An Introduction to Charged Particle Tracking

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Overview:

- *Outline for these lectures*
  - *Lecture 1:*
    - *Motivation*
    - *Tracking vocabulary*
    - *Detector Techniques*
  - *Lecture 2:*
    - *Algorithmic Techniques for Pattern Recognition, Fitting*
    - *Tracking system designs*
  - *Lecture 3:*
    - *Commissioning/Calibrating a tracking system*
    - *Environmental Challenges*
      - *Radiation damage, occupancy, etc.*
    - *Tracking information used in event triggers*
    - *Tracker upgrades*

Reminder: Design Criteria

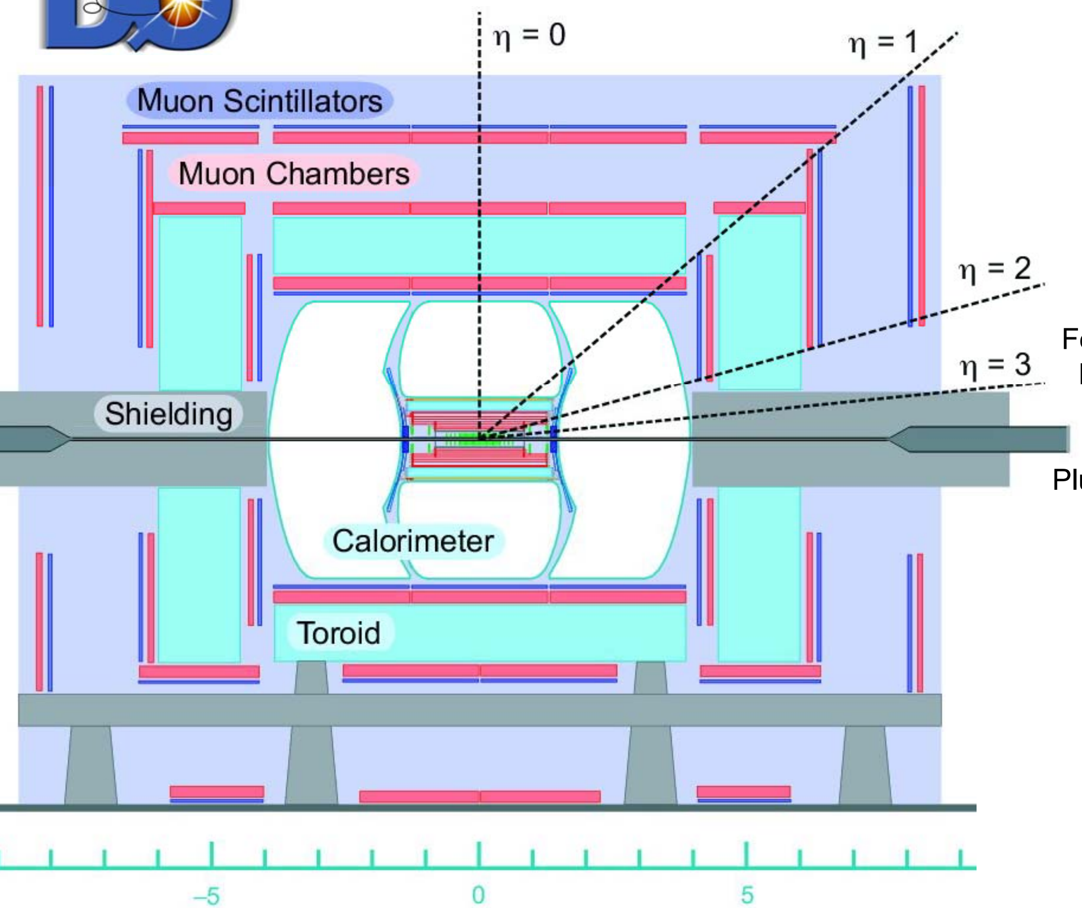
Physics-motivated, of course…

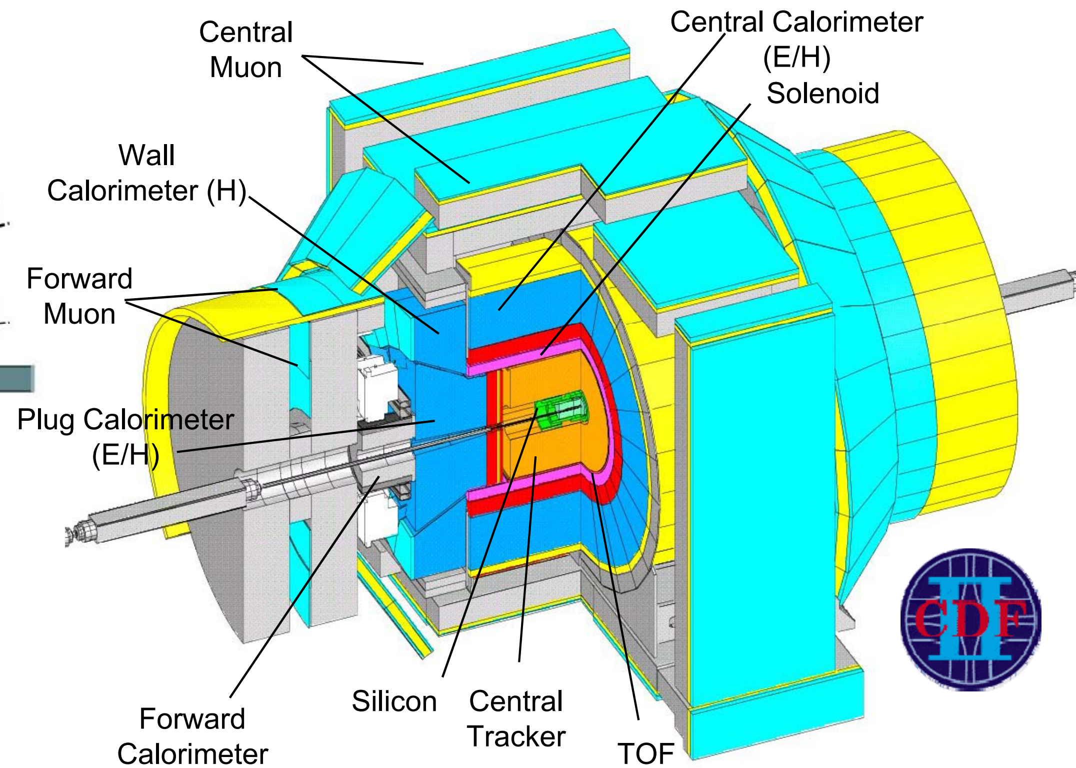
- Good Momentum Resolution
  - combination of large B, L
  - large N, or small σ_x to compensate
  - small number of radiation lengths (minimal material)
- Good Impact Parameter Resolution
  - thin/small beampipe
  - high-precision detectors very close to IP
- Good Efficiency
  - hermetic
- Robust against high occupancy
  - granularity (small effective detector size)
  - fast (information from ~few beam crossings at most)

Tevatron Trackers

- Note: neither experiment at the Tevatron has pixels. Why?
  - Design choices frozen ~1997
  - hybrid pixel technology not mature at that time
    - or even to be considered for Run IIb upgrades

~ same scale:





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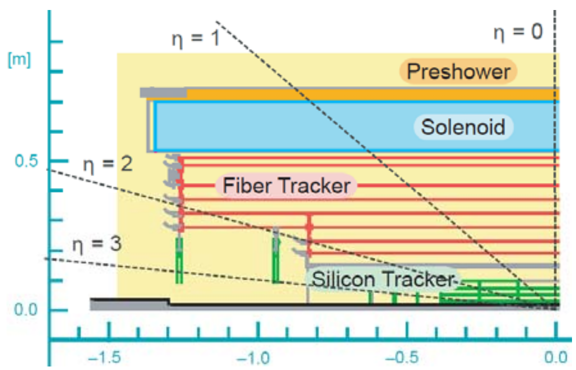
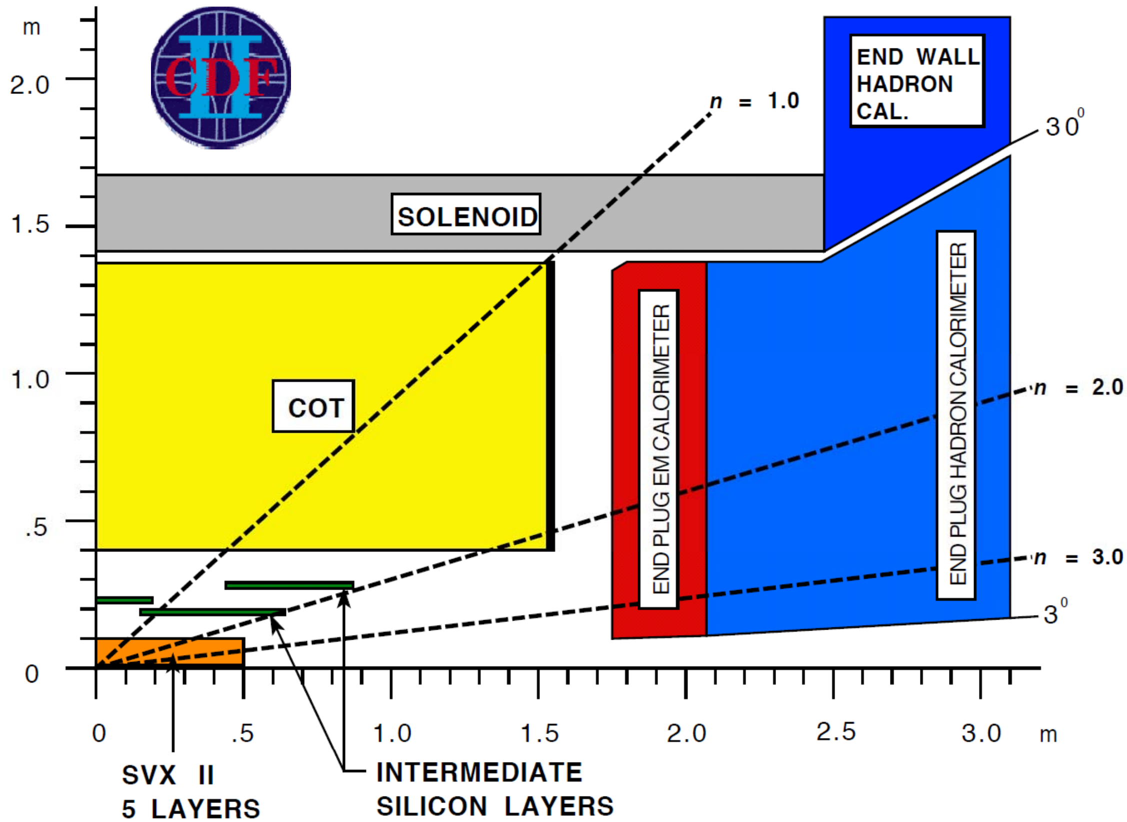
Tevatron Trackers

- Side-by-side comparison



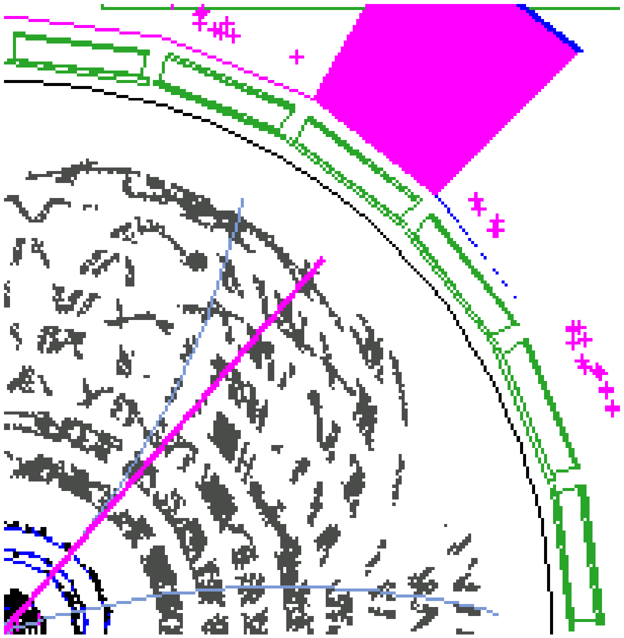


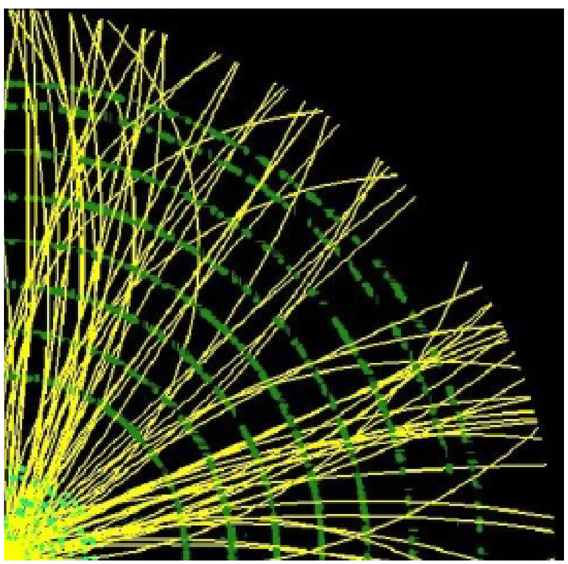
- Magnetic tracking: upgrade that had to fit in existing calorimeter
- 2T Magnetic Field
- maximum radius (L) = 0.52m
- length: ~2.5m

- large tracking volume
- 1.4T Magnetic Field
- maximum radius (L) = 1.37m
- length: ~3.1m

Tevatron Trackers

- Outer Trackers:





CDF Central Outer Tracker:

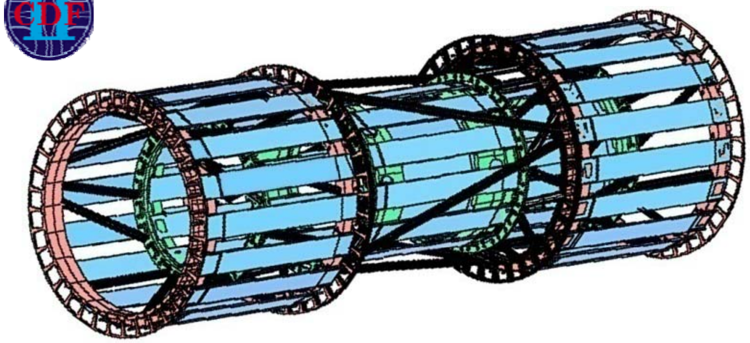
- 96 layers of sense wires
- single hit resolution 140μm
- full coverage $|\eta| < 1.0$
- $\sigma(p_T)/p_T = 0.15\% \times p_T$ (GeV)
- combined with silicon, hit count plus large L gives superior track resolution overall

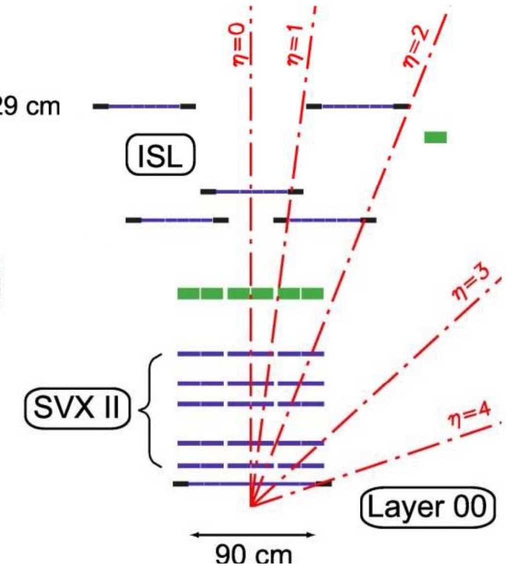
DØ Central Fiber Tracker:

- 8 barrels of fibers: 16 hits
- 77k fibers: 200 km of scintillating fiber and 800 km of clear fiber for readout
- single hit resolution 100μm
- full coverage $|\eta| < 1.7$
- $\sigma(p_T)/p_T = 0.17\% \times p_T$ (GeV)

Tevatron Trackers

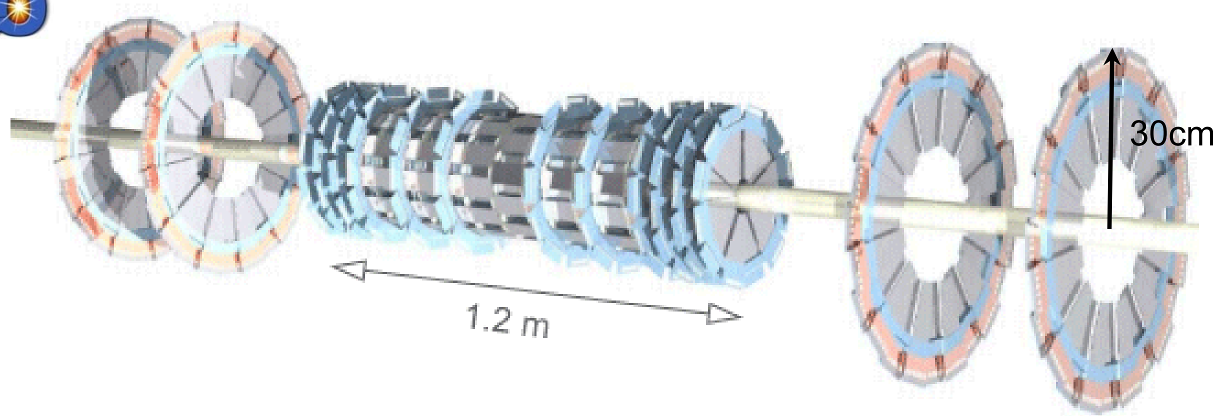
- Silicon Detectors

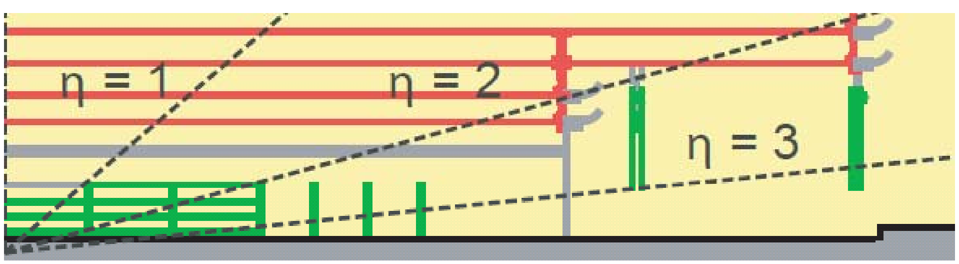




CDF:

- Barrel-only structure
- 722k channels
- Layer00 on beampipe
- full coverage $|\eta| < 2.0$
- σ_b = 35 μm @ p_T = 2 GeV





DØ:

- Barrels and disks
- 800k channels
- Layer 0 on beampipe
- full coverage $|\eta| < 2.5$
- σ_b = 15 μm for p_T >10 GeV

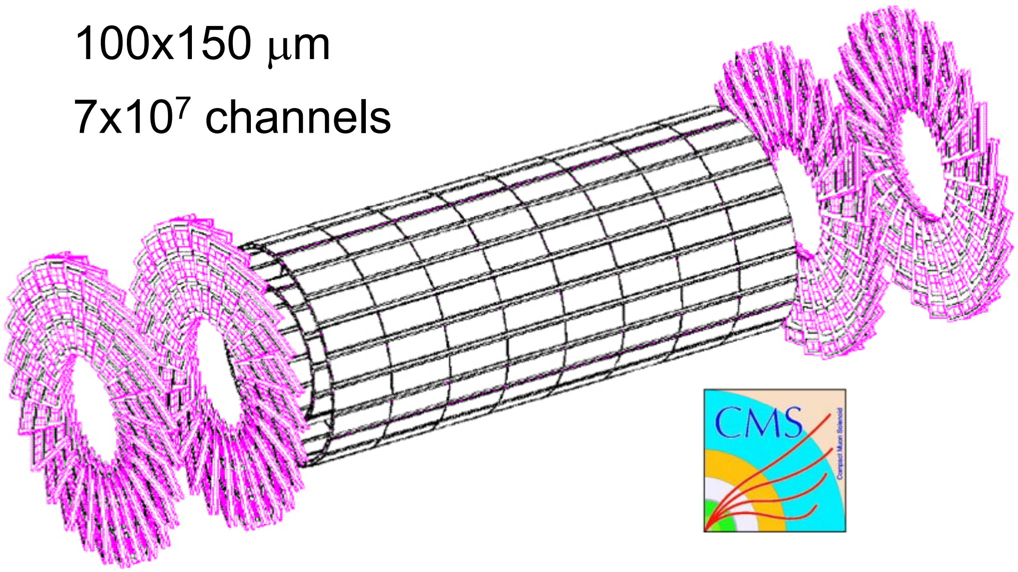
LHC Design Solutions

- Start Small: Collider Pixel Detectors

CMS Pixels:

100x150 μm

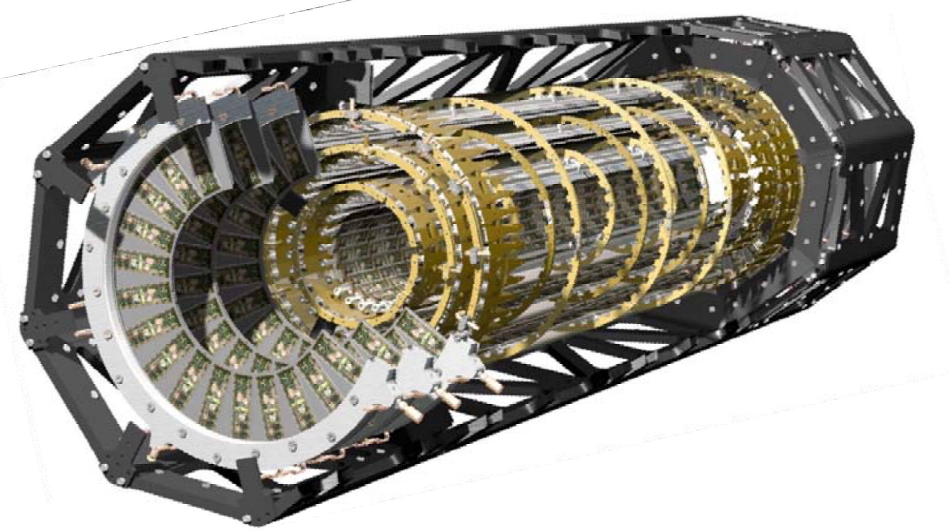
7×10^7 channels



ATLAS Pixels:

50x400 μm

8×10^7 channels



CMS:

- $\sigma(z) \sim \sigma(r\varphi) \sim 15\mu m$
- 3 barrel layers: r =   4.3cm, 7.2cm, 11.0cm
  - $|\eta| < 1.6$
- 2 disks: $1.8 < |\eta| < 2.4$
- Tracking volume: ~1m long, 0.2m radius
- 1.06 m^2 of silicon

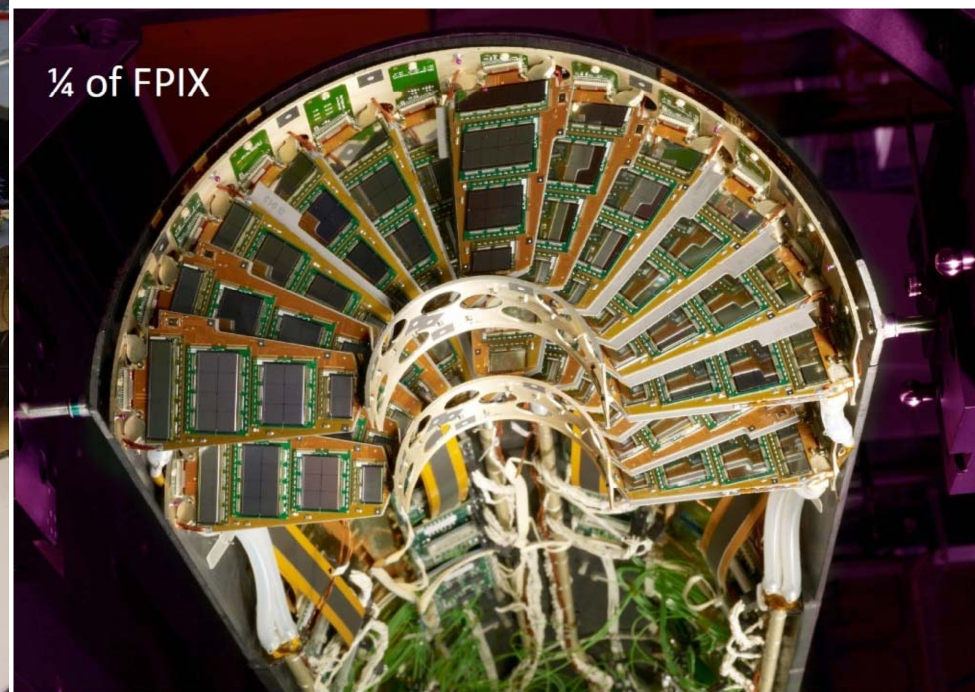
ATLAS:

- $\sigma(r\varphi) \sim 10\mu m$, $\sigma(z) \sim 115\mu m$
- 3 barrel layers: r =   5cm, 9cm, 12cm
  - $|\eta| < 1.9$
- 3 disks: $1.9 < |\eta| < 2.5$
- Tracking volume: ~1.6m long, 0.2m radius
- 1.8 m^2 of silicon

Size?

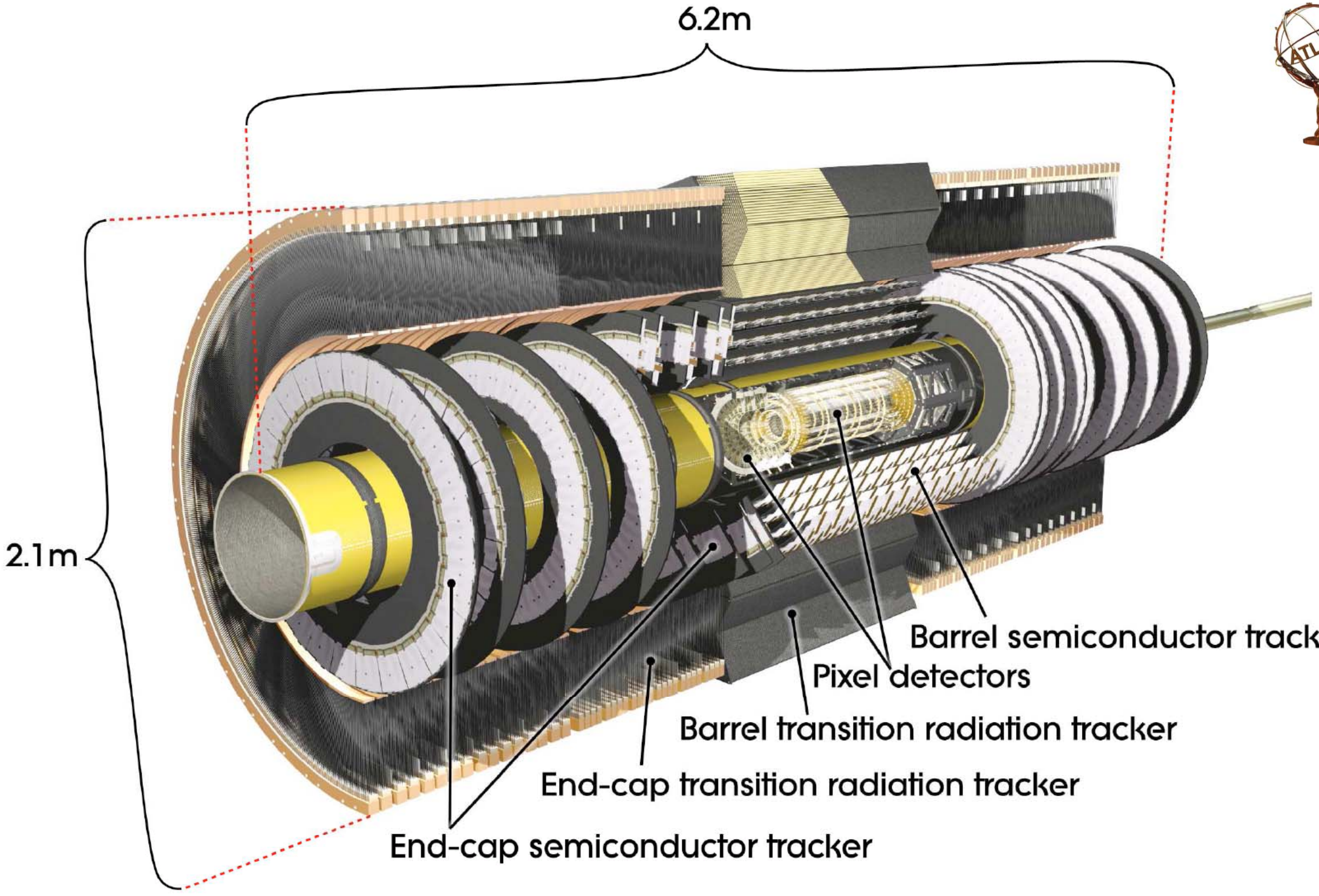
- Some parts of CMS are still small…

half of Barrel Pixels: under construction

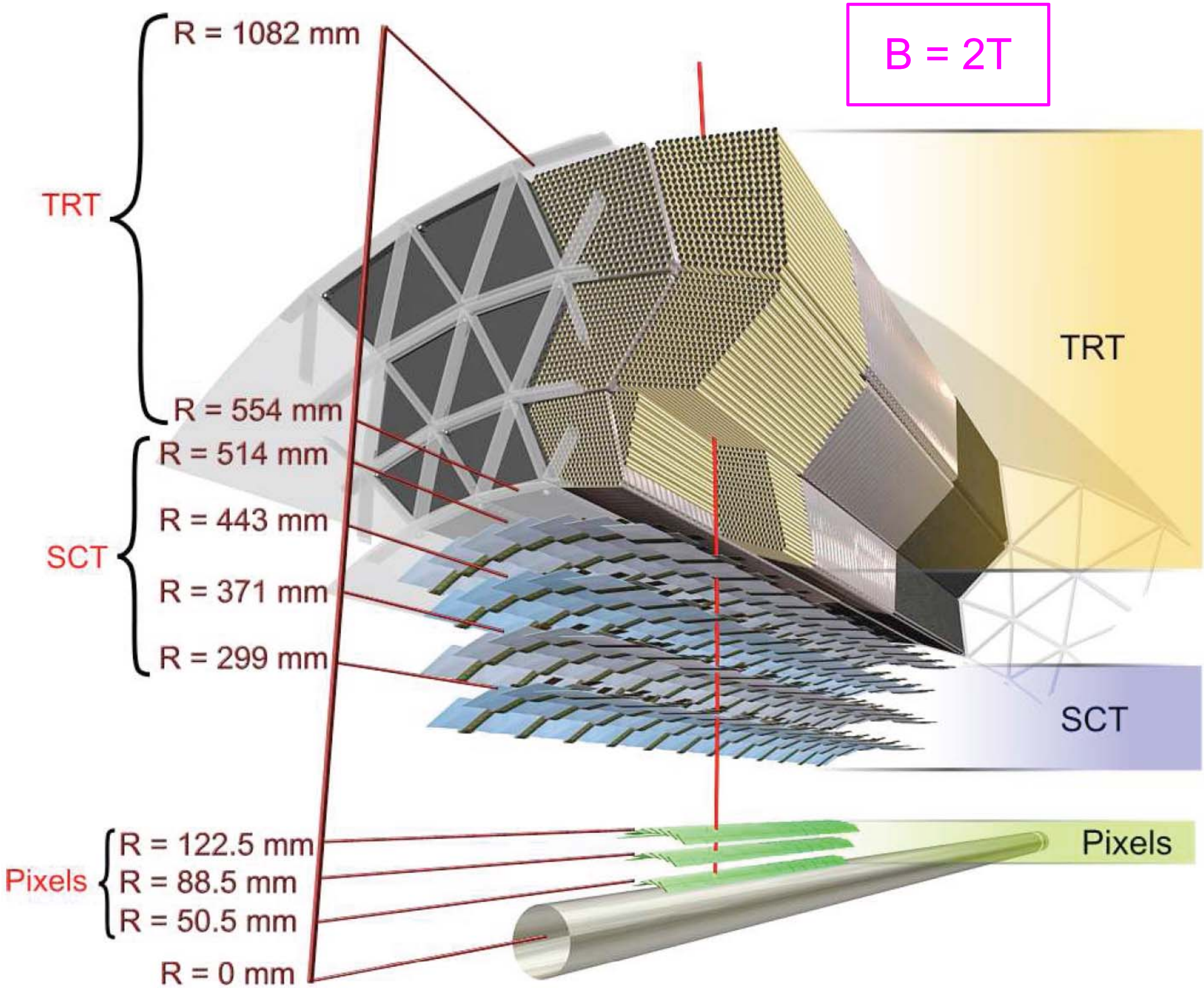


LHC pixel detectors ~ same size as Tevatron Silicon Trackers!

Main Tracking Systems: ATLAS



Main Tracking Systems: ATLAS Barrel



TRT:

- ~100k channels
- ~36 hits/track
- single hit σ_x = 130μm

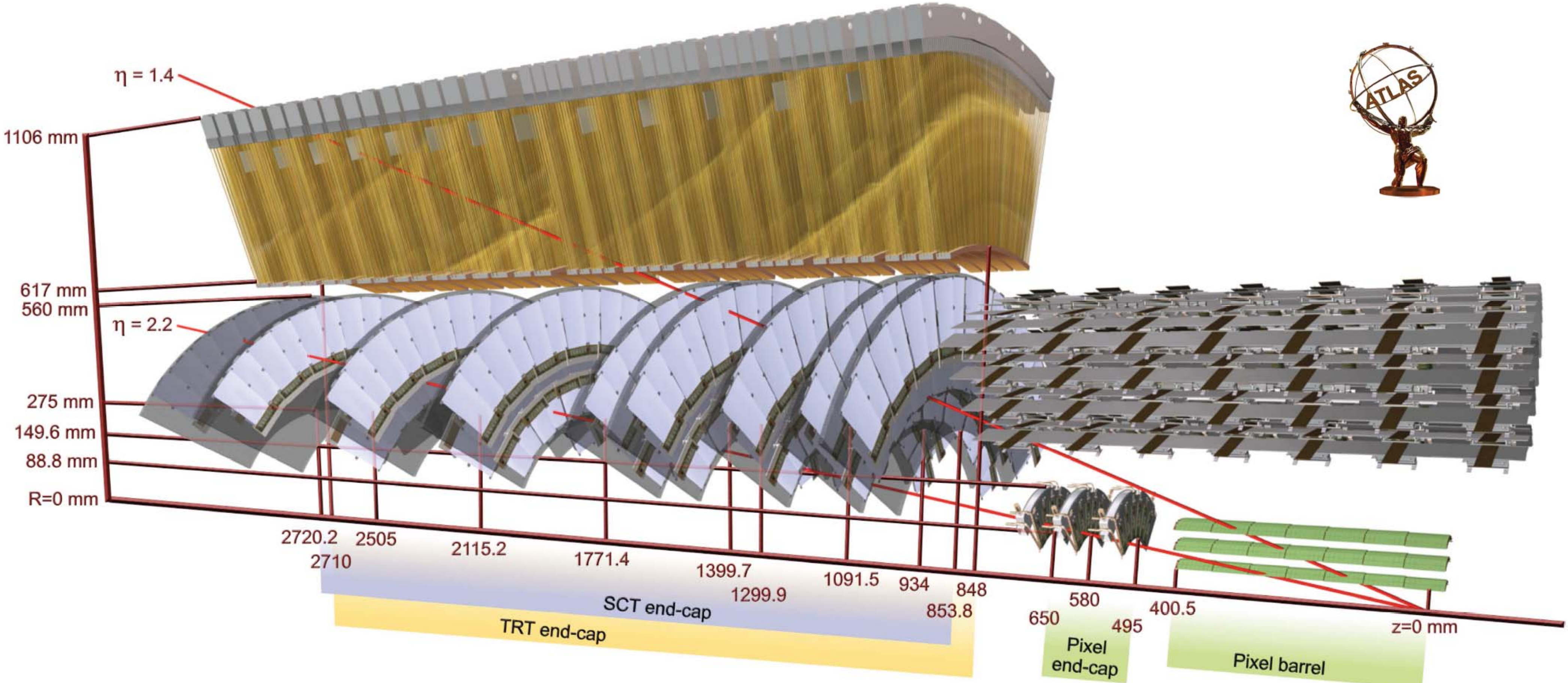
SCT:

- 6.3M channels
- 4 double barrel layers
  - 80mrad stereo angle
  - strip pitch 80 μm
  - binary readout

Performance: $(\eta = 0)$

- $\sigma(p_T)/p_T$ = 0.038% × p_T (GeV)
- σ_b = 11 μm @ p_T = 1 TeV

Main Tracking Systems: ATLAS Endcap



TRT: 160 straw planes, $0.85 < |z| < 2.7$m

- 250k channels

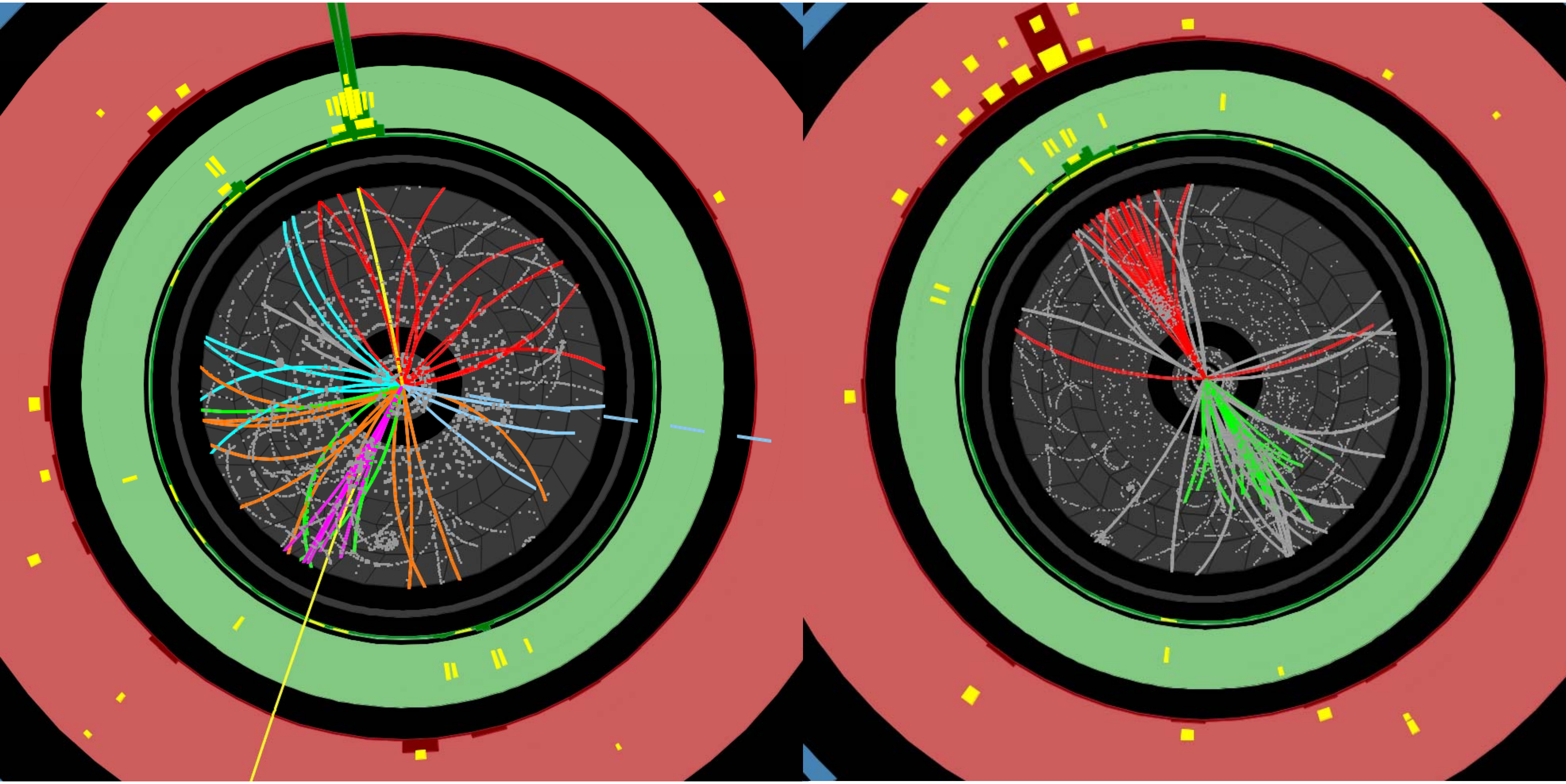
SCT: 9 double sided-disks (radial+40mrad)

- $1.5 < |\eta| < 2.5$

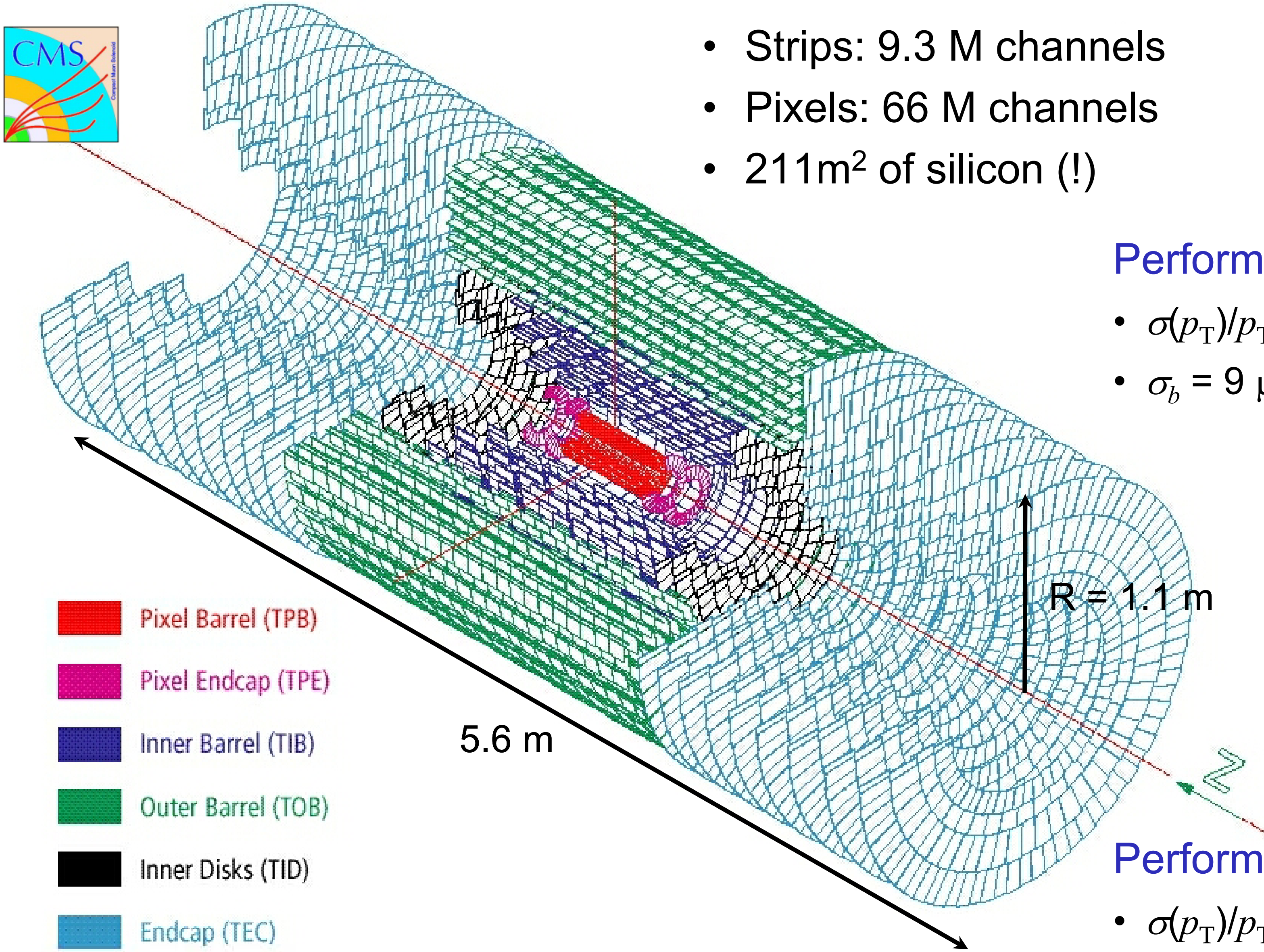
Performance: $(\eta = 2.5)$

- $\sigma(p_T)/p_T = 0.11\% \times p_T$ (GeV)
- $\sigma_b = 11\ \mu$m @ $p_T = 1$ TeV

some nice event displays



Main Tracking Systems: CMS



- Strips: 9.3 M channels
- Pixels: 66 M channels
- 211m^2 of silicon (!)

B = 4T

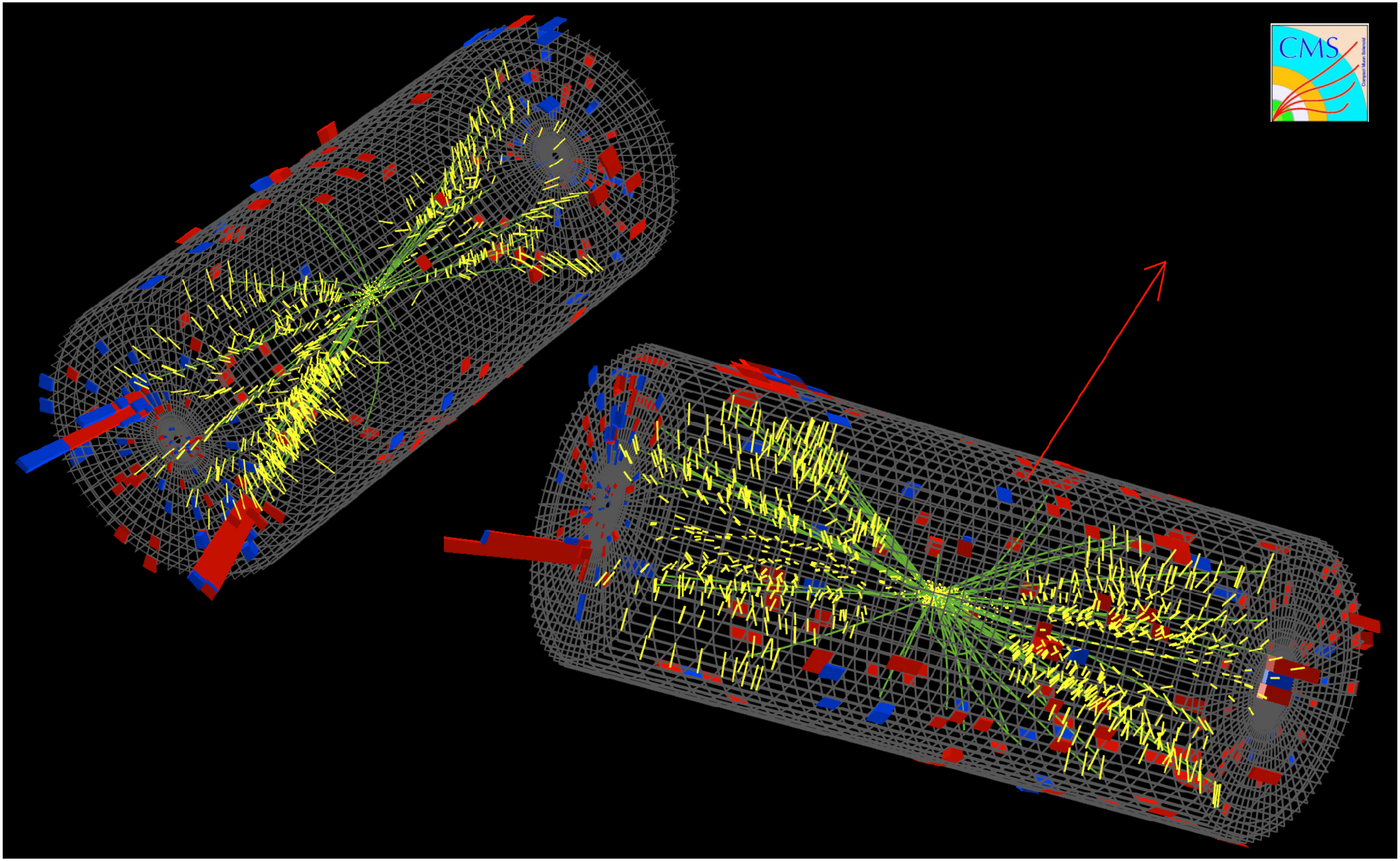
Performance: $(\eta = 0)$

- $\sigma(p_T)/p_T$ = 0.015% × p_T (GeV)
- σ_b = 9 μm @ p_T = 1 TeV

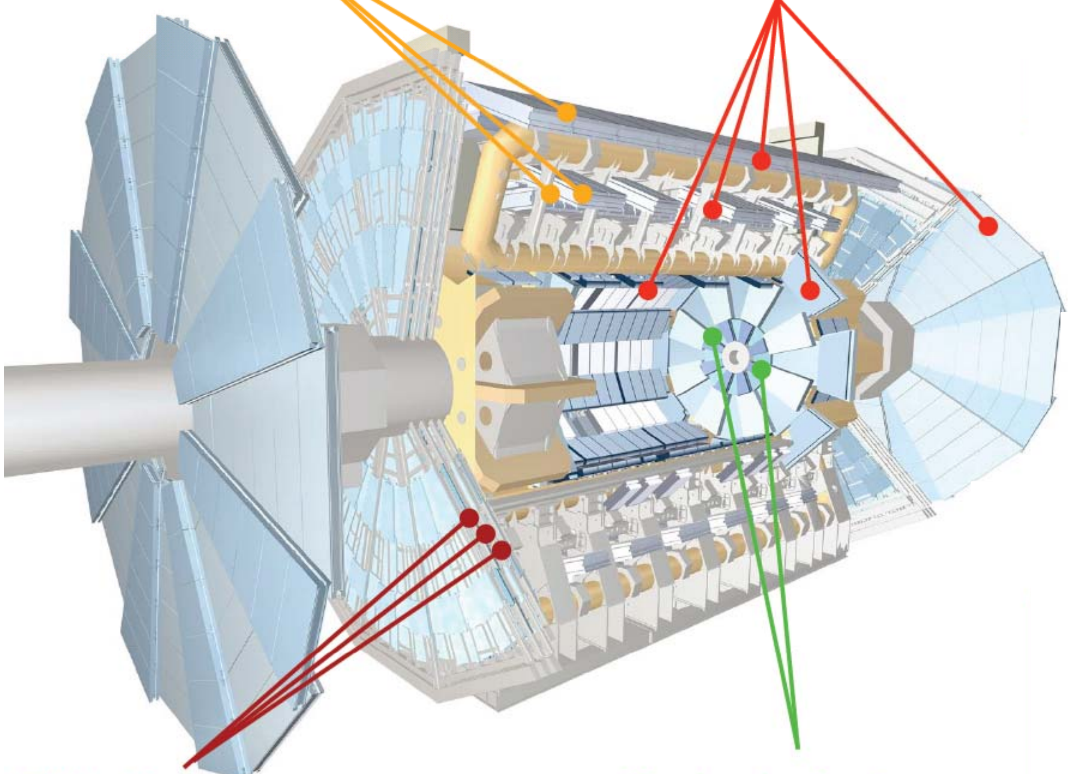
Performance: $(\eta = 2.5)$

- $\sigma(p_T)/p_T$ = 0.07% × p_T (GeV)
- σ_b = 11 μm @ p_T = 1 TeV

some nice event displays



Muon systems: also trackers!

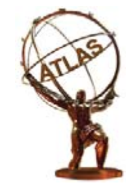


Complicated systems:

- Must track with good precision
- nasty magnetic field variation
- must be fast enough to trigger

ATLAS:

- four different technologies
- huge area: 10,000m^2
- 1 M channels
- high-precision!
- highly-evolved internal alignment system

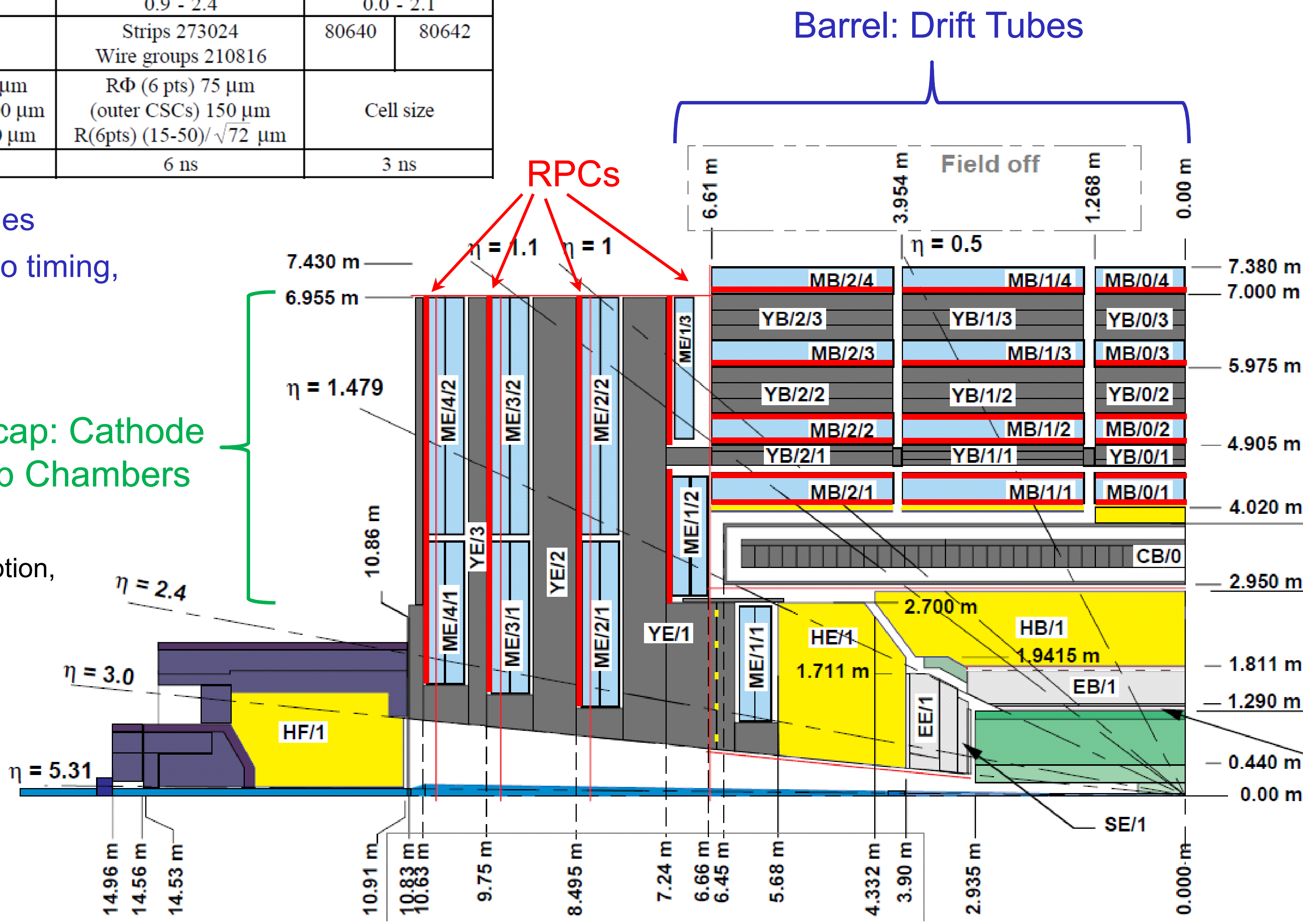


		Chamber resolution (RMS) in			Measurements/track		Number of	
Type	**Function**	z/R	ϕ	time	barrel	end-cap	chambers	channels
MDT	tracking	35 μm (z)	—	—	20	20	1088 (1150)	339k (354k)
CSC	tracking	40 μm (R)	5 mm	7 ns	—	4	32	30.7k
RPC	trigger	10 mm (z)	10 mm	1.5 ns	6	—	544 (606)	359k (373k)
TGC	trigger	2–6 mm (R)	3–7 mm	4 ns	—	9	3588	318k

More muons

Detector	Drift Tubes	Cathode Strip Chambers	Resistive Plate
Function	Tracking p_T trigger BXID	Tracking p_T trigger BXID	BXID p_T trigger Resolve tracking ambiguities
η region	0.0 - 1.3	0.9 - 2.4	0.0 - 2.1
Channels	195000	Strips 273024 Wire groups 210816	80640	80642
Spatial resolution (σ)	per wire 250 μm RΦ (6/8 pts) 100 μm Z (3/4 pts) 150 μm	RΦ (6 pts) 75 μm (outer CSCs) 150 μm R(6pts) (15-50)/$\sqrt{72}$ μm	Cell size
Time resolution	5 ns	6 ns	3 ns

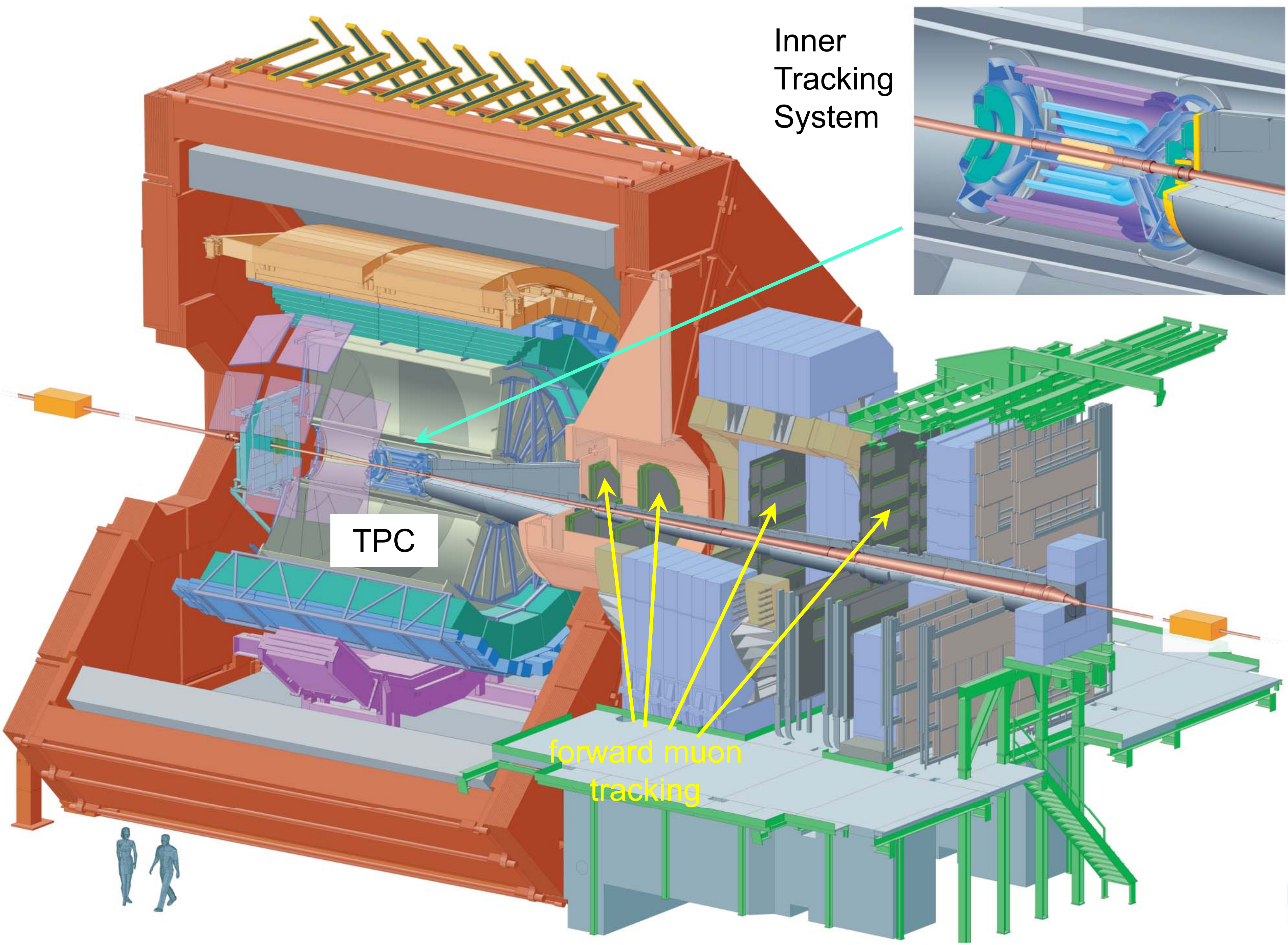
- Three technologies
- all subsystems do timing, BX resolution
- 840k channels



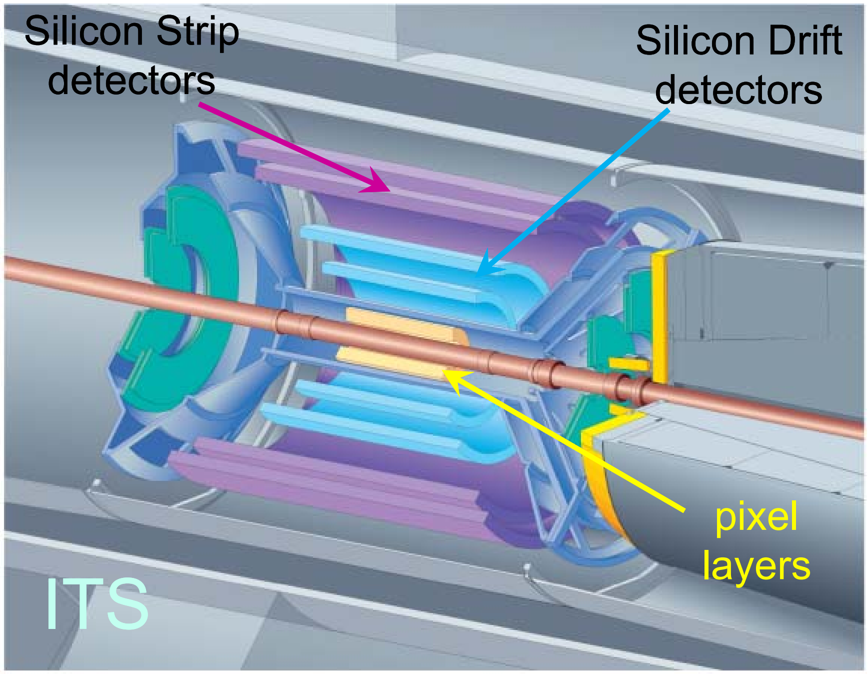
Endcap: Cathode Strip Chambers

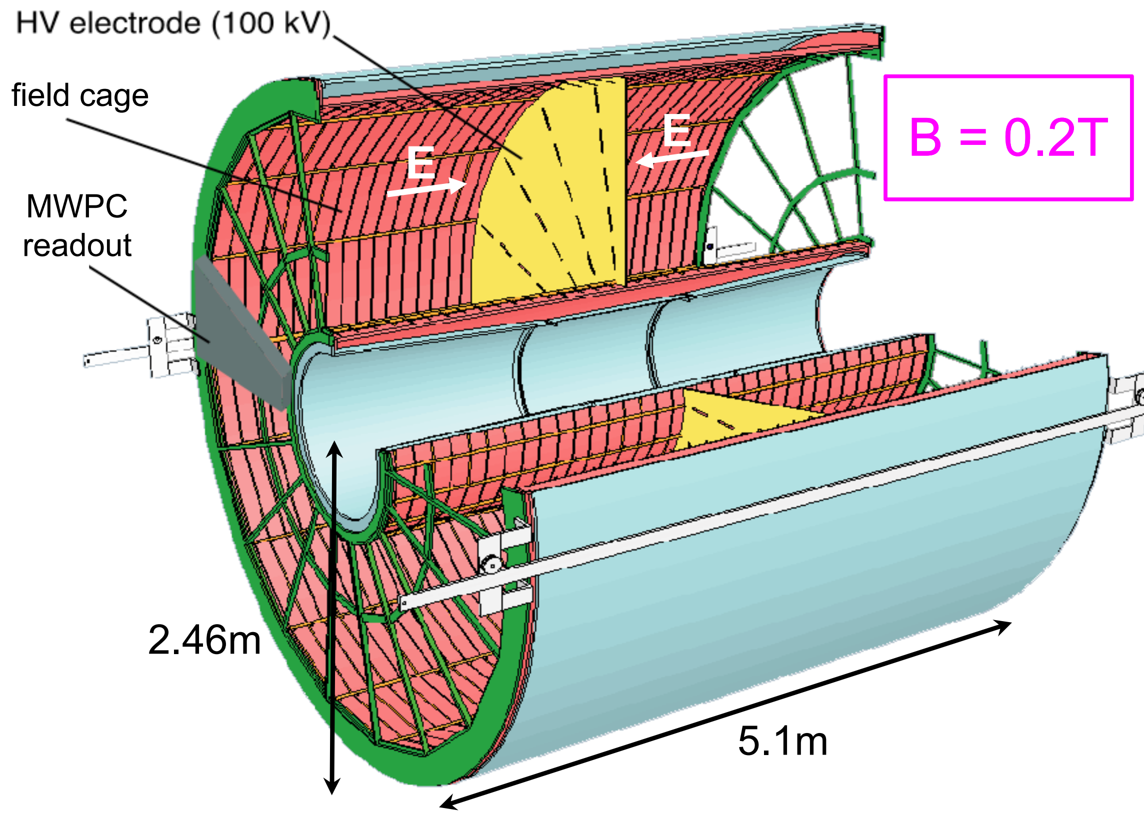
steel for absorbtion, flux return

ALICE

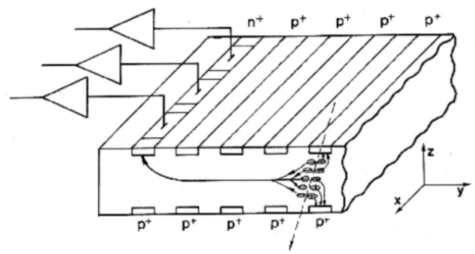


ALICE Tracking



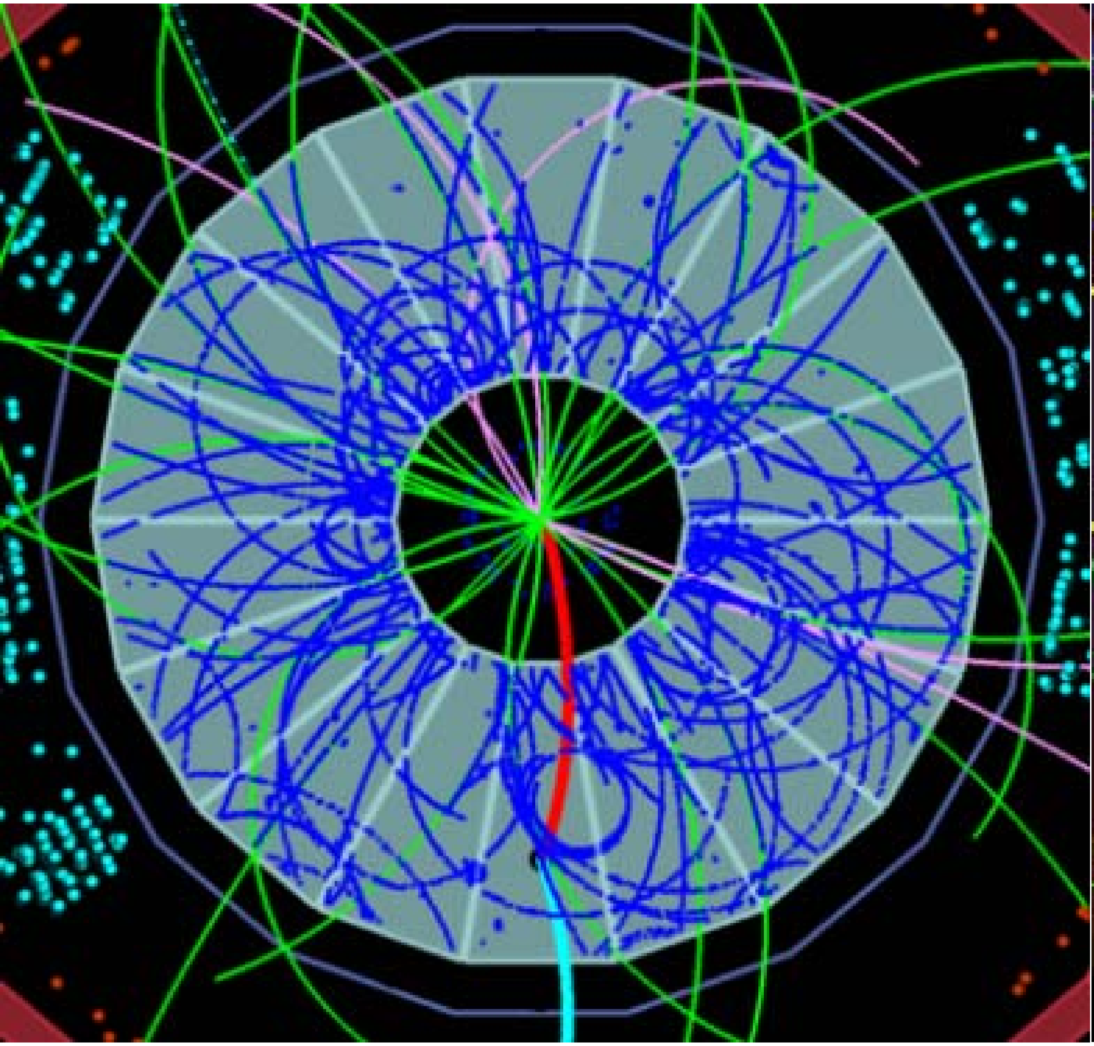


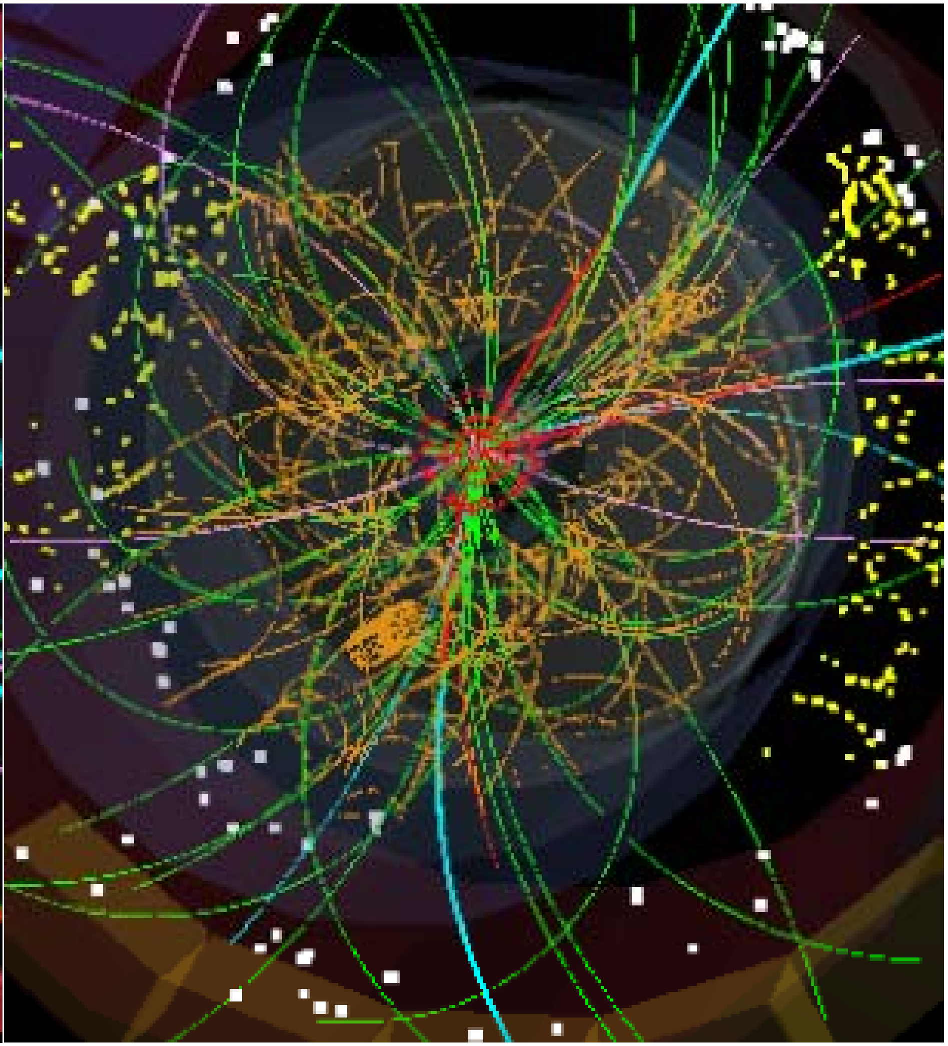
- optimized for dE/dx, stand-alone particle tracking for p_T < 100 MeV/c
- high-density, low-rate environment
- SSD: 2 layers of double-sided silicon
  - 2.7 M channels
- SDDs: 133k channels
  - *transverse* drift
- Pixels: 15.6M channels
- σ_b = 20μm, σ_z = 100μm @ p_T = 10 GeV



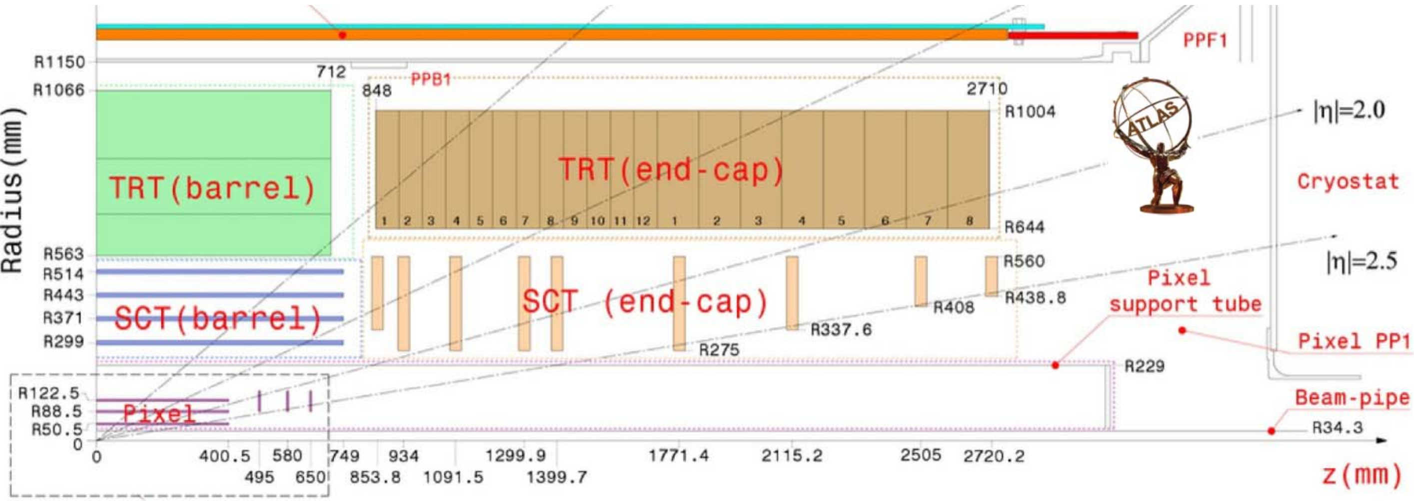
- Most ambitious TPC ever constructed
- 95m³ gas volume; overall coverage $|\eta|$ < 0.9
- 557k readout pads
- total drift time 92μs
- 1000 samples per drift time
- 8000 particles per unit of rapidity!
- $\sigma(p_T)/p_T$ = 0.45% × p_T (GeV)

ALICE event pictures

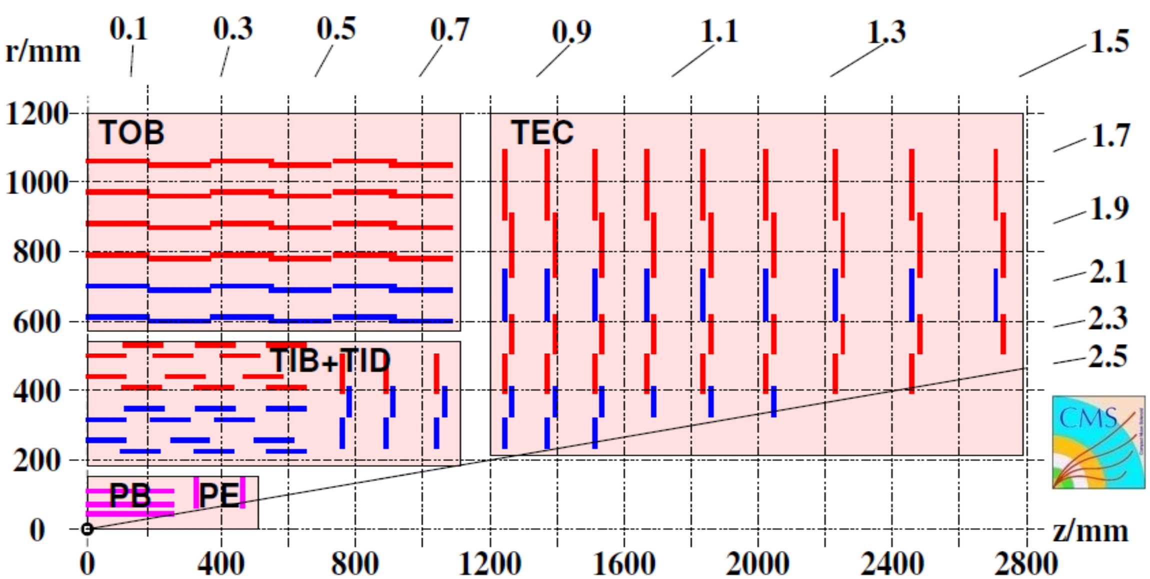


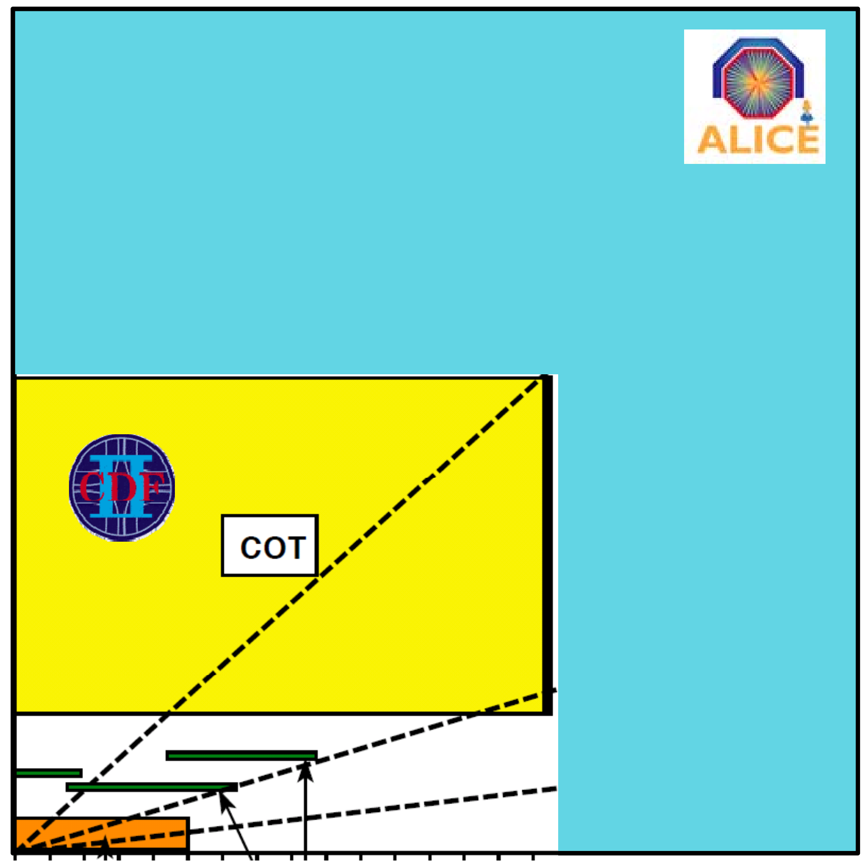


Tracker size comparison: quadrants



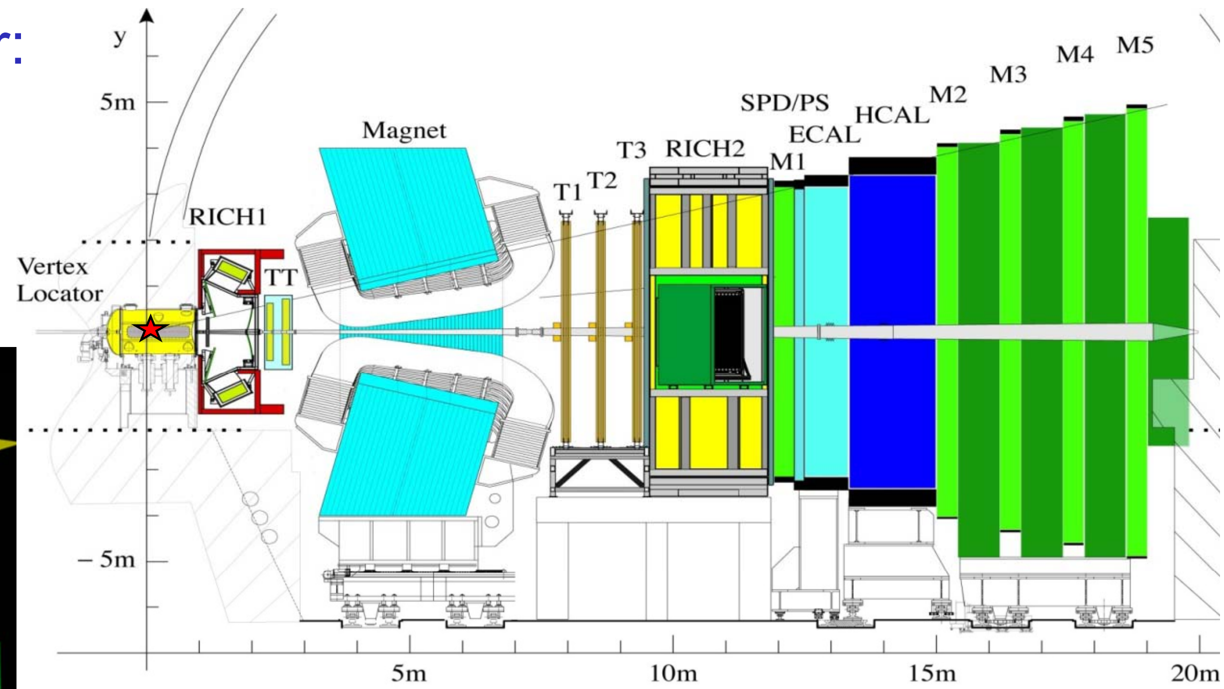
LHC 4π tracking systems make CDF look tiny!

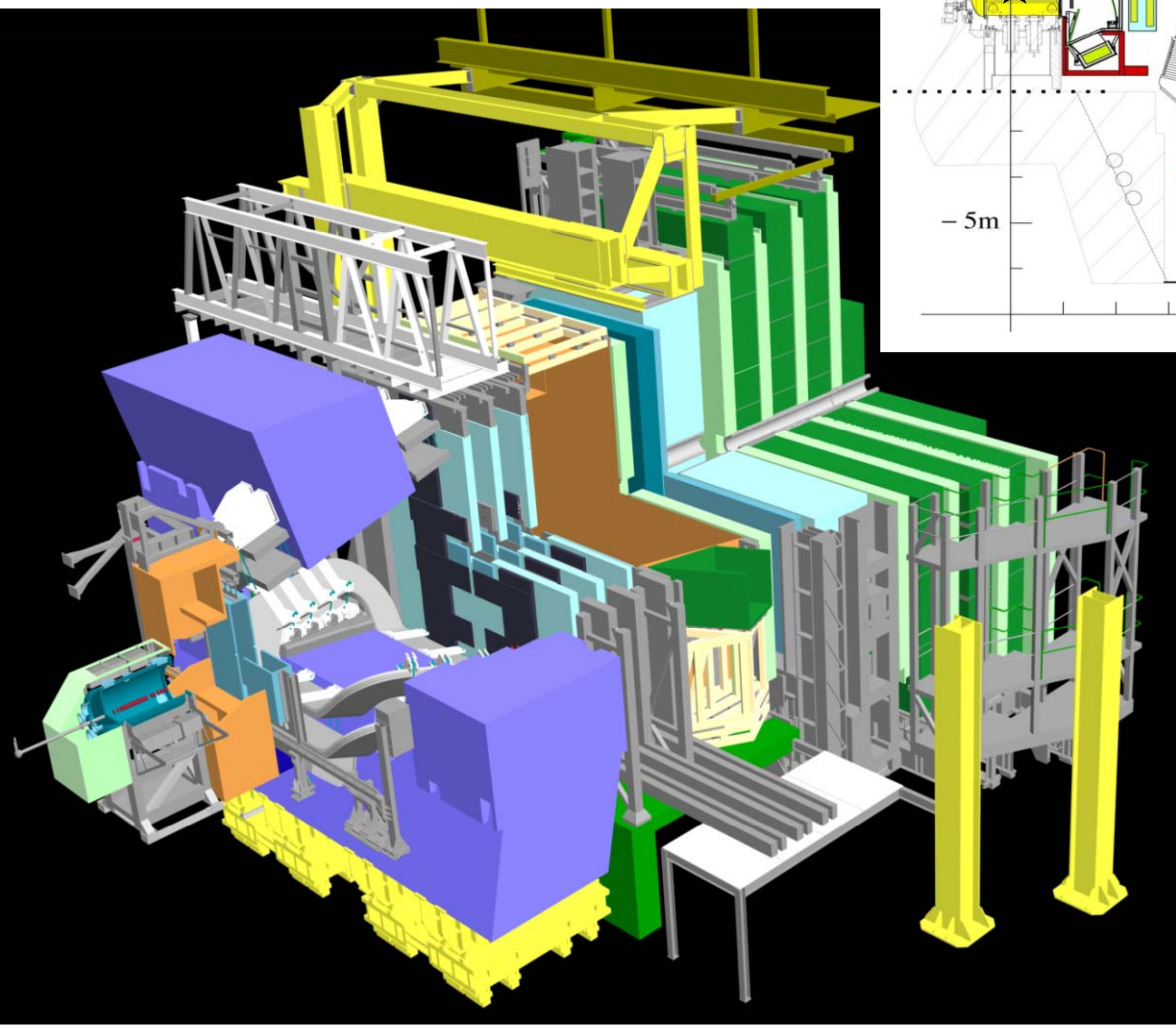




LHCb

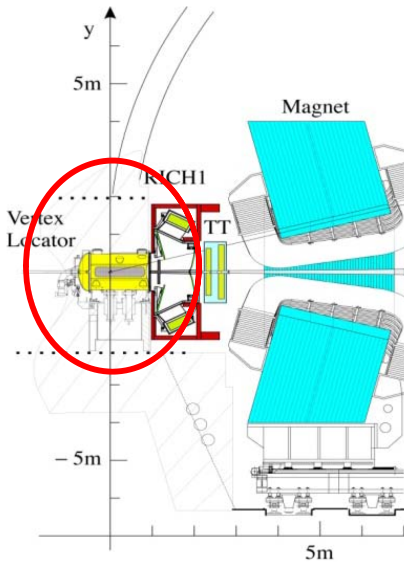
- Single-arm spectrometer:
  - *very* different geometry
  - similar requirements on precision/resolution



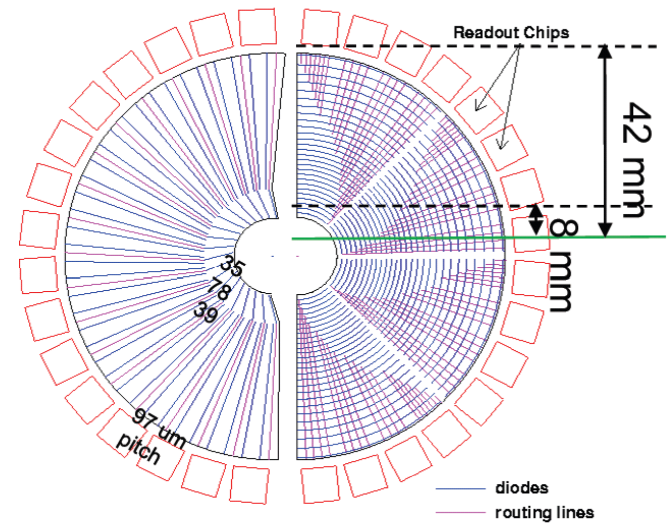


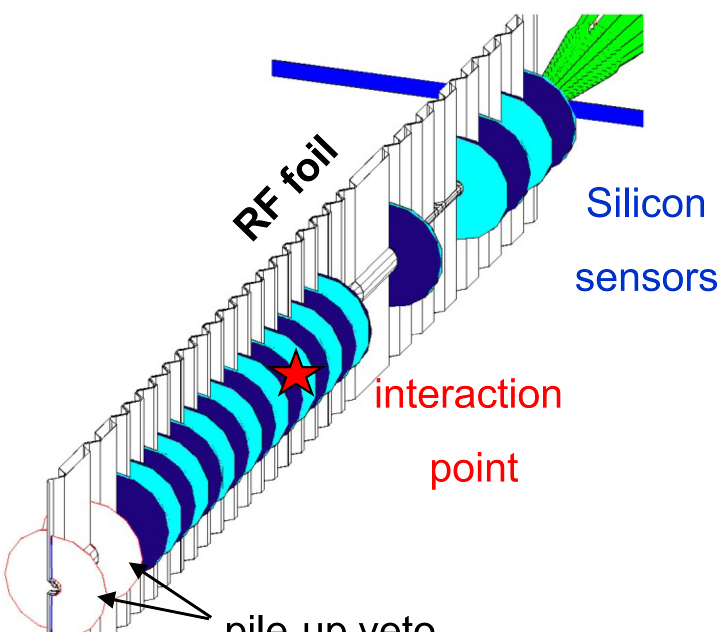
- Extremely high-rate environment
- High-precision vertexing
- Five separate tracking planes
- Dipole for momentum measurement
- Muon system: MWPC or triple GEMs
- premium placed on thin detectors

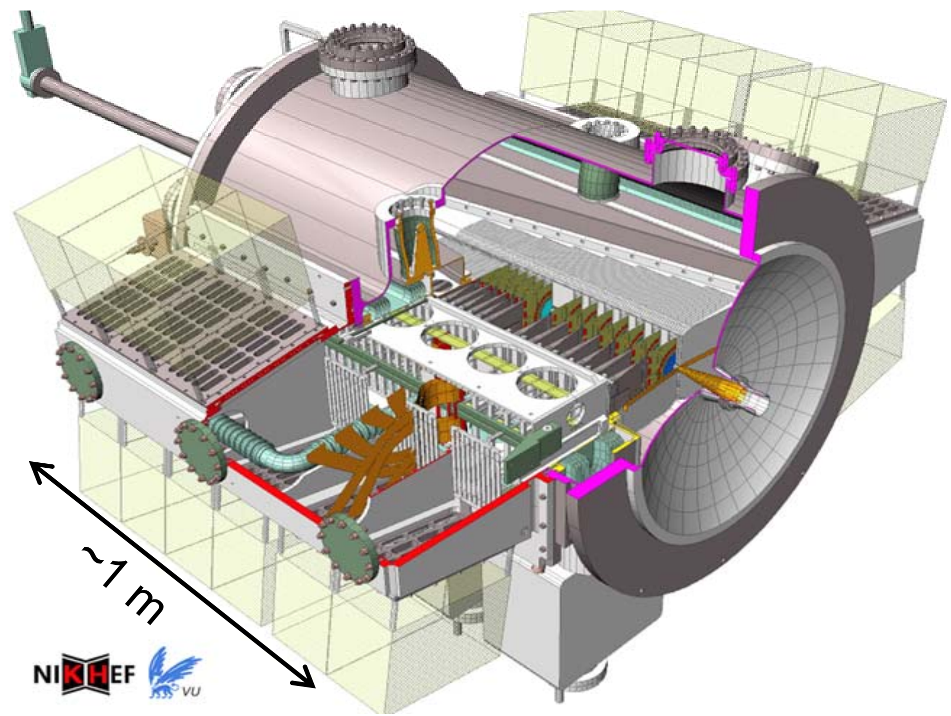
LHCb VErtex LOcator (VELO)

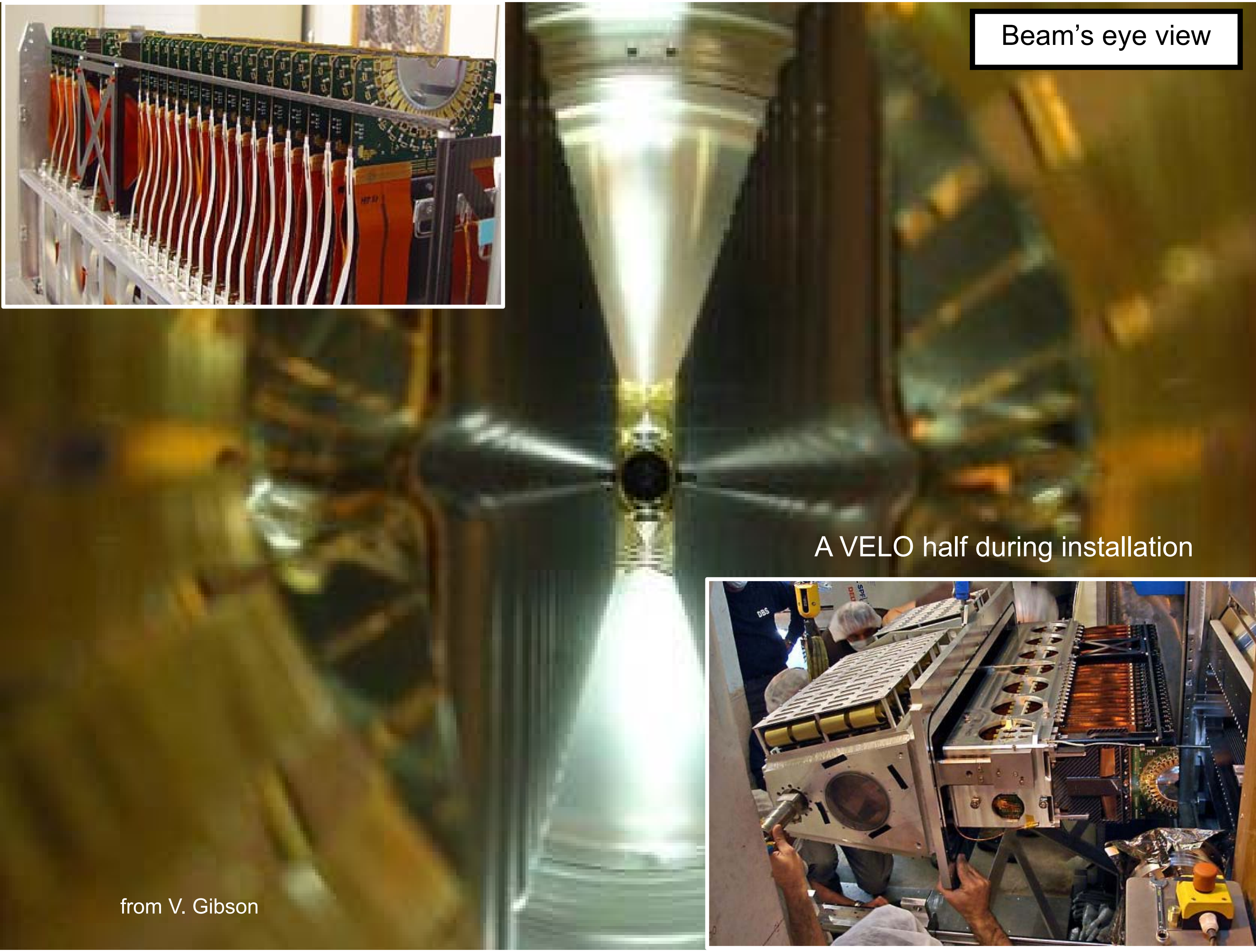


- 21 VELO stations (r and ϕ silicon sensors)
  - sensor pitch 35-100μm
  - 2x2048 channels per station
- placed in a secondary vacuum vessel
- 3cm separation, 8mm from beam!
- separated by a 300 μm of Al RF foil
- detector halves retractable for injection
- 4μm resolution, ~5μm variation fill-to-fill

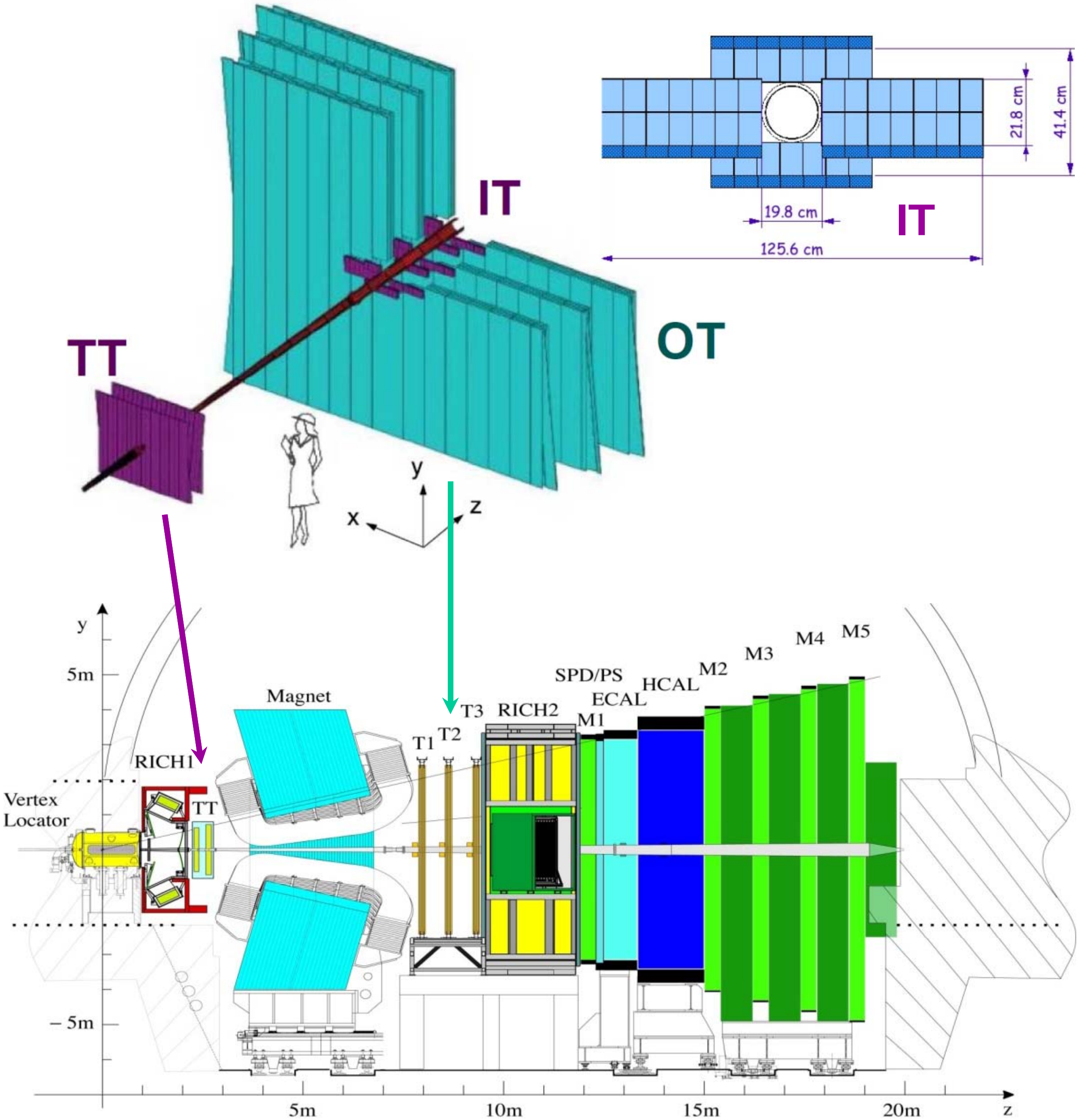







Beam's eye view
A VELO half during installation
from V. Gibson

LHCb: other tracking



TT:

- four planes of Silicon Strips
  - 0°, +5°, -5°, 0° (XUVX)
  - 183μm readout pitch
  - 55μm resolution/hit
  - 8.2 m^2; 140k channels

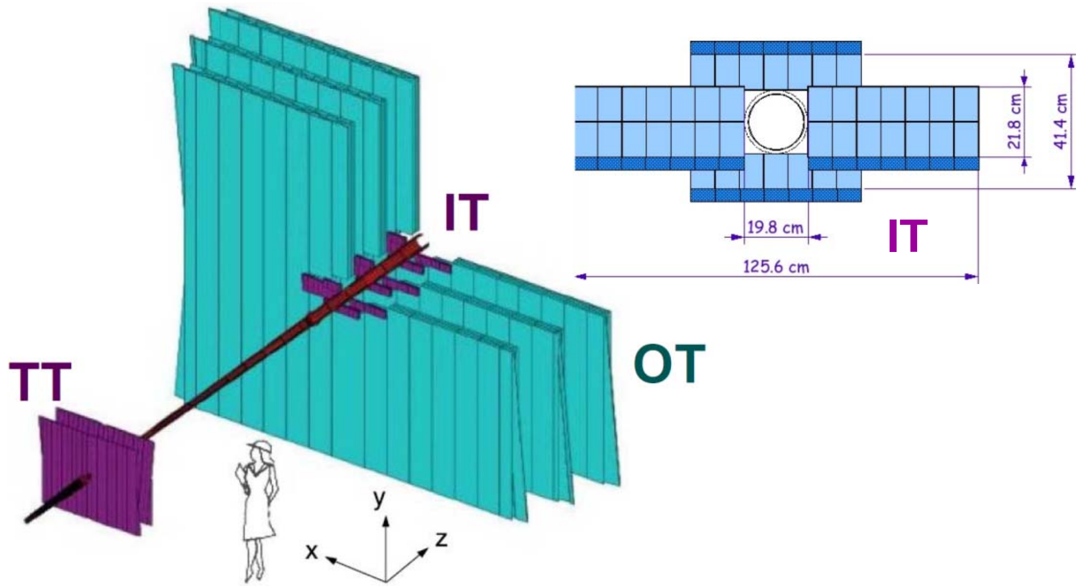
IT:

- three stations of Silicon Strips
  - 4 XUVX layers each
  - 198 μm readout pitch
  - 55μm resolution/hit
  - 4 m^2; 130k channels

OT:

- three layers of straw tubes
  - each 0°, +5°, -5°, 0° (XUVX)
  - 5mm straws
  - 250μm resolution/hit
  - 56k channels

LHCb: other tracking



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  - 55μm resolution/hit
  - 4 m^2; 130k channels

OT:

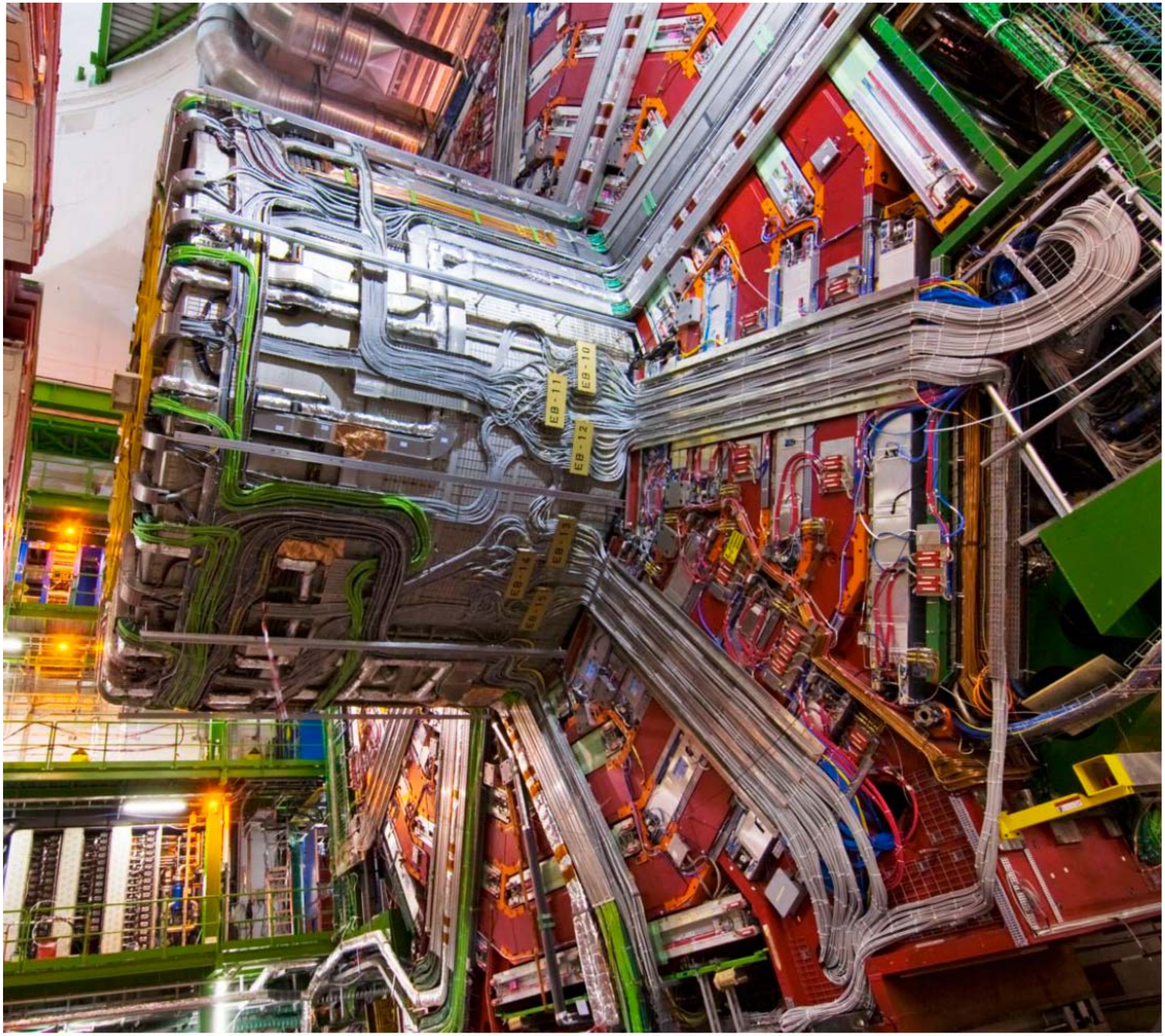
- three layers of straw tubes
  - each 0°, +5°, -5°, 0° (XUVX)
  - 5mm straws
  - 250μm resolution/hit
  - 56k channels

Performance:

S. Borghi (ICHEP)

- Primary vertex resolution (x,y,z):
  - achieved (16, 15, 91) μm
  - expect (11, 11, 57) μm
- Impact parameter resolution (both planes):
  - achieved 16μm, expect 11μm ultimately
- $\sigma(p_T)/p_T \sim 0.45\% \times p_T$ (GeV)

Engineering considerations



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Services:

- Example: CMS

Microstrip tracker	Pixels
~210 m^2 of silicon, 9.3M channels	~1 m^2 of silicon, 66M channels
73k APV25s, 38k optical links, 440 FEDs	16k ROCs, 2k olinks, 40 FEDs
27 module types	8 module types
~34kW	~3.6kW (post-rad)

  - Translations: APV = ROC = readout chip, FED = front end electronics
  - 40k individual optical links for readout: thousands of cables
  - Mechanically complicated: 35 different structures x thousands of pieces
  - Cooling! ~ 40kW to conduct out of a volume cooled to -10C
  - Don't forget about support structure engineering:
    - must be stiff, thin, with zero thermal expansion coefficient
  - built-in alignment infrastructure: Laser systems, other optics

Cost per channel (CHF)

Item	ALICE	ATLAS	CMS	LHCb
pixel sensors	0.02	0.05	0.02	3.23
pixel Total	0.17	0.18	0.13	24.56
Si Strips	1.88	3.46	0.99	9.82
Si Total	5.82	7.23	6.68	24.71
Outer Sensors	7.68	25.39		49.47
Outer Total	30.60	48.40		169.14
Total Cost (kCHF)	**35976**	**77211**	**70685**	**21055**

- Note: My numbers, taken from TDRs and inflation-adjusted to 2004 CHF
- for LHCb, pixel = VELO
- looks like CMS got a volume discount
    - ATLAS cost breakdown for sensors probably includes some other items
- silicon sensors are very cheap compared to infrastructure, readout electronics

Conclusions on Tracking Systems

- All “modern” experiments require state-of-the-art tracking systems
  - highest possible resolution commensurate with cost, engineering
  - performance parameters not that different overall
    - optimized for the physics goals

Tracker Commissioning

Ok, you've installed your multi-MCHF tracking detector, and now you want to use it to do physics. First things first:

Two pieces:

Work has to be done in this order

1. Does it work?
   - is the cabling correct?
   - are the voltage settings correct?
   - are the timing delays optimal?
   - are pieces dead/noisy/inefficient?
2. Do you understand it?
   - is the efficiency what you expect?
   - is the resolution what you expect?
   - is the overall performance what you expect?

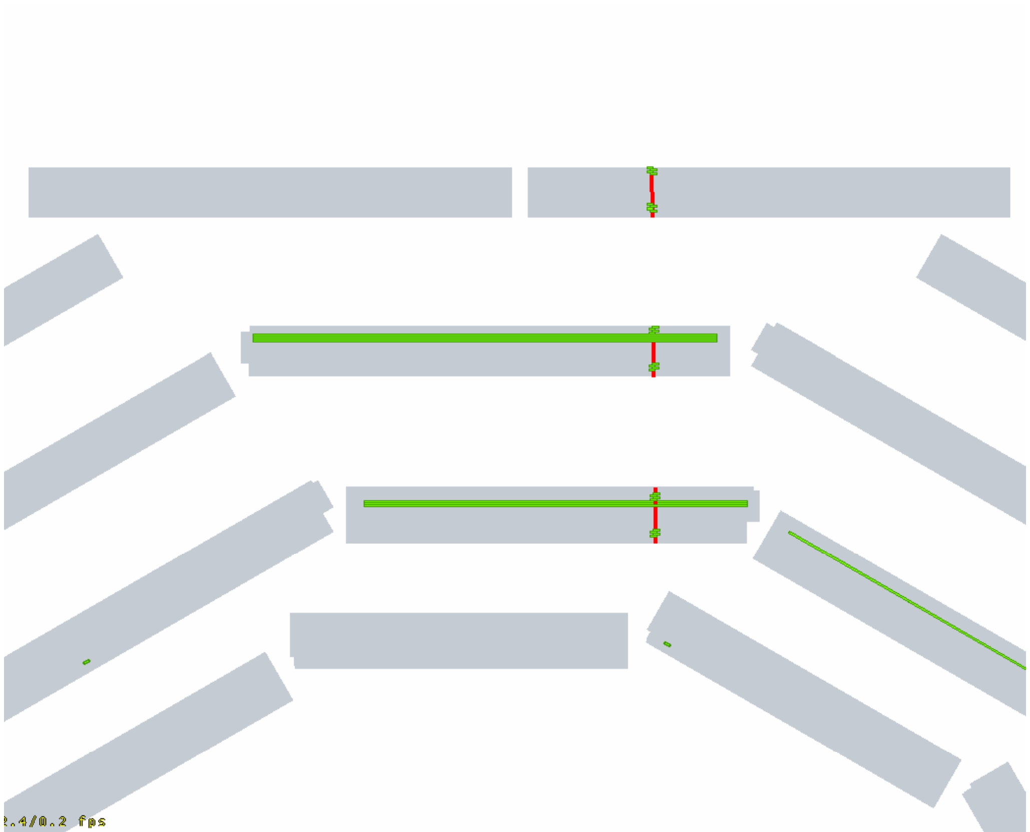
hardware questions → physics questions

Here: "expect" means what your detailed simulation tells you

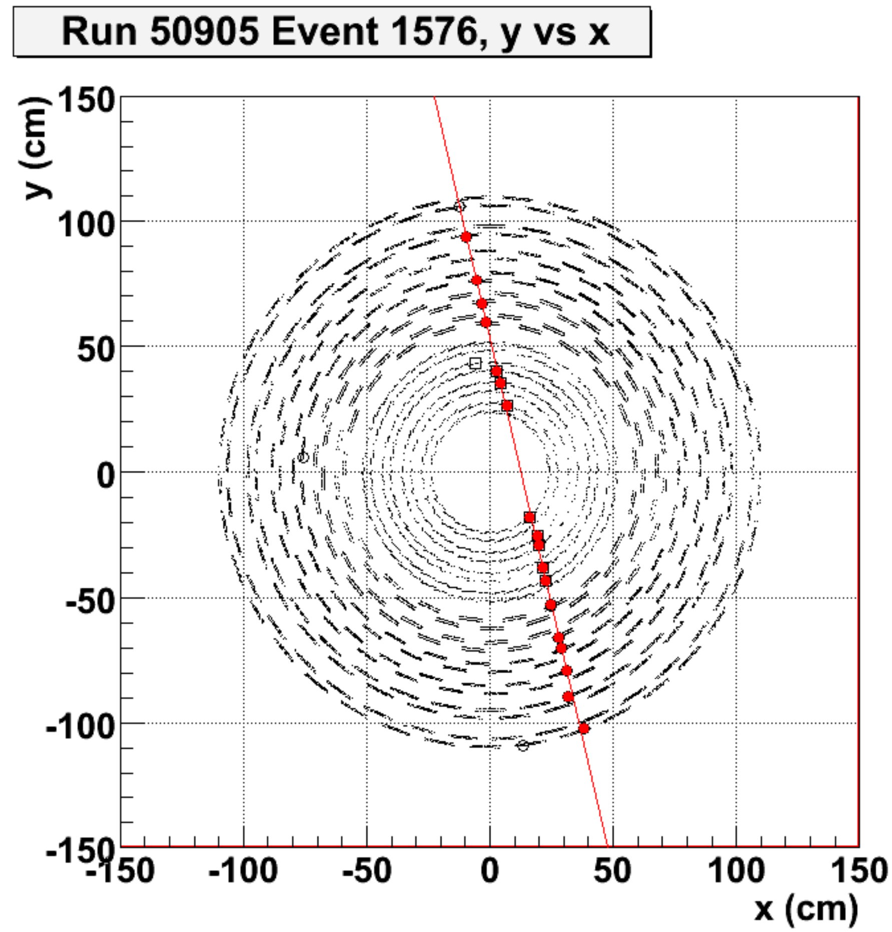
⇒ simulation usually has to be updated to match "real" detector

Tracker Commissioning: How?

- After the tracker is installed, you only have two sources of particles with which you can calibrate: cosmics and collisions
  - movies from CMS: Cosmics muons in the DTs, central tracker

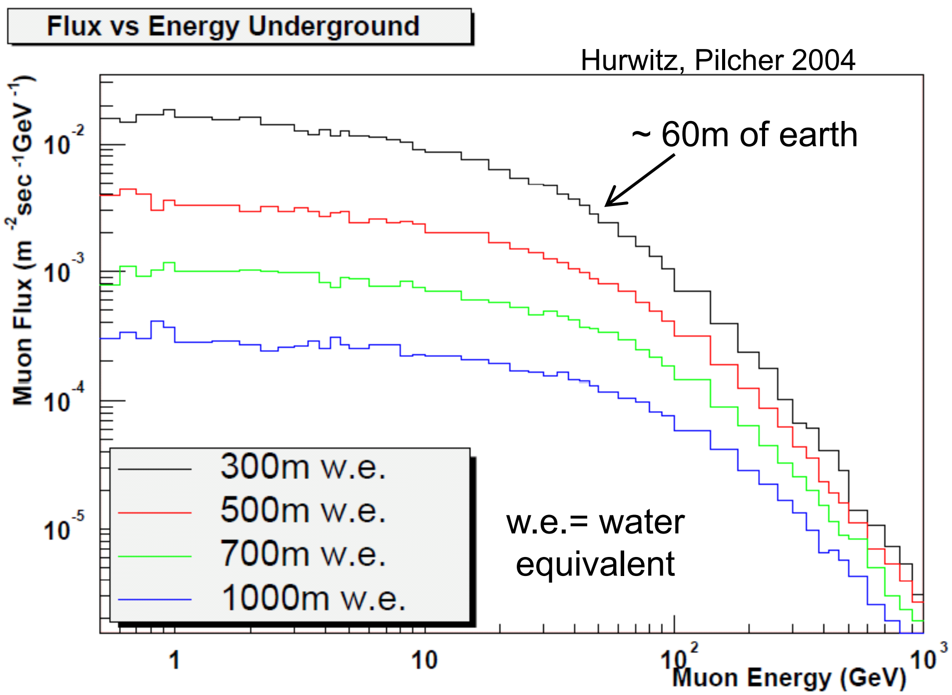


(movies in .ppt version)



Cosmics

- Free high-energy particles (muons) from Mother Nature
  - underground energy spectrum:



- Standard steeply falling spectrum

$$\frac{dN_\mu}{dE_\mu d\Omega} \approx \frac{0.14\, E_\mu^{-2.7}}{\mathrm{cm}^2 \;\; \mathrm{s} \;\; \mathrm{sr} \;\; \mathrm{GeV}}$$

gets flattened somewhat at the low end by traversing lots of rock/earth

- At 60m below surface, one 10 GeV/c muon every 100 sec

- One issue: Mother Nature has no beam clock. Asynchronous arrival of cosmic rays means special care has to be taken to deal with precision timing in detectors.
  - limited “live” periods
  - potentially use other detectors to set t_0

Tracker Commissioning

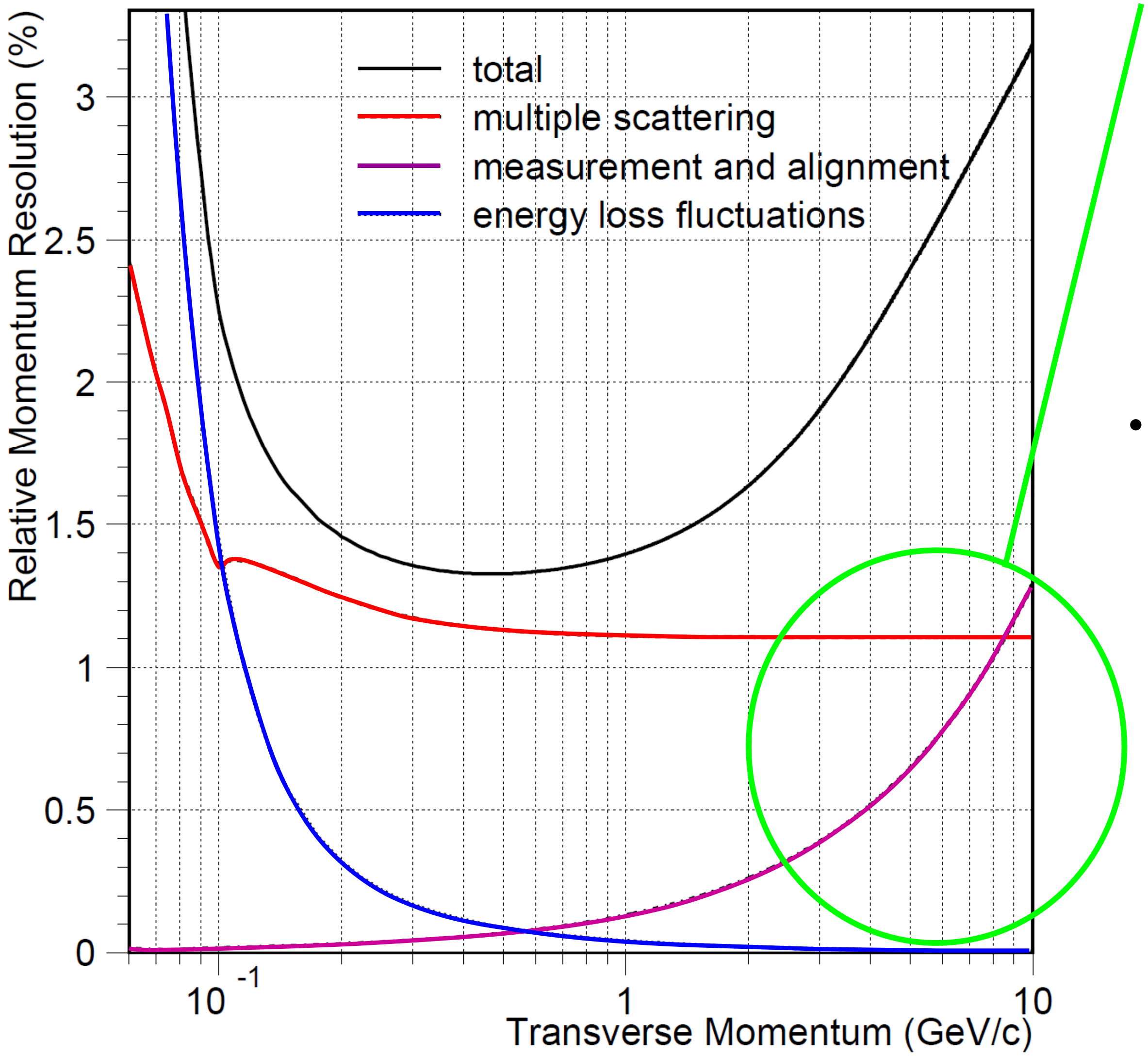
Cosmic ray muons can be used to answer most of these questions:

1. Does it work?
   - is the cabling correct?
   - are the voltage settings correct?
   - are the timing delays optimal?
   - are pieces dead/noisy/inefficient?
2. Do you understand it?
   - is the efficiency what you expect?
   - is the resolution what you expect?
   - is the overall performance what you expect?

- Simple, low-multiplicity events with high-energy, straight tracks are the tracking commissioner's dream test sample
  - with enough statistics, one can systematically map the detector performance (modulo precision timing and azimuth issues)
  - no beam needed (yet)

Tracker Alignment

- Back to ALICE:



- Reminder: Tracker alignment and measurement error dominate track parameter resolutions at high p_T.
  - Measurement errors are intrinsic to detector technology
  - Alignment can be corrected

- Basic effect:

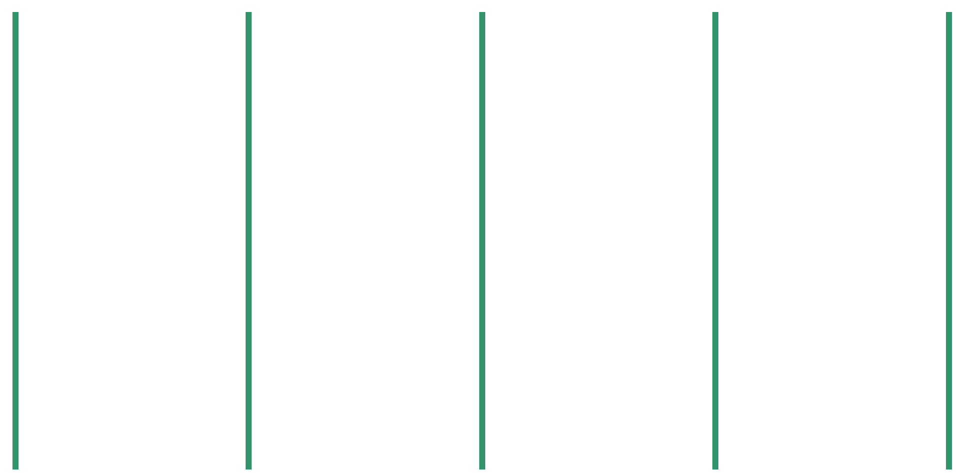
random hit offsets due to mechanical misalignment effectively enlarge the single hit measurement error, leading to worse resolution

Systematic mechanical shifts lead to biases in momentum measurement

Tracker Alignment

How do you fix this?

Toy Alignment:



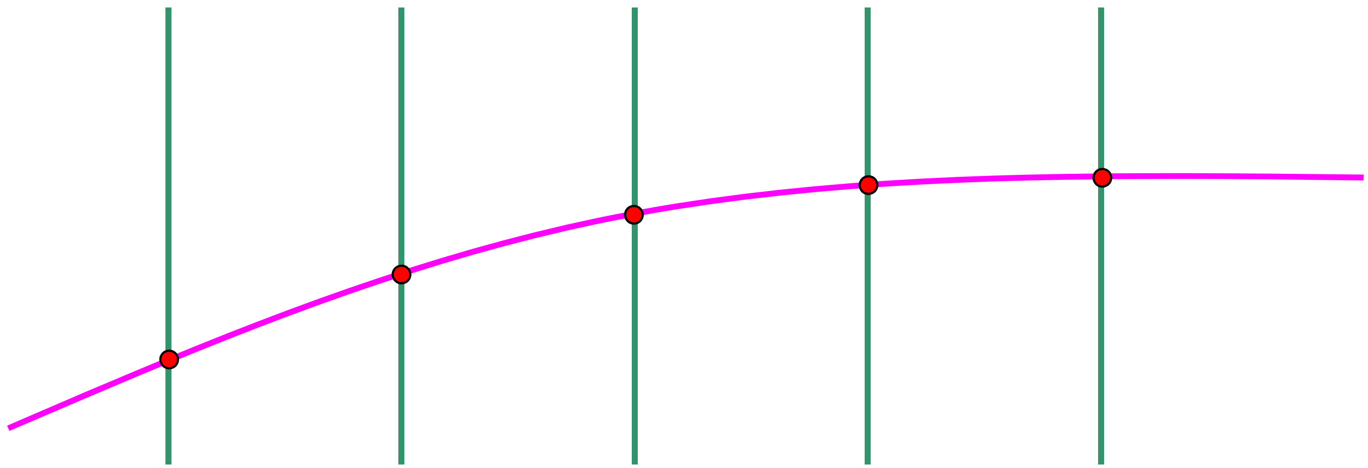
Consider a five-layer tracker

borrowed from F. Meier

Tracker Alignment

How do you fix this?

Toy Alignment:

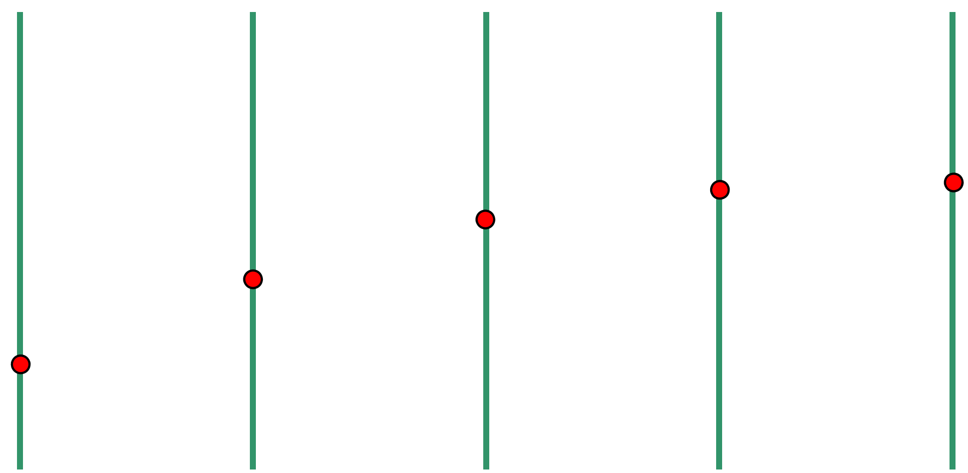


A track goes through, leaving hits

Tracker Alignment

How do you fix this?

Toy Alignment:

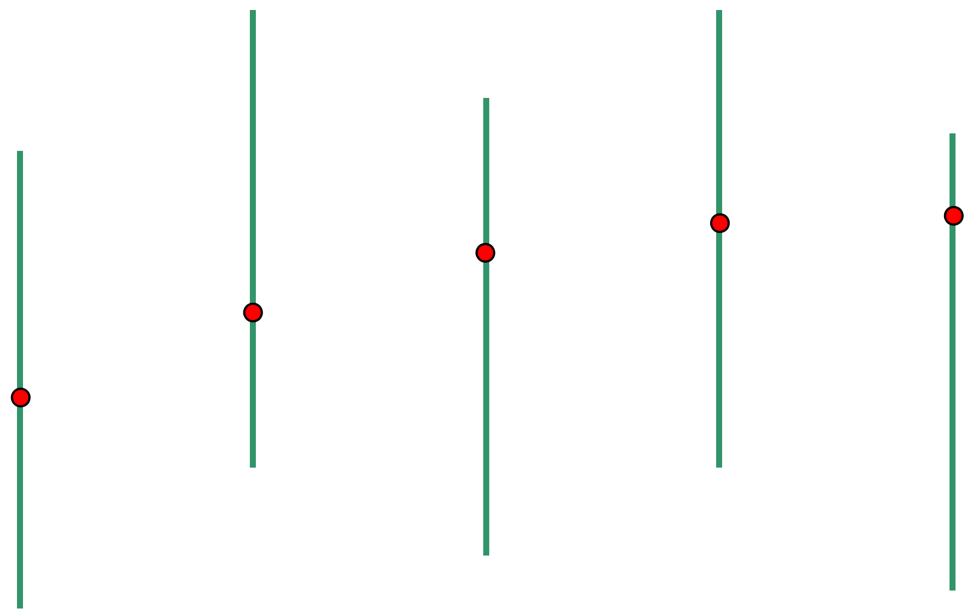


All you really see are the hits, actually

Tracker Alignment

How do you fix this?

Toy Alignment:

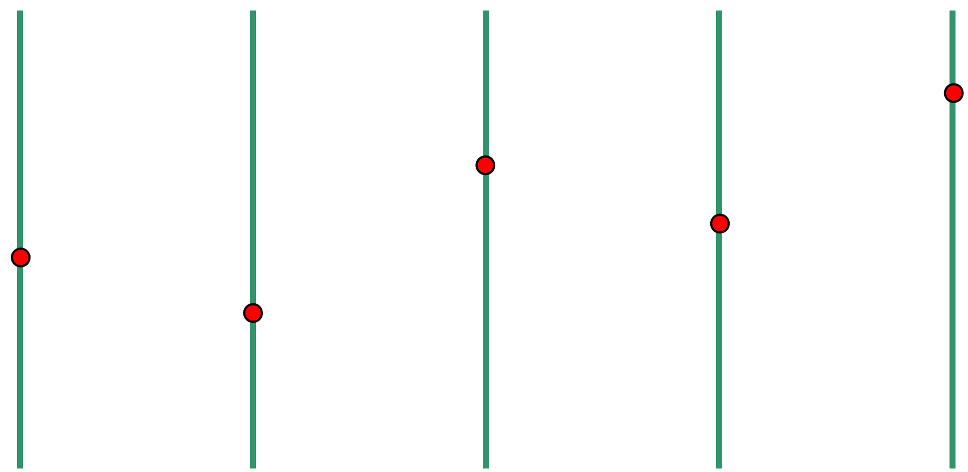


Now, if your tracker is misaligned, the hits positions really look like this

Tracker Alignment

How do you fix this?

Toy Alignment:

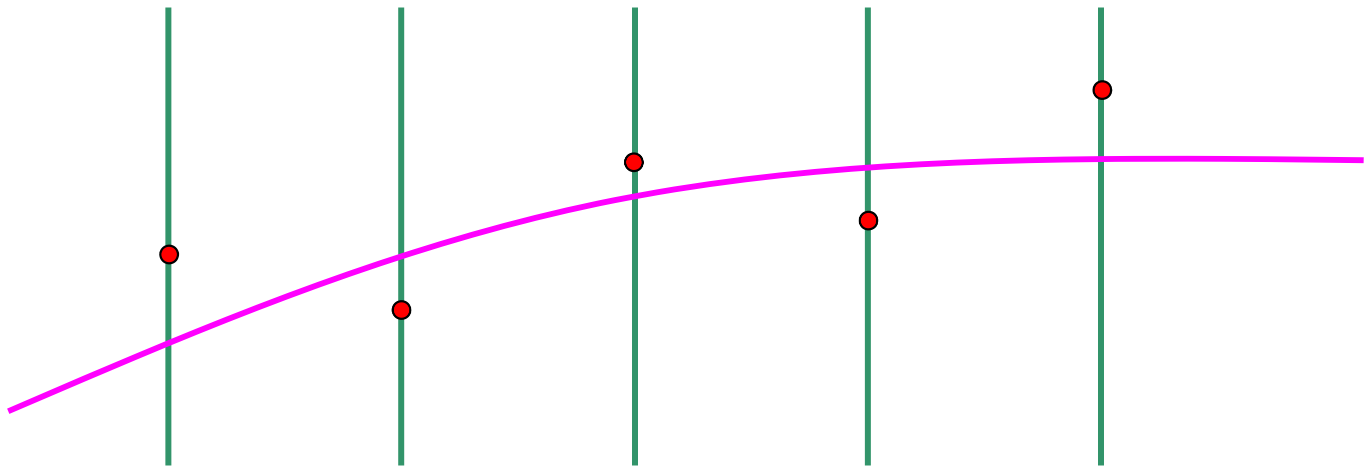


If you assume the module positions are "ideal", you see this

Tracker Alignment

How do you fix this?

Toy Alignment:

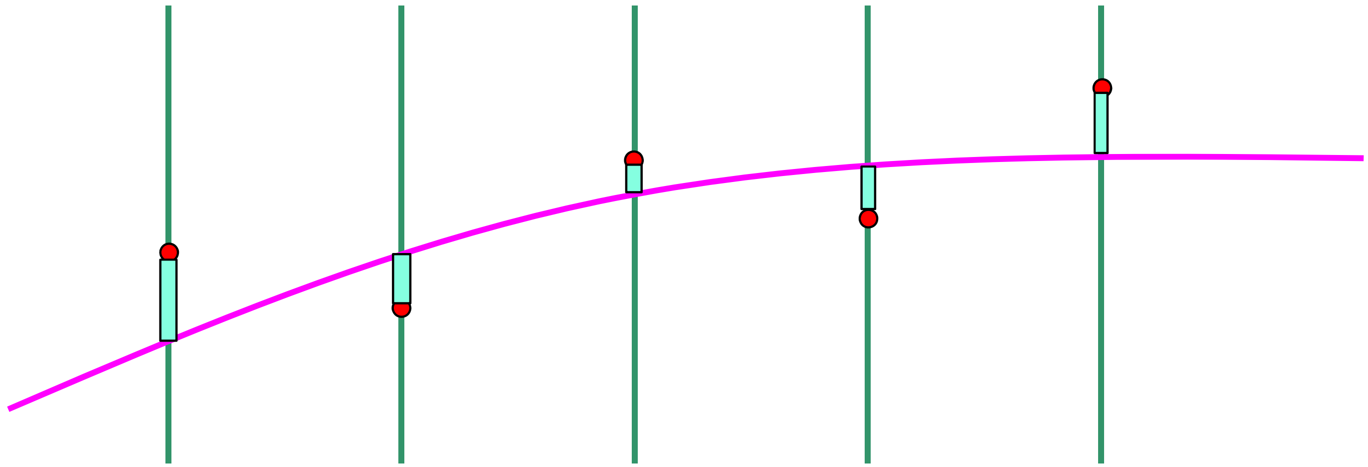


So your track really looks like this

Tracker Alignment

How do you fix this?

Toy Alignment:



To “align”, we keep track of the “residuals” between the hits and the projected track positions (shown as ▭) for many tracks, then adjust the positions of the actual detectors to minimize the residuals across the whole tracker.

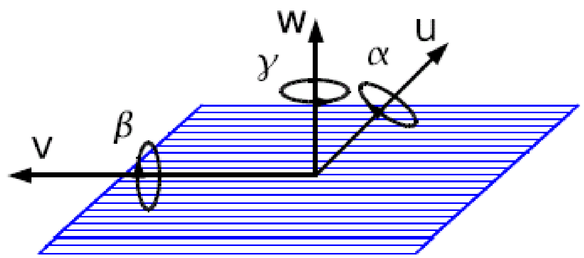
Tracker Alignment: technical description

Another χ^2 minimization:

$$\chi^2(\mathbf{p},\mathbf{q}) = \sum_j^{\text{tracks}} \sum_i^{hits} \mathbf{r}_{ij}^T(\mathbf{p},\mathbf{q}_j)\,\mathbf{V}_{ij}^{-1}\,\mathbf{r}_{ij}(\mathbf{p},\mathbf{q}_j)$$

where **p** are the tracker geometry parameters, $\mathbf{q}_j$ are the track parameters, and $\mathbf{r}_{ij}$ are the residuals: $\mathbf{r}_{ij} = \mathbf{m}_{ij} - \mathbf{f}_{ij}(\mathbf{p},\mathbf{q}_j)$, where **m** is the measured position and **f** is the predicted one

Scale of the Problem: (e.g. CMS Tracker)



- Each module has 6 degrees of freedom:
  - 16588 modules x 6 = ~10^5 parameters
- Each track has 5 degrees of freedom, need 10^6 tracks or more
  - $\Rightarrow$ ~10^7 parameters to deal with

Not easy!

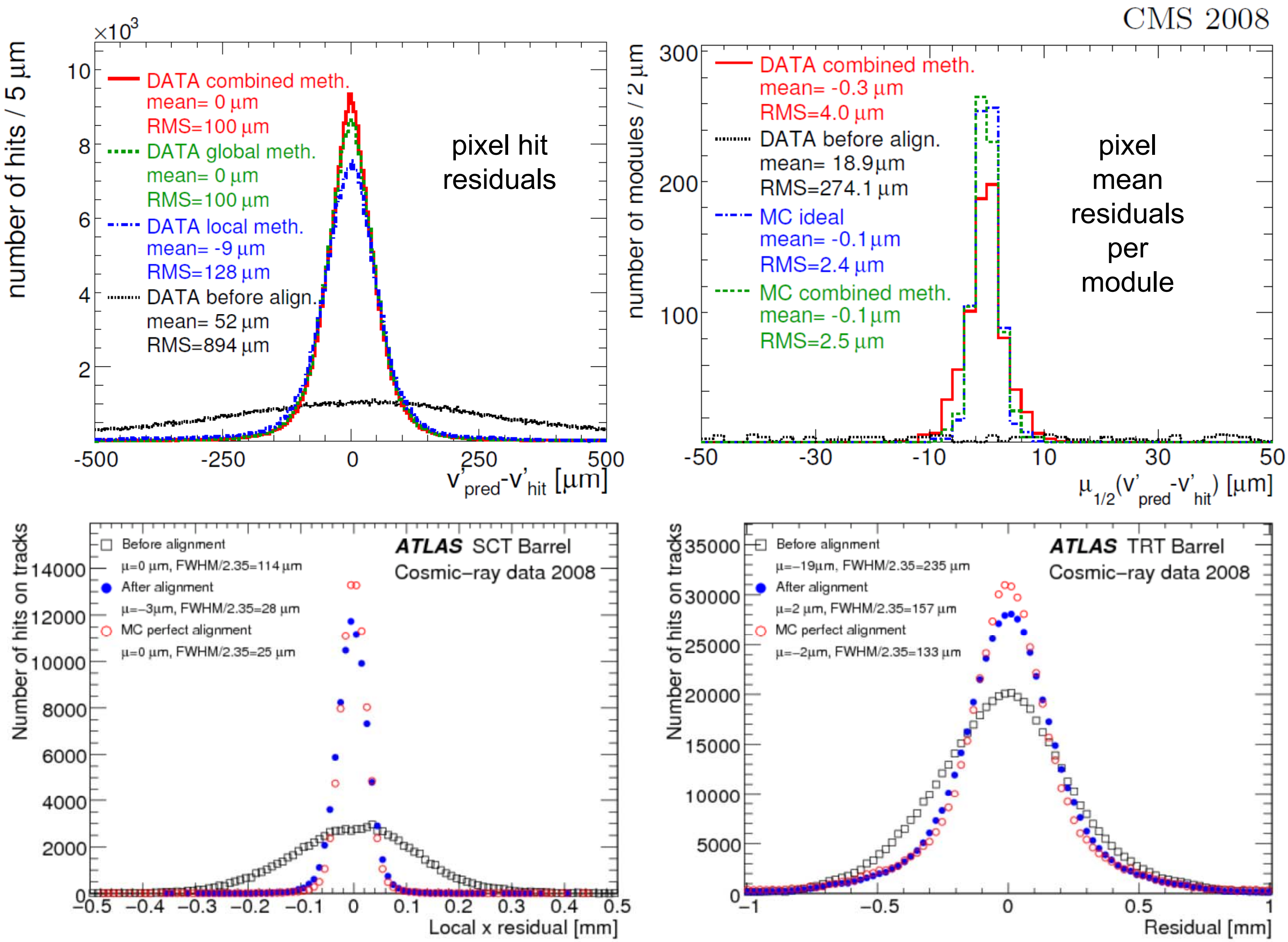
Alignment Techniques

1. Global (e.g. “Millepede-II” for CMS)
   - Matrix inversion concerned with module parameters only:
     - ~10^5x10^5 matrix
     - Correlations between modules included
     - simplified tracking parameterization: no Eloss, MS
     - few iterations
2. Local (“HIP” (= Hit Impact Parameter) for CMS, 3 different ones for ATLAS)
   - Local minimization of residuals: ~10 parameters at a time
   - can incorporate survey data as a constraint
   - Full Kalman track extrapolation with MS, Eloss
   - includes local correlations between adjacent
   - can have many iterations if starting values are far off

Cross checked for consistent results…

CMS uses both in an iterative sequence

Alignment Results (cosmics)

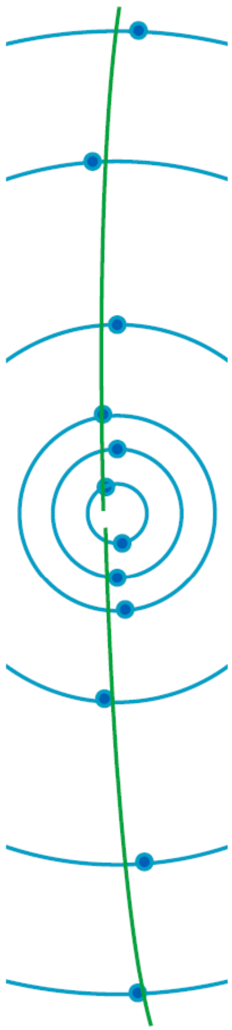


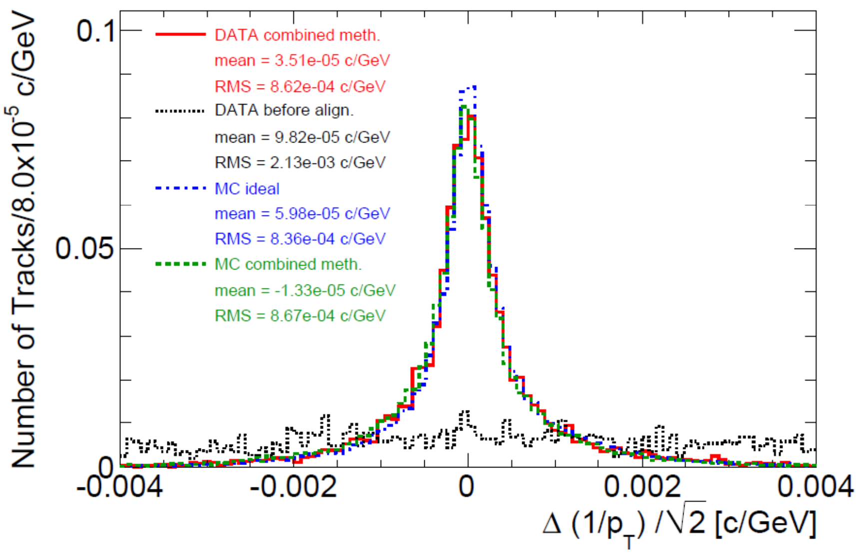
⇒ Basically, all detectors reached near-optimal alignment before collisions

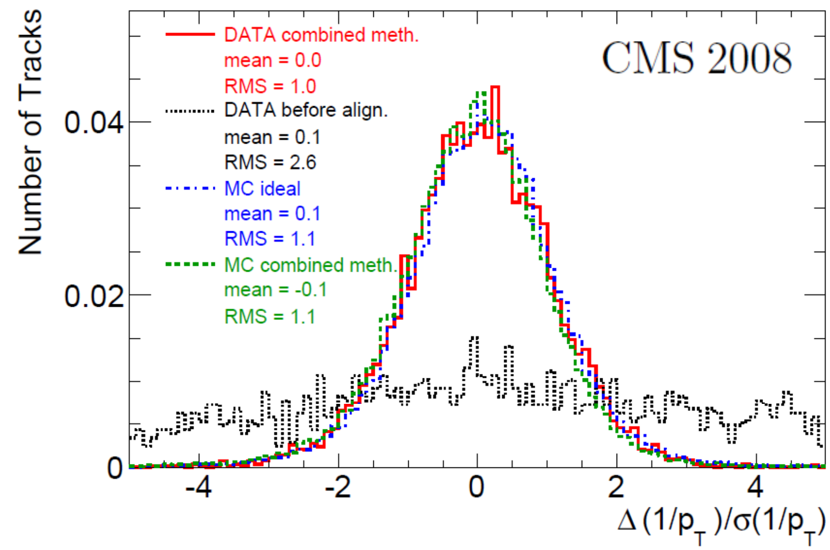
Alignment Results (cosmics)

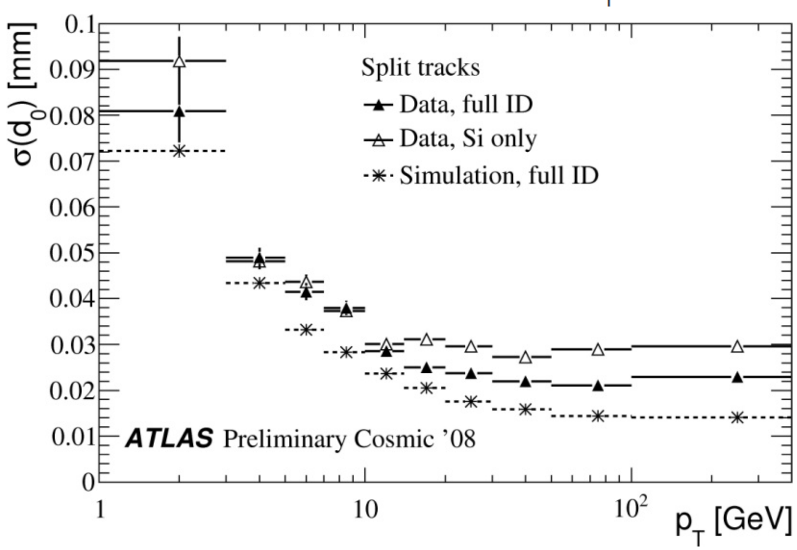
⇒ better results available, especially for endcaps, with collision data

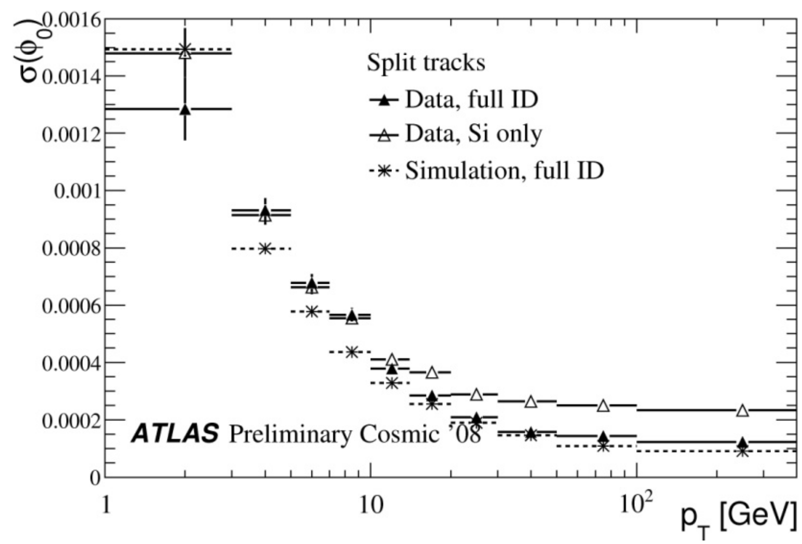
- Split cosmic track in half, fit each half separately, use comparison of results to evaluate track parameter resolution





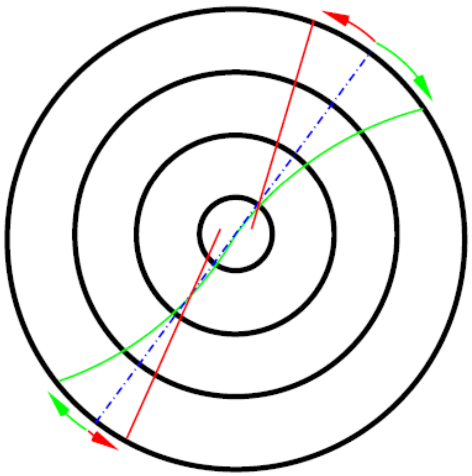






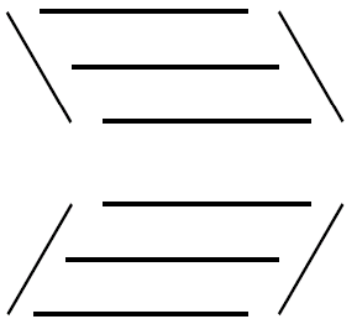
Alignment pitfalls

- There exist modes of detector deformation for which there is no change in total χ^2, yet the physical locations are not “ideal”

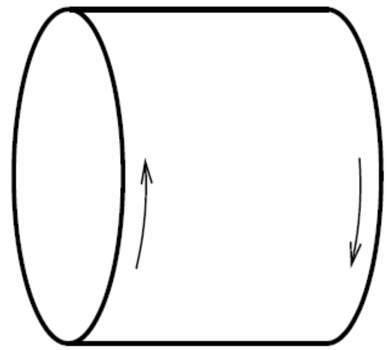


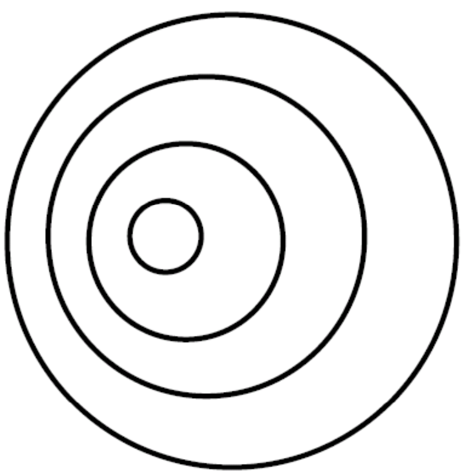
shear (red) or bend (green) in r-ϕ

z shear

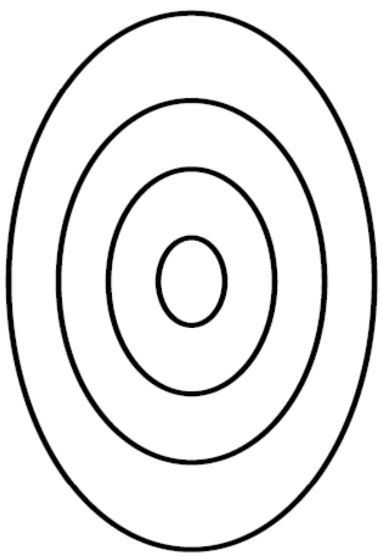


z twist





r-$r\phi$ mode 1



r-$r\phi$ mode 2

This is tricky…

Need orthogonal sets of tracks to constrain these modes:

- cosmics, which don’t pass through the tracker origin
- collision tracks
- collision tracks with B=0

Detector Material

To correctly account for energy loss and multiple scattering, you need to know where the material is inside your detector

Photon conversion probability in a thin cylindrical shell:

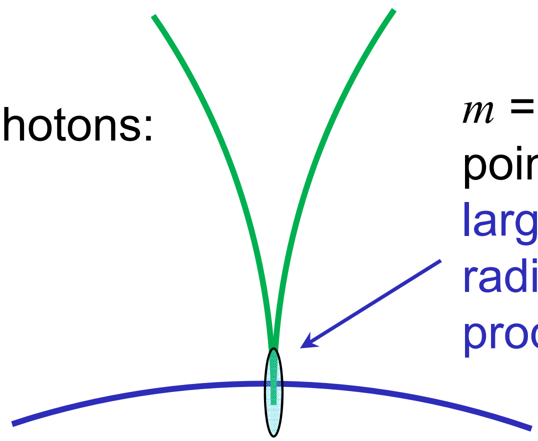
$$dN_{conv} = N_\gamma(R,\theta,\phi) \cdot R^2 \sin\theta \; d\theta \; d\phi \frac{P}{X_0} dR \qquad N_\gamma(R,\theta,\phi) \propto 1/R^2 \sin\theta$$

Can also have Nuclear Interactions:

– swap P(photons) ~7/9 to P = 1, $X_0 \rightarrow \lambda_0$

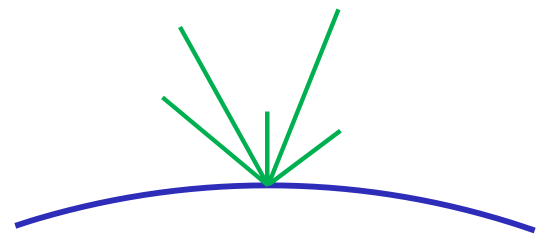
- Different reconstruction characteristics:

Photons:



m = 0: tracks parallel at point of production $\Rightarrow$ large-ish uncertainty in radial position of production point

Nuclear interactions:



Good vertex resolution, but many soft tracks with large impact parameters: $\Rightarrow$ need special tracking cuts

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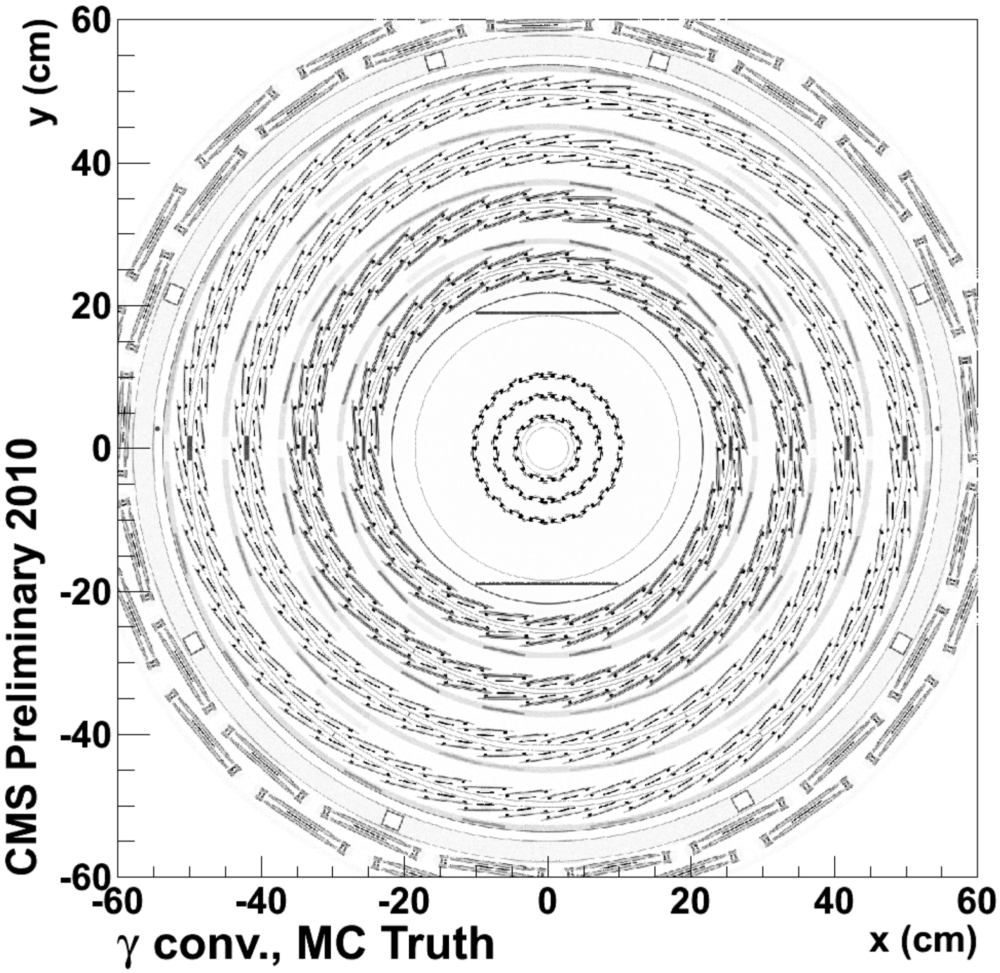
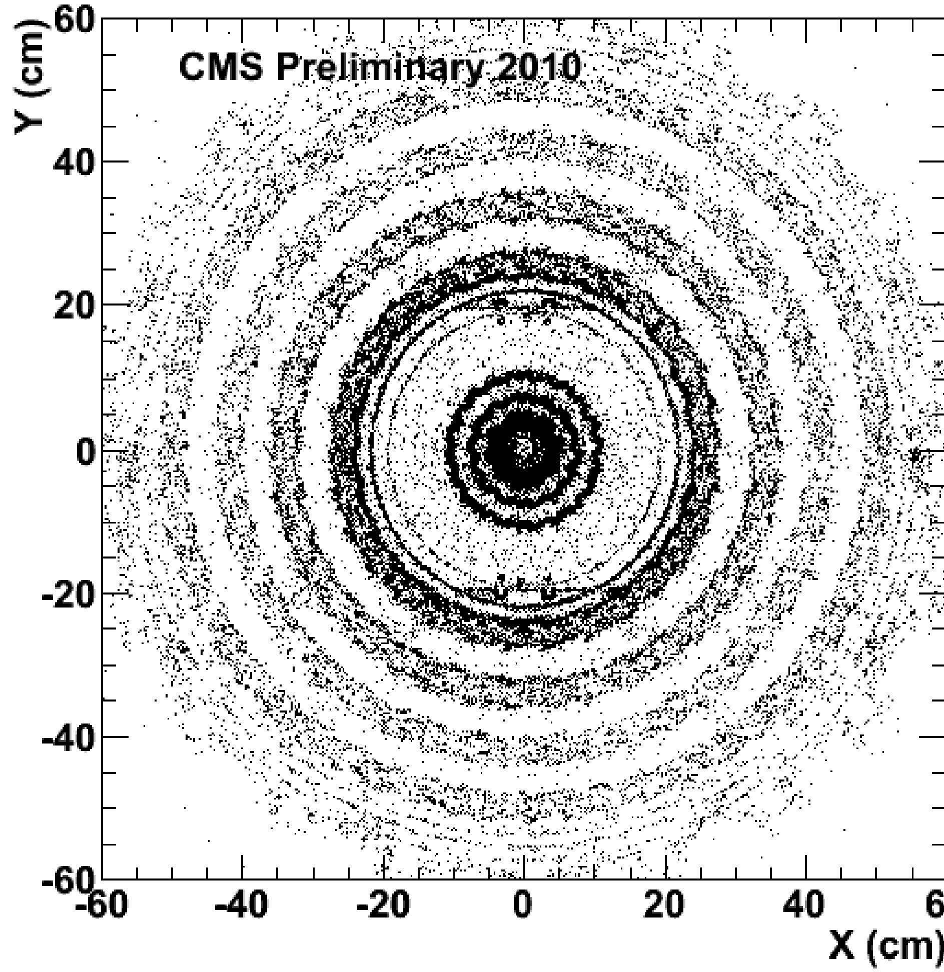
Some examples:

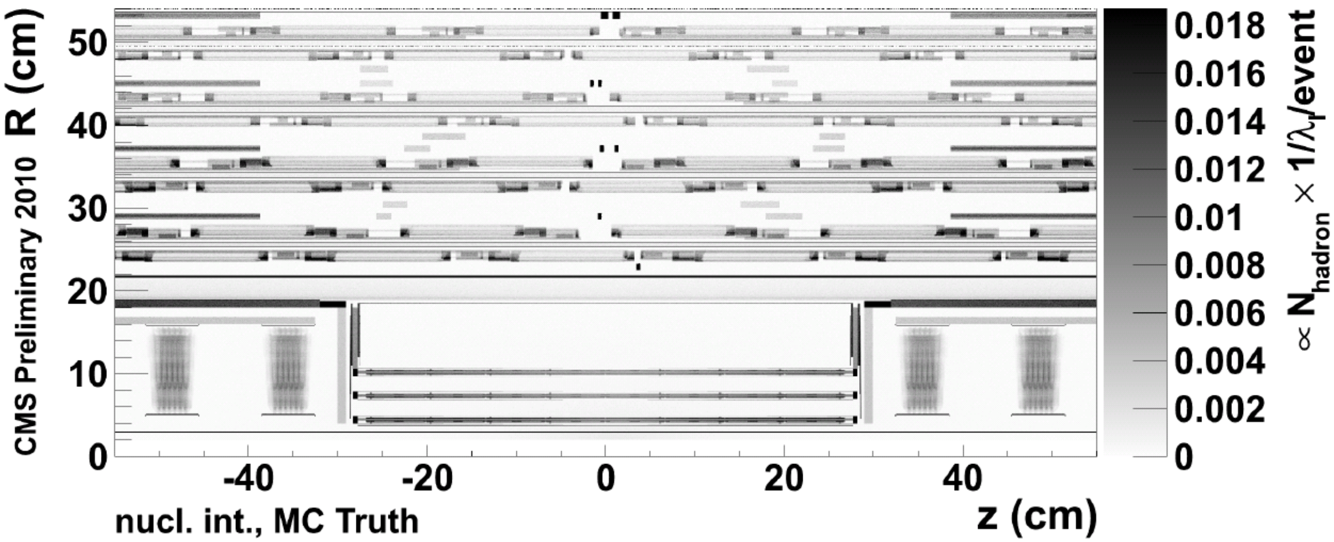




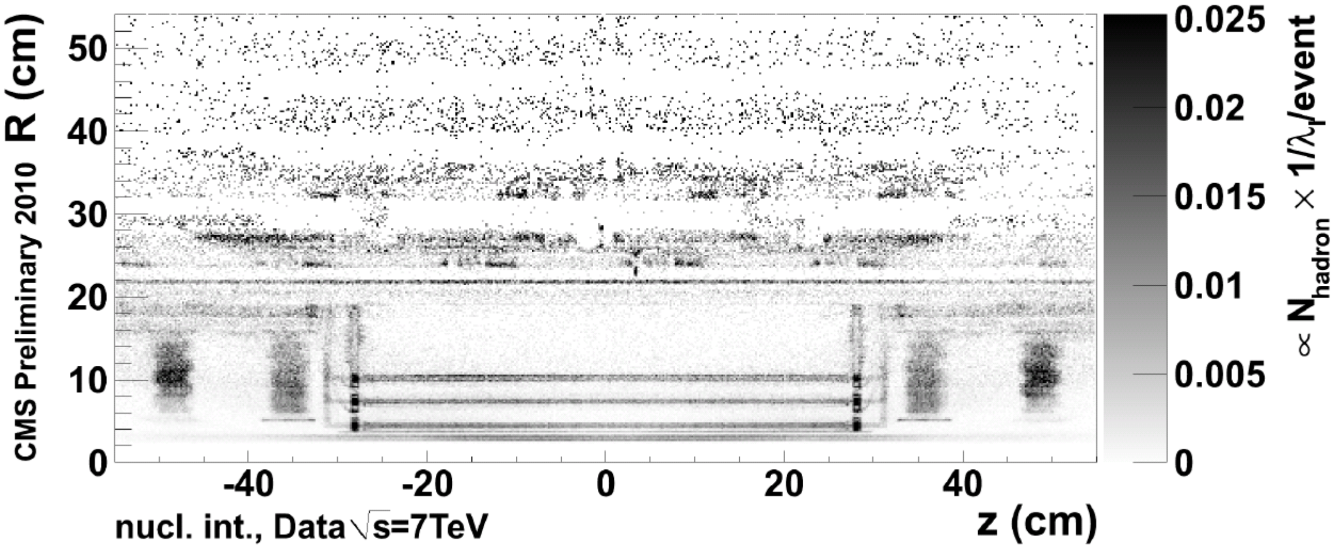
MC: distribution of material weighted by photon conversion probability

Data: positions of reconstructed photon conversions

Some examples:



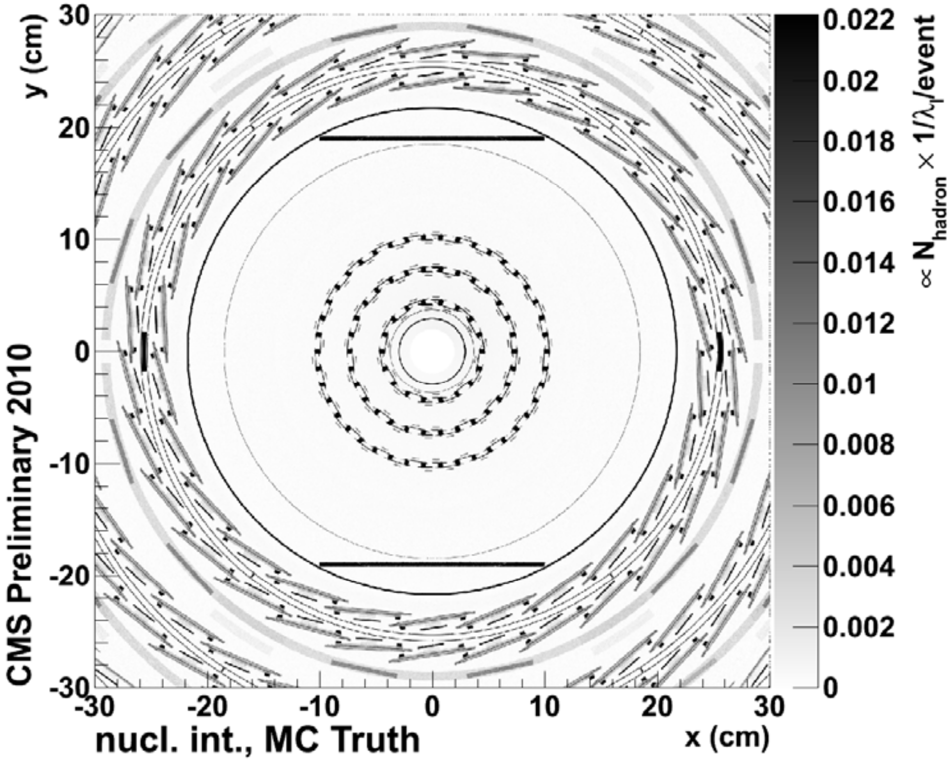
MC: distribution of material weighted by nuclear interaction probability

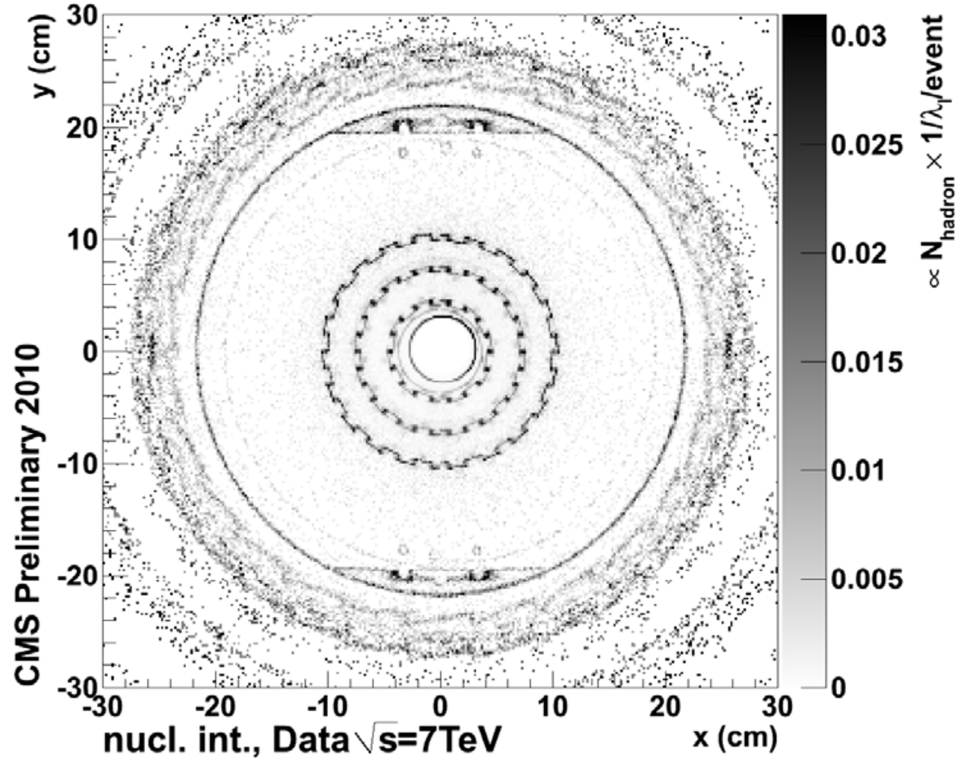


Data: positions of reconstructed nuclear interactions

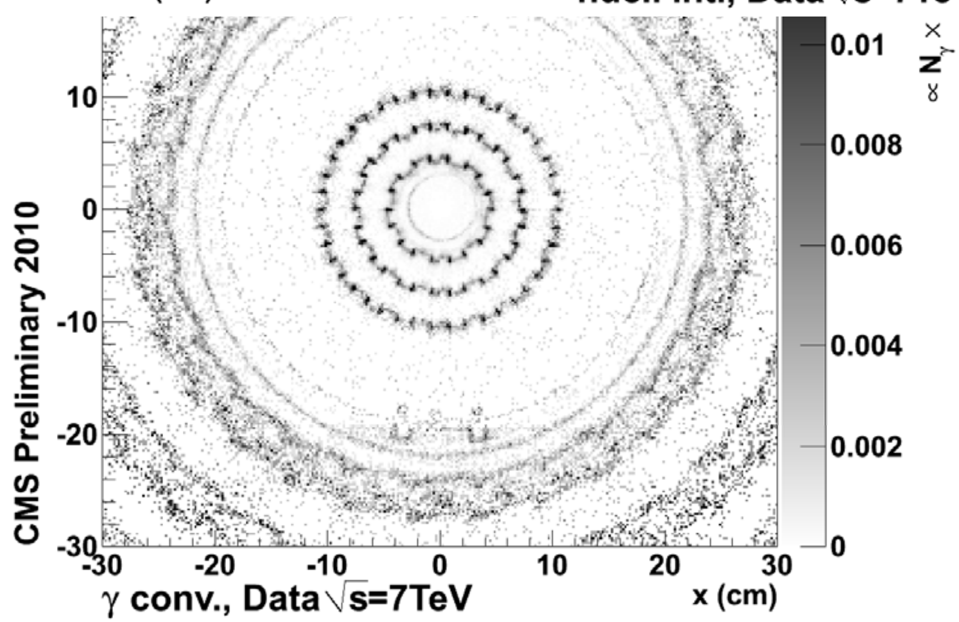
note the effects of lower reconstruction efficiency at high radius

Some examples:



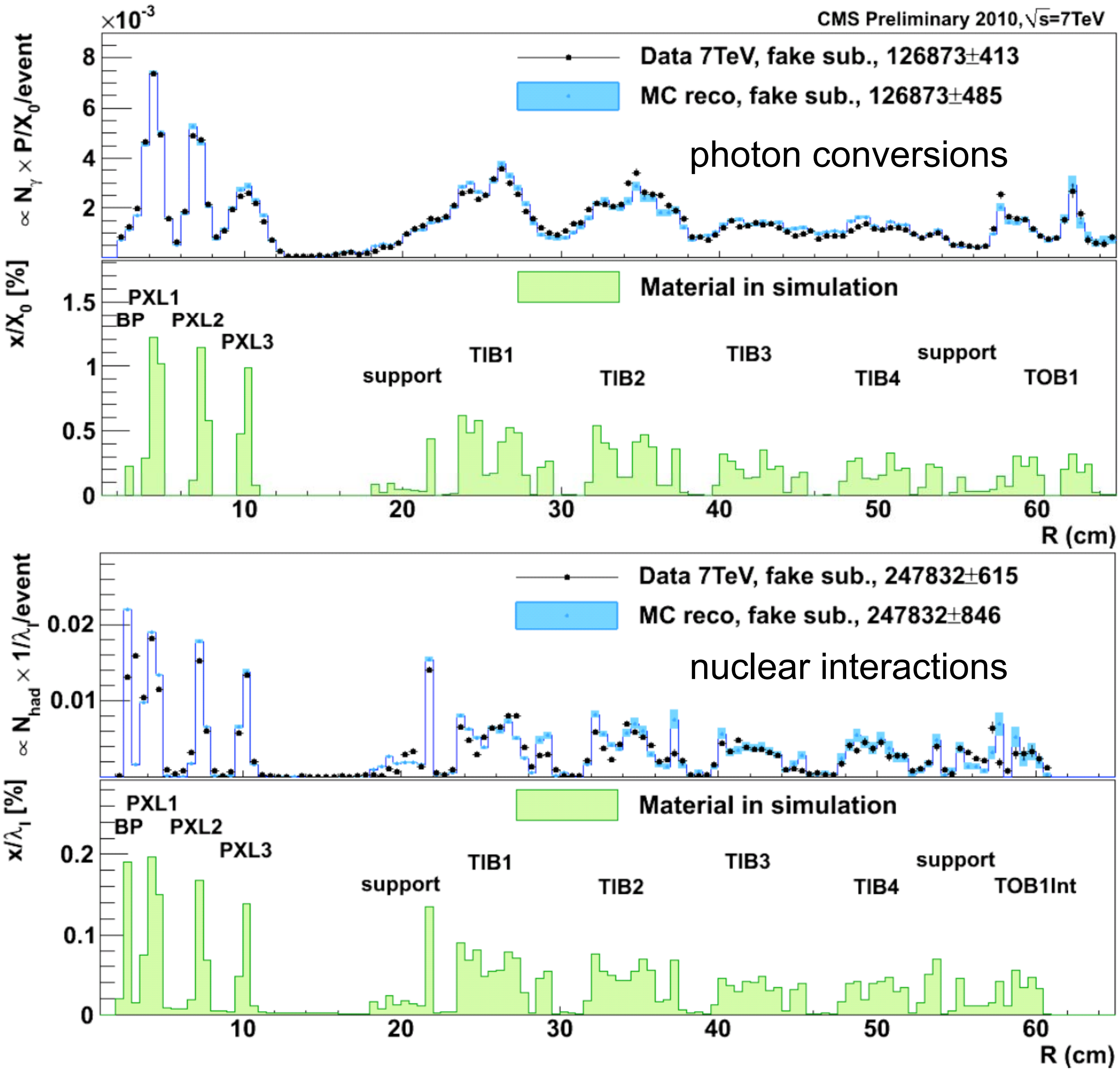


Note the superior position resolution of the nuclear interaction data



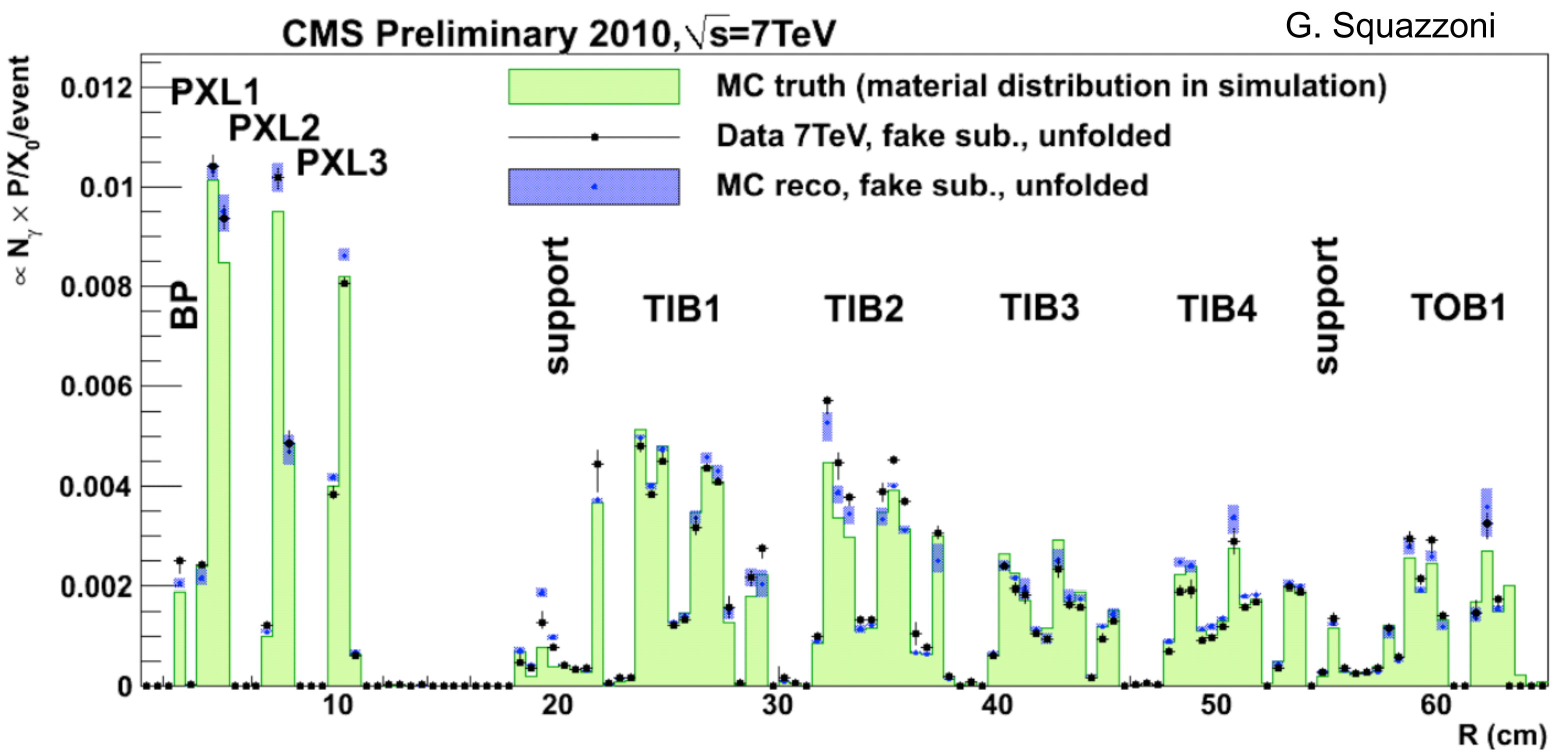
The beampipe isn't centered!

Extracting the material budget



can “unfold” this distribution using estimates of the photon position resolution

Extracting the material budget



astonishingly good agreement between data and simulation

- Some other ways to study the material (there are many):
  - errors in track fit due to MS: compare $\sigma(x)/x$ ("pull distribution") in various regions of the detector to see if errors are correct ($\sigma(x)/x \cong 1$)
  - study evolution of reconstructed resonance (e.g., K_s) masses across different layers of the detector. Wrong energy loss correction will result in mass shifts (c.f. ATLAS)

Tracking Systematics

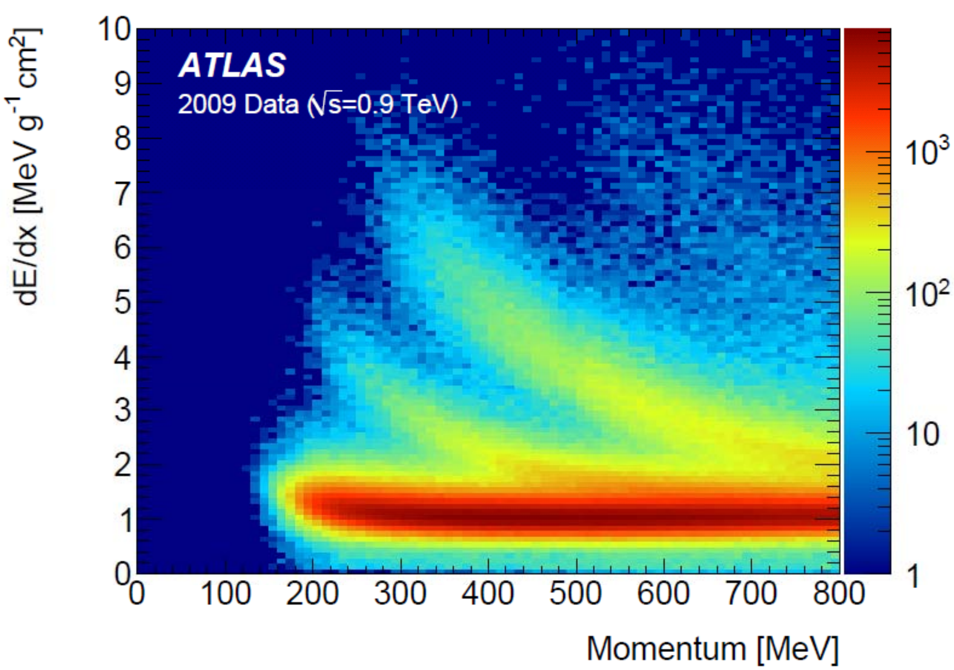
There are many other systematic studies of tracker performance one ***needs*** to make (and that I don't have time to discuss…)

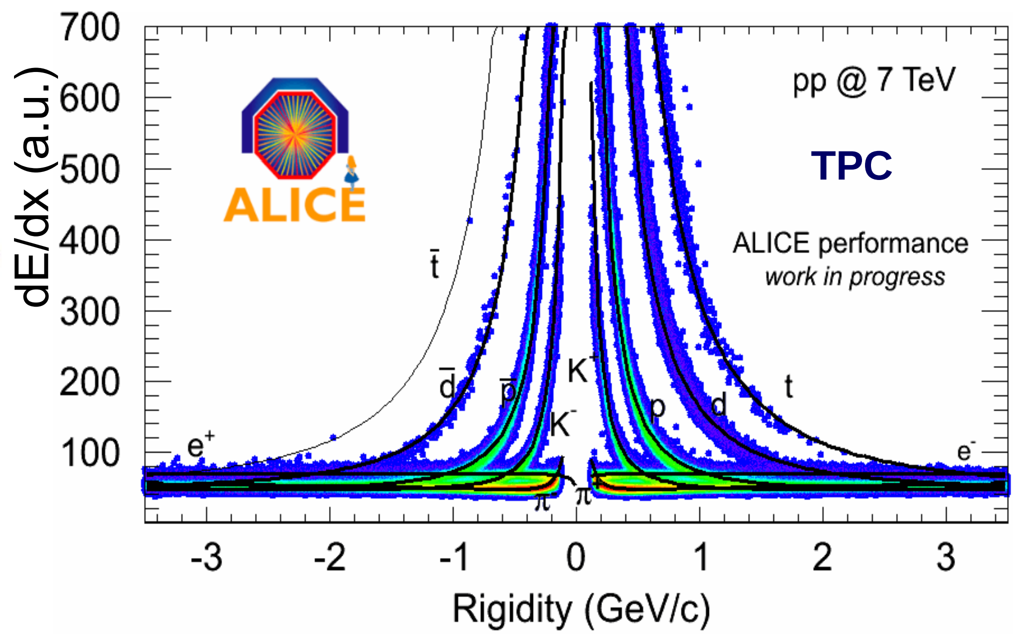
- using track properties themselves or properties of resonances

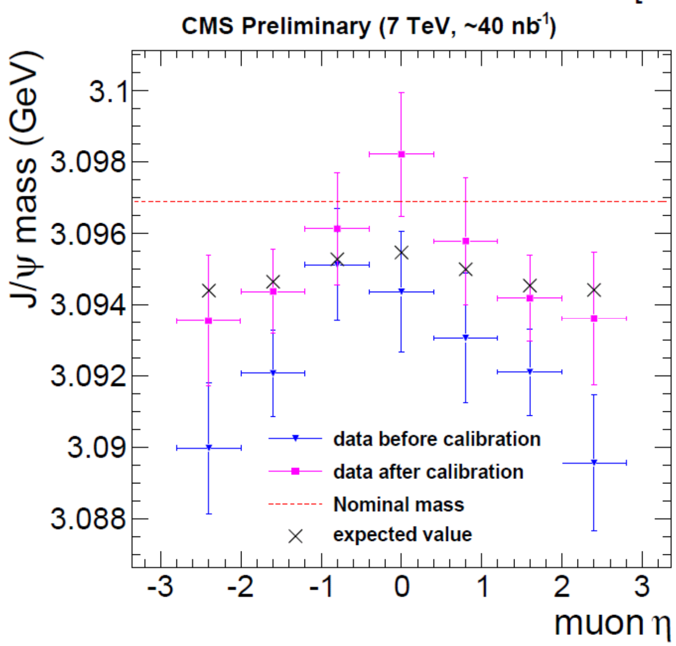
- Charge Collection:
  - for dE/dx calibration $\rightarrow$ particle ID
- Efficiencies:
  - single-hit level $\rightarrow$ tracking efficiency per particle type
- Momentum Scale:
  - studies of magnetic field map, reconstruction biases, etc.

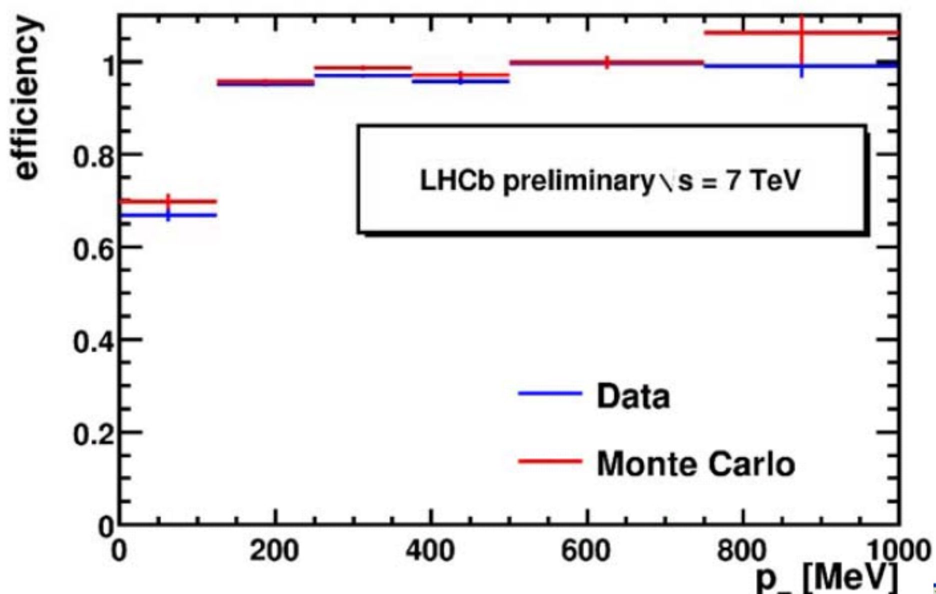
…

Tracking Systematics: Results



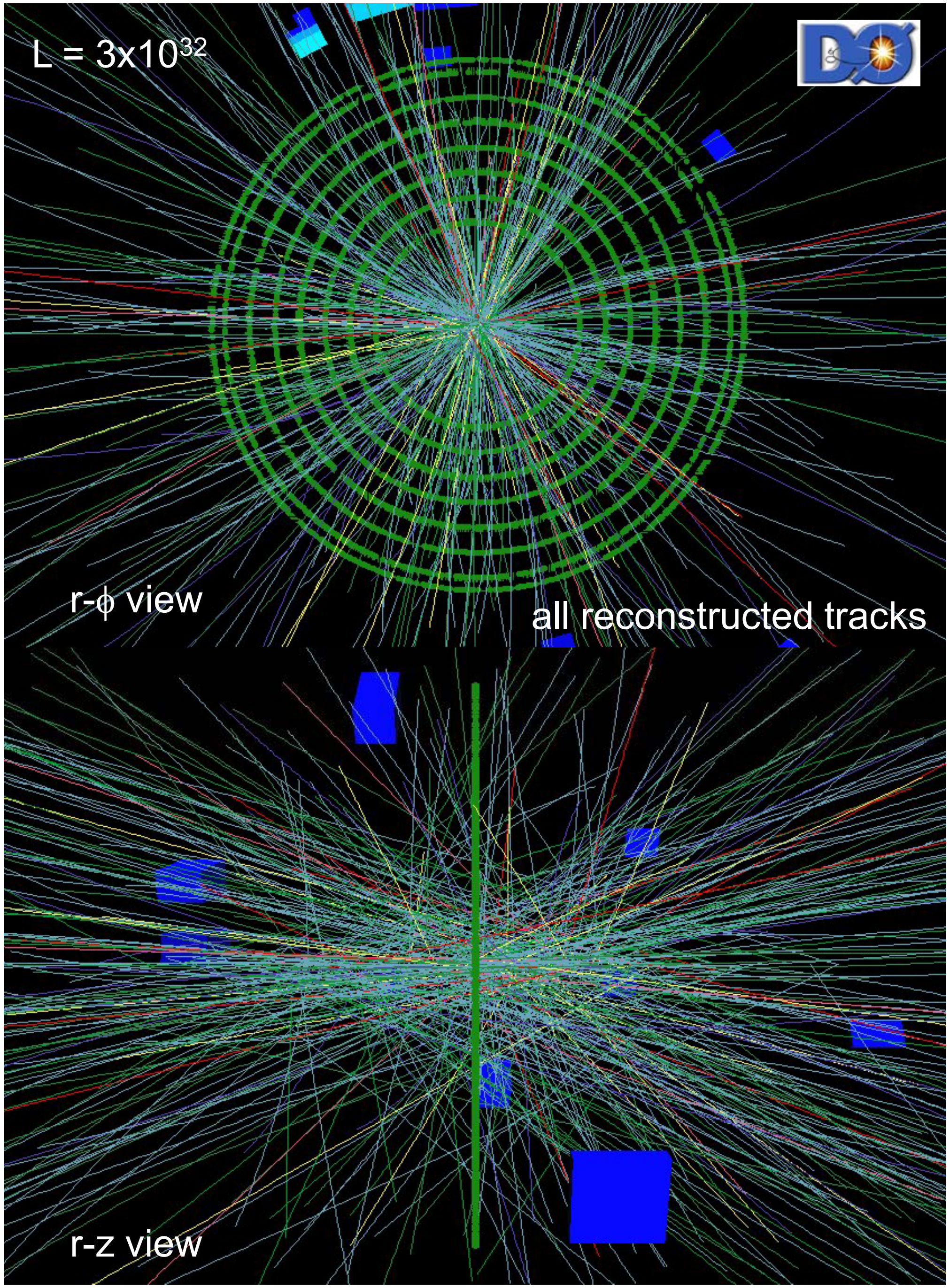


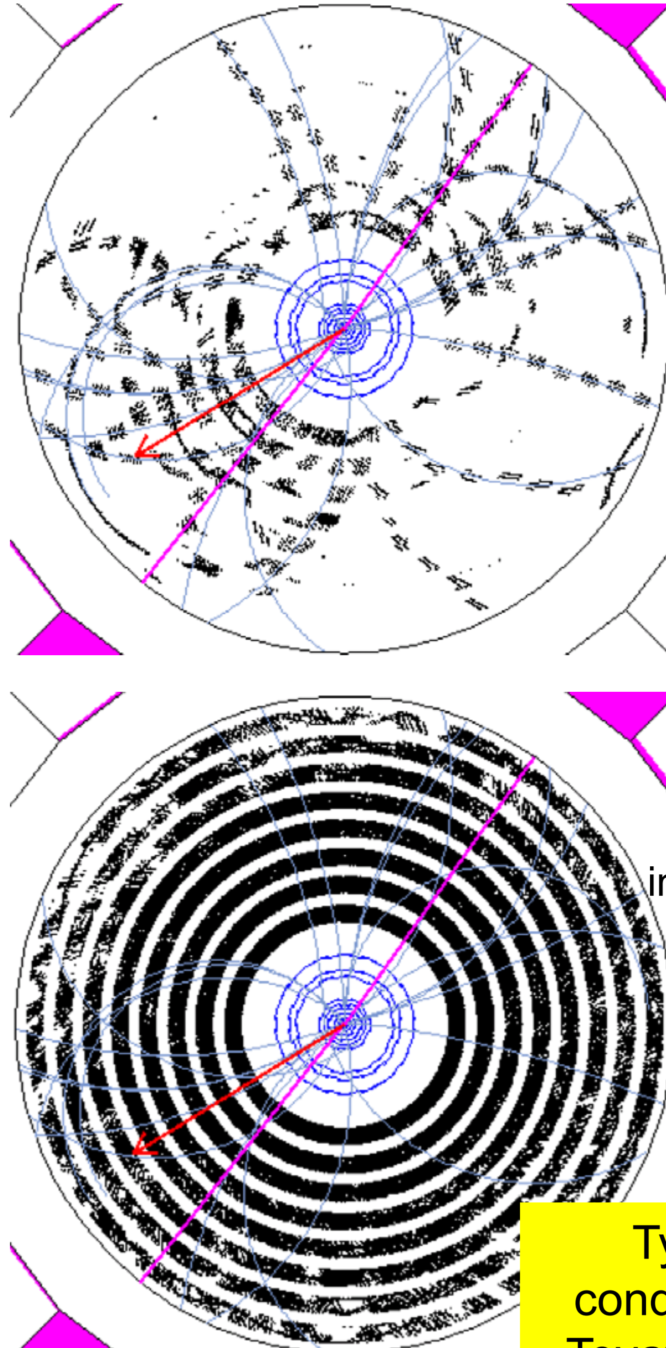




Health Hazards: Occupancy

(Granularity required!)





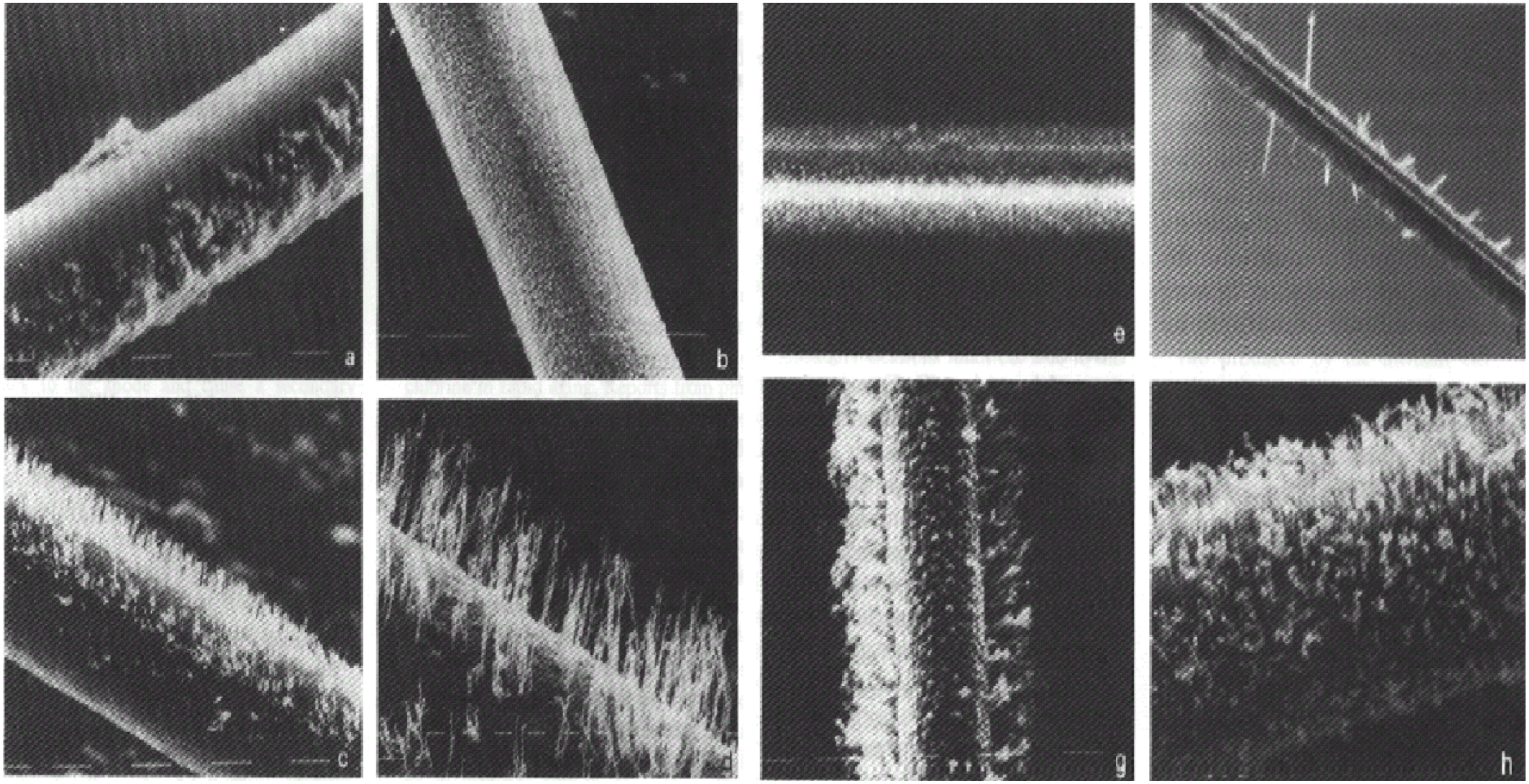
COT: one interaction/ crossing

COT: nine interactions/ crossing

Typical conditions at Tevatron now

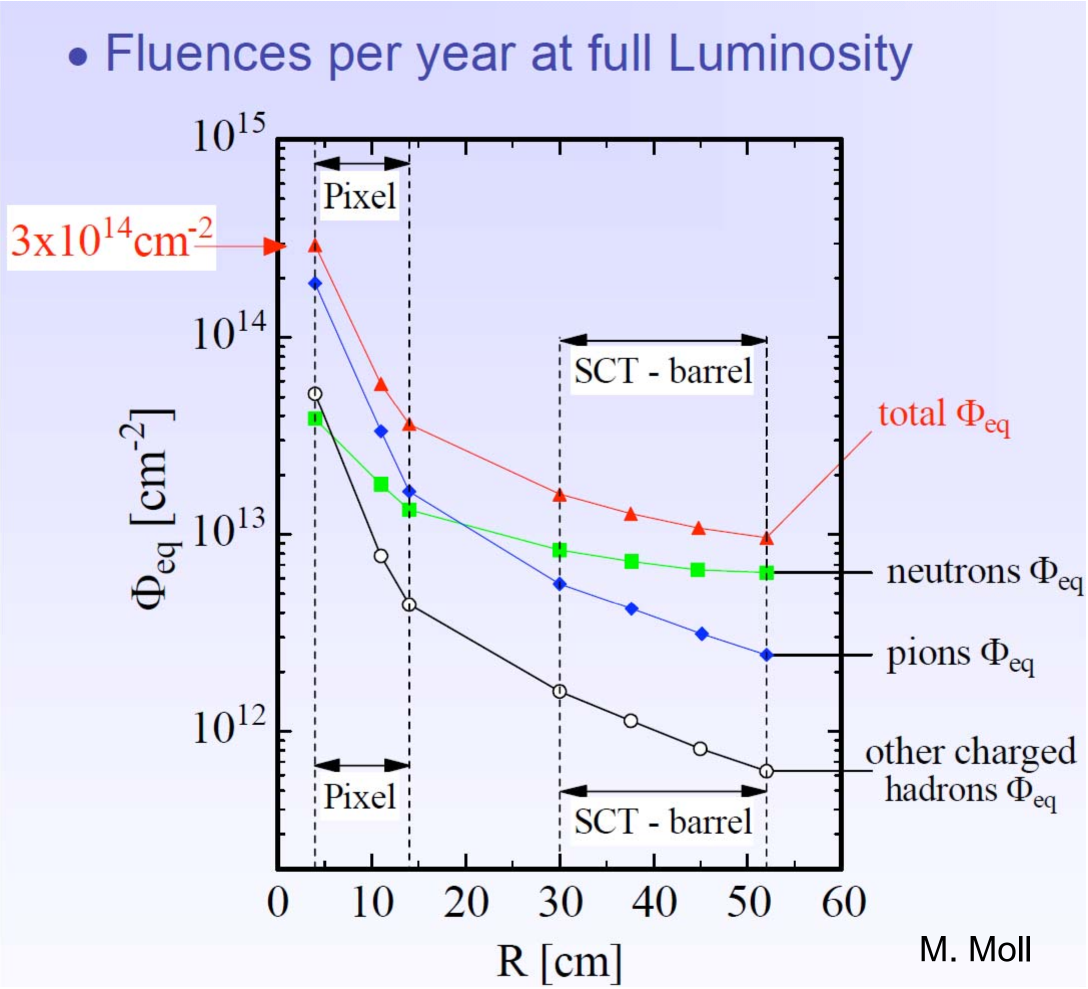
Health Hazards: Radiation Damage

- Wire chambers are susceptible to “ageing” effects due to high-rate operation (many discharges)
  - e.g. whiskers growing on anode wires – bad for uniform E field



Health Hazards: Silicon Radiation Damage

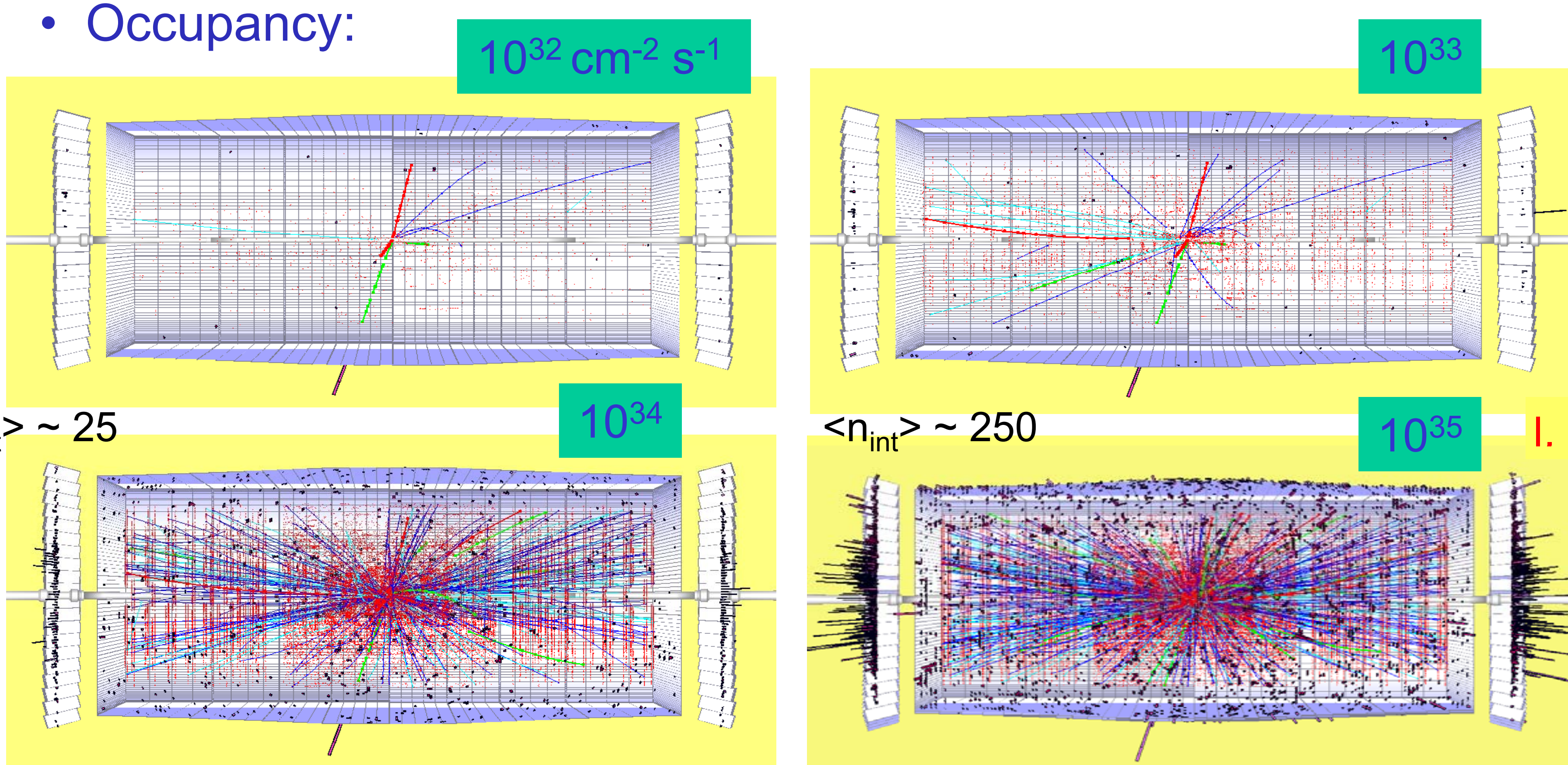
- Many particles produced means much flux through detectors
  - example: ATLAS



- Two general types of radiation damage
  - "Bulk" damage due to physical impact within the crystal
    - induced defects can be electrically active
  - "Surface" damage in the oxide or Si/SiO_2 interface
- Sensors can fail from radiation damage by virtue of…
  - Noise too high to operate effectively
  - Depletion voltage too high for sensor/power supply
  - Loss of inter-strip isolation (charge spreads out too much)
- pixels inherently more robust because of much smaller area

Solution: new detectors!

- Radiation: for example, ATLAS pixels were designed to withstand 1×10^{15} 1MeV n_{eq}/cm^2 fluence (~3 years at full nominal LHC luminosity)
  - BUT sLHC : 2×10^{16} 1MeV n_{eq}/cm^2 dose at the inner pixel radius
  - not only do you need new detectors, you need new detector technology that is more radiation-hard
- Occupancy:

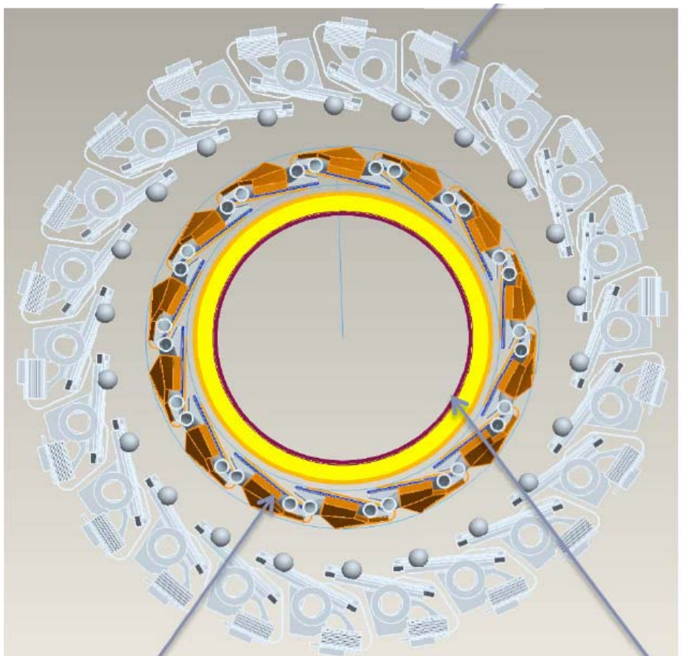


“High Luminosity LHC” Upgrades

- All detectors planning some sort of tracker replacement to deal with radiation damage and occupancy issues

ATLAS

current B layer

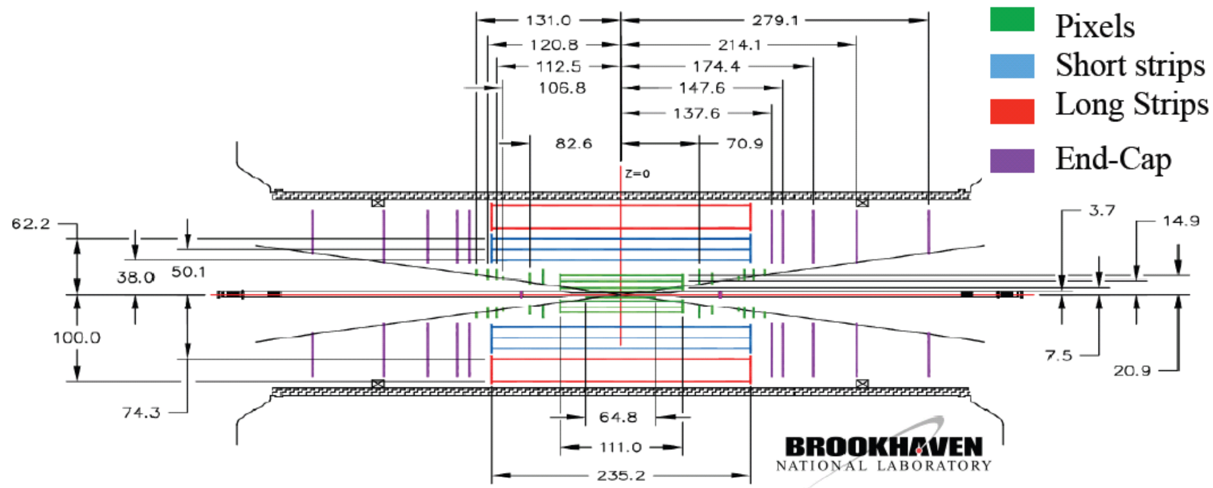


possible new B layer

new beampipe

2014: insert new radiation-hard tracking layer to maintain performance as old one ages

New Tracker: ~2016

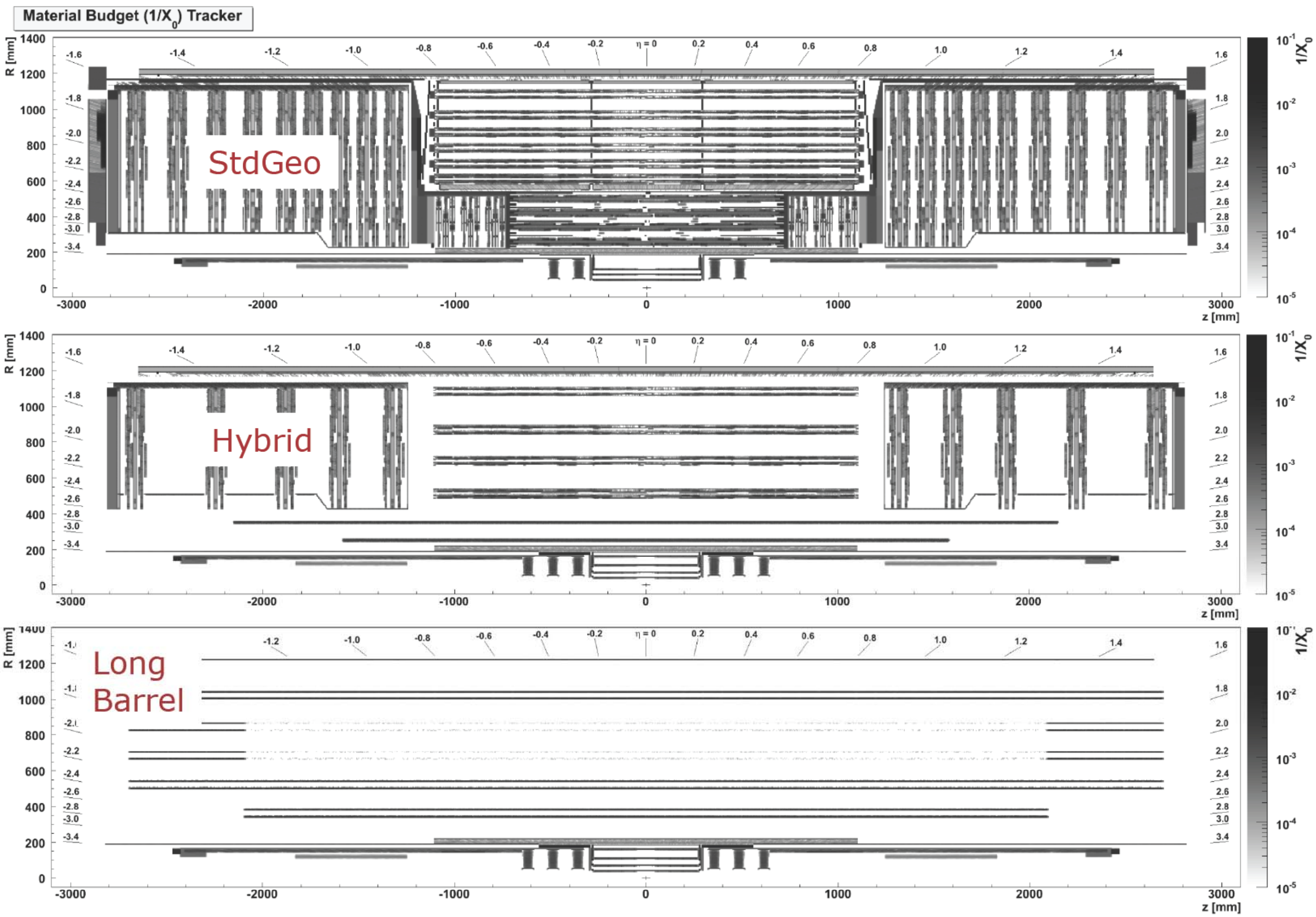


- **Pixels:** 4 pixel layers, 6 pixel disks 3.7-20.9 cm
- **Strips**: 5 barrel layers: between 38 and 95 cm
  - 3 inner layers: SHORT STRIPS: 24 mm long
  - 2 outer layers: LONG STRIPS: 96 mm long
  - 5 double sided disks on each End-Cap

Vigorous (frenzied?) R&D programme to find appropriate radiation-hard technologies for these detector replacements

“High Luminosity LHC” Upgrades

- CMS: alternative tracker designs, incorporating L1 Track Trigger

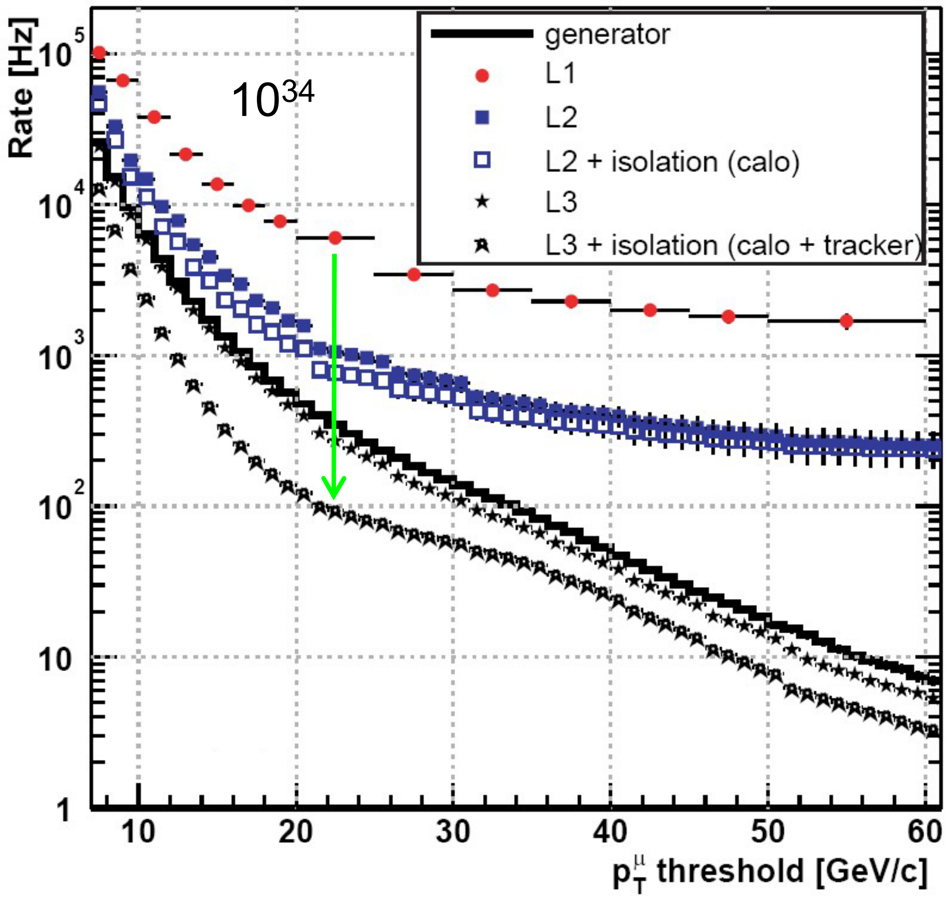


2016: work toward increased performance (resolution, granularity) with dramatically reduced material budget

(also planning phased pixel upgrade: 2014)

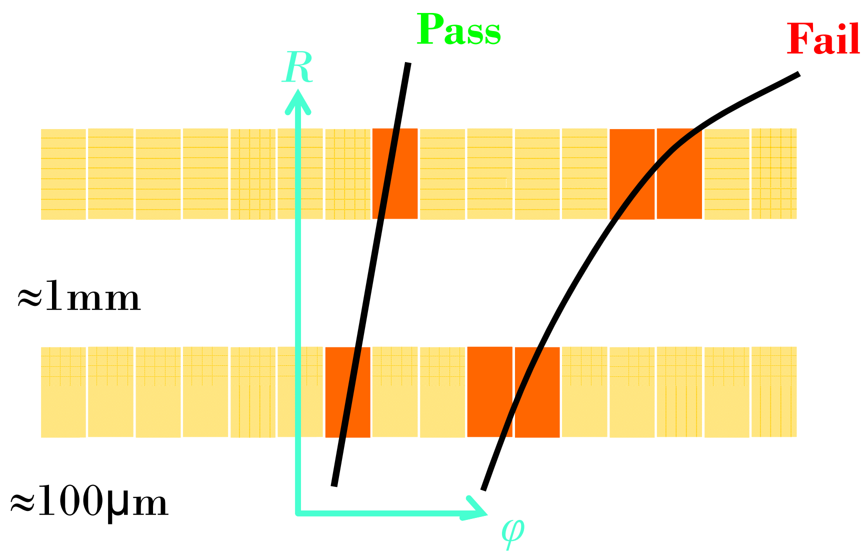
Track Triggering with Silicon?

- The problem:



- L1 muon trigger rate plateaus, will be 200kHz at L = 10^{35}
- combining track information: x100 reduction
- Need a track trigger at L1

- A solution?
  - closely spaced layers with "big" pixels (100μmx1mm?) can provide local momentum measurements



  - the hard part is building the readout infrastructure to service such a large channel count at the requisite speeds

Conclusions

- Tracking is a rich and complex field
  - nearly always at the edge of the technically-possible
    - advances in tracking technology have done more to drive the advances in detector capability (and, hence, discovery) than any other technology
      - rate & resolution are both key
  - explosion of new detector techniques
  - have nearly realized the electronic 25ns bubble chamber
  - many design challenges remain for high-luminosity high-radiation regimes
- Always a shortage of experts
  - good way to insure indefinite employability

Go out and Track!

Bibliography

- The LHC Experiments:
  - Tracker TDRs for each of the experiments
    - a wealth of information, references
  - Detector performance papers
  - Compendium of talks by each of the experiments
    - most lists are searchable by detector group, or “upgrade”
      - lots of technical information from special topical conferences
- The Tevatron Experiments
  - slightly less well-documented, but NIM papers, technical talks available
- General books about particle detectors
  - W. R. Leo – “Techniques for Nuclear and particle Physics Experiments”
  - K. Kleinknecht – “Detectors for Particle Radiation”
  - C. Grupen – “Particle Detectors”
  - G. Lutz – “Semiconductor Radiation Detectors”
  - W. Blum, W. Riegler, G. Rolandi – “Particle Detection with Drift Chambers”
- The PDG, and references within
- Past lectures in this (and other) series