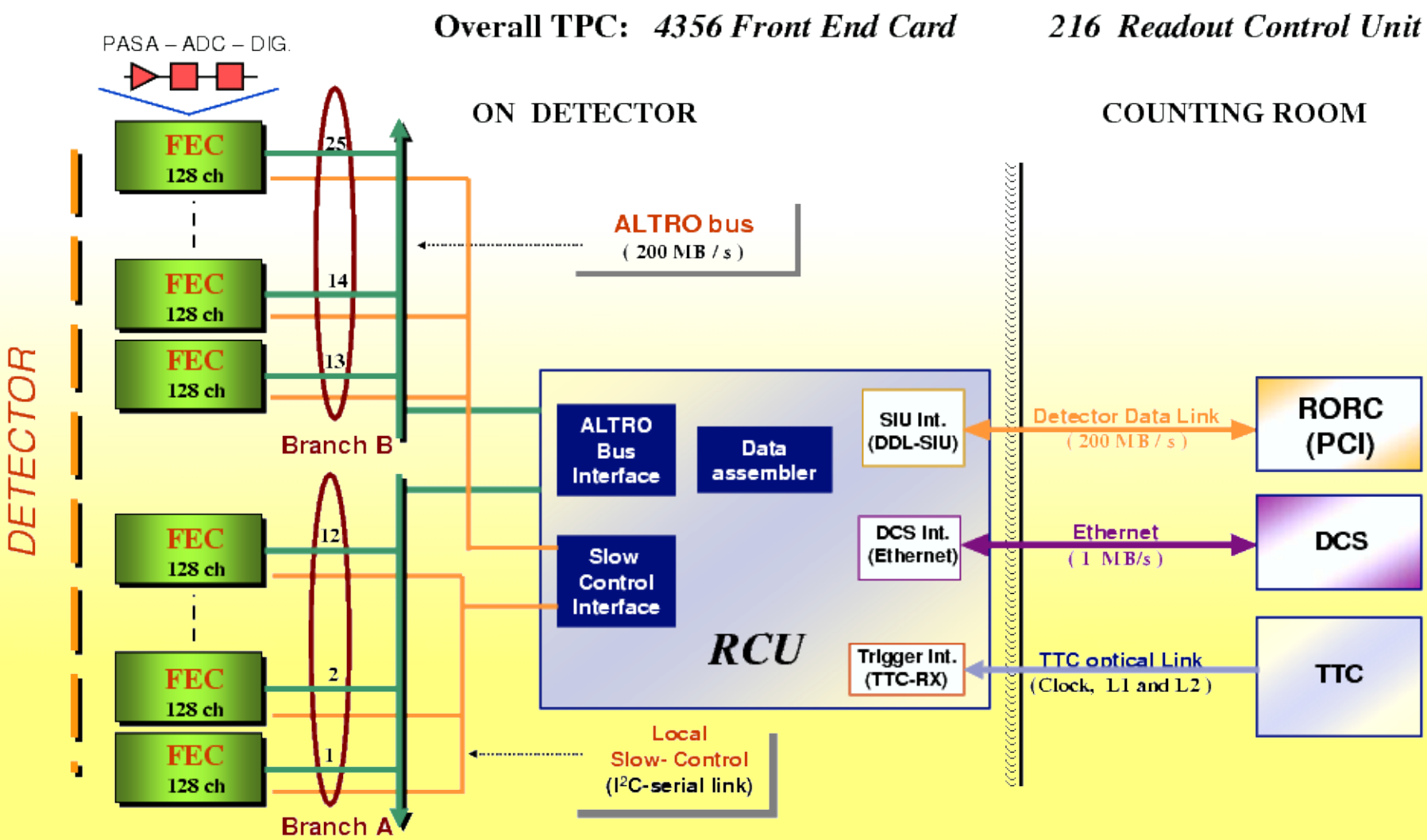
Readout of the TPC



ALTRO signal correction

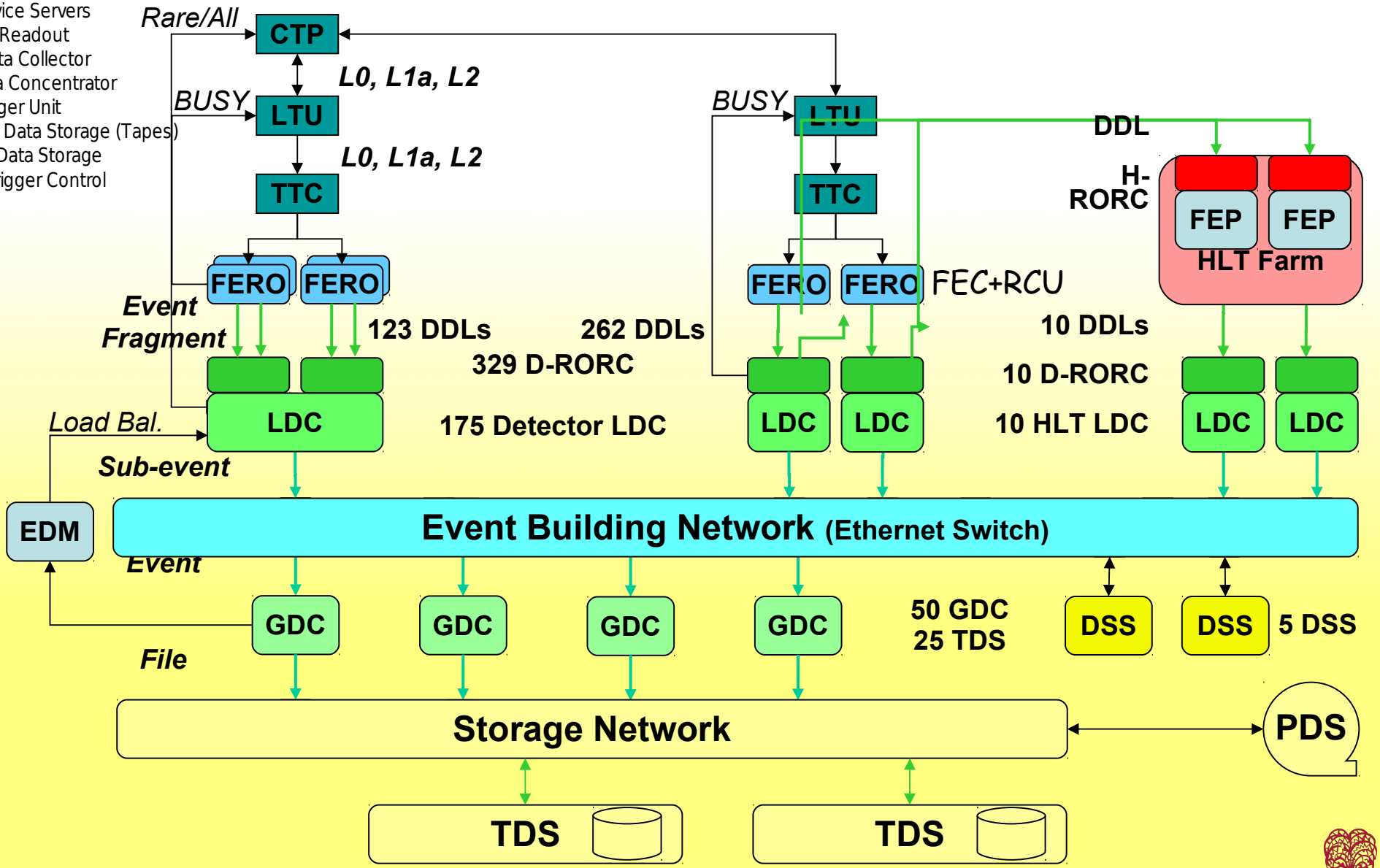


Readout chain

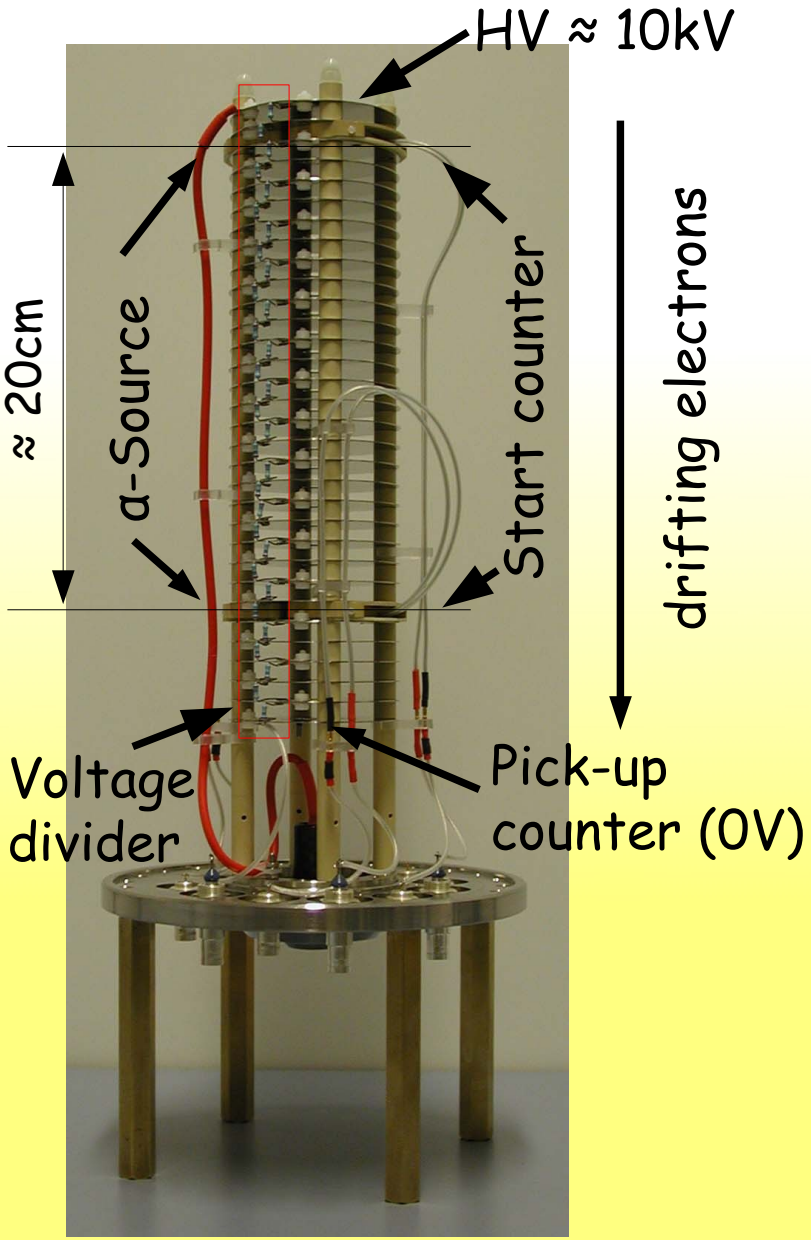


Data AcQuesition

CTP Central Trigger Processor
DSS DAQ Service Servers
FERO Frontend Readout
GDC Global Data Collector
LDC Local Data Concentrator
LTU Local Trigger Unit
PDS Permanet Data Storage (Tapes)
TDS Transien Data Storage
TTC Time & Trigger Control

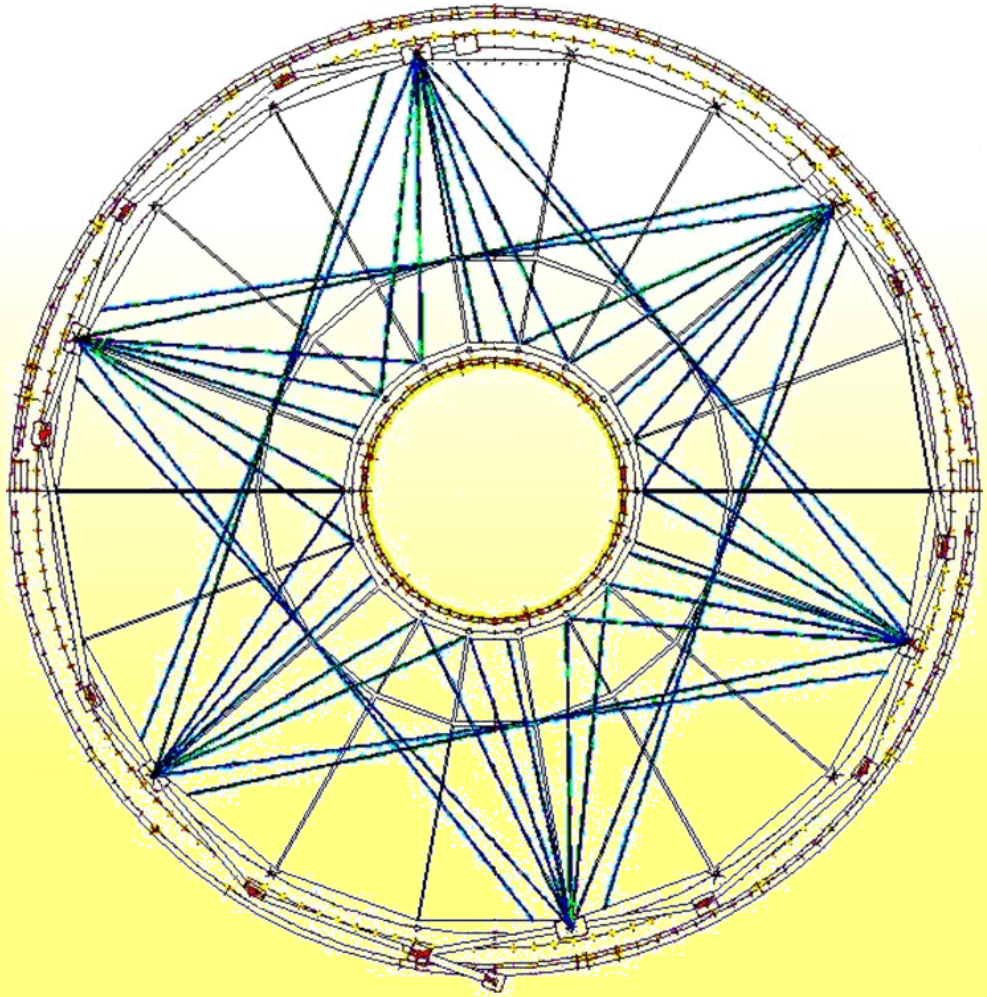


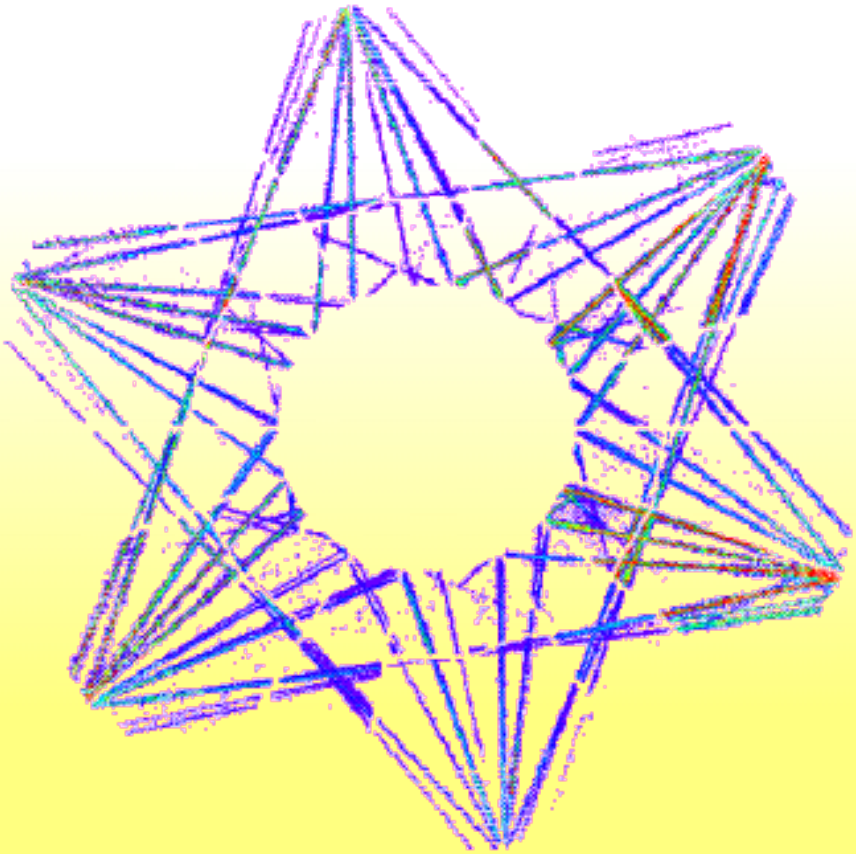
Gas quality monitor (Goofie)



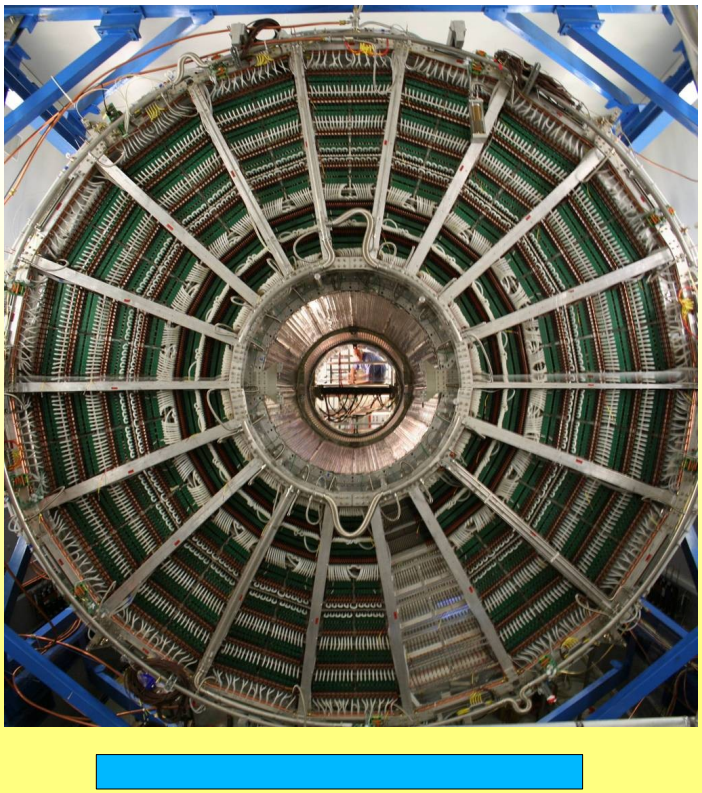
- measure drift velocity
- measure gas gain
- ✓ calibrate curves for changes of N_2 and CO_2 in Ne
- → monitor N_2
- → monitor CO_2 change

Laser calibration system



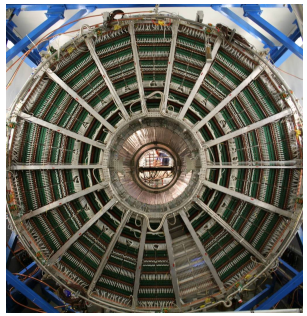
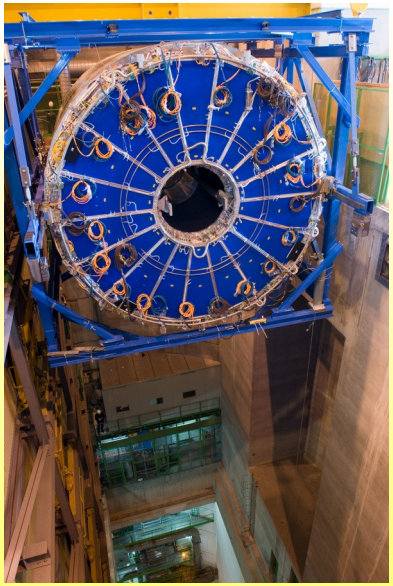


Pre-comissioning 2006



- Only 2 sectors operated simultaneously
- Cosmic and laser events taken

Status in 2007



- TPC is fully equipped and operational (not yet with all final systems)
- Two commissioning phases successfully accomplished (no major problems occurred)