High-Energy Collisions with ALICE at the LHC

2. The Alice Experiment

Graduate Days

of the Graduate School of Fundamental Physics
Heidelberg, 5. - 9. October 2009

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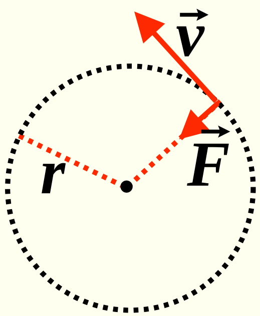
Physikalisches Institut
Universität Heidelberg

2.1 Overview: Experimental Methods

Momentum Measument in Magnetic Fields



centripetal force → Lorentz force

$$F = \frac{\gamma \cdot m \cdot v^2}{r} = q \cdot v \cdot B$$

$$\Rightarrow \quad p = \gamma \cdot m \cdot v = q \cdot B \cdot r$$

Useful pocket formula:
p **in GeV,** $q = z \cdot e$

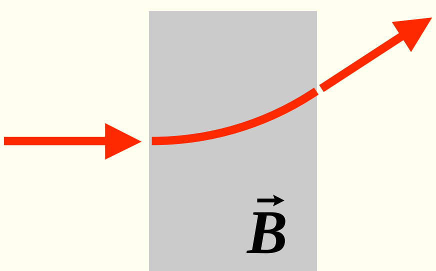
$$p = 0{,}3 \cdot z \cdot B \cdot r$$

B field in Tesla

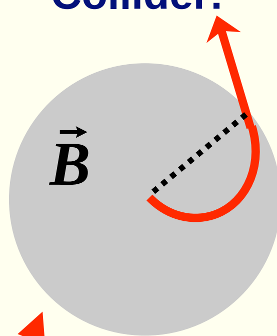
Deflection radius in m

1 m in a 1 Tesla field deflects a 1 GeV particle by 17°

Fixed Target:



Collider:



B parallel to beam axis
→ Measurement of p_T

Typical resolution:

$$\frac{\sigma_p}{p} = (\sim 1\%) \oplus (\sim 1\%) \cdot p \ \ [\mathrm{GeV/c}]$$

Multiple scattering (dominant at low p_T)

Uncertainty in the measurement of the deflection angle (dominant at large p_T)

Particle Identification via dE/dx (I)

Bethe-Bloch formula:

$$-\left\langle \frac{dE}{dx} \right\rangle = K \cdot z^2 \cdot \frac{Z}{A} \cdot \frac{1}{\beta^2} \left(\frac{1}{2} \ln\left[\frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} \right] - \beta^2 - \frac{\delta}{2} \right)$$

x in g/cm²

$$K = 4\pi N_A r_e^2 m_e c^2 = 0{,}307 \text{ MeVg}^{-1}\text{cm}^2$$

m_e: Masse des Elektrons

r_e : klassischer Elektronenradius = 2,82 fm

N_A :Avogadro-Zahl

β: Geschwindigkeit des Teilchens (γ=1/$\sqrt{1-\beta^2}$)

z: Ladung des einfallenden Teilchens

Z: Ladungszahl des Mediums

A: Massenzahl des Mediums

T_{max}: Maximale in einem Stoß auf ein Elektron übertragbare Energie

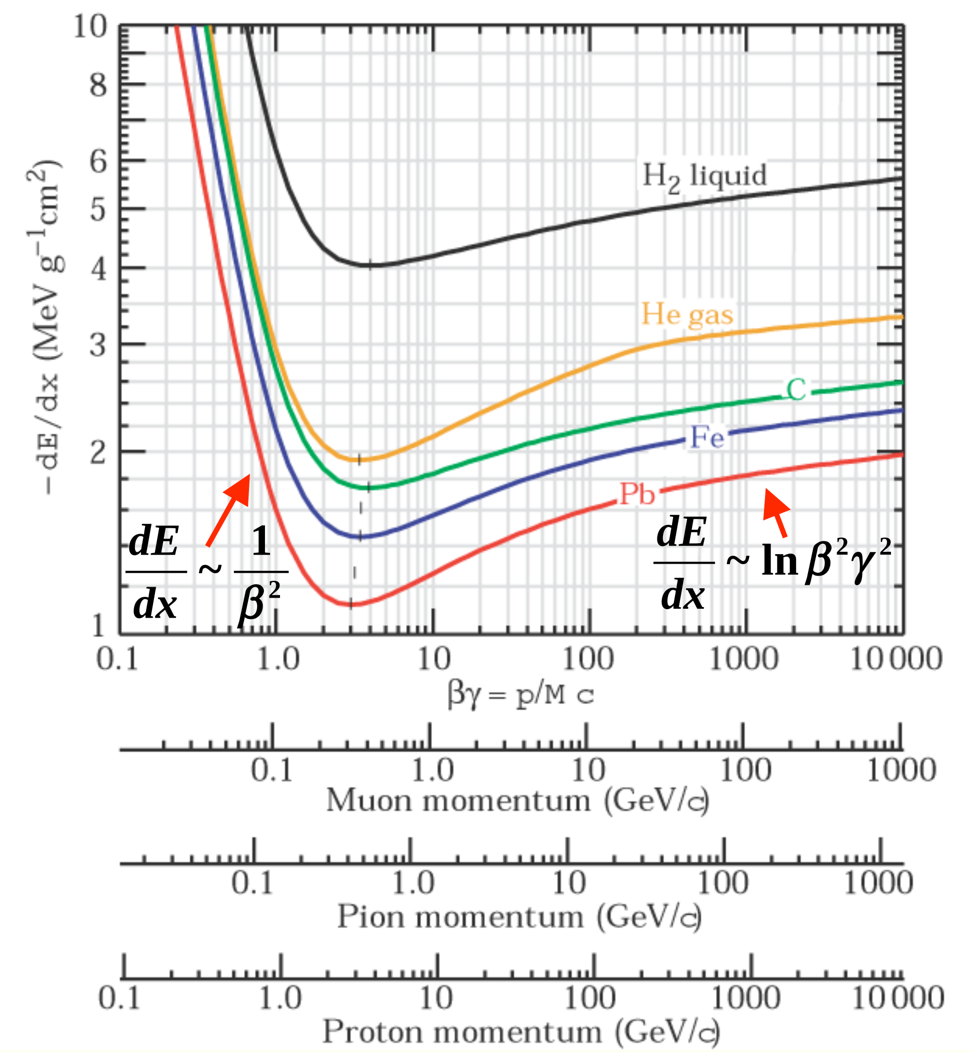
$$T_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma \frac{m_e}{m} + \left(\frac{m_e}{m} \right)^2}$$

m :Masse des einfallenden Teilchens

I : Mittlere Anregungsenergie des Mediums

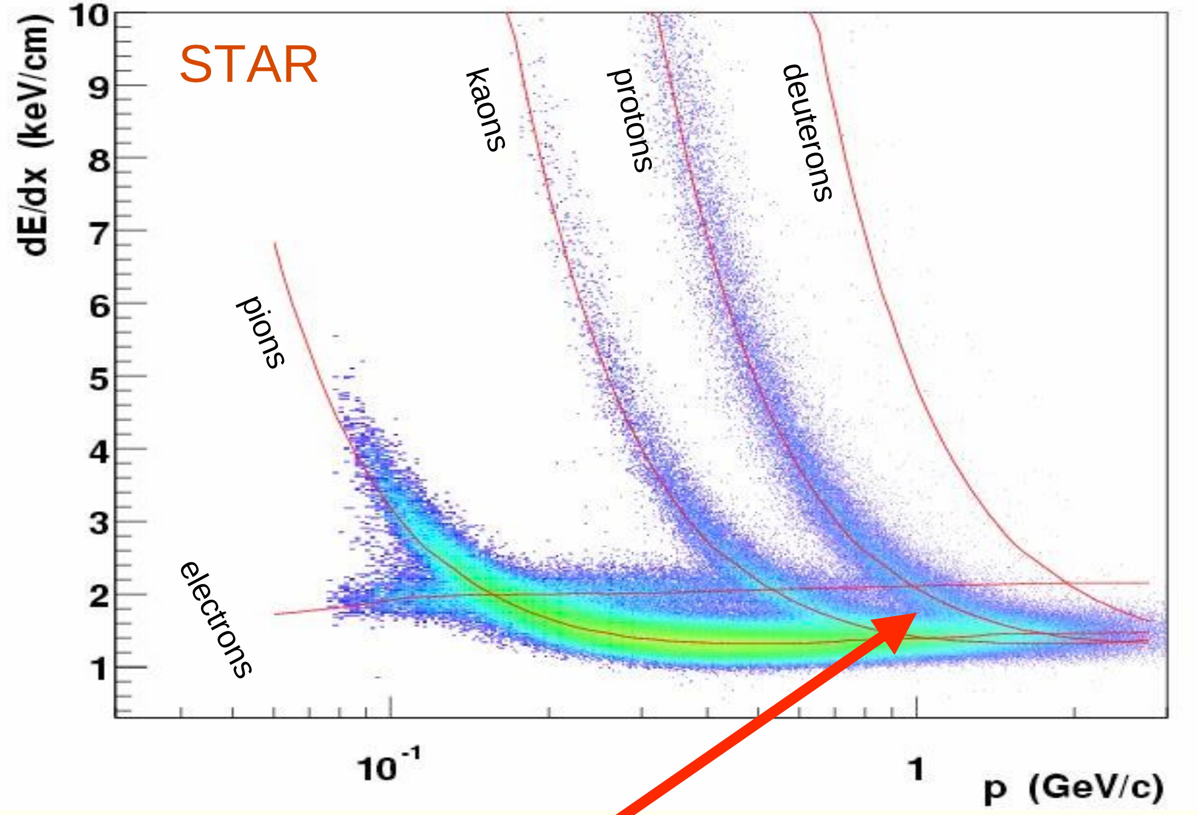
δ: Dichte-Korrektur (transversale Ausdehnung des e.m. Feldes)

Particle Identification via dE/dx (II)



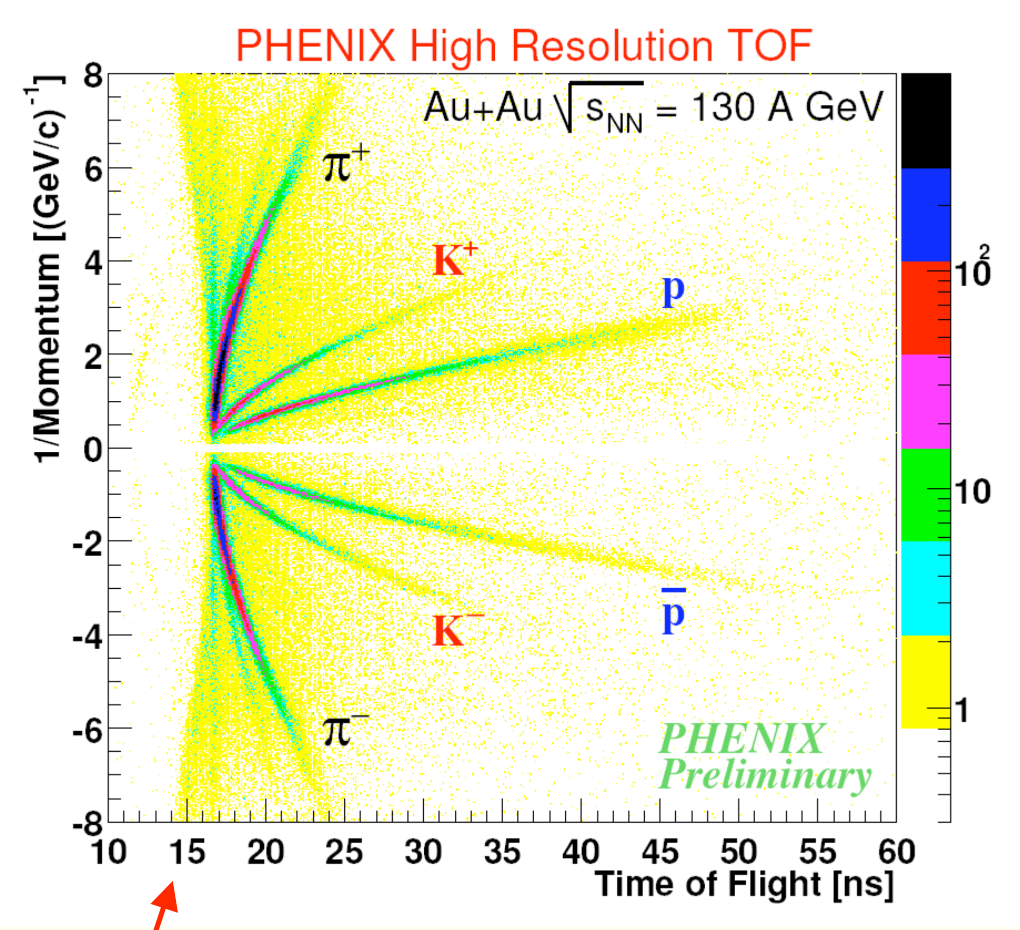
- *x* = thickness in g/cm^2
  = distance *z* · density ρ,
  i.e. d*E*/dz = ρ · d*E*/dx
- Minimum at βγ = 3 – 4, i.e., at β ≈ 0,96 *c*
  „minimum ionizing particles" (Mips)
- d*E*/dx fall-off: ~ $1/\beta^2$
- Rise at relativistic energies
  - Due to increase of the transverse component of the *E* field with Lorentz γ
  - Rise for solids less strong than for gases
- Typical values for $(dE/dx)_{min}$
  - 1 – 2 MeV g^{-1} cm^2

Specific Energy Loss dE/dx



proton/pion separation up to *p* = 1.1 GeV/c

Time of Flight



Distance to TOF detector ~ 5 m
(*c* = 30 cm/ns)

Mass from *p* and ToF *t*:

$$m = \frac{p}{\beta \cdot \gamma}, \quad \beta = \frac{s}{c \cdot t}$$

Non-relativistic:

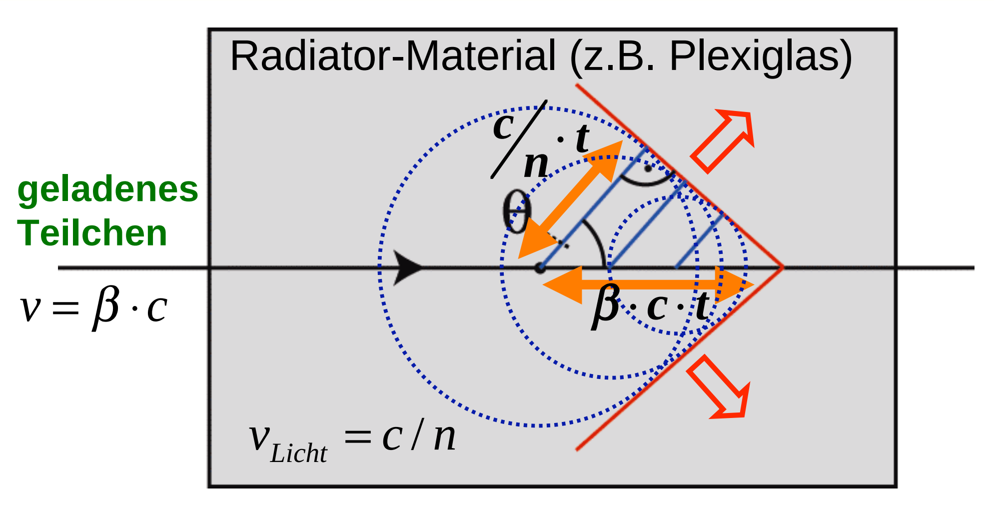
$$\frac{1}{p} = \frac{1}{m\beta} = \frac{1}{m}\frac{ct}{s}$$

Relativistic:

$$\frac{1}{p} = \frac{1}{m}\sqrt{\left(\frac{ct}{s}\right)^2 - 1}$$

Relativity works:
the curves are not straight lines in this plot

Čerenkov Radiation



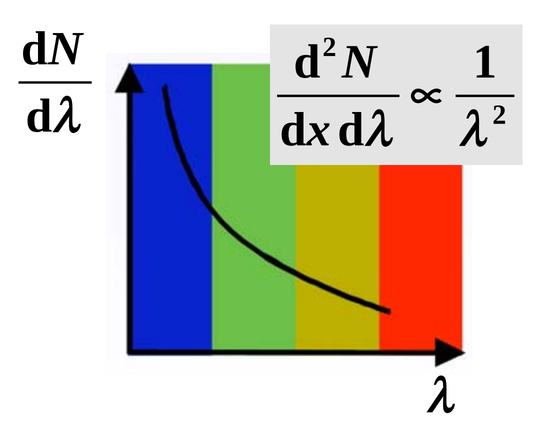
Durchquert ein geladenes Teilchen mit *v* > *c*/*n* (= Lichtgeschw. im Medium) ein Medium, dann bildet das Licht der angeregten Atome eine Wellenfront unter festem Winkel θ zur Teilchenbahn

$$\cos\theta = \frac{c/n \cdot t}{\beta \cdot c \cdot t} = \frac{1}{\beta \cdot n}$$

Anzahl abgestrahlter Photonen pro Wegstrecke und Wellenlängenintervall:

$$\frac{\mathrm{d}^2 N}{\mathrm{d}x\,\mathrm{d}\lambda} = \frac{2\pi z^2 \alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right), \; n = n(\lambda)$$

Abgestrahlte Photonen überwiegend im blauen Frequenzbereich:



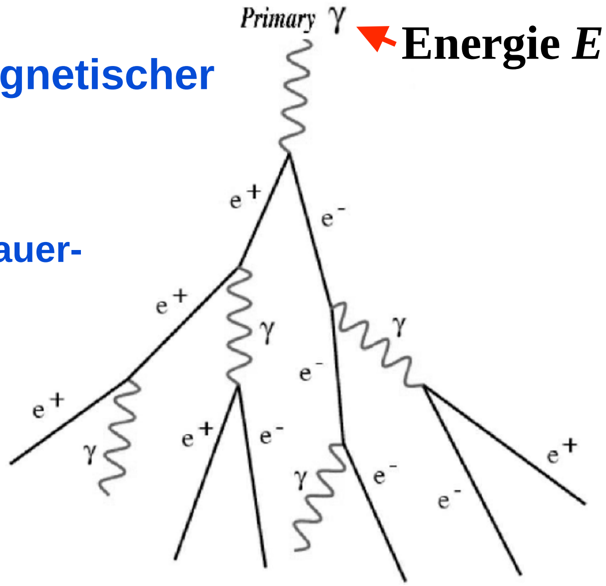
Bsp.: Teilchen (*z* = 1) mit β = 1 in Wasser (*n* = 1,33):

$$\mathrm{d}E / \mathrm{d}x = 400 \text{ eV/cm}$$

klein gegenüber gesamtem E-Verlust!

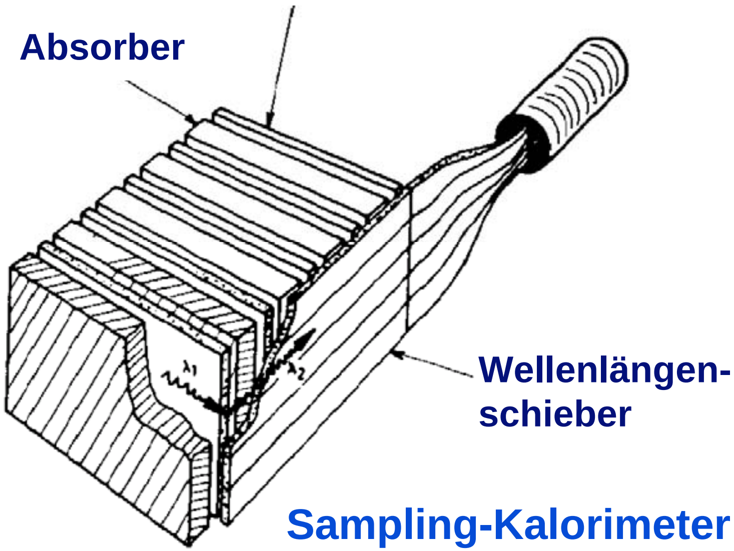
Calorimeters

elektromagnetischer Schauer:



Anzahl Schauer-teilchen:

$$N_{tot} \propto E$$



Sampling-Kalorimeter

2 Typen:

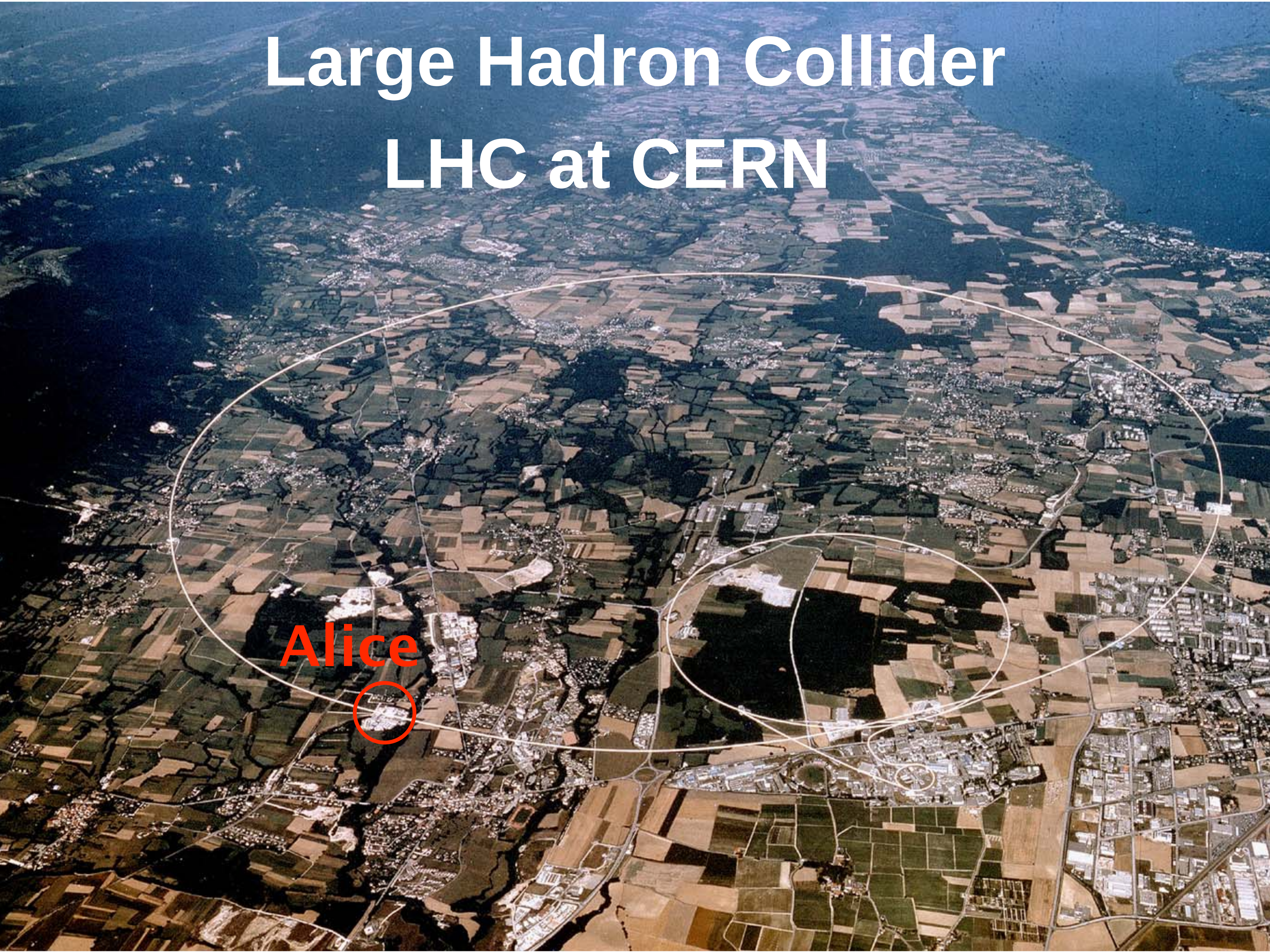
- Homogene Kalorimeter (z.B. Bleiglas)
- Sampling-Kalorimeter

Energieauflösung:

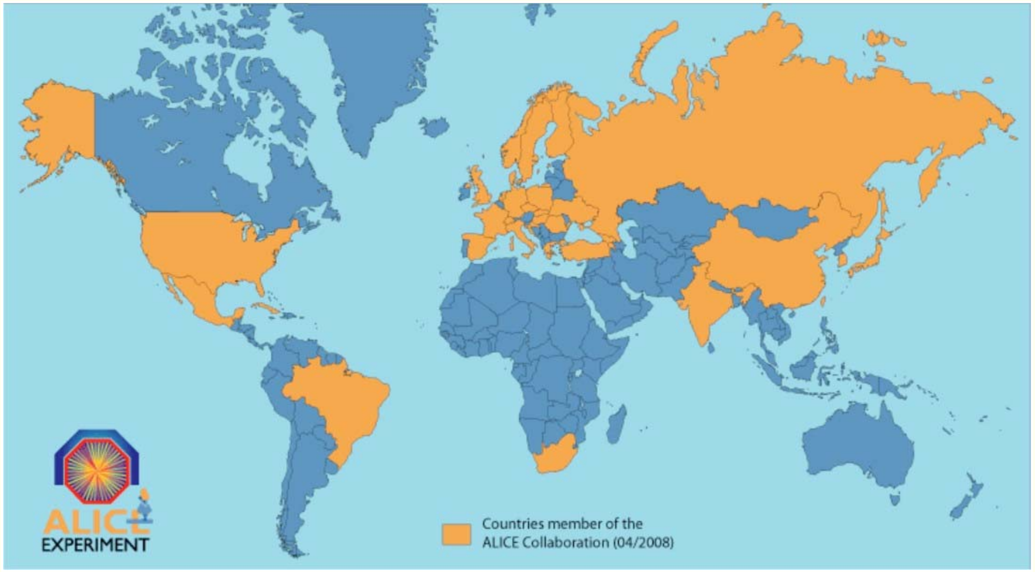
$$\frac{\sigma_E}{E} \approx \frac{\sqrt{N_{tot}}}{N_{tot}} = \frac{1}{\sqrt{N_{tot}}} \propto \frac{1}{\sqrt{E}}$$

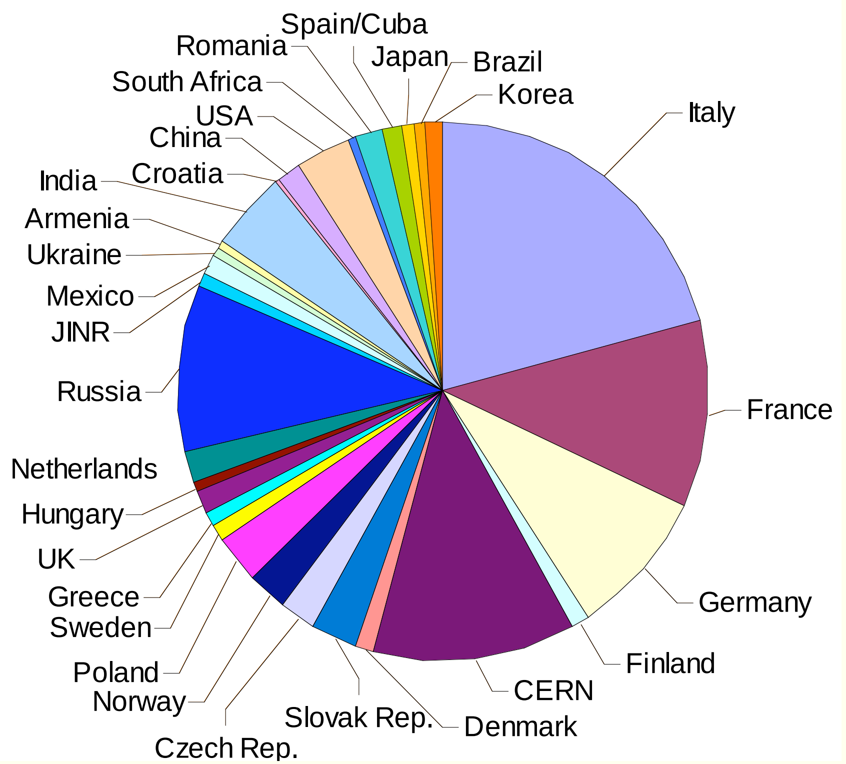
Gute homogene Kalorimeter erreichen

$$\frac{\sigma_E}{E} \approx \frac{6\%}{\sqrt{E\,/\,\mathrm{GeV}}}$$


Large Hadron Collider
LHC at CERN
Alice

ALICE Collaboration





> 1000 Members

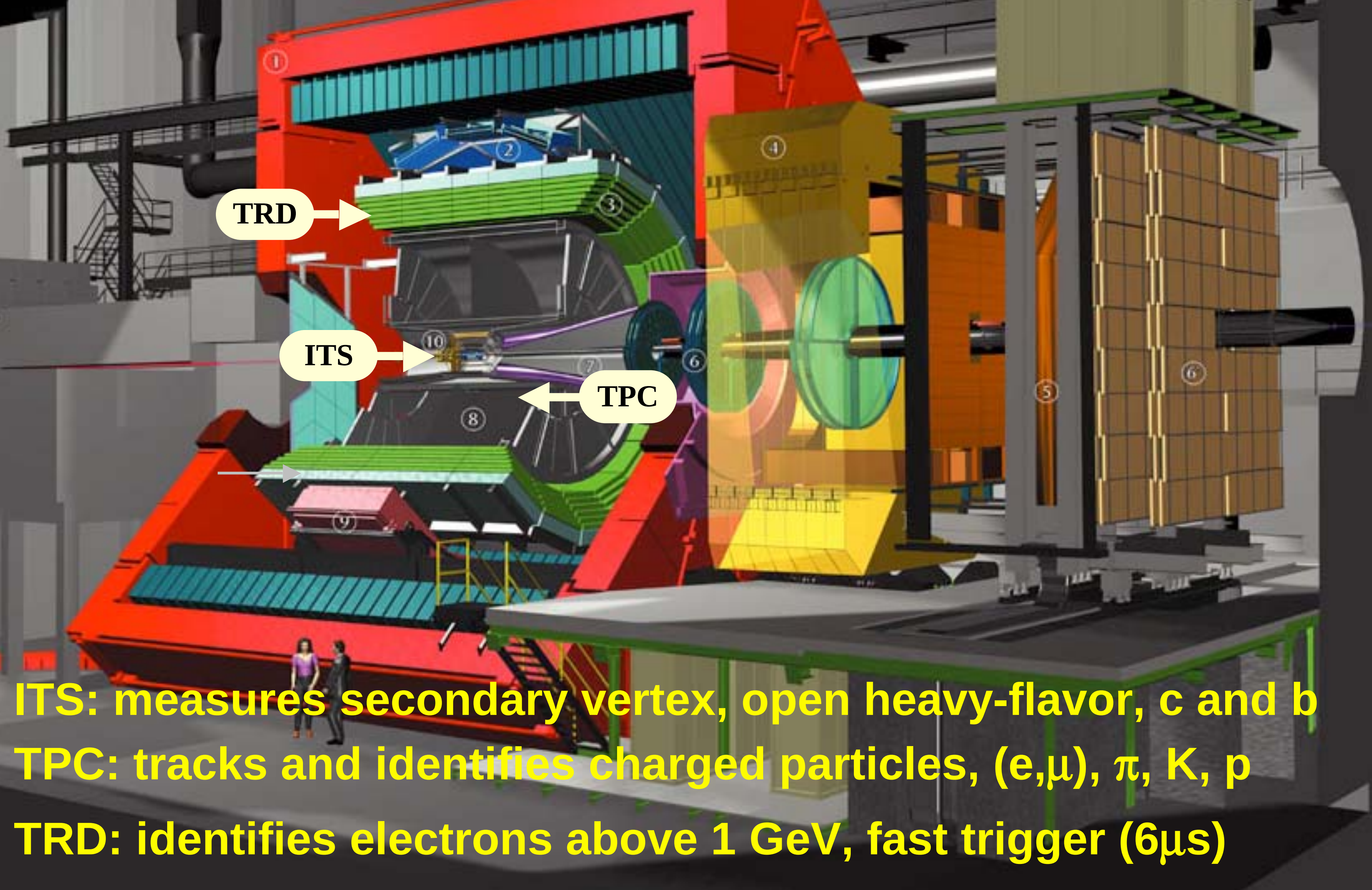
~ 100 Institutes

~ 30 Countries

150 MCHF

ALICE at LHC

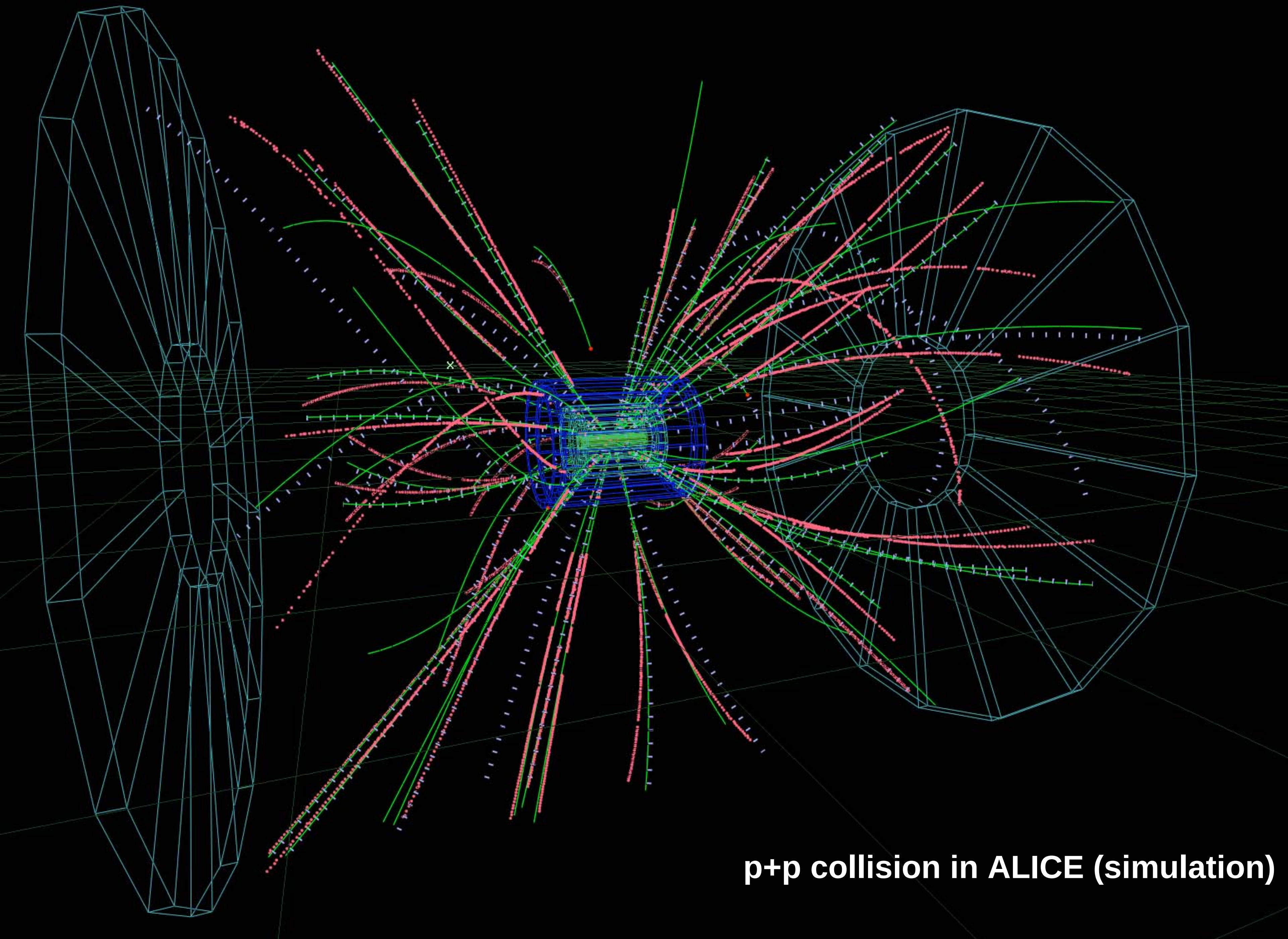
1000 scientists, 30 nations



ITS: measures secondary vertex, open heavy-flavor, c and b

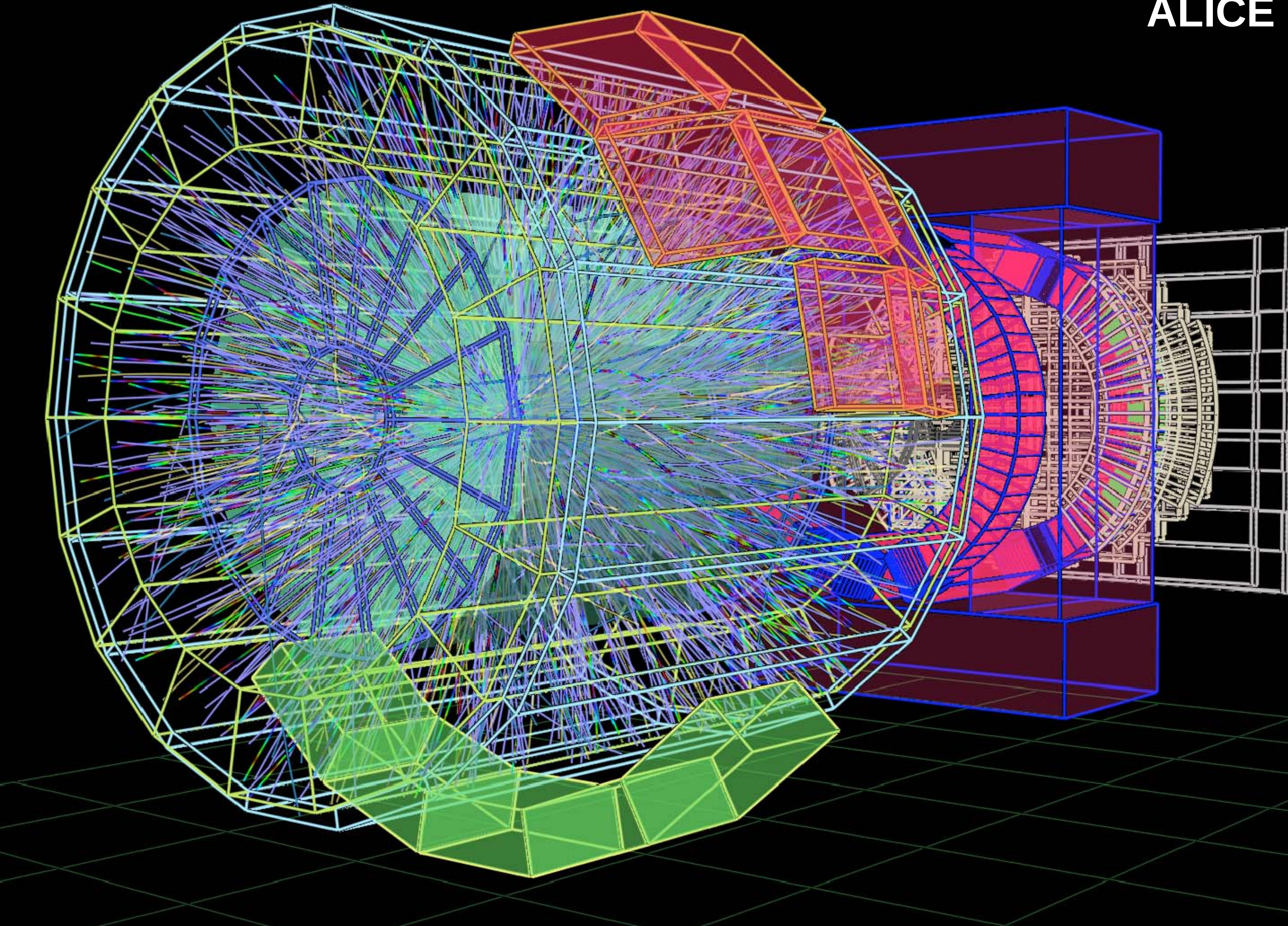
TPC: tracks and identifies charged particles, (e,μ), π, K, p

TRD: identifies electrons above 1 GeV, fast trigger (6μs)

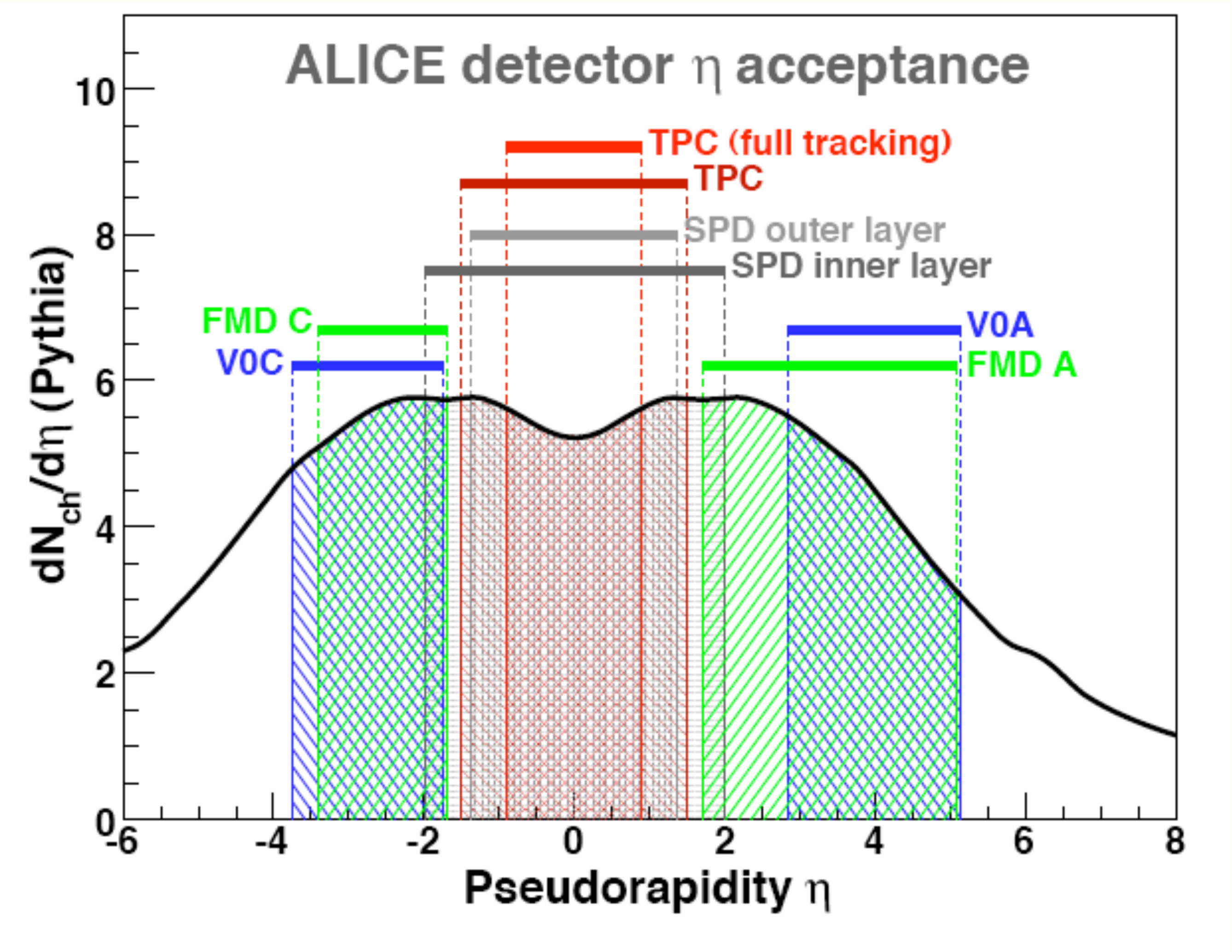


p+p collision in ALICE (simulation)

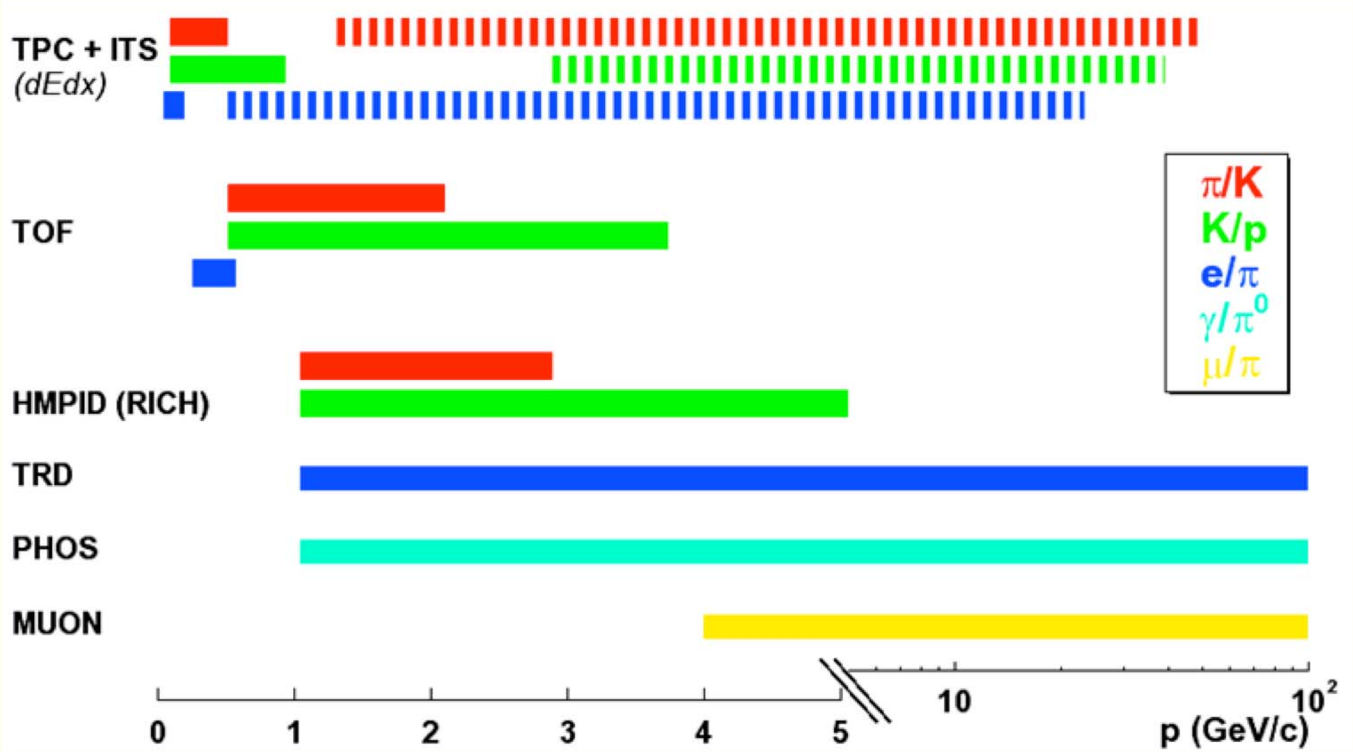
ALICE



ALICE Detectors: Pseudorapidity Coverage

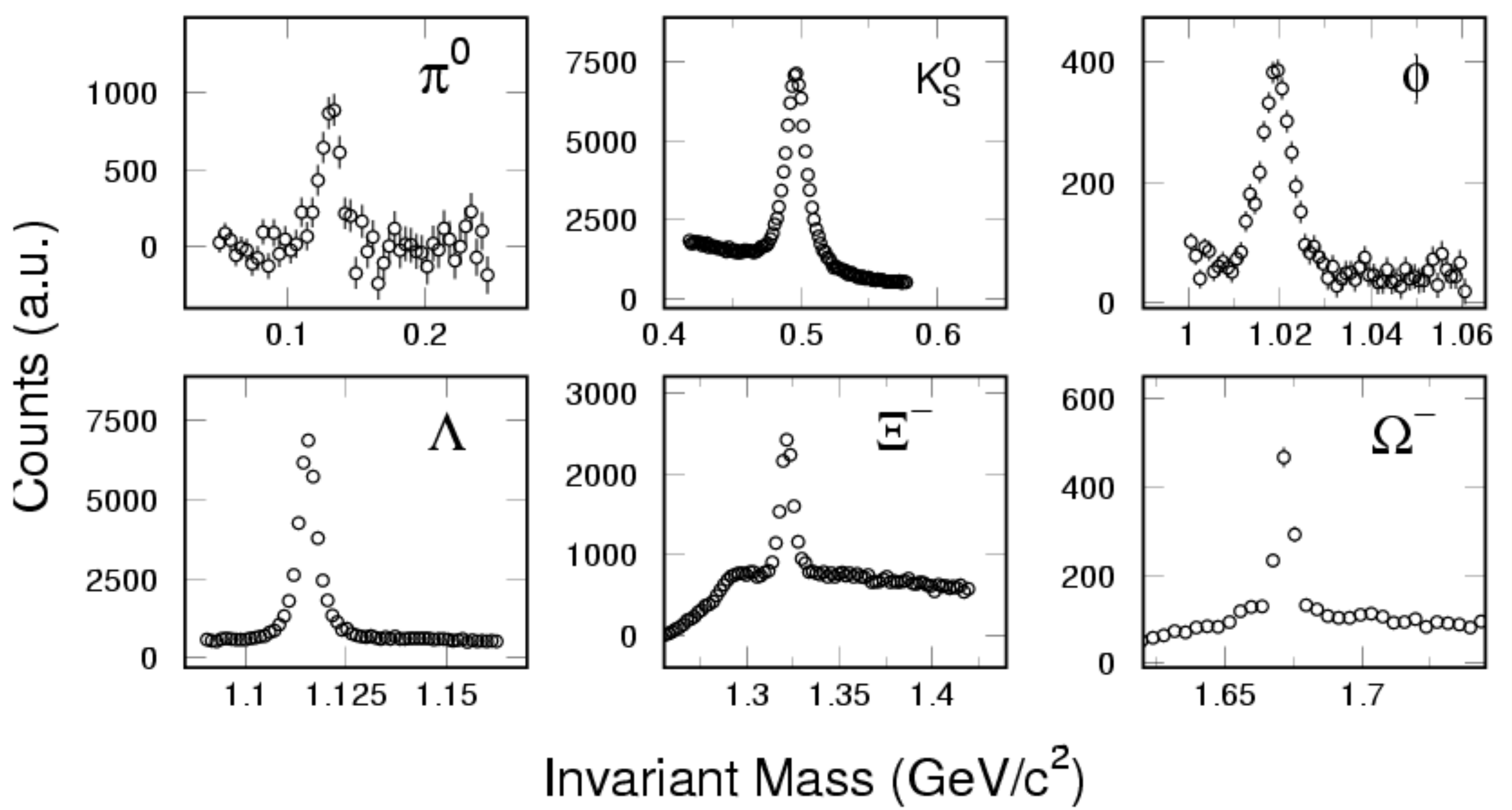


Particle Identification in ALICE

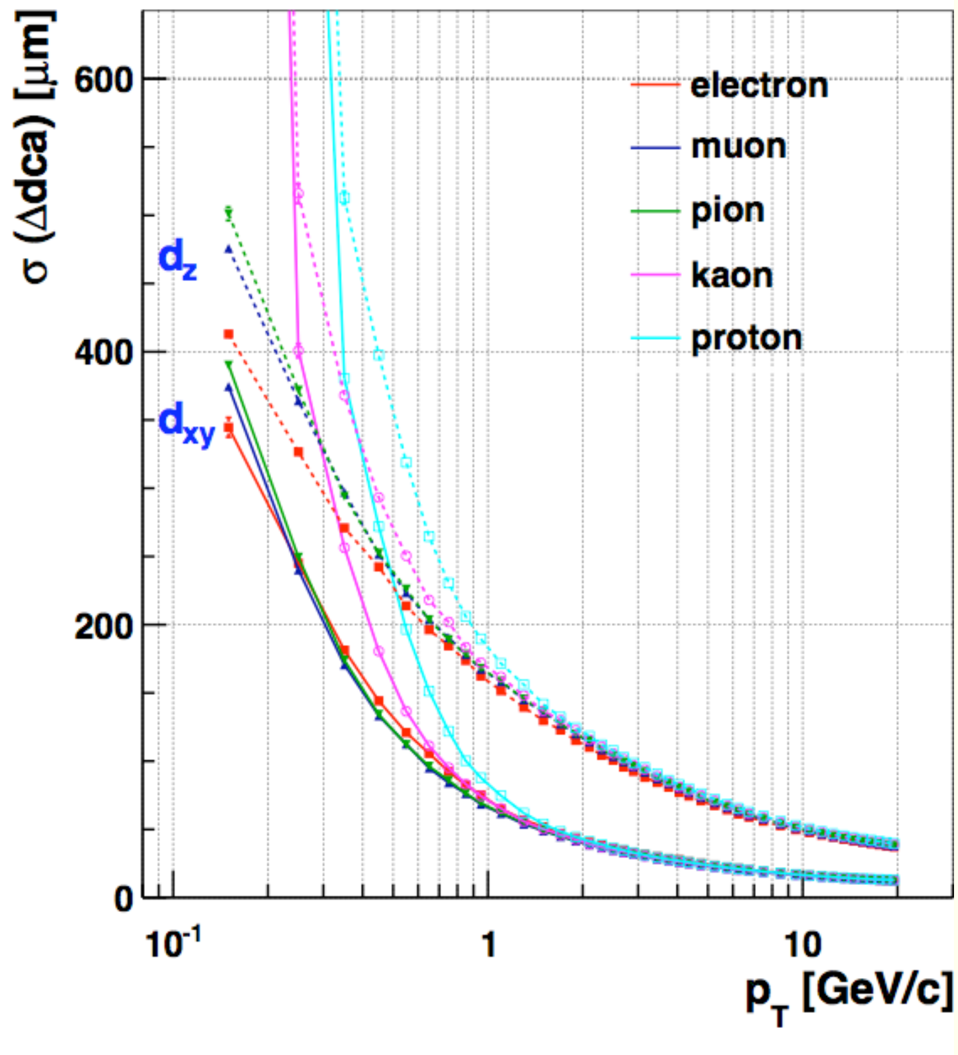


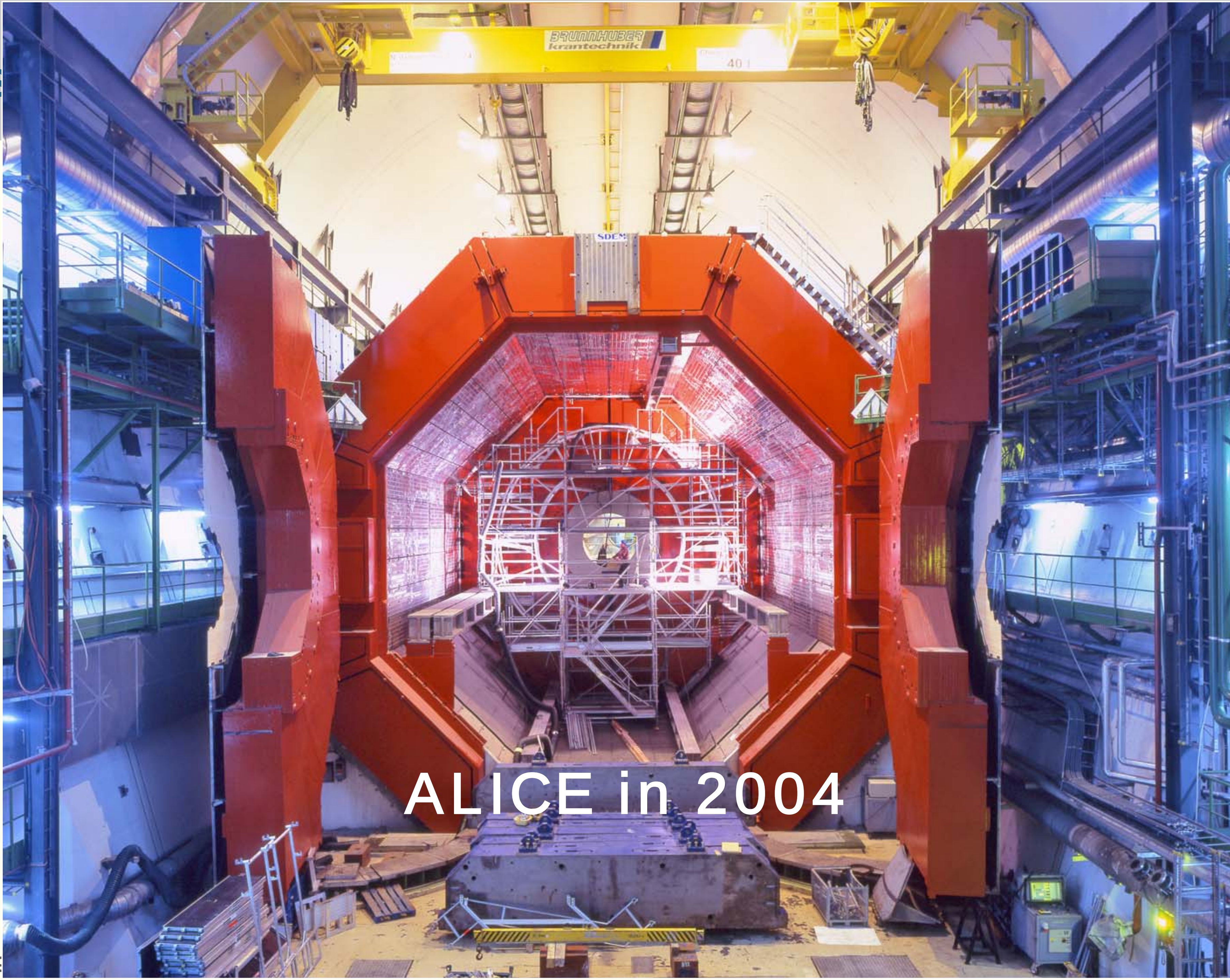
- ‘stable’ hadrons (π, K, p): 100 MeV < *p* < 5 GeV (few 10 GeV)
  - d*E*/d*x* in silicon (ITS) and gas (TPC) + time-of-flight (TOF) + Cherenkov (RICH)
- decay topologies (K_S^0, K^+, K^-, Λ, ϕ, D)
  - K_S^0 and Λ decays below 10 GeV (secondary vertex reconstruction)
- leptons (e, μ), photons, η, π^0
  - electrons TRD: *p* > 1 GeV, muons: *p* > 5 GeV, π^0 in PHOS: 1 < *p* < 80 GeV

Invariant Mass



Pointing Resolution



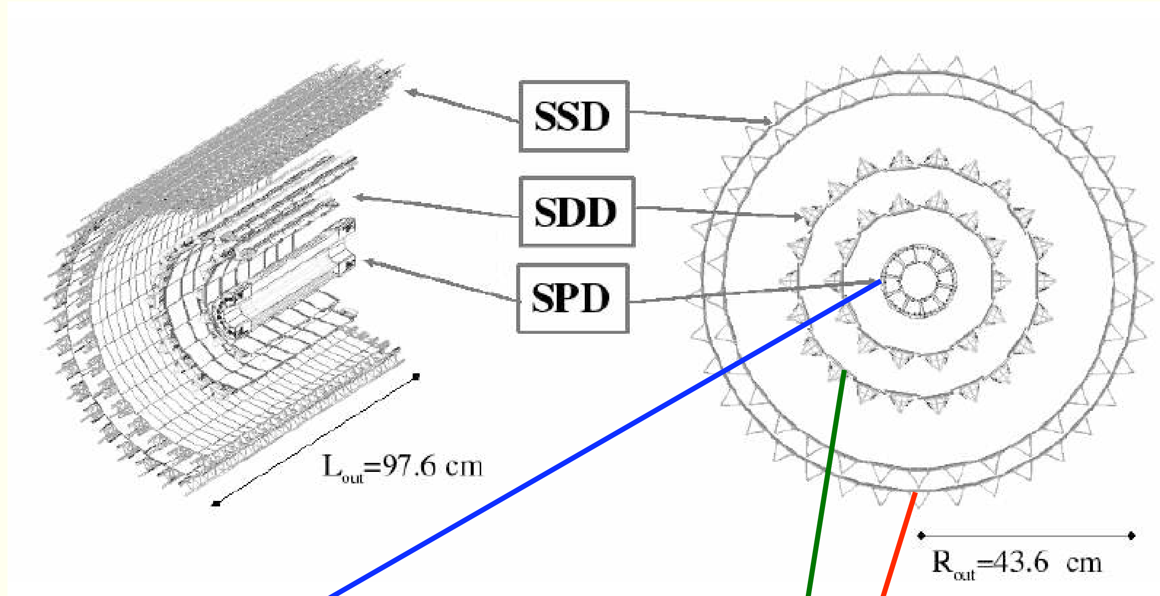


ALICE in 2004

2.2 Inner Tracking System (ITS)

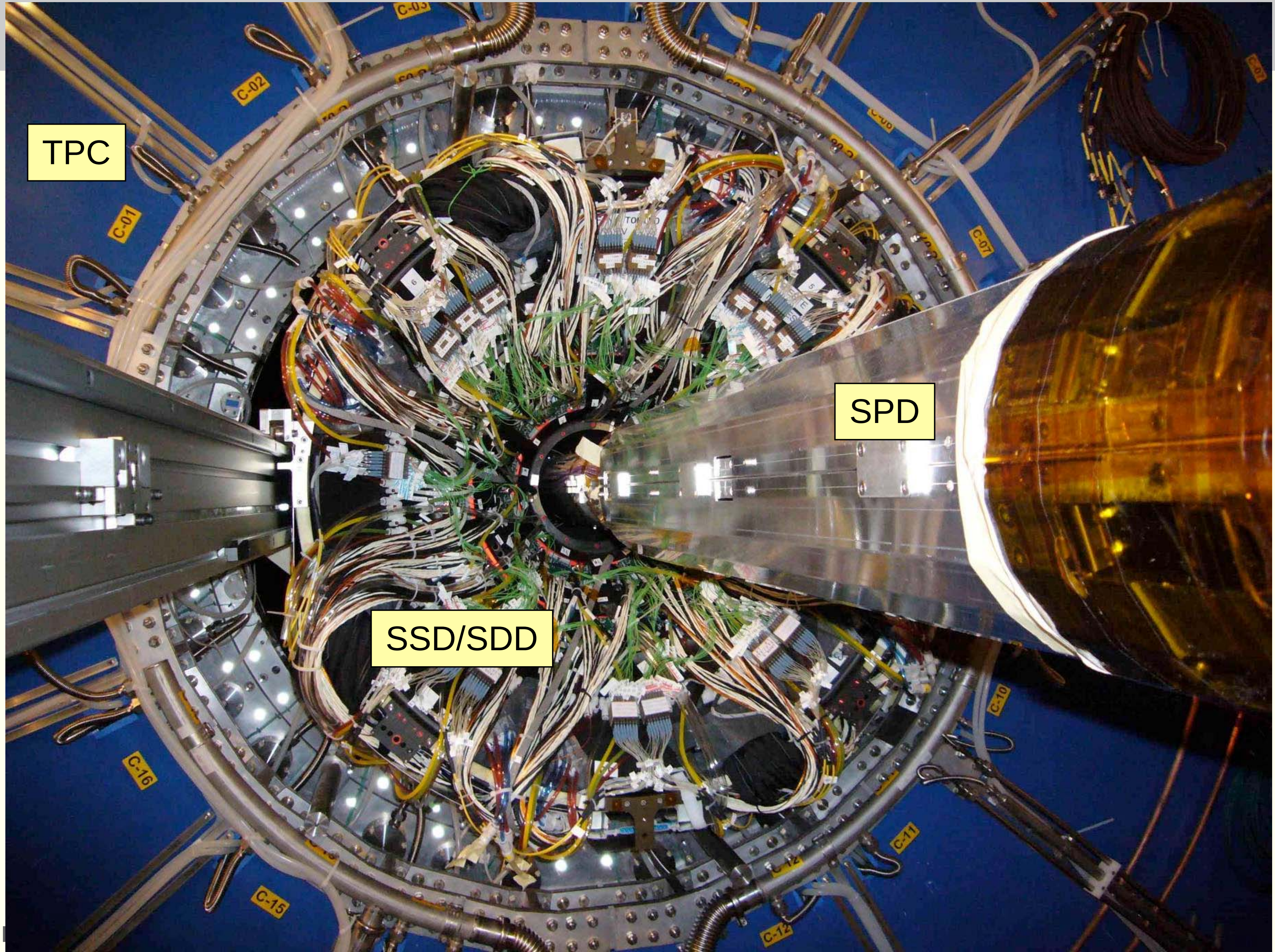
Inner Tracking System (ITS)

- **6 layers silicon**
  - **2 pixel detectors (SPD)**
  - **2 drift detectors (SDD)**
  - **2 strip detector (SSD)**
- **Reconstruction of primary vertex (σ < 100 μm)**
- **Secondary vertex, e.g., for heavy-quark measurements**



3 x 2 Layers Silicon Technology

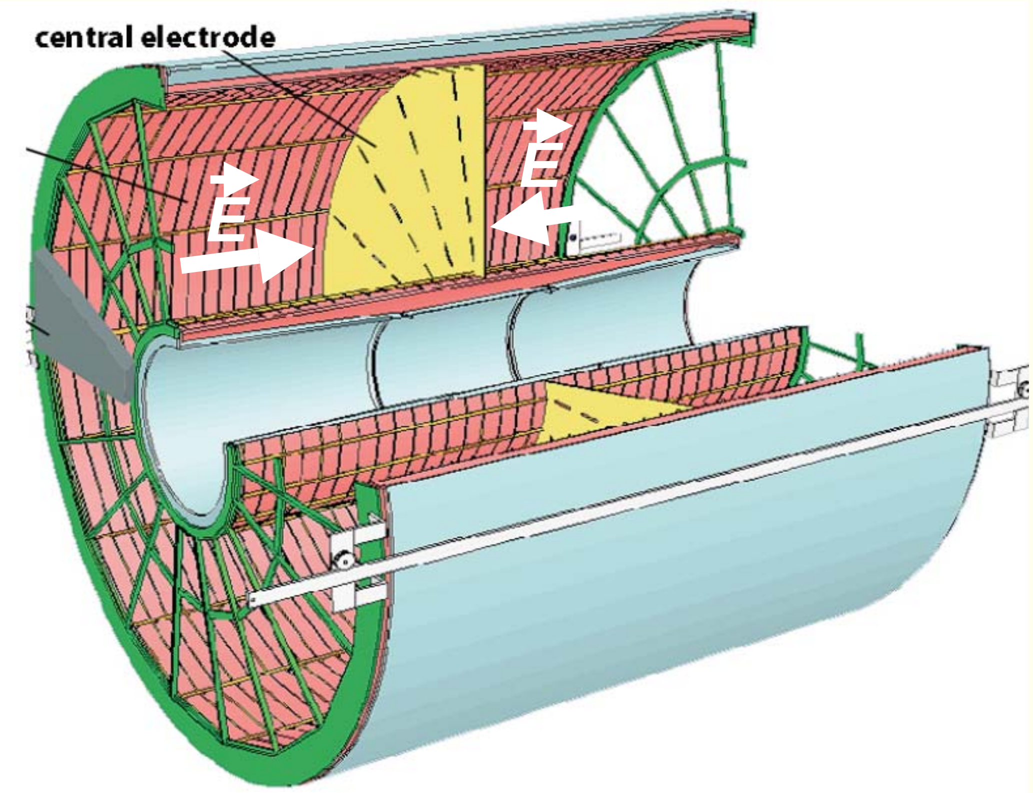
ITS - Sliding the SSD/SDD over the SPD



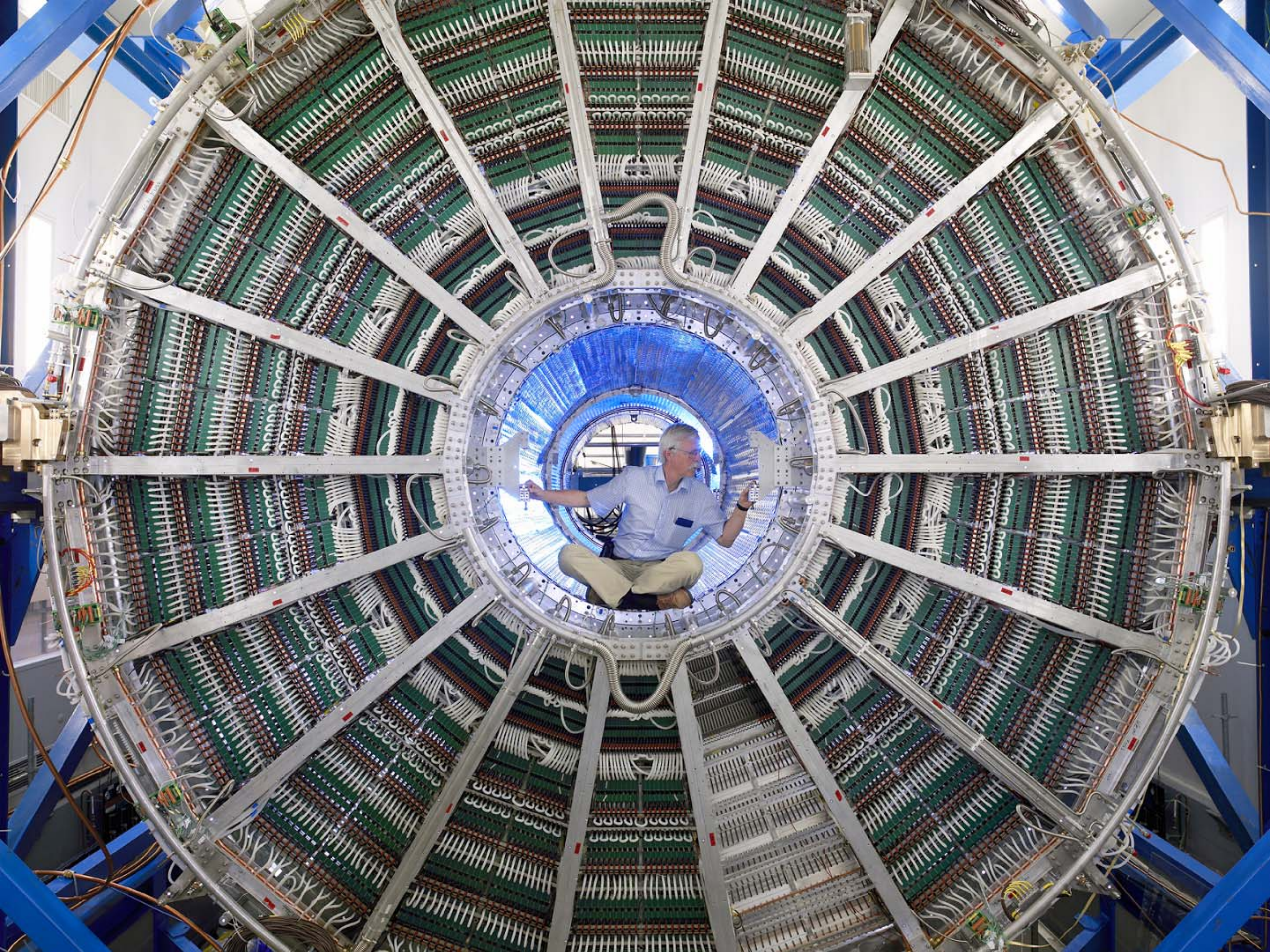
2.3 Time Projection Chamber (TPC)

ALICE TPC: The world's largest Time Projection Chamber

- Radius: 85 cm – 247 cm
- Length: 2×2.5 m
- ~ 90 m^3 gas: Ne/CO_2 (90/10)
- Drift field: E = 400 V/cm
- Drift length: 2×2.5 m
- Drift time: 88 µs (500 bins)
- MWPC readout
- #channels: 560,000
- Max. trigger rate: 200 Hz
- 180 space points/track: ($\sigma_{x,y,z}$ < 500 µm)
- Can handle up 15000 tracks



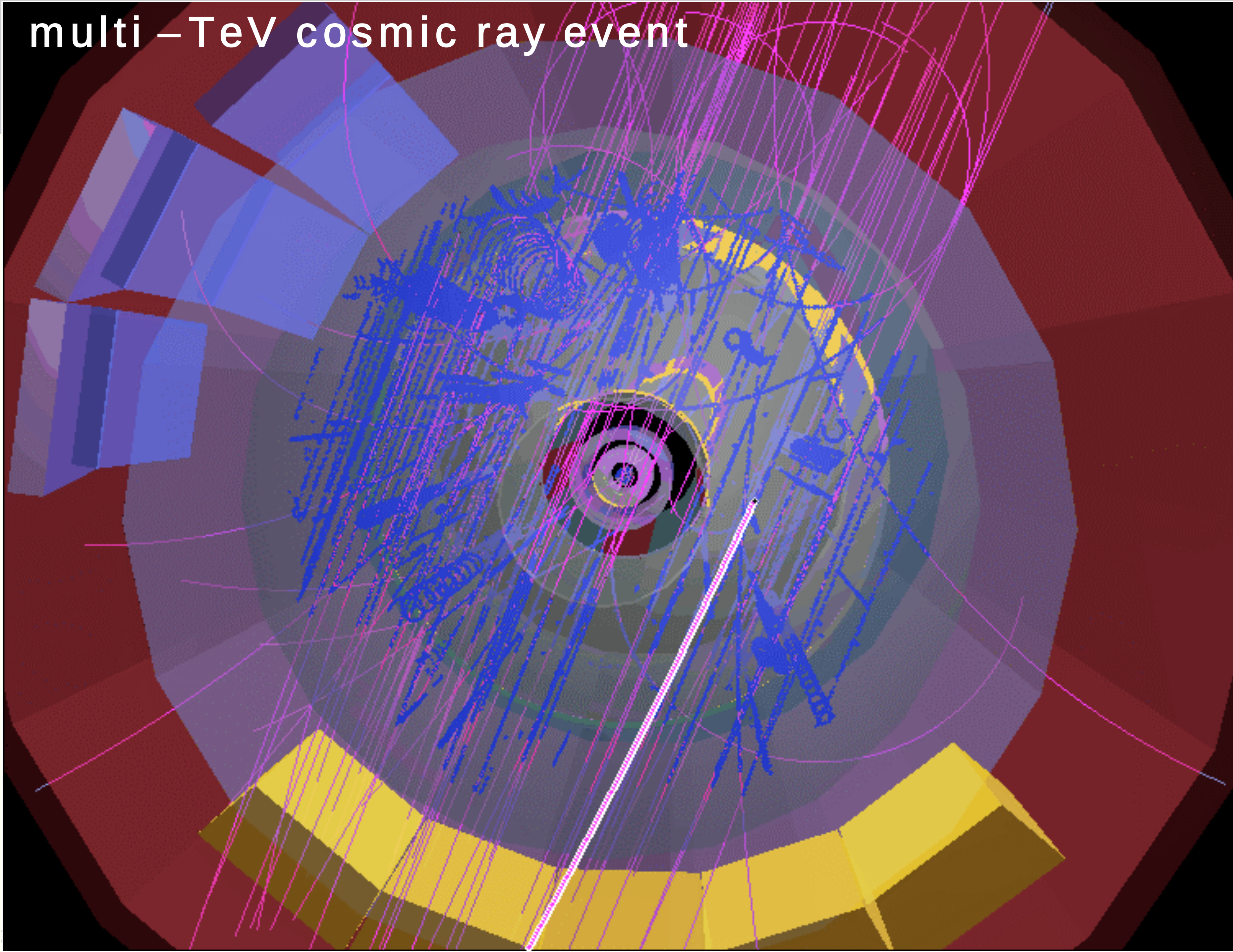
Nominal B field: 0.5 T
→ particle ID down to p_T ~ 100 MeV/c
(cf. ATLAS: 2 T, CMS: 4 T)



TPC Installation (January 2007)

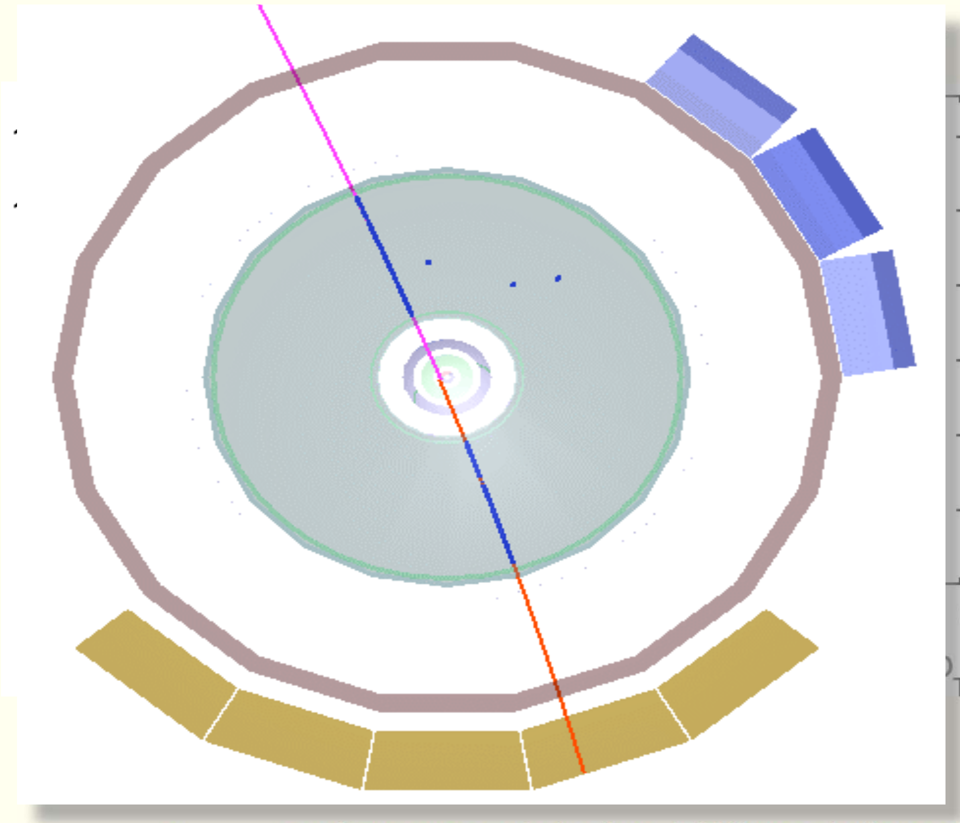
< 100 m horizontal, < 100 m vertical in 2 days
<v> = 4 m/hour

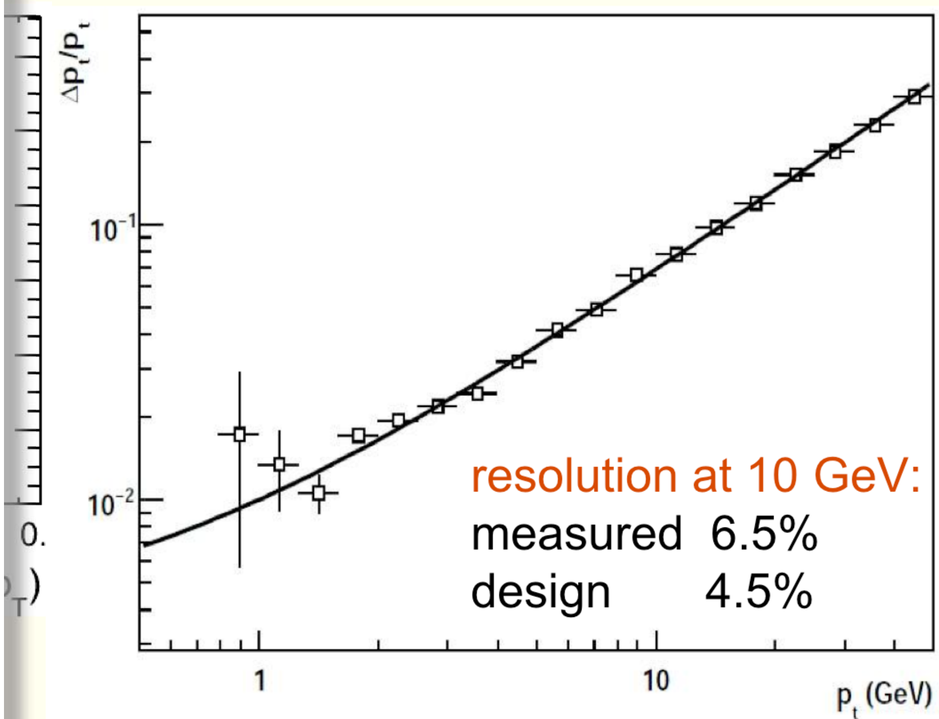
multi – TeV cosmic ray event



TPC commissioning

- **TPC installed in ALICE, running continuously May-October 2008, and since Aug 2009**
- **60 million events (cosmics, krypton, and laser) recorded**





- performance at design, TPC ready for collisions

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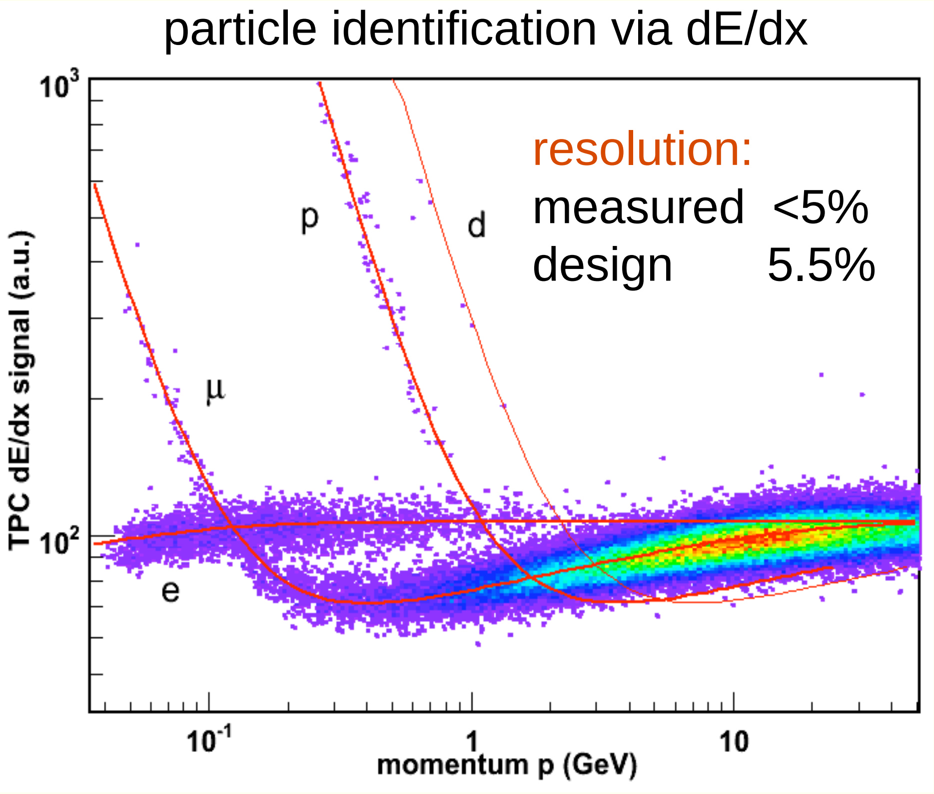
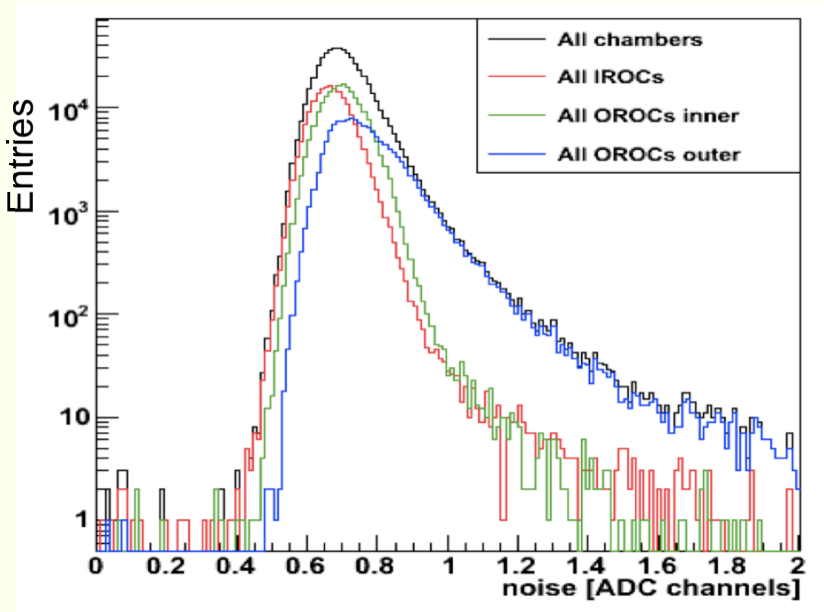


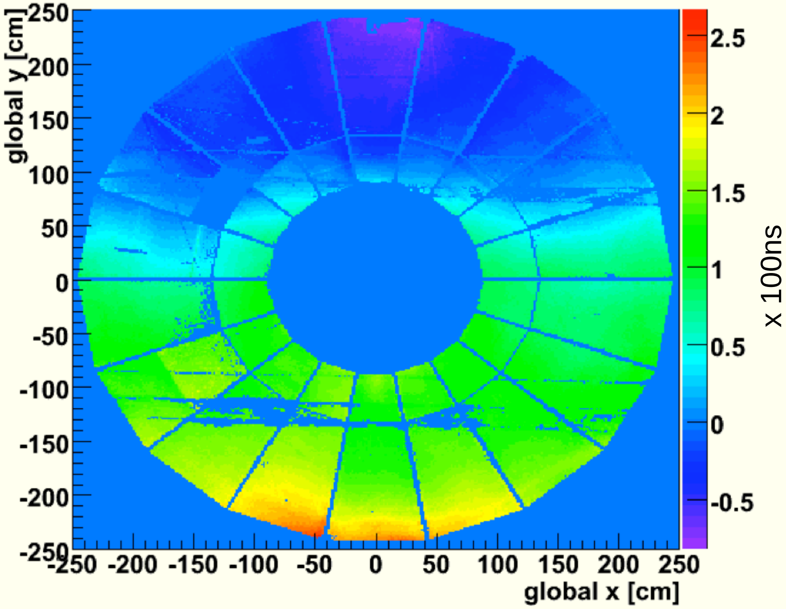
performance at design, TPC ready for collisions

Electronic Noise and Drift Velocity



average noise = 700 electrons close to theoretical limit

Rel. arrival time



required drift velocity uniformity: 0.3‰
measured: 1‰, consistent with ΔT = 0.3 K vertical variation

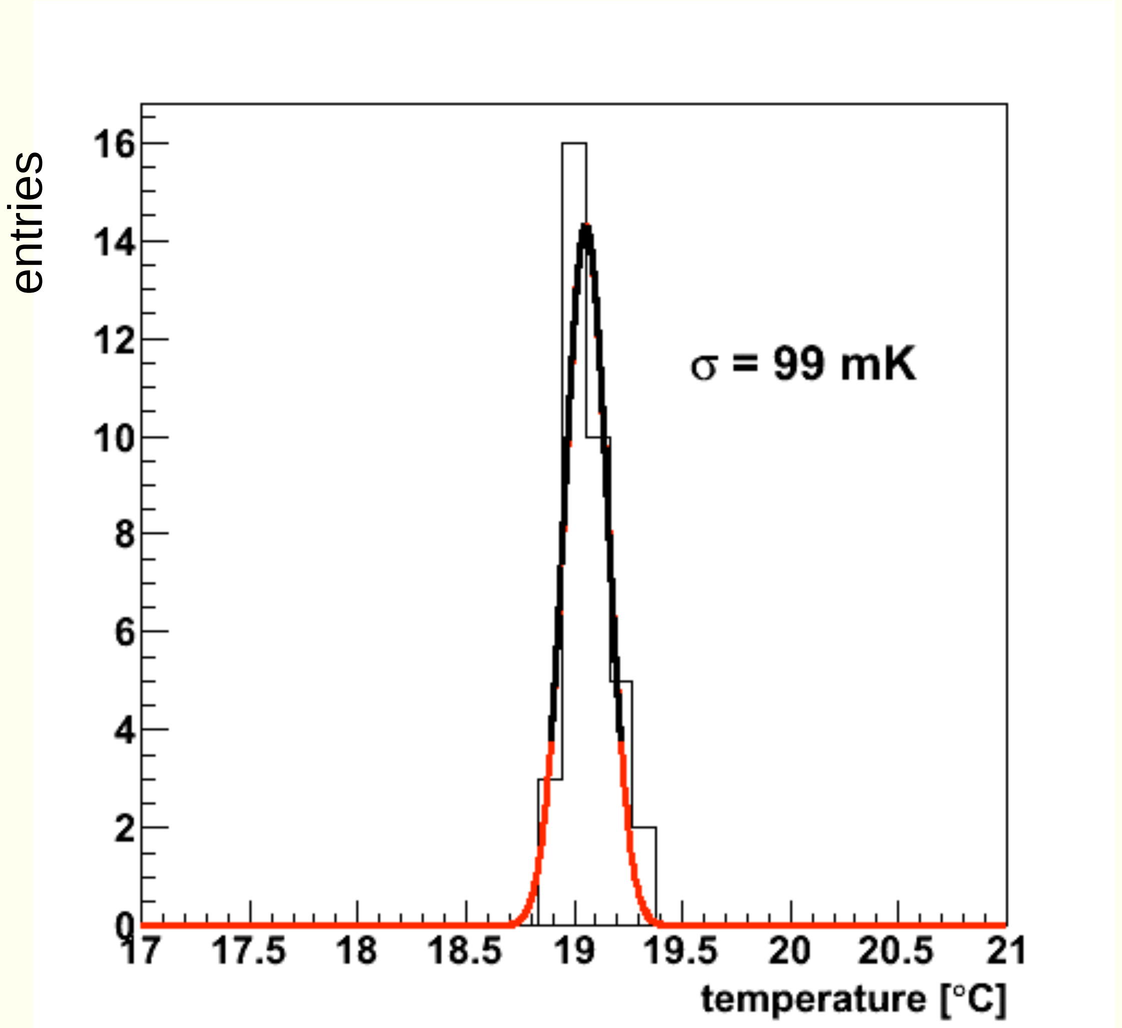
drift time map with laser (before optimization of cooling)

Temperature homogeneity

- Requirement: σ < 0.1 K

- Achieved by actively stabilizing 50 cooling loops using information from 500 temperature sensors (36 inside gas volume).

- Further improvements down to 80 mK in progress.

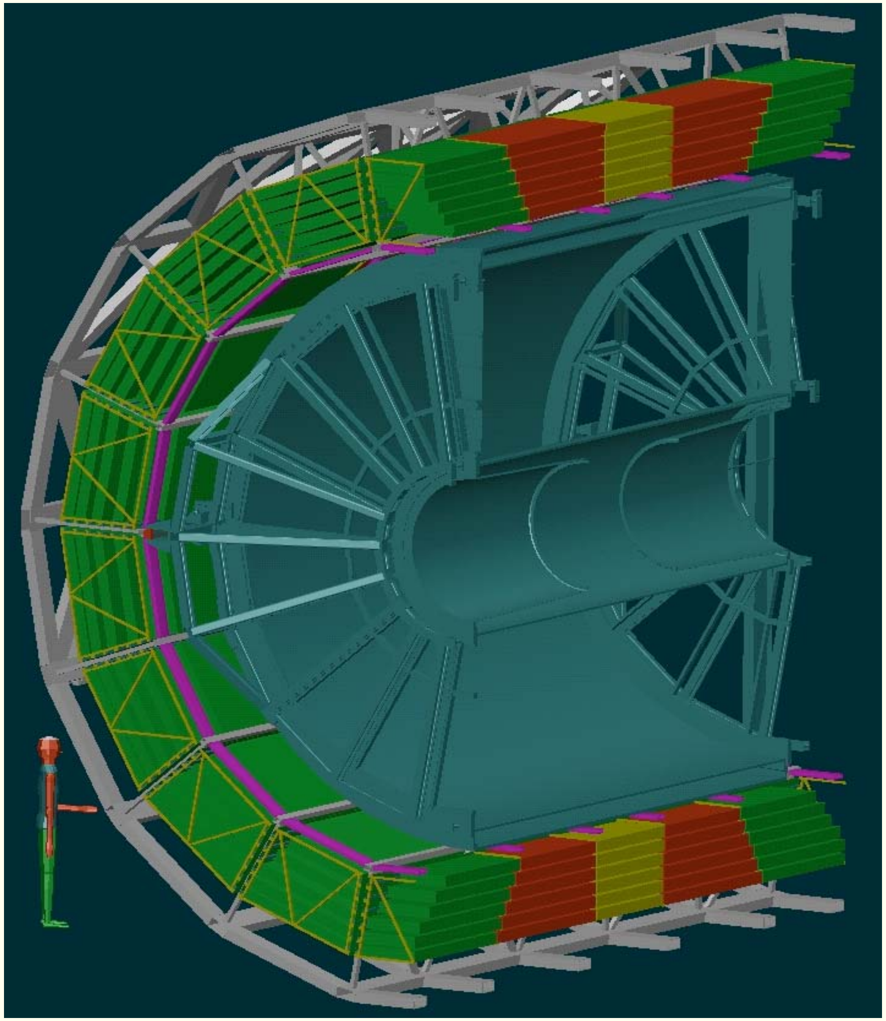


2.4 Transition Radiation Detector (TRD)

Transition Radiation Detector

- **electron identification and trigger**
- **quarkonia → e^+e^-**
- **charm and beauty**

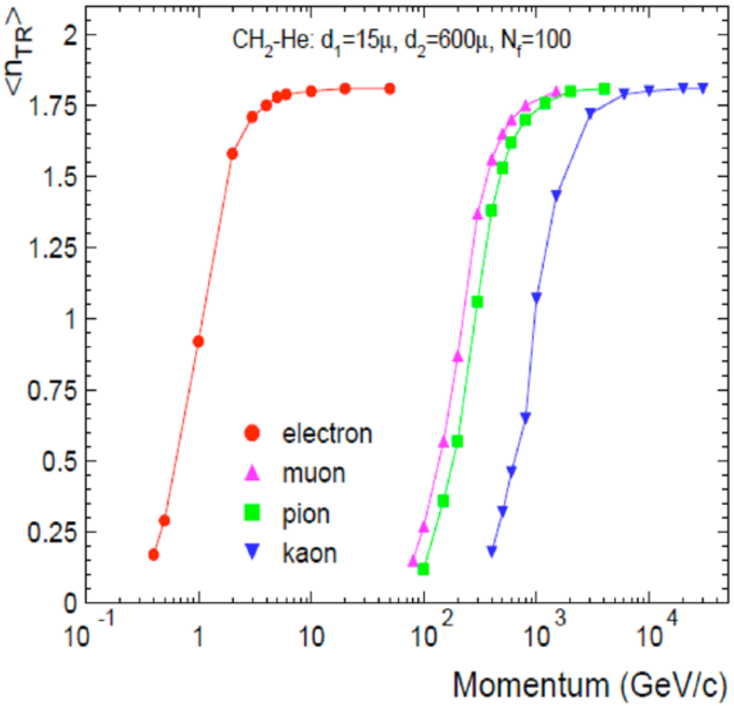
- 540 chambers /18 supermodules
- total area: **694 m^2**
  (3 tennis courts)
- gas volume: **25.8 m^3**
  ($Xe\text{-}CO_2$)
- resolution (rφ): **400 µm**
- read-out channels: **1.2×10^6**
  (30 million pixels)
- power dissipation: **70 kW**



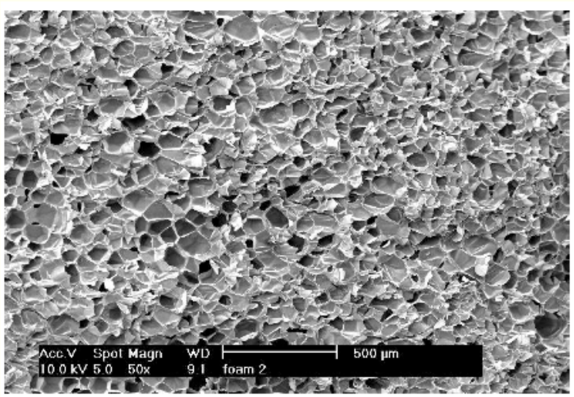
- **chamber production finished**
- **7 supermodules in 2009**
- **completion 2010**

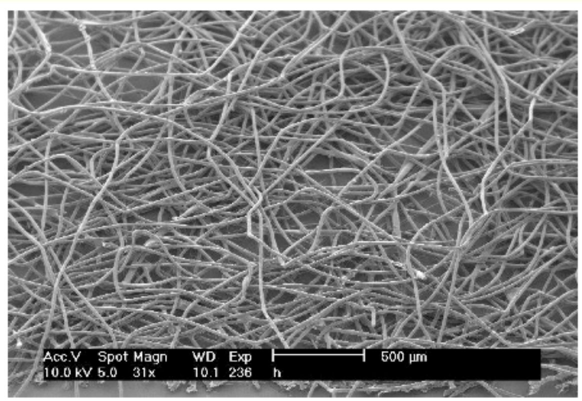
90% funded by Germany: GSI,
Univ. DA, HD,FRA,MS, FH Cologne, Worms

Transition Radiation

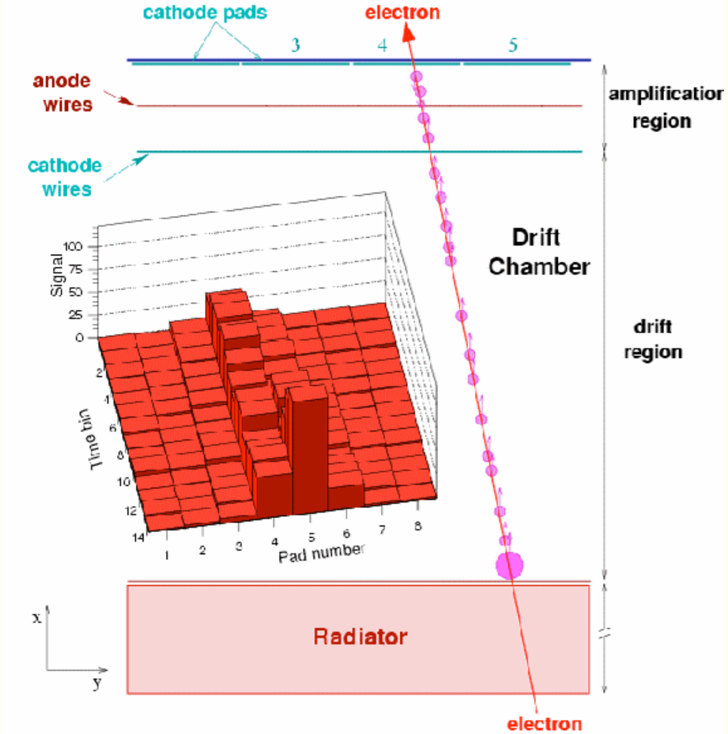


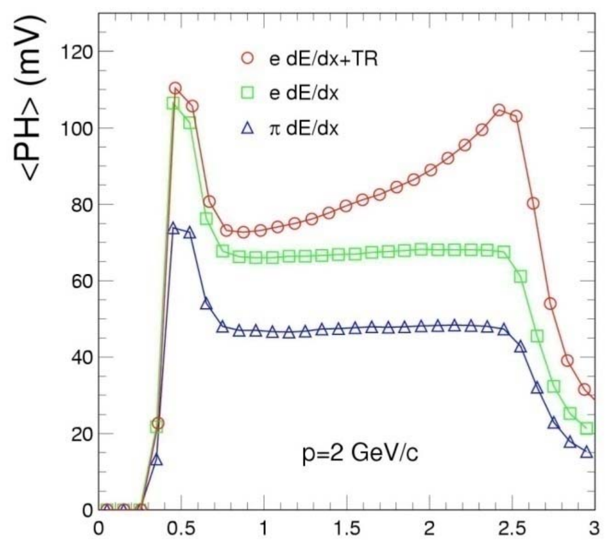
- **Charged particles** emit **transition radiation** when cross **boundaries** of media with **different ε**
- Small probability
  ⇒ many boundaries
- Here: **Lorentz factor** γ > 1000
  ⇒ **only electrons emit TR**
  ⇒ **identify electrons !**

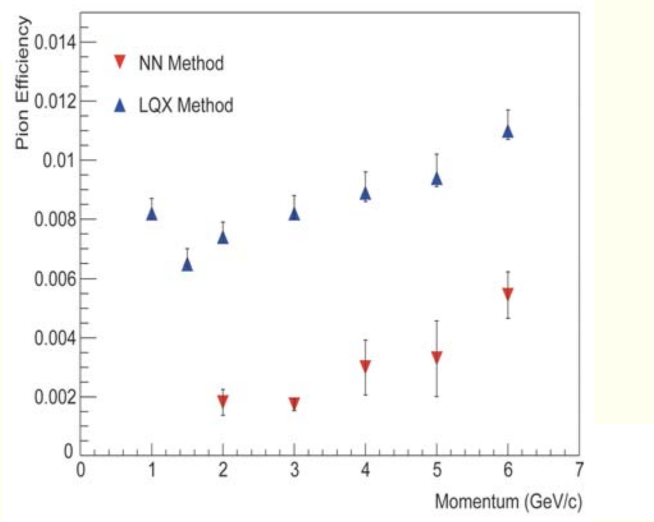




TRD – Signal Generation





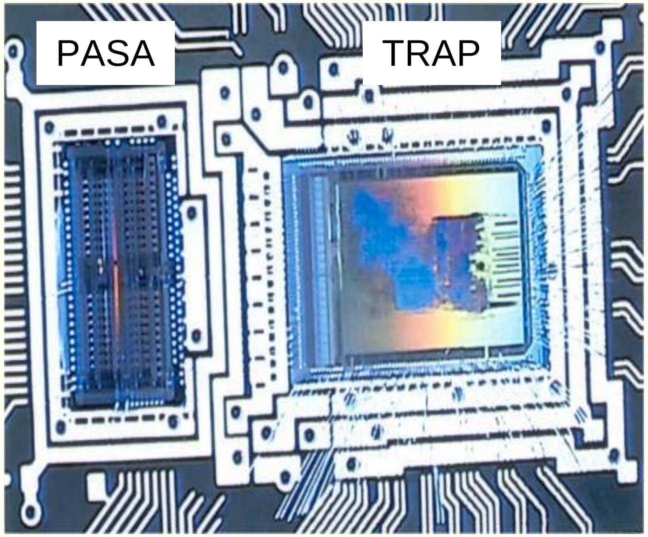


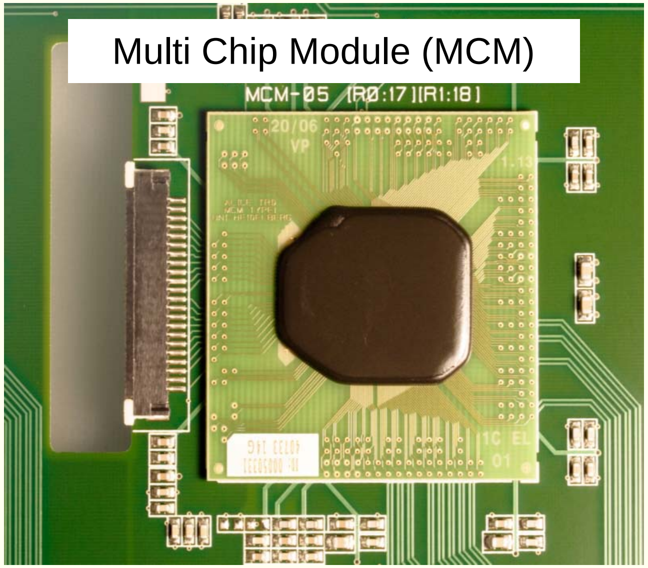
Charged particles induce a signal in the detector

Only electrons produce transition radiation

Electron ID, misidentified pions 1 % or less

TRD – Signal Processing





- **2 custom designed ASICS**

- pre-amplifier/shaper (PASA)
- ADC/tracklet-processor (TRAP):

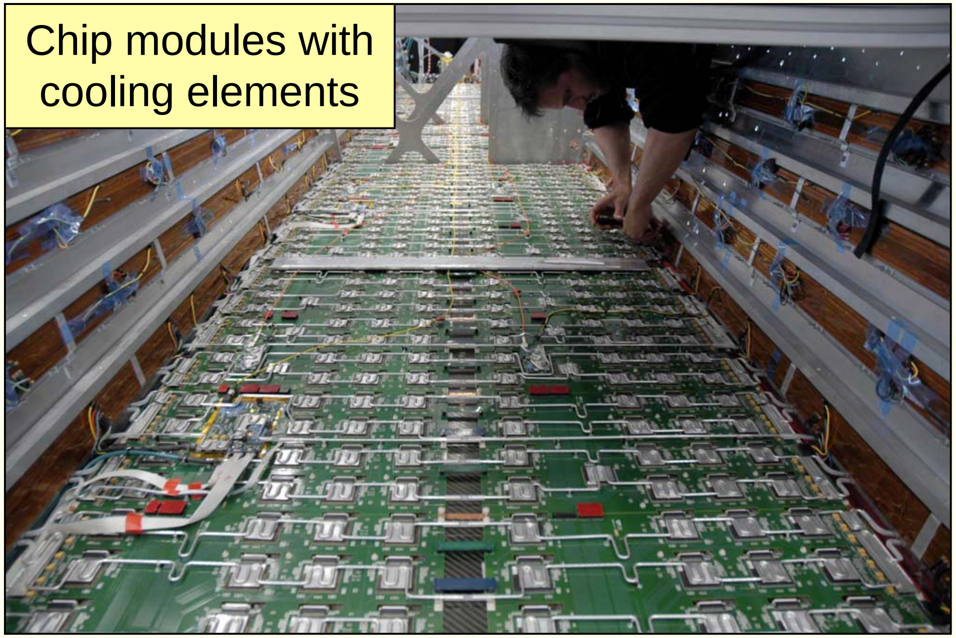
contain 275k CPUs to process 65 MBytes of raw data

- **tracking** and **trigger** decision within 6.5μs

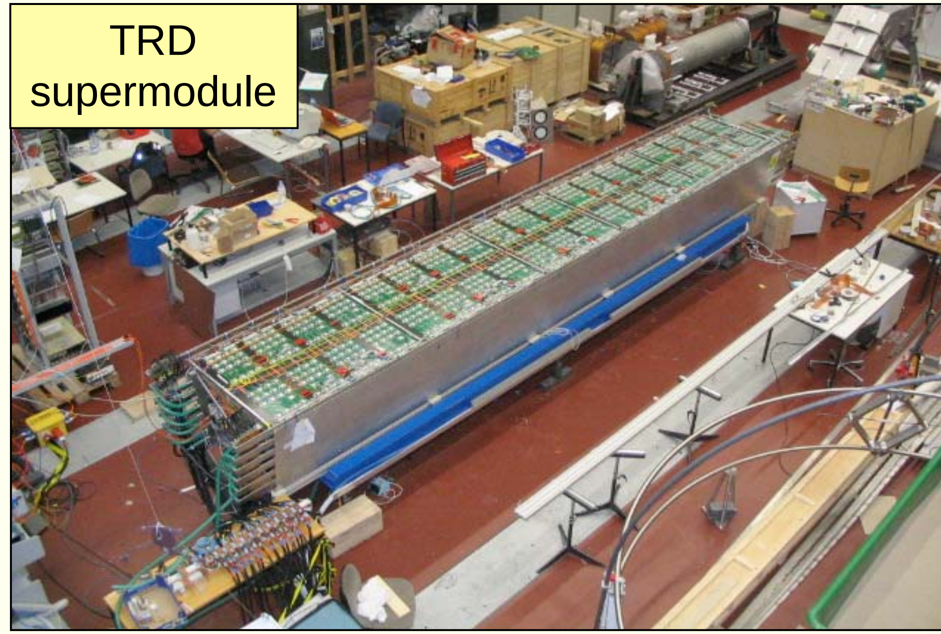
- selection of **high momentum electrons**

- 70kW cooling power required

First supermodule assembly – Heidelberg



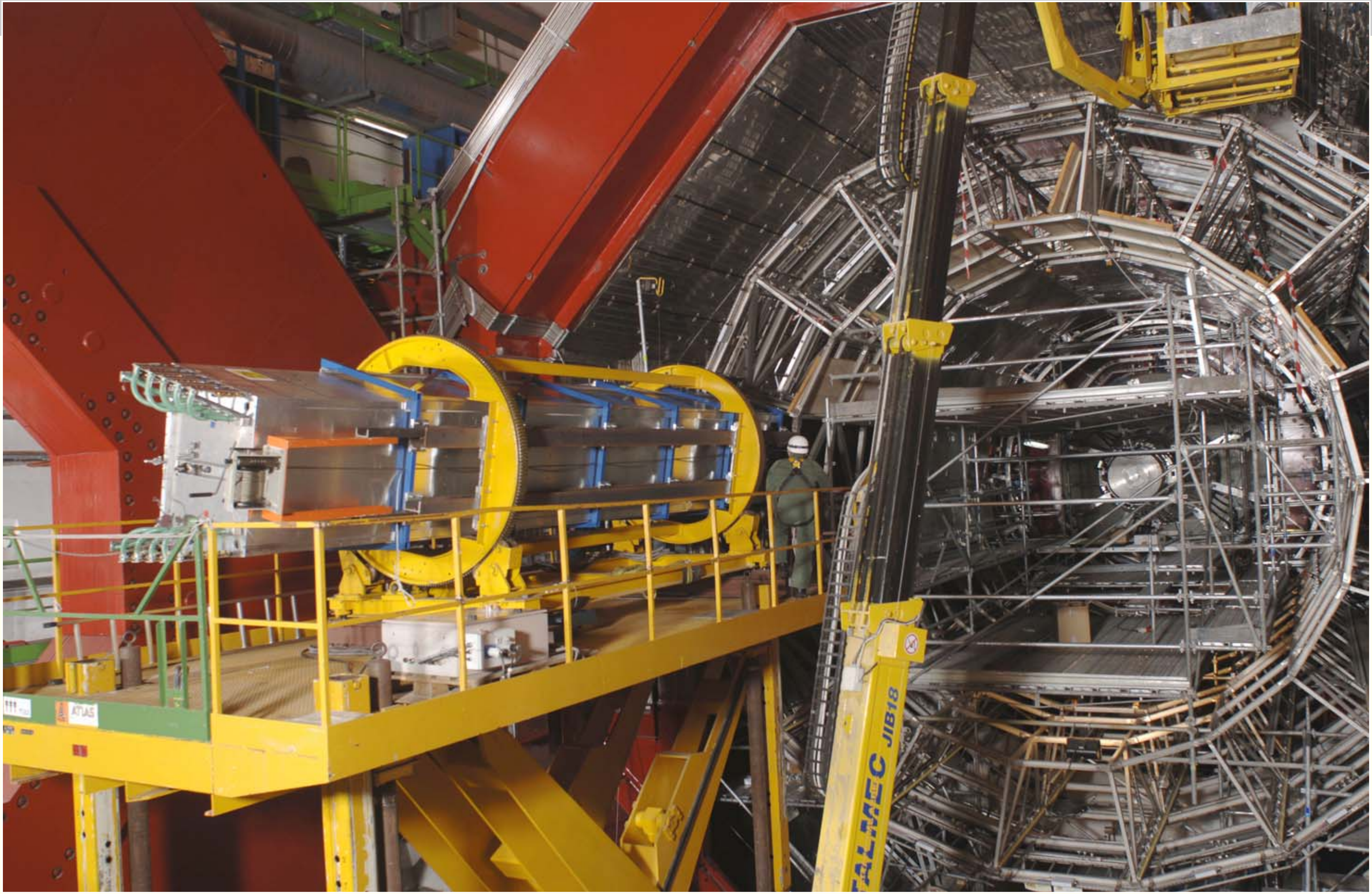
Installation of 2nd layer

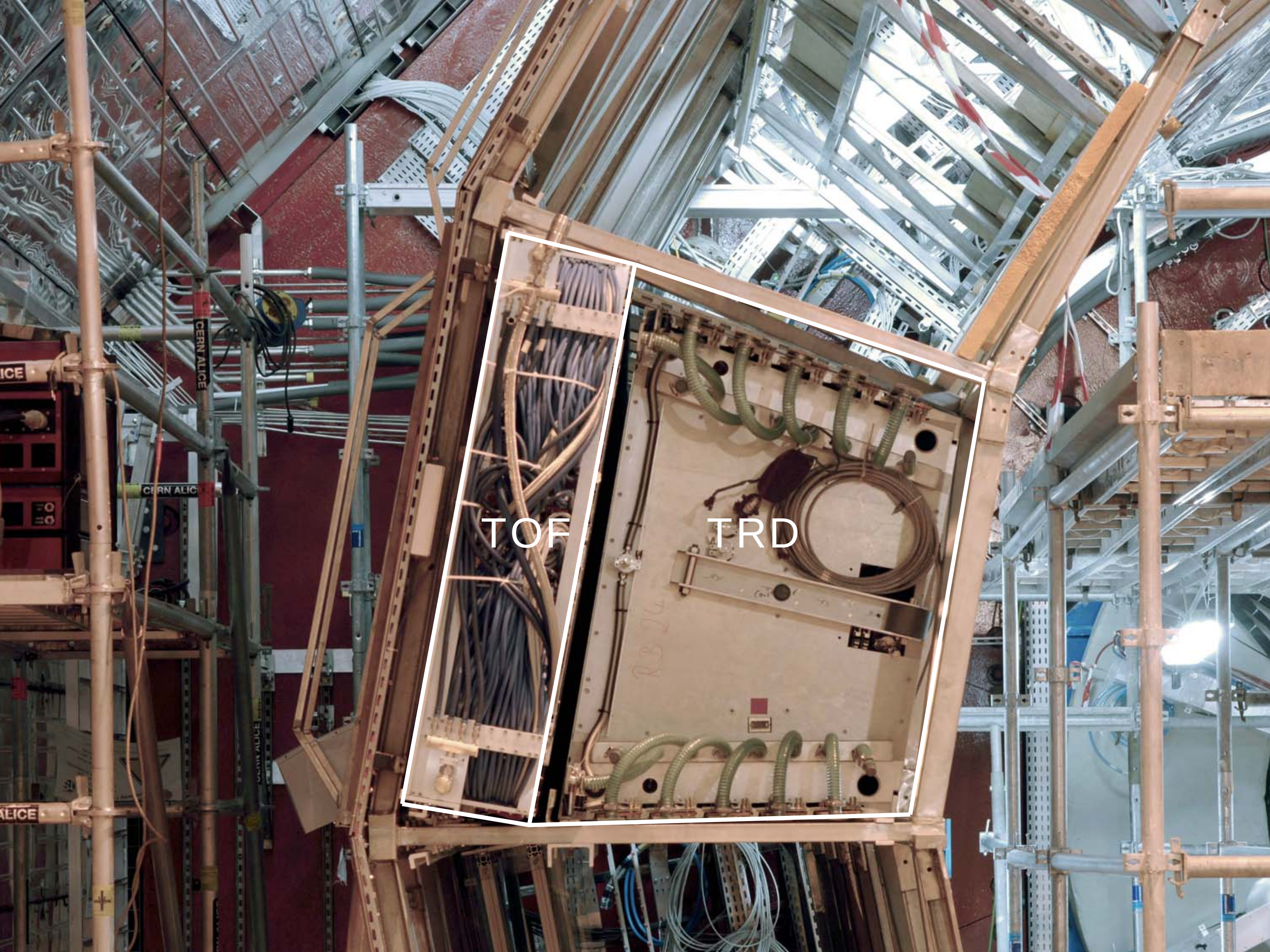


6th layer finished

getting ready for transport to CERN, shipped in Sep 2006

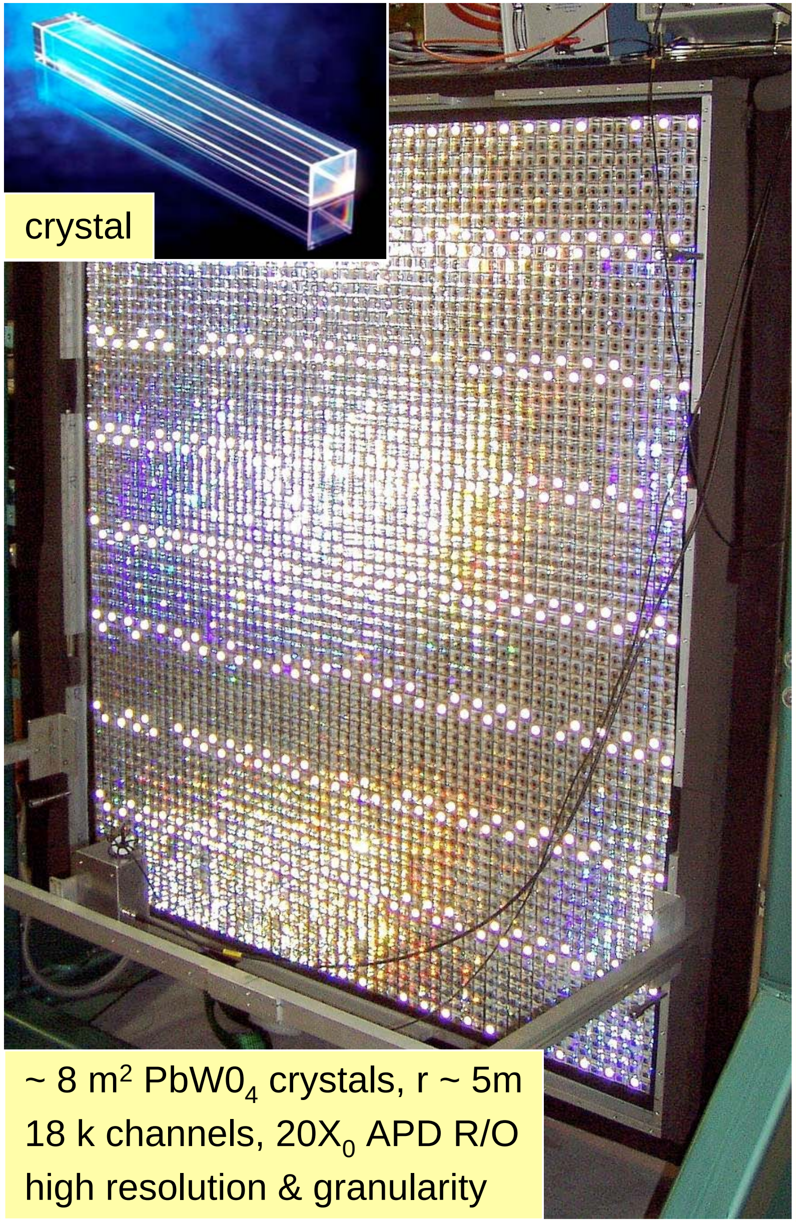
First TRD supermodule in ALICE – Oct 2006




TOF
TRD
CERN ALICE
CERN ALICE

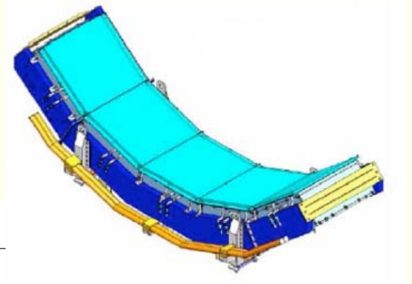
2.5 Calorimeters and more

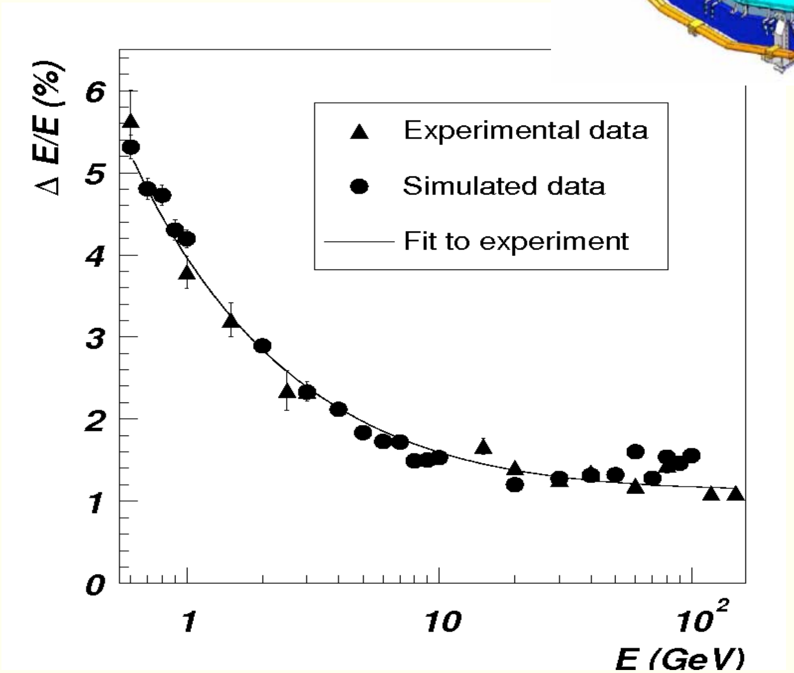
Photon Spectrometer



~ 8 m[2] $PbW0_4$ crystals, r ~ 5m
18 k channels, $20X_0$ APD R/O
high resolution & granularity

- Status: 3/5 constructed
  - 1 module installed & commissioned
  - 2 more modules to be constructed
  - complete by 2010

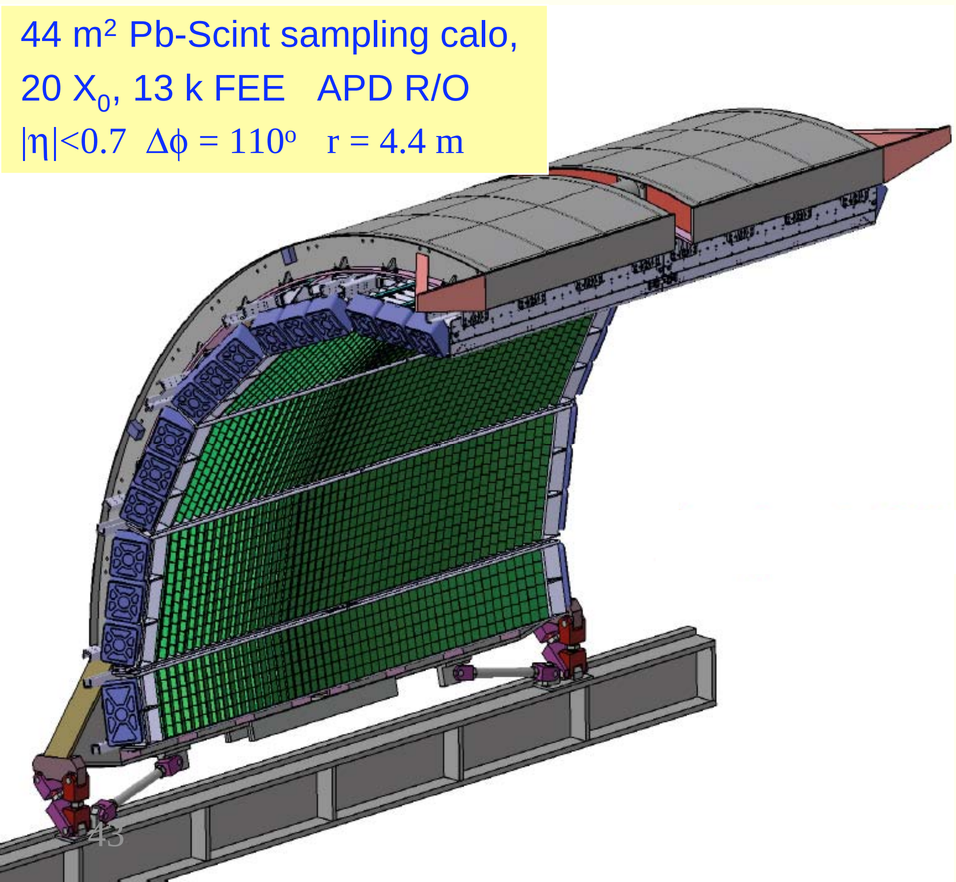




Electromagnetic Jet Calorimeter

- construction start April 2008
- approved & funded Dec 2008
- US, Italy, France, Finland
- approx. 20% to be installed by May
- complete early 2010

44 m^2 Pb-Scint sampling calo,
20 X_0, 13 k FEE APD R/O
$|\eta|<0.7$ $\Delta\phi = 110^o$ $r = 4.4$ m

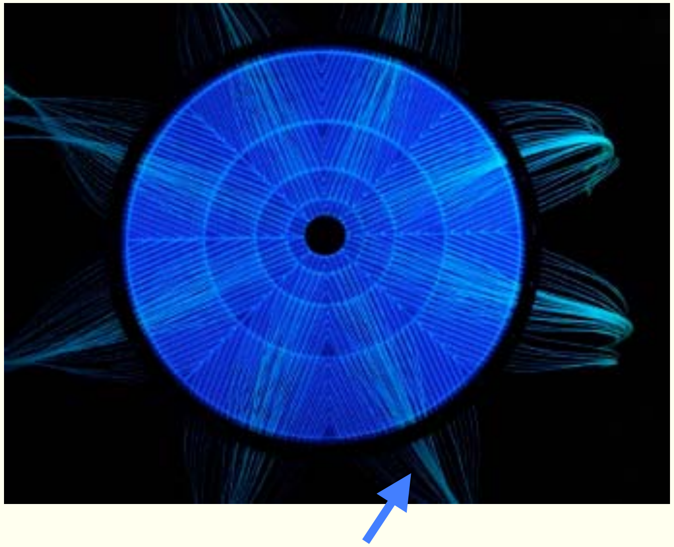


Nov 2007: EMCAL support

Forward Detectors

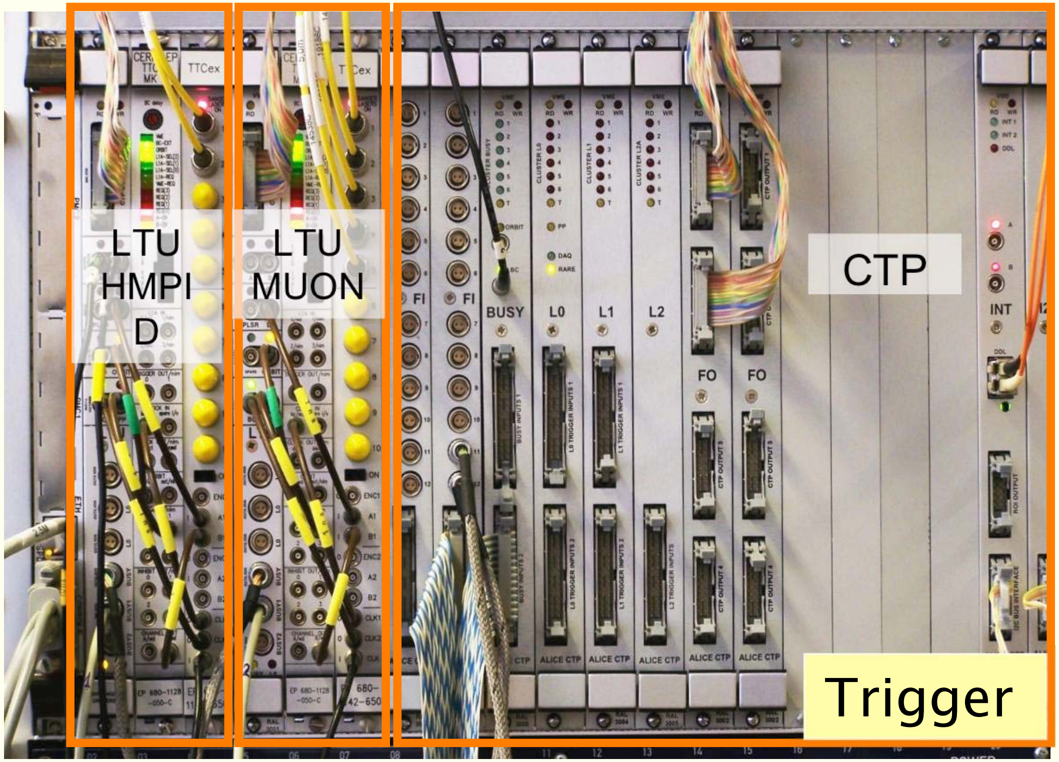
- FMD (Forward Multiplicity Detector)
  - 3 planes Si-pad, $-3.4 < \eta < -1.7$, $1.7 < \eta < 5.0$
- T0
  - 2-arrays 12 quartz Cherenkov counters
  - 30ps res.
  - Start for TOF detector
- V0
  - 2 scintillator arrays, 32 tiles
  - V0A: $1.7 < \eta < 5.0$, V0C: $-3.7 < \eta < -1.7$
  - Minimum bias trigger in p+p and A+A
- ZDC (Zero Degree Calorimeter)
  - 2-neutron, 2-proton calorimeters, 116m from IP
- PMD (Photon Multiplicity Detector)
  - $2.3 < \eta < 3.5$

V0A detector:



wave length shifting fibers

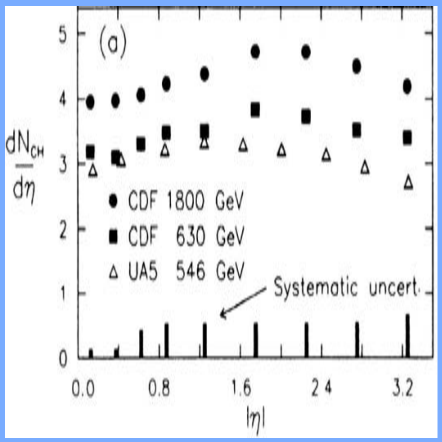
Trigger and Data Acquisition



- Trigger: **three level architecture L0, L1, L2**
- Continuous online operation
  from March to September 2008 (24/7):
  - **up to 500 (1200) MB/s transfer**
  - **raw data rate of 2.5 PBytes / year**

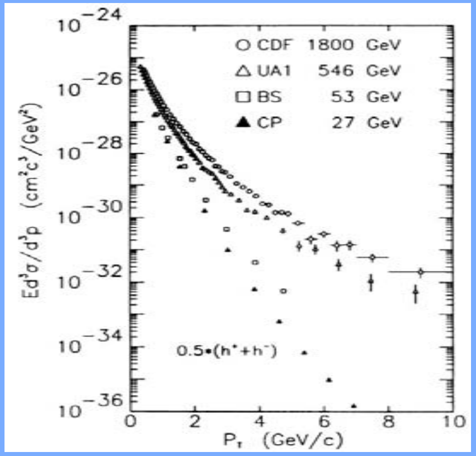
ALICE: First Physics Topics

Claus Jorgensen



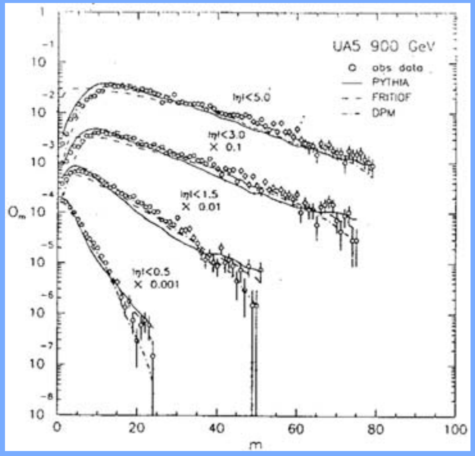
Pseudorapidity density $dN/d\eta$

CDF:
Phys. Rev.
D41, 2330 (1990)



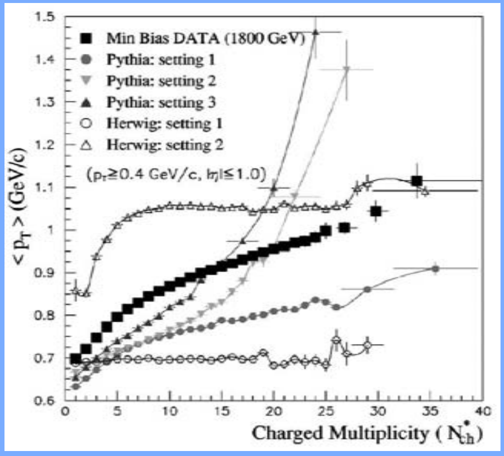
p_T spectrum of charged tracks

CDF:
Phys. Rev. Lett.
51, 1819 (1988)



Multiplicity distribution

UA5:
Z. Phys
43, 357 (1989)



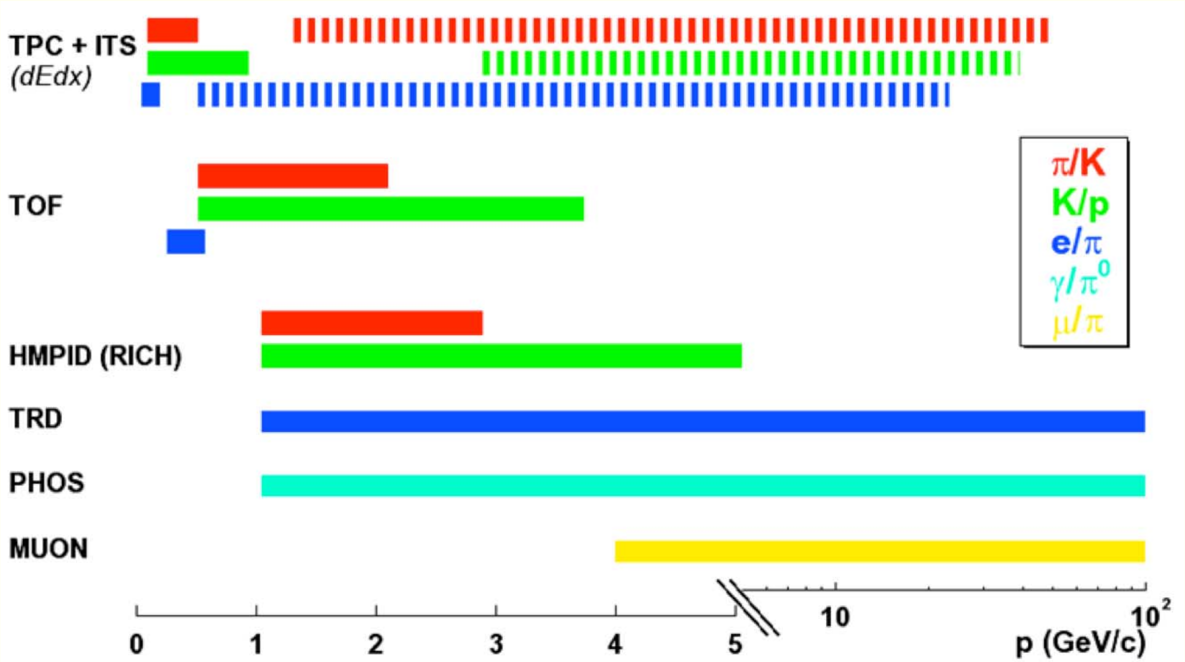
Mean p_T vs multiplicity

CDF:
Phys. Rev.
D65,072005(2002)

Only a few ten thousand events are necessary for these analyses

Extra Slides

Particle Identification in ALICE



5 'stable' particle species: e, μ, π, K, p
Instable particles through decay products

Central Barrel

- velocity & momentum → mass of e, μ, π, K, p
- invariant mass → quarkonia, e.g. J/ψ, ϒ
- decay topology → K^0, K^+, K^-, Λ, D

Forward Rapidity
muon: p > 5 GeV/c

e,μ, photons, π^0

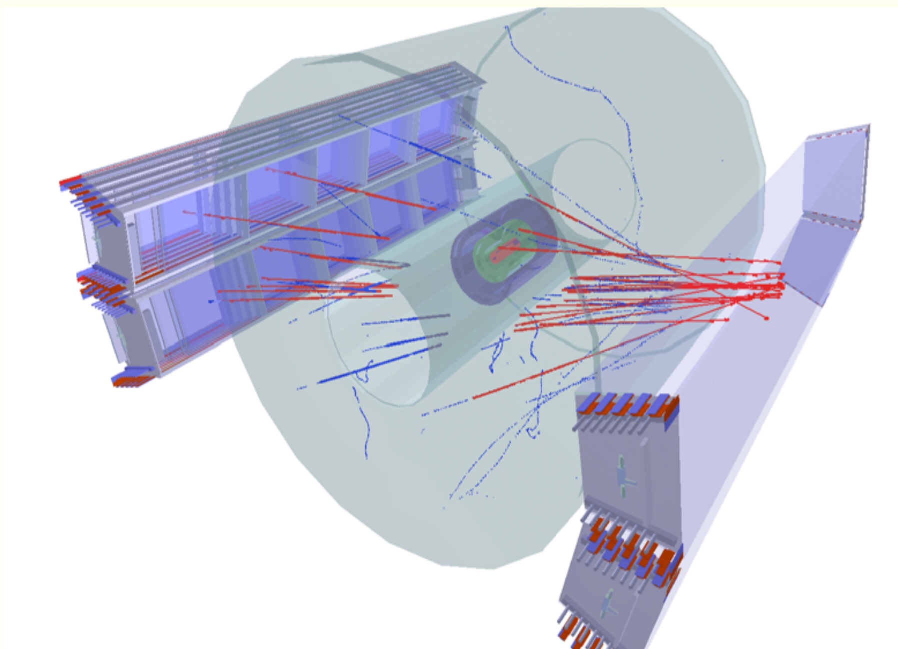
- e in TRD: p > 1 GeV/c
- π^0 in PHOS: 1 < p < 80 GeV/c

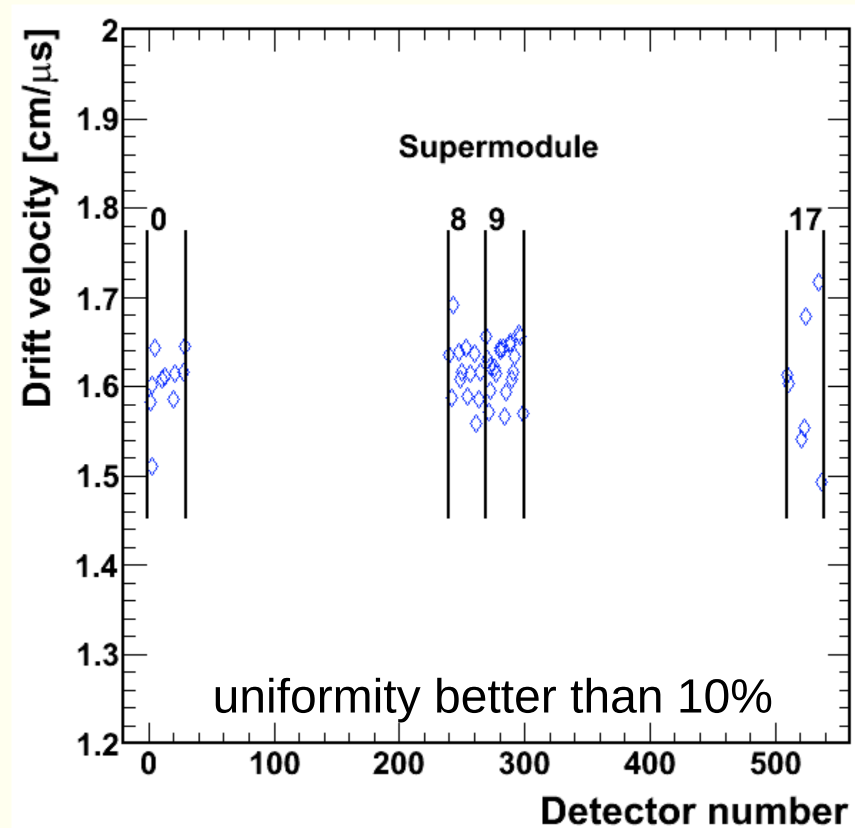
- excellent particle ID up to ~ 50 to 60 GeV/c

TRD commissioning

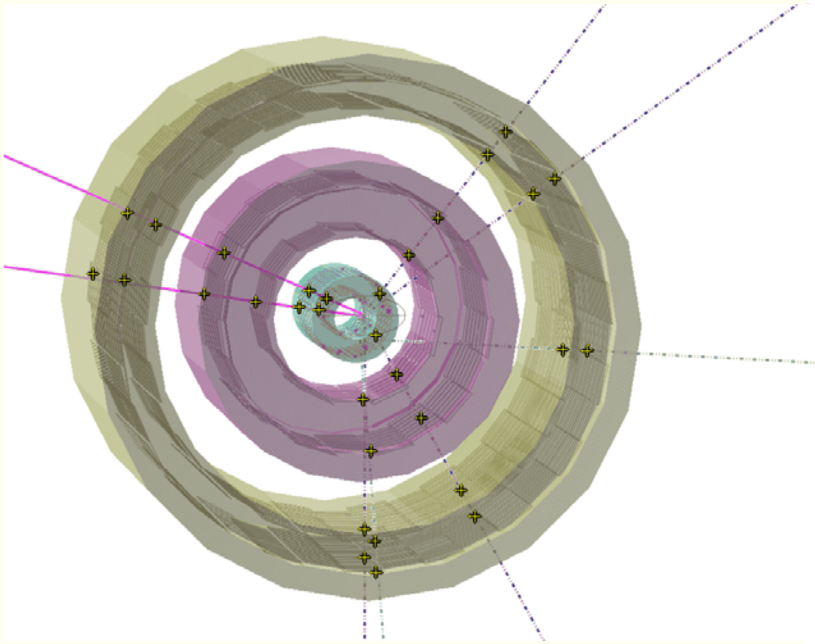
- 4 supermodules installed in ALICE, cosmic ray data taking in 2008
- 50 000 horizontal tracks acquired (TRD L1 trigger commissioned and used)
- Reconstruction and first iteration for calibration parameters (gain, drift velocity) completed

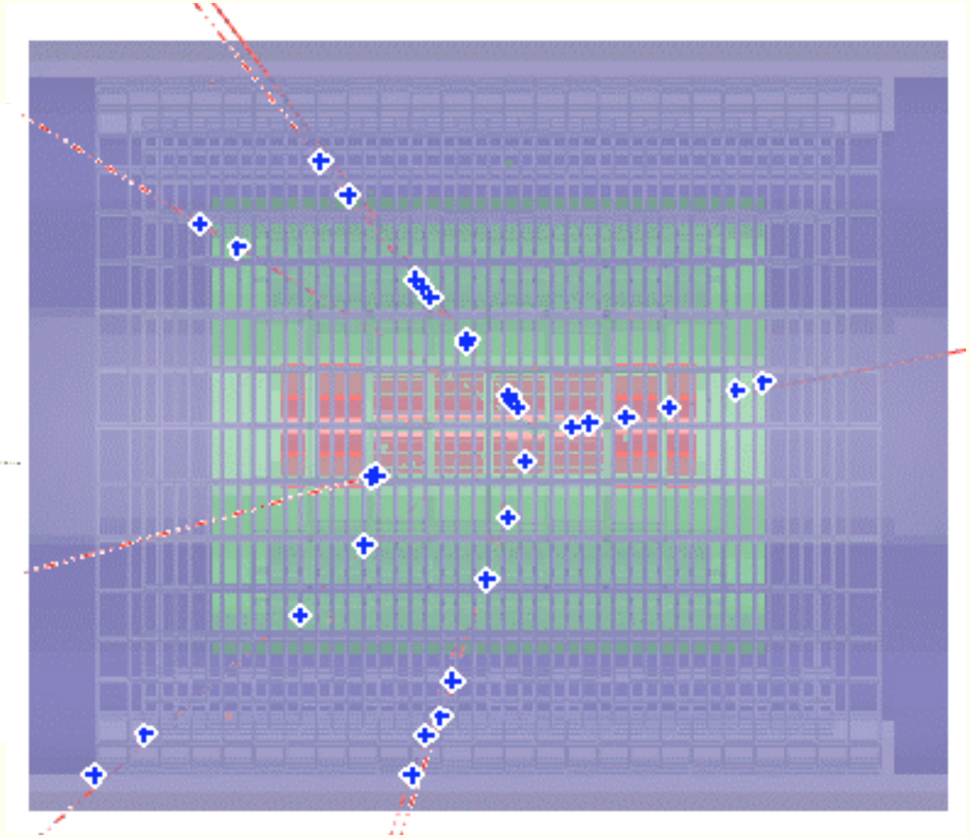
cosmic event triggered by TRD L1





Circulating Protons in LHC





ITS tracks on 12.9.2008
7 reconstructed tracks, common vertex

Circulating beam 2:
stray particle causing an interaction in the ITS