Gas detectors and intrinsic space-point resolution

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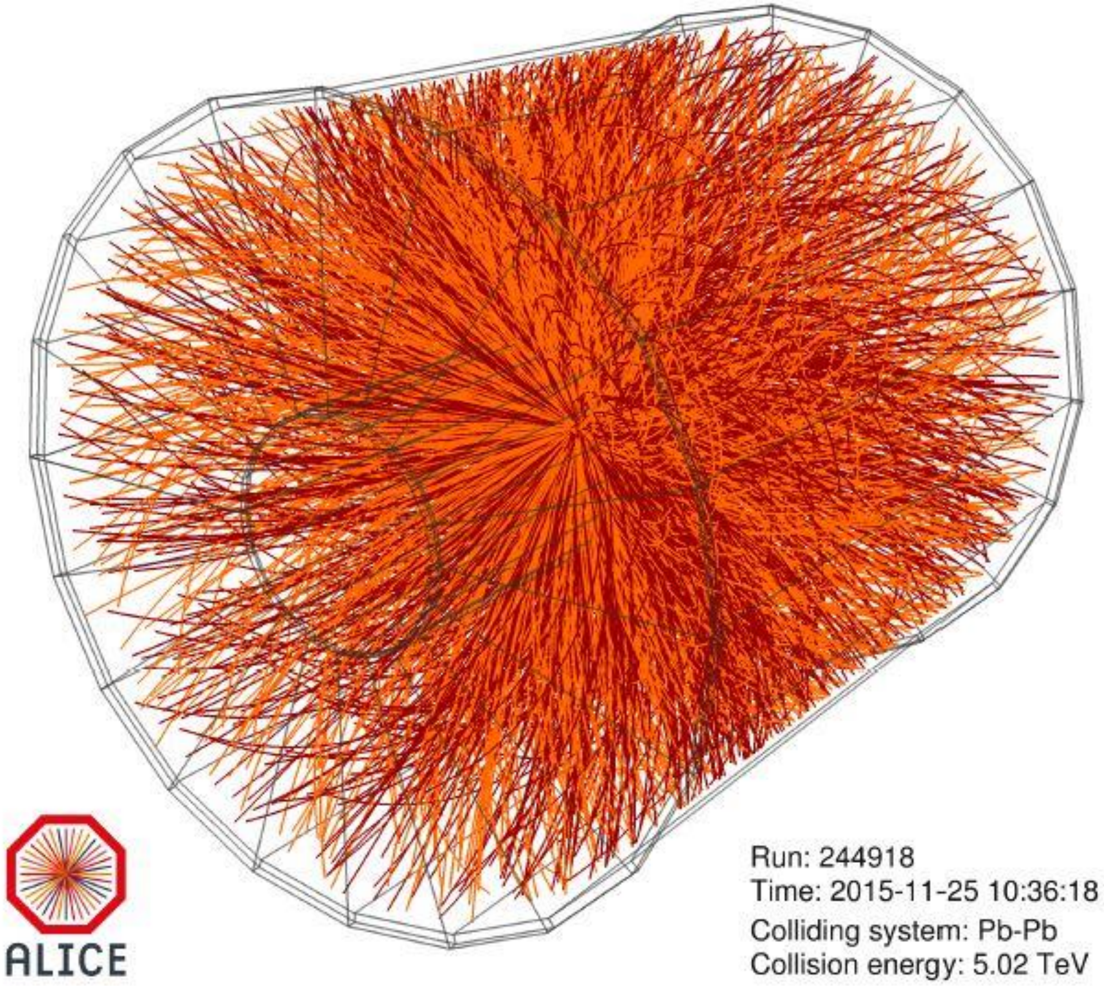
PARTICLE TRACKING AND IDENTIFICATION AT HIGH RATES
WS2017/18, HEIDELBERG

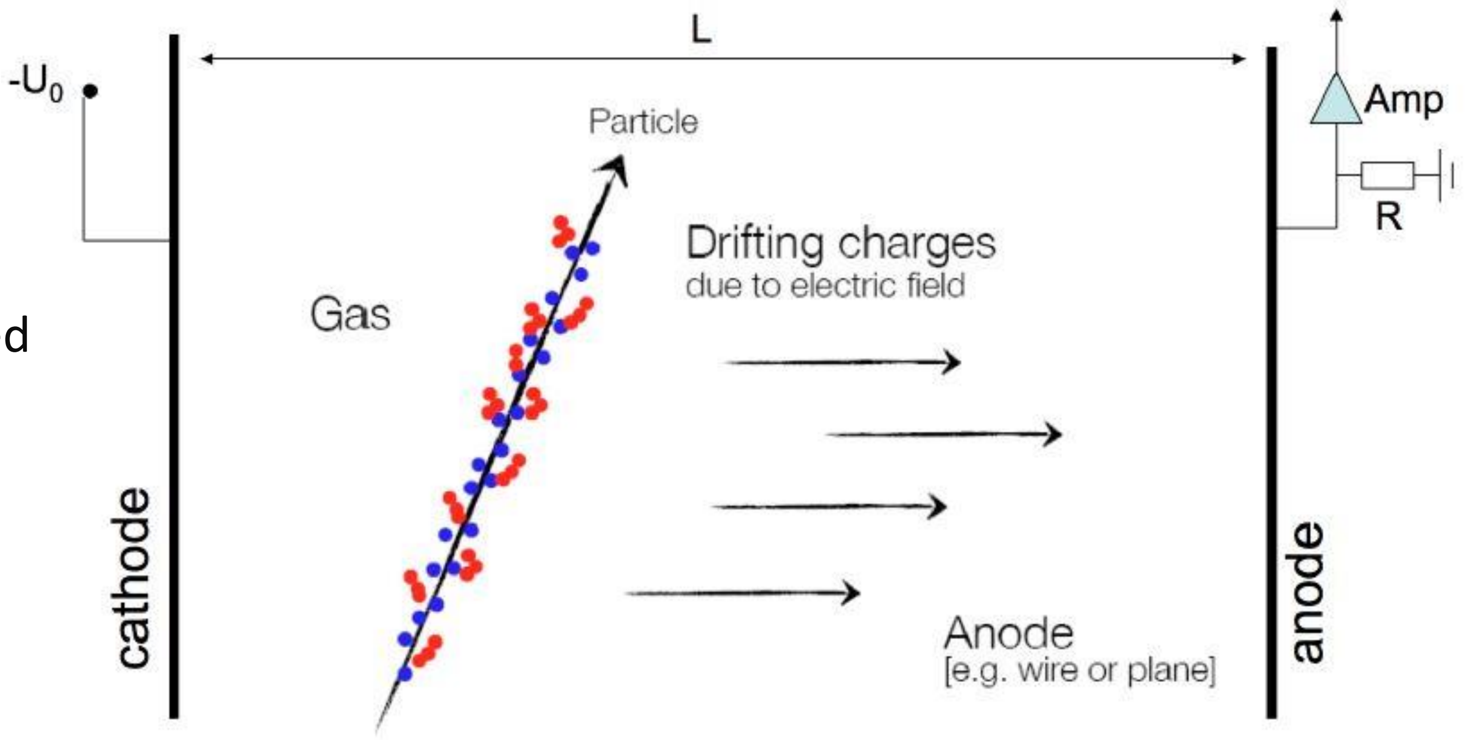
Gas Detectors - Motivation

- Large area coverage
- Coordinate measurement
- Time-of-flight
- Charge collection → dE/dx
- TPC: 3D reconstruction in high multiplicity events ($\sim 20{,}000$ tracks)



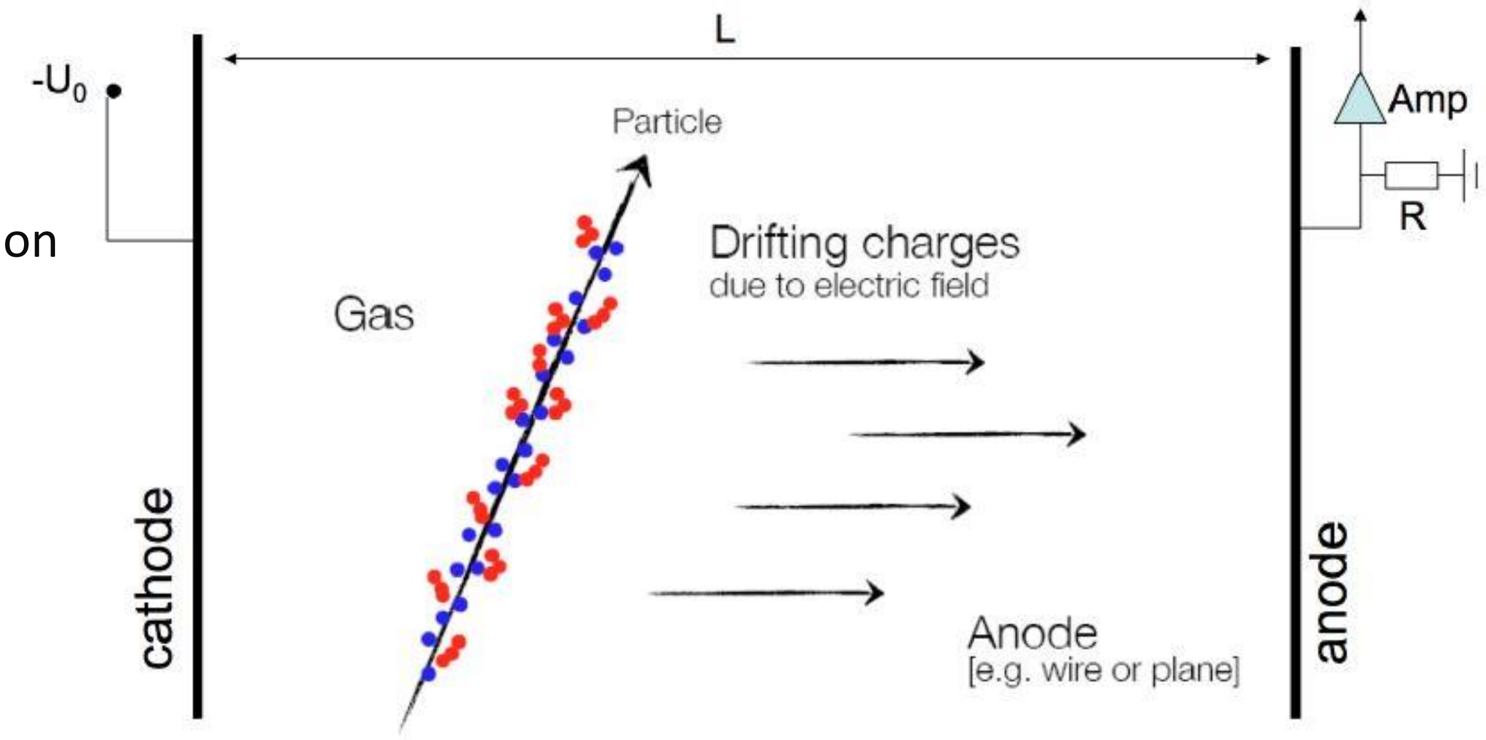
Gas Detectors - Principle

- Enclosed gas volume
- Applied electrical field
- Traversing charged particle ionizes gas
- Electrons and ions drift to electrodes
- Measure position, time and/or collected charge



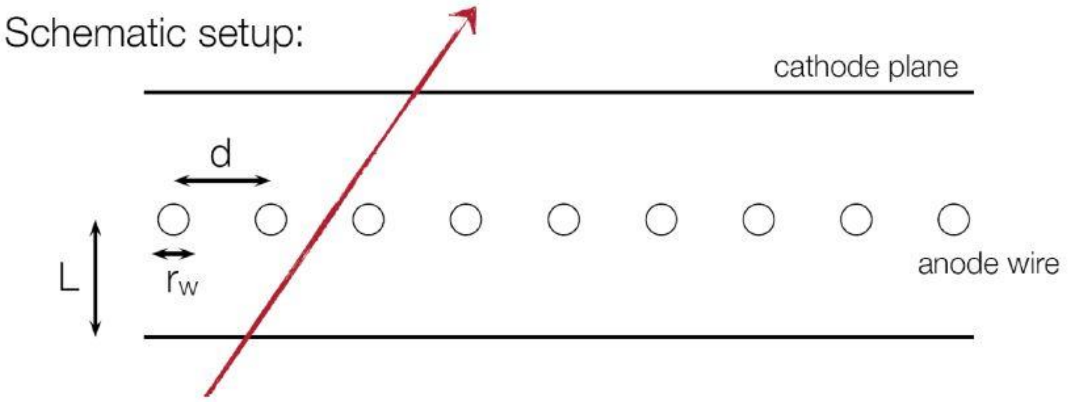
Agenda

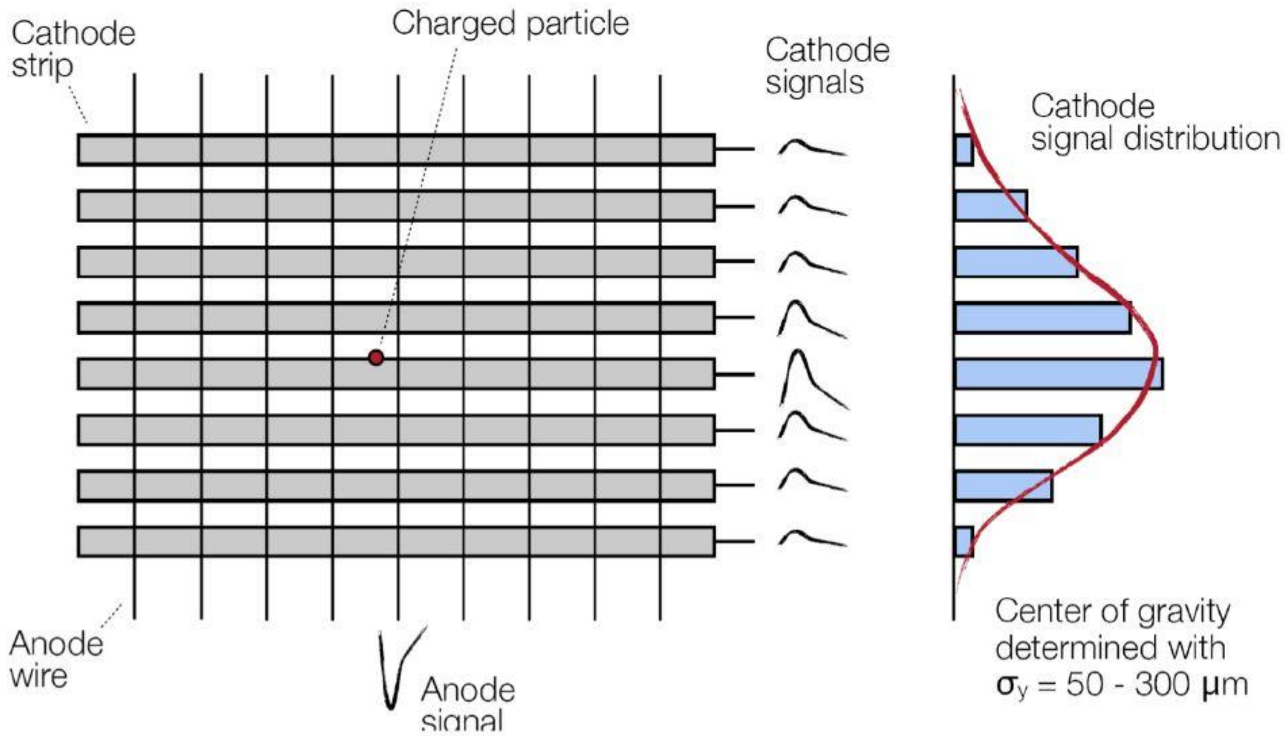
1. Gas Detectors and ALICE TPC
2. Ionization
3. Drift and diffusion
4. Signal creation and gas gain variation
5. Space point resolution
6. Momentum measurement



Gas Detectors – Examples (MWPC)

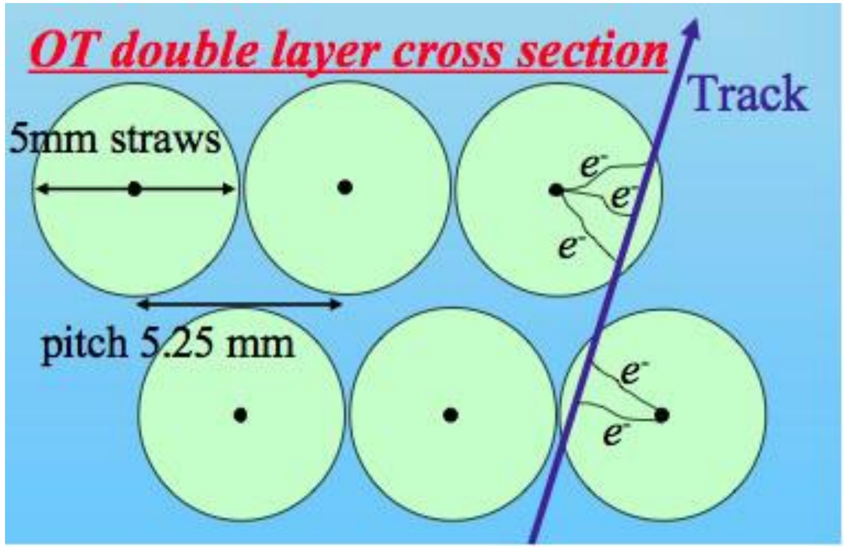
- Multi-Wire Proportional Counter
  - Anode wires + cathode strips
  - Measure 2D position
  - $\sigma_{wire} \sim 570\ \mu\text{m}$ for $d = 2mm$
  - $\sigma_{strip} \sim 50 - 300\ \mu\text{m}$

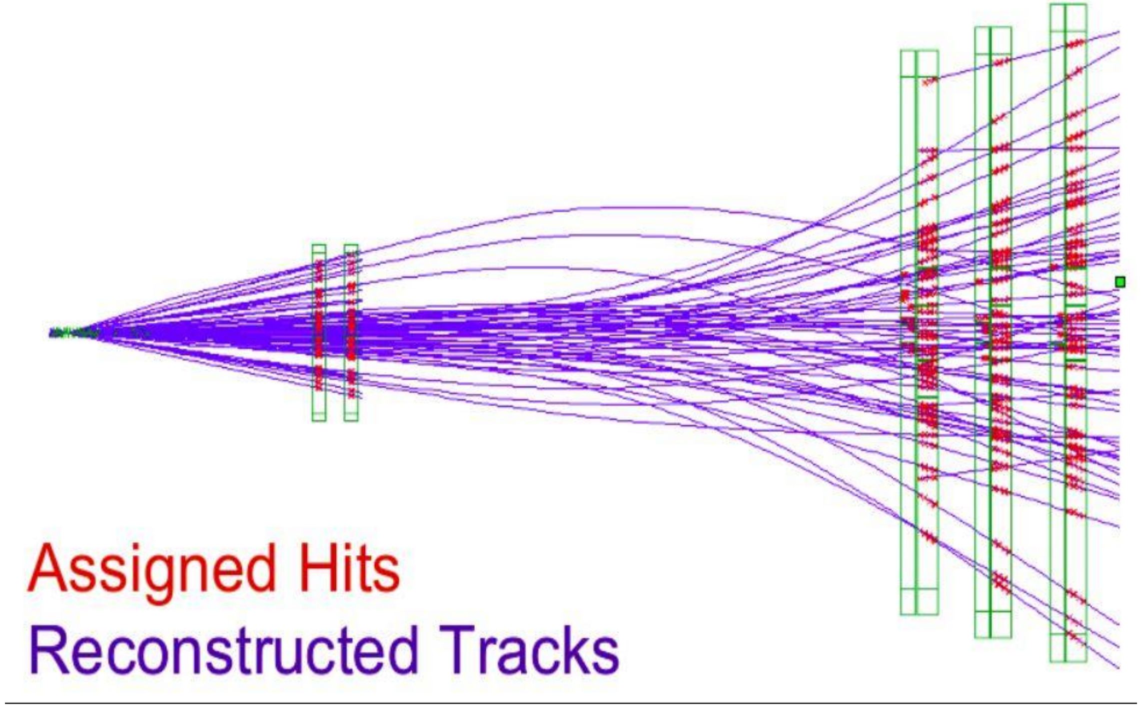




Gas Detectors – Examples (straw tubes)

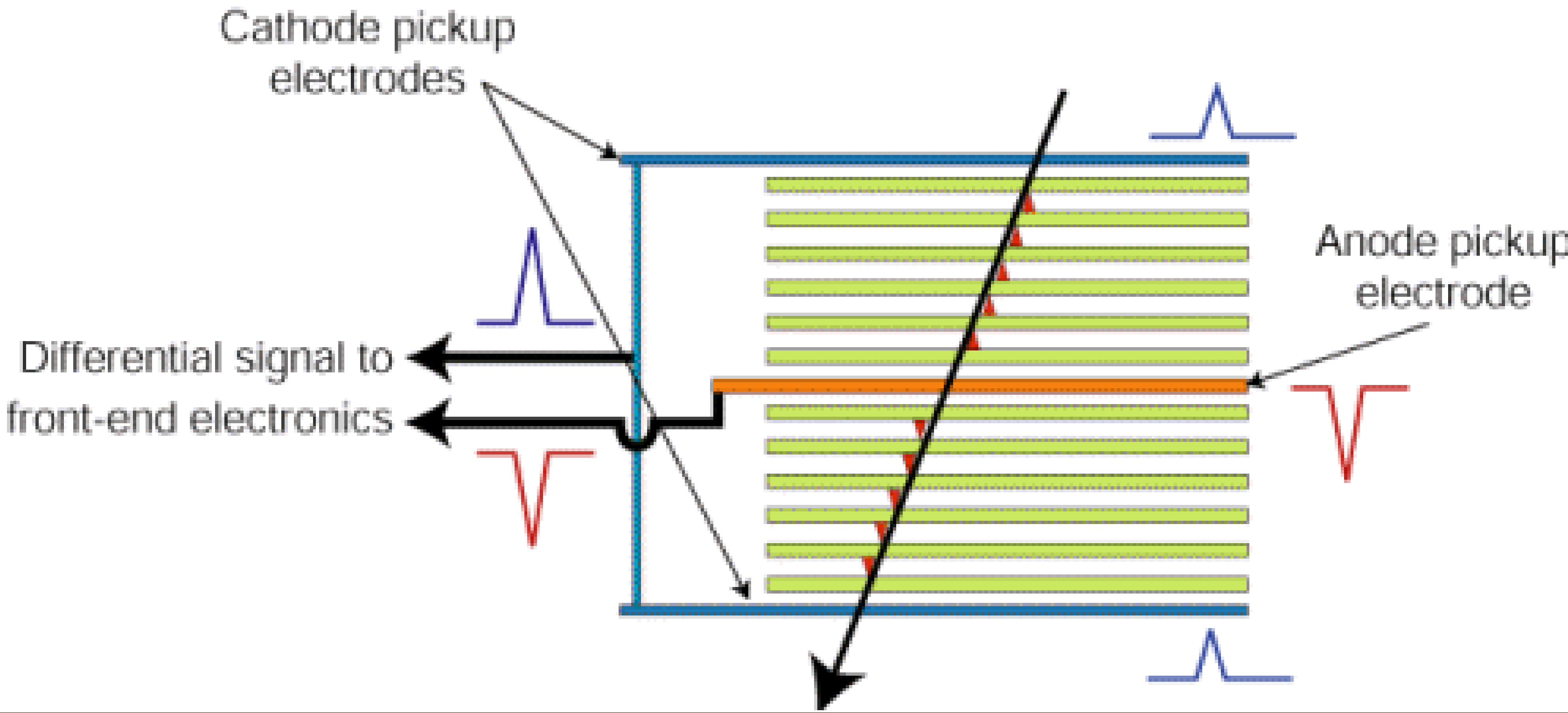
- Straw tubes (e.g. LHCb outer tracker)
  - Stack of small single wire gas tubes
  - Measure 2D position
  - Stack → track reconstruction
  - $\sigma \sim 200\ \mu\text{m}$



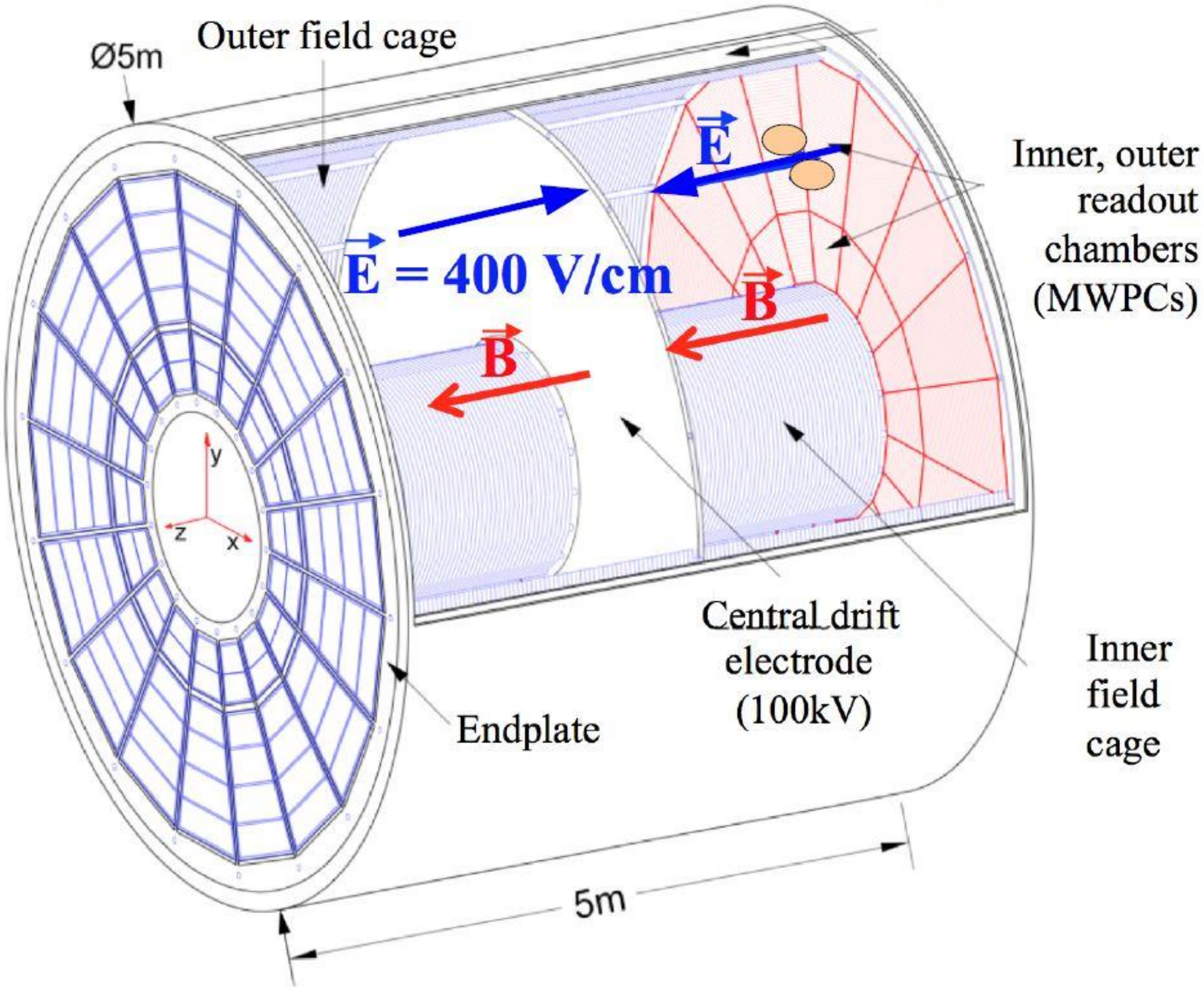


Gas Detectors – Examples (TOF)

- Time-Of-Flight (e.g. ALICE TOF)
  - Multigap Resistive Plate Chamber
  - Electron avalanche in each gap
  - Induce fast signal on pickup electrodes
  - $\sigma \sim 50\ \mathrm{ps}$



ALICE Time Projection Chamber (TPC)



TPC

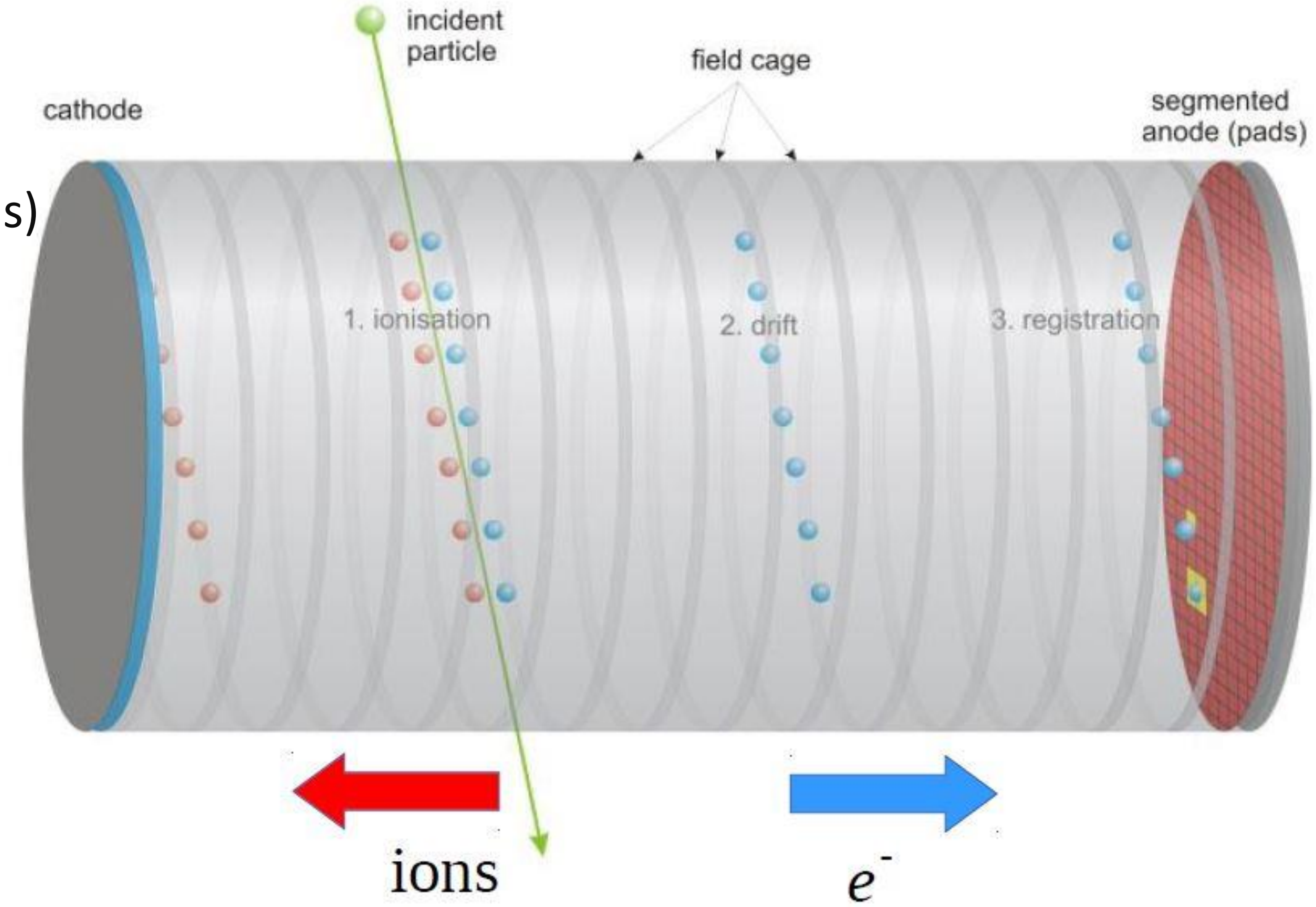
- Incident particle ionizes gas
- Uniform E-field induces drift
- Multiplication of e^- at readout (MWCP, GEMs)
- x-y-coordinate: projection on pad
  - $\sigma_x \sim 150 - 300\ \mu\text{m}, \sigma_y \sim 1\ \text{mm}$
- z-coordinate: drift time
  - $\sigma_z \sim 1\ \text{mm}$

3D

- Charge measurement
  - $\rightarrow dE/dx\ \ \rightarrow velocity$
- B-Field → momentum
  - Parallel to E-field

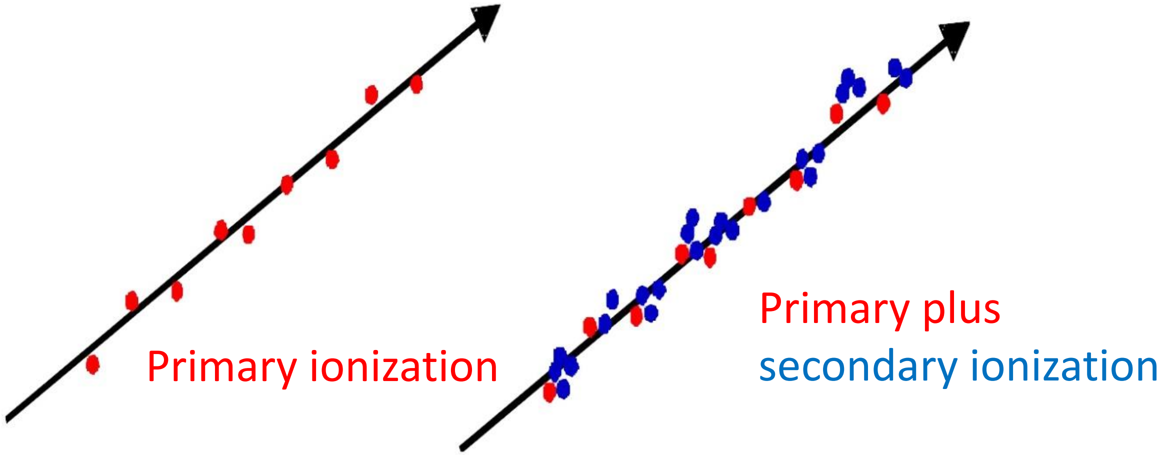
PID

- Very high multiplicity ($\sim$20,000 tracks)



Ionization

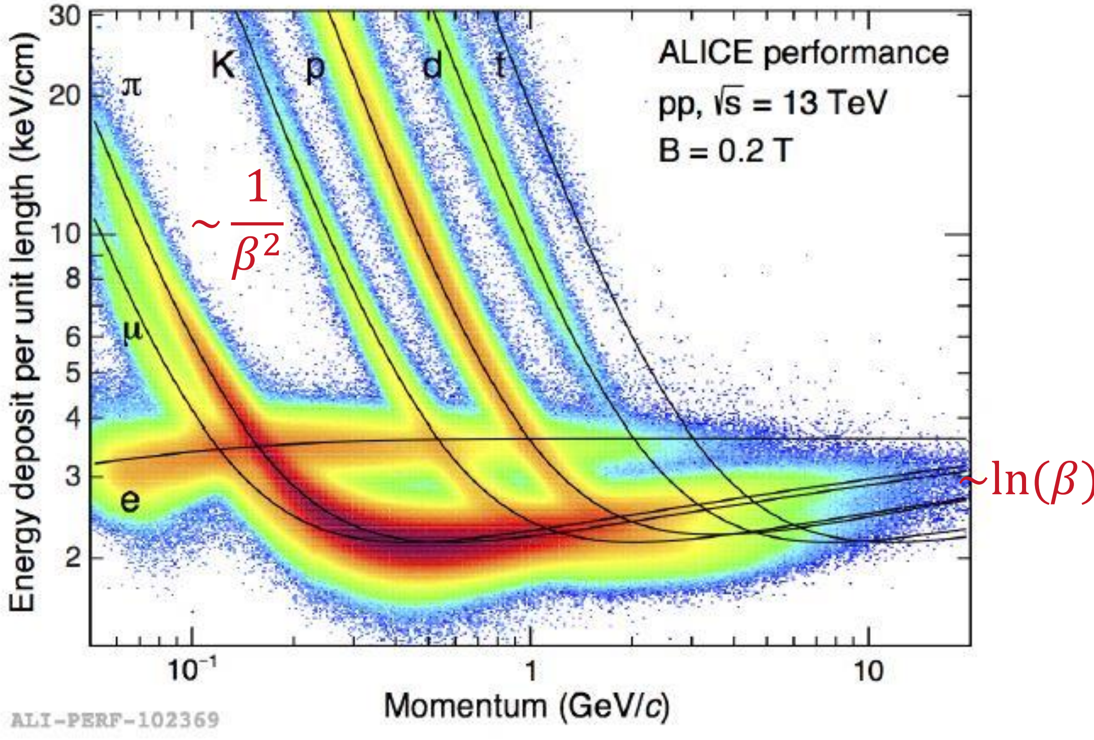
- Primary ionization: $X + p \rightarrow X^{+} + p + e^{-}$
- Secondary ionization: $X + e^{-} \rightarrow X^{+} + e^{-} + e^{-}$
- Mean energy loss:



Bethe Bloch formula

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

z: charge incident particle
Z: Charge of medium
A: Atomic mass of medium
$\beta = \mathrm{v}/\mathrm{c}$ of incident particle



Ionization II

Primary Ionization

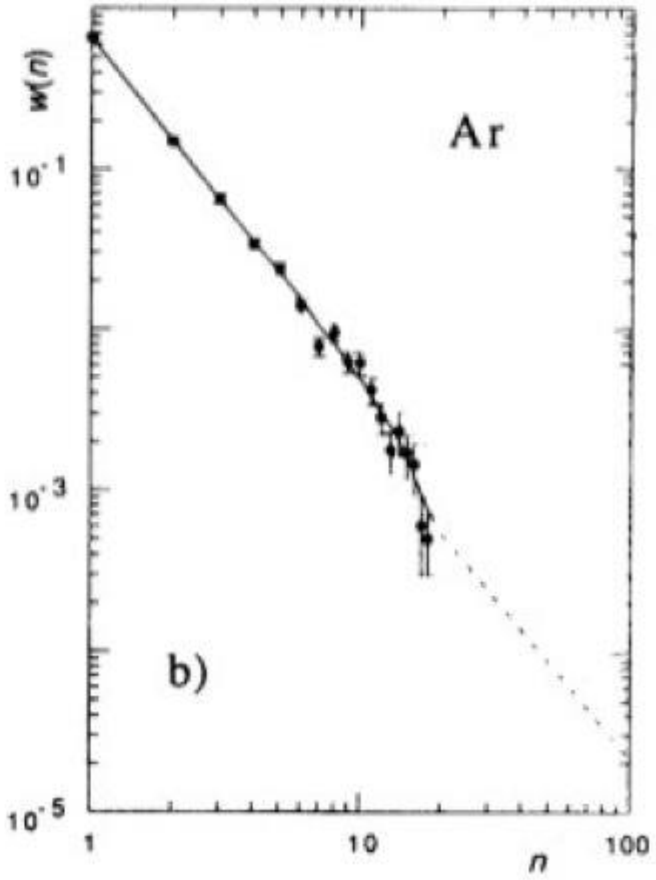
- $\#e^-$ per cm: $\langle N_P \rangle = 1/\lambda \approx 15/cm$ ($\mathrm{Ne{-}CO_2}$ [90-10])
  - λ: mean free path
- Number of primary e^- Poisson distributed

Secondary Ionization

- High energy e^- $\rightarrow$ further ionization
- Secondary ionization near primary ionization

$\Longrightarrow$ Cluster formation

- $N_{tot} \approx 3 - 4\ N_p$



Cluster size distribution in Argon

Space point resolution

Main contributions:

- Diffusion σ^2_{drift}
- Detection σ^2_{pad}
- Angular pad effect σ^2_{ang}
- ExB effects σ^2_{ExB} → talk by Pascal Becht
- $\sigma^2_{total} = \sigma^2_{pad} + \sigma^2_{drift} + \sigma^2_{ang} + \sigma^2_{ExB}$

Drift (macroscopic)

- Eq. of motion (Langevin):

$$m\frac{d\mathbf{u}}{dt} = e\mathbf{E} + e[\mathbf{u}\times\mathbf{B}] - K\mathbf{u}$$

- K: friction from microscopic collisions, $\tau = m/K$ characteristic time between two collisions

- Stationary eq. $\xrightarrow{\frac{du}{dt}=0}$ $\frac{\mathbf{u}}{\tau} - \frac{e}{m}[\mathbf{u}\times\mathbf{B}] = \frac{e}{m}\mathbf{E}$

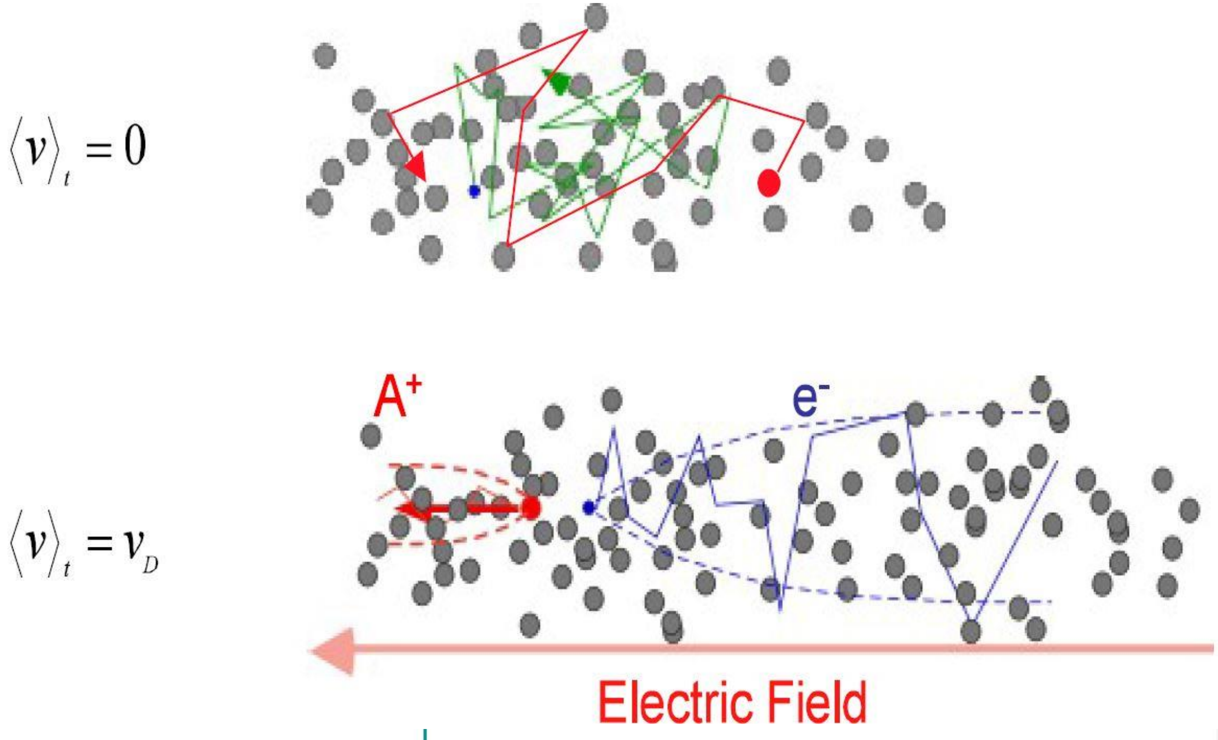
- $B = 0$: $u = \frac{e}{m}E\tau \approx 2 - 3\frac{cm}{\mu s}$ for ALICE TPC with Argon or Neon

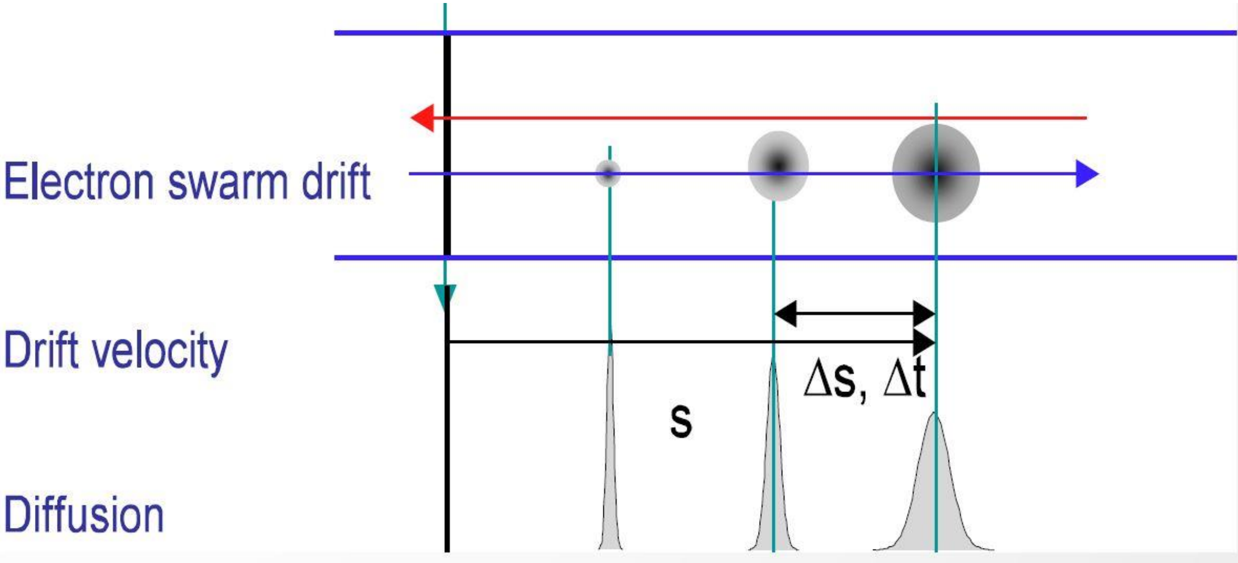
- With B-Field: helix motion with cyclotron frequency $\omega = \frac{eB}{m}$

Drift (microscopic)

- Light e^- scatter isotropically („friction“)
- Gaussian spread $n = \frac{1}{(4\pi Dt)^3}\exp(-\frac{r^2}{4Dt})$

  $\Longrightarrow$Diffusion
- Ions ~ 1000 times slower, non-isotropic



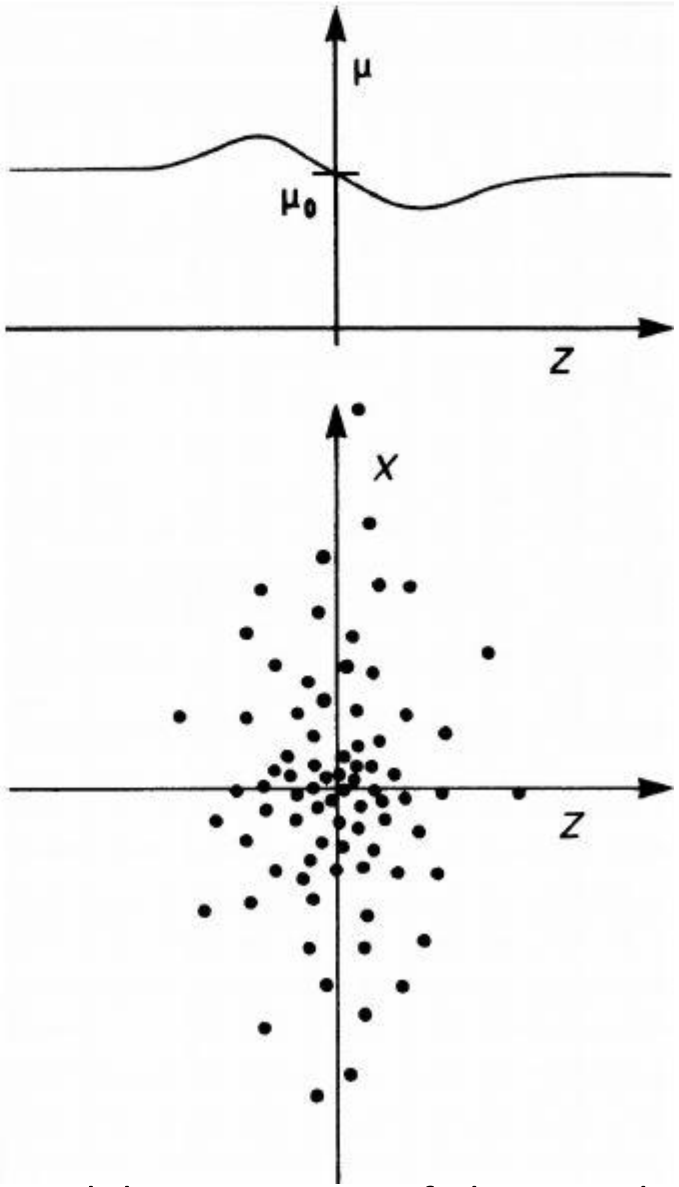


Electric anisotropy

- Statistical diffusion superimposed with ordered drift along field

$\Longrightarrow$Different mobilities μ at center/edges reduces longitudinal diffusion

- High E-field → small longitudinal diffusion



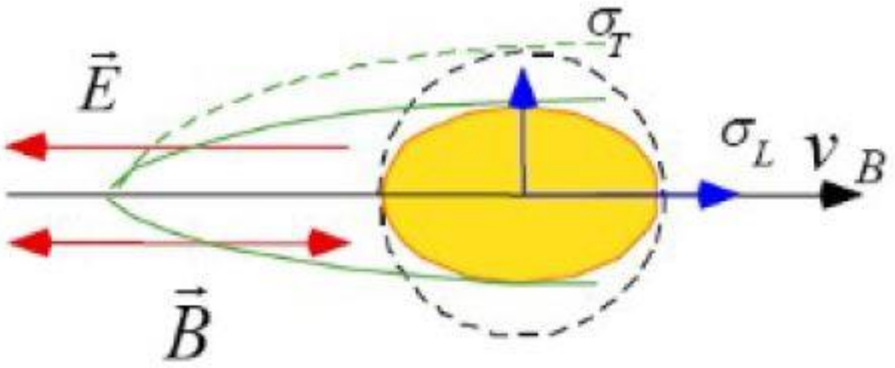
Mobility variations of electron cloud traversing in z-direction

Magnetic anisotropy

- Magnetic field → Lorentz force in transversal direction

⟹Reduced transversal diffusion

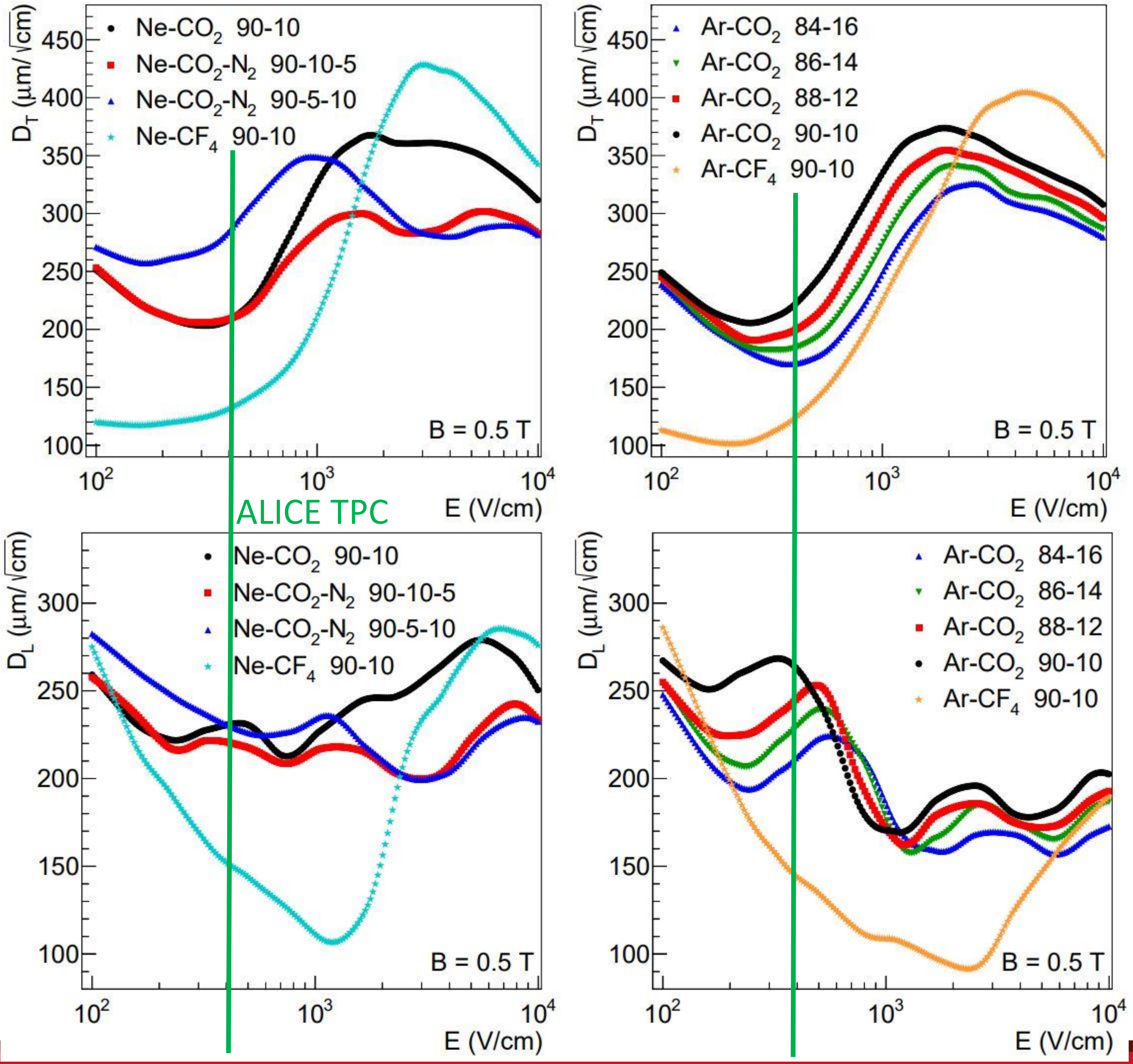
- $\frac{D_T(\omega)}{D_T(0)} = \frac{1}{1+\omega^2\tau^2}$
- High B-field wanted



		$\omega\tau$	B
Ne- CO2 (90-10)	ALICE TPC Run 1	0.34	0.5 T
Ne-Co2-N2 (85-10-5)	ALICE TPC Run 1/3	0.32	0.5 T
Ar-Co2 (90-20)	Run2	0.43	0.5 T
Ar-CH4(90-10)	STAR TPC	2.3	0.5 T
Ar-CH4(90-10)	ALEPH TPC	7	1.5 T

Diffusion for different gas mixtures

- ALICE TPC: $\mathrm{D}_{T/L} \approx 220\ \mu m/\sqrt{cm}$



Ernst Hellbär: Ion Movement and Space-Charge Distortions in the ALICE TPC, Master Thesis, 2015

Signal creation

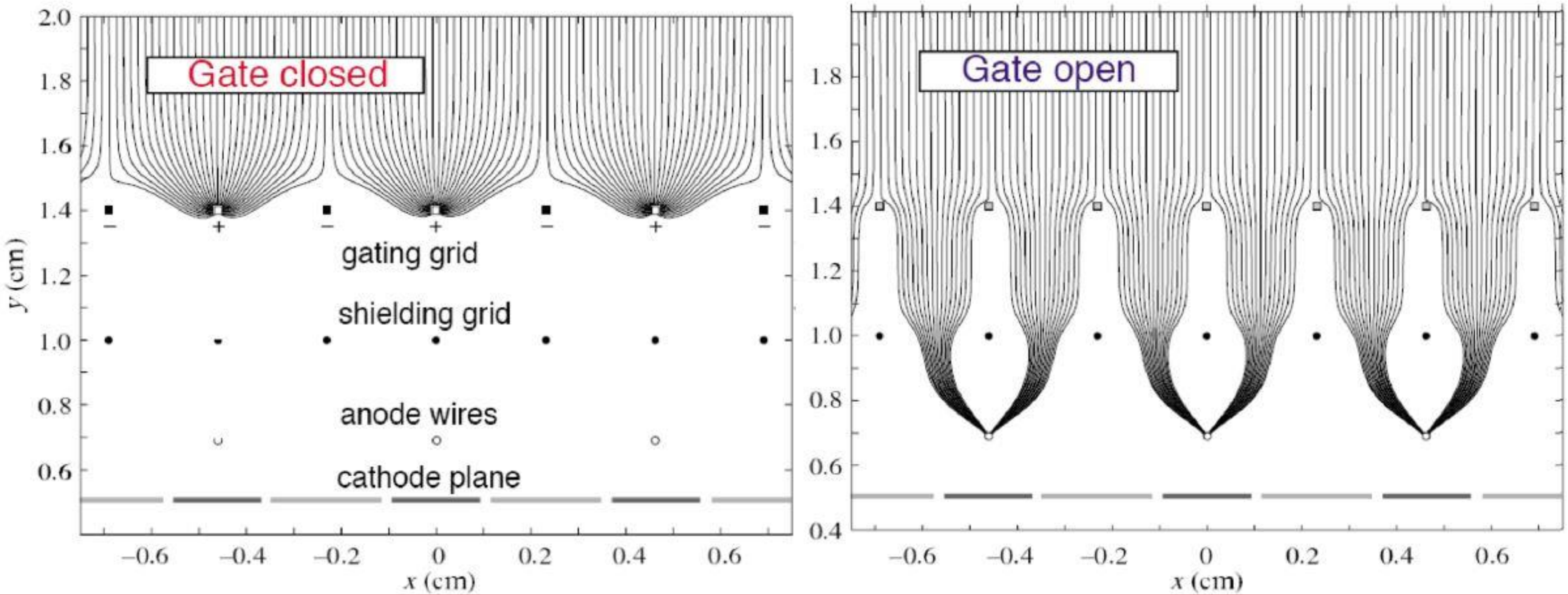
- $\sim 40\ e^{-}/cm$ for $\mathrm{Ne{-}CO_2}$ (90-10)
- Electric noise $\sim 1000\ e^{-}$

$\Longrightarrow$Signal amplification

- Current ALICE TPC: Multi Wire Proportional Chamber (MWPC) with gating grid
- Run 3: Gas Electron Multiplier (GEM) stack

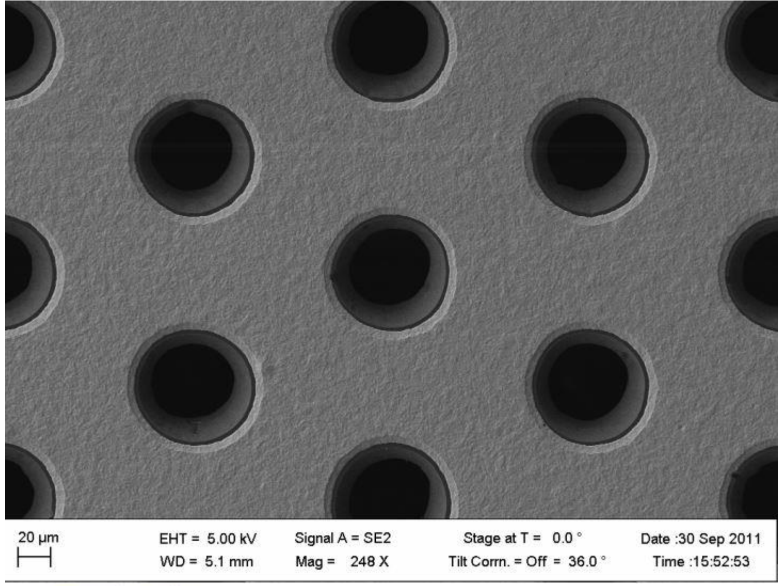
Signal creation: ALICE MWPC

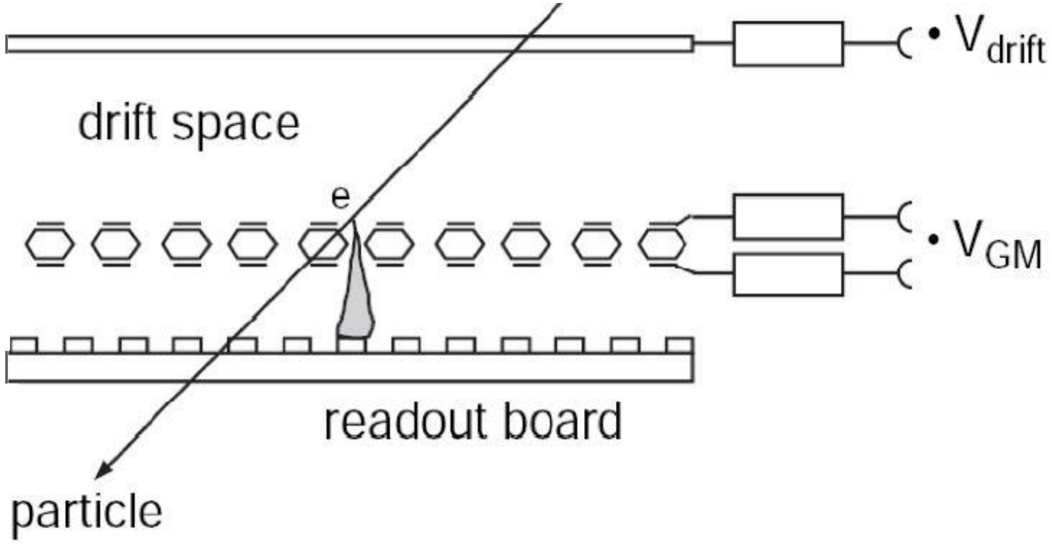
- Grid of wires with applied voltage → High E-field close to wires
- e^- accelerated → electron avalanche (Gas gain $\sim 6 - 10 \cdot 10^3$)
- Gating grid to handle ion backflow (IBF) with max. readout rate ~ 8 kHz
- Ions induce signal on readout plane

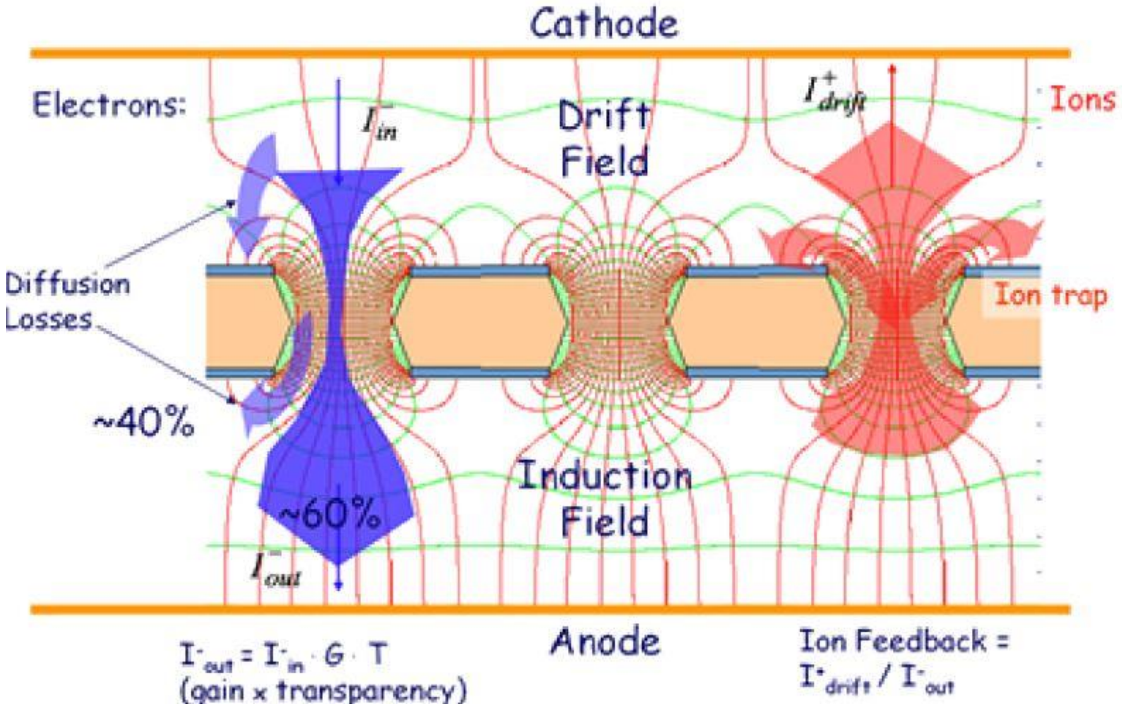


Signal creation: GEM

- LHC Run 3: Pb-Pb collision rates up to 50 kHz → Gating grid too slow
- GEM continuous readout and intrinsic IBF suppression
- Ion trapping and electron transparency depends on asymmetry
- Ideally: suppress all ion backflow, however…

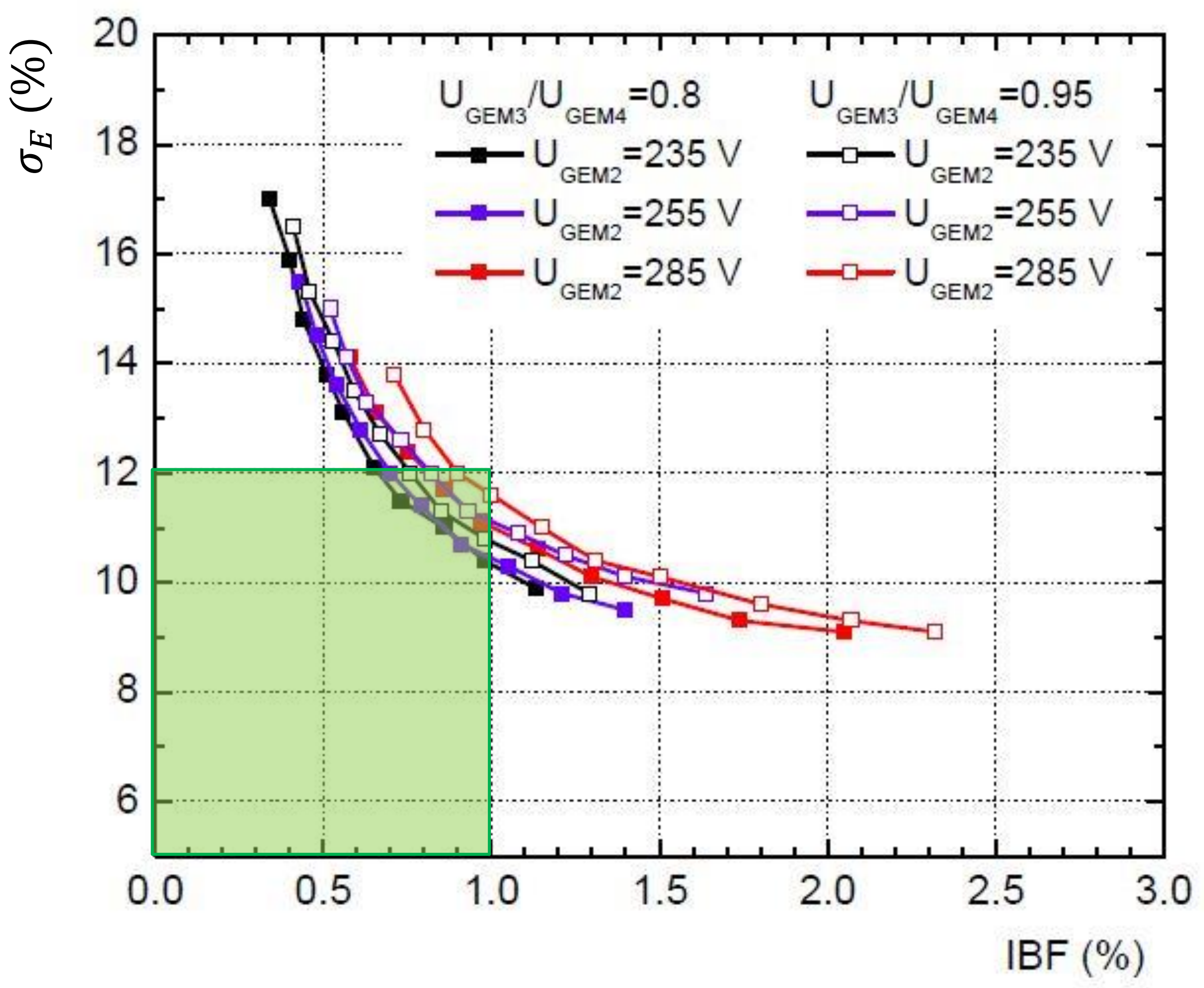






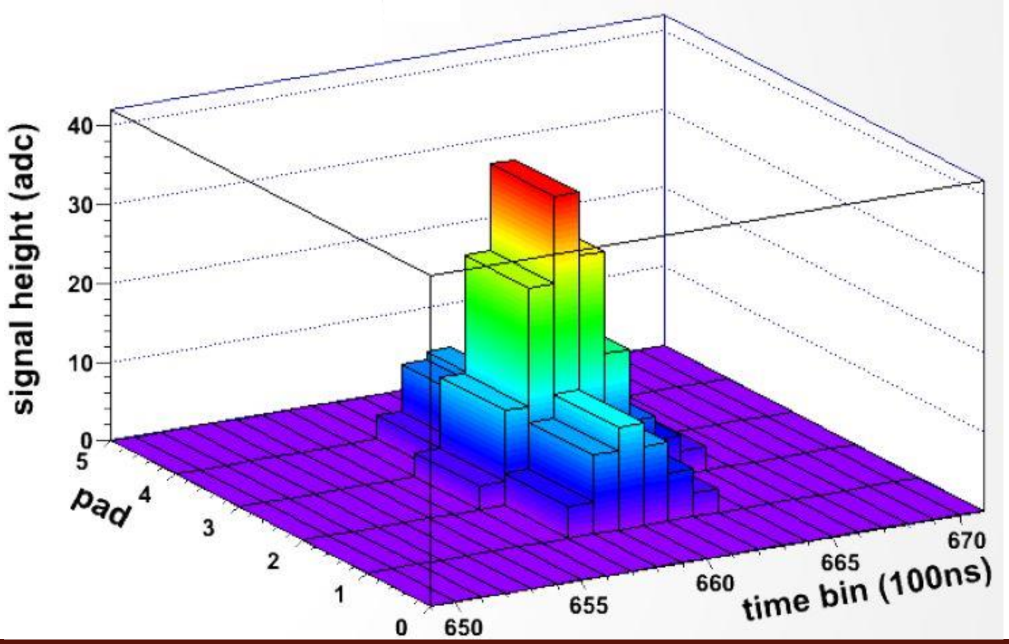
GEM ion backflow reduction

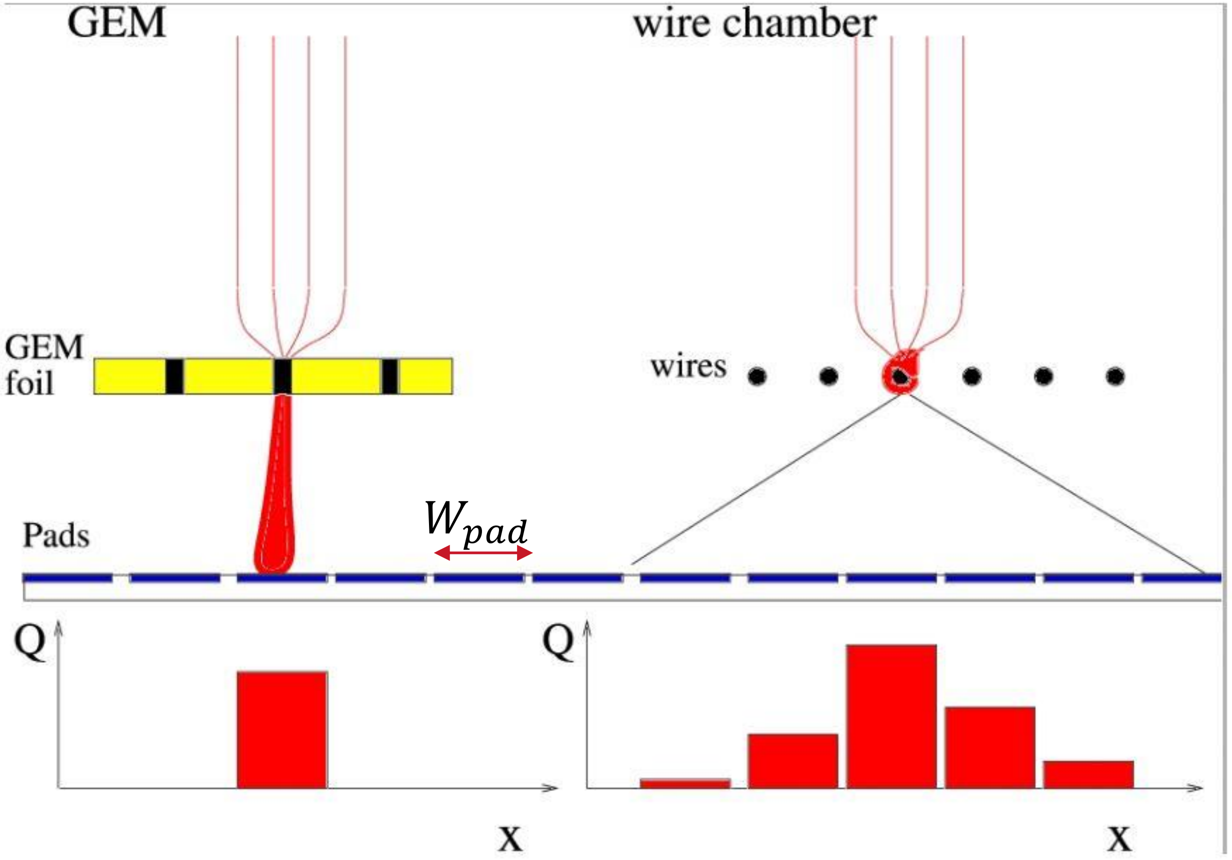
- Reducing ion backflow reduces electron transparency
  - → worsens energy resolution
- Compromise between energy resolution and ion backflow
- $\sigma_E\left(\mathrm{Fe}^{55}\right) < 12\%, IBF < 1\%$
- Stack of 4 GEMs



Pad response

- Center of gravity (COG) improves resolution
- $x_{COG} = \sum_{i=0}^{N} n_i x_i \, / \sum_{i=0}^{N} n_i$
- COG resolution $\sigma_{pad} \sim W_{pad} \cdot \frac{\sigma_{el.noise}}{Q}$,
- However GEMs have narrow pad response functions → $\sigma_{pad,GEM} = \frac{W_{pad}}{\sqrt{12}}$

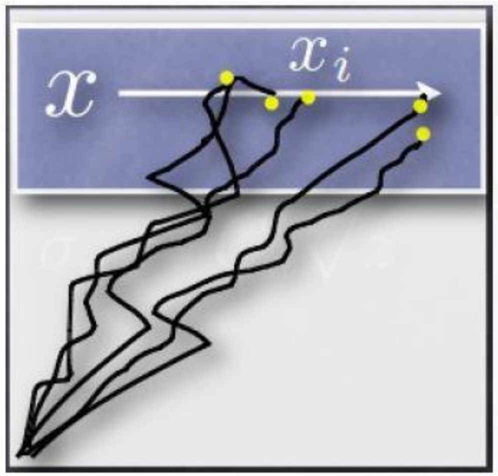




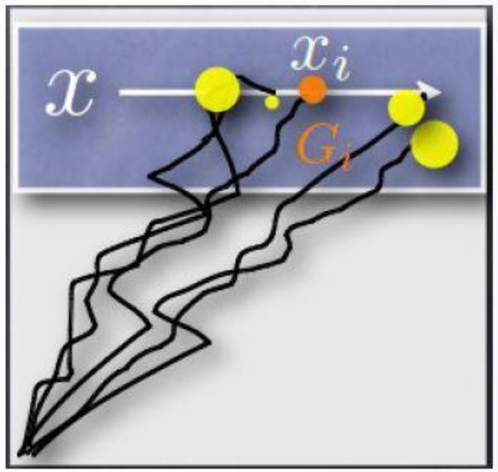
https://web.physik.rwth-aachen.de/~tpcmgr/downloads/talks/ICATPP-como03-roth.pdf

Gas Gain Fluctuation

- Gain fluctuations impact coordinate measurement
- Every e^- of cluster amplified independently
- gain $G \sim \exp(-\alpha n)$ → exponential fluctuations
- Shifts center of gravity → weigh coordinate with gain



No gas gain fluctuations



With gas gain fluctuations

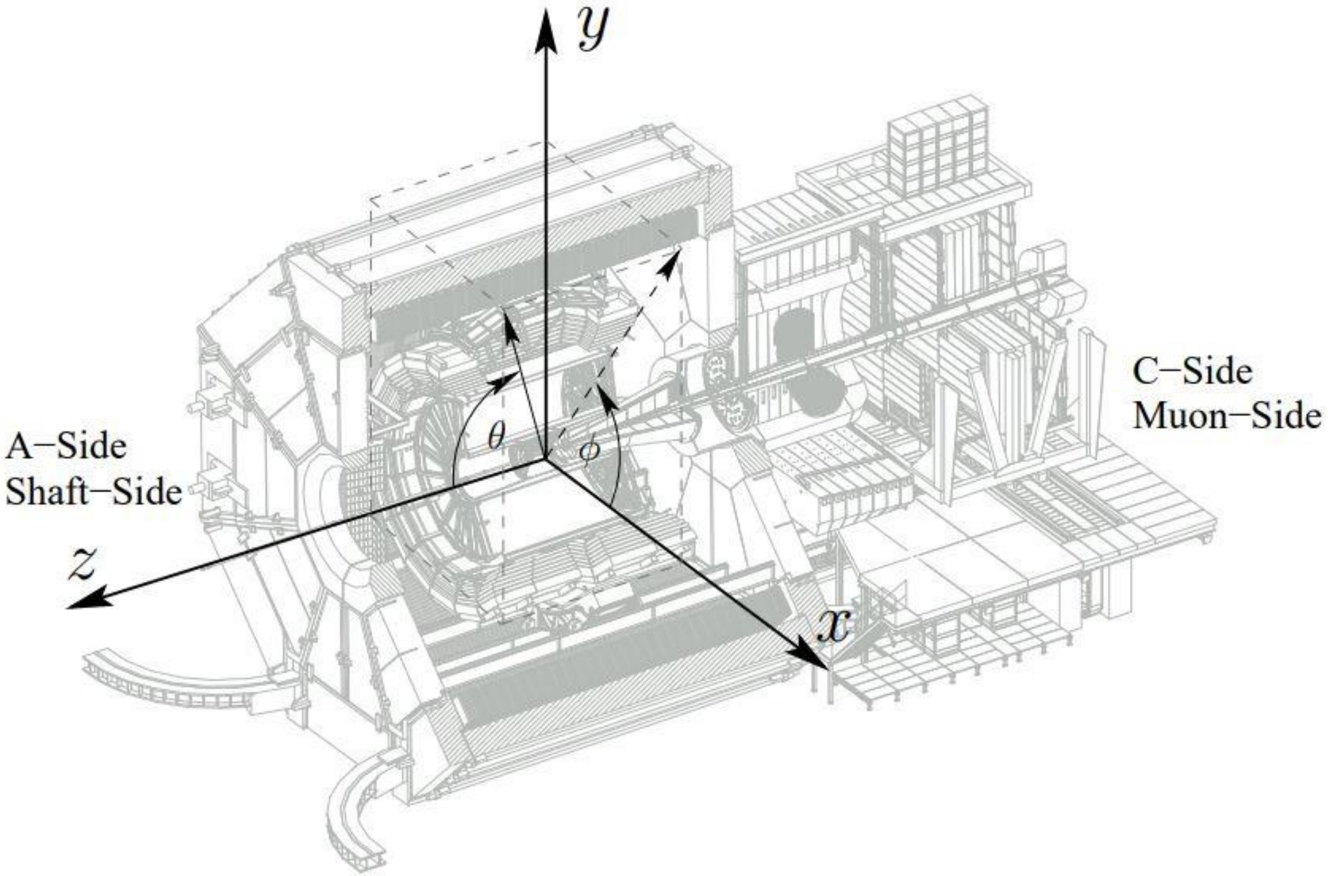
$$\sigma^2_{drift} = \frac{D^2 L_{drift}}{N} \cdot G^2_{gfactor}$$

Diffusion constant

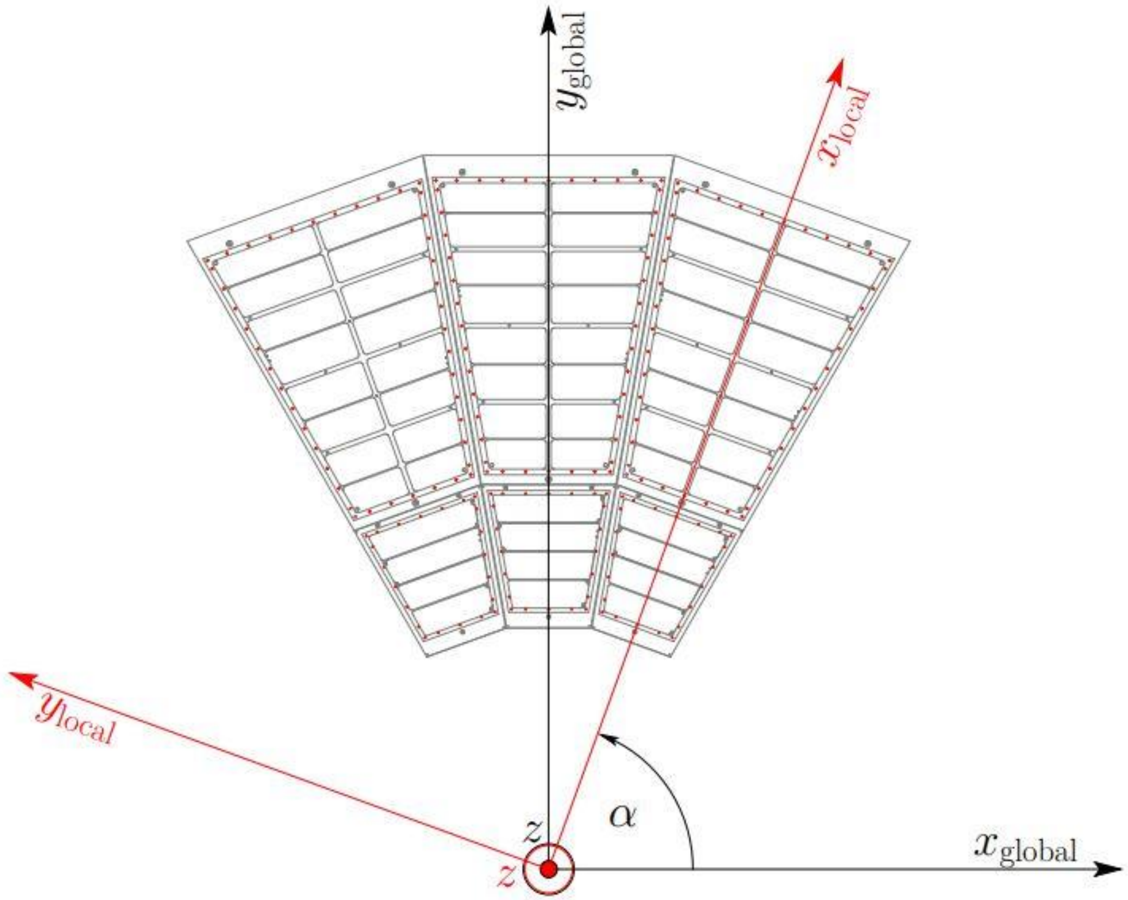
$$G^2_{gfactor} = N \frac{\sigma_g^2/\overline{g}^2 + 1}{N + \sigma_g^2/\overline{g}^2} = \frac{2\mathrm{N}}{\mathrm{N}+1} \approx 2$$

ALICE coordinate system

Global coordinate system



Local coordinate system

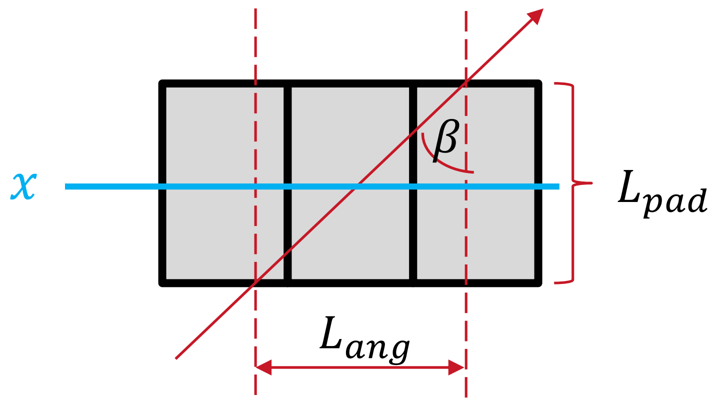


Angular pad effect

- x-position fixed at middle of pad row
- y-position random variable with uniform width

$$L_{ang} = L_{pad} \cdot \tan\beta$$

$$\sigma_{ang}^2 = \frac{tan^2(\beta) L_{pad}^2 G_{Lfactor}(N_{prim})}{12 N_{prim}}$$

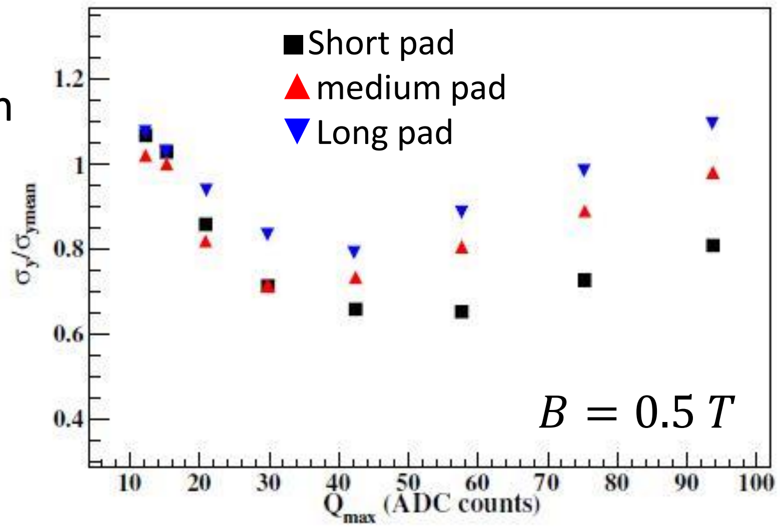


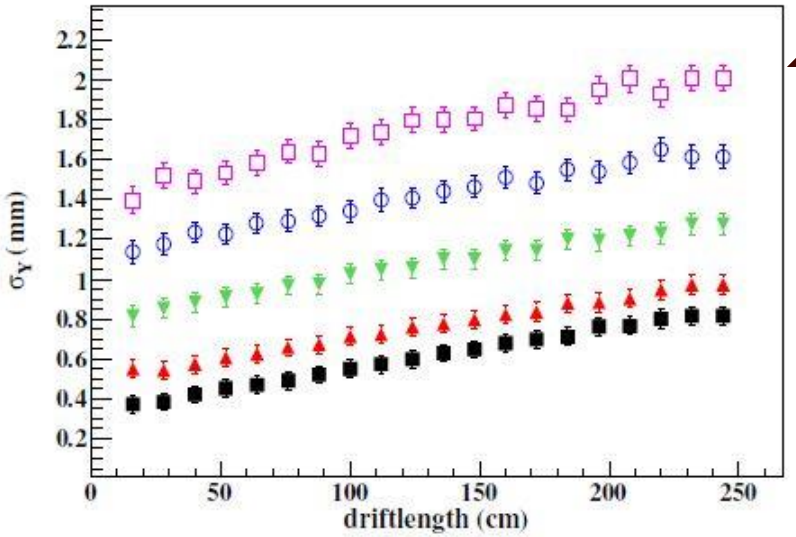
Other effects

- ExB effects, space charge → talk by Pascal Becht
- Electron attachment
- Gas impurities
- Wire vibrations

Resolution of ALICE TPC

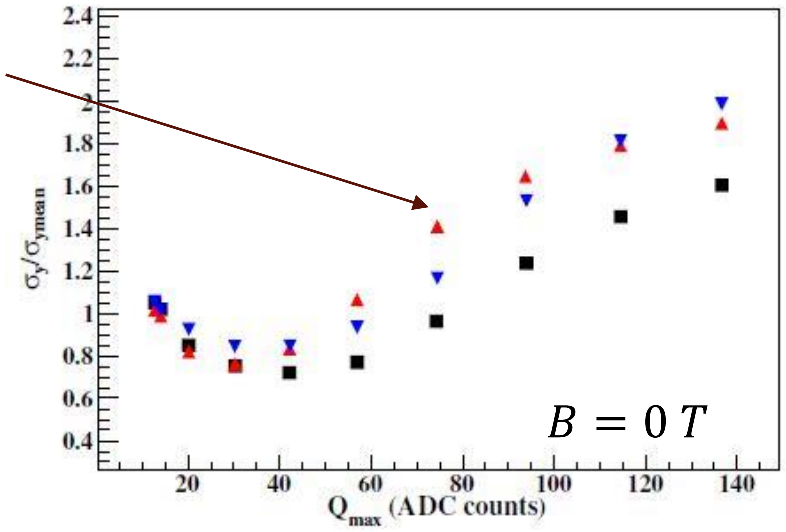
Space point resolution in $r\phi$ direction as function of the maximum of deposited charge within a cluster Q_{max}

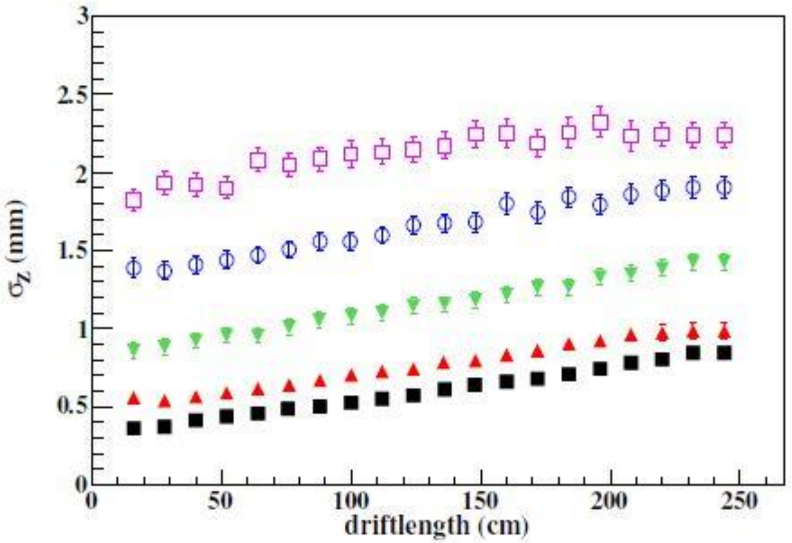




Small to high inclination angle

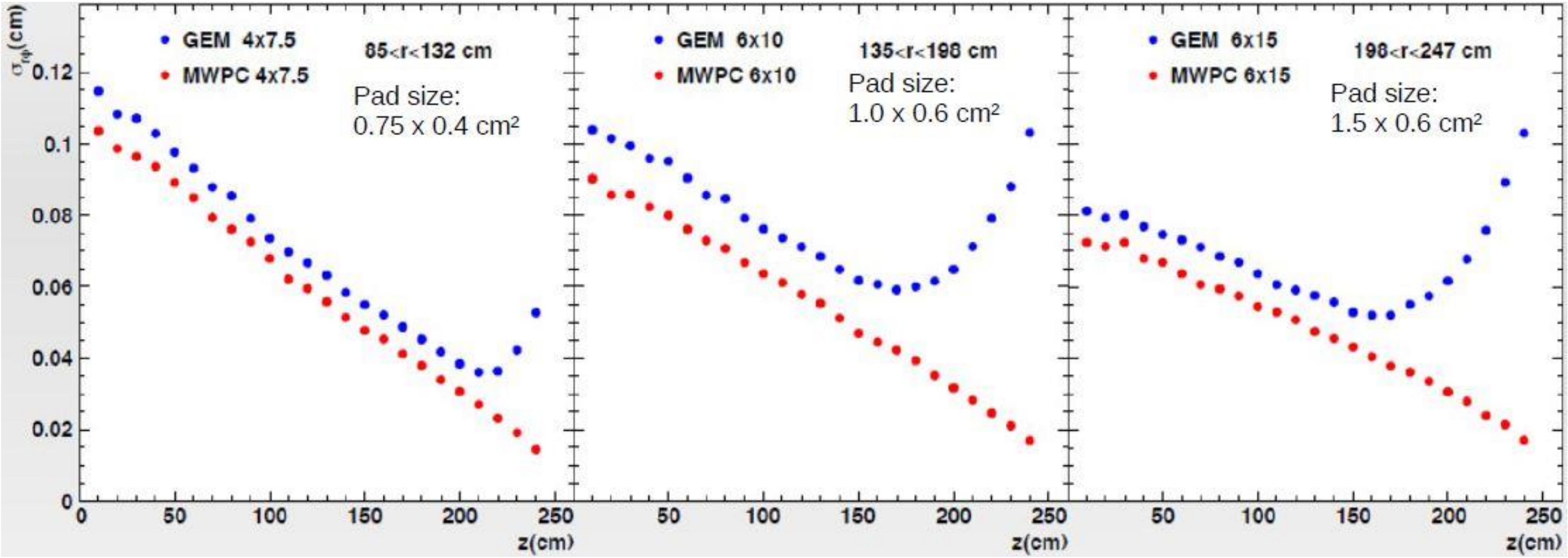
δ-electrons worsen resolution





Space point resolution in $r\phi$ and z-direction as function of the drift length.

Resolution of MWCP vs GEM readout



- Gem slightly worse resolution
- Narrow pad response of GEM → worse space point resolution near readout

Jens Wielchua: ALICE-TPC upgrade with GEMs

Momentum resolution

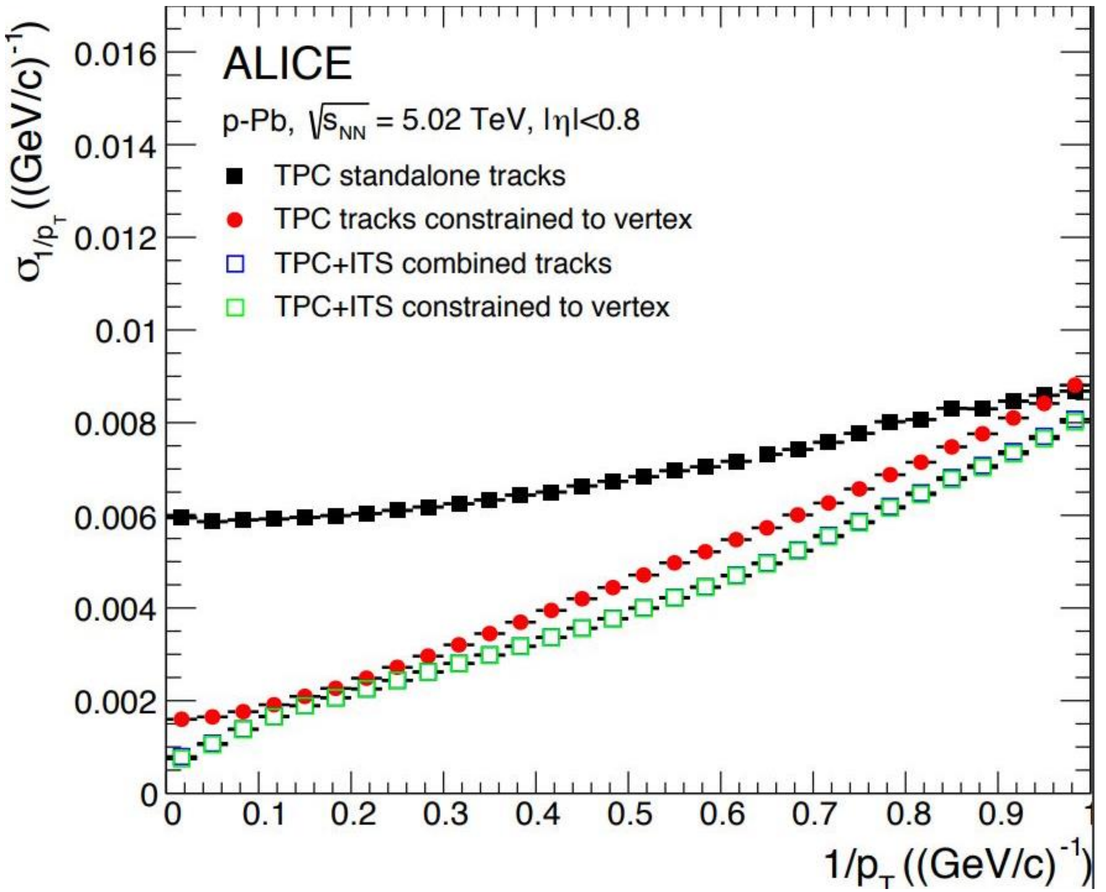
- Track curvature influenced by space point resolution
- Uncertainty:

$$\left|\frac{dp_T}{p_T}\right|_{tot} = \left|\frac{dp_T}{p_T}\right|_{res} + \left|\frac{dp_T}{p_T}\right|_{MS} + \left|\frac{dp_T}{p_T}\right|_{B}$$

- N equidistant measurements: Gluckstern formula

$$\left|\frac{dp_T}{p_T}\right|_{res} = \frac{\sigma_{point}}{eB_0L^2}\sqrt{\frac{720}{N+4}}p_T$$

L: projected length of track onto bending plane



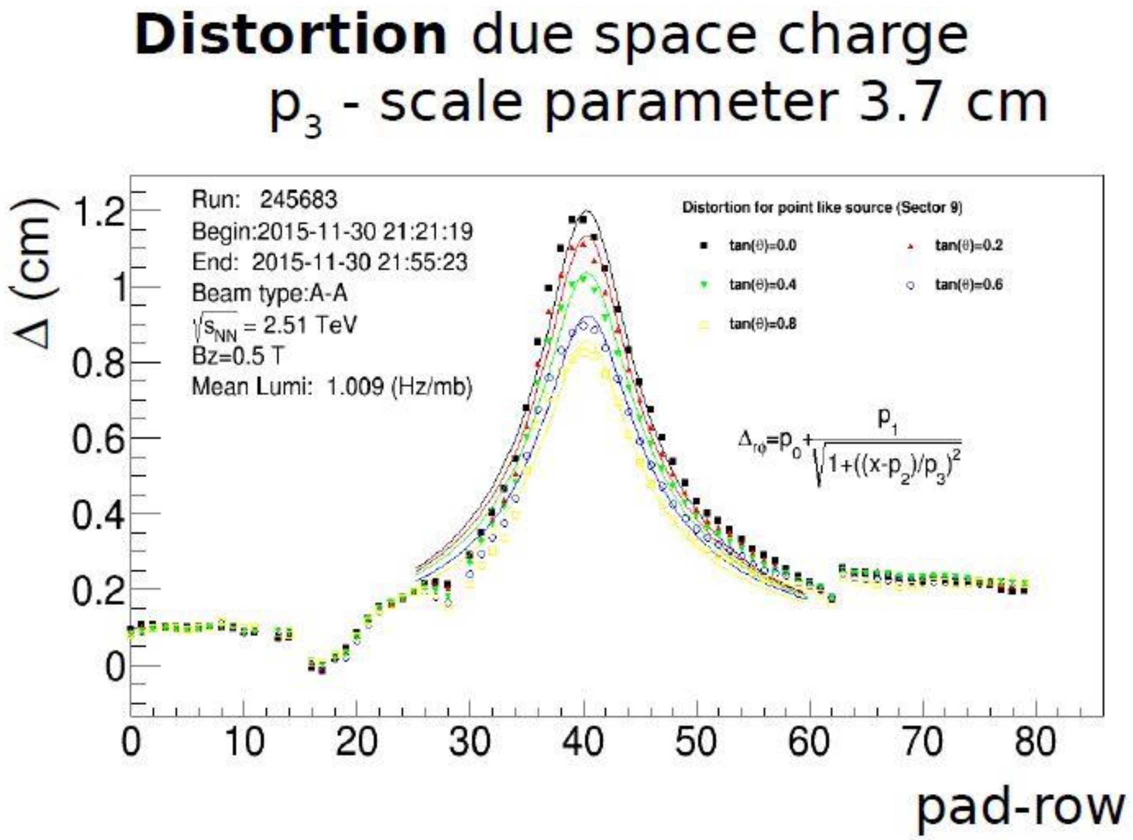
p_T resolution of ALICE the ALICE TPC (2014)

ALICE Collaboration: Performance of the ALICE Experiment at the CERN LHC, arXiv:1402.4476

Correlation of space points

- Space points can be correlated
- Example: point-like space charge → several electrons attracted to/repulsed by same point
- Group space points according to correlation length
- Reduces effective space points, but takes correlation into account
- $N_{eff} \sim N_{all}/N_{corr} = 159/20 \approx 8$

$\Longrightarrow$ Need higher space point resolution for given track resolution than naively expected



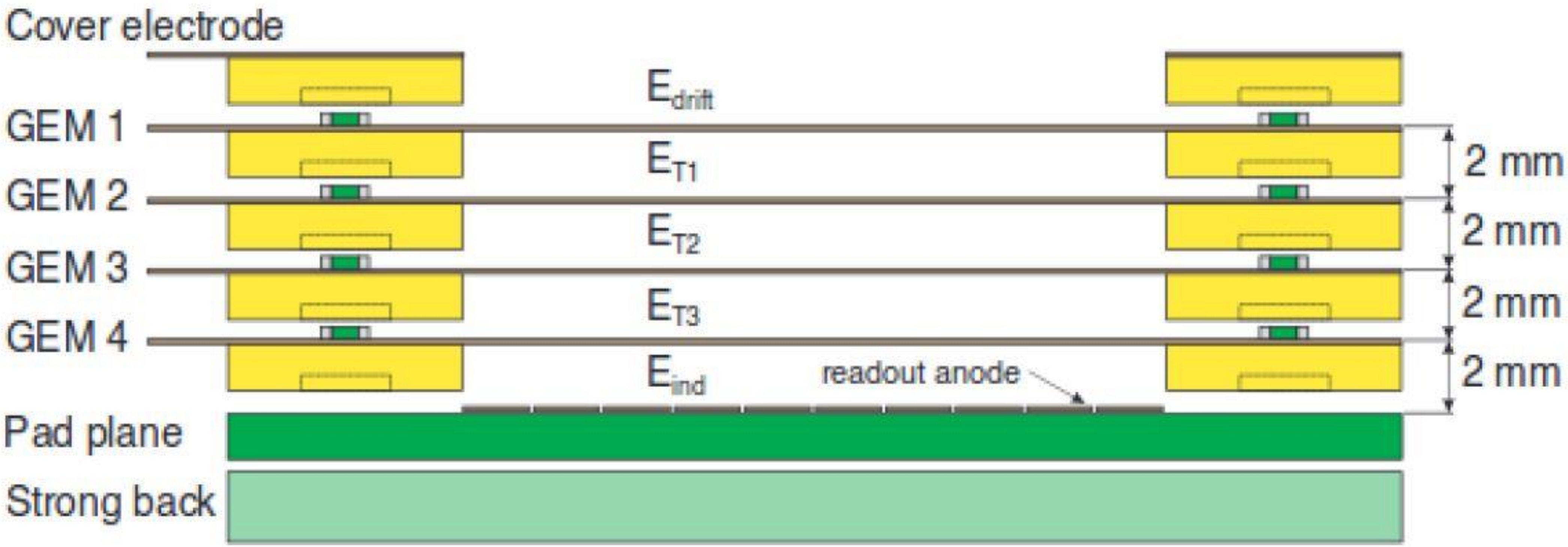
Summary

- TPC‘s especially well suited for high multiplicity environments
- Full track reconstruction
- Large coverage
- Relatively slow → New continuous readouts needed, large research effort
- Resolutions dependent on field strengths, pad sizes and gas mixture

Sources

- Marian Ivanov
- Particle detectors lectures by Silvia Masciocchi (SS 2017, Heidelberg)
- *Particle Detection with Drift Chambers*, W. Blum and L. Rolandi, Springer-Verlag, 1994
- *The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events*, ALICE Collaboration, 2010
- *Technical Design Report for the Upgrade of the ALICE Time Projection Chamber*, ALICE Collaboration, 2014
- *TPC tracking and particle identification in high-density environments*, Y.Belikov, M.Ivanov, K. Safarik, 2003
- Jens Wiechula: TPC lectures

GEM stack



Cover electrode
GEM 1
GEM 2
GEM 3
GEM 4
Pad plane
Strong back
E_{drift}
E_{T1}
E_{T2}
E_{T3}
E_{ind}
readout anode
2 mm
2 mm
2 mm
2 mm

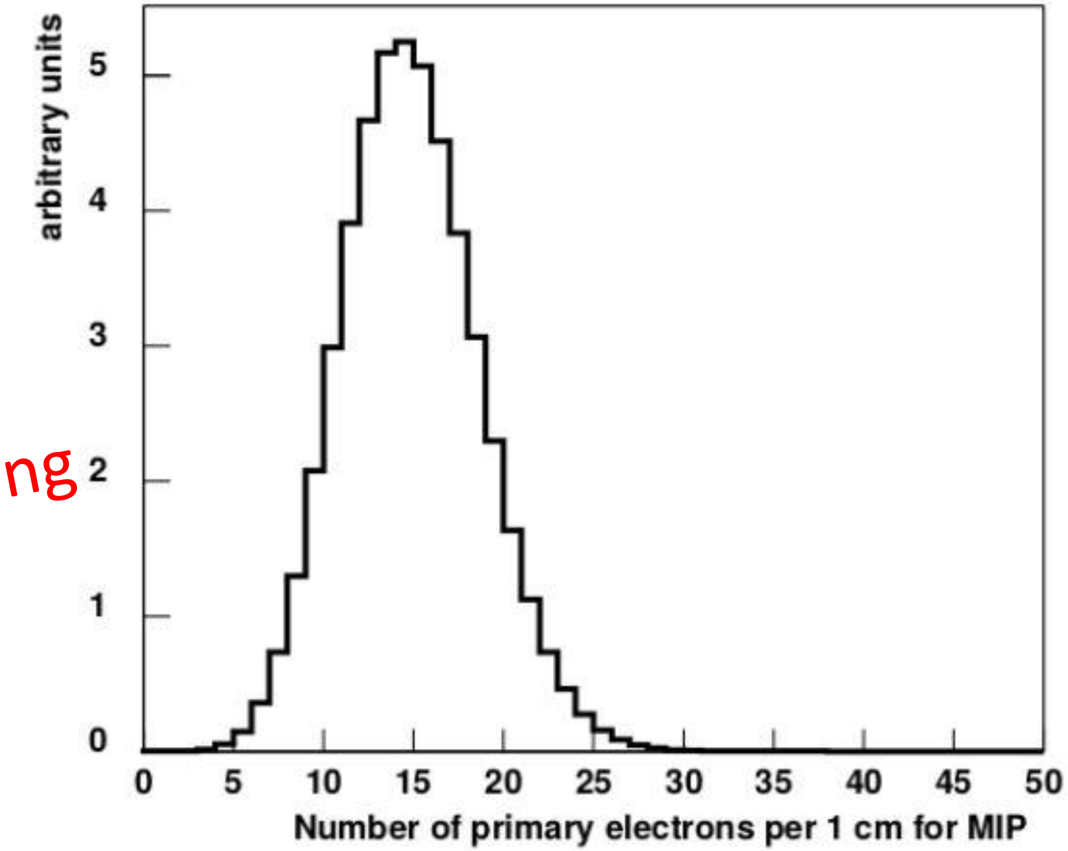
Primary Ionization

- $\#e^-$ per cm: $\langle N_P \rangle = 1/\lambda$
  - λ: mean free path
- Number of primary e^- poisson distributed

$$P(N_P, \langle N_P \rangle) = \frac{\langle N_P \rangle^{N_P} e^{-\langle N_P \rangle}}{N_P!}$$

Combine with secondary if presentation too long

Simulation for ALICE TPC with $\mathrm{Ne/CO_2}$ (90-10)



Secondary Ionization

- High energy e^- $\rightarrow$ further ionization
- Secondary clusters near primary ionization

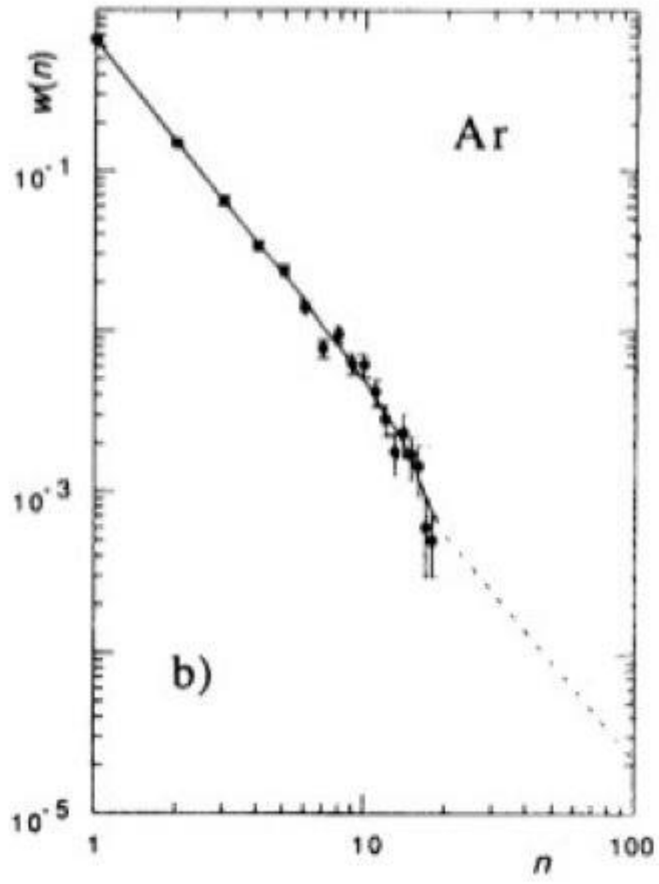
$\Longrightarrow$ Cluster formation

- $N_{tot} \approx 3 - 4\ N_p$

Range e^- for Argon Primaries?

Energy	Range
$1\ keV$	$30\ \mu m$
$10\ keV$	$1.5\ mm$
$30\ keV$	$1\ cm$
$60\ keV$	$3\ cm$

$30\ keV$ and $60\ keV$: Outside of cluster, not detected



Cluster size distribution in Argon