FRONTIER DETECTORS FOR FRONTIER PHYSICS -
13th Pisa Meeting on Advanced Detectors

24-30 May 2015 - *La Biodola, Isola d'Elba (Italy)*
Europe/Rome timezone

A continuous read-out TPC for the ALICE upgrade

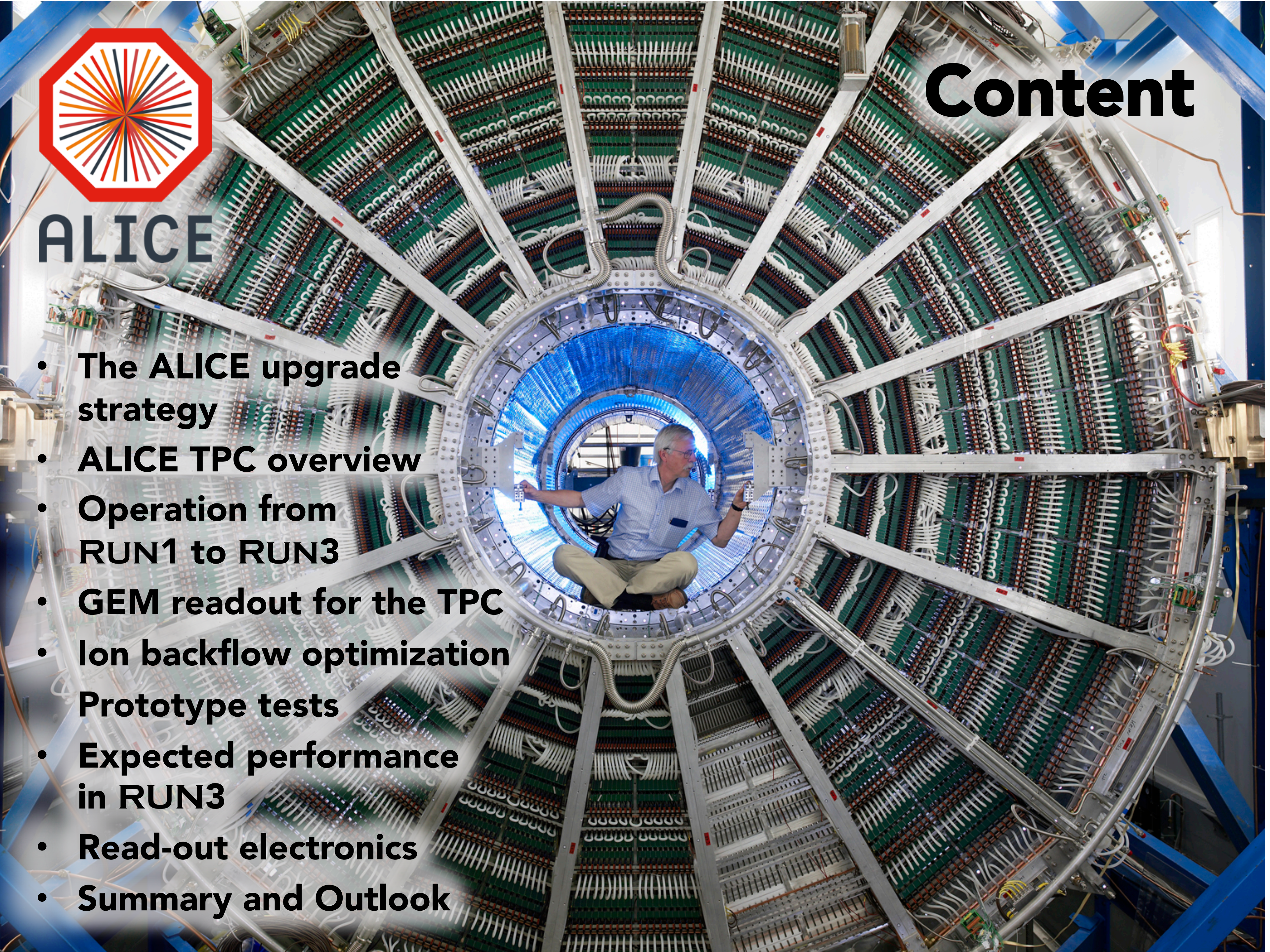
27th May 2015

Christian Lippmann

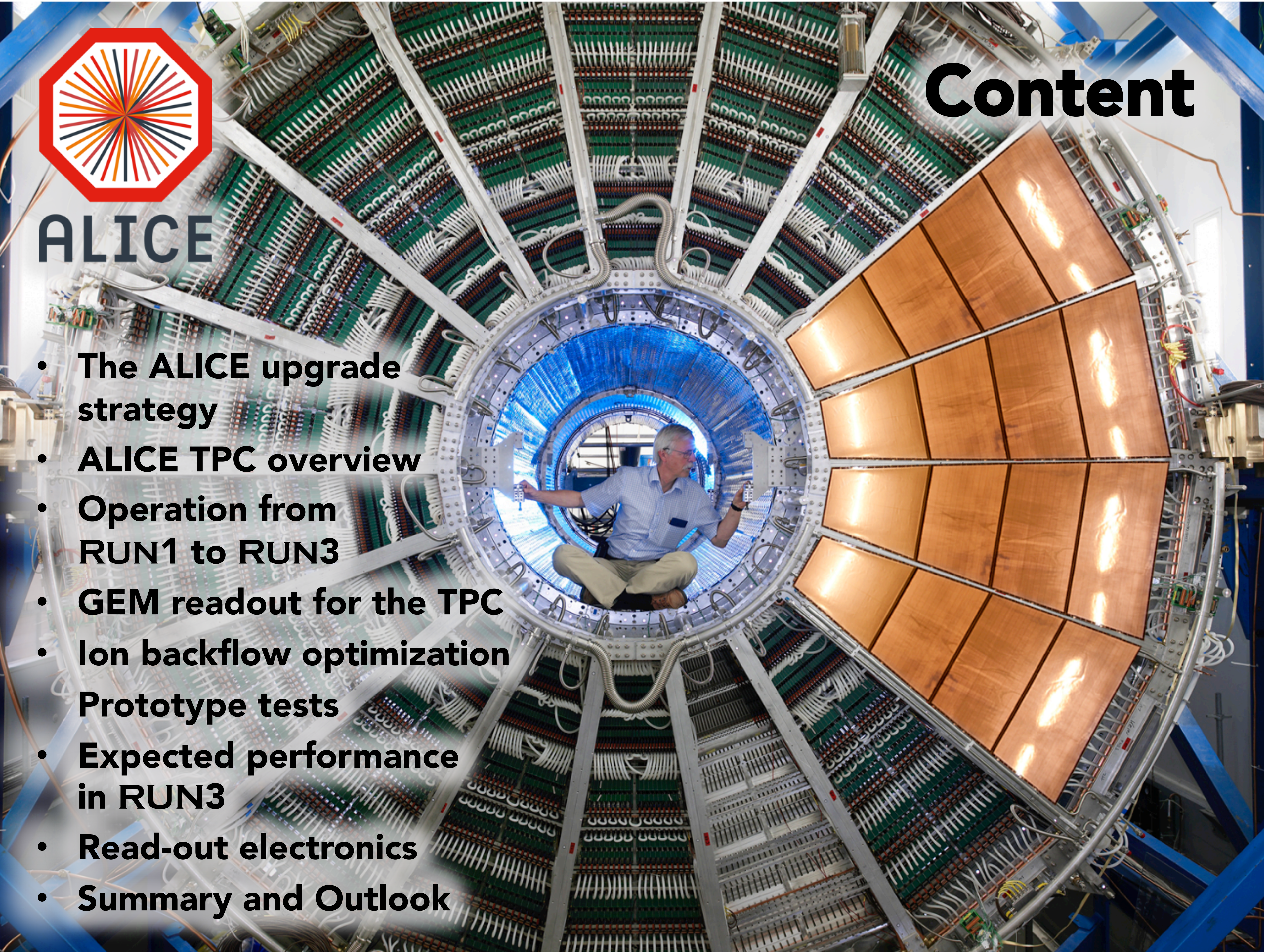
GSI

on behalf of the ALICE collaboration

Content



- The ALICE upgrade strategy
- ALICE TPC overview
- Operation from RUN1 to RUN3
- GEM readout for the TPC
- Ion backflow optimization
- Prototype tests
- Expected performance in RUN3
- Read-out electronics
- Summary and Outlook



ALICE

Content

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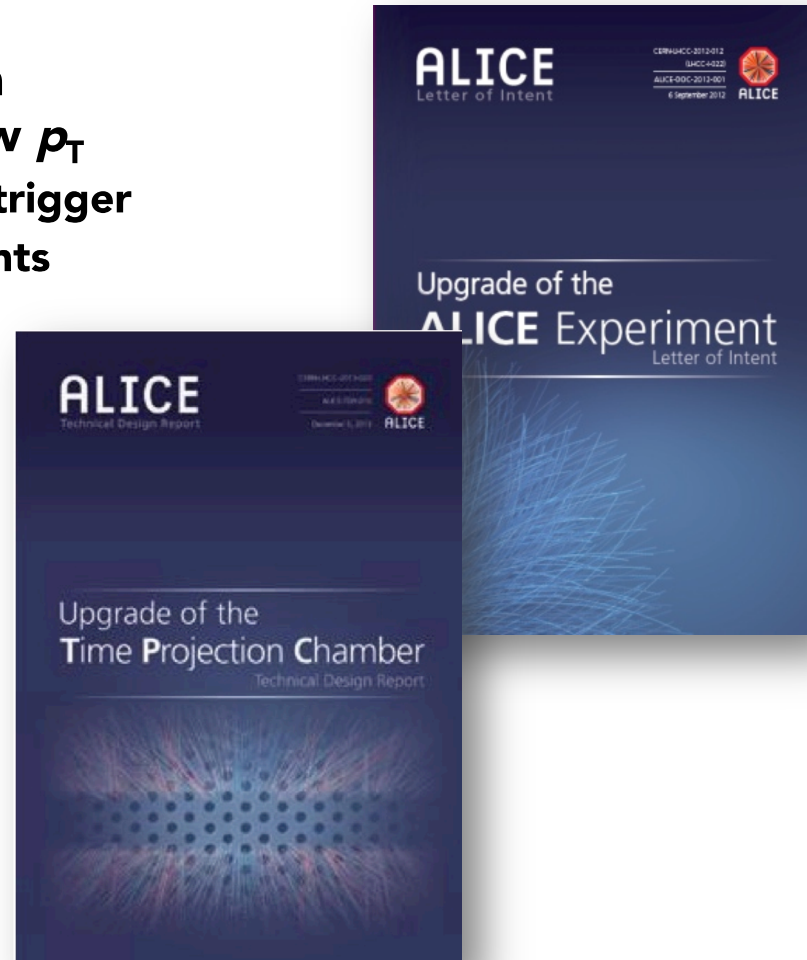
ALICE upgrade strategy (1)

- **Motivation:** Focus on high-precision measurements of rare probes at low p_T
  - can not be selected with hardware trigger
  - need to record large sample of events
- **Strategy:** Read out all Pb–Pb interactions at maximum interaction rate of 50 kHz
- **When:** 2^{nd} LHC Long Shutdown (LS2): 2018/19

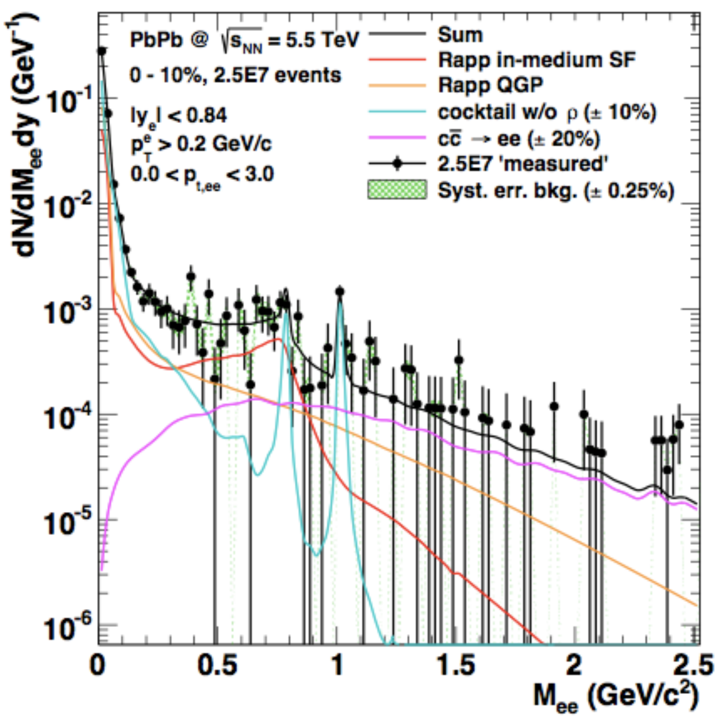


- ALICE Upgrade LOI: https://cds.cern.ch/record/1475243
- ALICE TPC Upgrade TDR: https://cds.cern.ch/record/1622286
- Addendum to the TPC TDR: https://cds.cern.ch/record/1984329

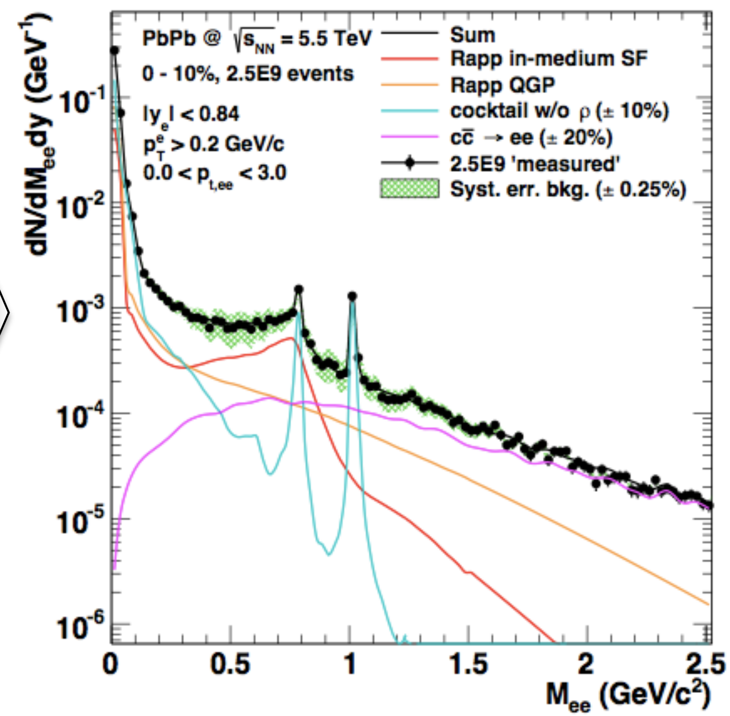
ALICE upgrade strategy (2)

– **Example: Low mass di-leptons**

Simulation: Current data rate

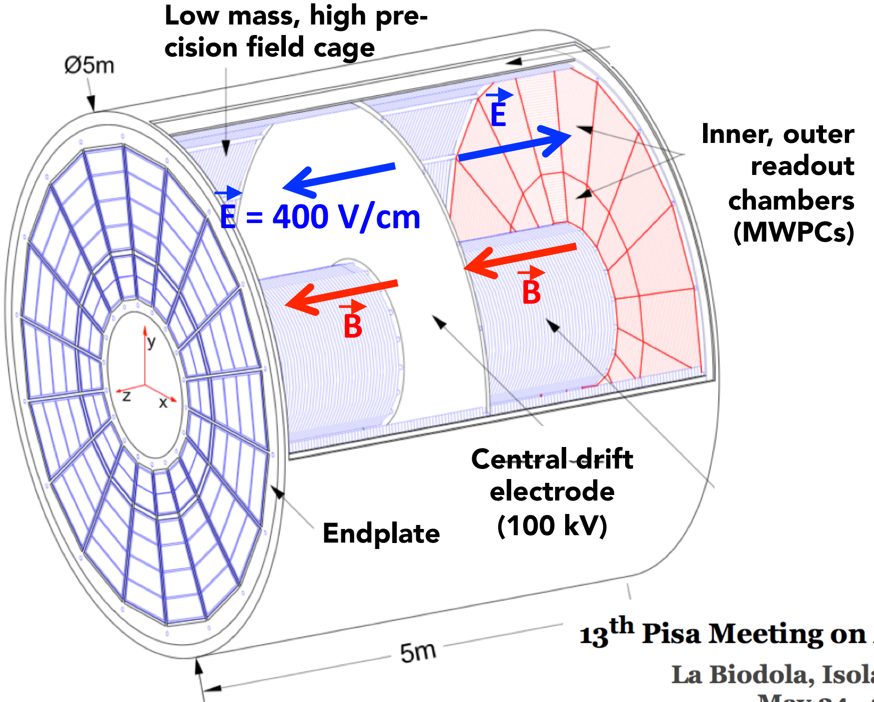


Simulation: Upgrade scenario



ALICE TPC overview (1)

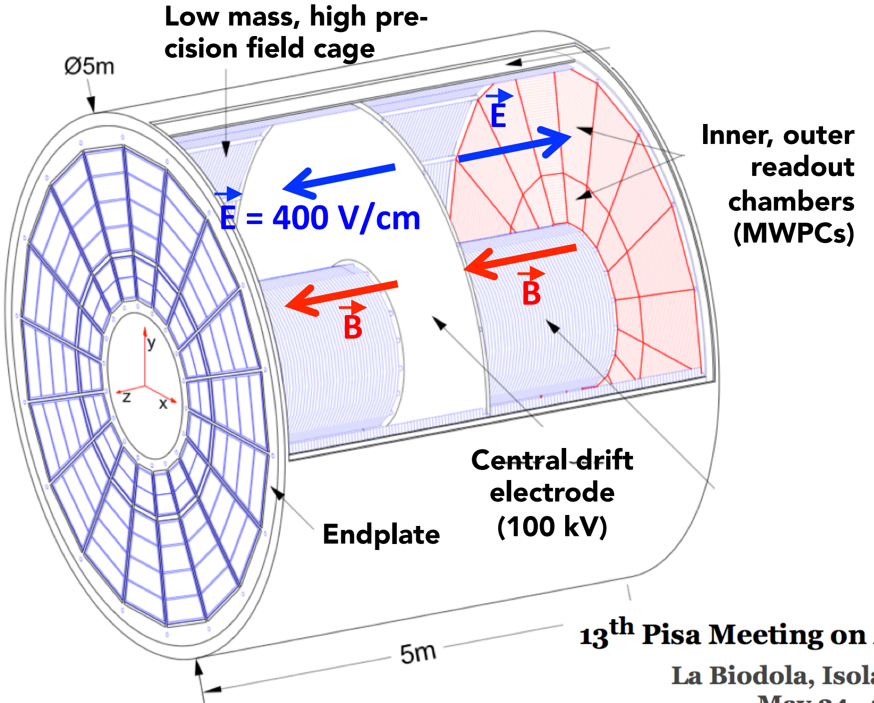
- Diameter: 5 m, length: 5 m
- Acceptance: $|\eta| < 0.9$, $\Delta\phi = 2\pi$
- Gas:
  - $Ne–CO_2(–N_2)$ 90–10(–5) in RUN1
  - $Ar–CO_2$ 90–10 in RUN2
- $v_d \approx 2.7$ cm/μs, max. drift time: 92 μs

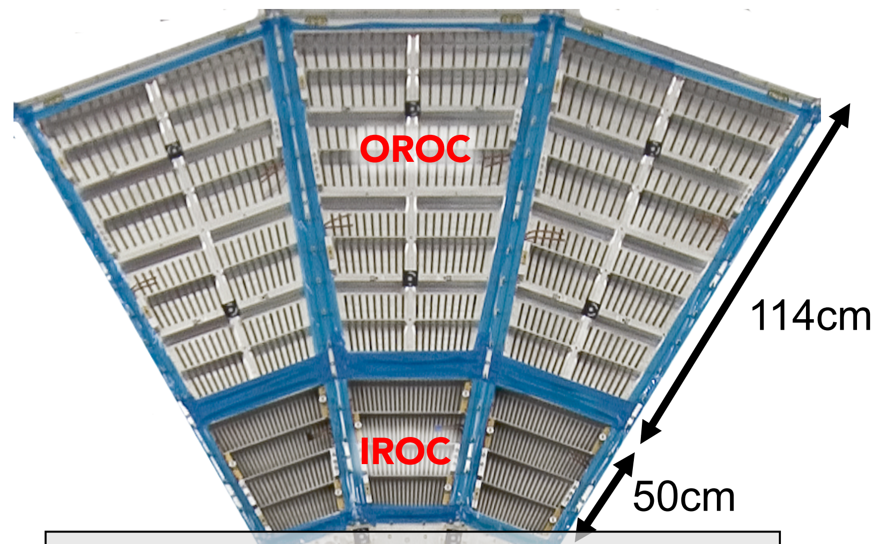


ALICE TPC overview (2)

- Diameter: 5 m, length: 5 m
- Acceptance: |η| < 0.9, Δϕ = 2π
- Gas:
  - $Ne–CO_2(–N_2)$ 90–10(–5) in RUN1
  - $Ar–CO_2$ 90–10 in RUN2
- $v_d \approx 2.7$ cm/μs, max. drift time: 92 μs

- Read-out Chambers: 2 x 18 × 2
  - outer (OROC) and inner (IROC)
- Current detector (RUN1):
  - 557 568 cathode pads (sizes: 4 × 7.5, 6 × 10, 6 × 15 mm^2)
  - MWPC, gated grid operation
  - Rate limitation: ~1 kHz

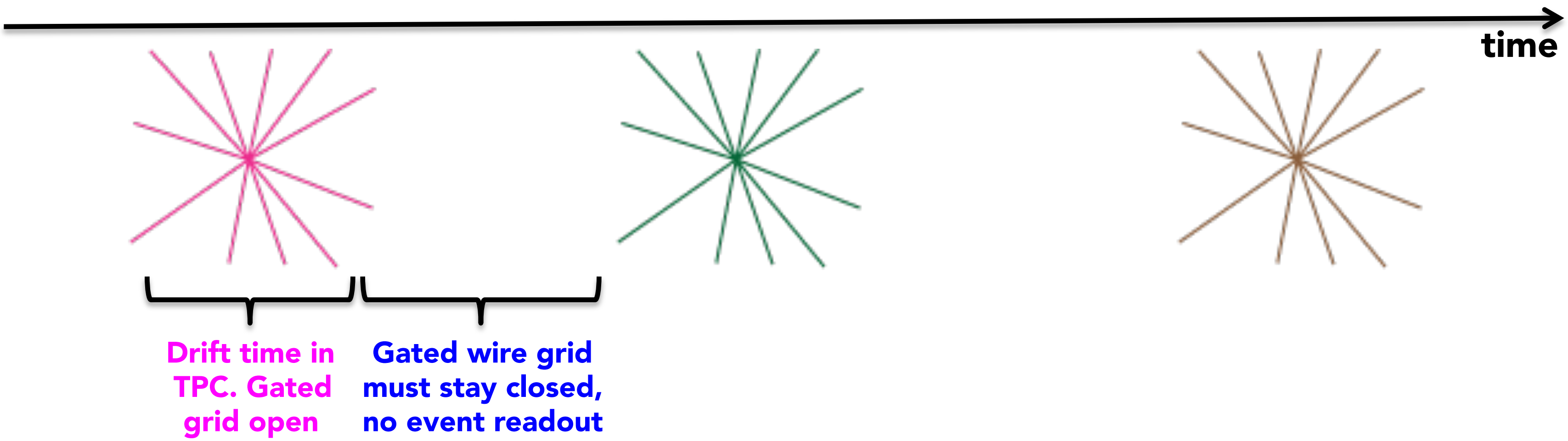




Read-out chambers arranged in sectors

Gated operation in RUN1

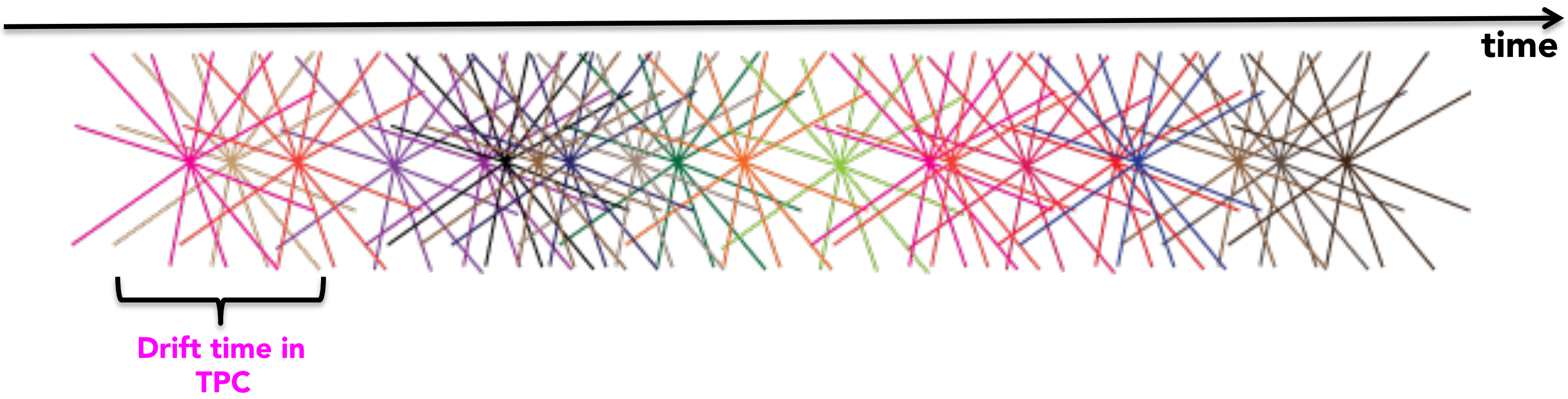
Typical data taking with TPC in RUN1: Low luminosity Pb-Pb collisions



- Triggered operation with gated grid (max rate: few kHz)
- Maximum drift time of electrons in TPC: ~ 100us
- Additional gated grid closure time: 180us (to minimize ion backflow and drift distortions)

Continuous operation in RUN3

Typical data taking with TPC in RUN3: High luminosity Pb-Pb collisions



- Maximum drift time of electrons in TPC: ~ 100us
- Average event spacing: ~20us

- Event pileup
- Triggered operation does not make sense
- Minimize ion backflow (IBF) in different way

→ Continuous read-out
Micro Pattern Gas Detectors

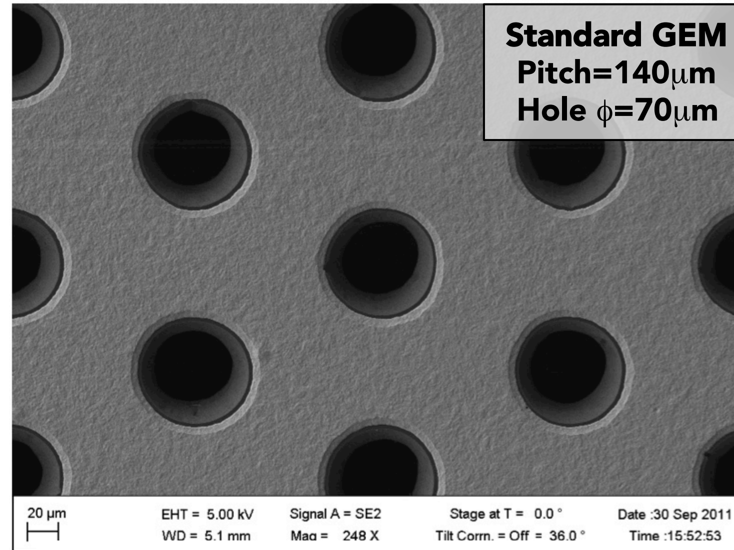
GEM read-out (1)

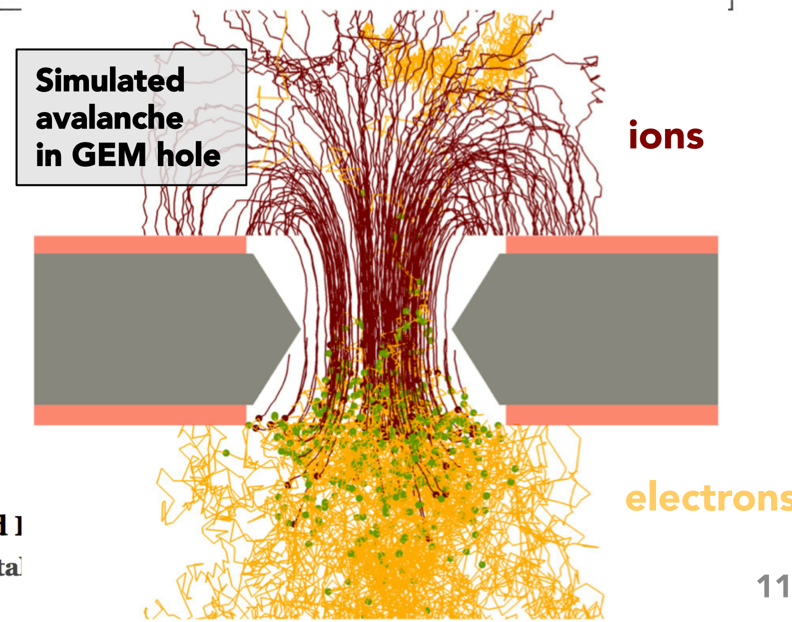
- Requirements for read-out system:
  - IBF < 1% at effective gas gain 2000
  - Local energy resolution <12% (σ) for ^{55}Fe
  - Stable operation under LHC condition

GEM read-out (2)

- **Requirements** for read-out system:
  - IBF < 1% at effective gas gain 2000
  - Local energy resolution <12% (σ) for ^{55}Fe
  - Stable operation under LHC condition

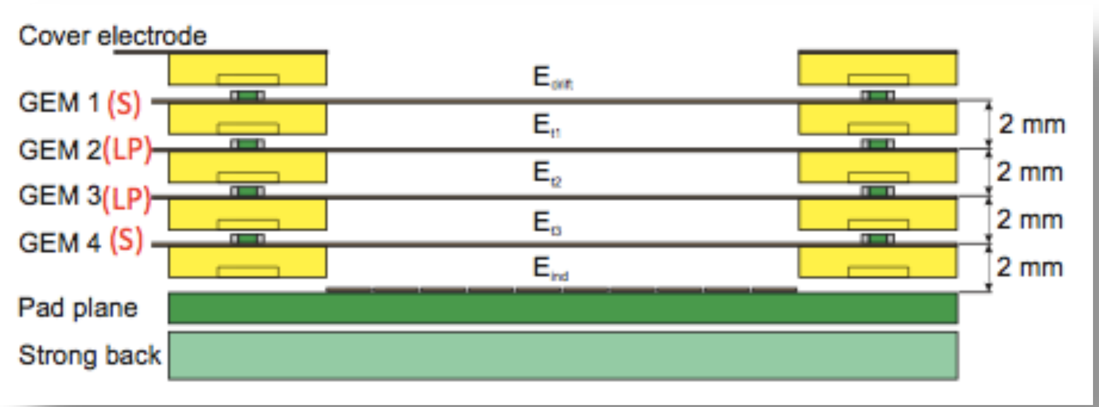
- **Implementation**:
  - Replace MWPC read- out system with GEMs
    - low ion backflow (IBF)
    - high rate capability
    - no ion tail
    - continuous read-out possible
  - Gas with fast ion drift: $Ne\text{-}CO_2$
  - New read-out electronics





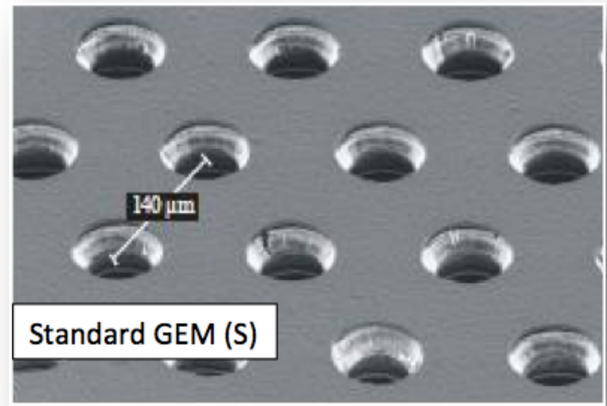
IBF optimized configuration (1)

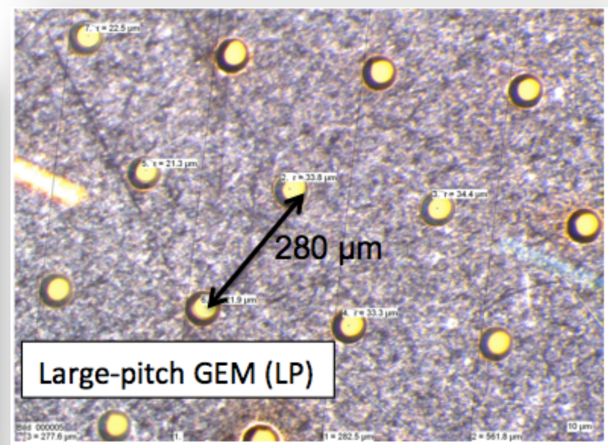
- Satisfactory performance could not be achieved with 3 GEM stack
- Best results in terms of IBF and energy resolution:
  - 4 GEM stack

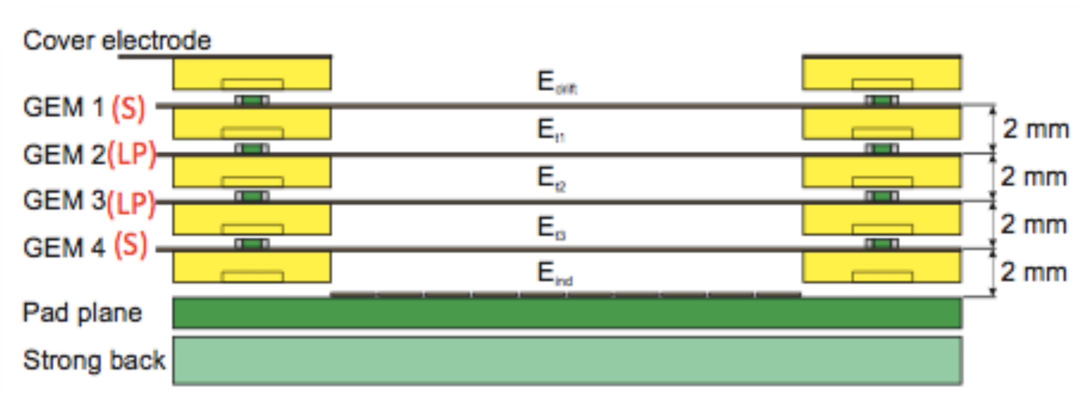


IBF optimized configuration (2)

- **Satisfactory performance could not be achieved with 3 GEM stack**
- **Best results in terms of IBF and energy resolution:**
  - **4 GEM stack**
  - **S-LP-LP-S configuration**
  - **S: standard GEM foils**
  - **LP: large hole pitch foils**
  - **Optimized V settings: V_{GEM}, E_T (transfer fields)**







IBF optimized configuration (3)

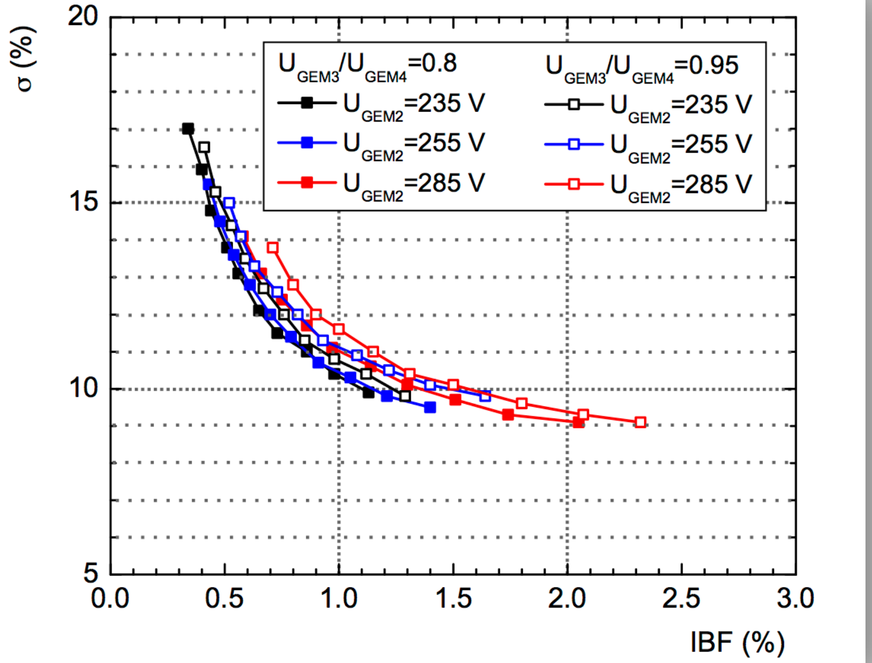
Drift Field			$= 0.4\,\mathrm{kV/cm}$
Potential at top of GEM 1		$= 3150\,\mathrm{V}$	
ΔU_{GEM1}	$= U_{1\mathrm{top}} - U_{1\mathrm{bot}}$	$= 270\,\mathrm{V}$	
Transfer Field 1 (E_{T1})	$= (U_{1\mathrm{bot}} - U_{2\mathrm{top}})/0.2\,\mathrm{cm}$		$= 4.0\,\mathrm{kV/cm}$
Potential at top of GEM 2		$= 2080\,\mathrm{V}$	
ΔU_{GEM2}	$= U_{2\mathrm{top}} - U_{2\mathrm{bot}}$	$= 250\,\mathrm{V}$	
Transfer Field 2 (E_{T2})	$= (U_{2\mathrm{bot}} - U_{3\mathrm{top}})/0.2\,\mathrm{cm}$		$= 2.0\,\mathrm{kV/cm}$
Potential at top of GEM 3		$= 1430\,\mathrm{V}$	
ΔU_{GEM3}	$= U_{3\mathrm{top}} - U_{3\mathrm{bot}}$	$= 270\,\mathrm{V}$	
Transfer Field 3 (E_{T3})	$= (U_{3\mathrm{bot}} - U_{4\mathrm{top}})/0.2\,\mathrm{cm}$		$= 0.1\,\mathrm{kV/cm}$
Potential at top of GEM 4		$= 1140\,\mathrm{V}$	
ΔU_{GEM4}	$= U_{4\mathrm{top}} - U_{4\mathrm{bot}}$	$= 340\,\mathrm{V}$	
Collection/Induction Field (E_{ind})	$= U_{4\mathrm{bot}}/0.2\,\mathrm{cm}$		$= 4.0\,\mathrm{kV/cm}$

- **IBF optimized settings:**
  - **high E_{T1} & E_{T2}**
  - **low E_{T3}**
  - **$V_{GEM1} \approx V_{GEM2} \approx V_{GEM3} < V_{GEM4}$**

IBF optimized configuration (4)

Drift Field				$= 0.4\,\mathrm{kV/cm}$
Potential at top of GEM 1			$= 3150\,\mathrm{V}$	
ΔU_{GEM1}	$= U_{1\mathrm{top}} - U_{1\mathrm{bot}}$	$= 270\,\mathrm{V}$		
Transfer Field 1 (E_{T1})	$= (U_{1\mathrm{bot}} - U_{2\mathrm{top}})/0.2\,\mathrm{cm}$			$= 4.0\,\mathrm{kV/cm}$
Potential at top of GEM 2			$= 2080\,\mathrm{V}$	
ΔU_{GEM2}	$= U_{2\mathrm{top}} - U_{2\mathrm{bot}}$	$= 250\,\mathrm{V}$		
Transfer Field 2 (E_{T2})	$= (U_{2\mathrm{bot}} - U_{3\mathrm{top}})/0.2\,\mathrm{cm}$			$= 2.0\,\mathrm{kV/cm}$
Potential at top of GEM 3			$= 1430\,\mathrm{V}$	
ΔU_{GEM3}	$= U_{3\mathrm{top}} - U_{3\mathrm{bot}}$	$= 270\,\mathrm{V}$		
Transfer Field 3 (E_{T3})	$= (U_{3\mathrm{bot}} - U_{4\mathrm{top}})/0.2\,\mathrm{cm}$			$= 0.1\,\mathrm{kV/cm}$
Potential at top of GEM 4			$= 1140\,\mathrm{V}$	
ΔU_{GEM4}	$= U_{4\mathrm{top}} - U_{4\mathrm{bot}}$	$= 340\,\mathrm{V}$		
Collection/Induction Field (E_{ind})	$= U_{4\mathrm{bot}}/0.2\,\mathrm{cm}$			$= 4.0\,\mathrm{kV/cm}$

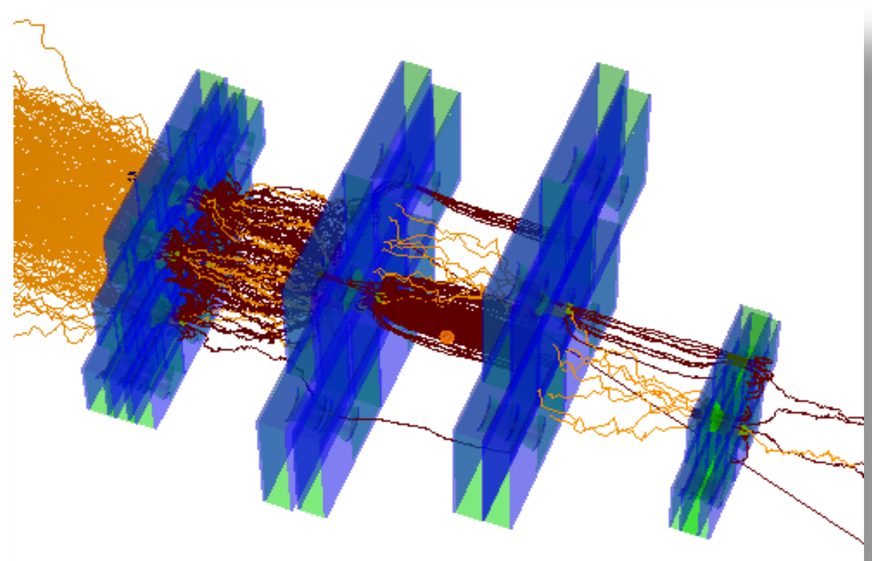
- **IBF optimized settings:**
  - **high E_{T1} & E_{T2}**
  - **low E_{T3}**
  - **$V_{GEM1} \approx V_{GEM2} \approx V_{GEM3} < V_{GEM4}$**



- **Achieved performance:**
  - **0.63 % IBF at σ(5.9 keV) ≈ 11.3 %**
- **Typical voltage settings are shown above (eff. gas gain is always 2000)**

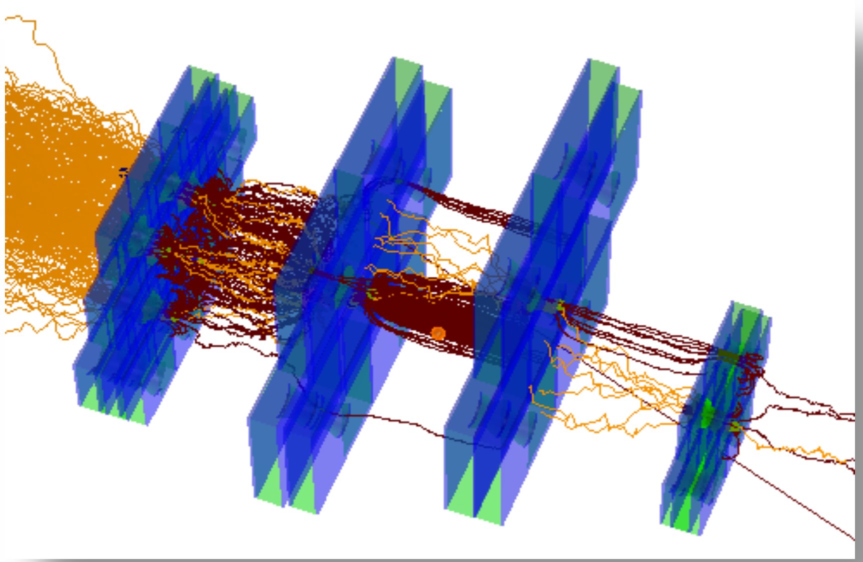
IBF optimized configuration (3)

- **Electron transport properties for IBF optimized voltage settings**
- ε_{coll} = collection efficiency
- ε_{extr} = extraction efficiency



	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%)		

IBF optimized configuration (4)



- **Electron transport properties for IBF optimized voltage settings**
- **ε_{coll} = collection efficiency**
- **ε_{extr} = extraction efficiency**
- ***M* = gas multiplication factor**
- ***G* = $\varepsilon_{coll} \times M \times \varepsilon_{extr}$ = effective gain**

	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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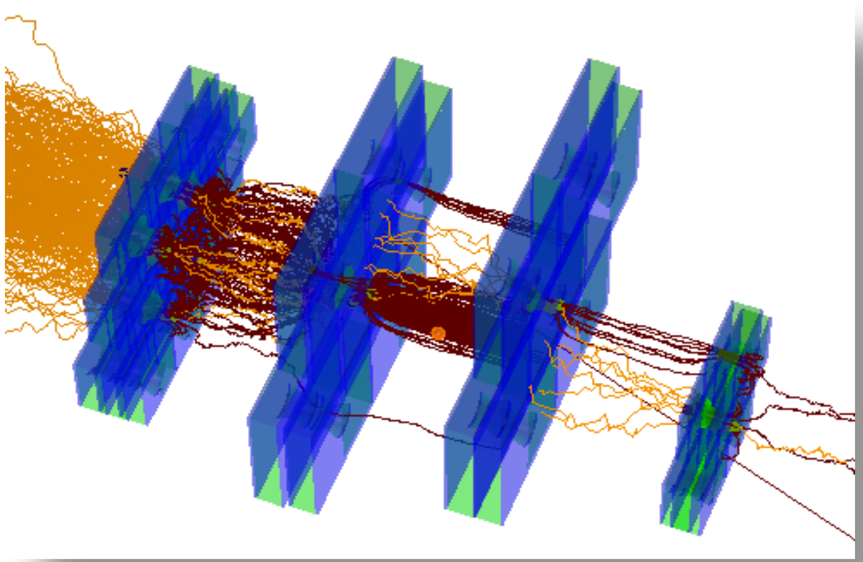
Total				3183		1830	1830	9 (0.28%)		

IBF optimized configuration (5)

- **Electron transport properties for IBF optimized voltage settings**

- ε_{coll} **= collection efficiency**
- ε_{extr} **= extraction efficiency**
- M **= gas multiplication factor**
- $G = \varepsilon_{coll} \times M \times \varepsilon_{extr}$ **= effective gain**
- $n_{e\text{-}ion}$ **= number of produced e-ions pairs**



	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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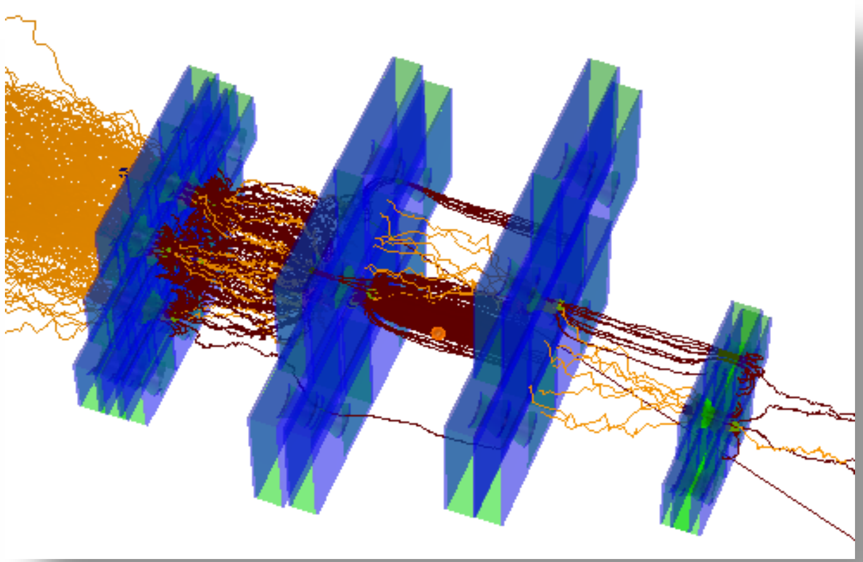
GEM4 (S)	1	12.7	240	3053	0.6	1830	144	0.84 (0.03%)	9%	24%
Total				3183		1830	1830	9 (0.28%)		

IBF optimized configuration (6)

- **Electron transport properties for IBF optimized voltage settings**

- **ε_{coll} = collection efficiency**
- **ε_{extr} = extraction efficiency**
- **M = gas multiplication factor**
- **$G = \varepsilon_{coll} \times M \times \varepsilon_{extr}$ = effective gain**
- **$n_{e\text{-}ion}$ = number of produced e-ions pairs**
- **$n_{ion,back}$ = number of ions drifting back into the drift volume**



	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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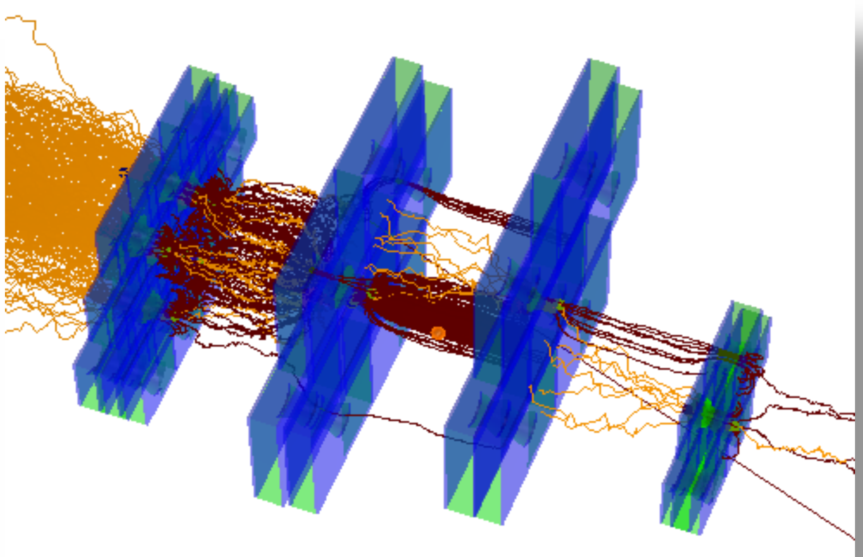
GEM4 (S)	1	12.7	240	3053	0.6	1830	144	0.84 (0.03%)	9%	24%
Total				3183		1830	1830	9 (0.28%)		

IBF optimized configuration (7)

- **Electron transport properties for IBF optimized voltage settings**

- ε_{coll} = **collection efficiency**
- ε_{extr} = **extraction efficiency**
- M = **gas multiplication factor**
- $G = \varepsilon_{coll} \times M \times \varepsilon_{extr}$ = **effective gain**
- $n_{e\text{-}ion}$ = **number of produced e-ions pairs**
- $n_{ion,back}$ = **number of ions drifting back into the drift volume**



	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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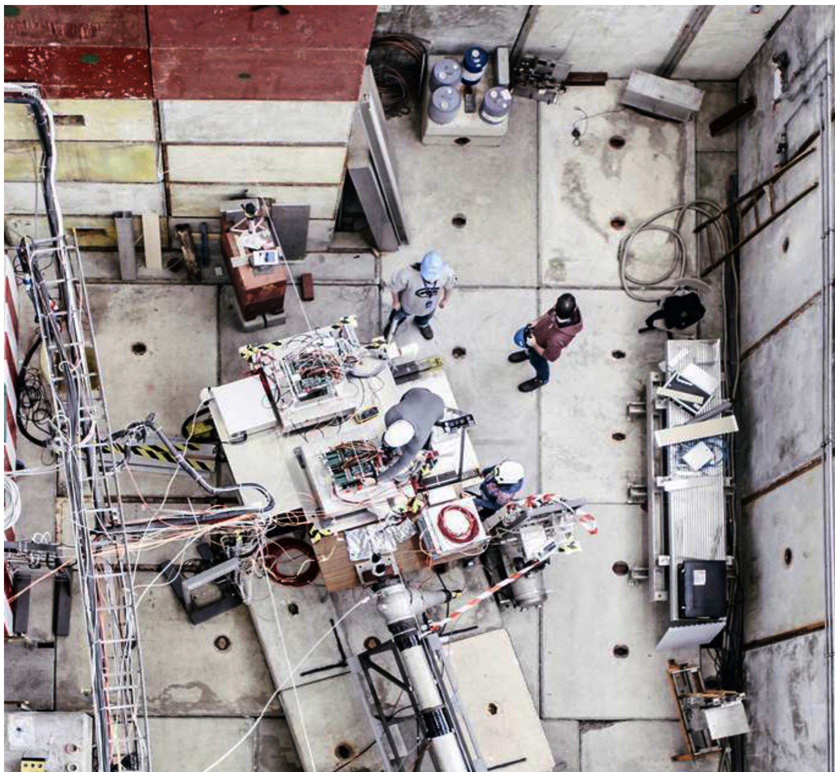
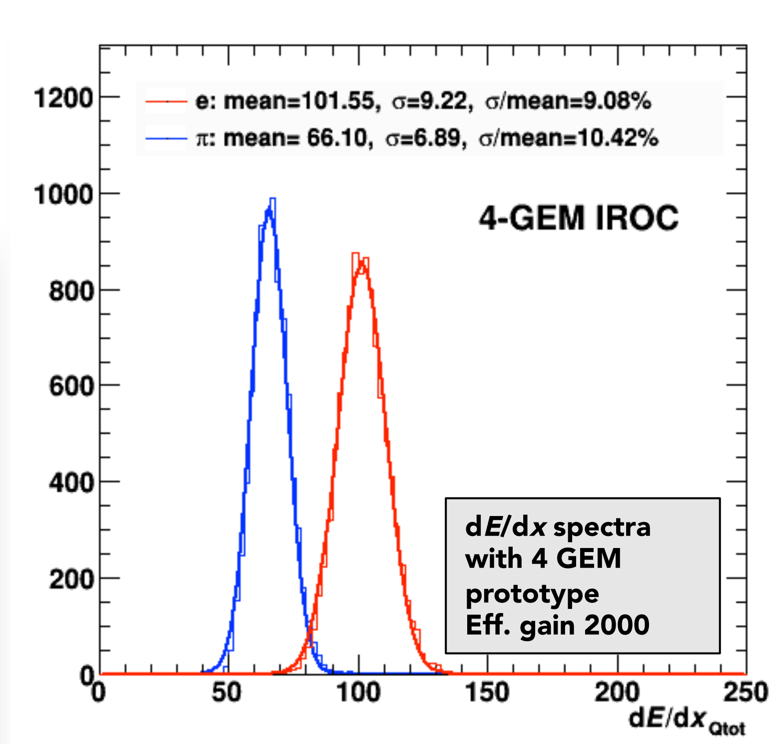
GEM4 (S)	1	12.7	240	3053	0.6	1830	144	0.84 (0.03%)	9%	24%
Total				3183		1830	1830	9 (0.28%)		

Prototype beam tests: PID

- 4GEM IROC prototype tests: d*E*/d*x* resolution measurements at CERN PS

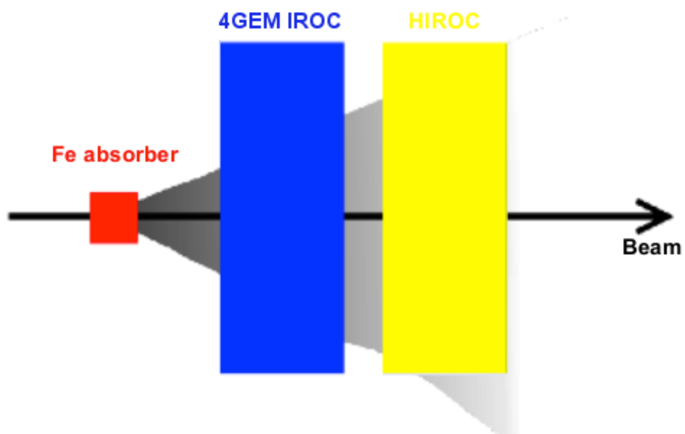


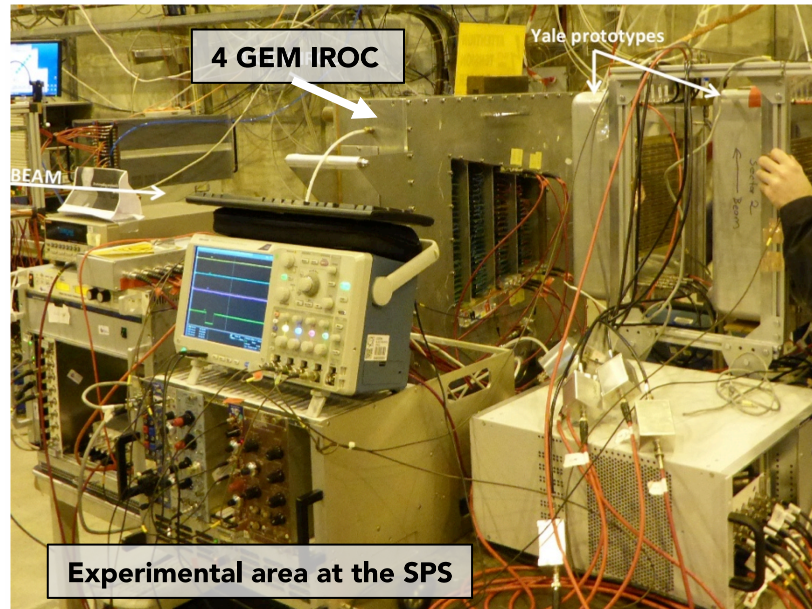


– Excellent d*E*/d*x* resolution: ~10% (IROC only)
– Performance equal to existing MWPC IROCs

Prototype beam tests: Stability

- **Discharge tests at CERN SPS**

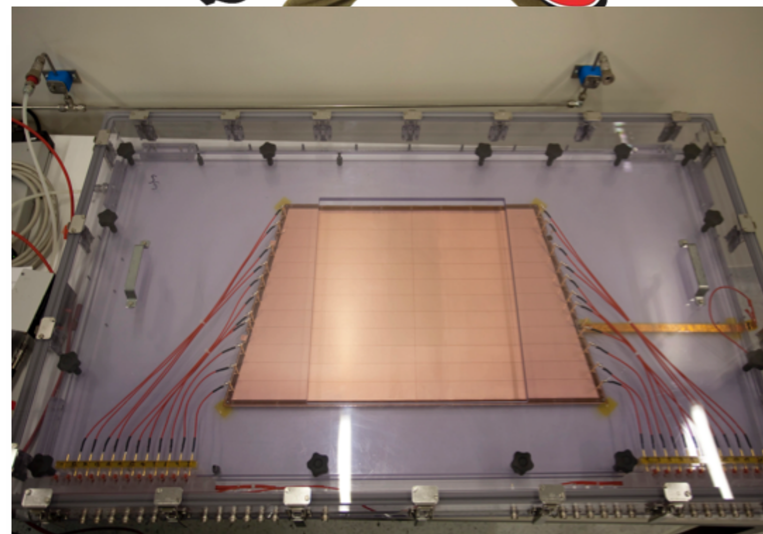


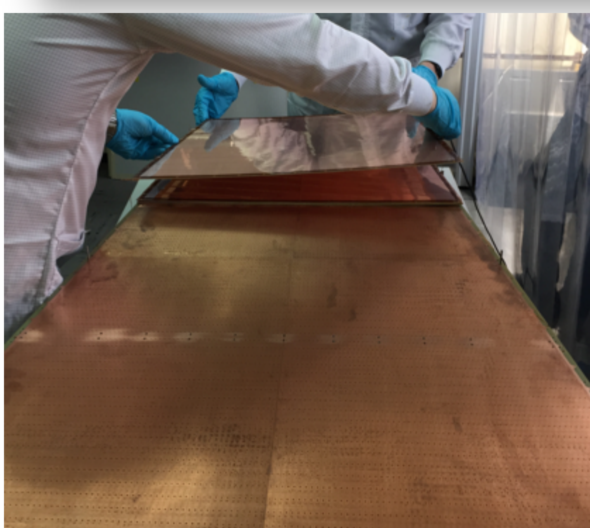


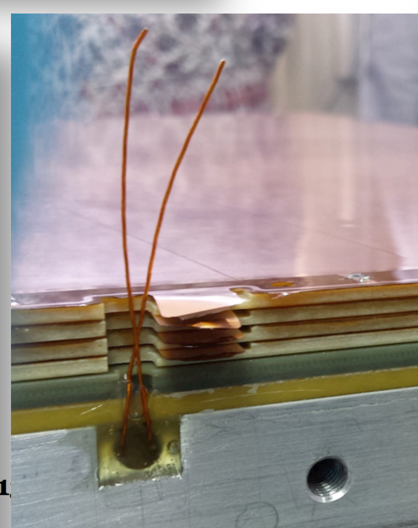
- **Discharge probability: $(6.4\pm3.7)\times10^{-12}$ per hadron**
- **Additional lab measurements with α and β particles**
- **Performance similar to standard triple GEMs**
- **Odd voltage settings compensated by addition of 4th GEM foil**
- **Expected number of discharges in full TPC per typical yearly heavy-ion run at 50 kHz**
  - **4.5 discharges per GEM stack, 650 discharges for the whole TPC**
  - **Not expected to create any damage to the GEM detectors**

School Of ROC

- 2015: **First OROC prototype** built, all institutes that will be involved in the ROC mass production took part
- Largest GEM detector built so far!



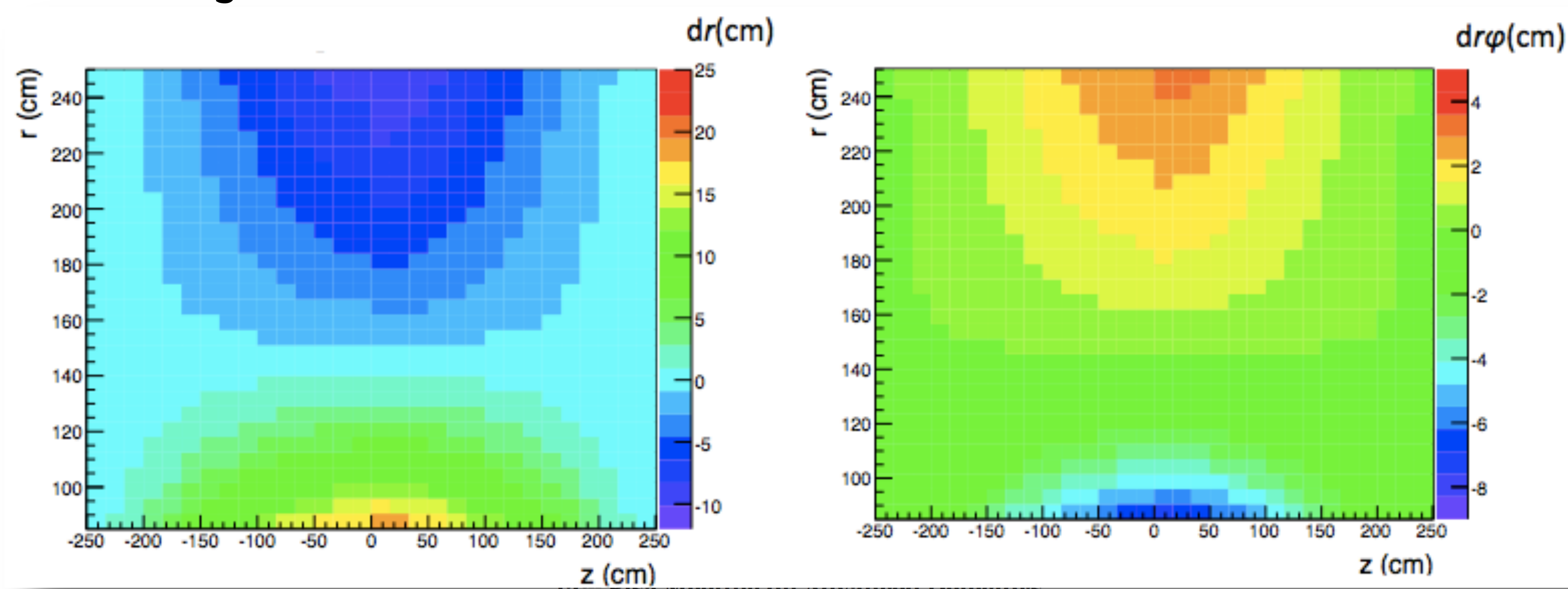




May 24 - 30, 2015

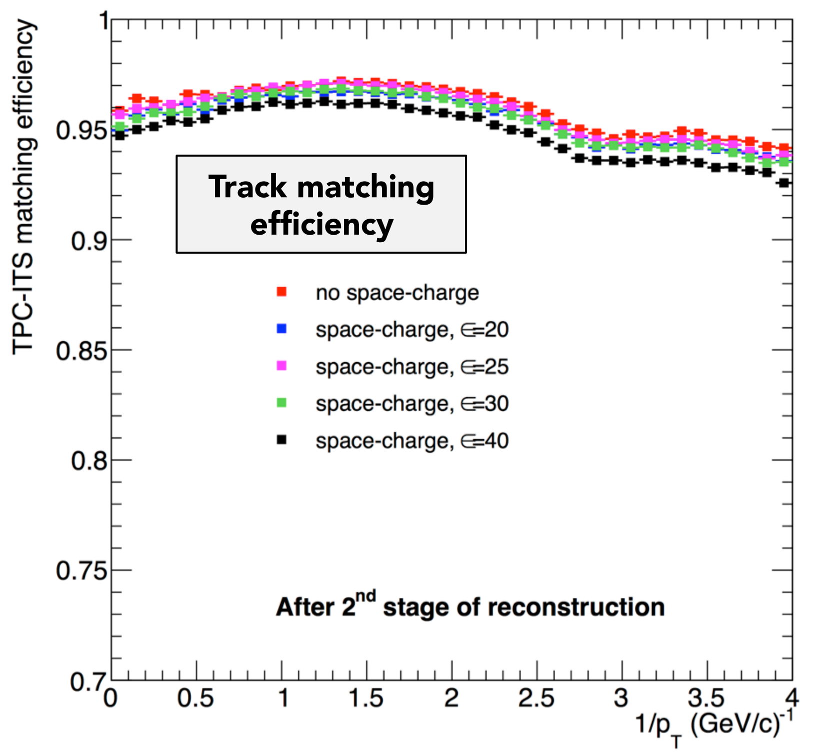
Space charge distortions

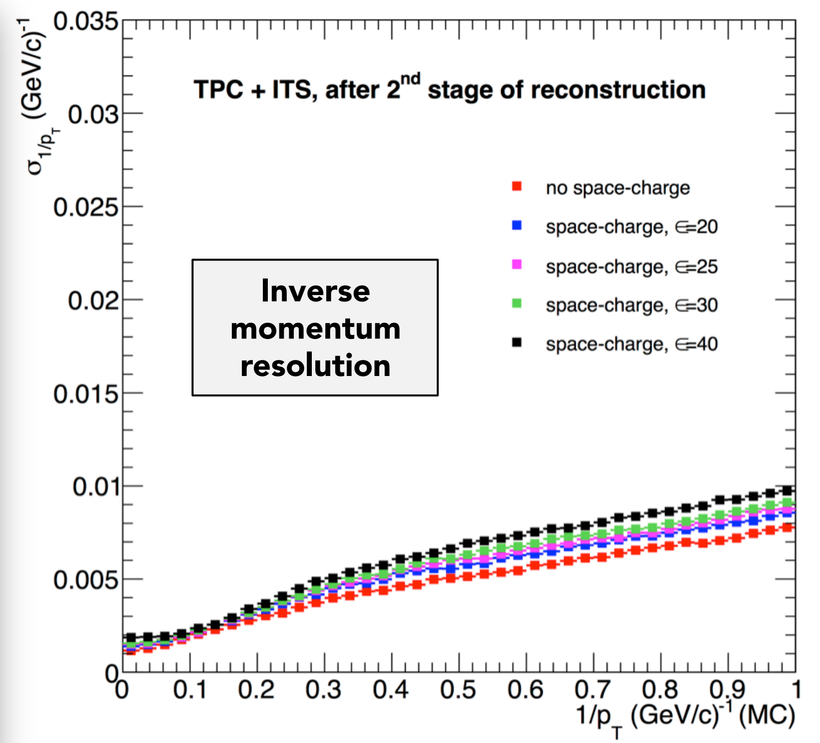
- See poster by M. Ljunggren (Performance simulation studies for the ALICE TPC GEM Upgrade)
- Even with required IBF = 1% there will still be considerable space charge!
  - For 50kHz Pb-Pb collisions ion pile-up from on average 8000 events (t_{ion}=160ms)
- Expect distortions on the cm level
- Corrections to few 10^{-3} to achieve final resolution ($\sigma(r\phi) \approx 200$ µm)
- 2 stage calibration and reconstruction scheme



Expected performance (1)

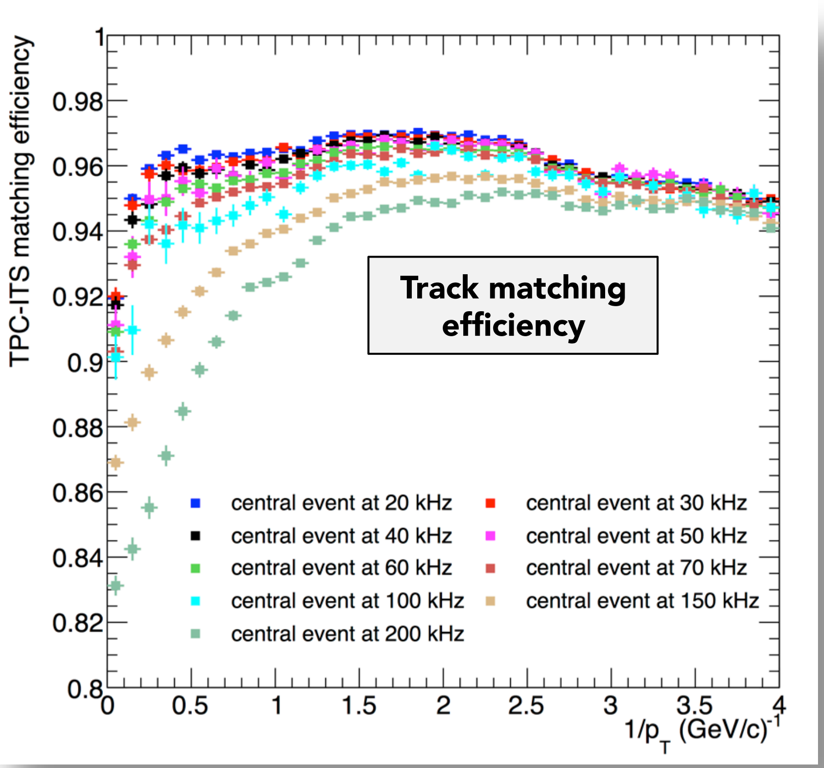
- See poster by M. Ljunggren (Performance simulation studies for the ALICE TPC GEM Upgrade)
- Influence of space charge distortions: Track matching efficiency and transverse momentum resolution are retained up to twice the design IBF (2%; ε=40)

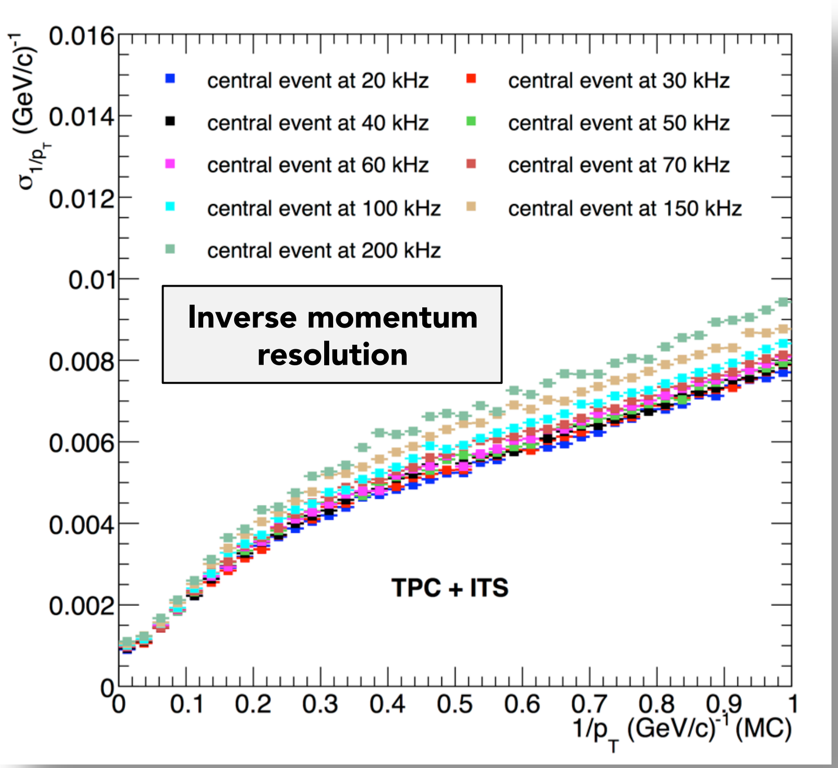




Expected performance (2)

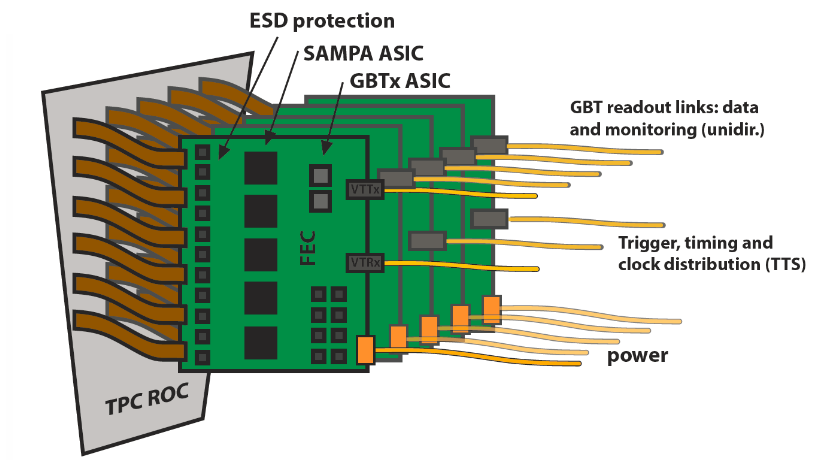
- **Influence of track density: Track matching efficiency and transverse momentum resolution deteriorate only for interaction rates >100 kHz (design 50 kHz)**

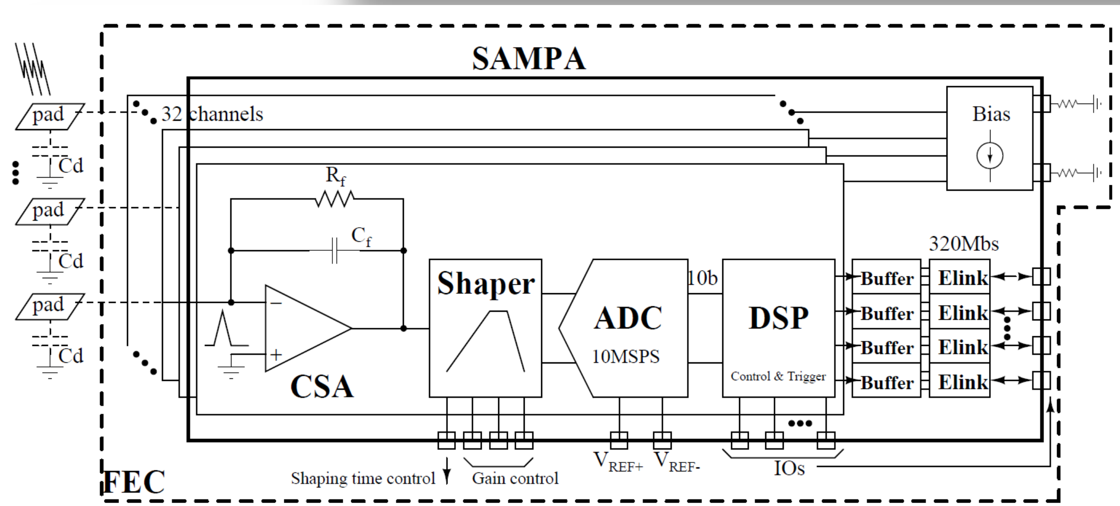




Front-end Electronics

- New FE ASIC: SAMPA
  - Continuous or triggered read-out
  - Positive or negative input
  - Programmable conversion gains and peaking times
- Digital filters for baseline correction (common mode effect in GEM ROCs)
- Aim for a system noise of 670 e$^-$ as currently achieved
- Use CERN–developed GBT and Versatile Link components for read-out (radiation hard)
- Average data output for 50 kHz Pb–Pb collisions: 1 Tbyte/s





Summary and outlook

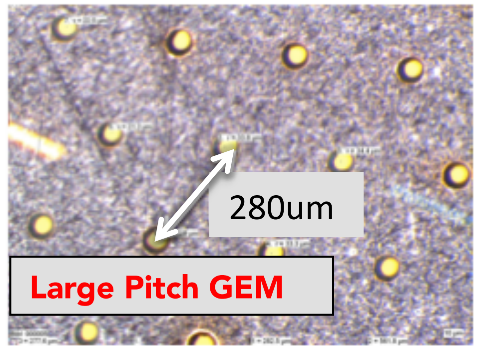
- Major upgrade of the ALICE experiment for installation in 2018/19
- Continuous TPC read-out to inspect 50 kHz Pb-Pb collisions
- New read-out chambers based on 4 GEM stacks
- Required ion backflow, energy resolution and stability achieved
- New electronics for continuous read-out
- 2-stage reconstruction scheme able to retain physics performance
- Technical Design Report endorsed
- Successfully tested ROC prototypes

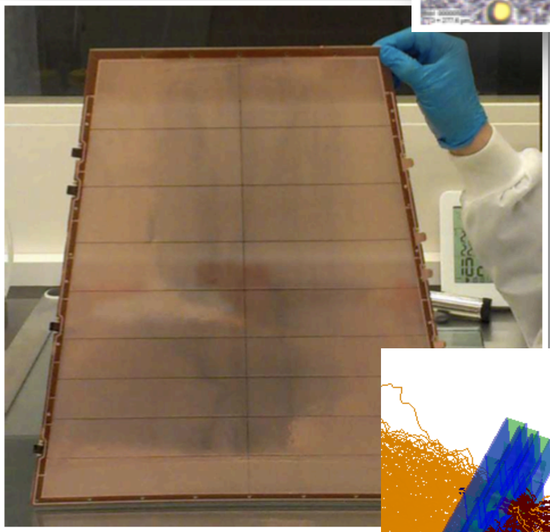
- GEM foil production starts in August
- ROC assembly starts next year

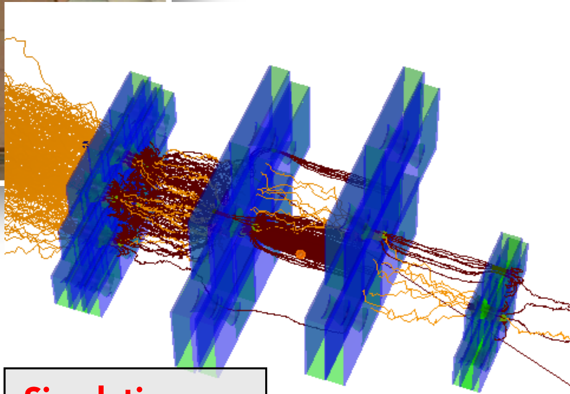
More slides

TPC upgrade R&D program

- **Extensive studies started in 2012**
  1. characterization of 3 or 4-GEM configurations and of other MPGD technologies
  2. technology choice
  3. optimisation of operational voltages and IBF suppression
  4. gain stability
  5. discharge probability
  6. large-size prototypes, single mask technology
  7. electronics R&D
  8. Garfield++ simulations
  9. physics and performance simulations: Remaining drift-field distortions must be calibrated
- **Collaboration with RD51 at CERN**

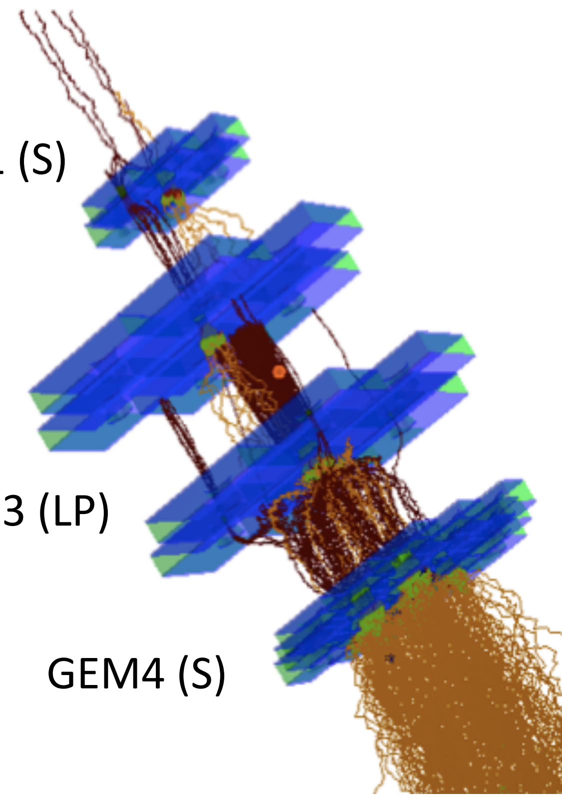


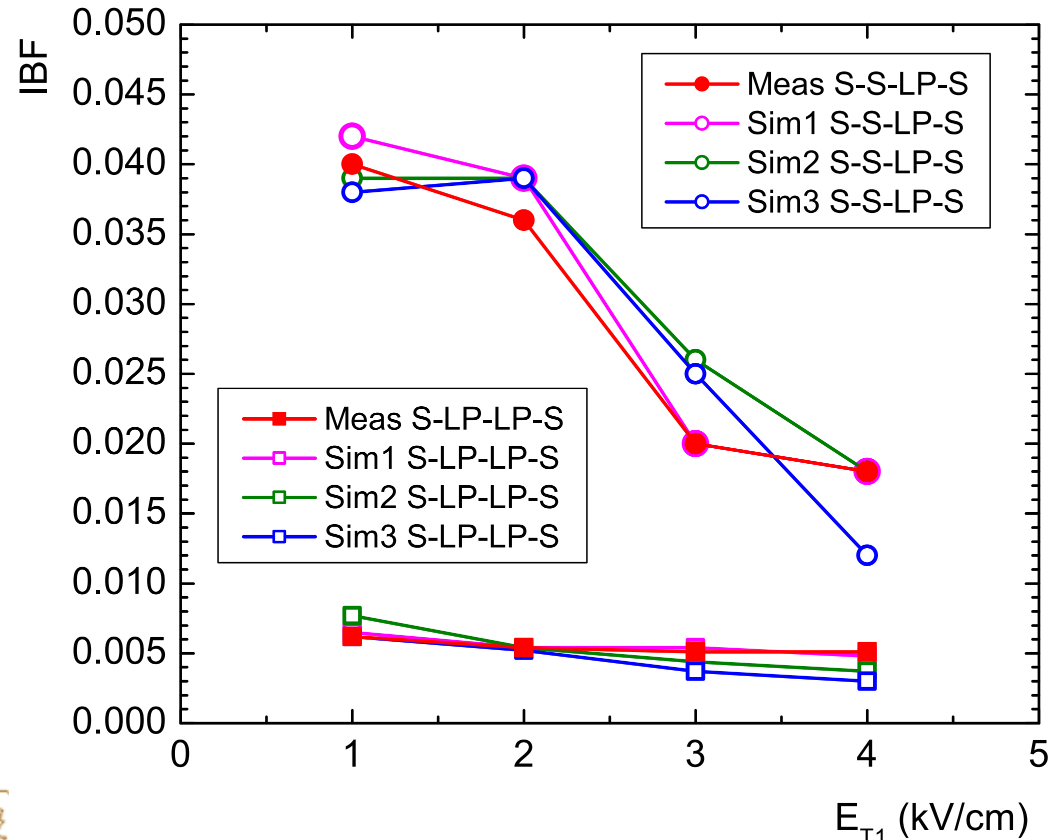




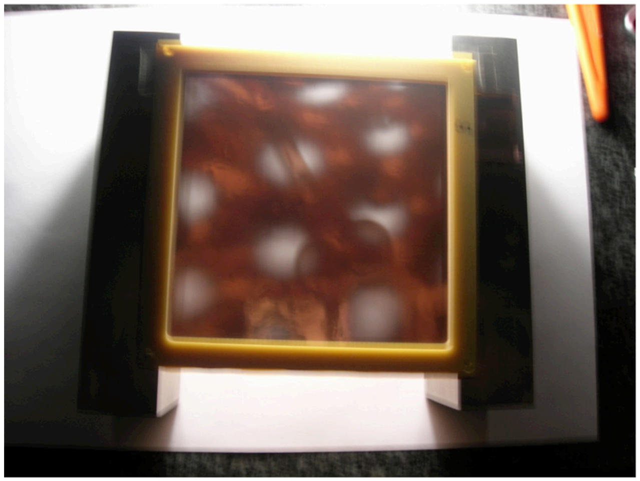
TPC: Garfield Simulations

- Garfield++/Magboltz simulations for different 4GEM setups (S-LP-LP-S)
  - Field calculation by ANSYS
  - IBF quantitatively well described by simulations using Garfield++

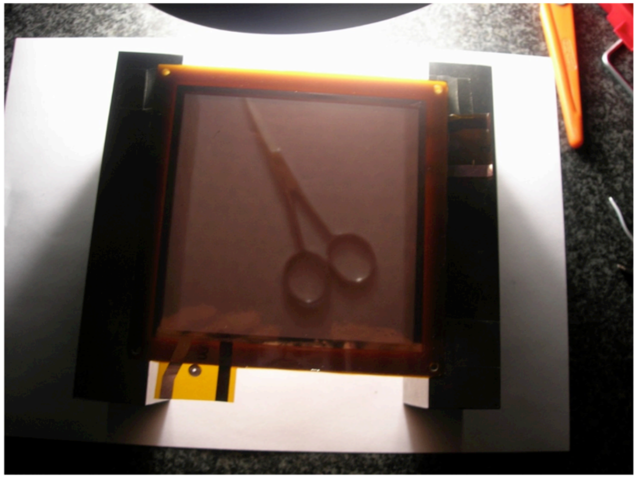


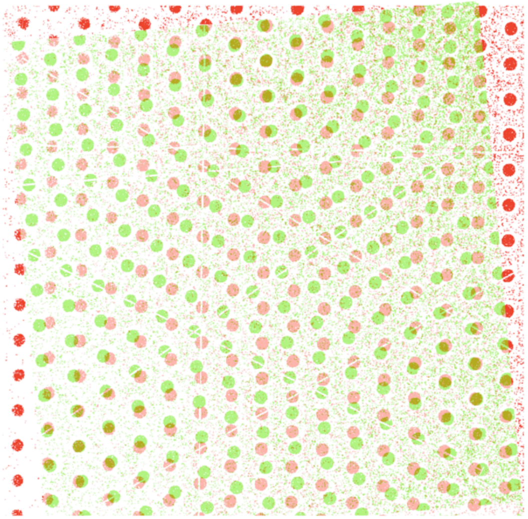


Alignment (1)



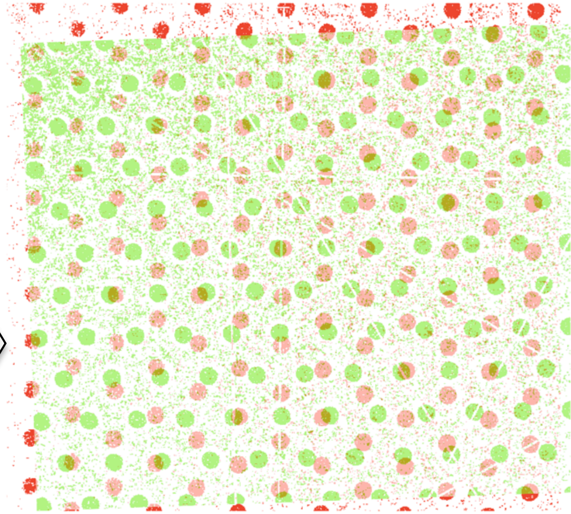
The IBF is related to hole alignment and thus optical transparency



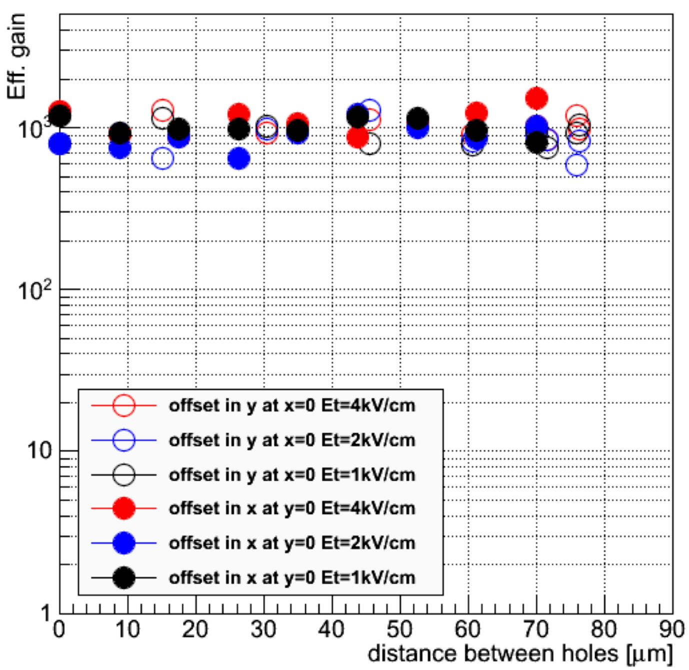


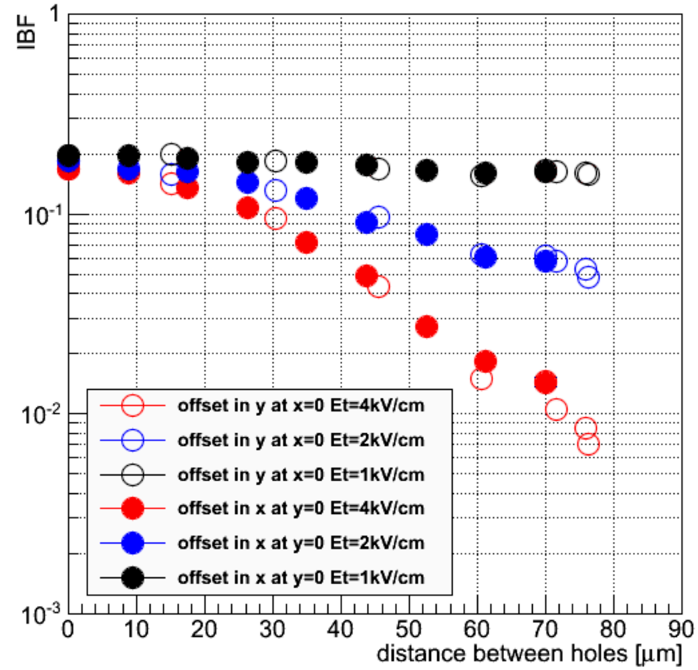
Effect of slight rotation of foils

Randomization of the relative hole positions after rotation of one foil by 90°



Alignment (2)

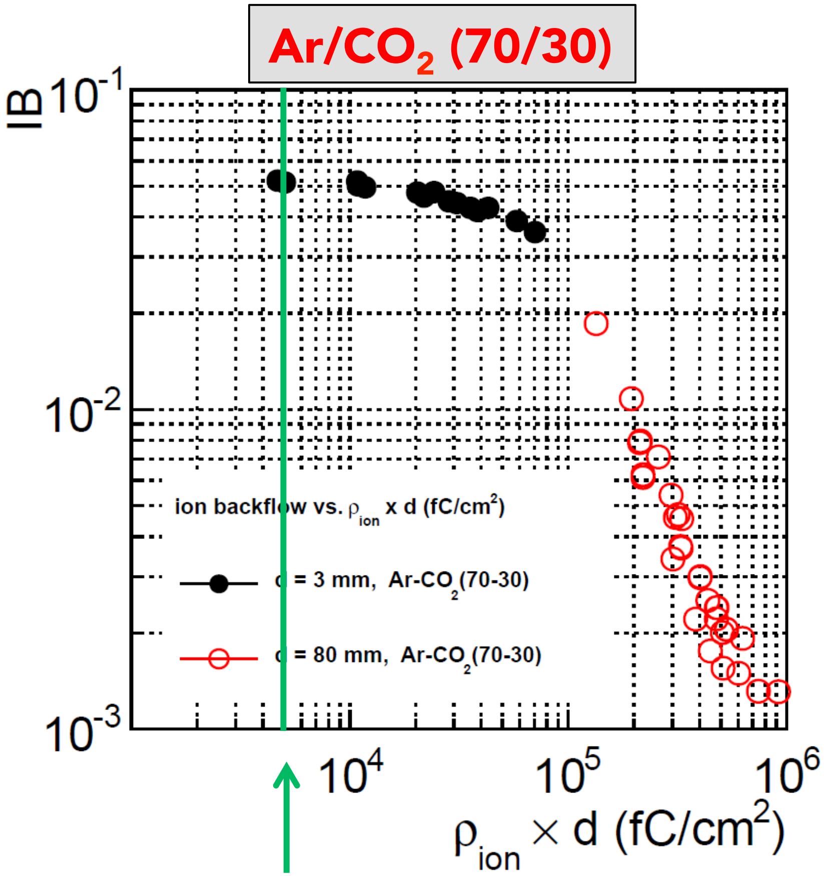




- **Garfield++ simulation: Gas gain (left) and ion backflow (right) in a double GEM system vs GEM hole offset between the two layer**

Need random misalignment between holes → turn foils by 90°

TPC: IBF – Rate Dependence



Expected after LS2: 5000 fC/cm²

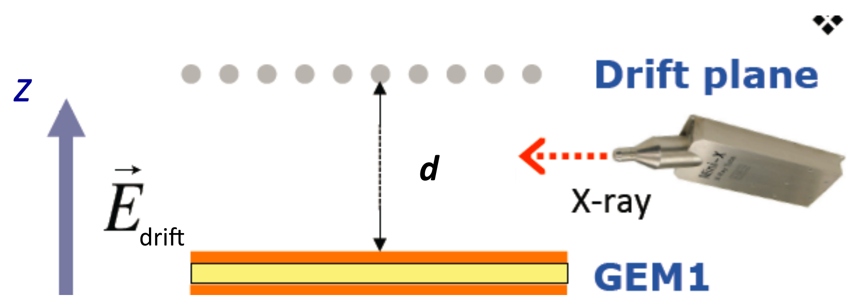
Poisson equation:

$$\Delta\varphi(\boldsymbol{r}) = -\frac{\rho(\boldsymbol{r})}{\varepsilon\varepsilon_0}$$

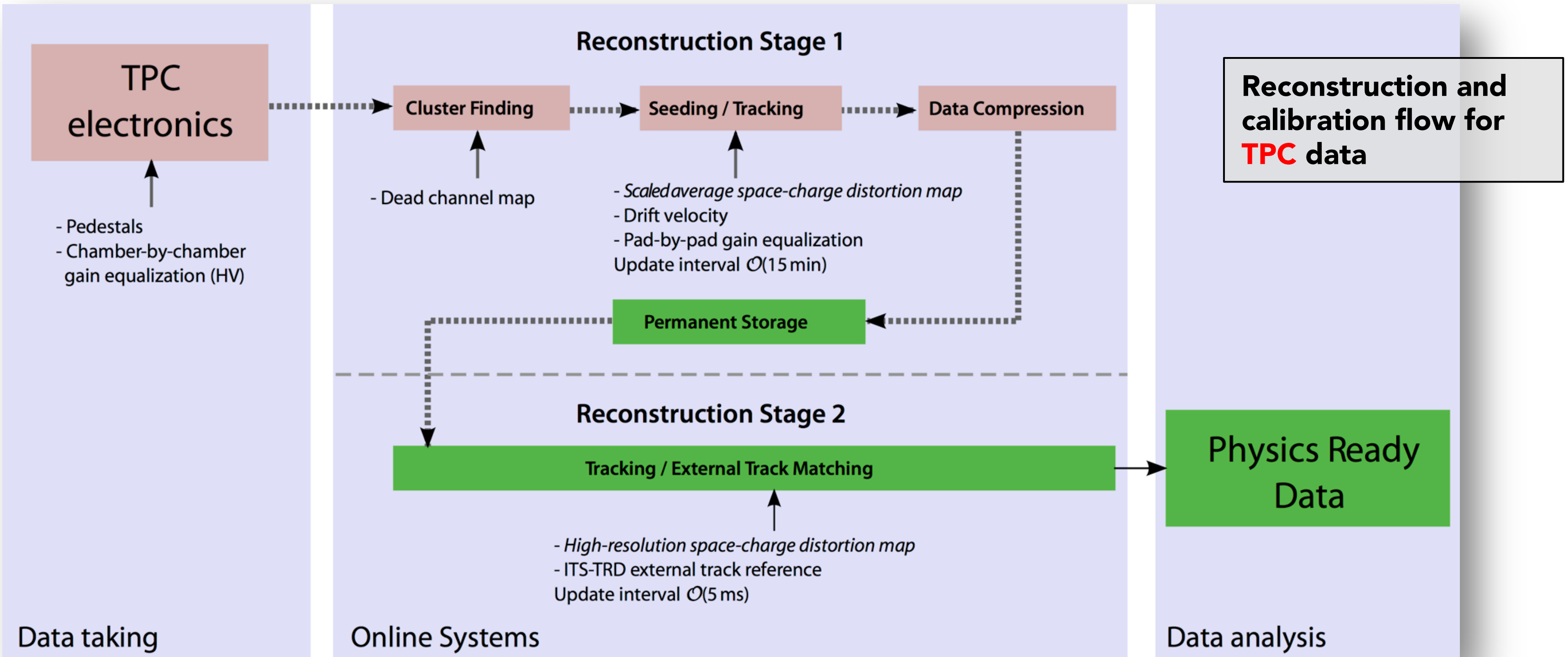
For homogenous space charge density and parallel plate boundary conditions:

$$E(z) = E_{\text{drift}} - \frac{\rho d}{2\varepsilon\varepsilon_0} + \frac{\rho z}{\varepsilon\varepsilon_0}$$

$z \ll d$



Run3 reconstruction scheme



- **Two stage reconstruction scheme**
  1. **Cluster finding and cluster-to-track association in the TPC**
     - **data compression by factor 20 : 1 TB/s → 50 GB/s**
     - **use scaled average space-charge distortion map**
  2. **Full tracking with matching to inner and outer detectors (ITS and TRD)**
     - **full space-charge distortion calibration**
     - **use high resolution space-charge map (time interval ~5 ms)**

Front-end Electronics

- **FE parameters for current ALICE TPC FEE and for SAMPA (upgrade)**

		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 $6\times10\,\mathrm{mm}^2$ pads)		20:1	30:1
(OROC $6\times15\,\mathrm{mm}^2$ pads)		28:1	30:1
MIP signal	(fC)	1.5 – 3[14]	2.4 – 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