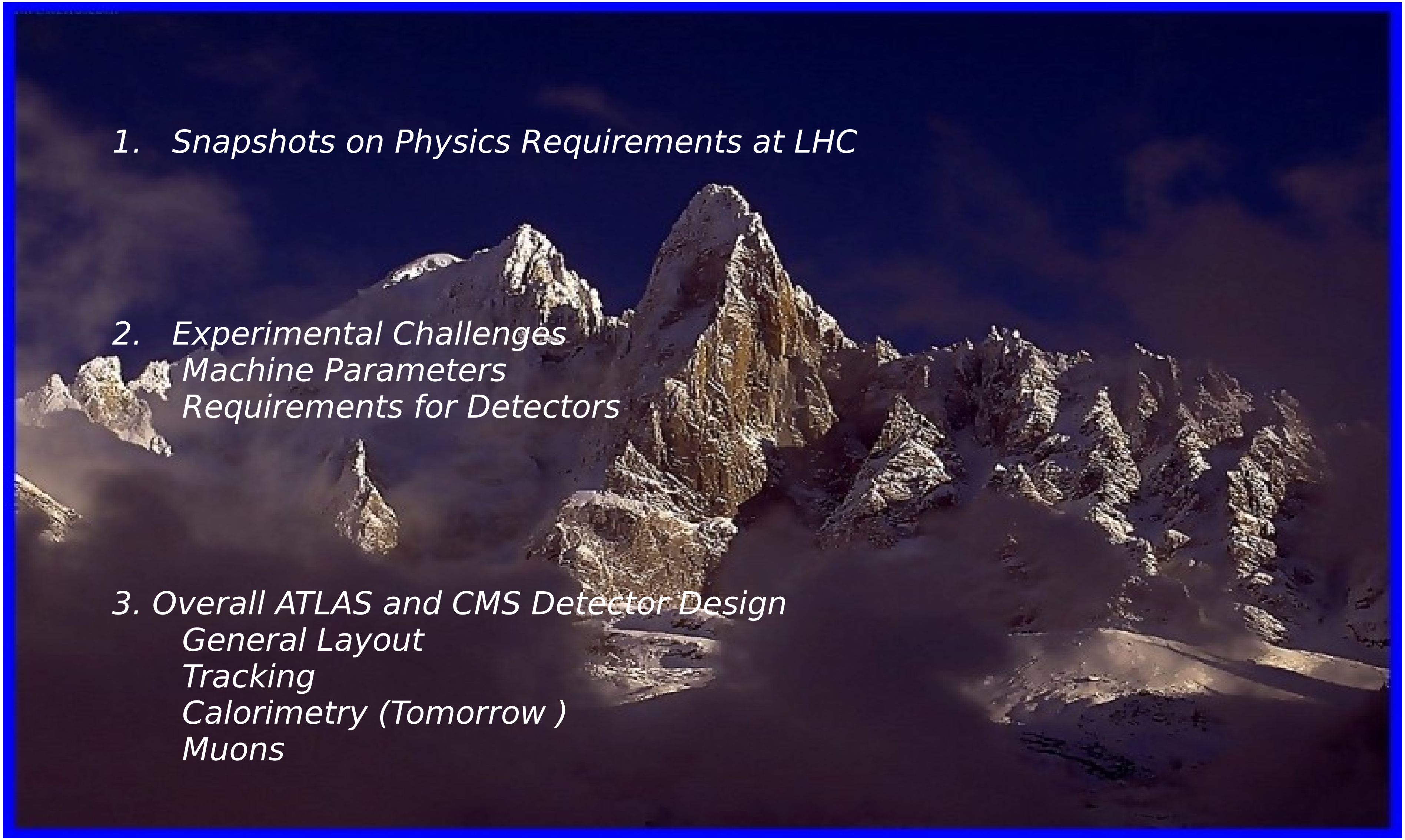
ÉCOLE DE PHYSIQUE
LES HOUCHES
XXVII

Detectors at LHC part.I



1. *Snapshots on Physics Requirements at LHC*

2. *Experimental Challenges*
   Machine Parameters
   Requirements for Detectors

3. *Overall ATLAS and CMS Detector Design*
   General Layout
   Tracking
   Calorimetry (Tomorrow)
   Muons

Notes

Bibliography

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

D. Fournier and L. Serin, Experimental Techniques, European School of Particle Physics, CERN 96-04

T. S. Virdee, Experimental Techniques, European School of Particle Physics, St. Andrews, CERN 99-04

CERN Academic Training Lectures

ATLAS and CMS outreach pages

Important Lecture Note

In this lecture I use many exemples from CMS , only because of my better knowledge of this experience. This must not be taken as a ranking between ATLAS and CMS.

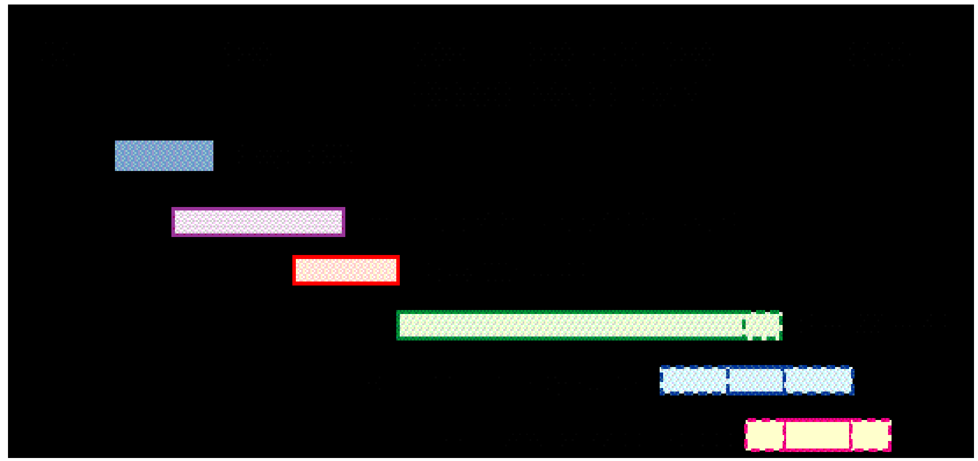
Part.I

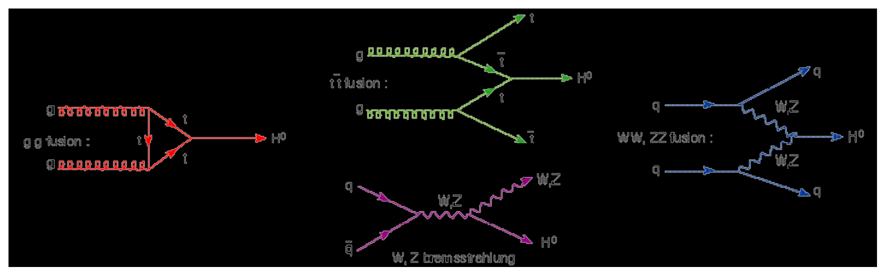
. *Snapshots on Physics Requirements at LHC*

SM Higgs Boson

At the LHC the SM Higgs provides a good benchmark to test the performance of a detector

Natural Width - 0.01 1 10 100 GeV

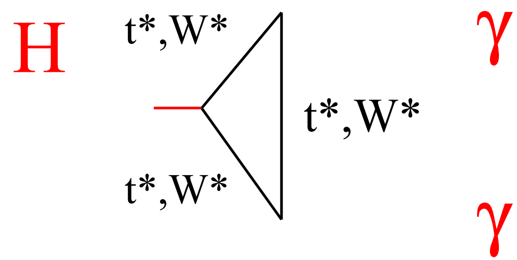




Fully hadronic final states dominate but cannot be used due to large QCD bkg.
a look for final states with isolated leptons and photons despite smaller BR

SM Higgs a γγ

Most promising channel for mH < 150 GeV



(σ.B ~ 50.10-3 pb @ mH ~ 150 GeV) a Signal: ~ 1000's of events/yr

Backgrounds are large (2pb/GeV), H natural width is small (~MeV)

a **excellent mass resolution** required

$$\sigma_m/m = 0.5\,[\sigma_{E1}/E_1 \otimes \sigma_{E2}/E_2 \otimes \cot(\theta/2)\Delta\theta]$$

a energy resolution and precise vertex localisation

Typical Cuts

2 isolated photons: pT > 25, 40 GeV with |η| < 2.5

No track or em cluster with pT > 2.5 GeV in a cone size ΔR = 0.3 around γs **Good energy resolution, measurement of photon direction, π0 rejection, efficient photon isolation**

SM HaZZ* or ZZ a 4l

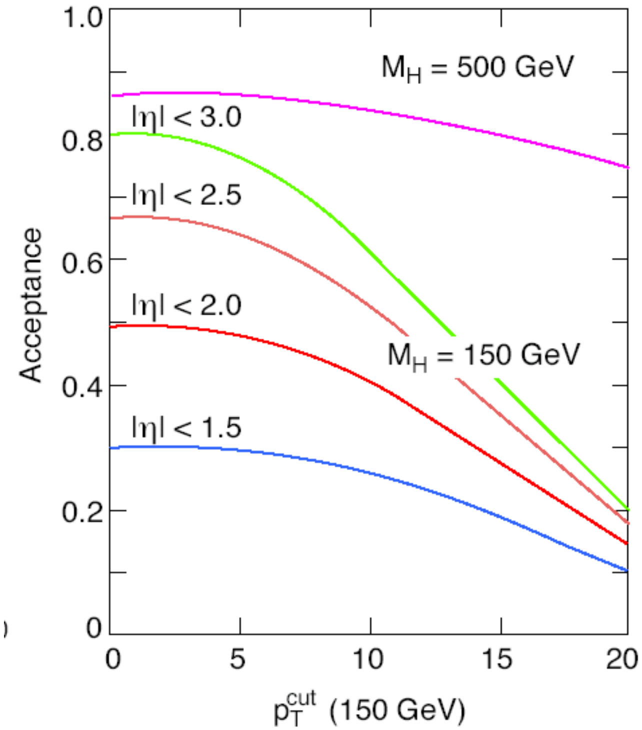
130 < MH < 800 GeV

ZZ*

ΓH (MH=150 GeV) ~ 15 MeV
Observed width is dominated by instrumental mass resolution

ZZ

ΓH (MH=500 GeV) ~ 65 GeV
For MH>350 GeV observed width is dominated by natural width



- **Di-muon or di-electron mass resolution should be better than ΓZ**
- **Good momentum resolution for low momenta leptons**
- **Large geometric acceptance**
- **Efficient lepton isolation at hi-L**

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SUSY Higgs Boson

H, h□γγ, bb̄ (H bb̄ in WH, t t̄H)

h γγ in WH, t t̄h l γ γ

h, H ZZ*, ZZ 4 l

h, H, A τ+τ– (e/μ)+ + h– + ETmiss

e+ + μ– + ETmiss inclusively and in bb̄HSUSY

h+ + h– + ETmiss

H+ τ+ ν from t t̄

H+ τ+ ν and H+ t b̄ for MH>Mtop

A Zh with h bb̄; A γγ

H, A χ̃02χ̃02, χ̃0iχ̃0j, χ̃+iχ̃–j

H+ χ̃+2χ̃02

qq qqH with H τ+τ–

H ττ, in WH, t t̄H

Abundance of b, τ and significant Etmiss

Physics with Jets, (Vertex (pixel detector), Detector Hermiticity

Part. II.1

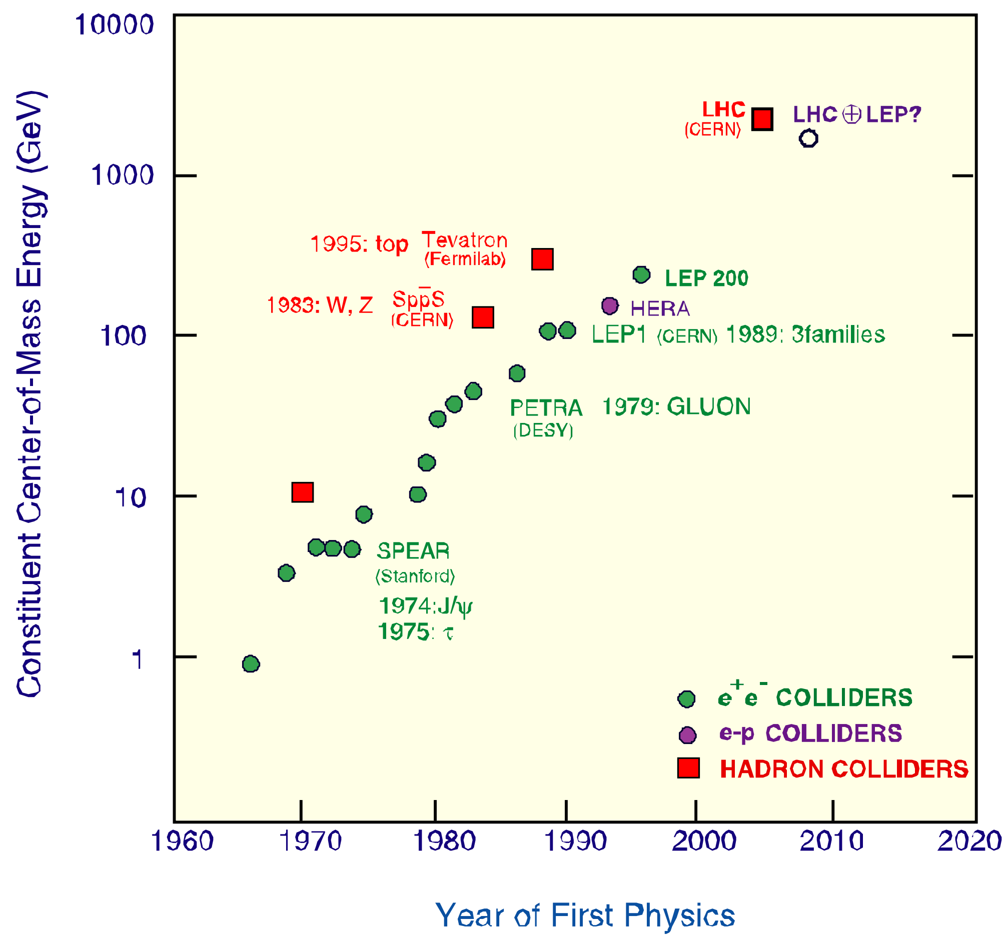
Experimental Challenges
Machine Parameters

Enerav Frontier

New Energy Domain
Search for the unexpected
Cover domain ~ 1 TeV in which SM without the Higgs (or equivalent) gives nonsense

Exploratory machine required
a hadron-hadron collider with:
Largest possible primary energy
Size of the tunnel x Max B field
Largest possible luminosity:
interesting and easily detectable final states involve leptons and photons with low σ.BR

Hadron Colliders can provide these
BUT
At the expense of 'clean' experimental conditions



LHC Lavout and Parameters

$$L = \frac{\gamma \, f \, k_b N_p^2}{4\pi \ \varepsilon_n \beta^*} F$$

f revolution frequency
kb no. of bunches
Np no. of protons/bunch
εn norm transverse emittance
β* betatron function
F reduction factor xing angle

Magnetic Field

p (TeV) = 0.3 B(T) R(km)
For p= 7 TeV, R= 4.3 km
a B = 8.4 T

Energy at collision	E	7	TeV
Dipole field at 7 TeV	**B**	**8.33**	**T**
Luminosity	**L**	**1034**	**cm-²s-¹**
Beam beam parameter	ξ	3.6	10-3
DC beam current	Ibeam		0.56 A
Bunch separation		24.95	ns
No. of bunches	**kb**	**2835**	
No. particles per bunch	**Np**	**1.1**	**1011**
Normalized transverse emittance (r.m.s.)	εn	3.75	µm
Collisions			
β-value at IP	β*	0.5	m
r.m.s. beam radius at IP	**σ***	**16**	**µm**

Part. II.2

Experimental Challenges
Requirements for Detectors

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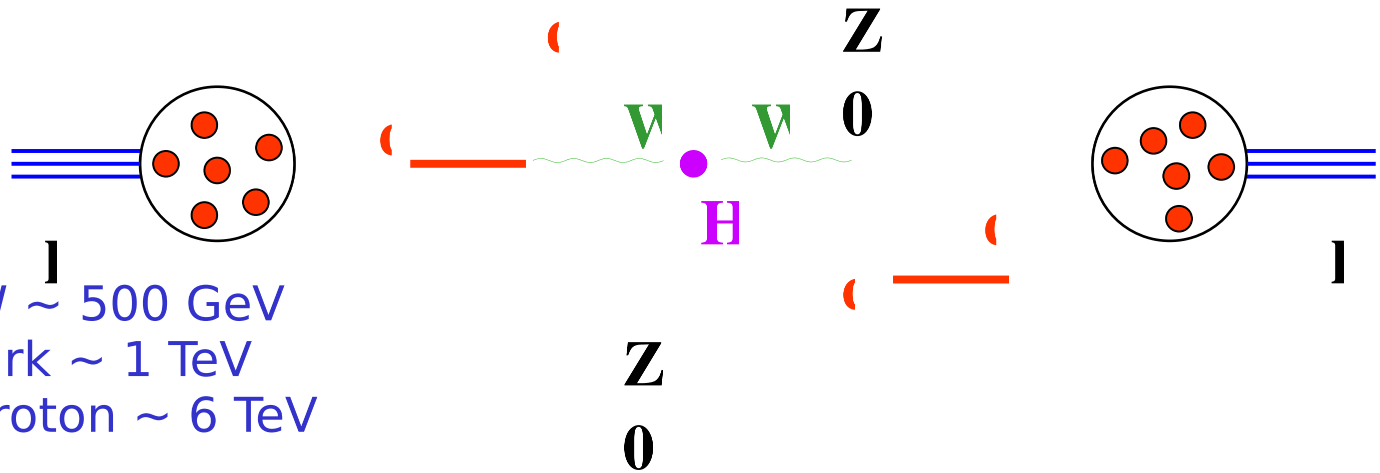
Energy and Luminosity

Hadron colliders are broad-band exploratory machines

May need to study WL-WL scattering at a cm energy of ~ 1 TeV



a EW ~ 500 GeV
a Equark ~ 1 TeV
a Eproton ~ 6 TeV

a LHC: pp collisions at 7 + 7 TeV

Event Rate = L.σ.BR

e.g. H(1 TeV) g ZZ g 2e+2μ or 4e or 4μ

For L ~1034 , Evts/yr = **1034** 10-37.10-3.107 ~ 10 /yr !!

2. Detector Challenges I

Multipurpose :

Good Performances for

leptons, jets, muons,…..

Fast decaying particles (vertex)

Hermitic

ET_miss

High Interaction Rate

pp interaction rate 109 interactions/s

Level-1 trigger decision will take ~2-3 μs

a electronics need to store data locally (pipelining)

data for only ~100 out of the 40 million crossings can be recorded per sec

a fast and accurate high-level trigger and data acquisition (DAQ)

Large Particle Multiplicity

~ <20> superposed events in each crossing

~ 1000 tracks stream into the detector every 25 ns

need highly granular detectors with good time resolution for low occupancy

a large number of channels

High Radiation Levels

2. Detector Challenges II

Very good muon identification and momentum measurement

trigger efficiently and measure sign of a few TeV muons

High energy resolution electromagnetic calorimertry

With good isolation performance

Powerful inner tracking systems

factor 10 better momentum resolution than at LEP

With a factor 100 in sensitive surface

High granularity

Hermetic calorimetry

good missing ET resolution

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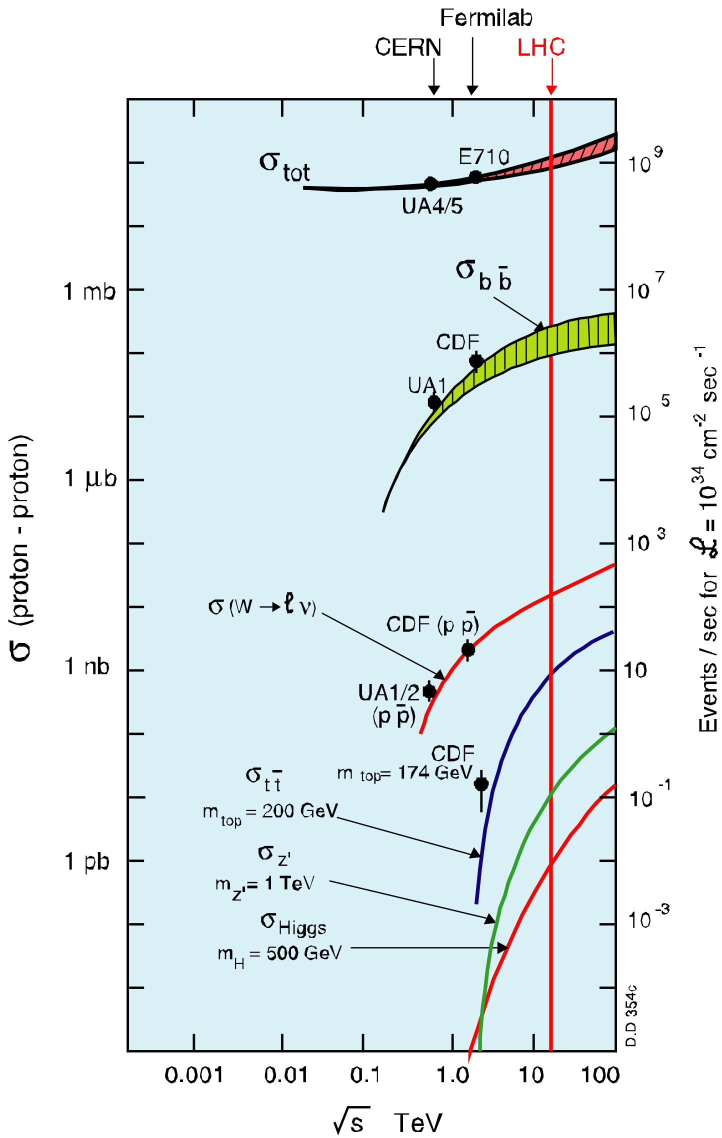
Production Cross-sections



At sqrt(s)=14 TeV

σtot ~ 105 mb

σelastic ~ 28 mb

σsingle diffractive ~ 12 mb

σdouble diffractive ~ few mb

σinel ~ 65 mb

Evt rate = L.σ = 1034 x 65 10-27 /s

= 6.5x108 /s

Not all bunches are full (2835/3564)

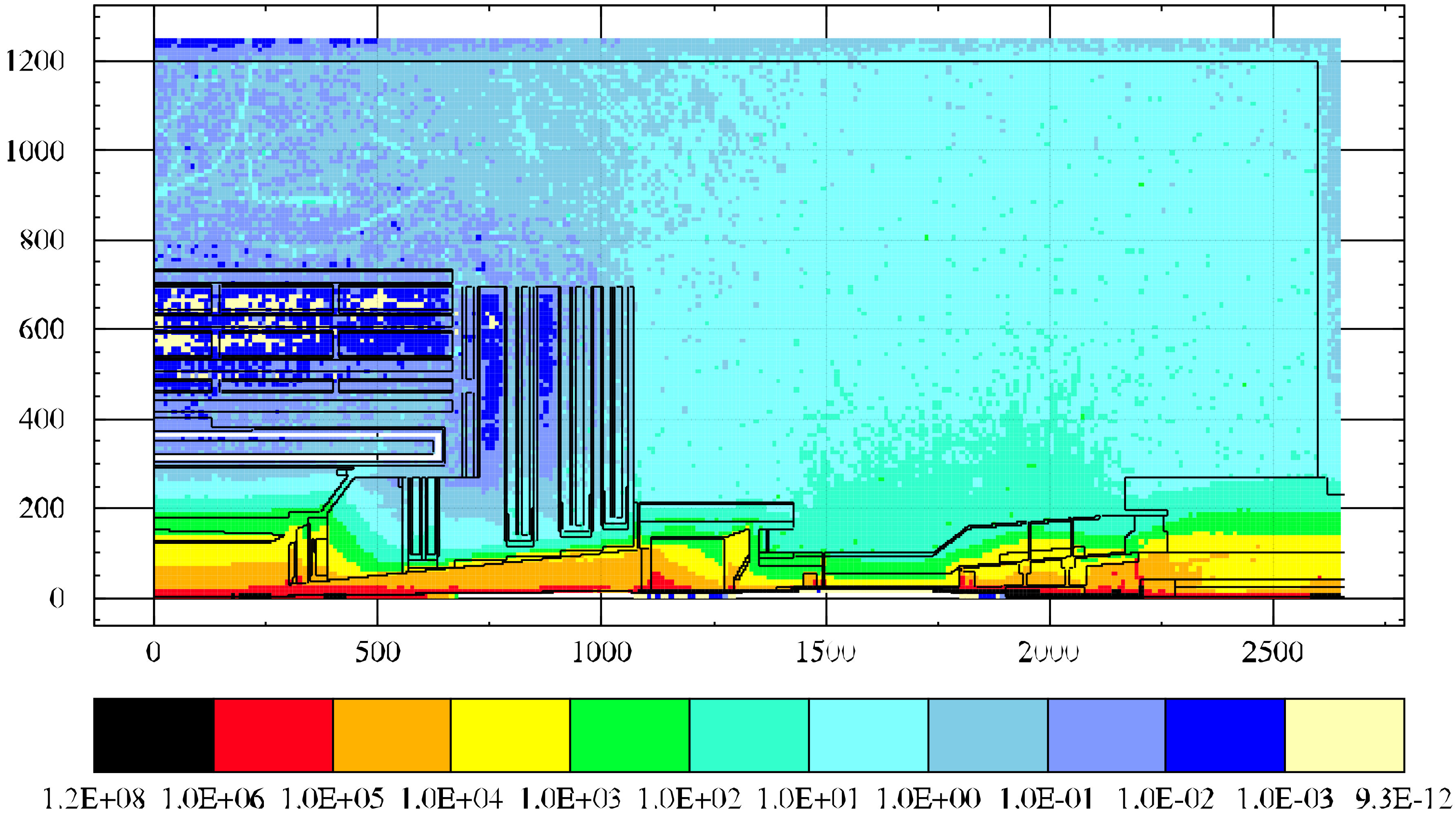
a events/crossing ~ 20

Operating Conditions

For every ‘good’ event containing a Higgs decay there are ~ 20 extra ‘unwanted’ minimum bias interactions superposed

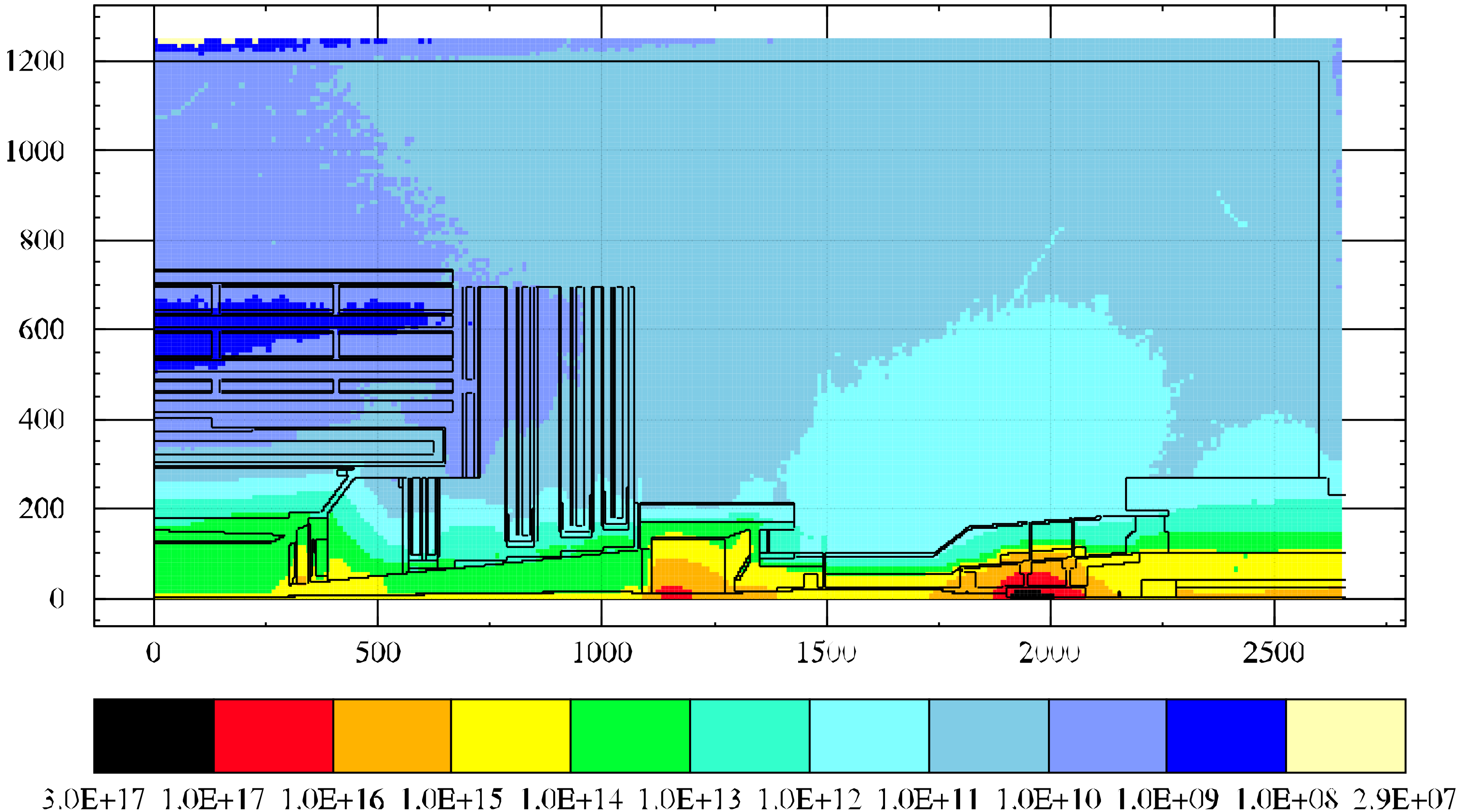
Radiation Levels: Dose

Dose (Gy) in CMS for an integrated luminosity of 5.105 pb-1 (~ 10 years)



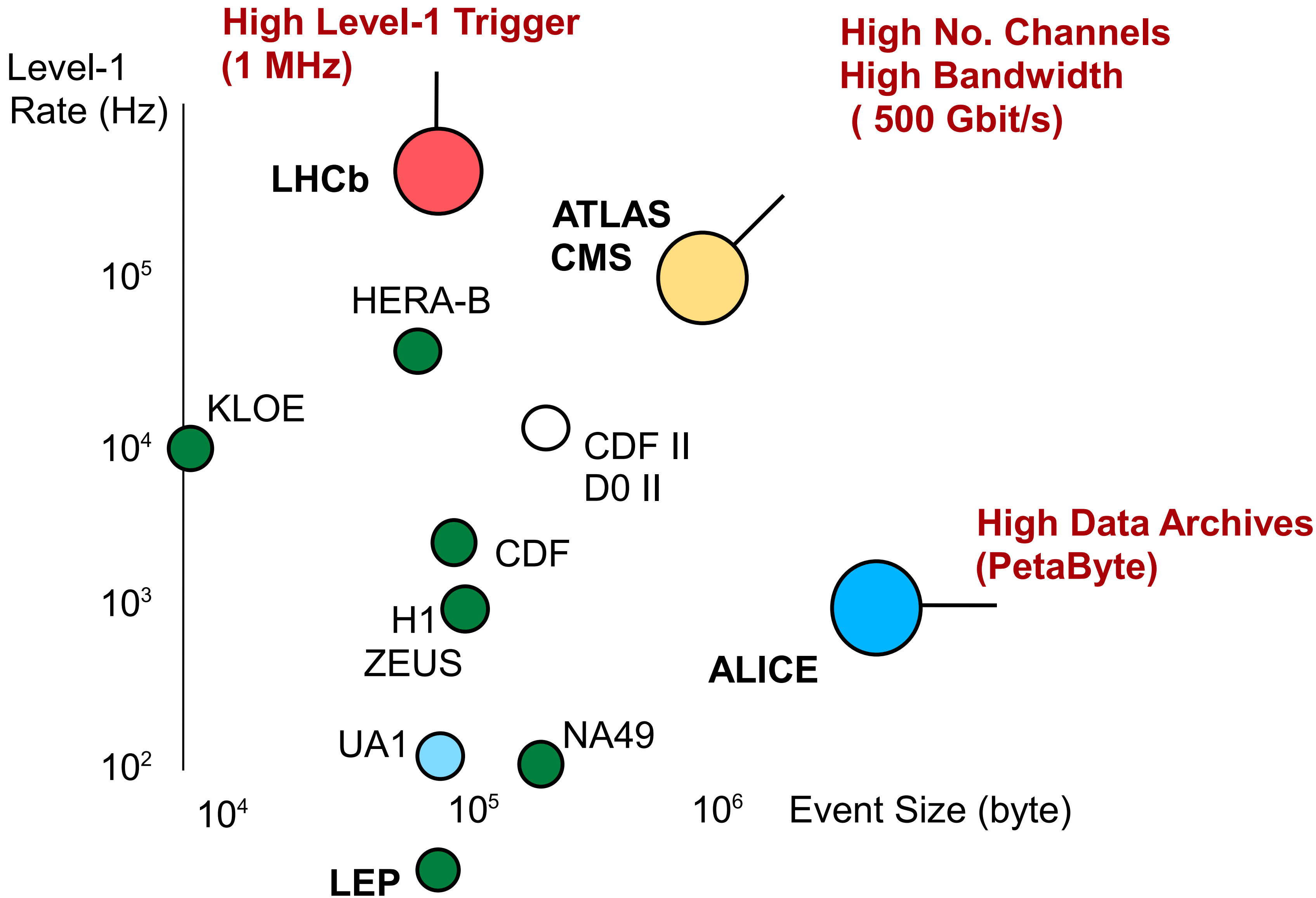
Radiation Levels: Neutron Fluence

uence (E>100 keV) in CMS for an integrated luminosity of 5.105 pb-1 (~ 10 y



Challenges: Event Selection

Challenges Data Acquisition



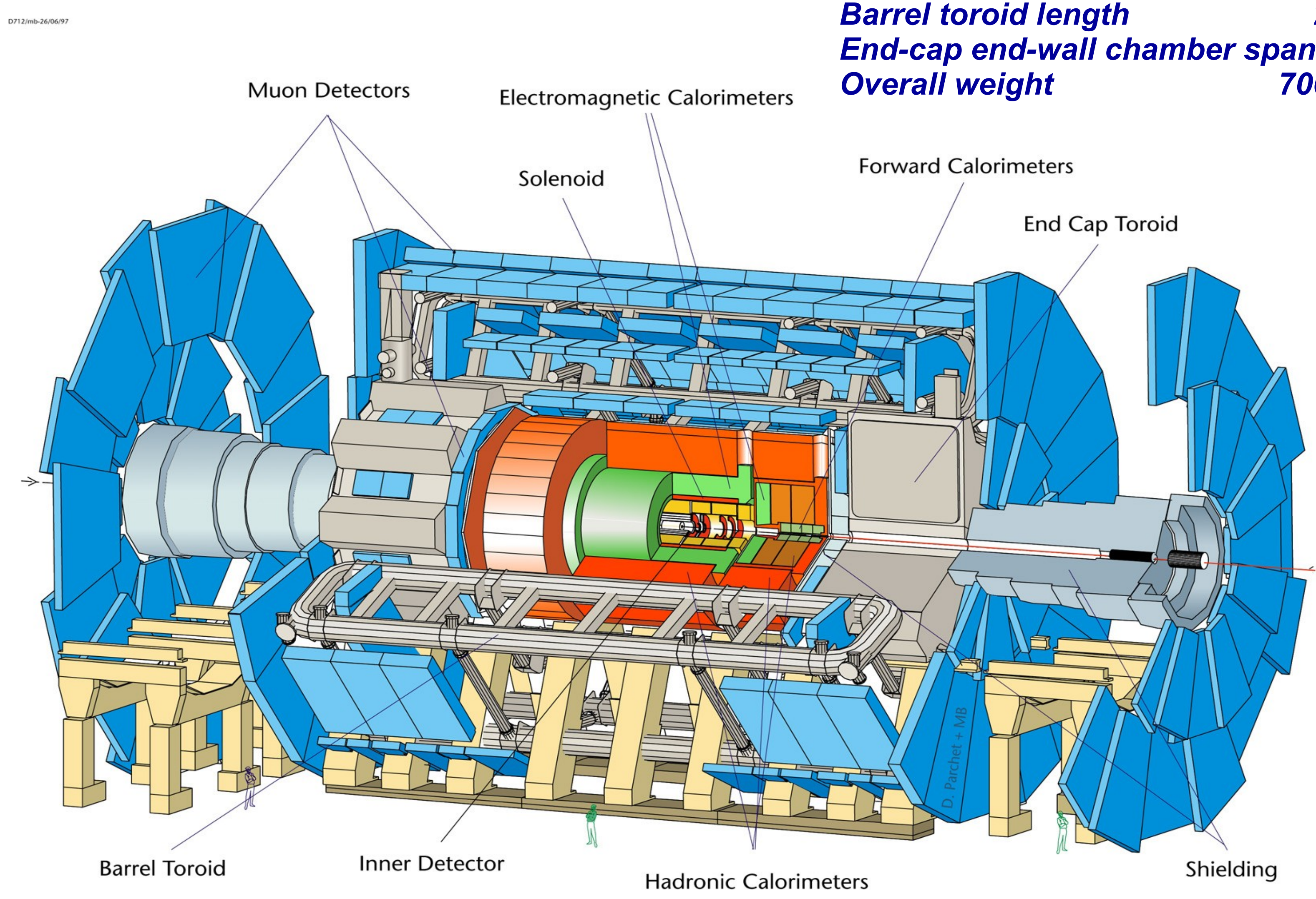
Part. III.1

ATLAS and CMS Detector Design
General Layout

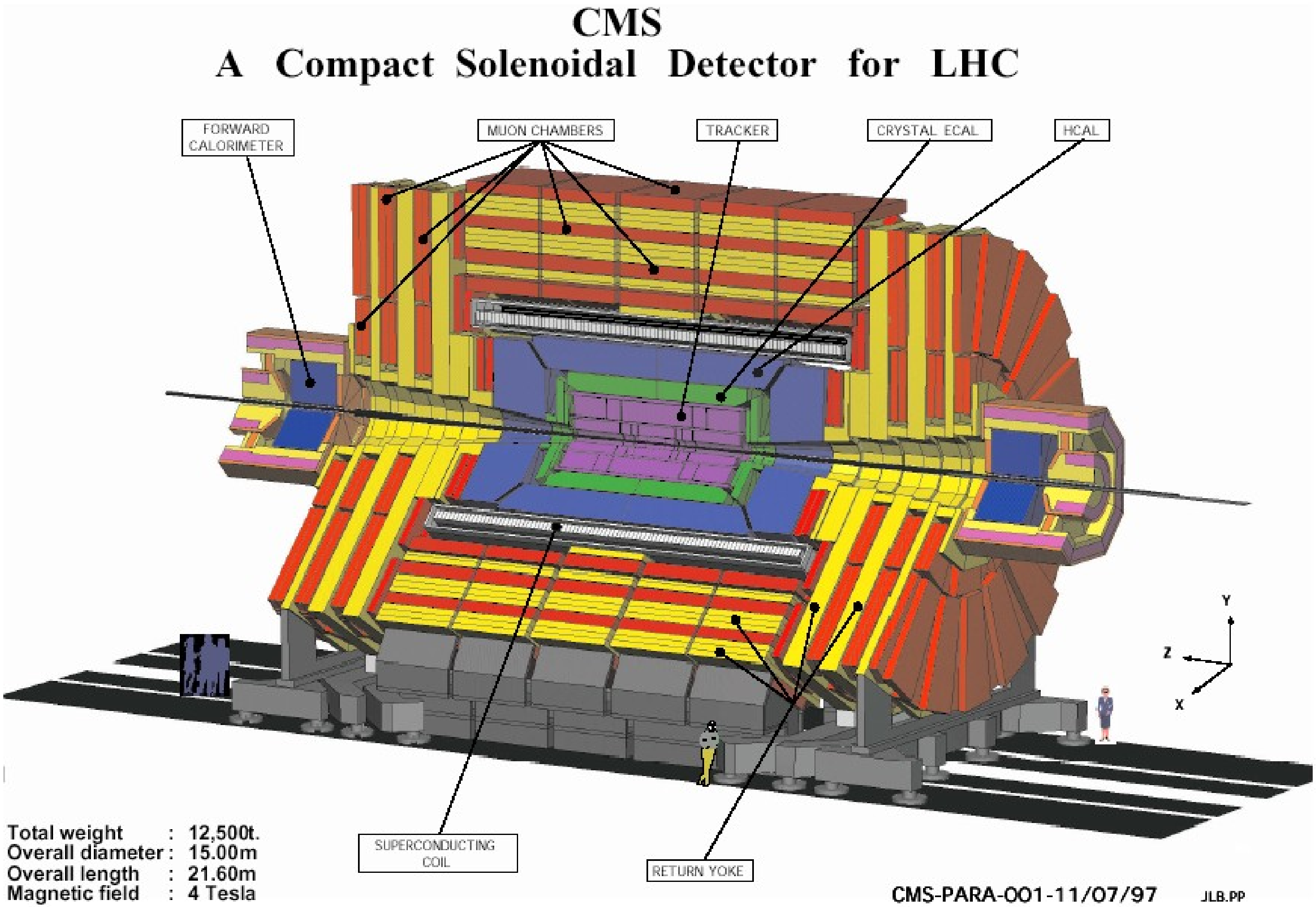
‘Cylindrical Onion-like’ Structure

The ATLAS Detector

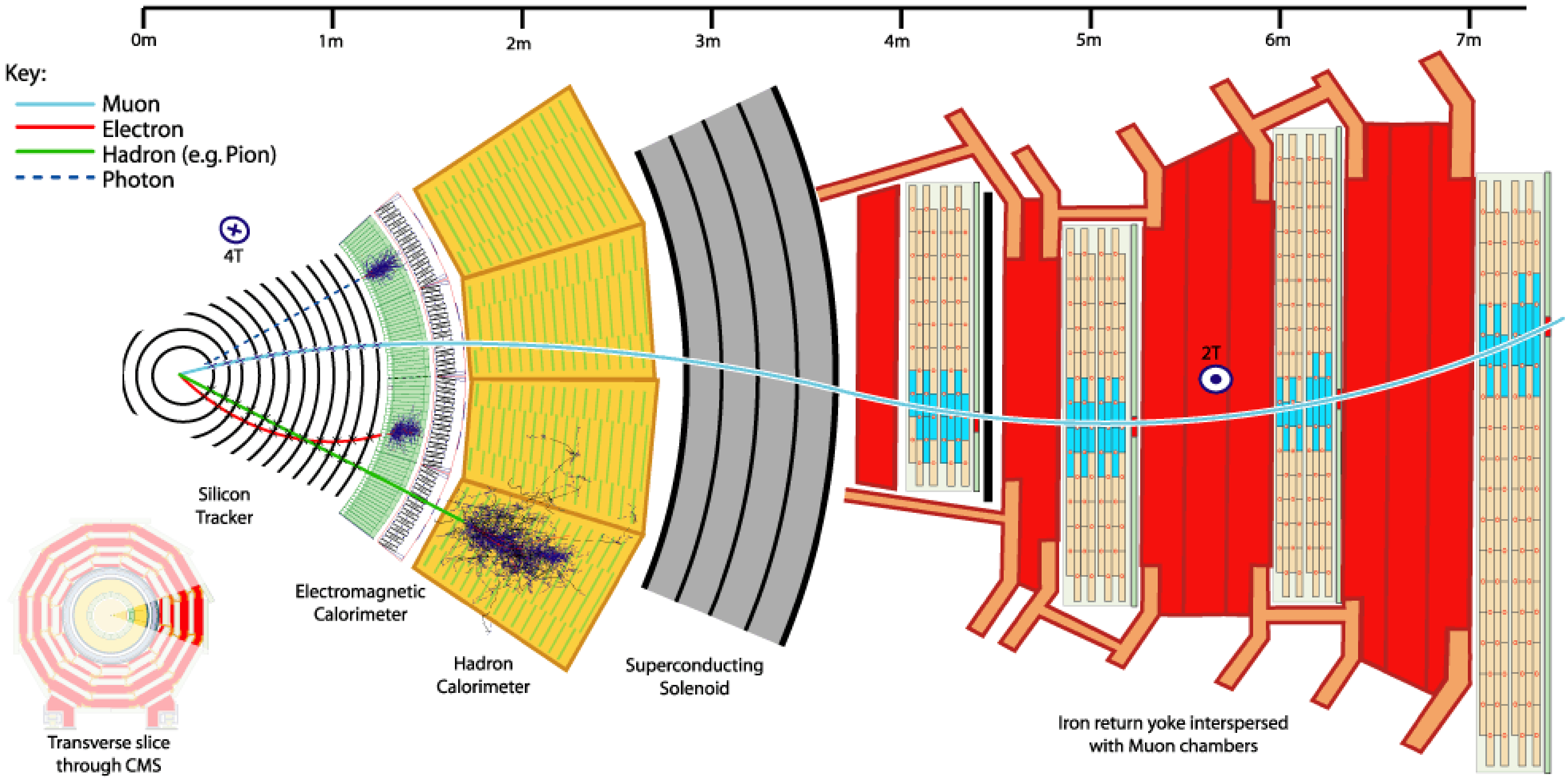
Diameter 25 m
Barrel toroid length 26 m
End-cap end-wall chamber span 46 m
Overall weight 7000 Tons



The CMS Detector



A Slice through CMS



Part. III.2

ATLAS and CMS Detector Design
Tracker

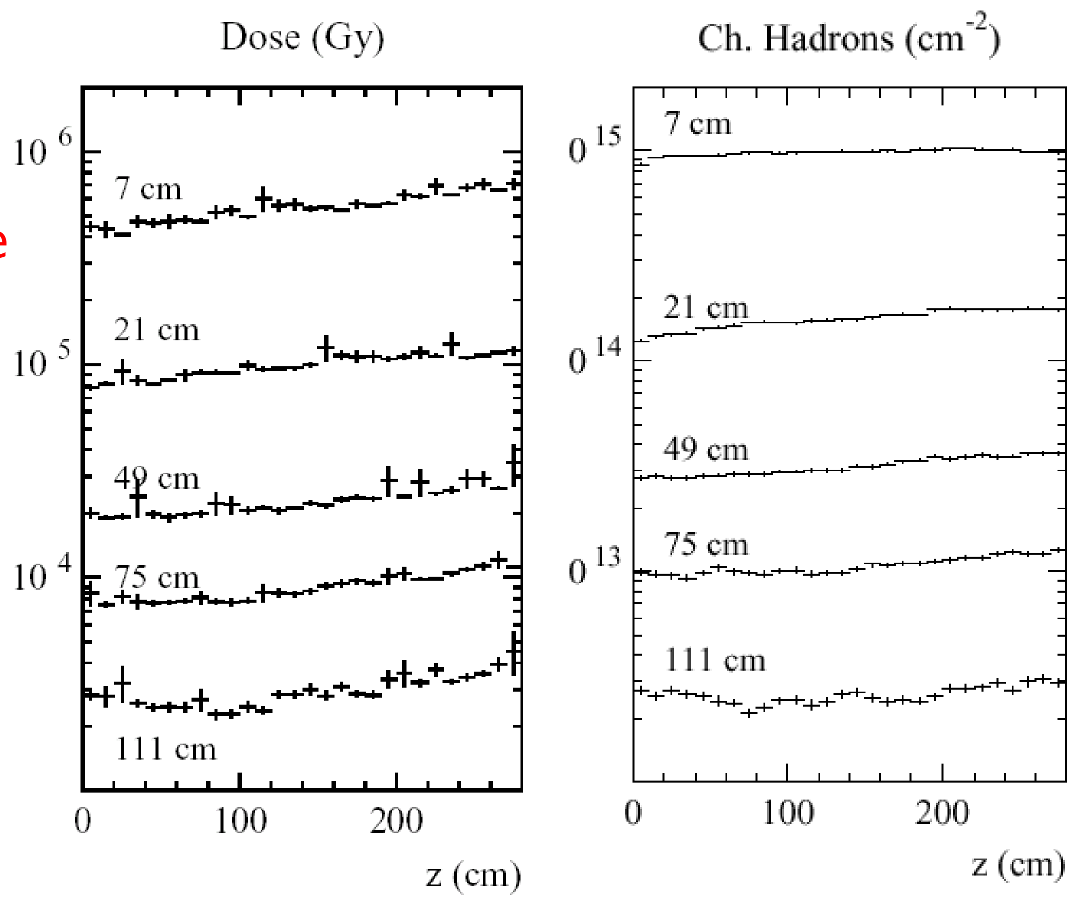
Factors that determine performance

Track finding efficiency – occupancy/crossing

Momentum resolution

Secondary vertex reconstruction

Dose & Fluence over 10 years

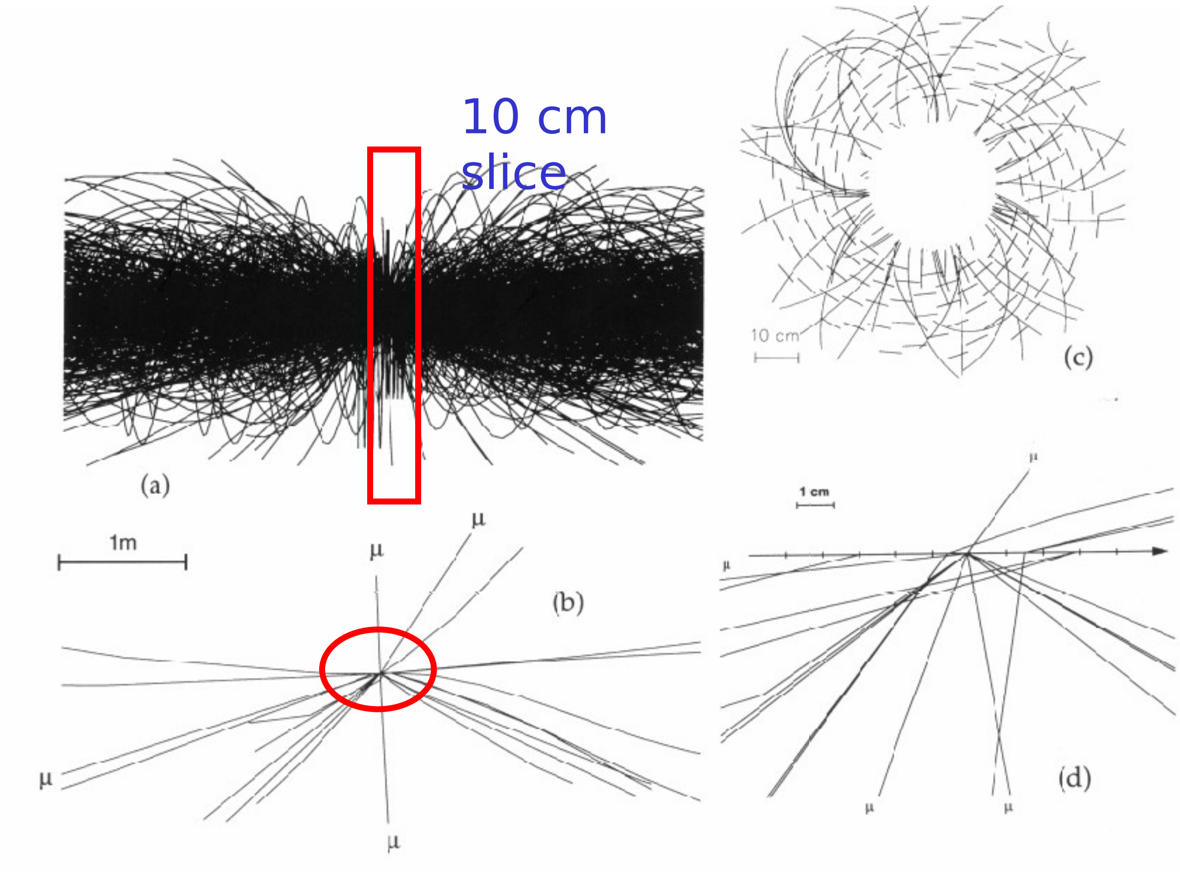


$\leq 4.10^7$ h$^\pm$/cm^2/s
pixels ($\approx 10^4$ μm^2)
occupancy $\approx 10^{-4}$

$\leq 4.10^6$ h$^\pm$/cm^2/s
Si μ-strip det.
($\approx$10 mm^2)
occupancy $\approx$ 1%

$\leq 4.10^5$ h$^\pm$/cm^2/s
Si or Gas detectors.
($\approx$1 cm^2)
occupancy $\approx$ 1%

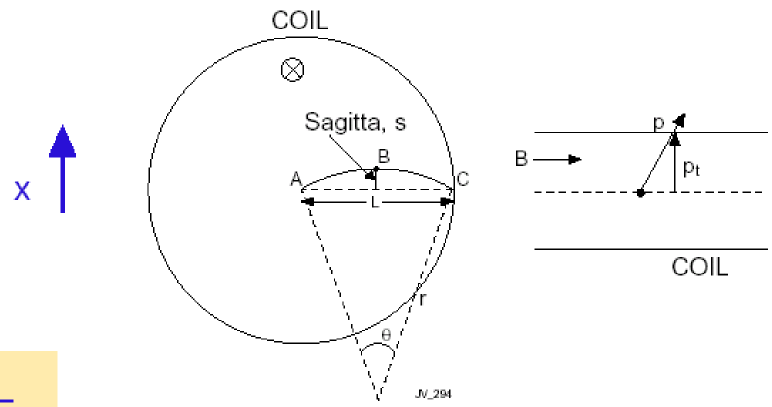
Event Pileup



Overlap of 30 min bias events
H□ μμ)

Answer:
High Granularity

Measurement of Momentum I



Radius of curvature $r = \dfrac{p_T}{0.3B}$

If r>>L then $\sin\dfrac{\theta}{2} = \dfrac{L}{2r} \Rightarrow \dfrac{\theta}{2} \approx \dfrac{L}{2r} \Rightarrow \theta \approx \dfrac{0.3BL}{p_T}$

Sagitta

$$
\begin{aligned}
s &= r - r\cos(\theta/2) \\
&\approx r\left[1 - \left(1 - \frac{1}{2}\frac{\theta^2}{4}\right)\right] \\
&= \frac{r\theta^2}{8} \approx \frac{0.3BL^2}{8p_T}
\end{aligned}
$$

e.g. s ≈ 3.75 cm
for p_T=1 GeV/c, L=1m and B=1T

Measurement of Momentum II

$$\frac{dp_T}{p_T} = \frac{\sigma_s}{s} = \frac{\sqrt{(3/2)}\ \sigma_x}{s}$$

$$\frac{dp_T}{p_T} = \frac{\sqrt{3}}{2}\sigma_x \frac{8p_T}{0.3BL^2} \qquad (2)$$

Momentum resolution degrades linearly with increasing momentum, improves for higher field and the larger radial size of tracking cavity (quadratic in L)

Arrangement of measuring points

Uniform spacing

$$\frac{dp_T}{p_T} = \frac{\sigma_x p_T}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$

e.g. $dp_T/p_T \approx 0.5\%$ for p_T=1 GeV/c, L=1m, B=1T, σ_x = 200 µm and N=10

$$\left.\frac{dp}{p}\right|_{ms} \approx 0.05\ \frac{1}{B\sqrt{LX_0}}$$

BUT in a real tracker errors due to multiple scattering has to be included .

Measurement of Momentum III

s_p - sagitta in plane

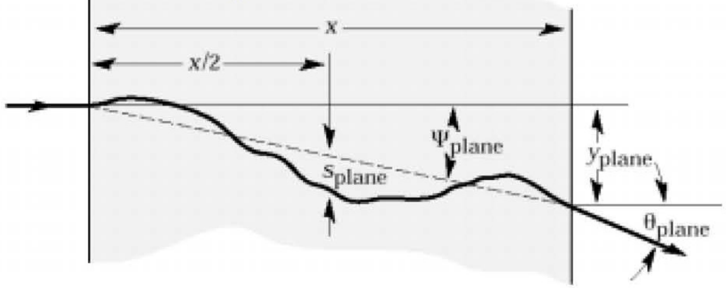
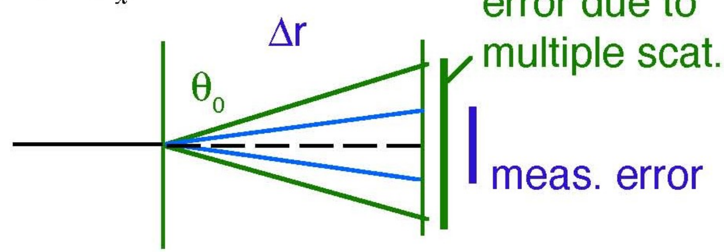


Figure 23.5: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

If extrapolation error from one plane to next is larger than the point resolution then momentum resolution is degraded i.e. if

$$\theta_0 \;\; \Delta r \; > \; \sigma_x$$



Apparent sagitta due to multiple scattering

$$s_p \; = \; \frac{L\theta_0}{4\sqrt{3}}$$

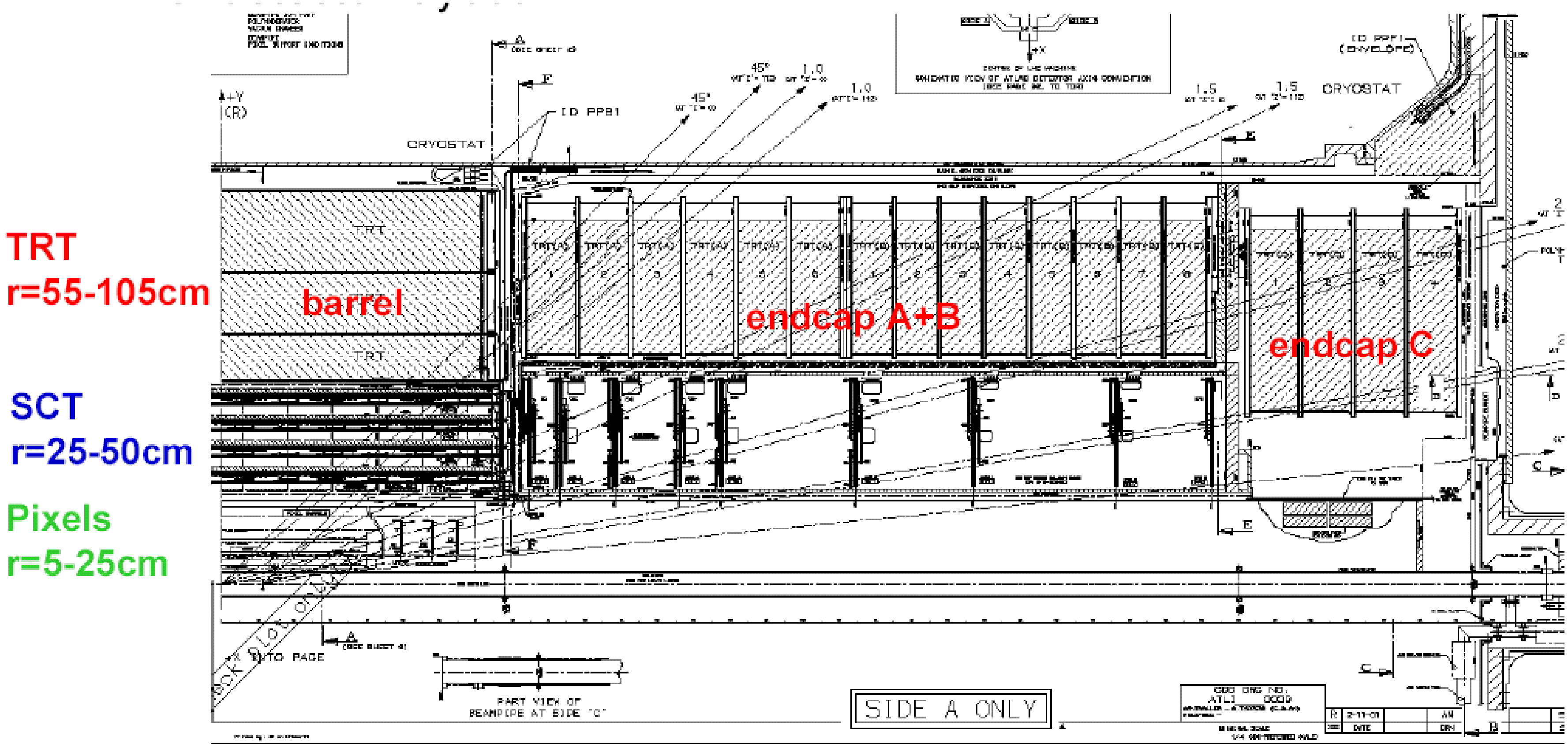
Relative momentum resolution due to multiple scattering is

$$\therefore \; \frac{s_p}{s} \; = \; \left.\frac{dp}{p}\right|_{ms} \; \approx \; 0.05 \, \frac{1}{B\sqrt{LX_0}} \qquad since \;\; s \; = \; \frac{0.3BL^2}{8p}$$

B in T, L and X_0 in m

i.e. Resolution is independent of p and α 1/B

ATLAS Tracker Layout



Hybrid Pixels: ~ 2.3 m2 of silicon sensors, 140 M pixels, 50x300 μm2, r = 5, 10, 13 cm

Si μ-strips : 60 m2 of silicon sensors, 6 M strips, 4 pts, r = 30 - 50 cm

Straws TRT: 36 straws/track, Xe-CO2-CF4 ϕ=4mm, r = 56 - 107 cm

Electron Identification using Tracker in ATLAS (I)

Transition radiation is emitted when a charged particle moves from a medium of refractive index n_1 to a medium of a different index n_2 (= an apparent acceleration)

$$p = \gamma m v \Rightarrow m = \frac{1}{\beta c \gamma} p$$

$$\therefore \left(\frac{\Delta m}{m}\right)^2 = \frac{1}{\beta^2 c^2}\left(\frac{\Delta \gamma}{\gamma}\right)^2 + \left(\frac{\Delta p}{p}\right)^2$$

If $\Delta p/p$ is small, mass resolution at high momenta is $\alpha\ \gamma$

- Radiated energy /boundary to vacuum

$$W = \frac{1}{3}\alpha\ \hbar\omega_p\ \gamma \quad i.e.\ W \propto \gamma \qquad E_{ph} = \frac{\gamma}{3}\hbar\omega_p$$

where $\hbar\omega_p$ *is the plasma frequency* (≈ 20 *eV for polyethylene*)

Hence can use it for particle identification

- X-rays are emitted at small angle ($\theta \approx 1/\gamma$). TR stays close to the charge particle track
- Number of emitted photon/boundary is small $N_{ph} \approx \frac{W}{\hbar\omega_p} \propto \alpha \approx \frac{1}{137}$!
- Need many transitions → stack of many thin foils with high Z gas to absorb the X-rays

Electron Identification using Tracker in ATLAS (II)

4mm diameter ttraw tube proportional chambers embedded in polyethylene fibres

Gas 70% Xe + 20% CF_4 + 10%CO_2

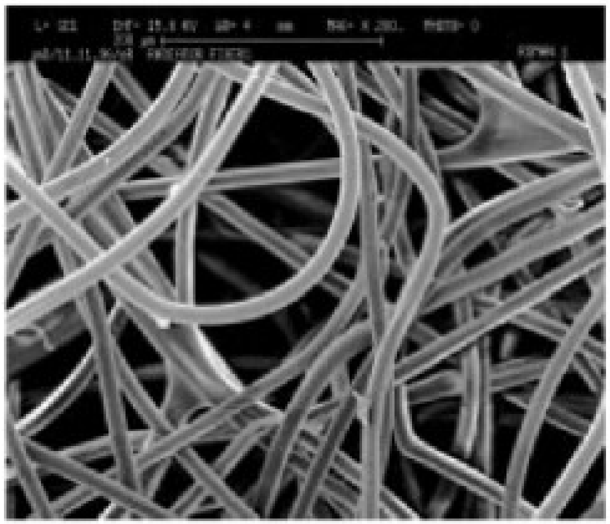


Figure 12-38 Micro-photograph of a sample of polyethylene fibre radiator (scale: 70 μm per 1 cm).

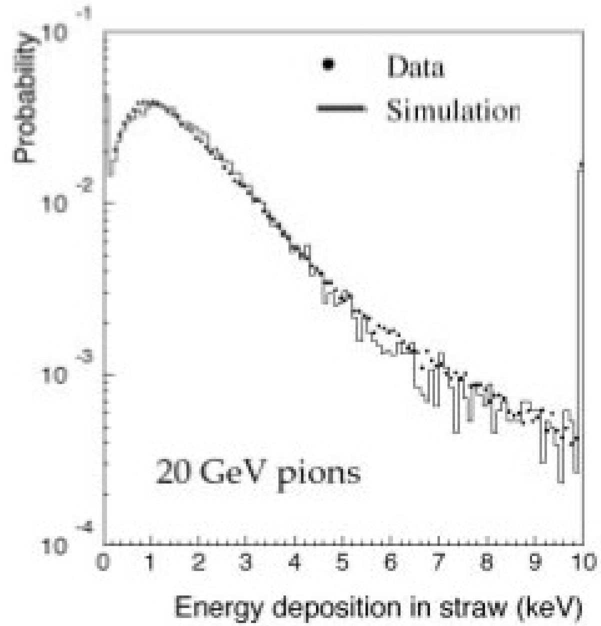


Figure 12-41 Normalised dE/dx spectra for 20 GeV pions for data and simulation.

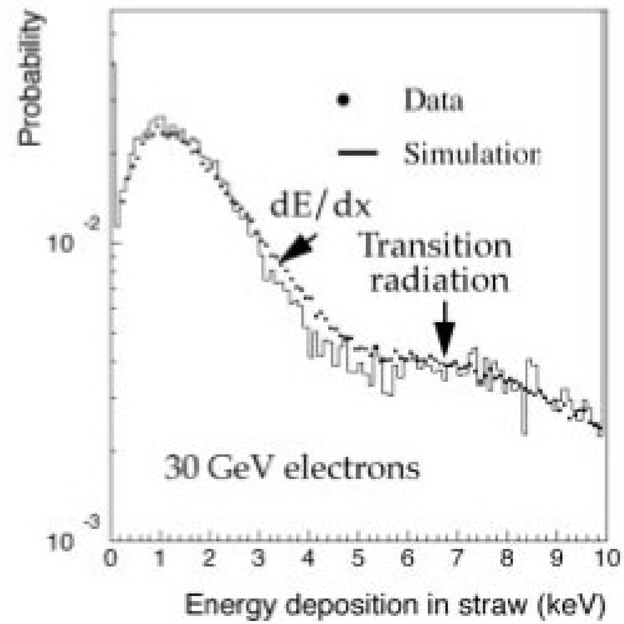
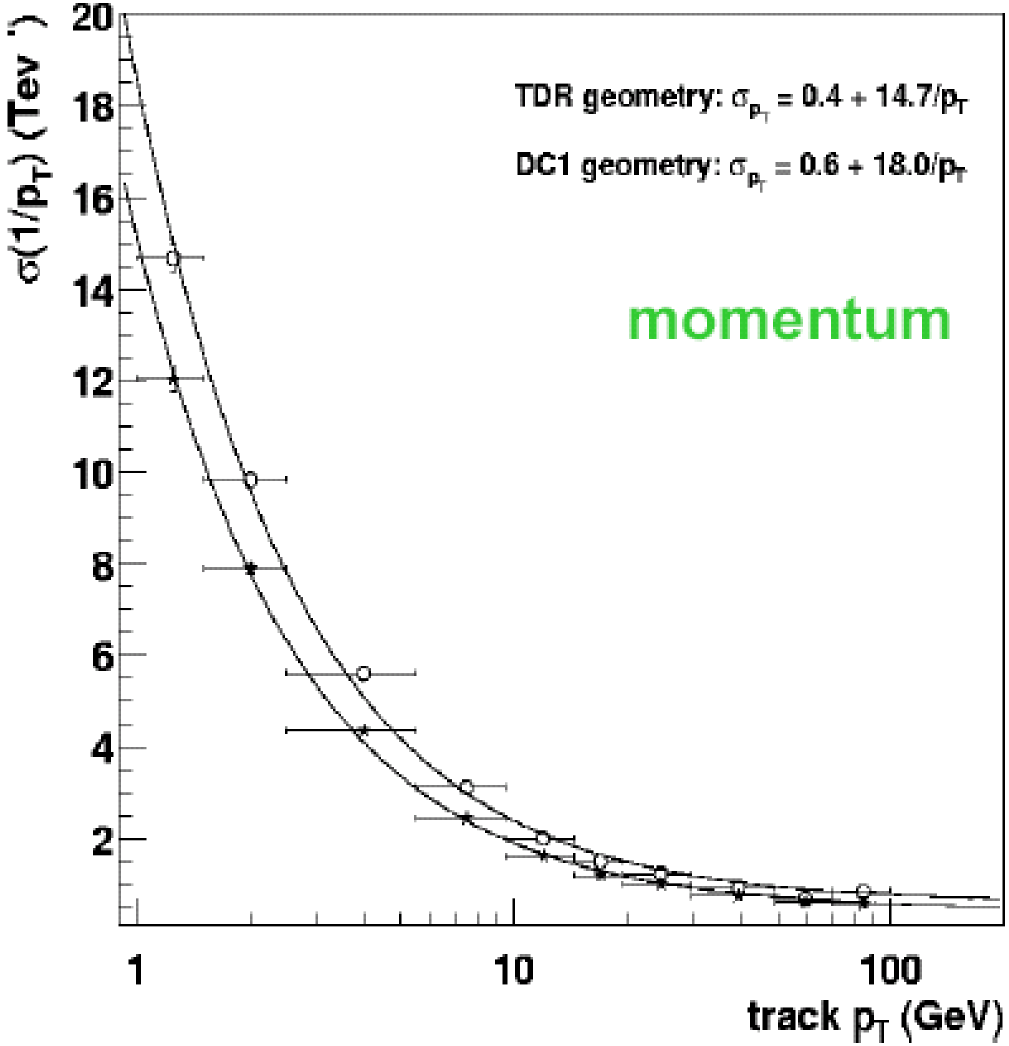


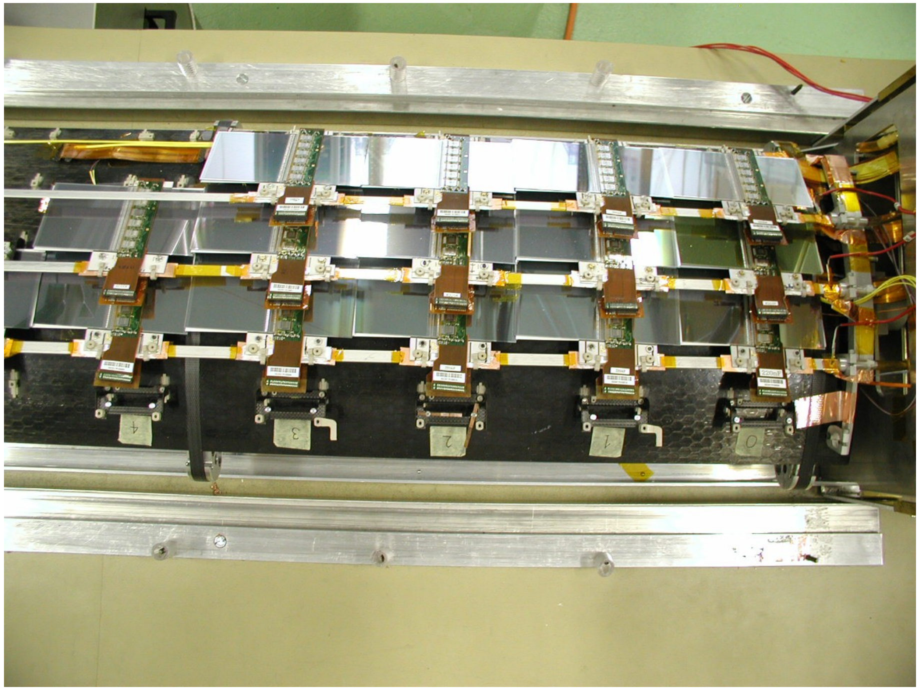
Figure 12-42 Normalised dE/dx and transition-radiation spectra for 30 GeV electrons for data and simulation.

ATLAS Tracker Performance

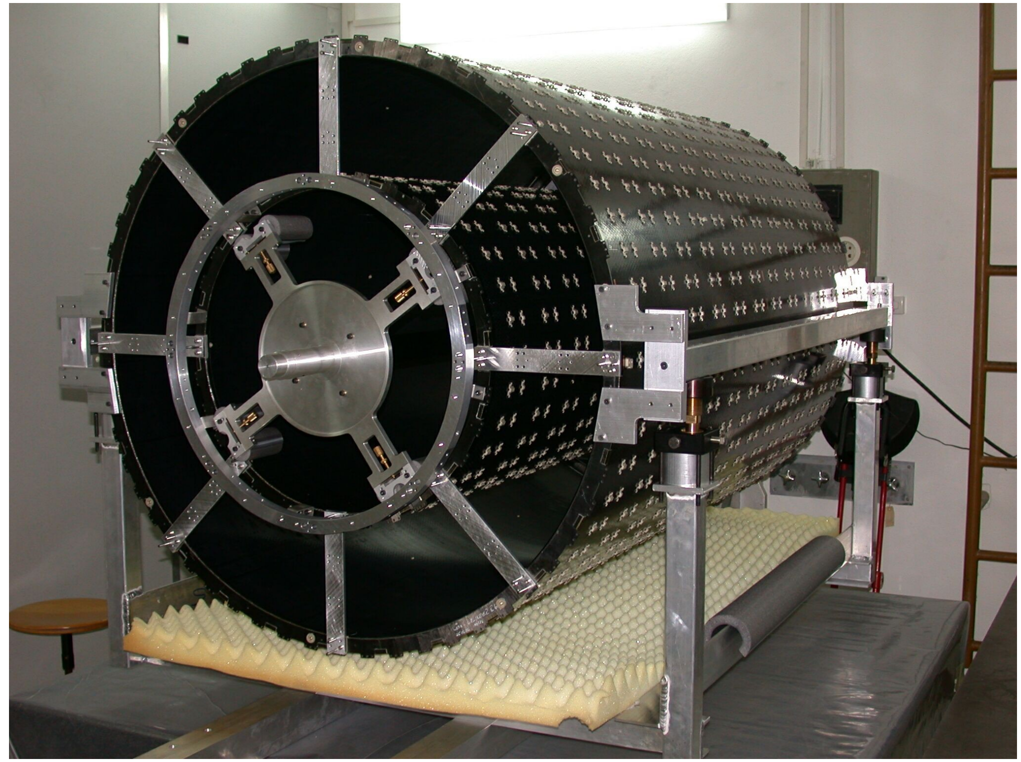


σ(pT)/pT ~ 0.6+18pT (pT in TeV)

ATLAS Tracker: Some Components



SCT barrel system test



Two of the SCT barrel
support structures

CMS Tracker Layout

double

single

1.2m

500 μμ σενσορσ
Ηιγη ρεσιστιϖιτψ, π–ον–ν

320 μμ σενσορσ
Λοω ρεσιστιϖιτψ, π–ον–ν

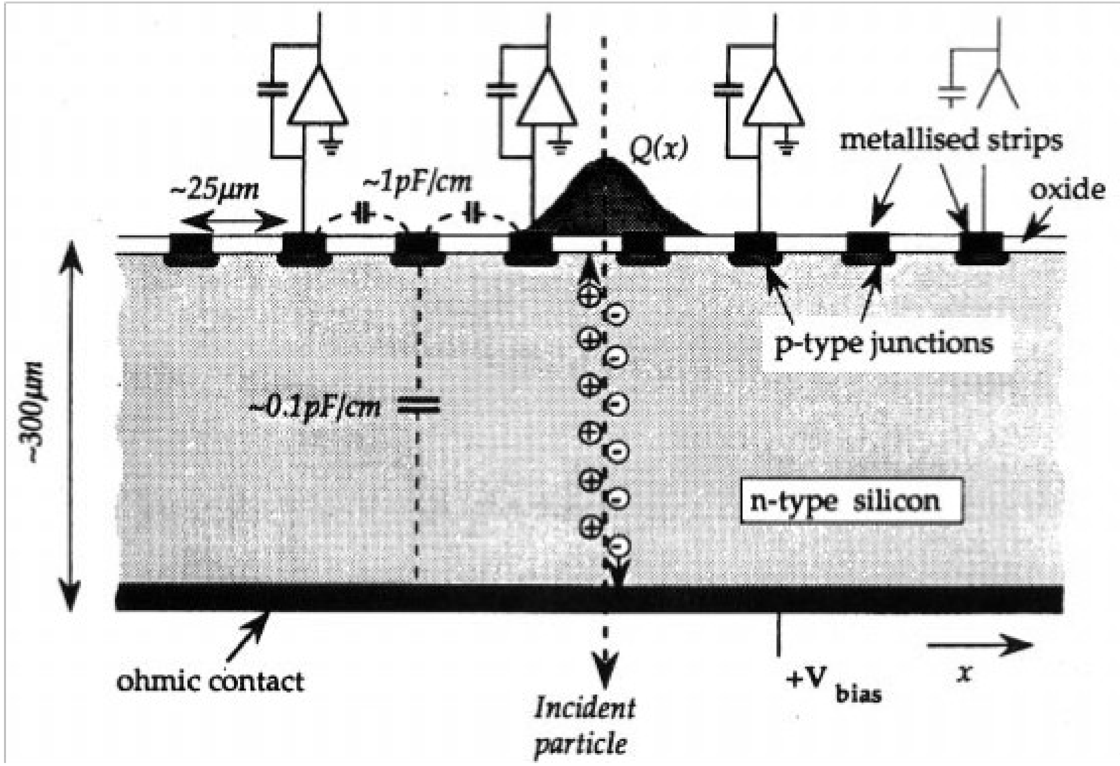
Pixels
High resistivity, n-on-n

3m

Hybrid Pixels: ~ 1 m2 of silicon sensors, 67 M pixels, 100x150 μm2 , 3 pts, r = 4, 7, 11 cm

Si μ-strips : 223 m2 of silicon sensors (15 k modules) , 10 M strips, 10 pts, r = 20 – 120 cm

Silicon Tracker

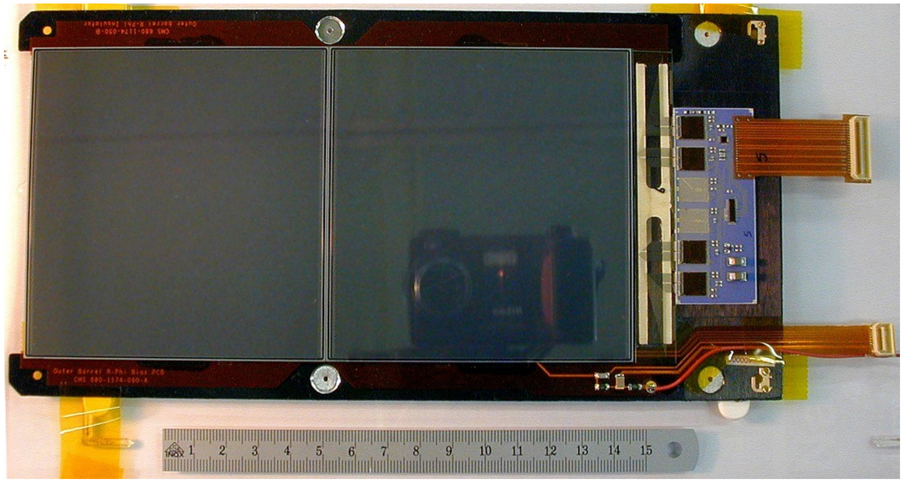


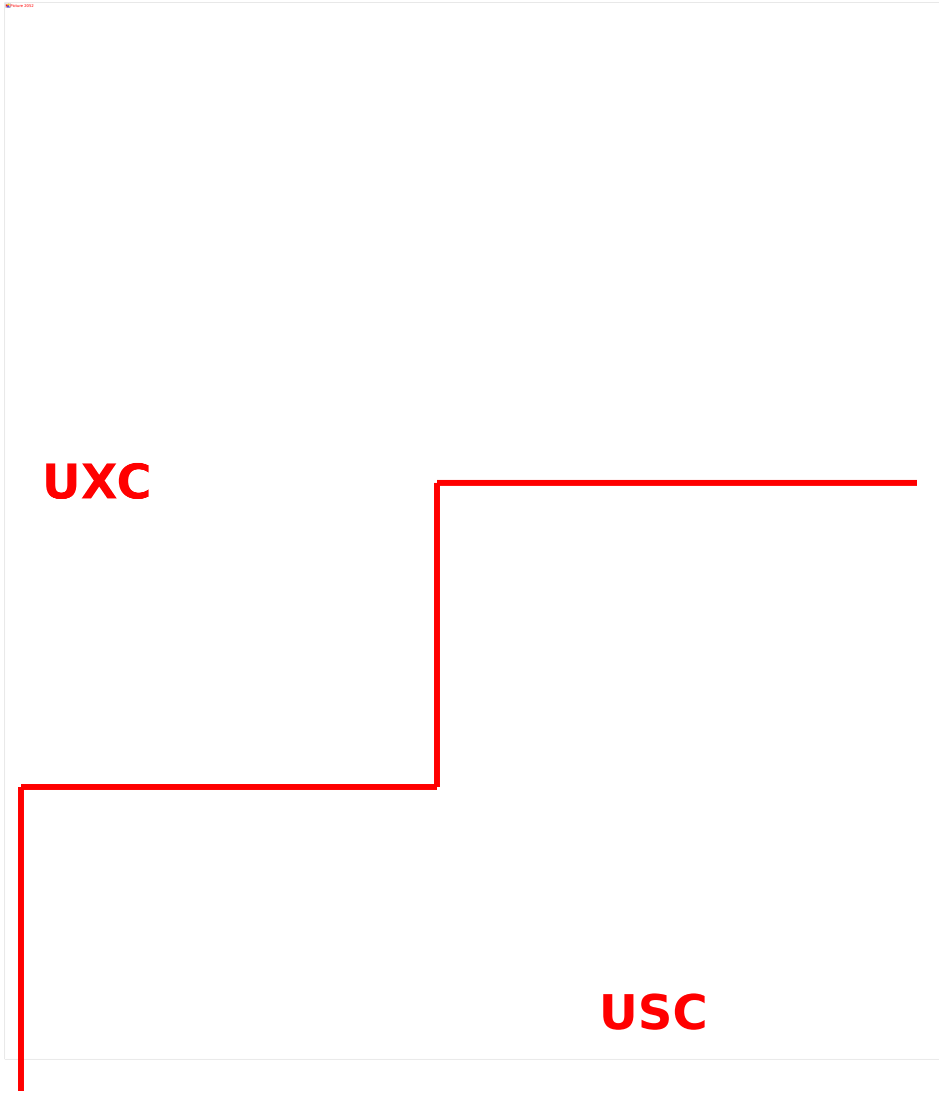
Schematic cross-section through a silicon microstrip detector. Diffusion distributes charge over multiple strips and capacitive charge division between readout amplifiers allows position interpolation.

CSS99

This implies analog buffering and readout

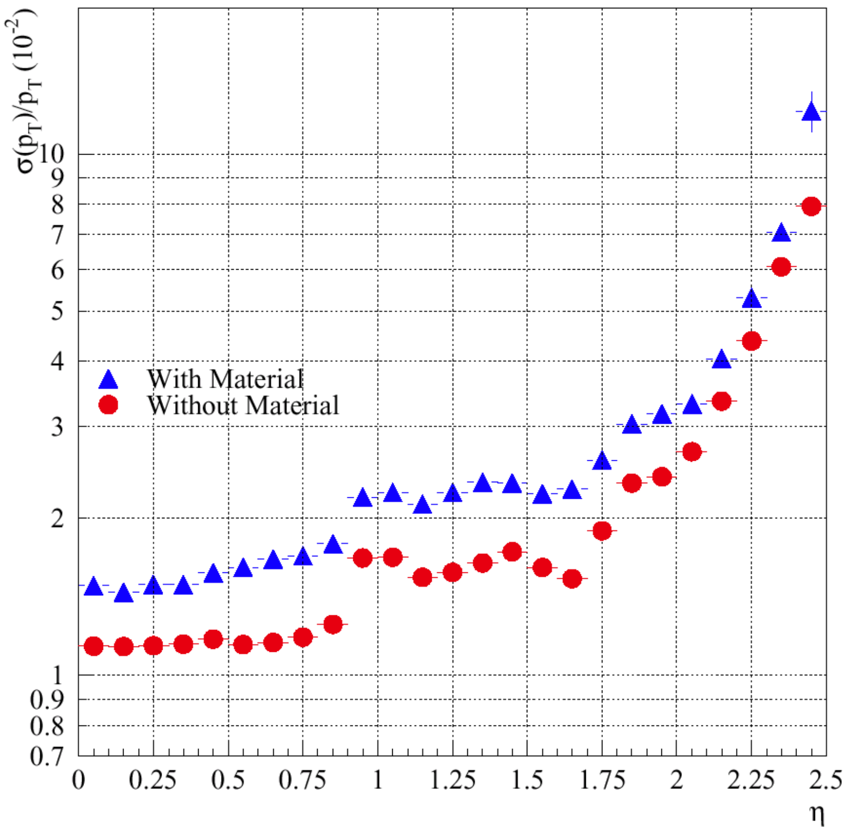
Challenges: Front-end Electronics





Each microstrip is read out by a charge sensitive amplifier with τ= 50 ns.
The o/p voltage is sampled at the beam crossing rate of 40 MHz.
Samples are stored in analog pipeline for up to Level-1 latency (3.2 μs)
Following a trigger form a weighted sum of 3 samples in analog circuit
This confines signal to single bx and gives pulse height
Buffered pulse height data multiplexed out on optical fibres
Output of laser modulated by the pulse height for each strip

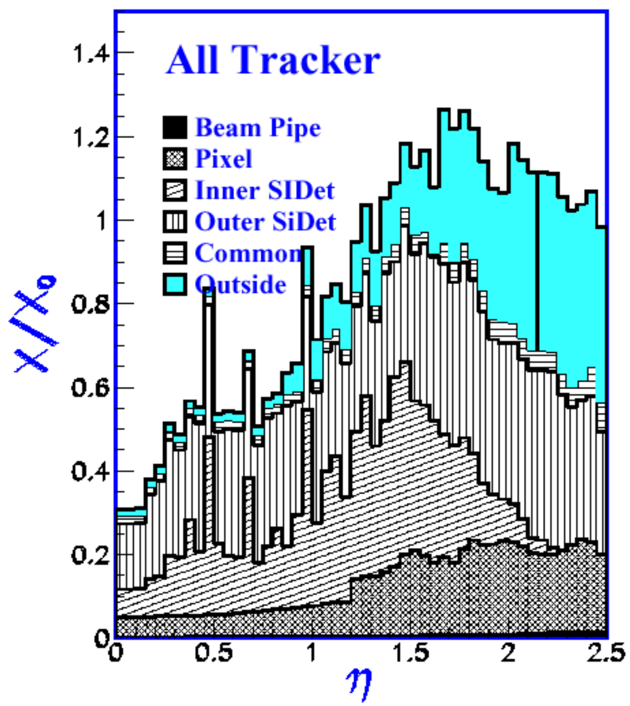
CMS Tracker Performance



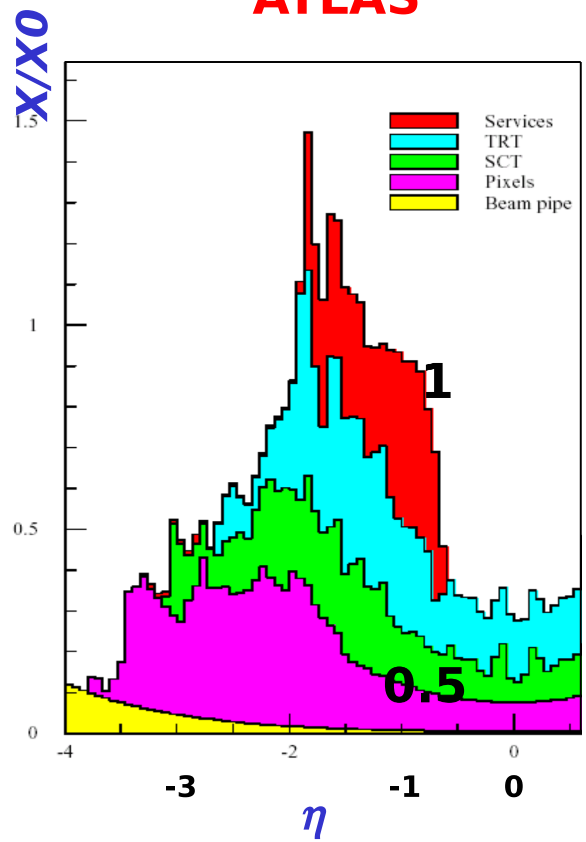
To minimize the leakage currents induced by radiation (neutron)
The whole tracker must be kept at low temperature ~ -18 deg.Celsius
This requires not only a cooling but also a environment screen. Both bringing material....

Material in Trackers

CMS



ATLAS



In ATLAS
 also in front the calorimeters, is the thin (0.66 X/X0) Solenoide

Also very important figures for Electromagnetic Calorimeter which is behin
Through electron bremstrallung and photon conversion

Part. III.3

ATLAS and CMS Detector Design
Muon System

Identification of Muons

Muons identified by their penetration through about 10 λ of calorimeter material
The material of calorimeters absorbs the e's, γ's and h±.

Energy Loss in Absorber

- for $E_\mu \leq$ 20-30 GeV - energy loss fluctuations dominate
- high energy muons generate their own background.

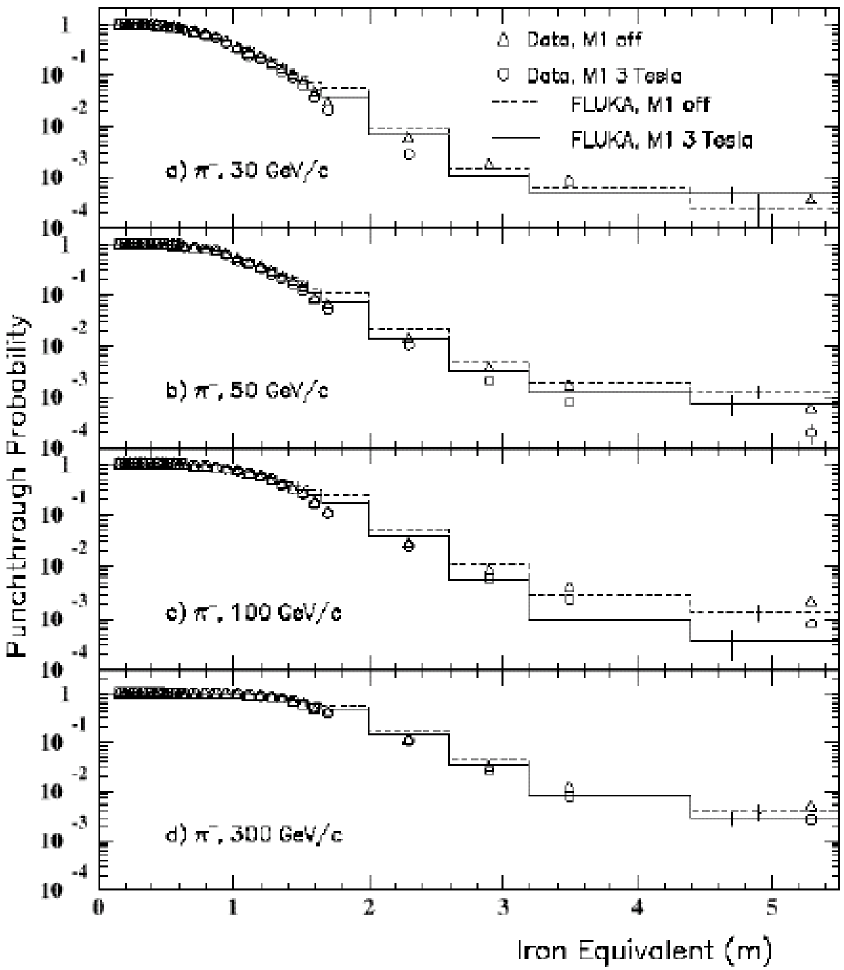
Hard bremstrahlung (catastrophic energy loss can spoil μ-tracking. The critical energy for μ i Fe is $E_c \approx$ 350 GeV.

Hadron Punch-through

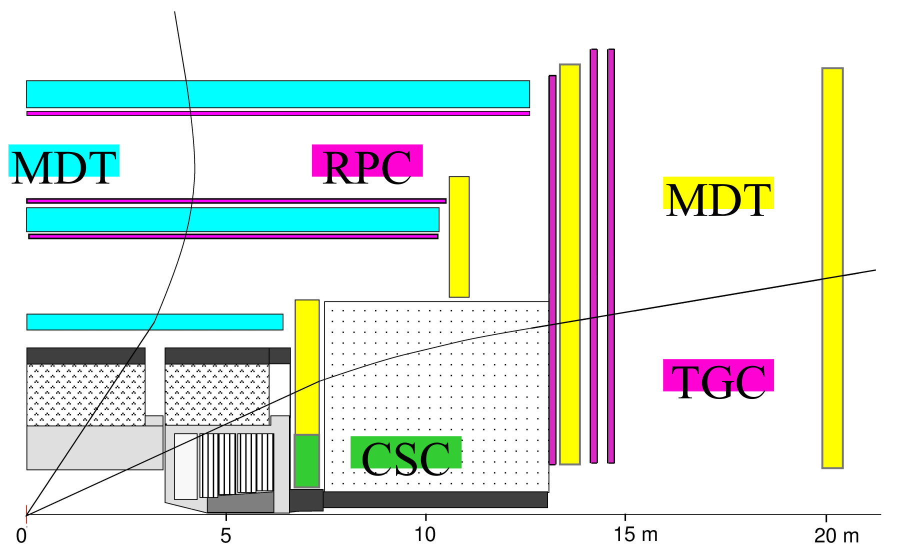
Debris from hadronic showers can accompany muons leading to:

- mis-identification of hadron as μ
- confusion and difficulty in matching μ-tracks (in jets)
- increase in μ trigger rate

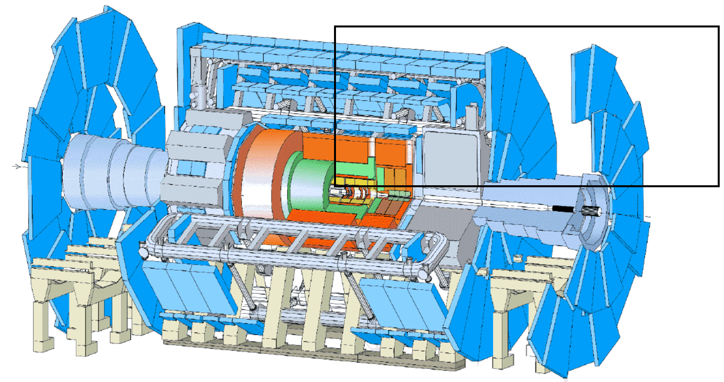
Hadron Punchthough



ATLAS Muon Detectors



Each detector has 3 stations.
Each station consists of 2-4 layers.



Precision chambers

Monitored **D**rift **T**ubes (|η| < 2)
with a single wire resolution of 80 μm
1194 chambers, 5500m2
Cathode **S**trip **C**hambers (2 < |η| < 2.7)
at higher particle fluxes
32 chambers, 27 m2

Trigger chambers

Resistive **P**late **C**hambers (|η| < 1.05)
with a good time resolution of 1 ns
1136 chambers, 3650 m2
Thin **G**ap **C**hambers (1.05 < |η| < 2.4)
at higher particle fluxes
1584 chambers, 2900 m2

ATLAS Muon System: Monitored Drift Tubes

End-cap MDT chamber

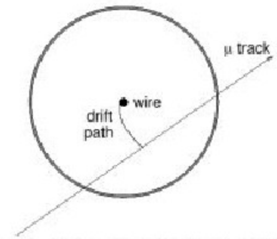
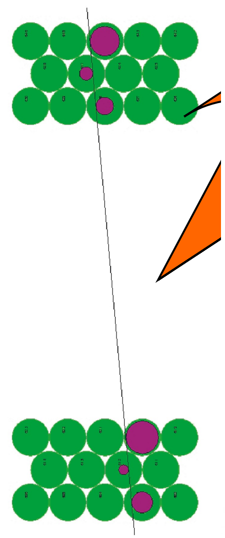


Figure 5-2 Drift tube operation in a magnetic field with curved drift path.

ϕwire = 50μm (W-Re)
3 bar, 3270V,
td = 500ns
Gas gain = 2.104

Measured Spatial Resolution



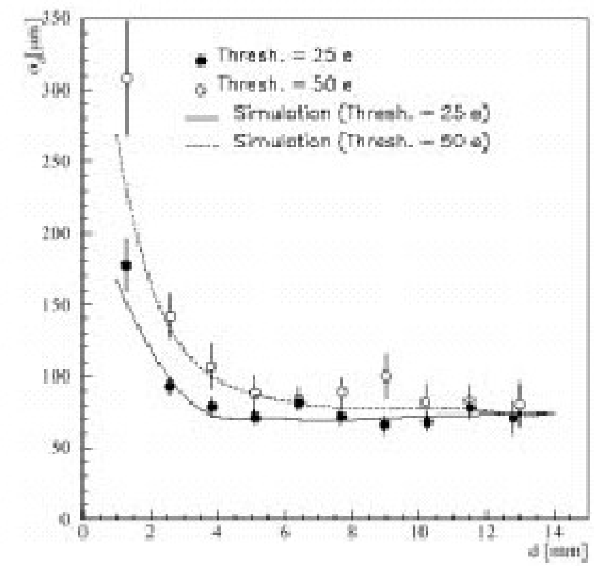
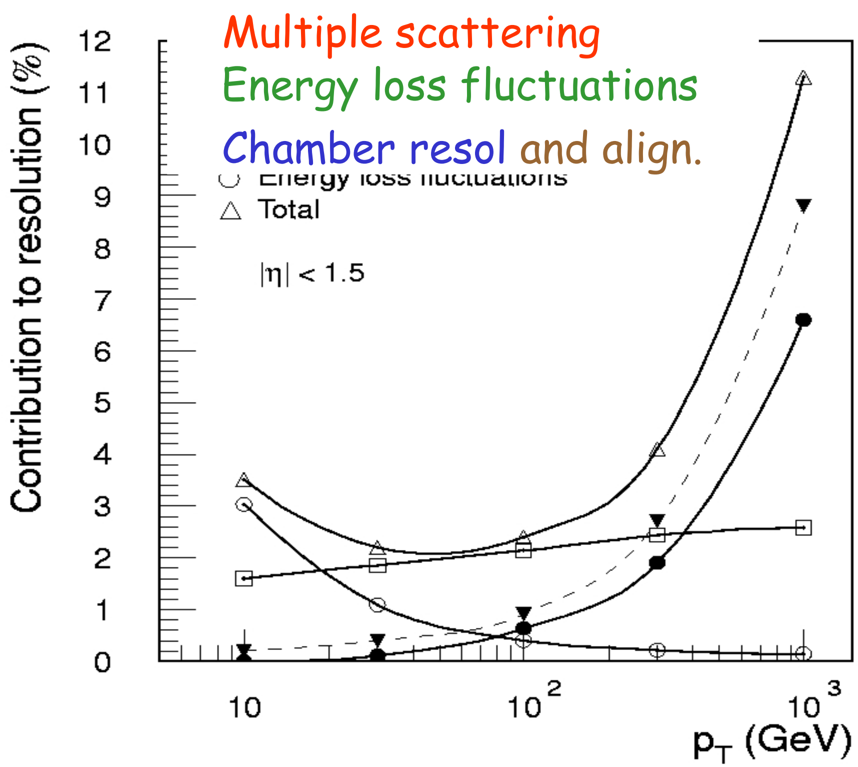
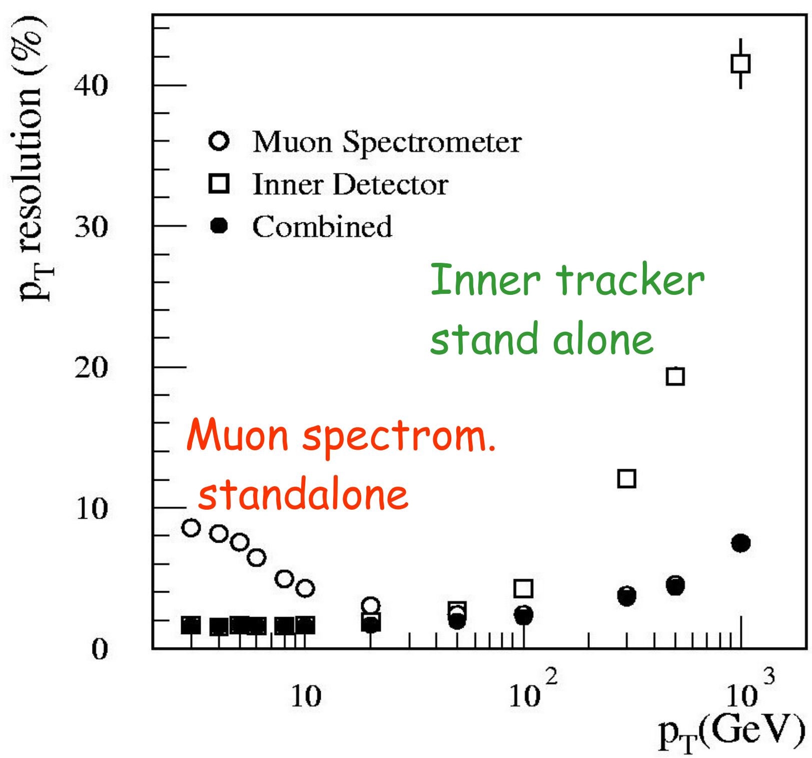


Figure 5-4 MDT resolution as a function of the drift distance, to an Ar/N2/CH4 (91/4/5 mixture). The curves correspond to two discriminator threshold settings.

ATLAS Muon System: Performance



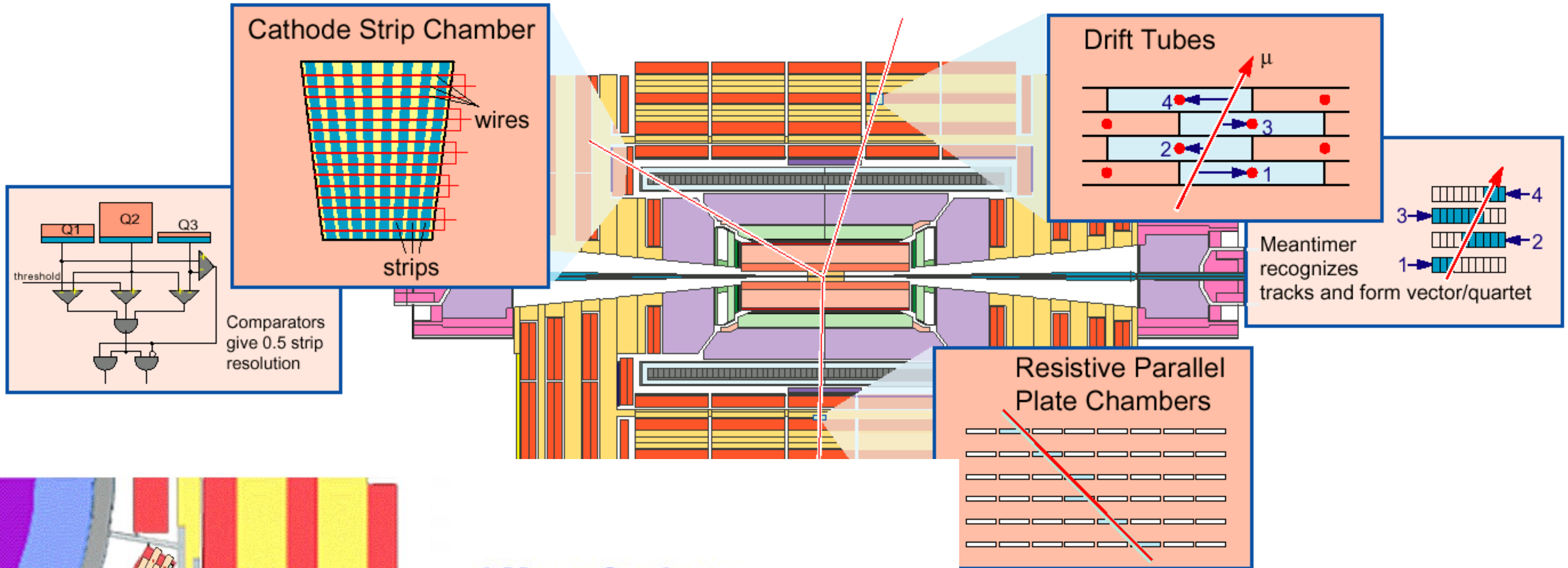
The muon spectrometer resolution dominates for pT > 100 GeV/*c*

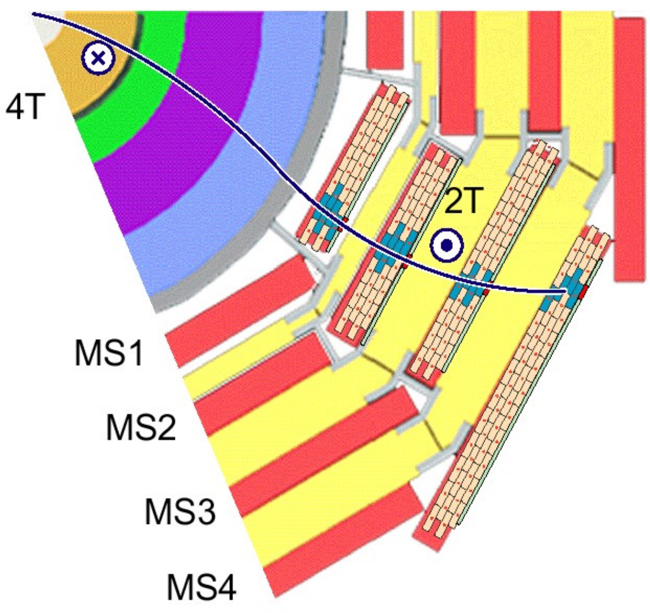


Resolution limited by :
m.m. and Energy Loss Fluct. @ 3%
for 10 < pT < 250 GeV/*c*
Chamber Resolution and Alignment
for pT > 250 GeV/*c*

ÉCOLE DE PHYSIQUE
LES HOUCHES
XXVII

CMS Muon Detectors



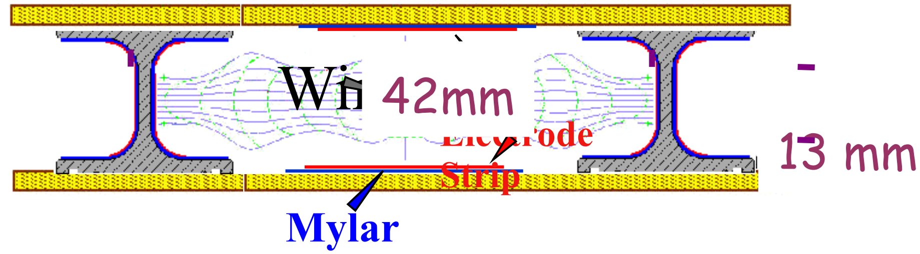


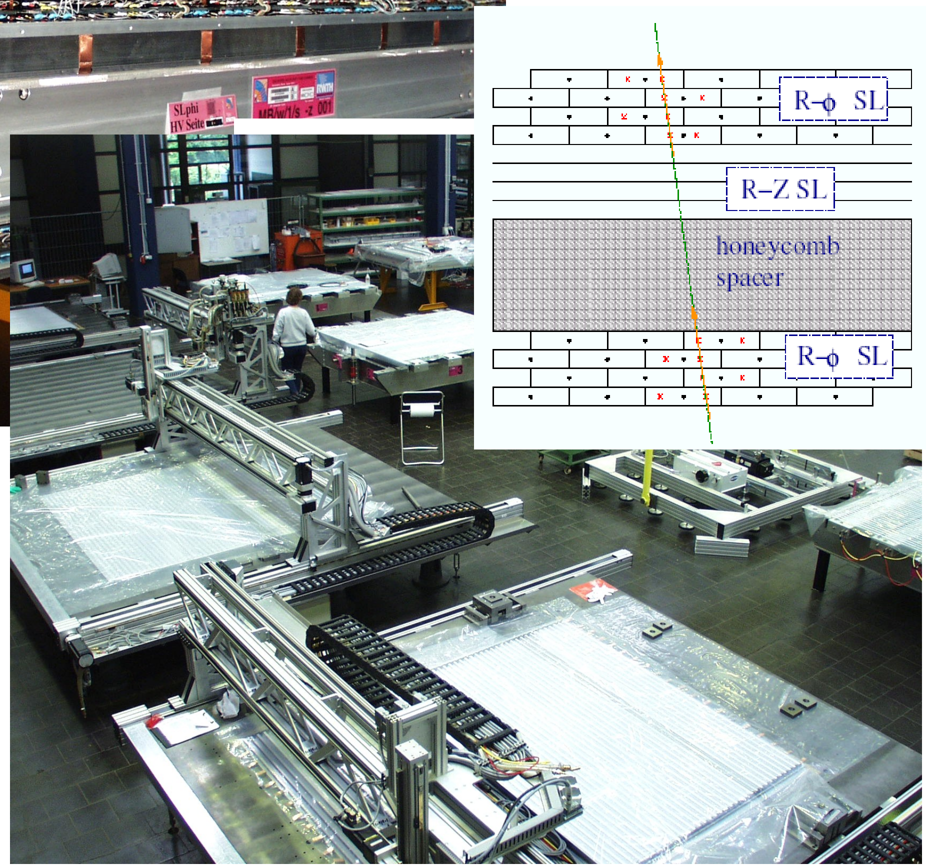
4 Muon Stations
- redundancy
- acceptance

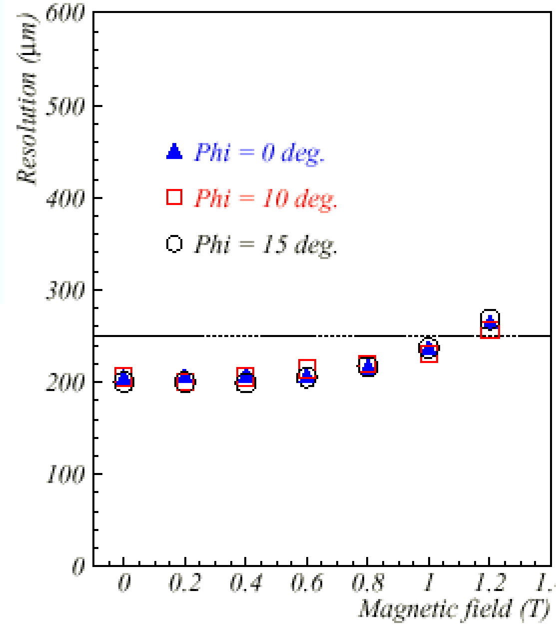
Per Station
- barrel – 12 measuring planes
- endcap – 6 measuring planes

Measurement Accuracy
- position 70 – 100 μm /station
- direction ~ 1 mrad

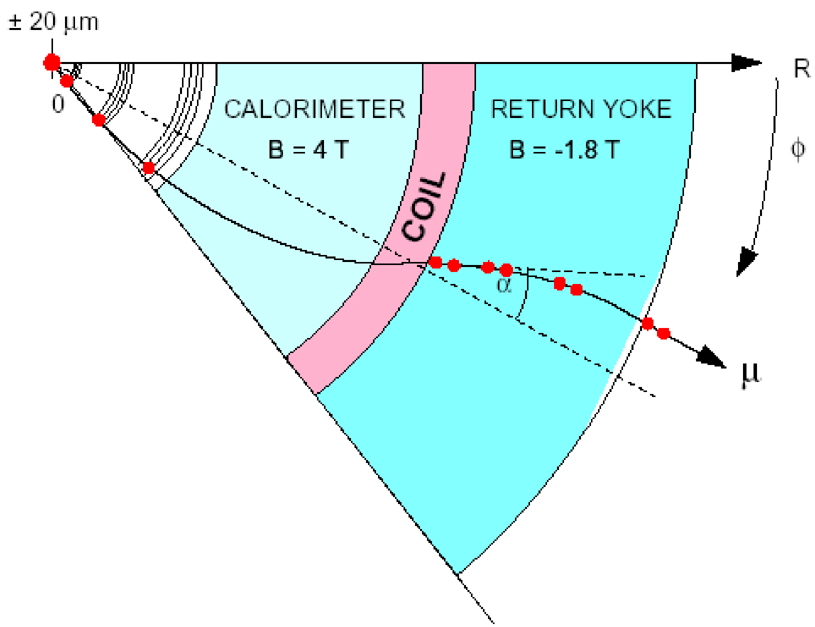
CMS Muon System: Drift Tubes



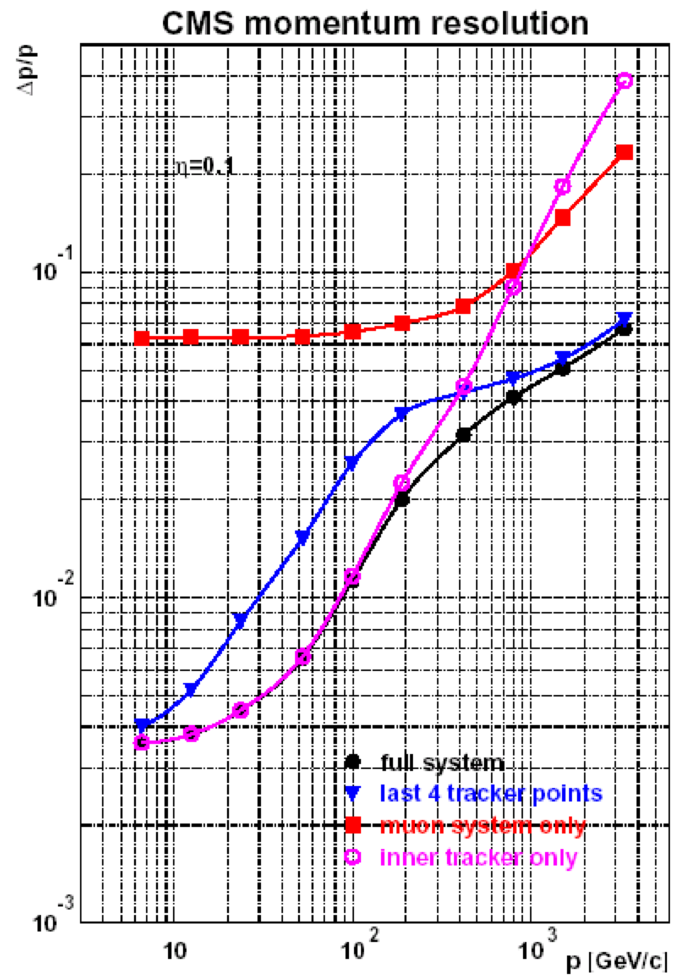




CMS Muon Svstem: Performance



p resolution worsens at |η| > 1.5

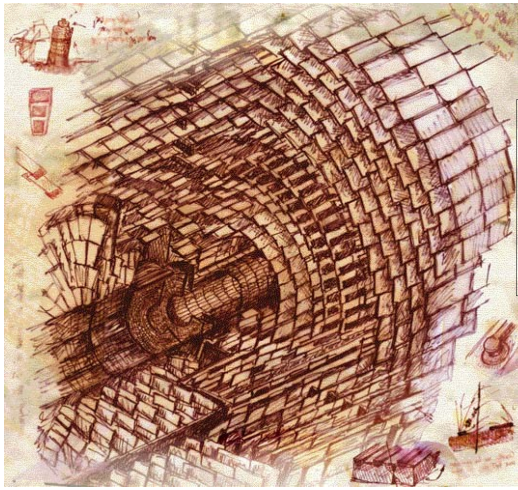


Tracking in Magnetized Iron (CMS)
(in multiple scattering dominated regime)

$$\frac{\Delta p}{p} \approx \frac{40\%}{B\sqrt{L}}$$

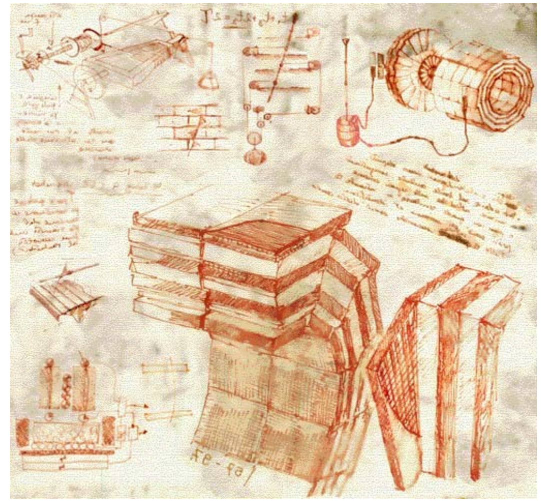
B~1.8T, and L ≈ 1.5 m
BUT measurement is much better !

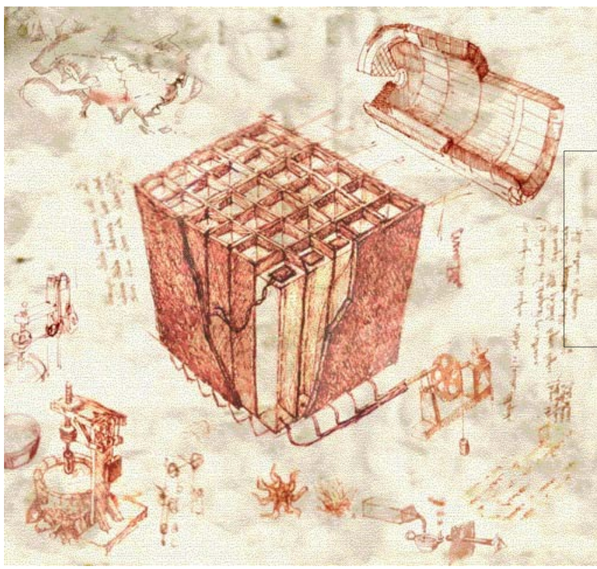
Detectors at LHC part.I end



Today

Traker Muon





Tomorrow

Ecal Hcal