LHC experiments: the Detectors

- **Disclaimer**
  - This lecture was assembled at very short notice. As a consequence, I have mostly concentrated on the two multi-purpose experiments ATLAS and CMS. Apologies to ALICE and LHCb teams .

  - Thanks to G.Hall, P.Sphicas and J.Virdee for giving access to recent presentations.

LHC Experiments: the detectors

1. **LHC parameters**
2. **Physics Requirements**
3. **Experimental Challenges**
4. **The choice of the magnet and the Muon system**
5. **Calorimetry**
6. **Tracking and b tagging**
7. **Data Challenge**
8. **A few slides on LHCb and ALICE**

1. LHC Parameters

- **Why the TeV region**
- **Why such high luminosity ?**
- **Timeline for LHC startup**

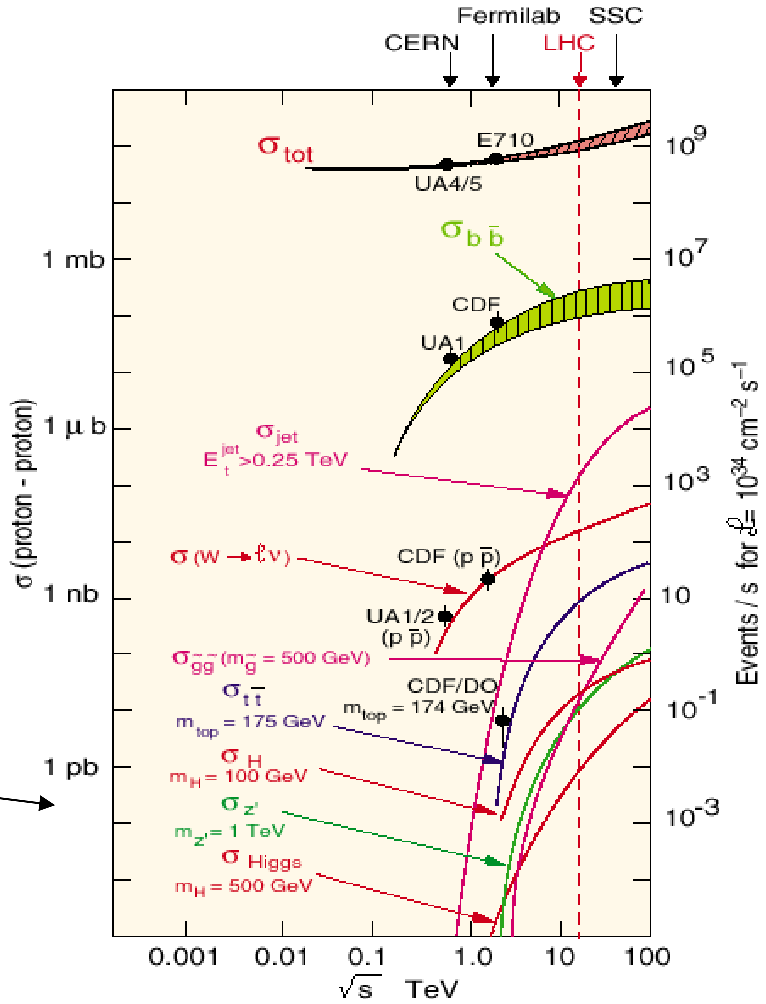
The TeV scale

- LEP, SLC and the Tevatron: established that we really understand the physics at energies up to 100 GeV
  - And any new particles have masses above 100-300 GeV and in some cases TeV
- The Higgs itself can have a mass up to ~700-800 GeV;
  - if it's not there, something must be added by ~1.2 TeV, or WW scattering exceeds unitarity
- Even if the Higgs exists, all is not 100% well with the Standard Model alone: next question is why is the (Higgs) mass so low?
  - The same mechanism that gives all masses would drive the Higgs to the Planck scale. If SUSY is the answer, it must show up at O(TeV)
  - Recent: extra dimensions. Again, something must happen in the O(1-10) TeV scale if the above issues are to be addressed
- Conclusion: we need to study the TeV region

LHC: Luminosity requirements

- **LHC: make up for the lower production cross section**

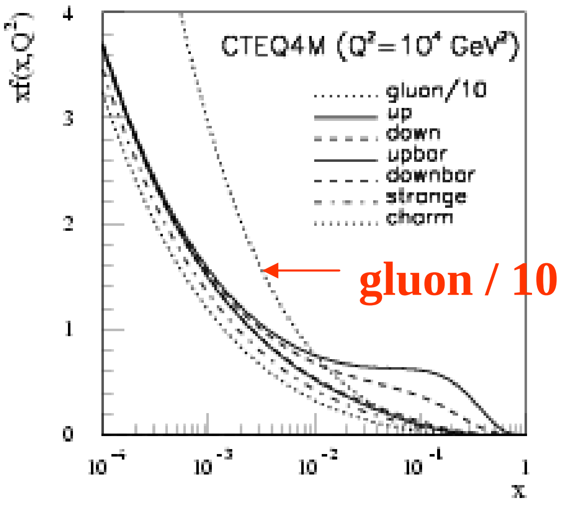
σ <= O(1 pb)



LHC: Luminosity requirements

- **Need for very high Luminosity**
  - e^+e^-, $\sigma \sim 1/s$, so a factor x in c.m. energy needs a factor x^2 in luminosity (for the same number of events; $N = \sigma L$)
    - Not true at a hadron-hadron collider:

$$\sigma = \frac{1}{s}\sum_{a,b}\int_{x_a x_b = m^2/s}^{1} \hat{\sigma}_{ab}\, dx_a\, dx_b\, F_a(x_a,Q^2)\, F_b(x_b,Q^2)$$



    - Very rapid increase of structure functio
    - at low x
      - ➔ Very significant increase in σ as
      - ➔ s increases
  - Rough rule of thumb: a factor 2 in s is
  - equivalent to a factor ~10 in luminosity
  - Energy limited by tunnel size and dipole field
    - LHC must run at a very high luminosity
  - Full “design” luminosity: 10^{34} cm^{-2}s^{-1}
    - SLHC (> 2015?) luminosity: 10^{35}cm^{-2}s^{-1}

LHC Layout and Parameters

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

f	revolution frequency
k_b	no. of bunches
N_p	no. of protons/bunch
ε_n	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

➪ **B = 8.4 T**

Energy at collision	E	7	TeV
Dipole field at 7 TeV	**B**	**8.33**	**T**
Luminosity	**L**	**10^{34}**	**$cm^{-2}s^{-1}$**
Beam beam parameter	ξ	3.6	10^{-3}
DC beam current	I_{beam}	0.56	A
Bunch separation		24.95	ns
No. of bunches	**k_b**	**2835**	
No. particles per bunch	**N_p**	**1.1**	**10^{11}**
Normalized transverse emittance (r.m.s.)	ε_n	3.75	μm
Collisions			
β-value at IP	β^*	0.5	m
r.m.s. beam radius at IP	**σ^***	**16**	**μm**
Total crossing angle	ϕ	300	μrad
Luminosity lifetime	τ_L	10	h
Number of evts/crossing	**n_c**	**17**	
Energy loss per turn		7	keV
Total radiated power/beam		3.8	kW
Stored energy per beam		**350**	**MJ**

Timeline for Year 1 of LHC Running

1^{st} Beam to 1^{st} Collisions (Pilot Run)
t_0=Apr-Jun 2007
Single Beam: t_0 to t_0+2mo.
Machine: Set-up the machine for safe operation
Experiments: Synchronization, beam-gas studies and rejection, vacuum quality, profile of beam-gas interactions, muon halo triggers, catalogue any detector problems

Colliding Beams: t_0+2 mo to t_0+3mo.
Machine: One bunch on one bunch → 43 x 43 at close to nominal bunch intensity with zero crossing angle → carefully squeeze beams
Experiments: Synchronization, record first pp collisions! Catalogue detector problems

Colliding Beams: t_0+3mo to t_0+4mo.
Machine: Introduce crossing angle and larger no. of bunches
75 ns, 936 bunches or 25 ns, 2808 bunches at few x 10^{32} cm^{-2} s^{-1},
Scrubbing to address electron cloud issues?
Shutdown (3 mo.)

1st Collisions to 1033 cm-2 s-1 (Physics Run > t0 = 7mo).
Increase bunch intensities. When pileup becomes > 2 evts/crossing move to 25ns, 2808 bunches

Run for ~ 7 mo. (integrating ~ 10fb-1 per ATLAS/CMS)

Just before a 'LONG' shutdown conduct a 2-week Pb-Pb run

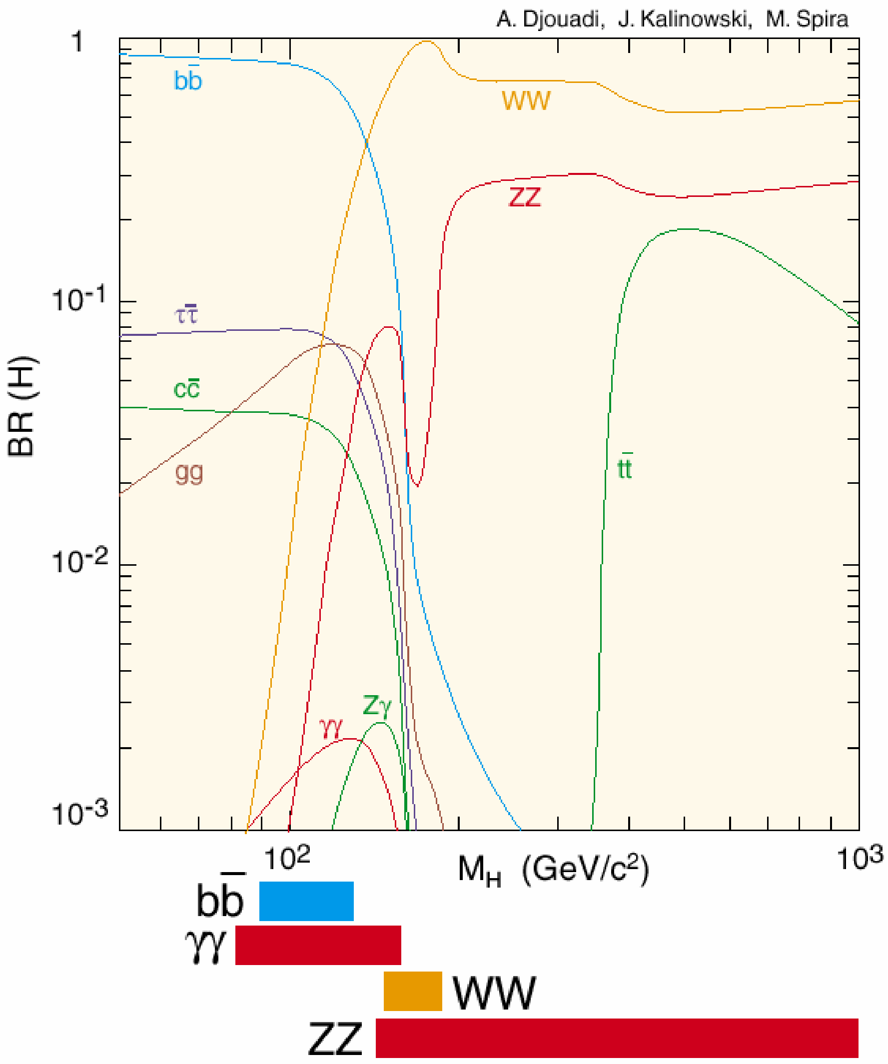
Experiments: Synchronization, set-up for physics running, 'pilot' physics

2. Physics Requirements

- **What should be detected ?**
  - **Benchmark processes**
  - **Detector requirements**

Requirements for LHC detectors: SM Higgs Boson

- **Decays & discovery channels**
  - Higgs couples to m_f^2
    - Heaviest available fermion (b quark) always dominates
    - Until WW, ZZ thresholds open
  - Low mass: b quarks→ jets; poor resolution , background
    - Only chance is EM energy (use γγ decay mode)
  - Once $M_H > 2M_Z$, use this
    - W decays to jets or lepton+neutrino (E_T^{miss})



SM Higgs Boson: decay channels

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

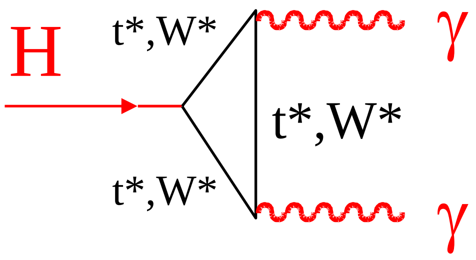
Region 1: Intermediate mass region (LEP limit 114.5 GeV < m_H < 2 m_Z)
m_H < 120 GeV: pp → WH → $\ell\nu$ bb or tt H → $\ell\nu$X bb (associated production)
m_H < 150 GeV: H → $\gamma\gamma$, Zγ
130 < m_H < 2 m_Z : qq → qqH with H → $\tau\tau$, H → WW etc
130 < m_H < 2 m_Z : H → WW* → $\ell\nu$ $\ell\nu$
130 < m_H < 2 m_Z : H → ZZ* → $\ell\ell$ $\ell\ell$

Region 2: High mass region (2 m_Z < m_H < 700)
H → ZZ → $\ell\ell$ $\ell\ell$

Region 3: Very high mass region (700 < m_H < 1 TeV)
H → ZZ → $\ell\ell$ $\nu\nu$, H → ZZ* → $\ell\ell$ jet-jet
H → WW → $\ell\nu$ jet-jet

Benchmark: SM Higgs → γγ

Most promising channel for $m_H < 150$ GeV



($\sigma.B \sim 50.10^{-3}$ pb @ $m_H \sim 150$ GeV) ⇨ Signal: ~ 1000's of events/yr
Backgrounds are large (2pb/GeV), H natural width is small (~MeV)
⇨ **excellent mass resolution** required

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

⇨ energy resolution and precise vertex localisation

Typical Cuts

2 isolated photons: $p_T > 25, 40$ GeV with $|\eta| < 2.5$
No track or em cluster with $p_T > 2.5$ GeV in a cone size $\Delta R = 0.3$ around γs

Good energy resolution, measurement of photon direction, π^0 rejection, efficient photon isolation

SM Higgs Boson $H \rightarrow ZZ^*$ or $ZZ \rightarrow 4l$

$130 < M_H < 800$ GeV

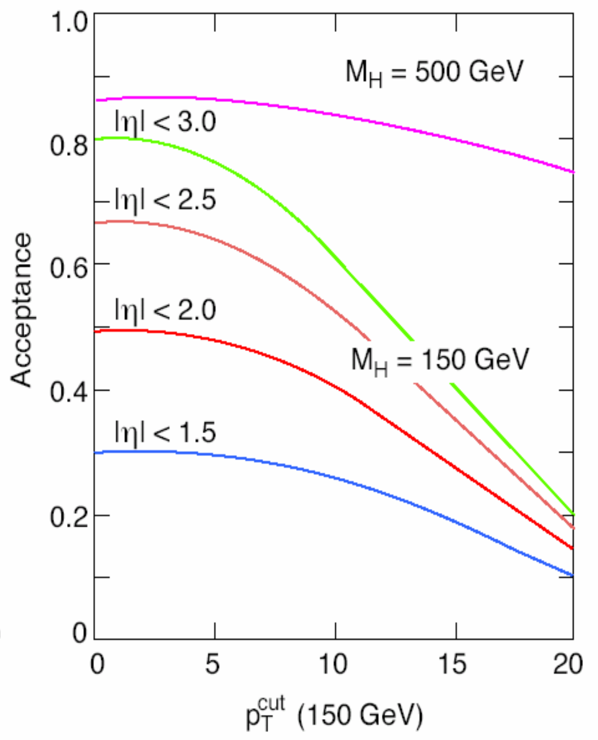
ZZ*

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

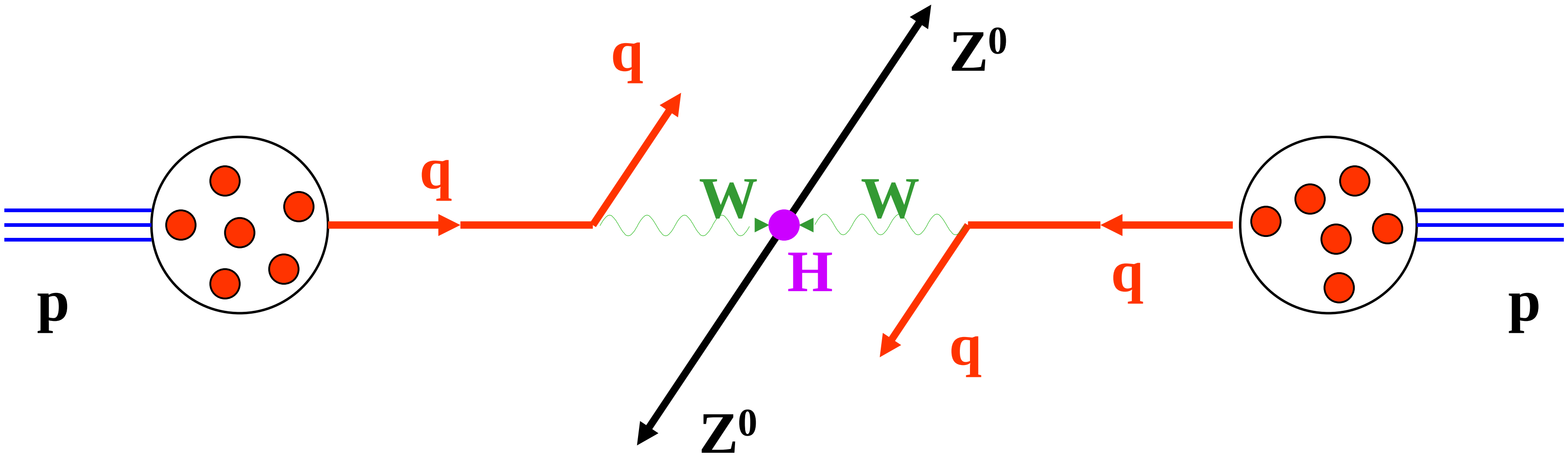
ZZ

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

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



Very High Mass Higgs



$M_H \sim 1000$ GeV

$E_W \geq 500$ GeV

$E_q \geq 1000$ GeV (1 TeV)

$E_p \geq 6000$ GeV (6 TeV)

WW fusion → Tagging jets $2<\eta<5$

An other example : SUSY Higgs Boson

$H, h \to \gamma\gamma, b\bar{b}$ ($H \to b\bar{b}$ in WH, $t\bar{t}H$)

$h \to \gamma\gamma$ in WH, $t\bar{t}h \to \ell\,\gamma\,\gamma$

$h, H \to ZZ^*, ZZ \to 4\,\ell$

$h, H, A \to \tau^+\tau^- \to (e/\mu)^+ + h^- + E_T^{miss}$
$\to e^+ + \mu^- + E_T^{miss}$
$\to h^+ + h^- + E_T^{miss}$

$H^+ \to \tau^+\,\nu$ from $t\bar{t}$

$H^+ \to \tau^+\,\nu$ and $H^+ \to t\,\bar{b}$ for $M_H > M_{top}$

$A \to Zh$ with $h \to b\bar{b}$; $A \to \gamma\gamma$

$H, A \to \tilde{\chi}^0_2\tilde{\chi}^0_2, \; \tilde{\chi}^0_i\tilde{\chi}^0_j, \; \tilde{\chi}^+_i\tilde{\chi}^-_j$

$H^+ \to \tilde{\chi}^+_2\tilde{\chi}^0_2$

$qq \to qqH$ with $H \to \tau^+\tau^-$

$H \to \tau\tau$, in WH, $t\bar{t}H$

Isolated Leptons
Abundance of b, τ
Significant E_{Tmiss}

Summary of requirements

- Good electromagnetic resolution for $|\eta|<2.5$
    - < 1% di-electron mass resolution at 100 GeV/c^2
    - Primary vertex localization and/ or γ angular measurement
    - π^0 rejection
    - Lepton isolation
- Good muon identification and momentum resolution for $|\eta|<2.5$
    - < 1% di-muon mass resolution at 100 GeV/c^2
    - Ability to measure unambiguously charge up to >1 TeV/c
- Good missing ET and di-jet mass resolution .
    - Large hadronic calorimeter coverage $|\eta|\sim5$
    - Lateral segmentation $\Delta\eta \times \Delta\phi < 0.1 \times 0.1$
- Good charged particle reconstruction in inner tracker
    - B and τ tagging (pixel detector)

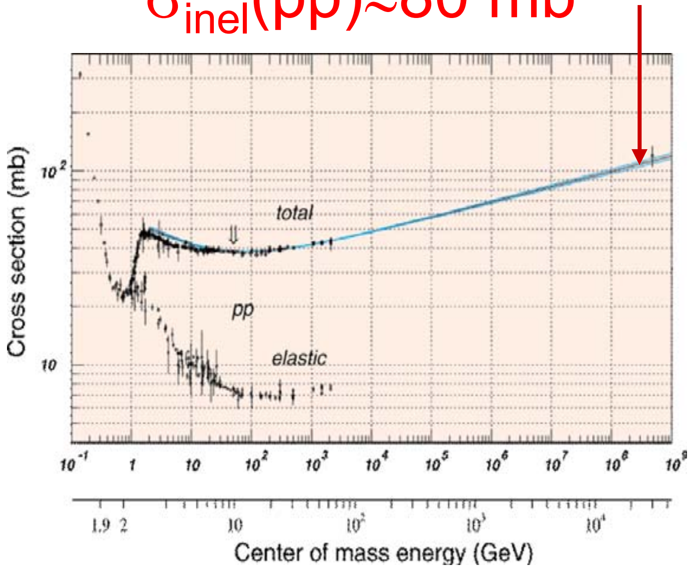
3. Experimental Challenges

- Pile up of minimum bias events
- Radiation hardness
  - Impact on detectors
  - Rad-hard electronics
- Selectivity of physics
- Data Acquisition

pp cross section and min. bias

- **# of interactions/crossing:**
  - **Interactions/s:**
    - **Lum = 10^{34} $cm^{-2}s^{-1}=10^{7}mb^{-1}Hz$**
    - **σ(pp) = 80 mb**
    - **Interaction Rate, R = 8×10^{8} Hz**
  - **Events/beam crossing:**
    - **Δt = 25 ns = 2.5×10^{-8} s**
    - **Interactions/crossing=20**

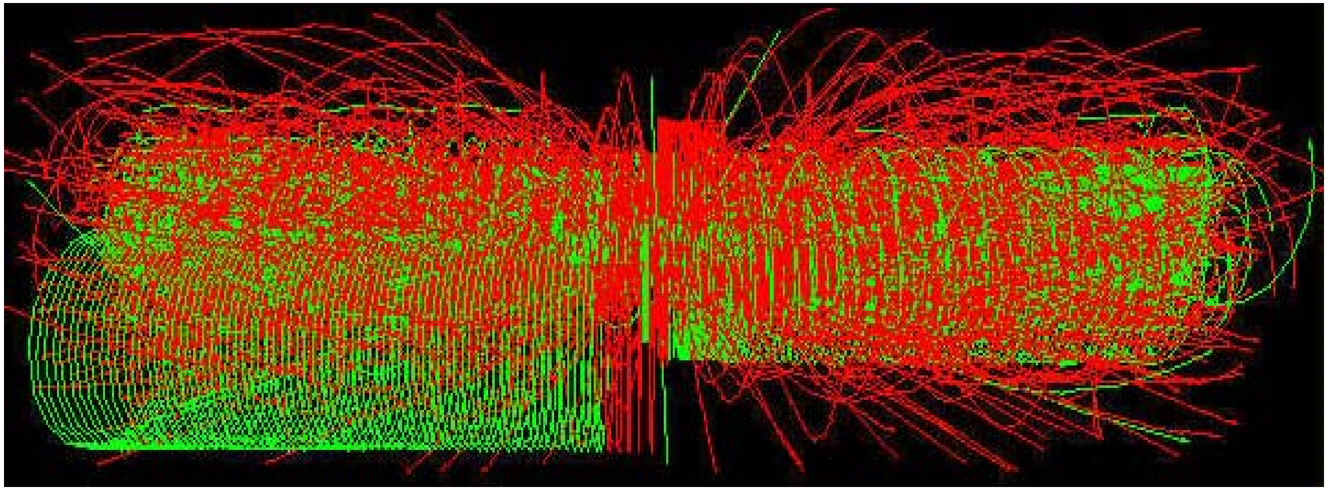
$\sigma_{inel}(pp)\approx 80$ mb

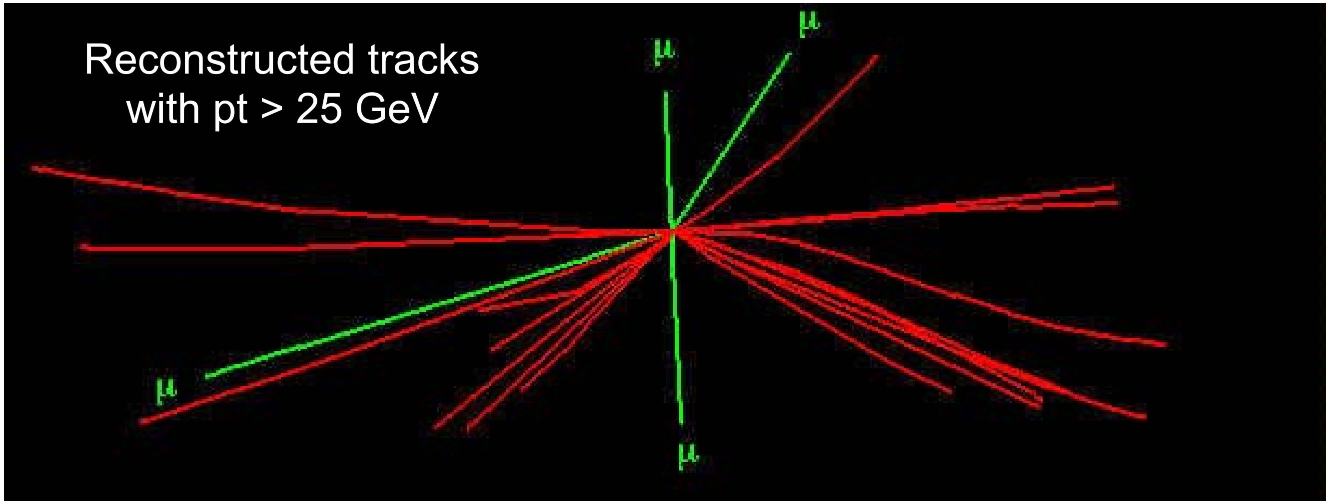


Operating conditions:
(1) A "good" event containing a Higgs decay +
(2) ~ 20 extra "bad" (minimum bias) interactions

pp collisions at 14 TeV at 10^{34} $cm^{-2}s^{-1}$

- 25 min bias events overlap
    - H→ZZ
    - Z →μμ
- H→ 4 muons:
- the cleanest
- (“golden”)
- signature





Reconstructed tracks with pt > 25 GeV

Impact on detector design

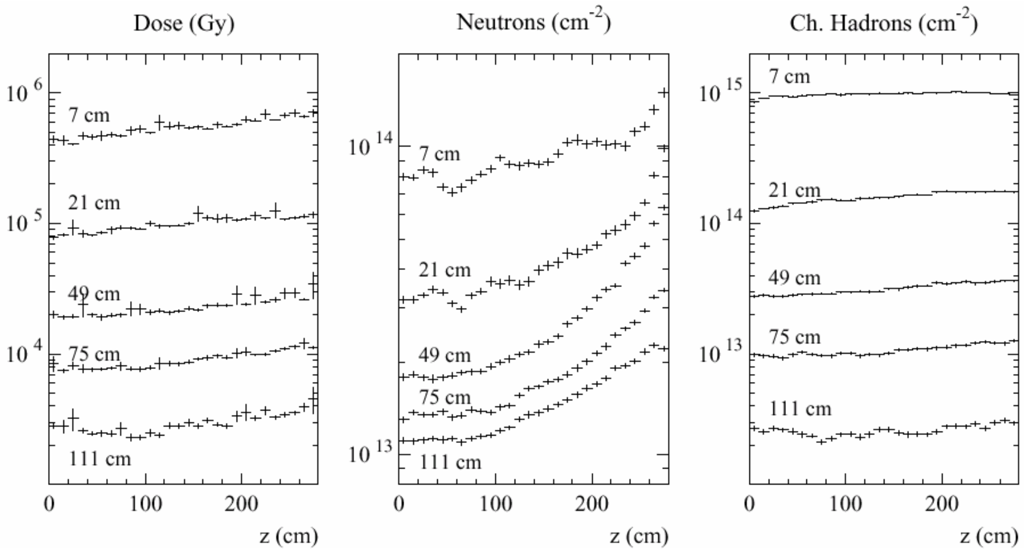
- LHC detectors must have fast response
  - Otherwise will integrate over many bunch crossings → large "pile-up"
  - Typical response time : 20-50 ns
    - → integrate over 1-2 bunch crossings → pile-up of 25-50 min-bias
    - → very challenging readout electronics

- LHC detectors must be highly granular
  - Minimize probability that pile-up particles be in the same detector element as interesting object (e.g. γ from H → $\gamma\gamma$ decays)
    - → large number of electronic channels ex: CMS ~40×10^6
    - → high cost

Radiation levels

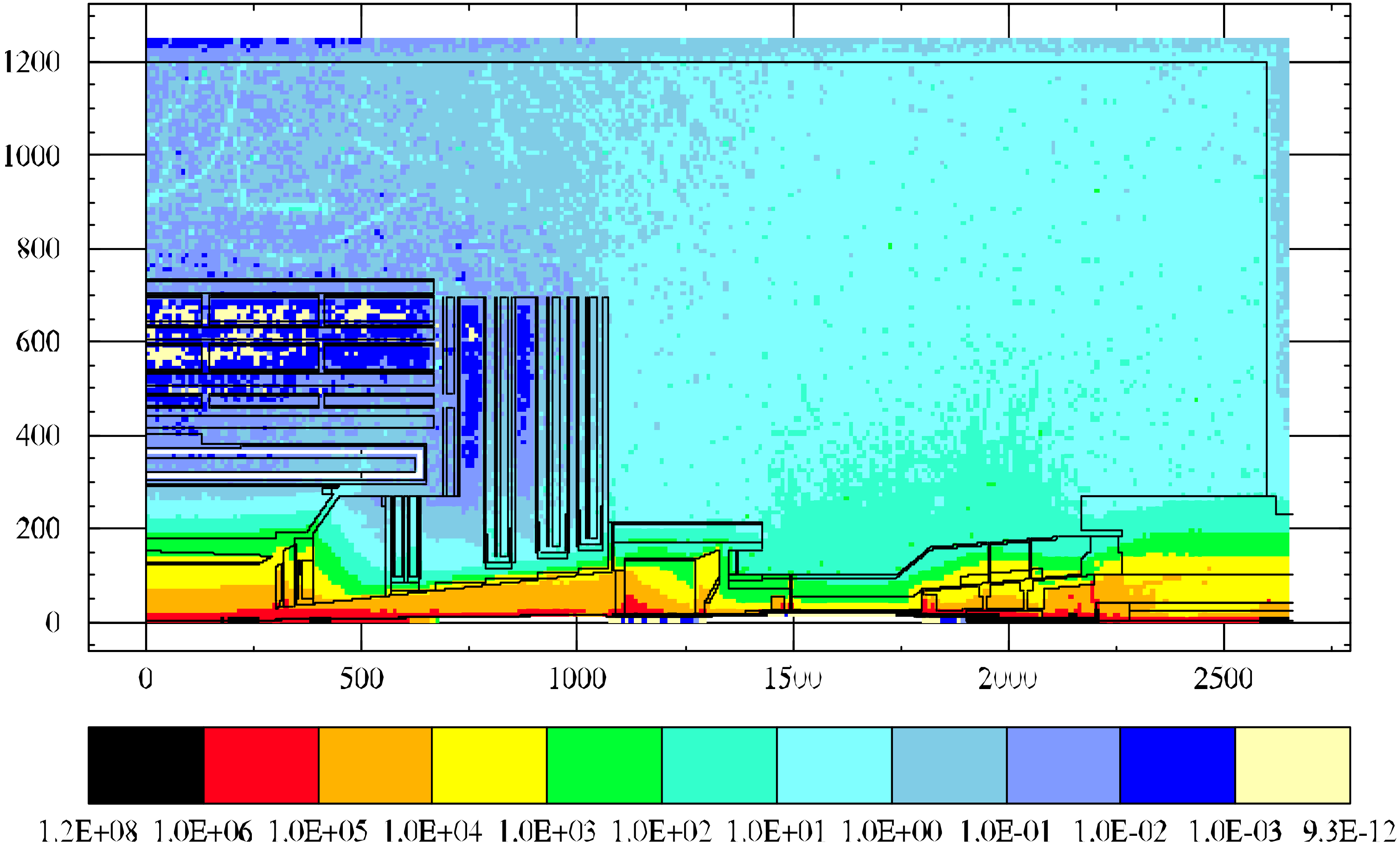
- LHC detectors must be radiation resistant:
  - high flux of particles from pp collisions → high radiation environment e.g. in forward calorimeters:
    - up to 10^{17} n/cm^2 in 10 years of LHC operation
    - up to 10^7 Gy (1 Gy = unit of absorbed energy = 1 Joule/Kg)
  - decreases like distance^2 from the beam → detectors nearest the beam pipe are affected the most

CMS tracker cavity



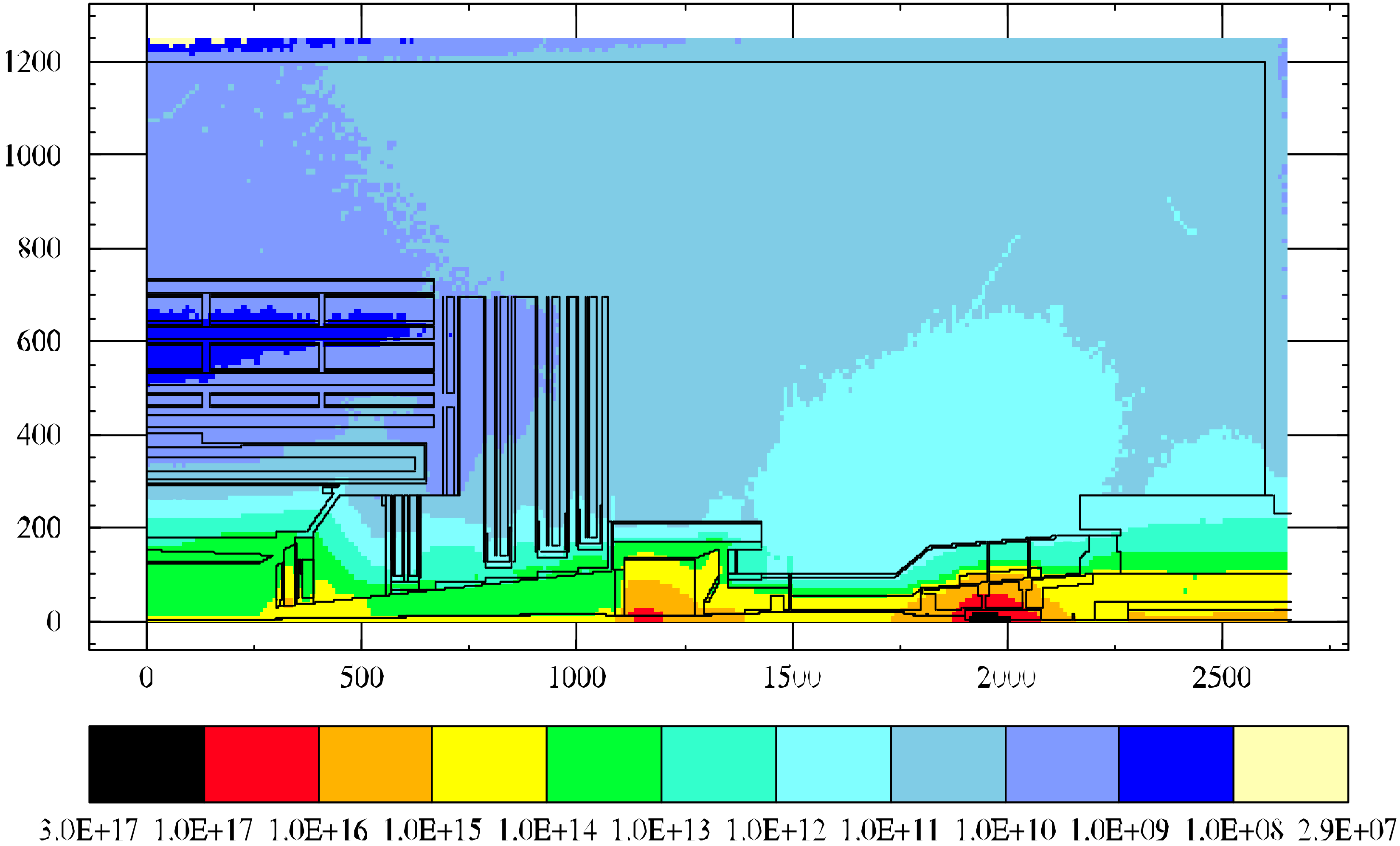
Radiation Levels: Dose

Dose (Gy) in CMS for an integrated luminosity of 5.10^5 pb^{-1} (~ 10 years)



Radiation Levels: Neutron Fluence

n fluence (E>100 keV) in CMS for an integrated luminosity of 5.10^5 pb^{-1} (~ 10 yr)



Radiations: Impact on detectors

- May need special environment for long term viability
  - ex: silicon must be run at low temperature (-10ºC) to limit leakage current and avoid reverse annealing (= high bias operation)
- Deteriorates performances & Induces time-dependent variations
  - ex : attenuation of light transmission in crystals or scintillators
- Forbids the use of some rather usual materials
  - Many plastics or glues (ex: loctite) are not radiation hard.
  - Tantalum capacitors are forbidden !
  - Some materials become highly activated by neutrons ; their use would prevent maintenance. ex: Ag
- Restricts access for maintenance (high reliability as space expt)

- <u>Need quality control for every piece of material</u>
  - Passive elements are the most dangerous as one tends to forget about them !
- Detector + electronics must survive 10 years of operation

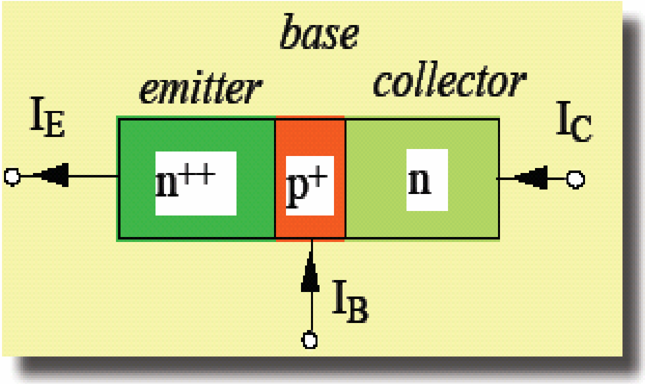
Impact of radiations on electronics (1) Latch-up and SEU

- Latch-up can affect all technologies
  - charging of surface layers influences charge in substrate
  - *parasitic* bipolar devices draw current, and can be **destructive**
  - Needs to be avoided by technology design

- Single event effects - **non-permanent**
  - large ionisation charge deposited within device, usually from recoiling ion
  - Some of the charge collected on sensitive circuit node
  - Influences voltage and can change state of node (Important for digital logic)
  - Essentially undetectable at the time
  - Must be mitigated by design, for example majority (triple voting) logic circuits

Impact of radiation in electronics (2) Bipolar transistors

- Transistor operation
  - Carriers flow from emitter to collector, via base
  - Recombination in base controls transistor action (gain)
- Effects of radiation
  - Hadrons cause atomic displacement
    - Traps (band gap energy levels)
    - Increased carrier recombination in base



- Consequences
  - gain degradation, transistor (mis-)matching, dose rate dependence
- NB bipolar processes can also be sensitive to surface effects
  - like CMOS

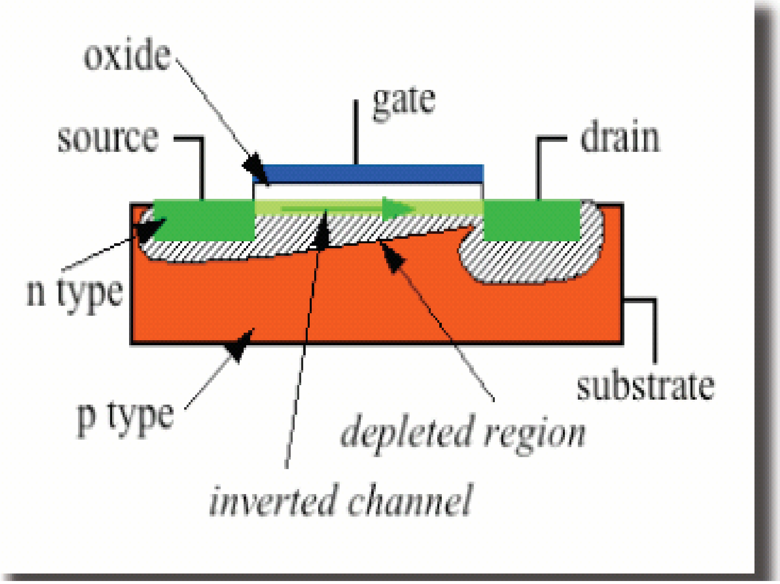
Deep Sub-micron CMOS electronics

- Inversion layer is so shallow that bulk damage has no effect
  - so CMOS is hard against neutrons

- Real oxide contains trapped (positive) charge at interface
  - Compensated for during manufacturing process

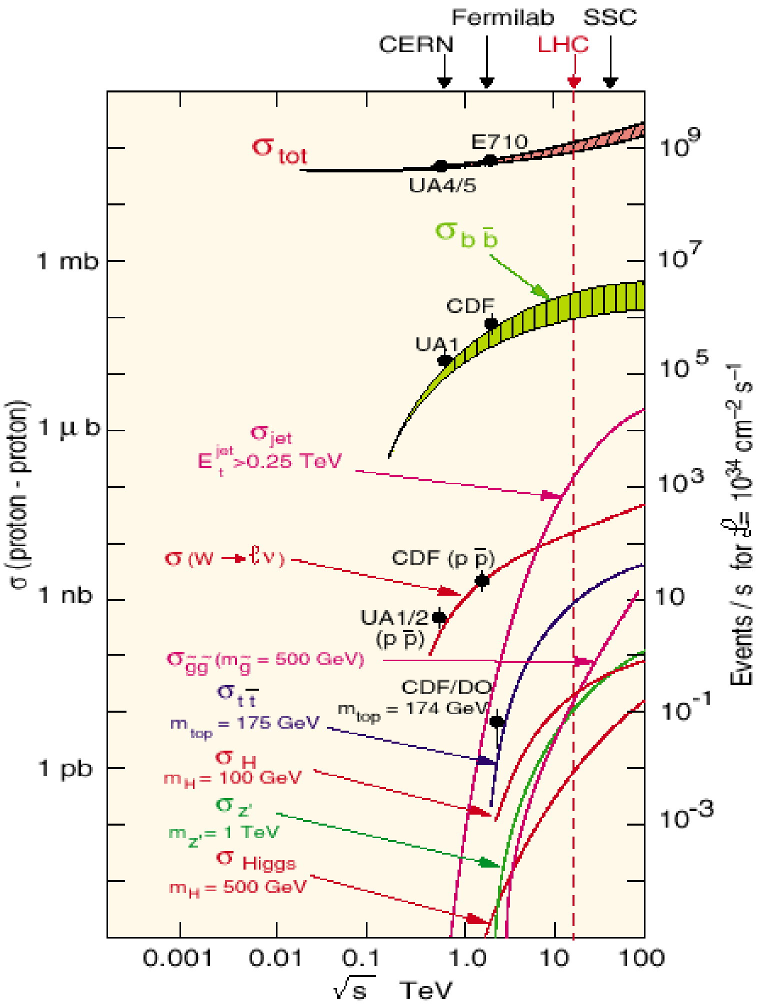
- Charged particle and gamma irradiation generates carriers in oxide
  - become trapped at Si-SiO$_2$ interface
  - interface traps influence short-term behaviour
    - details depend on bias

- Consequences
  - threshold (gate) voltage shift,
  - leakage current through or around transistor (especially NMOS)

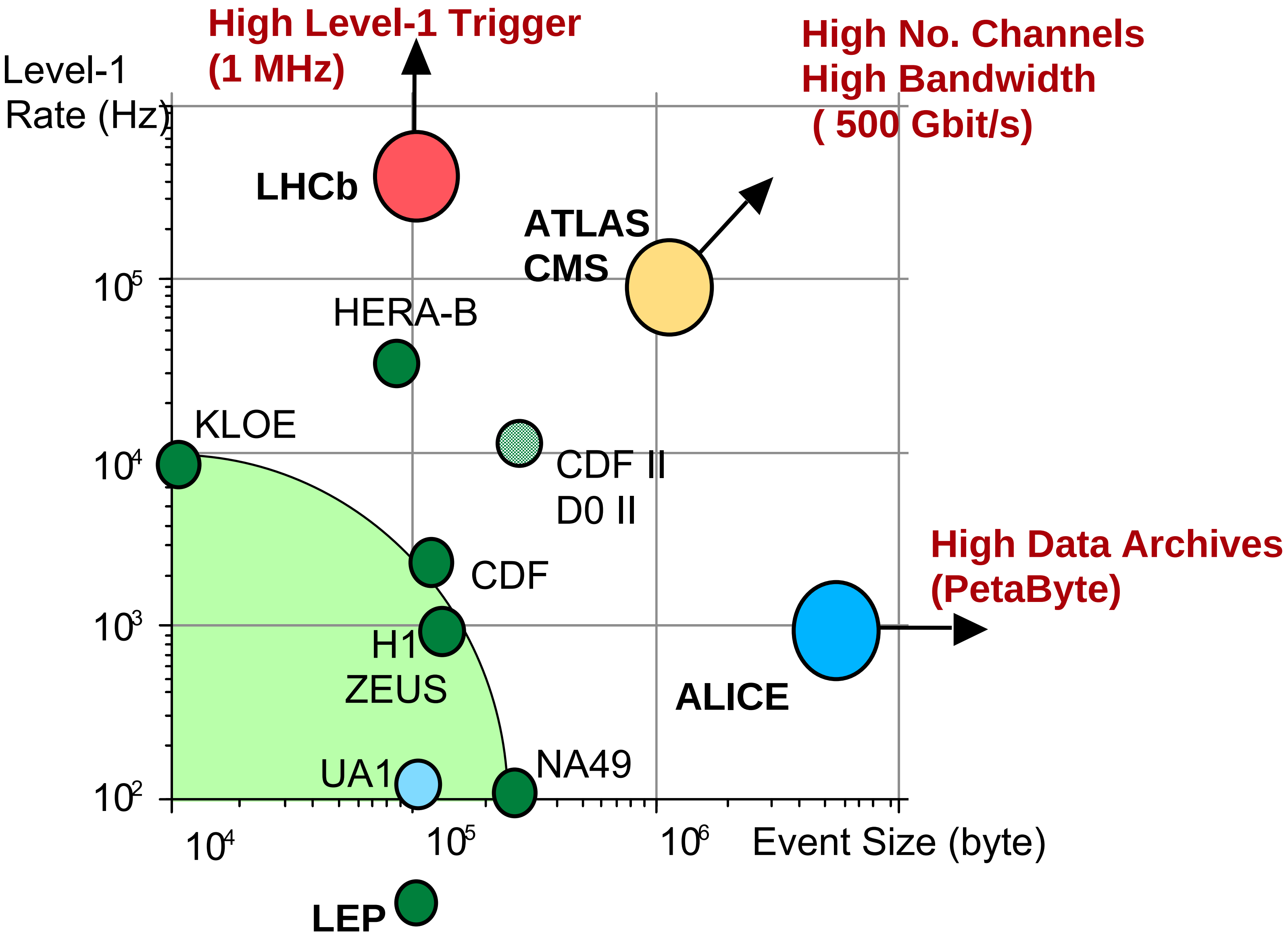


Challenges: Selectivity

- **Cross sections for various physics processes vary over many orders of magnitude**
  - **Inelastic: 10^9 Hz**
  - **W→ ℓ ν: 10^2 Hz**
  - **t t production: 10 Hz**
  - **Higgs (100 GeV/c^2): 0.1 Hz**
  - **Higgs (600 GeV/c^2): 10^{-2} Hz**
- **Selection needed: 1:10^{10-11}**
  - **Before branching fractions...**



Challenges Data Acquisition



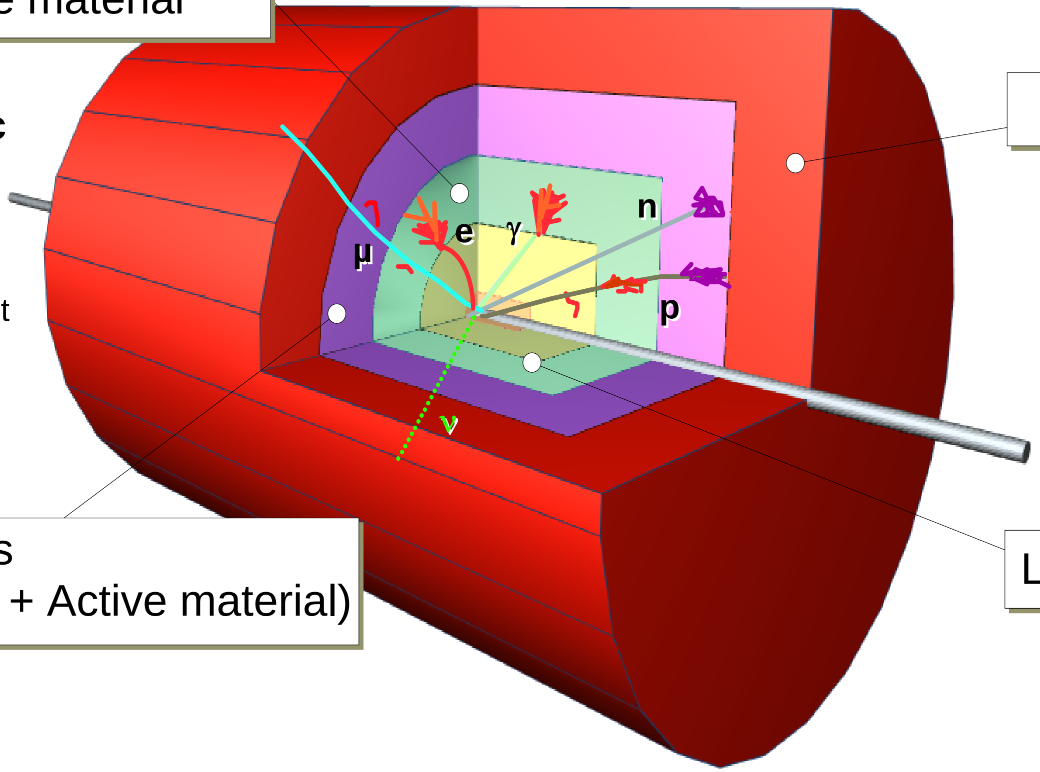
4. Choice of Magnet and Muon system

- **ATLAS and CMS detectors**
- **Choice of Magnet**
- **Muon detection performance**
- **Muon systems**

ATLAS & CMS detectors

- Basic principle: need “general-purpose” experiments covering as much of the solid angle as possible (“4π”) since we don’t know how New Physics will manifest itself
  - → detectors must be able to detect as many particles and signatures as possible: e, μ, τ, ν, γ, jets, b-quarks, ….
- Momentum / charge of tracks and secondary vertices (e.g. from b-quark decays) are measured in central tracker (Silicon layers plus gas detectors).
- Energy and positions of electrons and photons measured in electromagnetic calorimeters.
- Energy and position of hadrons and jets measured mainly in hadronic calorimeters.
- Muons identified and momentum measured in external muon spectrometer (+central tracker).
- Neutrinos “detected and measured” through measurement of missing transverse energy (E_T^{miss}) in calorimeters.

‘Cylindrical_Onion-like’ Structure of HEP Experiments



Materials with high number of protons + Active material

Hermetic calorimetry
- Missing Et measurements

Electromagnetic and Hadron calorimeters
- Particle identification (e, γ Jets, Missing $\not{E}_T$)
- Energy measurement

Heavy materials

Muon detector
- μ identification

Heavy materials (Iron or Copper + Active material)

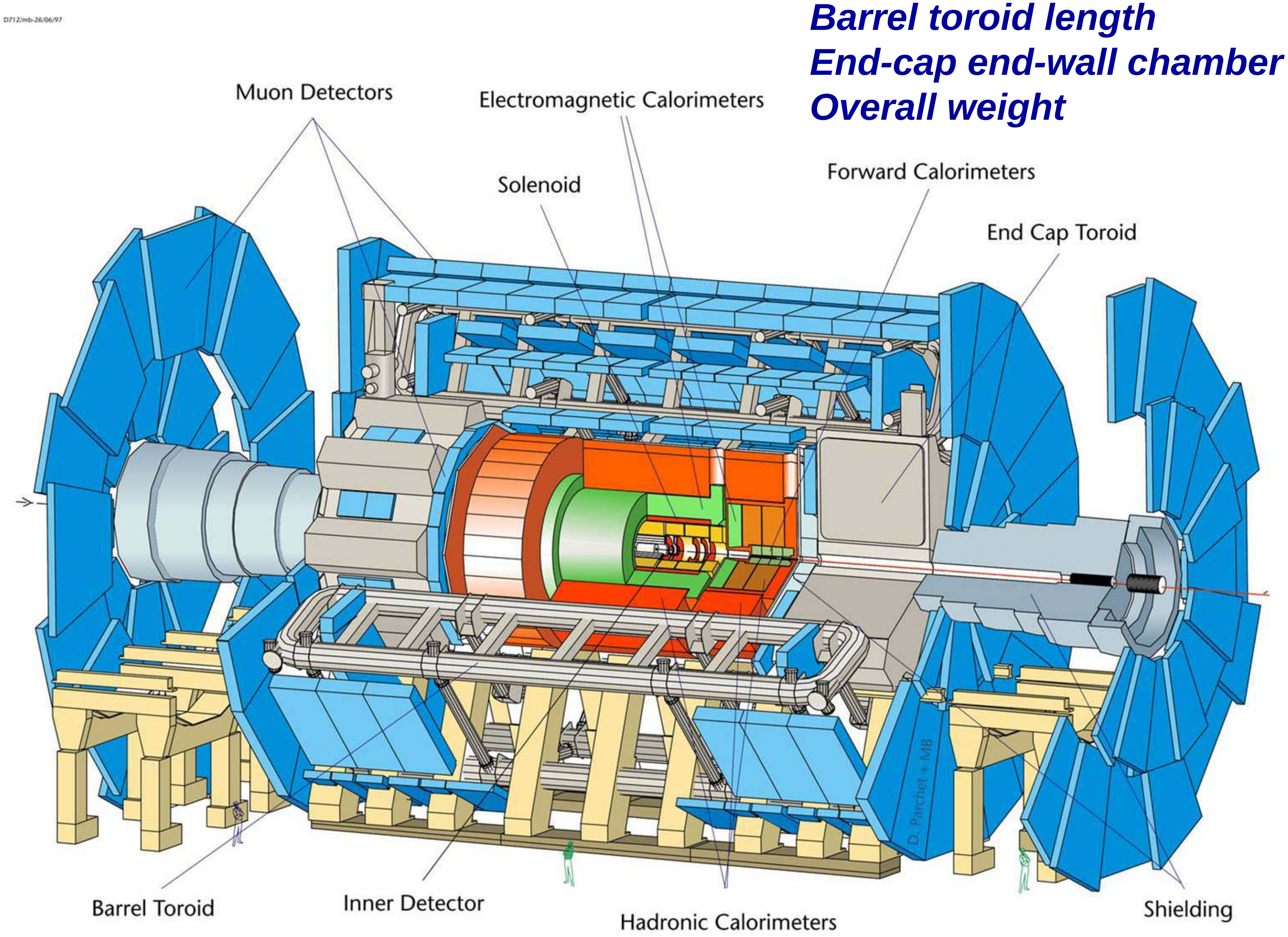
Light materials

Central detector
- Tracking, p_T, MIP
- Em. shower position
- Topology
- Vertex

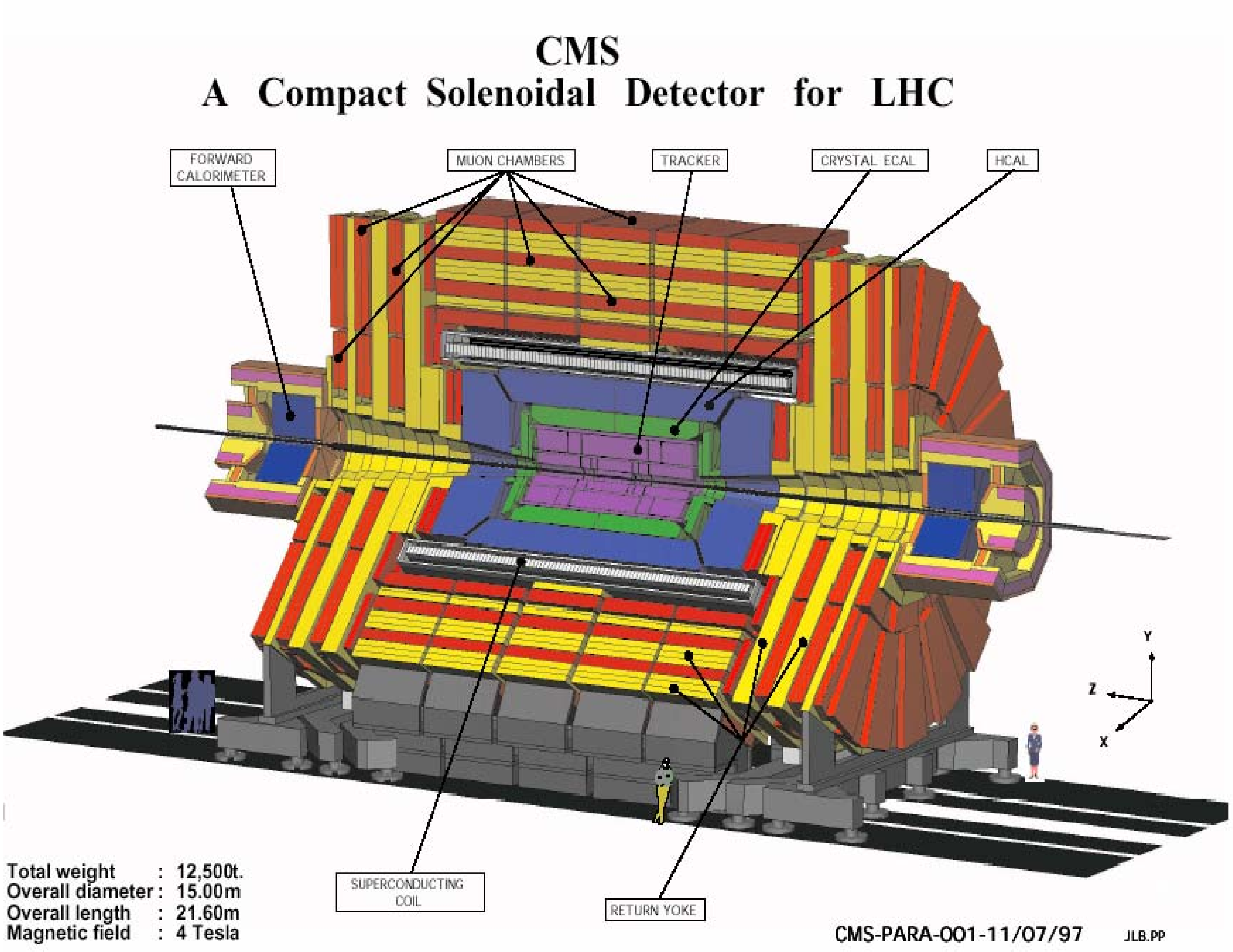
Each layer identifies and enables the measurement of the momentum or energy of the particles produced in a collision

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

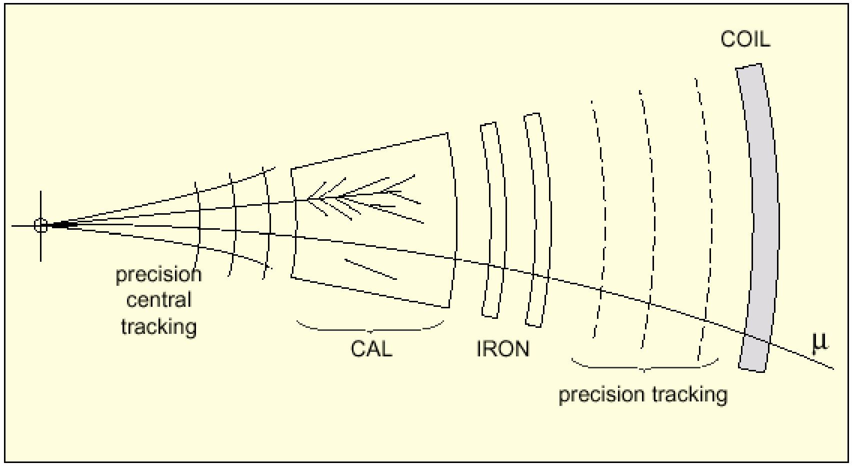


Total weight : 12,500t.
Overall diameter : 15.00m
Overall length : 21.60m
Magnetic field : 4 Tesla


μ
6.920 m
5.635 m
4.645 m
3.850 m
2.950 m
2.864 m
1.840 m
1.320 m
Y
φ
X
Towards
Center of LHC
40
40
CMS-TS-00079
Transverse View

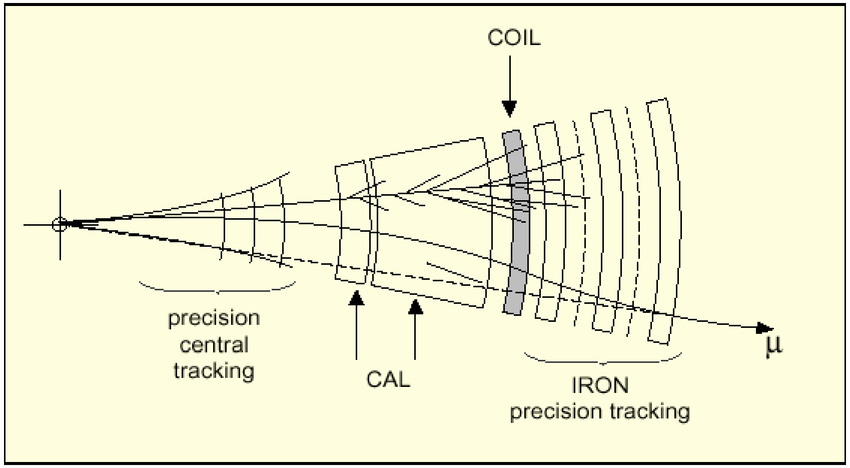
Designing an LHC experiment

- **THE issue: measure momenta of charged particles (e.g. muons); so which measurement "architecture"?**



ATLAS

Standalone p measurement;
safe for high multiplicities;
Air-core torroid
Property: σ flat with η



CMS

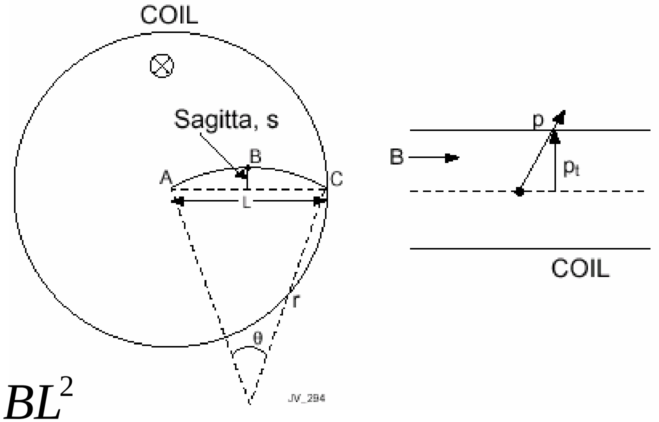
Measurement of p in
tracker and B return flux;
Iron-core solenoid
Property: muon tracks
point back to vertex

Momentum measurement

- **Need high BL^2 or small σ_s:**
  - **Quick reminder: $P_T = 0.3\ B\ r$**
    - **In practice, measure s, not r**

$$\sin(\theta/2) = \frac{L}{2r} \Rightarrow \theta \approx \frac{L}{r} = \frac{0.3BL}{r}$$

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



- **Thus, resolution on p given by** $\dfrac{\sigma(P_T)}{P_T} = \dfrac{\sigma_s}{s}$

- **Toy detector with 3 points measured, each with σ_p:** $\sigma_s = \sqrt{\dfrac{3}{2}}\sigma_p$

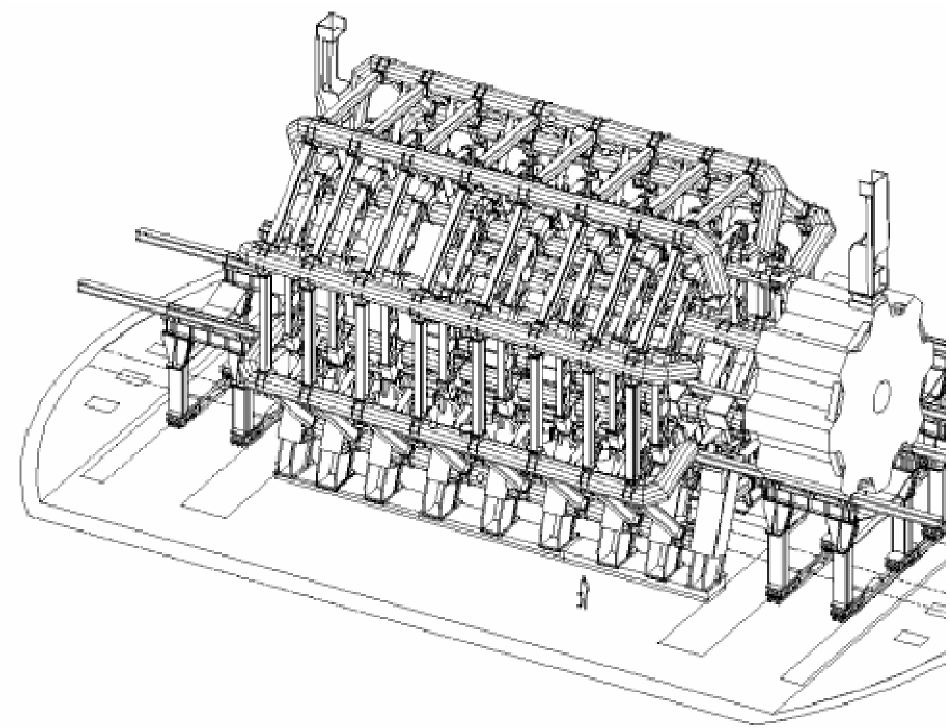
$$\frac{\sigma(P_T)}{P_T} \approx 4\sqrt{3}\ \sigma_x\ \frac{p_T}{0.3BL^2}$$

- **In more realistic detector with N points (equally spaced):**

$$\frac{\sigma(P_T)}{P_T} \approx \sqrt{\frac{720}{N+4}}\sigma_x\ \frac{p_T}{0.3BL^2}$$

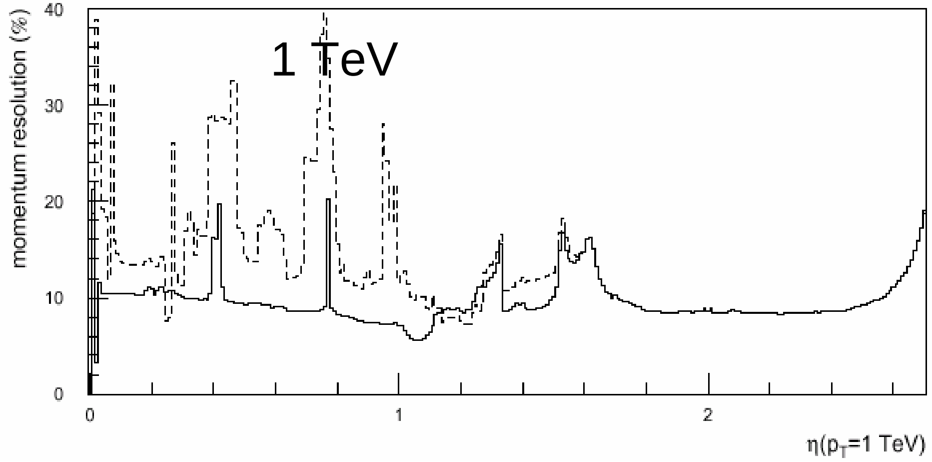
Choice of magnet (I)

- **Basic goal: measure 1 TeV muons with 10% resolution**
  - **ATLAS: <B>~0.6T over 4.5 m → s=0.5mm → need σ_s<50μm**
    - Ampere's thm: $2\pi RB=\mu_0 nI \rightarrow nI=2\mathrm{x}10^7$ At
    - With 8 coils, 2x2x30 turns: I=20kA (superC)
    - Challenges: mechanics, 1.5GJ if quench, spatial & alignment precision over large surface area



Choice of magnet (II)

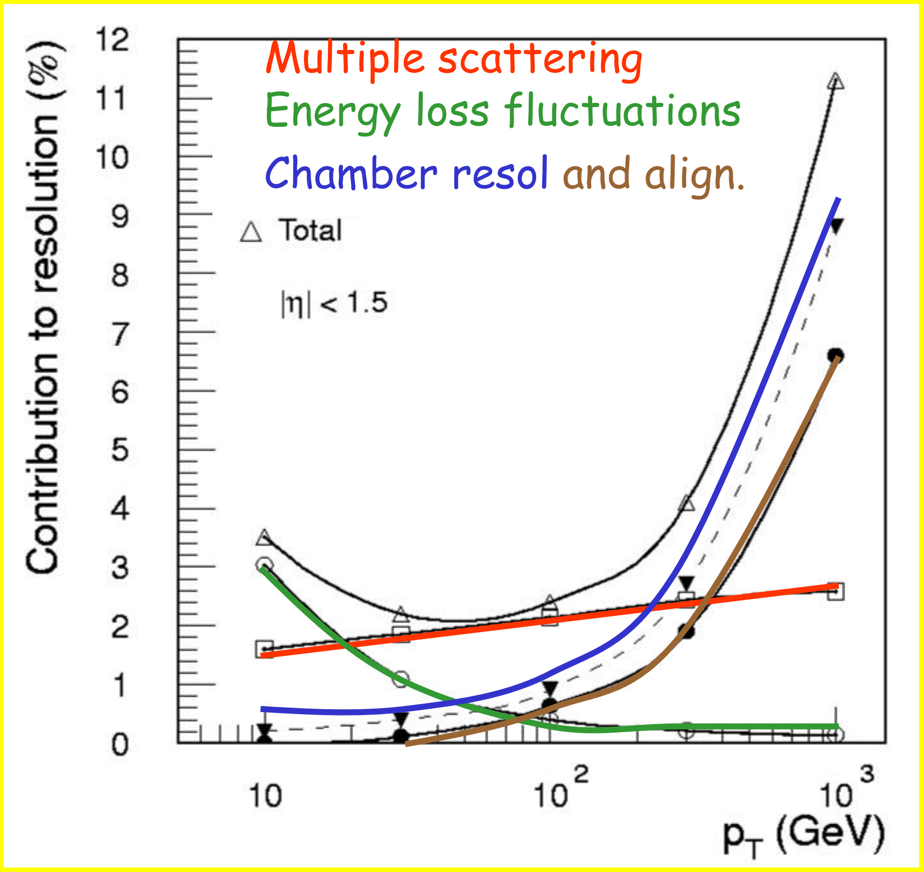
- **Torroid: gives flat σ vs η:**



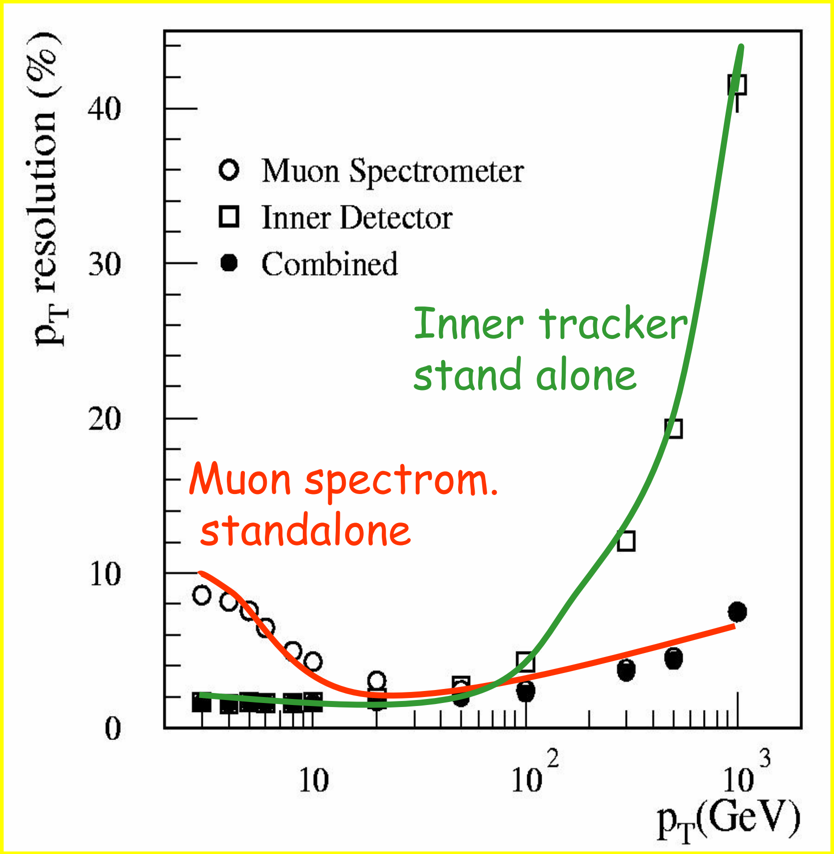
◆ **But: (a) does not benefit from beam spot (20 μm @ LHC)**
(b) need additional solenoid for internal track measurement

  - **ATLAS: B=2T solenoid**
  - **ATLAS Calorimetry: outside solenoid**

ATLAS Muon System: Performance



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



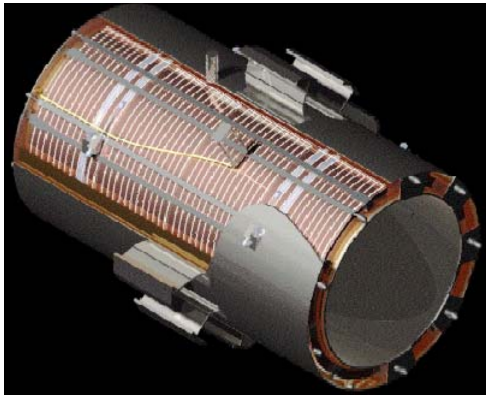
Resolution limited by :

m.m. and Energy Loss Fluct. @ 3% for $10 < p_T < 250$ GeV/*c*

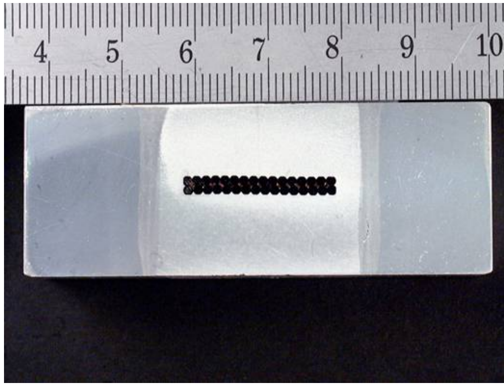
Chamber Resolution and Alignment for $p_T > 250$ GeV/*c*

Choice of magnet (I)

- **Basic goal: measure 1 TeV muons with 10% resolution**
  - **CMS: B=4T over 1.2m + 2T over 3m**
  - **Needs σ_s=100μm**
  - **Solenoid = measures P_t (and becomes worse in P as η increases)**

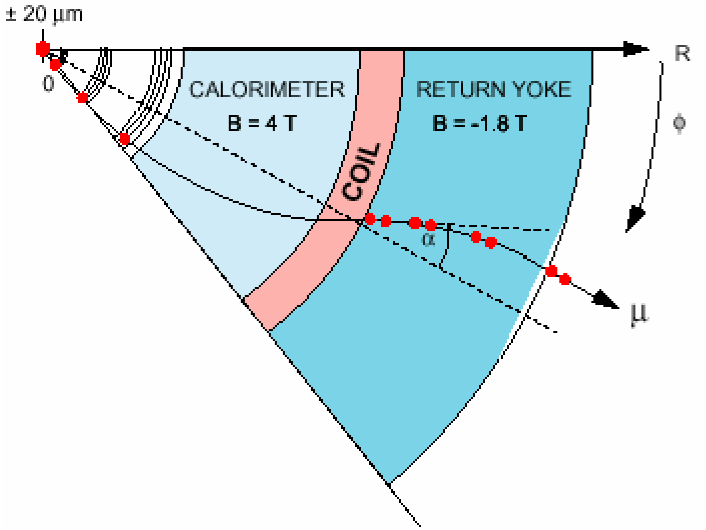


- B=μ_0nI; @2168 turns/m→ I=20kA (SuperC)
- Challenges: 4-layer winding to carry enough I, design of reinforced superC cable
- 2.4 GJ



Choice of magnet (III)

- **Solenoid:**



Bending in transverse plane

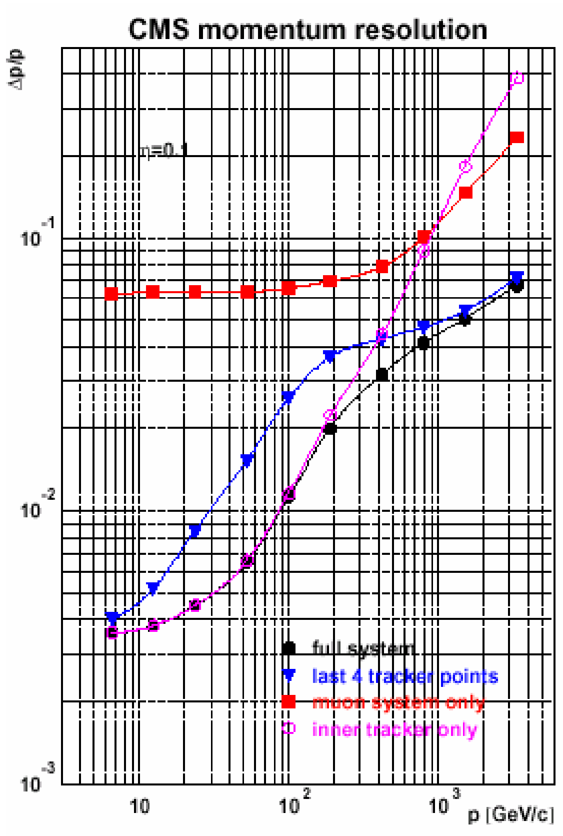
Use 20μm beam spot

redundancy

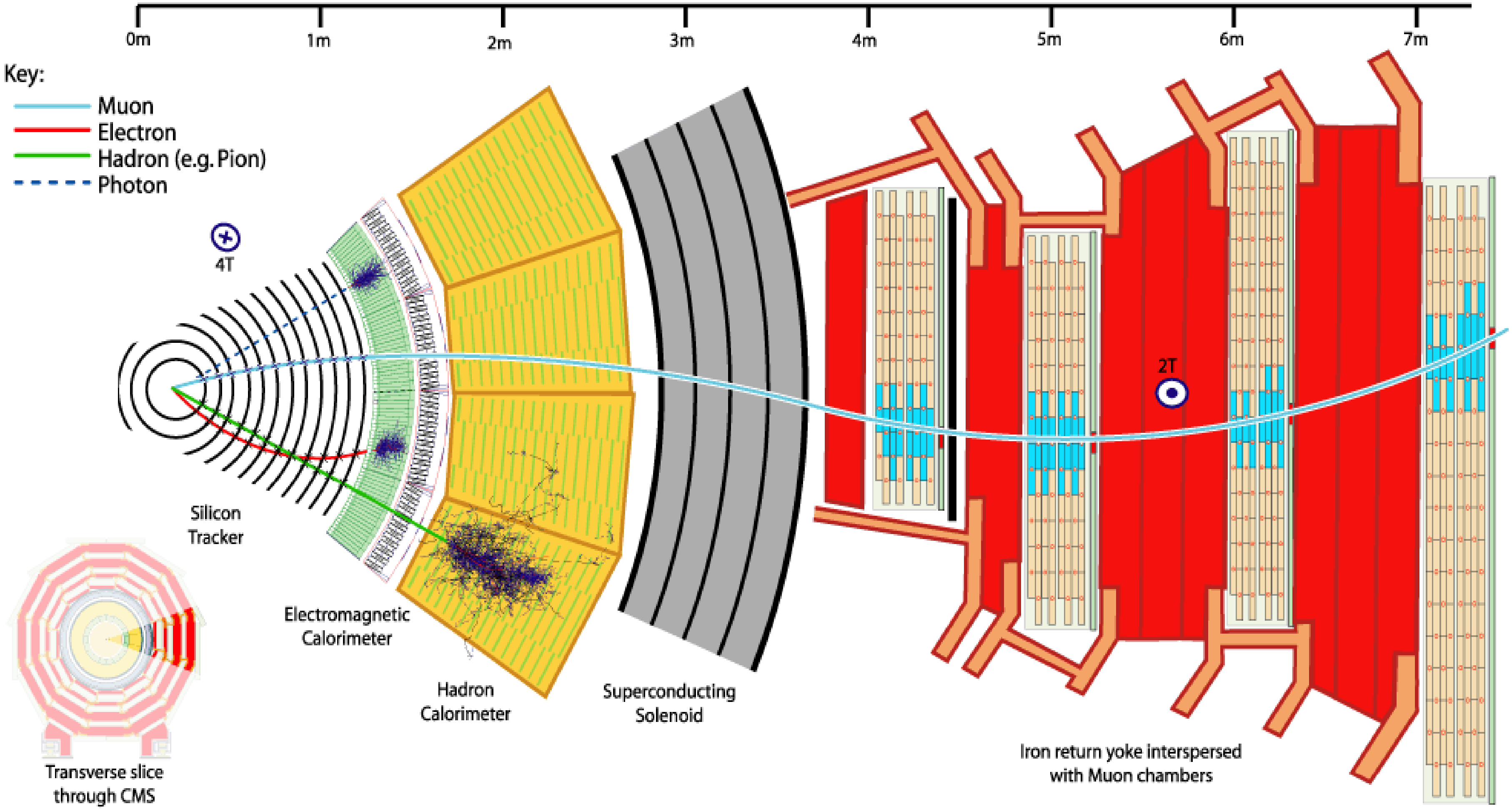
- **Iron-core → multiple scattering**
  - **Tracking in magnetized iron:**

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

  - **BUT measurement much better when combined with the tracker**

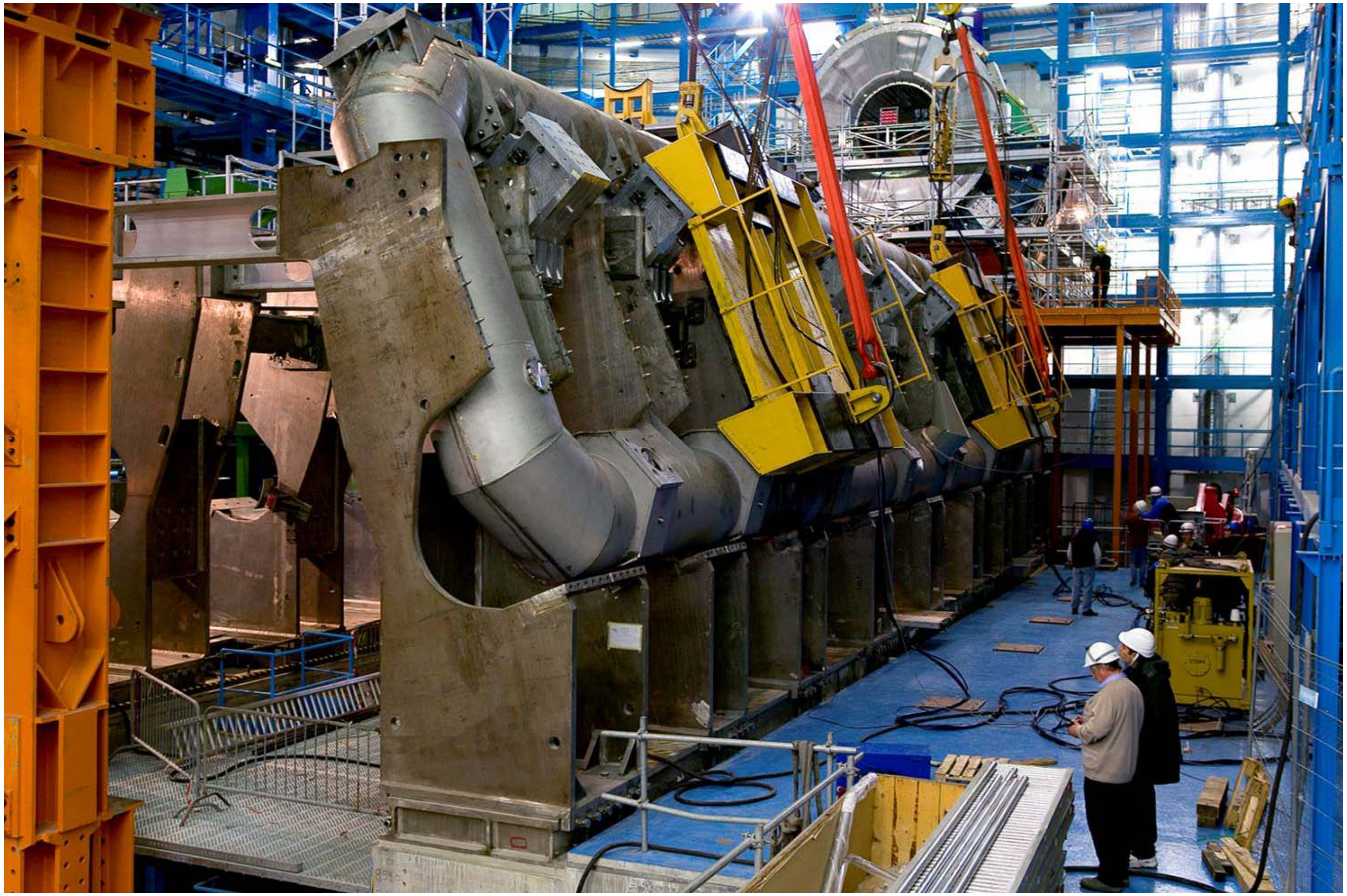


A Slice through CMS

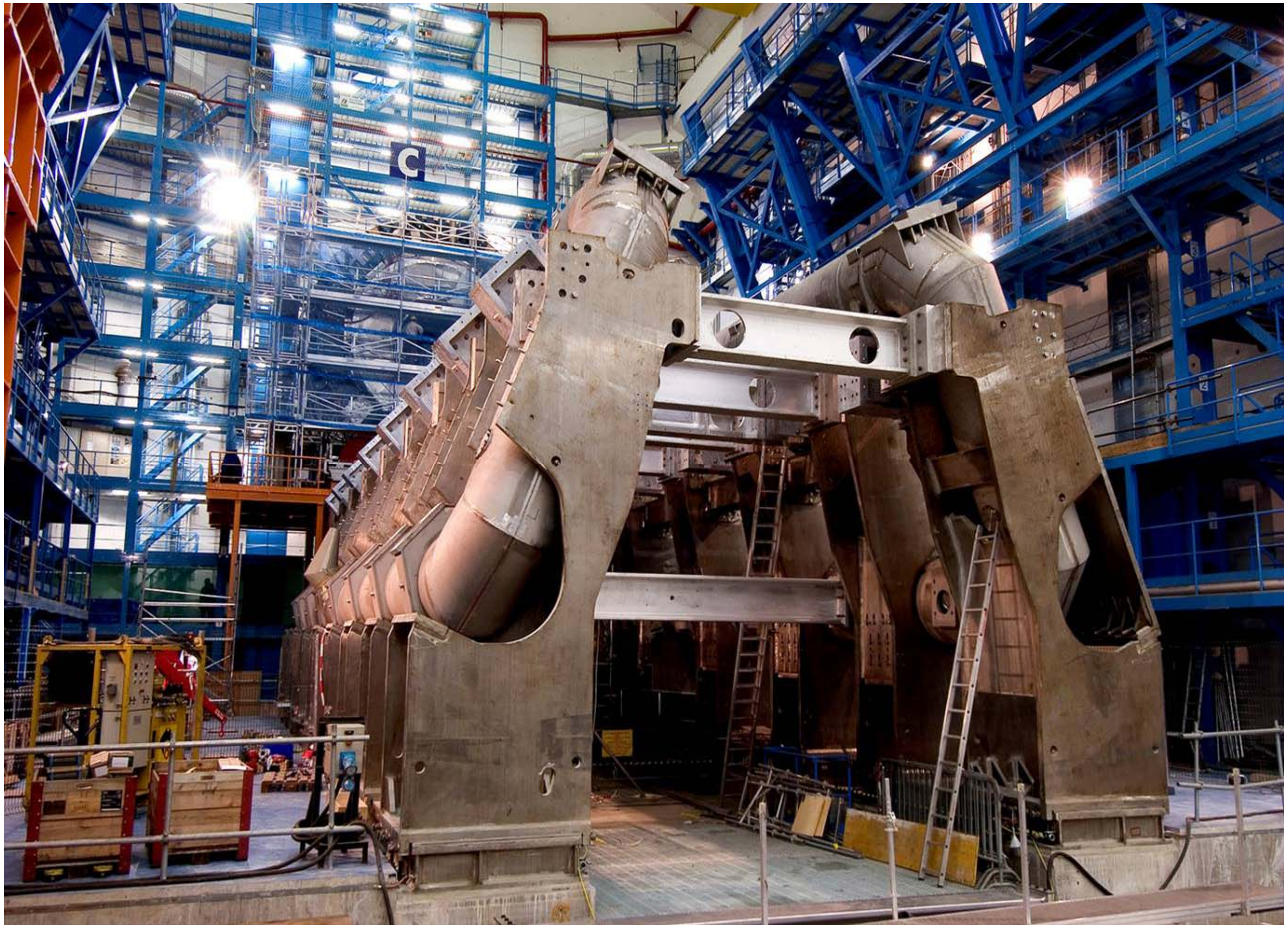


Calorimetry CMS inside solenoid

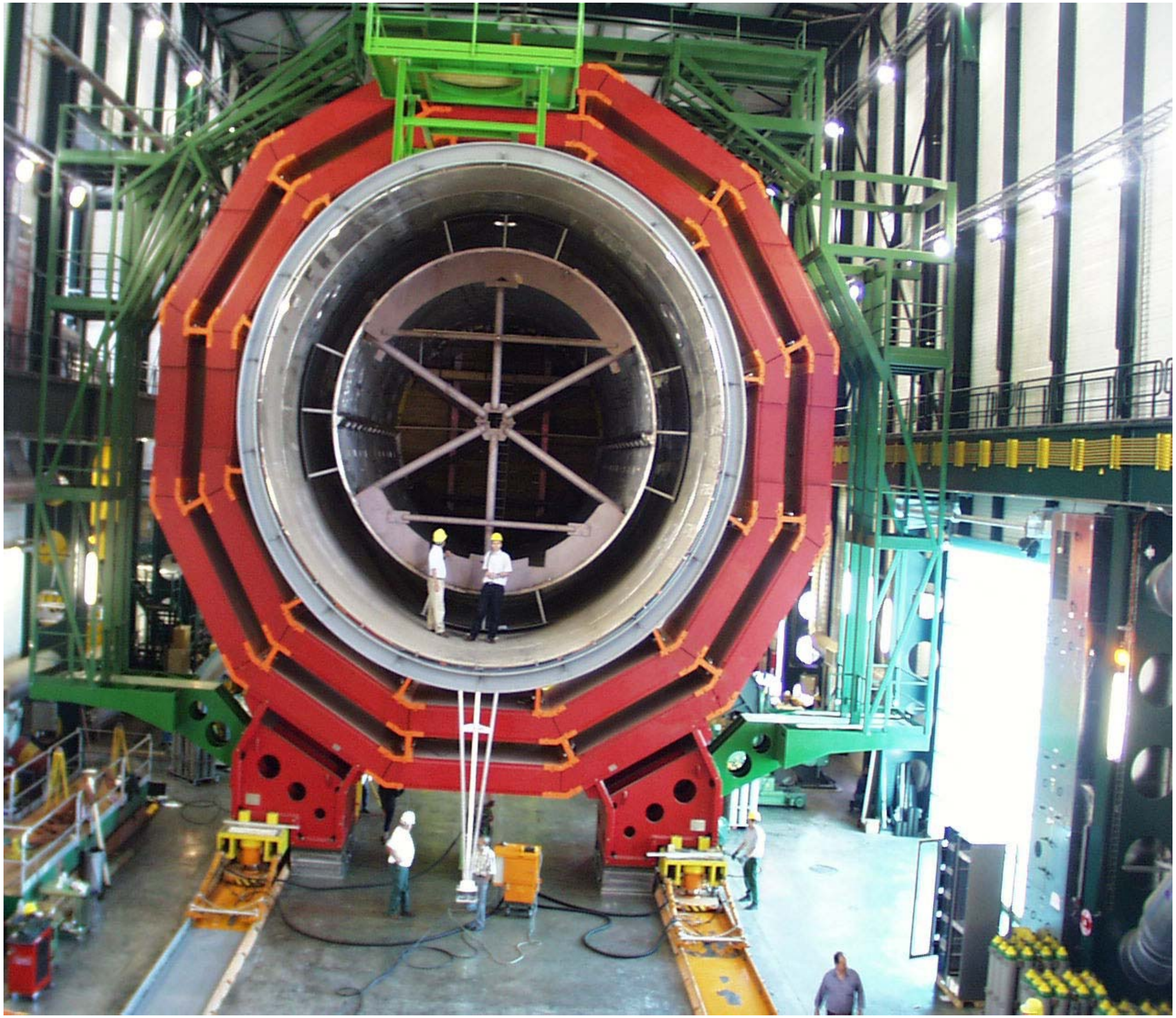
ATLAS: Toroid Coils



ATLAS: Toroid Coils



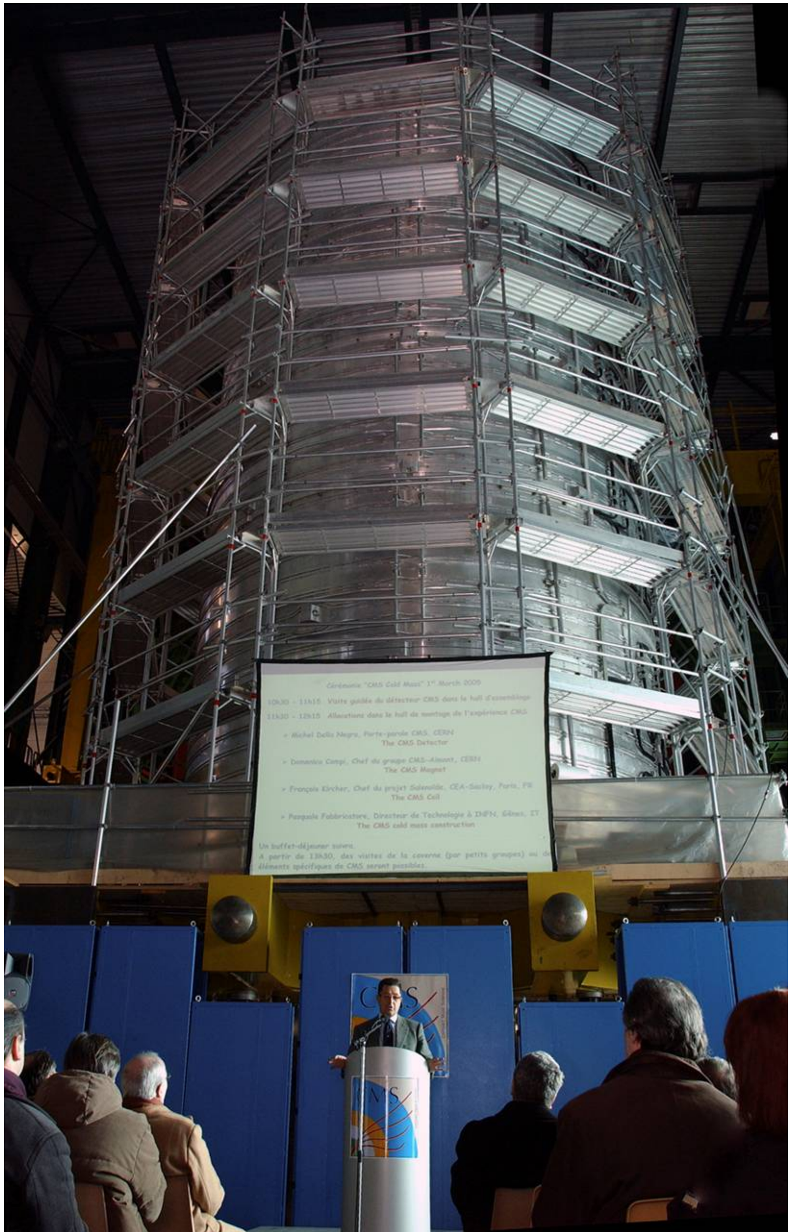
CMS Solenoid Assembly



CMS Solenoid Coil

Coil Reception ceremony March 1st 2005 at CERN

Magnet will be complete and tested Fall 05



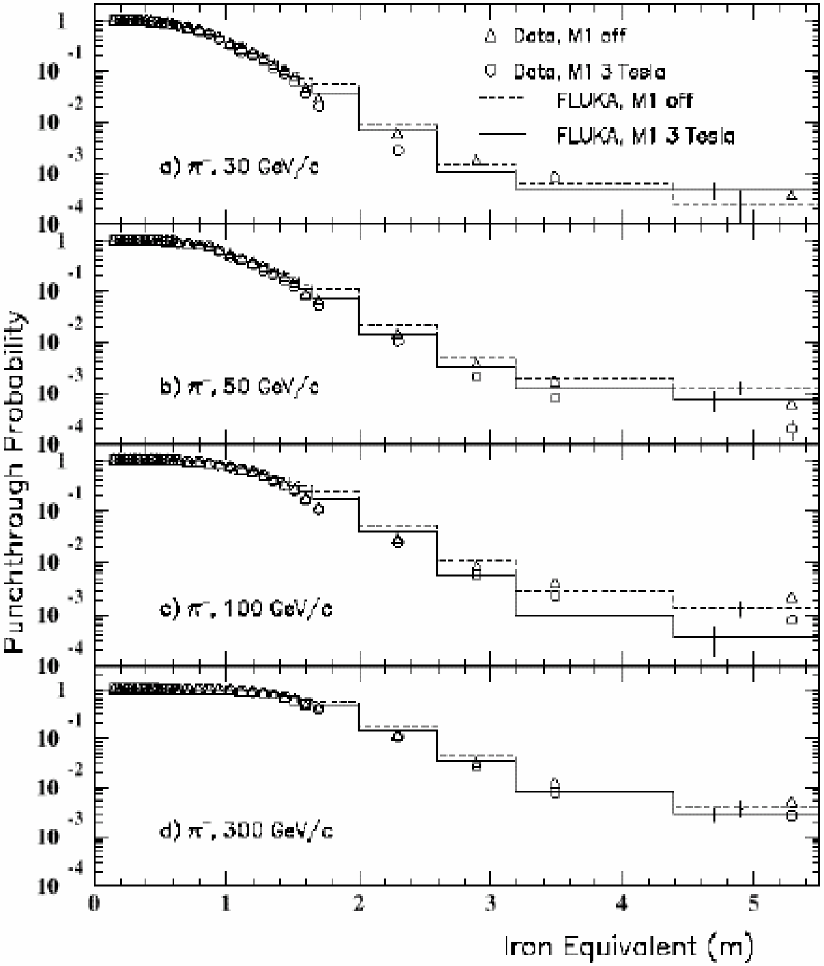
Muon system

- **Muon identification should be easy at L=10^{34}cm^{-2}s^{-1}**
  - **Muons can also be identified inside jets**
    - **b-tagging, also control efficiency of isolation cuts**
- **Factors that affect performance**
  - **Level-1 trigger**
    - **Rate from genuine muons ($b,c \to \mu$) is very high. Must make a P_T cut with very high efficiency, and a flexible threshold (P_T in the range 5-75 GeV)**
  - **Pattern recognition**
    - **Hits can be spoiled by correlated backgrounds: δ's, EM showers, punchthrough. Uncorrelated bkgs: neutrons and associated photons**
  - **Momentum resolution**
    - **High momenta: need large int(B.dl); good chamber resolution (<100μm) and alignment. Low momenta: inner tracking better**
- **Both detectors: multiple stations with multiple hits <u>(angular measurement)</u>**

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 $h^{\pm}$.

Hadron Punchthough



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.

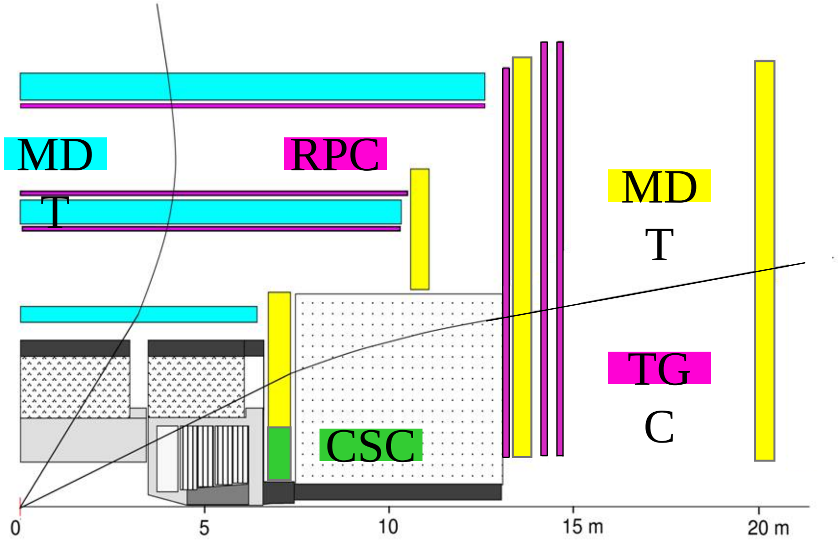
Hadron Punch-through

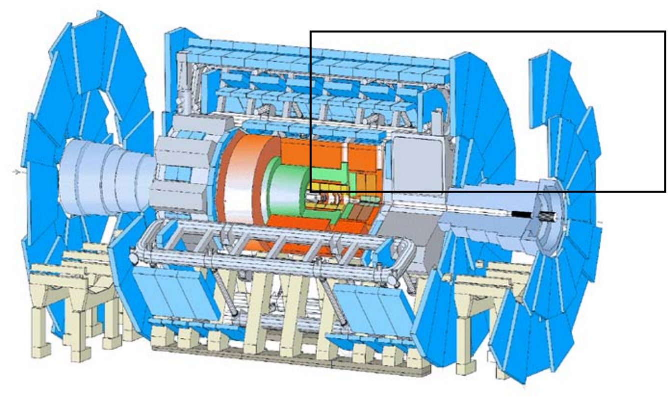
Debris from hadronic showers can accompany muons leading to:

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

ATLAS Muon Detectors

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





Precision chambers

Monitored **D**rift **T**ubes ($|\eta| < 2$)

with a single wire resolution of 80 μm

1194 chambers, 5500m^2

Cathode **S**trip **C**hambers ($2 < |\eta| < 2.7$)

at higher particle fluxes

32 chambers, 27 m^2

Trigger chambers

Resistive **P**late **C**hambers ($|\eta| < 1.05$)

with a good time resolution of 1 ns

1136 chambers, 3650 m^2

Thin **G**ap **C**hambers ($1.05 < |\eta| < 2.4$)

at higher particle fluxes

1584 chambers, 2900 m^2

ATLAS Muon System: Monitored Drift Tubes

End-cap MDT chamber

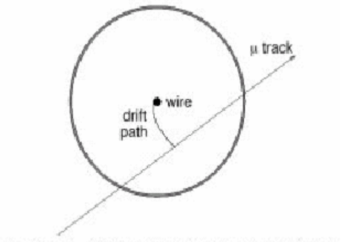
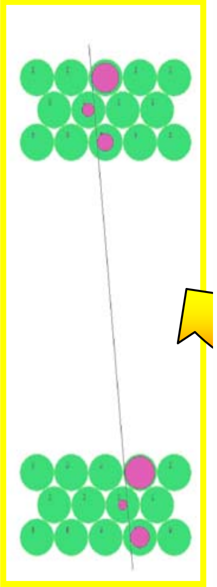


Figure 5-2 Drift tube operation in a magnetic field with curved drift path.

ϕ_{wire} = 50µm (W-Re)
3 bar, 3270V,
t_d = 500ns
Gas gain = 2.10^4



Measured Spatial Resolution

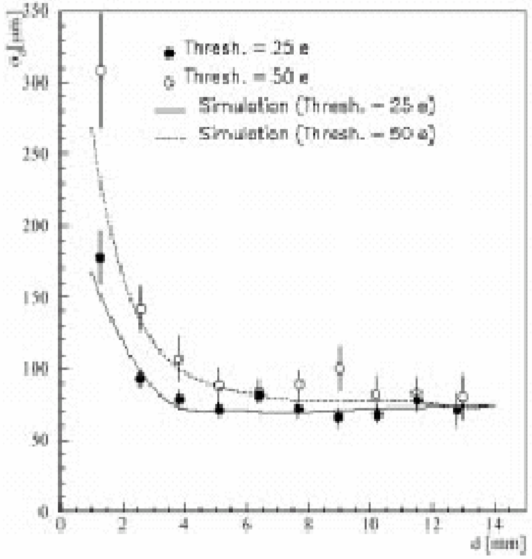
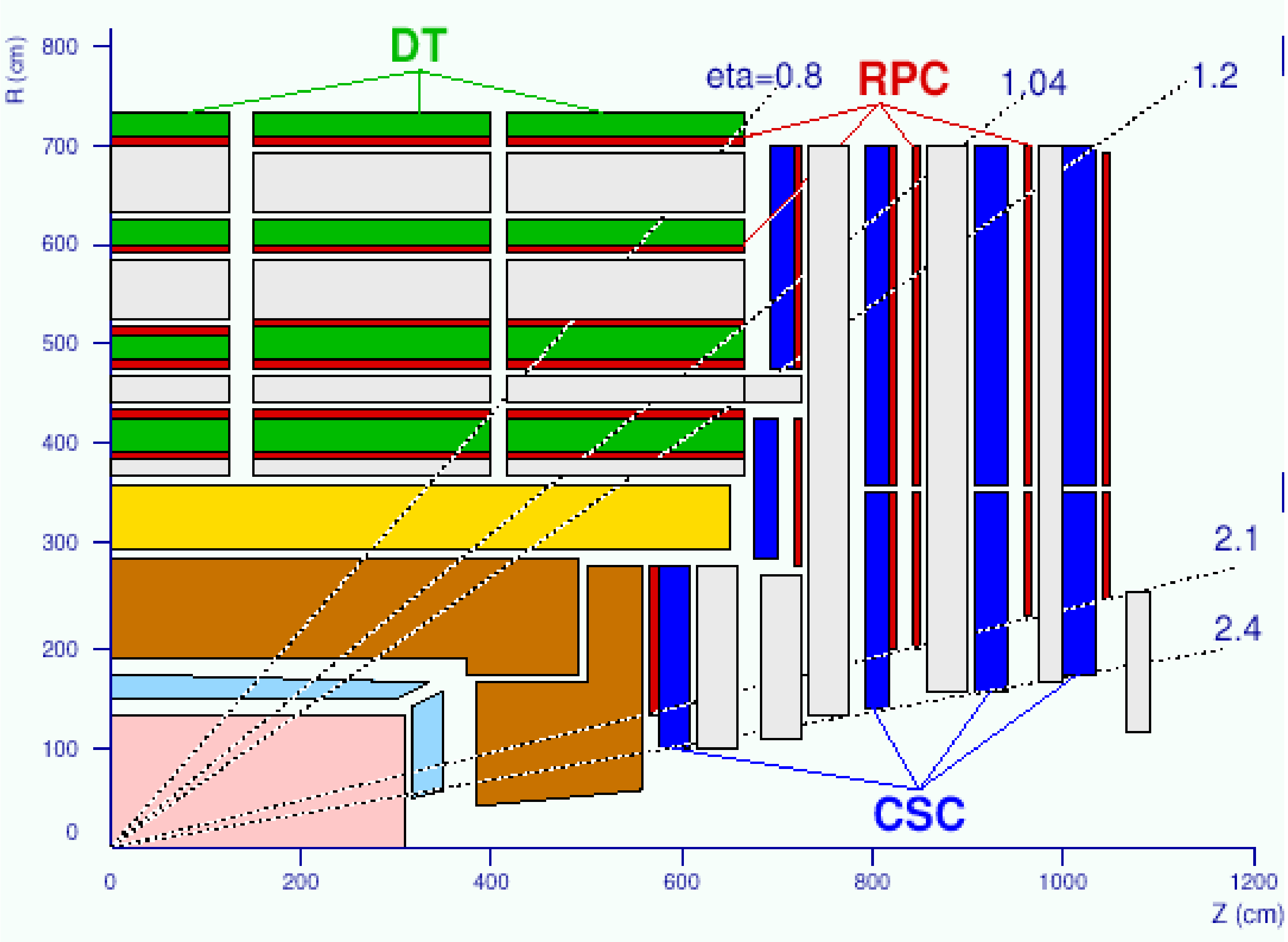


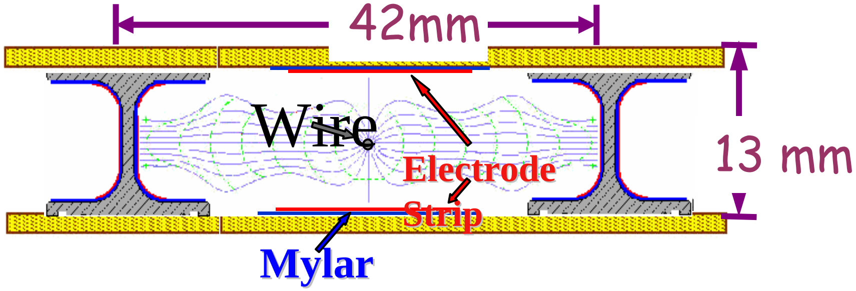
Figure 5-4 MDT resolution as a function of the drift distance, to an Ar/N2/CH4 (91/4/5 mixture). The curves correspond to two discriminator threshold settings.

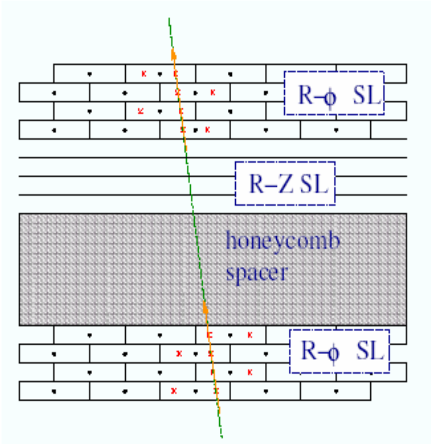
CMS Muon System



250 DTs 468 CSCs 480 RPCs

CMS Muon System: Drift Tubes





CMS Muon System: CSC’s