The ALICE TPC Upgrade

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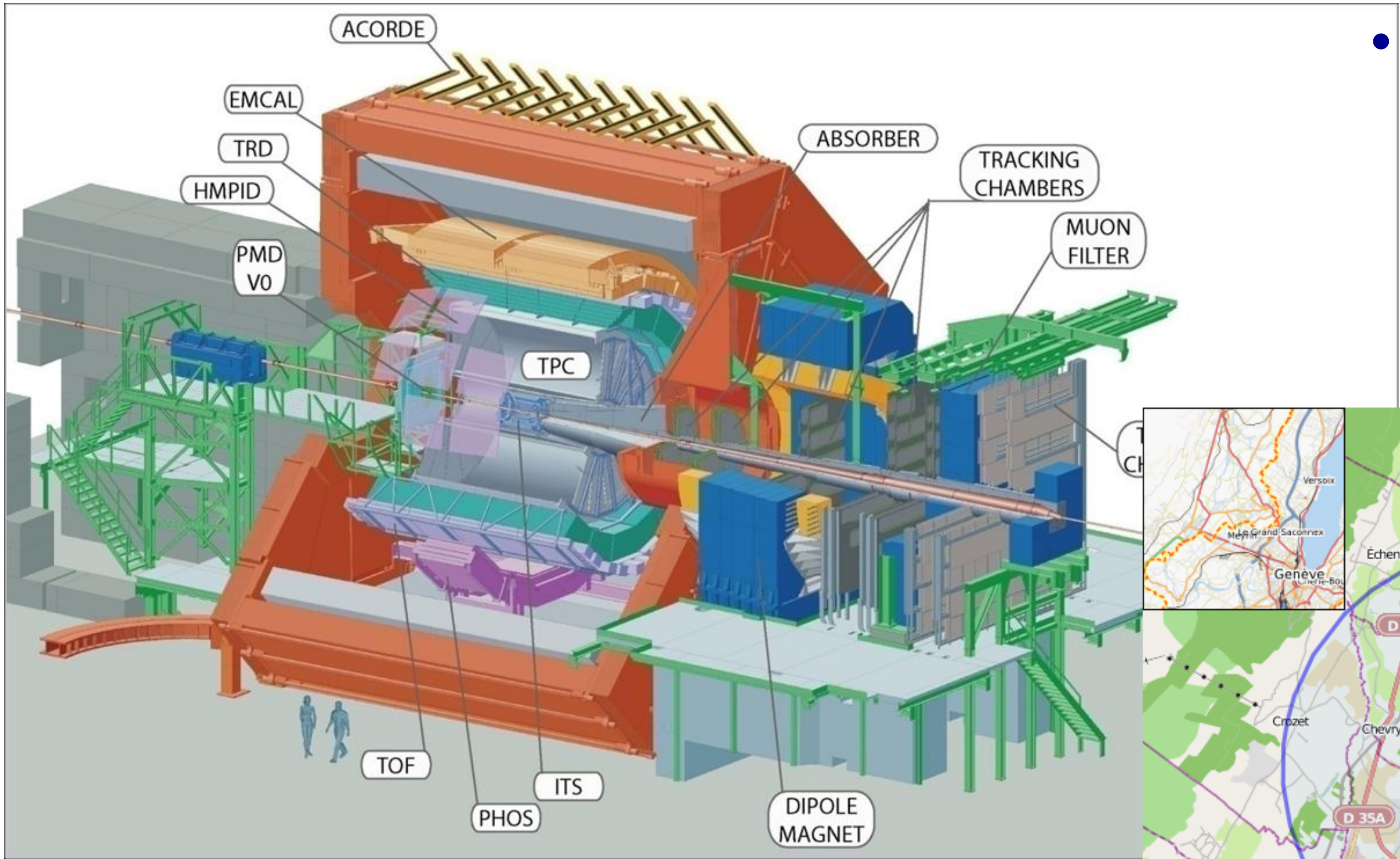
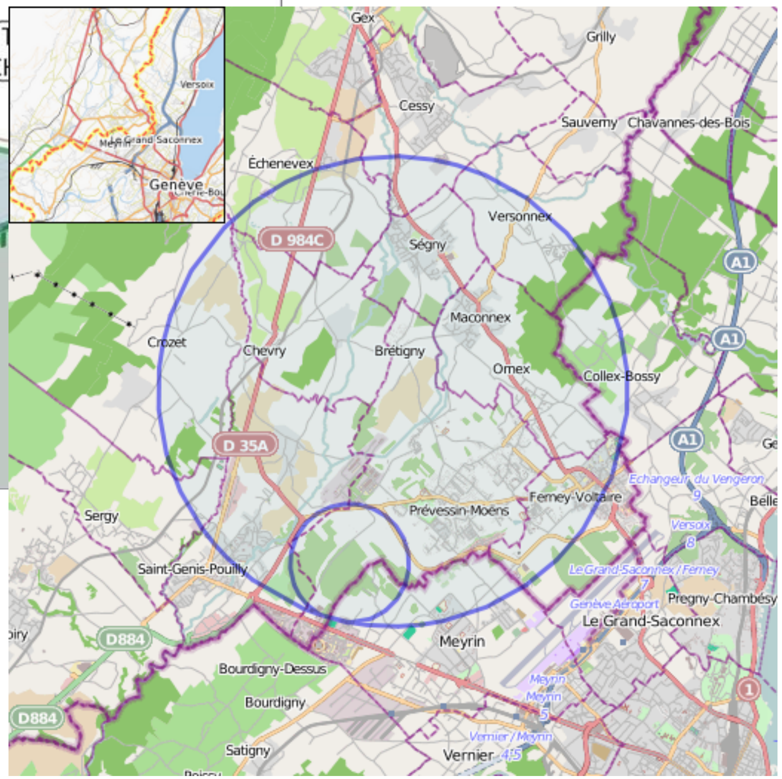
Instrumentation days on gaseous detectors

12-13.10.2016, Clermont-Ferrand

ALICE at the LHC

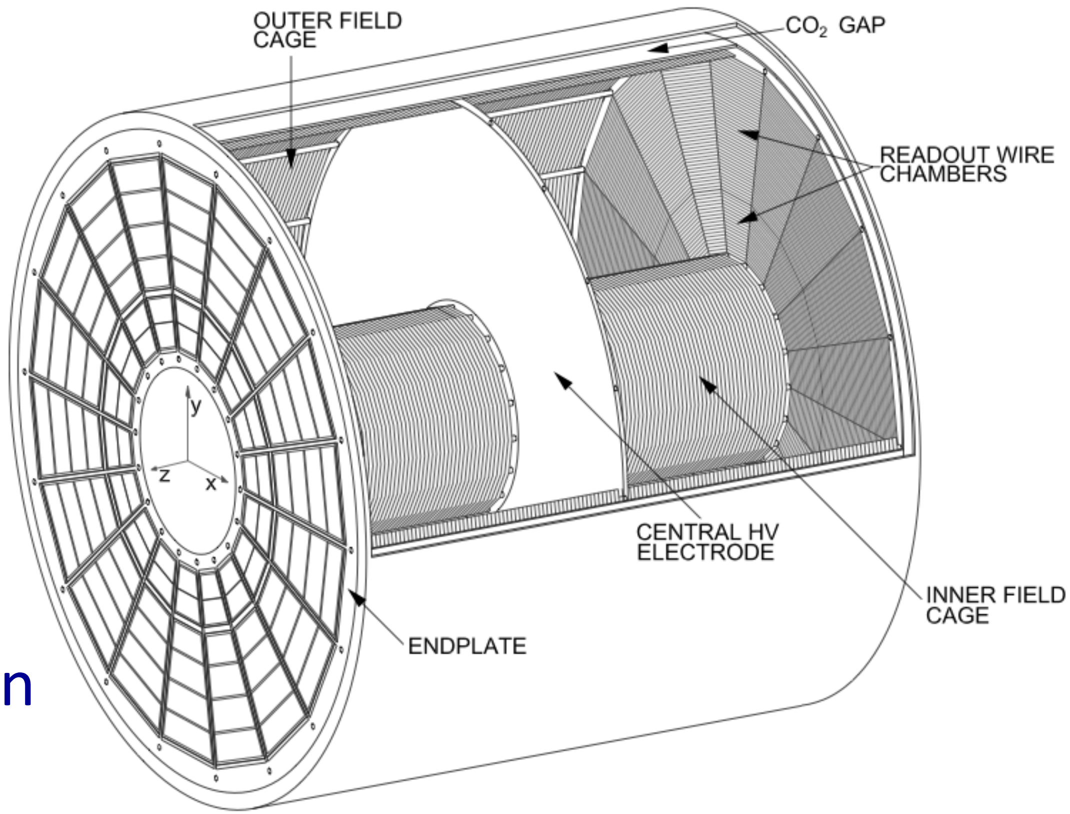


- ALICE is the dedicated heavy-ion experiment at the LHC



The largest TPC

- 5 m x 5 m, 90 m^3
- 100 kV in CE
- ~90 µs drift time
- 2x2x18 = 72 ROCs
- 557568 readout pads
- Gain 7000-8000
- Noise ~700 e^-
- X/X_0 = 3.5 % near η=0
- ~1 mm position resolution => 250 µm matching resolution with inner tracker



The largest TPC

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- 100 kV in CE
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- 2x2x
- 557 568 readout pads
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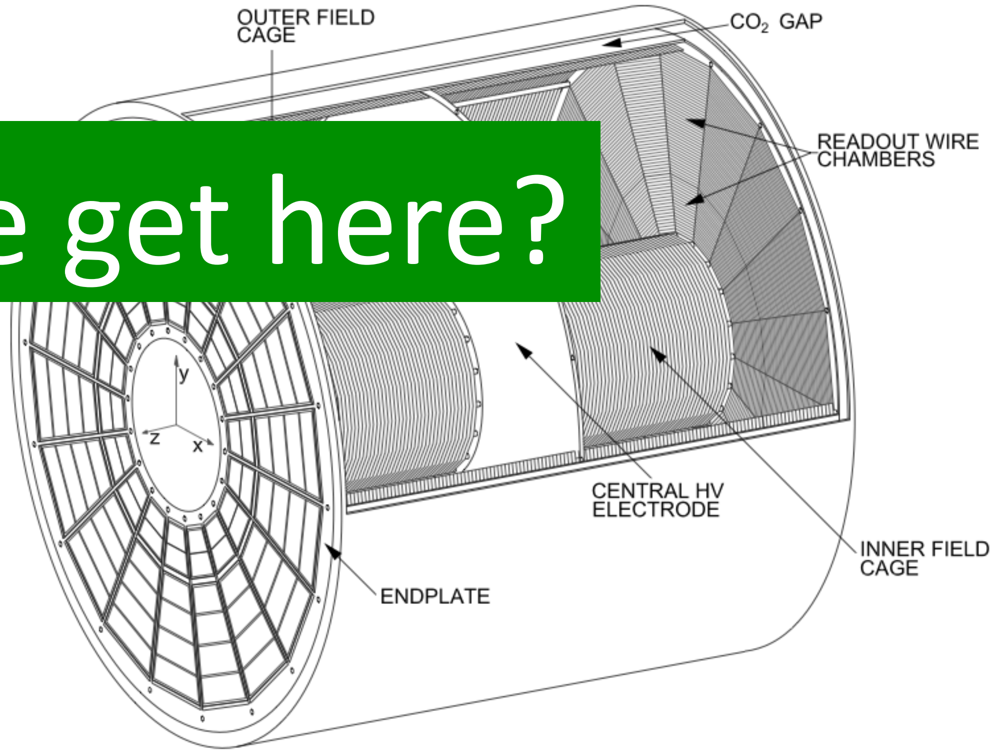
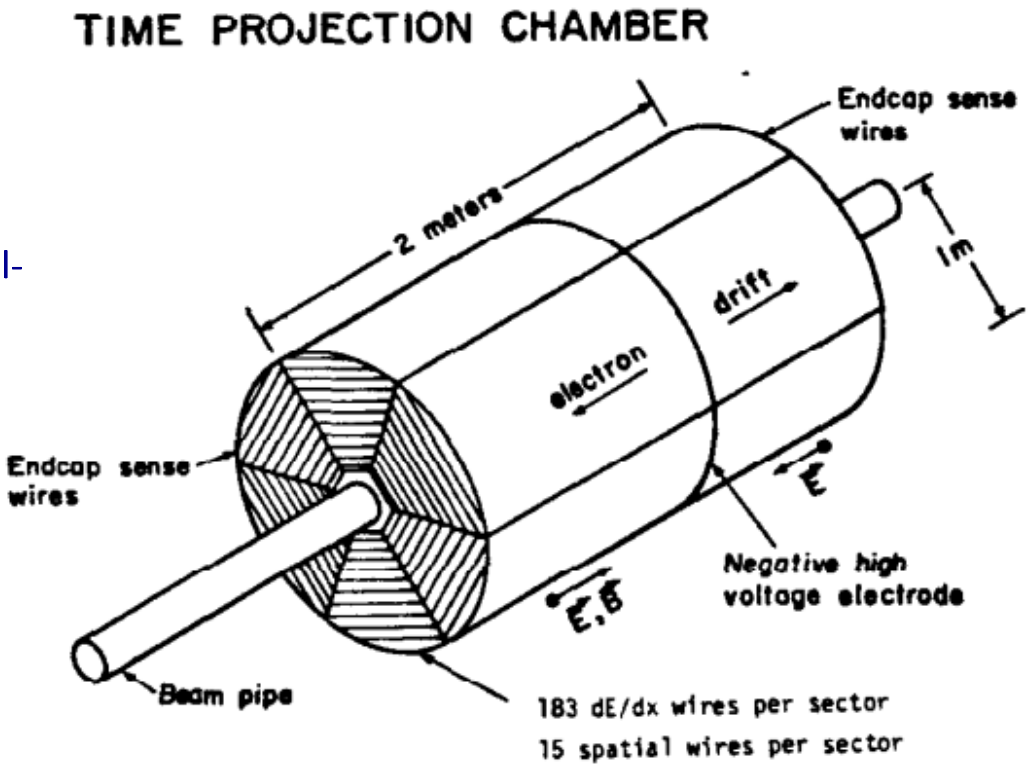
How did we get here?



A few features of TPCs

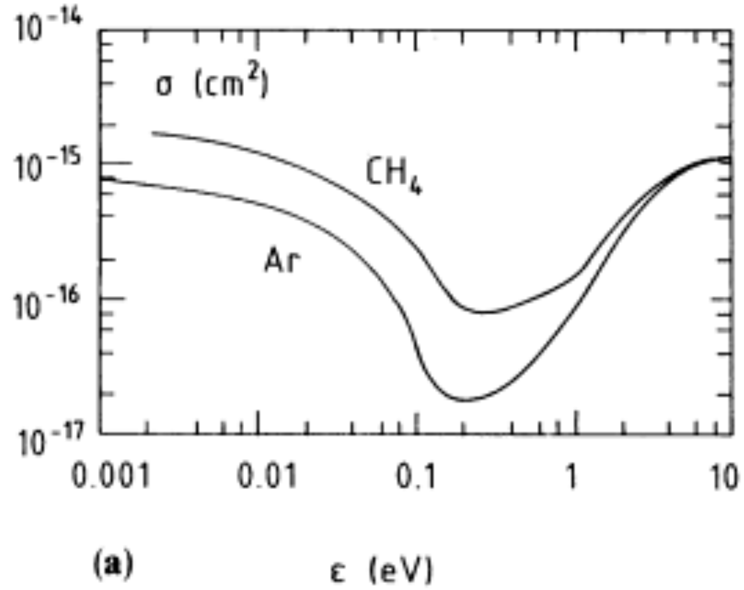
PEP-4 TPC

- First TPC, with many innovations
- AGS e^+e^- collider
- Ar-CH_4 (80-20) at 8.6 bar
  - ☞ primary statistics, and therefore signal-to-noise, increase with p
  - ☞ If E scaled accordingly, diffusion decreases as ~1/p
  - – high pressure also used in the TOPAZ TPC
- Sense wire readout for dE/dx measurement
  - – interleaving field wires
- A few pad rows (circular arrangement) for position measurement
- B = 0.4 T
- σ_{xy} ~ 300 µm



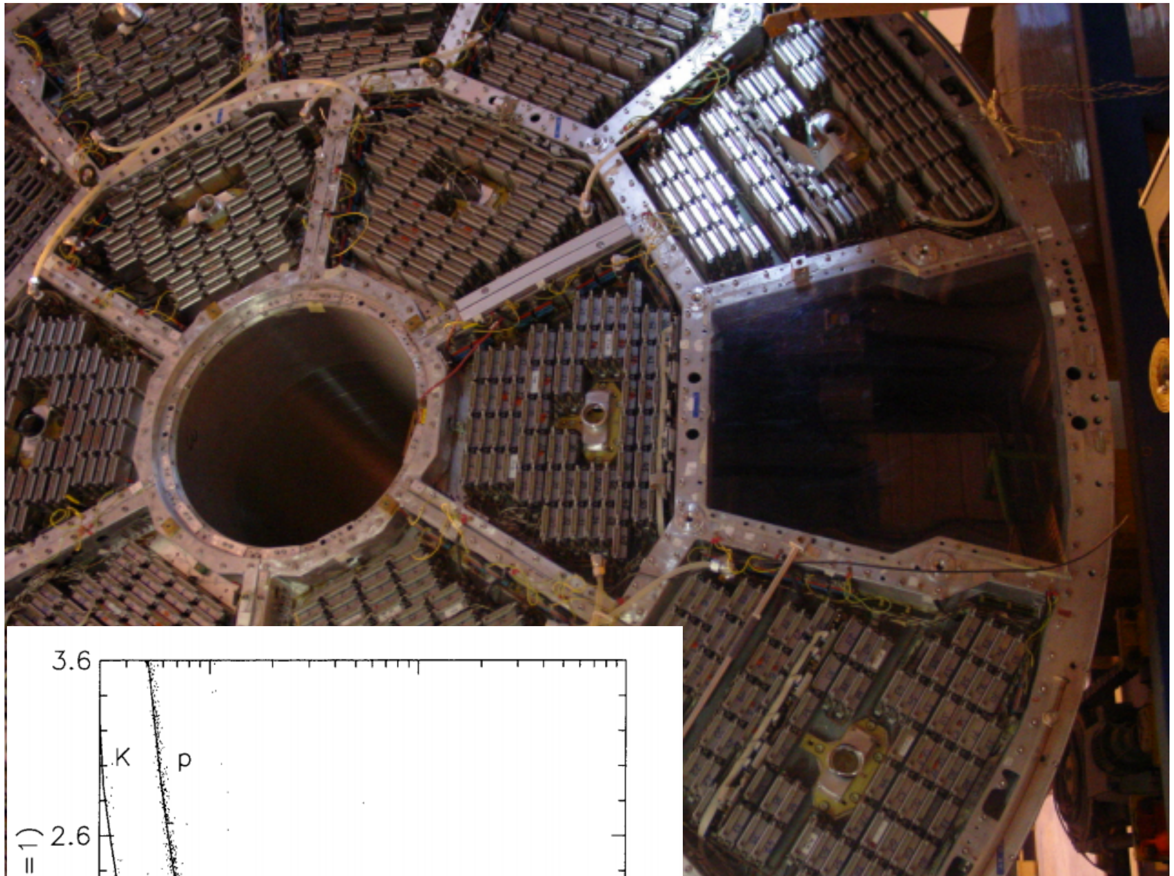
$Ar\text{-}CH_4$: Ramsauer dip and diffusion

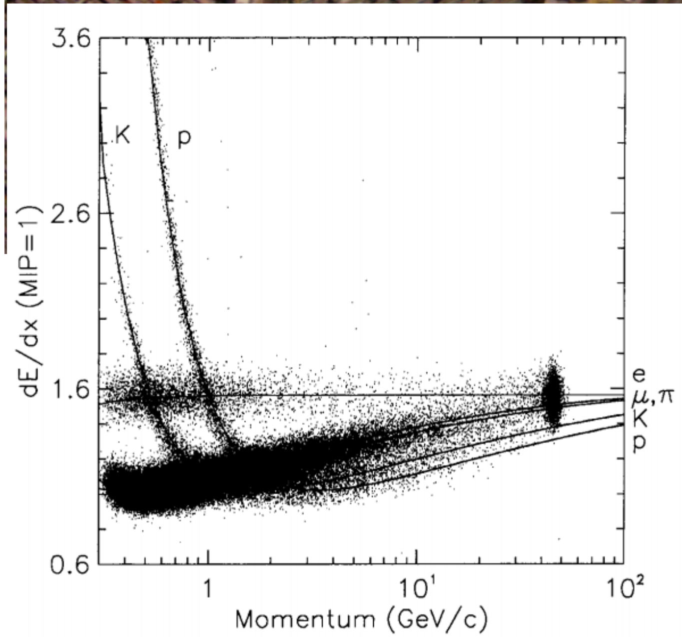
- Chose the drift velocity such that the average electron energy falls in the Ramsauer dip: minimum elastic cross section
  - e.g. ~100 V/cm in $Ar\text{-}CH_4$ (90-10)
- The magnetic field then helps focusing the electrons
- High drift velocity achieved like this



ALEPH TPC

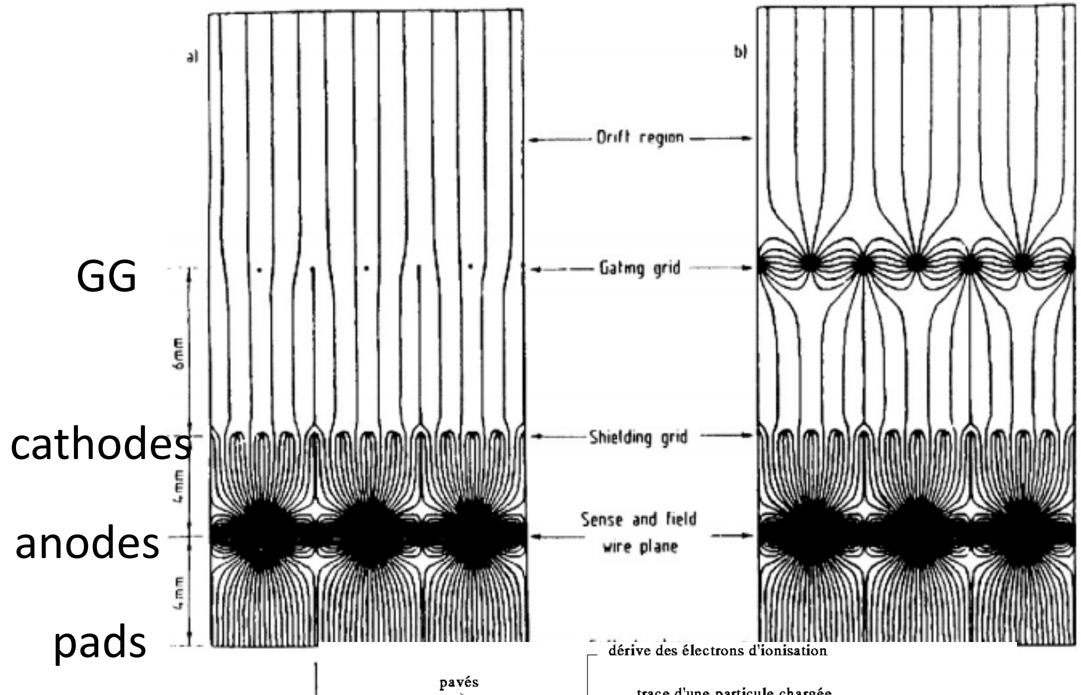
- LEP e^+e^- collider
- Length 4.7 m
- Outer radius 1.8 m
- 43 m^3
- Ar-CH_4 (91-9) at atmospheric pressure
- Readout sense wires and pads (~50k channels)
- Optimised acceptance for high p_T tracks
- Optimised acceptance by backwards mounting
- Gating grid
  - also Delphi
- Excellent momentum and dE/dx resolution
- $\Delta p/p^2 < 1$ % c/GeV

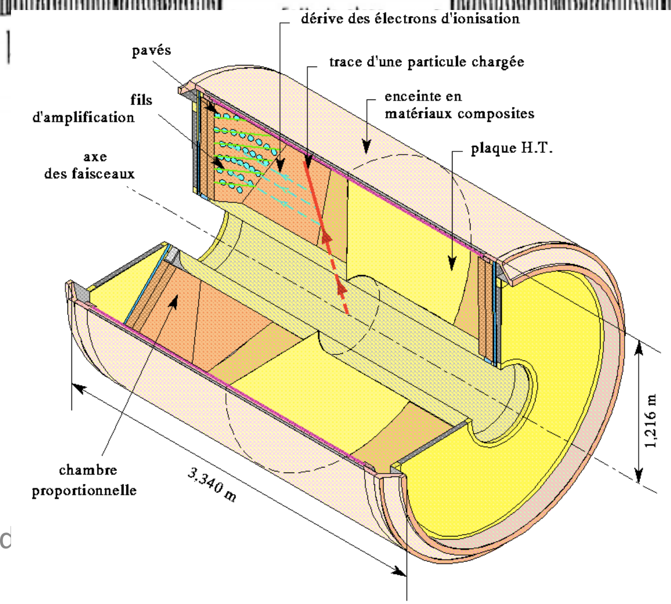




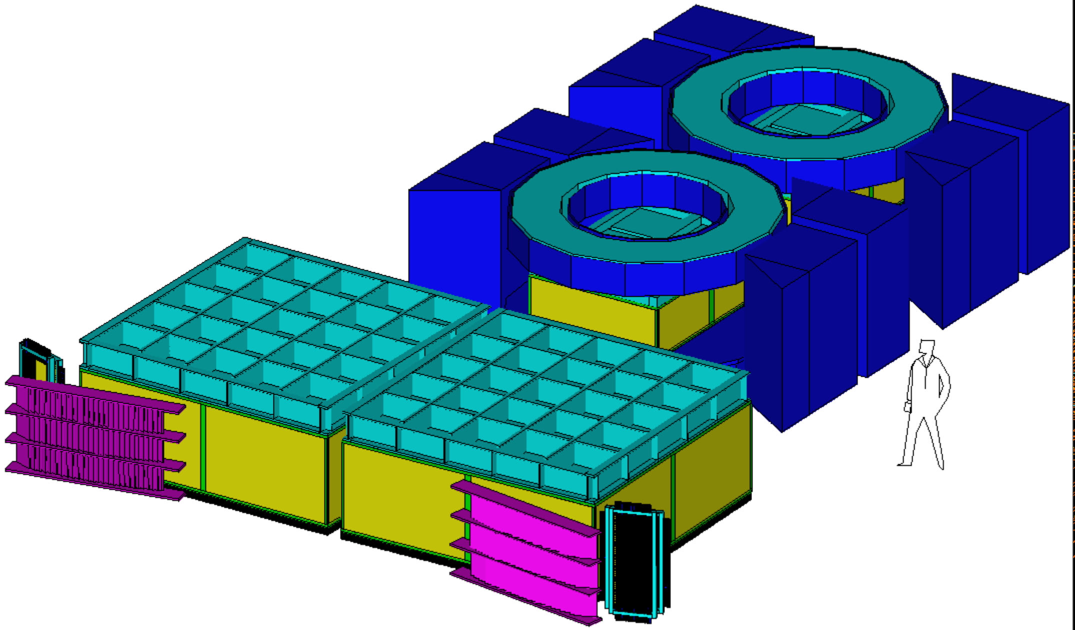
Gating grid (Aleph + Delphi)

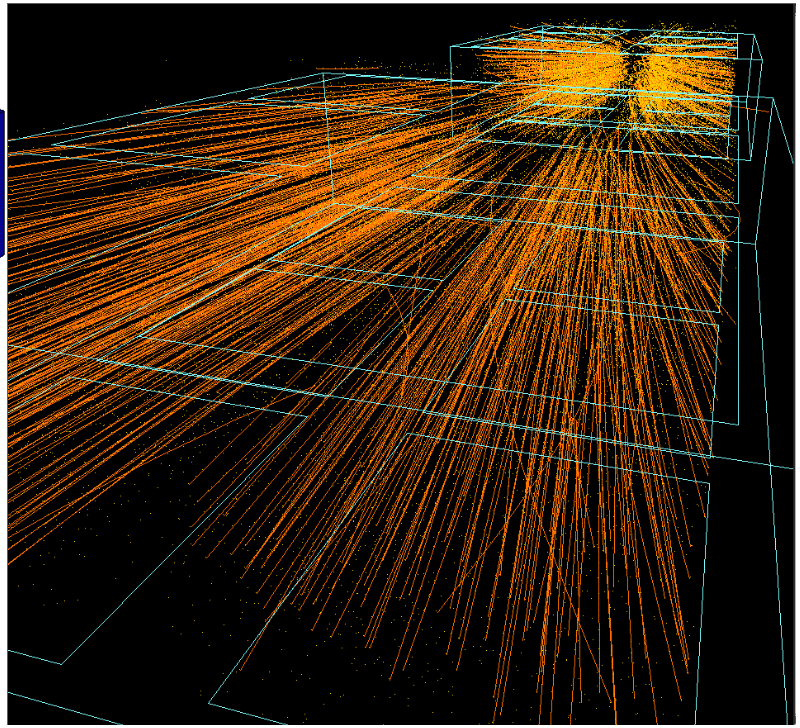
- electrons reach the chambers –and amplification occurs- only when an event is triggered upon
- Gate is open during the maximum drift time only (t_e)
- Then the gate closes to prevent ions to invade drift volume (t_{ions})
- This technique *opens the gate* to higher rates and multiplicities without substantial space-charge distortions





NA49 TPCs



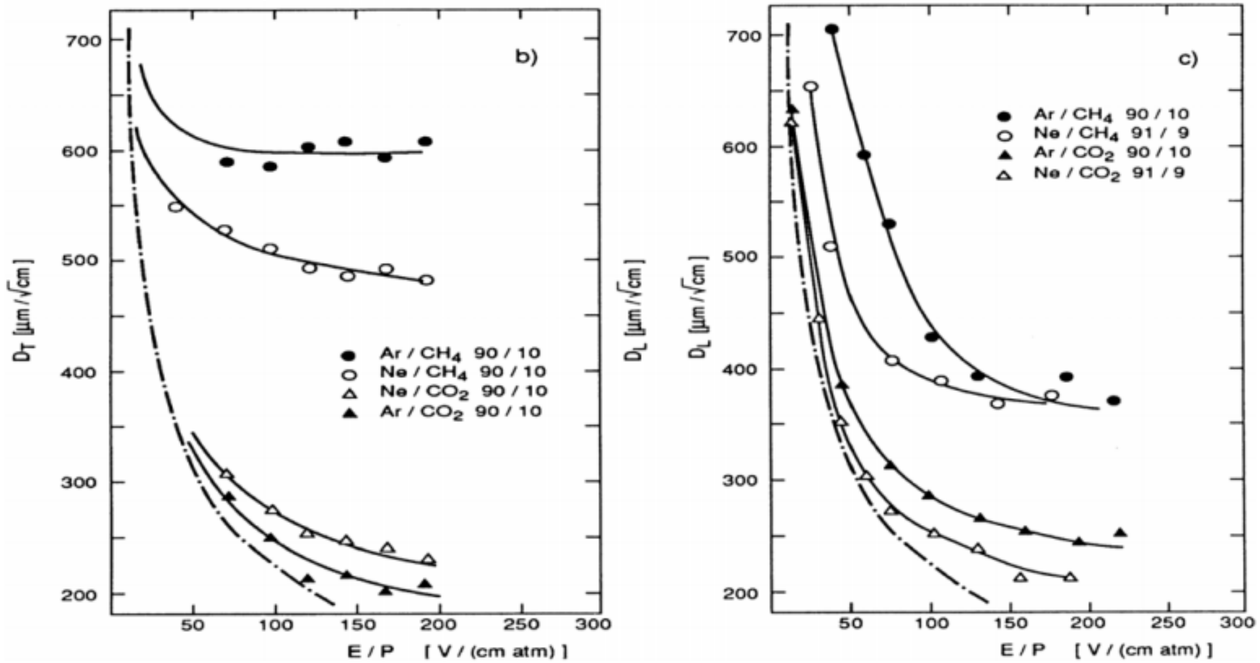


- Heavy ions at the SPS fixed target
- FC strips suspended on rods
- Neon introduced as alternative to argon
  - less multiple scattering
  - less space charge
- CO_2 introduced as quencher: low diffusion
- Full pad readout, no sense wire readout
  - keep the field wires
- Excellent control of the gas quality

And also:
Efficient gating
Optimised Pad Response Function,
resulting in tight geometry

CO_2 as quencher

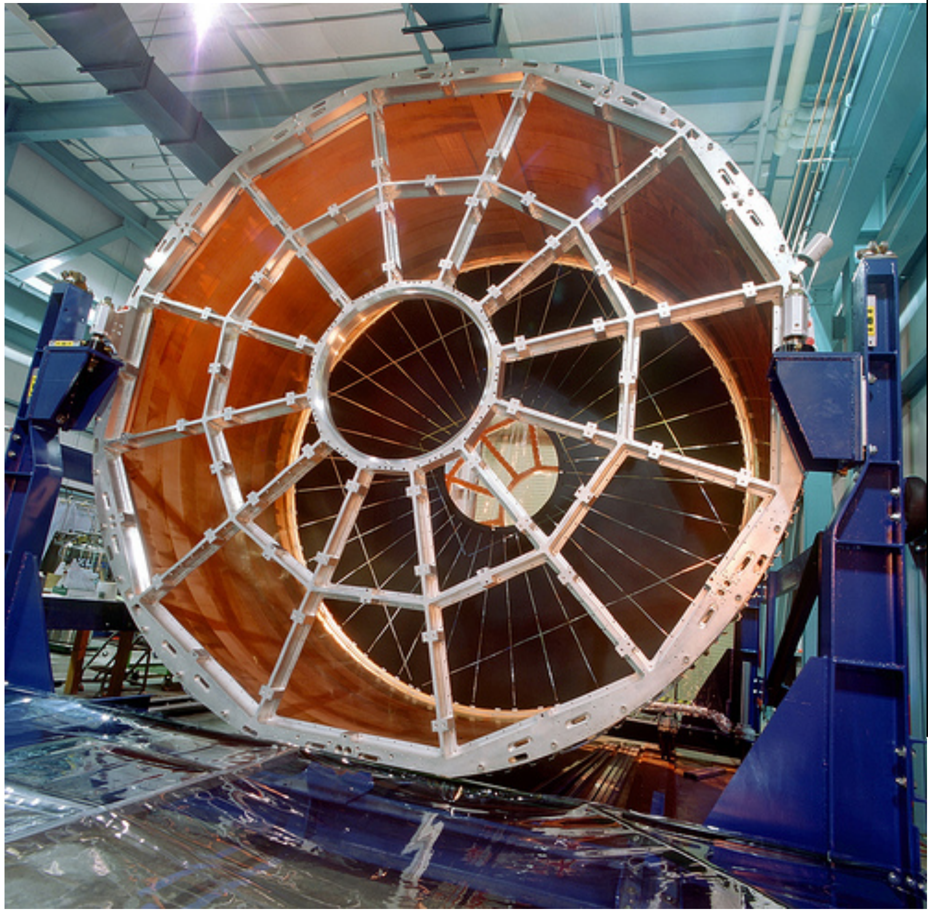
- CO_2 mixtures provide low diffusion coefficients
  - Don't need the Ramsauer dip ☹



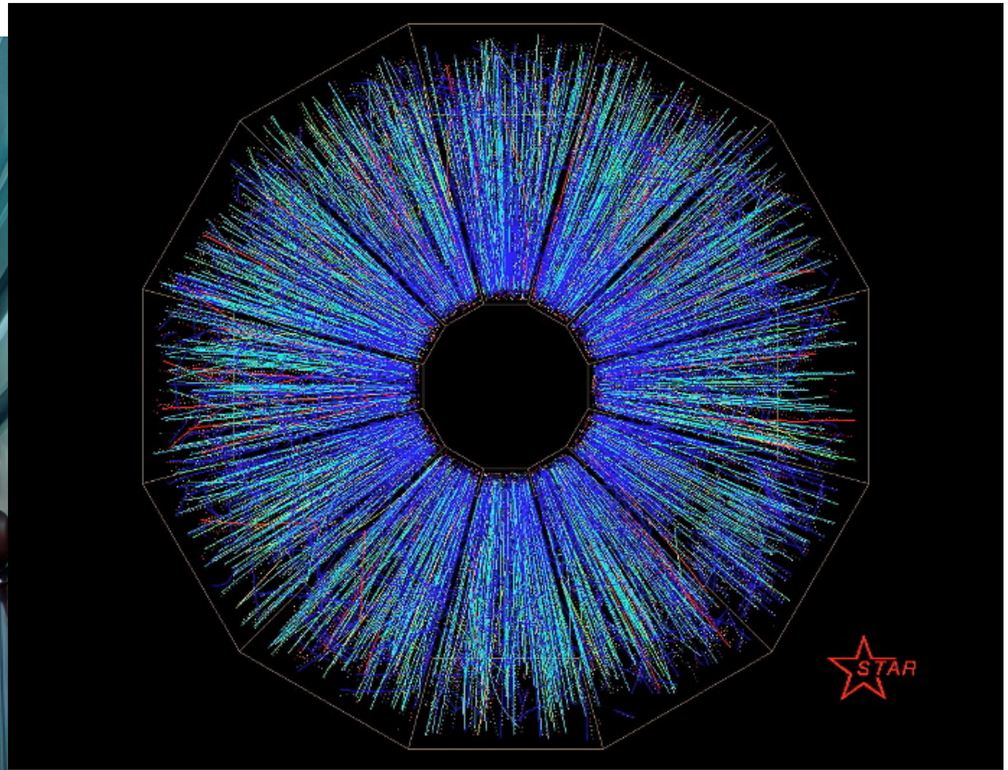
- In addition, CO_2 has 3 crucial advantages over CH_4
  - it is not flammable (safety)
  - it does not polymerize (ageing)
  - it does not contain hydrogen (thermal neutron capture)
- But has disadvantages
  - it is slow
  - drift velocity and gain highly dependent on T and P
  - It is not a very good quencher

CO_2 is the choice in the LHC era (also together with N_2)

STAR TPC

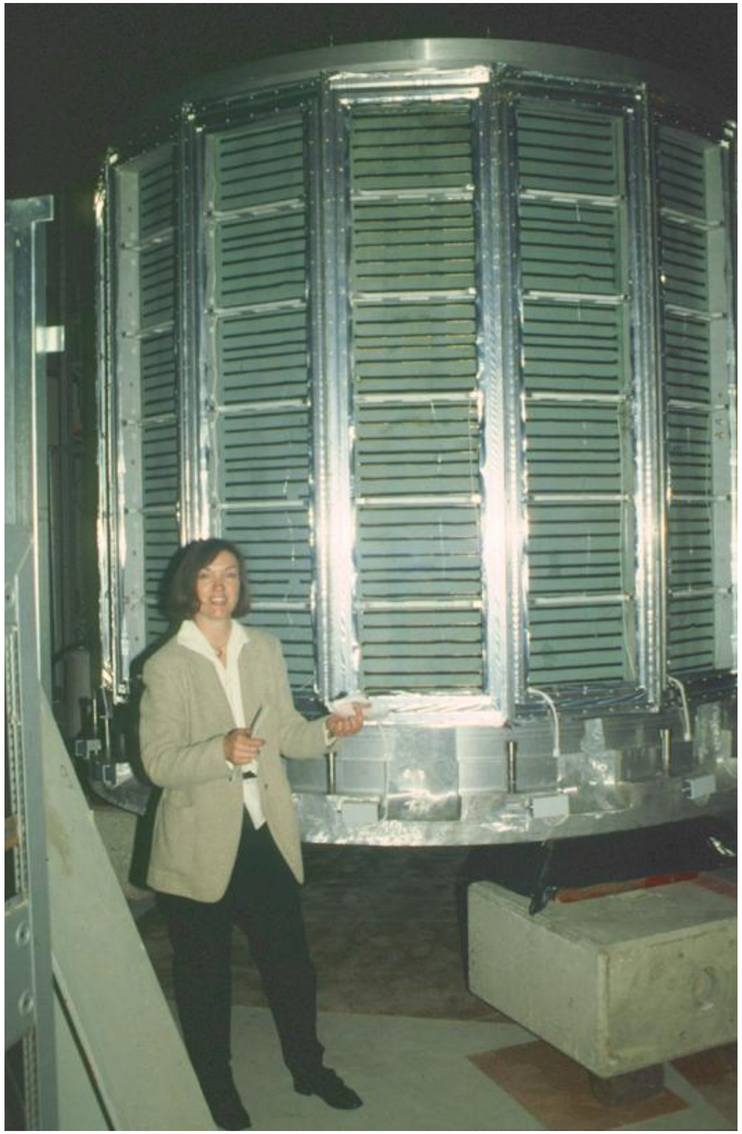


4 m x 4.2 m

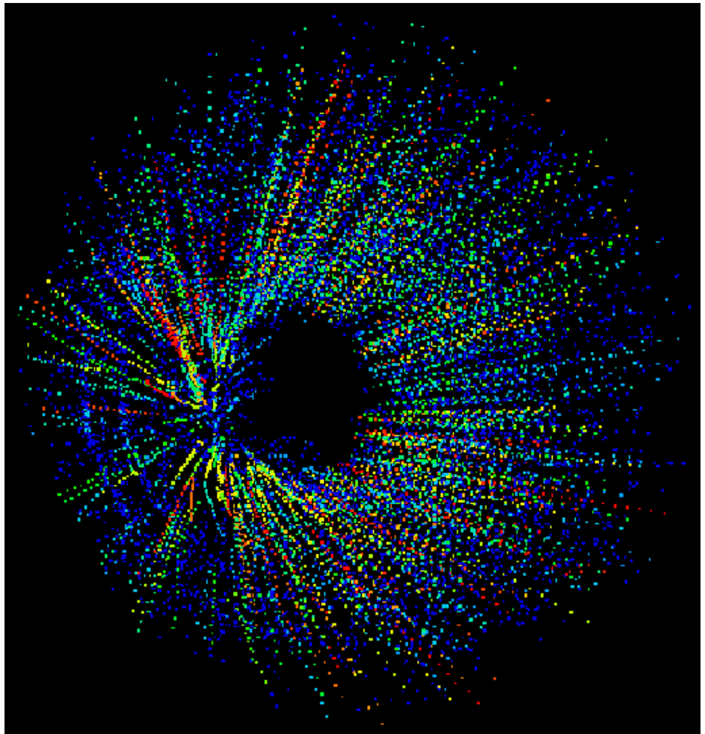


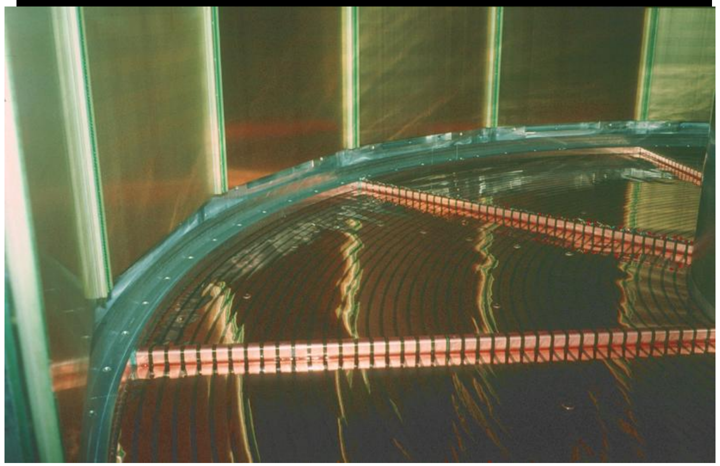
- Ar-CH_4 (90-10)
- FC voltage divider on walls made of a nomex honeycomb
- Designed for a HI collider
- Al strips on central electrode for V_d calibration with a laser system

CERES TPC



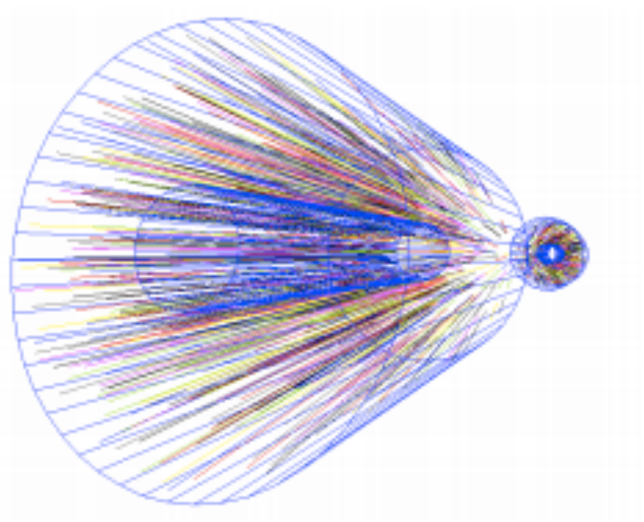
- Fixed target HI
- Radial drift field
- Chambers on the outer cylinder
- Doube O-ring sealing of chambers: decouple alignment from tightness
- Ne-CO_2 (80-20)
- Drift field up tp 600 V/cm at low radii

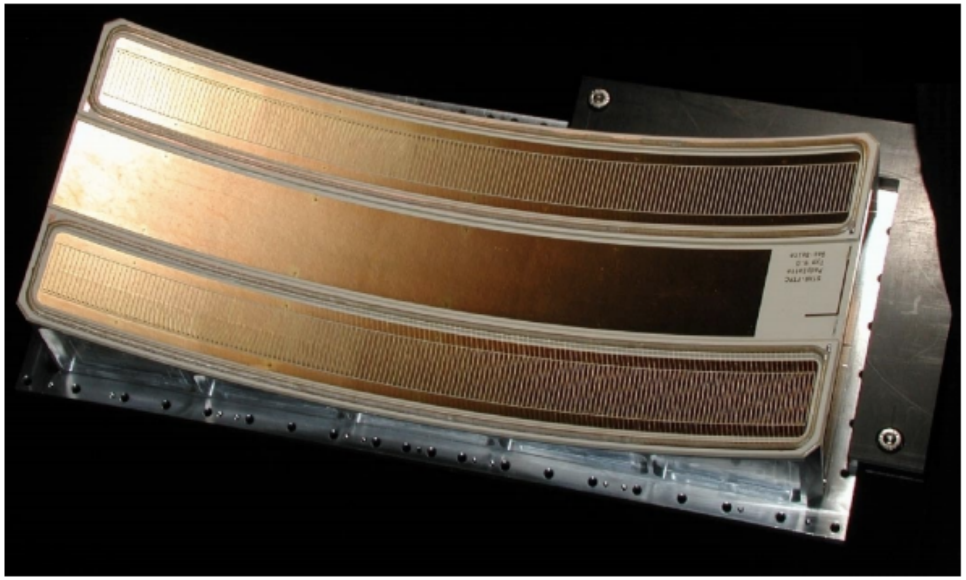




START Forward TPCs

- Another example of radial drift
- Readout chambers are truly cylindrical
- High precision drift velocity monitors developed for these TPCs now (modified) in ALICE

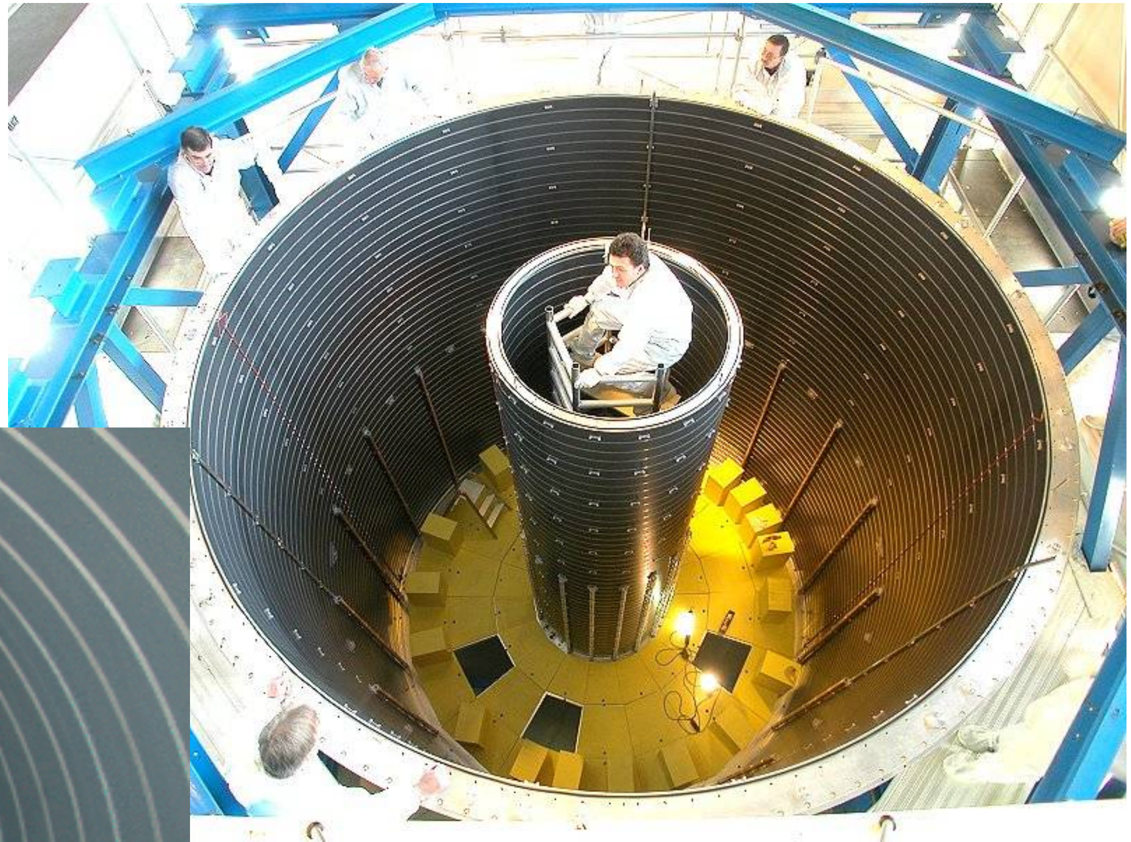




The current ALICE TPC

The ALICE TPC Field Cage

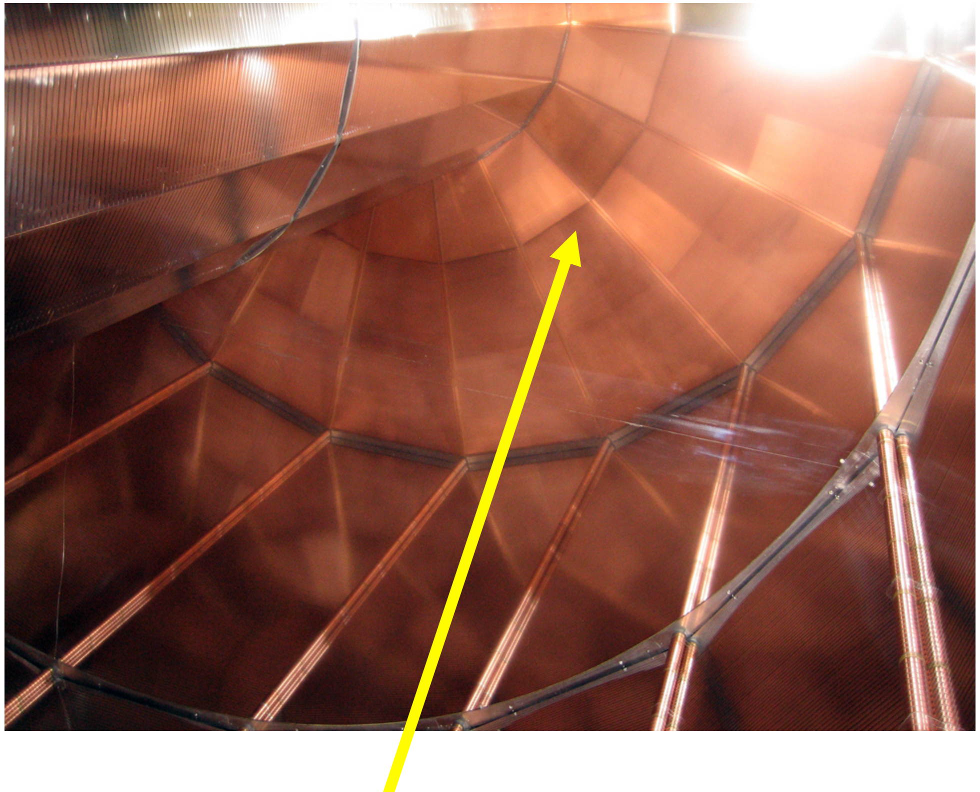
- Four cylinders made with composite material: sandwich of Nomex honeycomb between two epoxy-fiber glass layers, and a Tedlar foil for tightness
  - Composite materials used before



On the walls, the mechanics – rods- to hold the field-defining suspended strips are installed with high precision (O(100 µm))

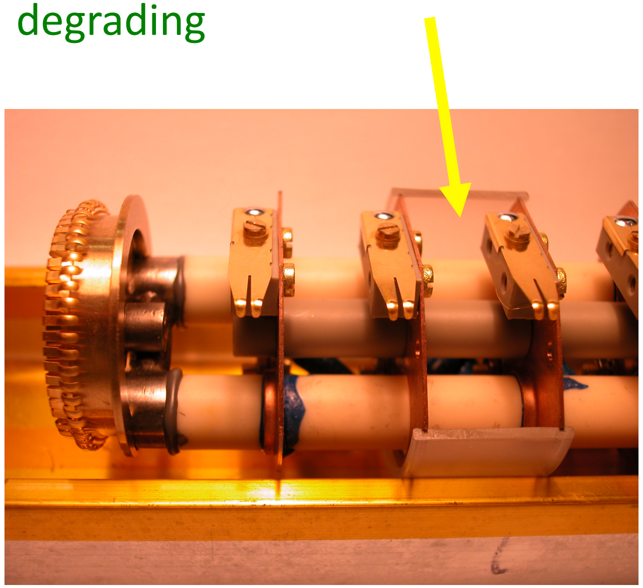
The ALICE Field Cage

5 m x 5 m, ~90 m^3



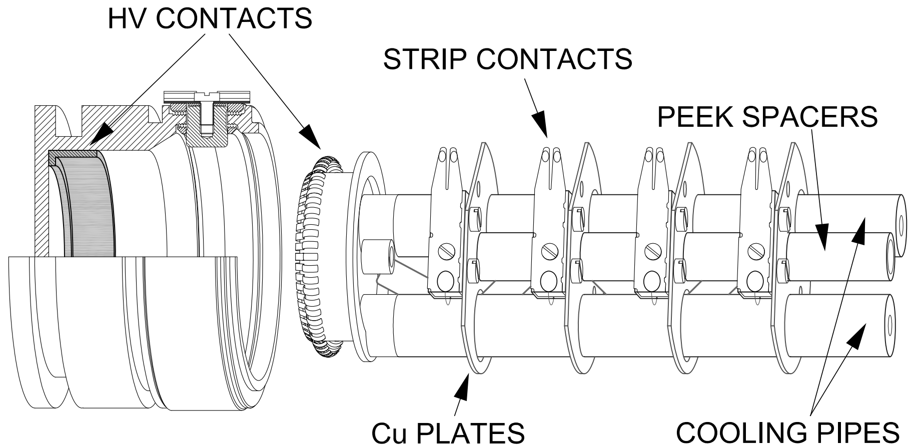
Central Electrode (aluminised mylar, 100 kV) reflects the image of the Readout Chambers (IROCs, OROCs)

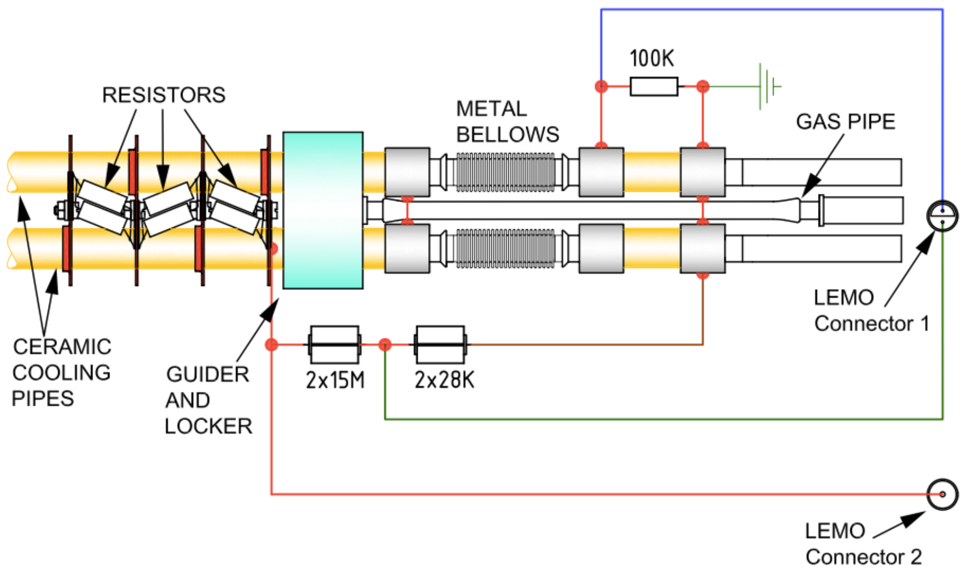
- 400 V/cm drift field defined by suspended strips held by rods
- Rods used also to:
  - circulate the gas through small holes
  - introduce laser tracks
  - house water cooled, removable resistor chains for voltage degrading



The resistor rods

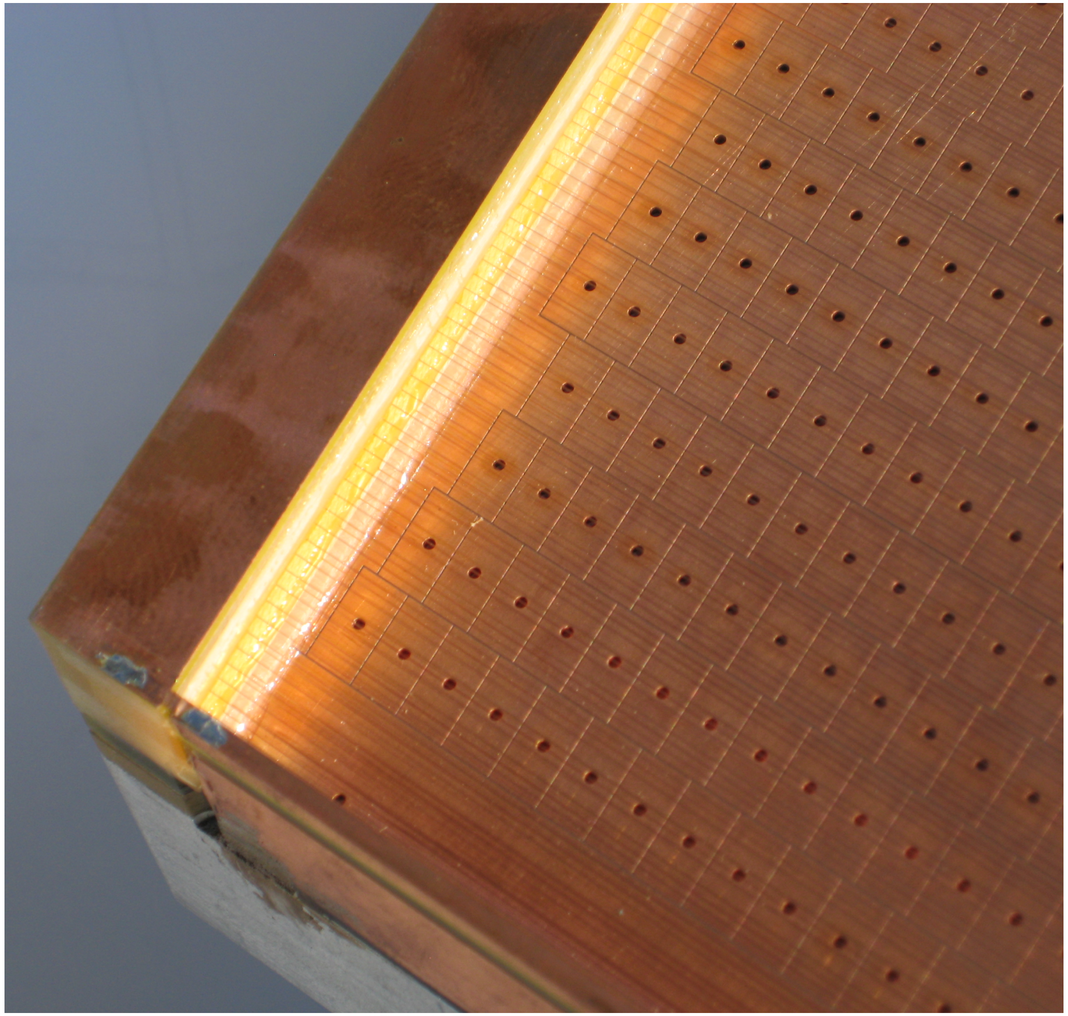
- The few tens of Watts dissipated by the resistor chain is water-cooled in a removable rod
  - highly resistive water
  - ceramic pipes with Platinum ends
  - no leaks!





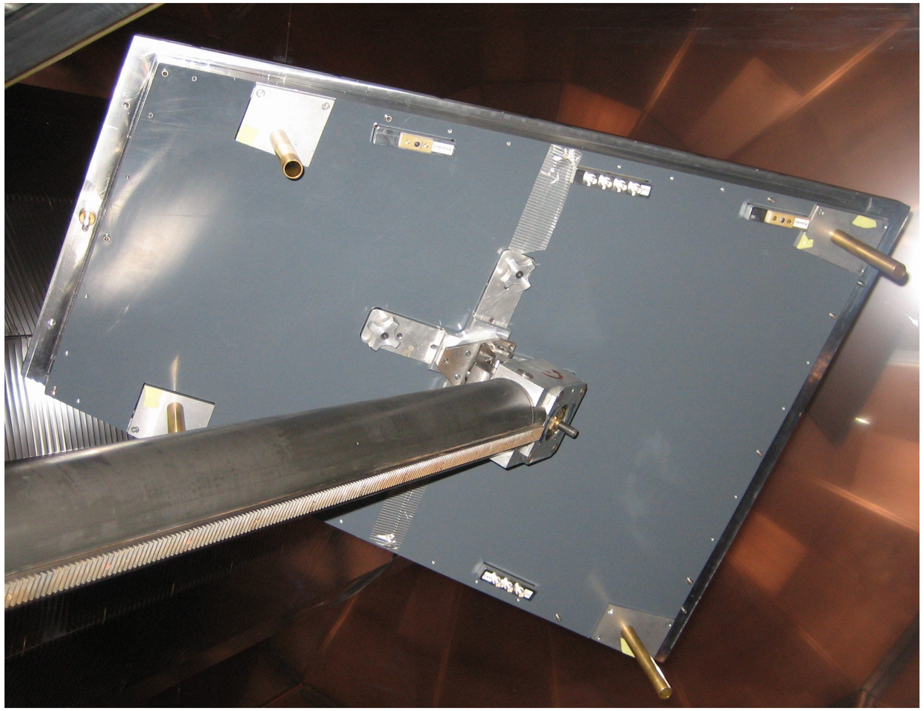
Readout chambers

- Adopt a tight geometry as NA49
  - relatively small pads: 4x7.5, 6X10, 6X15 mm^2
- No field wires
- Surround chambers with a ‘cover’ electrode to avoid field distortions and avoid leakage of ions



Other features

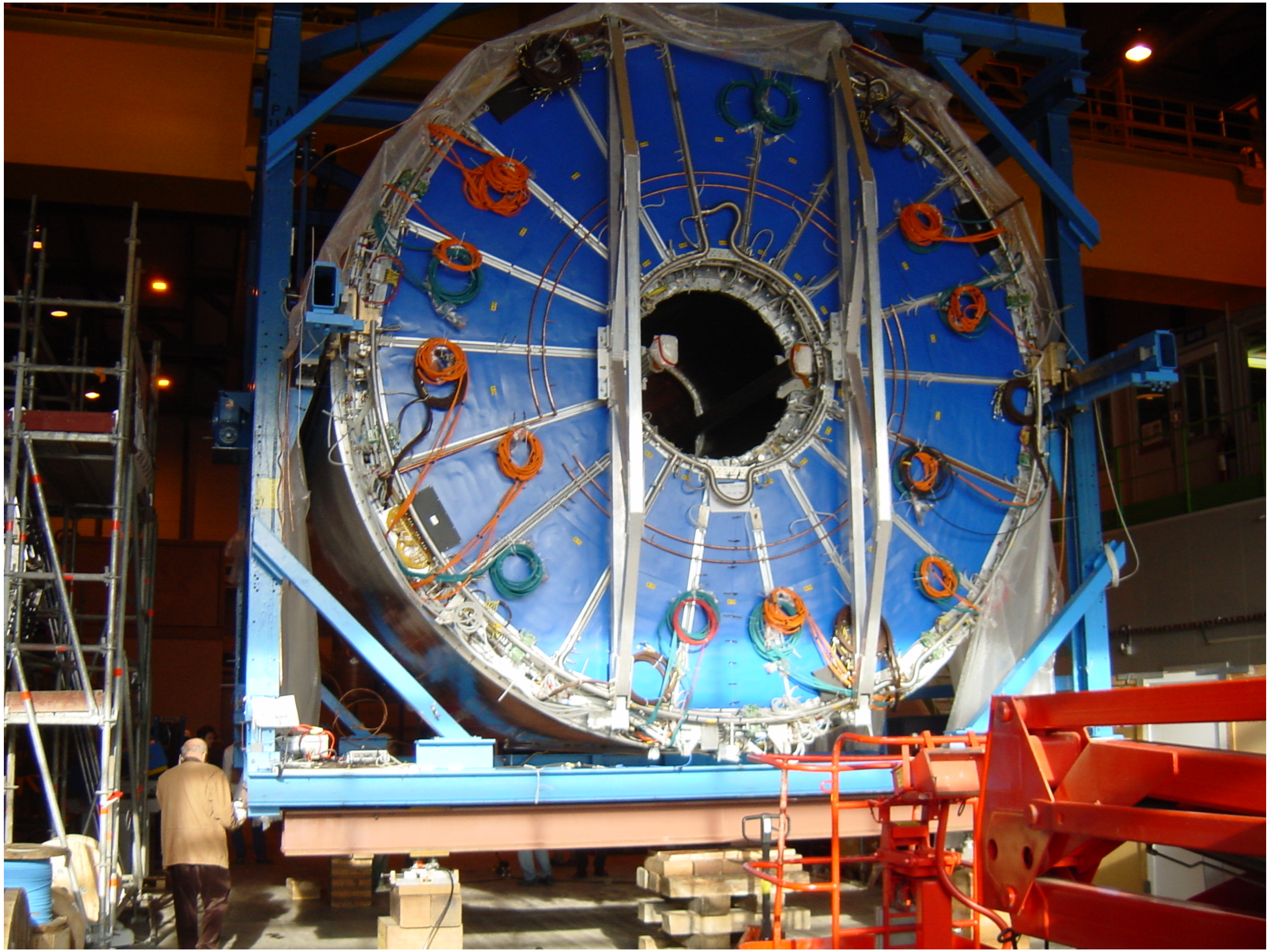
- Insertion of chambers à la ALEPH
  - A few mm clearance with critical FC structures
- Double O-ring sealing
- Electronics connected via flexible kapton cables and supported by an independent structure (the Service Support Wheel)



Gas

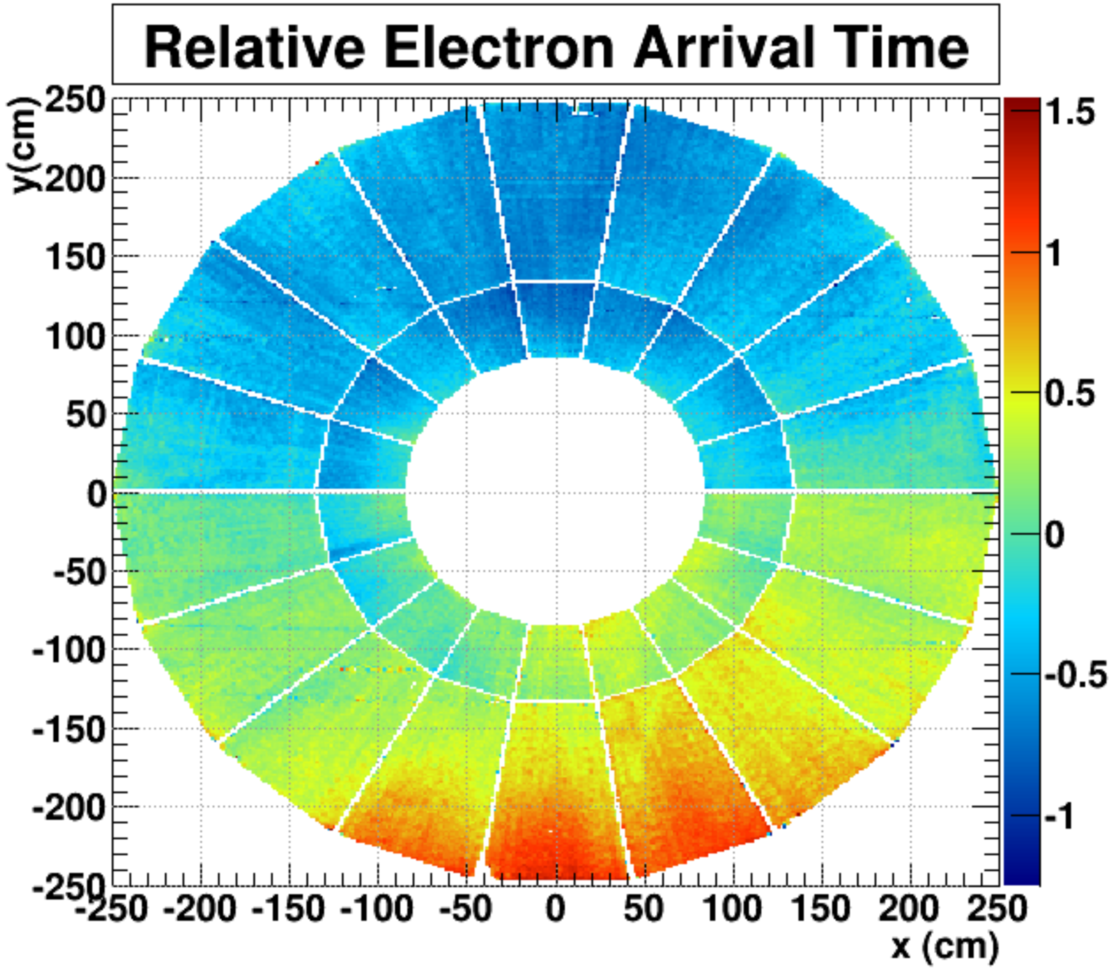
- Started operation with Ne-CO_2-N_2 (90-10-5)
  - N_2 provides further stability against discharges at no cost in transport properties
- Very good tightness leads to negligible e^- attachment to O_2
- In 2011 N_2 was removed ☹
- Now Ne is replaced by Ar
- In either case, max. drift time is $\lesssim$ 100 μs

Thermal insulation



- Inner, outer, and endplate thermal screens, in addition to electronics and RR cooling
- Goal of 0.1 K temperature uniformity achieved

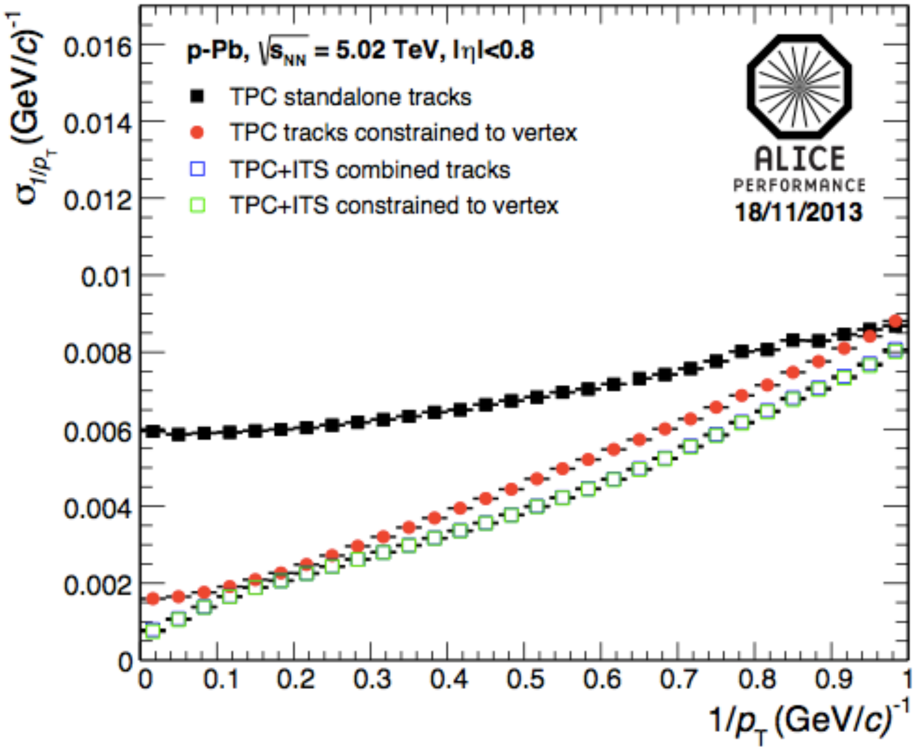
V_d uniformity



Ne-CO_2 mixtures are very sensitive to gas density
The drift velocity is measured with precision via the signal produced by stray laser light on the aluminised central electrode (by photoelectric effect)
The drift time gradient due to the pressure grandient is observed (1 time bin = 100 ns)

ΔV_d ~ 0.35 % per K
Δgain ~ 1 % per K

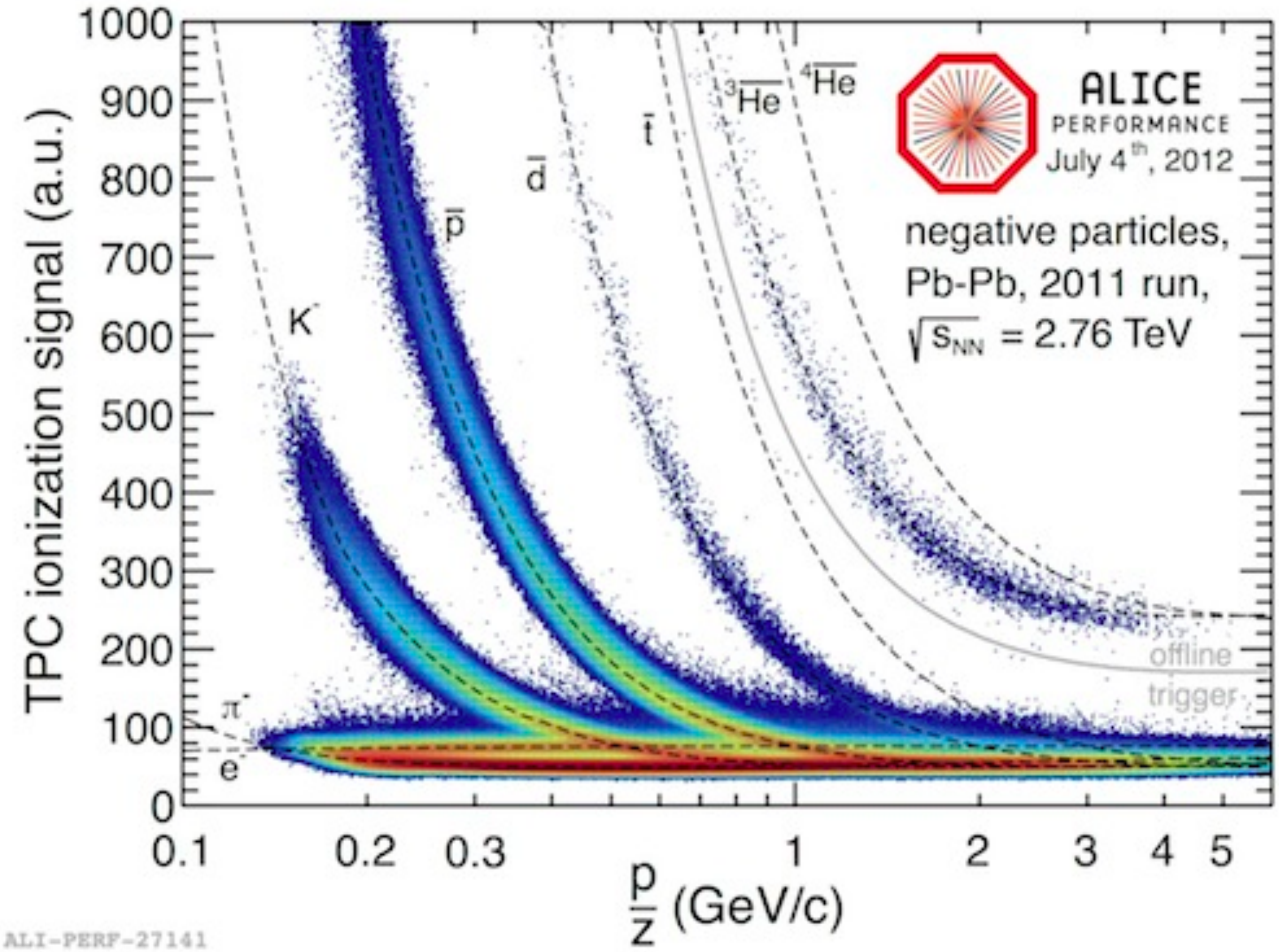
Momentum resolution



Or, in other words:

- $\sigma_{pT}/p_T \lesssim$ 3.5 % at 50 GeV/c
- $\sigma_{pT}/p_T \lesssim$ 1 % at 1 GeV/c
- Matching to external detectors significantly improves resolution at high p_T

dE/dx performance

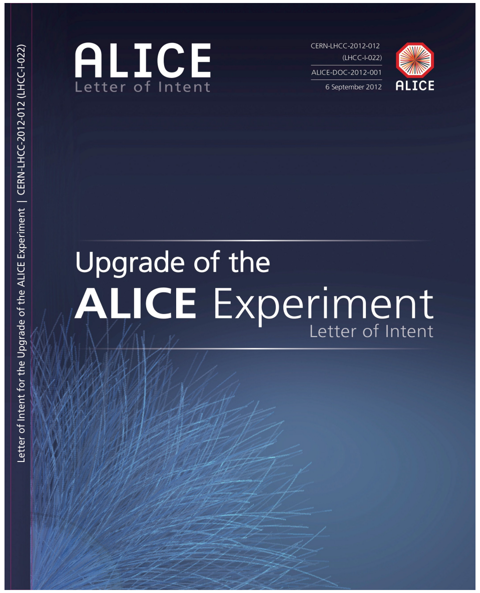


- The gain of each pad is calibrated using ^{83}Kr decays in the gas (like NA49, CERES, …)
- Achieve 5.5% in pp and 7% in Pb-Pb

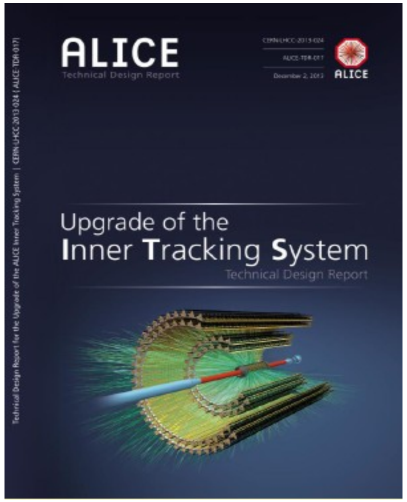
Upgrade with GEMs

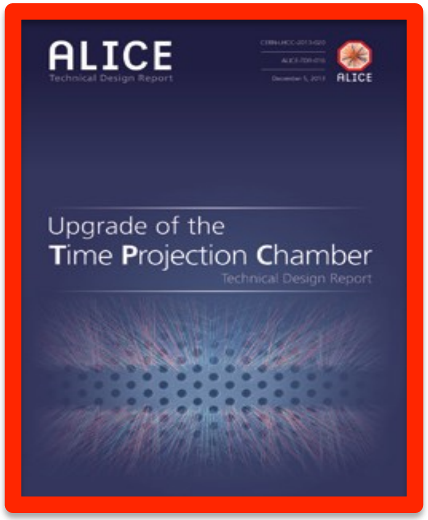
ALICE UPGRADE for RUN 3

- **Motivation**: high precision measurements of rare probes at **low p_t**
  - ✓ cannot be selected with hardware trigger
  - ✓ need to record large sample of events
- **Goal**: operate ALICE at high rate, record all MB events
  - ✓ 50 kHz in Pb-Pb (~10 nb^{-1} in RUN 3 and RUN 4)
  - ✓ no dedicated trigger, reduce data size (compression)
  - ✓ preserve PID
- **Significant detector upgrades:**
  - ✓ e.g. **TPC with continuous readout**
  - ✓ LHC Long Shutdown 2 (2019/2020)



LoI: https://cds.cern.ch/record/1475243

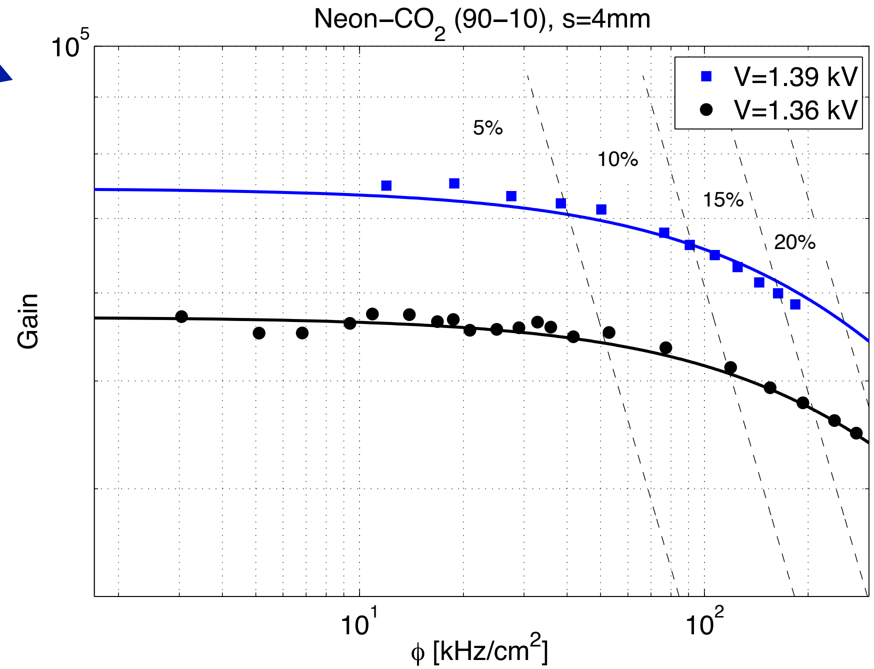




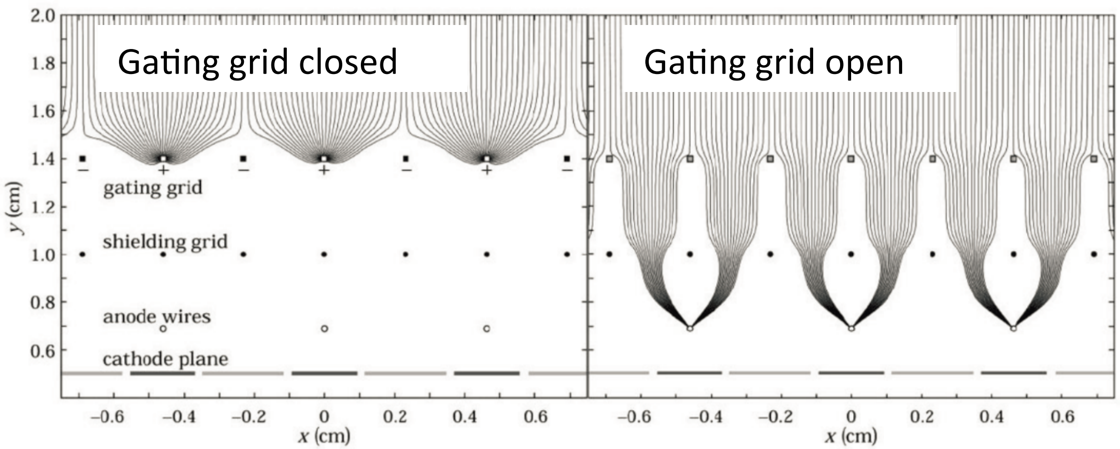
TDR: https://cds.cern.ch/record/1622286
Addendum: https://cds.cern.ch/record/1984329

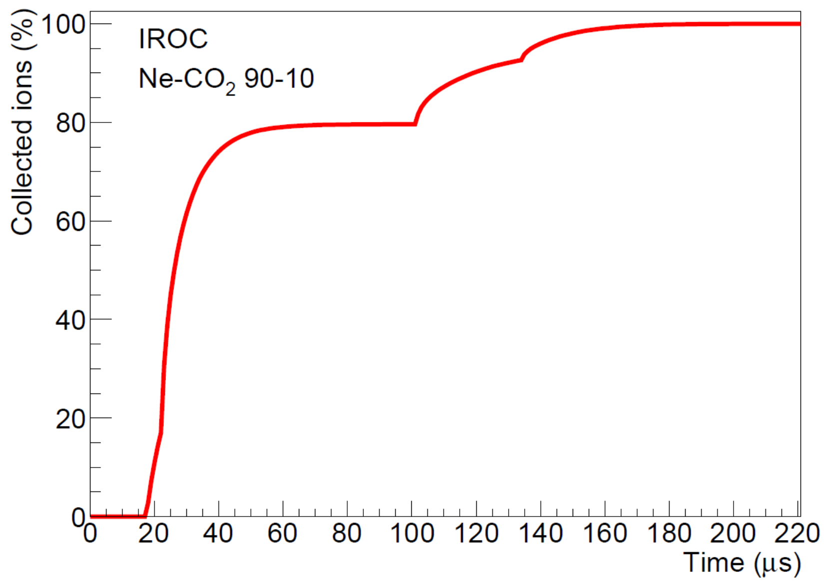
Upgrade of the TPC

- In 2020 the LHC will deliver 50 kHz Pb-Pb collision rate
- At ~100 kHz/cm² the space charge near the anode wires would affect dE/dx resolution
- With a gating grid, only 3 kHz can be achieved
  - GG must stay closed while ions from the avalanche reach the wires, otherwise 10% of them escape and would produce ~1 m distortions in the drift volume



Limitations of the GG system

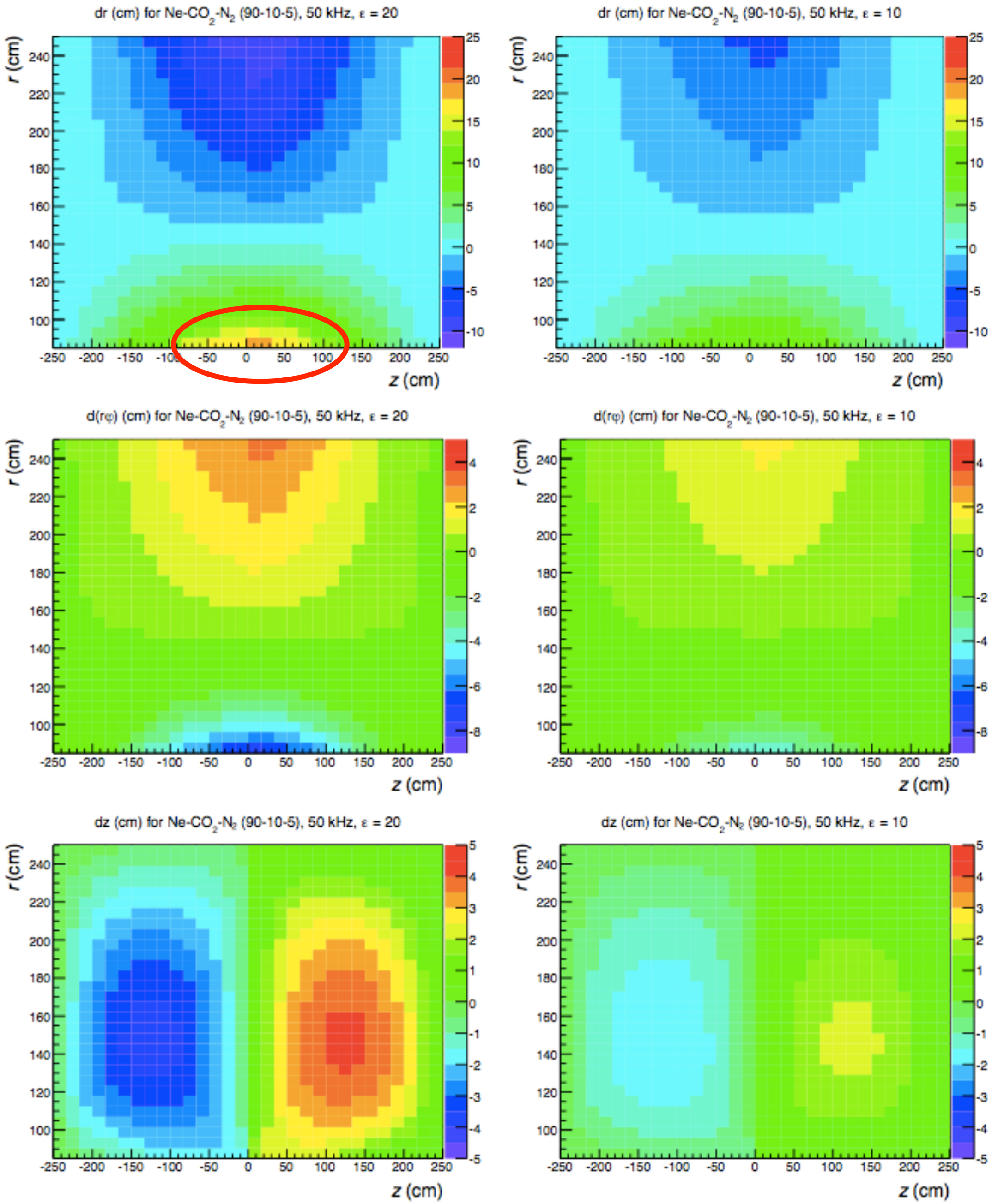




- Current MWPCs employ gating grid (GG) to neutralize ions produced in amplification process
  - otherwise sizeable distortions due to space charge
- GG limits operation to 3.5kHz
  - electron drift (90 µs) + ion blocking with GG (200 µs)
- Readout rate in Pb-Pb limited to 300 Hz

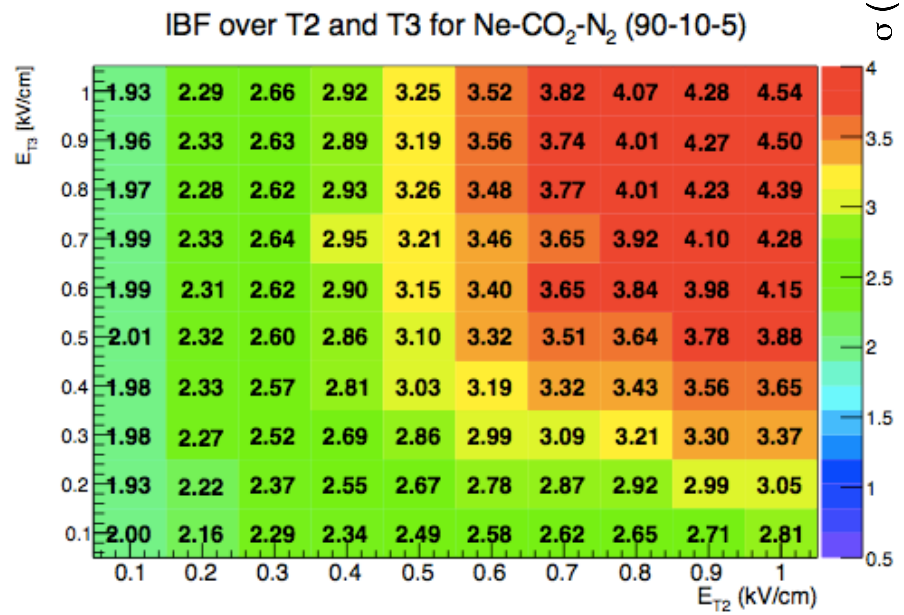
The Ion Back-Flow challenge

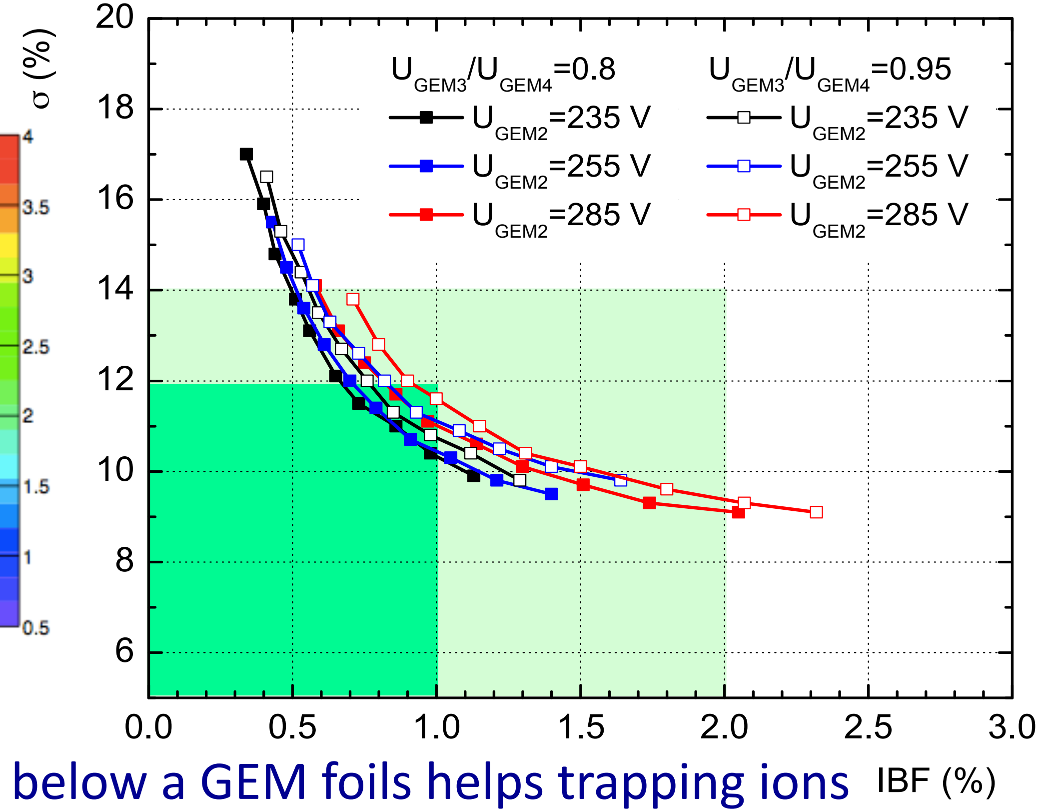
- GEMs are good at blocking ions from invading the drift volume, but this ‘good’ is not good enough
- We aim at IBF ~ 1% at gain 2000
  - ε ~ 20
  - Gas: Ne-CO_2-N_2 (90-10-5)
- Then, distortions of up to 20 cm must be corrected for
  - At inner radii, near the central electrode



A bit of homework is needed…

Minimise IBF and keep energy resolution

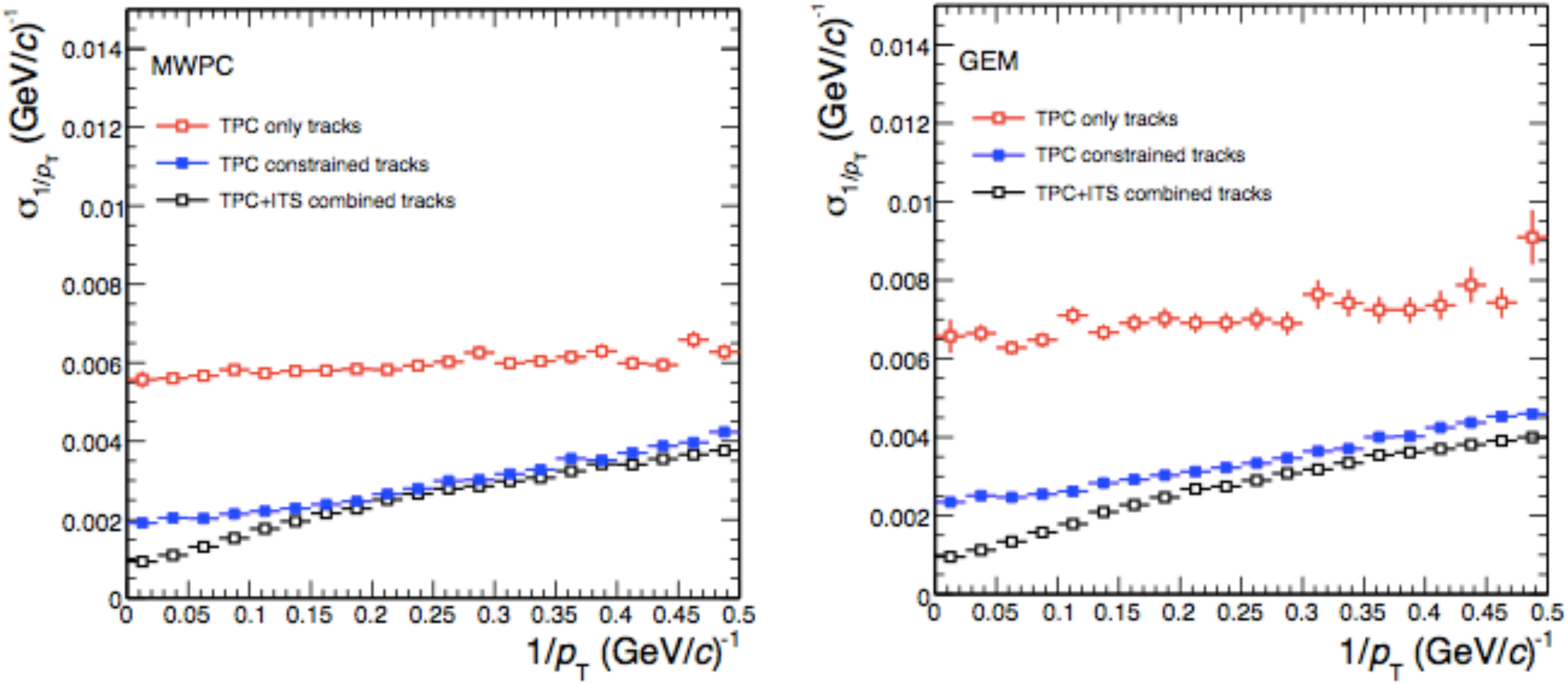




- **Asymmetric fields** above and below a GEM foils helps trapping ions
  - a **quadruple GEM stack** is used to best arrange this trap
- Misalignment between holes of different foils also helps blocking ions
  - use a combination of **Standard and Large-Pitch** GEMs (140 and 280 μm)
- However, the more ions are blocked, the more electrons are lost (same Maxwell for both), the latter resulting in deterioration of dE/dx

GEM performance

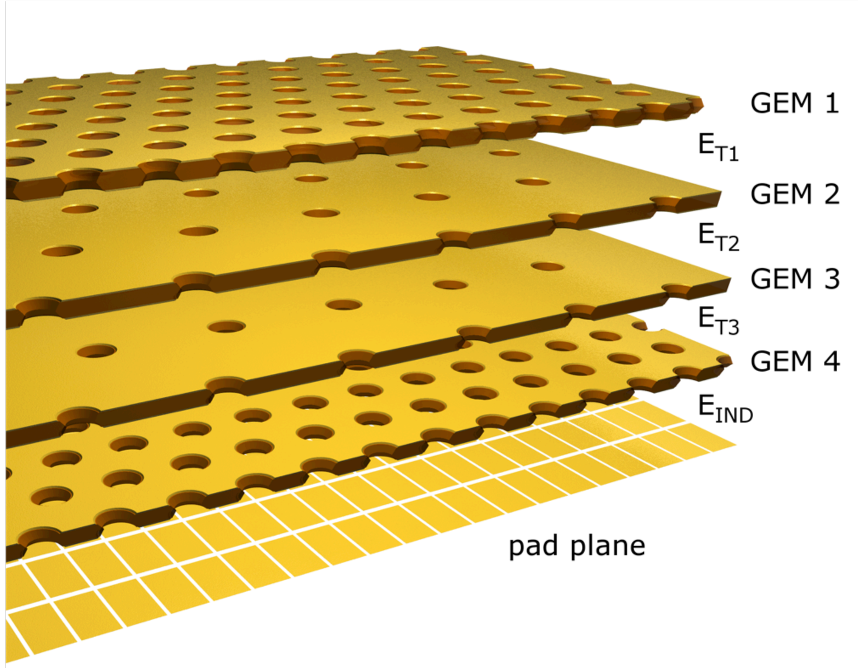
(high rate, but no space charge distortions here)



- GEMs produce no PRF, so clusters originated near the chambers induce signals in only one pad
- At high multiplicities this helps occupancy and overlap of clusters
- No need to replace the pad geometry!

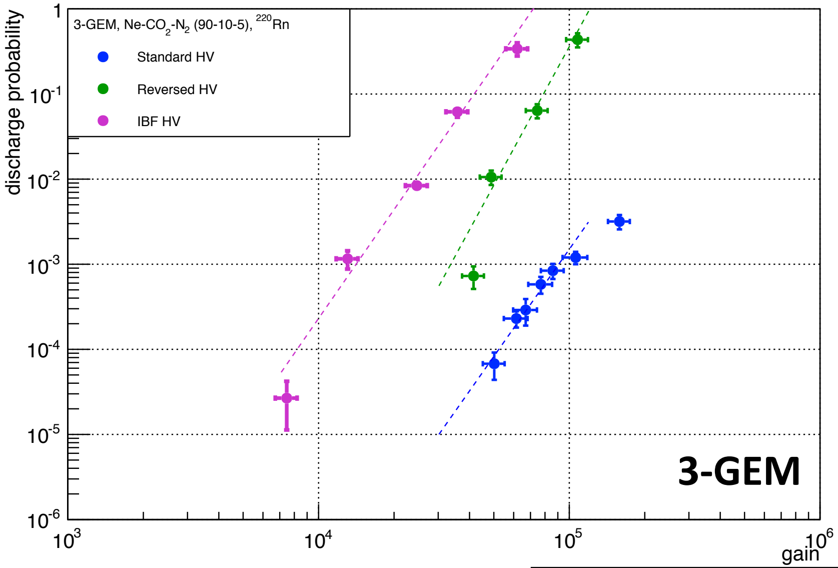
More on the ALICE TPC upgrade

- dE/dx resolution not to be compromised
  - Maintain excellent particle ID
- Robustness against discharges
- Large sizes (single-mask)
- QA, QA, QA
- Distortion corrections
- All this looks good
- R&D still ongoing
  - discharges, ageing, …



Extensive discharge studies

- Influence of HV settings

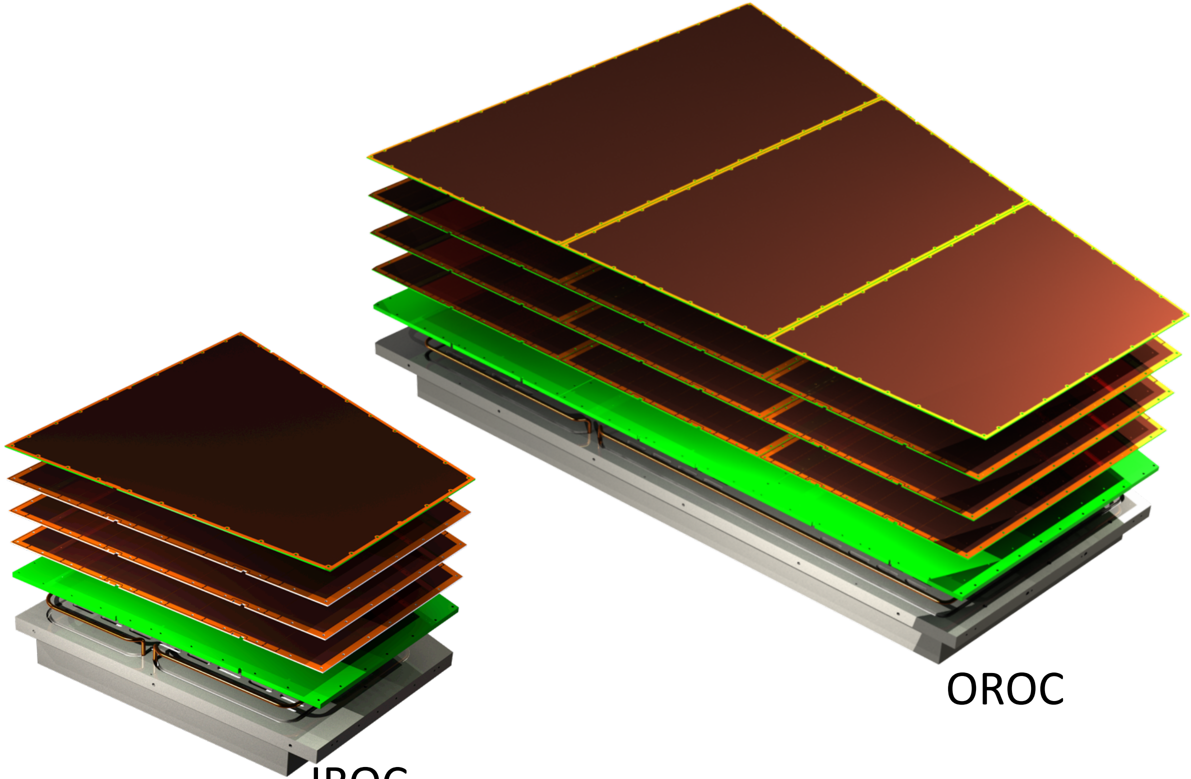


- Different HV settings have been tested with a 3-GEM configuration
- "Standard" → "IBF"
  - Standard – optimized for stability (COMPASS)
  - IBF → optimized for IBF
- Significant drop of stability while using IBF settings with a typical 3-GEM configuration

- **4-GEM configuration,** optimized for energy resolution and IBF is also stable against electrical discharges

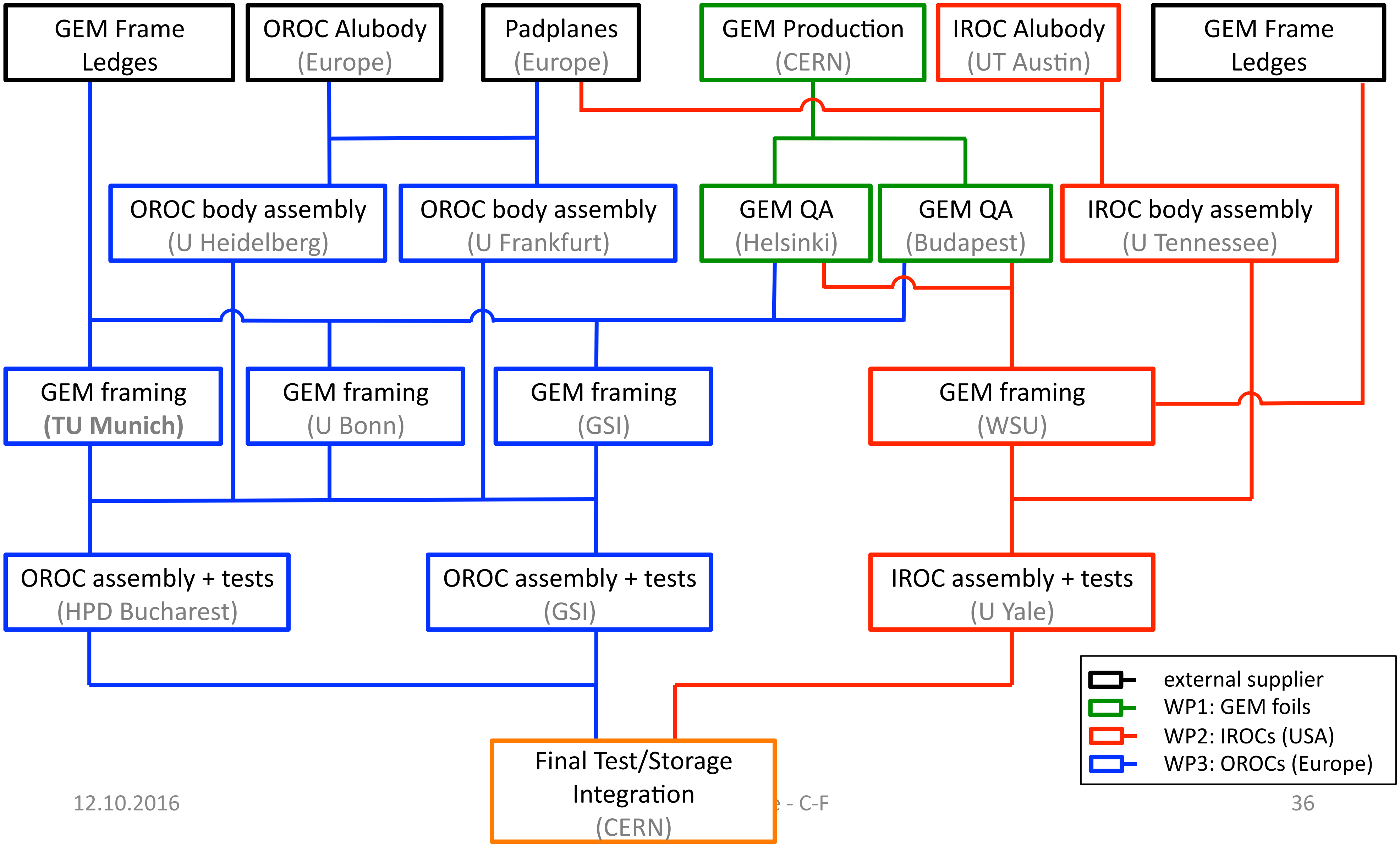
	S-S-S	S-S-S-S		S-LP-LP-S		
	'standard' HV, G = 2000	*IB* = 2.0%, G = 2000	*IB* = 0.34%, G = 1600	*IB* = 0.34%, G = 3000	*IB* = 0.34%, G = 5000	*IB* = 0.63%, G = 2000
^{220}Rn, $E_\alpha = 6.4$ MeV, rate = 0.2 Hz	$\sim 10^{-10}$			$< 2\times10^{-6}$	$< 7.6\times10^{-7}$	
^{241}Am, $E_\alpha = 5.5$ MeV, rate = 11 kHz						$< 1.5\times10^{-10}$
^{239}Pu+^{241}Am+^{244}Cm, $E_\alpha = 5.2+5.5+5.8$ MeV, rate = 600 Hz		$< 2.7\times10^{-9}$	$< 2.3\times10^{-9}$	$(3.1\pm0.8)\times10^{-8}$		$< 3.1\times10^{-9}$
^{90}Sr, $E_\beta < 2.3$ MeV, rate = 60 kHz					$< 3\times10^{-12}$	

GEMS for the upgrade



- Large-size single-mask foils from CERN PCB workshop
- 1 stack in IROC, 3 stacks in OROC
- Mass production started: installation in 2019-2020

ROC Material Flow



Conclusions

- We did our bit for the ALICE TPC, but we have also profited from 30 years of development of TPCs
  - mechanical precision
  - gas choice
  - charge gating
  - readout techniques
  - simulations and calibration
- We are doing well
- Now we profit from ≈15 years of GEM development and, with more people, we are doing another bit
  - ion backflow minimisation
  - energy resolution
  - stability against discharges
  - ageing tests

- Production phase: bookkeeping, shipping, QA, QA, QA

Backup

Drift velocity in an electric and magnetic field

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

Langevin equation

ω = eB/m

Pad Response Function

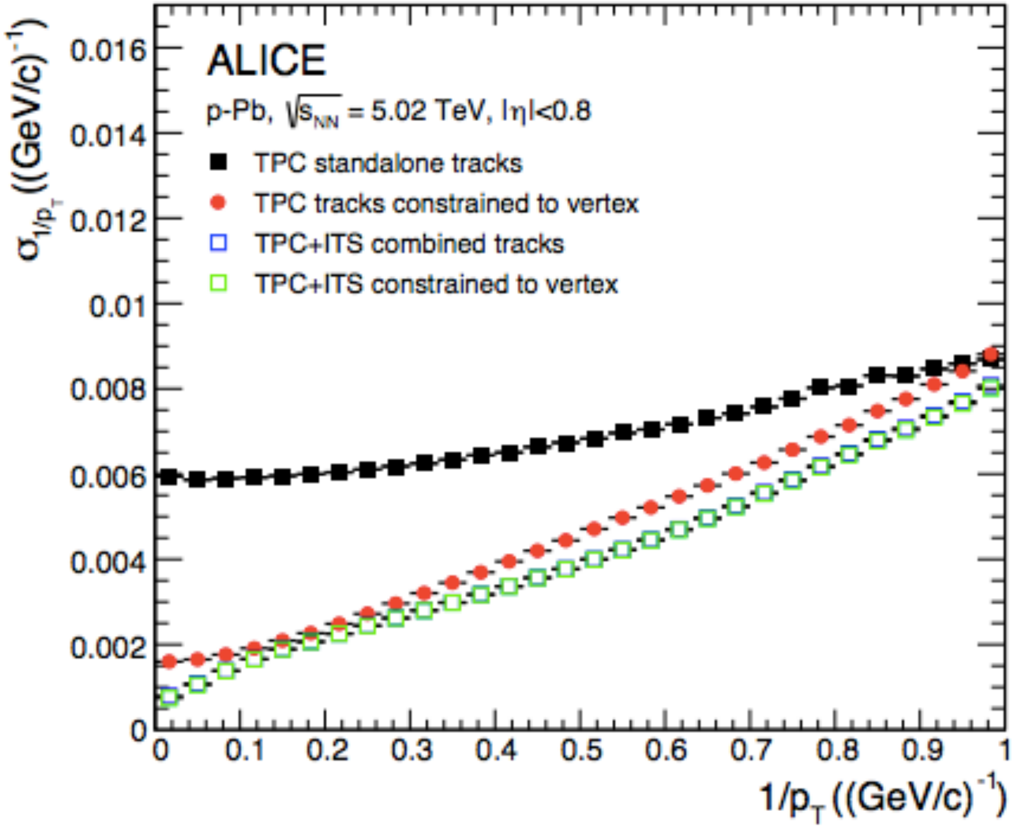
$$P_i(x) = C\exp\left(-\frac{(x-x_i)^2}{2\sigma^2_{\mathrm{PRF}}}\right)$$

σ_{PRF} depends on the electrode geometry only

Performance: p_T resolution

- For 2013 p-Pb data with Ne-CO_2 (90-10):
  - $\sigma_{p_T}/p_T \lesssim 3.5$ % at 50 GeV/c
  - 10% degradation in Pb-Pb
  - $\sigma_{p_T}/p_T < 1$ % at 1 GeV/c

- Best performance with combined TPC-ITS tracks



Performance of the ALICE Experiment at the CERN LHC, Int. J. Mod. Phys. A 29 (2014) 1430044

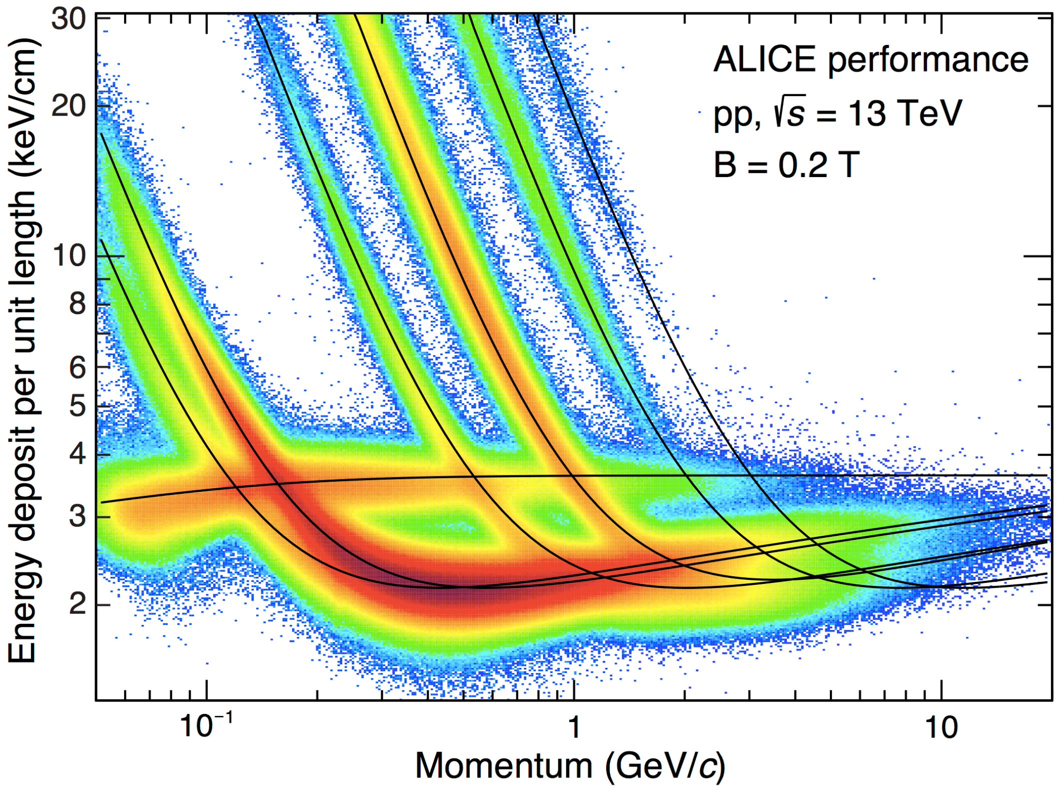
Performance: dE/dx

Current TPC

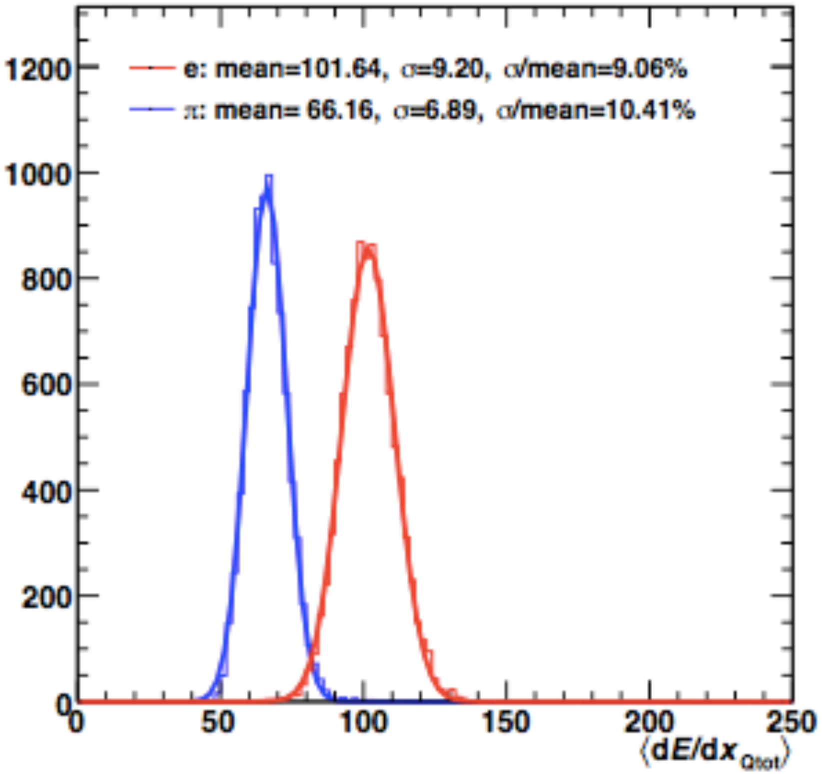
2015 pp data at B = 0.2 T, Ar-CO_2 (88-12)

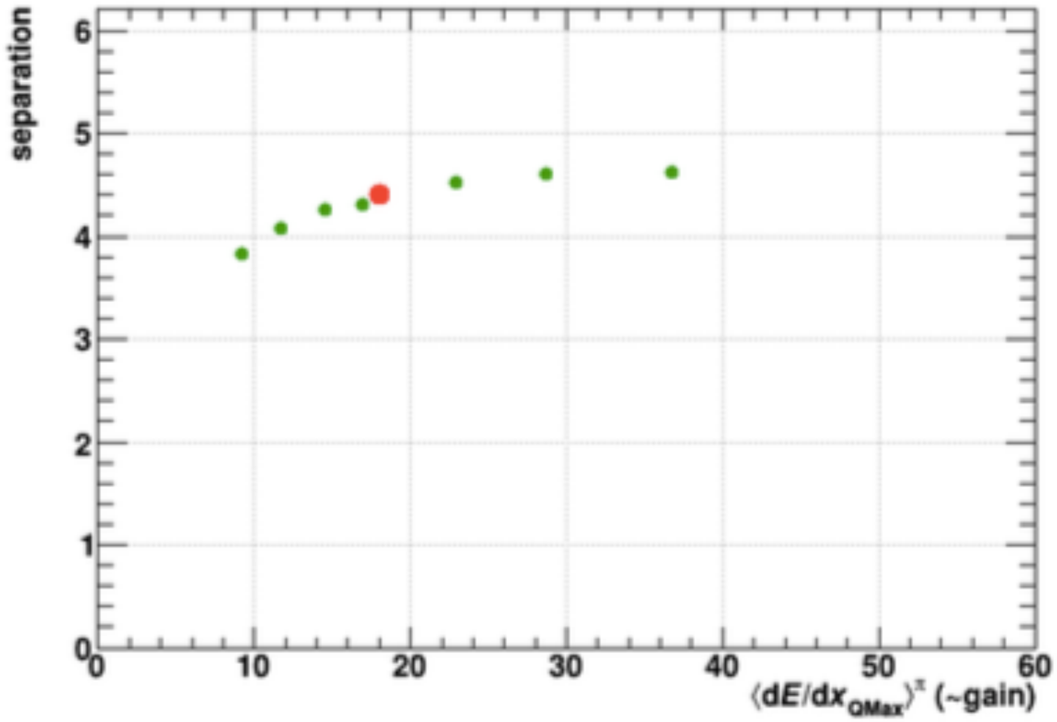
- With Ne-CO_2:
- $\sigma_{dE/dx} \approx 5.5$ % in pp
- $\sigma_{dE/dx} \approx 7$ % in central Pb-Pb
  - deterioration due to overlapping clusters

☞ Single-pad gain calibration with ^{83}Kr decays in the gas



dE/dx with IROC prototype





dE/dx for π and e at gain 2000

Separation power as a function of gain

Expected space-charge distortions

No B Average B = 0.5 T

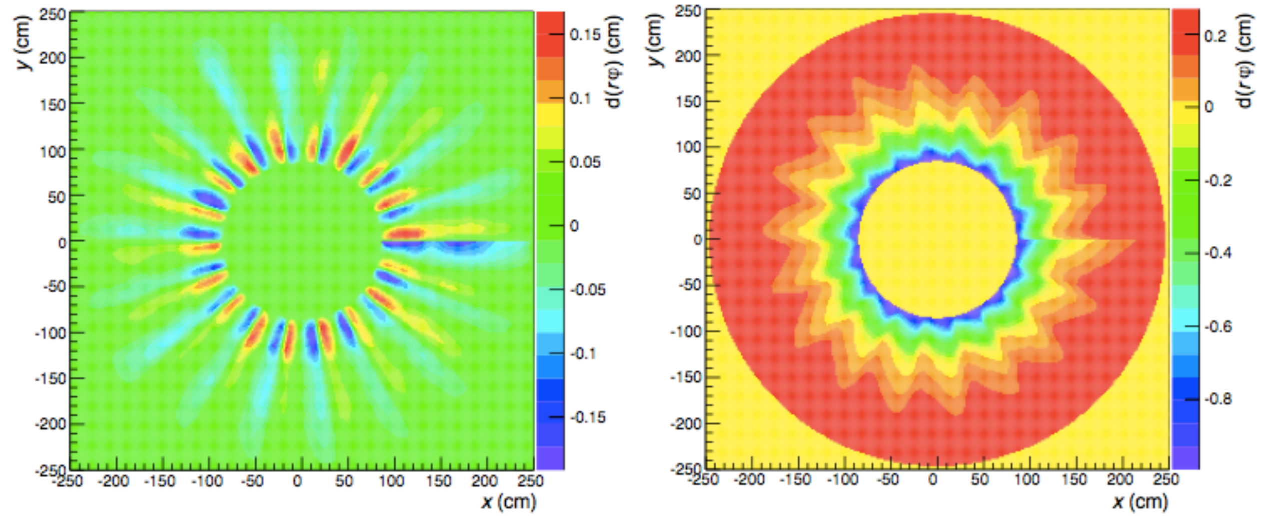
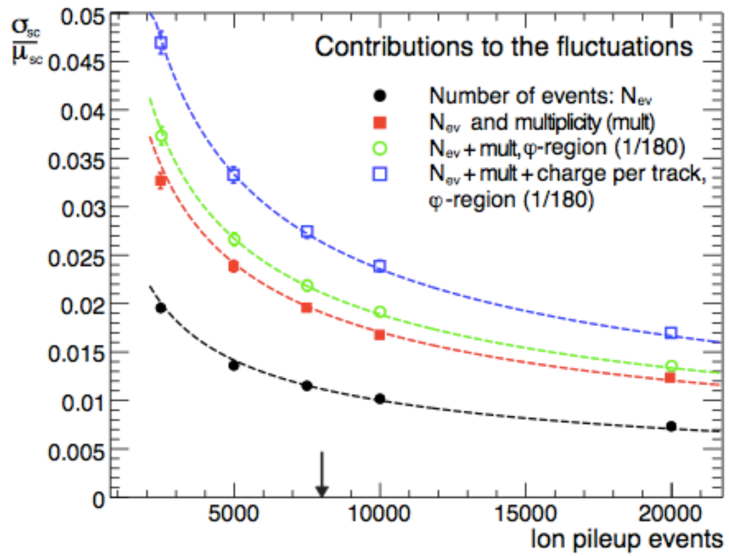


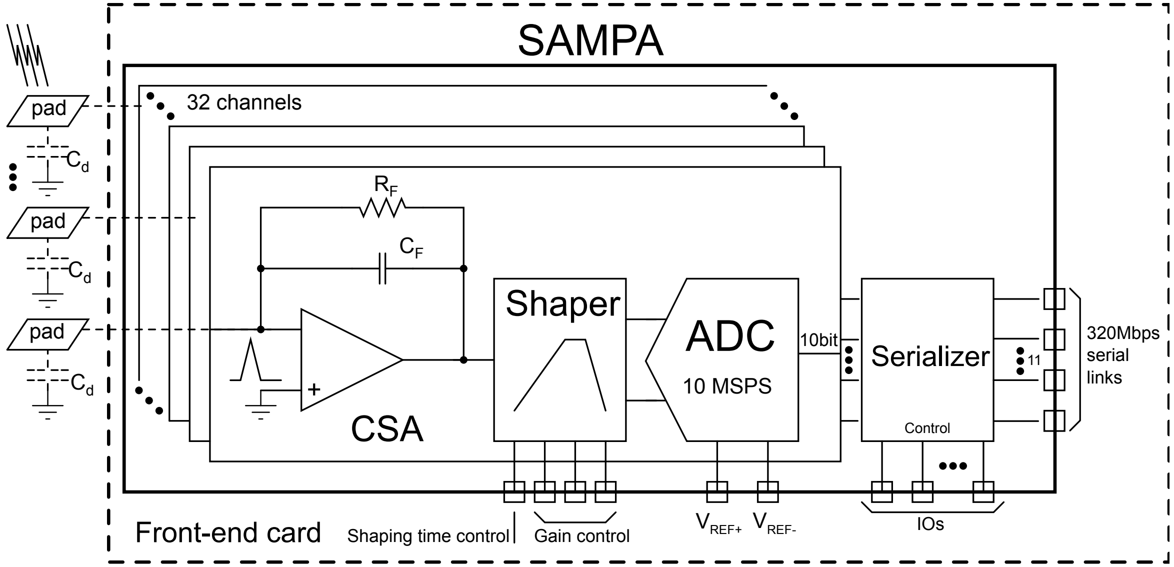
Figure 7.13: xy projection of the $r\varphi$ distortion map close to the TPC central electrode (at $z = 10$ cm). The data are base detailed 3-dimensional space charge map for $\varepsilon \approx 5$ without magnetic field (left) and with $B = 0.5$ T (right).

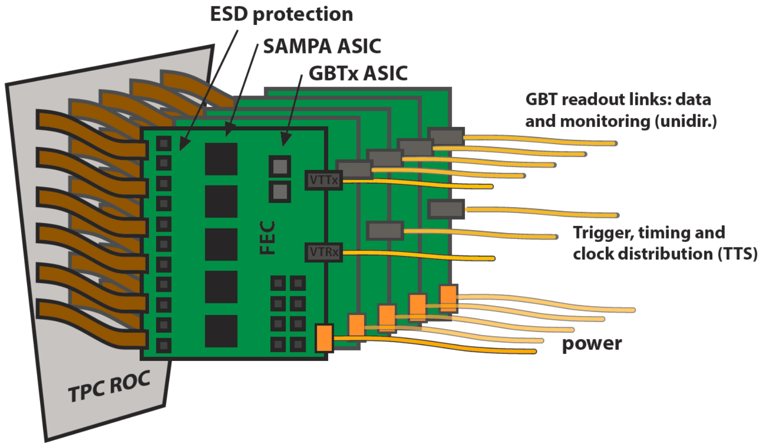
With fluctuations



Readout electronics

The continuous readout scheme necessitates the development of electronics that can concurrently sample the detector signals and transfer the acquired data off the detector





- **New FE ASIC "SAMPA"** (130 nm TSMC CMOS)
  - Positive or negative input
  - Programmable conversion gains and peaking times
  - Different readout modes: triggered, continuous with DSP, continuous with DSP by-pass
- **For required Signal-to-Noise ratio excellent noise figure of 670e⁻ (as currently) is needed**
- **All ADC values are read out: data output for 50 kHz Pb-Pb collisions ≈ 3.28 TByte/s** (5 MHz sampling)
- **Baseline correction and data compression off detector**
- **Use CERN developed GBT and Versatile Link for readout**