# Sensor for gaseous TPC readout in high energy Physics experiments

C. Garabatos, GSI

V Seminario Nazionale Rivelatori Innovativi

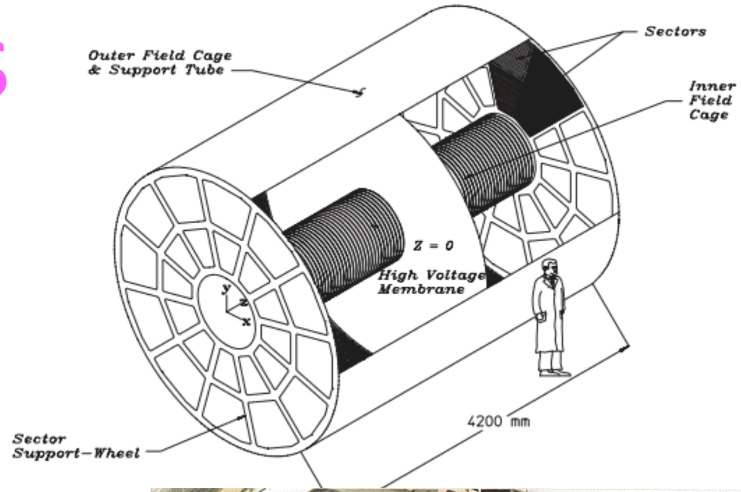
SNRI 2016, Padova

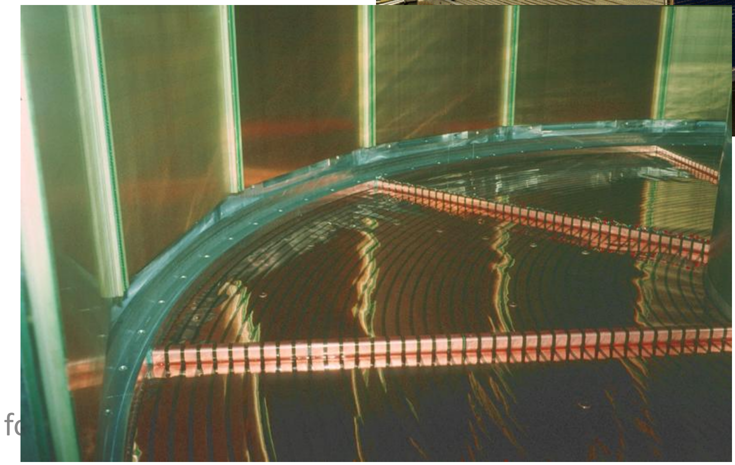
# What is a TPC

- A TPC is a box filled with gas, into which an electric field brings electrons, produced by ionising radiation, to one or two sides where the sensors are placed
  - true 3-dimensional tracking
  - usually embedded in a magnetic field for momentum measurement
  - low material budget
- Large number of track samples can be used to identify particles through dE/dx measurement

# Shapes

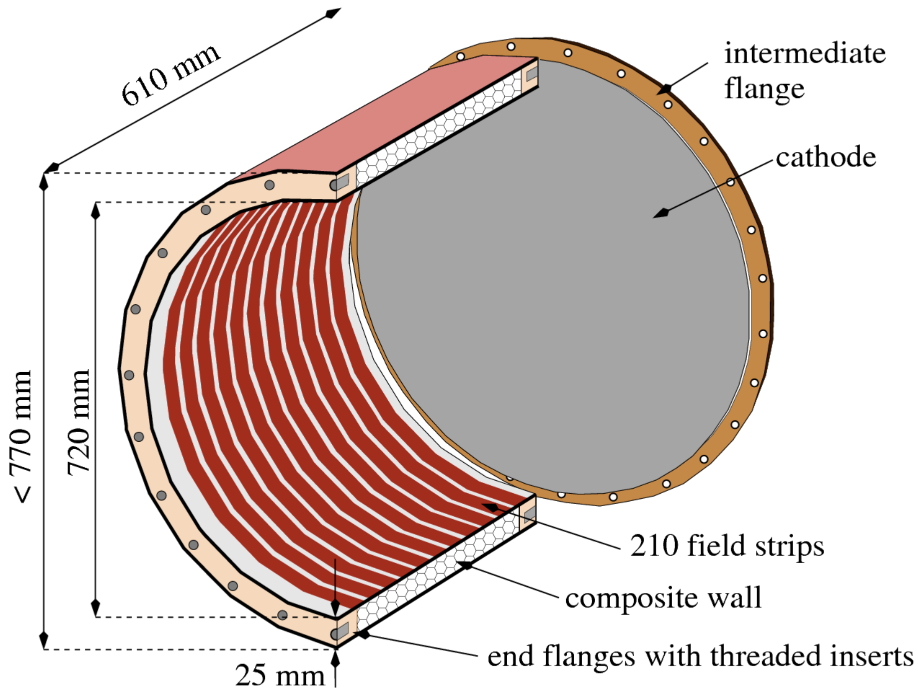
- Cylindrical TPCs with sensors in two endplates are used in collider experiments
- Cubic shape with sensors on one side are used in fixed-target experiments
- Forward TPCs use a radial drift field with sensors on the outer wall



# The Field Cage

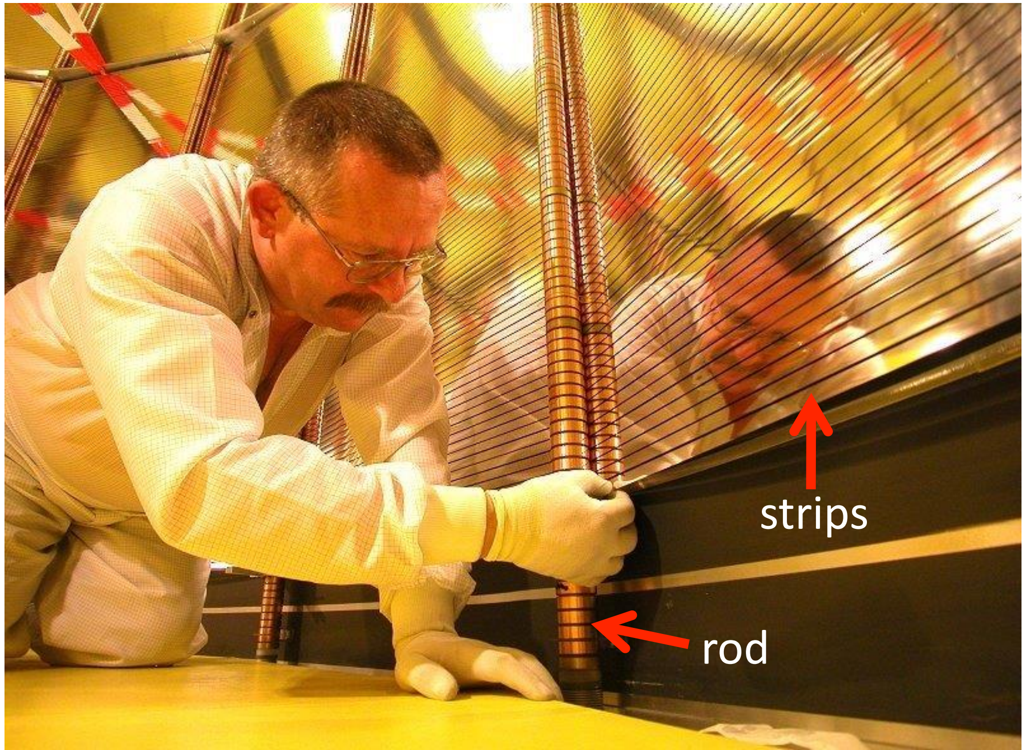
- The Field Cage provides an electric field by means of a main electrode (cathode) and a voltage divider arranged as a set of strips on the FC walls, powered by a resistor chain
- Its aim is to drift the electrons with a well-known velocity to the sensors, in order to measure the drift time –the 3rd co-ordinate
- The drift field is matched to the field at the sensors
- Performance requirements and momentum window define size and magnetic field

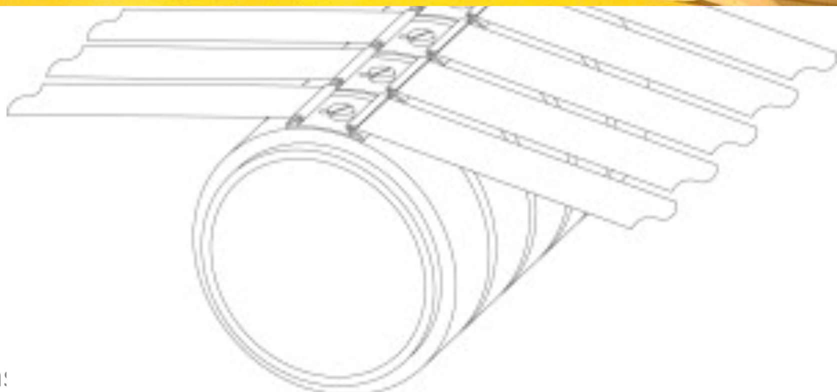



Example of a FC: strips laid on a light wall

# Requirements for FC

- High precision resistors for precise drift field
- Current through divider should be larger than the expected currents from ionisation: choice depends on expected event rate and multiplicity
  - mind the dissipated power
- Avoid problems due to surface charging up or dust deposition on walls: suspended strips first used in NA49, then in ALICE
- Choose potential according to gas choice
- Provide insulation from very high voltages



# Gas choice

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

- Gas is chosen according to:

1. Charge transport properties: drift velocity, transverse and longitudinal diffusion, Lorentz angle, ion mobility, electron attachment
2. Gain stability against discharges
3. Flammability, ageing, neutron cross section
4. Purity, cost

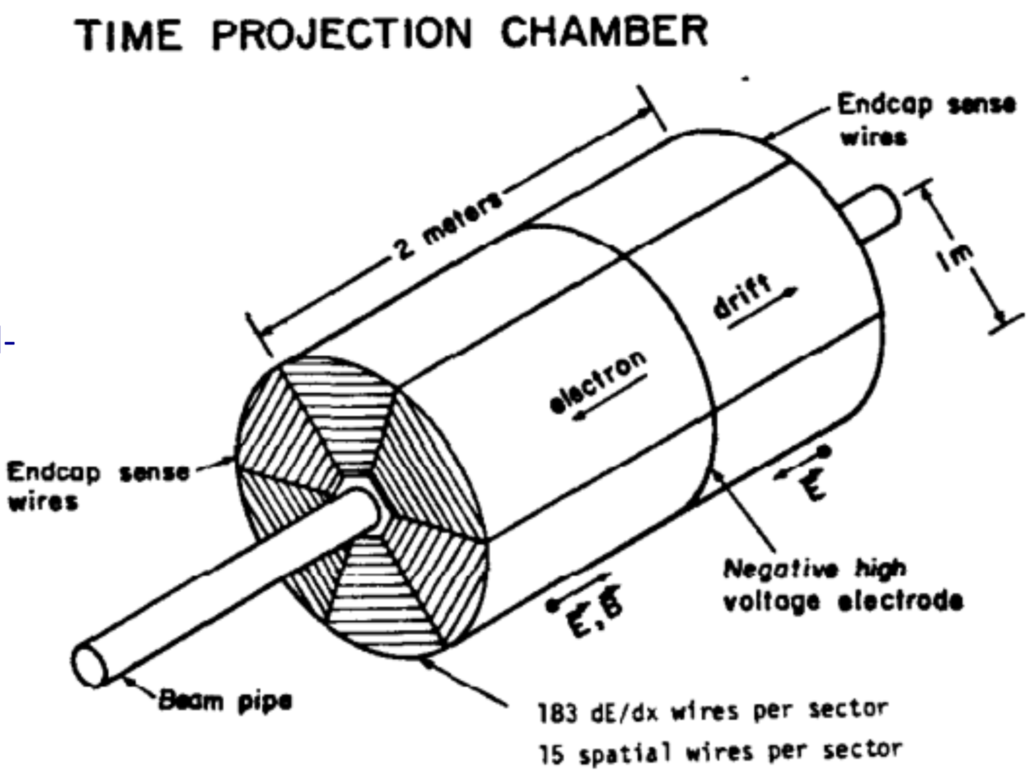
- All this is driven by the experimental conditions and expected performance

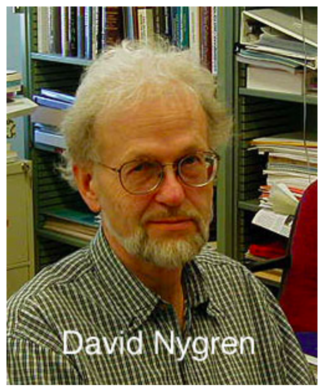
# Readout sensors: MWPC

Since its invention, 38 years ago, Multi-wire proportional chambers were for decades the only choice

# The first TPC: PEP-4

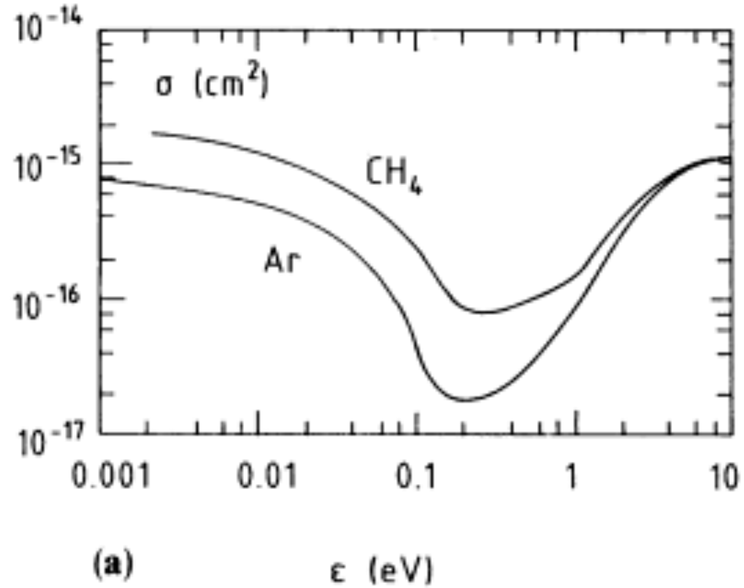
- Innovative detector design (1978)
- 3D device for momentum and particle ID
- AGS $e^+e^-$ collider
- Ar-$CH_4$ (80-20) at 8.6 bar
  - ☞ primary statistics, and therefore signal-to-noise, increase with p
  - ☞ If E scaled accordingly, diffusion decreases as ~1/p
  - – high pressure also used in the 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
- $\sigma_{xy}$ ~ 300 µm



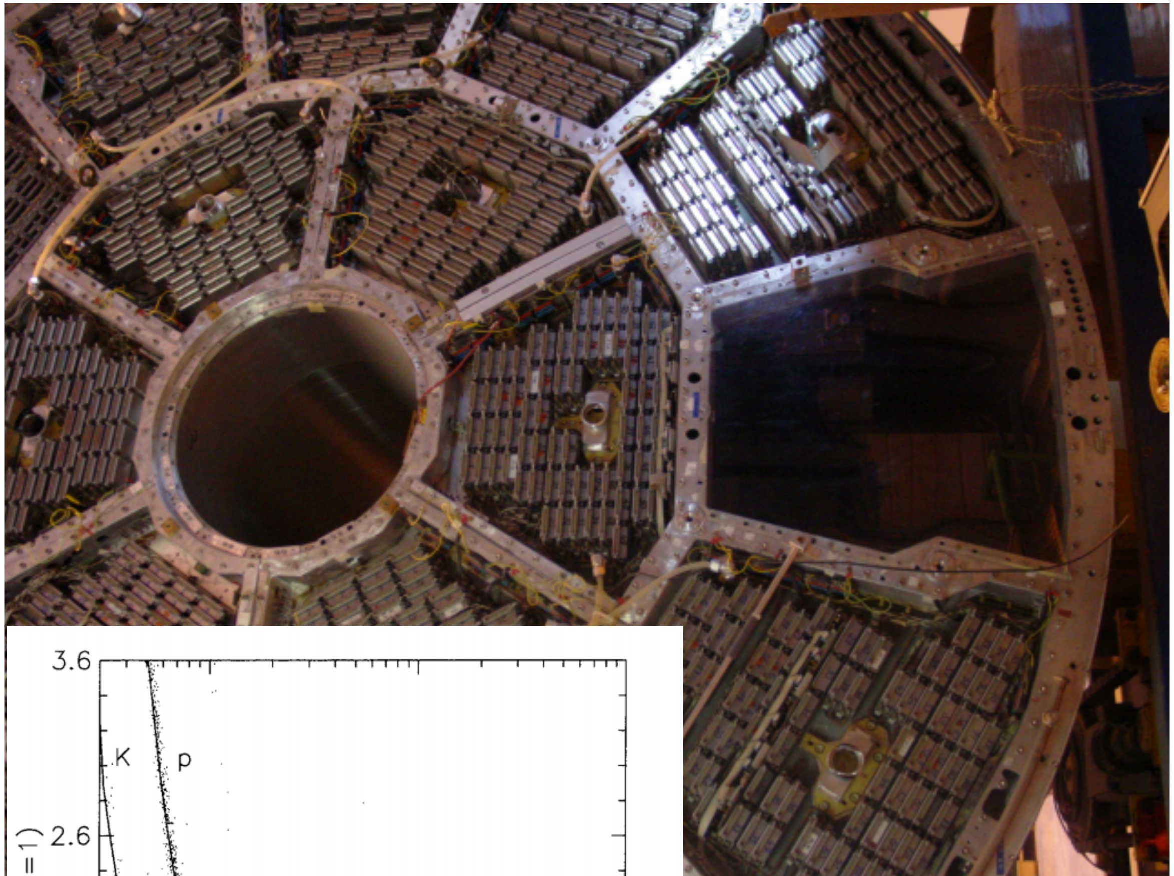
# Ar-$CH_4$: Ramsauer dip and diffusion

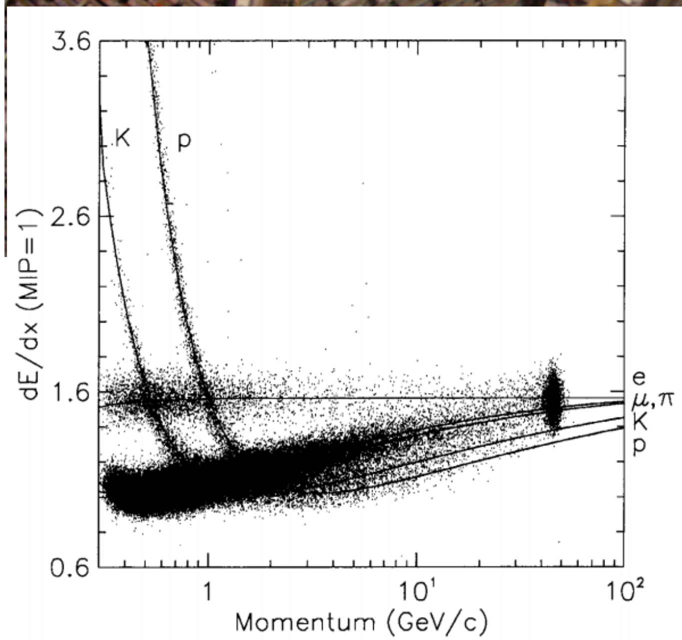
- Chose the drift velocity such that the average electron energy falls in the Ramsauer dip: minimum elastic cross section
  - e.g. ~100 V/cm in Ar-$CH_4$ (90-10)
- The magnetic field then helps focusing the electrons
- High drift velocity achieved like this



# ALEPH TPC

- LEP $e^+e^-$ collider
- Length 4.7 m
- Outer radius 1.8 m
- 43 $m^3$
- $Ar\text{-}CH_4$ (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)

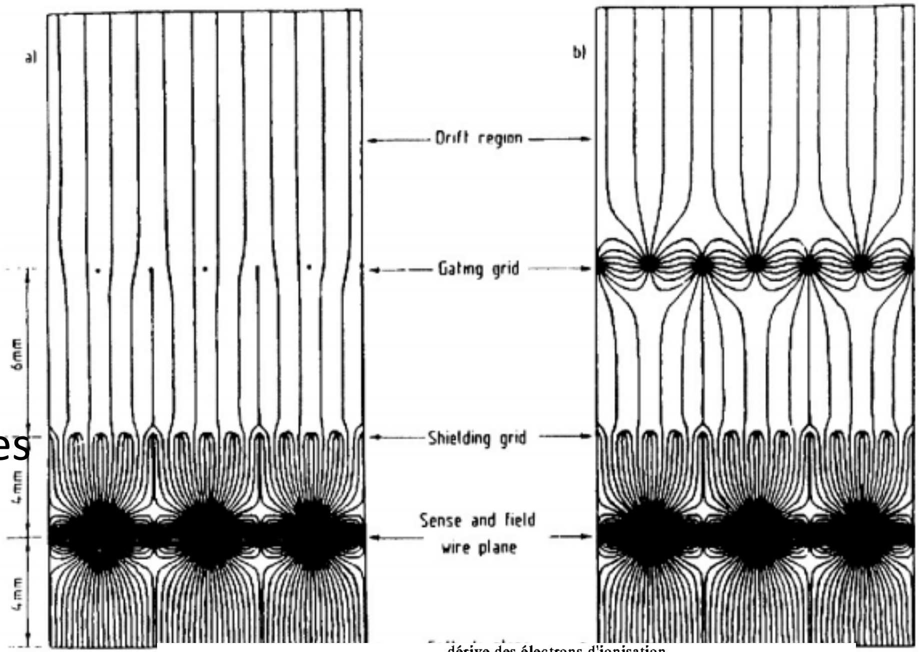
- electrons reach the chambers –and amplification occurs- only when an event is triggered upon
- Gate is open during the maximum drift time only ($t_e$)
- Then the gate closes to prevent ions to invade drift volume ($t_{ions}$)
- This technique *opens the gate* to higher rates and multiplicities without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

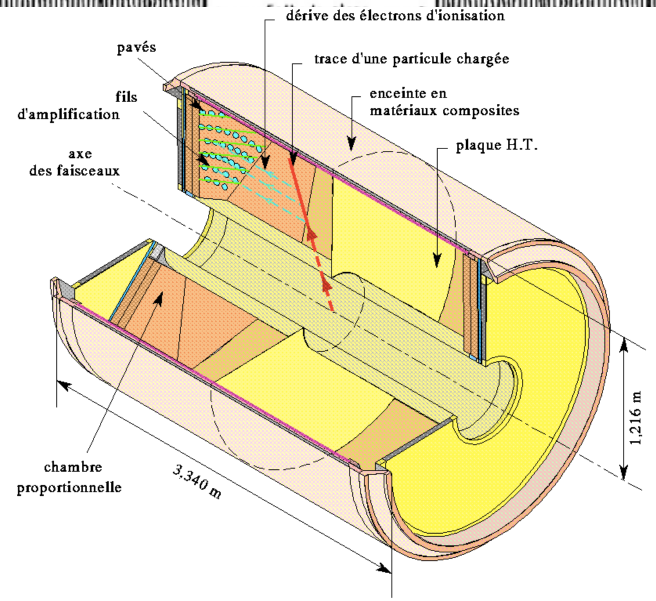
GG

cathodes

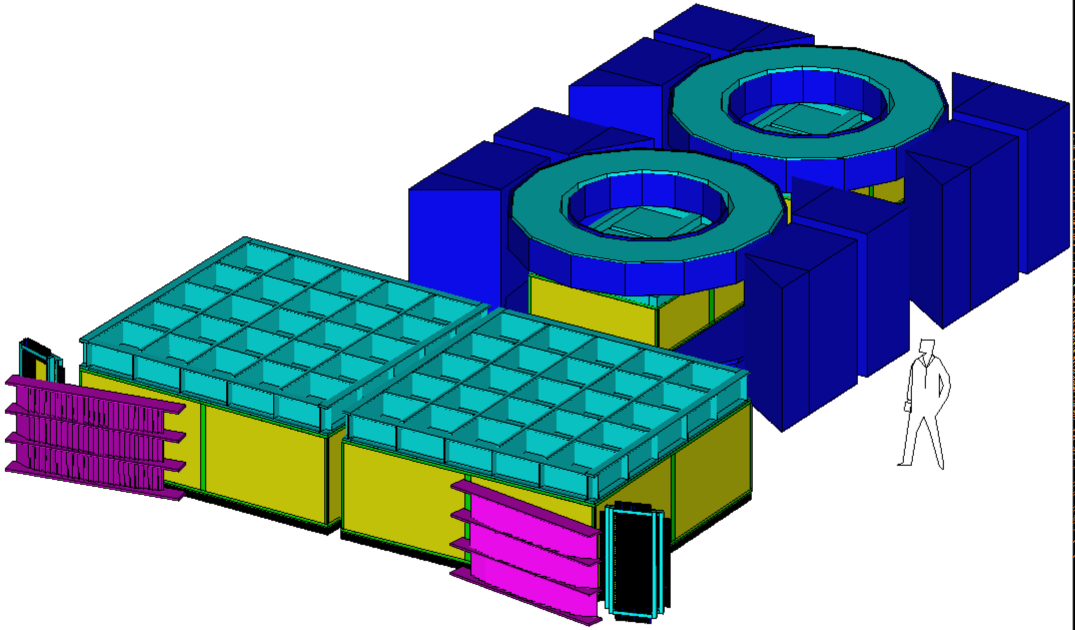
anodes

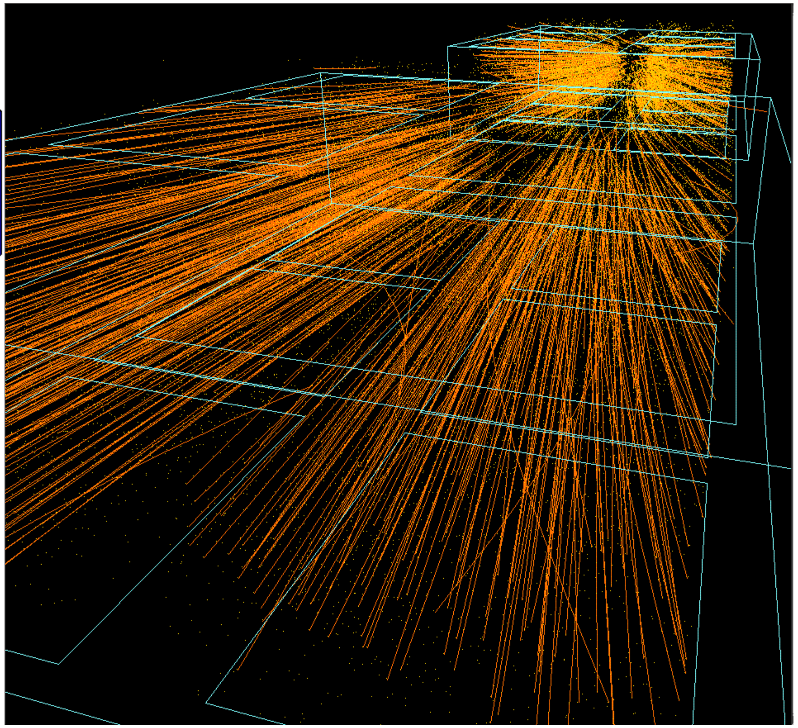
pads



# NA49 TPCs



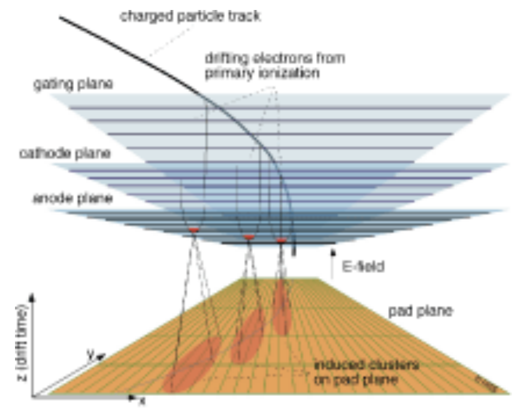


- Neon introduced as alternative to argon
  - less multiple scattering
  - less space charge
- $CO_2$ introduced as quencher: low diffusion
- Full pad readout, no sense wire readout
  - keep the field wires
- Excellent control of the gas quality

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

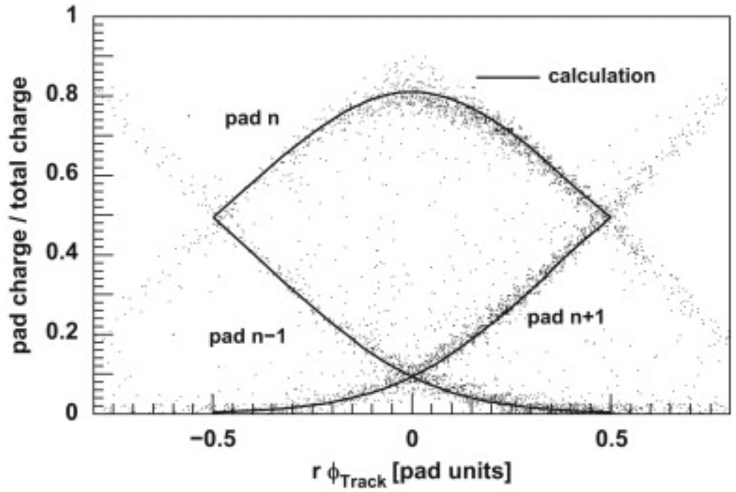
# The Pad Response Function

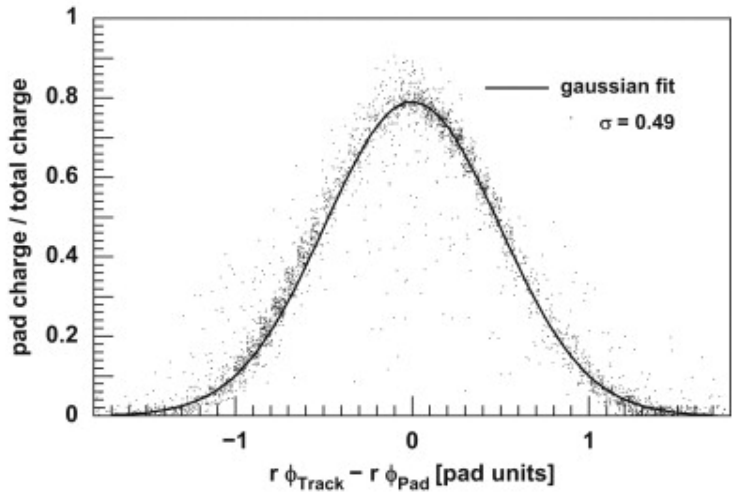
- The induced signal on the pad plane, due to the movement of positive ions away from the anode wires, follows a distribution which depends only on the electrode geometry
- This allows to achieve O(100 $\mu$m) resolution with O(1 cm) pads




Occupancy ⇒ pad size ⇒ cost

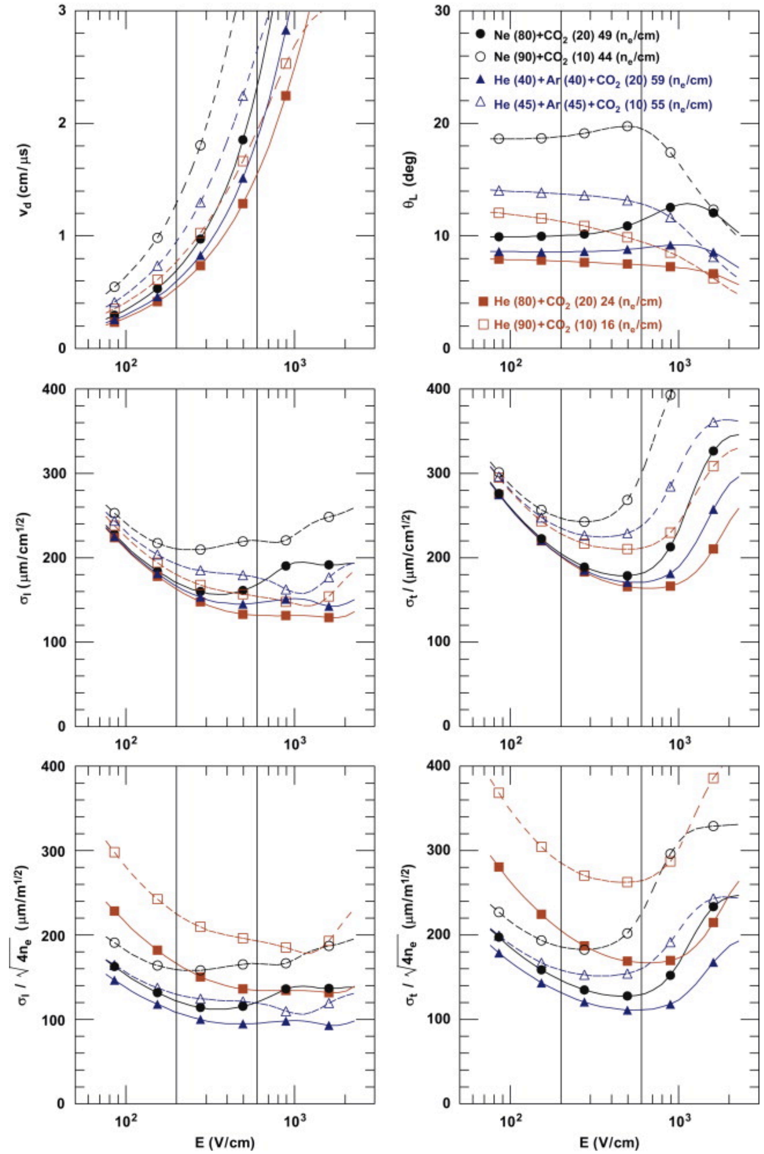
$$P_0(x) = \int_{x-W/2}^{x+W/2} \sigma(x')\,\mathrm{d}x'$$



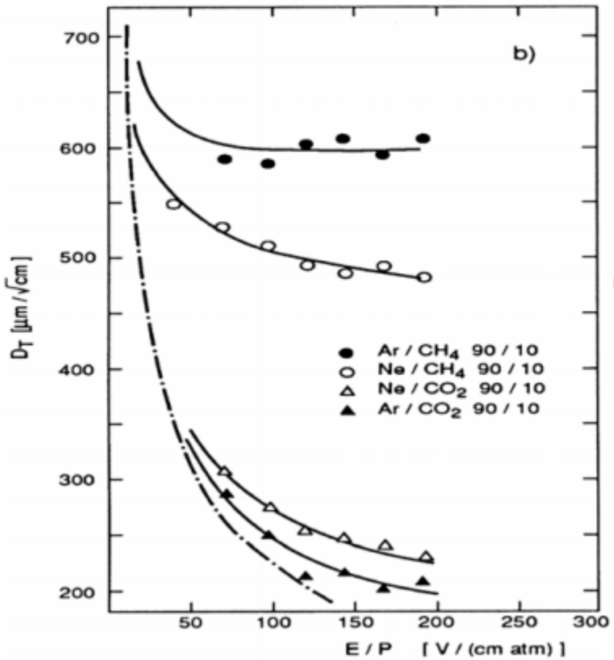
# Back to gas choice

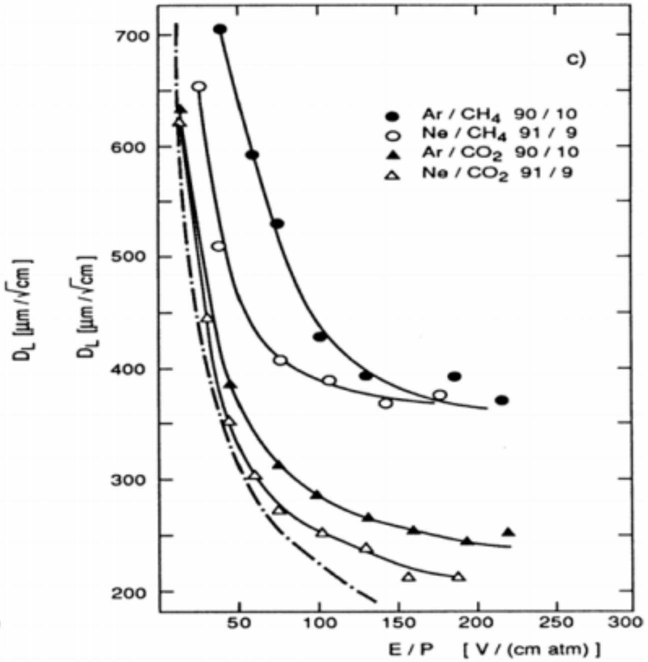
- Tuning of the PRF allows for use of a cool gas ($CO_2$) in the mixture
- Avoid ageing (hydrocarbons) in high luminosity experiments
- But $CO_2$ mixtures are slow and non-saturated: drift velocity highly dependent on gas density



# $CO_2$ as quencher

- $CO_2$ mixtures provide low diffusion coefficients
  - don't need the Ramsauer dip



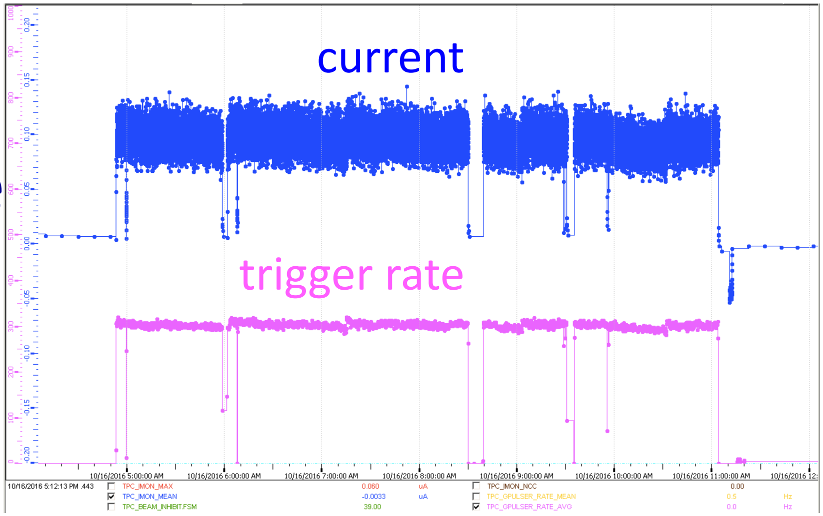



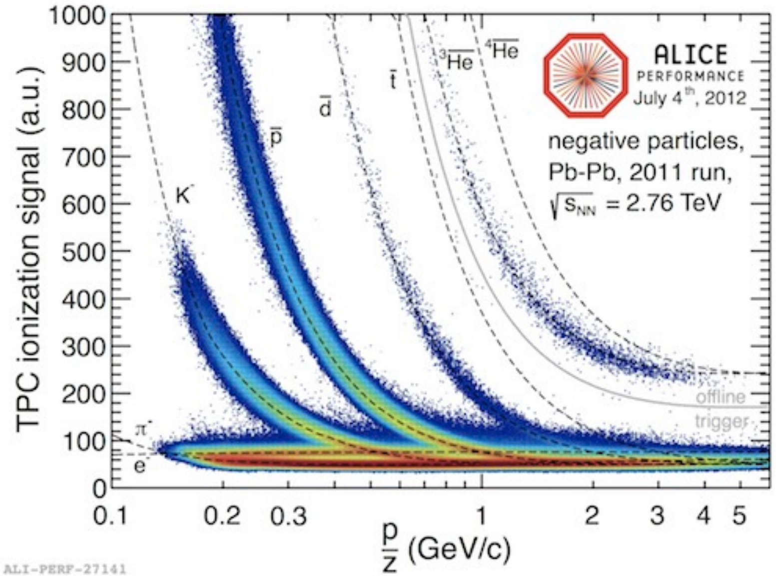

- In addition, $CO_2$ has 3 crucial advantages over $CH_4$:
  - it is not flammable (safety)
  - it does not polymerize (ageing)
  - it does not contain hydrogen (thermal neutron capture)
- But it has disadvantages:
  - it is slow
  - drift velocity and gain highly dependent on T and P
  - It is not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

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

# Gain stability of wire chambers

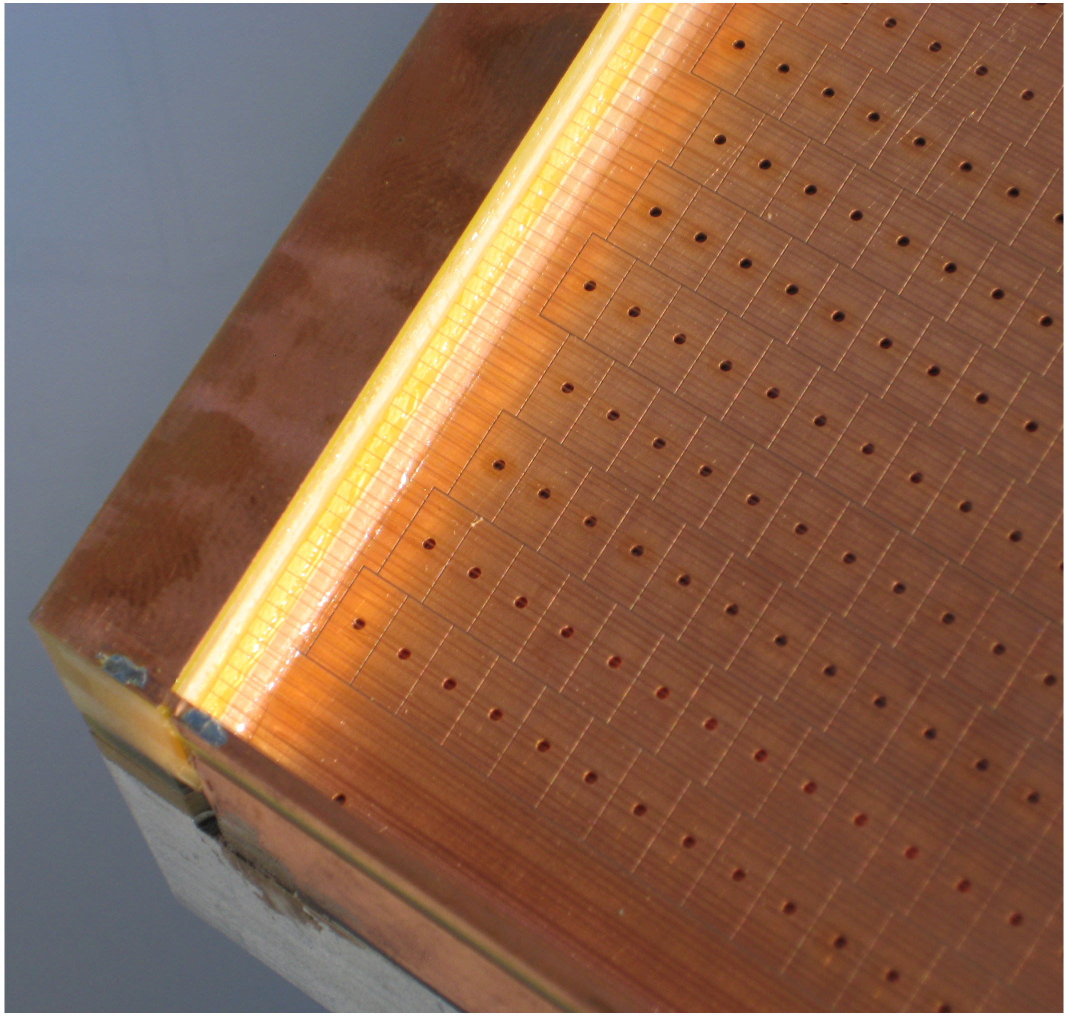
- At typical electronics noise of <1000 $e^-$, gains of a few $10^3$ are enough for good position and energy resolution
- Few discharges are reported, very few broken wires
- Wire sag limits size to about 1 m
- Typical gain uniformity in sensor area: ± 20%



# Example of wire chamber

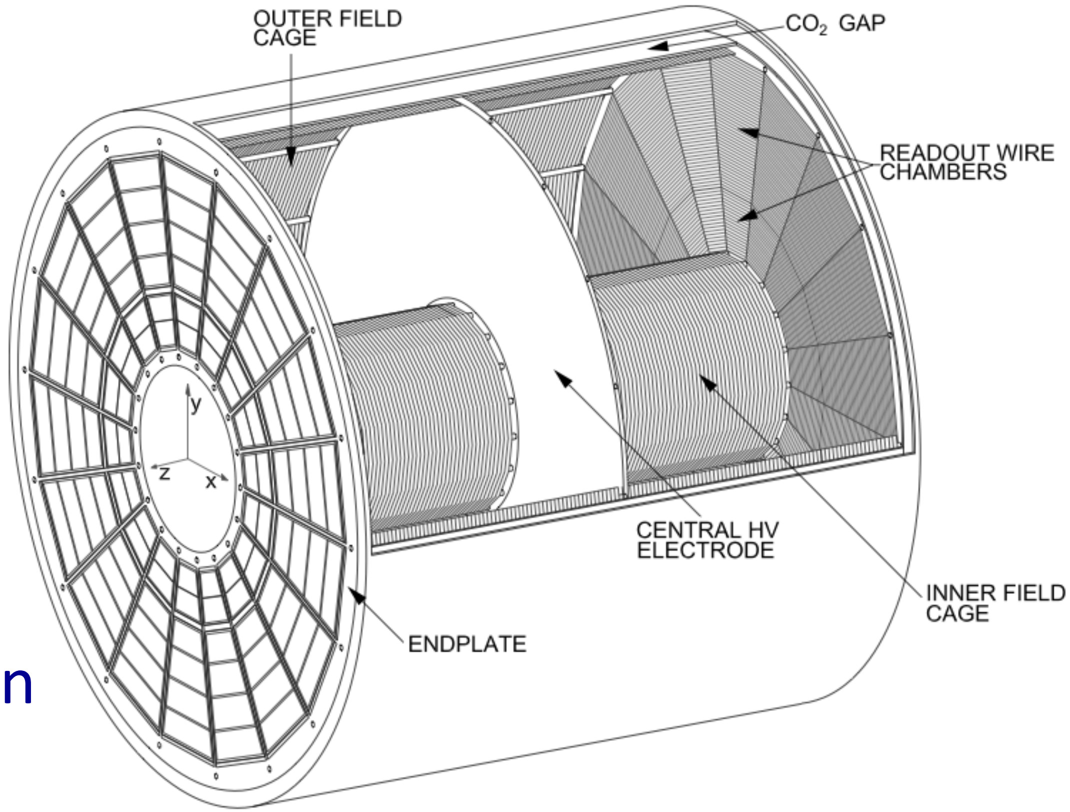
- Relatively small pads: 4x7.5, 6X10, 6X15 mm$^2$
- Tight geometry (2 mm)
- No field wires
- Surround chambers with a ‘cover’ electrode to match drift field and avoid leakage of ions
- Use winding machines for easy production



ALICE TPC MWPC

# 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 $\eta$=0
- ~1 mm position resolution => 250 μm matching resolution with inner tracker

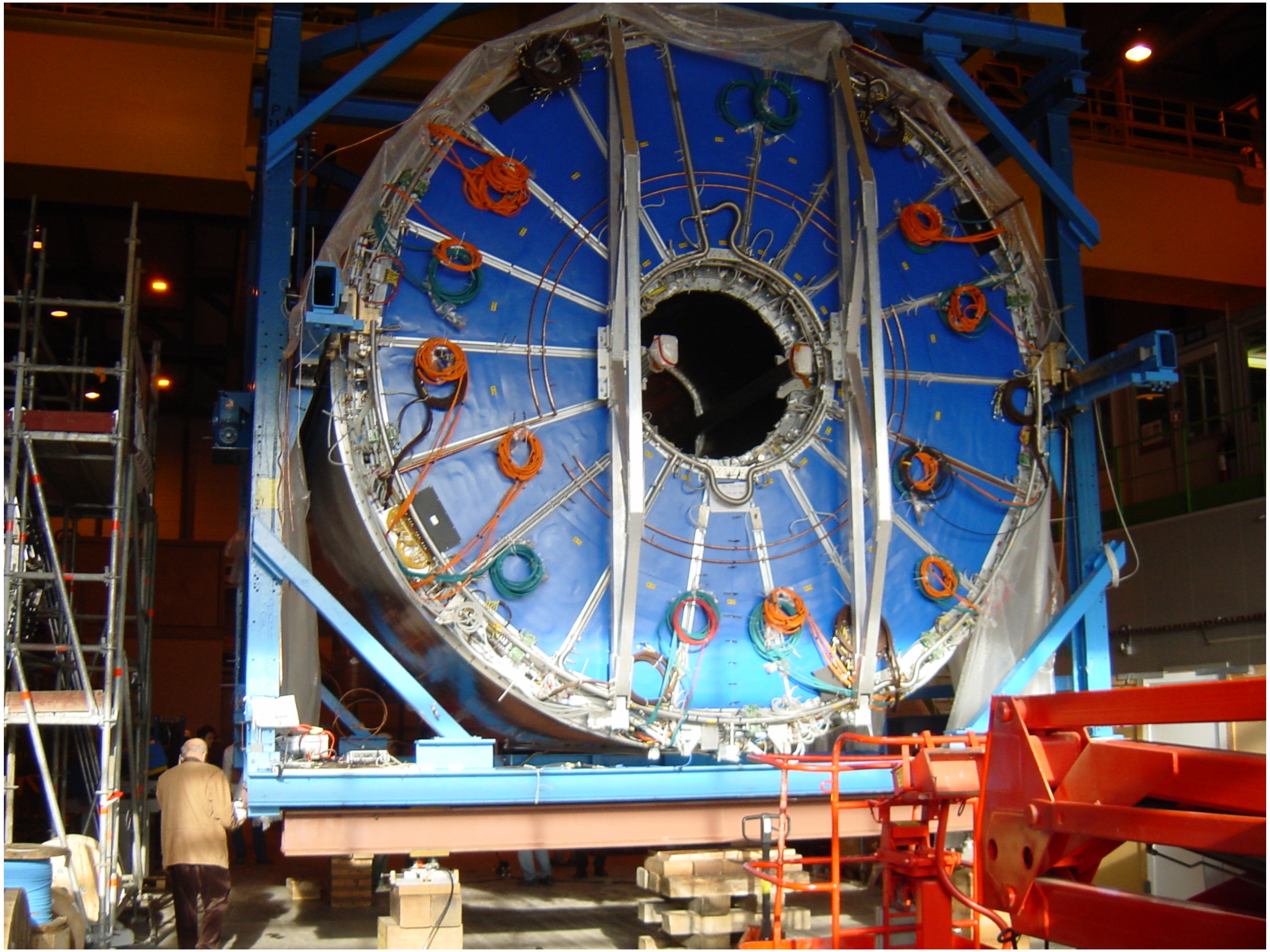



ALICE TPC

# Other features of the ALICE TPC

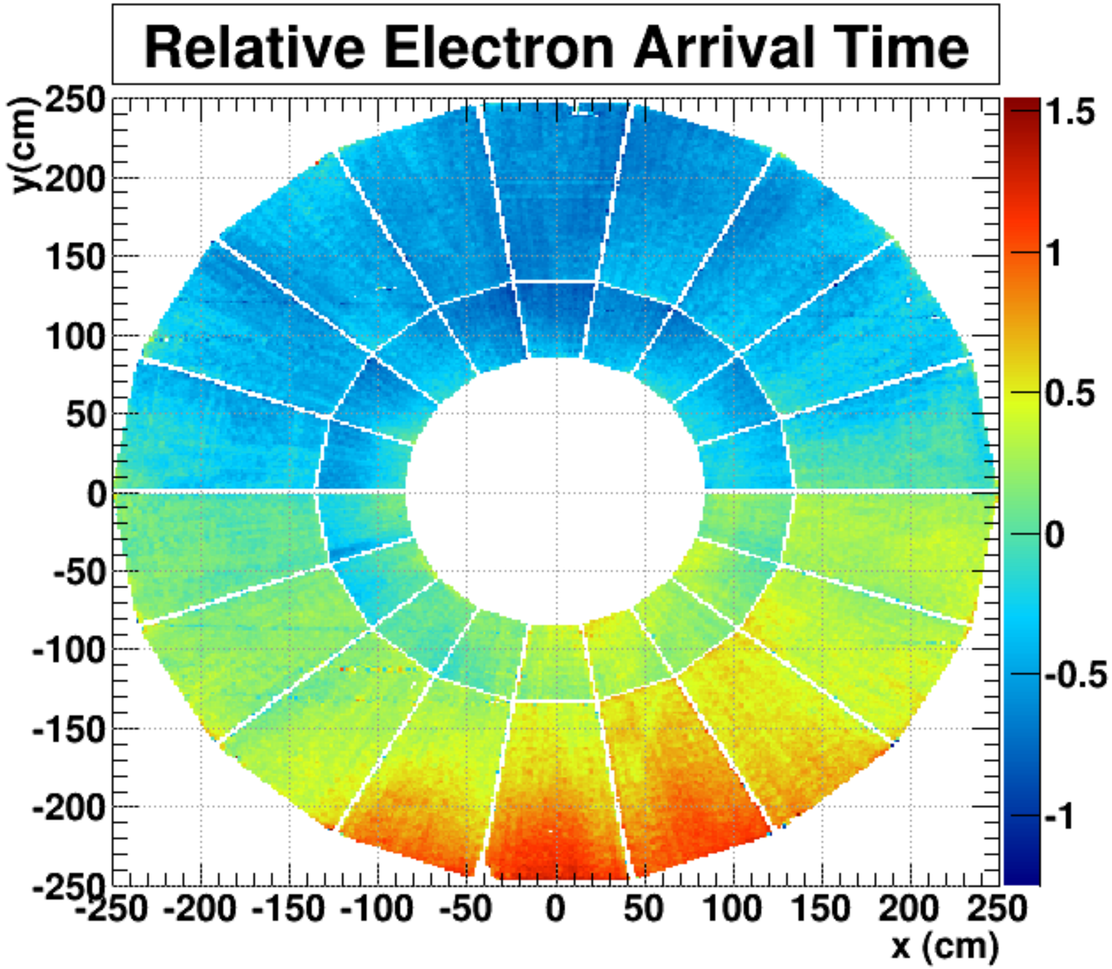
- Insertion of chambers à la ALEPH
  - A few mm clearance with critical FC structures
- Double O-ring sealing allows for independent mechanical alignment
- Electronics connected via flexible kapton cables and supported by an independent structure (the Service Support Wheel)

# Thermal insulation



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

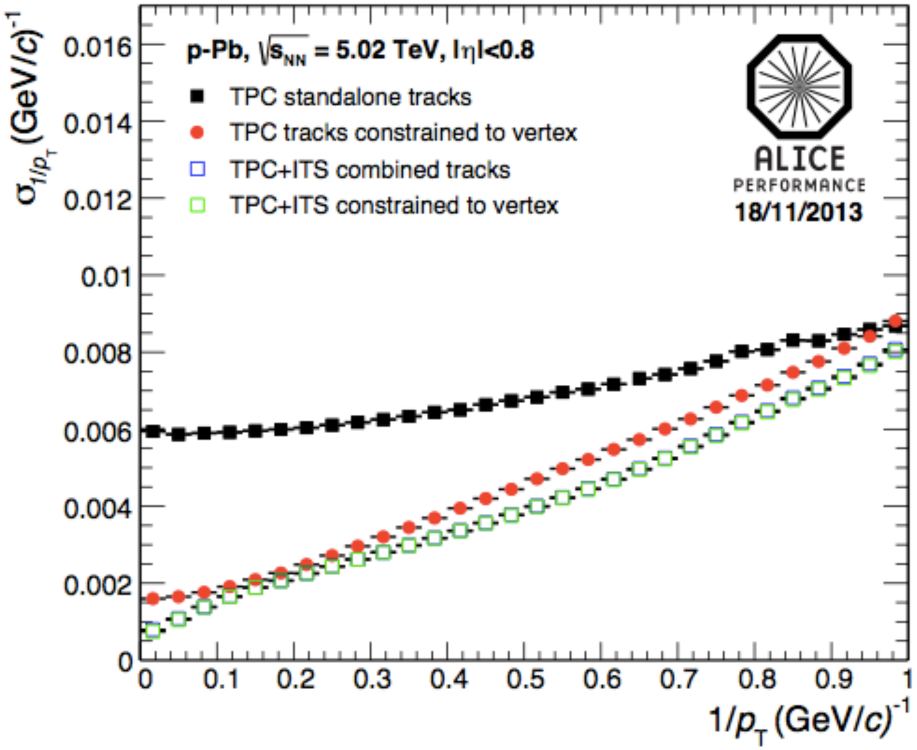
# $V_d$ uniformity




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)

$\Delta V_d$ ~ 0.35 % per K
$\Delta$gain ~ 1 % per K

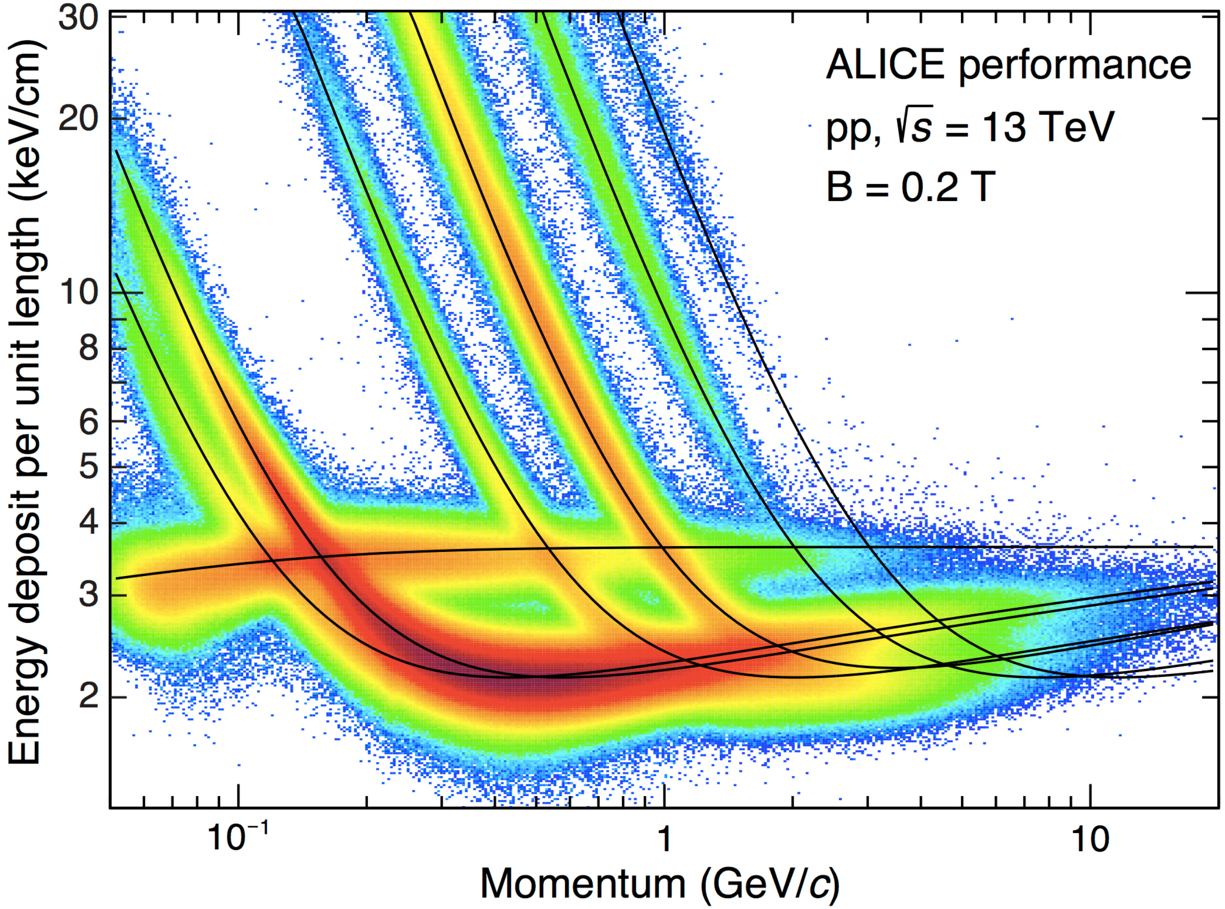
# Momentum resolution of the ALICE TPC




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 $p_T$

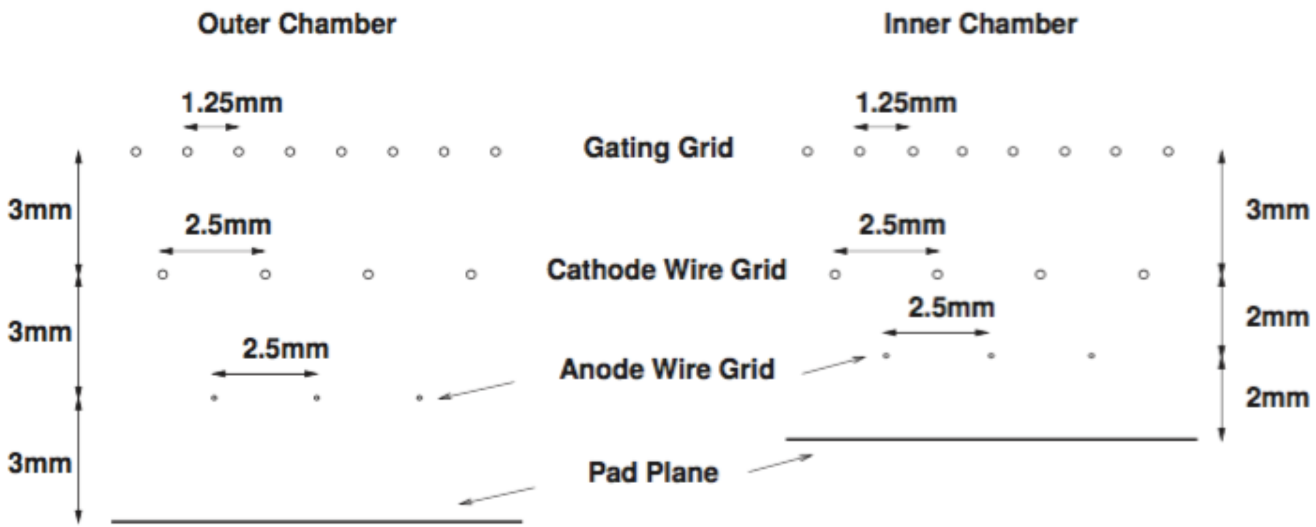
# dE/dx performance of the ALICE TPC




- 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

# Challenges to wire sensors

- Rate capability (few kHz/cm$^2$)
- Position resolution: ExB effects limit: few 100 $\mu$m
- Ion backflow (distortions due to space-charge density: up to 1 m)
- Tendency to go for what is ‘new’
- Loss of know-how

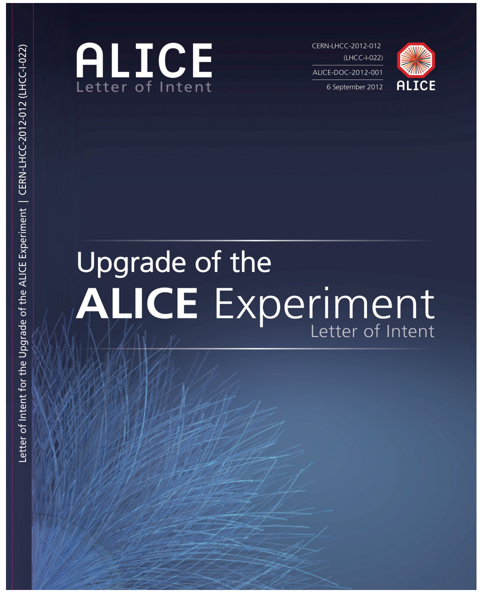


# Modern sensors: Micro-pattern devices

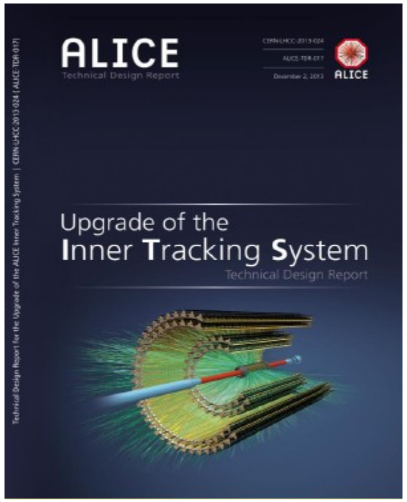
GEM, Micromegas, THGEM, etc, and combinations
are good for high rates and good position resolution

# ALICE UPGRADE for RUN 3

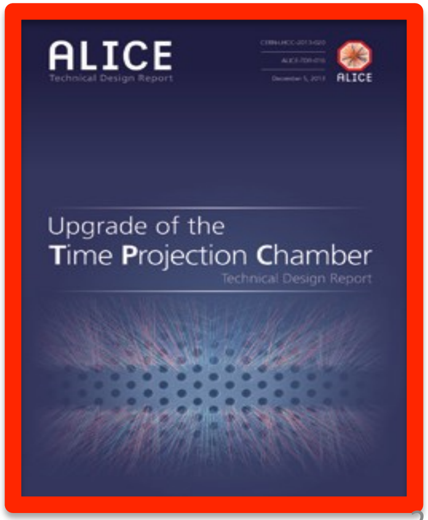
- **Motivation**: high precision measurements of rare probes at **low $p_t$**
  - ✓ cannot be selected with hardware trigger
  - ✓ need to record large sample of events
- **Goal**: operate ALICE at high rate, record all MB events
  - ✓ 50 kHz in Pb-Pb (~10 $nb^{-1}$ in RUN 3 and RUN 4)
  - ✓ no dedicated 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



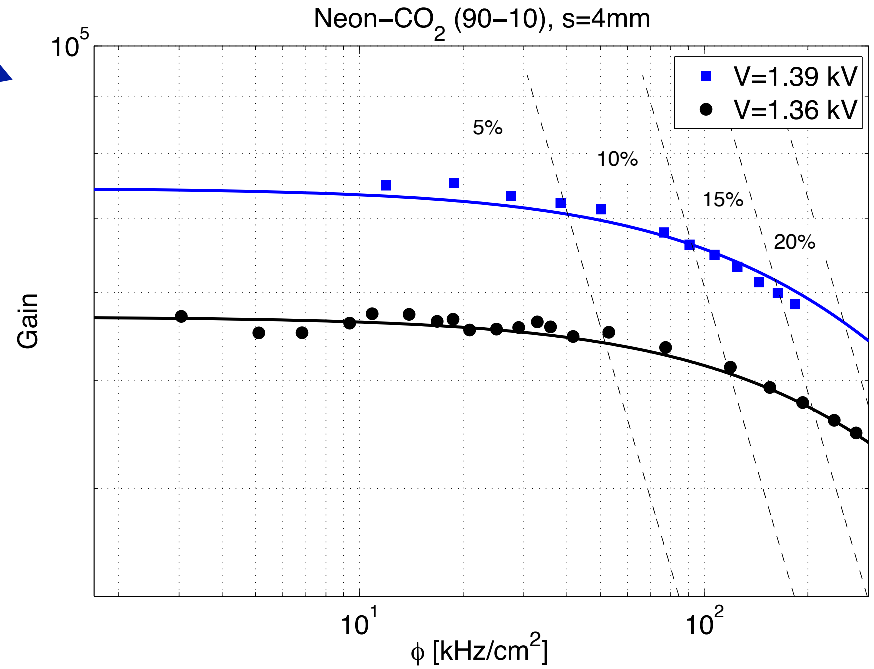




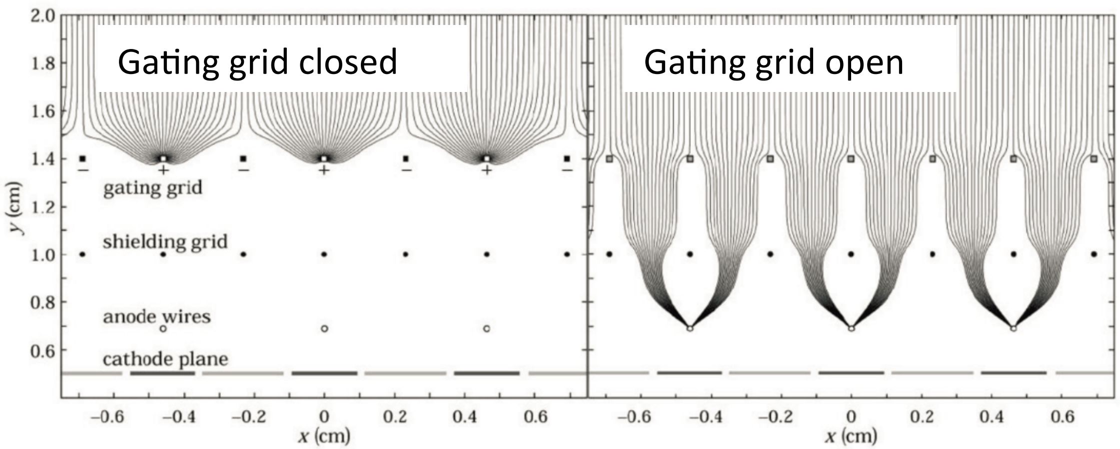

**TDR:** https://cds.cern.ch/record/1622286
**Addendum:** https://cds.cern.ch/record/1984329

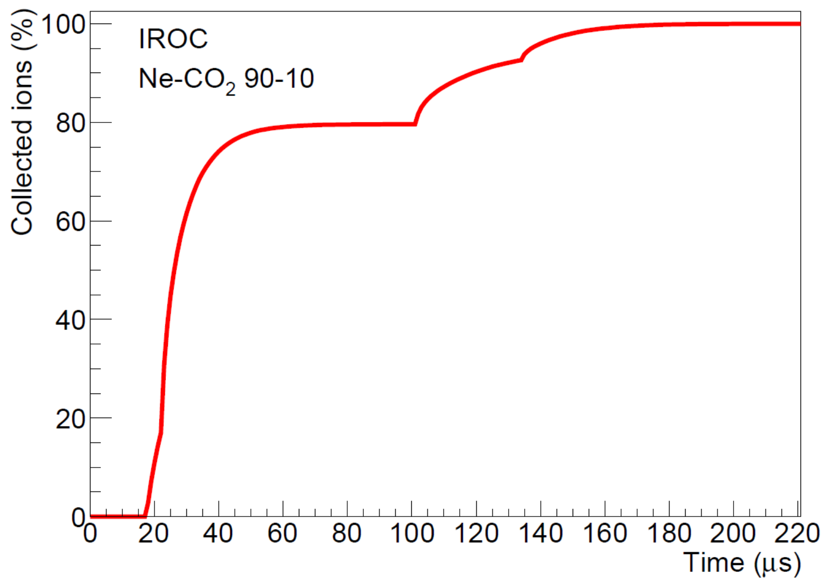
# MWPC won't work anymore

- In 2020 the LHC will deliver 50 kHz Pb-Pb collision rate
- At ~100 kHz/cm$^2$ 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

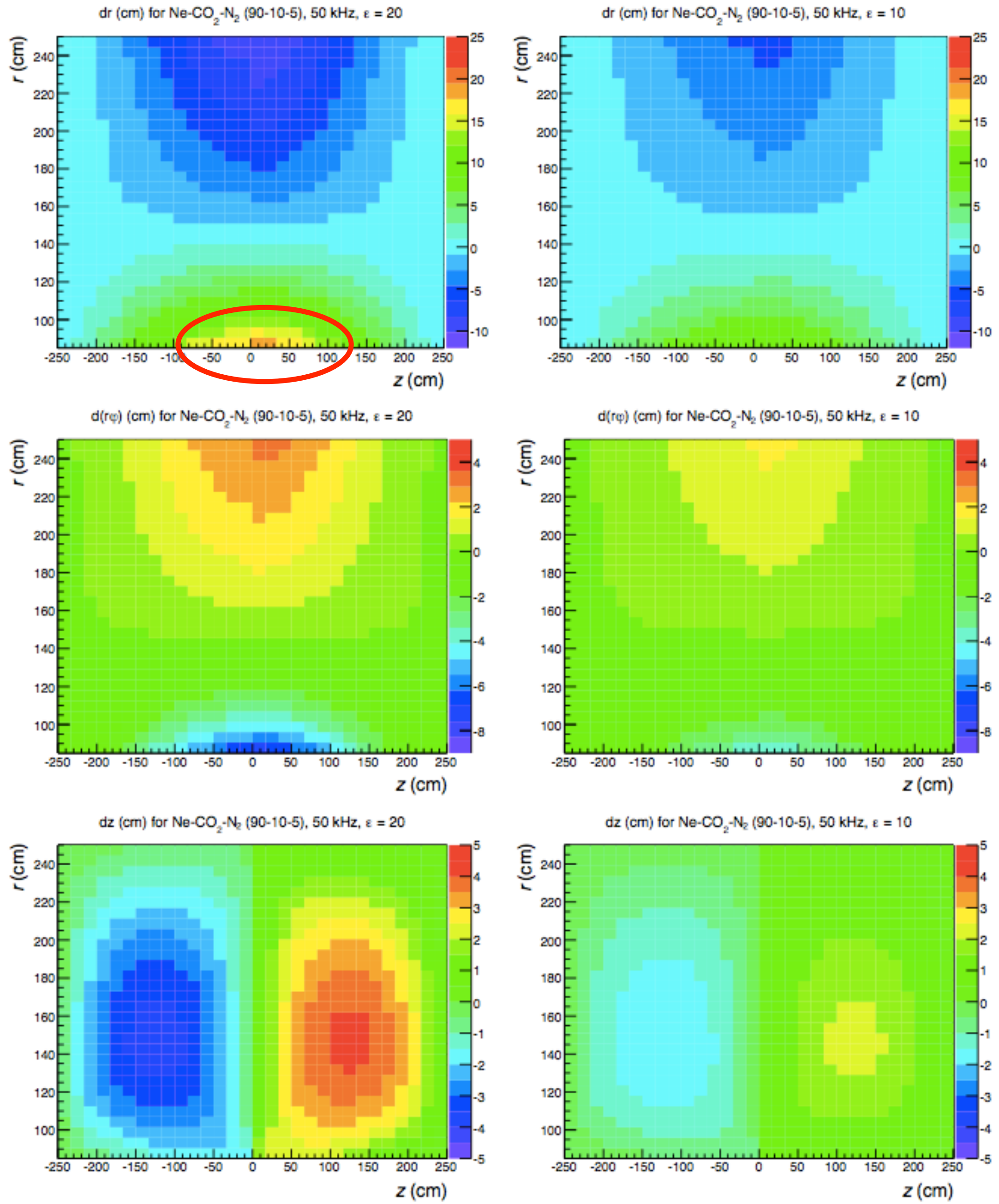



- Current MWPCs employ gating grid (GG) to neutralize ions produced in amplification process
  - otherwise sizeable distortions due to space charge
- GG limits operation to 3.5kHz
  - electron drift (90 μs) + ion blocking with GG ( 200 μs)
- Readout rate in Pb-Pb limited to 300 Hz

# The Ion Back-Flow challenge

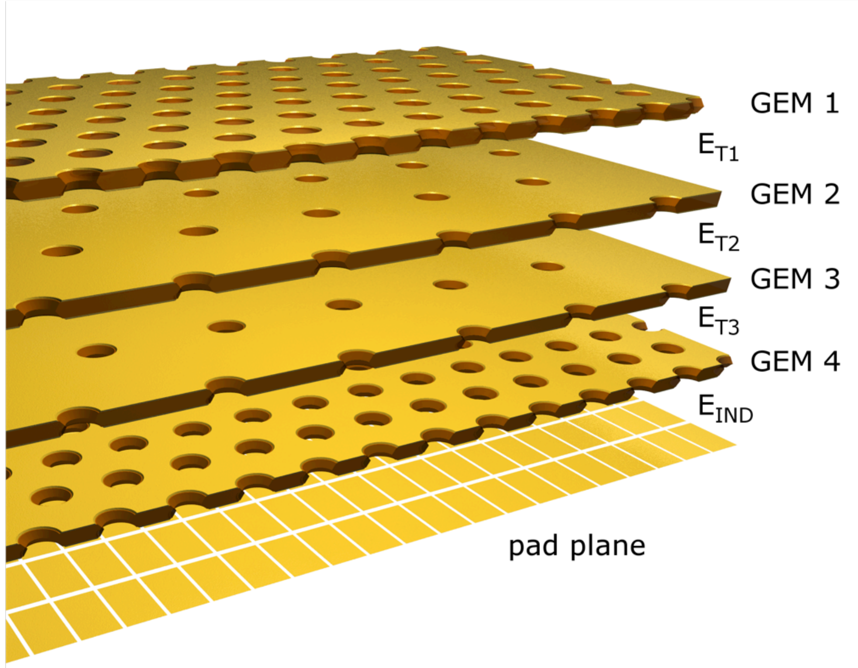
- GEMs are good at blocking ions from invading the drift volume, but this 'good' is not good enough
- We aim at IBF ~ 1% at gain 2000
  - $\varepsilon$ ~ 20
  - Gas: Ne-$CO_2$-$N_2$ (90-10-5)
- Then, distortions of up to 20 cm must be corrected for
  - At inner radii, near the central electrode




**A bit of homework is needed…**

# ALICE TPC upgrade with 4-GEM stacks

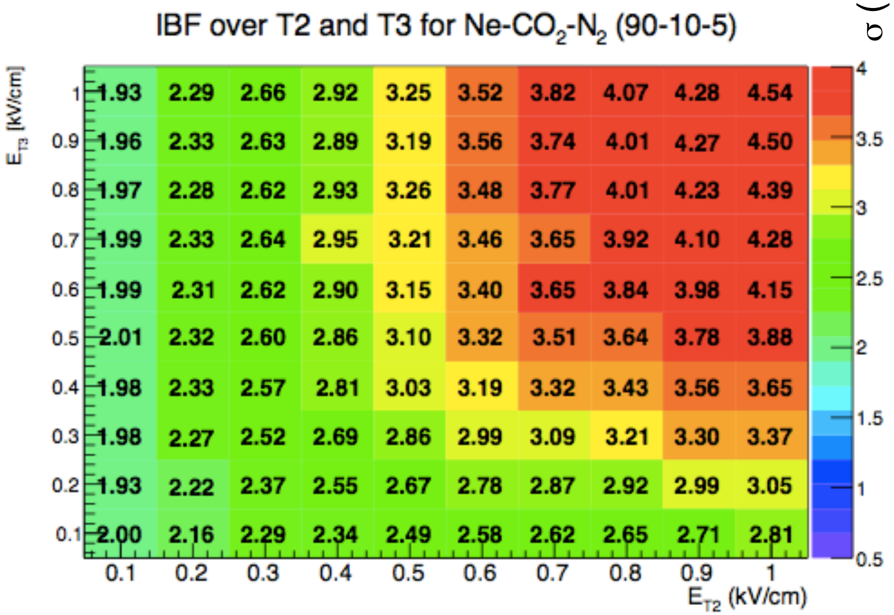
- Maximum distortions ~20 cm
- dE/dx resolution not to be compromised
  - maintain excellent particle ID
- Robustness against discharges
- Large sizes (single-mask)
- QA, QA, QA
- Distortion corrections
- All this looks good
- R&D still ongoing
  - discharges, ageing, …

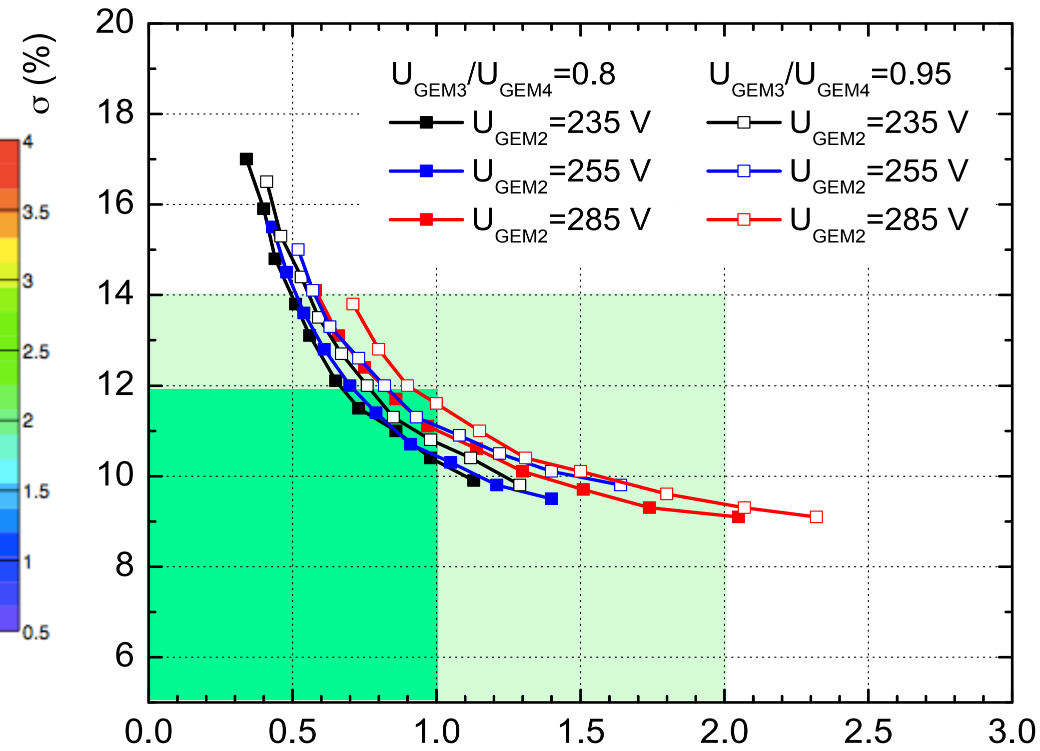



Replace wires with GEMs

$\left.\begin{array}{l}\text{Pad plane becomes an anode}\\ \text{Continuous readout}\end{array}\right\}$ new electronics

# Minimise IBF and keep energy resolution

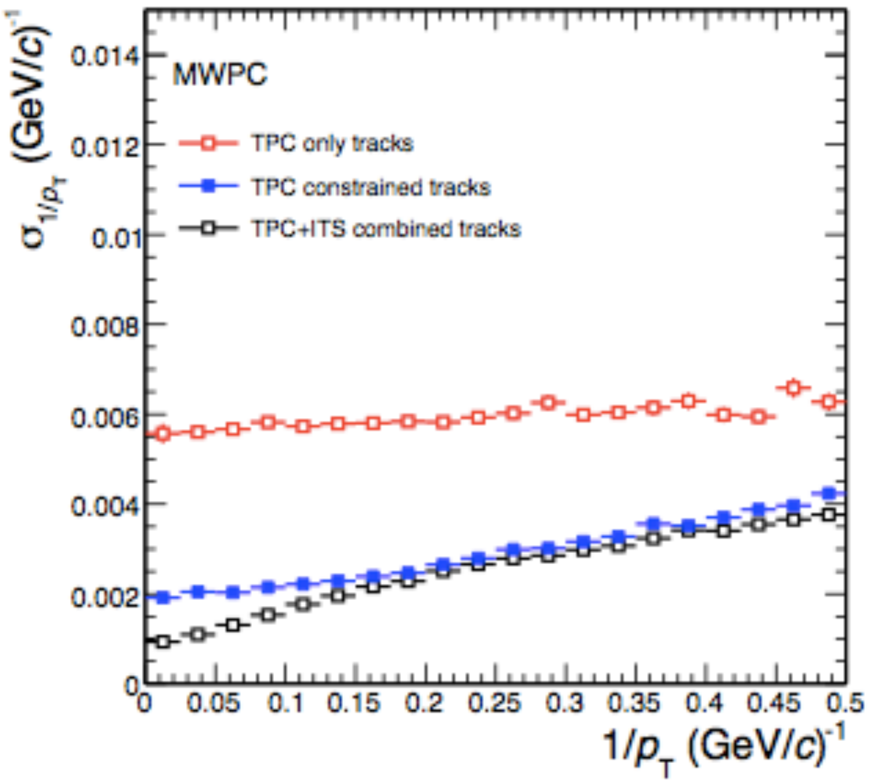


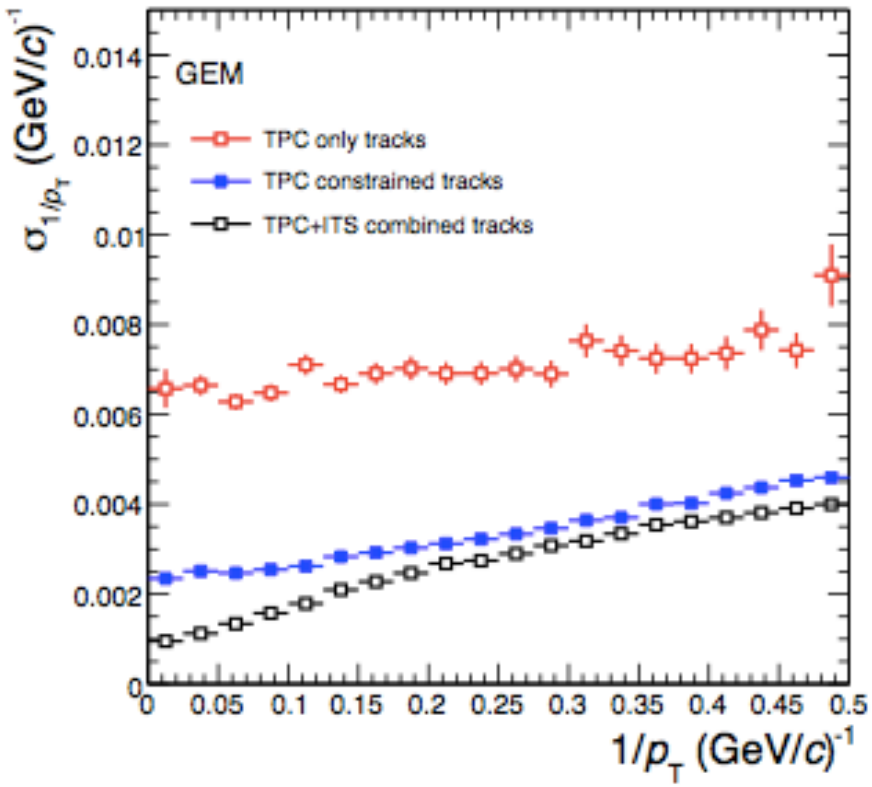




- **Asymmetric fields** above and below a GEM foils helps trapping ions
  - a **quadruple GEM stack** is used to best arrange this trap
- Misalignment between holes of different foils also helps blocking ions
  - use a combination of **Standard and Large-Pitch** GEMs (140 and 280 µm)
- However, the more 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)

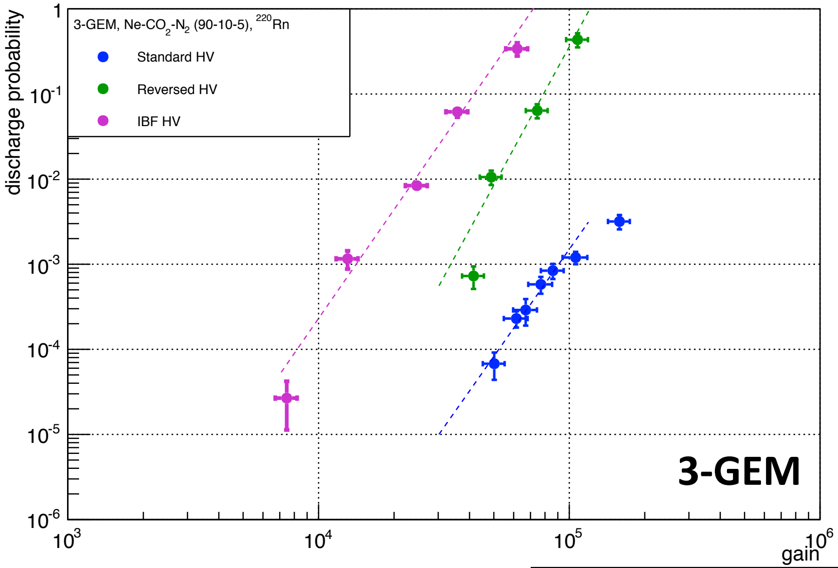



- GEMs produce no PRF, so clusters originated near the chambers induce signals in only one pad
- At high multiplicities this helps occupancy and overlap of clusters
- No need to substantial changes to the pad geometry!

# Extensive discharge studies

- Influence of HV settings

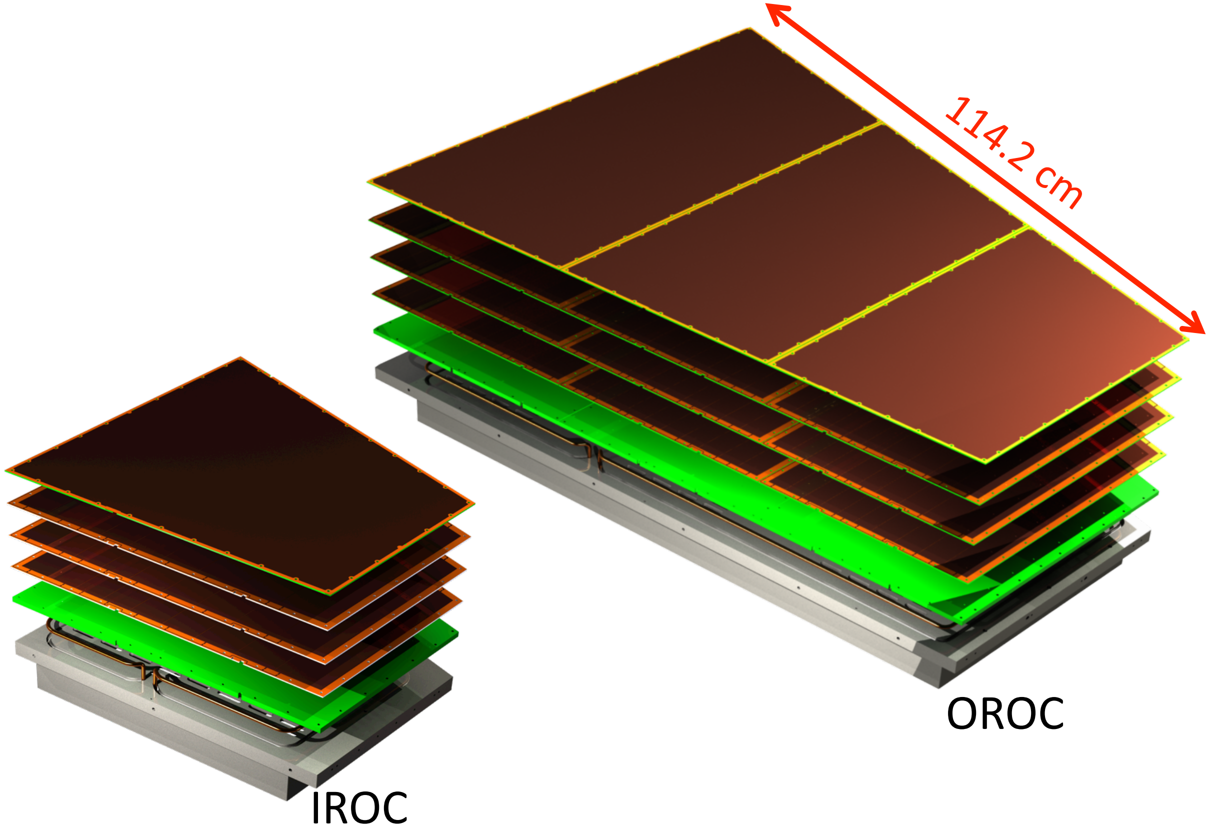



- Different HV settings have been tested with a 3-GEM configuration
- "Standard" → "IBF"
  - Standard – optimized for stability (COMPASS, LHCb)
  - IBF → optimized for IBF
- Significant drop of stability while using IBF settings with a typical 3-GEM configuration

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

| | **S-S-S** 'standard' HV G = 2000 | **S-S-S-S** *IB* = 2.0% G = 2000 | **S-LP-LP-S** *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 | | | | | $< 3\times10^{-12}$ | |

# Quadruple GEM for ALICE 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

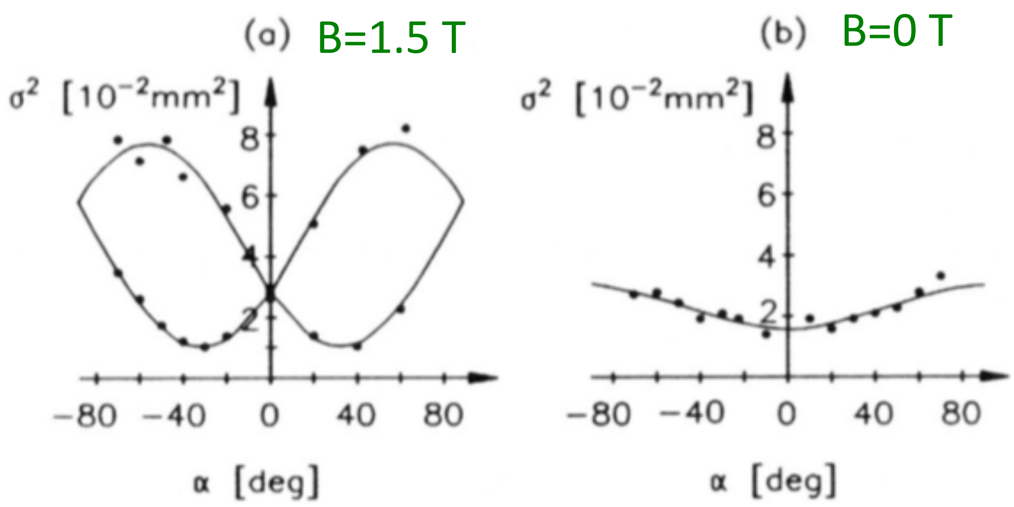
# ILD TPC

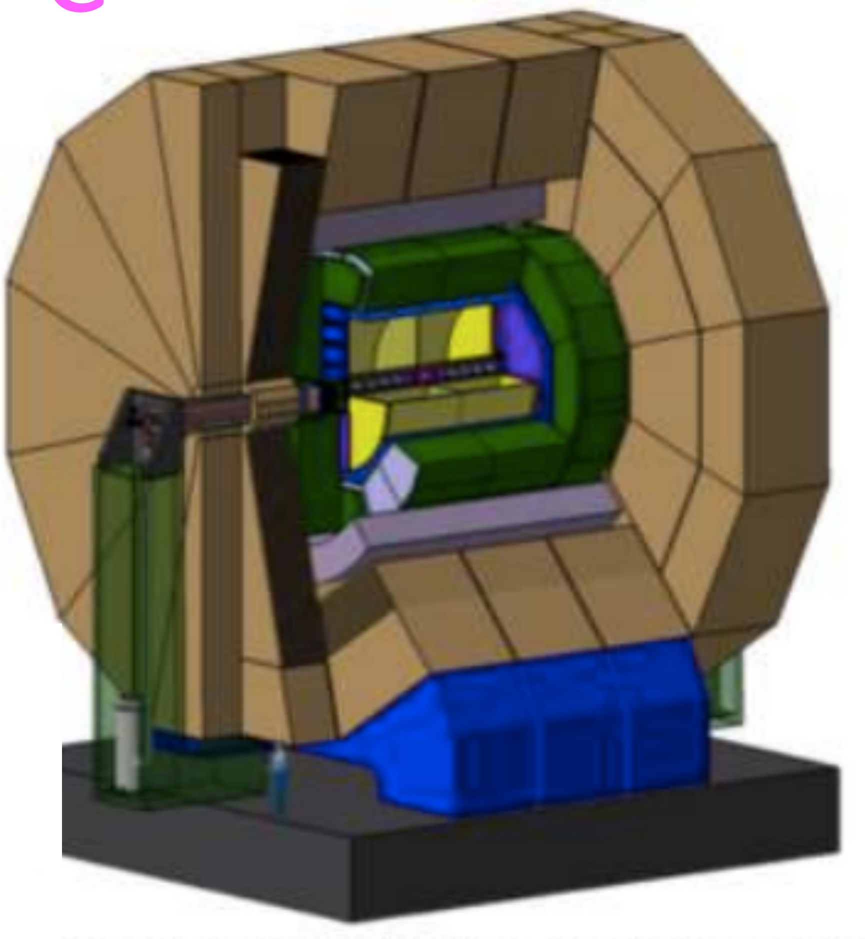
- Here, ExB effects in the amplification region, at 3.5 T, rules out wires due to limited resolution

$$\sigma_m^2 = \sigma_0^2 + \frac{b^2}{12N_{\text{eff}}\left(h, \frac{\sigma}{b}\right)}(\tan\theta - \tan\psi)^2\cos^2\theta$$

$$= \sigma_0^2 + \frac{b^2}{12N_{\text{eff}}\left(h, \frac{\sigma}{b}\right)}\frac{\sin^2(\theta-\psi)}{\cos^2\psi},$$

Blum
Rolandi
Riegler



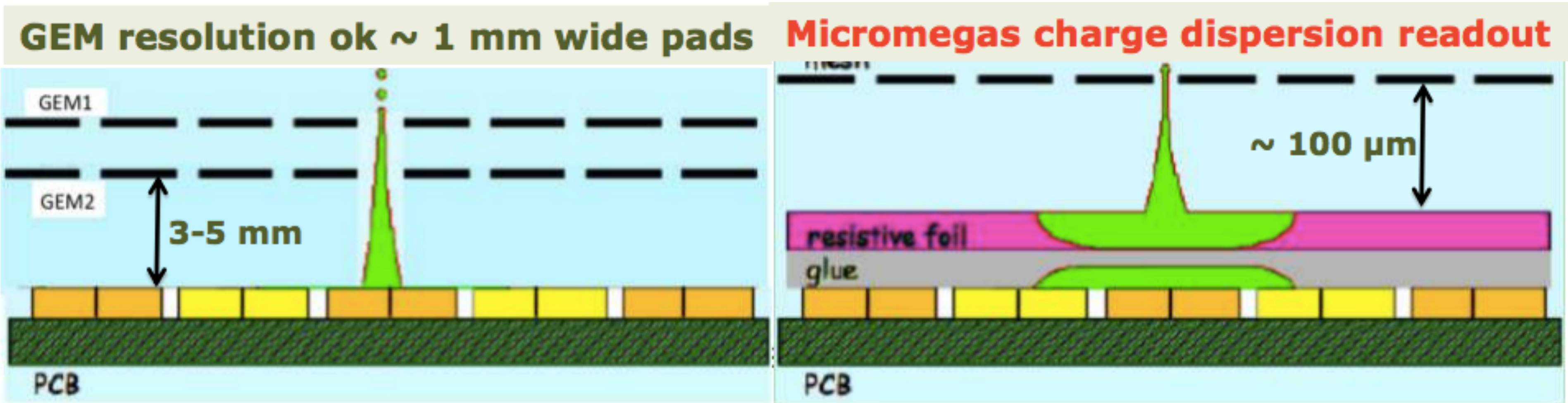



In ALICE TPC (0.5 T) ExB contributes to a smearing of the position resolution of about 200 μm

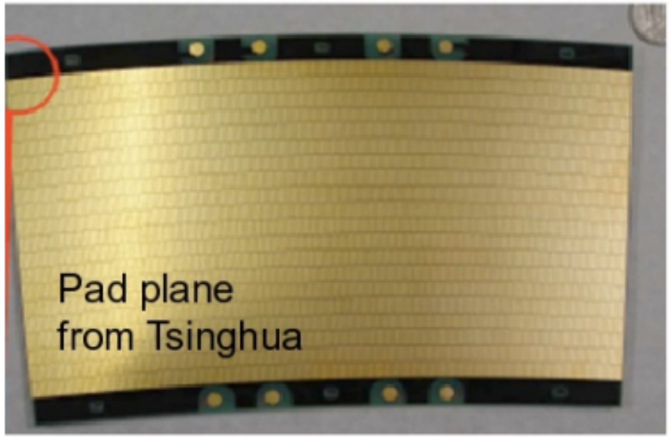
# ILD TPC: GEMs or MM

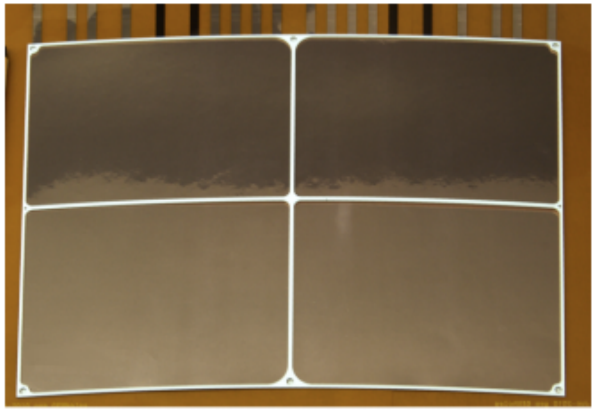
- Both solutions being studied
- Extensive prototype tests ongoing
  - position resolution
  - IBF (ion gating)

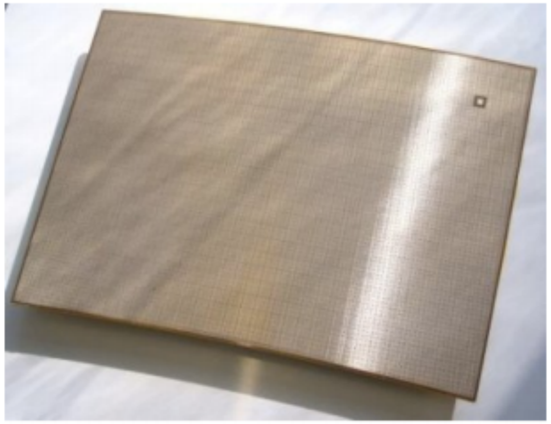
- $\sigma(r, \varphi) \leq 100\ \mu m$
- $\sigma(z) \approx 500\ \mu m$
- 2 hit resolution
  $\approx$ 2mm in $(r,\varphi)$
  $\approx$ 6 mm in z
- dE/dx ~ 5%

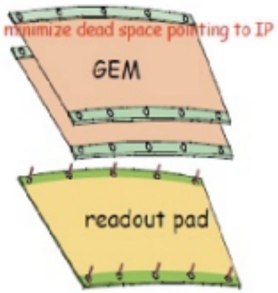


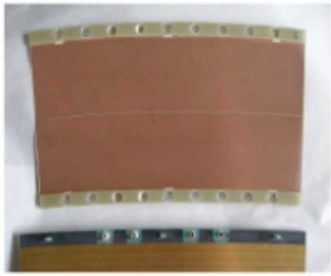
# ILD TPC: GEM or MM

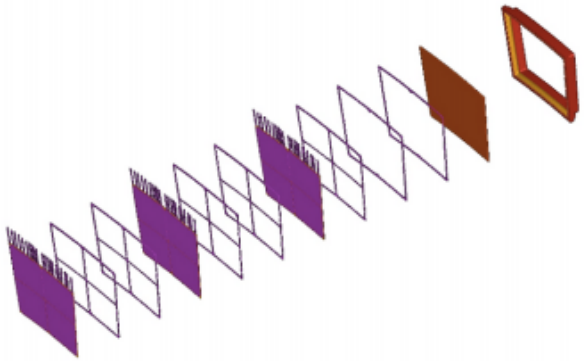


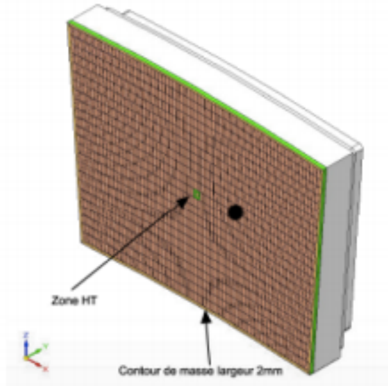







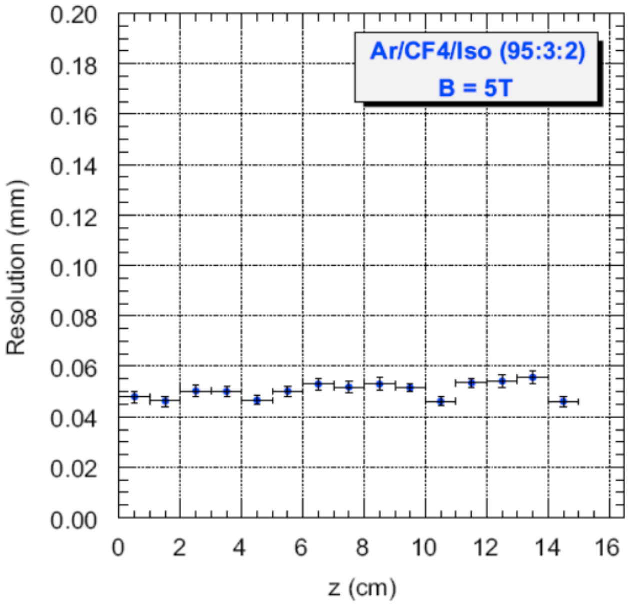








Final choice not yet done AFAIK

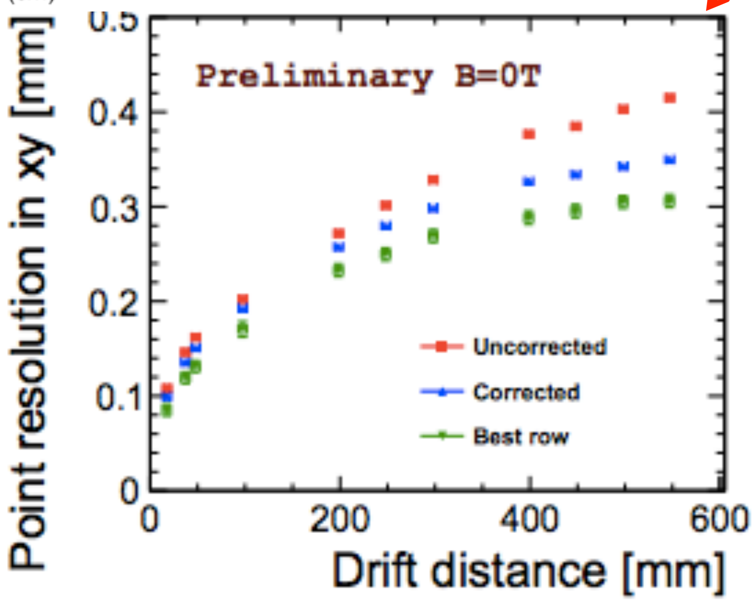
# Ongoing ILD R&D

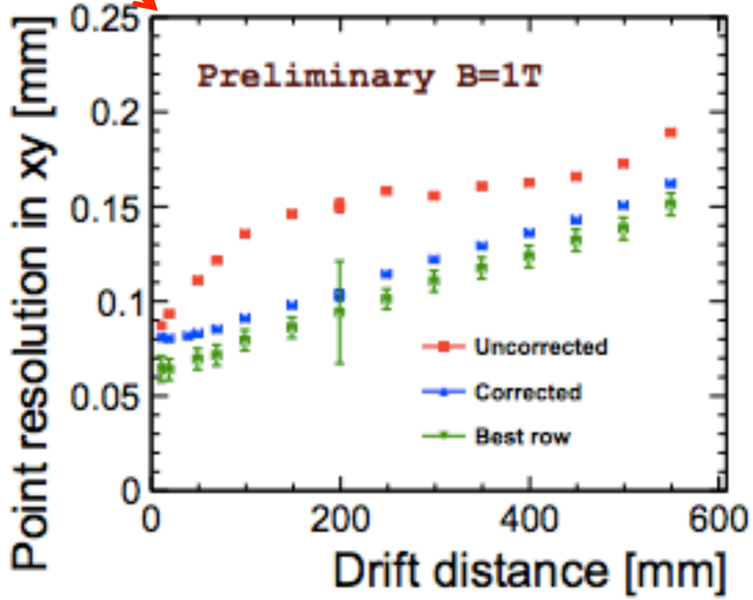



- Small MM prototype (M. Dixit, 2010)
  - resolution well below 100 μm

Mind the alignment and mechanical precision

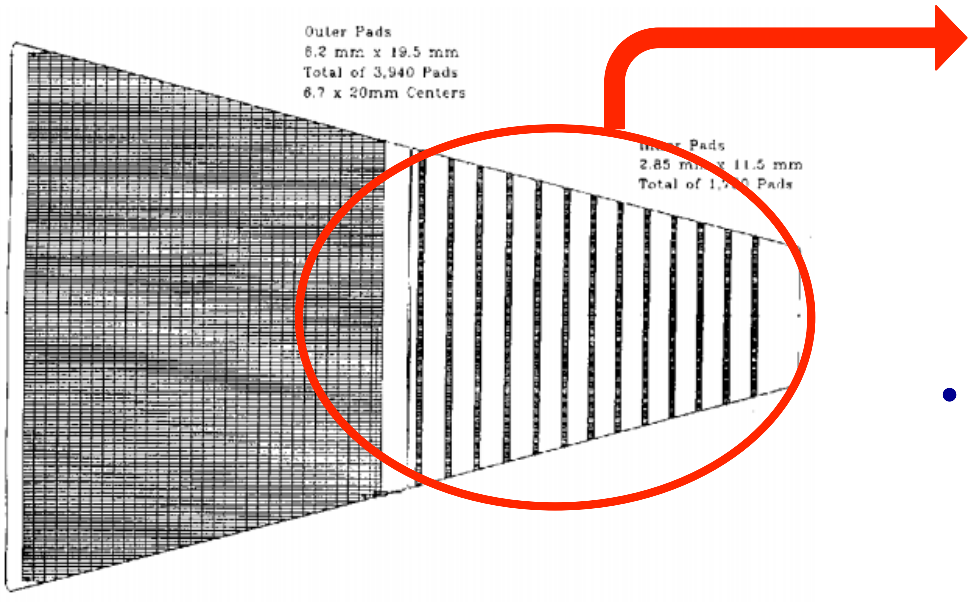
- Large prototype with 3 GEM modules, at 0 and 1 T (T. Behnke et al. 2013)



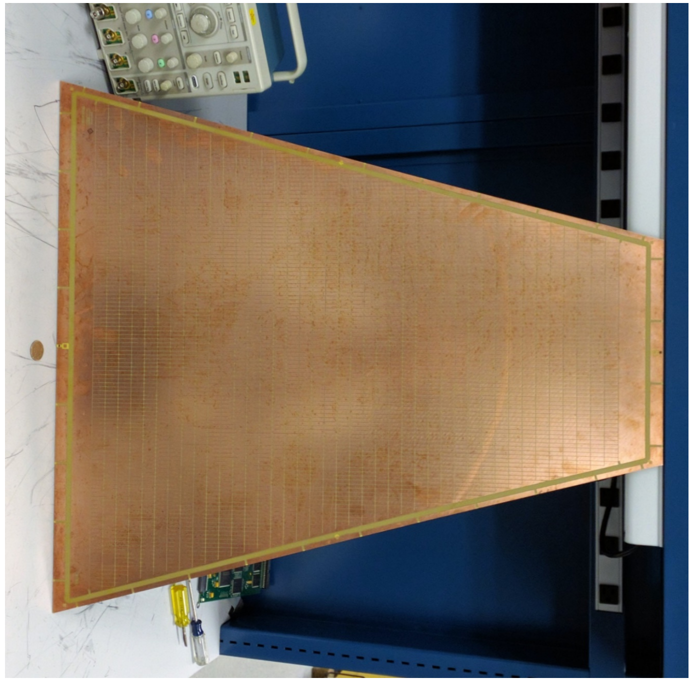



# STAR TPC

- Upgrade of inner chambers

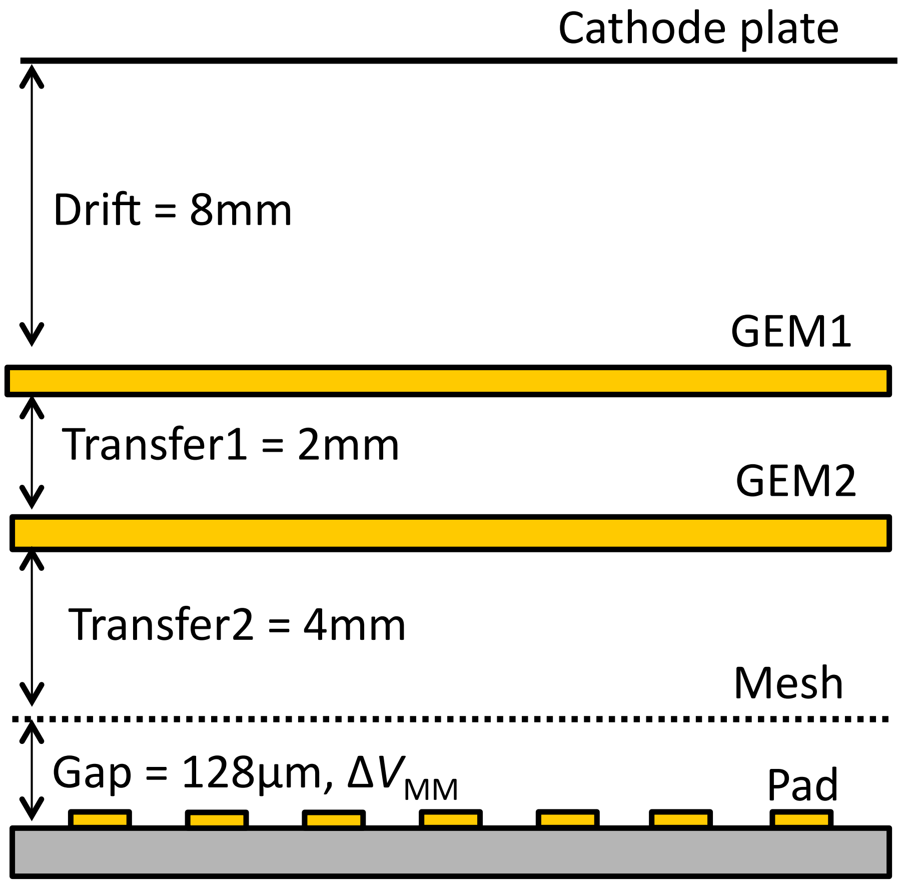



Heavy-ion collisions at several kHz rate



- Replace wire chambers with wire chambers
  - new pad planes with all active area covered with pads for dE/dx
  - close chamber edges to avoid leaking of ions
  - Prevent deterioration by ageing effects

# 2 GEMs + MM

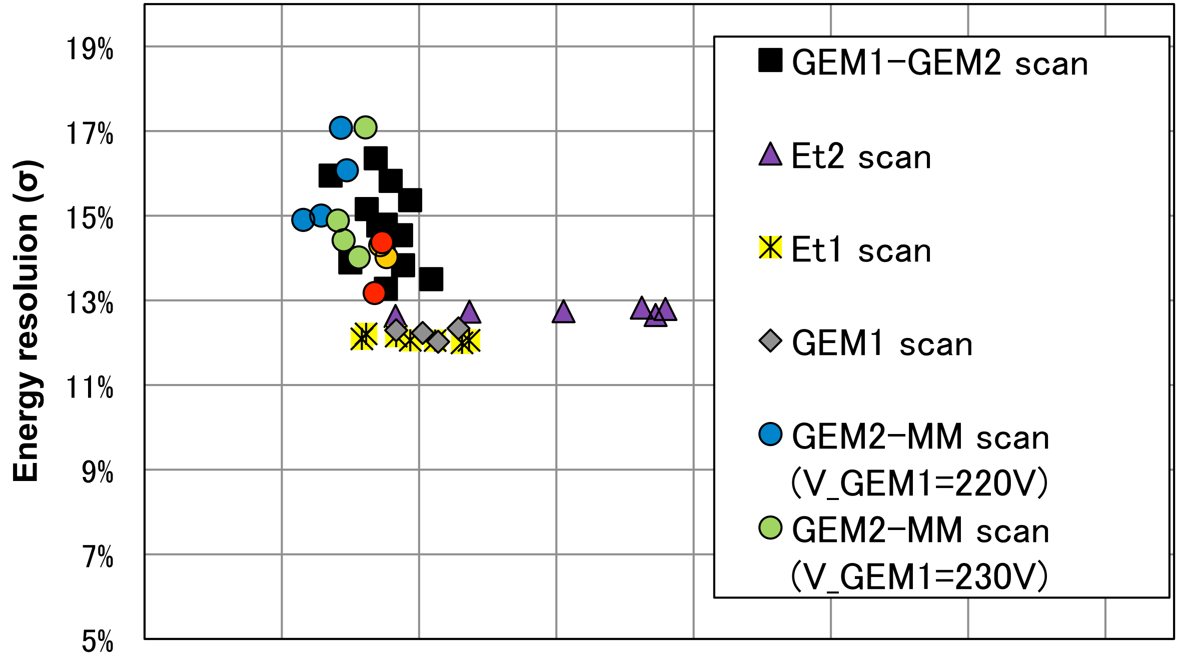



- R&D effort for ALICE (Yale, Tokyo) based on work by S. Procureur
- Preamplification stage with 2 GEMs allows for limiting the charge density in MM and to effectively block ions

# 2 GEMs + MM

- Excellent IBF performance
- dE/dx at the limit
- Discharge probability 2 orders of magnitude higher than with a 3 or 4 GEM stack

K. Teresaki (ALICE R&D)

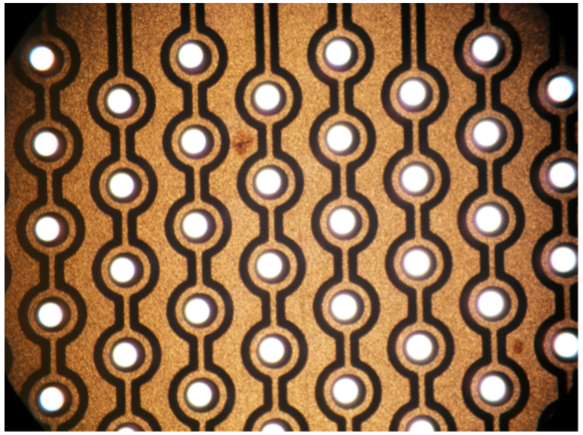



| # | $\Delta U_{GEM1}$ (V) | $\Delta U_{GEM2}$ (V) | $\Delta U_{MMG}$ (V) | gain | Discharge probability |
|---|---|---|---|---|---|
| 1 | 232 | 210 | 460 | 2000 | $(3.0 \pm 0.3) \times 10^{-9}$ |
| 2 | 250 | 210 | 440 | 1800 | $(3.1 \pm 0.7) \times 10^{-10}$ |
| 3 | 260 | 220 | 420 | 1600 | $(1.5 \pm 1.1) \times 10^{-11}$ |

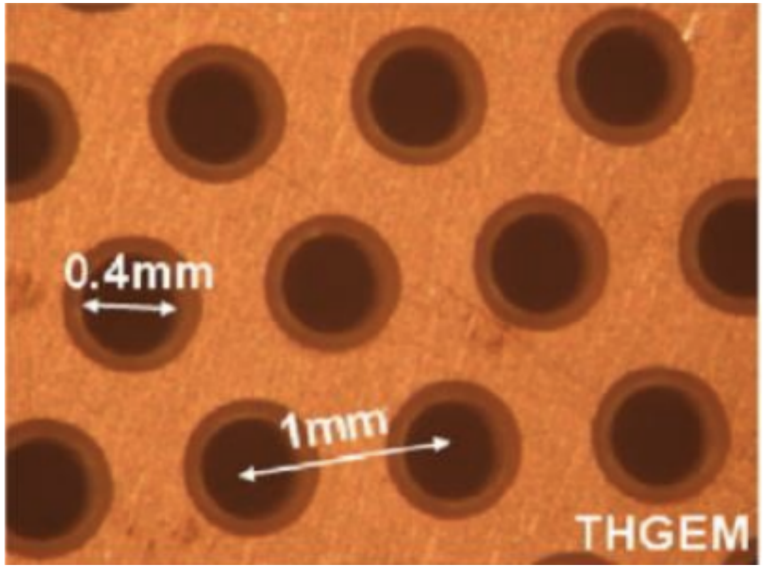
ALICE full prototype at the SPS (RD51)

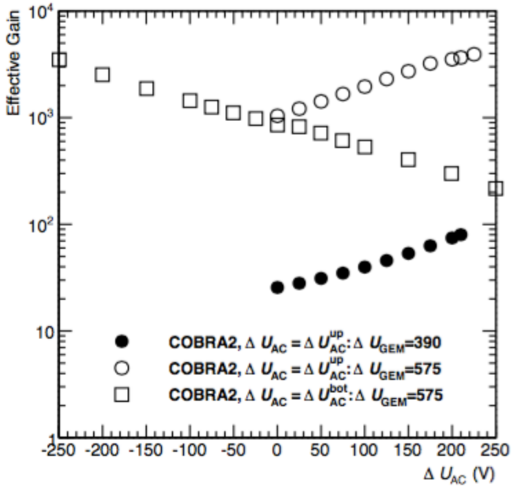
# Other possible sensors

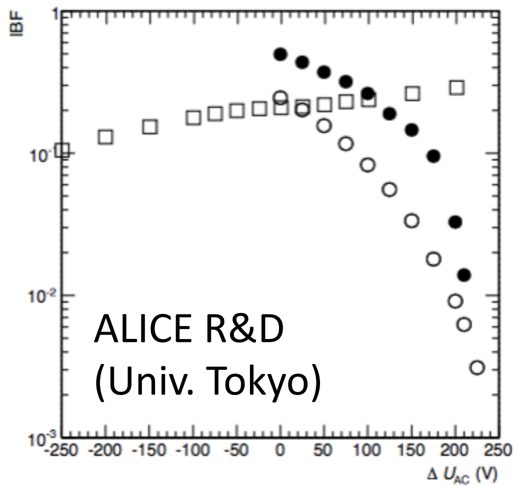
- THGEM
  - Thick GEMs are easily fabricated on normal PCBs or resistive electrodes
  - ☞ choice of rim and stacking



Cobra patterned on GEM




☞ Challenges: larges sizes, stability

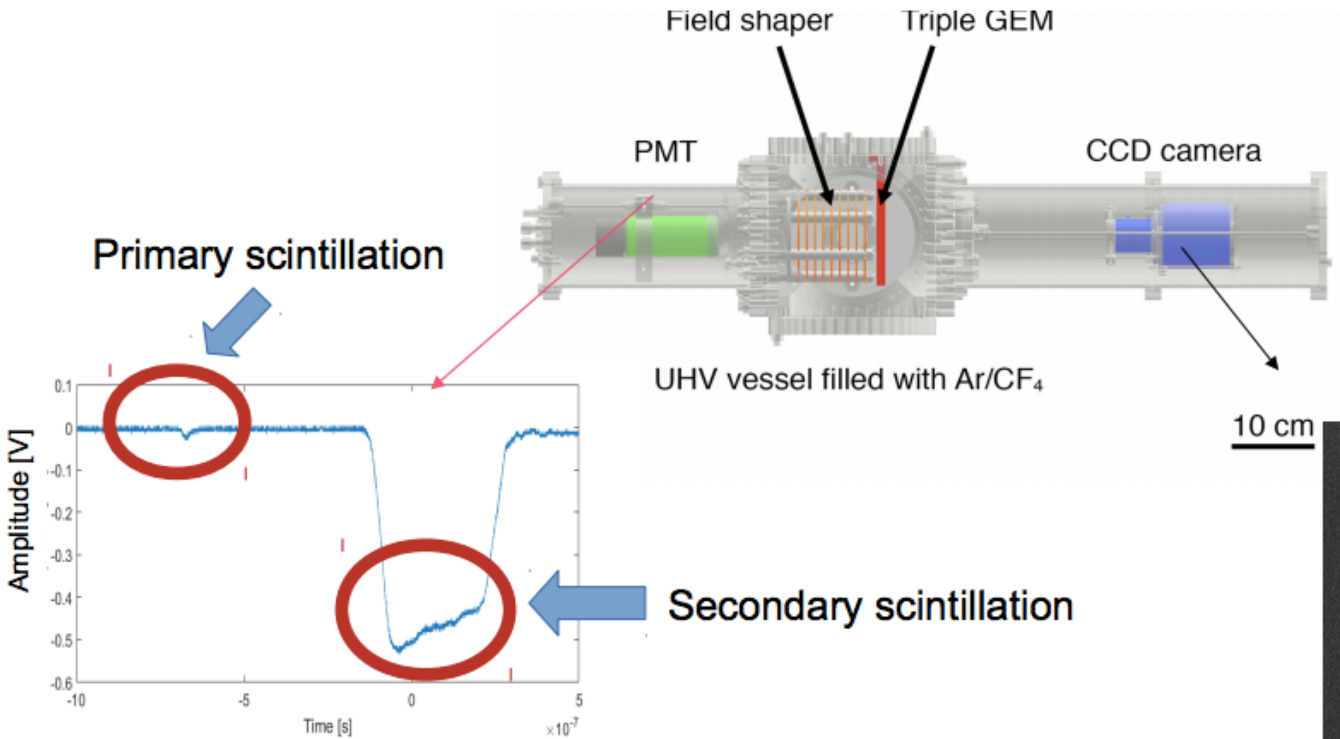
# Conclusions

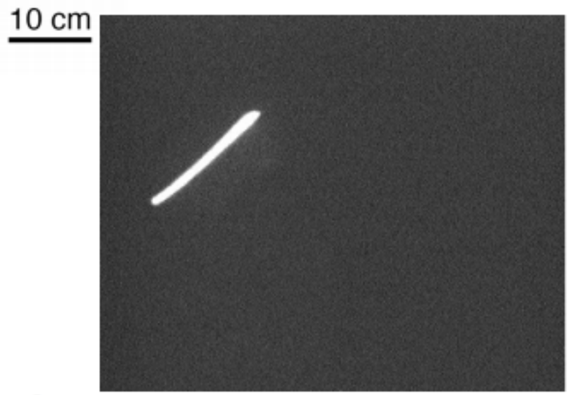
- MWPC-based TPCs have developed over ~40 years
  - mechanical precision
  - gas choice
  - charge gating
  - readout techniques
  - simulations and calibration
- New experimental challenges call for new solutions: MPGD
  - higher rates, multiplicities, occupancies
  - better position resolution
  - ion backflow minimisation
  - ☞ stability against discharges
  - ☞ QA, QA, QA

# Backup

# Light readout with a GEM TPC

G. Galgóczi and F. Resnati

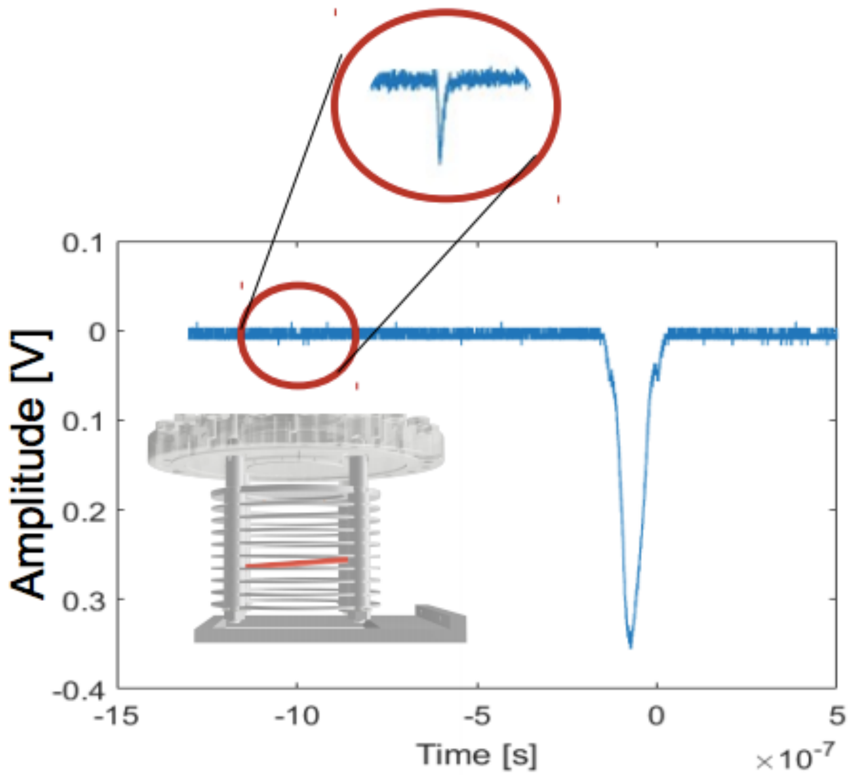


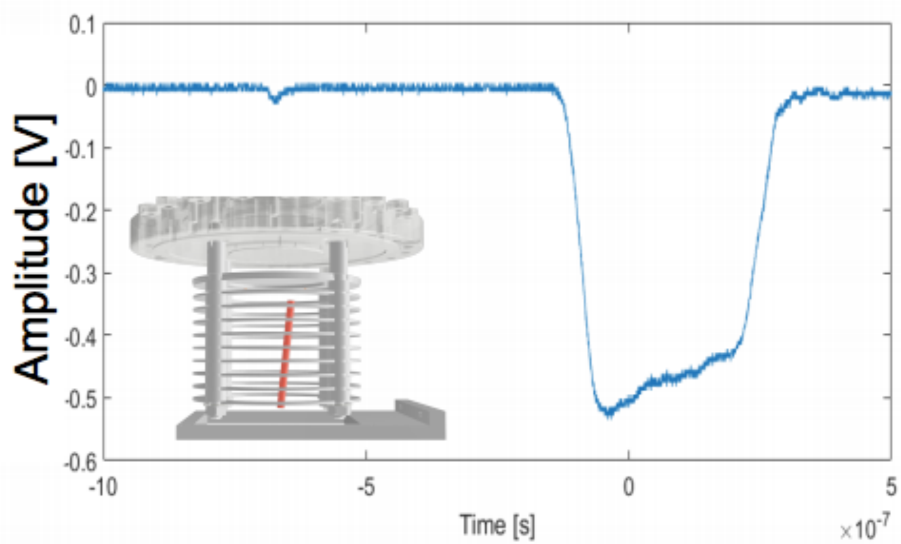




- Camera → 2D projection of the track
- PMT → Projection of the track in 3. dimension

6

# Light readout with a GEM TPC



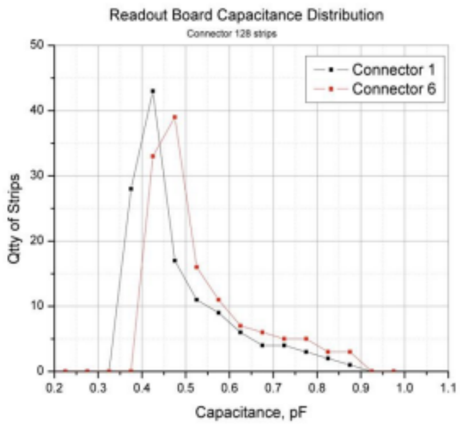



# GEM TPC for the super-FRS at FAIR

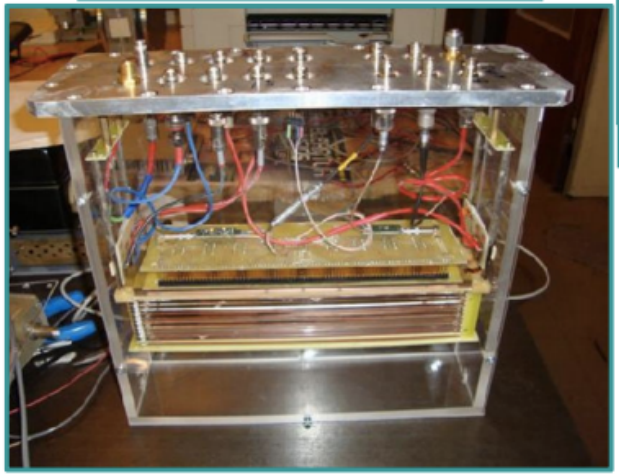
F. García

## PROTOTYPE DEVELOPMENTS

Capacitance measurement setup

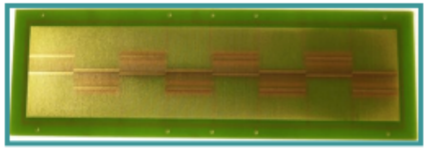


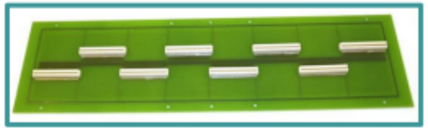

Flange of the GEM-TPC HB1, read out by delayed lines



Right: The electrodes of the board with strips of 200 µm width and 500 µm pitch

And 8 Header Panasonic connectors with 130 Pin each

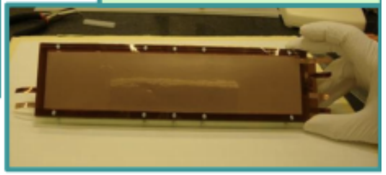




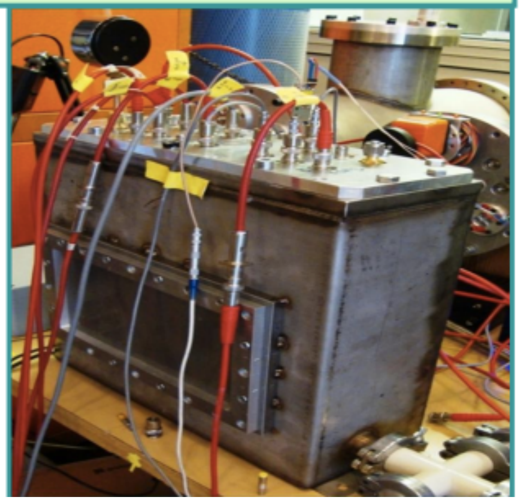
Comenius University - Bratislava

Field cage of 40 mm drift

Triple GEM stack



First GEM-TPC called HB1 detector (Helsinki Bratislava prototype 1)



# Super-FRS TPC: from Ni to U

## LARGE DYNAMIC RANGE - FROM PHYSICS (cont.)

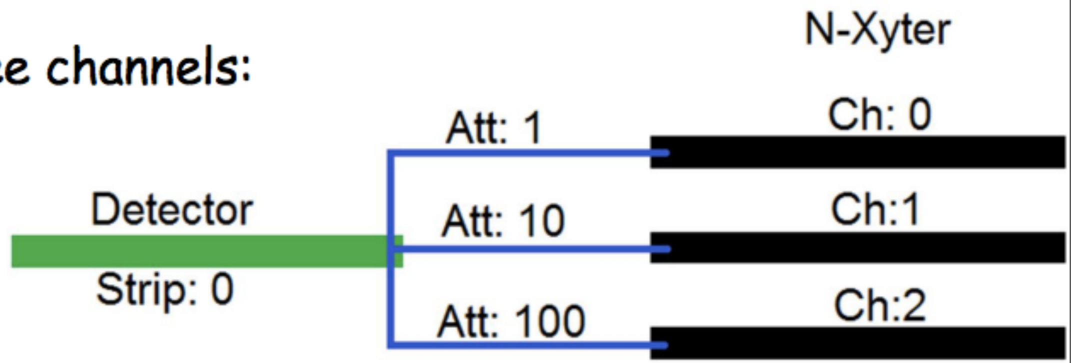
One solution for large dynamic range is shwon below....

Split the incoming charge into three channels:

1 channel with attenuation of 1

1 channel with attenuation of 10

1 channel wth attenuation of 100




As a result one can have up to 1.5 pC per strip dyamic range → based on the assuption of the current n-Xyter v.2.0 with a dynamic range of 15 fC per channel.

# IBF minimisation – various lternatives

The presence of ions is an inevitability in gaseous detectors. The higher the gain and rate, the more problematic they become.

MPGD provides us several solutions to decrease the IBF to acceptable values.

| | GEM Cascade | Reversed MHSP | PACEM | ZERO IBF |
|---|---|---|---|---|
| **Current Status** | 4 GEM - ALICE upgrade | . Successful operation of Visible Sensitive GPM | Novel Solution | Operation in noble gases and Mixtures |
| **Strengths** | GEM are solid and well established technology | Extra strips makes it versatile | . Gain can be increased without affecting IBF<br>. Low Voltages | IBF at the level of the primary ionization |
| **Limitations** | . IBF dependent on GAIN | . IBF dependent on GAIN<br>. Not yet produced in large areas | Noble gases/CF4 mixtures (purification) | Noble Gases (purification) |
| **Future Developments** | Misalignment / different pitch GEM | Large Area MHSP | Double PACEM (?) | Test beam |

F. Amaro

# 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

$\omega = eB/m$

## Pad Response Function

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

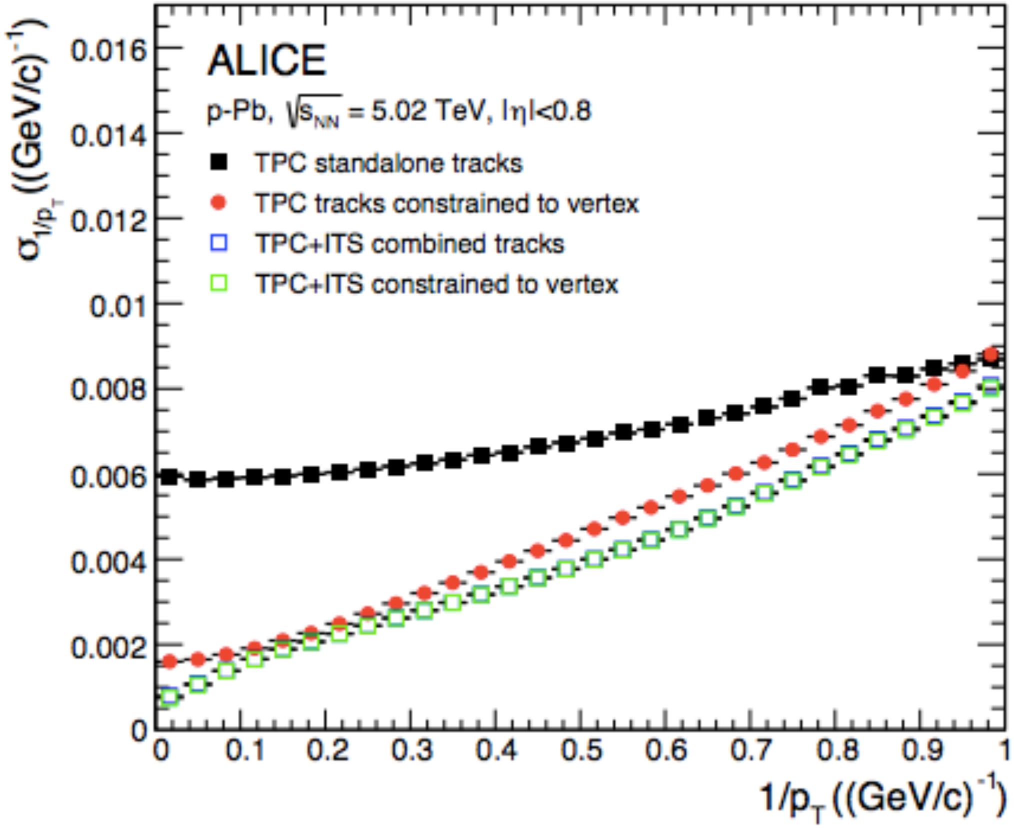
$\sigma_{PRF}$ depends on the electrode geometry only

# ALICE TPC 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

# Performance: $p_T$ resolution

- For 2013 p-Pb data with $Ne\text{-}CO_2$ (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

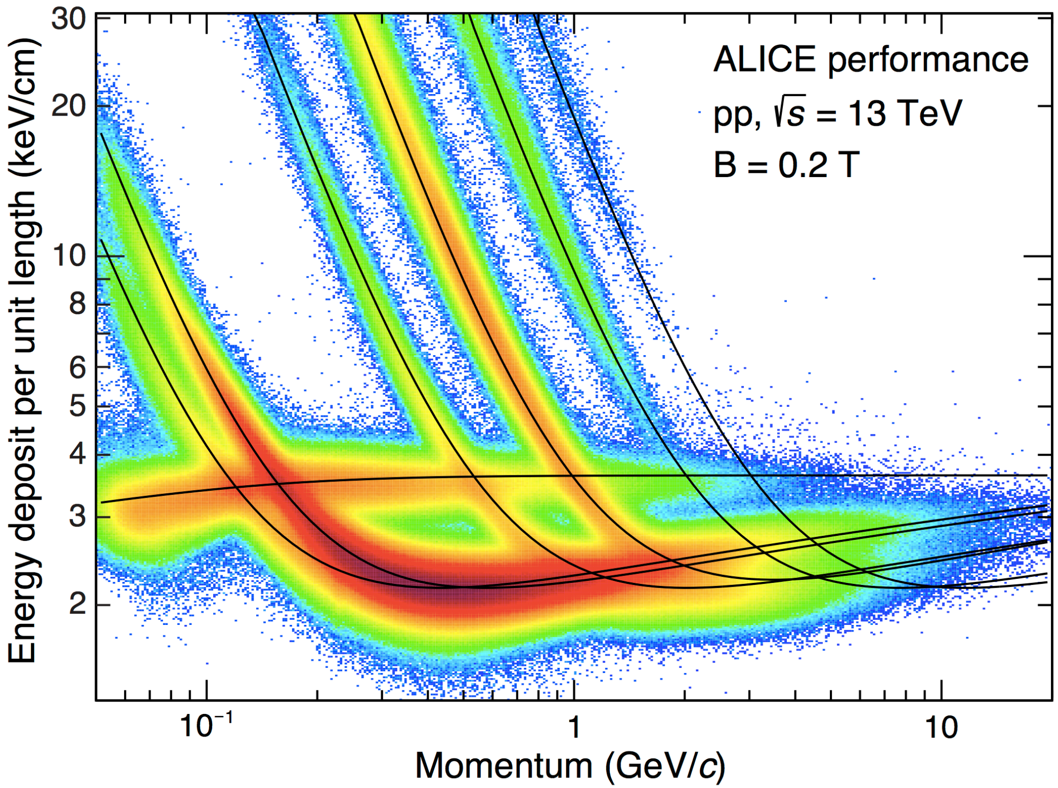
# Performance: dE/dx

## Current TPC

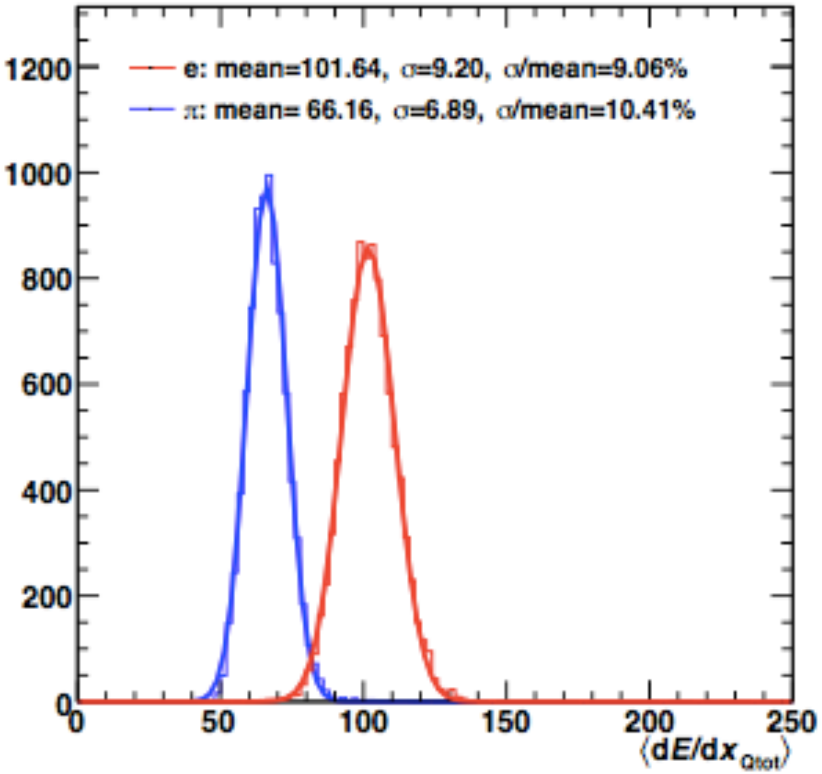
- With Ne-$CO_2$:
- $\sigma_{dE/dx} \approx 5.5$ % in pp
- $\sigma_{dE/dx} \approx 7$ % in central Pb-Pb
  - deterioration due to overlapping clusters

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

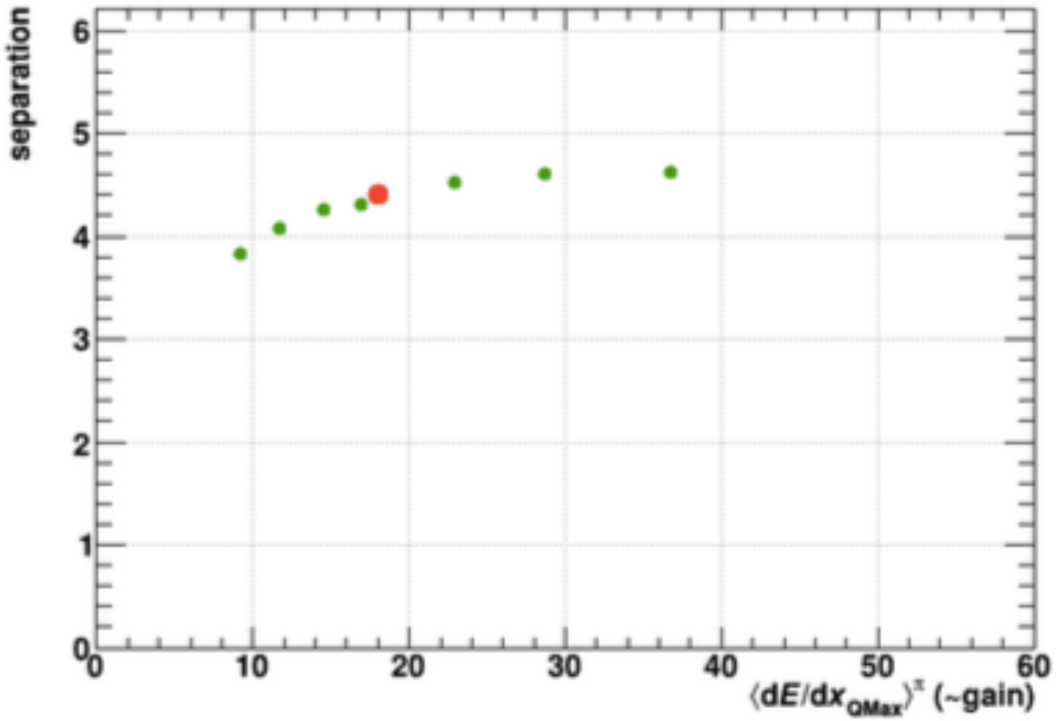
2015 pp data at B = 0.2 T, Ar-$CO_2$ (88-12)



# dE/dx with 4-GEM 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

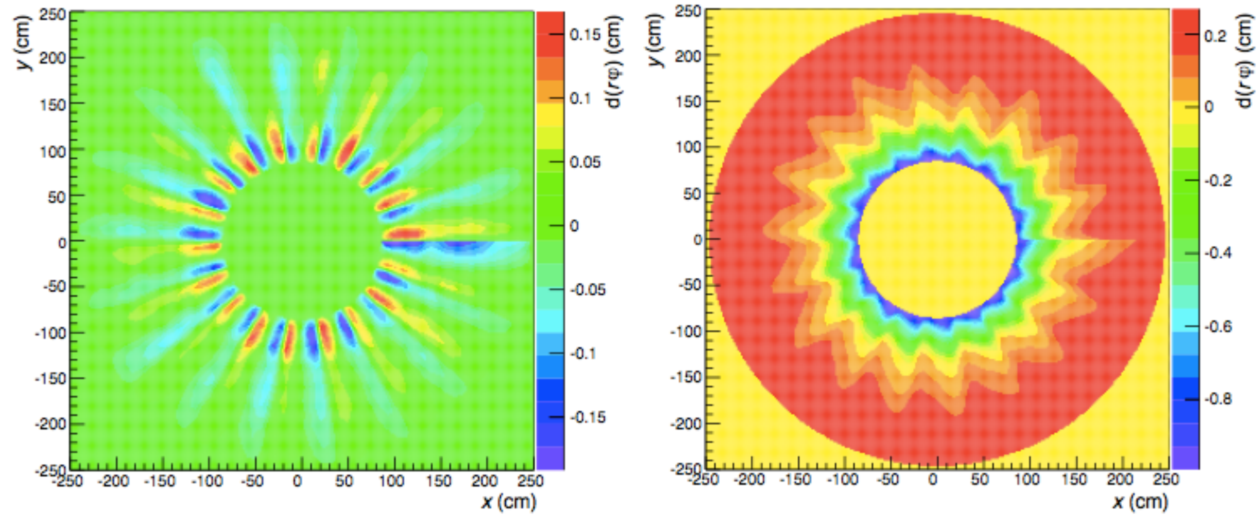
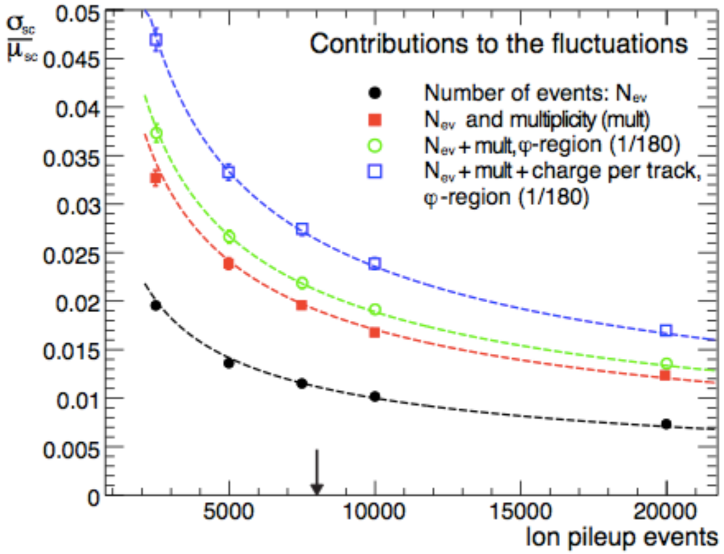


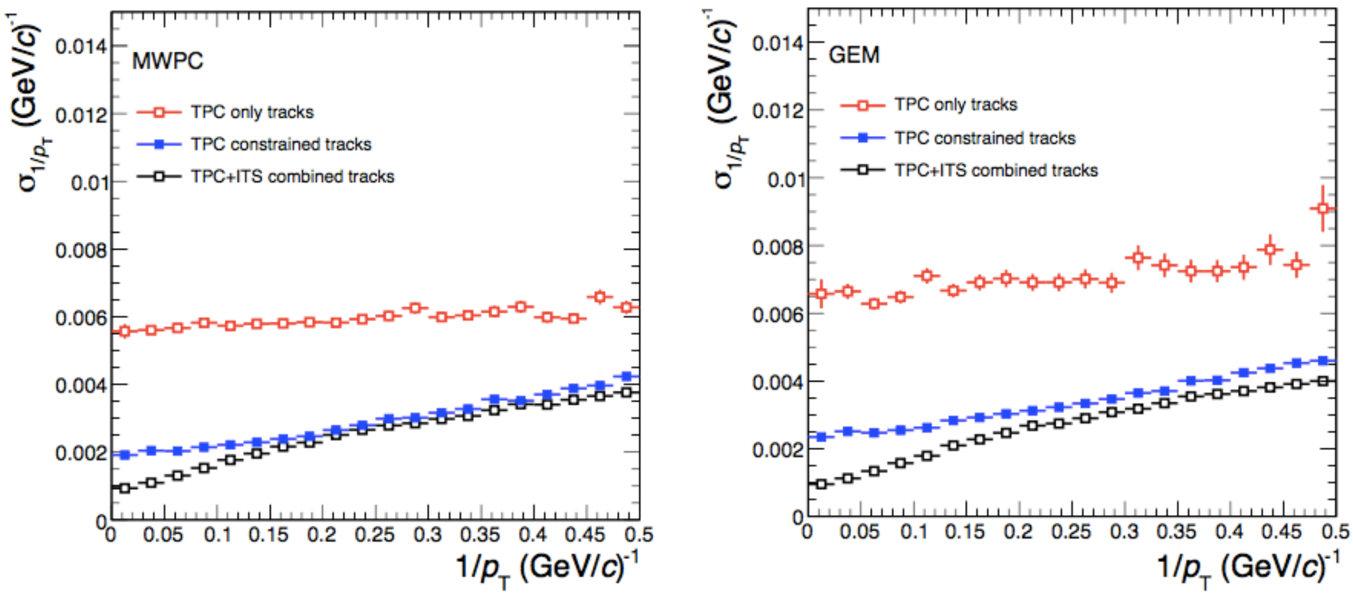

Figure 7.13: $xy$ projection of the $r\varphi$ distortion map close to the TPC central electrode (at $z = 10\,\mathrm{cm}$). The data are base
detailed 3-dimensional space charge map for $\varepsilon \approx 5$ without magnetic field (left) and with $B = 0.5\,\mathrm{T}$ (right).

With fluctuations

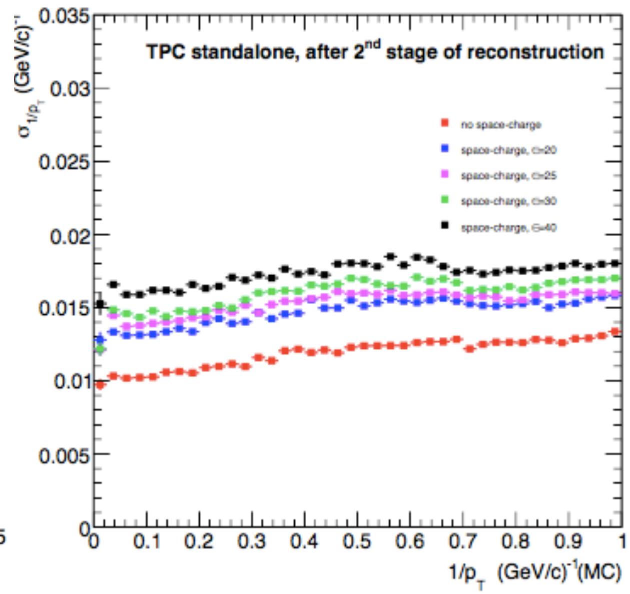


# Reconstruction and corrections

- Main challenge are space-charge distortions of up to 20 cm
- Real-time map of distortions is used for online track reconstruction
- In a second stage, the required momentum resolution, with combined TPC-ITS tracking, is achieved

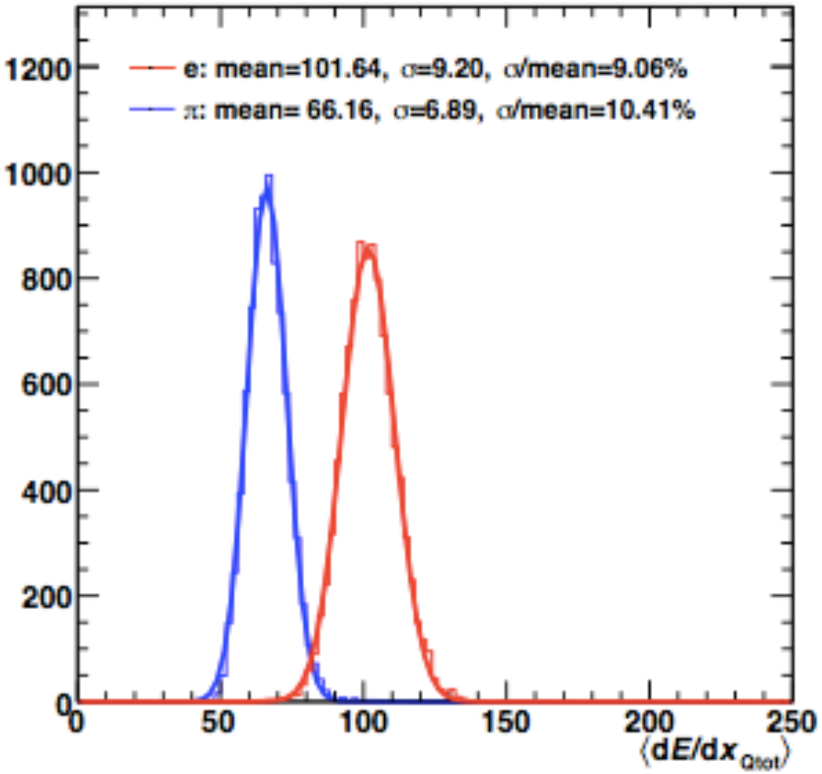



Comparison of $1/p_T$ resolution for wires and GEMs

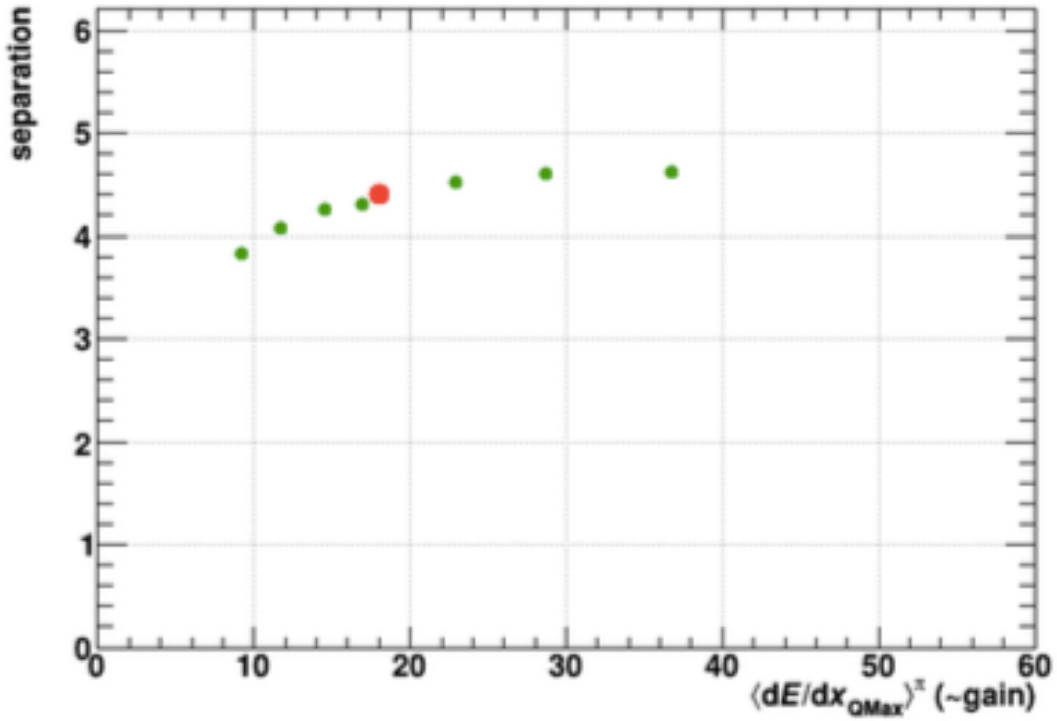



GEM performance at increasing multiplicities.
Expected: blue points

# dE/dx with IROC prototype




dE/dx for π and e at gain 2000




Separation power as a function of gain