LHC Detectors and Early Physics

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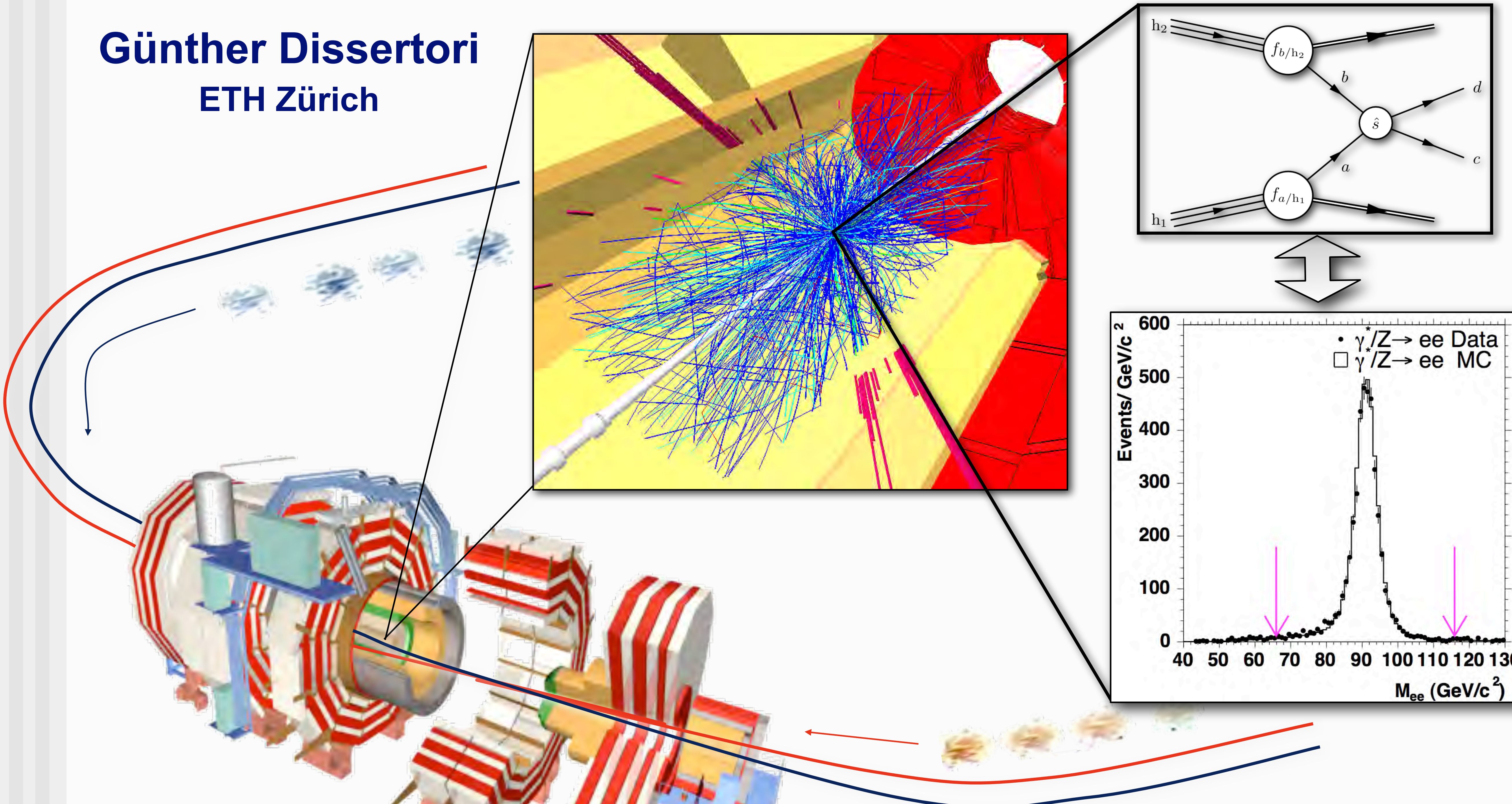
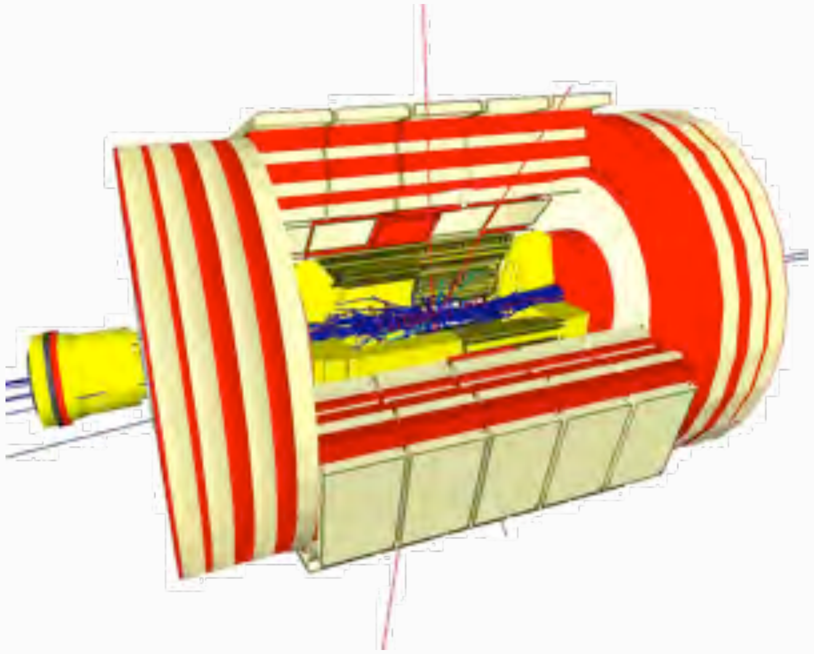


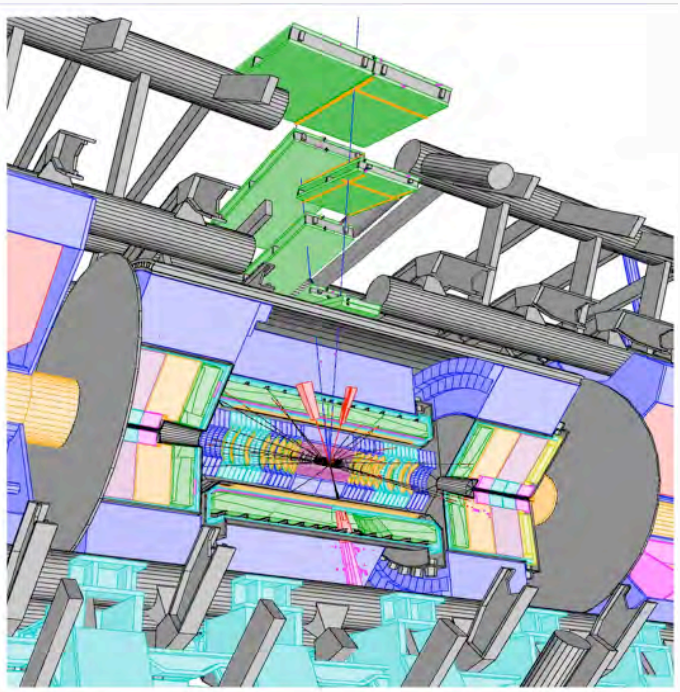
PART 1

Outline Part 1

- What is measured, how and why?
  - Basic processes, rates
  - Resulting difficulties and requirements
  - How to design your detector



- ATLAS and CMS
  - Overview
  - Comparison
  - Achieved performance, current commissioning

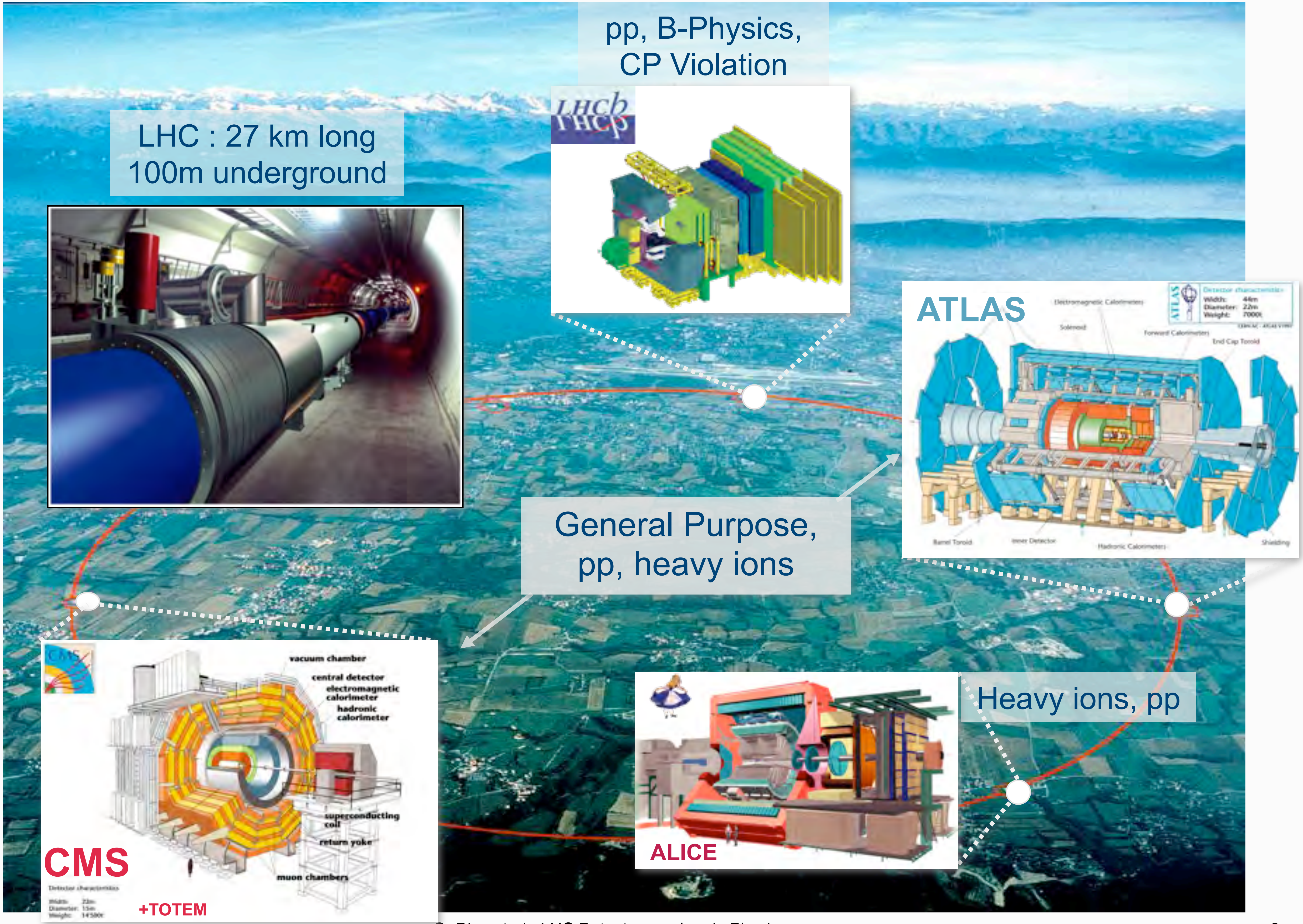


Disclaimer 1 : I concentrate on multi-purpose detectors ATLAS and CMS
and high-p_T physics.
Some bias towards CMS, for practical reasons only ;-)
Nothing on LHCb and ALICE....

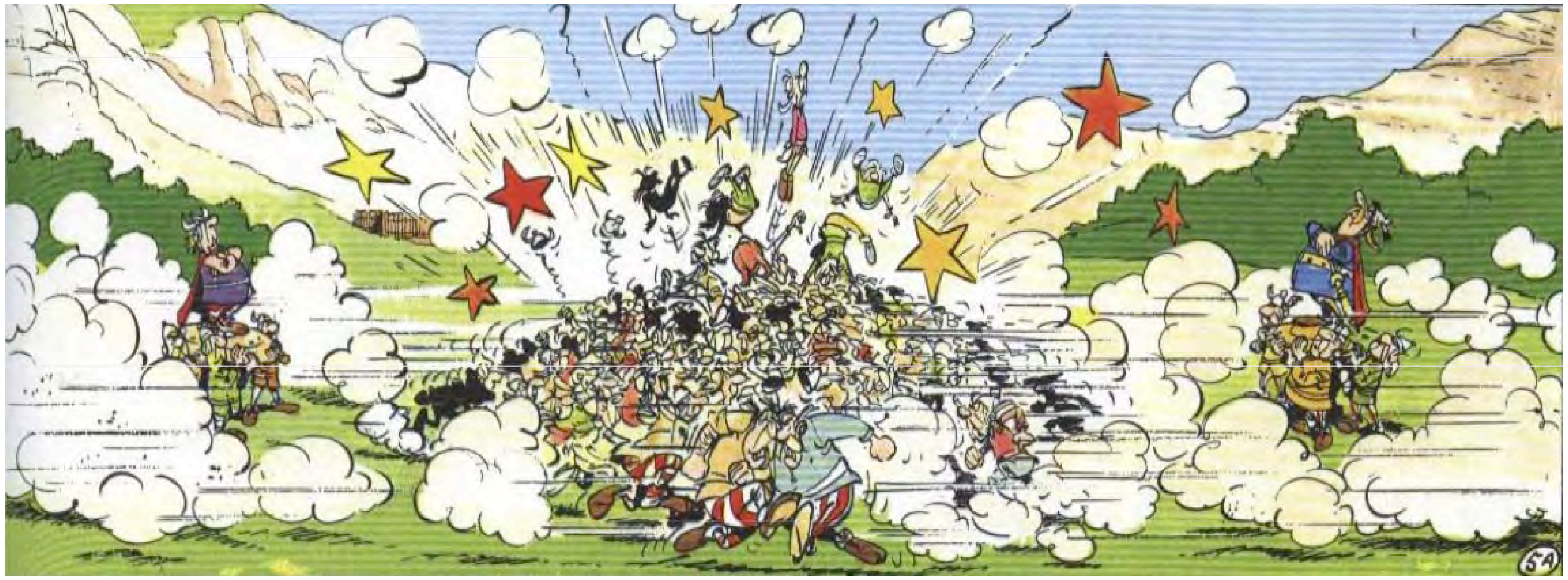
Disclaimer 2 : Some slides or slide content taken from seminars/lectures/write-ups of other LHC colleagues,
eg. K. Jakobs, O. Buchmüller, L. Dixon, M. Dittmar, D. Froidevaux, F. Gianotti, D. Green, J. Virdee, ...

Excellent resource : D. Froidevaux, P. Sphicas, Annu.Rev.Nucl.Part.Sci. 2006 56:375-440

Our future play ground

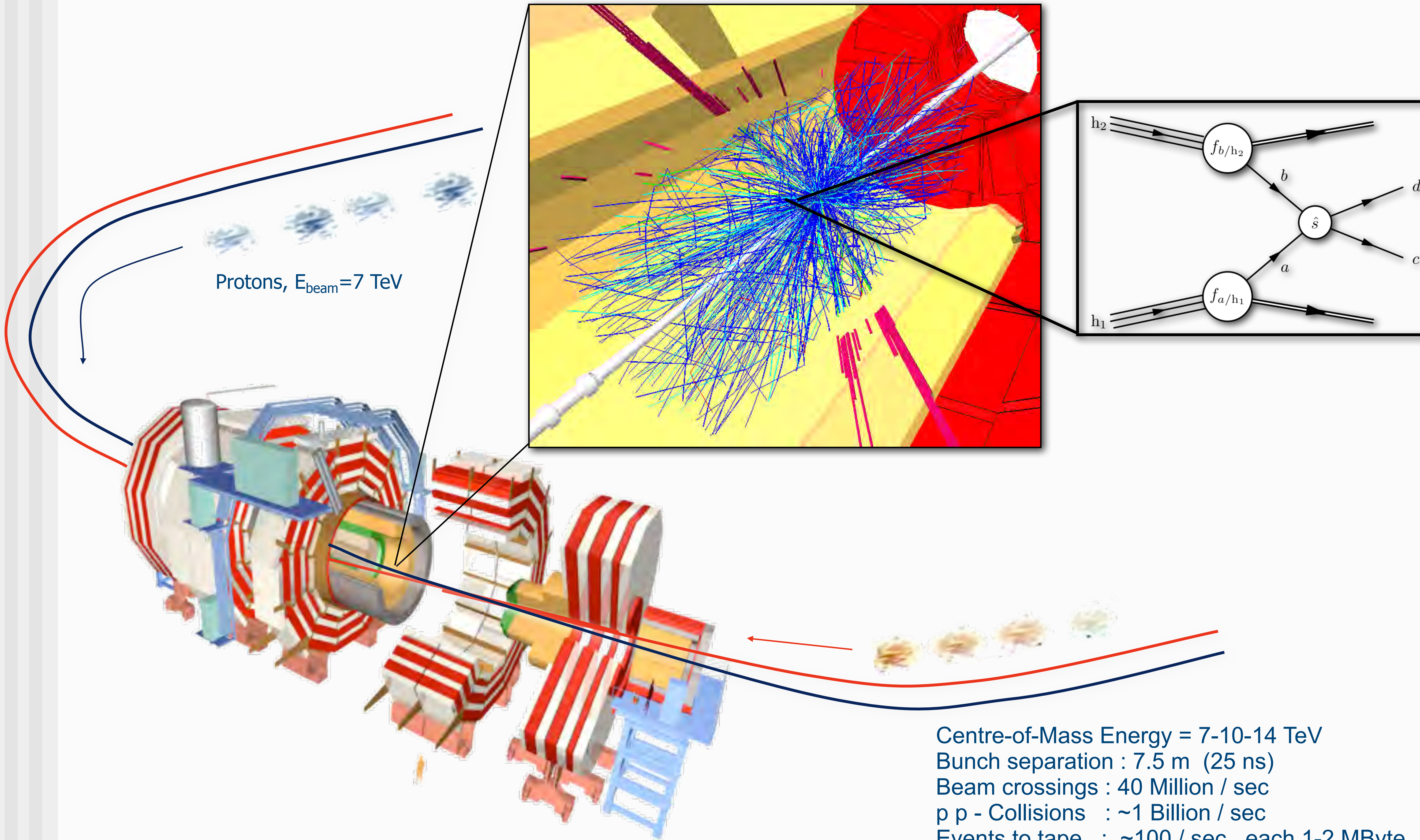


The experiments: What is measured, why and how?



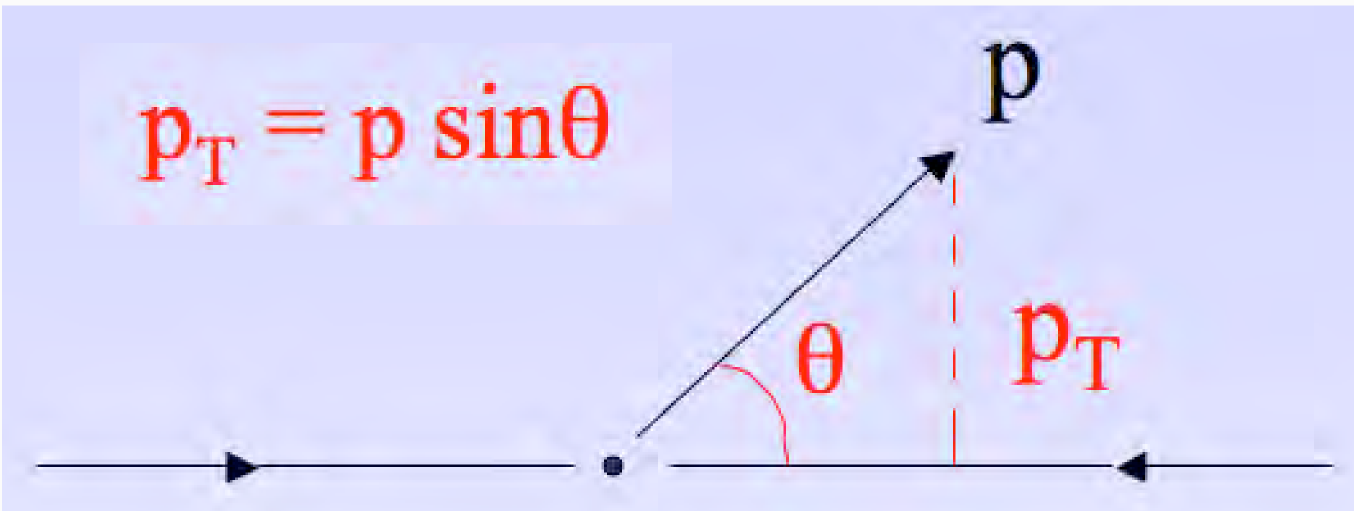
proton - proton collisions are complex....

Collisions at the LHC



Centre-of-Mass Energy = 7-10-14 TeV
Bunch separation : 7.5 m (25 ns)
Beam crossings : 40 Million / sec
p p - Collisions : ~1 Billion / sec
Events to tape : ~100 / sec, each 1-2 MByte

Variables used in pp collisions

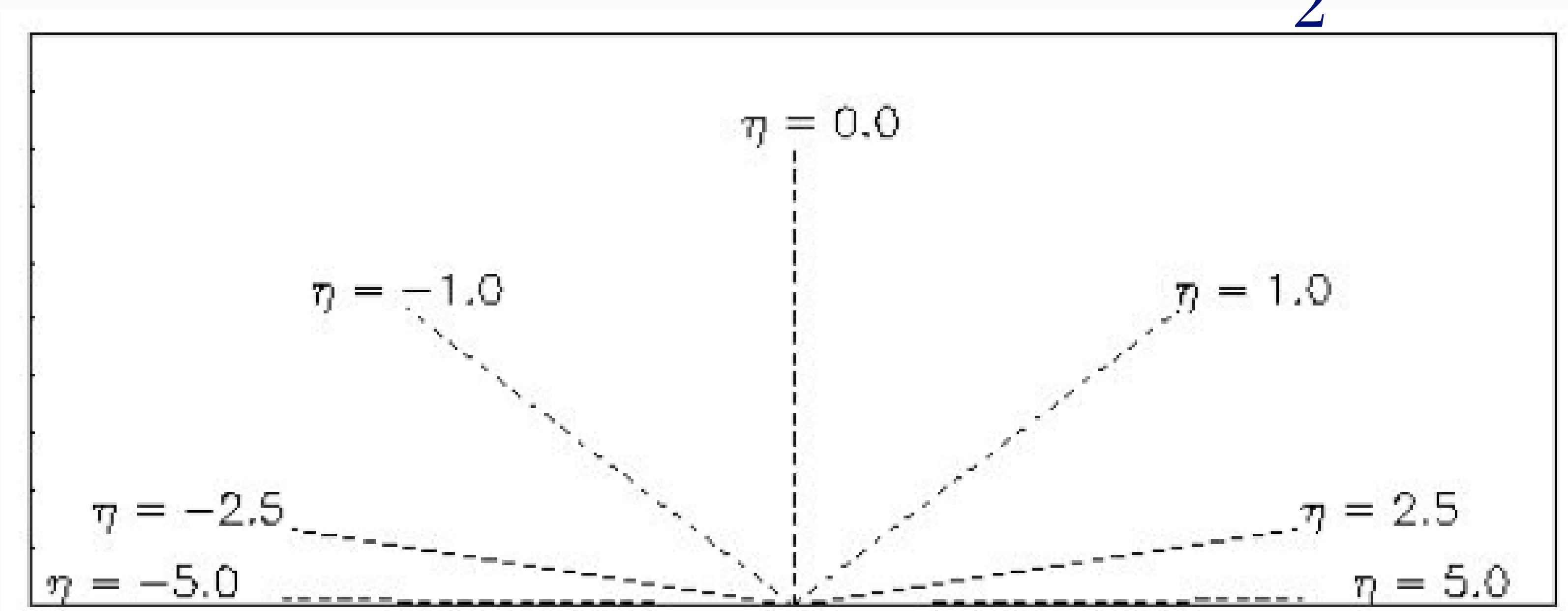


Transverse momentum

(in the plane perpendicular to the beam)

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

(Pseudo)-Rapidity $\eta = -\ln\tan\frac{\theta}{2}$



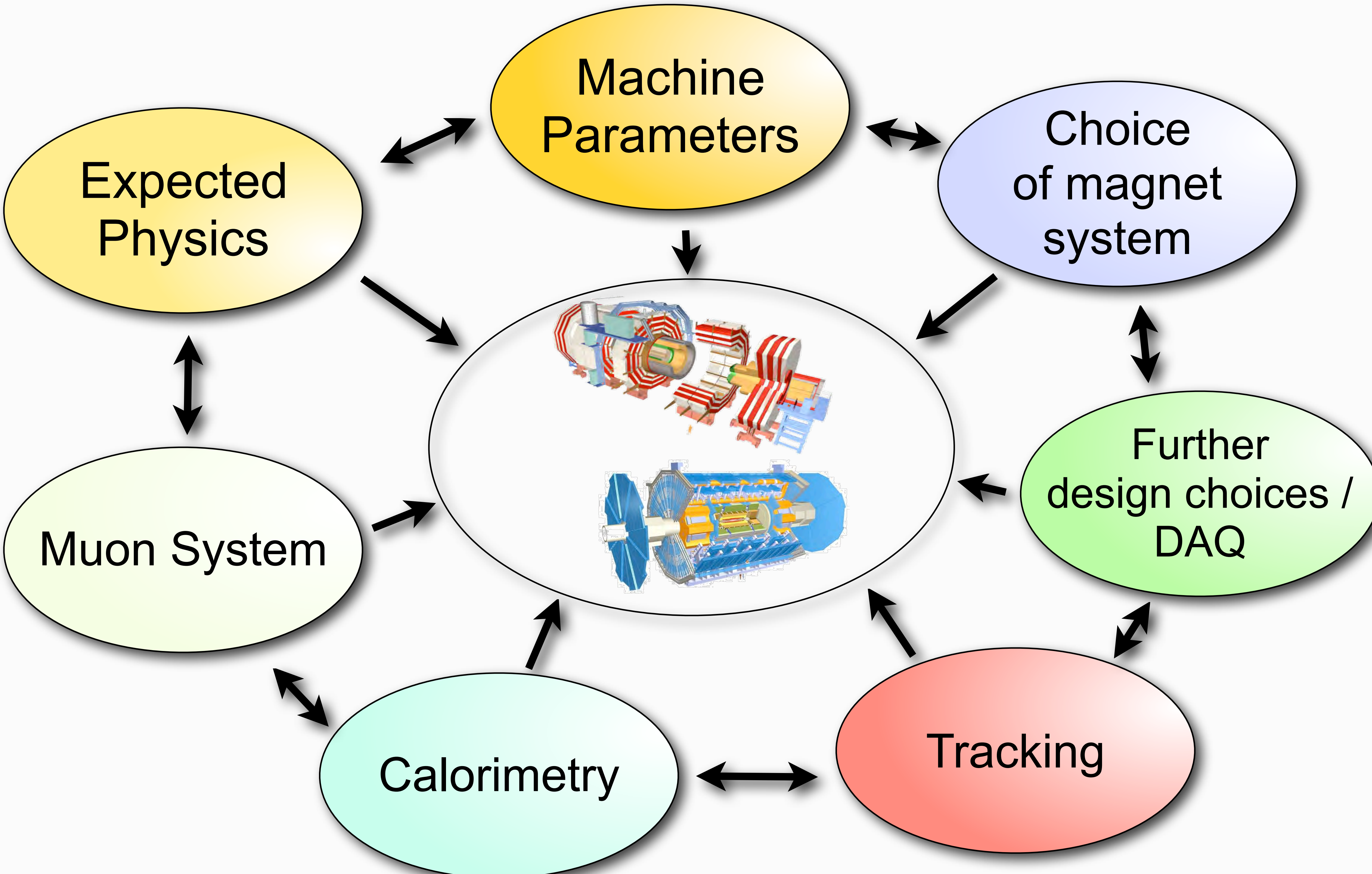
$\theta = 90^\circ \rightarrow \eta = 0$

$\theta = 10^\circ \rightarrow \eta \cong 2.4$

$\theta = 170^\circ \rightarrow \eta \cong -2.4$

$\theta = 1^\circ \rightarrow \eta \cong 5.0$

How to design your detector

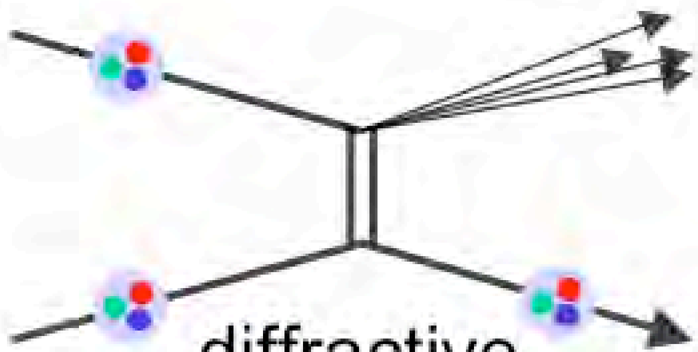


Note : all numbers in the following are orders of magnitude!

pp-Interactions at the LHC

σ_{tot} =

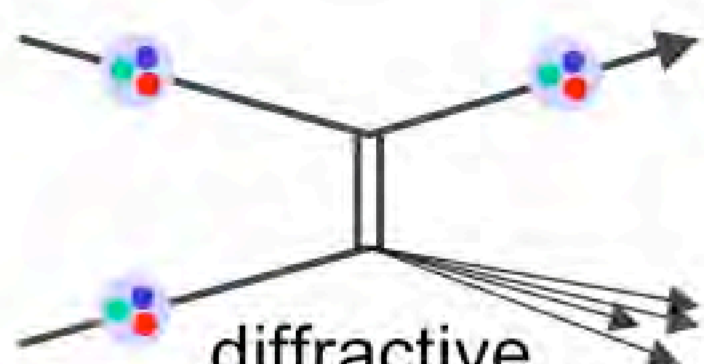
≈100mb



diffractive

≈10mb

+



diffractive

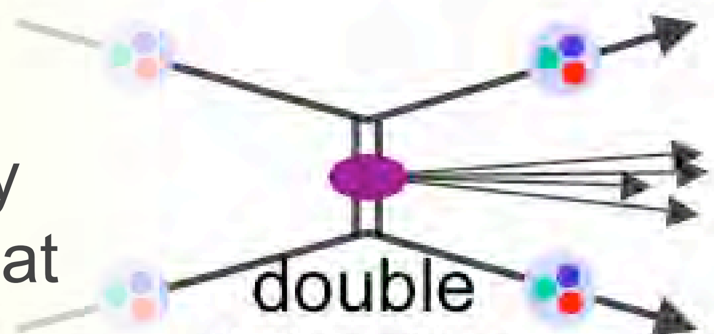
≈10mb

+

For diffractive and elastic scattering:

Put dedicated very forward detectors at small angles,

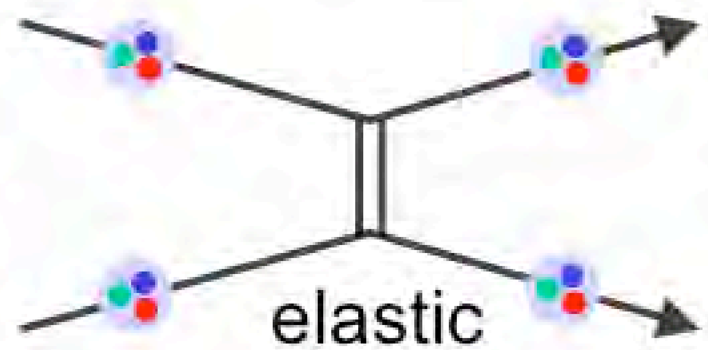
ie. very close to beam pipe



double diffractive

≈"small"

+



elastic

≈10mb

+

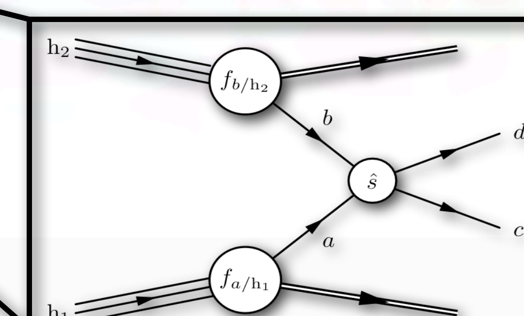
C. Schwick

non-diffractive

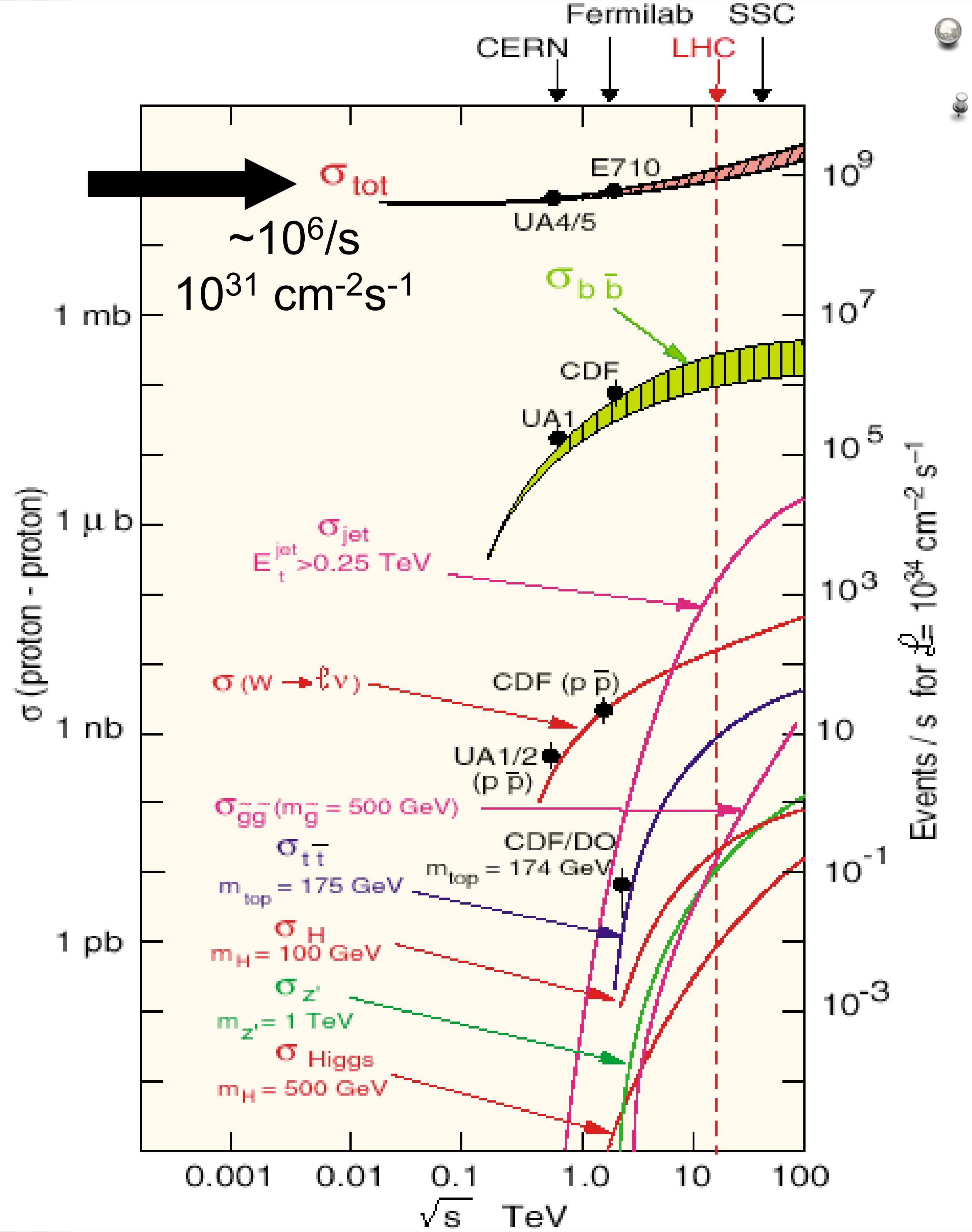
inelastic

≈70mb

Interesting Physics

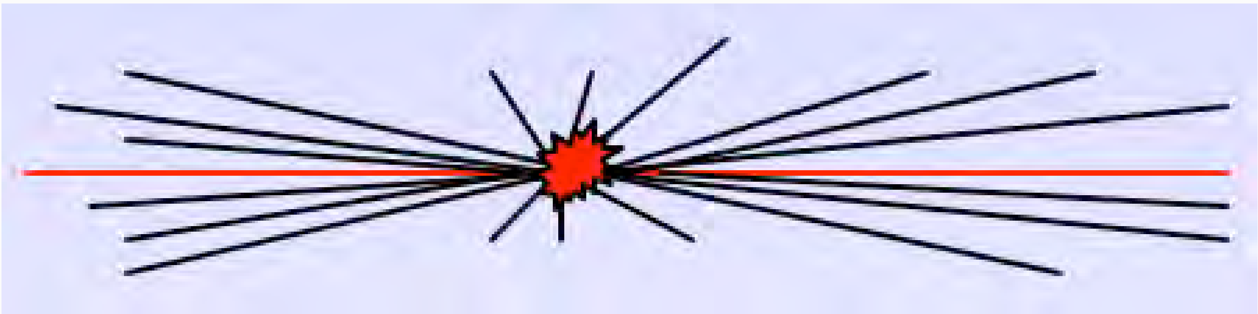


Expected Physics : 1



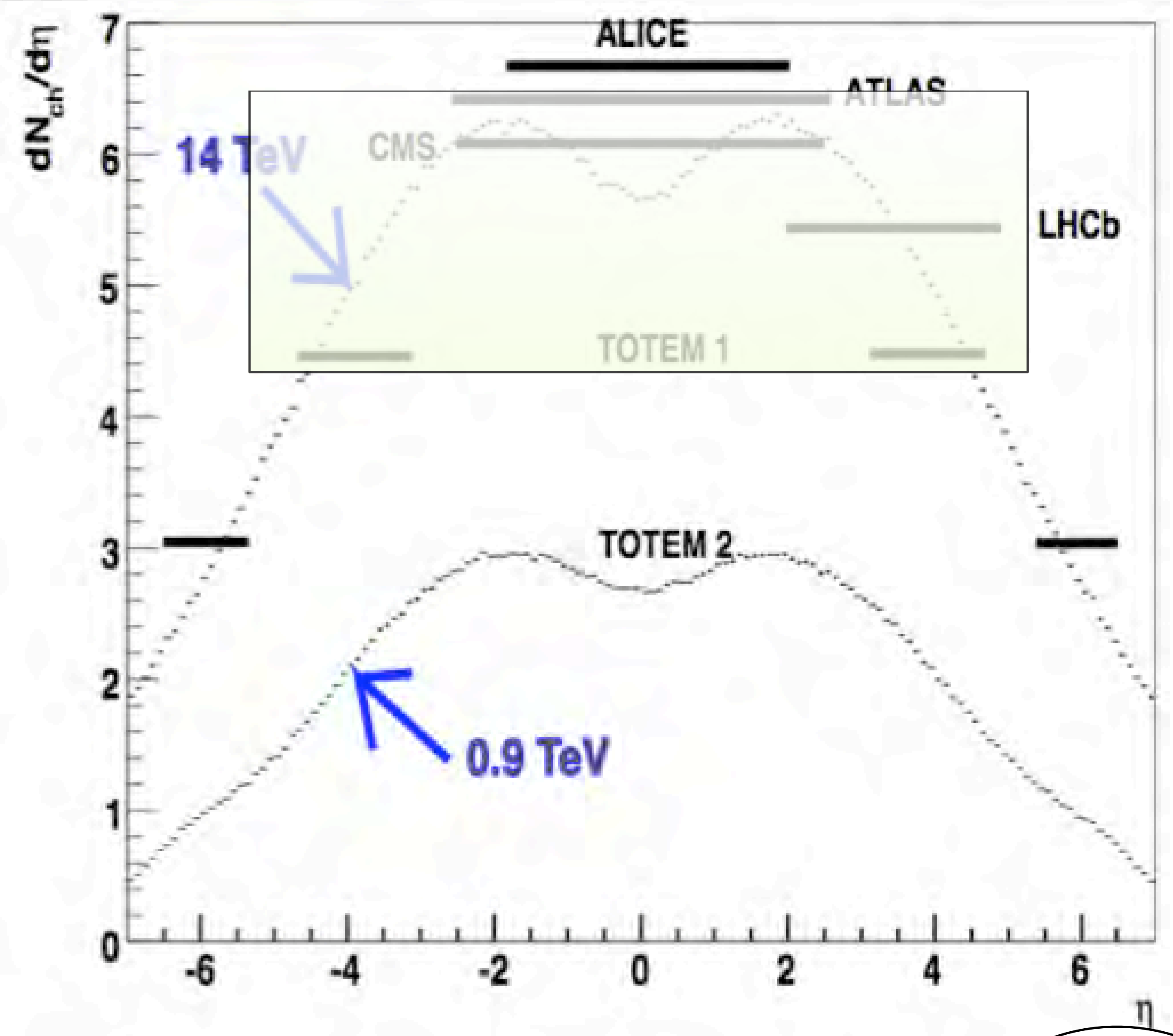
- Inelastic low-p_T pp collisions
  - Most processes are due to interactions at large distance between incoming protons
    - particles in the final state have large longitudinal, but small transverse momentum -> small momentum transfer

$$\langle p_T \rangle \approx 800\,\mathrm{MeV}$$



Low-p_T inelastic pp-collisions:
"Minimum Bias events"
Parameters (multiplicity etc) poorly known!
(~50% or worse)
Important for tuning MC simulations

Particle Distributions



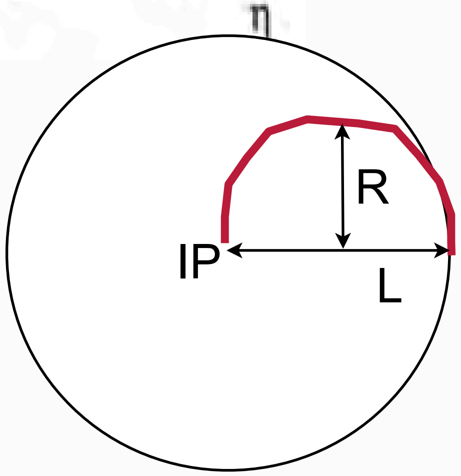
$$\frac{d^3p}{2E} = \frac{\pi}{2}\, dp_T^2\, dy$$

- for low-mass particles (eg. pions) : "flat" in (pseudo)-rapidity
- in order to collect most of them (also to ensure hermeticity, eg. for E_{Tmiss}): need detector up to $y_{\max} \approx 5$
- particle density: ~ 4 - 6 charged particles (pions) plus ~ 2 - 3 neutrals (π^0) per unit of pseudorapidity in the central detector region
- uniformly distributed in φ

$$\langle p_T \rangle \approx 800\,\mathrm{MeV}$$

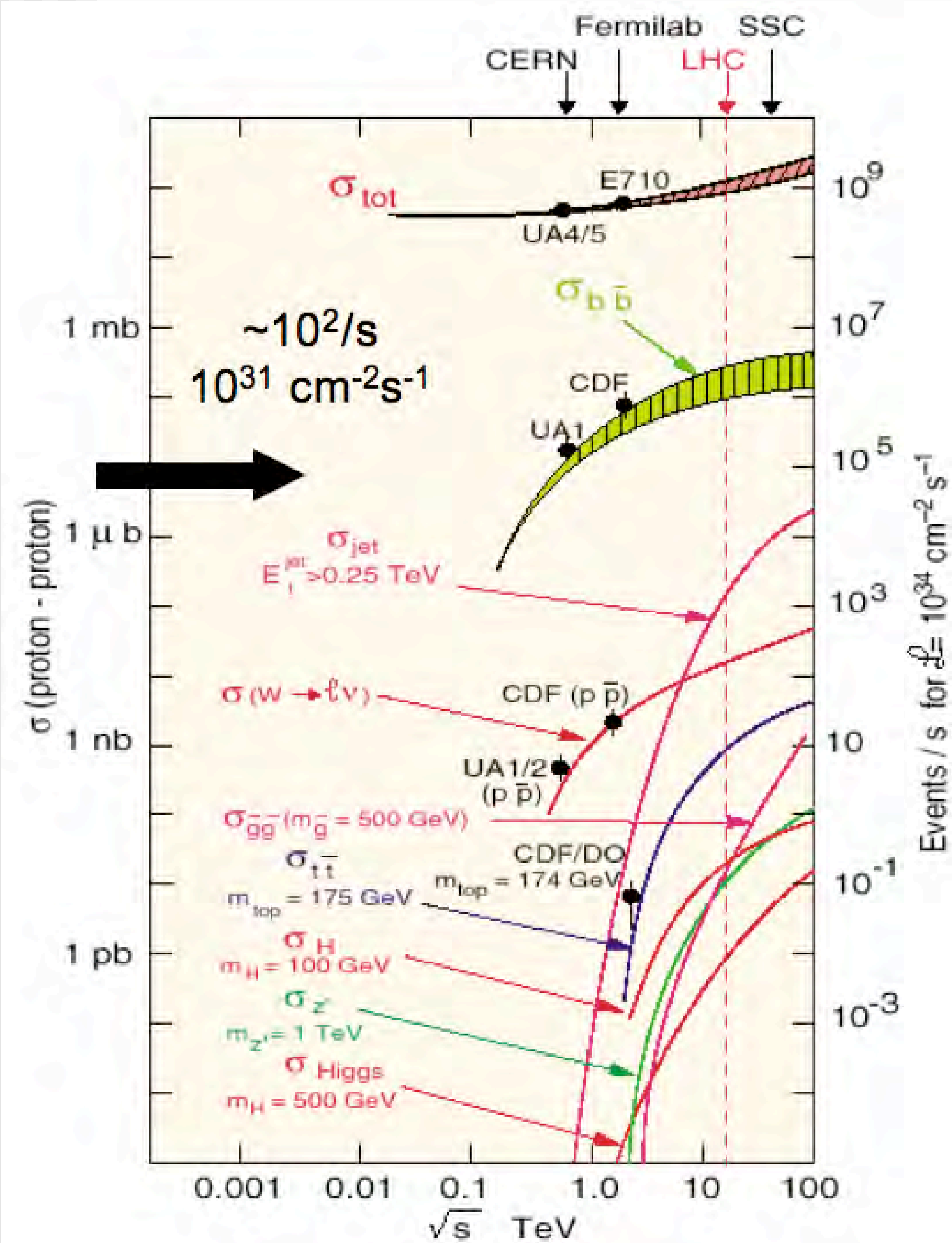
$$p[\mathrm{GeV}] = 0.3\, R[\mathrm{m}]\, B[\mathrm{T}]$$

$$\Longrightarrow L \leq 2\,R\; = \frac{p}{0.15\,B}$$

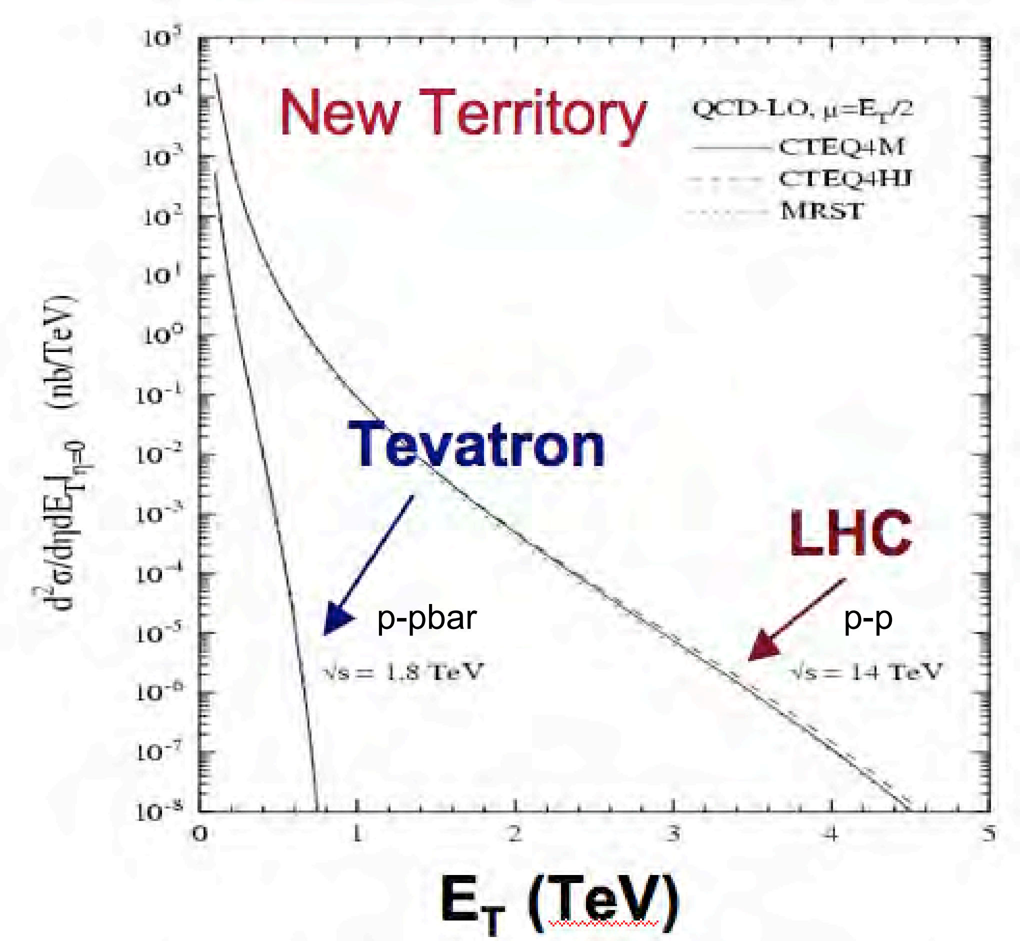


- to avoid too many "curling" tracks which do not reach the calorimeter: tracker/calo boundary at about L ~ 1.2m for B = 4T

Expected Physics : 2

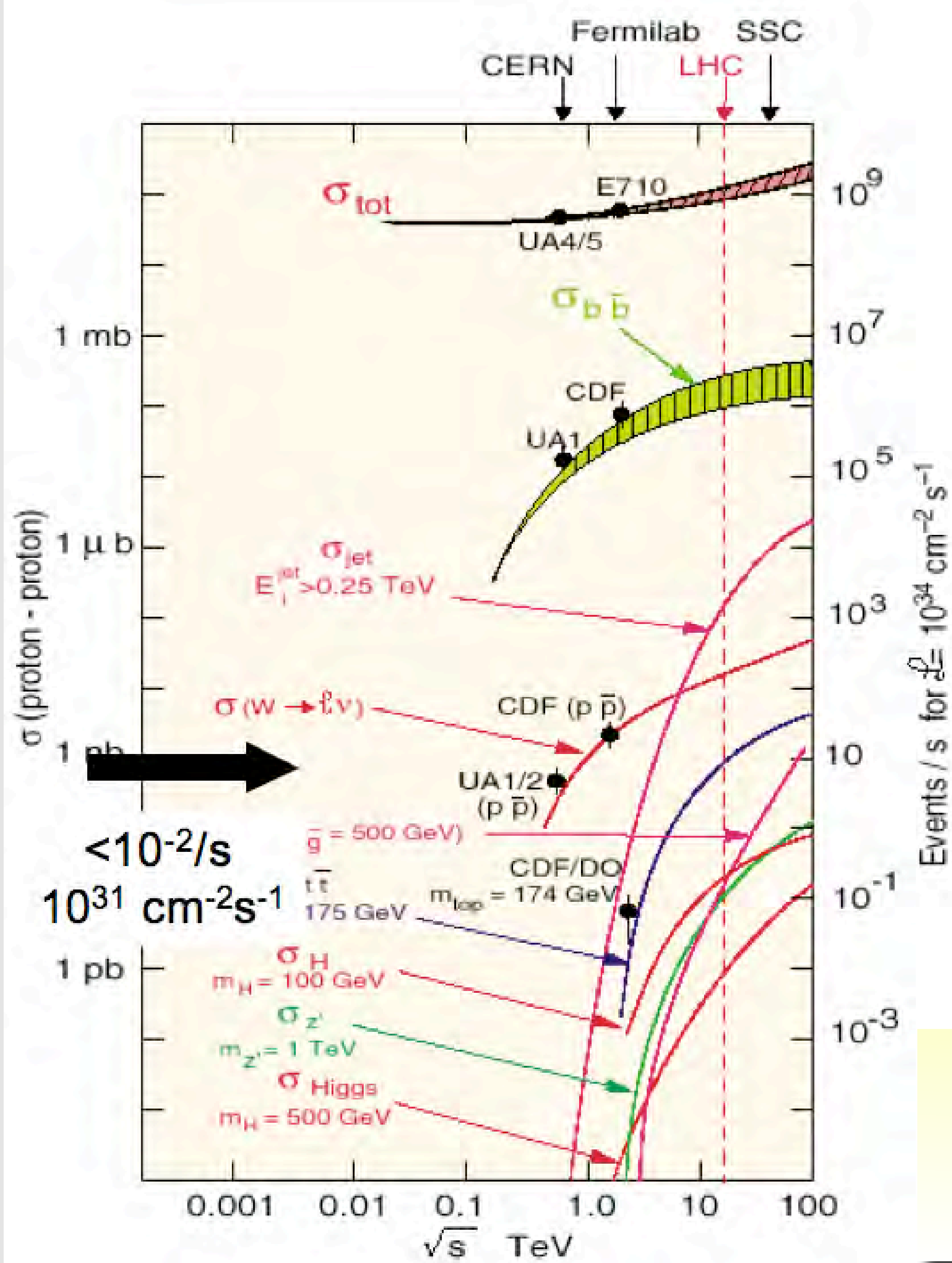


- Measure Jet cross sections
  - E_T^{Jet} > 500 GeV after a few weeks at startup
  - Going fast beyond the TEVATRON reach
    - early sensitivity to compositiness



- requires good understanding of jets (algorithms, production, jet energy scale), PDFs, pile-up, underlying event, ...
- Thus : good calorimetry!!

Expected Physics : 3



The Electroweak Sector

- test (re-establish the SM) and then go beyond
- most SM cross sections are significantly higher than at the TEVATRON
  - eg. 100x larger top-pair production cross section
  - the LHC is a top, b, W, Z, ..., Higgs, ... factory

Rates for L = 10^{31} cm^{-2} s^{-1}: (LHC)

• Inelastic proton-proton reactions:	10^6 / s
• bb pairs	5 10^3 / s
• tt pairs	0.01 / s
• W → e ν	0.15 / s
• Z → e e	0.015 / s
• **Higgs (150 GeV)**	**0.0002 / s**
• **Gluino, Squarks (1 TeV)**	**0.00003 / s**

Important:
Concentrate on final states with high-p_T and isolated **leptons and photons** (+ jets)

Otherwise overwhelmed by QCD jet background!!

Benchmarks

- Some benchmark processes of the early days, which influenced certain design parameters:
  - Basic processes relevant for studying electro-weak symmetry breaking:

$$pp \to W^+ W^- \to \mu^+ \nu_\mu \mu^- \bar{\nu}_\mu$$

$$pp \to H \to ZZ \to \mu^+ \mu^- \mu^+ \mu^-$$

$$pp \to H \to ZZ \to \mu^+ \mu^- \nu_\mu \bar{\nu}_\mu$$

$$pp \to H \to \gamma\gamma$$

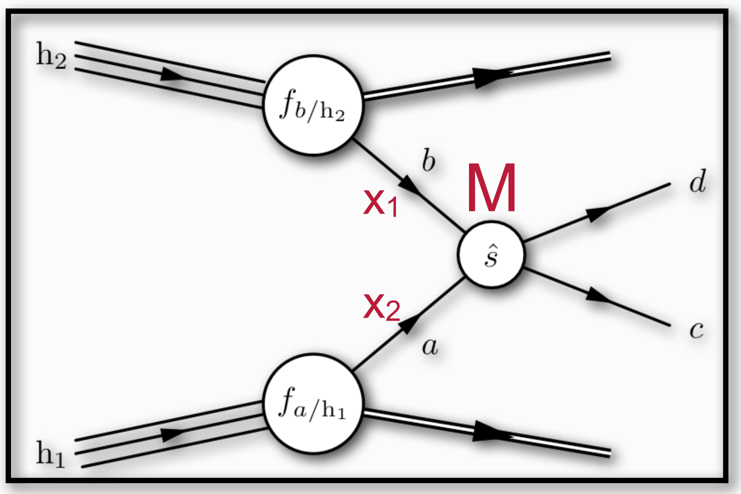
$$pp \to H \,\mathrm{jet\,jet} \quad (\mathrm{VBF})$$

$$pp \to Z' \to \mu^+ \mu^-$$

  - All cross sections (times BR) of order 1 - 100 fb : determines needed luminosities for sizeable statistics

Production of heavy states

- Heavy particles are produced “more centrally”
  - example: single heavy resonance (eg. Z’) of mass M, Energy E, rapidity y :

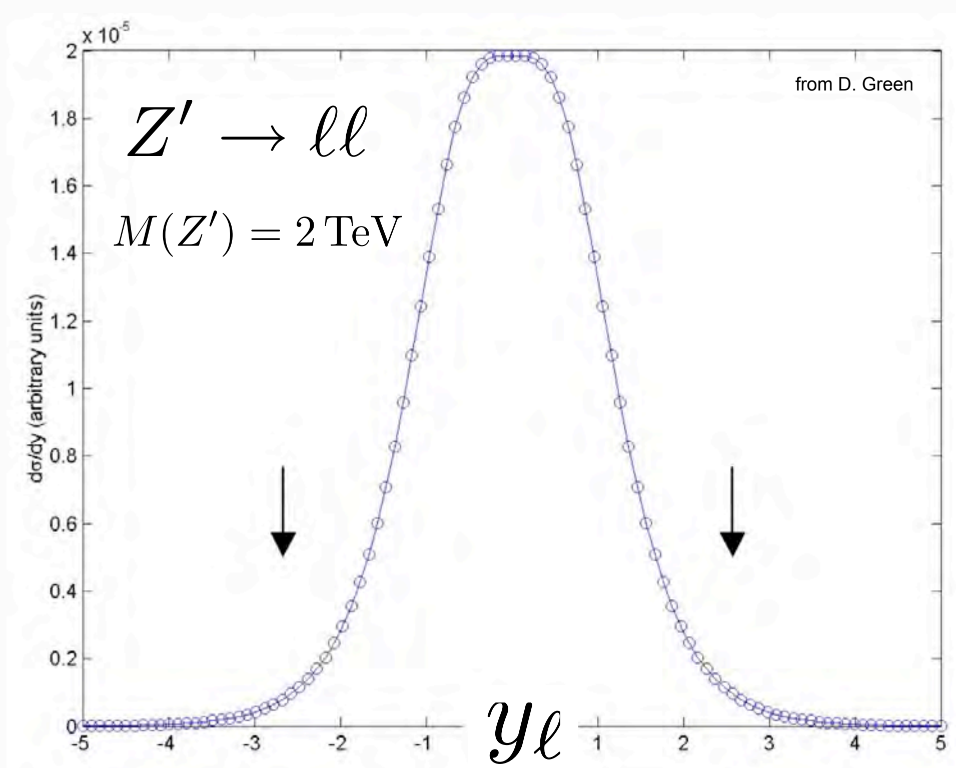


$$\hat{s} = x_1\, x_2\, s = M^2 \qquad x_1 \approx x_2 \rightarrow x_{1,2} = \frac{M}{\sqrt{s}}$$

$$E = \frac{\sqrt{s}}{2}(x_1 + x_2) \qquad p_L = \frac{\sqrt{s}}{2}(x_1 - x_2)$$

$$y = \frac{1}{2}\ln\frac{E + p_L}{E - p_L} \quad \Rightarrow \quad e^y = \sqrt{\frac{x_1}{x_2}} \Rightarrow y \rightarrow 0 \text{ for } x_1 \approx x_2$$

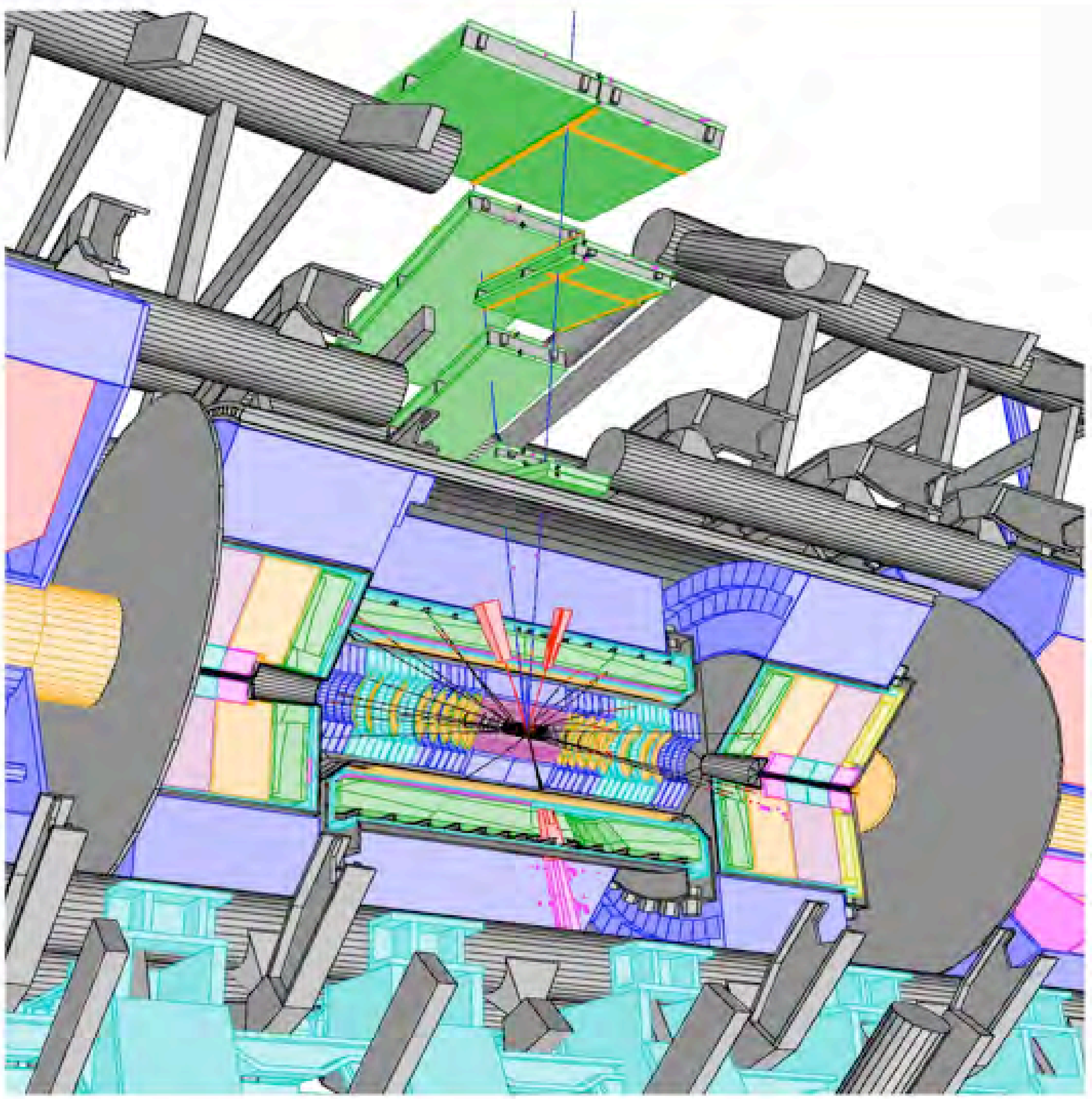
$$x_{1,2} = \frac{M}{\sqrt{s}}\, e^{\pm y}$$



- Thus important to concentrate on precision tracking/calorimetry in area of approx. |y| < 2.5

Detector requirements

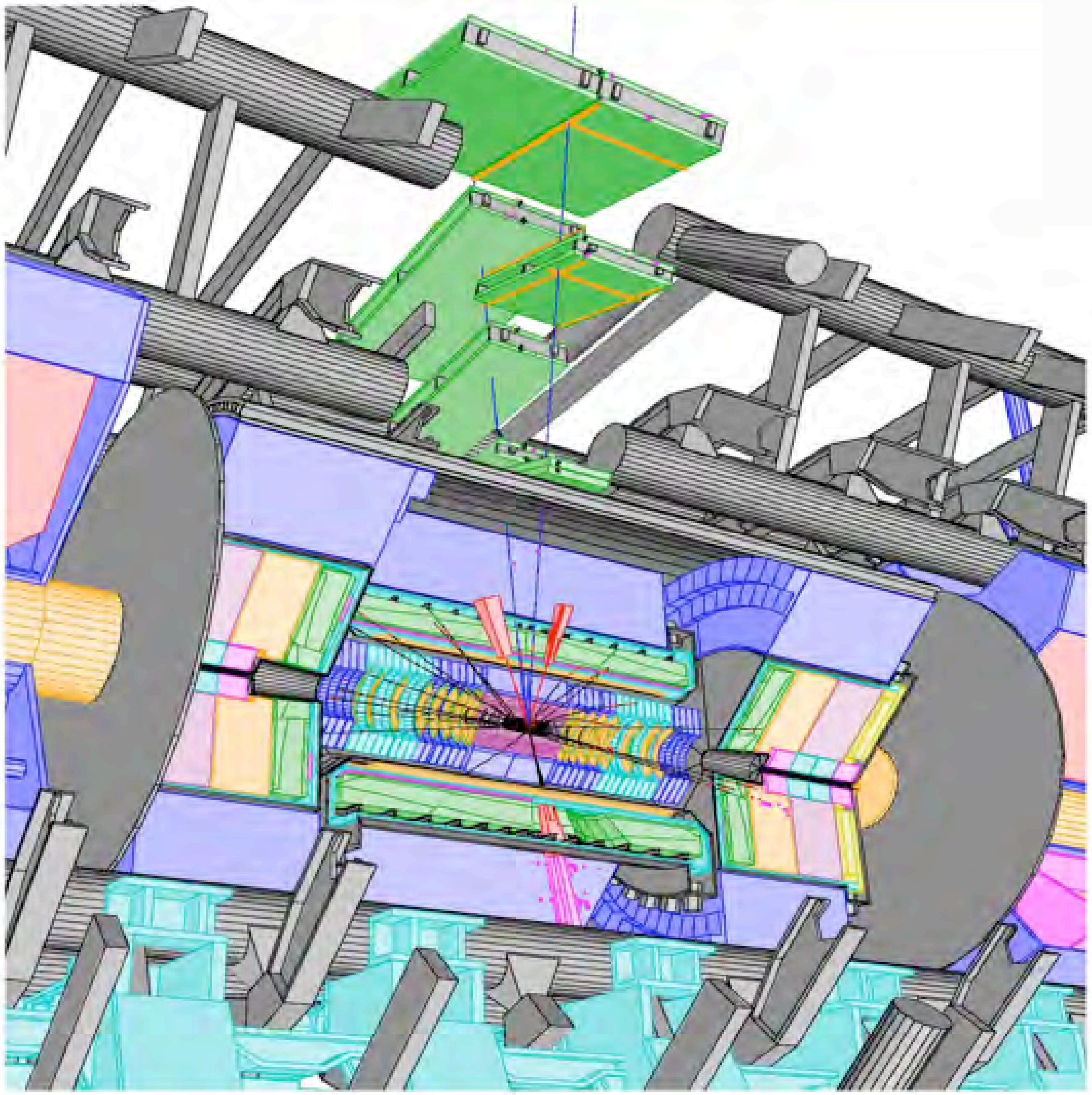
- Detectors must identify extremely rare events, mostly in real time
  - lepton identification above huge QCD background
  - e/jet ratio ~ 10^{-5}, ~10-100x worse than at Tevatron
  - signal cross section as low as 10^{-14} of total cross section : NEW!
  - Online rejection to be achieved : ~ 10^{7} NEW!
  - Store huge data volumes to disk/tape : ~10^{9} events of ~1 Mbyte / year NEW!



Detector requirements

- Good measurement of leptons (e, μ) and photons with large transverse momentum p_T
  - electromagnetic calorimetry, muon systems
- Good jet reconstruction
  - good resolution, absolute energy measurement, low fake-rate
- Good measurement of missing transverse energy ($E_{T\ miss}$)

  and
- energy measurements in the forward regions
  - thus, hermetic detector and
  - calorimeter coverage down to rapidity ~ 5



- Efficient b-tagging and tau identification (silicon strip and pixel detectors)
  - top physics, Higgs couplings to b and tau enhanced in certain models (eg. MSSM)

Examples of detector performance requirements

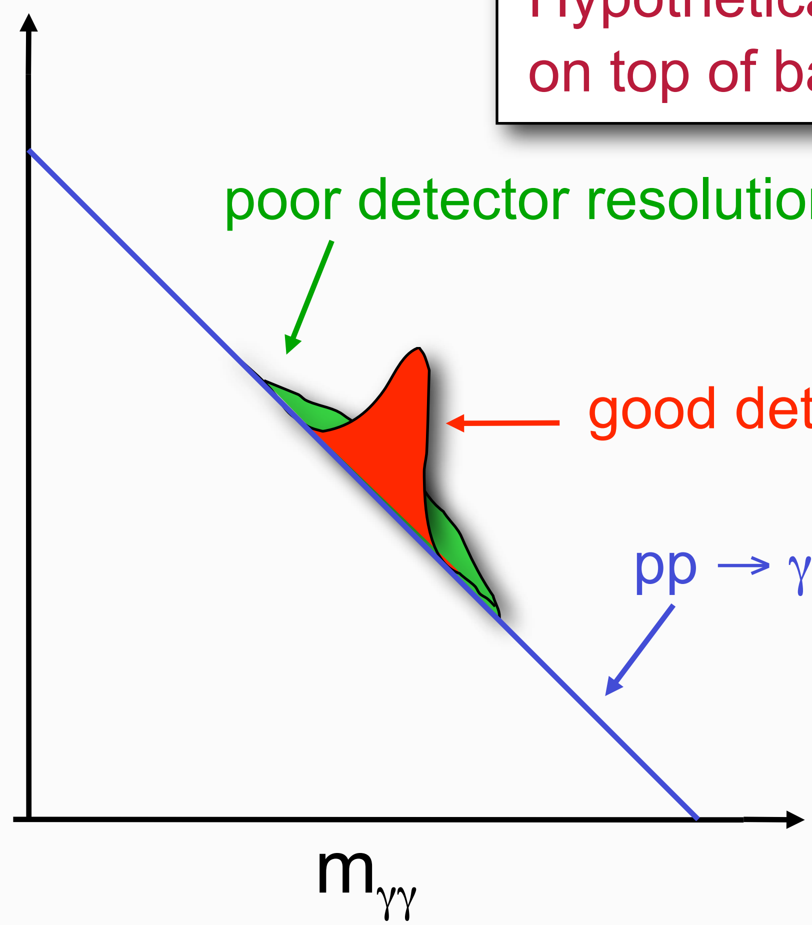
Lepton measurement: $p_T \approx$ GeV $\rightarrow$ 5 TeV (b $\rightarrow$ l+X, W/Z, W'/Z', …)

Hypothetical X $\rightarrow \gamma\gamma$ signal on top of background

Mass resolutions:

≈ 1% decays into leptons or photons
(Higgs, new resonances)

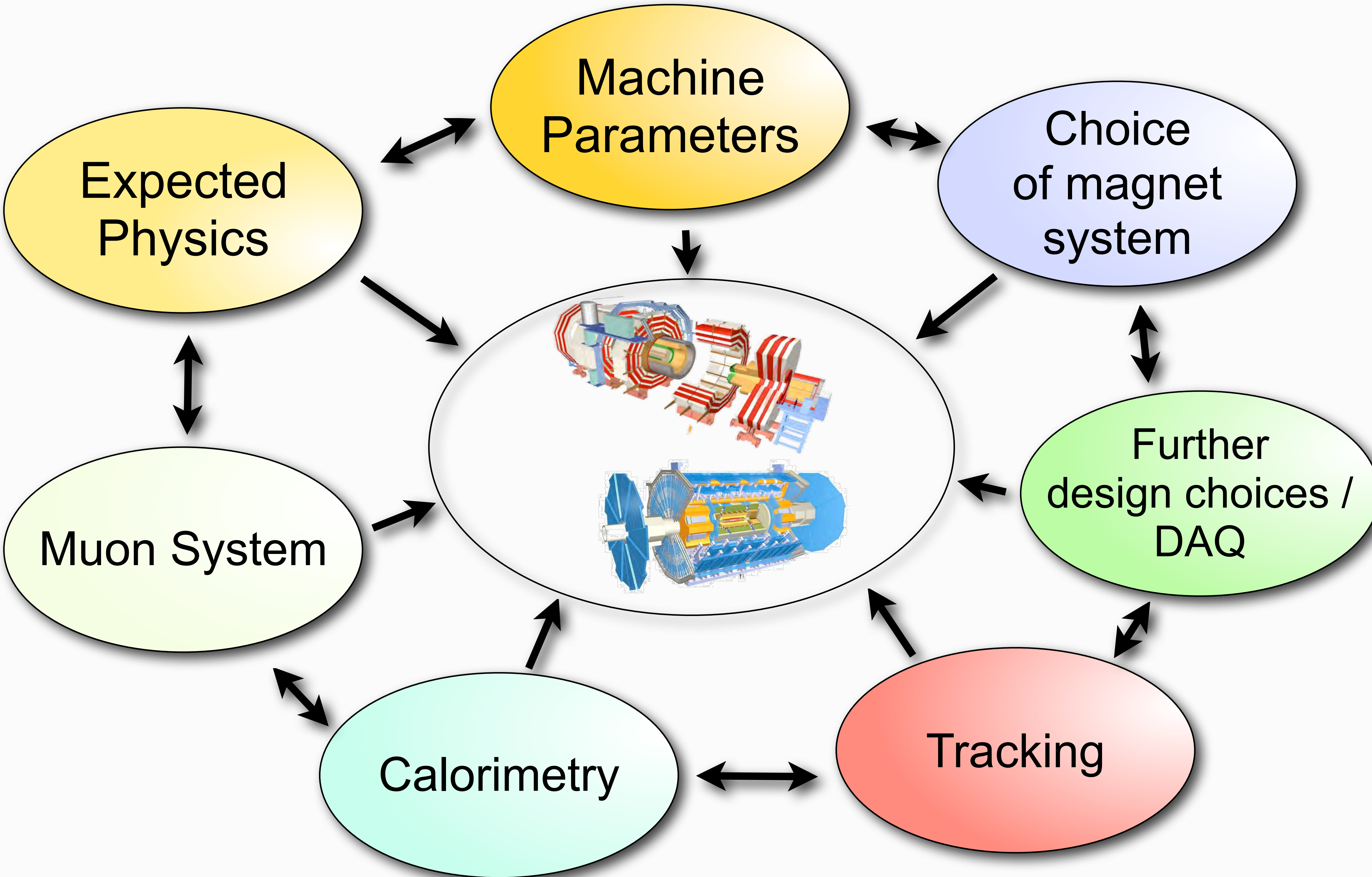
≈ 10% W $\rightarrow$ jj, H $\rightarrow$ bb
(top physics, Higgs, …)



Particle identification:

- b/jet separation : ε (b) ≈ 50% R (jet) ≈ 100 (H $\rightarrow$ bb, SUSY, 3rd generation !!)
- τ/jet separation : ε (τ) ≈ 50% R(jet) ≈ 100 (A/H $\rightarrow \tau\tau$, SUSY, 3rd generation !!)
- γ/jet separation : ε (γ) ≈ 80% R(jet) > 10^3 (H $\rightarrow \gamma\gamma$)
- e/jet separation : ε (e) > 70% R(jet) > 10^5 (inclusive electron sample)

How to design your detector



The LHC parameters

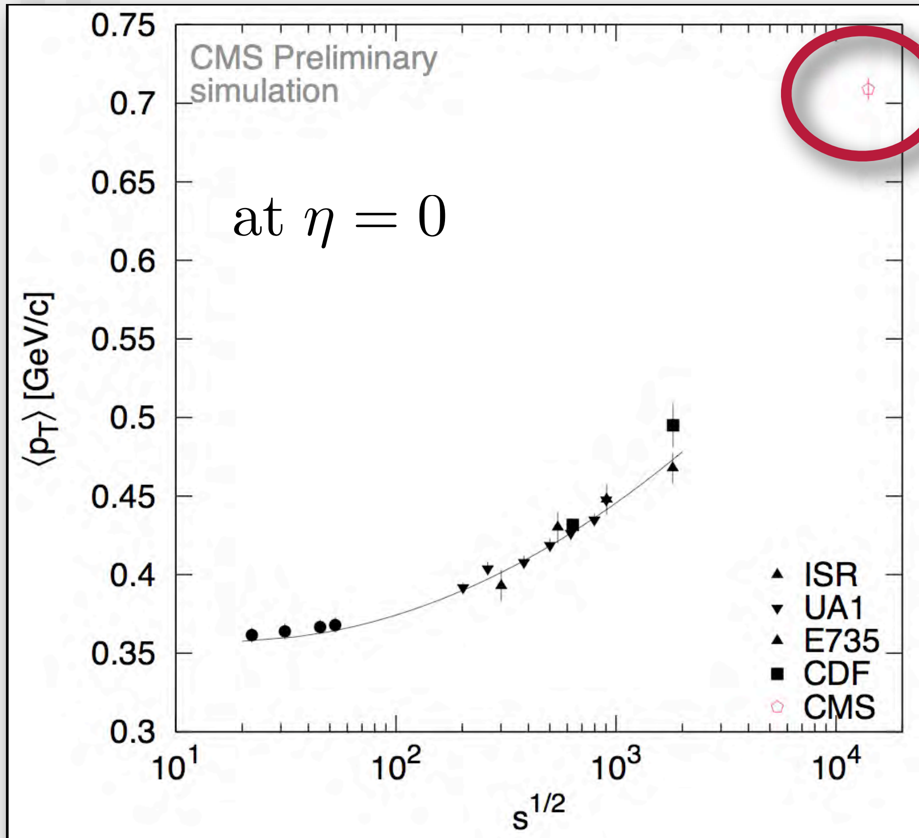
- E_{cm} = 14 TeV (reached in steps 0.45 - 7 - 10 - 14? TeV)
  - basically fixed by LEP tunnel parameters (Radius) and superconducting magnets technologies
  - Was considerably lower than SSC (20 TeV / beam)
- Lumi :
  - by some considered to "must be 10x SSC" in order to compensate lower E_{CM}
  - RF bunch spacing = 25 ns
  - relevant cross sections for testing of EWK symmetry breaking of order 1 - 100 fb^{-1}
  - Running time per year T ~ 10^7 secs

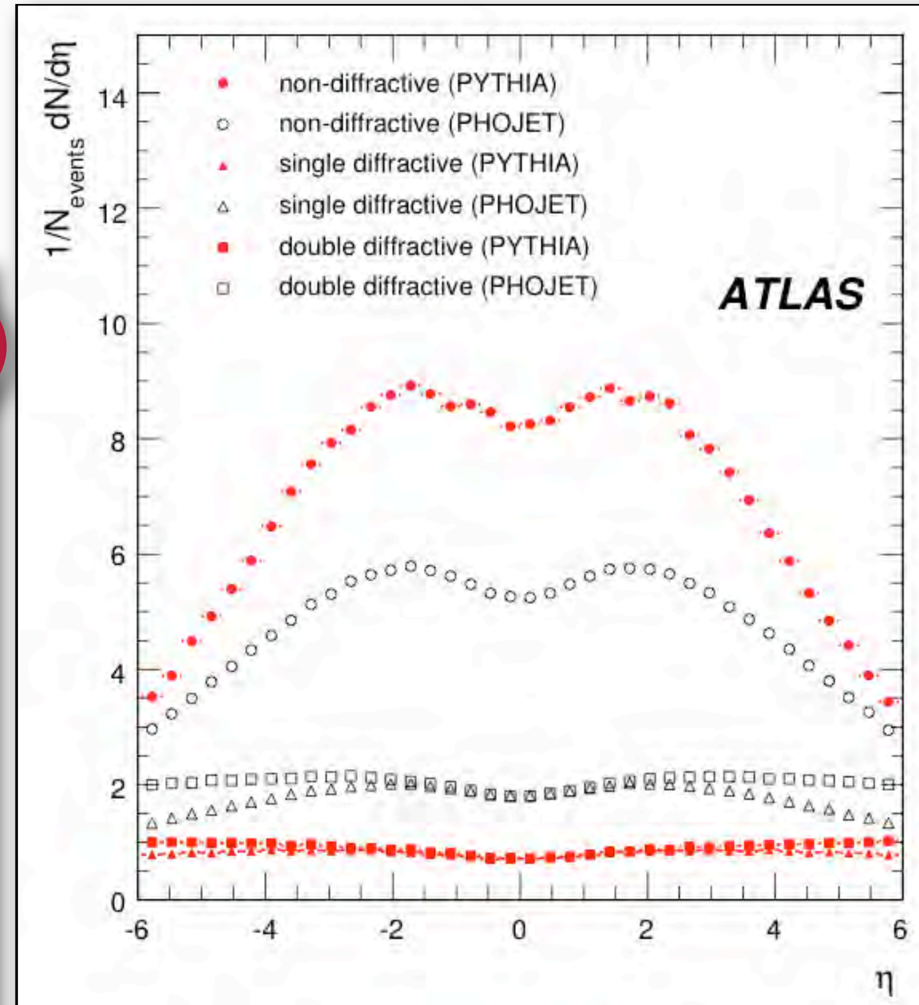
$$\text{for } \mathcal{L} = 10^{34}/\text{cm}/\text{sec} = 10^{-5}\,\text{fb}^{-1}/\text{sec}$$

$$N = (\mathcal{L} \cdot T)\,\sigma \Rightarrow 100\,\text{events per year for } \sigma = 1\,\text{fb}$$

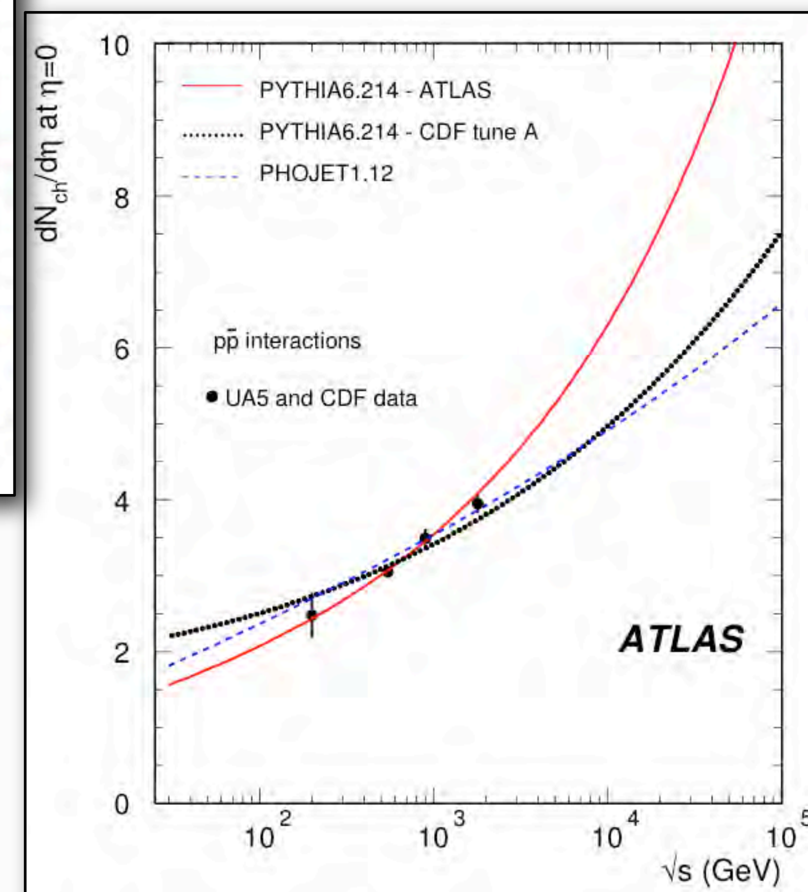
  - Total rate of inelastic events $R = \sigma_{\text{inel}}\,\mathcal{L} \approx (100\,\text{mb})\,(10^7\text{mb}^{-1}/\text{sec}) = 10^9\,\text{events/sec}$
  - Number of inelast. events per bunch crossing = 10^9/sec * 25 10^{-9} sec = 25 (pile-up)!
  - Number of chg. particles per bunch x-ing : 25 * N(pions)/rap * (2 y_{max}) ~ 2000 !!
  - Thus have an issue with **radiation levels**! (and pile up ...)

Particle Densities





- seen before:
- total particle density:
  ~ 6 charged particles (pions)
  plus ~3 neutrals (pizeros)
  per unit of pseudorapidity
  in the central detector region
- uniformly distributed in φ

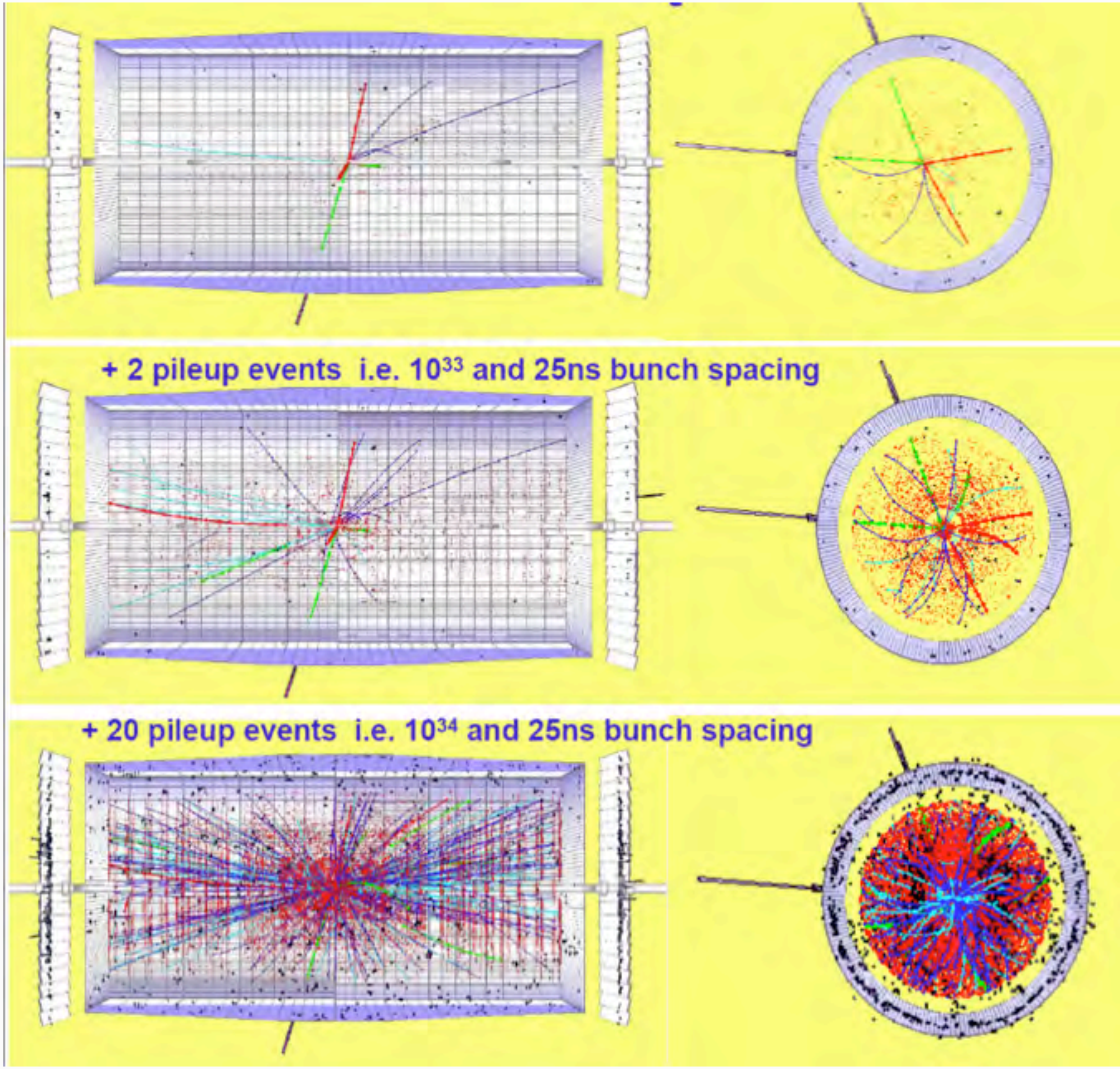


$$\langle p_T \rangle \approx 700 - 800\,\mathrm{MeV}$$

$$\Longrightarrow N_{\mathrm{int}} \cdot 9\,\mathrm{pions/rap} \cdot (2y_{\mathrm{max}}) \approx 2250\,\mathrm{particles/crossing}$$

$$\Longrightarrow \sum p_T \approx 2250 \cdot 0.8 = 1.8\,\mathrm{TeV}$$

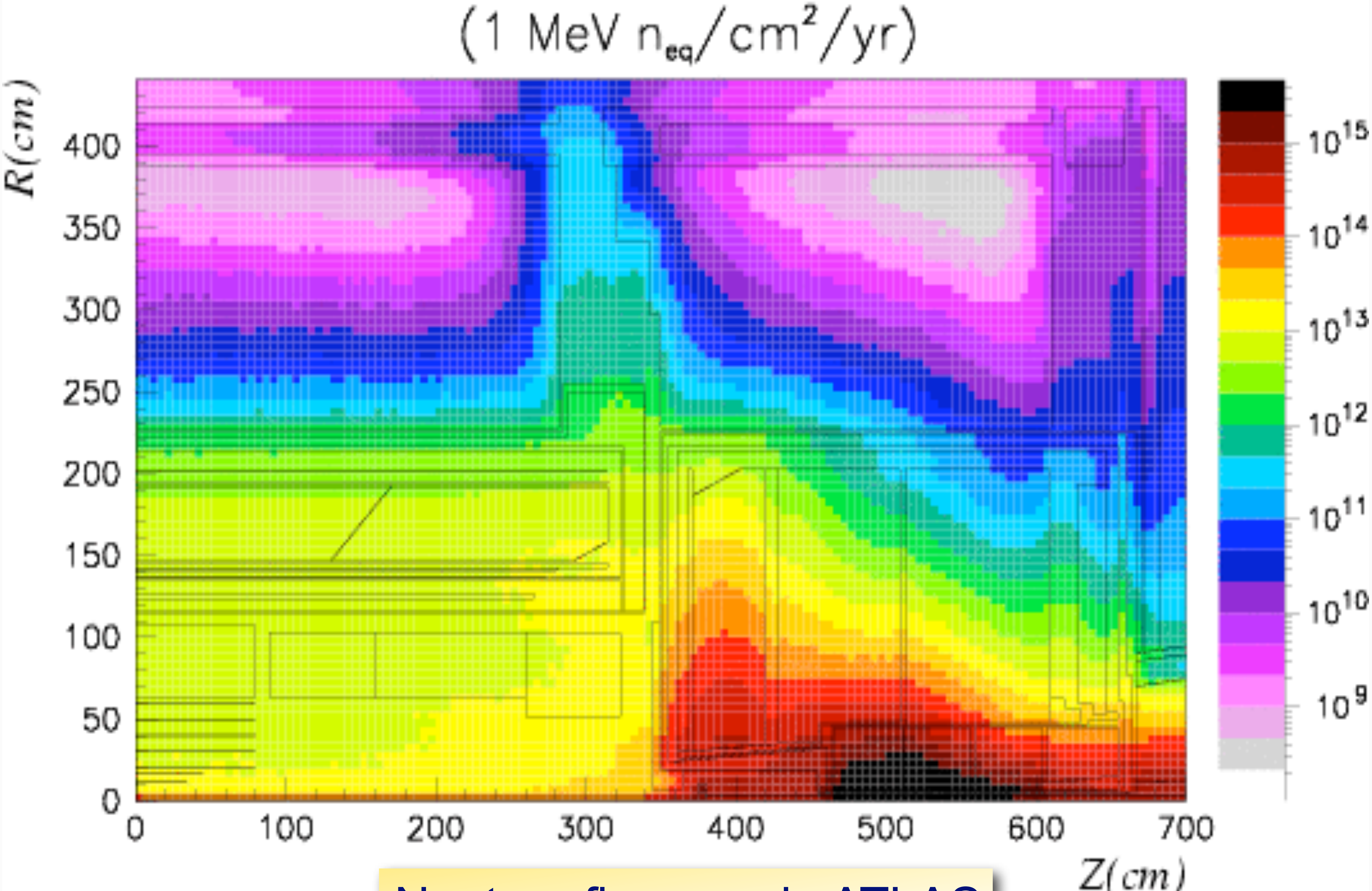
Challenge : Pile-up events



S. Tapprogge, Nov06

- at high lumi:
  up to 25 additional min bias events
- ~1500 charged particles in the detector
- Example of golden Higgs channel
  $H \rightarrow ZZ \rightarrow 2e2\mu$
- Large magnetic field and high granularity helps
- Need to understand detector first before able to exploit full lumi…

The LHC environment...



Neutron fluences in ATLAS

Damage caused by ionising radiation

- caused by energy deposited by particles in the detector material
  - ~ 2 MeV g^{-1} cm^{-2} for a min. ionizing particle

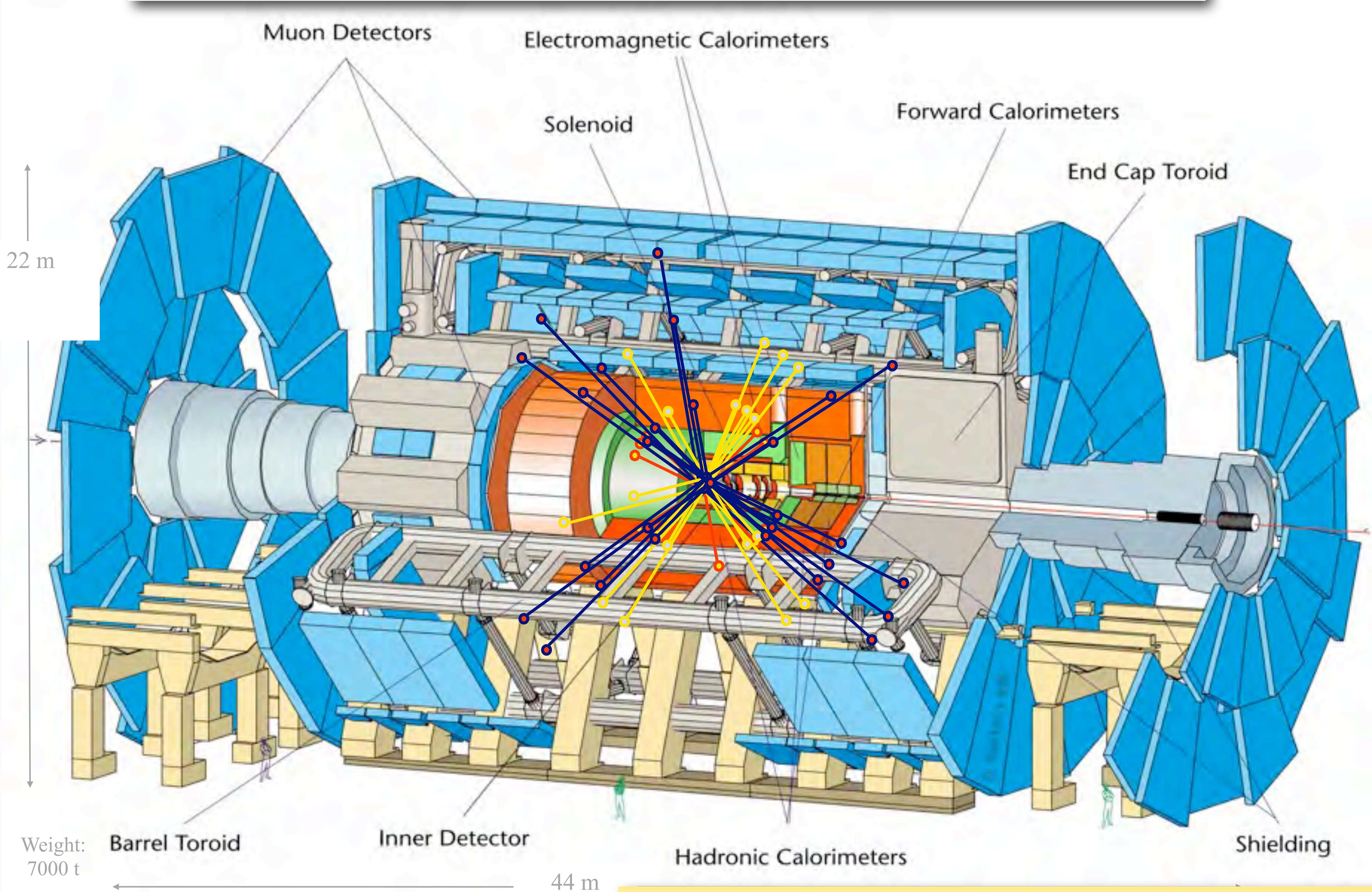
- also caused by photons created in elmg. showers

- damage is proportional to the deposited energy or dose measured in Gy (Gray)
  - 1 Gy = 1 Joule / kg = 100 rads
  - 1 Gy = 3 10^9 particles per cm^2 of material with unit density

at LHC design luminosity :
Ionising dose is ~ 2 10^6 Gy / r_T^2 / year
r_T [cm] : transverse distance to beam

The Timing Challenge

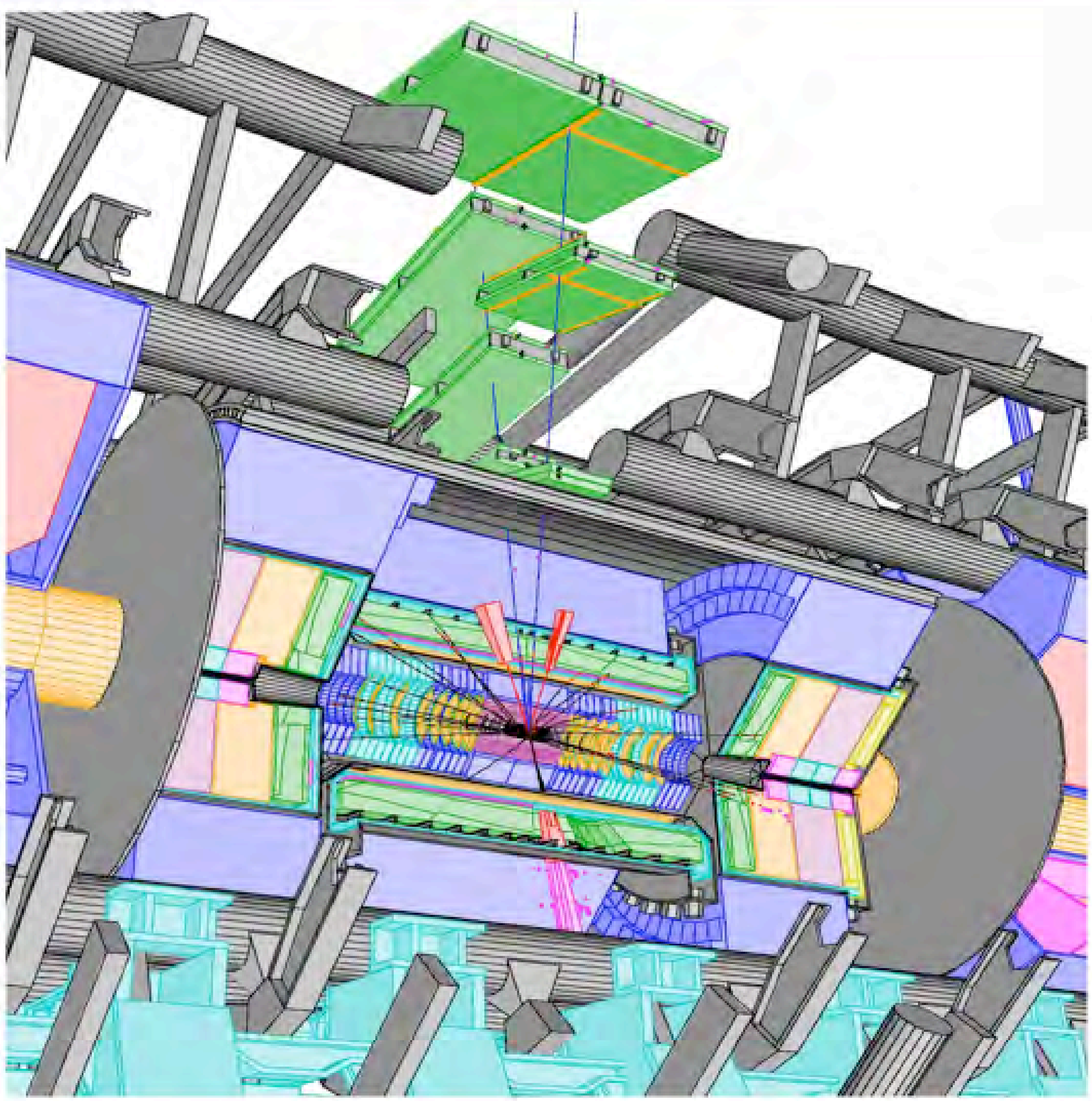
Interactions every 25ns : In 25 ns particles travel 7.5m



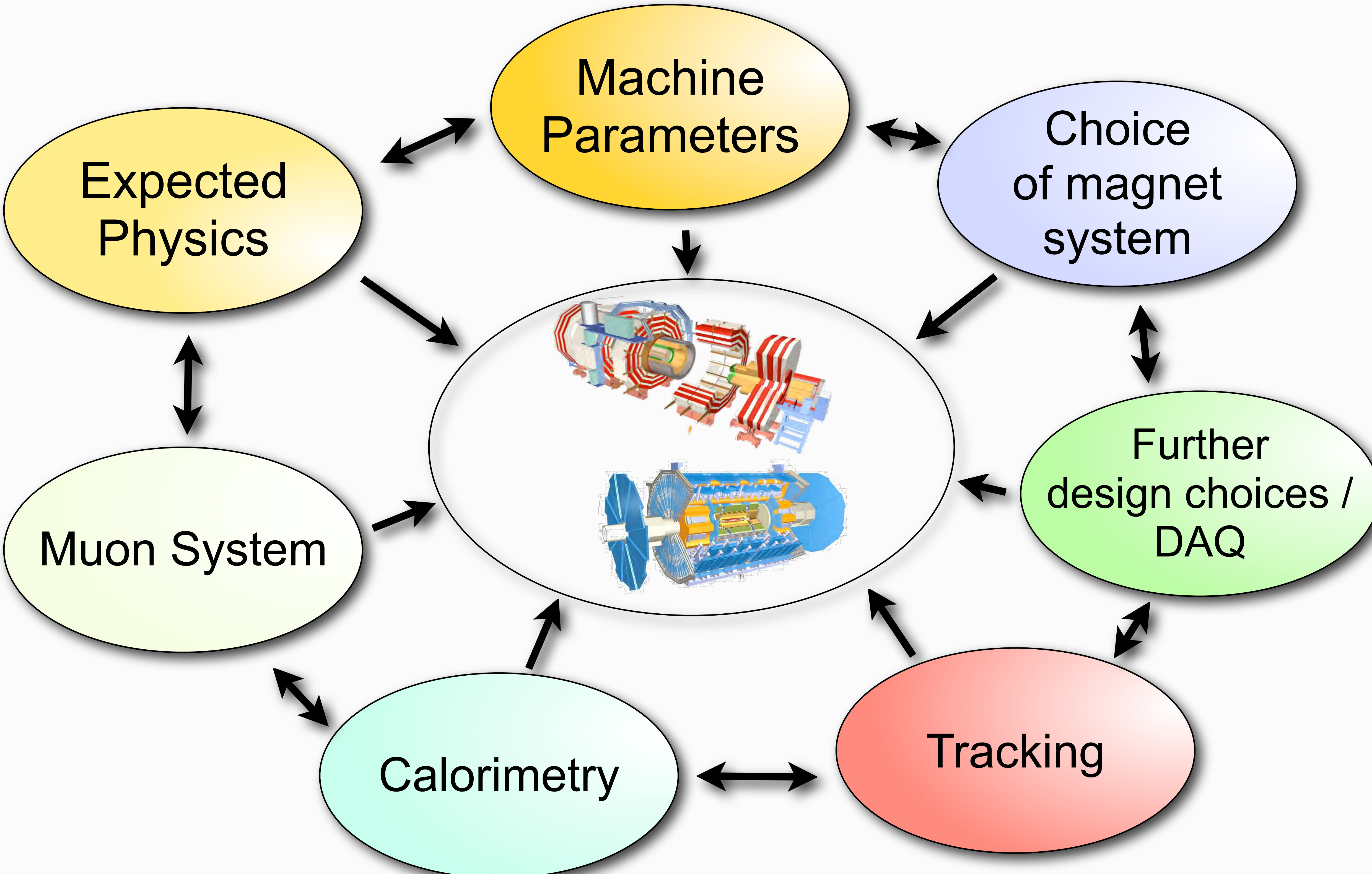
Cable length ~100m : In 25 ns signals travel 5 m

Detector requirements

- High granularity (NEW!),
  fast readout (NEW!),
  radiation hardness (NEW!)
  - minimize pile-up particles in same detector element
  - many channels
    eg. 100 million pixels,
    200’000 cells in electromagnetic calorimeter
  - cost !
  - 20-50 ns response time for electronics !
  - in forward calorimeters : up to 10^{17} n/cm^2 over 10 years of LHC operations



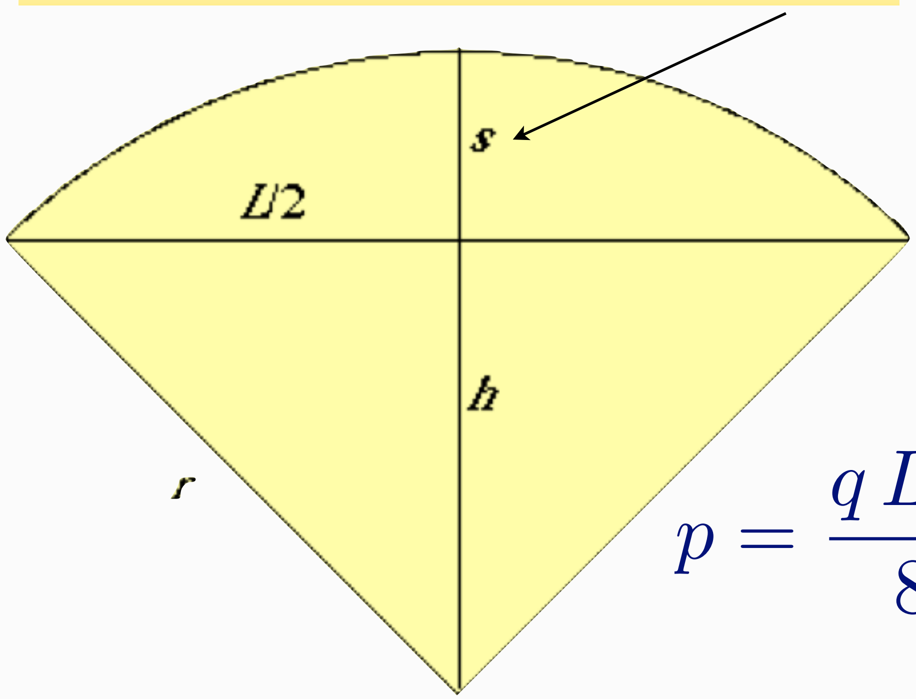
How to design your detector



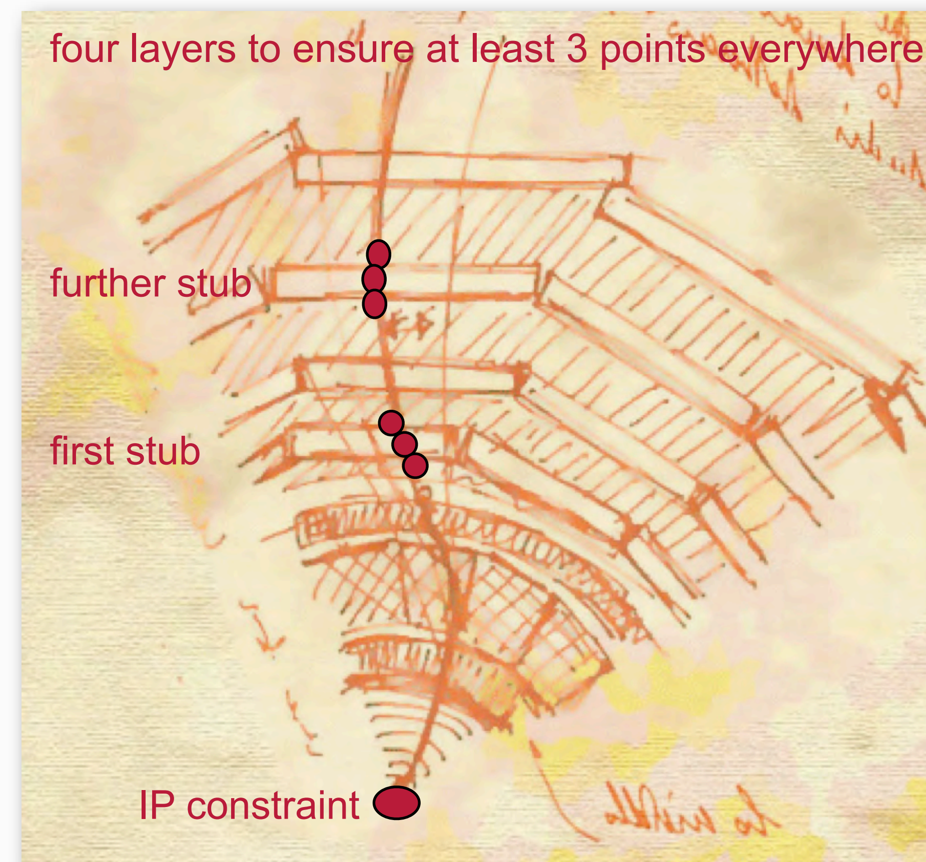
Magnet Systems

- Among the most important design choices
  - fixes many other parameters/sizes
- Example of CMS, early days:
  - assumed that a tracking system might not be possible (too harsh backgrounds), rad-hard Si-Detectors not yet sufficiently developed
  - so, put all effort on muons, in a robust manner; put absorber to get rid of the rest (a strong magnetic field also helps here) and try to get best possible muon measurement.

Momentum measurement via sagitta:



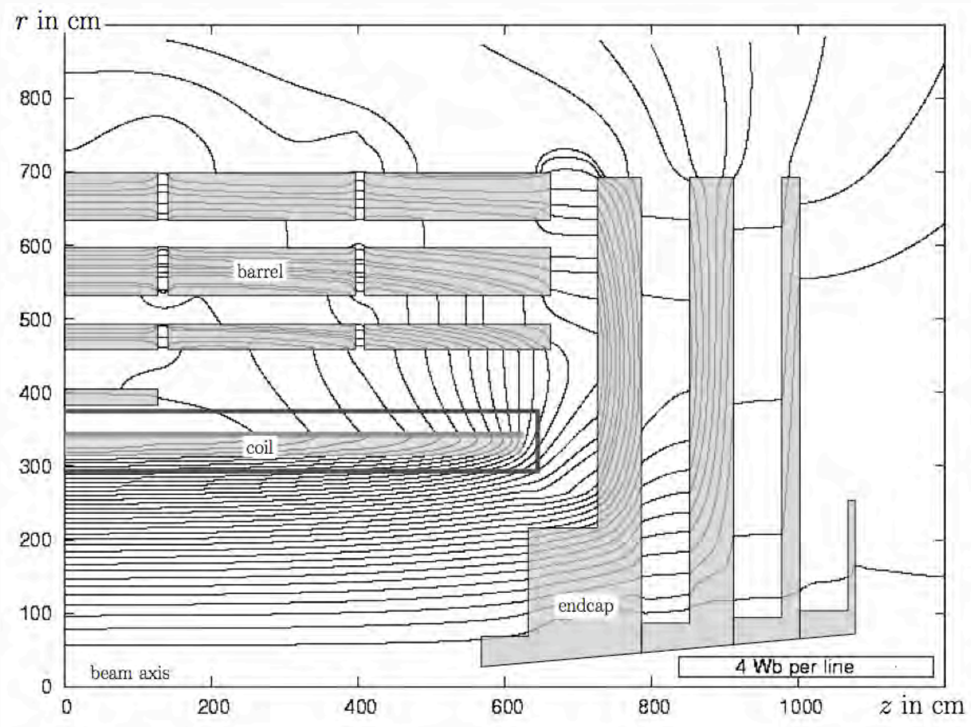
$$p = \frac{q\,L^2 B}{8s}$$



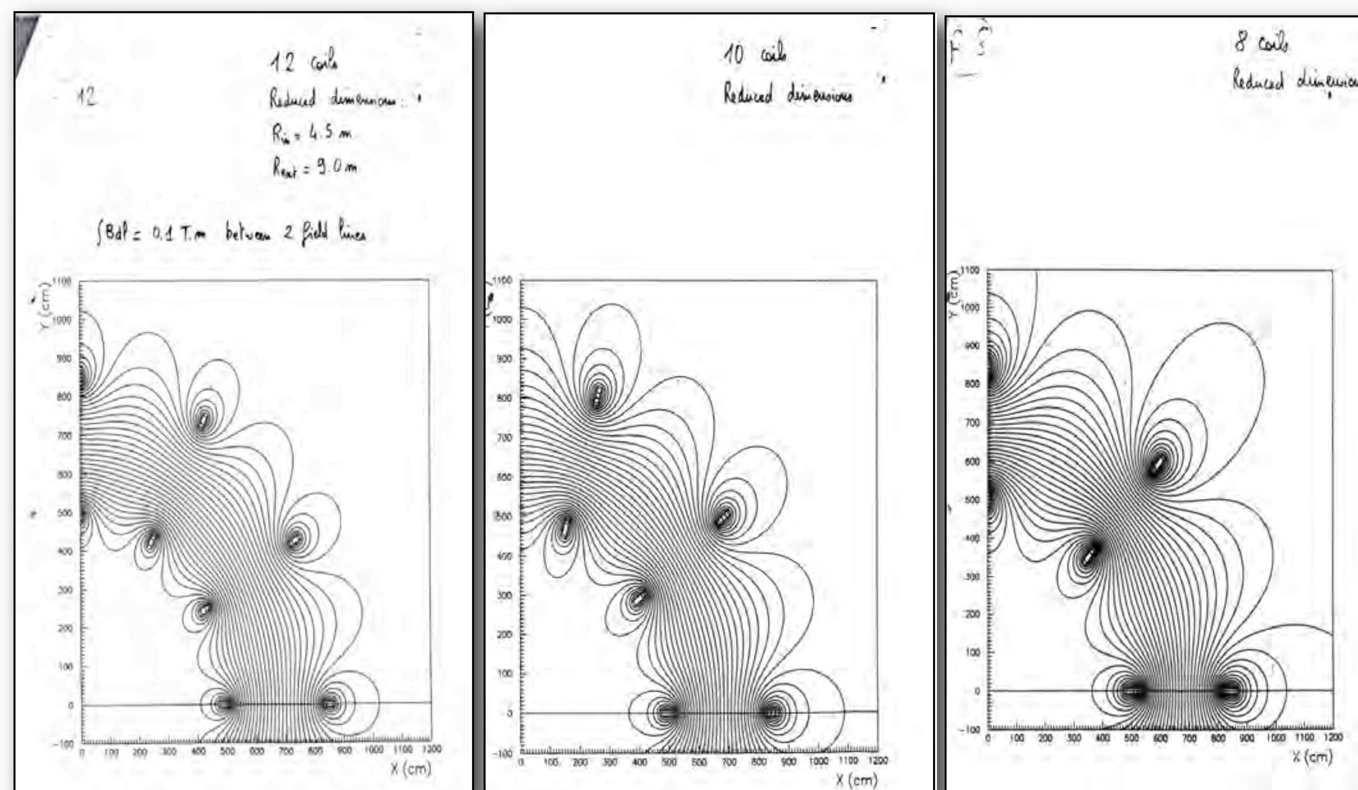
$$\frac{\delta p}{p} = \frac{8}{q}\,\frac{1}{L^2 B}\,p\,\delta s = \frac{\delta s}{s}$$

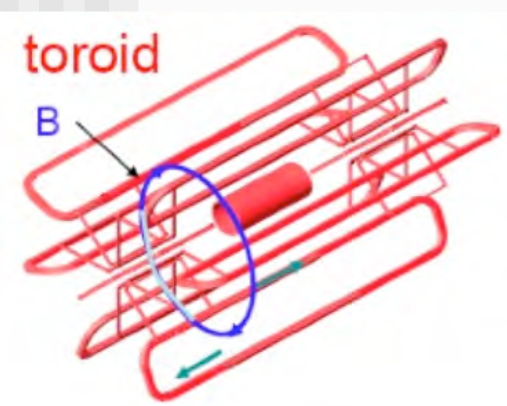
maximize... but note that L drives cost of detector very much.

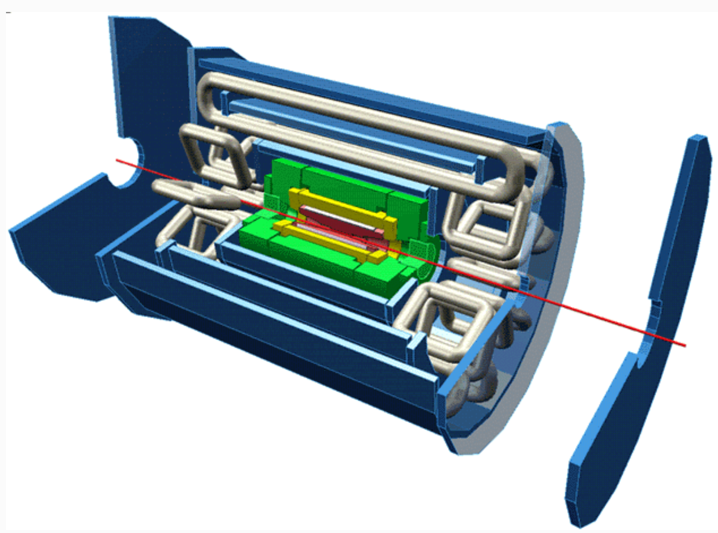
Various topologies...



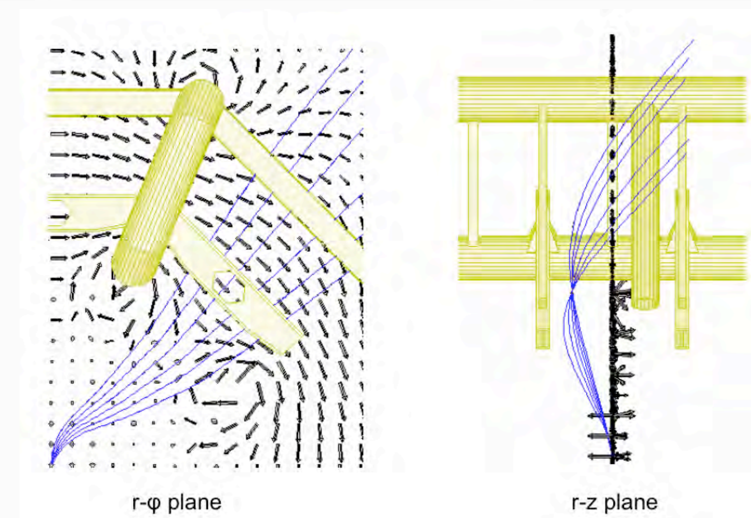
- But : Pending power prop.to. of path perpendicular to B field. $\int Bdl$
- Solenoid not optimal in forward direction
- For large solenoid radius: have to make it long in order to cover large rapidity



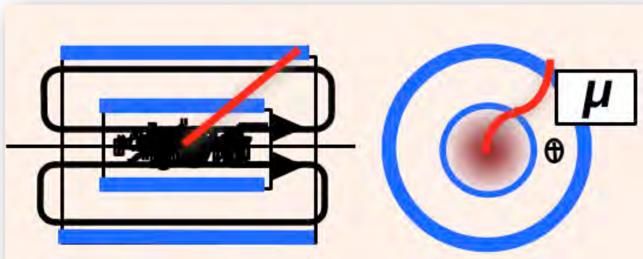


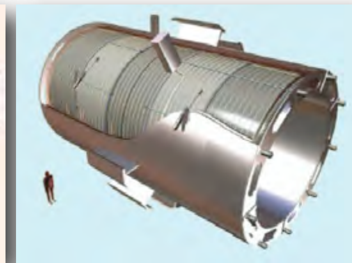


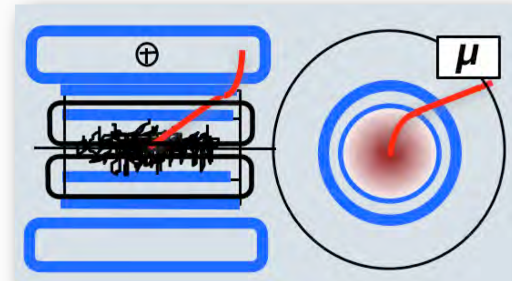
- Alternative: Toroid system. Large BL^2. Good pending power over also in forward direction
- Keeps detectors inside toroids free of B field
- But : for large system: becomes expensive, needs very precise knowledge of (complicated) B-field

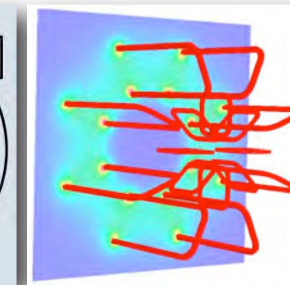


Solenoid vs Toroid









- Only one magnet system
  - simple and compact overall design
  - excellent momentum resolution using inner tracker
- R_{sol} determines cost, R=3m was doable
- B=4 T was realizable, 3.5 T would still deliver good physics
- Needs (instrumented) return yoke
  - limits momentum resolution at low p because of multiple scattering
  - might be problem for standalone muon triggering at high rate running (SLHC)
  - understanding of stray field
- Tracking limited at large rapidities
- All calorimeters inside coil
  - good for resolution, but puts size constraints on Tracker+Calos
  - eg. with R_{sol}=3m, $R_{Tracker}$=1.2-1.3m, <2m left for ECAL+HCAL !

- Two magnet systems, because need smaller solenoid for inner tracking near IP
  - determines very large size, complex structure
- Large toroids determine cost
  - less coils (12->8): cheaper, but less uniform field
  - Thus need very precise field map !
- No return yoke needed
  - closed flux in air -> much less multiple scatt.
  - better standalone muon triggering/tracking at high rates
  - keeps calorimeters field free
  - a “lot of space” for calorimeters
- Good tracking at large rapidities
- Calorimeters outside small solenoid
  - material affects resolution of calorimeters

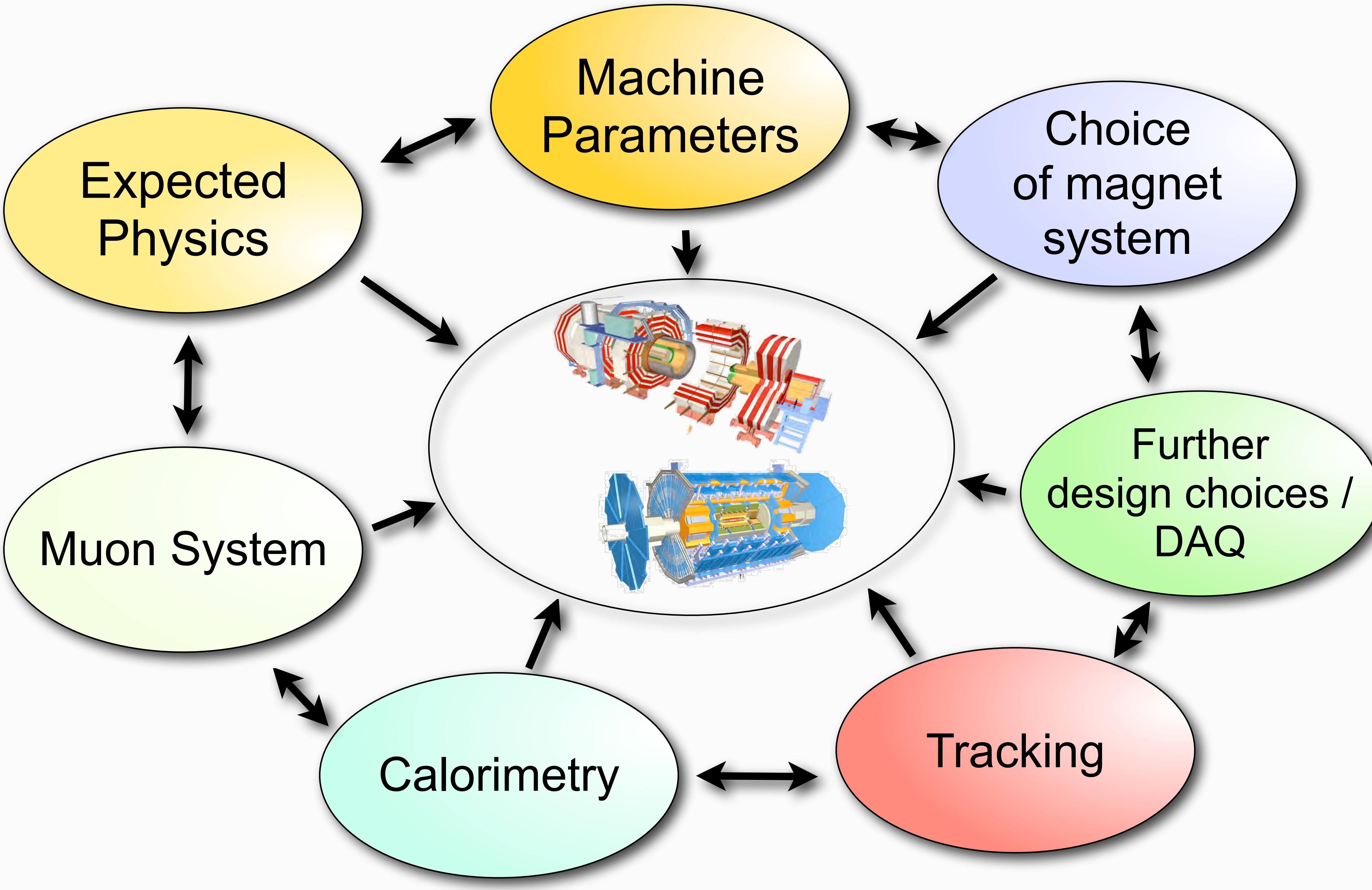
The final parameters....

TABLE 3 Main parameters of the CMS and ATLAS magnet systems

	CMS	ATLAS		
Parameter	**Solenoid**	**Solenoid**	**Barrel toroid**	**End-cap toroids**
Inner diameter	5.9 m	2.4 m	9.4 m	1.7 m
Outer diameter	6.5 m	2.6 m	20.1 m	10.7 m
Axial length	12.9 m	5.3 m	25.3 m	5.0 m
Number of coils	1	1	8	8
Number of turns per coil	2168	1173	120	116
Conductor size (mm^2)	64×22	30×4.25	57×12	41×12
Bending power	$4\ T \cdot m$	$2\ T \cdot m$	$3\ T \cdot m$	$6\ T \cdot m$
Current	19.5 kA	7.6 kA	20.5 kA	20.0 kA
Stored energy	2700 MJ	38 MJ	1080 MJ	206 MJ

Three magnets have reached their design currents: a major technical milestone!

How to design your detector



Basic tracking requirements

- Robust and redundant pattern recognition
  - efficient and precise reco of all charged particles with p_T >~ 1 GeV, up to rapidity ~ 2.5
- High-Level triggering capabilities for electrons, taus, b-jets
- Reconstruction of secondary vertices, impact parameters
  - heavy flavours, b-jets, B decays
- Electron-ID via matching to ECAL
  - or electron/pion separation via other tech, such as transition radiation
- Reconstruction of hadronic tau decays (one-prong, three-prong, thin jets)
- “Conflict of interest” :
  - many layers (many hits) for robust track reco -->
    many channels; lots of supports (cables, cooling, ...)
  - but not too much material, bad for ECAL resolution and multiple scatt.
- Remember: momentum resolution

$$\boxed{\frac{\delta p}{p} = \frac{\delta s}{s} = \frac{8}{q}\,\frac{1}{L^2 B}\,p\,\delta s}$$

$$\text{for } L = 1\,\mathrm{m}\ ,\ B = 4\,\mathrm{T}\ ,\ p = 100\,\mathrm{GeV}$$

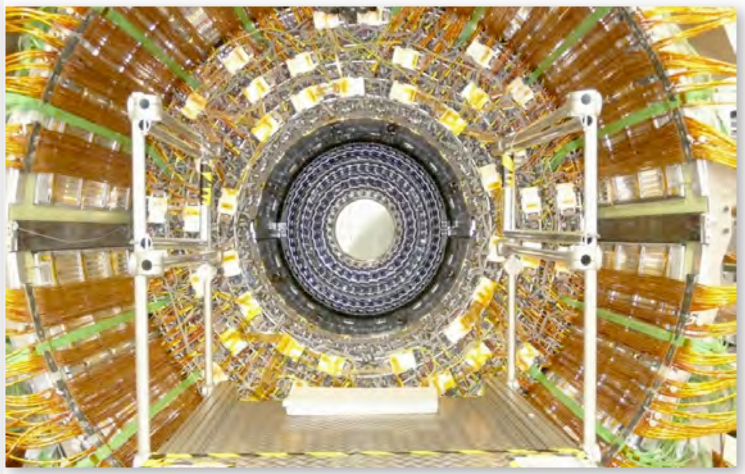
$$\frac{\delta p}{p} = 1\,\% \ \text{ for } \quad \delta s \approx 15\,\mu\mathrm{m}$$

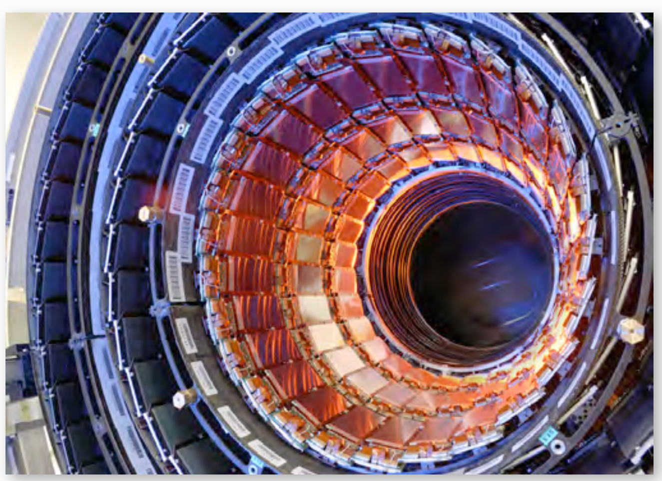
➡ need hit reconstruction at this level of prec. !

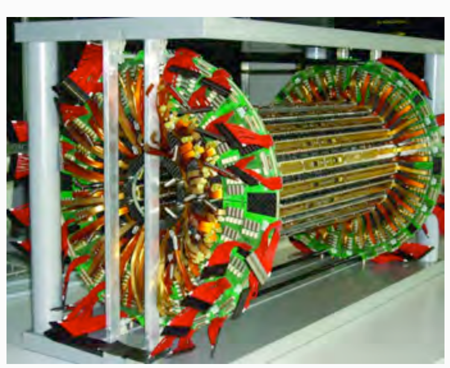
➡ e.g. Si-Tracker : optimize carefully pitch vs. strip length vs. # channels (material) vs. occupancy

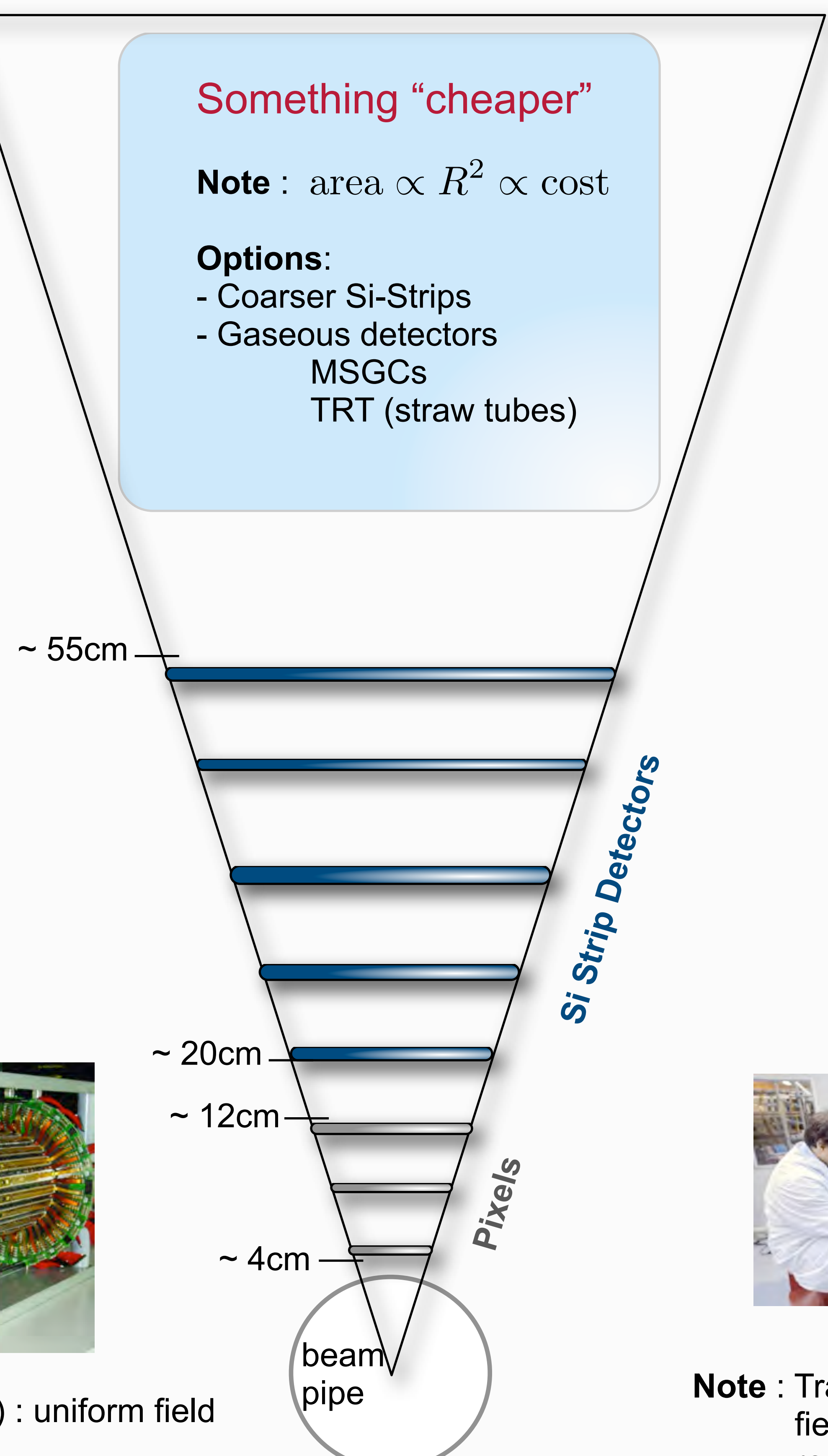
Basic layout

CMS









Something "cheaper"

Note : area $\propto R^2 \propto$ cost

Options:
- Coarser Si-Strips
- Gaseous detectors
  MSGCs
  TRT (straw tubes)

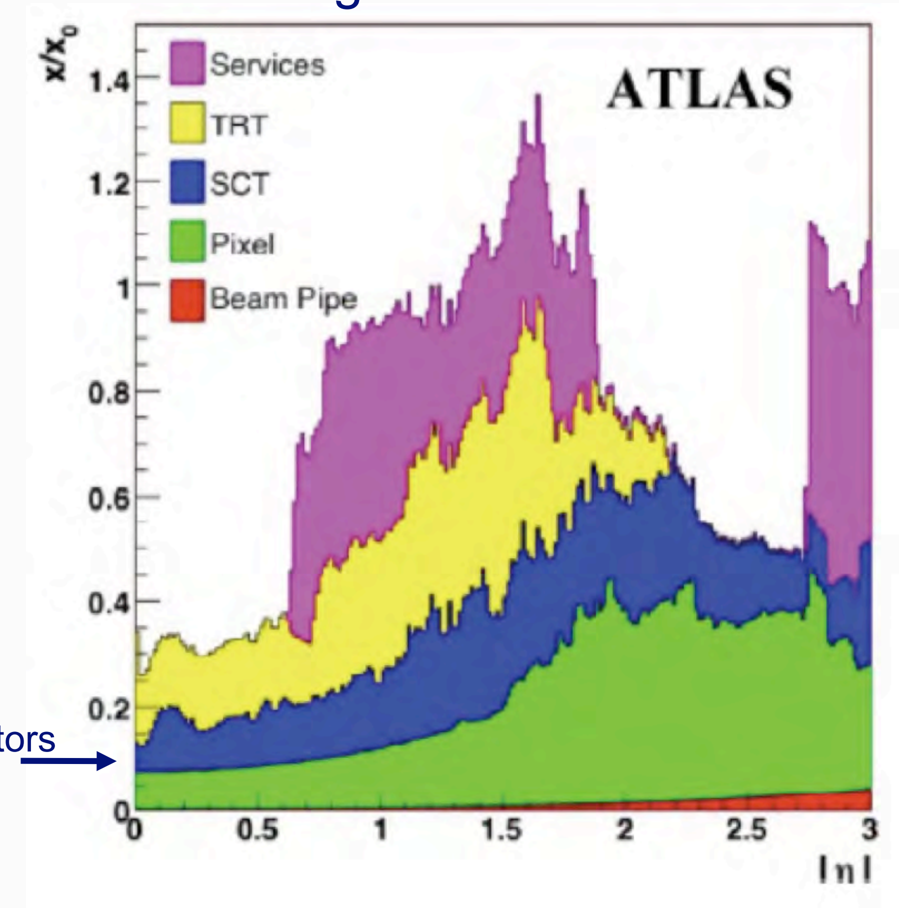
ATLAS

Note : Tracker well within solenoid (3.8 T) : uniform field

Note : Tracker slightly longer than solenoid (2 T) : field non-uniformities and worse momentum resolution at each end

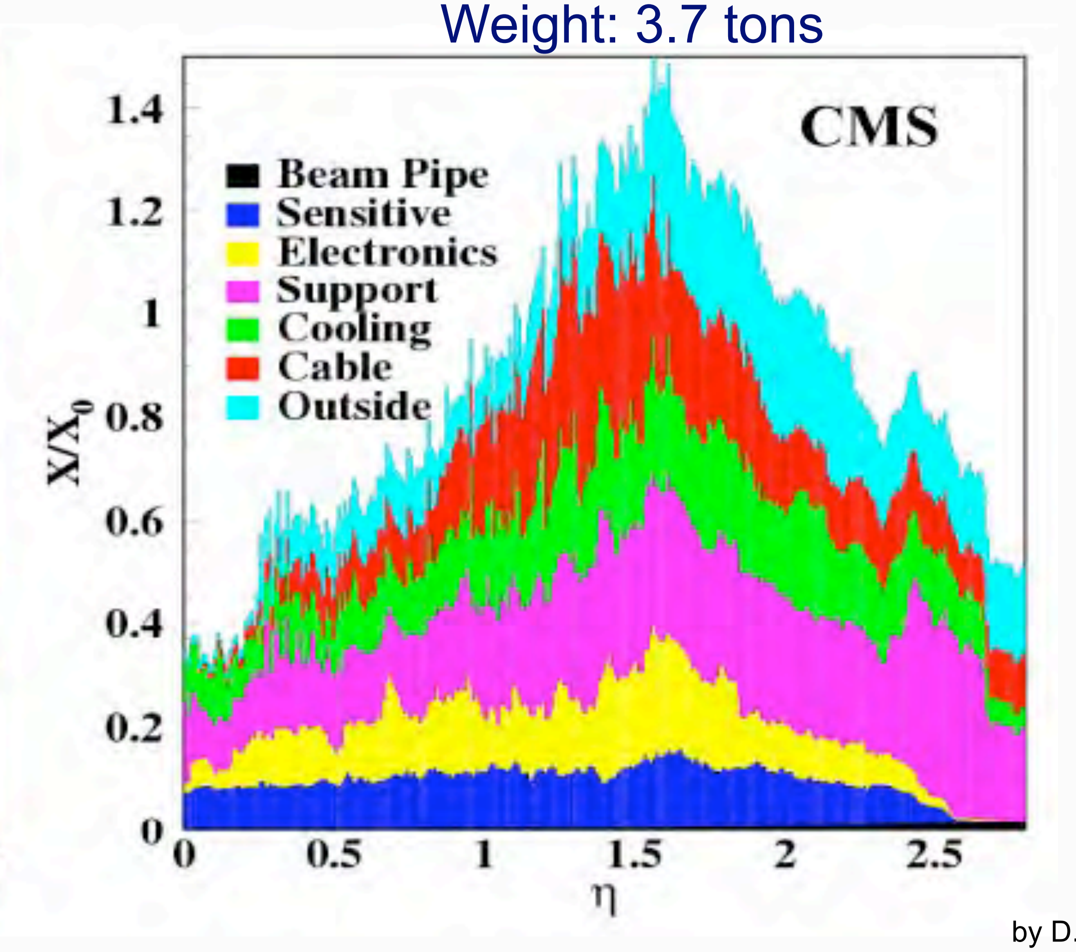
Big Issue : Material !

Weight: 4.5 tons



LEP detectors

Weight: 3.7 tons



by D. Froidevaux

- Apparently an unfortunate similarity....
- Material **increased by ~ factor 2-2.5 from 1994** (approval) to now (end constr.) !
- Electrons lose between 25% and 70% of their energy before reaching EM calo
- Between 20% and 65% of photons convert into e^+e^- pair before EM calo
- Need to know material to ~ 1% X_0 for precision measurement of m_W (< 10 MeV)!

For reference

TABLE 7 Main performance characteristics of the ATLAS and CMS trackers

	ATLAS	CMS
Reconstruction efficiency for muons with $p_T = 1$ GeV	96.8%	97.0%
Reconstruction efficiency for pions with $p_T = 1$ GeV	84.0%	80.0%
Reconstruction efficiency for electrons with $p_T = 5$ GeV	90.0%	85.0%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 0$	1.3%	0.7%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 2.5$	2.0%	2.0%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 0$	3.8%	1.5%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 2.5$	11%	7%
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm)	75	90
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm)	200	220
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (μm)	11	9
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (μm)	11	11
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm)	150	125
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm)	900	1060
Longitudinal i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (μm)	90	22–42
Longitudinal i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (μm)	190	70

Examples of typical reconstruction efficiencies, momentum resolutions, and transverse and longitudinal impact parameter (i.p.) resolutions are given for various particle types, transverse momenta, and pseudorapidities.

Performance of CMS tracker is undoubtedly superior to that of ATLAS in terms of momentum resolution.
Vertexing and b-tagging performances are similar.
However, impact of material and B-field already visible on efficiencies.

by D. Froidevaux

For reference

TABLE 4 Main parameters of the ATLAS and CMS tracking systems (see Table 6 for details of the pixel systems)

Parameter	ATLAS	CMS
Dimensions (cm)		
-radius of outermost measurement	101–107	107–110
-radius of innermost measurement	5.0	4.4
-total active length	560	540
Magnetic field B (T)	2	4
BR^2 ($T \cdot m^2$)	2.0 to 2.3	4.6 to 4.8
Total power on detector (kW)	70	60
Total weight in tracker volume (kg)	≈4500	≈3700
Total material (X/X_0)		
-at $\eta \approx 0$ (minimum material)	0.3	0.4
-at $\eta \approx 1.7$ (maximum material)	1.2	1.5
-at $\eta \approx 2.5$ (edge of acceptance)	0.5	0.8
Total material (λ/λ_0 at max)	0.35	0.42
Silicon microstrip detectors		
-number of hits per track	8	14
-radius of innermost meas. (cm)	30	20
-total active area of silicon (m^2)	60	200
-wafer thickness (microns)	280	320/500
-total number of channels	6.2×10^6	9.6×10^6
-cell size (μm in $R\phi$ × cm in z/R)	80 × 12	80/120 × 10
-cell size (μm in $R\phi$ × cm in z/R)		and 120/180 × 25
Straw drift tubes (ATLAS only)		
-number of hits per track ($\lvert\eta\rvert < 1.8$)	35	
-total number of channels	350,000	
-cell size (mm in $R\phi$ × cm in z)	4 × 70 (barrel)	
	4 × 40 (end caps)	

TABLE 6 Main parameters of the ATLAS and CMS pixel systems

	ATLAS	CMS
Number of hits per track	3	3
Total number of channels	$80\ 10^6$	$66\ 10^6$
Pixel size (μm in $R\phi$ × μm in z/R)	50 × 400	100 × 150
Lorentz angle (degrees), initial to end	12 to 4	26 to 8
Tilt in $R\phi$ (degrees)	20 (only barrel)	20 (only end cap)
Total active area of silicon (m^2)	1.7 (n^+/n)	1.0 (n^+/n)
Sensor thickness (μm)	250	285
Total number of modules	1744 (288 in disks)	1440 (672 in disks)
Barrel layer radii (cm)	5.1, 8.9, 12.3	4.4, 7.3, 10.2
Disk layer min. to max. radii (cm)	8.9 to 15.0	6.0 to 15.0
Disk positions in z (cm)	49.5, 58.0, 65.0	34.5, 46.5
Signal-to-noise ratio for minimum ionizing particles (day 1)	120	130
Total fluence at $L = 10^{34}$ (n_{eq}/cm^2/year) at radius of 4–5 cm (innermost layer)	3×10^{14}	3×10^{14}
Signal-to-noise ratio (after $10^{15}\ n_{eq}/cm^2$)	80	80
Resolution in $R\phi$ (μm)	≈10	≈10
Resolution in z/R (μm)	≈100	≈20

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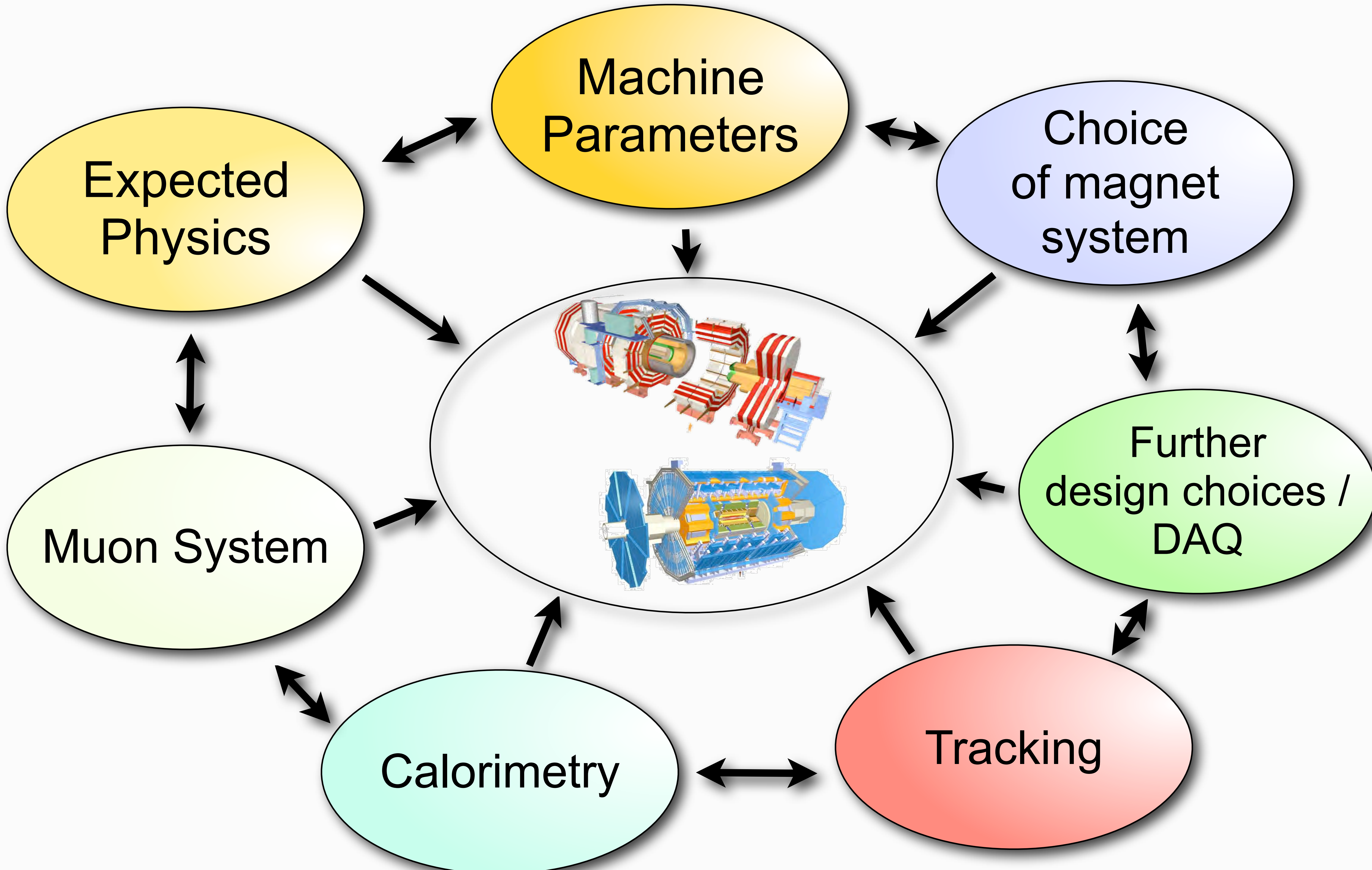
How to design your detector

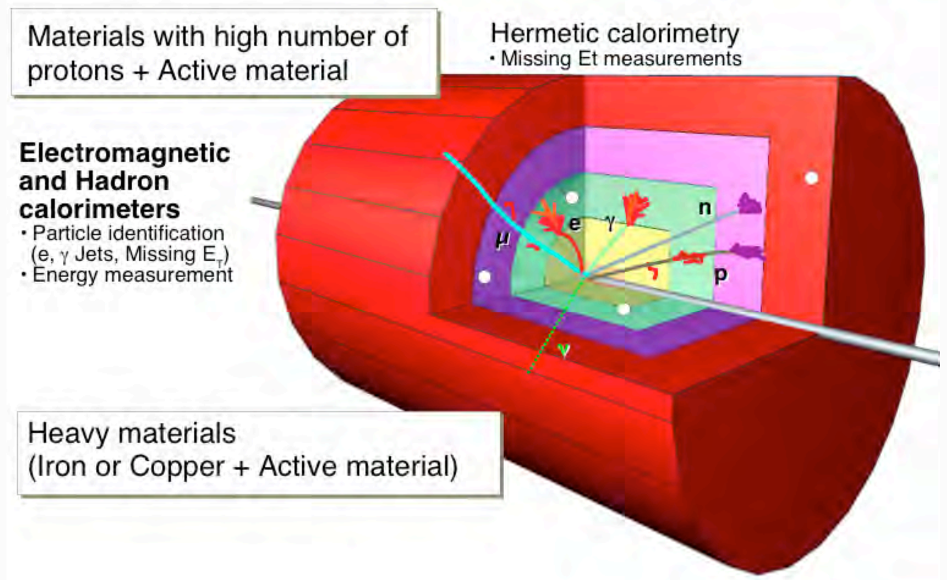


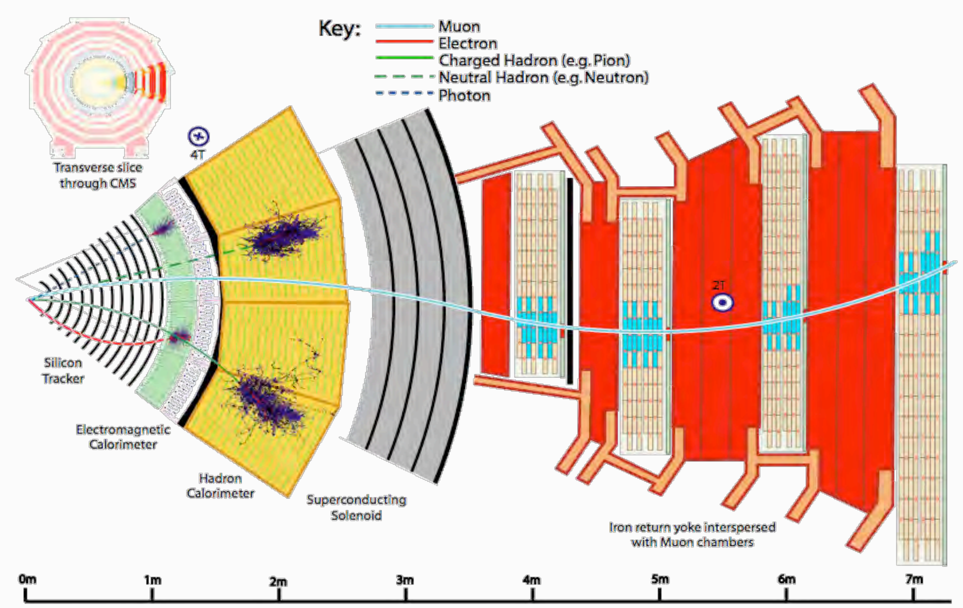
Main principles

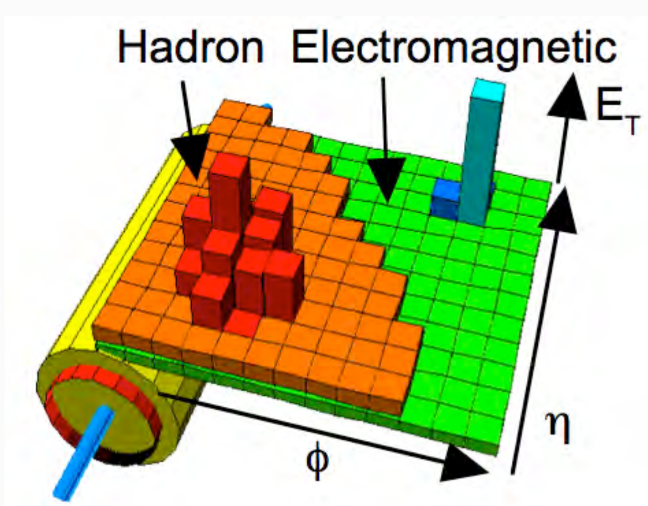
- Excellent energy measurement of electrons, photons, jets
  - good coverage up to $\eta \sim 5$, also for E_{Tmiss}

$$\text{Calorimeter} \quad \frac{\delta E}{E} \propto \frac{1}{\sqrt{E}} \qquad \text{Spectrometer} \quad \frac{\delta p}{p} \propto p$$

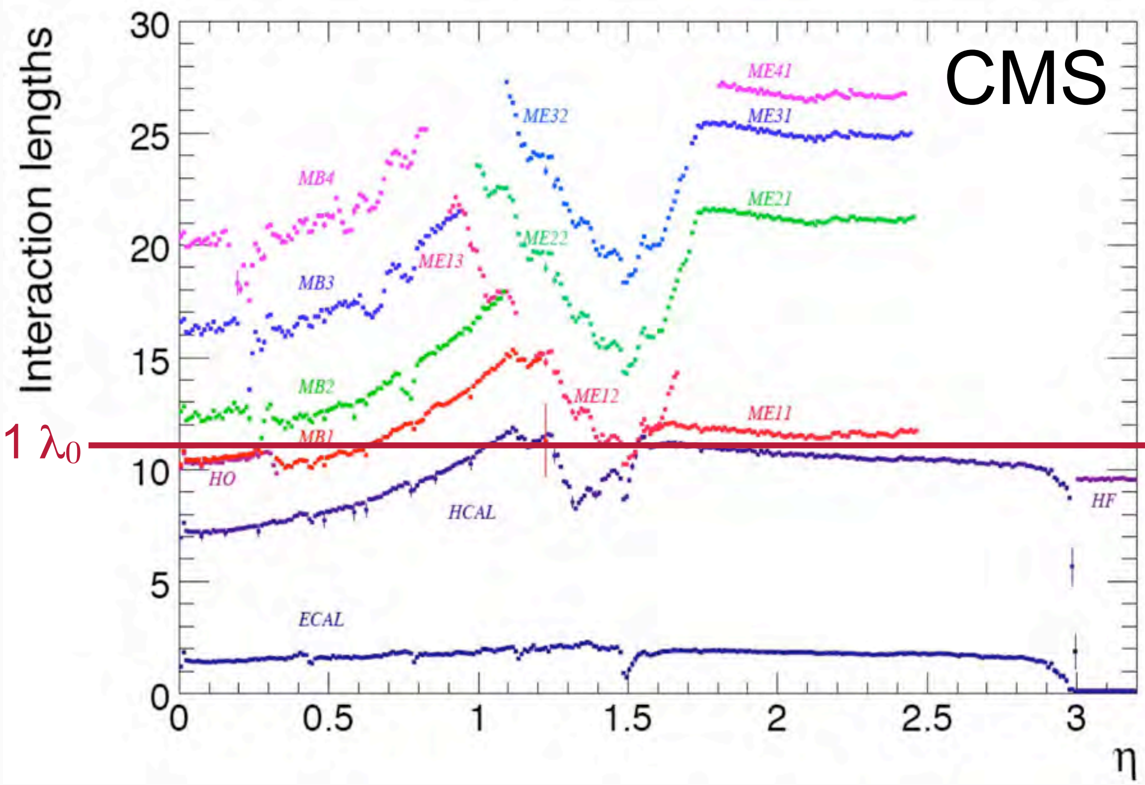
- Trigger on high-p_T objects
- Fine segmentation (lateral, longitudinal) for shower analysis
- Have to absorb ~ TeV objects (e,gamma,jets)
  - shower max position $x_{\max} \propto x_0 \ln E$
  - to cover elmg. shower of ~ 1 TeV : ~ 25 X_0
  - to contain hadronic jets of ~ 1 TeV : 11 λ_0
  - take $(X_0)_{PbWO4}$ = 0.89 cm
    - plus space for electronics : need ~ 50 cm
  - take $(\lambda_0)_{Fe}$ = 16.8 cm : would need ~ 180 cm
- CMS : R_{coil} - $R_{tracker}$ - ECAL (+electronics) ~ 1 m !!
  - only space for 6 λ_0 , 7 λ_0 including ECAL
  - added tail catcher (HO) after coil
- Further considerations
  - Homogenous vs. sampling calorimeter
  - Very forward calo : at large distance (less radiation) or closer (better uniformity of rap coverage)
  - Projective Tower sizes
    - relevant parameters: Moliere Radius, Occupancy
    - eg. $\Delta\eta \times (\Delta\Phi/2\pi) = 0.1 \times 0.1 \quad \text{over} \quad 2 \cdot y_{\max} = 10 \ \Rightarrow \mathcal{O}(10000) \text{ towers}$



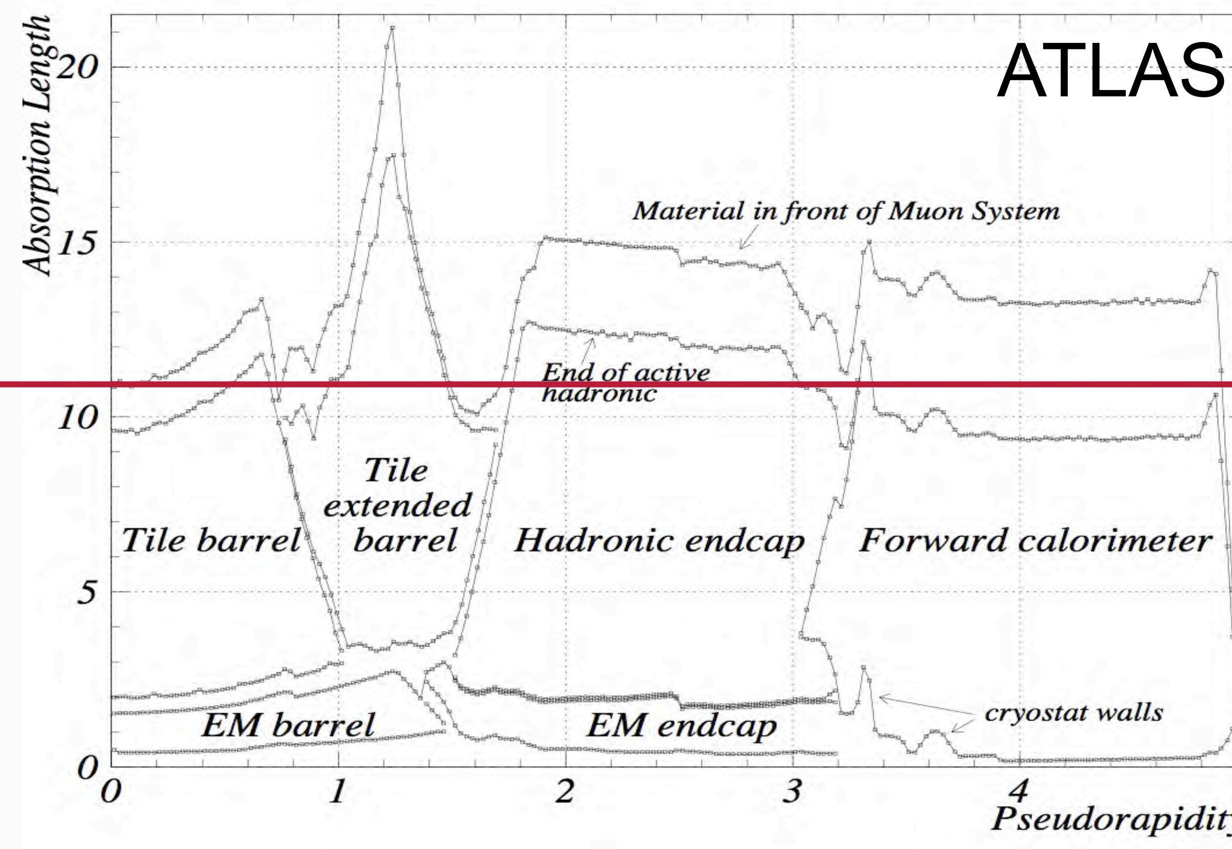


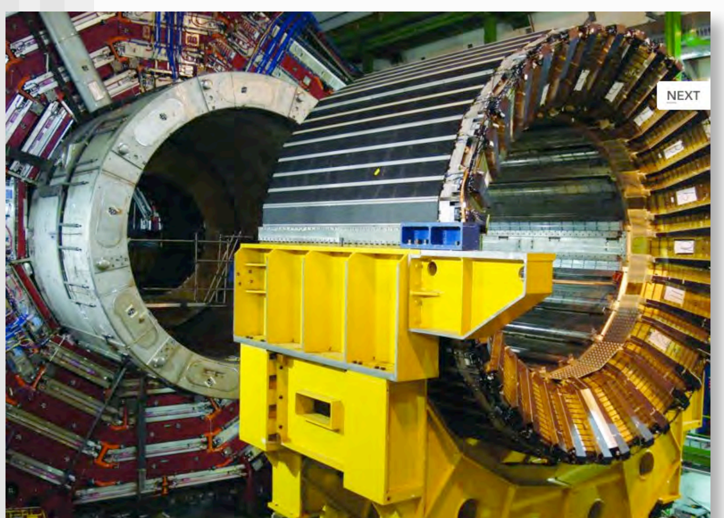


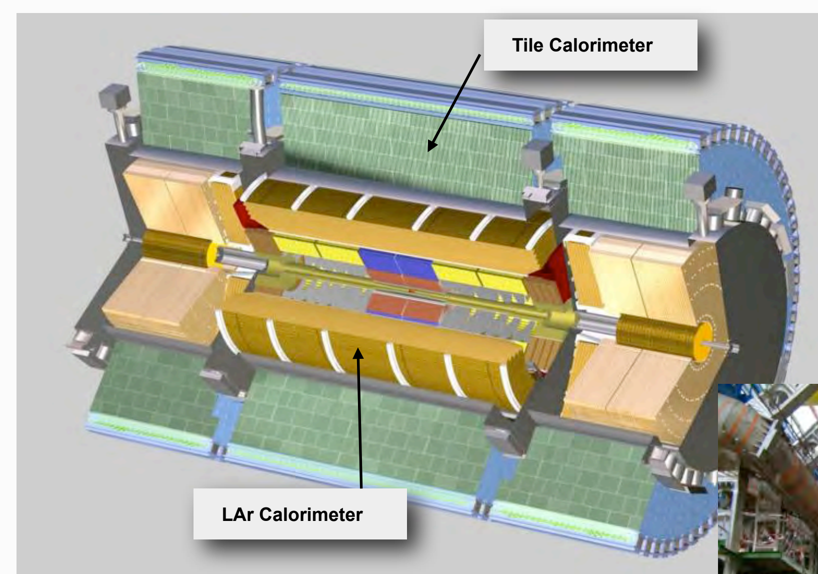
Coverage



11 λ_0







For reference

TABLE 8 Main parameters of the ATLAS and CMS electromagnetic calorimeters

	ATLAS		CMS	
Technology	Lead/LAr accordion		$PbWO_4$ scintillating crystals	
Channels	Barrel	End caps	Barrel	End caps
	110,208	63,744	61,200	14,648
Granularity	$\Delta\eta \times \Delta\phi$		$\Delta\eta \times \Delta\phi$	
Presampler	0.025×0.1	0.025×0.1		
Strips/ Si-preshower	0.003×0.1	0.003×0.1 to 0.006×0.1		32×32 Si-strips per 4 crystals
Main sampling	0.025×0.025	0.025×0.025	0.017×0.017	0.018×0.003 to 0.088×0.015
Back	0.05×0.025	0.05×0.025		
Depth	Barrel	End caps	Barrel	End caps
Presampler (LAr)	10 mm	2×2 mm		
Strips/ Si-preshower	$\approx 4.3\ X_0$	$\approx 4.0\ X_0$		$3\ X_0$
Main sampling	$\approx 16\ X_0$	$\approx 20\ X_0$	$26\ X_0$	$25\ X_0$
Back	$\approx 2\ X_0$	$\approx 2\ X_0$		
Noise per cluster	250 MeV	250 MeV	200 MeV	600 MeV
Intrinsic resolution	Barrel	End caps	Barrel	End caps
Stochastic term a	10%	10 to 12%	3%	5.5%
Local constant term b	0.2%	0.35%	0.5%	0.5%

Note the presence of the silicon preshower detector in front of the CMS end-cap crystals, which have a variable granularity because of their fixed geometrical size of $29 \times 29\ \text{mm}^2$. The intrinsic energy resolutions are quoted as parametrizations of the type $\sigma(E)/E = a/\sqrt{E} \oplus b$. For the ATLAS EM barrel and end-cap calorimeters and for the CMS barrel crystals, the numbers quoted are based on stand-alone test-beam measurements.

TABLE 9 Main parameters of the ATLAS and CMS hadronic calorimeters

	ATLAS	CMS
Technology		
Barrel/Ext. barrel	14 mm iron/3 mm scint.	50 mm brass/3.7 mm scint.
End caps	25–50 mm copper/8.5 mm LAr	78 mm brass/3.7 mm scint.
Forward	Copper (front) - Tungsten (back)/0.25–0.50 mm LAr	Steel/0.6 mm quartz
Channels		
Barrel/Ext. barrel	9852	2592
End caps	5632	2592
Forward	3524	1728
Granularity ($\Delta\eta \times \Delta\phi$)		
Barrel/Ext. barrel	0.1×0.1 to 0.2×0.1	0.087×0.087
End caps	0.1×0.1 to 0.2×0.2	0.087×0.087 to 0.18×0.175
Forward	0.2×0.2	0.175×0.175
Samplings ($\Delta\eta \times \Delta\phi$)		
Barrel/Ext. barrel	3	1
End caps	4	2
Forward	3	2
Abs. lengths (min.-max.)		
Barrel/Ext. barrel	9.7–13.0	7.2–11.0 10–14 (with coil/HO)
End caps	9.7–12.5	9.0–10.0
Forward	9.5–10.5	9.8

Note that the CMS barrel calorimeter (HB) is complemented by a tail catcher behind the coil (HO) to minimize problems with longitudinal leakage of high-energy particles in jets.

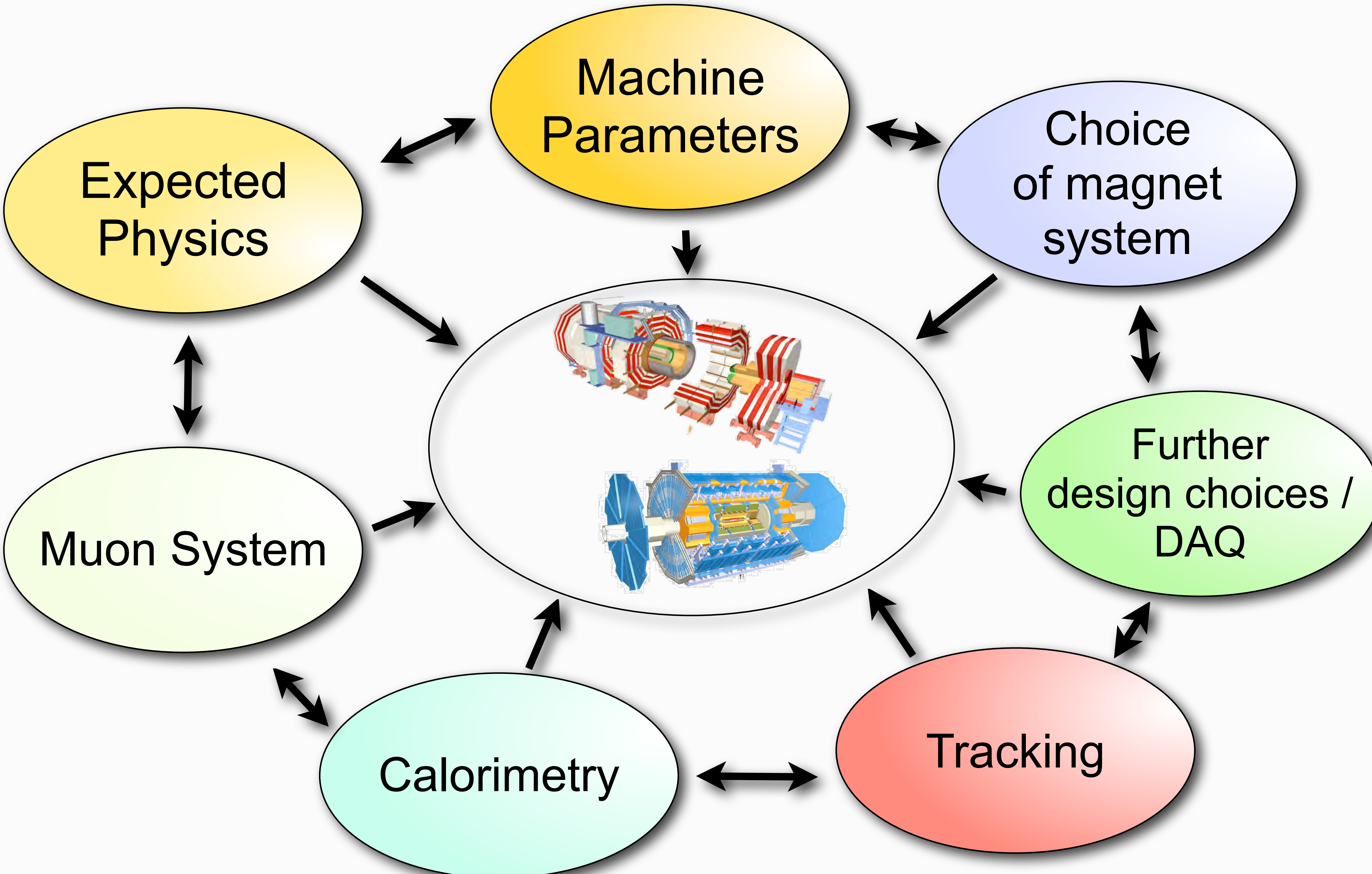
TABLE 10 Main performance parameters of the different hadronic calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions in both stand-alone and combined mode with the ECAL

	ATLAS				CMS	
	Barrel LAr/Tile		End-cap LAr			
	Tile	Combined	HEC	Combined	Had. barrel	Combined
Electron/hadron ratio	1.36	1.37	1.49			
Stochastic term	$45\%/\sqrt{E}$	$55\%/\sqrt{E}$	$75\%/\sqrt{E}$	$85\%/\sqrt{E}$	$100\%/\sqrt{E}$	$70\%/\sqrt{E}$
Constant term	1.3%	2.3%	5.8%	$< 1\%$		8.0%
Noise	Small	3.2 GeV		1.2 GeV	Small	1 GeV

The measured electron/hadron ratios are given separately for the hadronic stand-alone and combined calorimeters when available, and the contributions (added quadratically except for the stand-alone ATLAS tile calorimeter) to the pion energy resolution from the stochastic term, the local constant term, and the noise are also shown, when available from published data.

Froidevaux, Sphicas

How to design your detector

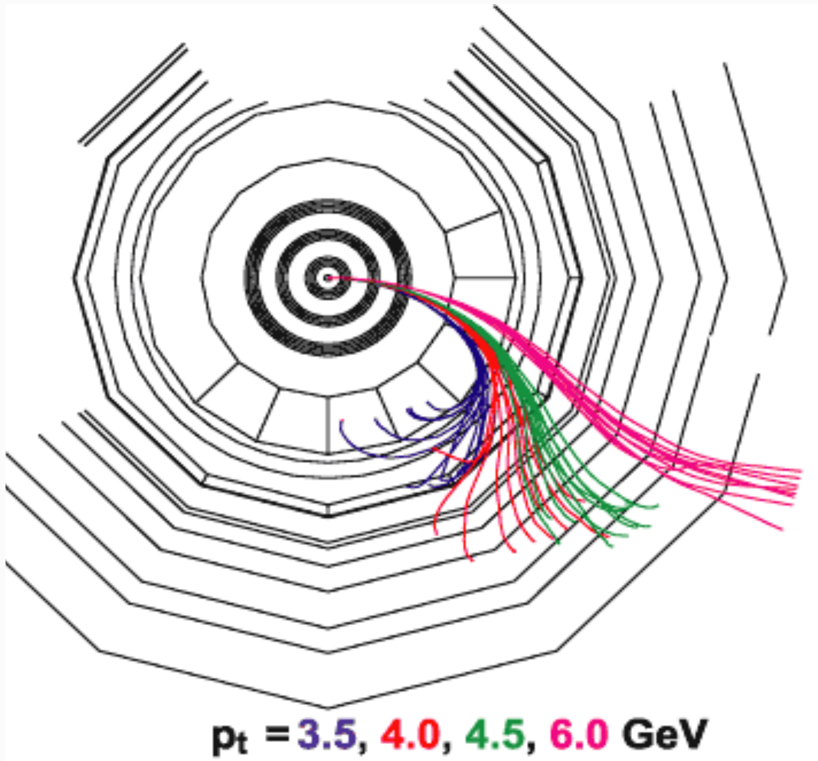


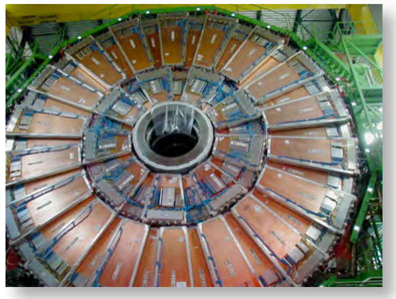
Requirements

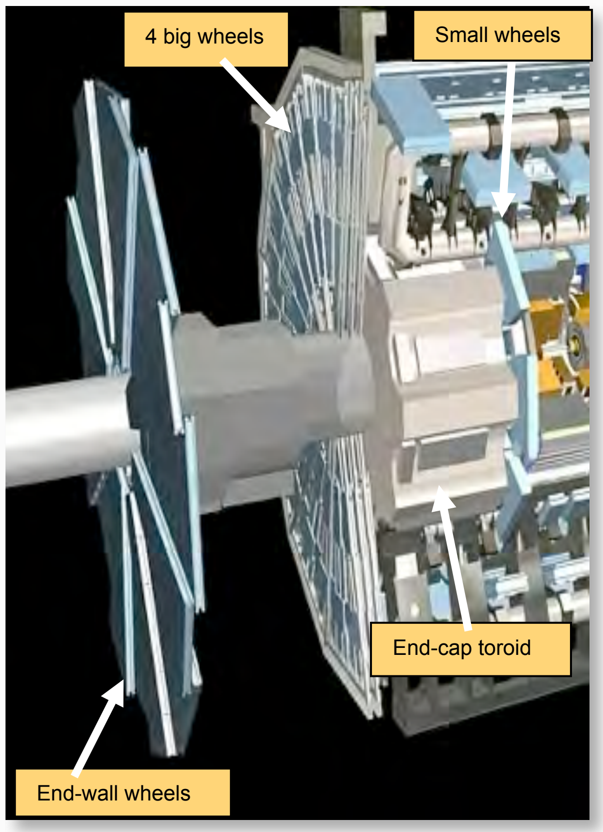
- Reconstruct mass of narrow 2-muon state (eg. Z mass) at 1% precision
- Reconstruct 1 TeV muons with 10% precision
- Over wide rapidity range
- Identification in dense environment
- Measure and trigger on muons in standalone mode, for momenta above ~ 5 GeV
  - CMS can use IP as further constraint
  - ATLAS has much less multiple scattering
- Combine different technologies for chambers
  - redundancy, robustness, radiation hardness, different speed
- Issues
  - Alignment (30 micron! for ATLAS)
  - Punch-through
  - Multiple scattering $\frac{\delta p_{\mathrm{MS}}}{p} \approx \frac{52 \cdot 10^{-3}}{\beta\, B \sqrt{L\, x_0}}$

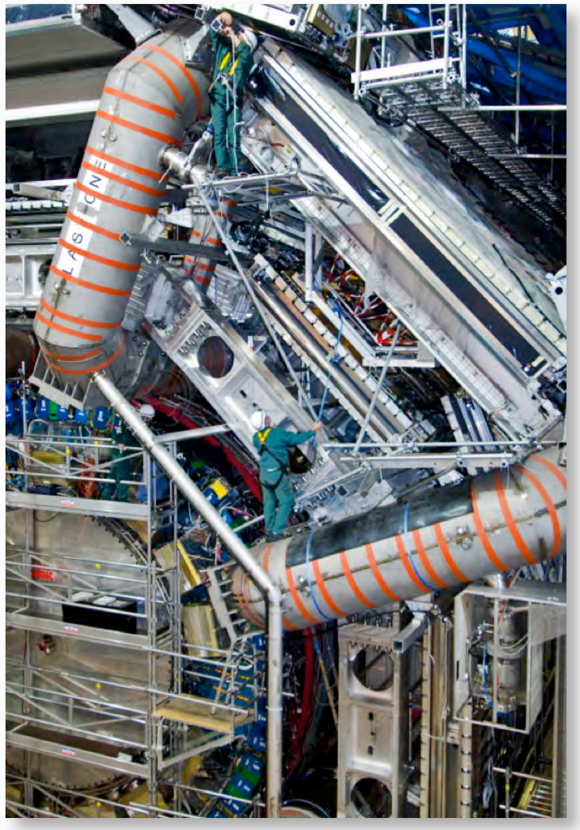
$$\text{for } \beta \approx 1\,,\ B = 2\,\mathrm{T}\,,\ L \approx 2\,\mathrm{m}\,,\ x_0 = 0.14\,\mathrm{m} \quad \Rightarrow \quad \frac{\delta p_{\mathrm{MS}}}{p} \approx 5\,\%$$

  - will limit standalone triggering capabilities in very high rate environment

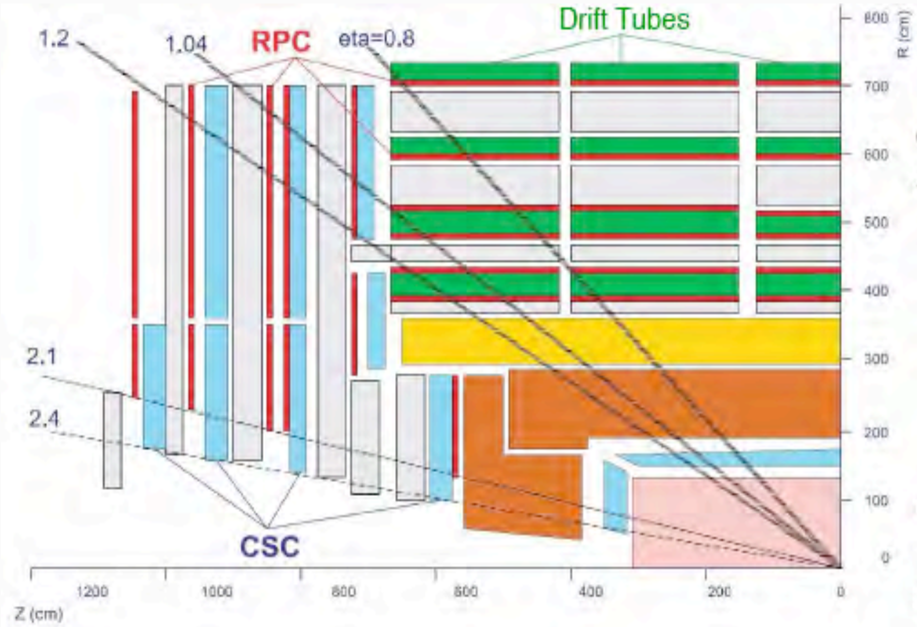


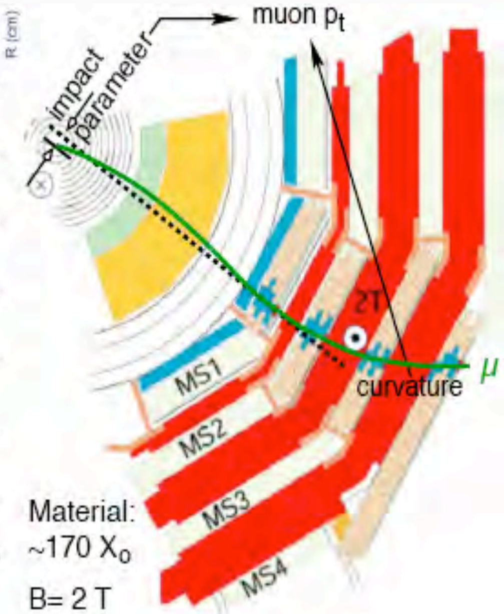


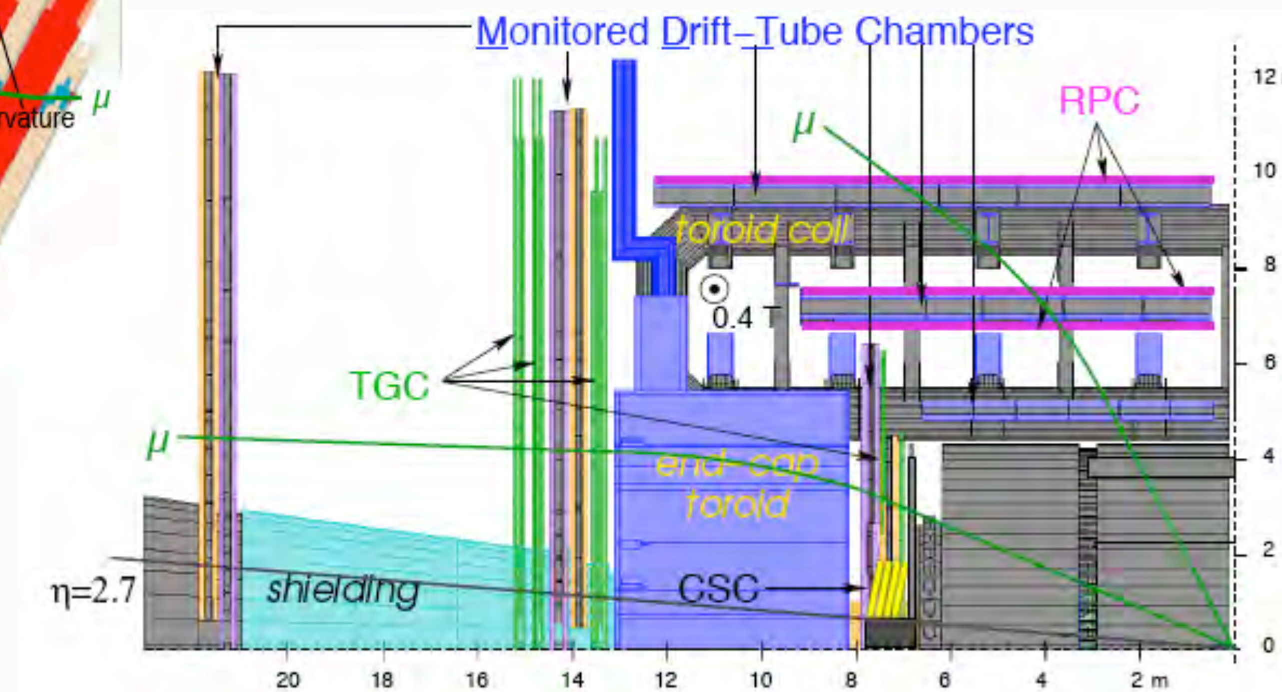




Comparison







CMS muon spectrometer

- Superior combined momentum resolution in central region
- Limited stand-alone resolution and trigger (at very high luminosities) due to multiple scattering in iron
- Degraded overall resolution in the forward regions ($|\eta| > 2.0$) where solenoid bending power becomes insufficient

ATLAS muon spectrometer

- Excellent stand-alone capabilities and coverage in open geometry
- Complicated geometry and field configuration (large fluctuations in acceptance and performance over full potential η x φ coverage ($|\eta| < 2.7$)

by D. Froidevaux

For reference

TABLE 11 Main parameters of the ATLAS and CMS muon chambers

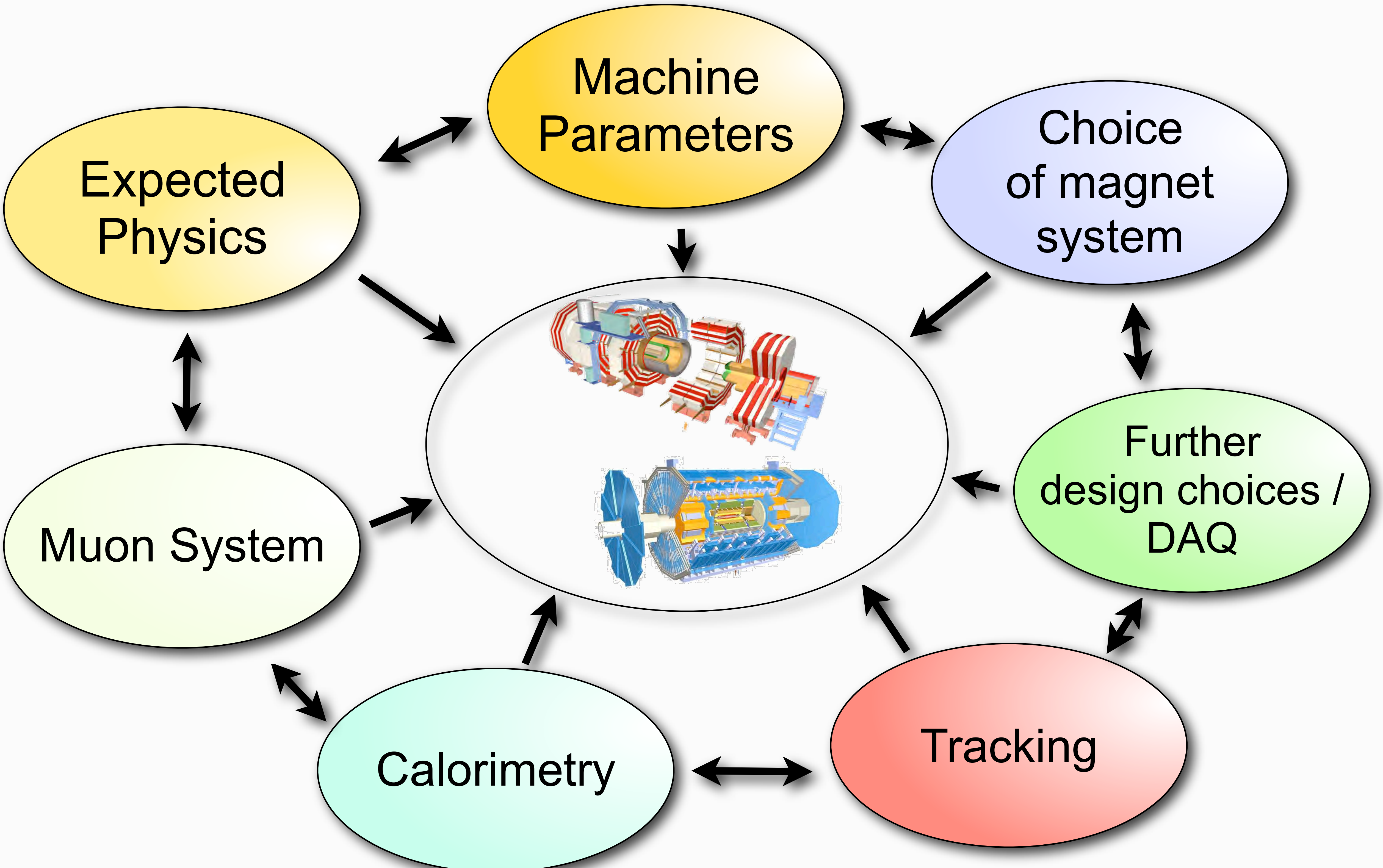
	ATLAS	CMS
Drift Tubes	MDTs	DTs
-Coverage	$\lvert\eta\rvert < 2.0$	$\eta\rvert < 1.2$
-Number of chambers	1170	250
-Number of channels	354,000	172,000
-Function	Precision measurement	Precision measurement, triggering
Cathode Strip Chambers		
-Coverage	$2.0 < \lvert\eta\rvert < 2.7$	$1.2 < \lvert\eta\rvert < 2.4$
-Number of chambers	32	468
-Number of channels	31,000	500,000
-Function	Precision measurement	Precision measurement, triggering
Resistive Plate Chambers		
-Coverage	$\lvert\eta\rvert < 1.05$	$\lvert\eta\rvert < 2.1$
-Number of chambers	1112	912
-Number of channels	374,000	160,000
-Function	Triggering, second coordinate	Triggering
Thin Gap Chambers		
-Coverage	$1.05 < \lvert\eta\rvert < 2.4$	—
-Number of chambers	1578	—
-Number of channels	322,000	—
-Function	Triggering, second coordinate	—

TABLE 12 Main parameters of the ATLAS and CMS muon measurement systems as well as a summary of the expected combined and stand-alone performance at two typical pseudorapidity values (averaged over azimuth)

Parameter	ATLAS	CMS
Pseudorapidity coverage		
-Muon measurement	$\lvert\eta\rvert < 2.7$	$\lvert\eta\rvert < 2.4$
-Triggering	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.1$
Dimensions (m)		
-Innermost (outermost) radius	5.0 (10.0)	3.9 (7.0)
-Innermost (outermost) disk (z-point)	7.0 (21–23)	6.0–7.0 (9–10)
Segments/superpoints per track for barrel (end caps)	3 (4)	4 (3–4)
Magnetic field B (T)	0.5	2
-Bending power (BL, in T· m) at $\lvert\eta\rvert \approx 0$	3	16
-Bending power (BL, in T· m) at $\lvert\eta\rvert \approx 2.5$	8	6
Combined (stand-alone) momentum resolution at		
-p = 10 GeV and $\eta \approx 0$	1.4% (3.9%)	0.8% (8%)
-p = 10 GeV and $\eta \approx 2$	2.4% (6.4%)	2.0% (11%)
-p = 100 GeV and $\eta \approx 0$	2.6% (3.1%)	1.2% (9%)
-p = 100 GeV and $\eta \approx 2$	2.1% (3.1%)	1.7% (18%)
-p = 1000 GeV and $\eta \approx 0$	10.4% (10.5%)	4.5% (13%)
-p = 1000 GeV and $\eta \approx 2$	4.4% (4.6%)	7.0% (35%)

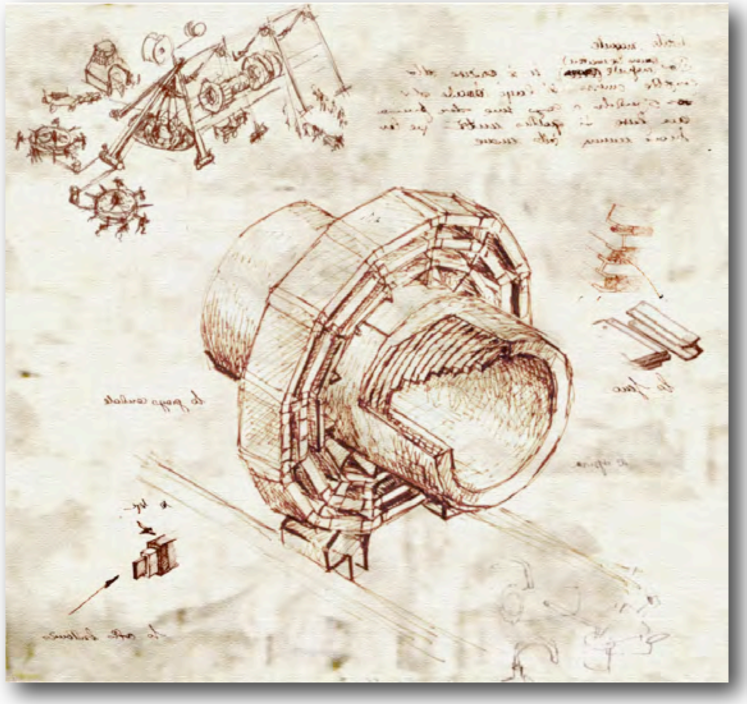
Froidevaux, Sphicas

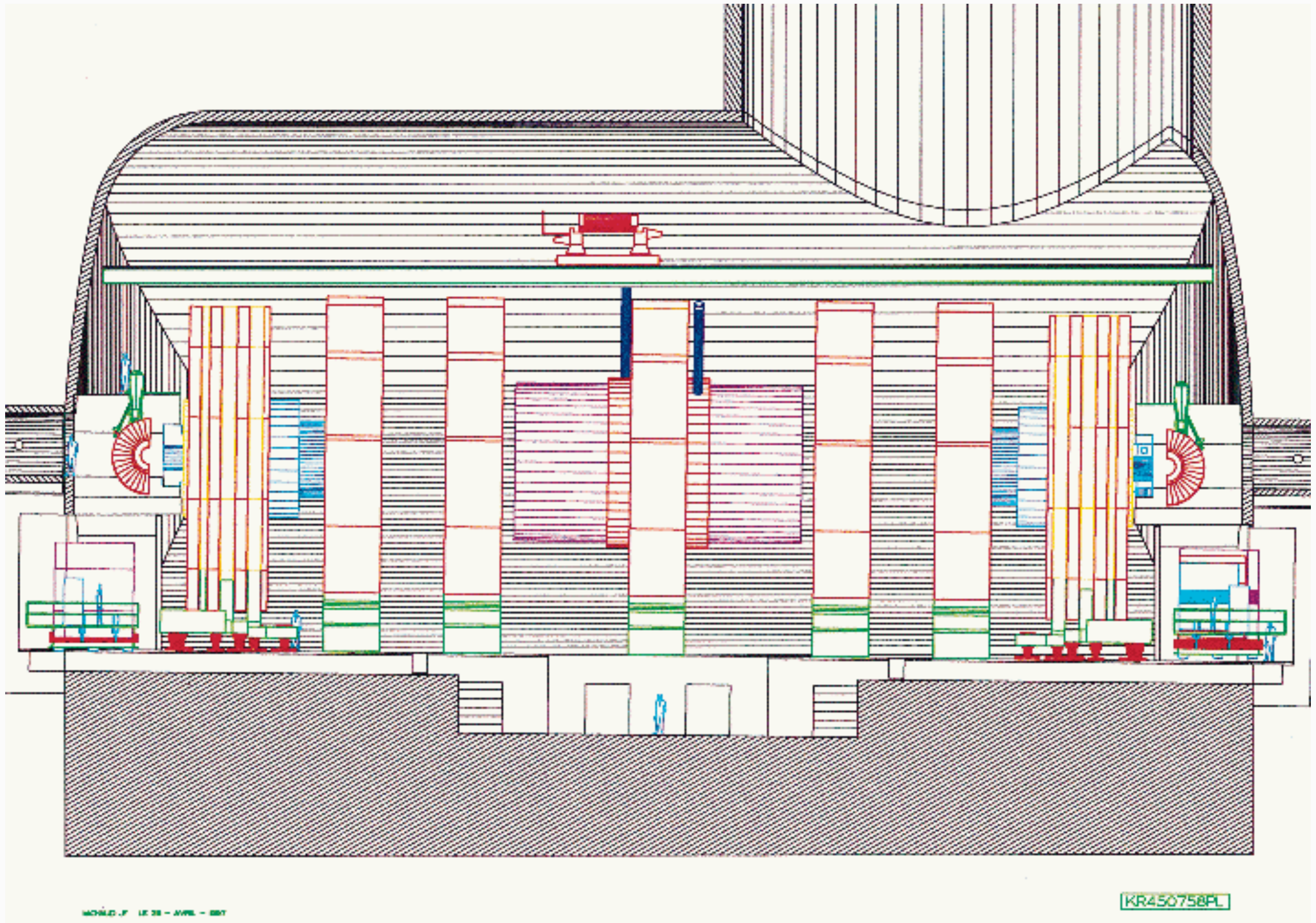
How to design your detector



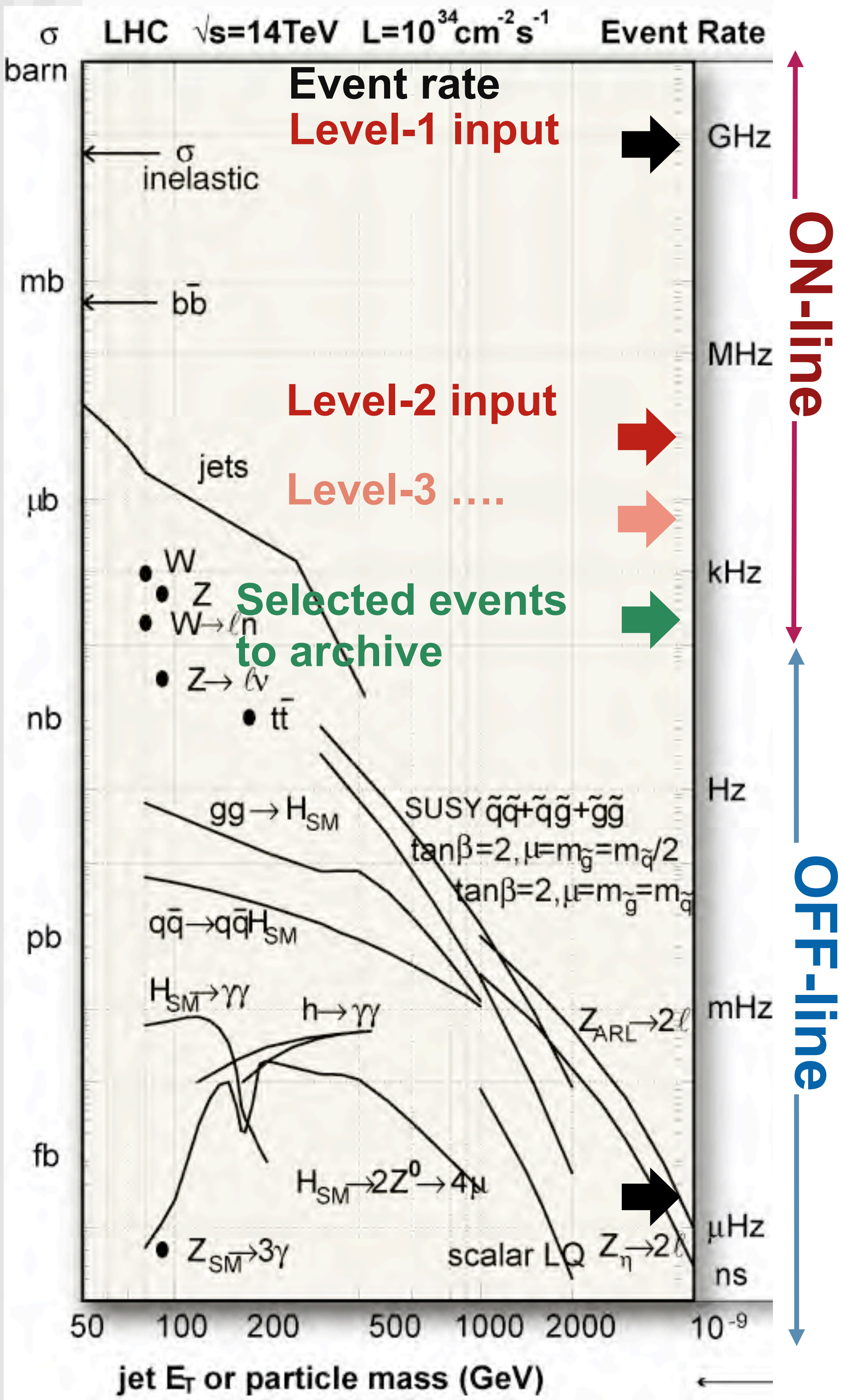
Some CMS examples...

- Modular structure
  - eg. CMS Barrel 13m long:
    not possible to build such long muon-chambers
  - Idea of wheels. All cabling independent. Flexibility.
  - Original idea: build/test everything at surface.
  - Every part of detector "easily" accessible during shutdowns
  - CMS Pixel detector is dramatic example

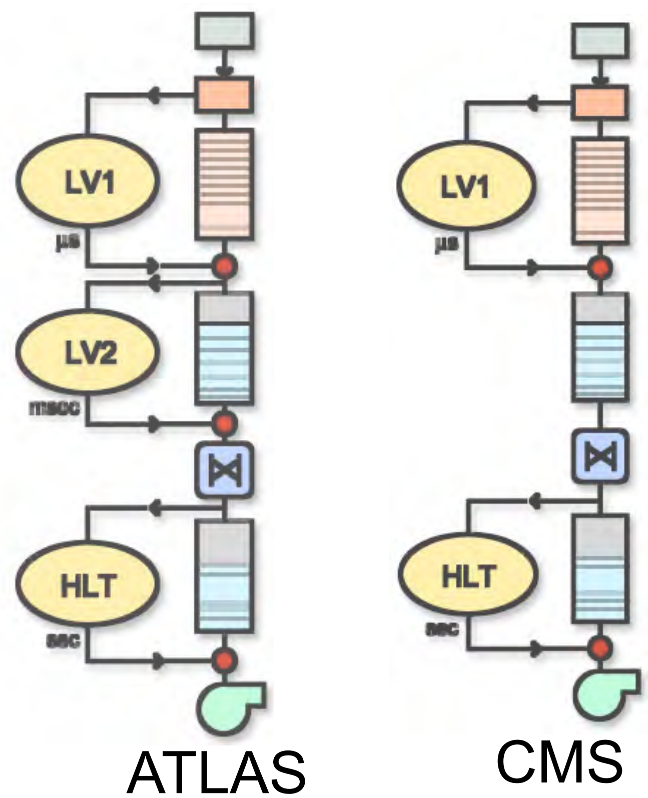




Multi-level trigger DAQ architecture



S. Cittolin. CERN/CMS/RT2009



On-line requirements

Collision rate	40 MHz
Event size	1 Mbyte
Level-1 Trigger input	40 MHz
Level-2 Trigger input	100 kHz
Level-3 Trigger input	xx kHz
......	
Mass storage rate	~100 Hz
Event rejection power	$\sim 10^7$
System dead time	~ %

DAQ design issues

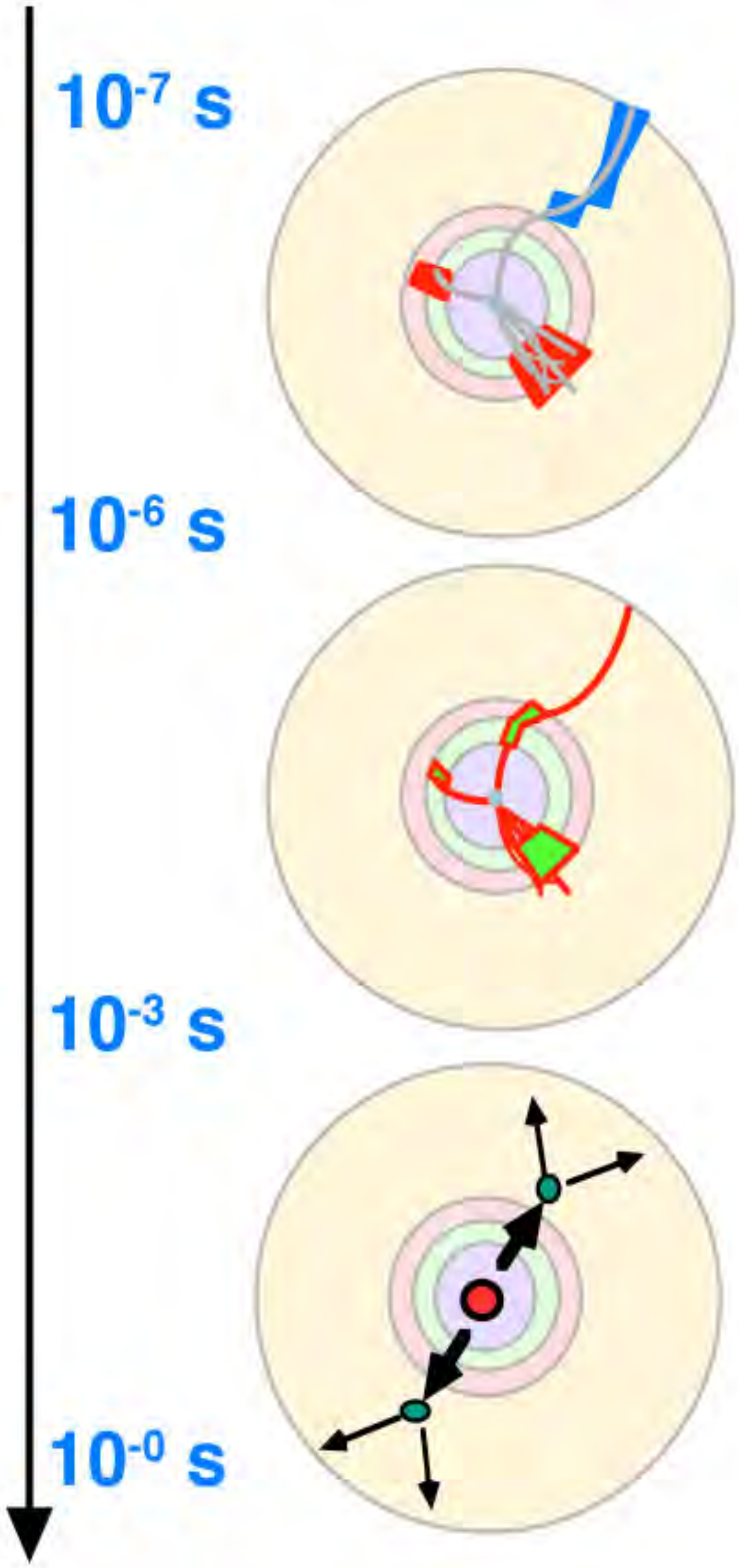
Data network bandwidth (EVB)	~ Tb/s
Computing power (HLT)	~ 10 Tflop
Computing cores	~ 10000
Local storage	~ 300 TB

Minimize custom design
Exploit data communication and computing technologies
DAQ staging by modular design (scaling)

Further requirements

Robustness, ie. operational efficiency independent of noise/machine conditions
Multiple overlapping triggers for estimating efficiency (without MC)
Provide also triggers/data streams for calibration

Trigger Levels ("The first second)"



Collision rate 10^9 Hz

Channel data sampling at 40 MHz

Level-1 selected events 10^5 Hz

Particle identification (High p_T e, μ, jets, missing E_T)

- Local pattern recognition
- Energy evaluation on prompt macro-granular information

Level-2 selected events 10^3 Hz

Clean particle signature (Z, W, ..)

- Finer granularity precise measurement
- Kinematics. effective mass cuts and event topology
- Track reconstruction and detector matching

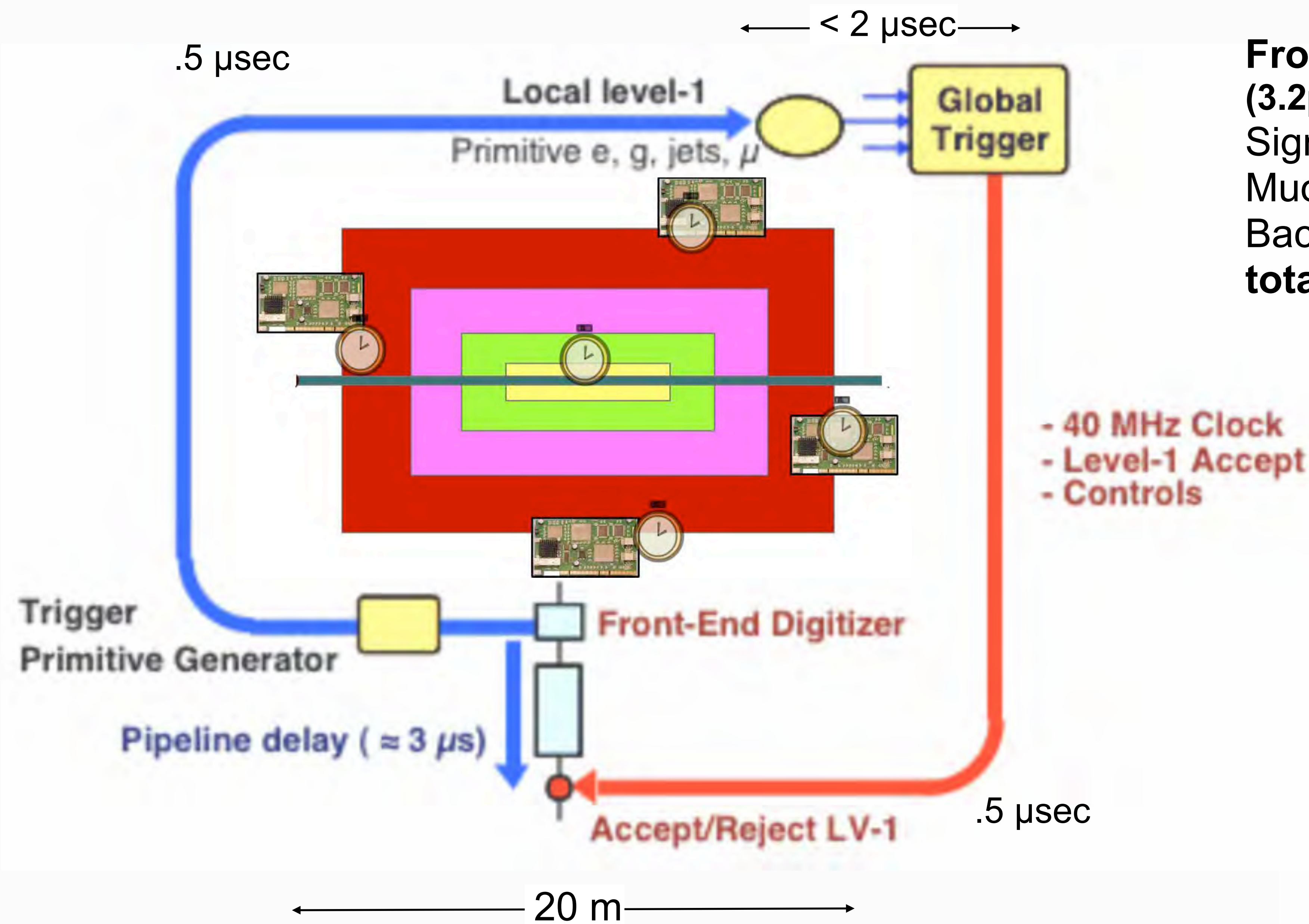
Level-3 events to tape 10..100 Hz

Physics process identification

- Event reconstruction and analysis

S. Cittolin. CERN/CMS/RT2009

40 MHz event selection and front-end structure



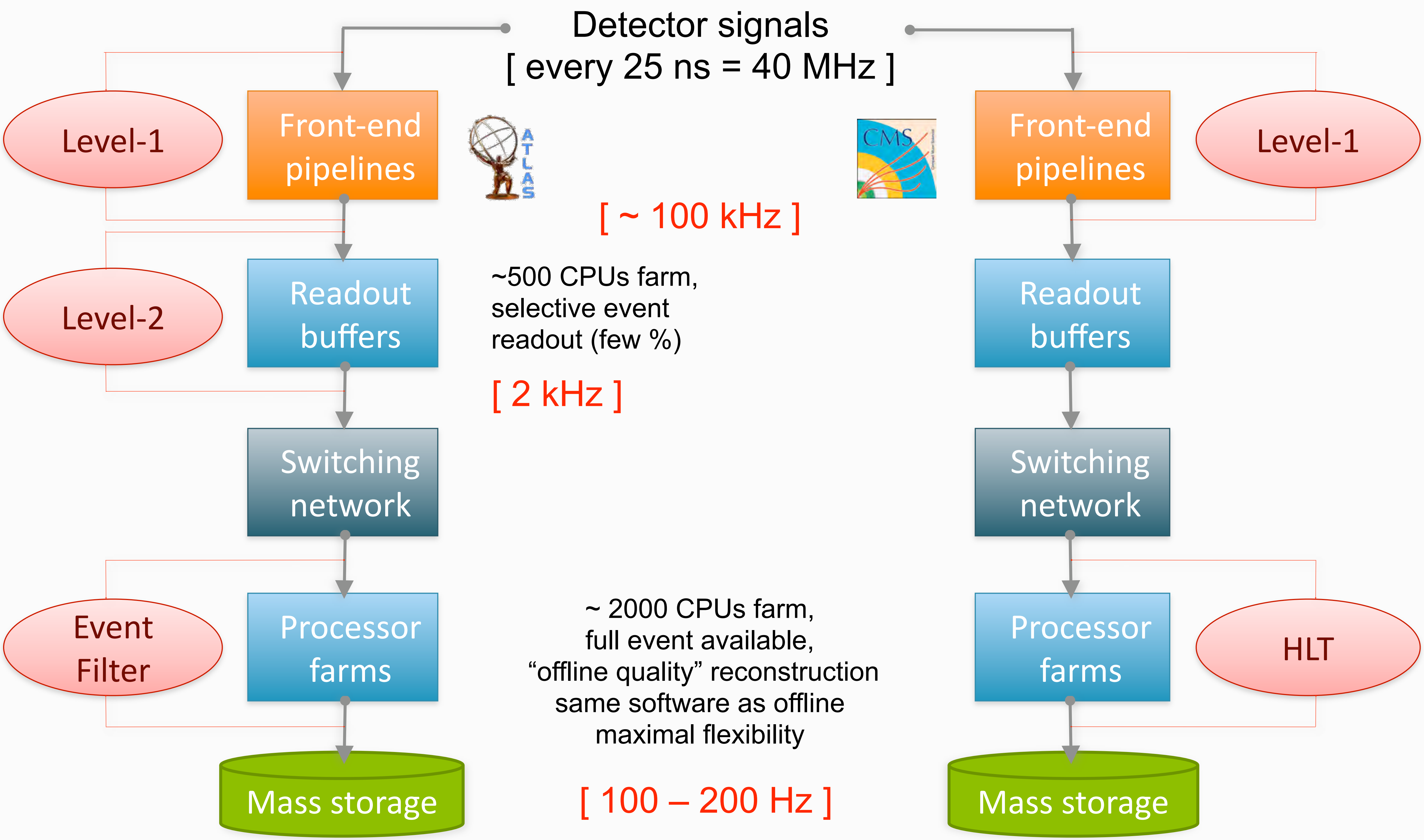
Front-end time budget
(3.2μs = 128 Bunch crossings)

Signals to central logic	18bx
Muon/Calo logic	90bx
Back to detectors	18bx
total latency ≤128bx	

40 MHz digitizers and 3.2μs x 25ns step **pipeline readout buffers**
40 MHz Level-1 trigger (**massive parallel pipelined processors**)
High precision (~ 100ps) **timing, trigger and control distribution**

S. Cittolin. CERN/CMS/RT2009

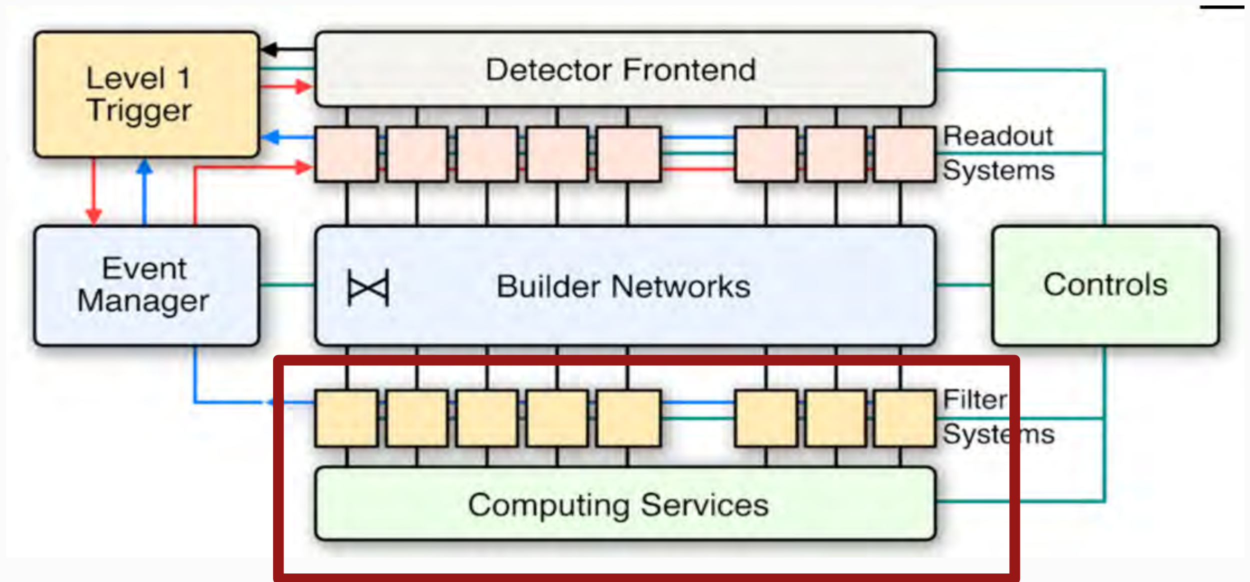
ATLAS and CMS HLT Concepts



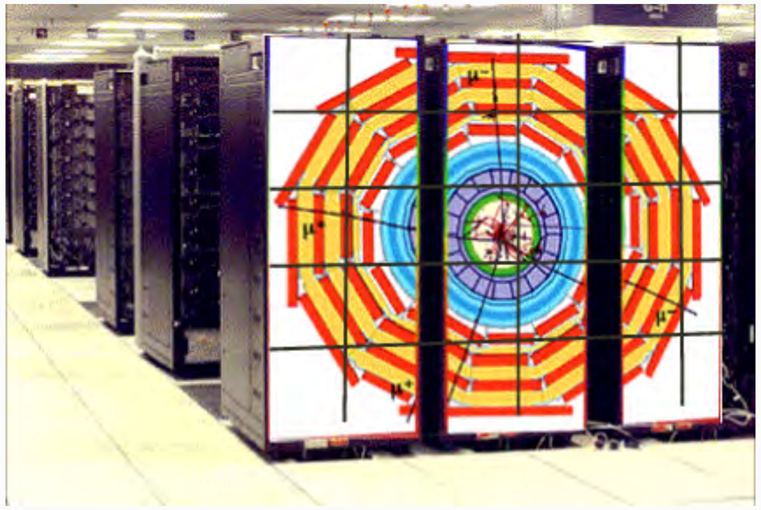
A. Höcker,HCPSS 09

Event selection parallel processing

Level 1 trigger: Massive parallel



Farm of processors
ONE Event, ONE processors
- Simple interconnect
- Sequential programming
- 100 kHz, 10000 cores, 100 ms x event
- **Scale free. High latency (large memory)**



Massive parallel system
ONE Event, ALL processors
- Complex I/O
- Programming complexity
- **Low latency. Exponential scaling.**

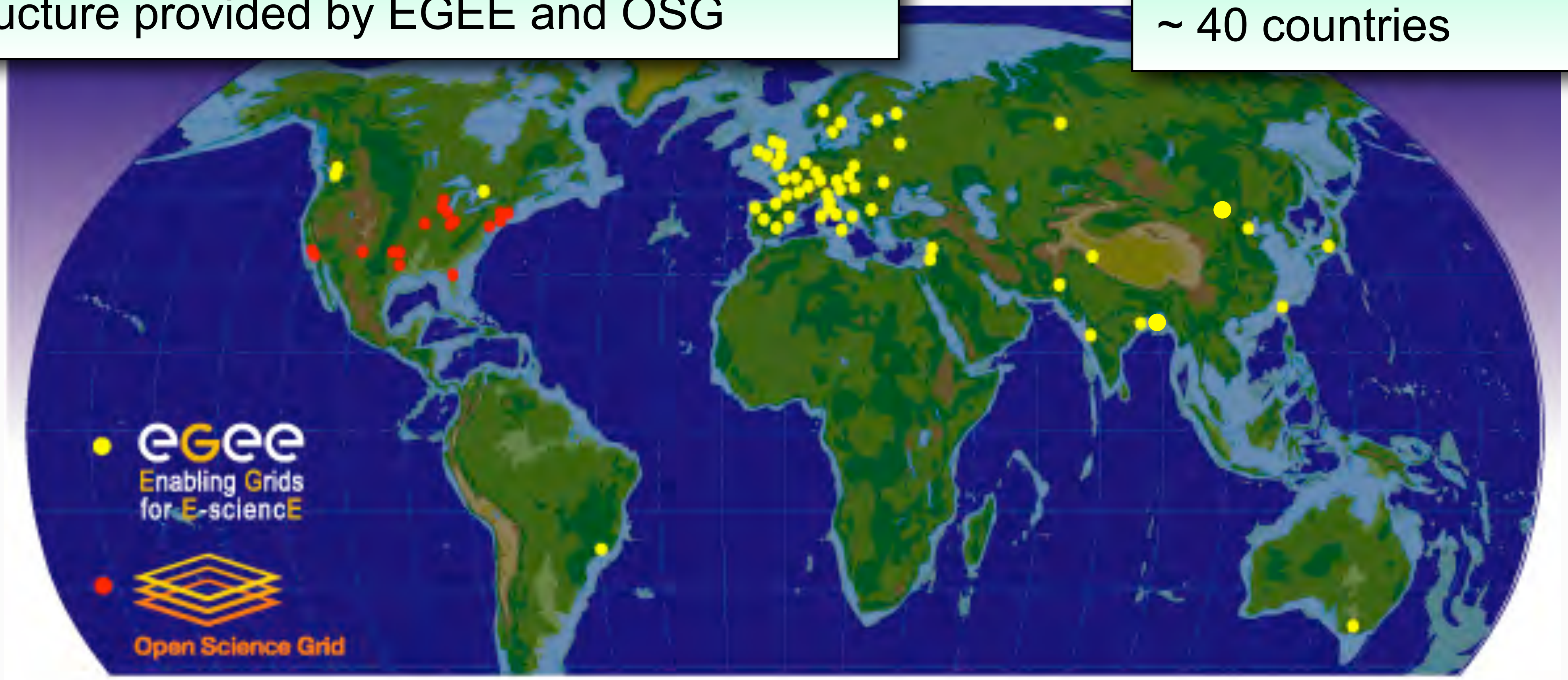
S. Cittolin. CERN/CMS/RT2009

Finally, need massive (distributed) computing resources (CPU, storage)

- The LHC experiments will produce 10-15 PB of data per year:
  - corresponds to ~ 20 million CD (a 20 km stack …)
- Data analysis requires computing power equivalent to ~10^5 today's fastest PC processors
- The experiment Collaborations are spread all over the world
  - Computing resources must be distributed.
- The Grid provides seamless access to computing power and data storage capacity distributed over the globe.

A map of the worldwide LHC Computing Grid infrastructure provided by EGEE and OSG

~120 computing centers
~ 40 countries



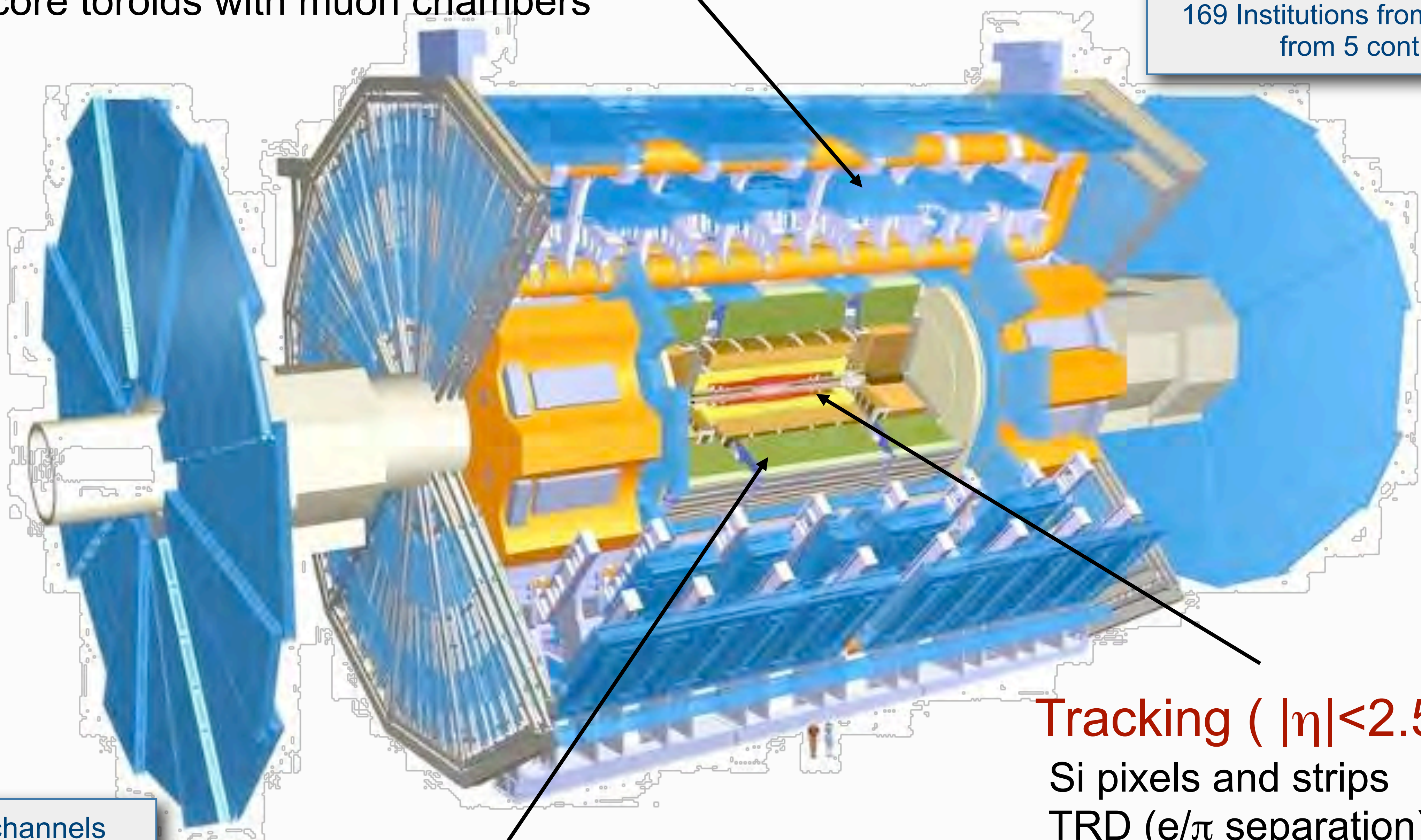
Finally:
The Detectors
ATLAS and CMS

ATLAS

and …. 2800 physicists
(800 PhD students) from
169 Institutions from 37 countries
from 5 continents

Muon Spectrometer ($|\eta|<2.7$)

air-core toroids with muon chambers



Tracking ($|\eta|<2.5$, B=2T)

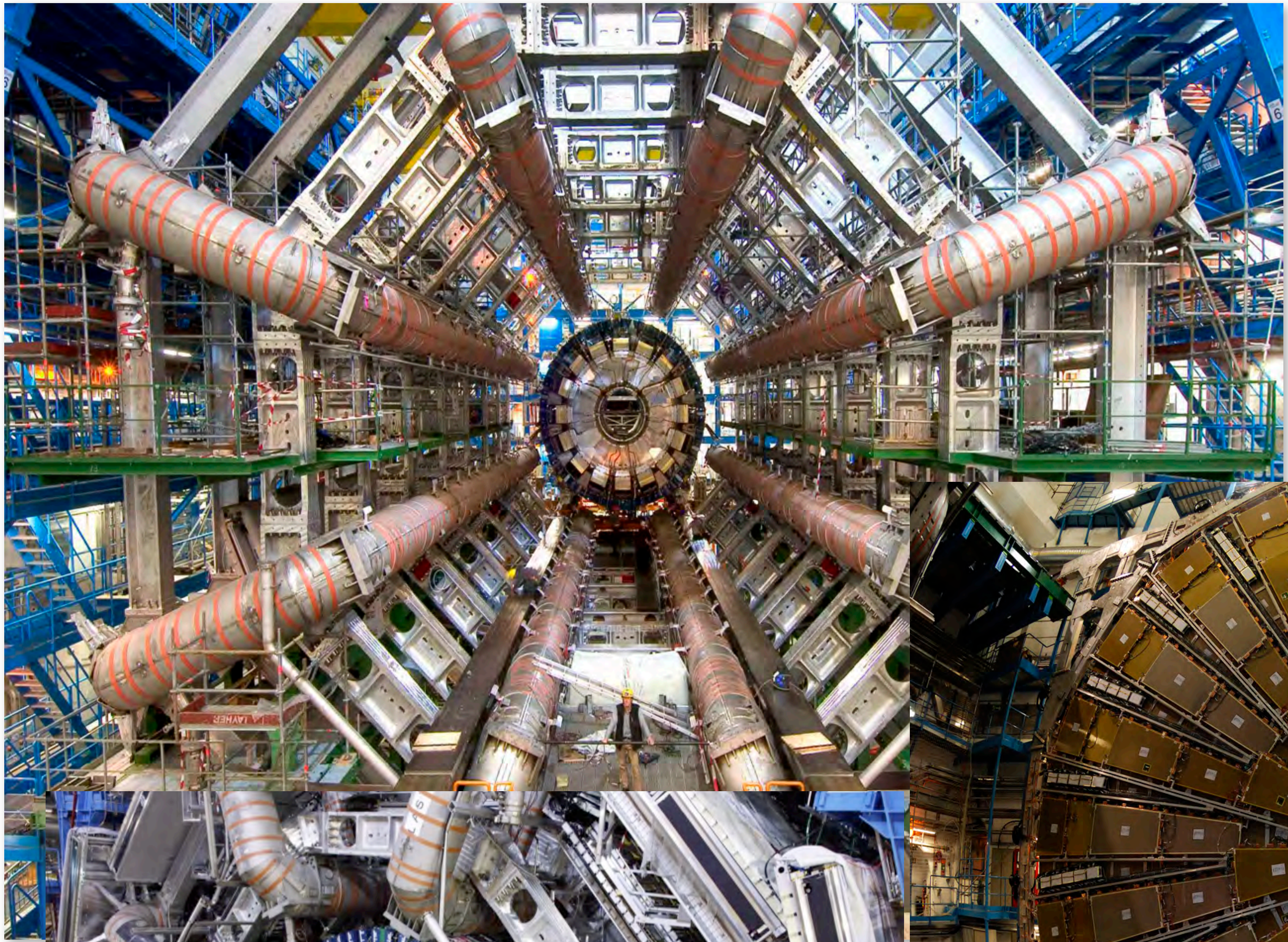
Si pixels and strips
TRD (e/π separation)

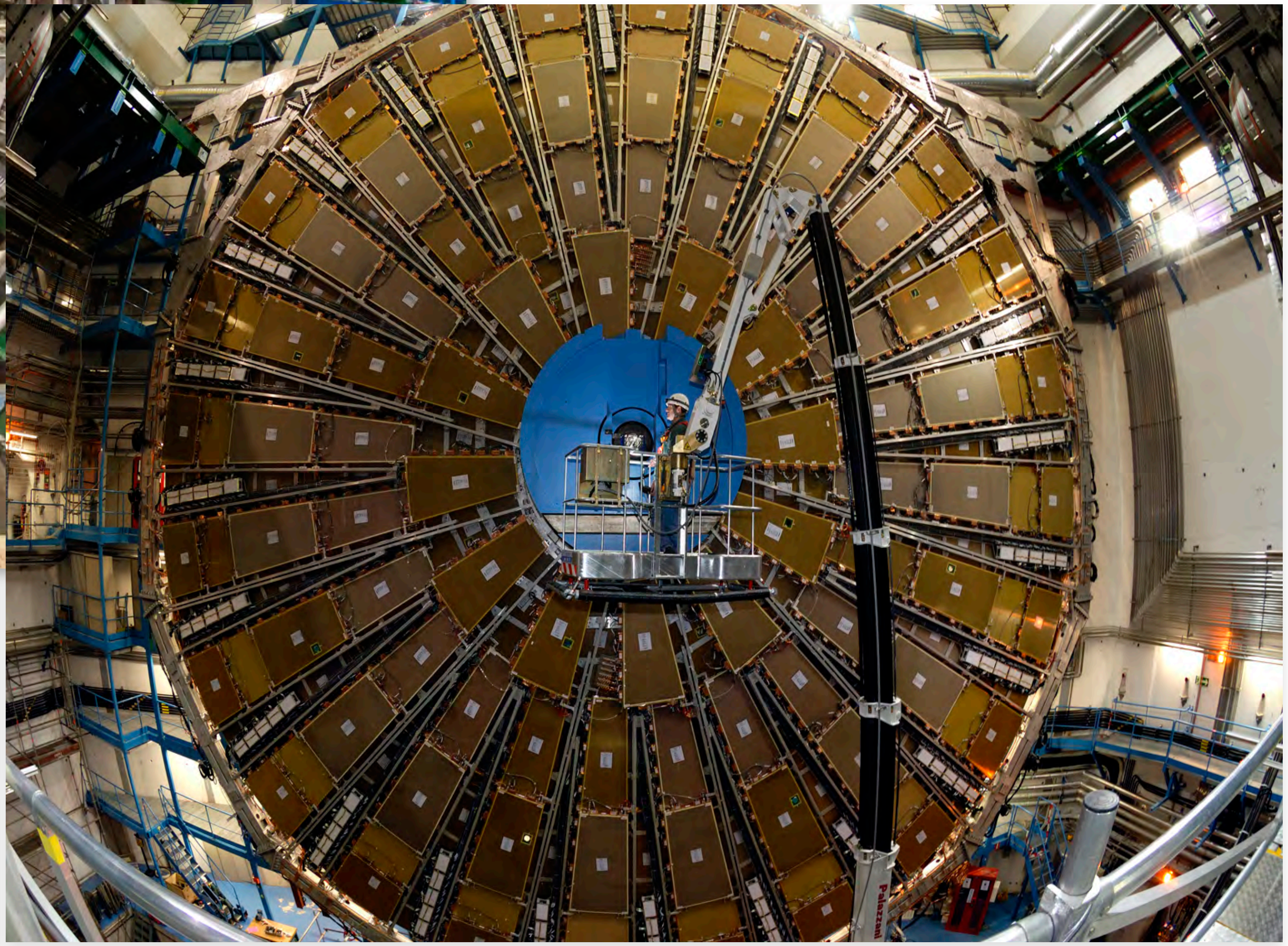
$\sim 10^8$ electronic channels
~3000 km cables

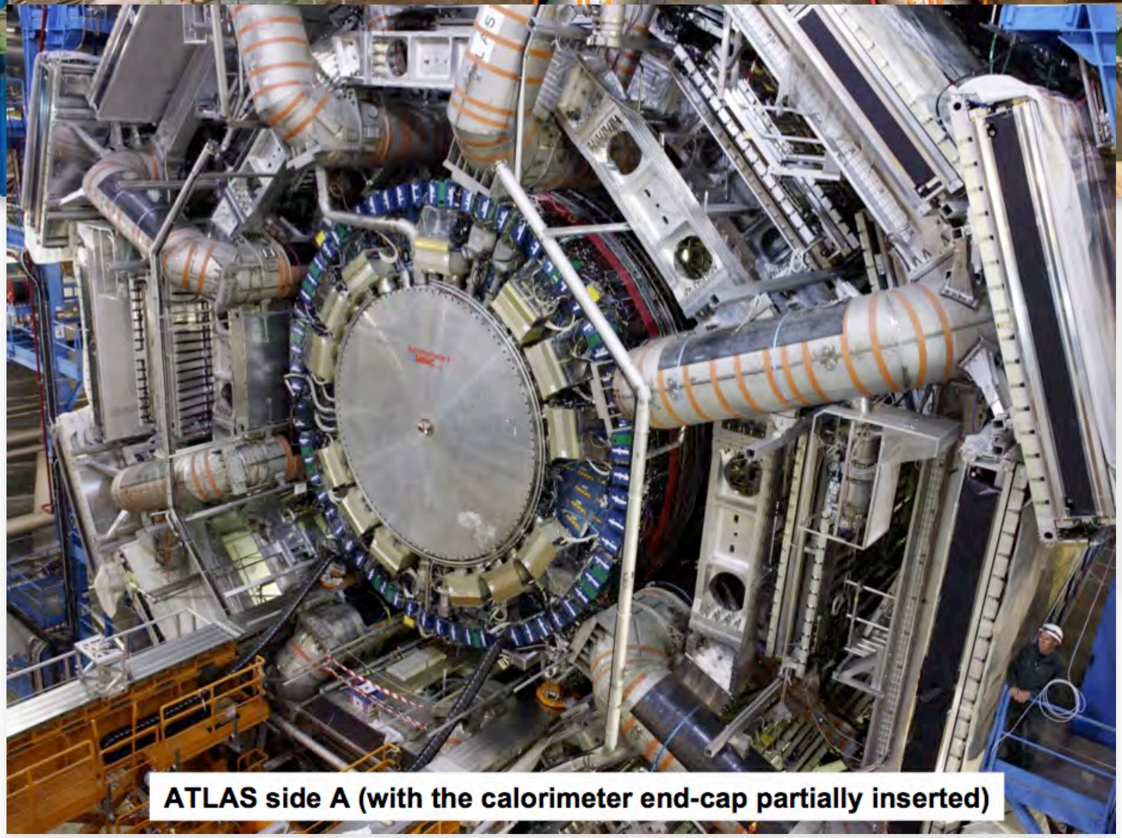
Calorimetry ($|\eta|<5$)

EM : Pb-LAr
HAD : Fe/scintillator (central),
Cu/W-Lar (fwd)

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



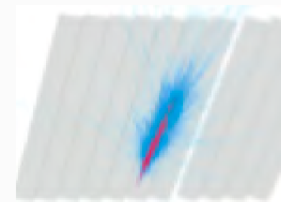




ATLAS side A (with the calorimeter end-cap partially inserted)

Compact Muon Solenoid

Superconducting Coil, 4 Tesla



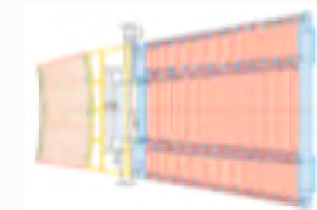
CALORIMETERS

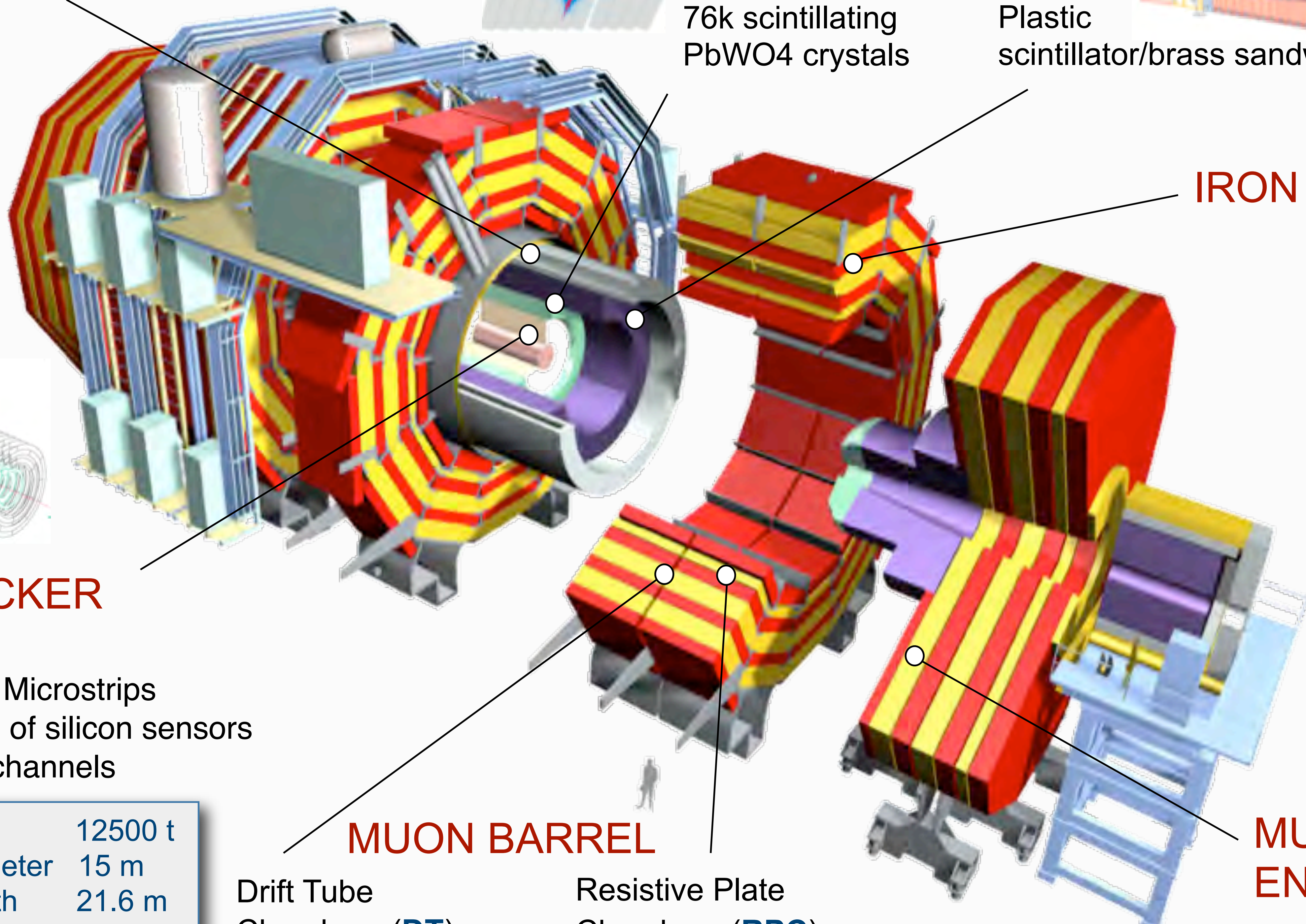
ECAL

76k scintillating PbWO4 crystals

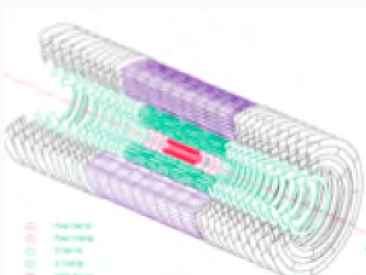
HCAL

Plastic scintillator/brass sandwich





IRON YOKE



TRACKER

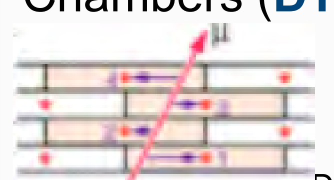
Pixels
Silicon Microstrips
210 m^2 of silicon sensors
9.6 M channels

Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

2900 scientists from
183 Institutes from
38 countries

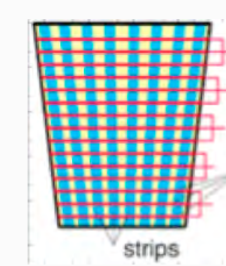
MUON BARREL

Drift Tube Chambers (**DT**)

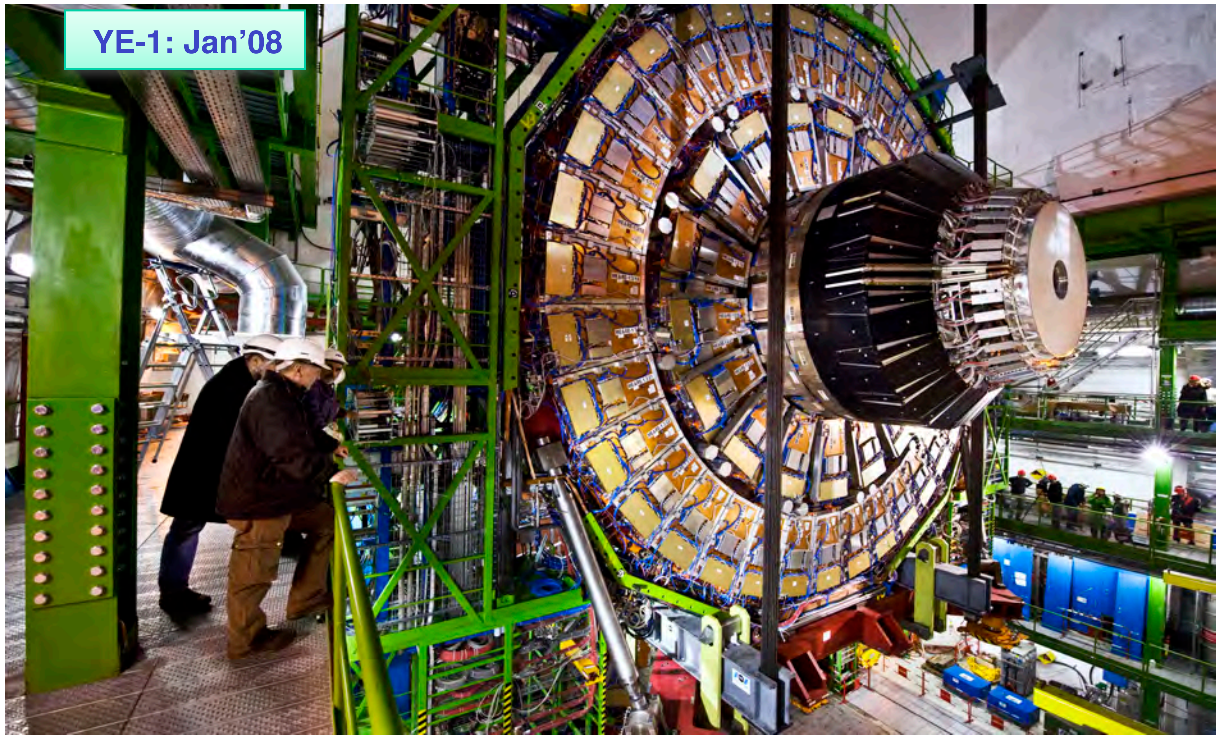


Resistive Plate Chambers (**RPC**)

MUON ENDCAPS

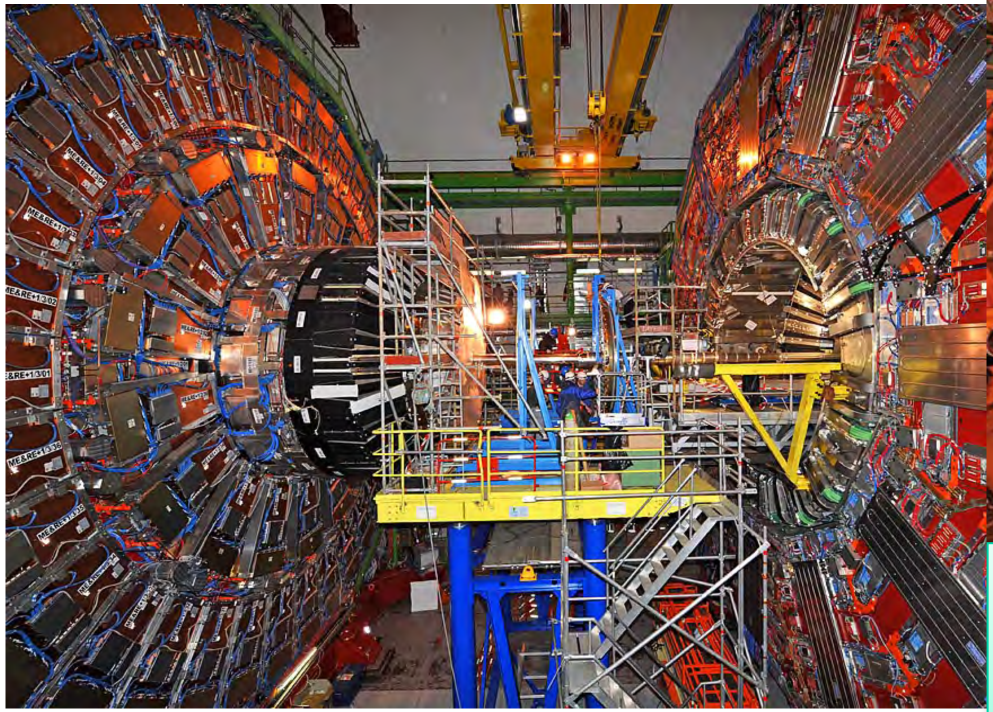


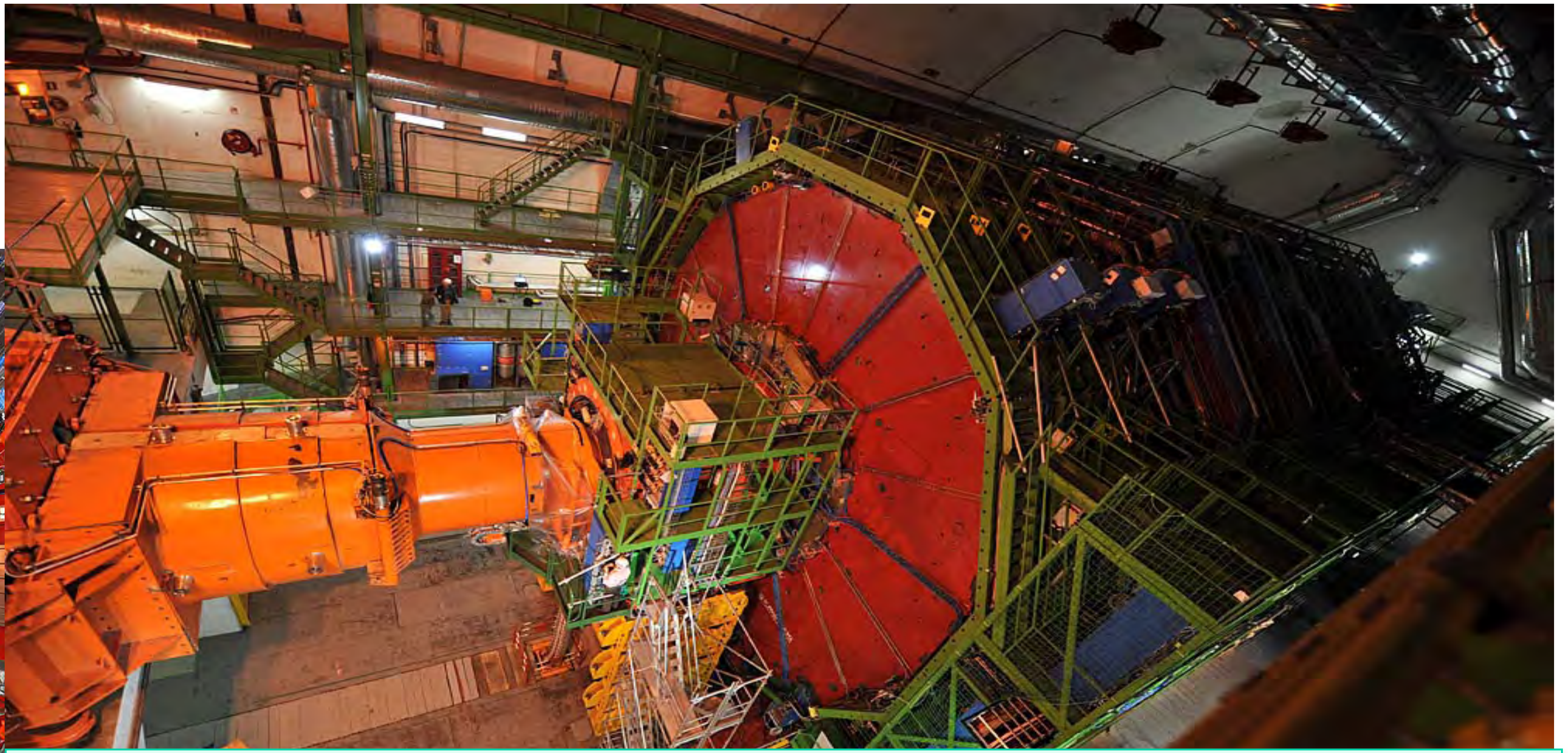
Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)



YE-1: Jan'08

Tracker Insertion: Dec'07



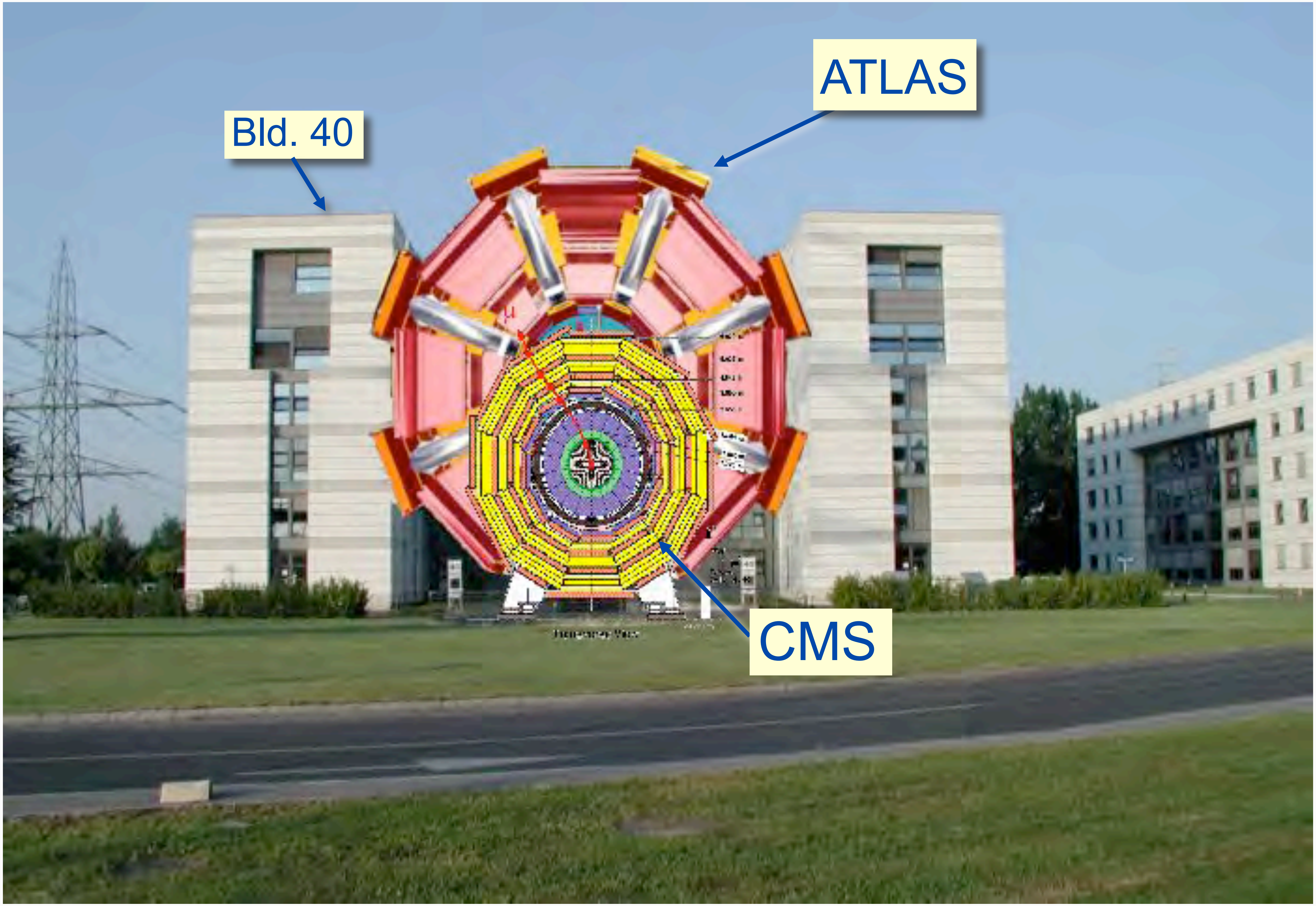


After almost 20 years, from conception, design, construction and commissioning

CMS became a working experiment in September 2008

Virdee, EPS09

Dimensions…



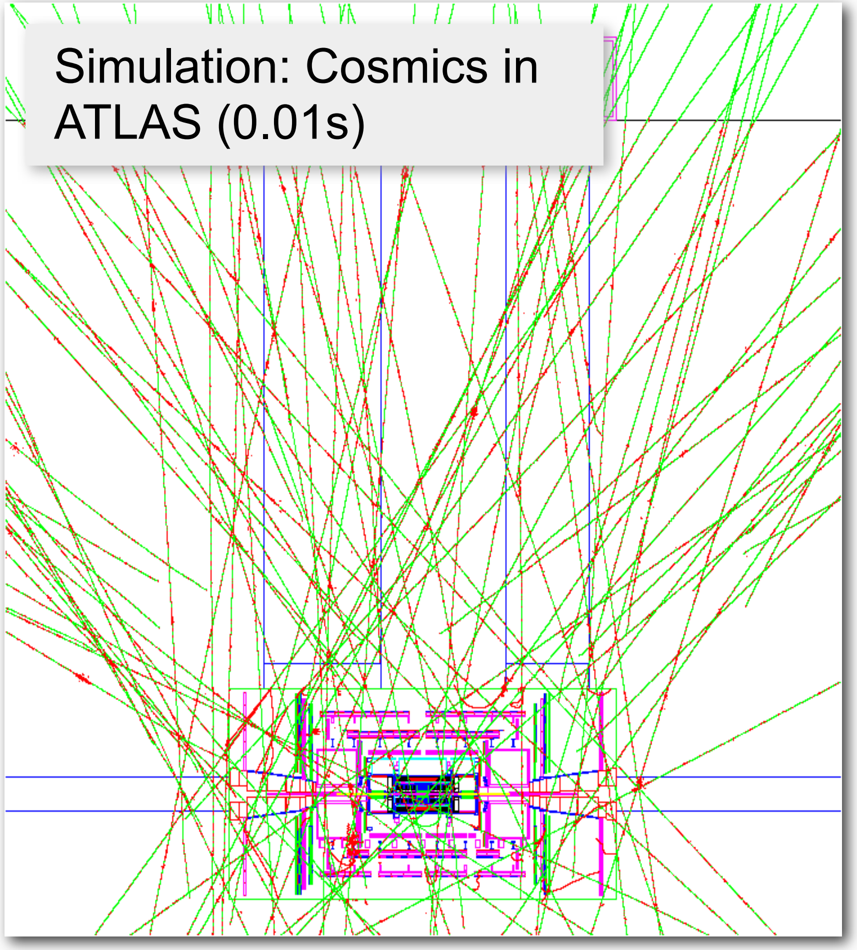
Comparison

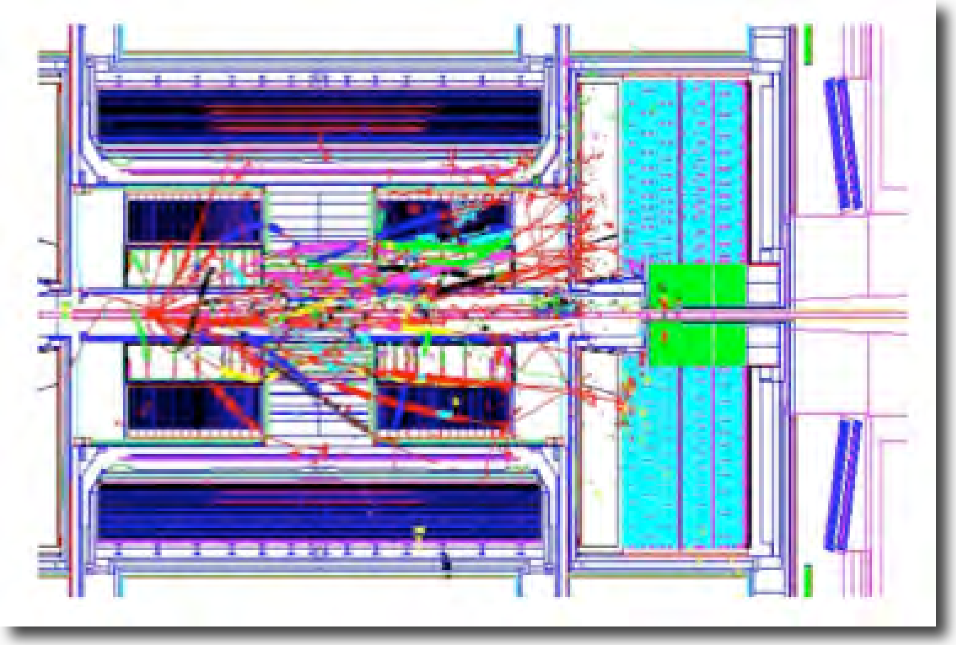
	ATLAS ≡ A Toroidal LHC ApparatuS	CMS ≡ Compact Muon Solenoid
MAGNET (S)	Air-core toroids + solenoid in inner cavity 4 magnets Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\text{x}10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E} + 0.007$ longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 3\%/\sqrt{E} + 0.003$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. (~7 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim$ 2%(@50GeV) to 10% (@1 TeV) standalone	Fe → $\sigma/p_T \sim$ 1% (@50 GeV) to 10% (@1 TeV) combining with tracker

Commissioning and current performance

Detectors : Commissioning

- No Beam :
  - Cosmic Muons
  - Initial alignment/detector calibration (barrel)
  - Debugging, dead-channels mapping
- One Beam :
  - Beam-Splash and Beam-Halo Muons
    - Timing
    - Alignment/calibration in end-caps
  - Beam-Gas events
    - resemble pp, with soft spectrum (p_T < 2 GeV)
    - eg. first alignment of inner trackers to about 100 μm or better
- Two Beams :
  - very early low lumi : Min Bias interactions, QCD di-jet events
  - then : get quickly access to SM processes as standard calibration candles: W, Z, top production

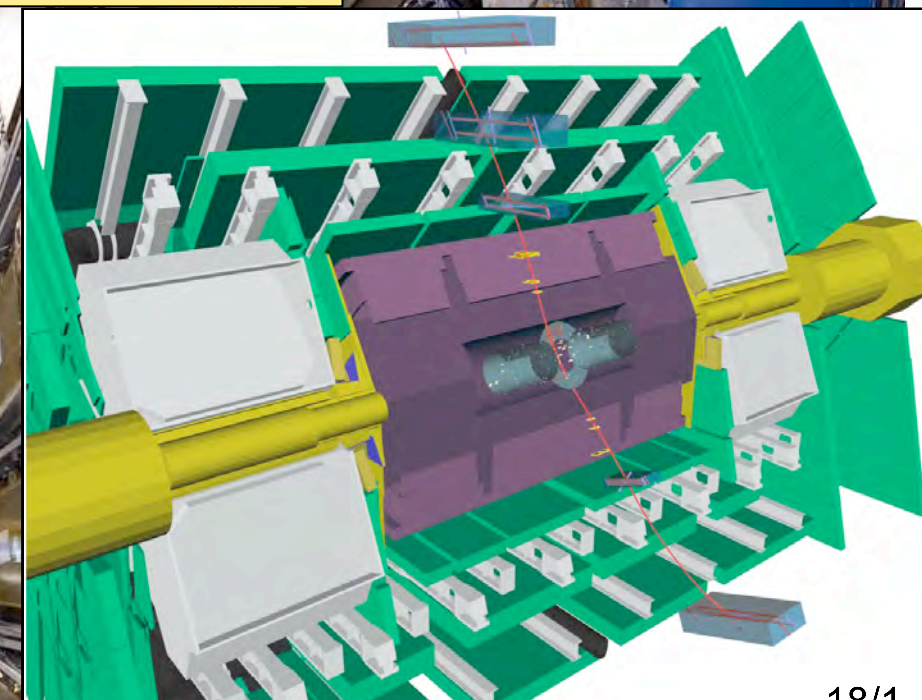




Getting ready

(Gianotti, EPS09)

A historical moment: closure of the LHC beam pipe inside the ATLAS cavern on 16 June 2008.



ATLAS was ready for LHC data-taking in August 2008

Since then:

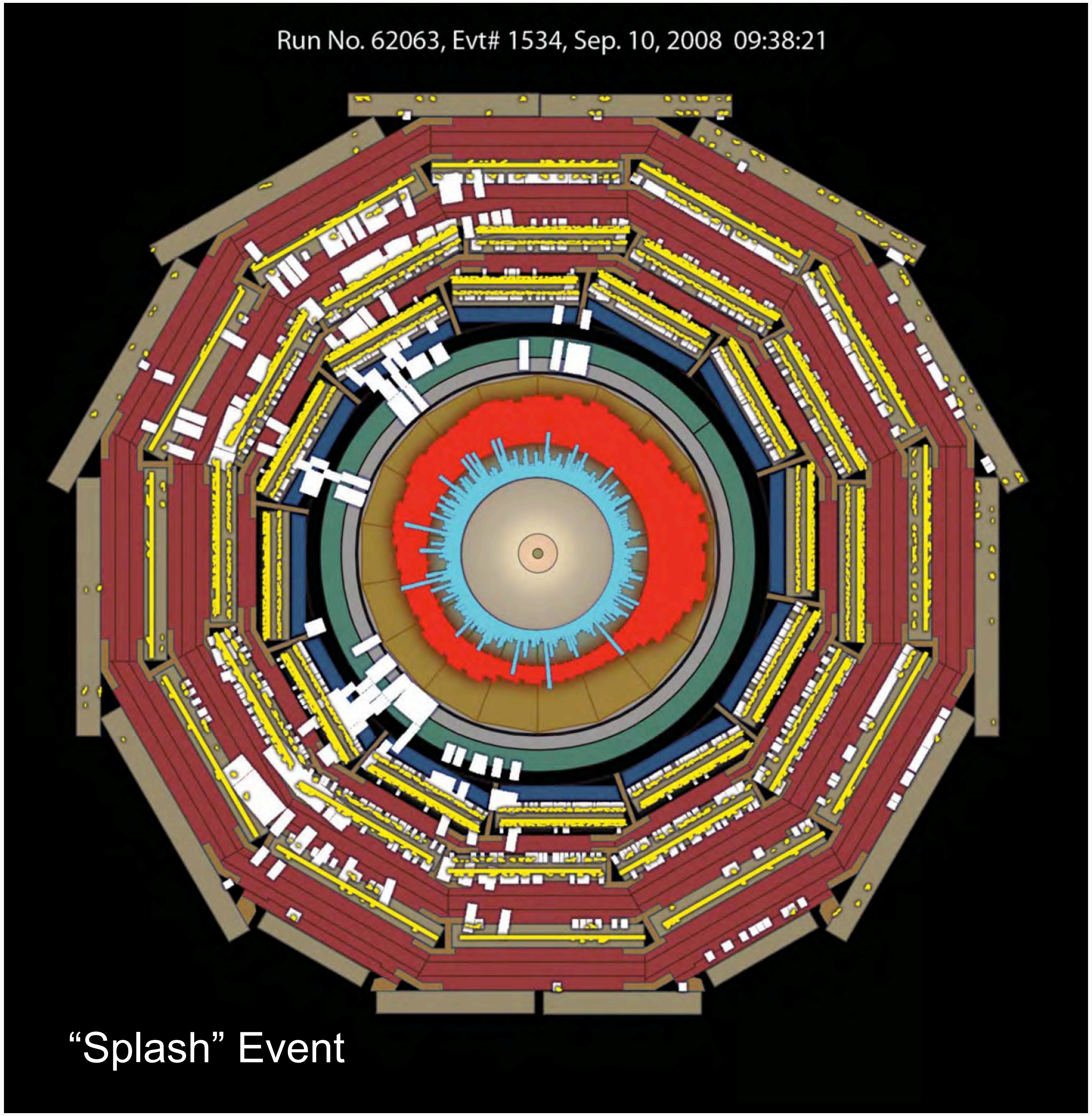
- global cosmics runs (with full detector operational)
  (~ 500 M events collected August-October 2008, 1.2 PB of raw data)
- first calibration and alignment studies:
  achieved precision far better than expected at this stage !
- single-beam events recorded in September 2008
- detector opened in October 2008
  (maintenance, consolidation, a few repairs)
- detector closed again beginning of June 2009
- global cosmics runs restarted end of June (100 M events collected)

First LHC Beam in 2008

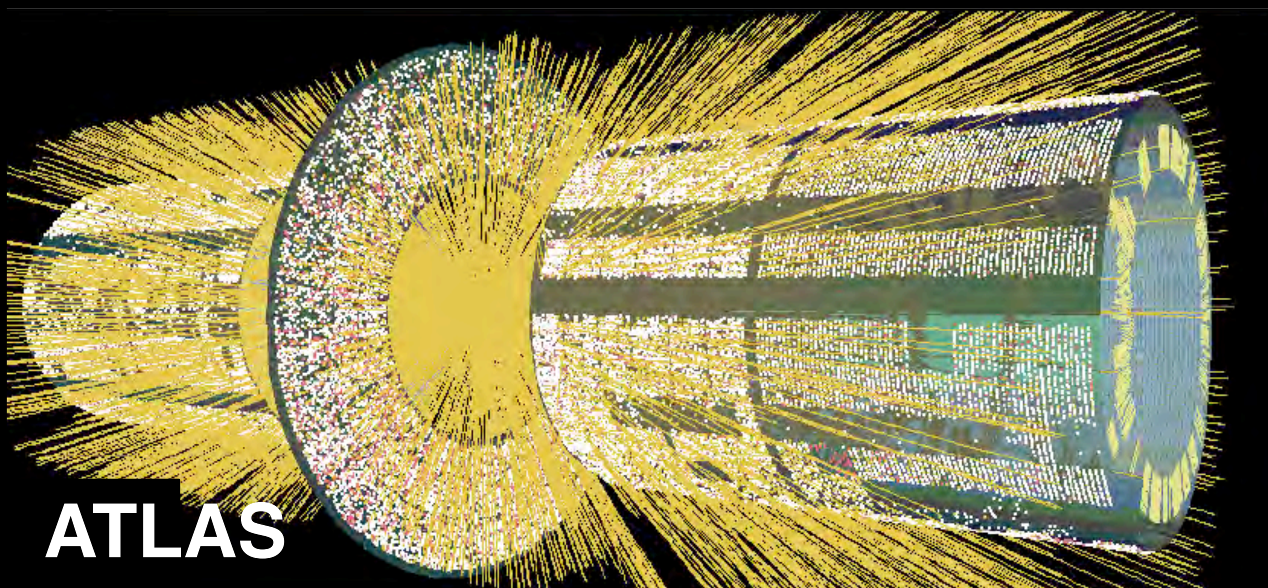
Virdee, EPS09

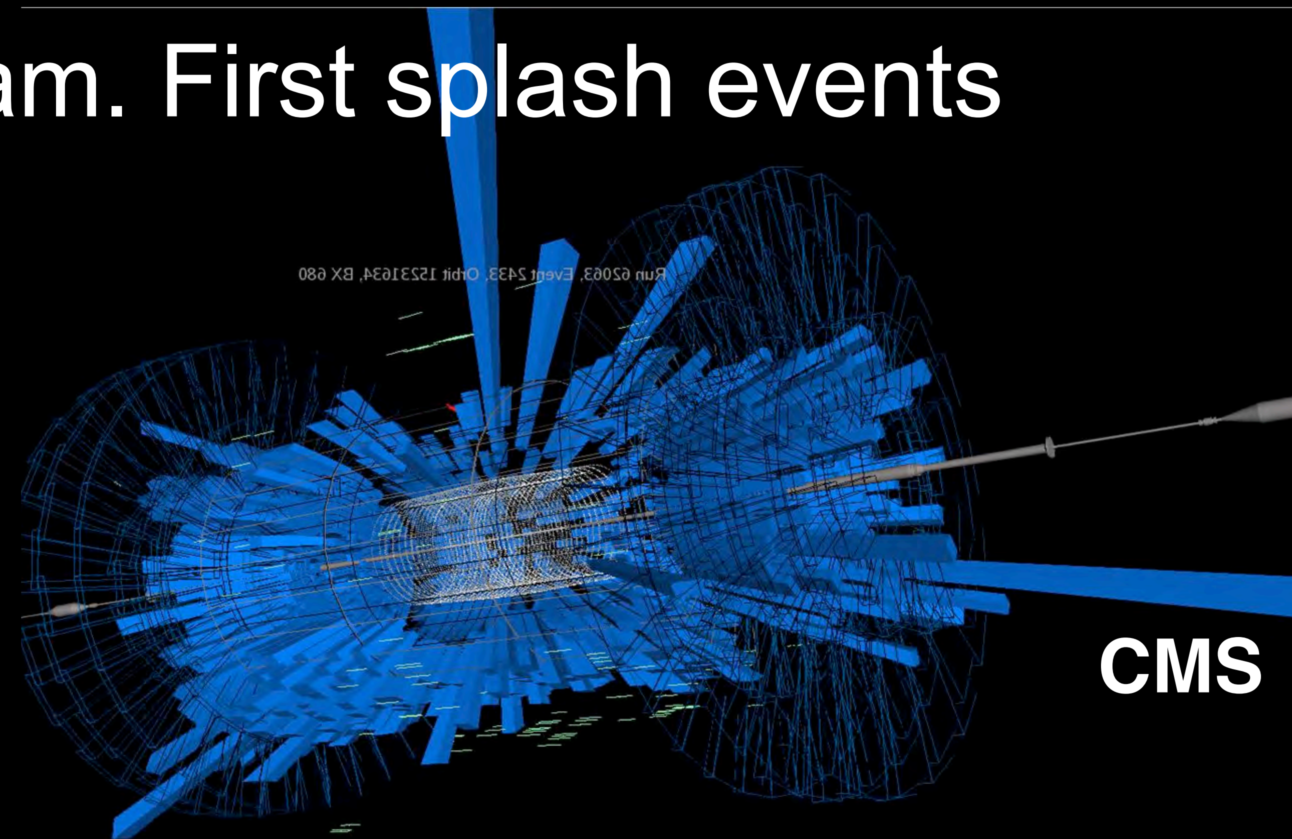
Wed, 10 Sept. 2008

- “Splash” events observed when beam (450 GeV, 4.10^9 p) struck collimators 150m upstream of CMS (O(100k) muons)
- Halo muons observed once beam (uncaptured and captured) started passing through CMS
- Extremely useful for timing studies
- even obtained best ECAL EE intercalibration

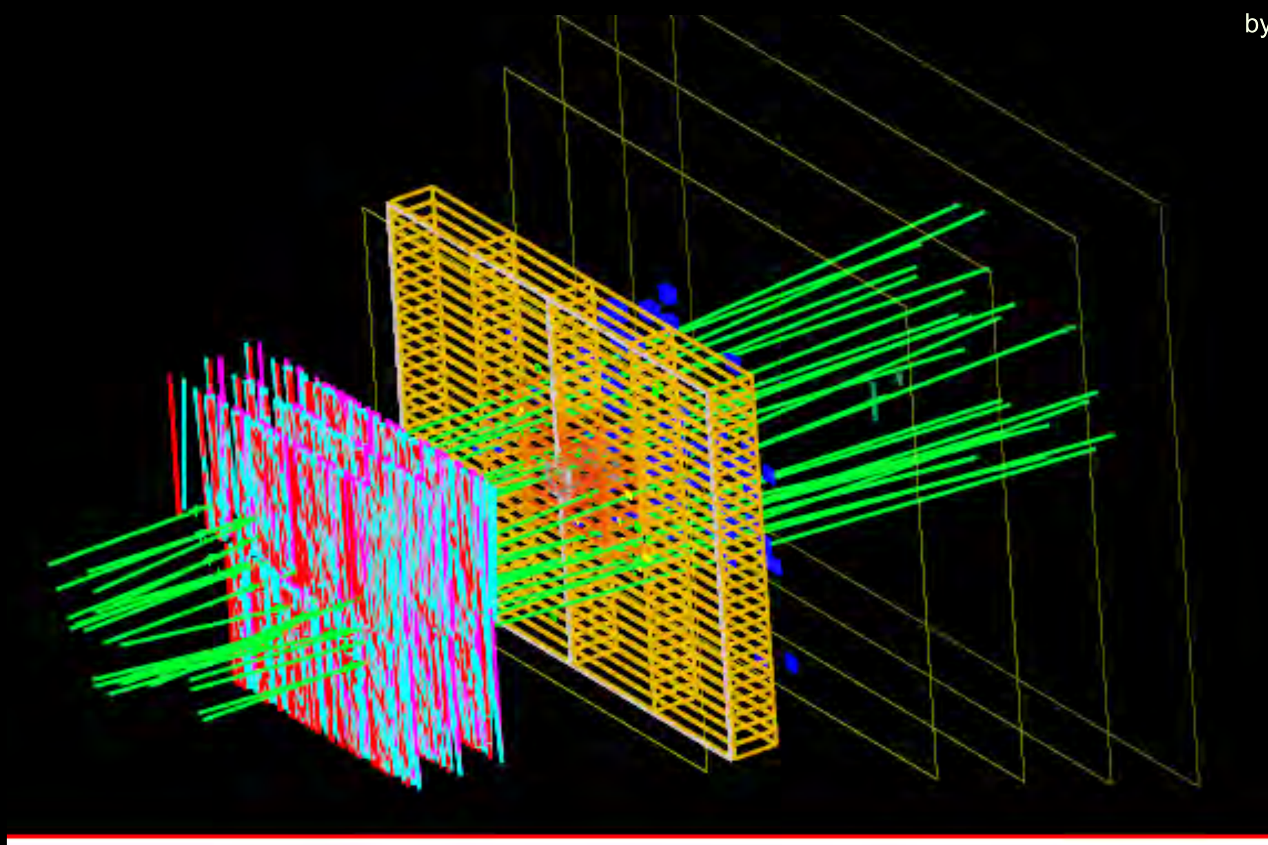


Sept. 2008 LHC circulating beam. First splash events

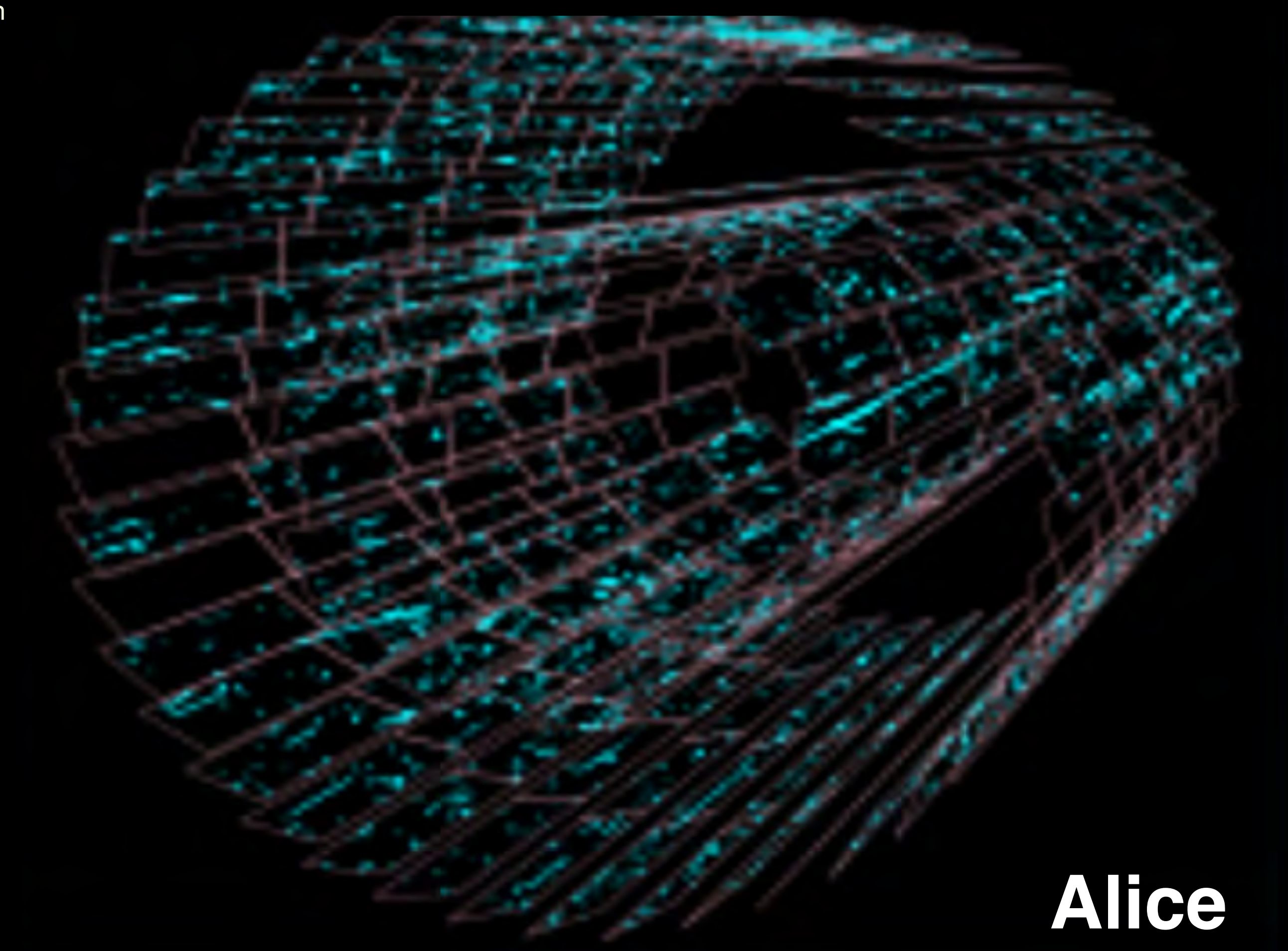




by S. Cittolin



LHCb



Continuous Operation of CMS

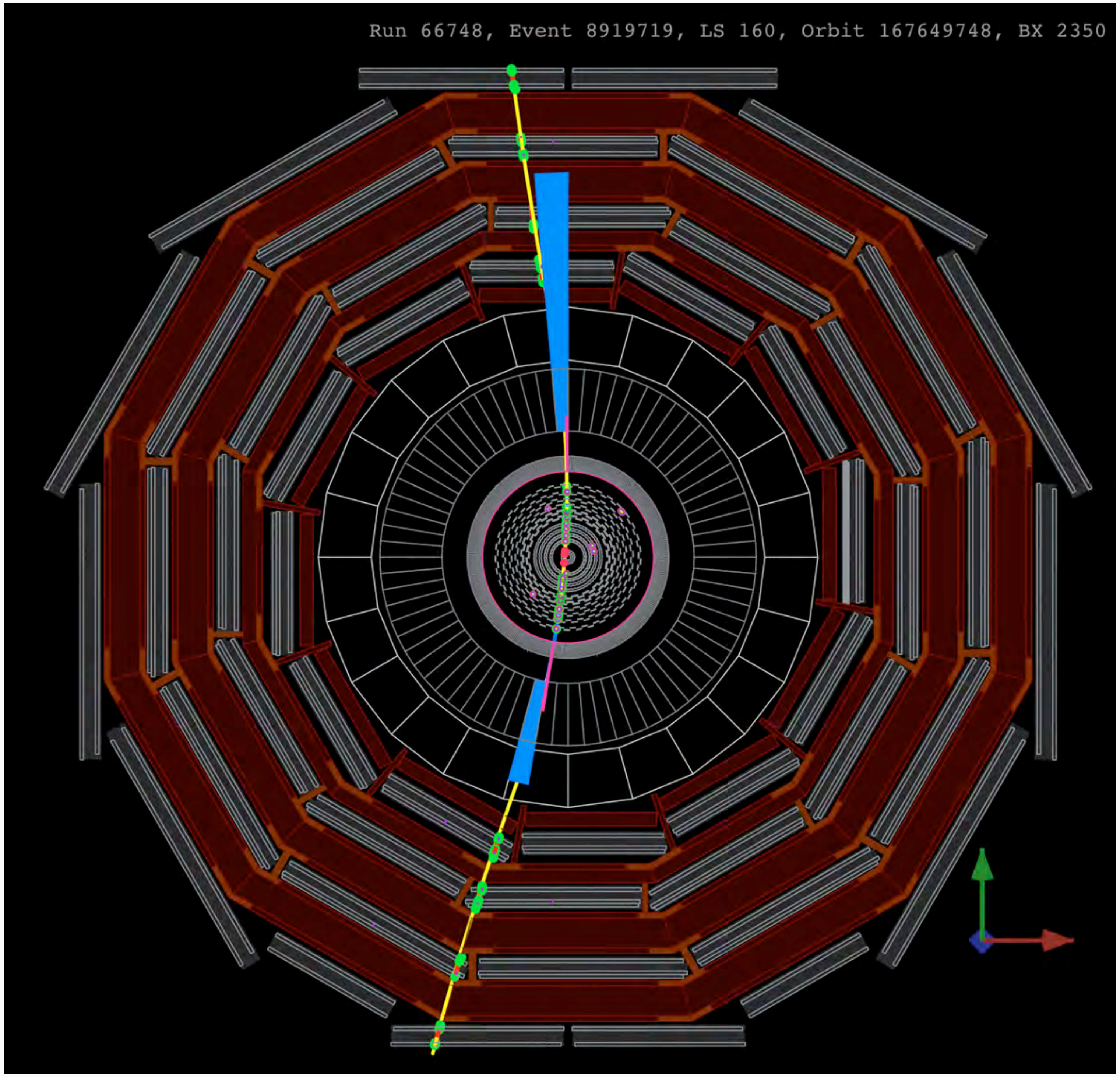
ETH Institute for Particle Physics

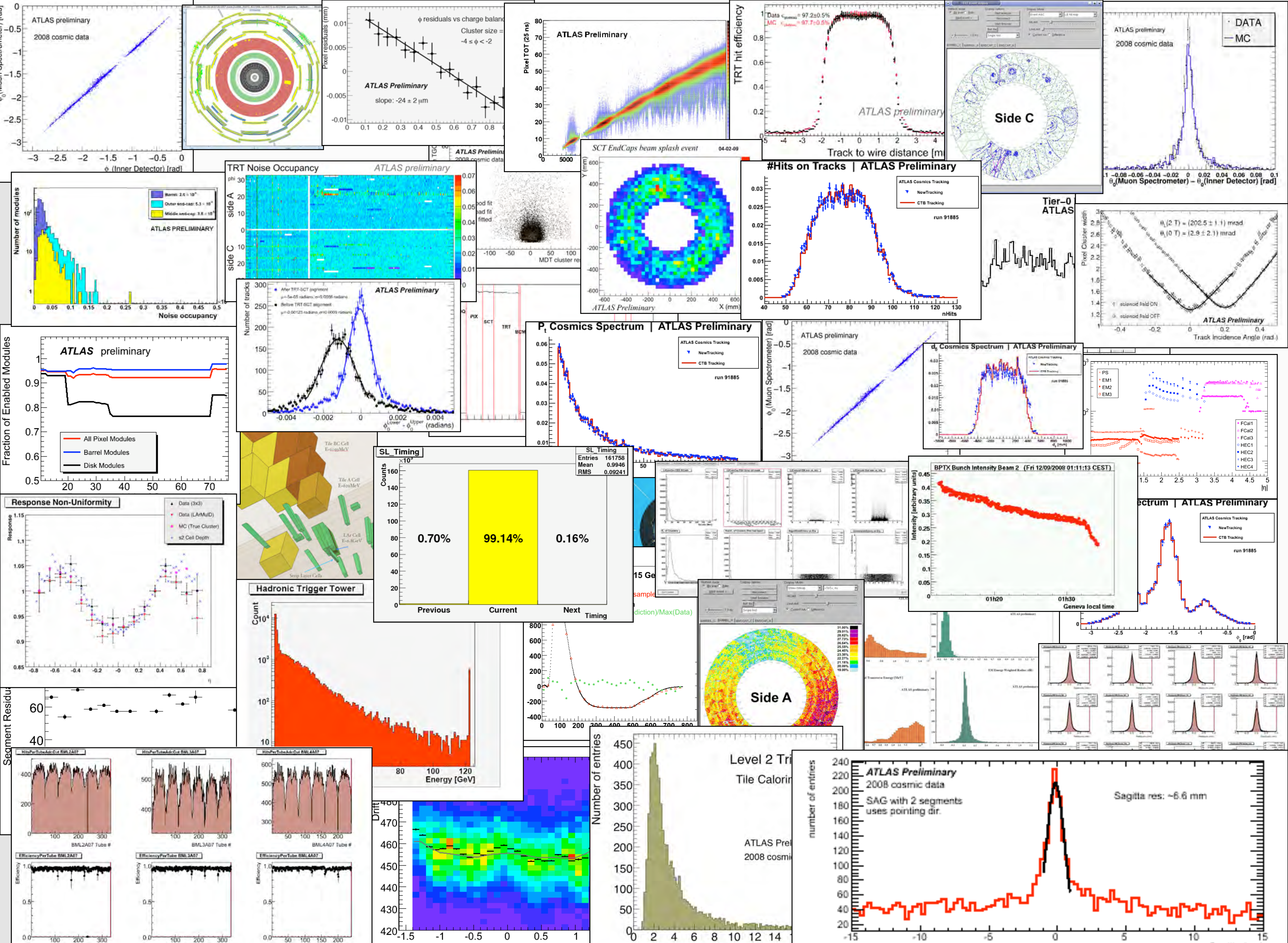
Virdee, EPS09

CRAFT*: Cosmics Run at Four Tesla

* Operating field of CMS is 3.8T

- Ran CMS for 6 weeks (Oct Nov'08) continuously to gain operational experience, stability of infrastructure.
- Collected 300M cosmic events. About 400 TB of data distributed widely.
- ε ~ 70% (24/7)
- wealth of data – for ascertaining health and performance of detector, detector cleanup studies (e.g. for alignment - equivalent to >10 pb^{-1} !)
- ~ 25 publications planned for end Sep



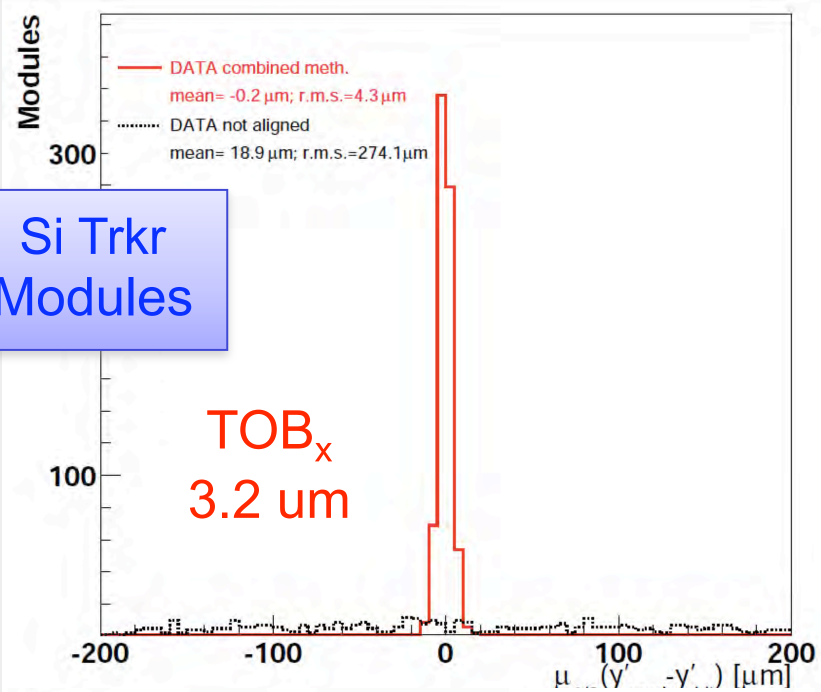


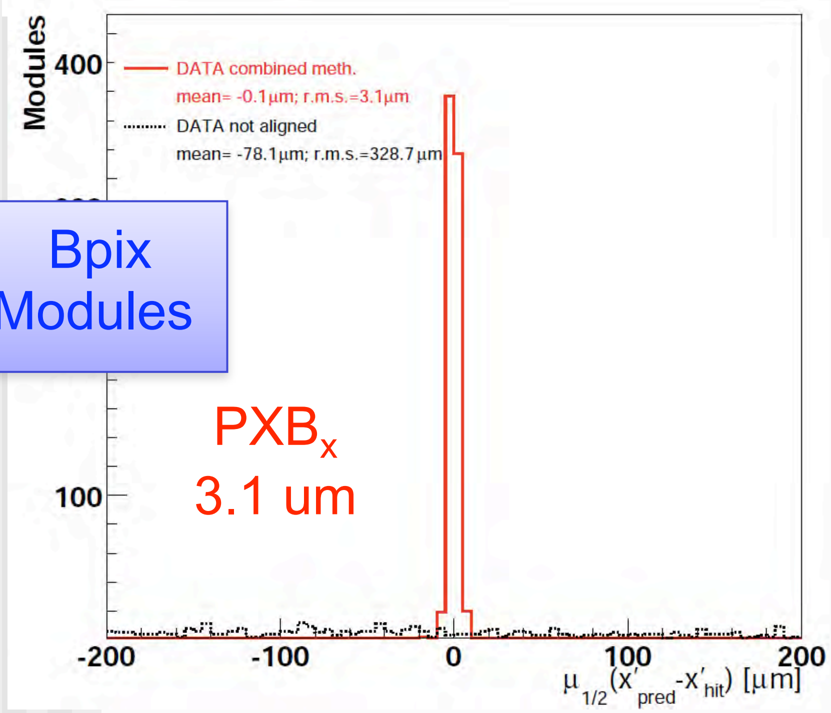
Gianotti, EPS09

CRAFT: Performance Plots

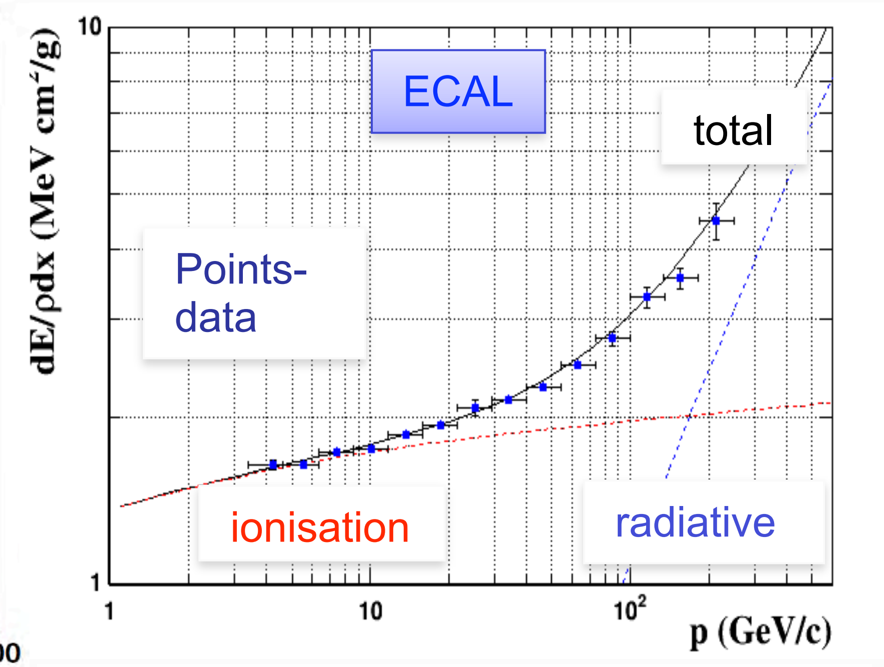
Alignment in Inner Tracker

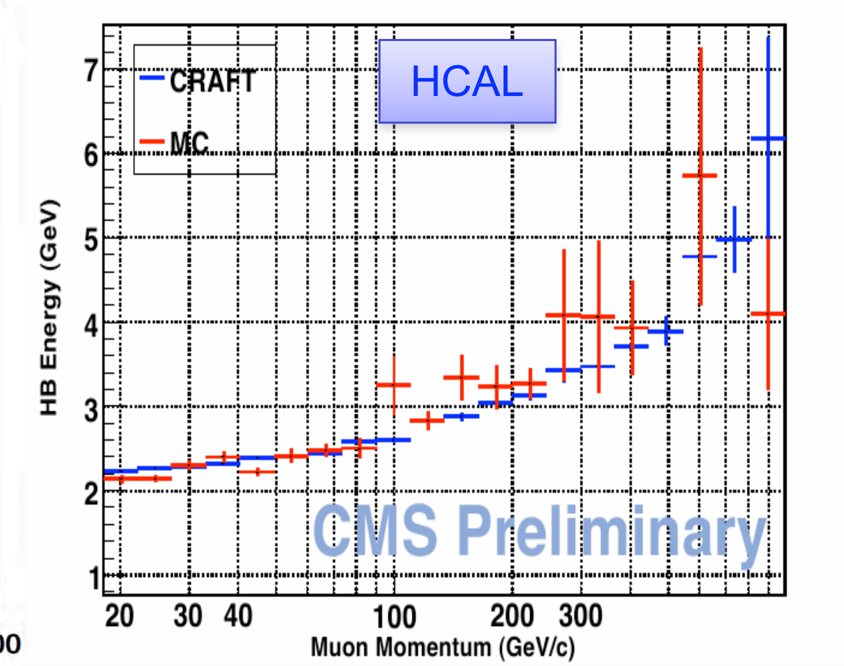
Distn of Mean Residuals



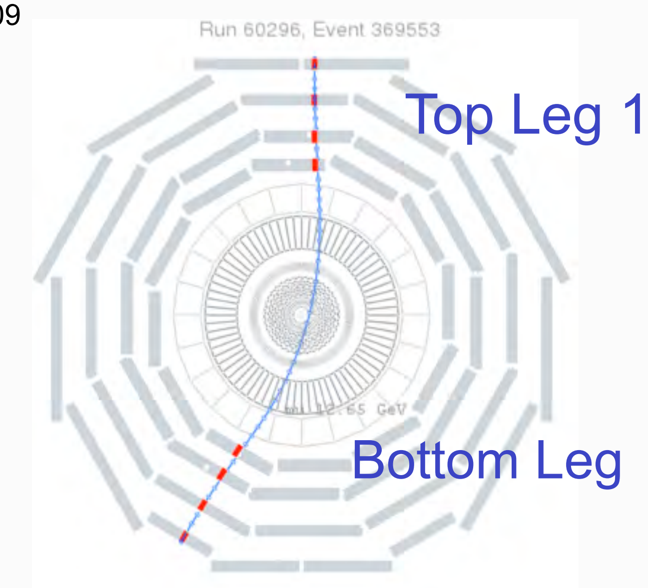


Energy deposited by muons

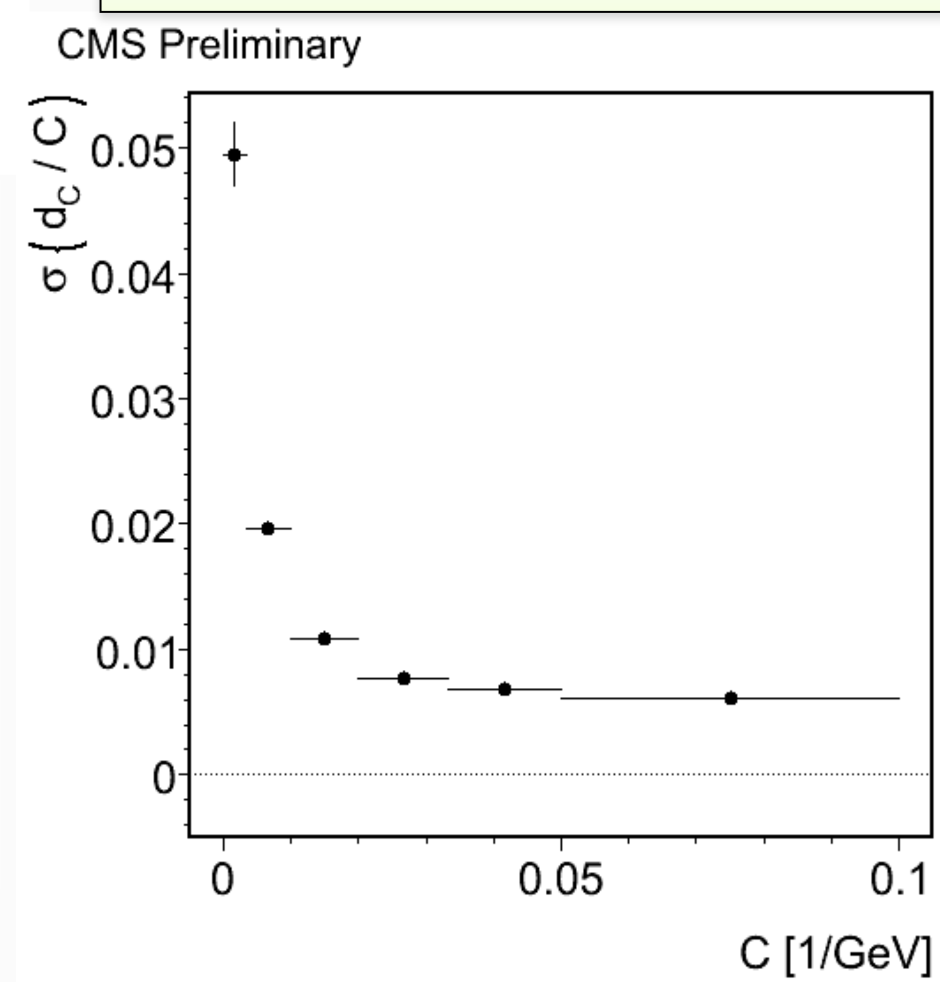




T. Virdee EPS Jul09



Momentum Resolution <2-leg>



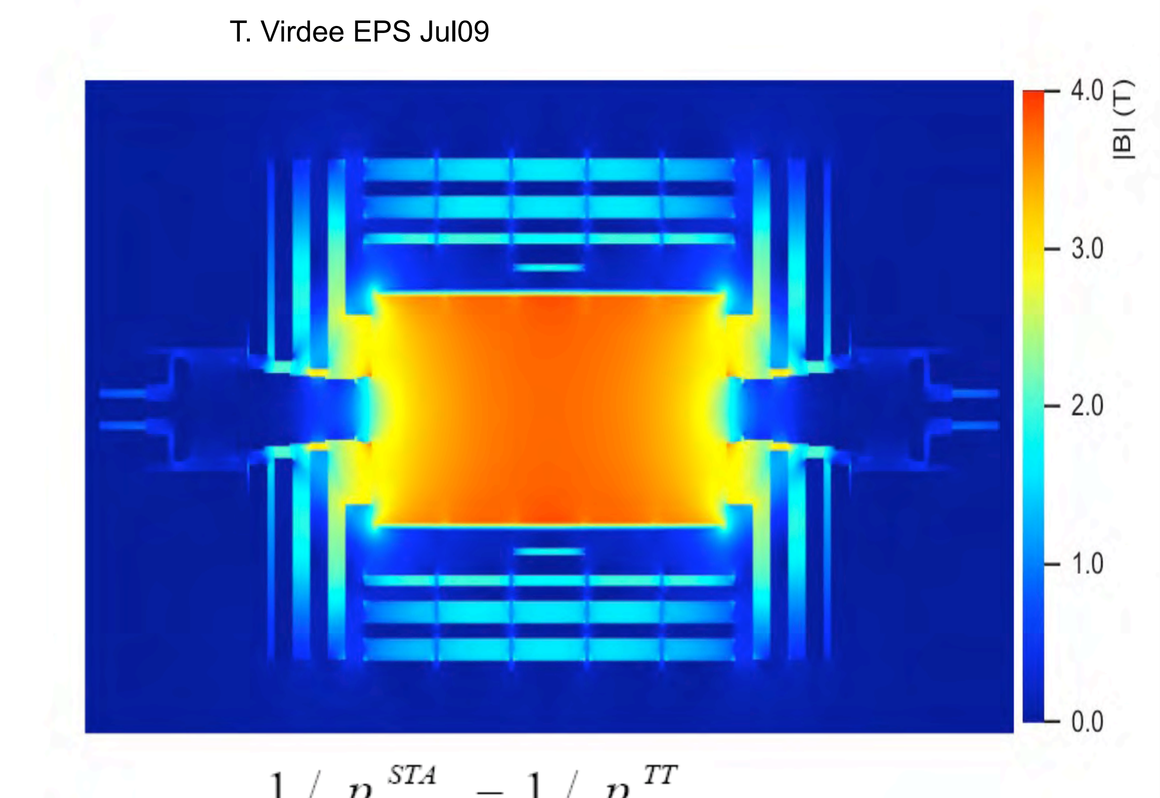
CRAFT Results: CMS Magnetic Field Map

In the Tracker Region

Measured by Field Mapper (at 2, 3, 3.5, 3.8, 4 T) in 2006 MTCC

TOSCA field map agrees < 0.1%

NMR probes inside solenoid confirm agreement scale < 0.1% between 2006 and 2008



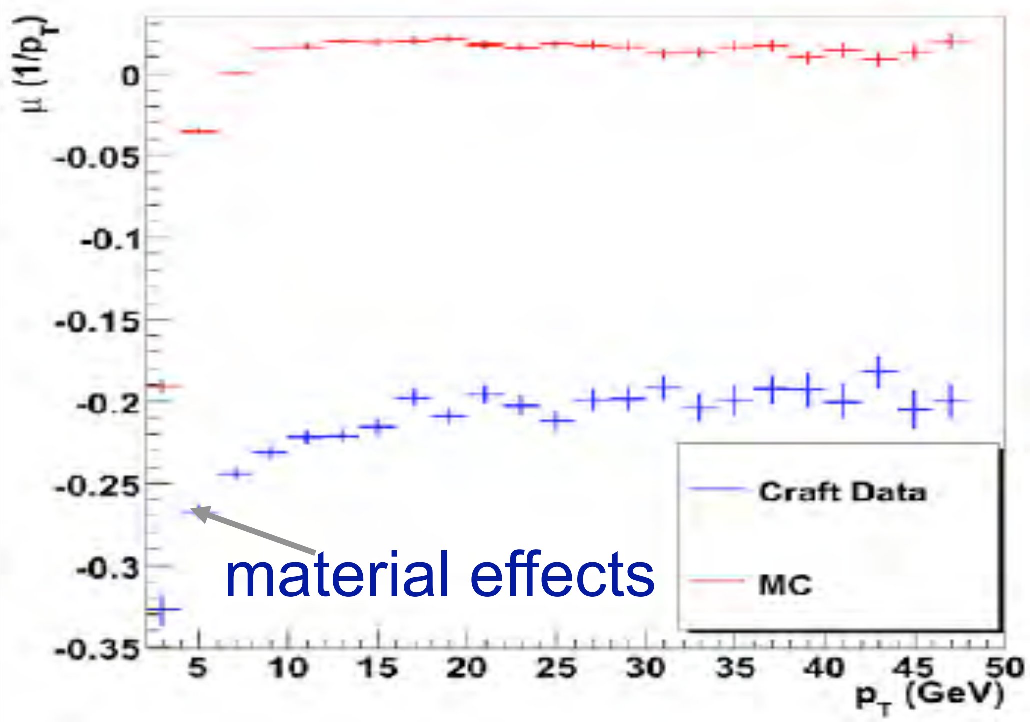
In the Return Yoke

Compare tracker vs stand-alone muon momentum scale:

-stand-alone muons, momentum is over-estimated by 20%

Field model overestimated the field in the iron yoke.

$$R = \frac{1/p_T^{STA} - 1/p_T^{TT}}{1/p_T^{TT}}$$



With new modeling of B field map : agreement data/MC now better than 2%

ATLAS present status

Sub-Detector	# of channels	Fraction of working detector (%)
Pixels	80 x 106	98.5
Silicon Strip Detector (SCT)	6 x 106	~99.5
TRT	3.5 x 10^5	98.2
ECAL LAr	1.7 x 105	99.5
Fe/scint (Tilecal)	9800	~99.5
HCAL endcap LAr	5600	99.9
Forward LAr calorimeter	3500	100
MDT	3.5 x 105	99.3
RPC	3.7 x 105	~99.5 (aim: > 98.5 by first beam)
TGC	3. x 105	>99.5

Gianotti, EPS09

CMS present status

T. Virdee July 09

Sub-detector	No. of ch.	Working (%)
Pixels	66×10^6	98.6 (+ ...)
Silicon strip detector	9.3×10^6	98.3 (+0.6%?)
ECAL $PbWO_4$ calorimeter	7.58×10^5	99.5
ECAL ES	1.37×10^5	99.95
HCAL HB (HO) calorimeter	2592 (2160)	100 (99.1)
HCAL HE calorimeter	2592	100
HCAL_HF calorimeter	1728	100
Muon DTs	1.55×10^5	99.6
Muon CSC (CFEB)	2.18×10^5	99.3
Muon RPC RB (RE)	$8.3(4.1) \times 10^4$	99.7 (99.5*)

CMS comprises 66M pixel channels, ~ 9.3M Si microstrip ch, ~76k crystals, 150k Si preshower ch, ~15k HCAL ch, 250 DT chambers (170k wires), 450 CSC chambers (~200k wires), 480 Barrel RPCs and 432 endcap RPCs, muon and calorimeter trigger system, 50 kHz DAQ system (~ 10k CPU cores), Grid Computing (~ 50k cores), offline (> 2M lines of source code).

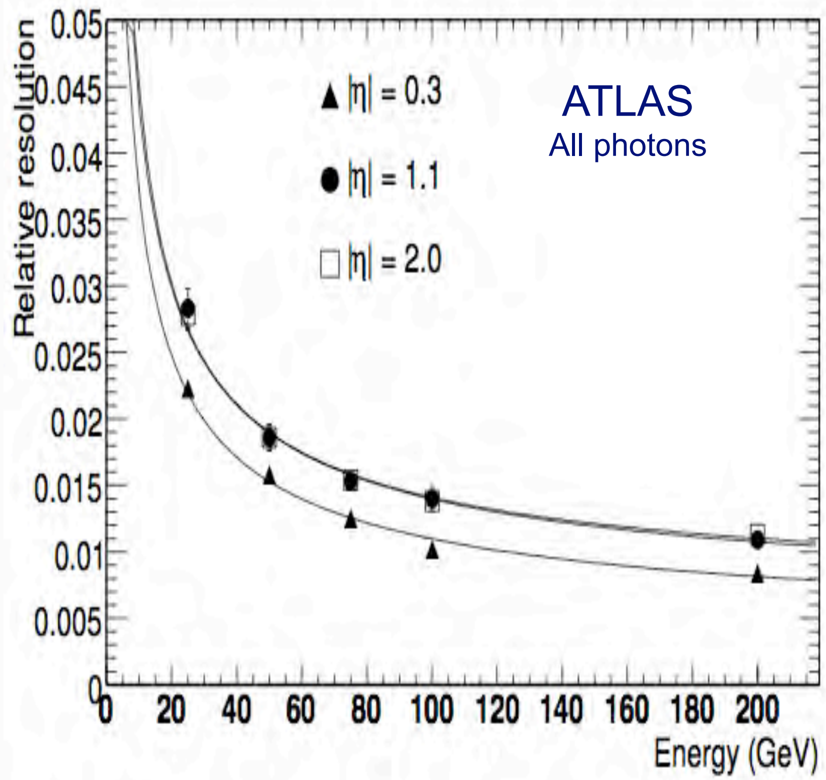
Some performance comparisons

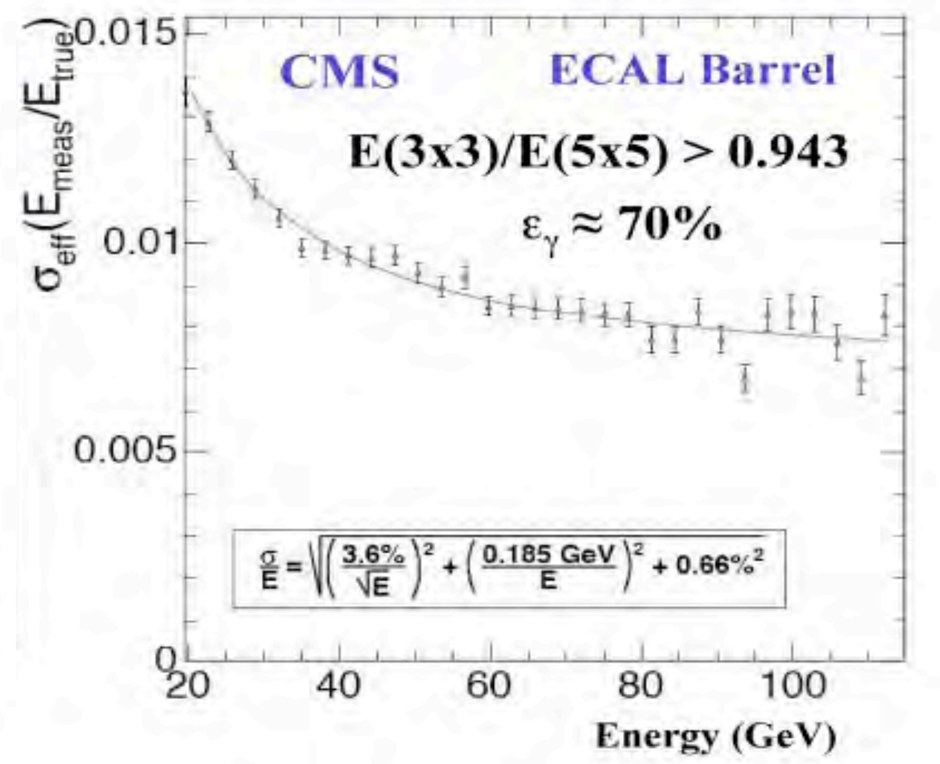
Froidevaux, Sphicas

Photons at 100 GeV

ATLAS:
1-1.5% energy resol.

CMS:
0.8% energy resol.
(ε_γ ~ 70%)

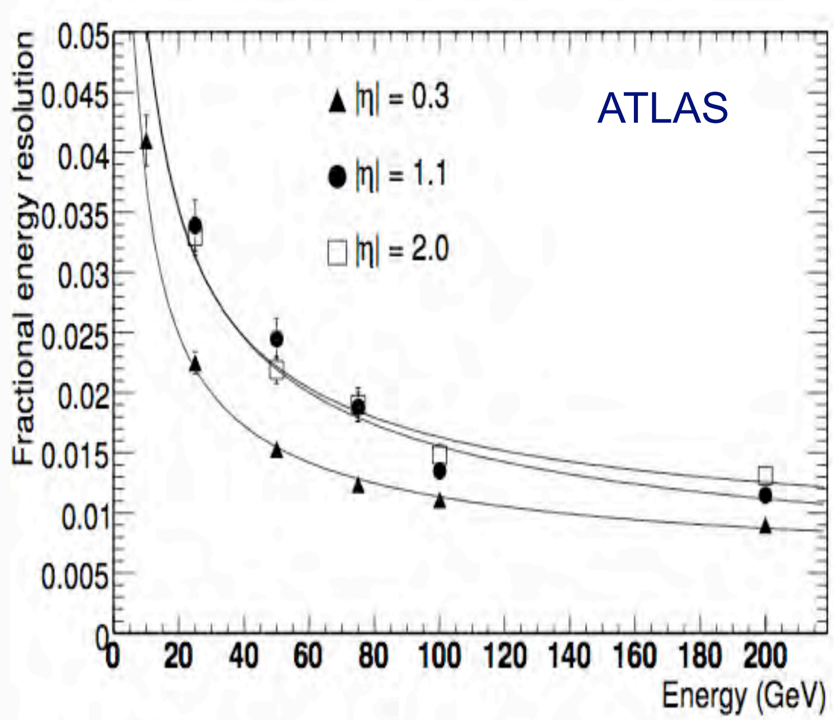


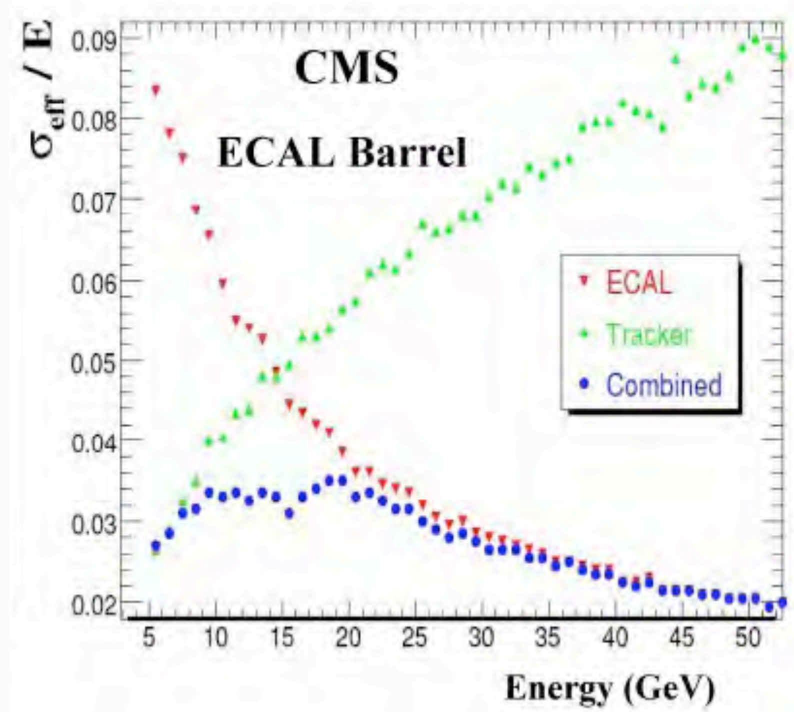


Electrons at 50 GeV

ATLAS:
1.5-2.5% energy resol.
(use EM calo only)

CMS:
~ 2.0% energy resol.
(combine EM calo and tracker)



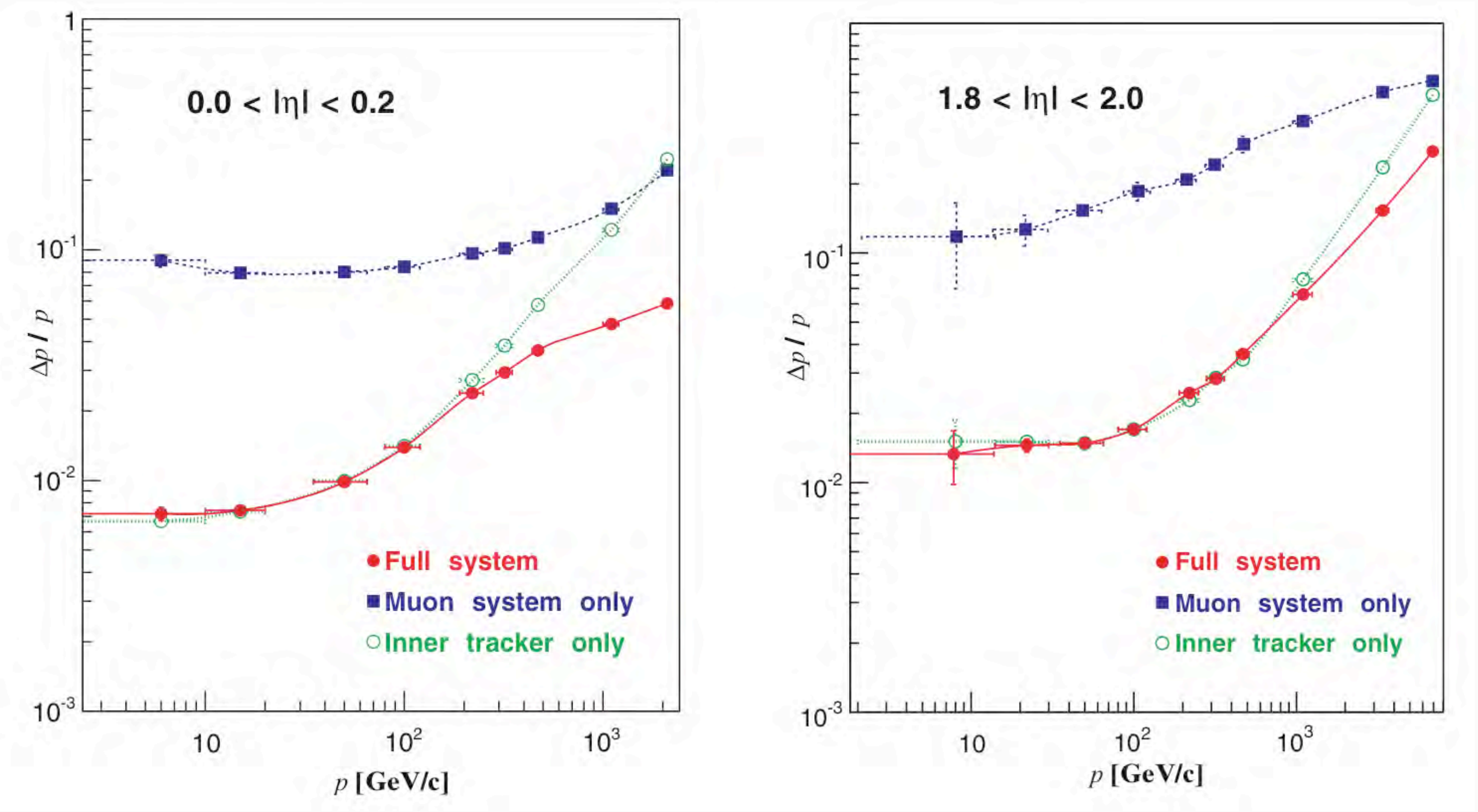


Systematic uncertainty on efficiencies ~ 1 %

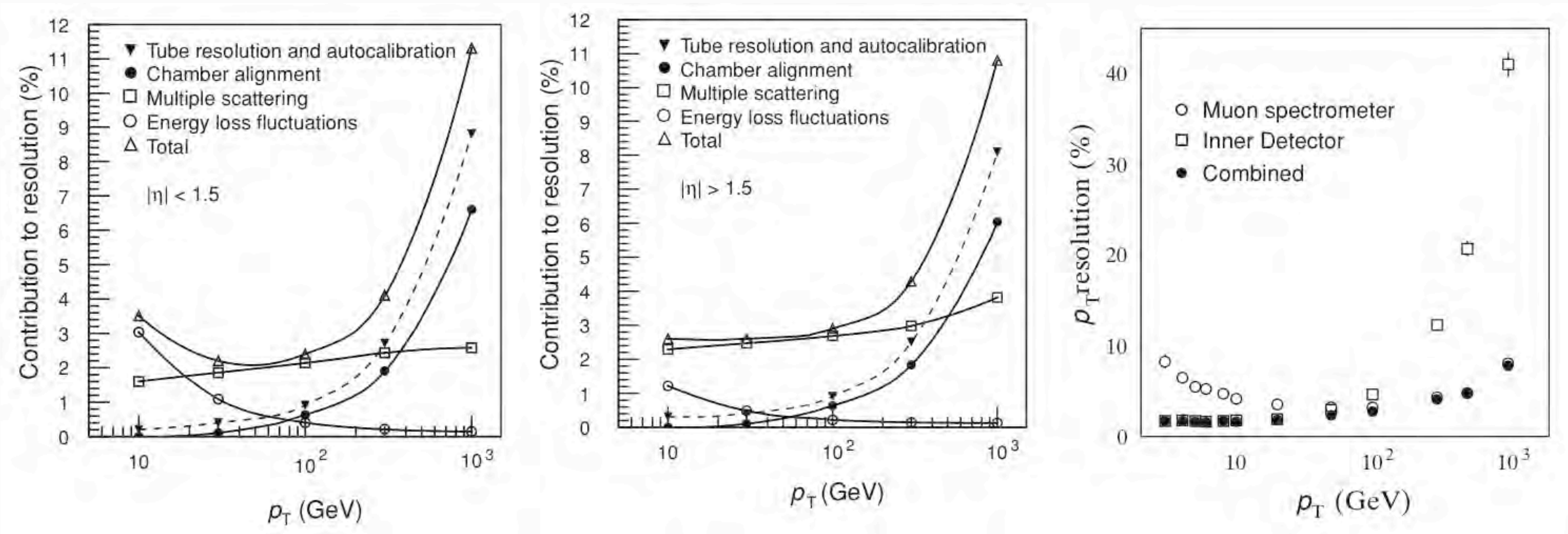
Froidevaux, Sphicas

Muon momentum resolution

CMS



ATLAS



Systematic uncertainty on efficiencies ~ 1 %

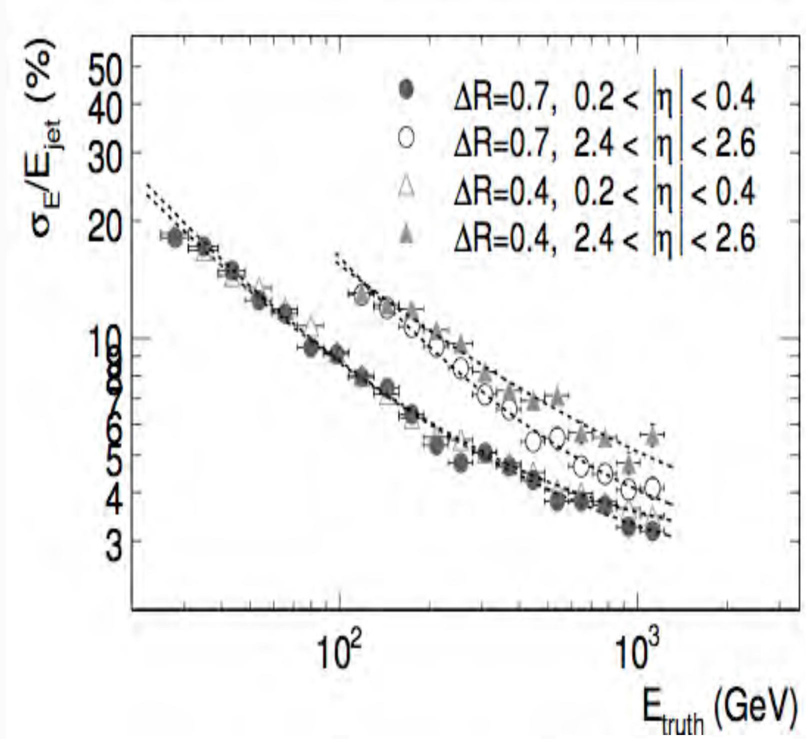
Some performance comparisons

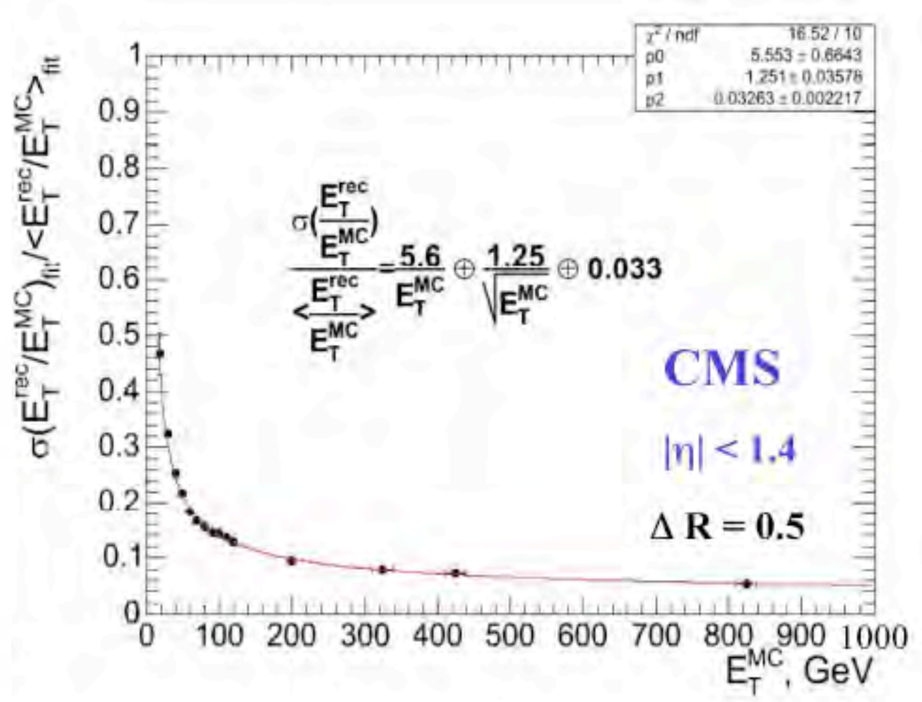
Froidevaux, Sphicas

Jets at 1000 GeV

ATLAS:
~3% energy resol.

CMS:
~5% energy resol.
(at lower energy big improvement using tracks and Particle Flow)

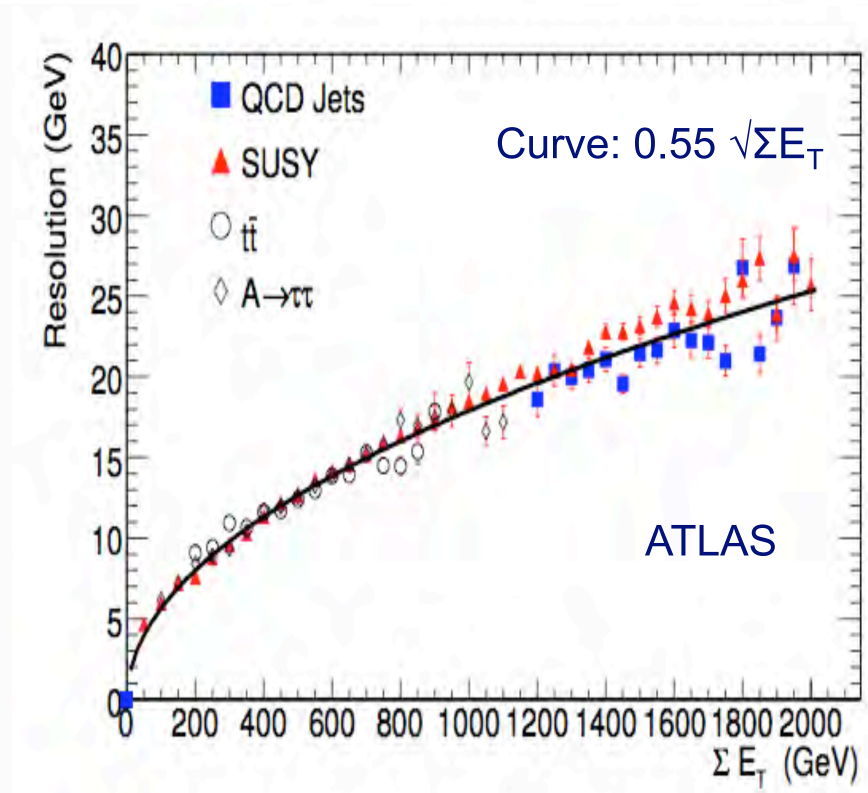


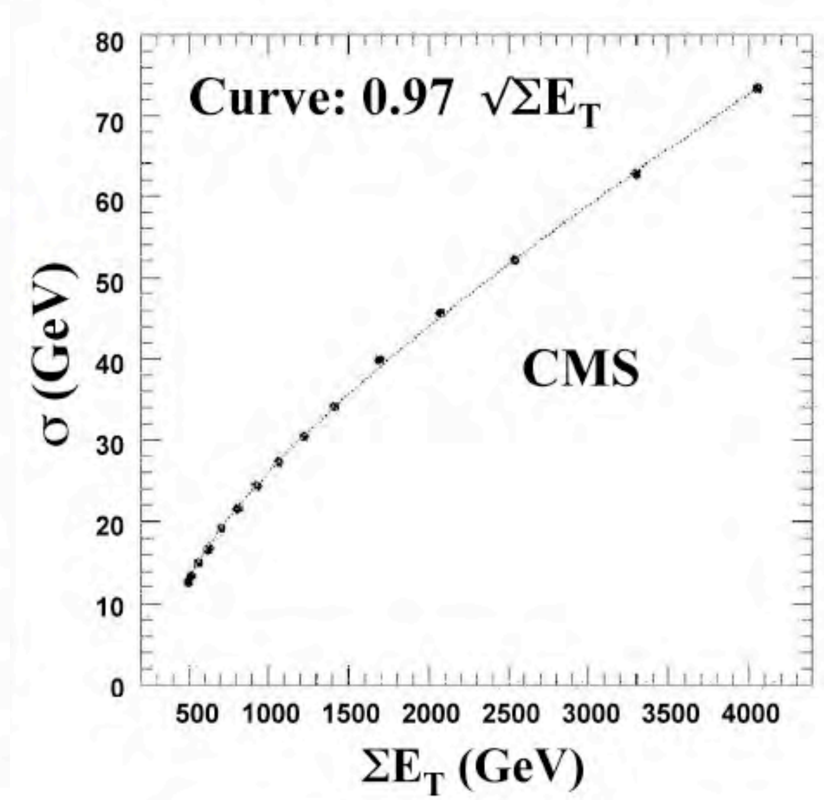


E_{Tmiss} at $SumE_T$=2 TeV

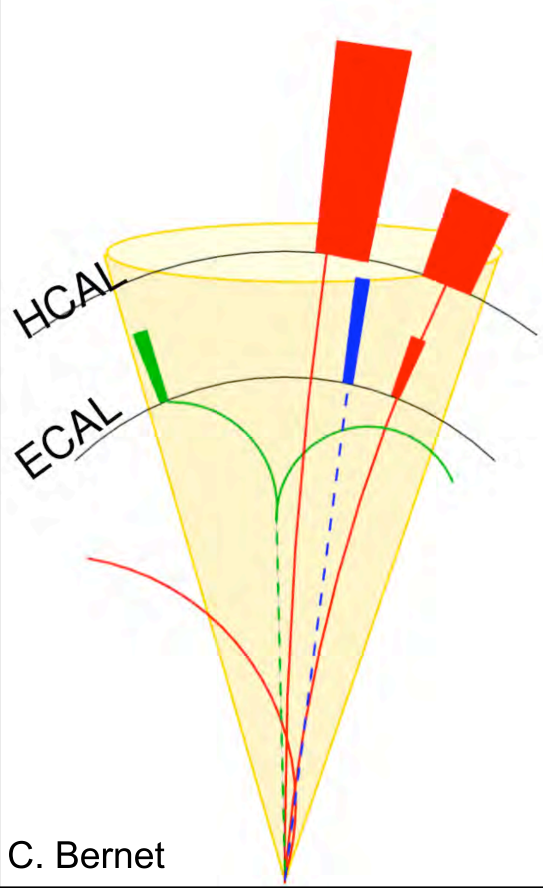
ATLAS:
~25% resolution

CMS:
~ 40% resolution
(calo info only)



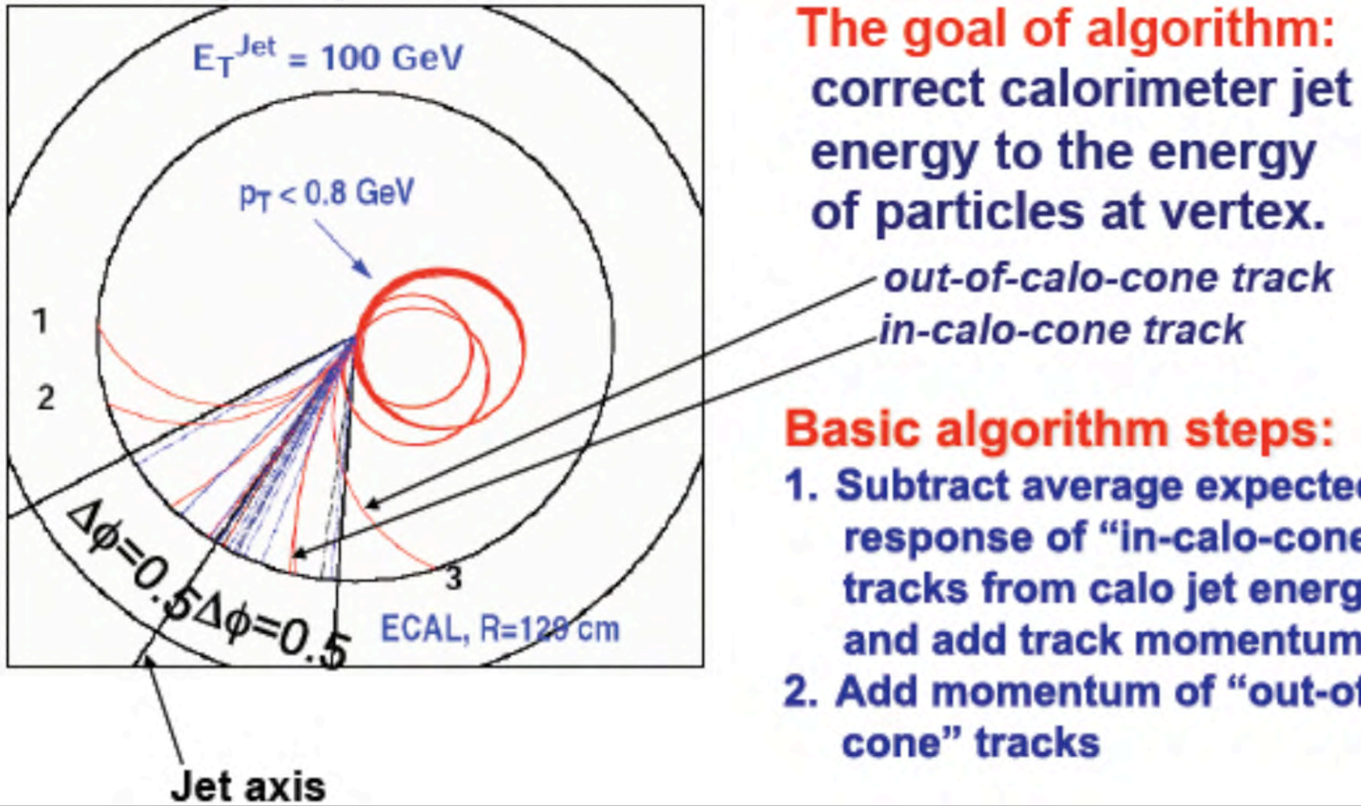


Particle Flow, JetsPlusTracks



- Reconstruct/identify all stable particles in the event:
  - Photons, charged and neutral hadrons, electrons, muons
- By combining all subdetectors in the best possible way
  - Tracker, preshower, ECAL, HCAL, muon chambers
- The resulting list of particles is the input of
  - Jet clustering
  - Tau and b ID
  - MET reconstruction

S. Nikitenko



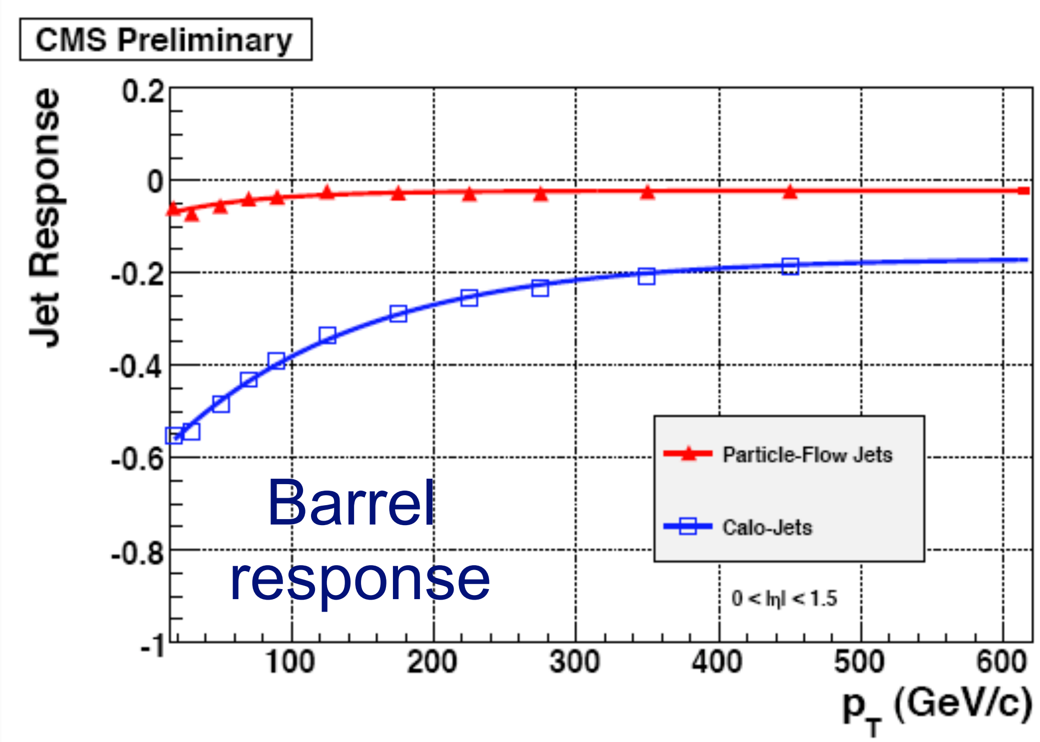
The goal of algorithm: correct calorimeter jet energy to the energy of particles at vertex.

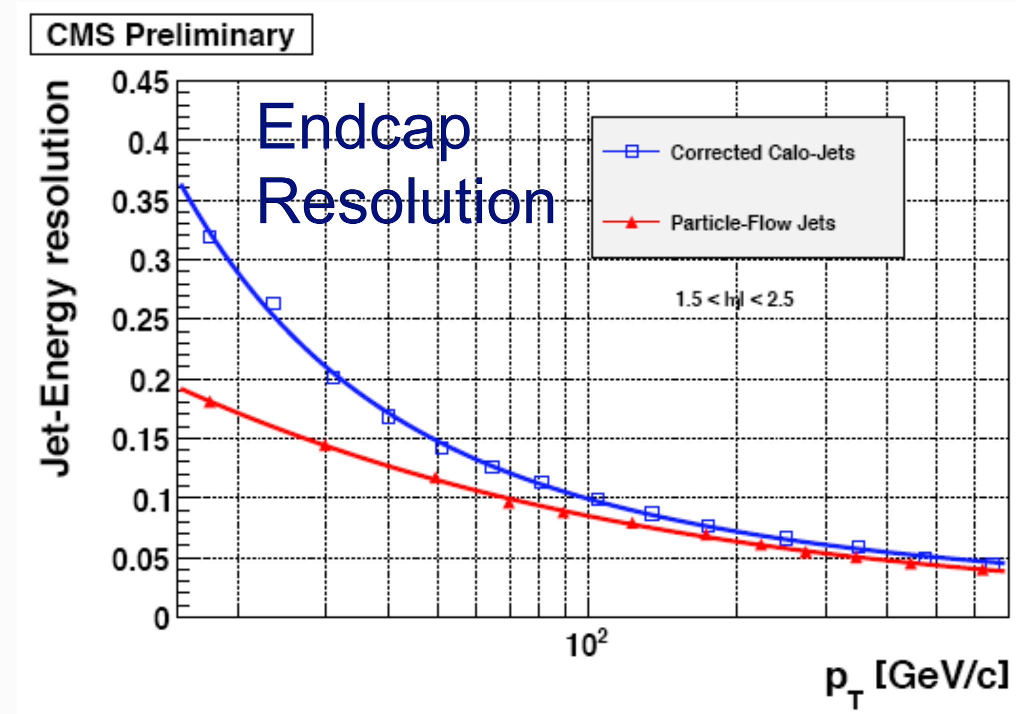
Basic algorithm steps:

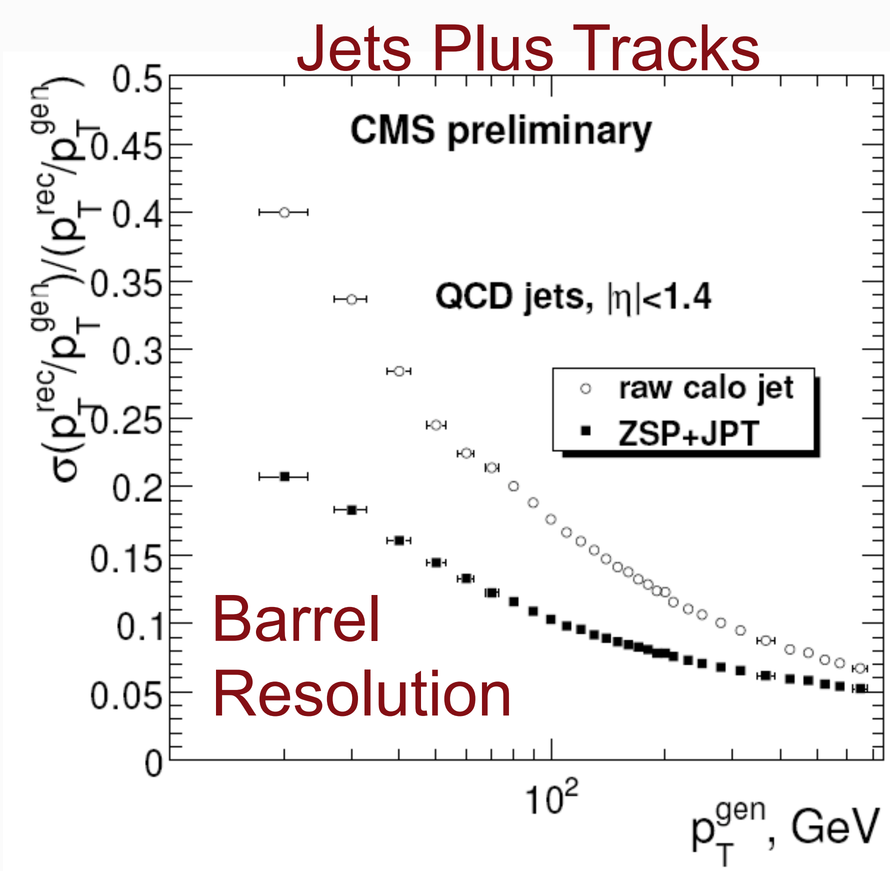
1. Subtract average expected response of "in-calo-cone" tracks from calo jet energy and add track momentum
2. Add momentum of "out-of-cone" tracks

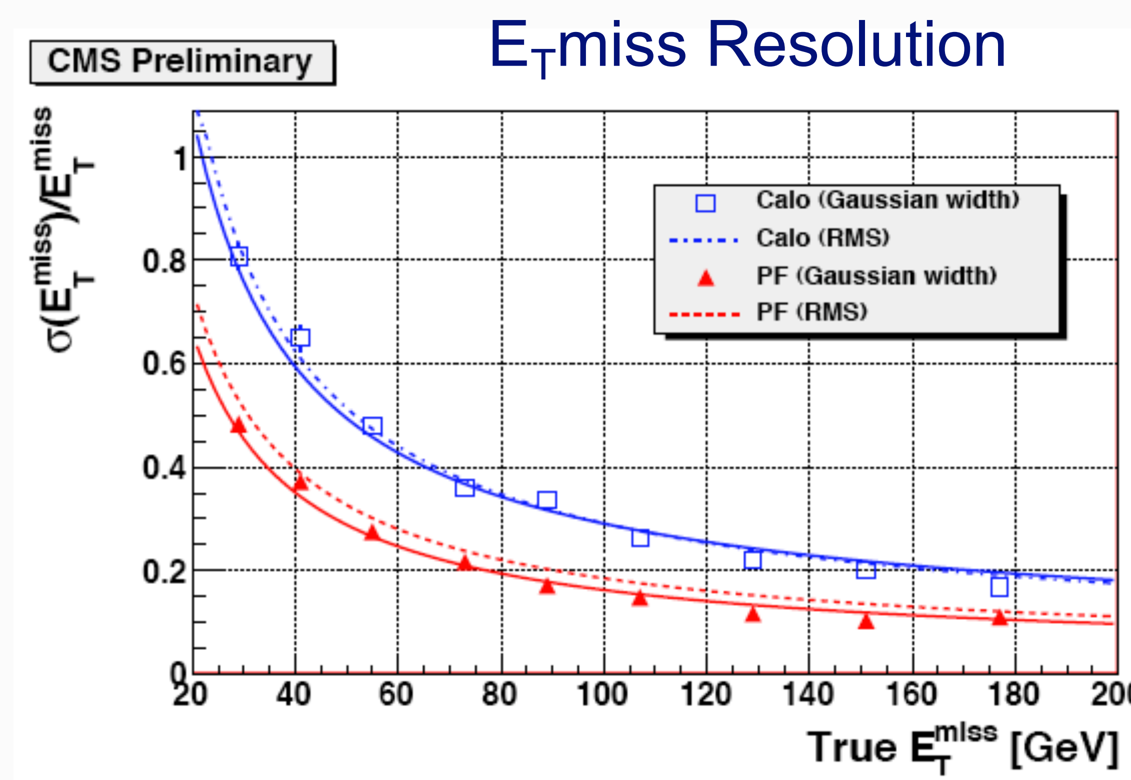
Example CMS : Performance improvements

Virdee, EPS09









Expected Detector Performance

- Construction quality checks and beam tests of series detector modules, as well as cosmics results, show that the detectors as built should give a good starting-point performance
- Example ATLAS (Gianotti, EPS09)

(examples)	Initial Day-1	Ultimate goal	Physics samples to improve
ECAL uniformity	~2.5%	0.7%	Isolated electrons, $Z \to ee$
e/γ E-scale	2-3%	<0.1%	J/ψ, $Z \to ee$, E/p for electrons
Jet E-scale	5-10%	1%	$\gamma/Z + 1j$, $W \to jj$ in $t\bar{t}$ eventsID
ID alignment	20-200 μm	5μm	Generic tracks, isolated μ, $Z \to \mu\mu$
Muon alignment	40-1000 μm	40 μm	Straight μ, $Z \to \mu\mu$

- However, a lot of data (and time …) will be needed at the beginning to
  - Commission the detector and trigger in situ
  - Reach the performance needed to optimize the physics potential
  - Understand “basic” physics at 7-10-14 TeV and normalize (tune) the MC generators
  - Measure backgrounds to new physics and extract “early” convincing signals

Summary of Part 1

“Hofstadter’s Law :
It always takes longer than you think,
even if you take into account Hofstadter’s Law”

Douglas R. Hofstadter

Summary Part 2

- The Detectors
  - are designed to optimally exploit the physics offered by the LHC
  - the LHC environment (physics, rates, backgrounds, radiation, ...) put unprecedented constraints on the detector
  - many years of R&D were needed to meet the challenges
- ATLAS and CMS
  - are both general purpose experiments
  - but are different in their overall layout and in their specific sub-detector (design) choices
  - from current knowledge (test beams, cosmics) we can expect excellent performance
- Preparations: We see the light at the end of the tunnel