ALICE-TPC upgrade with GEMs

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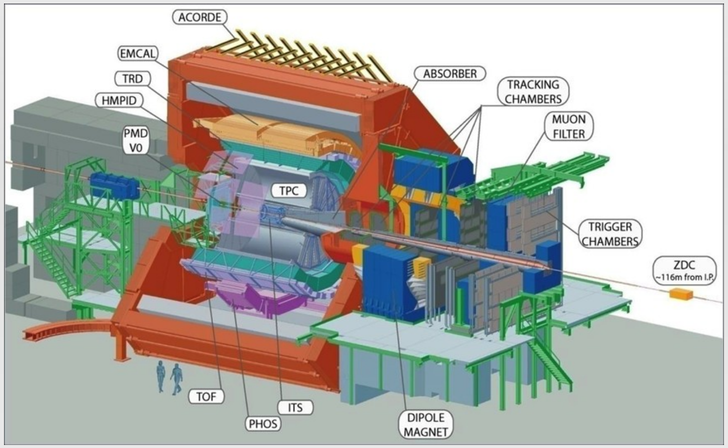
for the
ALICE TPC Upgrade collaboration

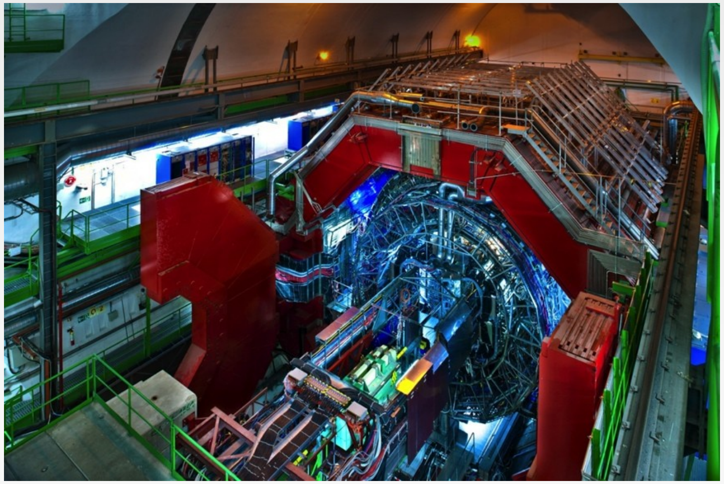
Outline

- Introduction
- R&D with small prototypes
- Results from a large prototype
- Reconstruction and calibration strategy
- Summary

Introduction

ALICE upgrade during LS2





- Operate ALICE at high luminosity ($L=6\times10^{27}$ $cm^{-2}s^{-1}$ for Pb-Pb)
- Significant detector upgrades:
  - Inner Tracking System (ITS)
    - improved vertexing and standalone tracking
    - increased readout speed and rate capability
  - Muon Forward Tracker
  - Electronics, Trigger, Readout systems
  - TPC with continuous readout.
    - high rate capability
    - preserve PID and tracking performance
- Rich physics program in RUN3 (>=2019)
- Detailed characterization of QGP
- Main physics topics:
  - Heavy flavors
  - Low-mass and low-pt di-leptons
  - Quarkonia (J/ψ, ψ',Y)
  - Jet quenching and fragmentation
  - Anti- and hypernuclei

The ALICE Time Projection Chamber

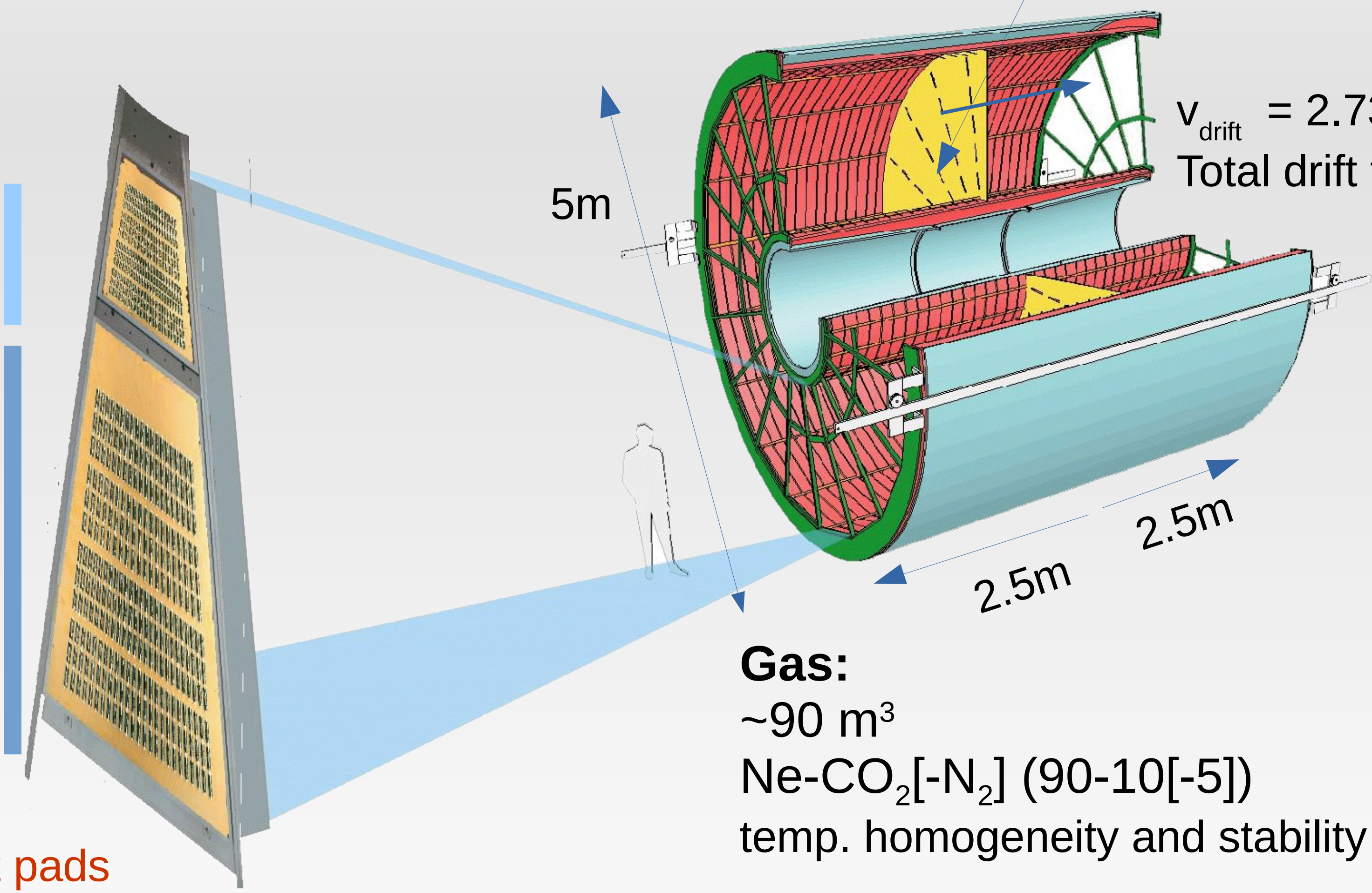
In numbers

Most challenging TPC ever built

Central HV electrode
100kV → 400 V/cm

2x18 Inner Readout Chambers

2x18 Outer Readout Chambers



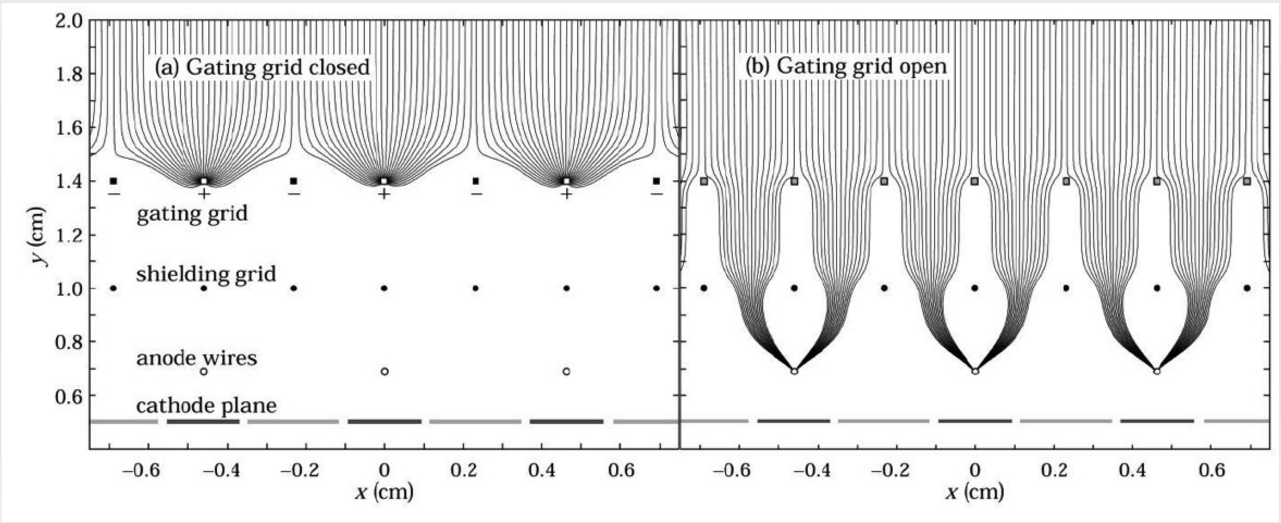
v_{drift} = 2.73 cm/µs
Total drift time 92 µs

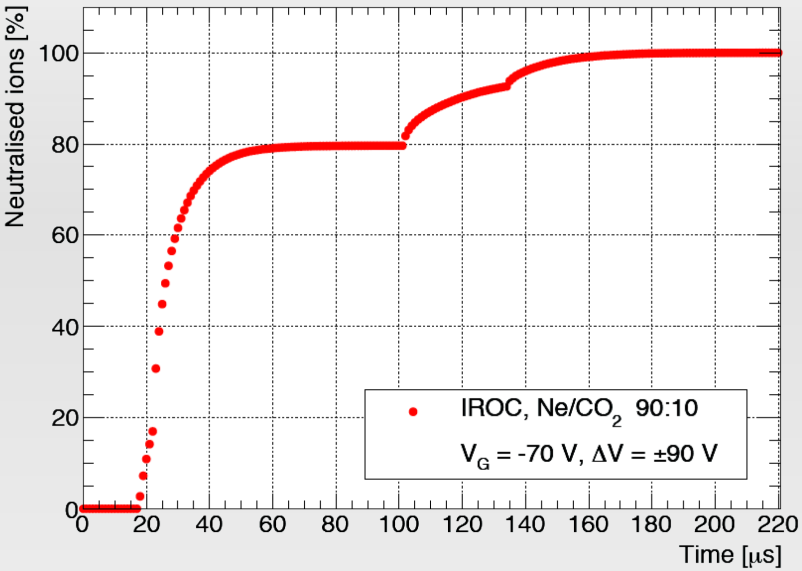
Gas:
~90 m^3
Ne-CO_2[-N_2] (90-10[-5])
temp. homogeneity and stability < 100mK

557568 readout pads
1000 samples in time direction
Designed for charged-particle tracking and dE/dx measurement
in Pb-Pb collisions with dNch/dη=8000, σ(dE/dx)/(dE/dx)<10%

The ALICE TPC

Limitations of the present system



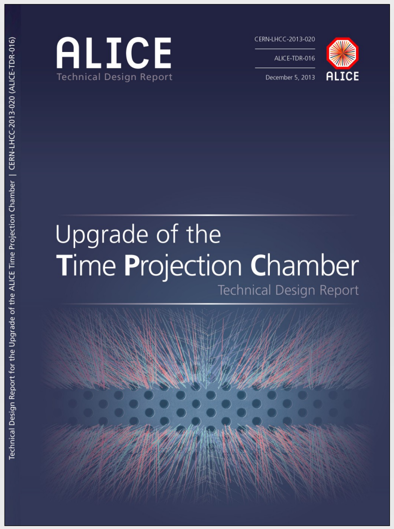


- MWPC with a gating grid (GG) limits operation to ~3.5kHz
- 100µs (electron drift) + 200µs (GG closing – full ion blocking)
  - Otherwise sizeable distortions due to space charge
- Change of read-out system required

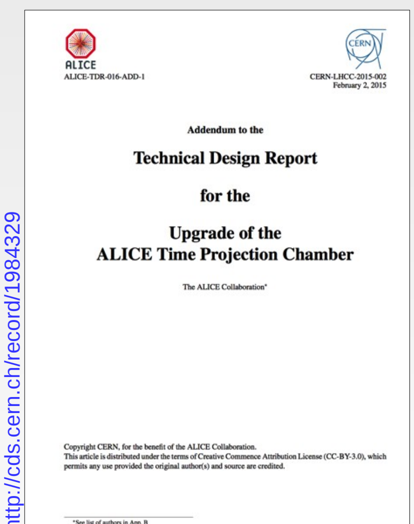
The ALICE TPC

Upgrade program

TDR
http://cds.cern.ch/record/1622286



TDR Addendum
http://cds.cern.ch/record/1984329



Endorsed by LHCC

General requirements

- 50 kHz Pb-Pb collisions (100× higher than present)
- Record all minimum bias events

Solution

- No gating and continuous readout with GEMs

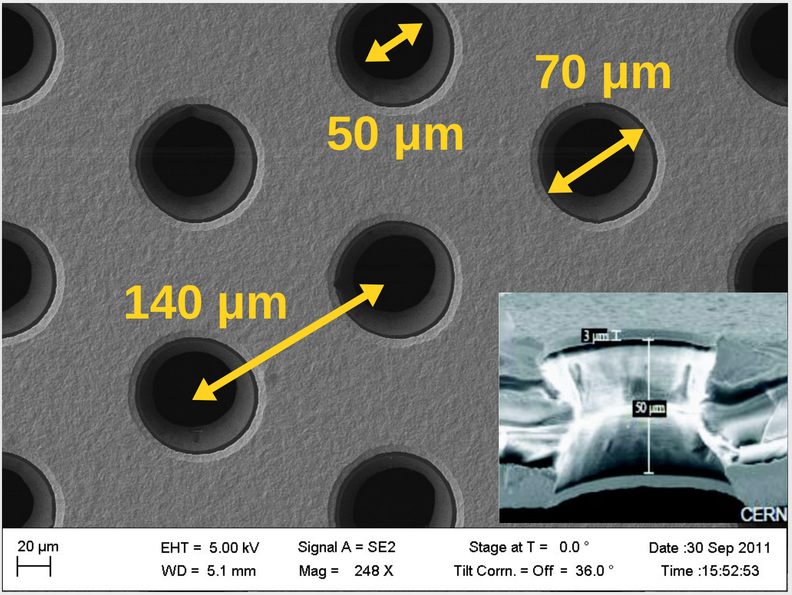
Implication

- Event pile-up in TPC: ~5 overlapping events

Requirements for GEM readout

- Operate at gain 2000 in Ne-CO_2-N_2 → Signal to noise
- IBF (ion back flow) < 1% → Impact on distortions
- $\sigma_E/E < 12\%$ for ^{55}Fe → Impact on dE/dx resolution
- Stable operation under LHC conditions
- + novel calibration and online reconstruction schemes
- + new electronics (negative polarity, self-triggered)
- (data compression by factor 20 and space charge distortions)

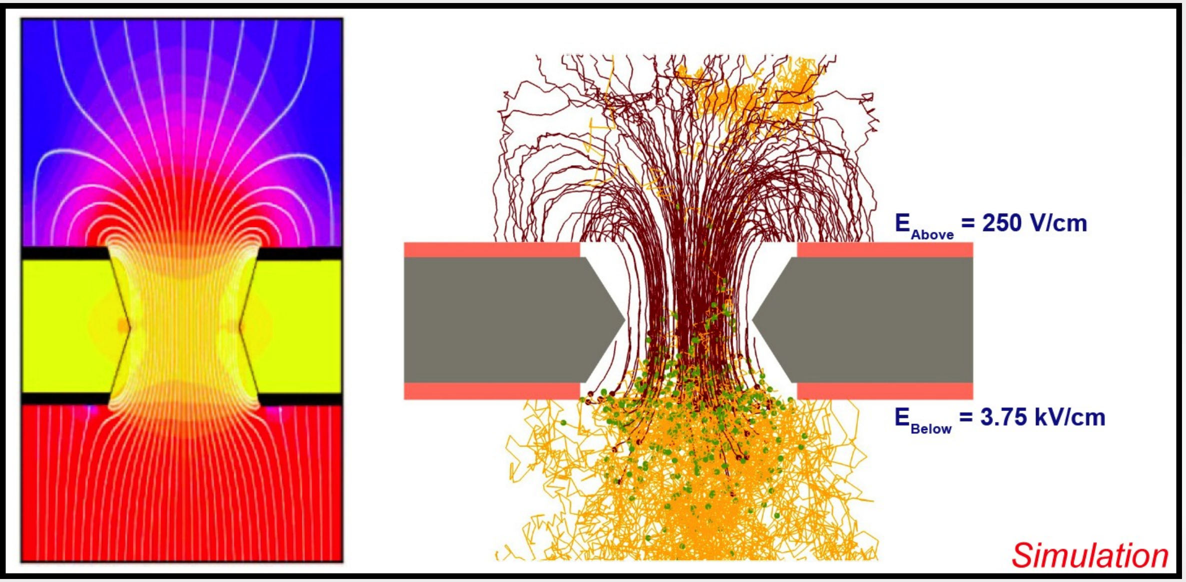
GEM technology
Introduction



- Thin polyimide foil ~*50* µm
- Cu-clad on both sides ~*5* µm
- Photolithography: ~10^4 holes/cm^2

Typical GEM geometry:

- Inner/Outer hole diameter: 50/70 µm
- **Pitch**: 140 µm
- Other geometries with different pitch sizes:
  - 90µm (SP), 200µm (MP), 280µm (LP)



- E_{Hole} up to 100 kV/cm with ΔV_{GEM} = 500 V
- $E_{Hole} >> E_{Above}$ most of the ions are collected on the top side of GEM
- $E_{Below} > E_{Above}$ electron extraction is improved

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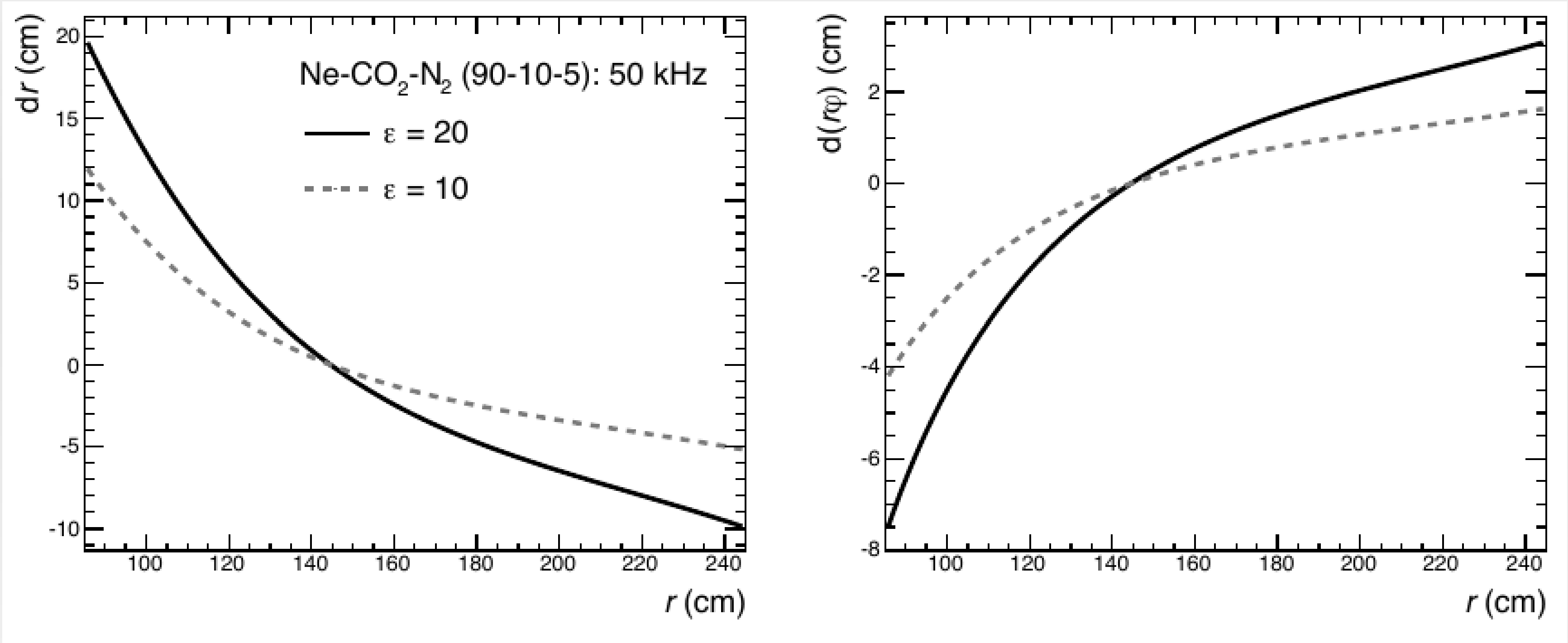
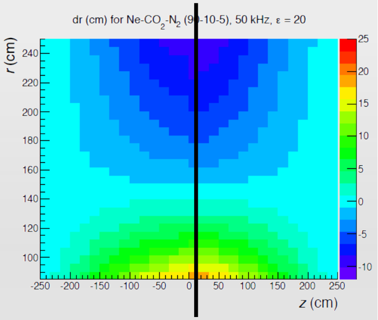
GEM technology

Impact of the Ion Back Flow



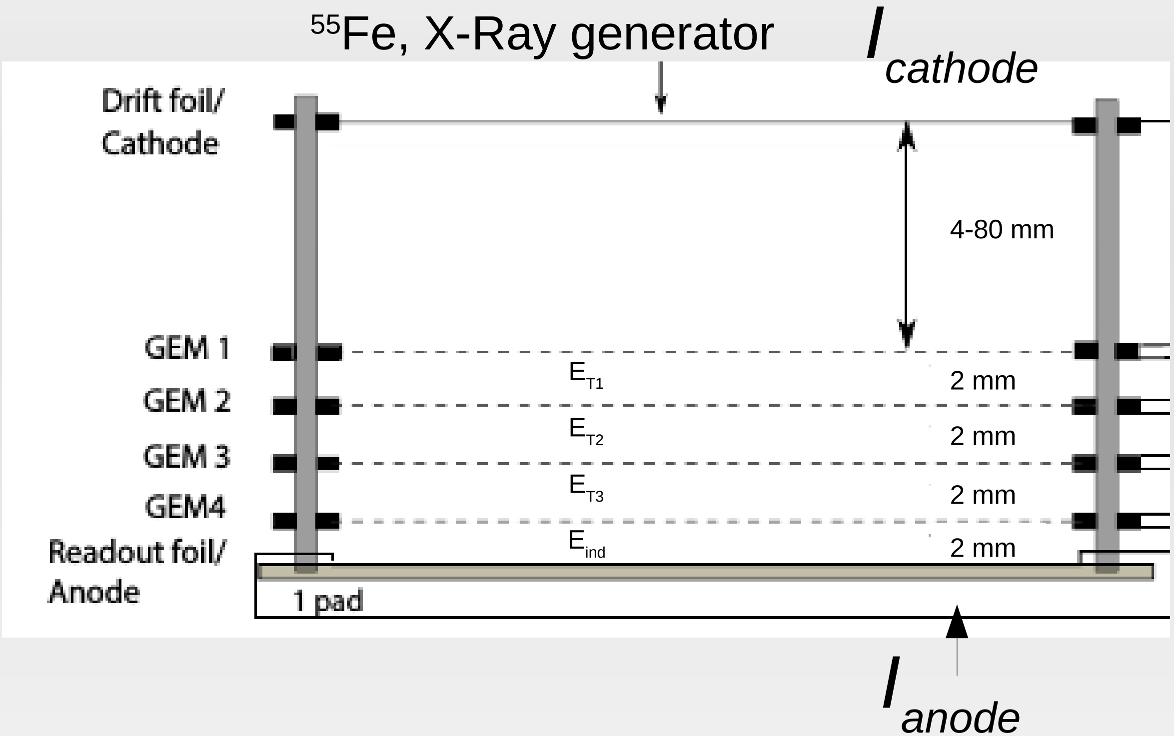


- 50kHz Pb-Pb, gain = 2000, IB=1% (ε=20)
  - $t_{d,ion}$= 160ms → ion pileup from 8000 events
- Distortions up to dr ≈ 20cm drφ ≈ 8cm (small *r* and *z*)
  - Final calibration to ~10^{-3} required

R&D with small prototypes

IBF measurements

Introduction – nomenclature



$$IB = I_{cathode}/I_{anode}$$

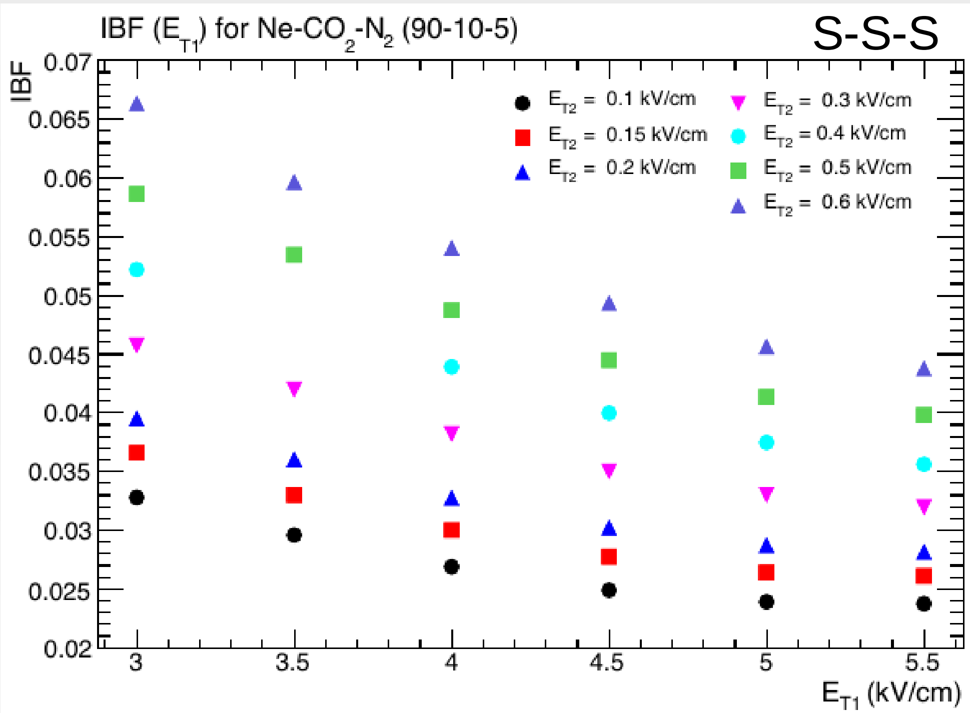
$$\varepsilon = IB * G_{eff} - 1$$

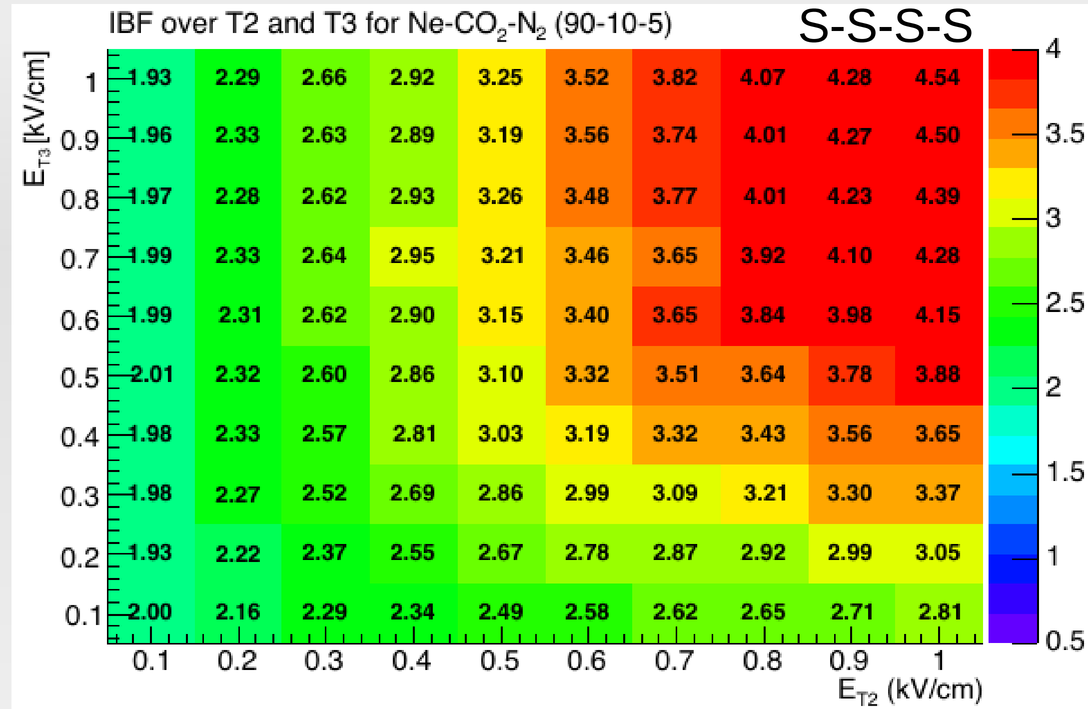
$$n_{tot} = n_{ion} * IB * G_{eff}$$

- Ion blocking not as efficient as with gating grid (10^{-5})
- Total ions in drift volume (n_{tot}) strongly depending on IBF
- Use lower GEMs (3, 4) to adjust the gain (usually $\Delta V_{GEM3}/\Delta V_{GEM4}$ = const.)
- Huge parameter space → N_{foils}, ΔV_{GEM1}, ΔV_{GEM2}, E_{T1}-E_{ind}

IBF measurements

Systematic scans – IBF minimisation



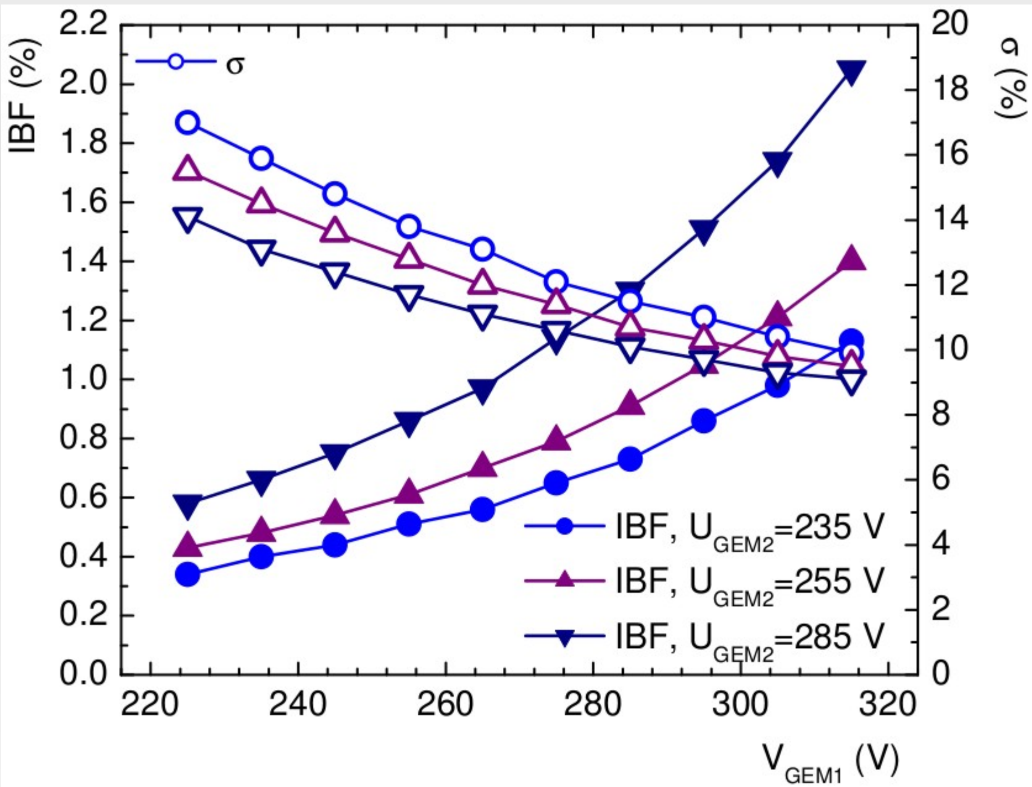


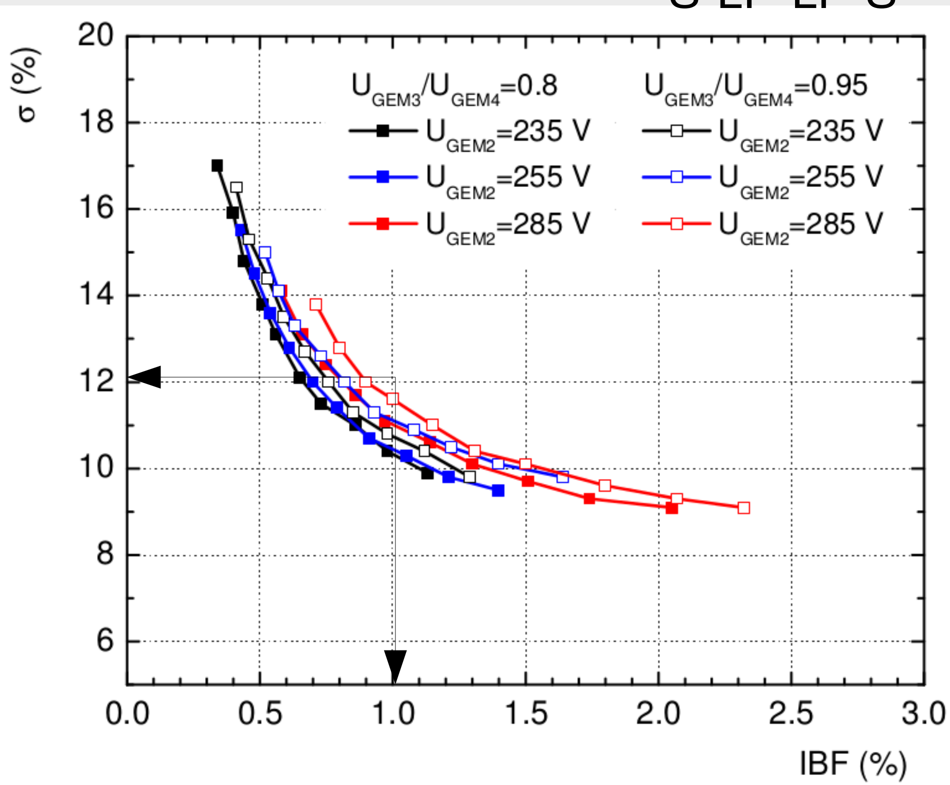
- Large parameter space scanned for triple GEM
  - IBF not lower than ~2.5%
- Move to quadruple GEM stack
  - IBF not lower than ~2% (S-S-S-S configuration)
  - → Test other GEM foil configurations

IBF measurements

Optimisation of IBF and local energy resolution

S-LP-LP-S



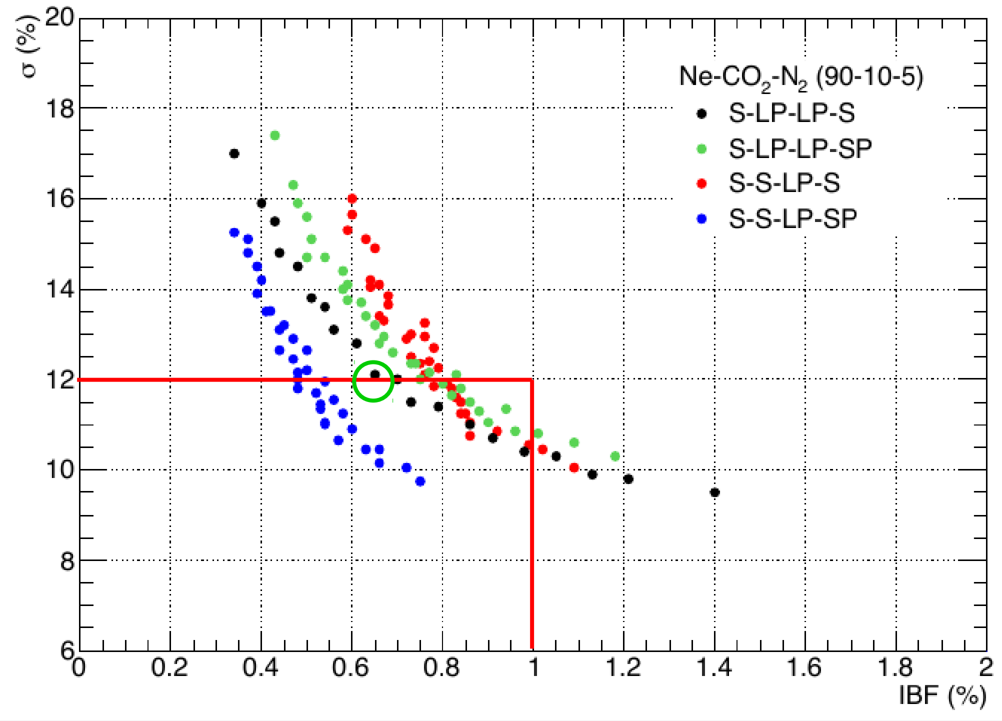


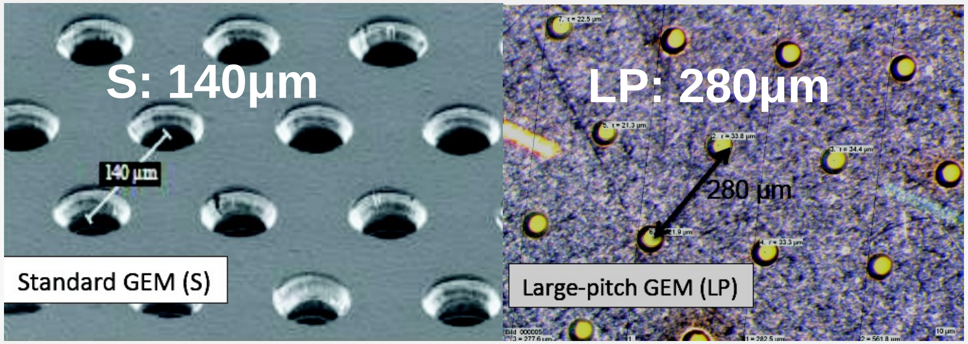
- ^{55}Fe resolution and IBF are competing
  - → always both parameters need to be monitored
- Mainly driven by ΔV_{GEM1}, ΔV_{GEM2}
- Plot variables against each other → show working point region

IBF measurements

Summary of best results

- Many more GEM configurations scanned
- Base line solution (S-LP-LP-S)
  - Working point: IB ~0.65%, σ~12%
  - ΔV_{GEM} = 275, 235, 284, 345 (V)
  - $E_{T/Ind}$ = 4, 2, 0.1, 4 (kV/cm)
- → Requirements fulfilled
- → Well characterised
- S-S-LP-SP under investigation

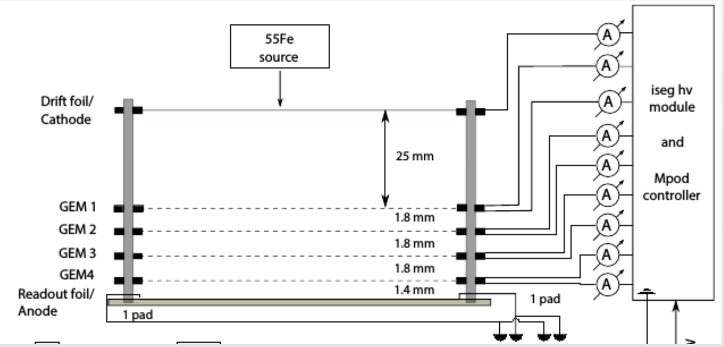




IBF measurements

Differential picture

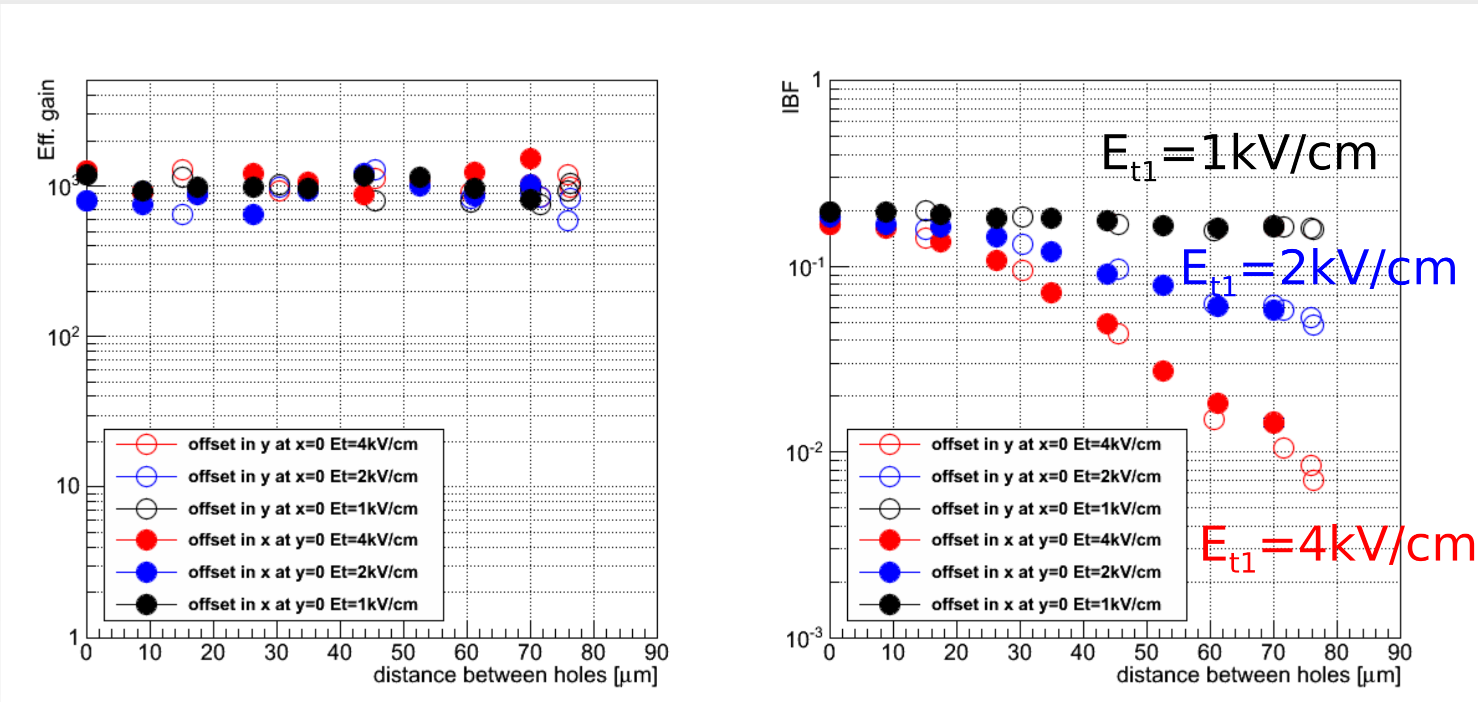
	ε_{coll}	$n_{e,in}$	M	n_{e-ion}	ε_{extr}	$n_{e,out}$	G	$n_{ion,back}$	fraction of total IBF (sim.)	fraction of total IBF (meas.)
GEM1 (S)	1	1	14	13	0.65	9.1	9.1	3.6 (28%)	40%	31%
GEM2 (LP)	0.2	1.8	8	12.7	0.55	8	0.88	3.3 (26%)	37%	34%
GEM3 (LP)	0.25	2	53	104	0.12	12.7	1.6	1.3 (1.3%)	14%	11%
GEM4 (S)	1	12.7	240	3053	0.6	1830	144	0.84 (0.03%)	9%	24%
Total				3183		1830	1830	9 (0.28%)		

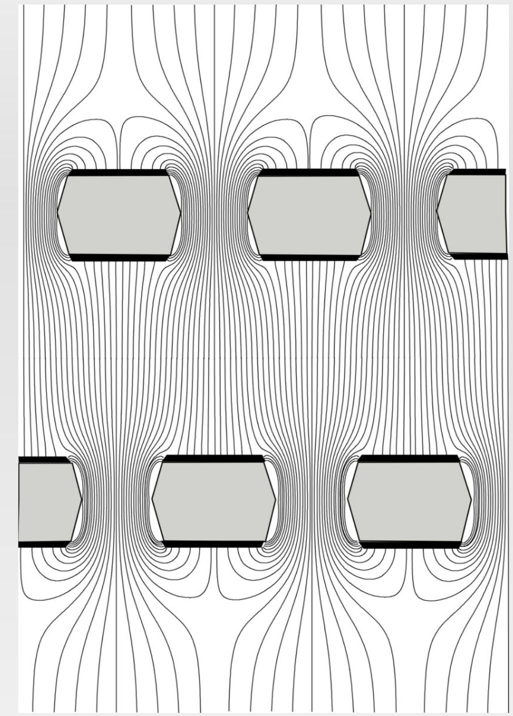


- Measure currents on all electrode
- Get differential picture of charge transport
- Main contribution to IBF from first two layers
- Main amplification from last layer
- Collection efficiency on first GEM drives the energy resolution

IBF simulations

Dependence on GEM hole distance





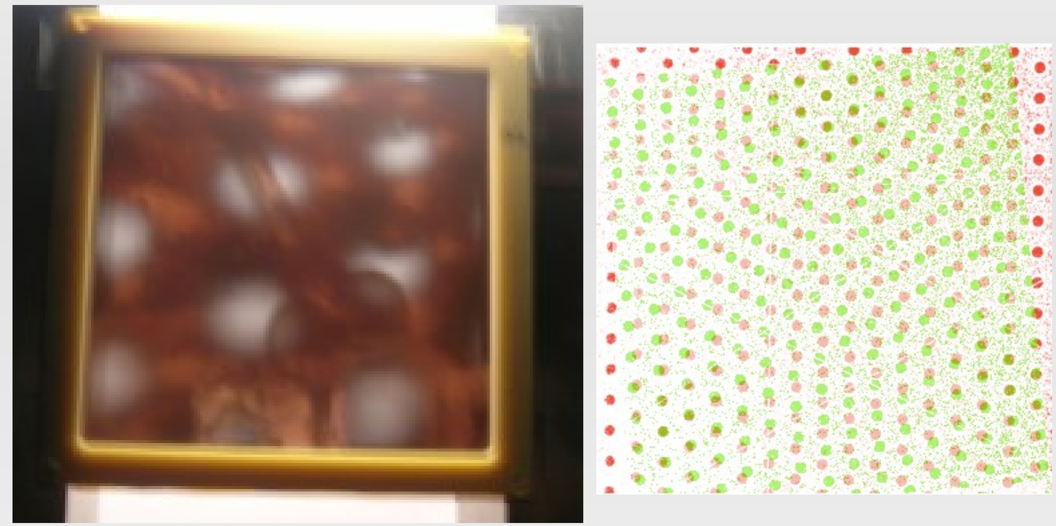
- Ne/CO_2 simulation studies
- In case of high Et1, alignment is an issue.
  - Gain and IBF vs. distance between holes in GEM1 and GEM2
- x10 difference in IBF w.r.t hole alignment

IBF simulations

Dependence on GEM hole distance – optical transparency

- Alignment cannot be controlled on µm level
- 'Optical' transparency very different over the GEM surface
  - Resulting from hexagonal GEM pattern
  - Would result in very inhomogeneous IBF → unfavourable
- Rotate adjacent foils by 90°
  - More homogeneous pattern

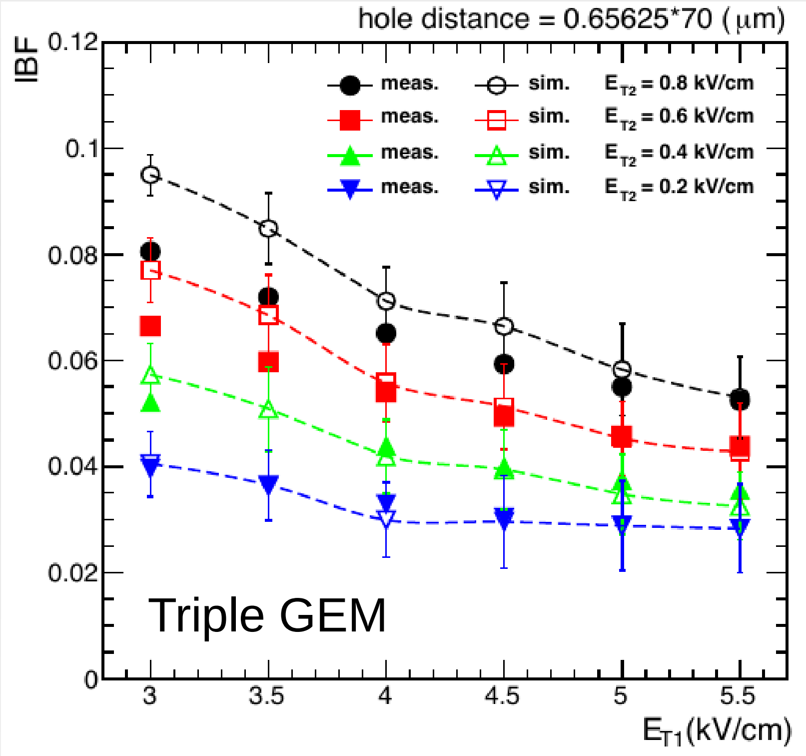
GEM Foils aligned

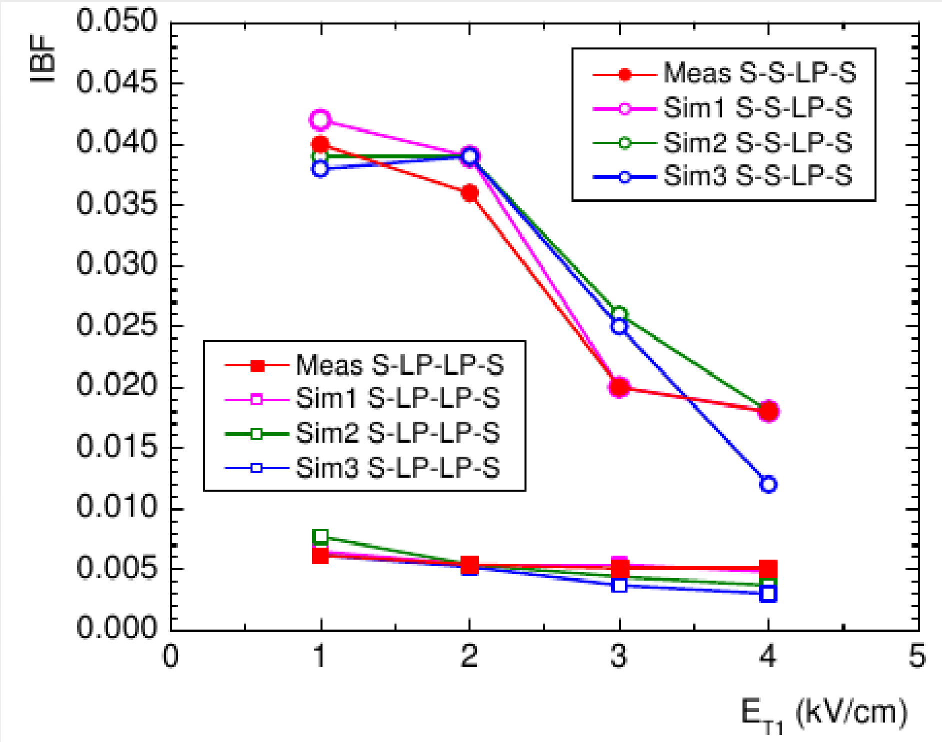


GEM Foils rotated by 90°

IBF simulations

Comparison to simulations

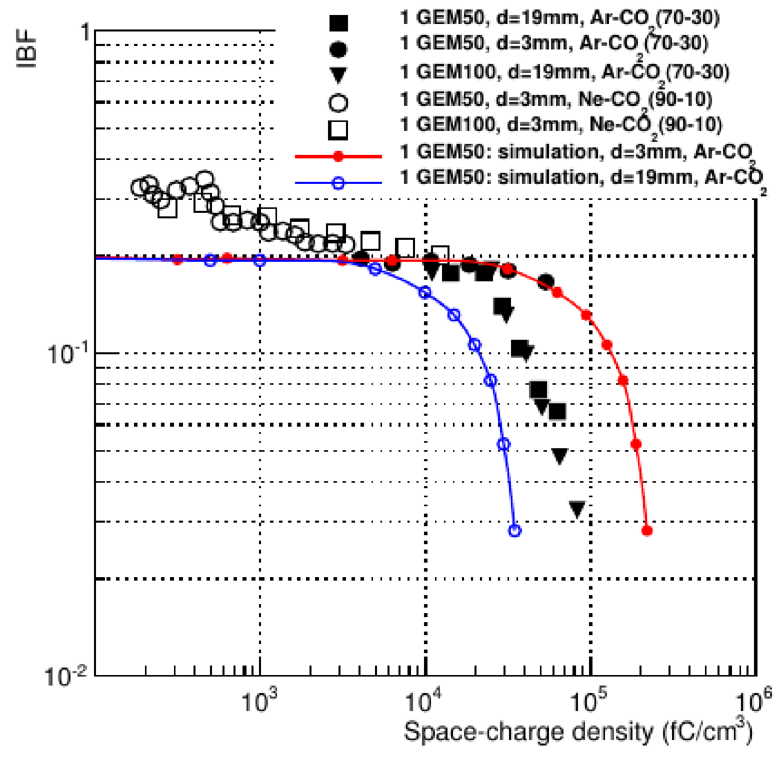


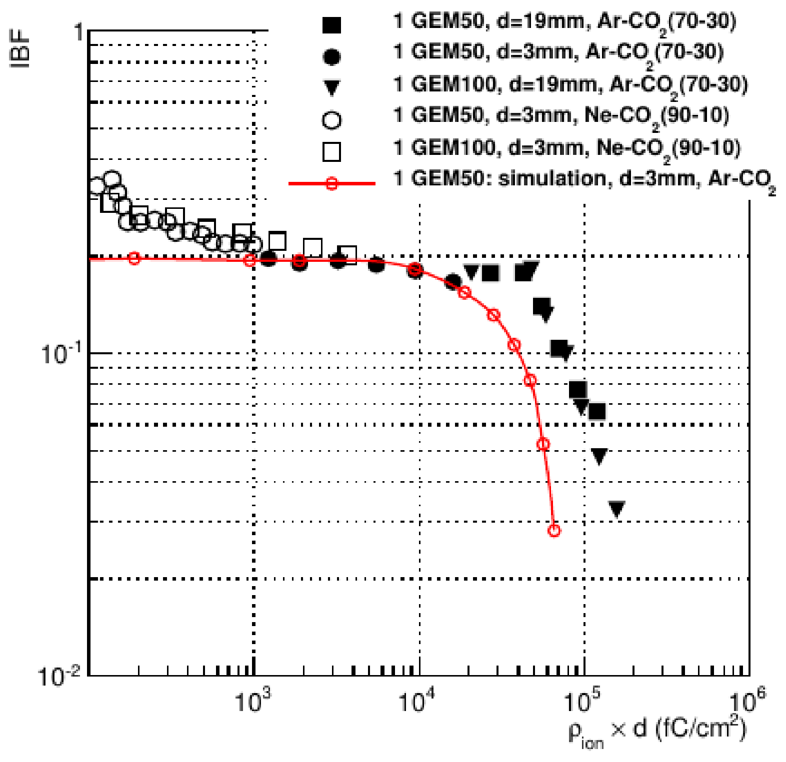


- Simulations available since a few years
- Hole distance critical parameter
  → use to tune the matching
- Good agreement between measurement and simulation

IBF simulations

Ionisation dependence

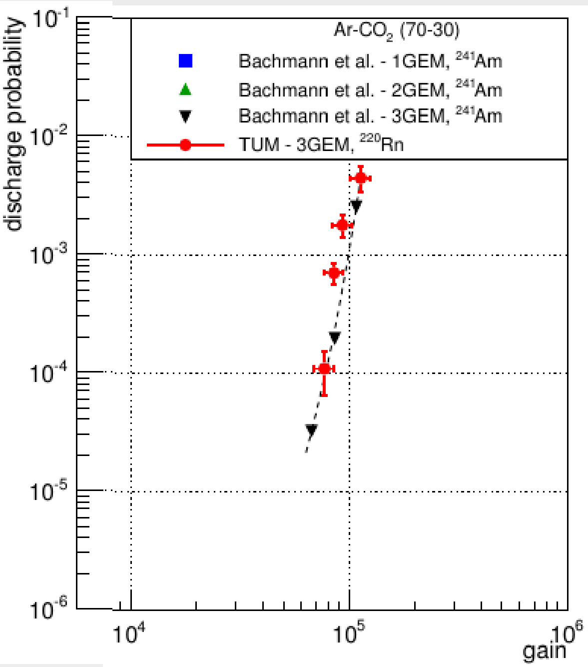




- Dependence of IBF on space-charge density (SCD) observed in measurements
- Trends reproduced well in simulations
  - SCD estimates in measurements coarse estimates
  - SCD in simulations assumed homogeneous
- At high SCD the effective drift field at GEM1 top is decreased
  - More filed lines end on GEM1 top → lower IBF

GEM stability tests

Discharge probability



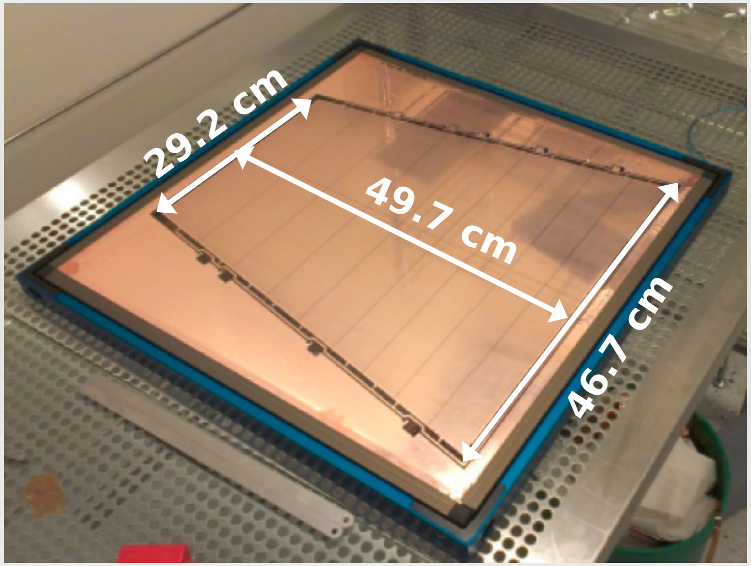
	S-S-S 'standard' HV G = 2000	S-S-S-S *IB* = 2.0% G = 2000	S-LP-LP-S *IB* = 0.34% G = 1600	 *IB* = 0.34% G = 3000	 *IB* = 0.34% G = 5000	 *IB* = 0.63% G = 2000
^{220}Rn $E_\alpha = 6.4$ MeV rate = 0.2 Hz	$\sim 10^{-10}$			$< 2\times10^{-6}$	$< 7.6\times10^{-7}$	
^{241}Am $E_\alpha = 5.5$ MeV rate = 11 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					$< 3\times10^{-12}$	

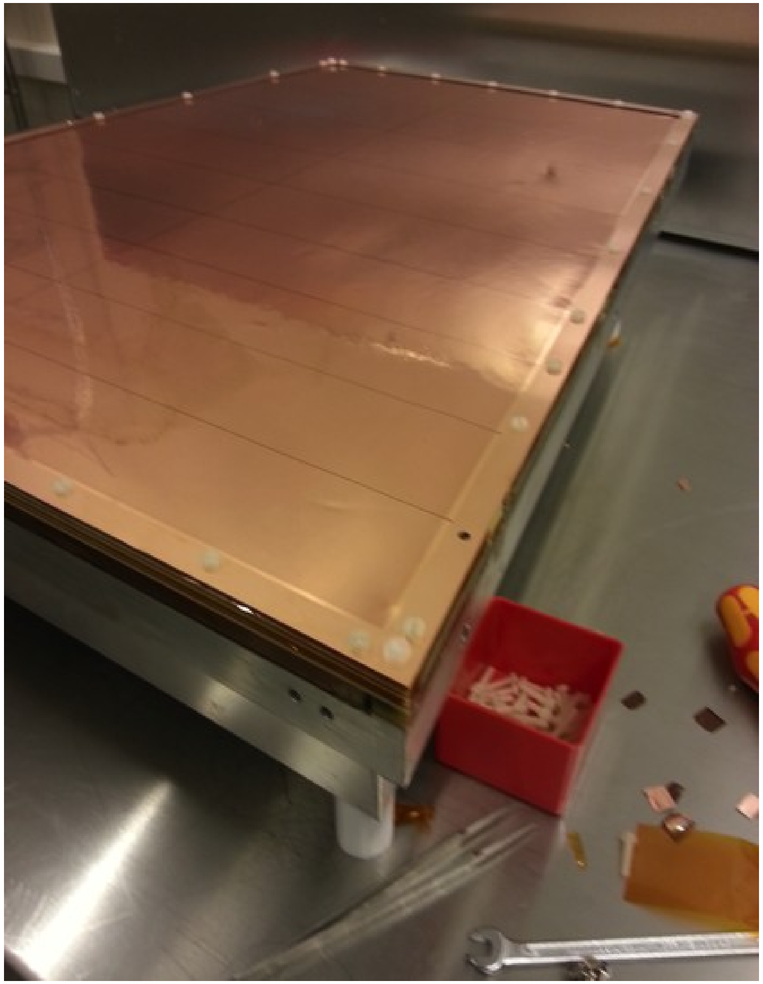
- Discharge probability for triple GEM in agreement with literature
- Quadruple GEM mostly upper limits (measurement time)
  - Suitable for LHC running conditions

Results from a large prototype

Results from a large prototype

Assembly of full size IROC



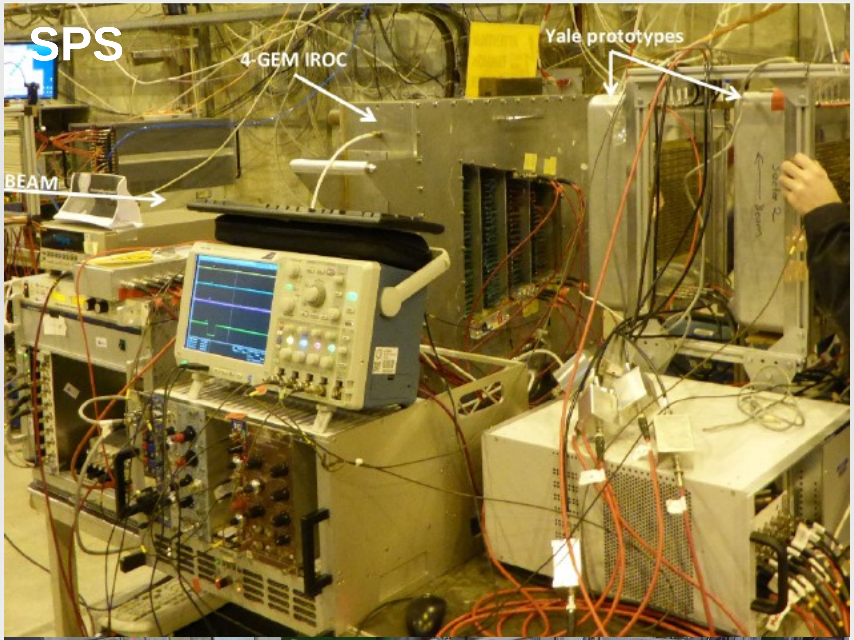


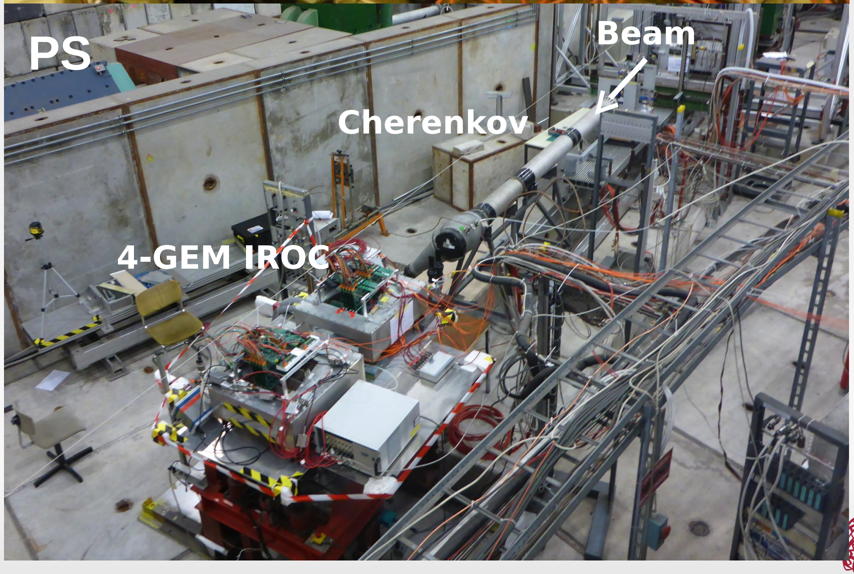
- 4 single-mask GEMs in the configuration S-LP-LP-S
- GEMs glued on 2 mm frames
- Prototype mounted in a test box with a field cage

Results from a large prototype

Test beam campaign

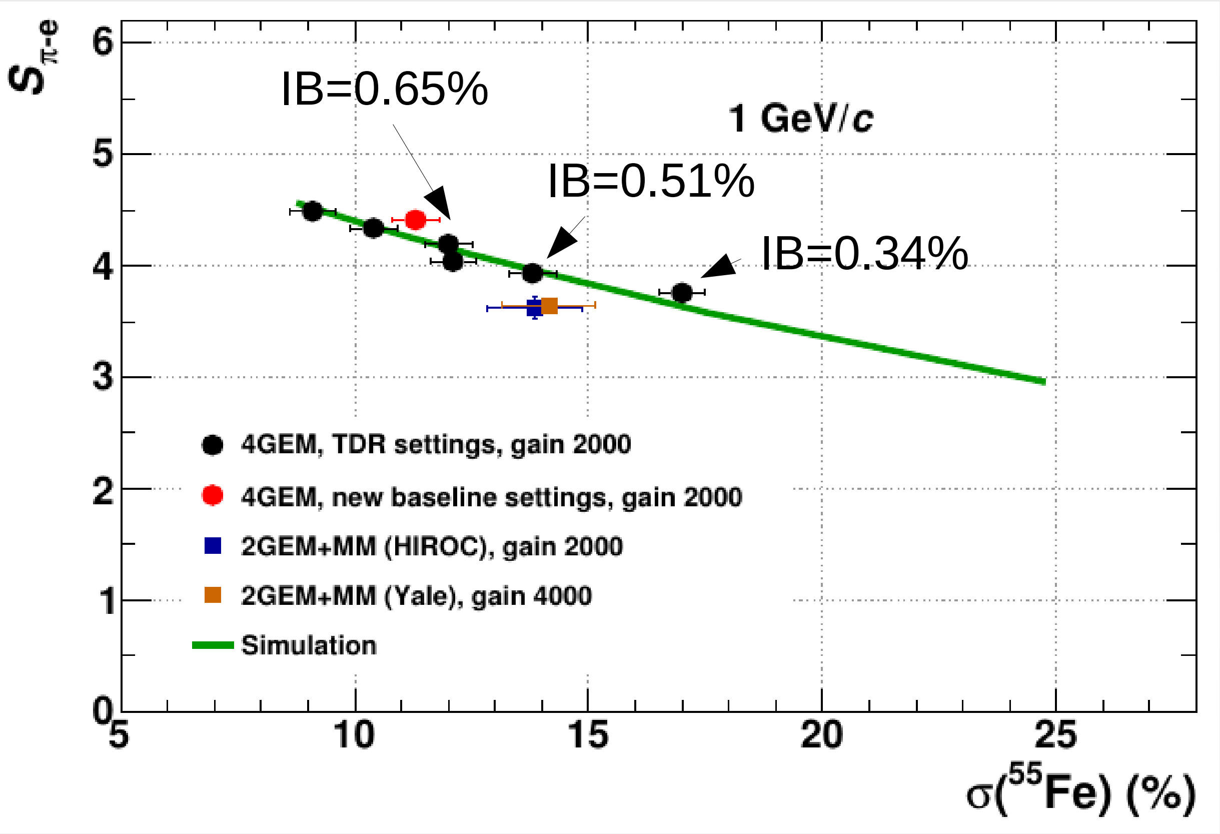
- Test beam studies at PS and SPS with full-sized IROC prototype
- Discharge probability
- d*E*/d*x* performance

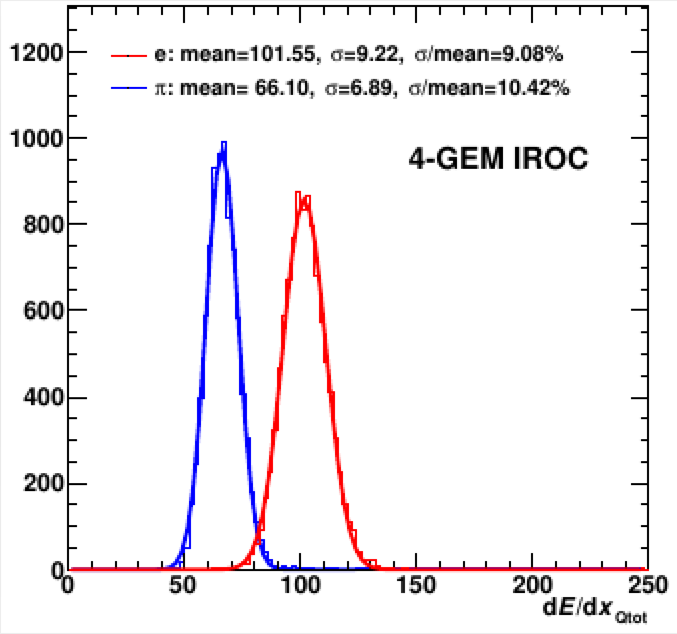




Results from a large prototype

PS test beam – dE/dx performance



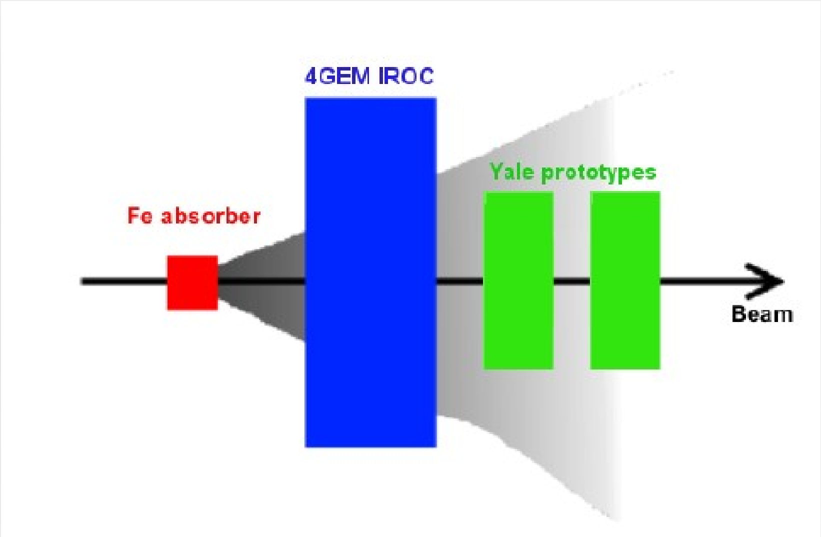


$$S_{AB} = \frac{2\left|\langle \mathrm{d}E/\mathrm{d}x\rangle_A - \langle \mathrm{d}E/\mathrm{d}x\rangle_B\right|}{\sigma(\mathrm{d}E/\mathrm{d}x)_A + \sigma(\mathrm{d}E/\mathrm{d}x)_B}$$

- d*E*/dx performance as expected from simulation
- Same performance as present MWPC IROC
- Physics performance not compromised up to σ=14%
  - → Allow for operation of IROC / OROC at different working points

Results from a large prototype

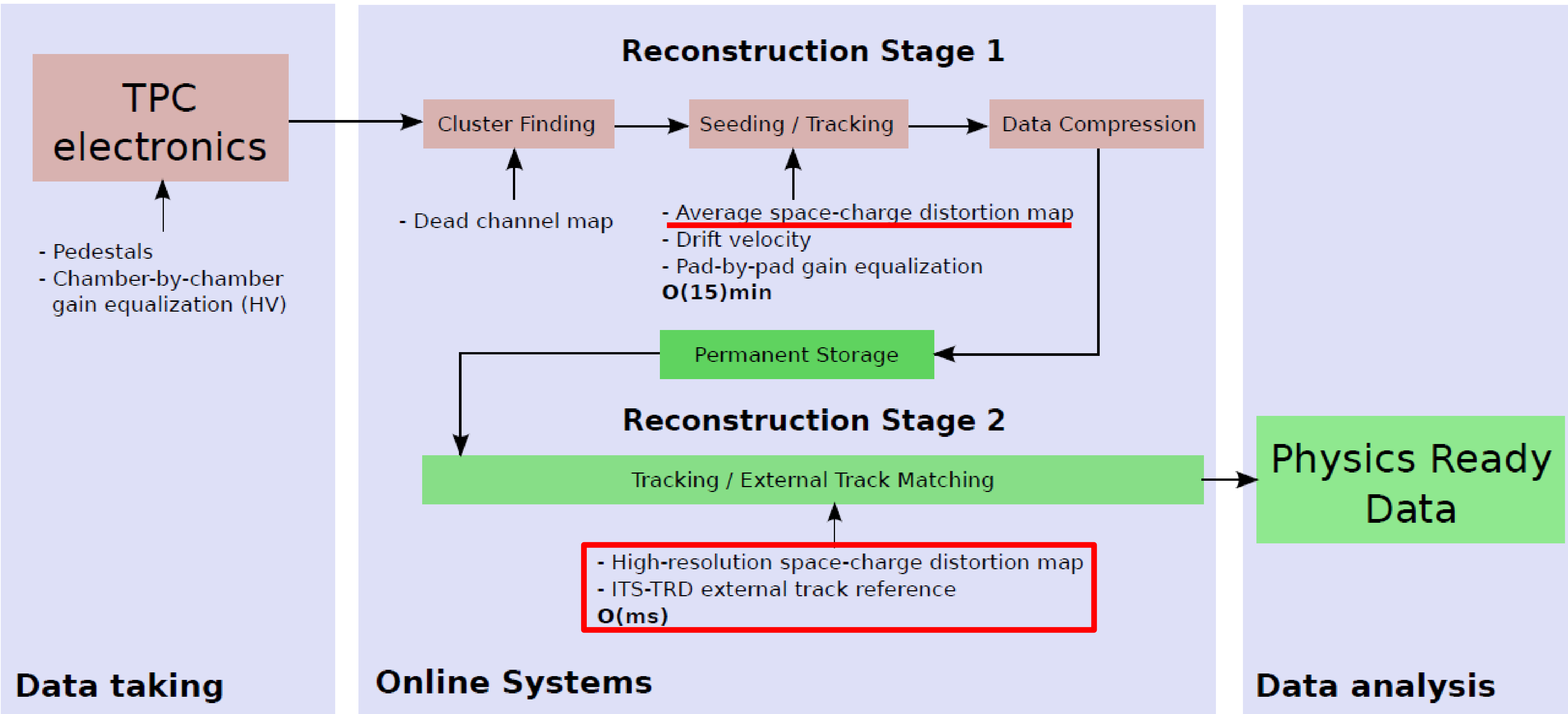
SPS test beam – discharge probability



- Number of accumulated particles $N_{tot} = (4.7\pm0.2)\times10^{11}$
  - Comparable to a typical Pb-Pb running year
  - Three discharges observed
- Estimate for run 3 based on PS results
  - About 650 discharges for whole TPC per typical yearly heavy-ion run at 50 kHz (5 per GEM stack)
- Safe operation guaranteed

Reconstruction and calibration strategy

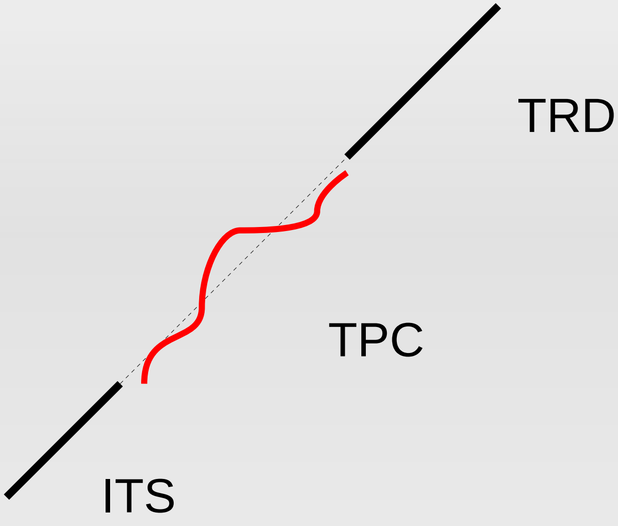
Reconstruction strategy

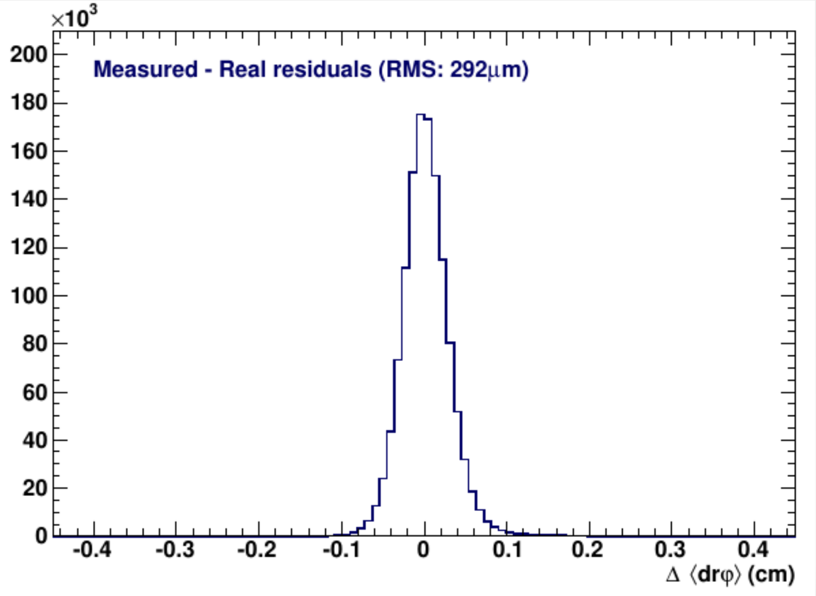


Calibration strategy

Measurement of residual distortions

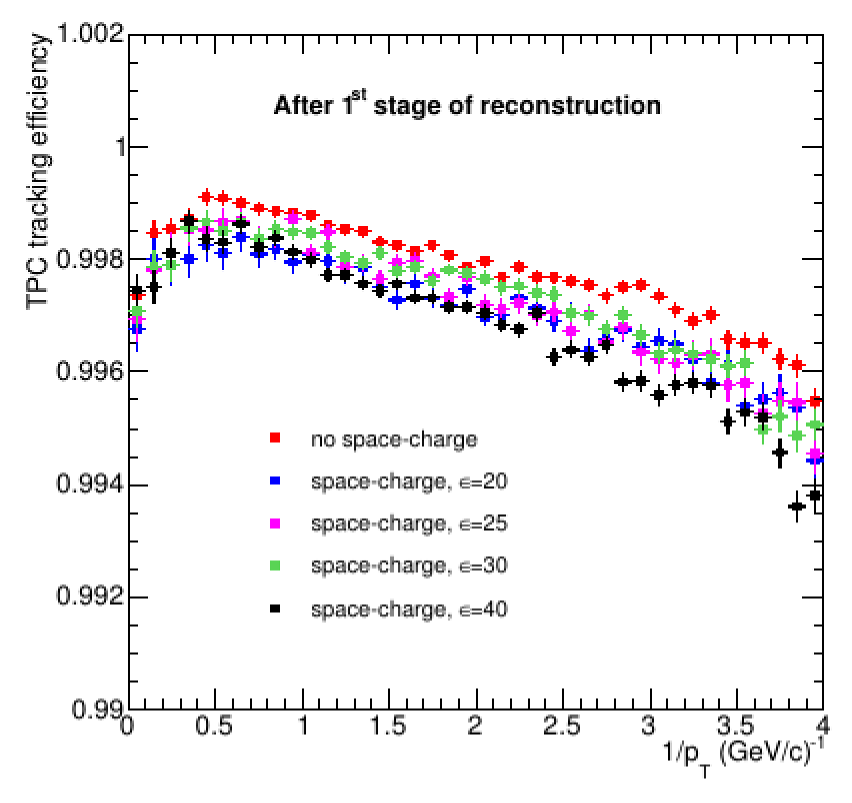
- Correct residual distortions using track interpolation from external detectors (ITS-TRD - TOF)
- Space charge fluctuations require an update of the correction maps in 5 ms intervals
- Final calibration on the level of 300 µm



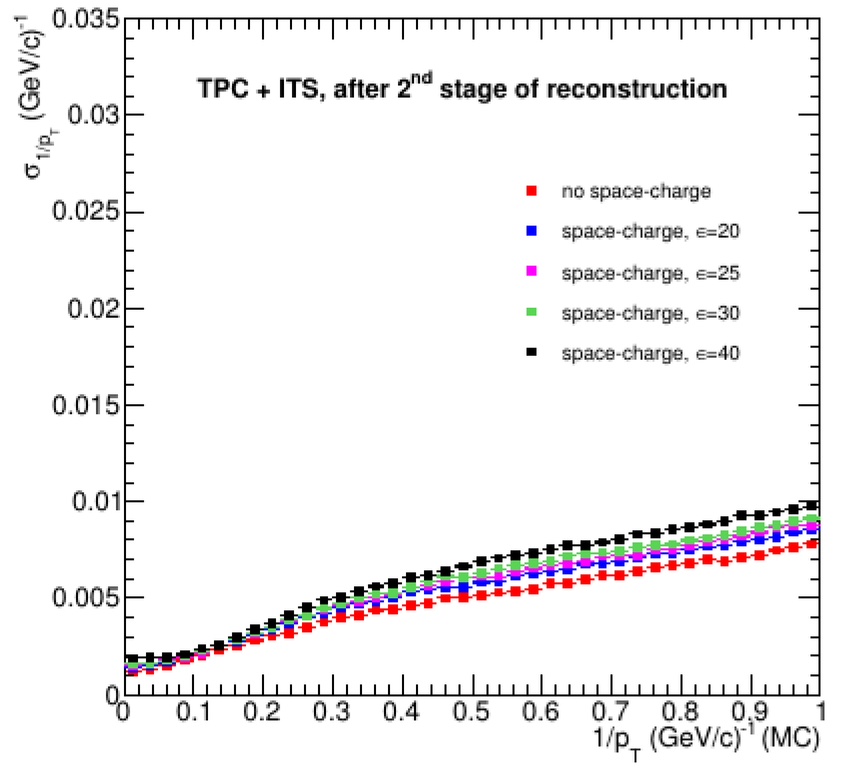


Calibration strategy

Calibration performance



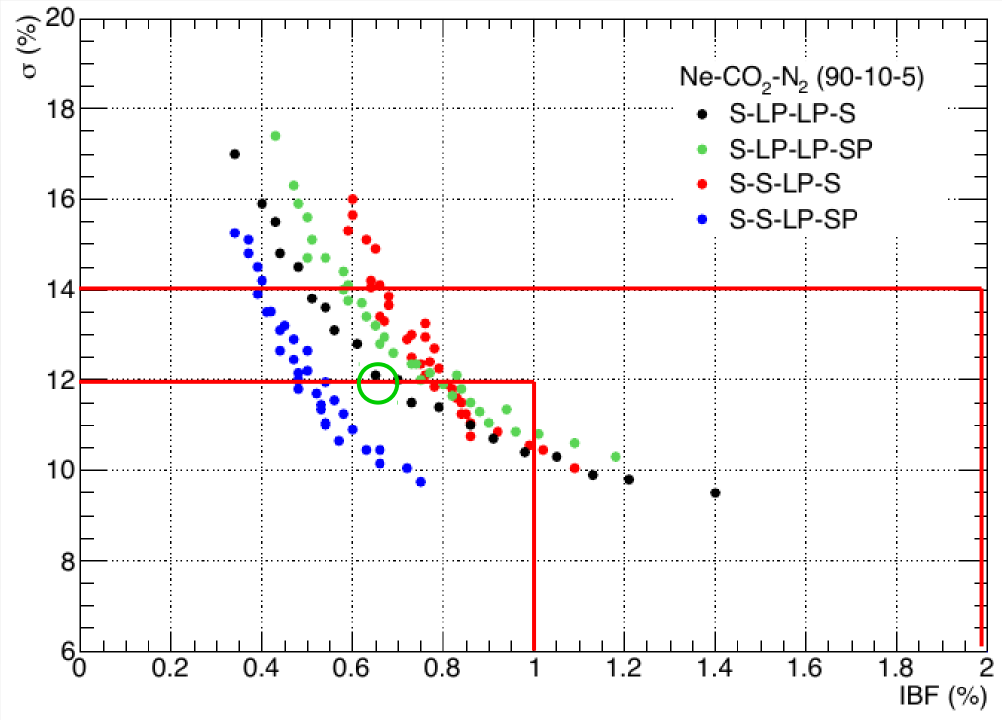
For findable tracks:
primaries, crossing at least half of the TPC



- Testing limits of calibration procedure
  - → Going up to twice the nominal ion density (ε=40)
  - Tracking efficiency not compromised
  - Slide decrease in p_T resolution at low momenta
    - → does not compromise physics program

Summary

- Extensive R&D program carried out during the last years
  - Thorough characterisation of several GEM configurations in terms of IBF, σ(^{55}Fe), discharge probability
  - Stable solution established as 4-GEM S-LP-LP-S
- Calibration strategy to correct distortion on the level of 10cm down to ~300µm demonstrated
  - Physics performance very close to present system
- Confidence limit of operation extended substantially
- TPC TDR was endorsed by the LHCC

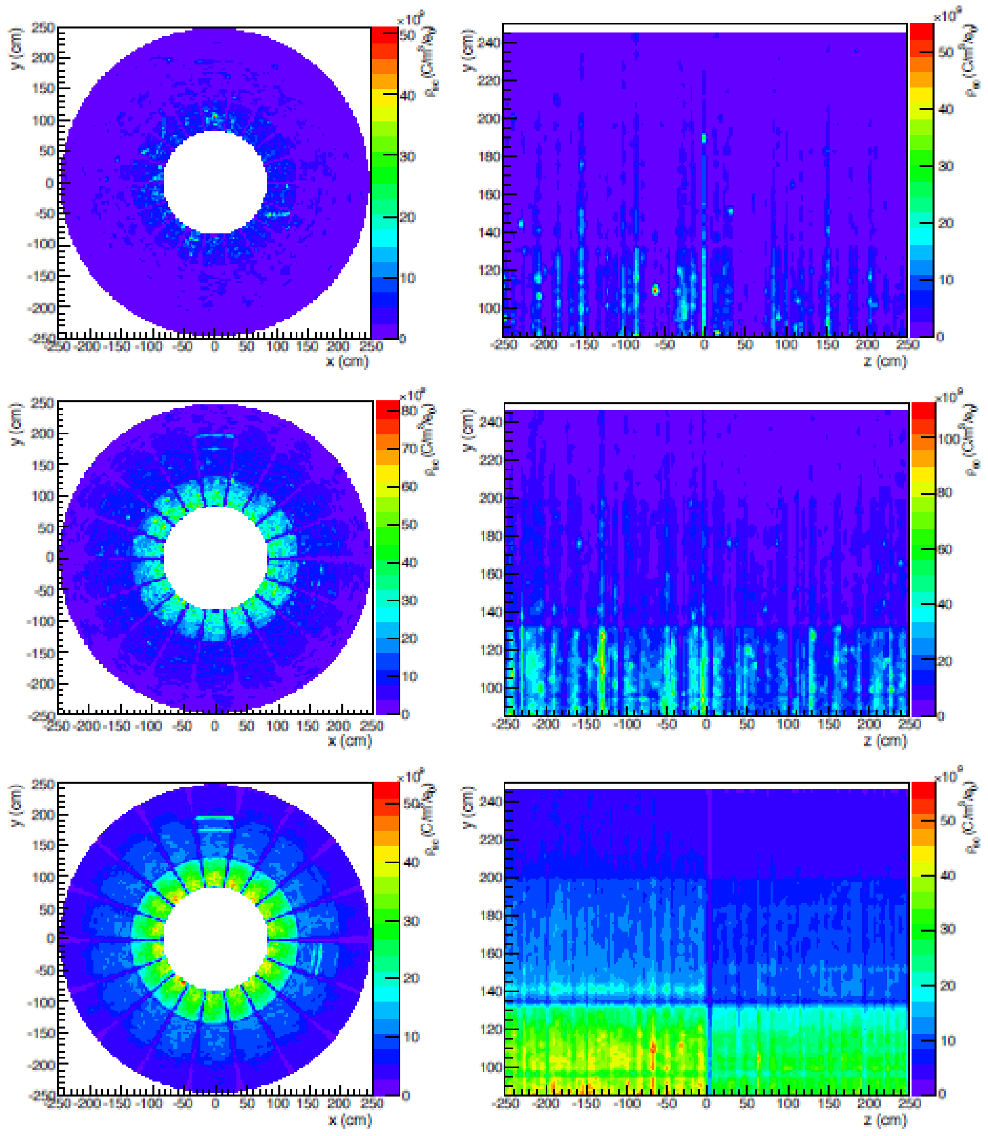


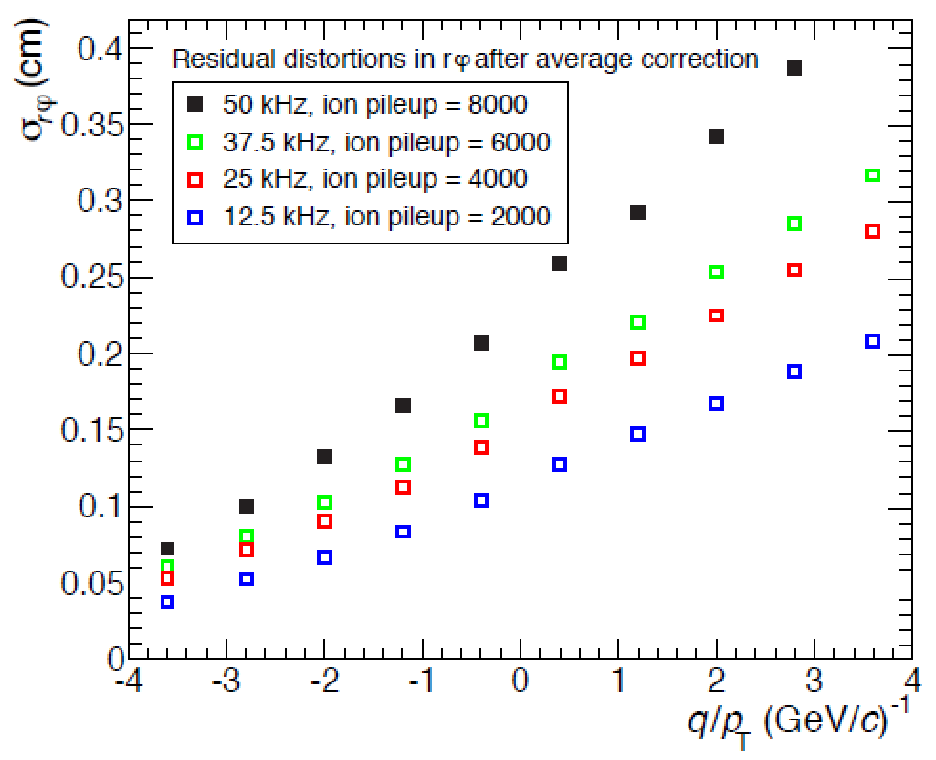
Backup

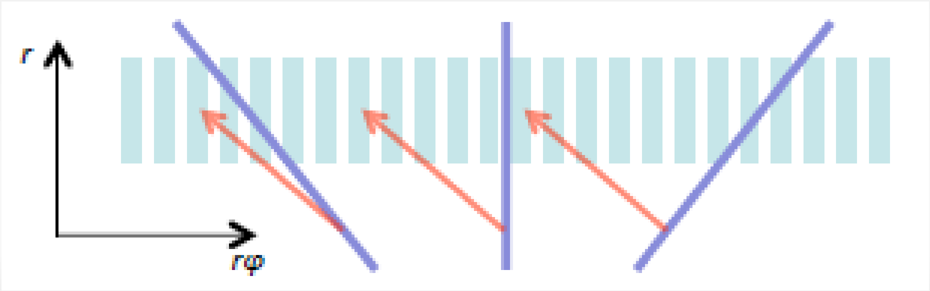
S-LP-LP-S default voltage setings

IB (%)	$\sigma(^{55}\mathrm{Fe})$ (%)	$\Delta U_{\mathrm{GEM3}}/\Delta U_{\mathrm{GEM4}}$	ΔU_{GEM1} (V)	ΔU_{GEM2} (V)	ΔU_{GEM3} (V)	ΔU_{GEM4} (V)	E_{T1} (kV/cm)	E_{T2} (kV/cm)	E_{T3} (kV/cm)	E_{ind} (kV/cm)
0.63	11.3	0.8	275	240	254	317	2	3	1	4
0.34	17.0	0.8	225	235	304	382	4	2	0.1	4
0.51	13.8	0.8	255	235	292	364	4	2	0.1	4
0.65	12.1	0.8	275	235	284	345	4	2	0.1	4
0.98	10.4	0.8	305	235	271	339	4	2	0.1	4
2.05	9.1	0.8	315	285	240	300	4	2	0.1	4
0.76	12.0	0.95	275	235	308	323	4	2	0.1	4

Space charge fluctuation

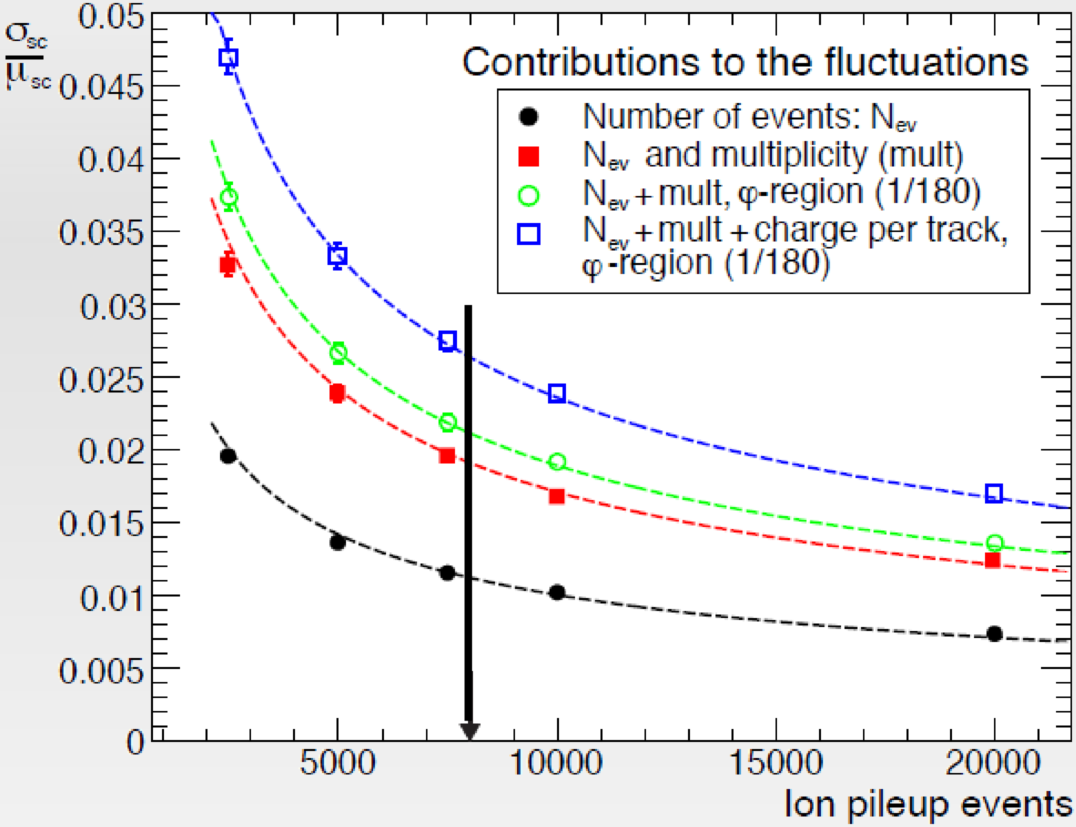






Space charge fluctuations

Magnitude of fluctuations



- Space-charge fluctuations at the level of 3%
- With knowledge of the average space-charge density this leads to
  - Max ± 6mm residual distortion in *r*
  - Max ± 2.5mm residual distortion in *rφ*
- Space-charge fluctuations are dominated by event and multiplicity fluctuations
- Sets constraints on the update interval for the final calibration: O(5ms)

Continuous readout

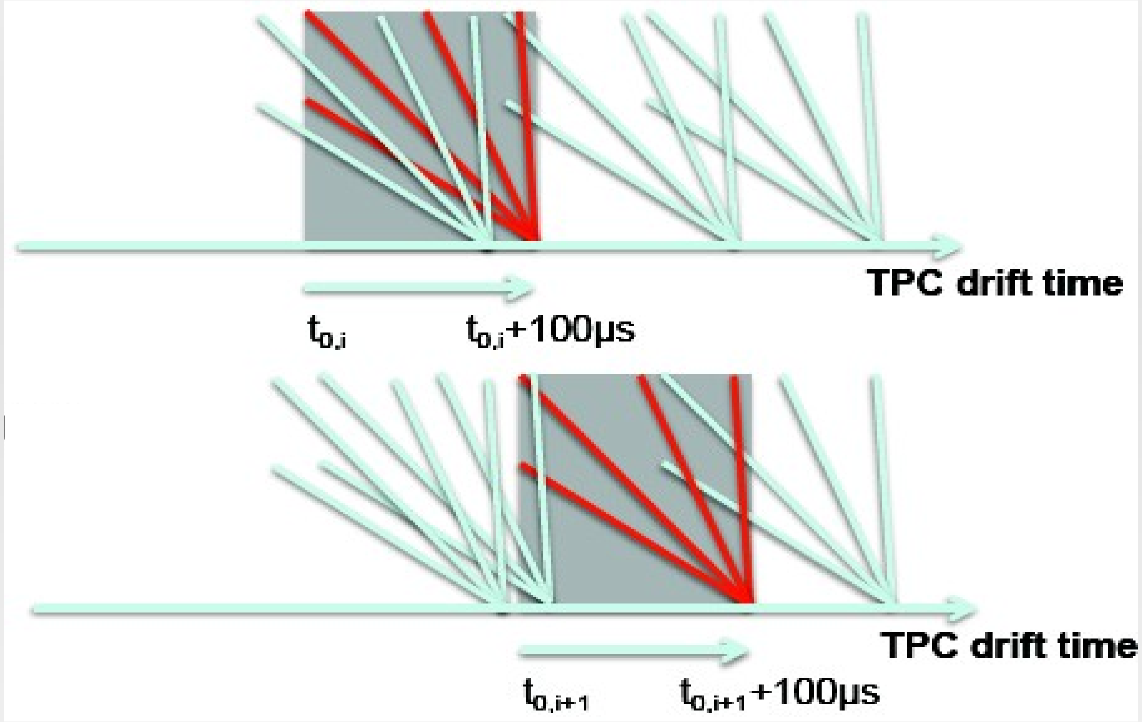
Implications and treatment of space-point corrections

$$\vec{r}_{\mathrm{cls}} = \vec{r}_{\mathrm{ro}} + \int_0^{-t_d} \vec{v}_{\mathrm{d}}(x, y, z)\,\mathrm{d}t$$

- Space-point reconstructions requires
  - Drift-velocity, $\vec{v}_{\mathrm{d}} = (0, 0, v_{\mathrm{d}})$ (ideal case – no distortions)
  - Drift-time, $t_{\mathrm{d}} = t_{\mathrm{digit}} - t_0$
- $\vec{r}_{\mathrm{cls}} = (x_{\mathrm{ro}}, y_{\mathrm{ro}}, z_{\mathrm{roc}} - v_{\mathrm{d}} t_{\mathrm{d}})$ – no distortions
- In continuous readout mode, t_0 not known a priori
- Distortions treated as effective corrections
  - $\vec{r}_{\mathrm{cls}} = (x_{\mathrm{ro}}, y_{\mathrm{ro}}, z_{\mathrm{ro}}) + \vec{\Delta}(x_{\mathrm{ro}}, y_{\mathrm{ro}}, z_{\mathrm{ro}})$ → requires t_0!

Tracking approaches

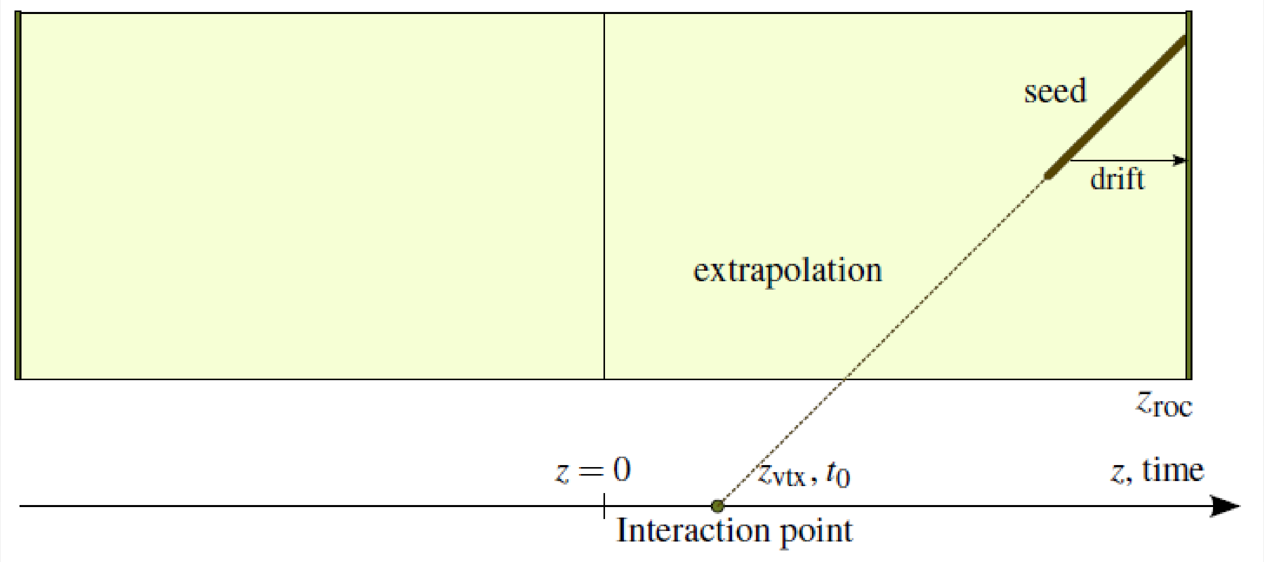
Straight forward reconstruction



- Scan all $t_{0,i}$ in current TPC drift time → external detector
- Apply SCD corrections to all clusters
  - clusters from central interaction will be corrected properly, others are background)
- SCD corr. applied multiple times → Computation issue

Tracking approaches

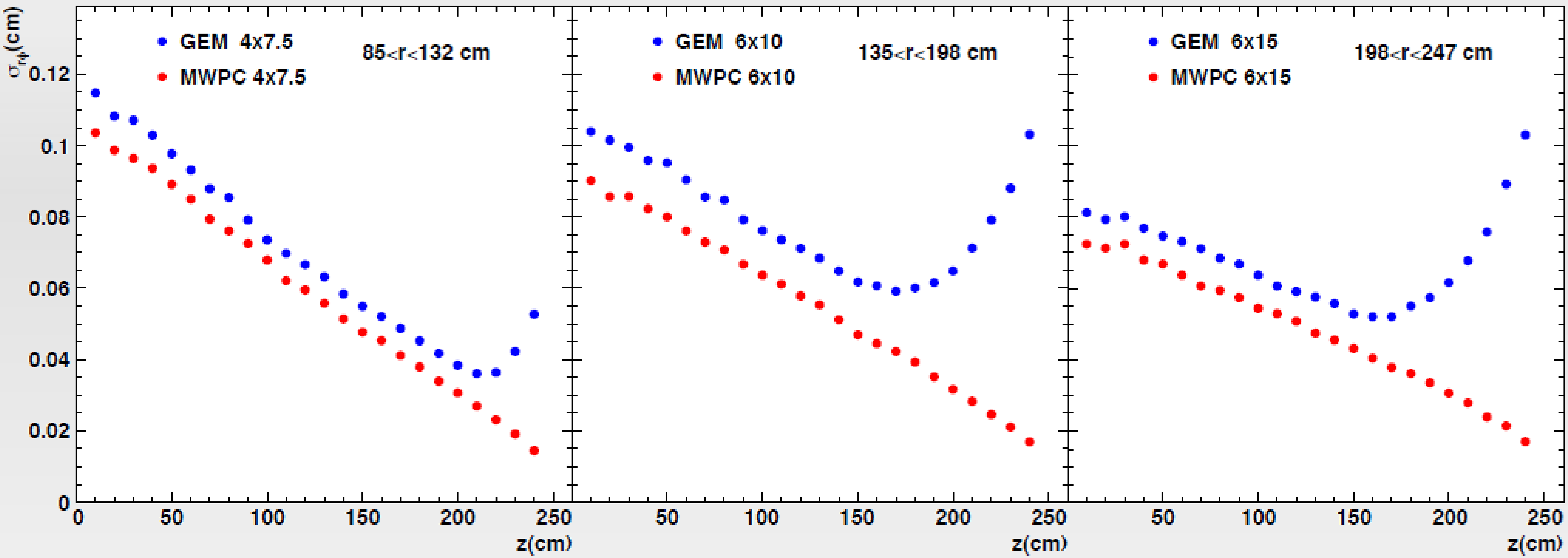
TPC standalone tracking

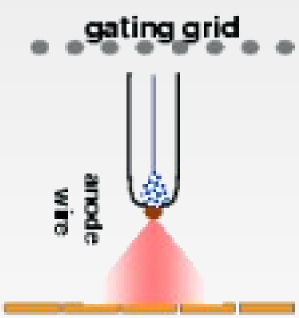


- Seeding in region with small distortions (ad-hoc SCD corr.)
- Extrapolation to x=y=0 → t_0 estimate: better SCD corr.
- Track following → Modify search road with SCD estimate
- Clusters corrected once (fast)
- TPC only information (robust)

Intrinsic performance

Space point resolution

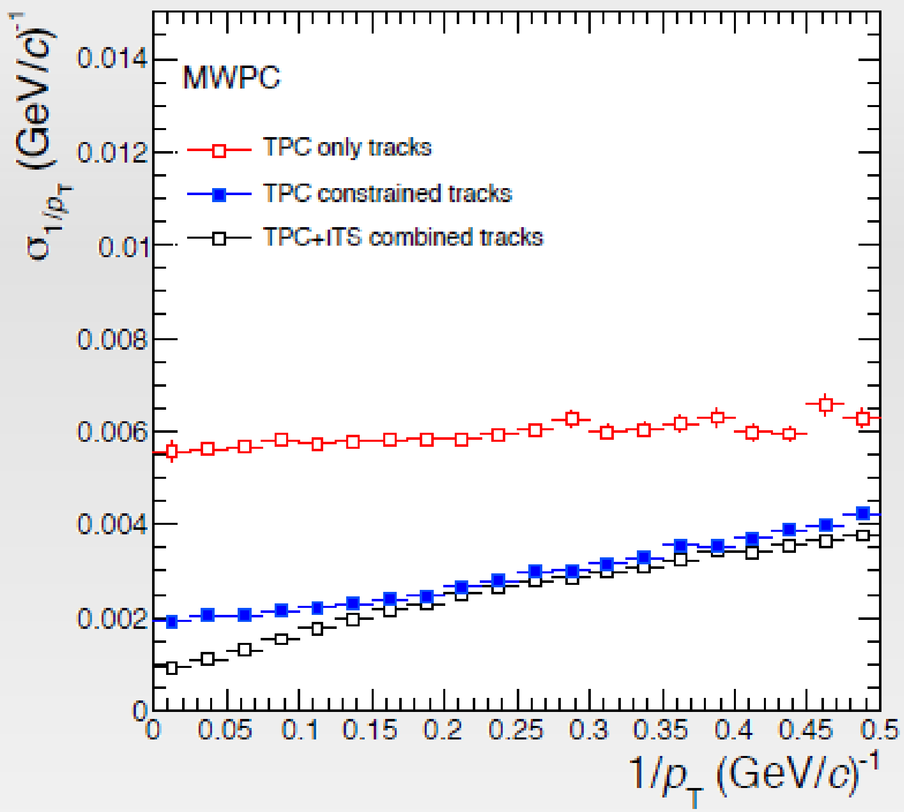


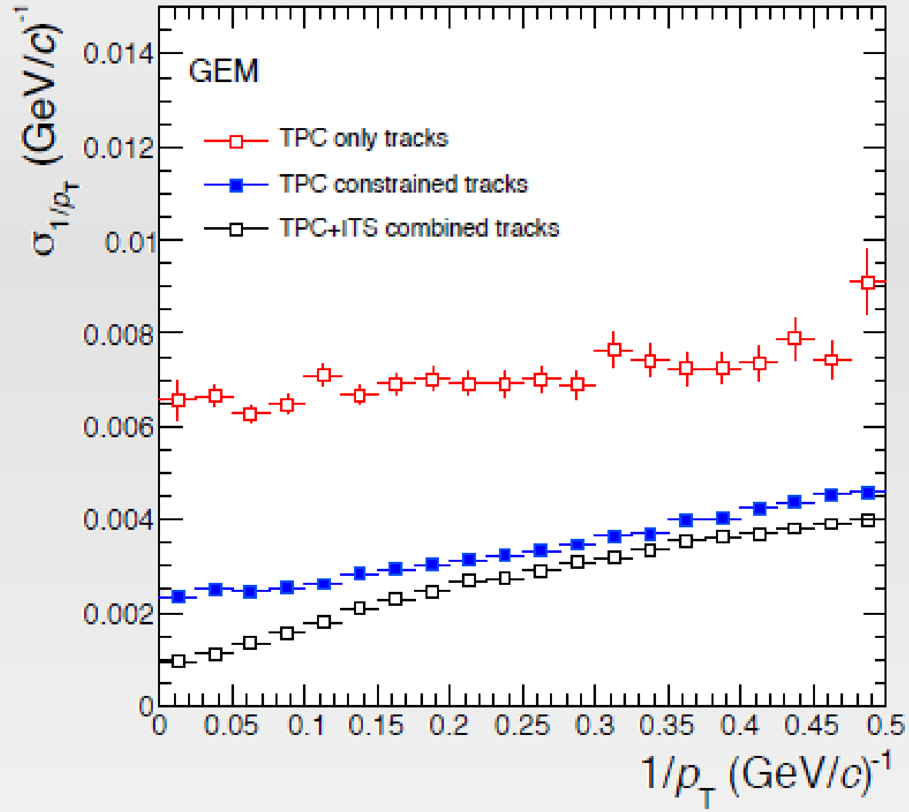


- Optmised **P**ad **R**esponse **F**unction for MWPCs
- PRF of GEMs very narrow → diffusion helps to spread signal over several pads
- Slightly worse overall resolution with GEMs

Intrinsic performance

Momentum resolution

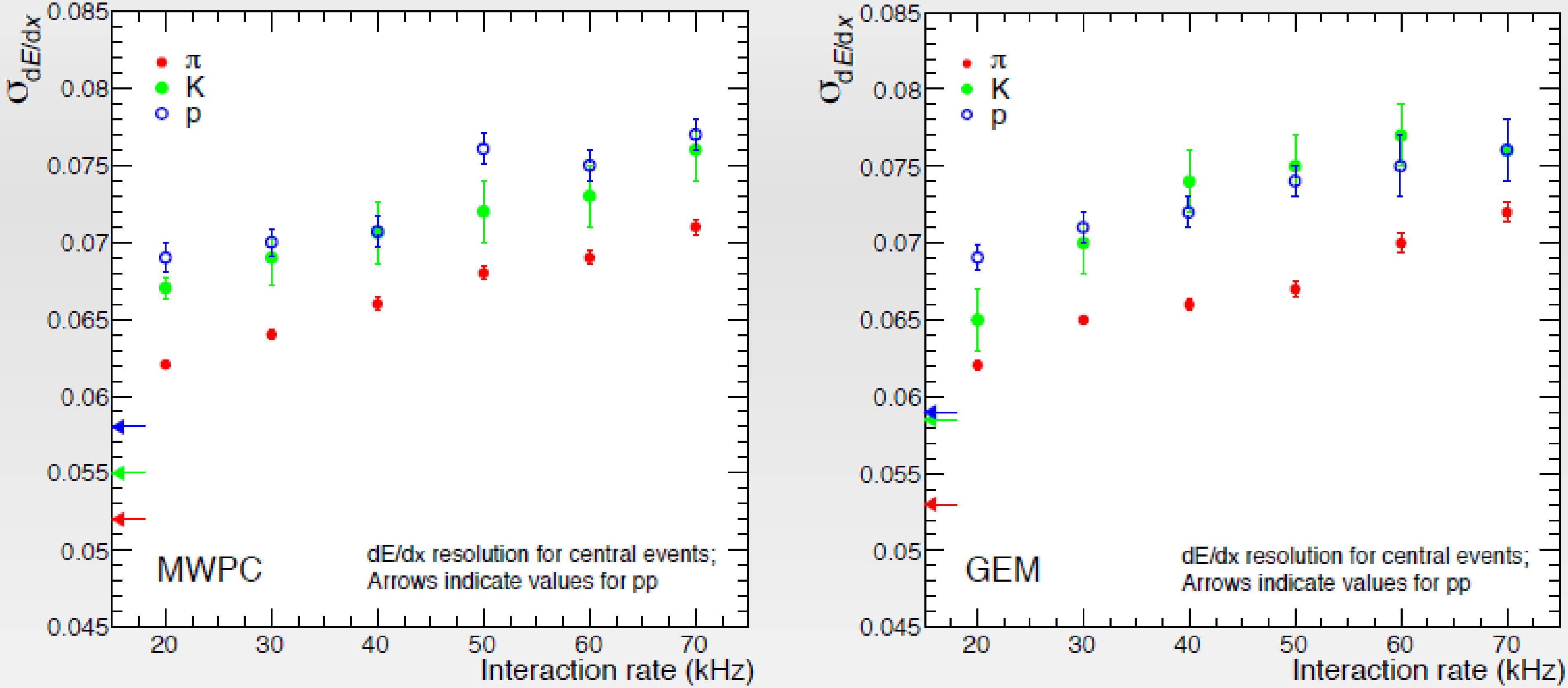




- Full detector simulation (central Pb-Pb event)
- Slightly worse resolution of TPC only tracks (space point resolution)
- Resolution restored matching tracks to the ITS

Performance with pileup

dE/dx resolution



- Moderate worsening with increasing pileup (cluster merging)
- No difference between MWPC and GEM system