A Large Ion Collider Experiment

ALICE

FROM GATED TO CONTINUOUS READOUT
- an upgrade of the ALICE TPC -

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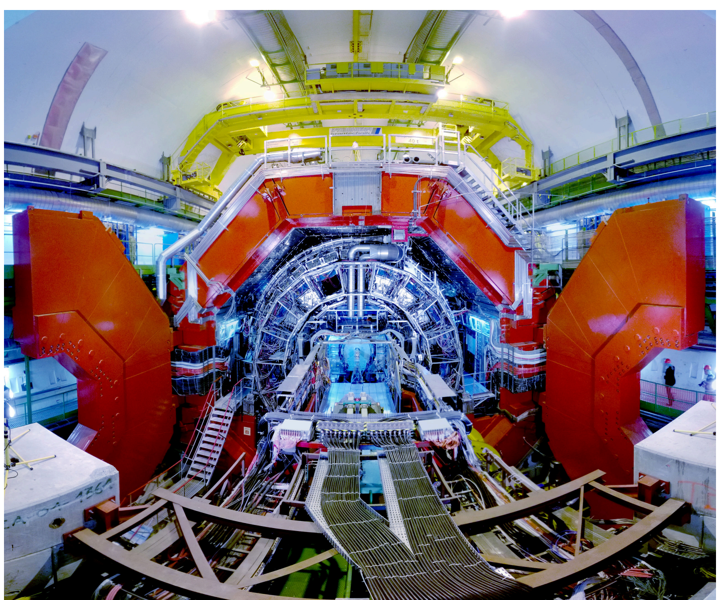
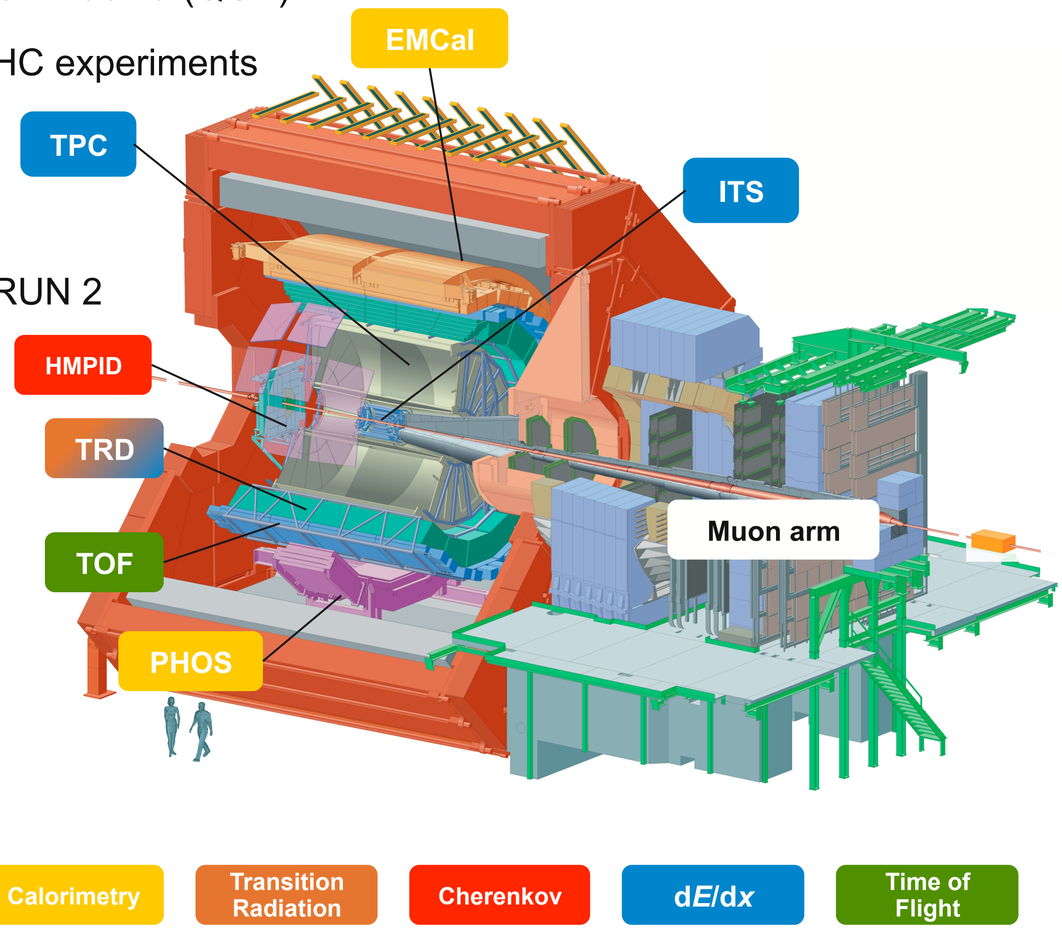
for the ALICE Collaboration

TUM
LMU
ESO

ALICE – A LARGE ION COLLIDER EXPERIMENT

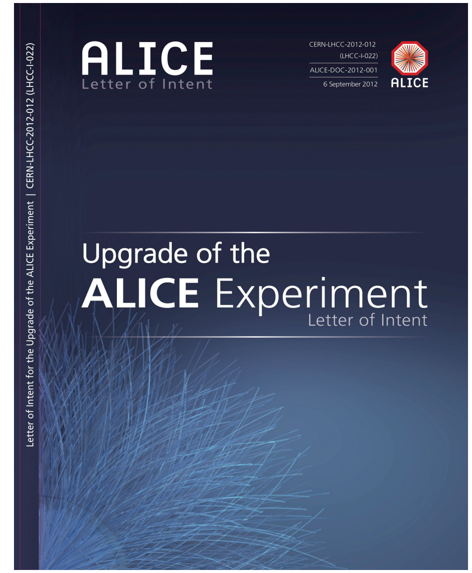
- A dedicated heavy-ion experiment at the CERN LHC
- Study of a high-density, high-temperature phase of strongly interacting matter: Quark-Gluon Plasma (QGP)
- **Unique PID capabilities** among all LHC experiments
- Covers broad kinematic range
- Many PID techniques
- Excellent performance in RUN 1 and RUN 2



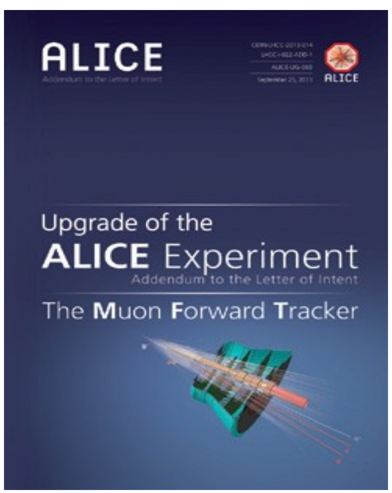


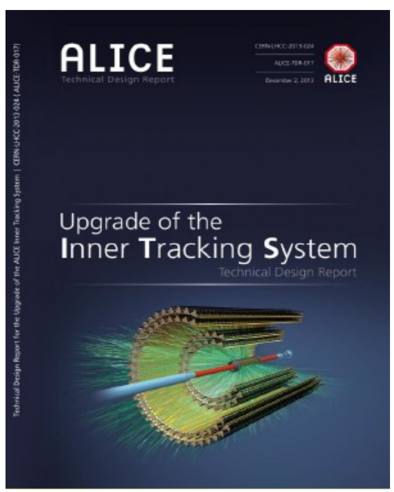
ALICE UPGRADE

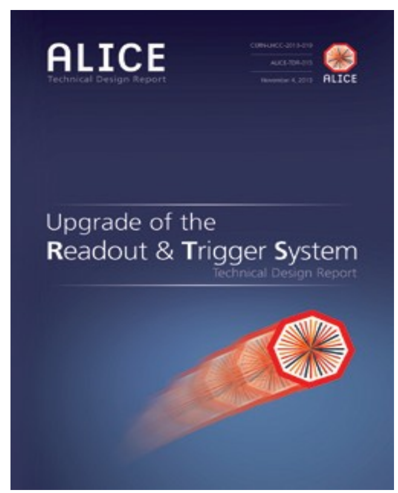
- **Motivation**: high precision measurements of rare probes at **low p_t**
  - ✓ cannot be selected with hardware trigger
  - ✓ need to record large sample of events
- **Goal**: operate ALICE at high rate, record all MB events
  - ✓ 50 kHz in Pb-Pb (~10 nb^{-1} in RUN 3 and RUN 4)
  - ✓ no dedicated trigger, reduce data size (compression)
  - ✓ preserve PID
- **Significant detector upgrades:**
  - ✓ e.g. **TPC with continuous readout**
  - ✓ LHC Long Shutdown 2 (2019/2020)

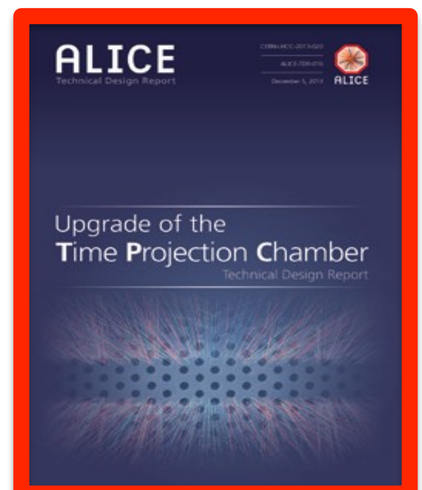


LoI: https://cds.cern.ch/record/1475243







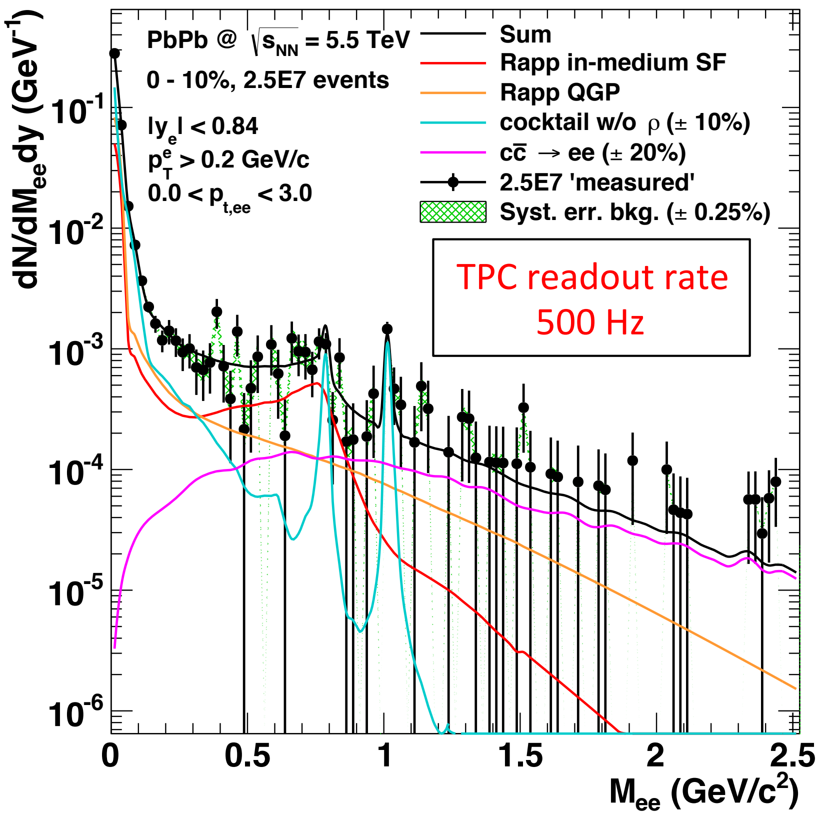


TDR: https://cds.cern.ch/record/1622286
Addendum: https://cds.cern.ch/record/1984329

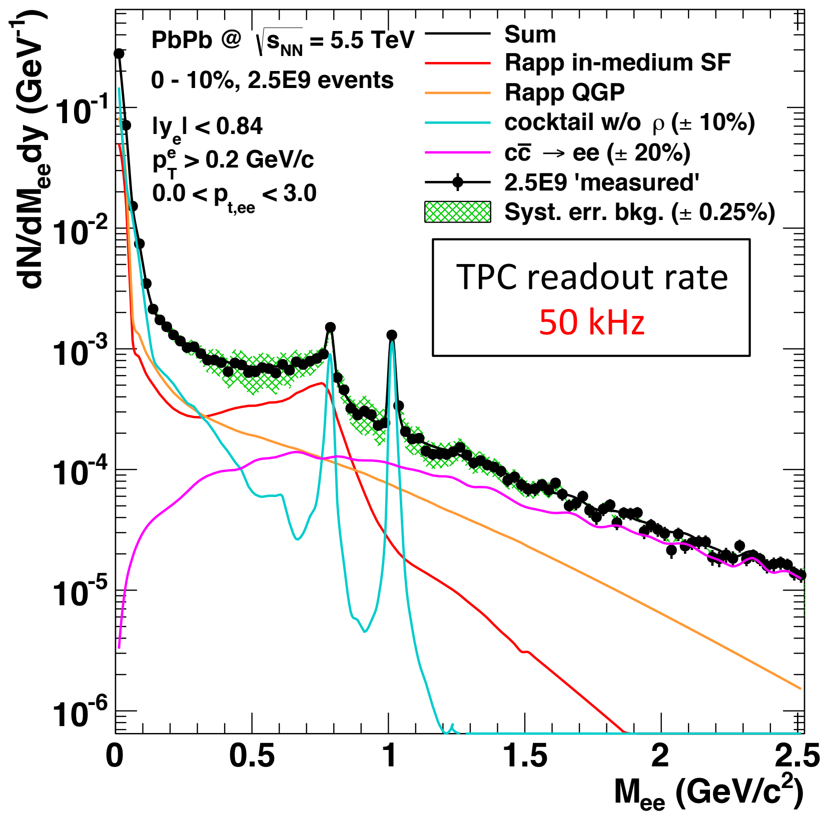
ALICE

EXAMPLE: LOW-MASS DI-ELECTRONS

2.5×10^{7} Pb-Pb (0-10%)



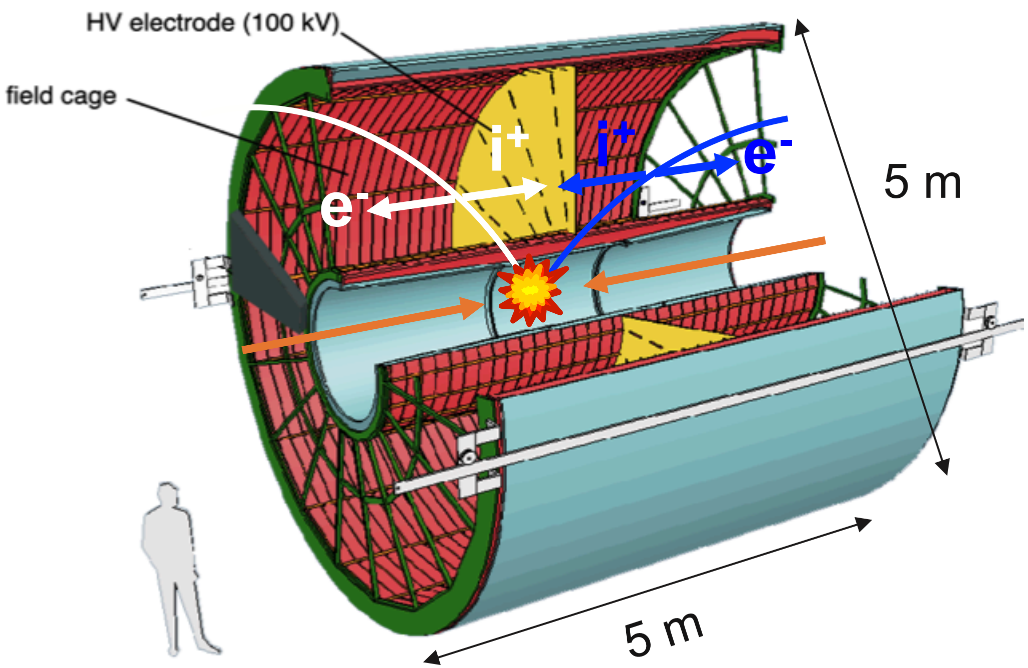
2.5×10^{9} Pb-Pb (0-10%)



Full exploitation of RUN 3 physics potential requires significant TPC upgrade

ALICE TPC

THE ALICE TPC

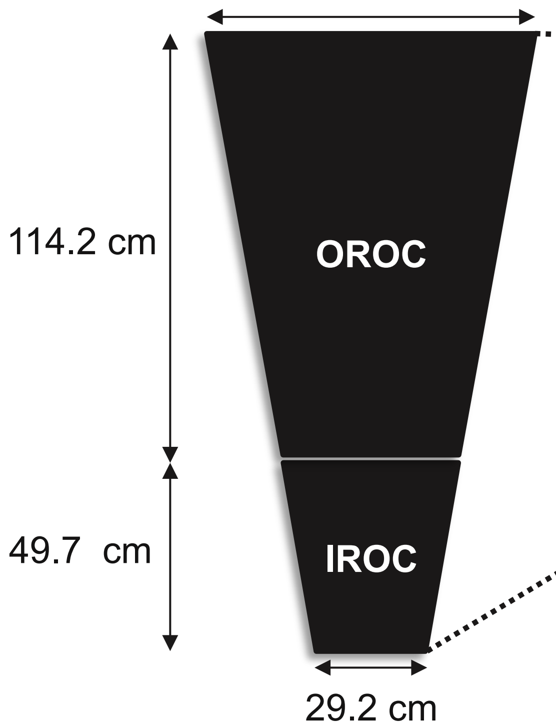


Gas volume

- Acceptance: $|\eta|<0.9$, $\Delta\phi = 2\pi$
- Low mass, high precision field cage
- ~90 m^3 active detector medium
- Gas:
  - $Ne\text{-}CO_2$ (90-10) in RUN 1
  - $Ar\text{-}CO_2$ (90-10) in RUN 2
- 100 kV at the Central Electrode
  - E_{drift} = 400 V/cm
  - v_{drift} = 2.7 cm/μs
  - max t_{drift} = 92 μs

THE ALICE TPC

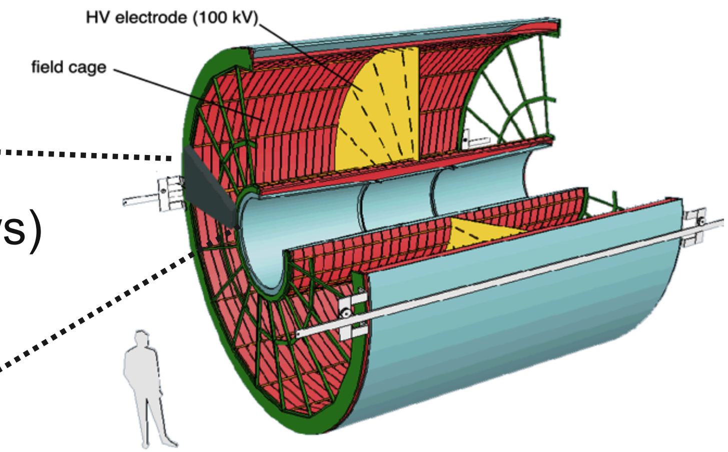
2 x 18 **O**uter **R**ead **O**ut **C**hambers



2 x 18 **I**nner **R**ead **O**ut **C**hambers

557,568 pads (159 rows)

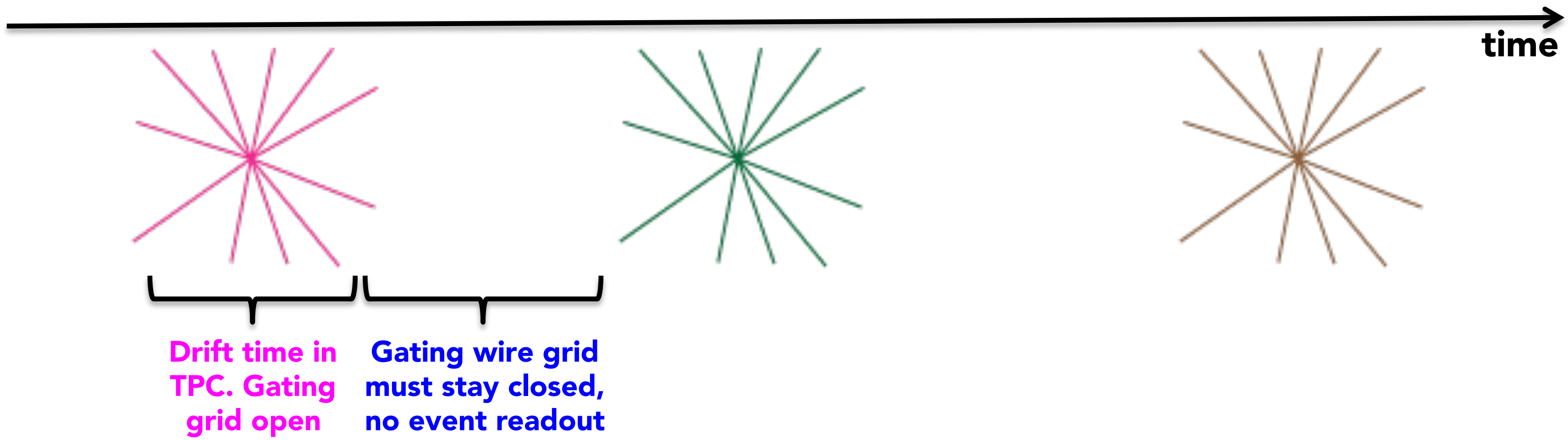
4 x 7.5 mm^2	(IROC)
6 x 10 mm^2	(OROC)
6 x 15 mm^2	(OROC)



Readout chambers

- 72 MWPCs with pad readout
- $\sigma_{dE/dx}$ = 5.5% (7%) in p-p (Pb-Pb)
- Gating grid

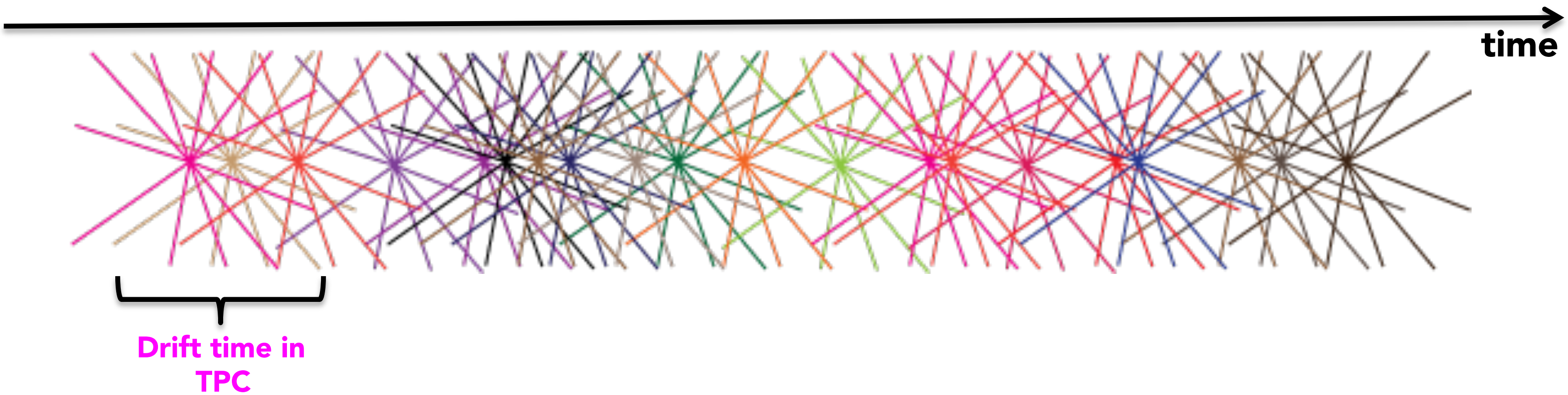
GATED OPERATION IN RUN 1 AND RUN 2



Multi Wire Proportional Chamber readout

- Employs gating grid
- Gating grid prevents back drifting ions from the amplification stage to distort the drift field (IBF suppression ~10^{-5})
- 100 µs electron drift time + 200-400 µs gate closed (Ne-Ar) to minimize ion backflow and drift distortions
- **300-500 µs** in total limits the maximal readout rate to **few kHz** (in p-p)
- Readout rate ~600 Hz for central Pb-Pb (300 Hz in RUN 1)

CONTINUOUS OPERATION IN RUN 3 AND BEYOND

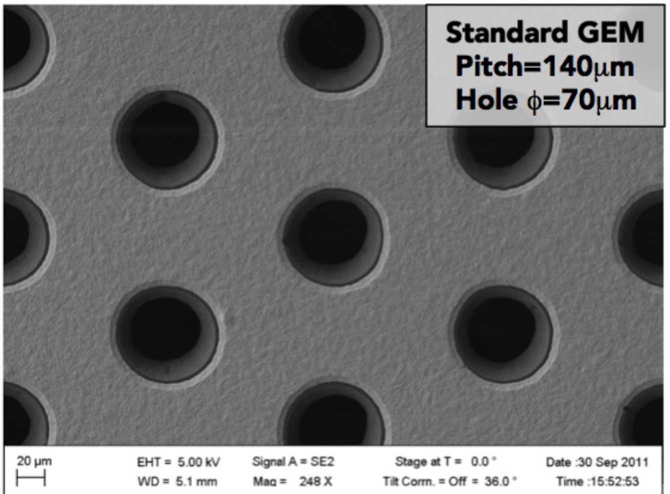


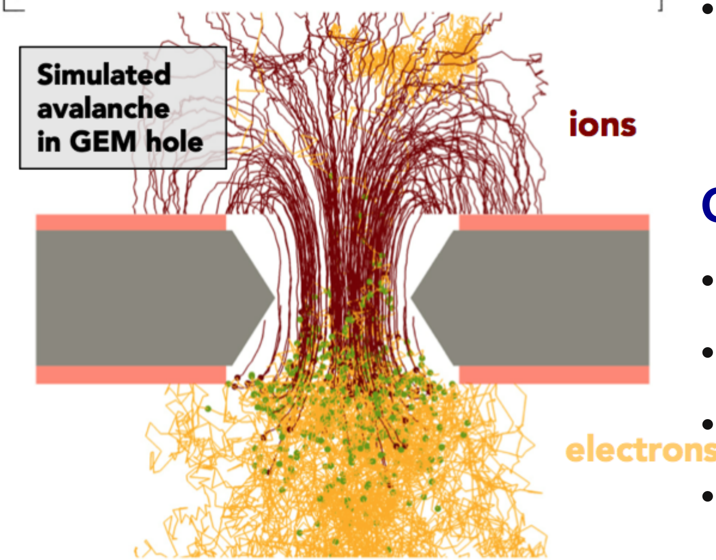
- Maximum drift time of electrons in the TPC: ~100 us
- Average event spacing: ~20 us
- Event pileup (5 in average)
- Triggered operation meaningless
- Minimize IBF in a different way

Continuous readout with GEMs

(Gas Electron Multiplier, F. Sauli 1996)

ALICE TPC UPGRADE FOR RUN 3





Requirements for GEM readout:

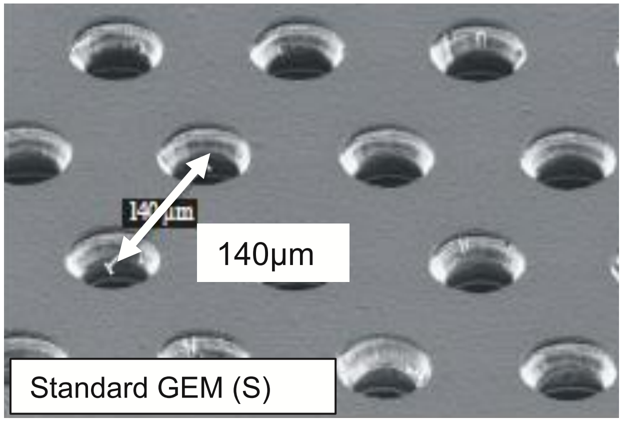
- Operate at the gain of 2000 in Ne-CO_2-N_2
- IBF < 1% at Gain = 2000 → ε = 20
- Local energy resolution < 12% for ^{55}Fe
- Stable operation under LHC conditions
- \+ new electronics *(negative polarity, continuous readout mode)*
- \+ novel calibration and online reconstruction schemes *(data compression by factor 20 and distortion corrections)*

GEM-based readout chamber

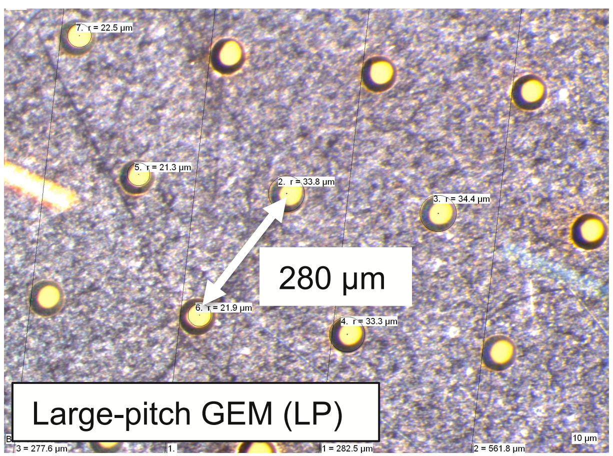
- Low ion backflow
- High rate capability
- No ion tail
- <u>Continuous readout possible</u>

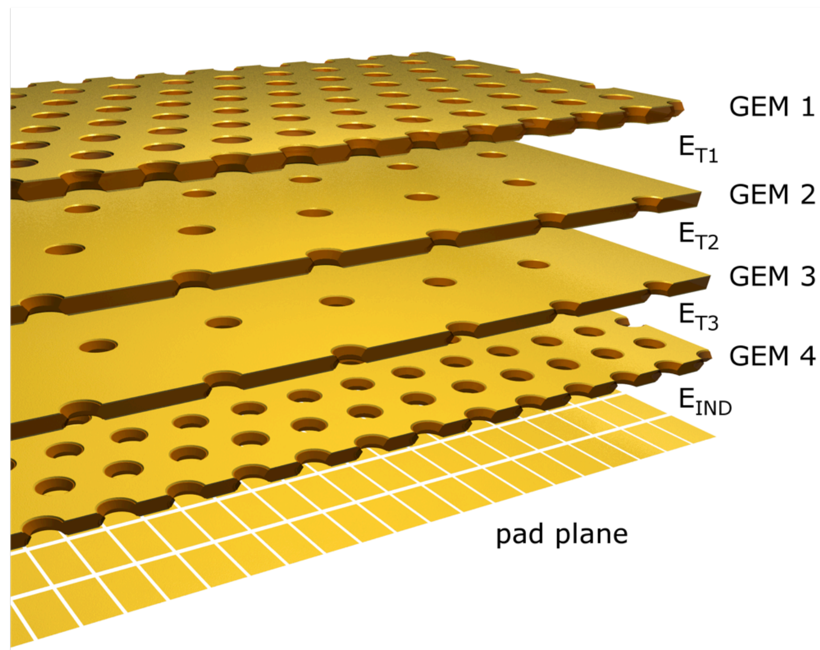
GEM R&D FOR THE UPGRADE

BASELINE SOLUTION: 4-GEM SETUP



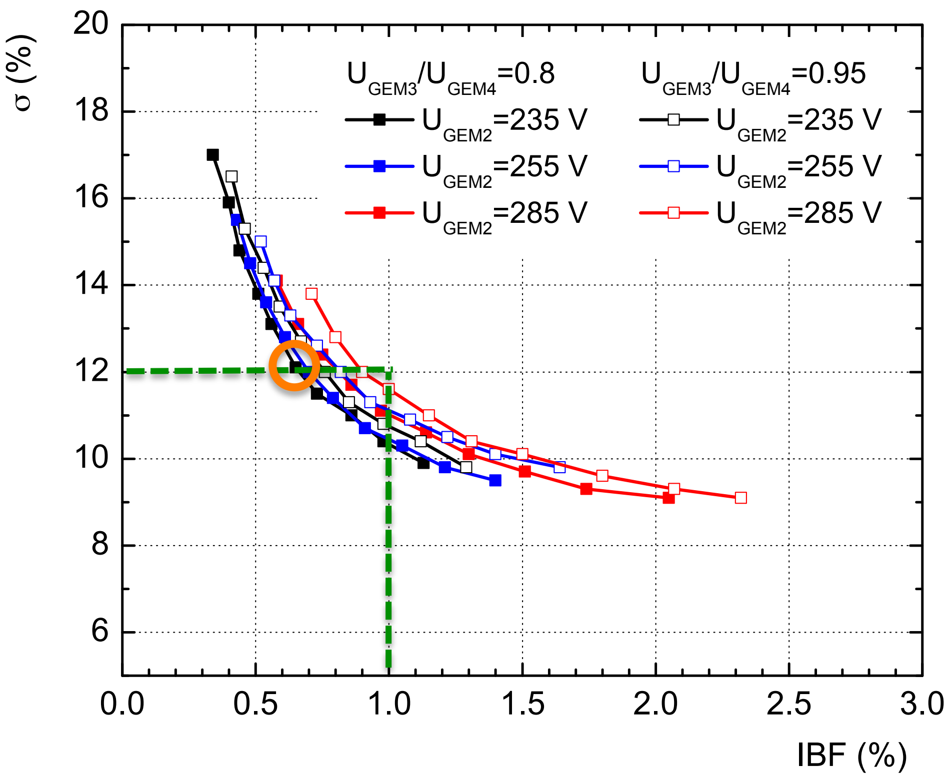
- Requirements not fullfilled with a standard 3-GEM configuration
- New readout chambers employ standard (S) and large-pitch (LP) GEMs in a configuration S-LP-LP-S
- Optimized HV settings





HV SETTINGS OPTIMIZATION

- "Standard" HV settings used with GEM detectors (e.g. COMPASS) not optimal for low IBF
- IBF optimized settings:
  - **$\Delta_{GEM1} > \Delta_{GEM2} \approx \Delta_{GEM3} << \Delta_{GEM4}$** (largest amplification in GEM4 → stability?)
  - **High E_{T1}, E_{T2}** (high electron extraction from the first GEM stages)
  - **Low E_{T3}** (ion blocking)



Gas mixture: Ne-CO_2-N_2 (90-10-5)

Effective gain G_{eff} = 2000

Baseline solution (S-LP-LP-S) performance:

IBF = 0.6 %

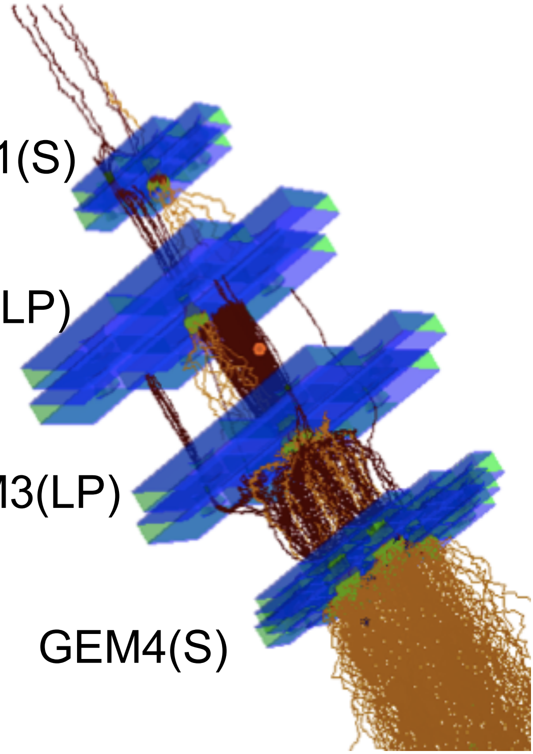
σ_E/E ≈ 12 % for 5.9 keV (^{55}Fe)

Alternative R&D:

2GEM + Micromegas

COBRA GEMs

ION TRAPPING WITH GEMS



Electron transport properties for IBF optimized voltage settings

ε_{coll} = collection efficiency

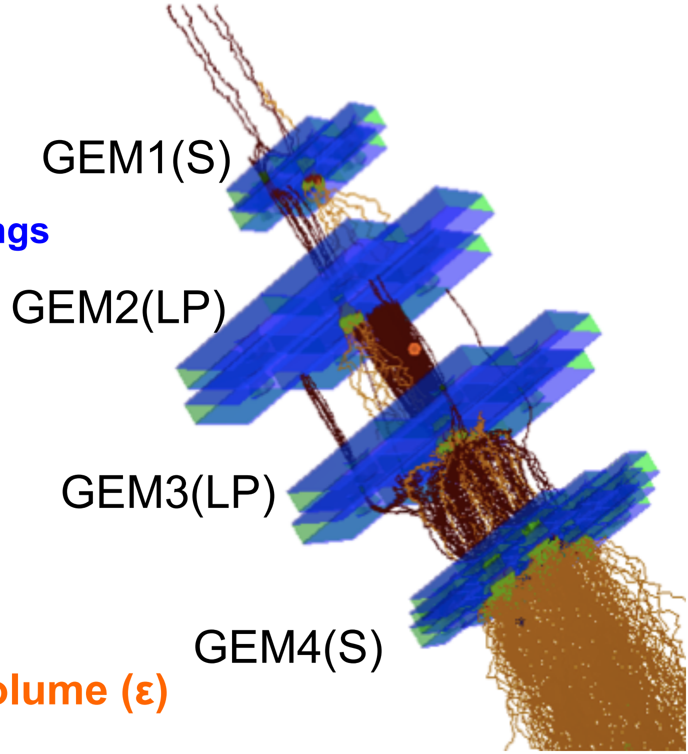
ε_{extr} = extraction efficiency

M = gas multiplication factor

$G_{eff} = \varepsilon_{coll} \times M \times \varepsilon_{extr}$ = effective gain

	$\varepsilon_{\mathrm{coll}}$	$n_{\mathrm{e,in}}$	M	$n_{\mathrm{e-ion}}$	$\varepsilon_{\mathrm{extr}}$	$n_{\mathrm{e,out}}$	G	$n_{\mathrm{ion,back}}$	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%)		

ION TRAPPING WITH GEMS



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$n_{e\text{-}ion}$ = number of produced e-ions pairs

$n_{ion,back}$ = number of ions drifting back into the drift volume (ε)

$$IB = (1+\varepsilon)/G_{eff}$$

	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.)
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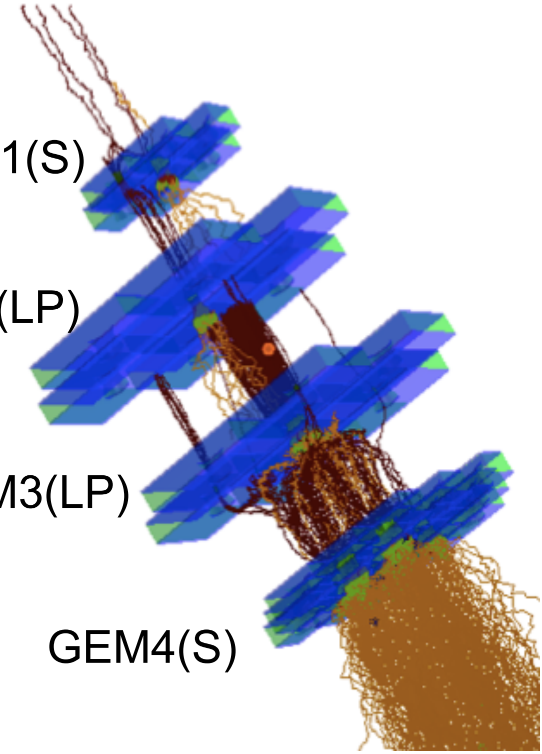

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fraction of total IBF: simulation vs. experiment

	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.)
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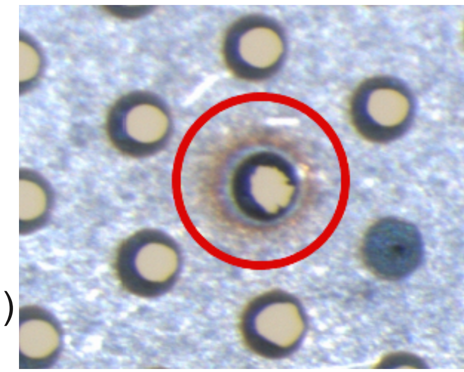
STABILITY AGAINST DISCHARGES

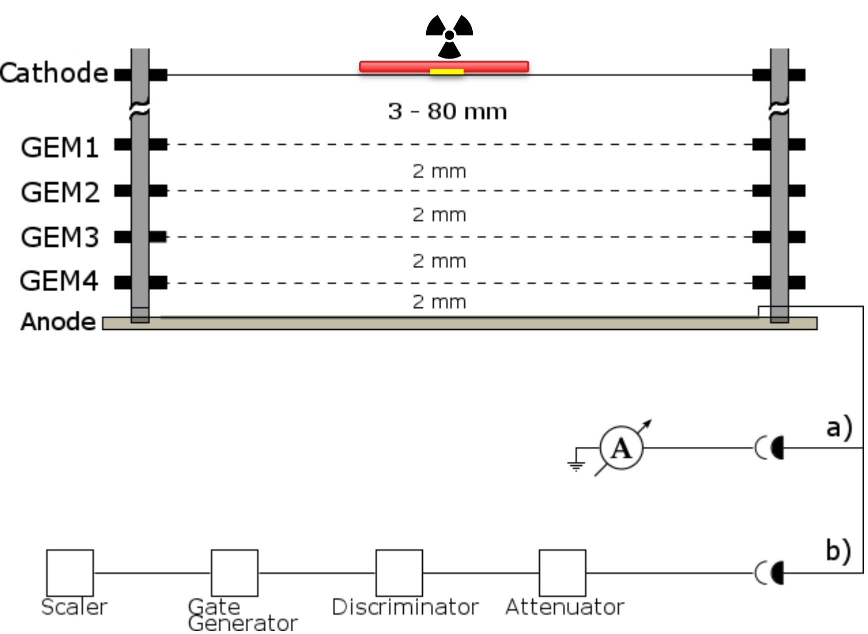
The breakdown appears when the total charge in the avalanche reaches critical value Q_{max}

Highly ionizing particles/high rate of radiation may induce creation of streamers which can then transform into sparks.



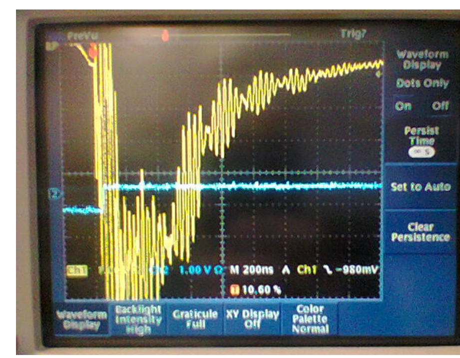
Spark in GEM:

- $\Delta V_{GEM} \rightarrow 0$
- may be harmful to the detector and electronics (large energy released)



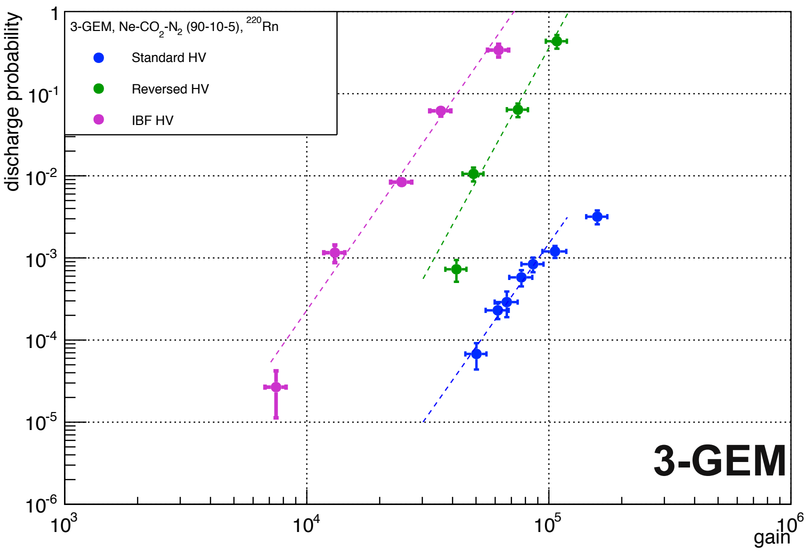
R&D:

- 10x10 cm^2 GEMs
- Modular setup
- 1-4 GEM stacks
- Adjustable drift gap
- Alpha sources: ^{239}Pu, ^{241}Am, ^{244}Cm; rate 0.5 – 10 kHz
- Current/discriminator readout



DISCHARGE STUDIES

Influence of HV settings



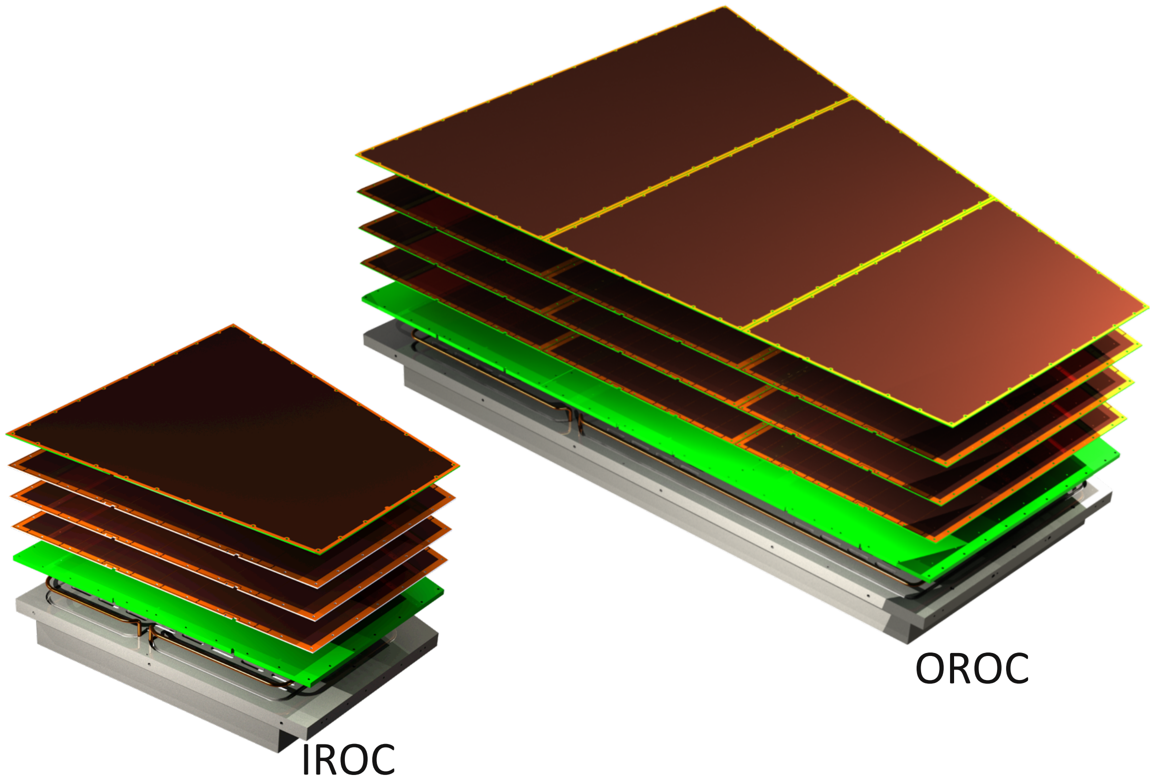
- Different HV settings have been tested with a 3-GEM configuration
- "<u>Standard</u>" → "<u>IBF</u>"
  - Standard – optimized for stability (COMPASS)
  - IBF → optimized for IBF
- Significant drop of stability while using IBF settings with a typical 3-GEM configuration

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

	S-S-S 'standard' HV G = 2000	S-S-S-S *IB* = 2.0% G = 2000	S-LP-LP-S *IB* = 0.34% G = 1600	*IB* = 0.34% G = 3000	*IB* = 0.34% G = 5000	*IB* = 0.63% G = 2000
^{220}Rn, $E_\alpha = 6.4$ MeV, rate = 0.2 Hz	$\sim 10^{-10}$			$< 2\times10^{-6}$	$< 7.6\times10^{-7}$	
^{241}Am, $E_\alpha = 5.5$ MeV, rate = 11 kHz						$< 1.5\times10^{-10}$
^{239}Pu+^{241}Am+^{244}Cm, $E_\alpha = 5.2+5.5+5.8$ MeV, rate = 600 Hz		$< 2.7\times10^{-9}$	$< 2.3\times10^{-9}$	$(3.1\pm0.8)\times10^{-8}$		$< 3.1\times10^{-9}$
^{90}Sr, $E_\beta < 2.3$ MeV, rate = 60 kHz					$< 3\times10^{-12}$	

FULL-SIZE PROTOTYPES

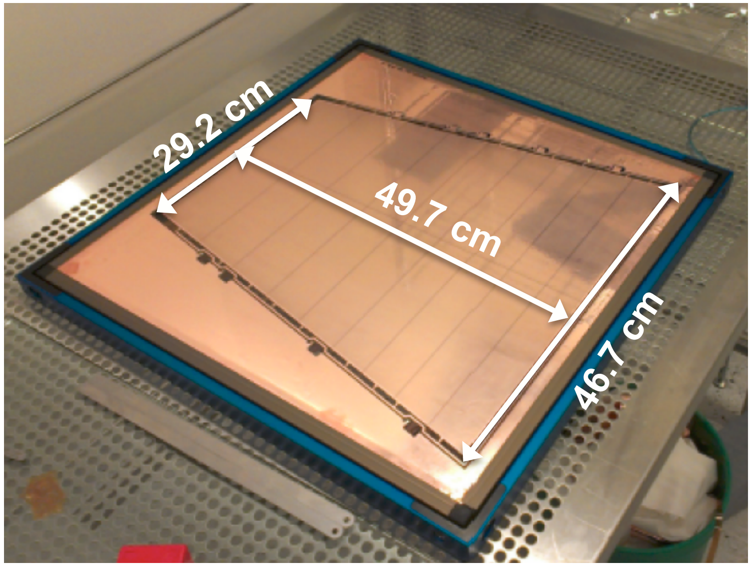
GEMS FOR THE UPGRADE

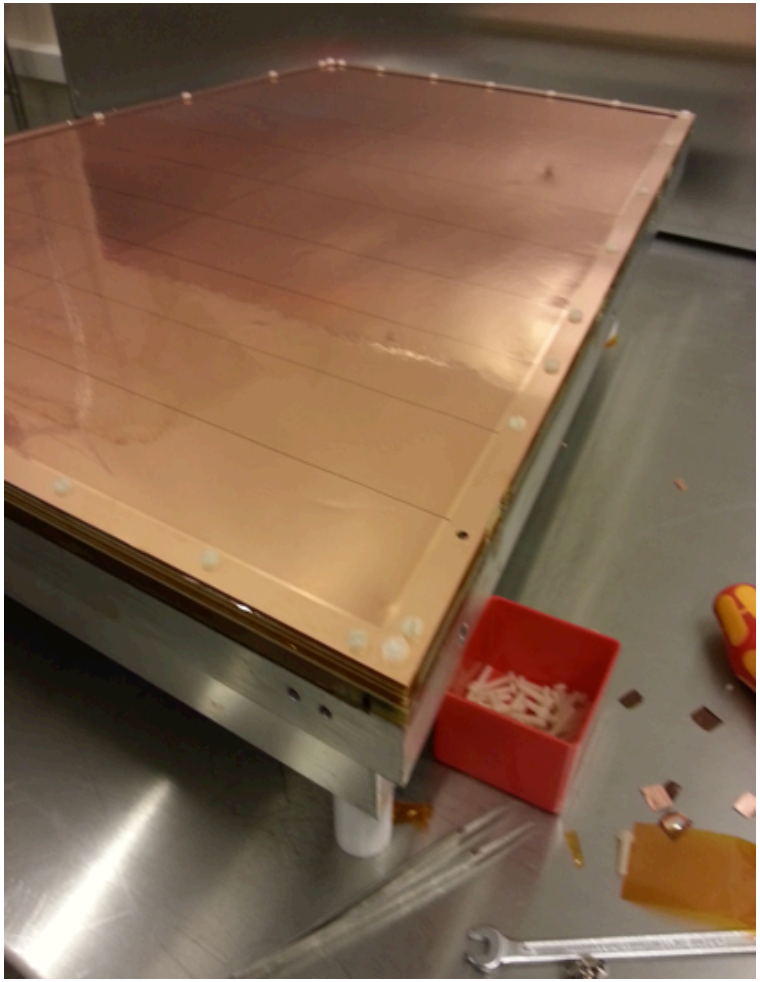


- Large-size single-mask foils from CERN PCB workshop
- 1 stack in IROC, 3 stacks in OROC

→ *Technical solution approved by the LHCC*

LARGE PROTOTYPES: 4-GEM IROC



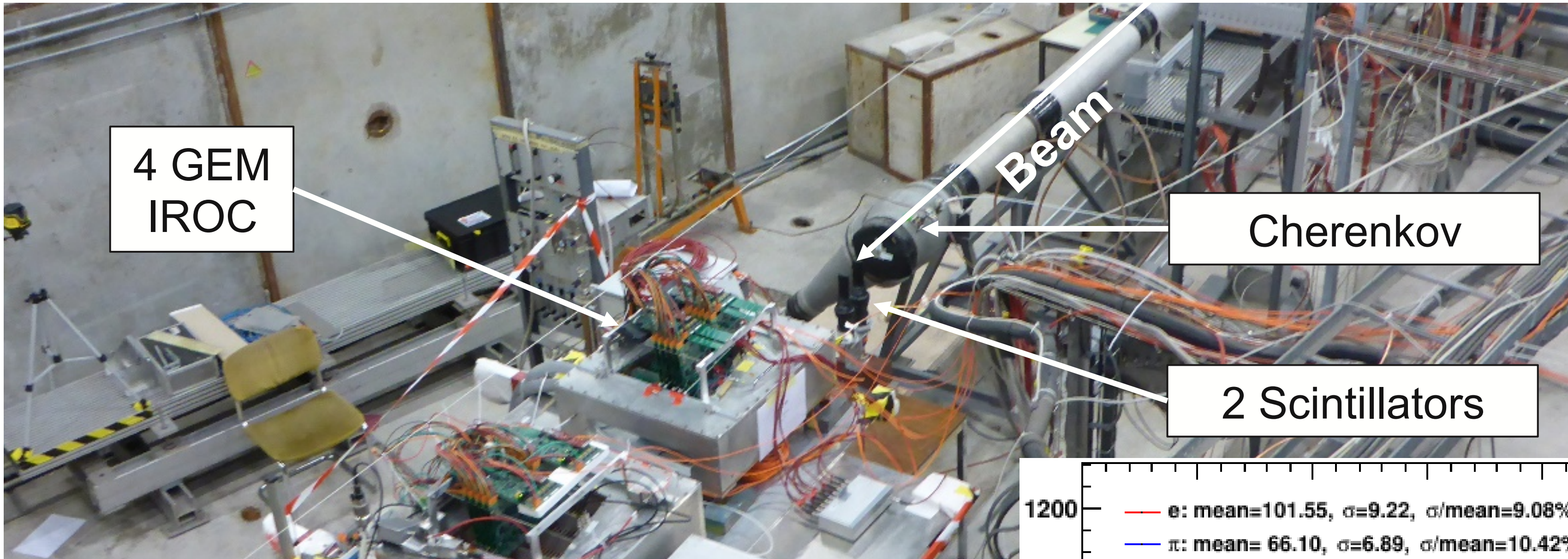


- 4 single-mask GEMs in the configuration S-LP-LP-S
- GEMs glued on 2 mm frames
- Prototype mounted in a test box with a field cage

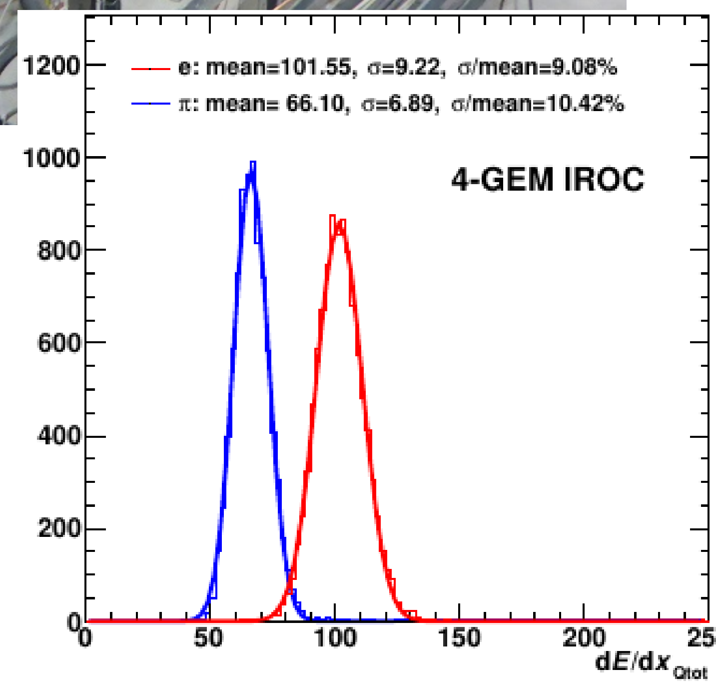
- d*E*/d*x* performance evaluated at CERN PS
- Stability at high-rate hadron beam tested at CERN SPS

- In addition, a Hybrid IROC (2-GEM + Micromegas) has been built and tested at PS and SPS

PS BEAMTIME (NOV. 2014)

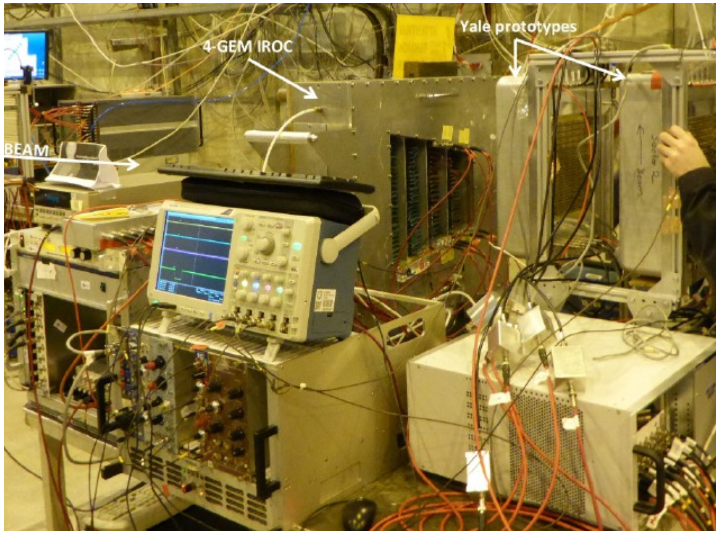


- Secondary $e^{\pm}$, $\pi^{\pm}$ beam; 1, 2, 3 GeV/c
- dE/dx performance as expected from simulations
- Relative energy resolution as in present MWPC
  - $\sigma_e/\mu_e \approx 9\%$
  - $\sigma_\pi/\mu_\pi \approx 10\%$
- Physics performance not compromised up to $\sigma(^{55}Fe) = 14\ \%$



4-GEM IROC AT SPS

RD51 beamtime, December 2015



150 GeV/*c* pion beam hitting Fe absorber

- ~5×10^{11} particles accumulated
- Comparable to the number of particles expected in the TPC during a typical yearly Pb-Pb run at a collision rate of 50 kHz (per GEM stack)

Discharge probability: $(6.4\pm3.7)\times10^{-12}$ per incoming hadron

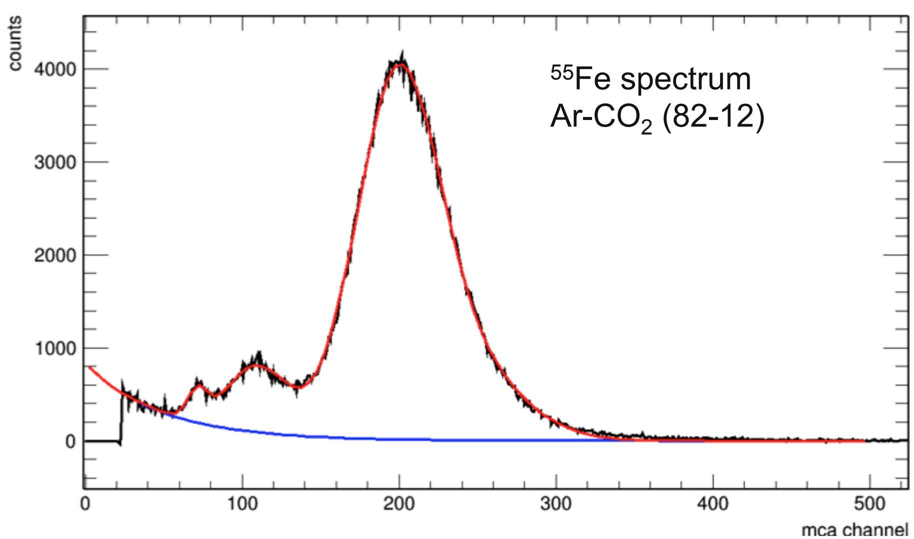
Estimate for RUN 3:

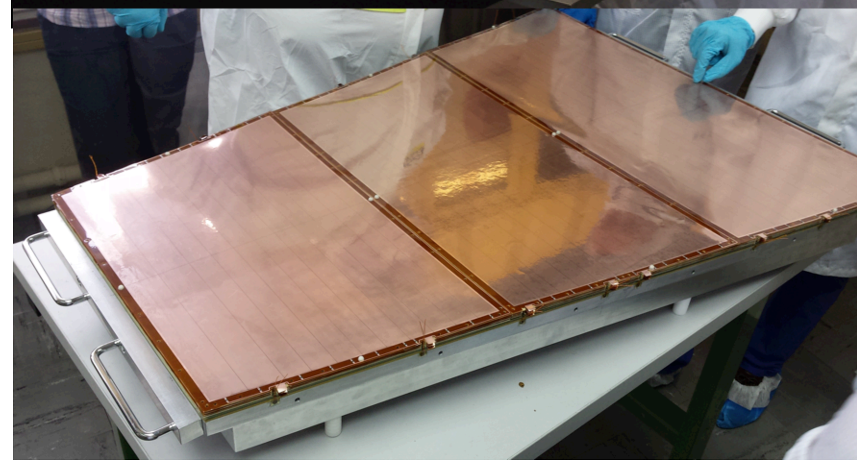
- 650 discharges in the TPC per typical yearly Pb-Pb run
- 5 per stack
- Safe operation guaranteed

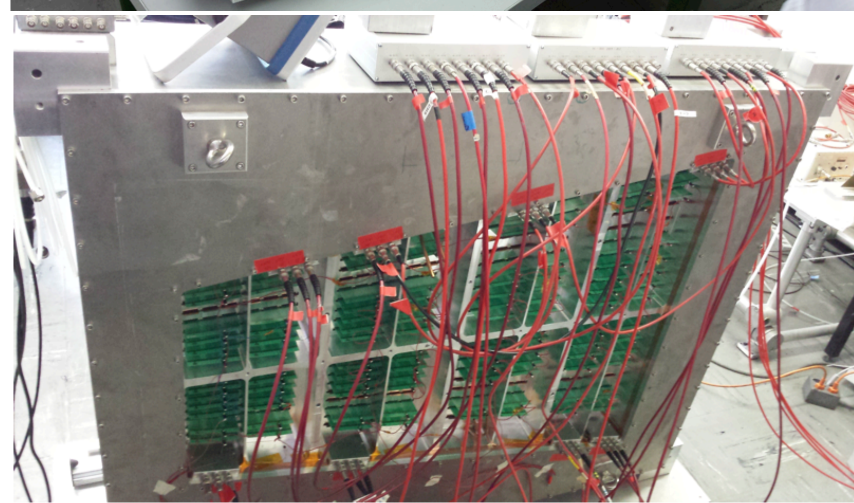
OROC PROTOTYPE

“School of ROC”

- The largest GEM-based detector to date
- 40 participants (11 institutes) took part in a “hands-on” workshop at TUM/CERN
- Padplane equipped in three 4-GEM stacks and installed in the box with a field cage
- Chamber operational under HV, tests with ^{55}Fe
- Mechanical studies afterwards (sagging of the large area GEM foils)







ELECTRONICS

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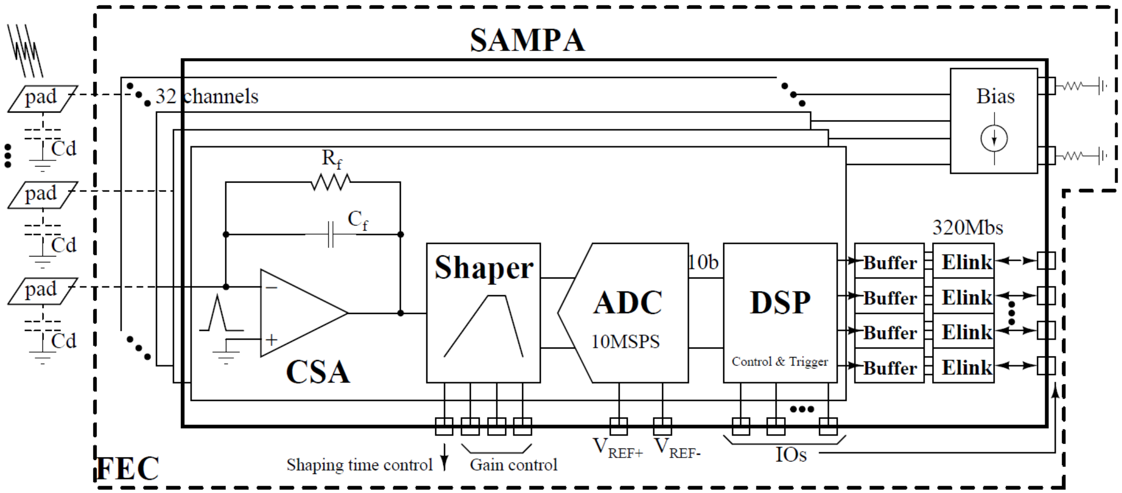
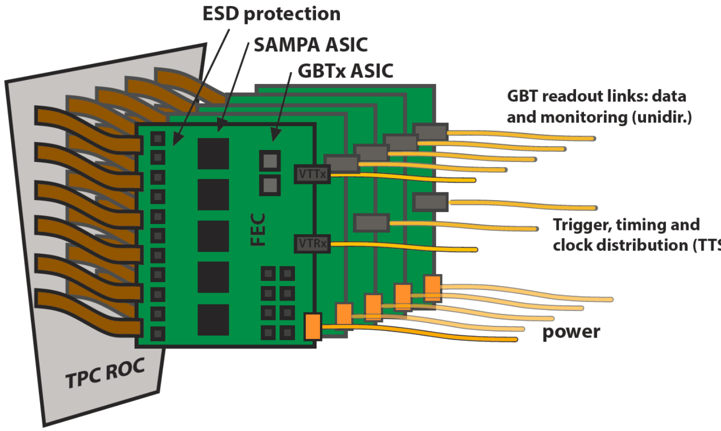




New FE ASIC "SAMPA" (130 nm TSMC CMOS)

- Positive or negative input
- Programmable conversion gains and peaking times
- Different readout modes: triggered, continuous with DSP, continuous with DSP by-pass

For required Signal-to-Noise ratio excellent noise figure of 670e$^-$ (as currently) is needed

All ADC values are read out: data output for 50 kHz Pb-Pb collisions ≈ 6.55 TByte/s

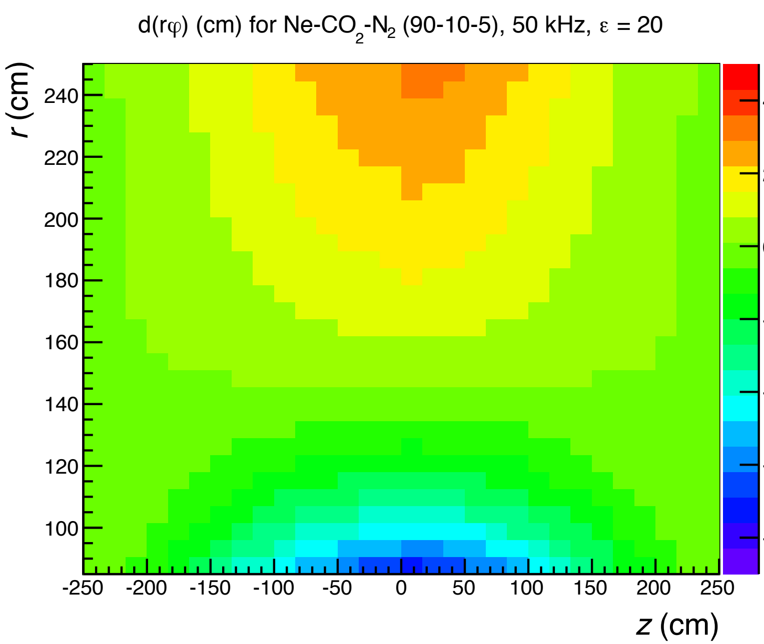
Baseline correction and data compression off detector

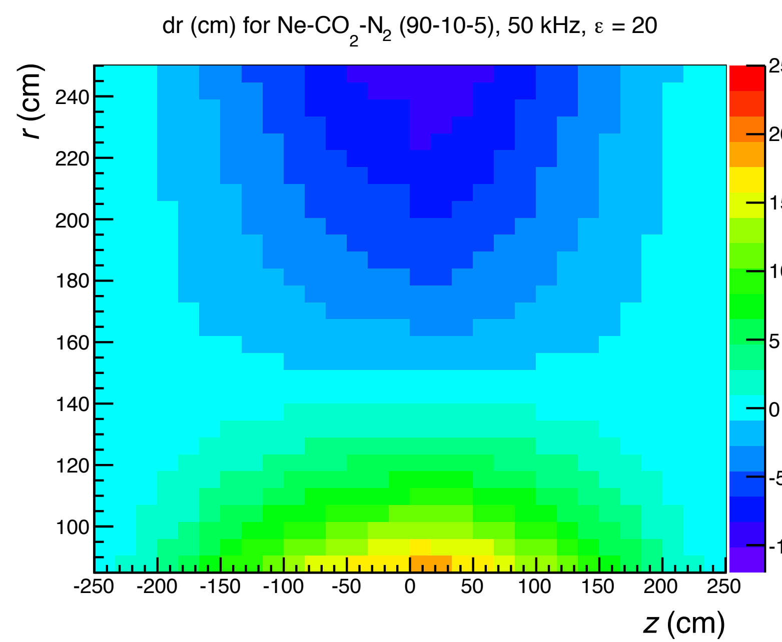
Use CERN developed GBT and Versatile Link for readout

PERFORMANCE

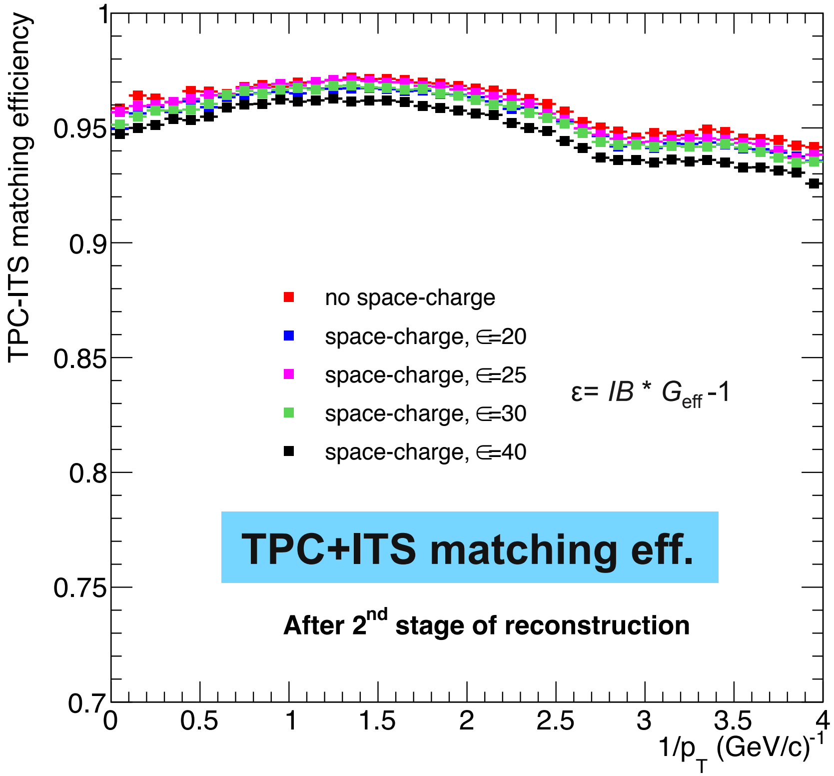
SPACE CHARGE DISTORTIONS

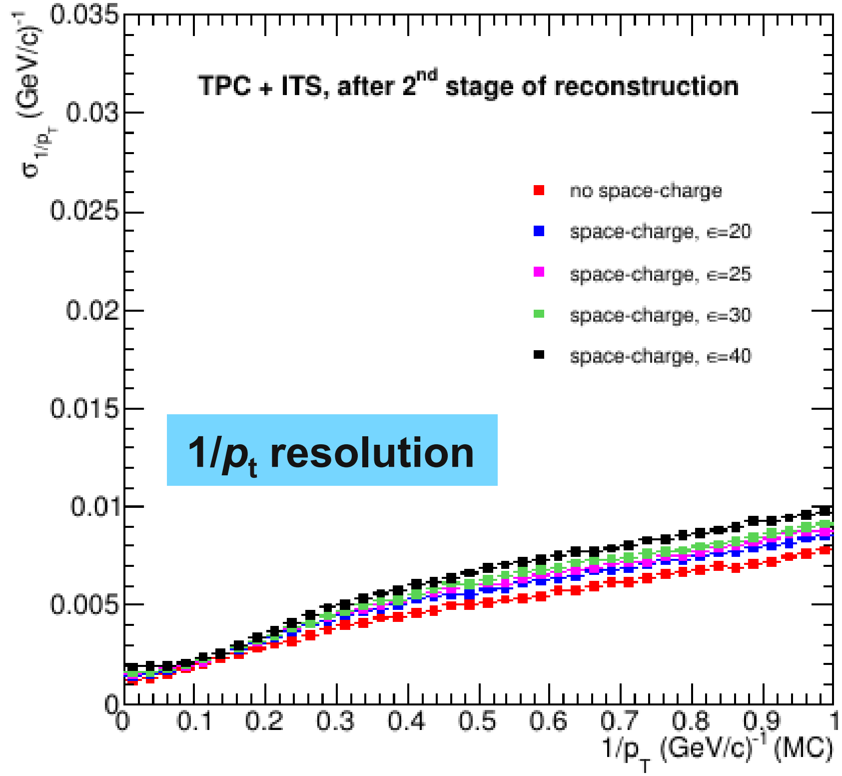
- Ion blocking in GEMs not as efficient as with gating grid
- Ions from 8000 events pile up in the drift volume at 50 kHz Pb-Pb collisions ($t_{d,ion}$ = 160 ms)
- Total number of ions in drift volume strongly depends on *IB*: $n_{tot} = n_{ion} * IB * G_{eff}$; $\varepsilon = IB * G_{eff} - 1$
- 1% of IBF at G_{eff} = 2000 (ε = 20)
  - distortions up to d*r* ≈ 20 cm and d*rφ* ≈ 8 cm (at small *r* and *z*)
  - well below 10 cm for the largest part of drift volume
- Corrections to $\mathcal{O}(10^{-3})$ are required for final calibration (to the level of intrinsic resolution, $\sigma_{r\varphi}$~ 200 μm)
- 2-stage calibration and reconstruction scheme





EXPECTED PERFORMANCE





Testing limits of calibration procedure at up to twice the nominal ion density (ε= 40)

- tracking efficiency not compromised
- slight decrease in p_t resolution at low momenta
  - does not compromise physics program

SUMMARY AND OUTLOOK

SUMMARY AND OUTLOOK

ALICE TPC will be upgraded for RUN 3 to operate at 50 kHz rate in Pb-Pb collisions

No gating and continuous readout with GEMs

Extensive R&D leads to the 4-GEM configuration, fulfilling all requirements:

- Low Ion backflow
- Good energy resolution
- Low discharge rate
- Gain stability and uniformity

New electronics for continuous readout

Upgrade of the online calibration and data reduction system

- Advanced techniques for online corrections of space-charge distortions

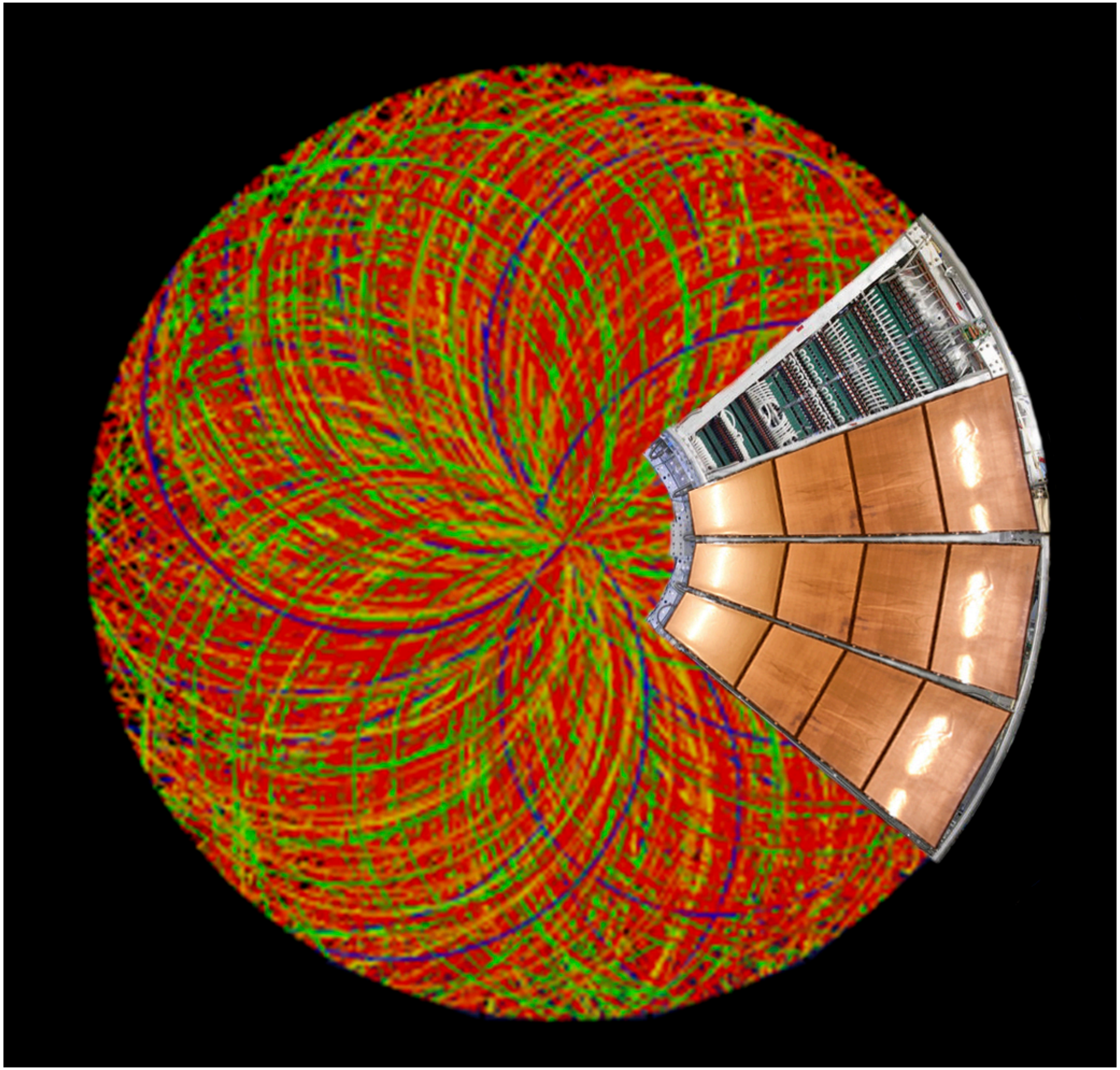
Full-size prototypes of IROC and OROC successfully built and tested

TDR (+Addendum) endorsed by the LHCC in 2015

Pre-production of final chambers ongoing, full production starts in Q2.2016

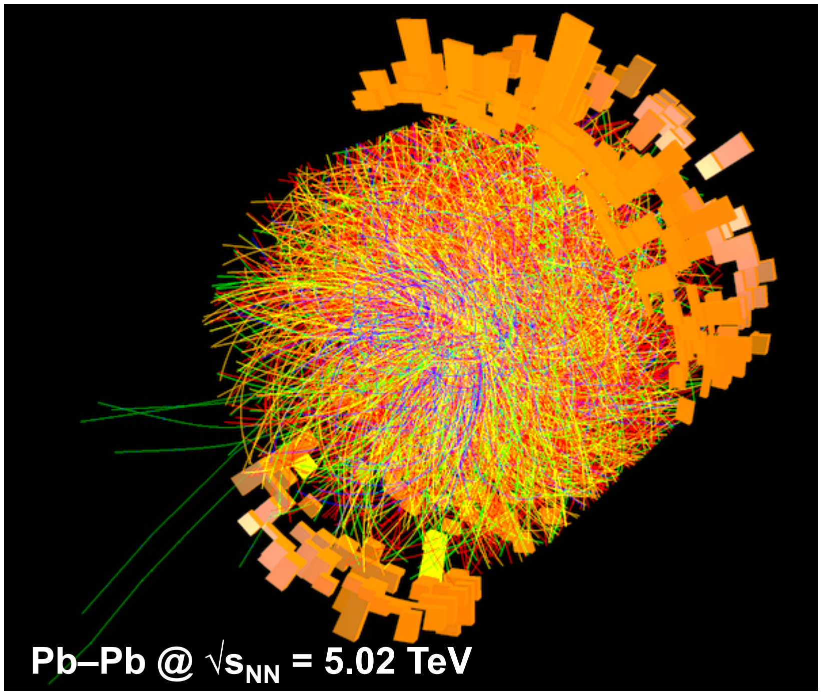
LHC Long Shutdown 2 in 2019-2020: chamber and FEE installation, commissioning

THANK YOU!



EXTRA SLIDES

TPC – A VERSATILE TRACKING DETECTOR



TPC – an (almost) ideal tracking detector

Large active volume and acceptance

Low material budget

3D spatial information about hits

→ simple pattern recognition

High particle densities

Good momentum resolution

Particle identification via measurement of the specific energy loss

Wide range of applications

- High energy physics
- Dark matter searches
- Neutrinoless double beta decay
- … and many more

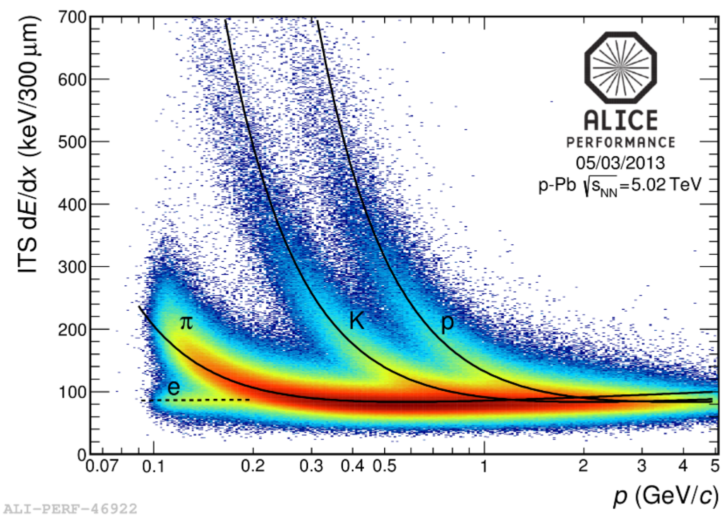
Limitations

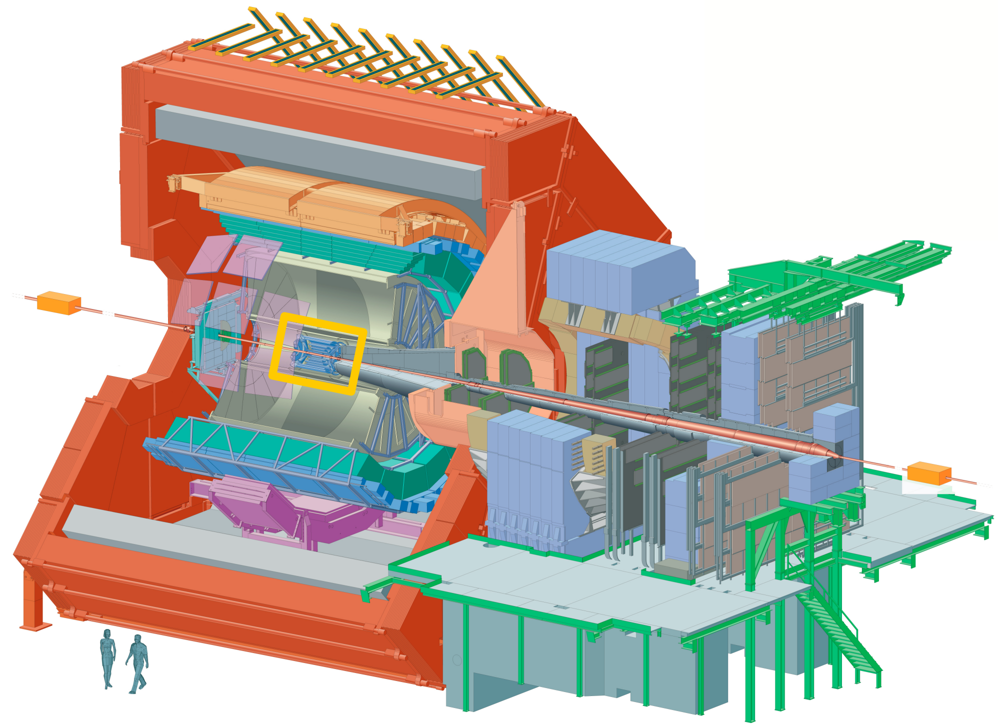
- Large parameter space for calibration
- Drift distortions due to backdrifting ions → gated operation
- Limited to low rate experiments

Particle Identification in ALICE

Inner Tracking System

- Silicon detector for vertex determination
- Identification of displaced vertices
- PID via measurement of dE/dx

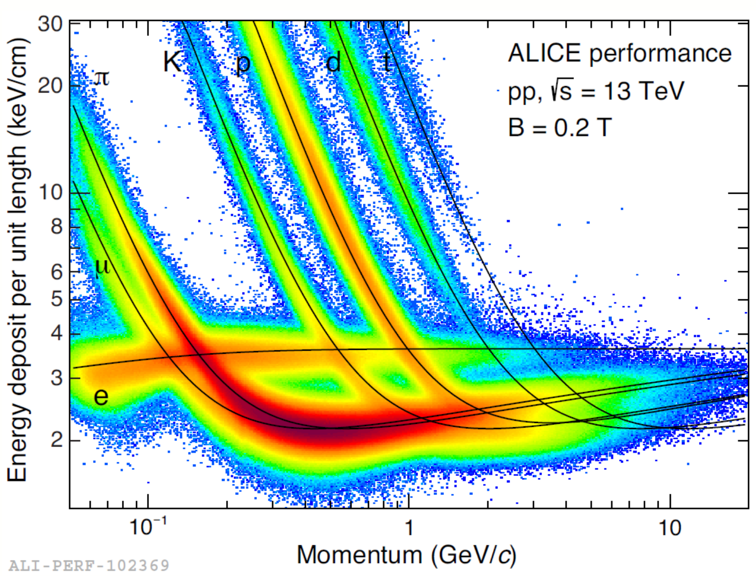


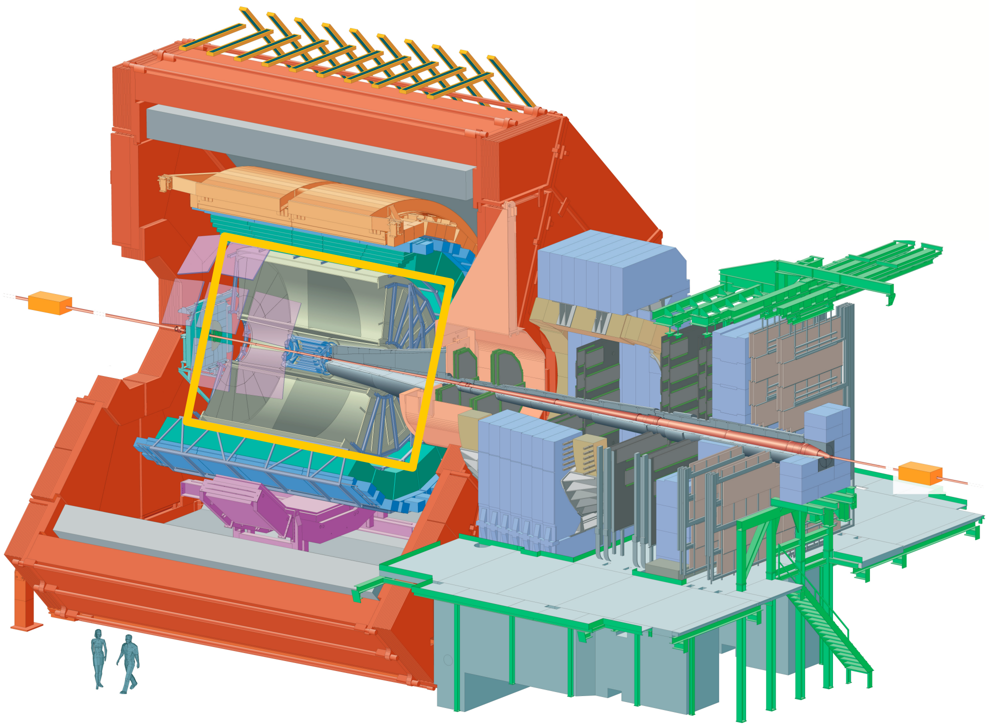


Particle Identification in ALICE

Time Projection Chamber

- Charged-particle tracking
- Momentum measurement
- PID via measurement of dE/dx

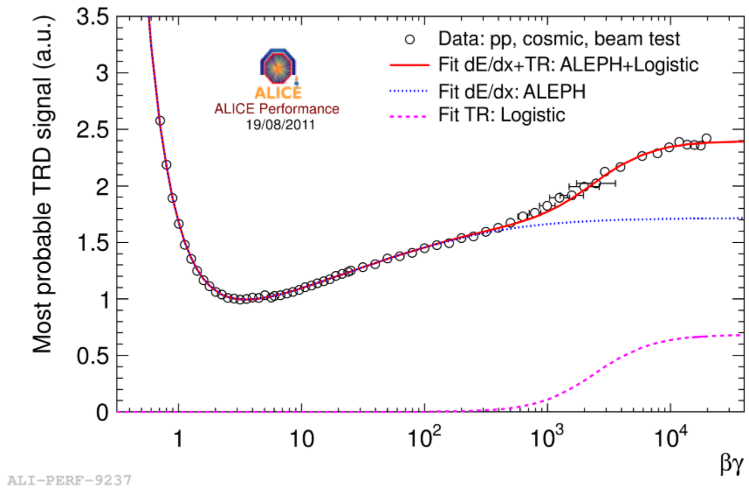


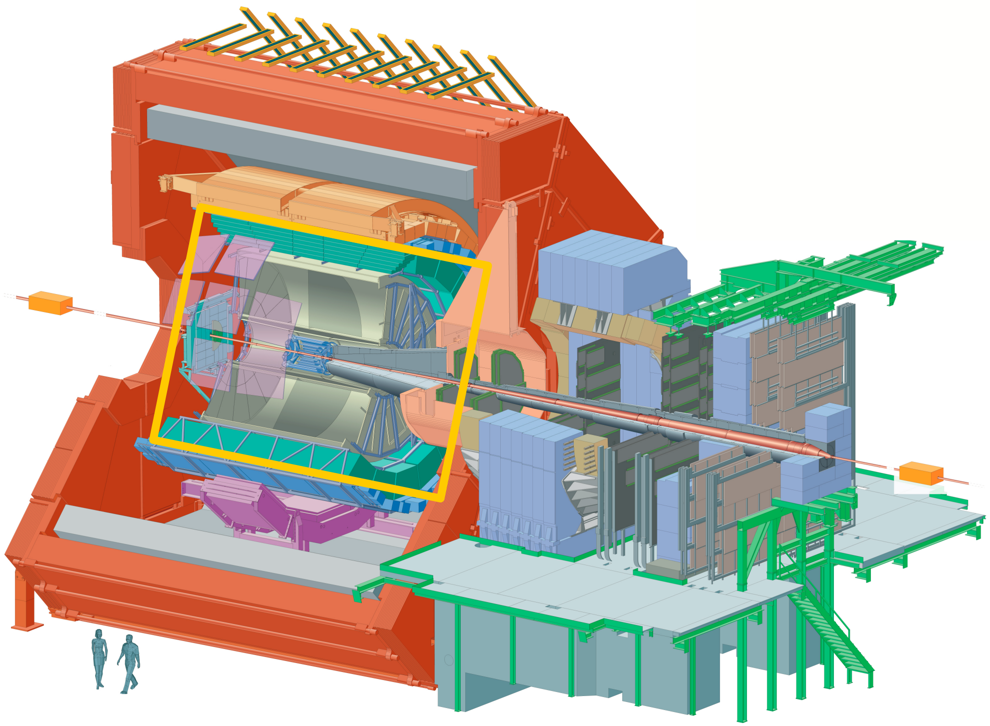


Particle Identification in ALICE

Transition Radiation Detector

- Provides electron identification at high βγ
- Measurement of d*E*/d*x* and transition radiation

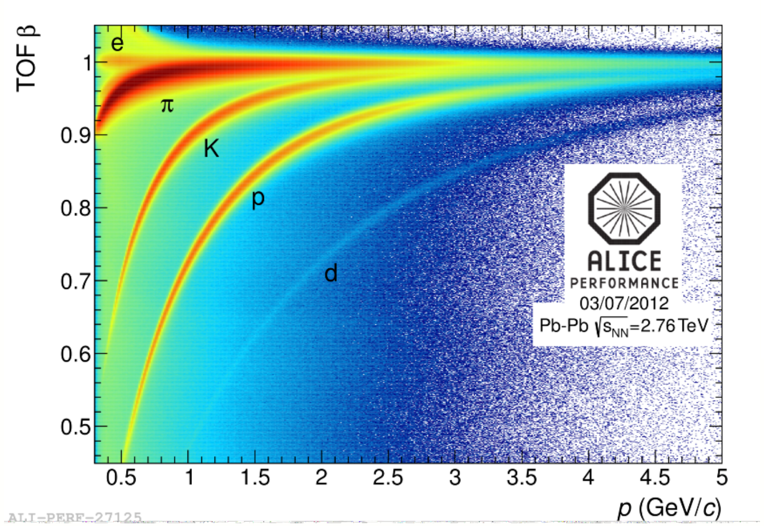


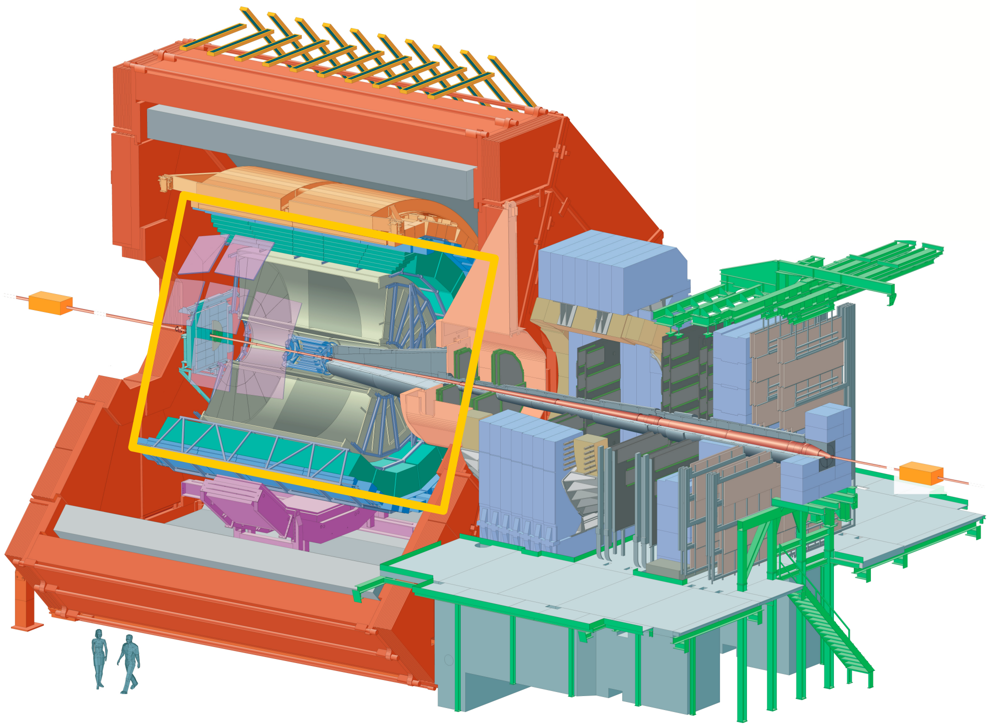


Particle Identification in ALICE

Time Of Flight

- Multigap Resistive Plate Chambers
- Provides PID in the intermediate momentum range





Particle Identification in ALICE

High Momentum Particle IDentification (HMPID)

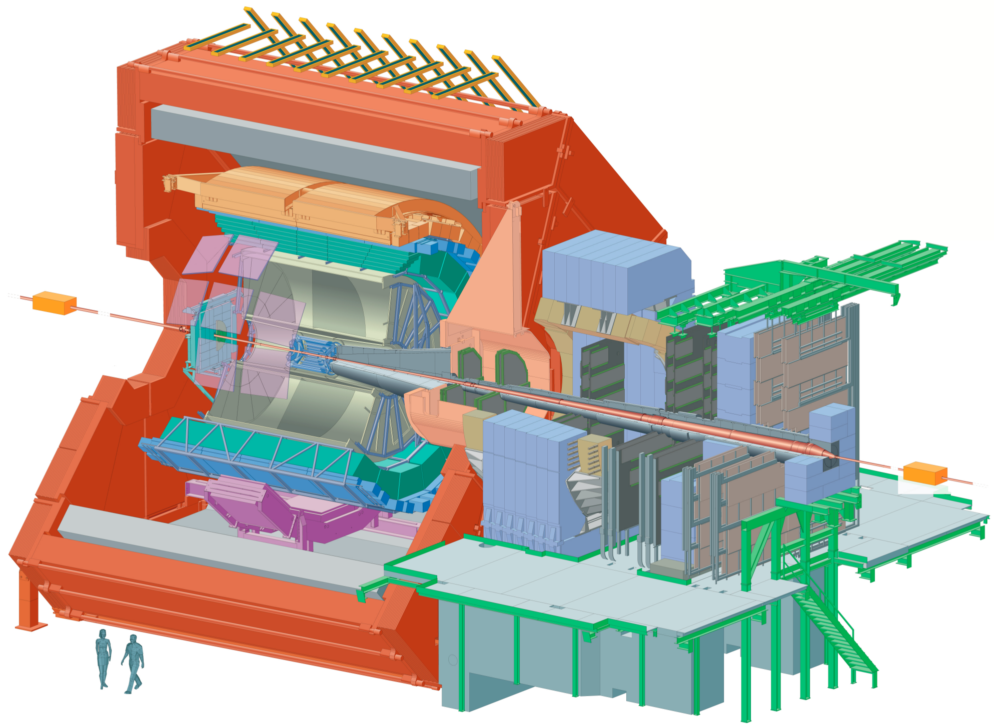
- RICH detector

Calorimeters (EMCal, PHOS)

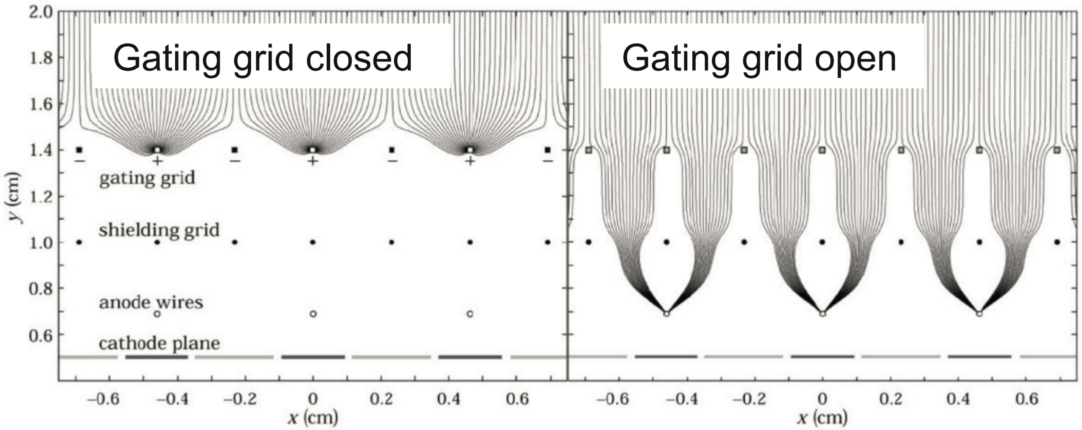
Muon Spectrometer

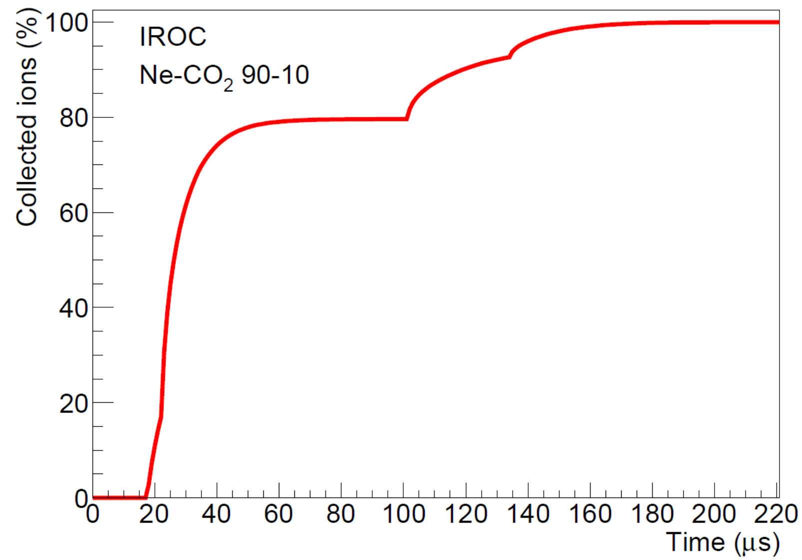
- Tracking planes behind absorber

(+ detectors for global event characterization)



LIMITATIONS OF THE PRESENT SYSTEM





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

➢ **Upgrade necessary to run at a higher interaction rate!**

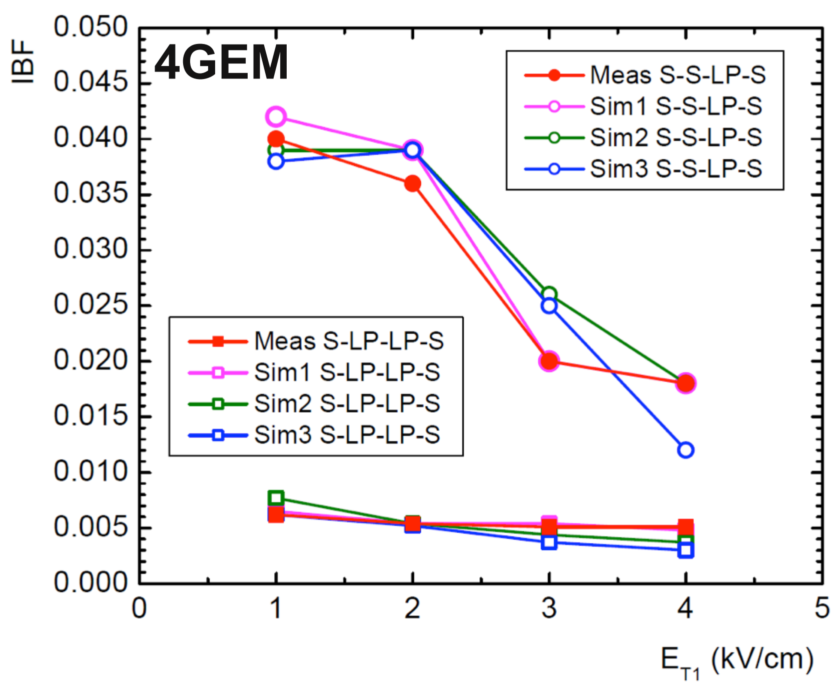
IBF SIMULATIONS

Garfield/Magboltz

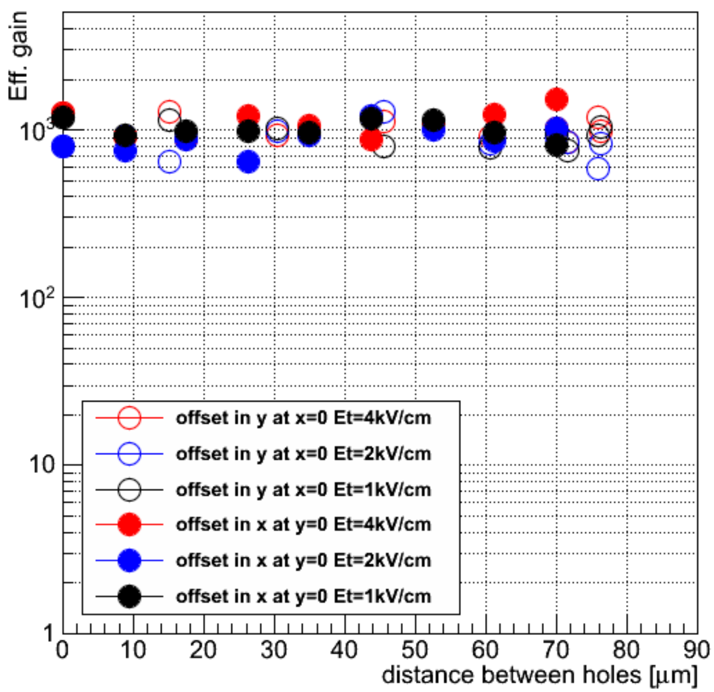
Systematic scan of parameter space

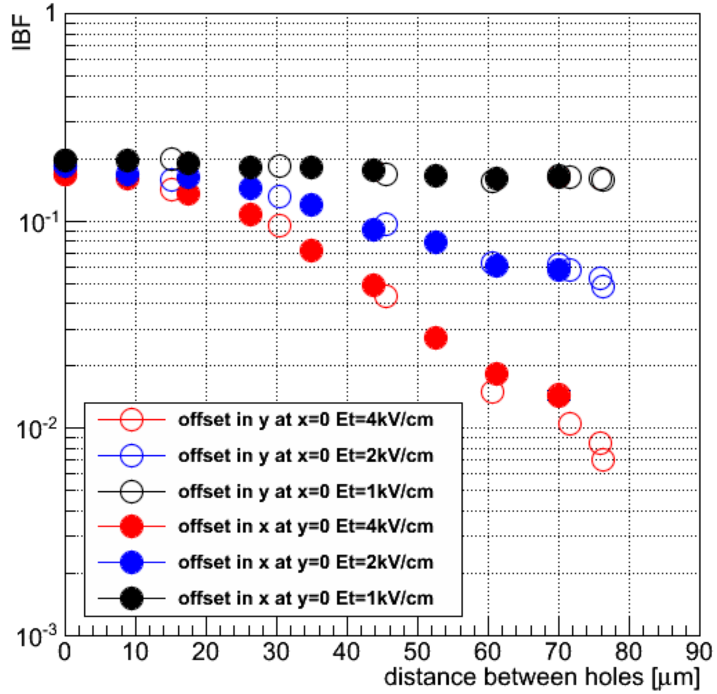
- gas composition
- 3- and 4-GEM configuration, different geometries
- tuning of simulations by adjusting hole alignment

IBF quantitatively well described by simulations



HOLE ALIGNMENT





- Gas gain (left) and the IBF (right) in a 2GEM system as a function of the hole offset between two layers
- **Need random misalignment: rotate foils (masks) by 90°**

DISCHARGE STUDIES

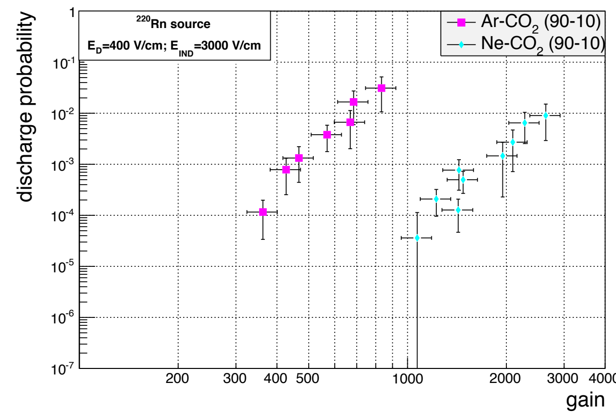
Influence of Z

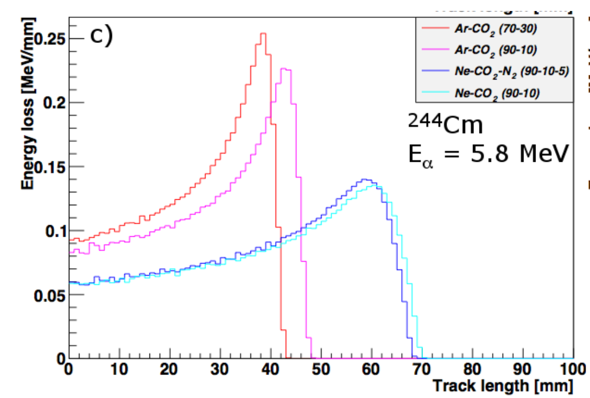
1GEM studies - gas influence

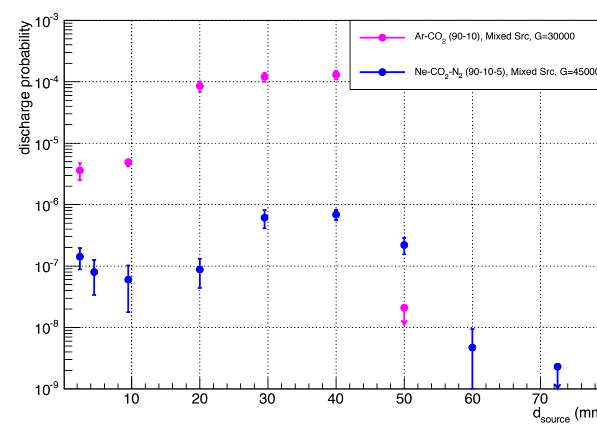
- ^{220}Rn source (gaseous)
- Comparison for TPC gas mixtures
- Lower probability in gas with lower Z

3GEM studies – charge density

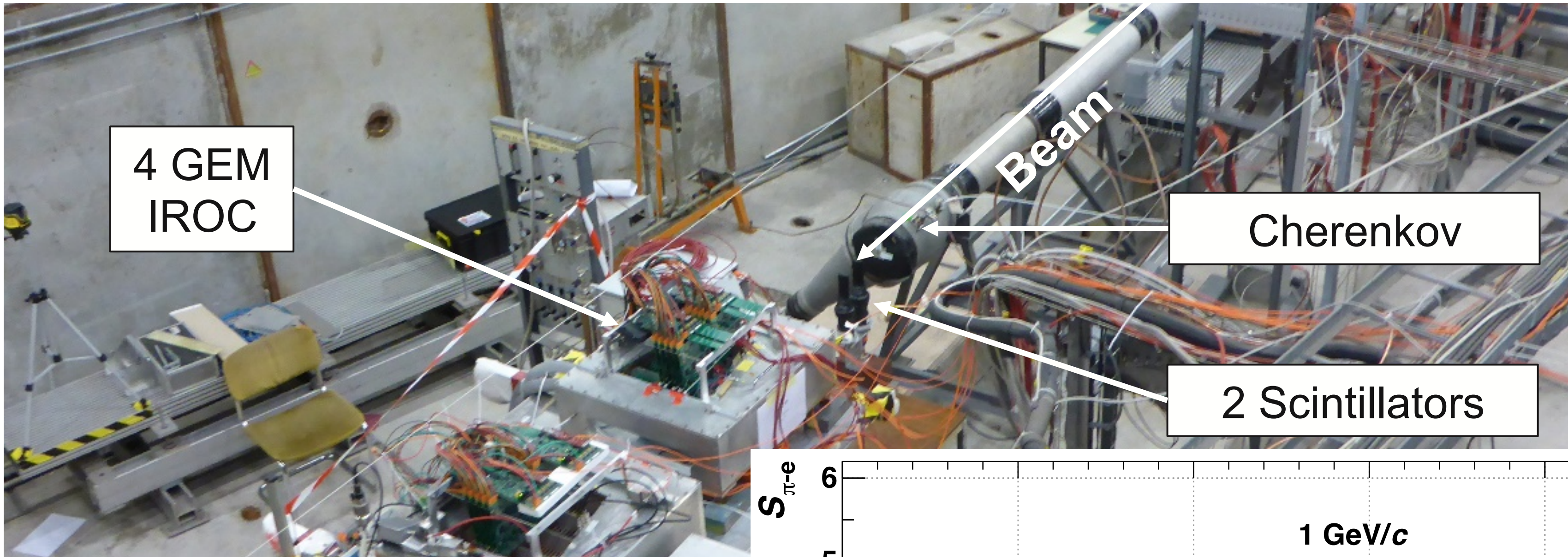
- Discharge probability measured as a function of a distance between the source and GEMs (d_{source})
- Gas:
  - Ar-CO_2 (90-10)
  - Ne-CO_2-N_2 (90-10-5)
- Sudden drop after a certain d_{source} value
- Associated with energy loss curves in different mixtures?
- Reproduced with simple G4 simulations

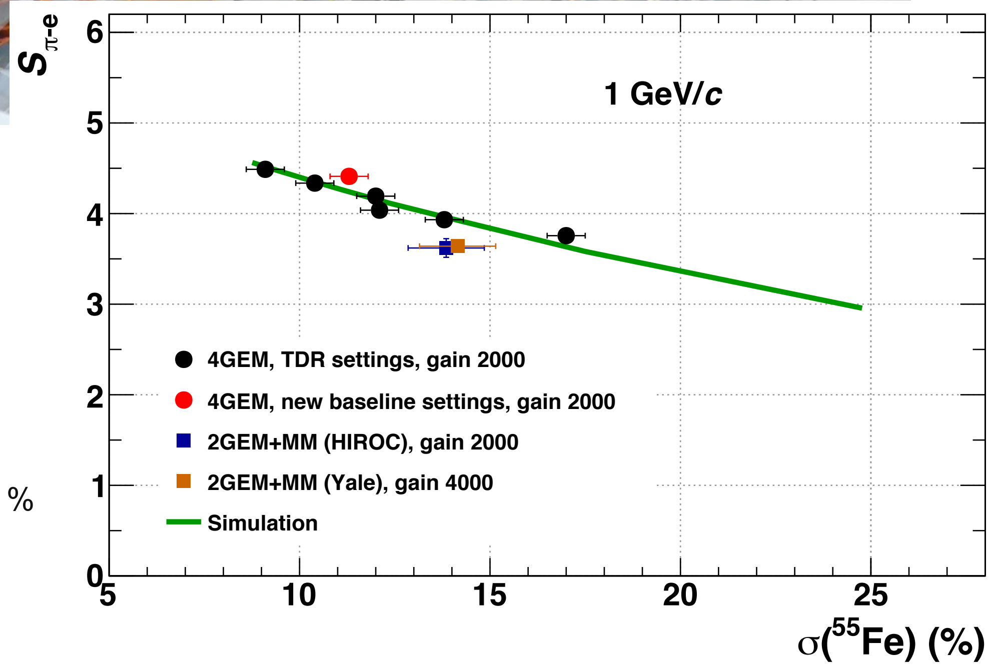






PS BEAMTIME (NOV. 2014)





- Secondary $e^{\pm}$, $\pi^{\pm}$ beam; 1, 2, 3 GeV/c
- dE/dx performance as expected from simulations
- Relative energy resolution as in present MWPC
  - $\sigma_e/\mu_e \approx 9\%$
  - $\sigma_\pi/\mu_\pi \approx 10\%$
- Physics performance not compromised up to $\sigma(^{55}Fe) = 14$ %

QUALITY ASSURANCE OF GEM FOILS

Basic and Advanced QA

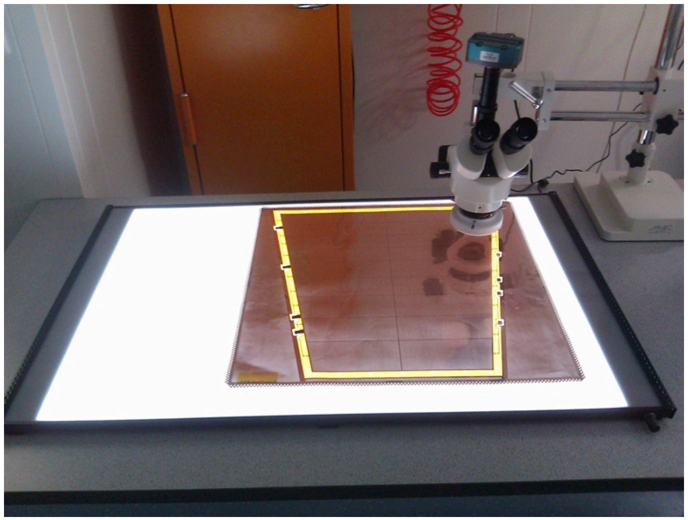
Basic QA (each production step)

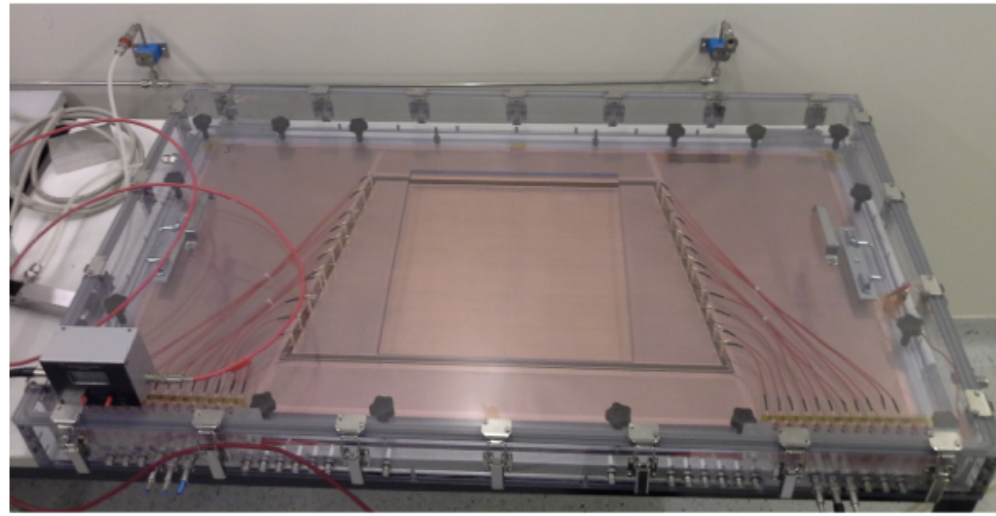
- “HV cleaning” of the GEM foils at 500-600 V in air
- Coarse optical inspection (note visible defects by eye)
- Leakage Current measurements

Advanced QA

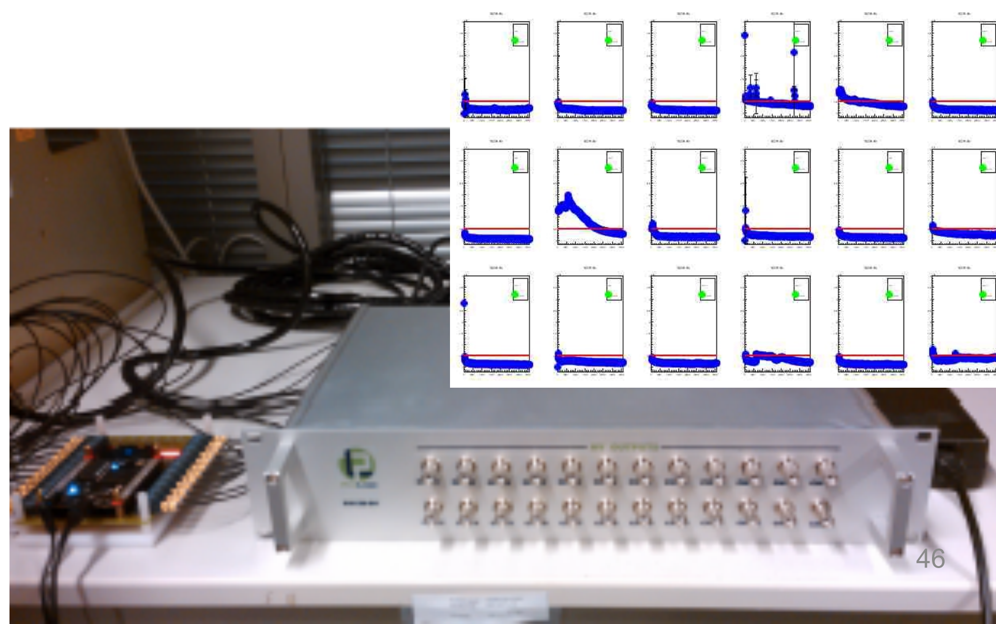
- High definition scanning
  (precise determination of defects and hole size distributions)
- Long term leakage current tests
- HV stability test
- Intersegment test
- Gain uniformity scan of one sample per GEM type

BASIC QA



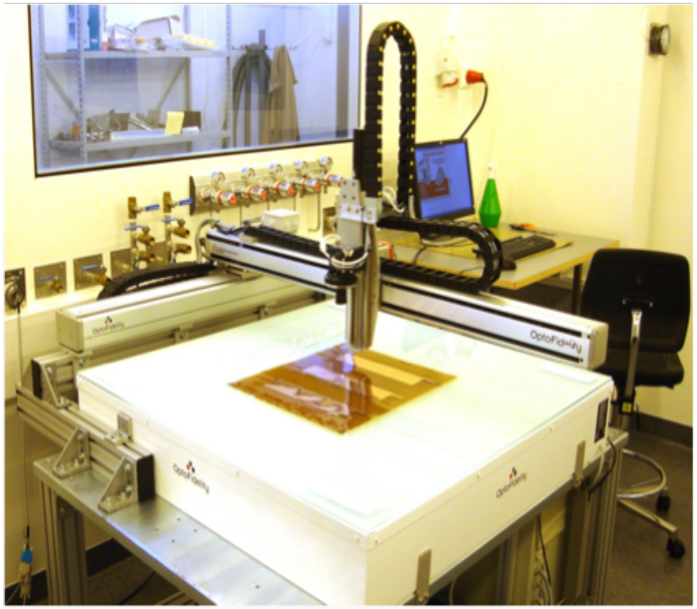


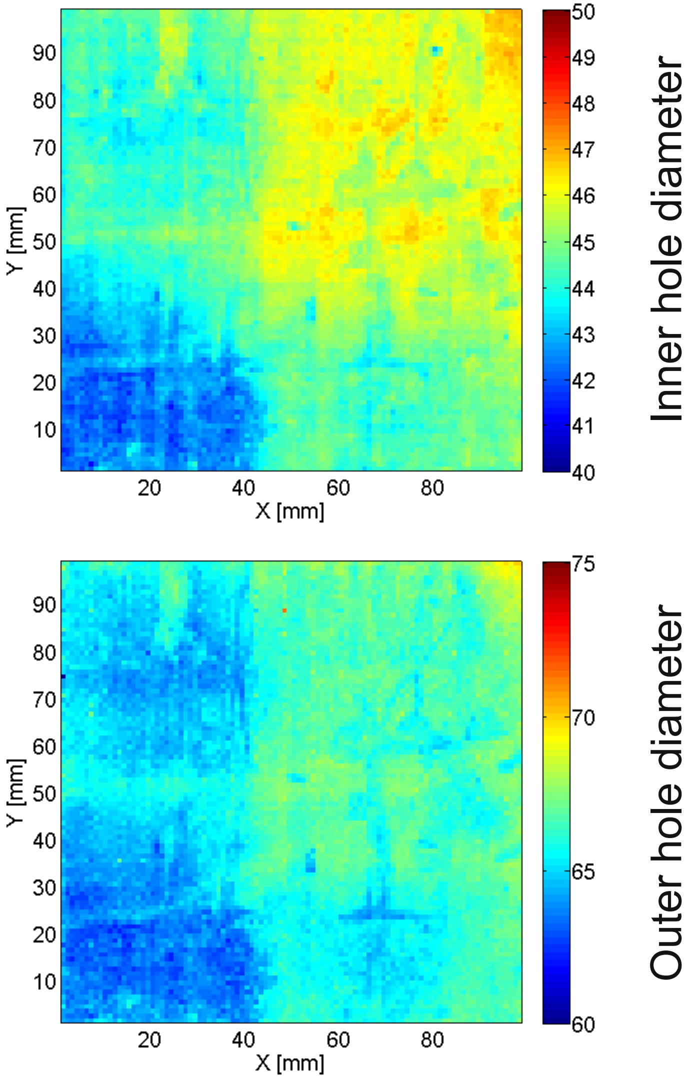
- Coarse optical check to spot major defects
- HV test (e.g. leakage current) of every GEM segment at 500V in air
- HV testing tools (boxes, pA-meters, software) in production



ADVANCED QA

HD scanning

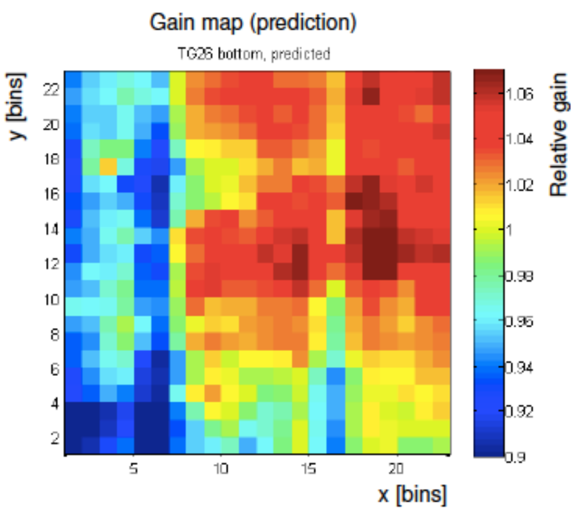


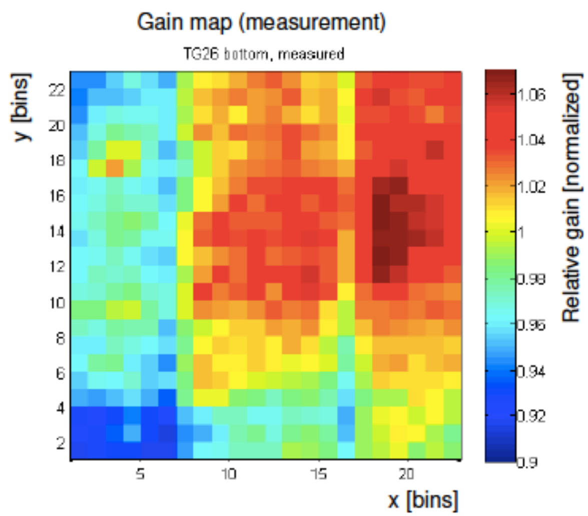


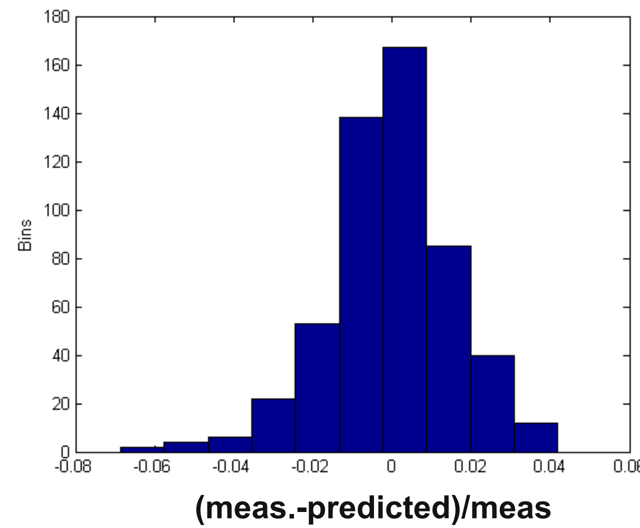
- **HD Optical Scanning Systems to measure distribution of inner/ outer hole diameters, pitch, GEM rim and spot hole defects**

GEM GAIN UNIFORMITY

- Hole diameter distribution allows to predict gain uniformity across the GEM area.
- Below: gain measurement compared to a prediction from a trained neural network





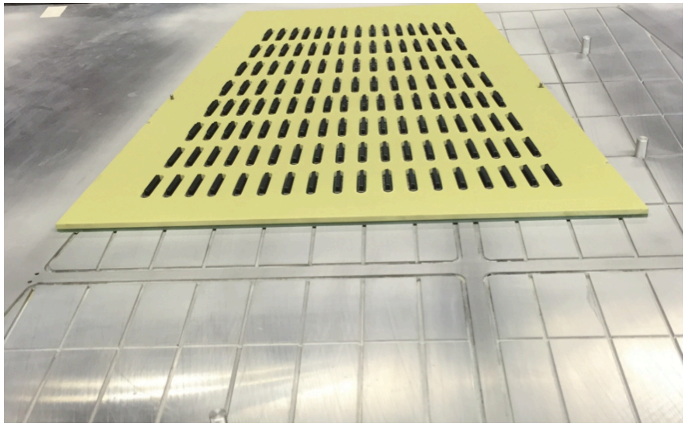


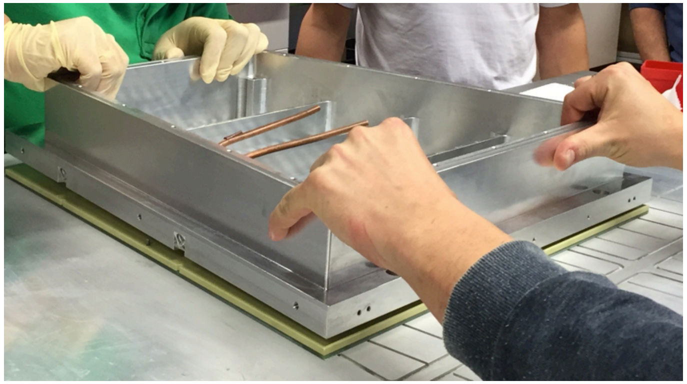
- Gain prediction is in agreement with measurement within 1-2%

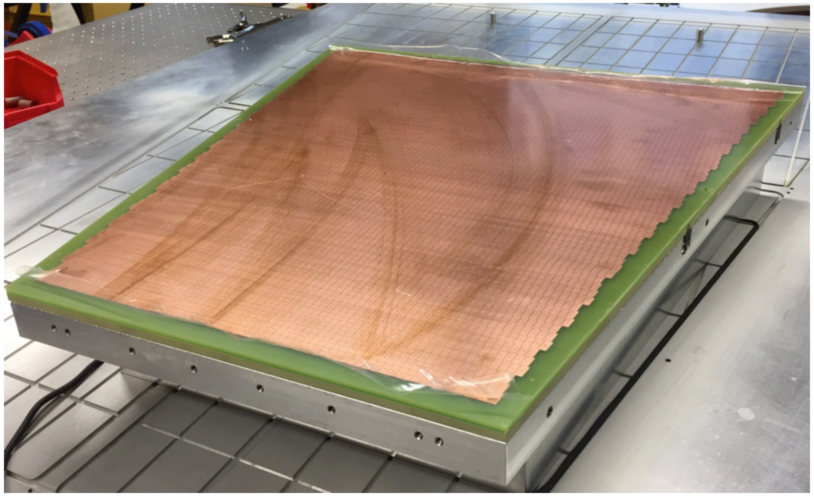
  (required gain uniformity of a foil is 10%)
- Optical HD scan allows for qualification of gain uniformity without gain measurement
- For x-check, gain uniformity of minimum one foil from each production batch will be measured in a setup employing a MWPC stage

CHAMBER BODY ASSEMBLY

IROC

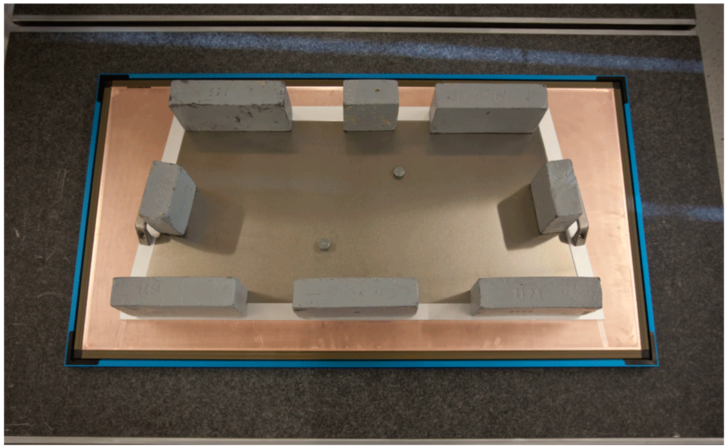


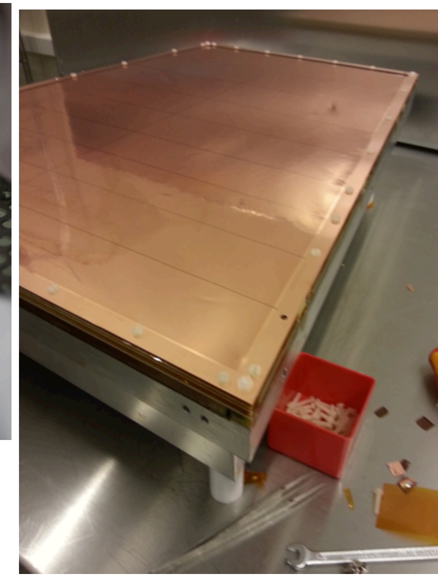




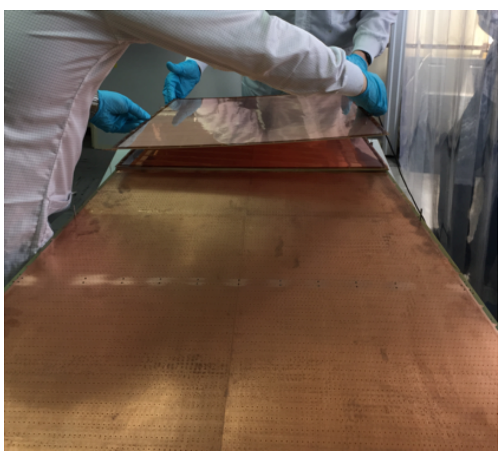
Assembly of the first OROC body, beginning of 2016 (awaiting for OROC1-2 padplanes)

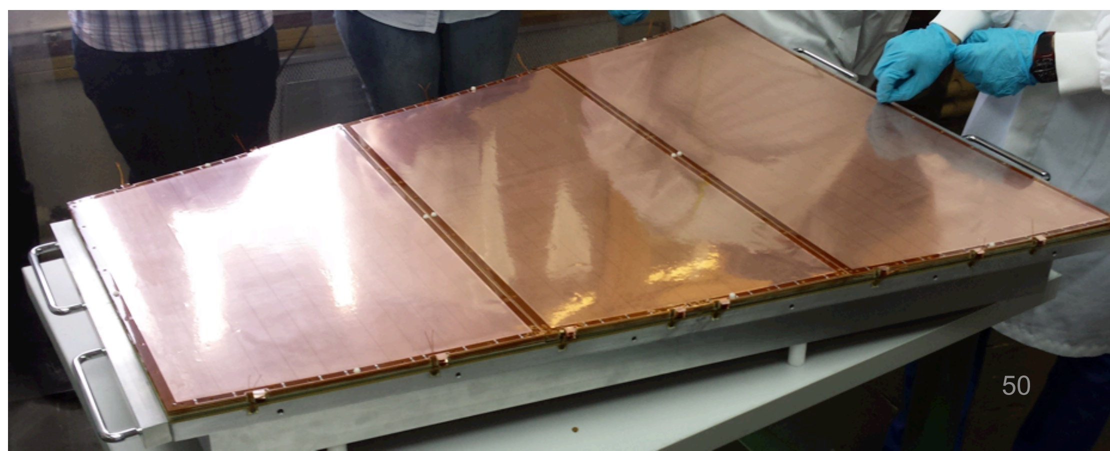
CHAMBER ASSEMBLY





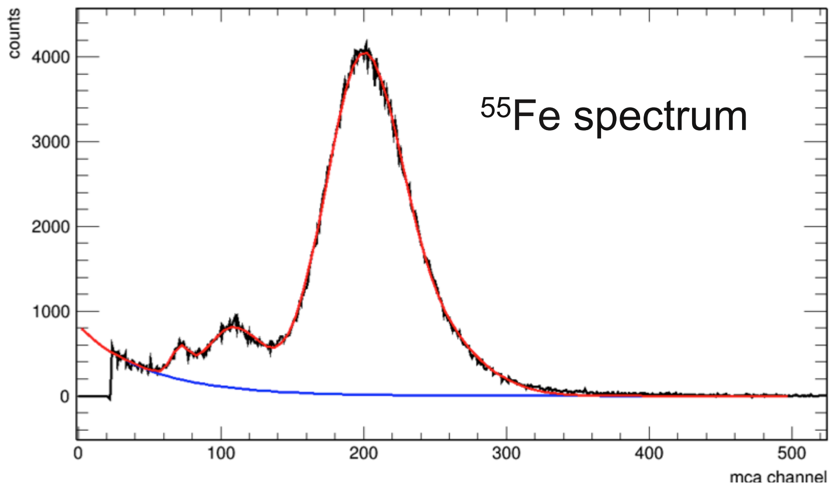
- Framing and assembly procedures well established
- Based on the experience gained in the prototyping phase
- Dedicated workshops: “School of ROC” in Munich, Gluing Workshop in Heidelberg

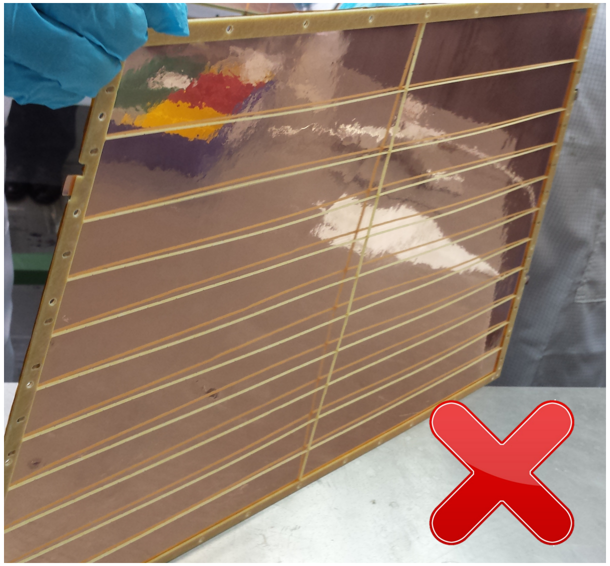


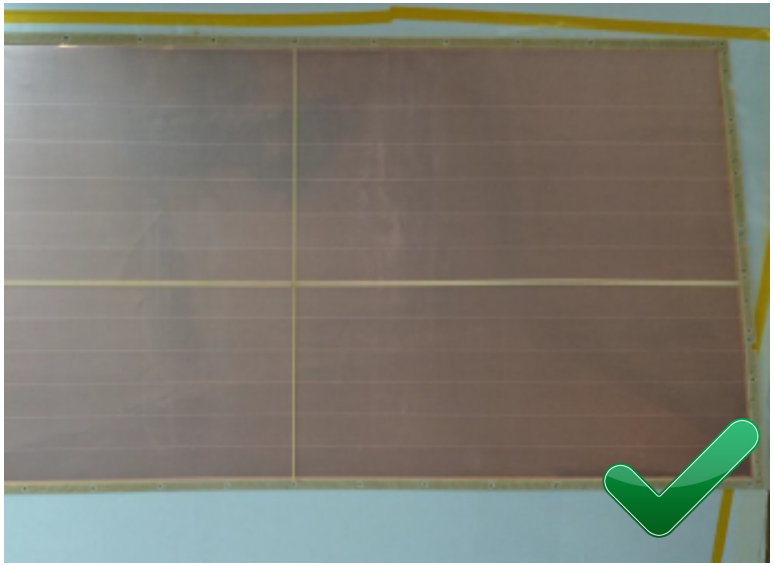


OROC PROTOTYPE

- Chamber operational under HV
- 55Fe spectrum
- Sagging studies: check the possible reduction of the spacer grid density in GEM frames







COMMISSIONING

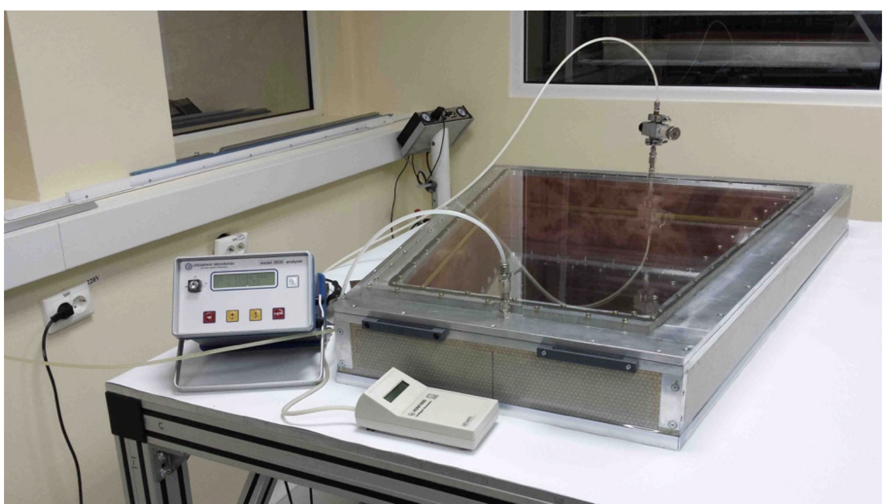
Goal: guarantee gas tightness and proper performance of all ROCs

Chamber body tests: pad plane connectivity, gas tightness, HV stability

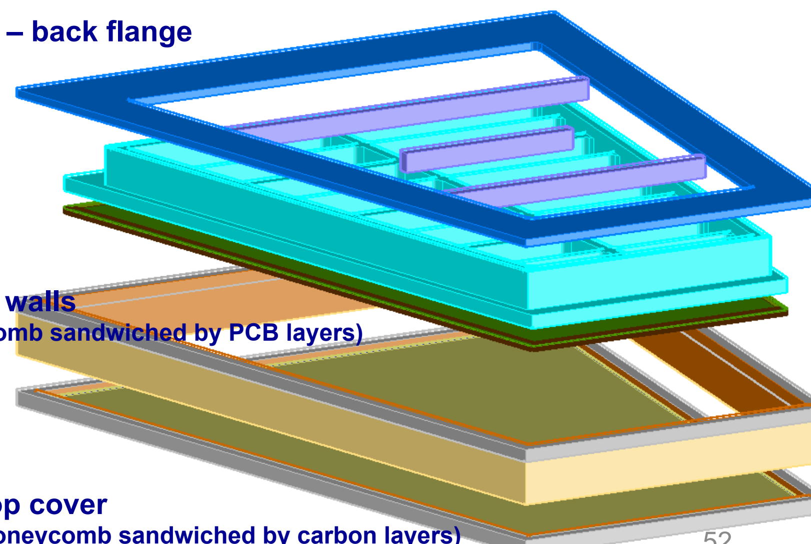
ROC commissioning:

- leak test
- gain curve
- gain and IBF uniformity tests with source
- two days long term test

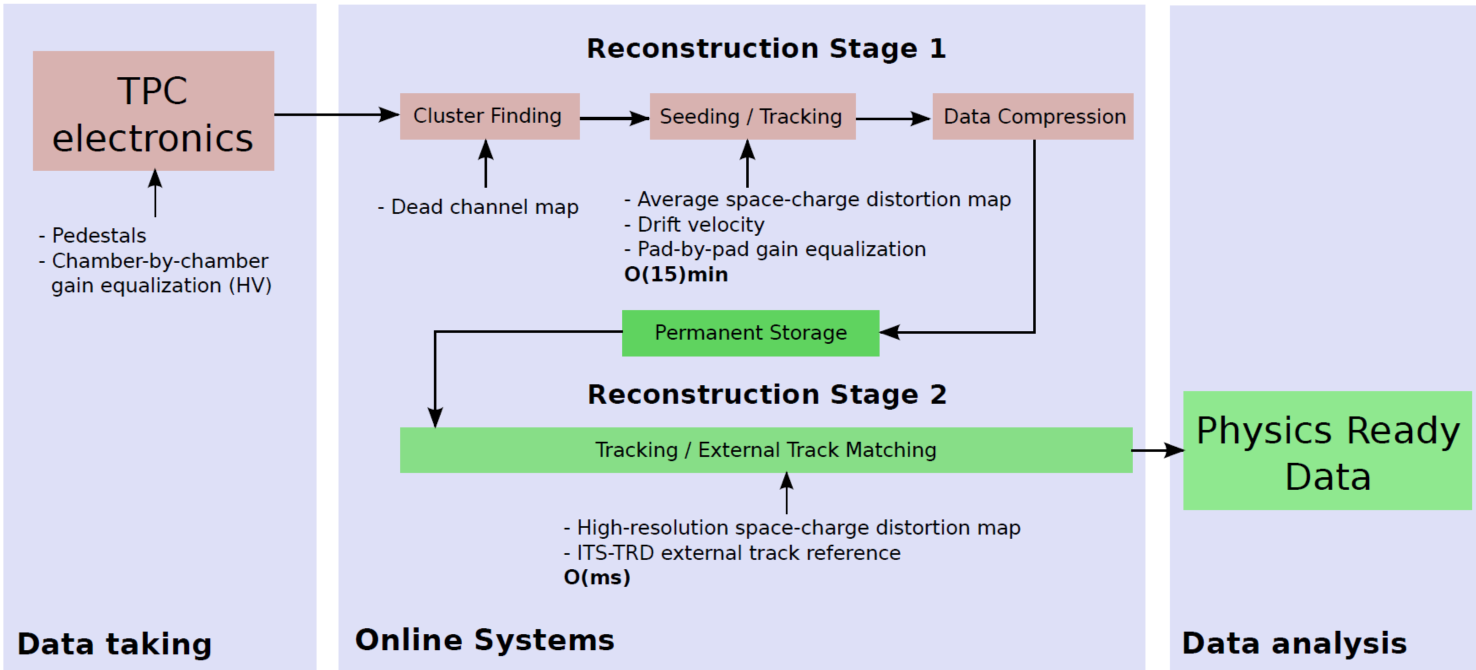
Chamber tests upon arrival at CERN



TEST VESSEL



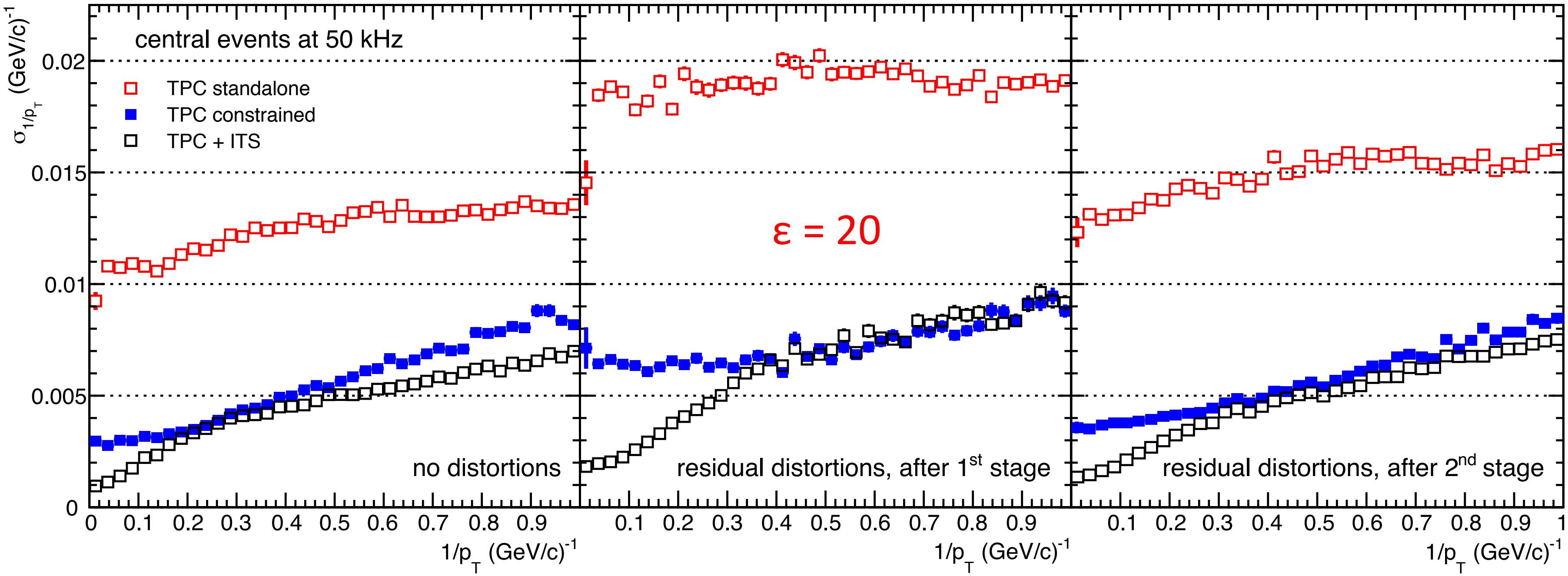
RECONSTRUCTION STRATEGY



Two-stage reconstruction scheme:

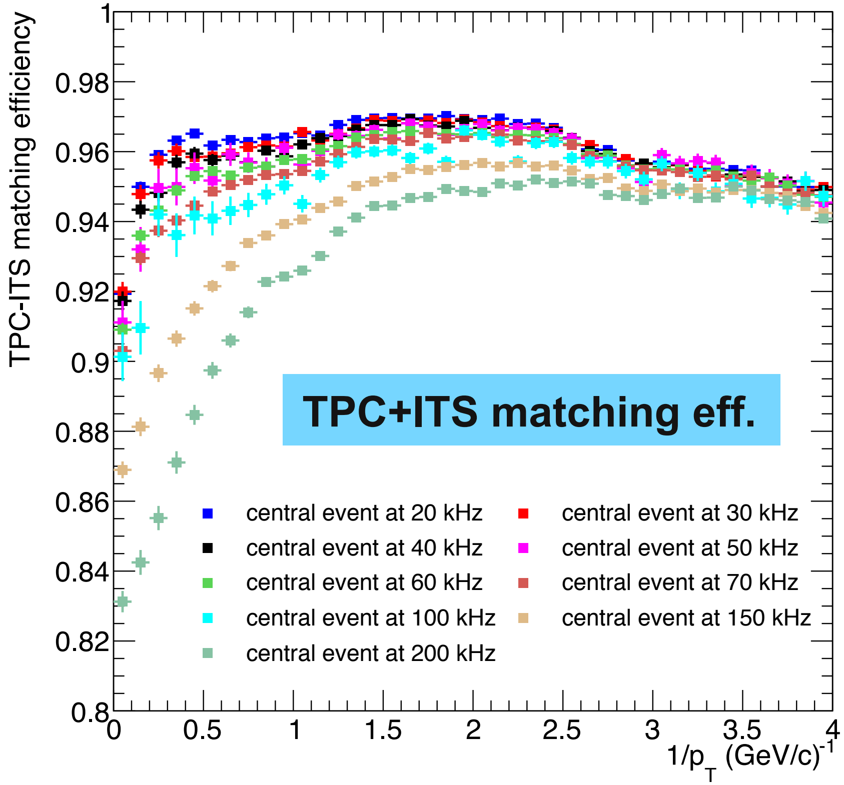
- Cluster finding, cluster-to-track association: 6.55 TB/s → 50 GB/s
  Scaled average space charge distortion map
- Tracking, ITS-TRD track matching
  High-resolution space charge correction for full distortion calibration → O(200 µm) in rϕ

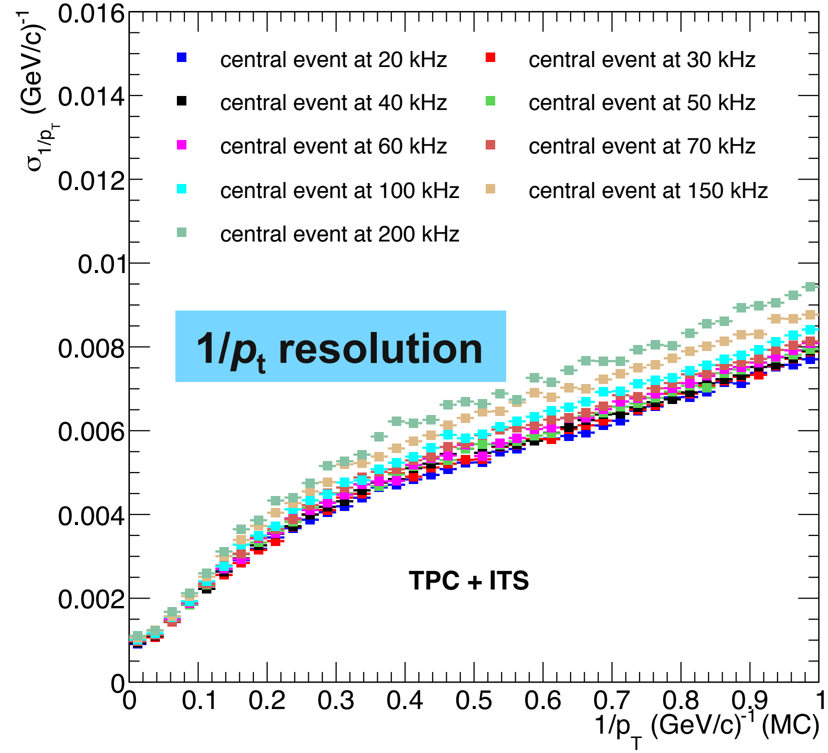
EXPECTED PERFORMANCE



- momentum resolution after first reconstruction stage factor 1.5 - 2 worse than ideal
- practically fully recovered after second reconstruction stage
- calibration procedure validated up to ε = 40

EXPECTED PERFORMANCE





Influence of track density

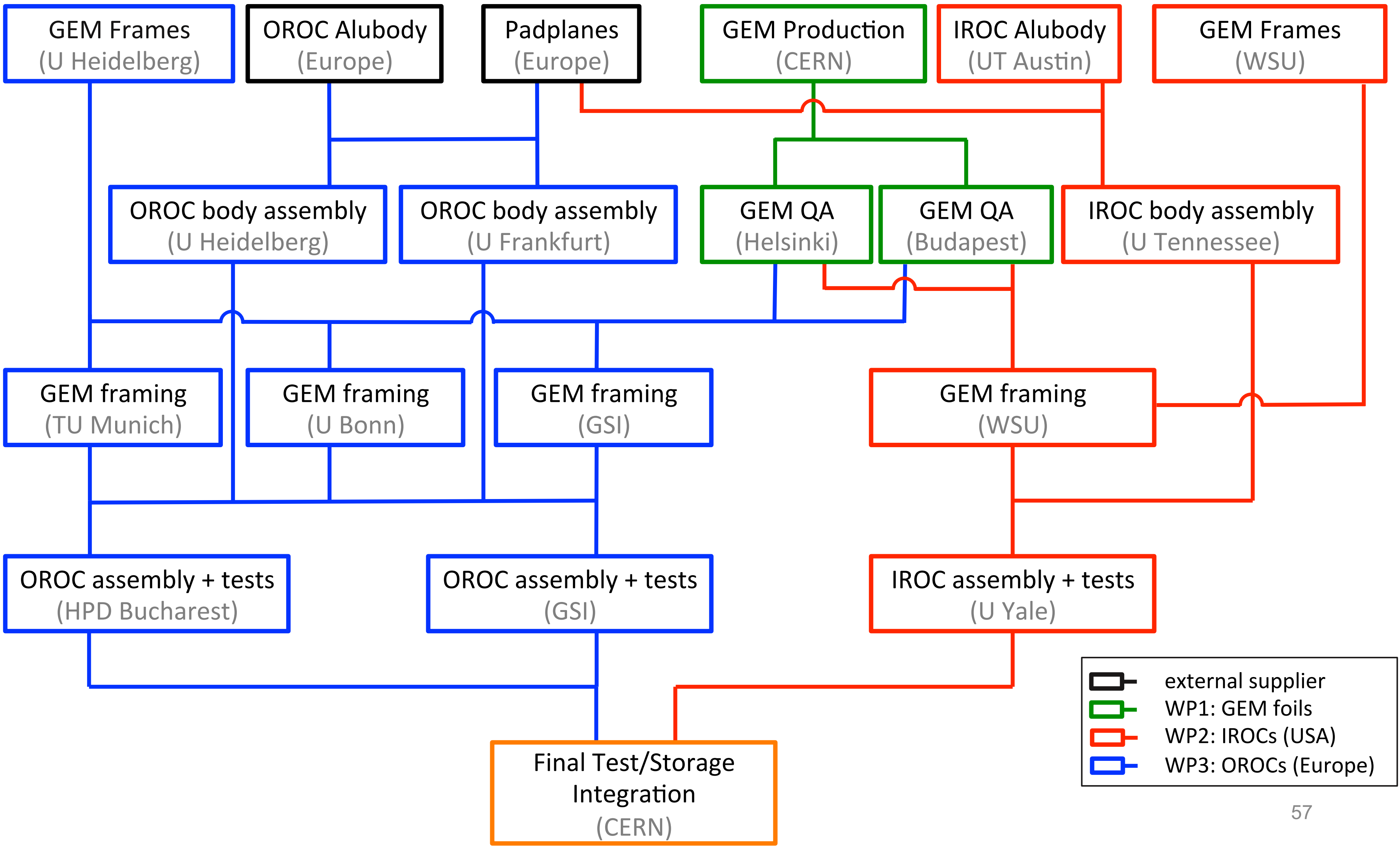
- track matching efficiency and $1/p_t$ resolution deteriorate for interaction rates > 100 kHz
- nominal interaction rate in RUN 3 and RUN 4: **50 kHz**

ALICE

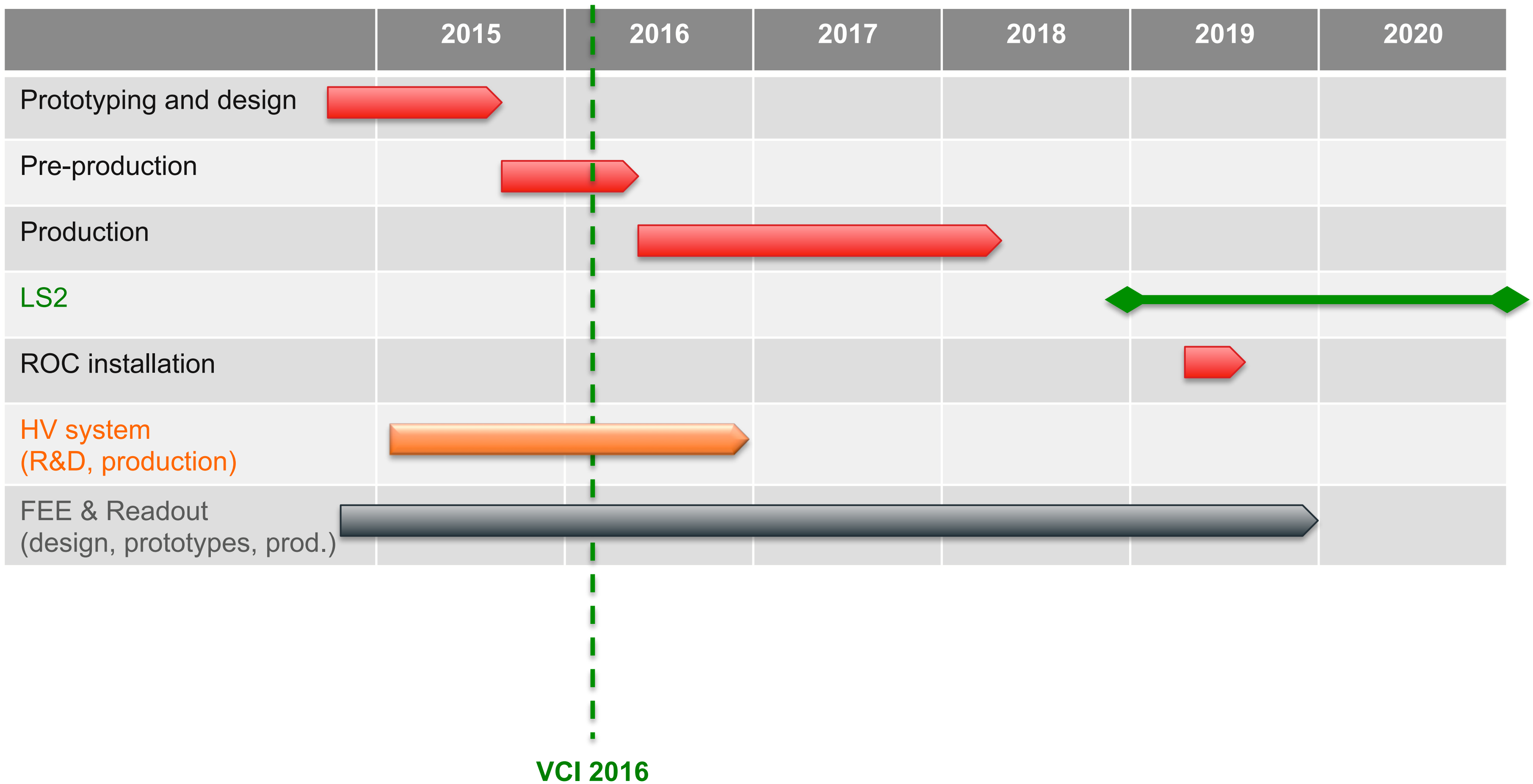
FEE SPECIFICATION

		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 $6\times10\,mm^2$ pads)		20:1	30:1
(OROC $6\times15\,mm^2$ 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

ROC MATERIAL FLOW



TIMELINE


2015
2016
2017
2018
2019
2020
Prototyping and design
Pre-production
Production
LS2
ROC installation
HV system
(R&D, production)
FEE & Readout
(design, prototypes, prod.)
VCI 2016

ALICE

ALICE GEM TPC

36 IROC and 36 OROC chambers will be installed
More than 520k electronic channels for readout

TOTAL TPC ROCs area = 34.29 m^2
TOTAL ACTIVE area = 30.5352 m^2

TOTAL FOILS area (4GEM) = 137.16 m^2
TOTAL (4)GEM area = 122.14 m^2

TOTAL number of GEM holes in ALICE GEM TPC = 3.9E+09