Experimental techniques in high-energy nuclear and particle physics

"Dottorato di Ricerca in Ingegneria dell'Informazione"

LECTURE 6a.

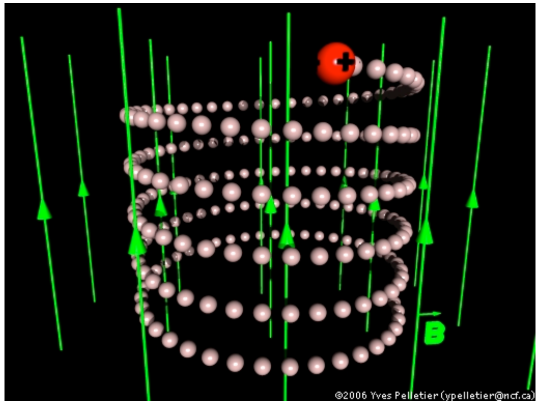
Tracking at LHC

Prof. Rino Castaldi
INFN-Pisa
rino.castaldi@pi.infn.it

Tracking: why

At hadron colliders the challenging aim is the full reconstruction of the events produced in the interaction under study. Therefore primary goals are:

✓ reconstruct the trajectories ("tracking") of charged particles and measure their momenta



Most common case: in a solenoidal uniform magnetic filed the Lorentz force

$$\vec{F} = \frac{d\vec{p}}{dt} = q\vec{E} + q\left(\vec{v} \times \vec{B}\right)$$

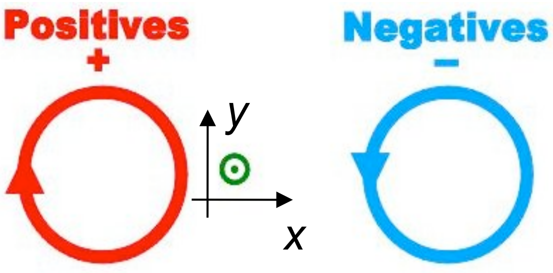
induce charged particles to follow a helicoidal path:

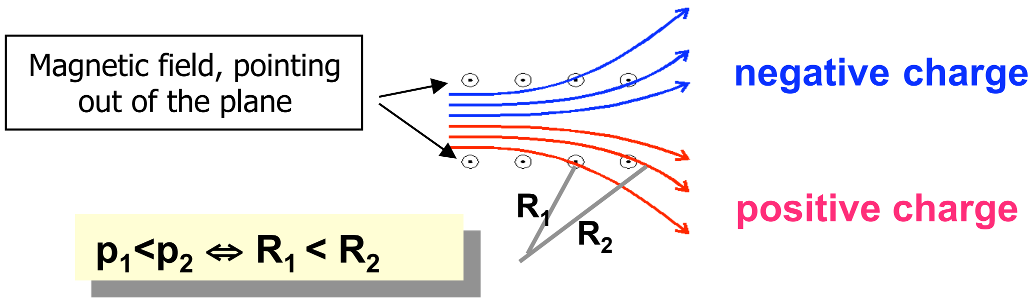
- describe circles in the transverse plane

- move uniformly along the magnetic field direction

$$P_T(GeV) = 0.3\ B(T)\ R(m)$$

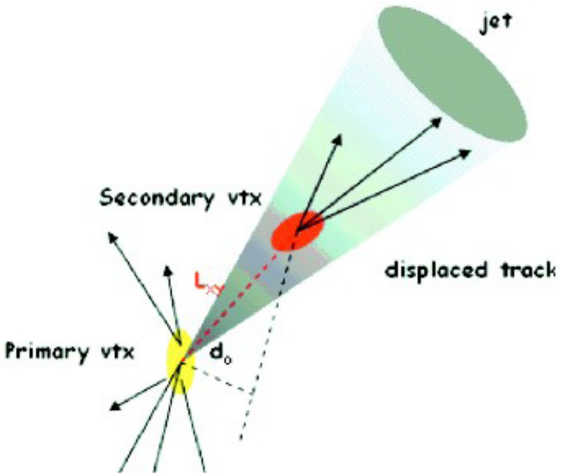
✓ identify the sign of the charge

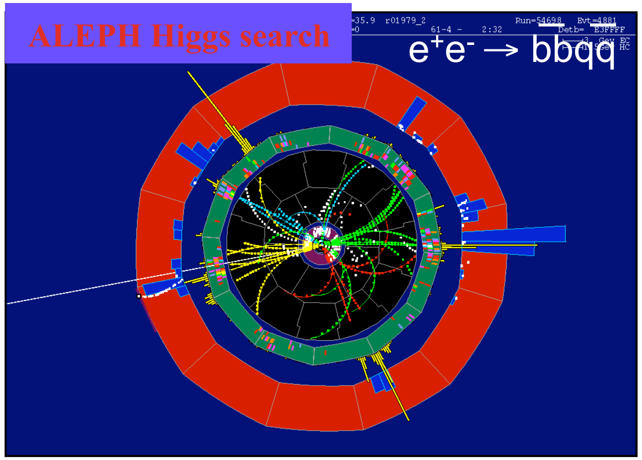


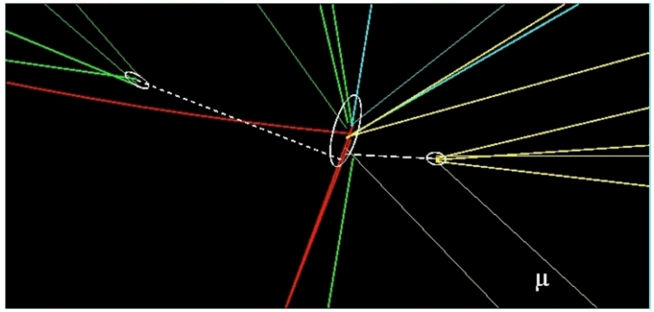


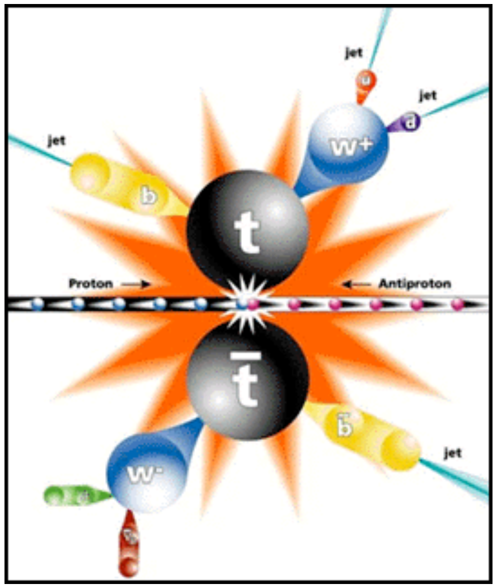
Tracking: why

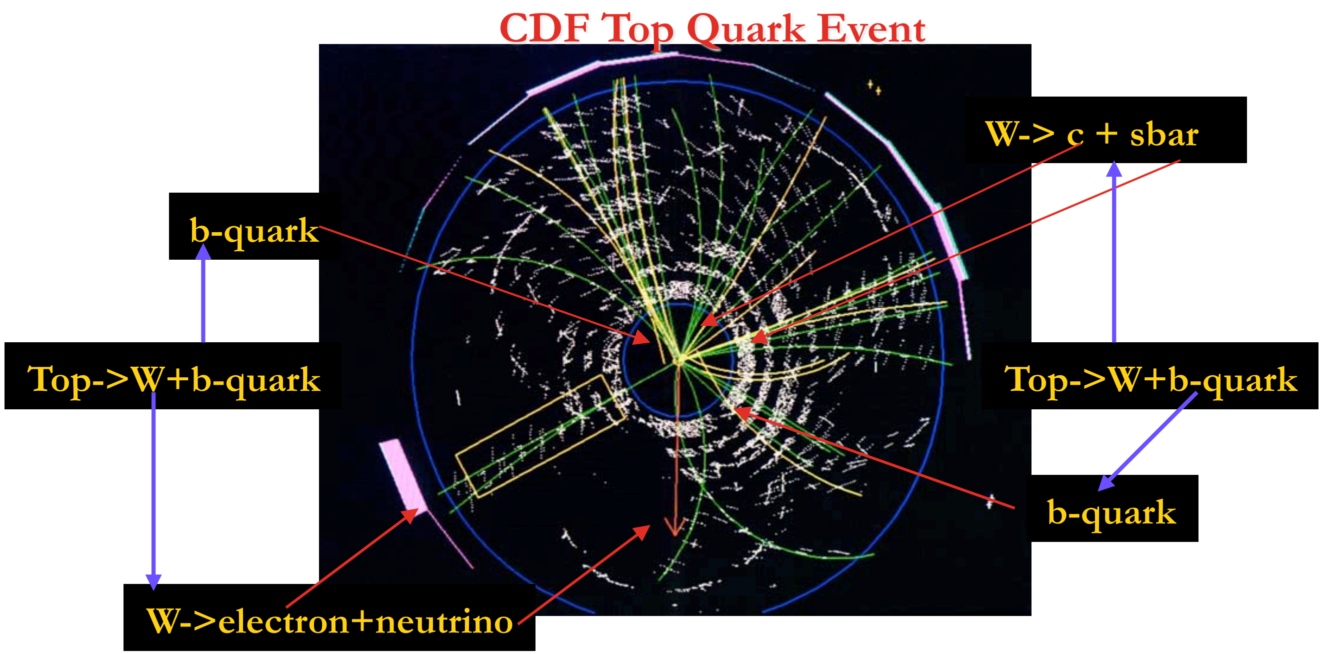
✓reconstruct the primary and secondary vertices of the interaction
(at LHC with large pile-up of events in the same bunch crossing !)











Tracking: a real challenge at LHC

- Tracking at LHC is a very complex procedure due to the high track density. It needs specific implementation adapted to the detector type and geometry

- Precise and efficient detector modules are required to measure where the particle crossed the module

- Fast and radiation hard detectors and electronics are needed

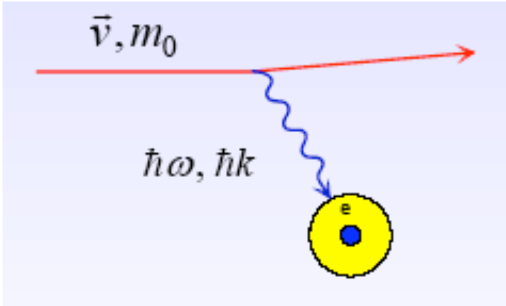
- Track reconstruction requires specific software implementation:
  - track finding (pattern recognition)
  - estimation of track parameters (fitting)

- Precise alignment of detector modules is a prerequisite for efficient tracking

Tracking: how

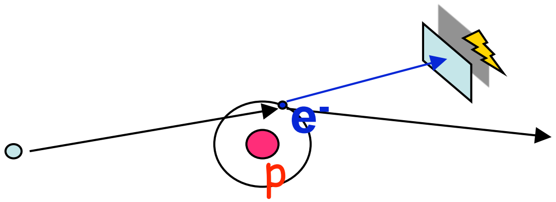
measureable signals occur via the interaction of particles with the detector material.

Dominant interaction is due to the coulomb interactions with the atomic *electrons* of the detector.



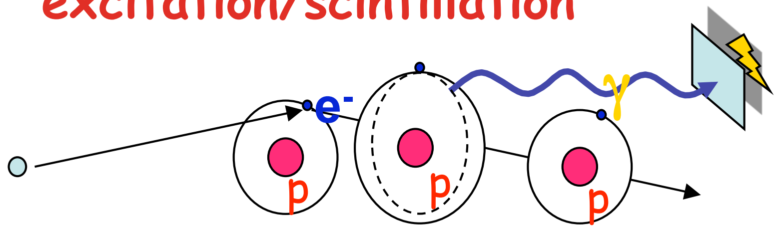
Depending on the $\hbar\omega$ value we may have:

- ionization



or

- excitation/scintillation



Ionization and excitation of atomic electrons in matter are the most common processes and allow to build precise tracking detectors .

Ionization: the Bethe-Bloch formula

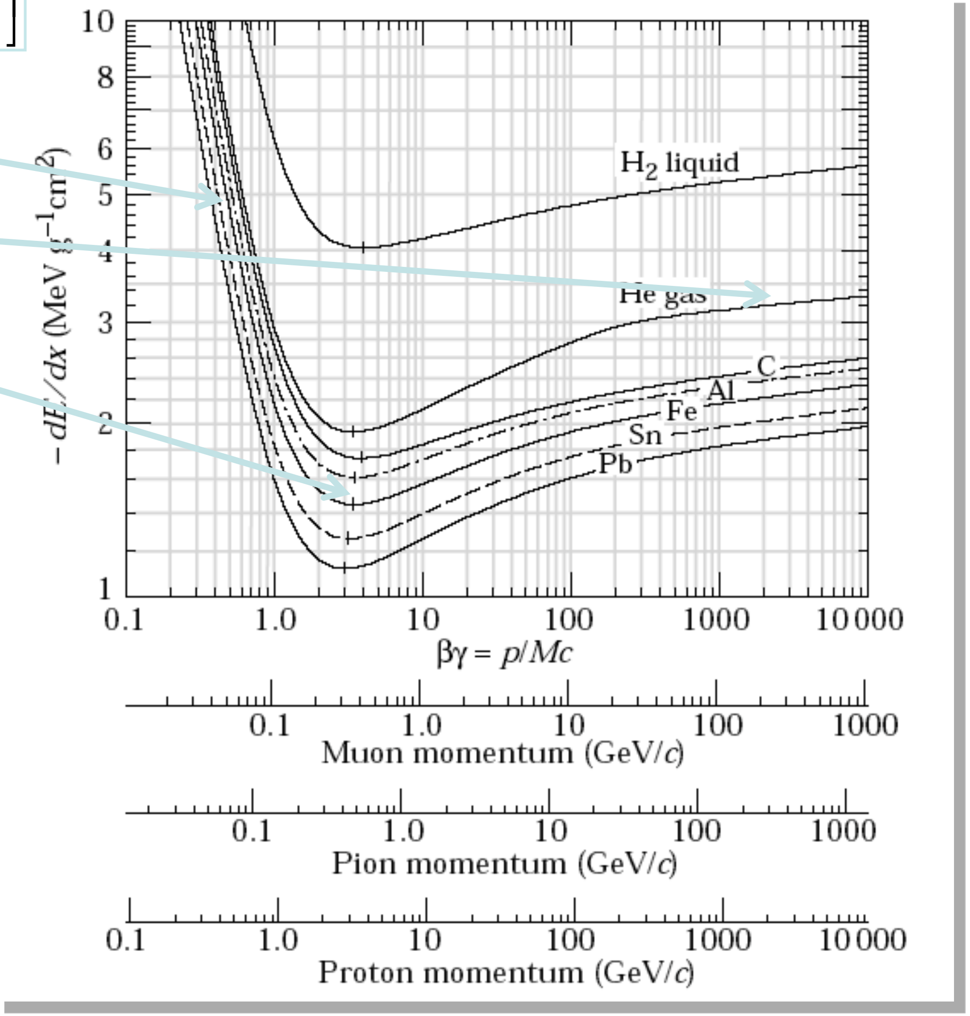
$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2}{I^2}T^{\max} - \beta^2 - \frac{\delta}{2}\right]$$

$$T_{\max} \approx 2m_e c^2\beta^2\gamma^2$$

$$-\frac{dE}{dx} \approx Kq^2\frac{Z}{A\beta^2}\left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I^2} - \beta^2\right]$$

Charaterized by:

- a fall off at low energy ~$1/\beta^2$
- a relativistic rise ~ $\ln \beta\gamma$
- a minimum at $\beta\gamma \approx 3$
- depends only on $\beta\gamma$ not on m



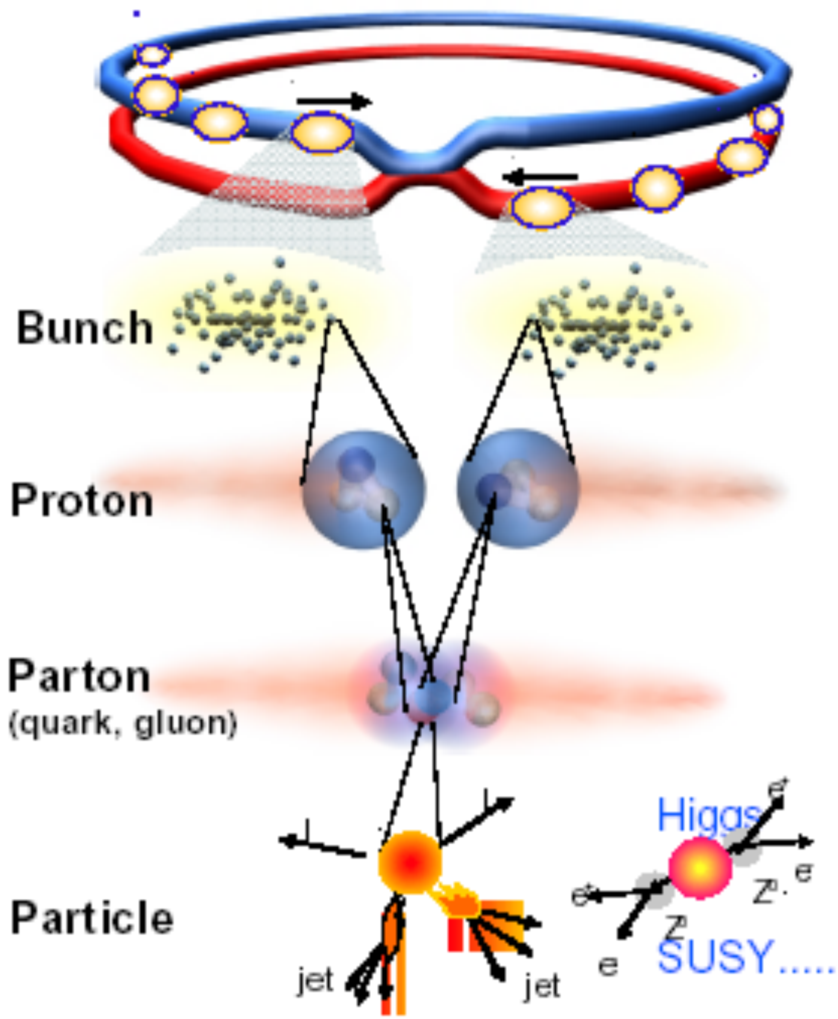
High energy charged particles lose energy slowly in material due to ionization leaving tracks as they pass (For $Z \approx 0.5A$ at $\beta\gamma \approx 3$ $1/\rho\ dE/dx \approx 1.4$ MeV cm ^{2}/g)

➔ many kinds of tracking detectors can be done !

LHC: a very hostile environment for tracking

(high event rate, high multiplicity of charged tracks, high radiation flux)

Collisions at LHC



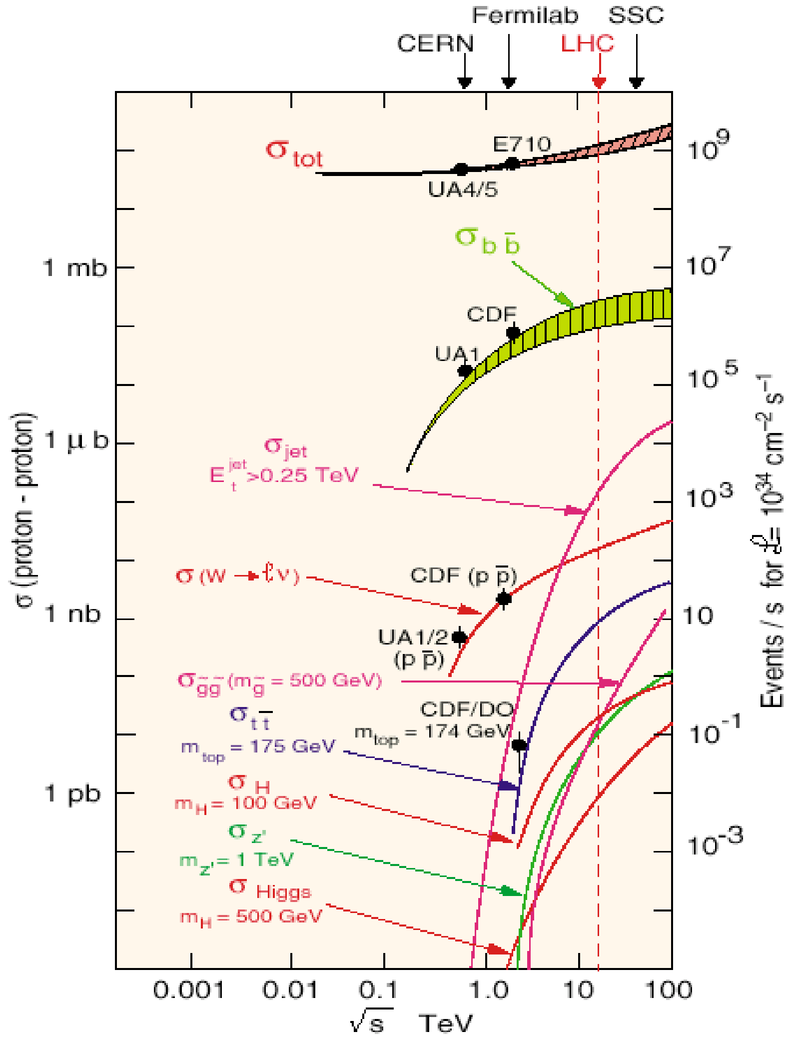
Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions rate ≈	10^{7} - 10^{9} Hz
New physics rate ≈	.00001 Hz

Event selection:
1 in 10,000,000,000,000

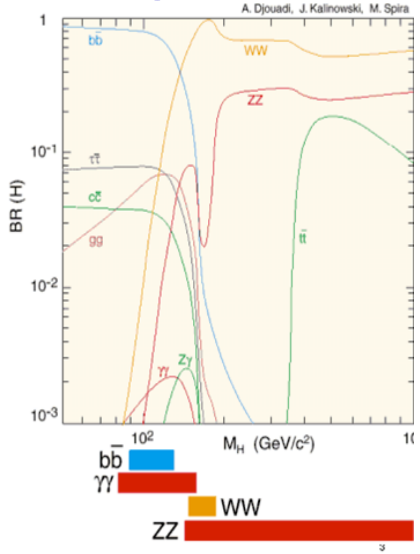
Signal and background → $\mathcal{L}=10^{34}\ cm^{-2}s^{-1}$

Cross sections for various physics processes vary over many orders of magnitude

Higgs (600 GeV/c^2): 1pb @10^{34} → 10^{-2} Hz
Higgs (100 GeV/c^2): 10pb @10^{34} → 0.1 Hz
t t production: → 10 Hz
W→ $\ell\nu$: → 10^2 Hz
Inelastic: → 10^9 Hz



Selection needed: 1:10^{10-11}
Before branching fractions...



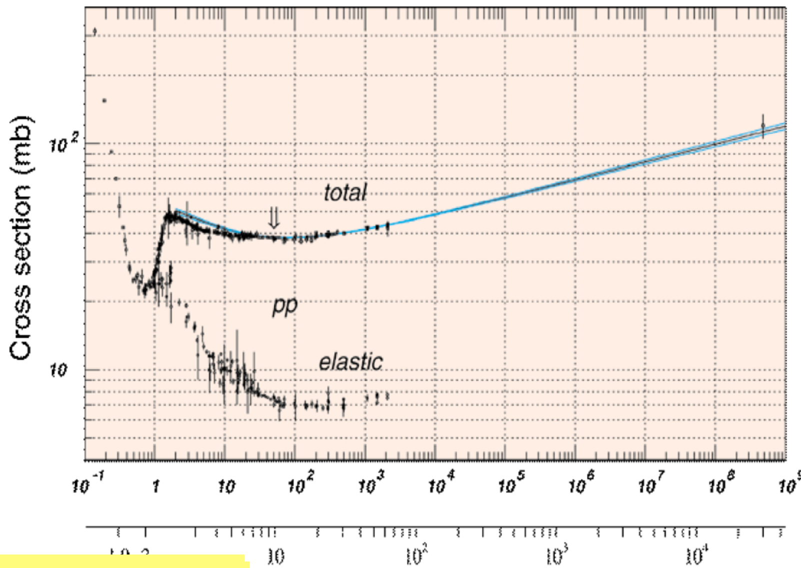
⇒ Needle in a Hay Stack

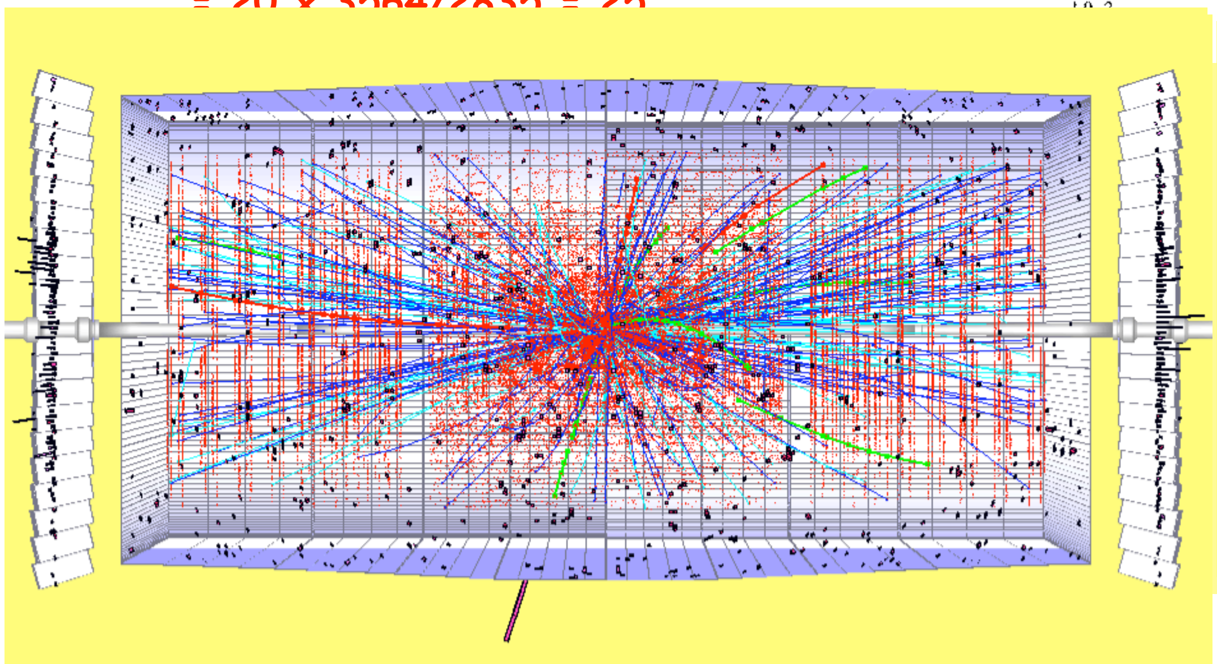
pp cross-sections and minimum bias

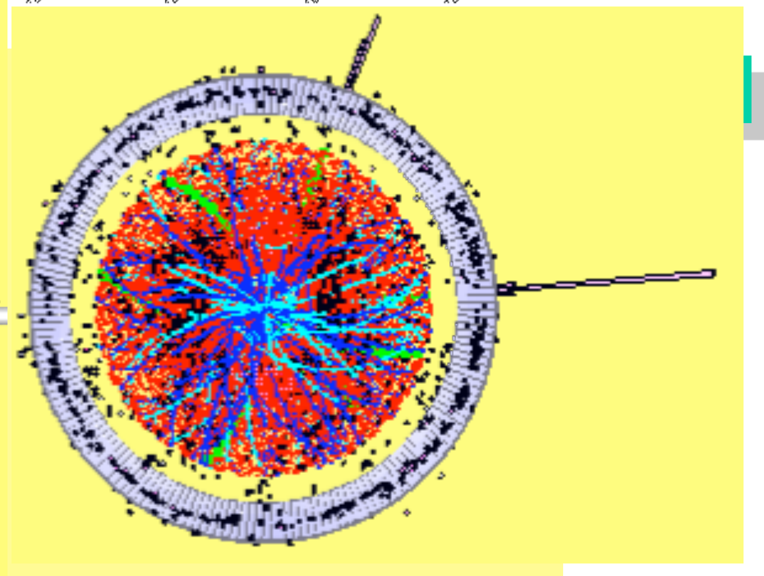
of interactions/crossing:

- Interactions/s:
  - Lum = 10^{34} $cm^{-2}s^{-1}$ = $10^{7} mb^{-1}Hz$
  - $\sigma_{inel}(pp)$ = 80 mb
  - Interaction Rate, R = 8×10^{8} Hz
- Events/beam crossing:
  - Δt = 25 ns = 2.5×10^{-8} s
  - Interactions/crossing=20
- Not all p bunches are full
  - 2835 out of 3564 only
  - Interactions/"active" crossing =
  - = 20 x 3564/2835 = 25

$\sigma_{inel}(pp) \approx 80$ mb@14TeV







Impact on detector design

LHC detectors must have fast response

- Otherwise will integrate over many bunch crossings
  - → large "pile-up"
- Typical response time : 20-50 ns
  - →integrate over 1-2 bunch crossings
  - → pile-up of 25-50 min-bias
  - → very challenging readout electronics

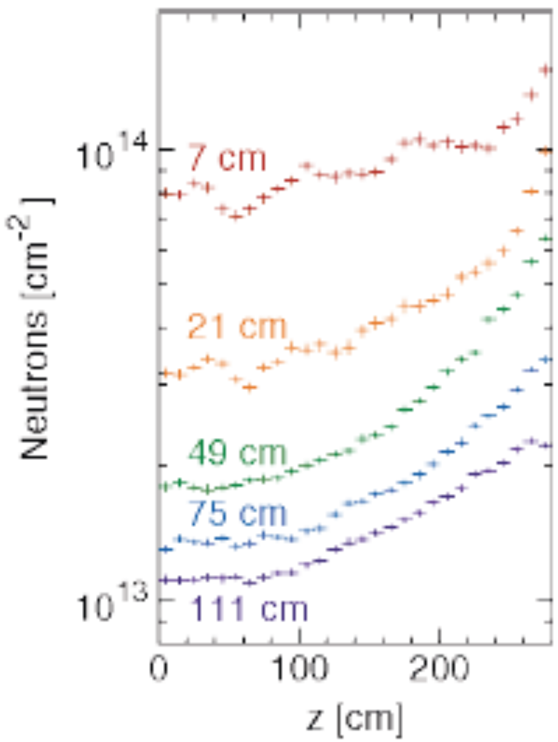
LHC detectors must be highly granular

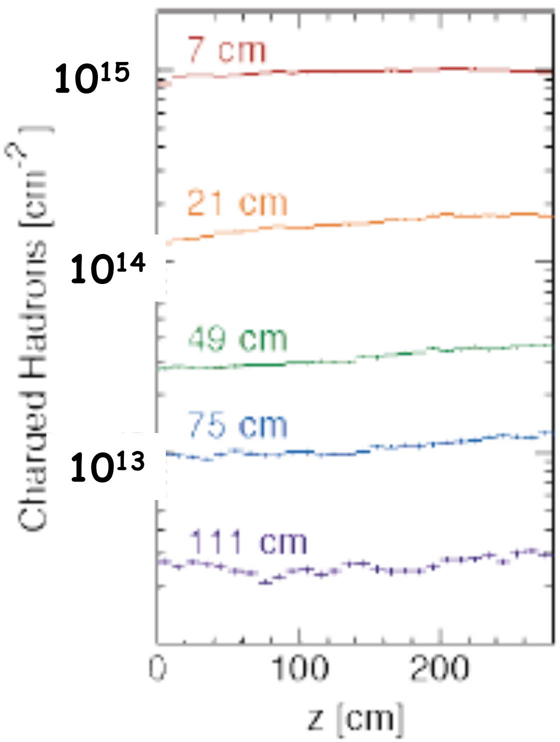
- Minimize probability that pile-up particles be in the same detector element as interesting object
  - → large number of electronic channels
  - → high cost

LHC detectors must be radiation resistant:

- high flux of particles from pp collisions
  - → high radiation environment

Radiation environment at the LHC





Expected particle fluences for the silicon detector inner layers in CMS integrated over 10 years as a function of the distance from the vertex point and for various radii.

Left: neutrons

Right: charged hadrons

Evian, March 1992: first meeting on experimental program at LHC

Evian, November 2009: more than 17 years later ready to start…..

Towards the LHC Experimental Programme
General Meeting on LHC Physics & Detectors
5-8 March 1992
Evian-les-Bains, France

LHC

Expressions of Interest

Hadron Collider Physics Symposium
HCP 2009 Evian

Hadron Collider Physics Symposium

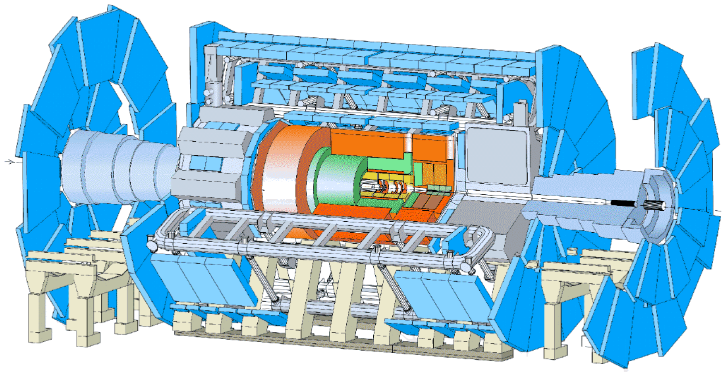
Evian, France

16 – 20 November, 2009

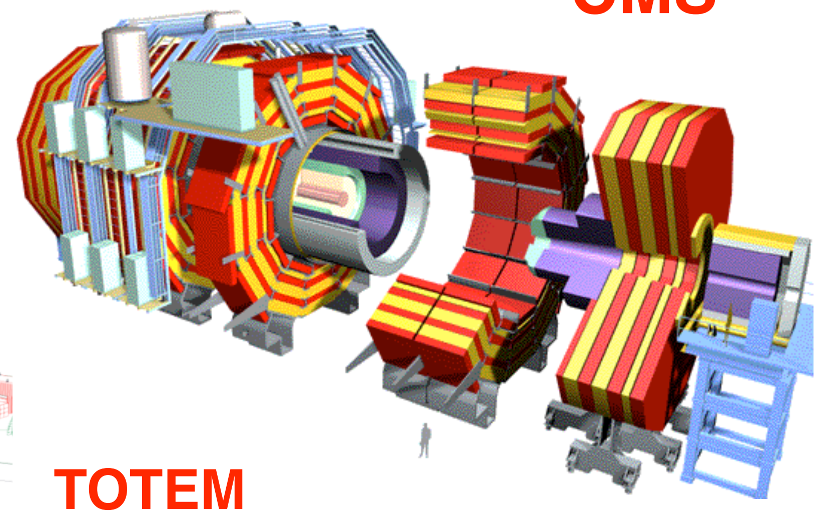
ATLAS, CMS, ALICE, LHCb, TOTEM, LHCF

The LHC Detectors

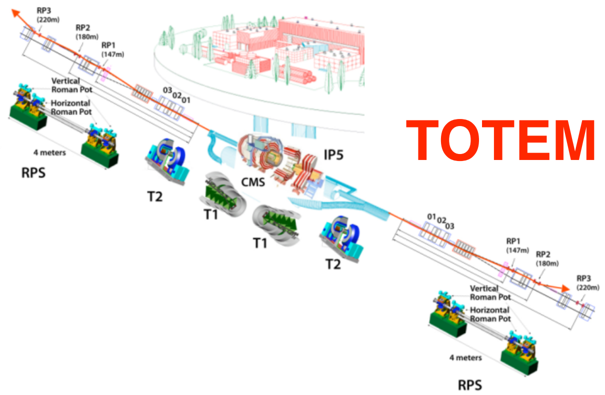
ATLAS

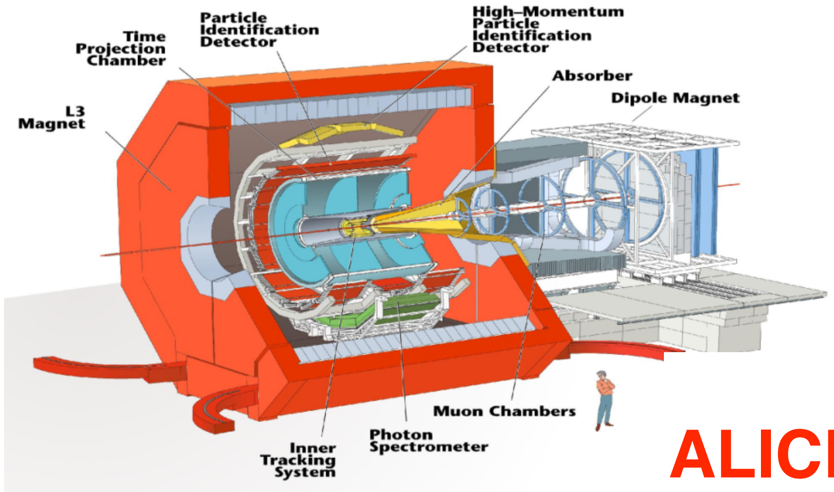


CMS

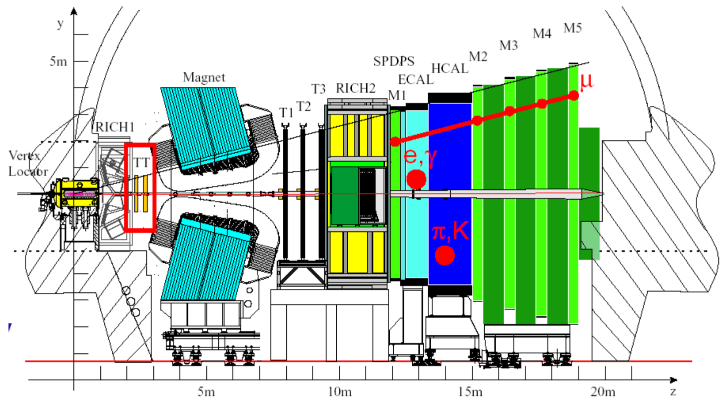


TOTEM





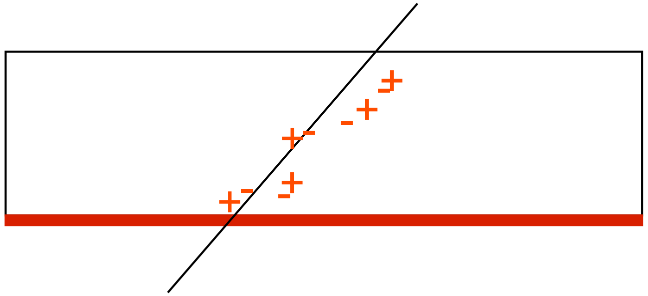
ALICE



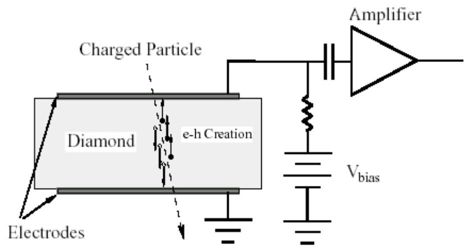
LHCb

Tracking Detectors

Charged particles crossing a material loose energy by ionizing (and exciting) atoms and thus leaving along their path a trace of electron-ion pairs in gases and liquids and electron-hole pairs in solids.



Measurable electronics signals can be induced by the charges produced in this way and can be read by dedicated electronics



- In solid state detectors the charges produced by the ionization due to the incoming particle are sufficient to provide a measurable signal.

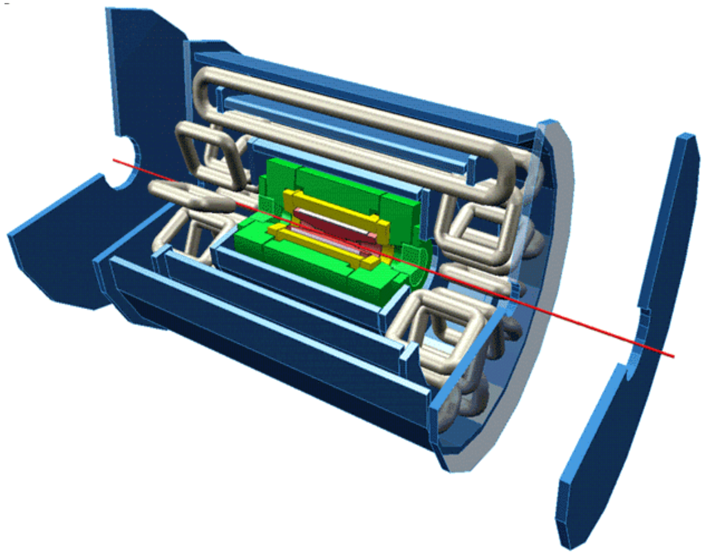
- Mean (most probable) energy loss: 116 (78) keV for 300μm Si thickness
- 3.6 eV to create an e-h pair
  - ⇒ 72 e-h/μm (mean)
  - ⇒ 108 e-h/μm (most probable)
- Mean charge (300μm Si) ≈ 22000 e ≈ 3.6 fC

- In gas detectors the charges produced by the primary ionization due to the incoming particle need amplification in order to provide a measurable signal.

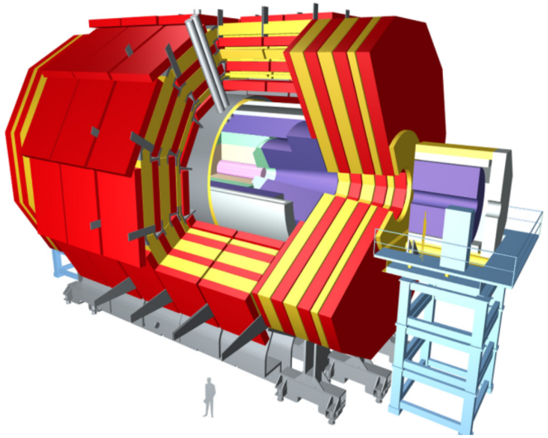
GAS)	Helium	Argon	Xenon	CH_4	DME
dE/ dx (keV/ cm)	0.32	2.4	6.7	1.5	3.9
<n>(ion-pair/ cm)	5.9	29	44	16	55

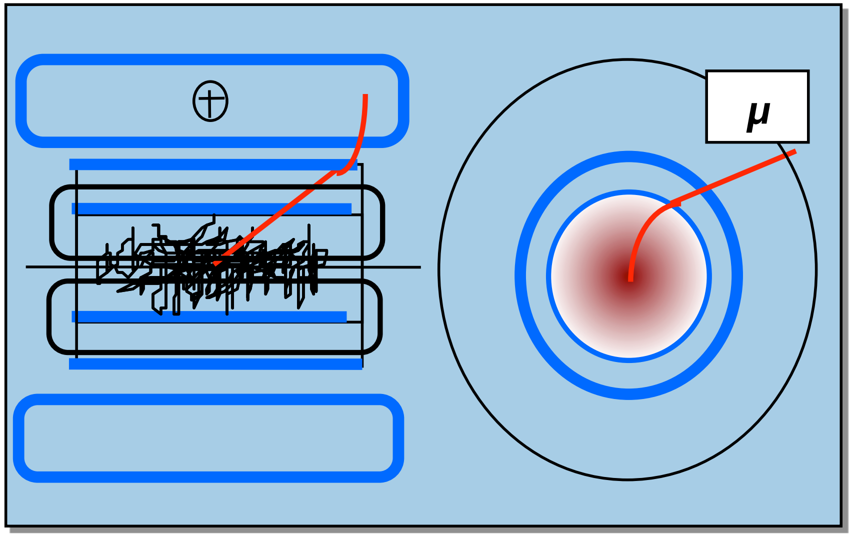
Two general-purpose pp detectors with different strategies

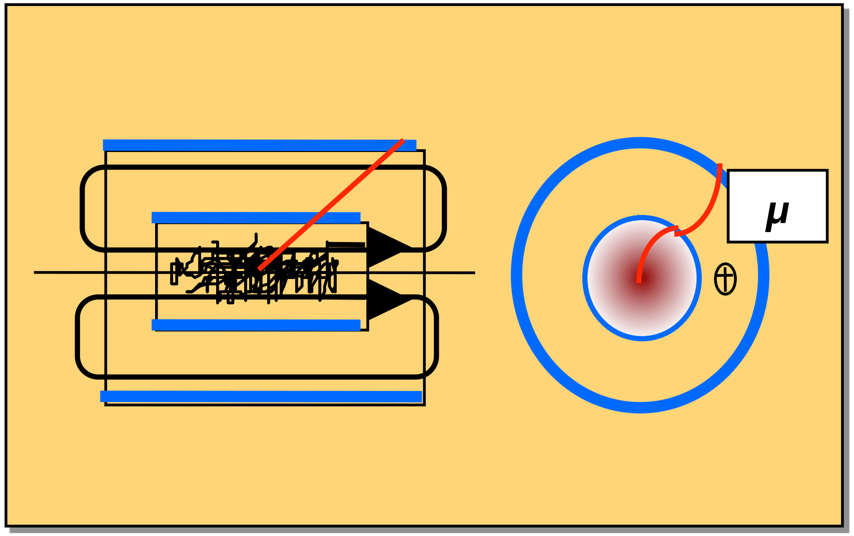
ATLAS A Toroidal LHC ApparatuS



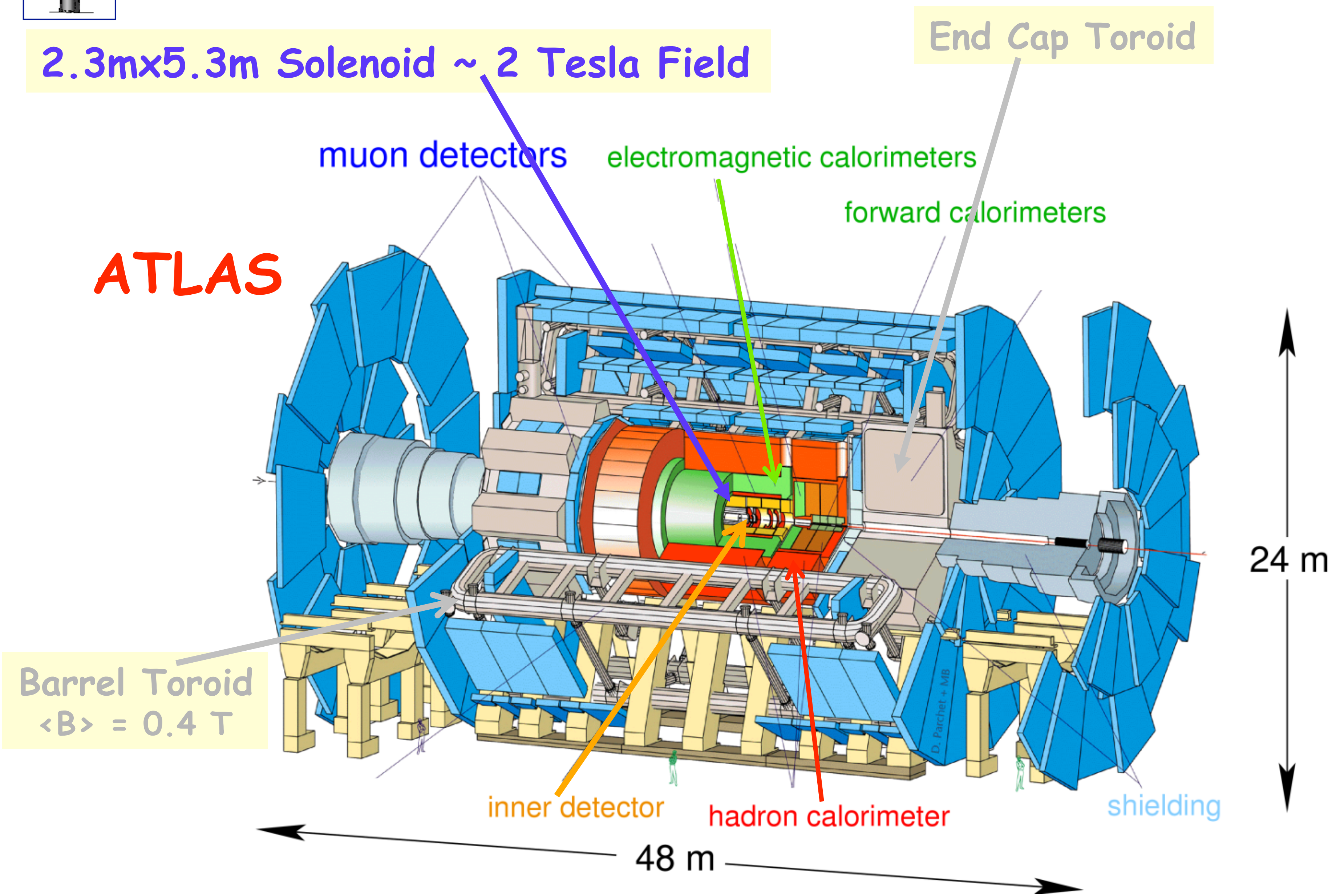
CMS Compact Muon Solenoid





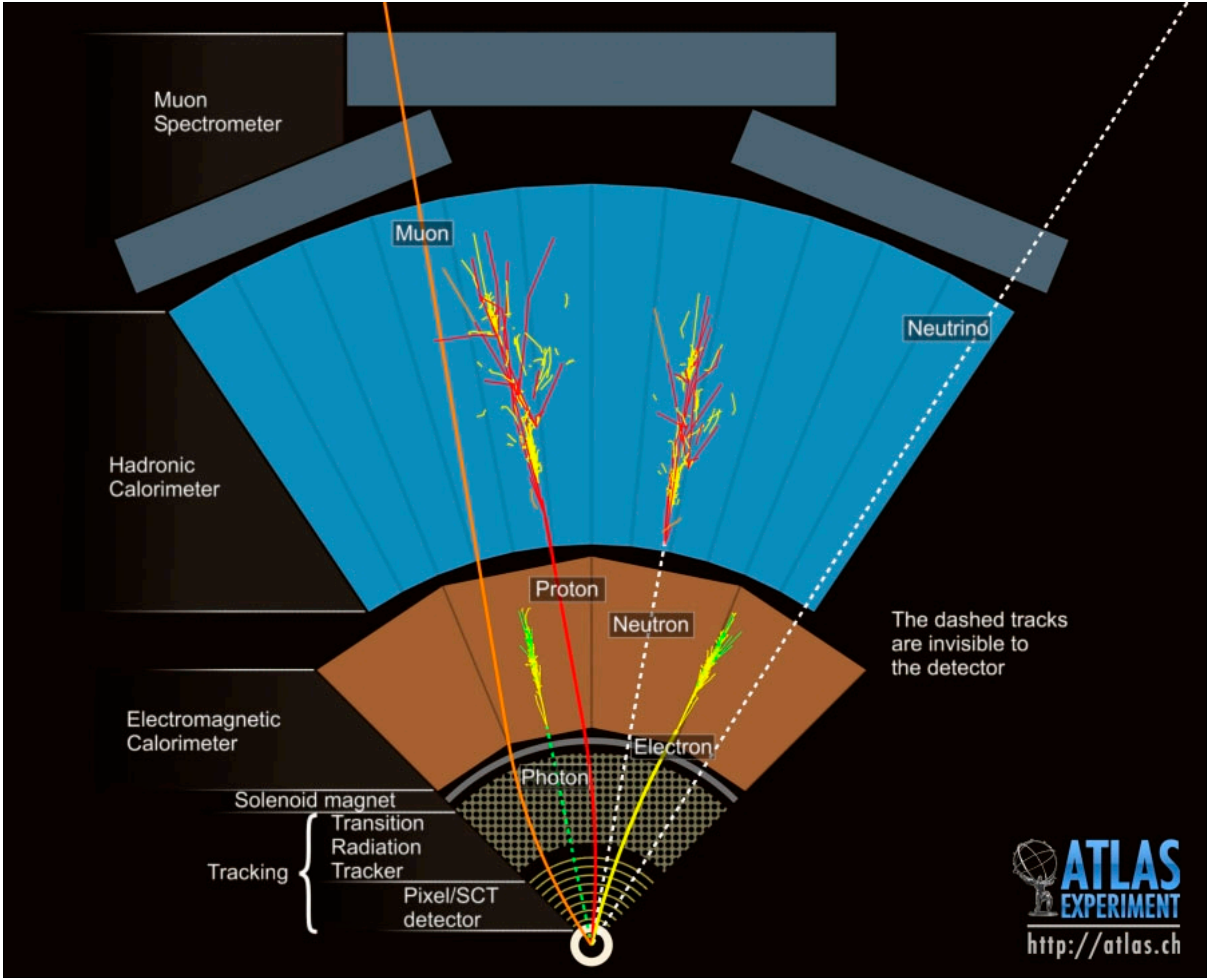


Different Strategies....



48m Long, 24m Diameter, 7'000 Ton Detector

Transverse slice of ATLAS



Different Strategies…

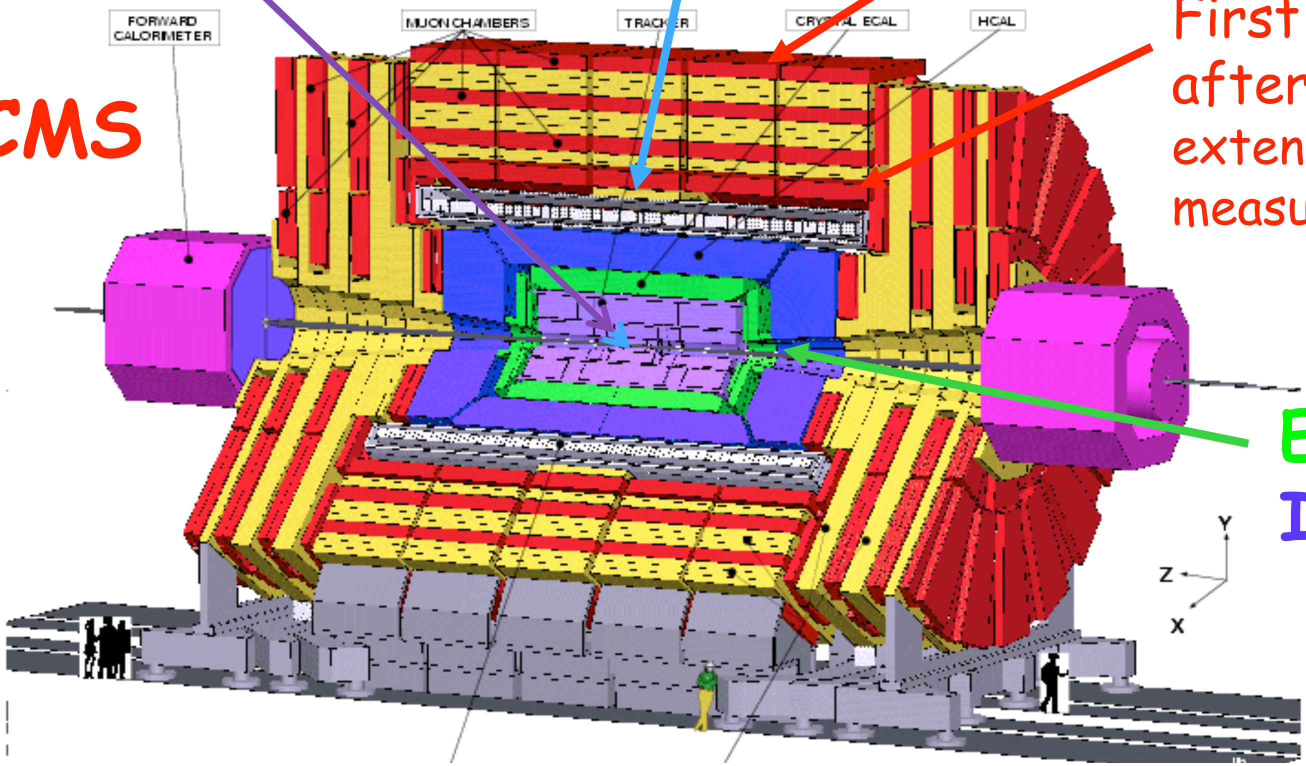
13m x 6m Solenoid: 4 Tesla Field

Tracking up to η ~ 2.4

Muon system in return yoke

CMS

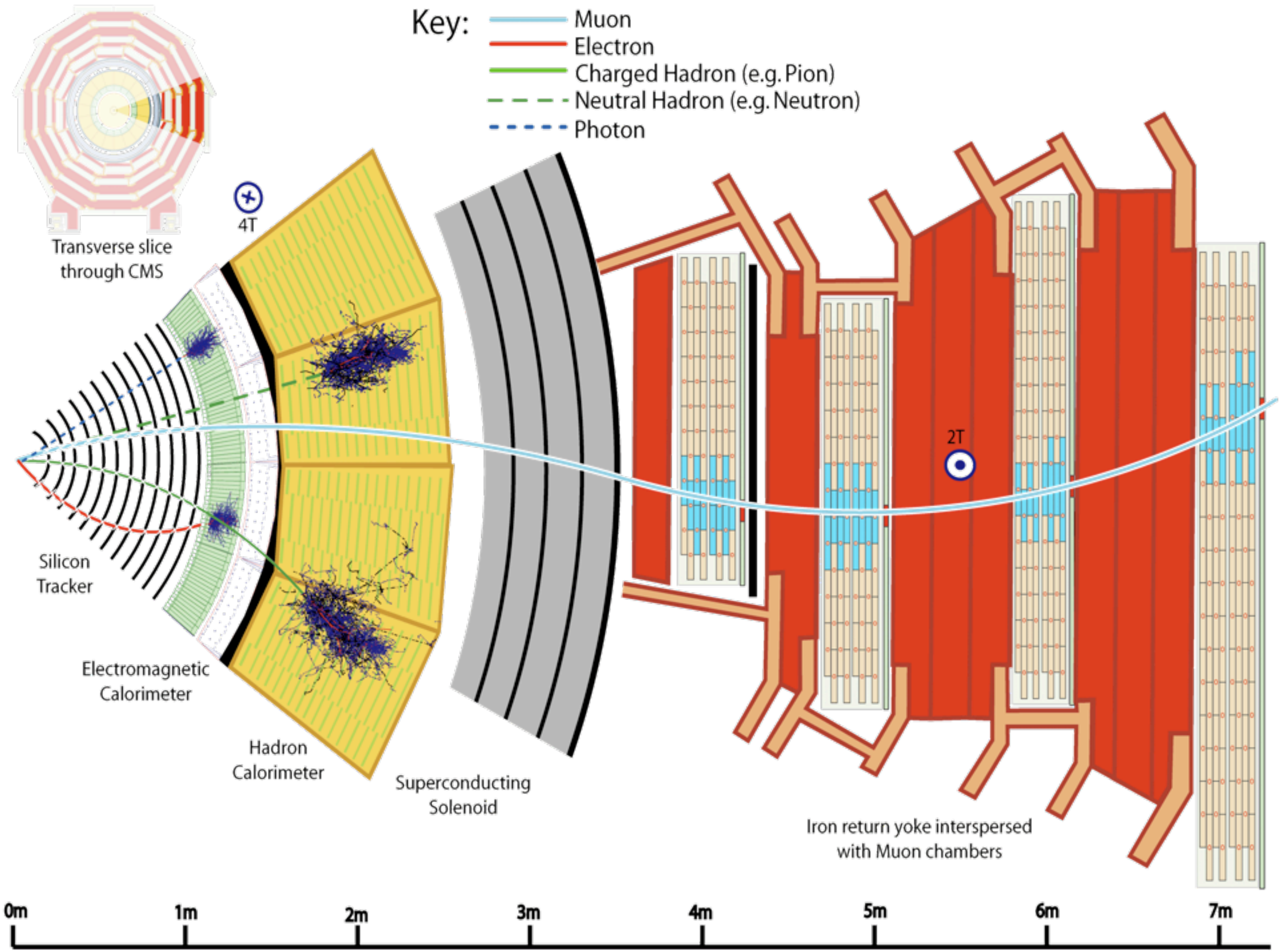
First muon chamber just after solenoid → extended lever arm for p_t measurement



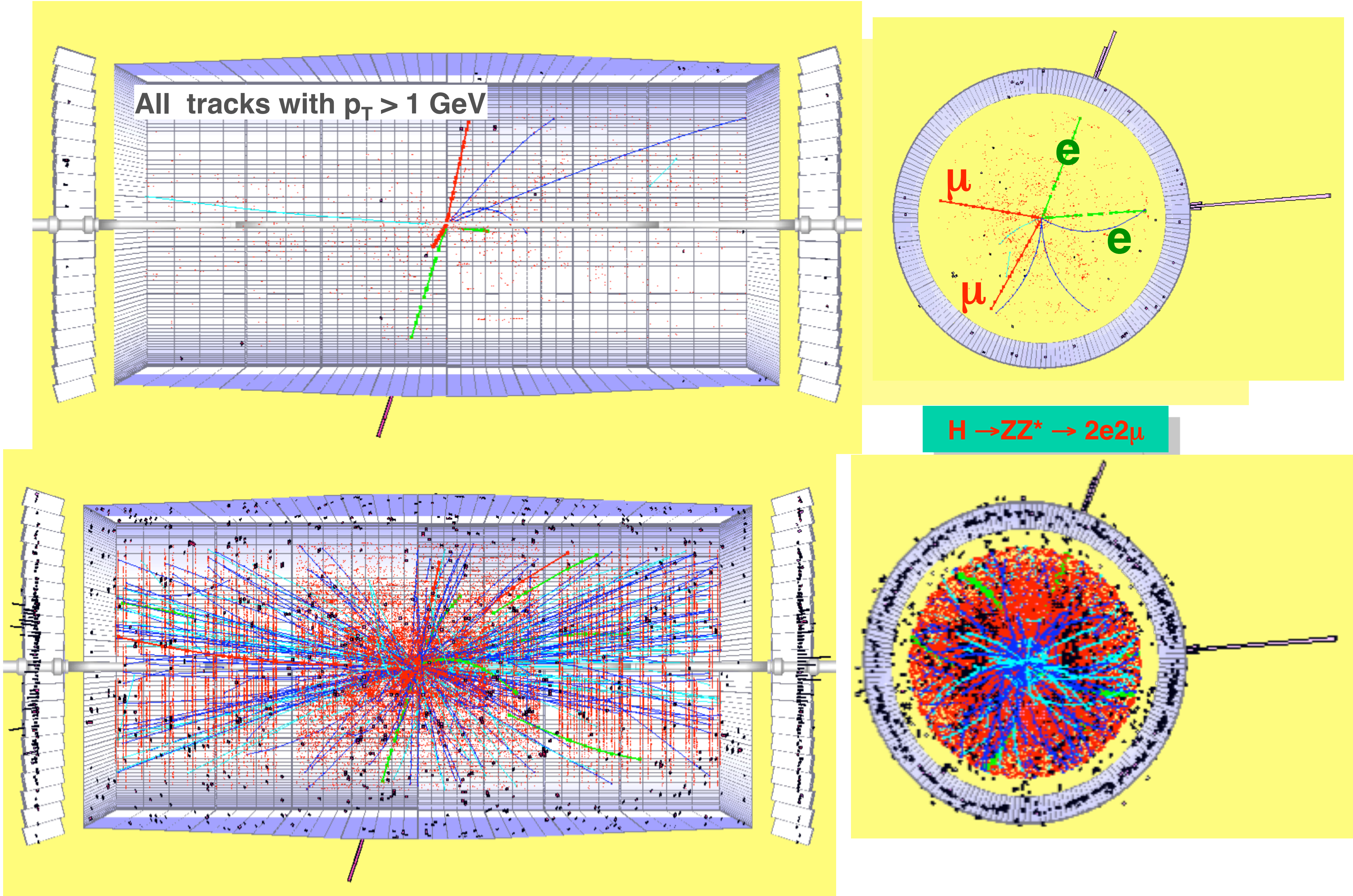
ECAL & HCAL Inside solenoid

22m Long, 15m Diameter, 14'000 Ton Detector

Transverse slice of CMS



What a luminosity of $10^{34} cm^{-2} s^{-1}$ means on Tracking ...



Tracking Requirements

Precise and efficient tracking at LHC is needed to extract physics signals from competitive but reducible background signals:

- Mass cut: precise invariant mass determination from precise momentum measurement of the decay products
- Isolation cut: high track reconstruction efficiency in dense environment (pile-up, jets…)
- Long-lifetime particles tagging: precise and efficient measurement of the track impact parameter and secondary vertices.

The approach

- Silicon microstrip detectors allow a very good point resolution (10-30 microns) that coupled to large lever arms m in solenoidal field of 2-4T would allow an adequate momentum resolution, good impact parameter resolution for b-tagging and excellent measurement of the charge up to 1TeV and beyond.
- Single bunch crossing resolution is feasible in silicon (collection time <10ns) with fast read-out electronics.
- The real challenge is pattern recognition for track reconstruction: the high density of tracks typical of the inner regions of high luminosity hadronic colliders can be tackled with extreme segmentations both in r-phi and r-z : pixel detectors and silicon microstrip modules.
- Silicon detectors are well radiation resistant ($\Phi > 10^{14}$ n/cm^2) and can be produced in large scale at rather low cost.

⇒**Pixel detector** (in the radial region 5cm<r<20cm: $10^{14}\text{cm}^{-2} < \Phi < 10^{15}\text{cm}^{-2}$)

⇒**Silicon microstrip** (in the radial region r>20cm: $10^{13}\text{cm}^{-2} < \Phi < 10^{14}\text{cm}^{-2}$)

Two different strategies

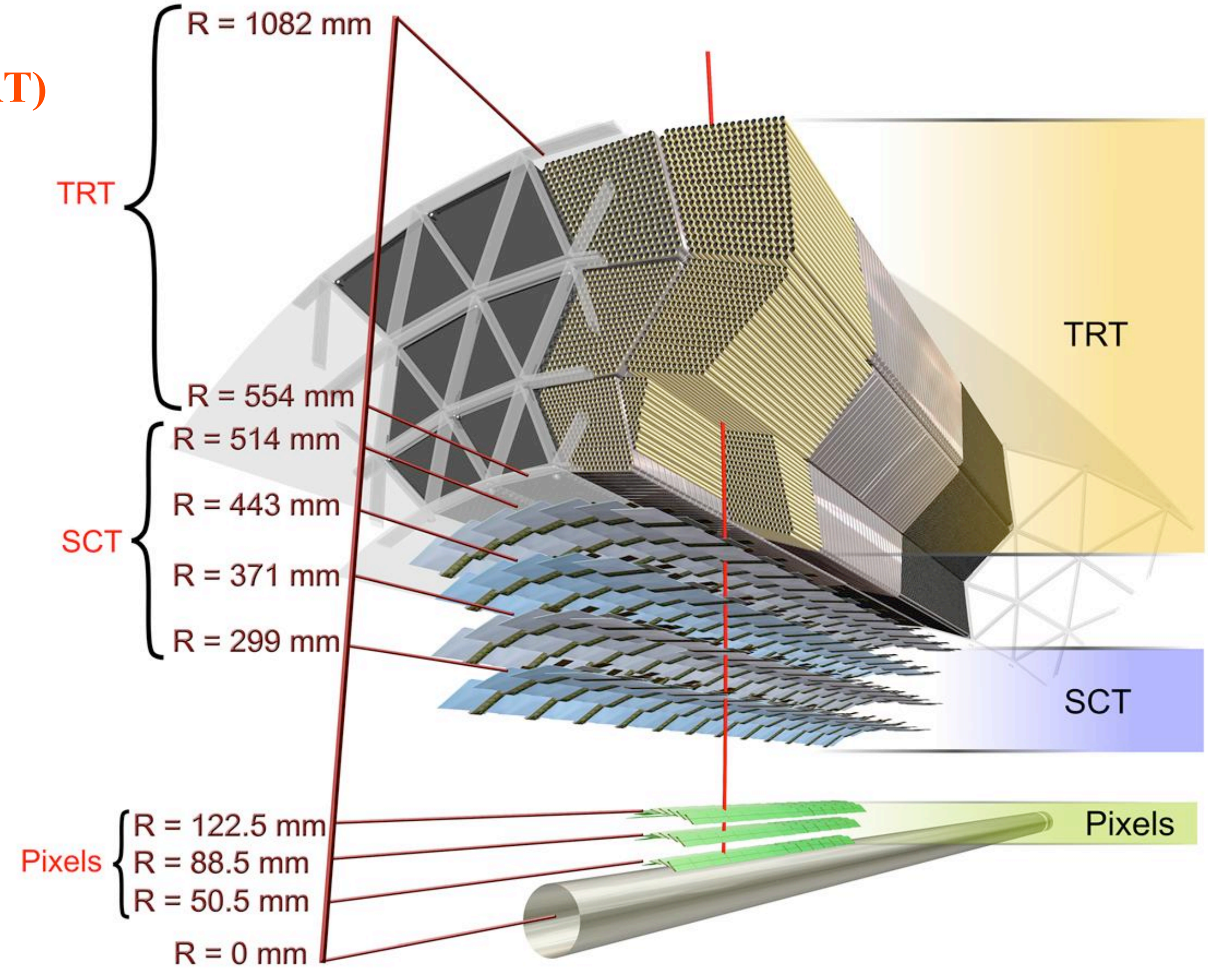
This approach has been followed very aggressively by CMS who decided to build the first full silicon tracker in HEP

- more challenge in terms of technology and costs
- higher performance particularly in pattern recognition

ATLAS has adopted a more traditional approach based on a hybrid tracker:
pixel and silicon microstrip detectors in the innermost part and a large gaseous detectors in the outer part (straw tubes).

ATLAS Inner Detector

- **Transition Radiation Tracker (TRT)**
  - **4 mm diameter straw tubes**
  - **351 k channels**
  - **resolution 130 μm**
  - **polypropylene/polyethylene as transition radiation material: electron id 0.5 GeV<E<150 GeV**
- **SemiConductor Tracker (SCT)**
  - **4088 modules**
  - **80 μm strips (40 mrad stereo)**
  - **6 M channels**
  - **resolution 17 μm × 580 μm**
- **Pixel**
  - **1744 modules of 46080 pixels**
  - **mostly 50 μm × 400 μm**
  - **80 M channels**
  - **resolution 10 μm × 110 μm**



- **7-points silicon (pixels + strips) tracker (|η|<2.5)**
- **straw tubes quasi-continuous tracker (36 points +electron id) (TRT) (|η|<2).**
- **2 T solenoidal magnetic field**

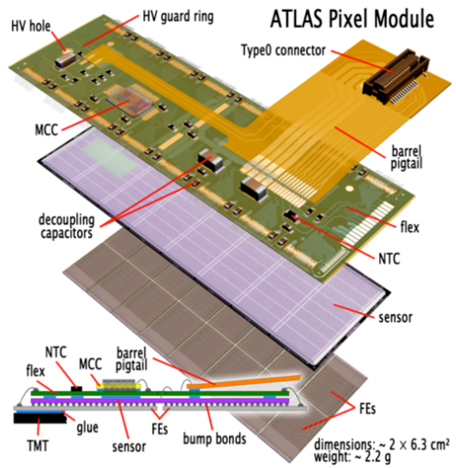
- Momentum resolution:
  $\sigma(p_t)/p_t = 0.05\% p_t(GeV/c) \oplus 1\%$
- IP resolution:
  $\sigma(d_0) = 10\mu m \oplus 140\mu m / p_t(GeV/c)$

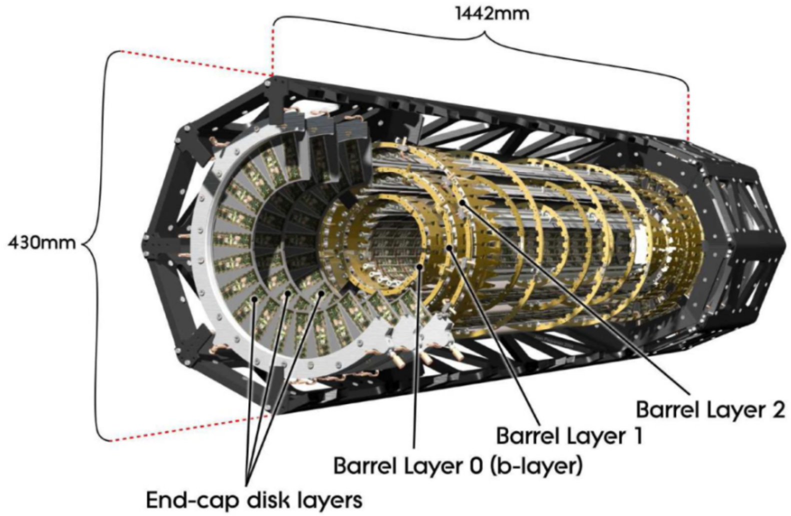
The ATLAS Pixel Detector

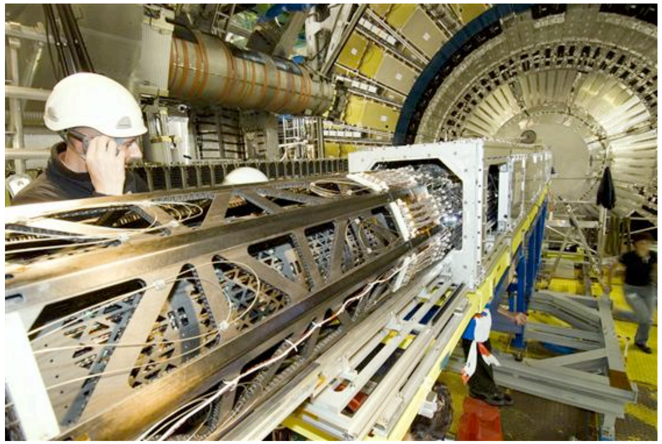
- **Requirements:**
  - Position resolution in rΦ-direction < 15µm
  - 3 track points for |η| < 2.5
  - Time resolution < 25 ns
  - Hit detection efficiency > 97%
- **3 barrel layers**
  - r = 5.05 cm, 8.85 cm, 12.25 cm
- **3 pairs of Forward/Backward disks**
  - z = 49.5 cm, 58.0 cm, 65.0 cm
- **Pixel size:**
  - 50 mm x 400 mm & 50 mm x 600 mm
- **~ 2.0 m^2 of sensitive area with 8 x 10^7 ch**
- **Modules are the basic building elements**
  - 1456 in the barrel + 288 in the endcaps
  - Active area 16.4 mm x 60.8 mm
  - Radiation tolerance 500 kGy / 10^{15} 1 $MeVn_{eq}cm^{-2}$

The same module is used in the barrel and in the disks:

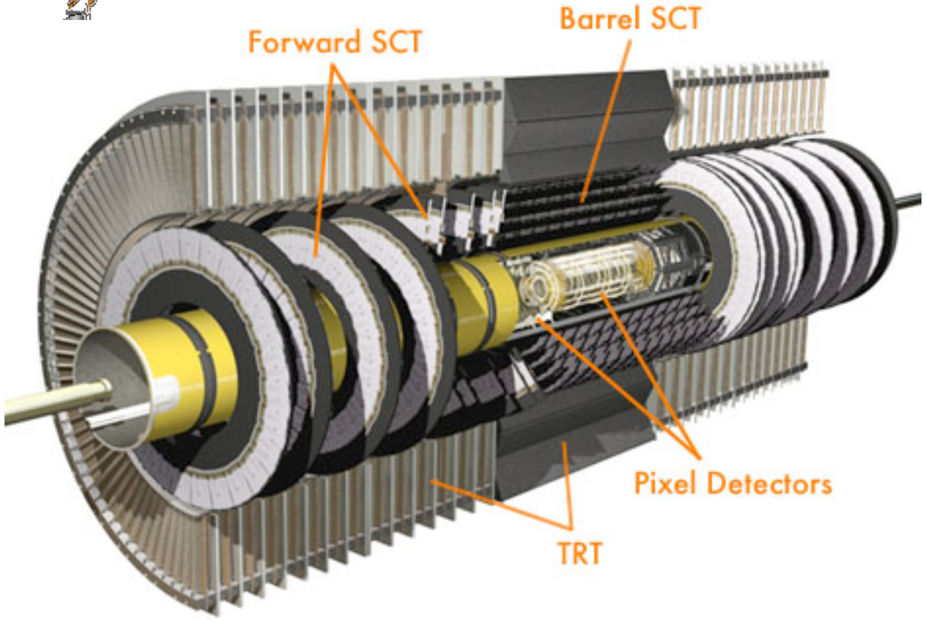
- staves (13 modules along the beam axis) for the barrel.
- sectors (6 modules on a two-sided octant) for the disks.







The ATLAS Semiconductor Tracker (SCT)



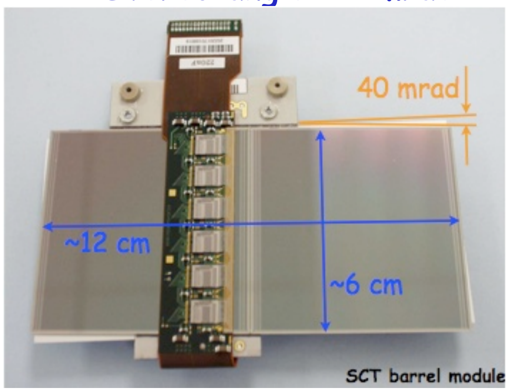
The SemiConductor Tracker (SCT) is a silicon strip detector. It's organized in 4 layers barrel, built with 2112 modules and two 9 disks end-caps, made of 1976 modules. The total number of strips is 6.3 10^6.

Physics requirements

- **Resolution (x* y):** 17 µm * 580 µm
- **Alignment tolerances (x*y):** 12 µm * 50 µm
- **Noise occupancy:** < 5 * 10^{-4}
- **Efficiency:** > 99%
- **Radiation :** ~ 2 * 10^{14} Neq cm^{-2} over 10 years

The barrel module consists of four single sided p-on-n strip detectors:

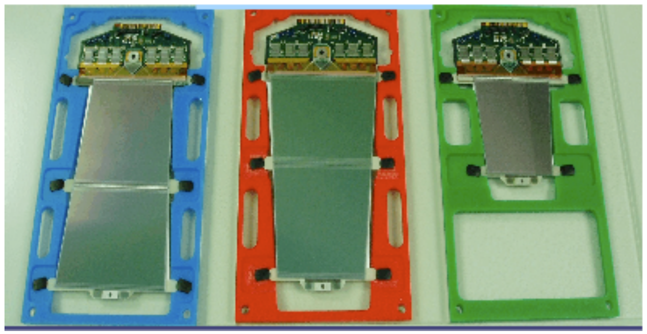
- Pitch 80 mm
- Strip length 120 mm
- Stereo angle 40 mrad

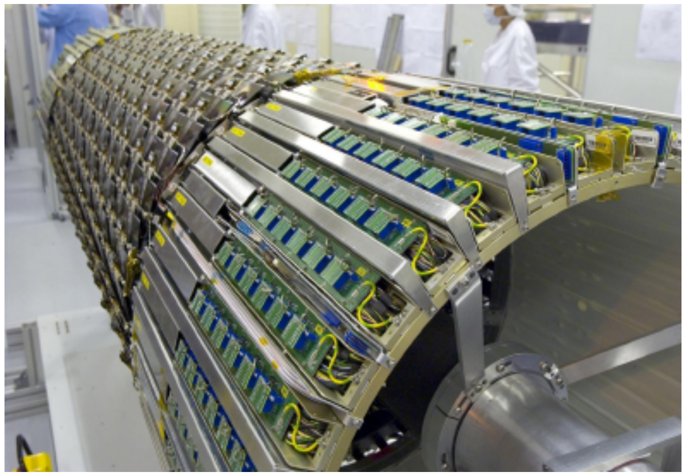


SCT barrel module

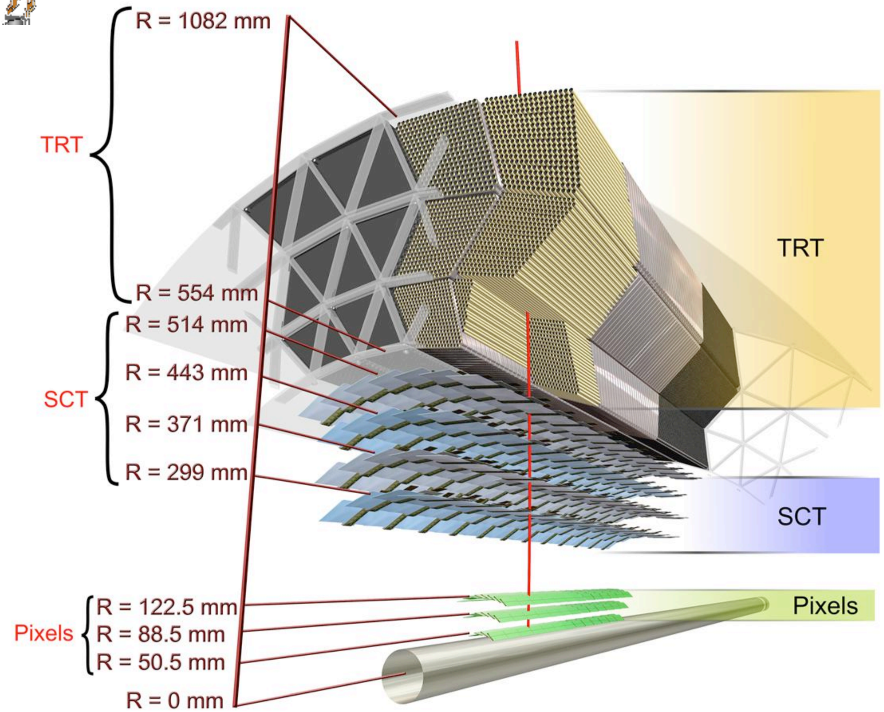
The end-caps are built with three different modules:

- Pitch 57-95 mm
- Strip length 55-120 mm





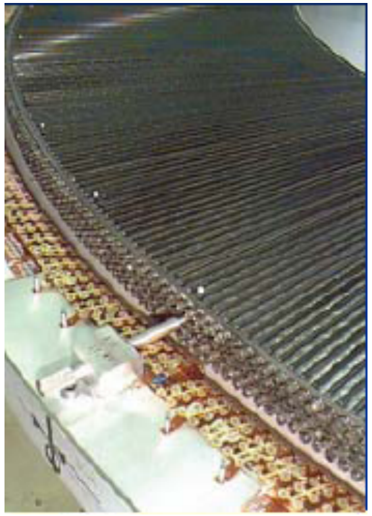
The ATLAS Transition Radiation Tracker (TRT)



TRT: 4 mm straw tubes, arranged in 2·160 disks (end-cap) and 73 layers (barrel), 40 K channels, acceptance $|\eta|<2$

TR (polypropylene foils/ fiber): pion-electron separation (TR γ's convert into e's in Xe)

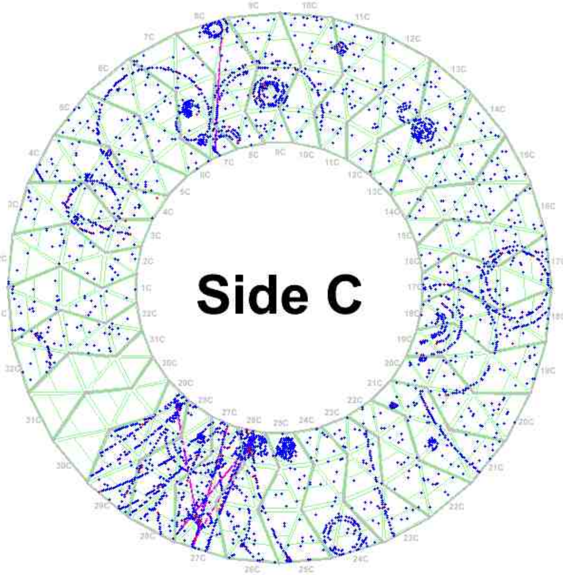
TRT end-cap during assembly



# Hits (Barrel):
3(Pixel)+4 (SCT)+<36>(TRT)

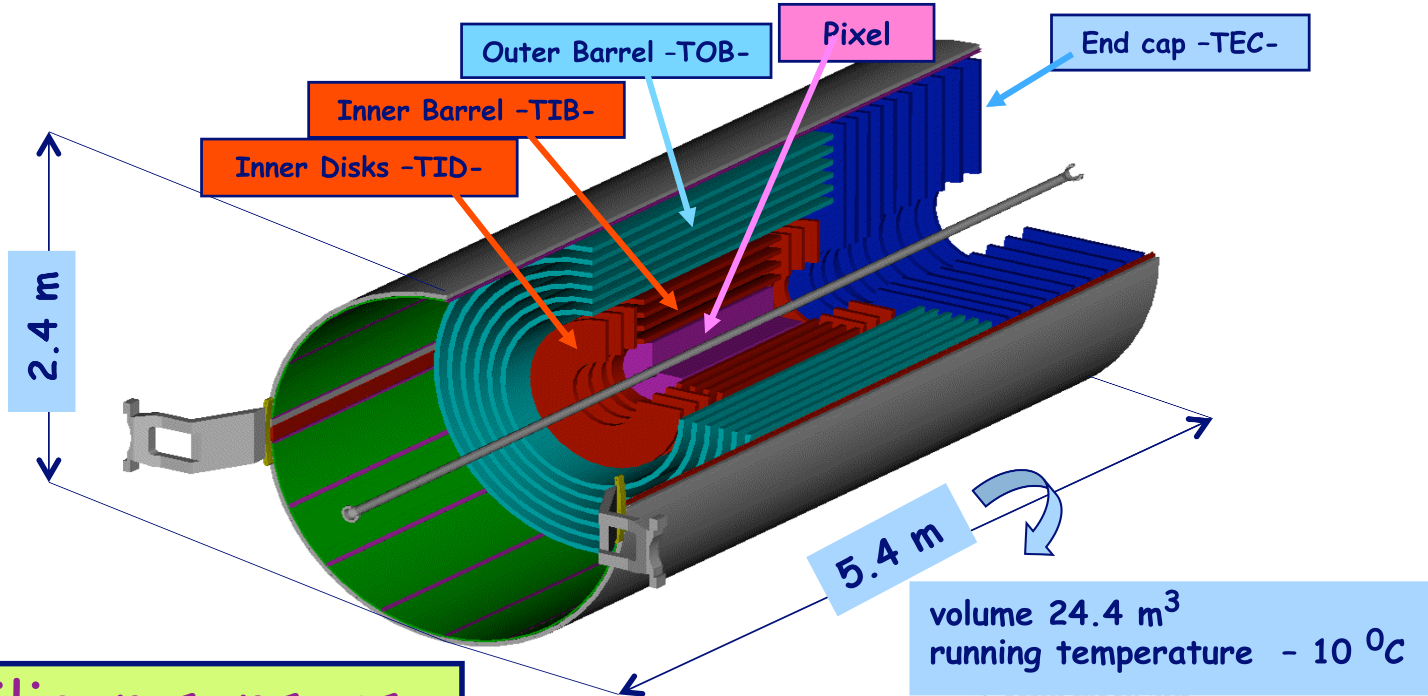
$\sigma/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$

Cosmic ray event in TRT

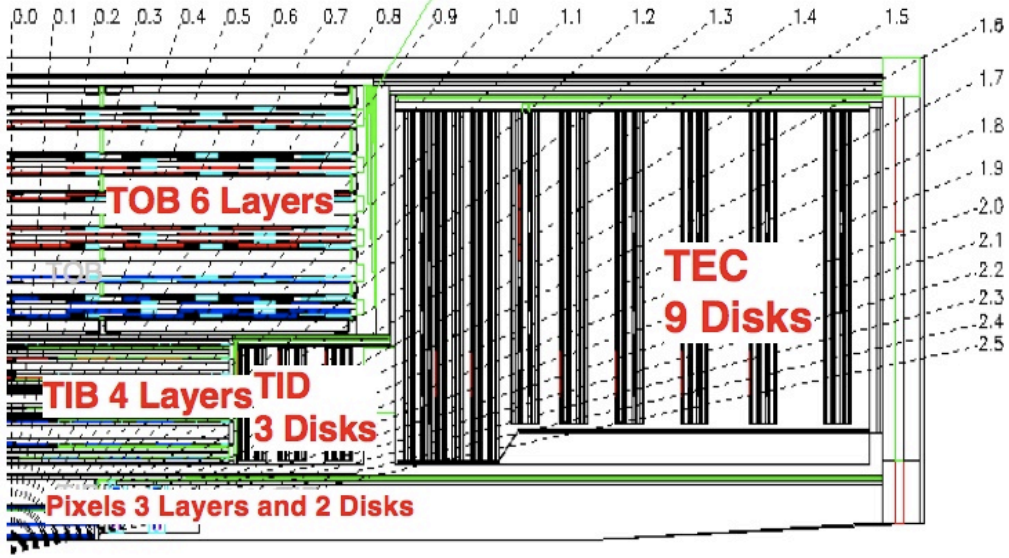


$\frac{1}{4}$ of TRT barrel during integration

CMS has chosen an all-silicon configuration



207m^2 of silicon sensors
10.6 million silicon strips
65.9 million pixels ~ 1.1m^2



Strips:

Pitch: 80 μm to 180μm

Hit Resolution: 20 μm to 50μm

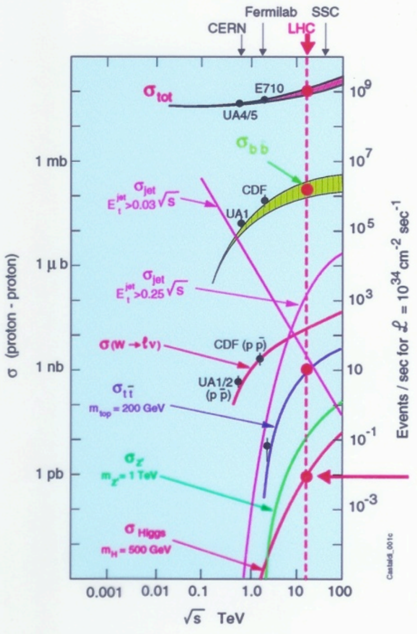
Pixels:

100 μm x 150μm

rϕ and z resolution: ~15 μm

CMS Tracking: very old slides presented to LHCC (towards a full silicon tracker)

LHC ENVIRONMENT



$\mathcal{L} = 10^{34}$ cm^{-2}sec^{-1} $\sigma_{INE} \sim 100$ mb

➡ $R_{INE} = 10^9$ ev/sec

40 MHz → 25 ev_{INE}/Crossing
~20 ev_{MB}/Crossing

➡ ~ 1000 Soft Tracks/Crossing

~ 1 ev / 10^{11} ev

4 Tesla Field

➡ Low P_T tracks loop in the solenoidal field increasing the cell occupancy

⇒

- • Fast Detector and Electronics: Bunch Crossing Ident.
- •• Radiation Hard Electronics and Detectors: Mrad. Doses
- ••• Very Difficult Pattern Recognition:

Efficient track finding requires small cell occupancies

⇒ $\geq 10^7$ channels are needed

⇒ High precision fast detectors with high granularity like

Pixels + Si-Strip + MSGC

Rino_001

Detector characteristics

- **Good quality detectors available in 6" technology from at least two producers each with over-capacity to produce all the silicon wafers in less than 2.5 years**

➢ **Longer strips and thicker detectors can be used in the outer Tracker**

❒ The strip capacitance (per unit length), (and therefore electronics noise), is almost independent of the sensor thickness:

(It is also ~ independent of the pitch and depends only on the ratio *w/p* of strip width to pitch)

$$C_{400\mu m}(6") = C_{300\mu m}(4"/6") = C(w/p)$$

❒ Charge collection:

$$Q(400\ \mu m) = 1.3 \times Q(300\ \mu m)$$

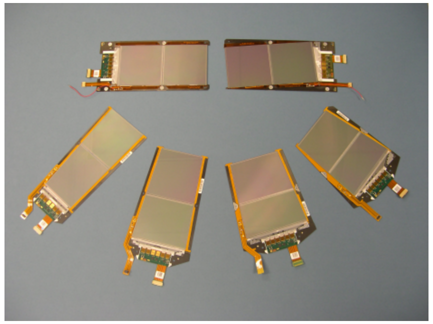
❒ Rad-hardness:

<100> 6" = <100> 4"

$V_{bdwn} > 500$ V for $w/p > 0.2$

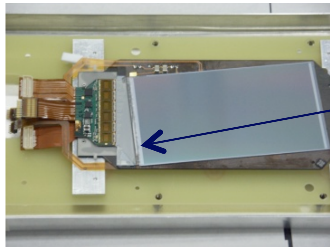
LHCC 8/3/2000, R. Castaldi 1

The CMS Silicon Strip Tracker



Outer Barrel (TOB): 6 layers
- Thick sensors (500 μm)
- Long strips

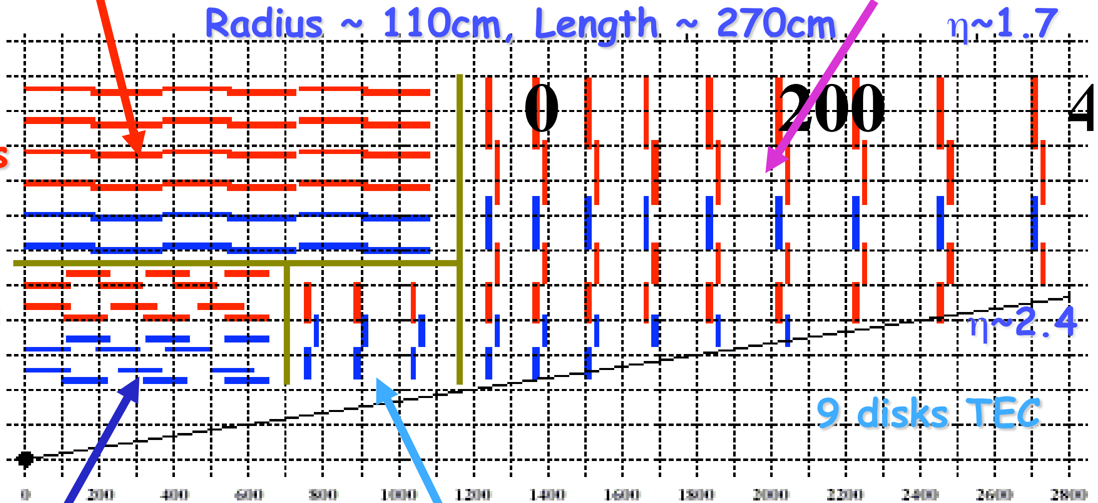
Endcap (TEC): 9 Disk pairs
- r < 60 cm thin sensors
- r > 60 cm thick sensors



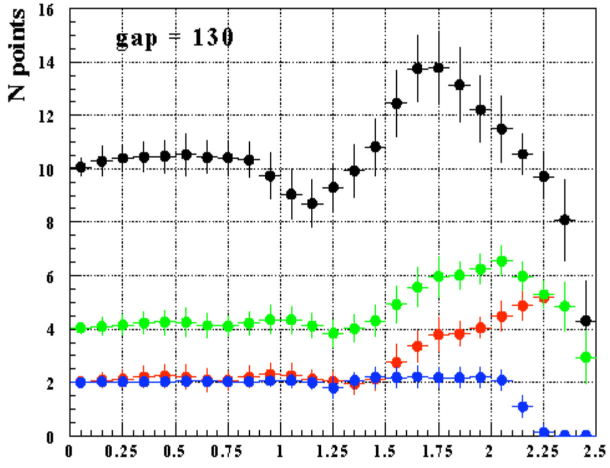
small angle tilt (100mrad) to provide second coordinate measurement

6 layers TOB

4 layers TIB



9'648'128 strips
75'376 APV chips
6'136 Thin sensors
18'192 Thick sensors
~17'000 modules
~25'000'000 Bonds



Inner Barrel (TIB): 4 layers
- Thin sensors (320 μm)
- Short strips

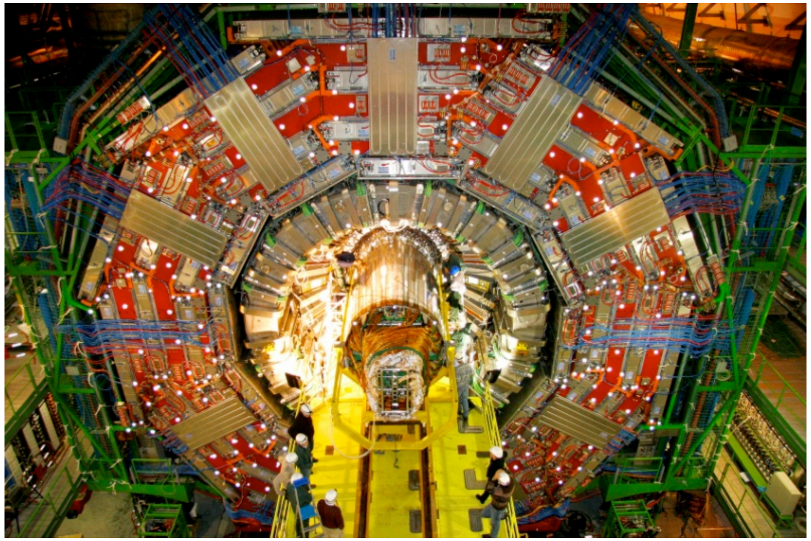
Inner Disks (TID): 3 Disk pairs
- Thin sensors

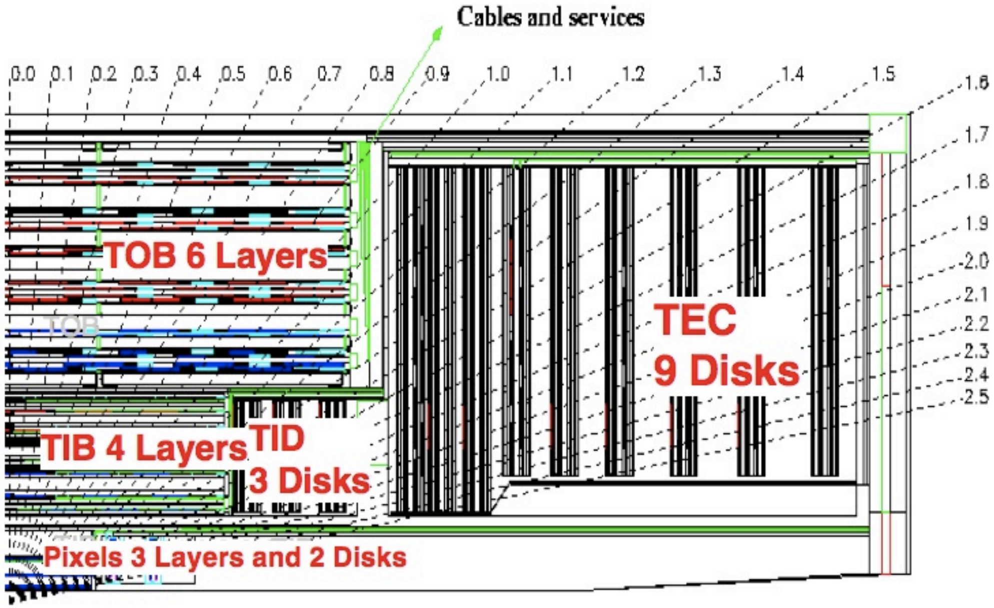
Black: total number of hits
Green: double-sided hits
Red: ds hits - thin detectors
Blue: ds hits - thick detectors

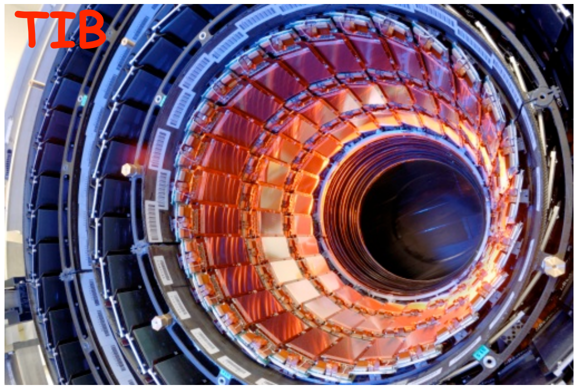
Strip length ranges from 10 cm in the inner layers to 20 cm in the outer layers.

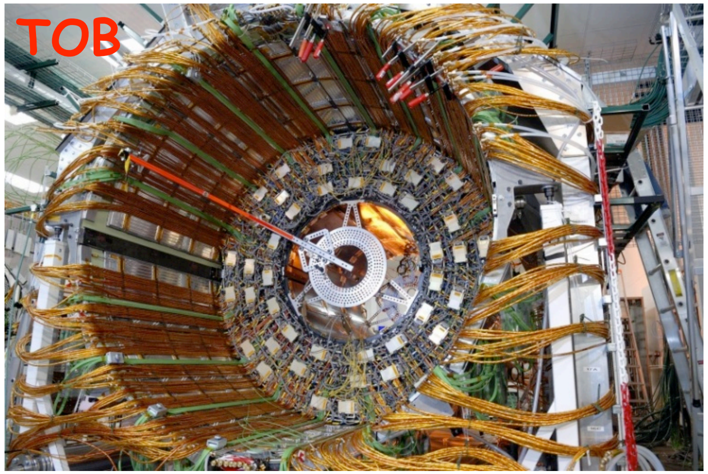
Pitch ranges from 80μm in the inner layers to near 200μm in the outer layers

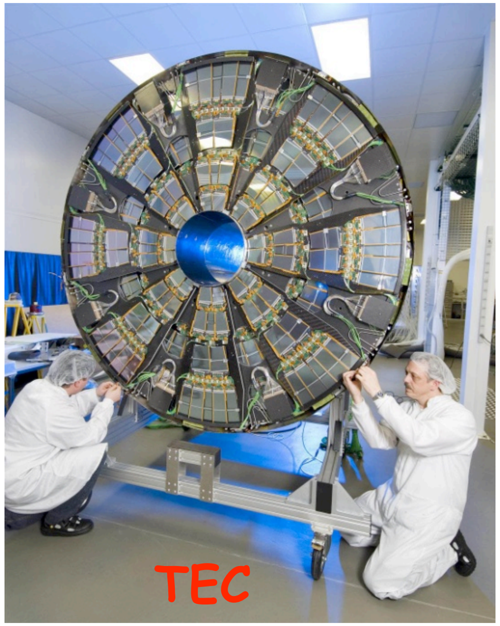
The CMS Silicon Strip Tracker



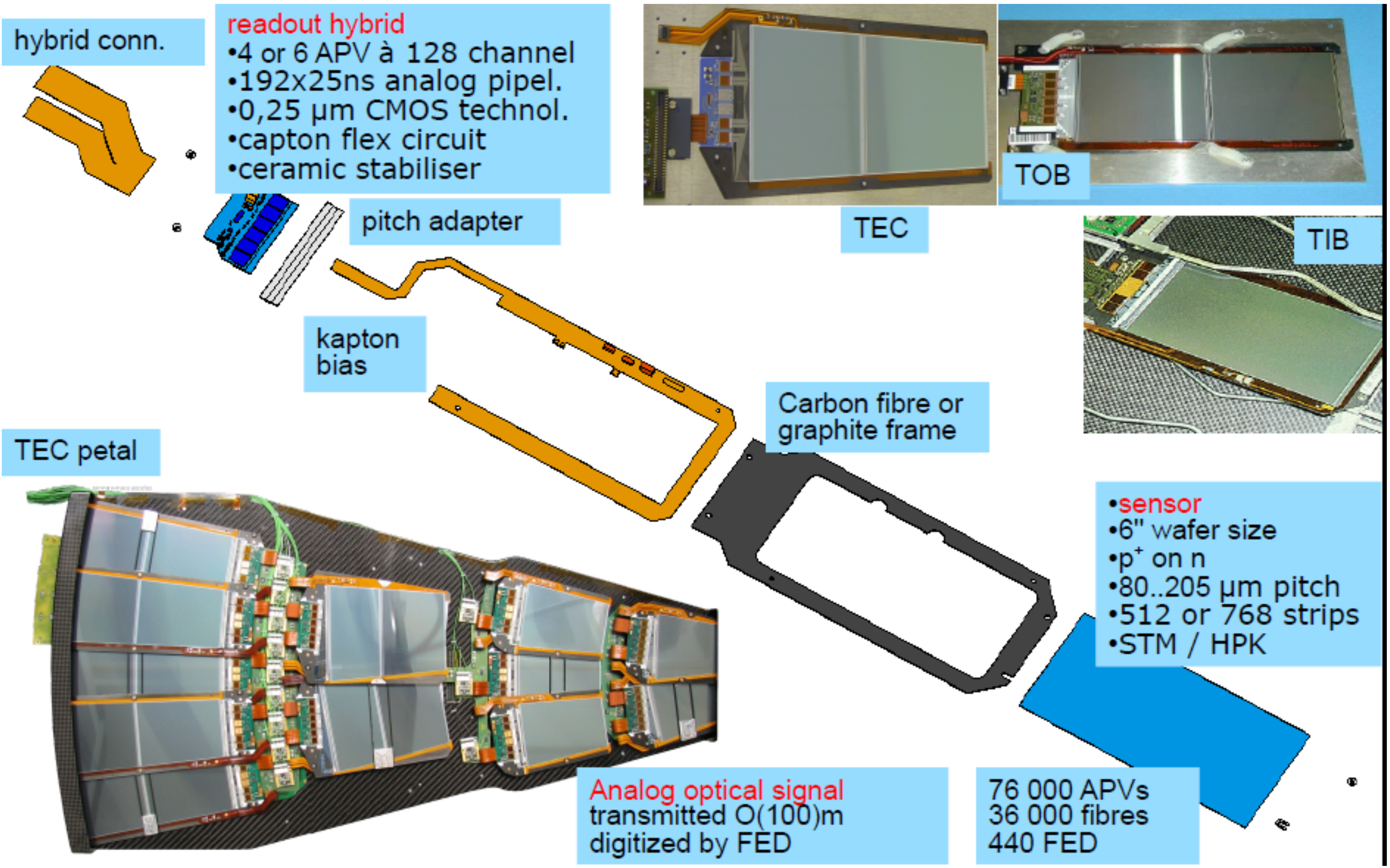






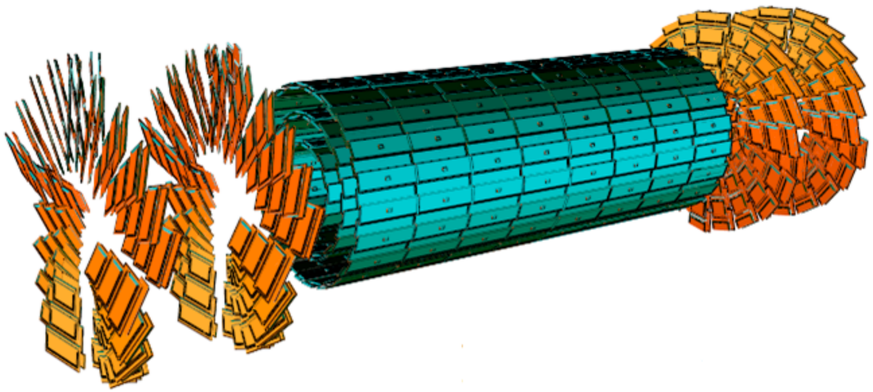


CMS modules of Silicon Strip Tracker



The CMS Pixel Detector

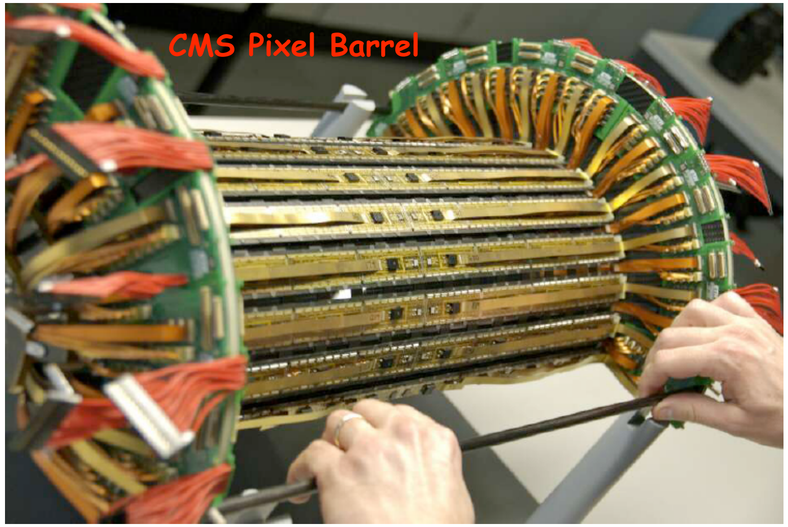
- 3 Barrel layers at 4.3, 7.2, 11.0 cm
- 2 Forward Disks
- 3-hit coverage for tracks $|\eta|<2.5$



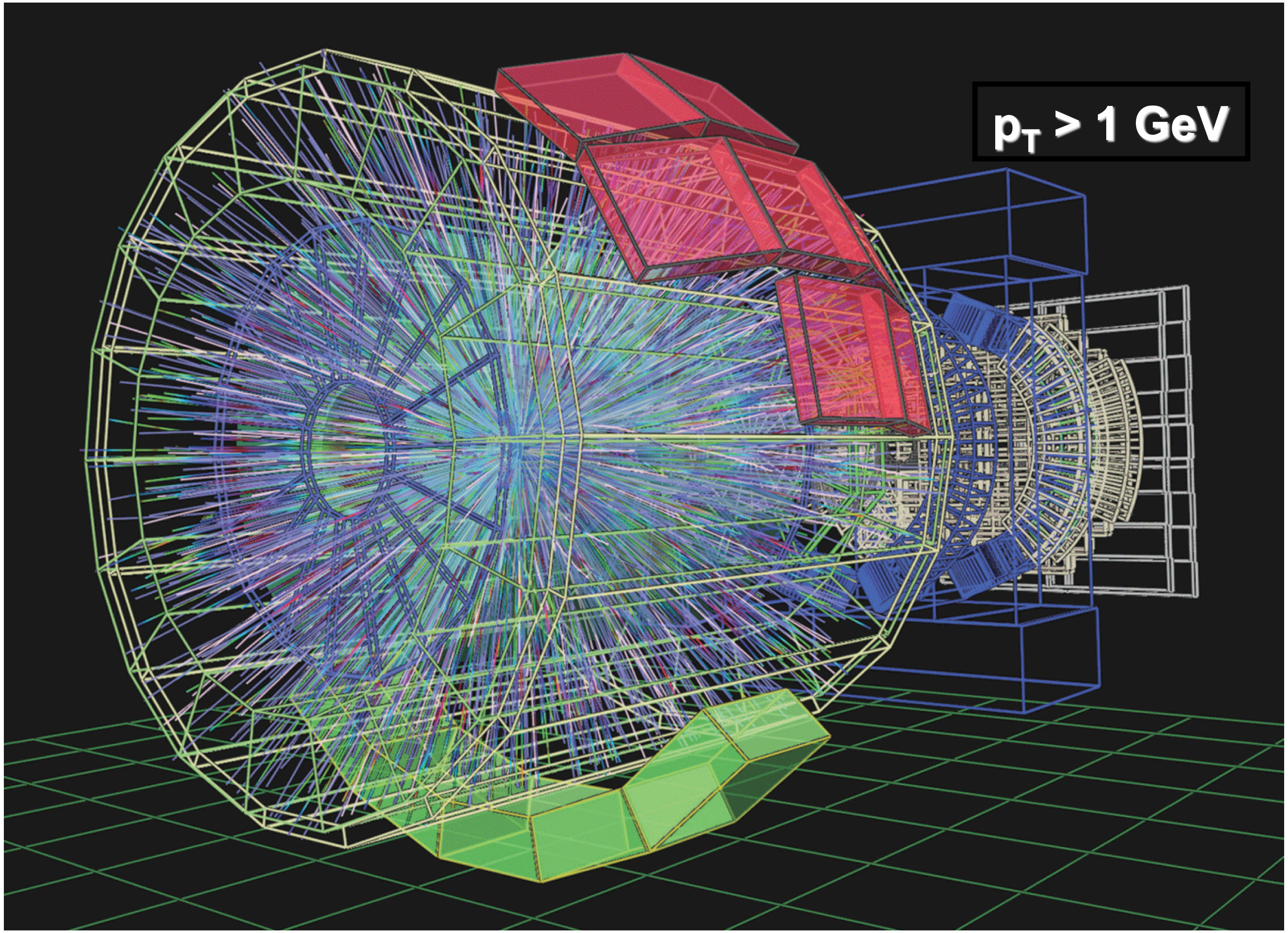
Total Area: 0.78+0.28 m^2
66 Million Pixels

Sensors: n on n Silicon 265 – 270 μm
150 x 100 μm pixels $\sigma(z) \sim \sigma(r\varphi) \sim 15\mu m$
Bump-bonded to PSI 46 Read Out Chips (analog readout)

Barrel module

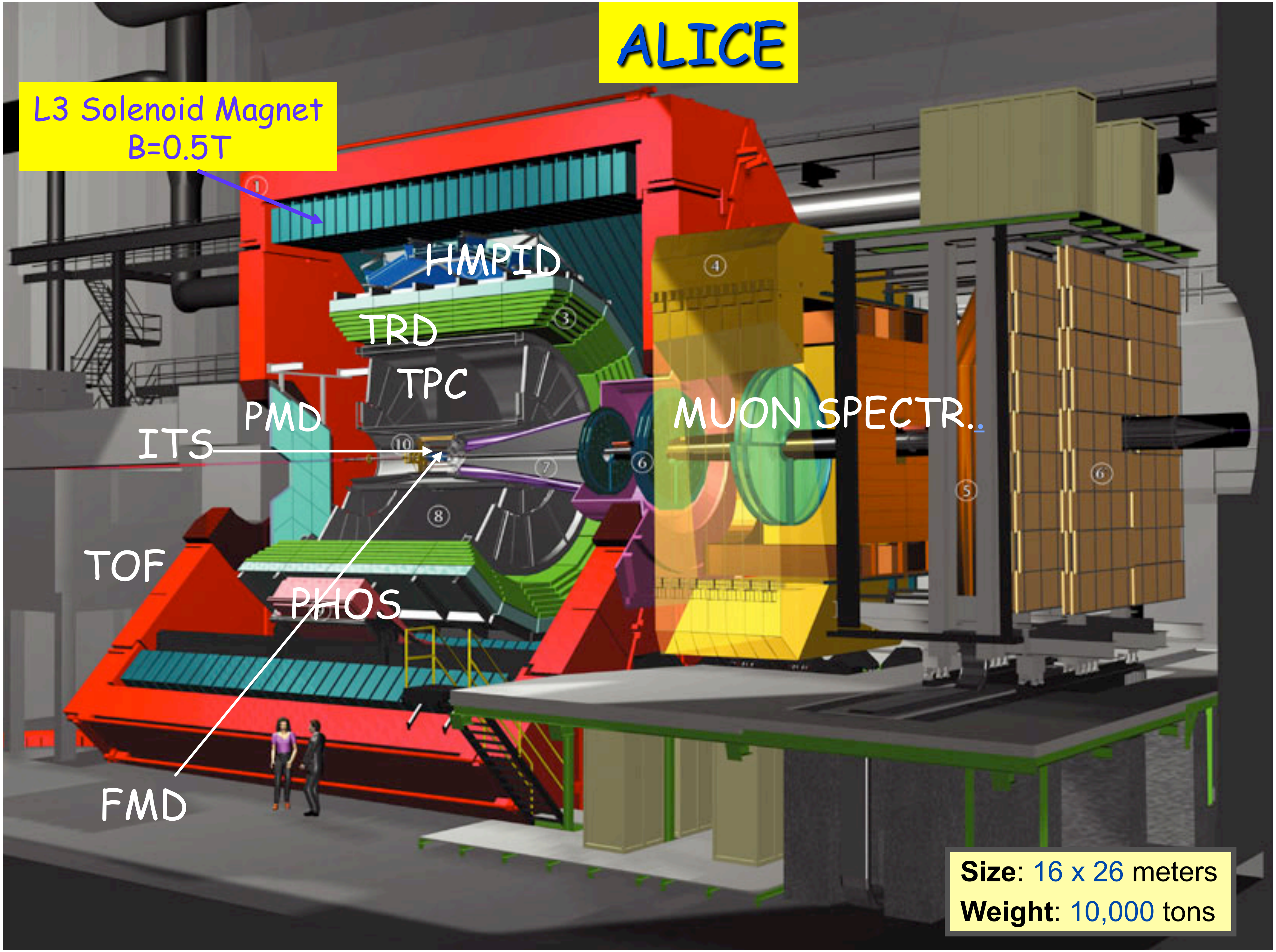


…and in ALICE tracking will not be easier….



An ALICE PbPb Event

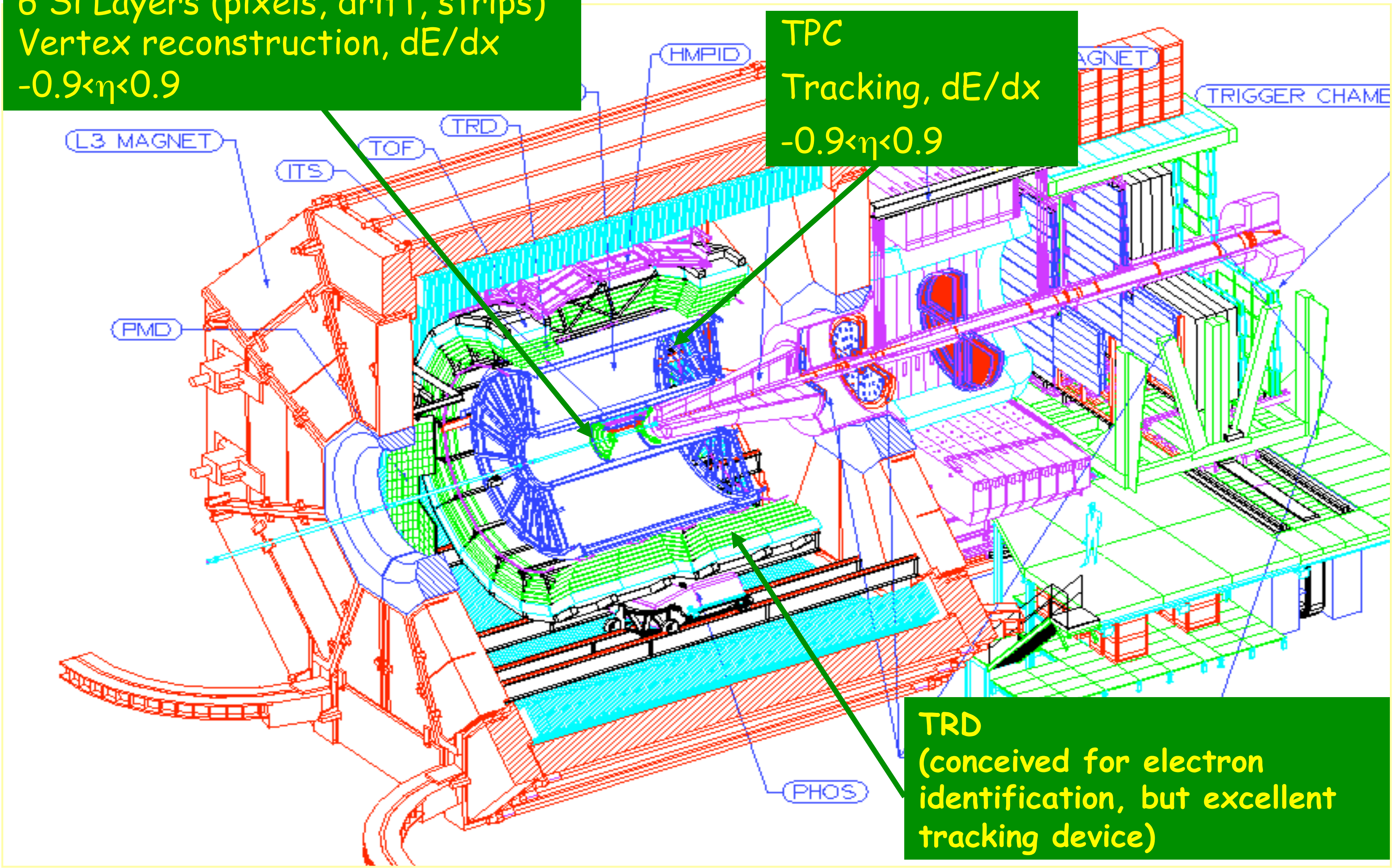
$N_{ch}(-0.5<\eta<0.5)=8000$!!


ALICE
L3 Solenoid Magnet
B=0.5T
HMPID
TRD
TPC
PMD
ITS
MUON SPECTR.
TOF
PHOS
FMD
Size: 16 x 26 meters
Weight: 10,000 tons

ALICE Tracking Layout

Inner Tracking System (ITS):
6 Si Layers (pixels, drift, strips)
Vertex reconstruction, dE/dx
$-0.9<\eta<0.9$

TPC
Tracking, dE/dx
$-0.9<\eta<0.9$



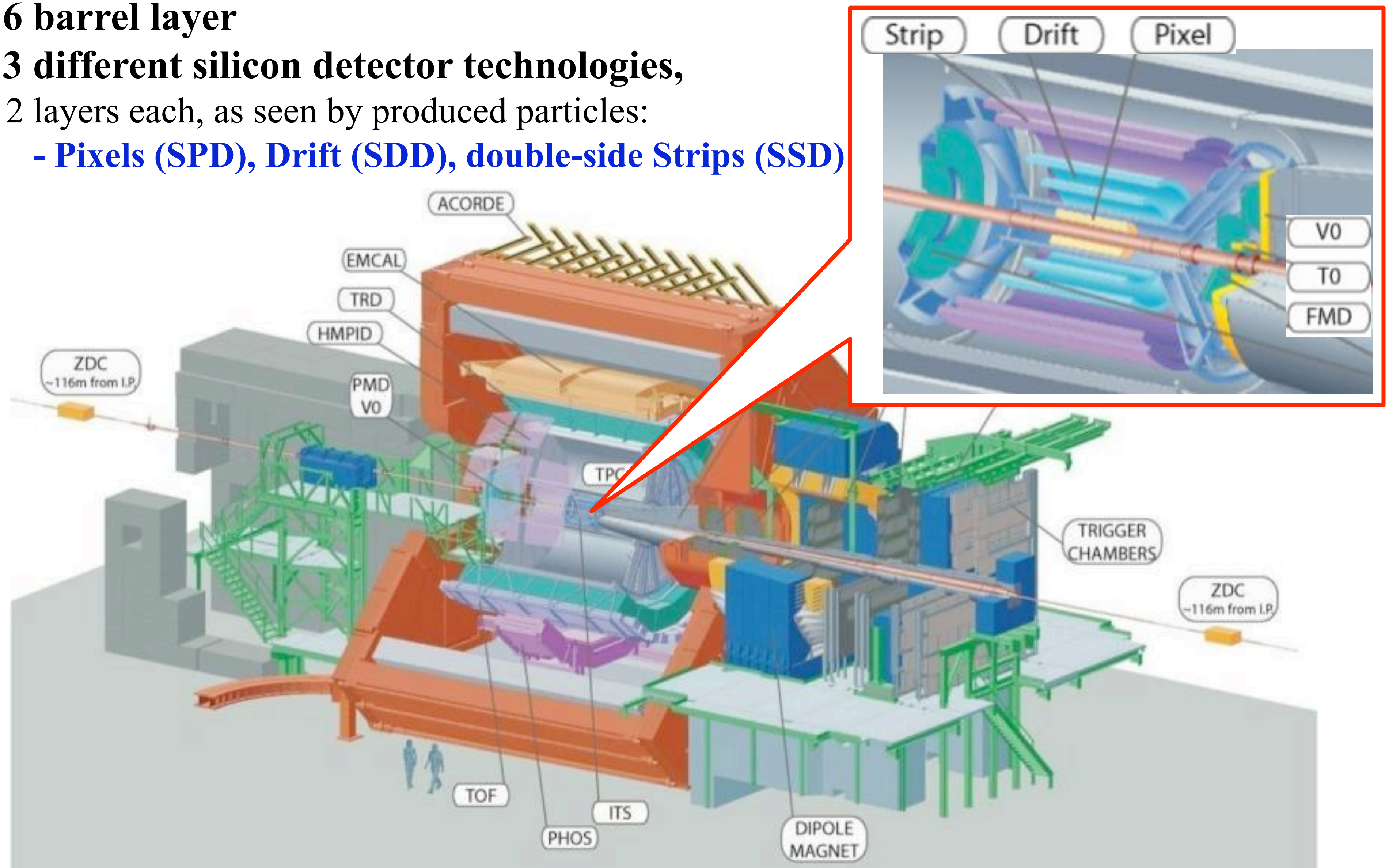
TRD
(conceived for electron identification, but excellent tracking device)

ALICE Inner Tracking System

- ➢ **6 barrel layer**
- ➢ **3 different silicon detector technologies,**

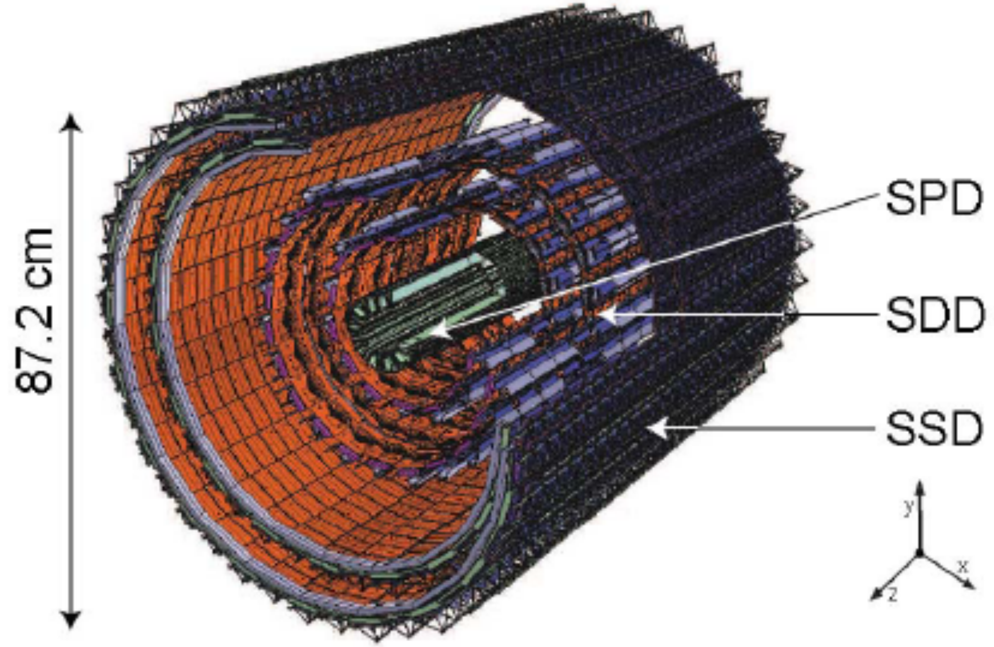
  2 layers each, as seen by produced particles:

  - Pixels (SPD), Drift (SDD), double-side Strips (SSD)



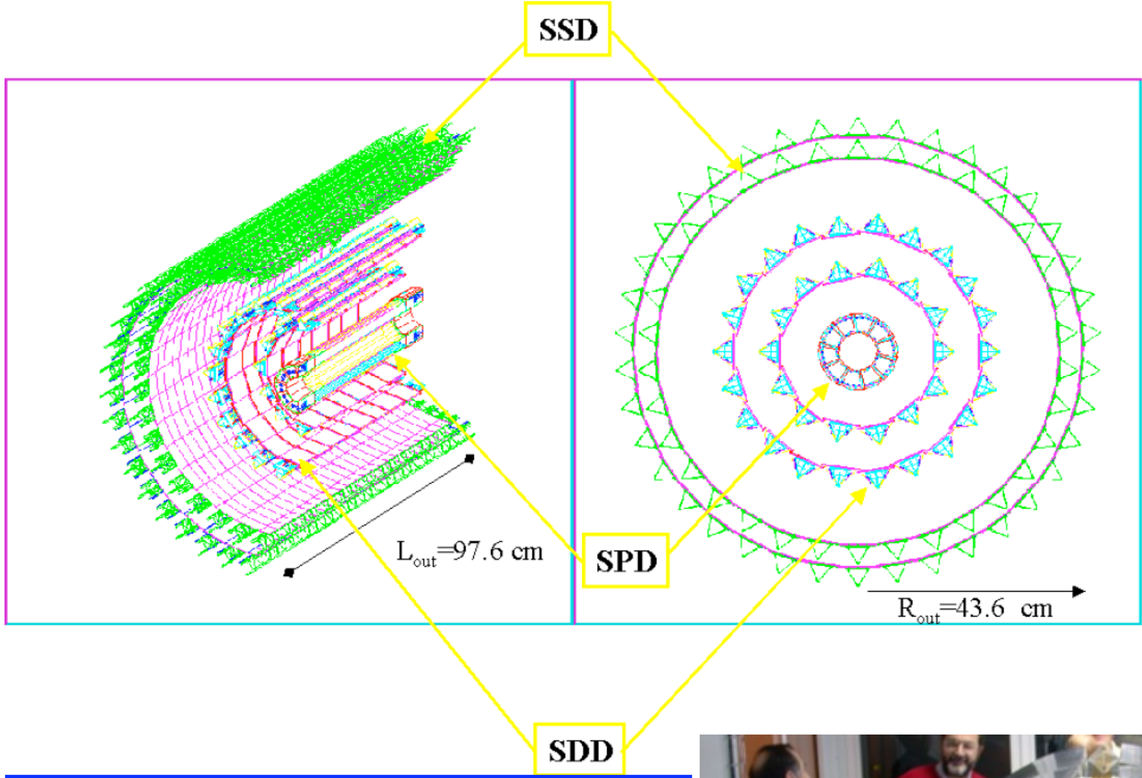
Inner Tracking System (ITS)

- Six layers of silicon detectors
  - ⇨ Coverage: |η|<0.9
- Three technologies
  - ⇨ Pixels (SPD)
  - ⇨ Drift (SDD)
  - ⇨ Double-sided Strips (SSD)
- Design goals
  - ⇨ Optimal resolution for primary vertex and track impact parameter
    - ✓ *Minimize distance of innermost layer from beam axis (<r>≈ 3.9 cm) and material budget*
  - ⇨ Maximum occupancy (central PbPb) < few %
  - ⇨ 2D devices in all the layers
  - ⇨ dE/dx information in the 4 outermost layers for particle ID in $1/\beta^2$ region



Layer	Det. Type	Radius (cm)	Length (cm)	Resolution (μm) rφ	Resolution (μm) Z
1	SPD	3.9	28.2	12	100
2	SPD	7.6	28.2	12	100
3	SDD	15.0	44.4	35	25
4	SDD	23.9	59.4	35	25
5	SSD	38.0	86.2	20	830
6	SSD	43.0	97.8	20	830

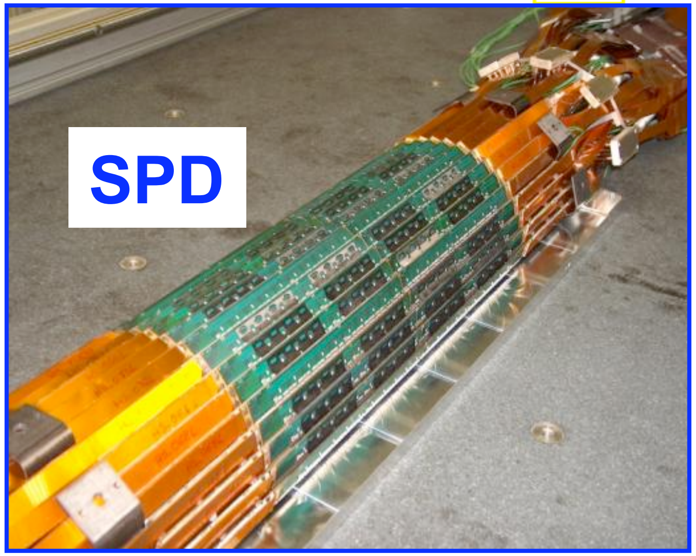
Inner Tracking System

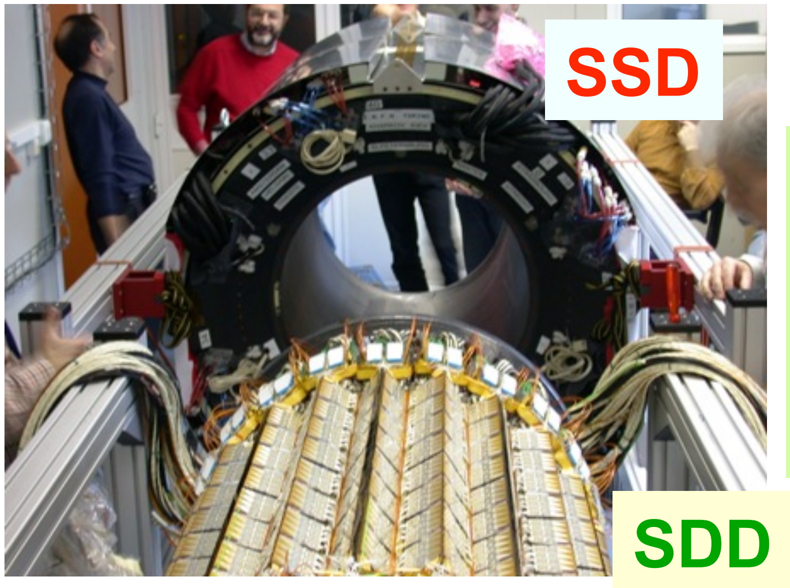


Silicon Pixel Detector (SPD):
- **~10M channels**
- **240 sensitive vol. (60 ladders)**

Silicon Drift Detector (SDD):
- **~133k channels**
- **260 sensitive vol. (36 ladders)**

Silicon Strip Detector (SSD):
- ~2.6M channels
- 1698 sensitive vol. (72 ladders)

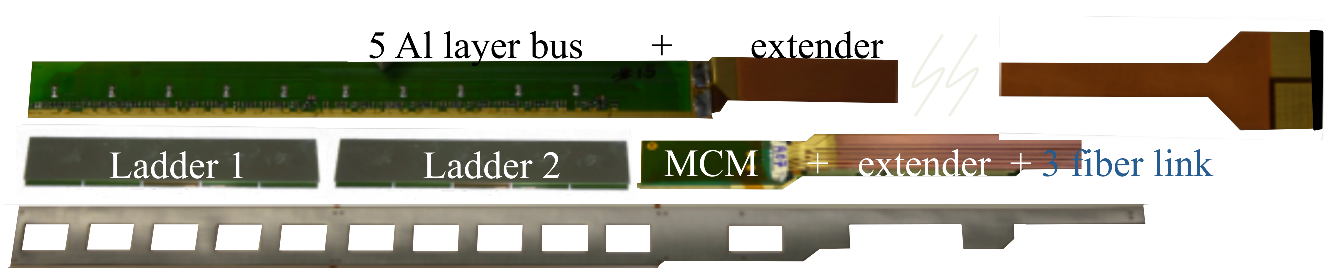


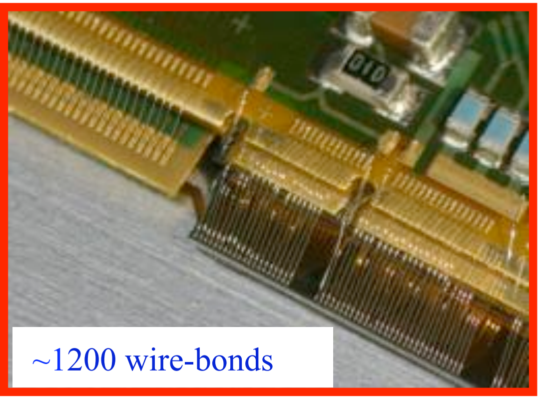


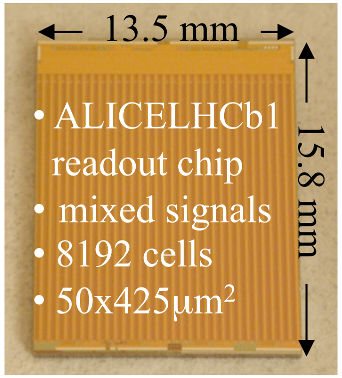
ITS total:
2198 alignable sensitive volumes
→ 13188 d.o.f.

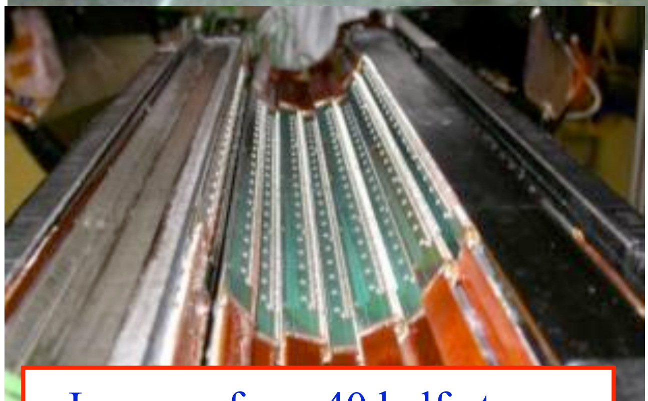
Pixel

- 2 layer barrel
- Total surface: ~0.24m^2
- Power consumption ~1.4kW
- Evaporative cooling C_4F_{10}
- Operating at room temperature
- Material budget per layer ~1% X_0

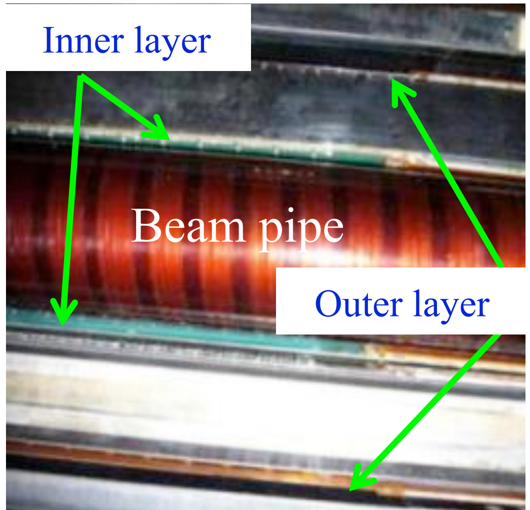






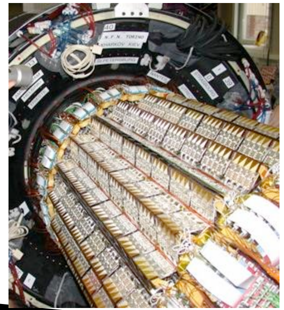


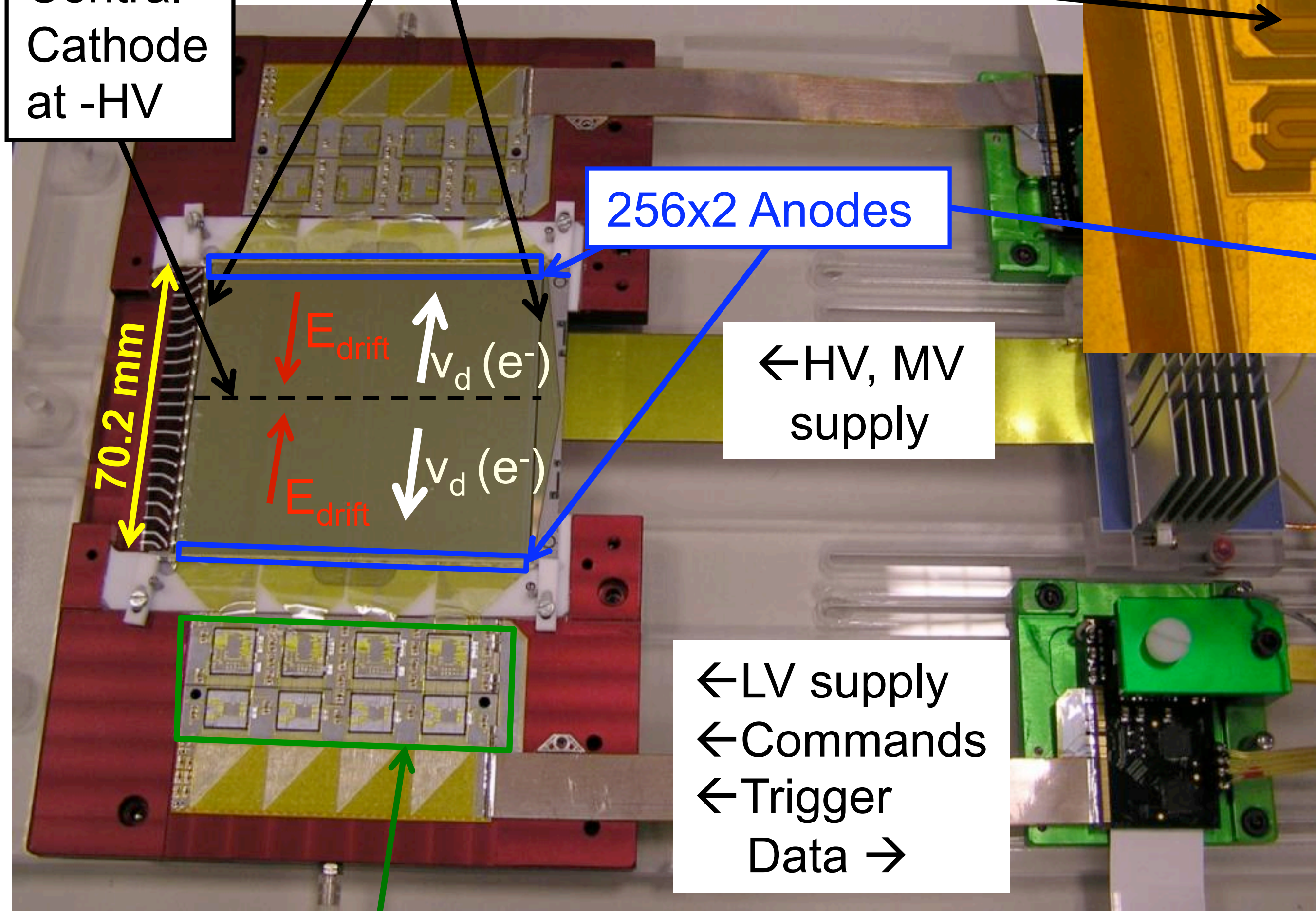
Unique L0 trigger capability
- Prompt FastOR signal from each chip
- Extract and *synchronize* 1200 FastOR signals from the 120 half-staves
- User defined programmable algorithms

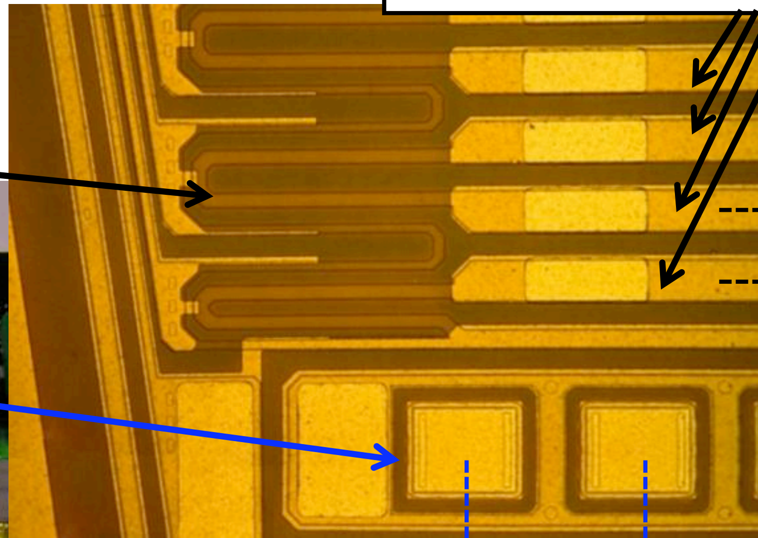


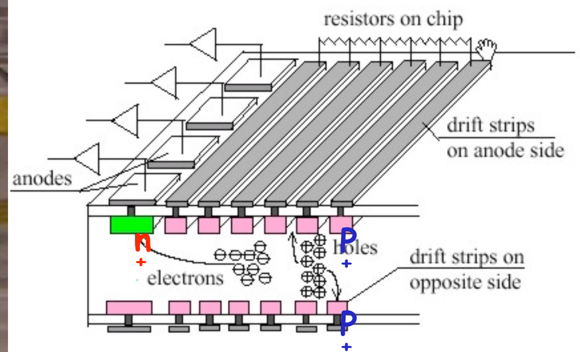
Minimum distance inner layer-beam pipe ≈5 mm

Silicon Drift Detector



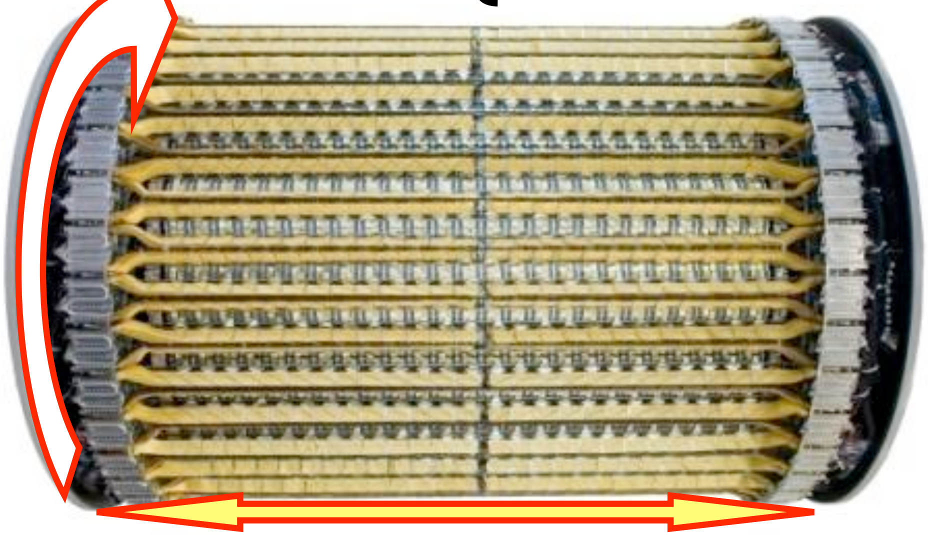




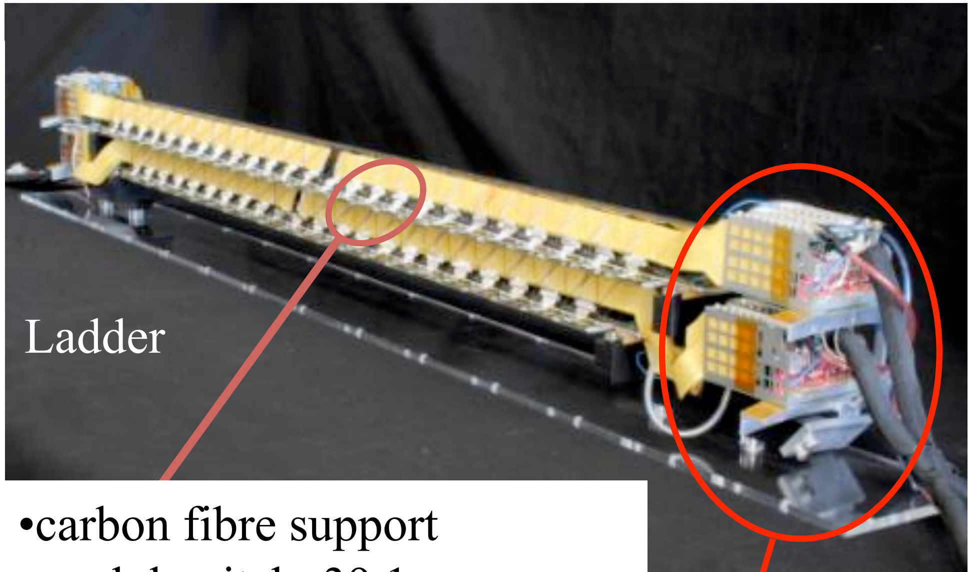


double-side Strip

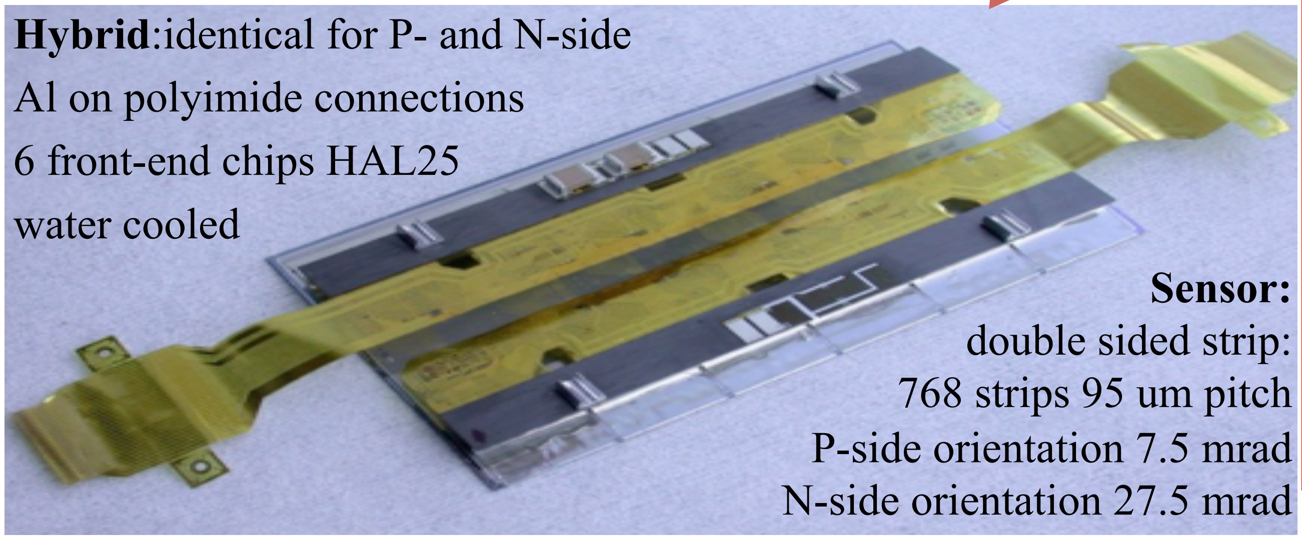
$r\phi$- overlap: { L5: 34 ladders, L6: 38 ladders }



z - overlap: { L5: 22 modules, L6: 25 modules }

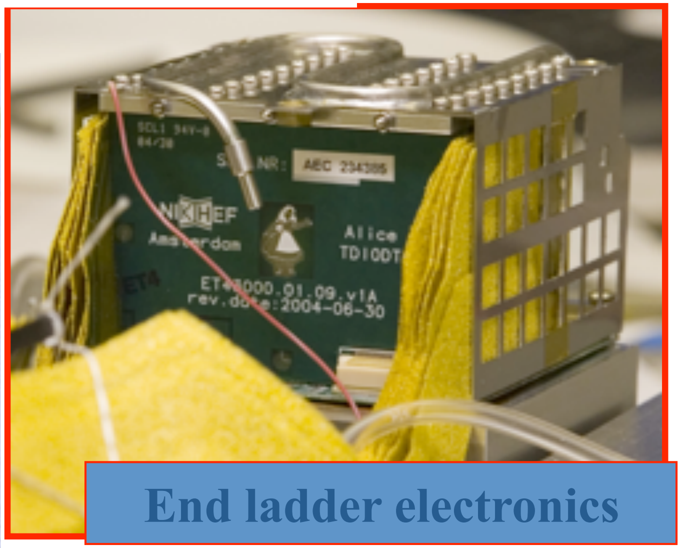


- carbon fibre support
- module pitch: 39.1 mm
- Al on polyimide laddercables



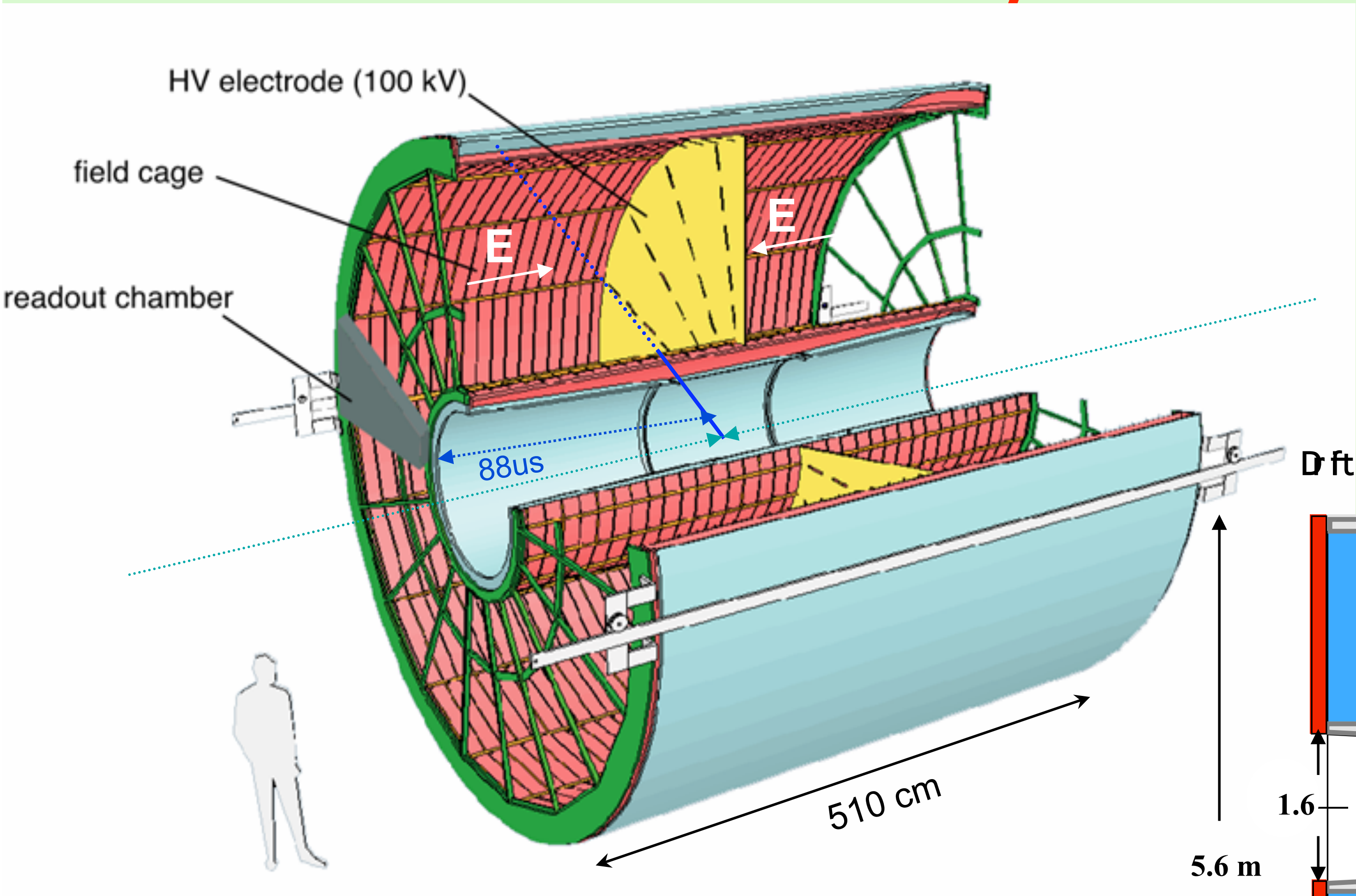
Hybrid:identical for P- and N-side
Al on polyimide connections
6 front-end chips HAL25
water cooled

Sensor:
double sided strip:
768 strips 95 um pitch
P-side orientation 7.5 mrad
N-side orientation 27.5 mrad



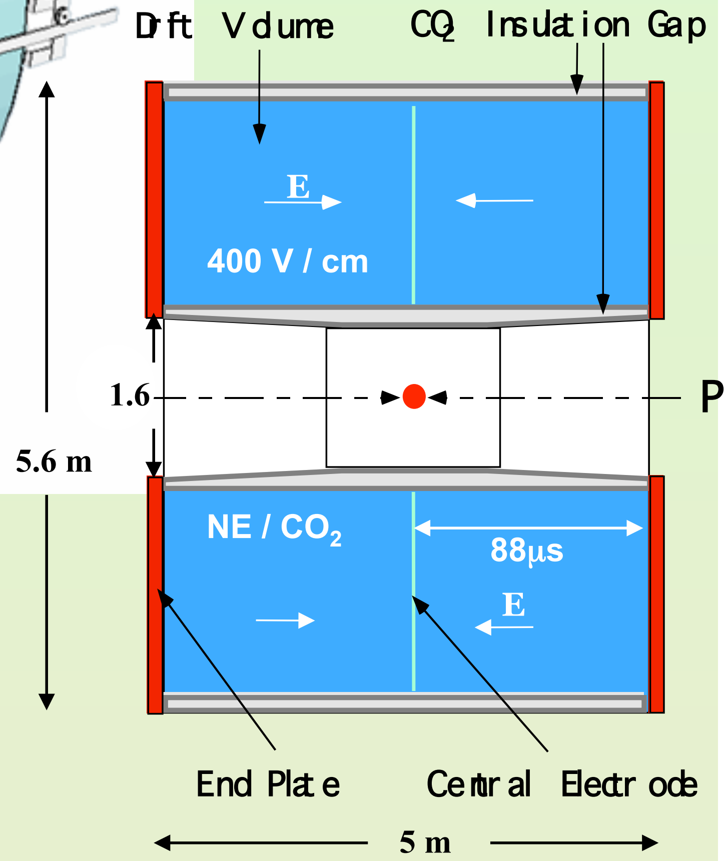
End ladder electronics

TPC layout



GAS VOLUME
88 m^3

DRIFT GAS
90% Ne - 10%CO_2



Readout plane segmentation

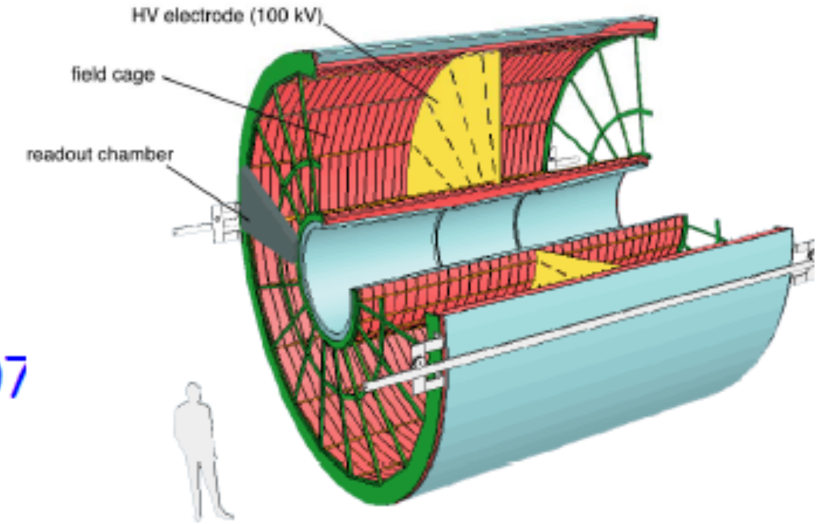
18 trapezoidal sectors

each covering 20 degrees in azimuth

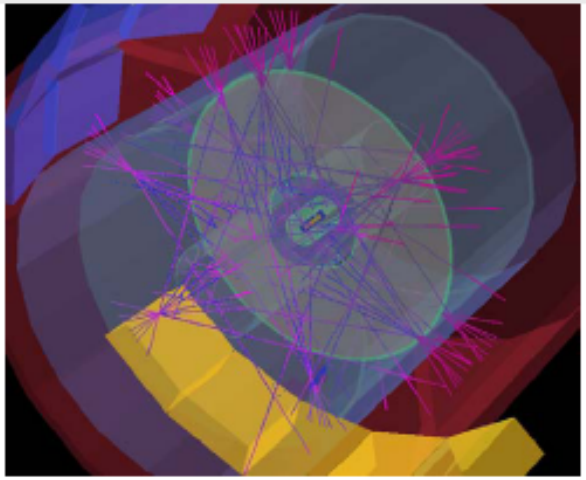
570k channels

Time Projection Chamber (TPC)

- Characteristics:
  - ⇨ 85 m^3 - $NeC_2O_2N_2$ gas mixture
  - ⇨ 557,568 readout channels
  - ⇨ Maximum drift time = 92 μs
  - ⇨ Many (>90) 3D points (+dE/dx) per track
- Installation in ALICE since 2007
- Running continuously from May to October 2008 and since August 2009
- Calibration:
  - ⇨ >750 million events (cosmics, krypton, and laser) recorded, with and without B
  - ⇨ First round of calibrations (dE/dx, momentum, alignment, gain) completed before p-p collisions



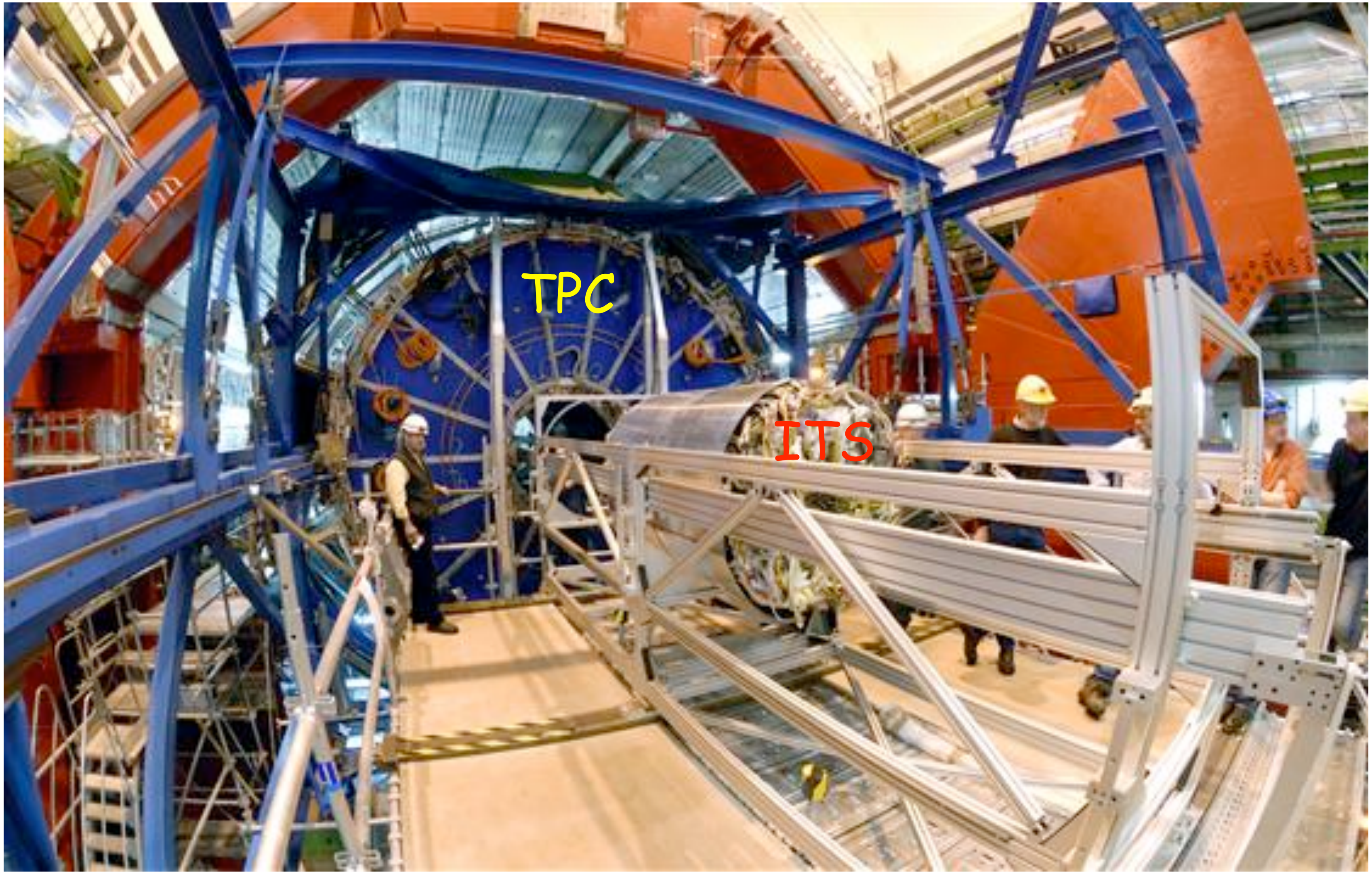
Laser event



J. Alme et al., TPC collab., arXiv:1001.1950

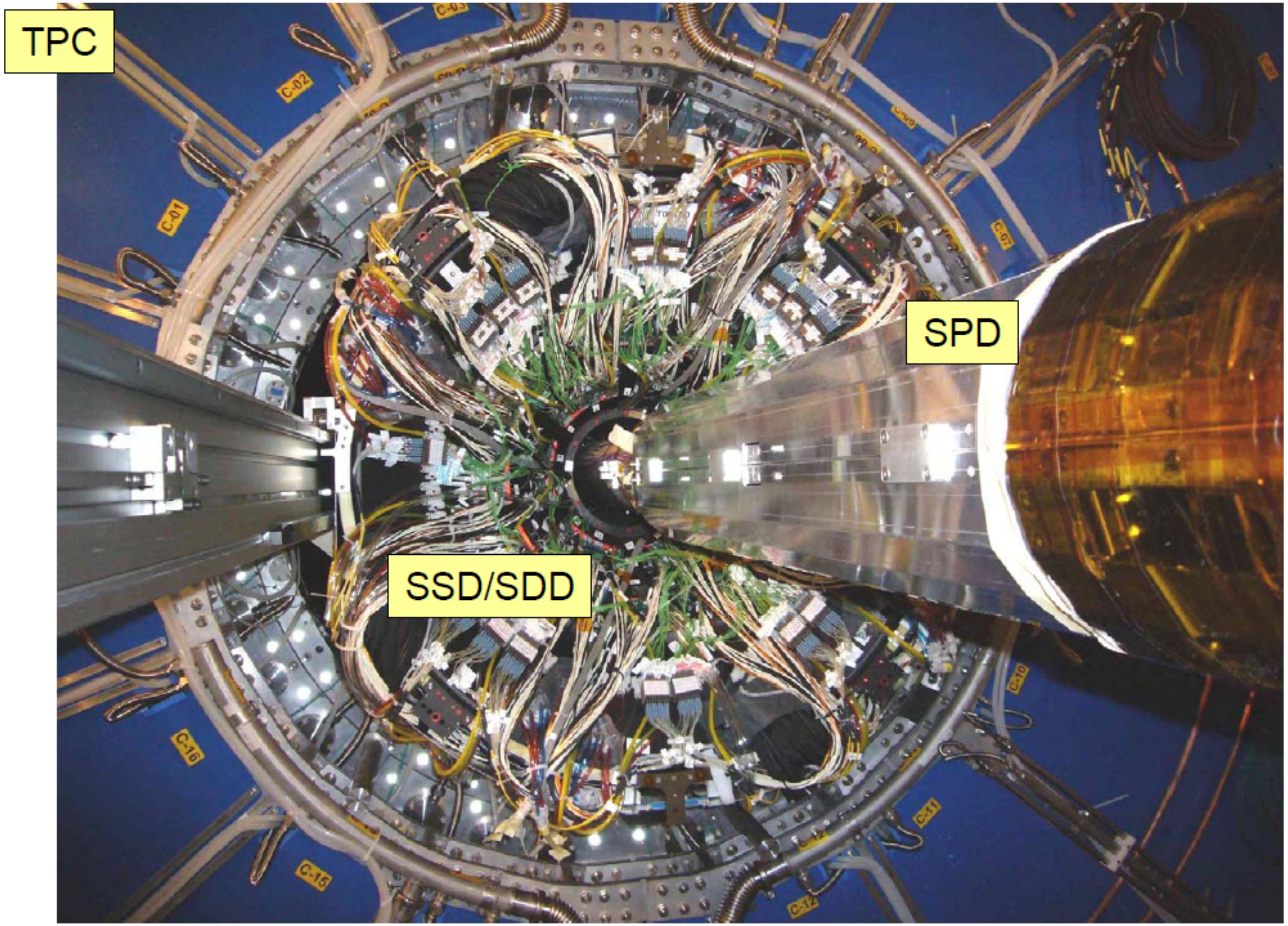
TPC

Largest TPC ever: R=2.5 m, length=5m



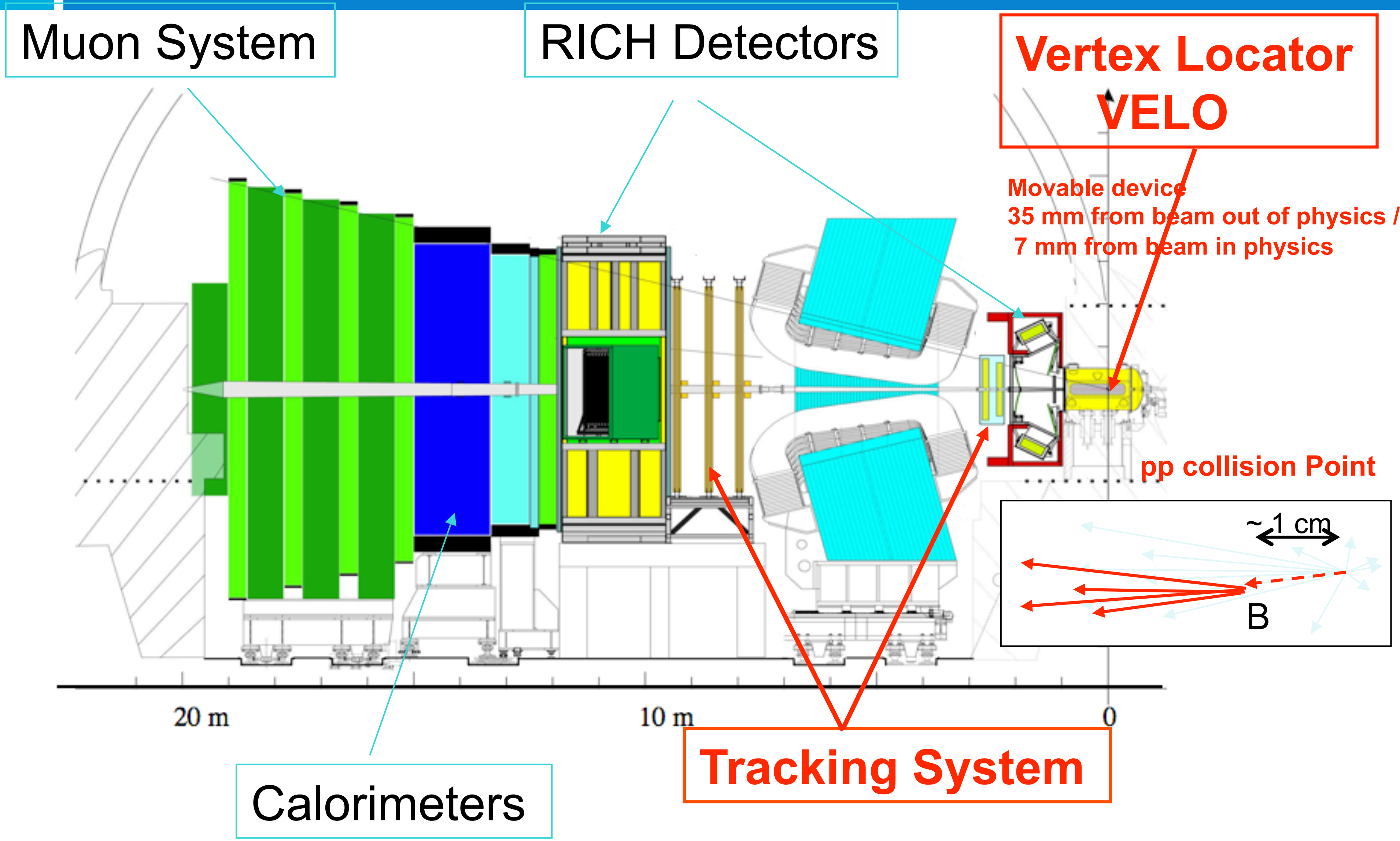
ALICE installation

SPD, SDD+SSD, TPC 'Russian Doll', sliding one after the other

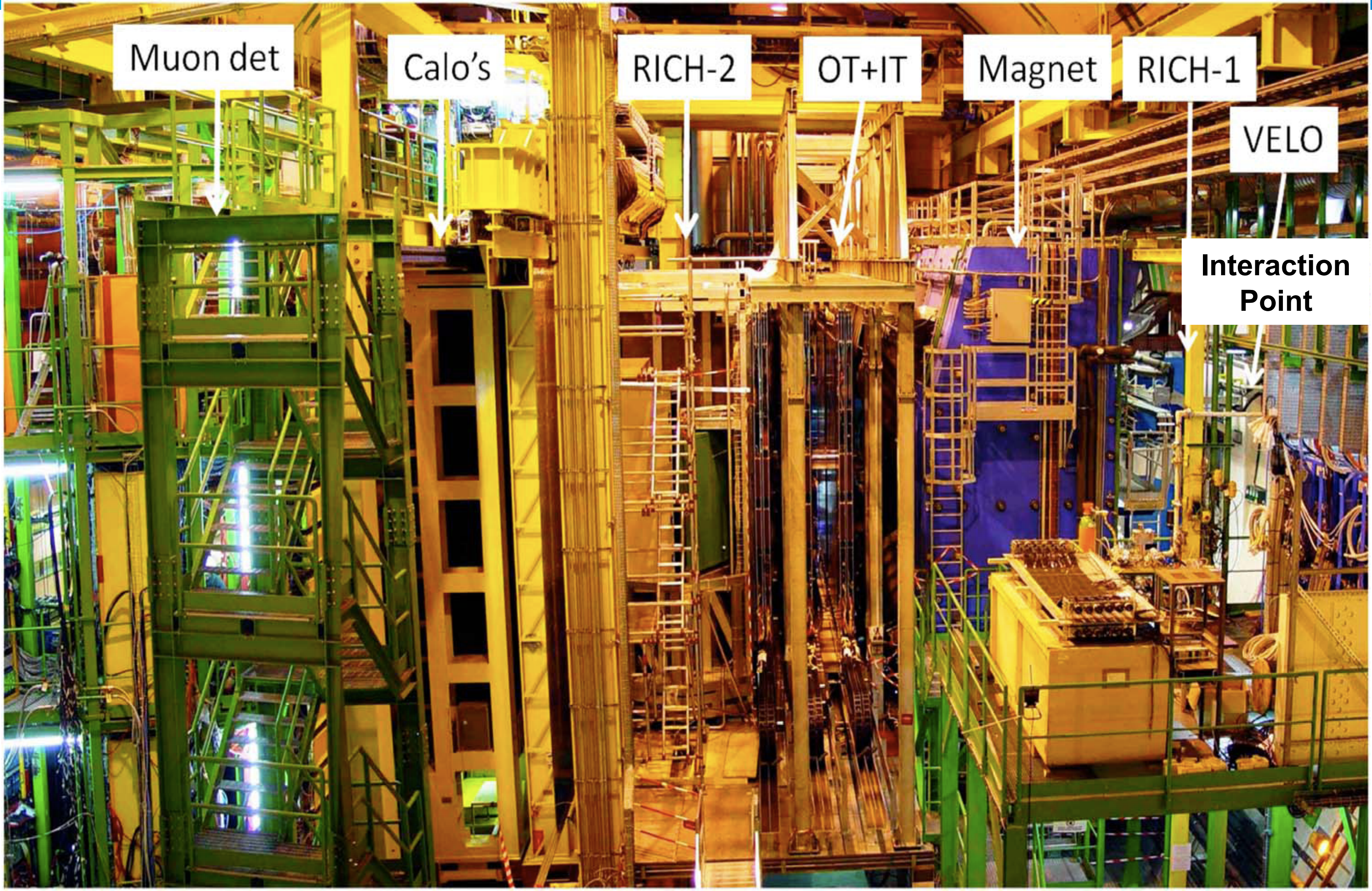


MORE
SLIDES

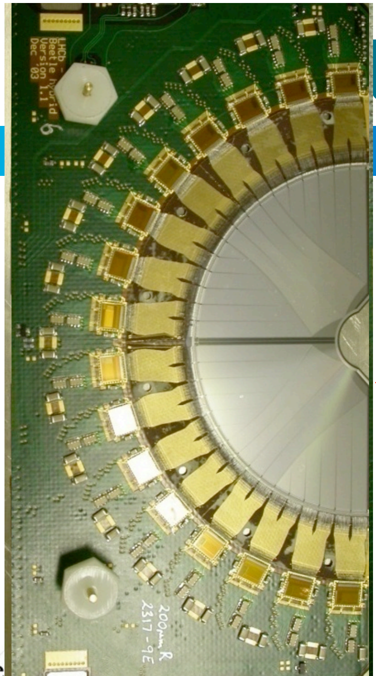
The LHCb Detector

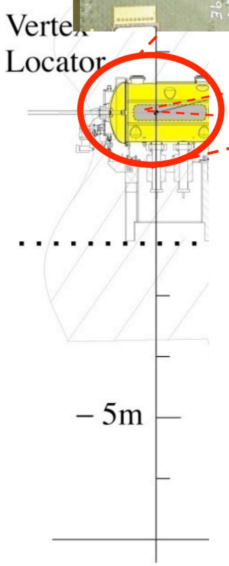


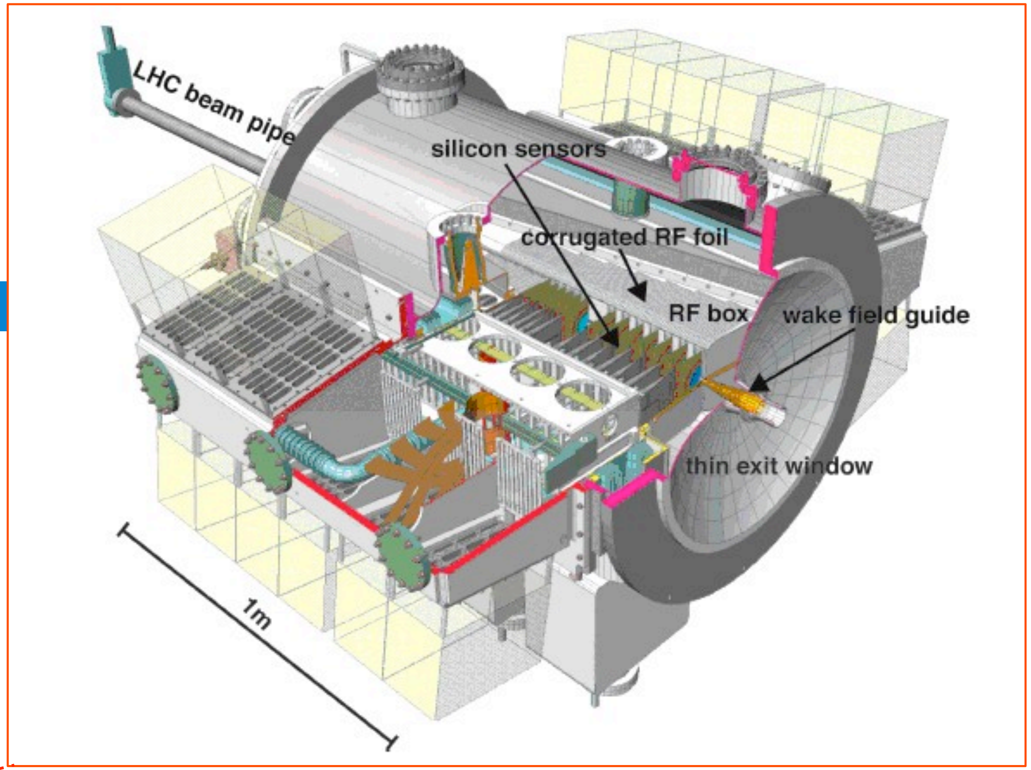
The LHCb Detector

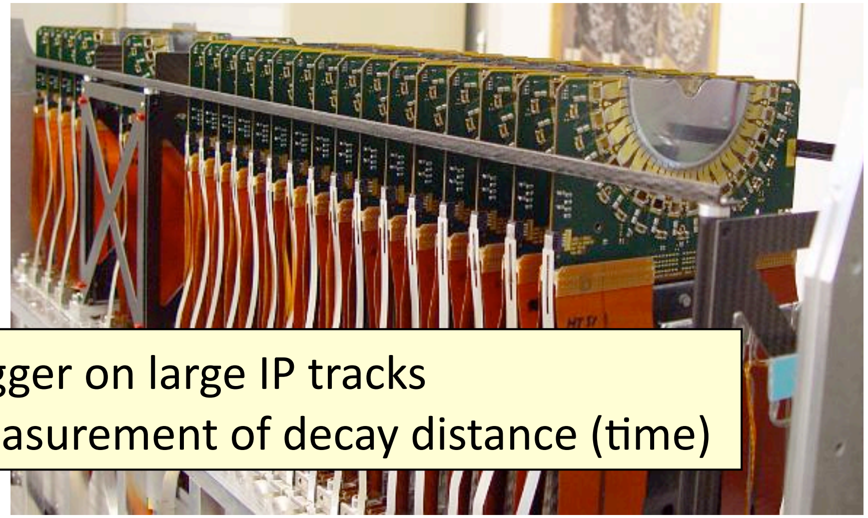


B-Vertex
urement









Vertex Locator (Velo)

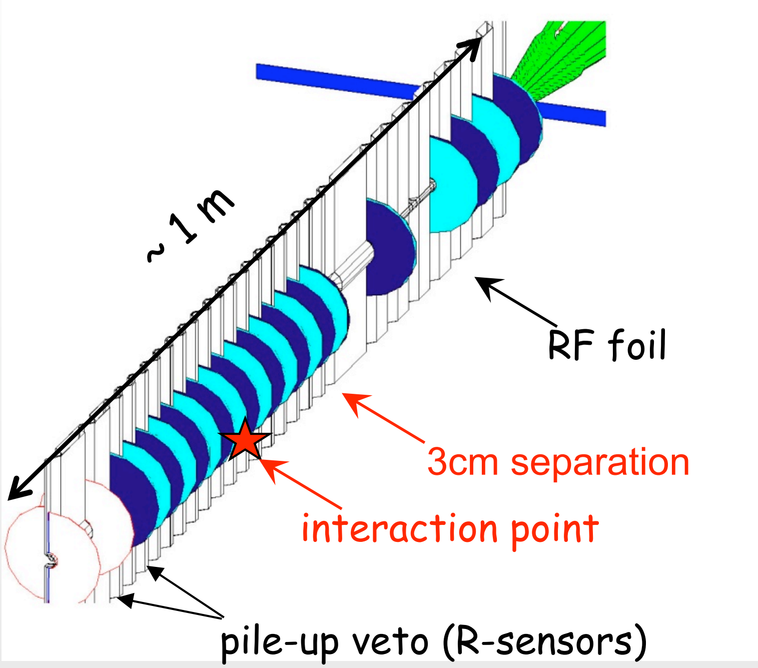
21 stations of silicon strip detectors (r-ϕ)

~ 8 μm hit resolution

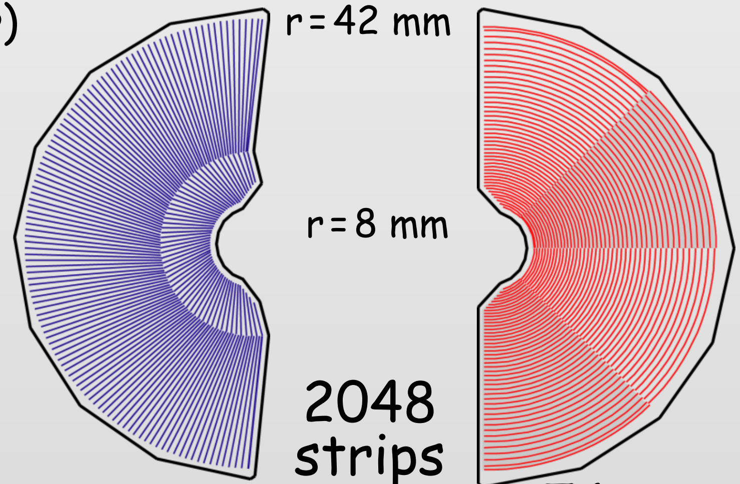
~25 μm IP resolution

- Trigger on large IP tracks
- Measurement of decay distance (time)

VELO - VErtex LOcator

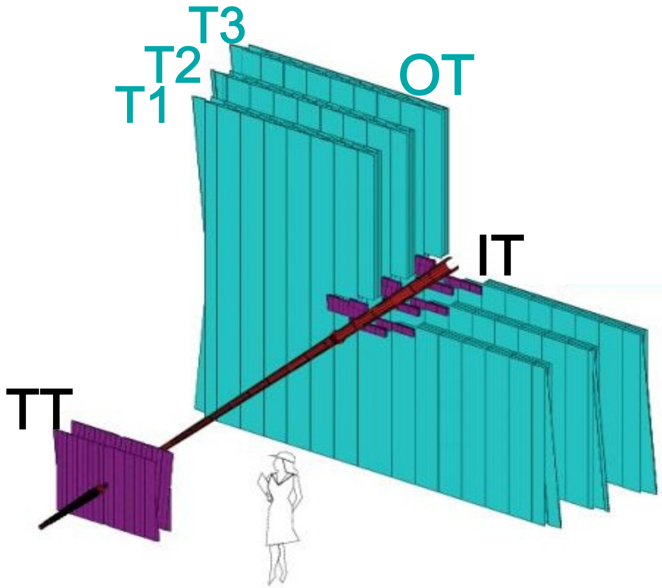


- Detector halves retractable (by 30mm) from interaction region before LHC is filled (to allow for beam excursions before injection and ramping)
- 21 tracking stations
- Unique R-Φ geometry, 40–100μm pitch, 300μm thick
- Optimized for
  - tracking of particles originating from beam-beam interactions
  - fast online 2D (R-z) tracking
  - fast offline 3D tracking in two steps (R-z then Φ)



Tracking System

TT + 3 stations (T1,T2,T3), each with 4 detection planes (0°,+5°,-5°,0°)

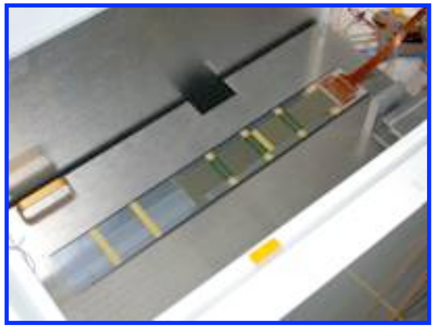


Similar sensors for TT & IT:

Si μ-strip with pitch ~ 200 μm

TT: 128 Modules (7 Si sensors)

IT: ladders with 1 or 2 sensors



Trigger Tracker

~1.4×1.2 m^2 (144k ch)

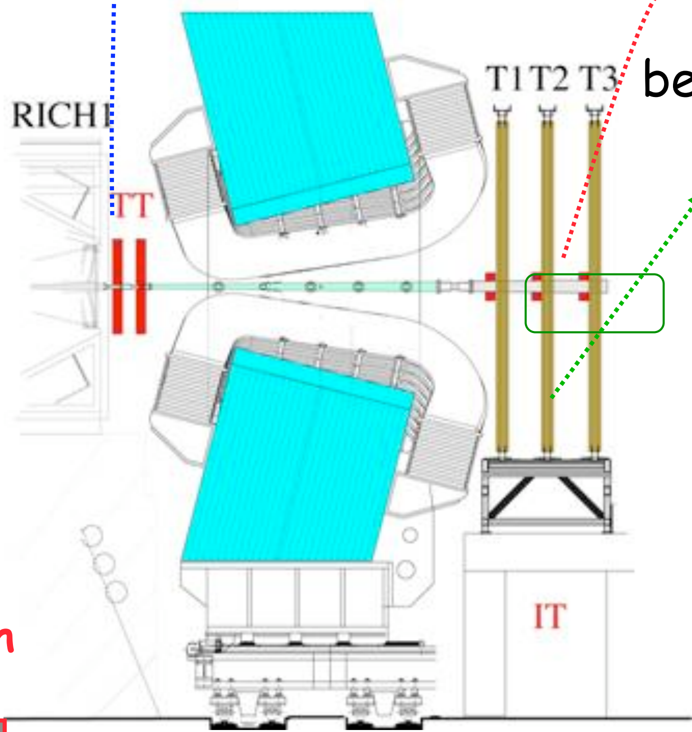
Inner Tracker

~0.5 m^2 around beam pipe (130k ch)

Outer Tracker

Straw Tubes

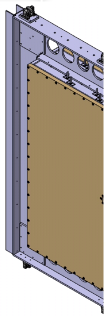
(56 k ch)

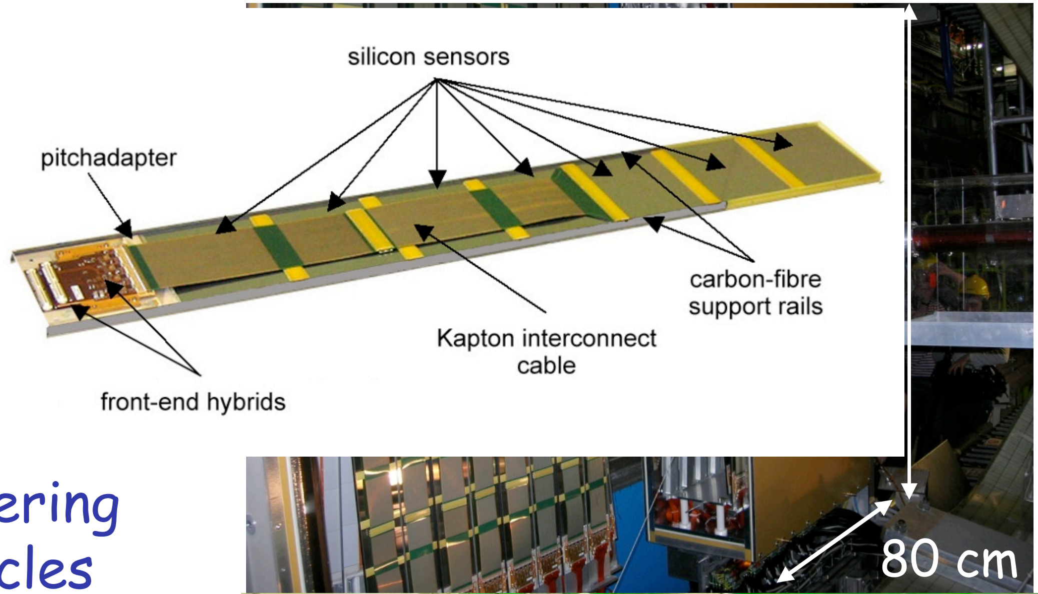


Silicon Trackers

Trigger Tracker:

- 500 μm thick Si μ-strip sensors
- 7-sensor long ladders, 183 μm pitch
- Area of 8.2 m^2 covered with 896 sensors, 280 r/o sectors,
- 99.7% of channels functional





→ Provides tracking info for triggering
→ Tracking of low momentum particles

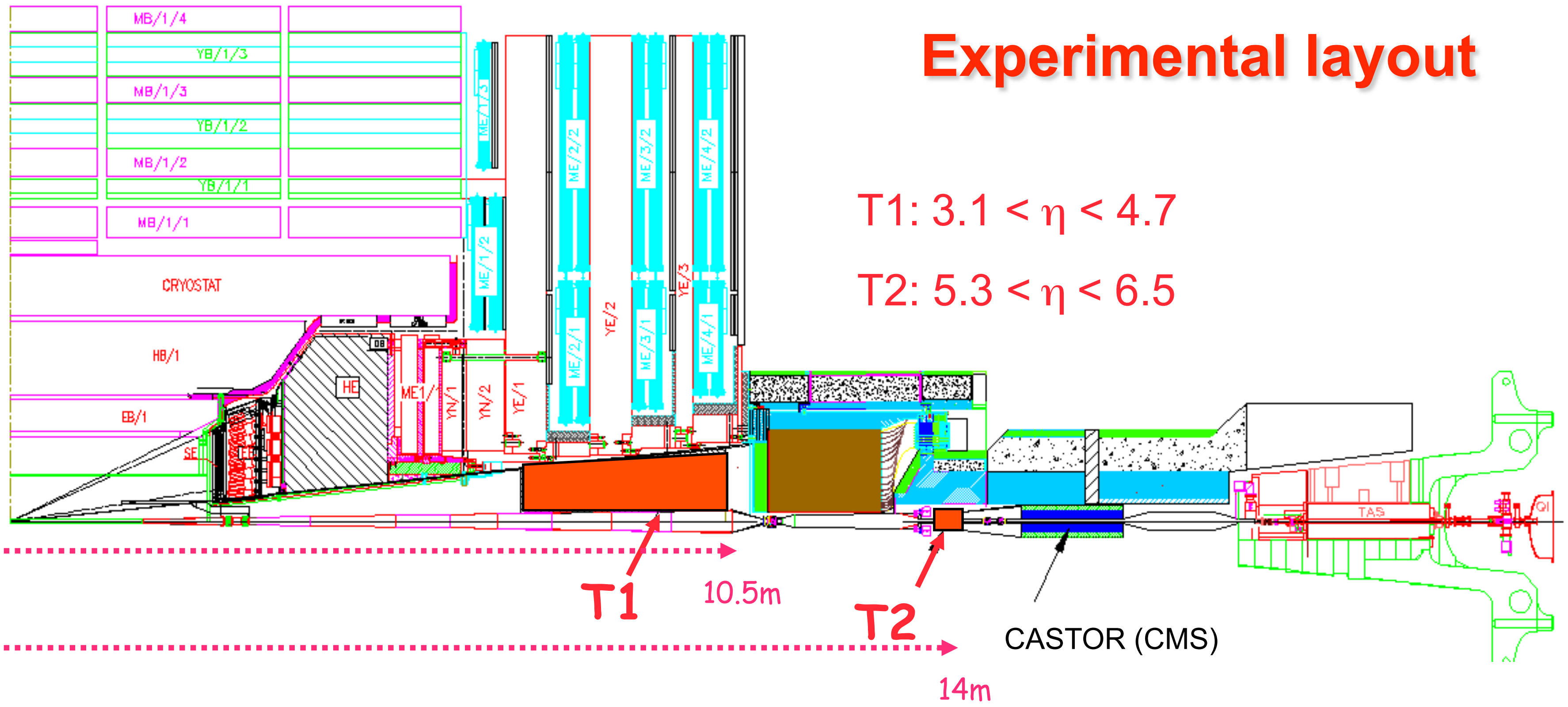
Inner Tracker:

- 320 (410) μm for 1 (2)-sensor ladders
- Readout pitch 198 μm pitch
- Area of 4.2 m^2 covered with 504 sensors, 336 ladders
- 99.4% of channels functional

→ Provides tracking in high flux region ($5 \times 10^5 cm^{-2}s^{-1}$), 2% of area 20% of tracks

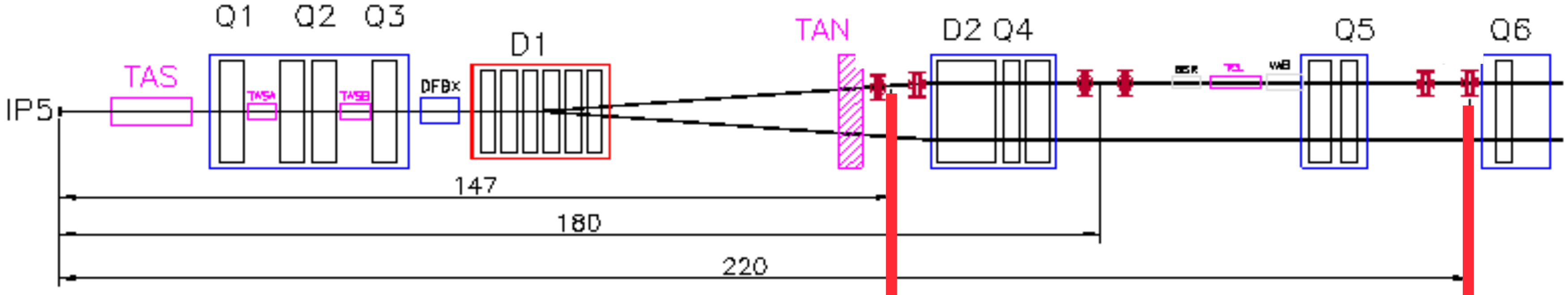
TOTEM

Experimental layout



T1: $3.1 < \eta < 4.7$

T2: $5.3 < \eta < 6.5$



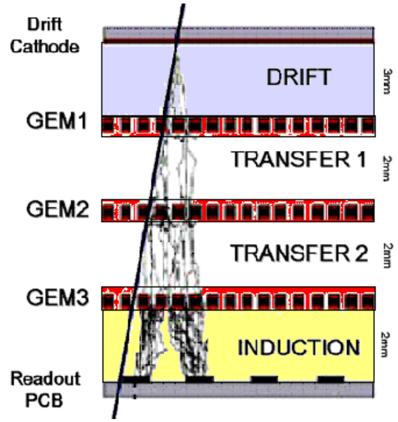
Roman Pot 1 (147 m)

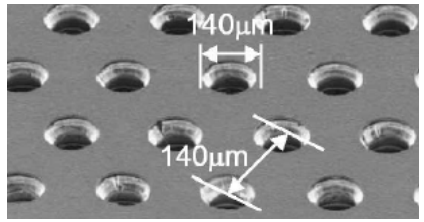
Roman Pot 3 (220 m)

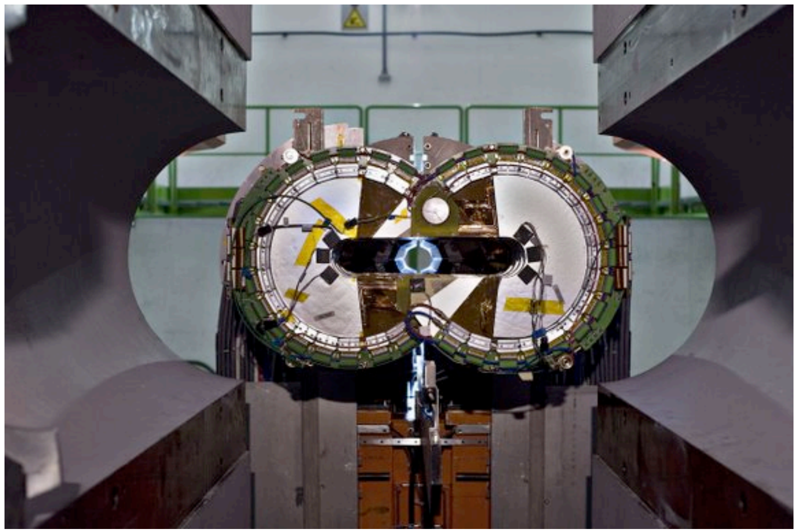
TOTEM

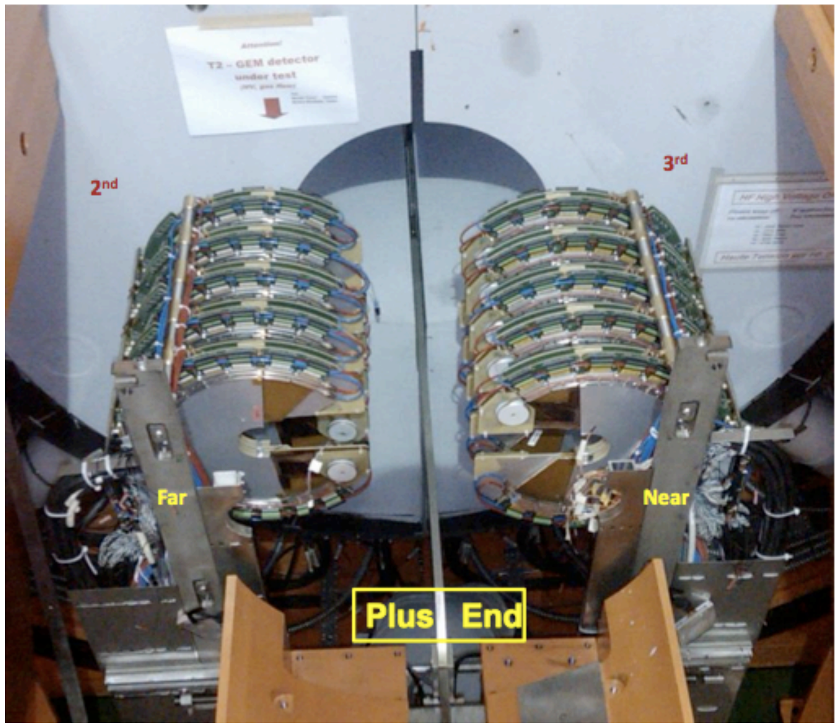
T2 Telescope

- Gas Electron Multiplier (GEM)
- $5.3 < |\eta| < 6.5$
- 10 half-planes @ 13.5 m from IP5
- Half-plane:
  - 512 strips (width 80 μm, pitch of 400 μm), radial coordinate
  - 65*24=1560 pads (2x2 mm^2 -> 7x7 mm^2), radial and azimuth coord.
  - Resolution: $\sigma(R) \sim 100$ μm, $\sigma(\varphi) \sim 1°$
- Primary vertex reconstruction (beam-gas interaction removal)
- Trigger using (super) pads

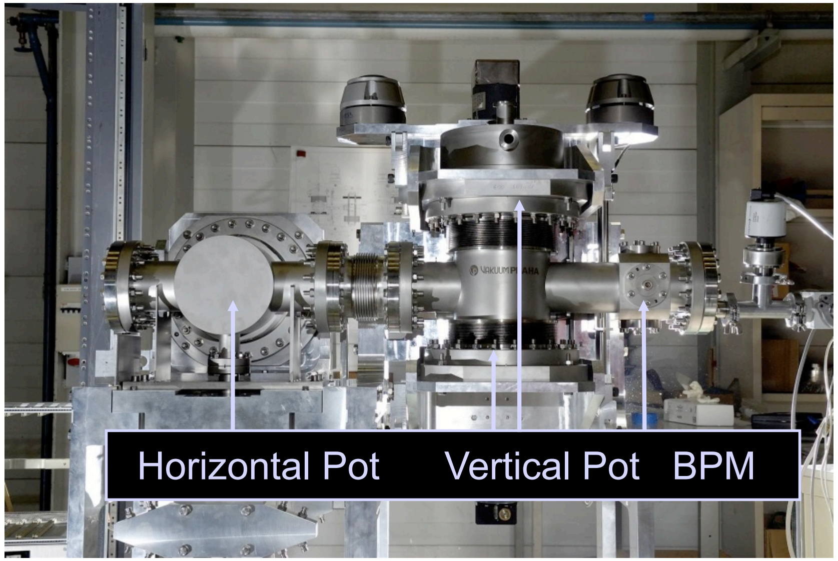


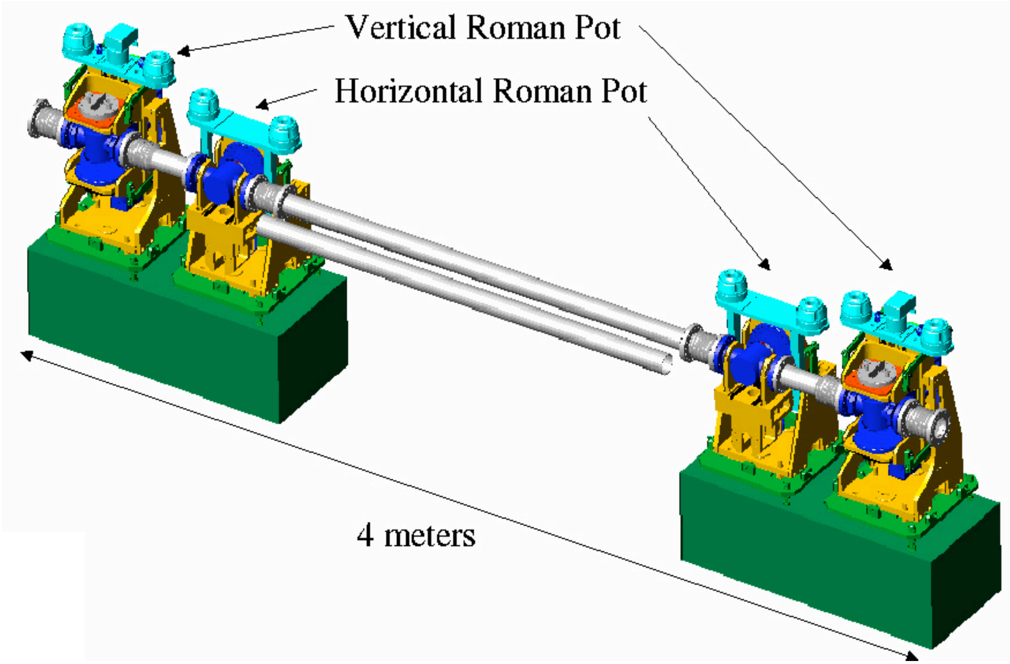




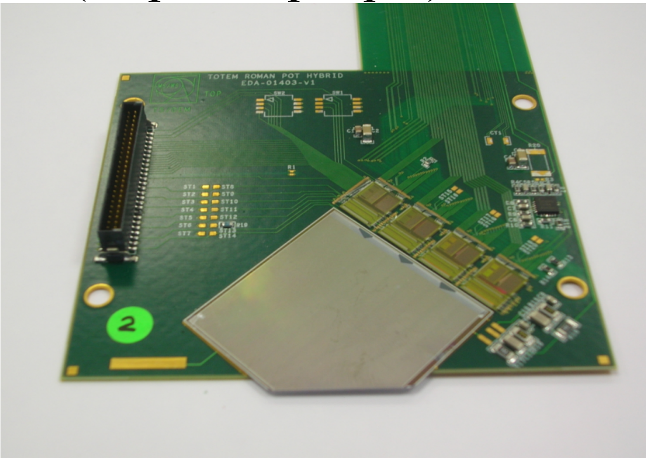


Leading Proton Detection: TOTEM Roman Pots





"edgeless" Si strip detectors
(10 planes per pot)

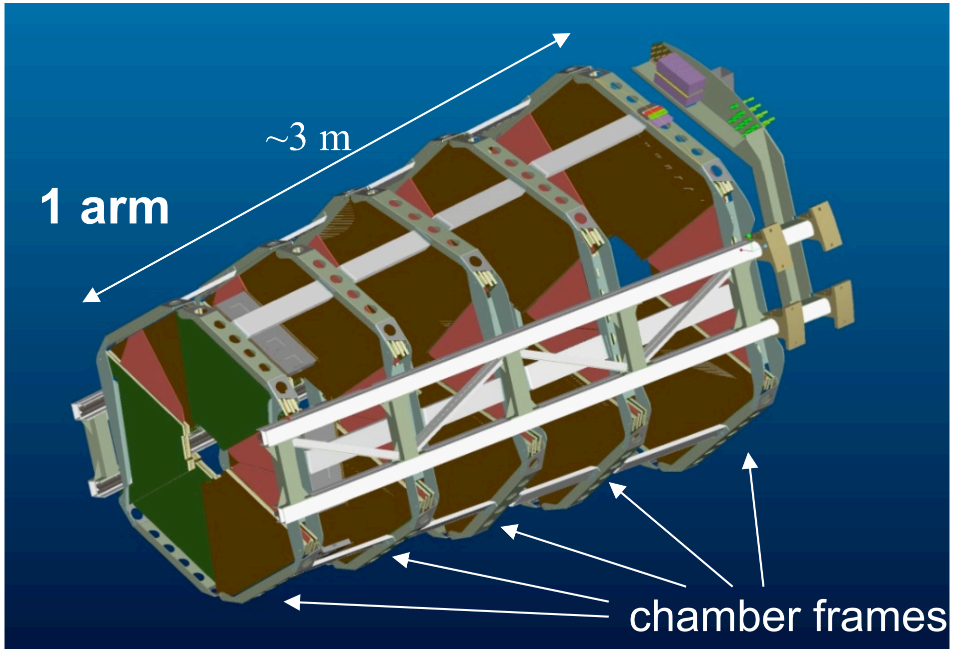


Leading proton detection at distances down 10 $\sigma_{beam} + d$

Need "edgeless" detectors (efficient up to physical edge) to minimise width d of dead space.

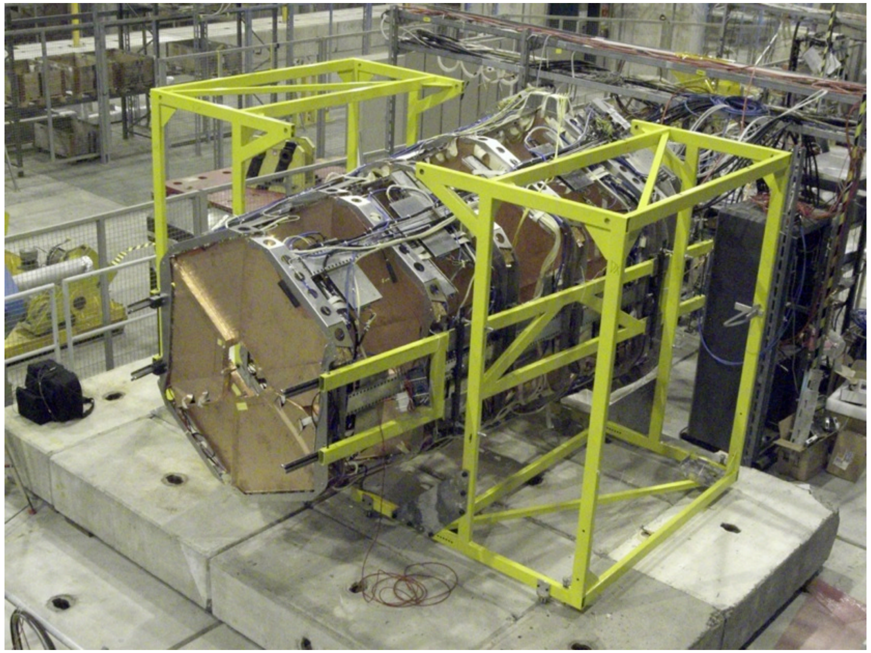
TOTEM: specially designed silicon strip detectors (CTS), efficient within 50 μm from the edge

T1 Telescope

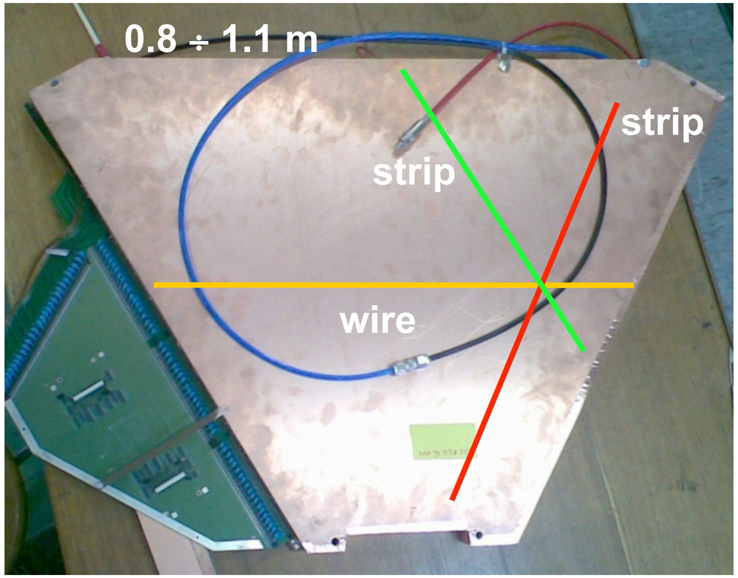


- Cathode Strip Chambers (CSC)
- $3.1 < |\eta| < 4.7$
- 5 planes with measurement of three coordinates per plane, $\sigma \sim 1$ mm
- Primary vertex reconstruction (beam-gas interaction removal)
- Trigger with anode wires
- Connected to VFAT chips
- Successful ageing studies

(~ 5 years at $L_{inst}=10^{30}$ cm^{-2}s^{-1})



Installation as soon as possible

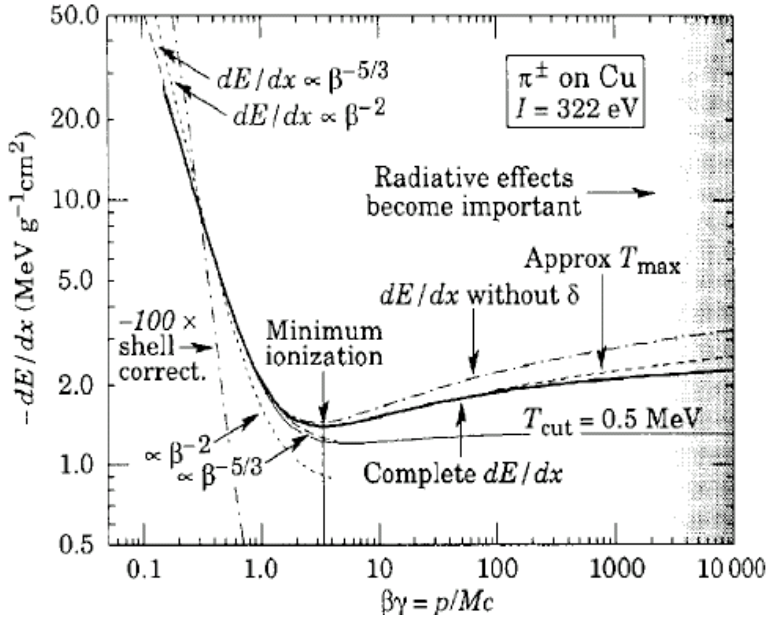


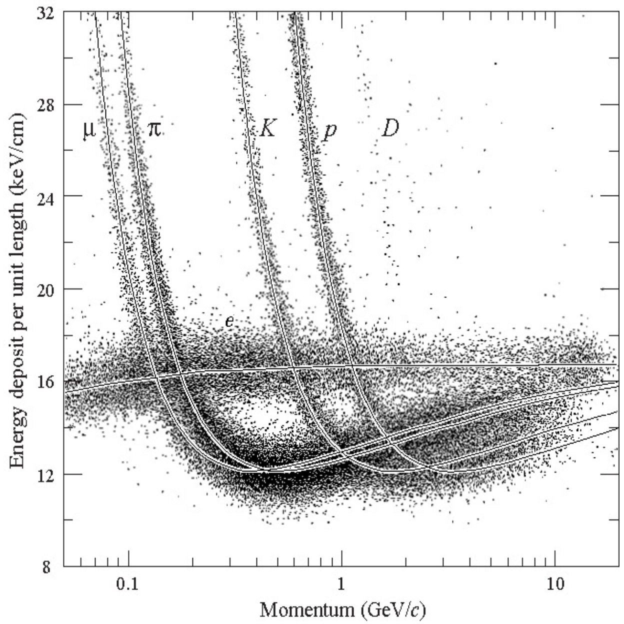
Backup slides

Particle Identification by Energy Loss

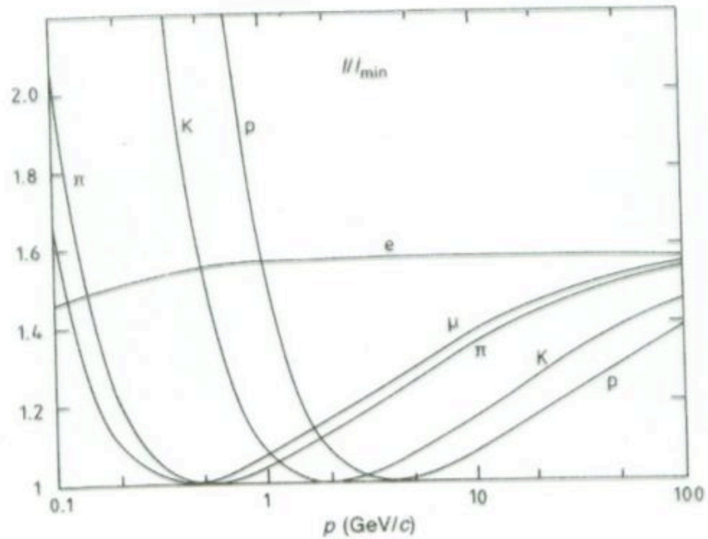
Energy loss depends on the $\beta\gamma$ of the particle and is ≈ independent from the mass of the particle. As a function of particle momentum $p = Mc\beta\gamma$ the energy loss depends on the mass of the particle.

By measuring the energy loss and the momentum of the particle, the mass of the particle can be measured: → Particle Identification !





TPC in magnetic field



$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2 m_e c^2 Z_1^2 \frac{p^2 + M^2c^2}{p^2} N_A \frac{Z}{A}\left[\ln\frac{2m_e c^2 F}{I}\frac{p^2}{M^2c^2} - \frac{p^2}{p^2 + M^2c^2}\right]$$

Ionization: the Bethe-Bloch formula

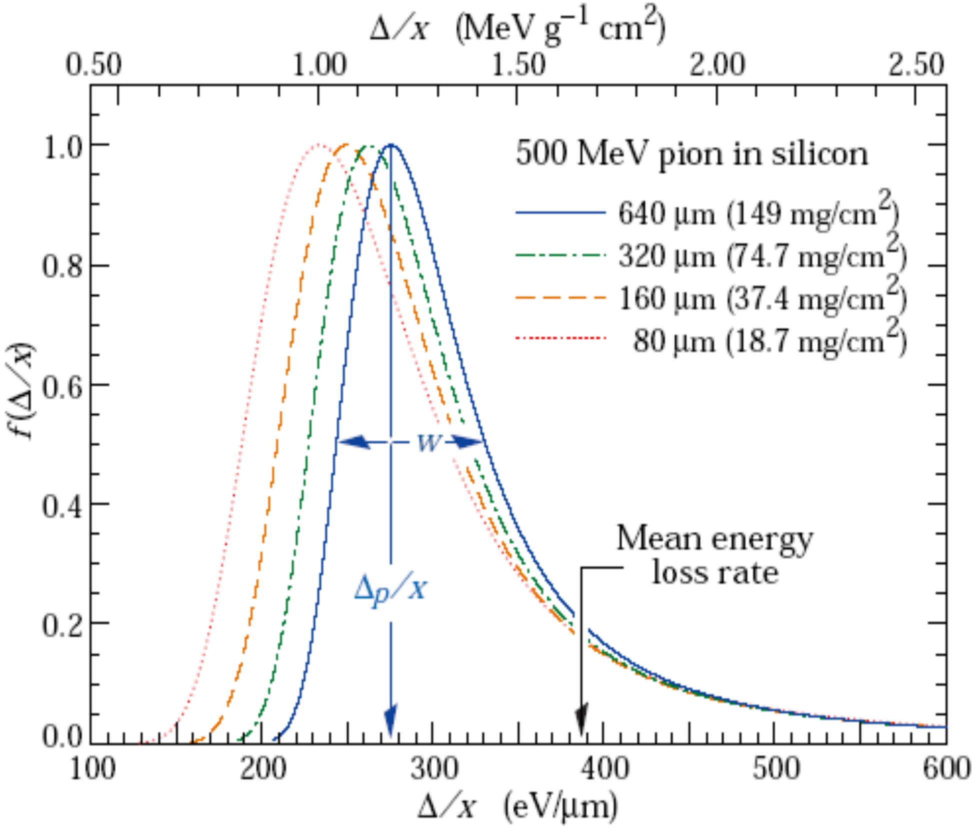
- Bethe-Block formula only gives the average energy loss, and do not take into account fluctuations from event to event.
- Large high energy tail – δ rays

δ -rays : electrons that have sufficient energy to ionize further atoms through subsequent interactions on their own.

Landau distribution:

f (Δ/X): Probability for energy loss Δ in a thickness X of matter.

Very asymmetric distribution: average and most probable energy loss must be distinguished !



Multiple Scattering

A particle traversing material undergoes successive deflections due to multiple elastic scattering from nuclei.

The probability that the particle is defected by an angle θ after travelling a distance x in the material is well approximated (actually tails are larger than Gaussian tails) by a Gaussian distribution with sigma of:

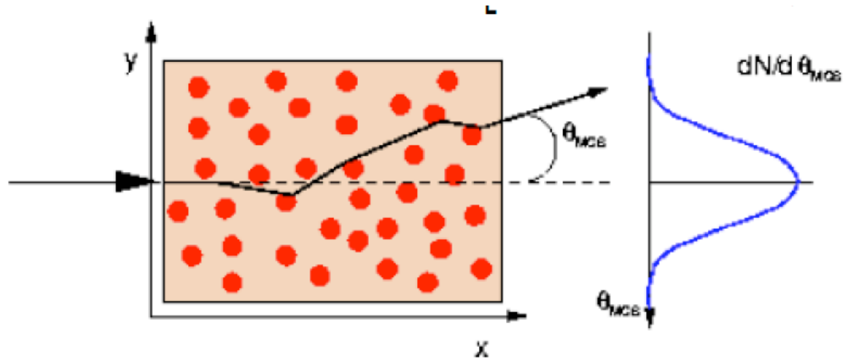
$$\theta_{MCS} = \theta_{rms} = \frac{13.6\,MeV}{\beta\, c\, p}\, z \sqrt{\frac{x}{X_0}}\left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

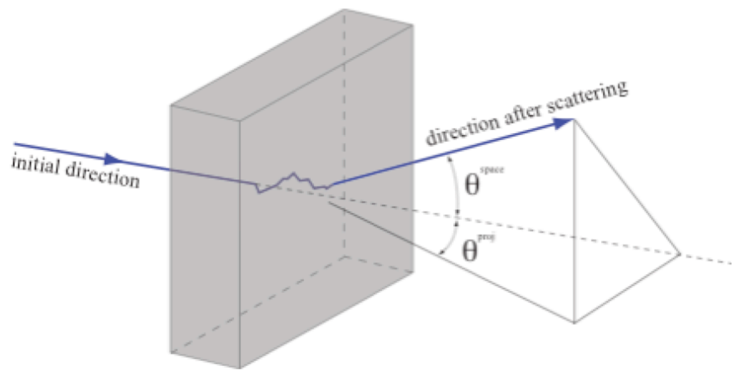
X_0 Radiation length of the material
z Charge of the particle
p Momentum of the particle

Radiation Length X_0 has 2 definitions:

- ◊ Mean distance over which high energy electron losses all but 1/e of its energy by Bremsstrahlung.
- ◊ 7/9ths of the mean free path for pair production by a high energy photon.

$$X_0 \approx \frac{716.4\, g cm^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$$





	X_0 (g cm^{-2})	X_0 (cm)
Air	37	30,000
Silicon	22	9.4
Lead	6.4	0.56