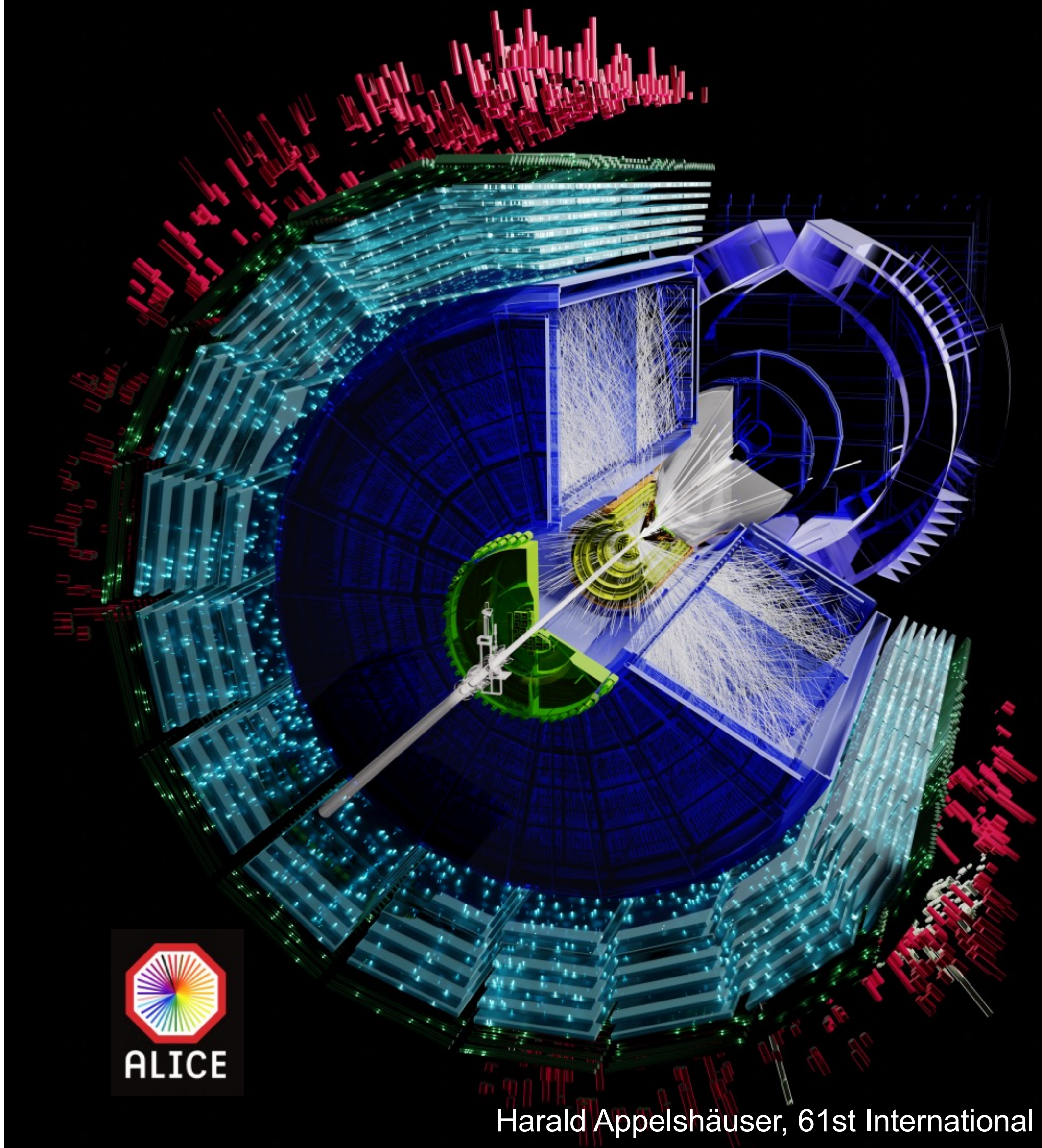


The Upgrade of the ALICE TPC

When pictures learned to walk

Harald Appelshäuser

Goethe University Frankfurt

ALICE Coll., JINST 19 (2024) P05062
ALICE TPC Coll., JINST 16 (2021) 03

1974 – The Time-Projector Detector

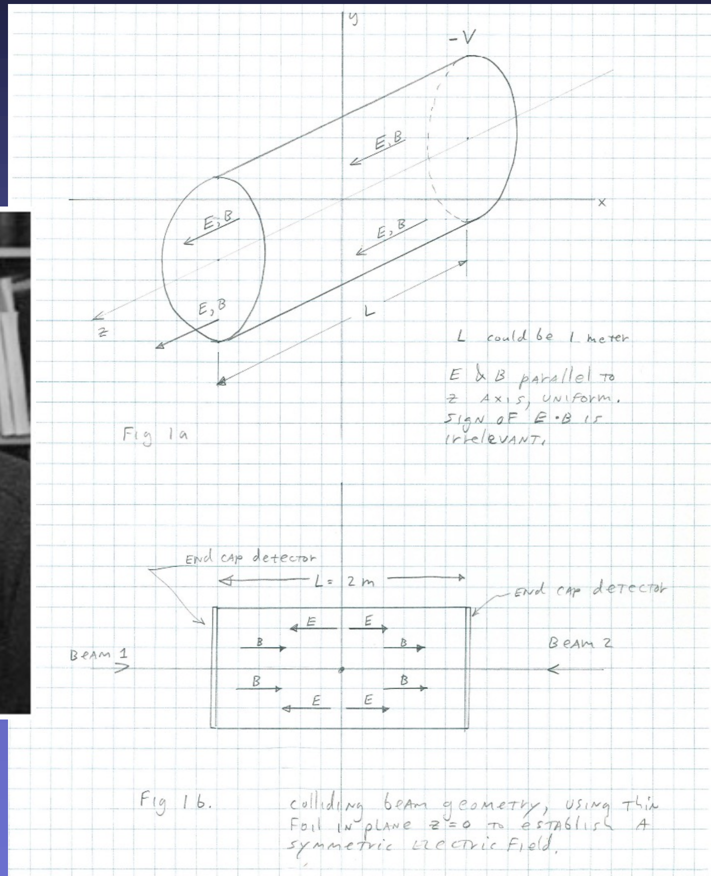
2 - 22 -74

PROPOSAL TO INVESTIGATE THE FEASIBILITY OF A
NOVEL CONCEPT IN PARTICLE DETECTION

David R. Nygren

Abstract

A new approach to the problem of high energy particle detection is described, in which parallel electric and magnetic fields are employed. It appears that a particular regime of operating conditions will allow a very substantial suppression of diffusion transverse to the fields in a suitably prepared drift chamber. If the more optimistic estimates are in fact achievable, single track-segment measurement errors of only a few tens of microns in a volume $\sim 1\ m^3$ should be feasible. Additional benefits are the possibilities of unambiguous spatial reconstruction, as well as high data rate capability, high multitrack efficiency, and easy applicability to 4π geometry. A program is outlined which is designed to gain further experience with the concept, provide needed data about electronic diffusion within various gas/field environments, and hopefully lead to practical detectors.



1975

1985

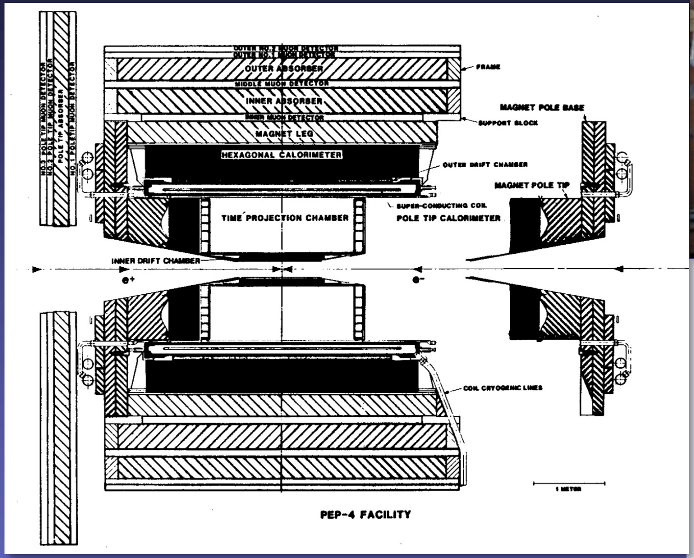
1995

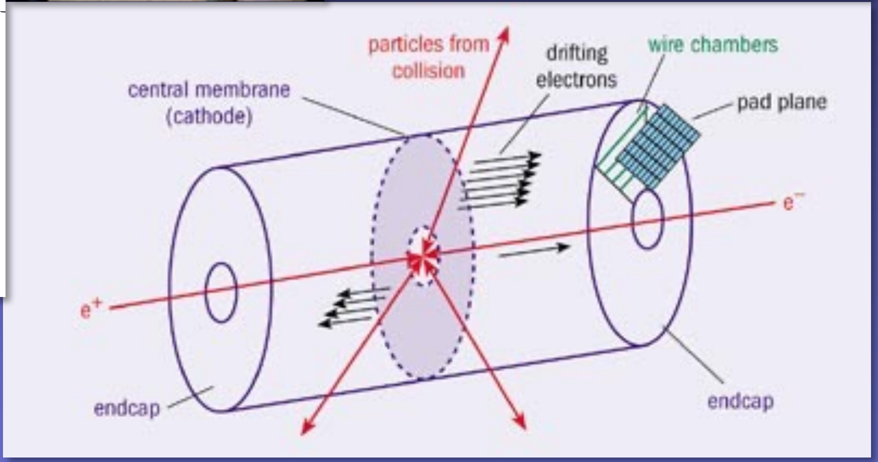
2005

2015

2025

PEP-4





- First TPC, started operation in 1982 at PEP (SLAC)
- Compact non-projective 3D tracking and PID device
- Operated at 8.5 bar, B=1.5 T, P-10 gas
- 13,824 readout pads for tracking
- dE/dx from anode wire readout (3.5%, 8.5 bar!)

1975

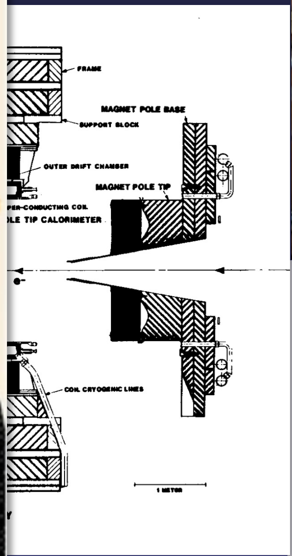
1985

1995

2005

2015

2025



at PEP (SLAC)

and PID device

s

- 13,824 readout pads for tracking
- dE/dx from anode wire readout (3.5%)

1975

1985

1995

2005

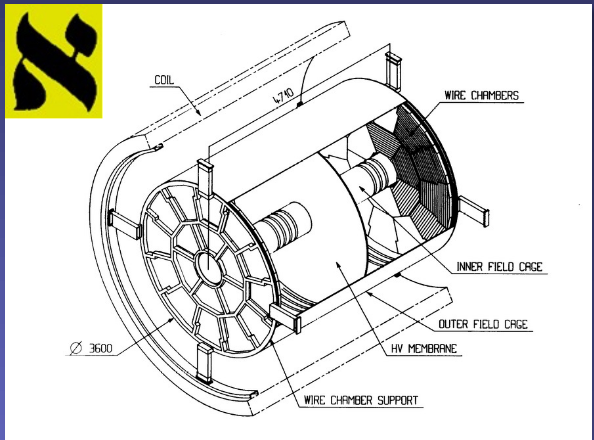
2015

2025

PEP-4

ALEPH

DELPHI



- ALEPH TPC at LEP, 1989-2000
- Drift length 2m, diameter 3.6 m
- B = 1.5 T, P-10
- Atmospheric pressure, active gating grid, 41,000 pads

1975

1985

1995

2005

2015

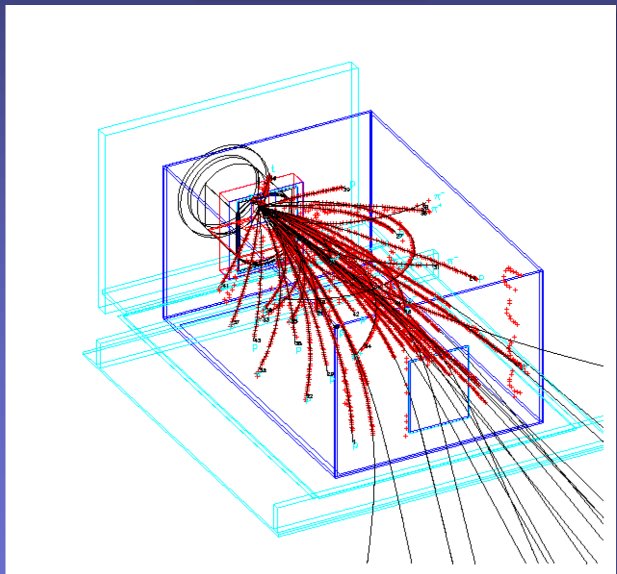
2025

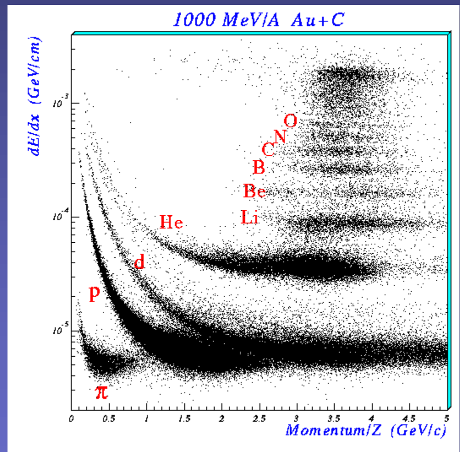
PEP-4

ALEPH

DELPHI

EOS





- First heavy-ion TPC
- At BEVALAC, later AGS

1975

1985

1995

2005

2015

2025

PEP-4

EOS

Bevatron
AGS

STAR

RHIC

NA35

NA36

NA49

CERES

SPS
Fixed Target

Heavy-Ion Physics

1975

1985

1995

2005

2015

2025

PEP-4

EOS

Bevatron
AGS

STAR

RHIC

sPHENIX

RHIC

NA35

NA36

NA49

CERES

SPS
Fixed Target

ALICE 1

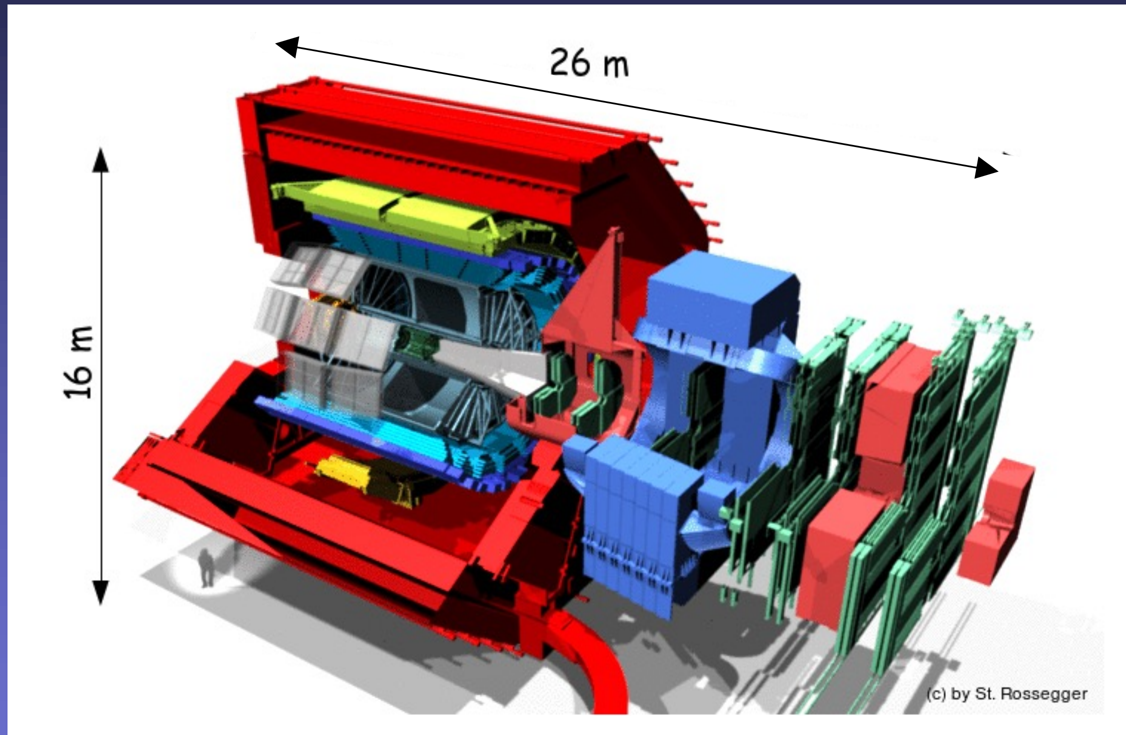
LHC

ALICE 2

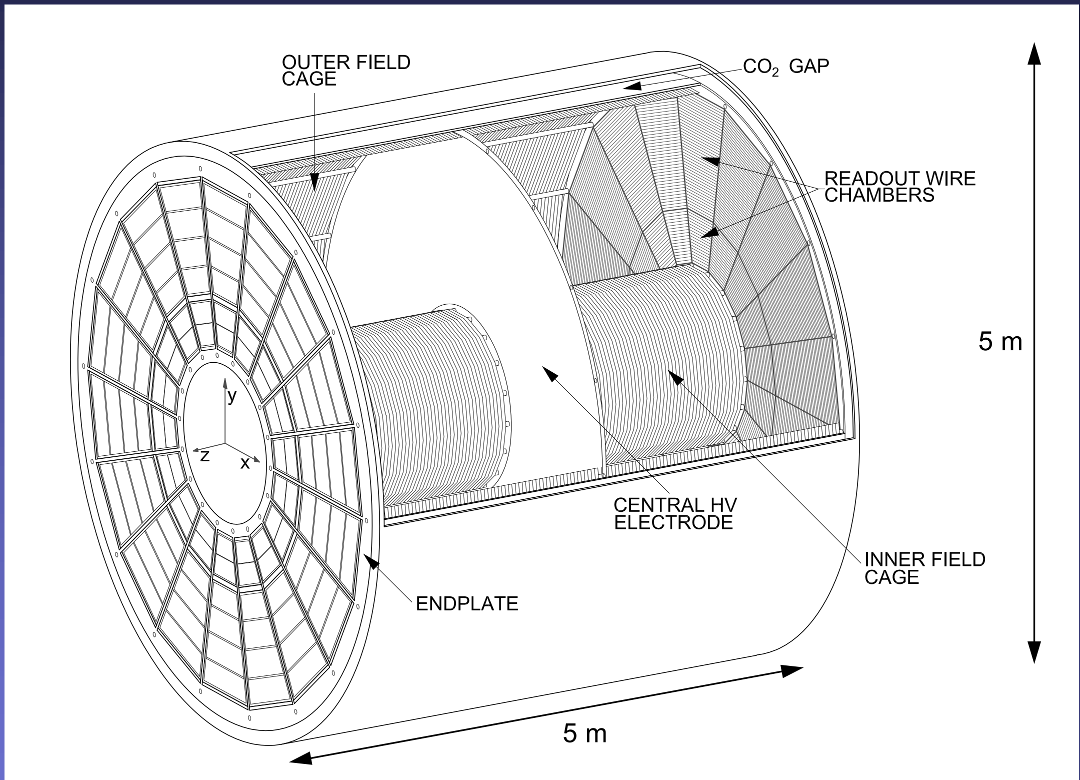
Heavy-Ion Physics

ALICE@LHC

- Dedicated heavy-ion experiment at the LHC
- In operation since 2009
- Pb-Pb, pp, p-Pb, Xe-Xe at up to 13.6 TeV
- Central barrel and forward muon system
- Main tracking and PID device: TPC

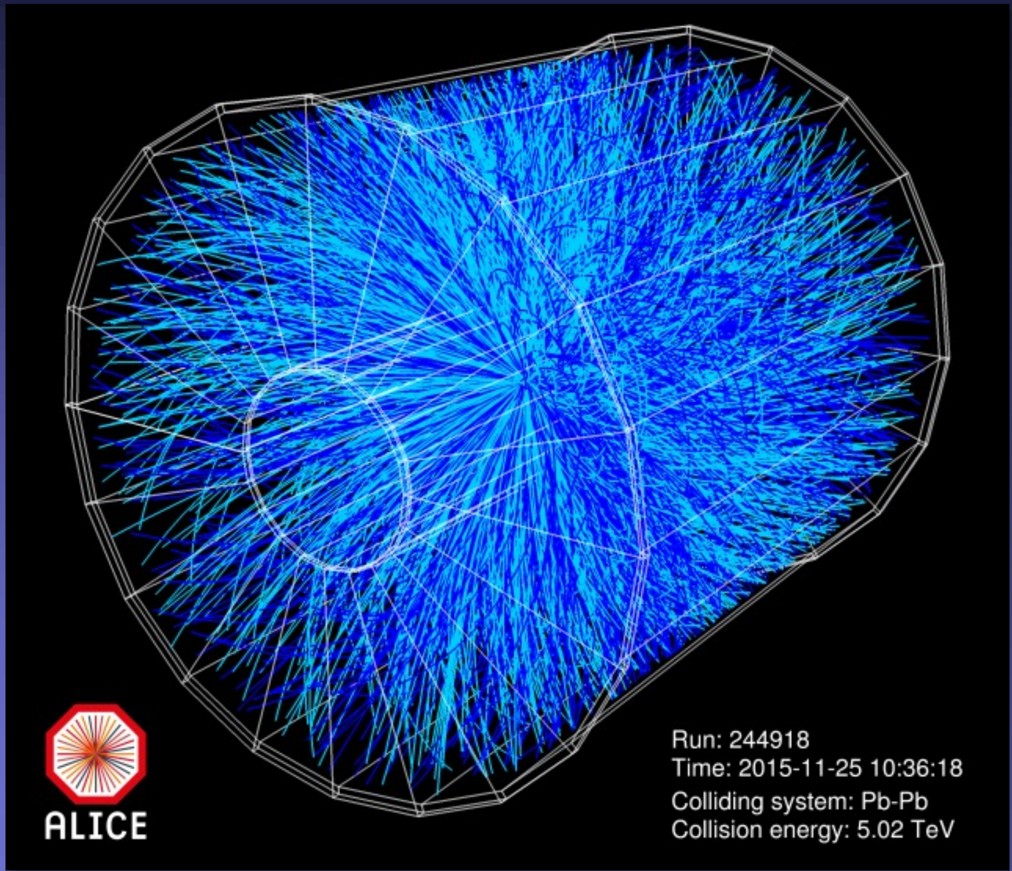


ALICE 1 TPC



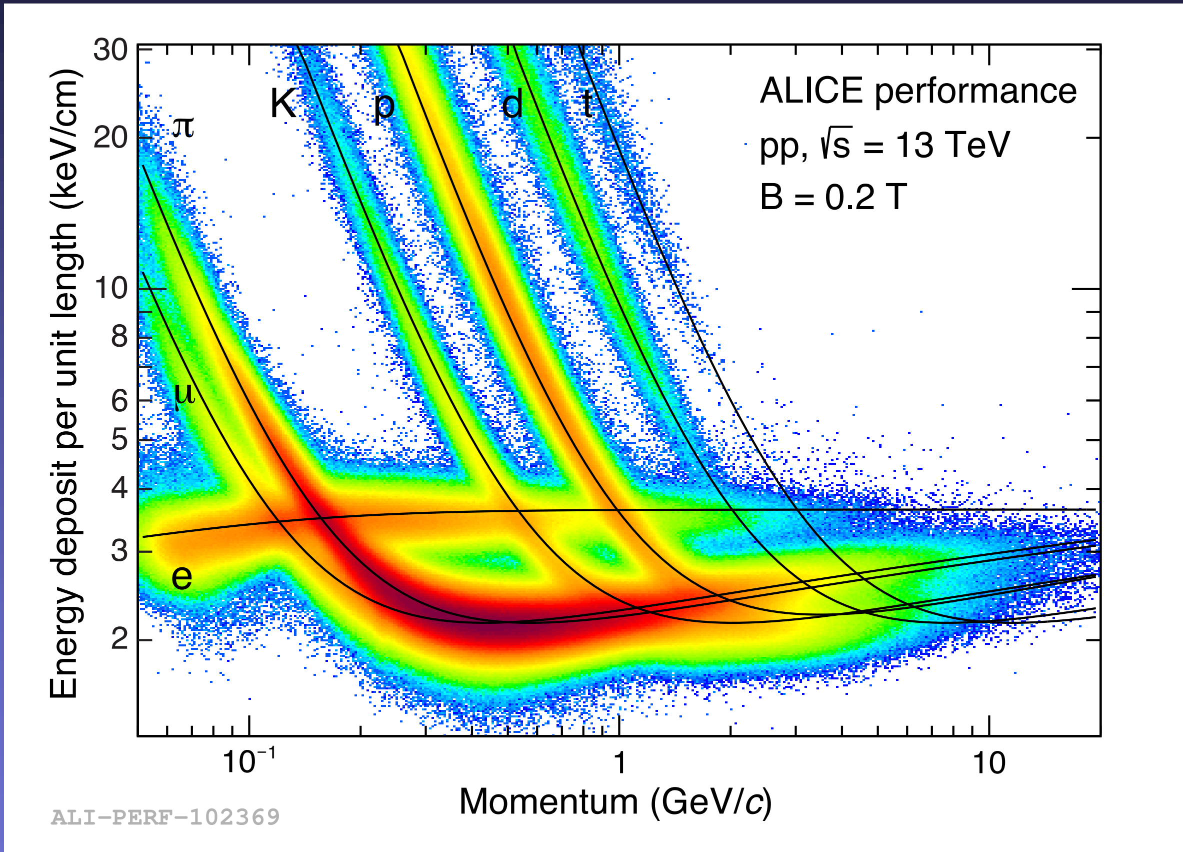
- 5m long, 5m diameter
- Active volume 88 m^3
- 2.5 m drift length, 100 kV
- Ne-CO_2-N_2 (90-10-5)
- Maximum electron drift time: 100 μs
- 72 MWPC Readout Chambers
- 550,000 readout channels
- PASA, ALTRO 10 bit ADC
- 10 MHz sampling frequency
- Readout rate 100-1000 Hz (live time 1-10%)

ALICE 1 TPC



- ALICE's main tracking and PID device through LHC Runs 1 and 2 (2009-2018)
- 5000 charged particles in a single central Pb-Pb collision

ALICE 1 TPC



- ALICE‘s main tracking and PID device through LHC Runs 1 and 2 (2009-2018)
- 5000 charged particles in a single central Pb-Pb collision, dE/dx resolution 5%

ALICE 1 TPC

40 *35. Particle Detectors at Accelerators*

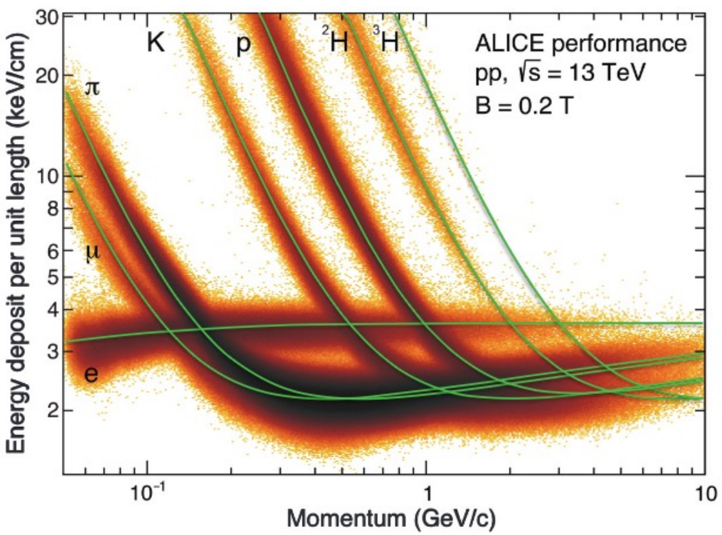


Figure 35.16: Energy deposit versus momentum measured in the ALICE TPC.

as the charge sign, are calculated from a helix fit to the particle trajectory in the presence of a magnetic field (typically parallel to the drift field). For this application, precise spatial measurements in the plane transverse to the magnetic field are most important. The specific energy deposit is

- ALICE‘s main tracking and PID device through LHC Runs 1 and 2 (2009-2018)
- 5000 charged particles in a single central Pb-Pb collision, dE/dx resolution 5%

40 *28. Detectors at accelerators*

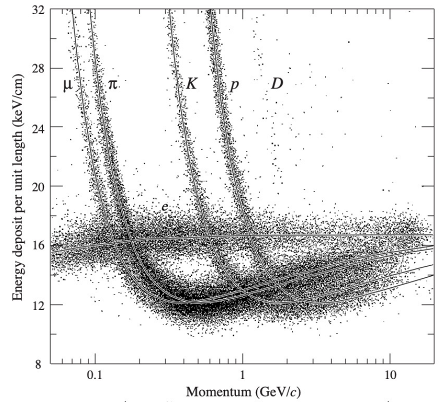
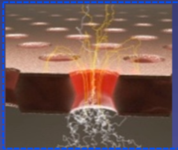


Figure 28.15: The PEP4/9-TPC energy deposit measurements (185 samples, 8.5 atm Ar-CH_4 80:20). The ionization rate at the Fermi plateau (at high β) is 1.4 times that for the minimum at lower β. This ratio increases to 1.6 at atmospheric pressure.

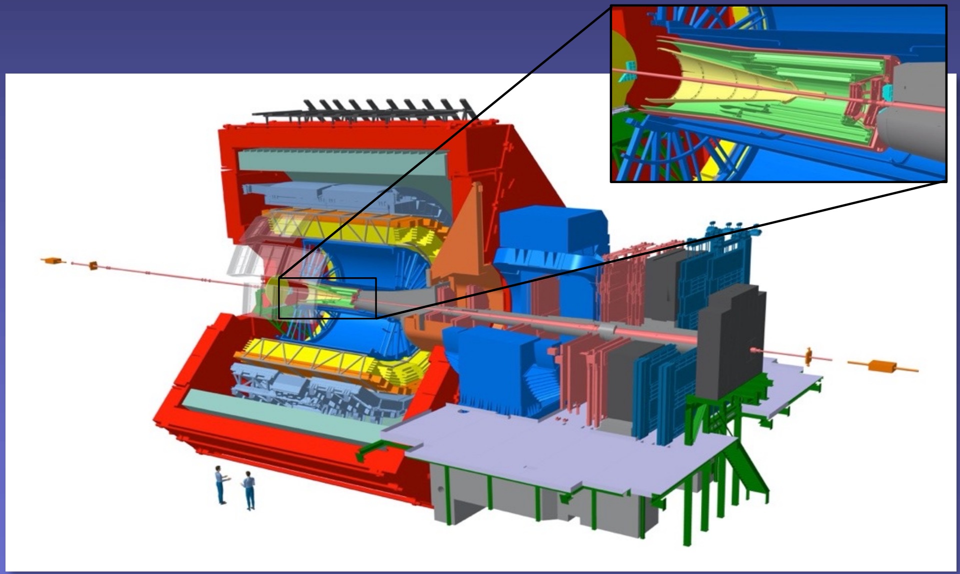
ALICE 2 Upgrade

New Inner Tracking System
- Complementary Metal-Oxide-Semiconductor (CMOS) Monolithic Active Pixel Sensor (MAPS) technology
- Improved resolution, less material, faster readout



New TPC Readout System
- ROCs with Gas Electron Multiplier (GEM) technology
- New electronics (SAMPA), continuous readout

Integrated Online-Offline System (O^2)
- Record MB Pb-Pb data at 50 kHz
- EPN without trigger

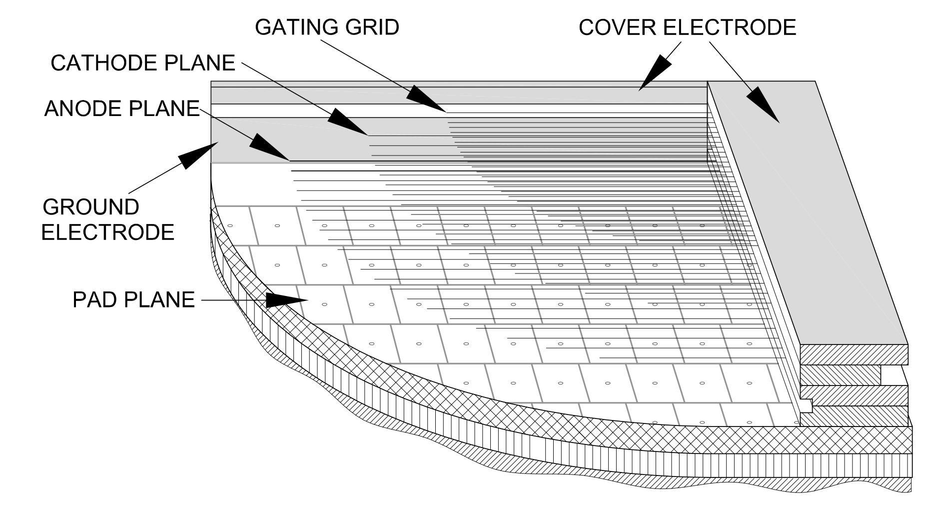


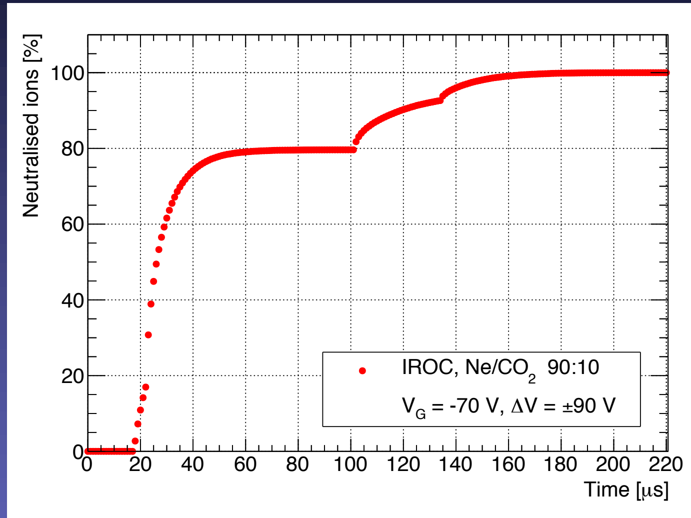
Goal: sample the full expected LHC Pb-Pb luminosity of 50 kHz in Run 3 and 4

→ Aim for continuous operation and untriggered readout

→ New readout chambers and new electronics

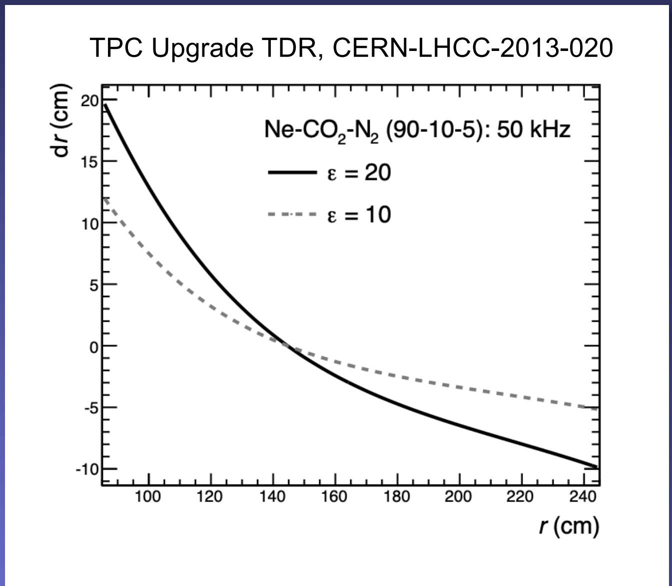
Limitation of the MWPC TPC





- The ALICE 1 TPC is operated with an active ion Gating Grid (GG) to avoid ion backflow (IBF) from the amplification gap into the drift region → drift field distortions
- TPC readout time (~100 μs) plus GG closure time (~200 μs) implies a trigger rate limitation of about 3 kHz
- Full exploitation of RUN3 physics potential requires novel technology that allows continuous readout of the TPC at low IBF and sufficient energy resolution to provide sufficient tracking and dE/dx resolution

Space-charge distortions

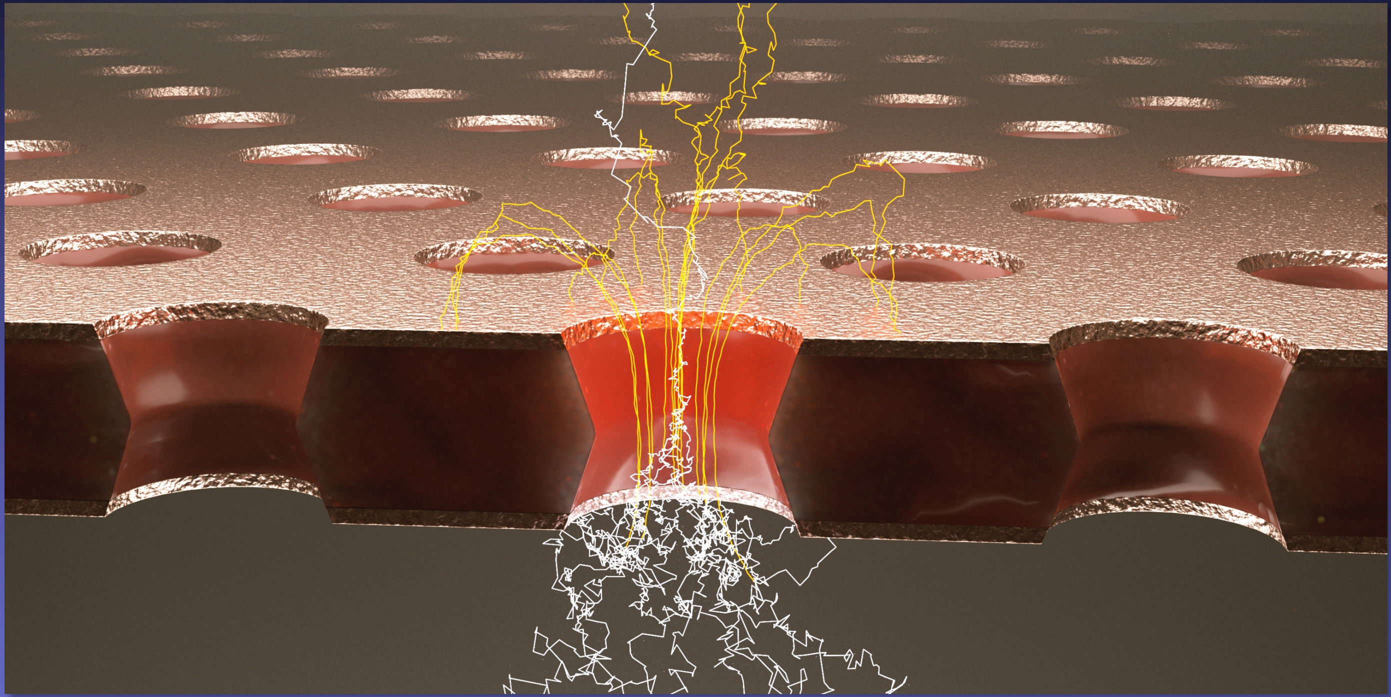


- Back-drifting ions from the amplification region cause severe distortions of the electron drift field

$$\varepsilon = IBF \cdot GG$$

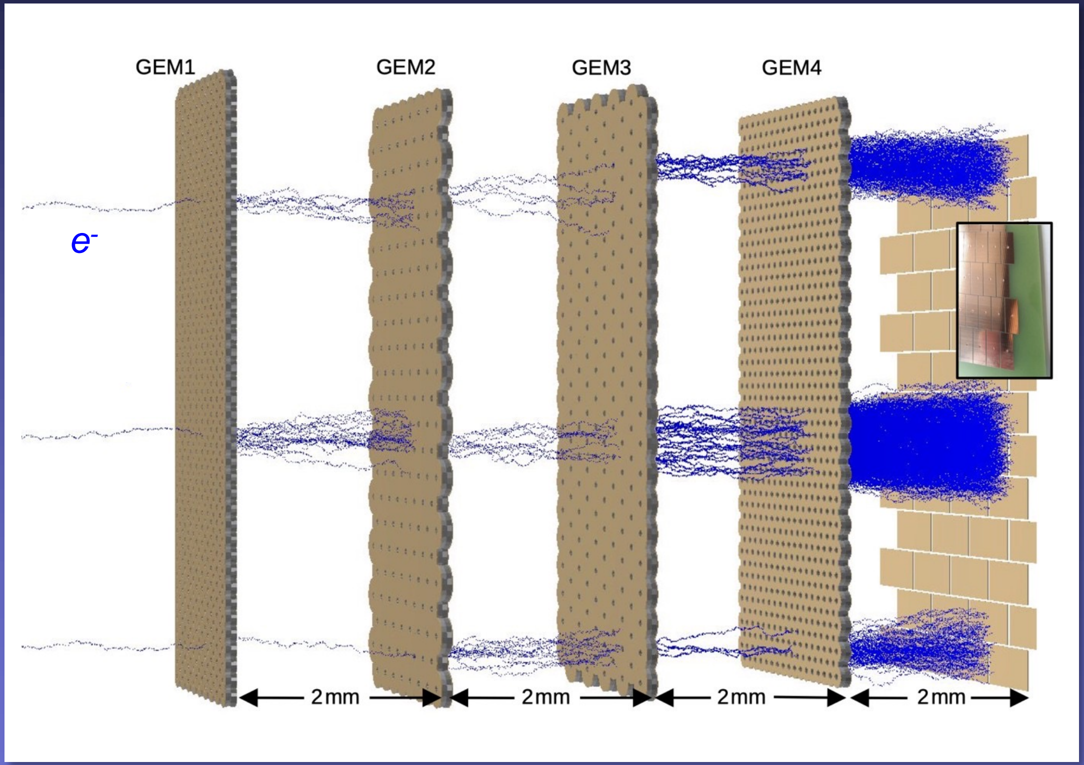
- *GG* : effective gas gain, target value 2000
- *IBF:* fraction of back-drifting ions $I_{ion,back}/I_{e,\, anode}$
- *ε:* number of back drifting ions per primary electron
- Need technical solution to provide **ε** = 10-20 (*IBF* = 0.5 - 1%)
- MWPC: *IBF* = O(10%)

GEMs



- 50 µm thin insulating polyimide foil with 2–5 µm thick Cu layers on both sides
- perforated by photolithographic processing
- hexagonal pattern of double-conical holes
- inner (polyimide) diameter 50 µm, outer (copper) diameter of 70 µm

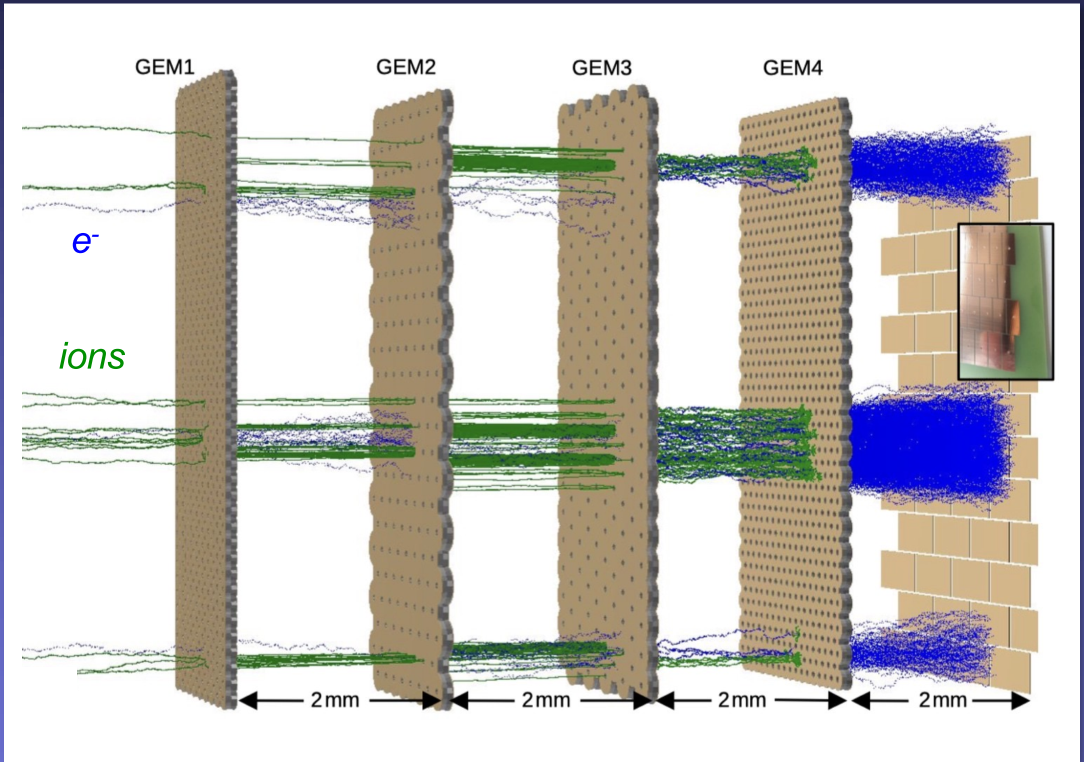
Multi-GEM layer



- Single GEM has *IBF* = O(10%)
  → need multi-layer solution

- Sub-divide into pre- and main amplification stage
- Two GEMs each are needed
- Configuration of transfer fields and GEM geometry (e.g. hole pitch) subject of extensive R&D activities

Multi-GEM layer



- Single GEM has *IBF* = O(10%)
  → need multi-layer solution

- Sub-divide into pre- and main amplification stage
- Two GEMs each are needed
- Configuration of transfer fields and GEM geometry (e.g. hole pitch) subject of extensive R&D activities

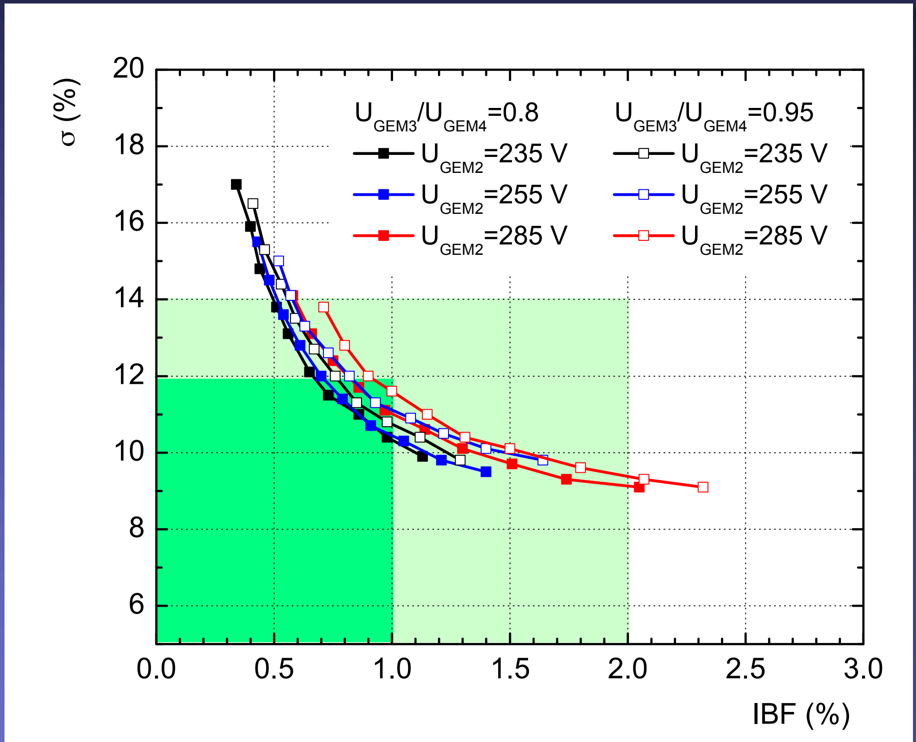
Solution:

- 4-GEM layer with S-LP-LP-S geometry
- Low transfer field $E_{T,3}$ = 0.1 kV/cm

S: Standard hole pitch 140 µm

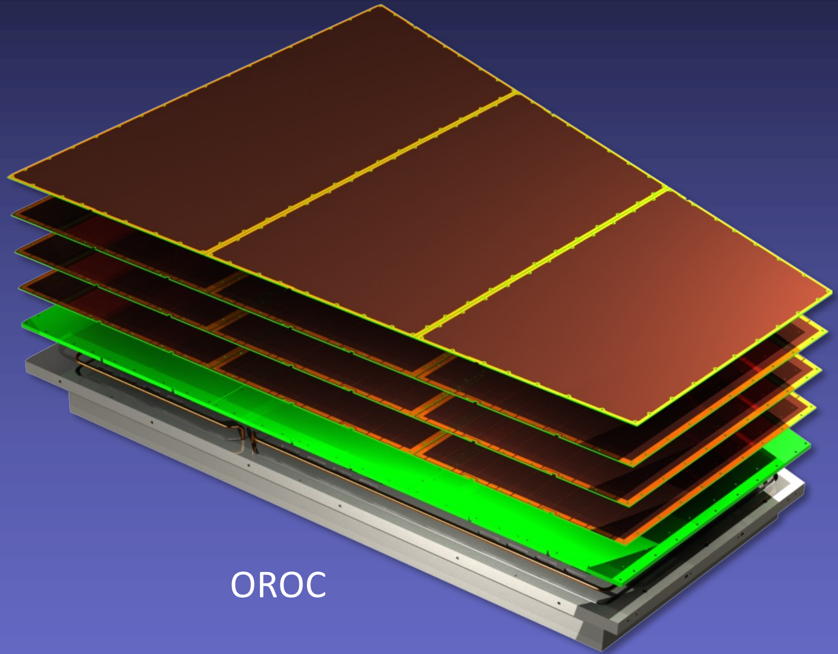
LP: Large hole pitch 280 µm

ALICE TPC 4-GEM system

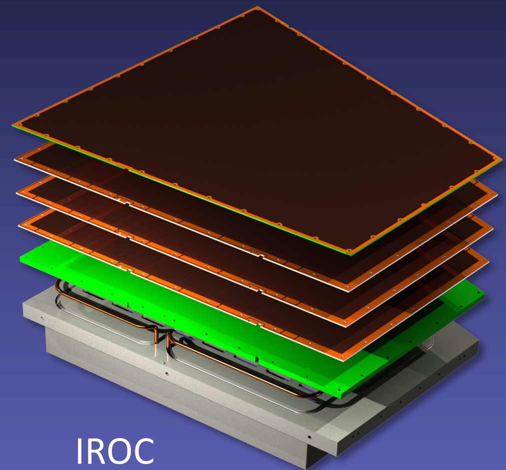


- Improvement on IBF is correlated with loss of energy resolution (^{55}Fe peak)
- required d*E*/d*x* performance preserved with **σ**(^{55}Fe) = 12-14%
- Suitable operational region identified
- Not shown: operational stability

GEM Readout Chambers



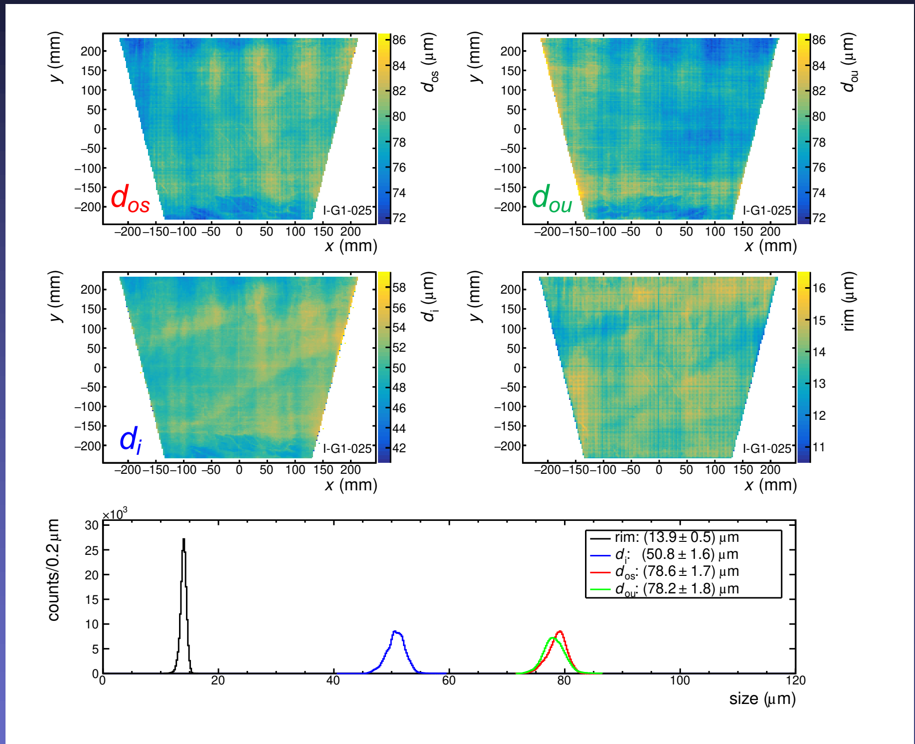
OROC

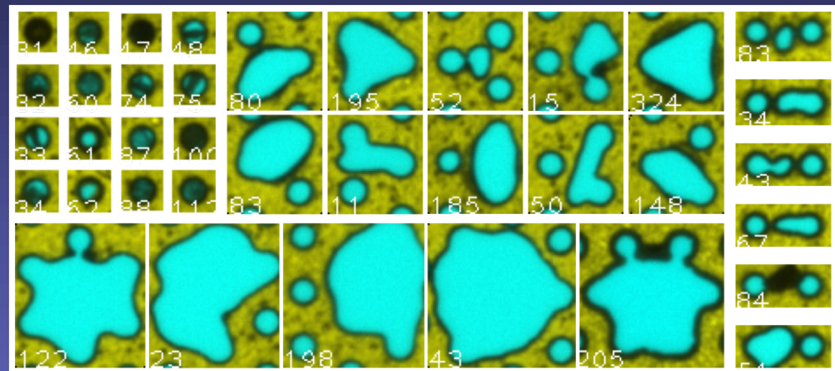


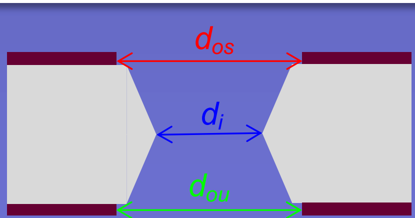
IROC

- 36 Inner (IROC) and 36 Outer Readout Chambers (OROC)
- large-size single-mask GEM foils from CERN PCB workshop
- 1/layer in IROC, 3/layer in OROC
- Total: 576 GEM foils (144 m^2) plus 40% spares
- ROC production campaign: 2016-2019

GEM QA - highlights

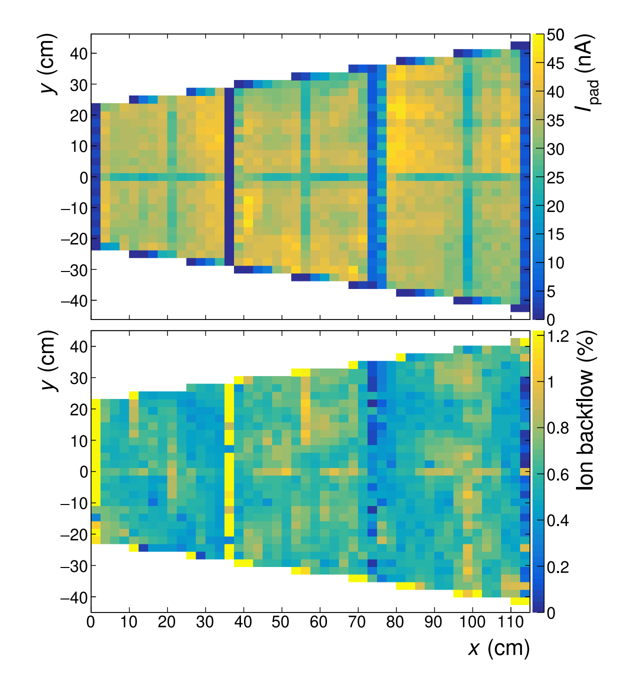


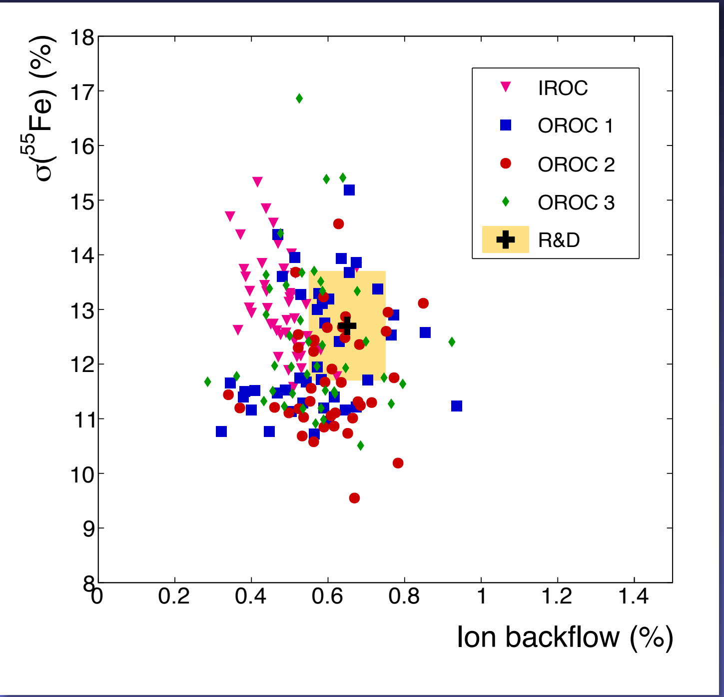




- Advanced QA campaign to monitor GEM hole size of every foil (total 3 billion holes)

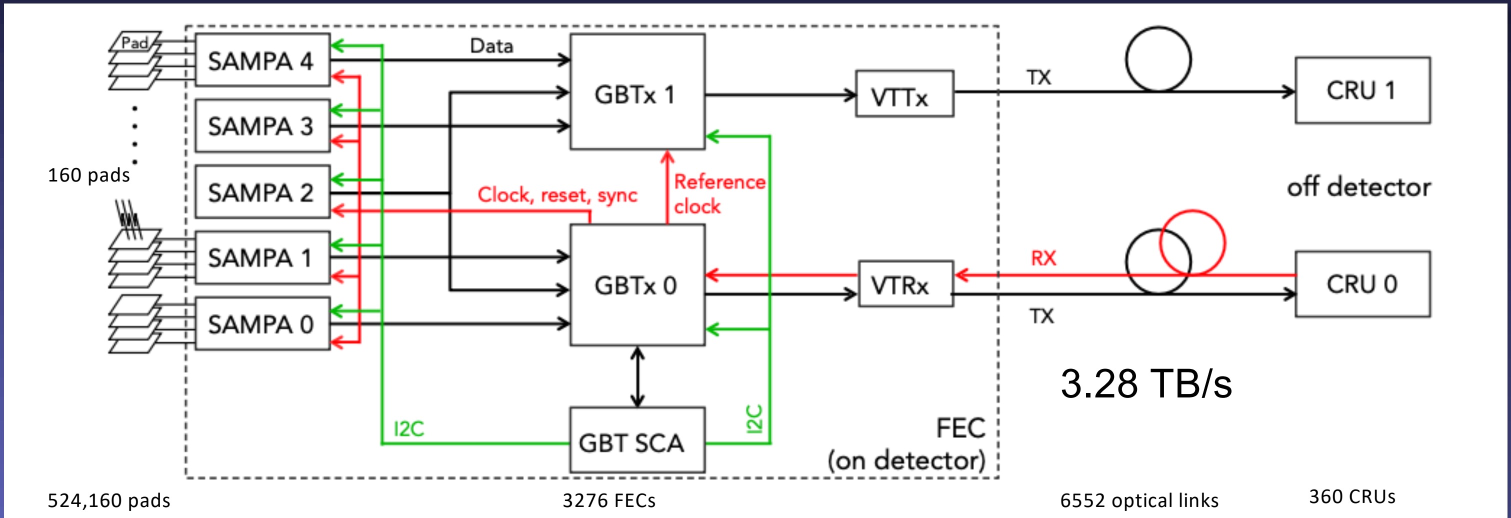
GEM QA - highlights





- Gas gain, IBF, and energy resolution uniformity checked with X-ray guns
- IBF and energy resolution performance of production ROCs compatible with prototype R&D

ALICE TPC readout



FE ASIC: SAMPA
- 32 channels
- continuous (or triggered) read-out
- Analog shaper/amplifier
- ADC 10 bit, 5 MHz
- Digital Signal Processing (bypassed)
- Readout through 6 (4+2) GBTeLinks

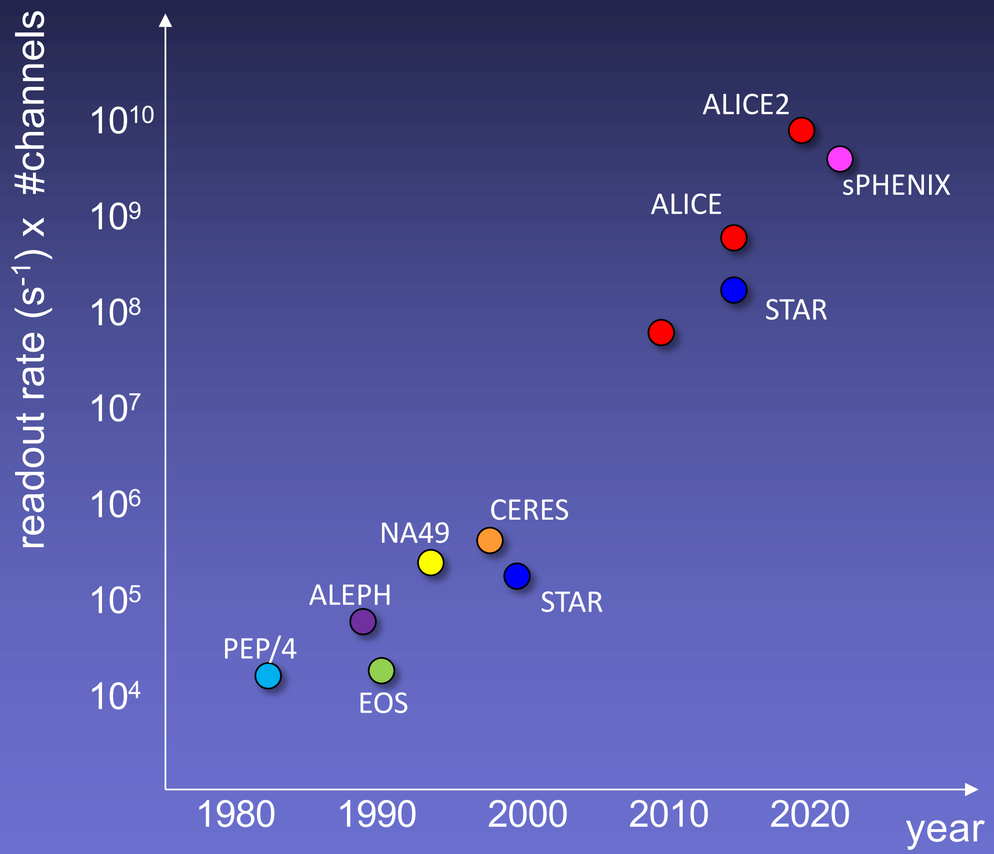
Common Readout Unit (CRU):
- FPGA based readout card
- signal processing:
  - Common mode correction
  - Tail cancellation
  - Zero suppression
  - Data packing

Online event processing

CR0 EPN computing center at Point 2

- Zero-suppressed raw data (1 TB/s) transported from CRU to EPN computing farm
- Synchronous event reconstruction and calibration on 50k CPUs and 2700 GPUs
- 170 GB/s to disk
- 160 PB disk pool

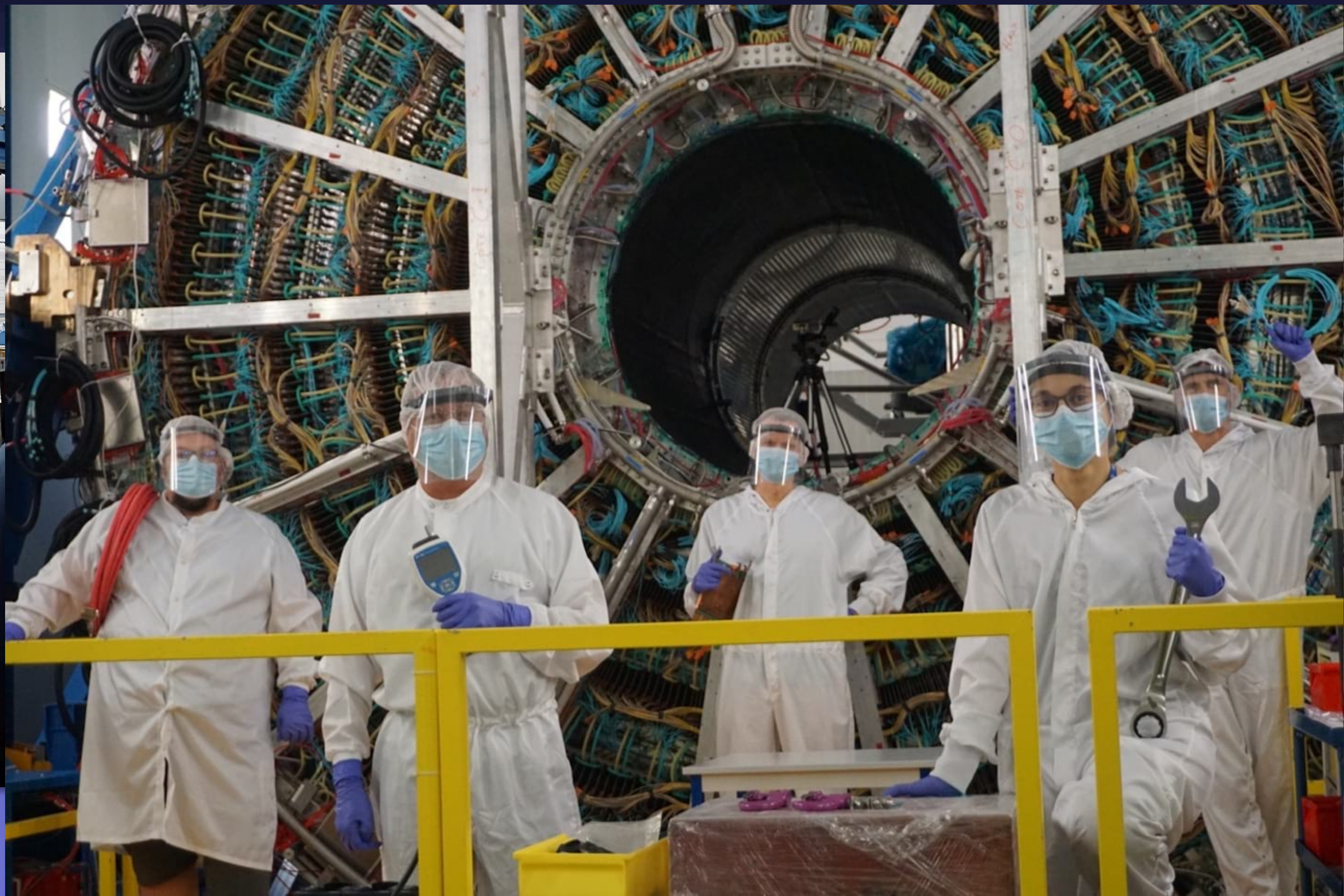
TPC evolution

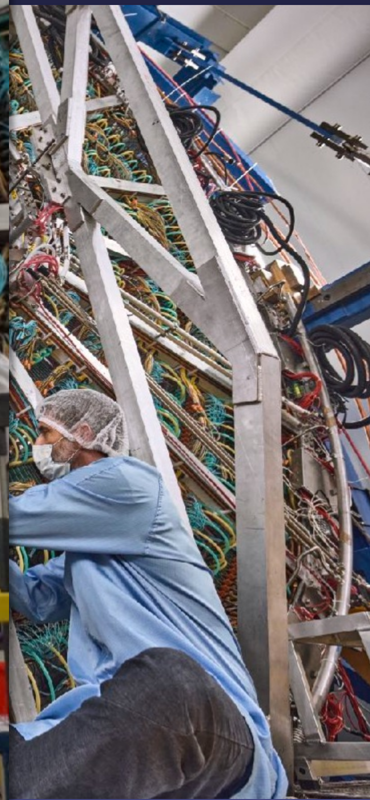


ROC and FEC installation

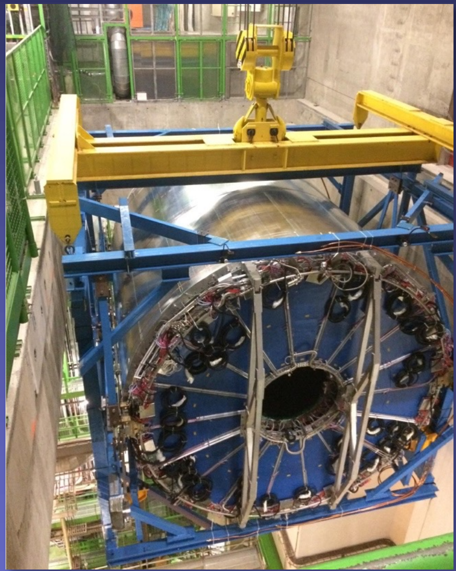
- During Long Shutdown 2 (2019/20) in SX2 clean room

ROC and FEC installation



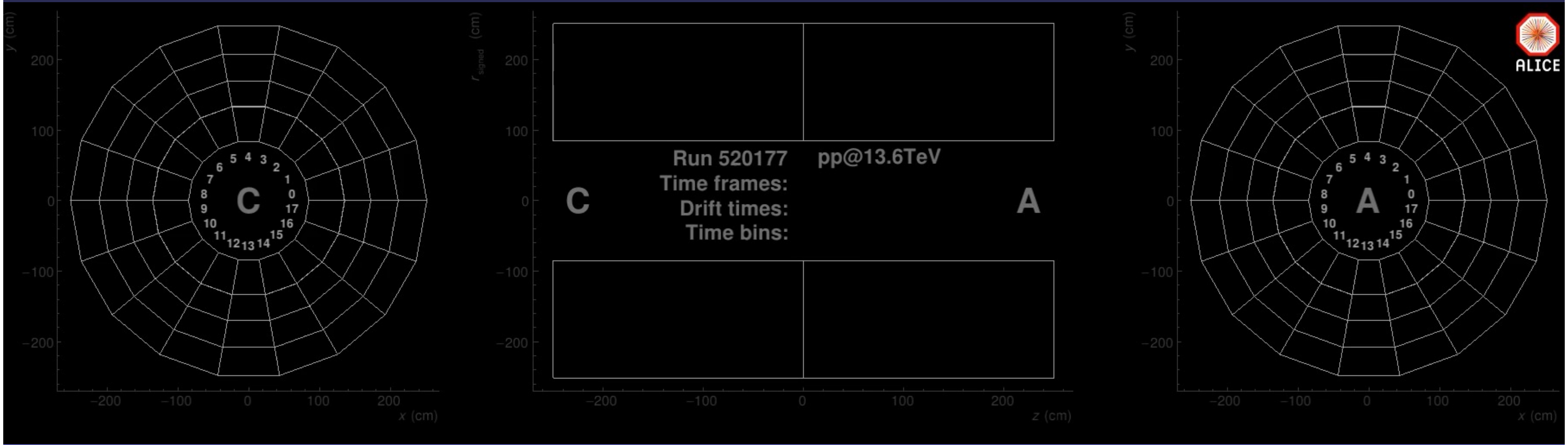


TPC recommissioning



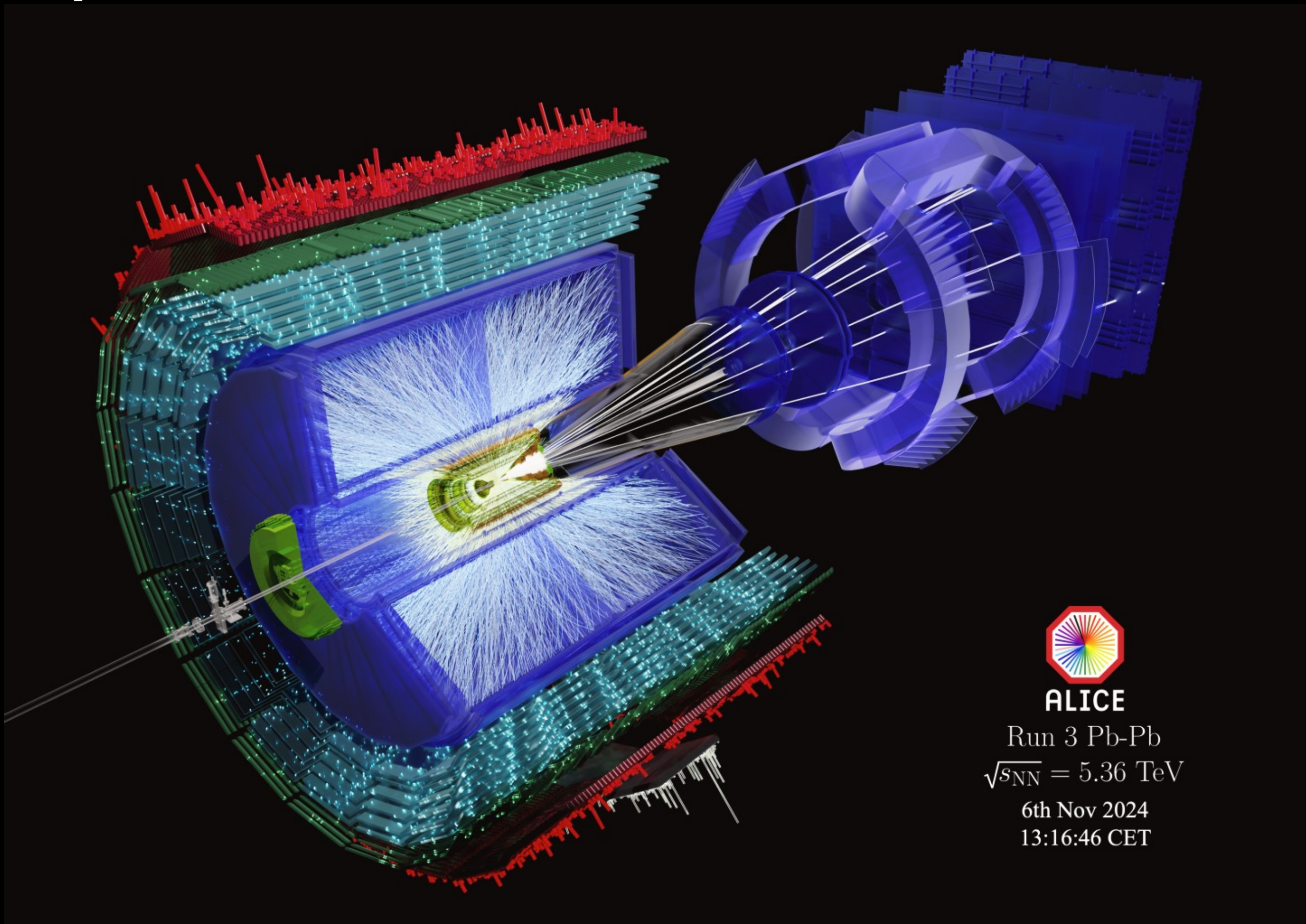
August 2020: TPC back to the cavern

pp collisions – continuous readout

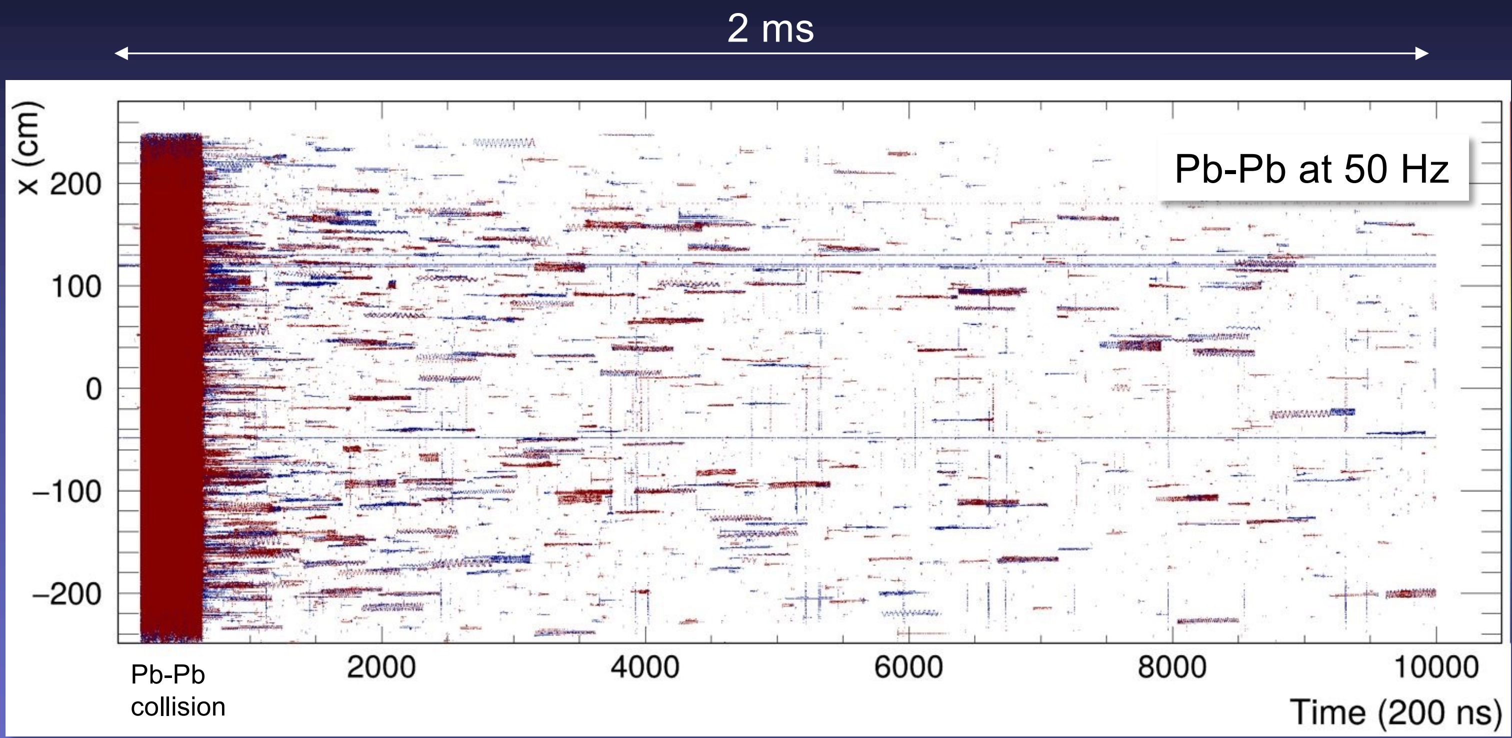


The pictures learned to walk

TPC operation in Pb-Pb

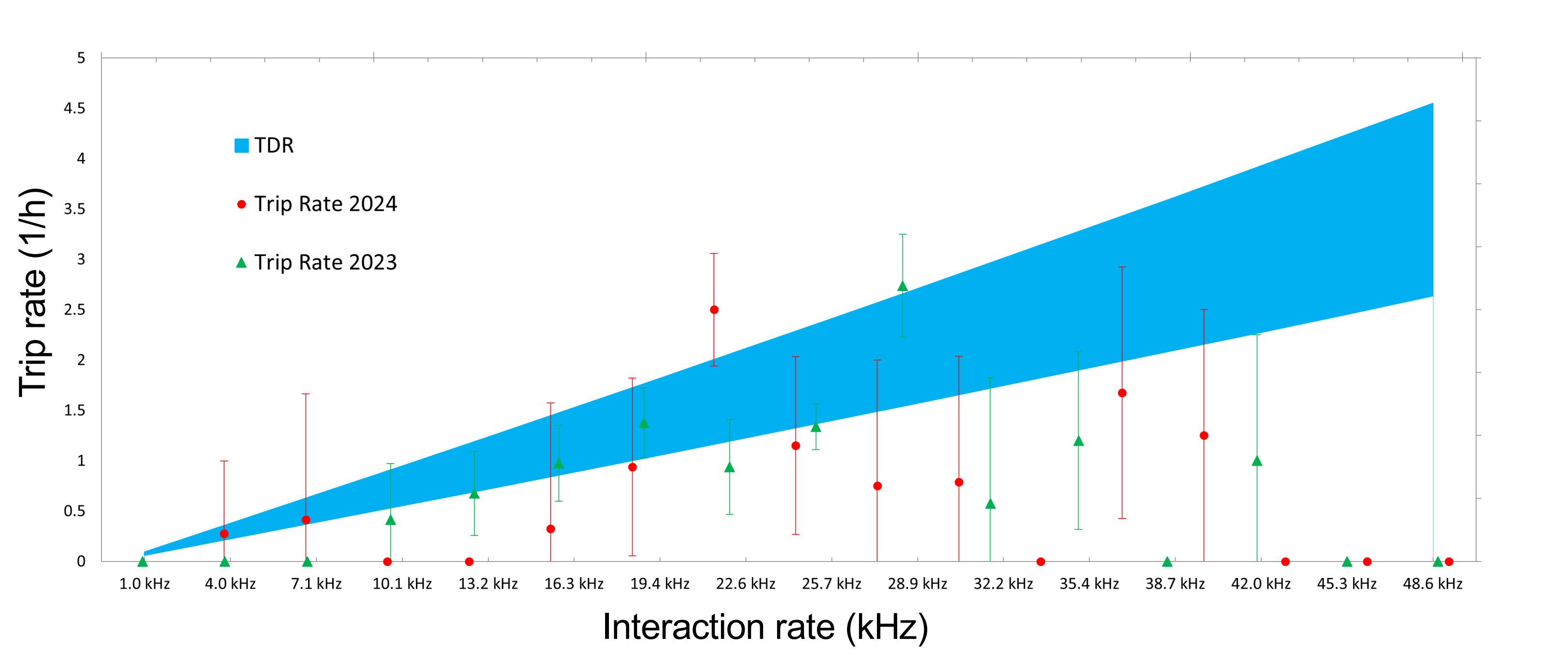


Neutron afterglow



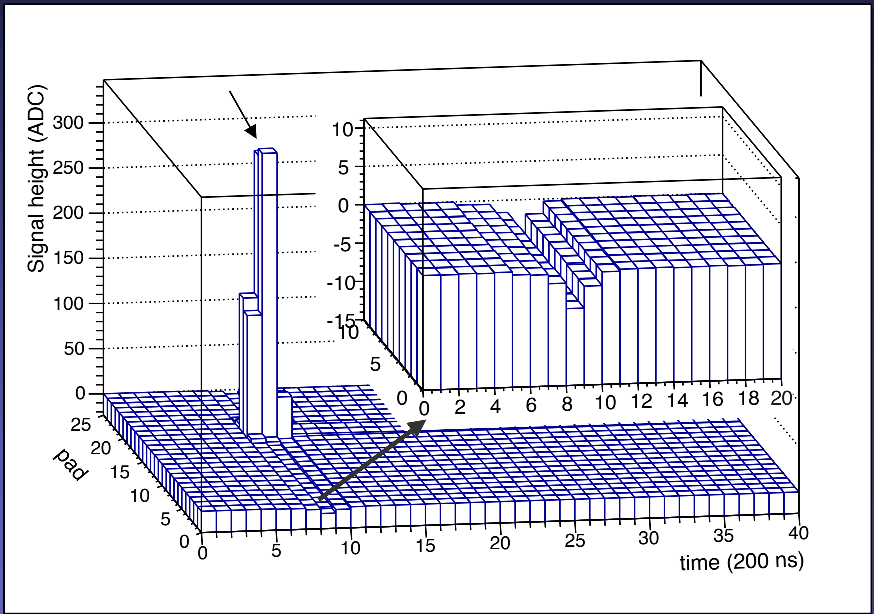
- Electron *loopers* from neutron background

Operational stability

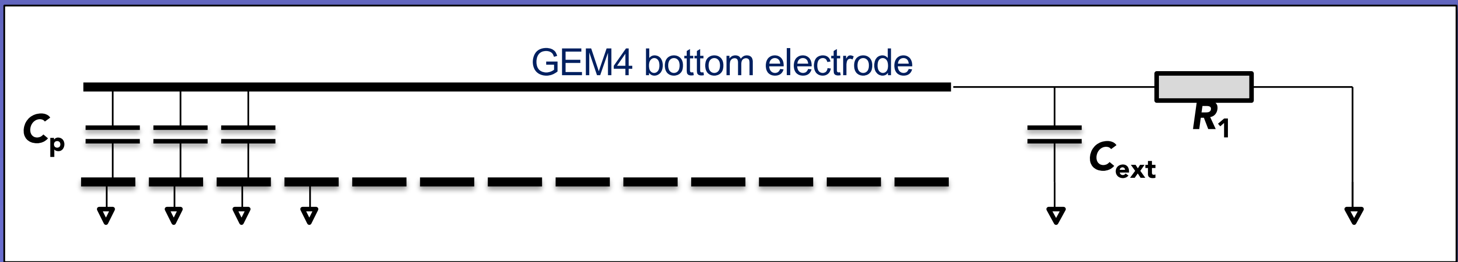


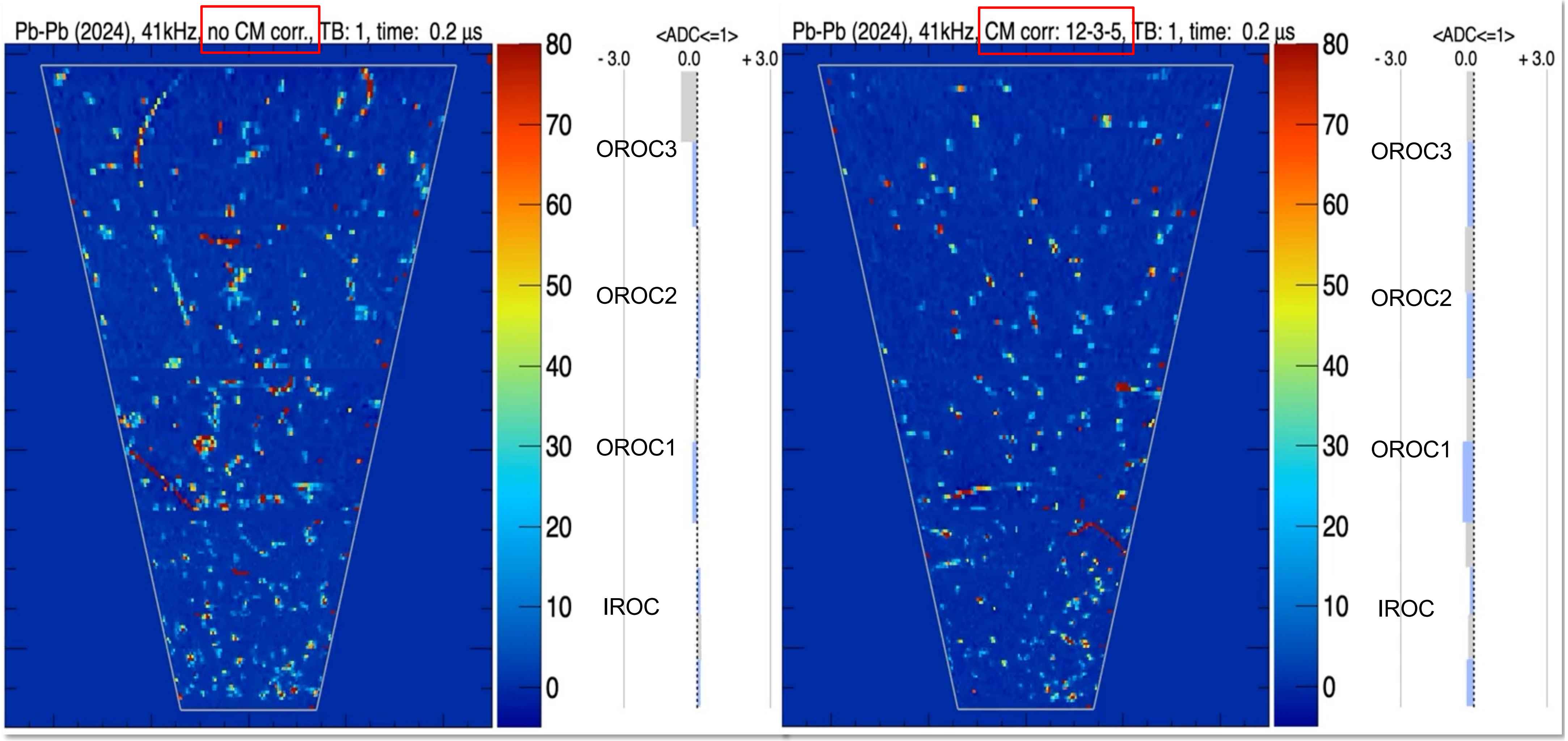
- ROC trip rate O(1-2/h) in Pb-Pb at 50 kHz
- Consistent with expectation from R&D

Common mode

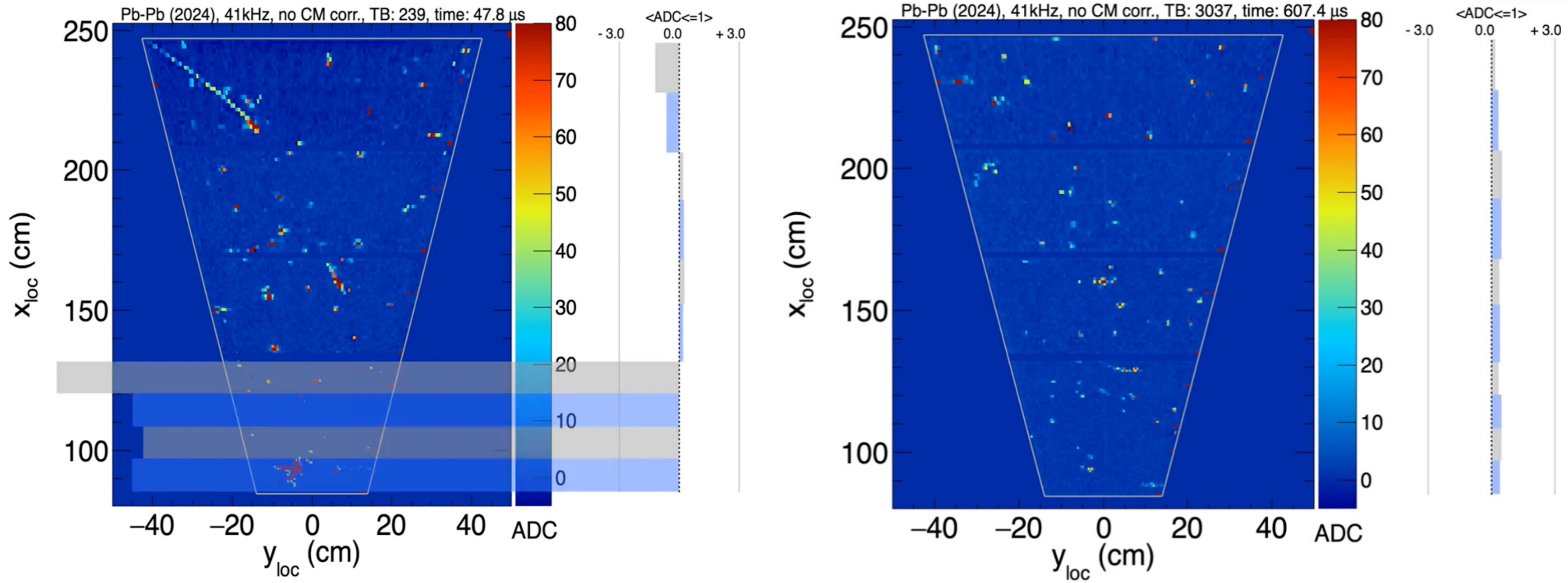


- Effective baseline shift due to capacitive coupling of amplification structure (wire, GEM) to pads
- Online correction necessary for proper zero suppression
- At high rate and continuous operation: CM signal can have both polarities



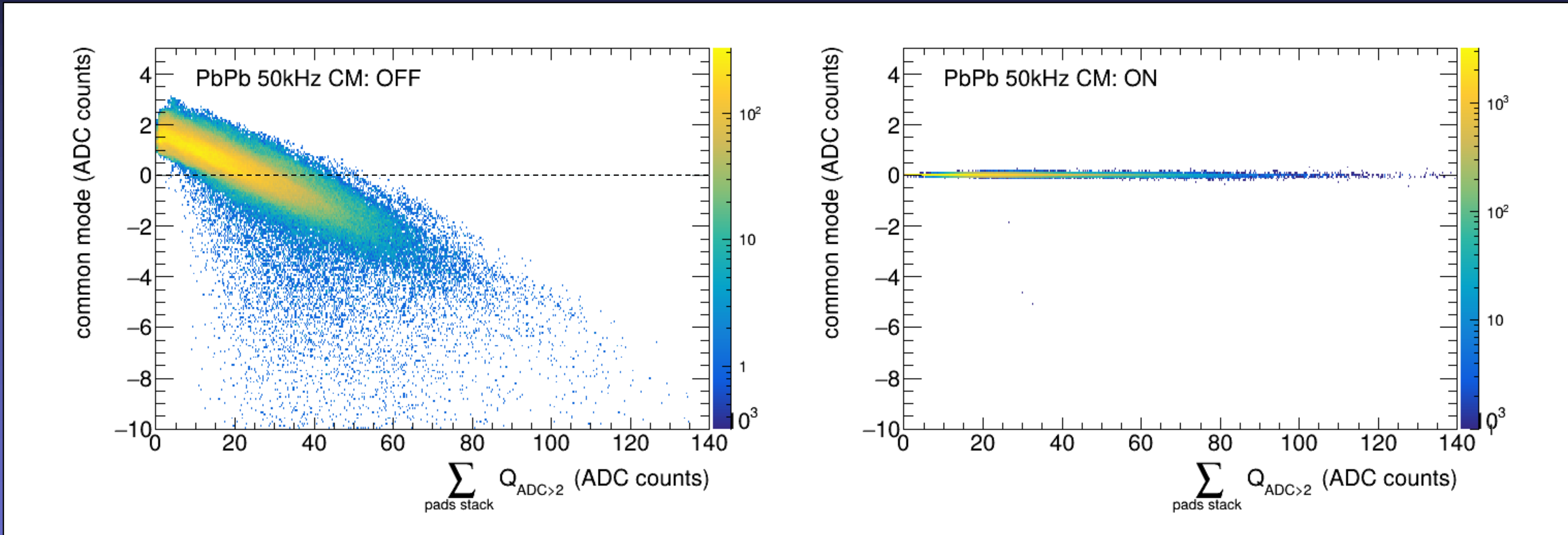

Pb-Pb (2024), 41kHz, no CM corr., TB: 1, time: 0.2 µs
80
70
60
50
40
30
20
10
0
<ADC<=1>
- 3.0
0.0
+ 3.0
OROC3
OROC2
OROC1
IROC
Pb-Pb (2024), 41kHz, CM corr: 12-3-5, TB: 1, time: 0.2 µs

Common mode



- Highly ionizing particle leads to negative CM
- Downward rate fluctuation leads to positive CM

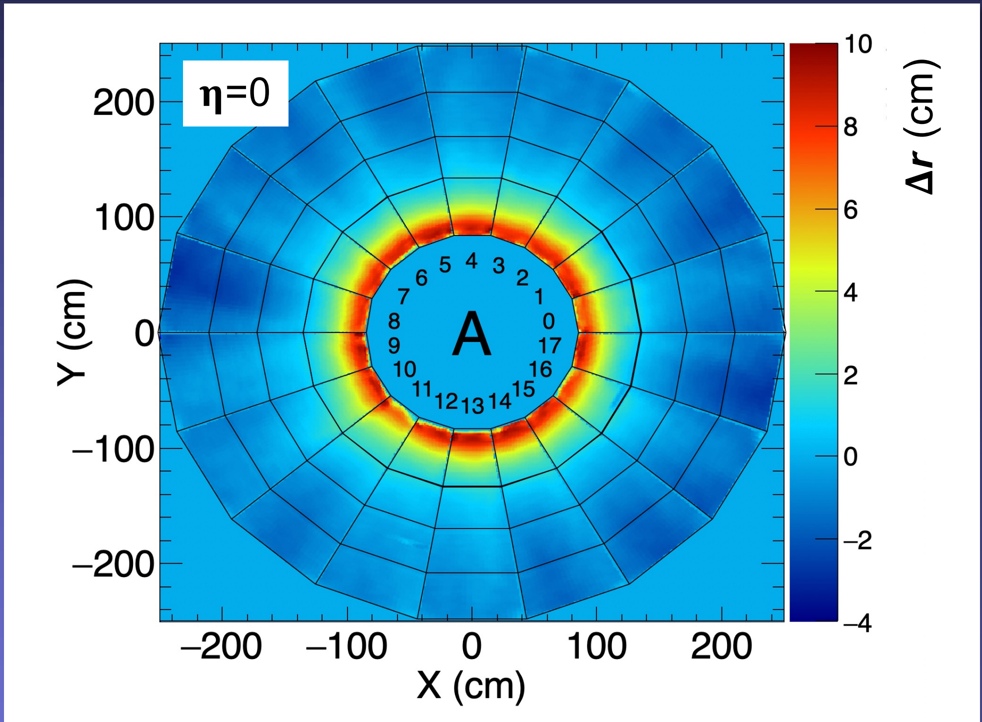
Common mode correction



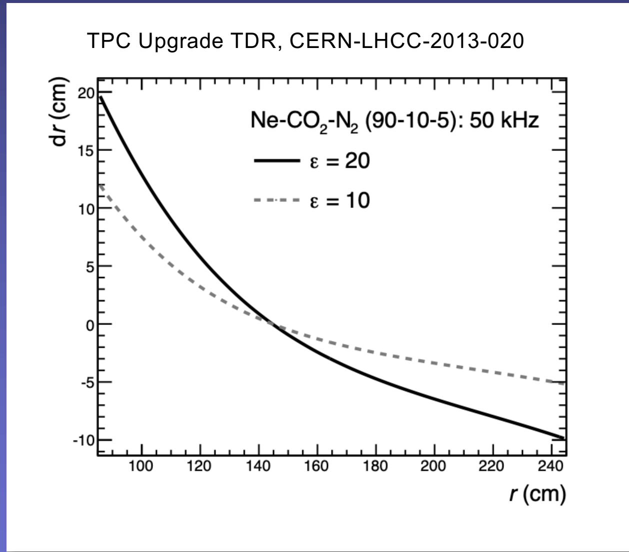
- Large CM effects in Pb-Pb, positive and negative
- Online correction in CRU FPGA achieves a very precise restoration of the baseline

Space charge distortions

Pb-Pb 47 kHz, 2024

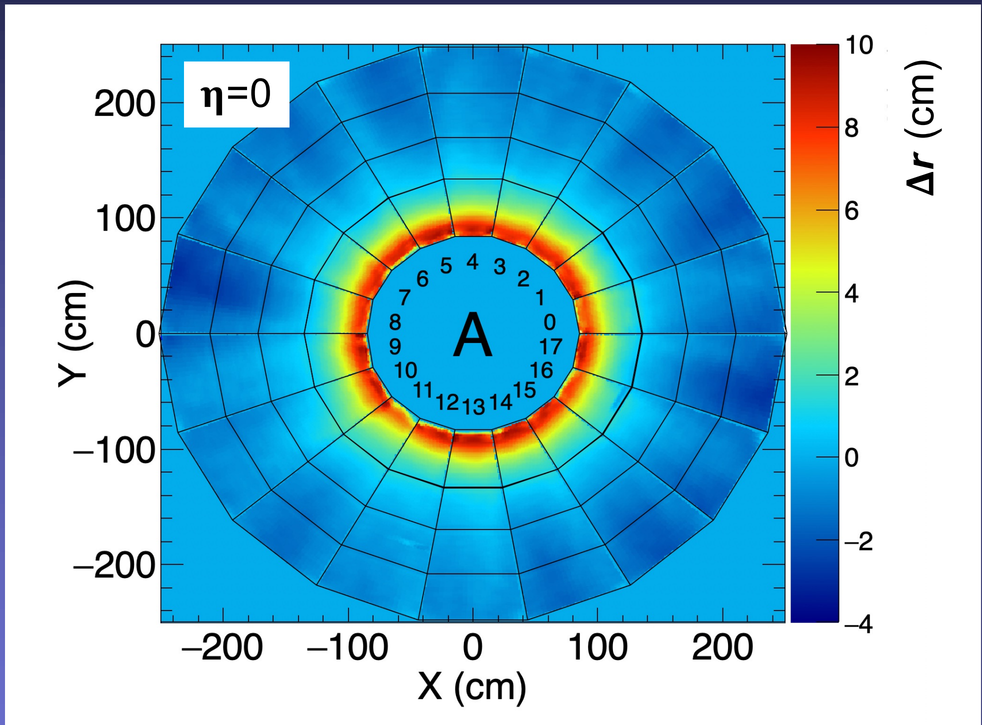


- Space-charge distortions from back-drifting ions up to 10 cm



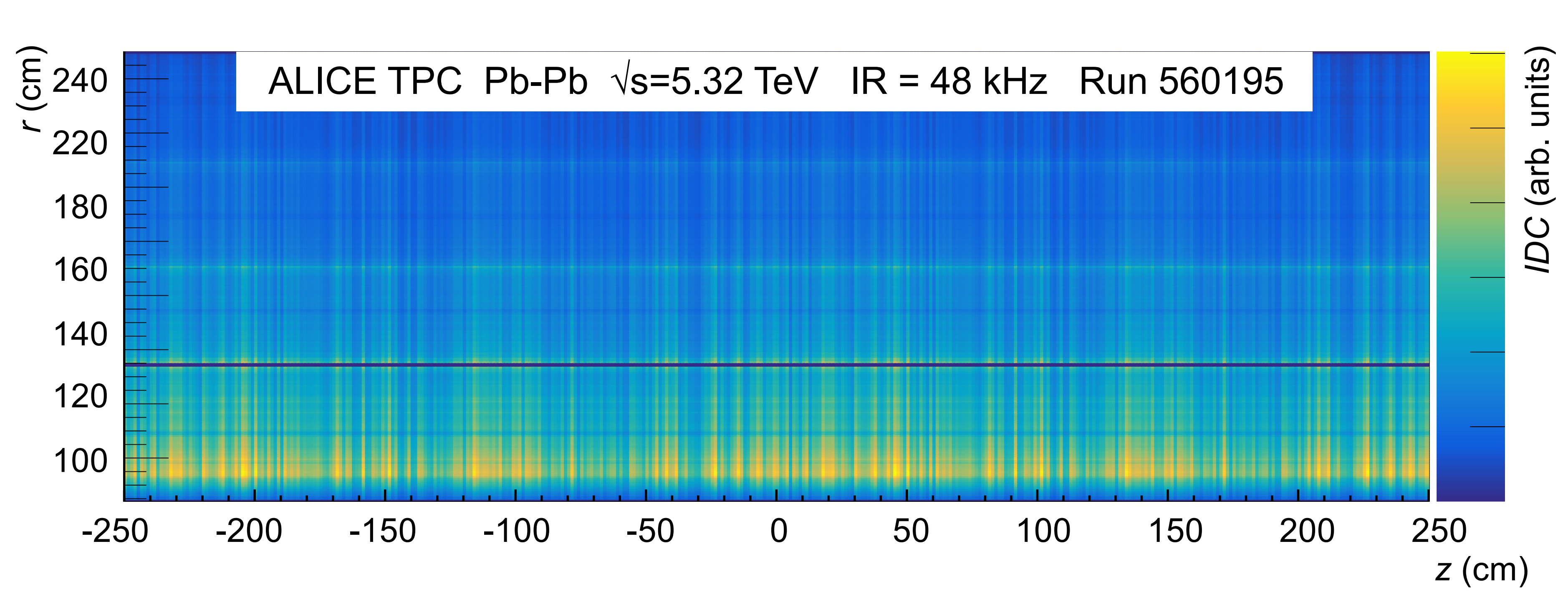
Space charge distortions

Pb-Pb 47 kHz, 2024



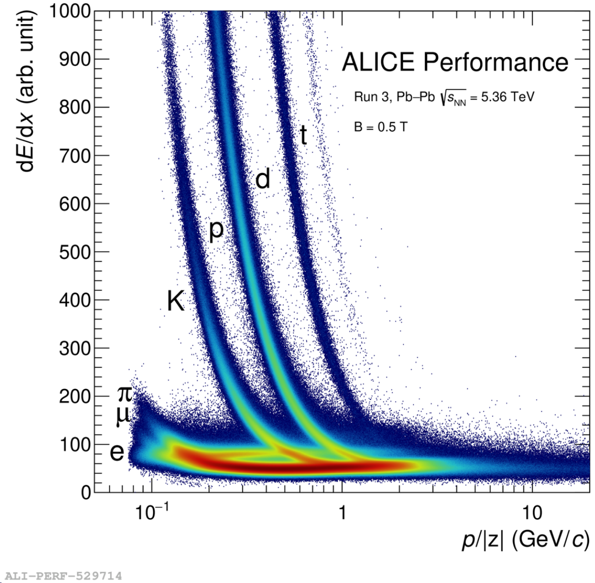
- Space-charge distortions from back-drifting ions up to 10 cm
- Average correction based on external track reference from Inner Tracking System (ITS)
- Fluctuations of 2% in Pb-Pb at 50 kHz require time-dependent correction
- In continuous readout mode, high granularity information of local ion density can be derived from raw ADC data (integrated digital currents, IDCs)
- IDCs are self-calibrating, follow variations in gas gain etc.

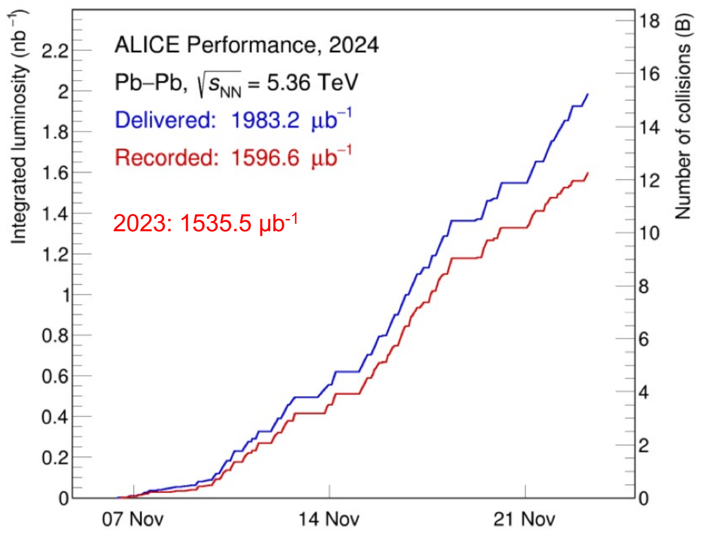
Ion density distribution

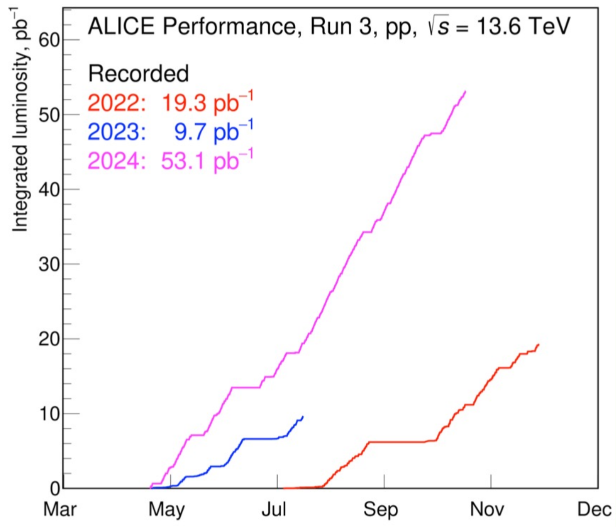


- Ion density distribution in TPC volume derived from IDC data
- At 50 kHz, ions from previous 10,000 Pb-Pb collisions are overlayed
- Local IDC information is used to scale distortion map

ALICE operation



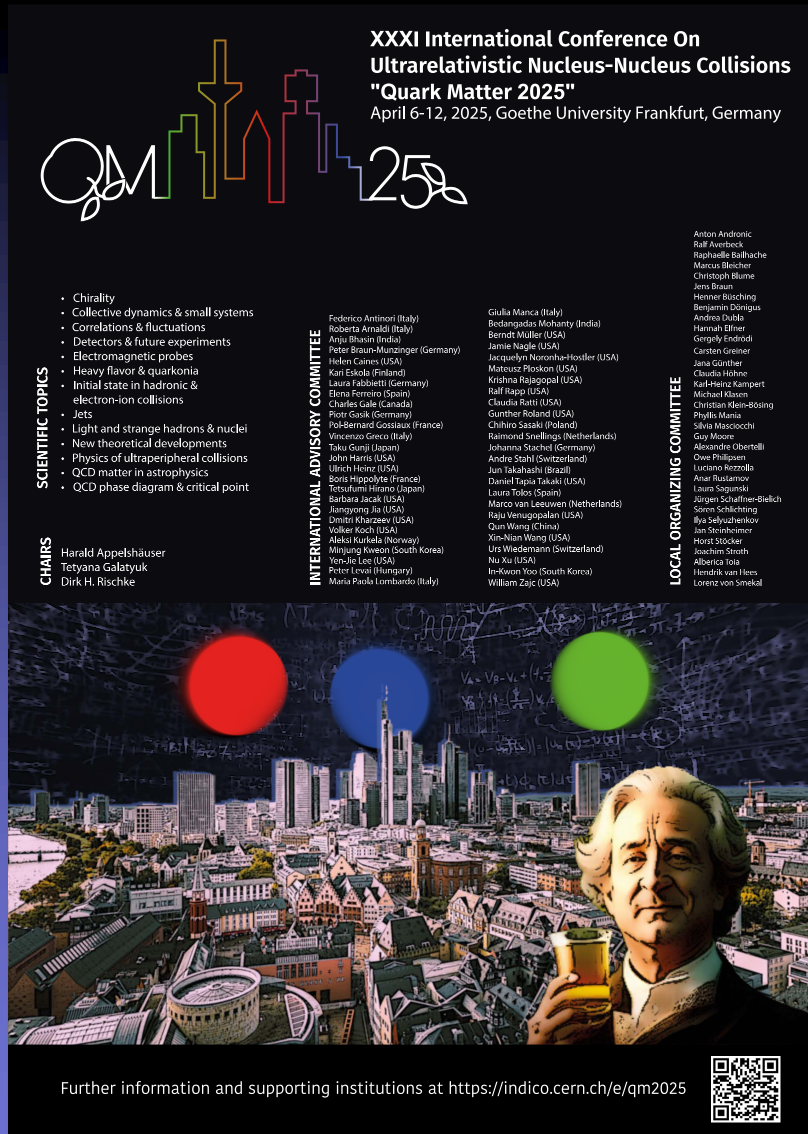




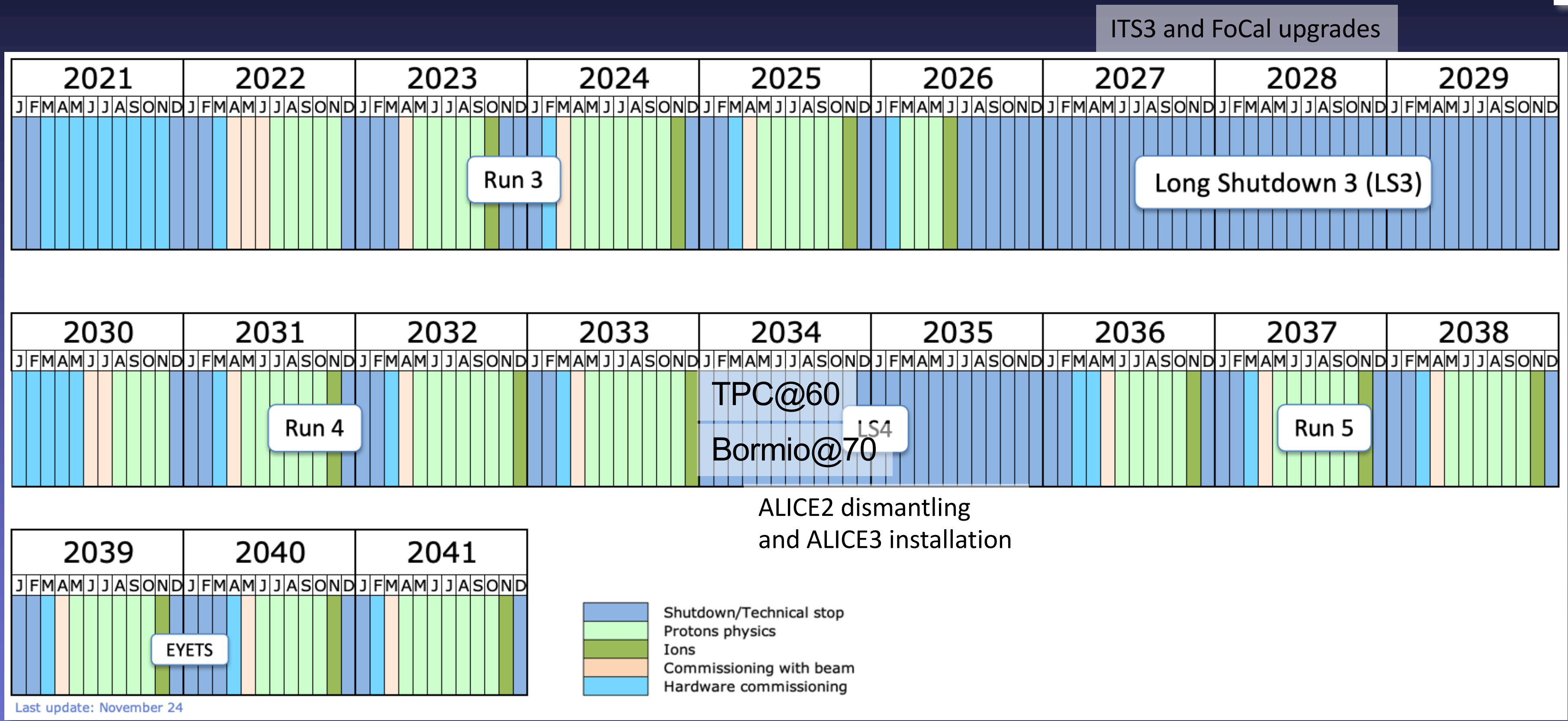
- Stable and smooth operation of the new ALICE TPC
- 2023+2024 Pb-Pb data set exceed statistics of Runs 1+2 by a factor 20 (central) and 80 (minimum bias)
- Run3 physics results being prepared for the Quark Matter 2025 conference

Quark Matter 2025

- Largest conference in the field
- 34 talks and 119 posters from ALICE with lots of new results from Run 3
- Deadline for registration: February 7

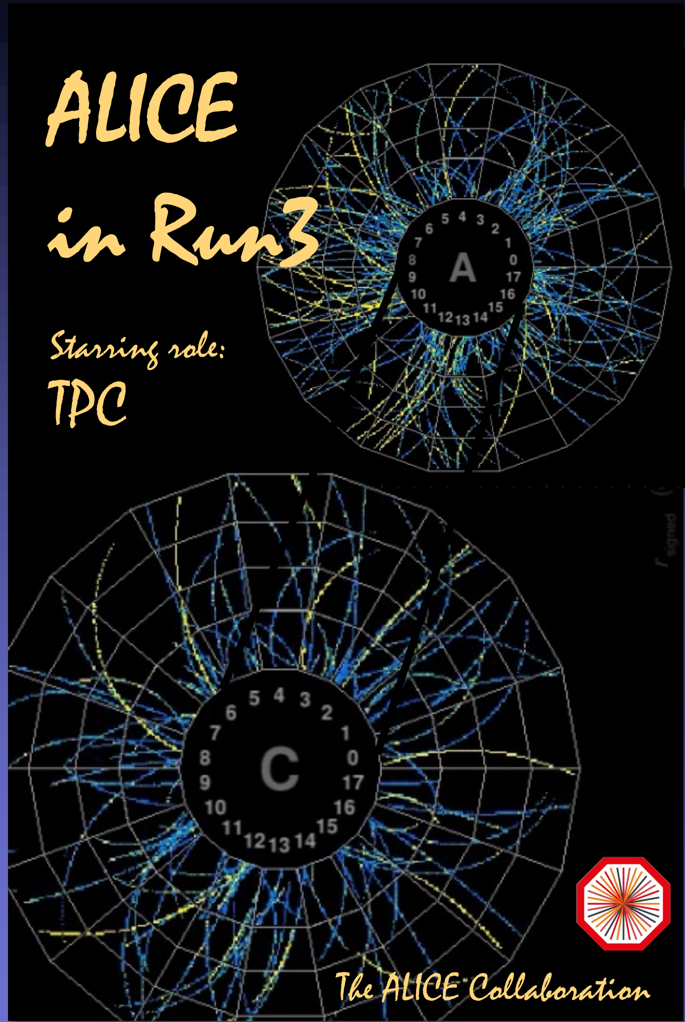


LHC schedule



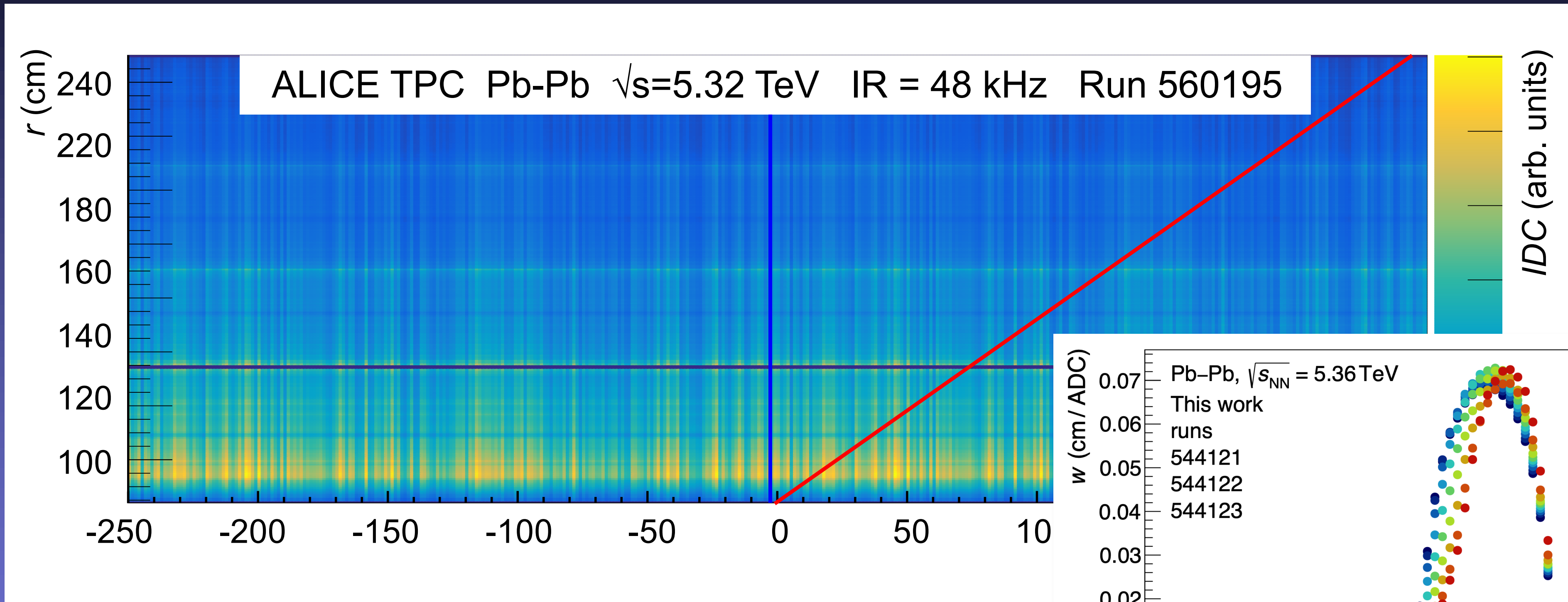
Summary

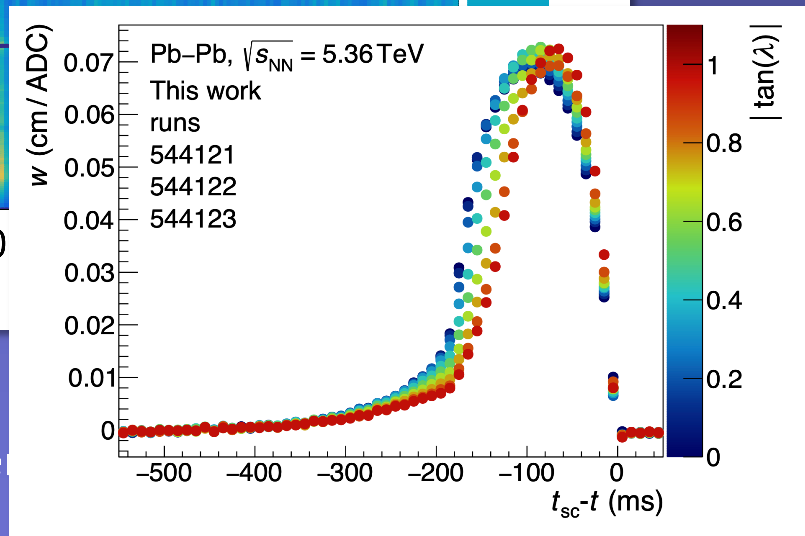
- TPCs have been of crucial importance for the development of heavy ion physics over the last 35 years
- With the successful upgrade of the ALICE TPC to continuous readout, the door was opened to a new era of TPC technology
- This will allow ALICE to dramatically increase the precision in QGP and hadronic physics in the coming years



Backup

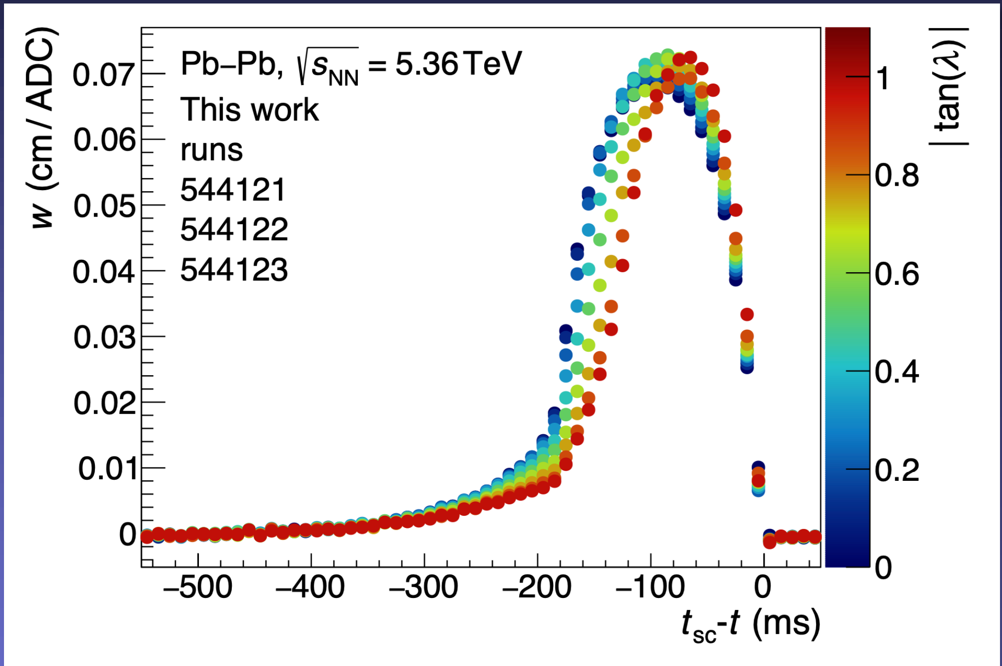
Ion density distribution





- Ion density distribution in TPC volume derived from IDC data
- At 50 kHz, ions from previous 10,000 Pb-Pb collisions are ove

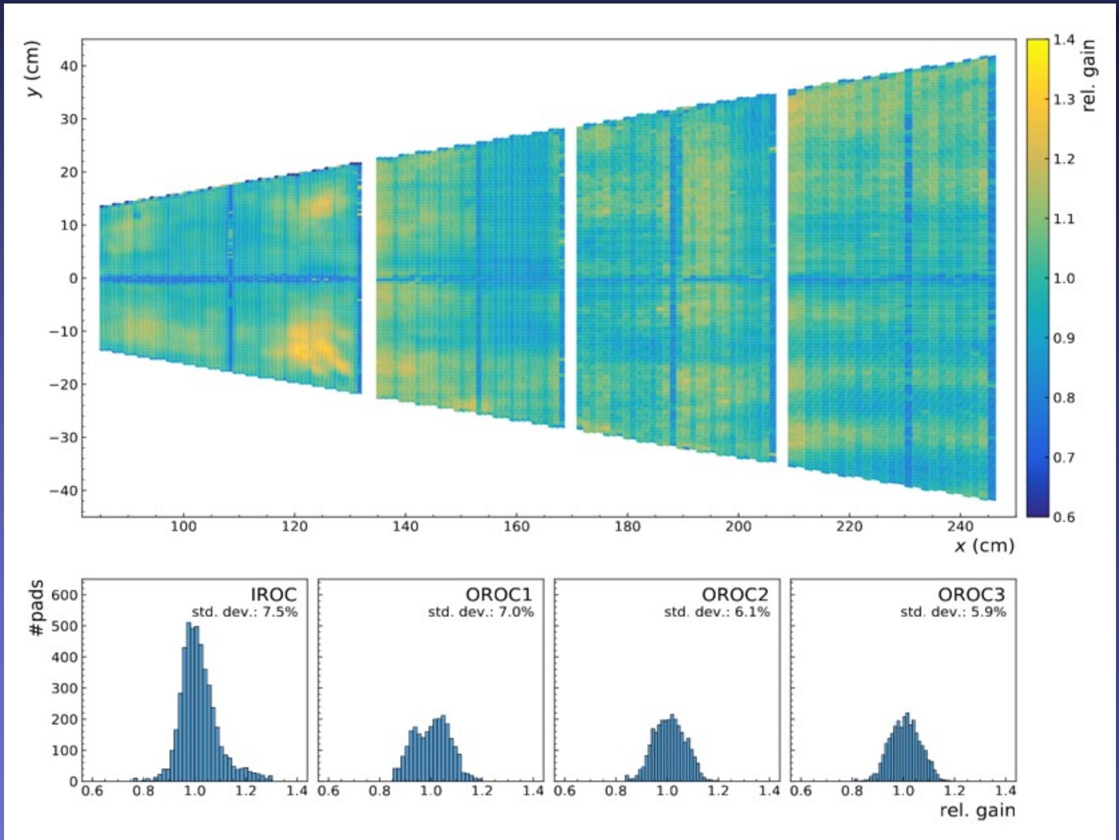
Ion density distribution

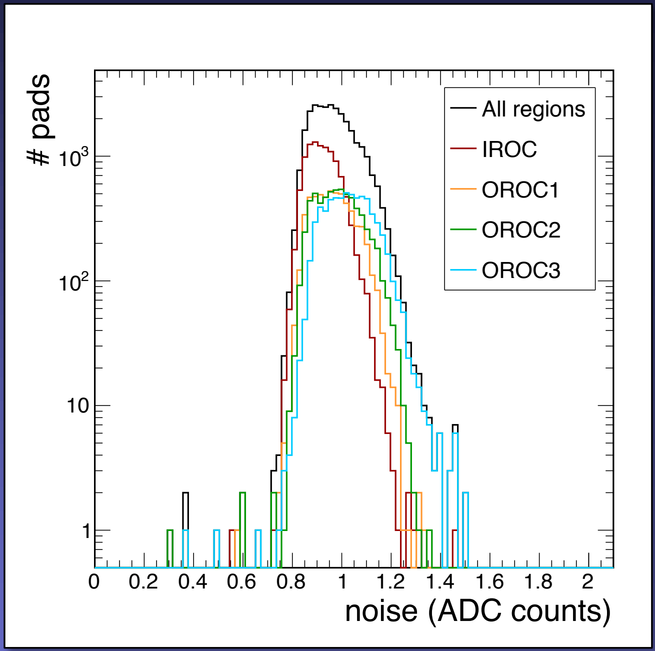


- Correlation strength w between track distortion and *IDC* value as function of time difference
- Compatible with total ion drift time of 200 ms
- Strongest correlation with ions in the center of the drift volume
- Track angle resp. drift length dependence

→ IDCs are most important tool to correct space-charge distortion fluctuations

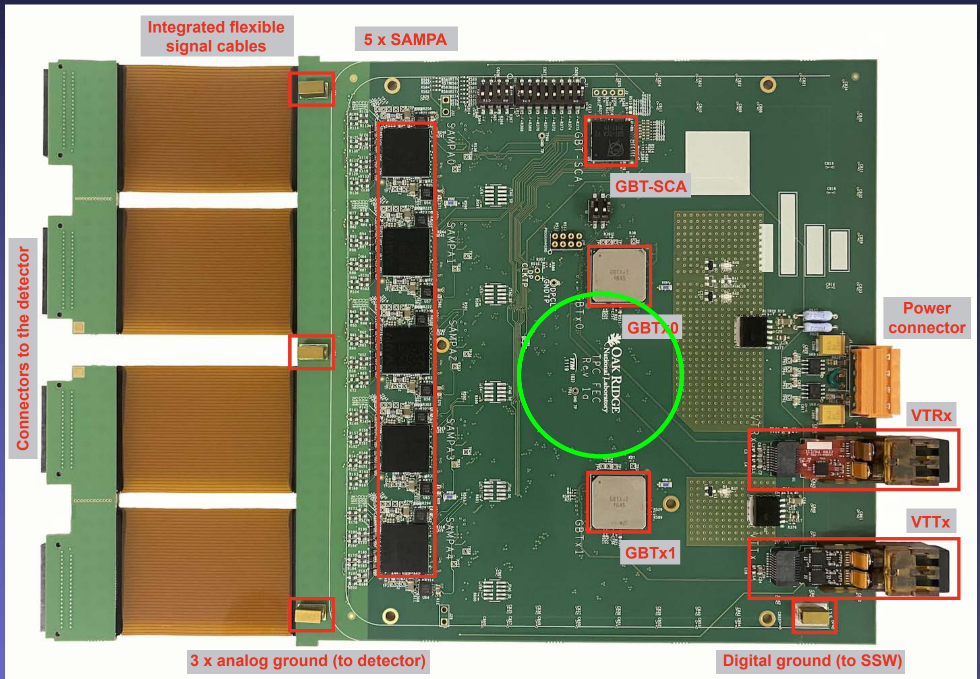
TPC is ready





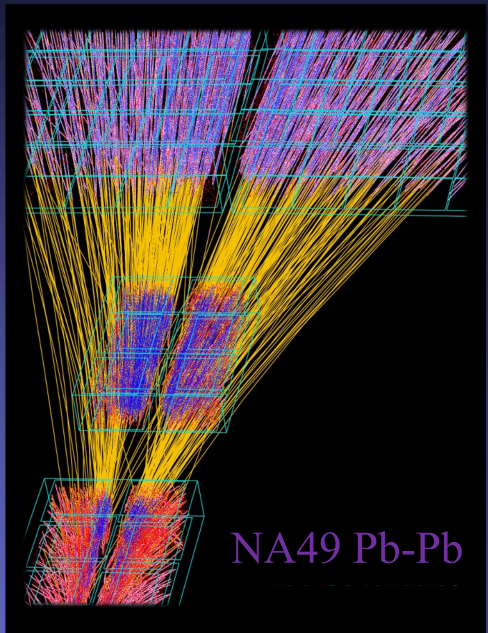
- Noise level 1 ADC (670 e-)
- Gas gain uniformity 6-8% (from X-ray illumination)

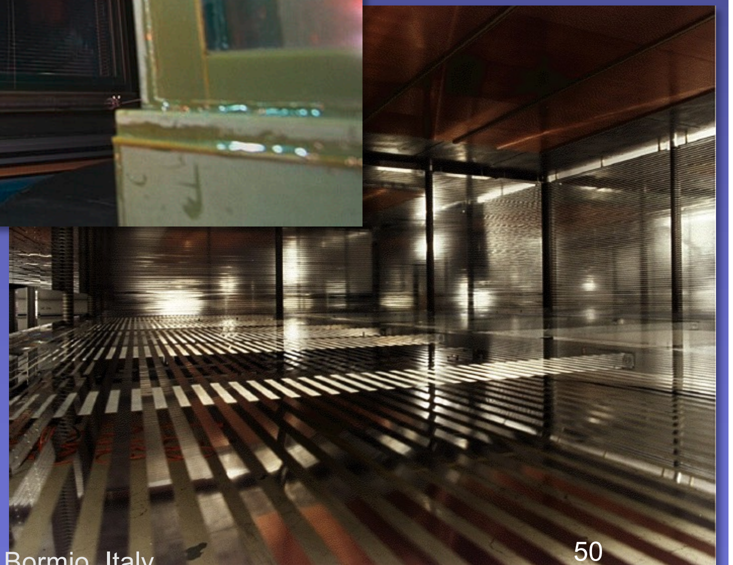
ALICE TPC upgrade



- FEC design, production, and mass test at ORNL
- Readout Chamber mechanics at UT Knoxville

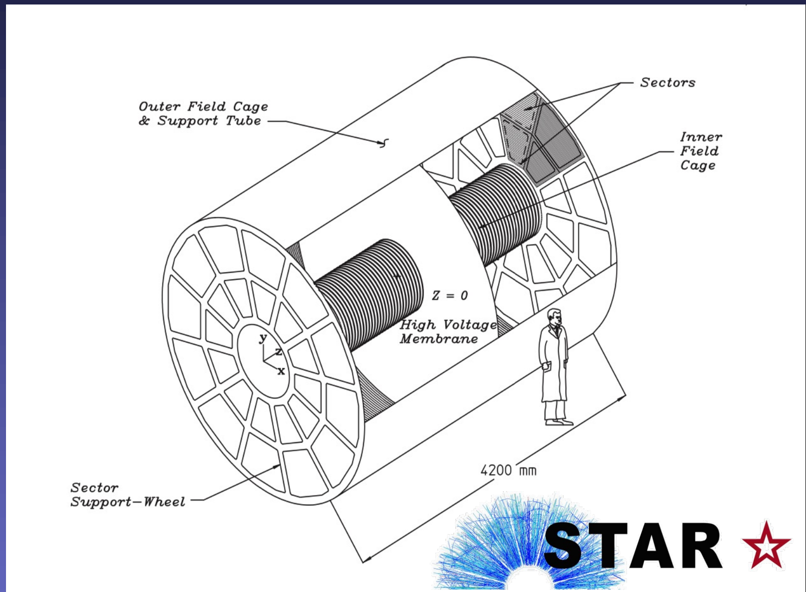
NA49

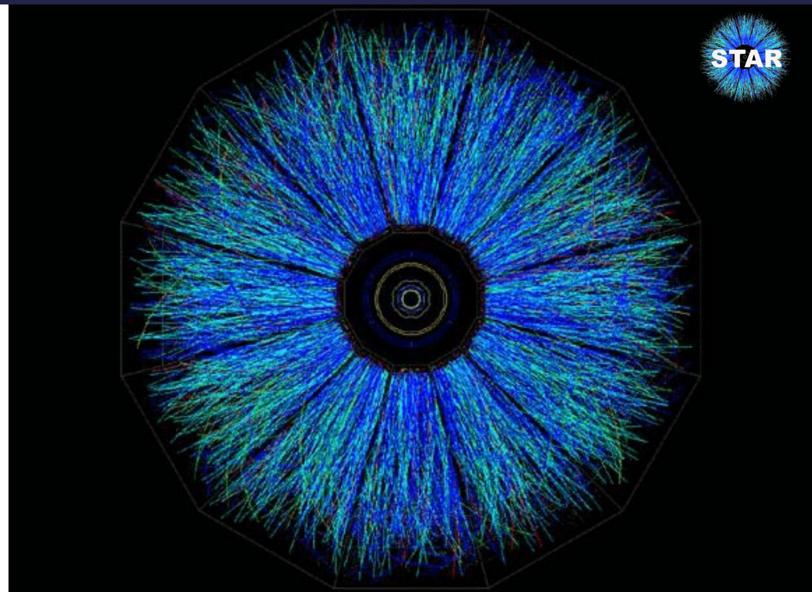




- operated at the SPS since 1994 (30 years of lead beams at CERN)
- 4 large scale TPCs (2 in dipoles, 2 in field-free region)
- low-Z and cool gases (Ne-CO_2, Ar-CO_2-CH_4)
- low-mass field cage structures

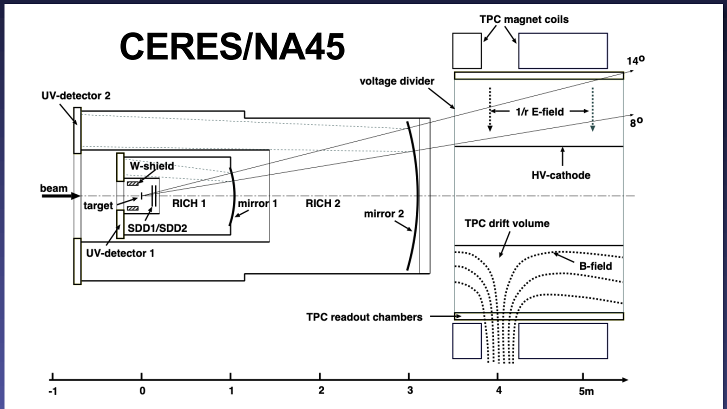
STAR

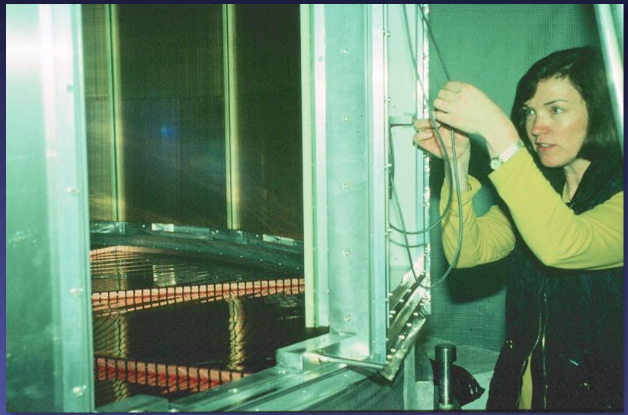


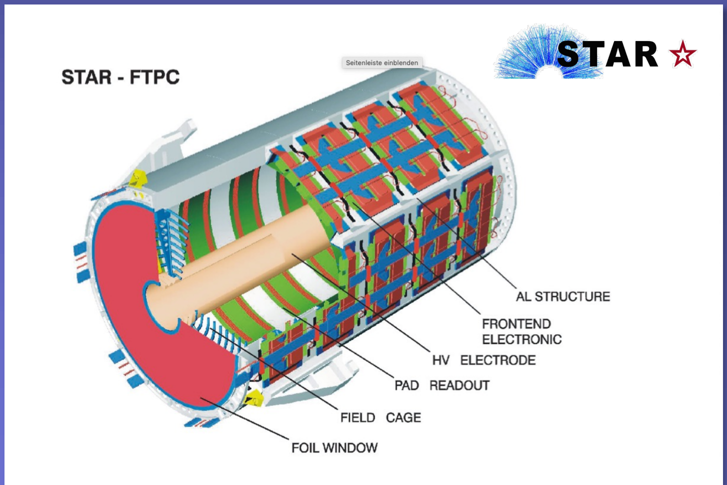


- at RHIC (BNL) since 2000
- Main design features and dimensions as in ALEPH, B = 0.5 T, P-10
- Innovative readout electronics, 140,000 channels (200,000 after Inner Sector upgrade)

radial drift TPCs



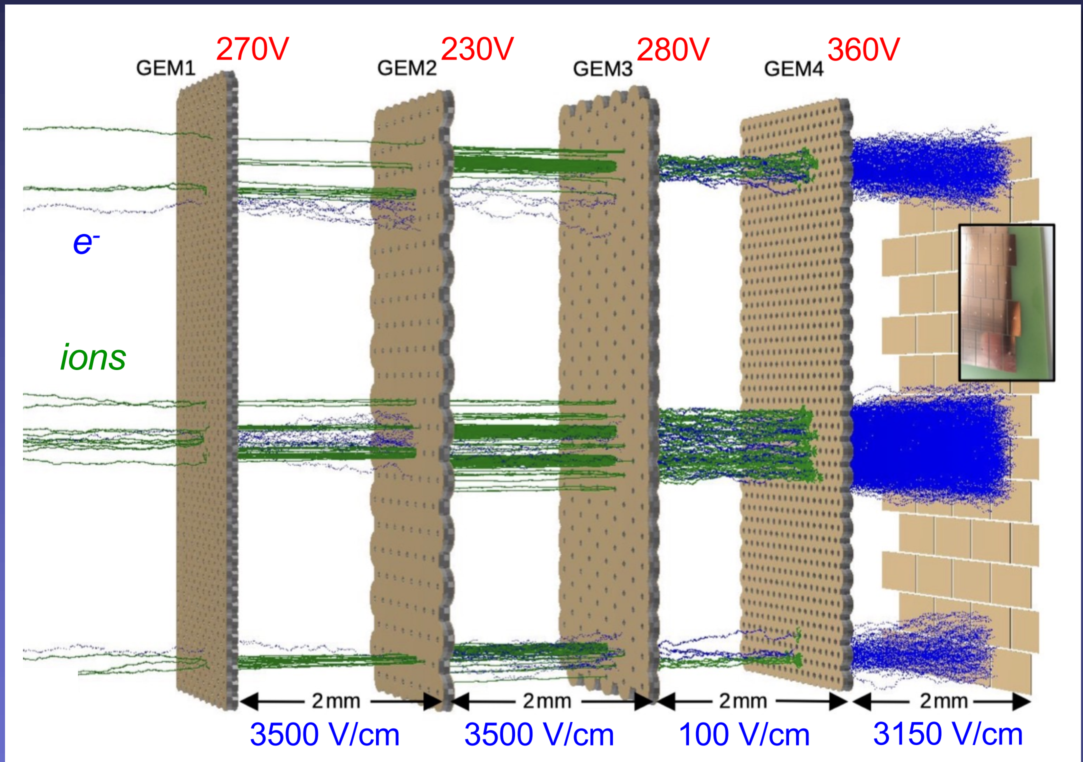




STAR FTPCs (2001-2014) and CERES/NA45 TPC (1998-2000)

- In forward direction and in azimuthally symmetric experiments
- ExB: cool gases preferred

Multi-GEM layer



- Single GEM has *IBF* = O(10%)
  → need multi-layer solution

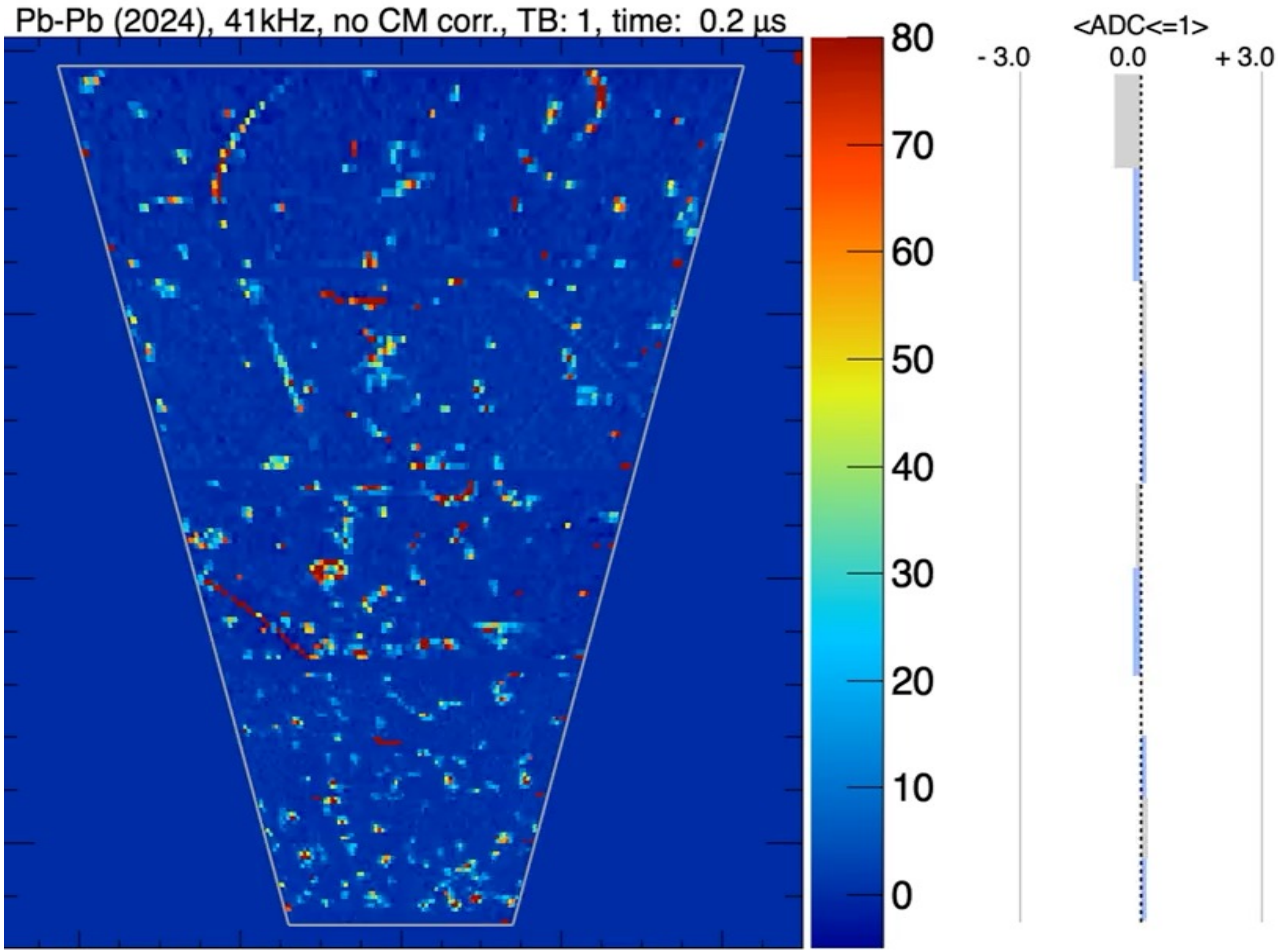
- Sub-divide into pre- and main amplification stage
- Two GEMs each are needed
- Configuration of transfer fields and GEM geometry (e.g. hole pitch) subject of extensive R&D activities

Solution:

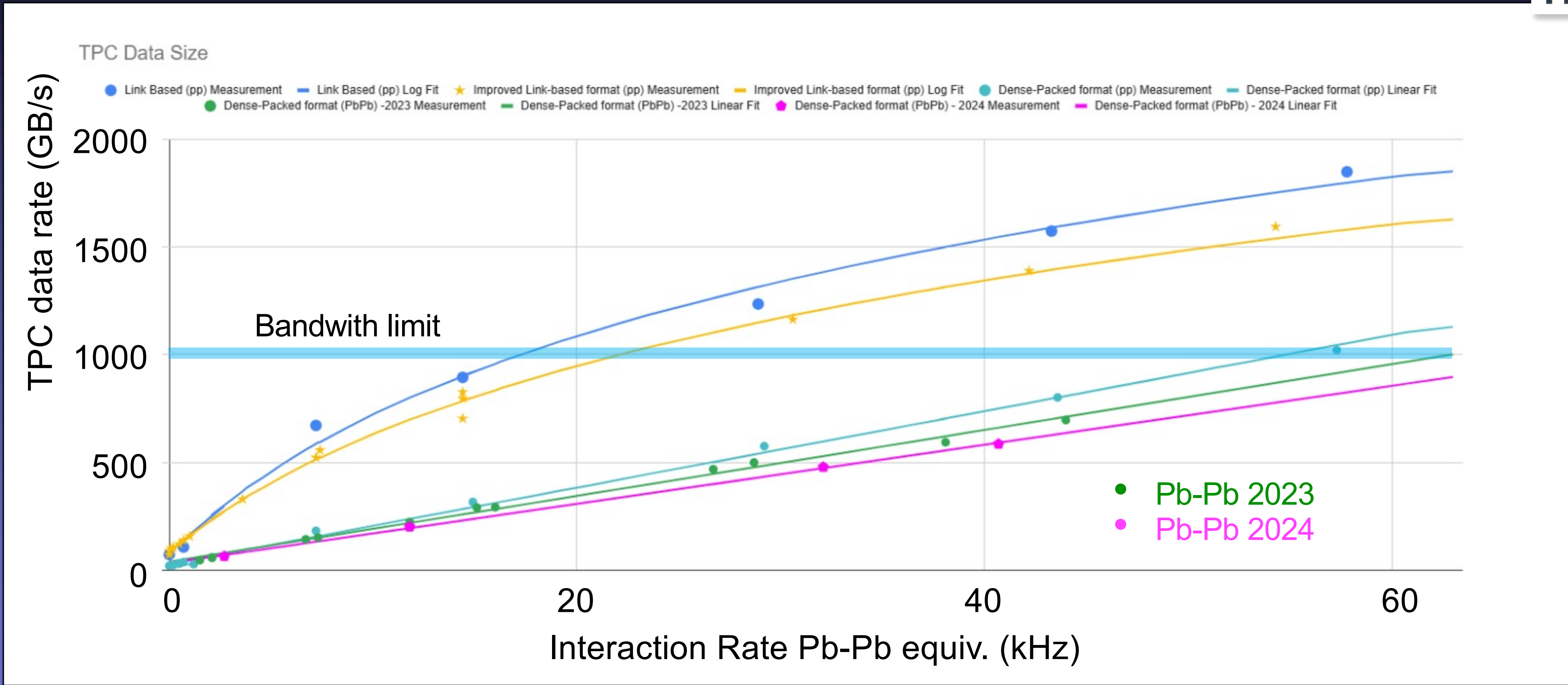
- 4-GEM layer with S-LP-LP-S geometry
- Low transfer field $E_{T,3}$ = 0.1 kV/cm

S: Standard hole pitch 140 μm

LP: Large hole pitch 280 μm


Pb-Pb (2024), 41kHz, no CM corr., TB: 1, time: 0.2 µs
80
70
60
50
40
30
20
10
0
<ADC<=1>
- 3.0
0.0
+ 3.0

TPC data size



- TPC data size in Pb-Pb at 50 kHz well below bandwidth limit