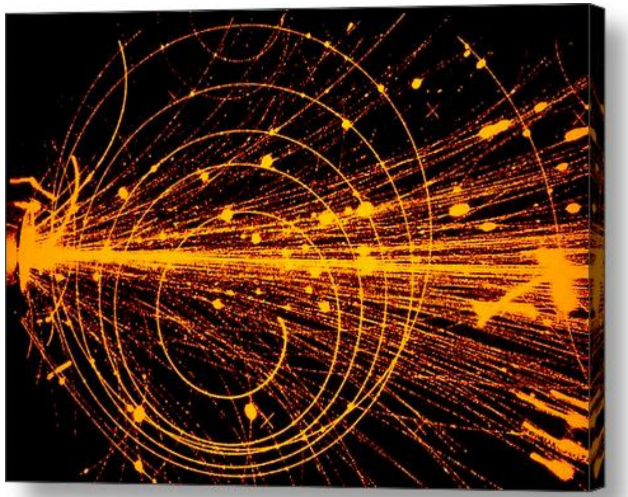
The Heavy Ion Tools :
from Streamer Chambers to Monolithic Pixel Detectors

Luciano Musa - CERN

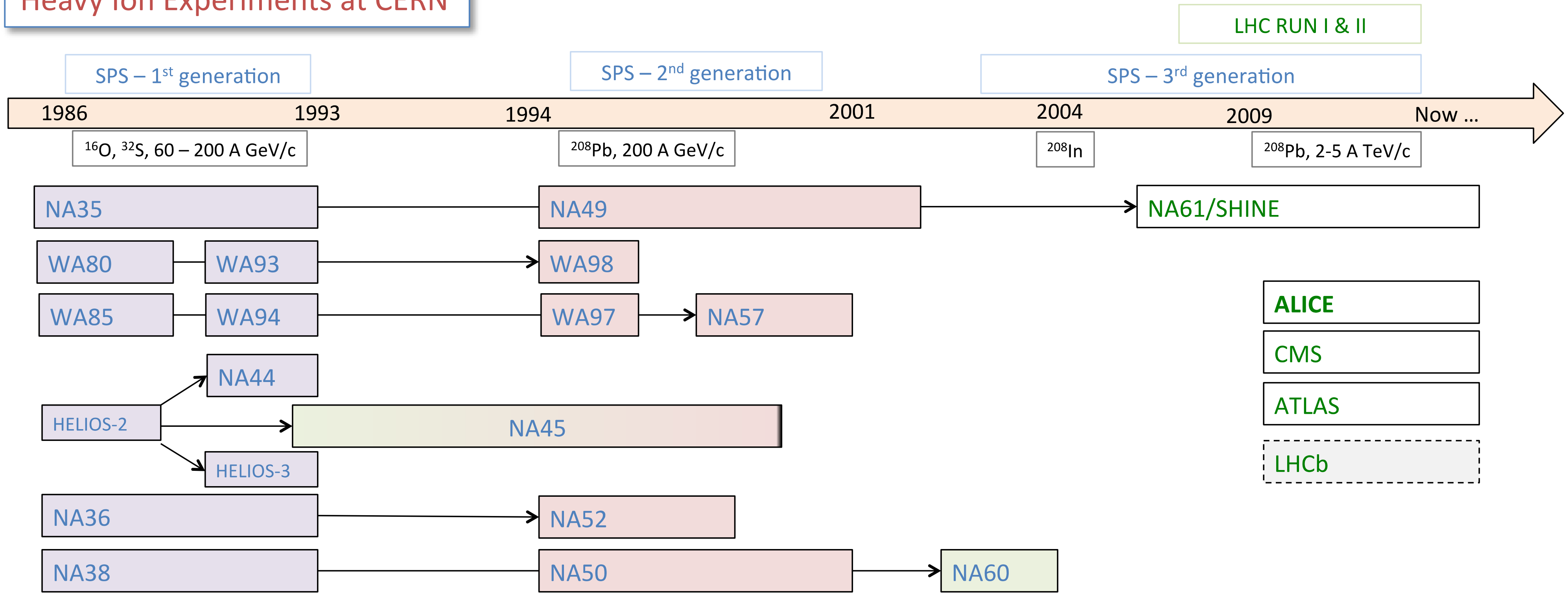


30 Years of Heavy Ions: … what next?
CERN, 9 November 2016

The Heavy Ion Tools
from Streamer Chamber to Monolithic Pixel Detectors

Accelerators | **Detectors** | Data Readout | Data Processing

Heavy Ion Experiments at CERN



The Beginning … NA35

"Survey study" (with WA80) of interactions induced by 60 and 200 GeV/nucleon ^{16}O (and later ^{32}S)

➡ Study of stopping power of nuclear matter

➡ Search for signature of the deconfinement transition

y and $<p_T>$ distributions for π^+, π^-, K^0_s, Λ^o ,

K/π yields

Two π correlations in a wide acceptance

Event-by-event multiplicity and rapidity correlations

Detector general requirements

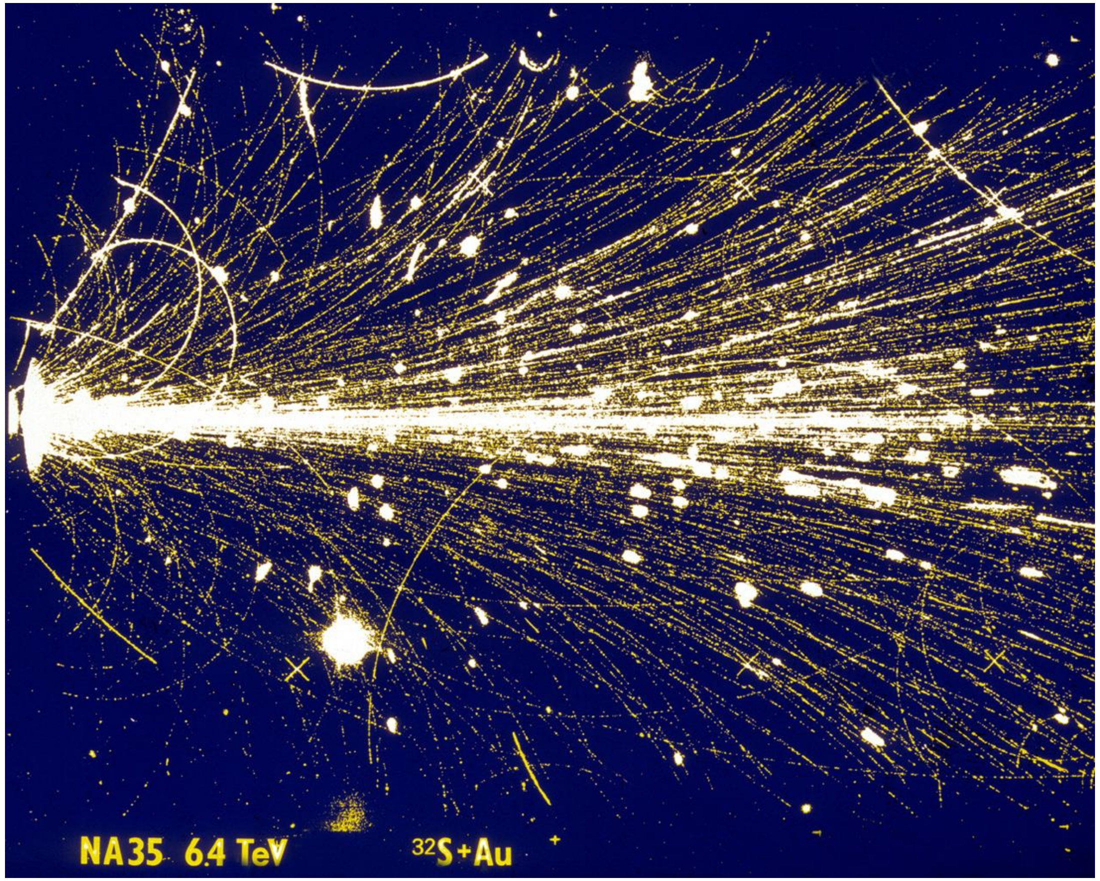
- Reliable detection of very high multiplicities — up to few hundred particles for central collisions
- Excellent two-track resolution — target <2mm
- 4π trigger-able detector with low X_0 — minimization of δ-rays
- Hadronic and EM calorimetry

⬇

Vertex Streamer Chamber triggered by a set of calorimeters covering interaction full rapidity range

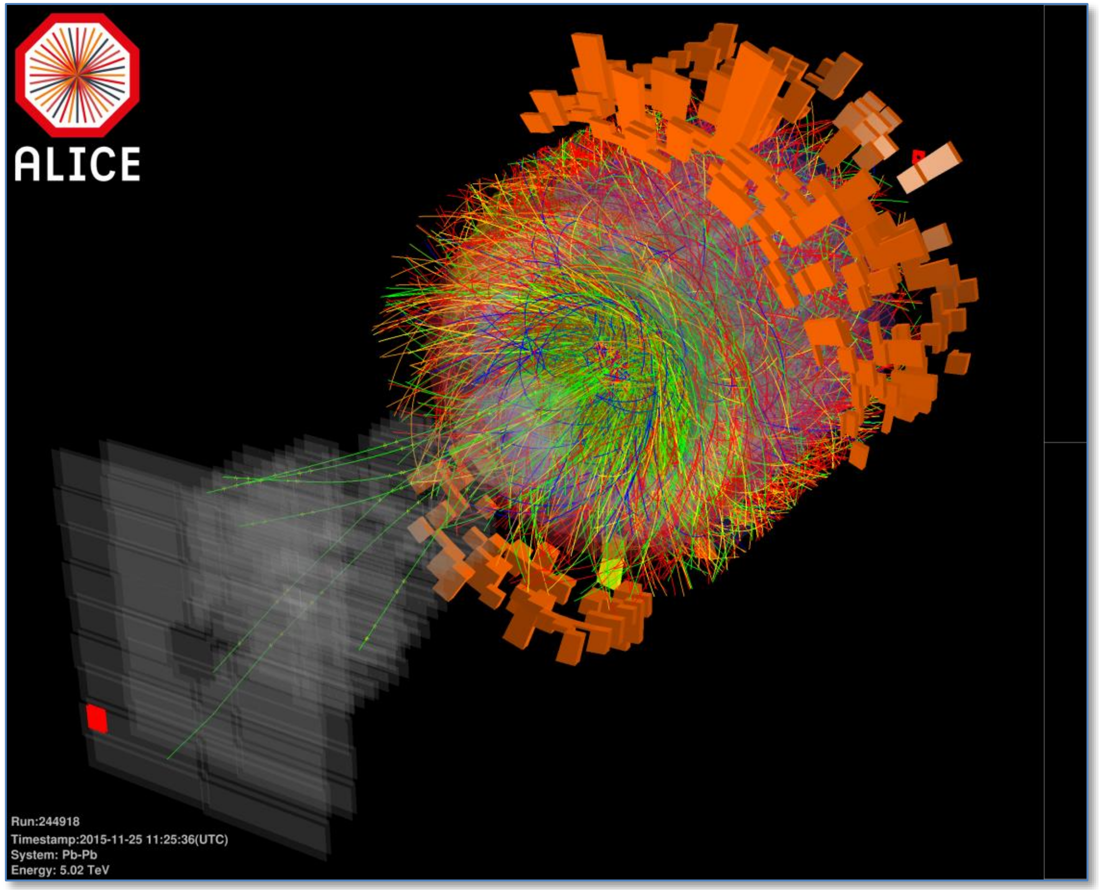
Tracking in HI experiments: a Challenging Task

~ hundred charged particles



NA35 - 200 A GeV ^{32}S + AU (~1990)

~ tens of thousands charged particles



ALICE – 5.02 A TeV Pb-Pb (2015)

The Beginning … NA35 (and WA80)

"Survey study" of interactions induced by 60 and 200 GeV/nucleon ^{16}O (and later ^{32}S)

➡ Study of stopping power of nuclear matter

➡ Search for signature of the deconfinement transition

y and <p_T> distributions for π^+, π^-, K^0_s, Λ^o ,

Two π^- correlations in a wide acceptance

K/π yields

Event-by-event multiplicity and rapidity correlations

Detector general requirements

- Reliable detection of very high multiplicities — up to few hundred particles for central collisions
- Excellent two-track resolution — target <2mm
- 4π trigger-able detector with low X_0 — minimization of δ-rays
- Hadronic and EM calorimetry

Vertex Streamer Chamber triggered by a set of calorimeters covering interaction full rapidity range

Why a Streamer Chamber?

Streamer Chamber Features

Tracking detection of good quality

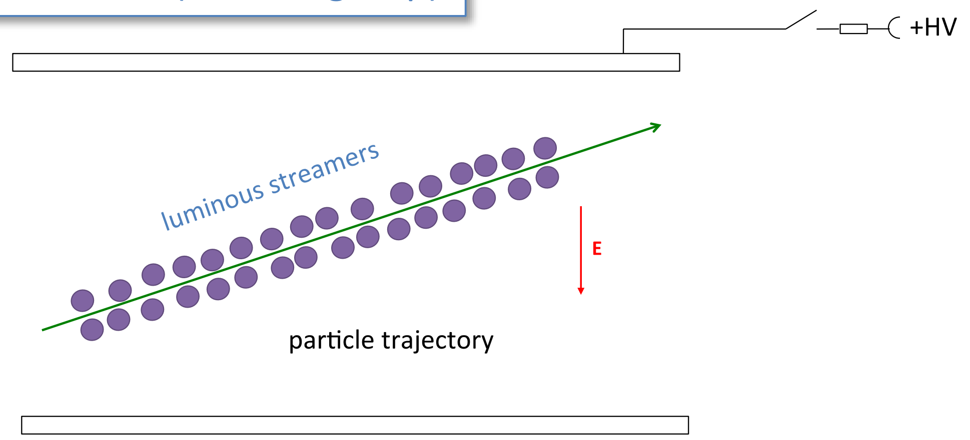
➡ continuous trail of small luminous streamer discharges along the particle path

➡ 100% efficiency and 4π detection (only tracks aligned with E could degenerate in a spark)

➡ Fast triggerable detection (~1μs)

➡ Low material budget: ~ few % X_0 for a 2m chamber

Invented in 1963
- Chicovani et al. (Georgian group)
- Doldgoshein et al. (Russian group)



Streamer chamber principle of operation

Bad reputation in the late 60s: "Bad" bubble chamber (much worse spatial resolution), "Slow" electronic track chamber: slow data taking rate (~Hz) and tedious picture analysis

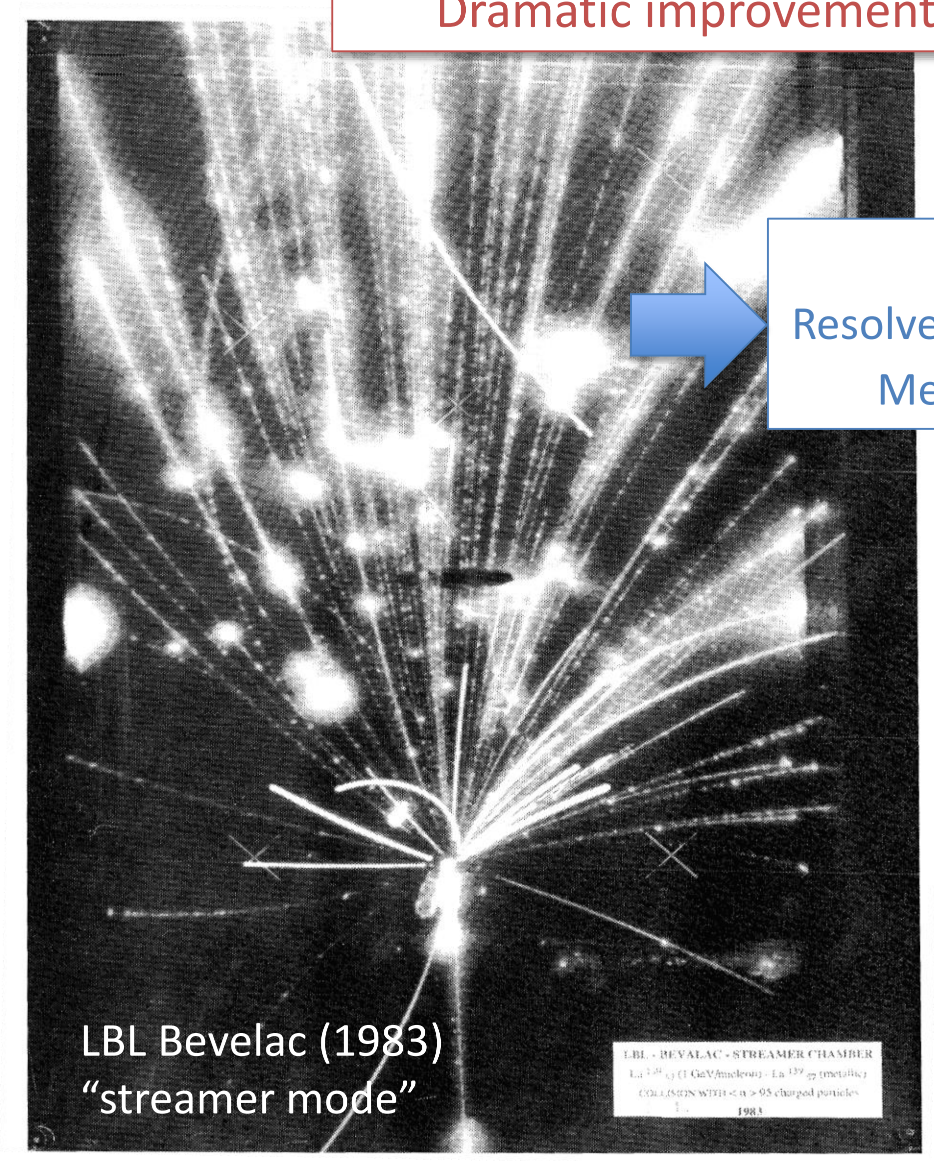
1st Breakthrough: large-scale high-resolution, high-gain image intensifier

"Avalanche Chamber"

➡ possible to photograph tracks before avalanches reach streamer regime (gain < 10^9)

Streamer Chamber ➔ Avalanche Chamber

Dramatic improvement of a picture of a streamer chamber

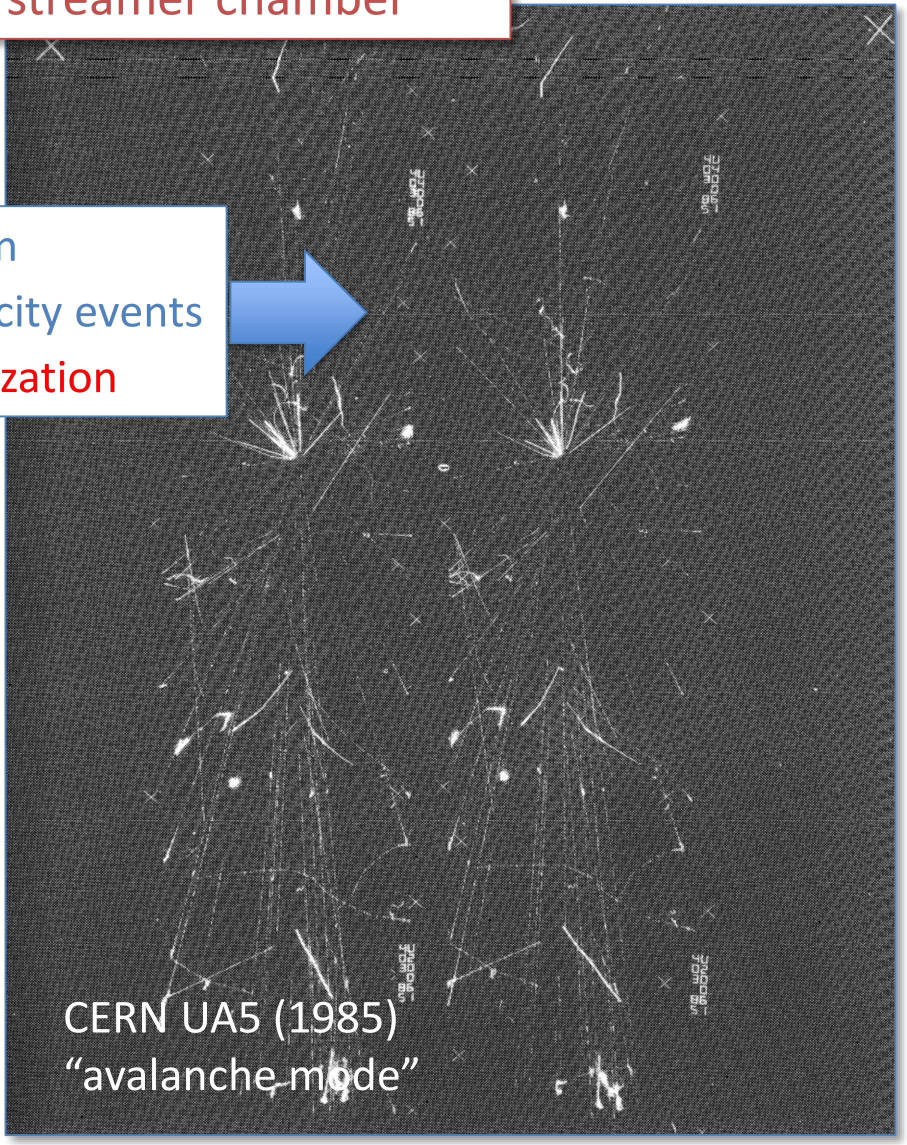


LBL Bevelac (1983)
“streamer mode”

Higher resolution

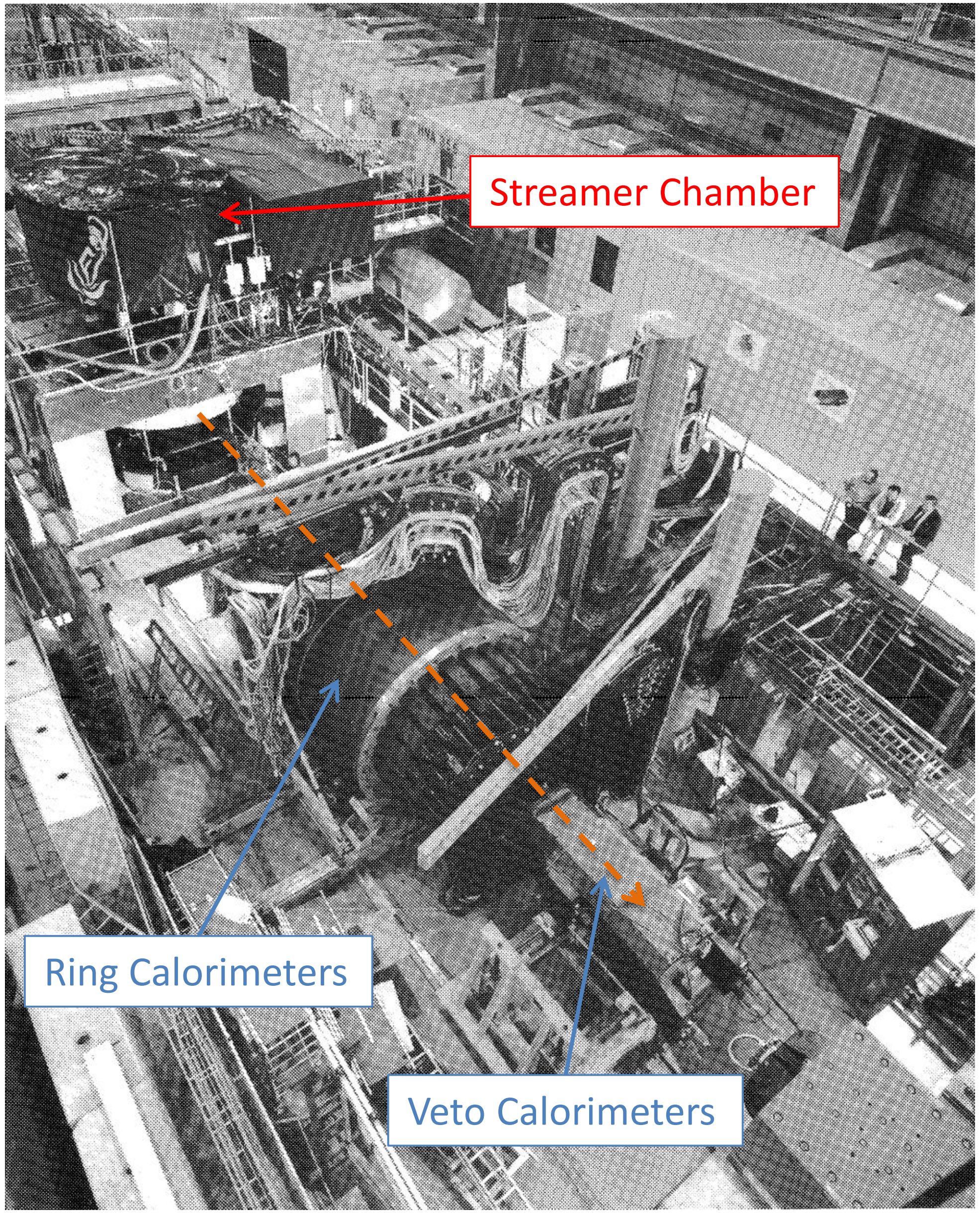
Resolve very high multiplicity events

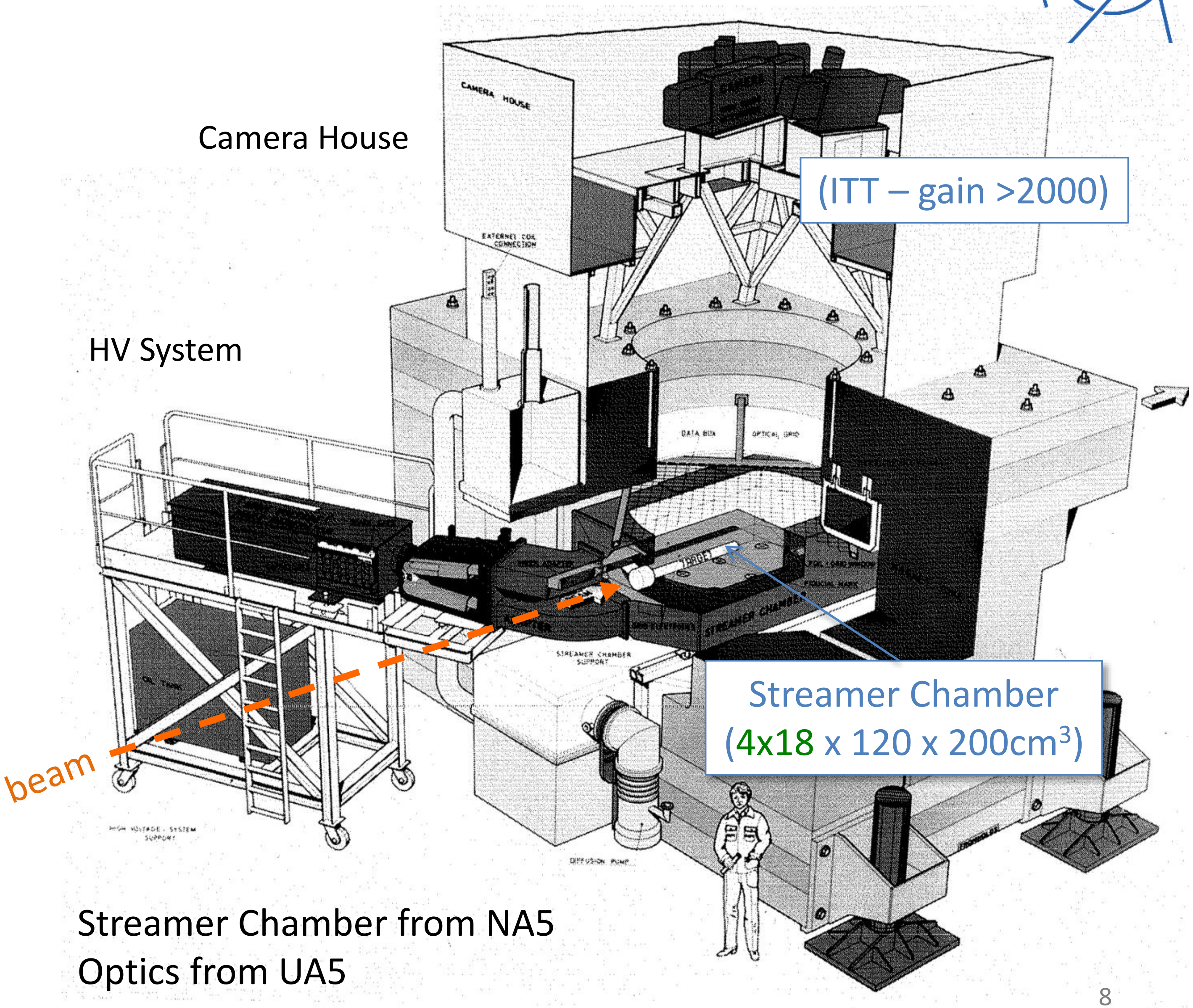
Measure primary ionization



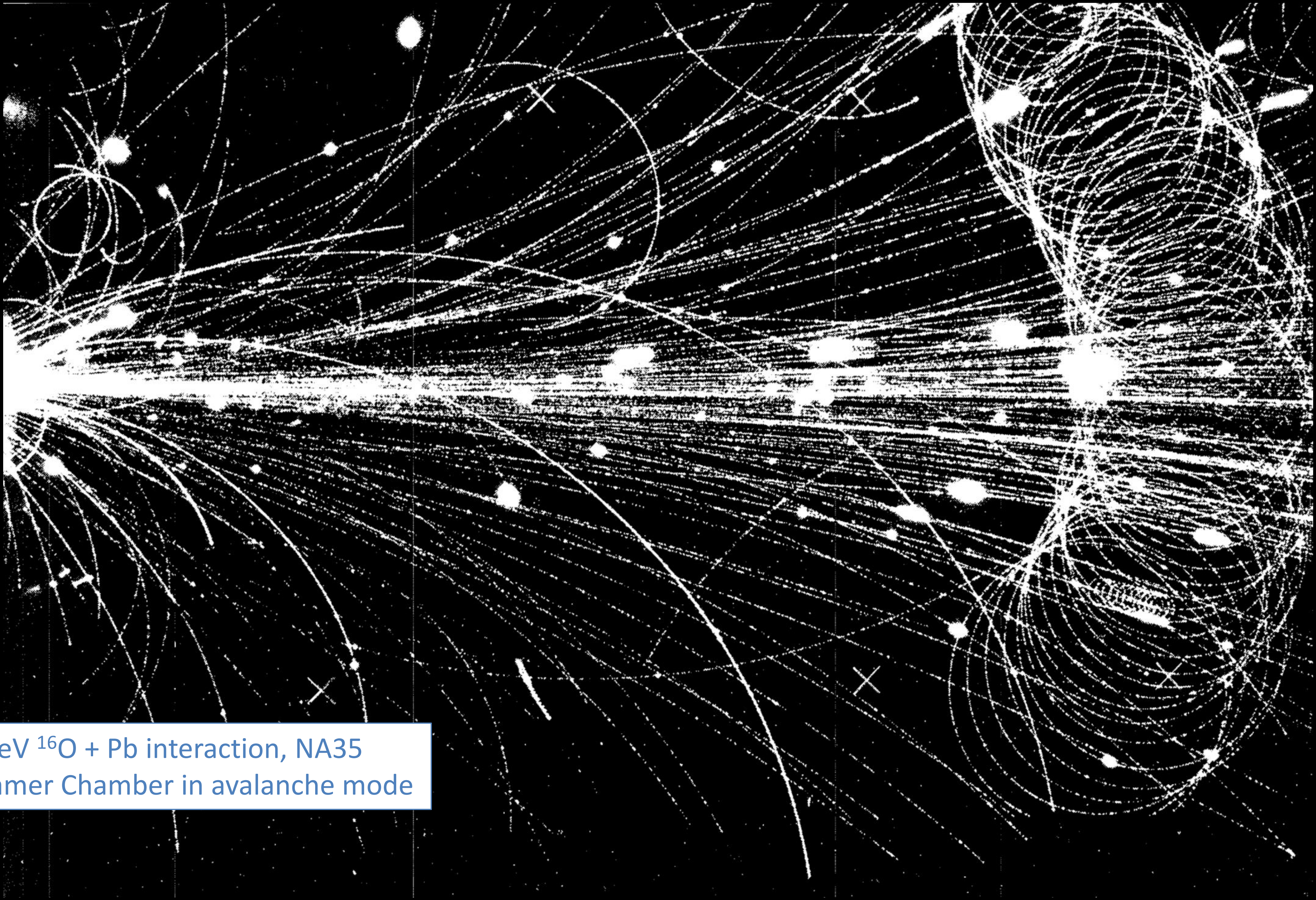
CERN UA5 (1985)
“avalanche mode”

NA35 – The Streamer Chamber Heavy Ion Experiment





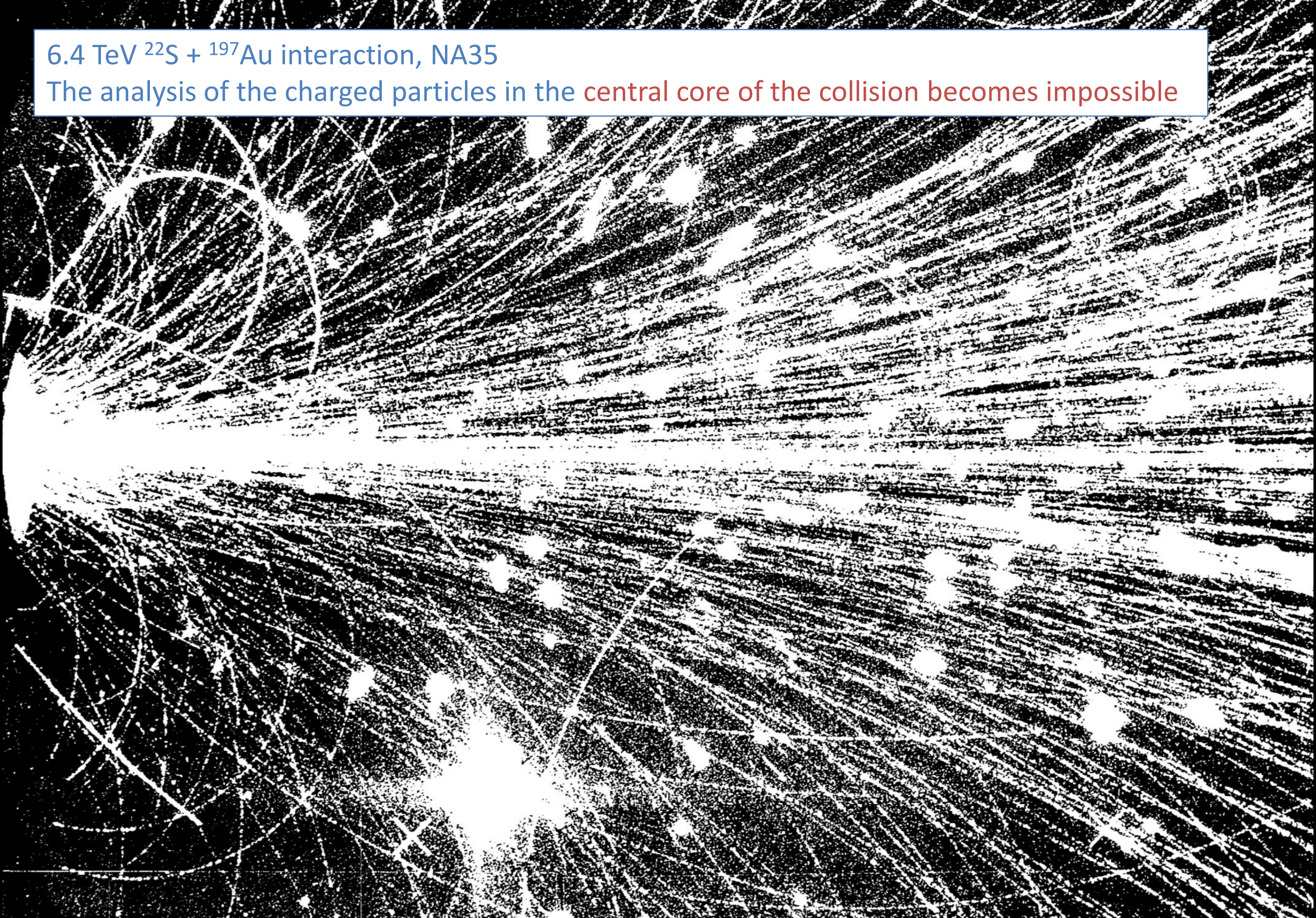
Streamer Chamber from NA5
Optics from UA5



3.2 TeV ^{16}O + Pb interaction, NA35
Streamer Chamber in avalanche mode

6.4 TeV ^{22}S + ^{197}Au interaction, NA35

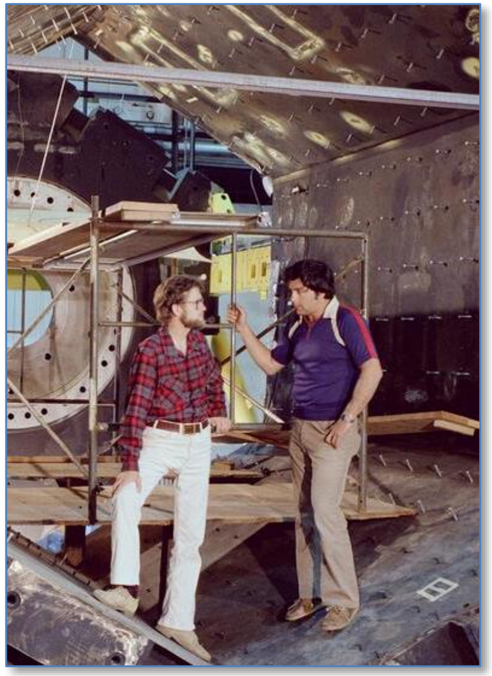
The analysis of the charged particles in the central core of the collision becomes impossible



The Advent of the Time Projection Chamber (TPC)

"The purest realization of the dream of an electronic bubble chamber …" (P. Galison)

Invented by David Nygren (LBL)



First informal report on the proposed detector: 22 February 1974

"Consider … the experimental difficulties confronting the physicist who wishes to detect in entirety an event occurring in PEP (Positron-Electron Project). It must operate in high backgrounds, have very good spatial resolution in order to measure momenta[,] … be able to reconstruct many tracks occurring over 4π [i.e. to detect in all directions] unambiguously, identify particle types, …"

Some of the large TPCs operated in HEP experiments

(particle-physics)		*(heavy ions)*
PEP4	1982/1984	
TRIUMF	1982/1983	
TOPAZ	1987	
ALEPH/DELPHI	1989	
	1990	NA35
	1992	EOS/HISS
	1995	NA49 (4)
	1999	CERES
	2000	STAR
HARP	2001	
	2008	ALICE
T2K	2009/2010	

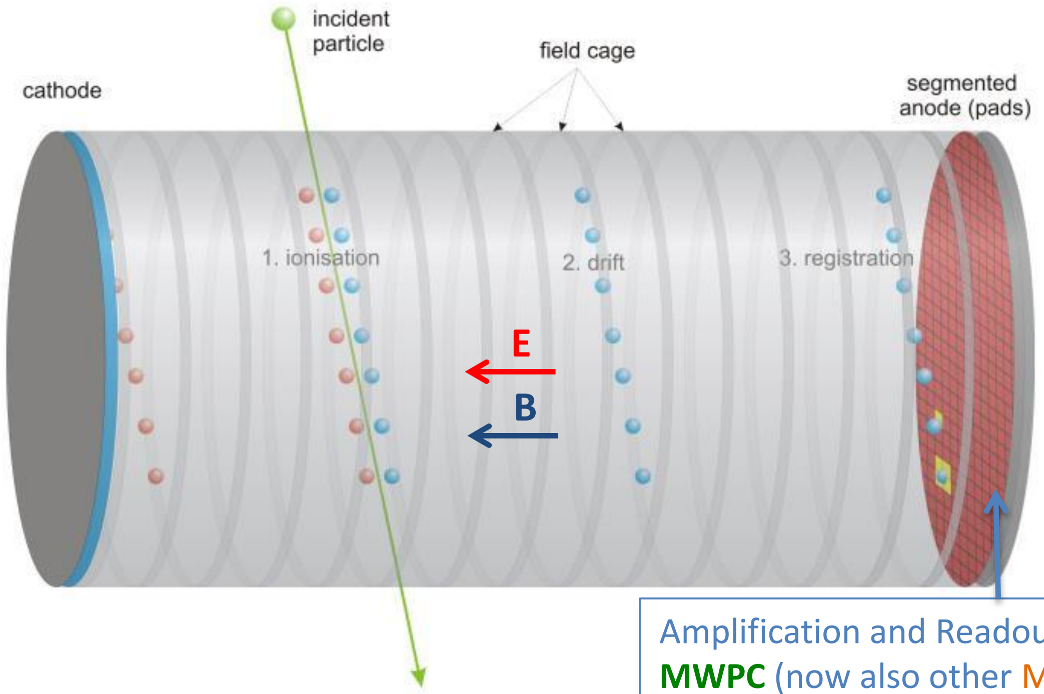
The Advent of the Time Projection Chamber (TPC)

Time Projection Chamber

It is a volume of gas with collinear electric and magnetic fields that guide the ionized tracks to the end caps, where the signals contained in the tracks are amplified and sampled (MWPC), and digitized

Main features

- Continuous 3-D track reconstruction
- Particle Identification by dE/dx
- Can handle very large track densities
- Only gas in active volume, small amount of material
- Long drift , up to several meters
- Slow detector , detector memory up to 100 μs



Amplification and Readout
MWPC (now also other MPGD)

Nygren's intuition: B collinear to E would suppress electron cloud diffusion by a factor dependent on the cyclotron frequency

NA35 TPC – First TPC in a HI experiment (1990)

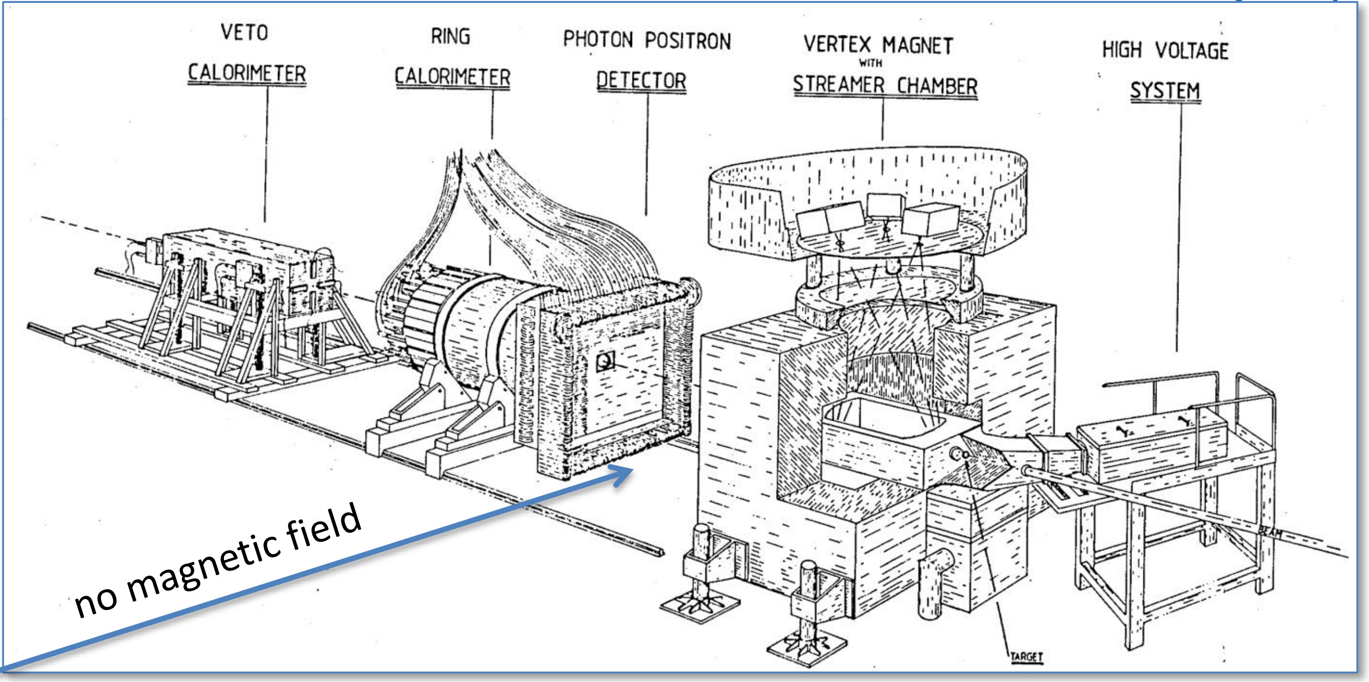
R. Bock and R. Brockmann
Gesellschaft für Schwerionenforschung, D-6100 Darmstadt 11, Germany

R. Renfordt, G. Roland, R. Stock and S. Wenig
Fachbereich Physik, Universität Frankfurt, D-6000 Frankfurt / M, Germany

T. Alber, V. Eckardt, H. Fessler, M. Kowalski, W. Rauch, J. Seyboth, P. Seyboth and J. Seyerlein
Max-Planck-Institut für Physik, D-8000 München 40, Germany

The NA35 collaboration has constructed a time projection chamber (TPC) with a sensitive volume of 240 × 1 chamber is operated without a magnetic field and uses pad readout only. During the 1990 run with the ^{32}S hea events were recorded. A description of the detector is given and the performance concerning the position me two-track resolution, and particle identification by ionisation measurement is discussed.

and J. Seyerlein
Max-Planck-Institut für Physik, D-8000 München 40, Germany



Layout of the NA35 relativistic heavy-ion experiment at CERN SPS in 1987

no magnetic field

NA35 TPC

33–38

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

only pad readout: 11520

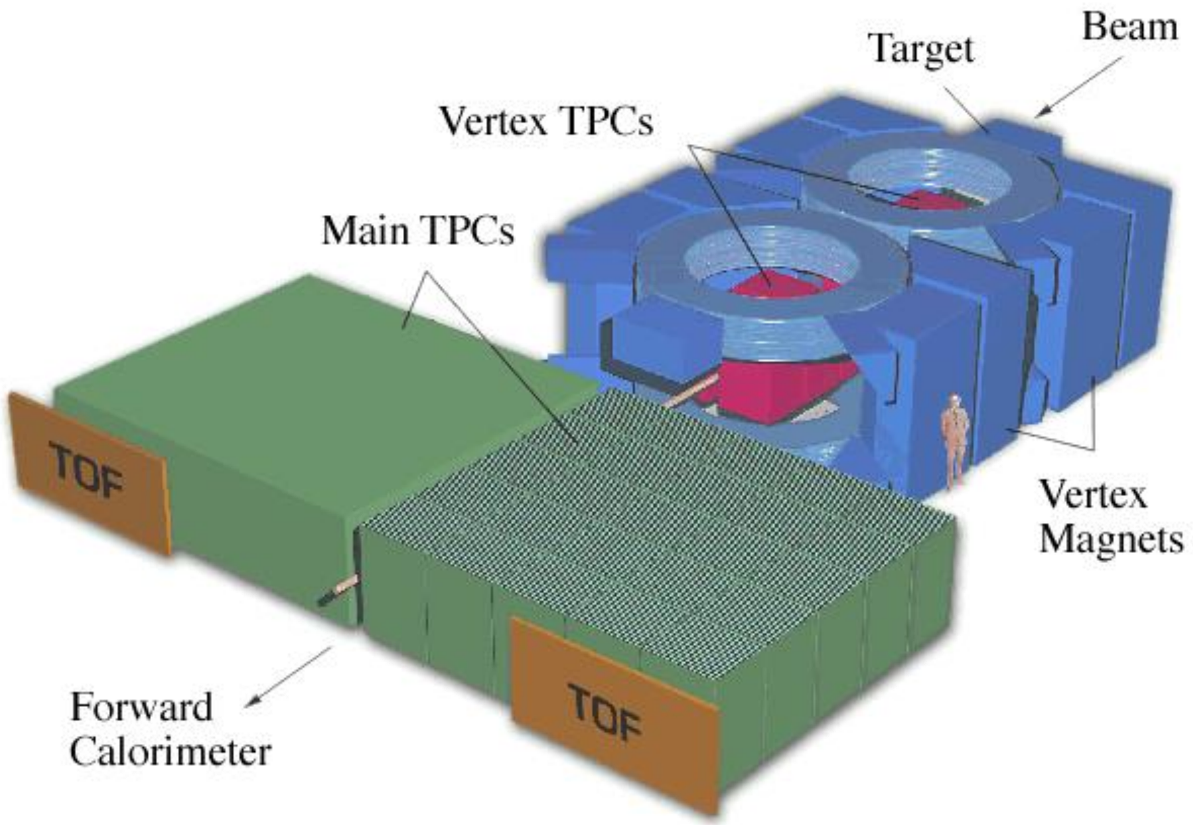
Motivations

- Extend useful acceptance (streamer chamber pictures are unsolvable in the forward cone of ±10^0 (rapidity y ≥ 3)
- Test for a detector system "to be used in experiments with Pb beams at CERN starting in 1994" *(NA49, editor's note)*

NA49 TPCs – A formidable challenge to experimental techniques

MTPCs - Two large-volume fine-granularity TPCs (~16m^3) to measure the ionization energy loss

VTPCs - Two intermediate size TPC's (~3m^3) inside dipole superconducting magnets (B = 1.5T) for momentum measurement and vertex tracking of neutral strange particle decays



The acceptance coverage ~ 70-80% of all charged particles

High-track density → pad readout only

Total nr pads: 180,000

Max readout rate: ~10Hz

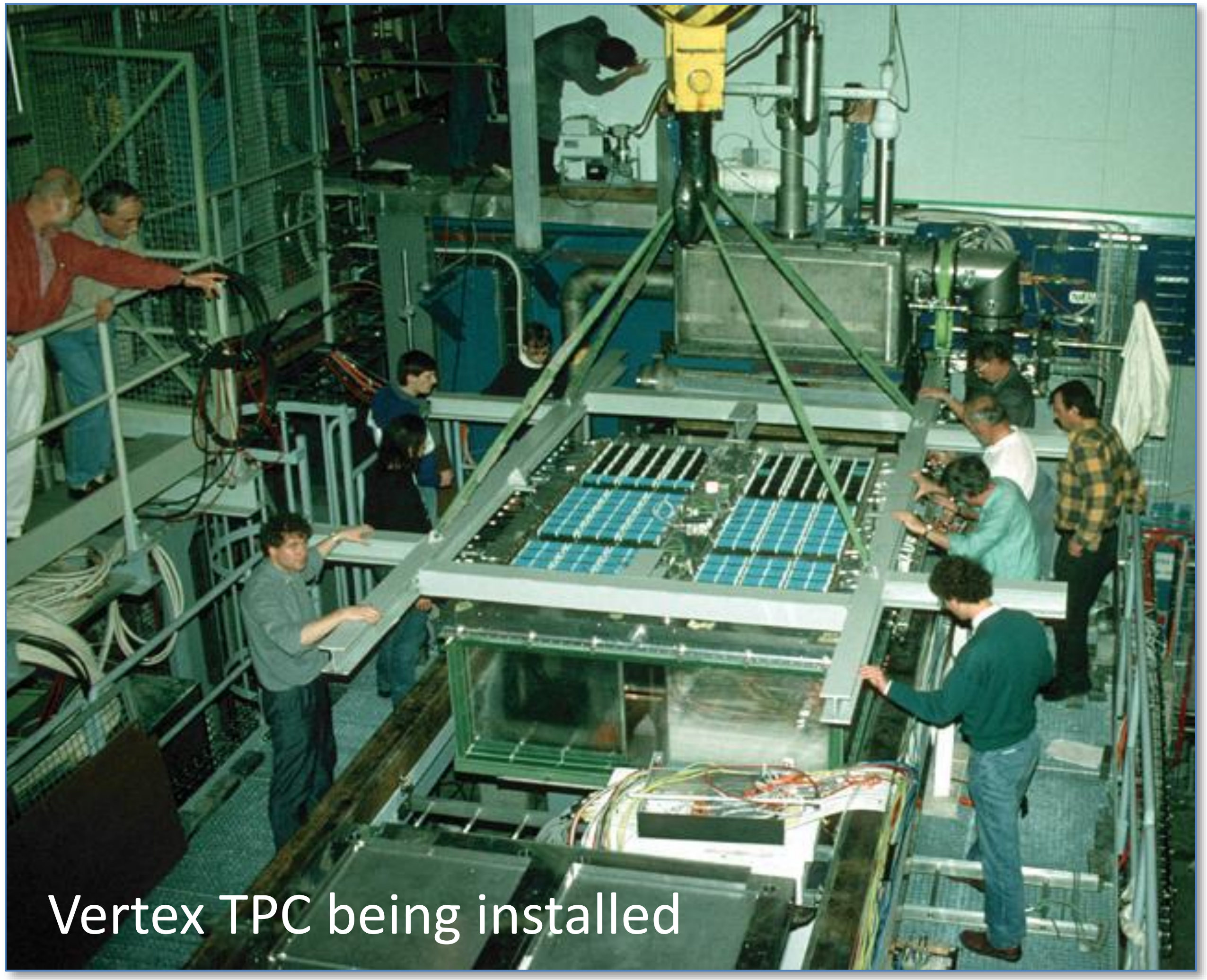
First time no use of the "standard gas" (Ar-CH_4)

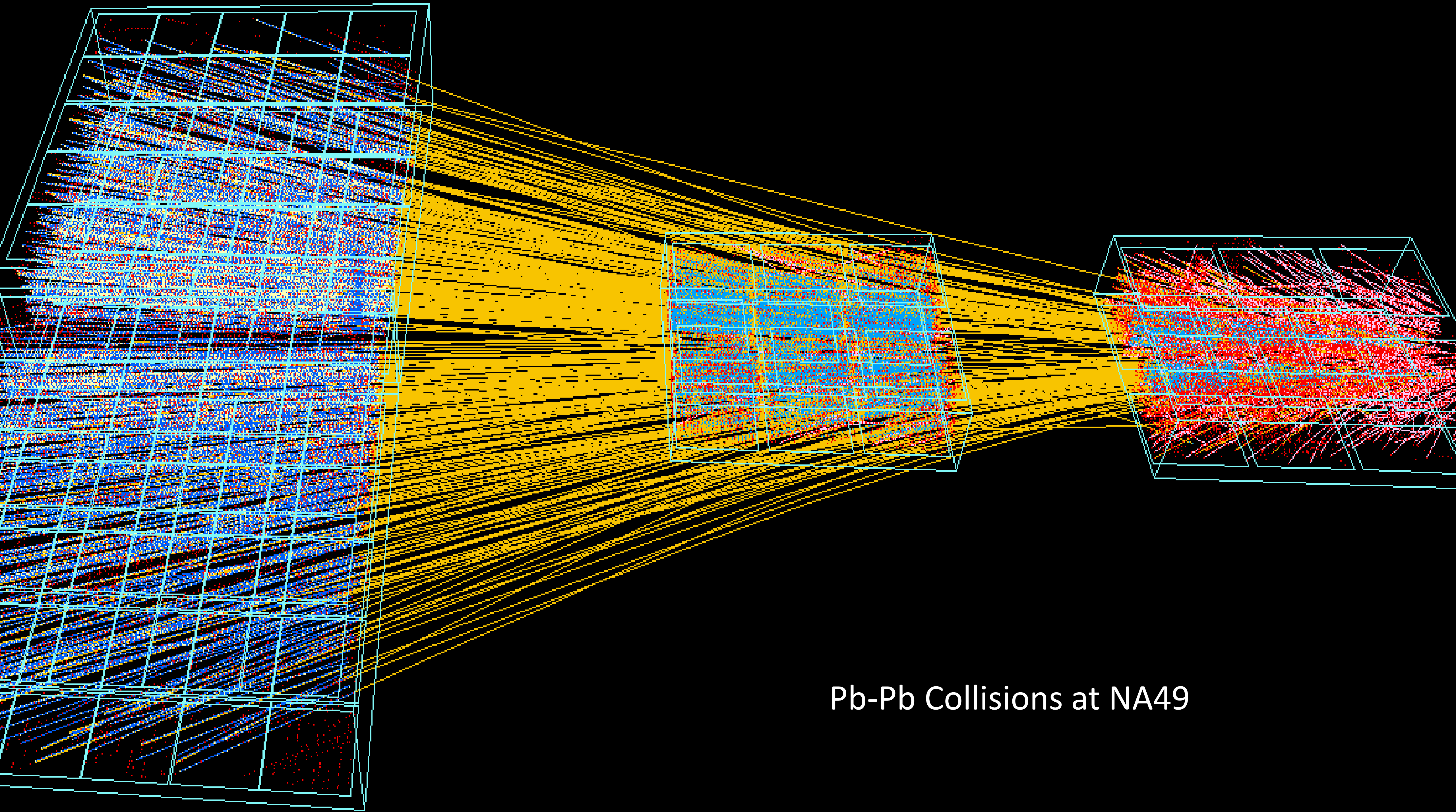
Reduce space charge and diffusion

VTPCs: Ne/CO_2 (90/10)

MTPCs: Ar/CH_4/CO_2 (90/5/5)

NA49 TPCs – A formidable challenge to experimental techniques





Pb-Pb Collisions at NA49

The ALICE TPC

WORLD Largest TPC

ALICE Key tracking and PID instrument

500 million (10bit) pixels

General features

- Active gas volume: 90 m^3
- Detector gas:
  - Ne-CO_2-N_2 (85.7-9.5-4.8) and Ar-CO_2 (90-10)
- Maximum drift time: ~100μs

Multi Wire Proportional Chamber

- Total nr pads: ~560,000
- Nr samples (time direction): ~1000

Material budget (near $\eta = 0$): X/X_0 =3.5%
(including counting gas)

High Readout Rate: 1kHz (Pb-Pb collisions)

ALICE TPC Readout – first examples of SoC (many ADCs, DSP, RAM)

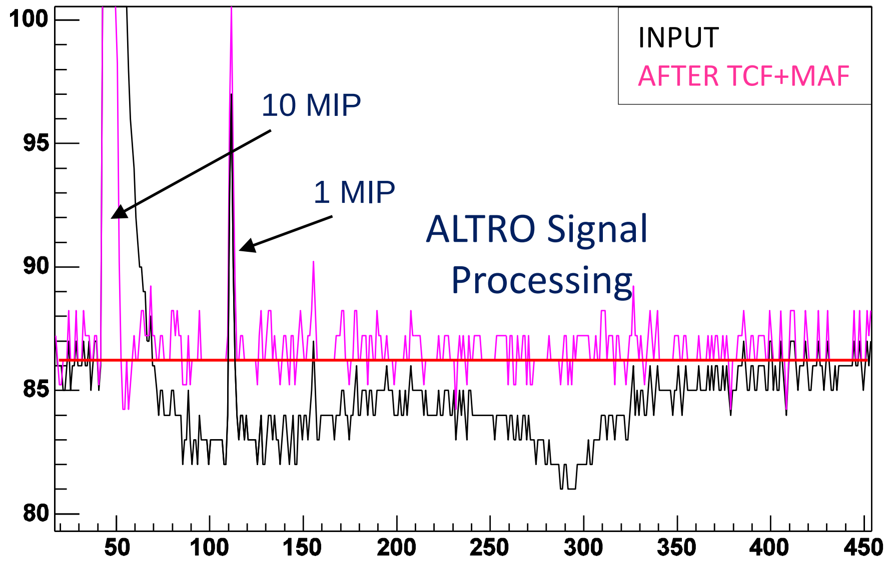
ALTRO Chip

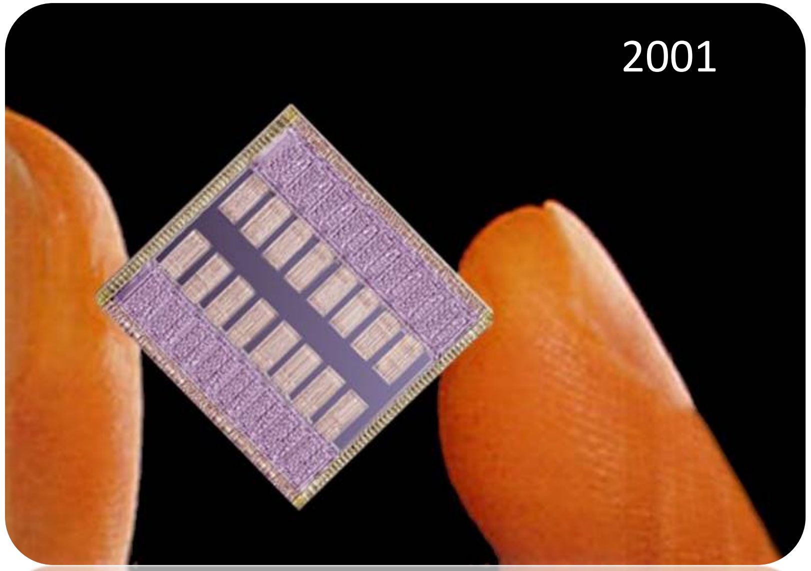
Mixed Analogue/Digital Chip

Very High Integration

16 low-power fast ADCs
16 DSP and 800K-bits Memory

Baseline restoration with advanced digital signal filters



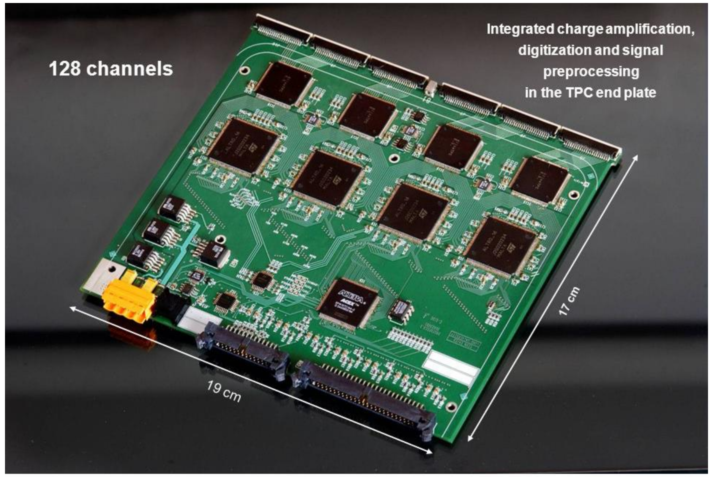


Large interest by most important specialized electronics magazines

Extreme Tech:
"Most Complex SoC Device Ever"

Electronic News:

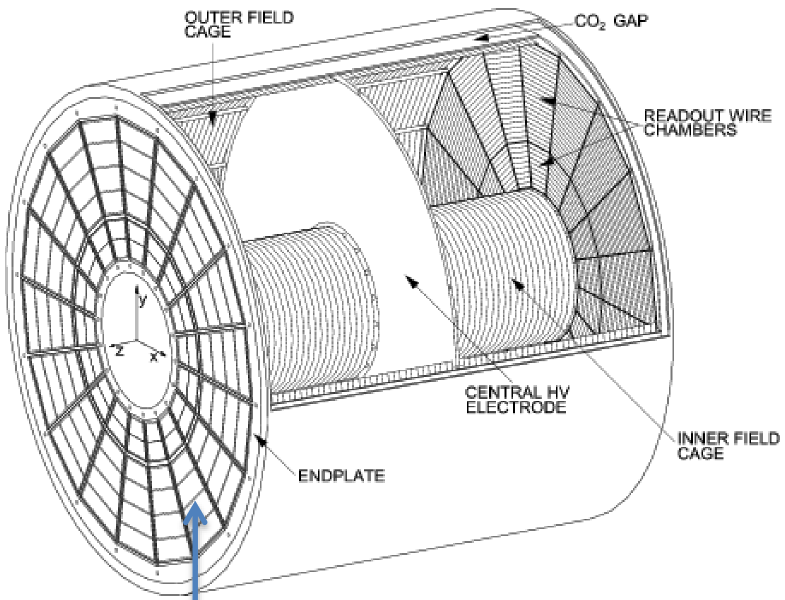
"SoC Device in Atomic Particle Experiment" Electronic News

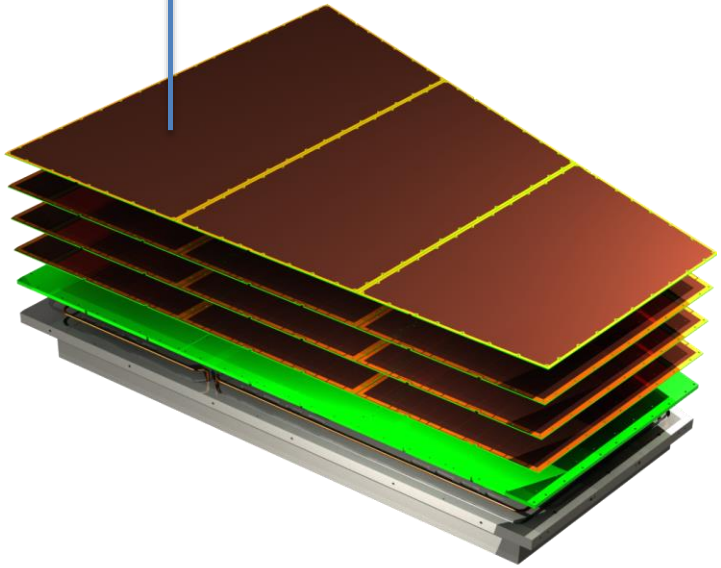


Streamer Chamber	~1Hz
NA49 TPC	~10Hz
STAR TPC(*)	~ 50Hz
ALICE TPC	~ 1kHz

(*) Later upgraded with ALICE electronics

ALICE TPC Upgrade with GEMs – Continuous Readout

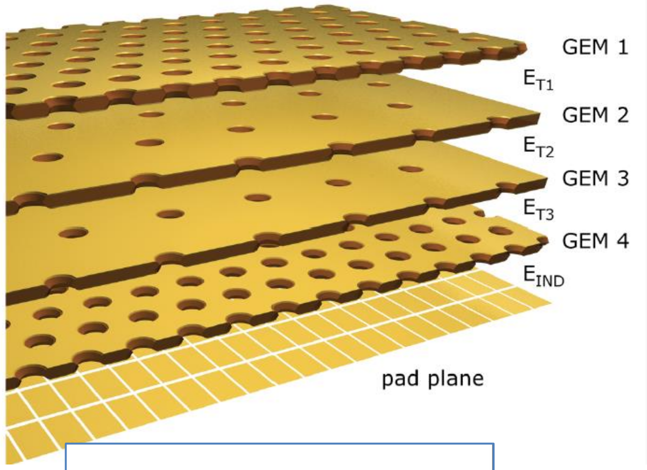




To operate at the 50 kHz rate => no gating grid => need to minimize Ion Back Flow to keep space charge distortions at a tolerable level

Replace wire-chambers with 4-GEMs

- **100 m^2 single-mask foils**
- Limit Ion Back Flow into drift volume
- Maintain excellent dE/dx resolution

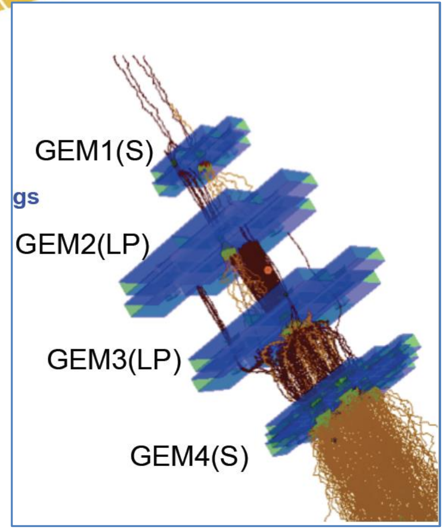


New electronics

CONTINUOUS READOUT

32 channels (PASA + ADC + digital readout) in one chip (SAMPA)

Data transmitted continuously at 5MHz off-detector via optical links



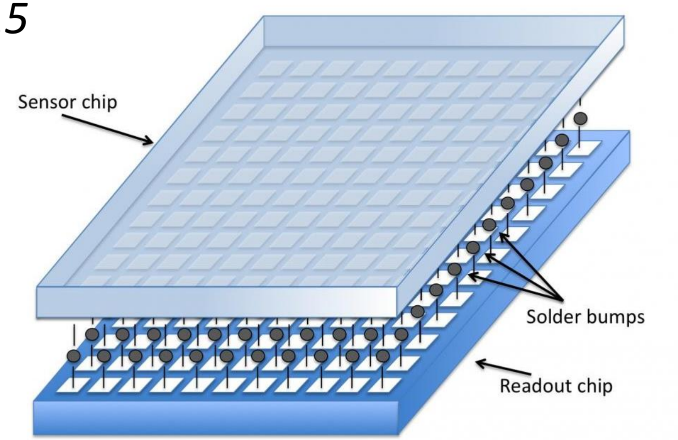
The Inception of Silicon Pixel Detectors

"The silicon micropattern detector: a dream?"

E.H.M Heijine, P. Jarron, A. Olsen and N. Redaelli , *Nucl. Instrum. Meth. A 273 (1988) 615*

"Development of silicon micropattern detectors"

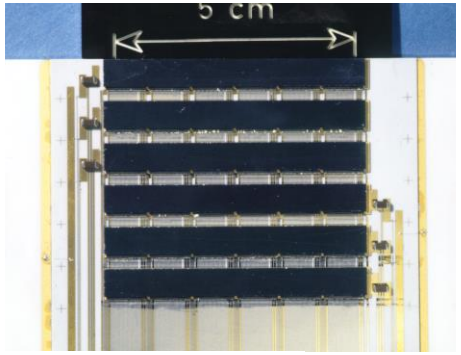
CERN RD19 collaboration, *Nucl. Instrum. Meth. A 348 (1994) 399*



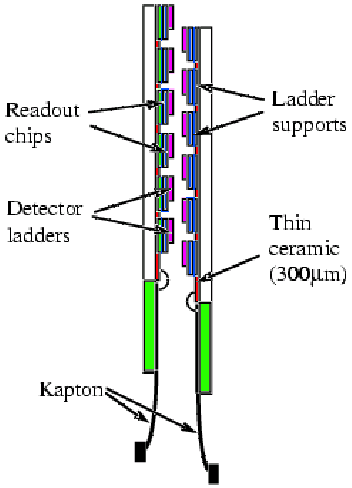
Hybrid pixel detector

1995 – First Hybrid Pixel detector installed in WA97 (CERN, Omega facility)

1996/97 – First Collider Hybrid Pixel Detector installed in DELPHI (CERN, LEP)



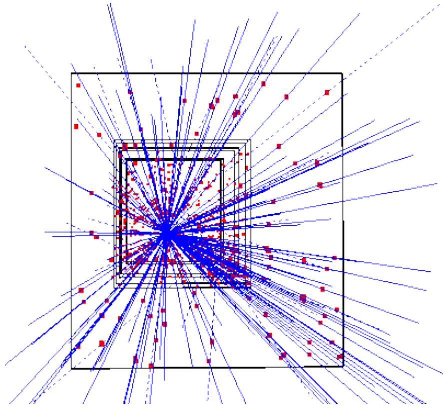
E. Heijne, E. Chesi



Work carried out by RD19 for WA97 and NA57/CERN

CERN – WA97 Experiment (1995)

- 5 x 5 cm^2 area
- 7 detector planes
- ~0.5 M pixels
- Pixel size 75 x 500 μm^2
- 1 kHz trigger rate
- Omega2 chip

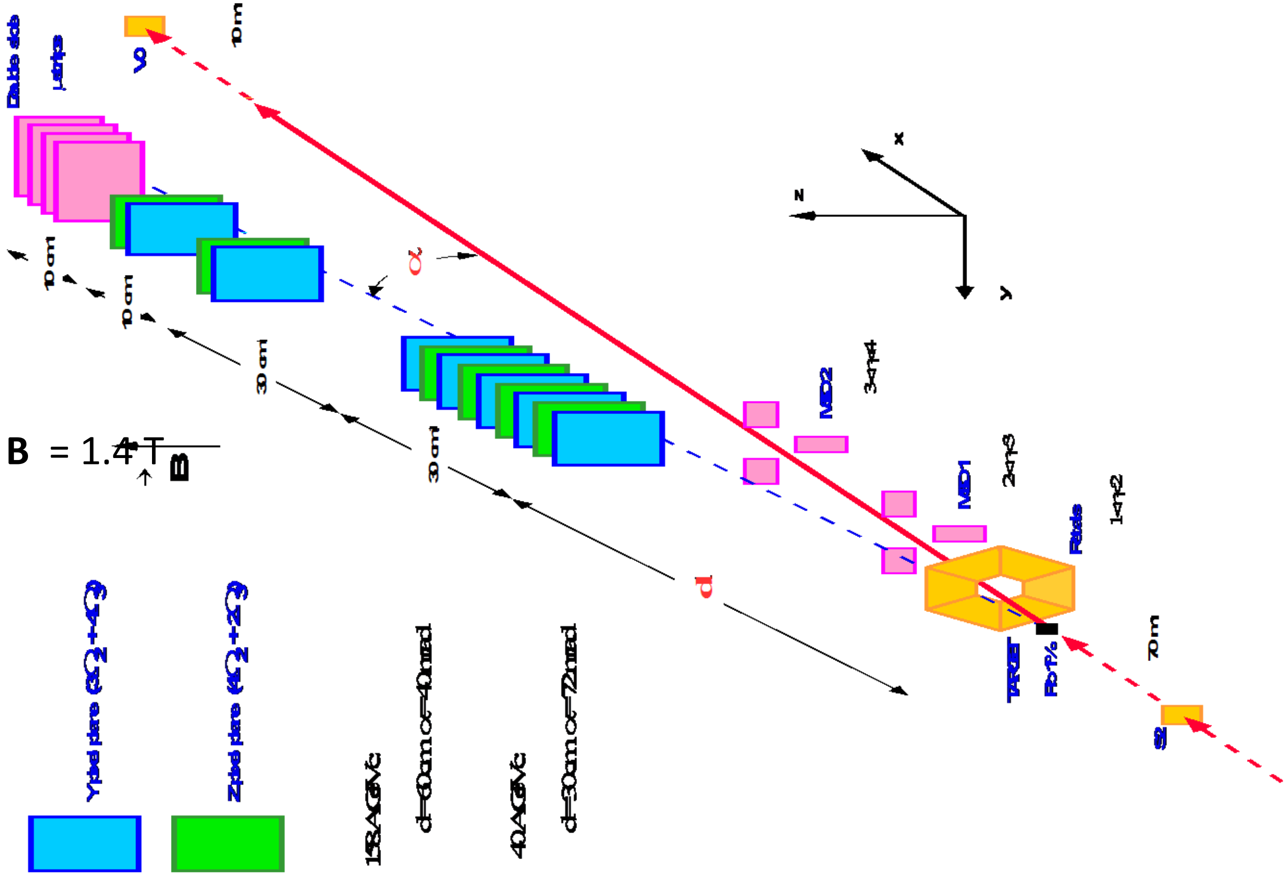

No-field, Pb-Pb, 153 reconstructed tracks

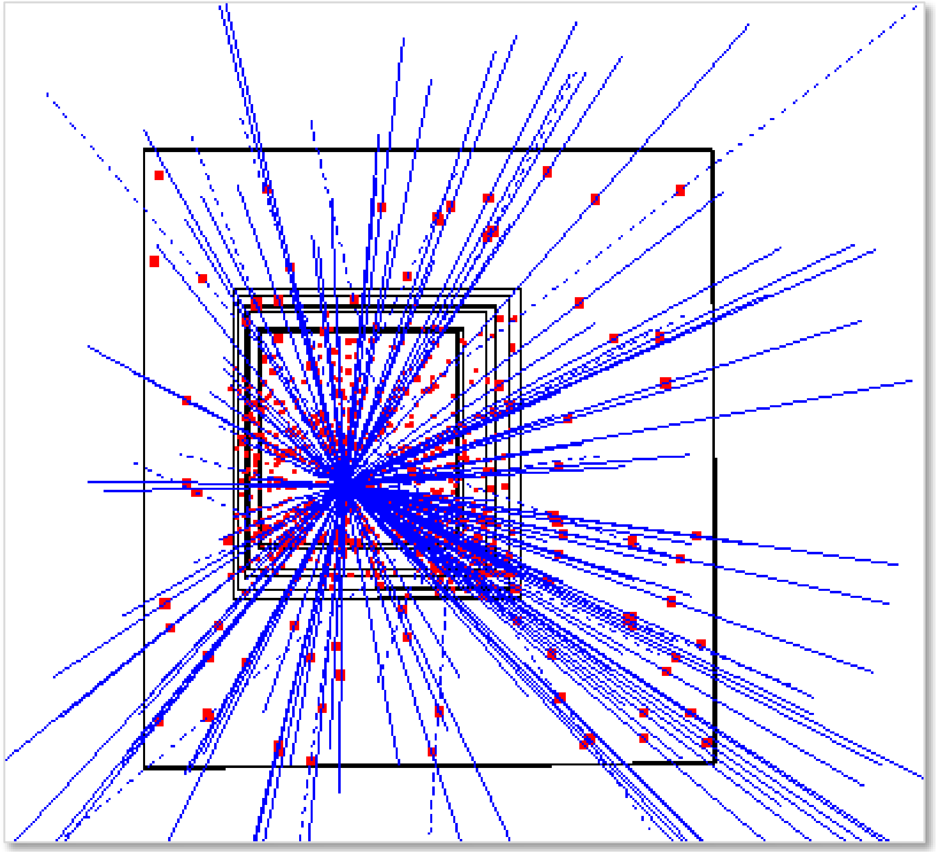
WA97/NA57 – First Pixel Detectors ever in HEP!

Search of strange baryon enhancement with Silicon Pixel Tracker in Pb beams

➔ precursor of hybrid pixel detectors developed for LHC

1995 – First Hybrid Pixel Detector installed in WA97

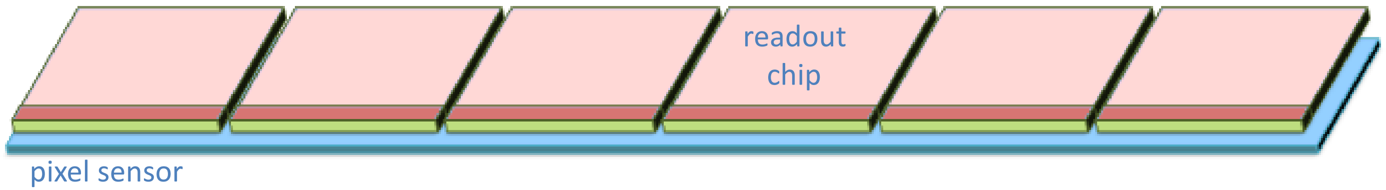




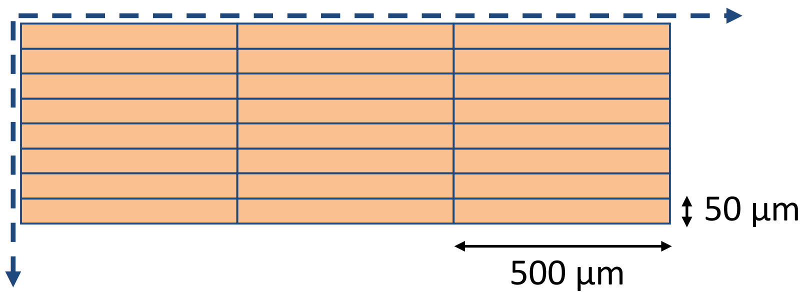
No field, Pb-Pb, 153 tracks through pixel telescope

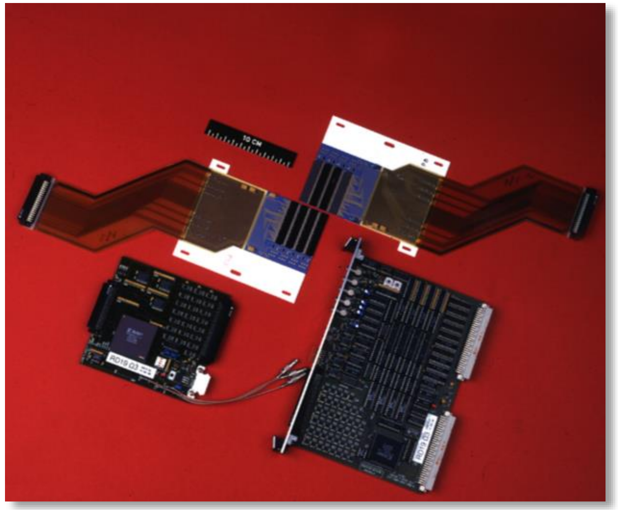
WA97/NA57 – The Omega3 Silicon Pixel Detector

Omega3 Pixel Detector Ladder



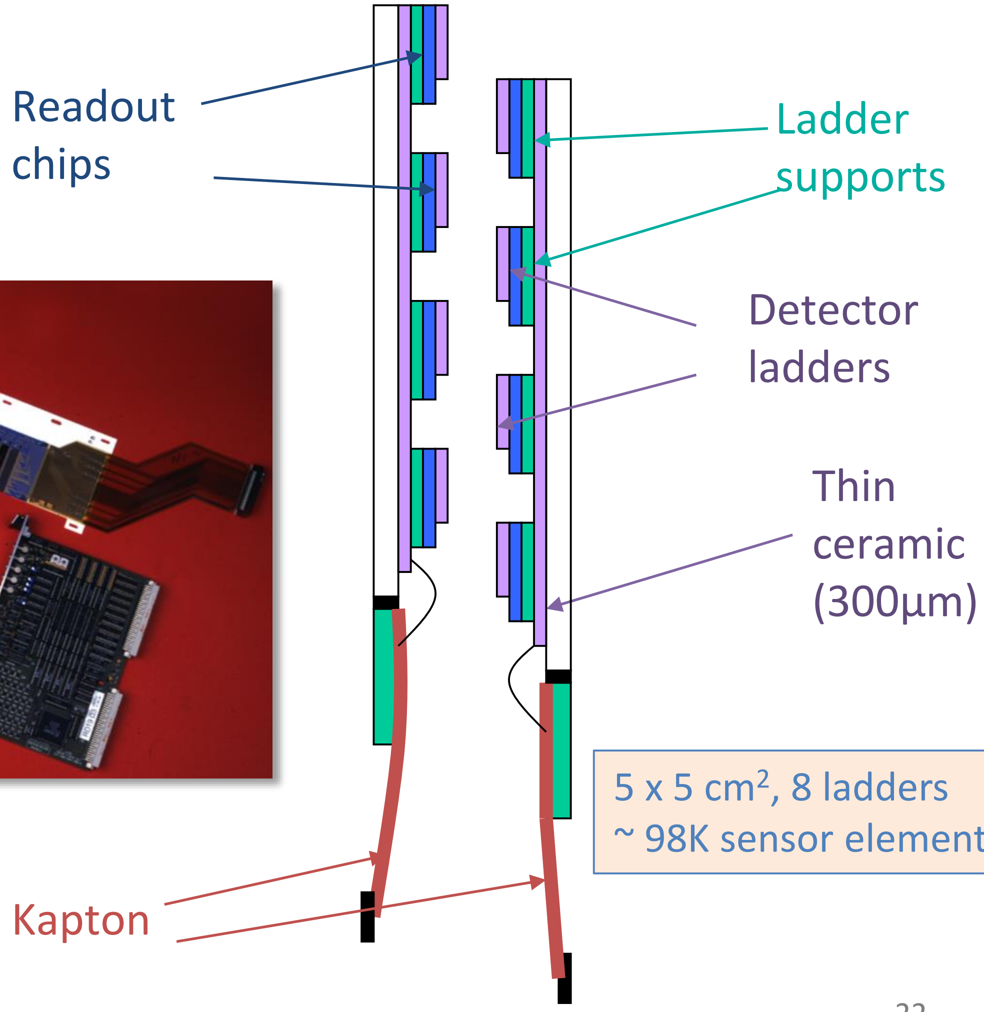
a high-resistivity silicon matrix of 96 x 128 pixels of size 500μm x 50μm





… bump-bonded onto 6 readout chips (“hybrid” technique) based on 0.5μm CMOS technology

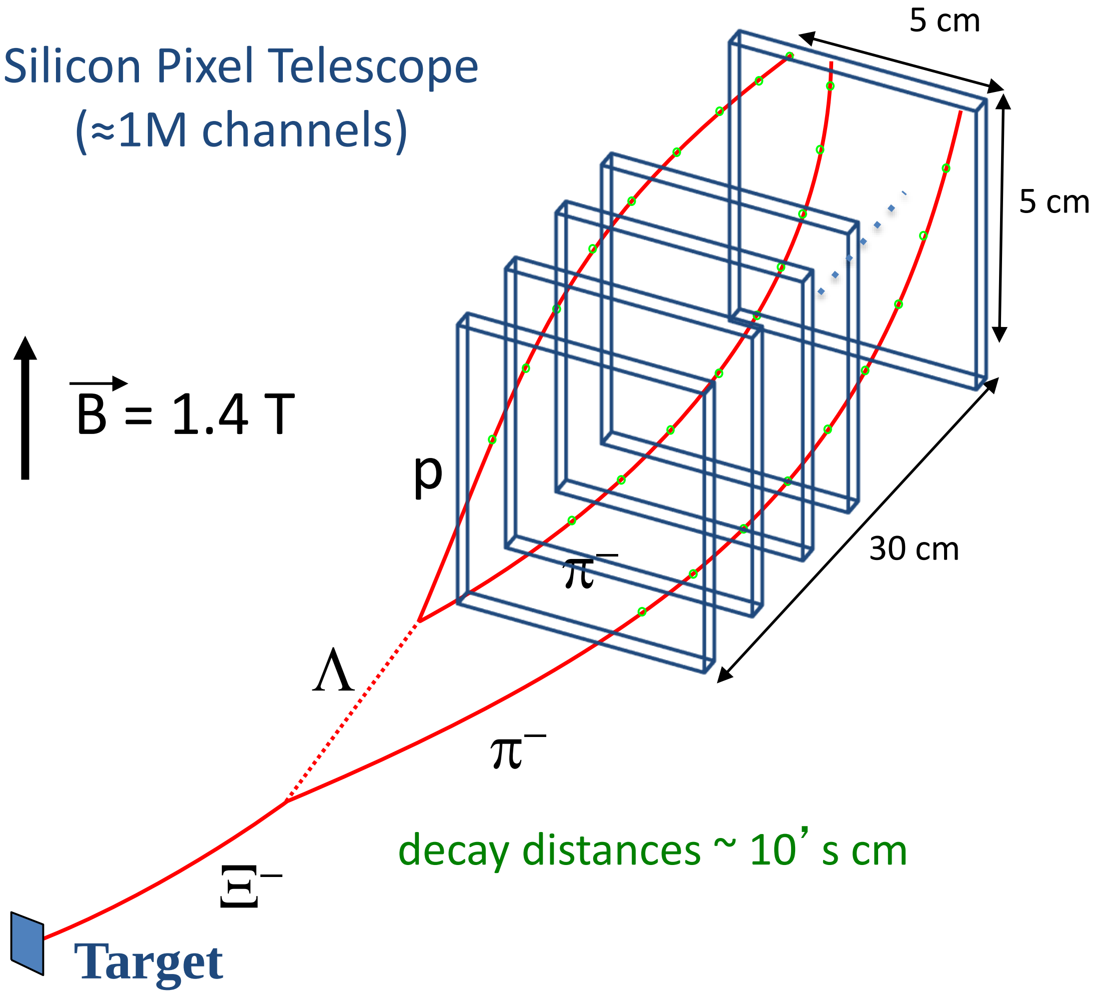
Omega 3 *arrays* and *logical plane*



5 x 5 cm^2, 8 ladders
~ 98K sensor elements

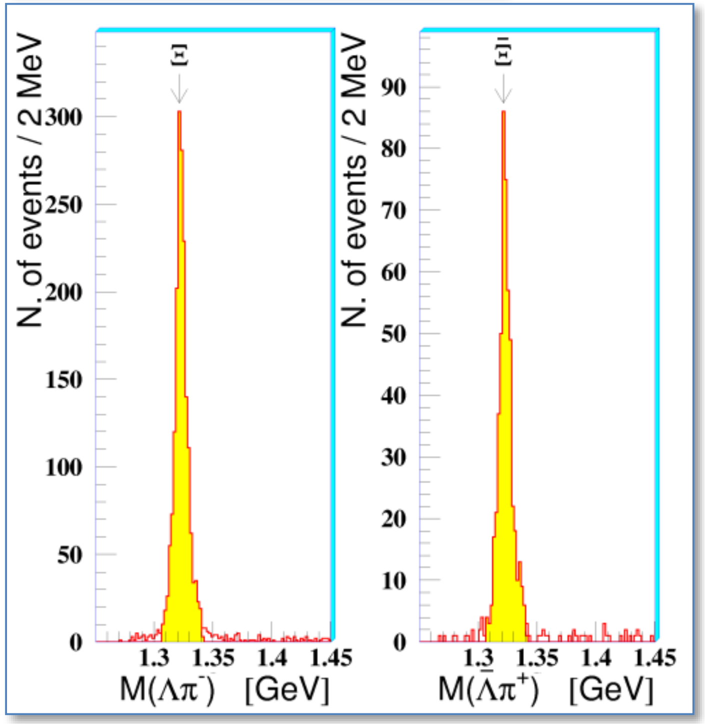
NA57 – Measurement of Hyperon Signals

Silicon Pixel Telescope
(≈1M channels)



decay distances ~ 10’ s cm

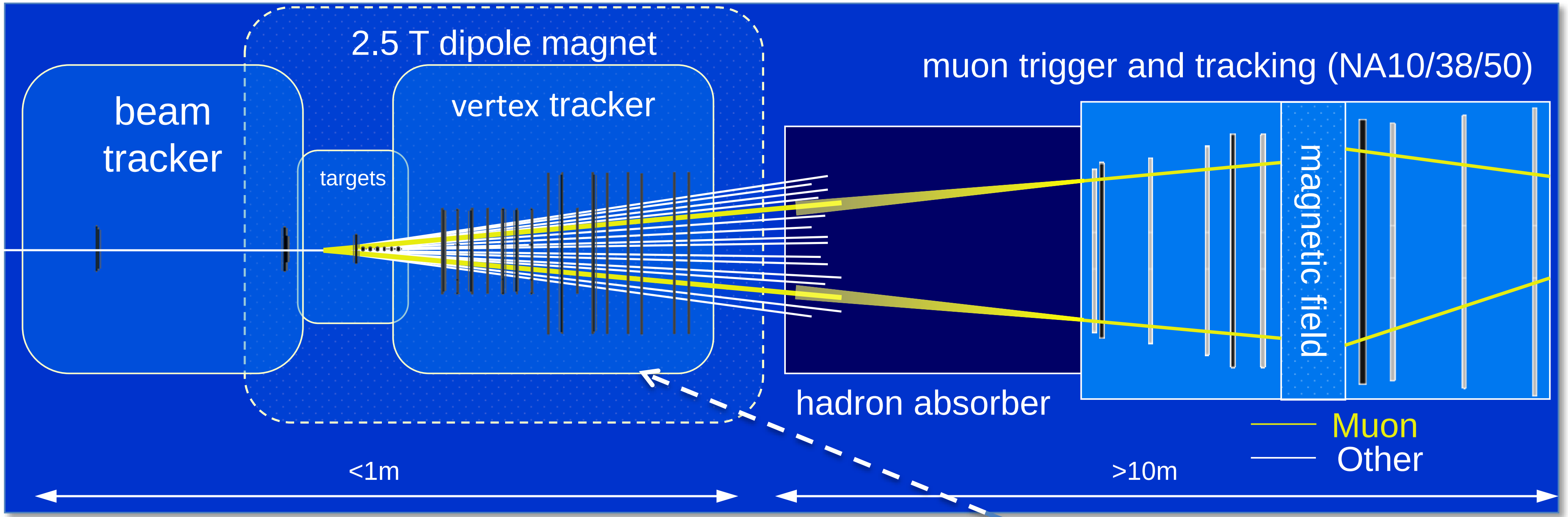
Pb + Pb @ 160 A GeV/c



Particle selection criteria based on topological cuts, e.g.:

- p-π closest approach in space
- V^0 candidate combined with a 3rd track → Ξ candidate
- Ξ decay distance
- p, Λ impact parameters at target plane

NA60 – (NA50) Muon Spectrometer + Silicon Tracking Telescope



Vertex tracker Tracker
Silicon Pixel Detectors

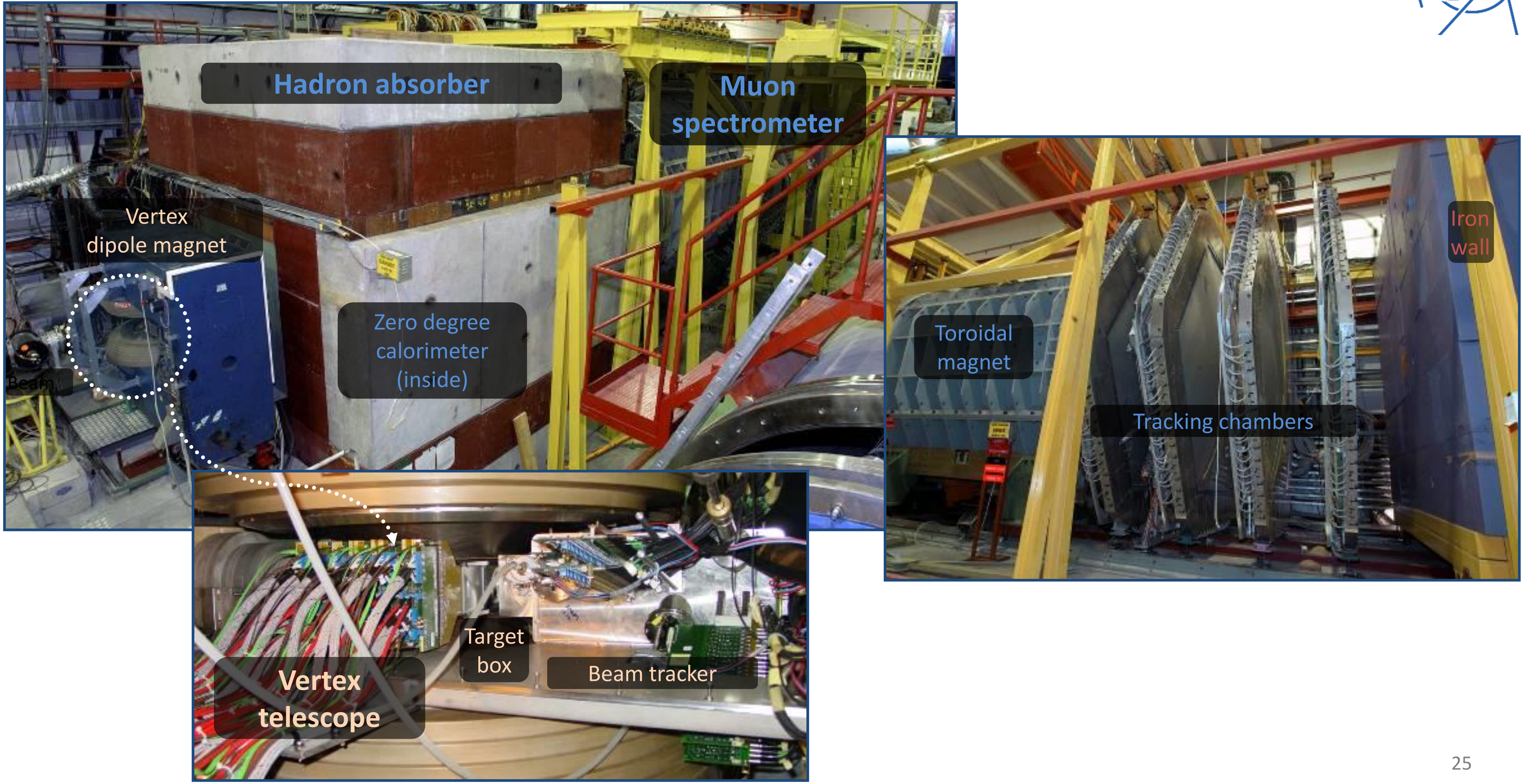
Track matching in coordinate <u>and</u> momentum space

- Improved dimuon mass resolution (from 70MeV to 20MeV for the ω)
- Distinguish prompt from decay muons (transverse plane resolution 40-50 μm)

➔ sufficient to separate prompt dimuons from open charm decay (D^+: cτ=312 μm; D^0: ct=123 μm)

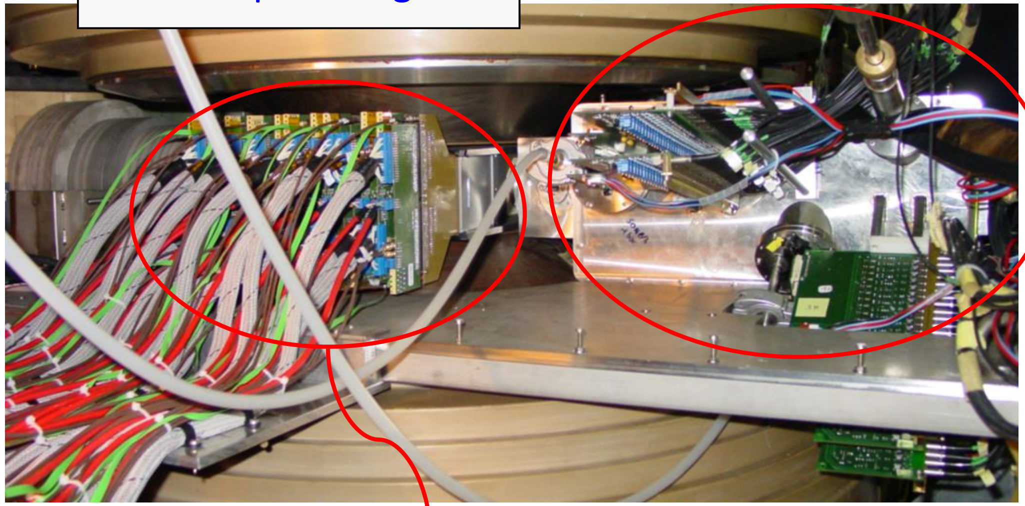
Similar scheme adopted by CBM, and ALICE Muon Upgrade

NA60 – (NA50) Muon Spectrometer + Silicon Tracking Telescope



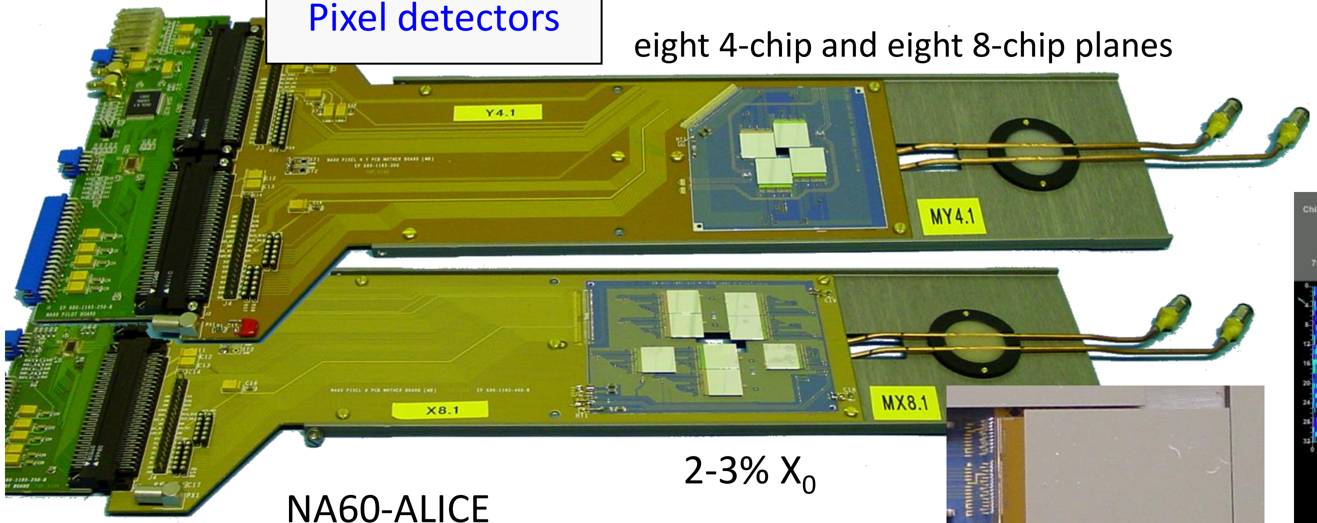
NA60 – Vertex Tracker

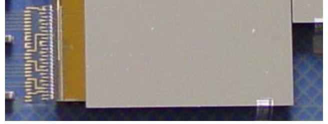
2.5 T dipole magnet



Pixel detectors

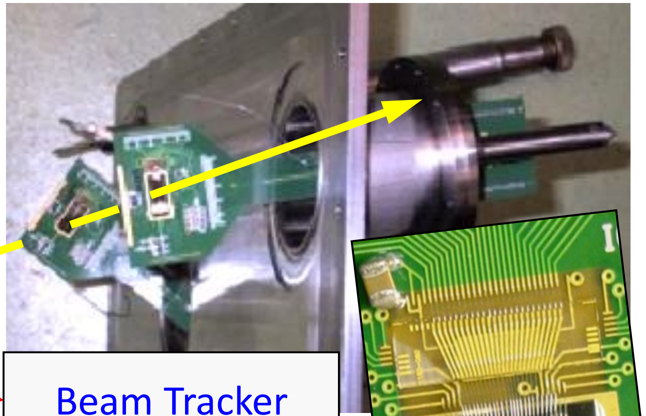
eight 4-chip and eight 8-chip planes





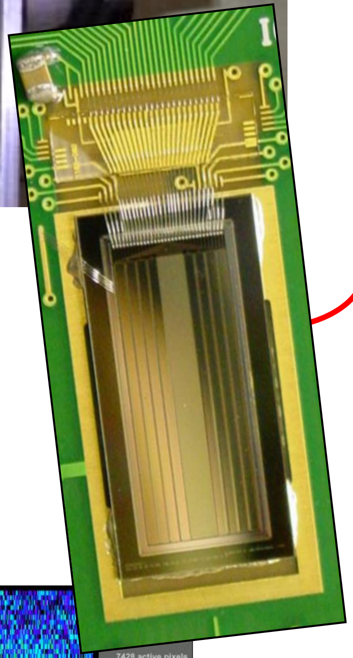
2-3% X_0

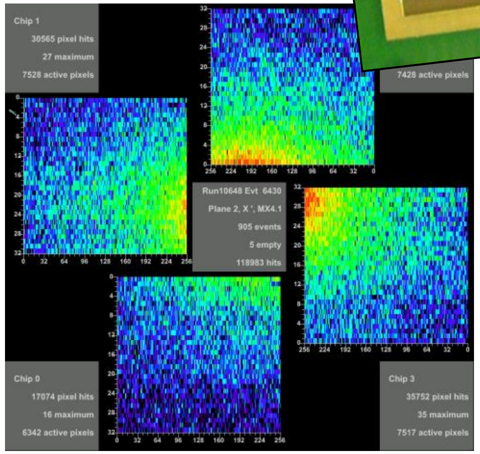
NA60-ALICE
pixel planes(10 MHz)

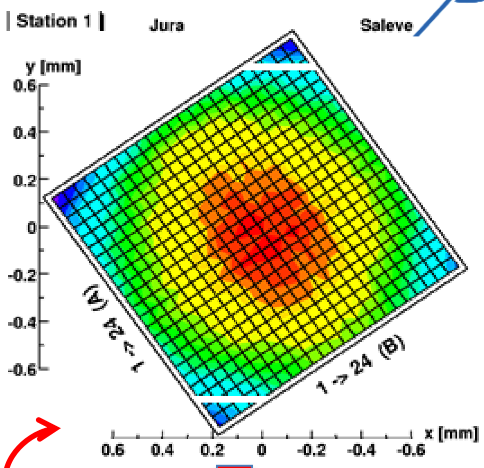


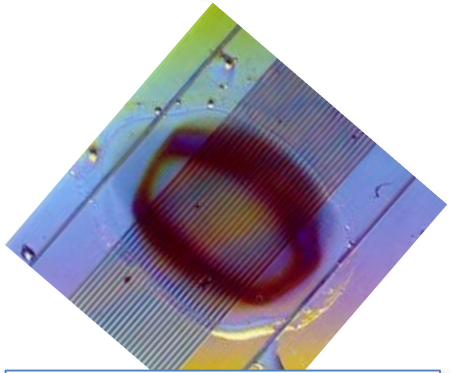
Beam Tracker

operated at 130 K, improved radiation hardness





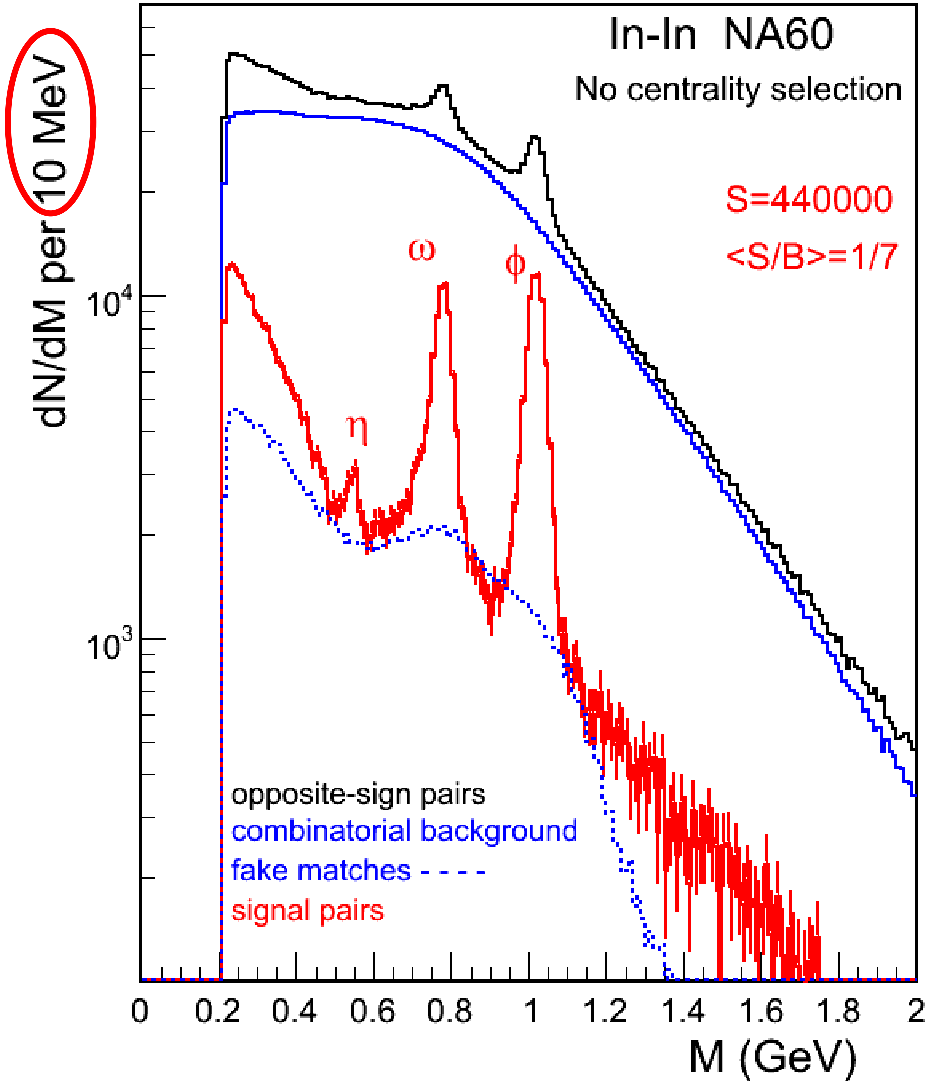




~10^{20} nucleons/cm^2

after 42 days (year 2000) at 7×10^7 Pb ions/burst

NA60 – Dimuon Low-mass Spectrum



Low-mass data sample for 158 AGeV In-In (2003)

Data net sample: 440 000 events

A sensational mass resolution

ω and ϕ perfectly resolved

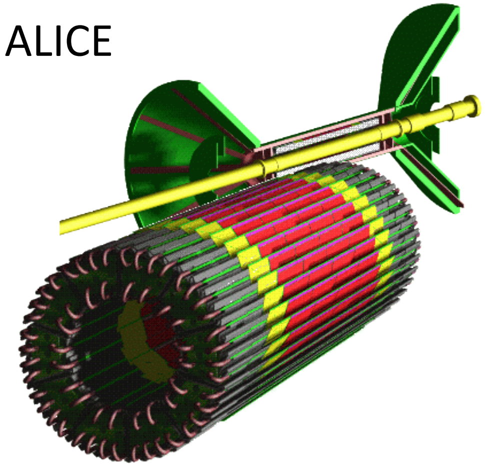
$\eta \rightarrow \mu^+\mu^-$ for the first time in nuclear collisions

Mass resolution:
20 MeV at the ω position

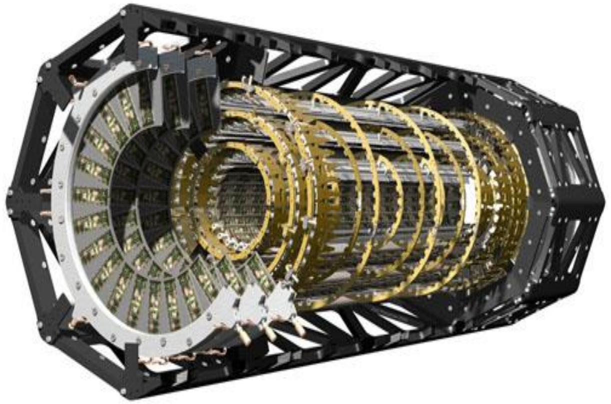
Pixel Detectors at the LHC

10 years after the first use in WA97… pixel detectors at the heart of the LHC Experiments

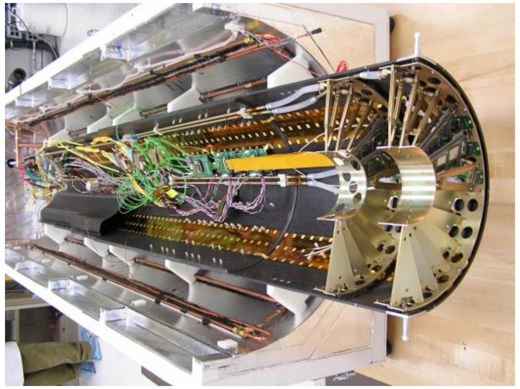
ALICE



ATLAS



CMS

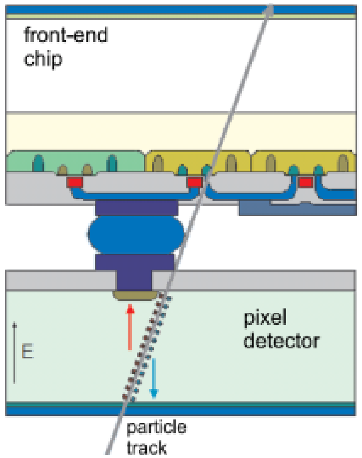


Different sensor technologies, designs, operating condition

Parameters	**ALICE**	**ATLAS**	**CMS**
Nr. layers	2	3	3
Radial coverage [mm]	**39** – 76	**50** – 120	**44** – 102
Nr of pixels	9.8 M	80 M	66 M
Surface [m^2]	0.21	1.7	1
Cell size (rf x z) [μm^2]	50 x 425	50 x 400	100 x 150
Silicon thickness (sens. + ASIC) x/X_0 [%]	0.21 + 0.16	0.27 + 0.19	0.30 + 0.19

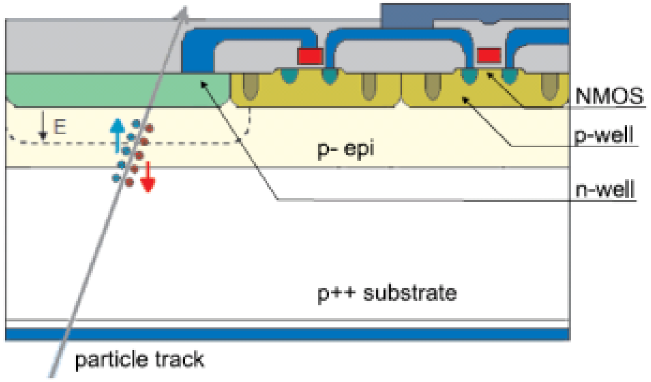
Beyond Hybrid Pixel Detectors …

Hybrid Pixel Detector



N. Wermes (Univ. of Bonn)

Monolithic Pixel Detector



N. Wermes (Univ. of Bonn)

Since the very beginning of pixel development (RD 19):

dream to integrate sensor and readout electronics in one chip

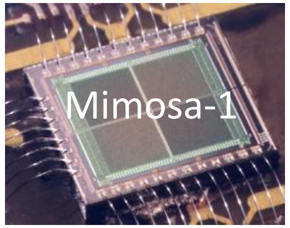
Motivation to reduce: cost, power, material budget, assembly and integration complexity

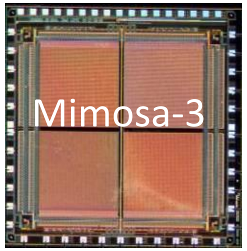
Several major obstacles to overcome for CMOS MAPS:

- CMOS generally not available on high resistivity silicon (needed as bulk material for the sensor) ✓
- Full CMOS circuitry not possible within the pixel area (only one type of transistor ➔ slow readout) ✓

Beyond Hybrid Pixel Detectors - Monolithic Pixel Detectors

Owing to the industrial development of CMOS imaging sensors and the intensive R&D work (IPHC, RAL, CERN)





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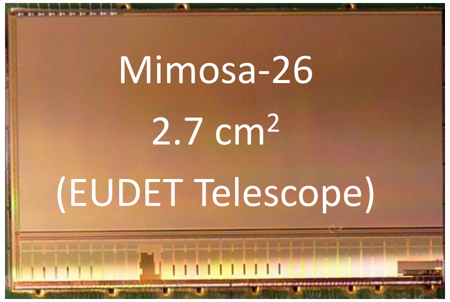
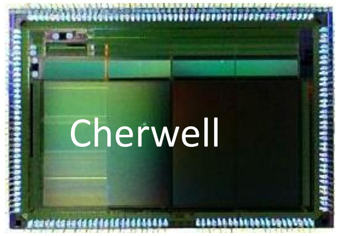
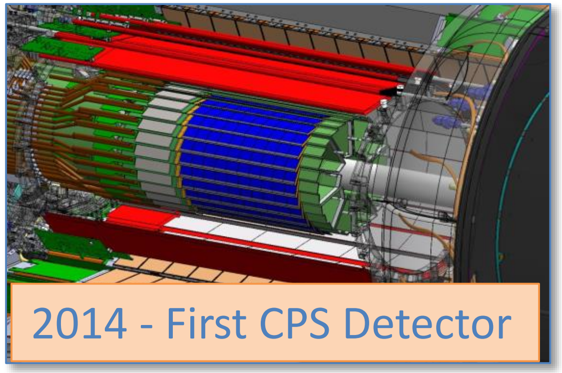
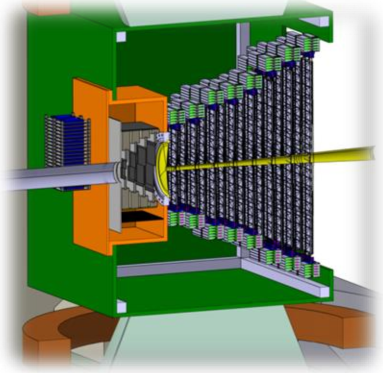




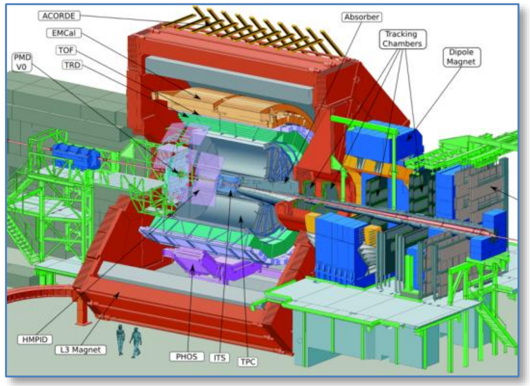
… several HI experiments have selected CMOS pixel sensors for their inner trackers



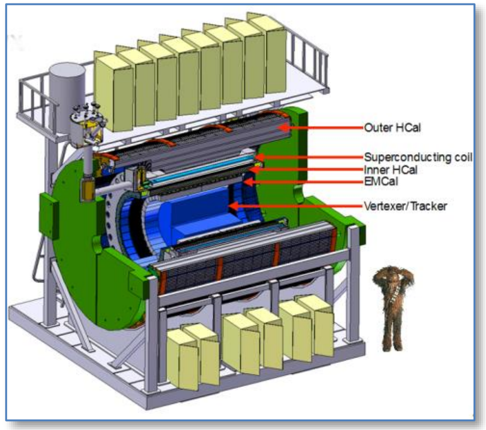
STAR HFT
0.16 m^2 – 356 M pixels



CBM MVD
0.08 m^2 – 146 M pixel



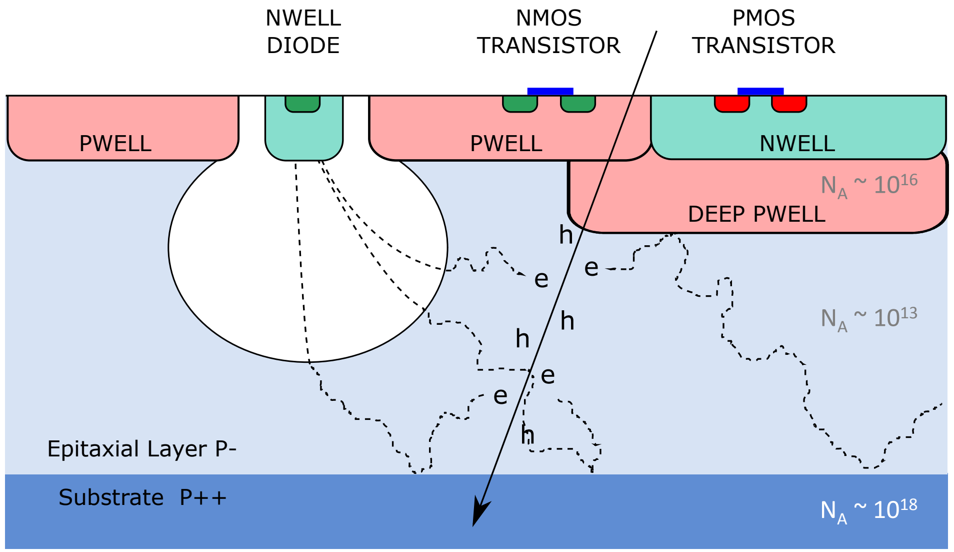
ALICE ITS Upgrade (and MFT)
10 m^2 – 12 G pixel

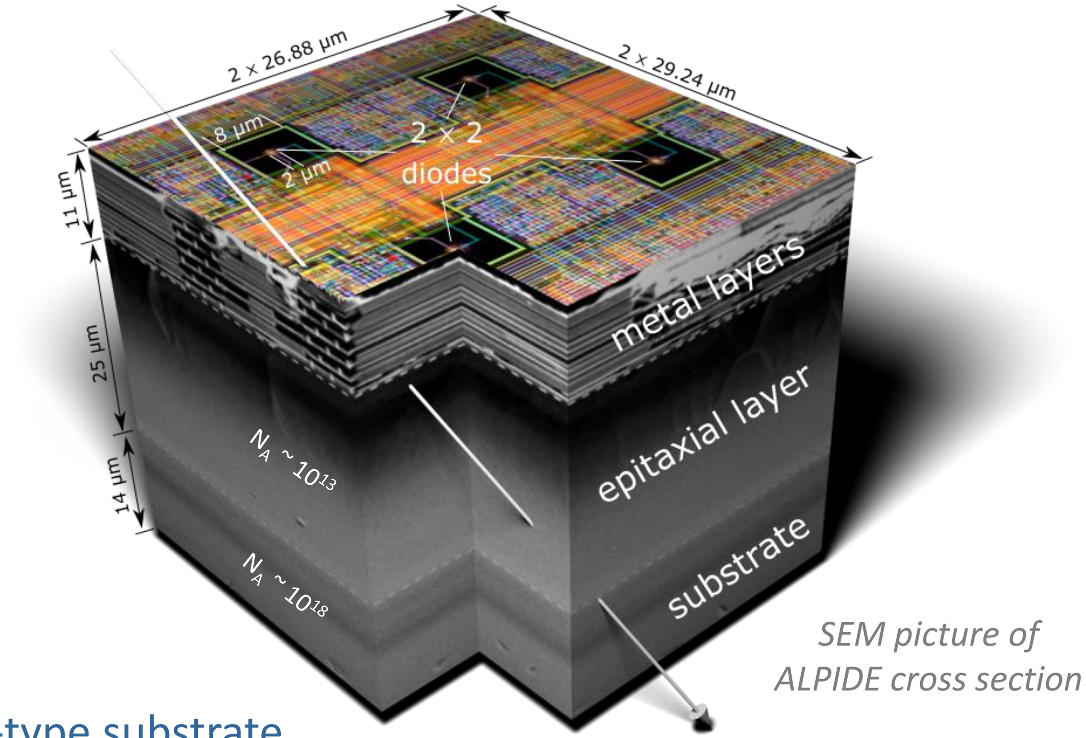


sPHENIX
0.2 m^2 – 251 M pixel

ALICE Monolithic Pixel Detector

CMOS Pixel Sensor using 0.18μm CMOS Imaging Process



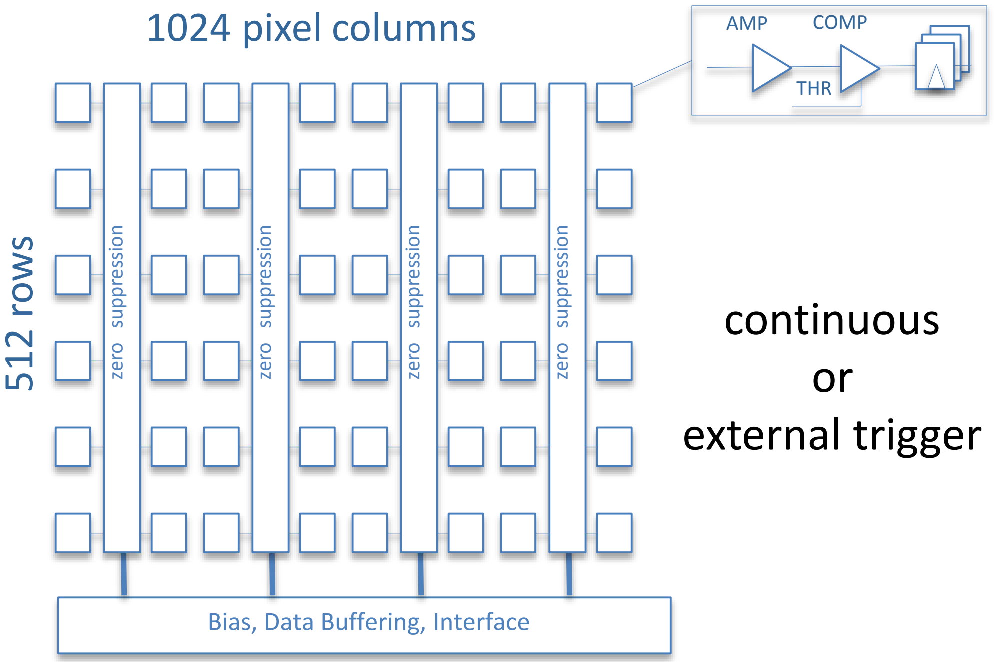


SEM picture of ALPIDE cross section

- High-resistivity (> 1kΩ cm) p-type epitaxial layer (25μm) on p-type substrate
- Small n-well diode (2 μm diameter), ~100 times smaller than pixel => low capacitance (~fF)
- Reverse bias voltage ($-6V < V_{BB} < 0V$) to substrate (contact from the top) to increase depletion zone around NWELL collection diode
- Deep PWELL shields NWELL of PMOS transistors

➔ full CMOS circuitry within active area

ALPIDE – **ALice PIxel DEtector**



continuous
or
external trigger

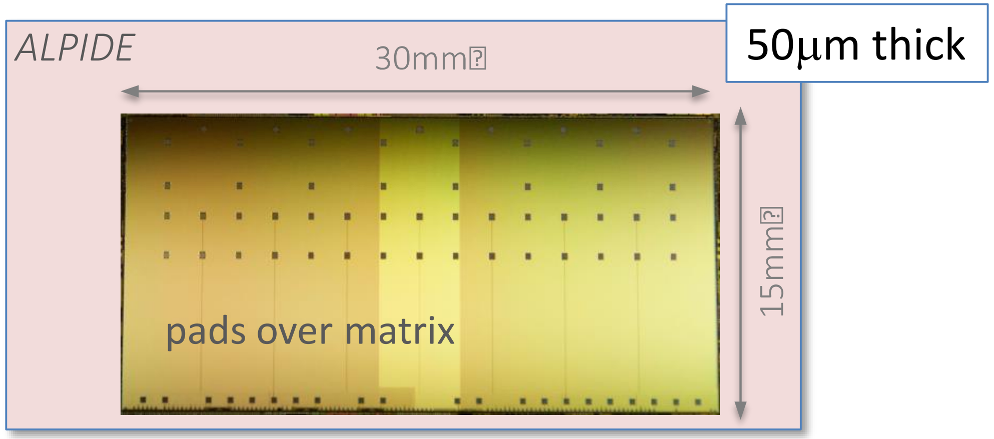
130,000 pixels / cm^2 O(30x30x30 μm^3)

spatial resolution: ~ 5 μm (3-D)

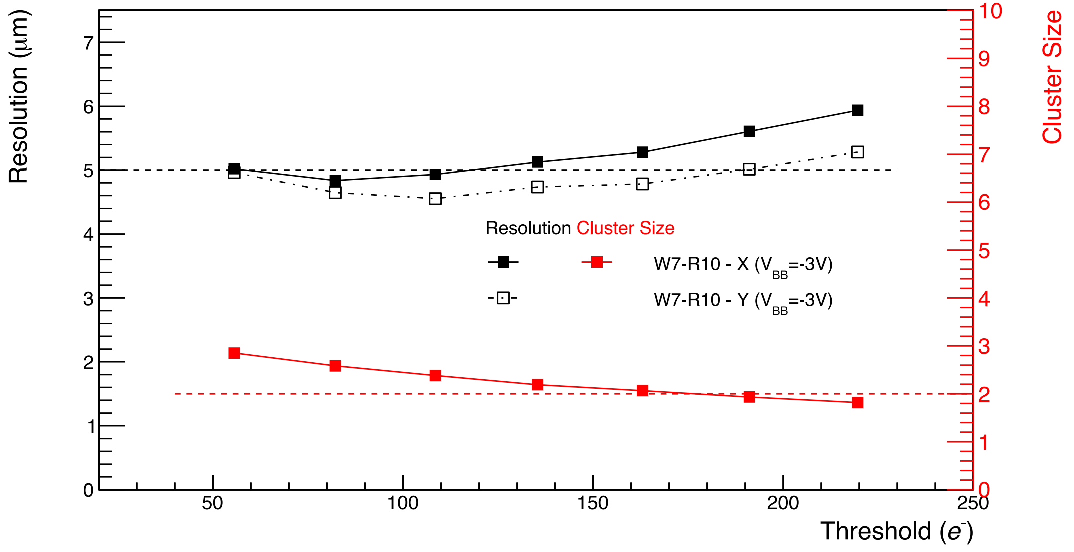
Max particle rate: 100 MHz / cm^2

fake-hit rate: < 10^{-10} pixel / event

Power : ~ 300 nW /pixel

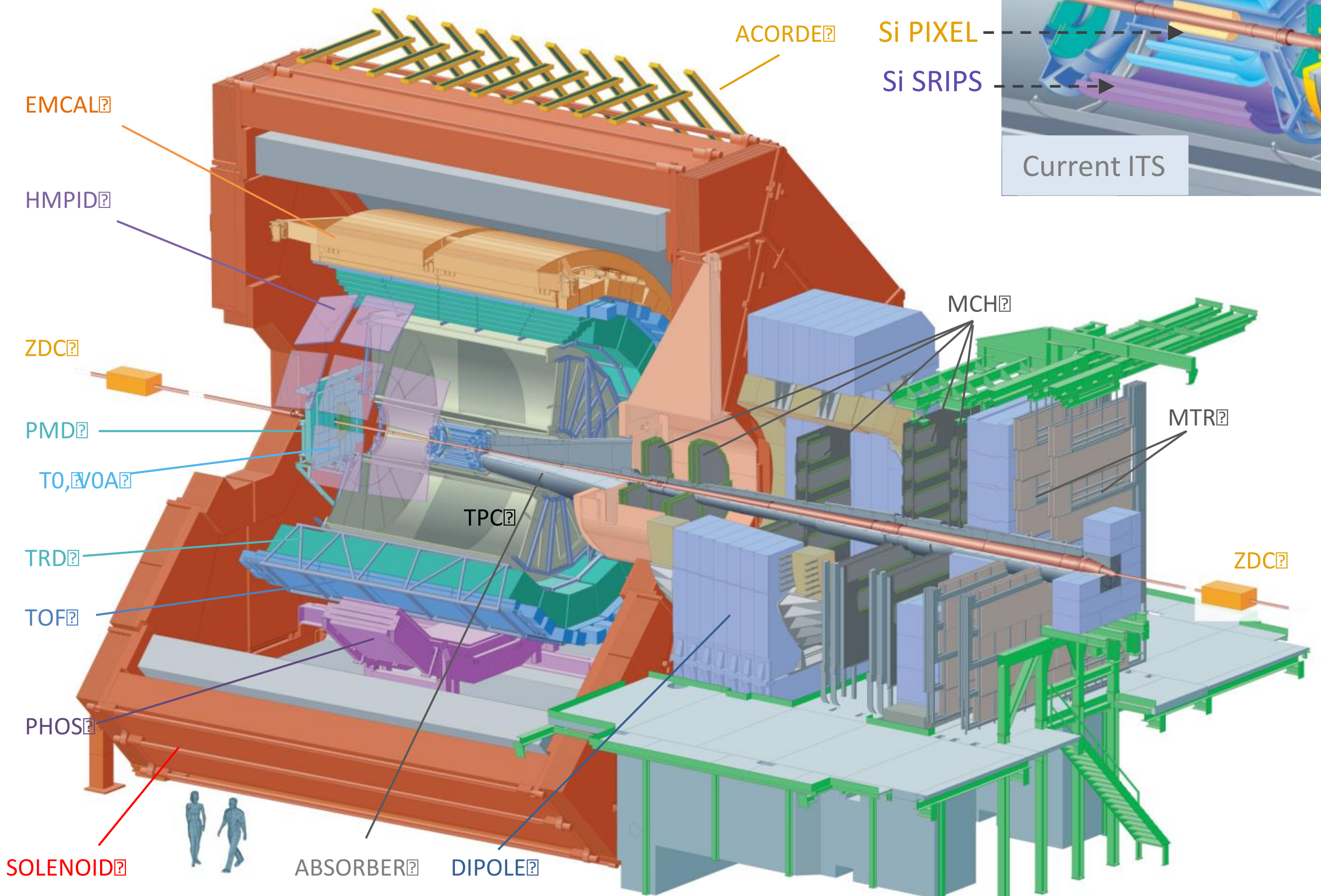


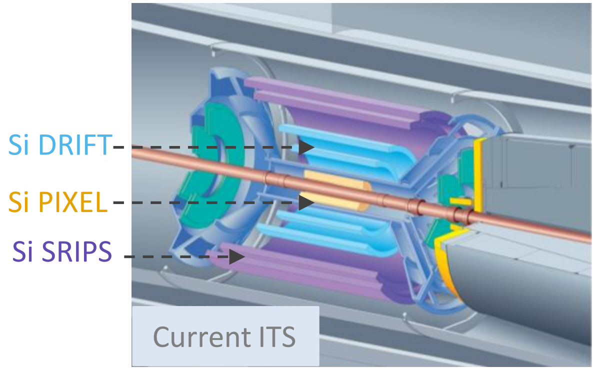
Spatial Resolution & Cluster Size

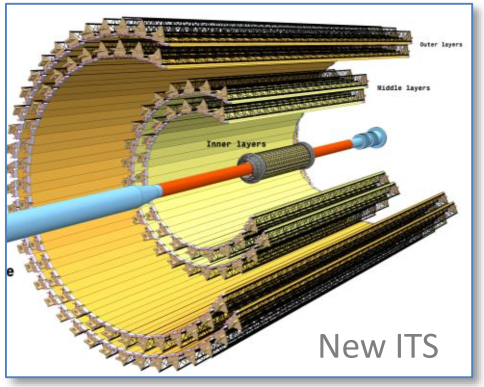


Upgrade of the ALICE Inner Tracking System

Current Inner Tracking System
Silicon: 39 – 430 mm







7-layer geometry (23 – 400mm, $|\eta| \leq 1.22$)

10 m^2 active silicon area (12.5 G-pixels)

Pixel pitch 28 x 28 μm^2

Power density < 40mW / cm^2

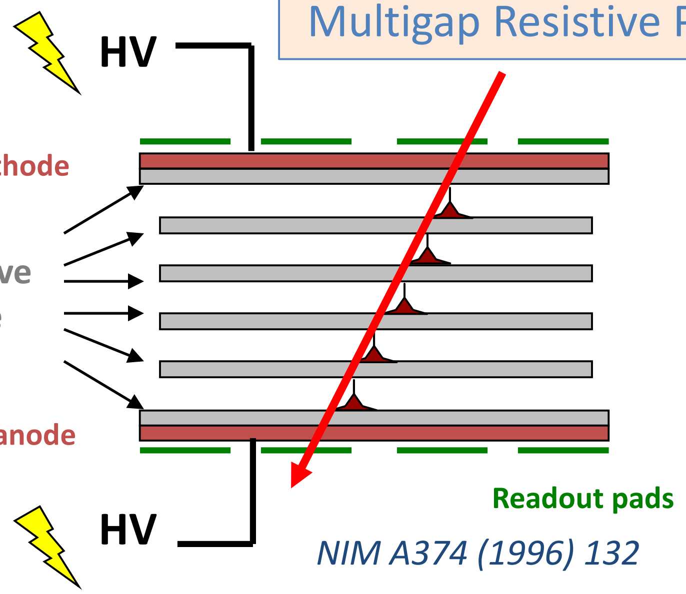
Material budget: ~0.3% / layer (inner)

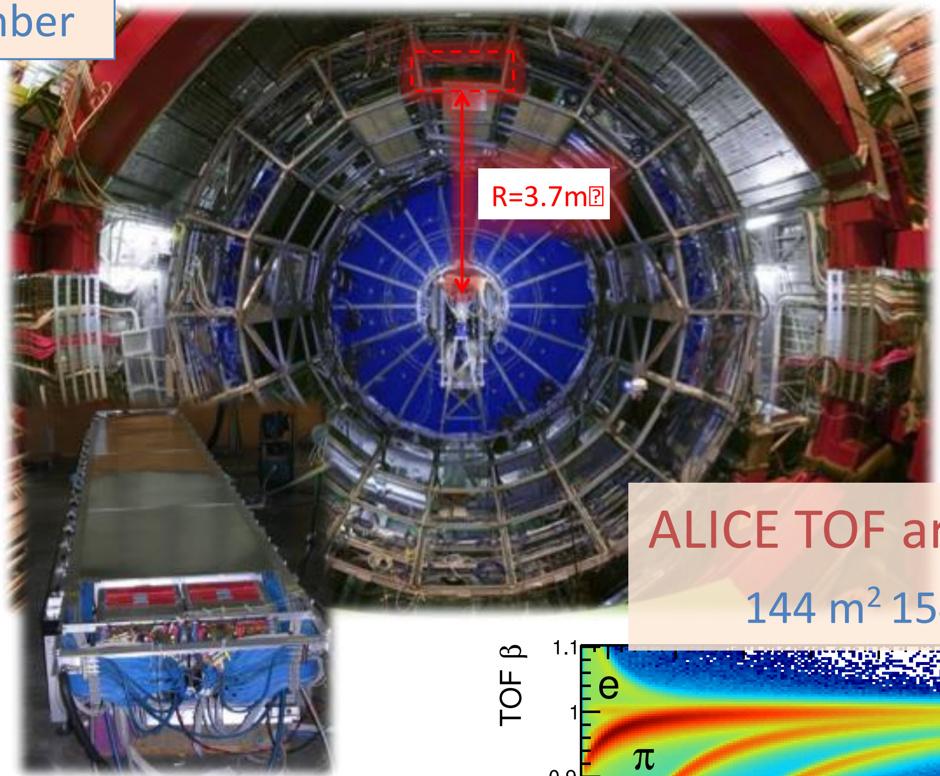
Readout rate: continuous or triggered

Readout rate currently limited to ~ 1kHz (Pb-Pb minimum bias)

Novel MRPC technology for STAR and ALICE TOF detectors

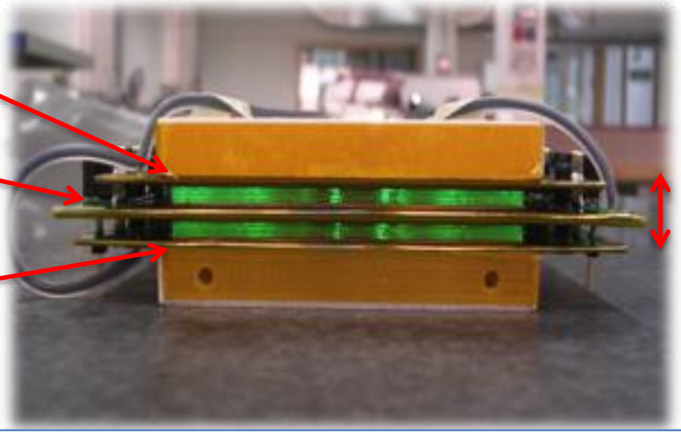
Multigap Resistive Plate Chamber





ALICE TOF array

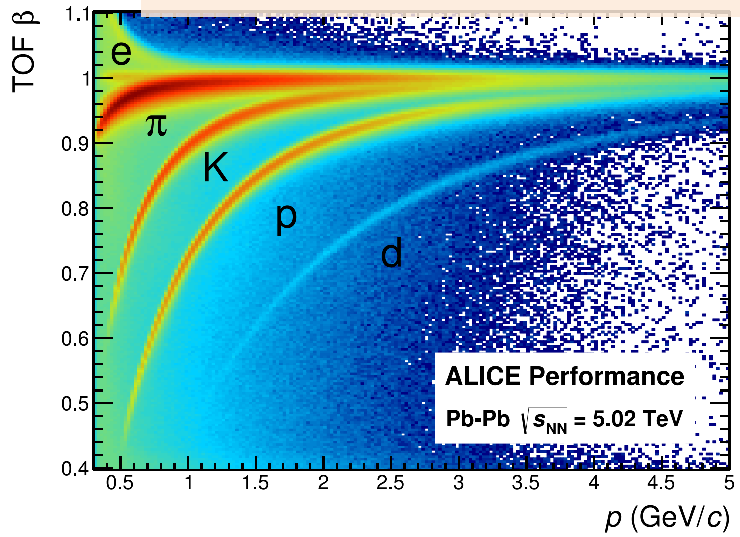
144 m^2 154,000 channels



Double-stack MRPC with sum-millimiter gas-gap

$\sigma_{TOF} \approx 80ps$

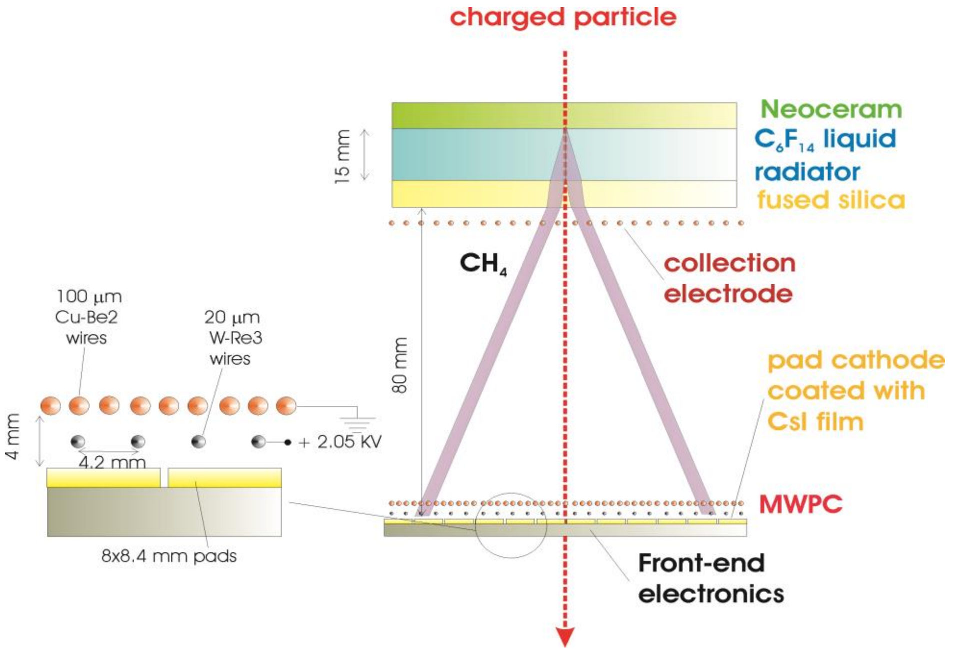
(in the experiment, intrinsic time resolution ~40ps)



CsI: A breakthrough in Cherenkov Photodetection

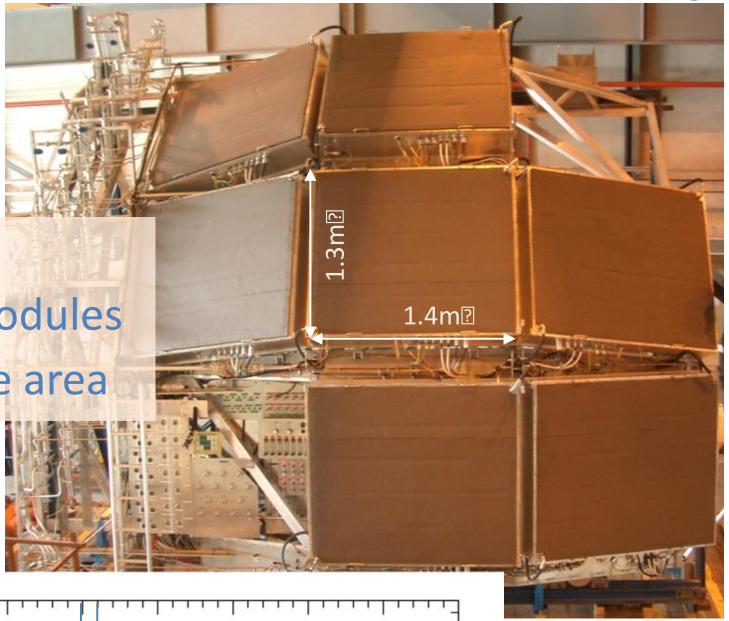
J. Seguinot e A. Breskin (End 1980s) - engineering and long-term reliability

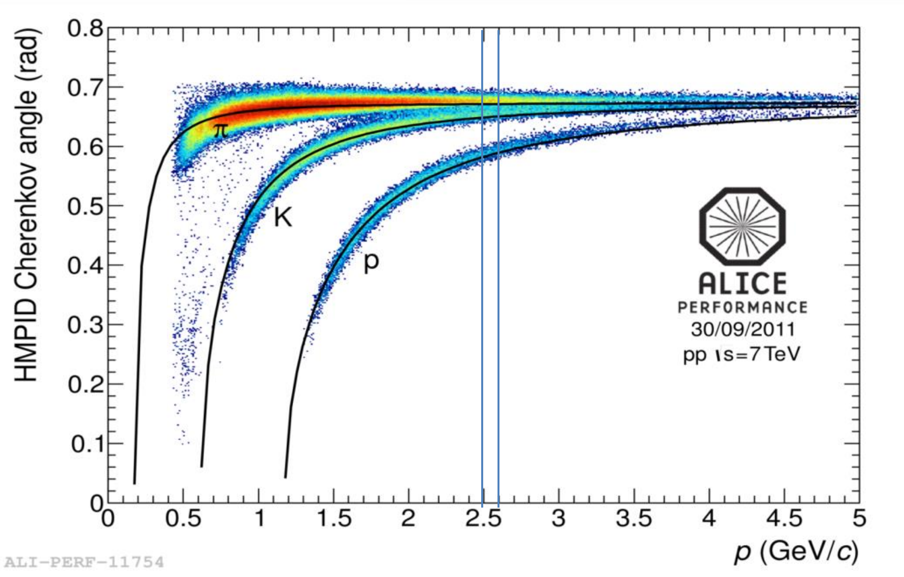
RD26@CERN (F. Piuz, E. Nappi and G. Paic)
Development of large area CsI photocathodes, 1992



Largest surface of CsI Detector

ALICE HMPID
7 proximity focusing RICH modules
~ 11 m^2 of CsI photosensitive area





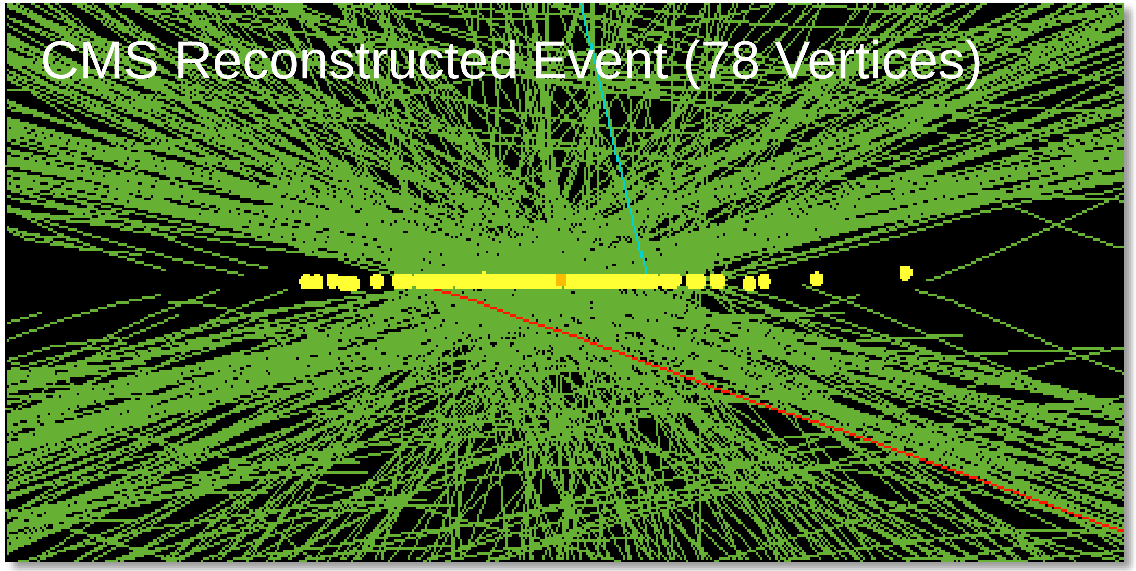
Many advantages wrt alternatives

- Photosensitive vapor (TMAE), heating
- Single photon counter (photomultipliers), expensive
- Higher QE in the near UV

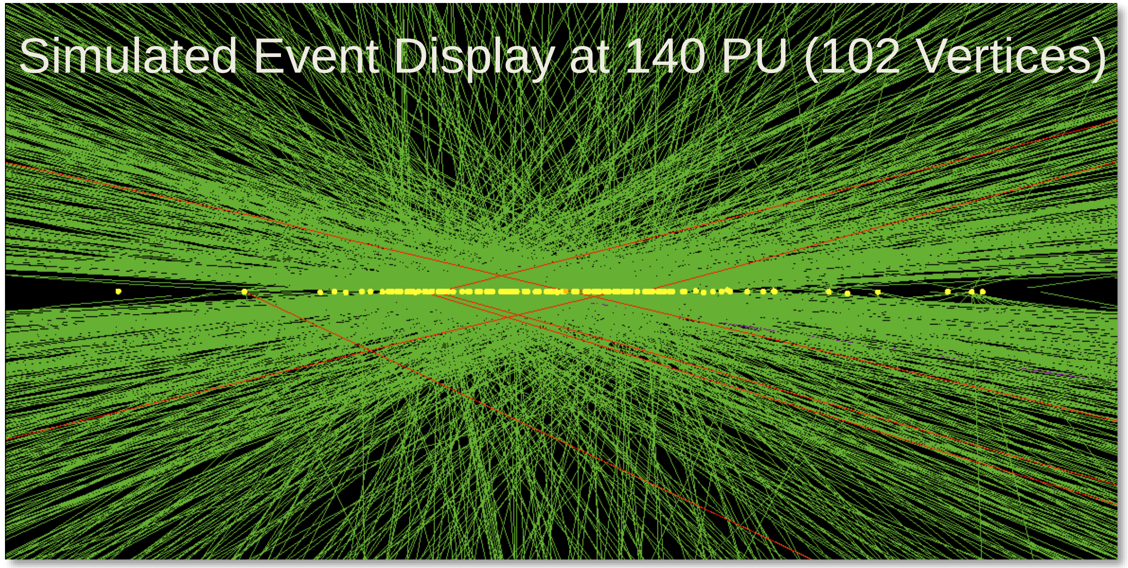
Distinctive needs of HI collisions in future

Is “event” high multiplicity still a distinctive feature of HI collisions?

not in the LHC era …



… even less in the HL-LHC era



Still, there are areas of HI collisions physics that will continue to benefit from **dedicated experiments** with **tools optimized to meet specific HI requirements**

- Measurement of particles at very low-momentum
    - Enhanced particle identification capabilities

THANK YOU

The rise of silicon detectors in HEP

End of 70s: intensive R&D on devices to measure short-lived particles (10^{-12} - 10^{-13} s)

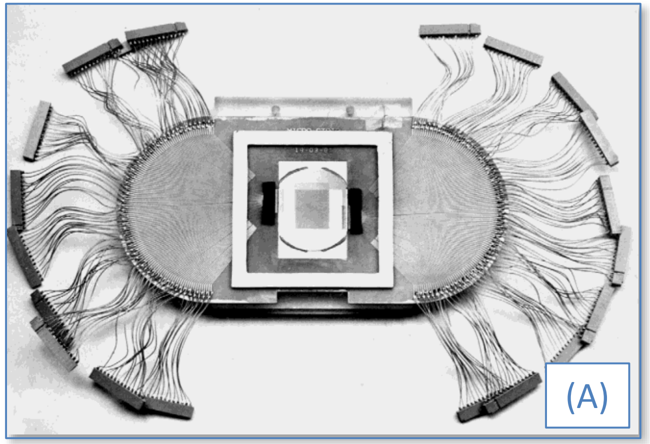
R&D at CERN (*Heijne et al., NIM 78, 1980*) and Pisa (*Amendolia et al., NIM 78, 1980*), strips 100-200μm pitch:

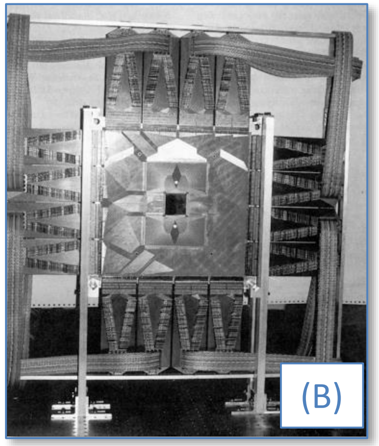
- high detection efficiency (>99%), good spatial resolution (~20μm) and good stability
- precise vertex reconstruction

Complex technology for the fabrication of these first devises ➔ limited their availability

1980 – fabrication of silicon detectors using standard IC planar process (PIN diode ➔ μstrip detector)

J. Kemmer, et al., *"Development of 10-micrometer resolution silicon counters for charm signature observation with the ACCMOR spectrometer", Proceedings of Silicon Detectors for High Energy Physics, Nucl. Instr. and Meth. 169 (1980) 499.*





First use of silicon strips detectors by NA11(CERN SPS) and E706 (FNAL)

(A) NA11 (1981): 6 planes (24 x 36mm^2): resistivity 2-3 kΩcm, thickness 280μm, pitch 20μm

(B) E706 (1982): 4 planes (3x3 cm^2) + 2 planes (5x5cm^2)

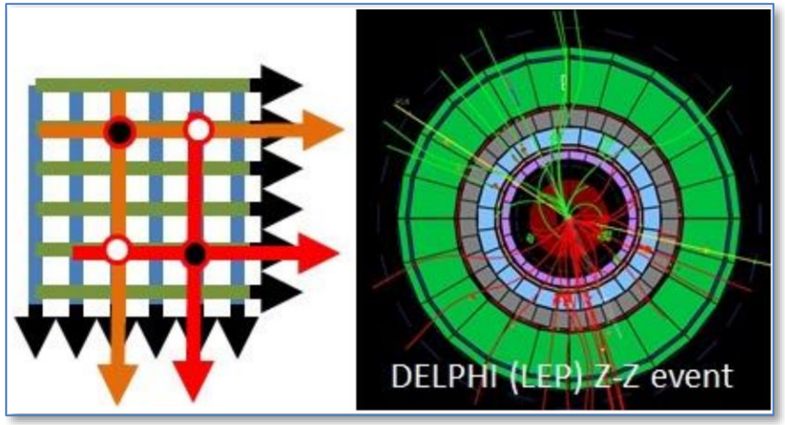
The rise of silicon detectors in HEP

Next step forward: advent of the VLSI technology ➔ coupling ASIC amplifier directly to the detectors

1990s - LEP, first silicon vertex detectors were installed in DELPHI and ALEPH experiments, then OPAL and L3

1989 - first DELPHI vertex detector, consisting of two layers of single-sided strip detectors

µstrip detector for vertex determination in HI experiments?



Projective geometry ➔ ambiguity at high multiplicities (high occupancy)

This started to become apparent already at DELPHI:

High number of ambiguities ➔ efficiency suffered (especially forward region)

Not usable close to IP in hadron colliders (LHC)

nor in HI experiments at SPS

Another problem at (very) high particle load ➔ degradation of the sensor by the high radiation dose

This implies starting with a larger signal-to-noise ratio ➔ **smaller detector capacitance**

Typical strip capacitance: ~ 10pF (1.5 pF/cm)