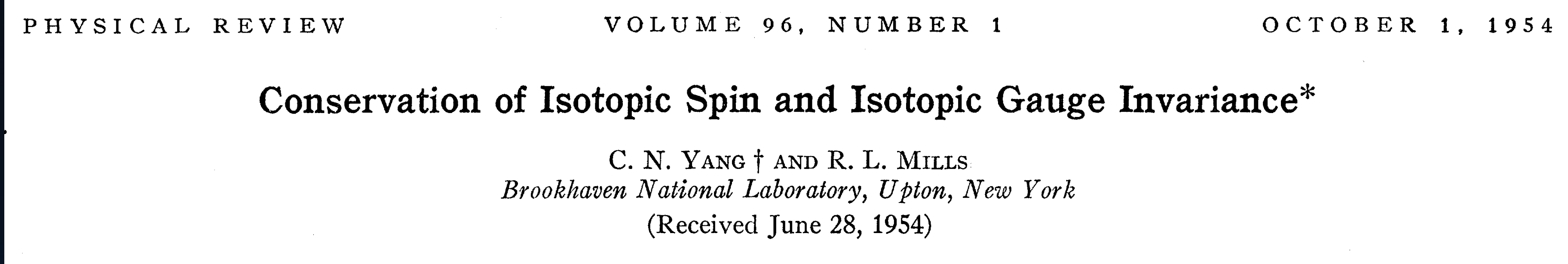
QGP, Heavy Ions and Detectors

Never at Rest: A Life Enquiring the QGP

Bad Honnef - 10 February 2025

Luciano Musa
CERN

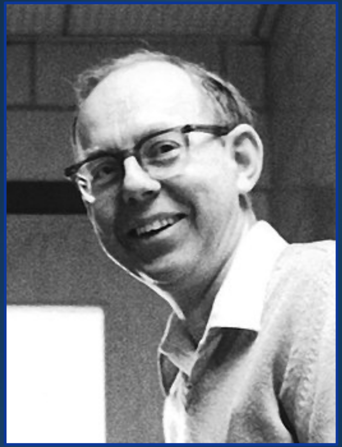
1954 - Yang-Mills theory: the foundation of QCD


PHYSICAL REVIEW VOLUME 96, NUMBER 1 OCTOBER 1, 1954

Conservation of Isotopic Spin and Isotopic Gauge Invariance*

C. N. Yang † and R. L. Mills
Brookhaven National Laboratory, Upton, New York
(Received June 28, 1954)

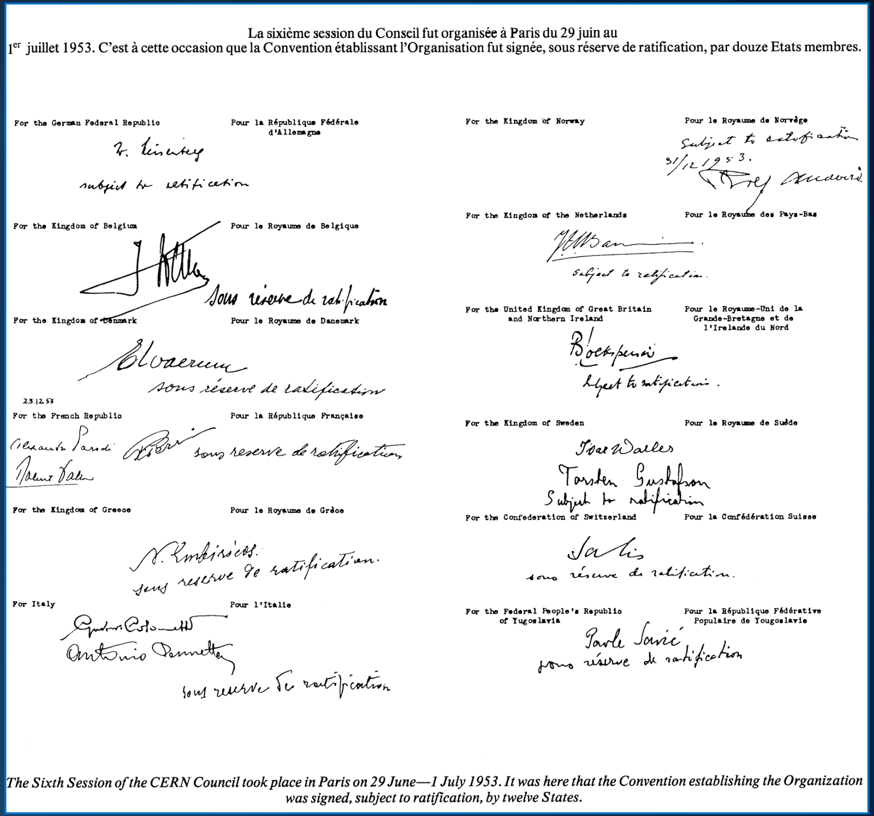
Chen Ning Yang
1 Oct 1922 -



Robert Laurence Mills
1927 - 1999

1954 – CERN is born

- The CERN Convention, established in July 1953, was ratified by 12 founding Member States: Belgium, Denmark, France, the Federal Republic of Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, the UK, and Yugoslavia.
- On 29 September 1954, the European Organization for Nuclear Research officially came into being.
- CERN was dissolved but the acronym remains.



La sixième session du Conseil fut organisée à Paris du 29 juin au 1er juillet 1953. C'est à cette occasion que la Convention établissant l'Organisation fut signée, sous réserve de ratification, par douze Etats membres.

For the German Federal Republic — Pour la République Fédérale d'Allemagne

subject to ratification

For the Kingdom of Belgium — Pour le Royaume de Belgique

Sous réserve de ratification

For the Kingdom of Denmark — Pour le Royaume de Danemark

sous réserve de ratification

23.12.53

For the French Republic — Pour la République Française

Alexandre Parodi

sous reserve de ratification

For the Kingdom of Greece — Pour le Royaume de Grèce

sous reserve de ratification.

For Italy — Pour l'Italie

Antonio Pennetta

sous reserve de ratification

For the Kingdom of Norway — Pour le Royaume de Norvège

Subject to ratification

31/12/1953.

For the Kingdom of the Netherlands — Pour le Royaume des Pays-Bas

Subject to ratification.

For the United Kingdom of Great Britain and Northern Ireland — Pour le Royaume-Uni de la Grande-Bretagne et de l'Irelande du Nord

Subject to ratification.

For the Kingdom of Sweden — Pour le Royaume de Suède

Ivar Waller

Torsten Gustafson

Subject to ratification

For the Confederation of Switzerland — Pour la Confédération Suisse

sous réserve de ratification.

For the Federal People's Republic of Yugoslavia — Pour la République Fédérative Populaire de Yougoslavie

Pavle Savić

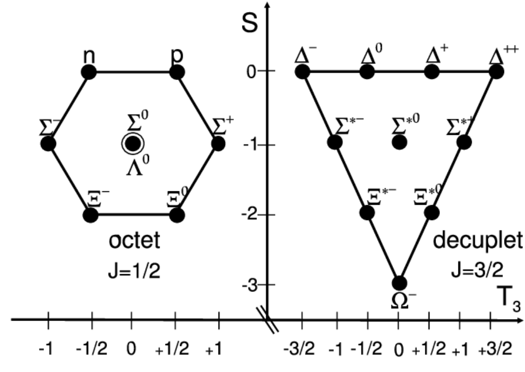
sous réserve de ratification

The Sixth Session of the CERN Council took place in Paris on 29 June—1 July 1953. It was here that the Convention establishing the Organization was signed, subject to ratification, by twelve States.

The convention was signed at the Sixth session of the CERN Council in Paris on 29 June - 1 July.

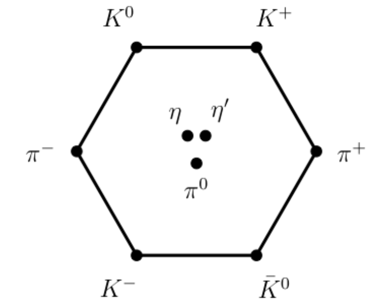
Proliferation of hadrons and emerging patterns

1950s: rapid increase in the number of known hadrons, primarily due to pion, kaon and proton beam experiments at BNL AGS, Berkeley Bevatron and CERN PS



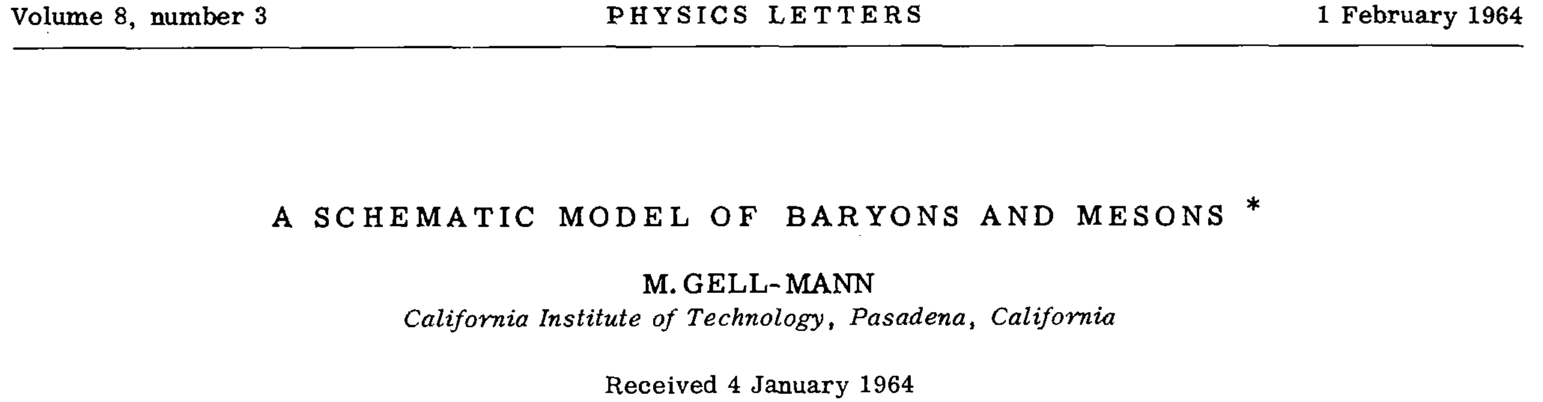
Major discoveries

- **K (1947)** – first evidence of "strange" particles
- **Δ(1232)** (**1952**) – confirming nucleon excitation states
- ***Σ (1953)*** – revealing excited states of strange baryons
- ***Ξ (1959)*** – extending the classification of strange baryons
- **η (1961)** → completed the pseudoscalar meson octet
- **Ω^- (1964)** – last missing piece of the baryon decuplet, predicted by SU(3)



Patterns in hadron properties (mass, charge, strangeness) emerged, suggesting an underlying **symmetry structure**

1964 – The Quark Model



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

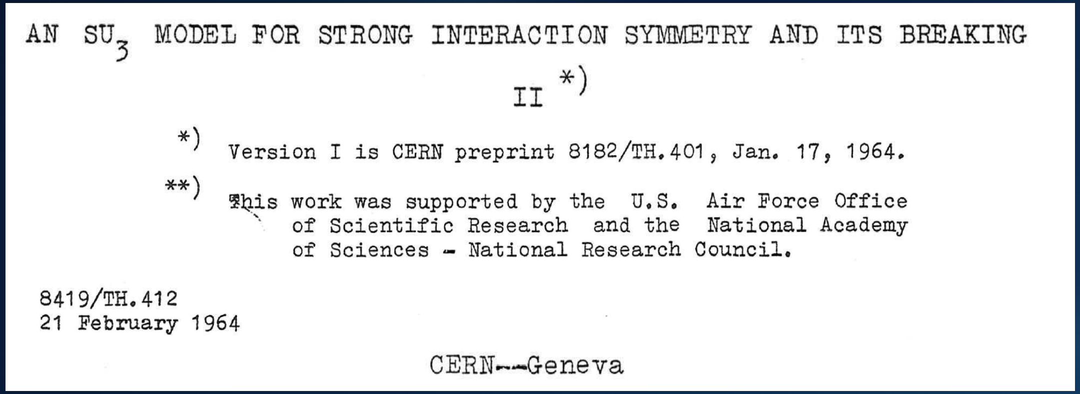
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

M. Gell-Mann (1929 – 2007)

The Ace Model (Zweig)



AN SU$_3$ MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

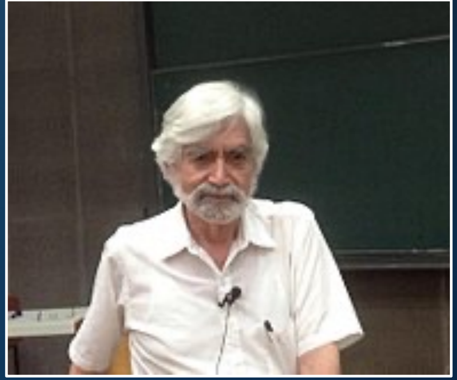
*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

**) This work was supported by the U.S. Air Force Office of Scientific Research and the National Academy of Sciences - National Research Council.

8419/TH.412
21 February 1964

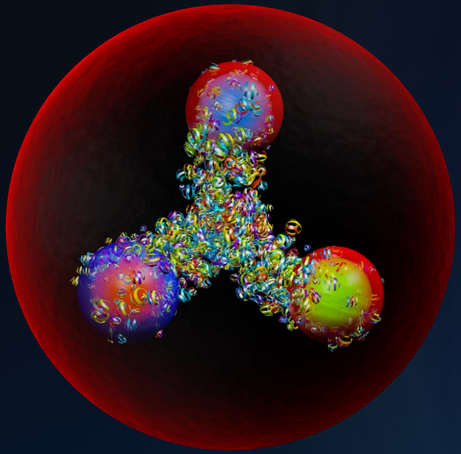
CERN--Geneva

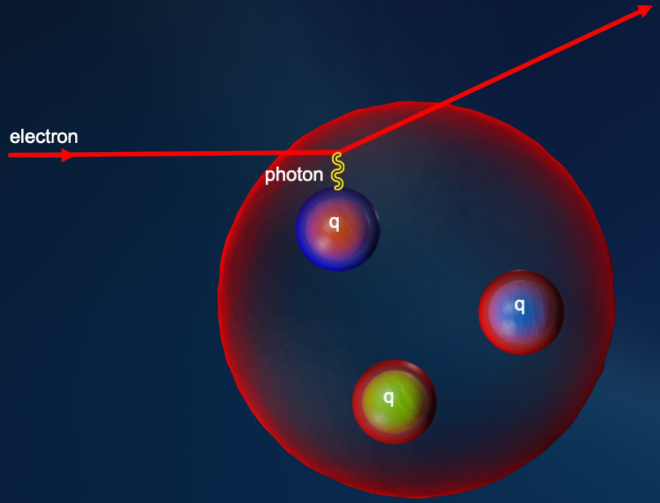
CERN-TH-401
CERN-TH-412



G. Zweig (1937 -)

Probing proton’s internal structure

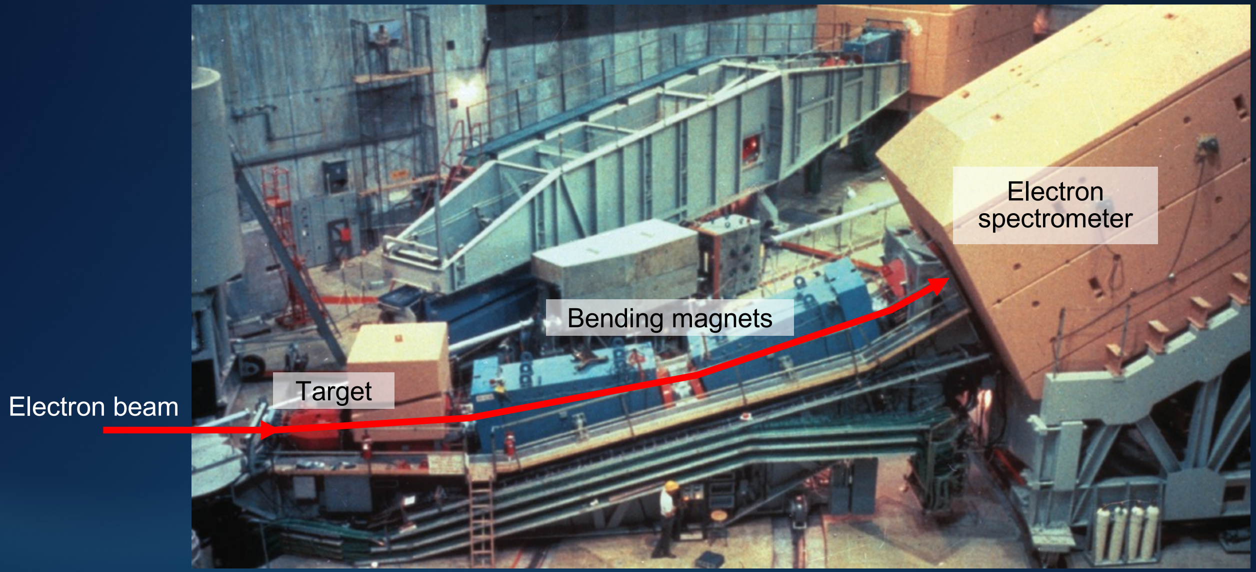




Jerome I. Friedman

Henry W. Kendall

Richard E. Taylor



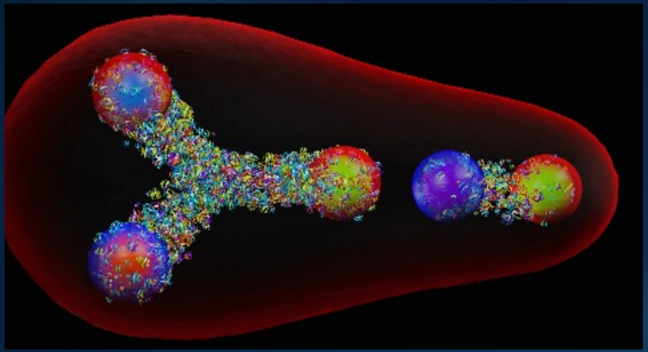
Proton microscope – SLAC, 1968

1973 – Asymptotic freedom

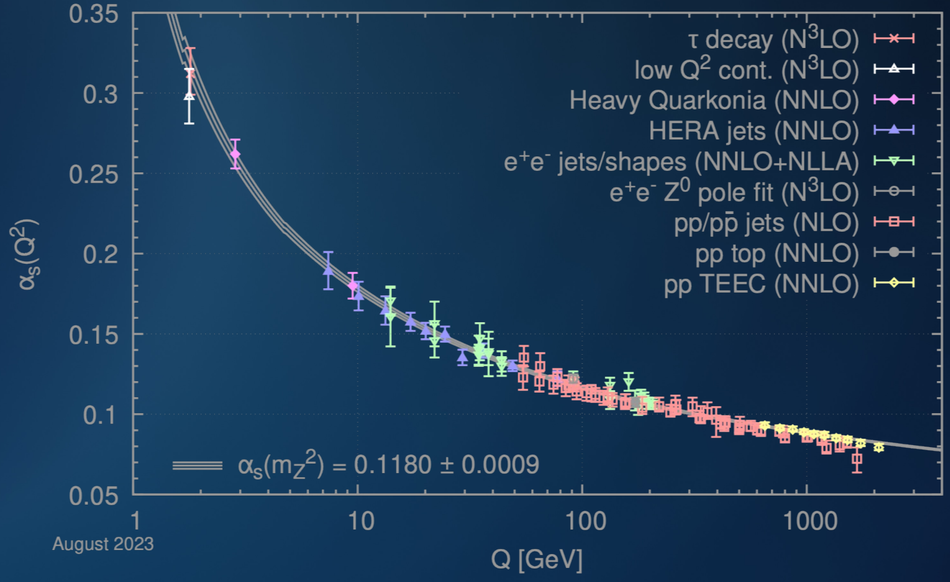
- **David Gross** and **Frank Wilczek** and, independently, **H. David Politzer**: **asymptotic freedom** in non-Abelian gauge theories.
- The discovery **solved the paradox** of why quarks behave as nearly free particles at high energy but are confined at low energy

D. Gross and F. Wilczek, "Ultraviolet Behavior of Non-Abelian Gauge Theories", Physical Review Letters 30, 1343 (1973)

Politzer, H. D., "Reliable Perturbative Results for Strong Interactions.", *Physical Review Letters*, 30(26), 1346–1349 (1973)



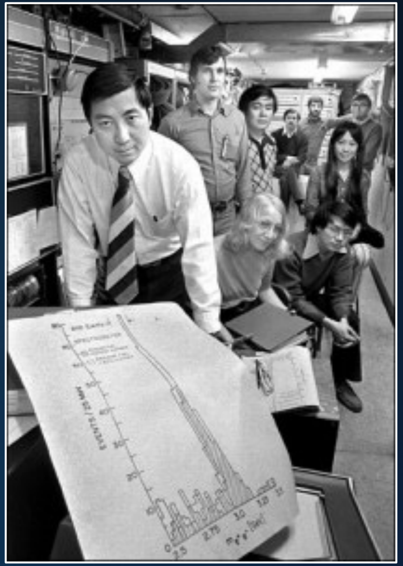
PDG, rev. Aug 2019



1974 – The November Revolution

Simultaneous discovery of the J/ψ meson in November 1974 by two experiments:

- SLAC-SPEAR (led by **Burton Richter**) - ψ
- BNL-AGS (team led by **Samuel Ting**) – J
- Narrow decay width (~100 keV), indicating long-lived bound state



Predicted by the GIM mechanism (1970)

Triggered the "November Revolution" in particle physics

➪ rapid shift in theoretical understanding of hadrons structure

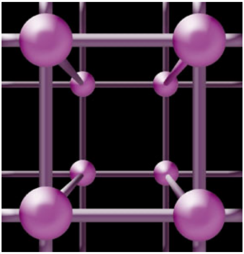
➪ evidence for the quark model and QCD

Led to an explosion of new discoveries in charmonium physics

Gross, Wilczek, and Politzer's work on asymptotic freedom in QCD gained immediate attention.

1974 - Lattice QCD (⇨ Phase Transition Predictions)

- **Kenneth G. Wilson (1974)** introduced the **lattice gauge theory** formulation of QCD.
- **Michael Creutz (1980)** performed the first **Monte Carlo Lattice QCD simulations** to study the phase transition.

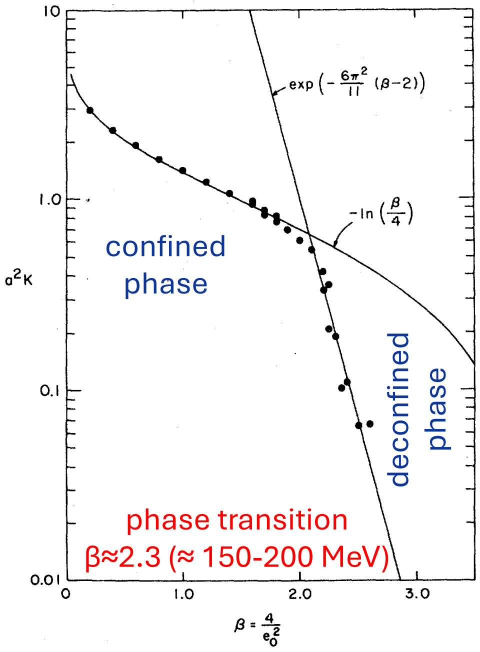


Creutz, M. (1980). “Monte Carlo Study of Quantized SU(2) Gauge Theory”. *Physical Review D*, 21(8), 2308–2315.

- Creutz’s simulations predicted phase transition at T_C ~ 150-200 MeV

⇨ first numerical evidence supporting QGP phase transition

- Established lattice QCD as a powerful tool for studying the strong interaction
- Inspired experimental searches for QGP at high-energy colliders
- Led to modern precision calculations using lQCD techniques



confined phase

deconfined phase

phase transition
β≈2.3 (≈ 150-200 MeV)

1974 - The advent of the Time Projection Chamber

“The purest realization of the dream of an electronic bubble chamber …” (“Image and Logic”, 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, …”

Large TPCs operated in HEP experiments

PEP4 TRIUMF TOPAZ ALEPH/DELPHI *(particle-physics)* HARP T2K

1982/1984 1982/1983 1987 1989 1990 1992 1995 1999 2000 2001 2008 2009/2010

(heavy ions) NA35 EOS/HISS NA49 (4) CERES STAR ALICE

1975 - The Birth of QGP

The Role of Asymptotic Freedom

J.C. Collins and **M.J. Perry**

“Superdense Matter: Neutrons or Asymptotically Free Quarks?”

Phys. Rev. Lett. **34**, 1353 – May, 1975 (received 6 January 1975)

J.C. Collins

M.J. Perry

- Proposed that nuclear matter at extreme densities transitions into a deconfined quark state
- First connection between asymptotic freedom and a new state of matter (later called QGP)
- Inspired future theoretical and experimental studies on quark deconfinement

The QCD Phase Transition: Early Foundations

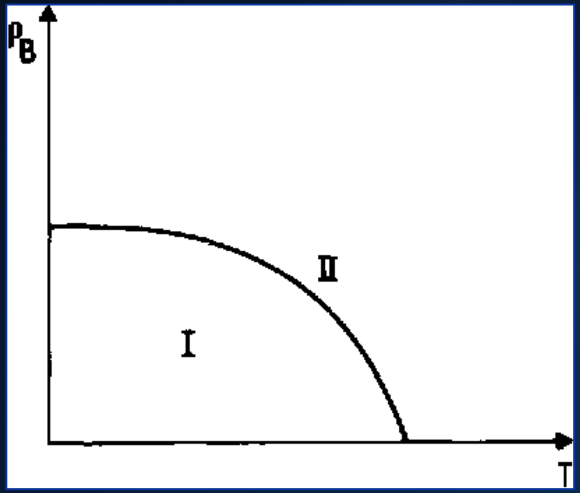
N. Cabibbo, G. Parisi

“Exponential hadronic spectrum of quark liberation”

Phys. Lett. B, Vol. 59, Issue 1, 67-69 (1975)

N. Cabibbo

G. Parisi



Proposed that QCD undergoes a phase transition

Used analogies with statistical physics to describe the behavior of QCD at high temperatures.

One of the first theoretical descriptions of the phase transition to partonic matter

1978 - The Birth of HI Physics and the path to QGP

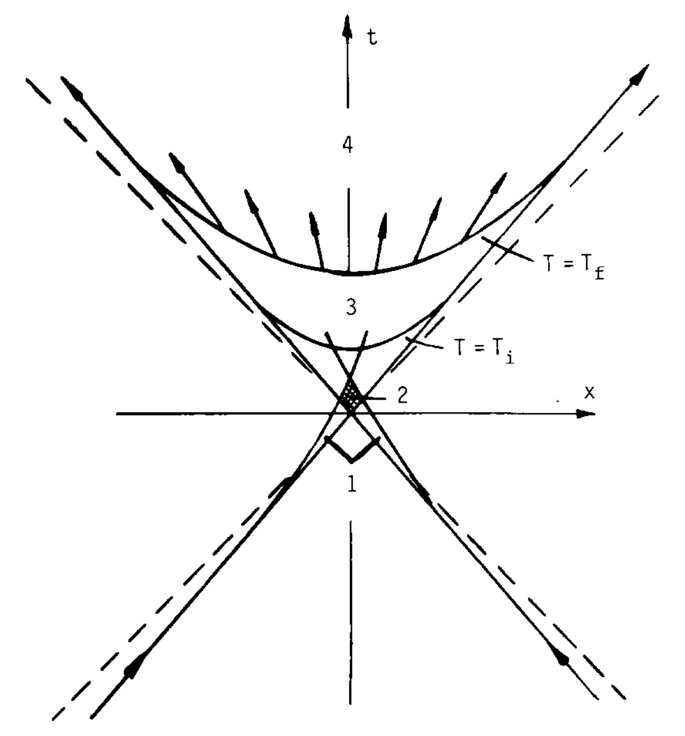
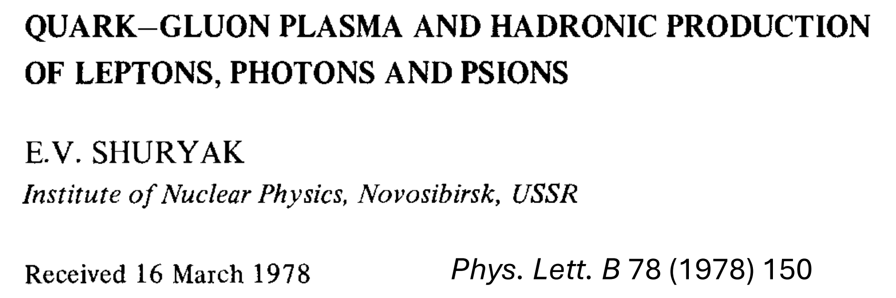


Fig. 1. The space–time picture of hadronic collisions, proceeding through the following stages: (1) structure function formation; (2) hard collisions; (3) final state interaction; (4) free secondaries.



QUARK–GLUON PLASMA AND HADRONIC PRODUCTION OF LEPTONS, PHOTONS AND PSIONS

E.V. SHURYAK
Institute of Nuclear Physics, Novosibirsk, USSR

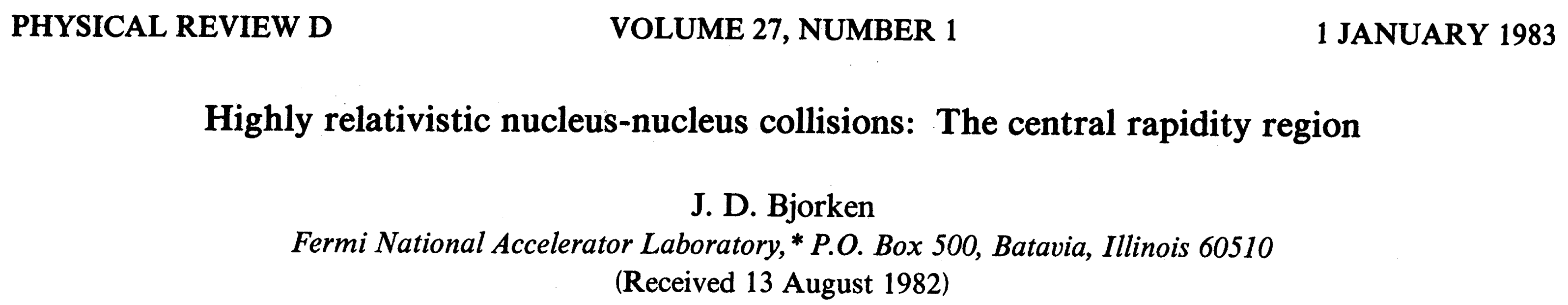
Received 16 March 1978 *Phys. Lett. B* 78 (1978) 150

QCD matter at high temperatures

- First systematic studies of QCD at high temperatures
- Introduced the concpet of the Quark-Gluon Plasma (QGP) in a thermal QCD framework
- Proposed that heavy-ion collisions could produce and study QGP

T.D. Lee (1974)*: suggested using heavy-ion collisions to study QCD and quark deconfinement*

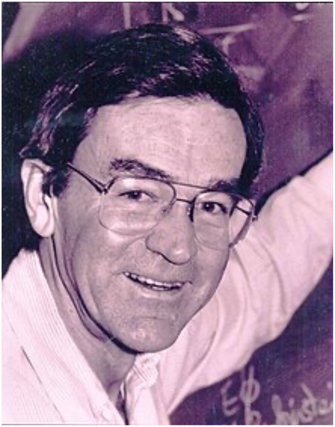
1982 – Bjorken’s Hydrodynamic Model



PHYSICAL REVIEW D **VOLUME 27, NUMBER 1** **1 JANUARY 1983**

Highly relativistic nucleus-nucleus collisions: The central rapidity region

J. D. Bjorken
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510*
(Received 13 August 1982)



D.J. Bjorken 1934 - 2024

- Proposed hydrodynamic model to describe the longitudinal expansion of the QGP in high-energy HI collisions
- Introduced the Bjorken energy density formula, allowing estimates of QGP formation from experimental data
- theoretical framework for QGP observables

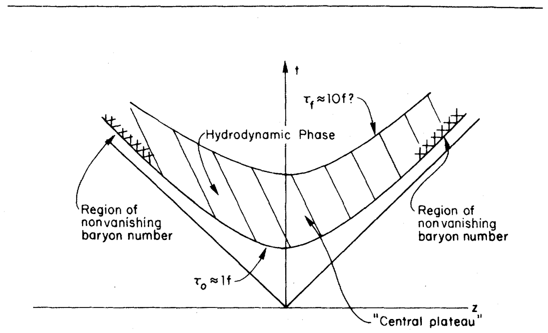
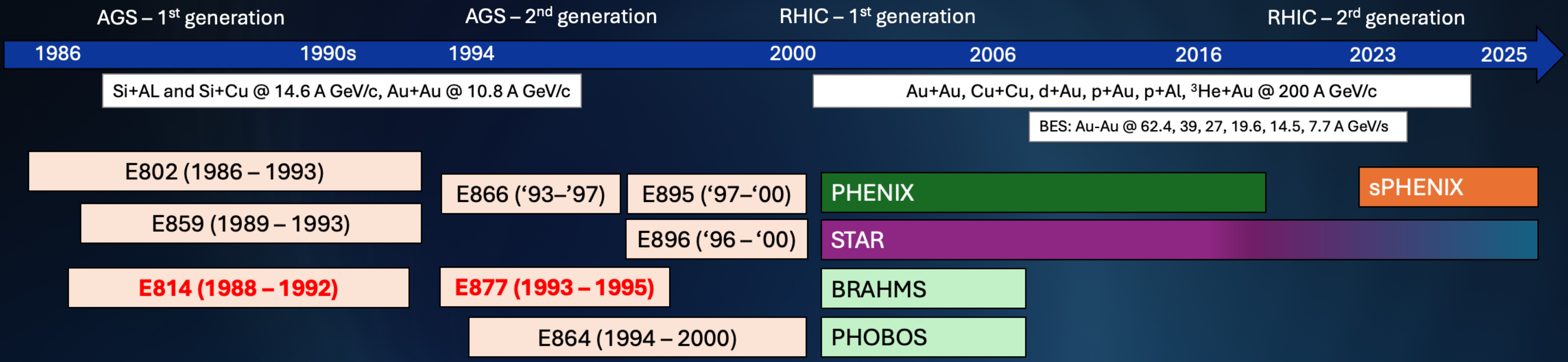


FIG. 3. Space-time diagram of longitudinal evolution of the quark-gluon plasma.

Experimental enquiry of QGP - BNL



AGS – 1st generation

AGS – 2nd generation

RHIC – 1st generation

RHIC – 2rd generation

1986 1990s 1994 2000 2006 2016 2023 2025

Si+AL and Si+Cu @ 14.6 A GeV/c, Au+Au @ 10.8 A GeV/c

Au+Au, Cu+Cu, d+Au, p+Au, p+Al, ^{3}He+Au @ 200 A GeV/c

BES: Au-Au @ 62.4, 39, 27, 19.6, 14.5, 7.7 A GeV/s

E802 (1986 – 1993)

E859 (1989 – 1993)

E814 (1988 – 1992)

E866 (‘93–’97)

E895 (‘97–‘00)

E896 (‘96 – ‘00)

E877 (1993 – 1995)

E864 (1994 – 2000)

PHENIX

STAR

BRAHMS

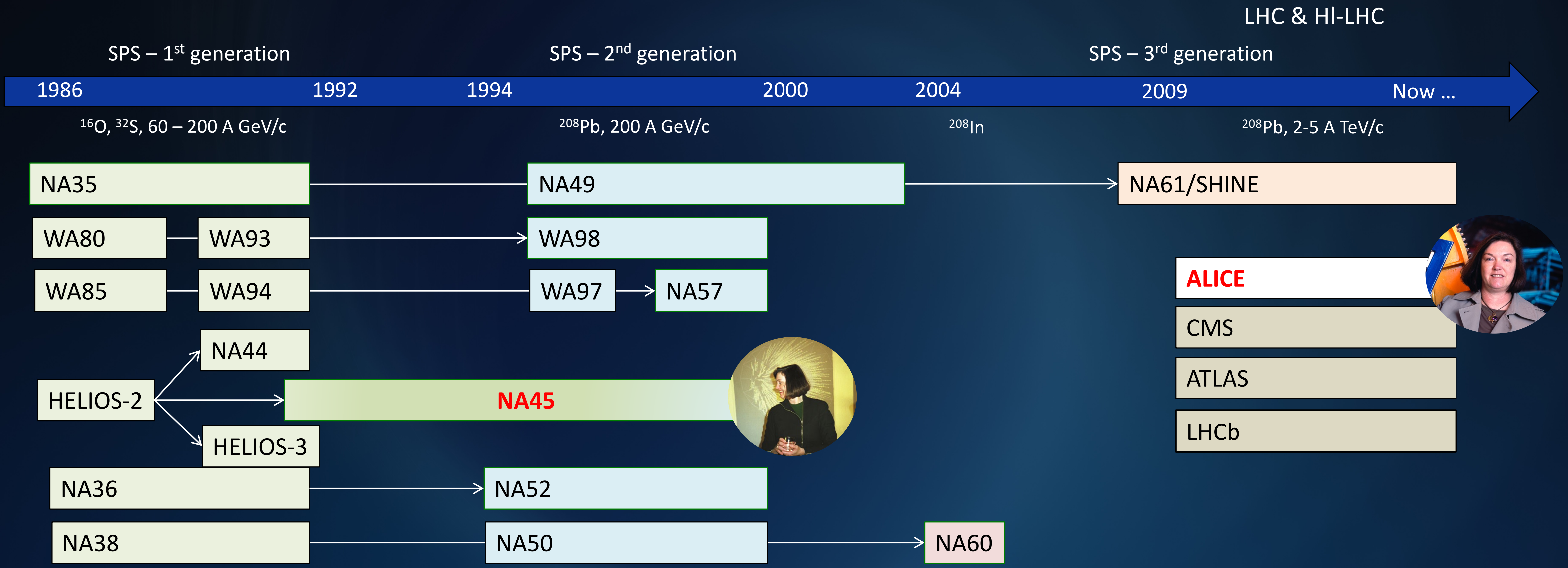
PHOBOS

sPHENIX

E814/E877

- particle production mechanisms;
- baryon stopping and energy deposition in the collision zone;
- flow phenomena (directed and elliptic flow);
- strangeness enhancement;

Experimental enquiry of QGP - CERN



LHC & HI-LHC

SPS – 1st generation

SPS – 2nd generation

SPS – 3rd generation

1986 1992 1994 2000 2004 2009 Now …

^{16}O, ^{32}S, 60 – 200 A GeV/c

^{208}Pb, 200 A GeV/c

^{208}In

^{208}Pb, 2-5 A TeV/c

NA35 → NA49 → NA61/SHINE

WA80 – WA93 → WA98

WA85 – WA94 → WA97 → NA57

HELIOS-2 → NA44

HELIOS-2 → **NA45**

HELIOS-2 → HELIOS-3

NA36 → NA52

NA38 → NA50 → NA60

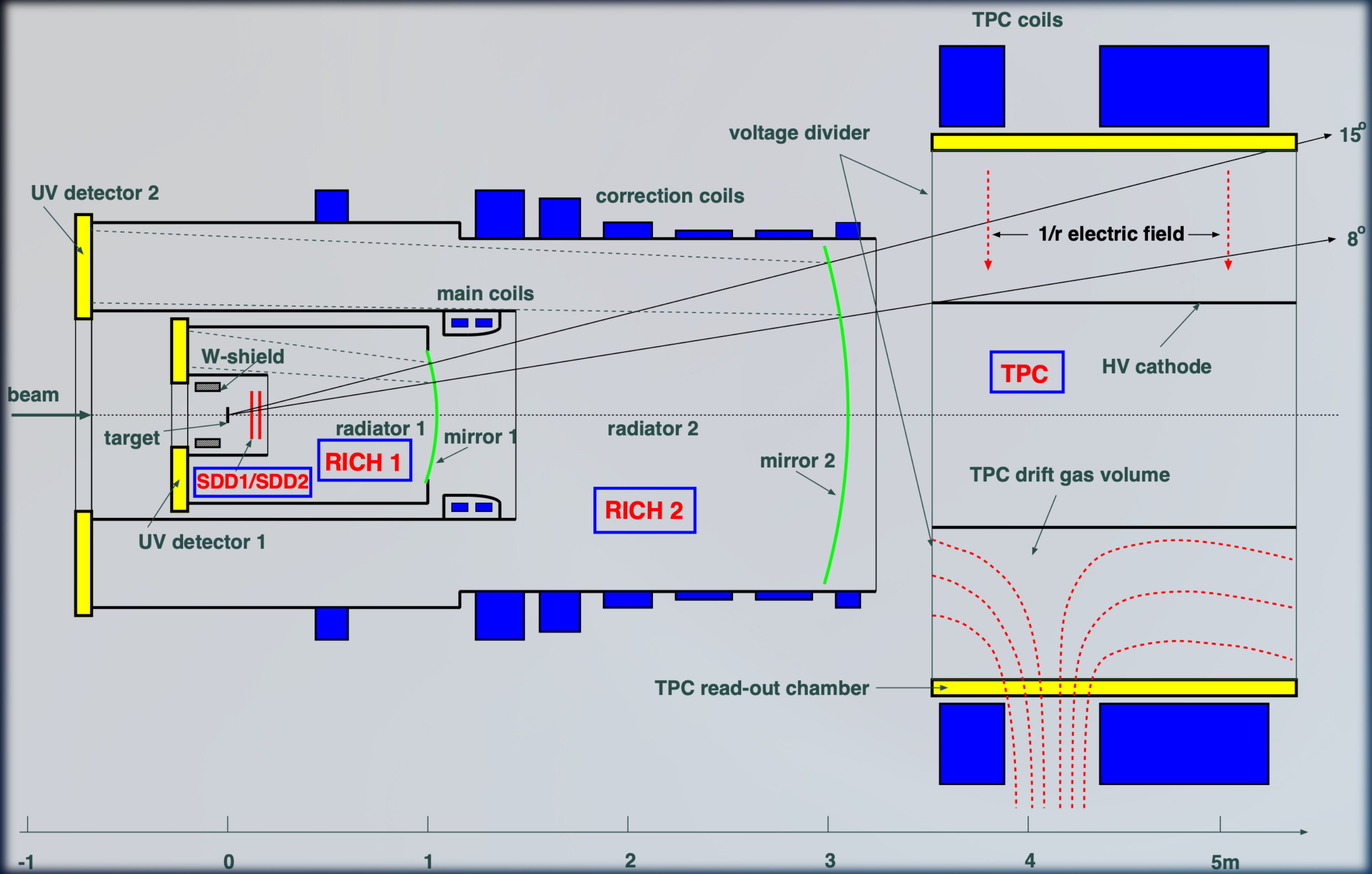
ALICE

CMS

ATLAS

LHCb

The CERES Spectrometer



1991 - 2000

ChErenkov Ring Electron Spectrometer

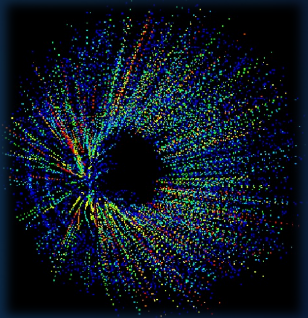
e^+e^- pairs in p–A and A–A

$$\boxed{0.1\ GeV/c^2 < m_{ee} < 1.2\ GeV/c^2}$$

Enhanced dilepton yield in S-Au, Pb-Au

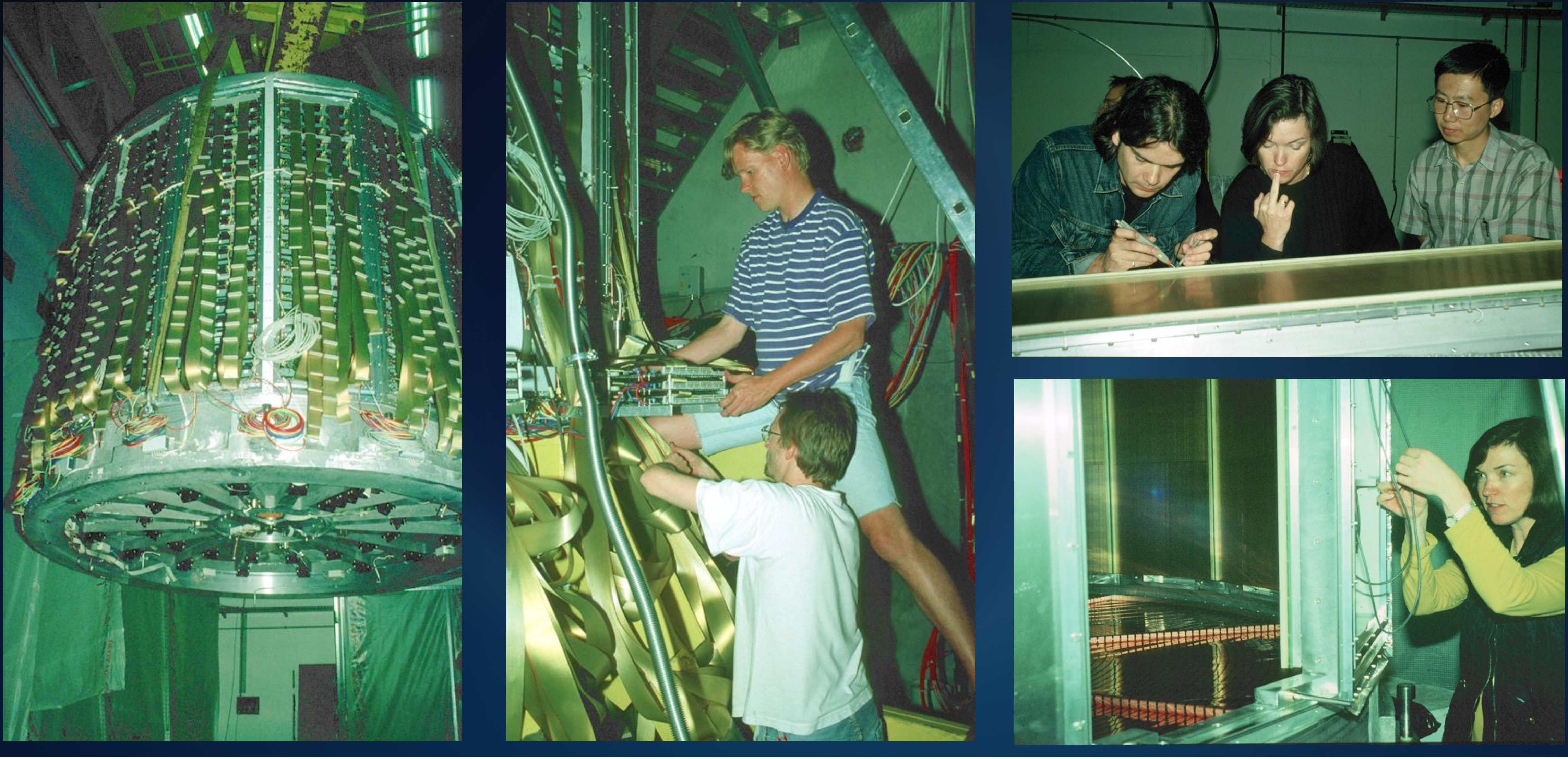
Upgraded in 1998 with a (radial!) TPC

$$\boxed{\frac{\Delta m}{m}:\ 7\% \ \rightarrow\ 3.8\%}$$



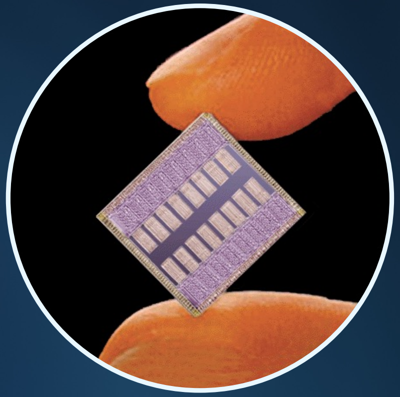
Extend program to hadronic observables

Building the CERES TPC: a pioneering upgrade



Advancing TPC Readout Electronics

First use in the CERES TPC!

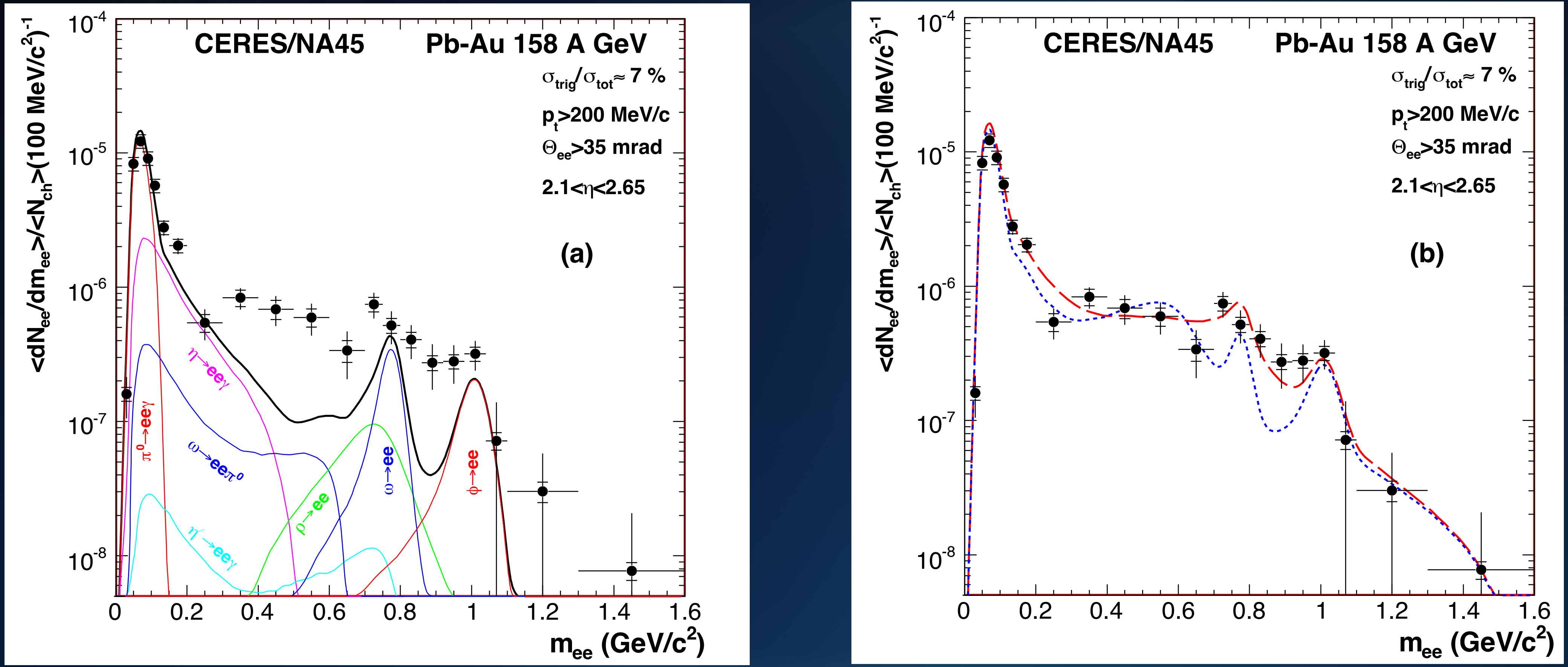


The end of analogue memories + multiplexed digitization

fast digital sampling + sparse readout ⇨ FAST TPCs

1998	1999	2001
CHANNELS / CHIP: 1	CHANNELS / CHIP: 4	CHANNELS / CHIP: 1
POWER / CH: 120mW	POWER / CH: 80mW	POWER / CH: 16mW
PRICE / CH: 50CHF	PRICE / CH: 8CHF	PRICE / CH: 5CHF

In-medium broadening of the ρ



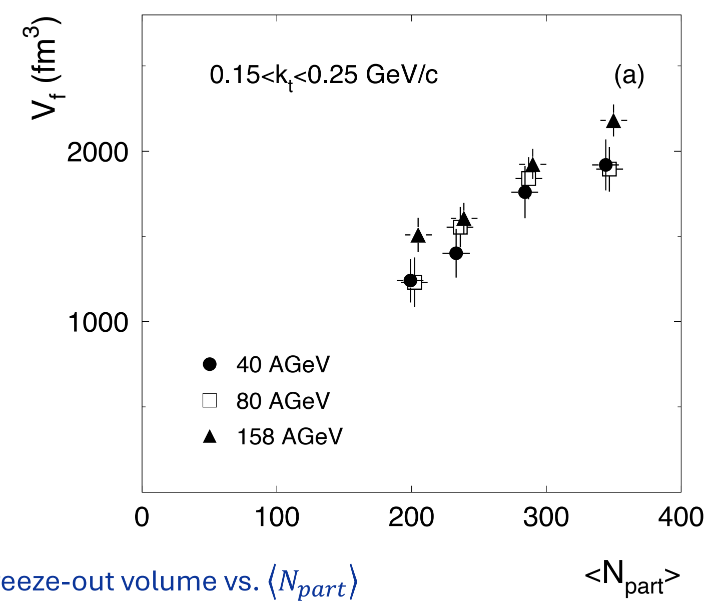
Phys.Lett.B666:425-429,2008

Universal Pion Freeze-out Conditions

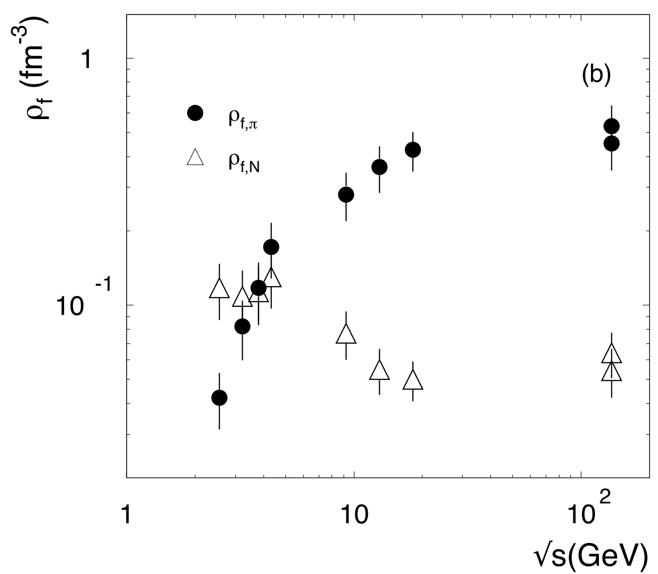
pion freeze-out always occurs when the pion mean free path reaches about 1 fm, independent of:

- collision centrality
- beam energy

⇨ freeze-out determined by a universal density condition



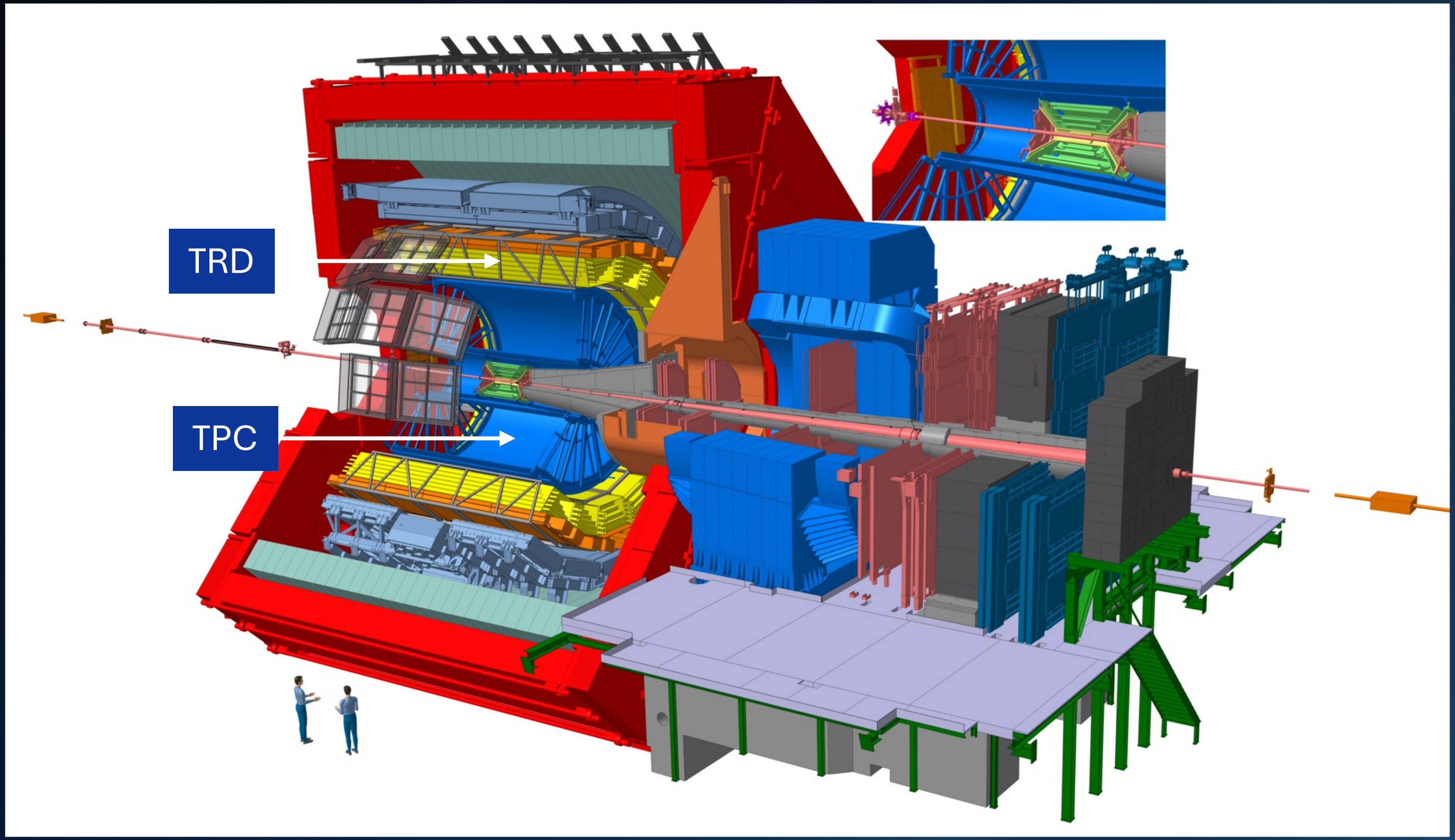
Freeze-out volume vs. $\langle N_{part} \rangle$



Freeze-out density for pions and nucleons

D. Adamová et al. (CERES Collaboration), Phys. Rev. Lett. **90**, 022301

30 years with ALICE

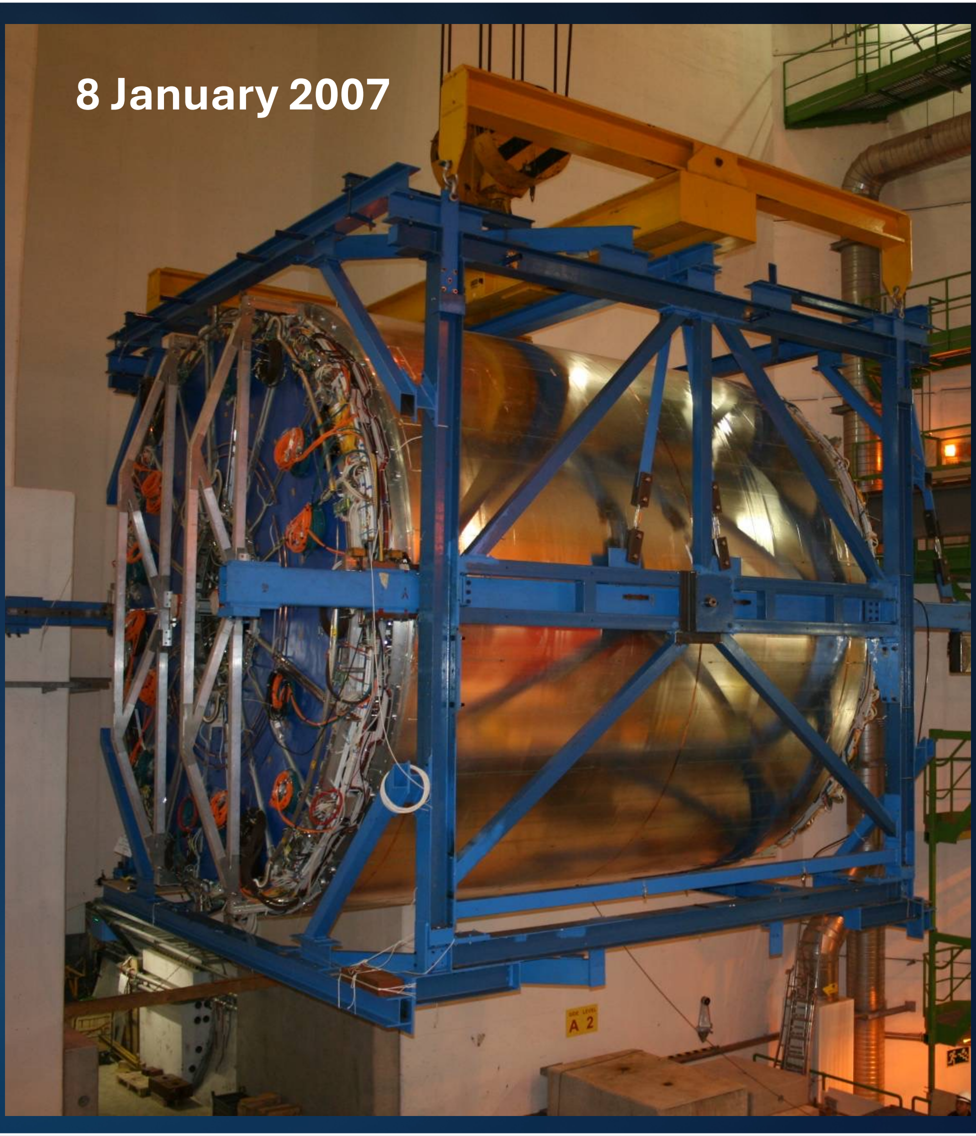


ALICE timeline

- 1992: Expression of interest
- 1997: ALICE approval
- 2000 – 2007: construction
- 2002 – early 2008: Installation
- 2009 – 2018: physics data taking
- 2019 - 2021: Phase I upgrades
- 2022 – now: physics data taking

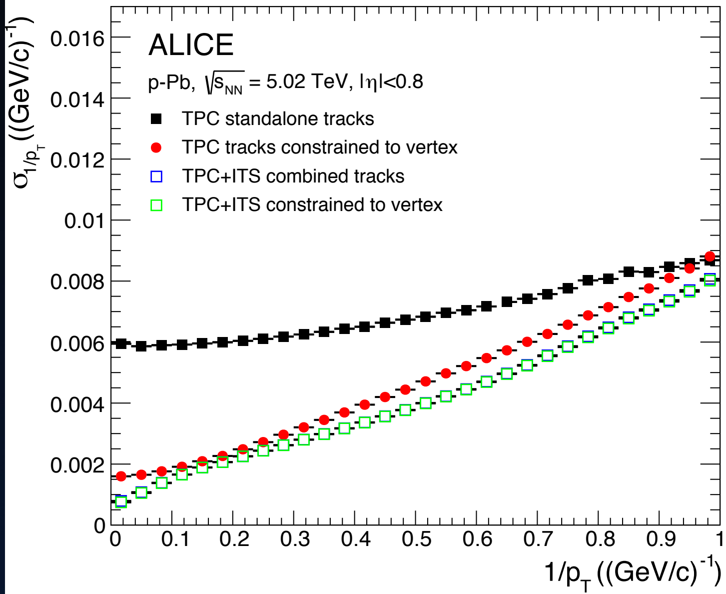
ALICE Time Projection Chamber

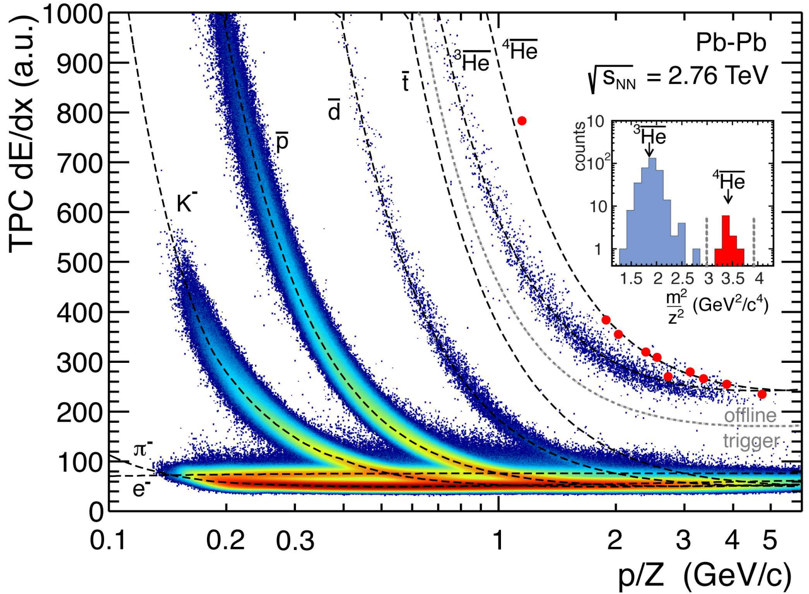

The interior of the TPC, 2004

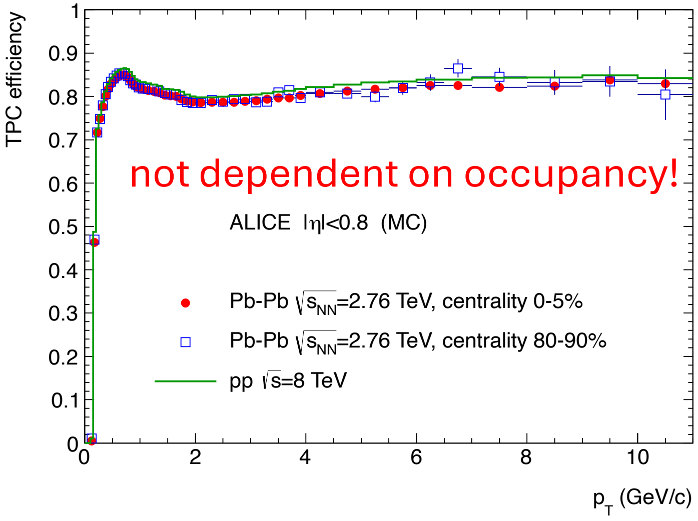

8 January 2007

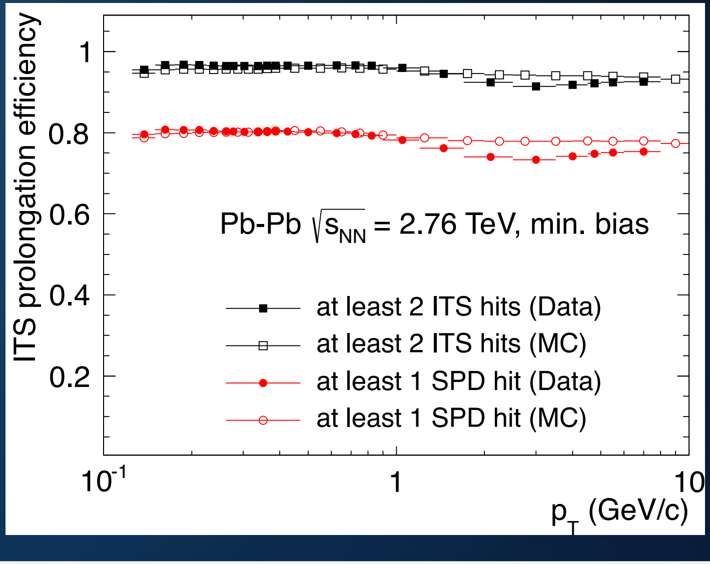
The ALICE Time Projection Chamber

ALICE Key tracking and PID instrument





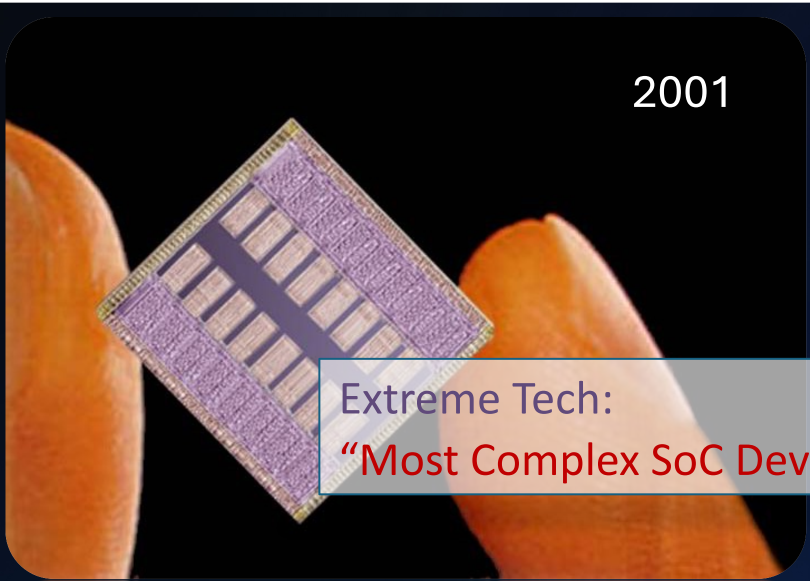

not dependent on occupancy!



so much for those who said it wouldn't work!

“Performance of the ALICE experiment at the CERN LHC”: arXiv:1001.1950

Innovative Readout



PASA + ALTRO Chip Set

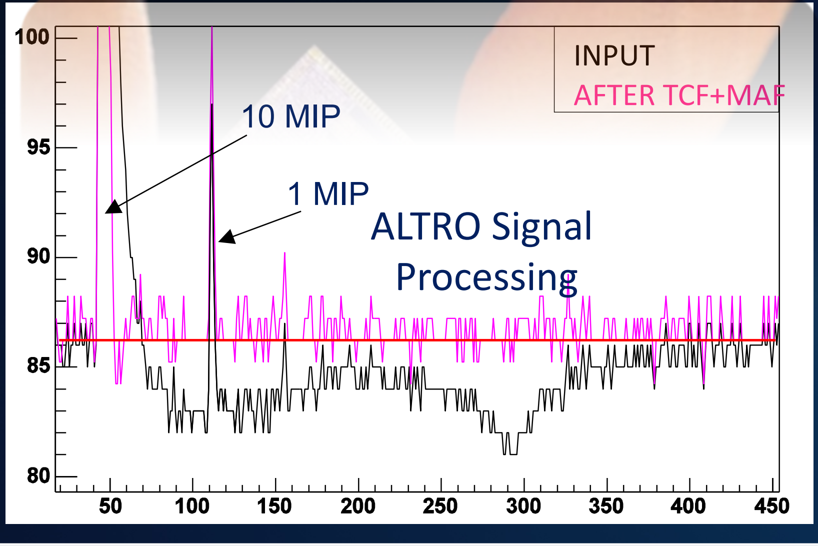
Very High Integration !!

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

4 nJ/bit

Extreme Tech:
“Most Complex SoC Device Ever”

Electronic News:
“SoC Device in Atomic Particle Experiment” Electronic News



ALTRO electronics used also for other ALICE detectors:

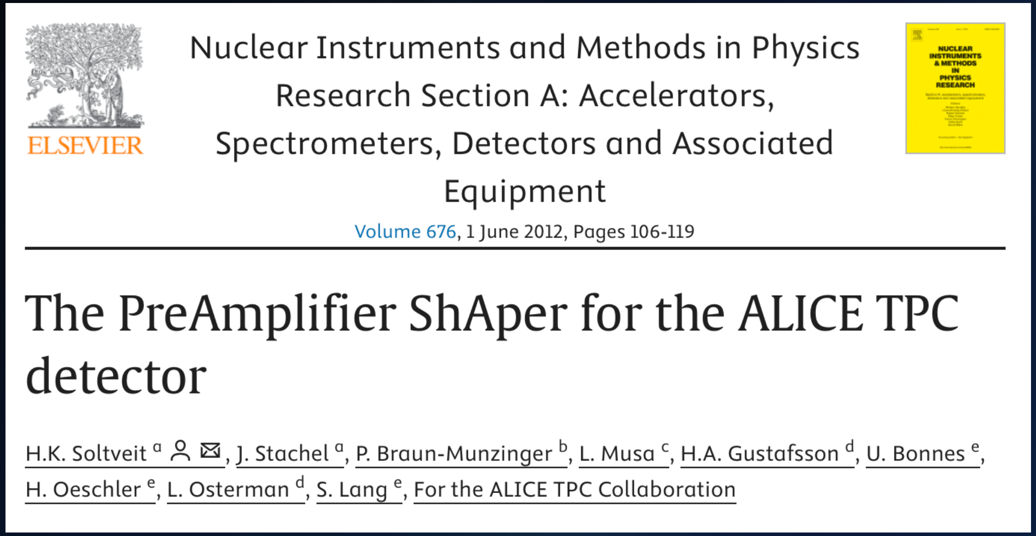
- EMCAL, PHOS, FMD

ALICE TPC Electronics adopted

- NA45, HARP, CAST
- STAR Upgrade, MIPP, BONUS

ALICE TPC- 2006

Shaping the TPC signals



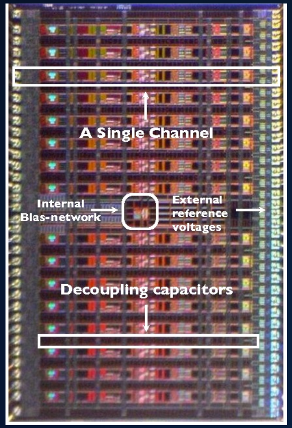
ELSEVIER

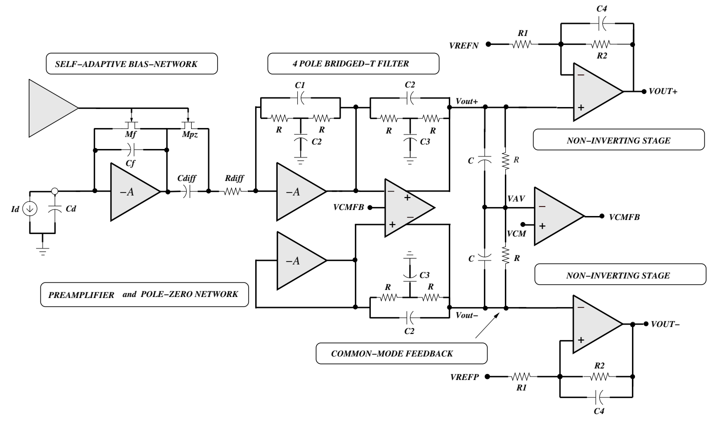
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 676, 1 June 2012, Pages 106-119

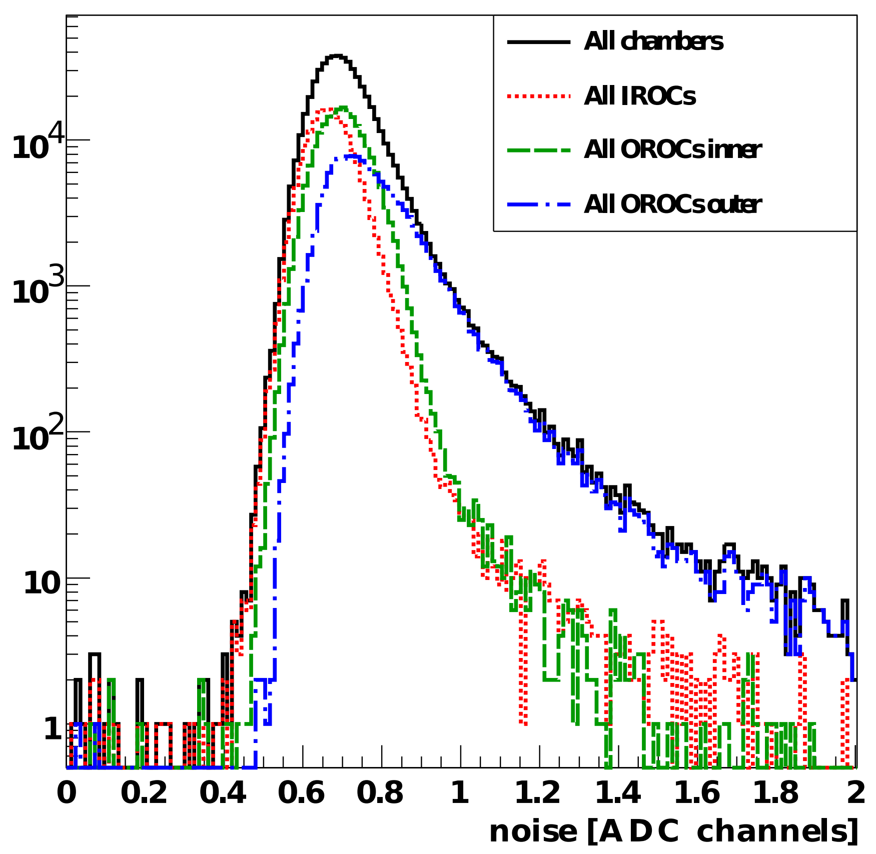
The PreAmplifier ShAper for the ALICE TPC detector

H.K. Soltveit [a], J. Stachel [a], P. Braun-Munzinger [b], L. Musa [c], H.A. Gustafsson [d], U. Bonnes [e], H. Oeschler [e], L. Osterman [d], S. Lang [e], For the ALICE TPC Collaboration

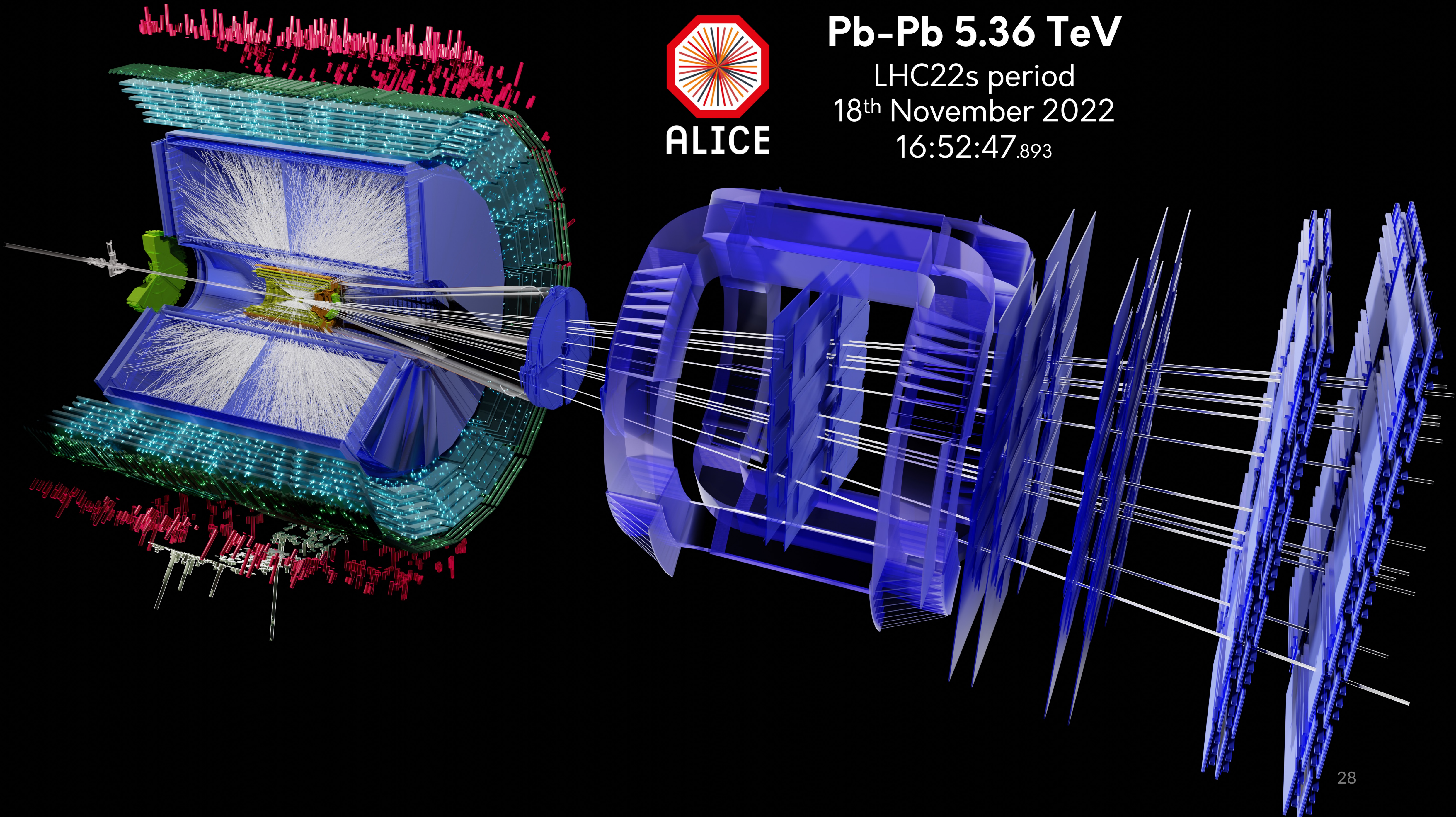




A quiet TPC



The Transition Radiation Detector



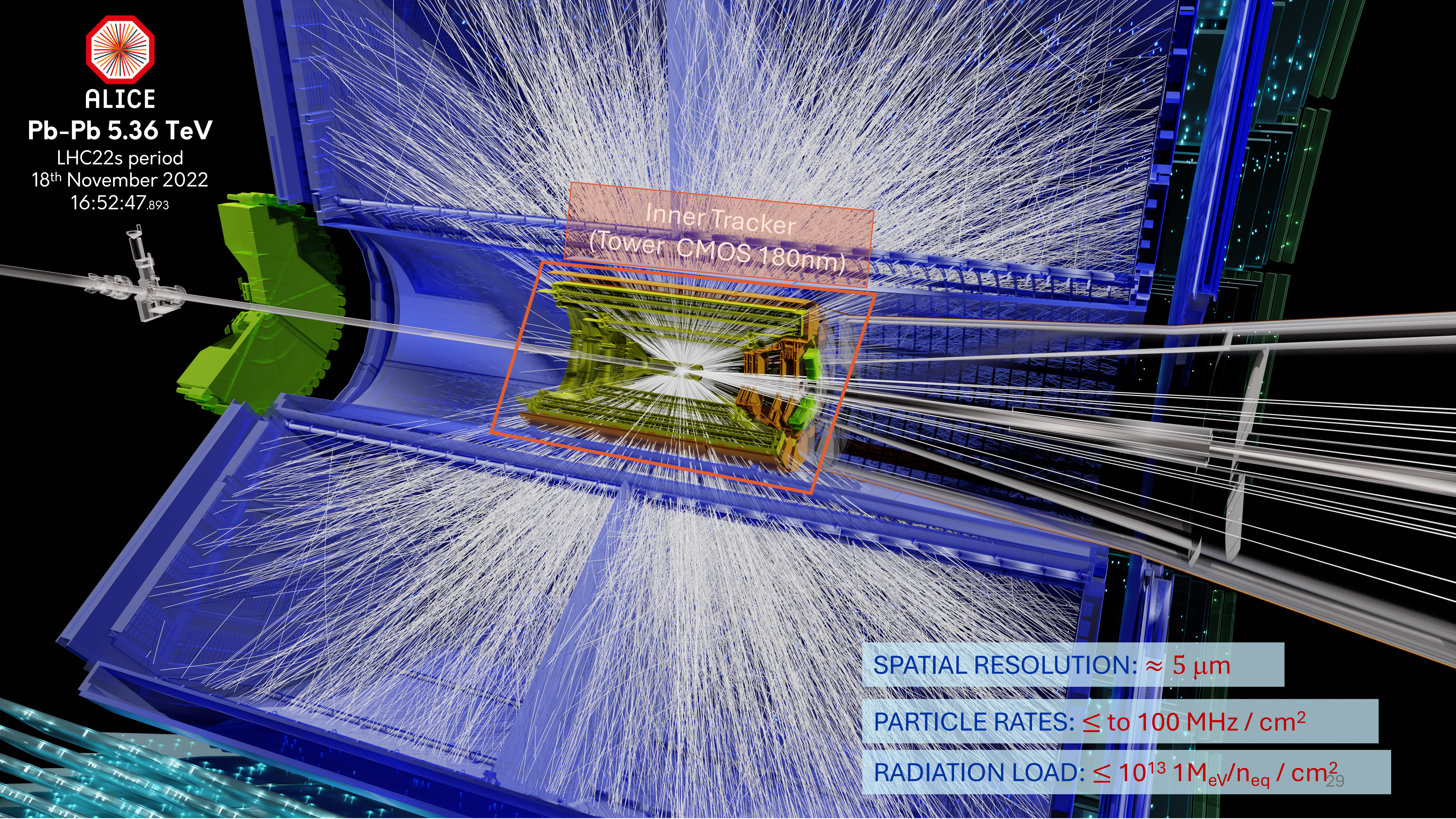
ALICE

Pb-Pb 5.36 TeV

LHC22s period

18th November 2022

16:52:47.893



Inner Tracker
(Tower CMOS 180nm)

SPATIAL RESOLUTION: ≈ 5 μm

PARTICLE RATES: ≤ to 100 MHz / cm^2

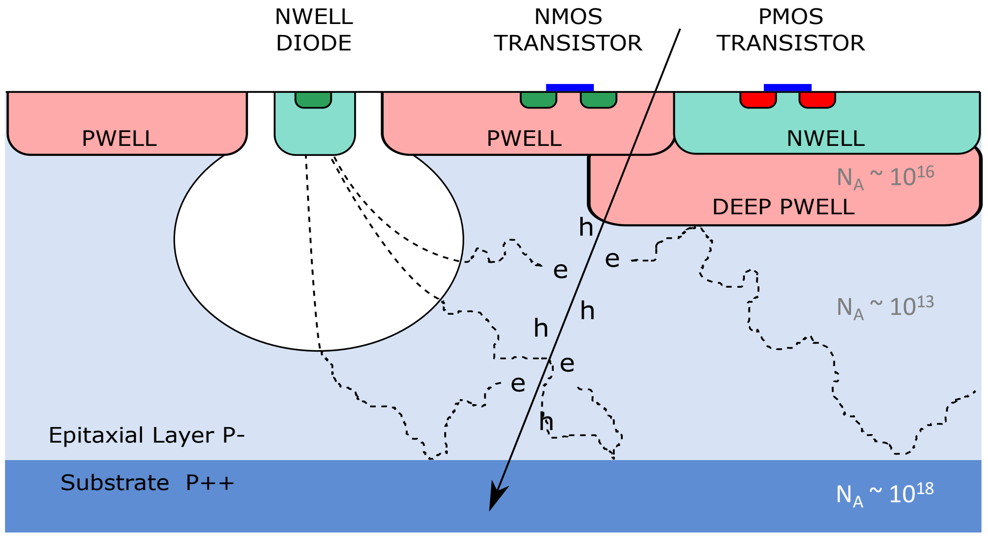
RADIATION LOAD: $\leq 10^{13}$ $1\mathrm{M_{eV}}/n_{eq}$ / cm^2

State-of-the-art CMOS APS for High Energy Physics

ALPIDE Sensors for ALICE Inner Tracking System

Based on **Tower CMOS 180nm**

- **10 m^2** active silicon area
- **12.5 G-pixels**
- **50 μm** thin sensor
- Spatial resolution **~5µm**
- Max particle rate ~ **100 MHz /cm^2**

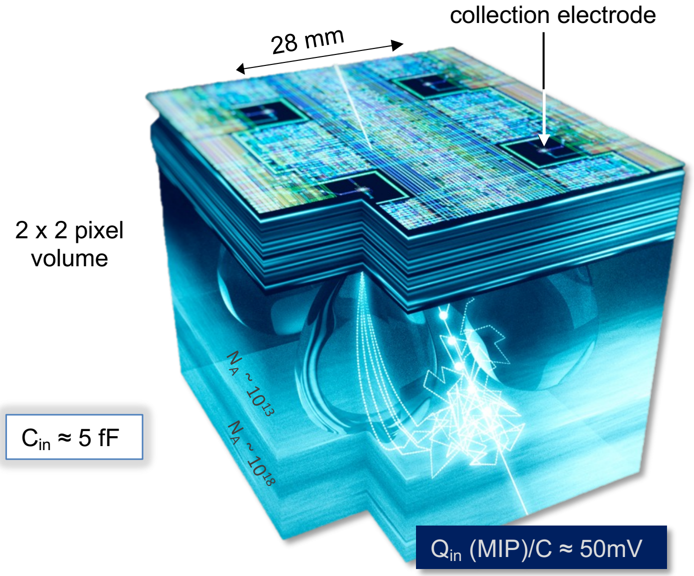


Detection layer: high-resistivity (> 1kΩ cm) epi layer (25µm)

Very small collection diodes (2 µm diameter) ⇨ low capacitance (~fF)

Reverse bias voltage to substrate (contact from the top)

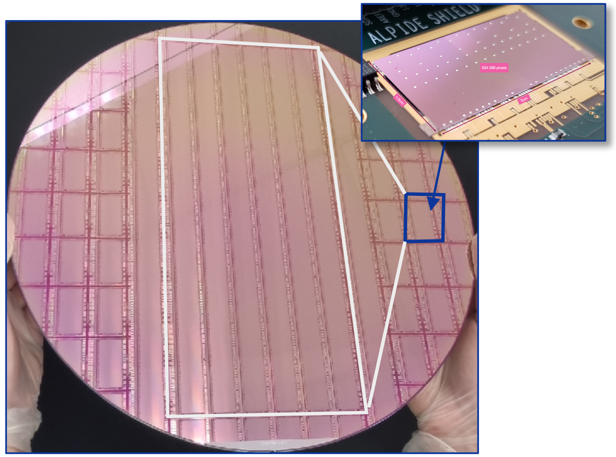
CMOS circuitry within active area



Innovations in CMOS Active Pixel Sensor technology

Wafer-scale flexible CMOS APS

TPSCo ISC 65nm CMOS Imaging
300mm wafers + stitching



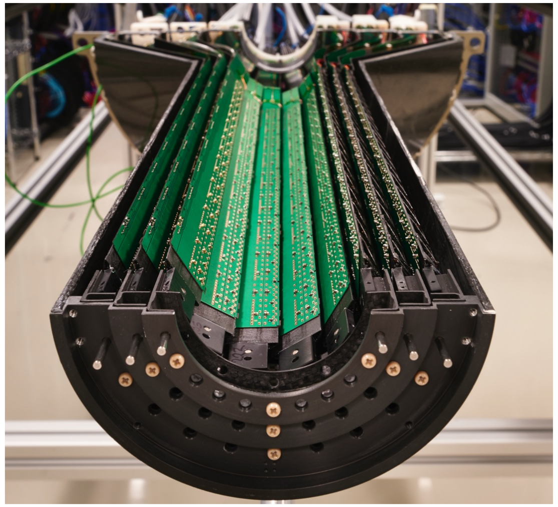
from reticule-size to wafer-size

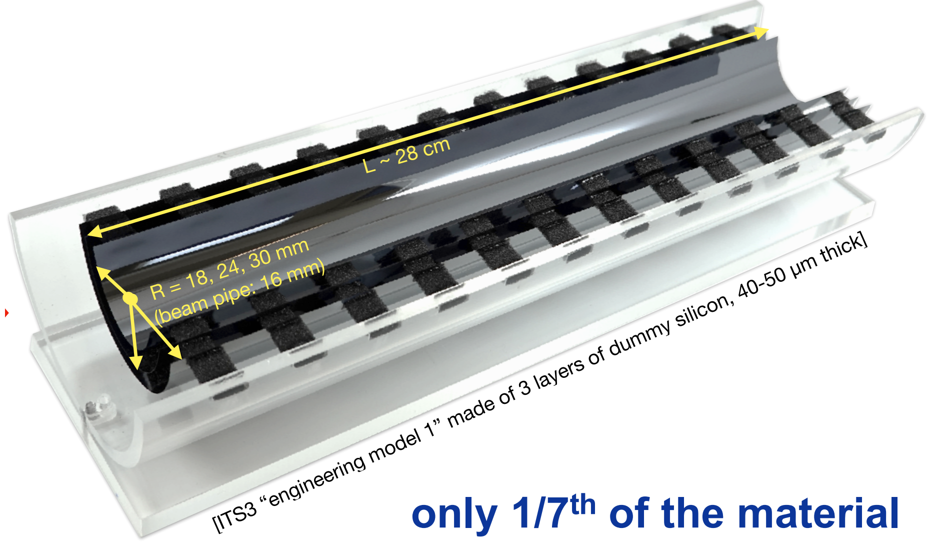
thin (<50μm CMOS can be curled)

Being developed for **ALICE ITS3)**

Baseline option also for:

- **EPIC**
- **ALICE 3** (++ improvements)





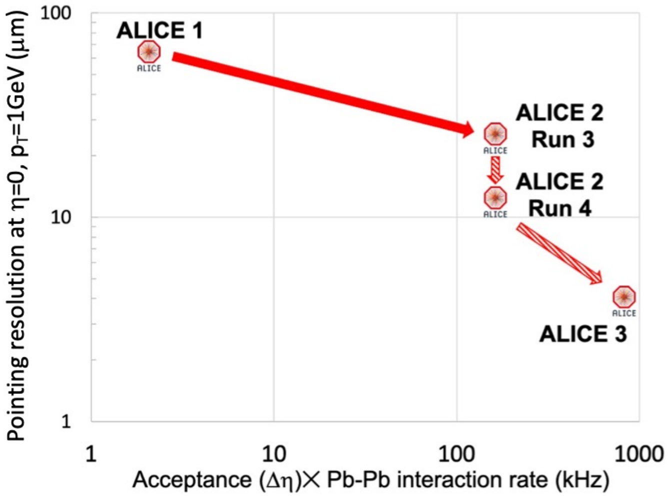
[ITS3 "engineering model 1" made of 3 layers of dummy silicon, 40-50 μm thick]

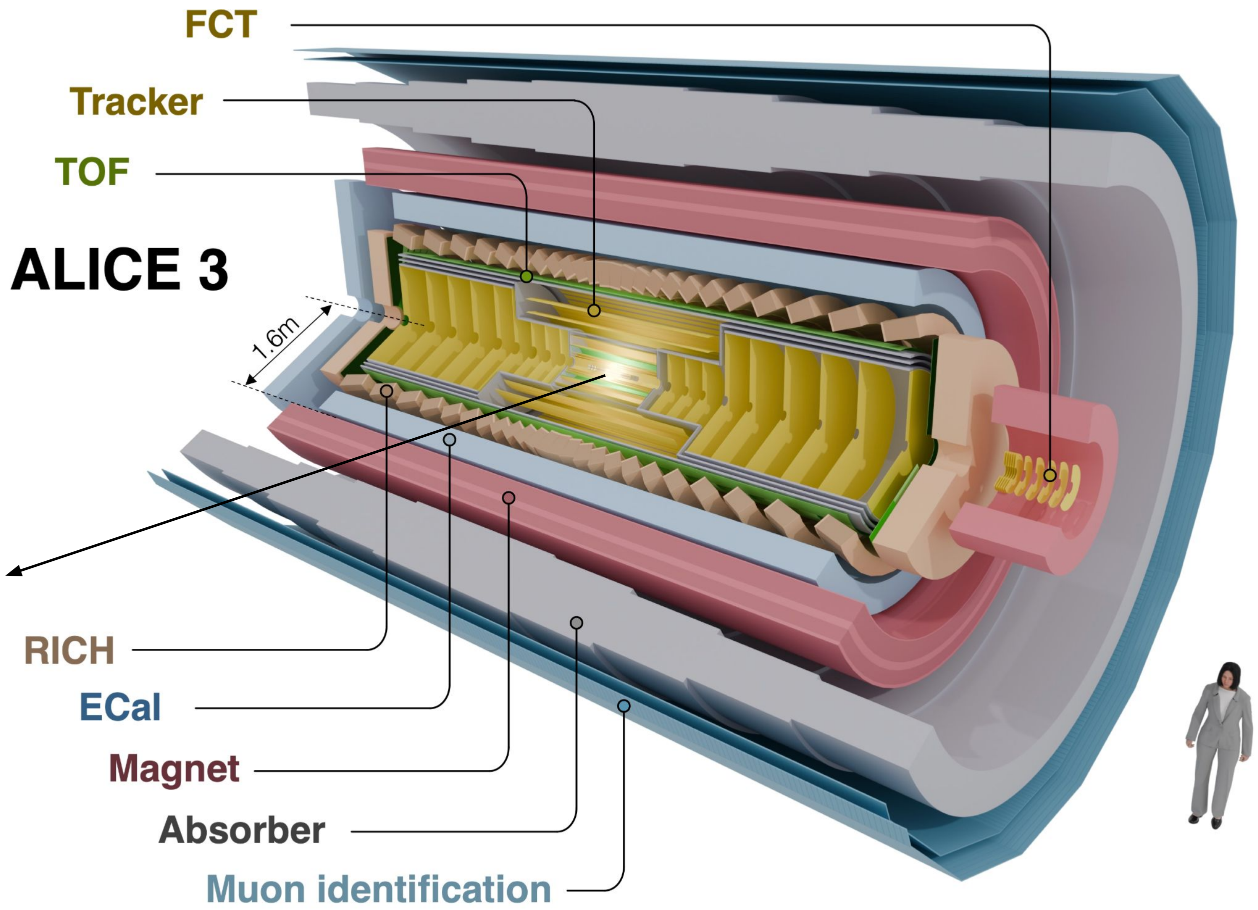
only 1/7th of the material

Next Generation HI Experiment: ALICE 3

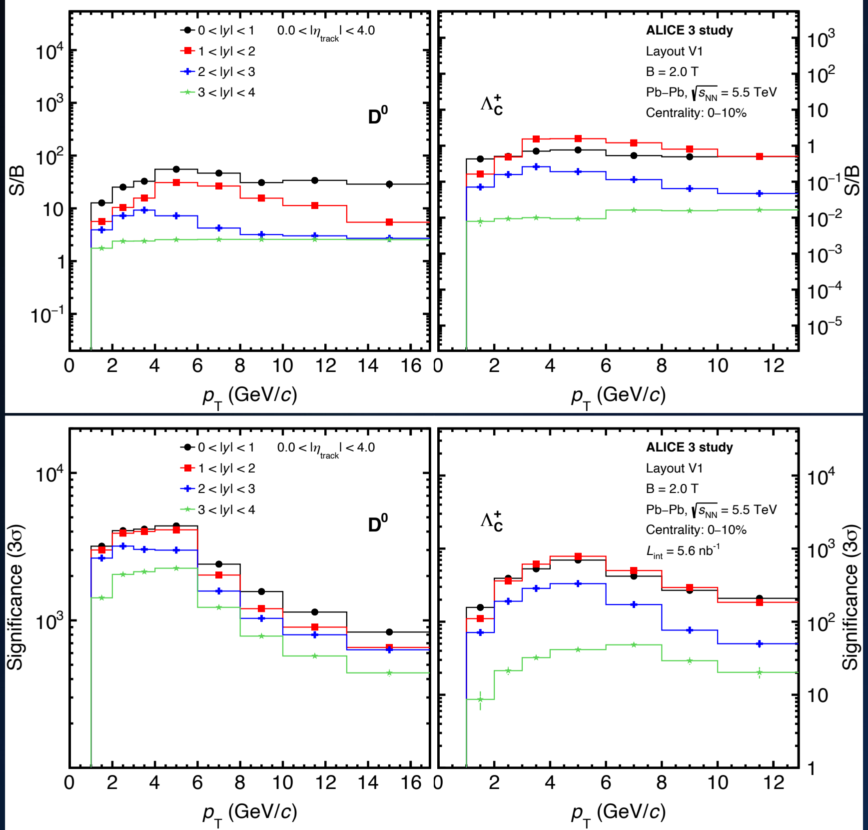
Novel and innovative detector concept

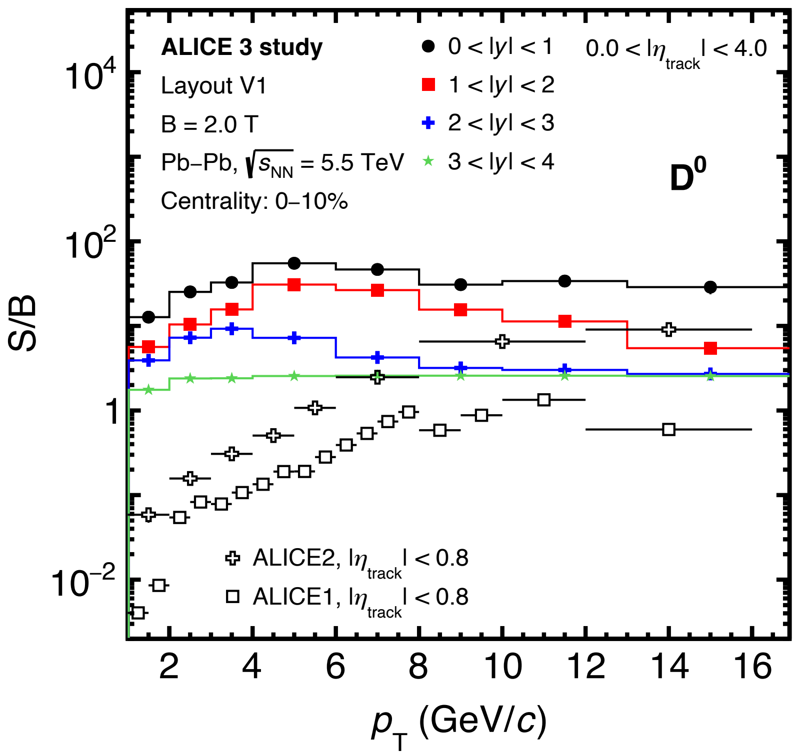
- Compact and lightweight all-pixel tracker
- Retractable vertex detector
- Extensive PID in TOF, RICH, MID
- Large acceptance $|\eta| < 4$
- Superconducting solenoid magnet B = 2T
- continuous readout and online processing





ALICE 3 – charm hadrons





ALICE 3 significantly outperforms ALICE 2

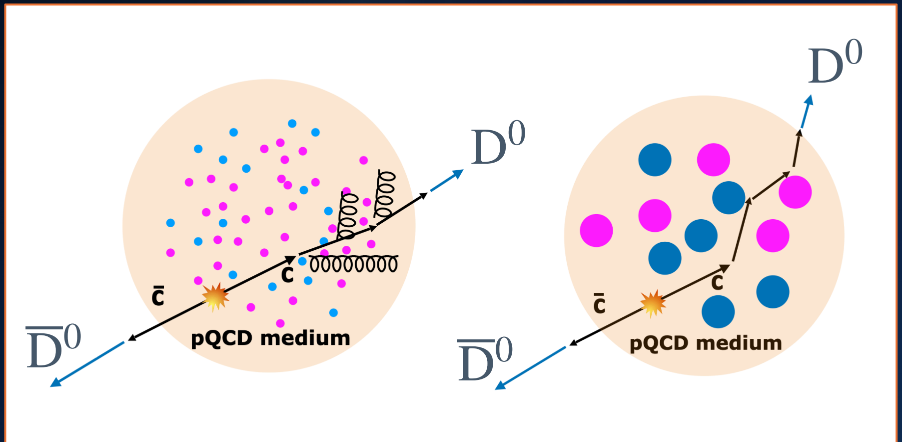
ALICE 3 - Excellent performance over eight units of rapidity and p_T from 0 to > 10 GeV/c: angular correlations, HBT correlations, net charm fluctuations

ALICE 3 LOI (CERN CDS: LHCC-2022-009)

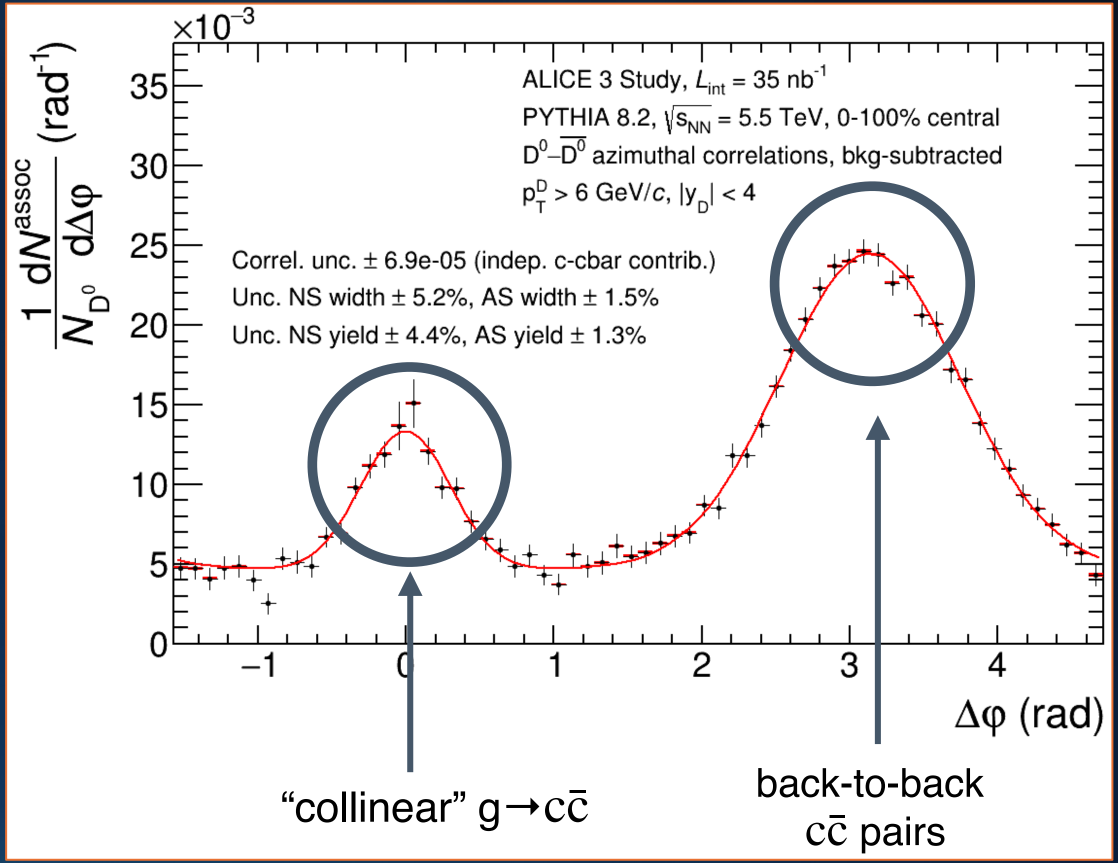
Multi heavy-quark physics: $D^0 - \overline{D^0}$ correlations

Heavy-flavour correlations (e.g. Δη–Δφ)

- ⇨ **properties** of in-medium interactions
- ⇨ constraints on **heavy-quark "equilibration"**



→ **partonic "structure" of the hot medium**



"collinear" g→cc̄

back-to-back
cc̄ pairs

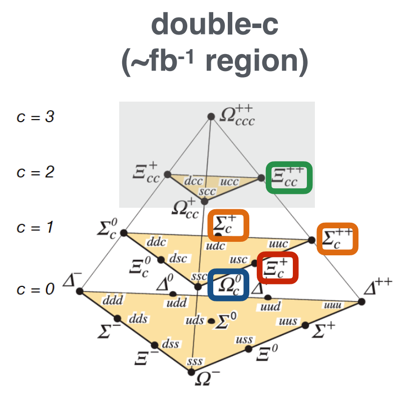
ALICE 3 LOI (CERN CDS: LHCC-2022-009)

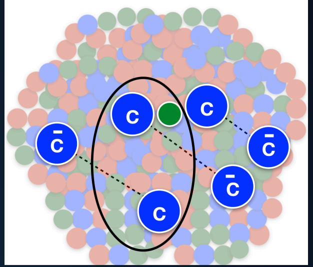
Multi heavy-quark physics: hadron formation

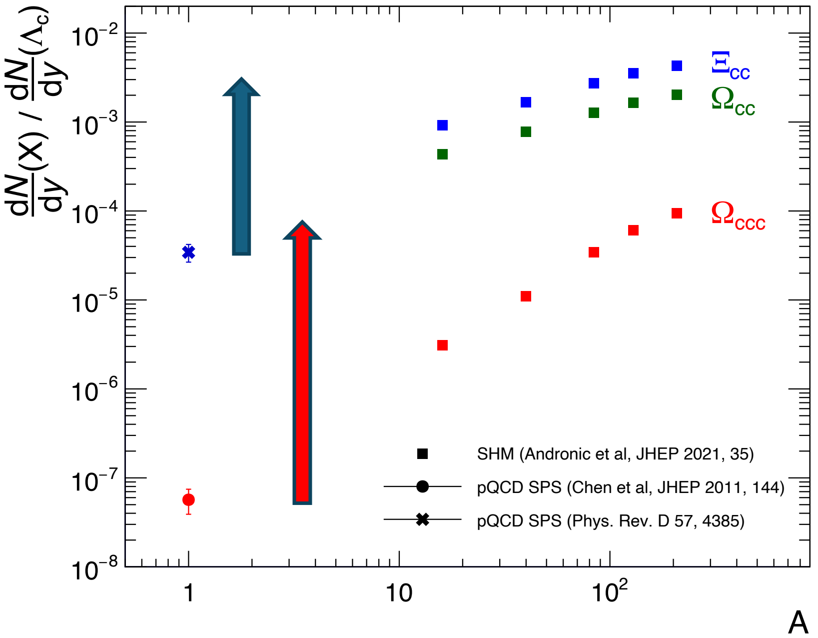
Multi-charm baryons: unique probe of hadron formation

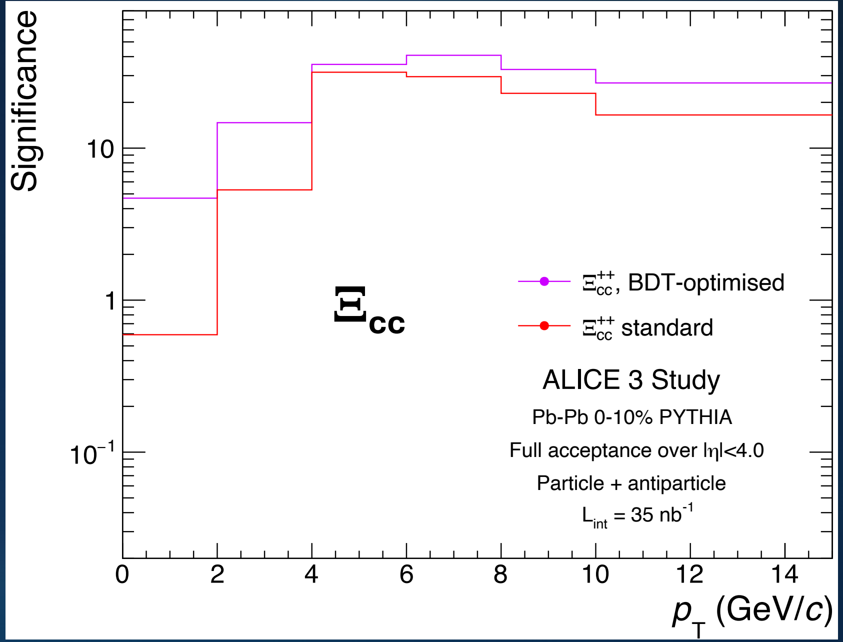
- combination of charm quarks from independent parton scatterings
- negligible same-scattering production

Statistical hadronization model: **very large enhancement** in AA

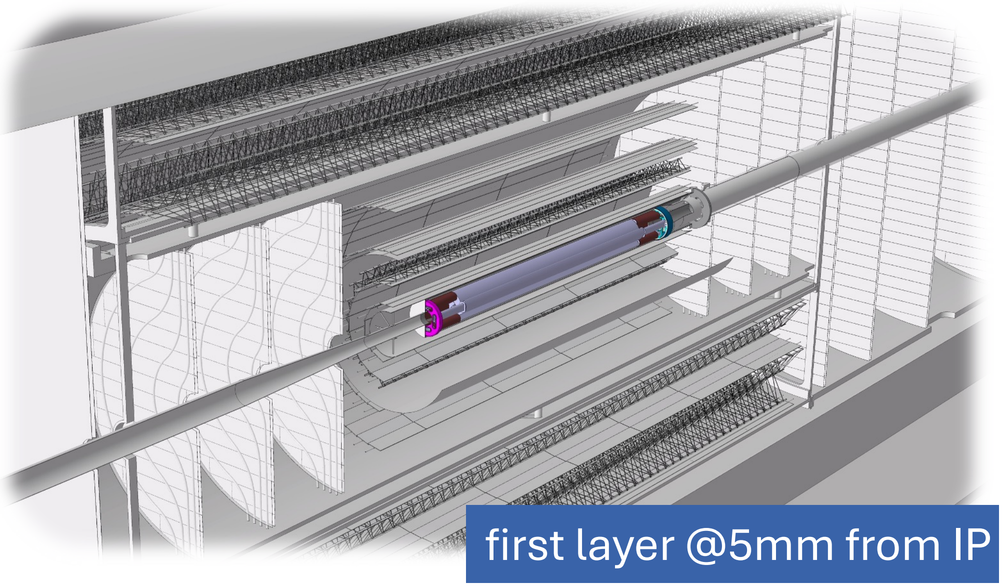




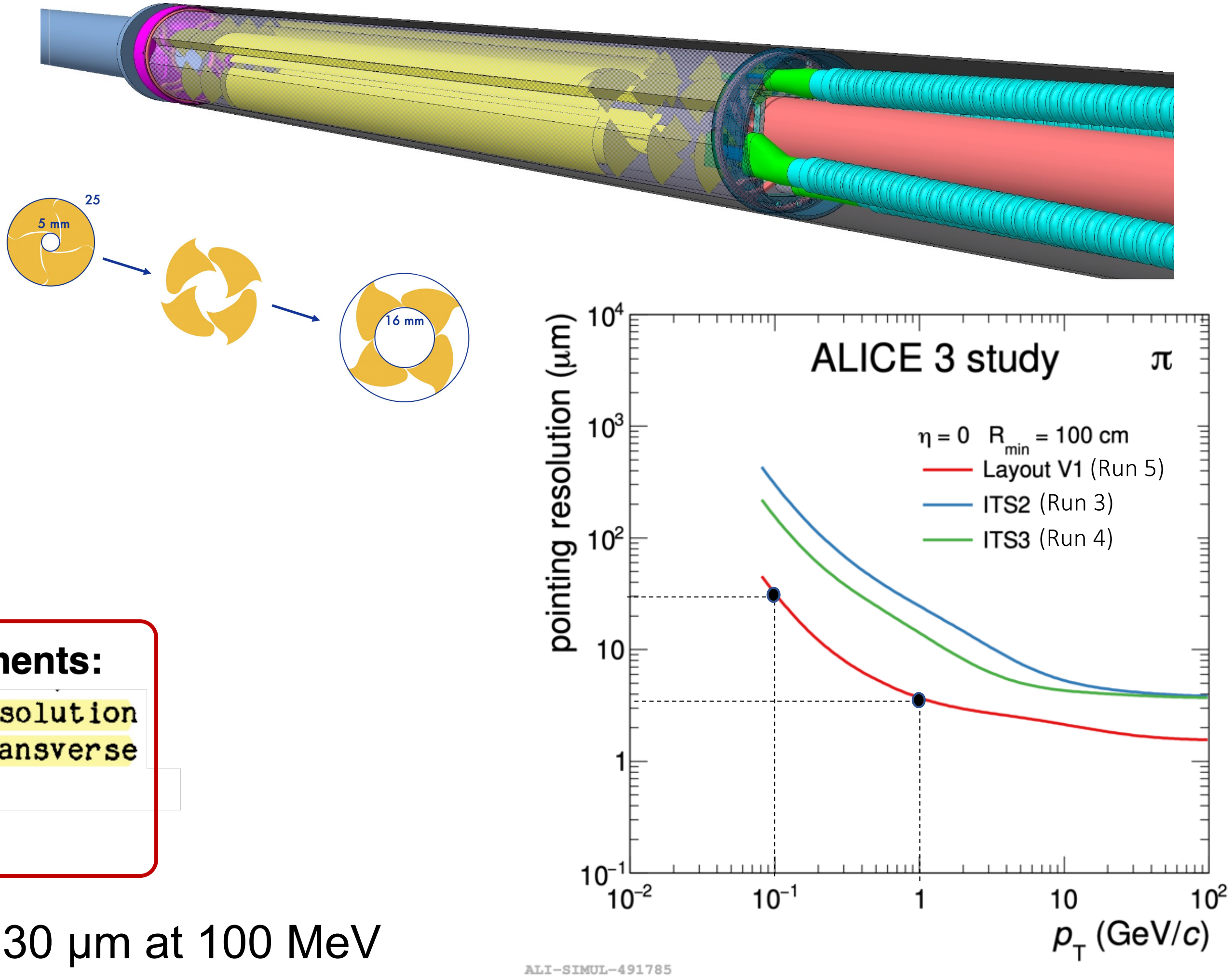




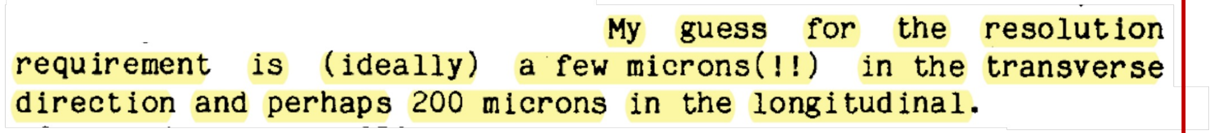
Retractable vertex detector



first layer @5mm from IP



J.D. Bjorken in a 1985 paper on Ξ_{cc} and Ω_{ccc} measurements:

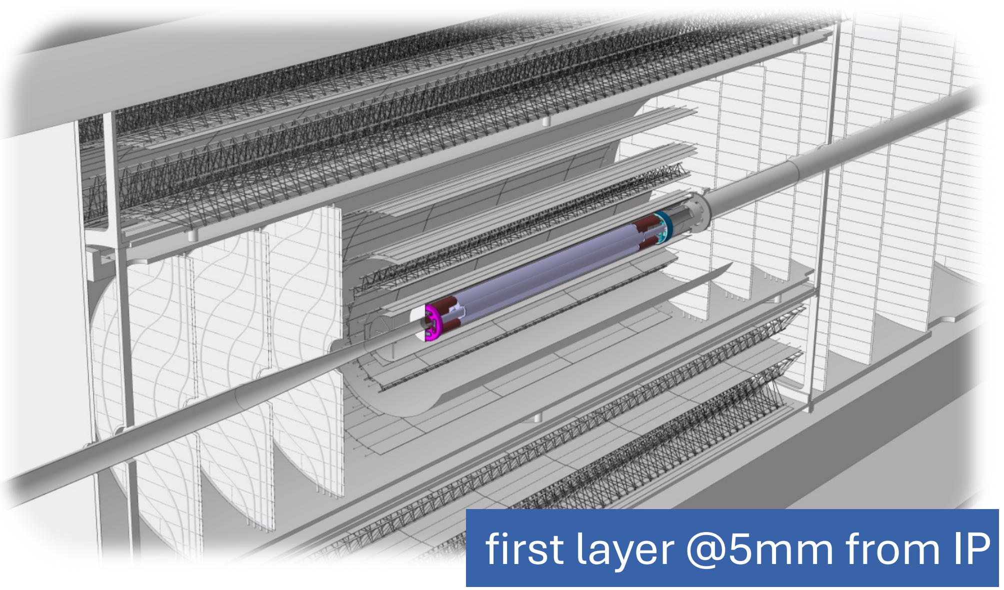


My guess for the resolution requirement is (ideally) a few microns(!!) in the transverse direction and perhaps 200 microns in the longitudinal.

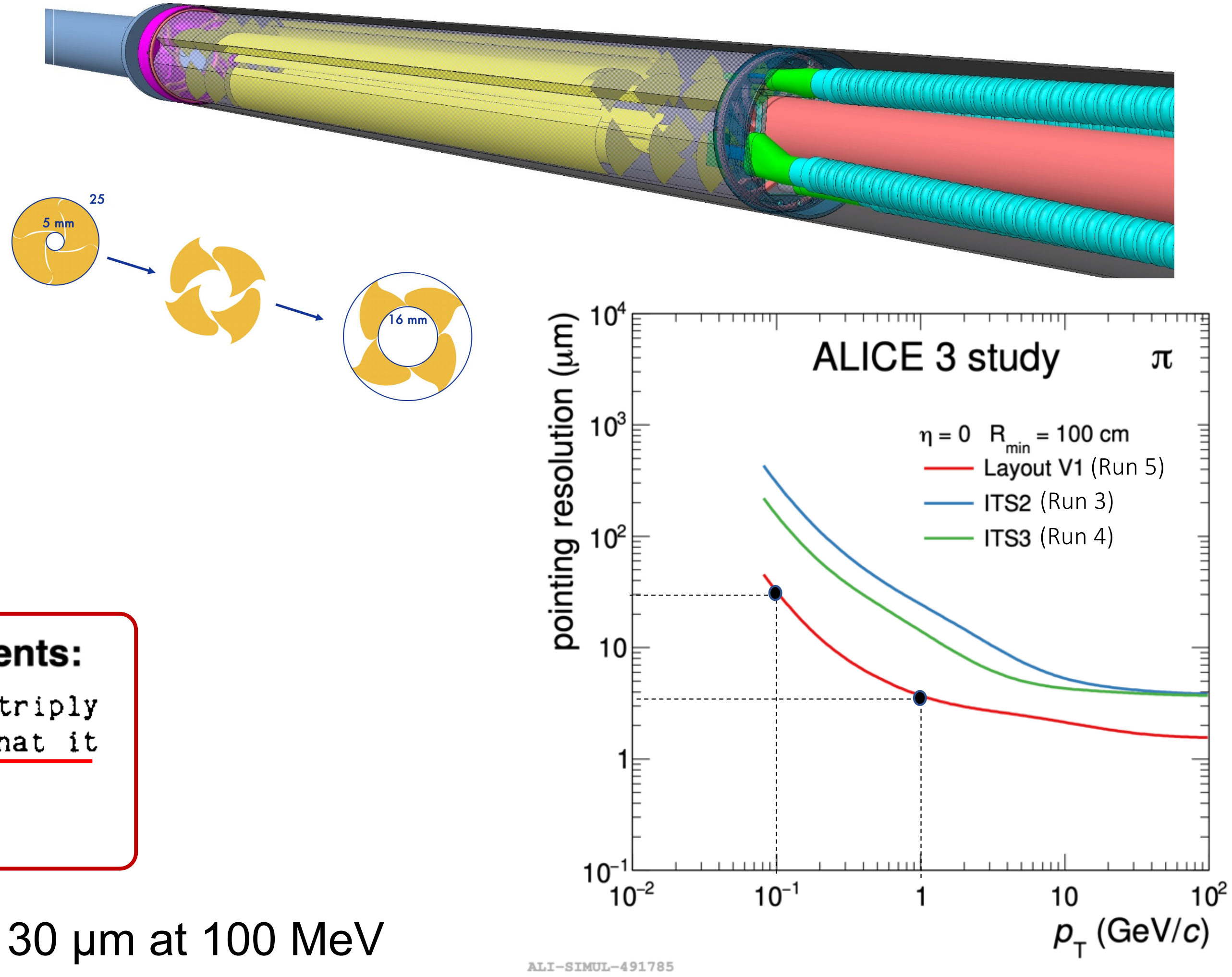
AIP Conference Proceedings 132, 390 (1985)

pointing resolution:~ few μm at 1 GeV/c, 30 μm at 100 MeV

Retractable vertex detector



first layer @5mm from IP



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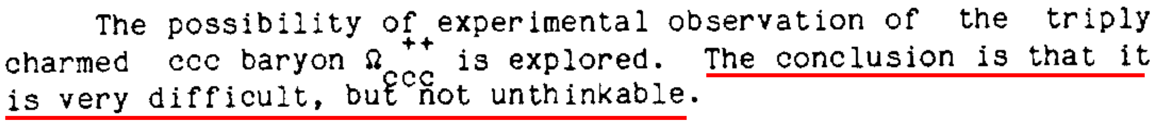
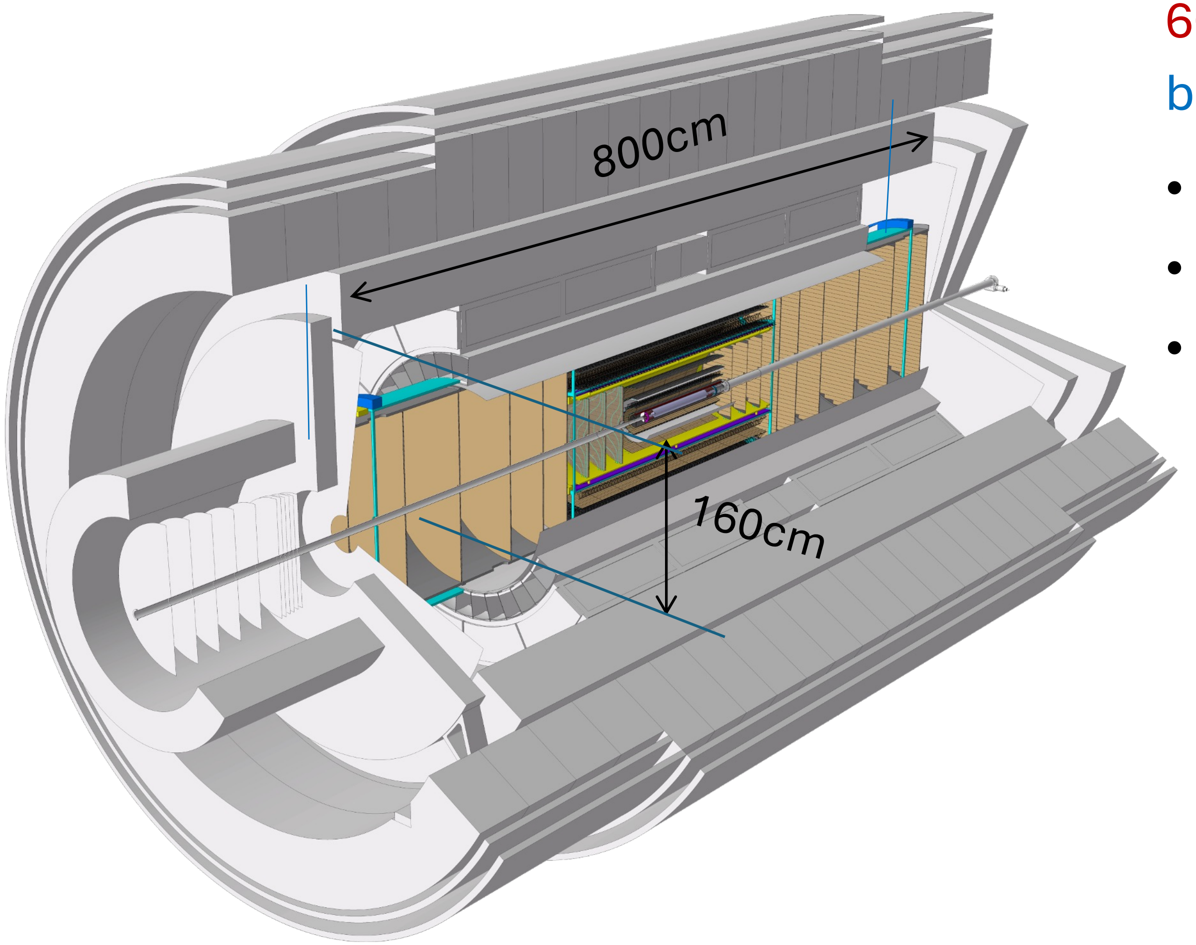


The possibility of experimental observation of the triply charmed ccc baryon Ω^{++}_{ccc} is explored. The conclusion is that it is very difficult, but not unthinkable.

AIP Conference Proceedings 132, 390 (1985)

pointing resolution:~ few μm at 1 GeV/c, 30 μm at 100 MeV

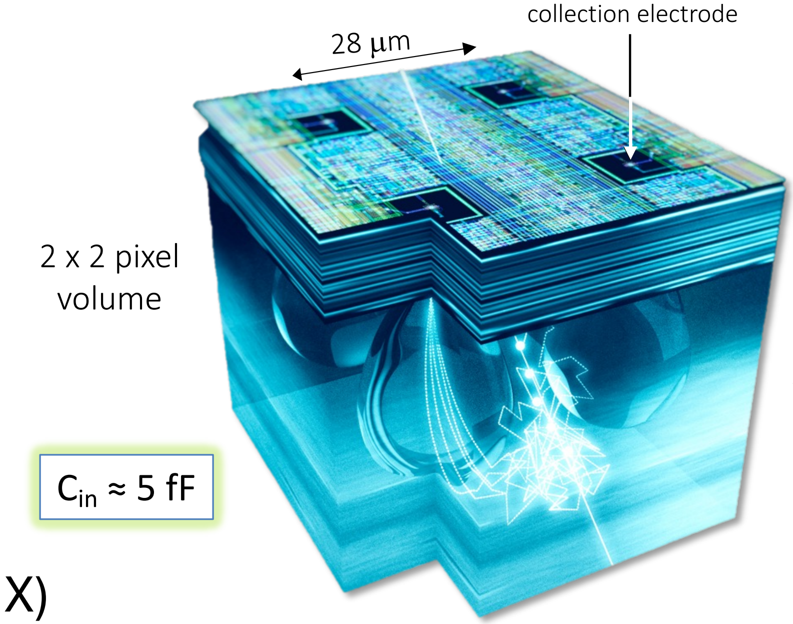
All-pixel tracker



60 m^2 silicon pixel detector

based on CMOS Active Pixel Sensor (APS) technology

- high-spatial resolution: $\sigma_{pos} \approx$ 5-10 μm
- hit timestamping: ≈100 μm (tbv)
- very low material budget: X/X_0 (total) $\lesssim$ 10%



Artistic view of a SEM picture of ALPIDE cross section

⇨ build on experience with ITS2 (ALPIDE) and ITS3 (MOSAIX)

11 Feb - International Day of Women in Science

Successful women scientists inspire future generations, showing that merit and excellence prevail over gender stereotypes

REGIONE PUGLIA
DIPARTIMENTO INTERATENEO DI FISICA
UNIVERSITÀ DEGLI STUDI DI BARI ALDO MORO
Politecnico di Bari

In occasione della
Giornata Internazionale delle Donne e Ragazze nella Scienza
e del 70° anniversario del CERN

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Organizza lo spettacolo

LA FORZA NASCOSTA
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Intervengono:
Prof. Antonio Zoccoli
Presidente INFN
Dott. Luciano Musa
CERN

TEATRO
KURSAAL SANTALUCIA
7 FEBBRAIO 2025
ORE 19,00
Largo Adua 5, Bari

Ingresso gratuito previa prenotazione su eventbrite.it

Ideazione e progettazione grafica: LNGS/studio grafico Civico 11 - L'Aquila

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Gabriella Bordin (Alma Teatro)
Elena Ruzza (TerraTerra)
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Elena Ruzza attrice
Fé Avouglan soprano
Gabriele Braga pianista
MUSICHE ORIGINALI
Ale Bavo musica elettronica
IDEAZIONE SPAZIO SCENICO
Adriana Zamboni

REALIZZAZIONE ELEMENTI SCENICI
Silvano Gallian
REGISTRAZIONE VOCI
Matteo Cantamessa
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Anna Parisi (annaparisi.com)

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Maggiori informazioni e programma completo su:
www.ba.infn.it/it/forza_nascosta

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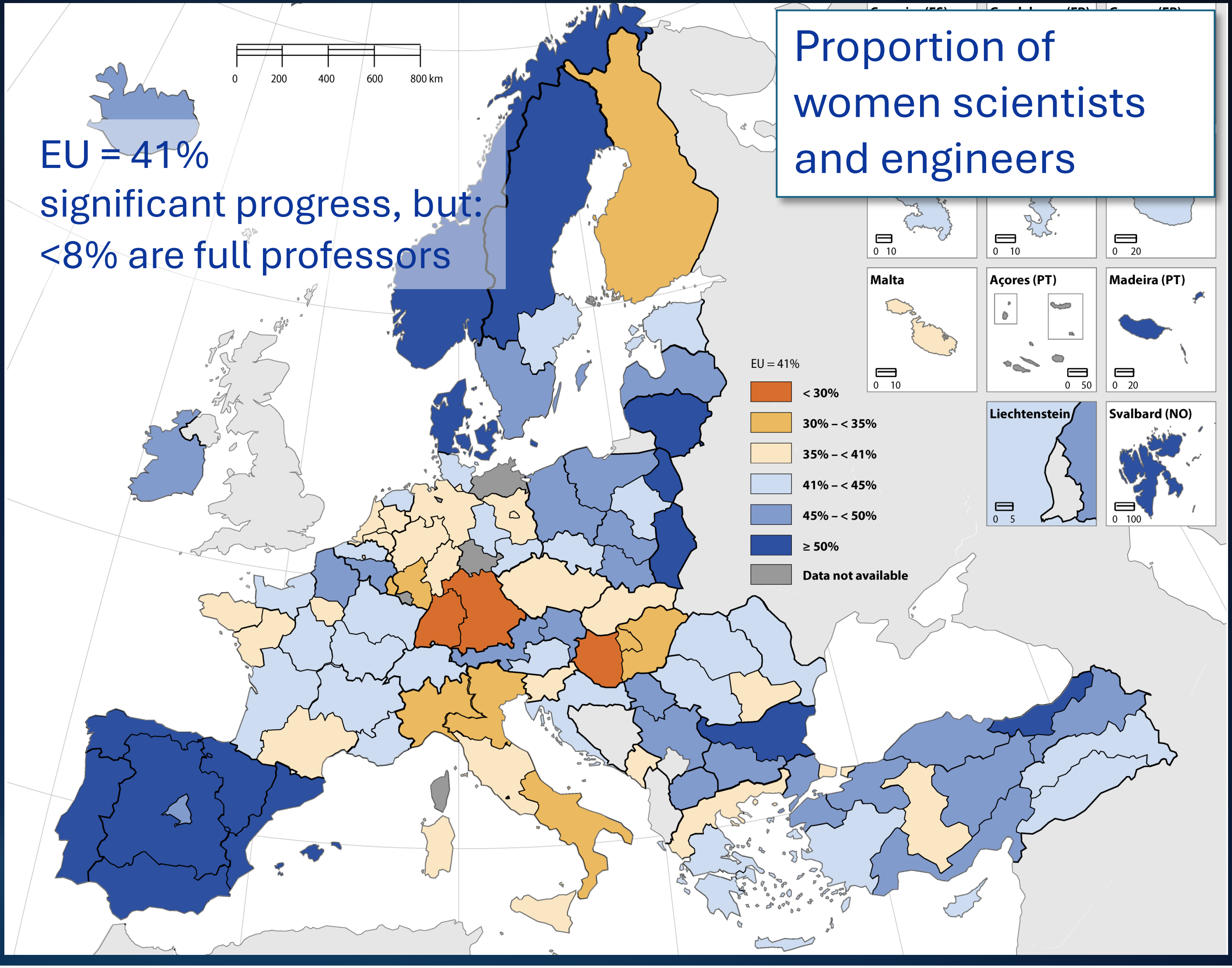
Sarà inoltre possibile visitare la mostra "**Pino Pascali Toti Scialoja. Confluenze**" *allestita nel Teatro Kursaal e promossa da Fondazione Pino Pascali e dal Dipartimento Turismo, Economia della Cultura e Valorizzazione del Territorio della Regione Puglia*



Proportion of women scientists and engineers

EU = 41%
significant progress, but:
<8% are full professors