Queen Mary
University of London
Science and Engineering

Radiation Detectors (SPA 6309)

Lecture 21

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Last revised 7 April 2020

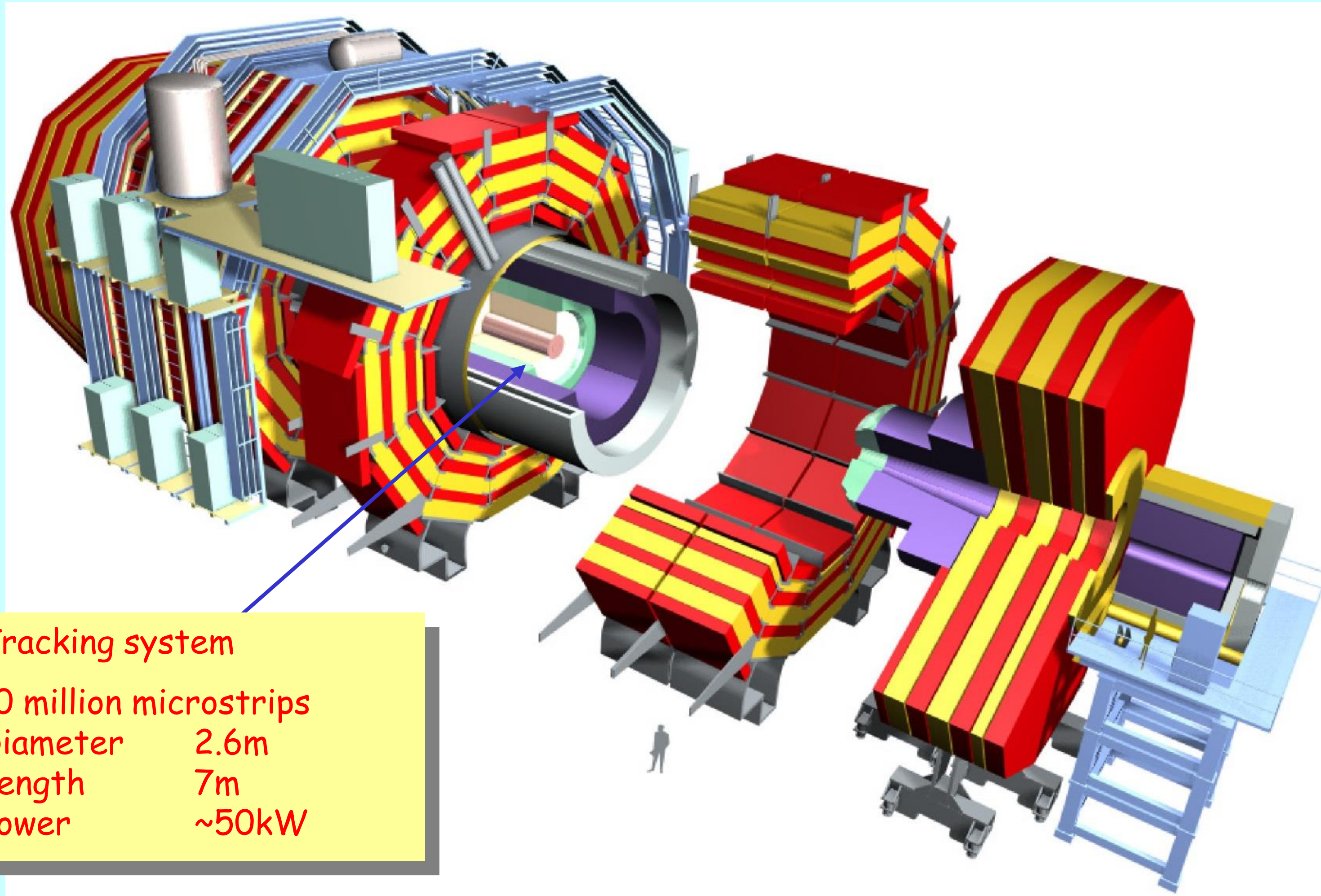
What is this lecture about?

- Tracking in CMS
  - Motivation
  - Design of the CMS tracker
  - Performance

CMS Tracking Detector case study

This lecture is based on a lecture generously provided by Prof G Hall of Imperial College, London

CMS = Compact Muon Solenoid detector



Tracking system

10 million microstrips
Diameter 2.6m
Length 7m
Power ~50kW

LHC parameters (CMS)

	pp	Pb-Pb
Luminosity	10^{34} cm^{-2}.s^{-1}	10^{27} cm^{-2}.s^{-1}
Annual integrated ***L***	5x10^{40} cm^{-2}	?
CM energy	14 TeV	5.5 TeV/ N
$\sigma_{inelastic}$	~70mb	~6.5 b
interactions/bunch	~20	0.001
tracks/unit rapidity	~140	3000-8000
beam diameter	20µm	20µm
bunch length	75mm	75mm
beam crossing rate	40MHz	8MHz
Level 1 trigger delay	- 3.2µsec	- 3.2µsec
L1 (average) trigger rate	Š100kHz	< 8kHz

- **Consequences**

High speed signal processing
Signal pile-up

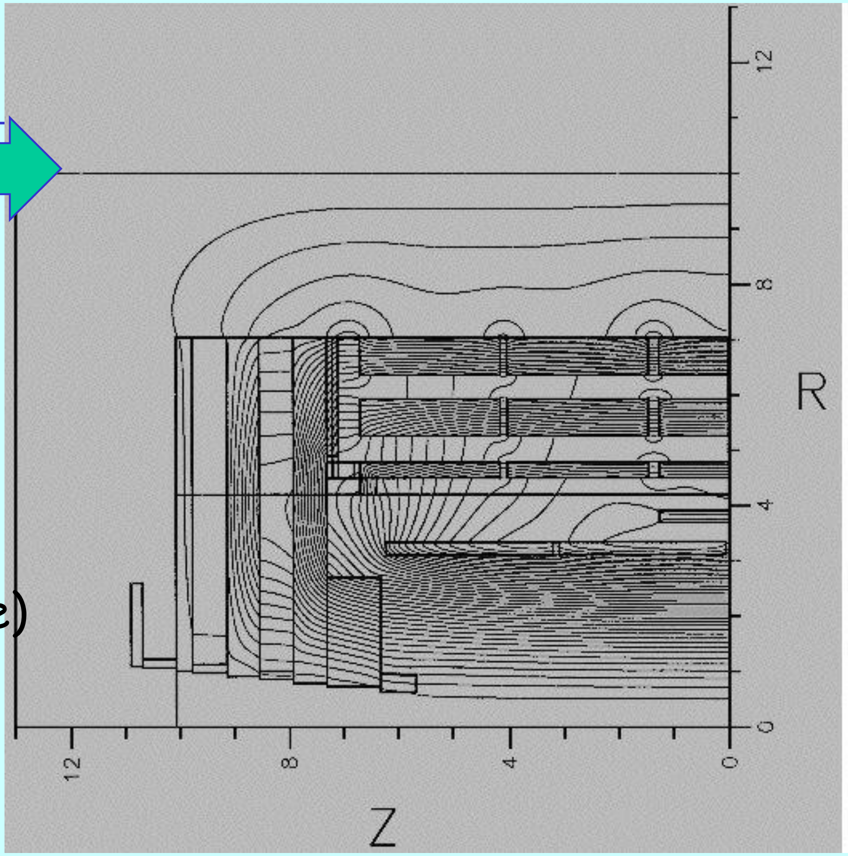
High (low) radiation exposure
High (low) B field operation

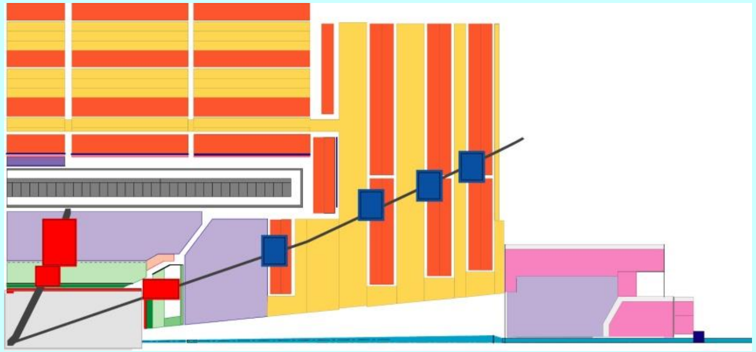
Very large data volumes

New technologies

Design philosophy

- Large solenoidal (4T) magnet
  - iron yoke - returns B field, absorbs particles
  - technically challenging but
    - *smaller detector, p resolution, trigger, cost*
- Muon detection
  - high p_T lepton signatures for new physics
- Electromagnetic calorimeter
  - high (ΔE) resolution, for $H \Rightarrow \gamma\gamma$ (low mass mode)
- Tracking system
  - momentum measurements of charged particles
  - pattern recognition & efficiency
    - *complex, multi-particle events*
  - complement muon & ECAL measurements
    - *improved p measurement (high p)*
    - *E/p for e/γ identification*





Physics requirements (I)

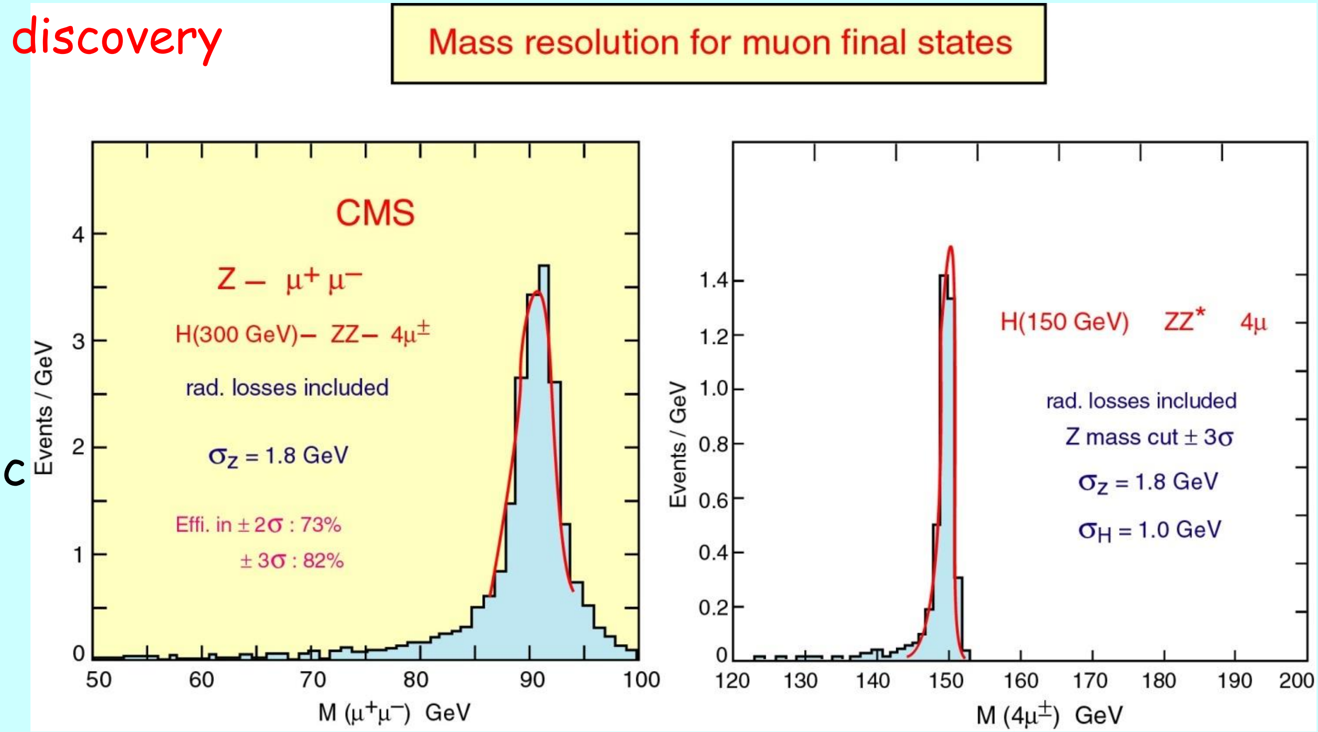
- Mass peak - one means of discovery

  $$m^2 = \sum_i E_i^2 - p_i^2$$

  => small $\sigma(p_T)$

  eg H => ZZ or ZZ* => $4\ell^{\pm}$

  typical $p_T(\mu)$ ~ 5-50GeV/c



- Background suppression

  measure lepton charges

  good geometrical acceptance - 4 leptons

  background channel *t => b => ℓ*

  require $m(l^+l^-) = m_Z$ Γ_Z ~ 2.5GeV

  precise vertex measurement identify b decays, or reduce fraction in data

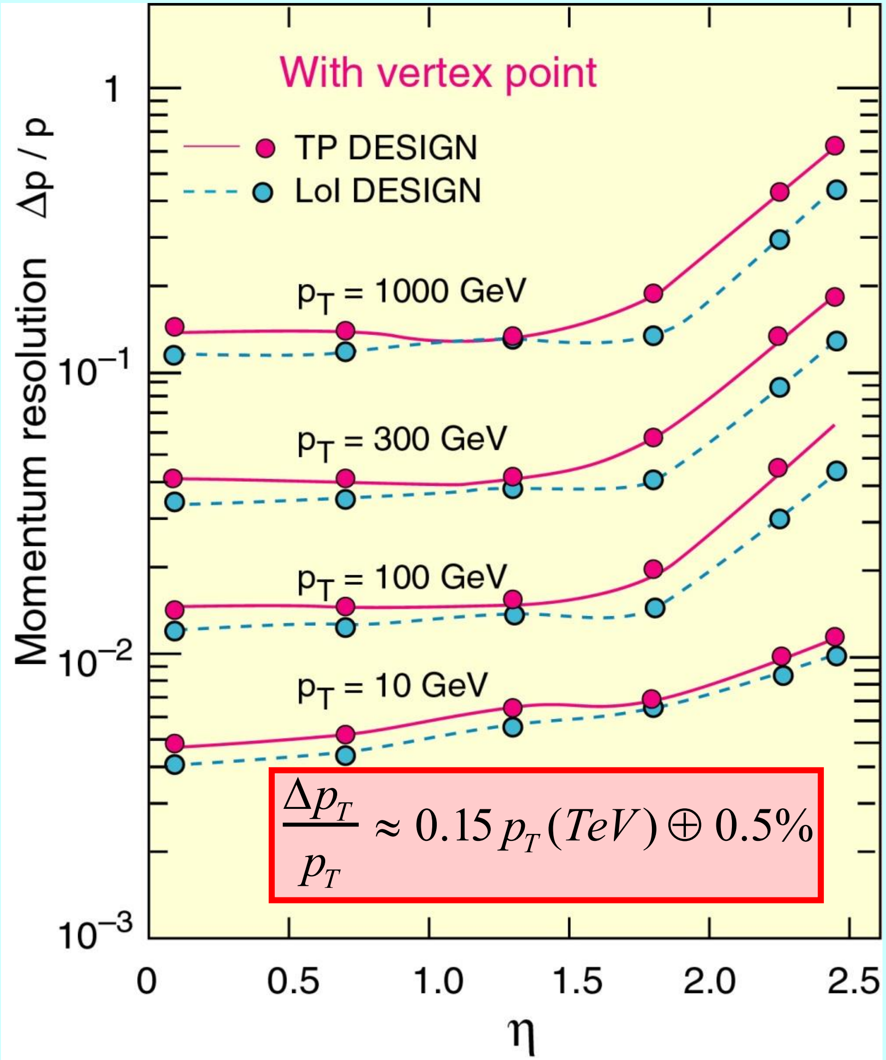
Physics requirements (II)

- p resolution

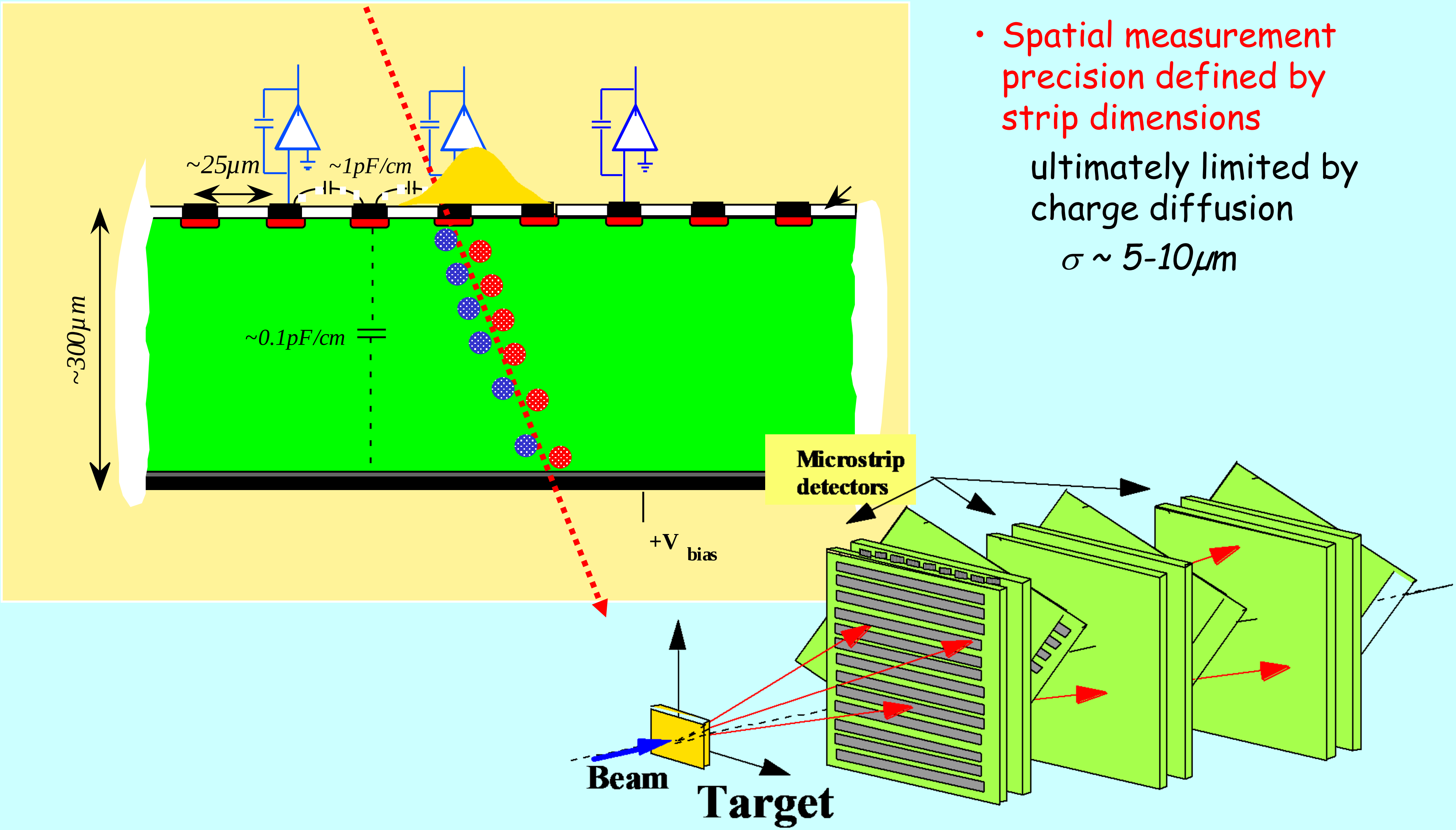
$$\frac{\sigma(p_T)}{p_T} \sim p_T \frac{\sigma_{meas}}{B.L^2.\sqrt{N_{pts}}}$$

  large B and L

- high precision space points
  detector with small intrinsic σ_{meas}
- well separated particles
  good time resolution
  low occupancy => many channels
  good pattern recognition
- minimise multiple scattering
- minimal bremsstrahlung, photon conversions
  material in tracker
  most precise points close to beam



Silicon diodes as position detectors

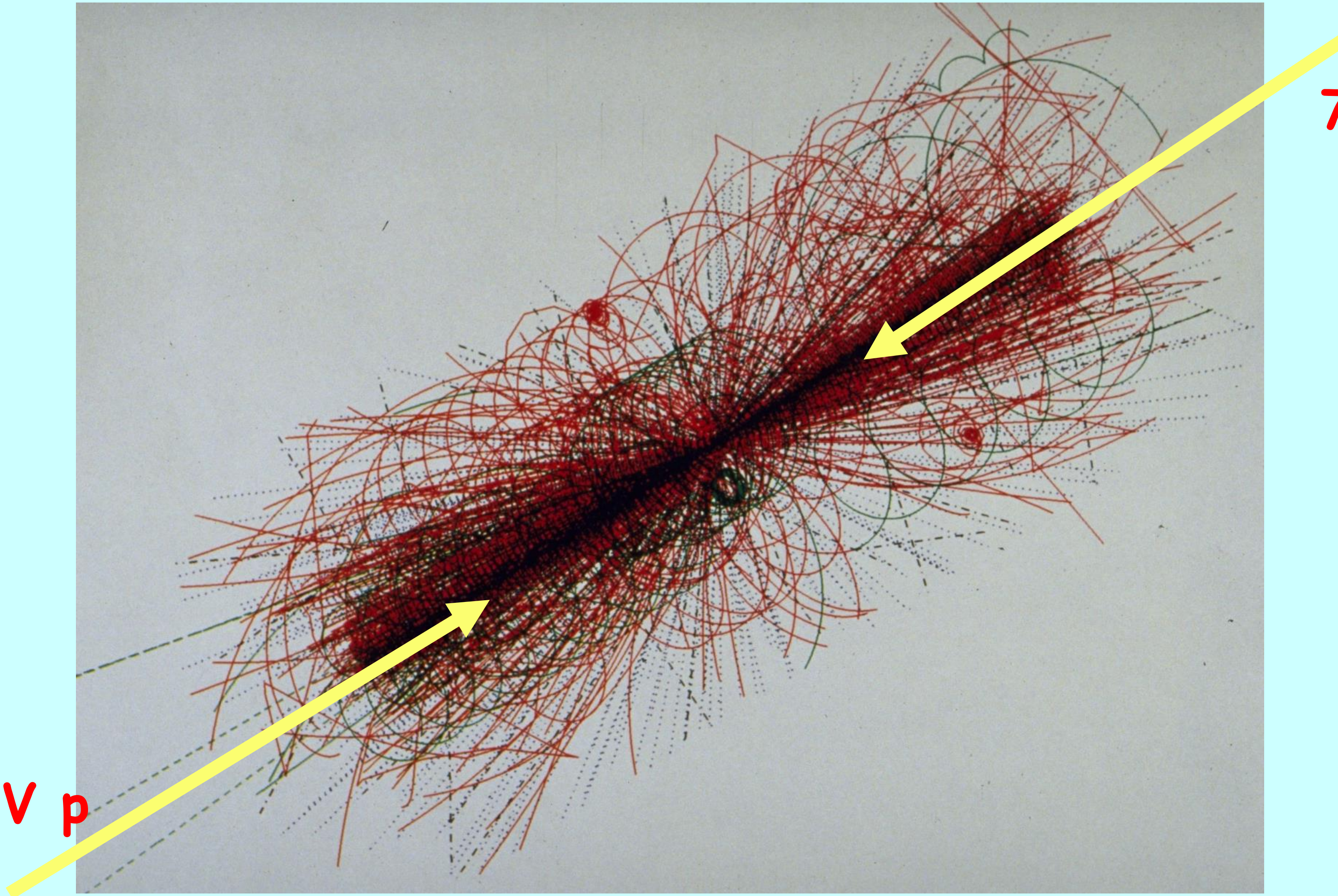


- Spatial measurement precision defined by strip dimensions

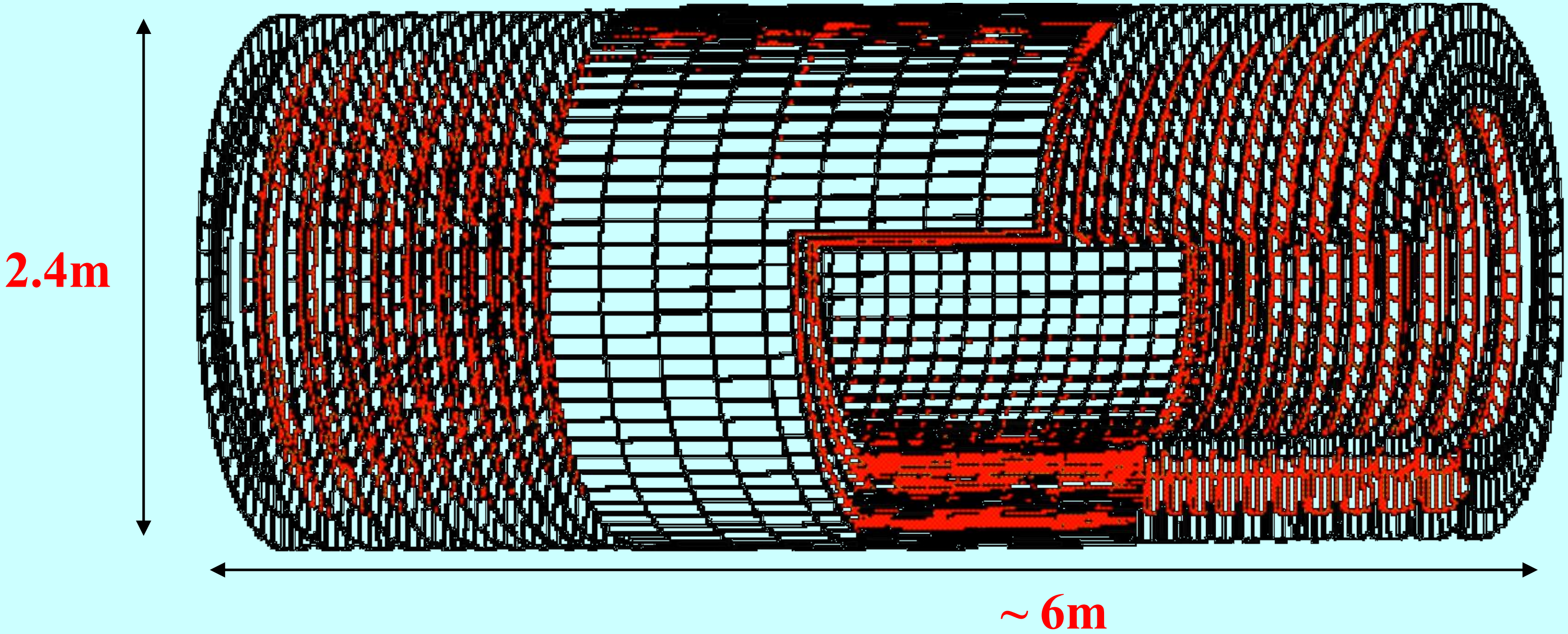
  ultimately limited by charge diffusion

  $\sigma \sim 5\text{-}10\mu m$

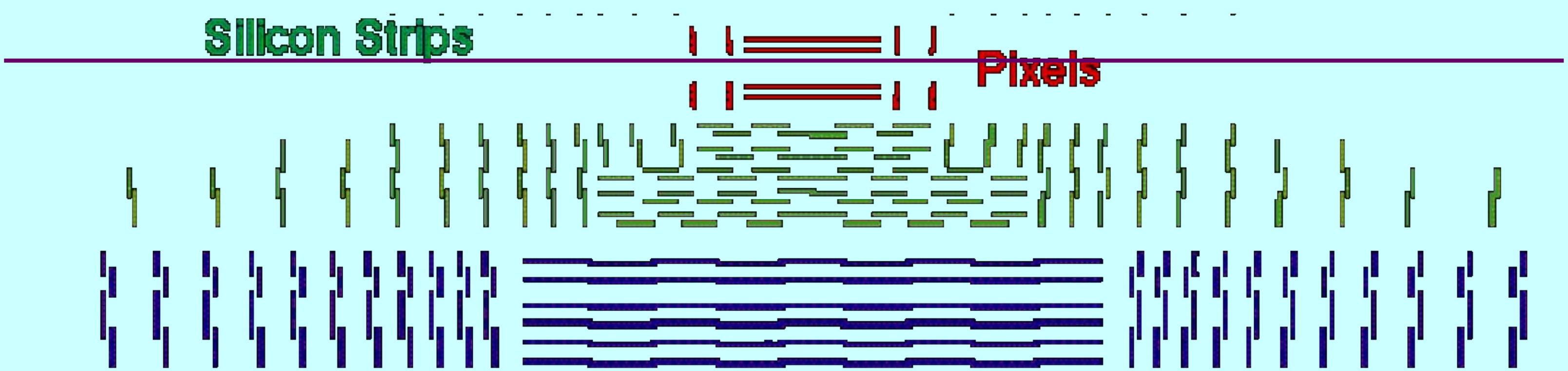
Interactions in CMS



Microstrip tracker system



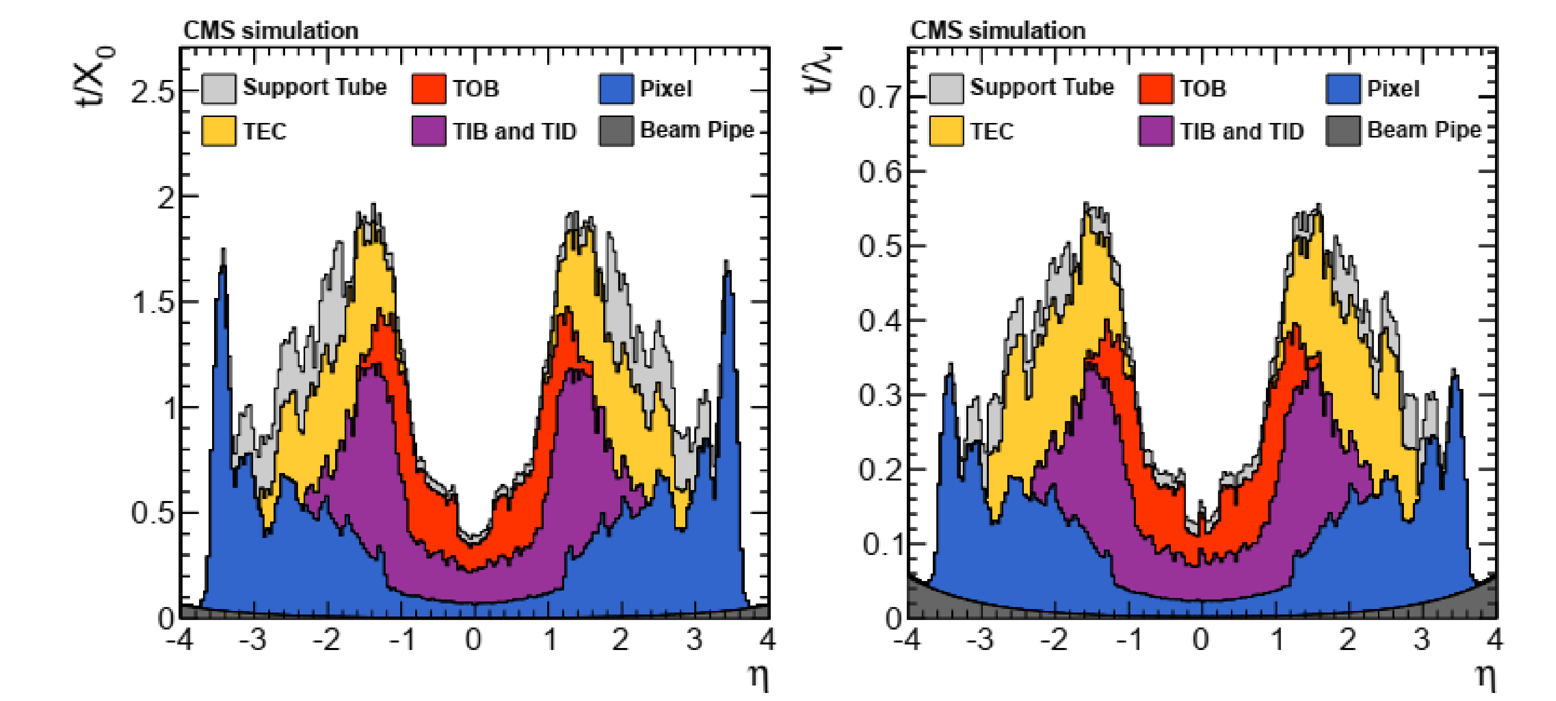
~10M detector channels



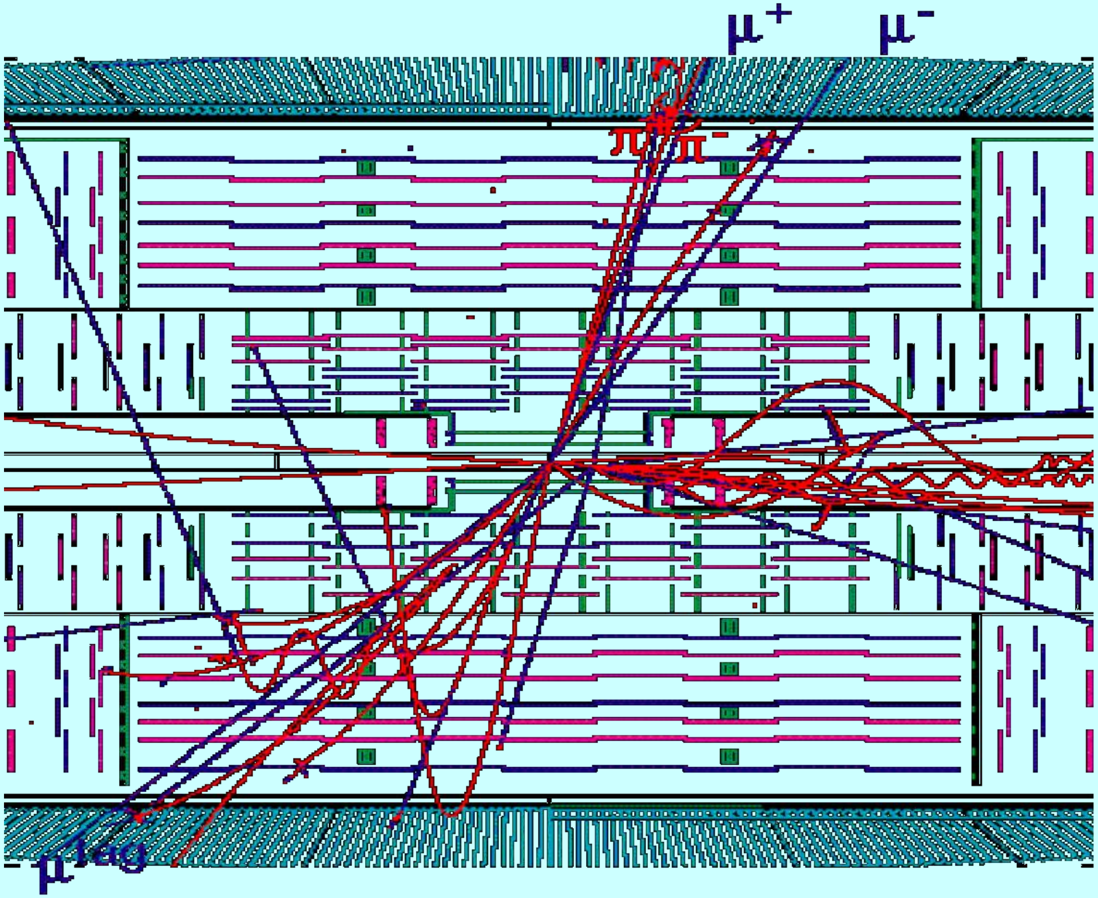
Main components and their X0 and λ as a function of "angle"

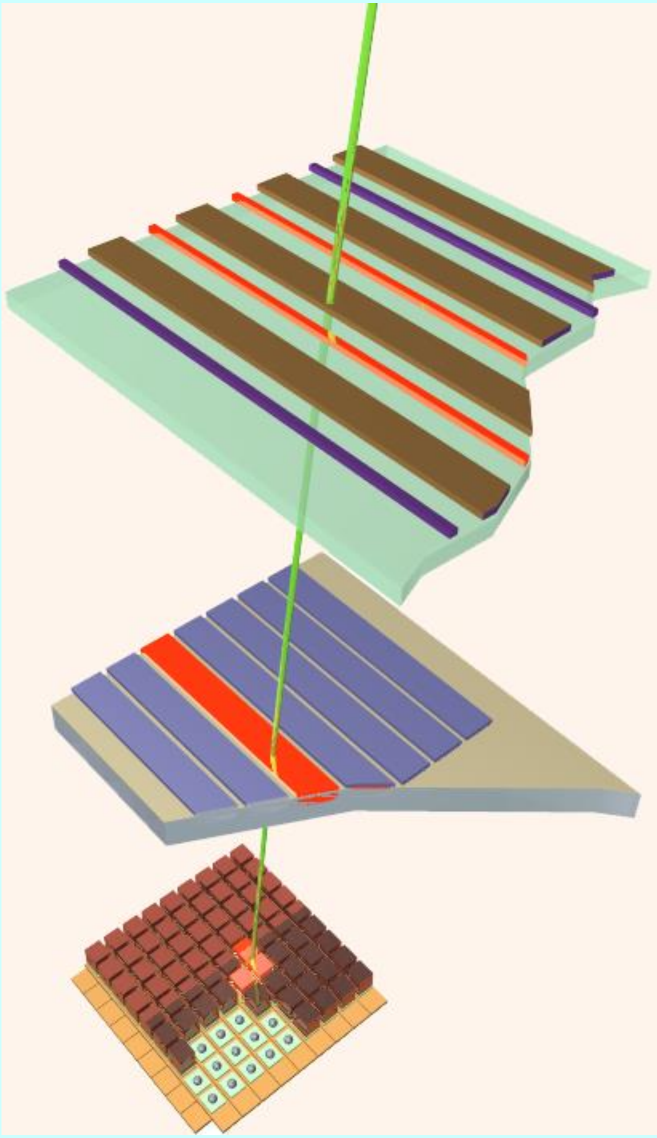
Table 1. A summary of the principal characteristics of the various tracker subsystems. The number of disks corresponds to that in a single endcap. The location specifies the region in r (z) occupied by each barrel (endcap) subsystem.

Tracker subsystem	Layers	Pitch	Location
Pixel tracker barrel	3 cylindrical	$100 \times 150\,\mu m^2$	$4.4 < r < 10.2$ cm
Strip tracker inner barrel (TIB)	4 cylindrical	80–120 μm	$20 < r < 55$ cm
Strip tracker outer barrel (TOB)	6 cylindrical	122–183 μm	$55 < r < 116$ cm
Pixel tracker endcap	2 disks	$100 \times 150\,\mu m^2$	$34.5 < \lvert z \rvert < 46.5$ cm
Strip tracker inner disks (TID)	3 disks	100–141 μm	$58 < \lvert z \rvert < 124$ cm
Strip tracker endcap (TEC)	9 disks	97–184 μm	$124 < \lvert z \rvert < 282$ cm



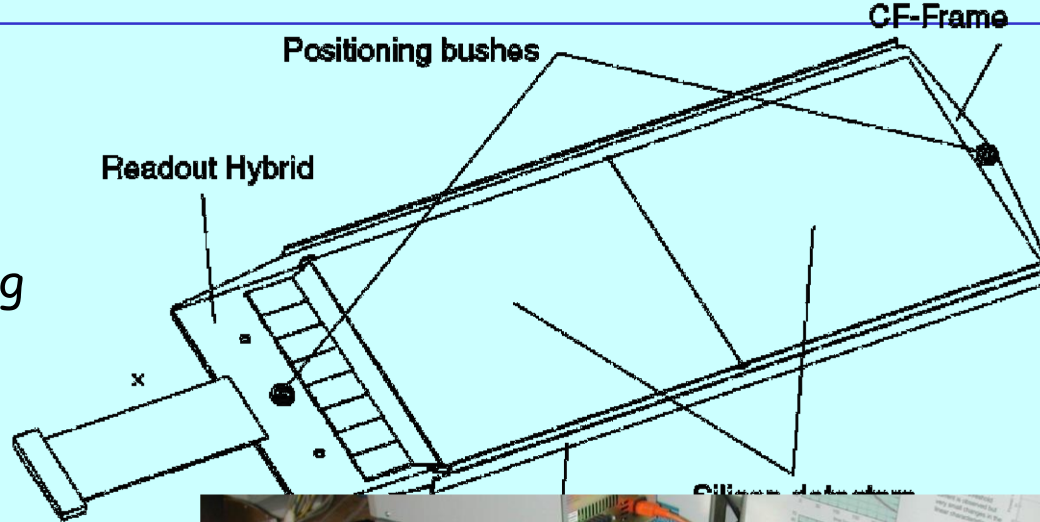
Event in the tracker



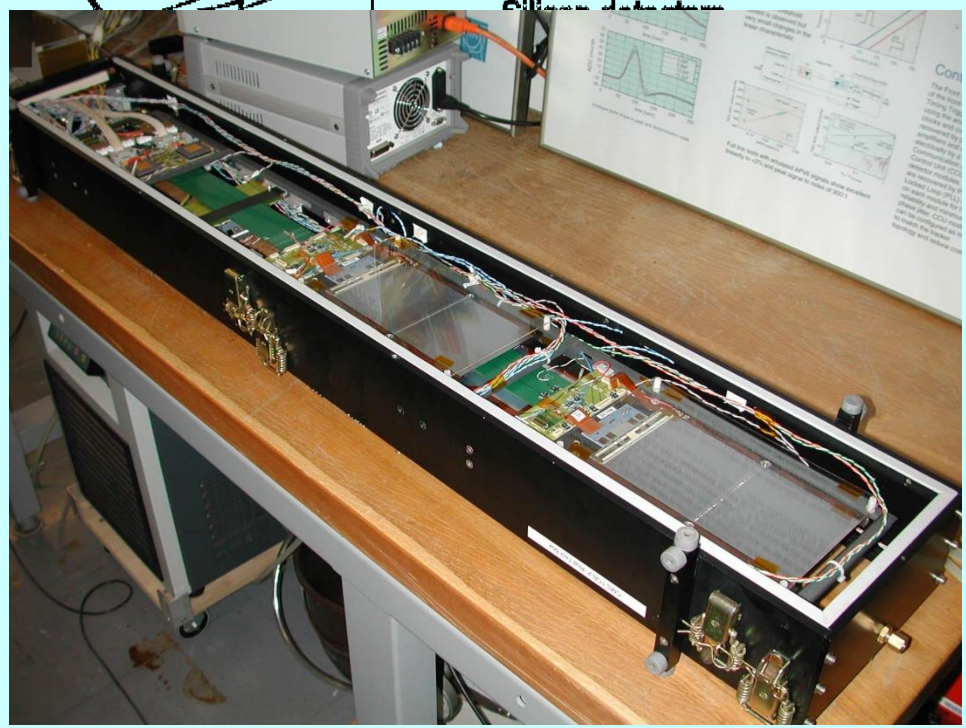


Silicon detector modules

- Constraints on tracker
  - minimal material
  - high spatial precision
  - sensitive detectors requiring
    - low noise readout
  - power dissipation ~50kW
    - in 4T magnetic field
  - radiation hard
  - Budget



- Requirements
  - large number of channels
  - limited energy resolution
  - limited dynamic range



Radiation environment

- Particle fluxes

  Charged and neutral particles from interactions ~ $1/r^2$

  Neutrons from calorimeter

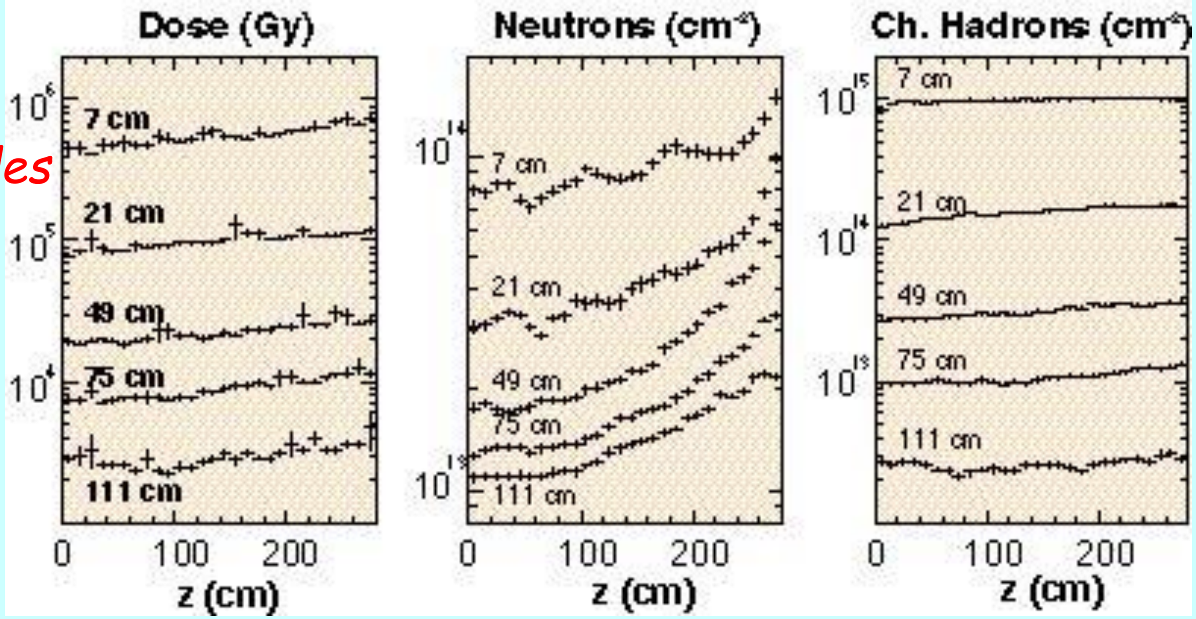
  nuclear backsplash + thermalisation ≈ more uniform gas

  only E > 100keV damaging

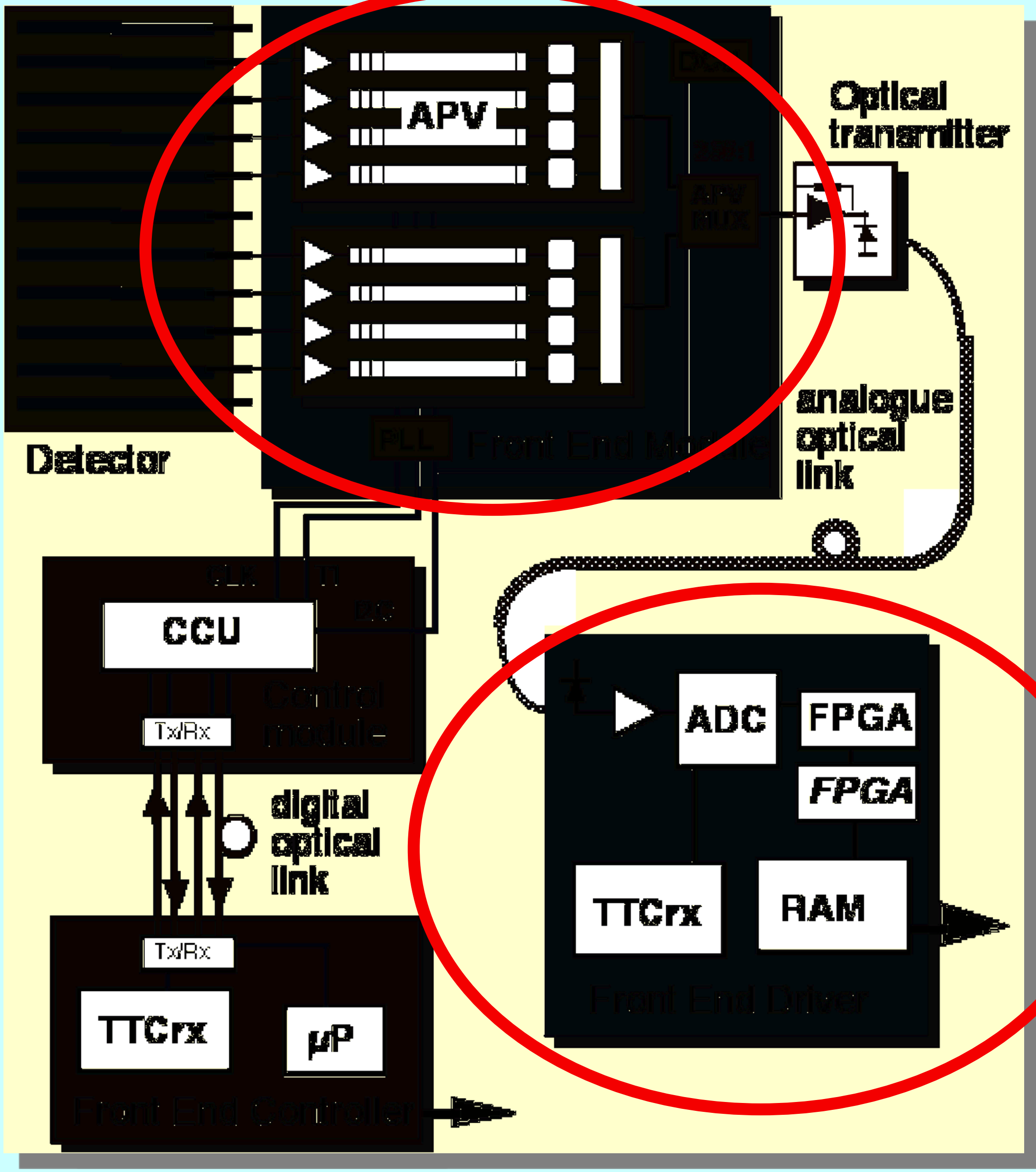
- Dose energy deposit per unit volume

  Gray = 1Joule/kg = 100rad

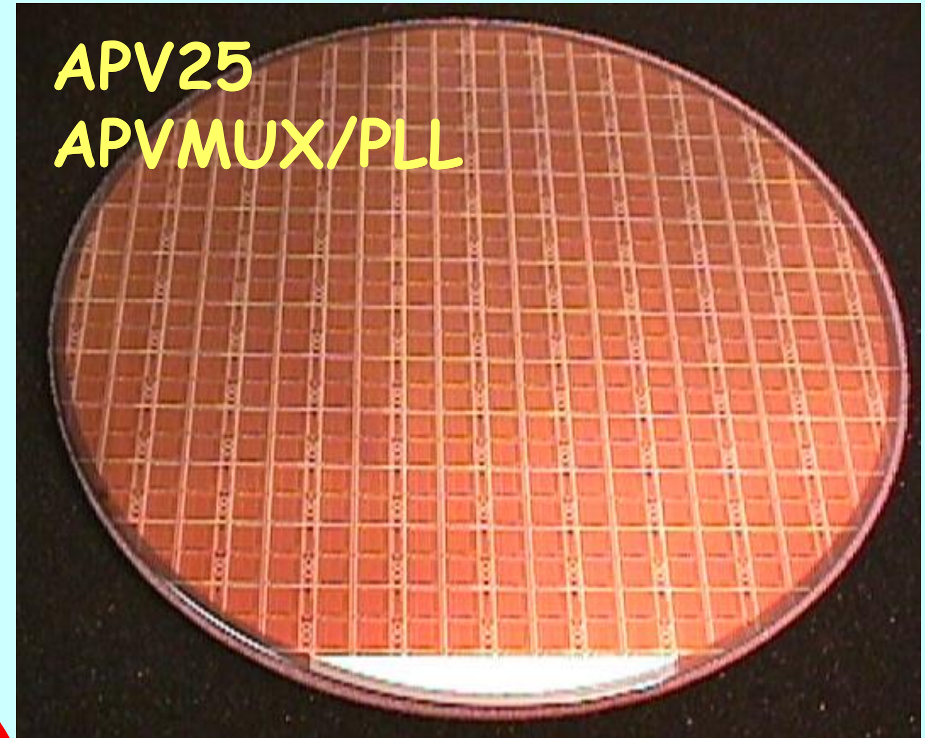
  mostly due to charged particles



Trackr readout electronics (APV and FED developed by Imperial College London)

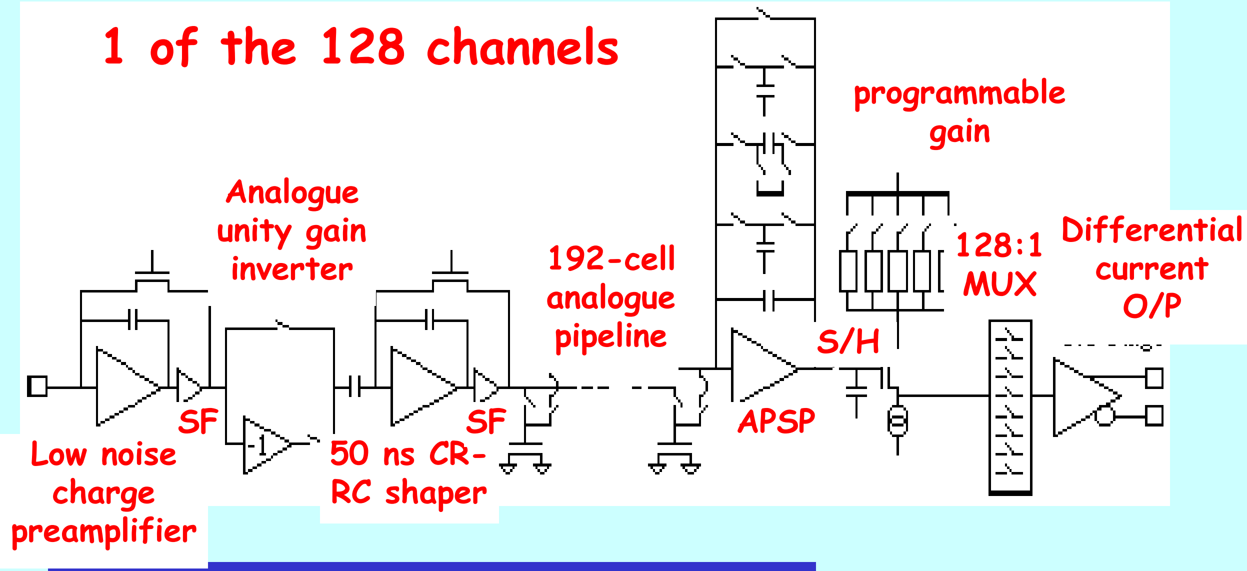


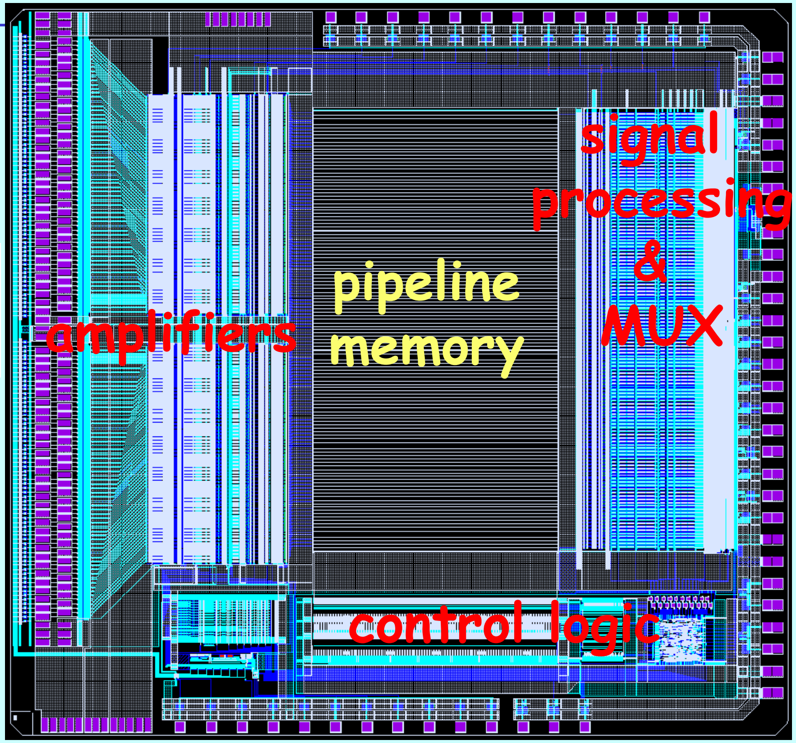
FED

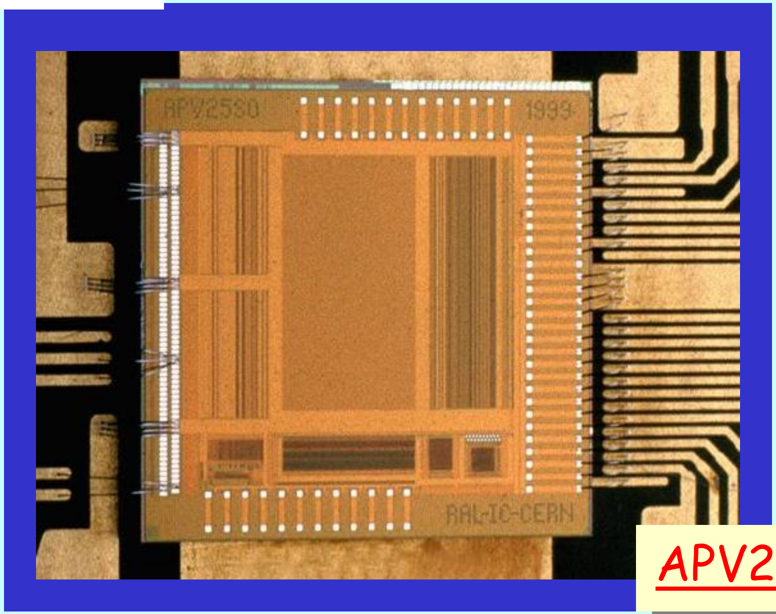


- Hardware development
- Hardware construction
- Beam tests & studies
- Preparation for physics

APV25 0.25μm CMOS







APV25-S0 (Oct 1999)

APV25-S1 (Aug 2000)

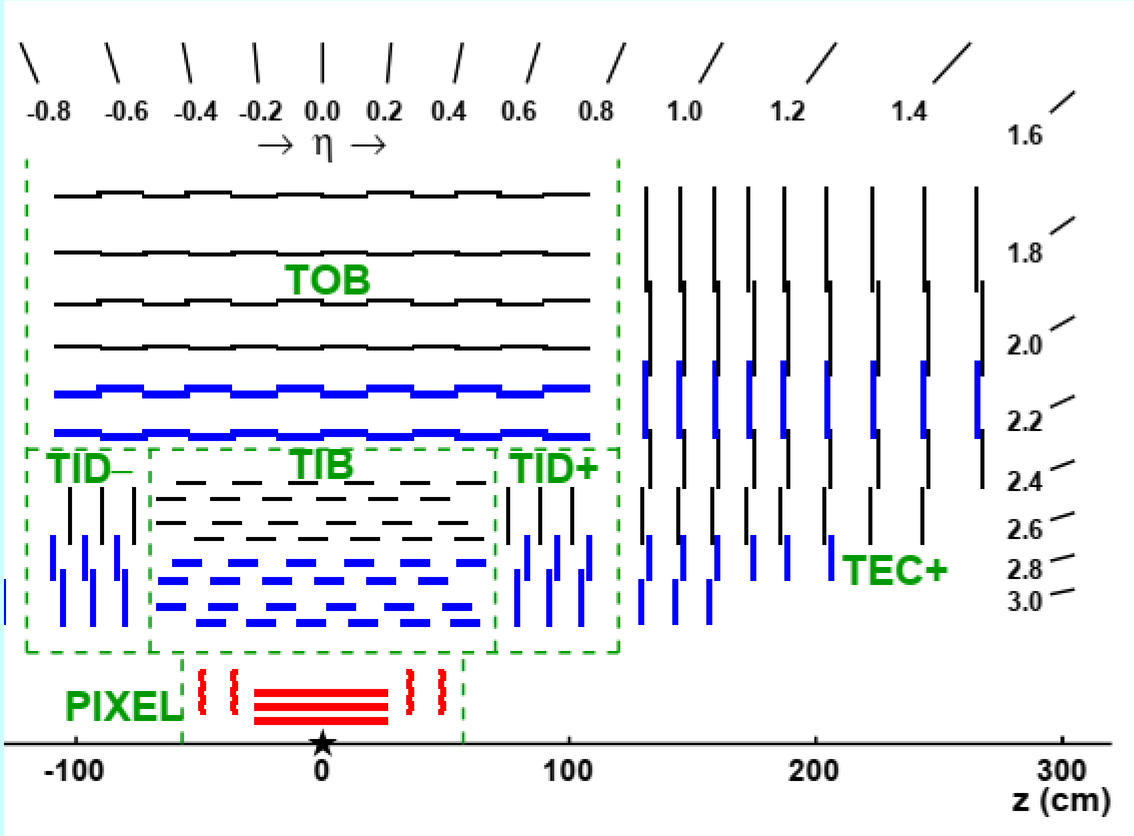
Chip Size 7.1 x 8.1 mm

Final

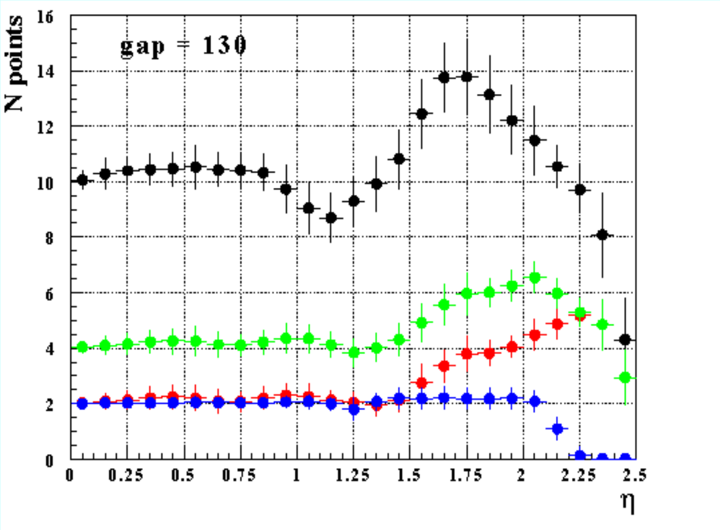
The CMS Tracking Strategy

- Rely on "few" measurement layers,
  each able to provide robust (clean) and precise coordinate determination

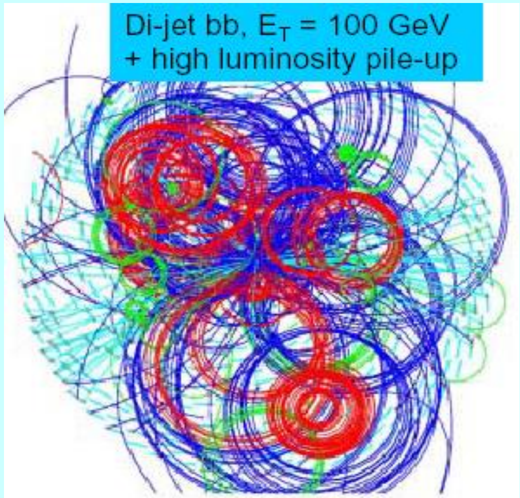
2-3 Silicon Pixel
10 - 14 Silicon Strip Layers



Number of hits by tracks:
Total number of hits
Double-side hits
Double-side hits in thin detectors
Double-side hits in thick detectors

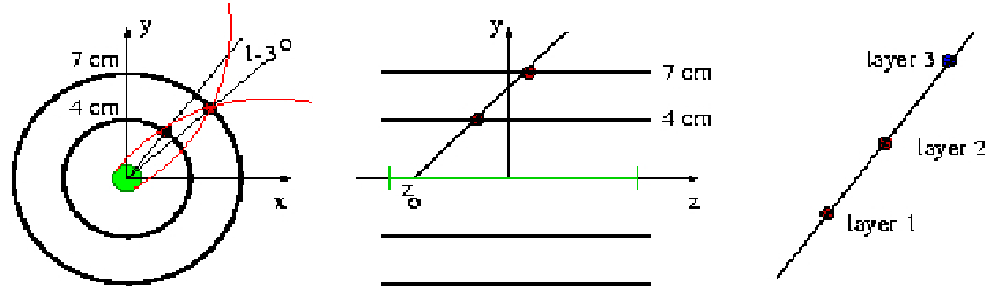


Vertex Reconstruction



Primary vertices: use pixels!

Simple algorithm using pixel detector



1. Match hit pairs from 1st two layers (barrel & endcaps) in R-φ and z-R
   - constraints from minimal p_T, maximal d_0
2. Valid pairs are matched with hit in 3rd layer → track candidates
3. Establish primary vertex candidates where ≥3 tracks cross the z-axis
4. Identify most likely "signal" vertex from Σp_T and number of tracks
5. Erase tracks not pointing to signal vertex

At high luminosity, the trigger primary vertex is found in >95% of the events

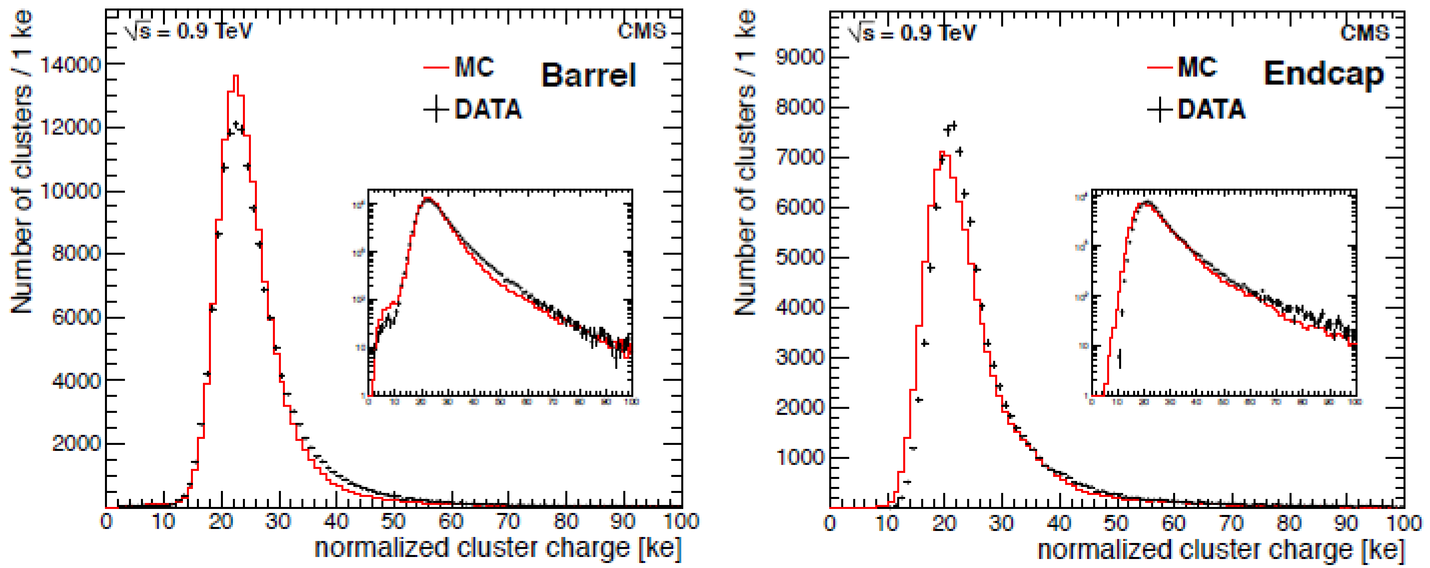
How does it perform at the LHC?

CERN-PH-EP/2010-019
2010/07/14

CMS-TRK-10-001

CMS Tracking Performance Results from Early LHC Operation

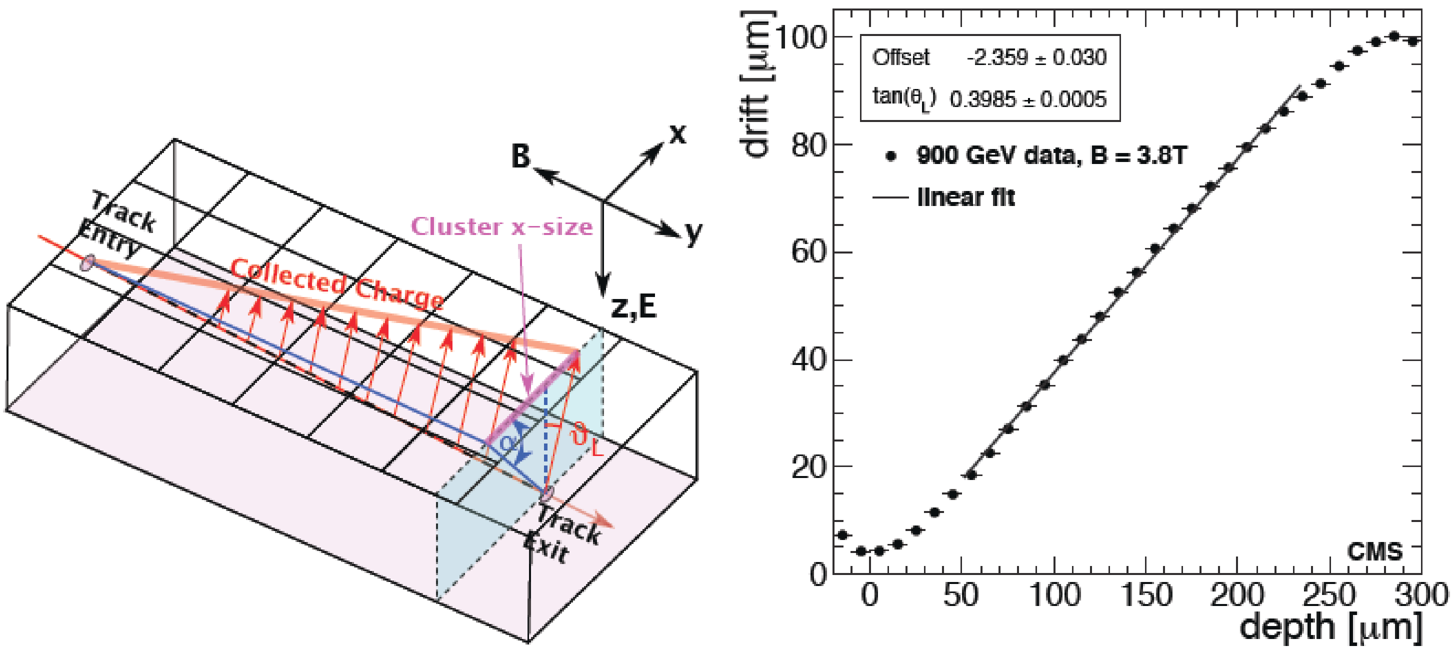
The CMS Collaboration*



(a) (b)

Figure 4: The normalized cluster charge measured in the (a) barrel and (b) endcap pixel detectors for the sample of 0.9 TeV minimum bias events. The insets show the same distributions on semi-log scales.

How does it perform at the LHC?



(a) (b)

Figure 5: (a) The pixel local coordinate system and track angle definitions. The local z axis coincides with the sensor electric field $\vec{E}$. The local x axis is chosen to be parallel to $\vec{E} \times \vec{B}$ where $\vec{B}$ is the axial magnetic field. The local y axis is defined to make a right-handed coordinate system. The angle α is the angle between the x axis and the track projection on the local xz plane. (b) The transverse cluster displacement of highly inclined barrel clusters as a function of depth for a sample of 0.9 TeV minimum bias events at a magnetic field of 3.8 T. The tangent of the Lorentz angle is given by the slope of a linear fit which is shown as the solid line.

How does it perform at the LHC?

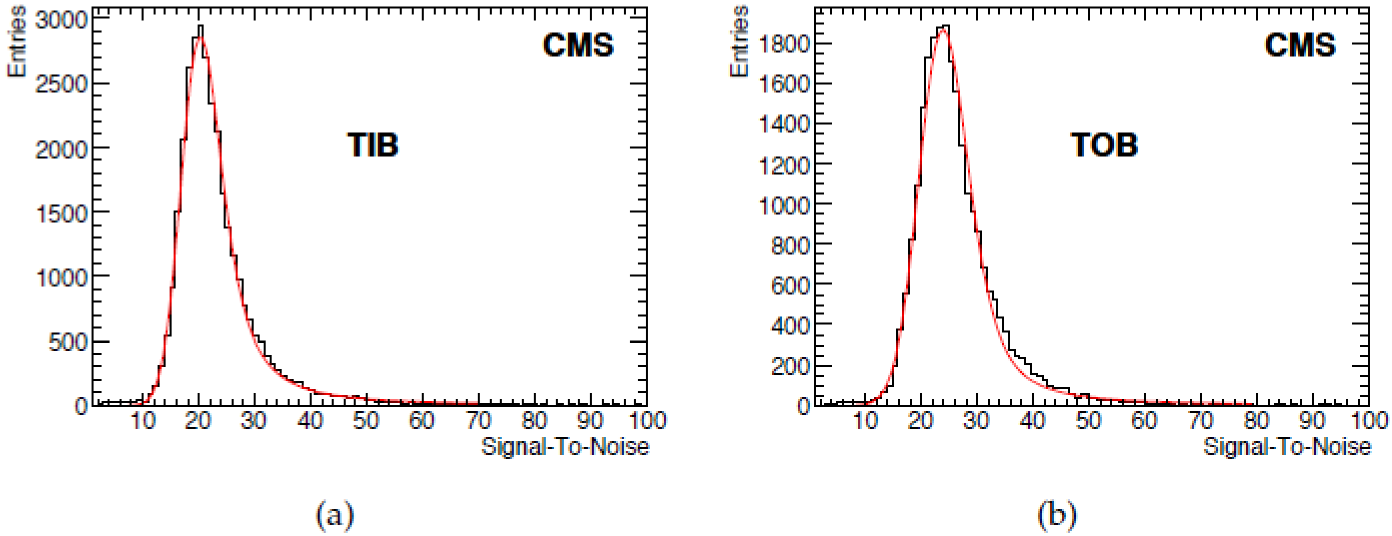
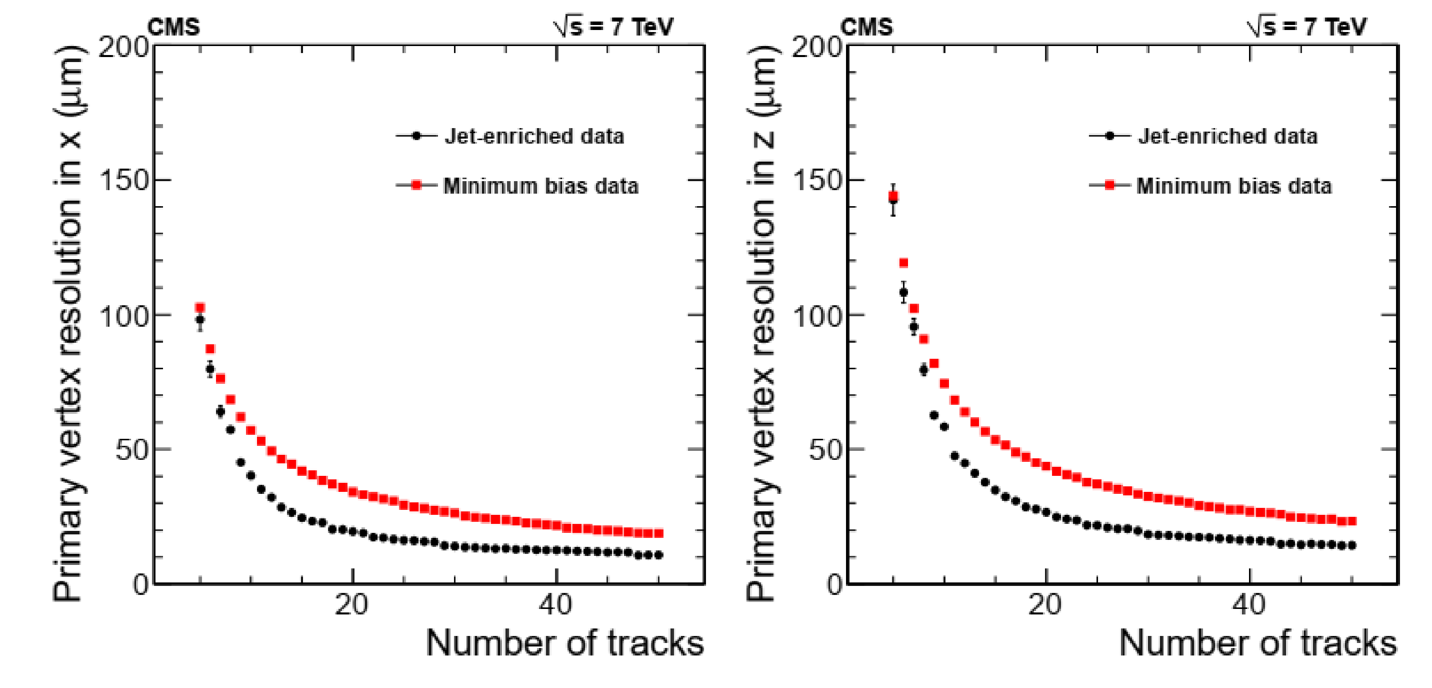
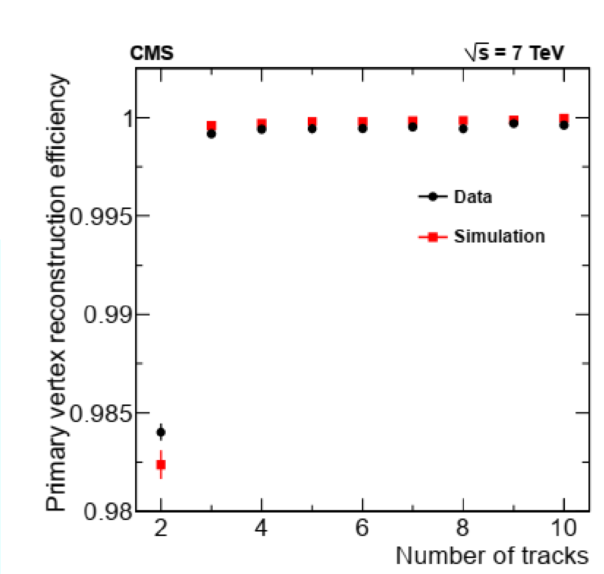


Figure 7: Signal-to-Noise distributions in deconvolution mode for (a) (thin sensor) TIB and (b) (thick sensor) TOB modules. The curves are results of the fits to a Landau distribution convoluted with a Gaussian distribution.

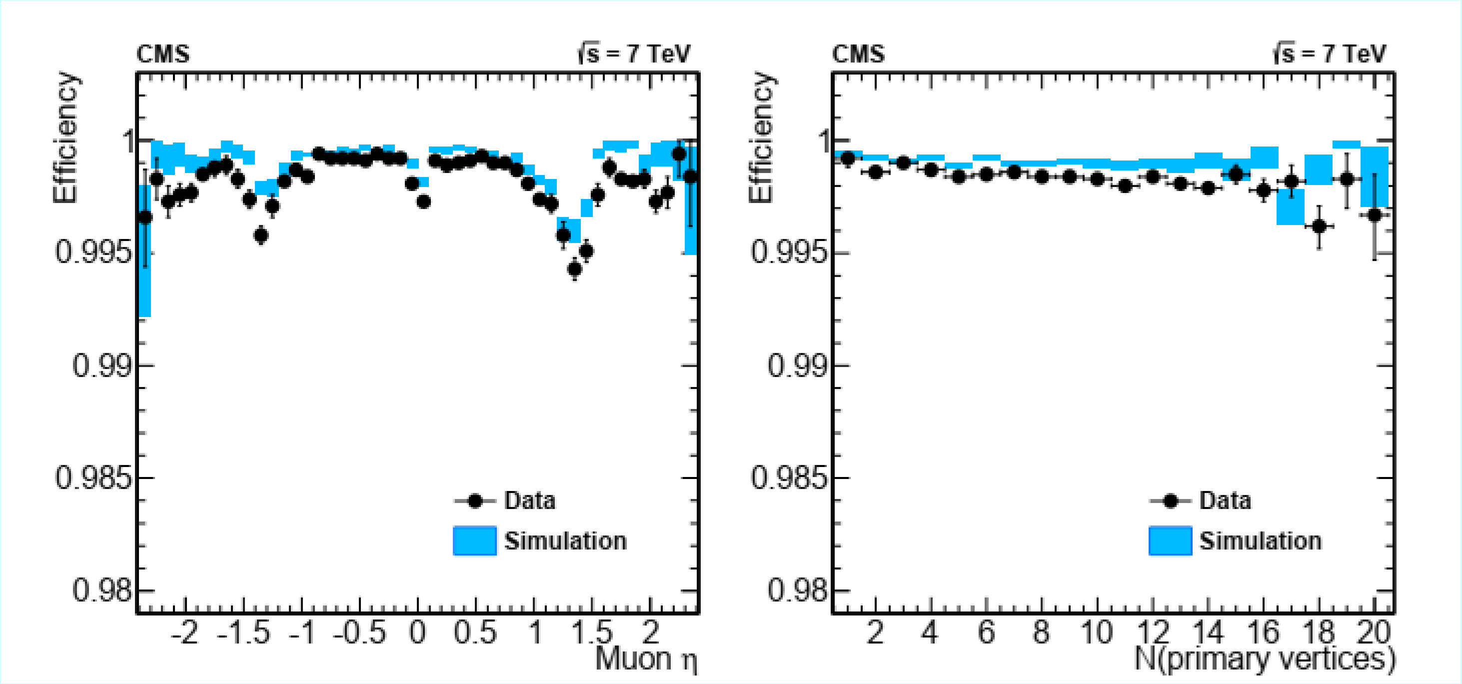
Published results

"Description and performance of track and primary-vertex reconstruction with the CMS tracker", *JINST* **9** (2014) P10009





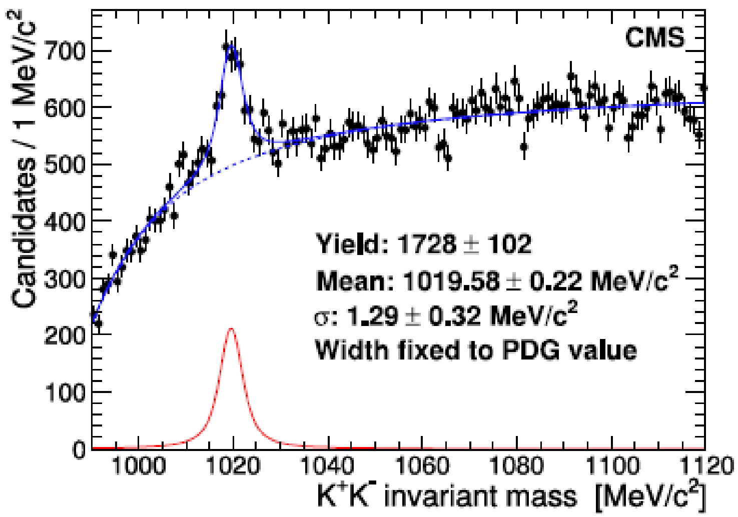
Efficiency for muons from Z boson decay



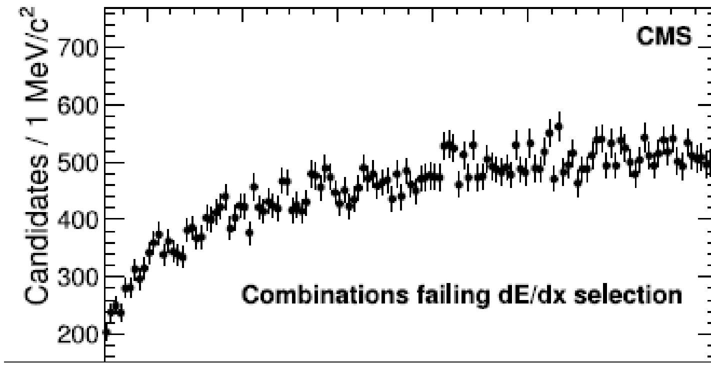
dE/dx

- Using dE/dx data to fit the KK invariant mass distribution to detect the $\phi(1020)$.

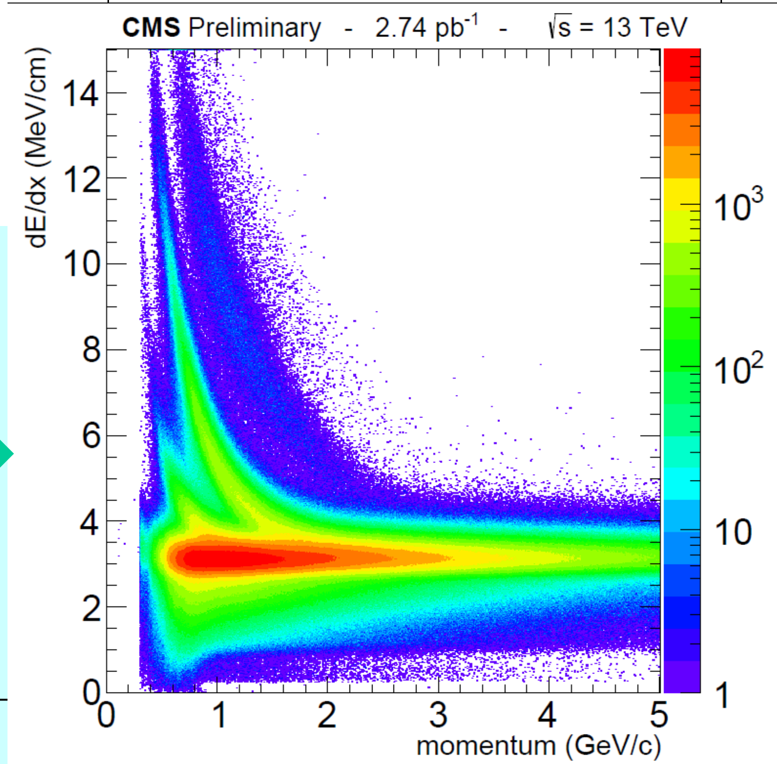
Fig. 15 K^+K^- invariant mass distribution, with (**a**) both kaons satisfying the dE/dx requirement and with (**b**) at least one particle failing that requirement. In (**a**) a fit to the $\phi(1020)$ hypothesis is shown



(a)

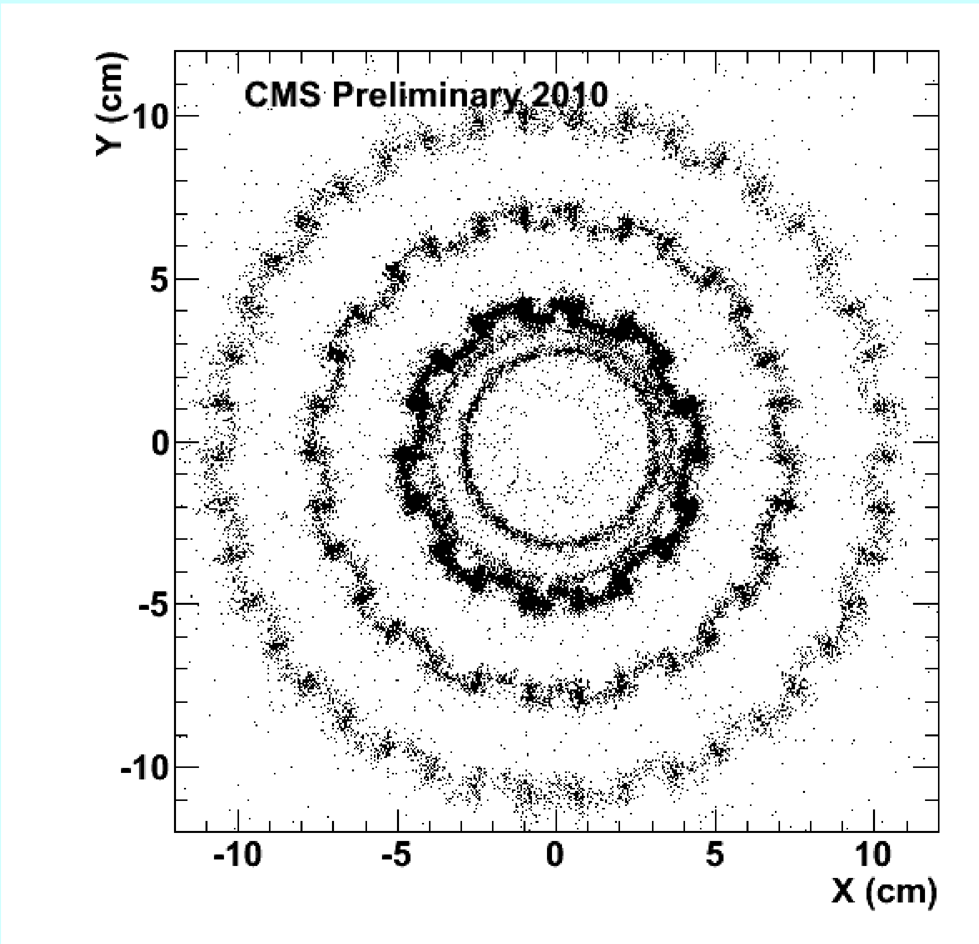


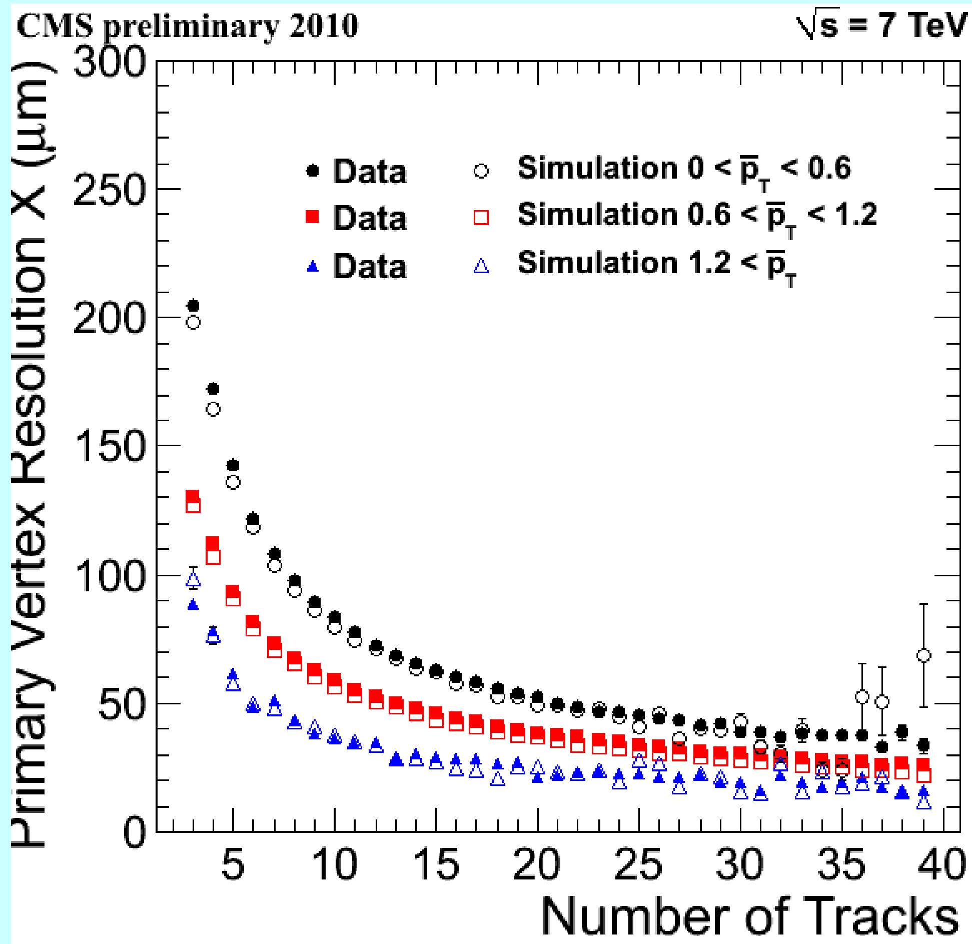
13 TeV data



Photon conversions in the pixel layers

- Reconstructed photon conversions (photon "radiography")





Finding the cooling pipes!

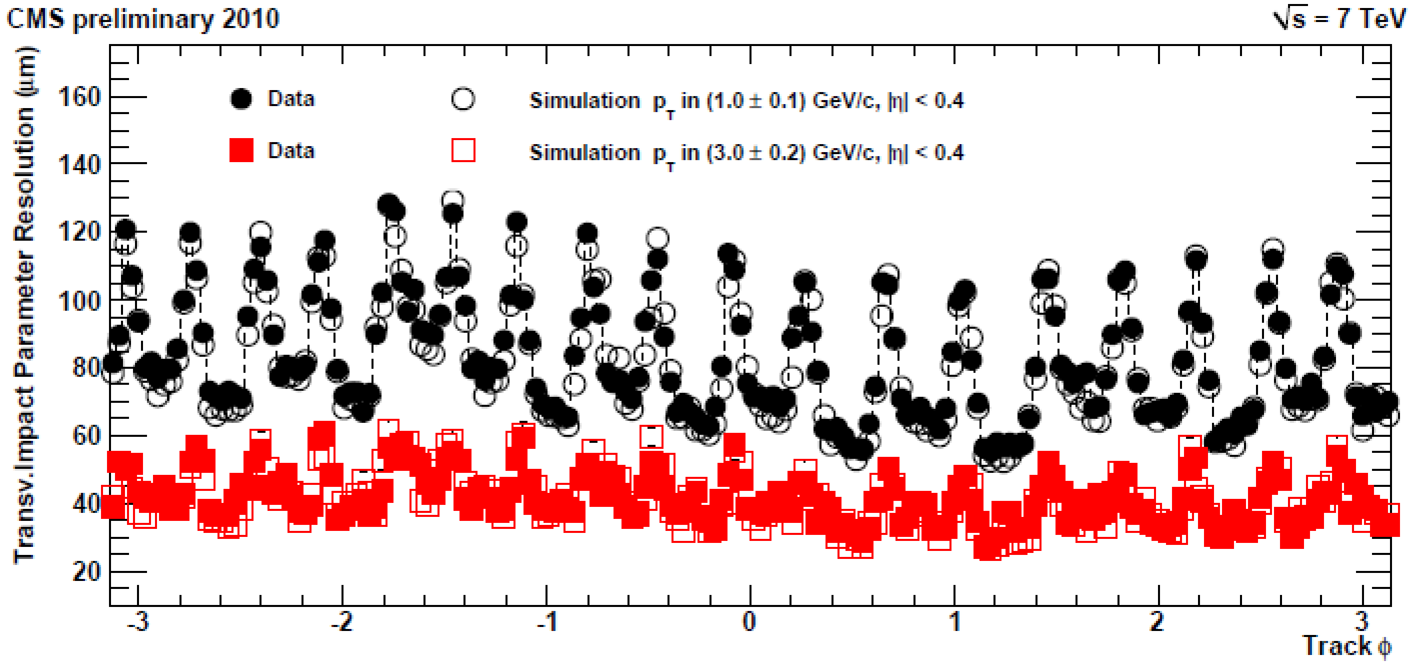
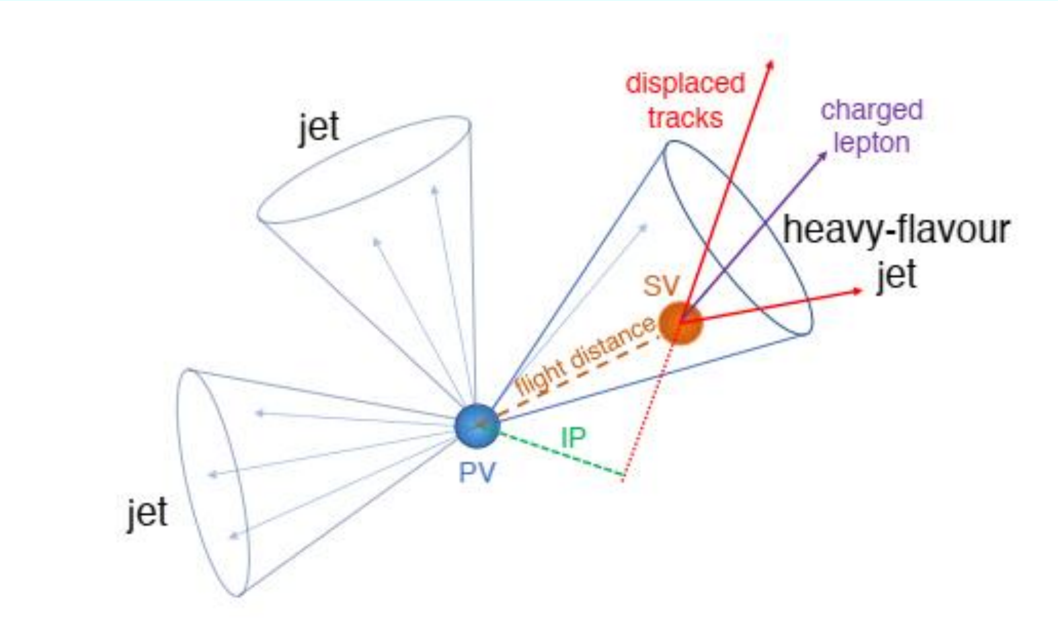
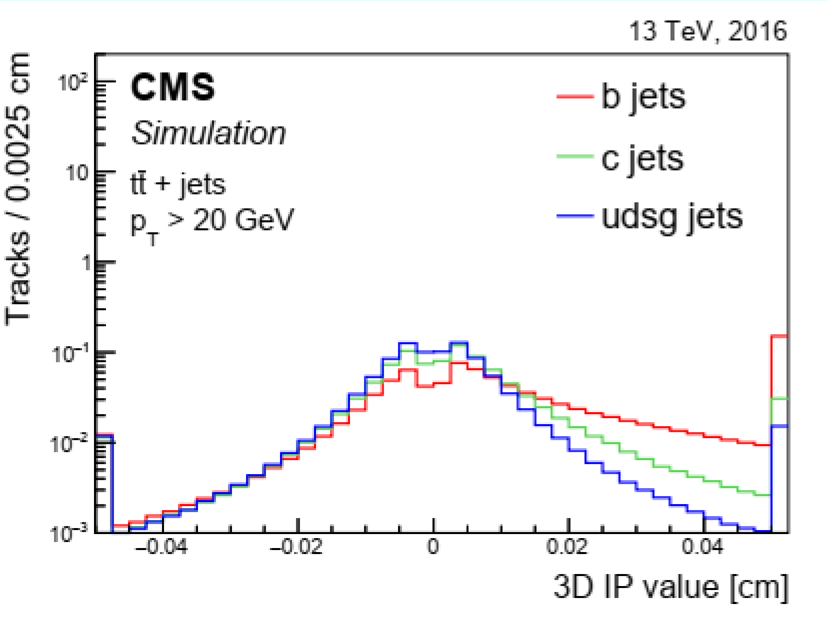


Figure 2: Resolution of the transverse impact parameter depending on the azimuthal angle ϕ for two different track p_t ranges. The "oscillating" structure is due to the cooling pipes of the inner layer of the pixel detector.

Secondary vertex b-tagging

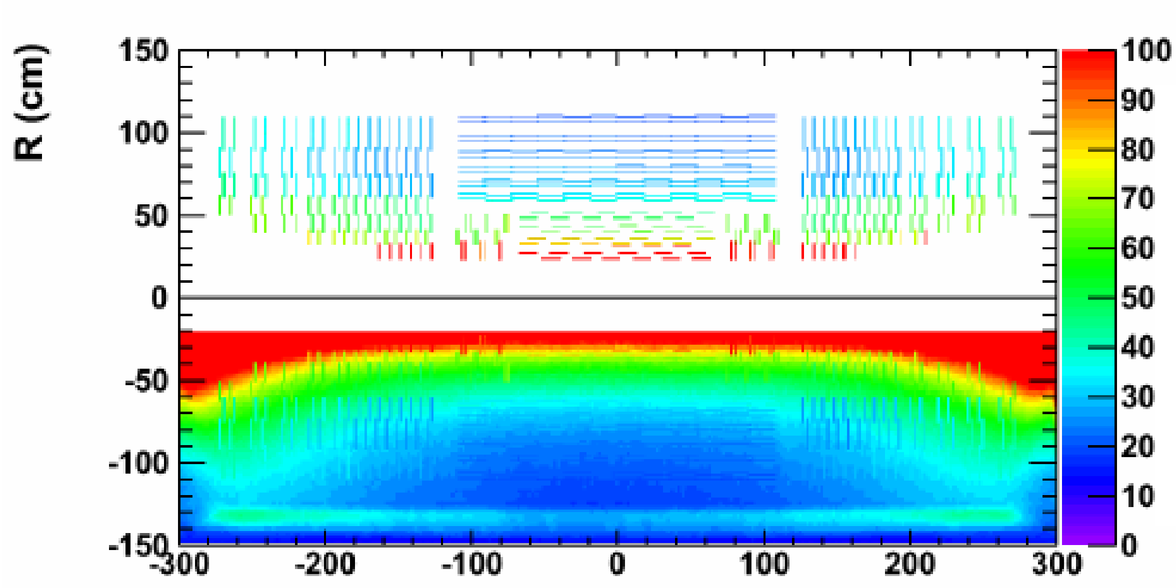




PV = primary vertex, SV = secondary vertex
IP = impact parameter
Jet = correlated collection of hadrons coming from an unseen primary quark or gluon

“Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018) P05011

Leakage Currents in Strips



Fluka sim.: 1MeV eq. neutrons with data overlapped

Leakage current (top) and simulated 1 MeV neutron equivalent dose (bottom)

Leakage current vs radius