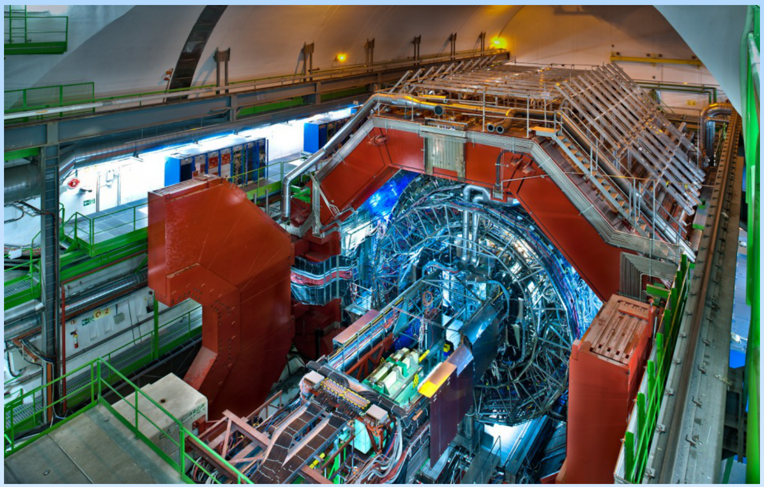
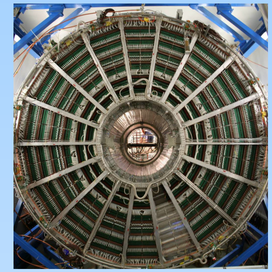
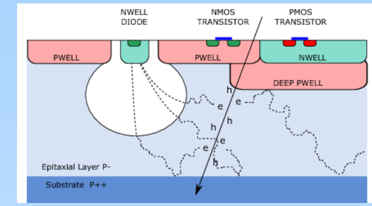
Results from the LHC

M. Dunford, M. De Cian, S. Masciocchi







May 2, 2014

&

The physics of particle detectors

July 19, 2017

The ALICE detector

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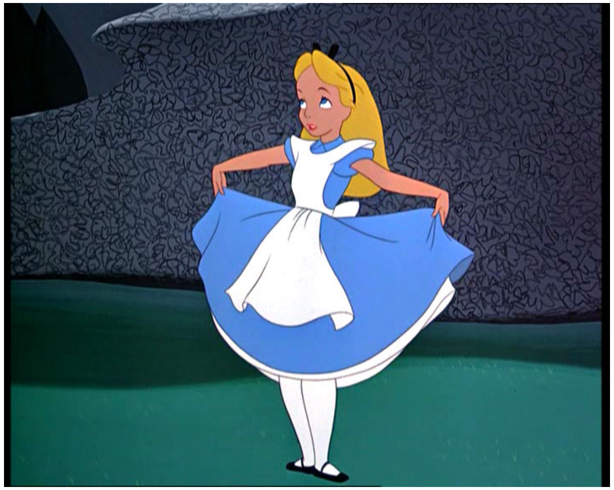
Outline

- ALICE: the heavy-ion experiment
- The quark-gluon plasma (QGP)
- Very few words about the LHC
- Heavy-ion collisions at the LHC
- ALICE:
  - The spectrometer
    - Inner Tracking System
    - Time Projection Chamber
    - Time of Flight detector
    - Transition Radiation Detector
  - Event centrality



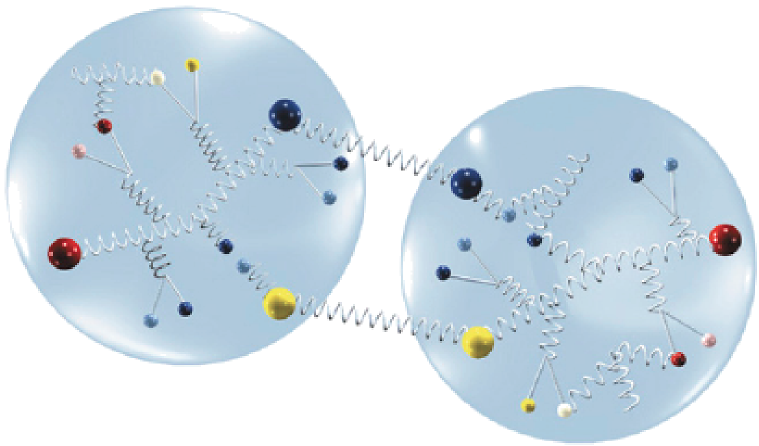
Some reading

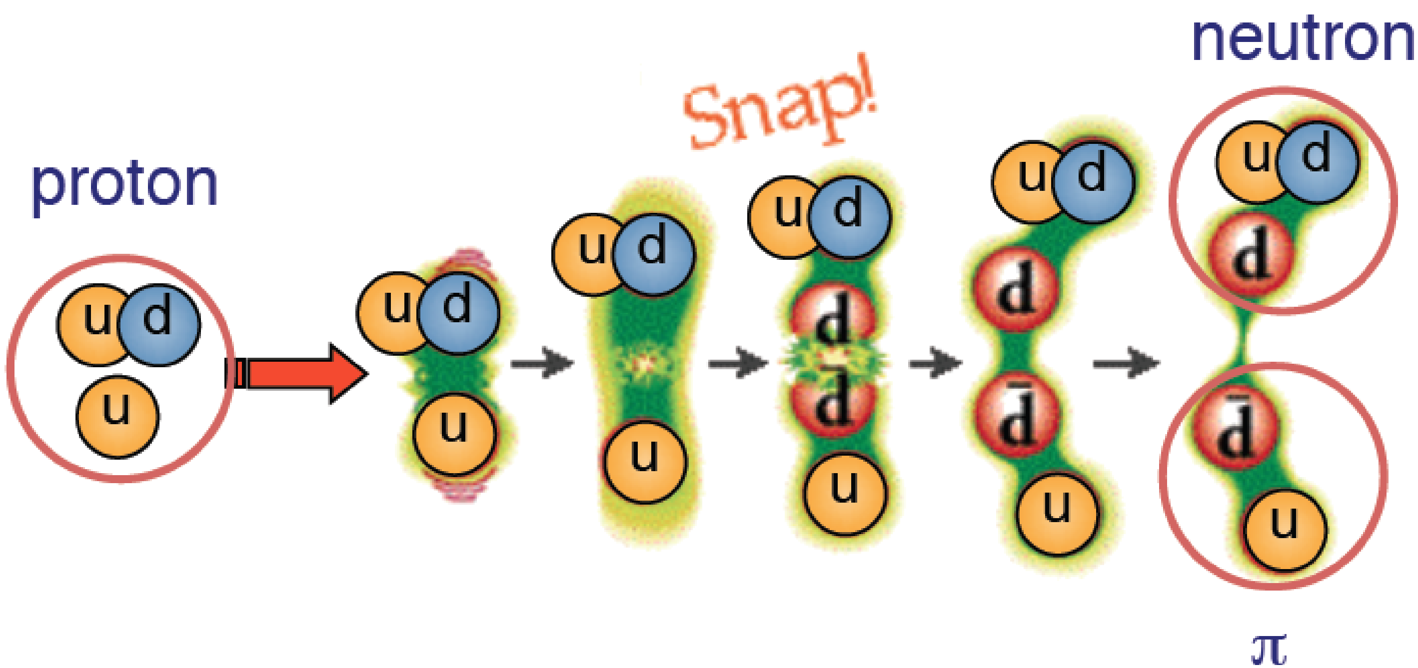
- ALICE detector: http://iopscience.iop.org/1748-0221/3/08/S08002/
- ALICE performance: http://arxiv.org/abs/arXiv:1402.4476/

Confinement

All matter we know, is confined:

colored quarks and gluons are confined in colorless hadrons

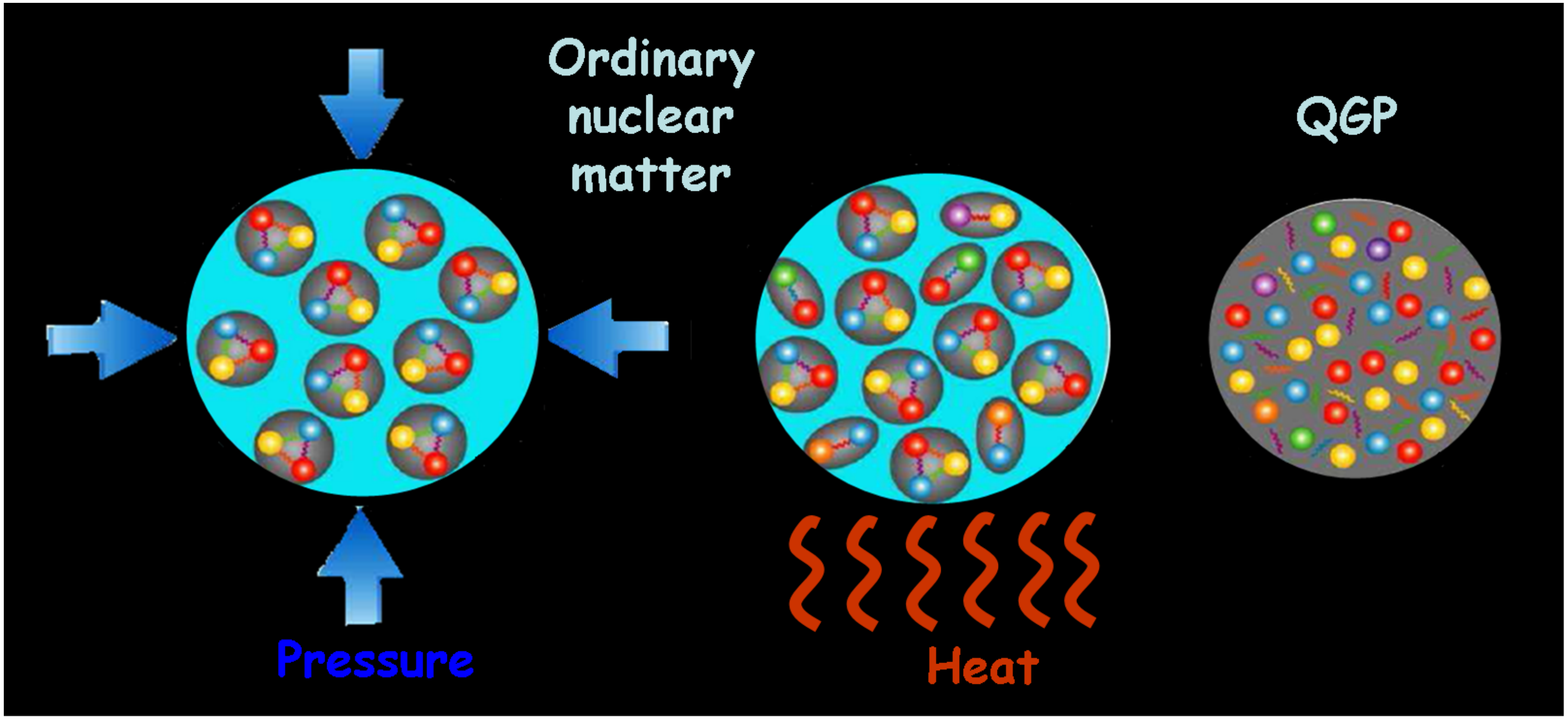




Quark-Gluon Plasma

Asymptotic freedom → at VERY HIGH densities or temperature, strongly interacting partons become free → deconfined phase of matter

Cabibbo, Parisi PLB 59, 67 (1975); Collins, Perry PRL 34, 1353 (1975)

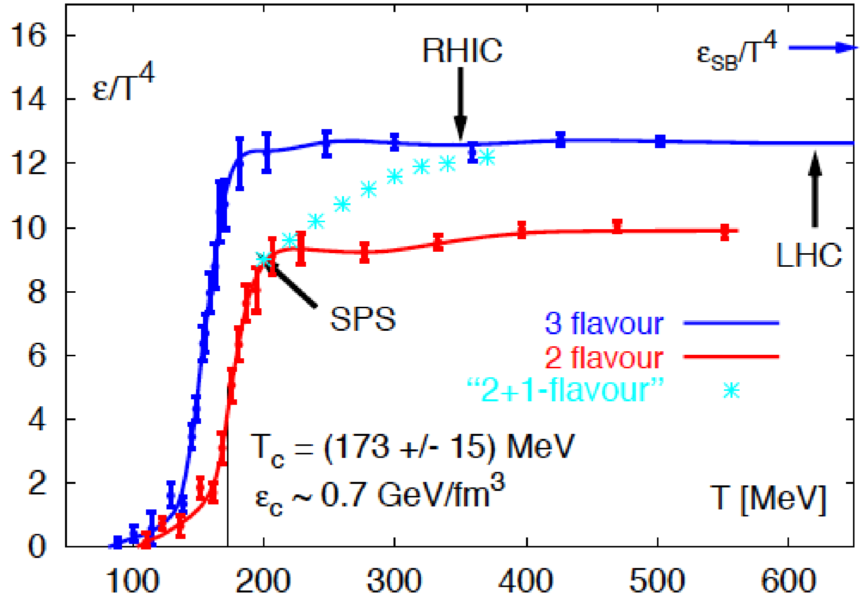


Hadrons → **Deconfined quarks and gluons**

Transition temperature

- Hagedorn 1965: limiting temperature for hadronic systems ~ 140 MeV
- QCD on space-time lattice
  → critical transition temperature from hadronic phase to the deconfined, plasma phase

Energy density



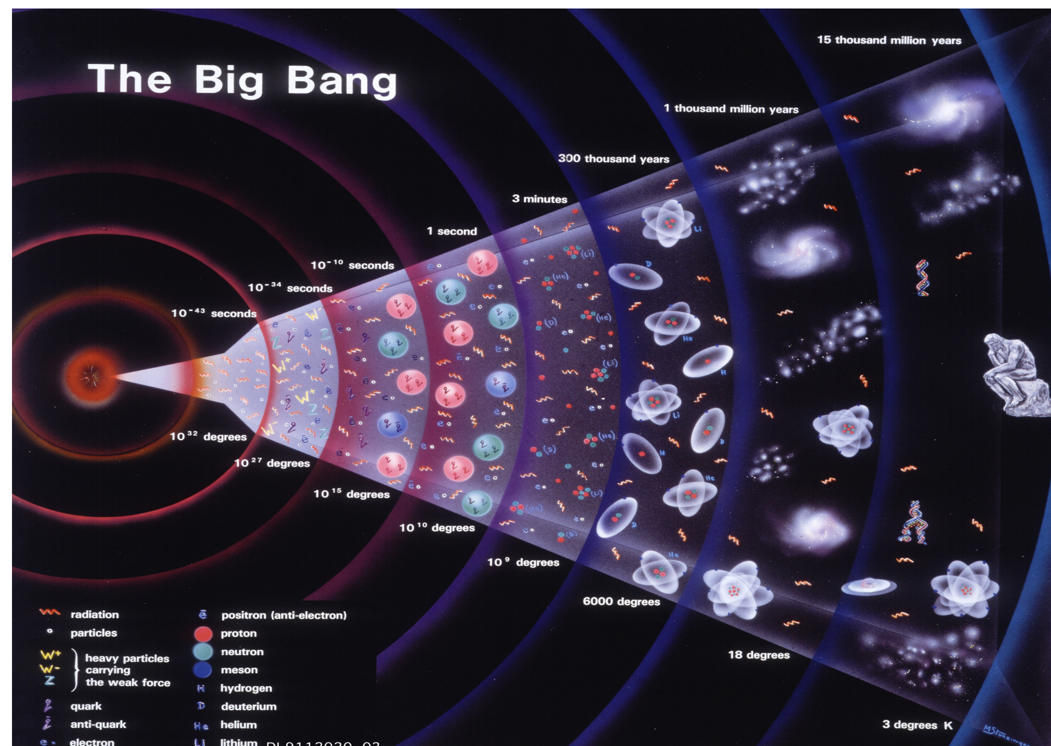
hep-lat/0106019

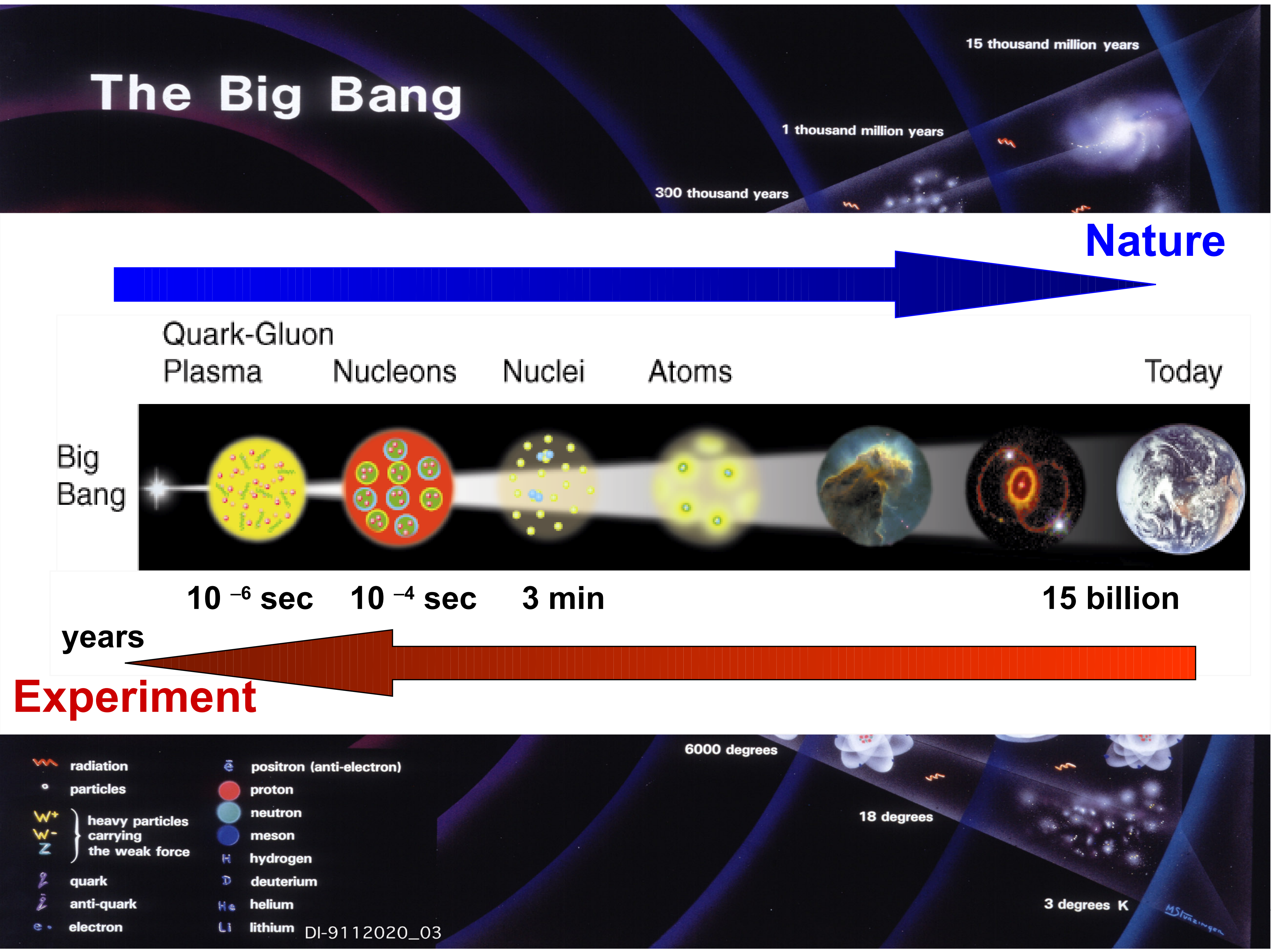
- Energy density ~0.7 GeV/fm^3 → 5 * nuclear matter!

Dense and hot nuclear matter: why?

Status of matter in:

- Neutron stars and core-collapse supernovae
- First instants of our universe
  - 10^{-12} sec: electroweak phase transition
  - lasting until 10^{-5} sec: quark-gluon plasma



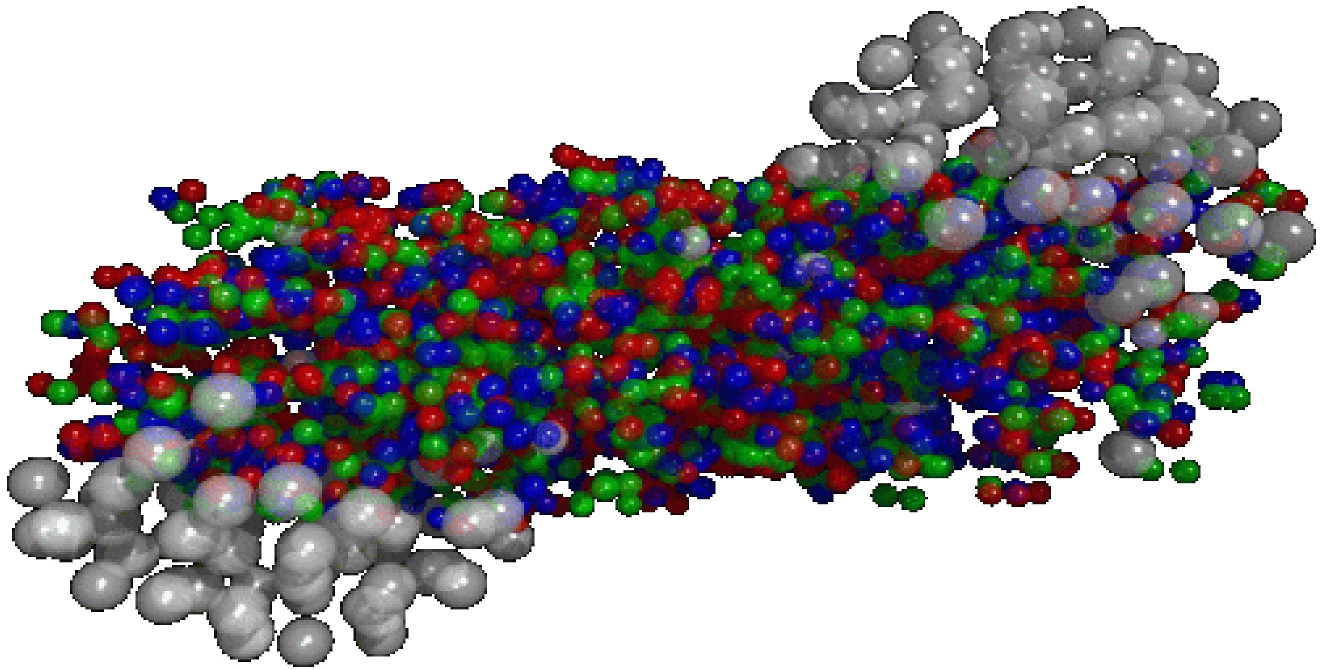


The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
Nature
Quark-Gluon
Plasma
Nucleons
Nuclei
Atoms
Today
Big
Bang
10 −6 sec
10 −4 sec
3 min
15 billion
years
Experiment
radiation
particles
W+
W-
Z
heavy particles
carrying
the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium
DI-9112020_03
6000 degrees
18 degrees
3 degrees K

QGP in the laboratory

Produced in the collisions of **heavy nuclei** at **high energies**

Since the early 1980s



A

A

(Au, Pb ...)

$\sqrt{s_{NN}}$ from few GeV at AGS, SPS, GSI

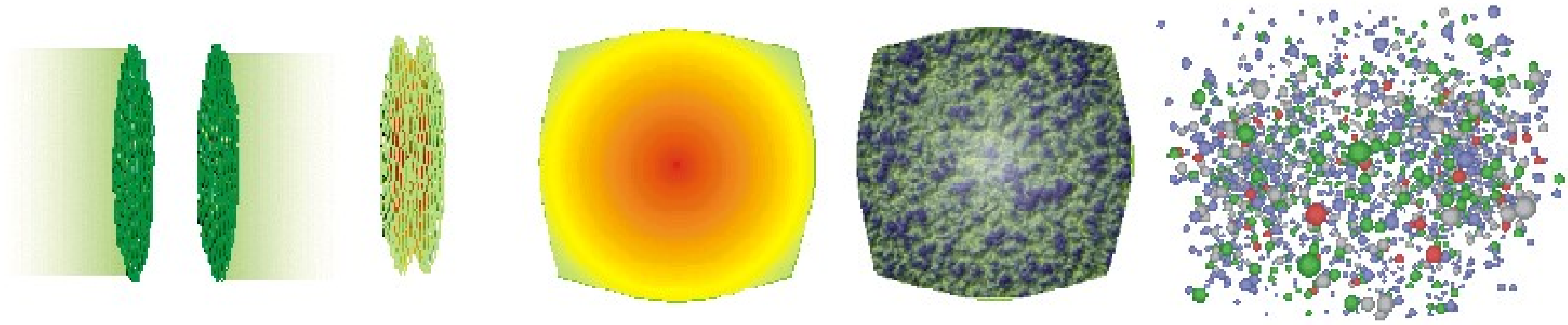
up to 200 GeV at RHIC

up to 2.76 TeV at LHC

UrQMD

Ultra-relativistic heavy-ion collisions

High energy heavy ions collide …



Under extreme conditions of temperature and density, they produce a state of matter called

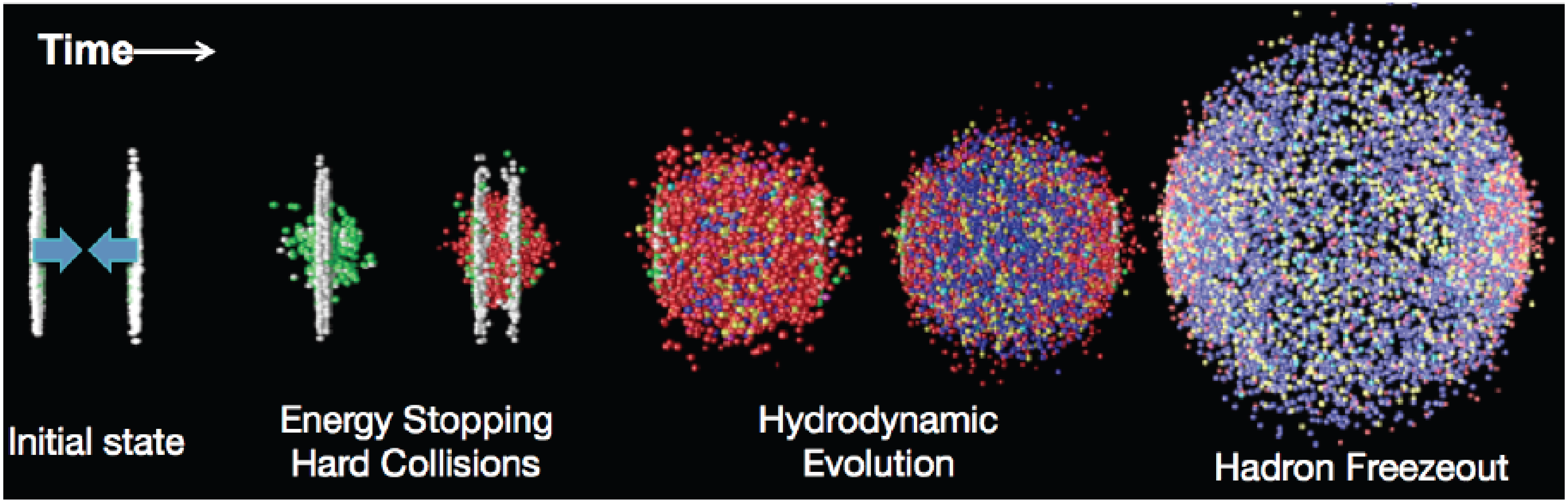
QUARK-GLUON PLASMA

where quark and gluons are deconfined,

followed by chemical freeze-out,

and kinetic freeze-out

Collision phases



Thermalization: equilibrium is established (t < 1 fm/c)

Expansion and cooling: (t < 10-15 fm/c)

Chemical freeze-out (particle yields)
Kinetic freeze-out (particle spectra)

Compress a very large amount of energy in a very small volume
→ "fireball" of hot matter, temperature O(10^{12} K)
- ~10^5 x T at the center of the sun
- ~T of the early universe (μs after Big Bang)

Collision phases: notes

Thermodynamic phases, phase transitions, temperatures …

IF

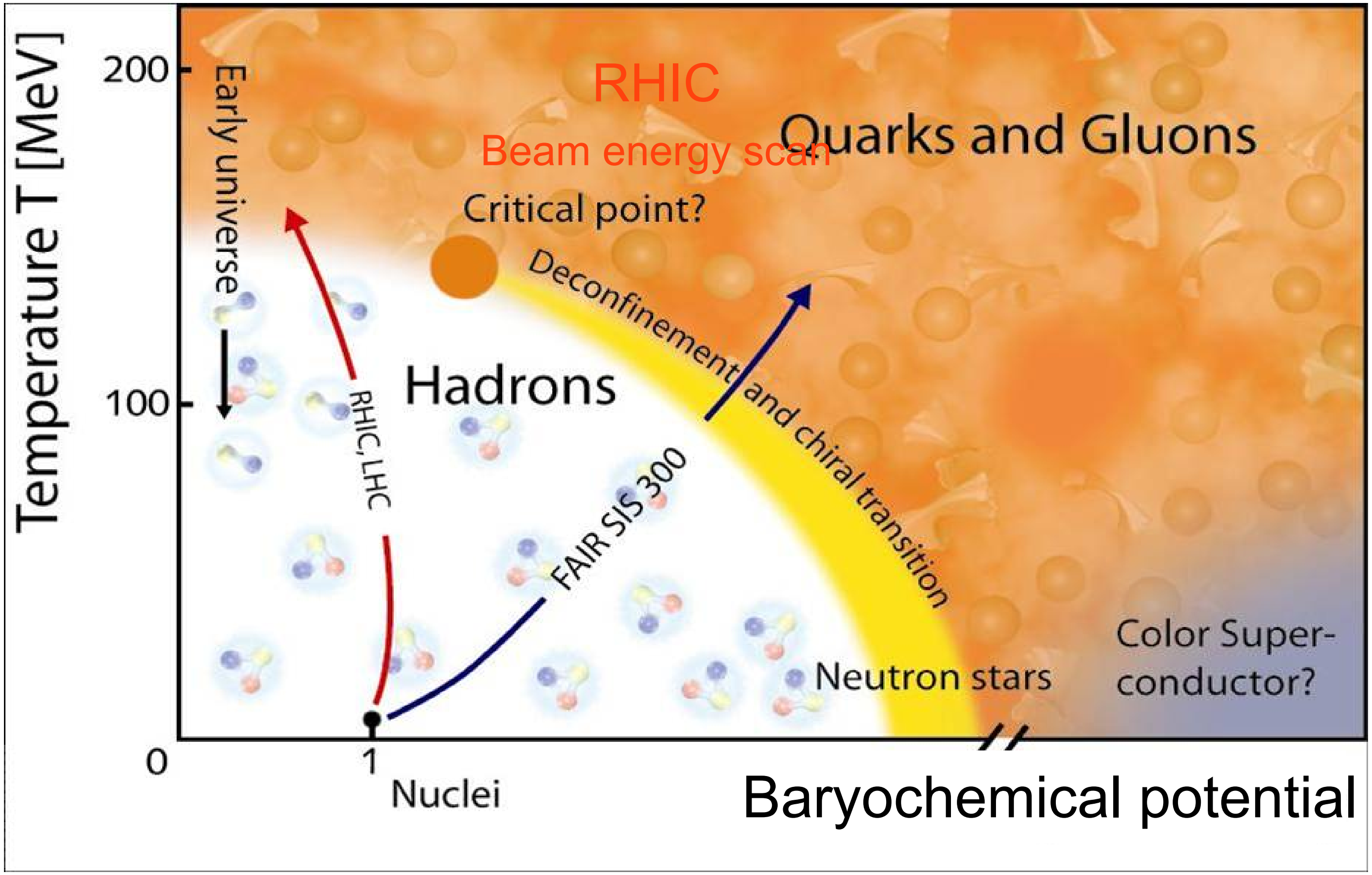
the system behaves like matter, not individual elementary particles:

- Large number of particles
- Local equilibrium (to define temperature, pressure, energy, entropy density, to investigate equation of state, speed of sound …)
- System lifetime > inverse rate of interactions

Fireball of deconfined partons expands and cools → passes the deconfinement temperature again → hadronization:

- After the Big Bang: ~ 10^{-5} sec
- In the lab: much less energy, much shorter lifetime: ~ 10^{-22} sec

Phase diagram



RHIC, LHC:
very high temperature
low baryochemical potential
(~pressure in the water phase diagram)

FAIR, NICA:
lower temperature
high baryochemical potential

The Large Hadron Collider (LHC)

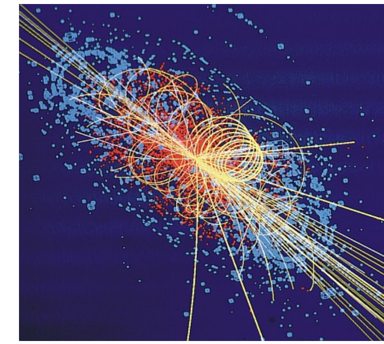
At CERN, Geneva, Switzerland

- 27 km length
- 4 main experiments

Colliding systems:

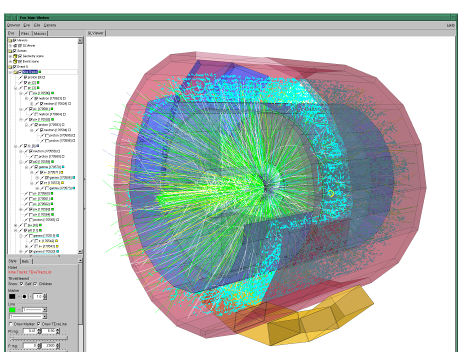
- **proton-proton**
  up to $\sqrt{s}$**=14 TeV**
  2010-2013: 7, 8 TeV
  2.76 TeV
- **Pb-Pb**
  up to $\sqrt{s_{NN}}$**=5.5 TeV**
  2010-2011: 2.76 TeV
- **p-Pb**
  2012-3: $\sqrt{s_{NN}}$**=5.02 TeV**

Physics at LHC



From proton-proton …

- **Generation of mass (Higgs)**
- **New elementary particles (supersymmetric)**
- **Matter dominance over antimatter (CP violation)**
- **Gravity unification (extra dimensions, black holes)**
- **Overall QCD aspects (multiplicities, charm, beauty …)**



... to lead-lead collisions

- **Study matter within the first microseconds of the Universe life (ALICE, but also CMS, ATLAS)**

LHC in Numbers

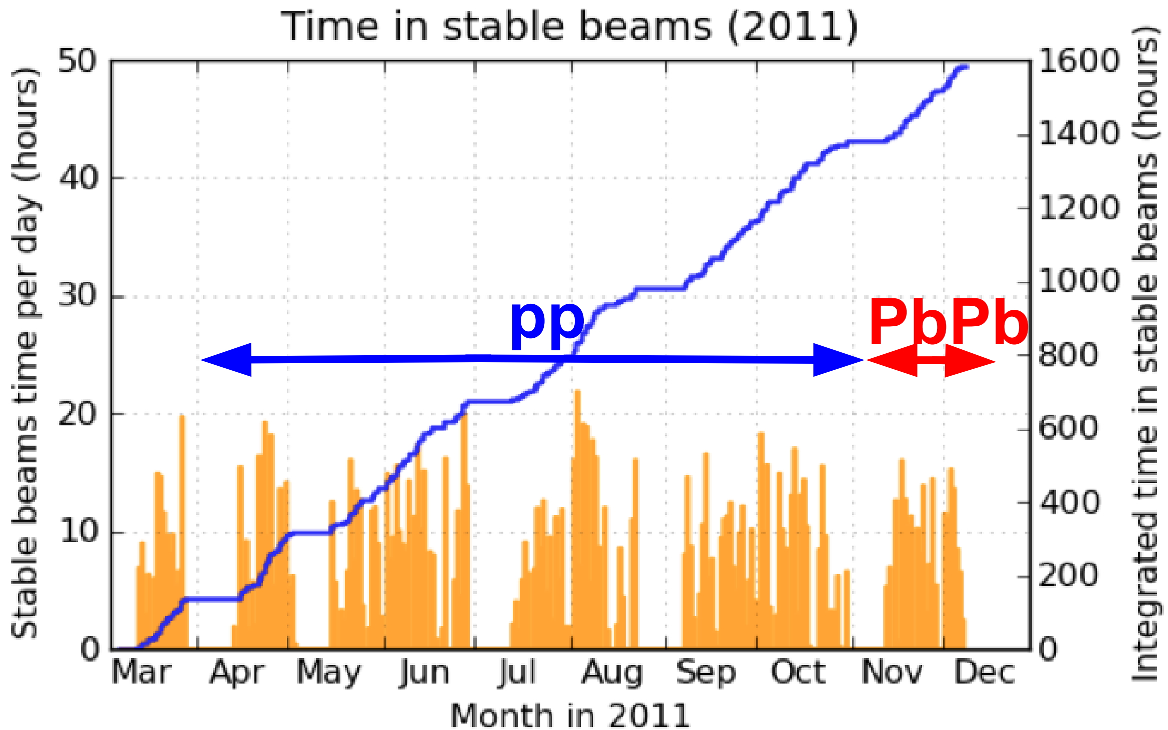
- 27 km long, 8 sectors
- **1232 dipole** magnets (15m, 30 tonnes each) to bend the beams
- Cooled with **120 tonnes of He at 1.9 K**
- pp: 2808 bunches/ring, each 1.15×10^{11} protons (8 min filling time)
  Design luminosity: **10^{34} $cm^{-2}s^{-1}$**
- PbPb: 592 bunches/ring, each 7×10^{7} Pb ions
  Design luminosity: 10^{27} $cm^{-2}s^{-1}$
- Transverse r.m.s beam size: **16 µm**, r.m.s. bunch length: 7.5 cm
- Beam kinetic energy: 362 MJ per beam (1 MJ melts 2 kg copper)
- Total stored electromagnetic energy: **8.5 GJ** (dipole magnets only)

LHC runs

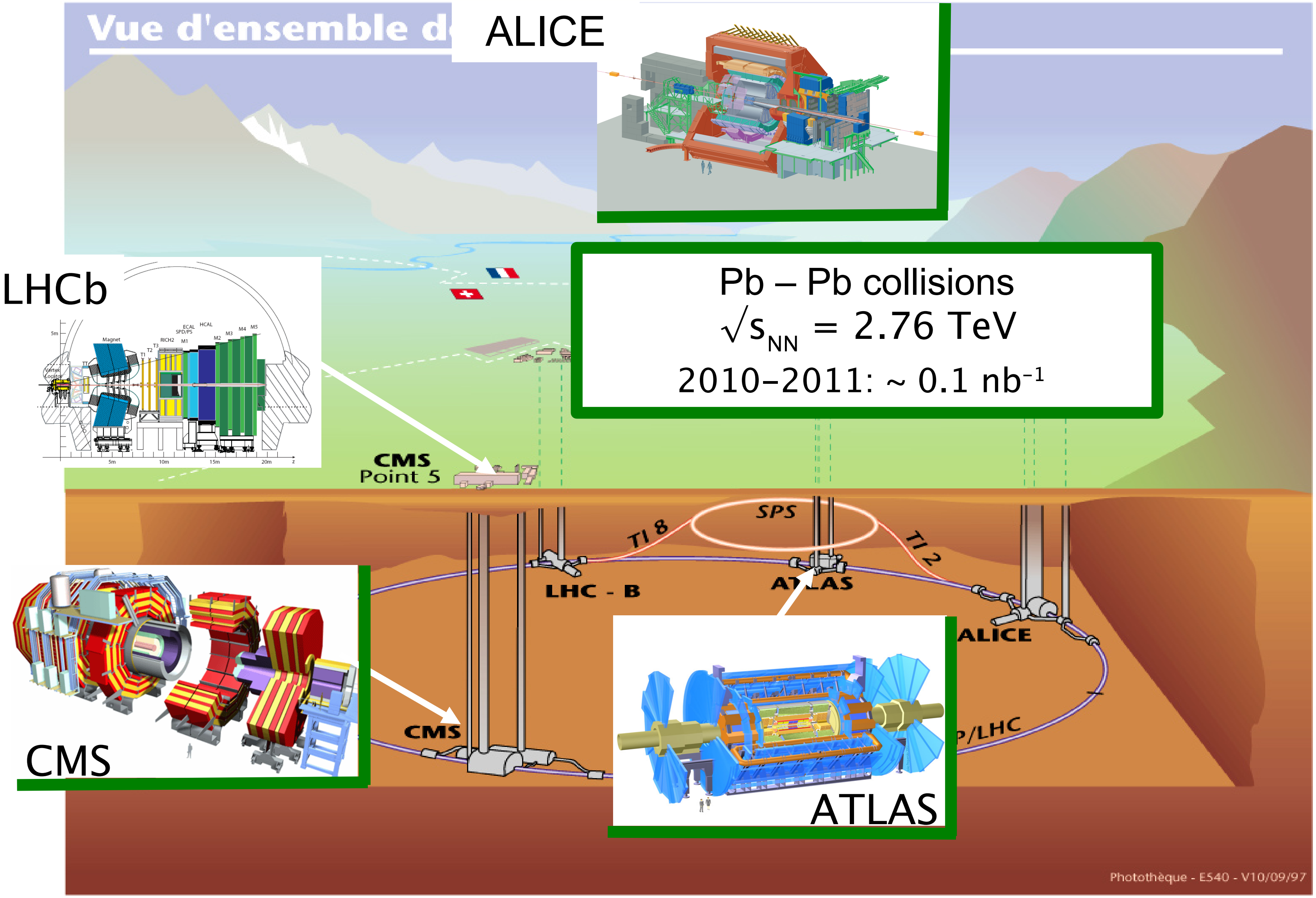
During the year:

- Proton-proton
  - 0.9 TeV: Nov 2009, Mar 2010
  - 2.76 TeV: Mar 2011
  - 7 TeV: 2010, 2011
  - 8 TeV: 2012
- Pb-Pb
  - 2.76 TeV: 2010, 2011
- p-Pb
  - 5.02 TeV: (2012), 2013

- March – October: pp collisions (~ 1400 hours of stable beams)
- November – December: 4 weeks of PbPb collisions (~ 200 hours)



Heavy ions at the LHC

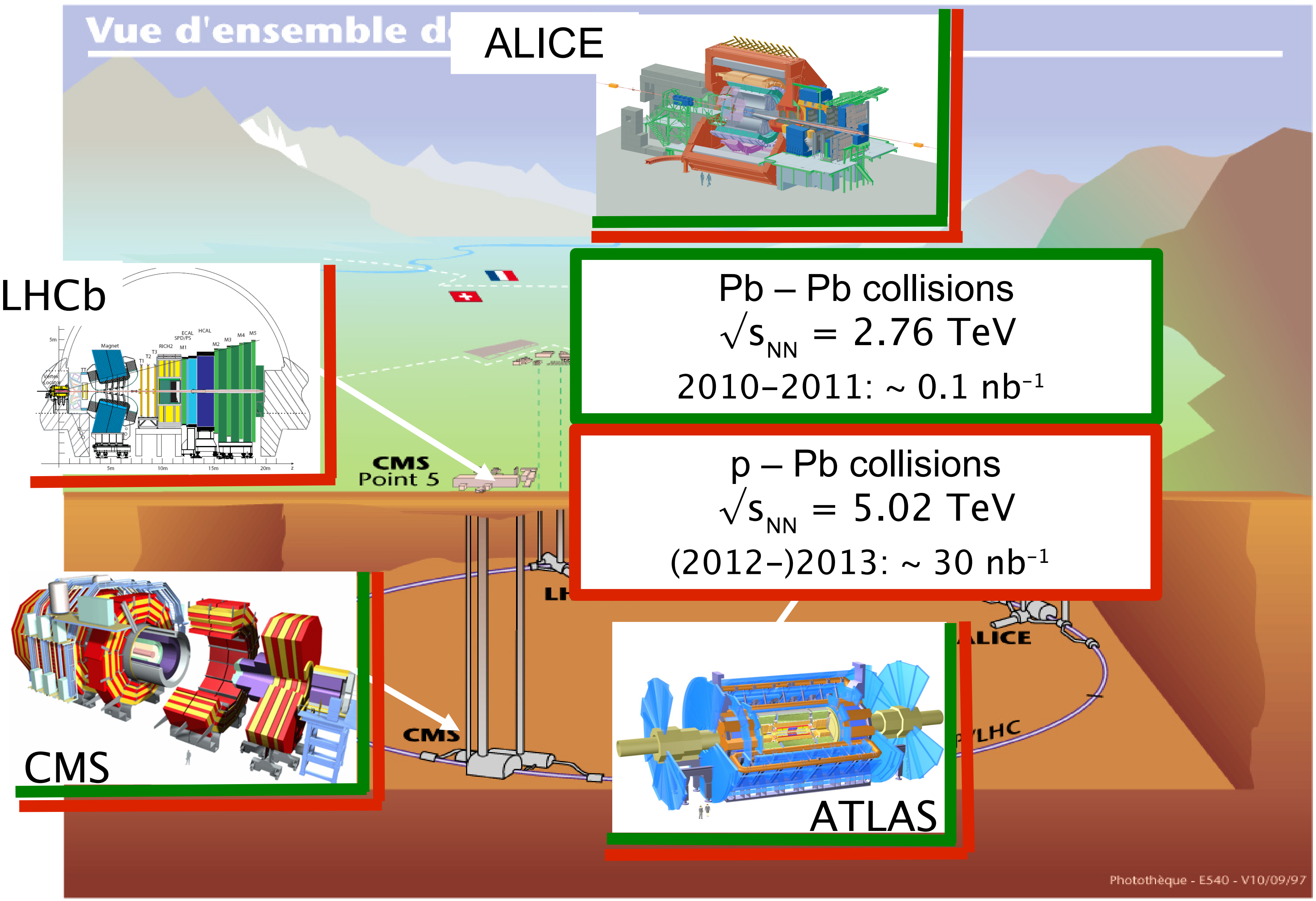


Pb – Pb collisions

$\sqrt{s_{NN}}$ = 2.76 TeV

2010–2011: ~ 0.1 nb^{-1}

Heavy ions at the LHC



Pb – Pb collisions

$\sqrt{s_{NN}}$ = 2.76 TeV

2010–2011: ~ 0.1 nb^{-1}

p – Pb collisions

$\sqrt{s_{NN}}$ = 5.02 TeV

(2012–)2013: ~ 30 nb^{-1}

Comparison SPS-RHIC-LHC

An old table!!!

PbPb central collisions

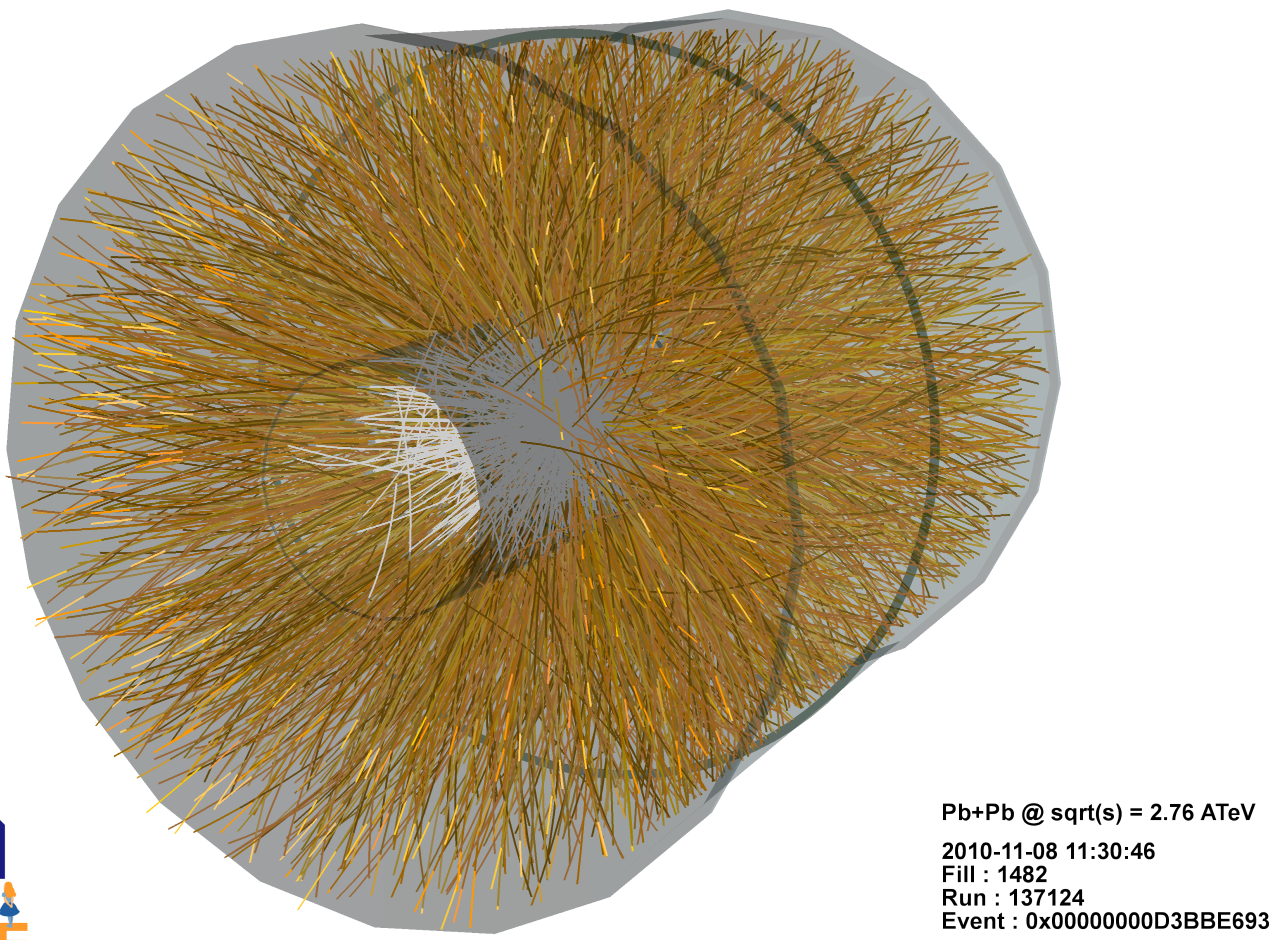
	SPS	RHIC	LHC
E_{cm} [GeV]	17	200	5500
dN_{ch}/dy	500	700	3000 - 8000
E [Gev/fm^3]$_{t_0=1fm/c}$	≈2.5	≈3.5	15 - 40
t_{QGP} [fm/c]	<1	≈1	≈4.5-12

Fireball initial temperature ≈220 MeV ≈4-700 MeV

Significant increase in relevant parameters (ε, V, τ)
Factor 10 from SPS to LHC

Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV

Pb ions accelerated to ~290 TeV → collision: 575 TeV !!!



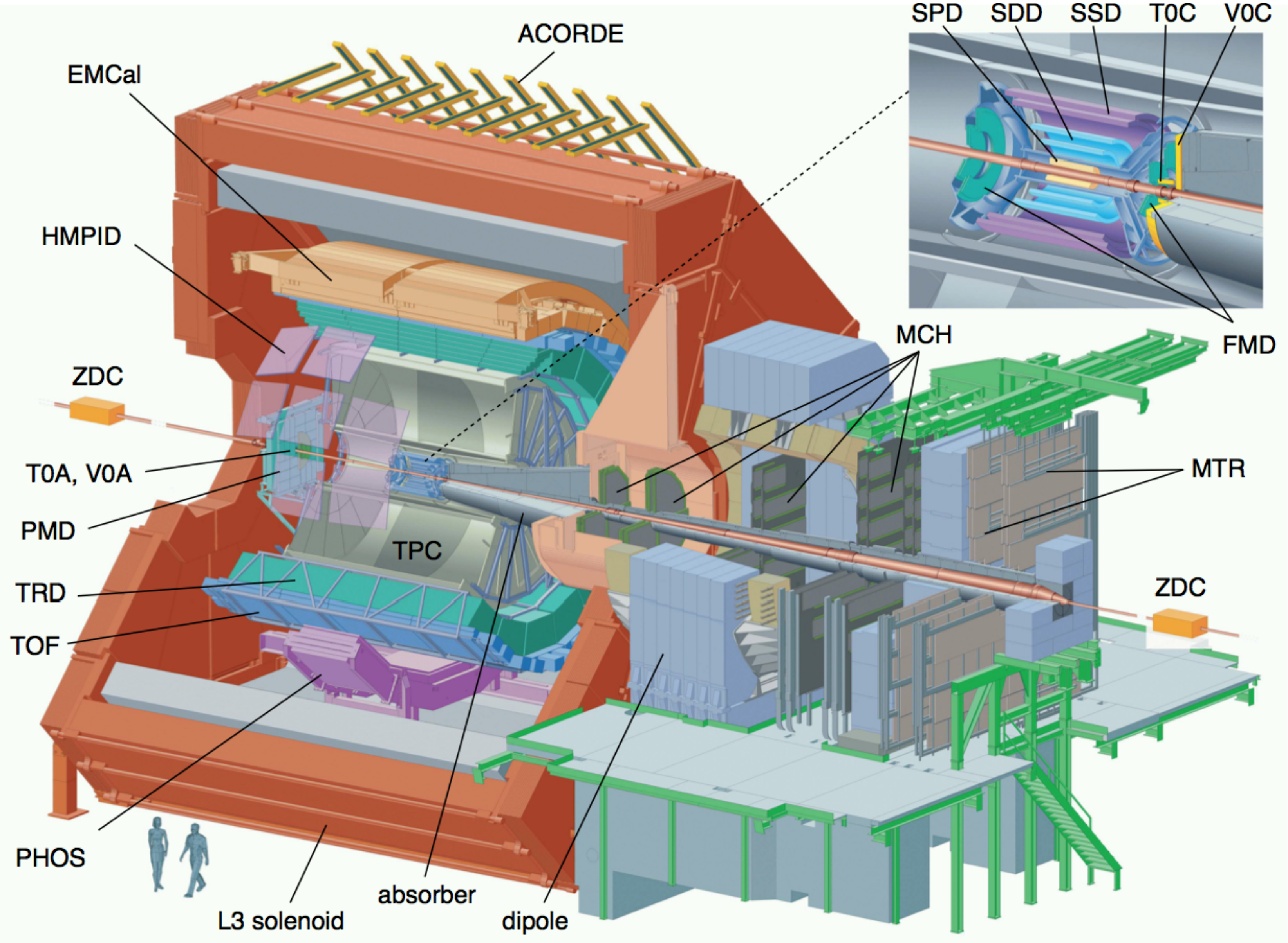
A Large Ion Collider Experiment

Dedicated experiment to study heavy-ion collisions

35 countries, 120 institutes, 1300 members

The ALICE Spectrometer

LHC Point 2
52 m
underground

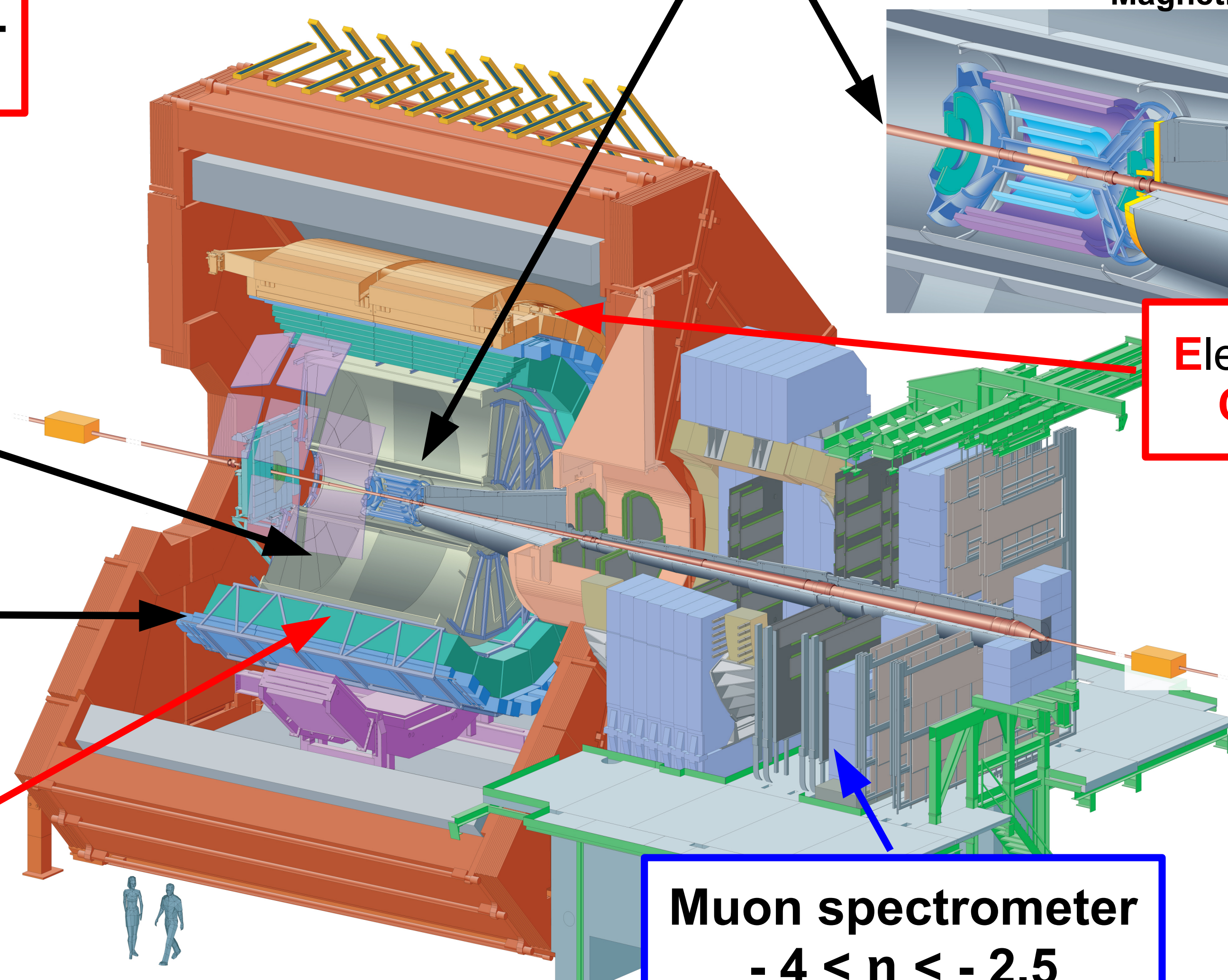


The ALICE Spectrometer

Central barrel
|η| < 0.9
L3 magnet: 0.5 T

Inner Tracking System

Total weight : 16000 T
Overall diameter : 16 m
Overall length : 26 m
Magnetic field : 0.5 Tesla



Time Projection Chamber

Time Of Flight

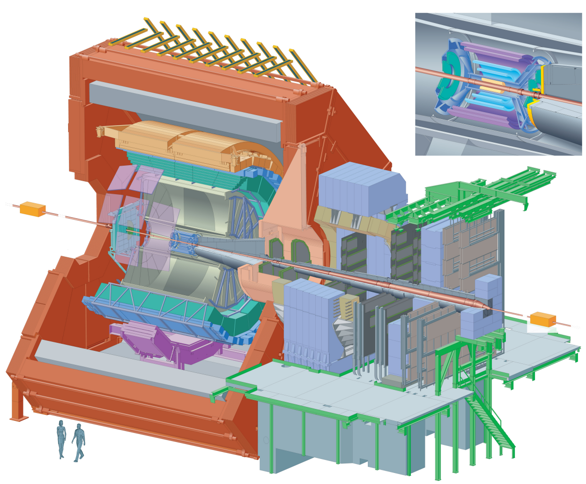
Transition Radiation Detector

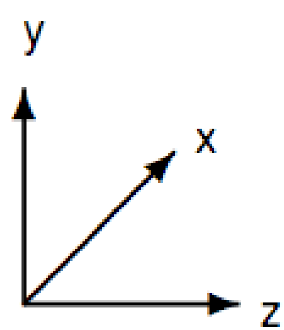
ElectroMagnetic Calorimeter

Muon spectrometer
- 4 < η < - 2.5

Coordinate system

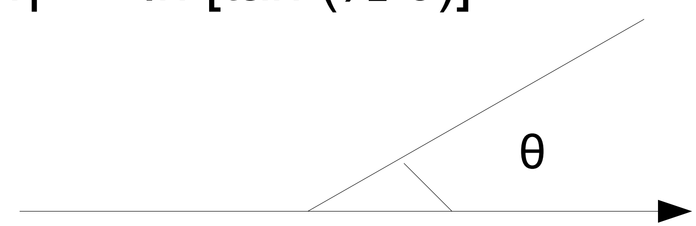
The ALICE coordinate system is defined as follows: x-axis is perpendicular to the mean beam direction, aligned with the local horizontal and pointing to the accelerator centre; y axis is perpendicular to the x-axis and to the mean beam direction, pointing upward; z-axis is parallel to the mean beam direction. The positive z-axis is pointing in the direction opposite to the muon spectrometer





- Azimuthal angle φ
- Rapidity y
- Pseudorapidity η

$$\eta = -\ln[\tan(\tfrac{1}{2}\theta)]$$



Beam axis

Minimum bias, low momenta

The focus of ALICE is on maximal coverage of the (transverse) momentum spectra, because much of the most interesting physics for us sits at low momentum:

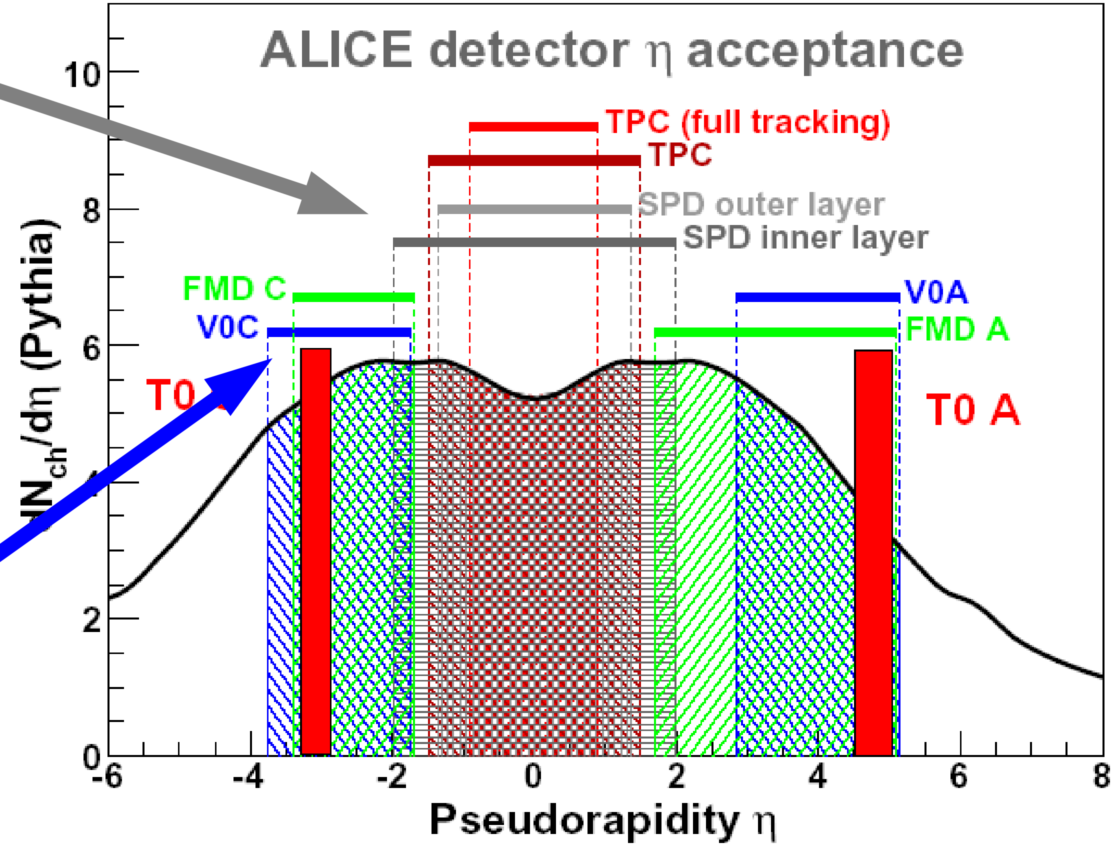
- Very moderate use of triggers (which are rather aimed at selecting high momentum, rare probes)
- Mostly so-called minimum bias data taking
- → huge data volumes
- Low value of the magnetic field (0.5 Tesla) for optimal tracking of low p_T tracks

ALICE Minimum Bias Trigger

Silicon Pixel Detector (SPD):
inner: 3.9cm radius, |η|<2
outer: 7.6cm radius, |η|<1.4

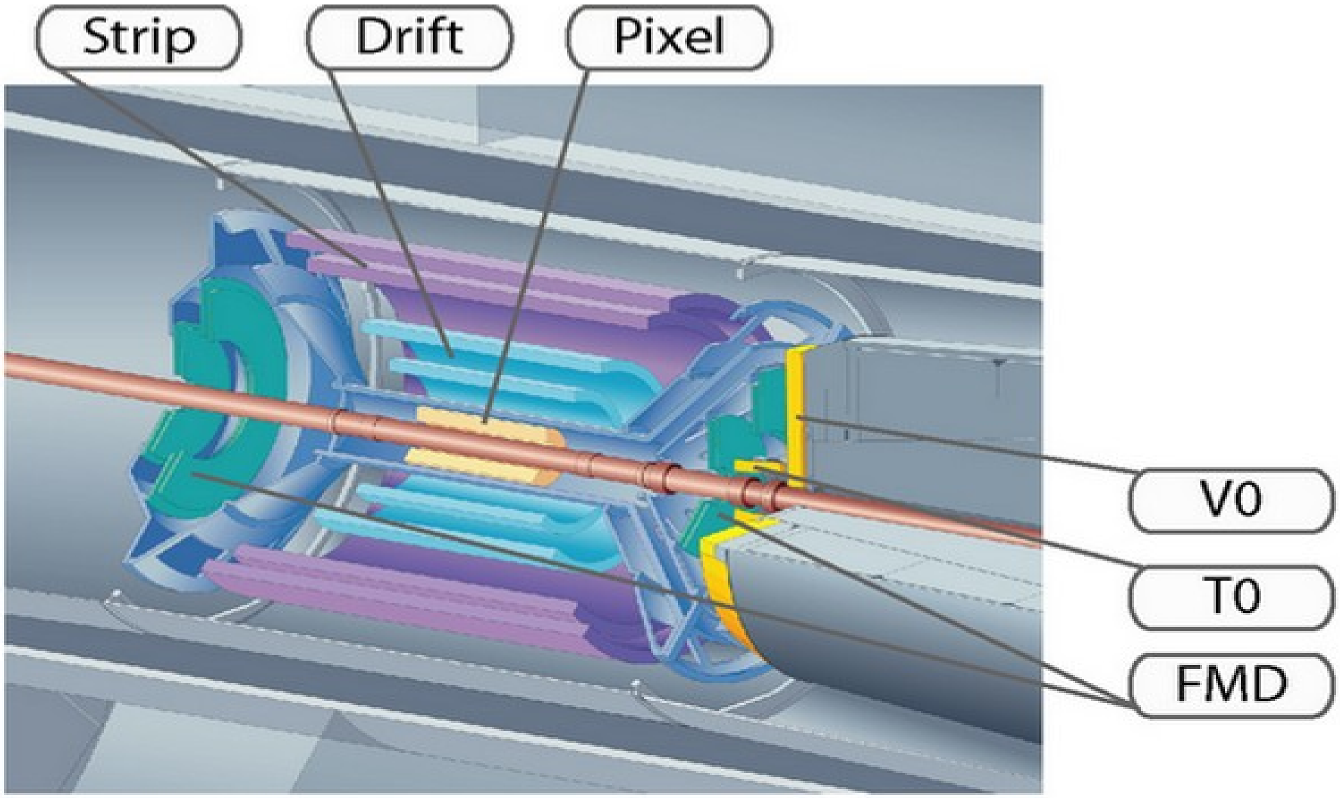
OR

Scintillator Hodoscopes:
V0A: z=3.3m, 2.8< η <5.1
V0C: z=-0.9m, -3.7< η <-1.7

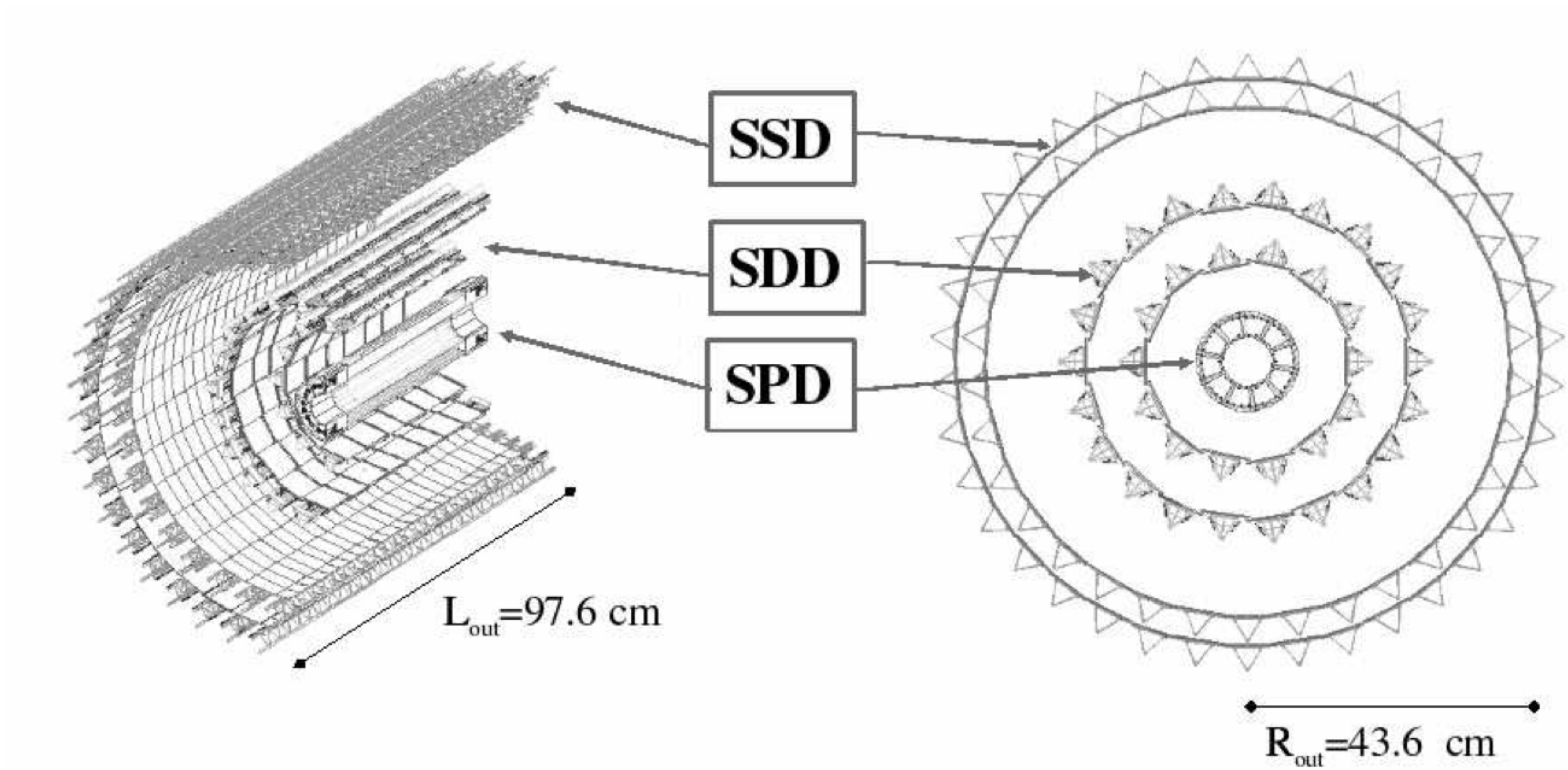


Plus coincidence with beam pickups

The Inner Tracking System



The Inner Tracking System

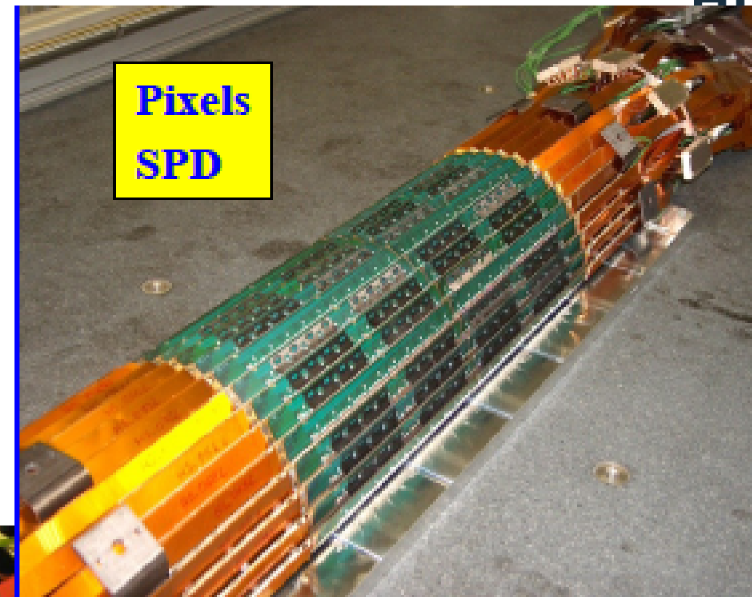


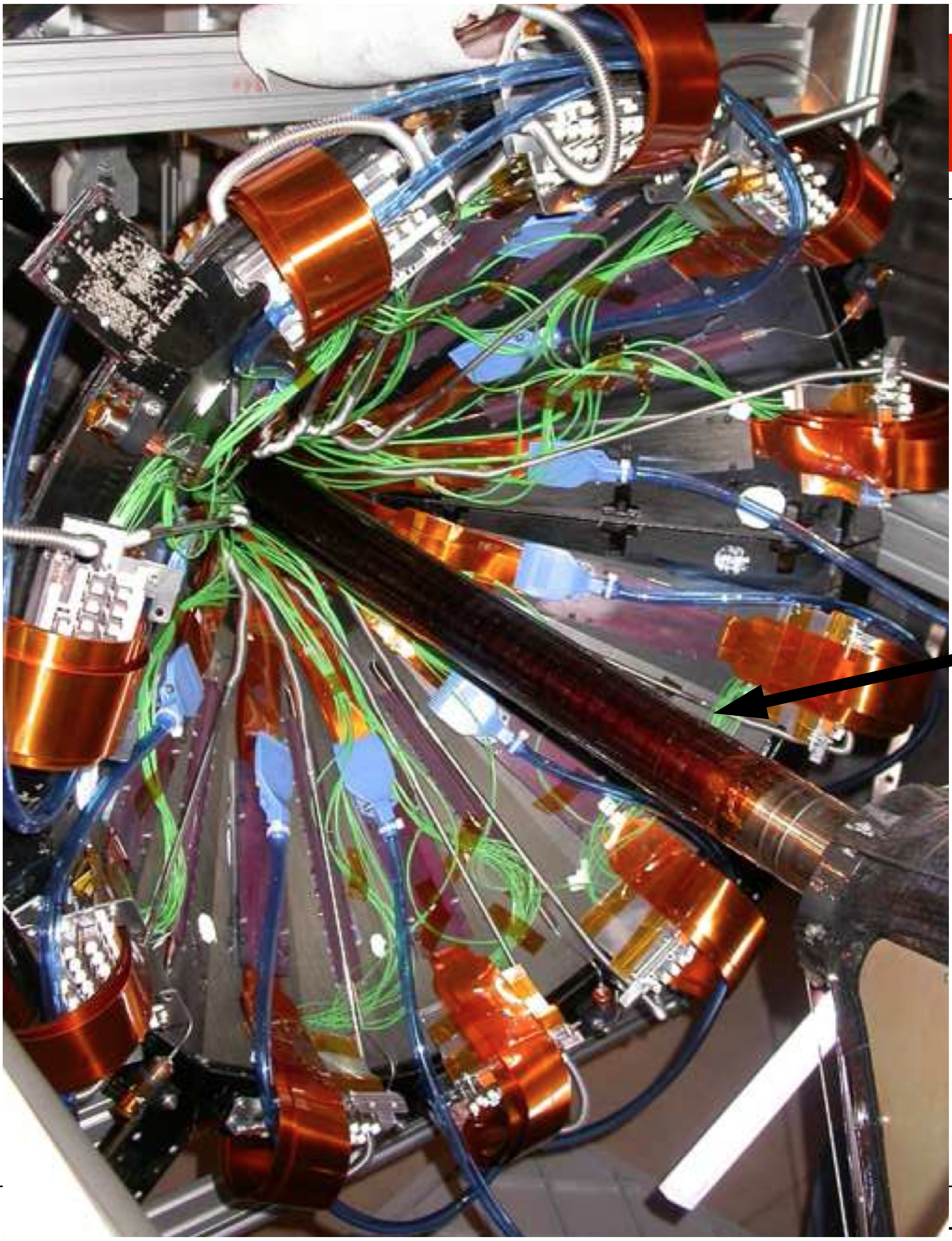
ITS

Inner Tracking System

~10 m^2 Si detectors, 6 layers

Pixels, Drift, double sided Strips





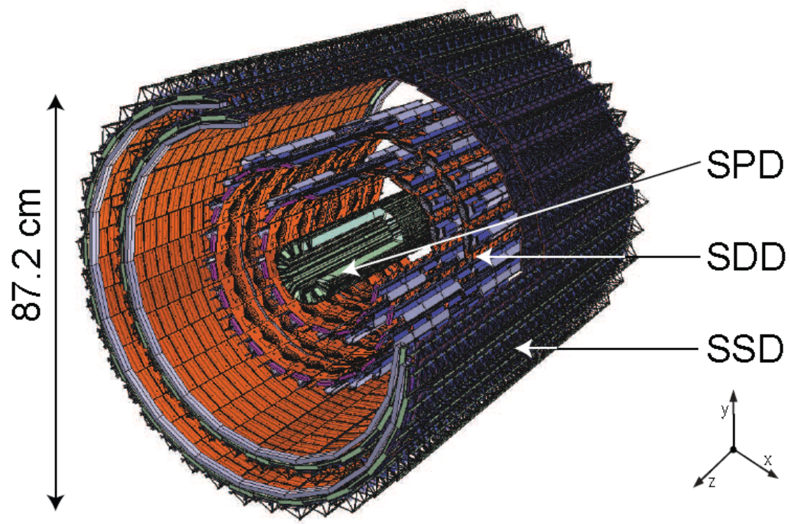
SPD

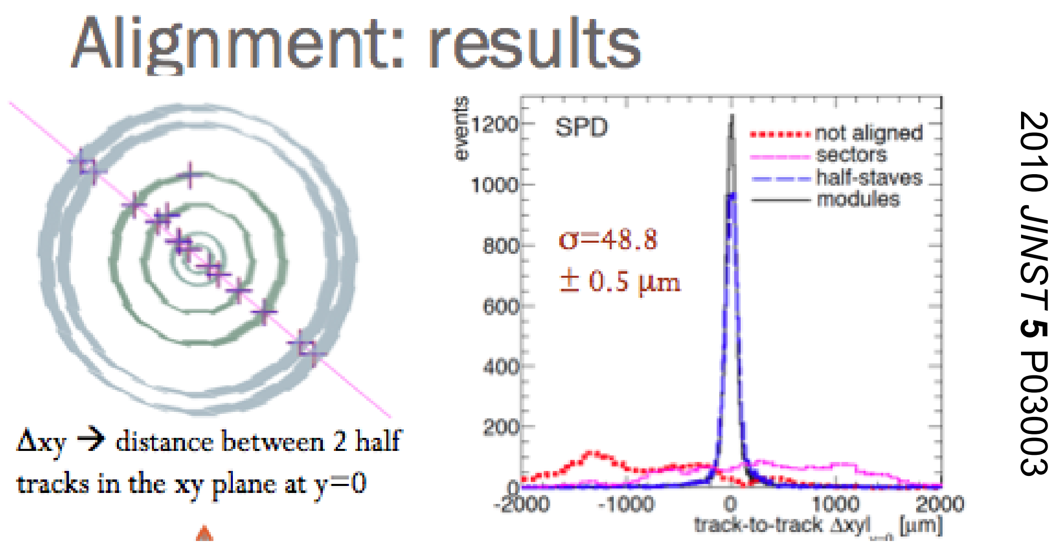
Beryllium beam pipe

4 m long
58 mm inner diameter
0.8 mm thickness

Innermost SPD layer at radius of 3.9 cm

The Inner Tracking System

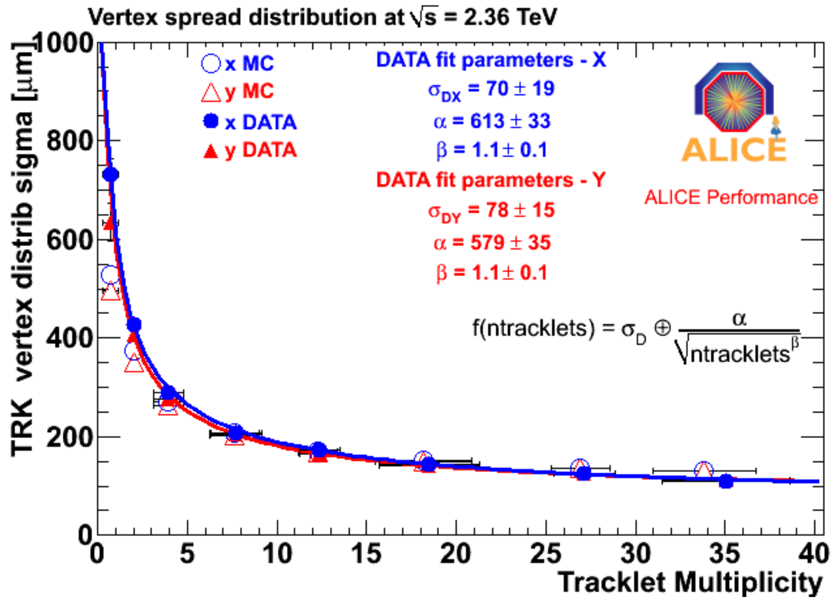




Silicon vertex detector

3 technologies:

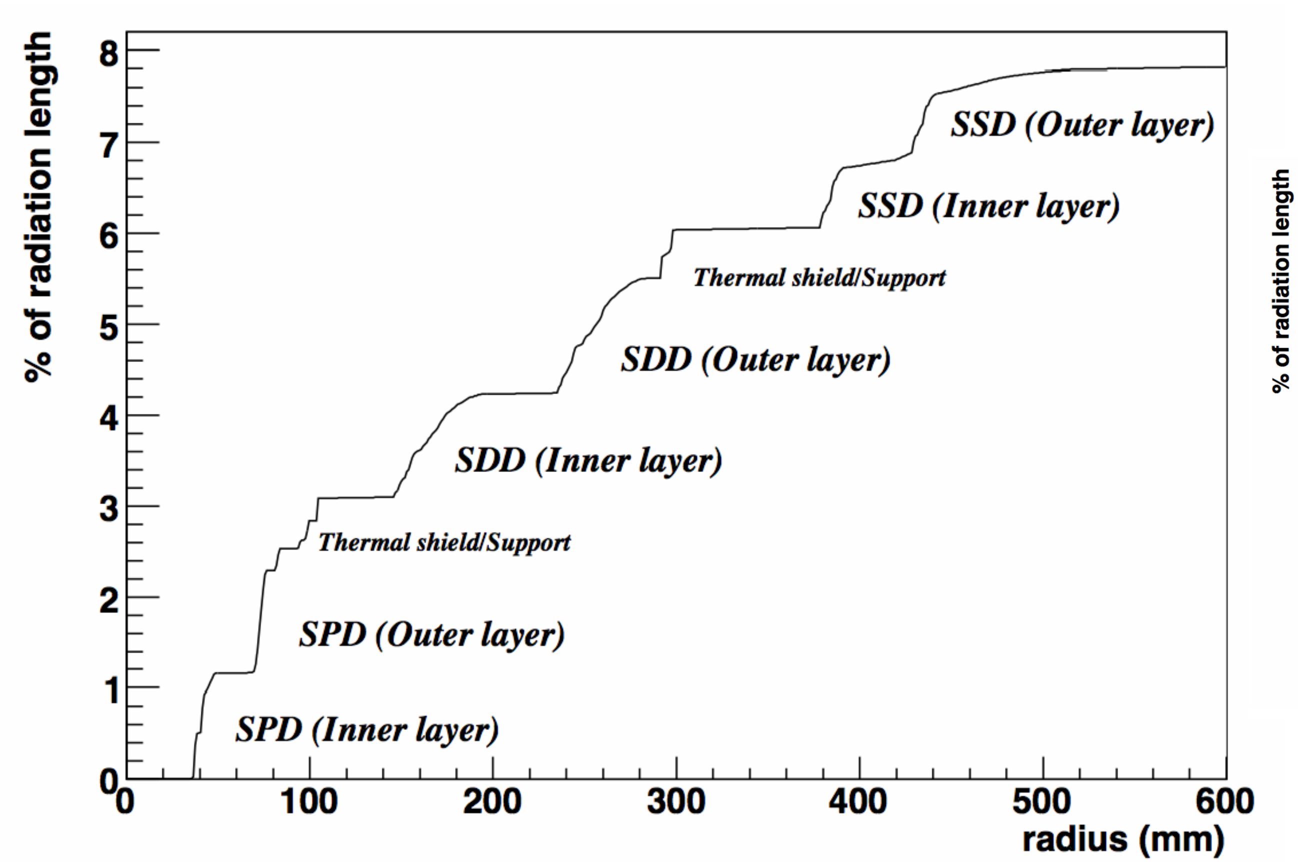
- 10 million pixels
- 133 k drift detector channels
- 2.6 million microstrips

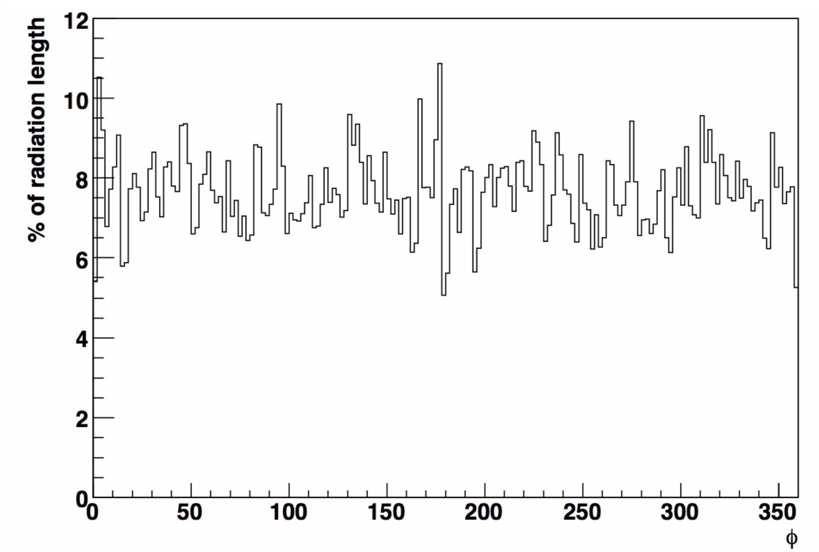


Excellent tracking and vertexing!

Material thickness

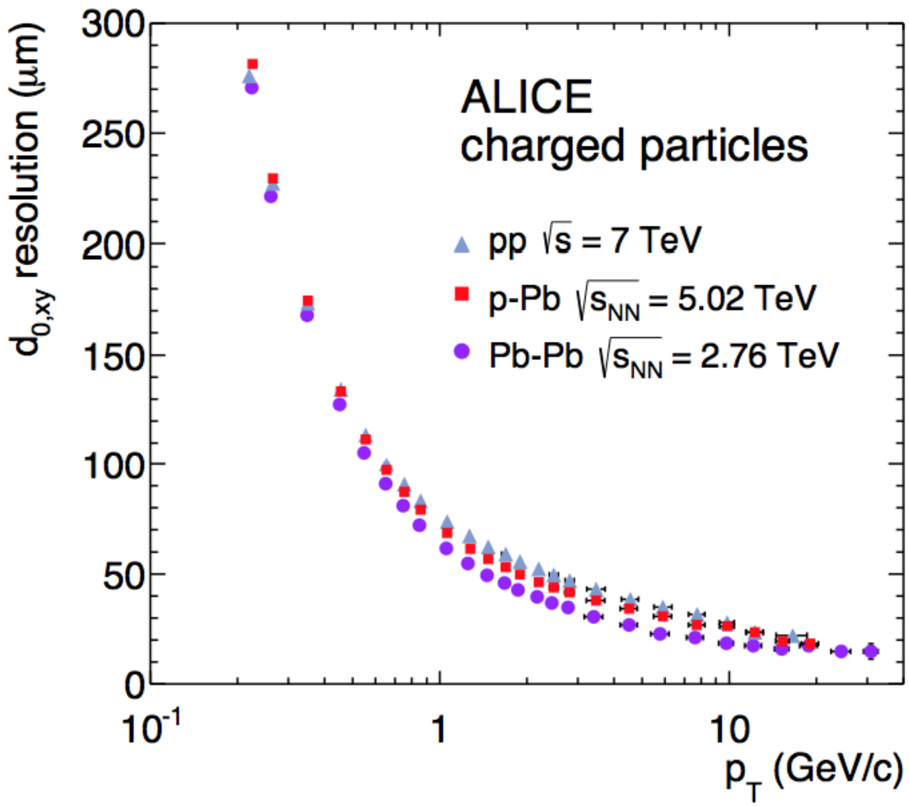
Resolution is dominated by the multiple scattering experienced by particles in the detector material





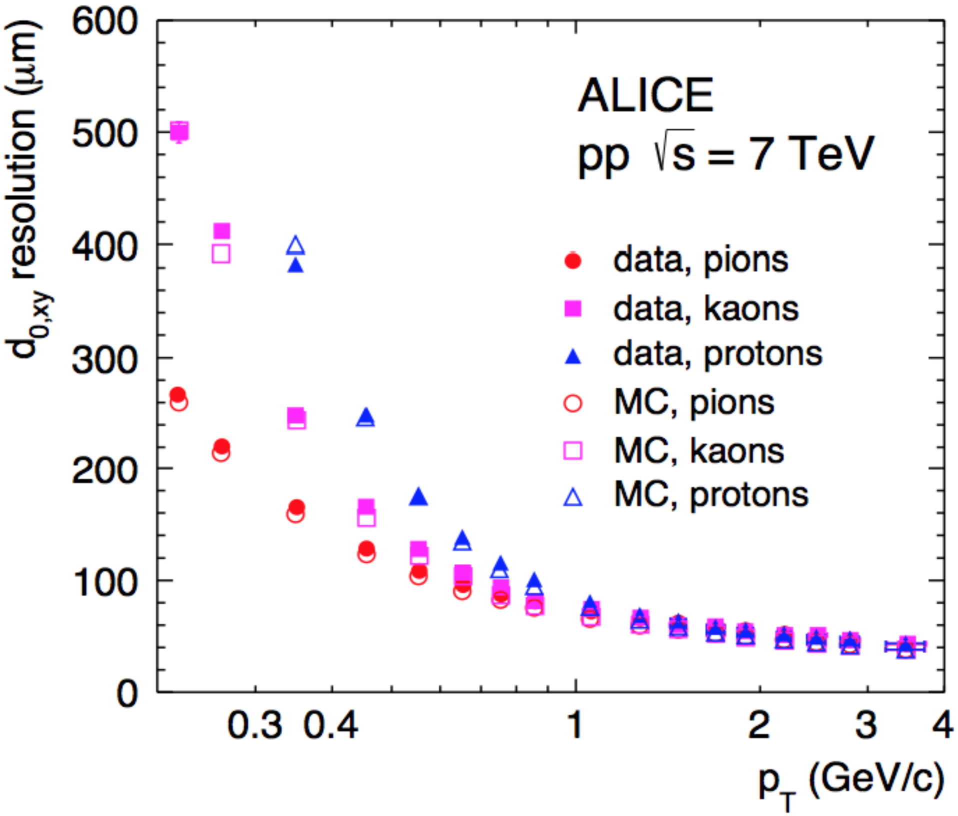
Spatial resolution - 1

Resolution on the impact parameter of **charged tracks** to the primary interaction vertex:



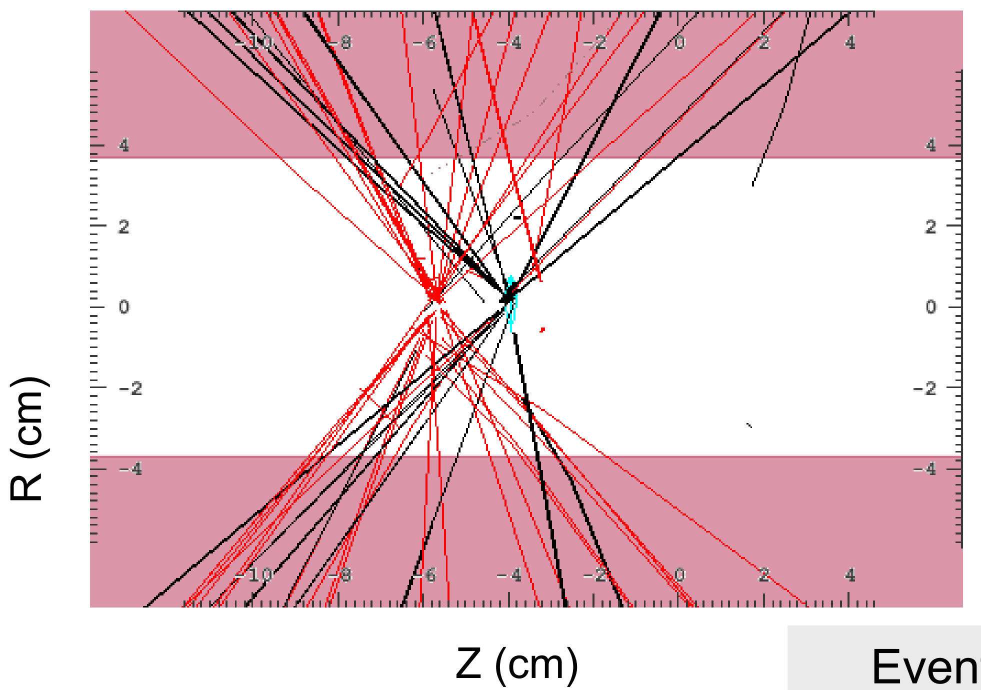
Spatial resolution - 2

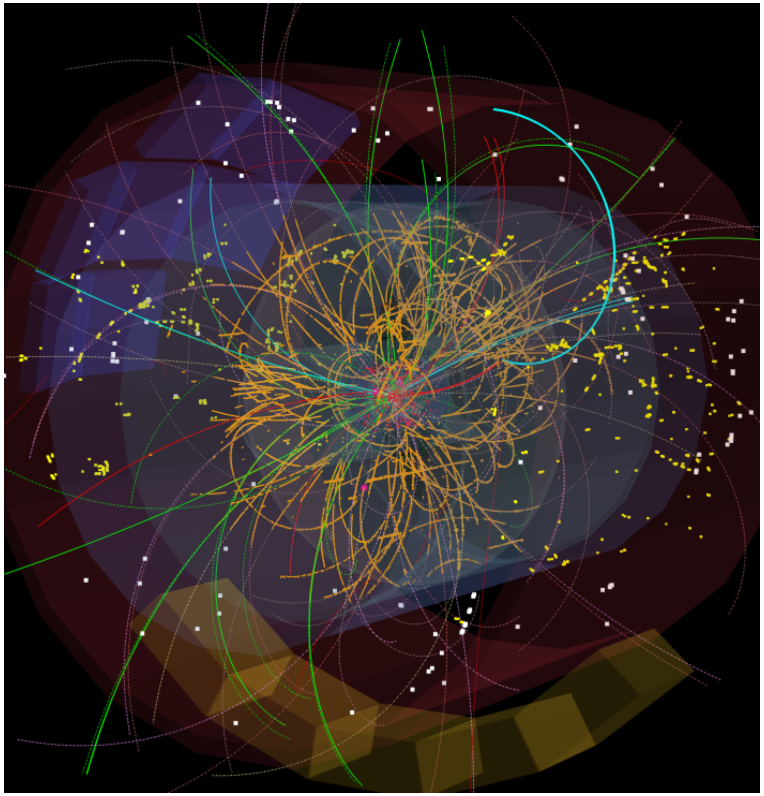
Resolution on the impact parameter of **identified particles** to the primary interaction vertex:



ALICE Specialties

- Very low momentum cutoff (~0.1 GeV/c)
- p_T reach up to 100 GeV/c
- Excellent particle identification
- Efficient minimum bias trigger
- **Excellent vertex capabilities**



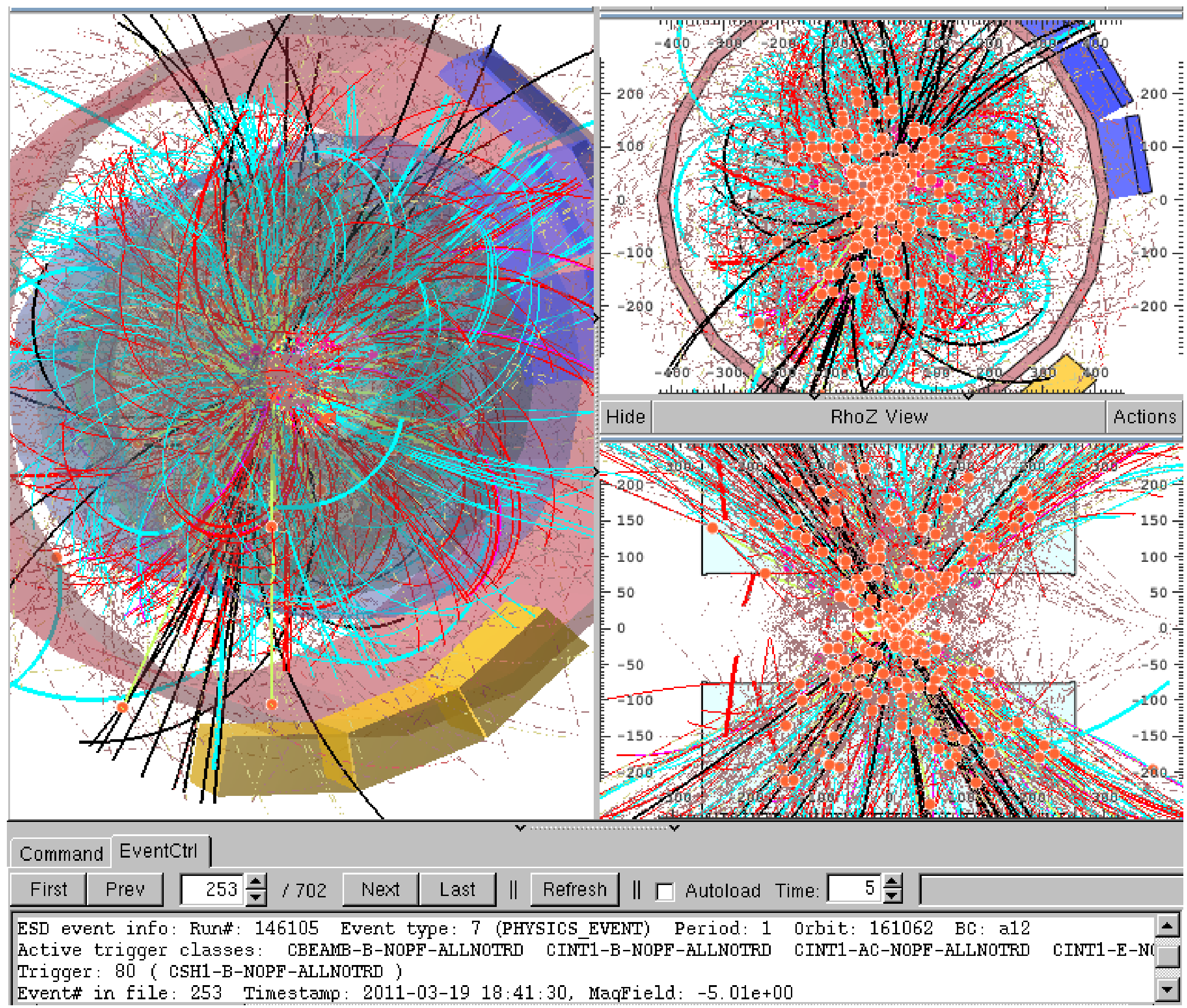


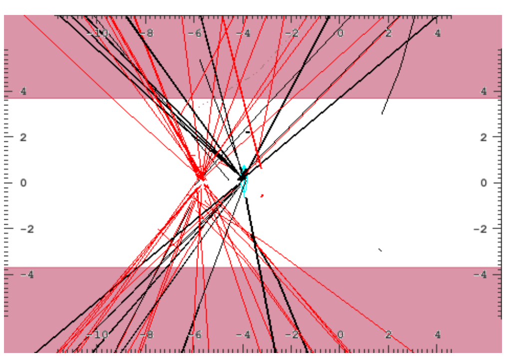
Event display of a pile-up event at 900 GeV

Pile-up in pp

Events become a real "mess".

We need to learn to handle this in reconstruction and in analysis !!! (e.g. normalization to cross sections)

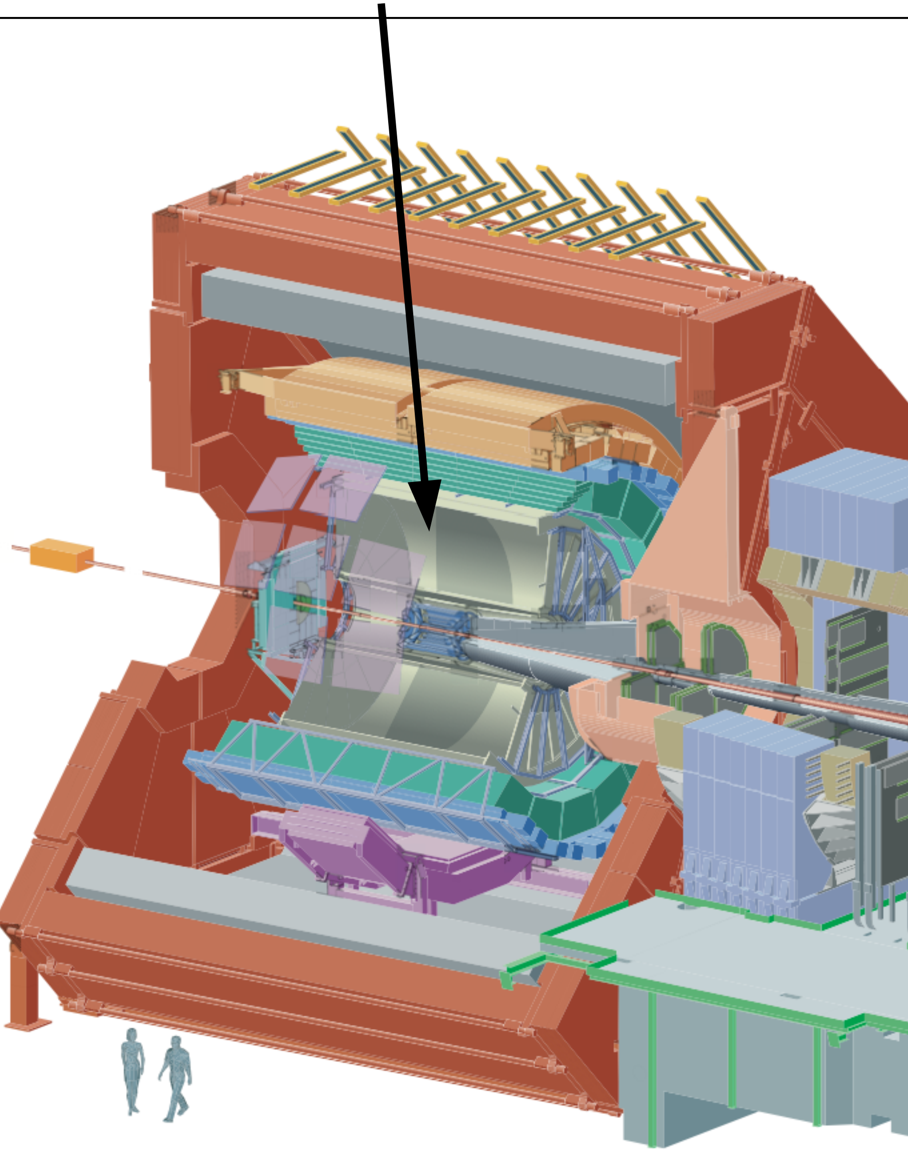




R (cm)

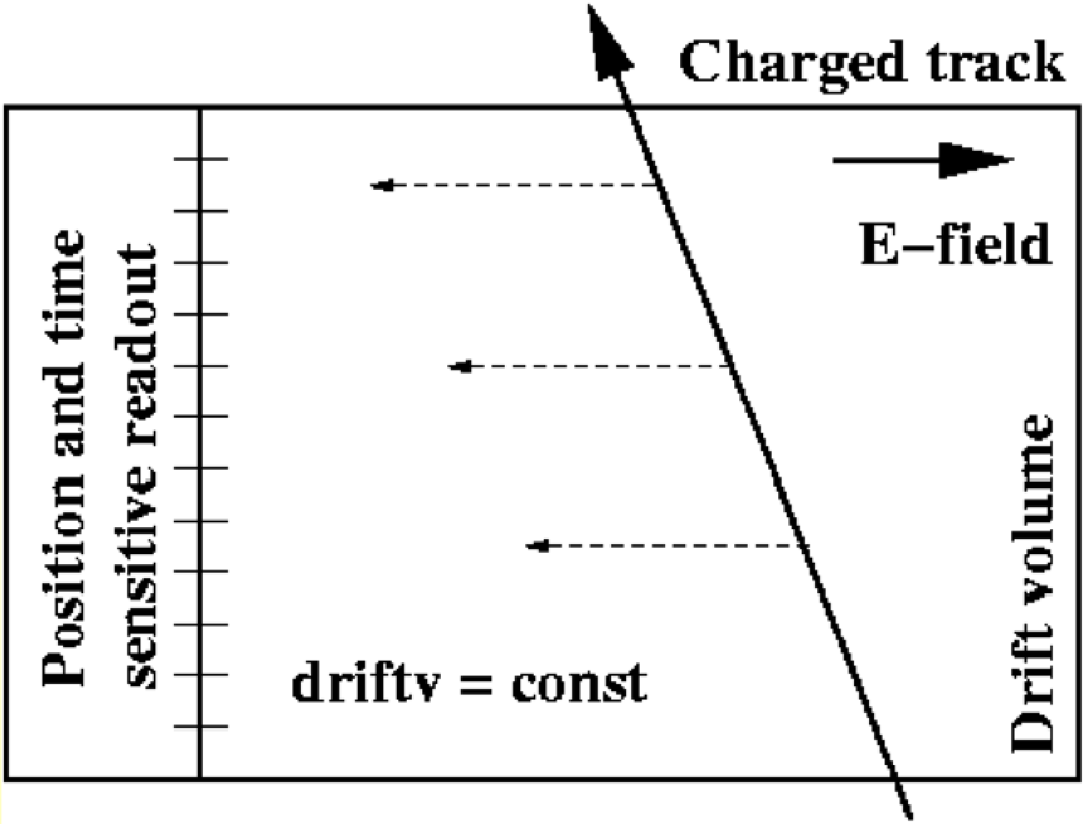
Z (cm)

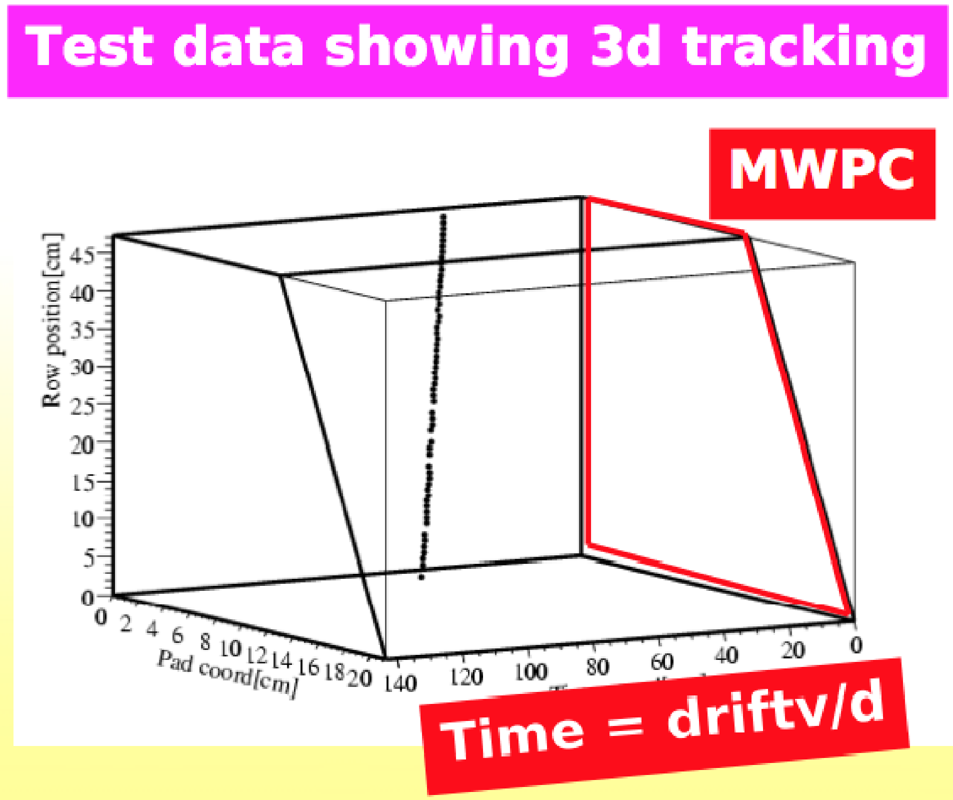
Time Projection Chamber



- The heart of ALICE
  - Tracking
  - Particle identification
- The largest ever built in the world: ~90 m^3
- Designed to track up to 8000 particles per rapidity unit!!!
- Badly challenged by LHC (background, rates) but anyhow exceptional performance!

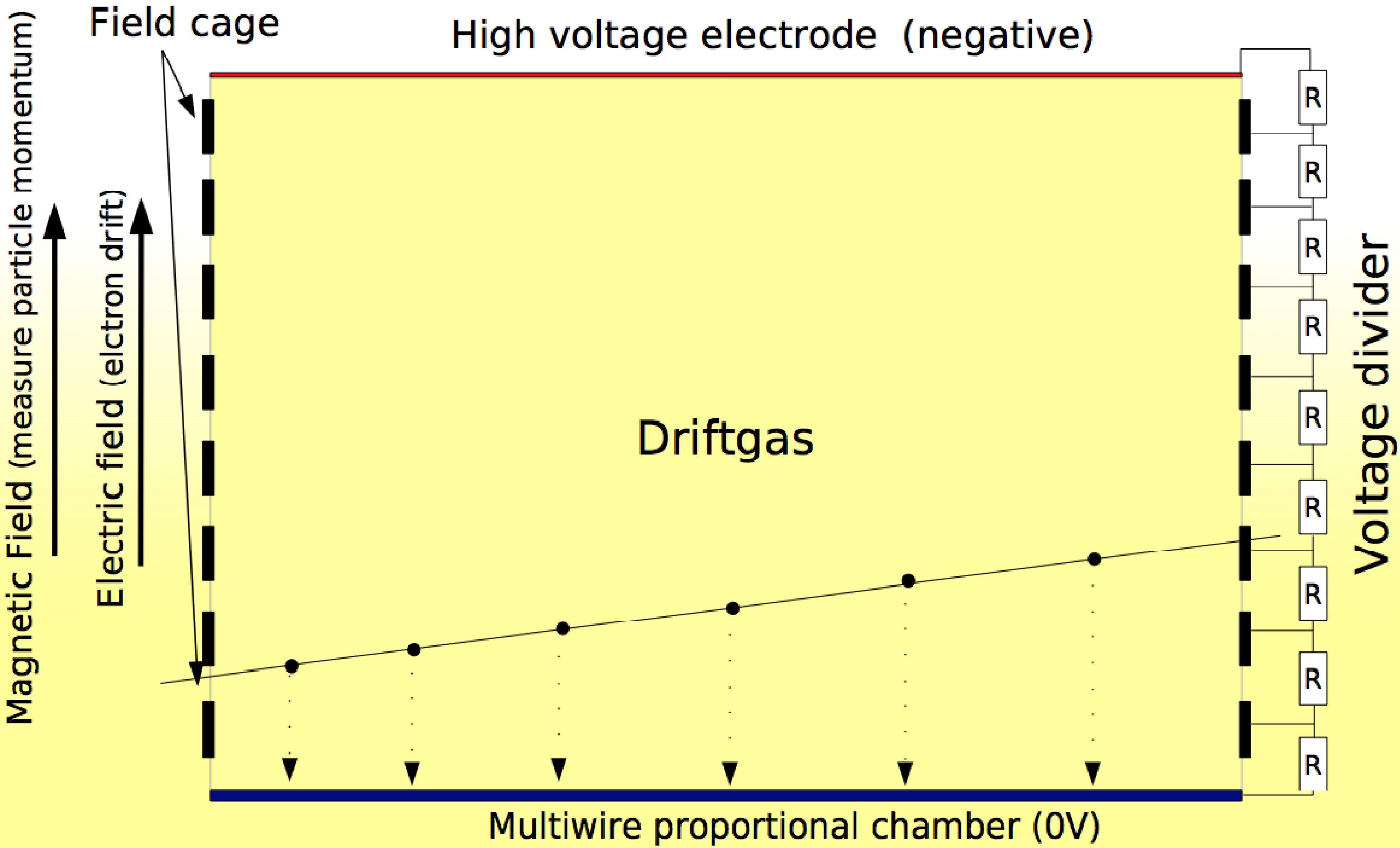
TPC Working Principle



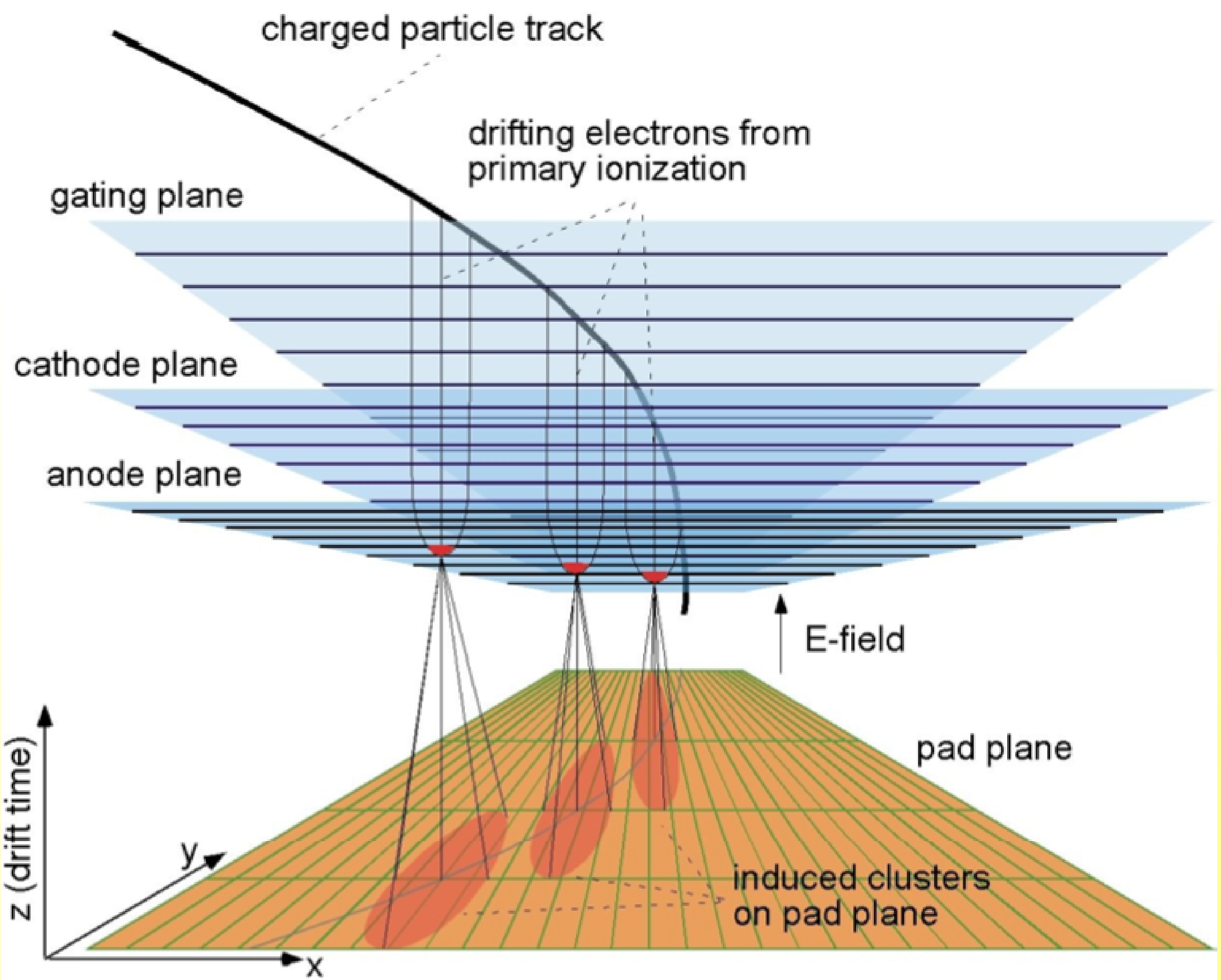


- Charged track ionizes gas molecules
- Ionized electrons drift (because of E-field) to readout
- Read out measures the 2d position (x,y) as a function of time (z = time*drift velocity) => 3d tracking

Structure of a TPC



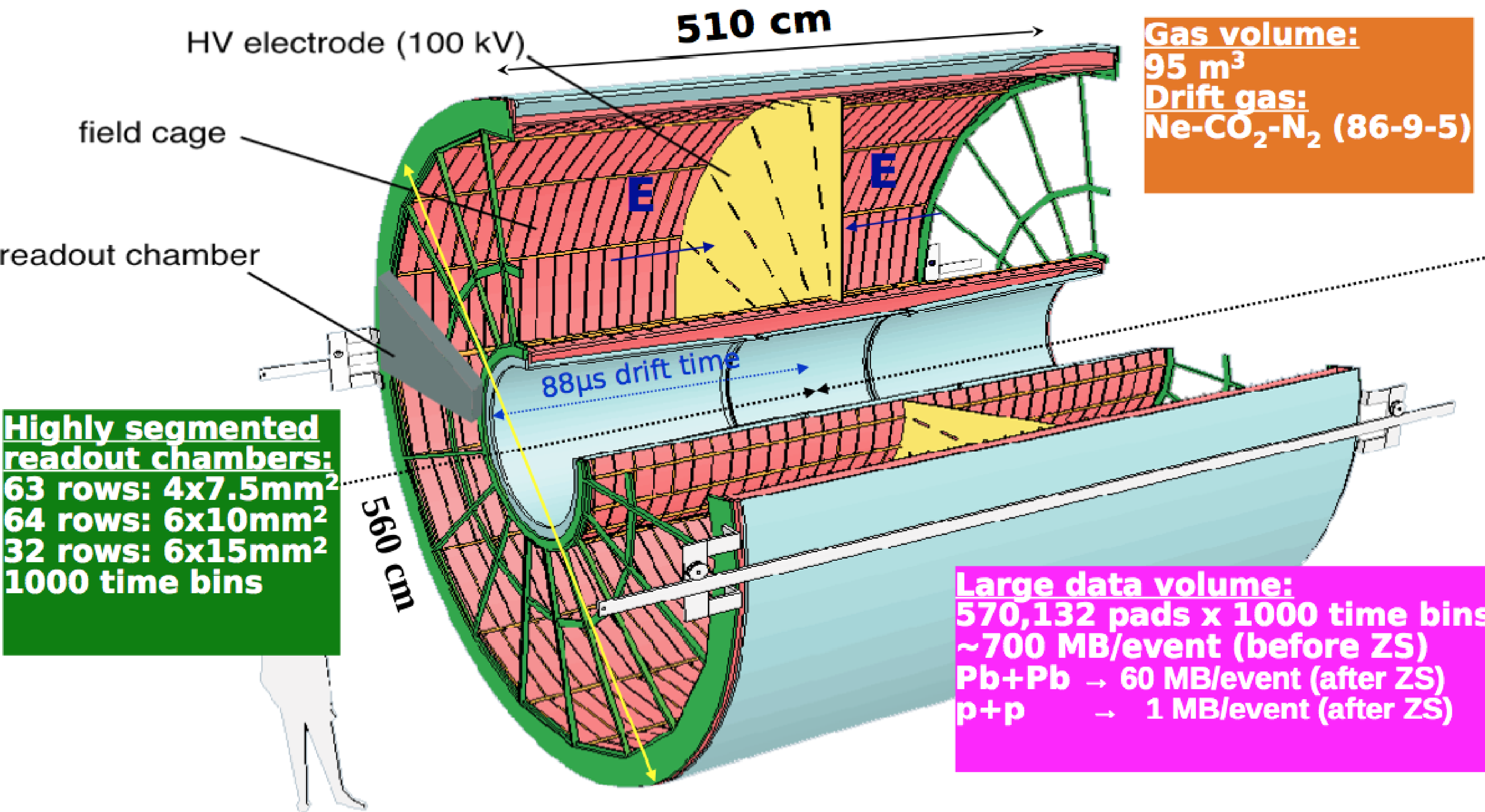
Amplification in the TPC



- Two coordinates (x,y) given by the projection on the pad plane
- Third coordinate (z) given by the drift time and drift velocity ($z = v_{Drift} \times t_{Drift}$)
- Anode: 1400 - 1650 V
- Cathode: 0 V
- Gating: -100 ± 90 V
  open closed

- Gas gain ≈ $2 \cdot 10^4$

ALICE TPC Layout:
The worlds largest TPC



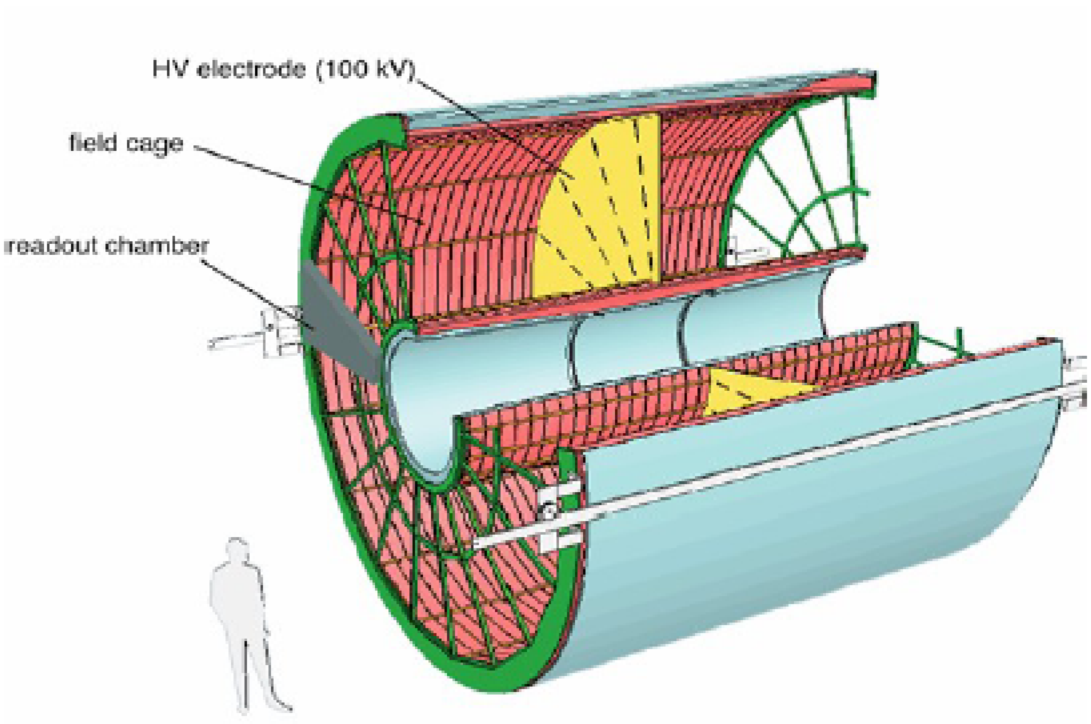
Gas volume:
95 m^3
Drift gas:
Ne-CO_2-N_2 (86-9-5)

Highly segmented readout chambers:
63 rows: 4x7.5mm^2
64 rows: 6x10mm^2
32 rows: 6x15mm^2
1000 time bins

Large data volume:
570,132 pads x 1000 time bins
~700 MB/event (before ZS)
Pb+Pb → 60 MB/event (after ZS)
p+p → 1 MB/event (after ZS)

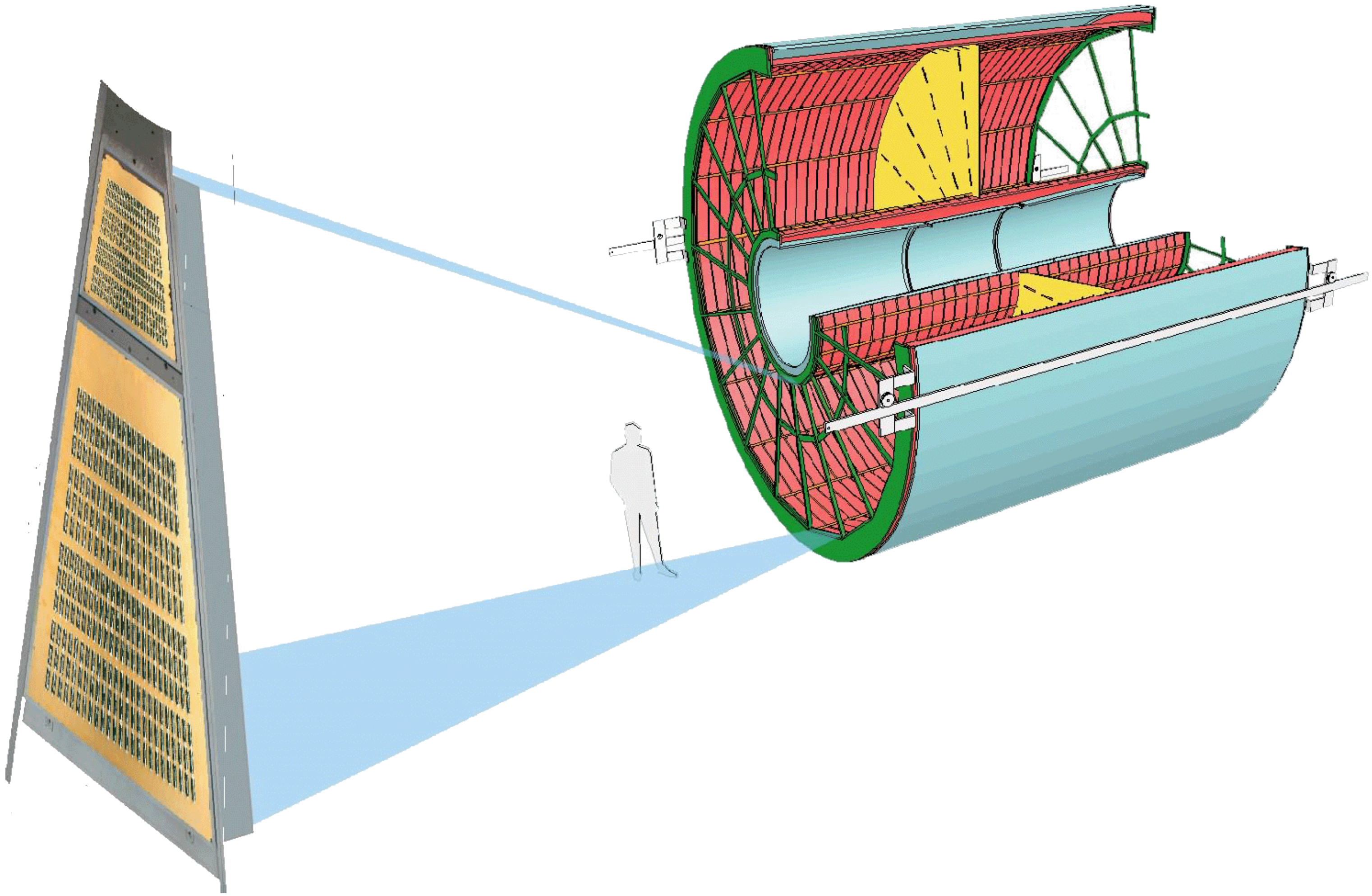
Time Projection Chamber

- Optimized for $dN/d\eta \approx 8000$
  - l = 5 m, Ø = 5.6m, 88 m3, 570 k channels,
  - up to 80 Mbytes/event (after 0 suppression)
- Features:
  - lightweight: 3% X_0 total material for perpendicular tracks
  - Drift gas:Ne (86) / CO_2 (9.5) / N_2(4.5) + ~1ppm O_2
  - novel digital electronics (ALTRO)
  - highly integrated, digital shaping; tail cancellation;0-suppression; Baseline restoration
  - Powerful laser calibration system



ALICE – TPC

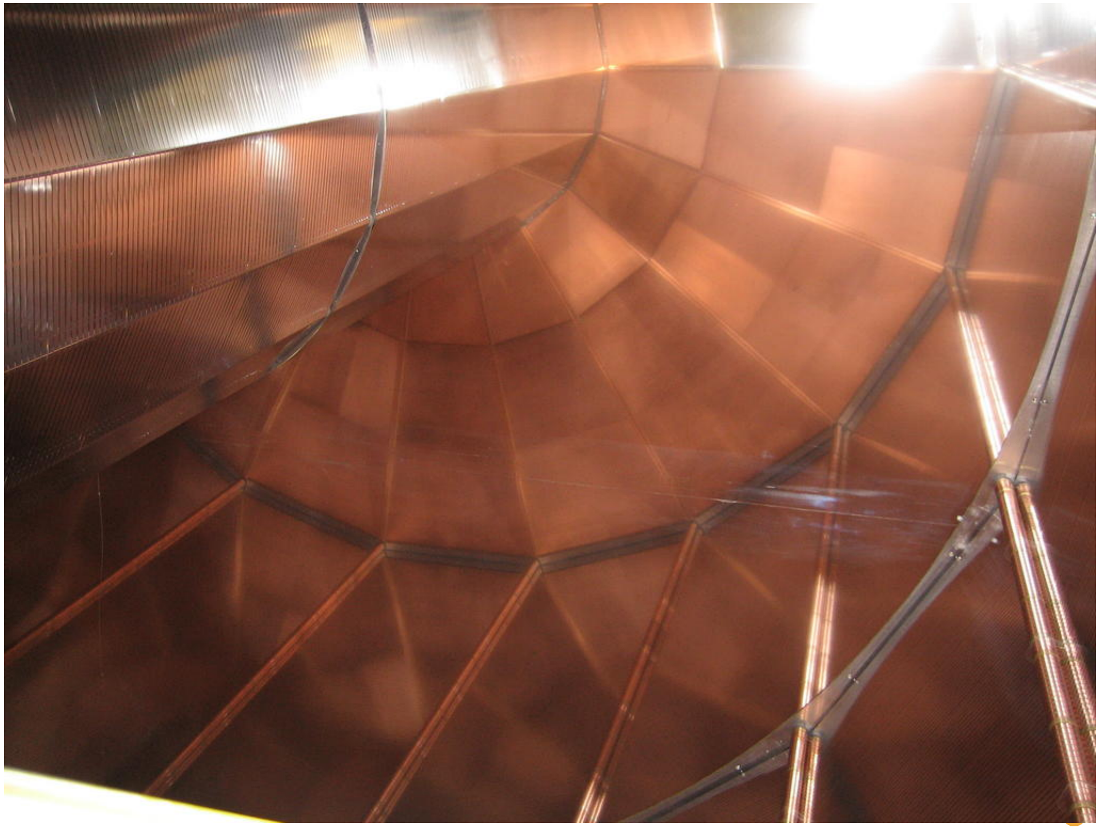
The TPC readout chambers



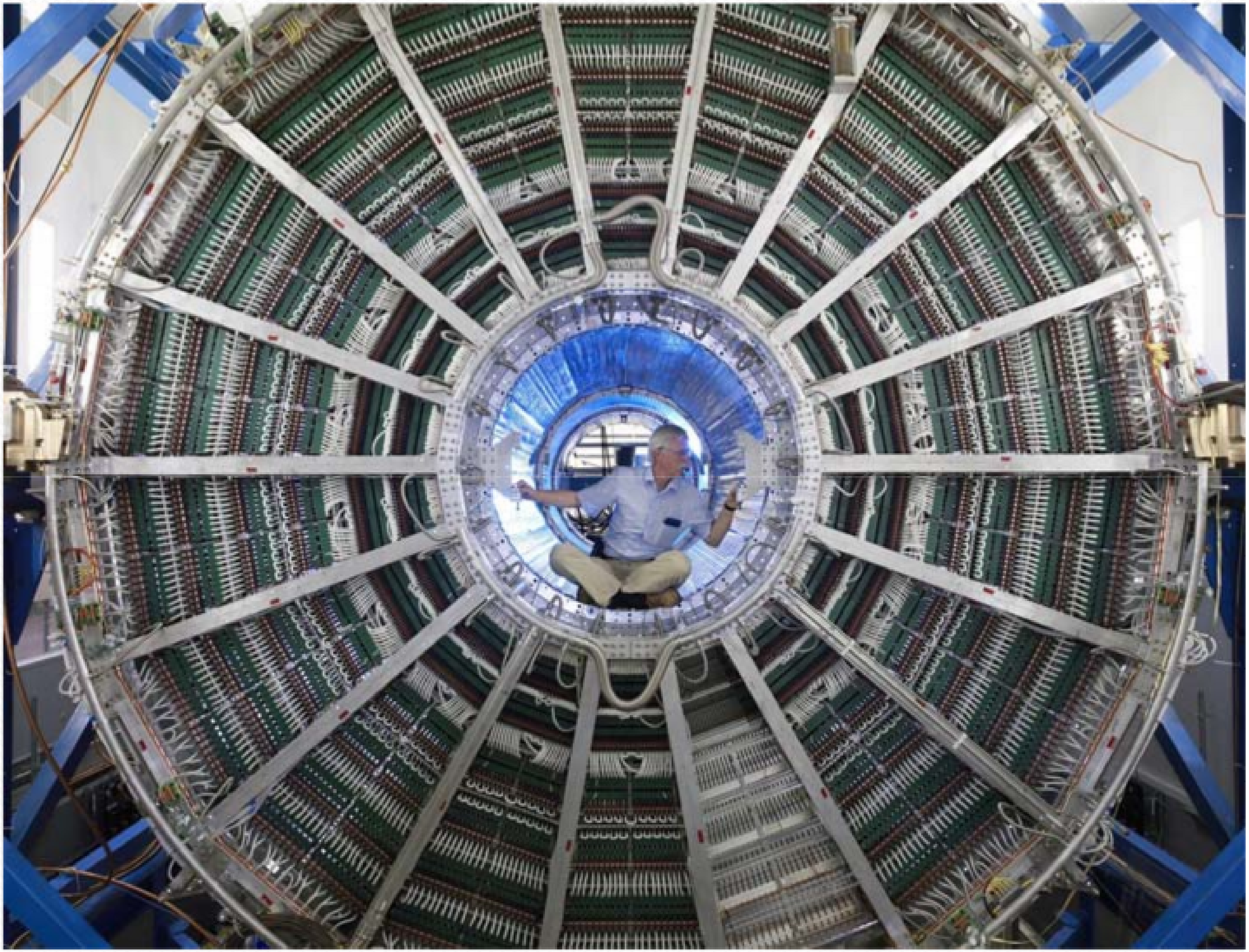
ALICE – TPC

One readout chamber: the wires are visible

Photograph of the inside of the ALICE TPC, showing the strips of the field cage and the central electrode. The image of the trapezoidal Inner ReadOut chambers (IROC) and Outer ReadOut Chambers (OROC) are reflected on the central electrode



ALICE – TPC



ALICE – TPC

The TPC as assembled above ground on its way to the ALICE cavern

Tracking efficiency - TPC

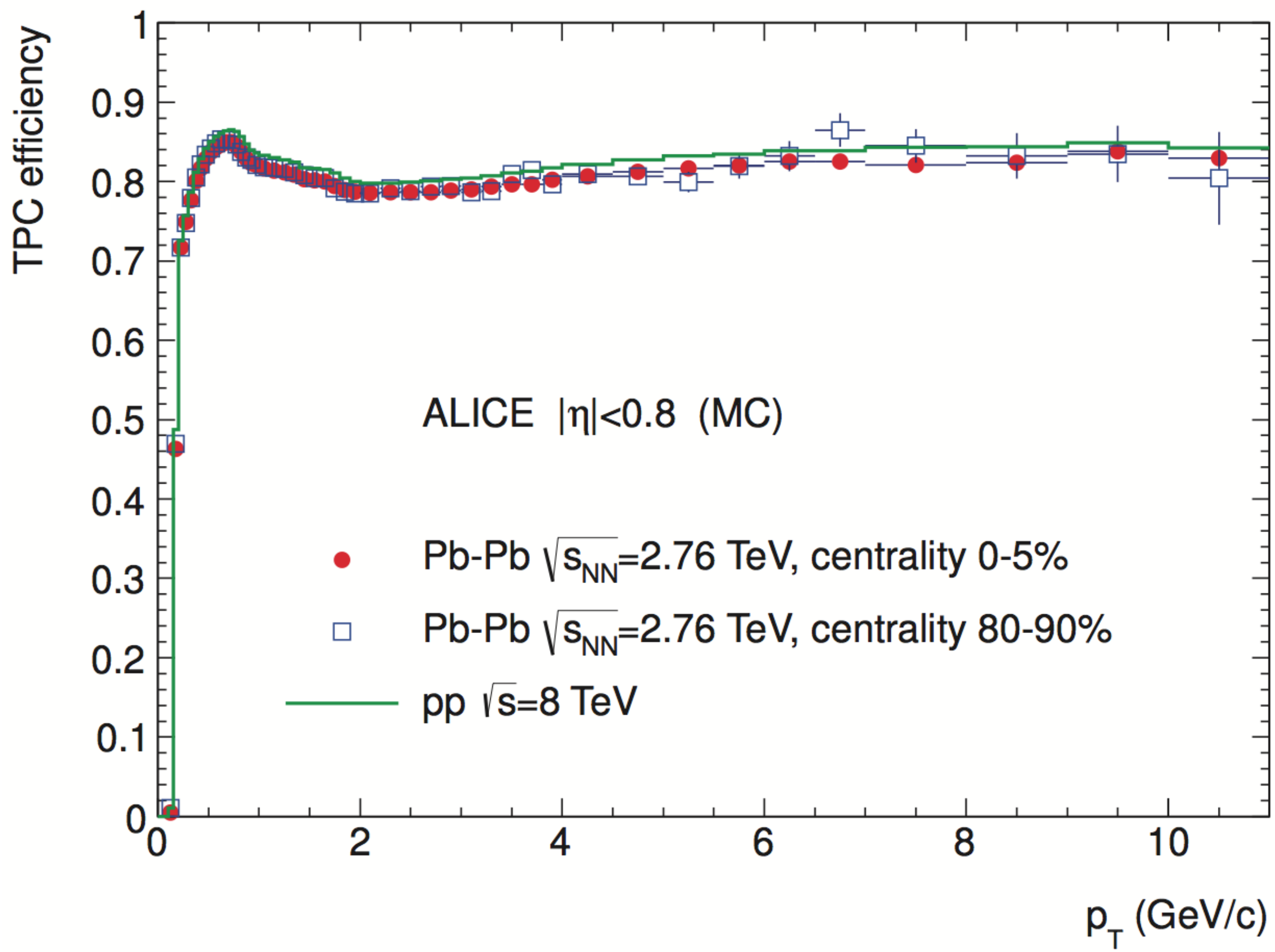


Fig. 19. TPC track finding efficiency for primary particles in pp and Pb–Pb collisions (simulation). The efficiency does not depend on the detector occupancy.

ITS – TPC matching efficiency

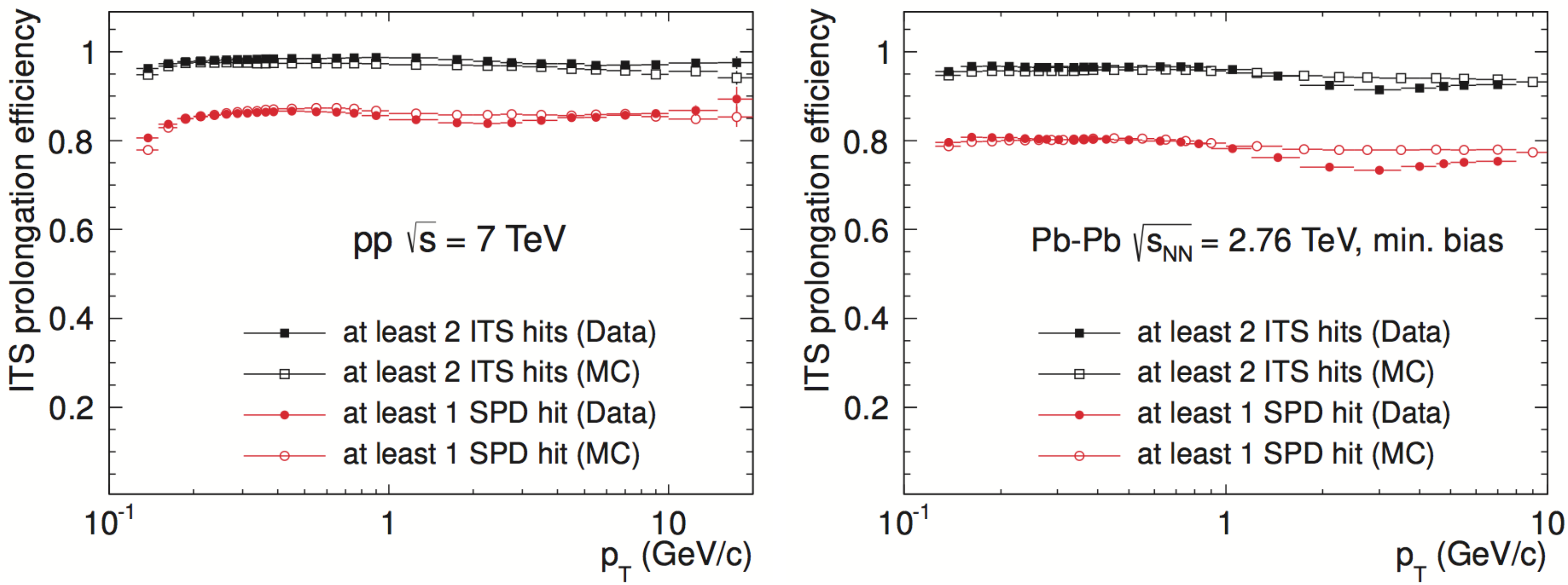
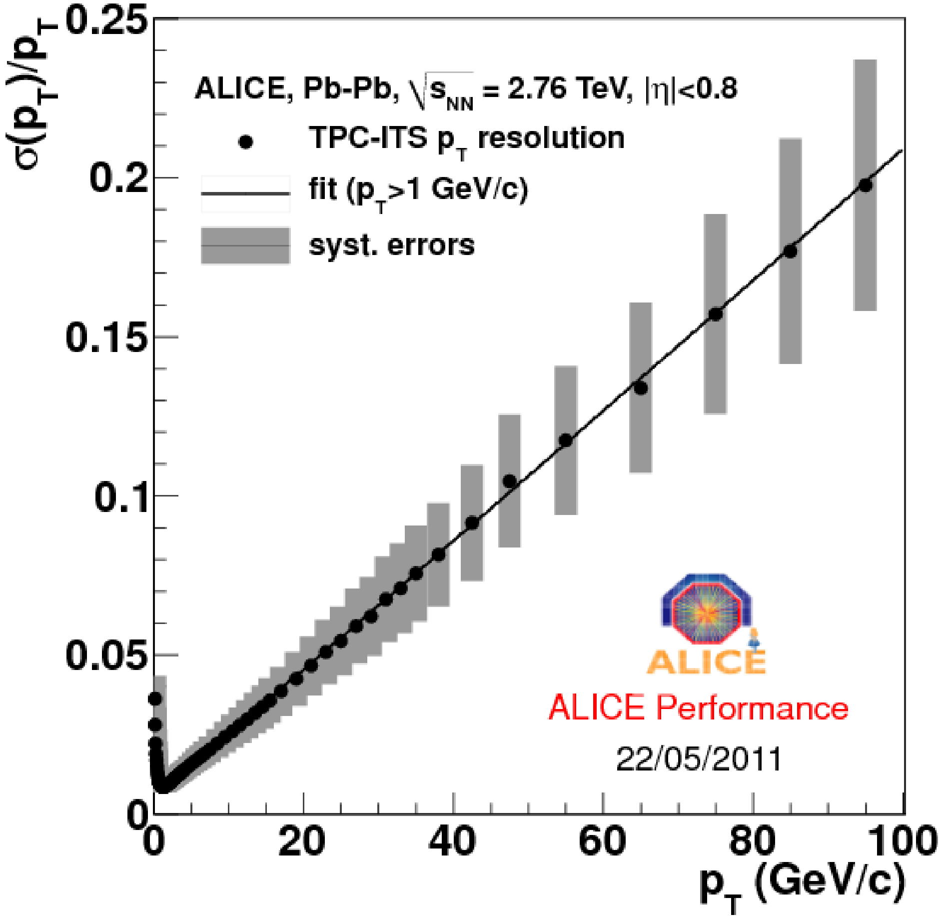


Fig. 20. ITS–TPC matching efficiency versus p_T for data and Monte Carlo for pp (left) and Pb–Pb (right) collisions.

Track Momentum Resolution



Track Momentum Resolution

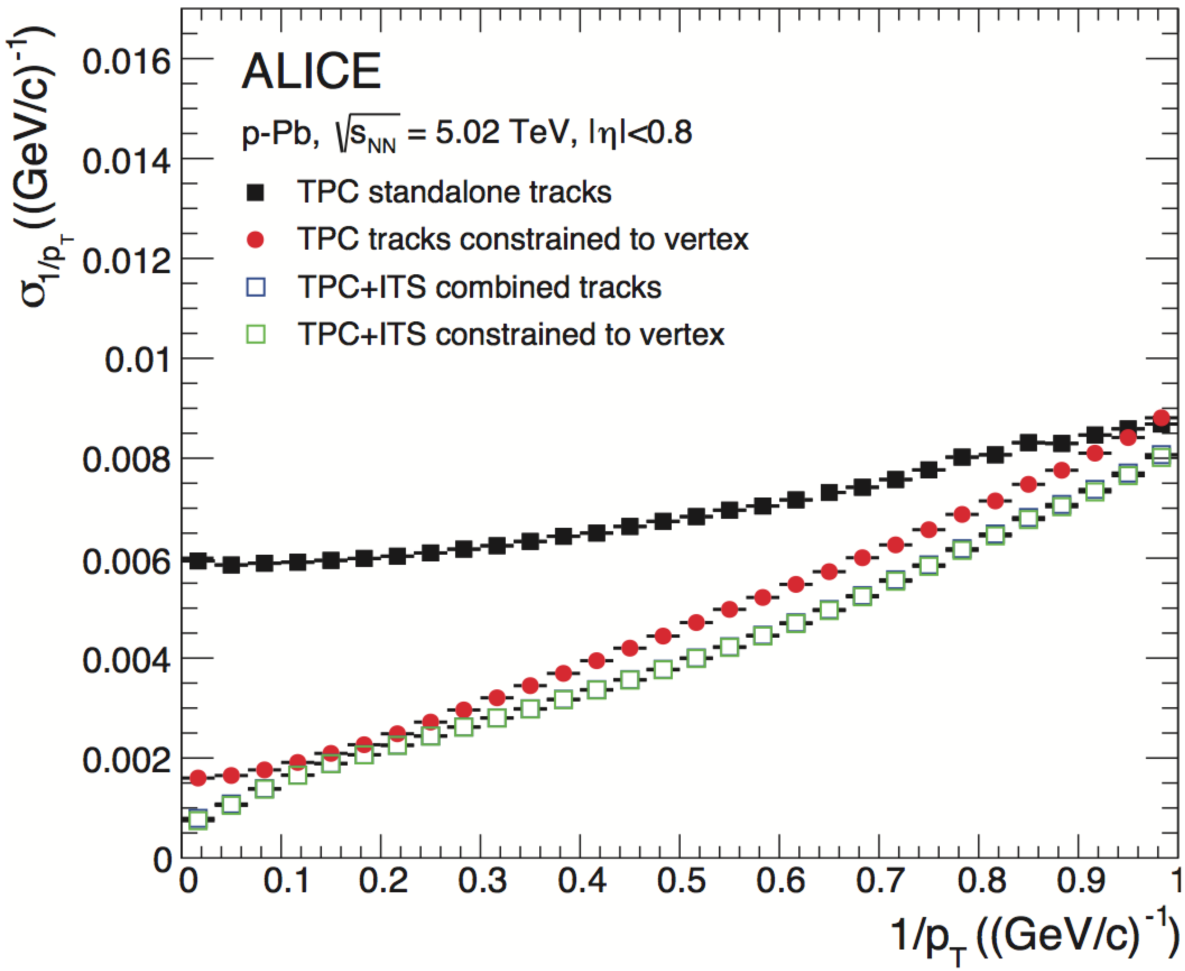


Fig. 23. (Color online) The p_T resolution for standalone TPC and ITS–TPC matched tracks with and without constraint to the vertex. The vertex constrain significantly improves the resolution of TPC standalone tracks. For ITS–TPC tracks, it has no effect (green and blue squares overlap).

Decay reconstruction

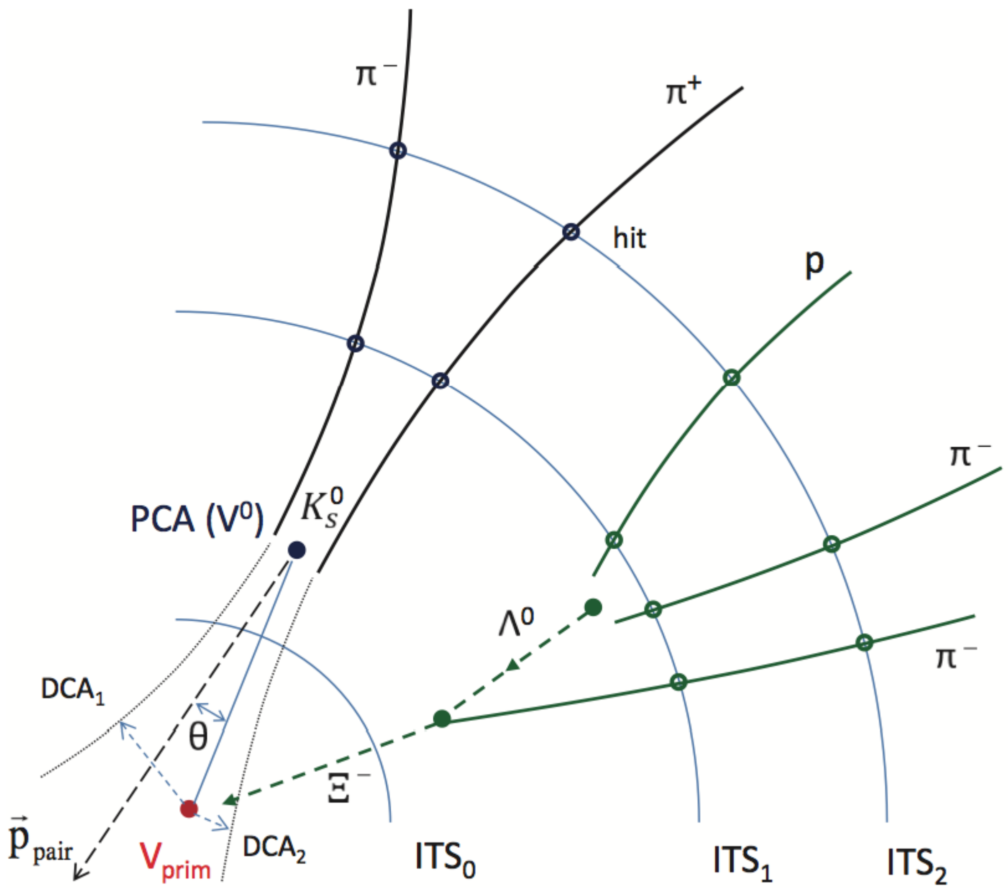
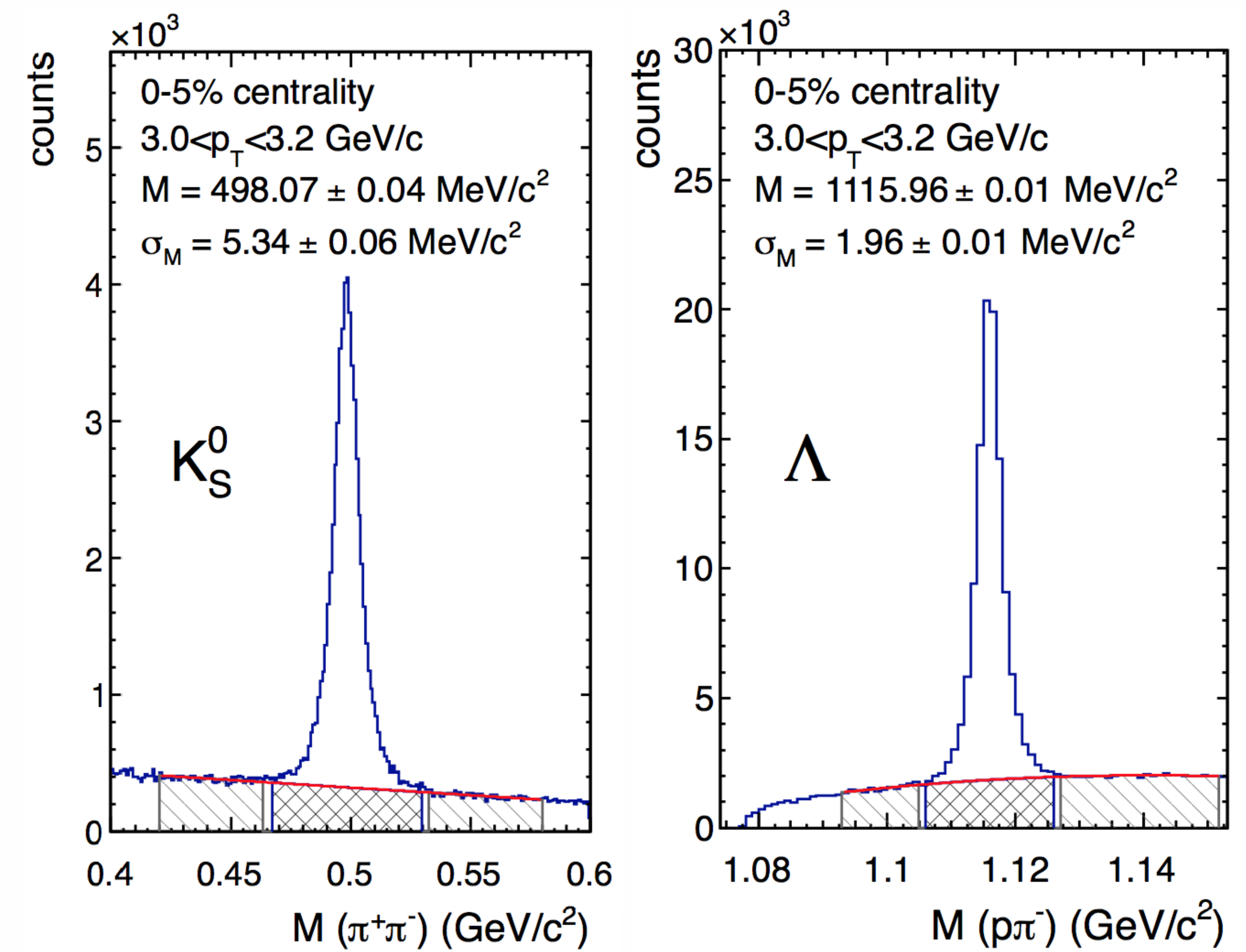


Fig. 28. Secondary vertex reconstruction principle, with K^0_S and Ξ^- decays shown as an example. For clarity, the decay points were placed between the first two ITS layers (radii are not to scale). The solid lines represent the reconstructed charged particle tracks, extrapolated to the secondary vertex candidates. Extrapolations to the primary vertex and auxiliary vectors are shown with dashed lines.

Mass Resolution



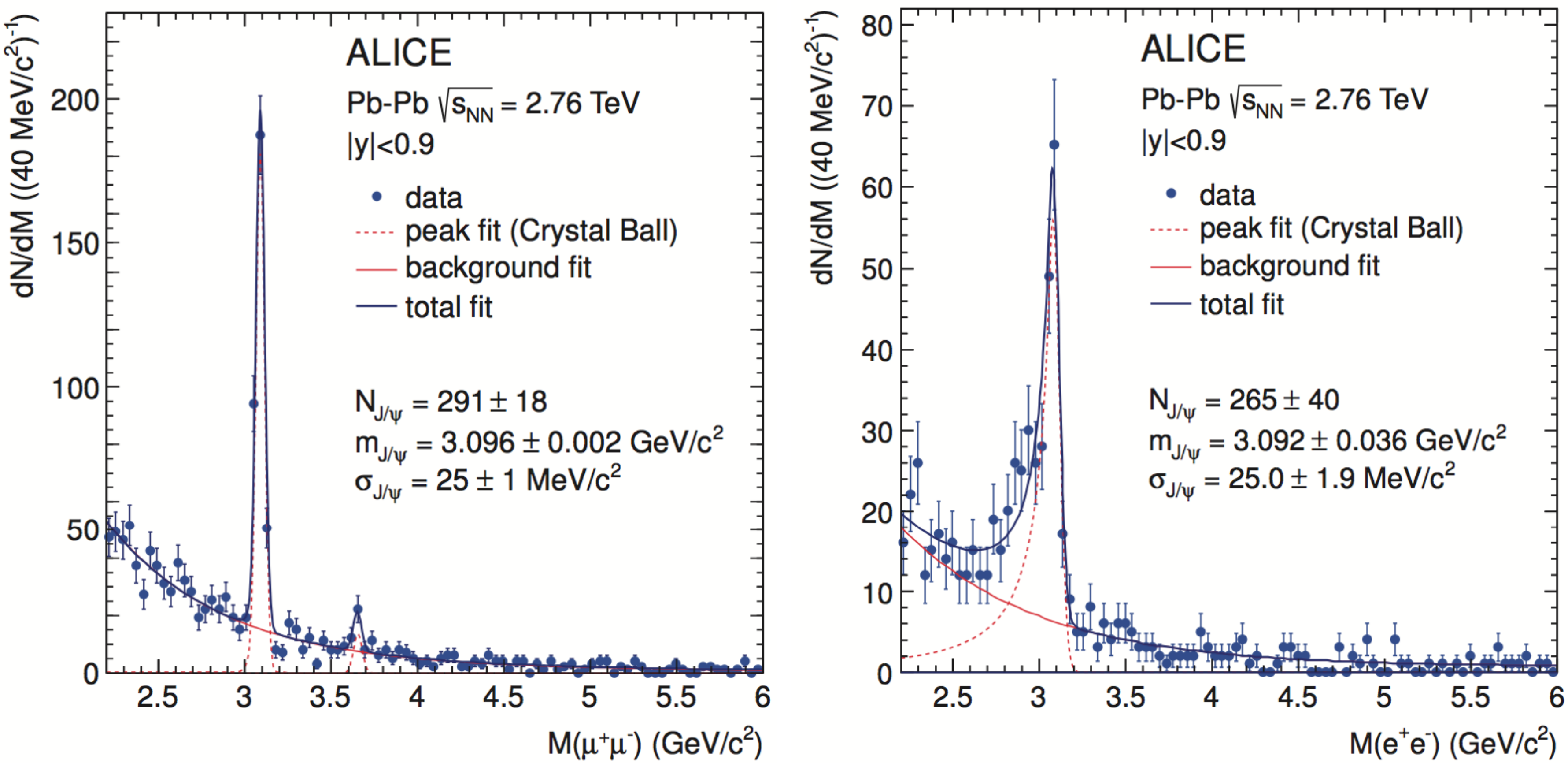


Fig. 24. Invariant mass spectra of $\mu^+\mu^-$ (left) and e^+e^- (right) pairs in ultraperipheral Pb–Pb collisions. The solid and dotted lines represent the background (exponential) and peak (Crystal Ball[50]) fit components, respectively. The bremsstrahlung tail in the e^+e^- spectrum is reproduced in simulation. The mass resolution is better than 1%.

Primary vertex resolution

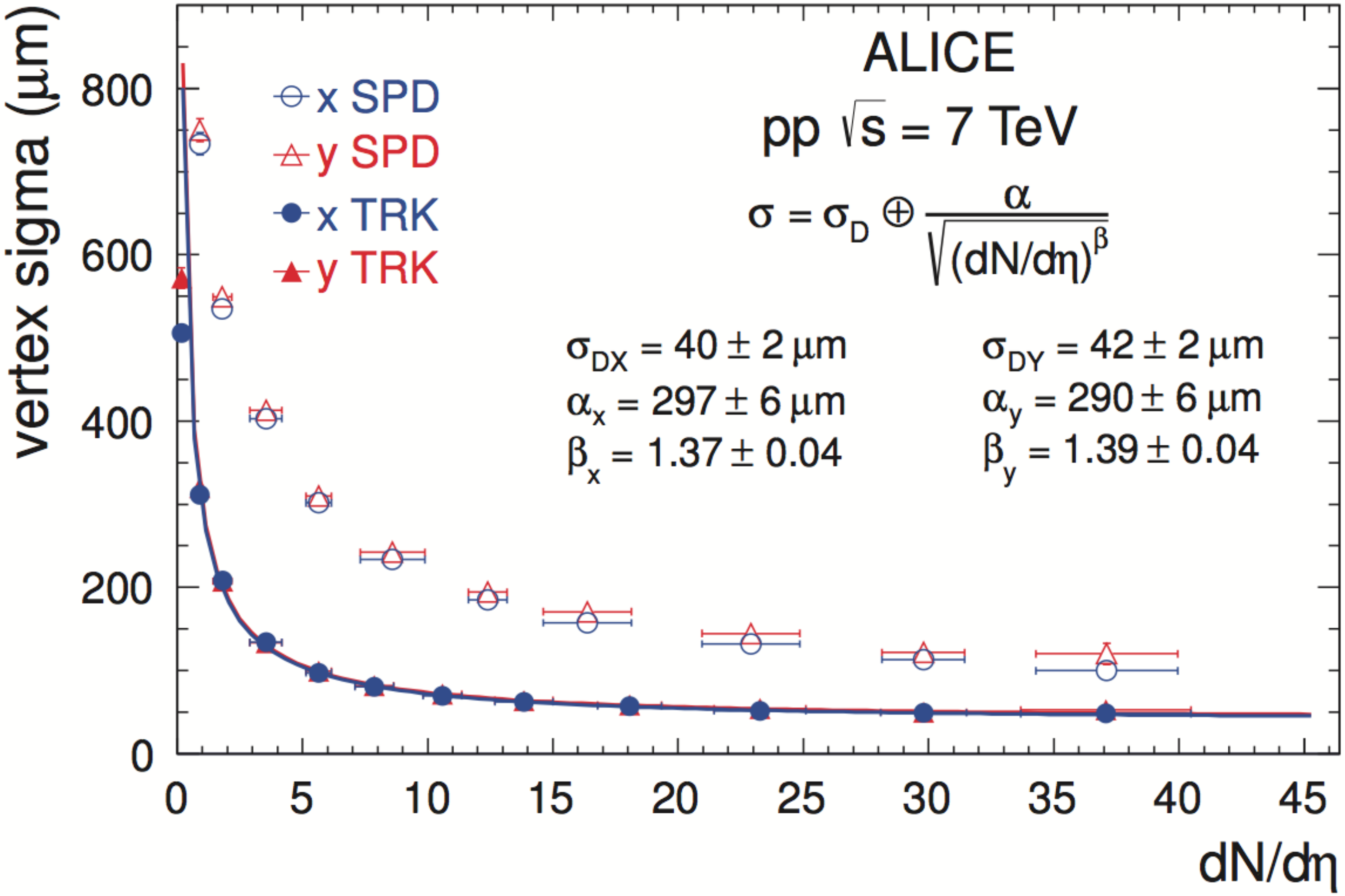


Fig. 27. Transverse width of the final vertex distribution (solid points), decomposed into the finite size of the luminous region σ_D and the vertex resolution $\alpha/\sqrt{(dN_{ch}/d\eta)^{\beta}}$. For comparison, the widths of the preliminary (SPD) interaction vertices are shown as open points.

Decay length

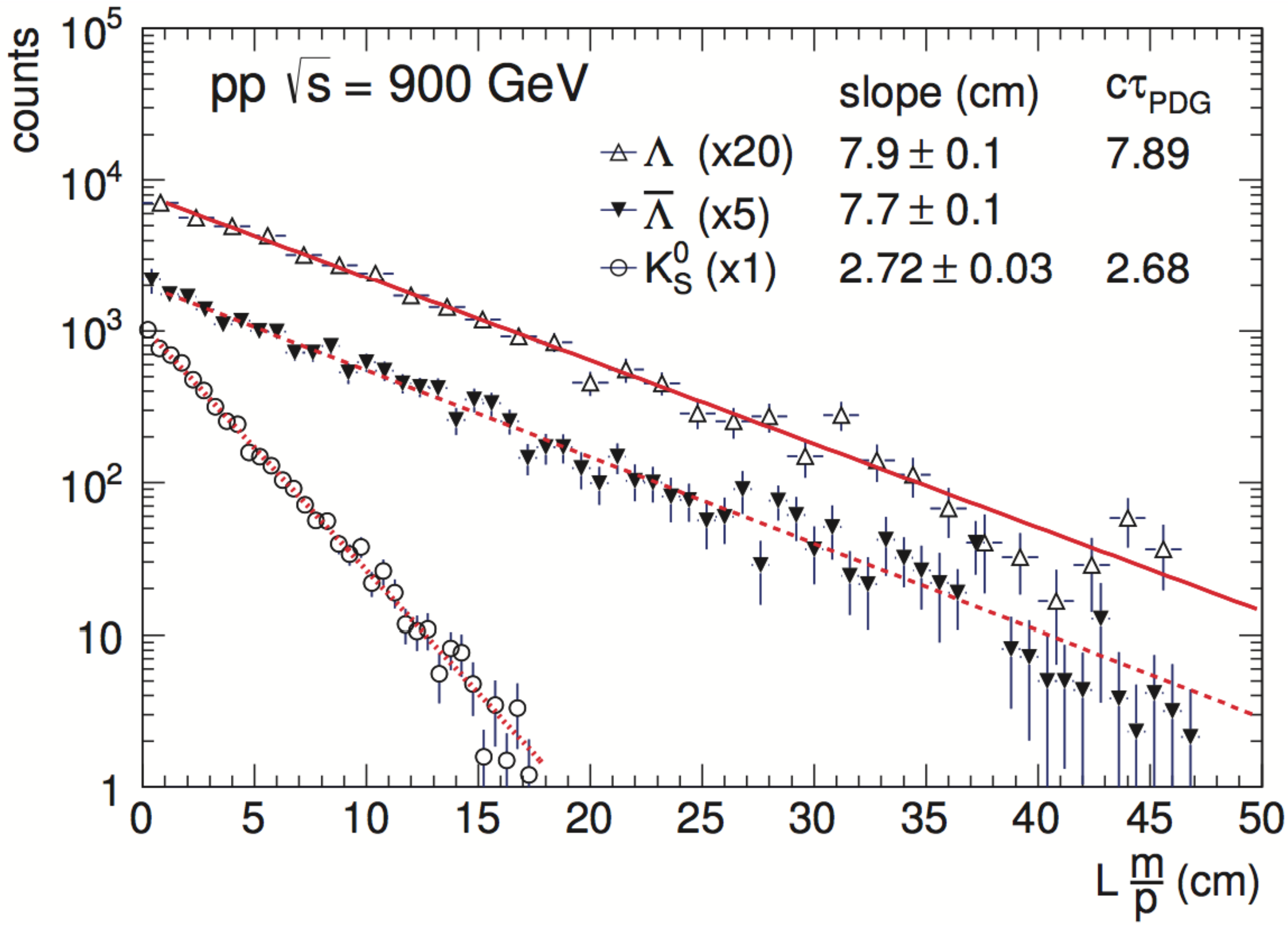
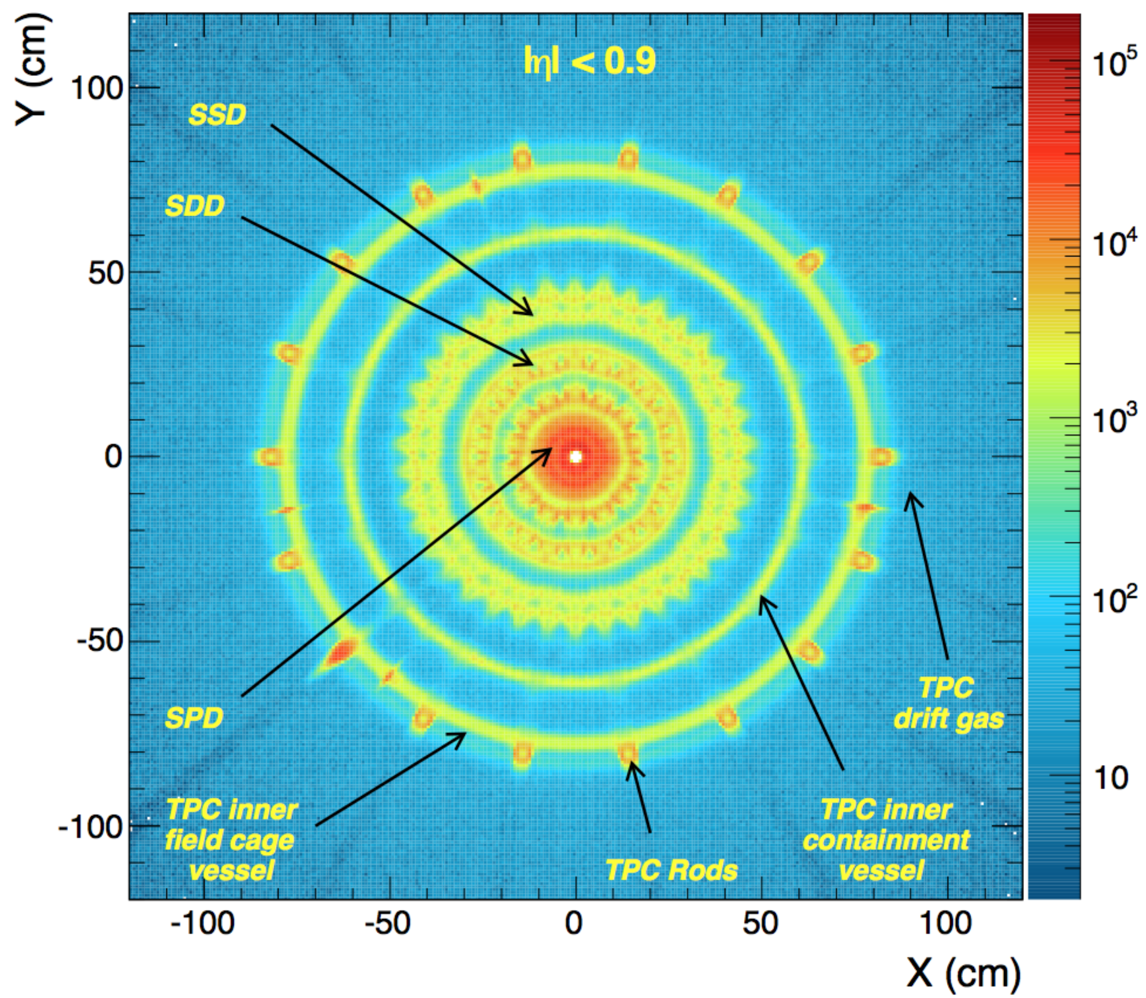


Fig. 30. Distance of the Λ, $\bar{\Lambda}$, and K^0_S decay vertex from the interaction vertex, scaled by p/m. The slopes of the distributions are consistent with the known lifetimes.

ALICE material budget

Via the reconstruction of photon conversion in the detector material



~ 4.5 % accuracy

ALICE material budget

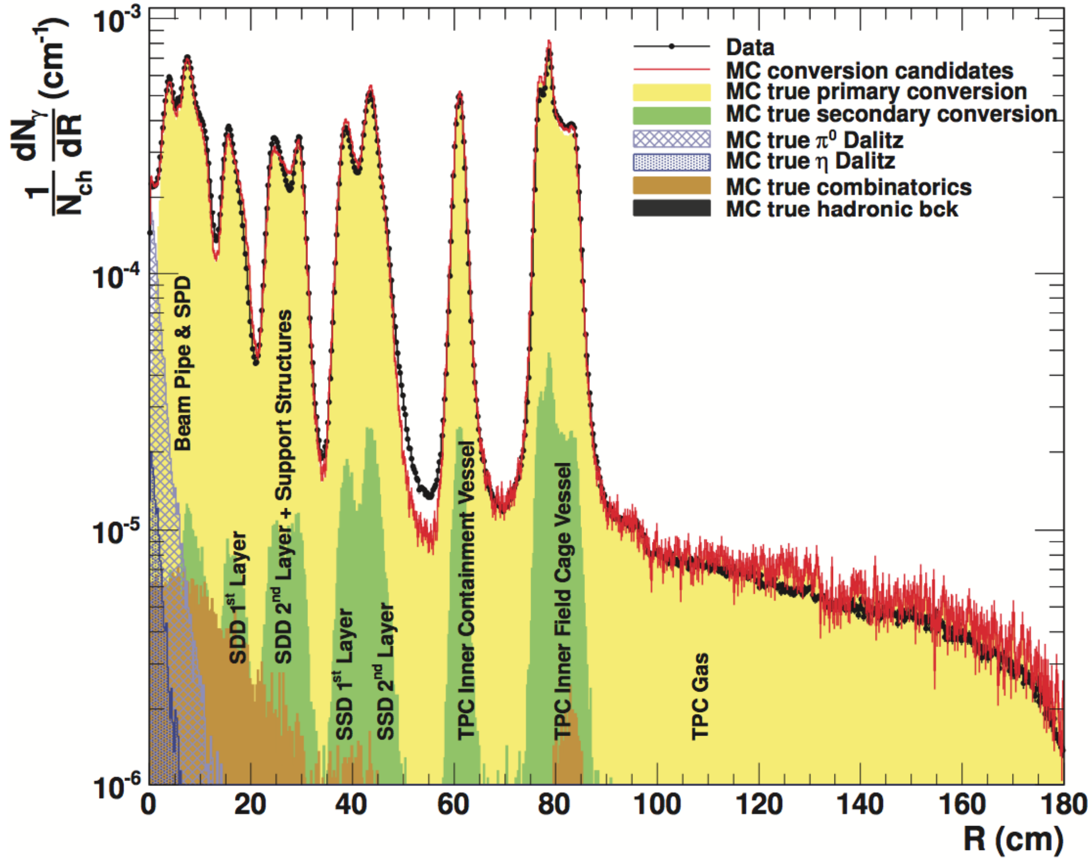
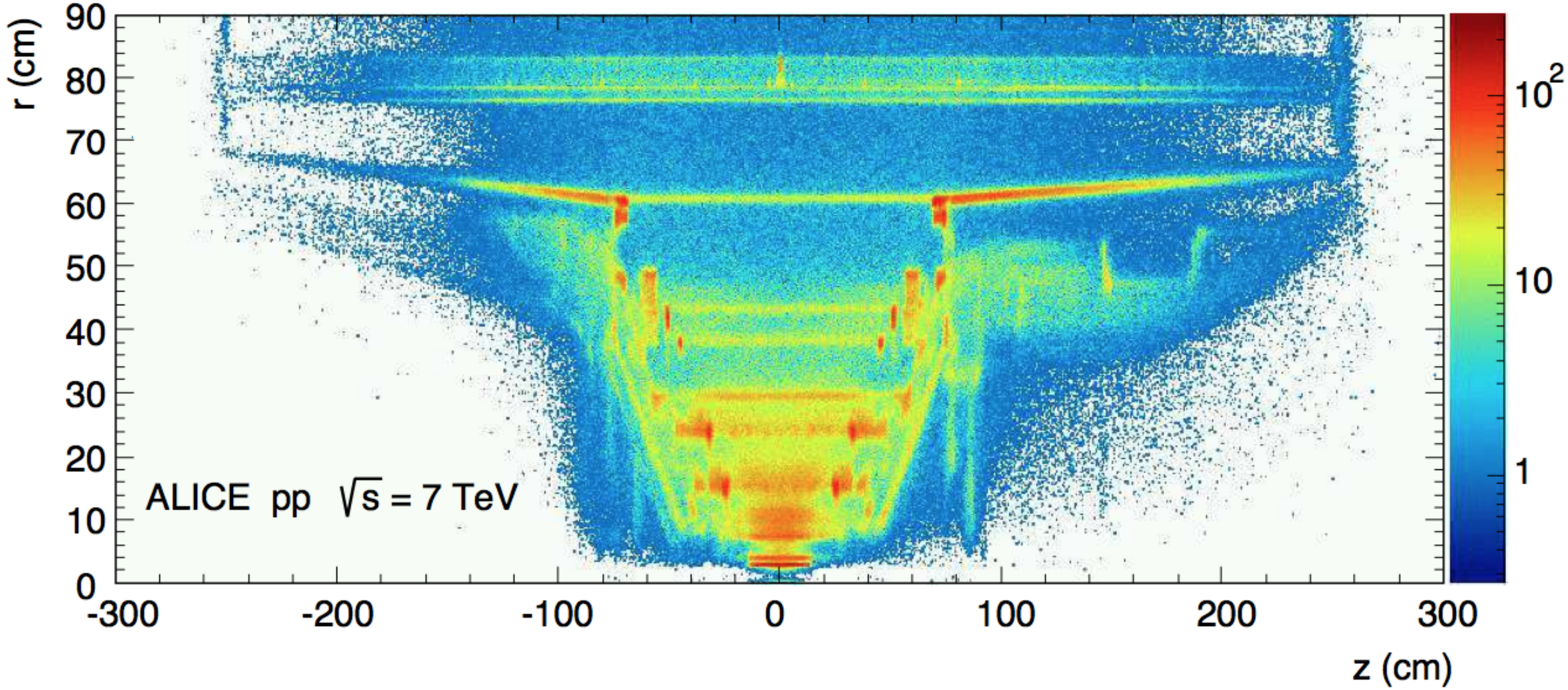


Fig. 67. (Color online) Radial distribution of the reconstructed photon conversion points for $|\eta| < 0.9$ (black) compared to MC simulations performed with PHOJET (red). Distributions for true converted photons are shown in yellow. Physics contamination from true π^0 and η Dalitz decays, where the primary e^+e^- are reconstructed as photon conversions, are shown as dashed blue histograms. Random combinatorics and true hadronic background are also shown.

ALICE material budget

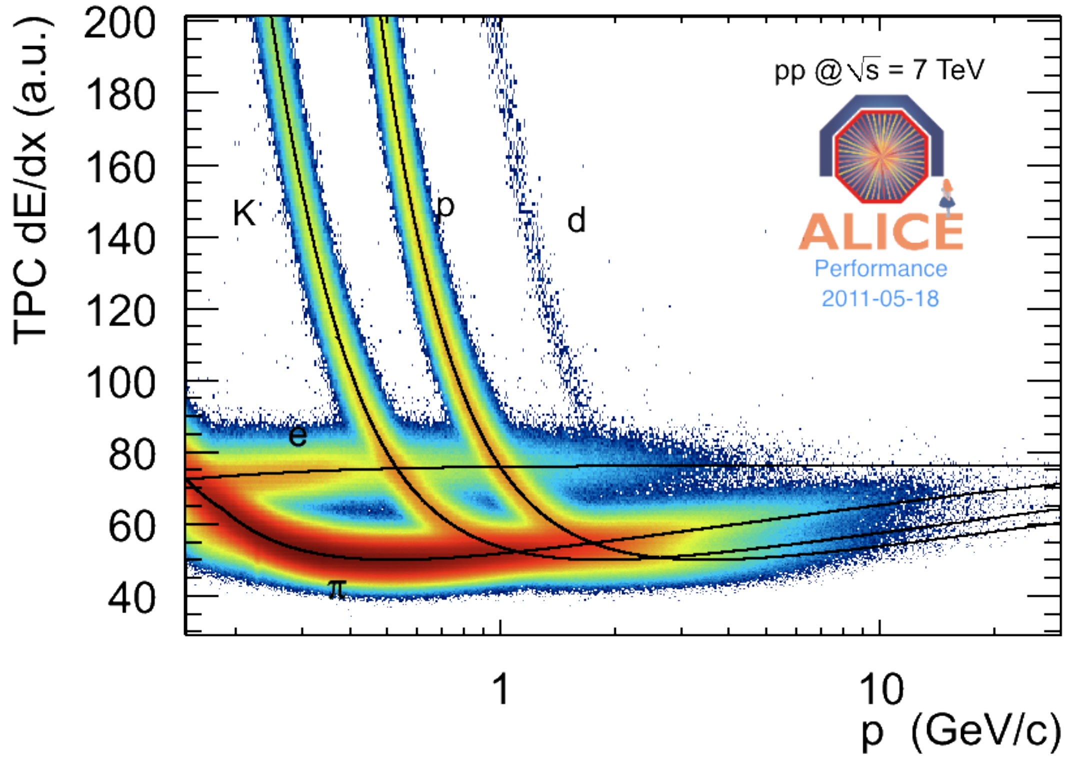
Material is mapped also by hadronic interaction vertices: they are found at the analysis level by identifying groups of two or more tracks originating from a common secondary vertex

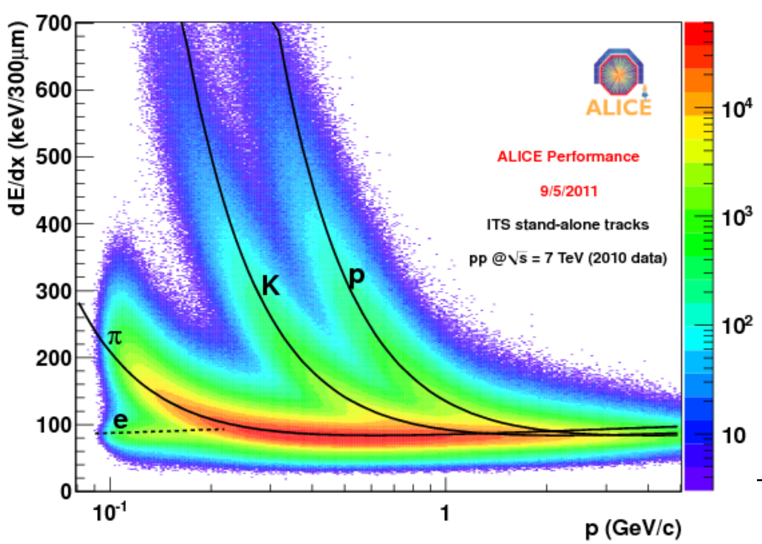


The ITS layers (r < 50 cm), the inner TPC containment vessel (60 cm < r < 70 cm), and the inner TPC field cage ($r \sim$ 80 cm) are visible.

Particle identification

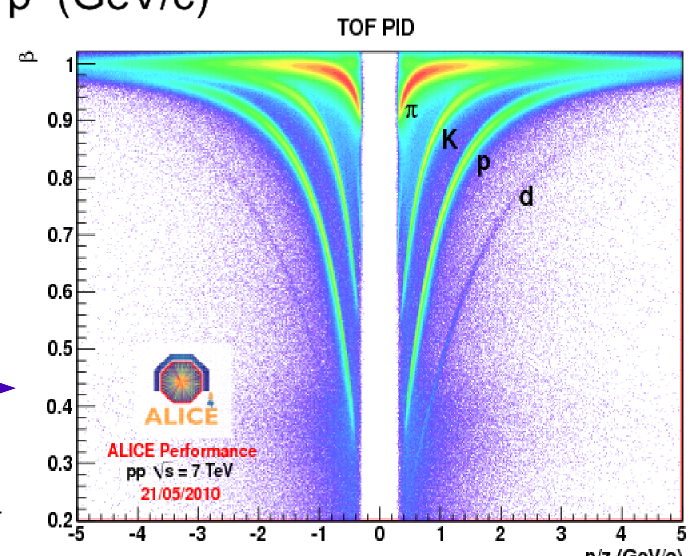
Time Projection Chamber





Inner Tracking System

Time of Flight

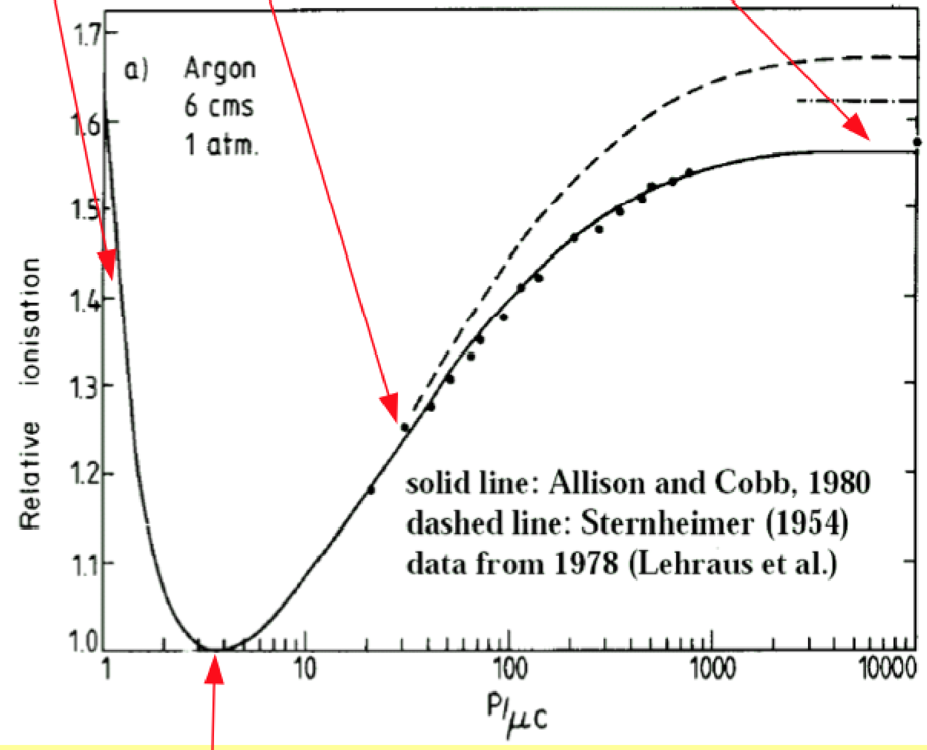


Energy loss: Bethe-Bloch

The Bethe-Bloch-Formula

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A \rho m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{2 m_e c^2 \beta^2 \gamma^2}{I_0} - \beta^2 - \frac{\delta(\beta)}{2} \right]$$

- dE/dx first falls ∝ $1/\beta^2$ (kinematic factor)
- a minimum is reached at $\beta\gamma \approx 4$ (Minimum Ionising Particle - MIP)
- then again rising due to the ln γ^2 term (relativistic rise: contributions of more distant particles due to the relativistic expansion of the transverse E-Field)
- at high γ the relativistic rise is cancelled by the "density effect" (fermi plateau: polarisation of medium screens more distant atoms; described by the δ parameter)



Minimum Ionising Particle (MIP)

ITS dE/dx

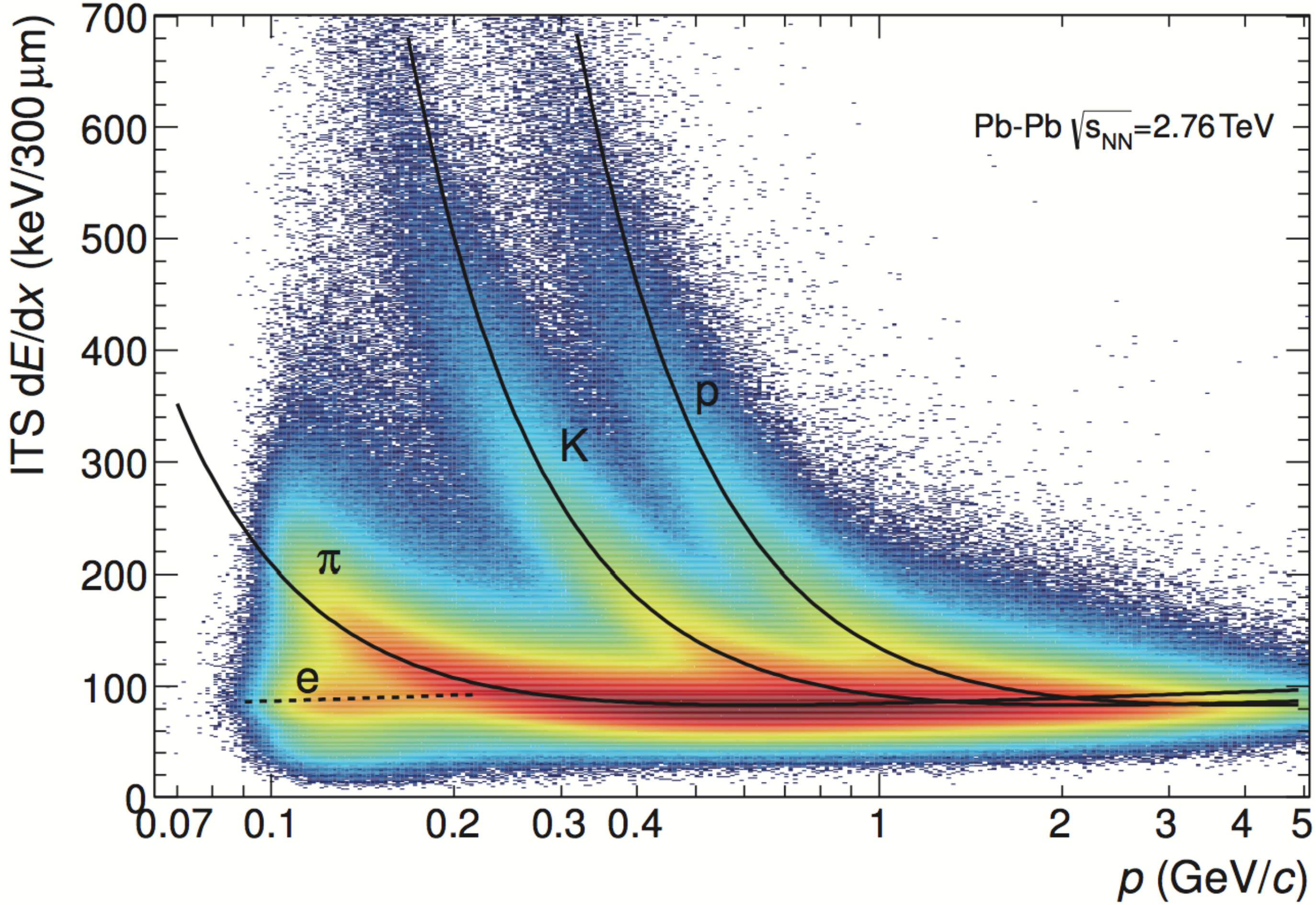


Fig. 33. Distribution of the energy-loss signal in the ITS as a function of momentum. Both the energy loss and momentum were measured by the ITS alone.

TPC dE/dx

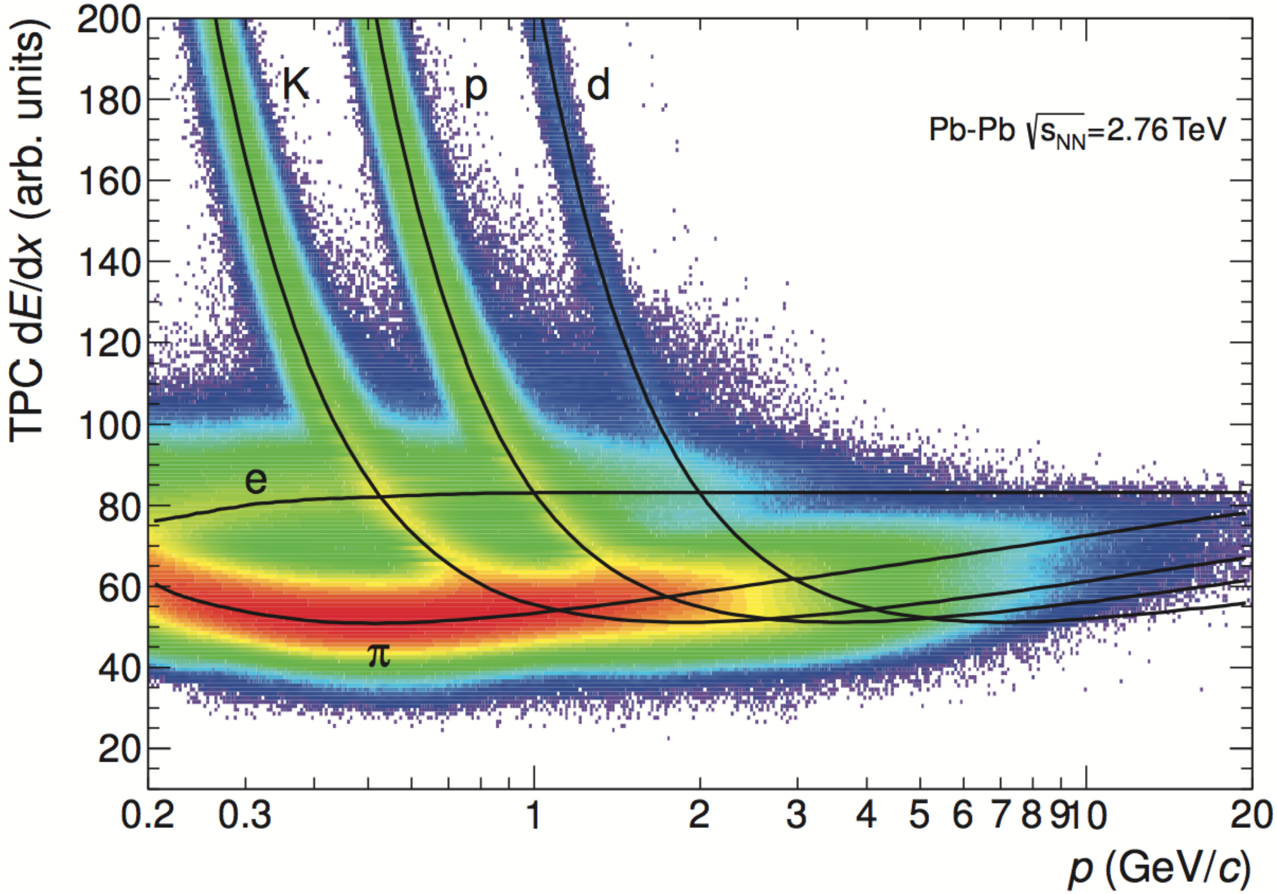
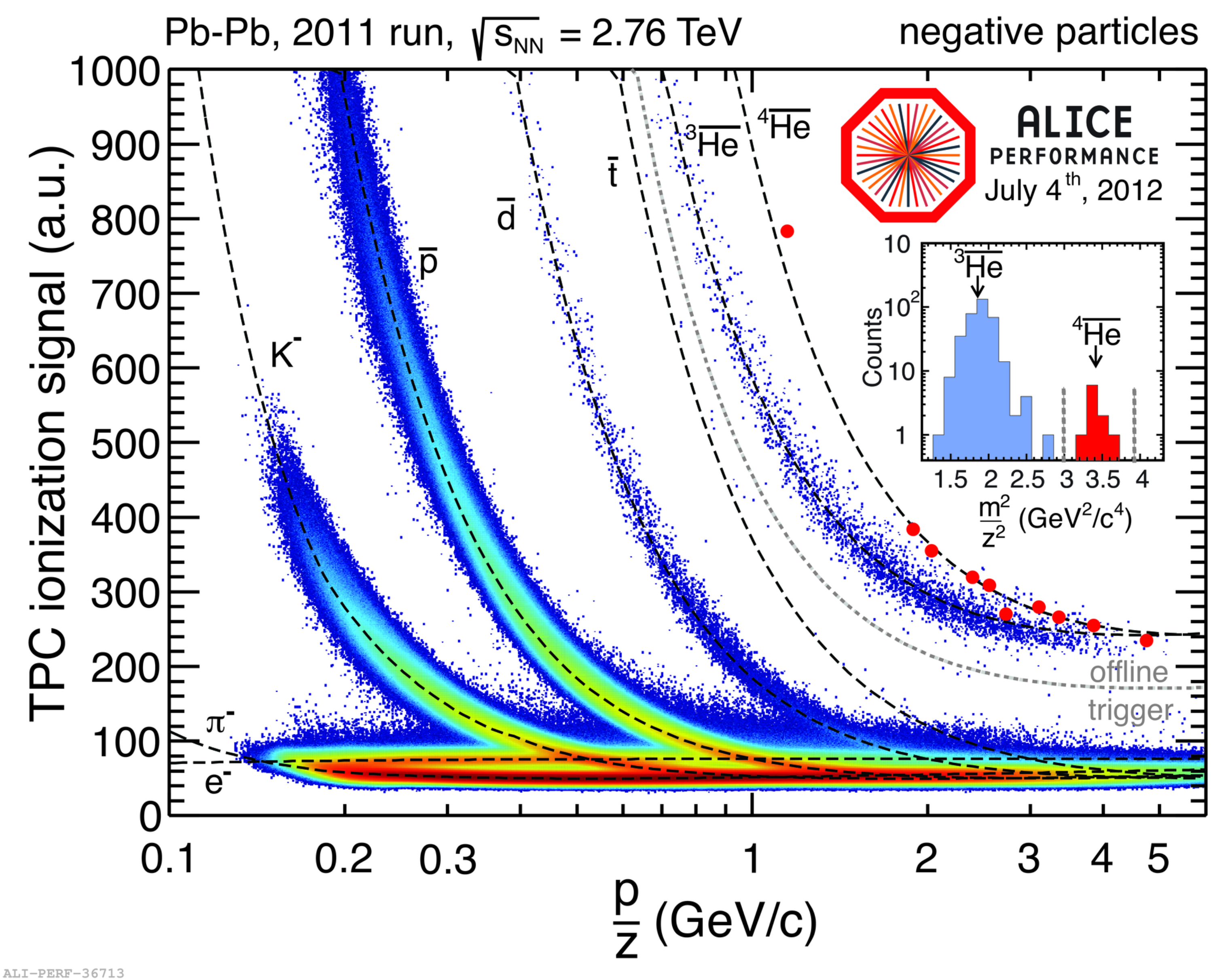
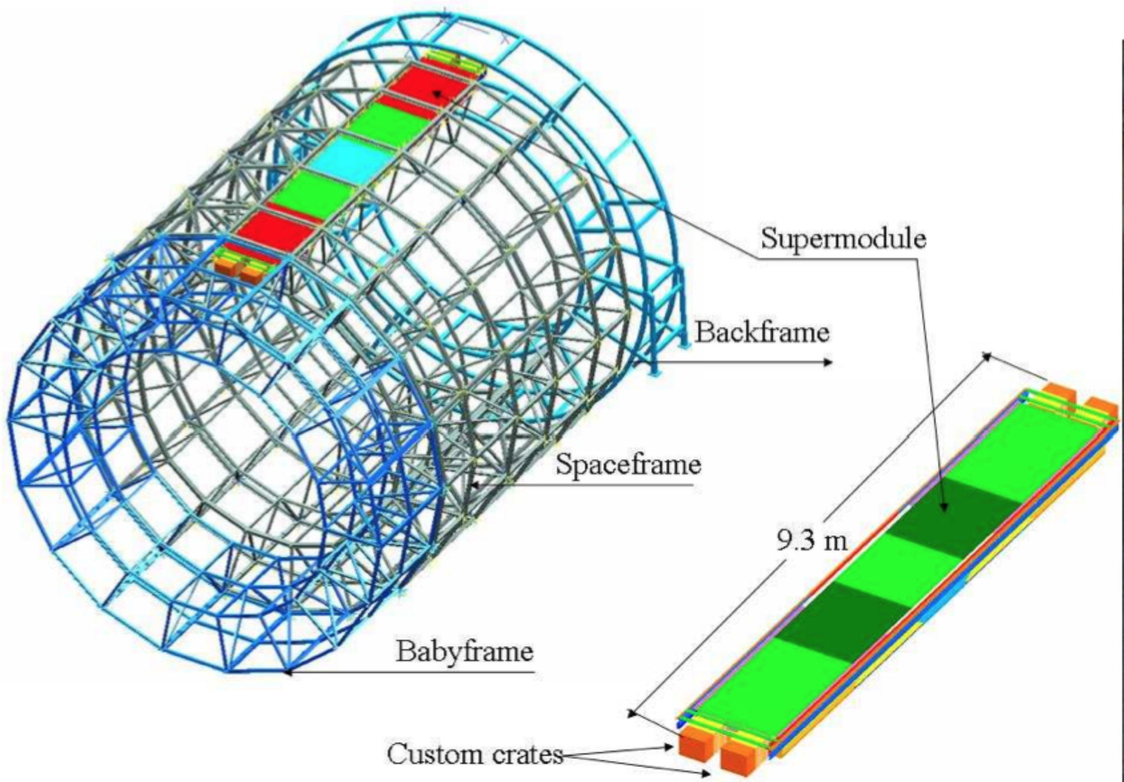


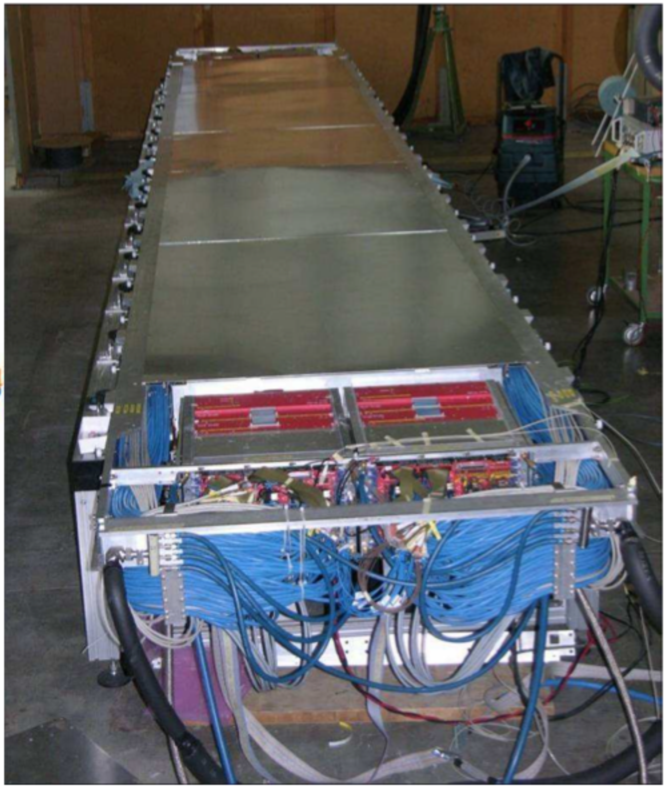
Fig. 34. Specific energy loss (dE/dx) in the TPC versus particle momentum in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The lines show the parametrizations of the expected mean energy loss.

TPC dE/dx


Pb-Pb, 2011 run, $\sqrt{s_{NN}}$ = 2.76 TeV
negative particles
TPC ionization signal (a.u.)
$\frac{p}{z}$ (GeV/c)
π^-
e^-
K^-
$\bar{p}$
$\bar{d}$
$\bar{t}$
$^3\overline{He}$
$^4\overline{He}$
ALICE PERFORMANCE
July 4th, 2012
Counts
$\frac{m^2}{z^2}$ (GeV^2/c^4)
offline
trigger
ALI-PERF-36713

Time Of Flight (TOF) detector





Multi-gap Resistive-Plate Chambers (MRPC)
Intrinsic time resolution better than 40 nsec

TOF matching efficiency

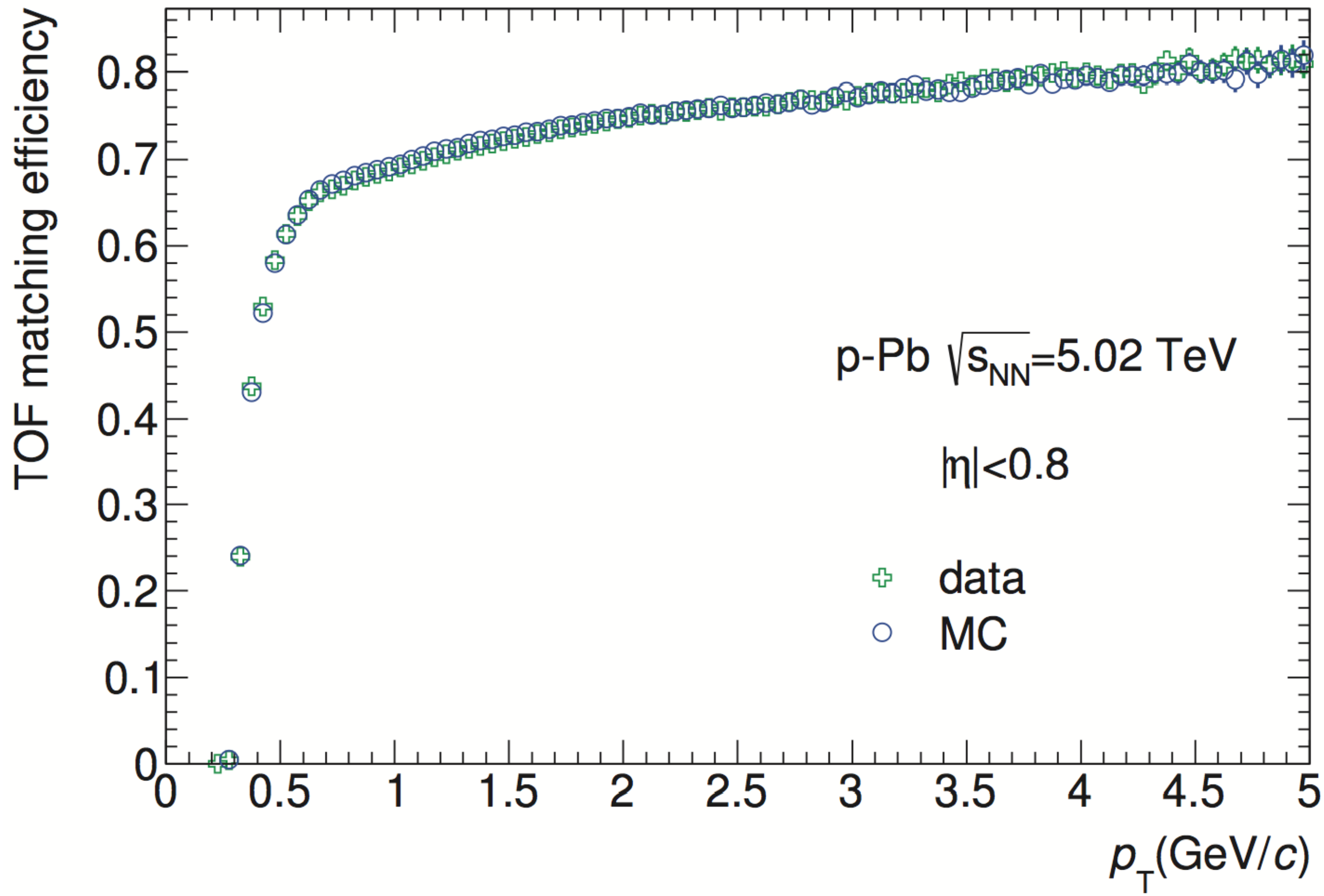
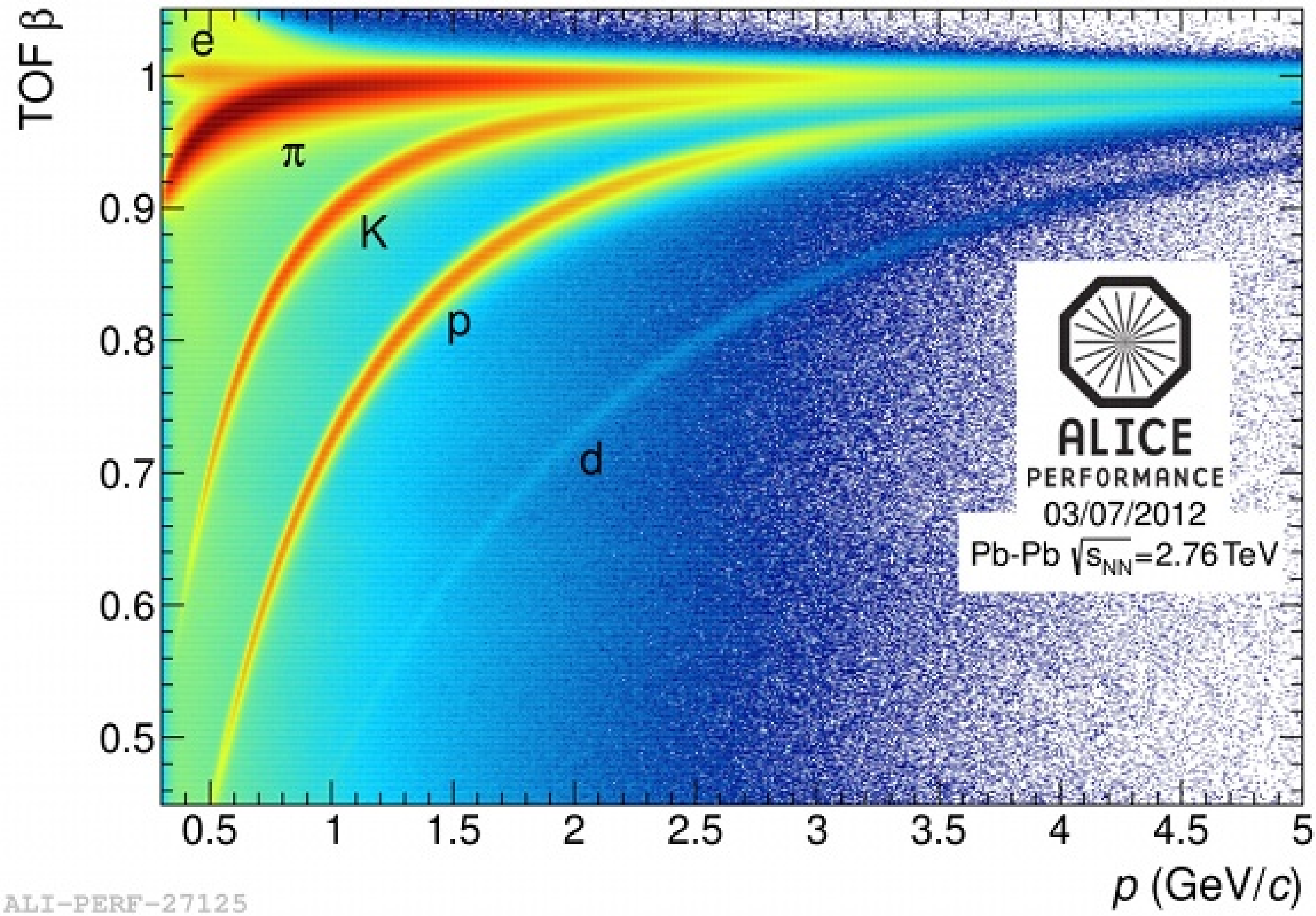
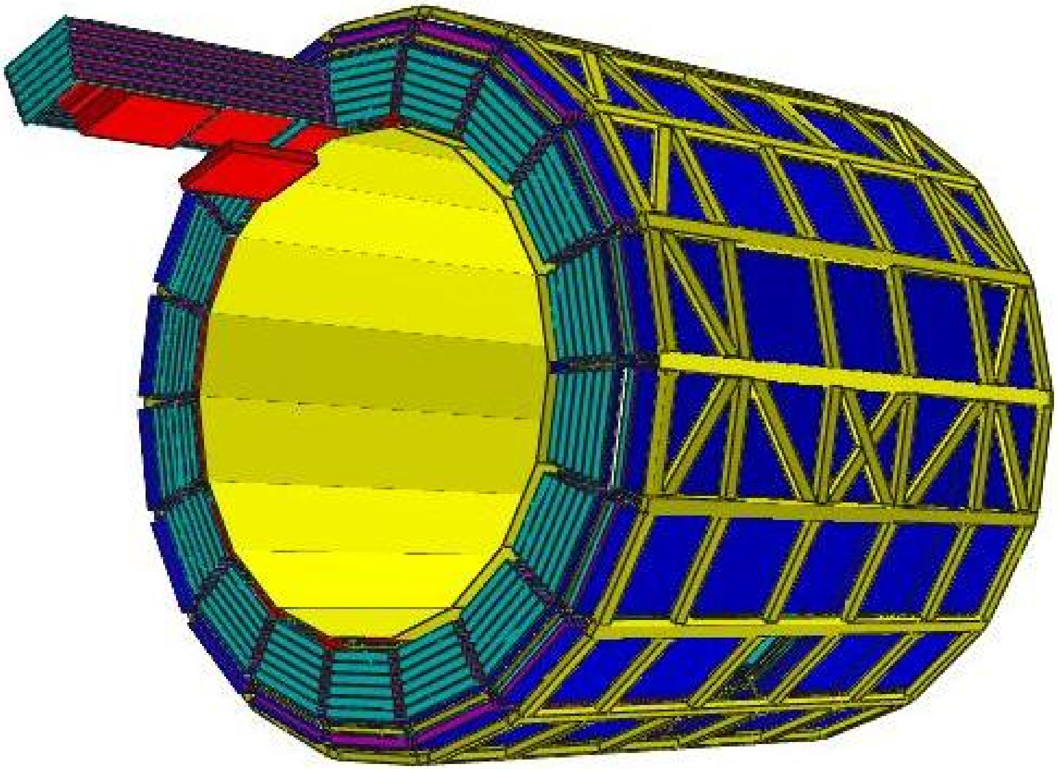


Fig. 37. Matching efficiency (including the geometric acceptance factor) at TOF for tracks reconstructed in the TPC in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared to Monte Carlo simulation.

Time Of Flight (TOF) detector



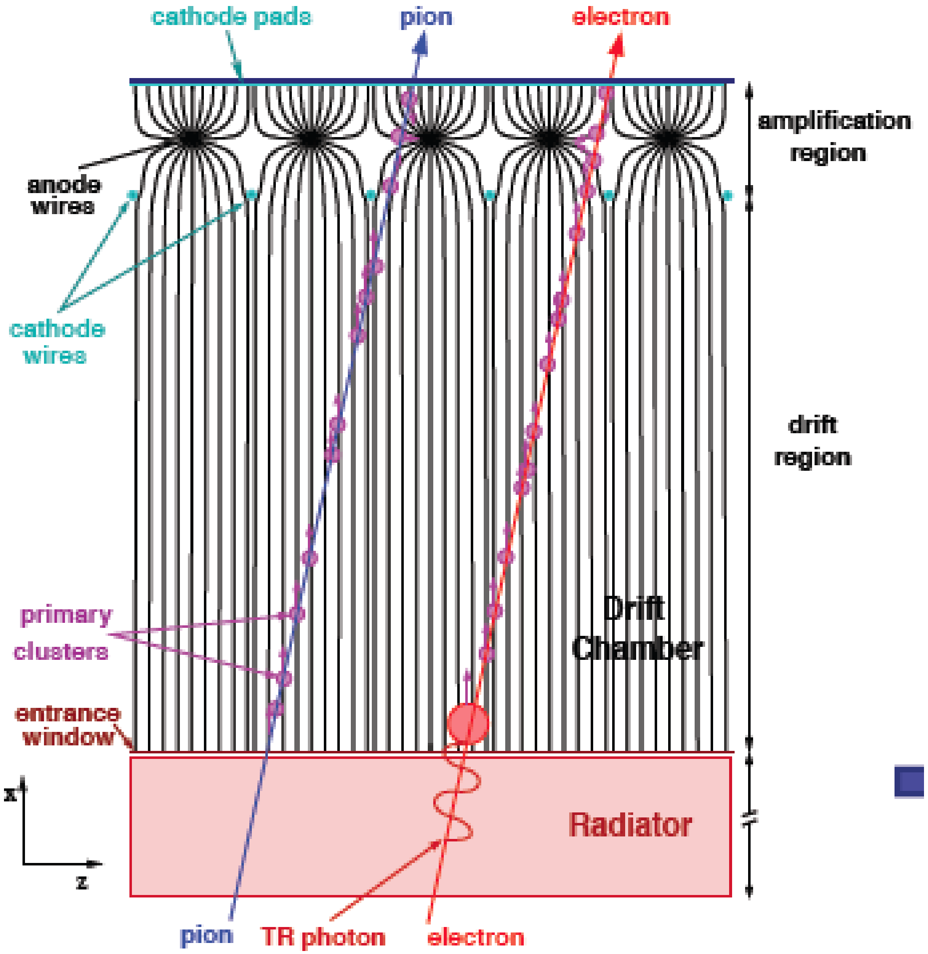
Transition Radiation Detector



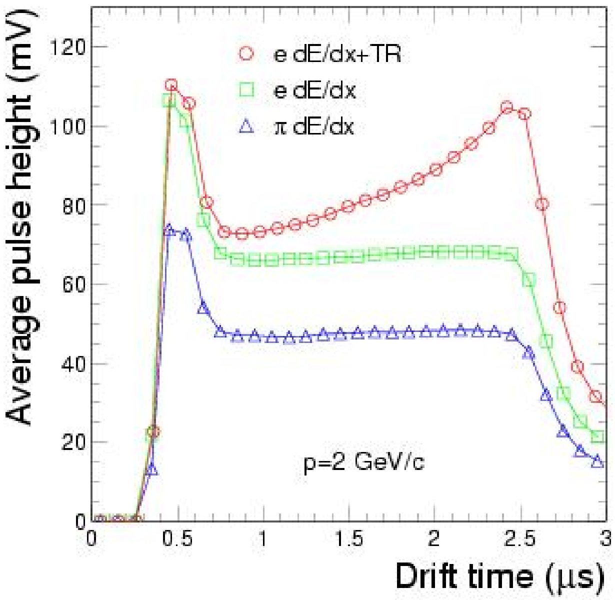
- For electron/pion separation
- For trigger on electrons at medium/high p_T

TRD in Numbers	
Supermodules	18
Stacks	5
Layers	6
Readout pads	1.2x106

Transition Radiation Detector



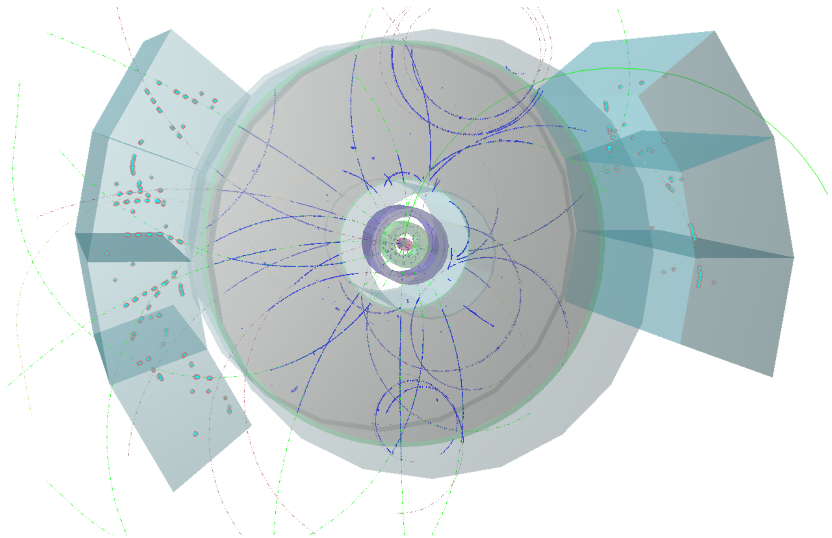
- For electron/pion separation
- For trigger on electrons at medium/high p_T

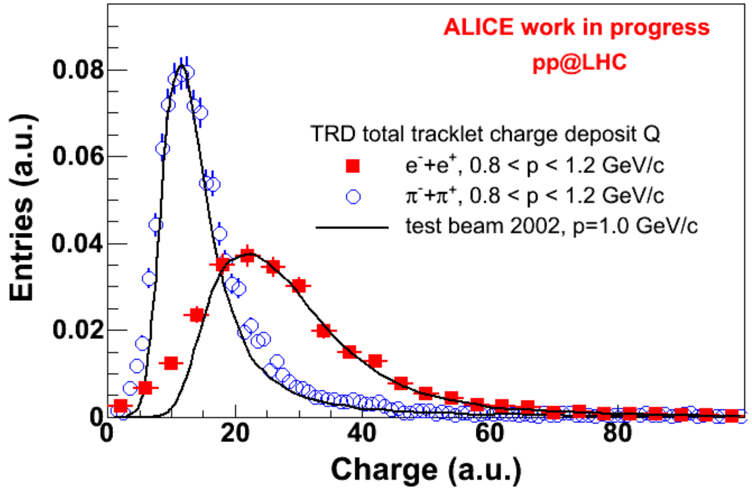


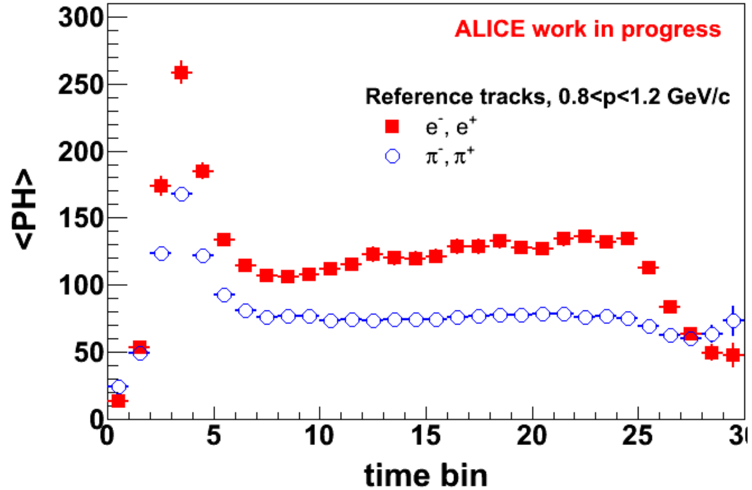
Identified Electrons

Transition Radiation Detector

- **Electron/pion discrimination**
- **Electron trigger (high pT, particle ID)**







From an inclusive electron spectrum (cocktail subtracted) we will measure the charm and beauty production cross sections

Transition Radiation Detector

Transition Radiation Detector

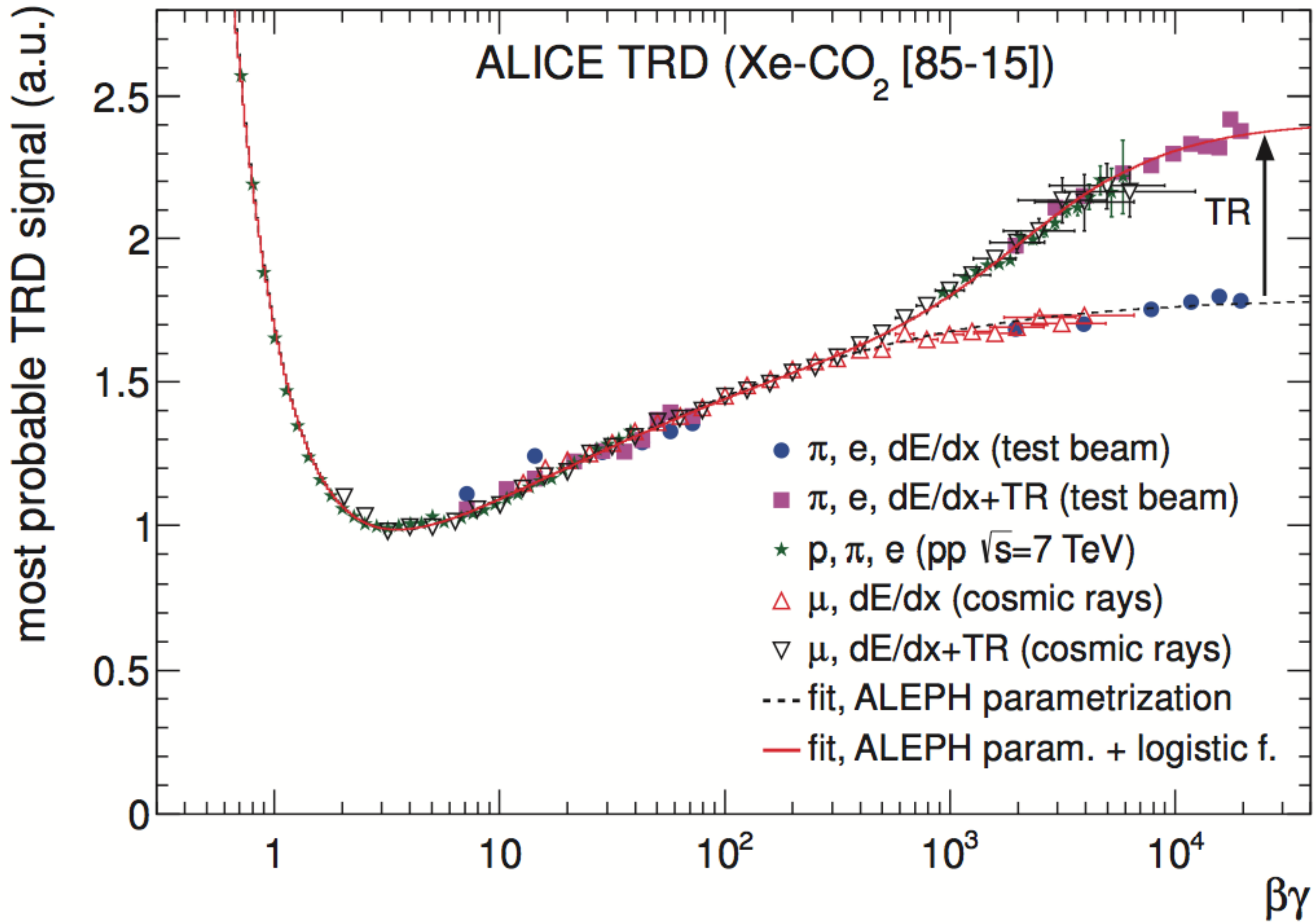


Fig. 56. The most probable TRD signal as a function of $\beta\gamma$. Measurements performed in test beam runs, pp collisions at $\sqrt{s} = 7$ TeV, and cosmic rays are compared.

Combined PID

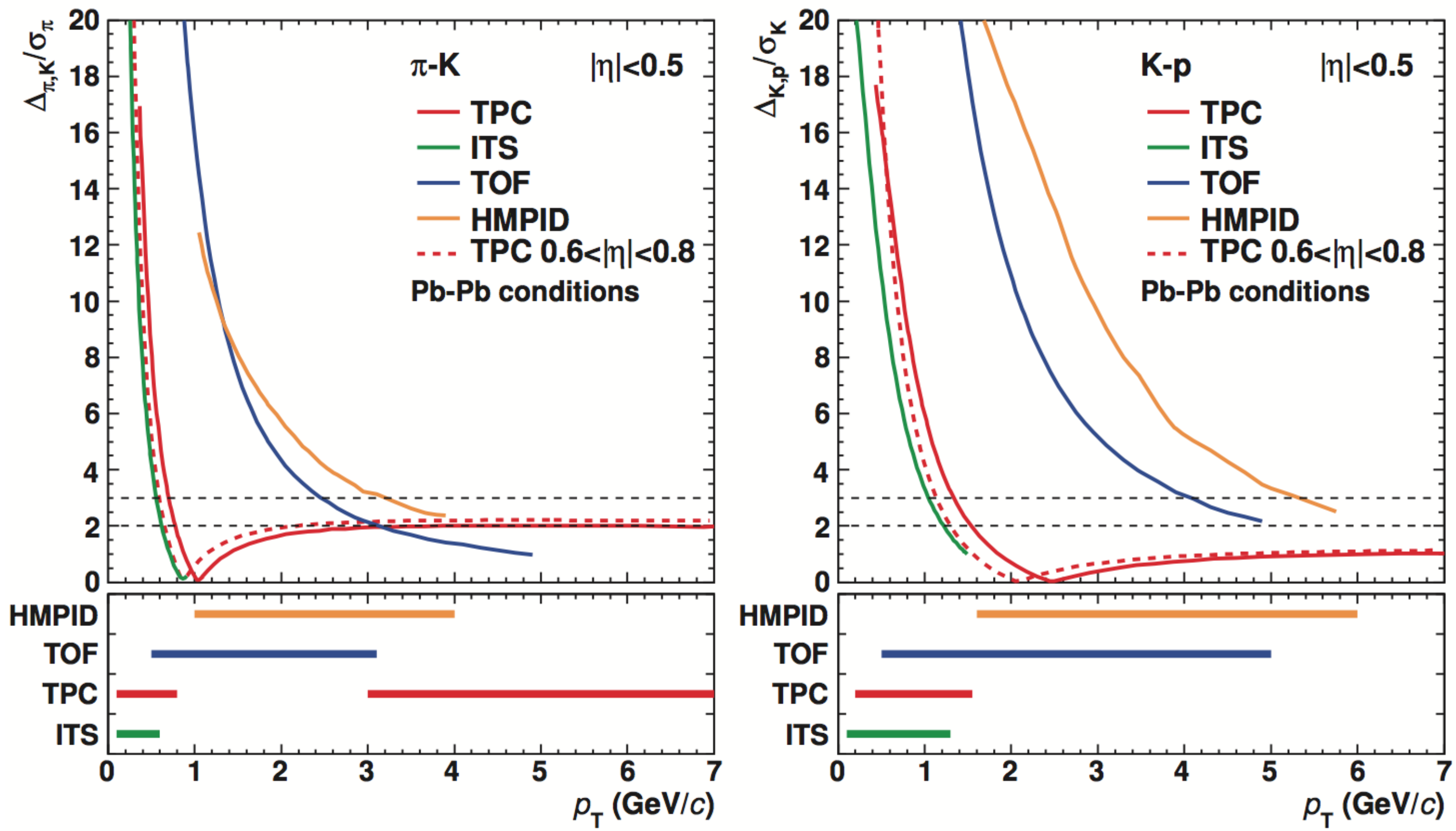


Fig. 46. Separation power of hadron identification in the ITS, TPC, TOF, and HMPID as a function of p_T at midrapidity. The left (right) panel shows the separation of pions and kaons (kaons and protons), expressed as the distance between the peaks divided by the resolution for the pion and the kaon, respectively, averaged over $|\eta| < 0.5$. For the TPC, an additional curve is shown in a narrower η region. The lower panels show the range over which the different ALICE detector systems have a separation power of more than 2σ.

Di-muon mass distribution (2.4<y<4.0)

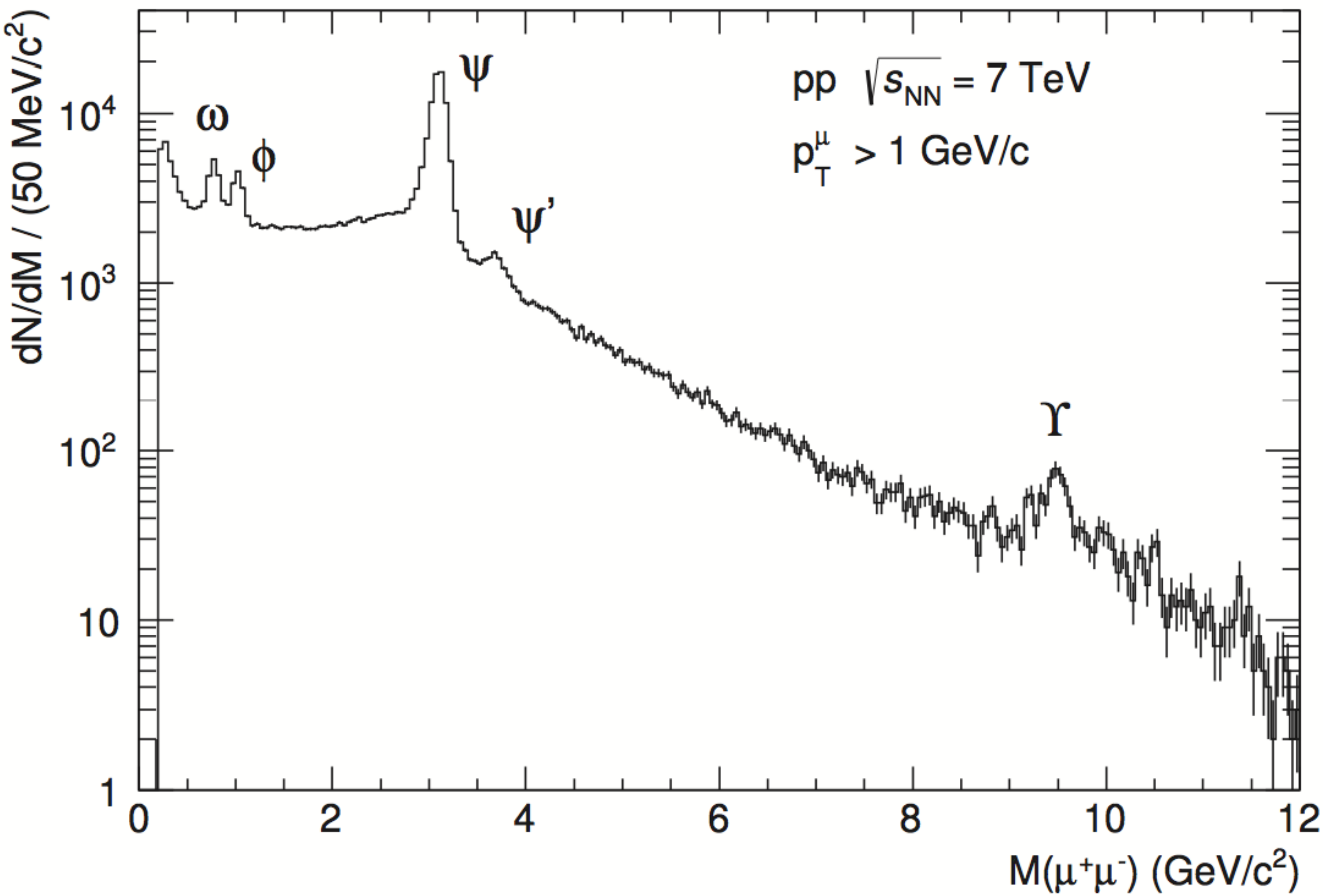
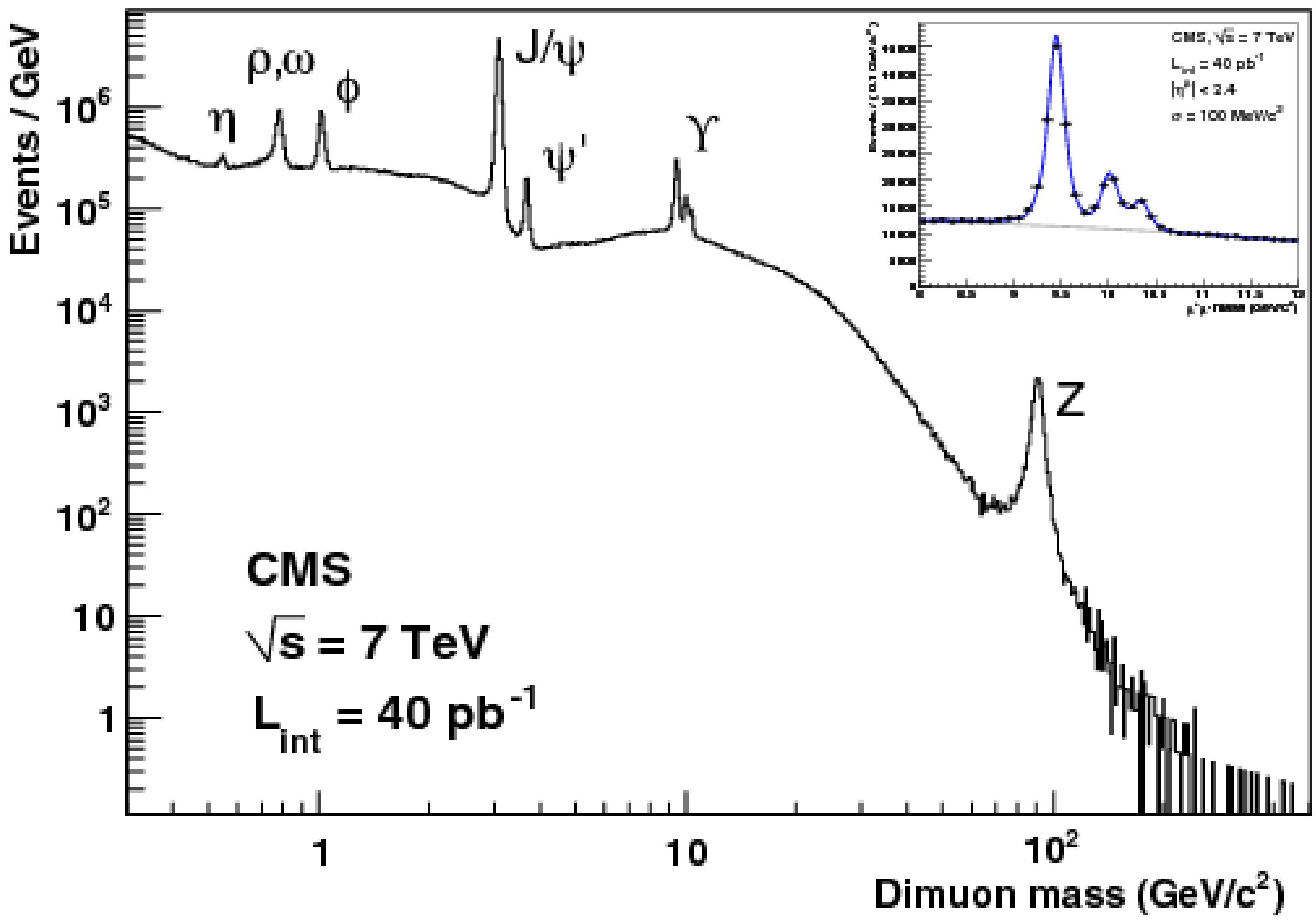
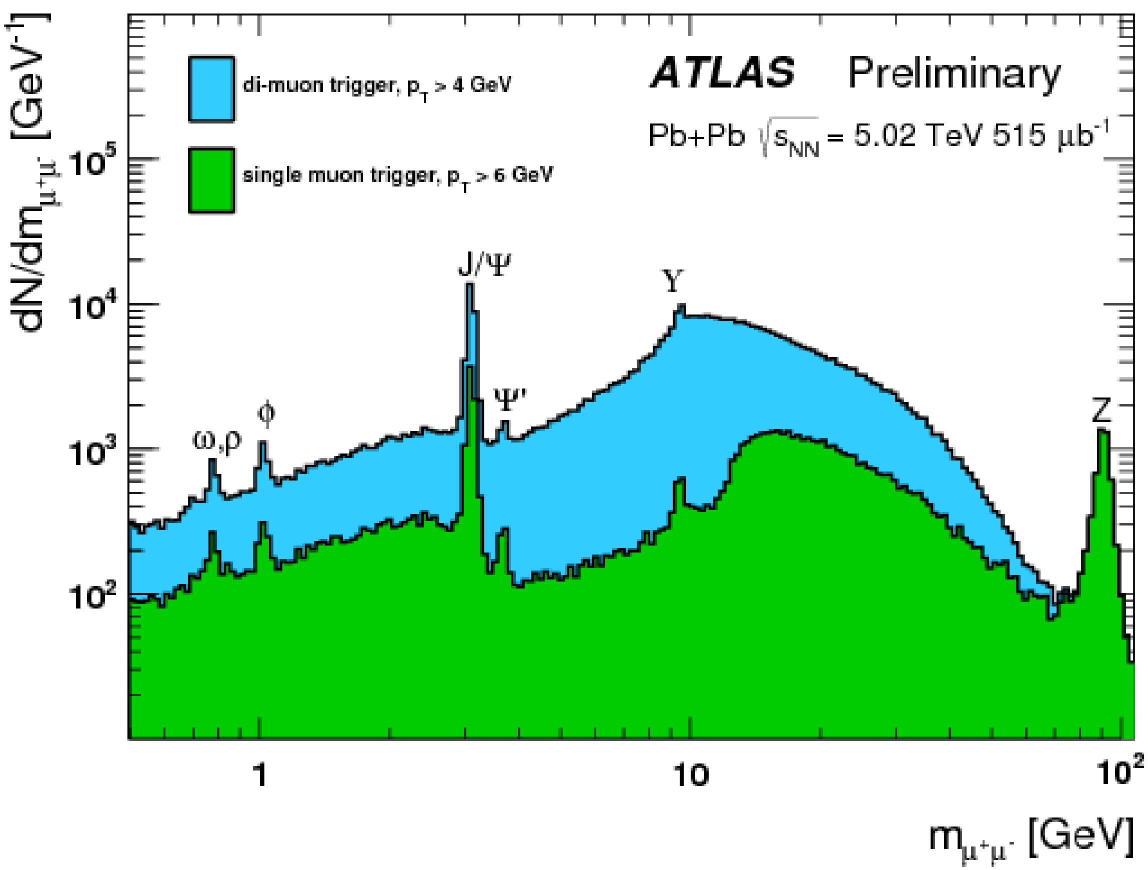


Fig. 81. Invariant mass distribution of $\mu^+\mu^-$ pairs measured by ALICE for pp collisions at $\sqrt{s} = 7$ TeV ($\mathcal{L} = 1.35$ pb^{-1}, corresponding to the full 2011 dimuon-triggered data sample).

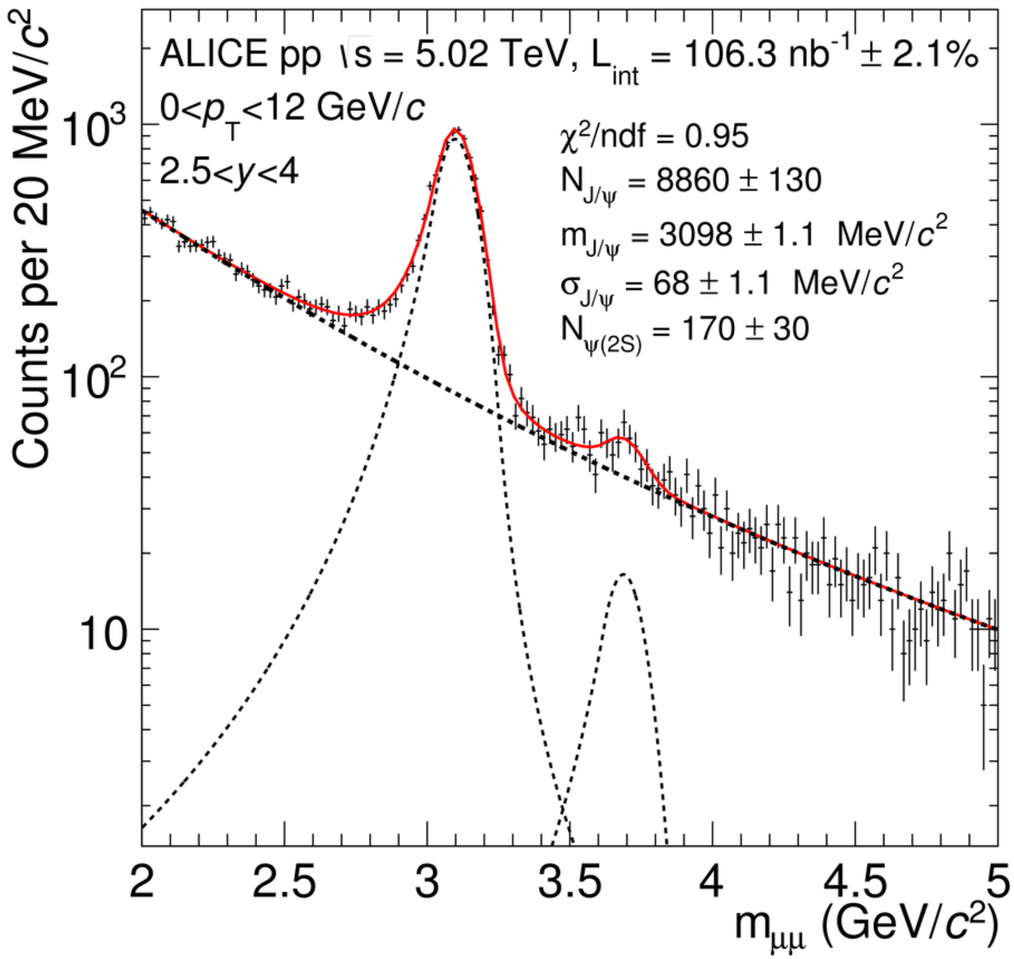
Di-muon mass distribution CMS

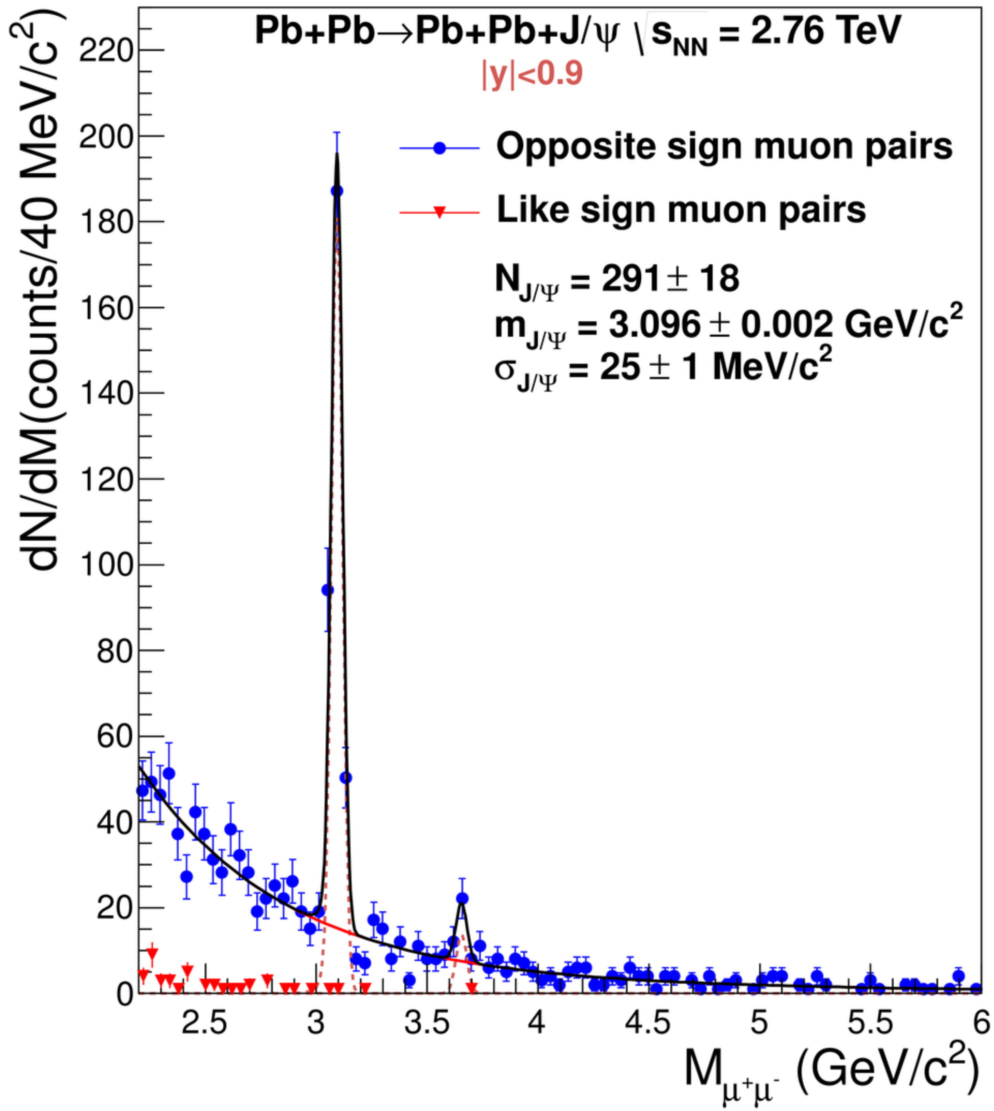


Di-muon mass distribution ATLAS

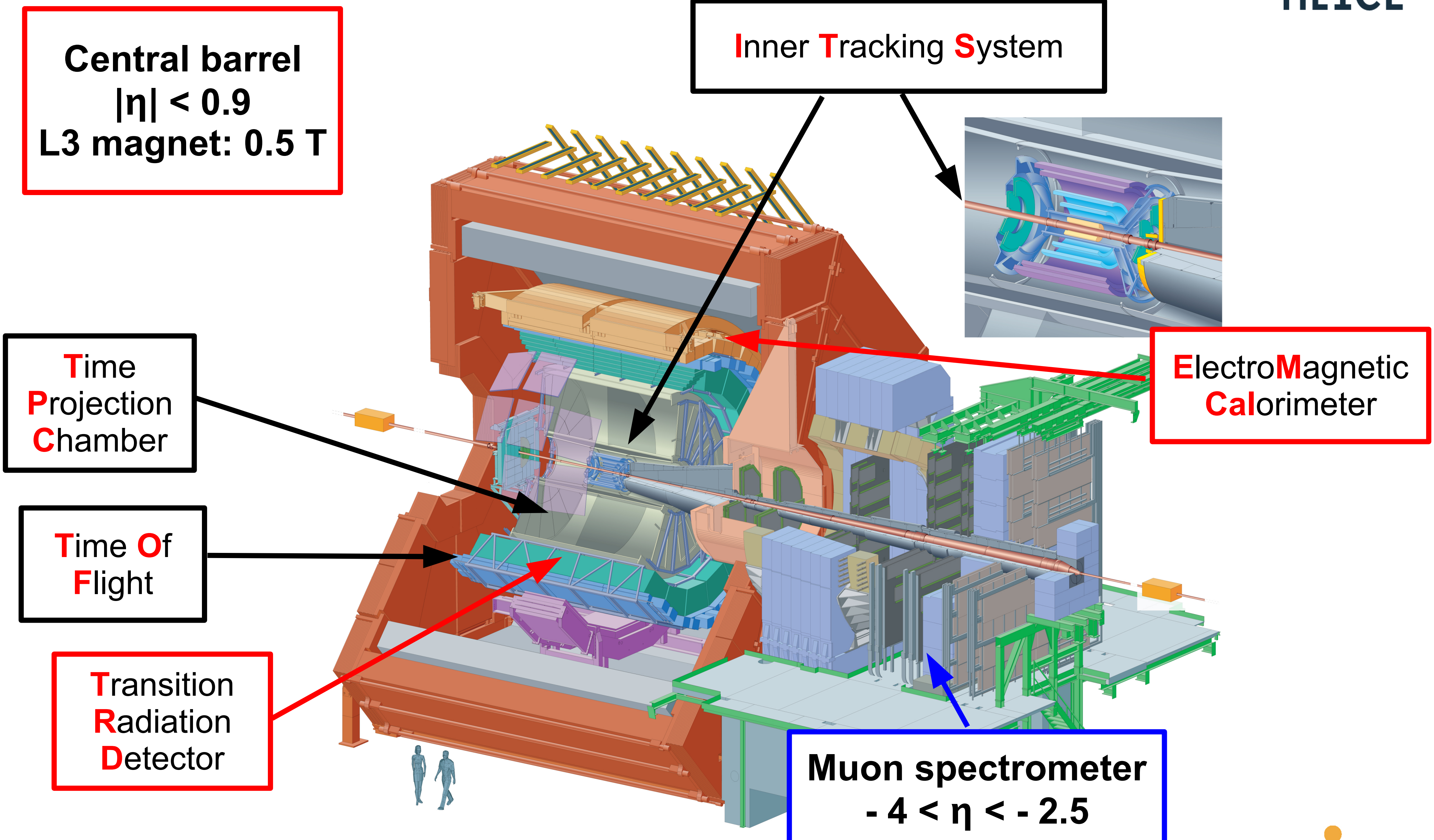


Also a matter of background

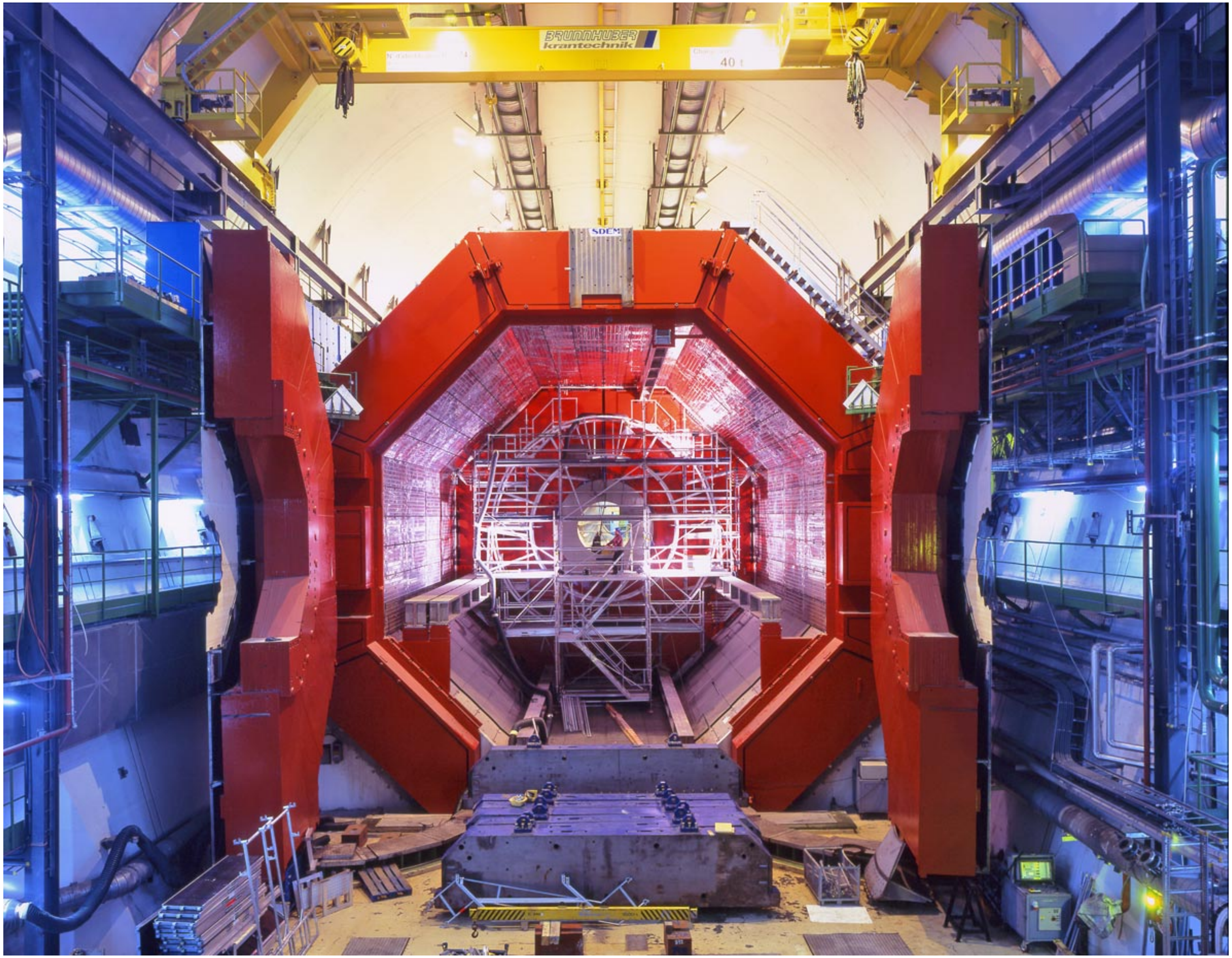




The ALICE Spectrometer

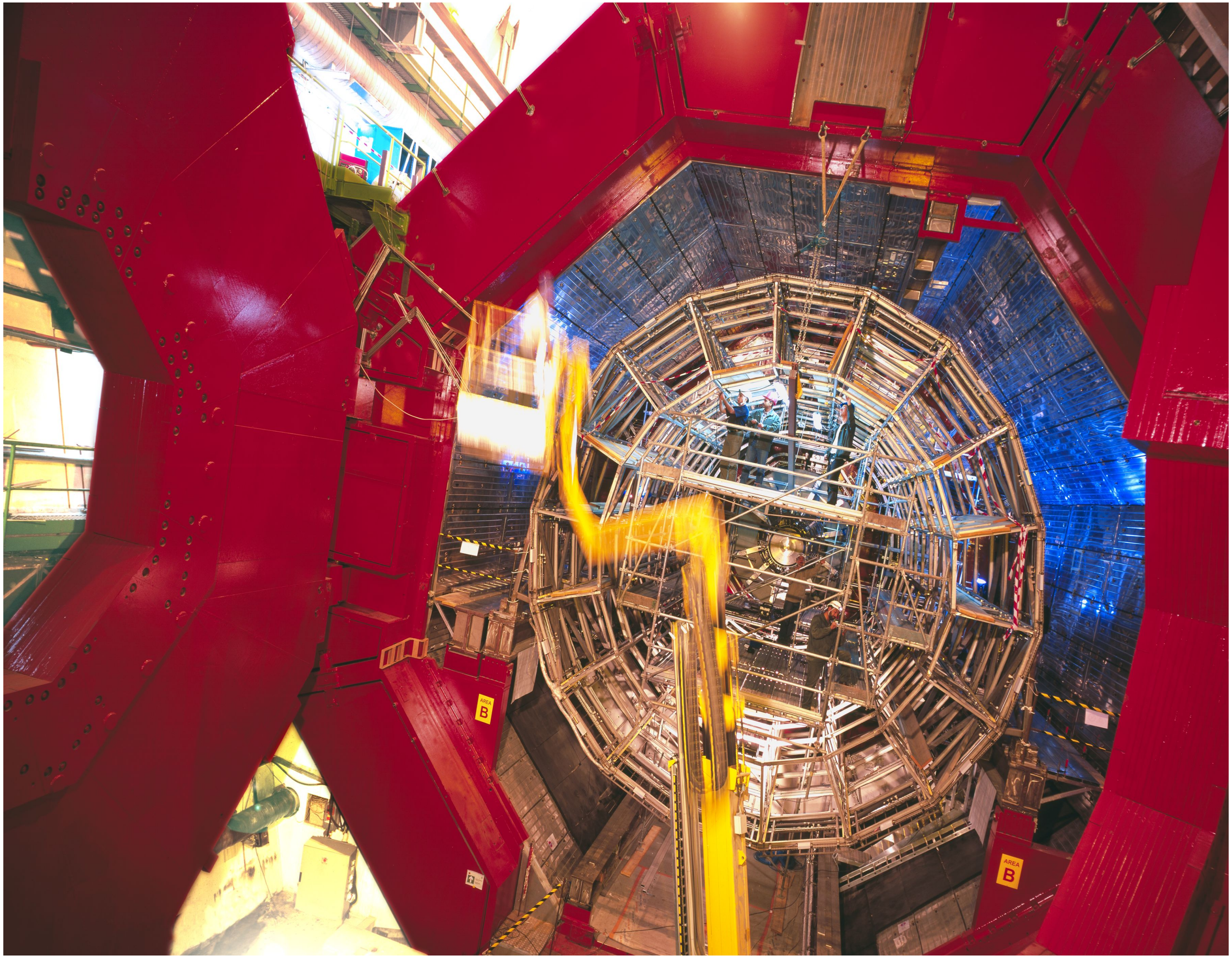


ALICE



2005

ALICE



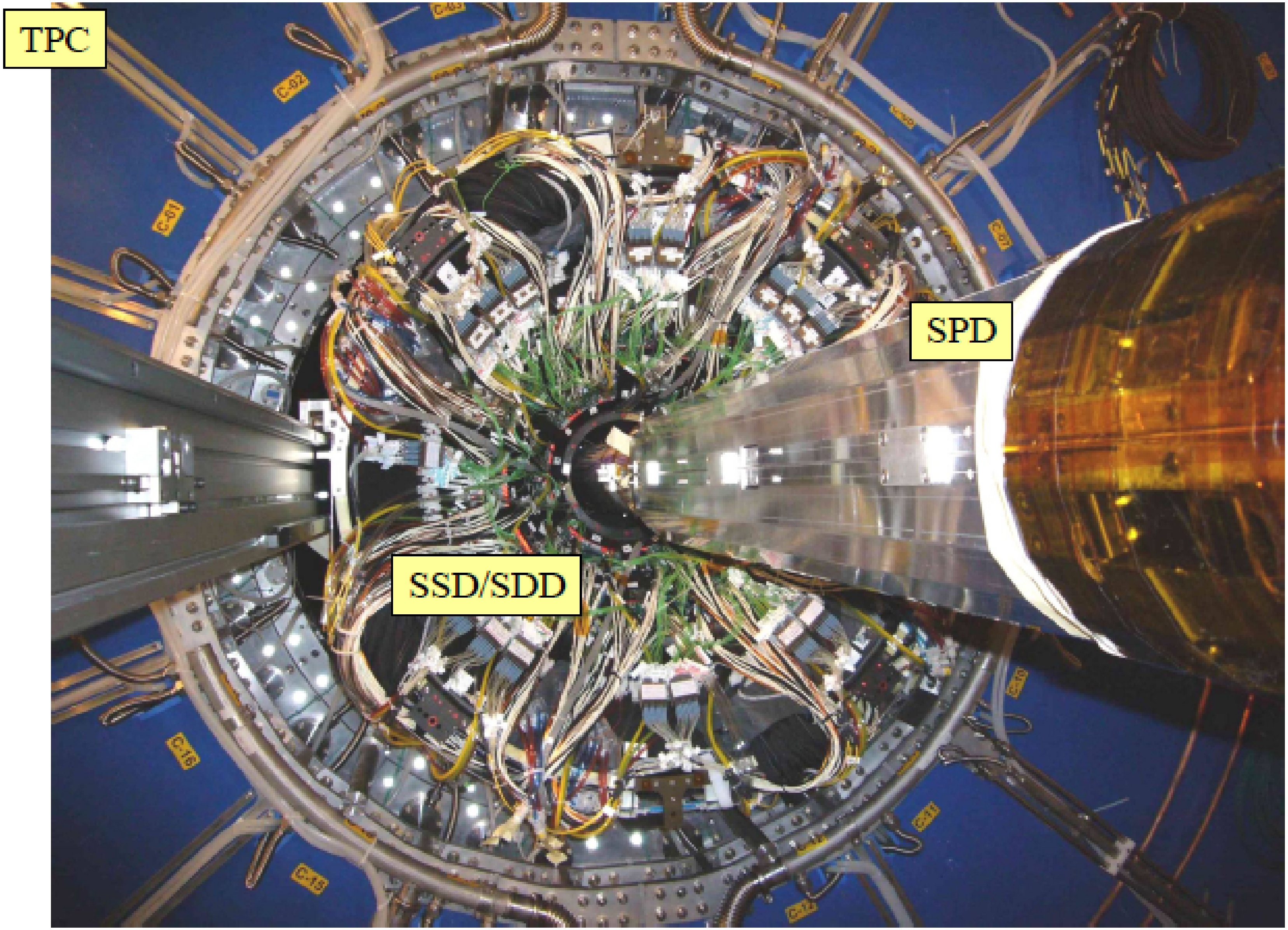
2006

ALICE – TPC

ALICE – TPC

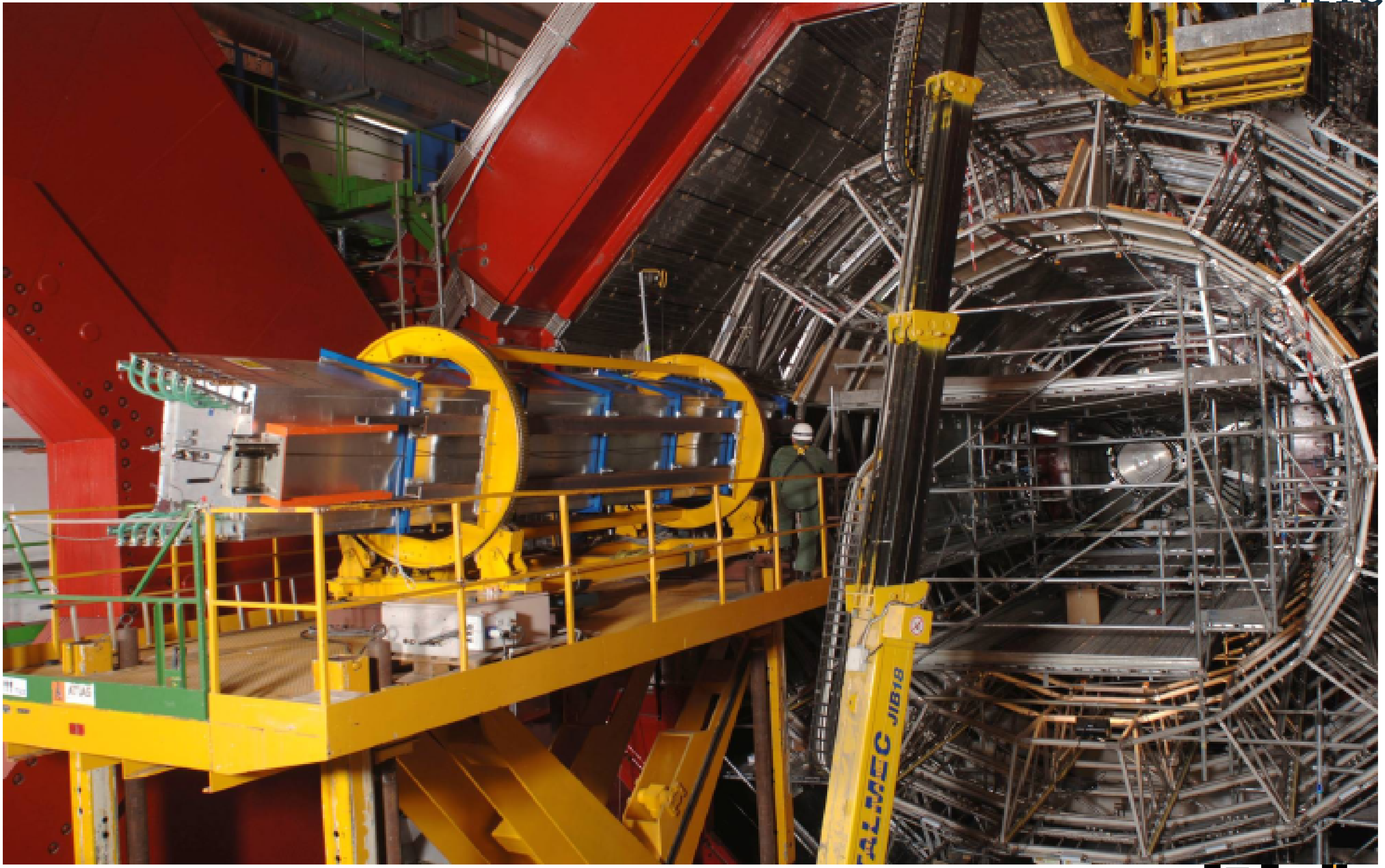
2007

ALICE – TPC and ITS



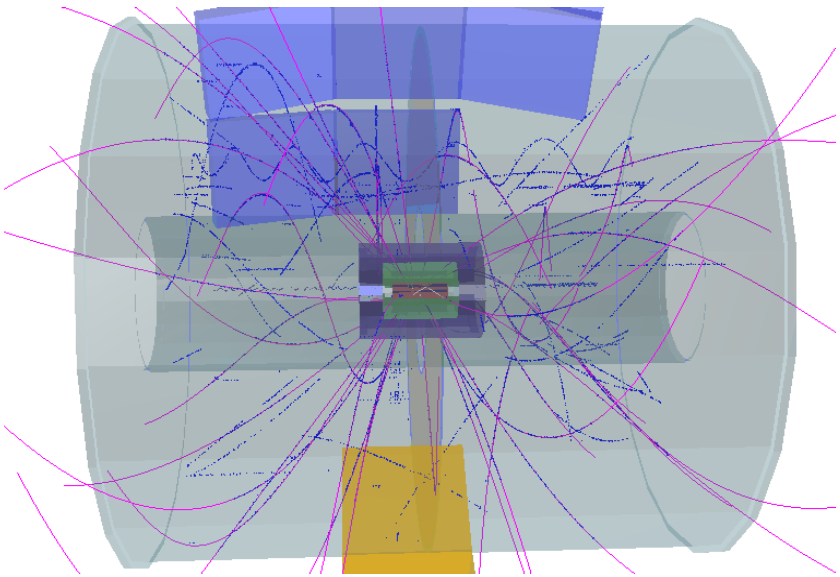
2007

ALICE – TRD

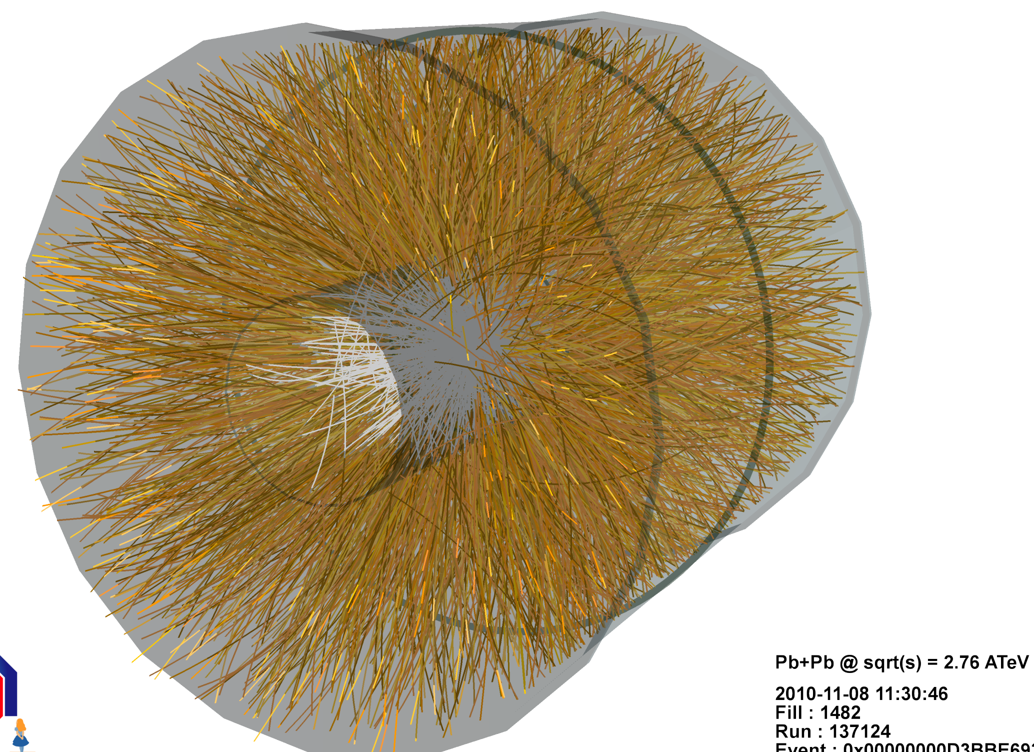


2008

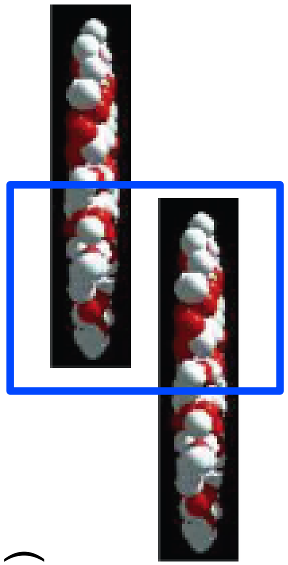
From proton-proton ...



... to Pb-Pb collisions !!!

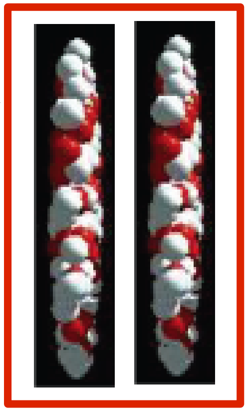


Geometry of a Pb-Pb collision

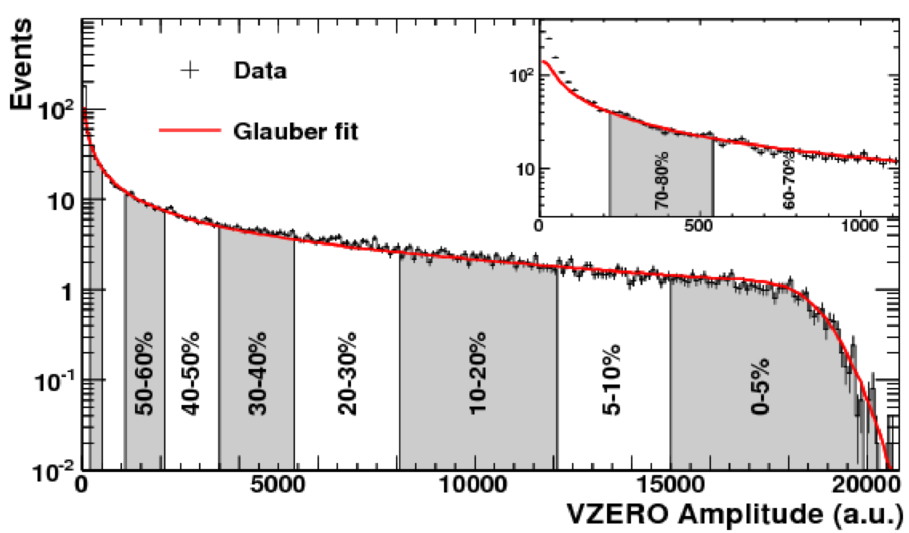


Central collisions → high number of **participants**
→ high multiplicity

Peripheral collisions → low number of **participants**
→ low multiplicity



E.g. measure by VZERO scintillators +
reproduced by Glauber model fit

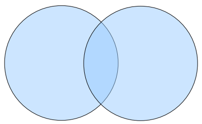


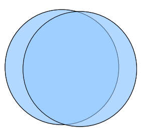
Centrality: percentile of total hadronic cross section

Phys. Rev. Lett. 106, 032301 (2011)

arXiv:1301.4361

peripheral





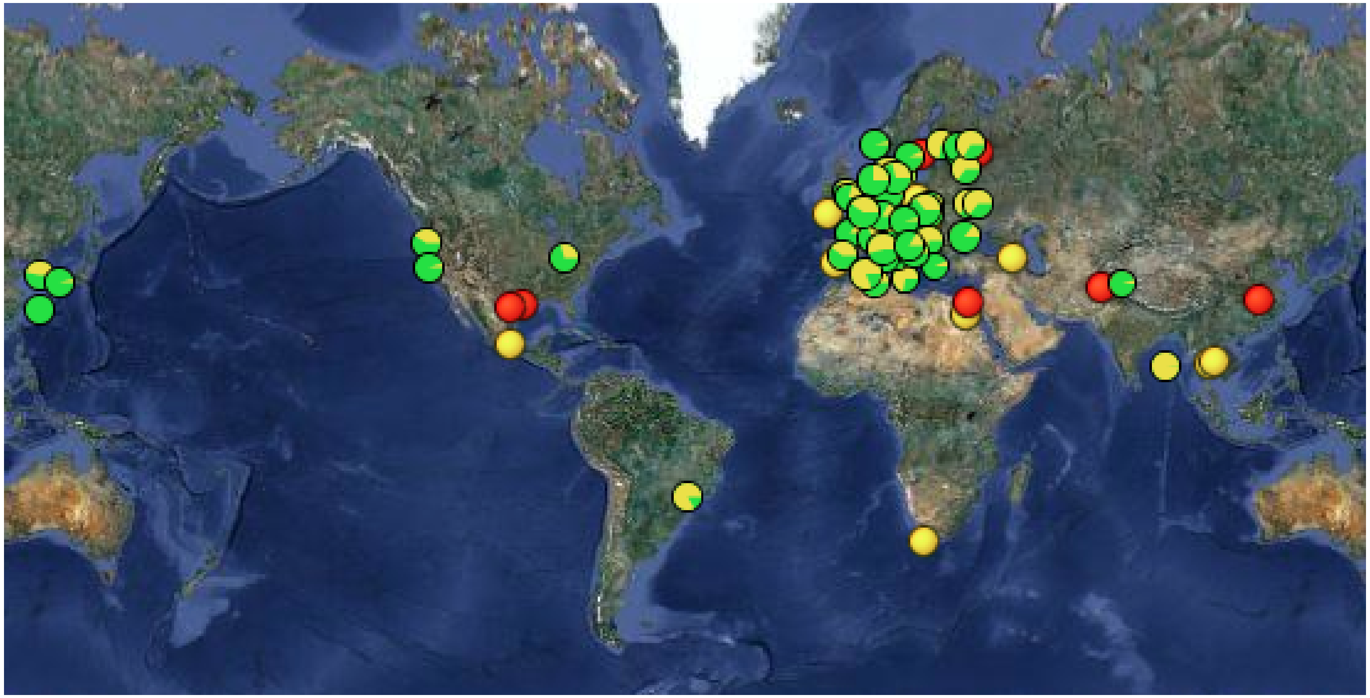
central

ALICE on the computing GRID

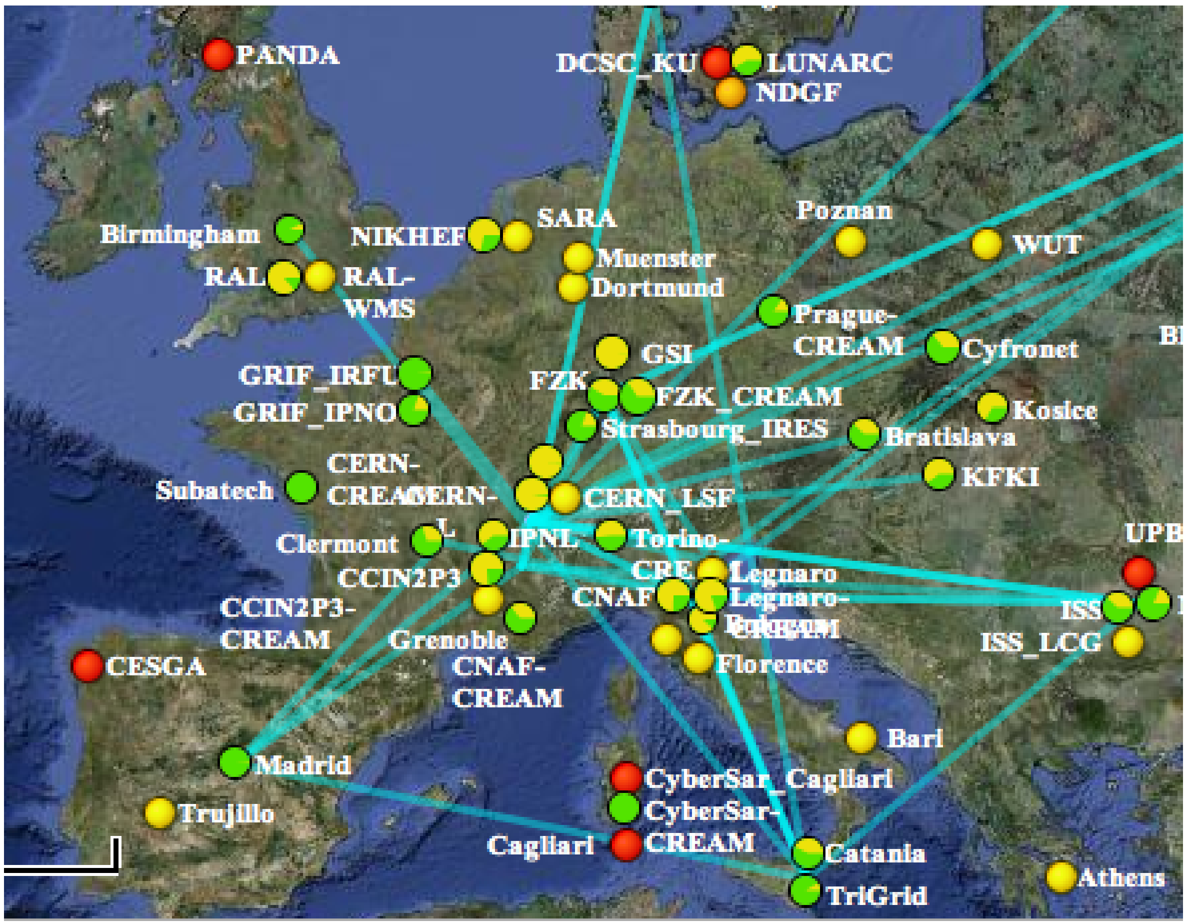
A Large Ion Collider Experiment

35 countries, 120 institutes, 1300 members

72 active computing sites



GSI TIER 2/3 in GRID



- GSI: very important TIER2 center, central role in ALICE
  20% of all TIER2s of ALICE
- Data analysis, detector calibration, MC production, MC and real data storage
- Excellent support to whole Germany

TIER2 continuously expands

Relative growth +30%/y !

GSI GRID group

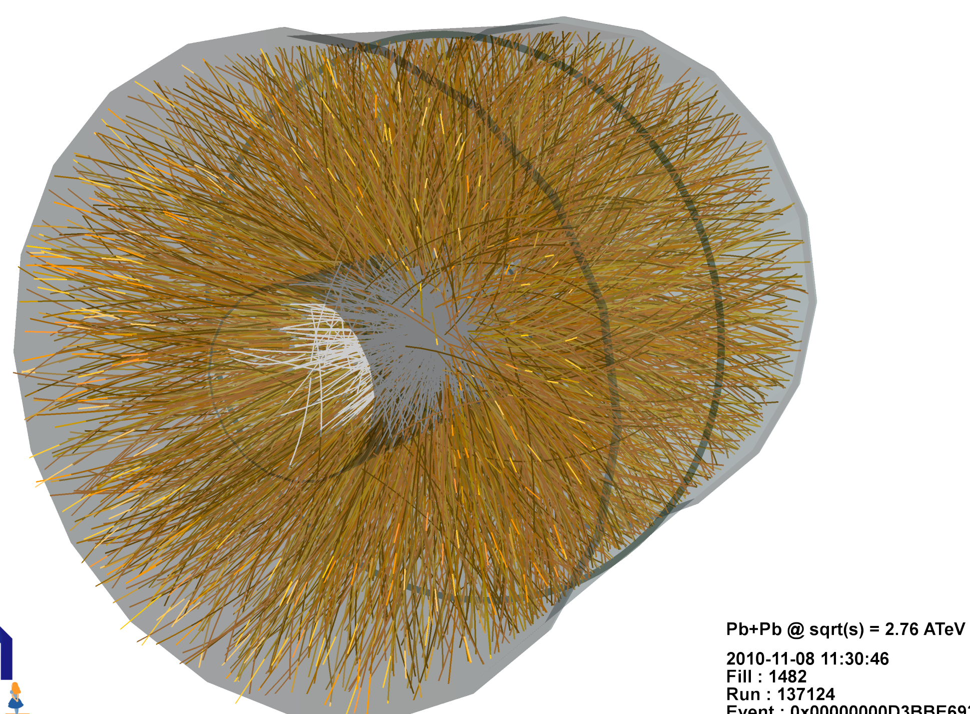
The future

- 2013-14: LHC long shutdown 1
  Detector consolidation in preparation for ...
- 2015-17: RUN 2 **FULL ENERGY !!**
  pp @ 14 TeV, Pb-Pb @ $\sqrt{s_{NN}}$ = 5.5 TeV ← **20 kHz !!!**
- 2018: LHC long shutdown 2
- ≥ 2019: **HIGH LUMINOSITY → 50 kHz Pb-Pb collisions**
  LHC experiment upgrades to cope with the higher rates!!
  New vertex detectors
  Faster readout, pipelining, continuous readout, TPC with GEM ...

This Physics ...

… is hot and dense! (many open questions and mysteries)

And these are extremely exciting times!!!



SPARES