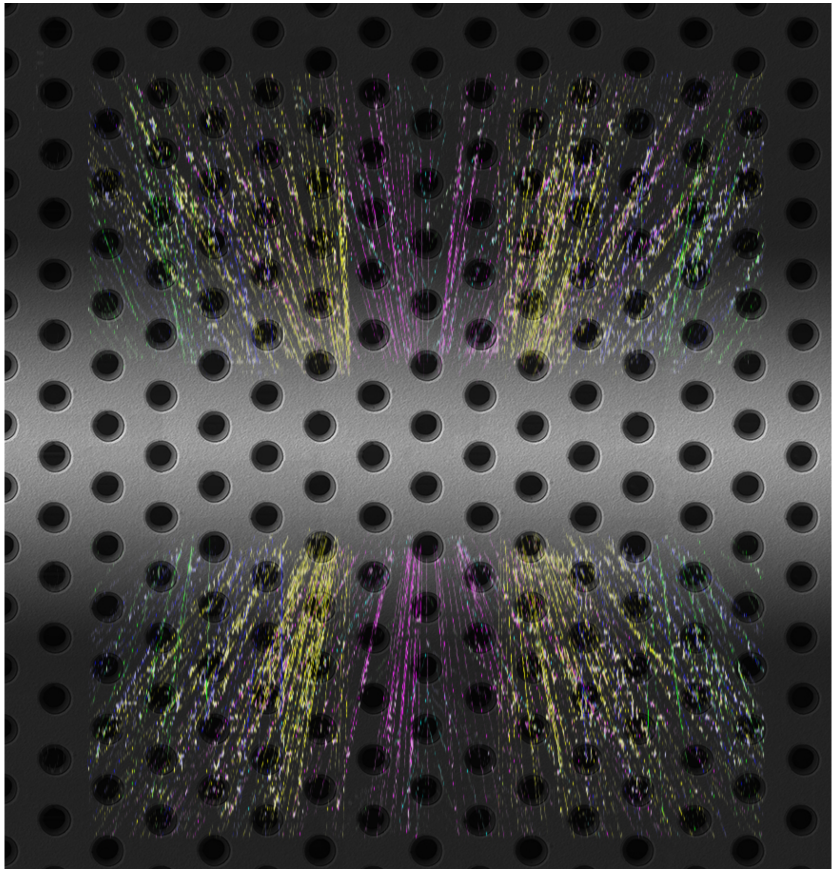
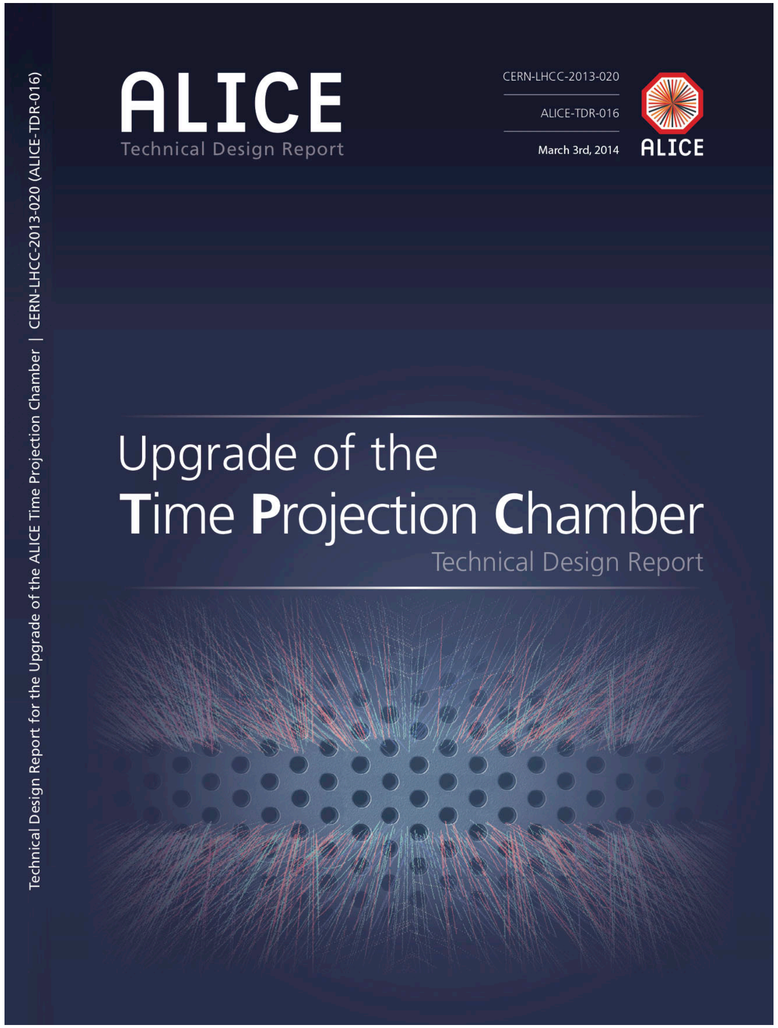


Upgrade of the ALICE TPC

Harald Appelshäuser
Goethe-Universität Frankfurt
LHCC Meeting 4.3.2014

ALICE upgrade after LS2



- Chief goal: improvement of ALICE measurements of key observables in Pb-Pb:

  - heavy flavor
  - quarkonia
  - low-mass dielectrons
  - jets
  - anti- and hypernuclei

- Implies TPC readout at full minimum bias rate, i.e. at 50 kHz in Pb-Pb

- Present TPC readout rate is limited to ~3 kHz

  → significant TPC upgrade:

  - readout chambers
  - frontend electronics
  - online calibration and reconstruction scheme

- TPC upgrade TDR submitted today to LHCC:
  CERN-LHCC-2013-020

key issues for the TDR

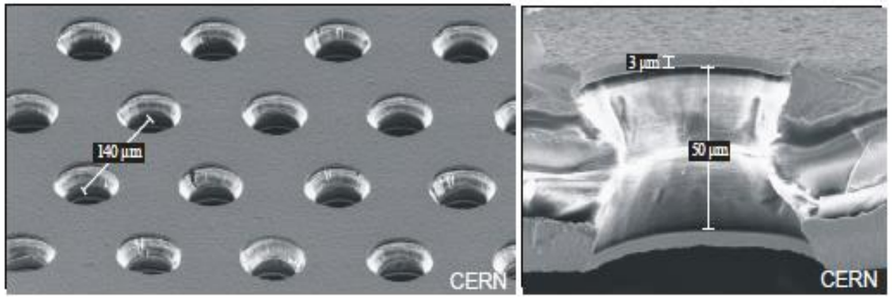
Development of a GEM-based readout system that minimizes IBF

Evaluation of online reconstruction strategies to allow efficient data compression on the online systems

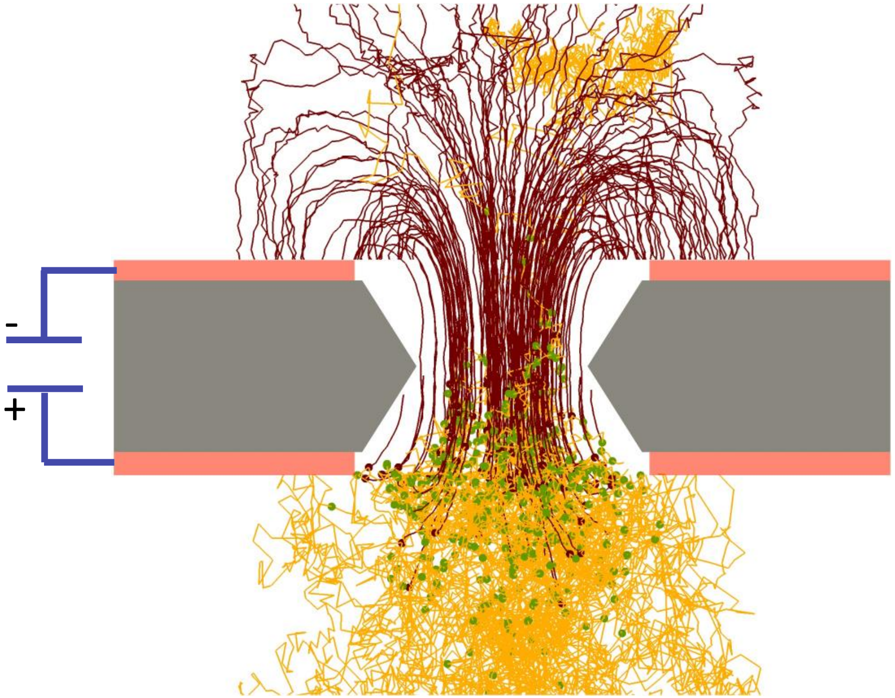
Validation of a calibration framework to account for space-charge distortions at a level that retains the momentum resolution of the TPC

GEM-based Readout Chambers

GEMs



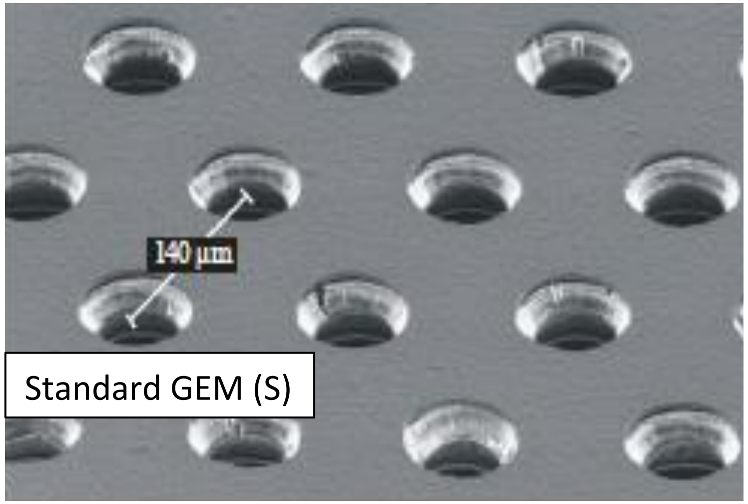
Electron microscope photograph of a GEM foil

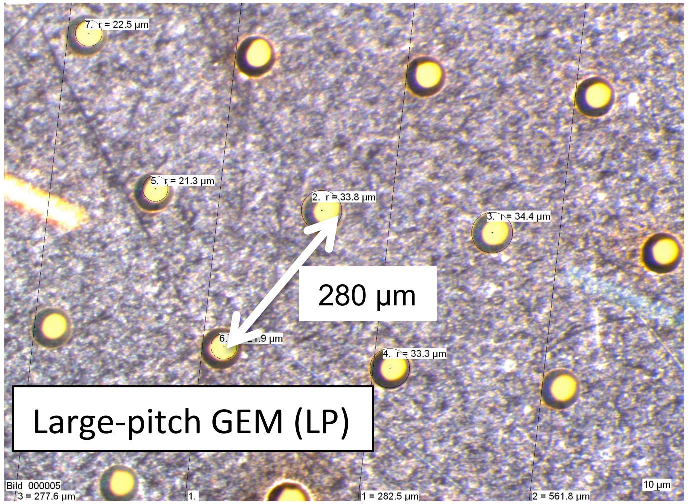


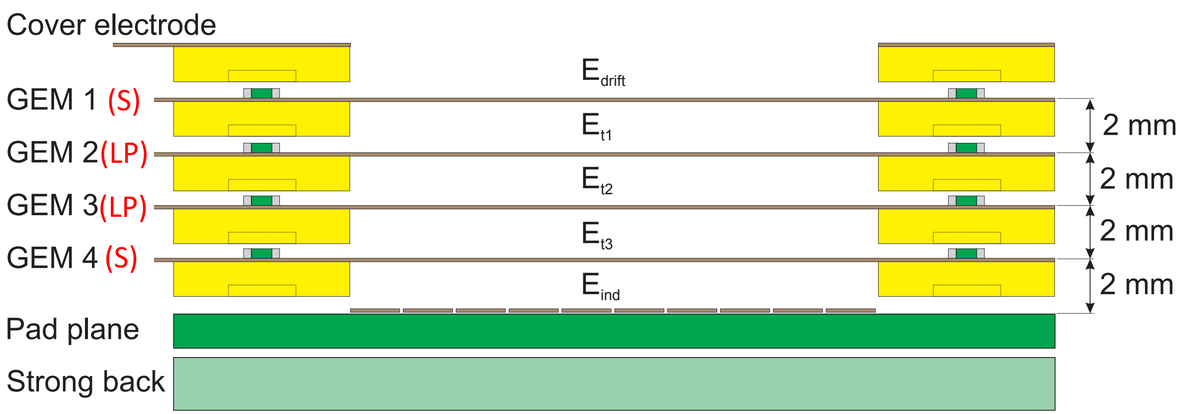
- micro-patterned gas detector for electron multiplication
- proven to work reliably in high-rate applications
- in a TPC with continuous readout: back-drifting ions into drift space
- GEMs feature intrinsic ion backflow (IBF) capabilities
- requirement:
  - $IBF = I_{cathode}/I_{anode} < 1\%$ at gain 2000 in Ne-CO_2-N_2 (90-10-5) i.e. $\varepsilon = IBF$ * gain < 20
  - $\sigma(^{55}Fe) < 12\%$

→ significant R&D effort

TDR baseline solution: 4-GEM stack



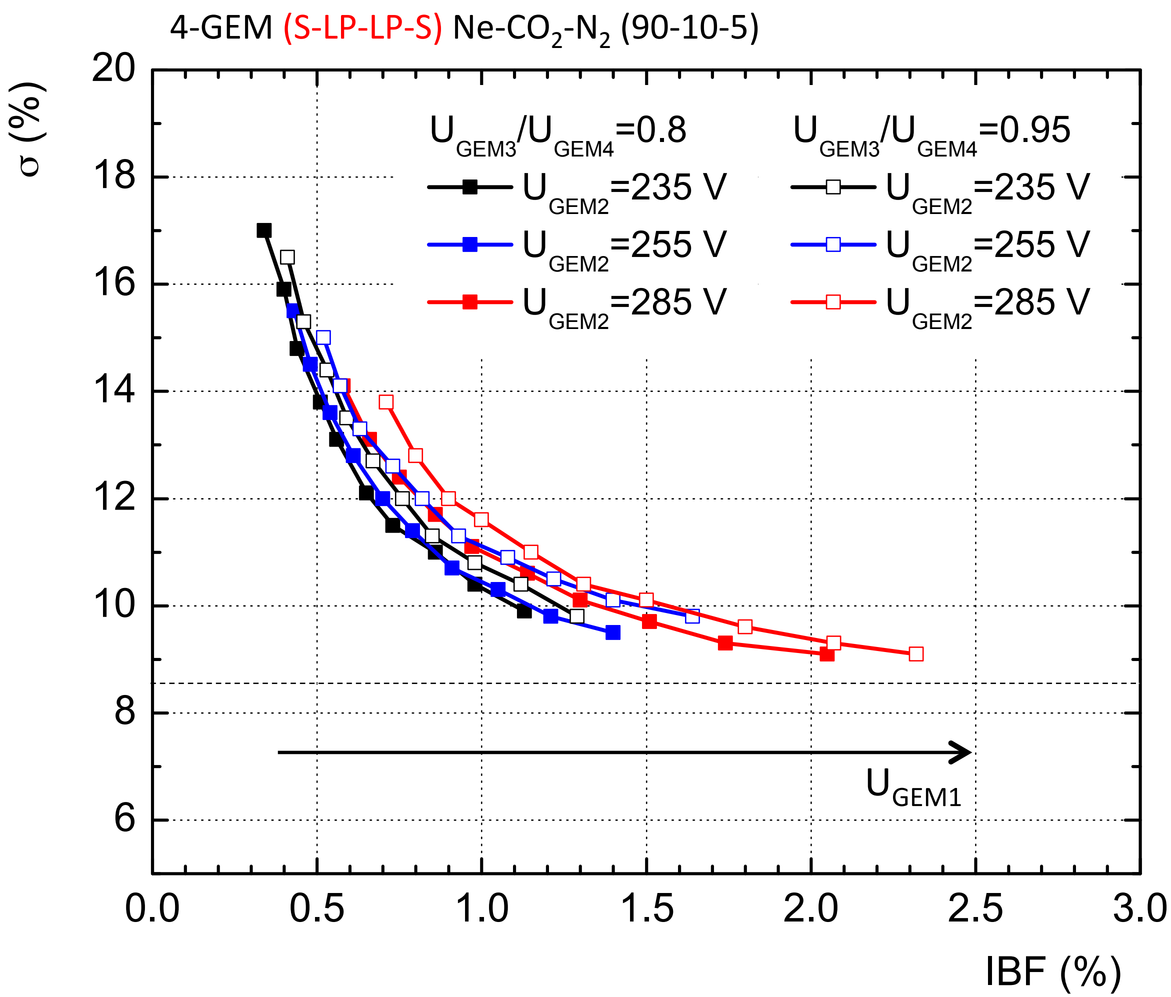




Baseline solution (S-LP-LP-S) employs standard (S) and large-pitch (LP) GEMs

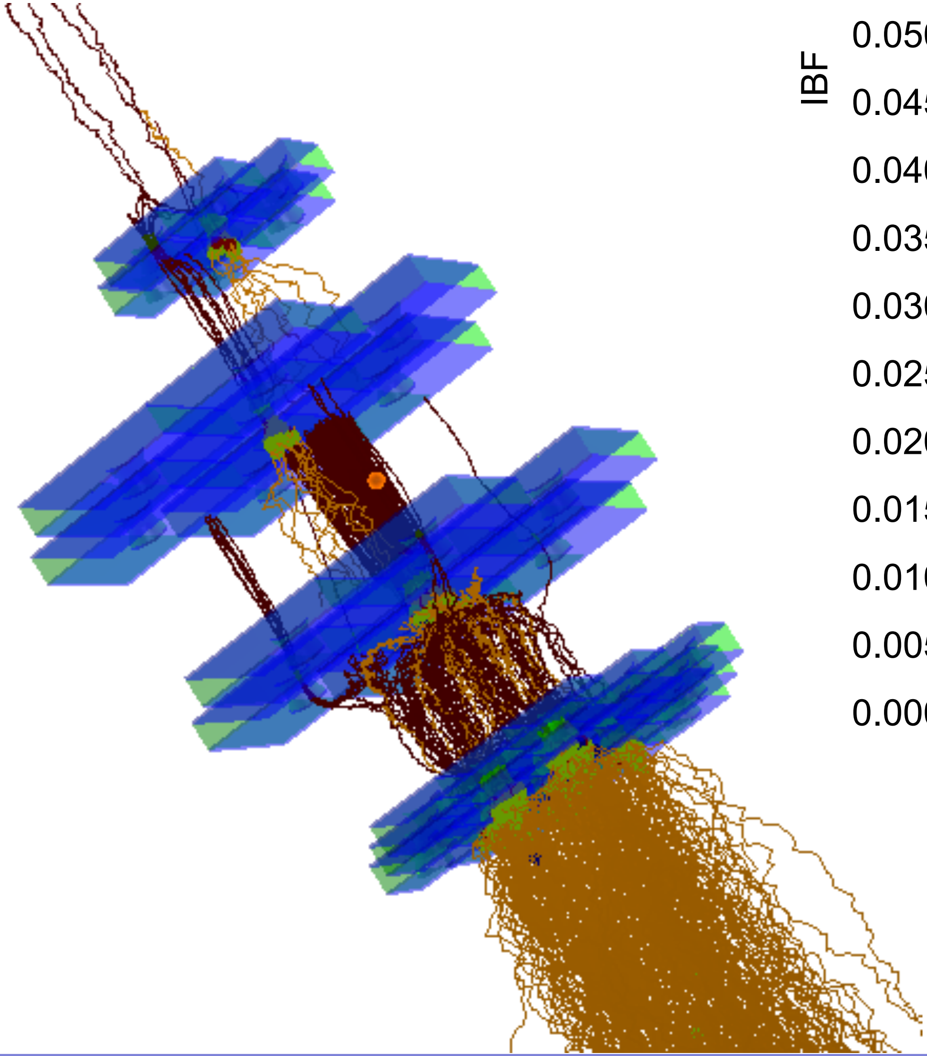
$U_{GEM1}<U_{GEM2}<U_{GEM3}<U_{GEM4}$

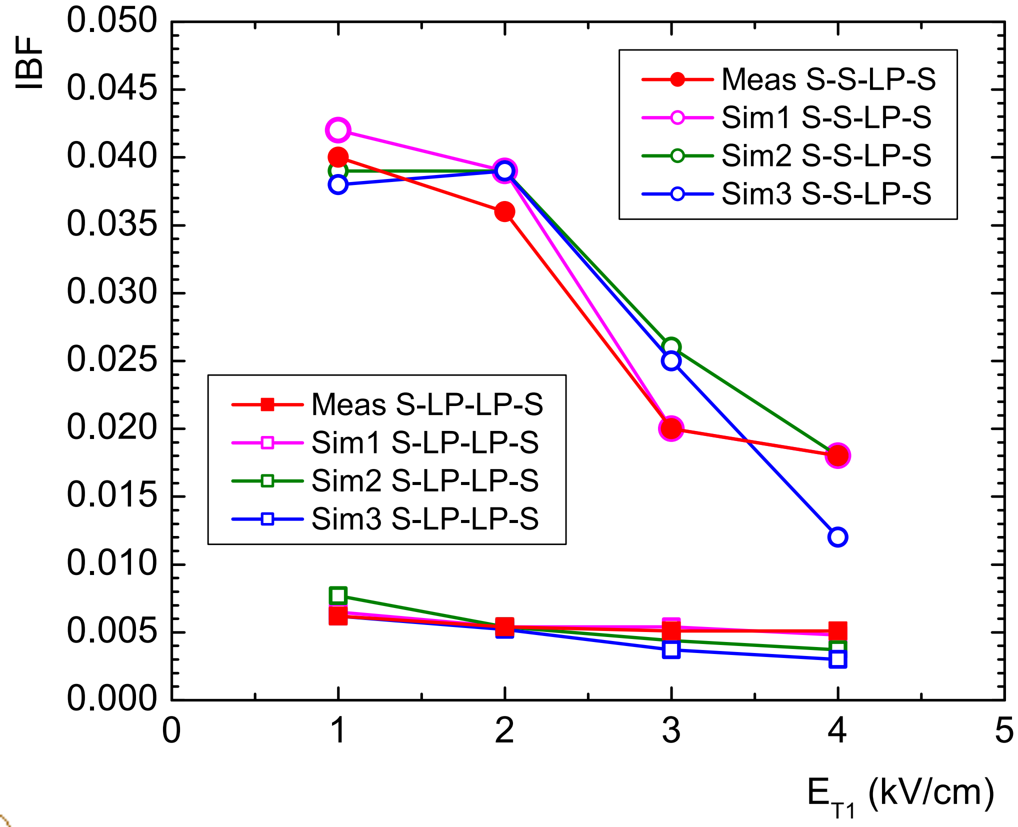
IBF performance and energy resolution



- Strong correlation between IBF and energy resolution
- Operational point with *IBF* < 1% and σ(^{55}Fe) is established

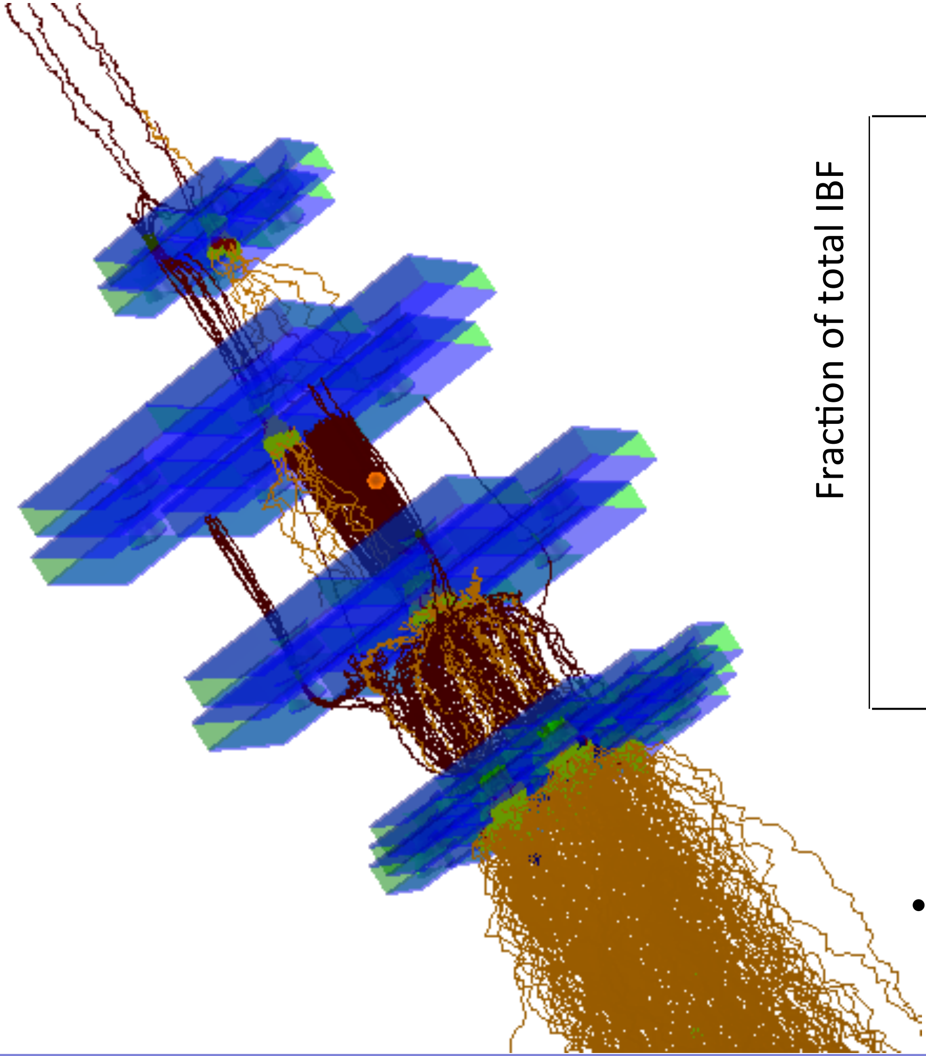
simulation: IBF in 4-GEM systems

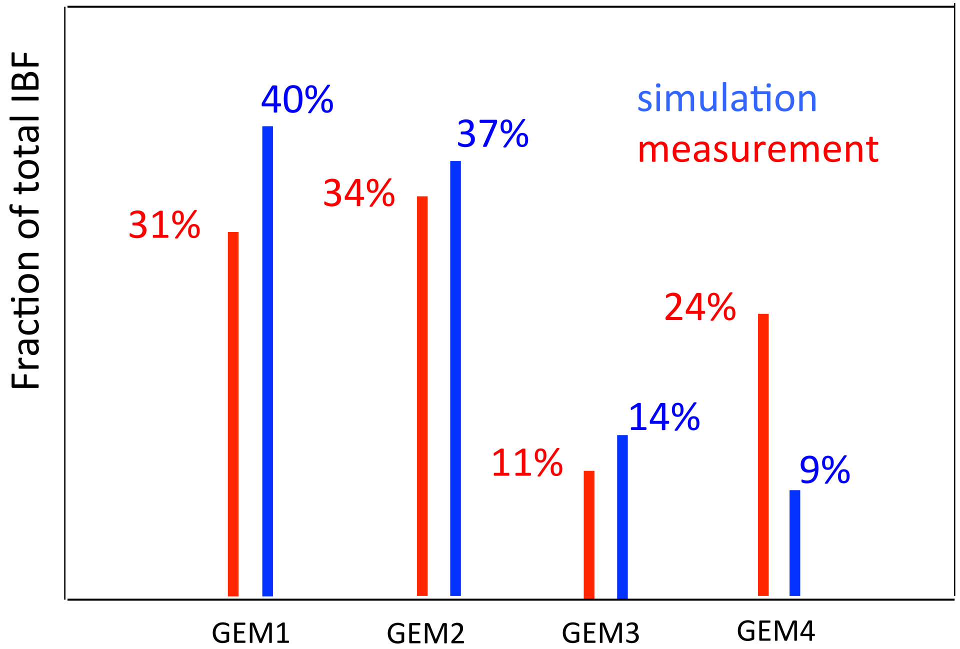




- IBF quantitatively well described by simulation based on Garfield++

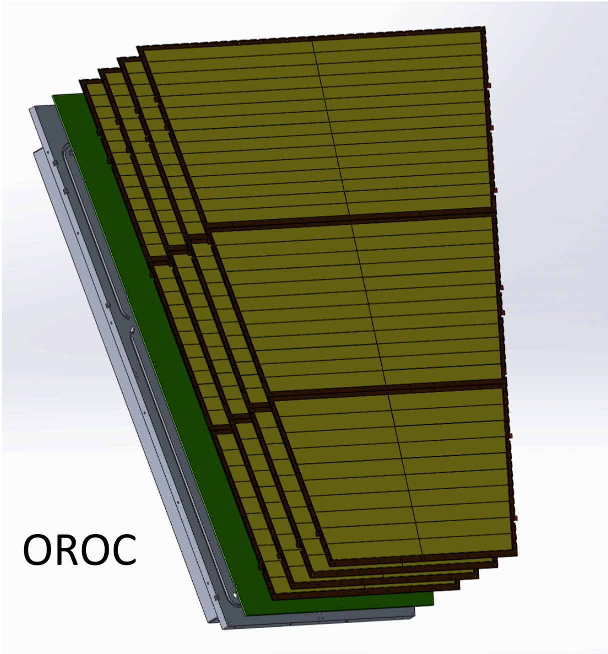
simulation: IBF in 4-GEM systems

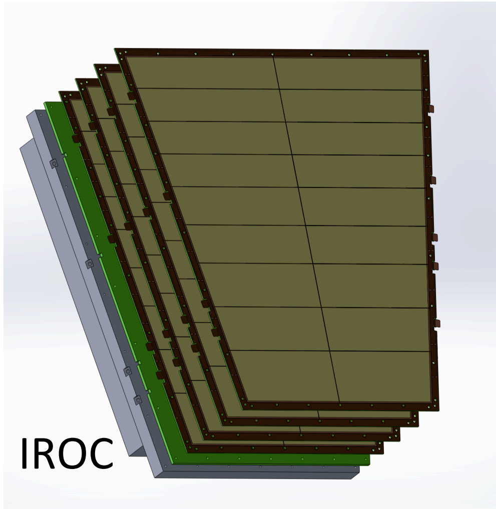


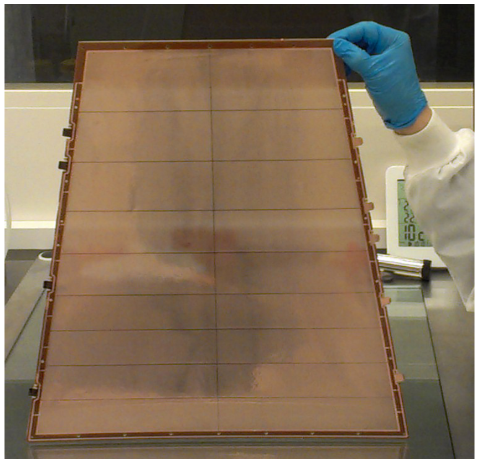


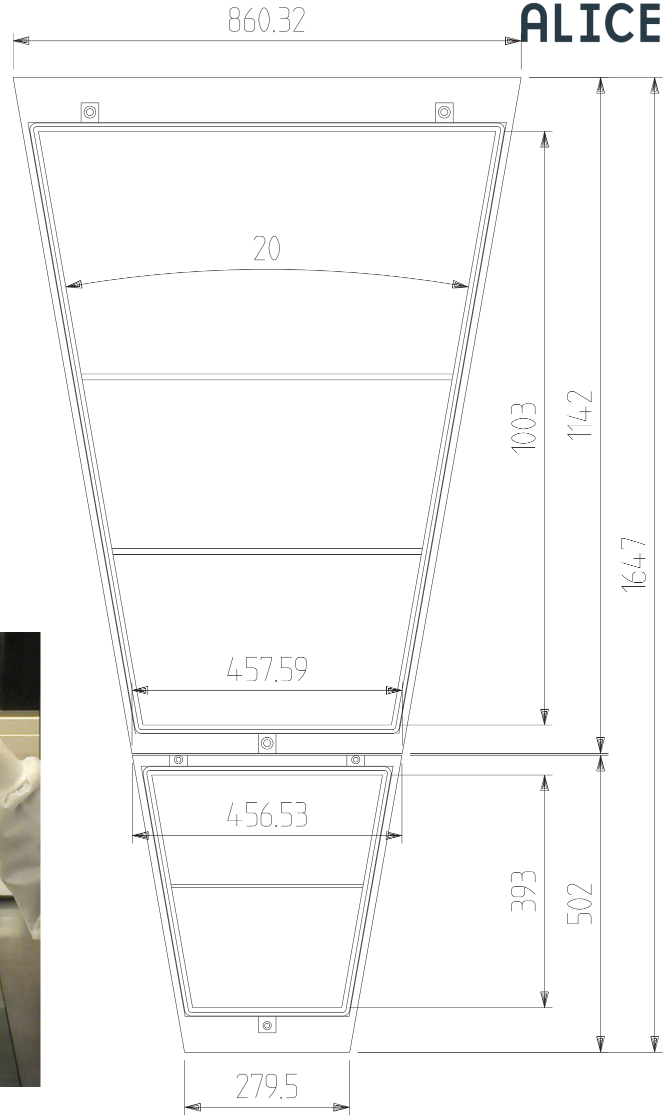
- effective blocking of ions from GEM3/4

TDR baseline solution: 4-GEM stack



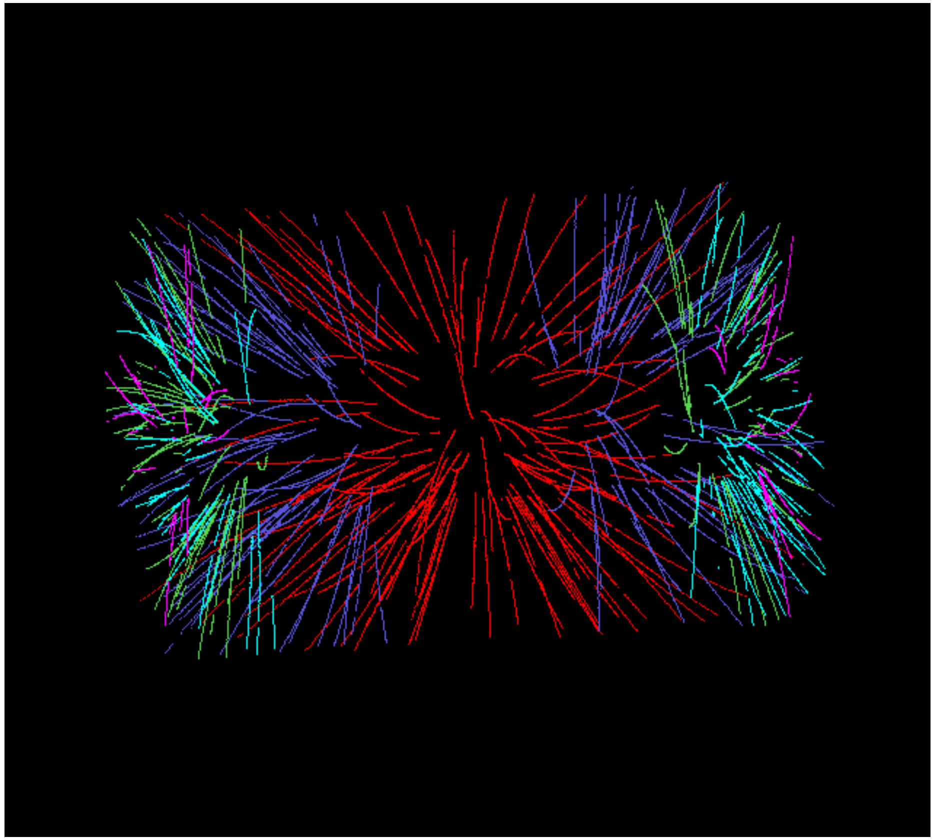






- large-size single-mask foils
- 1/layer in IROC, 3/layer in OROC

detector performance - summary

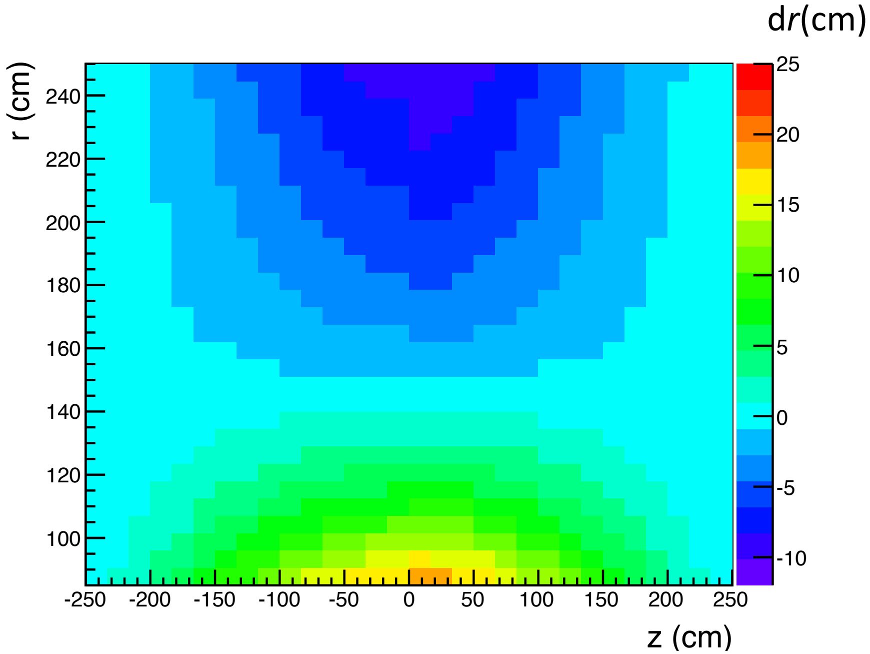


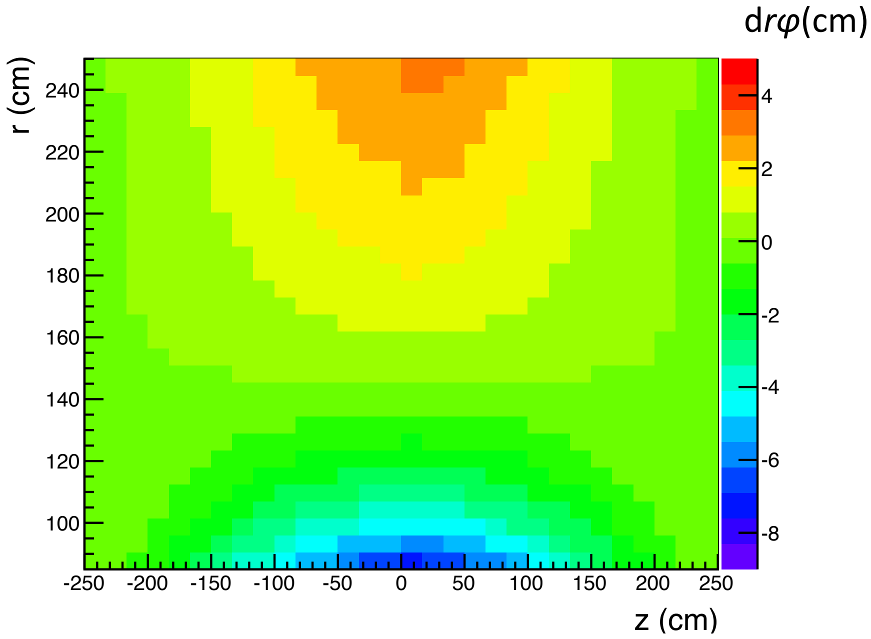
Validated with full microscopic simulation:

- intrinsic resolution with GEMs compatible with MWPC
- tracking efficiency and momentum resolution unaffected by event pile-up at 50 kHz
- slight increase of $\sigma(dE/dx)/\langle dE/dx \rangle$ with with event multiplicity due to cluster overlaps, same for GEM and MWPC

space charge distortions

50 kHz Pb-Pb, Ne-CO_2-N_2 (90-10-5), gain =2000, IBF = 1% (ε = 20), t_d^{ion} = 0.16 s
→ ions from 8000 events pile up in the drift volume



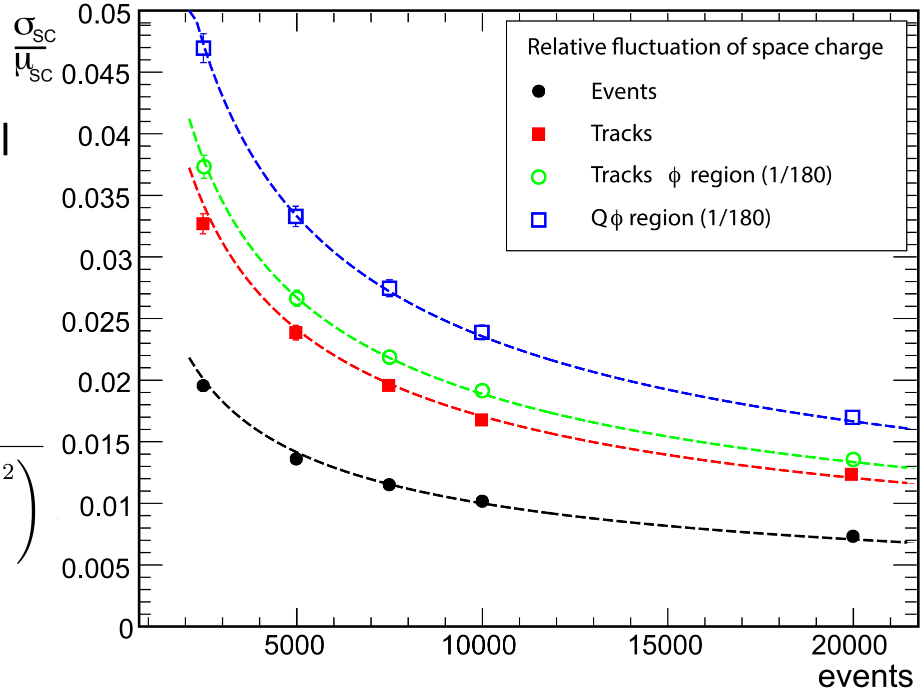


- at small *r* and *z* distortions reach *dr* = 20 cm and *drφ* = 8 cm
- corrections to a few 10^{-3} are required for final resolution

space charge fluctuations: magnitude

Fluctuations are due to:

- the number of events per time interval
- the number of tracks per event
- the phase space distribution of tracks
- the amount of charge per track



$$\frac{\sigma_{SC}}{\mu_{SC}} = \frac{1}{\sqrt{N_{pu}^{ion}}} \sqrt{1 + \left(\frac{\sigma_{N_{MB}}}{\mu_{N_{MB}}}\right)^2 + \frac{1}{F\mu_{N_{MB}}}\left(1 + \left(\frac{\sigma_{Qtrack}}{\mu_{Qtrack}}\right)^2\right)}$$

- Space-charge fluctuations are dominated by no-of-event and multiplicity fluctuations (~2% for <N>=8000)

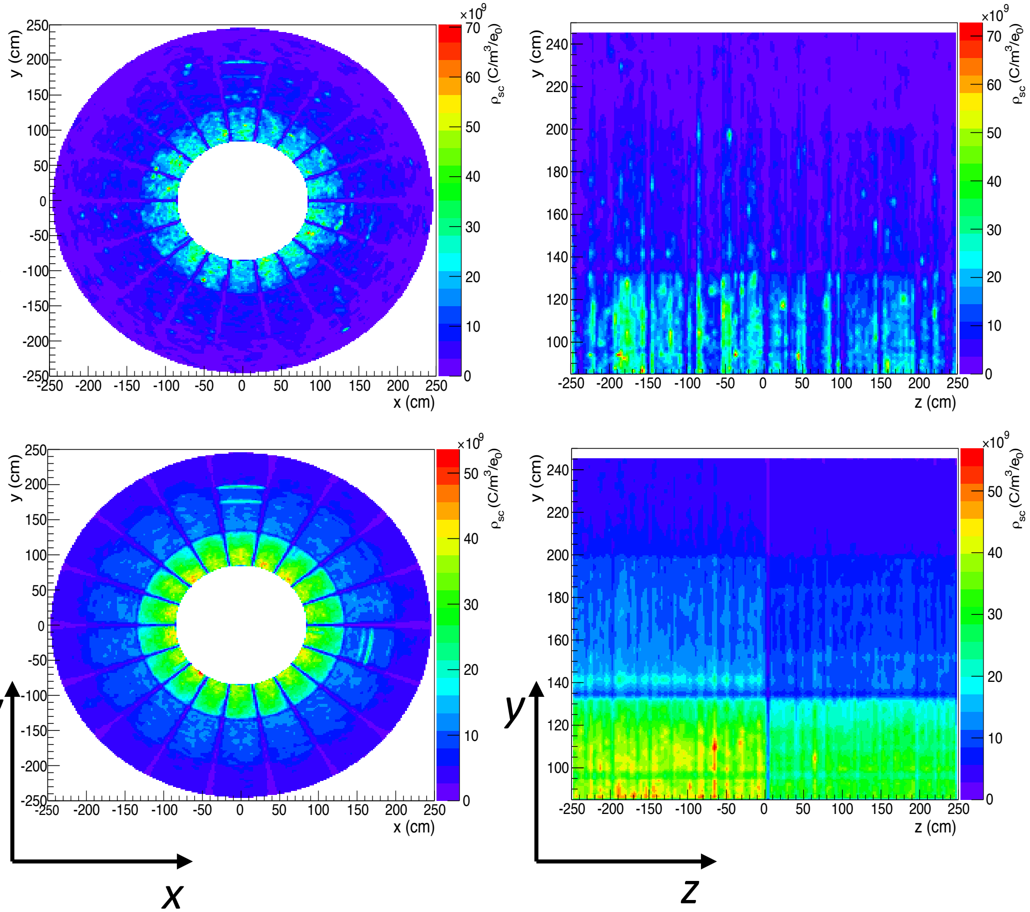
- the required precision is 10^{-3}

→ fluctuations need to be taken into account for distortion corrections

space charge distributions

8000 evs

130k evs



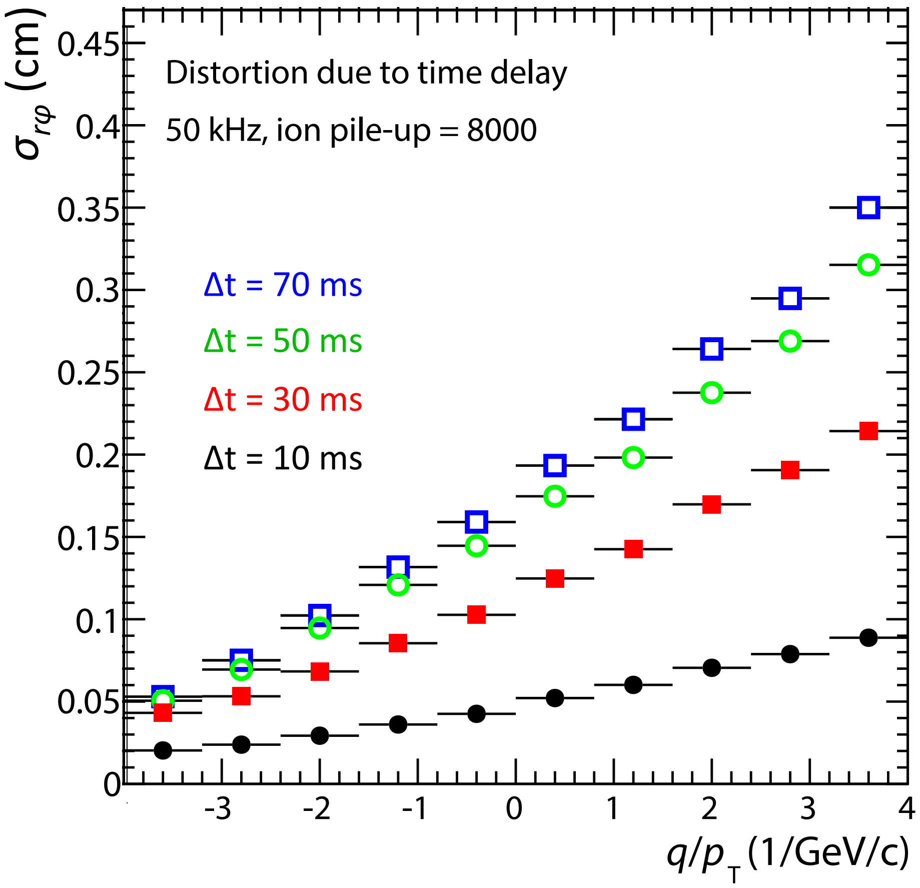
Study of space charge distributions and variations in space and time based on real Pb-Pb raw data

In Ne at 50 kHz, 8000 ion events pile up within 160 ms

Use overlap of 130k events to estimate time-averaged space-charge distribution

projections are shown in small slices in *z* and φ, respectively

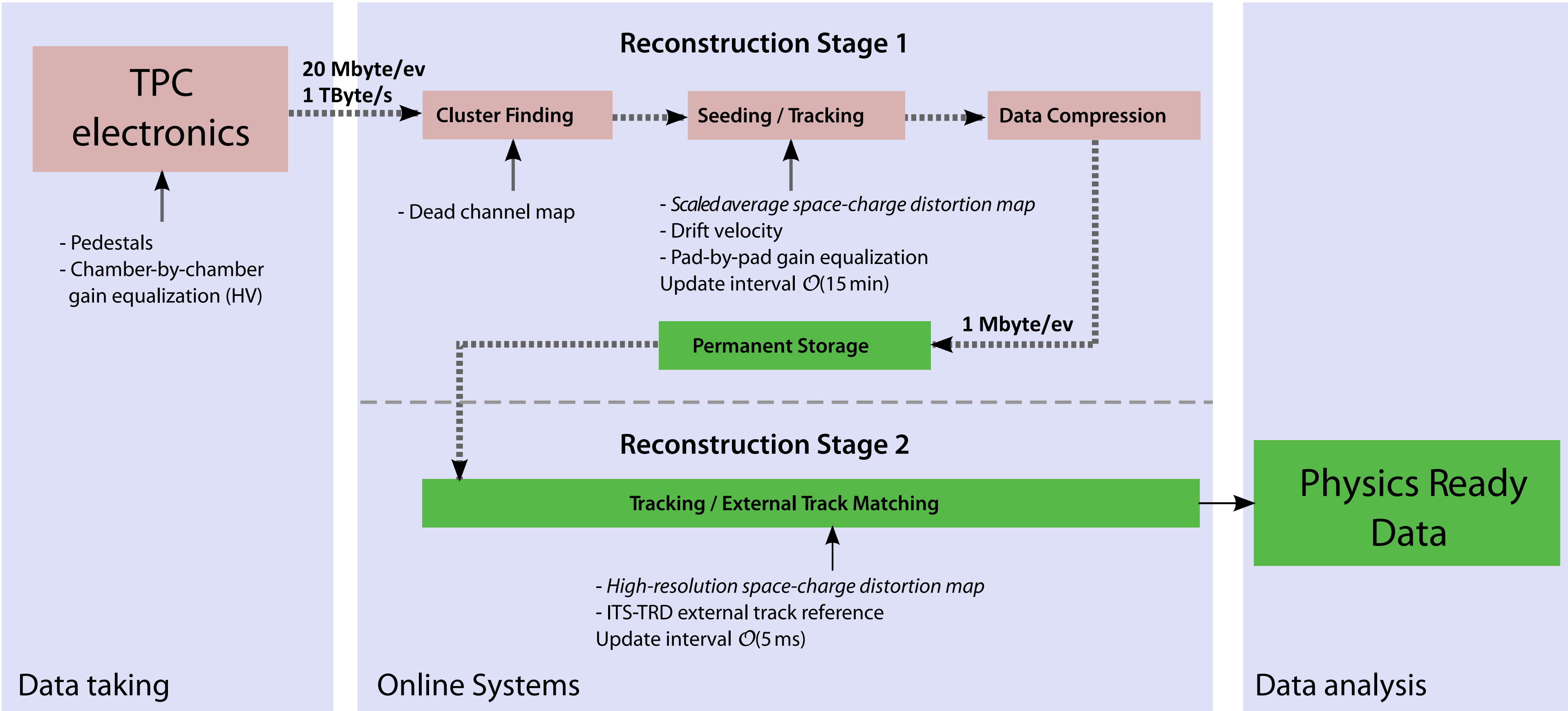
space charge fluctuations: temporal variations



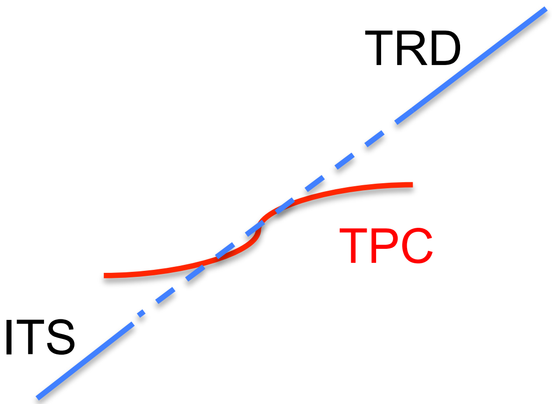
Simulation:
use fluctuating space-charge map for track distortion and a time-shifted map for correction

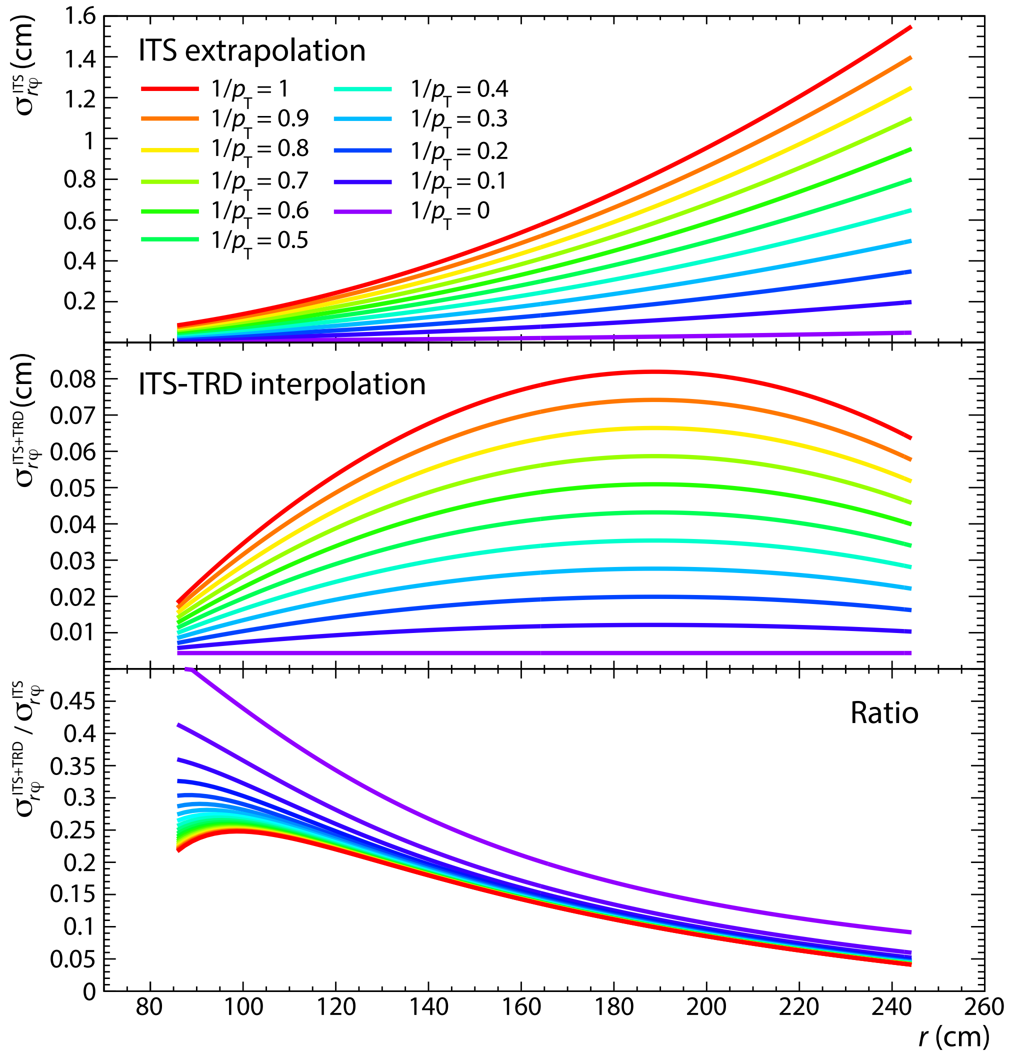
→ the space-charge map can be considered static on a time scale of ~5 ms

online reconstruction and calibration



second reconstruction stage: distortion correction

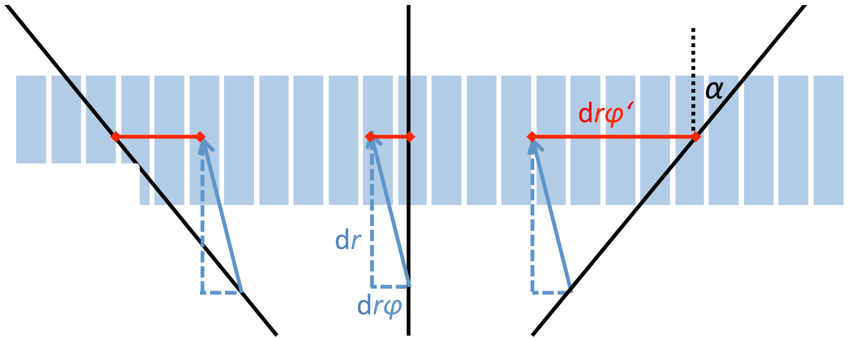


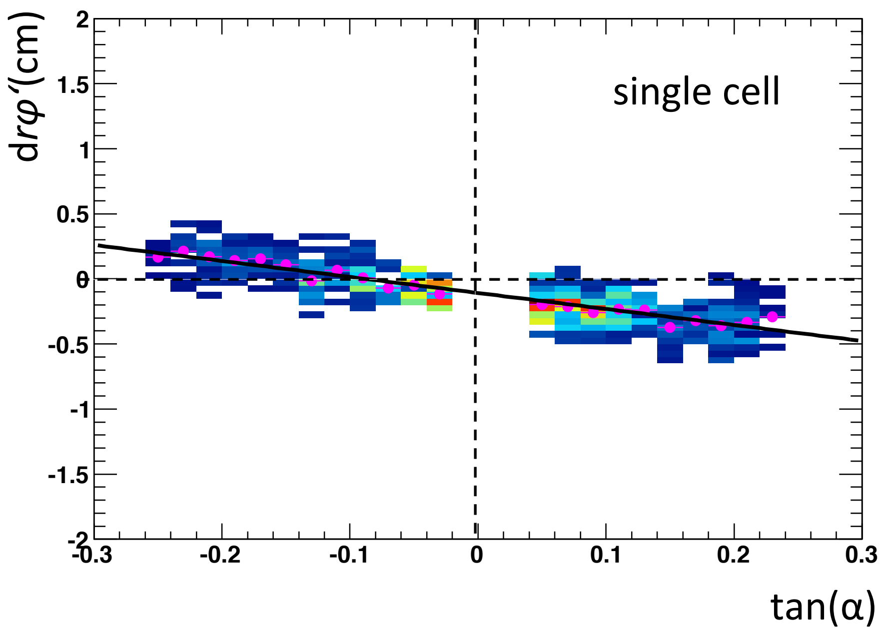


- use external track reference from ITS-TRD interpolation

→ validate with fast simulation

fast simulation



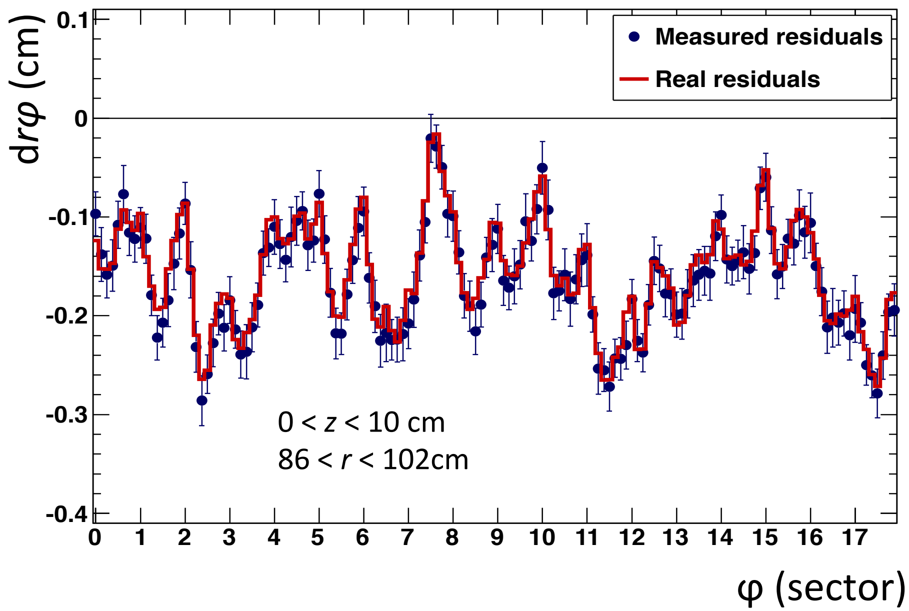


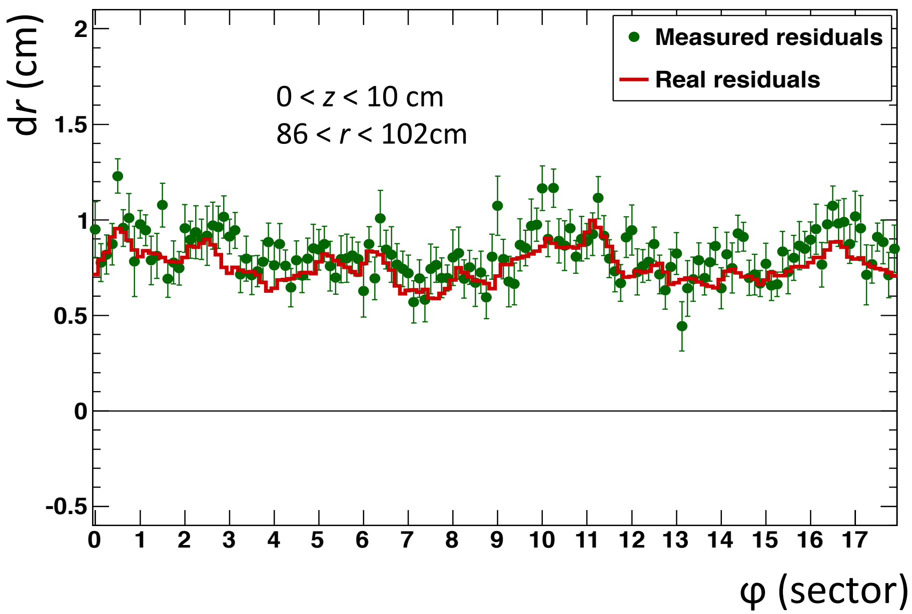
- assume static space-charge configuration within Δt_{calib} = 5 ms → 250 minimum bias events
- analyze residuals of TPC clusters with respect to ITS-TRD reference
- map residual distortions in 72,000 volume elements of size 16cm(*r*) x π/72(*φ*) x 10cm(*z*)
- 2D – analysis to disentangle *dr-drφ* correlations:

$$\mathrm{d}r\varphi' = \mathrm{d}r\varphi + \mathrm{d}r \cdot \tan\alpha$$

→ extract d*r* and d*rφ*

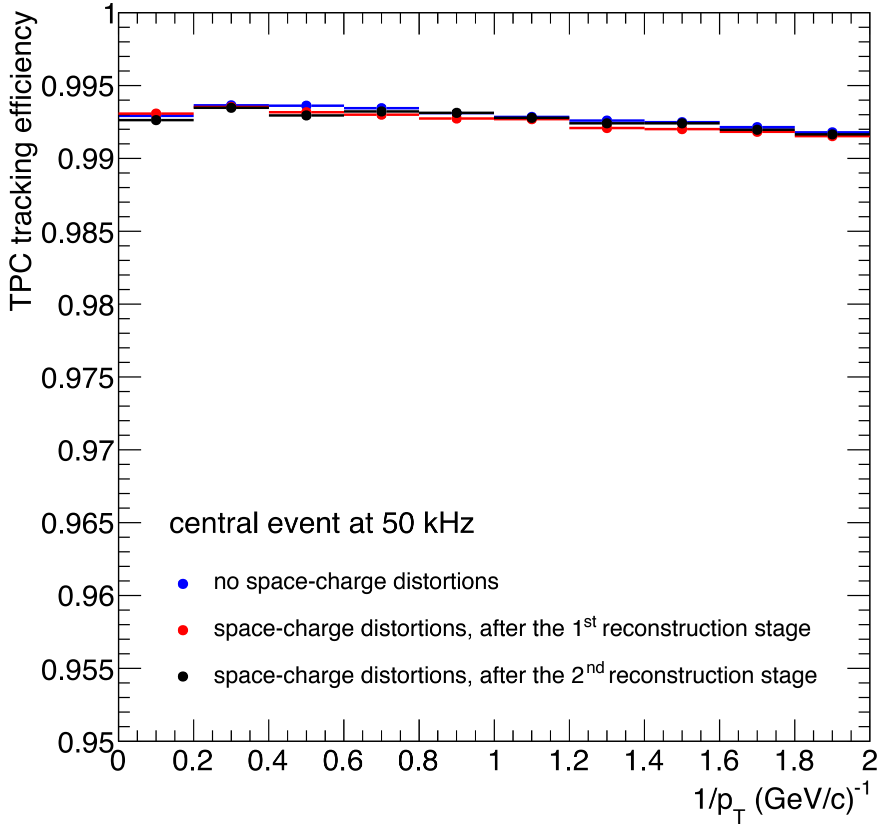
residual distortions

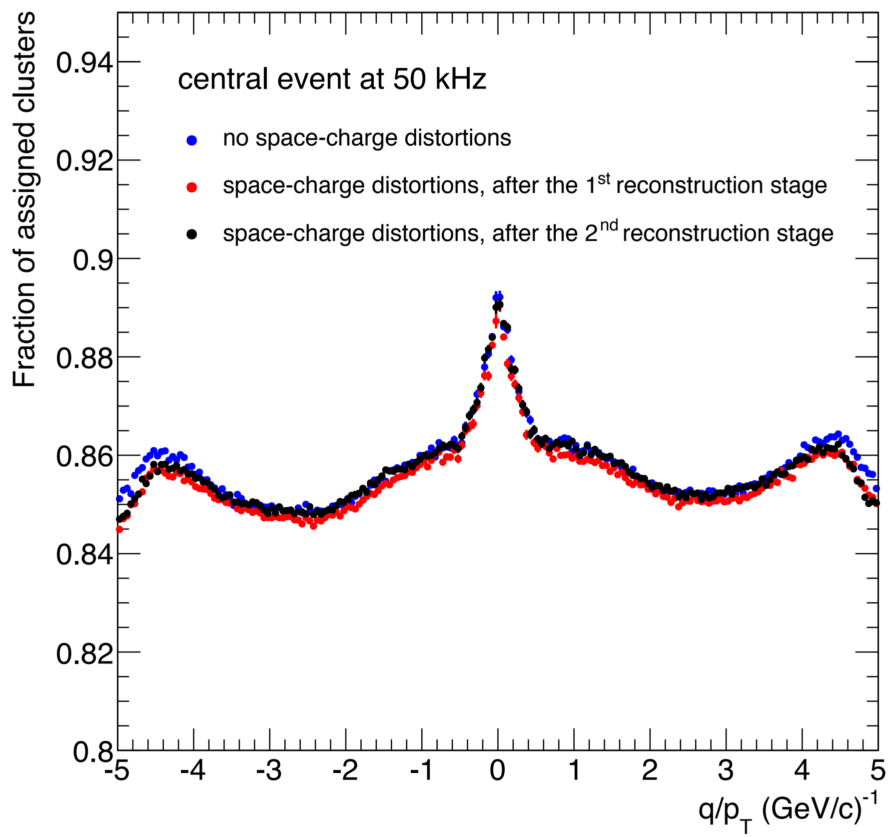




- spatial fluctuation pattern well described
- residual fluctuations significantly improved

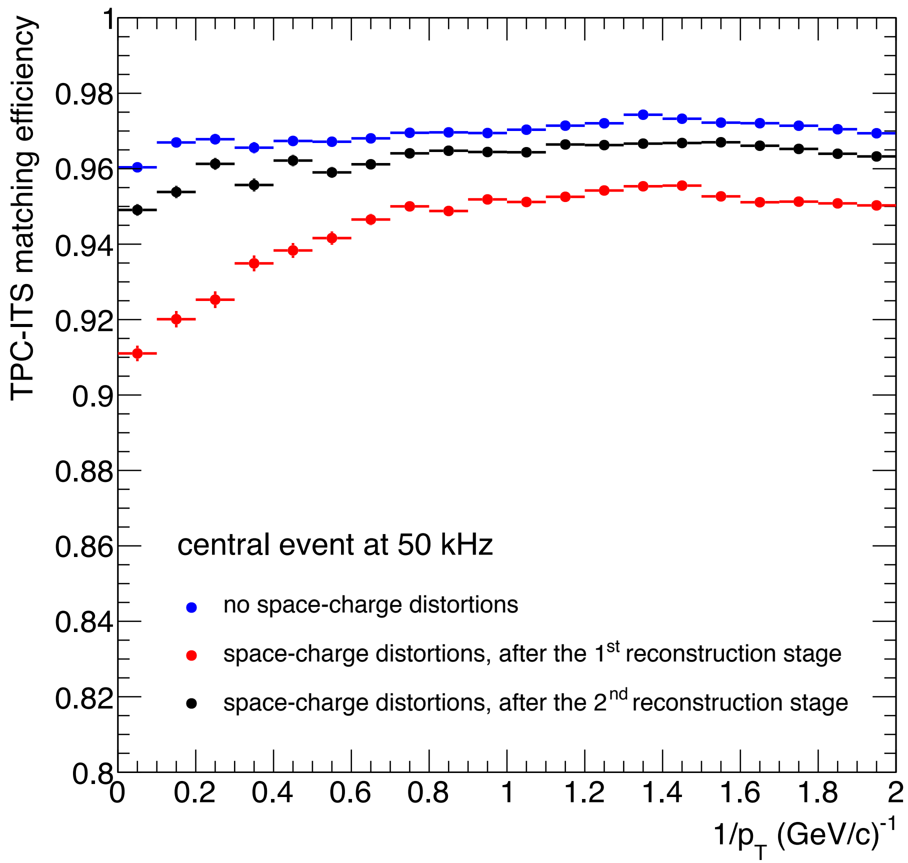
online tracking: performance





→ high tracking and cluster association efficiency
in the first and second reconstruction stage

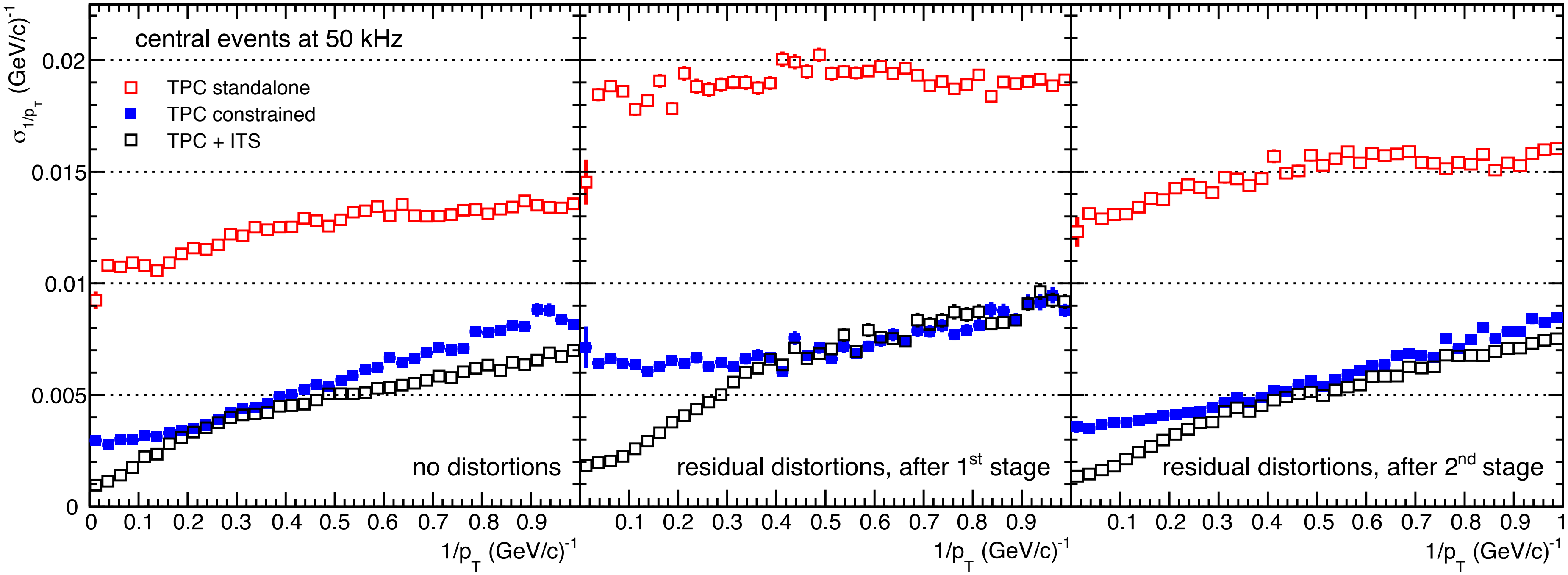
online tracking: performance



TPC-ITS matching efficiency

- slightly reduced in first reconstruction stage
- almost fully recovered in second reconstruction stage

online tracking: momentum resolution



- momentum resolution after first reconstruction stage factor 1.5 - 2 worse than ideal
- almost fully recovered after second reconstruction stage

Organisation, cost estimate, time schedule

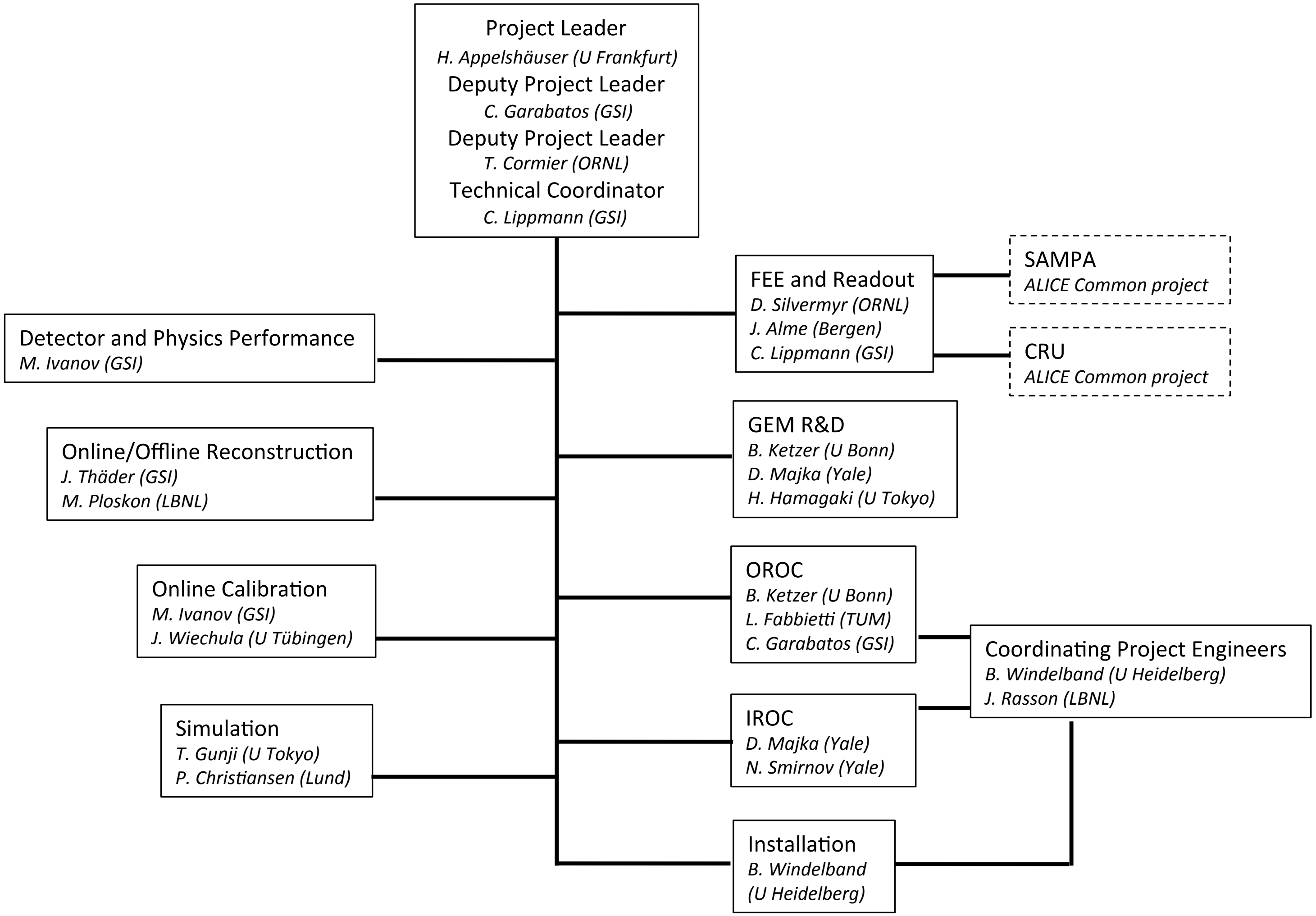
ALICE TPC collaboration

Country Funding Agency	City	Institute
Croatia	Zagreb	Department of Physics, University of Zagreb
Denmark	Copenhagen	Niels Bohr Institute, University of Copenhagen
Finland	Helsinki	Helsinki Institute of Physics
Germany BMBF	Bonn	Helmholtz-Institut für Kern- und Strahlenphysik, Rheinische Friedrich-Wilhelms-Universität Bonn
Germany BMBF	Frankfurt	Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt
Germany BMBF	Heidelberg	Physikalisches Institut, Ruprecht-Karls Universität Heidelberg
Germany BMBF	Munich	Physik Department, Technische Universität München
Germany BMBF	Tübingen	Physikalisches Institut, Eberhard Karls Universität Tübingen
Germany BMBF	Worms	FH Worms, Worms
Germany GSI	Darmstadt	Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung
Hungary	Budapest	Wigner Research Center for Physics, Budapest
India	Kolkata	Bose Institute
India	Bhubaneswar	Institute of Physics
India	Bhubaneswar	National Institute of Science Education and Research
India	Indore	Indian Institute of Technology
India	Mumbai	Indian Institute of Technology
India	Kolkata	Variable Energy Cyclotron Centre
Japan	Tokyo	University of Tokyo
Mexico	Mexico City	Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México
Norway	Bergen / Tonsberg	Department of Physics, University of Bergen, Vestfold University College, Tonsberg
Norway	Bergen	Faculty of Engineering, Bergen University College
Pakistan	Islamabad	Department of Physics, COMSATS Institute of Information Technology Islamabad
Poland	Cracow	The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Science
Romania	Bucharest	National Institute for Physics and Nuclear Engineering
Slovakia	Bratislava	Faculty of Mathematics, Physics and Informatics, Comenius University
Sweden	Lund	Division of Experimental High Energy Physics, University of Lund
USA DOE	Omaha	Creighton University, Omaha, Nebraska
USA DOE	Houston	University of Houston, Houston, Texas
USA DOE	Berkeley	Lawrence Berkeley National Laboratory, Berkeley, California
USA DOE	Livermore	Lawrence Livermore National Laboratory, Livermore, California
USA DOE	Oak Ridge	Oak Ridge National Laboratory, Oak Ridge, Tennessee
USA DOE	West Lafayette	Purdue University, West Lafayette, Indiana
USA DOE	Knoxville	University of Tennessee, Knoxville, Tennessee
USA DOE	Austin	The University of Texas at Austin, Austin, Texas
USA DOE	Detroit	Wayne State University, Detroit, Michigan
USA DOE	New Haven	Yale University, New Haven, Connecticut
USA NSF	San Luis Obispo	California Polytechnic State University, San Luis Obispo, California
USA NSF	Chicago	Chicago State University, Chicago, Illinois

38 institutions from 15 countries

new members bring in significant expertise and resources

Project organization



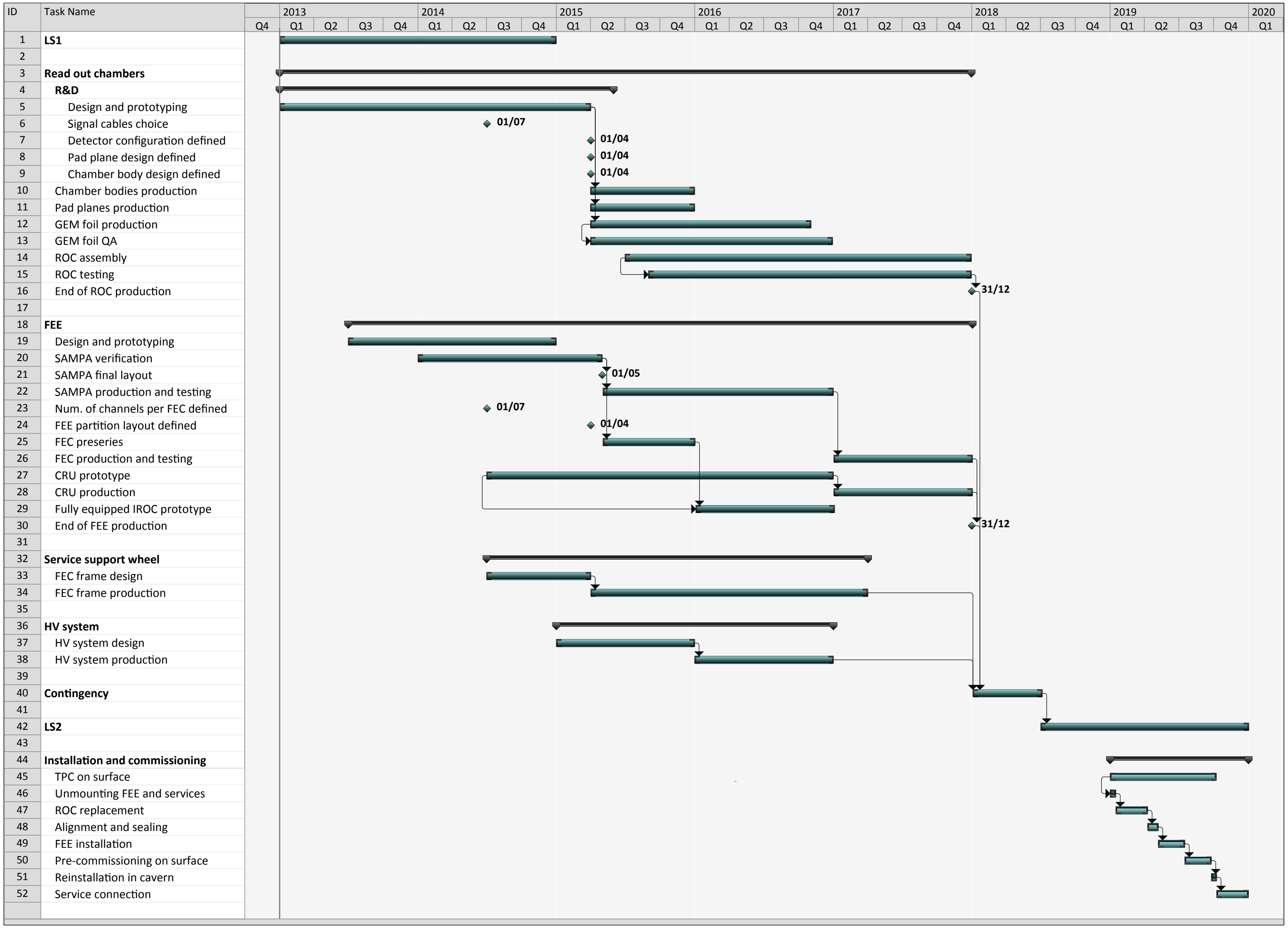
Project organization

Item	Institution
IROC	Yale, Detroit, Oak Ridge, Knoxville, Austin
OROC	Munich, Frankfurt, GSI, Heidelberg, Budapest, Bucharest
GEM R&D and QA	Helsinki, Munich, Tokyo, Yale, Zagreb, GSI
Frontend Card	Lund, Oak Ridge
FEE integration and test	Oak Ridge, Lund, Houston, Tokyo, Bergen, Oslo, GSI
HV, LV, cooling	Mexico-City, GSI, Munich
Detector Control	GSI, Worms
Installation and engineering	Heidelberg, Berkeley
Gas system and field cage	GSI
SAMPA ASIC	São Paulo, Bergen, Oslo
CRU	Budapest, Kolkata, Bergen

Cost estimate

Readout chambers	Quantity (incl. spares)	Cost (MCHF)
GEM foils[1]	480	0.5
Frames and components	960	0.1
Pad planes	160	0.4
Chamber bodies	80	0.3
HV divider	80	0.1
Assembly and installation tooling		0.4
Total Readout Chambers		**1.8**
Services		Cost (MCHF)
GEM HV system		0.2
Fast current monitoring		0.2
HV supply for last FC resistor		0.1
Other services		0.2
Total Services		**0.7**
FEE and Readout	Quantity (incl. spares)	Cost (MCHF)
SAMPA ASIC	19,500	0.78
Front-end card	3900	0.35
GBTx ASIC	7000	0.38
Optical transmitters/receivers	5500	0.79
CRU (control room, AMC40)		2.00
Optical fibers	9000	1.32
TPC Event Processing Nodes (TPC-EPN)		1.00
Other		0.02
Total Electronics		**6.64**
Total IROC	40	3.3
Total OROC	40	5.84
Total		**9.14**

Time schedule



summary

The ALICE TPC upgrade TDR is submitted

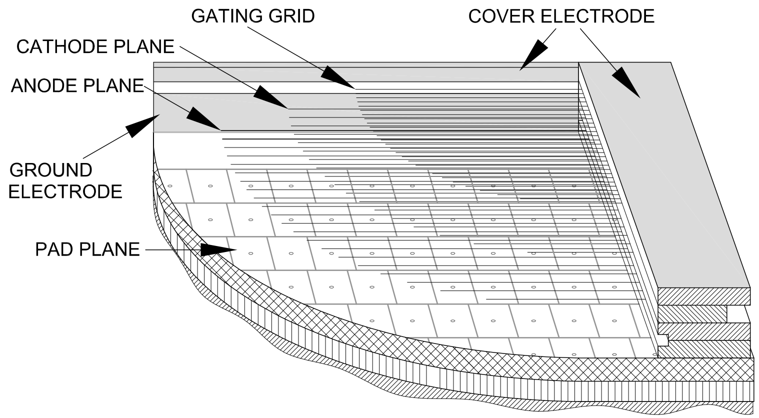
A technical solution for TPC readout chamber upgrade based on GEMs is proposed.

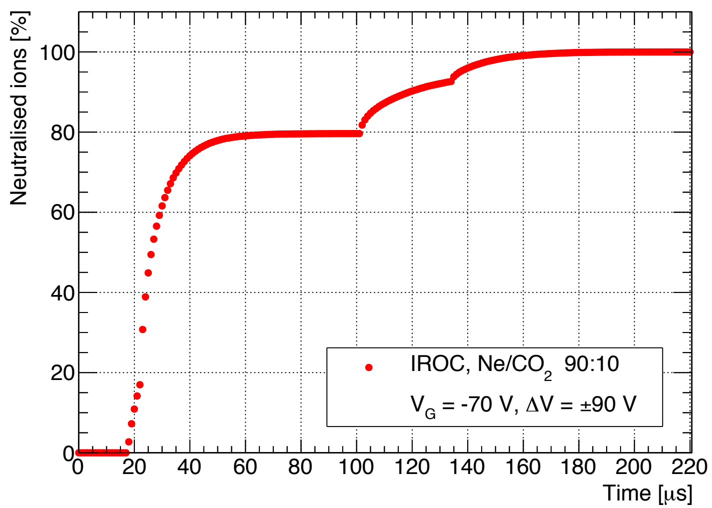
An online tracking scheme to provide efficient online data compression and high reconstruction efficiency at 50 kHz is developed.

Validation of the space-charge distortion correction scheme to restore the TPC tracking performance and momentum resolution concludes the studies for the TDR.

Backup

limitation of the present system





present MWPC-based readout chambers employ a gating grid:

after 100 μs of electron drift time, the gating grid needs to be kept close for ~200 μs to prevent back-drifting ions into the drift region

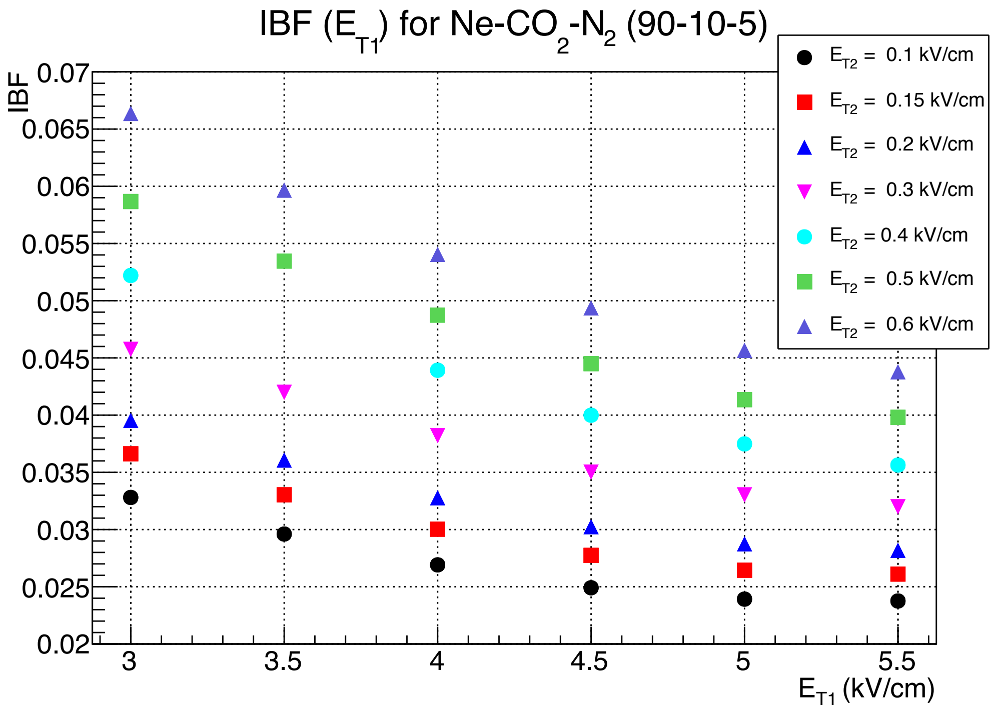
→ total time ~300 μs limits maximal readout rate to ~3 kHz

ignoring the GG closure time (i.e. keeping it open all the time) leads to excessive space point distortion due to space charge accumulation in drift volume.

→ novel technology required to block ions: GEMs

→ allows for ungated („continuous") readout
N.B.: on average 5 events pile up in the TPC at 50 kHz and $t_{d,max}$ = 100 μs

Ion Backflow in triple GEMs



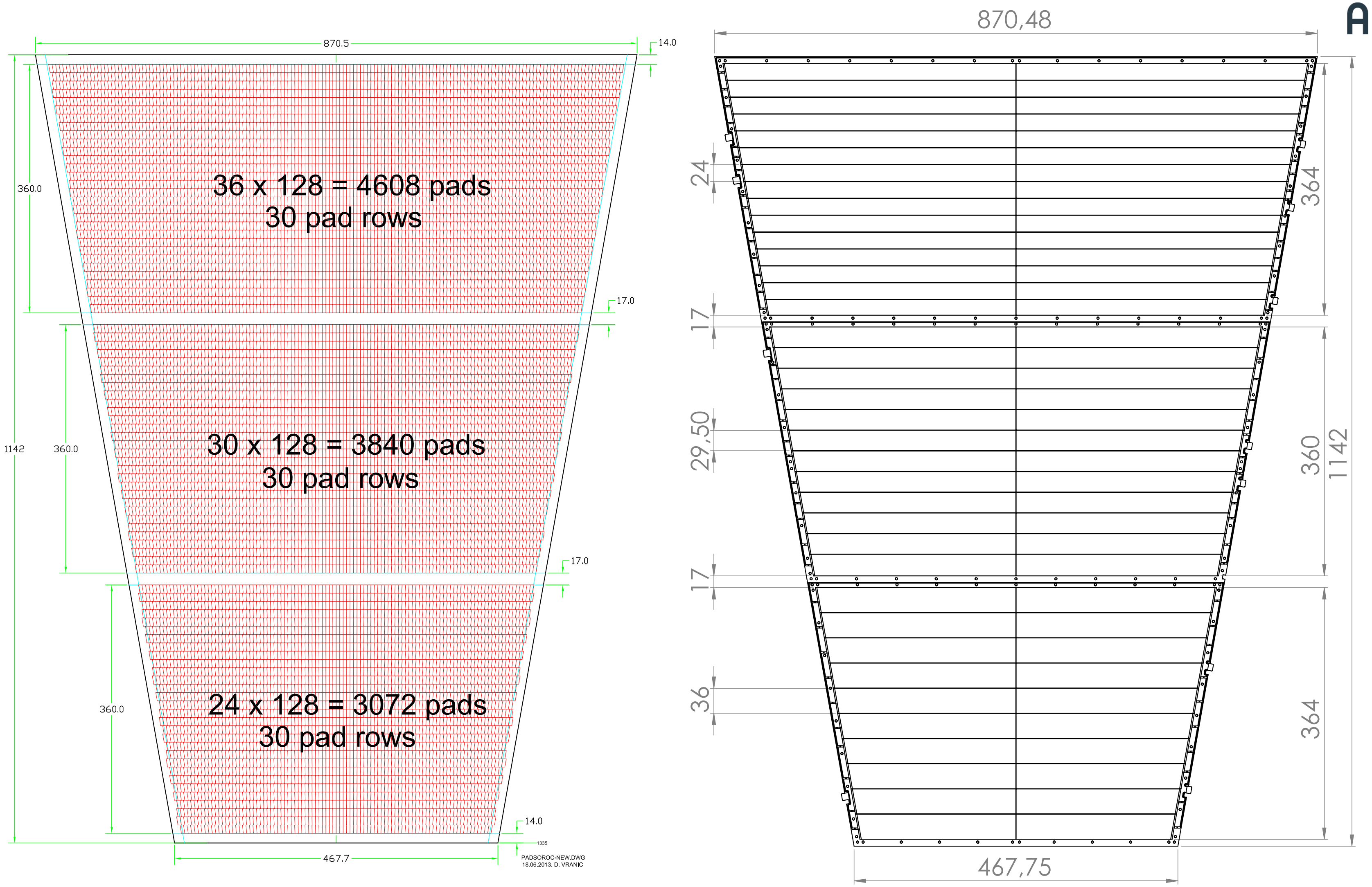
Comprehensive study of triple standard GEM system (gas mixture, E_{T1}, E_{T2})

→ *IBF* requirement not achieved with triple GEMs

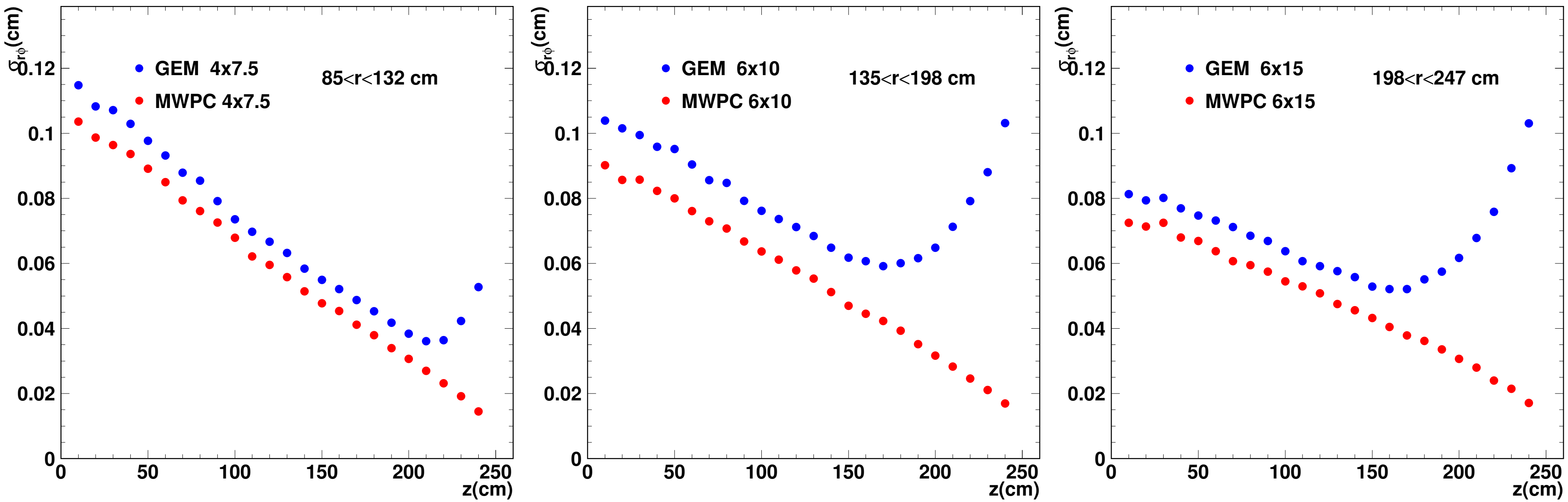
→ add a fourth GEM

→ introduce GEMs with large hole pitch

TDR baseline solution: 4-GEM system



intrinsic performance: position resolution

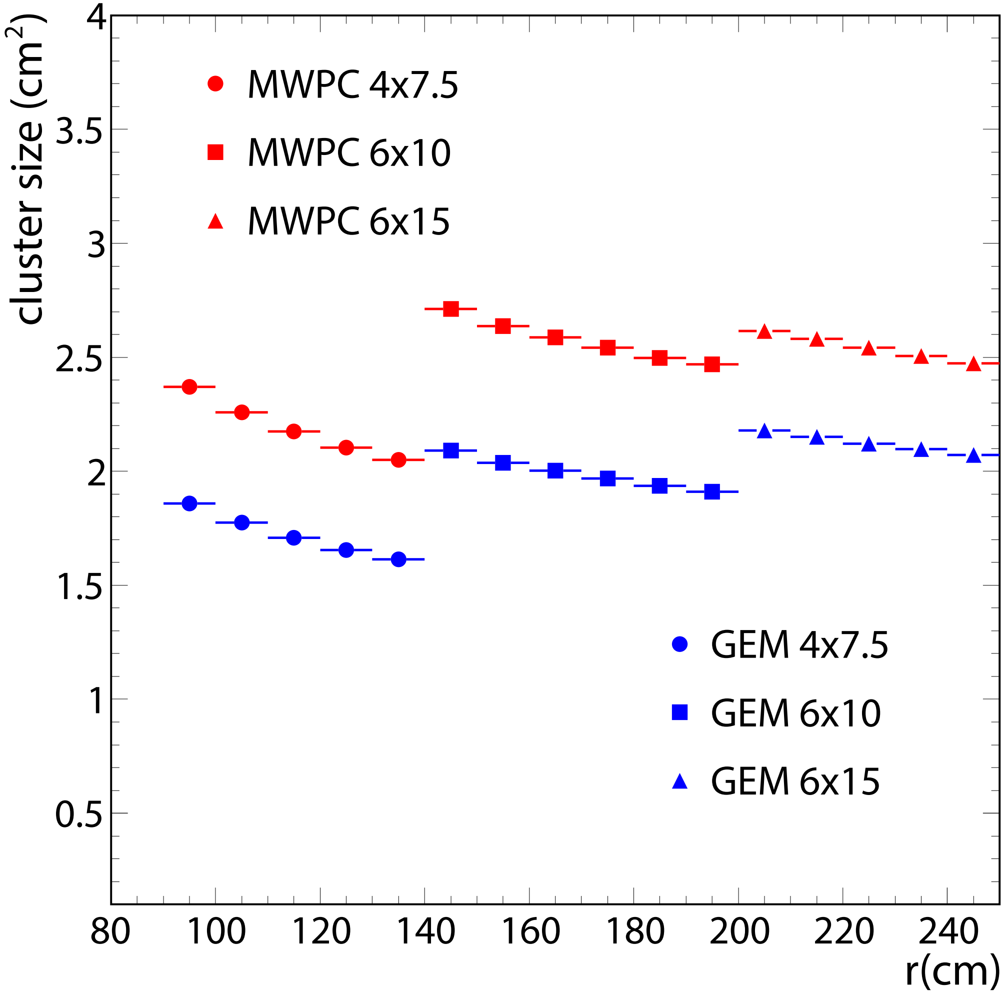


Preserve present pad sizes and rectangular shape (optimized for occupancy)

→ resolution with GEMs is slightly worse due to lack of Pad Response Function:

- more prone to fluctuations
- at short drift: one-pad clusters (but mainly $|\eta| > 1$)

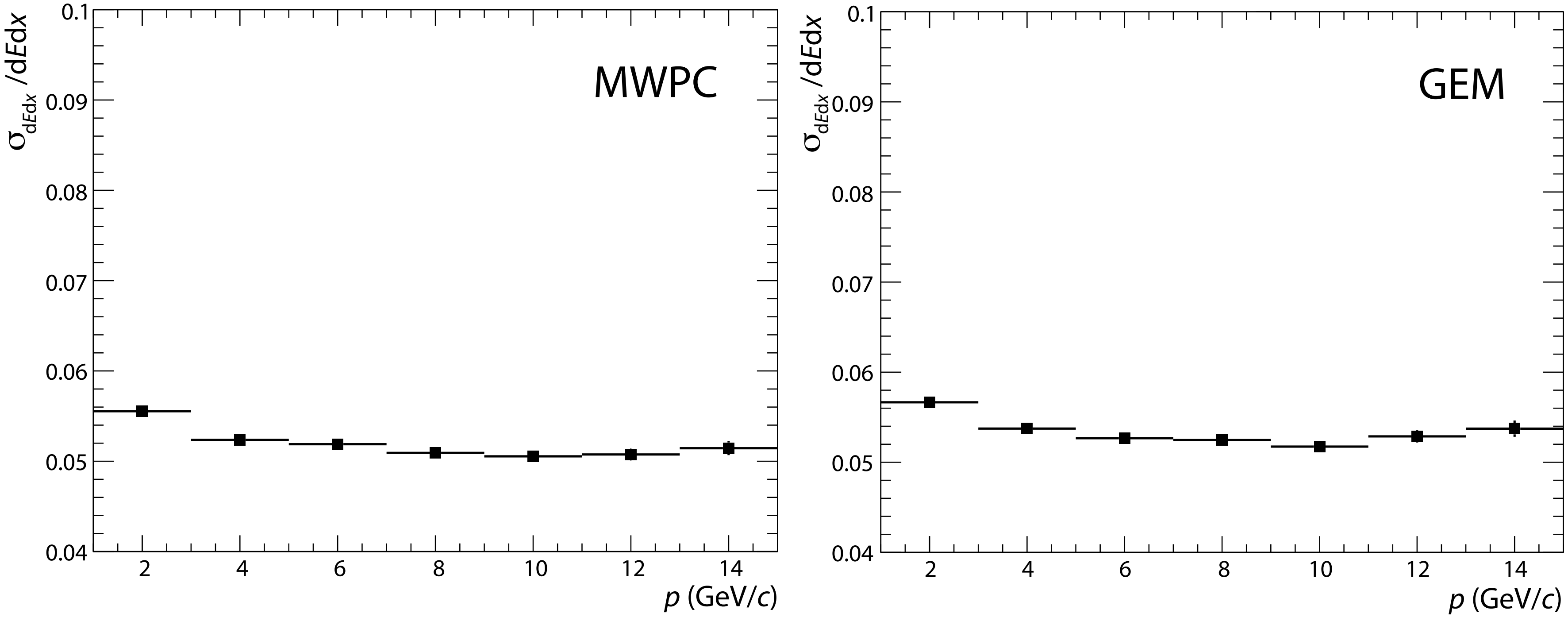
intrinsic performance: cluster size



Lack of PRF in GEMs reduces average cluster size (i.e. occupancy) by 20% wrt. MWPC

intrinsic performance: dE/dx

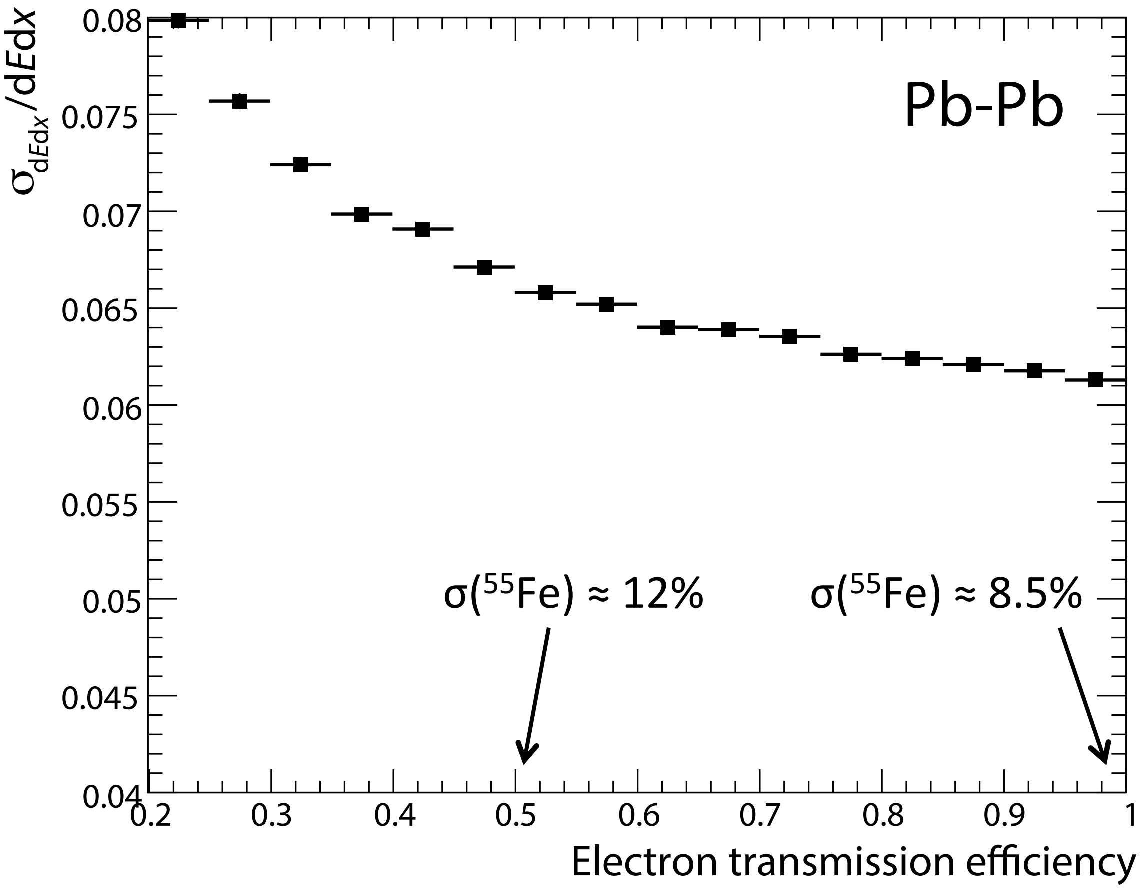
Simulated pp events : full MC, no pile-up



- Same resolution in GEM-based readout chambers as in MWPC

Energy resolution

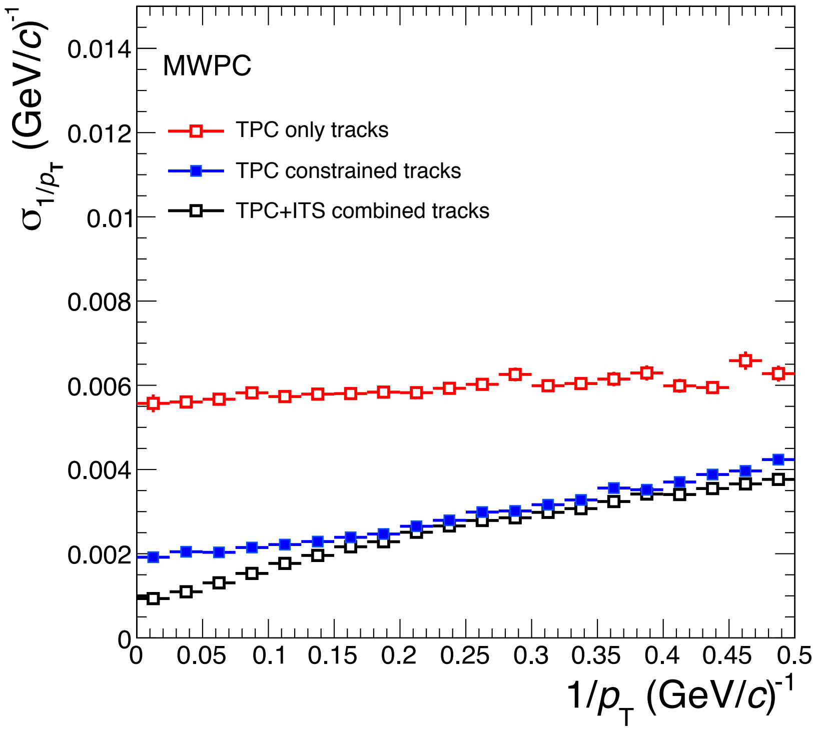
fast MC

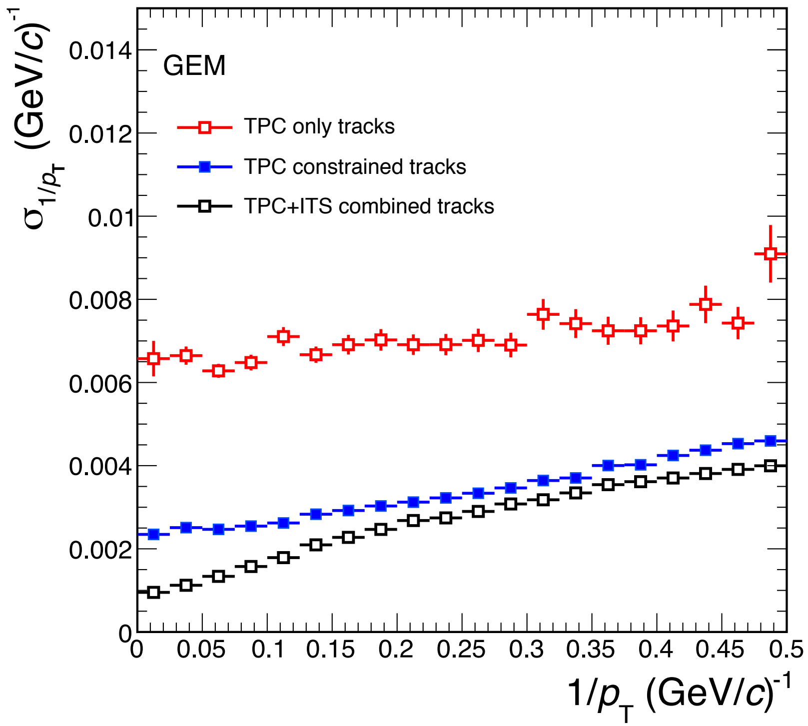


intrinsic performance: momentum resolution

ALICE

Simulated central Pb-Pb events at 5.5 TeV: full MC, no pile-up

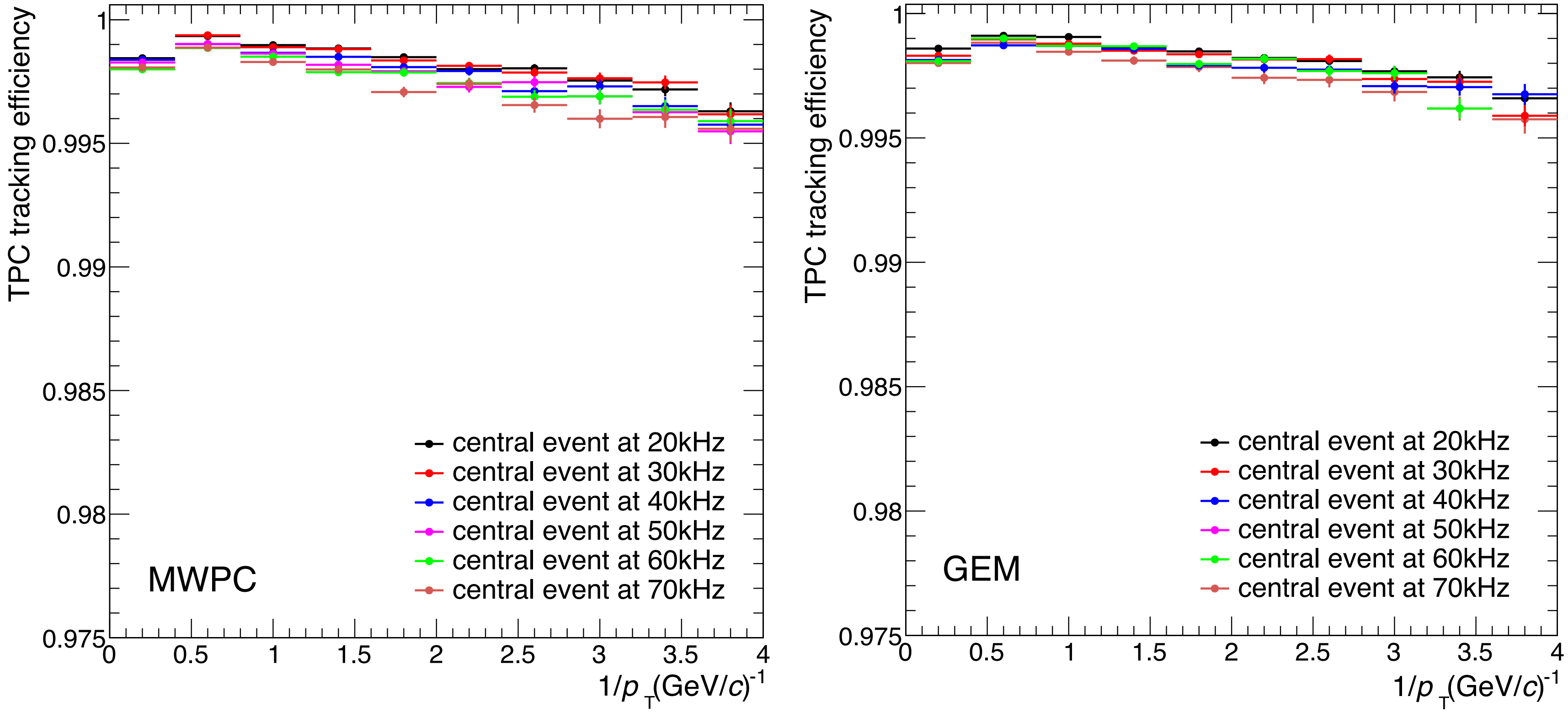




- TPC standalone: GEMs slightly worse than MWPC
- Global tracks: same resolution for GEM and MWPC

pile-up studies: tracking efficiency

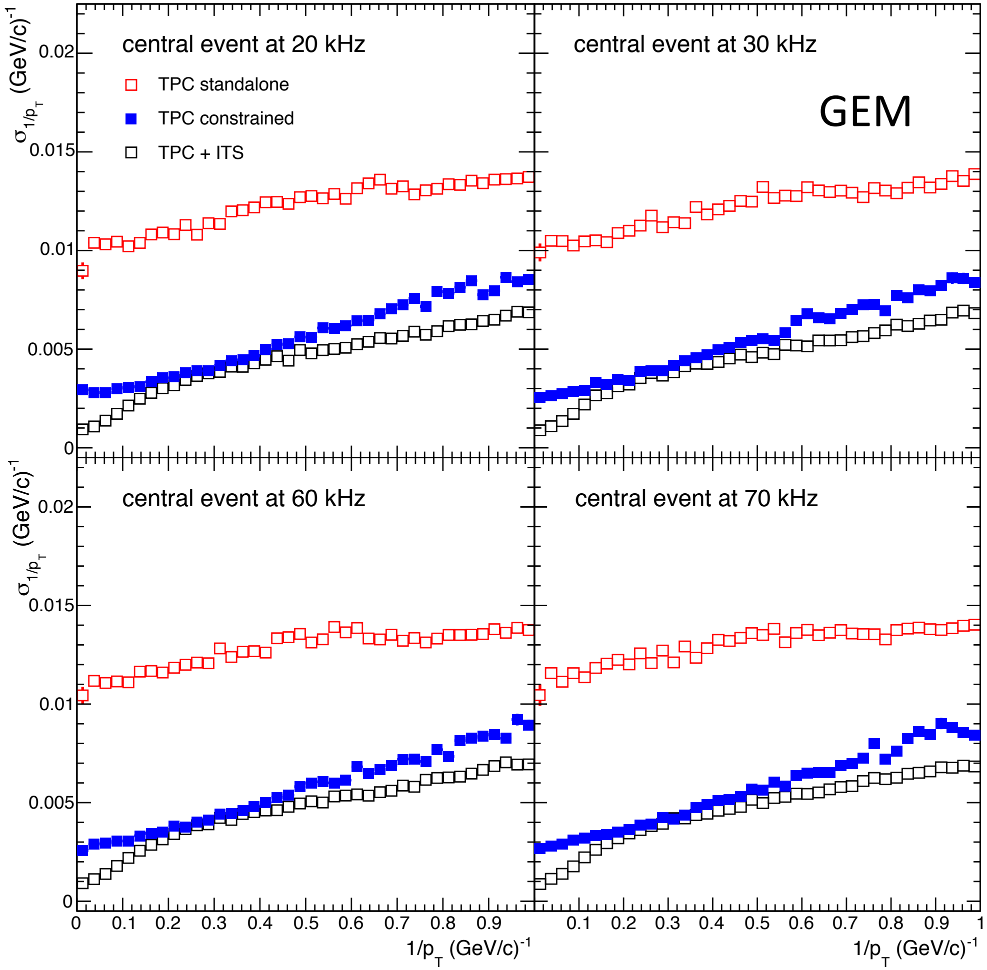
Simulated central Pb-Pb events at 5.5 TeV: full MC, with pile-up



- very high tracking efficiency for MWPC and GEM
- no dependence on pile-up

pile-up studies: momentum resolution

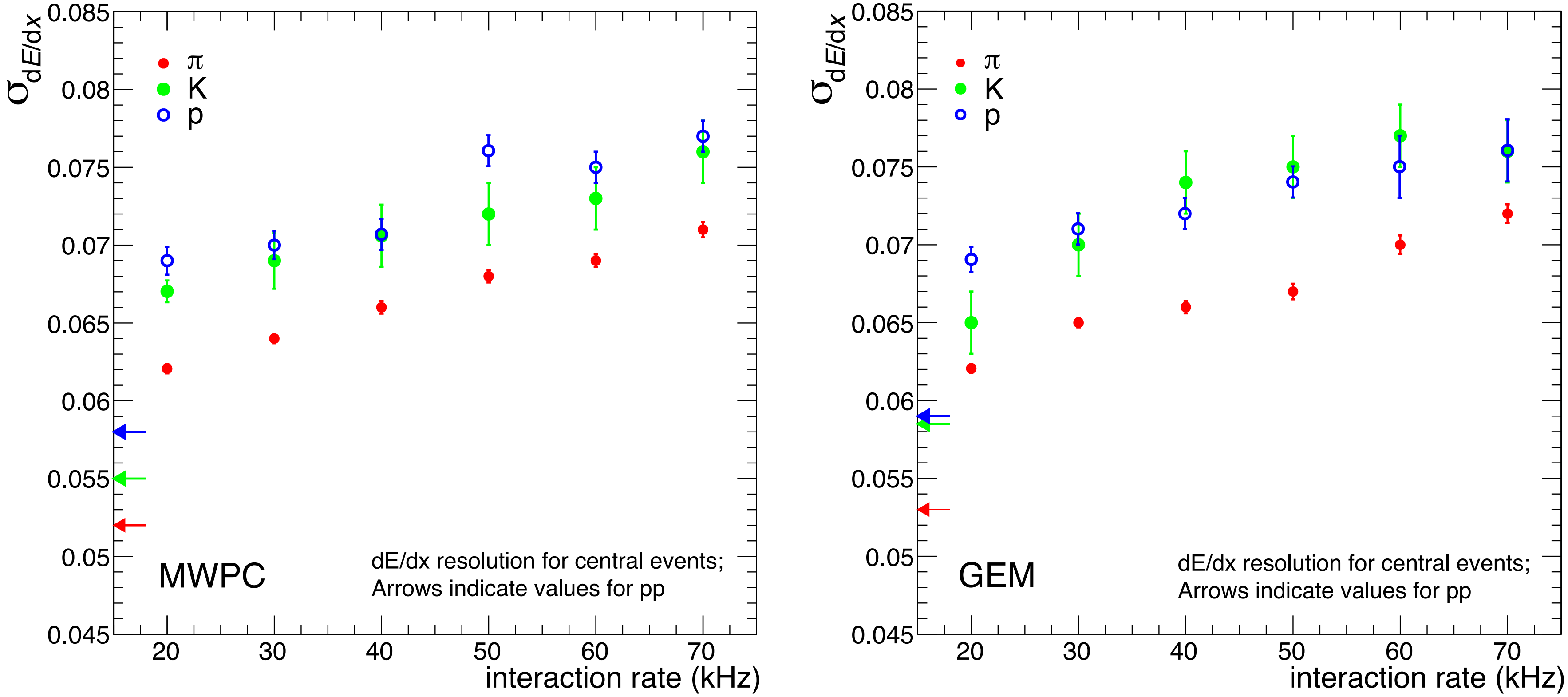
Simulated central Pb-Pb events at 5.5 TeV: full MC, with pile-up



- no dependence of momentum resolution on pile-up observed

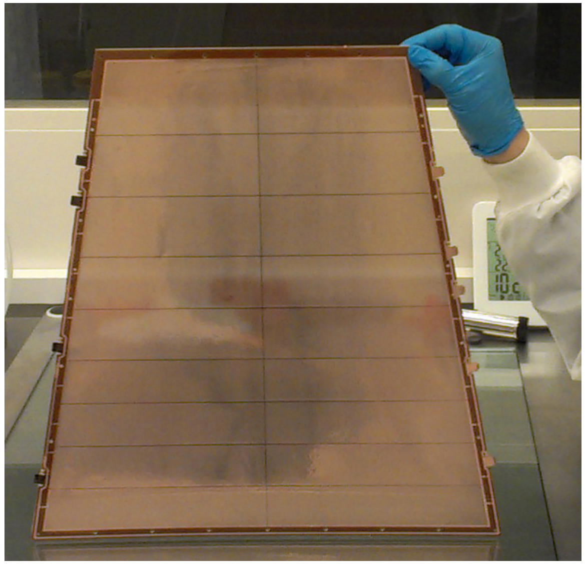
pile-up studies: dE/dx resolution

Simulated central Pb-Pb events at 5.5 TeV: full MC, with pile-up

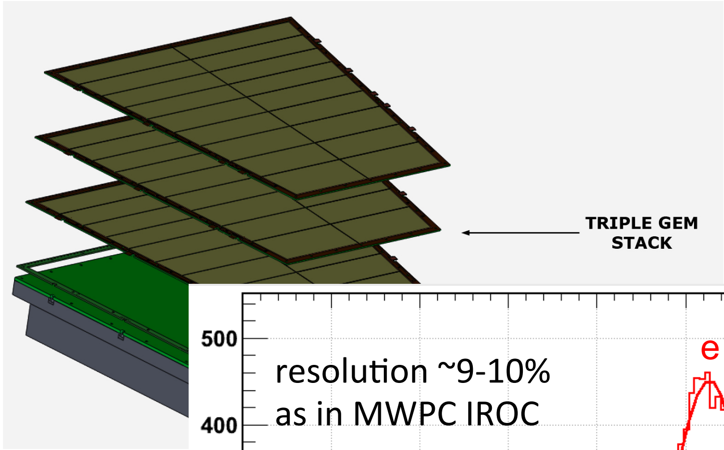


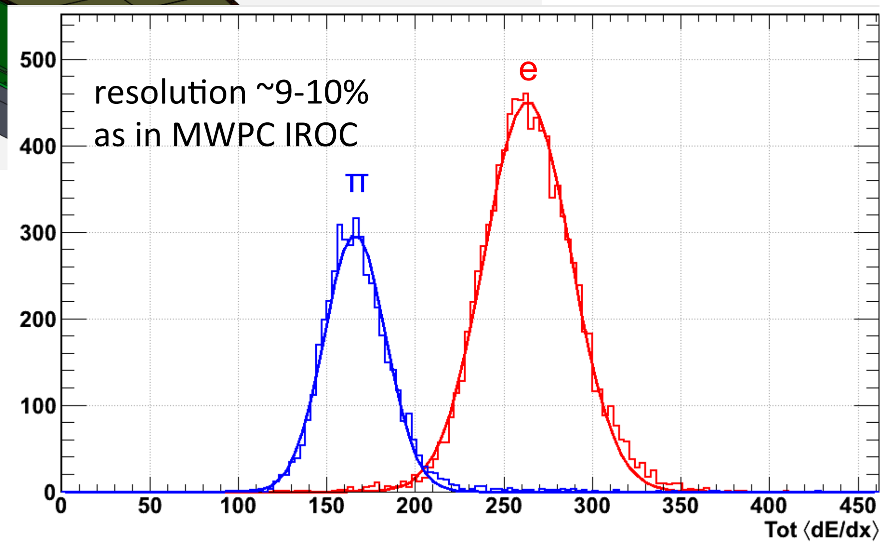
- Slight deterioration as function of occupancy due to cluster overlaps
- Similar dependence on multiplicity in MWPC and GEM

intrinsic performance: dE/dx



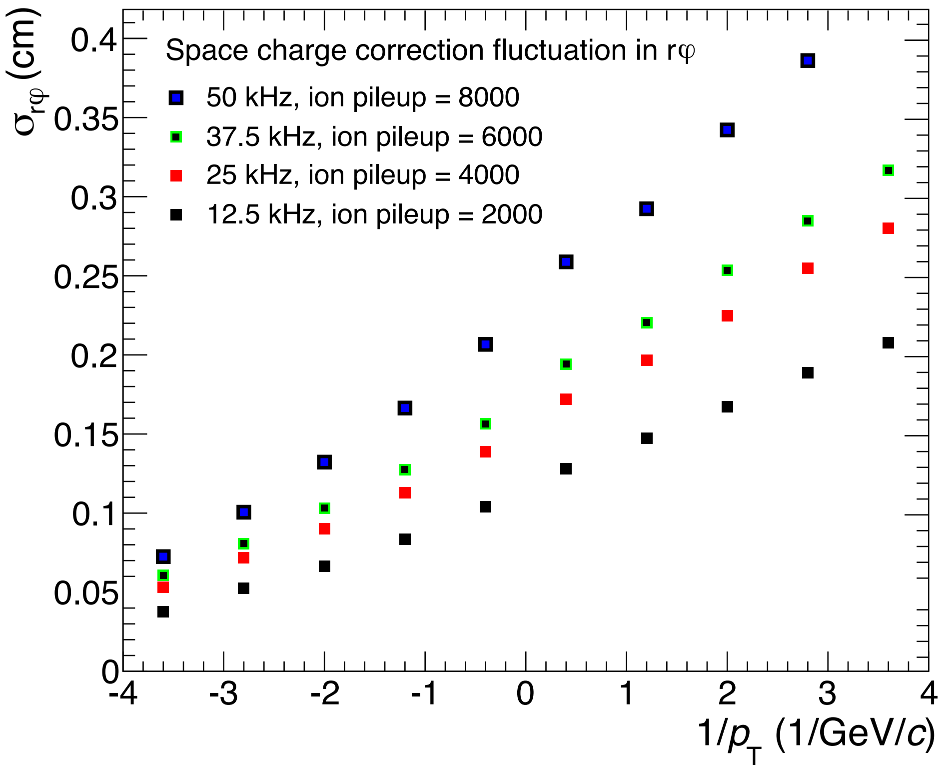
IROC GEM foil at TUM lab





- Same resolution in GEM-based readout chambers as in MWPC
- Confirmed in PS test beam with 3-GEM IROC prototype
- 4-GEM IROC prototype tests planned for 2014

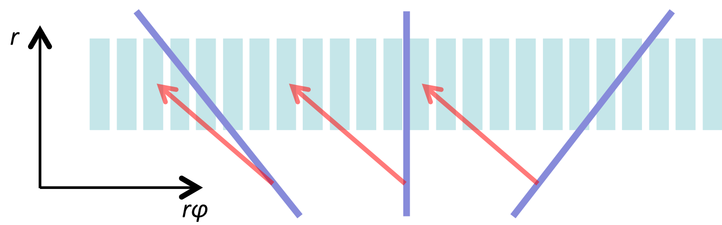
space charge fluctuations: residual distortions



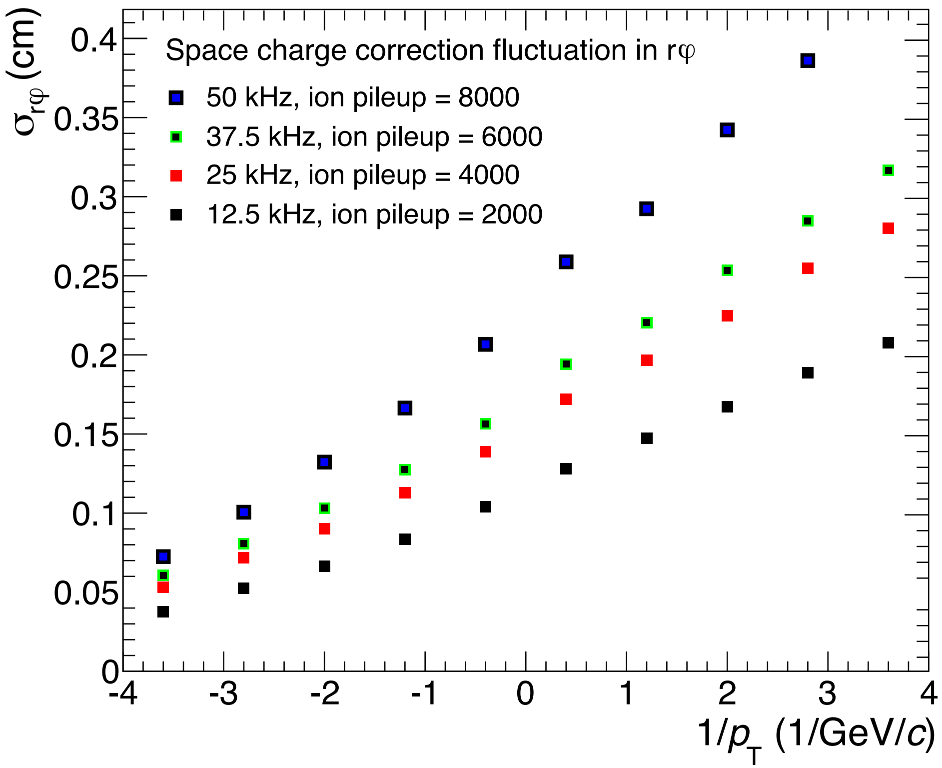
<u>Simulation:</u>
assume space-charge map with fluctuations for track distortion (map from real raw data), but time-averaged map for correction:

- significant residual distortions remain

- note asymmetric pattern



space charge fluctuations: residual distortions



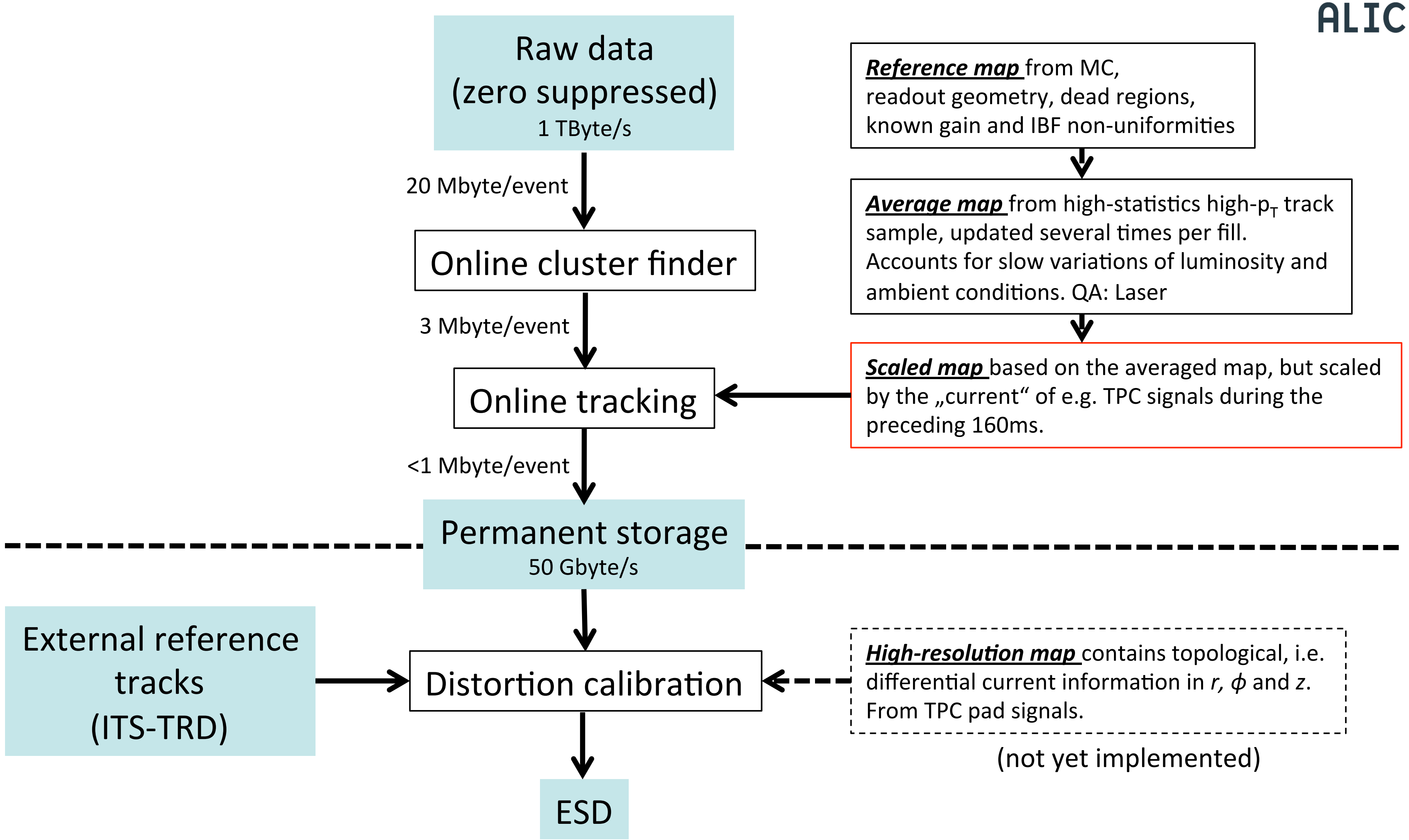
<u>Simulation:</u>
assume space-charge map with fluctuations for track distortion (map from real raw data), but time-averaged map for correction:

- significant residual distortions remain

- note asymmetric pattern

→ space-charge fluctuations need to be taken into account for distortion correction

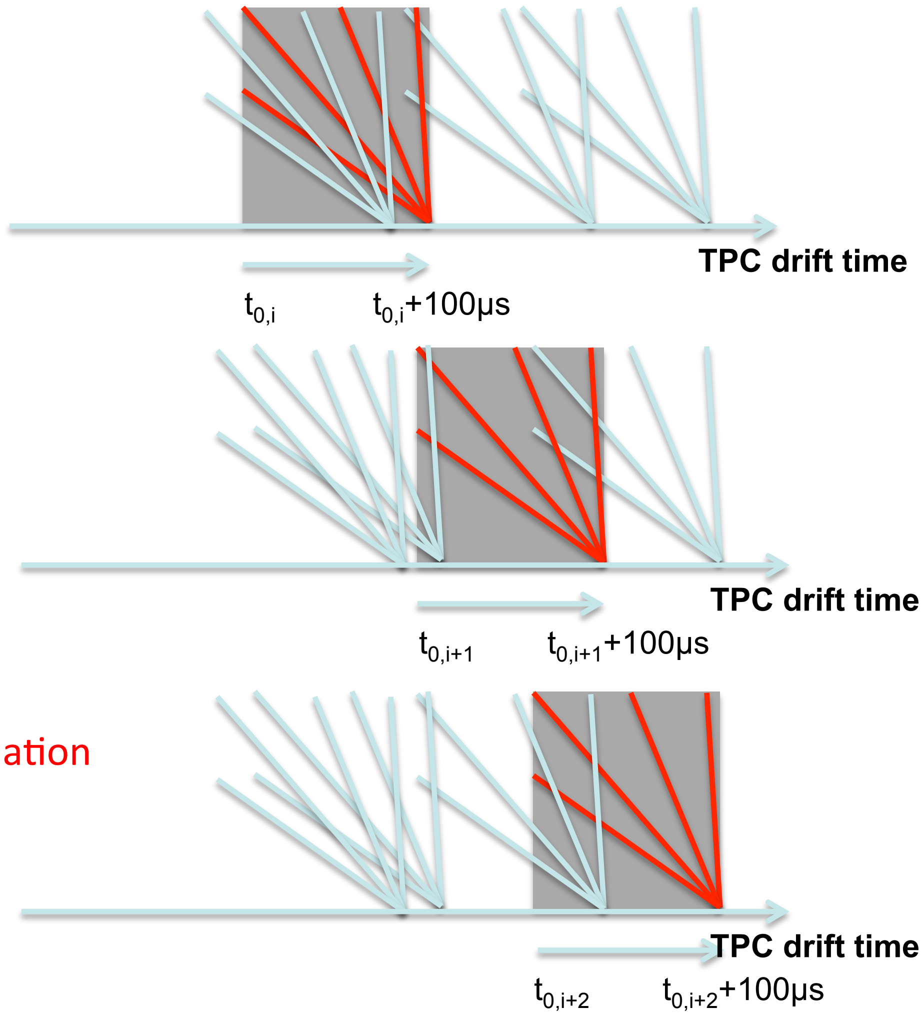
online reconstruction and distortion correction



first reconstruction stage: online tracking

- Scan the list of event $t_{0,i}$ and correct all clusters in a $t_{0,i}$+100µs window according to a given $t_{0,i}$
- Clusters belonging to the proper event are corrected properly, others are background
- Distortion correction based on a „scaled map“, residual distortions (fluctuations) remain (*O*(mm))

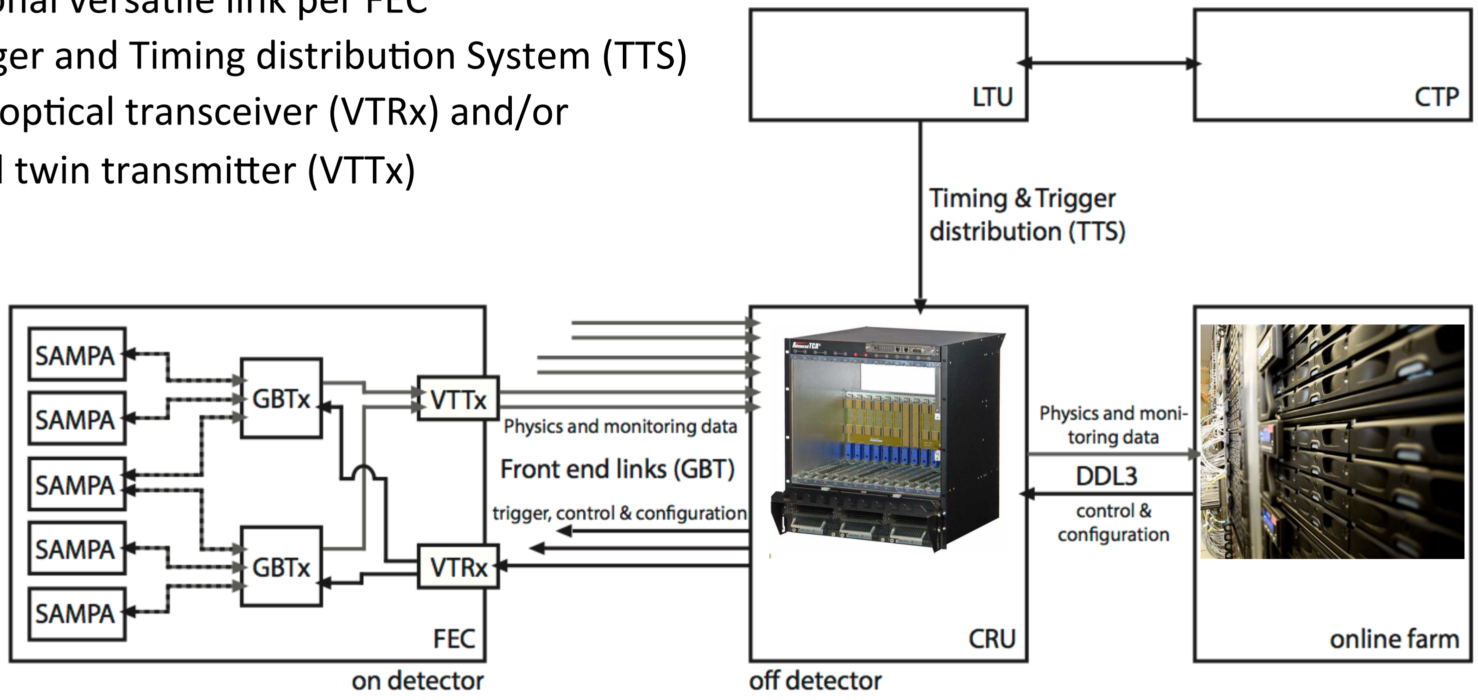
→ Tracking performance evaluated with full simulation



Readout Electronics

readout architecture

- The FEC receives the analog signals through flexible cables
- GBT system for readout and control on the FECs
- Control and monitoring: GBT-SCA
- GBTx ASIC for data multiplexing
- Physics and monitoring data to CRU and online farm: 2 uni-directional versatile links per FEC
- Trigger and timing information plus configuration data and control commands: 1 uni-directional versatile link per FEC
  - ALICE Trigger and Timing distribution System (TTS)
- Bi-directional optical transceiver (VTRx) and/or unidirectional twin transmitter (VTTx)



FE ASIC parameters

		RUN 1 (measured)	RUN 3 (requirement)
Signal polarity		Pos	Neg
Detector capacitance (range)	(pF)	12 – 33.5	12 – 33.5
S:N ratio for MIPs (IROC)		14:1	20:1
(OROC $6 \times 10\,\text{mm}^2$ pads)		20:1	30:1
(OROC $6 \times 15\,\text{mm}^2$ pads)		28:1	30:1
MIP signal	(fC)	1.5 – 3[14]	2.1 – 3.2
System noise (at 18.5 pF, incl. ADC)		670 e	670 e
PASA conversion gain (at 18 pF)	(mV/fC)	12.74	20 (30)
PASA return to baseline	(ns)	< 550	< 500
PASA average baseline value	(mV)	100	100
PASA channel-to-channel baseline variation (σ)	(mV)	18	18
PASA shaping order		4	4
PASA peaking time	(ns)	160	160 (80)
PASA crosstalk		$< 0.1\,\%$[15]	$< 0.2\,\%$
PASA integrated non-linearity		0.2 %	$< 1\,\%$
ENC (PASA only, at 12 pF)		385 e	385 e
ADC voltage range (differential)	(V)	2	2
ADC linear range (differential)	(fC)	160	100 (67)
ADC number of bits		10	10
ADC sampling rate	(MHz)	10 (2.5, 5, 20)	10 (20)
Power consumption (analog & digital)	(mW/ch)	35	< 35

Table 6.2: Measured PASA and ALTRO parameters for the current system (RUN 1) and the requirements for the upgraded front-end electronics (SAMPA parameters for RUN 3). The parameters are explained in the text.

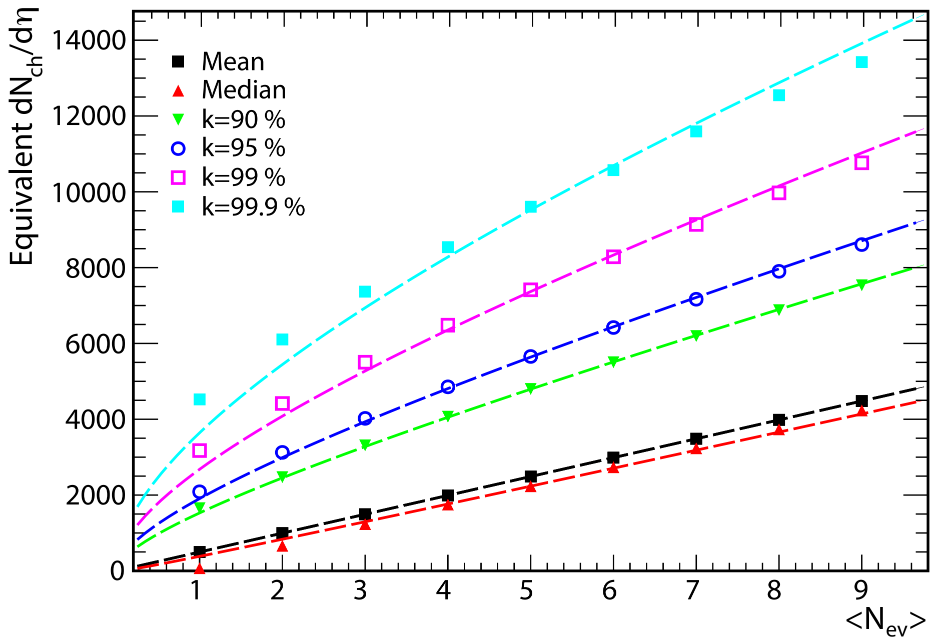
SAMPA ASIC requirements are derived from detector performance requirements

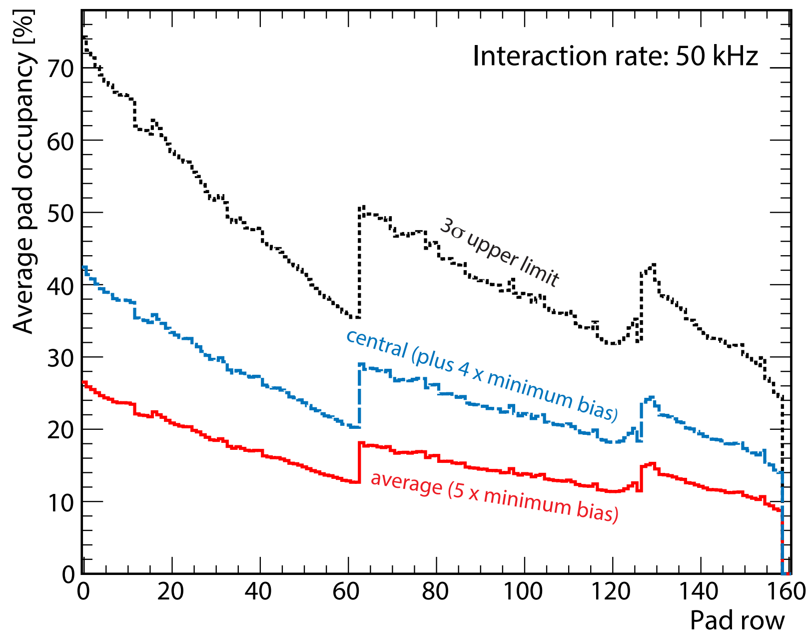
Based on the experience with the current TPC readout system

But: 3 changes
- Signal polarity
- Concurrent signal sampling and data transfer
- Strongly increased data throughput

Occupancy

Average pile-up: 5 min-bias events (~2500 tracks), one central + 4 min bias (~4000 tracks), but fluctuations..





Online reconstruction: motivation

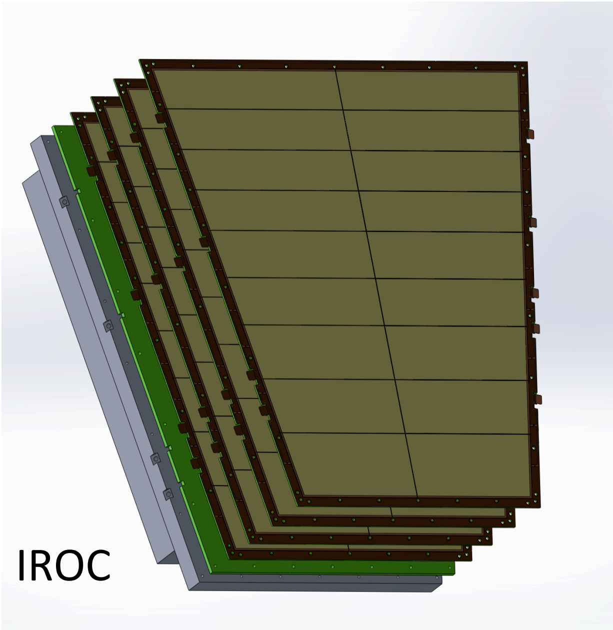
ALICE

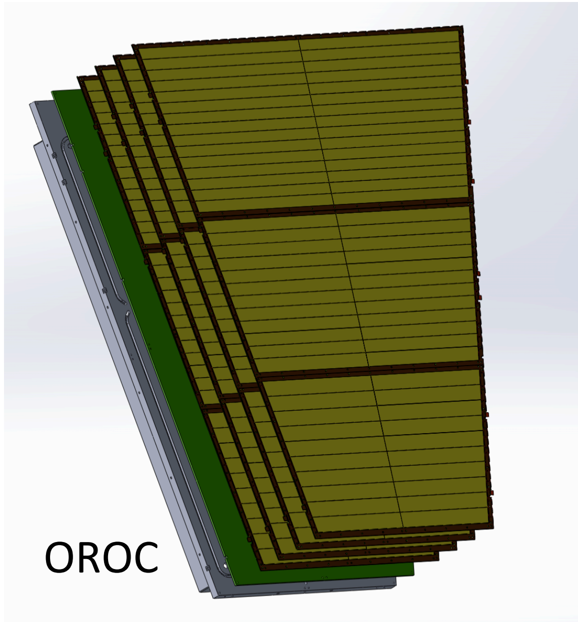
The issue is:

Provide sufficient data reduction online to allow for permanent storage of the data. This requires online tracking (i.e. association of cluster to tracks) to allow rejection of clusters not belonging to tracks.

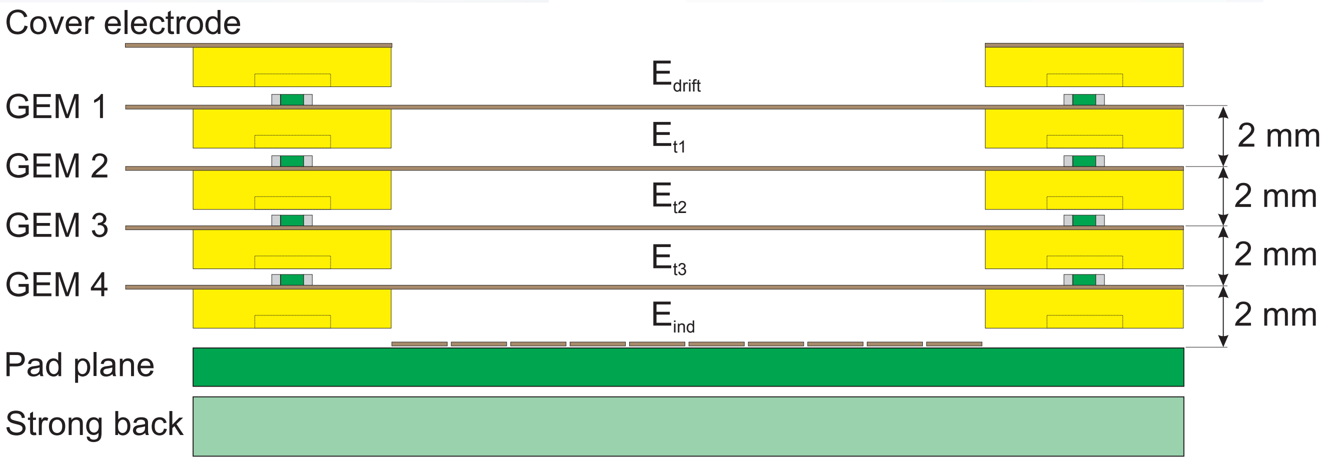
Data Format	Data Compression Factor	Event Size (MByte)	
Zero Suppression (FEE)		20	← i.e. 1 Tbyte/s
Clusterization	5-7	3	
Remove clusters not associated to relevant tracks	2	1.5	
Data format optimization	2-3	< 1	

TDR baseline solution: 4-GEM system

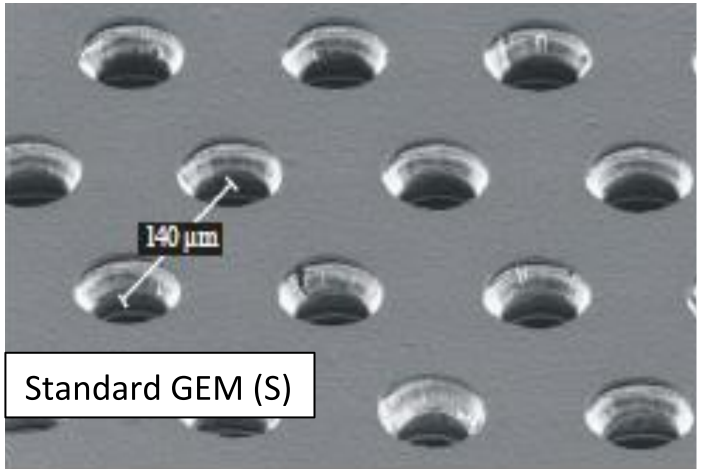


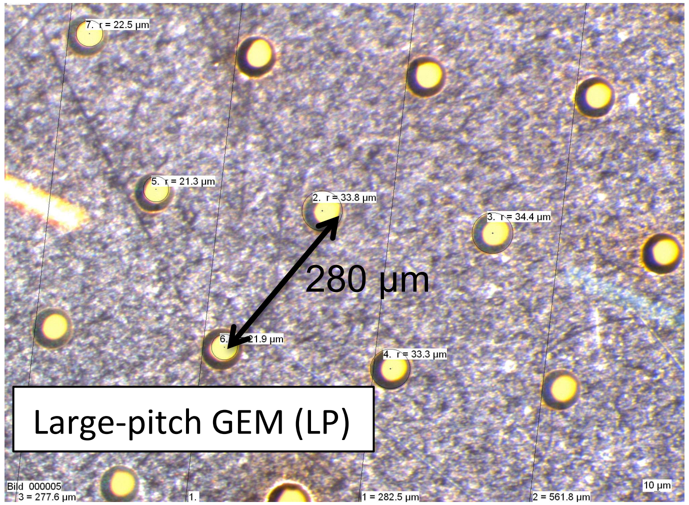


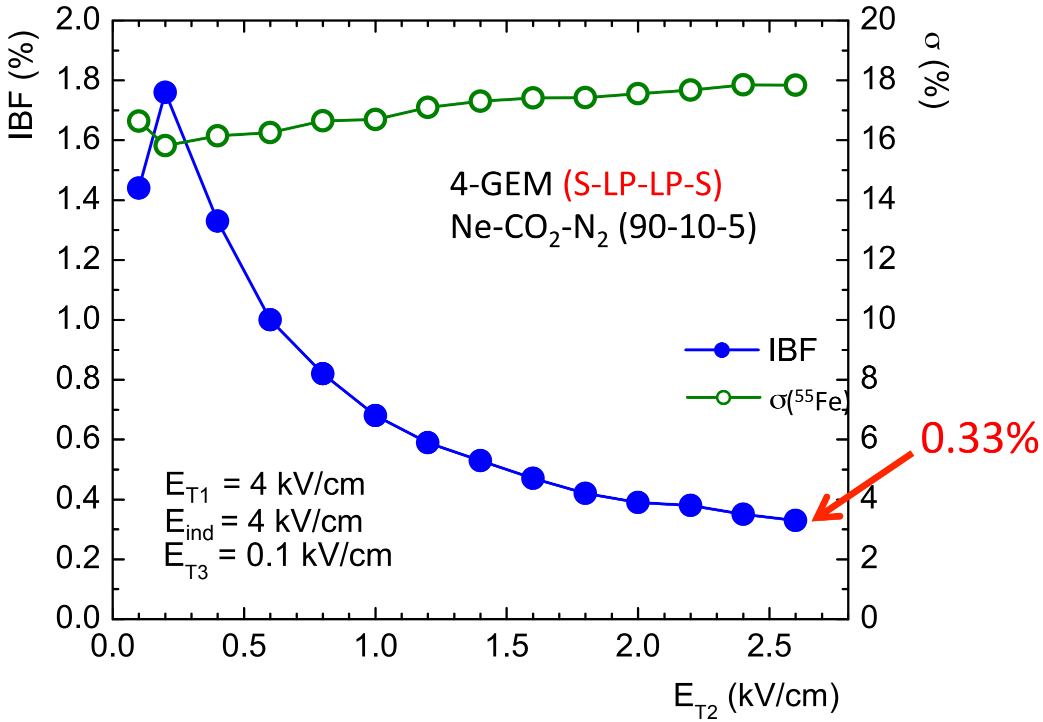
- large-size single-mask GEM foils
- one (three) per layer in IROC (OROC)



R&D status with quadruple GEMs

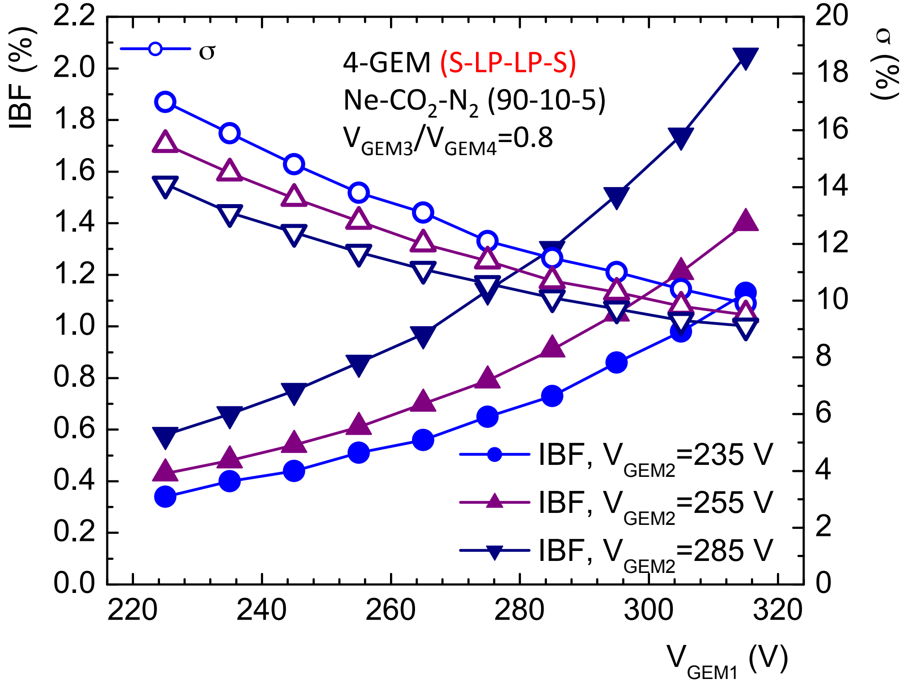


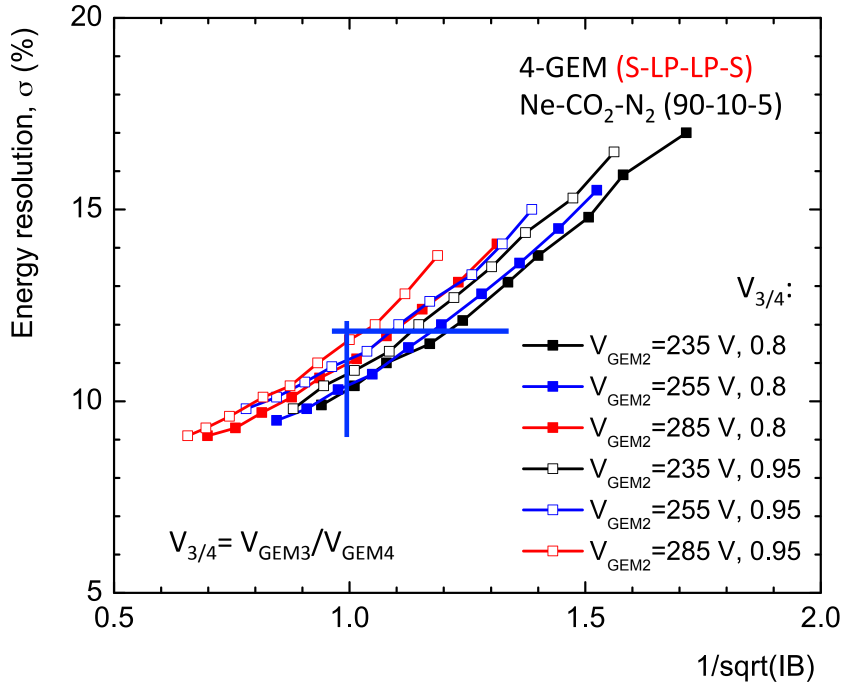




- further reduction of IBF in 4-GEM system with large-pitch GEMs (S-LP-LP-S)
- consideration of energy resolution is important: dE/dx performance requires $\sigma(^{55}Fe) \leq 12\%$

further optimization: IBF vs. energy resolution

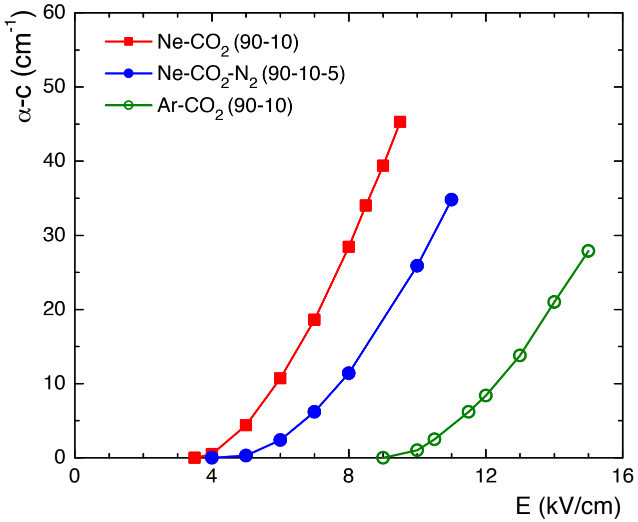


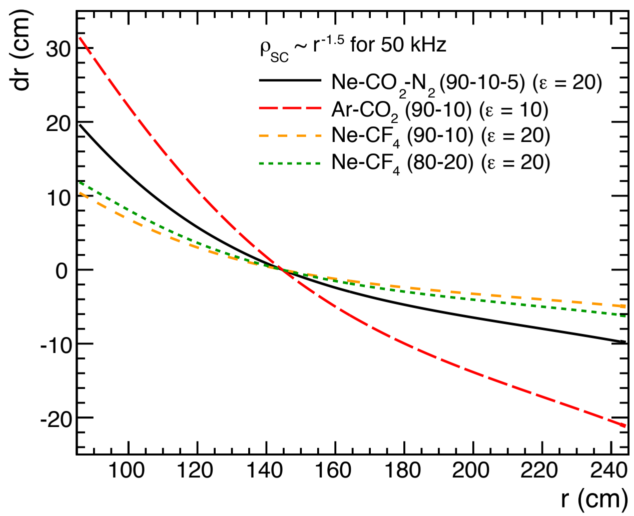


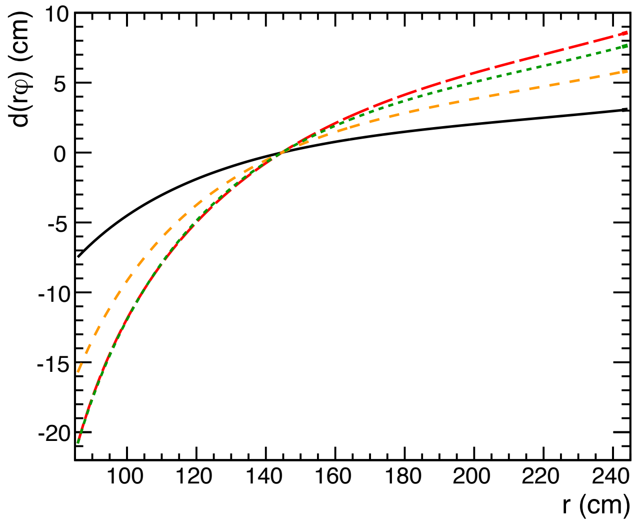
- Comprehensive voltage scan establishes operational point with IBF < 1% and energy resolution $\sigma(^{55}\text{Fe}) < 12\%$

→ All performance studies are for IBF = 1% at gain = 2000, i.e. ε = 20

choice of gas







- ion space-charge density:
  $\sim n_{prim}$ * gain * *IBF* * $1/v_{ion}$

→ baseline mixture Ne-CO_2-N_2 (90-10-5)

- requirement: *IBF* ≤ 1%,
  i.e. ε = gain * *IBF* <20
  at gain = 2000