The LHC Experiments

TASI 2006 - Lecture 2

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Outline

A. Interactions of Particles With Matter
B. Tracking Detectors
C. Calorimetry
D. CMS and ATLAS Design
E. The Mystery of Triggering
F. Physics Object Resonstruction

Interactions of Particles and Matter

- understanding the LHC detectors requires a basic understanding of the interaction of high energy particles and matter
- we will cover here:
  - photons/electrons in nuclear materials (em cal.)
  - bremsstrahlung
  - minimum ionization (charged tracks)
  - multiple scattering
  - secondary hadron production/nuclear interaction

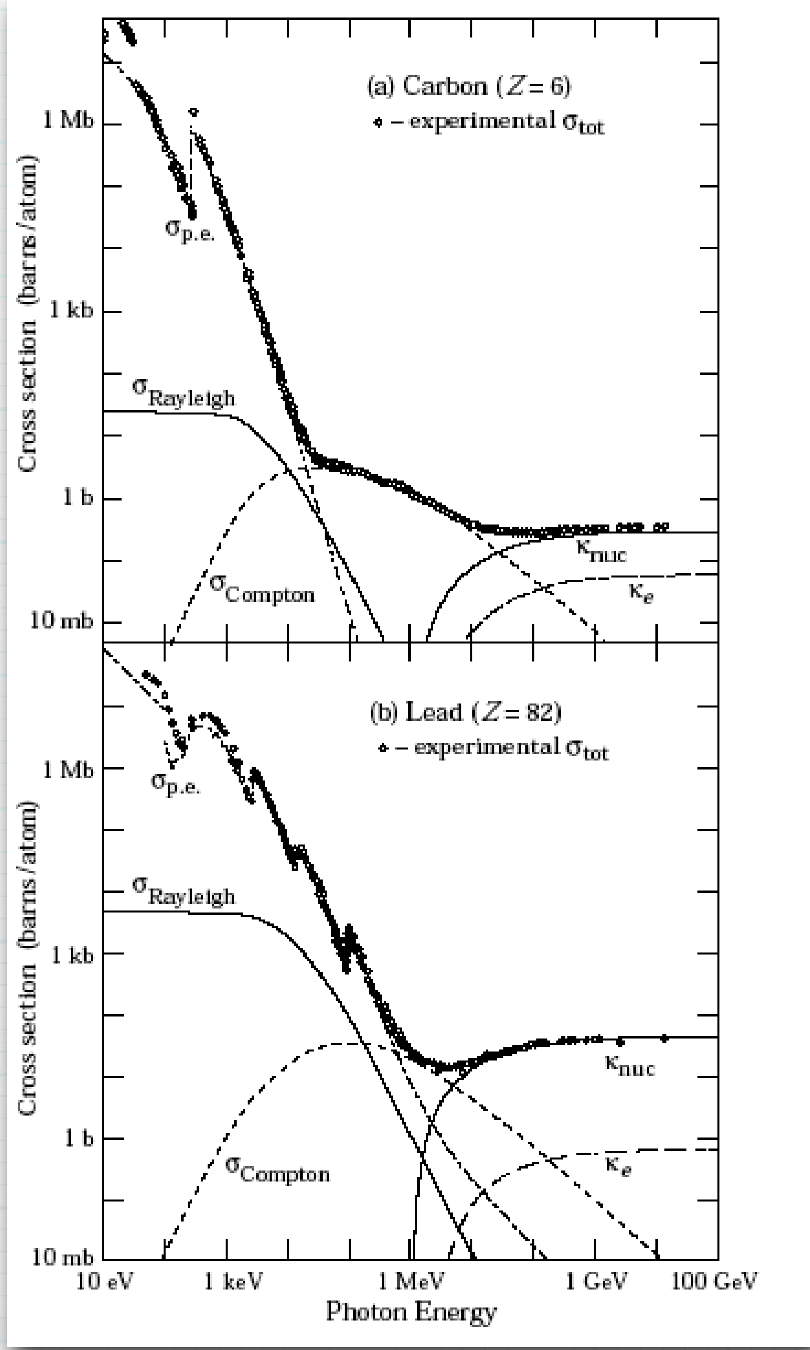
see http://pdg.lbl.gov/2005/reviews/passagerpp.pdf

Electromagnetic Interactions

Photons in matter:

- low energies (< 100 keV): photoelectric effect
- medium energy (~ 1 MeV): Compton scattering
- high energy (> 10 MeV): e^+e^- pair production

Each of these leads to electrons being ejected from atoms...e.m. showers



Photons and Matter

- we are mainly interested in very high energy photons, $E_\gamma > 1$ GeV where pair production dominates
- a beam of such high energy photons has an intensity which drops exponentially with depth:

$$I(x) = I_0 e^{-\mu x}$$

- μ is the linear absorption coefficient; probability of radiation per unit distance traversed:

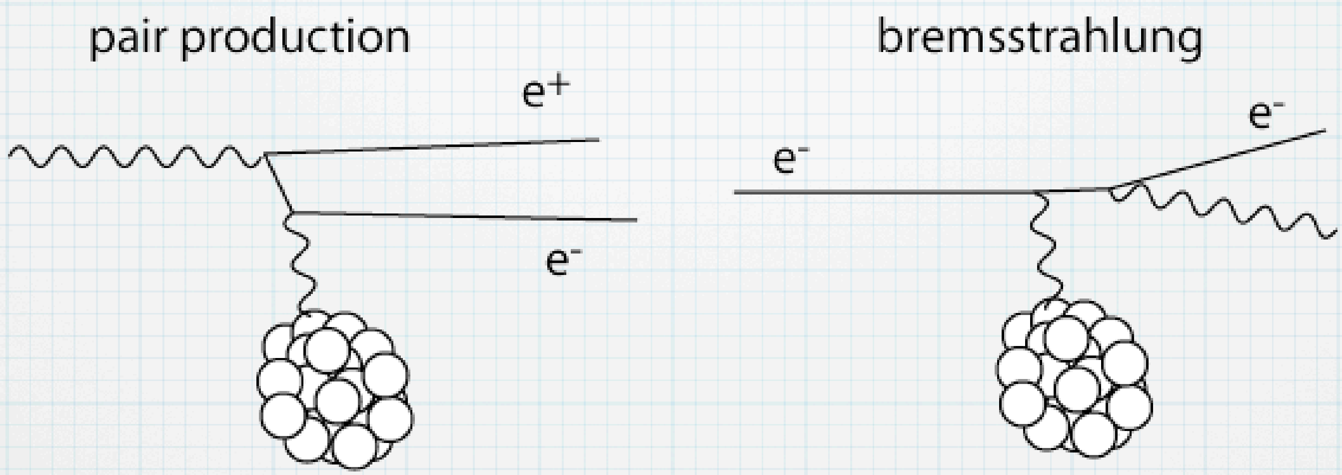
$$\mu = \frac{\sigma N_0 \rho}{A} \equiv \frac{7}{9X_0}$$

radiation length

- but then we have high energy electrons...process repeats

Electrons and Matter

- a high-energy electron encountering the strong field of a nucleus undergoes bremsstrahlung:



- clearly we need the field of the nucleus to conserve momentum and energy
- processes are very similar, except for 7/9 !

Radiation Length

$$1/X_0 = \frac{4\alpha N_A Z(Z+1) r_e^2 \log(183 Z^{-1/3})}{A}$$

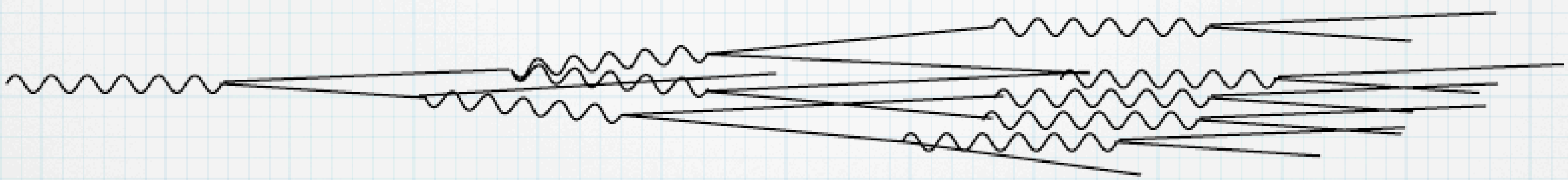
- higher Z materials have shorter radiation length
- want high-Z material for e.m. calorimeter
- want as little material as possible in front of the calorimeter!
- lead: ρ = 11.4 g/cm^3

  $\Rightarrow X_0$ = 5.5 mm

material	X_0 g/cm^2
H_2	63
Al	24
Fe	13.8
Pb	6.3

Electromagnetic Showers

- process of bremsstrahlung/pair production repeats itself until initial energy used up:



- electrons: linear absorption coefficient $\mu = 1/X_0$
- photons: linear absorption coefficient $\mu = 7/9X_0$
- to get a signal out, we ultimately rely on the ionization energy loss of electrons in some material
- Moliere radius: width of shower (~12 mm for Pb)

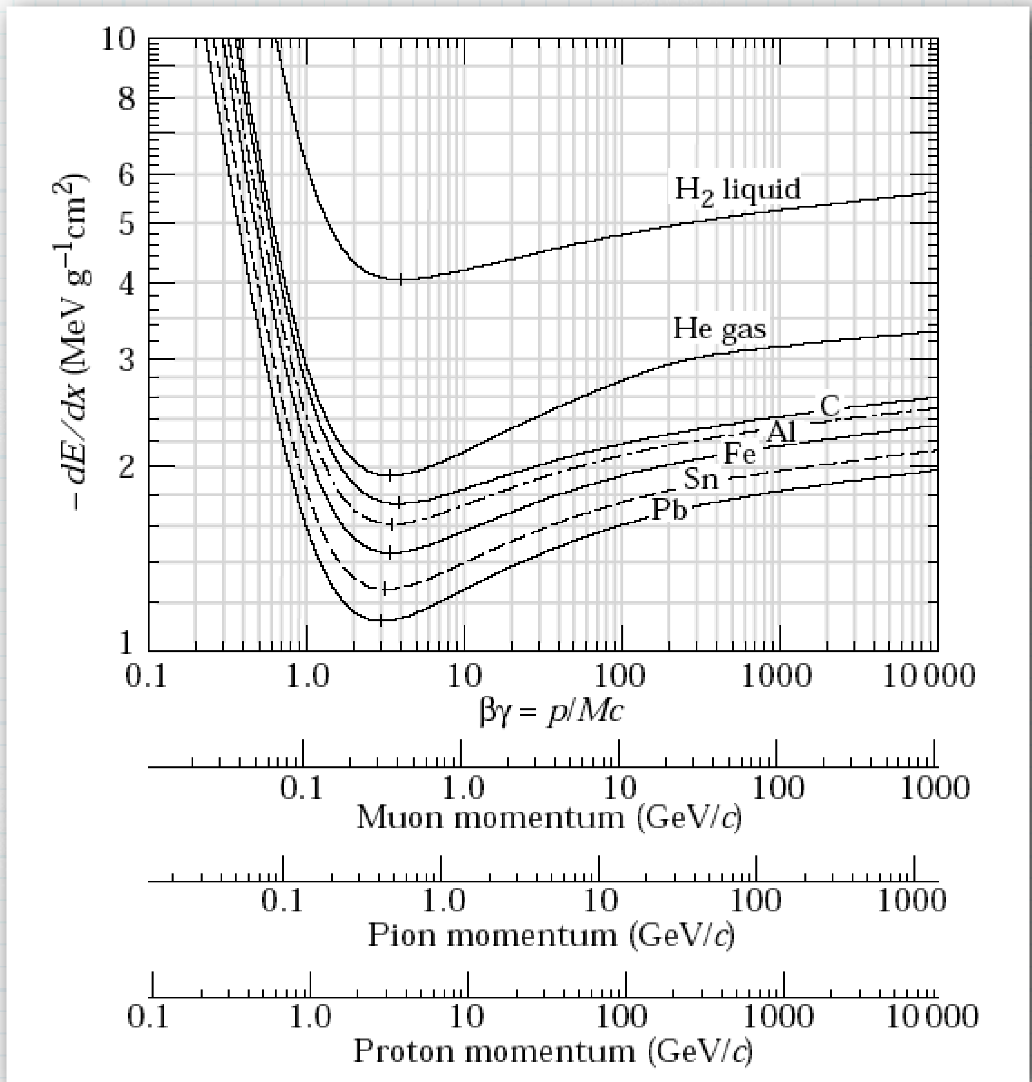
Hadronic Showers

- interactions of pions/kaons in material:
  nuclear interaction length
- lead ~ steel = 17 cm
- about 5% different for pi^+ and pi^-
- for heavy (high Z) materials we see that the nuclear interaction length is a lot longer than the electromagnetic one
- showers start late, more diffuse
- and don't forget charge exchange!

material	X_0 (g/cm^2)	λ_n (g/cm^2)
H_2	63	52.4
Al	24	106
Fe	13.8	132
Pb	6.3	193

Bethe-Bloch and MIPs

- high energy charged particles lose energy by ionization of atoms
- specific ionization (dE/dx) depends on material density
- express in terms of MeV/(g/cm^2)
- $1/\beta^2$, rel. rise.
- minimum at $\beta\gamma \sim 3$



Bethe-Bloch and MIPs

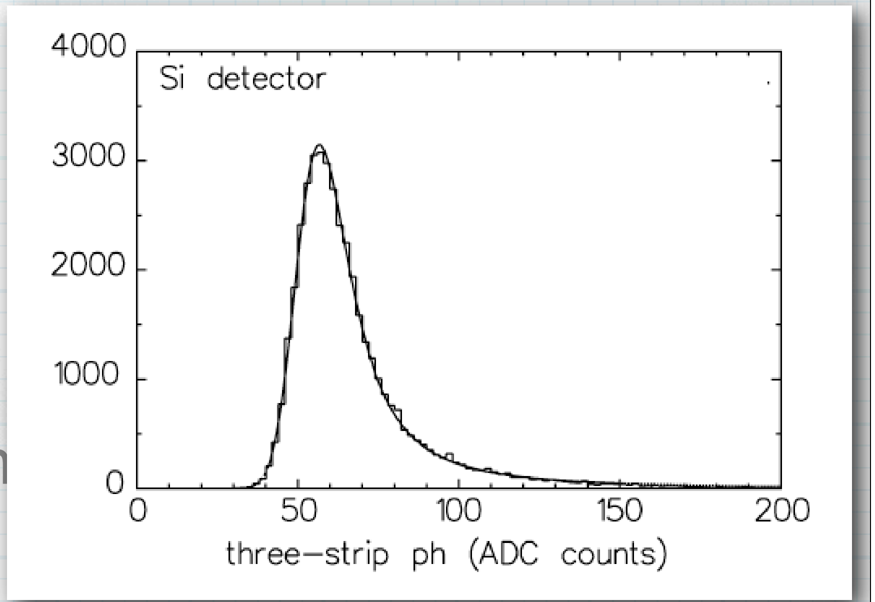
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}[\frac{1}{2}ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta}{2}]$$

- Bethe-Block formula describes average energy loss
- example: MIP in silicon

  dE/dx: 1.6 MeV/(g/cm2) x 2.33 g/cm^3

  = 3.7 MeV/cm (not much!)

- amount of ionization fluctuates according to "Landau" distribution (actually Vavilov)



Multiple Scattering

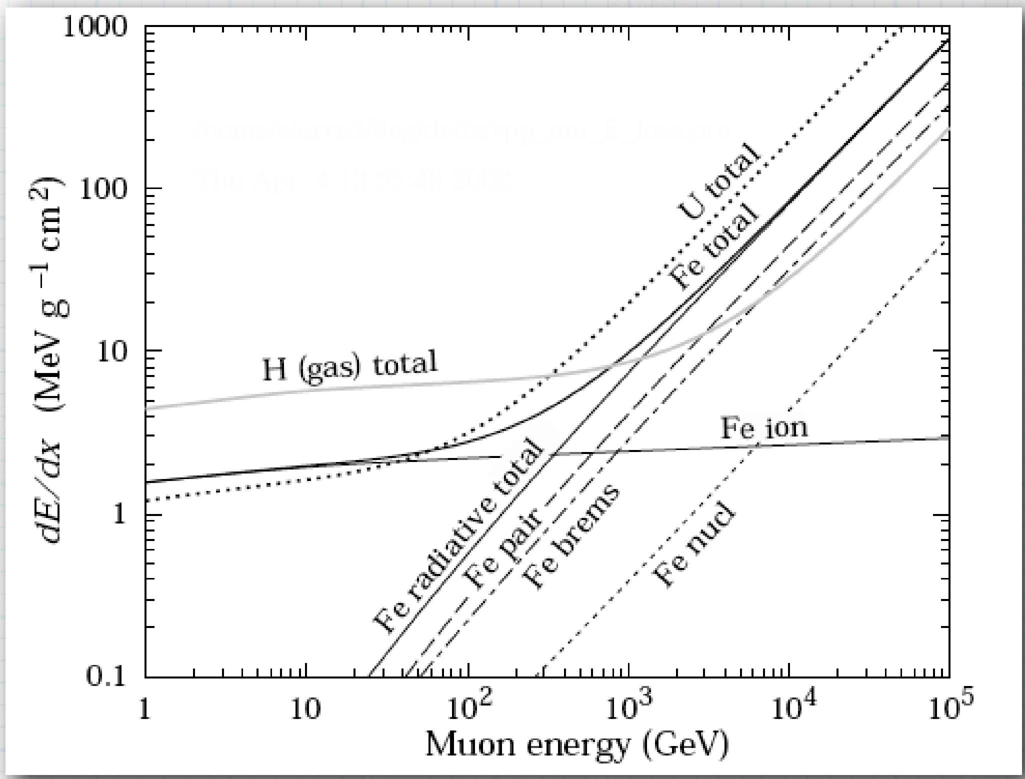
- as they ionize materials, high energy charged particles change their direction with each interaction
- distribution dominated by gaussian of width θ_0
- high angle scattering tail to distribution
- important for relatively low-energy particles (~ few GeV): rms angle given by

$$\theta_0 = \frac{13.6\mathrm{MeV}}{\beta c p} z \sqrt{x/X_0}\,[1 + 0.038\ln(x/X_0)]$$

- for a 1 GeV pion traversing 1 X_0, θ_0 ~ 14 mrad
- for a 10 GeV pion traversing 1 X_0, θ_0 ~ 1.4 mrad

Muon Bremsstrahlung

- muons are much heavier than electrons, but at high energies radiative losses begin to dominate:



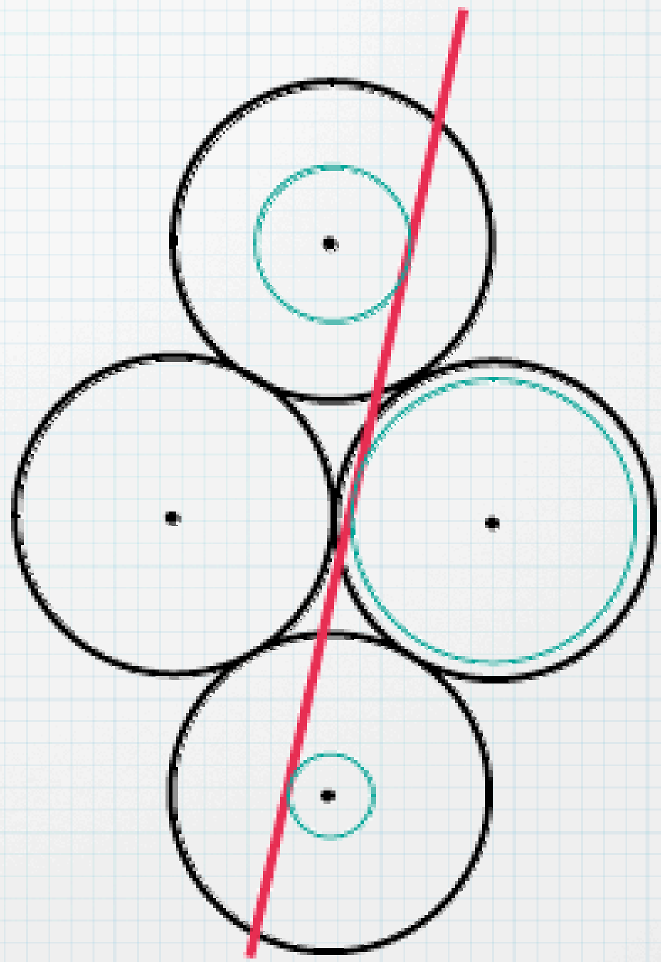
- in other words, at high energies muons can sometimes behave more like electrons!
- effective radiation length decreases at high energy and so (late) e.m. showers can develop in the detector
- pions, too, but that's less of a problem...

Tracking Detectors

- For tracking detectors we want as little material as possible to minimize multiple scattering; two approaches:
  - gas/wire chambers (like CDF's COT)
  - solid-state detectors (silicon)
- Silicon is now the dominant sensor material in use for tracking detectors at the LHC and we will focus on that
- however, first a word about drift chambers...

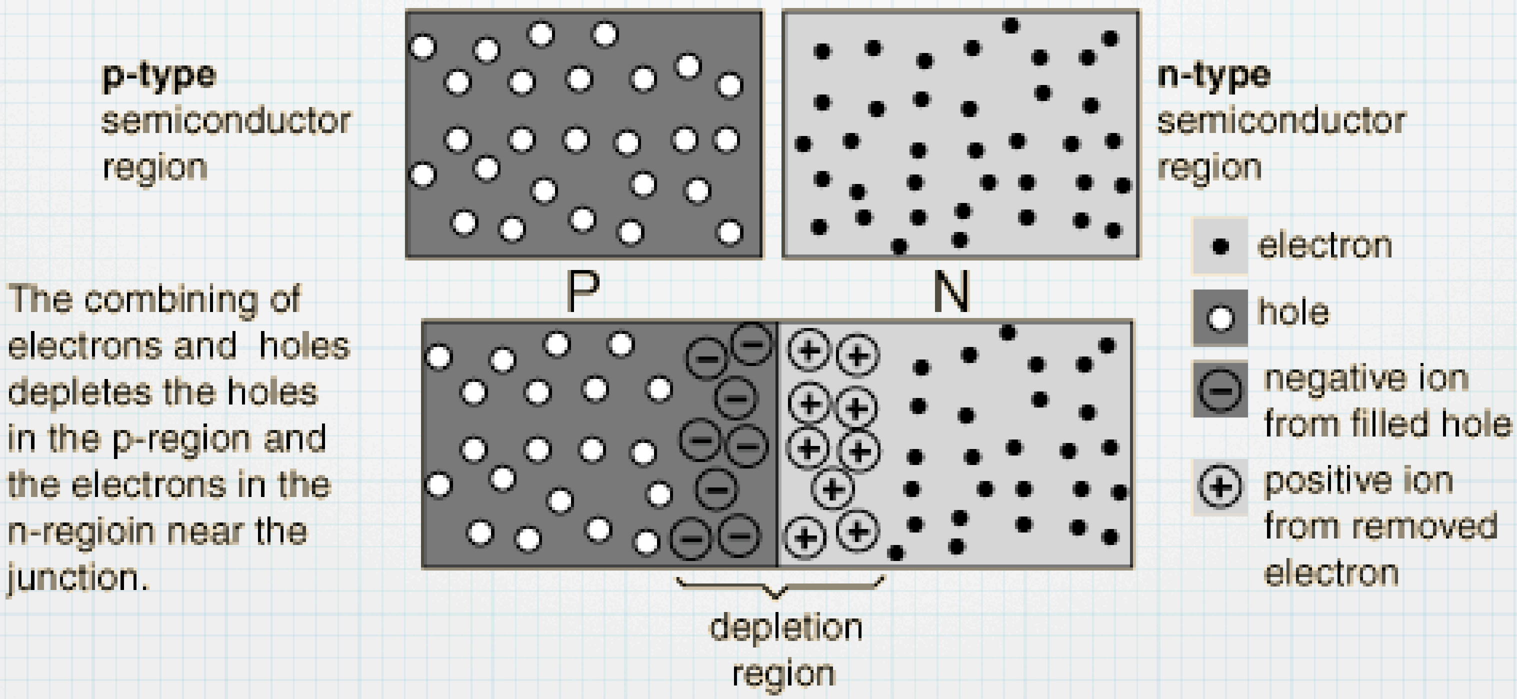
Drift Cells

- tubes with wire at +HV draw ionization electrons; avalanche near wire
- stack up the tubes, measure time of arrival of the ionization pulse
- drift: ~5 cm/μs (50 μm/ns)
- find track from tangents to circles
- can get about 150 μm position resolution
- but: a lot of material!



Silicon Detectors

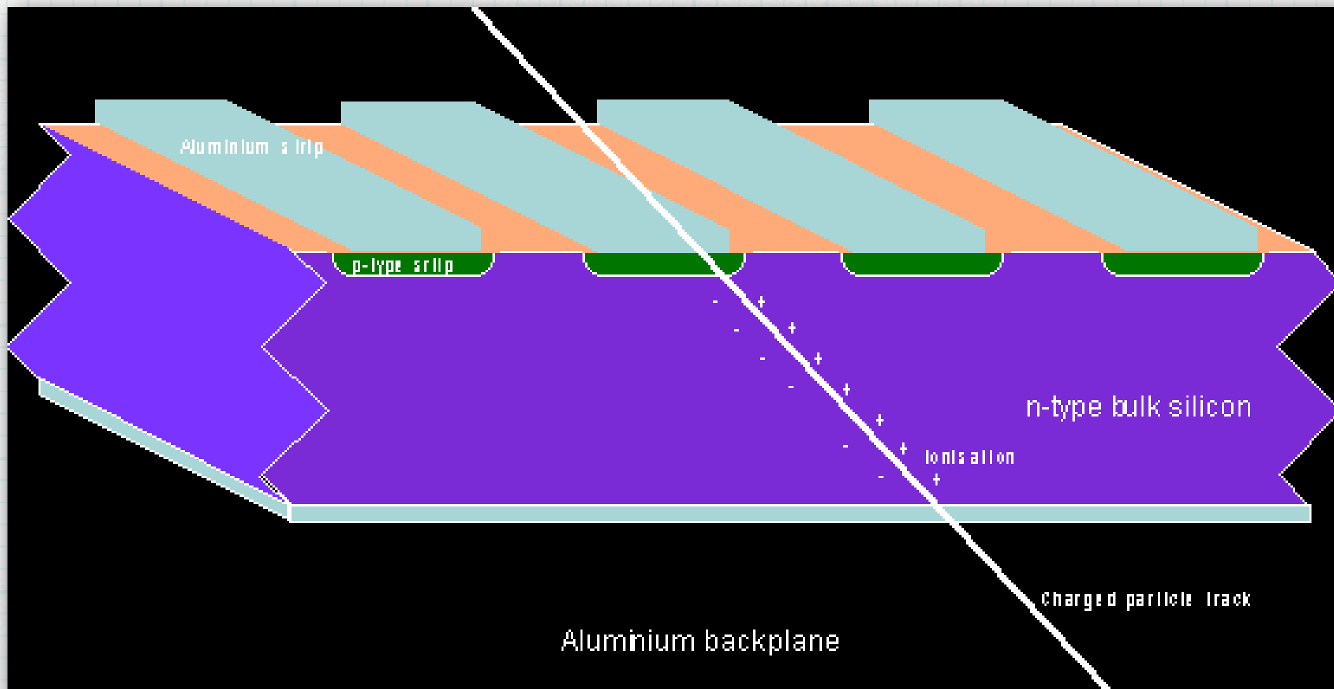
- in doped silicon can create "p-n" junction
- free carriers diffuse across junction, electrons neutralizing the holes:



- applying +V to N side (-V to P side) depletes more

Silicon Detectors

- applying very large reverse-bias voltage to p-n junction "fully depletes" the silicon, leaving E field
- for 300 μm thickness, typically $V_b \sim 100$ V
- geometry of typical silicon detector:



Silicon Detectors

- pixel detector: deposited charge sensed by small pixels on one side of sensor

  many channels, expensive

  more material

  easy pattern recognition

- strip detector: deposited charge sensed by long narrow strips

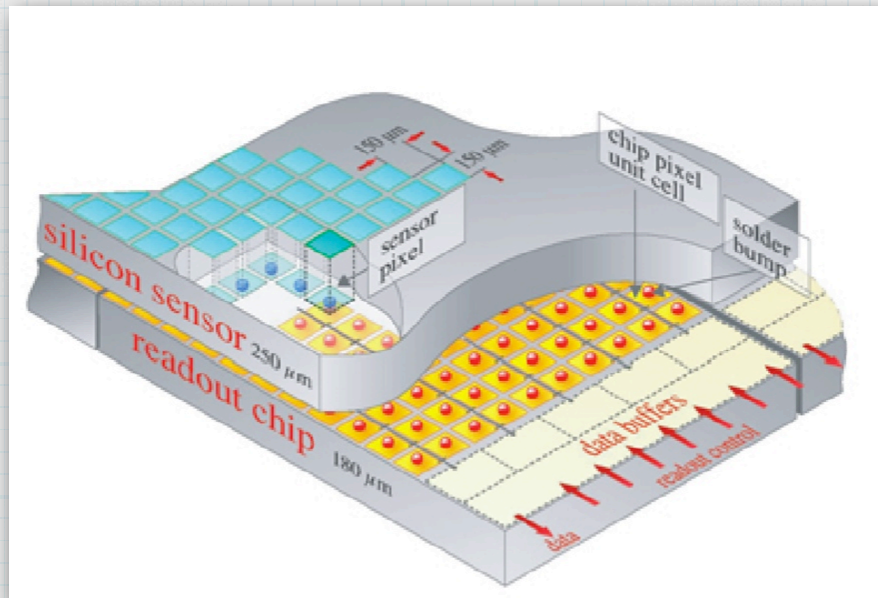
  fewer channels, less expensive

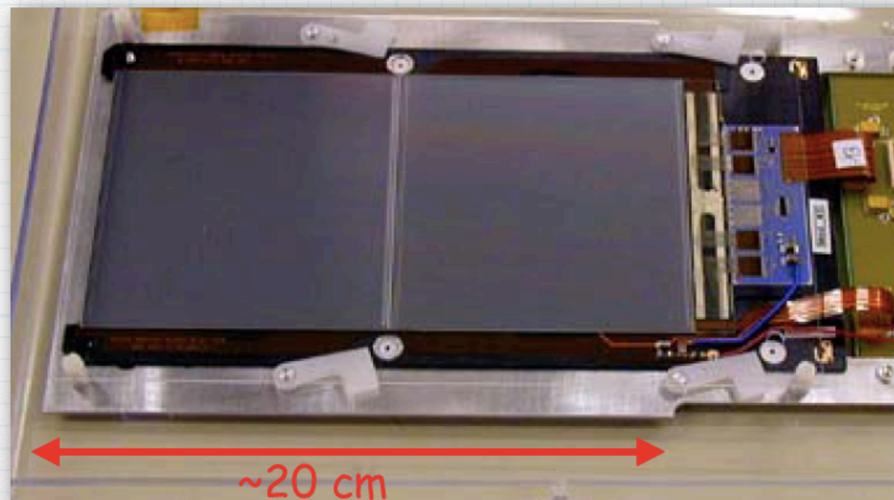
  less material

  pattern recognition difficult!

Silicon Detectors

- charge sharing used to determine where charged particle passed through detector
- can get resolution much smaller than strip or pixel size, onthe order of 10-20 µm





Tracking/p_T Resolution

- we get the p_T of a track from the sagitta of the track helix
- sagitta depends on tracking length ℓ, p_T, and magnetic field B:

$$\begin{aligned} s &= R - R\cos\frac{\theta}{2} \\ &\approx R\theta^2/4 = \frac{B\ell^2}{13.3 p_T} \end{aligned}$$

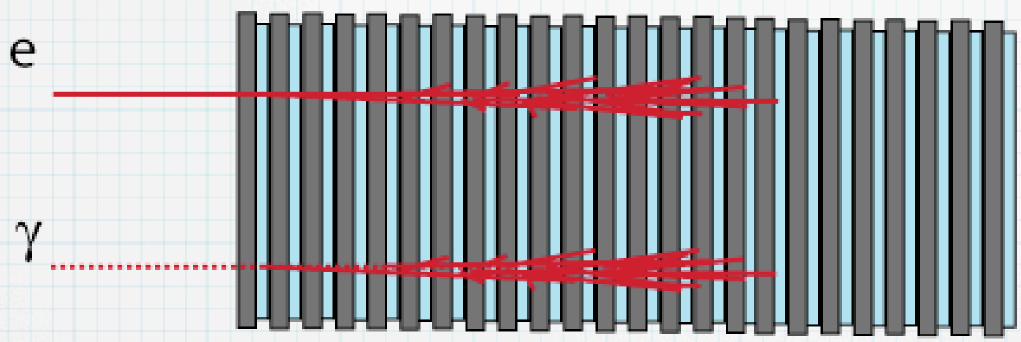
- for B = 4 T, ℓ = 1 m, p_T = 100 GeV we get
  s = 3 mm
- error is on 1/p_T so gets worse at high p_T!

Calorimetry

- want heavy material to cause brem/pair production for initial electromagnetic section, and fine sampling
- for hadron calorimetry, larger towers and coarser sampling in depth
- two technologies for em calorimeters:
  - exotic crystals (CsI, PbWO, BGO, ...)
  - liquid argon
- can achieve remarkable precision
- relative energy uncertainty <u>decreases</u> with E !

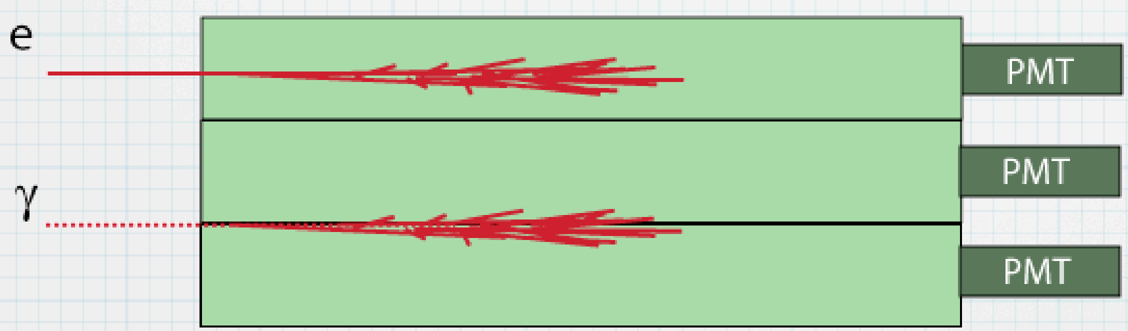
Typical E.M Calorimeters

- "lead-scintillator sandwich" calorimeter



$\Delta E/E \sim 20\%/\sqrt{E}$

- exotic crystals (BGO, $PbWO_3$, ...)



$\Delta E/E \sim 1\%/\sqrt{E}$

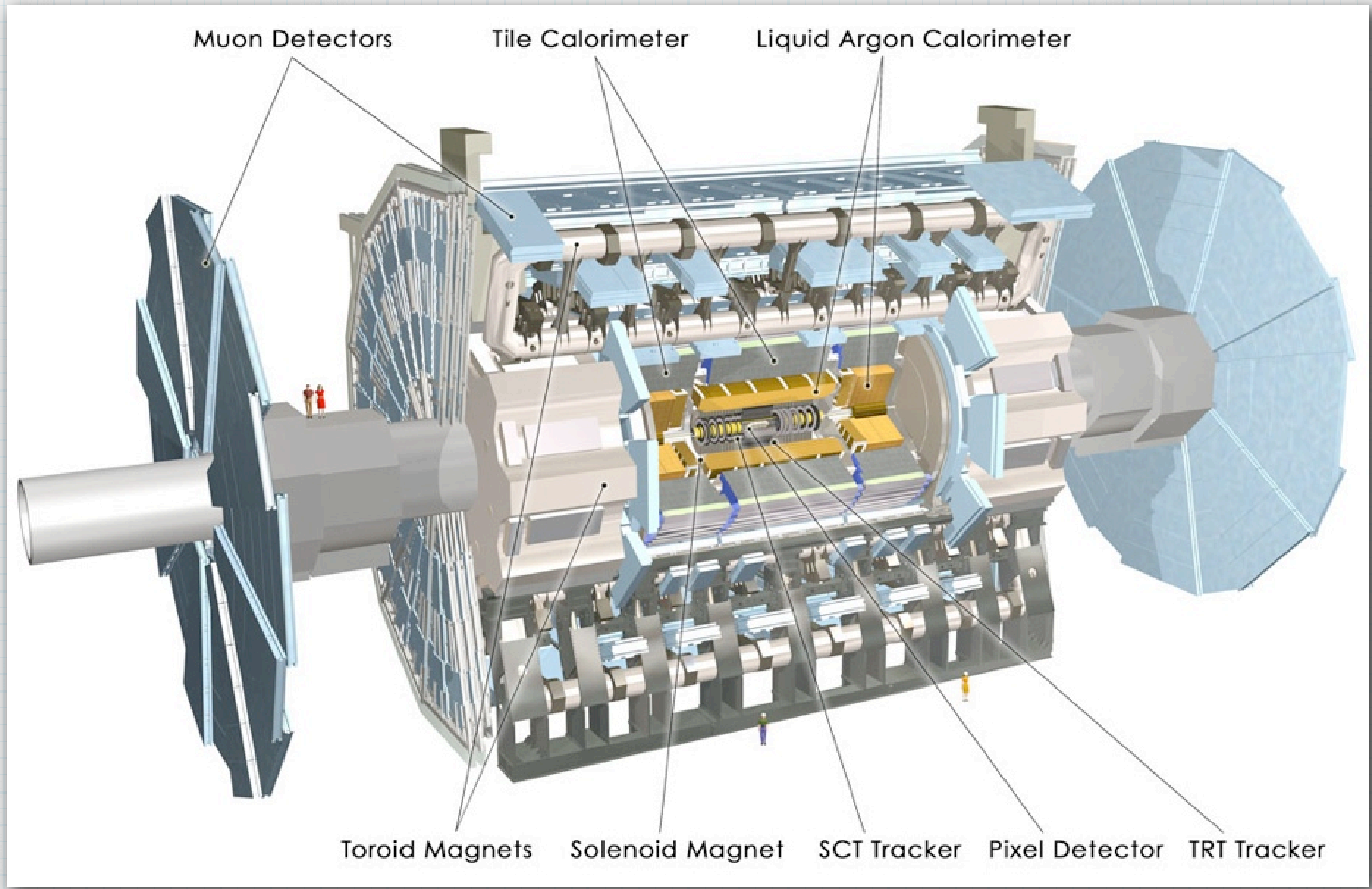
- liquid argon calorimeter

CMS and ATLAS

- two different approaches to the LHC problem!
- CMS sinks, ATLAS floats!
- both need to employ detectors with very fast signals and readout
- both need to be very radiation hard

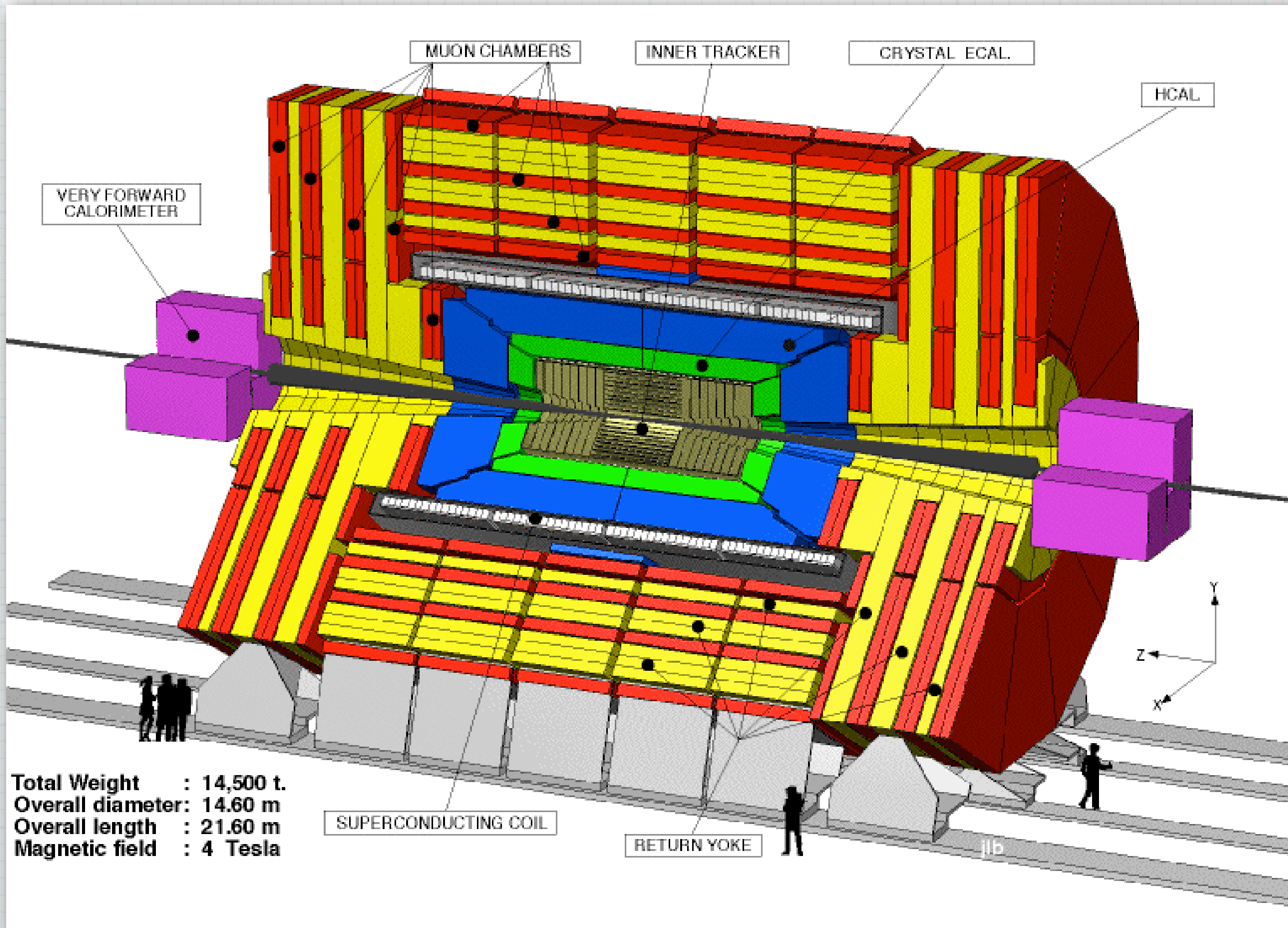
	ATLAS	CMS
tracking	silicon/gas	silicon
em cal	liquid Ar	PbWO
had cal	steel/scint.	brass/scint.
muon	RPCs/drift	RPCs/drift

ATLAS

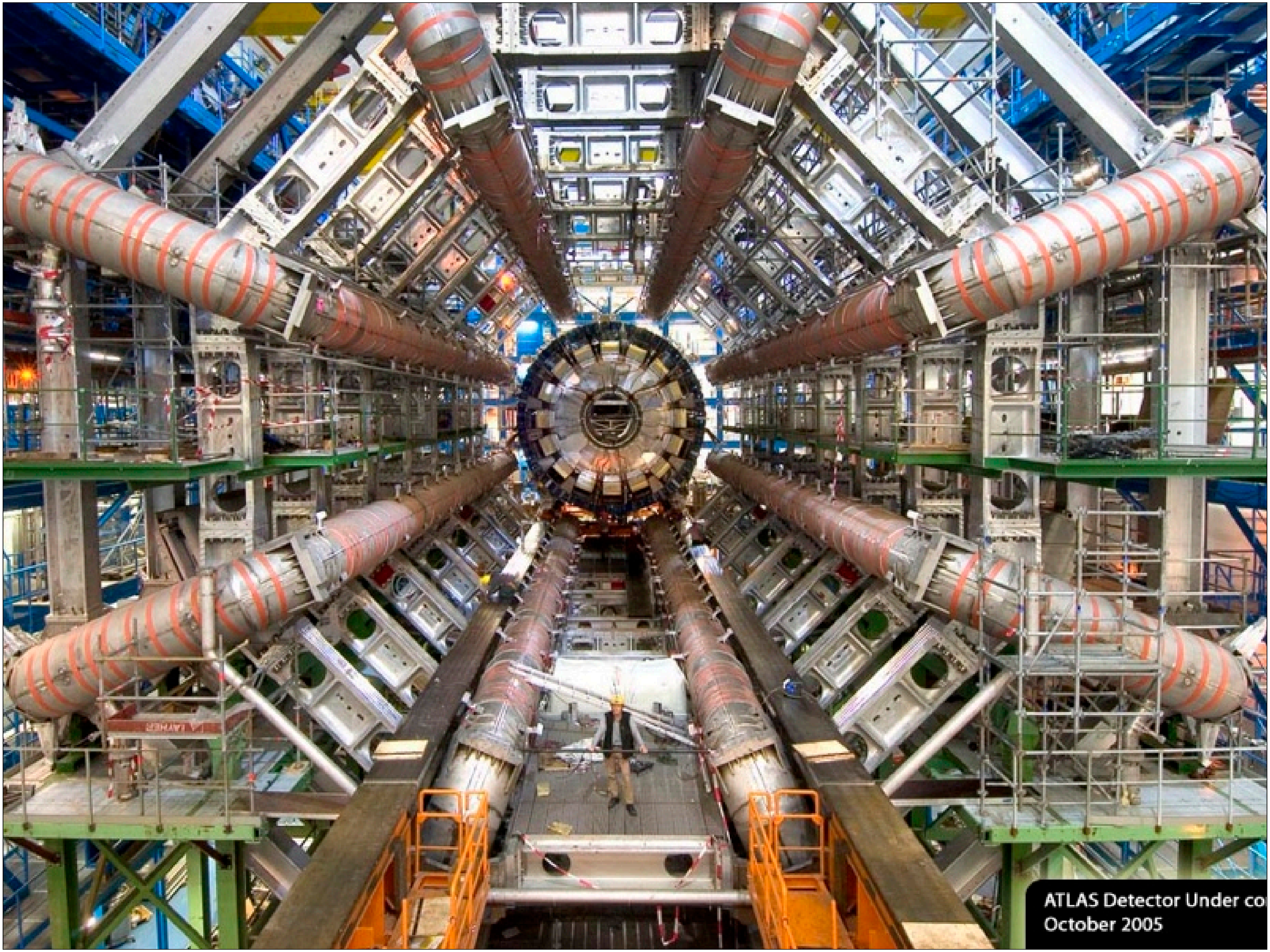


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

CMS

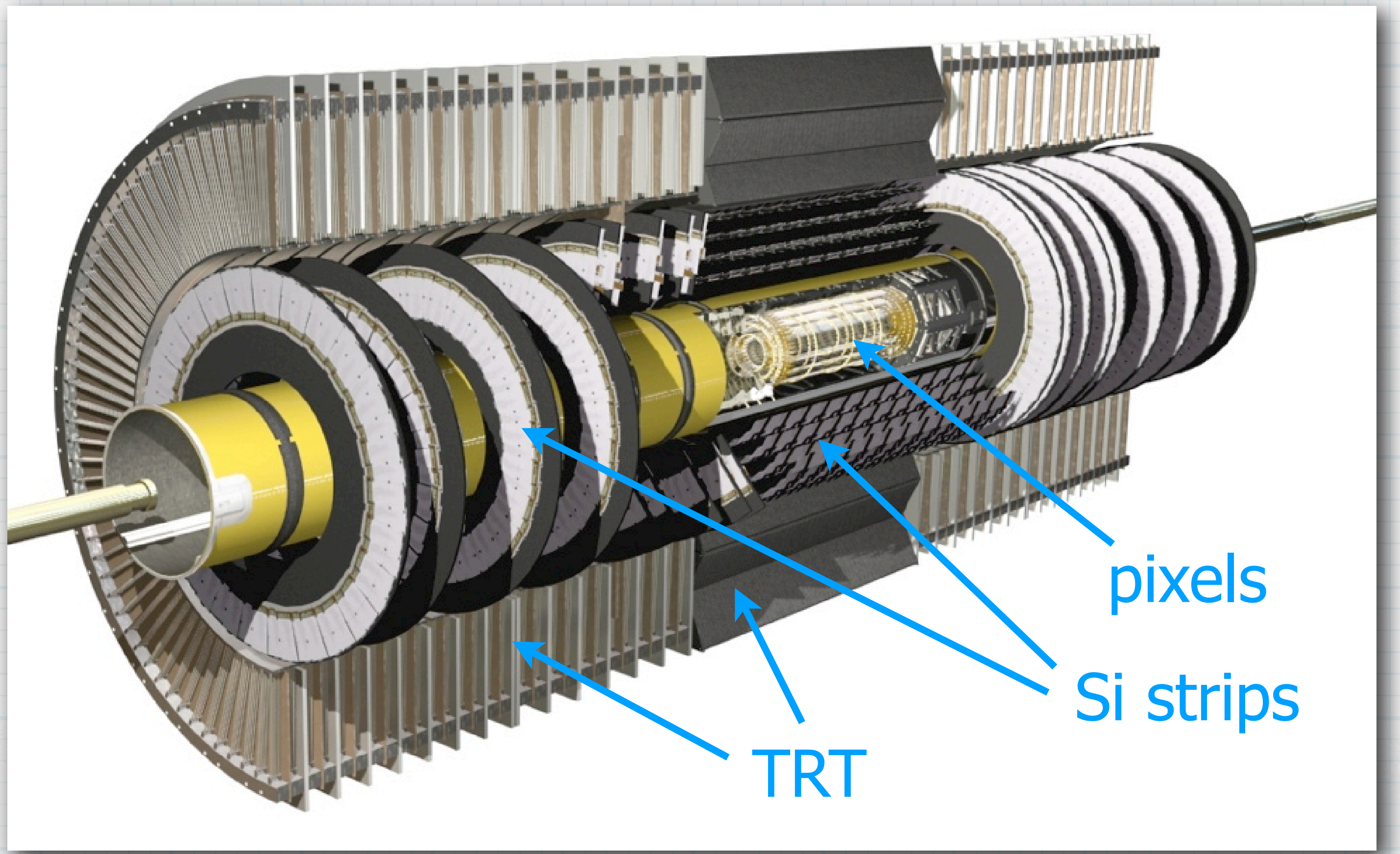


MUON CHAMBERS
INNER TRACKER
CRYSTAL ECAL.
HCAL
VERY FORWARD CALORIMETER
SUPERCONDUCTING COIL
RETURN YOKE
Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla
Y
Z
X

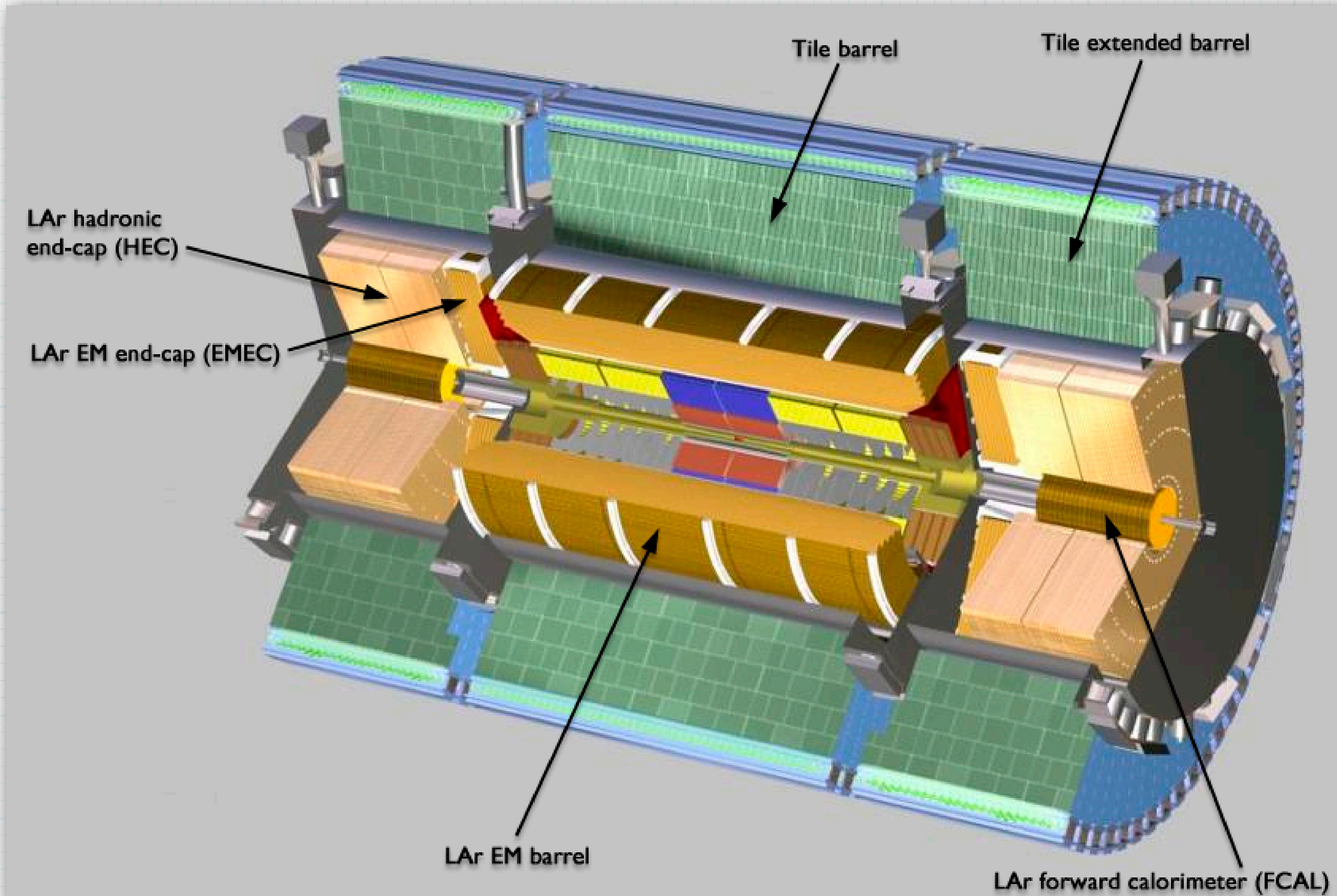

ATLAS Detector Under co
October 2005

ATLAS Inner Detector

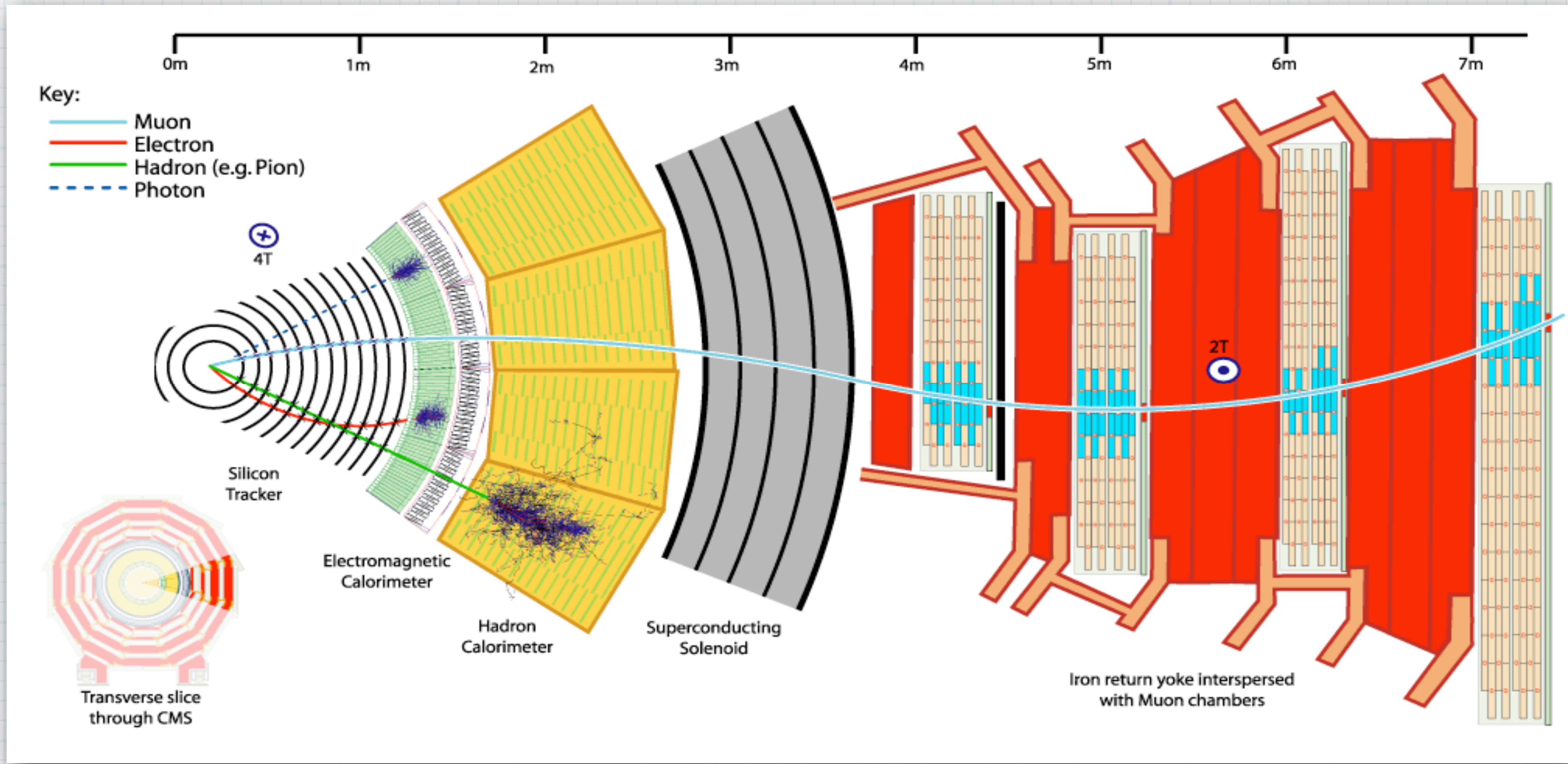
- silicon pixels surrounded by silicon strips:
- 2 Tesla solenoid immediately outside tracker



ATLAS Calorimetry



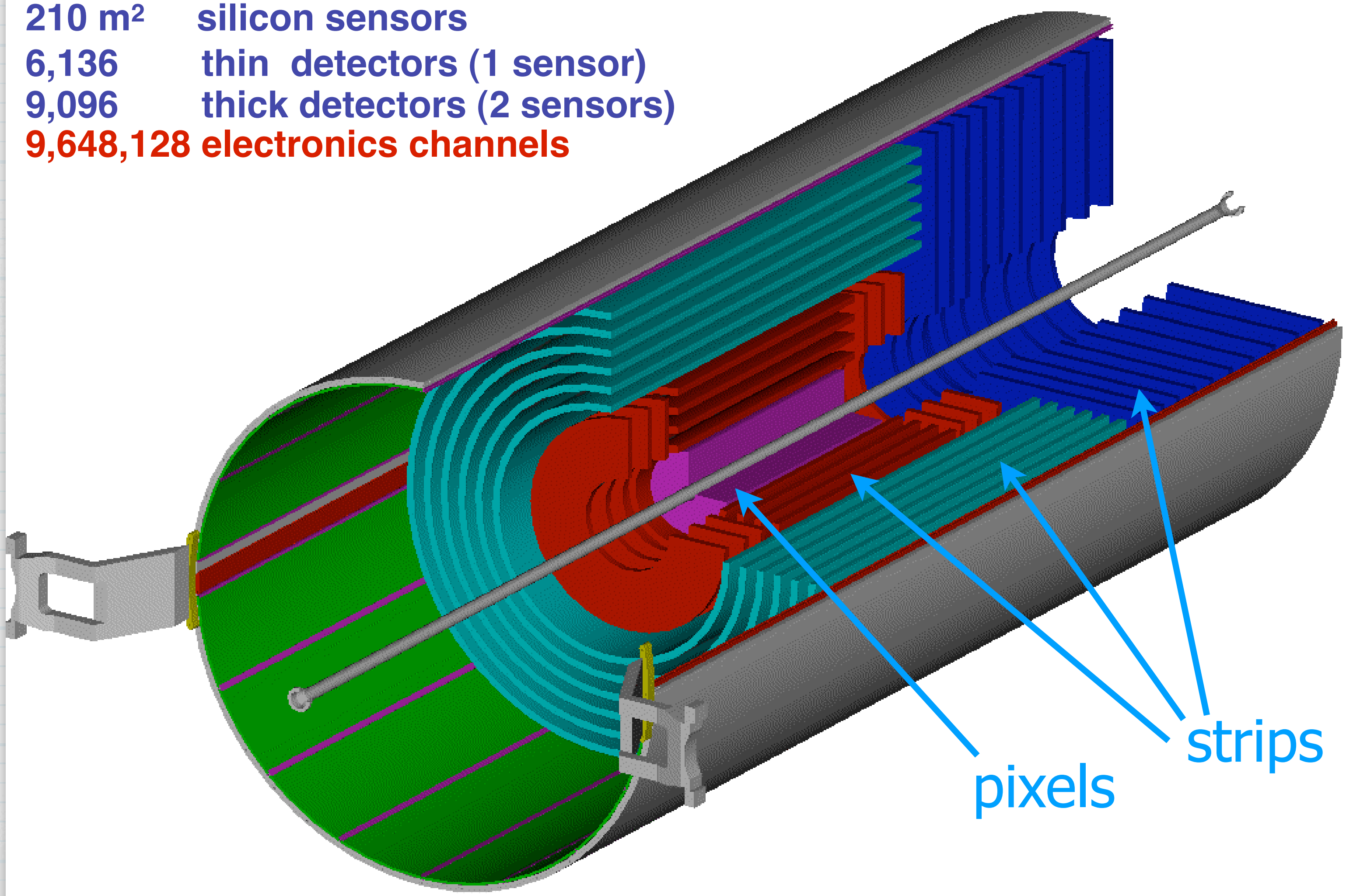
CMS slice



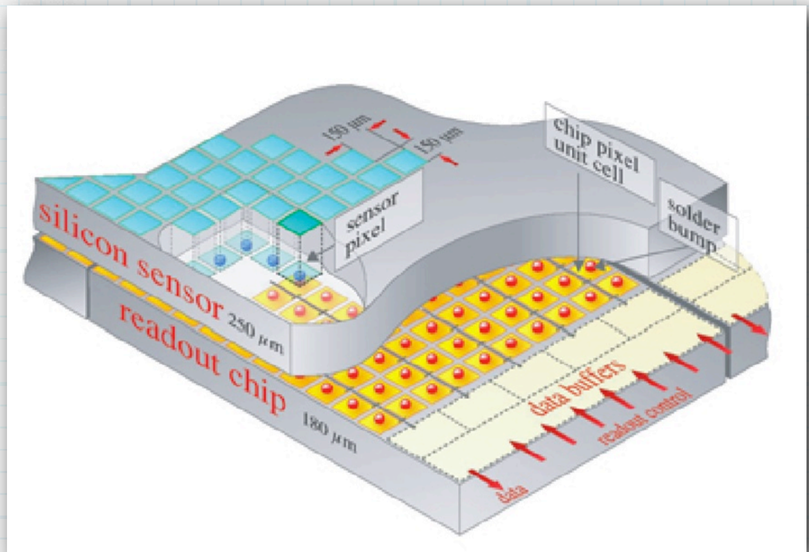
0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Hadron (e.g. Pion)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS

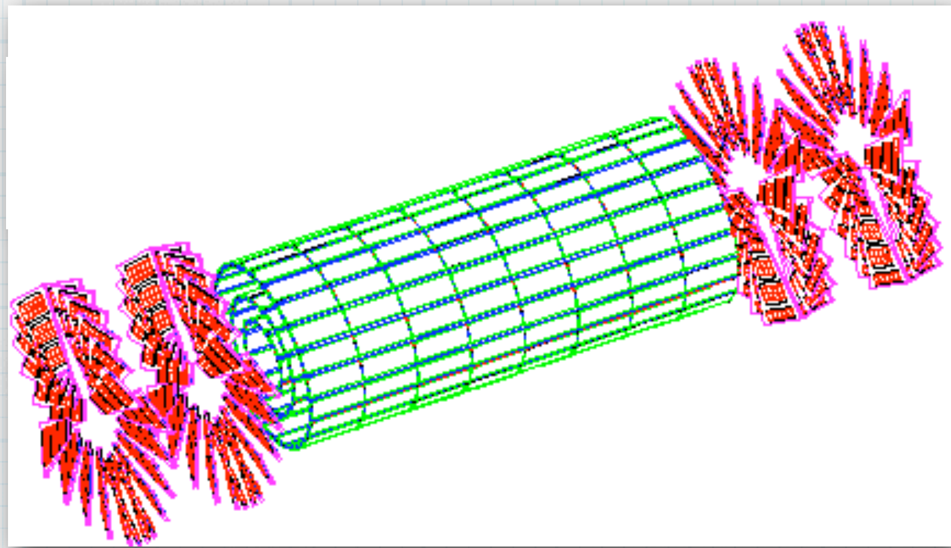
CMS Inner Detector

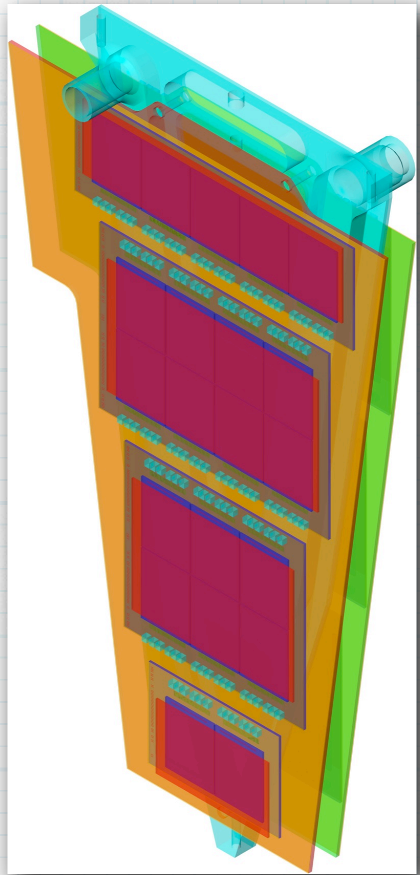
210 m² silicon sensors
6,136 thin detectors (1 sensor)
9,096 thick detectors (2 sensors)
9,648,128 electronics channels



CMS Pixel Detector

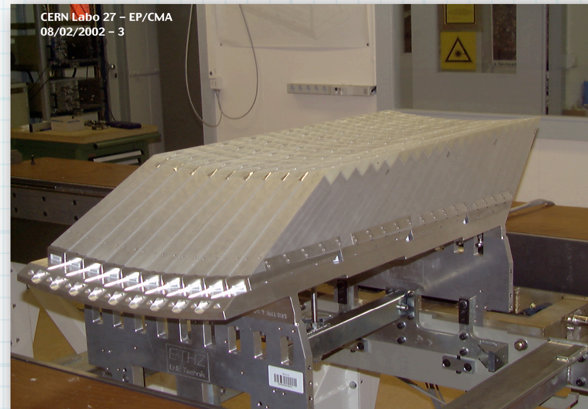


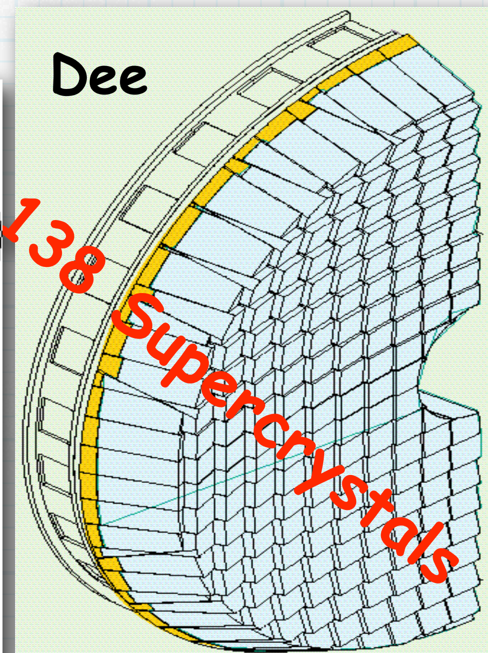




CMS Electromagnetic Calorimeter

- lead tungstate crystals
- projective geometry
- avalanche photodiode readout

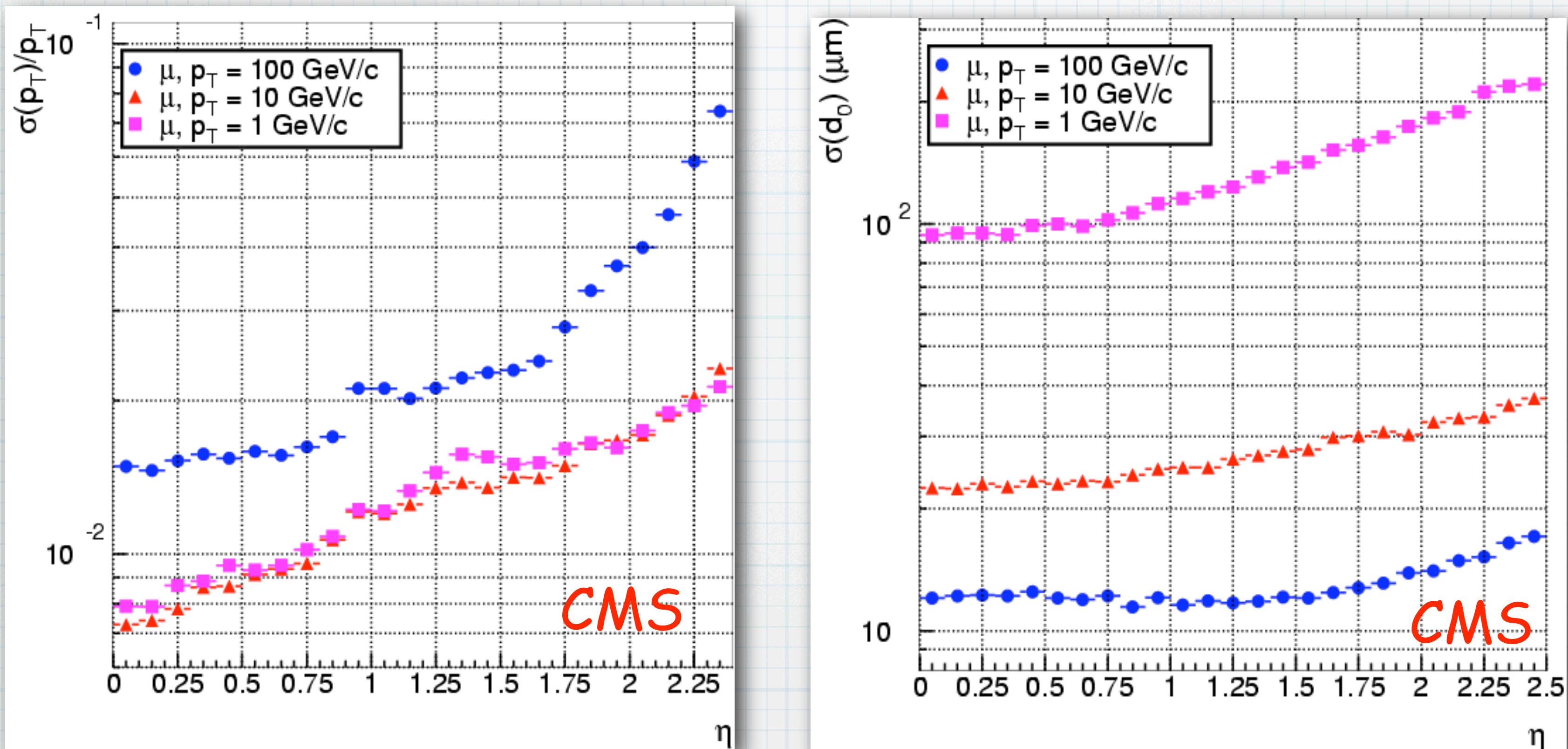




CMS Hadron Calorimeter

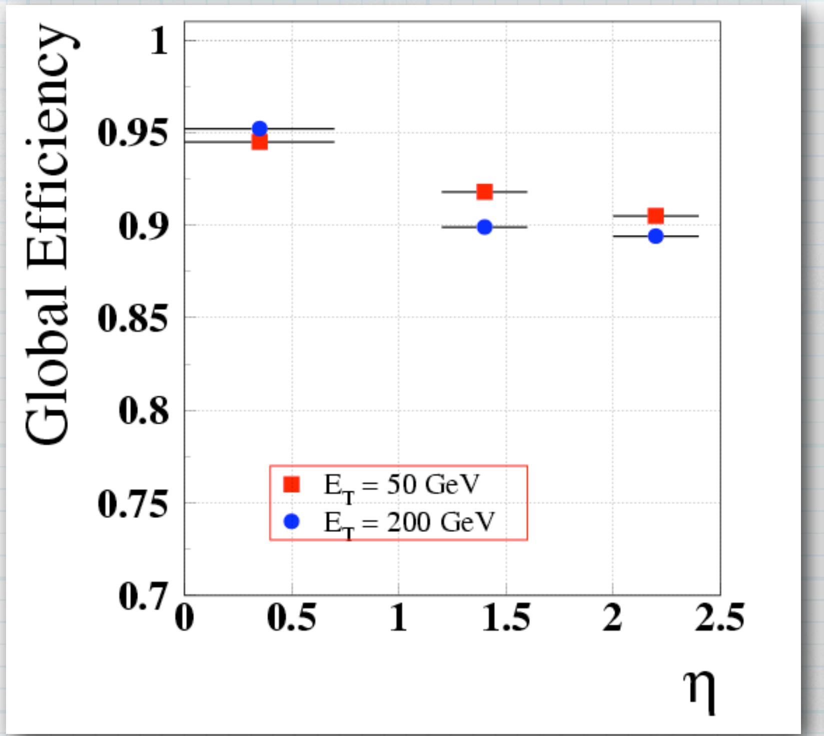
ATLAS/CMS Tracking

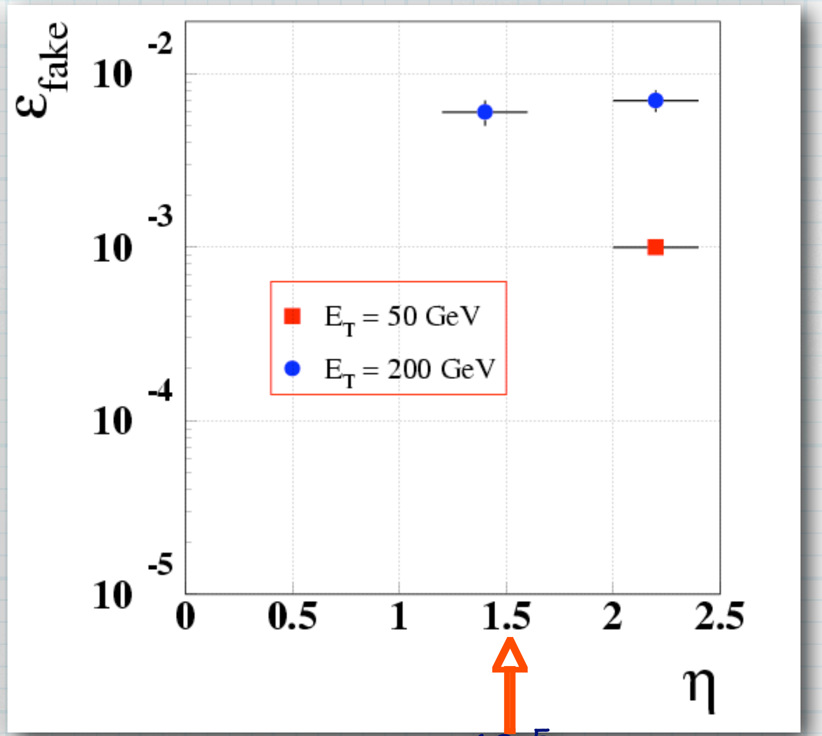
- this is for CMS, but ATLAS is very similar
- track resolution gets worse with pseudorapidity:



Tracking Efficiency/Fakes

- here again for CMS:



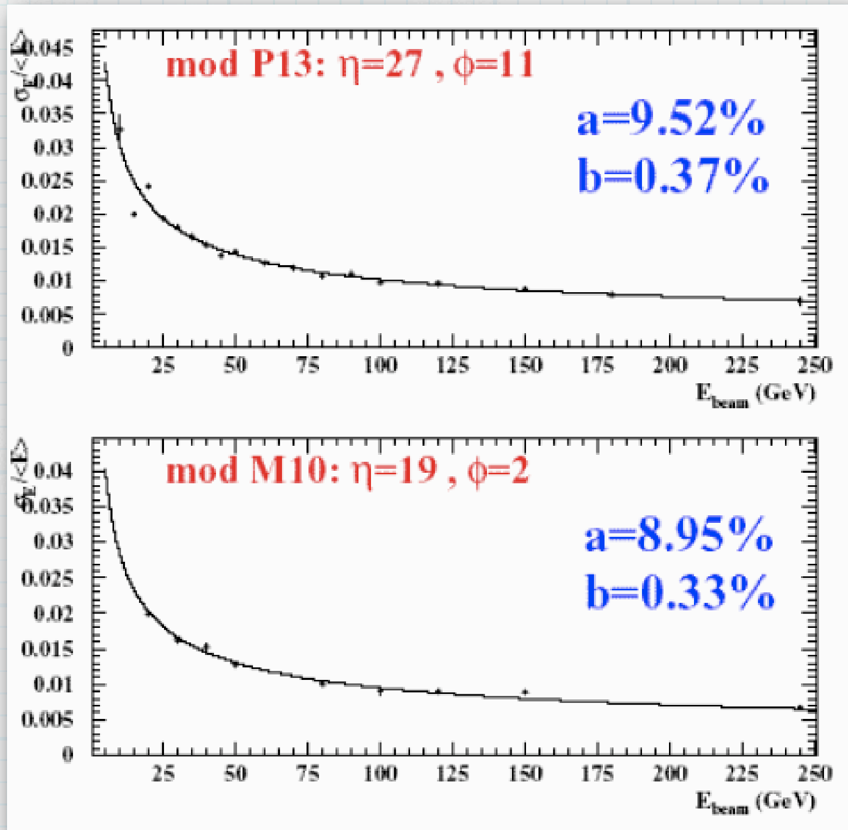


$<10^{-5}$

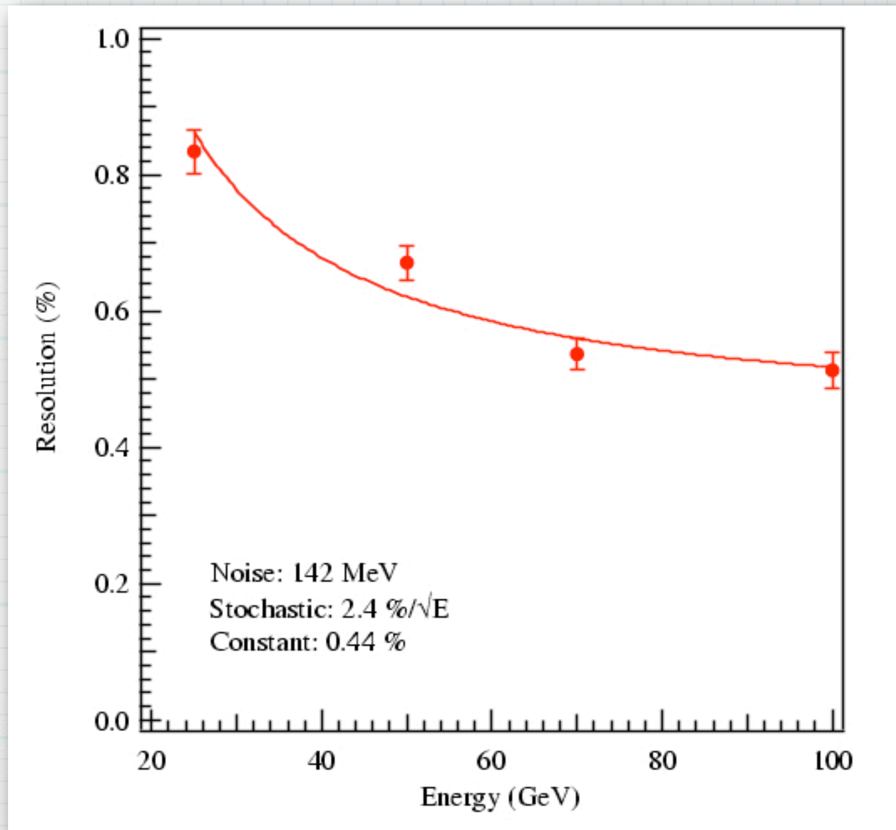
ET = 200 GeV Fake Rate < $8 * 10^{-3}$
ET = 50 GeV Fake Rate < 10^{-3}

ATLAS/CMS Calorimetry

ATLAS

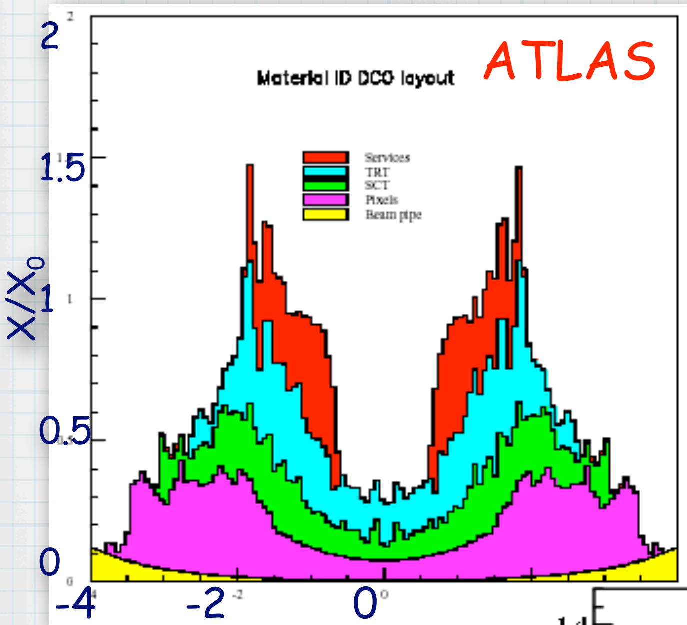


CMS

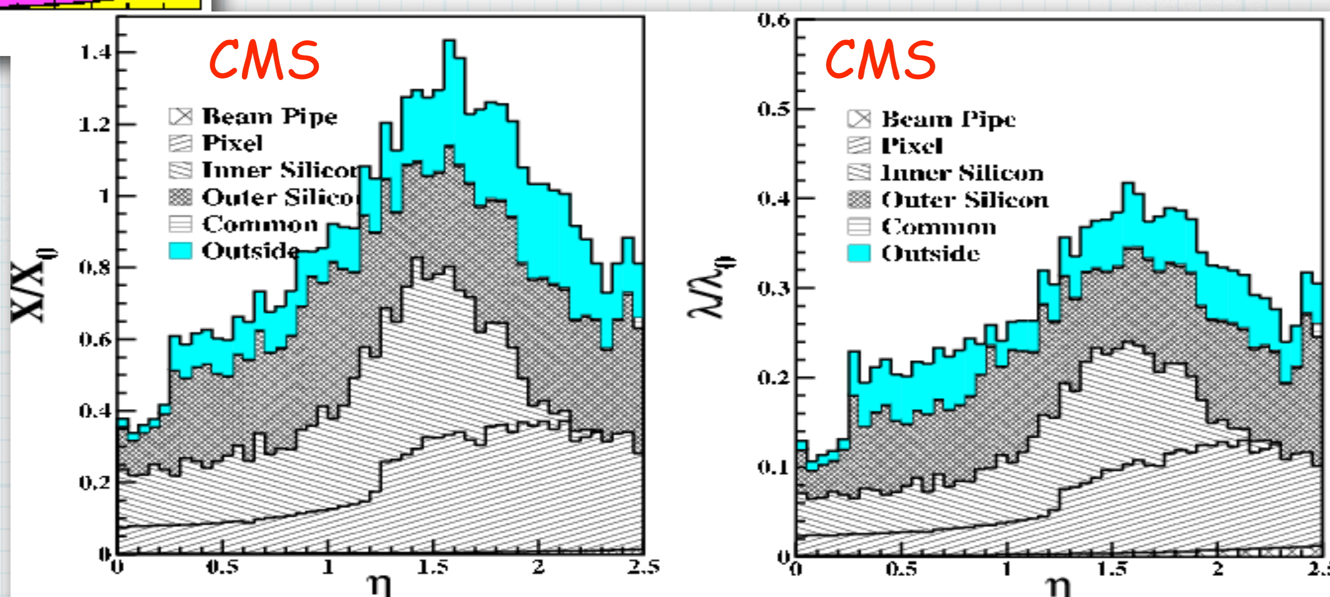


This is from test beams - does not tell the whole story!

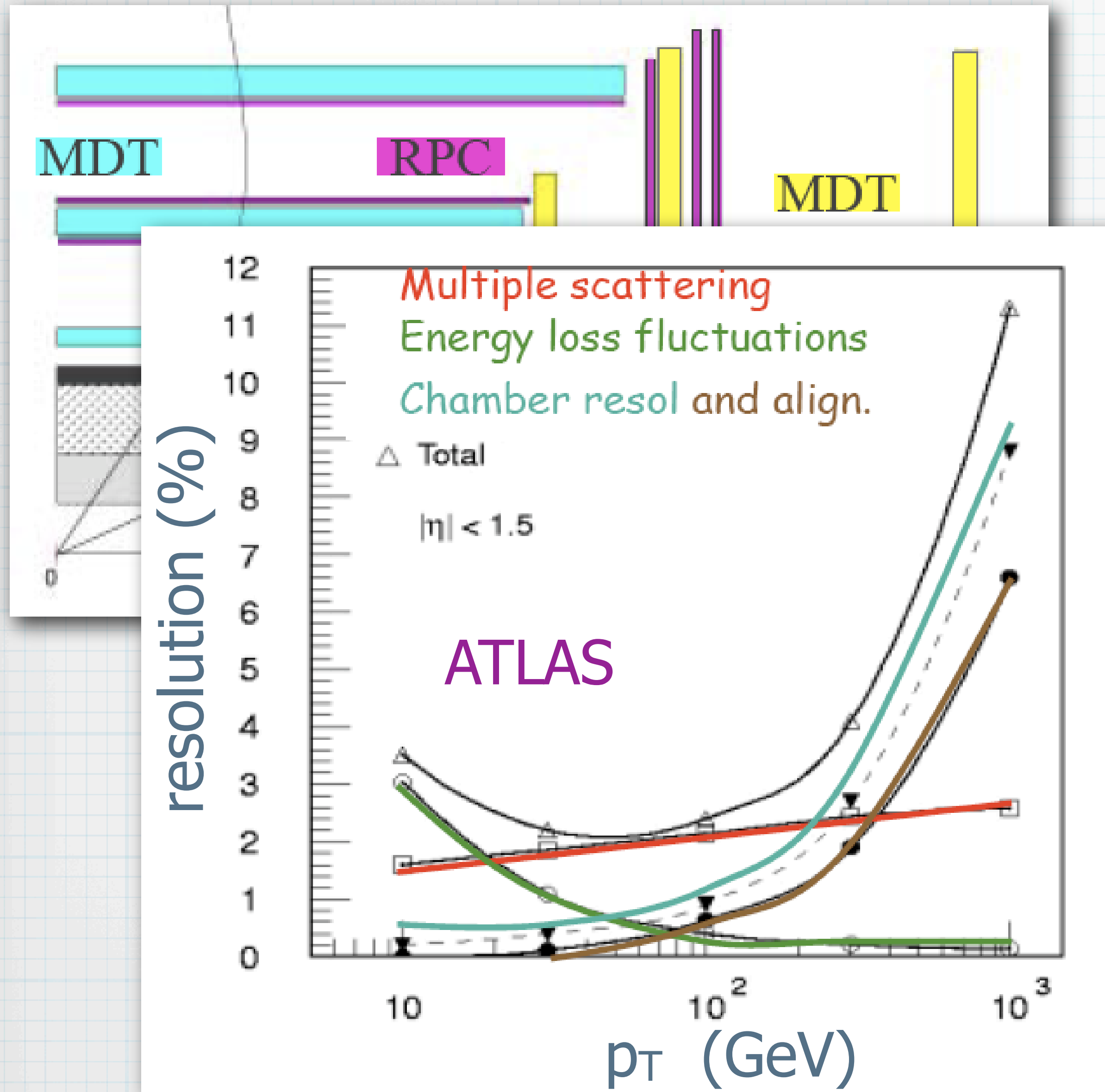
Material Budget

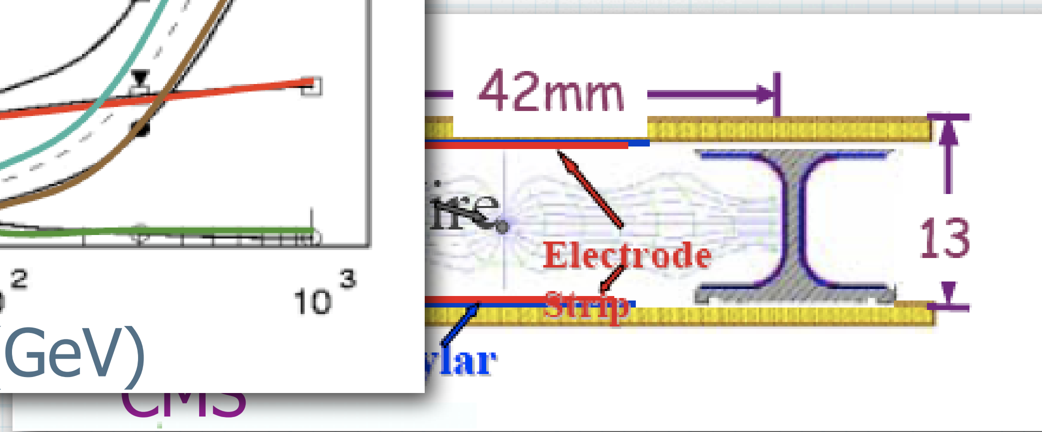


- degradation of calorimeter resolution due to bremsstrahlung and nucelar interactions
- high probability that photons convert in tracker



ATLAS/CMS Muons

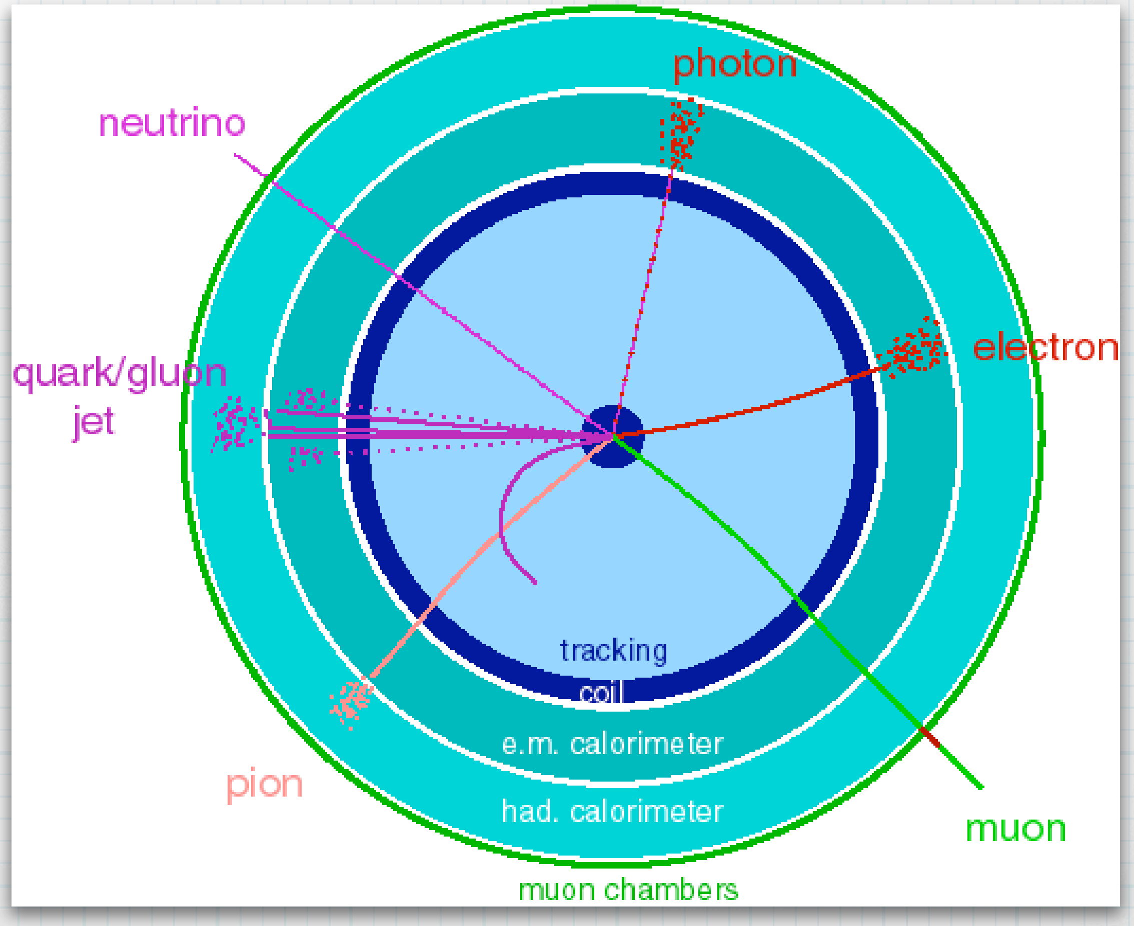




- Monitored Drift Tubes
- Resistive Plate Chambers
- Cathode Strip Chambers
- Thin Gap Chambers

Physics Object Reconstruction

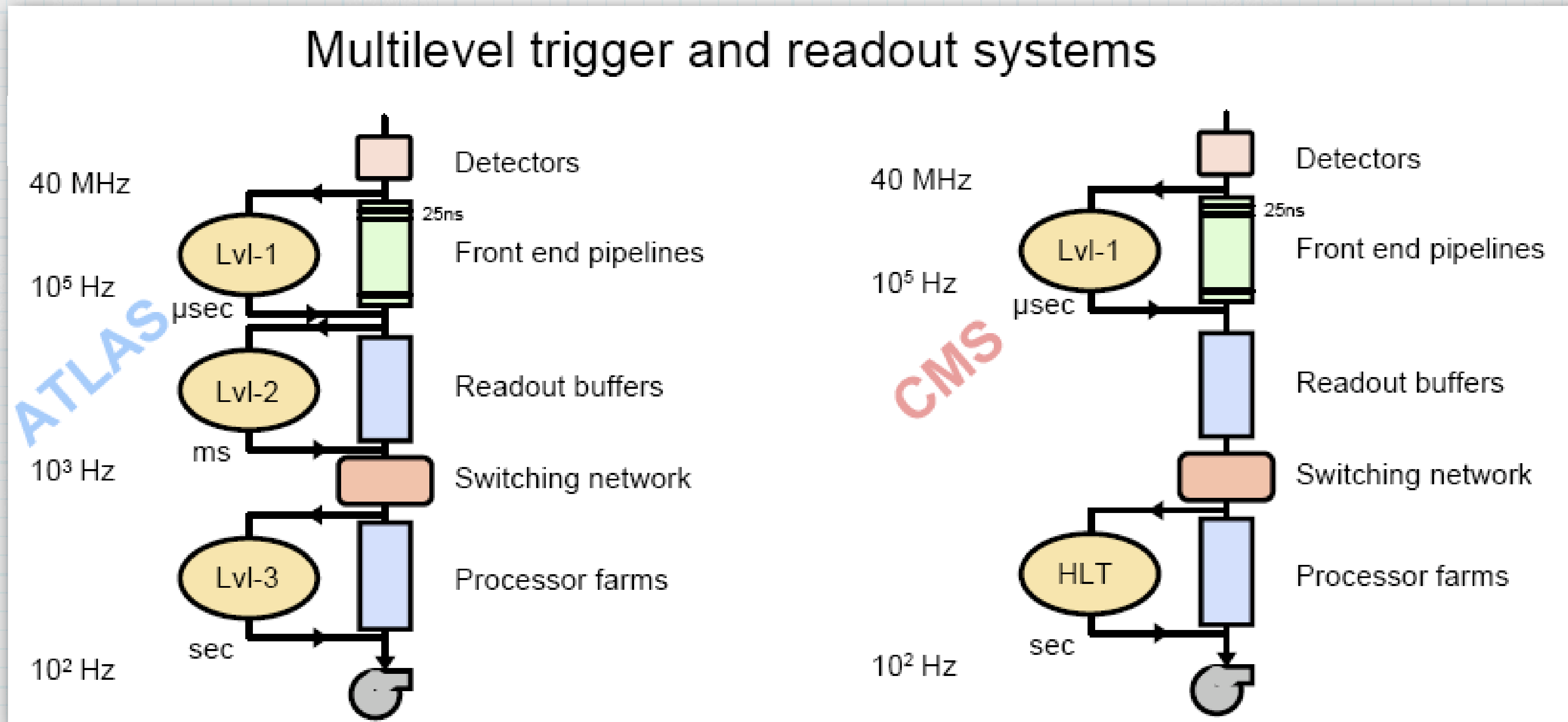
- need to use all the information from tracking, calorimetry, muon systems to identify
  - photons/electrons
  - muons
  - taus!
  - jets
  - b-tags
  - missing p_T



The Mystery of Triggering

- at the design rate, every beam crossing gives a collision (usually minimum bias)
- cannot read out detector on every event (1Mb/event)
- do not have bandwidth to store events
- cannot process every event later
- must have trigger to decide what to keep/reject
- trigger is very sophisticated and complicated!
- triggers are arranged in levels of increasing complexity, and decreasing rate

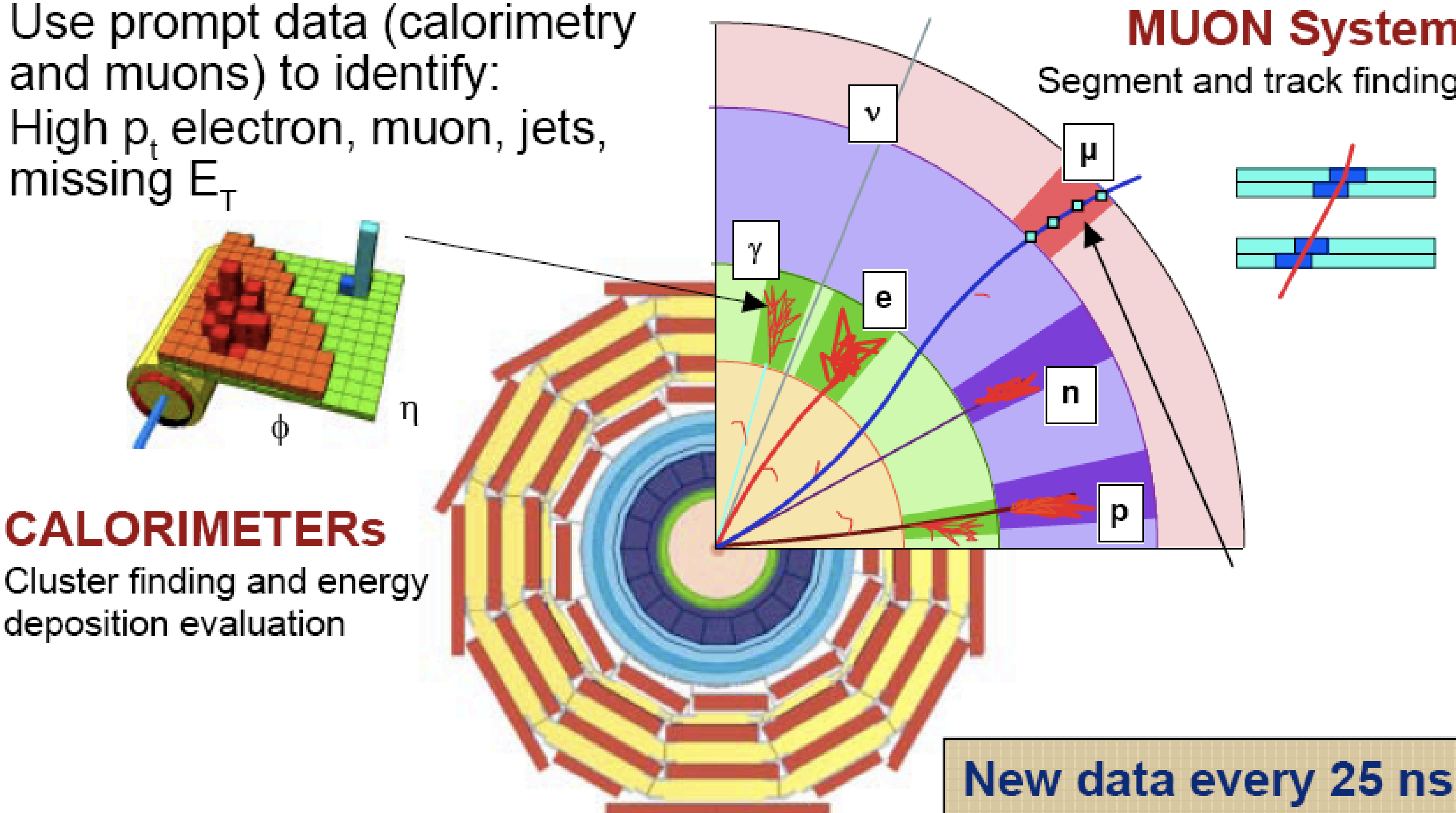
Trigger Rates



G. Rolandi - 3rd Workshop on Particle Physics - Islamabad, March 2004

CMS Level 1 Trigger

Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T



New data every 25 ns
Decision latency ~ μs

CMS L1 Thresholds

- need energy thresholds to control rates!

	e	ee	τ	ττ	j	jj	jjj	jjjj
Low $\mathcal{L}$	24	18	95	75	150	115	95	75
High $\mathcal{L}$	35	20	180	110	285	225	125	105
	τe	je	MET	e+MET	j+MET	e(NI)	ee(NI)	ΣET
Low $\mathcal{L}$	80,14	125,14	275	12,175	65,175	NA*	NA*	1000
High $\mathcal{L}$	125,20	165,20	350	18,250	95,250	58	28	1500
	μ	μμ	μe	μτ	μj	μ+ET	μ+MET	Rate:
Low $\mathcal{L}$	10	3	4,12	4,80	4,80	4,600	4,140	25 kHz
High $\mathcal{L}$	25	8,5	5,32	5,140	5,155	5,800	5,200	25 kHz

ATLAS L1 Thresholds

Selection	High-p_T Thresholds	2×10^{33} $cm^{-2}s^{-1}$	10^{34} $cm^{-2}s^{-1}$
MU20	(20)	0.8	4.0
2MU6		0.2	1.0
EM25I	(30)	12.0	22.0
2EM15I	(20)	4.0	5.0
J200	(290)	0.2	0.2
3J90	(130)	0.2	0.2
4J65	(90)	0.2	0.2
J60 + xE60	(100+100)	0.4	0.5
TAU25 + xE30	(60+60)	2.0	1.0
MU10 + EM15I		0.1	0.4
Others (pre-scales, calibration, ?)		5.0	5.0
Total		~ 25	~ 40

Analyzing the Data

- calibration/alignment studies
  - offline corrections
    - cal clusters → jets, electrons, etc.
    - tracker hit clusters → track segments →tracks
      - high level objects: e/γ, μ, τ, jets, ...
- perform primary reconstruction
- split into data streams
- distribute to computing centers for selection
- lather, rinse, and repeat...