Tracking in CMS

Under short notice, for the CMS tracking group,

Jean-Roch Vlimant

Acknowledgment and References

Material taken from K.Burkett, A.Dominguez,
B.Mangano, D.Stuart.

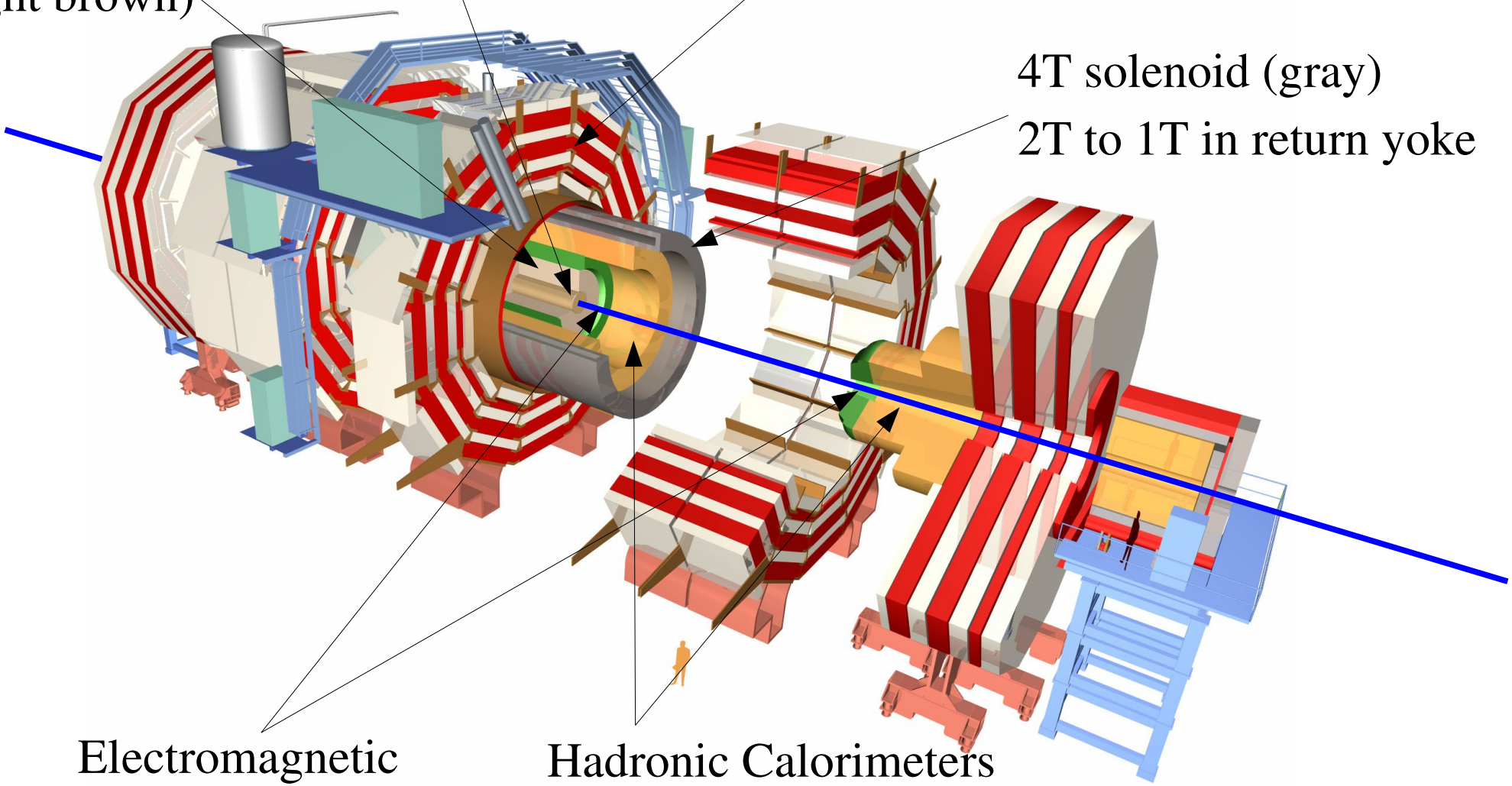
"CMS Physics TDR Volume I", 2006

"The CMS experiment at the CERN LHC", 2008
JINST 3 S08004

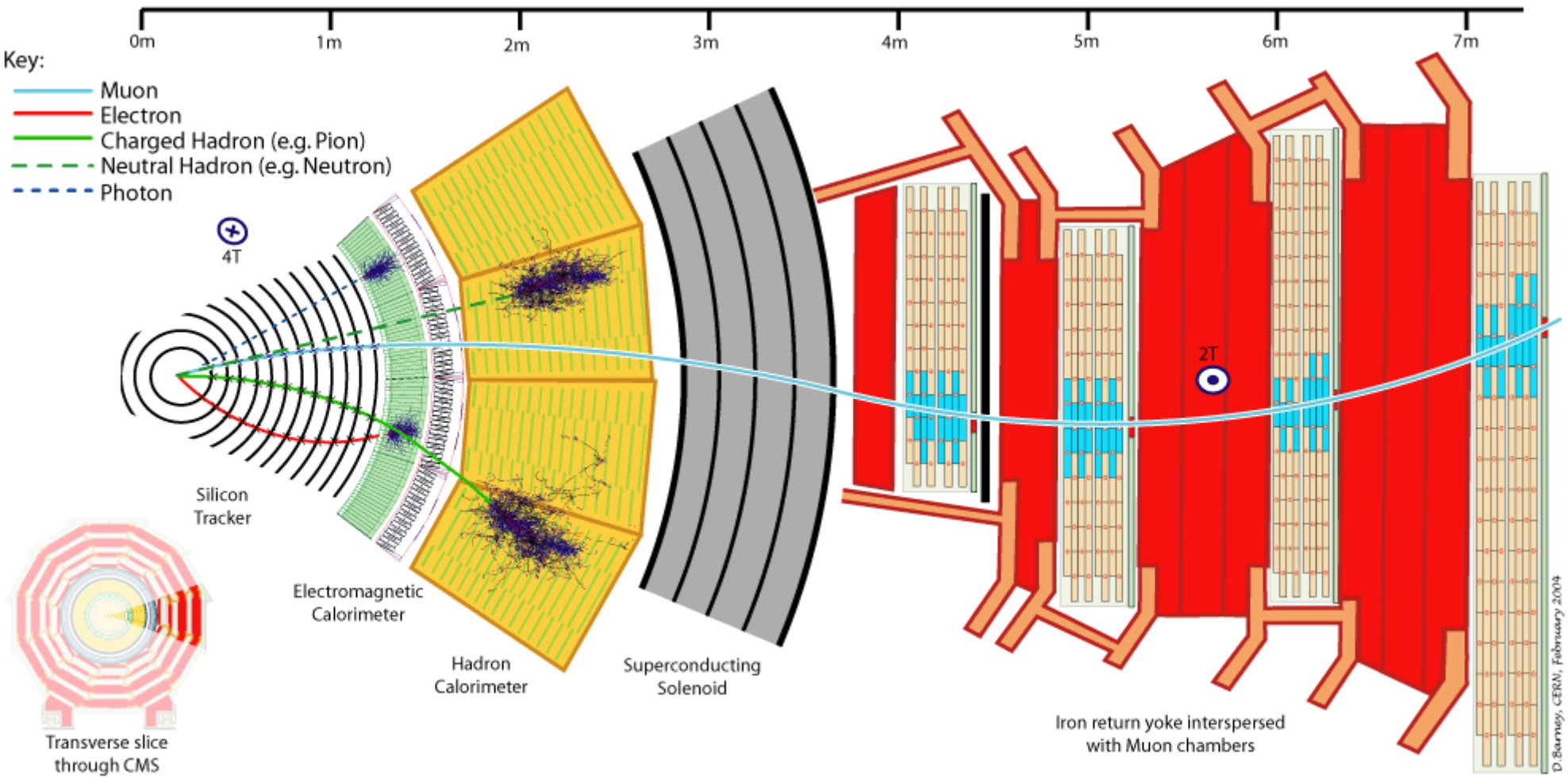
Outline

- Overview of the Inner Tracking System
- Principles of Track Reconstruction
- Track Reconstruction in CMS
- Performances with Cosmic Tracks
- Summary

The CMS Detector



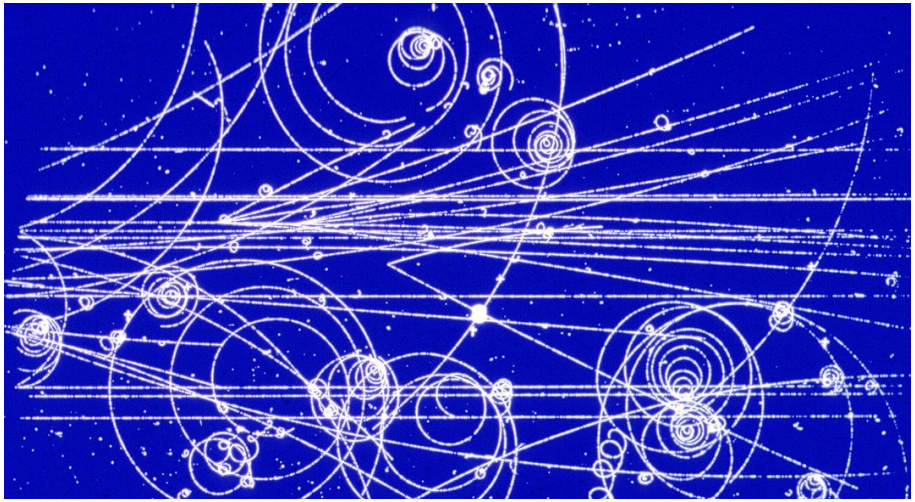
Particle Journey Through CMS

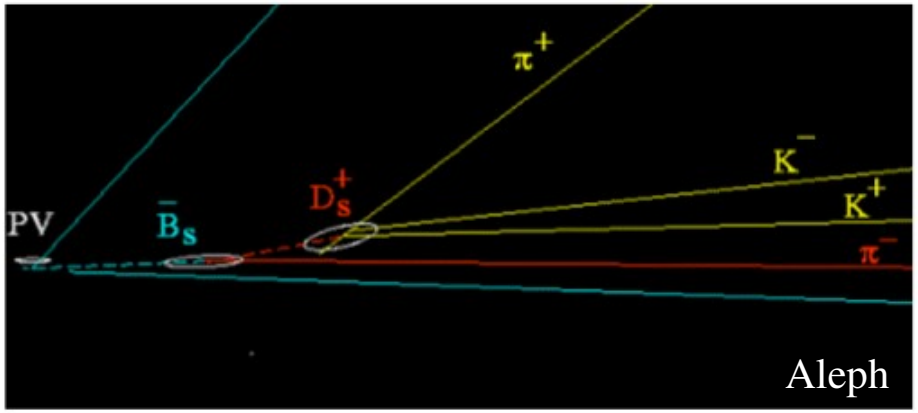


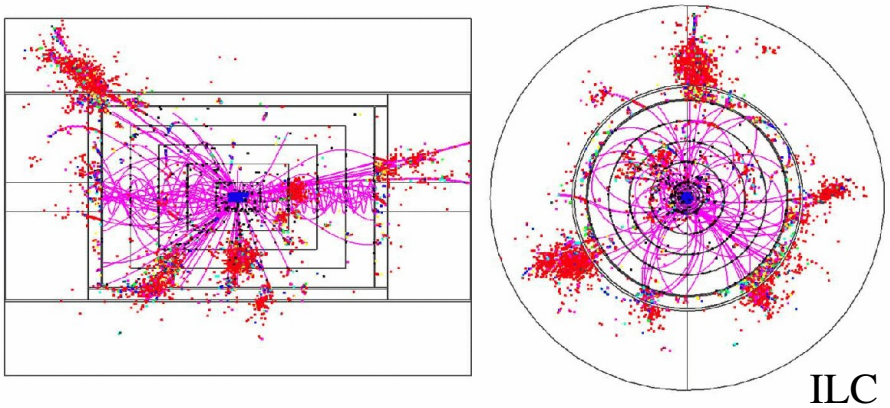
The muon system is a tracking detector too.
Will concentrate on the silicon tracker in this talk.

Track Reconstruction in HEP

- Essentially reconstruct the paths of charged particles.
- With magnetic field bending : aim at measuring the momentum of particles
- Determine the interaction point (primary vertex) and particle decays (secondary vertex)
- Confirm/complement reconstruction from other sub-detector: track-jets, tau decay track multiplicity, muon global fit, photon track veto, particle flow,...



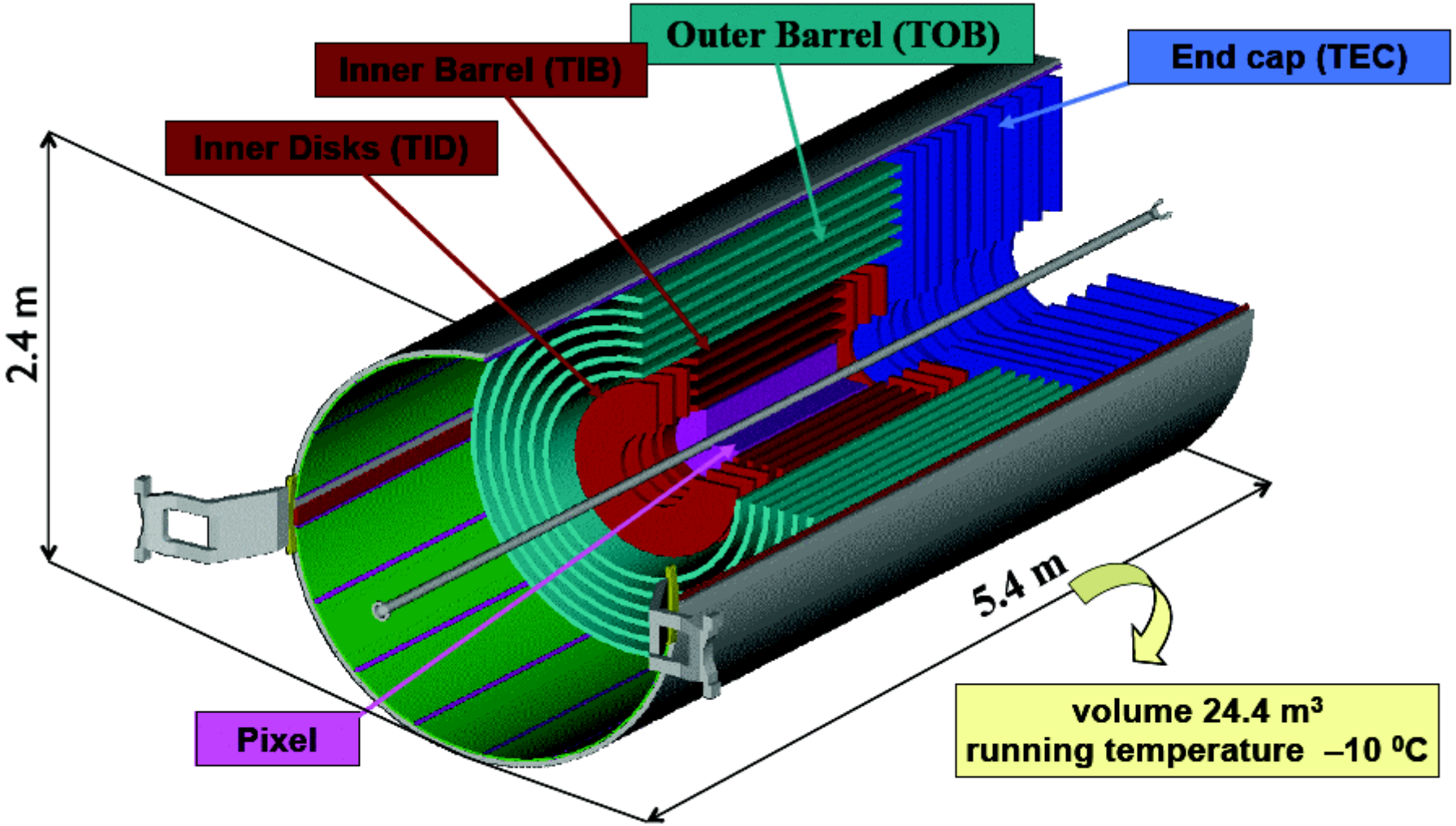




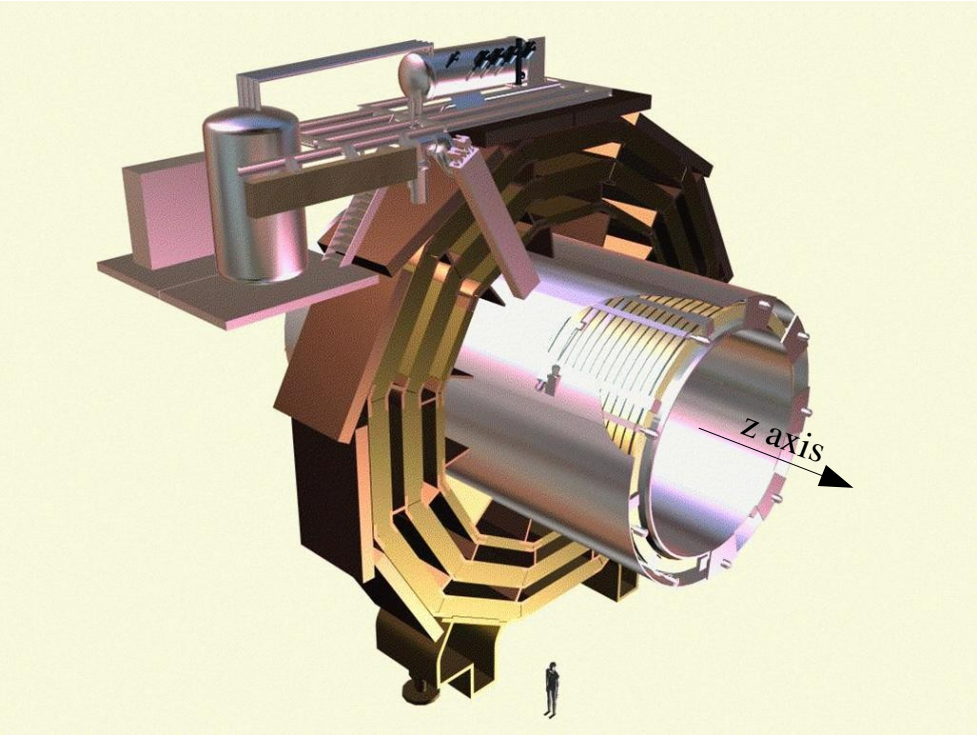
Overview of CMS Inner Tracker

"The CMS experiment at the CERN LHC", 2008 JINST 3 S08004

http://www.iop.org/EJ/journal/-page=extra.lhc/jinst

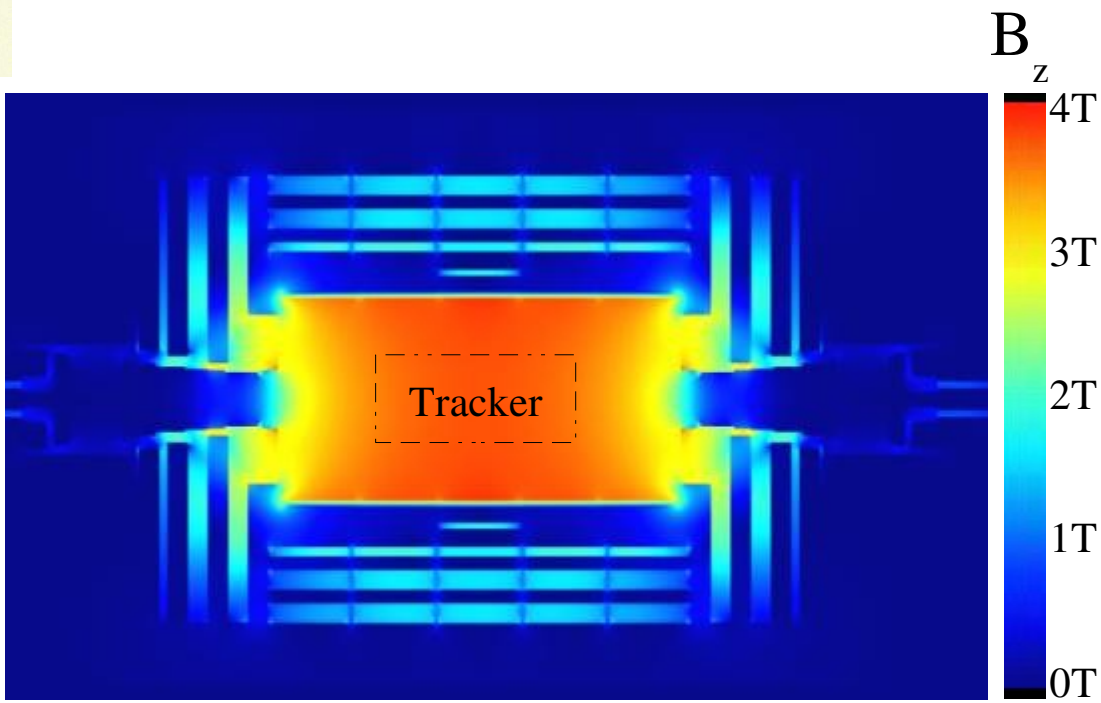


CMS Solenoid

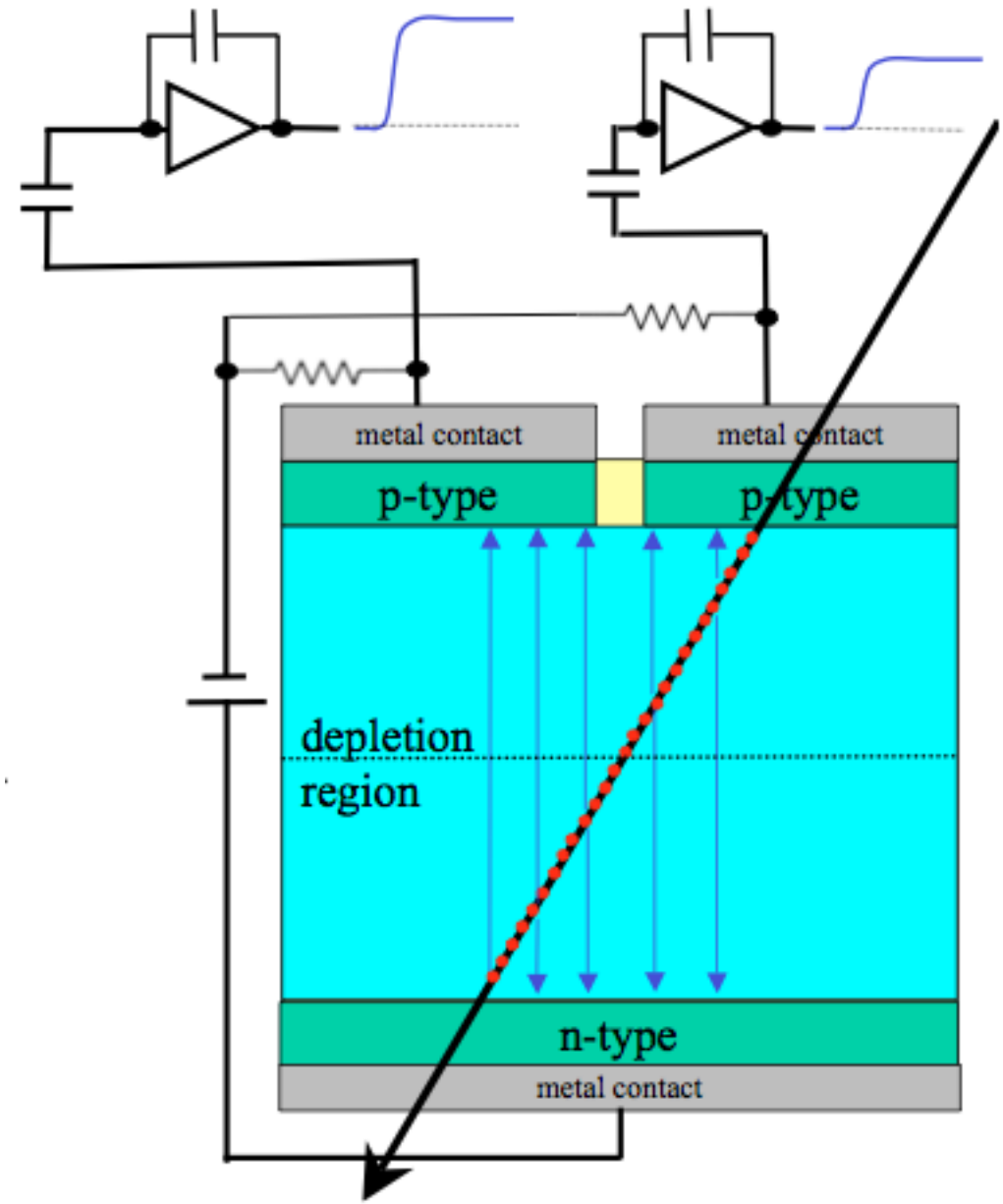


- Original design for CMS
  - Contains the calorimeters
- Largest super-conducting solenoid
  - 200 t at 4.5K with liquid Helium
  - 4T over ~1400 m^3
  - 2.7 GJ stored energy

- Inner magnetic field mostly uniform in tracker volume
- Slightly not uniform in end-caps
- Return flux channeled in the yoke



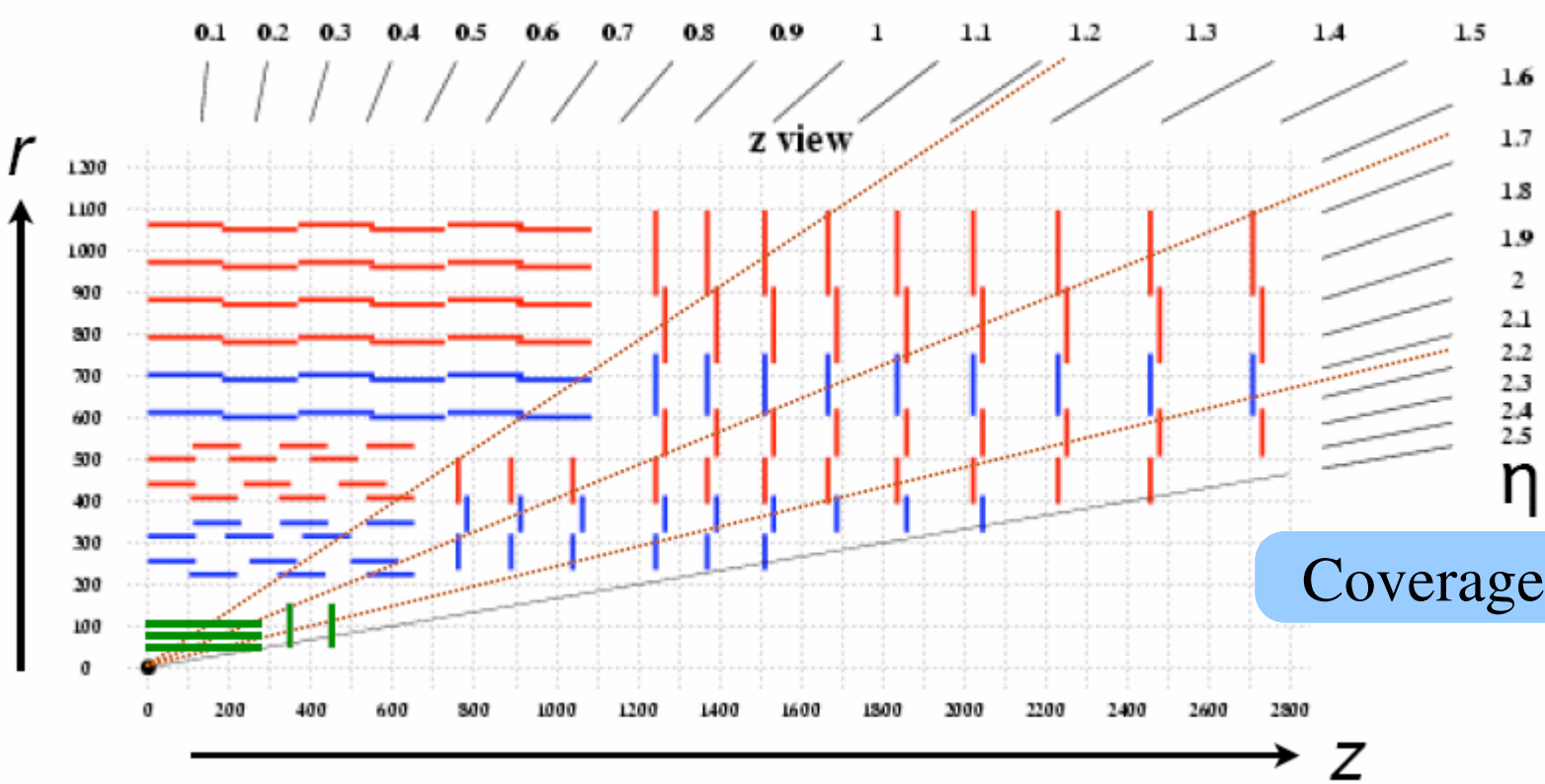
Silicon Detector Technology



- p-n diode under reverse bias.
- Large depletion rejection free of charge carrier.
- Ionization from charged particles creates a current in the diode.
- Amplification in electronics only.
- Pulse integration gives total ionization charge

- Shape of metal contact
  - Thin rectangle: **strip detector**.
  - Square: **pixel detector**.
- Compromise on thickness for total charge and material effects.

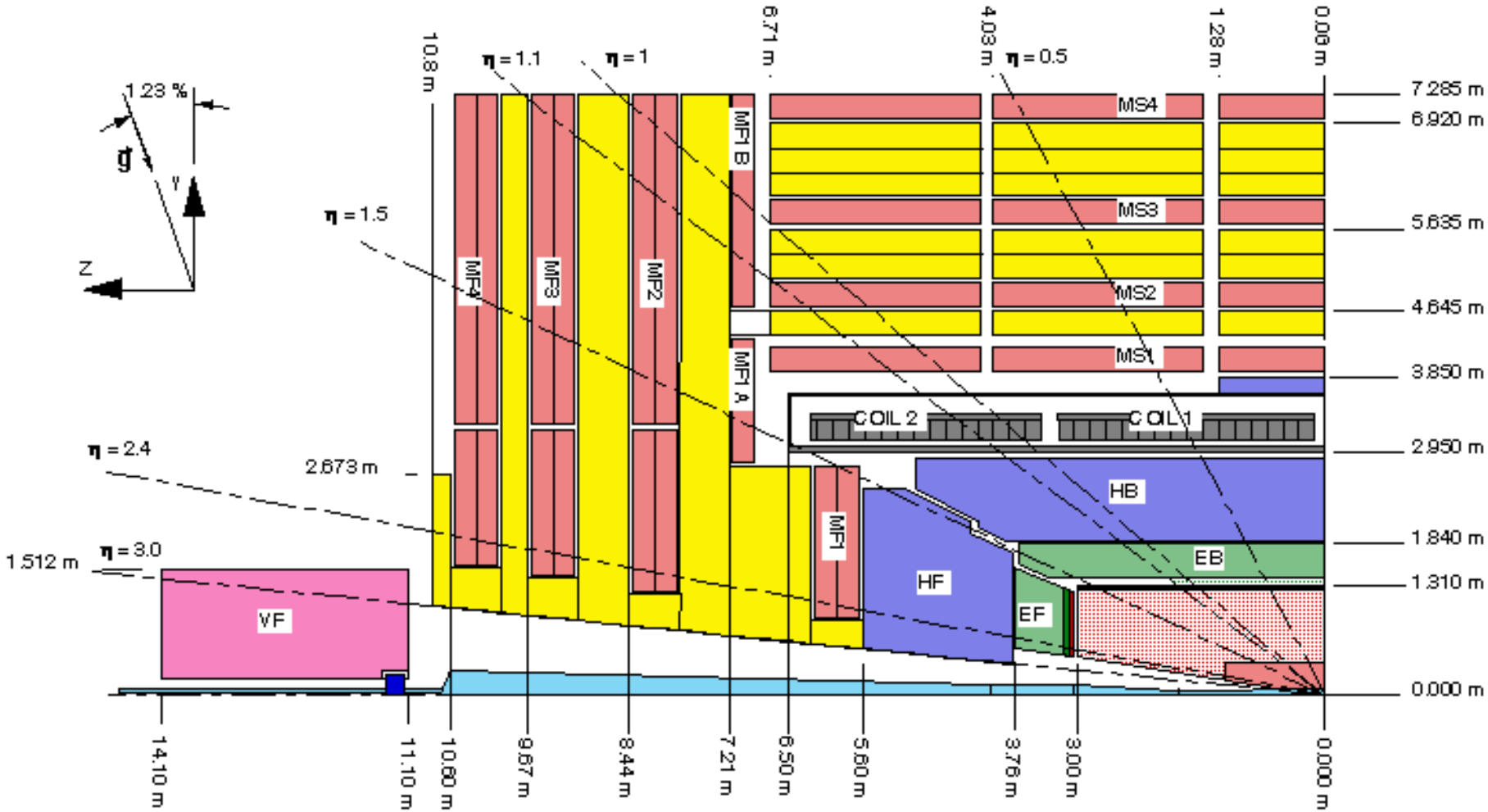
CMS Tracker Layout



Coverage up to 2.5

- **Pixel layers, 3D measurements (green)**
- **Double sided strip modules, 3D measurements (blue)**
- **Single sided strip modules, 2D measurements (red)**

CMS Coverage

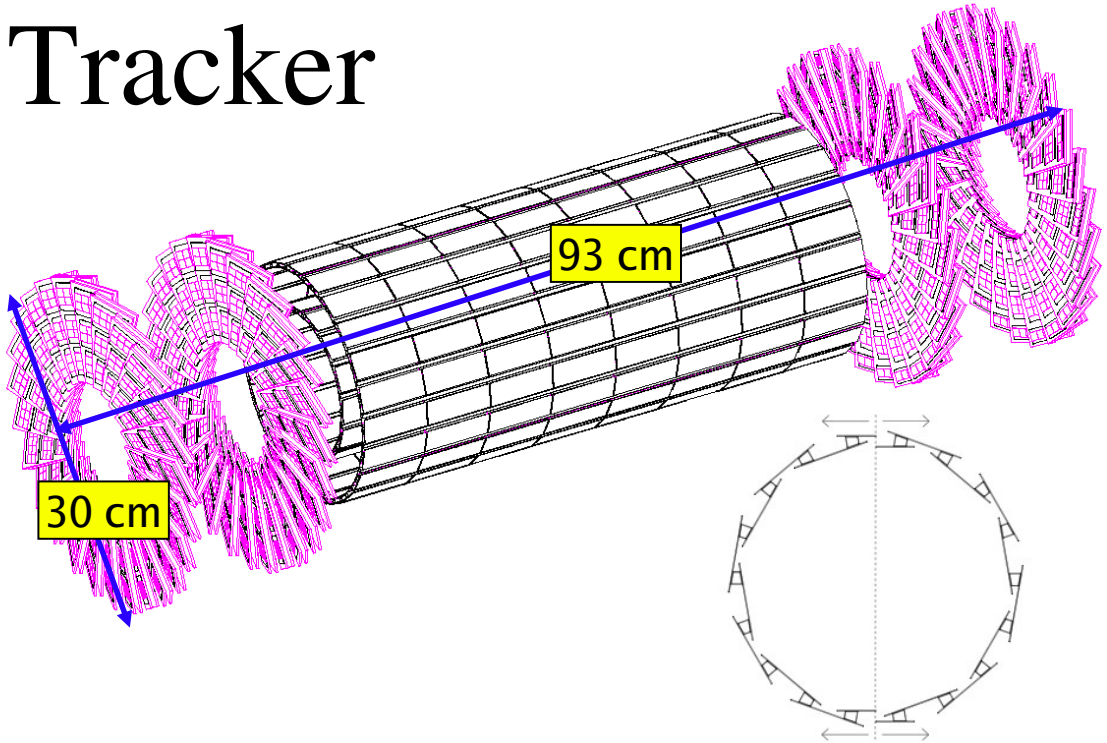


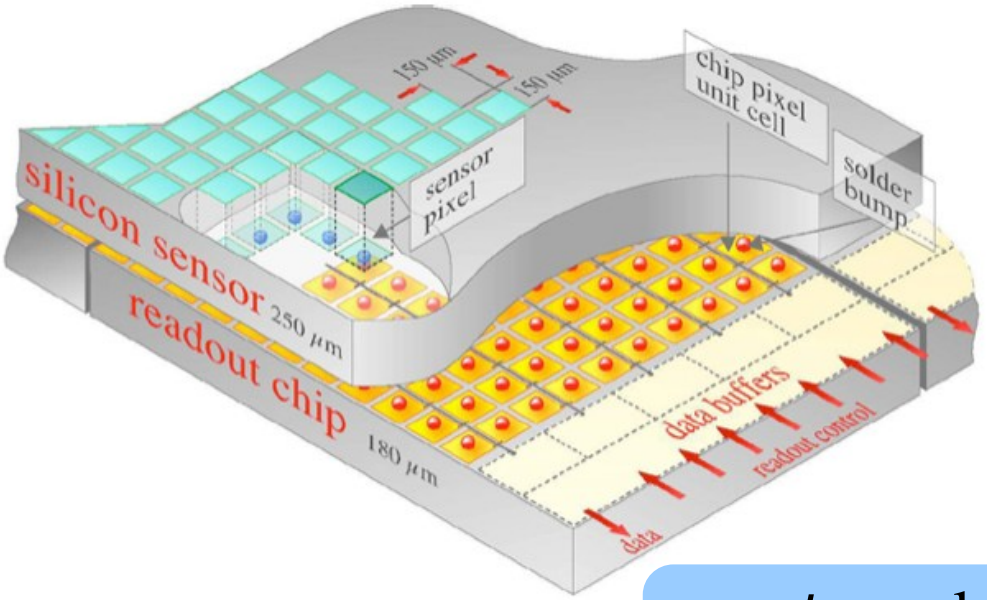
Tracker covers up to 2.5.

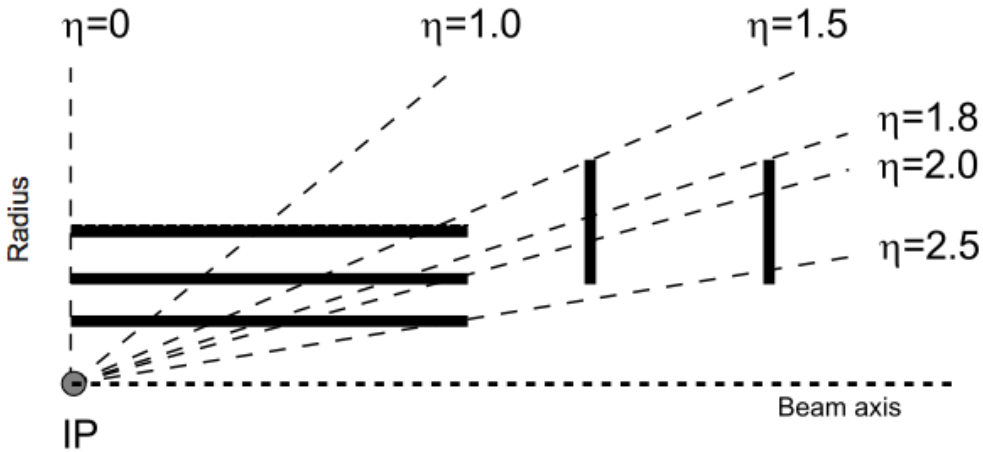
Hardly any detector after that anyways.

Pixel Tracker

- 3 barrel layers at r=4, 7, 11 cm
  - Overlapping in phi
- 2 disk on each side at z=34, 46 cm
  - Room for an extra one at 59 cm
  - Modules tilted by 20° for charge sharing
- Pixel of size 100 μm x 150 μm
- 250 μm sensor thickness
- 48M+18M channels (1m^2)



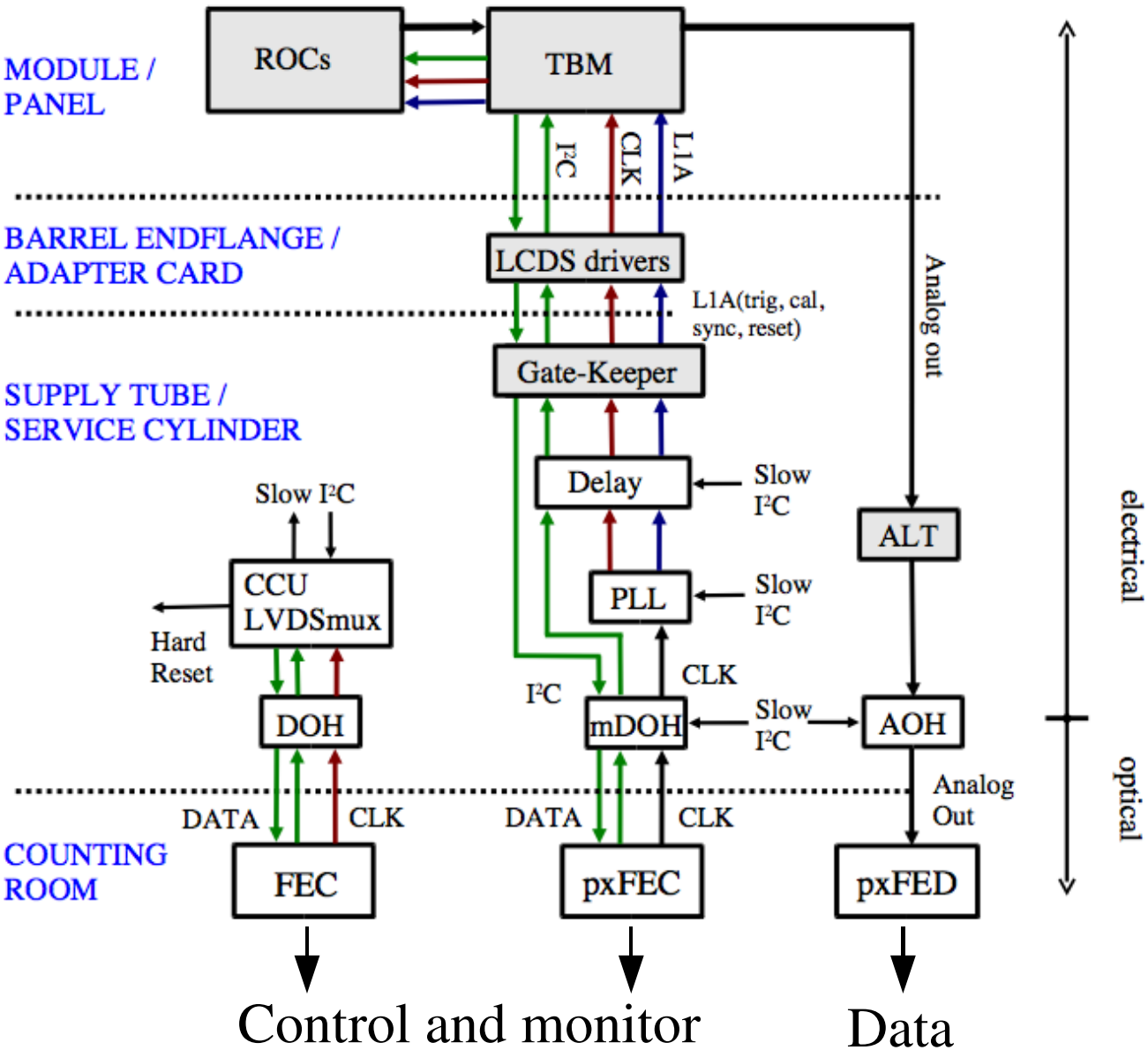




r-ϕ resolution 10 μm

r-z resolution 20 μm

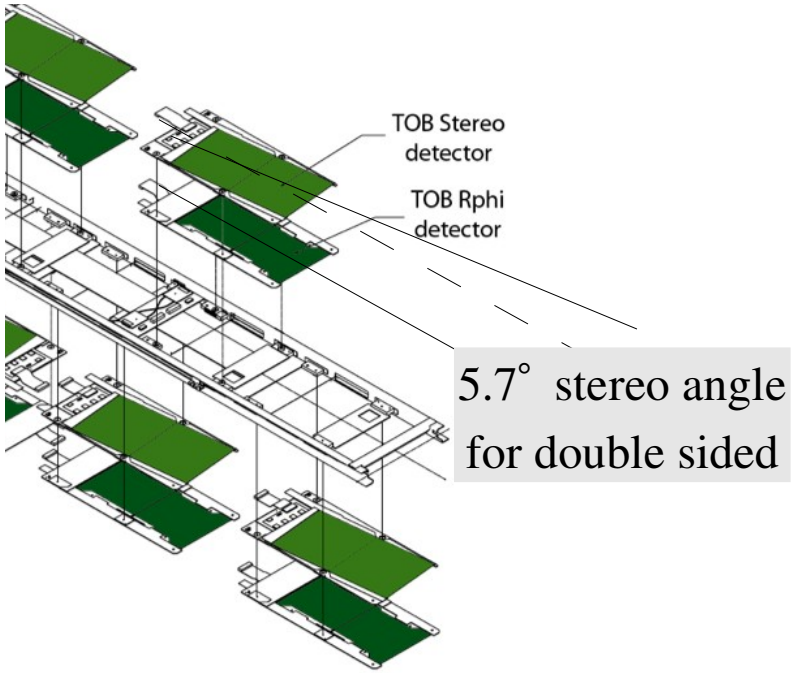
Pixel Tracker Read-Out

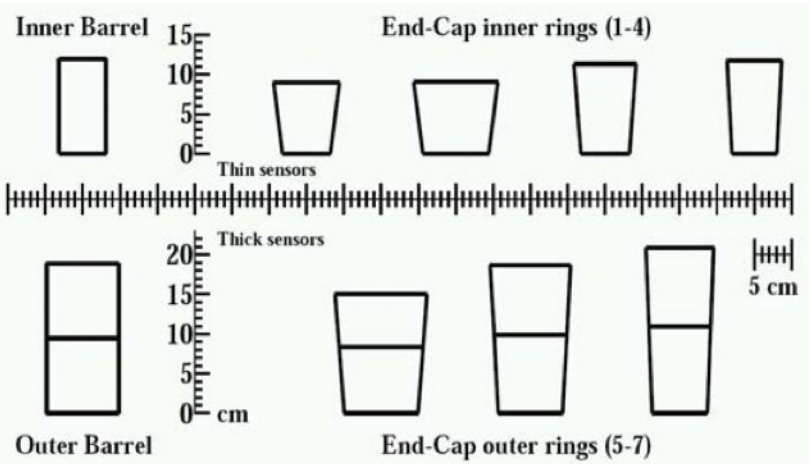


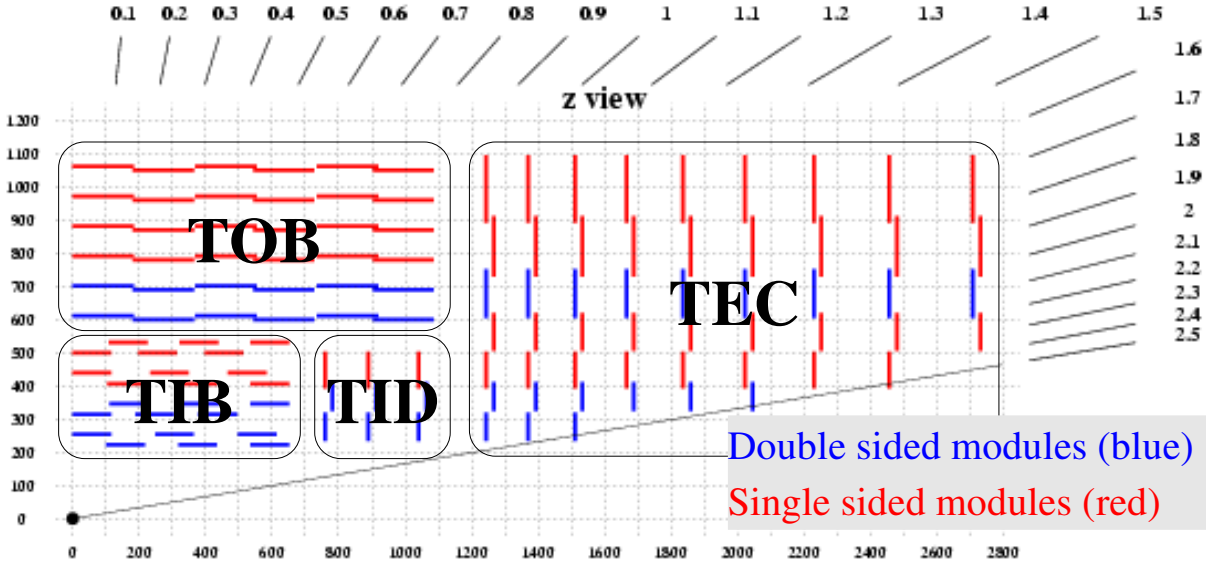
- Amplification, buffering and zero suppression done in the Read-Out Chip (ROC).
- Token Bit Manager (TBM) groups 8/24 ROCs.
- Analog signal from TBM send to FED via optical fibers.
- Trigger, clock and chip configuration send to TBM via FEC using optical fibers.

Micro Strip Tracker

- 10 barrel layers up to r=110 cm
  - 4 inner barrels (TIB), 9° tilt
  - 6 outer barrels (TOB)
- 12 disk on each side up to z=275 cm
  - 3 inner (TID)
  - 9 end cap (TEC)
- Strip of pitch 80 μm to 200 μm
  - Adaptable pitch in disks
- Strip length 10 to 20 cm
- 320 μm or 500 μm sensor thickness
- ~50% double sided modules
- 9.3M channels (200 m^2)

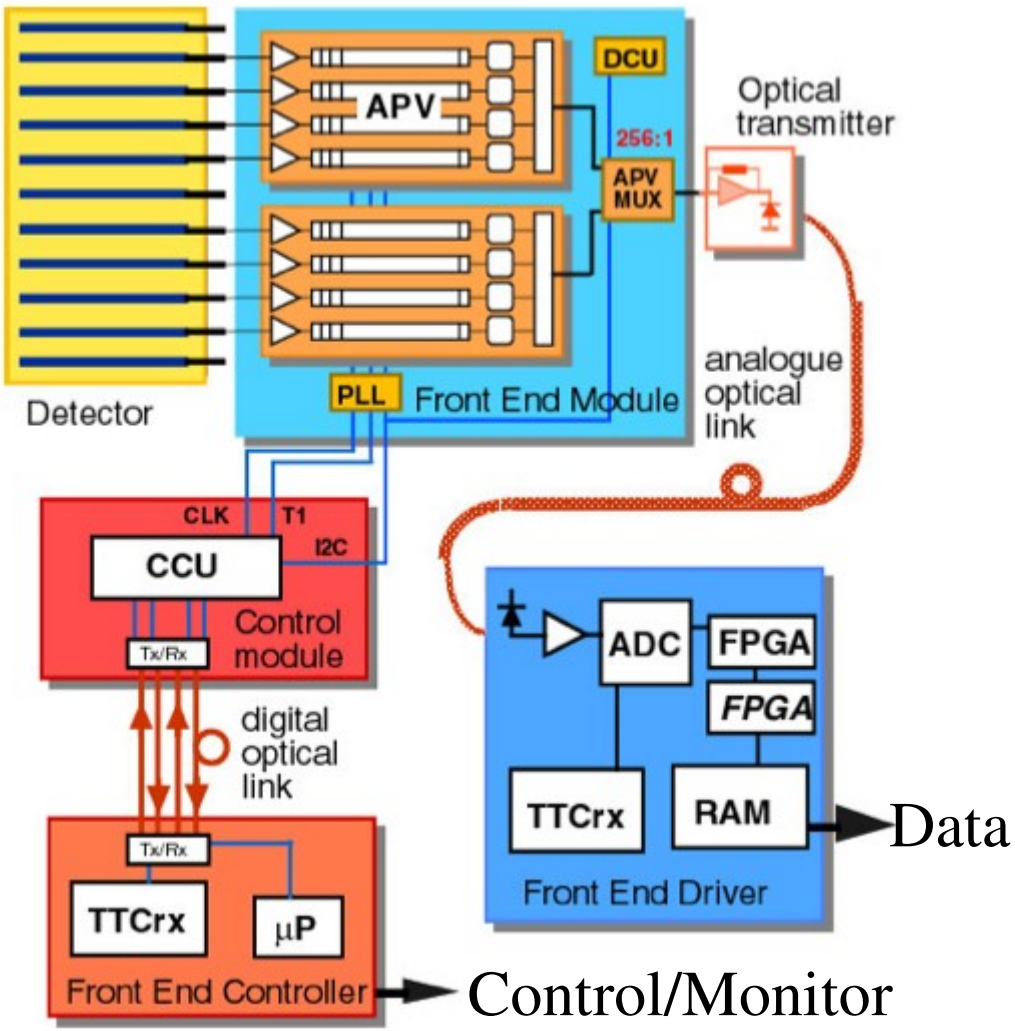






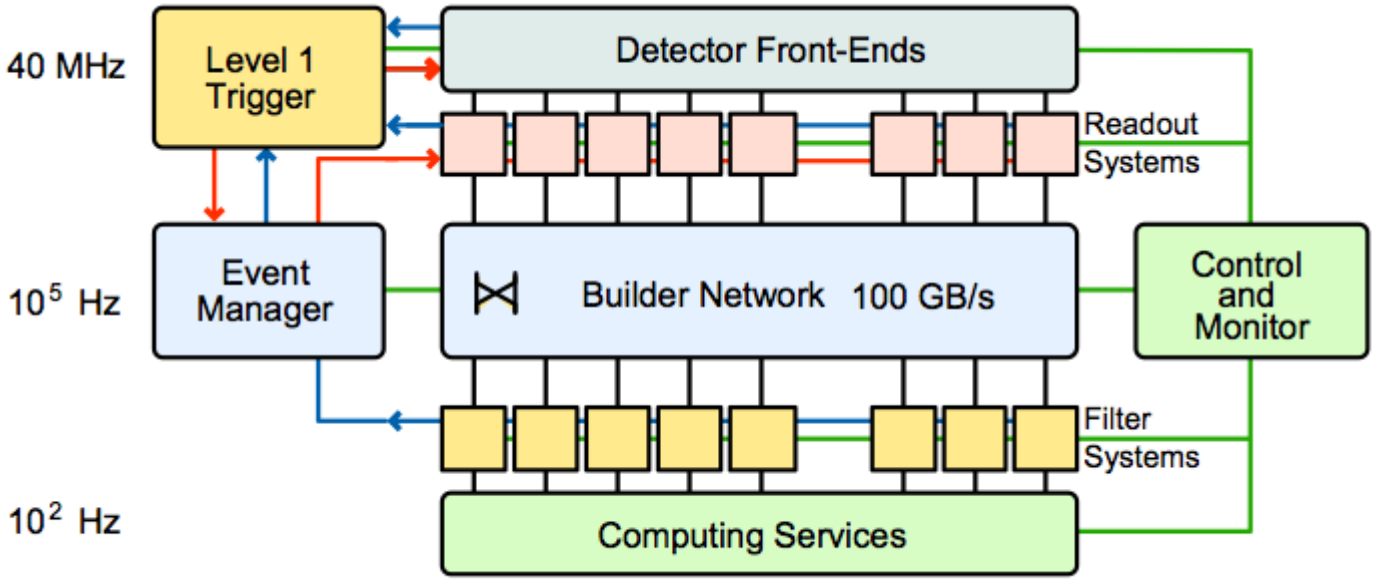
r-ϕ resolution 8 μm to 64 μm

Micro Strip Tracker Read-Out

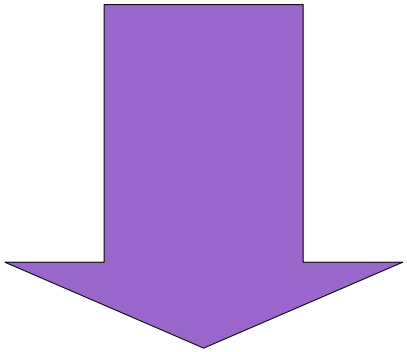


- Amplification, buffering and shaping done in the APV
- Signal send out to front end driver (FED) through optical fibers upon L1 decision (n.b. L1 does not use tracker)
- Temperature, currents, low voltages... are monitored via front end controller (FEC)
- Clock, trigger, gains,... are set via the FEC using optical fibers.

CMS DAQ System

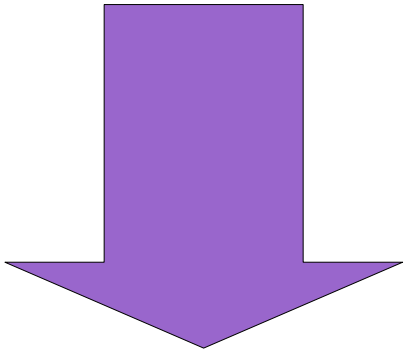


sub-detector	number of channels	number of FE chips	number of detector data links	number of data sources (FEDs)	number of DAQ links (FRLs)
Tracker pixel	≈ 66 M	15840	≈ 1500	40	40
Tracker strips	≈ 9.3 M	≈ 72 k	≈ 36 k	440	250 (merged)
Preshower	144384	4512	1128	56	56
ECAL	75848	≈ 21 k	≈ 9 k	54	54
HCAL	9072	9072	3072	32	32
Muons CSC	≈ 500 k	≈ 76 k	540	8	8
Muons RPC	192 k	≈ 8.6 k	732	3	3
Muons DT	195 k	48820	60	10	10
Global Trigger	n/a	n/a	n/a	3	3
CSC, DT Track Finder	n/a	n/a	n/a	2	2
Total	≈ 76M			626	458



Done with Tracker Hardware.

Move on to Track Reconstruction.



Principles Of Track Reconstruction

A) Pattern Recognition

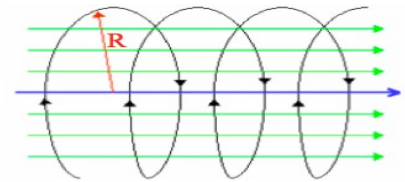
- Collect hits compatible with a particle crossing the detector.

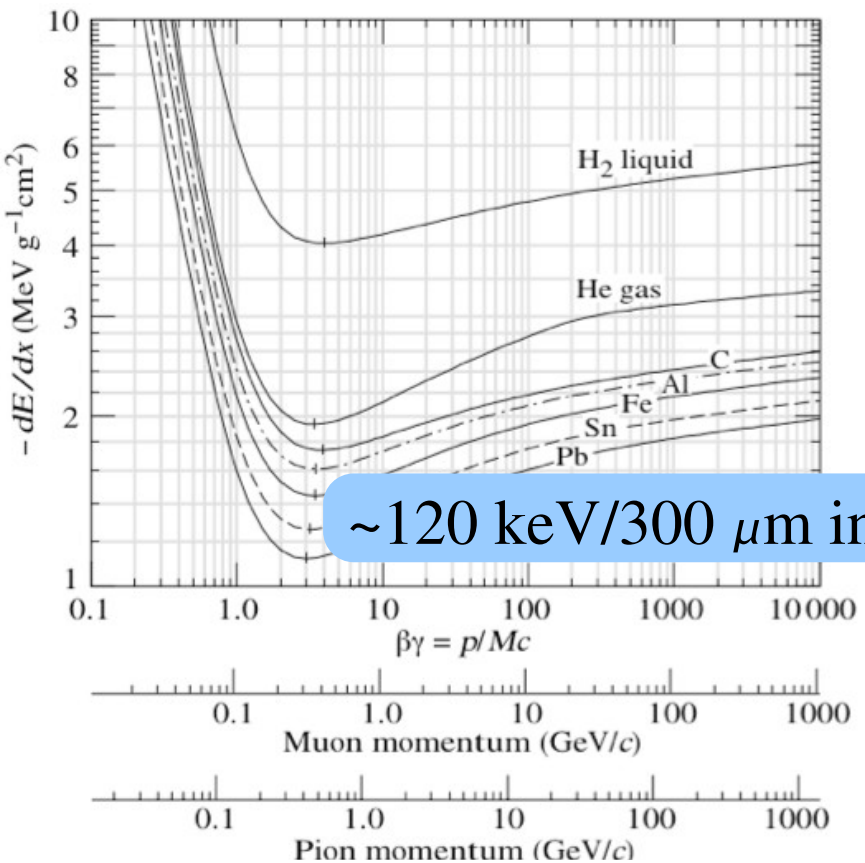
B) Final Fit

- Determine precisely the initial particle 3-vector.

Ideal Case

Charged particle in uniform magnetic field: helix. $p_T \simeq 0.3\ B\ R$





~120 keV/300 μm in Si

Realistic Scenario

- Particle looses energy in material (dE/dx)
- Particle scatters (multiple scattering)
- Magnetic field is not uniform.

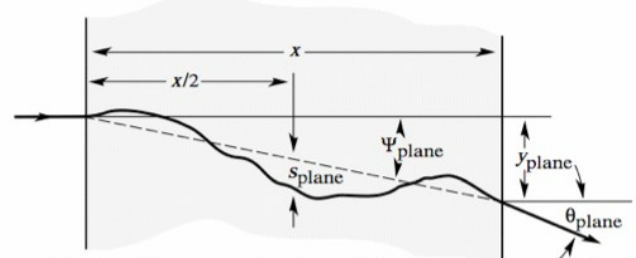
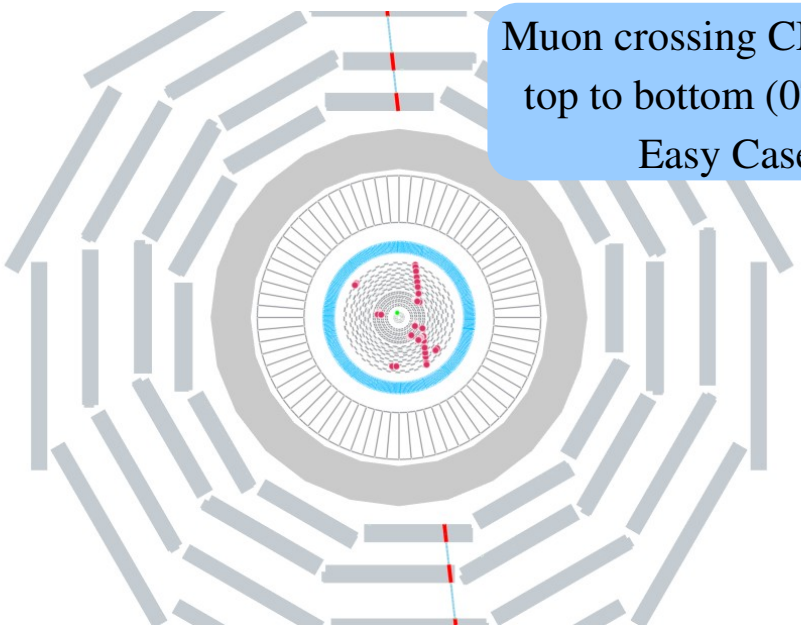


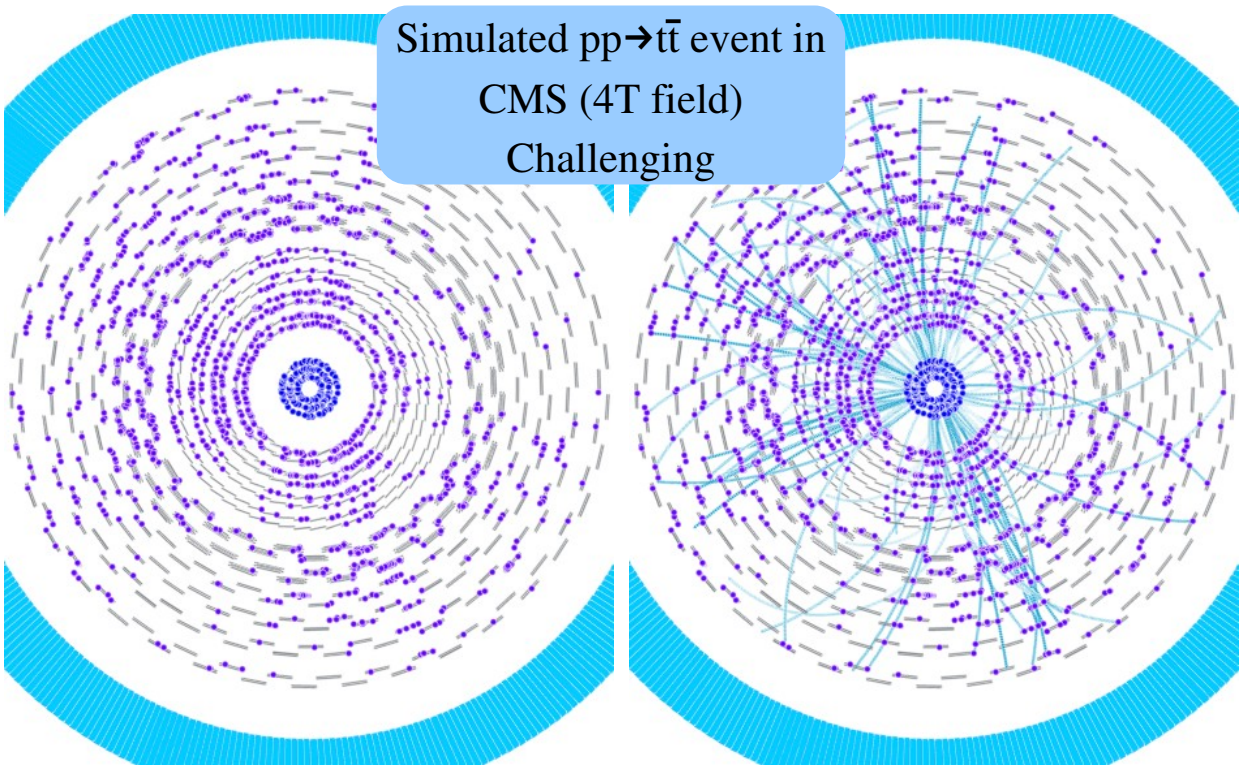
Figure 27.9: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

600 μm.GeV/300 μm per m in Si

Pattern Recognition



Muon crossing CMS from top to bottom (0T field)
Easy Case



Simulated pp→$t\bar{t}$ event in CMS (4T field)
Challenging

<u>Possible approaches</u>

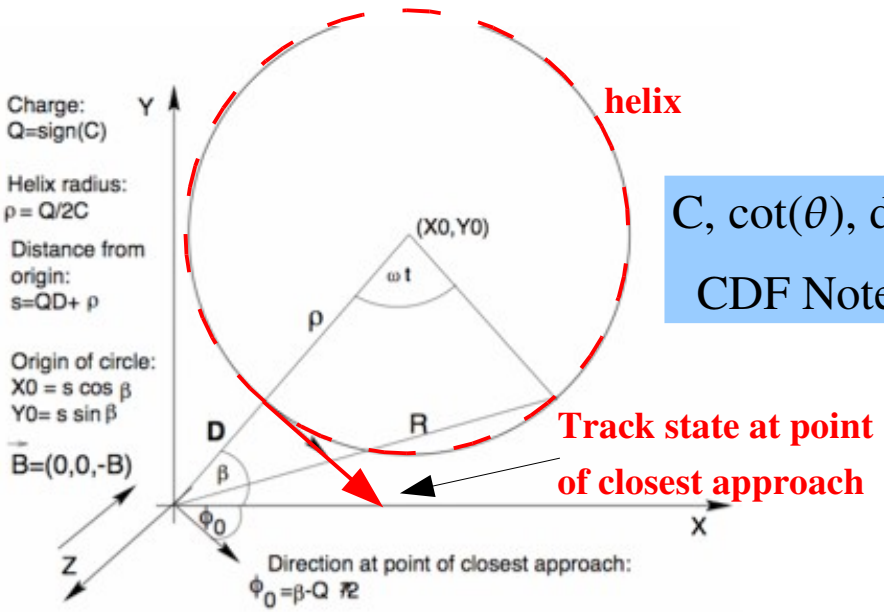
- Hit combinatorics.
- Pattern matching.
- Space transform.
- Constraint seeding.
- <your idea here>

Final Fit

Particle trajectories are helix locally and track parameters are given at a reference locus

⇩

Track parameters ≡Helix Parametrization.



C, $\cot(\theta)$, d_0, ϕ_0, z_0

CDF Note #1790

Helix Description = 5 parameters.

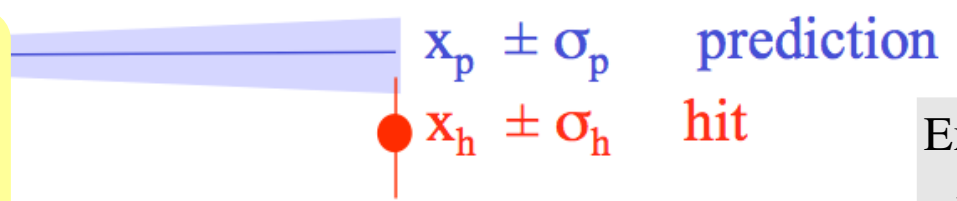
Different 5-parameter sets exist depending on the purpose:

- Curvilinear parameters ($q/|p|$, λ, ϕ, x_T, y_T)
- Perigee parameters (ρ, θ, ϕ, d_0, z_0)
- CMS tracks ($q/|p|$, λ, ϕ, d_0, z_0)
- ....

Helix only locally, no analytical function to fit to the hits.

⇒Recursive fitting ,Kalman Filtering

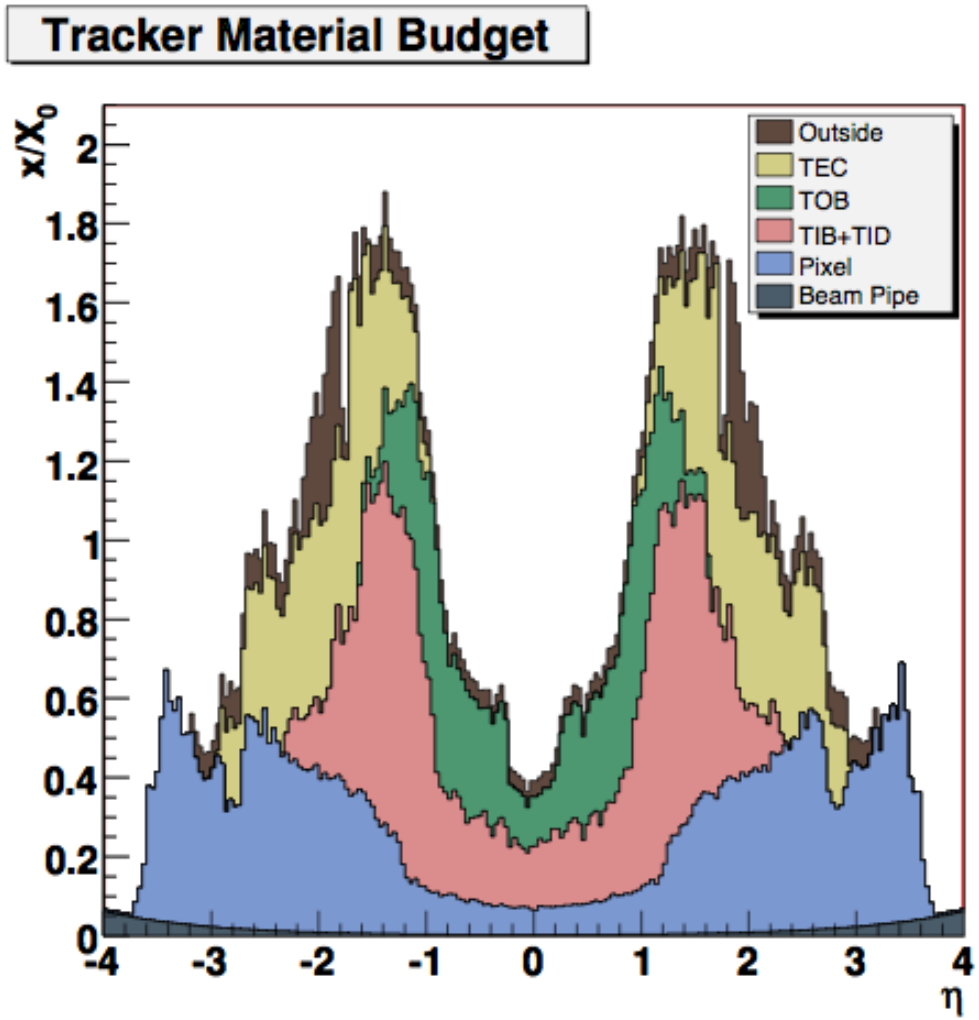
"prediction" takes into account dE/dX and Multiple scattering.

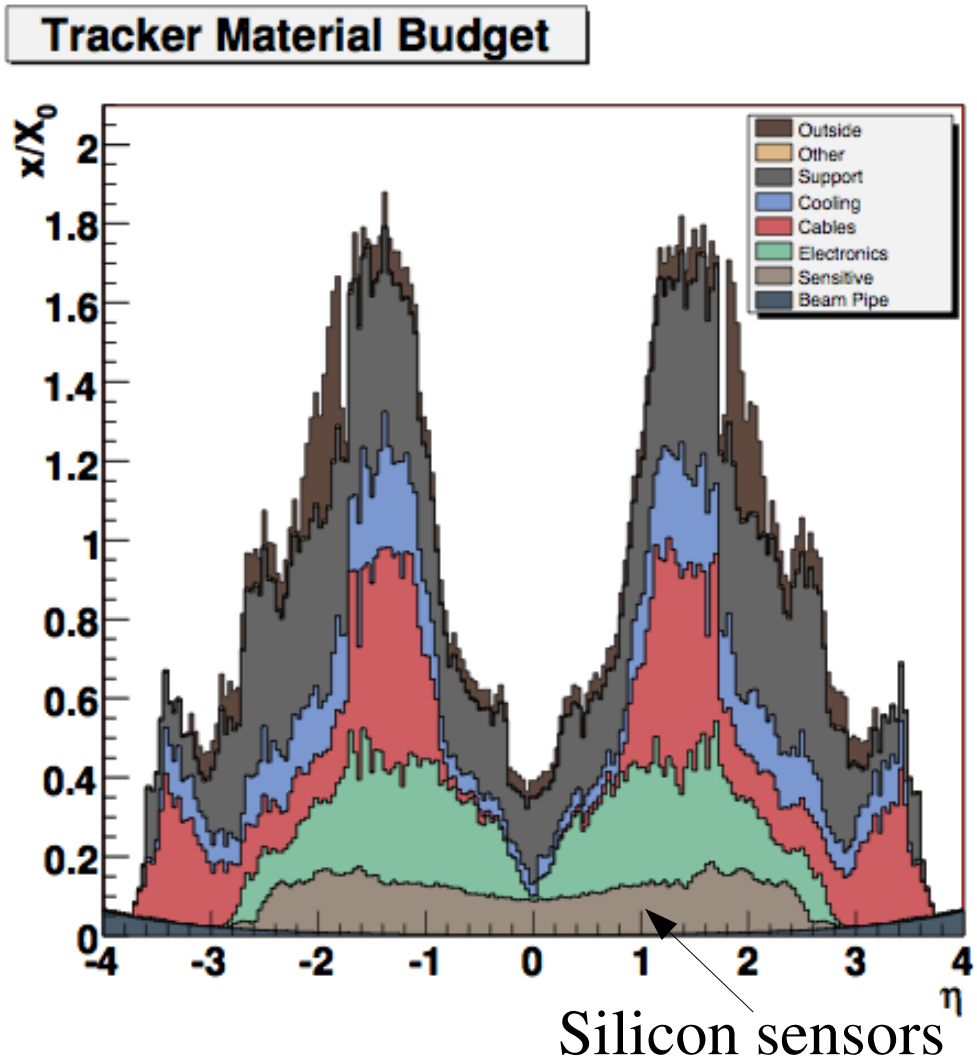


Example in 1D

$$\text{New } x = \frac{(x_p / \sigma_p^2) + (x_h / \sigma_h^2)}{(1 / \sigma_p^2) + (1 / \sigma_h^2)} = \text{weighted average}$$

Tracker Material

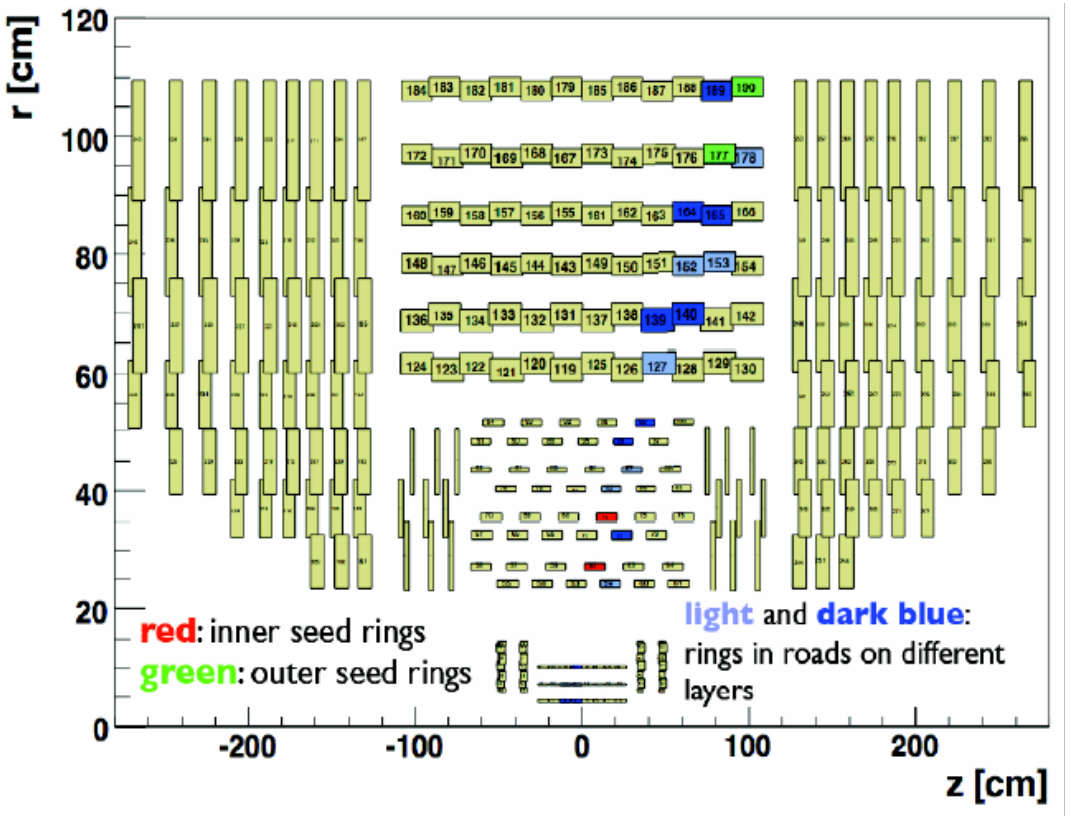




Significant amount of material. Mostly structure and cabling. Plays a significant role in track fitting and also has to be taken into account during pattern recognition.

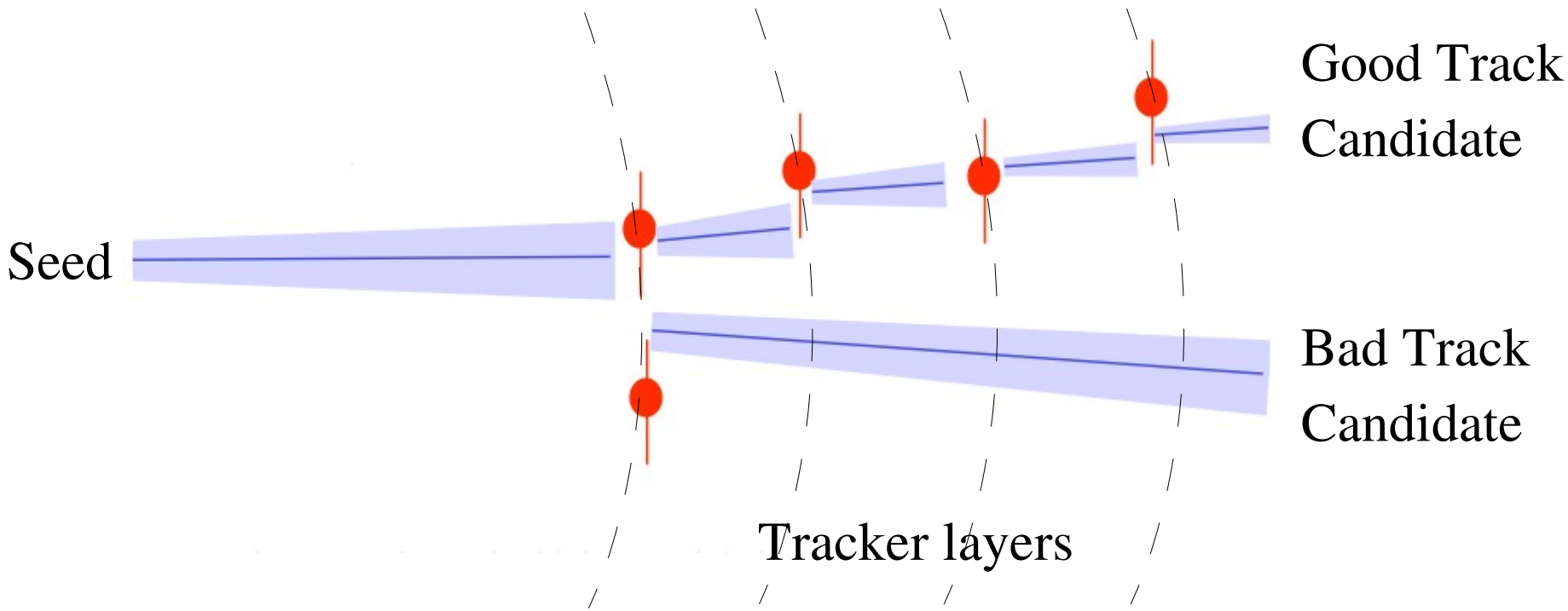
Road Search Track Reconstruction

- "Road" between inner and outer locations pre-calculated with charge and transverse momentum assumption.
- "Cloud" of reconstructed hits collected in the road
-

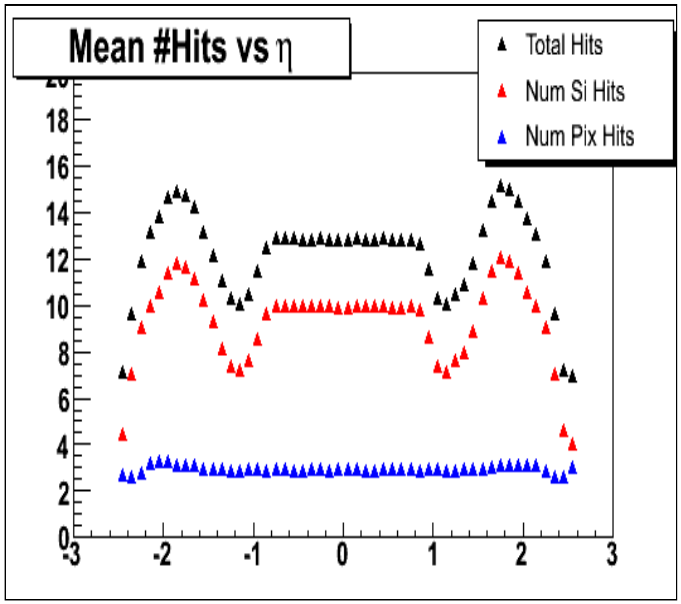


Combinatorial Track Finder (CTF)

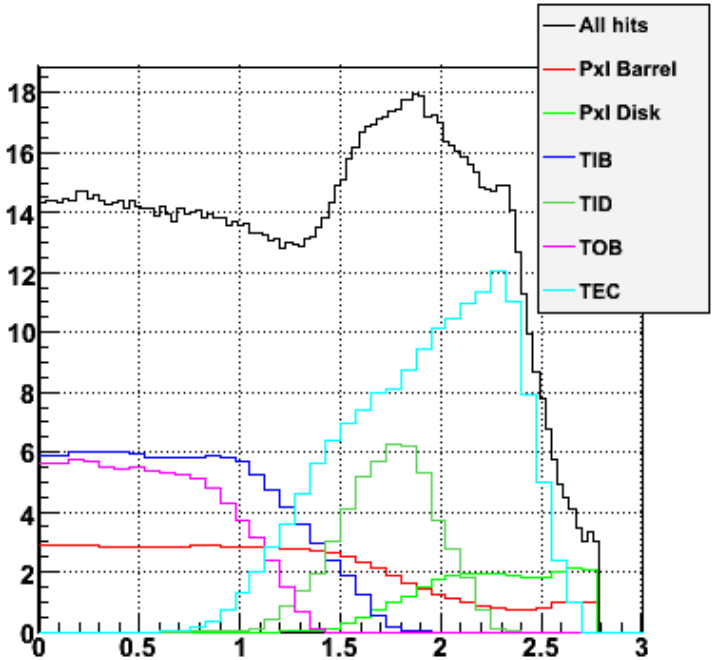
- Starts from a couple of hits (seed) with a very rough estimate of track parameters.
- Propagate to successive crossed tracker layer and search for compatible hits.
- Use Kalman update procedure at each step to determine new estimated track parameters.
- Repeat until stopping conditions are reached.

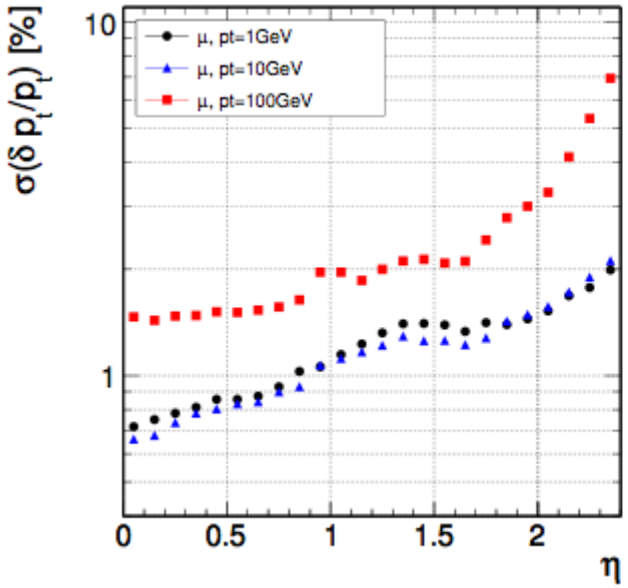


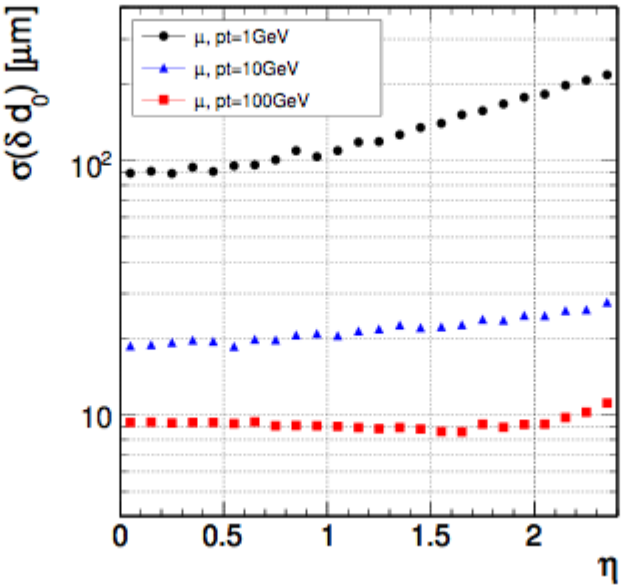
Predicted Performance

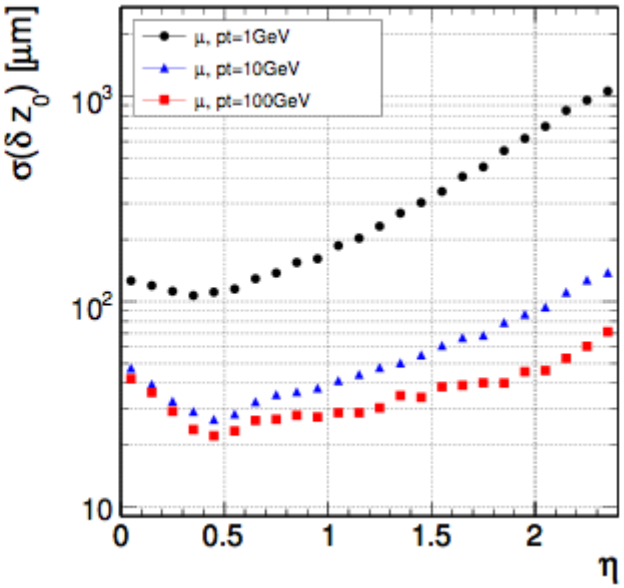


- Few but precise tracker layers
- Module overlap and stereo layers increases the number of measurement points





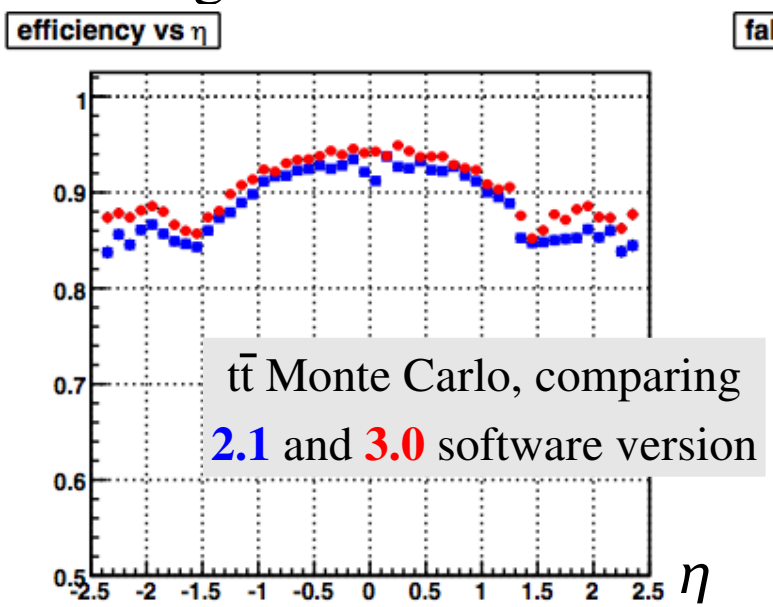


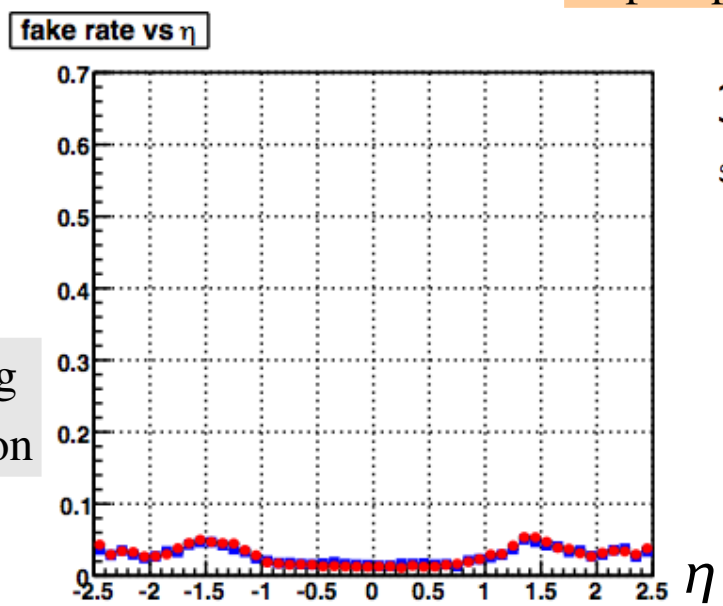


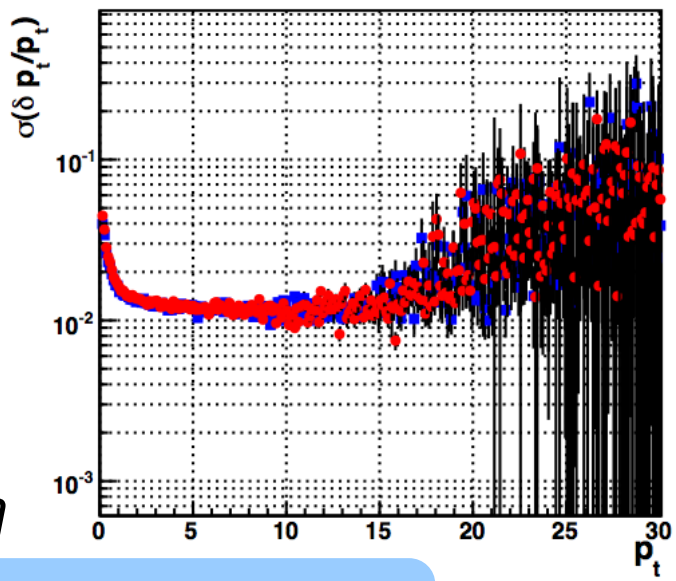
Iterative CTF Tracking

- CTF Pattern recognition with hit combinatorics is limited in by hit density.
- Perform pattern recognition in increasing phase space with hit removal.
  - Step **N** pattern recognition.
  - Track quality selection.
  - Removal of associated hits.
  - Step **N+1** pattern recognition.
- Merge all tracks

Step 0: pixel triplets (pT_{min}=0.5 GeV)
Step 1: pixel pairs
Step 2: pixel triplets (pT_{min}=0.3 GeV)
Step 3: mixed pairs
Step 4: pixel-less pairs



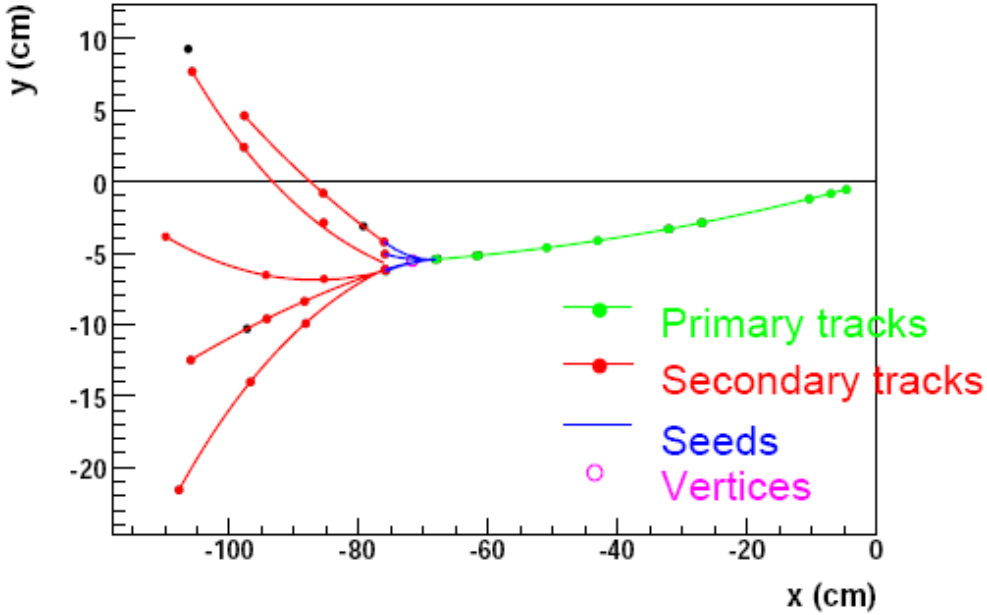




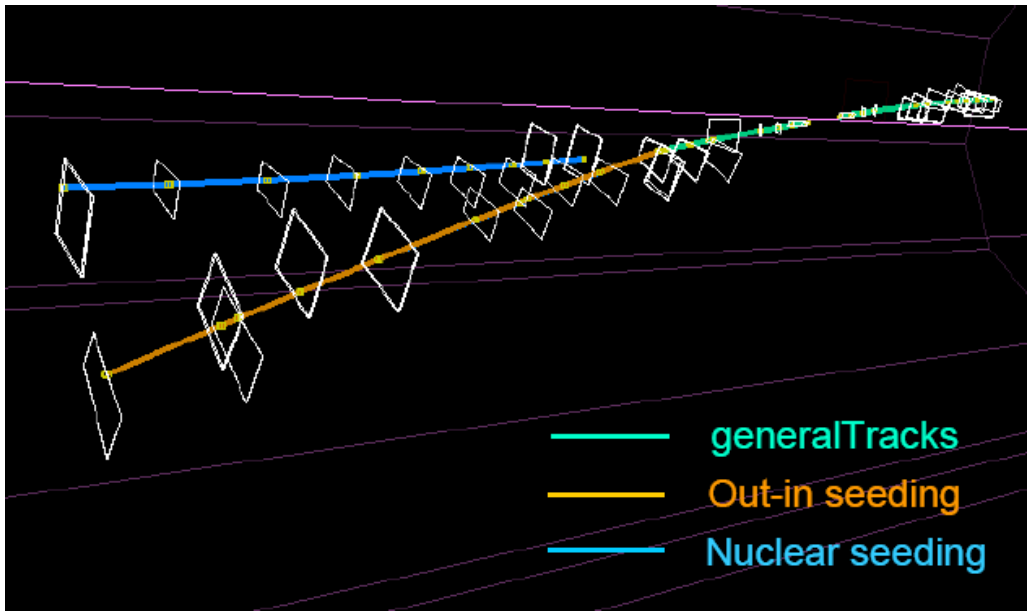
$t\bar{t}$ Monte Carlo, comparing **2.1** and **3.0** software version

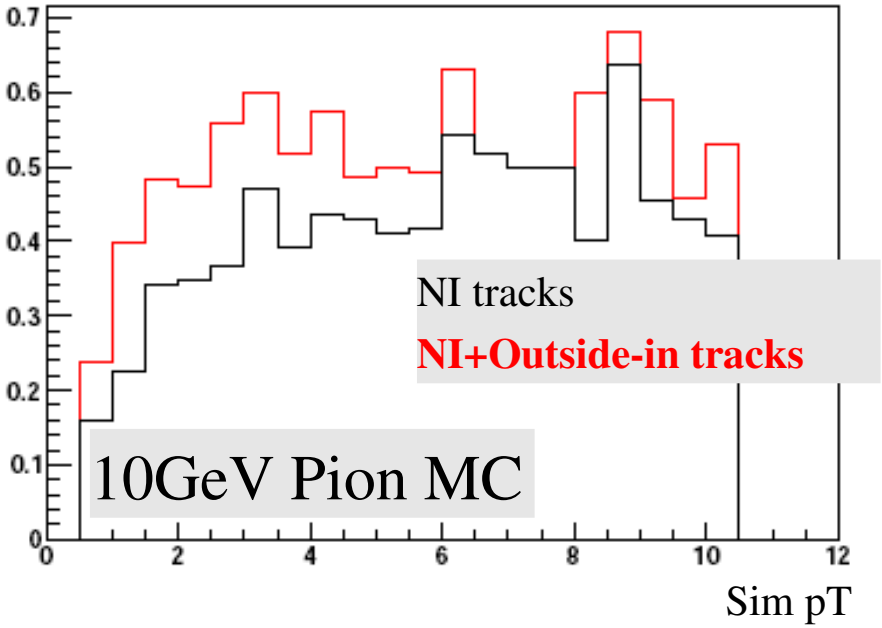
Good efficiency for general track reconstruction .
Single track reconstruction efficiency ~100% (not shown)

Nuclear Interaction



- Specific pattern recognition for secondary tracks.
- Use general tracks to look for extra compatible hits.
- Build secondary seeds and build tracks.



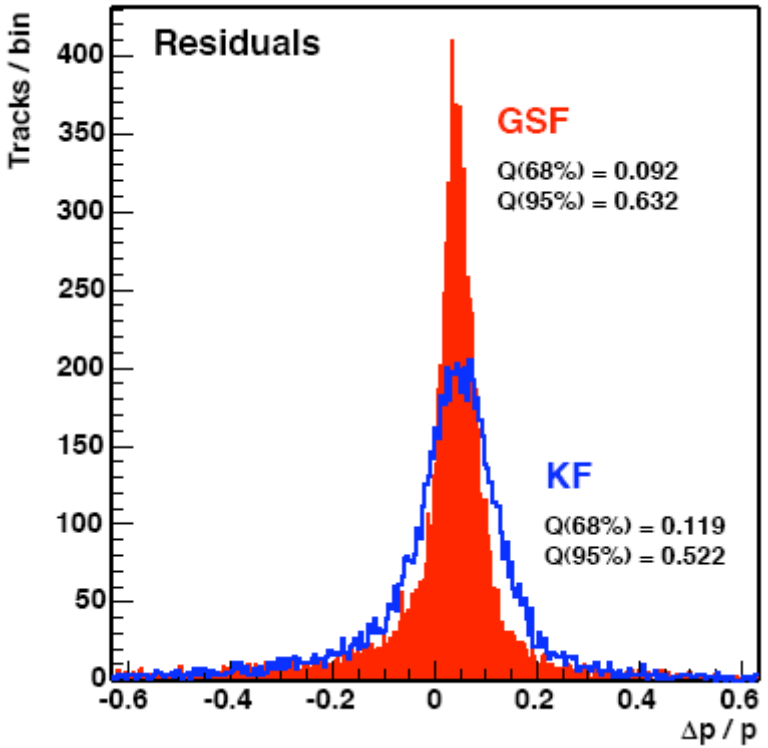


Promising. Orphan project to be pursued.

Electron Fit

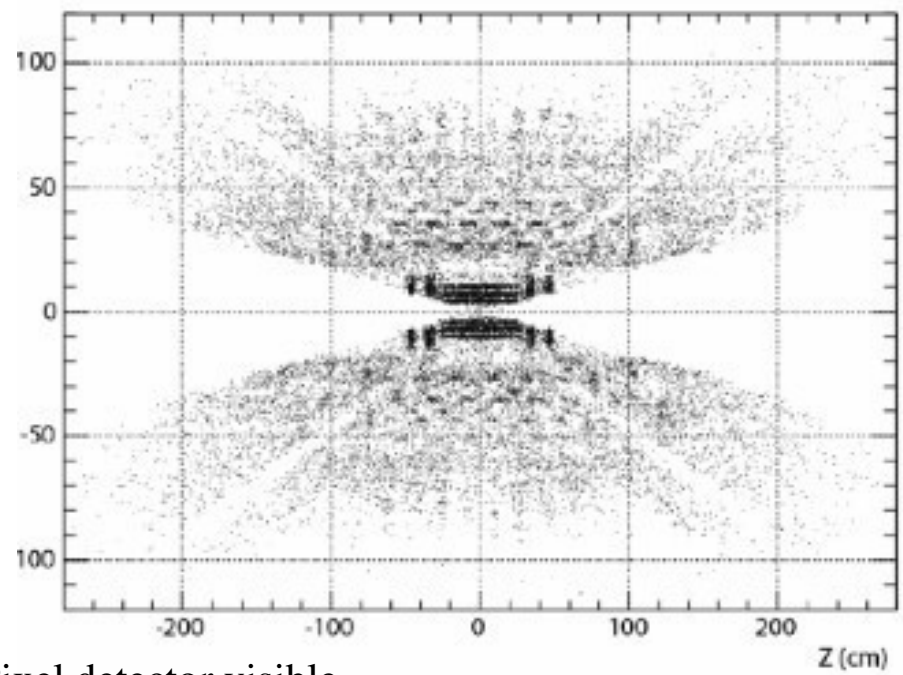
- Standard pattern recognition with calorimeter confirmation.

- Energy loss of electron is highly non-Gaussian due to Bremsstrahlung.
- Not modeled properly in standard Kalman Filtering.
- Use a dedicated weighted Gaussian sum to model energy loss.
- CPU intensive but yield better momentum resolution.

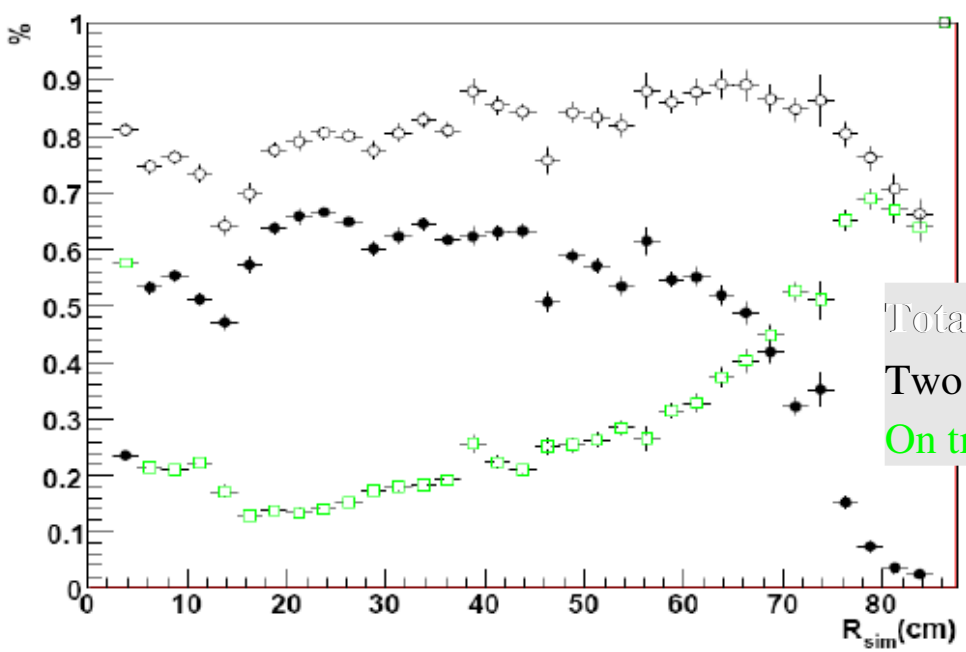


Photon Conversion

- Photons convert in tracker material
- Displaced track inefficiently seeded in pixel detector
- Seeding from outside required to limit the number of layers looked for seeds.



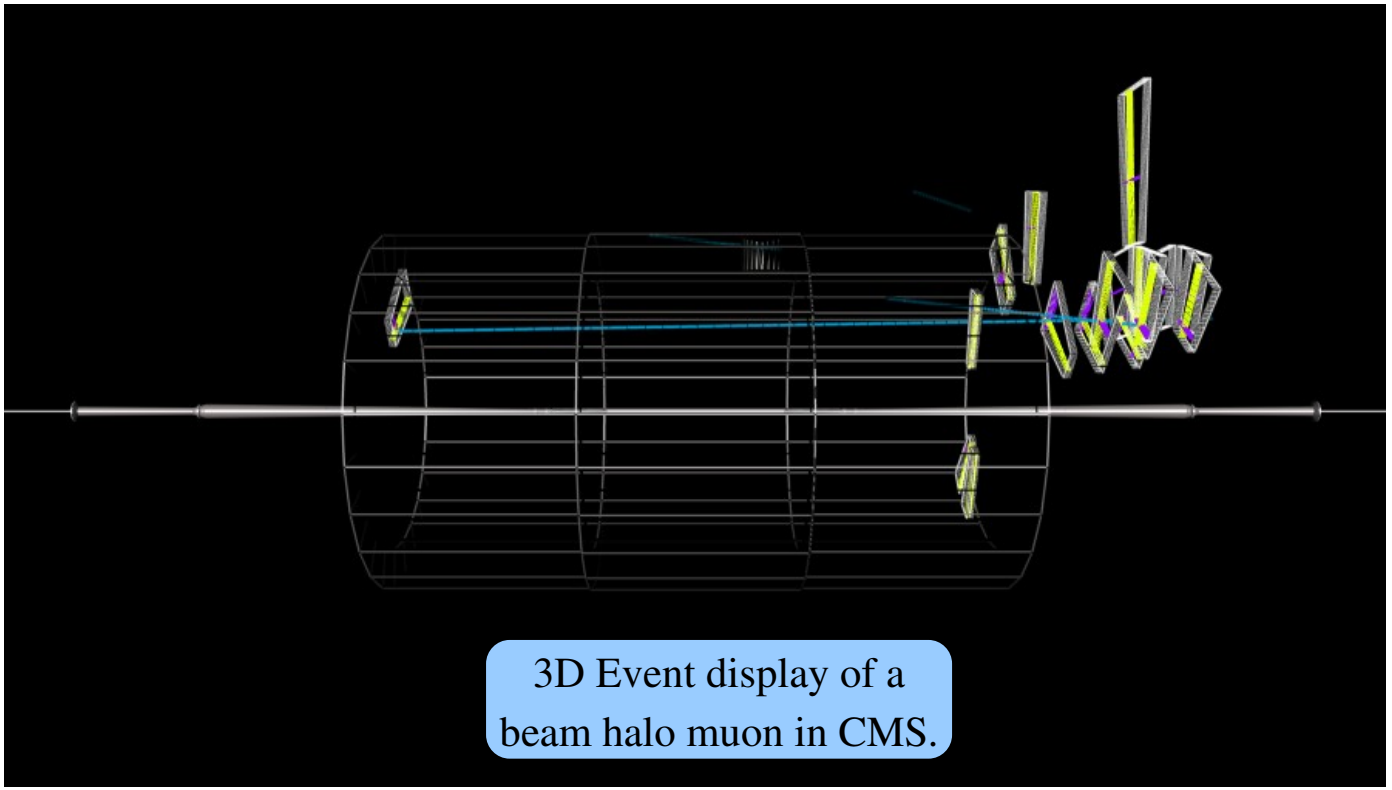
- Pixel detector visible.
- Inner strip layers faint.
- Not enough hits to have many tracks in outer strip layers



Total efficiency (white)
Two tracks reconstructed (black)
On track reconstructed (green)

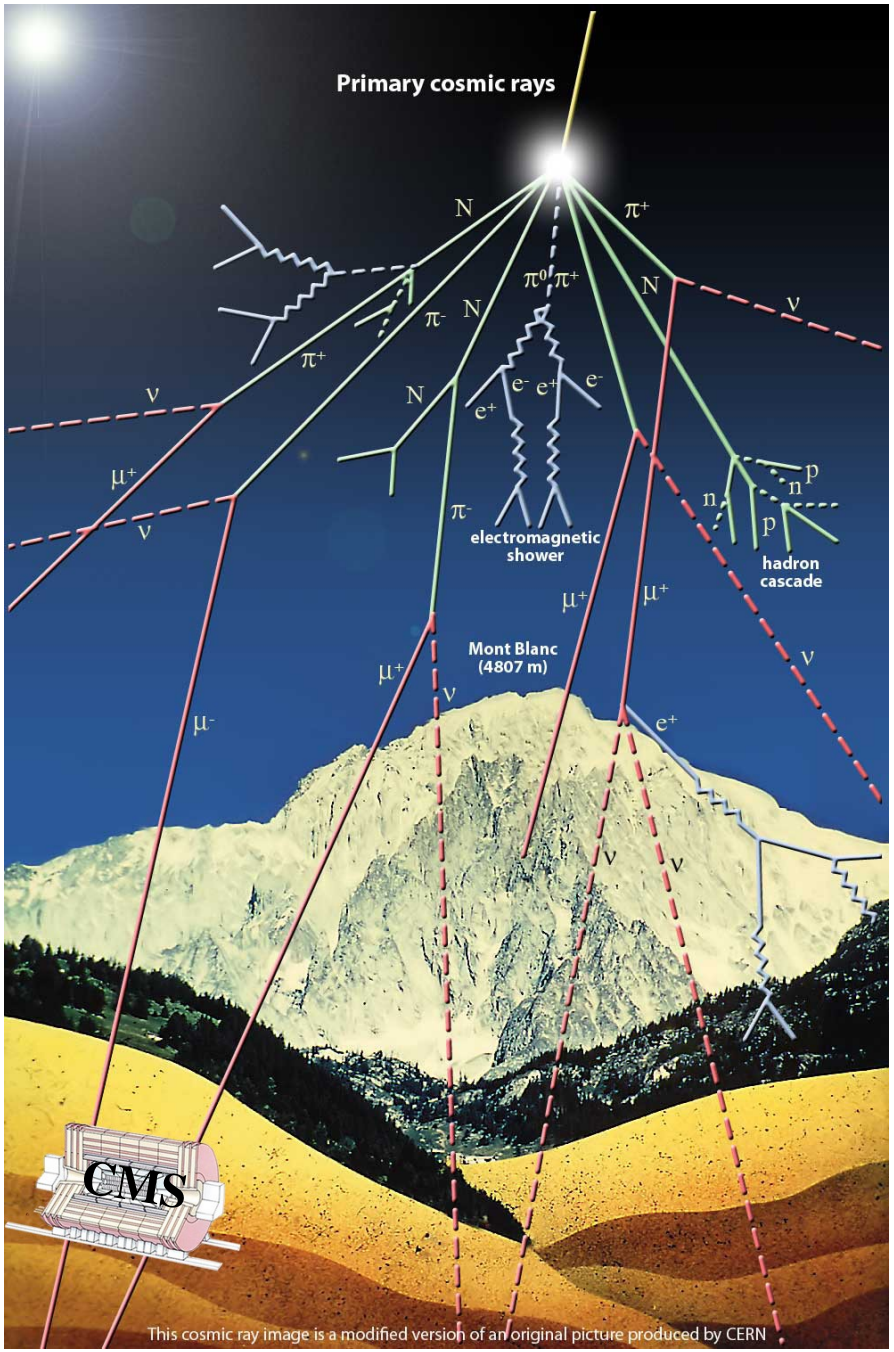
Beam Halo Muons

- Expected and observed beam halo splash in CMS during LHC commissioning in September 2008.
- Tracker **was not switched on** in order to limit the risk of damage to modules due to high voltage.
- Dedicated track reconstruction used on Monte Carlo.
- Track reconstruction in the muon system exercised in September 2008.

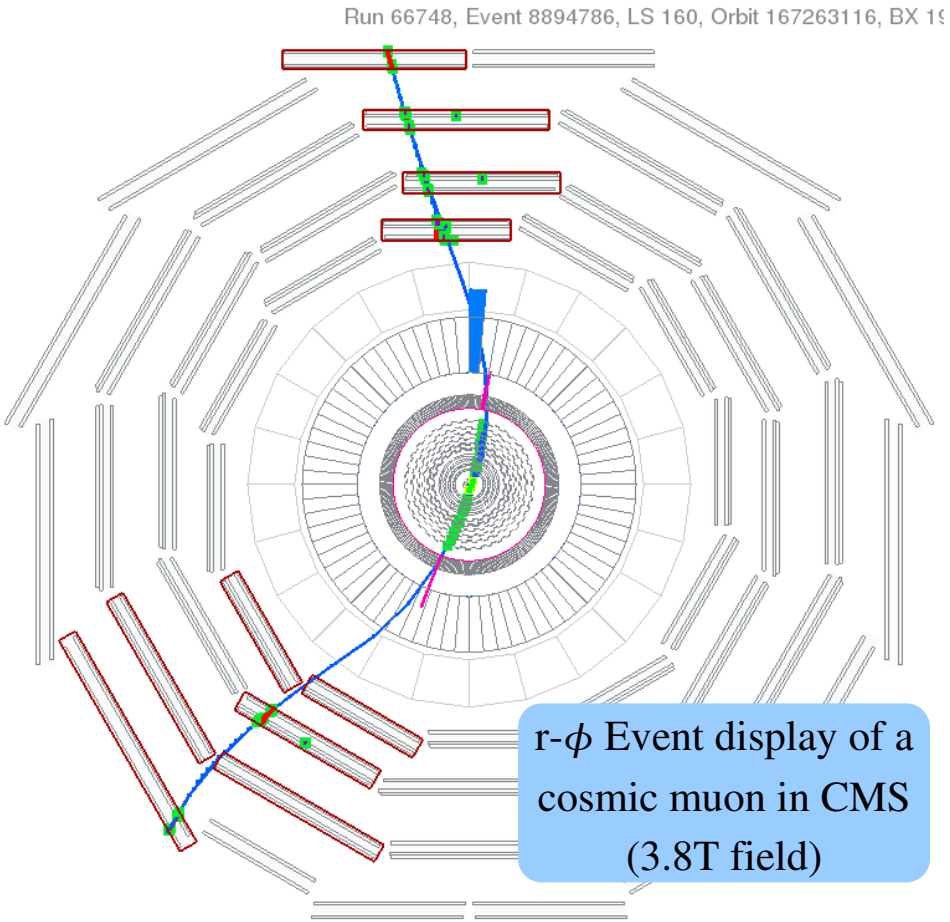


3D Event display of a beam halo muon in CMS.

Muons From Cosmic Shower



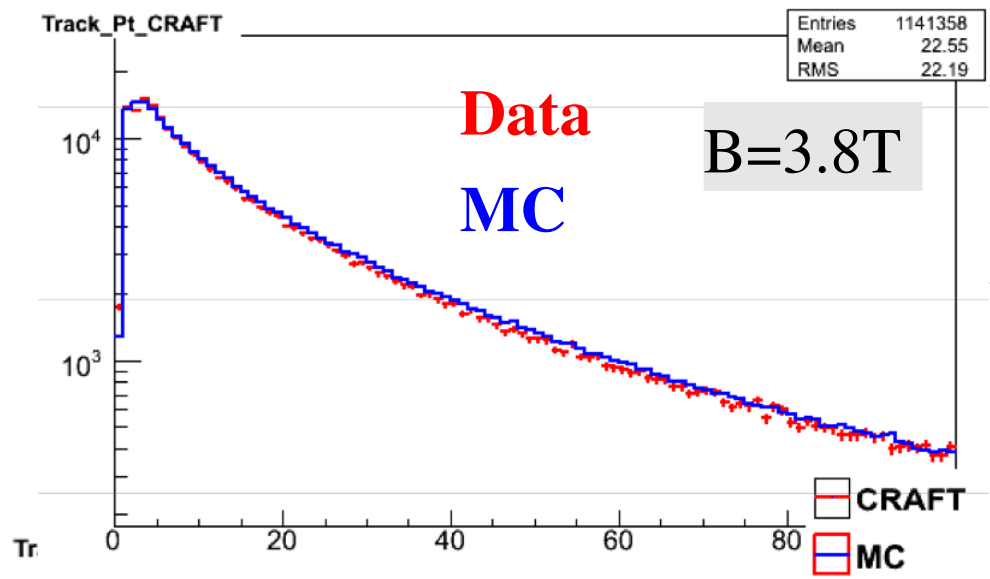
- Cosmic rays produce particle showers in the earth atmosphere.
- Most of the particles are stopped before reaching the ground.
- Muons reach CMS 100m underground.

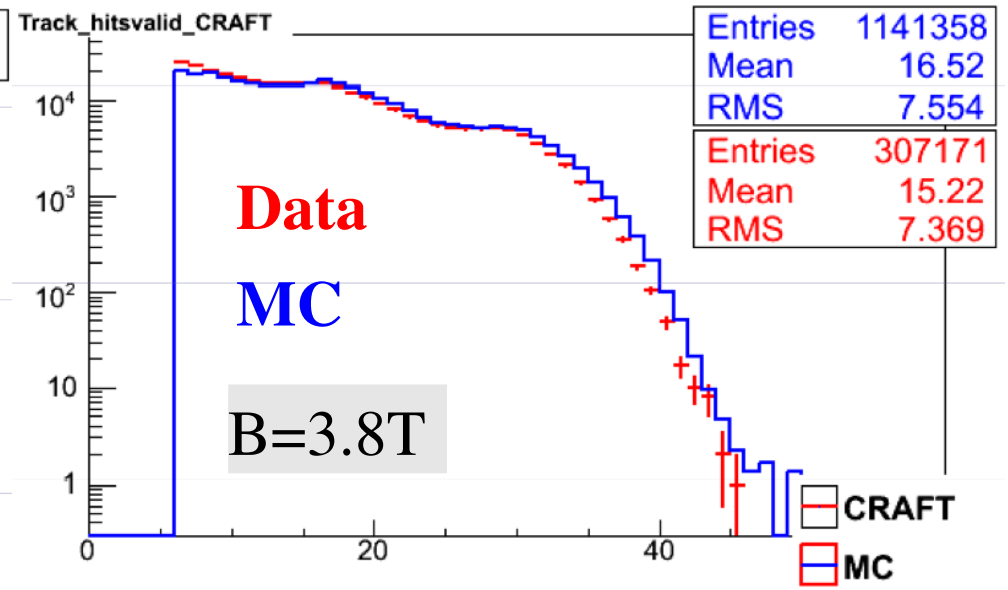


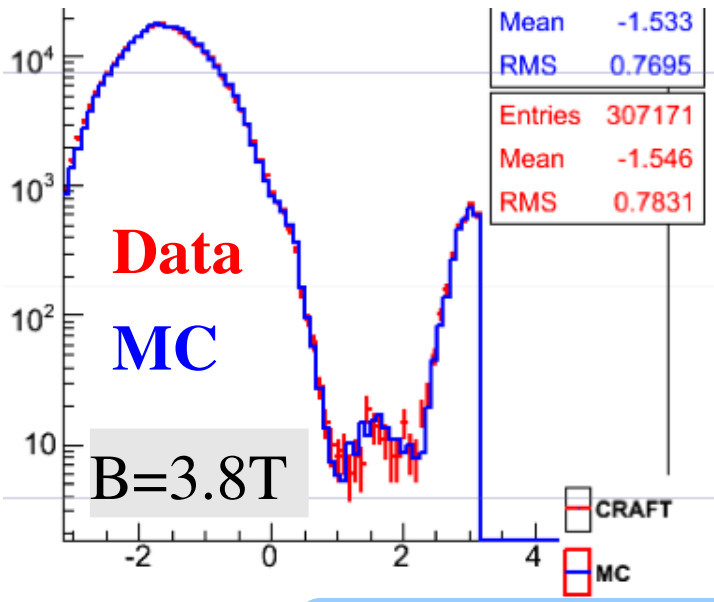
r-ϕ Event display of a cosmic muon in CMS (3.8T field)

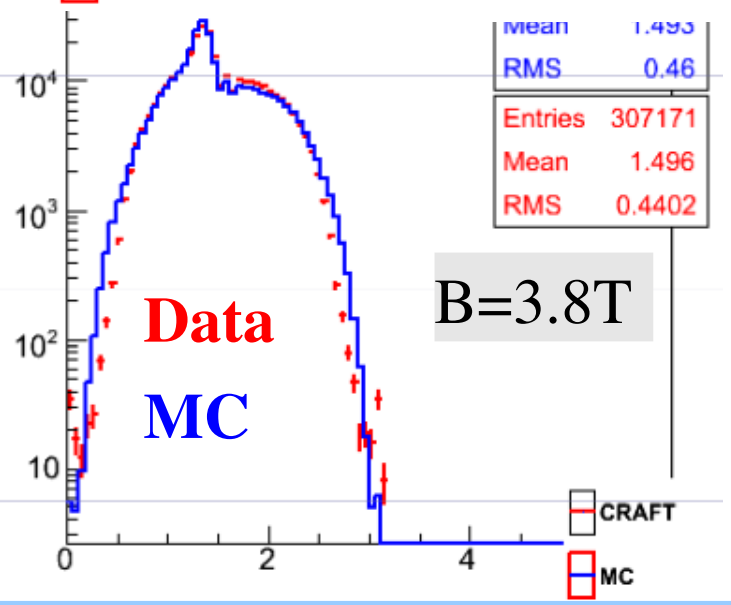
Data/Monte Carlo Comparison

R.Demina, Y.Gotra, B.Betchart







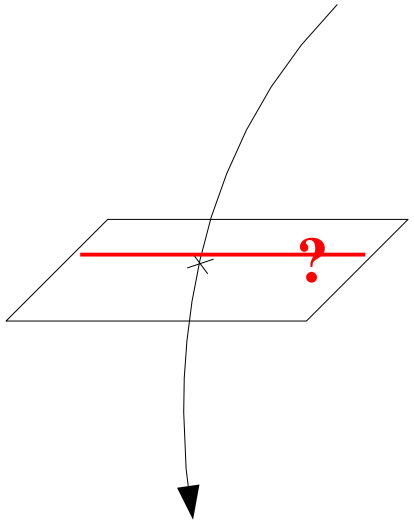


- Single track event
- $\chi^2/\text{ndof} \leq 10$
- ≥ 6 hits

Good agreement after good track selection

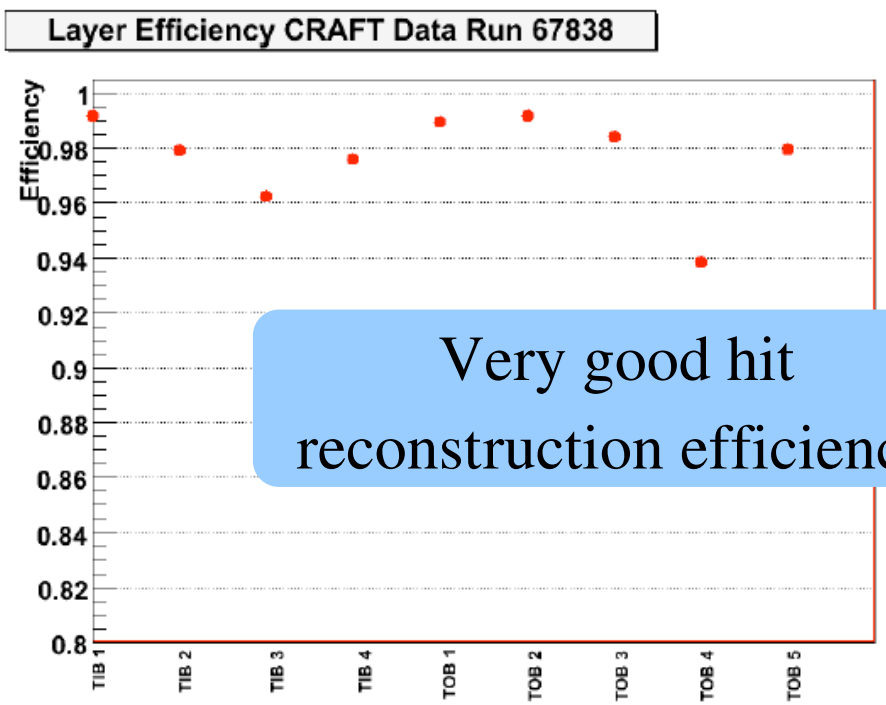
Hit Reconstruction Efficiency

K.Ulmer

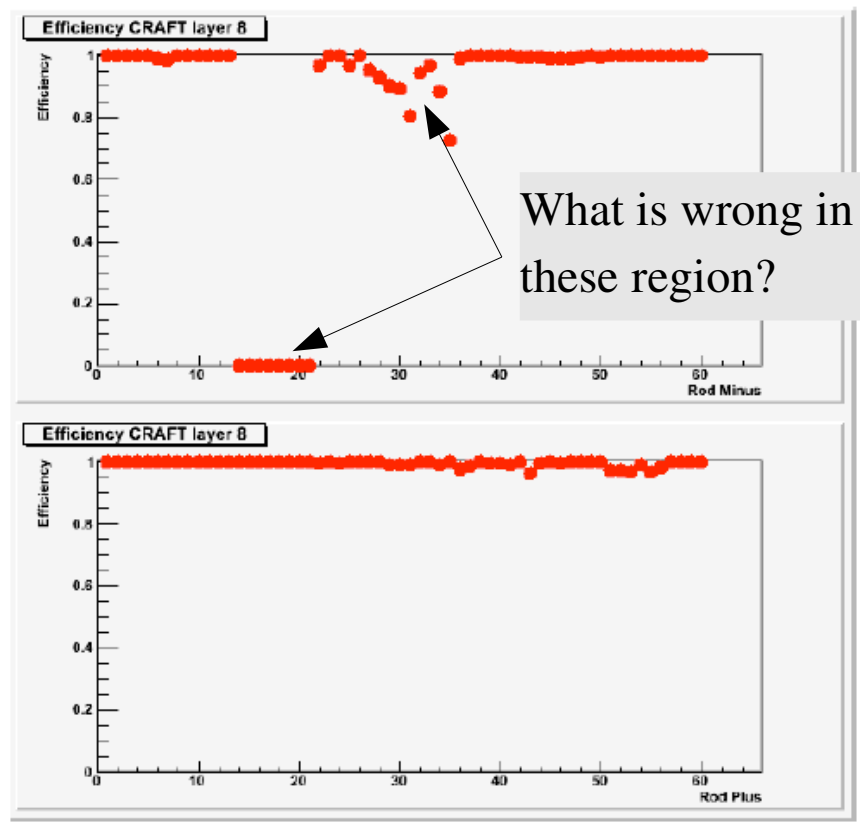


Idea:

- **Select good quality tracks, with a few missing hits allowed.**
- **Select module definitely crossed by the track**
- **Look for reconstructed hit on the module**



Very good hit reconstruction efficiency

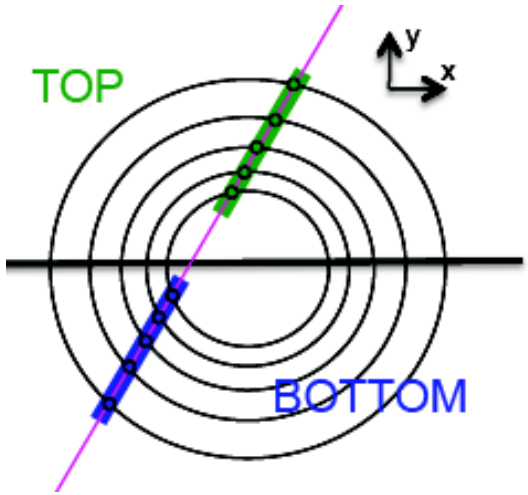


What is wrong in these region?

Fundamentals of detector commissioning

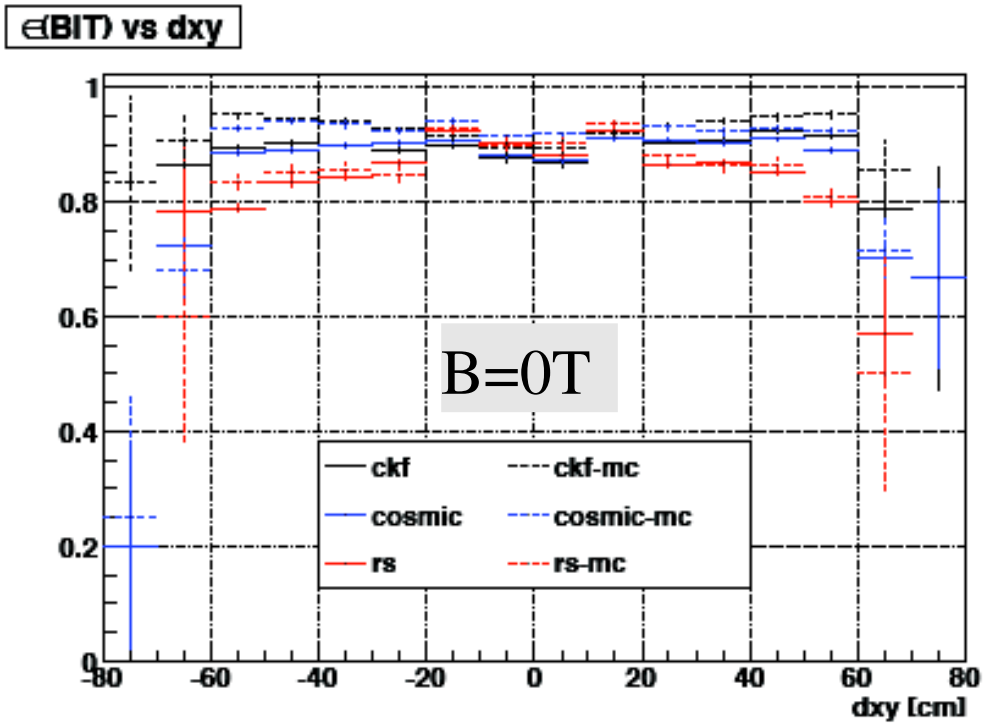
Top/Bottom Tracking Efficiency

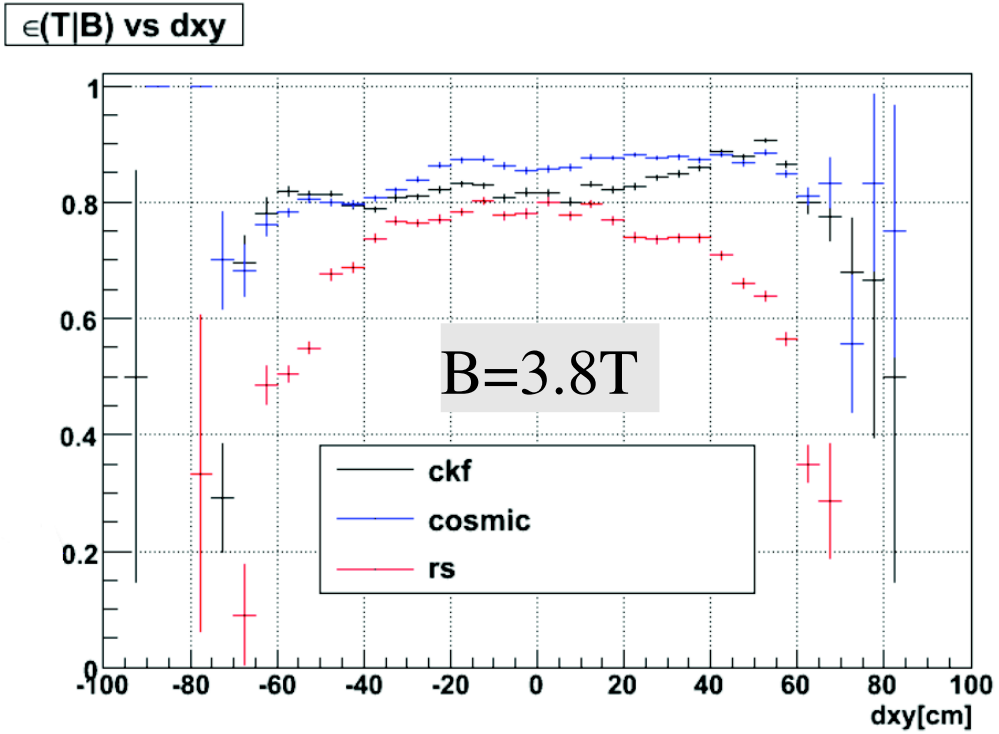
G.Cerati



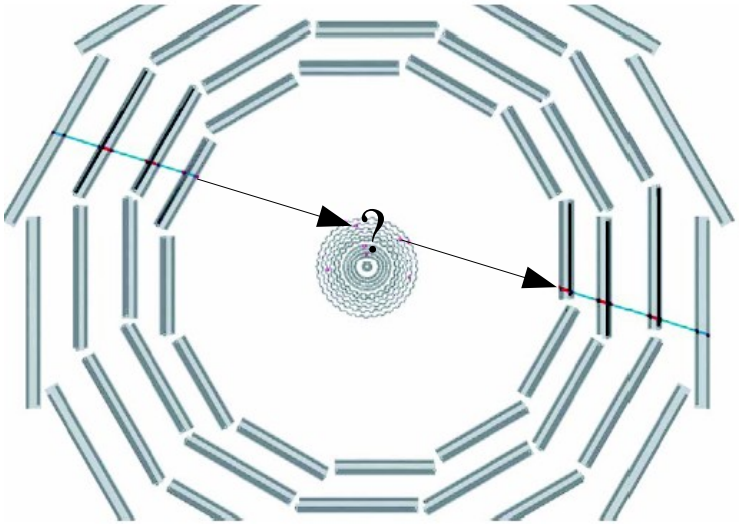
Idea:

- Divide the tracker in two halves along y=0.
- Reconstruct tracks from hits with y>0 (Top Tracks).
- Reconstruct tracks from hits with y<0 (Bottom Tracks).
- Use Top tracks as a tag to probe Bottom tracker efficiency: ε(B|T).
- Use Bottom tracks as a tag to probe Top tracker efficiency: ε(T|B).





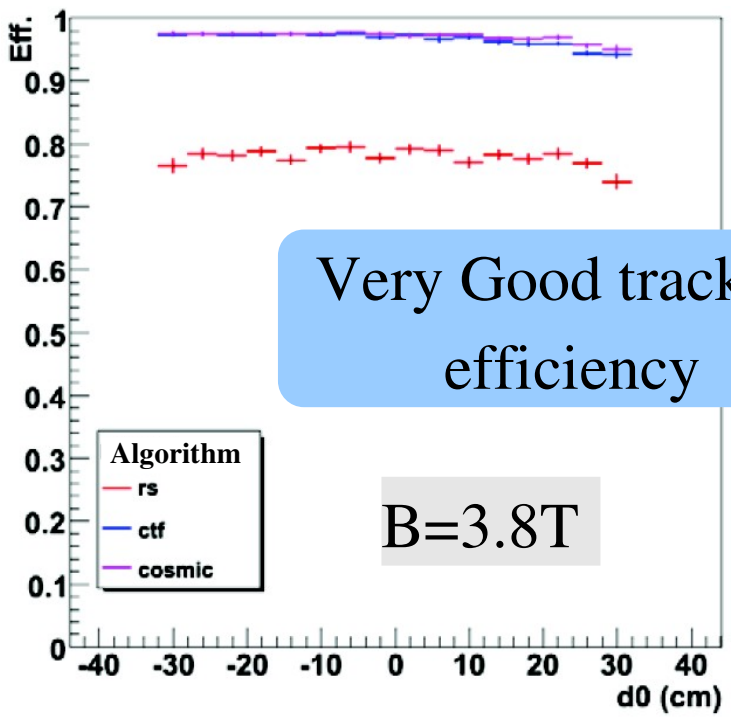
Muon System to Tracker Efficiency



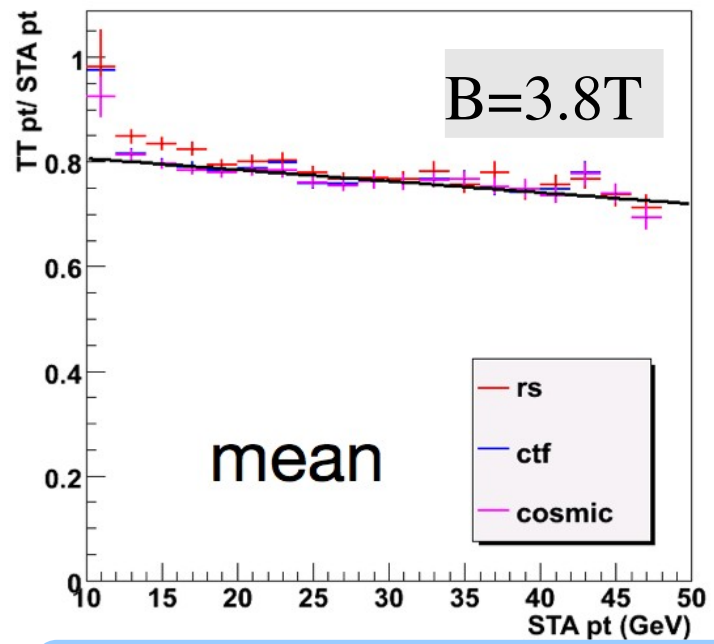
J.Andrea

Idea:

- **Select track pair reconstructed in muon system only**
- **Look for matching track in the tracker**



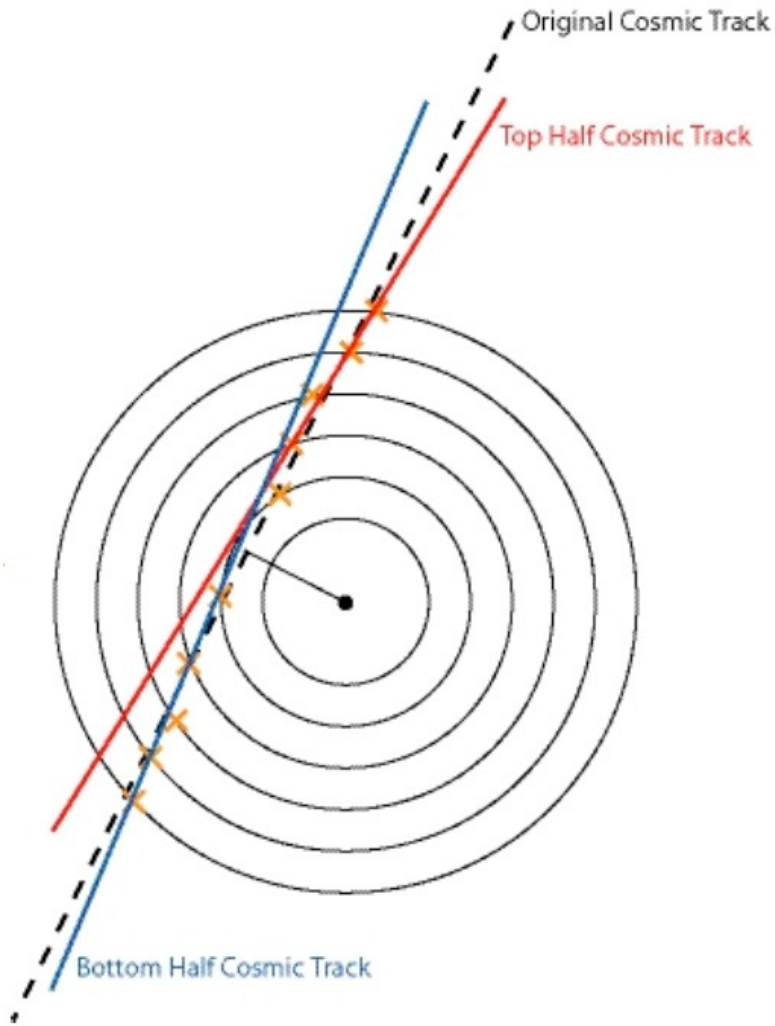
Very Good tracking efficiency



Mismatch of pT measurement between tracker and muon system to be understood. Magnetic field map?

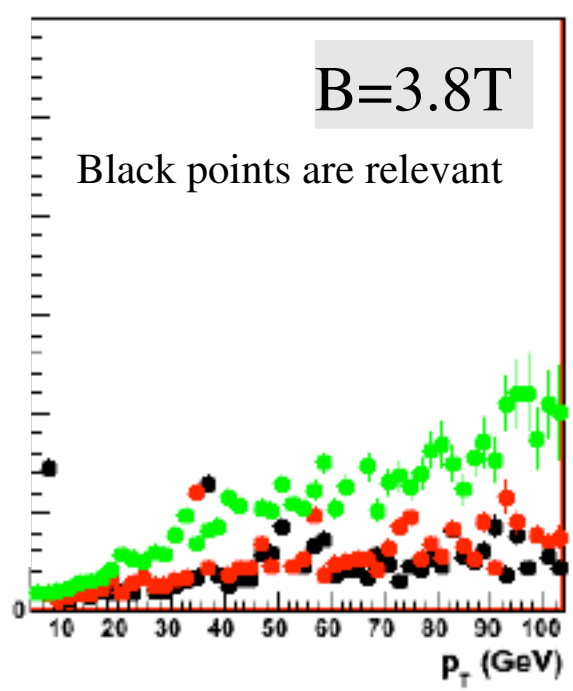
Resolution with Split Tracks

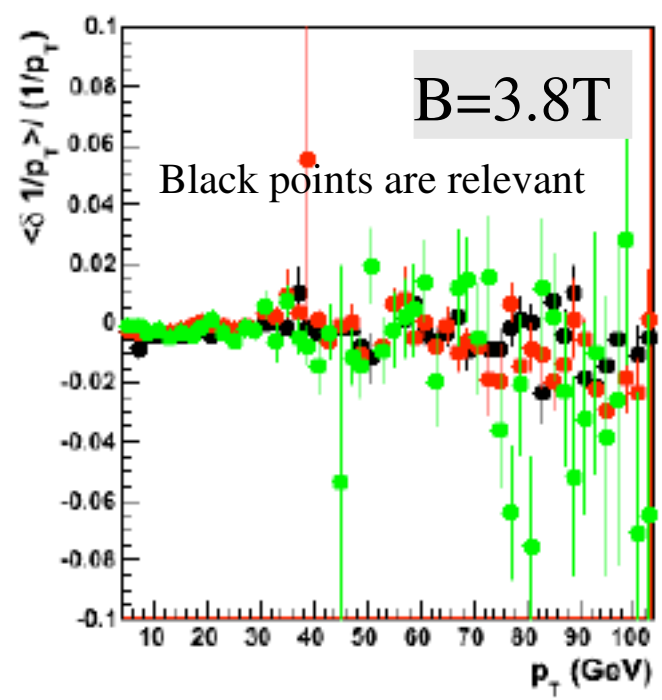
A.Bonato, A.Gritsan, N.Tran, S.Wagner



Idea:

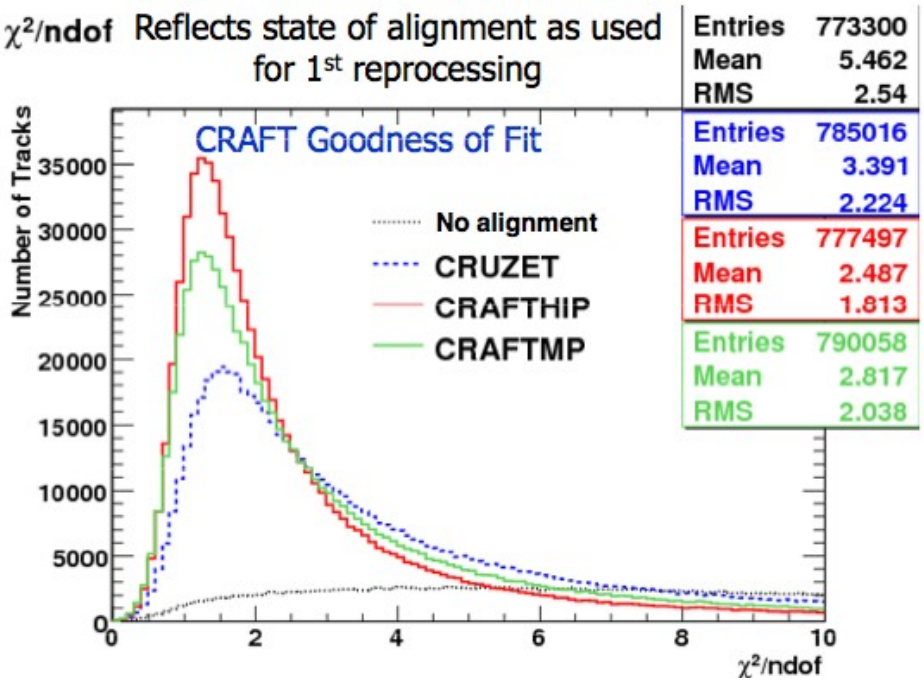
- **Select crossing track with no bias in pattern recognition (brute force combinatorics)**
- **Split the track in the middle and refit individually**
- **Compare track parameters**



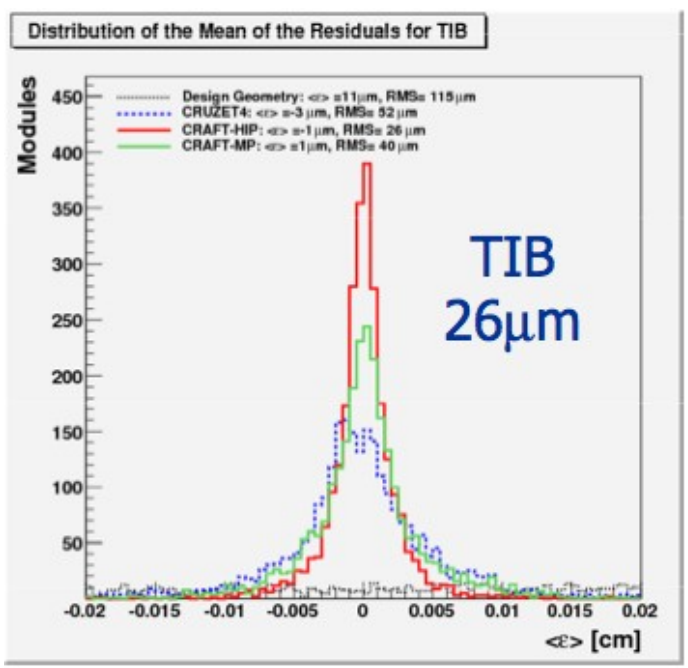


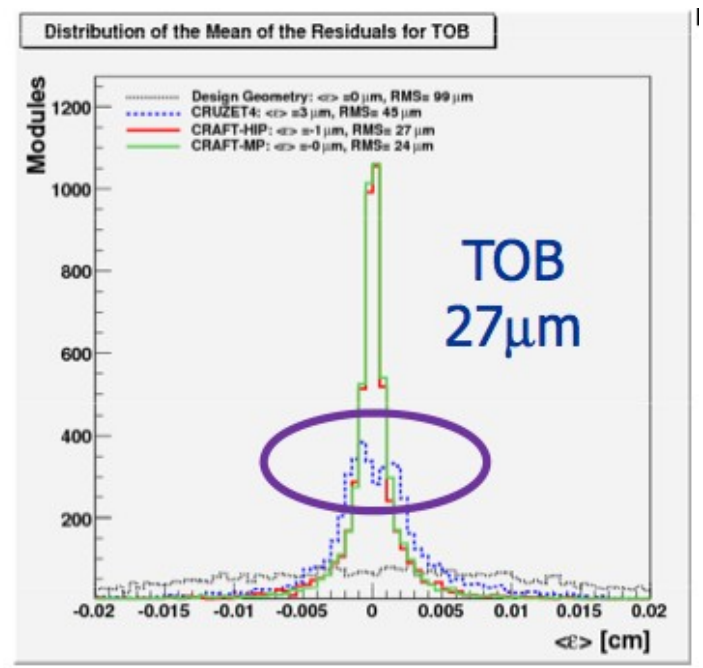
2%-10% pT resolution with bias ≪ 2%

Track Alignment With Cosmics



- Alignment procedure carried out during CruZet and CrafT runs.
- Tracker alignment improved significantly in CrafT.
- Importance of B on and B off data to disentangle effects.

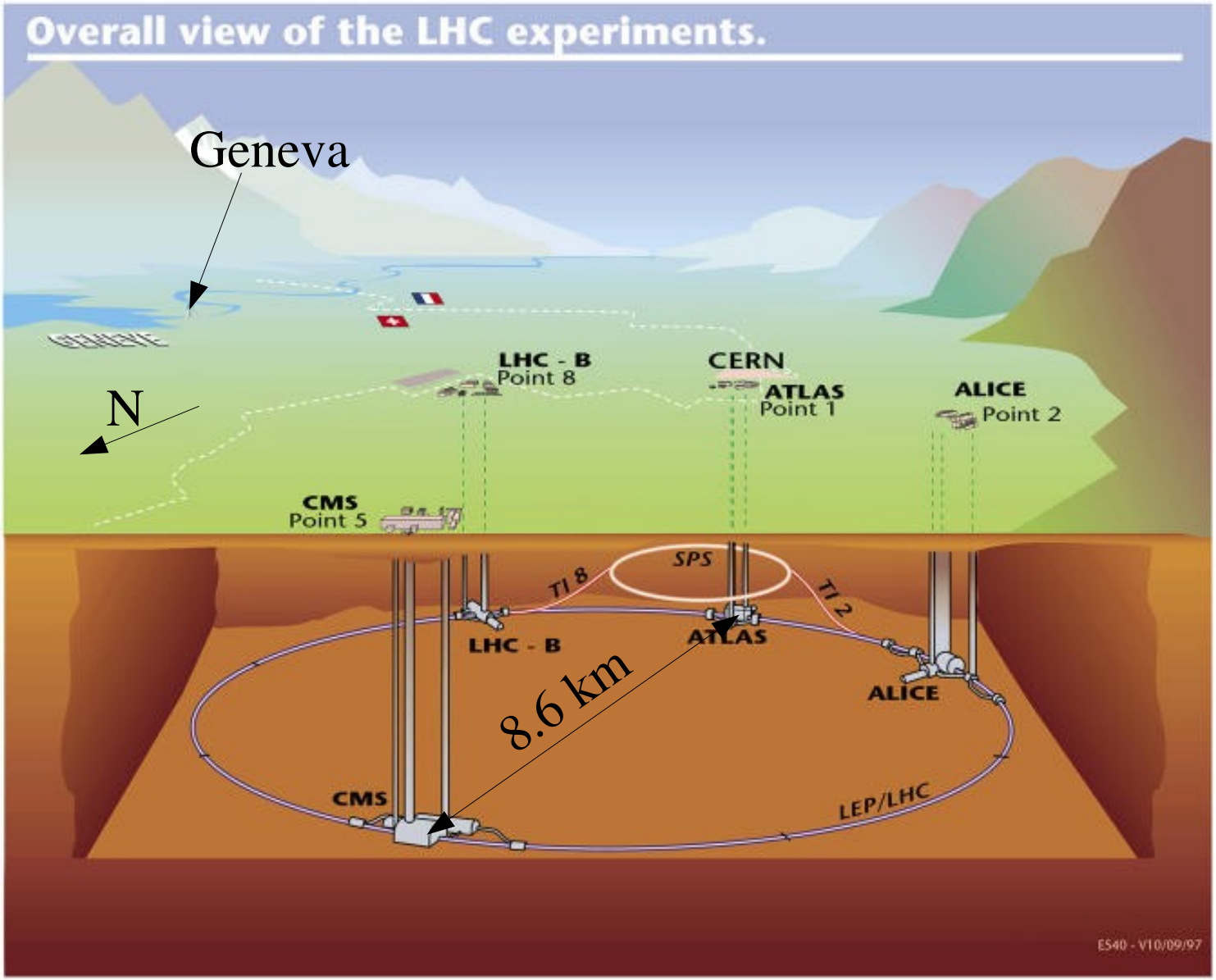




Summary

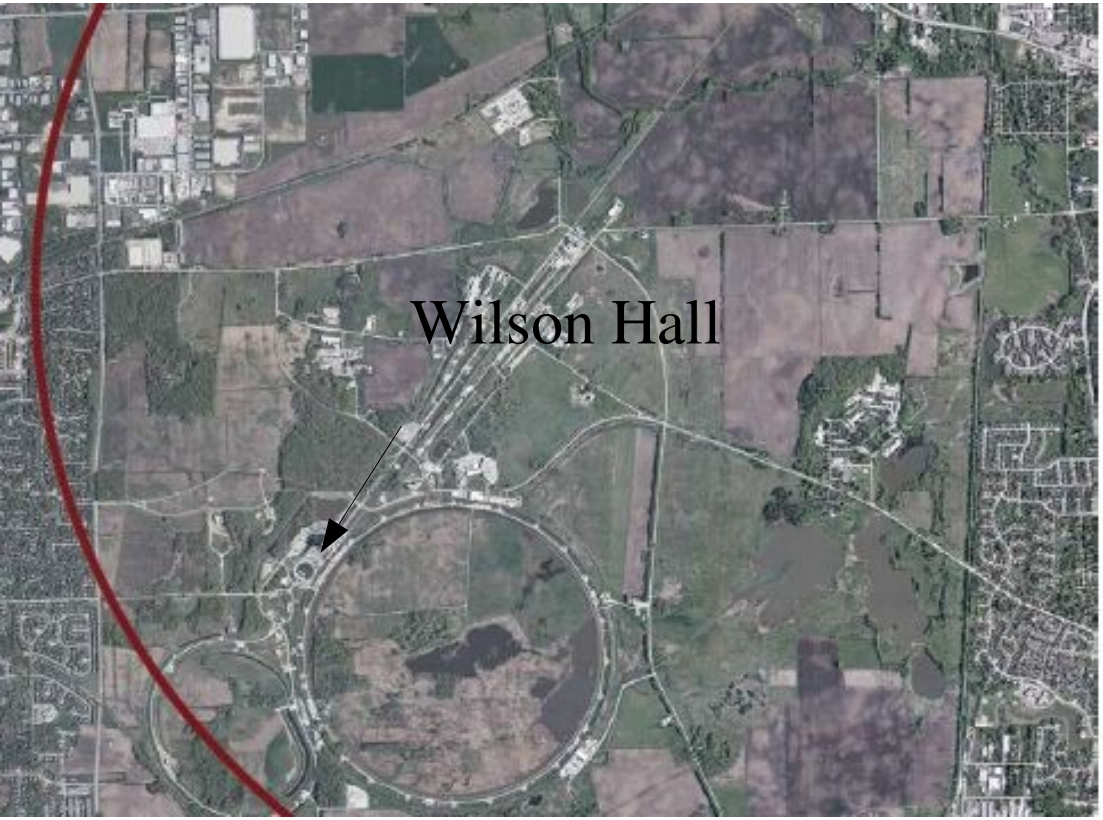
- CMS has a complex and high-performance Inner Tracking System.
- Track reconstruction in CMS for collision operation is foreseen to be very good.
- Experience with Cosmic data is vital for tracker commissioning.
  - Interesting ideas to be pursued.
- Waiting for the LHC, but CMS takes data...
  - Lots of room for vital contributions

CERN - LHC


Overall view of the LHC experiments.
Geneva
N
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
8.6 km
CMS
LEP/LHC
ES40 - V10/09/97

Tevatron .vs. LHC

LHC



	TEVATRON	*LHC*
beams	p-pbar	p-p
circumference	6 km	27 km
energy	2 TeV	14 TeV
luminosity	10^{32}	10^{34} cm^{-2}s^{-1}
	8 fb^{-1}	300 fb^{-1}
bunch spacing	392 ns	25 ns
collisions/xing	6	20
collab'n size	600 each	2000 each
running mo/yr	12	6

Collision rate at LHC is 40 Mhz
~300 times more collisions per second

Track Reconstruction at CMS

- General track reconstruction presented here.
- Dedicated track reconstruction detailed later on.