Gaseous Detectors

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XIV ICFA School on Instrumentation in Elementary Particle Physics
LA HABANA
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Summary of Second Lecture

- Transport of charge: drift and diffusion
  - electrons: instantaneous velocity $\gg$ drift velocity
  - drift velocity depends on $\sigma(\varepsilon)$ and $\Lambda(\varepsilon)$, which vary strongly with ε
  - diffusion depends on electron kinetic energy $\varepsilon(E)$
- Gas amplification
  - determined by 1. Townsend coefficient
  - gases used: noble gases with admixtures of molecular gases
- Signal formation: Ramo-Shockley Theorem

Plan of the Lecture

1. Introduction
2. Interactions of charged particles with matter
3. Drift and diffusion of charges in gases
4. Avalanche multiplication of charge
5. Signal formation and processing
6. Ionization and proportional gaseous detectors
7. Track reconstruction and momentum measurement
   ⇨ covered by D. Bortoletto

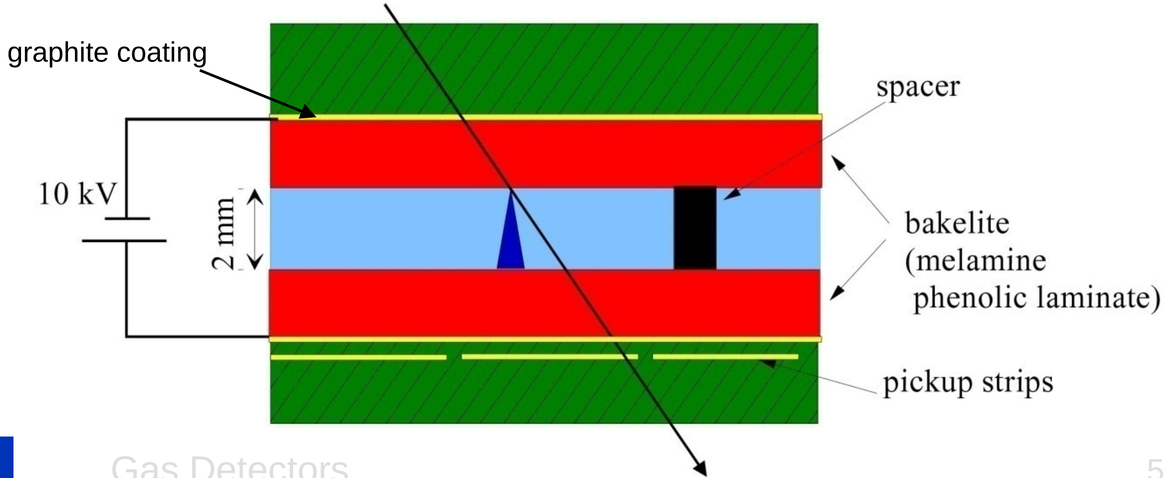
6 Proportional Gaseous Detectors

6.1 Resistive Plate Chamber

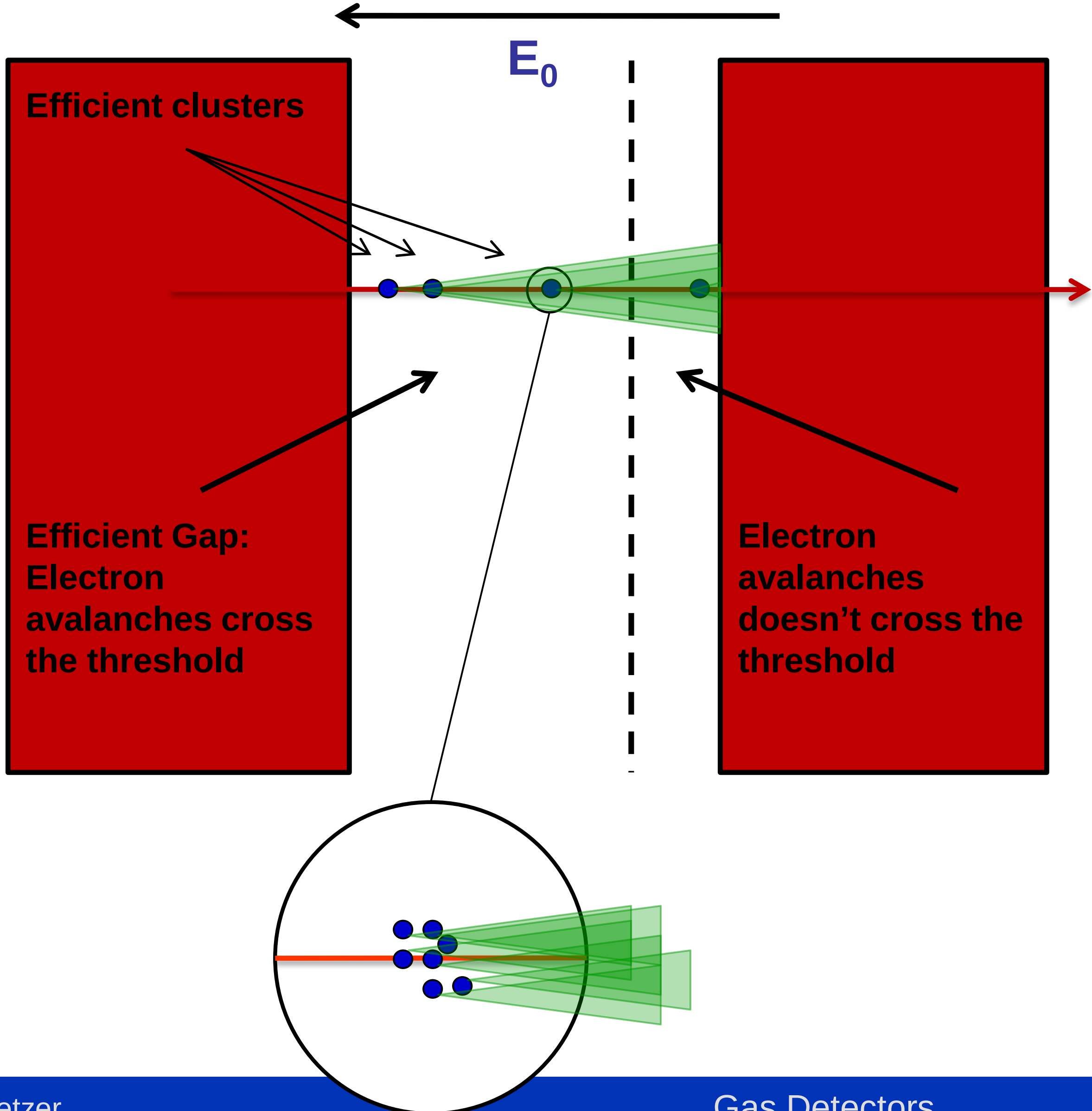
Principle:

[R. Santonico et al., NIM 187, 377 (1981)]

- Parallel plate counter with strong uniform electric field: ~50 kV/cm, 2 mm gap
  - ⇨very good time resolution: $\sigma_t < 1$ ns
    - – instant avalanche multiplication for all primary clusters
    - – dominated by avalanche statistics, not primary ionization statistics
- High-ohmic electrode material (glass: $\rho = 10^{12}\ \Omega\mathrm{cm}$, Bakelite: 10^{10}-$10^{11}\ \Omega\mathrm{cm}$)
  - ⇨ local decrease of electric field at position of avalanche
  - ⇨ blind spot for time $\tau \sim \rho\varepsilon_0\varepsilon_r$ (relaxation time, 10 ms – 1 s)
- Pickup strips for position information



Resistive Plate Chamber



Number of clusters per unit length follows strictly a Poisson distribution.

Number of efficient clusters follows to a good approximation the same Poisson distribution.

The number of electrons per cluster follows approximately a $1/n^2$ distribution.

→Number of efficient electrons follows approximately a "Landau" distribution.

Each individual electron starts an avalanche, inducing a signal which will cross a given threshold of the readout electronics → time.

[Slide courtesy of W. Riegler]

Resistive Plate Chamber

Operation:

- **Streamer mode**: L3, BaBar, BELLE
  - large signals (up to ~nC) ⇨ no amplifier needed
  - low rate capability: a few 100 Hz/cm^2
- **Proportional mode**: ATLAS, CMS μ trigger
  - suppression of streamers by addition of small amounts of SF_6
  - higher rate capability: a few kHz/cm^2
  - signal ~10× smaller ⇨ low-noise amplifier
  - less aging

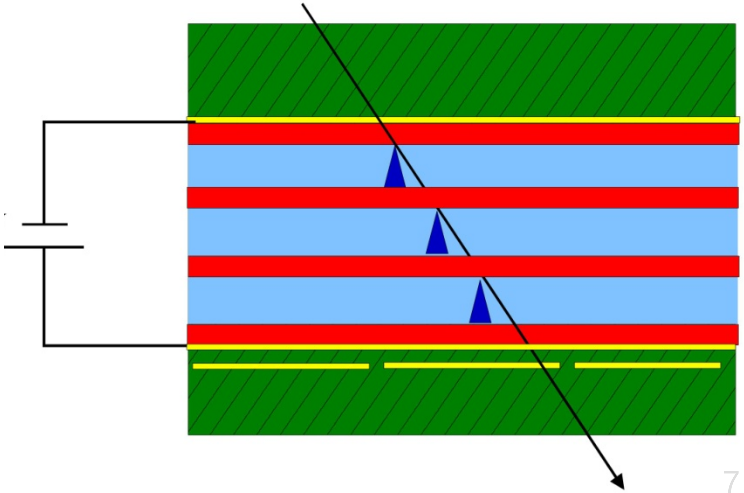
Multi-gap RPC: ALICE TOF barrel, FOPI

- 0.2 – 0.3 mm gaps

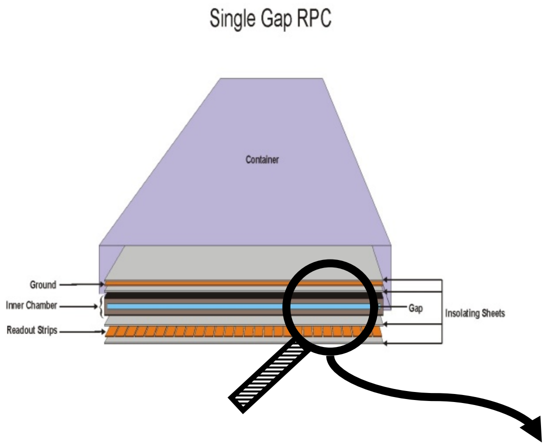
⇨ improved efficiency

⇨ improved time resolution (smaller gaps)

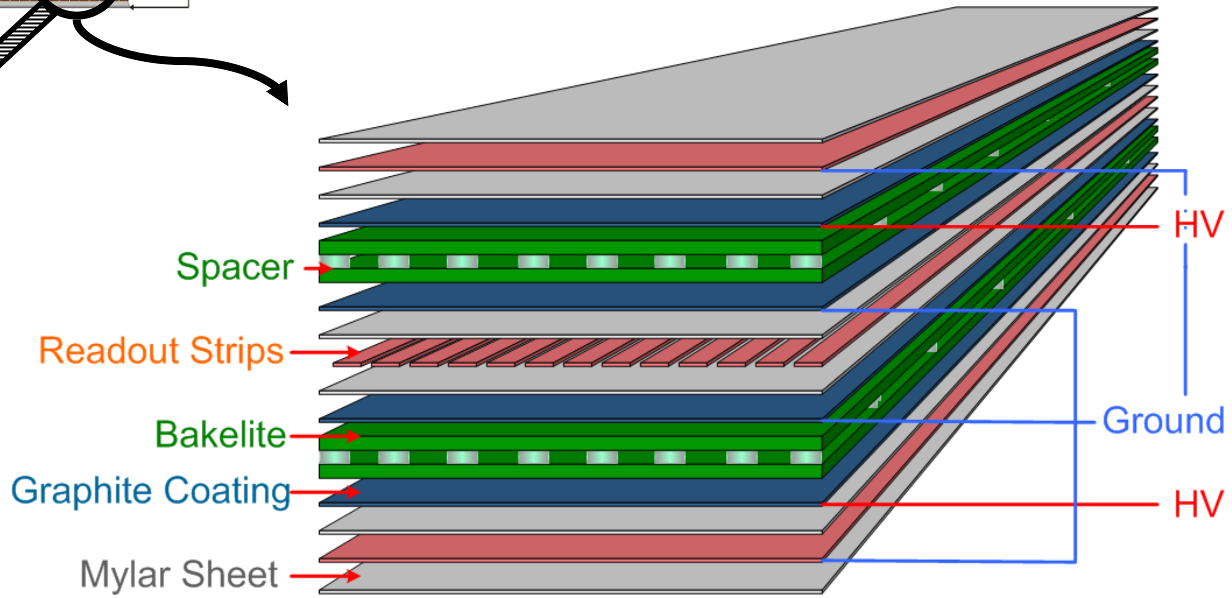
$\sigma_t = 50 - 100$ ps



CMS (CERN LHC): barrel/endcap trigger



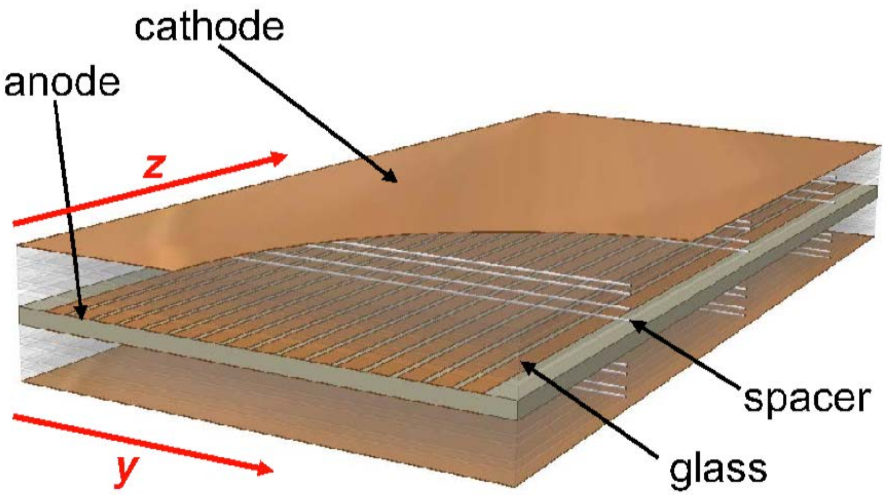
- Freon ($C_2H_2F_4$)/i-C_4H_{10}/SF_6 (95.5/3.5/0.3) + 5000 ppm H_2O
- *Gap: 2* mm
- *U=9000* V
- Total area: 2700 m^2, 105000 channels
- Time resolution <3 ns

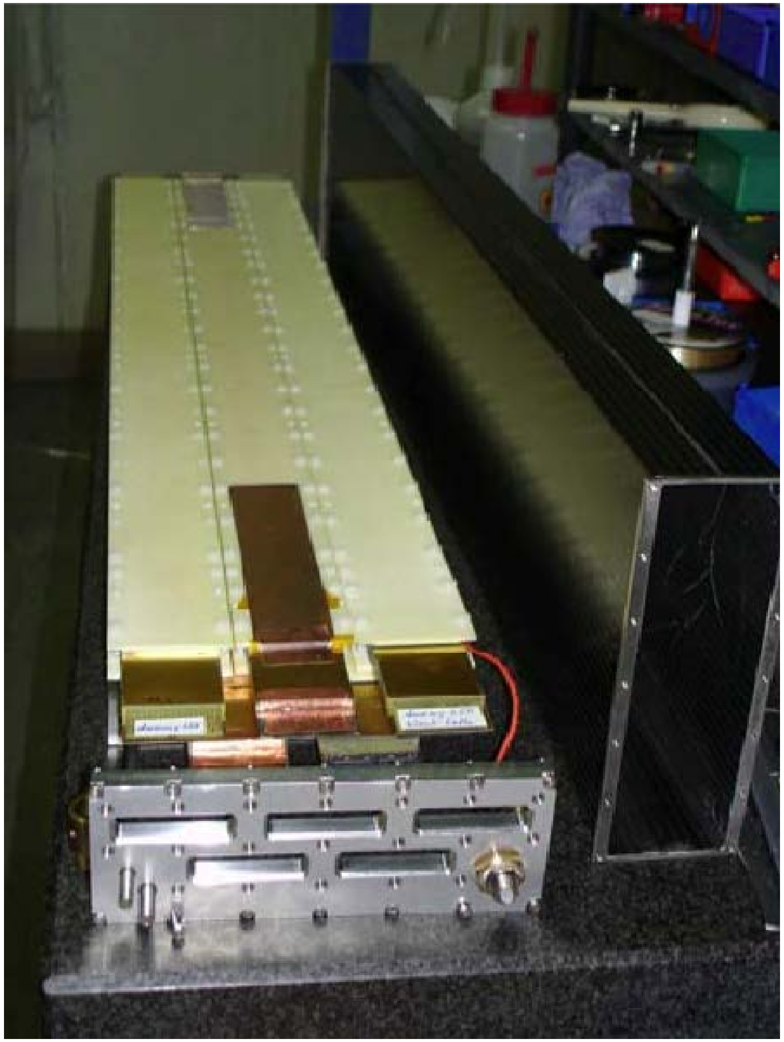


FOPI RPC

Multi-strip Multi-gap RPC:

- Active area: 90 × 4.6 cm^2
- Gaps: 8 × 220 μm
- Strips: 16, 2-sided readout
- HV: 9.6 kV
- Gas: $C_2H_2F_4$ / i-C_4H_{10} / SF_6 (80/5/15)
- Resolution: σ_{RPC} < 65 ps





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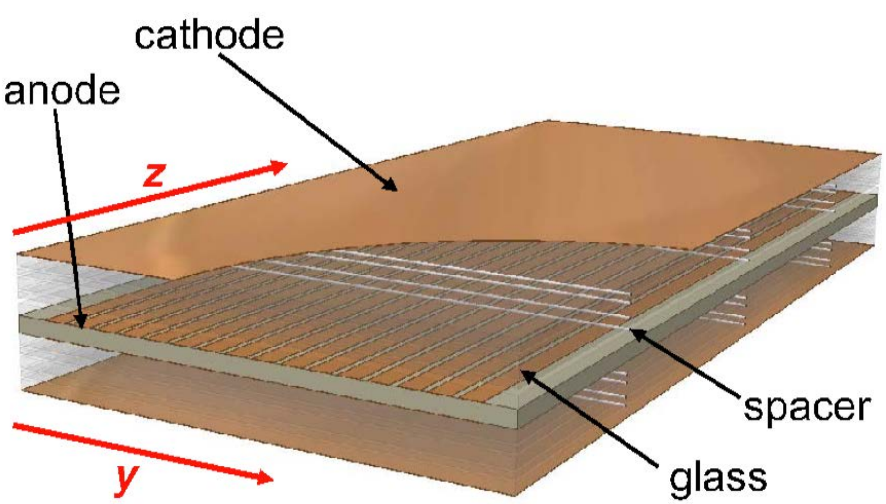
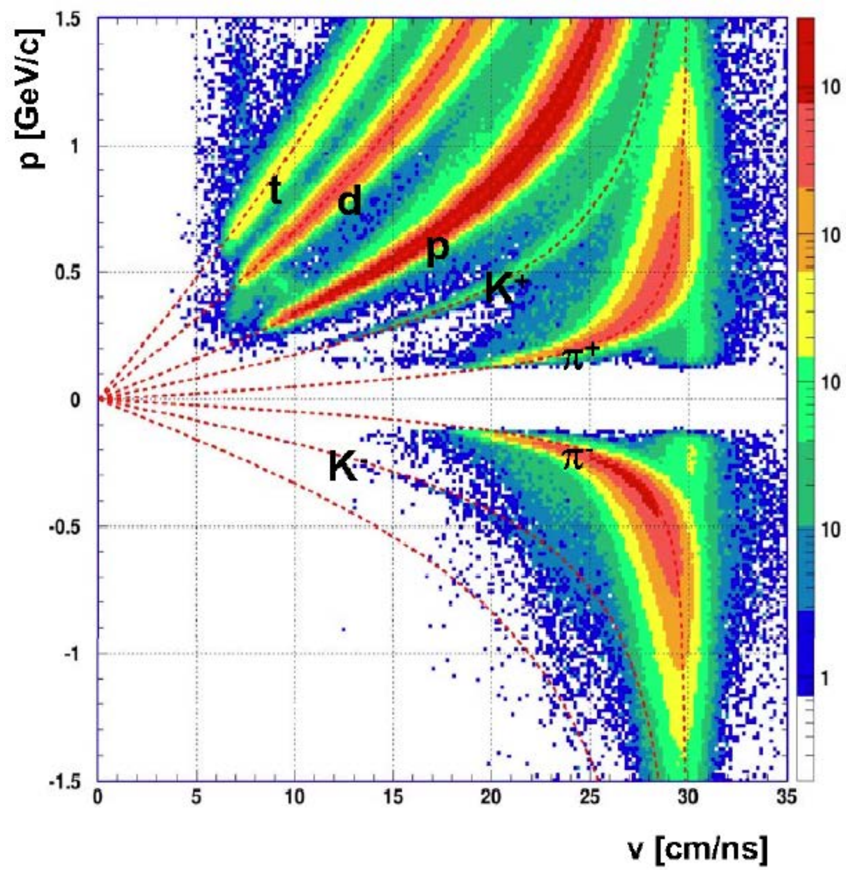




6.2 Multiwire Proportional Chamber

MWPC [G. Charpak et al., NIM 62, 262 (1968)]

NUCLEAR INSTRUMENTS AND METHODS 62 (1968) 262–268; © NORTH-HOLLAND PUBLISHING CO.

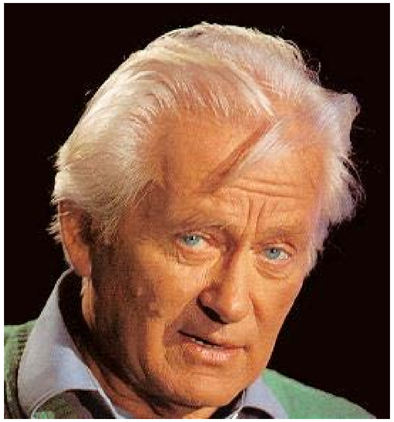
THE USE OF MULTIWIRE PROPORTIONAL COUNTERS
TO SELECT AND LOCALIZE CHARGED PARTICLES

G. CHARPAK, R. BOUCLIER, T. BRESSANI, J. FAVIER and Č. ZUPANČIČ

CERN, Geneva, Switzerland

Received 27 February 1968

Nobel Prize 1992



- Revolutionized particle physics
- Before: position measurement with bubble, cloud,
  spark chambers, emulsions ⇨ photograph
- Now: electronic measurement
  ⇨ higher rates, simpler + faster data acquisition

MWPC Principle

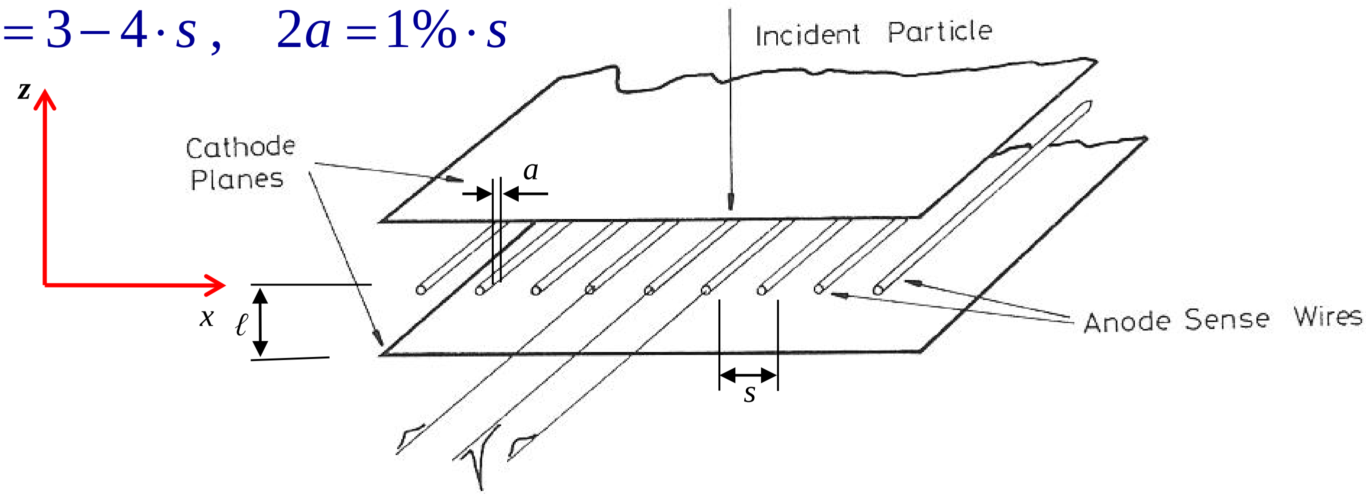
Array of closely spaced parallel proportional wires between two cathode planes

Typical dimensions: $l = 3 - 4 \cdot s\,,\quad 2a = 1\% \cdot s$

$\ell \sim 10$ mm

$s \sim 3$ mm

$2a \sim 20$ µm



Wire material: Au-coated tungsten (W) ⇨ good surface quality

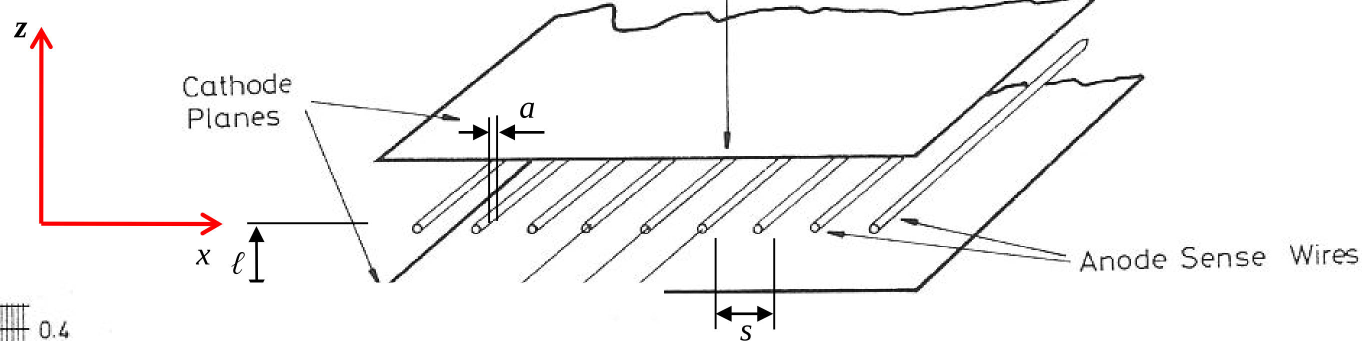
Frame: Fibre-glass material

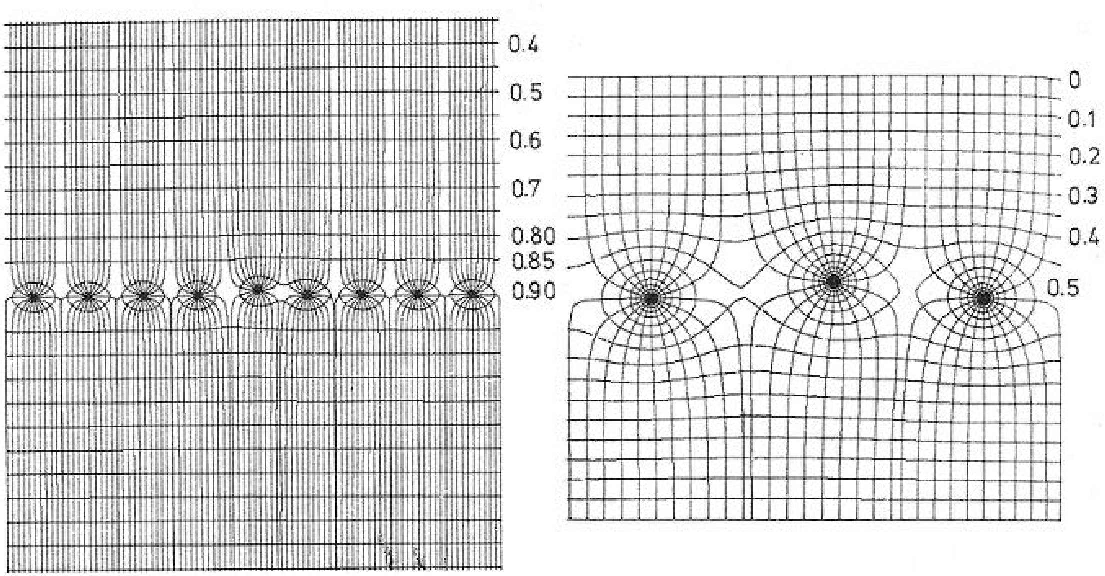
Cathode planes: metal foils, wires

Array of closely spaced parallel proportional wires between two cathode planes

Typical dimensions: $l = 3 - 4 \cdot s\,, \quad 2a = 1\% \cdot s$

$\ell \sim 10$ mm
$s \sim 3$ mm
$2a \sim 20$ µm

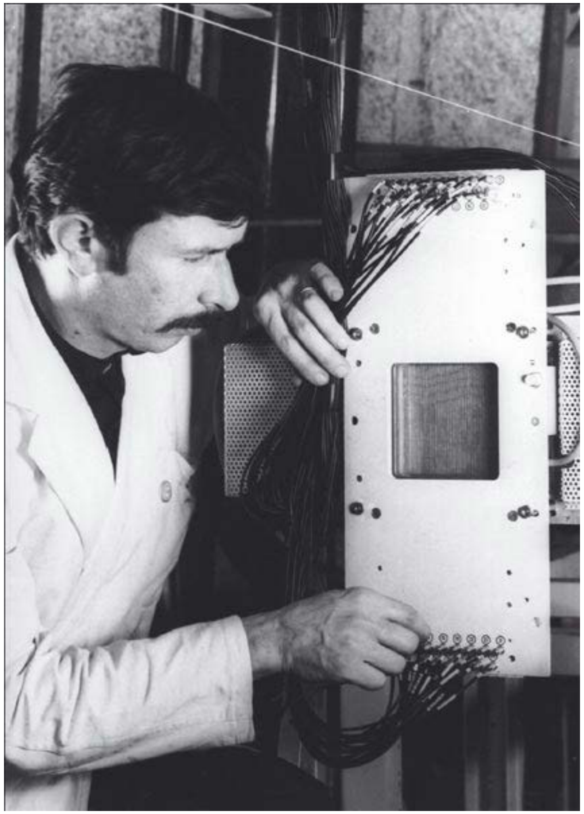




[G. Charpak et al., NIM 62, 262 (1968)]

Spatial resolution (anode readout):

$$\sigma \simeq \frac{s}{\sqrt{12}}$$



Cathode Readout

So far: only coordinate perpendicular to anode wires

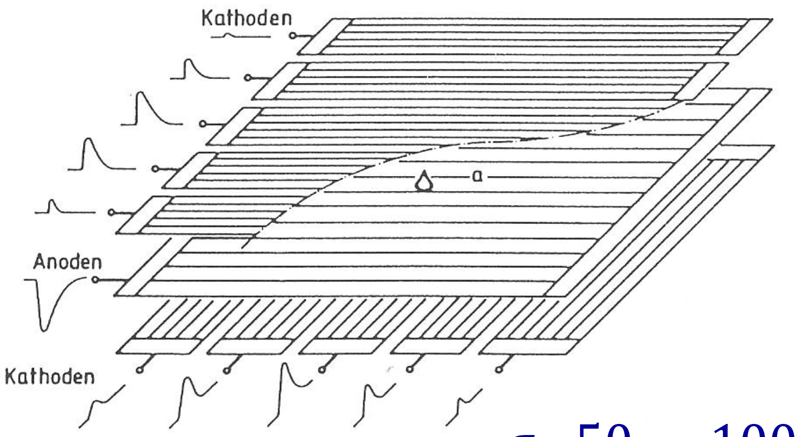
Many different methods to determine coordinates in space:

Segmented cathodes:

- cathode strips (perpendicular and parallel to anode wires)
- cathode wires
- pads

Avalanche induces signals on cathode strips / pads with amplitudes varying with distance to avalanche

⇨analog readout (ADC), center-of-gravity method



$\sigma \sim 50 - 100\ \mu m$

with clusterization

Cathode Readout

Position measurement with center-of-gravity method

⇨ measure amplitudes A_i of induced signals on neighboring wires i

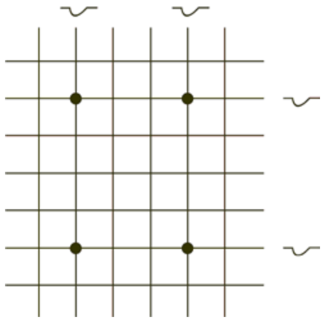
$$x = \frac{\sum A_i x_i}{\sum A_i}$$

y analogous

Spatial resolution: $\sigma_y \approx 50 - 100\,\mu\mathrm{m}$ (along anode wires)

$$\sigma_x > \sigma_y$$

Problem at higher particle rates: ambiguities (if >1 particle at the same time)

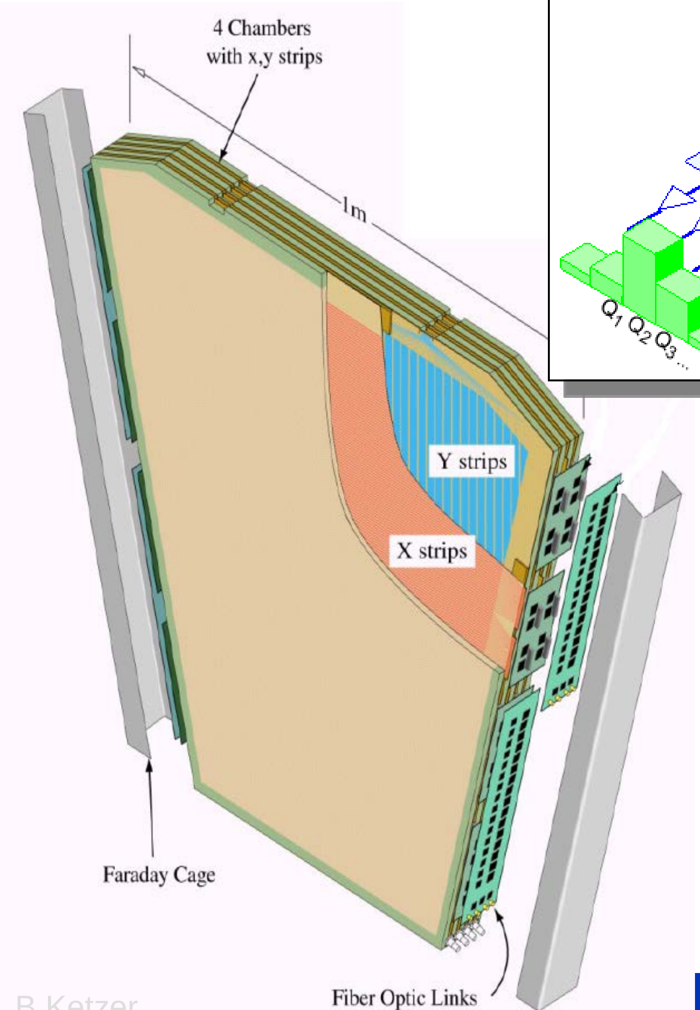


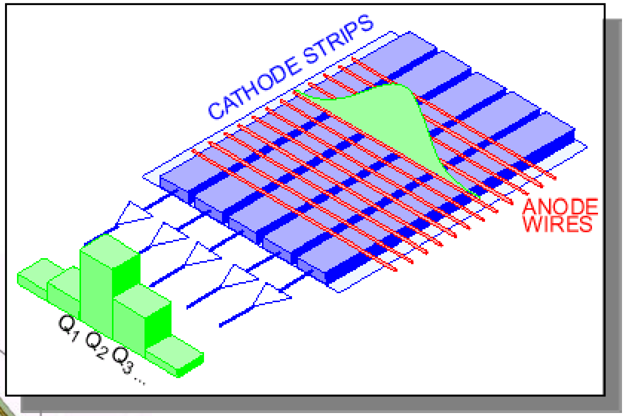
⇨ multiple projections, pads, pixels

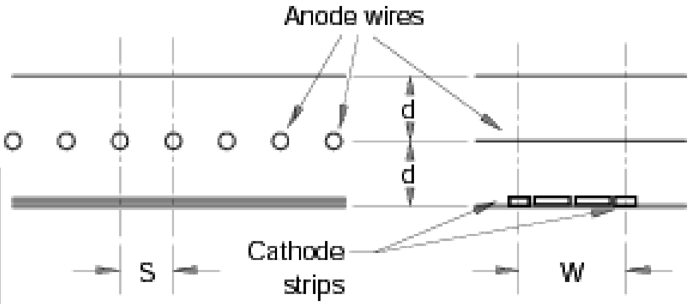
ATLAS Cathode Strip Chamber

Principle:

MWPC with cathode strip readout







ATLAS forward μ spectrom.

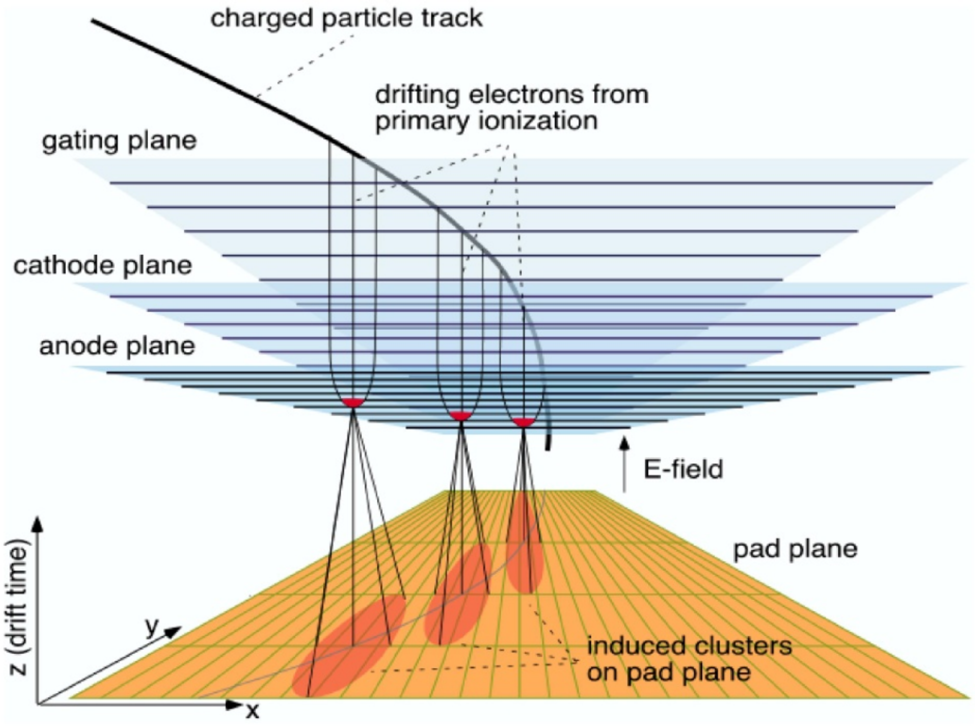
- *s=ℓ=2.54* mm, W=5.08 mm
- *2a=30* μm
- $Ar/CO_2/CF_4$ (30/50/20)
- *G=10*^{4} *(U=2600* V)
- 61440 strips + intermediate
- Total area: 27 m^2
- Spatial resolution: 75 μm
- Time resolution: 7 ns
- Hit rate several 100 kHz/strip

Time Projection Chamber

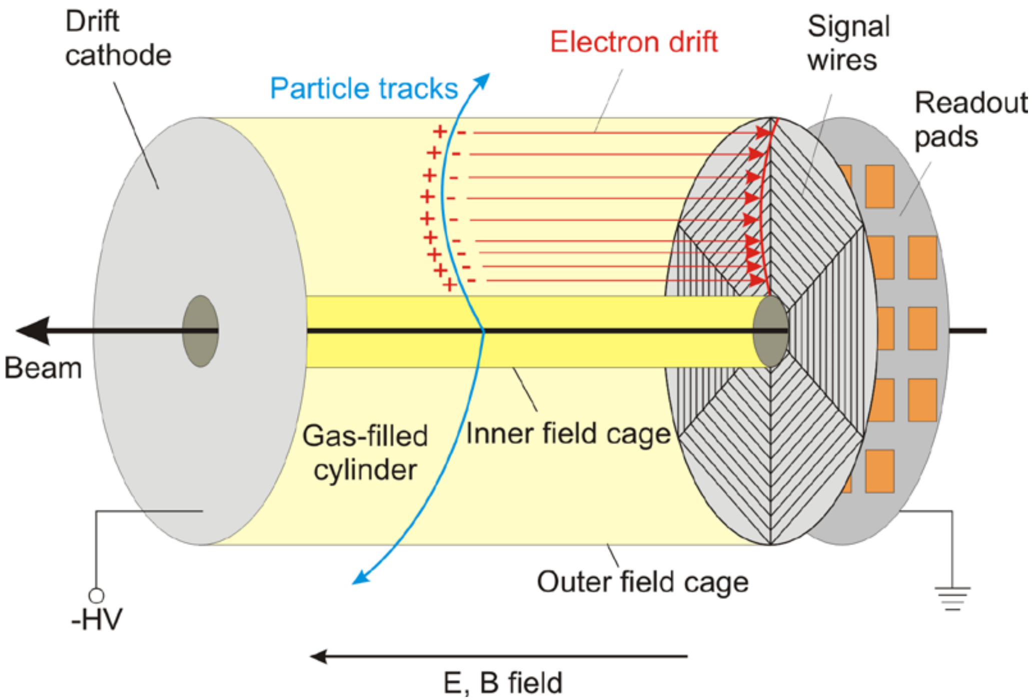
Time Projection Chamber [D.R. Nygren et al., Phys. Today 31, 46 (1978)]

Combination of MWPC and Drift Chamber: 3-D tracking device

- long drift path (~m) in gas-filled volume ⇨ z coordinate
- MWPC + pads perpendicular to drift path ⇨ x,y coordinates



TPC



Typical parameters:

- Gas: Ar (Ne) + 10-20% CH_4 (CO_2)
- E~100-200 V/cm
- u = 5-7 cm/µs
- p = 1-8.5 atm
- ωτ = 1 - 8

$$\sigma_{x,y} = 100 - 200\,\mu\text{m}$$

$$\sigma_z = 0.2 - 1\,\text{mm}$$

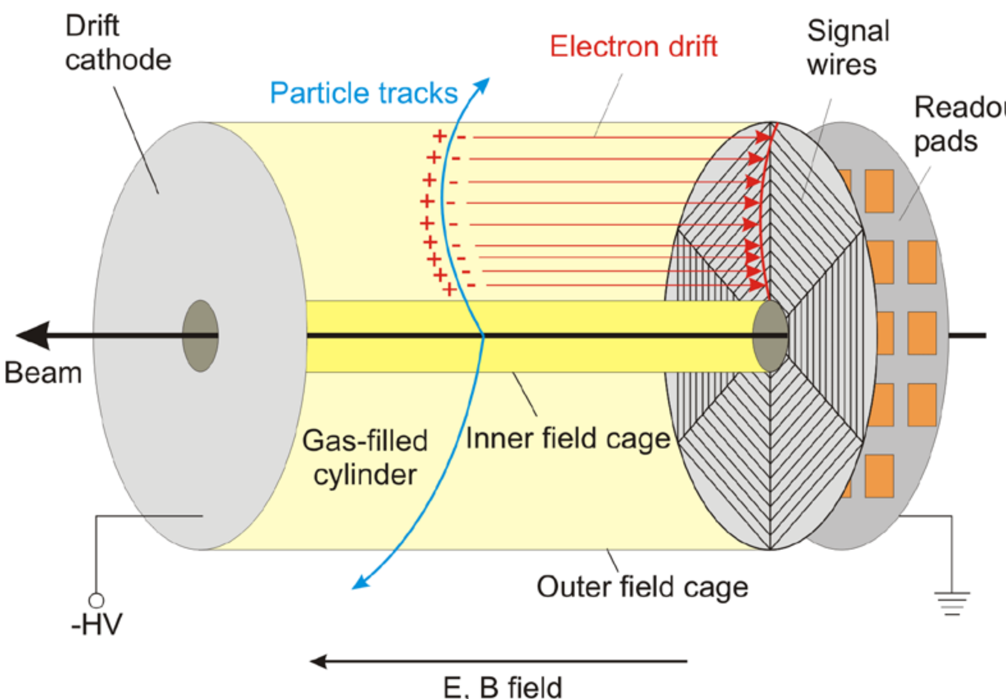
Typical application: collider

- cylindrical gas volume
- interaction point in center
  - ⇨ ~4π solid angle
- Solenoid field: **B ∥ E**
  - ⇨ momentum
  - ⇨ transverse diffusion suppr.:

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

- Large number of sampling points
  - ⇨ simple pattern recognition
  - ⇨ good momentum resolution
  - ⇨ dE/dx measurement for each single track possible

TPC

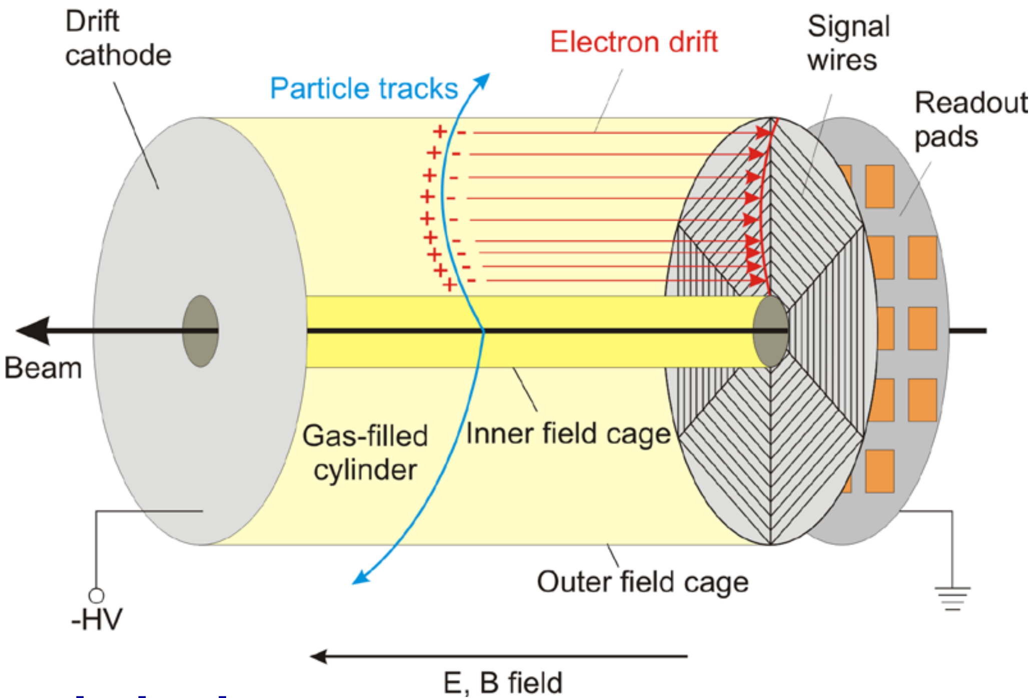


An (almost) ideal tracking detector:

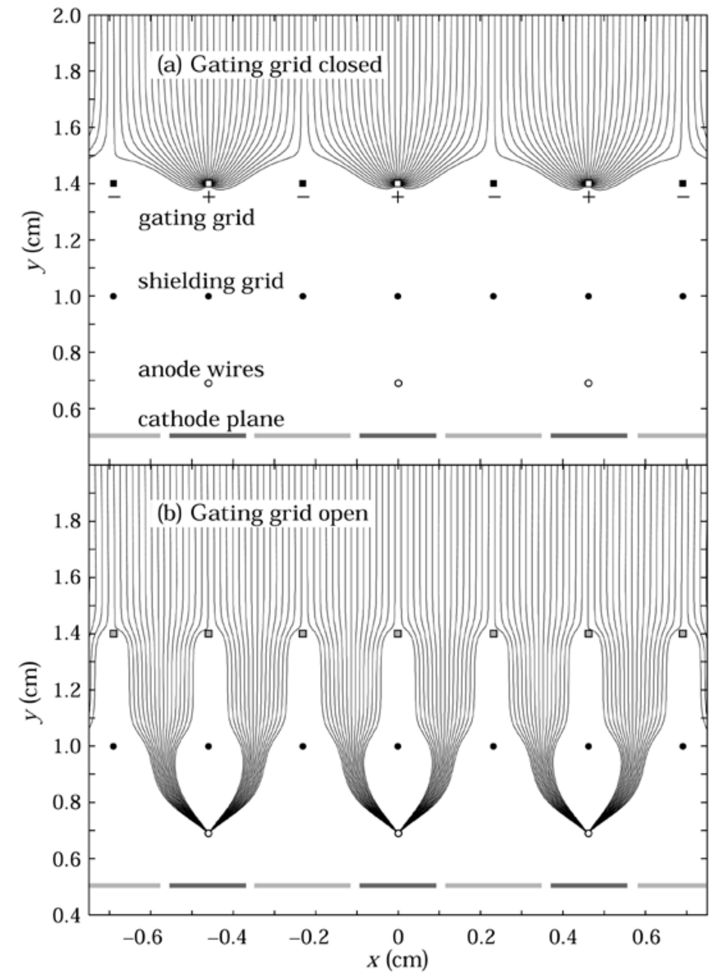
- Large acceptance
- Large active volume
- Low material budget
- **3D picture** of event
  - ⇨ simple pattern recognition
- Extremely high particle densities
  - ⇨ heavy ion experiments
- Good momentum resolution
- Particle identification

Limitations:

- E×B distortions close to anode
- E distortion by accumulation of space charge in drift volume
  - – ions from primary ionization
  - – backdrifting ions from amplification region



Gating necessary ⇨ slow

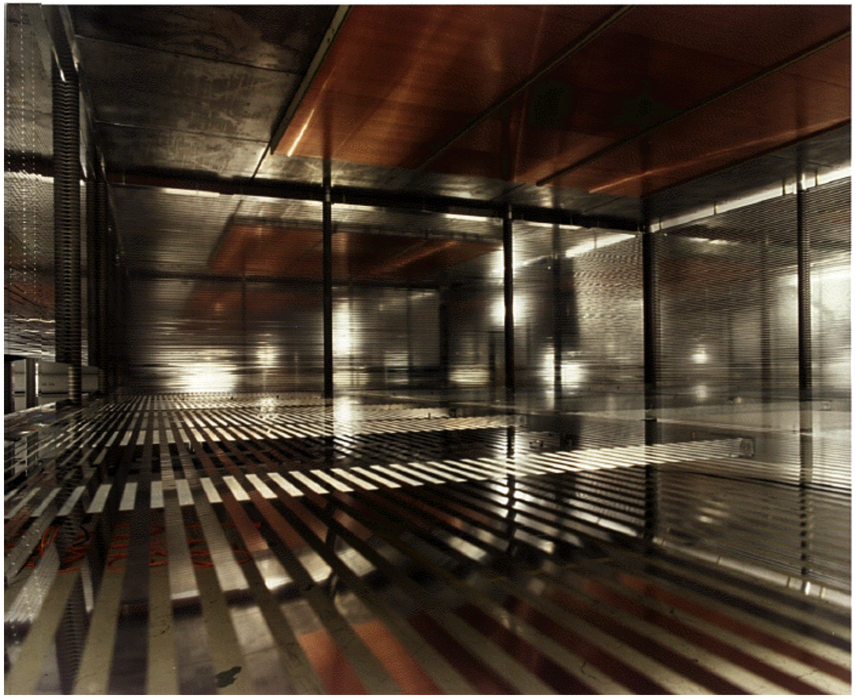


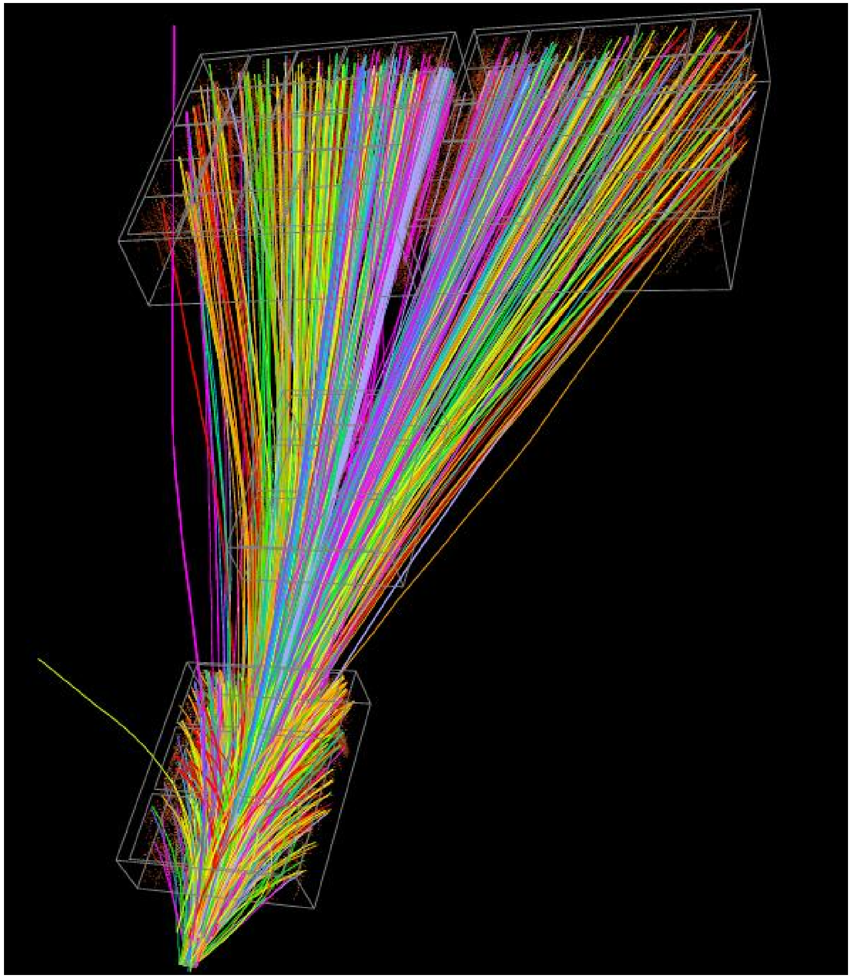
Limitations:

- E×B distortions close to anode
- E distortion by accumulation of space charge in drift volume
- Very good homogeneity of E, B fields: ~10^{-4}
- Calibration very demanding

Heavy ion experiment at SPS/CERN: study of strong interaction

- Track density ~0.6 particles / cm^2
- 4 TPCs
- VTPC-1/2: Ne/CO_2 (90/10)
- MTPC-L/R: $Ar/CH_4/CO_2$ (90/5/5)
- $\sigma_{dE/dx}$ ~ 3%

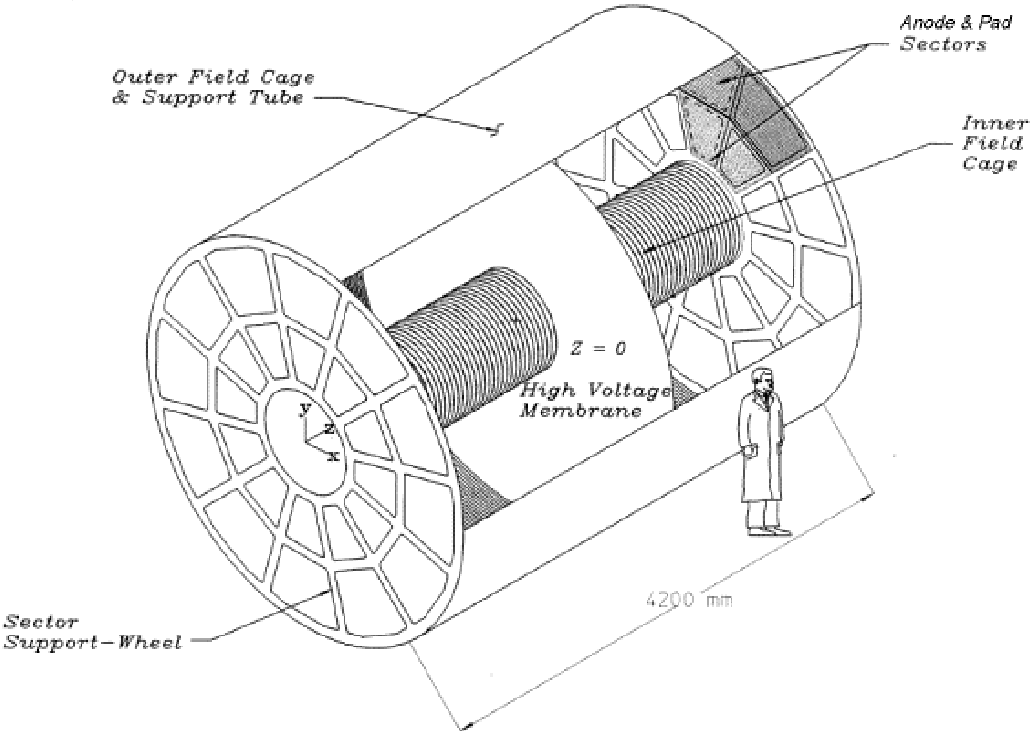


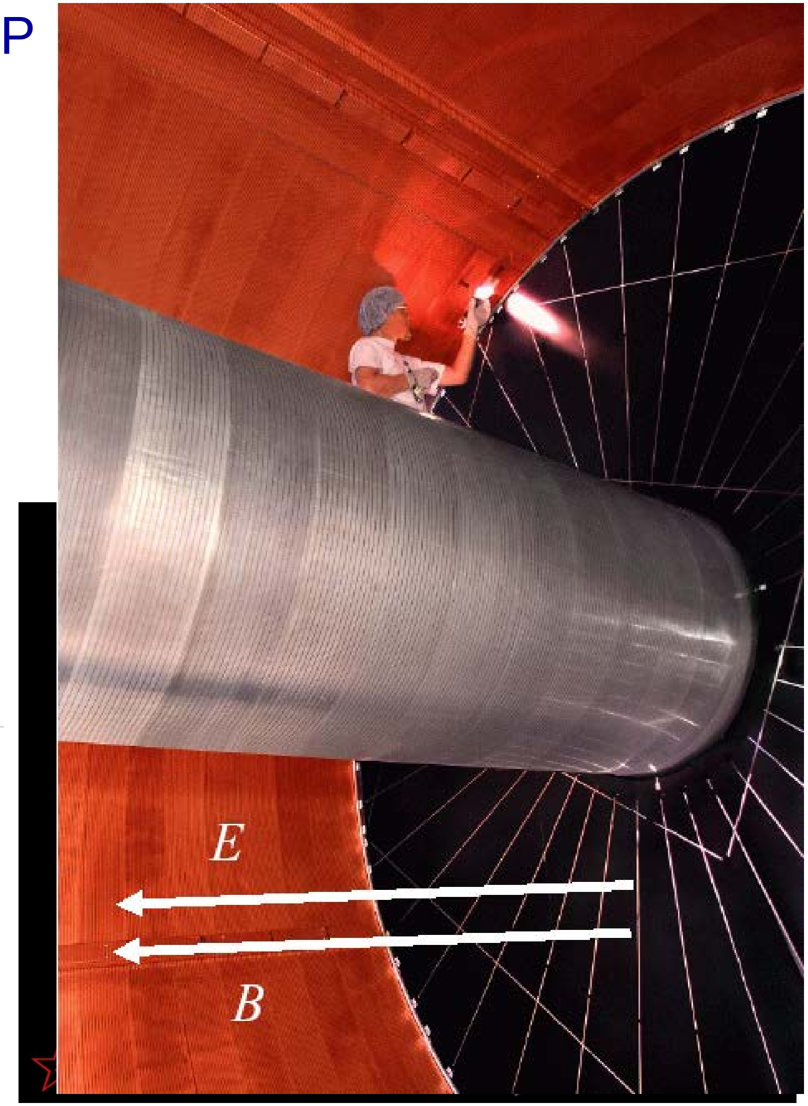


STAR TPC

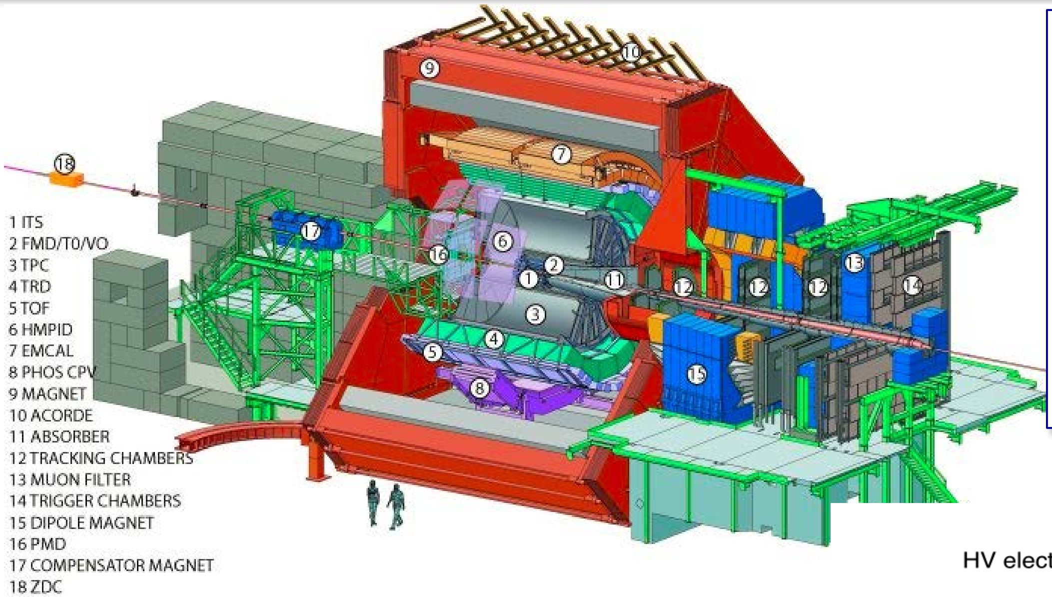
Heavy ion experiment at RHIC/BNL: QGP

- Au-Au collisions: $\sqrt{(s_{NN})}$=200 GeV
- 2000 tracks / event
- L = 4.2m, Φ = 4m
- MWPC, 136608 cathode pads



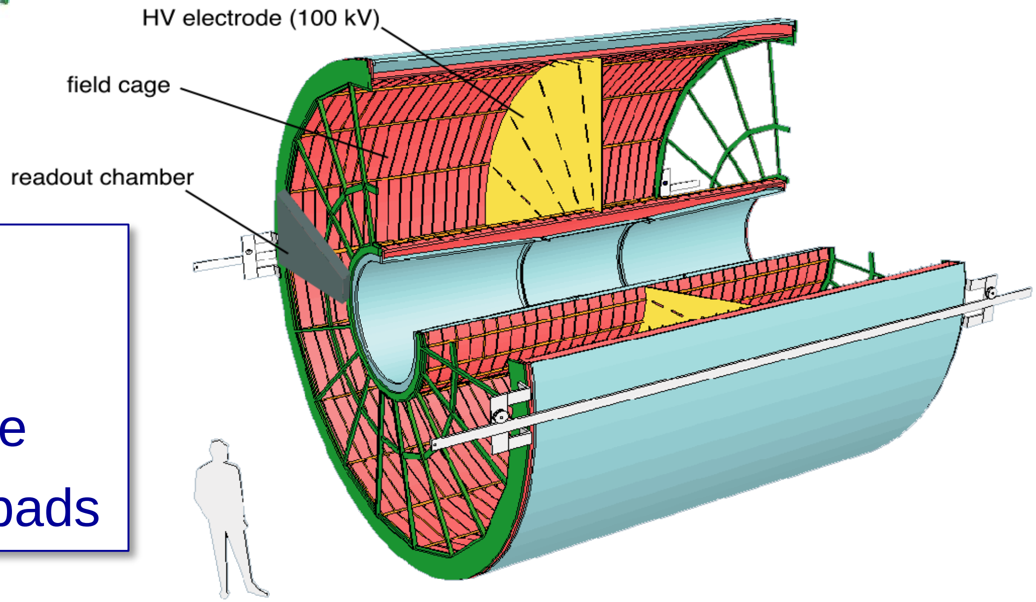


The ALICE Detector



Main tracking device: TPC

- $\sigma_p/p < 7\%$ at 10 GeV
- $-0.9 < \eta < 0.9$
- $\sigma_{dE/dx} = 5\%$ (159 clusters)
- Readout rate: 500 Hz (Pb-Pb)



Volume: ~ 90m^3

Gas: $Ne/CO_2(/N_2)$ (90/10/5)

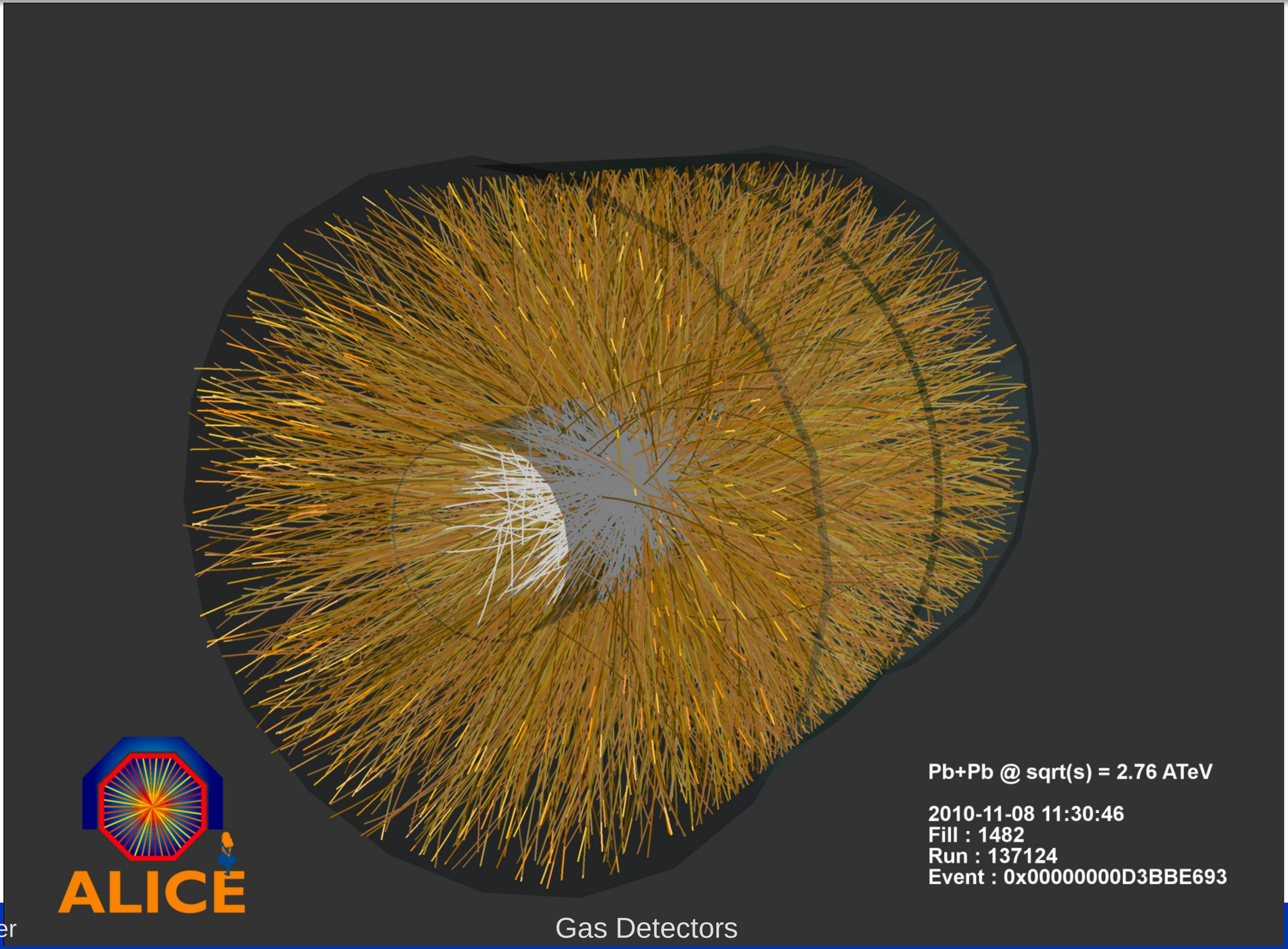
Drift voltage: 100kV, 94μs drift time

72 MWPCs with 557768 readout pads

Heavy ion experiment at LHC/CERN:

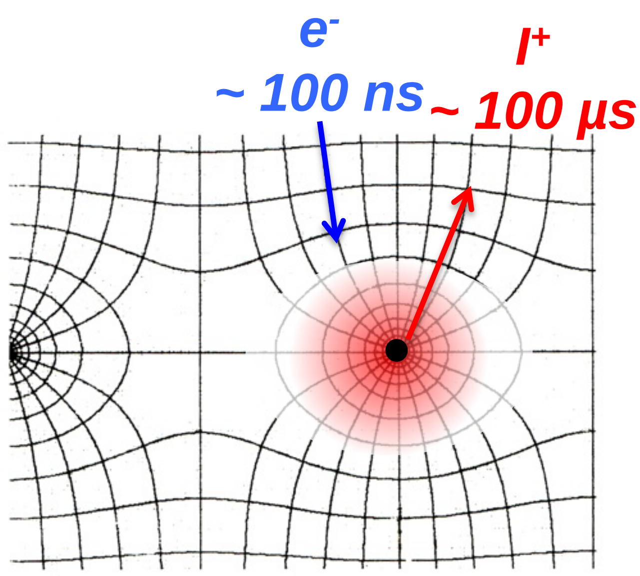
- p-p, Pb-Pb collisions
- L = 5.1m, Φ = 5.6m
- MWPC with 570132 cathode pads
- Ne/CO_2 (90/10)
- Drift field 400 V/cm

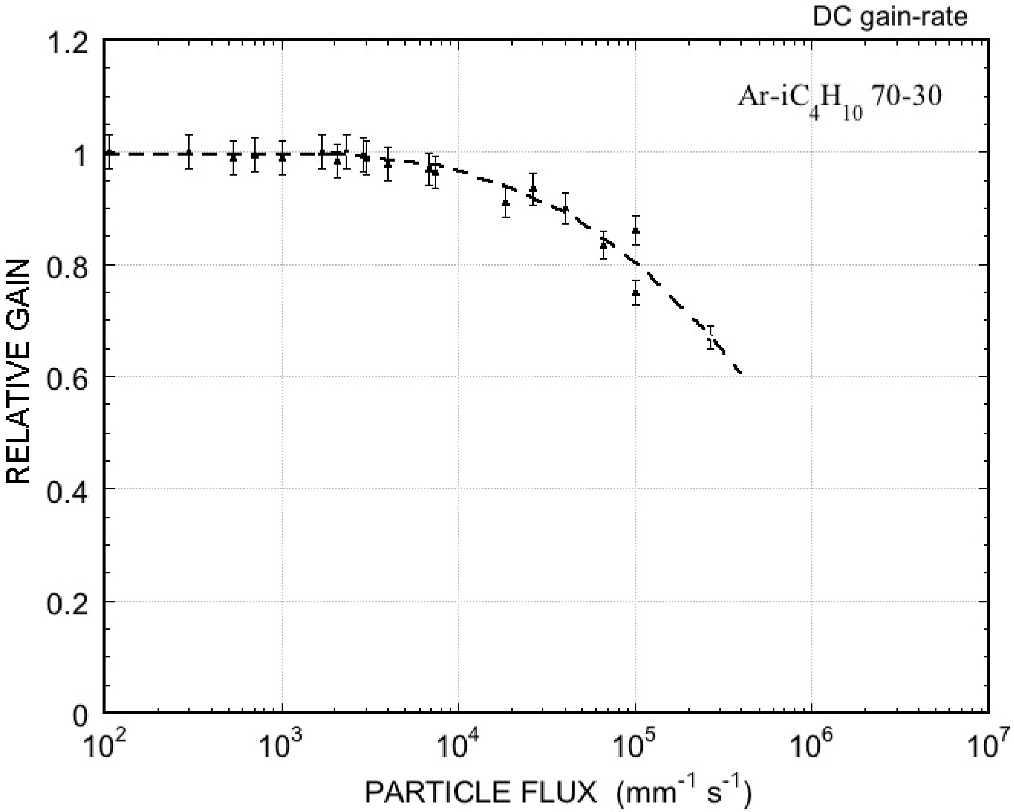
ALICE TPC


ALICE
Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

Limitations of Wire-based Detectors

- Localization accuracy: typ. 100-500 μm
- Volume / 2-track resolution: typ. 10×10×10 mm³ (signal induction on pads)
- Rate capability: limited by build-up of positive space-charge around anode





[A. Breskin et al., NIM 124, 189 (1974)]

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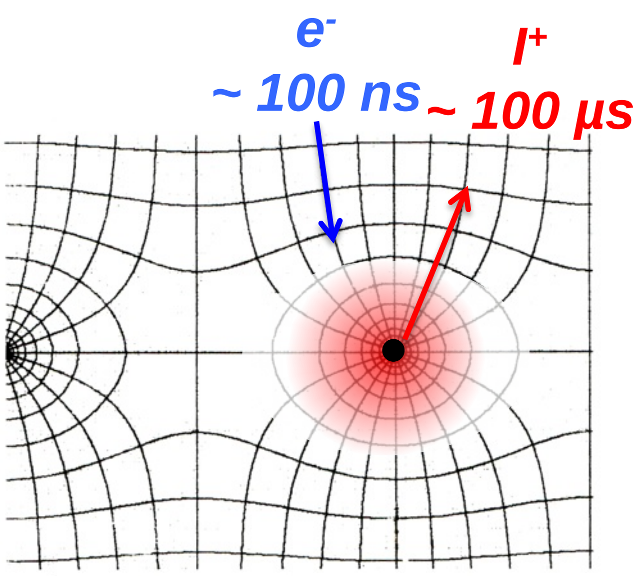

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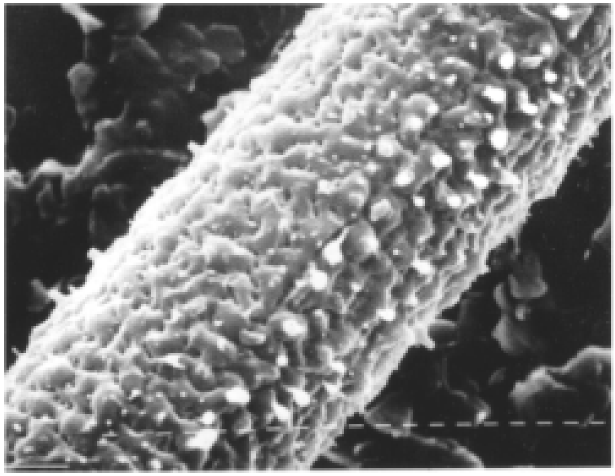
- Aging and discharge damage: polymerization of organic compounds



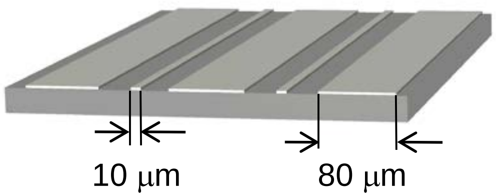
[O. Ullaland, LBL-21170, 107 (1986)]

⇨ Reduction of cell size by a factor of 10

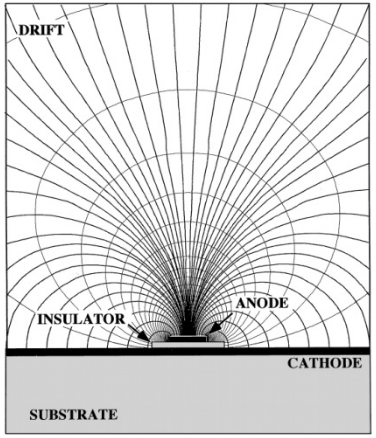
- Photolithography
- Etching
- Coating
- Wafer post-processing

6.3 Micropattern Gas Detectors

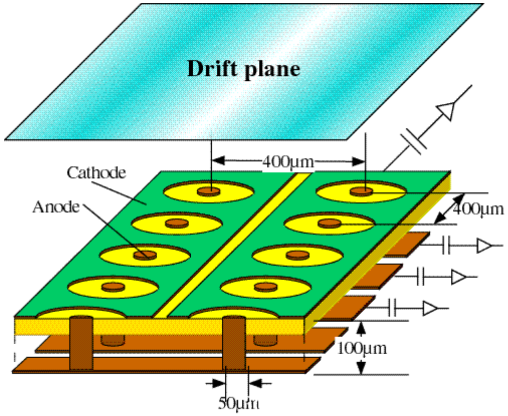
Microstrip Gas Chamber
[A. Oed, NIM A263, 351 (1988)]



Microgap Chamber (MGC)
[F. Angelini et al., NIM A335, 69 (1993)]

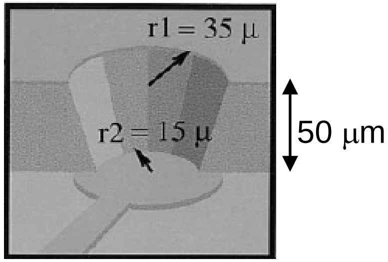


Microdot Chamber
[S.F. Biagi et al., NIM A361, 72 (1995)]

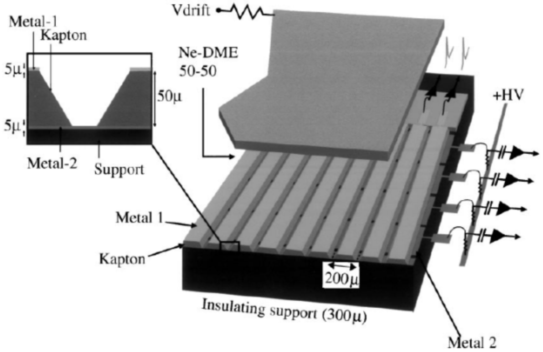


Compteur à Trous (CAT)
[F. Bartol et al., J. Phys. III 6, 337 (1996)]

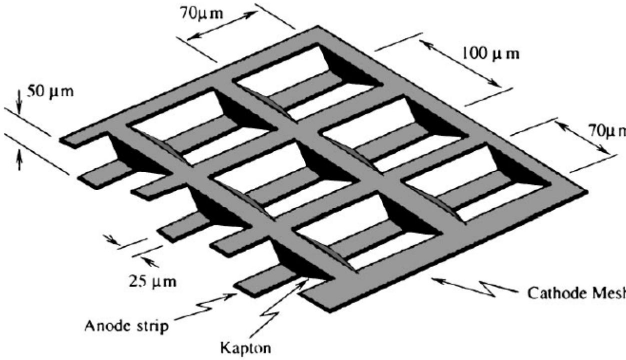
WELL Detector (μCAT)
[R. Bellazzini et al., NIM A423, 125 (1999)]



Micro Groove Counter
[Bellazzini et al., NIM A424, 444 (1999)]

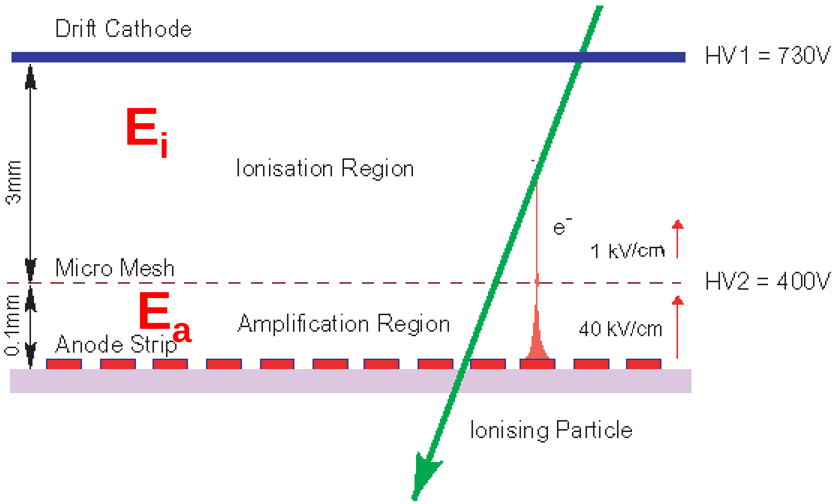


Micro Wire Detector
[B. Adeva et al., NIM A435, 402 (1999)]



and many more...

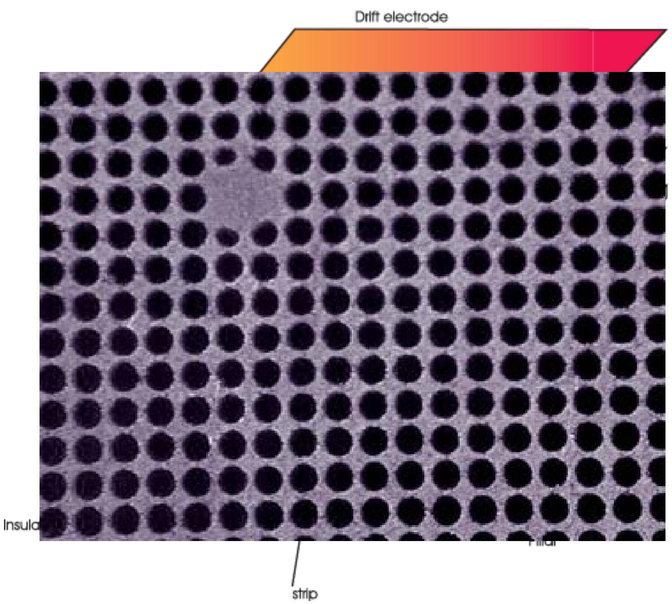
Micromegas

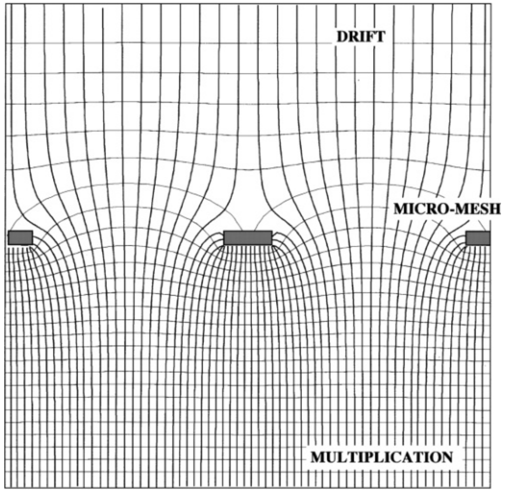


Micromesh Gaseous Structure

[I. Giomataris et al., NIM A376, 29 (1996)]

- Thin gap parallel plate structure
- Fine metal grid (Ni, Cu) separates conversion (~ 3 mm) and amplification gap (50-100 μm)
- Very asymmetric field configuration: 1 kV/cm vs. 50 kV/cm





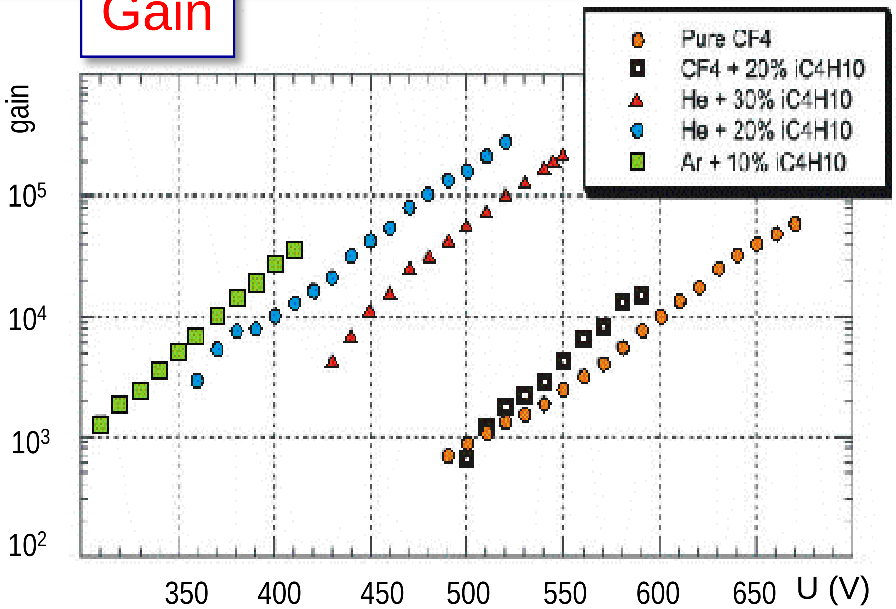
➡ Fast collection of ions (~ 100 ns)

➡ Saturation of Townsend coefficient (mechanical tolerances)

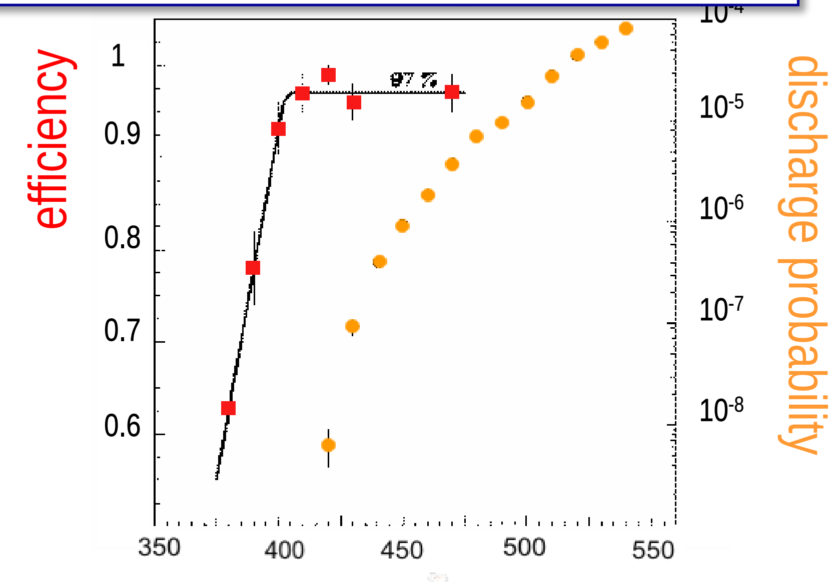
➡ good energy resolution

Micromegas Performance

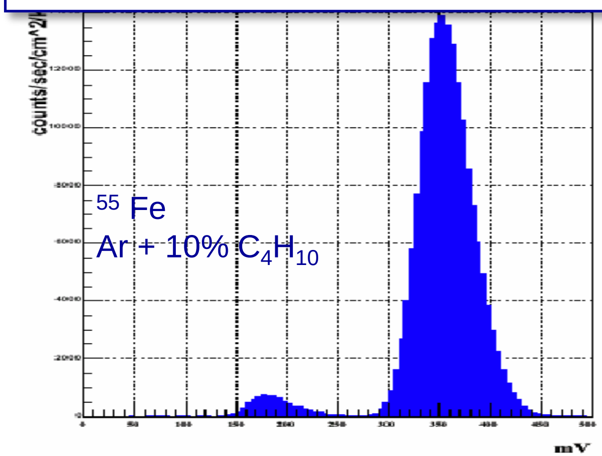
Gain



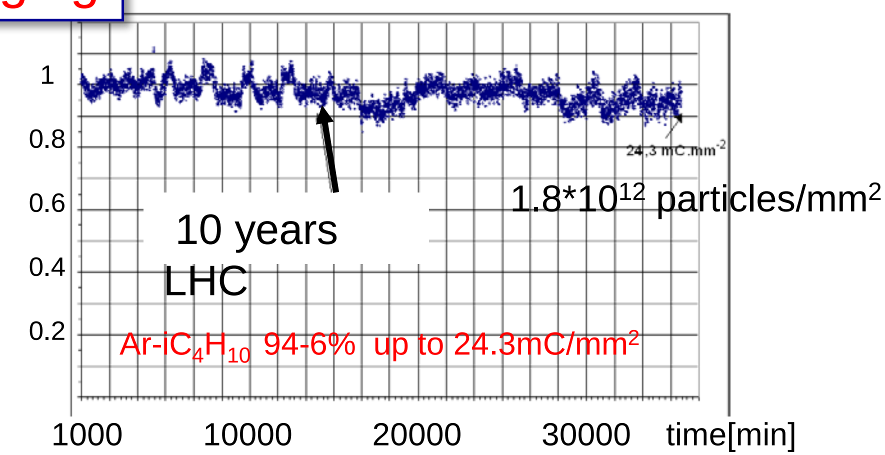
Efficiency & discharge probability



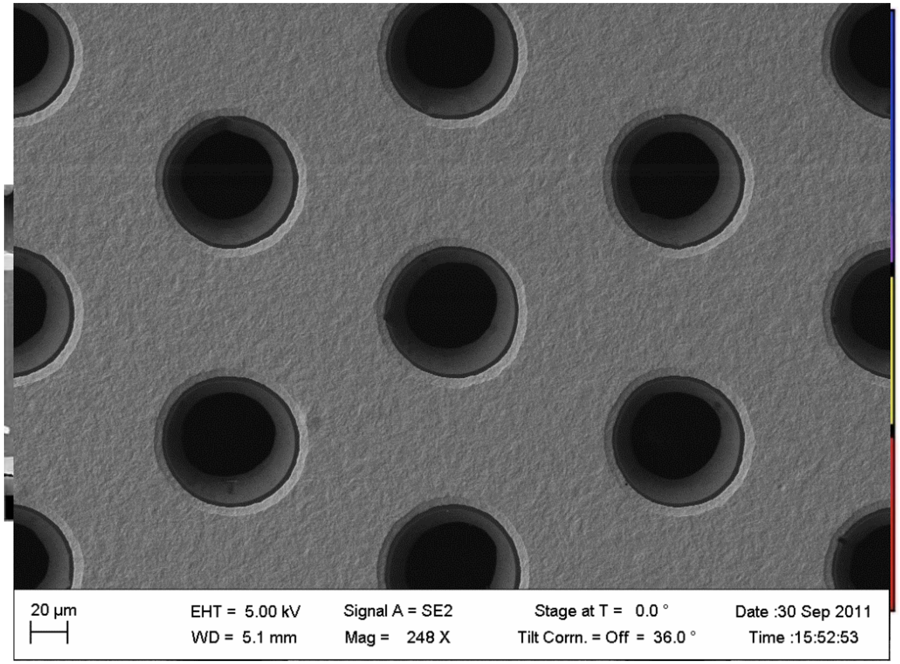
Energy resolution ~ 10%

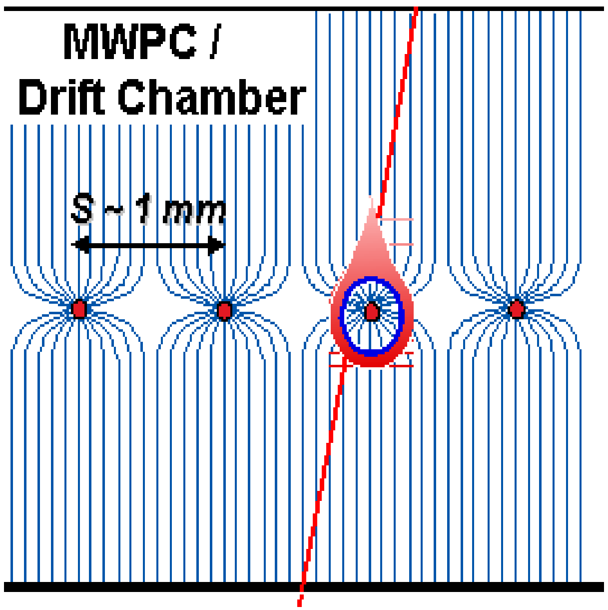


Aging



GEM

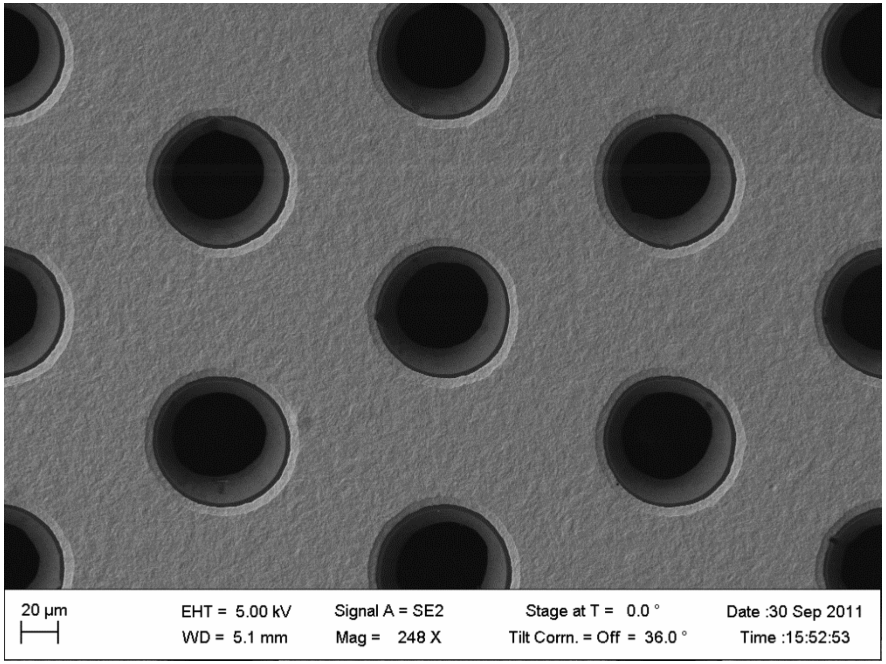




- GEM: **G**as **E**lectron **M**ultiplier

  [F. Sauli, NIM A386, 531 (1997)]
- Thin polyimide foil, typ. 50 μm
- Cu-clad on both sides, typ. 5 μm
- Photolithography: ~ 10^4 holes/cm^2
- Granularity 10×higher than MWPC

- ΔU=300-500 V
  - ⇨ high E-field: ~50 kV/cm
  - ⇨ avalanche multiplication



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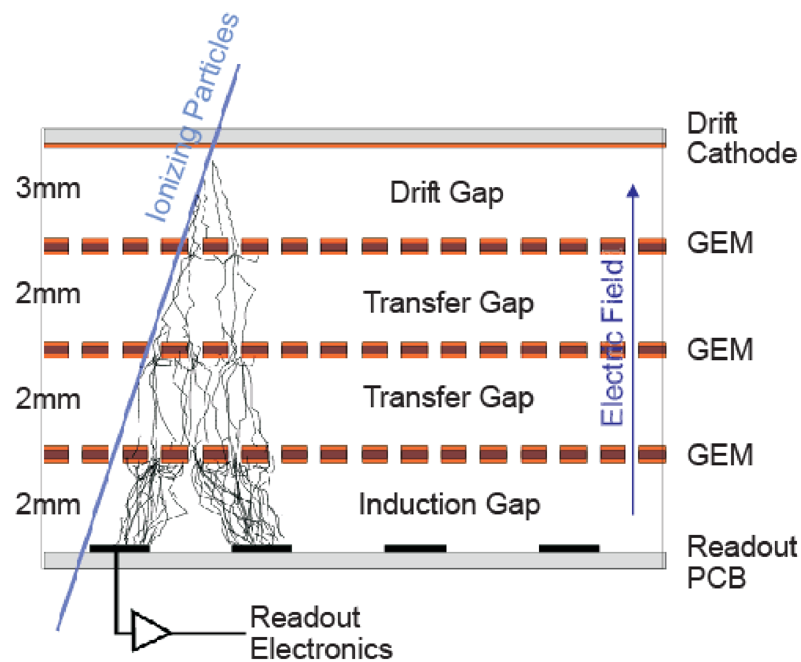
- Granularity 10×higher than MWPC

Triple GEM amplification

➡ higher gain at lower GEM voltages
[S. Bachmann, B. Ketzer et al., NIM A479, 294 (2001)]

➡ discharge prevention
[B. Ketzer et al., IEEE Trans. Nucl. Sci. 48, 1065 (2001)]

➡ no aging up to 7 mC/mm^2
[C. Altunbas, B. Ketzer et al., NIM A515, 249 (2003)]



GEM Performance

Spatial resolution: 400 μm strips

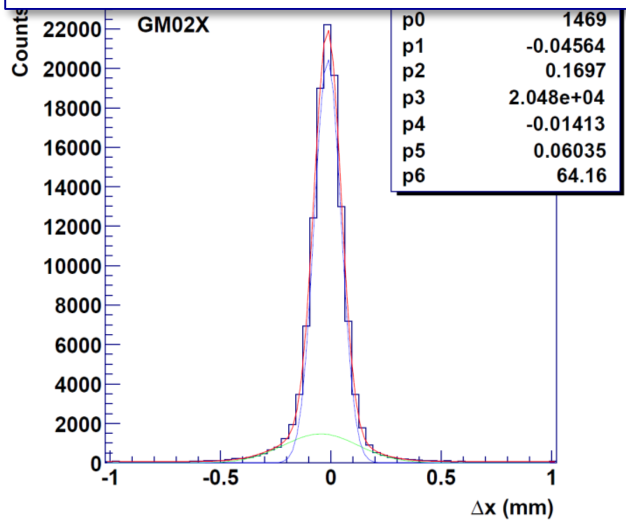
- low intensity: 50 μm
- $4 \cdot 10^7 s^{-1}$ μ: 70 μm

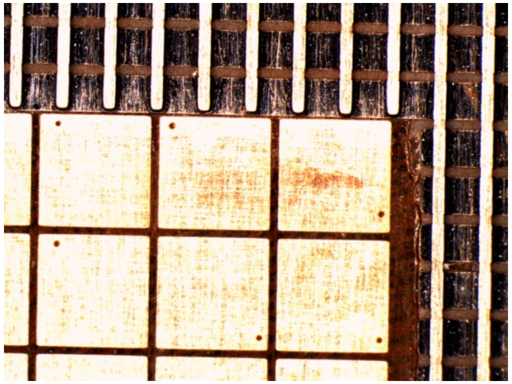
[B. Ketzer et al., NIM A535, 314 (2004)]

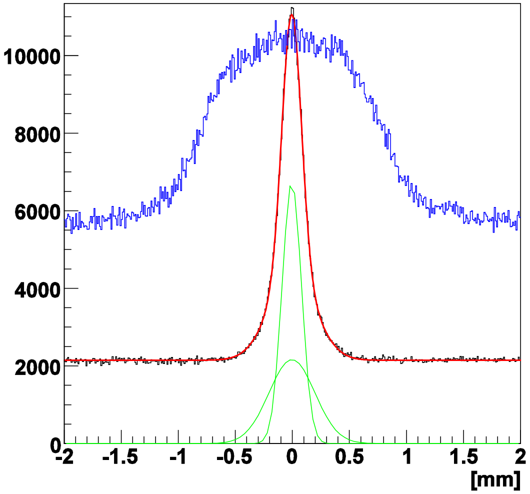
Spatial resolution: $1\ \mathrm{mm}^2$ pixels

- $10^5\ \mathrm{mm}^{-2}\mathrm{s}^{-1}$: $135\ \mu m$

[B. Ketzer et al., IEEE NSS 2007, N12-5 (2007)]

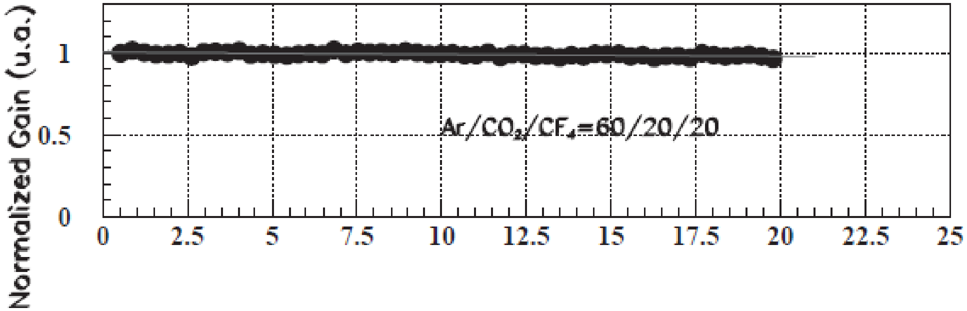






Aging: [M Alfonsi.et al., NIM A518, 106 (2004)]

- Ok up to 200 mC/mm²



New Challenges

Larger active areas
- Bulk Micromegas
- Single-mask GEMs

Higher rates
- Pixel readout
- Ion backflow suppression

Aging, discharge protection
- Materials
- Multi-stage amplification
- Segmentation
- Resistive coating

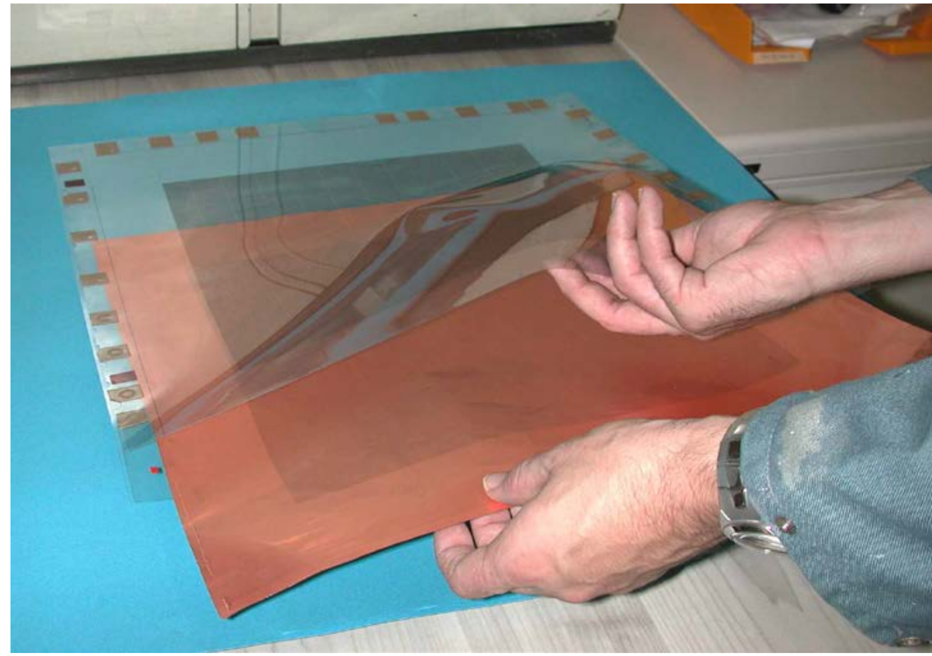
Higher resolutions
- μPixel
- InGrid

Special shapes
- cylindrical
- spherical

GEM Manufacturing

Limitations of double-mask technique

1. Image transfer using two film masks (photoplotted polyester)
   ⇨ Difficult above 400×400 mm^2 due to
   - Film accuracy
   - Temperature and humidity variations
   - Alignment of masks
2. Raw material:
   - rolls of 100 m × 0.457 m
   - new: 0.6 m width



GEM Single-Mask Process

Photoresist deposition on base material

Photoresist hole patterning (single mask)

Top copper etching

Resist stripping

Polyimide anisotropic etching

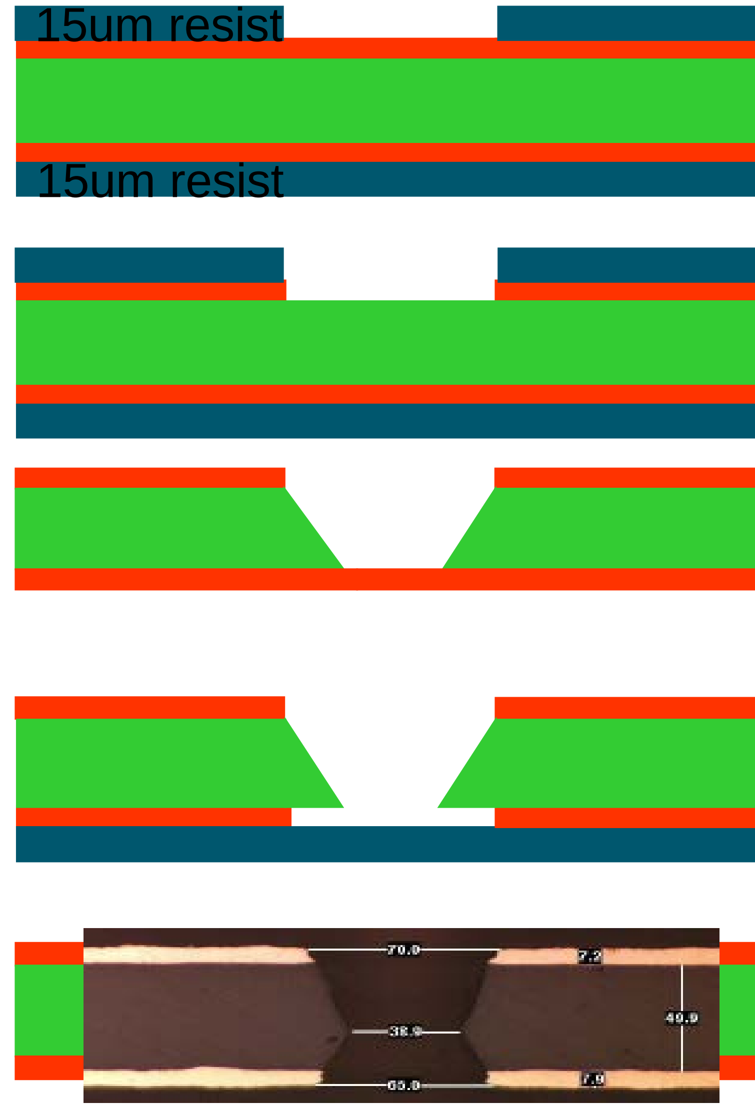
Bottom resist protection deposition

Bottom copper etching

Top copper protected by galvanic connection

Resist stripping

Soft polyimide etching

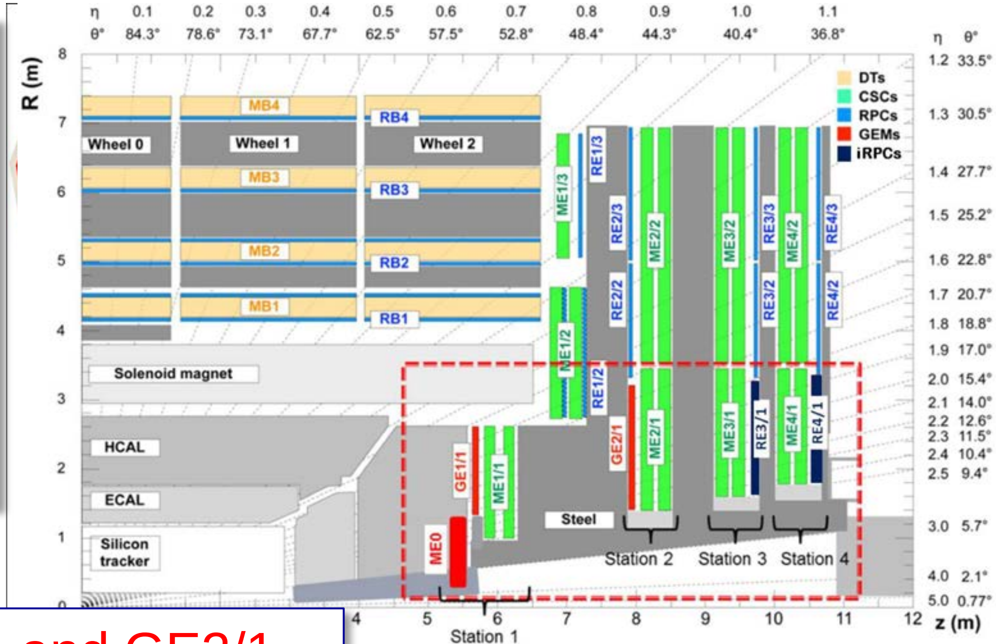


[M. Villa et al., arXiv 1007.1131v1]

CMS Muon Chambers

Present Muon System:

- Drift Tubes
- CSC
- RPC (triggering)
  - ⇨coverage for $|\eta|<1.6$
- coverage for $|\eta|>1.6$: CSC



HL-LHC: Requirements for GE1/1 and GE2/1

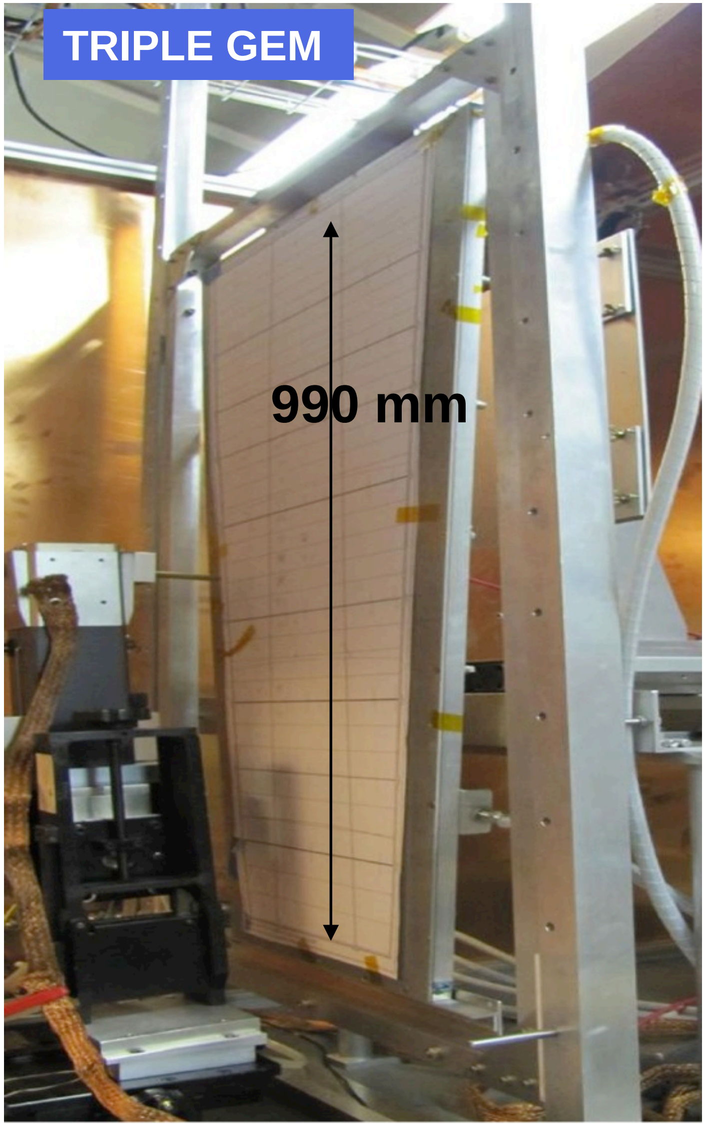
- $\Lambda \sim 10^{34\text{-}35}$ cm^{-2} s^{-1}
- Flux: several 10 kHz/cm^2
- Total integrated charge: several 10 C/cm^2
- Triggering capability

Upgrade project: **GE1/1**

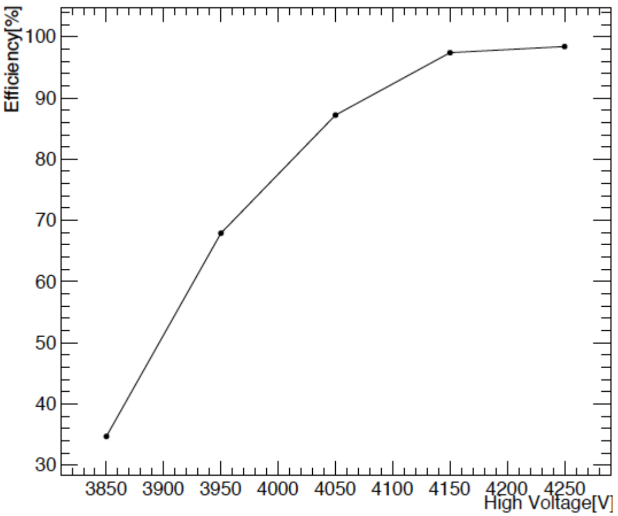
- triple GEM
- 990 × (220 - 455) mm^2

[D. Abbaneo et al., RD51-Note-2010-005-1]

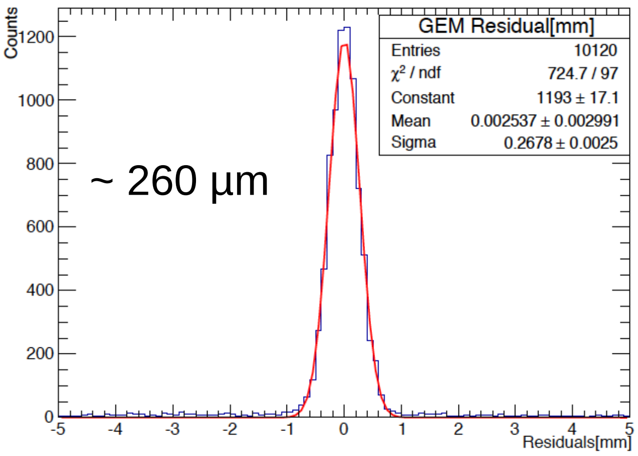
CMS Muon Chambers



EFFICIENCY



POSITION ACCURACY



D. Abbaneo et al, JINST 9(2014)C01053

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- Single-mask GEMs

Higher rates

- Pixel readout
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Aging, discharge protection

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- Multi-stage amplification
- Segmentation
- Resistive coating

Higher resolutions

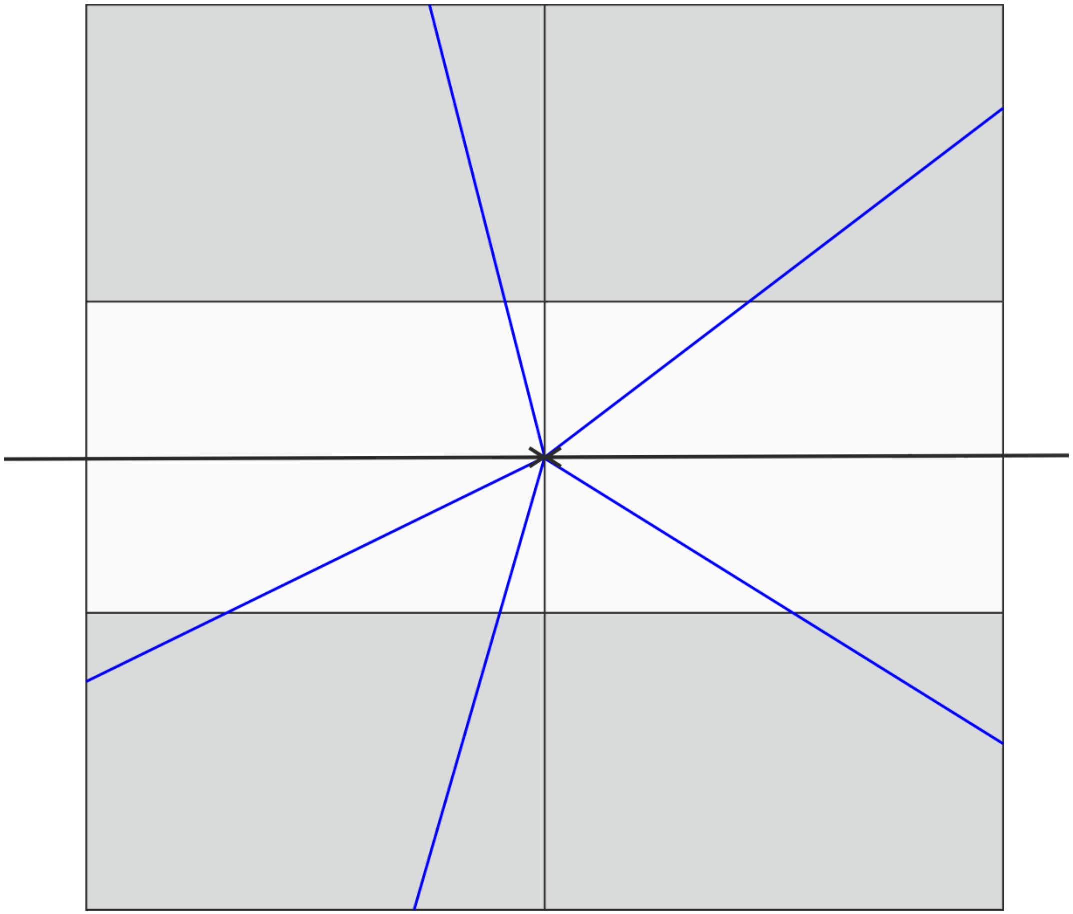
- µPixel
- InGrid

Special shapes

- cylindrical
- spherical

Operation at High Rates

- **High rates:** drift time > 1 / (event rate) ➪ overlapping events



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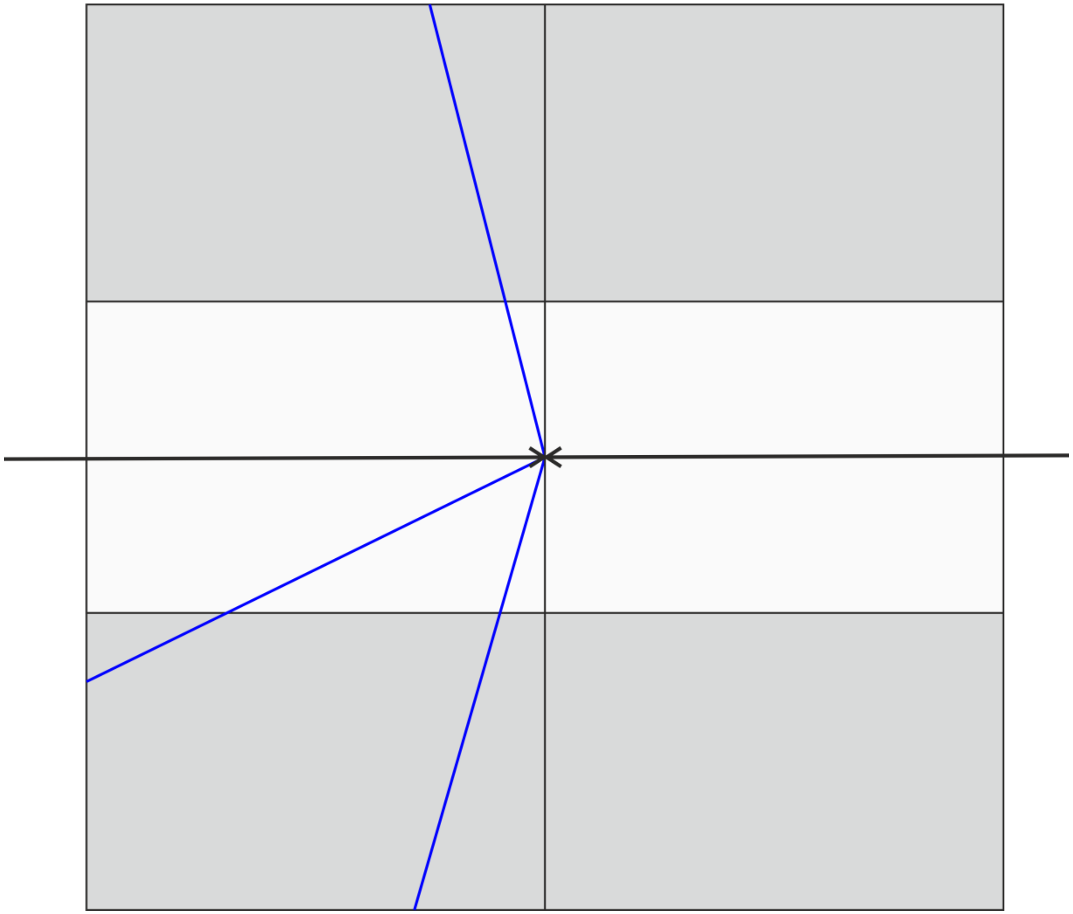

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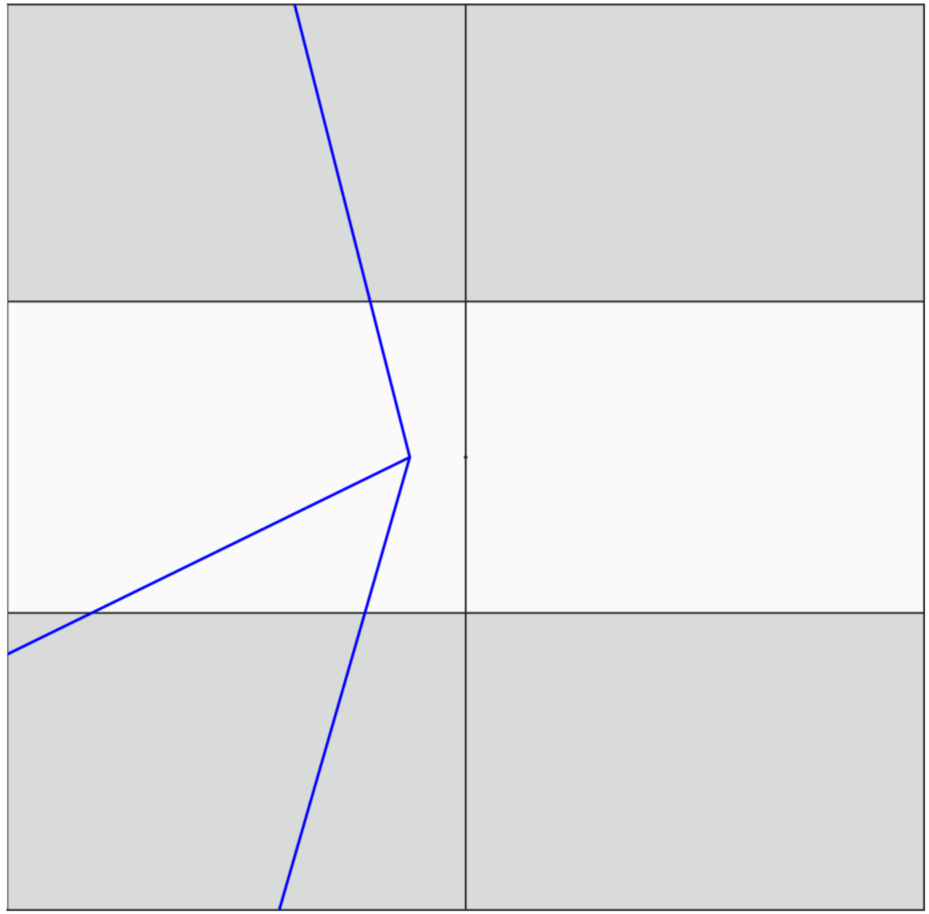

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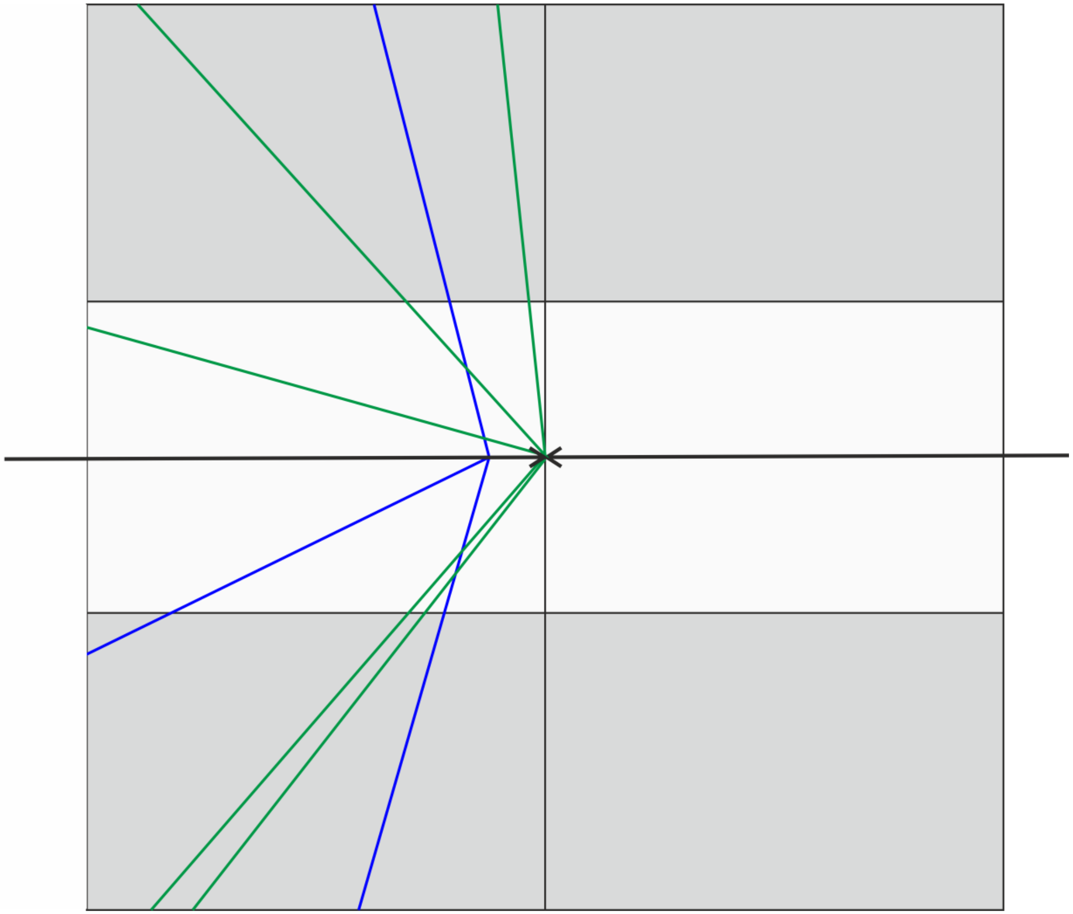

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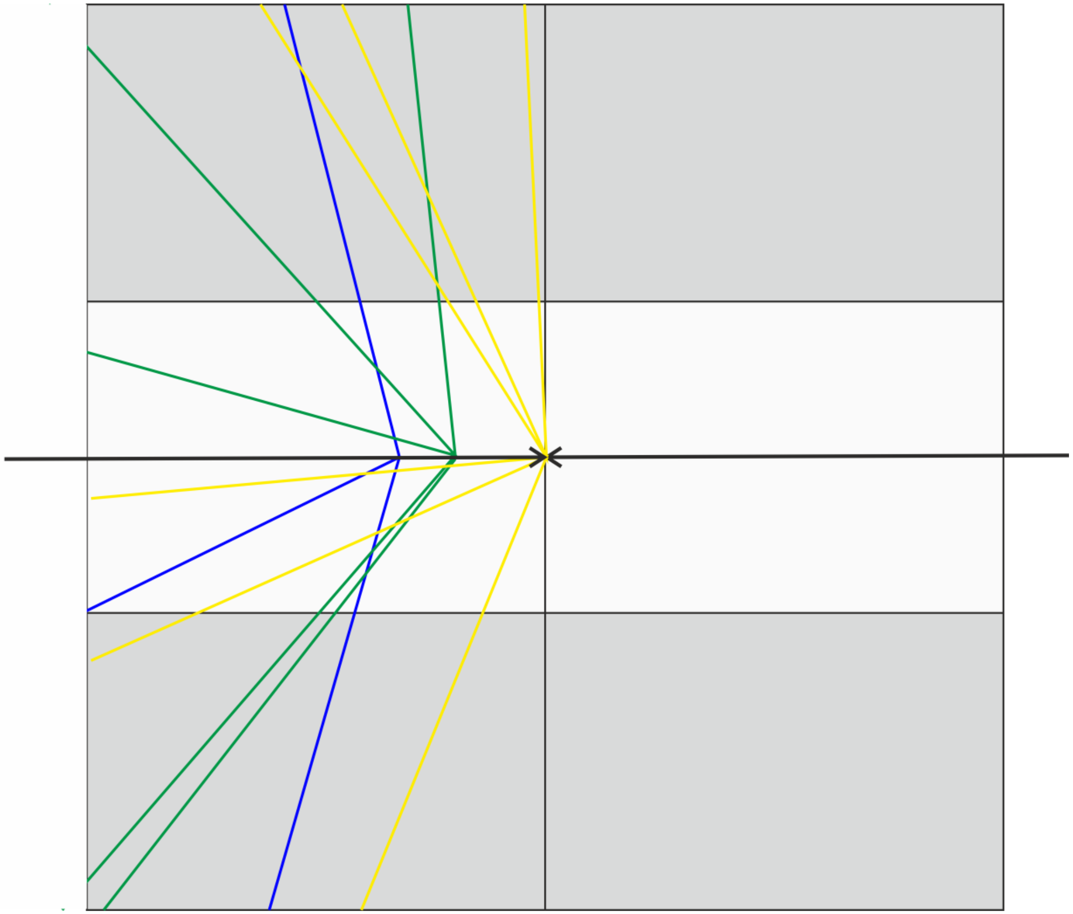

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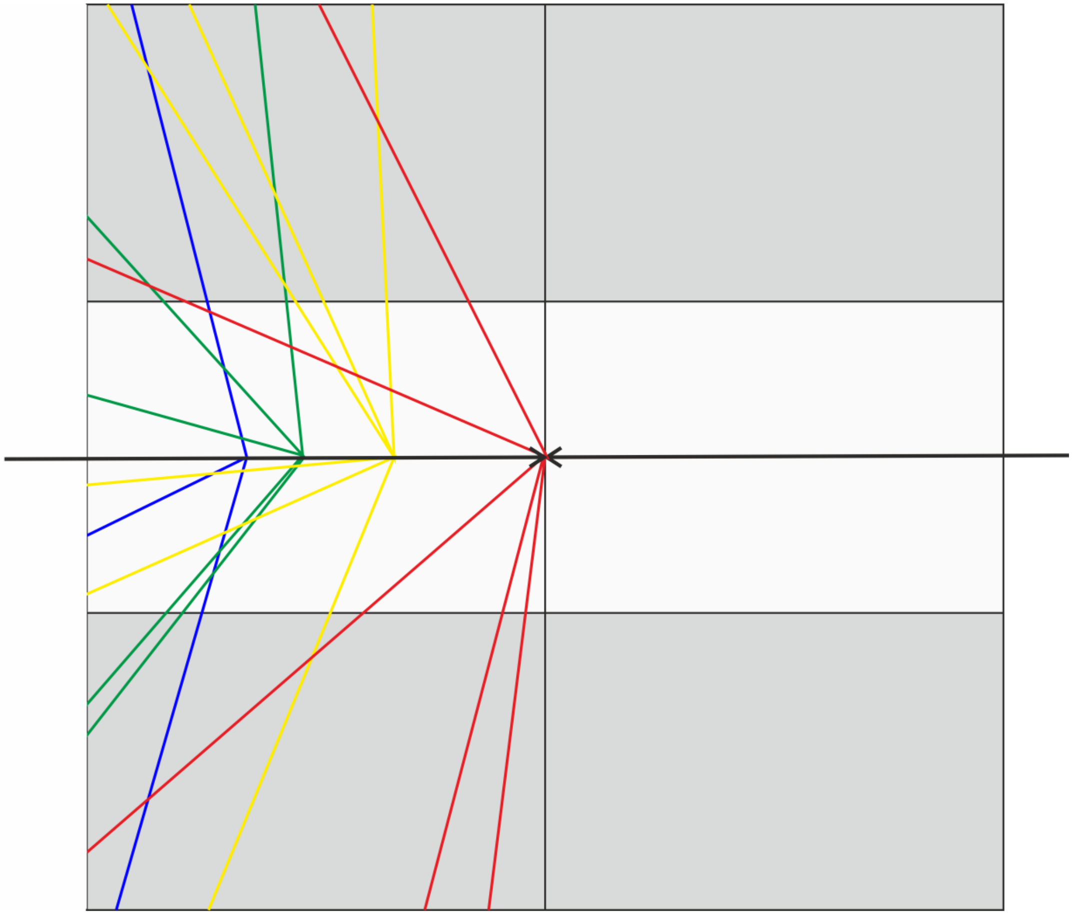

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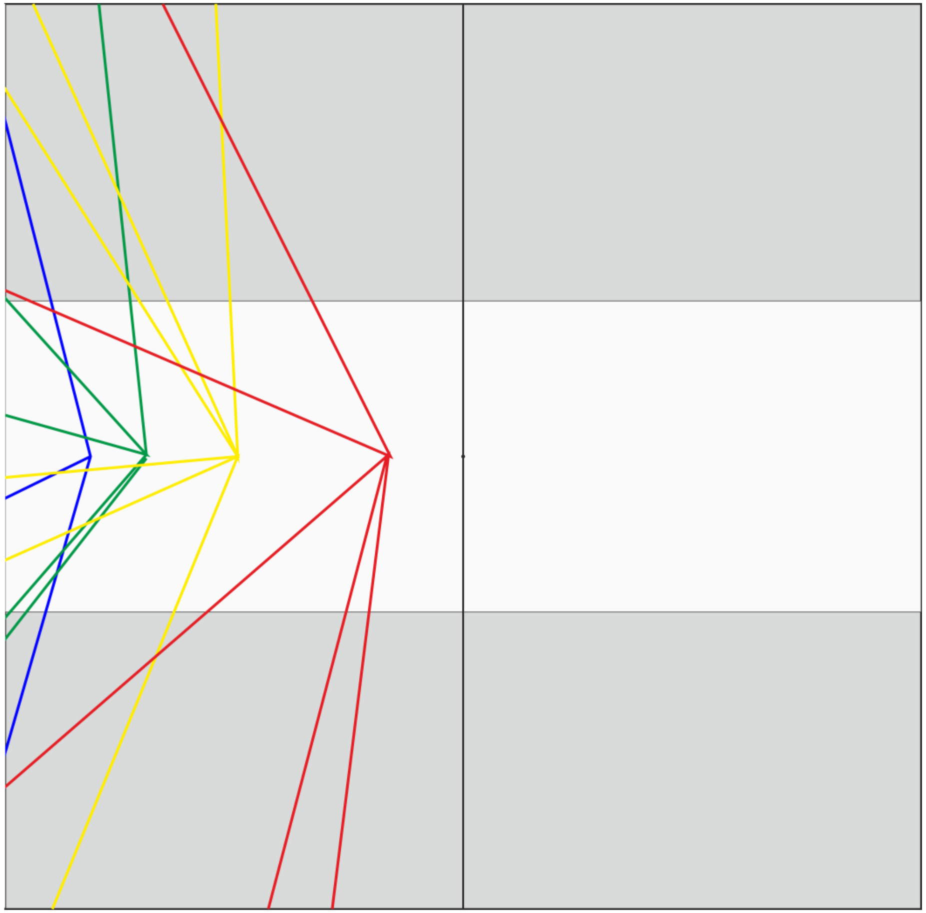
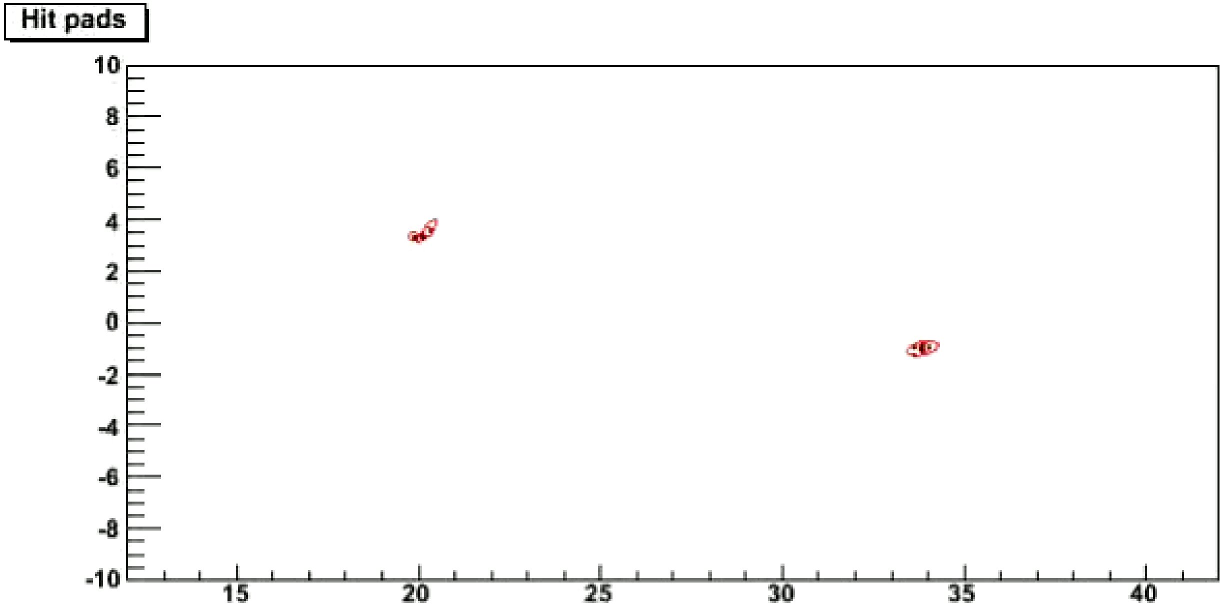


Operation at High Rates

- **High rates:** drift time > 1 / (event rate) ➪ overlapping events
- **Goal:** operate TPC continuously
  - ➪ no gating
  - ➪ analog event pipeline
  - ➪ **3D "Movie"**



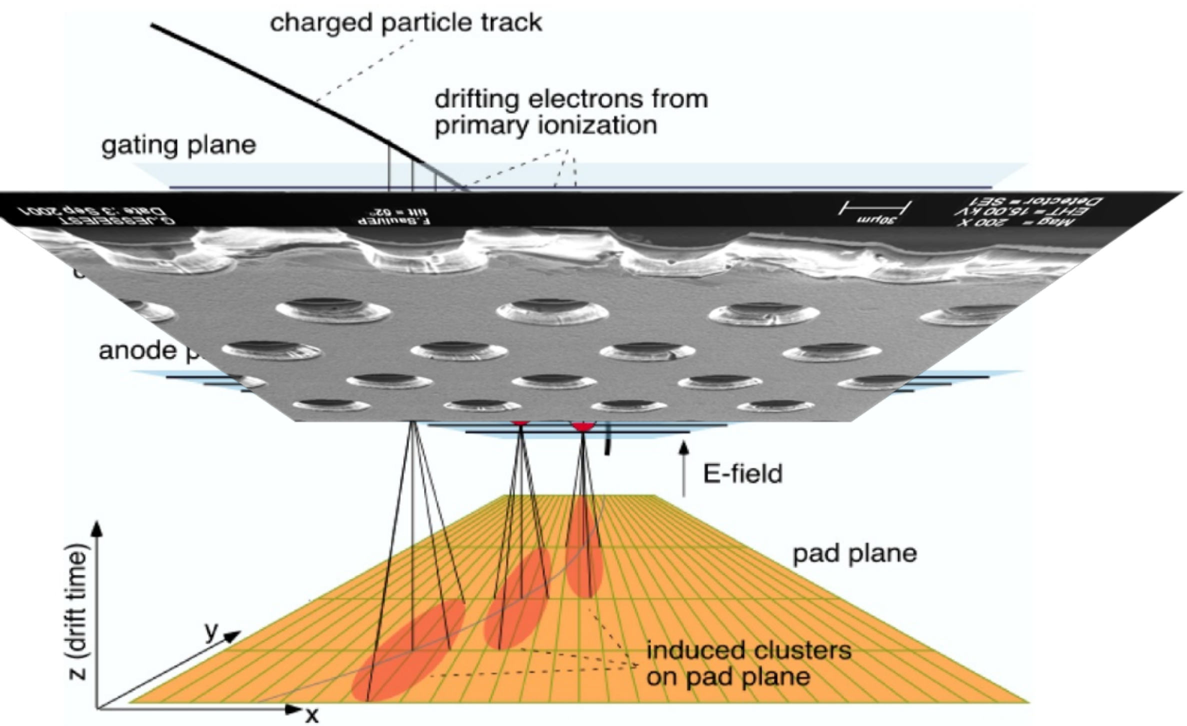
[S. Neubert, TUM]

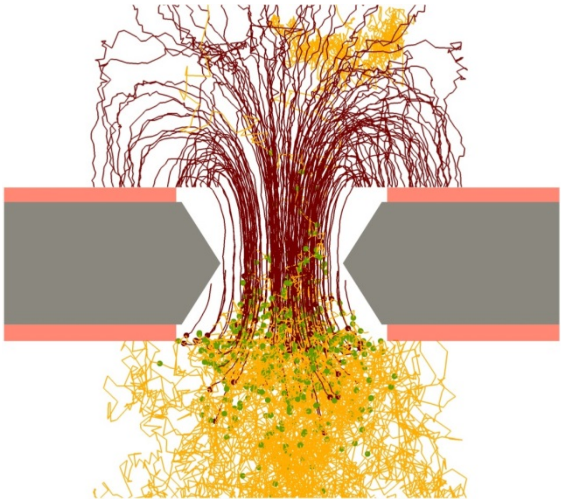
High-rate TPC

Gas Electron Multiplier TPC

Combination of GEM and Drift Chamber: continuous 3-D tracking device

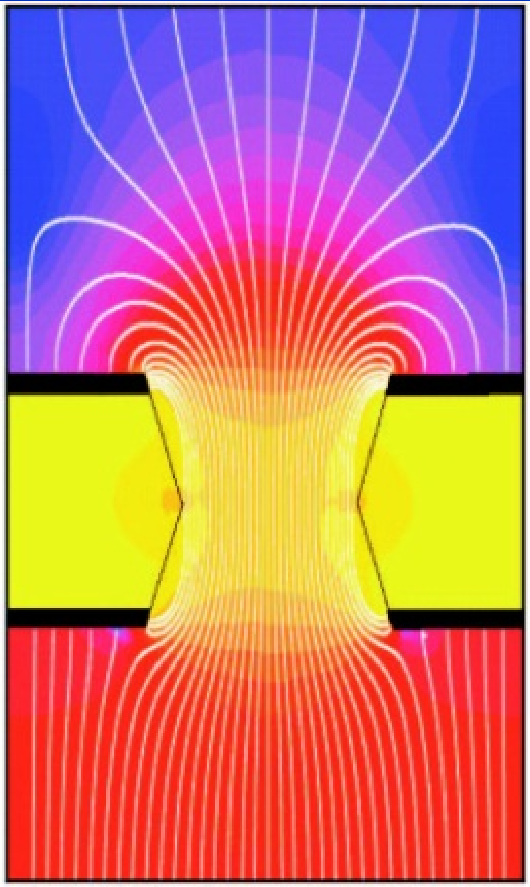
- long drift path (~m) in gas-filled volume ⇨ z coordinate
- GEMs + pads perpendicular to drift path ⇨ x,y coordinates

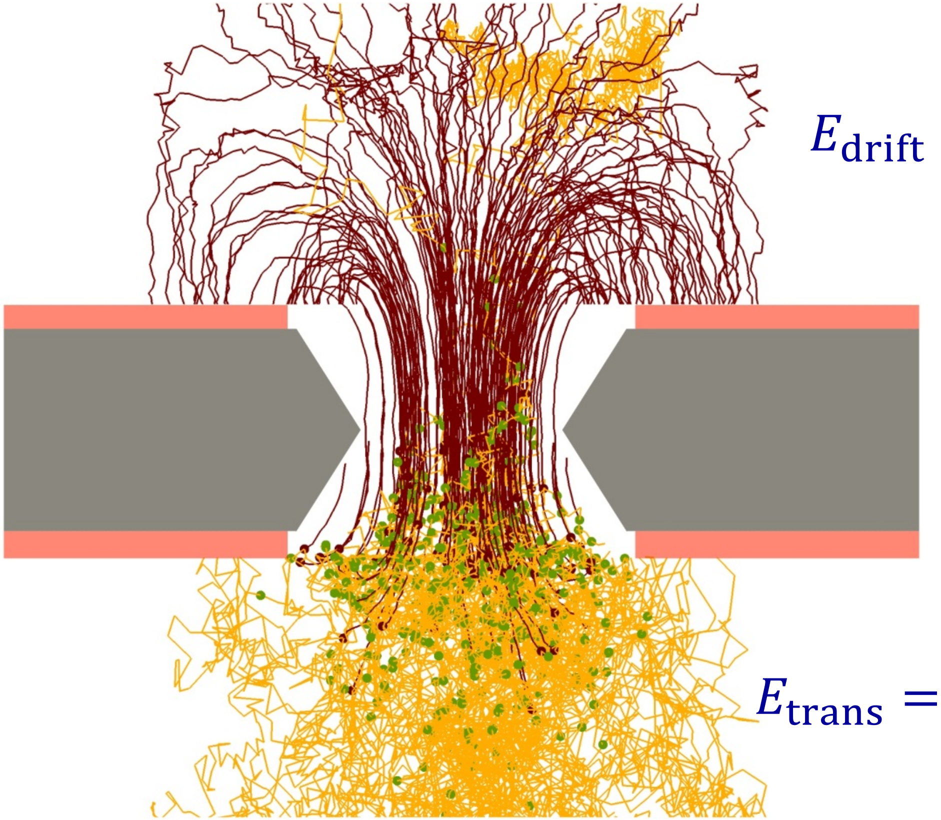




[B. Ketzer, NIM A 732, 237 (2013)]

Ion Backflow Suppression in GEM





Low ion density in drift region requires

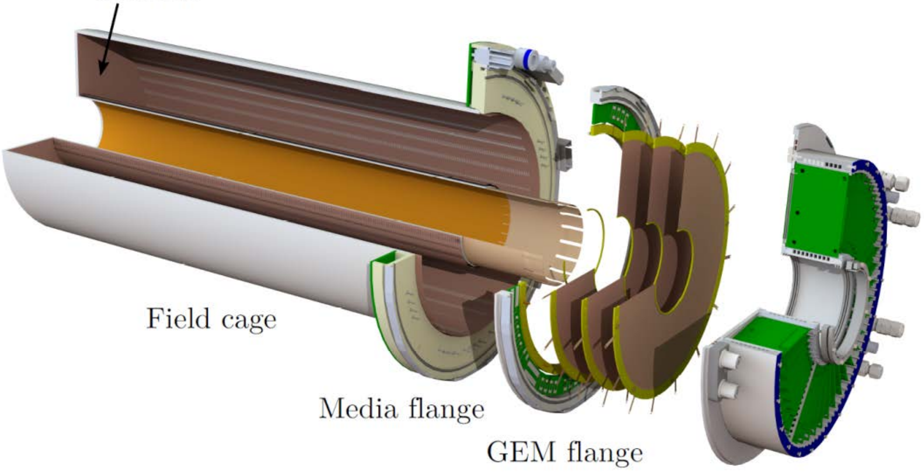
- low primary ionization
- low gain
- low ion backflow

$$G_{\mathrm{eff}} = \varepsilon_{\mathrm{coll}} G_{\mathrm{abs}} \varepsilon_{\mathrm{extr}}$$

$$n_{\mathrm{tot}} = n_{\mathrm{ion}} \cdot IB \cdot G_{\mathrm{eff}}$$

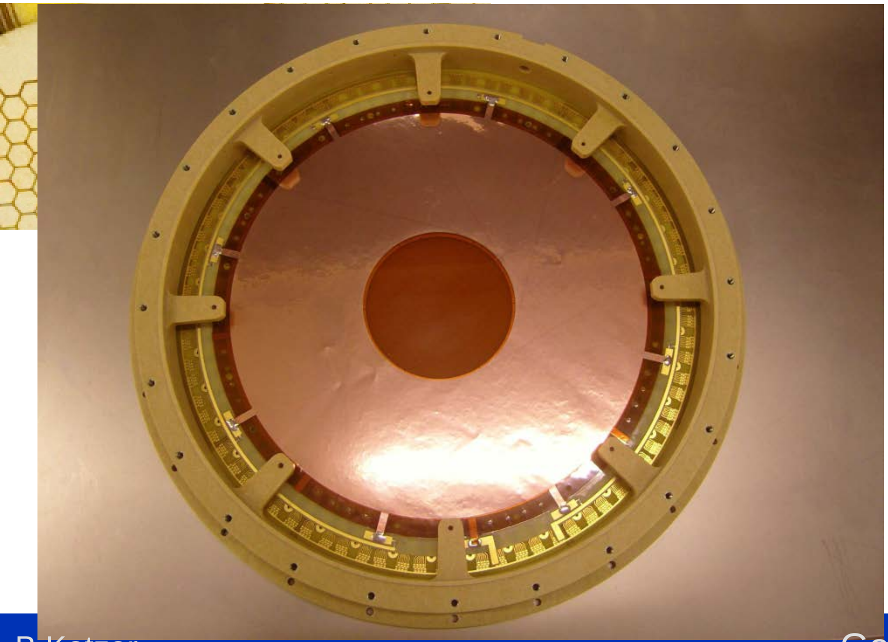
$$\varepsilon = IB \cdot G_{\mathrm{eff}} - 1$$

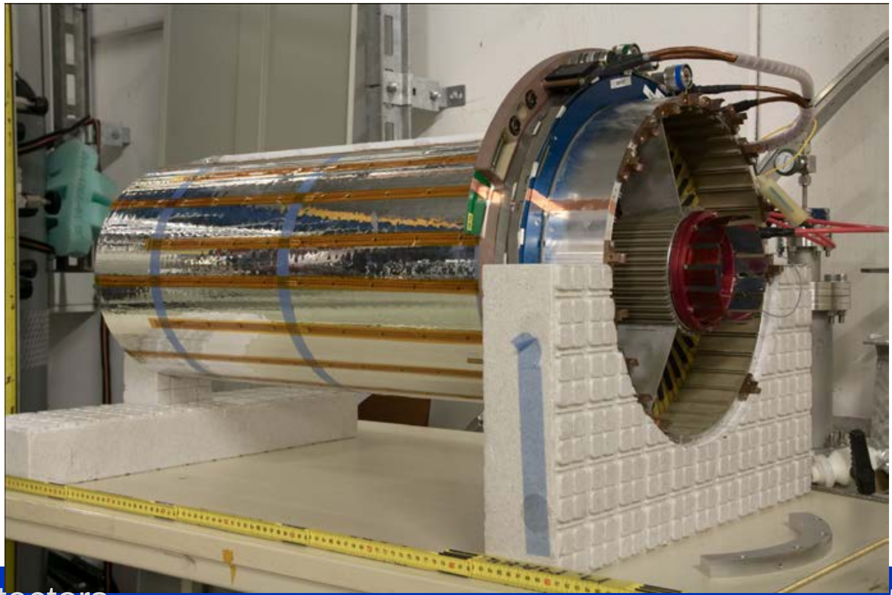
A Large GEM-TPC



- Light-weight field cage
- Drift length 725 mm
- Ø 105-300 mm
- Triple GEM amplification
- 10254 ch., AFTER ASIC
- Gas: Ar (Ne)/CO_2 (90/10)

[M. Ball et al., arXiv1207.0013, 2012]





Field Cage

Field cage:

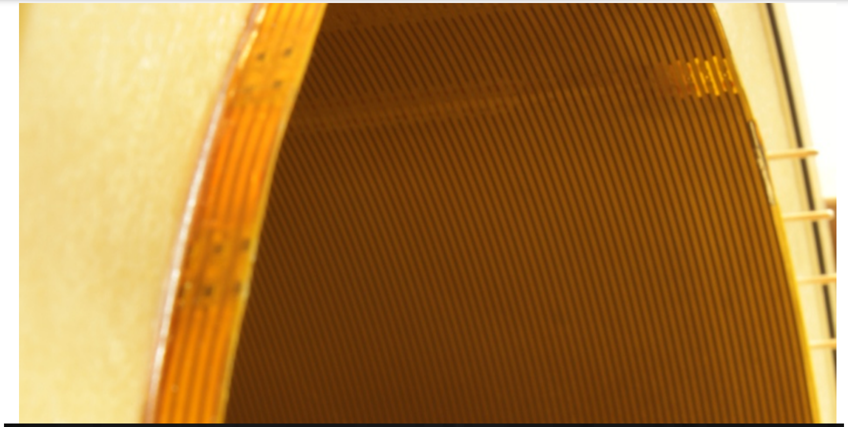
- Total length: 725 mm
- Kapton / Rohacell 4 mm
- Strip foil: 2+1 mm, double-sided
- Outer: Cu strips on FR4 (2 pc.)
- Inner: Cu strips on Kapton
- 4 rows of 4M2 resistors
- Al Mylar shielding
- Gas exhaust lines

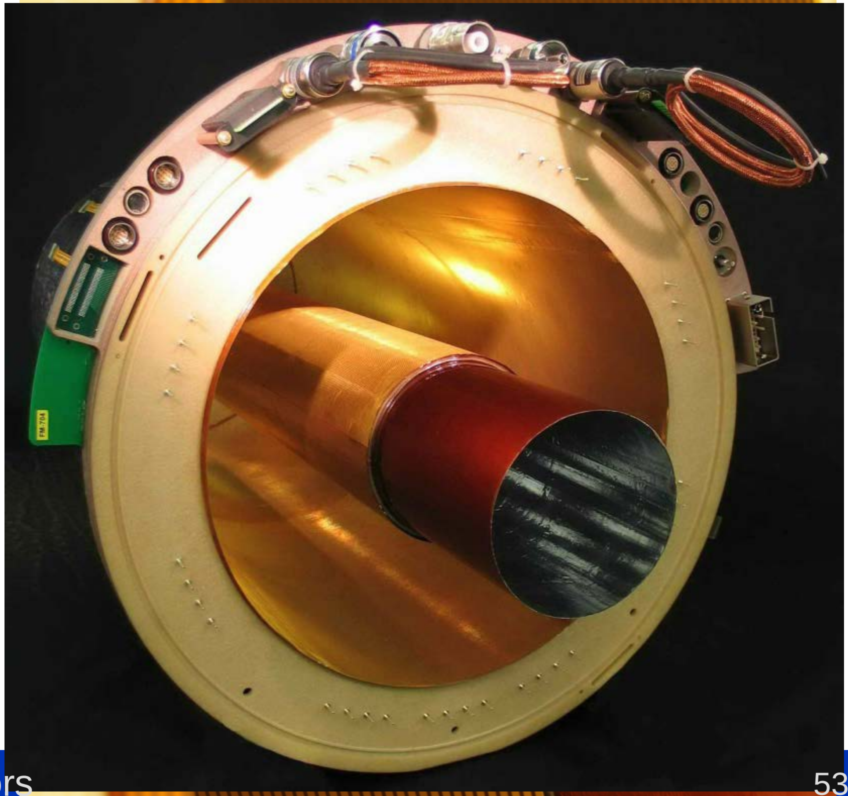
Drift cathode:

- Kapton / Rohacell

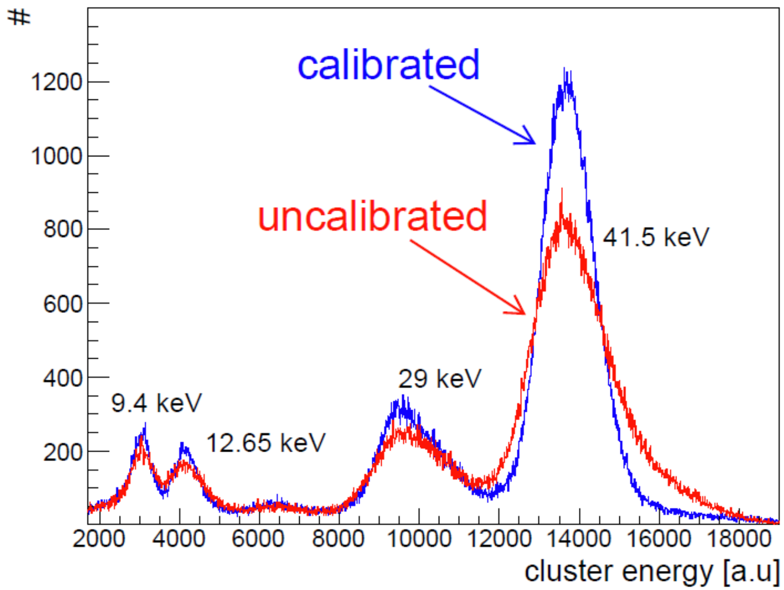
Media flange:

- glued to field cage

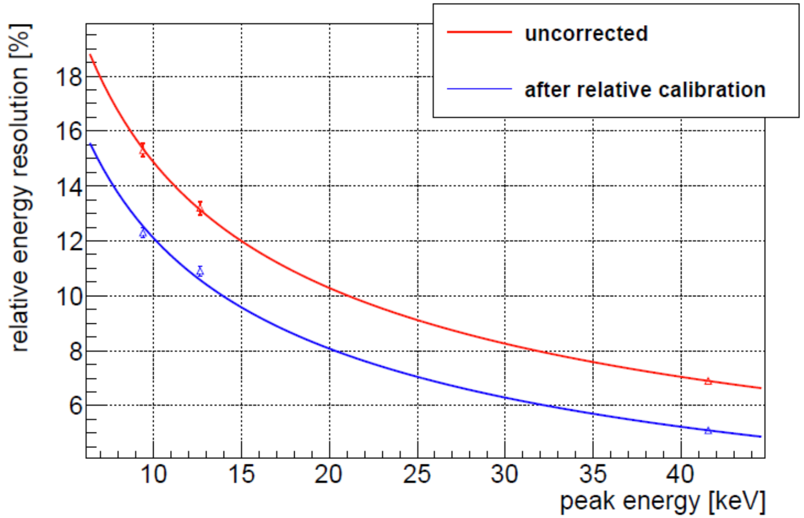




Gain Calibration with ^{83m}Kr



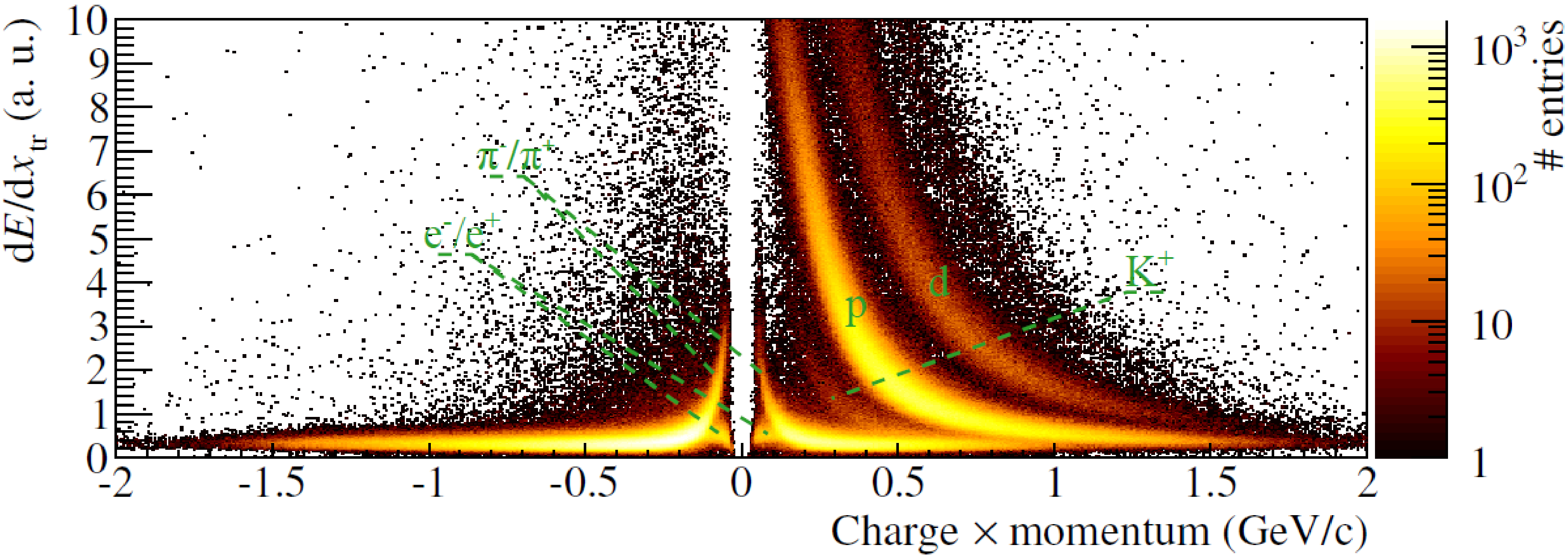
- Resolution before correction:
  - Main peak 6.9%
  - $\sigma_E/E \sim 0.49/\sqrt{E}$
- After correction:
  - Main peak 5.1%
  - $\sigma_E/E \sim 0.43/\sqrt{E}$
- Results similar for Ne/CO_2 (90/10)



peak [keV]	uncorrected	corrected
9.4	15.3 %	12.3 %
12.65	13.2 %	10.9 %
41.5	6.9 %	5.1 %

[R. Schmitz, HISKP]

Specific Energy Loss



- PID by measuring dE/dx: use truncated mean
  - Resolution ~ 15%
  - in agreement with expectation (parameterization by Allison & Cobb)
  - no density correction yet

First dE/dx measurement with GEM-TPC

[F.V. Böhmer et al., NIM A 737, 214 (2014)]

ALICE: The Space Charge Challenge

universität bonn

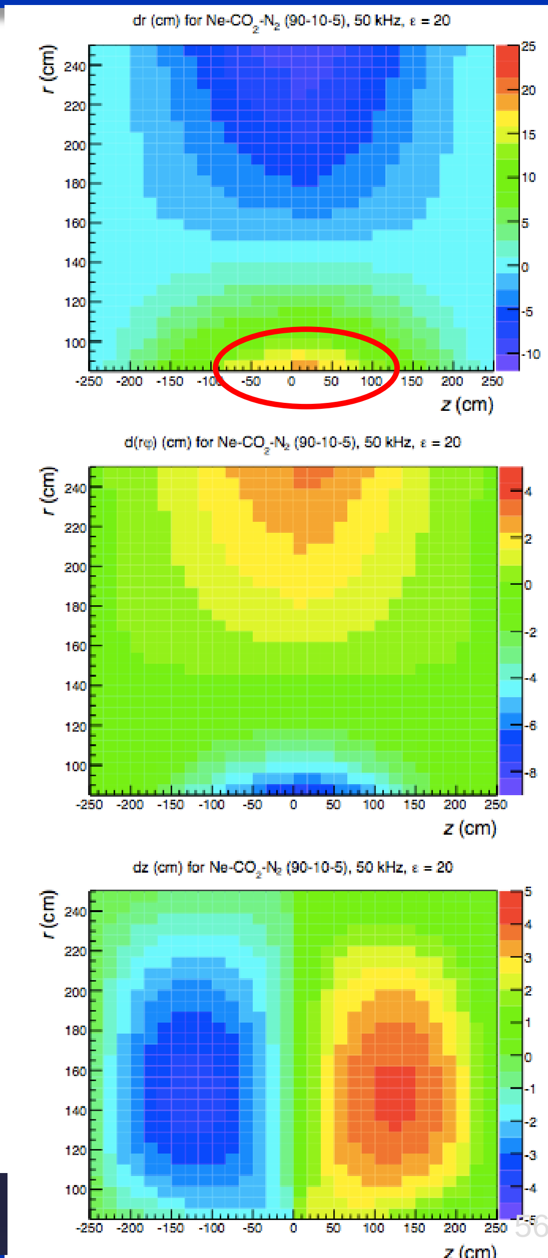
After LHC LS2: $\mathcal{L} = 6 \cdot 10^{27}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

⇨ Record all minimum bias events

⇨ 50 kHz in Pb-Pb collisions, i.e. 100× higher than present

- Ion blocking in GEMs not as efficient as with gating grid
- ALICE Goal: IB = 1%, ε = 20 at G = 2000
- $t_{\mathrm{d,ion}} = 160\ \mathrm{ms}$ ⇨ions from 8000 events in drift volume!
- Distortions up to 19 cm in r and 7 cm in $r\varphi$ (near drift cathode for small radii)
- A few cm for the largest part of drift volume

⇨ **to be corrected to the level of intrinsic resolution!**

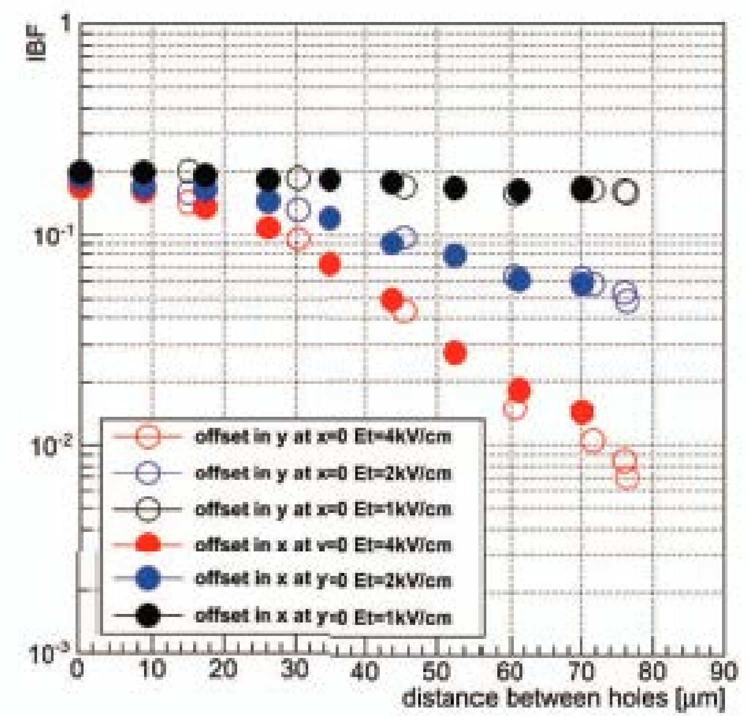


ALICE Technical Design Report

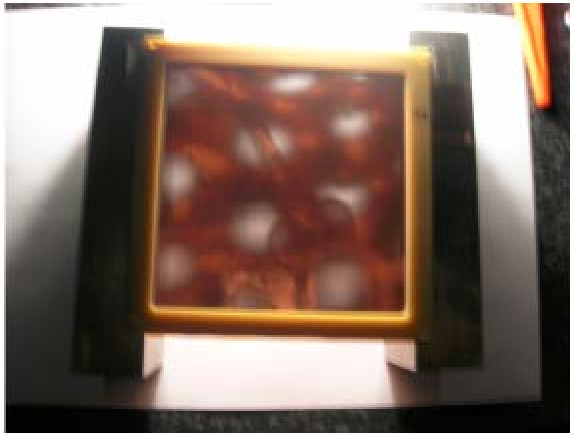
Ion Backflow

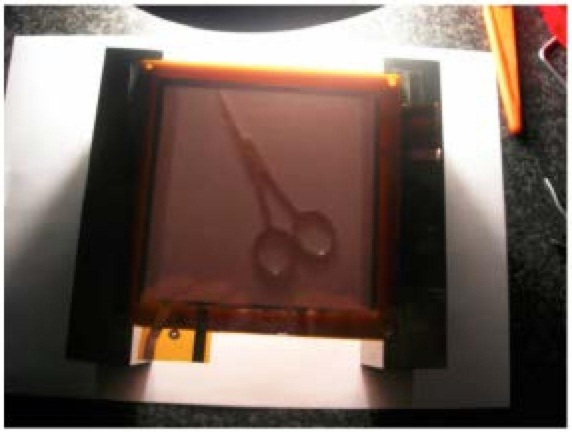
But: very little diffusion for ions

⇨ beware of hole alignment: critical for IB!

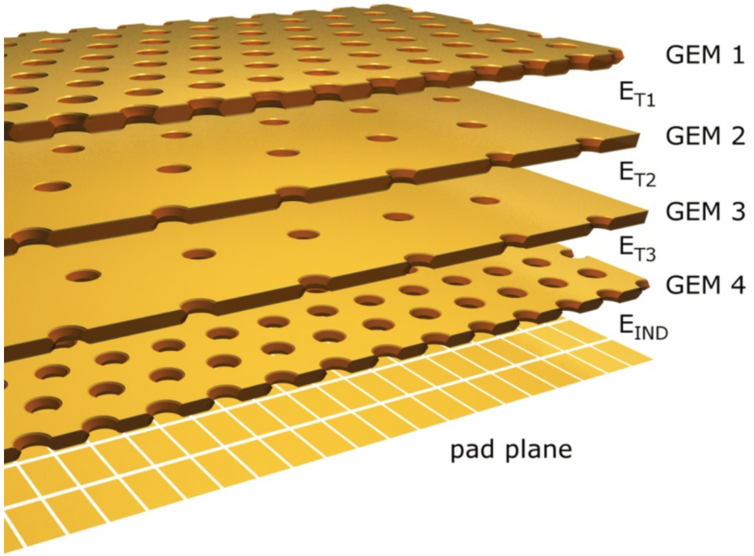


- Deliberate misalignment of holes difficult
- Rotate foils by 90° to avoid long-range variations: Moiré pattern

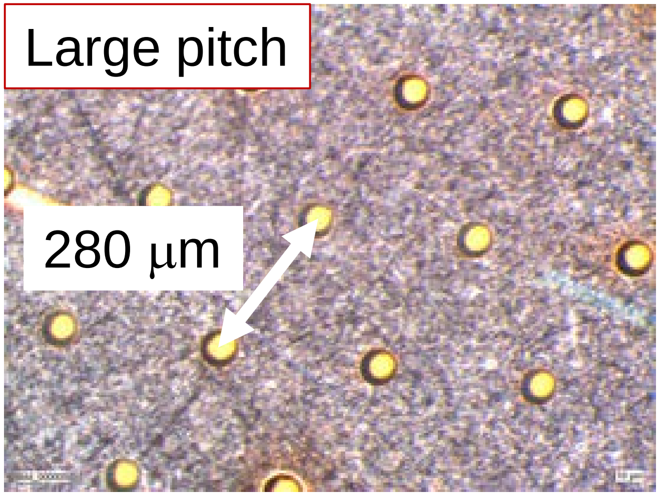


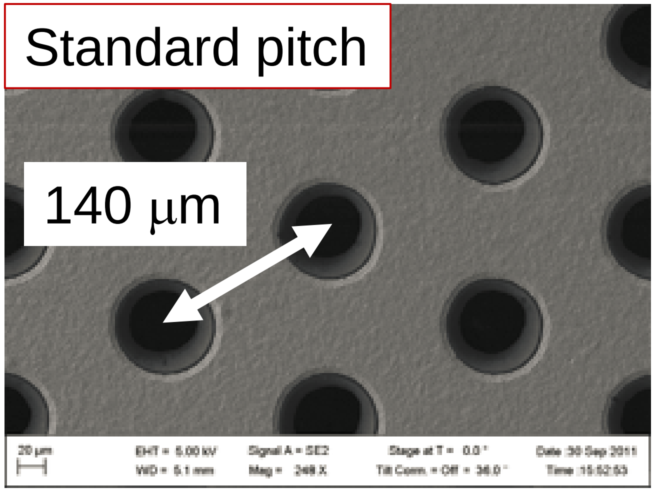


Ion Backflow – ALICE Solution

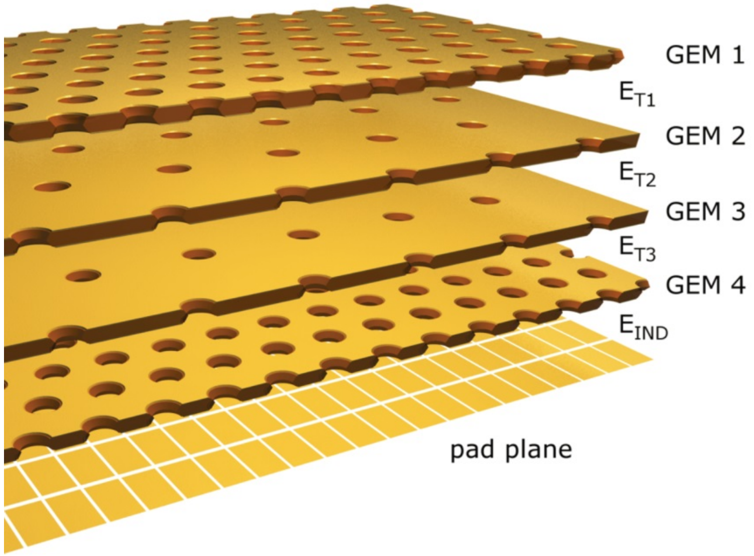


- Triple-GEM setup not sufficient
- New chambers: 4-GEM setup with standard (S) and large pitch (LP)
- Field configuration optimized to provide
  - IB < 1%
  - σ_E/E < 12% (for ^{55}Fe X-rays)
  - Discharge stability





Ion Backflow – ALICE Solution



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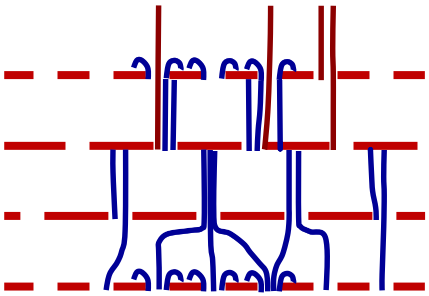


$E_{\mathrm{drift}} = 0.4\,\mathrm{kV/cm}$

$E_{\mathrm{T1}} = 4\,\mathrm{kV/cm}$

$E_{\mathrm{T2}} = 4\,\mathrm{kV/cm}$

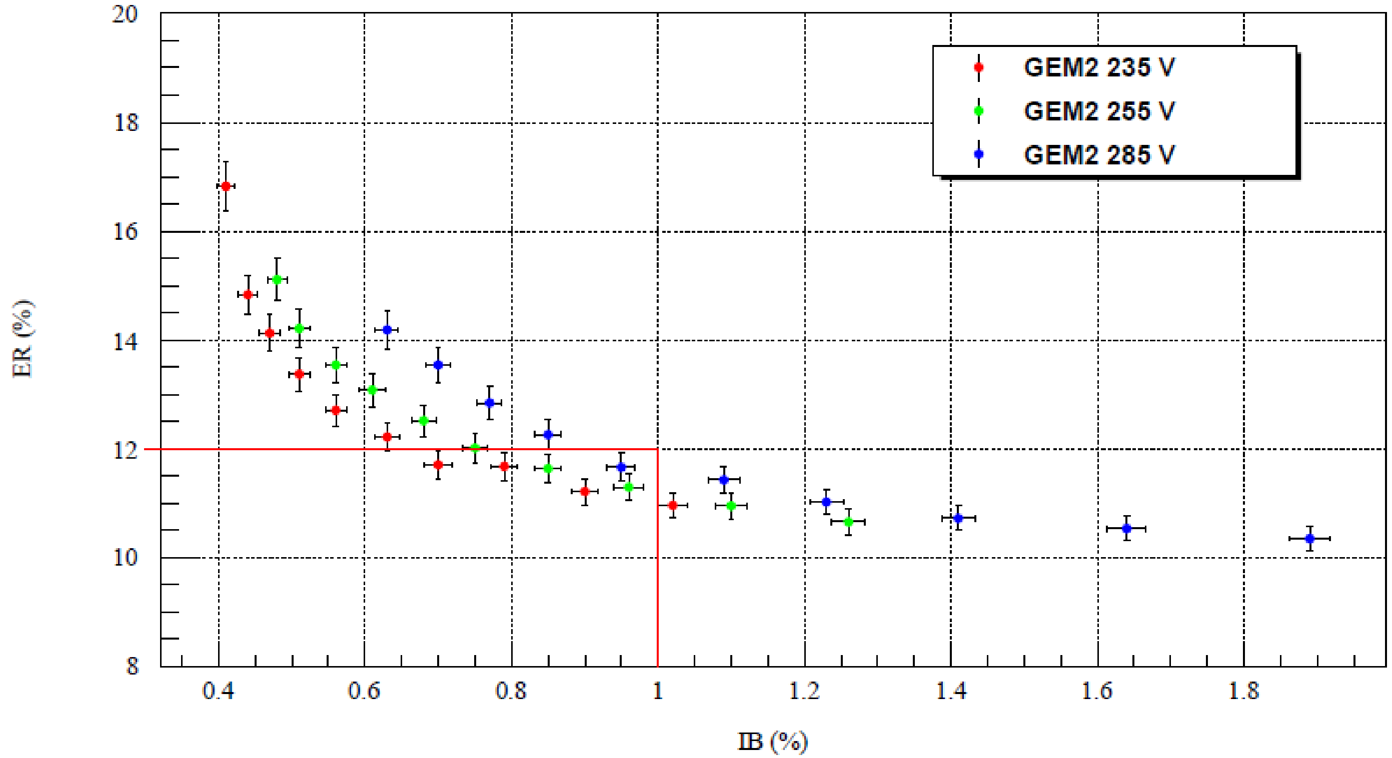
$E_{\mathrm{T3}} = 0.1\,\mathrm{kV/cm}$

$E_{\mathrm{ind}} = 4\,\mathrm{kV/cm}$

Ion blocking:

- GEM1: asymmetric field
- GEM2/GEM3: geometric blocking
- GEM4: asymmetric field

IB vs Energy Resolution



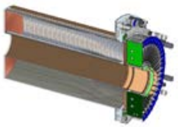
- IB and energy resolution are anticorrelated when U_{GEM1} is varied
- Goals have been reached, even with some margin for fine-tuning
- Much larger phase space scanned ⇨ no significant improvement expected

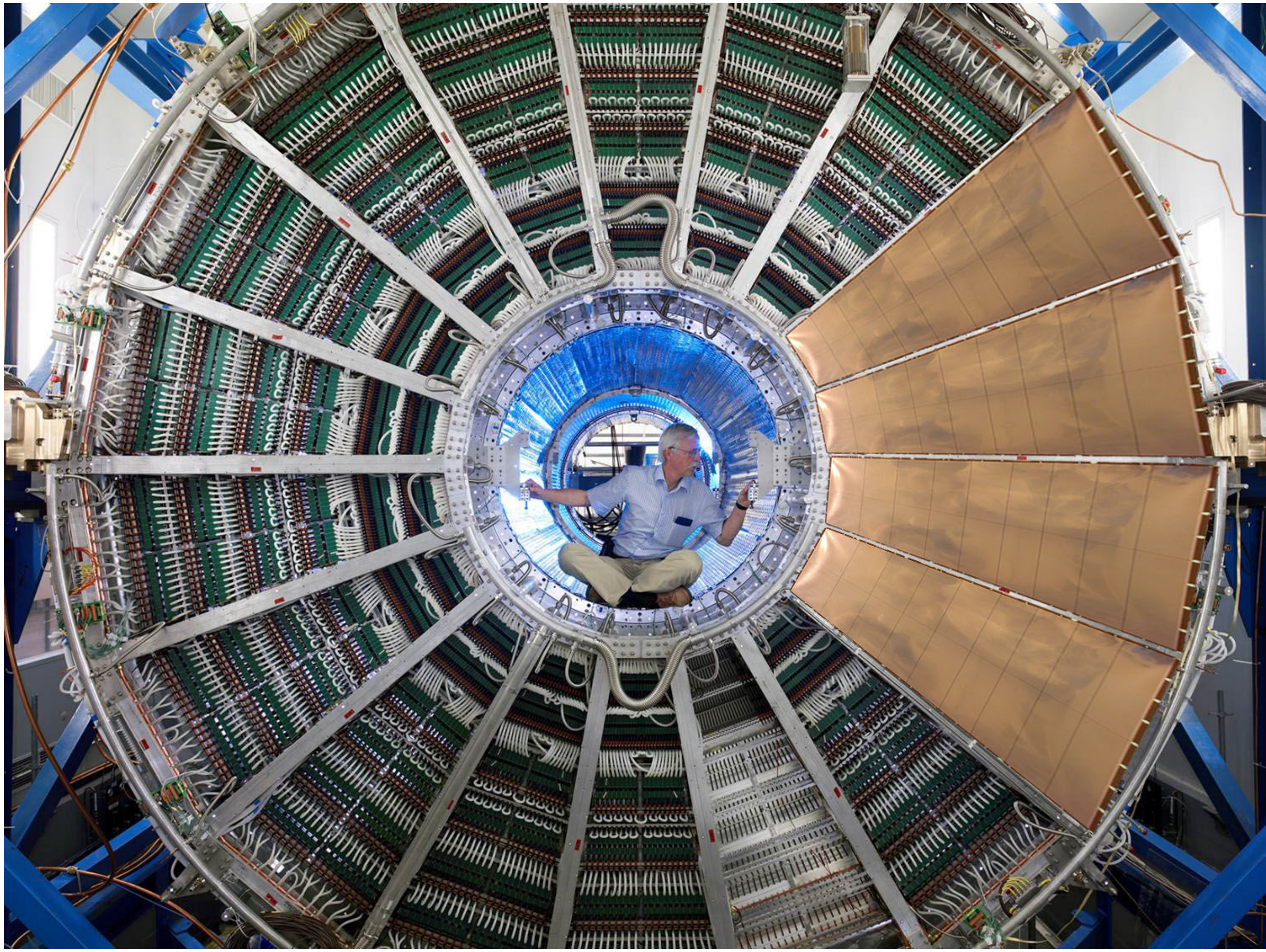
[A. Altingun, HISKP]

GEM-TPC

FOPI @ GSI

ALICE @ LHC



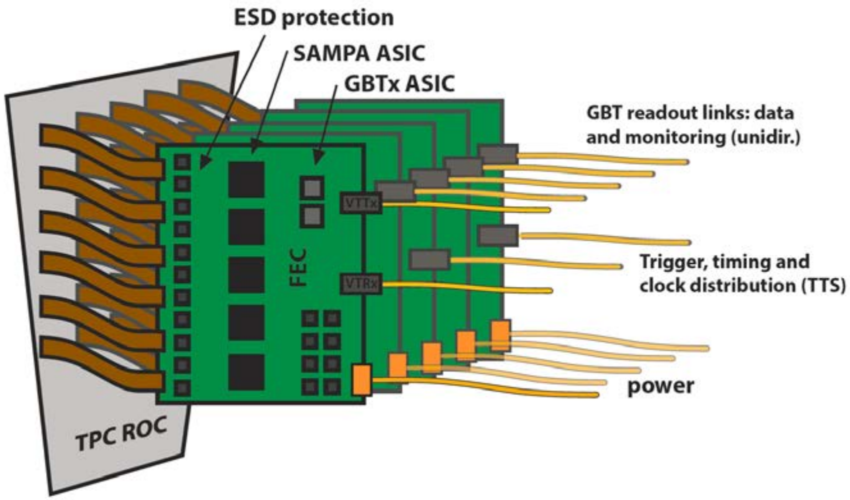


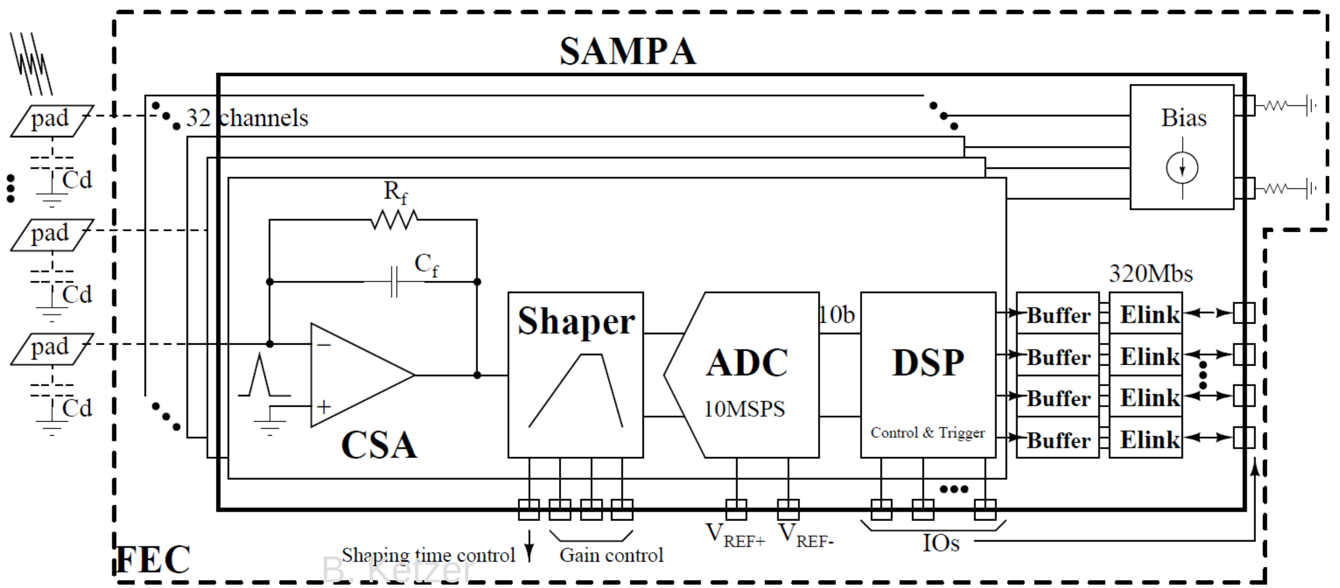
[B. Ketzer et al., NIM A 732, 237 (2013)]

Front-end Electronics

SAMPA ASIC:

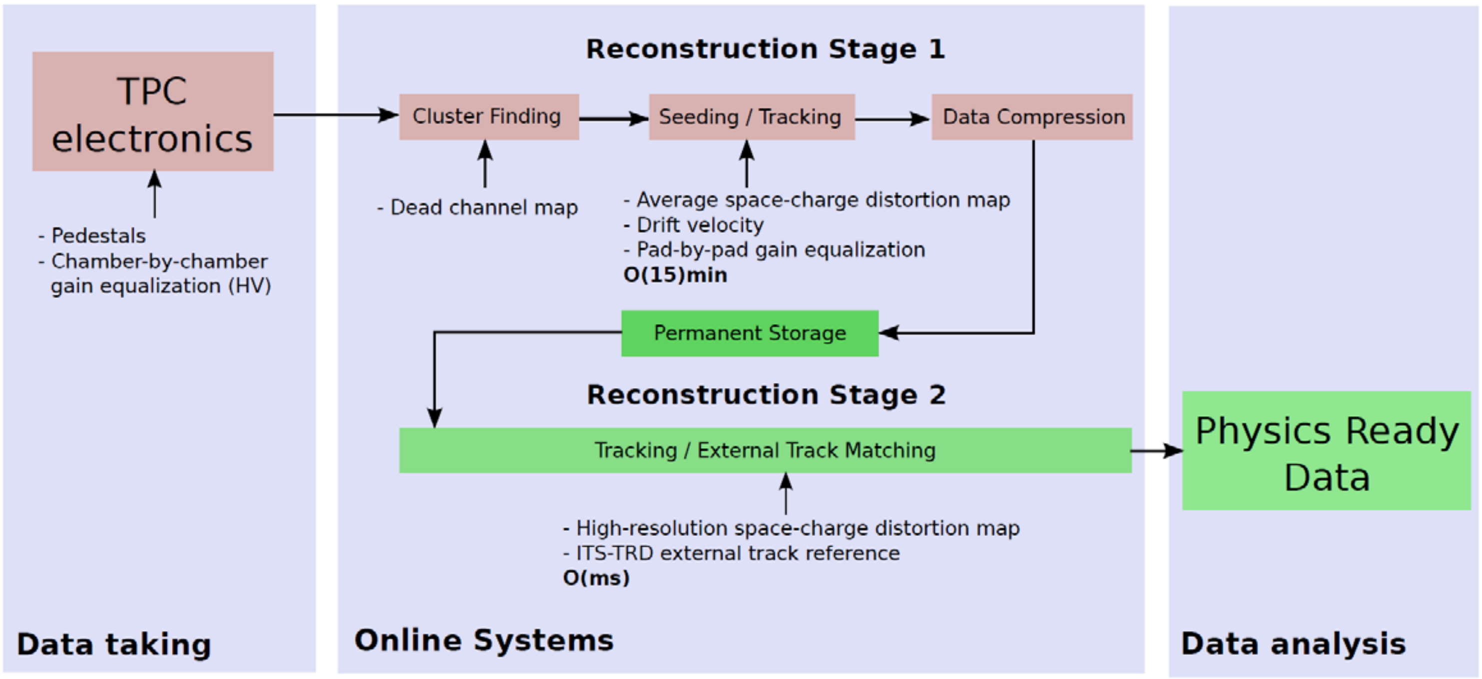
- Polarity opposite wrt MWPC
- Continuous readout ➪ simultaneous sampling and data transfer
- Data throughput: $50\ \mathrm{kHz}\ \times 100\ \mathrm{MB}{=}5\ \mathrm{TB/s}$ (of FEE, not written to disk)
- Triggered mode for calibration
- Digital filter for common mode correction in DSP





B. Ketzer

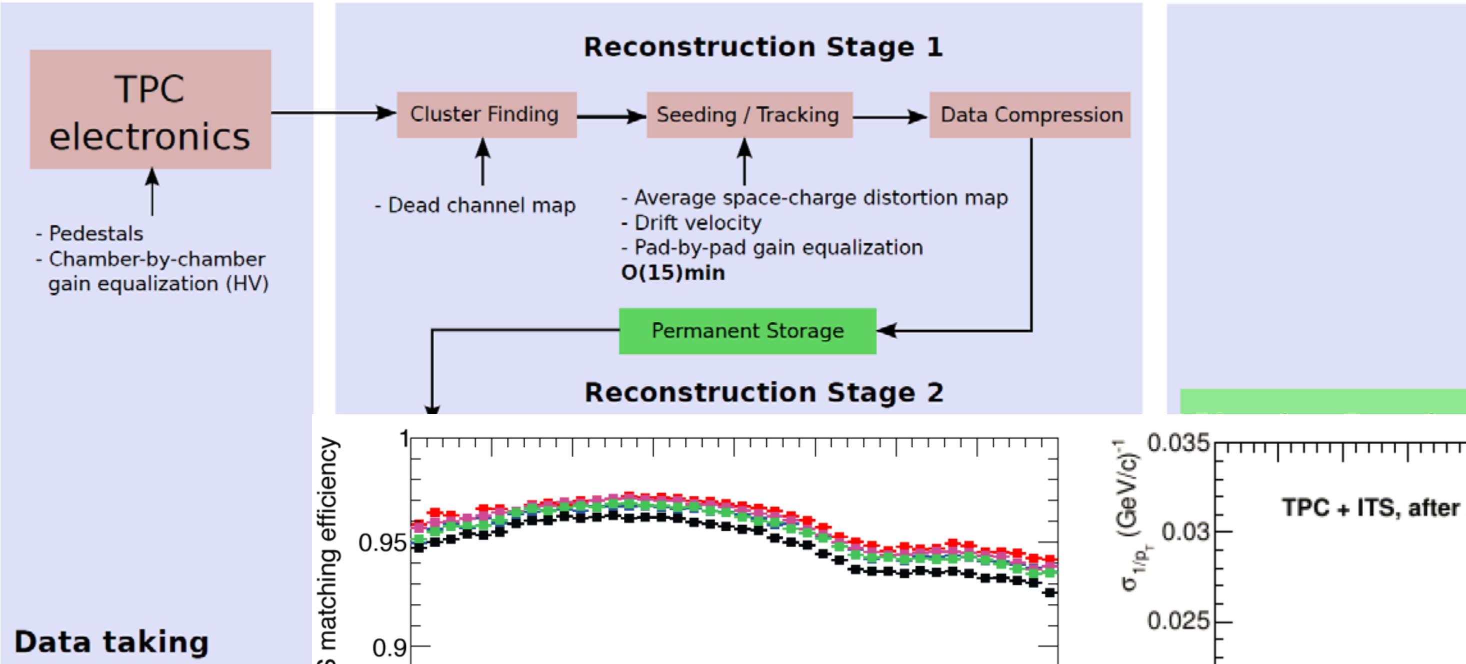
Reconstruction Strategy

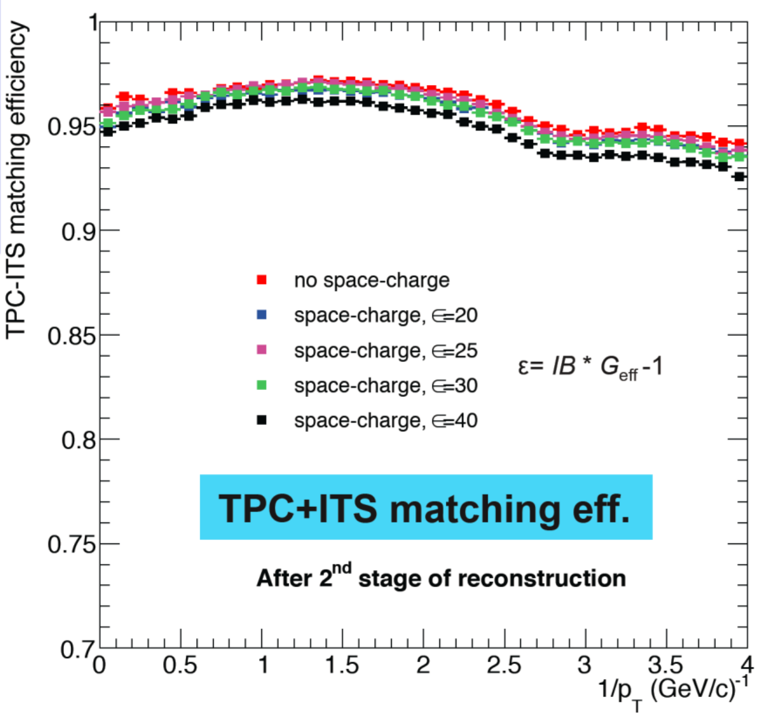


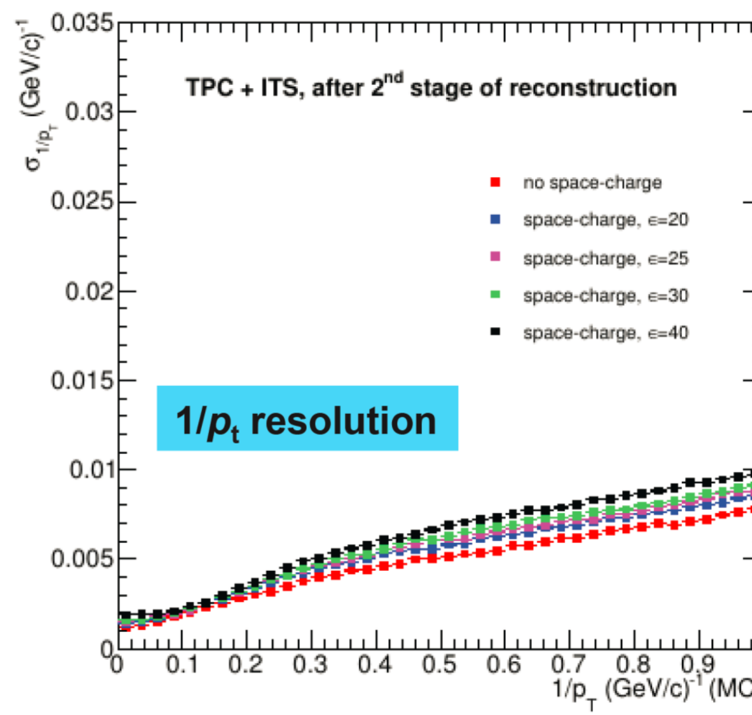
Two-stage reconstruction scheme:

1. Cluster finding, cluster-to-track association: 5 TB/s ⇨ 50 GB/s
   Scaled average space charge distortion map, u_d, gain eq. ⇨ $\mathcal{O}(1\ \mathrm{mm})$
2. Tracking, ITS-TRD track matching
   High-resolution space charge correction ⇨ $\mathcal{O}(200\ \mu\mathrm{m})$ in $r\varphi$

Reconstruction Strategy







Theory and Practice…

Many novel detector concepts for nuclear and particle physics experiments:

- tracking
- photon detection
- calorimetry…

Main challenges for the future:

- resolution
- rate capability
- power consumption
- radiation hardness
- trigger-less readout
- data reduction at front-end level

Basic understanding of underlying processes indispensable…

"Now, this is just a simulation of what the blocks will look like once they're assembled."