CMS Tracking Detector case study

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

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Prof Peter R Hobson C.Phys M.Inst.P.
Department of Electronic and Computer Engineering
Brunel University London, Uxbridge

Peter.Hobson@brunel.ac.uk

Development of a tracking detector for physics at the Large Hadron Collider

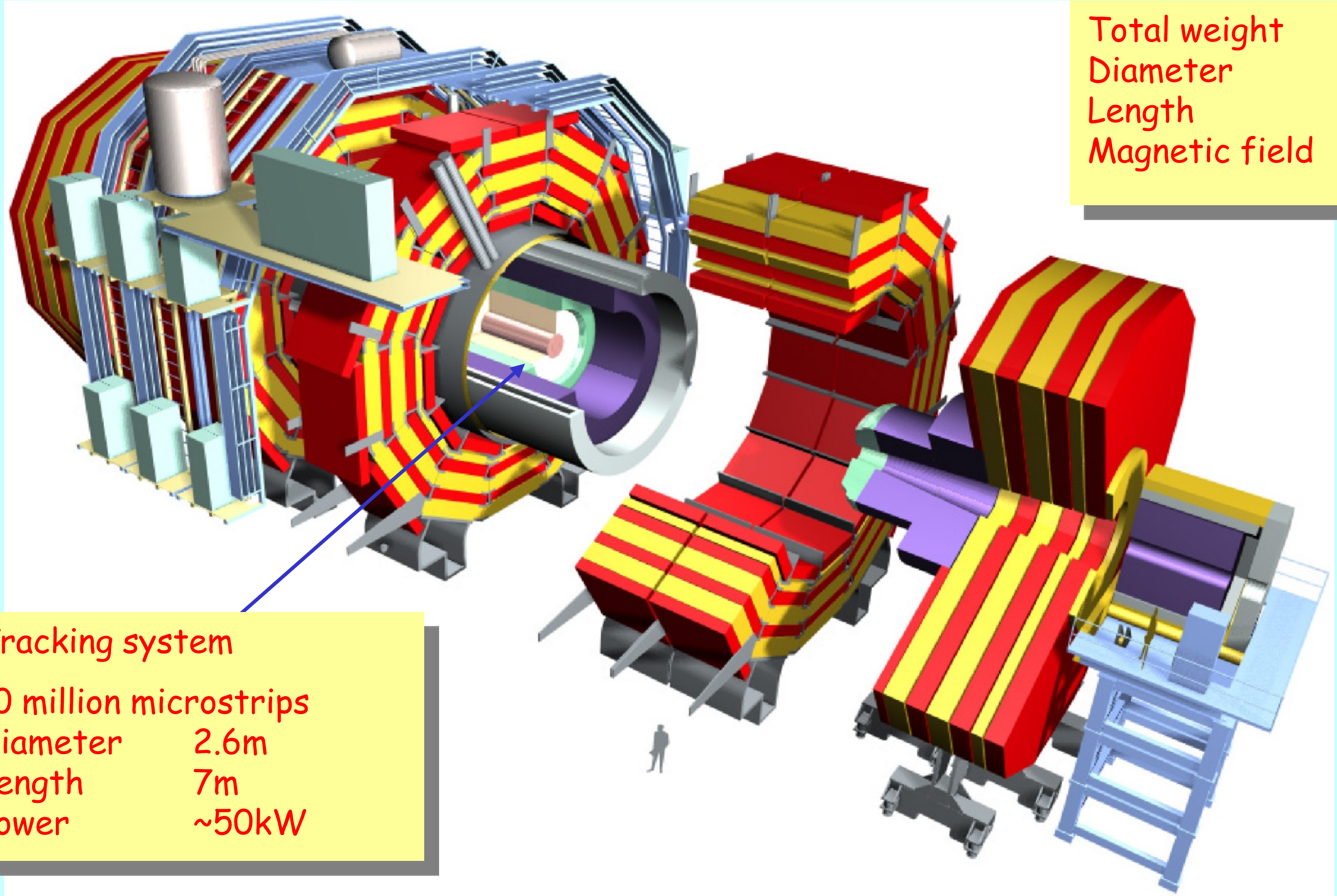
Geoff Hall

CMS = Compact Muon Solenoid detector

- missing element in current theoretical framework - mass

14000 t

Total weight	12,500 tons
Diameter	15m
Length	21.6m
Magnetic field	4T



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

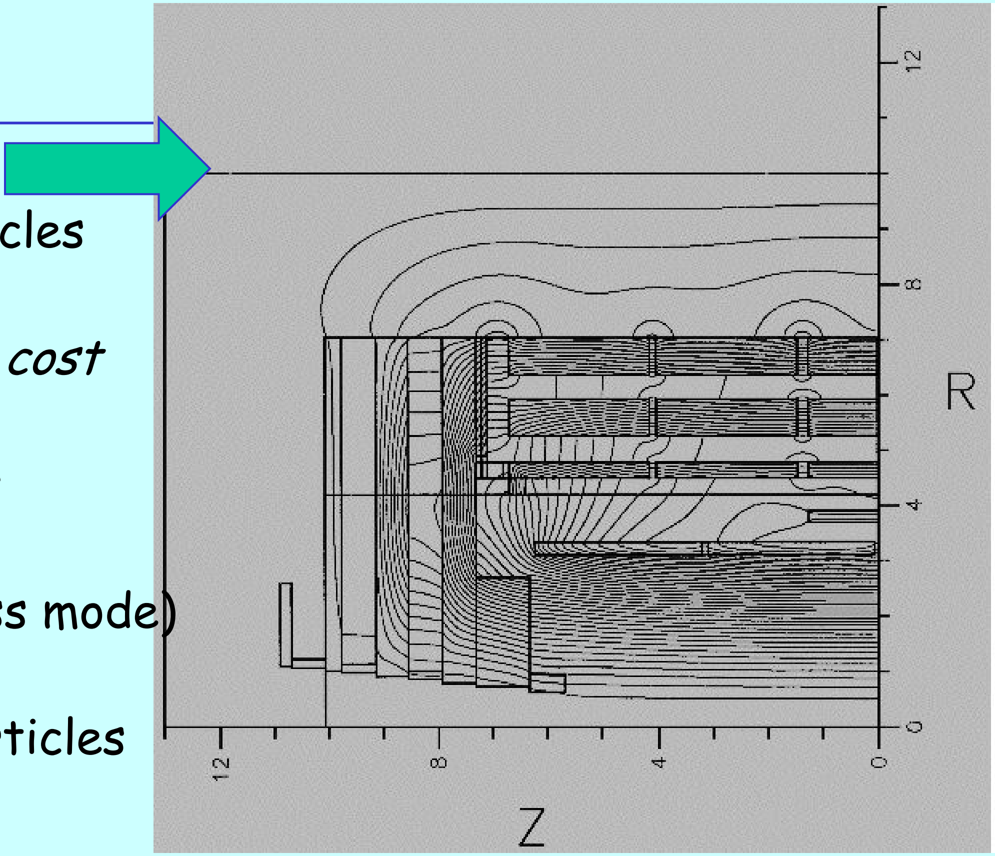
  High (low) radiation exposure
  High (low) B field operation

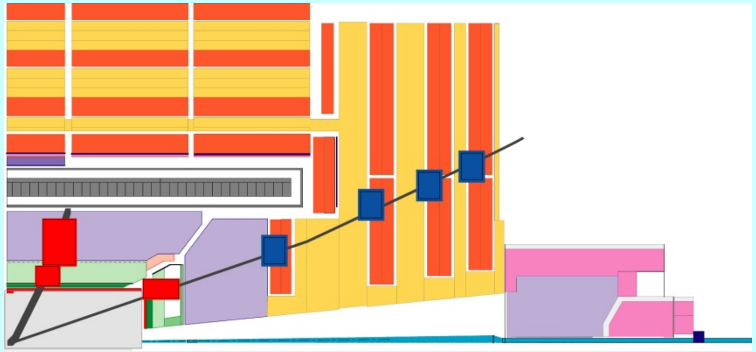
  Very large data volumes

  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*

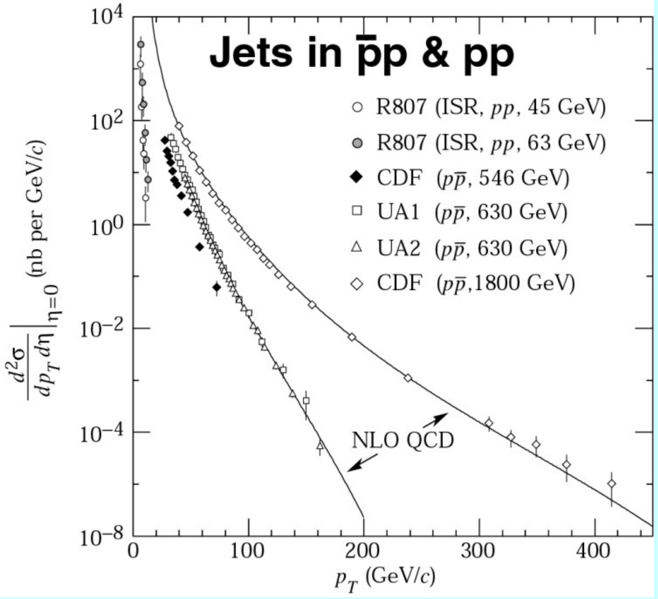




Parameters for hadronic collider physics

- E, *p*, *cos*θ, ϕ prefer variables which easily Lorentz transform *e.g E, p_T, p_L, ϕ*
- ***p_T*** *divergences from simple behaviour could imply new physics*

  eg heavy particle decay => high p_T lepton (or hadron)



- rapidity

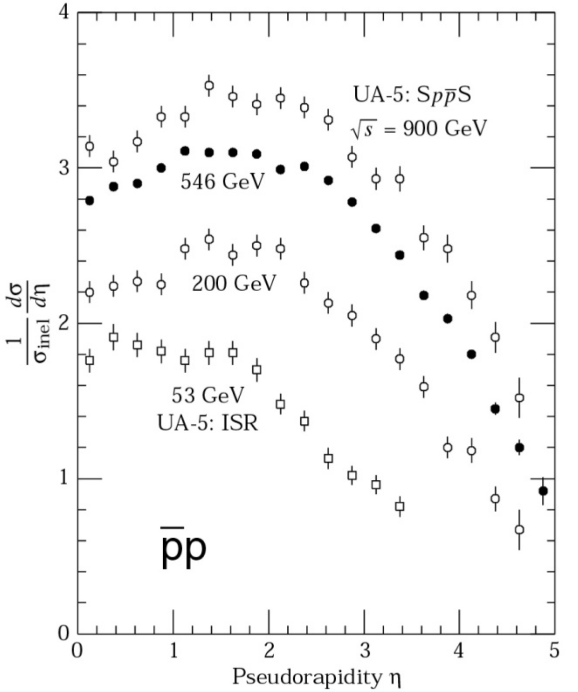
$$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right) \qquad dy = \frac{dp_L}{E}$$

Lorentz boost

$$y \rightarrow y' = y + \frac{1}{2}\ln\left(\frac{1+\beta}{1-\beta}\right) \;=>\; \frac{dN}{dy} \quad \textit{invariant}$$

- pseudorapidity

$$y = \frac{1}{2}\ln\left(\frac{\cos^2(\theta/2) + \frac{m^2}{4p^2} + \ldots}{\sin^2(\theta/2) + \frac{m^2}{4p^2} + \ldots}\right) \approx -\ln\tan(\theta/2) \equiv \eta$$



LHC

$$\frac{d^2 N_{charged}}{d\eta . dp_T} \approx H.f(p_T) \qquad \mathrm{H} \sim 6 \quad |\eta| < 2.5$$

Physics requirements (I)

- Mass peak - one means of discovery

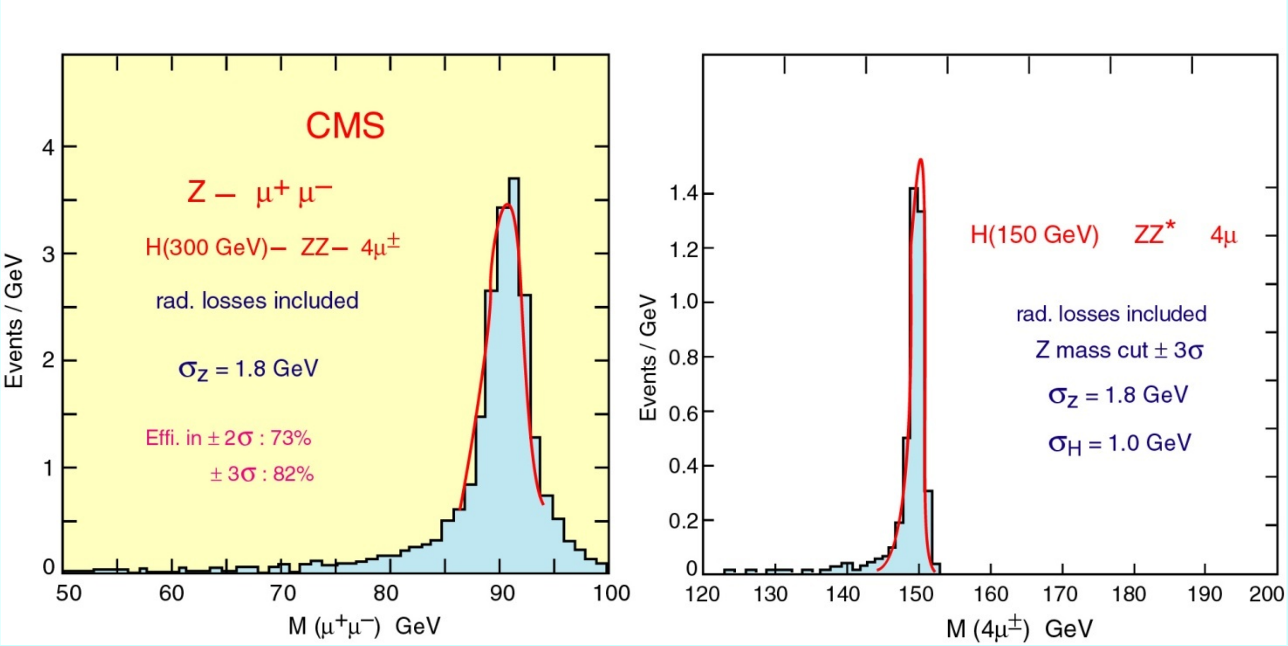
$$m^2 = \sum_i E_i^2 - p_i^2$$

=> small $\sigma(p_T)$

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

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

Mass resolution for muon final states



- 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

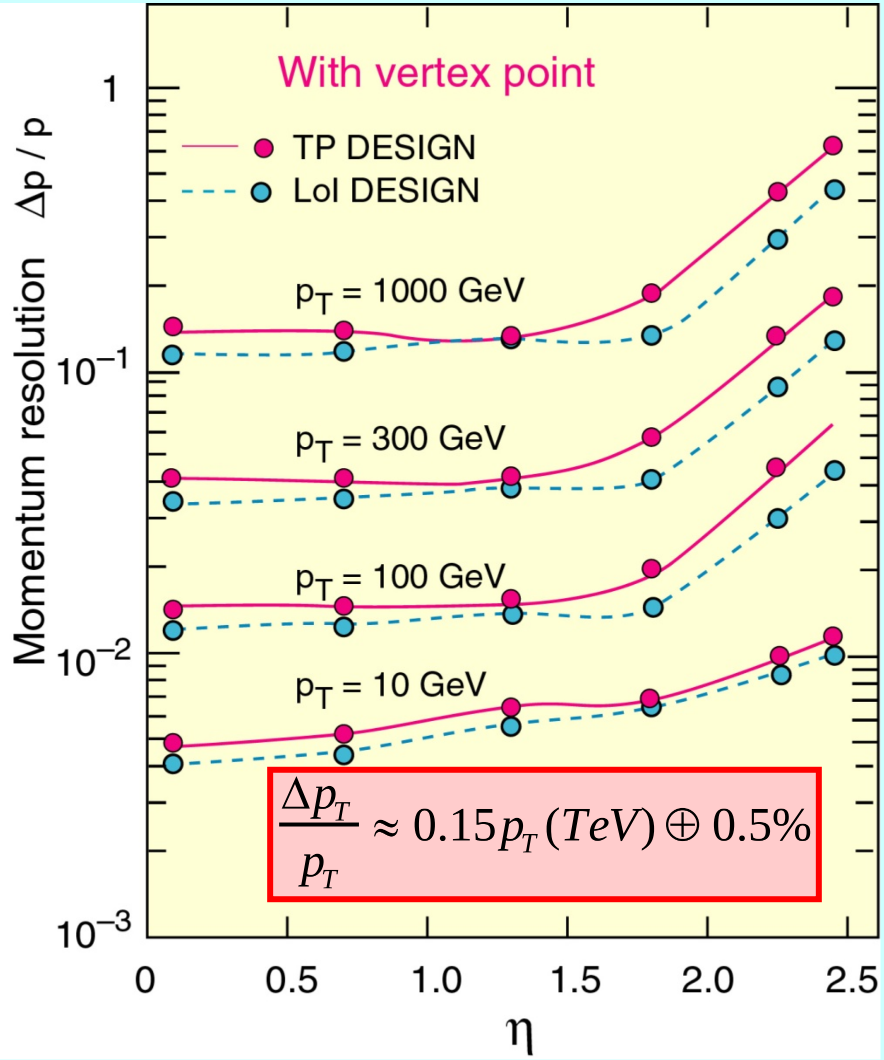
  low occupancy => many channels

  good pattern recognition

- minimise multiple scattering
- minimal bremsstrahlung, photon conversions

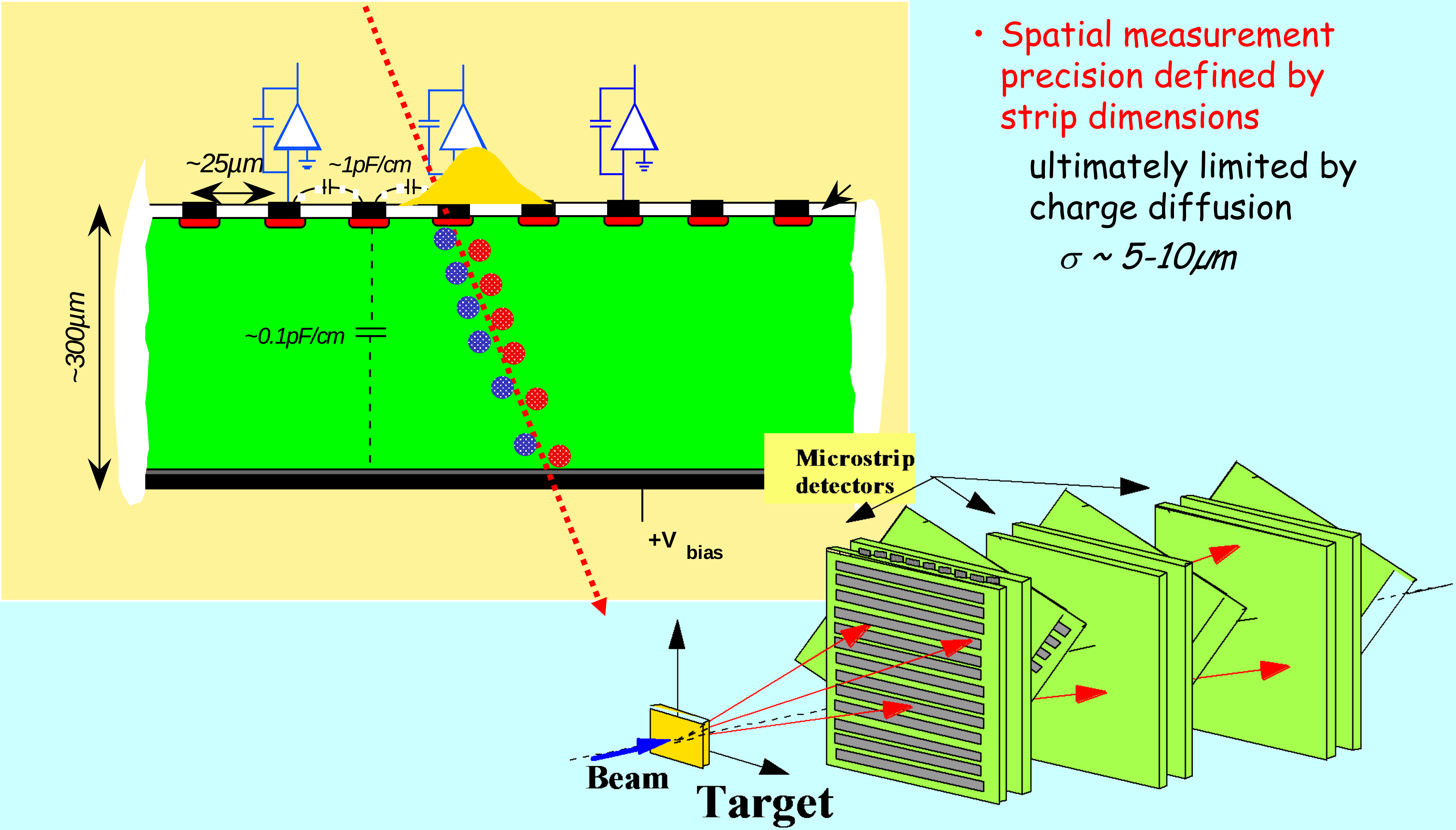
  material in tracker

  most precise points close to beam



$$\frac{\Delta p_T}{p_T} \approx 0.15 p_T(TeV) \oplus 0.5\%$$

Silicon diodes as position detectors

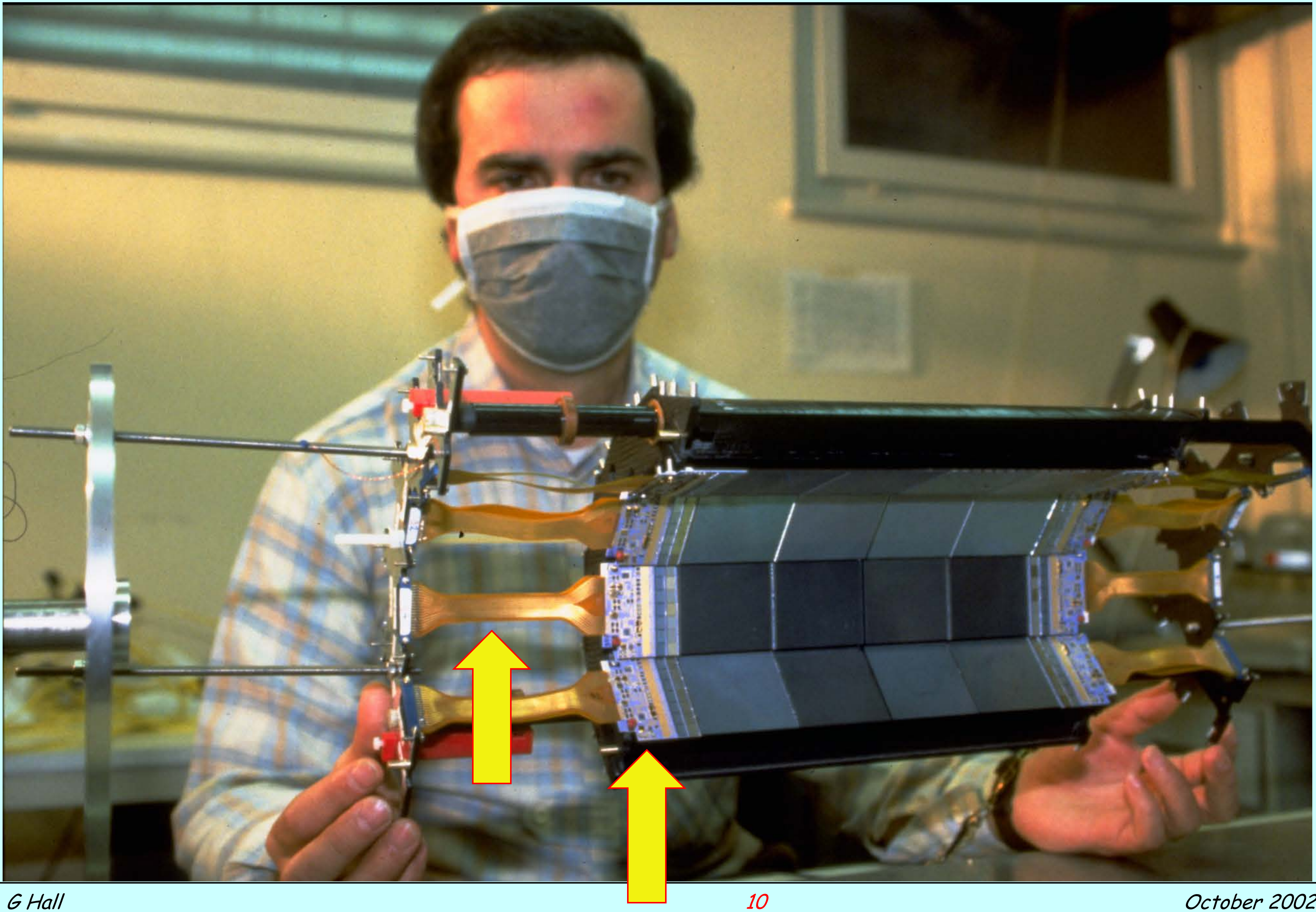


- Spatial measurement precision defined by strip dimensions

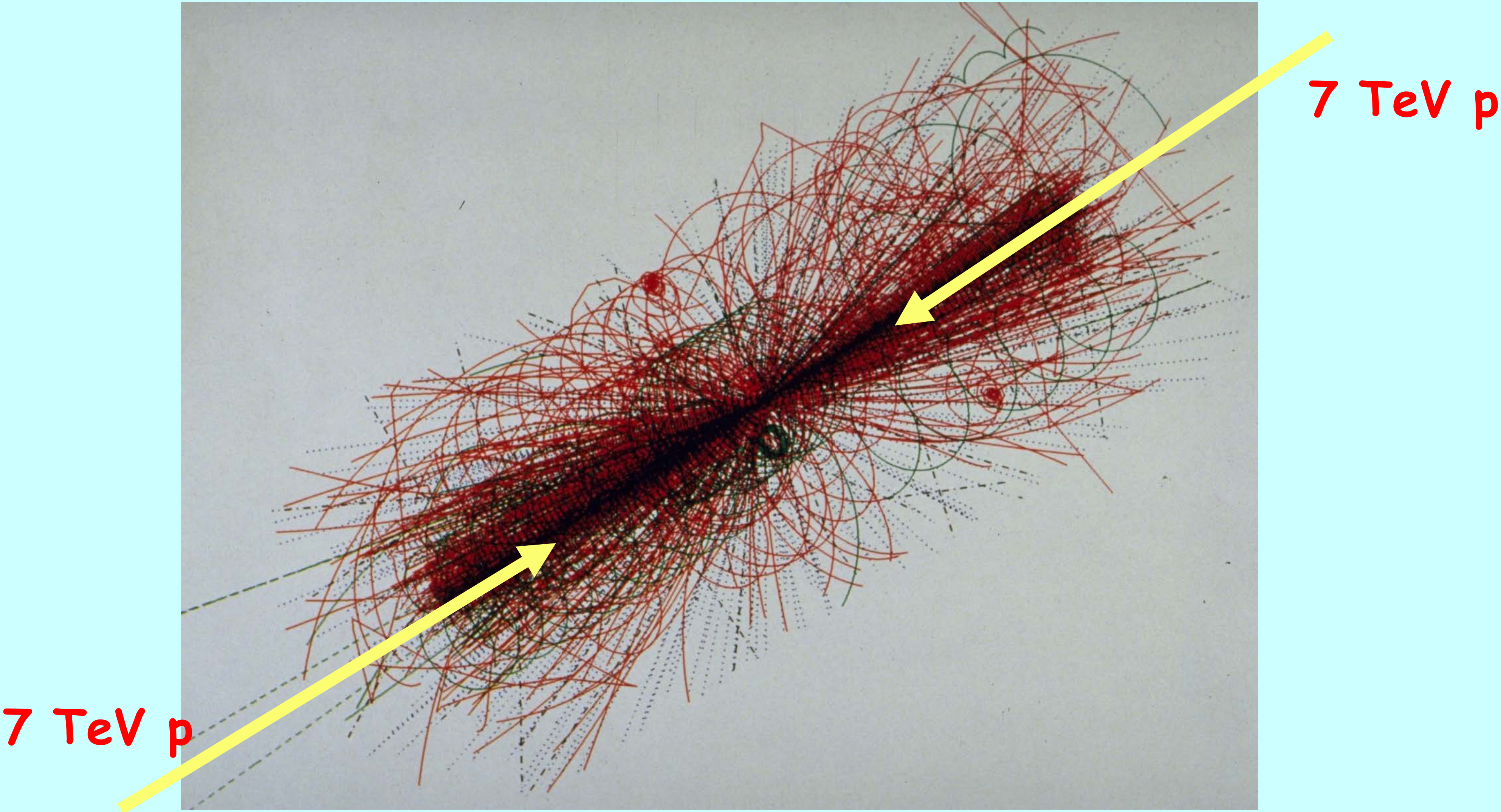
  ultimately limited by charge diffusion

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

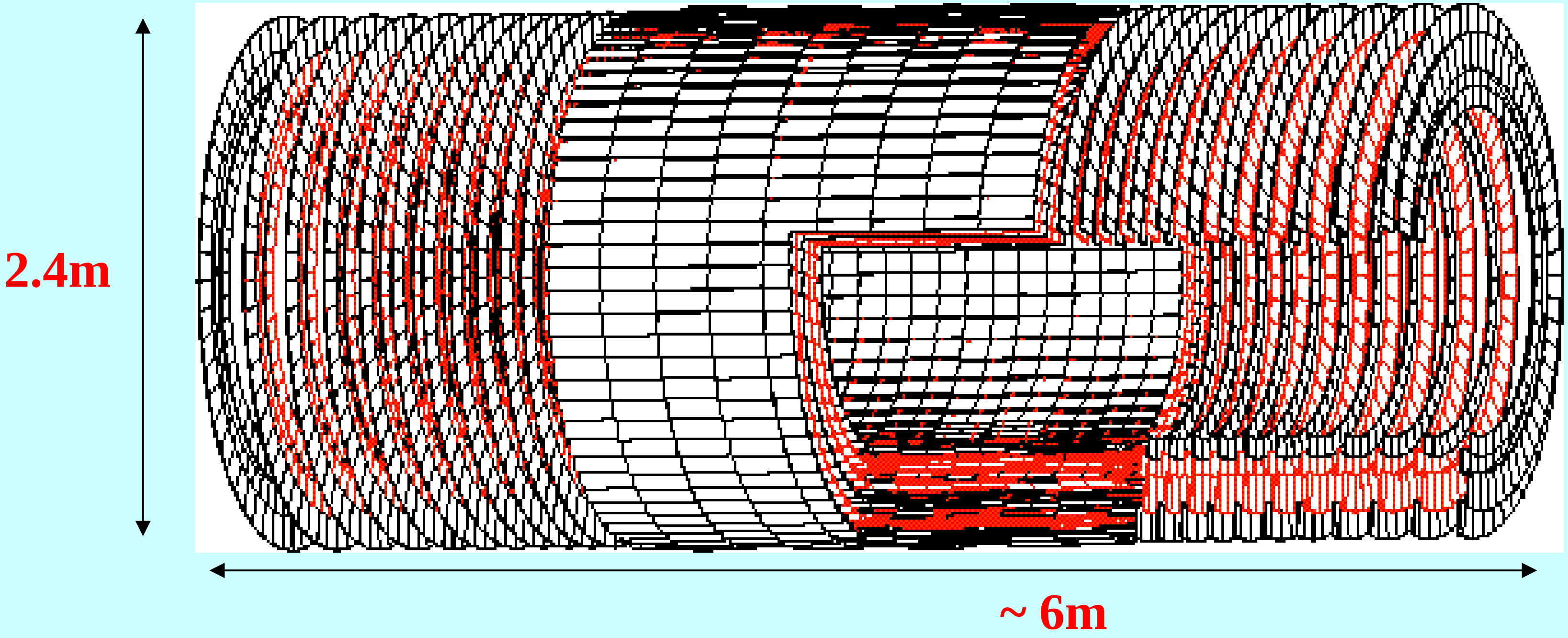
Vertex detector ~1990



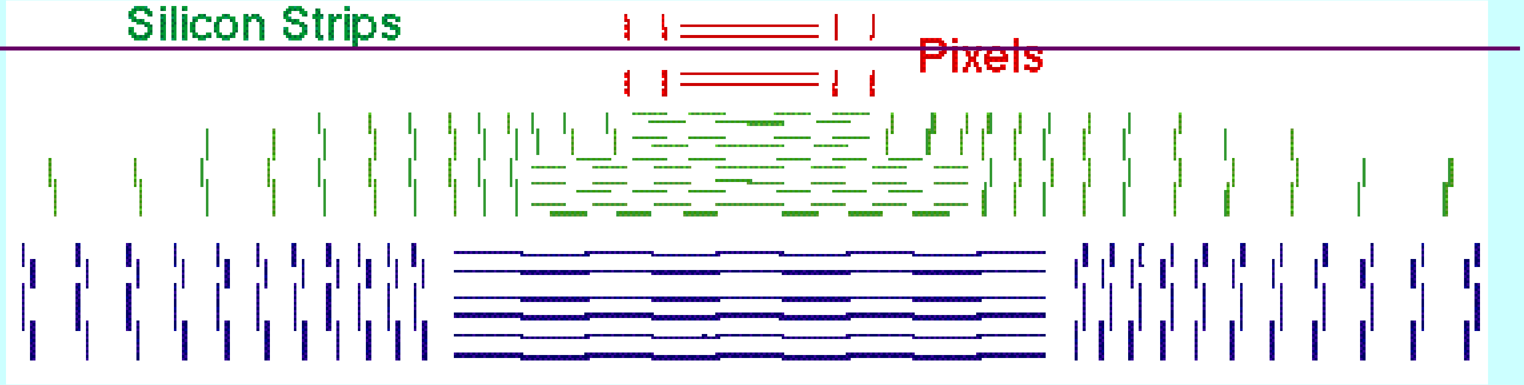
Interactions in CMS



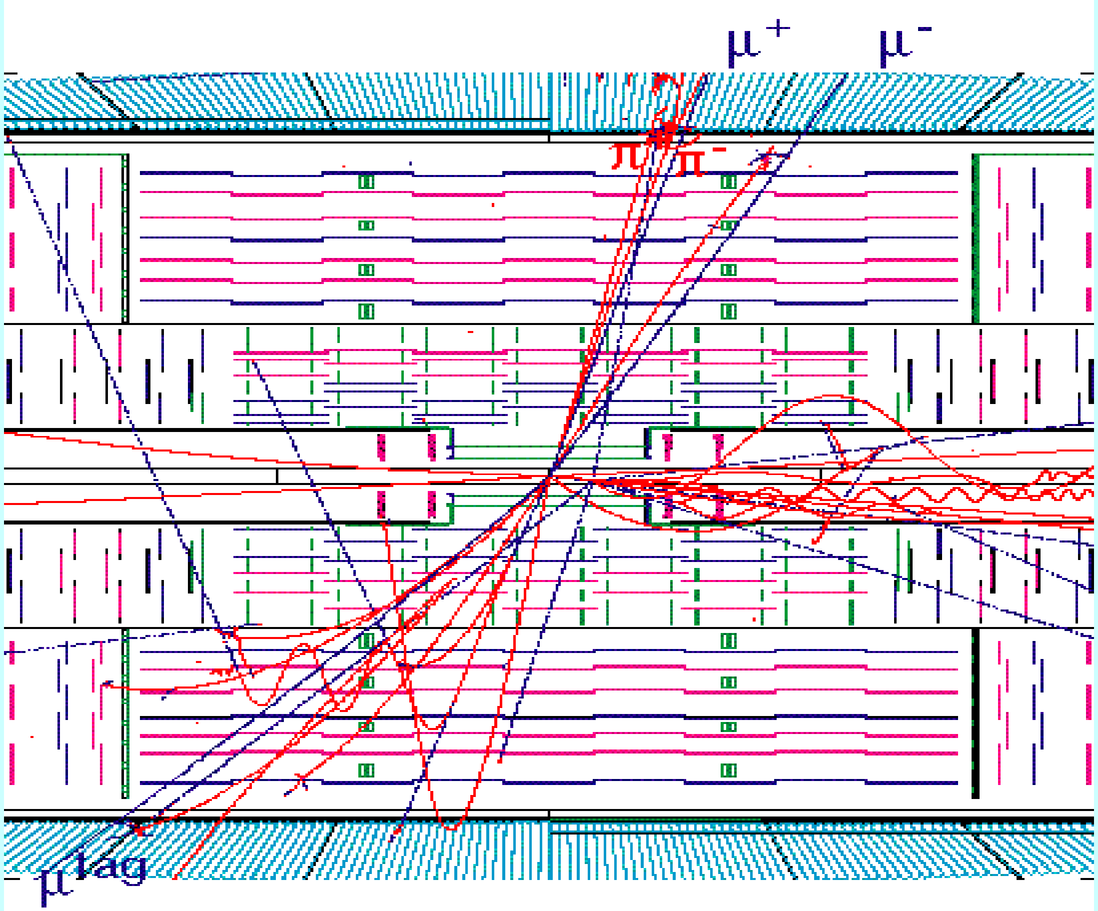
Microstrip tracker system

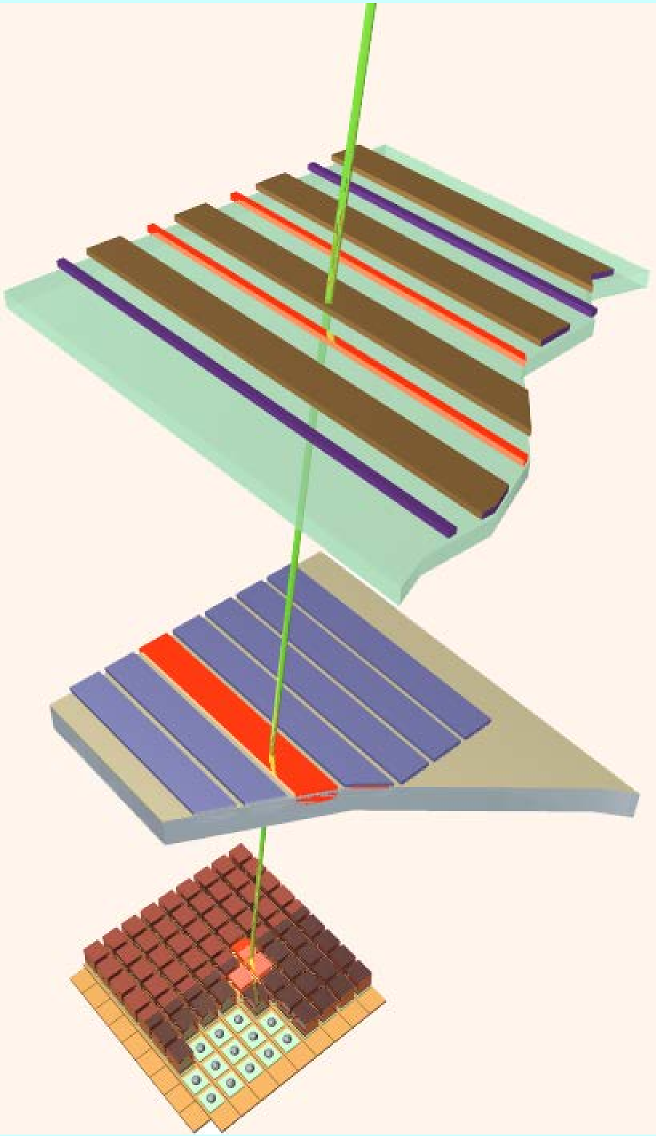


~10M detector channels



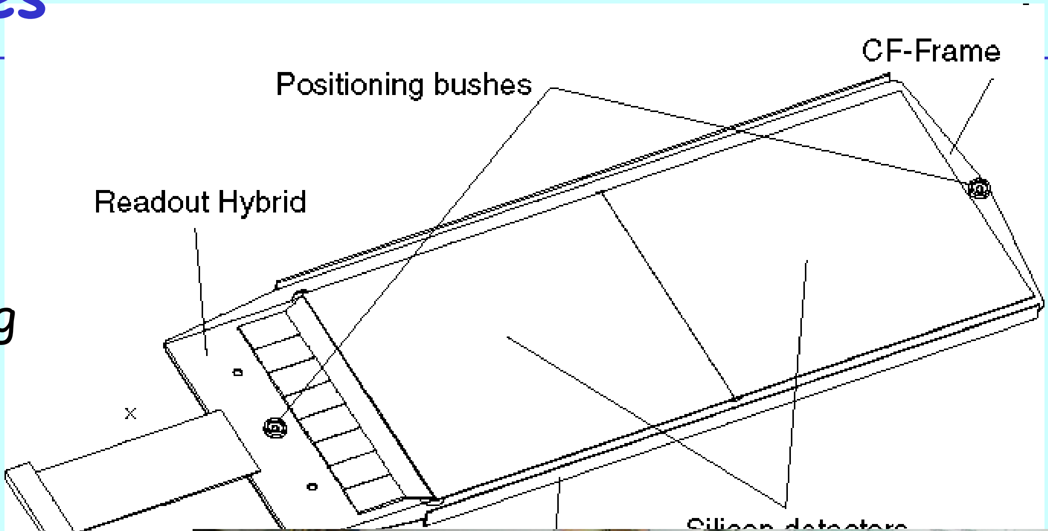
Event in the tracker

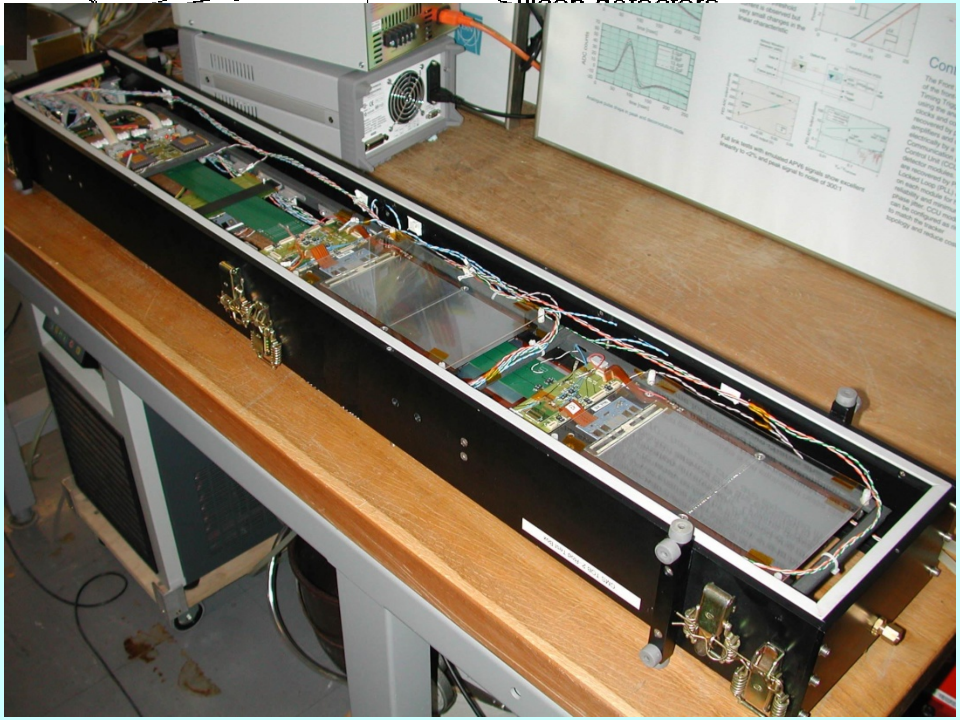




Silicon detector modules

- 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

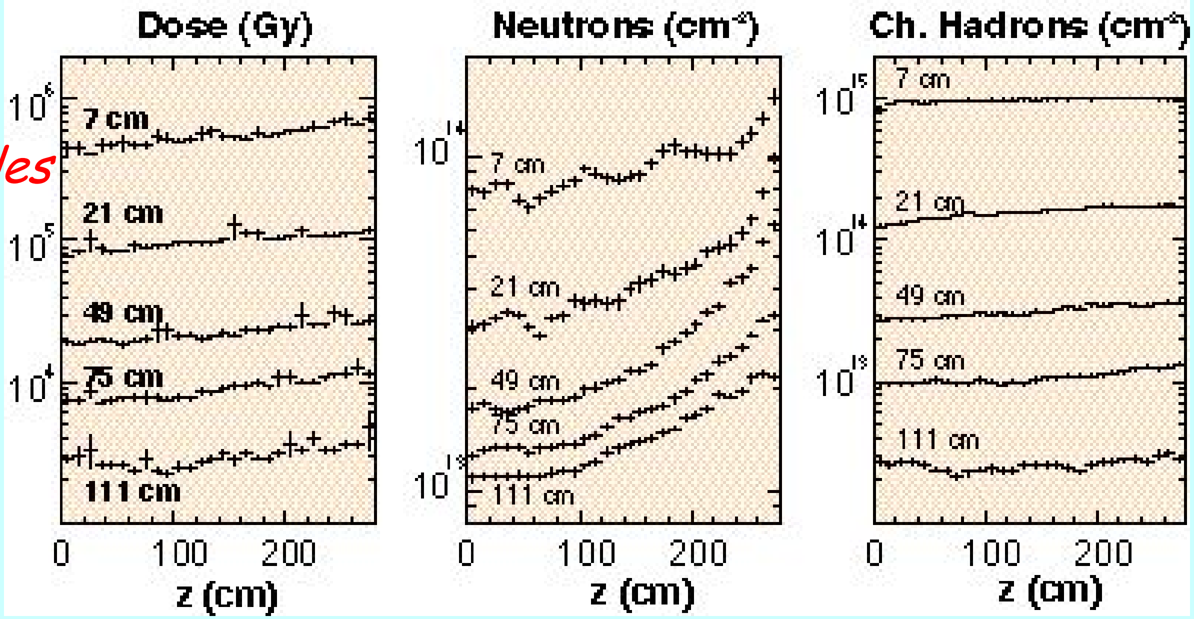
  nuclear backsplash + thermalisation ≈ more uniform gas

  only E > 100keV damaging

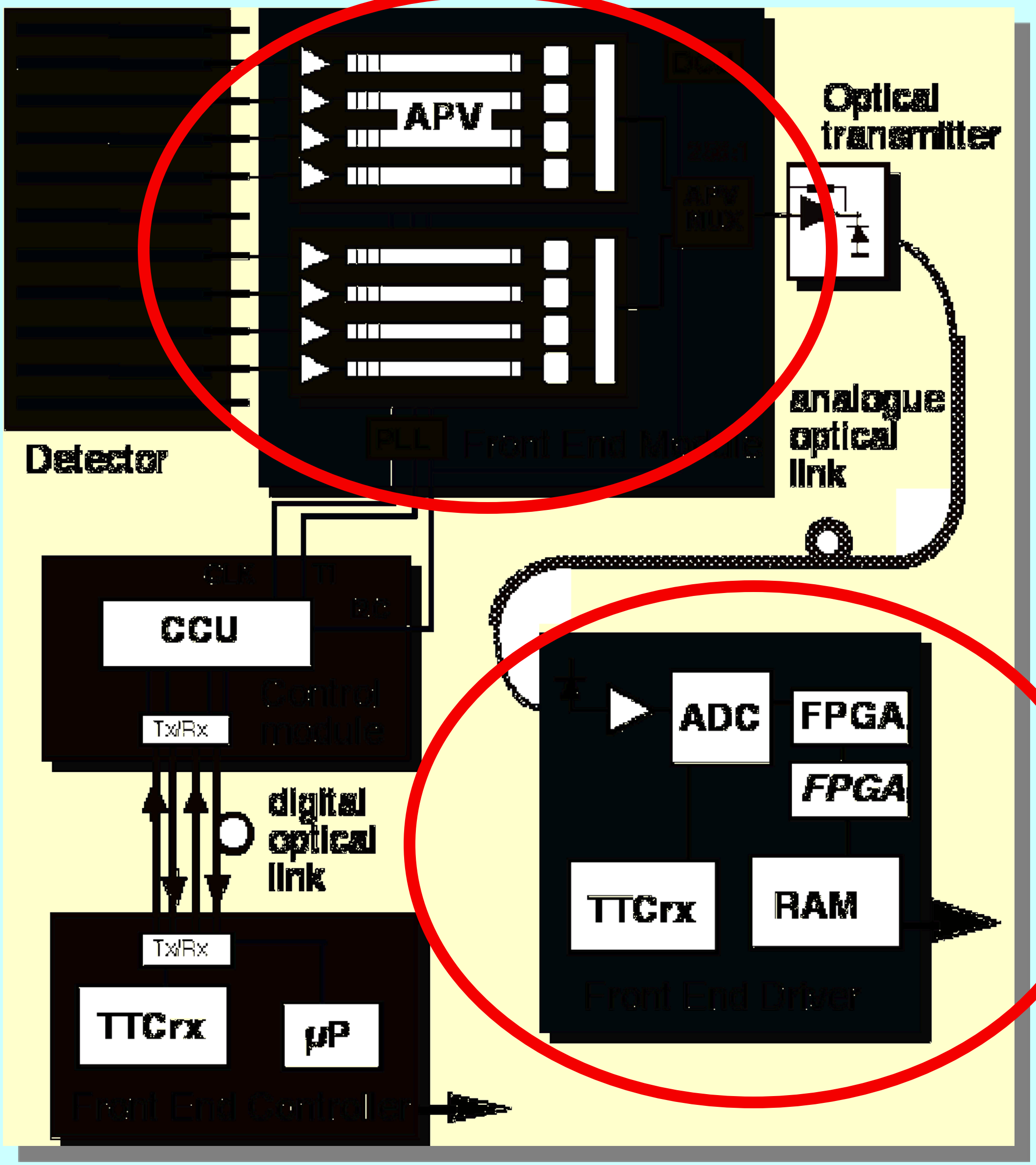
- Dose energy deposit per unit volume

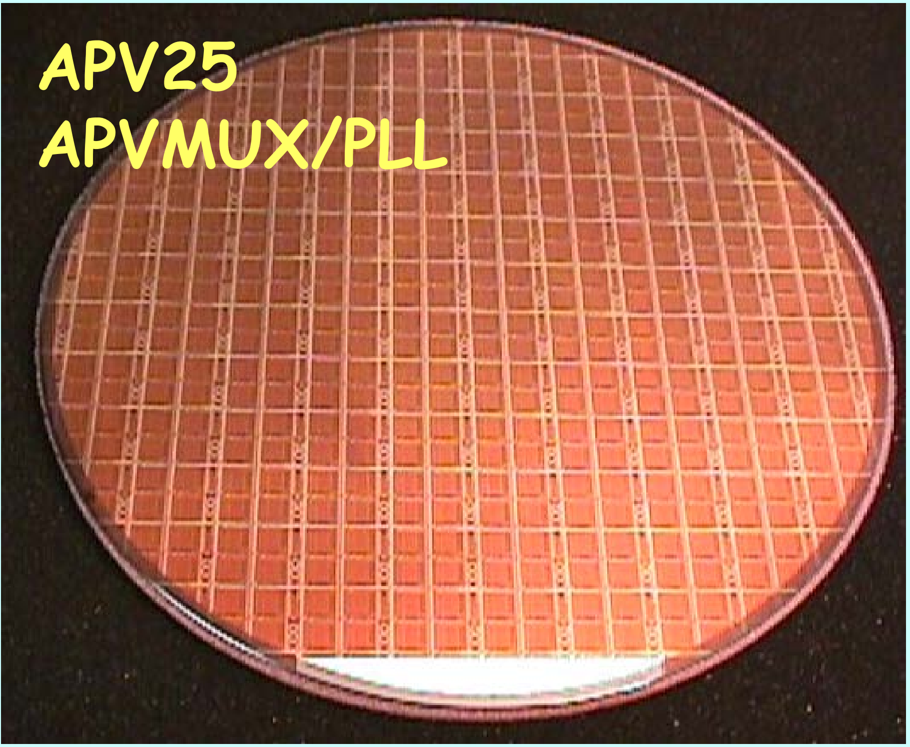
  Gray = 1Joule/kg = 100rad

  mostly due to charged particles



Imperial College contributions to Tracker



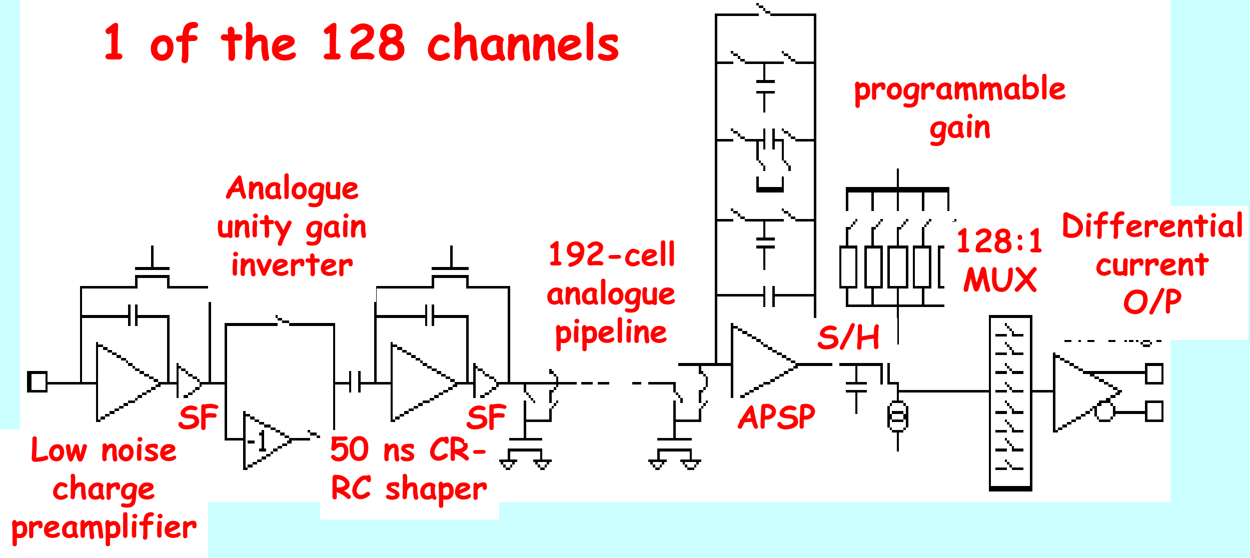


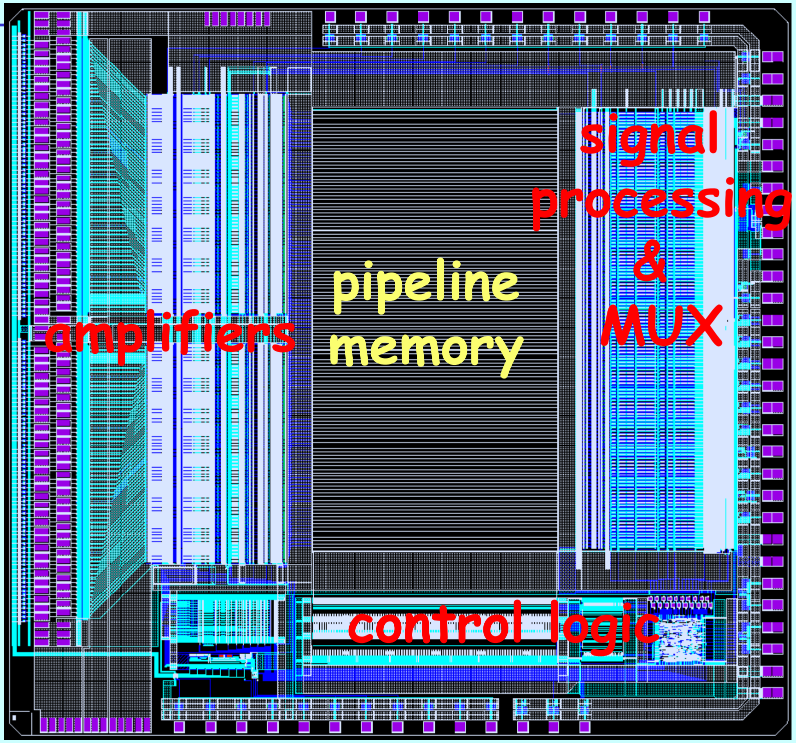
FED

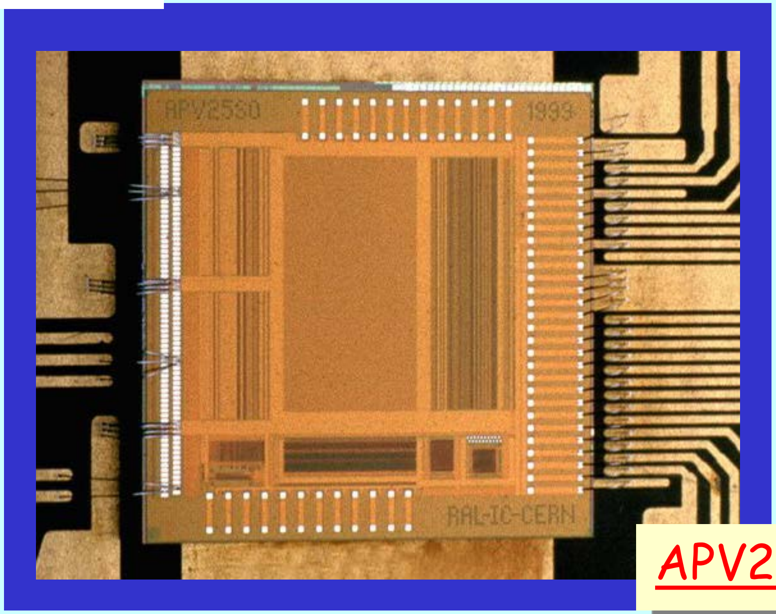
- Hardware development
- Hardware construction
- Beam tests & studies
- Preparation for physics

APV25 0.25μm CMOS

1 of the 128 channels







APV25-S0 (Oct 1999)

APV25-S1 (Aug 2000)

Chip Size 7.1 x 8.1 mm

Final

Irradiations of 0.25μm technology

- Extensive studies

  CMS tracker data from IC, Padova, CERN

  ALL POSITIVE and well beyond LHC range

- CMOS hard against bulk damage

  Qualify chips from wafers

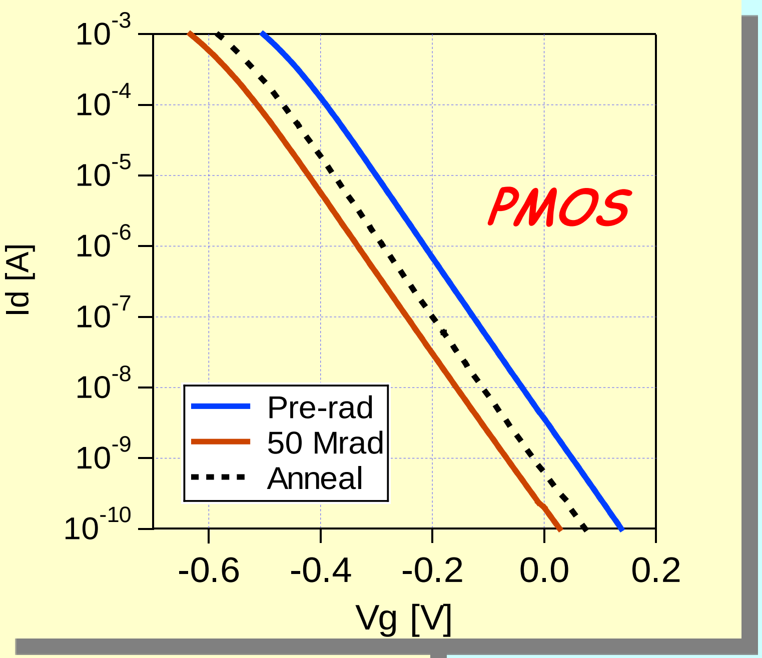
  with ionising sources

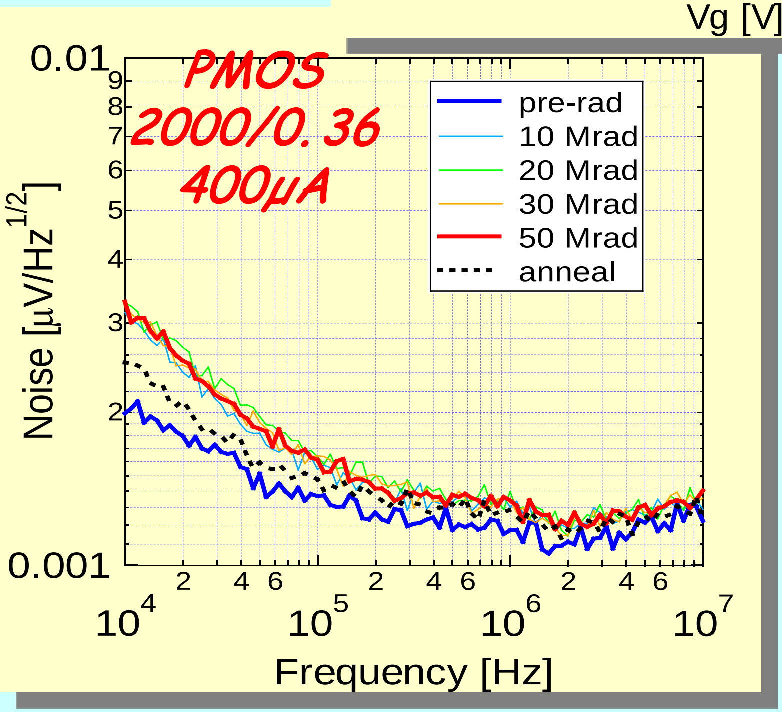
- Typical irradiation conditions

  50kV X-ray source

  Dose rate ~ 0.5Mrad/Hour

  to 10, 20, 30 & 50Mrad





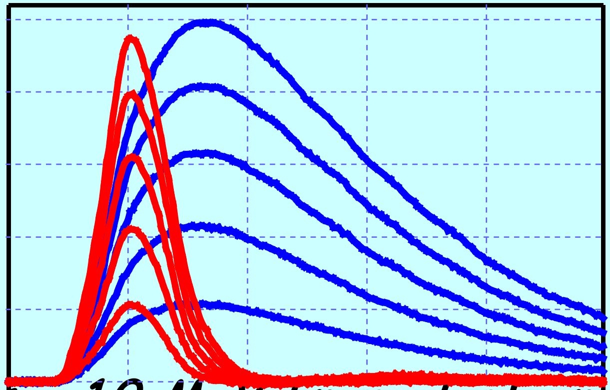
APV25 irradiations (IC & Padova)

- IC x-ray source

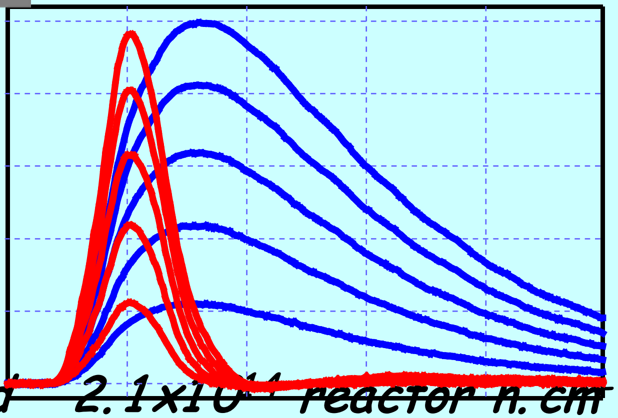
Normal operational bias during irradiation clocked & triggered

Post irradiation noise change insignificant

APV25-S1



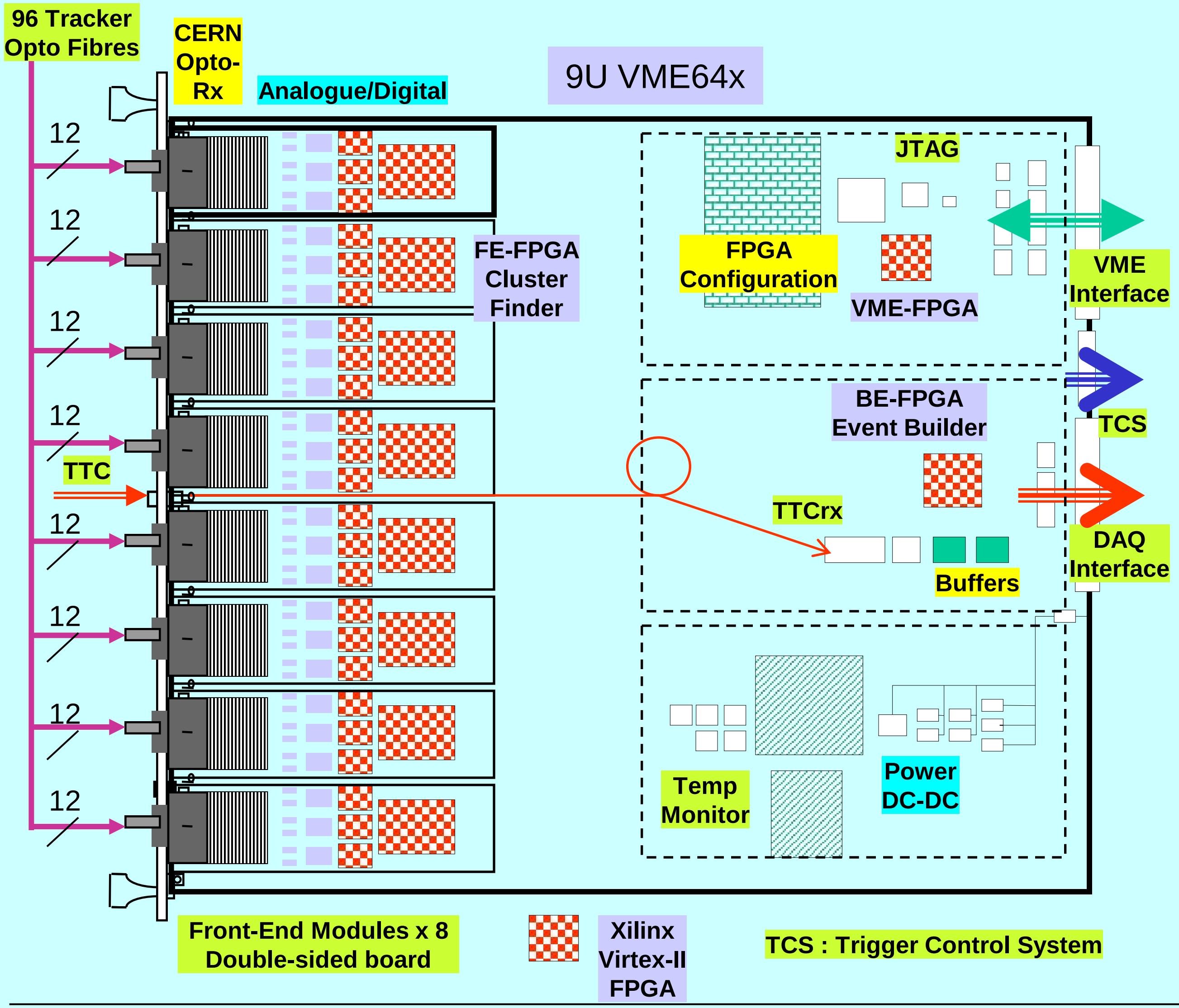
pre-rad



10 Mrad

also 10 MeV linac electrons(80Mrad) and 2.1×10^{14} reactor $n.cm^{-2}$

CMS Silicon Strip Tracker Front End Driver



Data Rates

9U VME64x Form Factor

Modularity matched Opto Links

Analogue: 96 ADC channels (10-bit @ 40 MHz)

@ L1 Trigger : processes 25K MUXed silicon strips / FED

Raw Input: 3 Gbytes/sec*

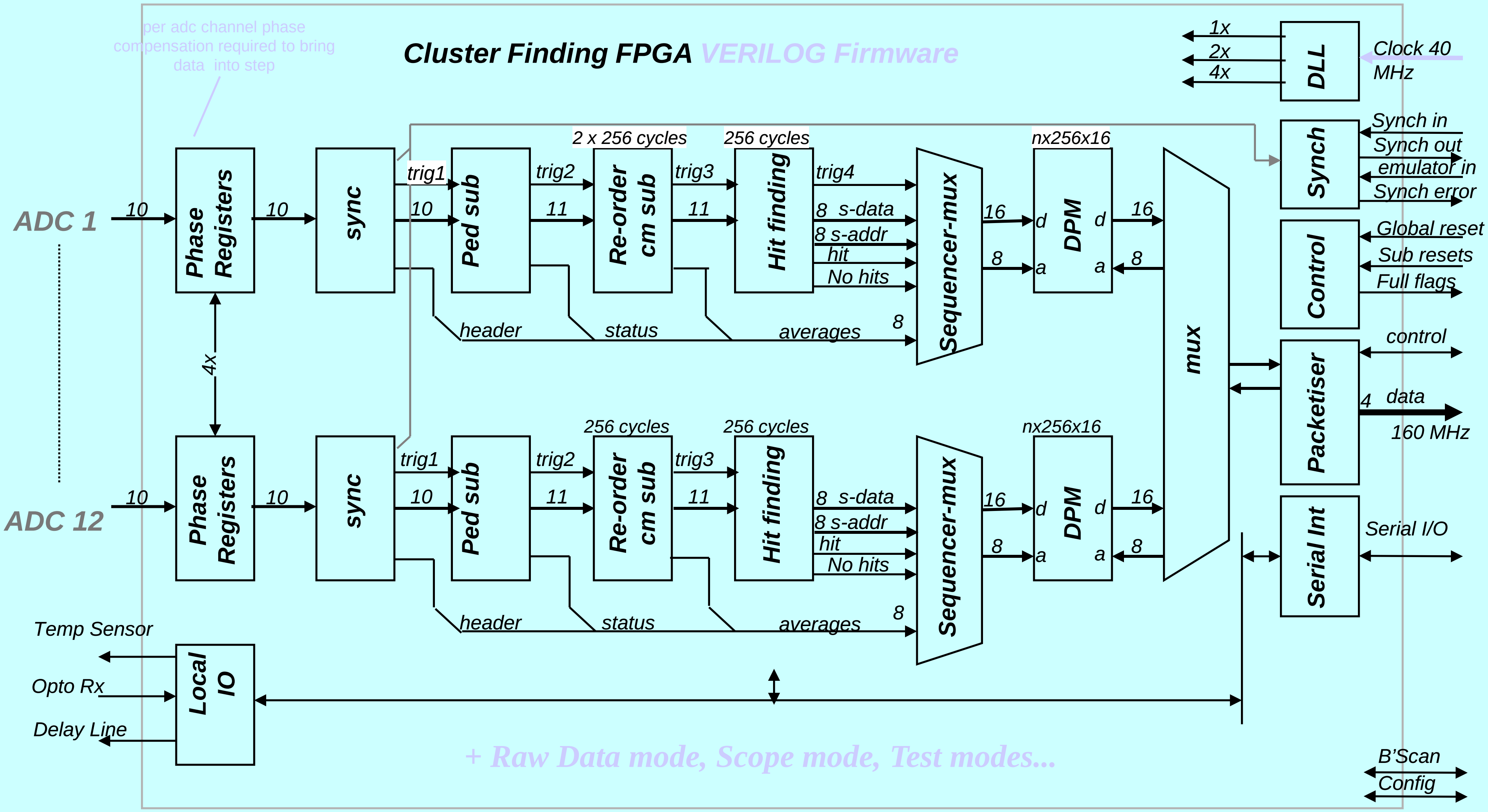
after Zero Suppression...

DAQ Output: ~ 200 MBytes/sec

~440 FEDs required for entire SST Readout System

*(@ L1 max rate = 100 kHz)

CMS Silicon Strip Tracker FED Front-End FPGA Logic


Cluster Finding FPGA VERILOG Firmware

per adc channel phase compensation required to bring data into step

+ Raw Data mode, Scope mode, Test modes...

The CMS Tracking Strategy

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

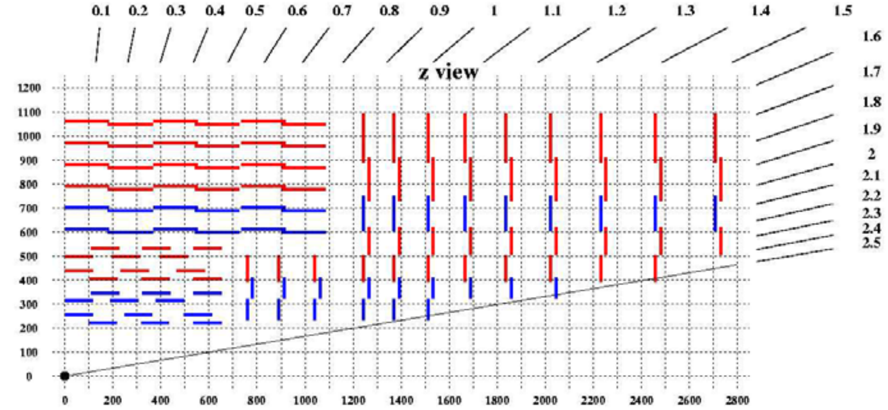
2-3 Silicon Pixel
10 - 14 Silicon Strip Layers

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

Radius ~ 110cm, Length/2 ~ 270cm

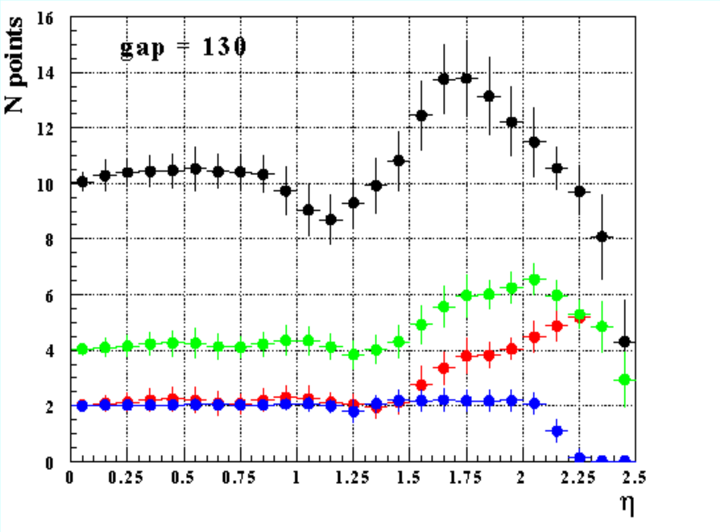
6 layers TOB

4 layers TIB

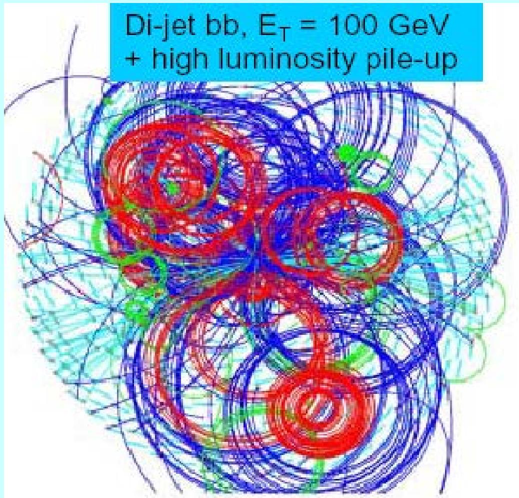


3 disks TID

9 disks TEC

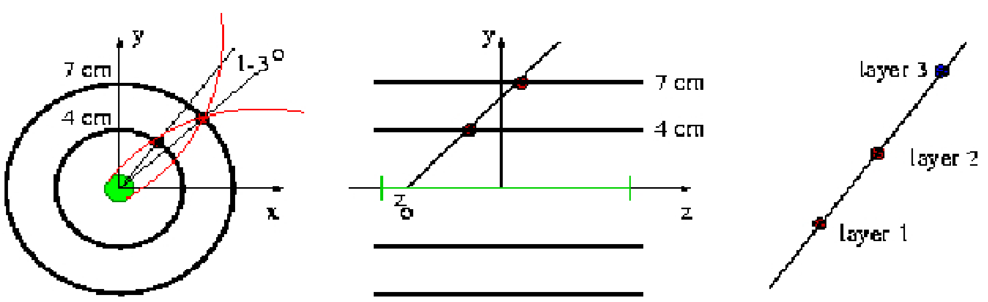


Vertex Reconstruction



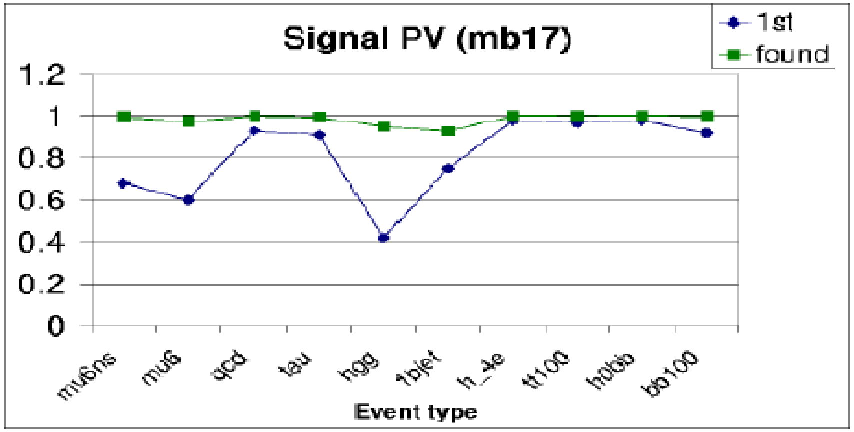
Primary vertices: use pixels!

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

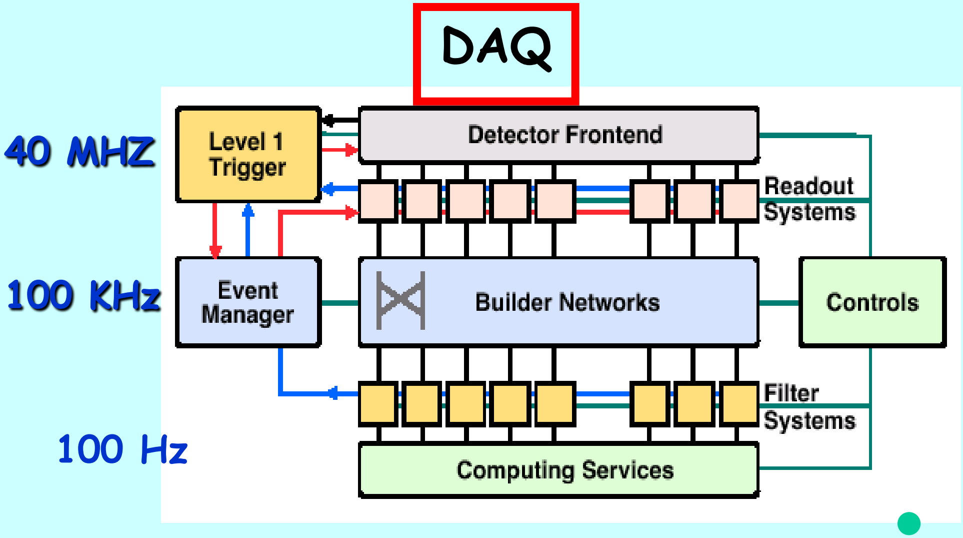
Primary vertex finding efficiency



mu6 - di-jets, ≥ 1 muon p_T > 6 GeV
qcd - di-jets, jet E_T = 60 GeV
tau - h(500) → ττ, hadronic τ decays
hgg - H(120) → 2 γ
h_4e - H(250) → 4 electrons
h0bb - H(100) → bb_bar
bb100 - bb jets, E_T = 100 GeV
tt100 - tt jets, E_T = 100 GeV
1bjet - tracks from 1 jet from bb100
These results: 3 barrel pixel layers, high luminosity

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

High Level Trigger & Tracker



In High Level trigger reconstruction only 0.1% of the events should survive.

"How can I kill these events using the least CPU time?"

This can be interpreted as:

- The fastest (most approx.) reconstruction
- The minimal amount of precise reconstructio
- A mixture of the two

HLT Track finding

Events rejected at HLT are irrecoverably lost!

Same SW would be use in HLT and off-line :

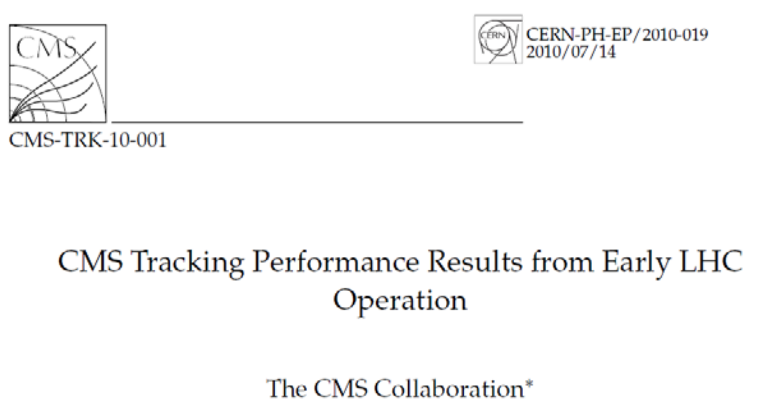
- algorithms should be high quality
- algorithms should be fast enough

References (updated by P Hobson)

N. Ellis & T. Virdee. Experimental Challenges in High Luminosity Collider Physics. Ann. Rev. Nucl. Part. Sci 44 (1994) 609-653.

- G.Hall *Modern charged particle detectors* Contemporary Physics 33 (1992) 1-14 & refs therein
- G.Hall *Semiconductor particle tracking detectors* Reports on Progress in Physics.57 (1994) 481-531
- A. Schwarz 1993 *Heavy Flavour Physics at Colliders with silicon strip vertex detectors.* Physics Reports 238 (1994) 1-133.
- C. Damerell *Vertex detectors: The state of the art and future prospects.* Rutherford Appleton Laboratory report RAL-P-95-008 *A pdf version is available on the CERN library Web site.(Search preprints)*
- *The CMS experiment at the CERN LHC,* Journal of Instrumentation, **3** (2008) S08004
- *Performance studies of the CMS Strip Tracker before installation* , Journal of Instrumentation, **4** (2009) P06009
- *Stand-alone cosmic muon reconstruction before installation of the CMS silicon strip tracker* , Journal of Instrumentation, **4** (2009) P05004

How does it perform at the LHC?

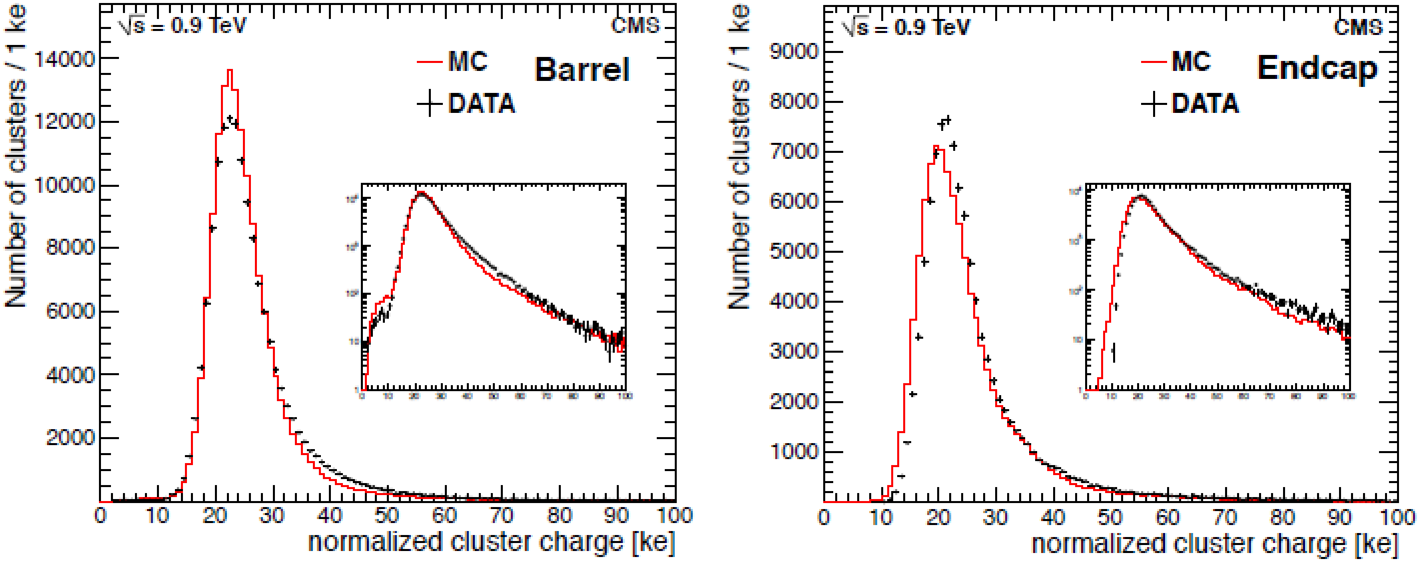


CERN-PH-EP/2010-019
2010/07/14

CMS-TRK-10-001

CMS Tracking Performance Results from Early LHC Operation

The CMS Collaboration*

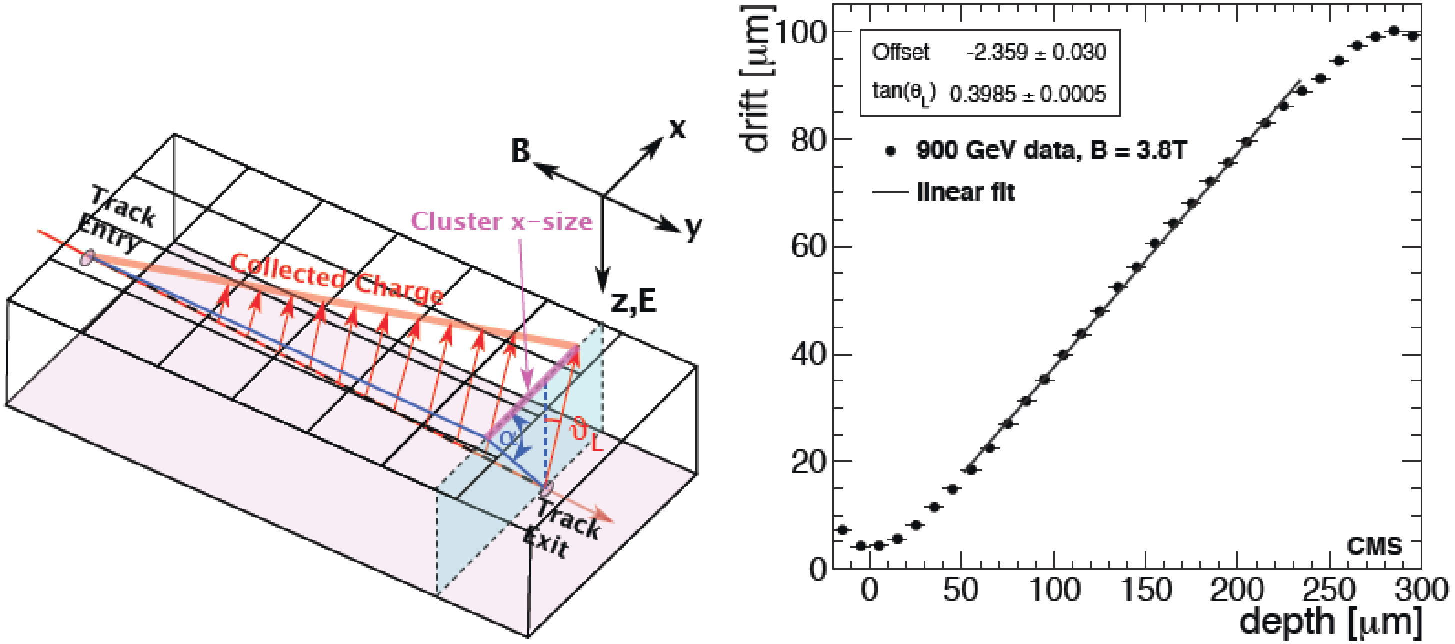


(a)

(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.

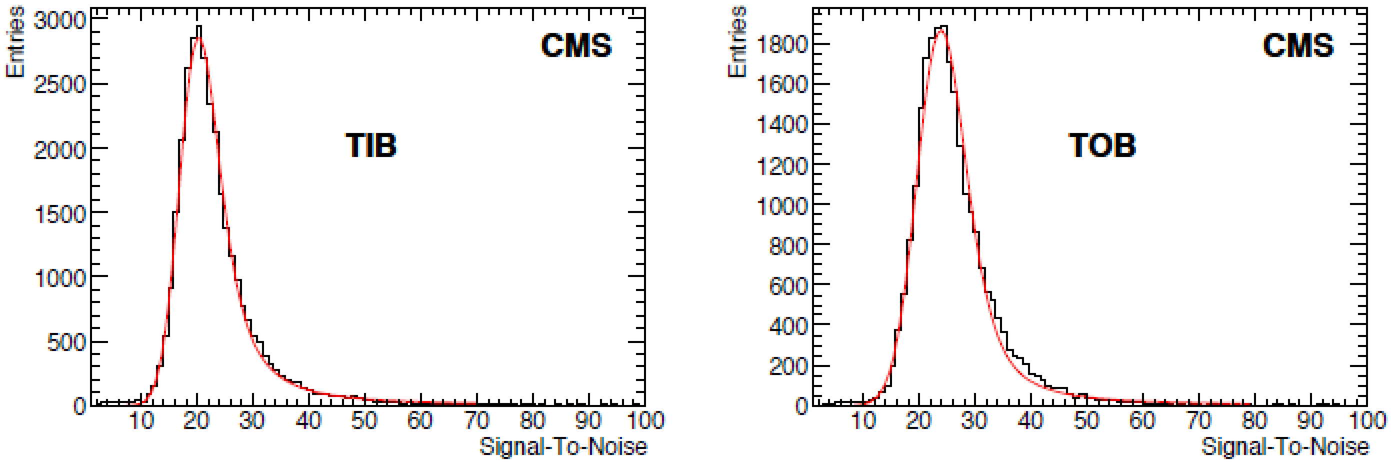
How does it perform at the LHC?



(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.

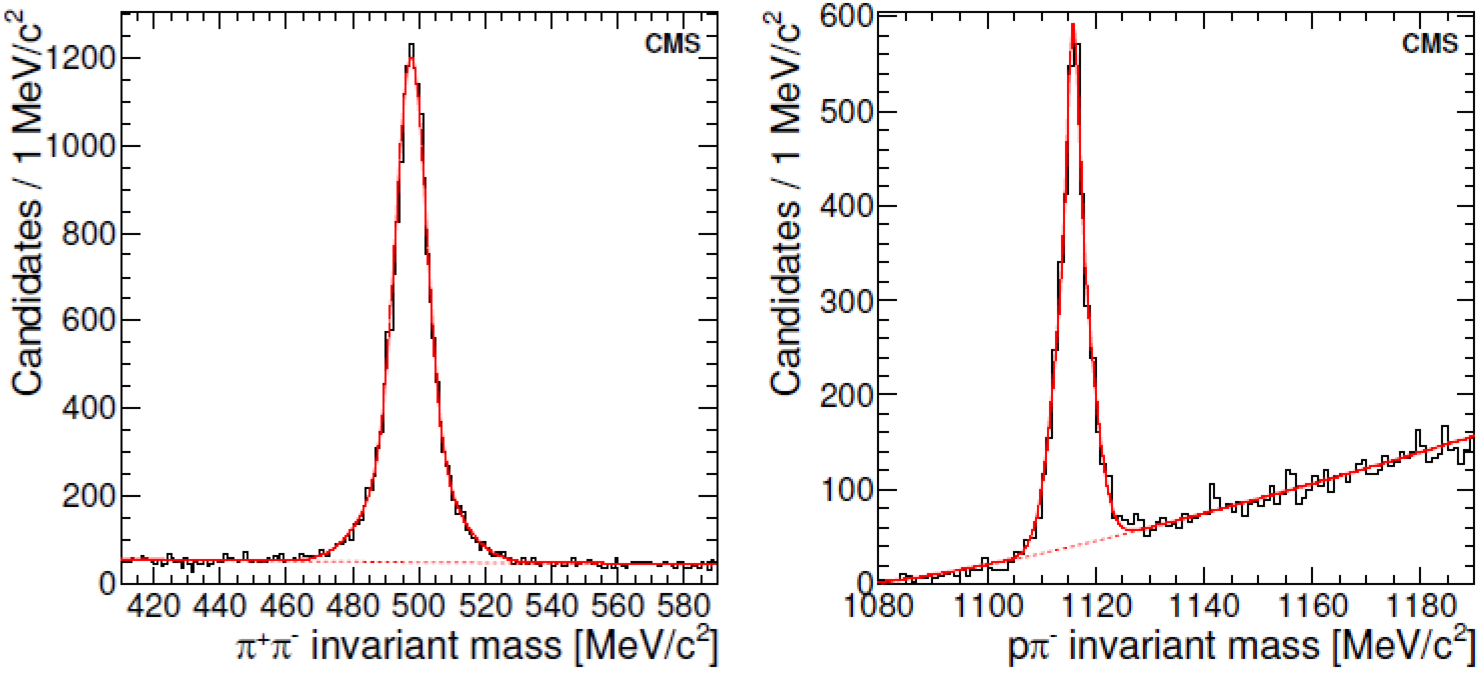
How does it perform at the LHC?



(a) (b)

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.

How does it perform at the LHC?

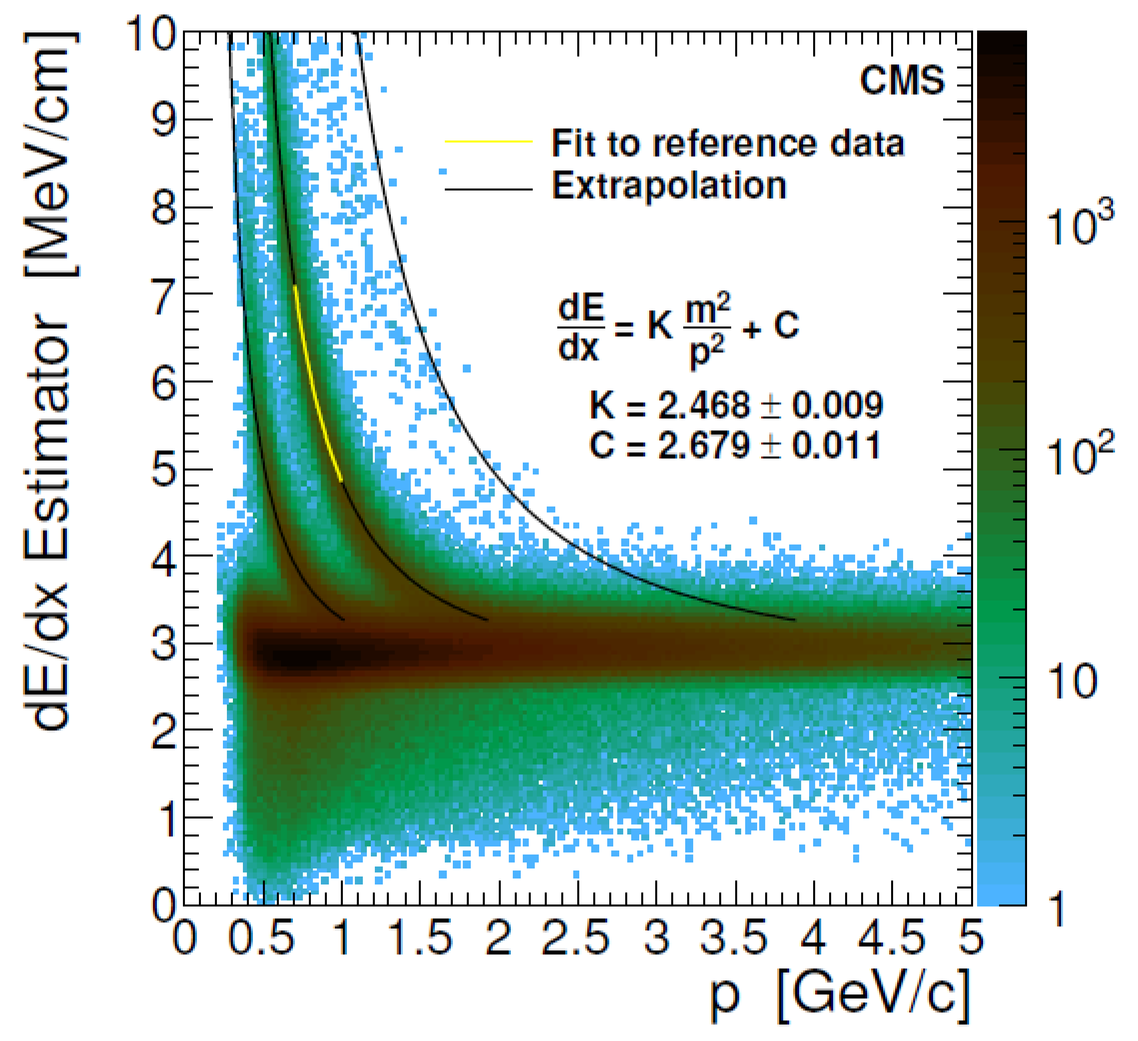


(a)

(b)

Figure 11: The invariant mass distributions of (a) $\pi^+\pi^-$ with a fit to the K^0_S and (b) $p\pi^-$ with a fit to the Λ^0.

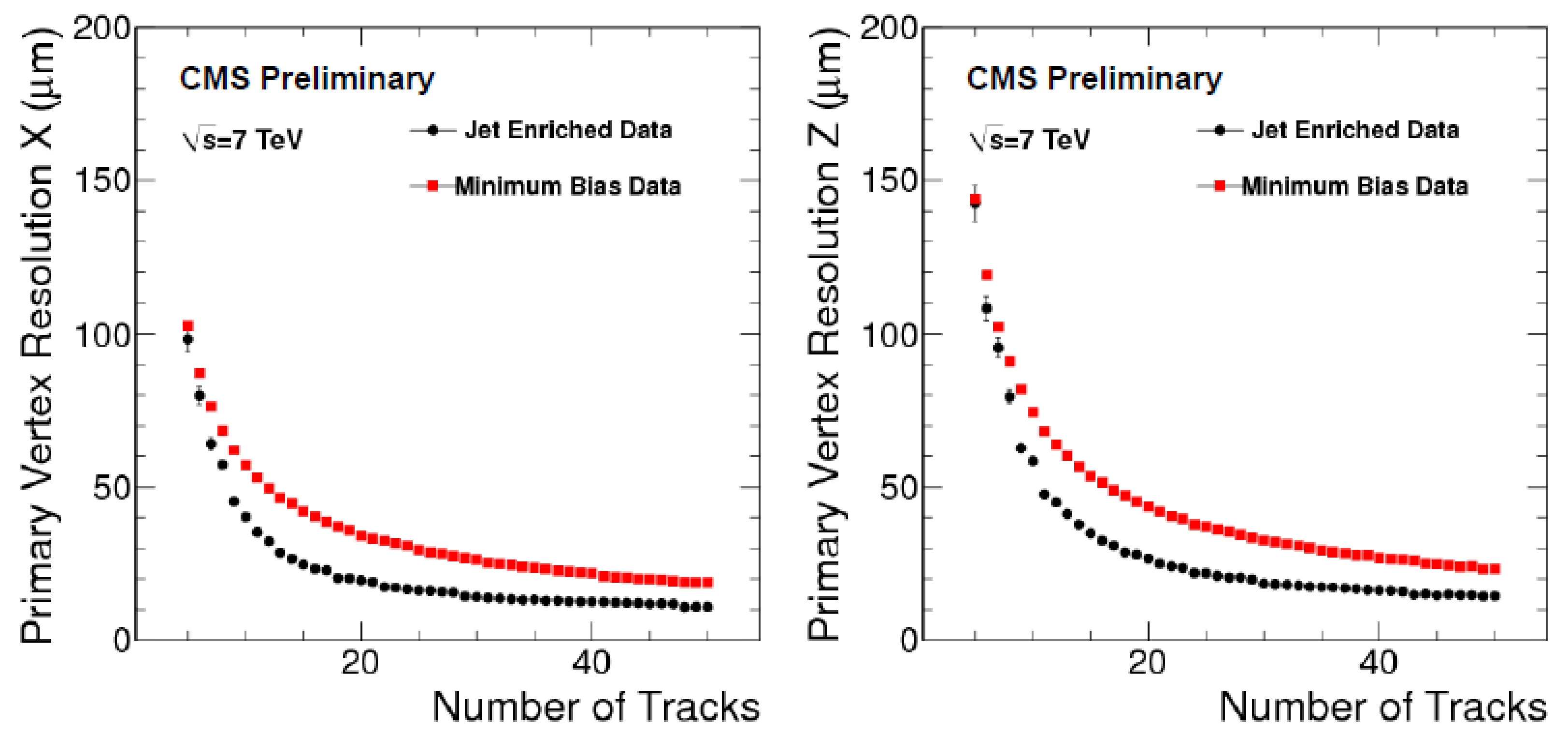
How does it perform at the LHC?



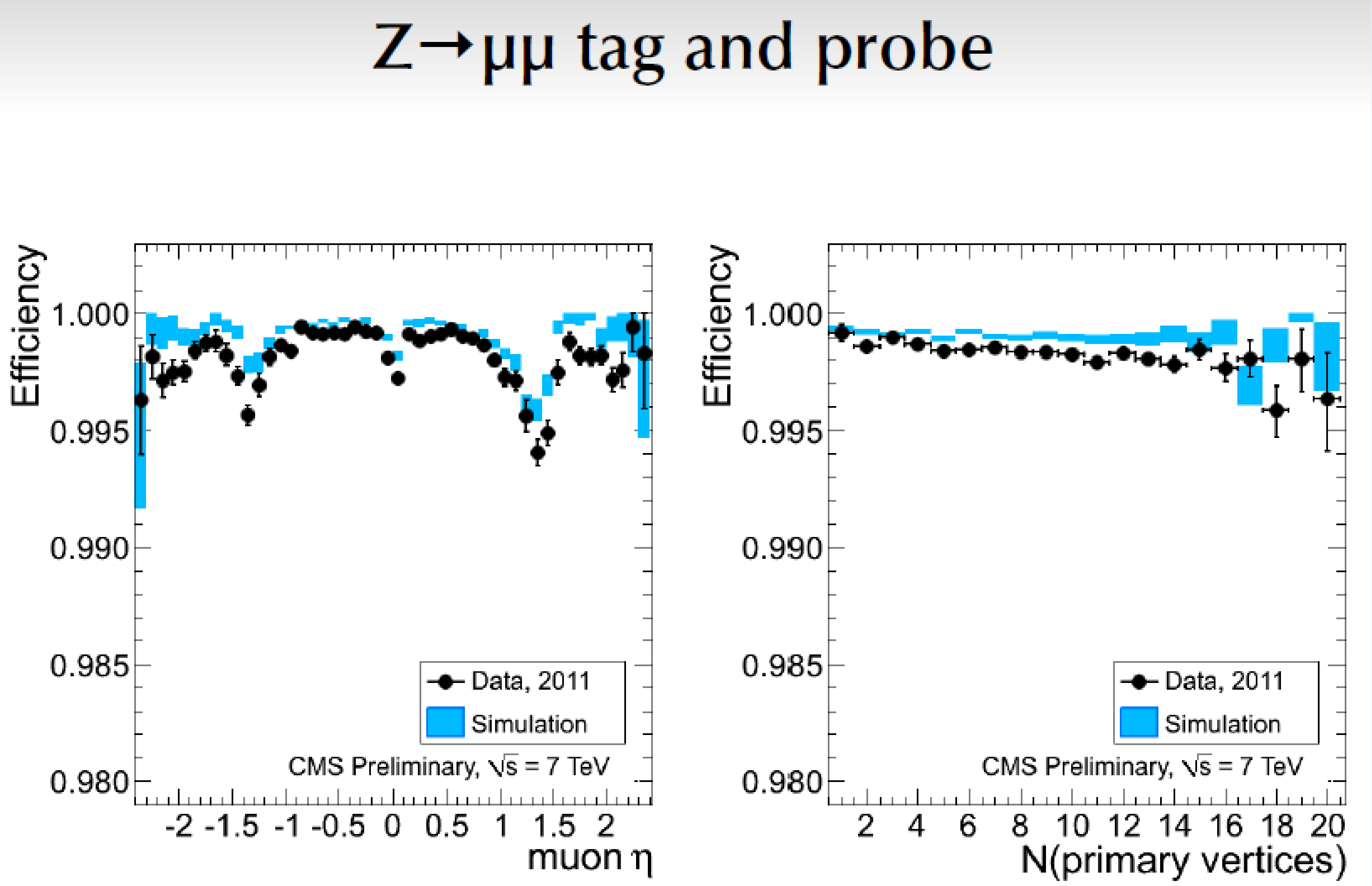
Kaons,
Protons,
Deuterons

Published results

- VERTEX 2012



Efficiency

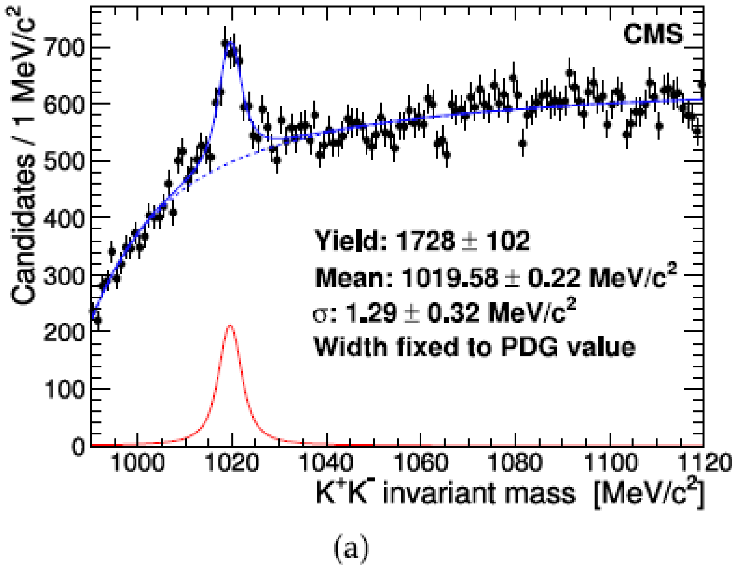


Z→μμ tag and probe

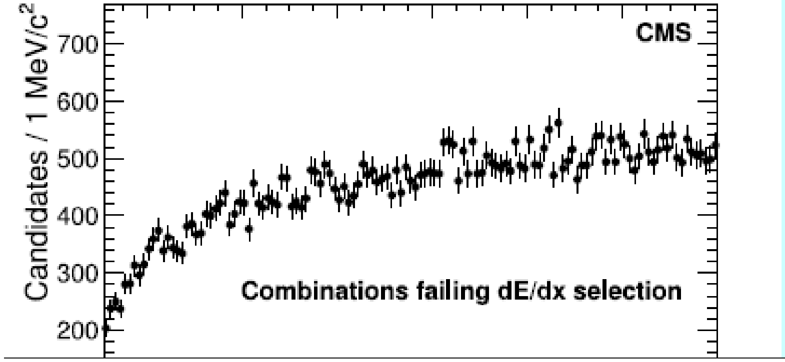
dE/dx

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

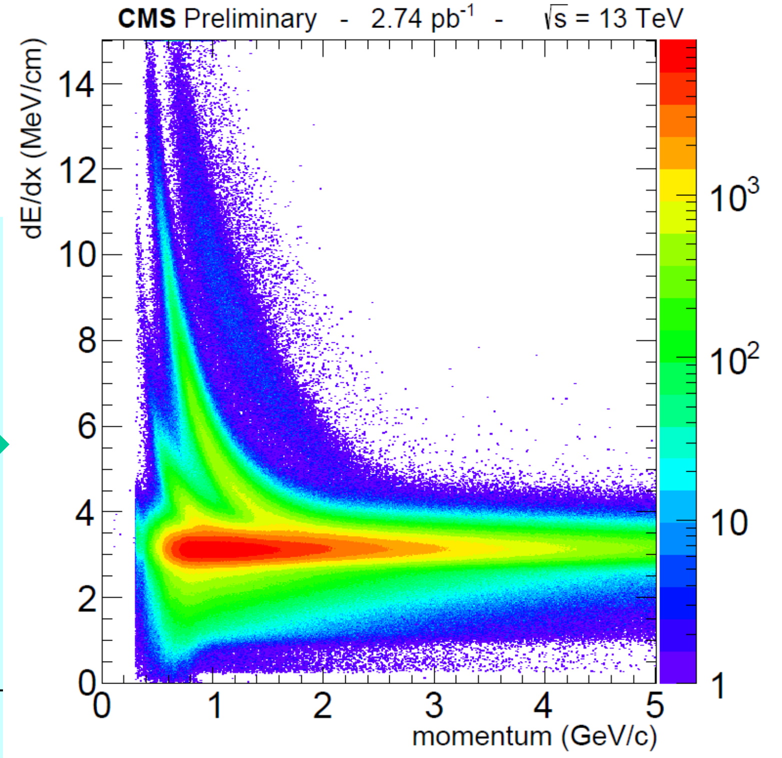
Fig. 15 K^+K^- invariant mass distribution, with (**a**) both kaons satisfying the dE/dx requirement and with (**b**) at least one particle failing that requirement. In (**a**) a fit to the $\phi(1020)$ hypothesis is shown



(a)

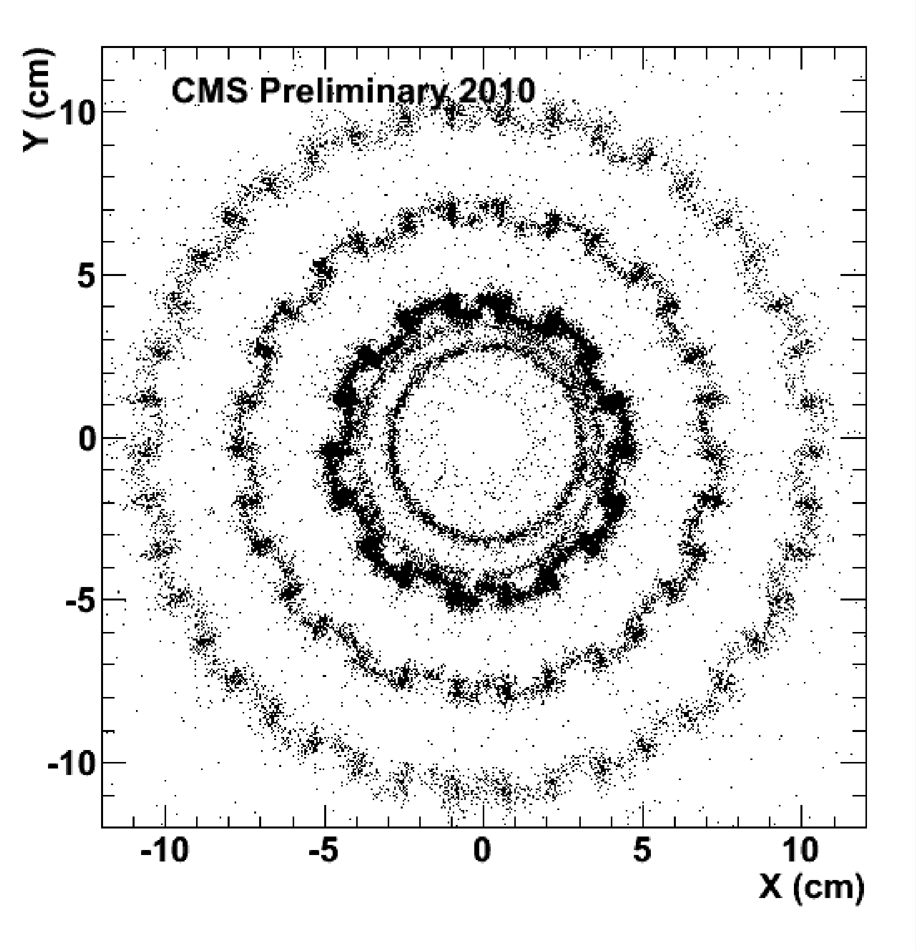


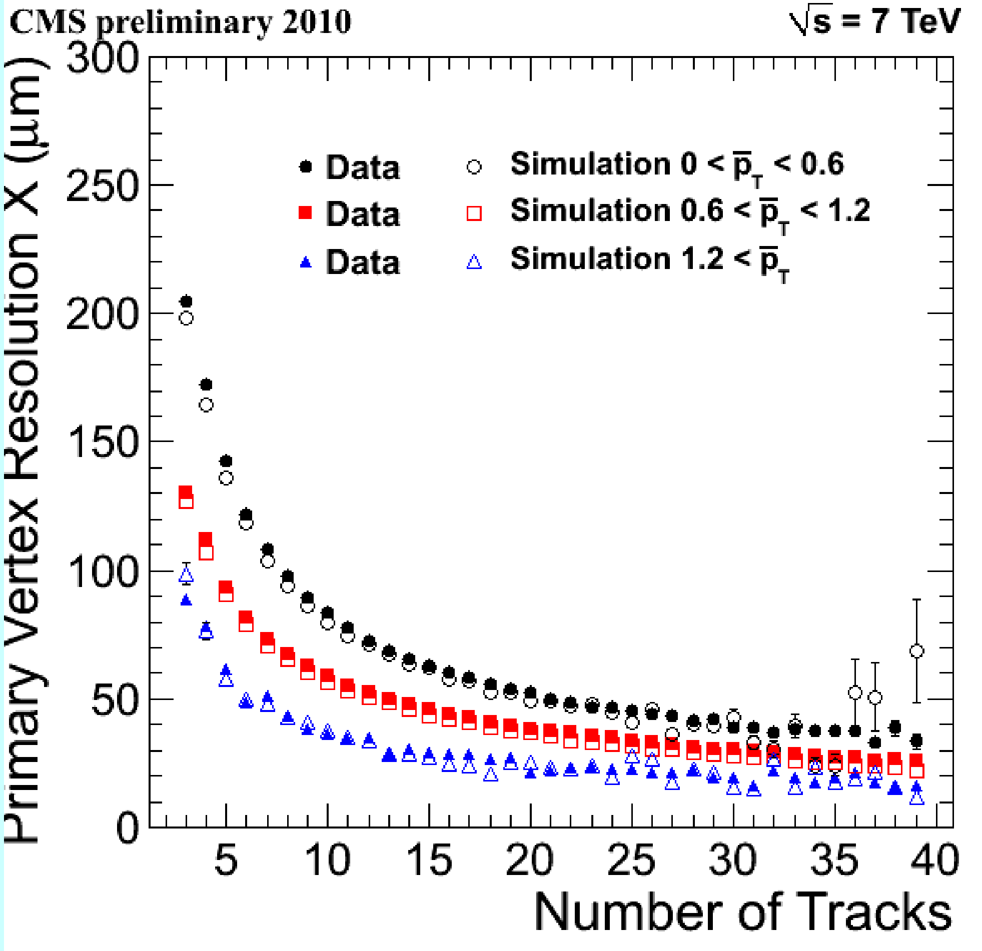
13 TeV data



Photon conversions in the pixel layers

- Reconstructed photon conversions (photon “radiography”)





Finding the cooling pipes!

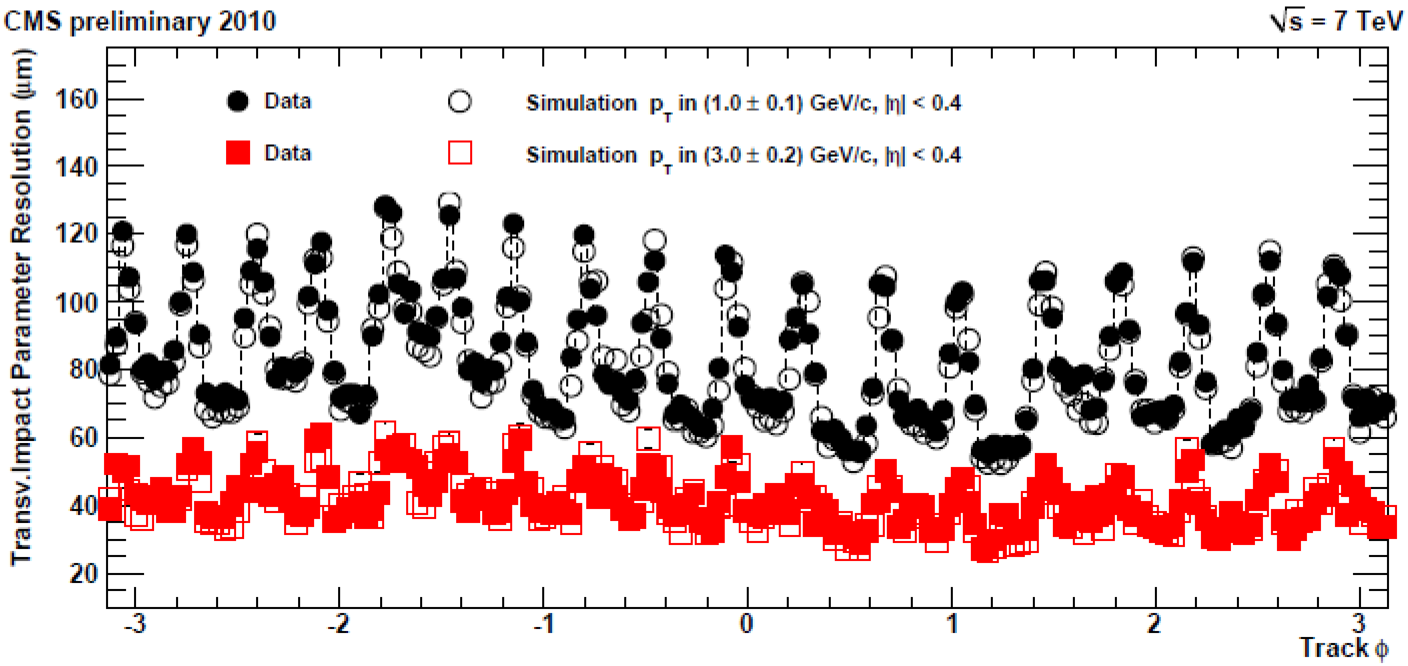


Figure 2: Resolution of the transverse impact parameter depending on the azimuthal angle ϕ for two different track p_t ranges. The "oscillating" structure is due to the cooling pipes of the inner layer of the pixel detector.

IP within jets

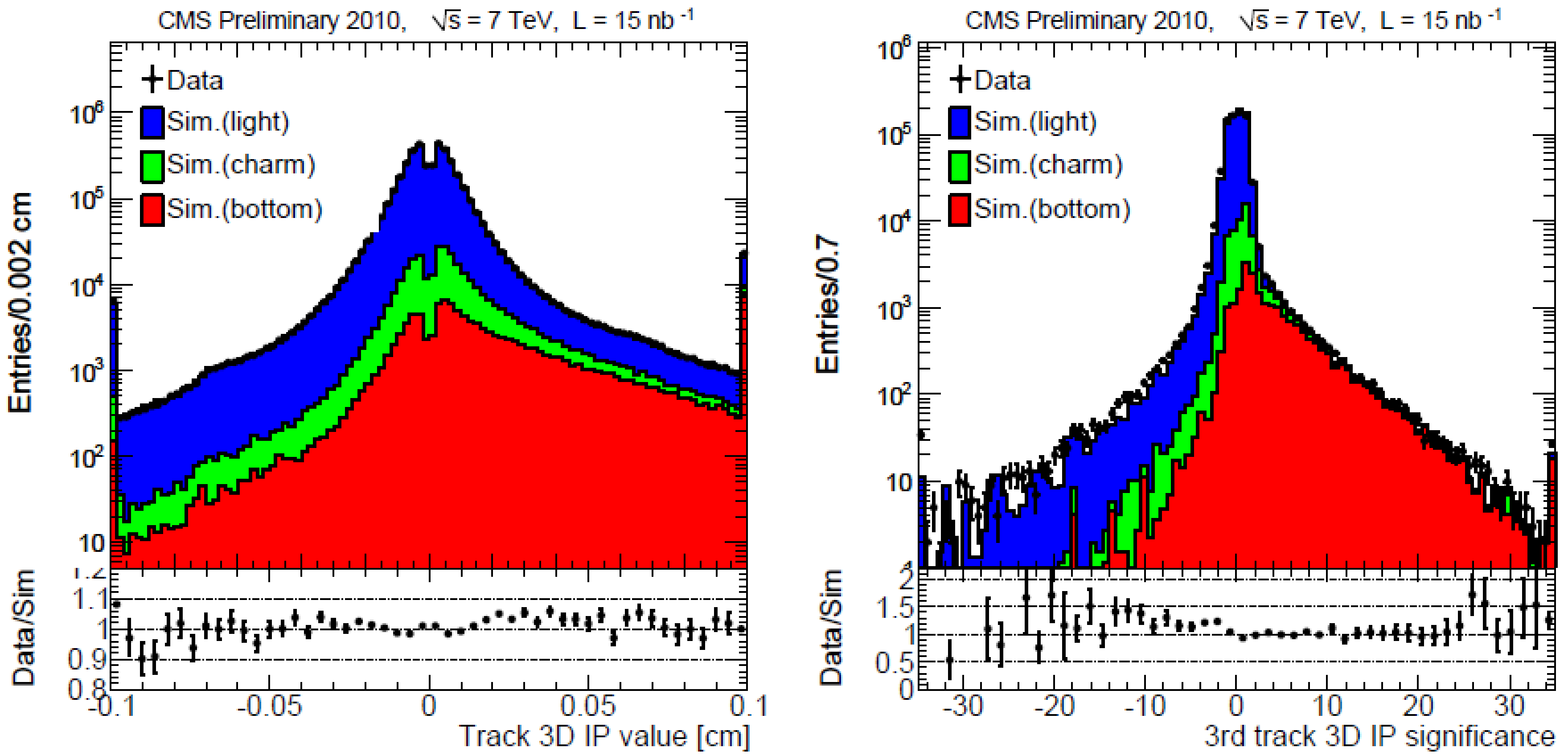


Figure 3: Left: impact parameter value of all selected tracks in a jet. Right: impact parameter significance of the third track in a jet (ordered by IP significance). The Monte Carlo simulation of light, charm and b-jets is shown in blue, green and red, while the data are represented as black markers.[8]

Secondary vertex b-tagging

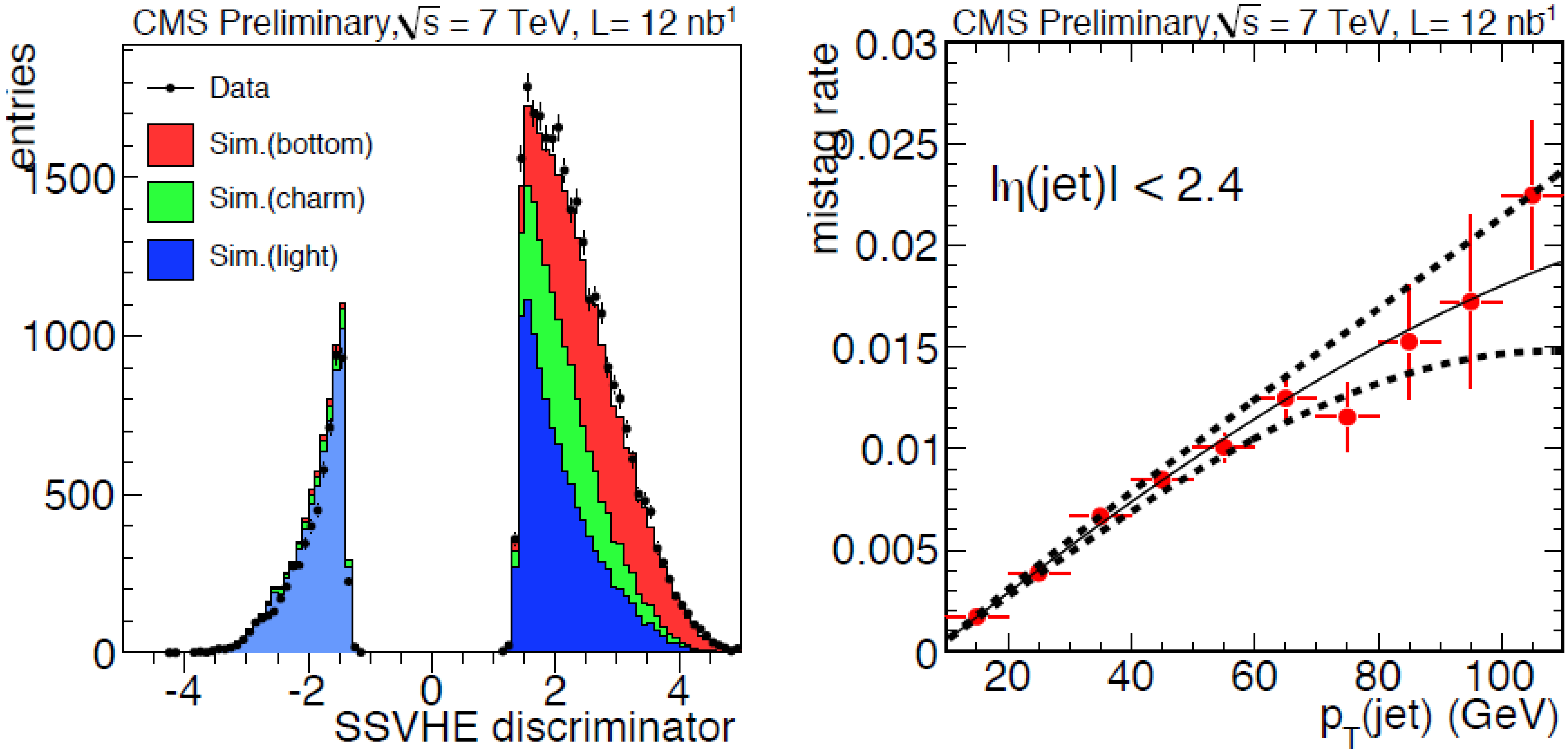
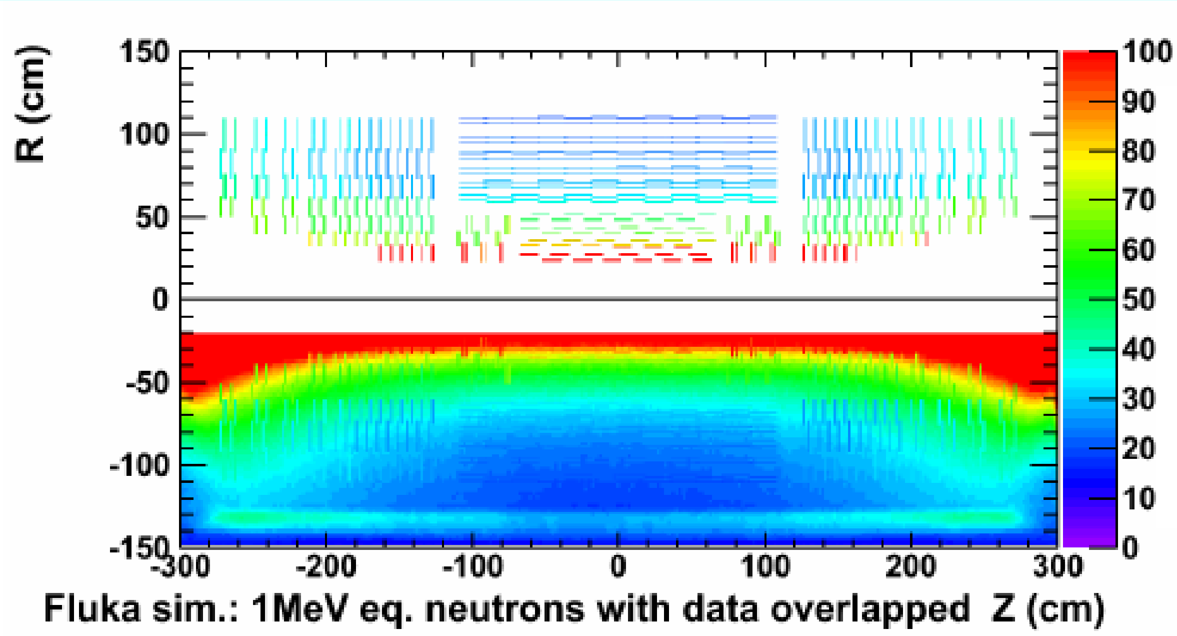


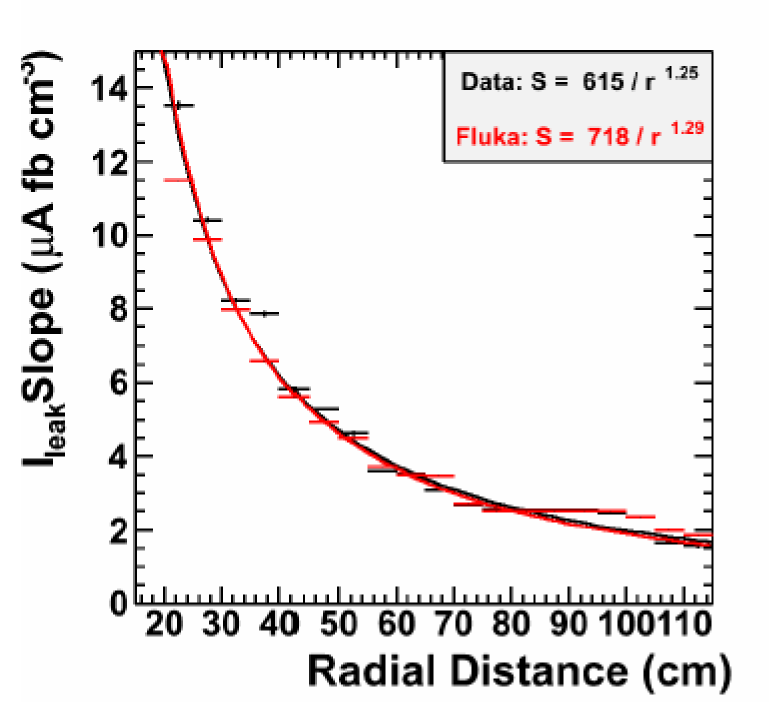
Figure 5: Left: discriminator of the secondary vertex b-tagging algorithm for negative and positive tags. Right: light flavour mistag rate as measured by the negative tag method depending on transverse jet momentum p_t for the secondary vertex b-tagging algorithm.

Leakage Currents in Strips



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

Leakage current vs radius



Even more from CMS …

From *JINST* **9** (2014) P1009
https://cms-results.web.cern.ch/cms-results/public-results/publications/TRK-11-001/index.html

Tracker performance plots (public)
https://twiki.cern.ch/twiki/bin/view/CMSPublic/DPGResultsTRK