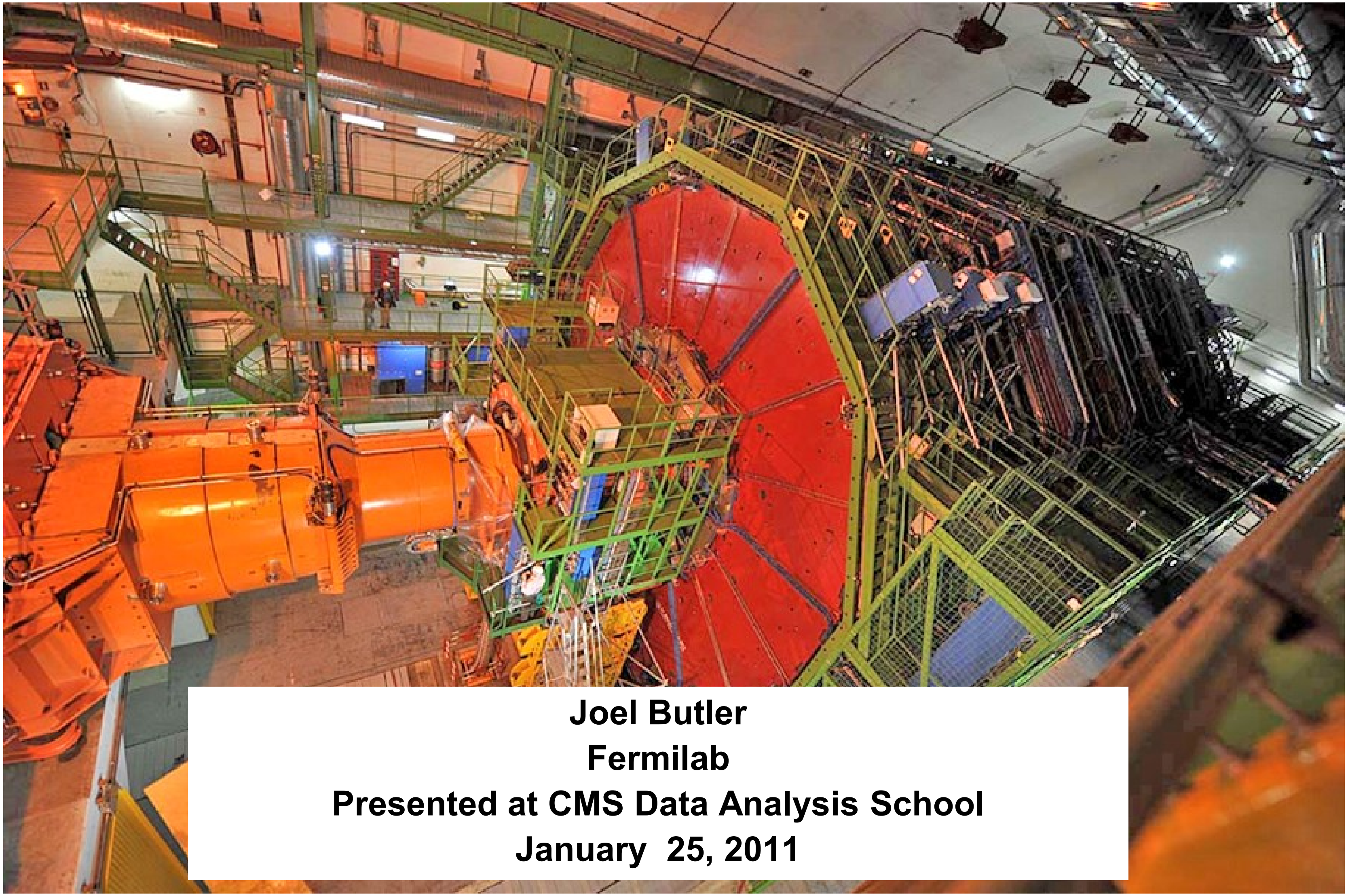
The CMS Detector: Present and Future



Joel Butler
Fermilab
Presented at CMS Data Analysis School
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Outline

- The Problem: What should a detector to explore electroweak symmetry breaking and search for new physics look like?
- The Answer: CMS
- Challenges for the future – upgrades to CMS as luminosity of LHC is increased
- Concluding remarks

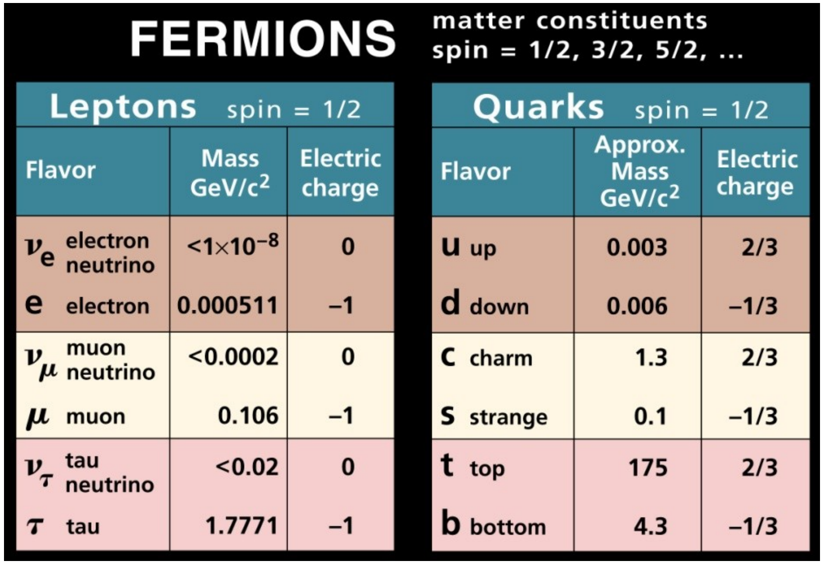
A Detector to Look for the Higgs Boson and Physics Beyond the Standard Model (BSM)

- There are a variety of possible decay modes for the Standard Model Higgs, depending on its mass
- There are many candidates for new physics
  - Supersymmetry
  - New interactions, e.g. Technicolor
  - Extra dimensions
  - Right-handed gauge bosons
  - Many, many more ….
- A “ discovery detector”, also called a “general purpose detector” at LHC must be able to study all these states and separate the interesting events from a much larger background of uninteresting stuff that has the nasty habit of mimicking new physics and misleading us

How can we do this?

- Heavy objects decay into lighter objects
  - **The "lighter objects" are the particles of the Standard Model**
    - Photons, electrons, muons, τ leptons, jets (light quarks u,d, s and gluons)- especially "b-jets", "charm jets", "top", Ws, and Zs
      - Only a few particles are stable enough to be measured directly: e,μ,γ, plus some hadrons: pions, kaons, protons, neutrons
    - Partons, quarks and gluons, manifest themselves as jets of particles so identifying "jets" and measuring their angle and energy becomes important
  - **It is a requirement for finding new physics to be able to measure all the known SM objects**
- Particles may leave the detector without interacting
  - Neutrinos are known SM particles that do that all the time
  - There may be NEW massive weakly interacting particles that behave similarly
  - **These can be "detected" by observing missing transverse energy , "MET", so it is a requirement to be able to detect it**

The Standard Model Elementary Particles



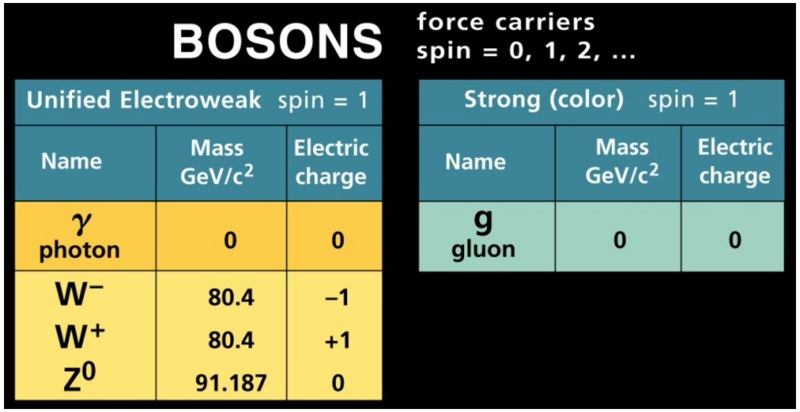
FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3



BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

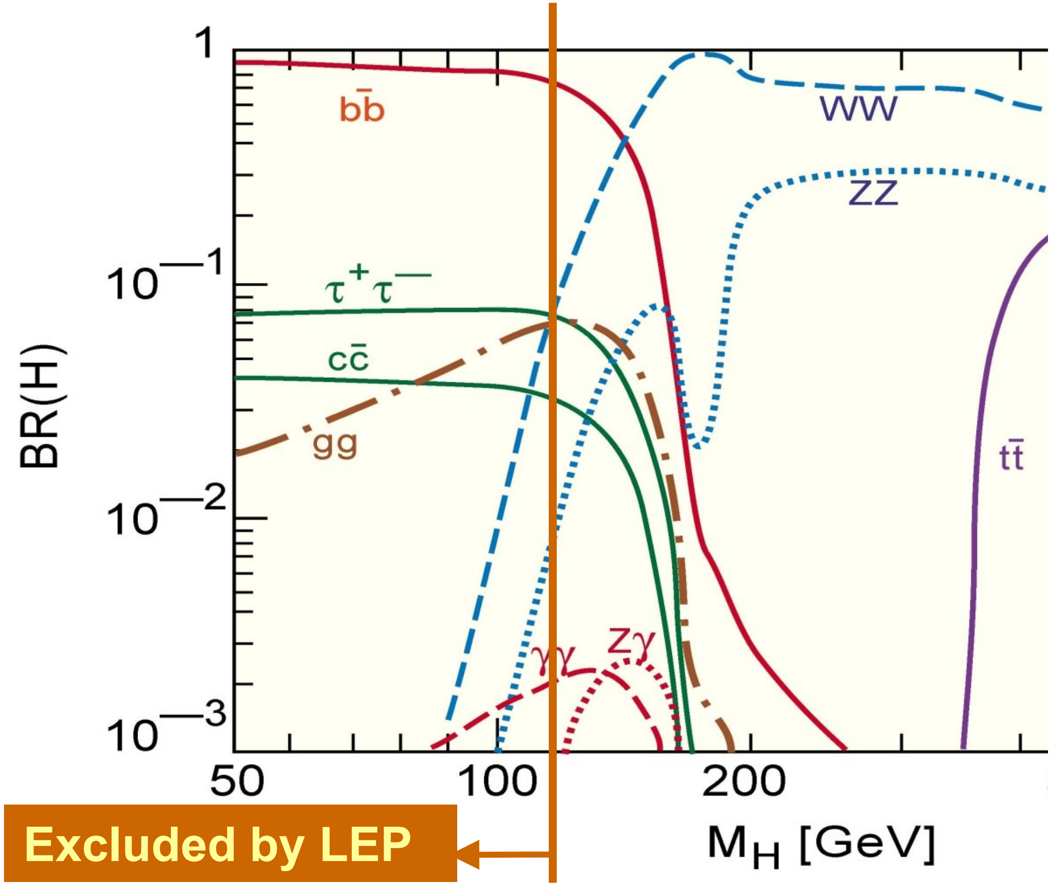
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

SM Higgs Decay Modes

Decay modes depend on(unknown) Higgs mass



Excluded by LEP

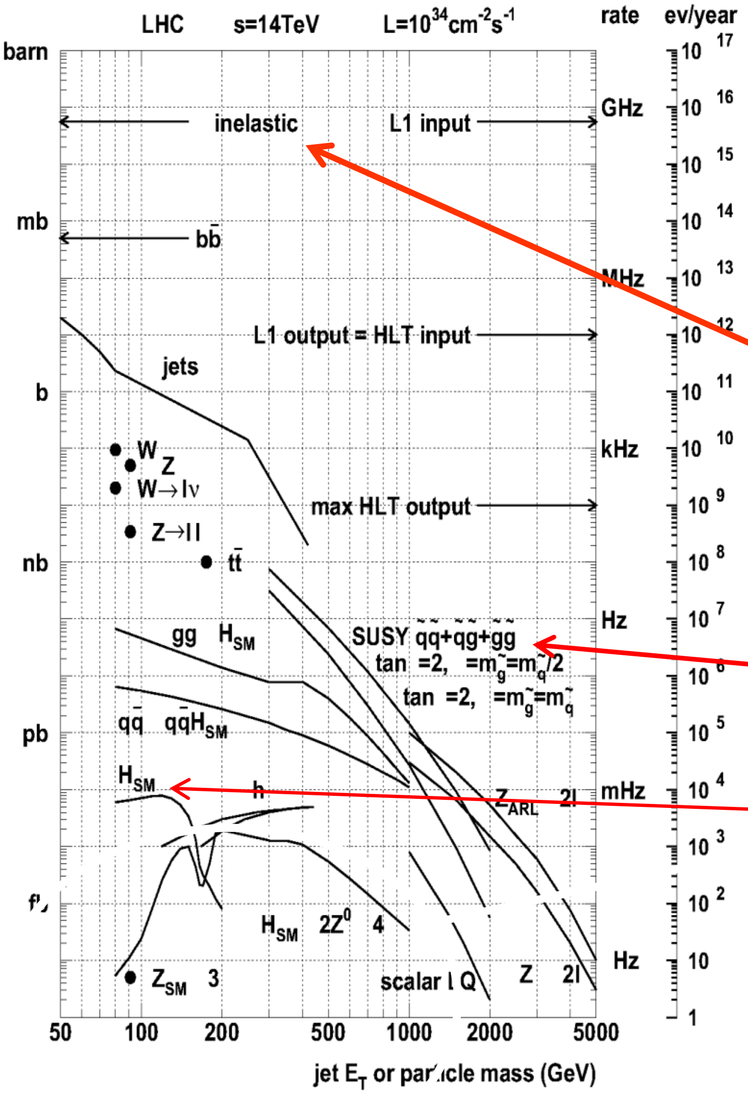
M_H range (GeV)	Decay mode
$M_H < 130$	$b\bar{b}$, $\gamma\gamma$, $\tau^+\tau^-$, $c\bar{c}$
$130 < M_H < 150$	$H \to ZZ^*$
$150 < M_H < 180$	$H \to WW$
$180 < M_H < 600$	$H \to ZZ$

$$Z \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \nu\bar{\nu}, q\bar{q}$$

$$W^+ \to e^+\nu, \mu^+\nu, \tau^+\nu, u\bar{d}, u\bar{s}, u\bar{b}, c\bar{s}, c\bar{d}, c\bar{b}$$

The Higgs search all by itself guides us to excel at measuring all SM objects and shaped the original design of CMS

Production Cross Sections at the LHC



- Cross sections and background estimates (measured, calculated) tell us what minimum energy and luminosity we need from the colliding beams and therefore what the detector must be able to handle
- Production dynamics determine the range of energies and angles we need to measure

Inelastic background events produced at a rate of 1 GHz.

Supersymmetry ~ 1Hz

Detectable Higgs production ~ 1 milliHz.

Luminosity

- Each beam consists of many bunches ~2808 planned, a few cm long, 25ns apart
- To maximize the interaction rate
  - **Maximize the number of particles in each bun**
  - **Minimize spatial extent of each bunch: highes**
  - **Don’t miss – hit them square on**
- But at a given luminosity, fewer bunches -
  - **Several interactions/bunch is a challenge to th superimposed**
    - **This is called “pileup”**

$$L = \frac{N_b^2 n_b f_r \gamma}{4\pi\varepsilon_n \beta^*} F$$

Symbol	Quantity	Affected by
N_b	Number of particles per bunch	Injector chain
n_b	Number of bunches	Limited by electron cloud effect
f_r	Revolution Frequency	Property of LHC
ε_n	Normalized emittance	Injector chain
β^*	Beta function value at Interaction Point (IP)	Interaction region focusing system
F	Reduction factor due to crossing angle	Beam separation schemes

The quantity “Luminosity” captures all these ideas into one number. It has units of $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. **The number of interactions produced =**

Luminosity x cross section (cm^2) x running time(s)

LHC design L=10^{34} cm^{-2} s^{-1}, ~20 interactions/crossing

After CM energy, luminosity is the most important parameter that defines the physics reach of a machine

Luminosity calculator: http://lpc.web.cern.ch/lpc/lumi.html

Typical Events and Hard Scatters

- The typical inelastic event is mostly π^+, π^-, and π^0s (which decay immediately to 2 γs) in ~ equal amounts. These are distributed with a relatively flat rapidity distribution, with about 6 tracks/unit of rapidity and reasonably small average P_T~0.150 GeV/c
  - So ~30 tracks in the $\eta = \pm 2.5$ of CMS
  - Less than 100 GeV of energy is deposited in the central region
  - About 500 GeV is deposited in the interval $\eta = 3$ to 5
  - These constitute the "pileup" events, many of which are superimposed on the occasional "hard scatter" we want to study
    - Pileup of 20 → 600 tracks and 600 photons
  - They also contribute to the "radiation damage" of the detector
  - All the rest of the energy, ~> 6 TeV, goes forward or backward near or in the beam pipe
- These events, often called "minimum bias", are not interesting for addressing Electroweak physics or Beyond the Standard Model Physics

The Nature of Hard Collisions

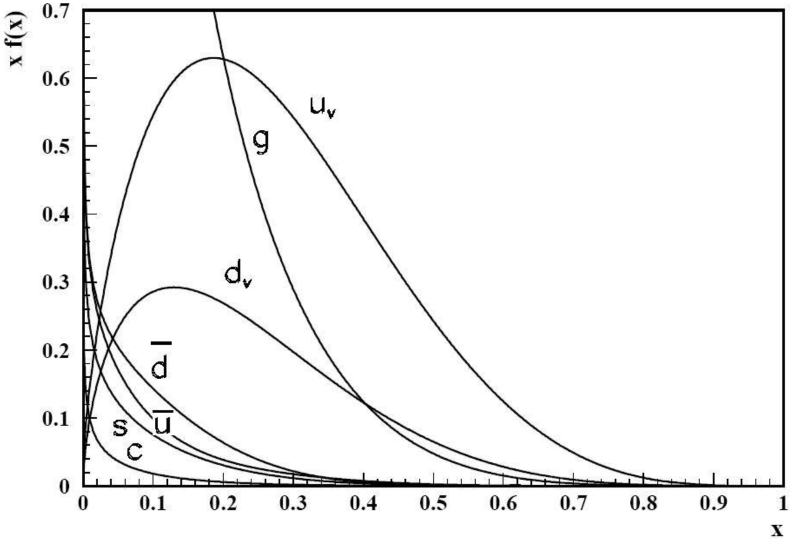
A proton is a "bag" containing partons: 3 "valence" quarks (u, u, d) and a whole spectrum of gluons, and virtual quark-antiquark pairs, called the "sea".

The partons are described by Parton Distribution Functions (PDF)s:

$f_j(x)$= probability density for having a parton of type j with fraction x of the proton's momentum $0 \leq x \leq 1$

"Hard" collisions between a parton "a" in one proton and a parton "b" in the other proton occur with probabilities given by the cross sections and PDFs:

$$\sigma(pp \to cX) = \sum_{a,b} dx_a dx_b \left[f_{a/p}(x_a) f_{b/p}(x_b) \right] \times \hat{\sigma}(ab \to cX)$$



At large x, u dominates over d.
At x<0.2, the gluon is dominant

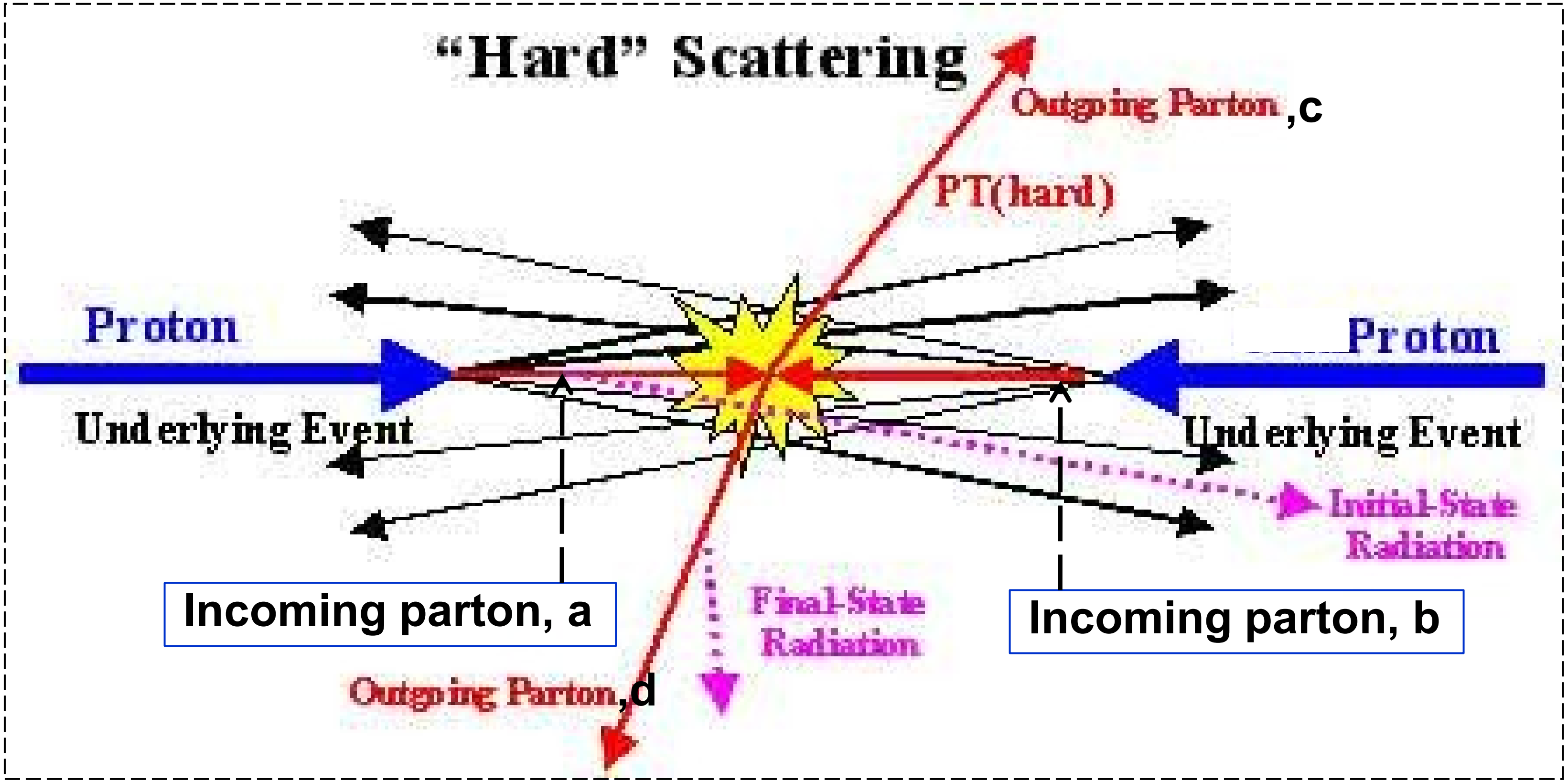
Higher total energy allows the collisions of lower "x" partons, that are more abundant, to have enough energy in the parton- parton CM to make heavy objects.

Cross sections are higher than at lower energy machines

The proton having M~1GeV, there is little intrinsic transverse momentum in the initial state

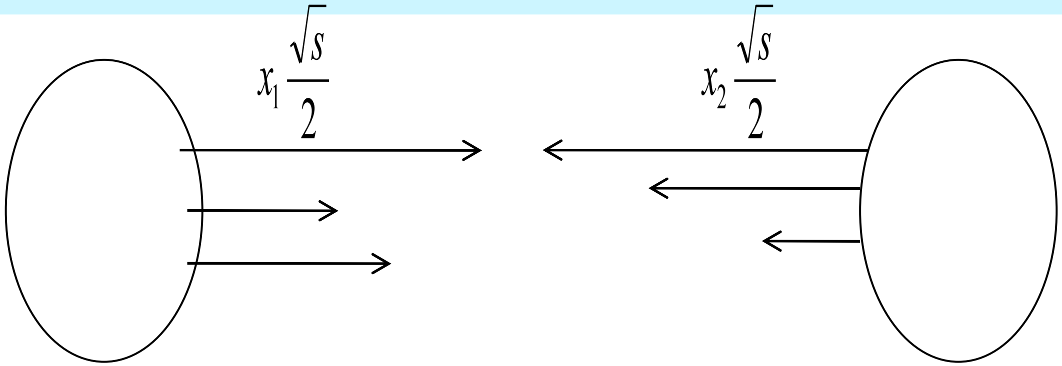
http://hepdata.cedar.ac.uk/pdf/pdf3.html

A Hard Scattering



Since parton a and parton b will rarely have the same energy, the center of mass of the parton-parton collision is moving in the proton-proton center of mass

Production Kinematics - 1



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

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

$$p_T\approx 0$$

$$M^2=\hat{s}=x_1x_2s$$

Since P_T is limited but P_L varies greatly, we need special variables that transform well under a Lorentz boost to handle a center of mass with very different energies. E and p don't work well, but $(E+P_L)$ and $(E-P_L)$ do (light cone variables)

A boost of a system by β is given by

$$\begin{pmatrix} E+P_L \\ E-P_L \end{pmatrix}=\begin{pmatrix} e^{y_B} & 0 \\ 0 & e^{-y_B} \end{pmatrix}\begin{pmatrix} E'+P_L' \\ E'-P_L' \end{pmatrix}\ \text{where}\ y_B=\frac{1}{2}\left(\ln\frac{1+\beta}{1-\beta}\right)$$

This suggests using as a variable, the "rapidity"

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

A boost of β simply adds Y_β to the rapidity of every particle and any rapidity interval is unchanged by a boost

Production Kinematics - 2

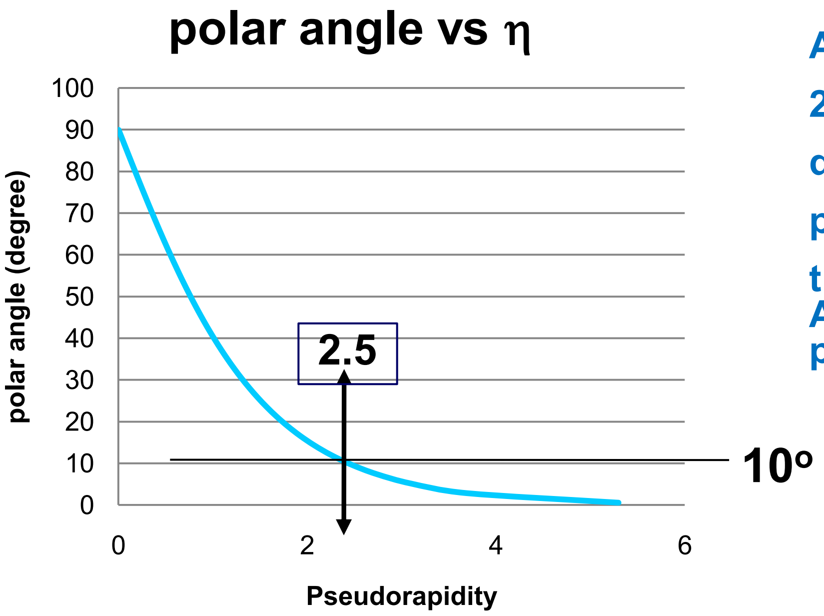
Since $y' = y + Y_B$, the “span” of a object $\Delta y = y_1 - y_2$ is independent of CM motion of the 2 colliding partons →central to definition of a “jet”

For relativistic particles, $\beta \sim 1$, the momentum drops out, only depends on angle. This new variable is called the “pseudorapidity”, η.

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

Relation to parton momentum fractions:

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



A spectrometer that covers 2π in azimuthal angle and down to 10^0 on each end in polar angle, covers 98% of the full solid angle. It will Accept the light decay products of heavy objects

Production Kinematics - 3

- What angular coverage is necessary?
  - **Heavy objects are produced more "centrally" e.g. y(or η)~ 0 so will not be moving too fast in the lab.**
  - **Light decay products are emitted over a large range of lab angles, momenta**
  - **A good P_t measurement at large polar angles requires a B field parallel to the beam axis. For forward particles requires a B field perpendicular to the beam axis**
    - **In practice must choose**
  - **You do not gain much solid angle coverage for light decay products by going to small polar angles (d $\Omega = \sin\theta \, d\theta \, d\phi$)**
  - **The small angles, being closest to the beams and the forward burst of energy have the hardest time being useful**

The total rapidity interval is limited and depends on the mass of the object produced

$$-\ln\frac{\sqrt{s}}{M} \le y \le \ln\frac{\sqrt{s}}{M}$$

√s	M(GeV/c^2)			
	0.140	100	350	1000
1.96	9.5	3.0	1.7	0.7
7.0	10.8	4.2	3.0	1.9
14.0	11.5	4.9	3.7	2.6

Y=0 corresponds to head on collisions at

$$x_{1,2} = \sqrt{\frac{M^2}{s}}, \text{ which is } p_l = \frac{M}{2}$$

Heavy objects are produced more centrally, so the detector should do the best job of instrumenting the central region!!!

Transverse Momentum

- There is little transverse momentum in the initial state
- Transverse momentum in the final state comes from
  - **The hard scattering process or**
  - **The decay of some heavy object made by the collision**
- Transverse momentum is also invariant to a longitudinal boost

Detector should focus on measuring P_t , η (polar angle), ϕ (azimuthal angle

How well do we have to measure it? Suppose an extreme case- a 2 TeV object decaying into two particles (Z'→ $\mu^+\mu^-$), then, P_T~1TeV/c x sin θ

Suppose we want P_T to ~10% in this extreme case

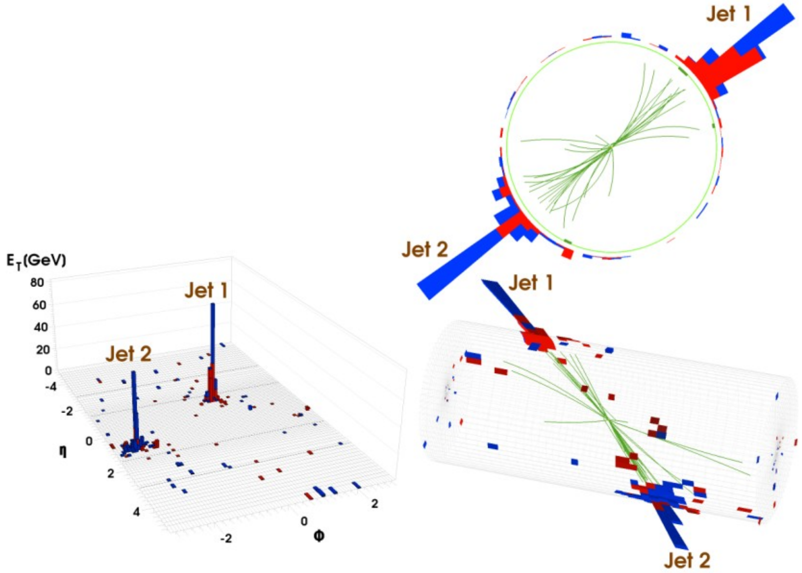
$$\frac{\sigma(P_T)}{P_T} = \frac{\sigma_{r\phi}}{0.3BL^2} \times \sqrt{\frac{720}{N+4}} \times P_T$$

(For a solenoid)

(B in Tesla, L and $\sigma_{r\phi}$ in m, P_T in GeV/c, N = number of tracking Layers)

If $\sigma_{r\phi}$~ 50-100 μm,BL^2 must be around 3-4 T-m^2

Complex Objects: Jets and Missing E_t



Jets are large deposits of energy in ~small regions of Δy (Δη) and Δφ:

$$\Delta R_{1,2} = \sqrt{(\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2}$$

To include a track or calorimeter energy deposit in a jet:

$$\Delta R_{i,\,\text{jet axis}} \approx 0.5, 0.7$$

Total area of plot shown is ~62.8, so Δη~0.1, Δφ~0.1 for calorimeter segmentation should be adequate even to resolve several jets within a single event

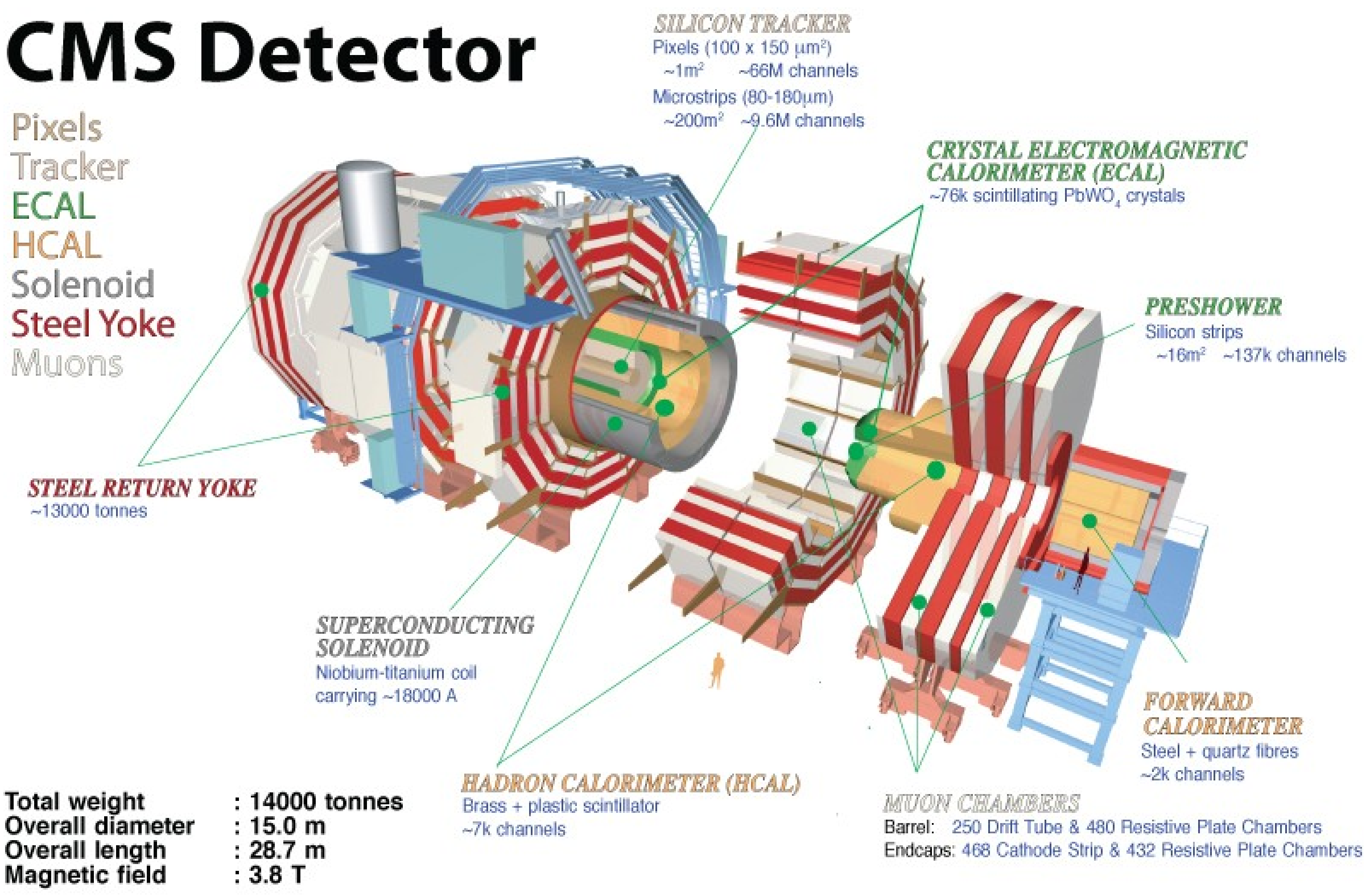
MET is the negative the vector sum of all the transverse components of observed energy including any muons. It Indicates the presence of weakly interacting particles, usually neutrinos, but possibly new exotic objects that interact only weakly.

The focus is on the transverse energy because an unknown amount of longitudinal energy may be lost down the beam. If the angular coverage is sufficient, missing components will not contribute much to the missing transverse energy

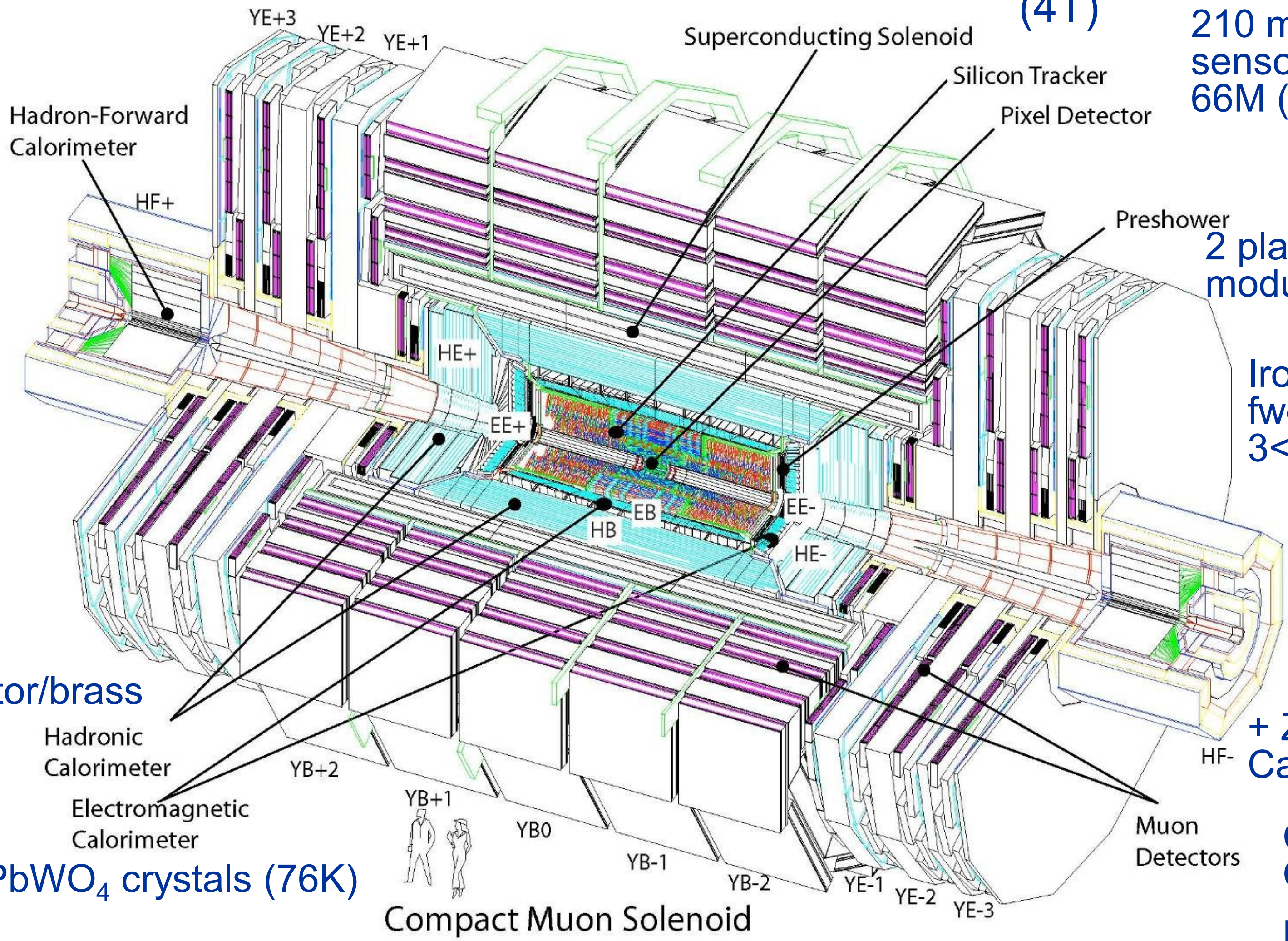
These and other complex objects, b-jets, τs Ws, Zs, top are discussed in next talk

CMS - The Compact Muon Solenoid

Electromagnetic and



CMS - The Compact Muon Solenoid



(4T)

210 m^2 of silicon sensors: 9.6M (Str) & 66M (Pix) channels

2 planes of silicon modules for ECAL

Iron / Quartz fiber fwd calorimeter, $3<|\eta|<5$;

+ Castor, $5<|\eta|<6.55$

+ Zero Degree Calorimeter

Cathode Strip Chambers,

Drift Tubes, Resistive Plates

Scintillator/brass

$PbWO_4$ crystals (76K)

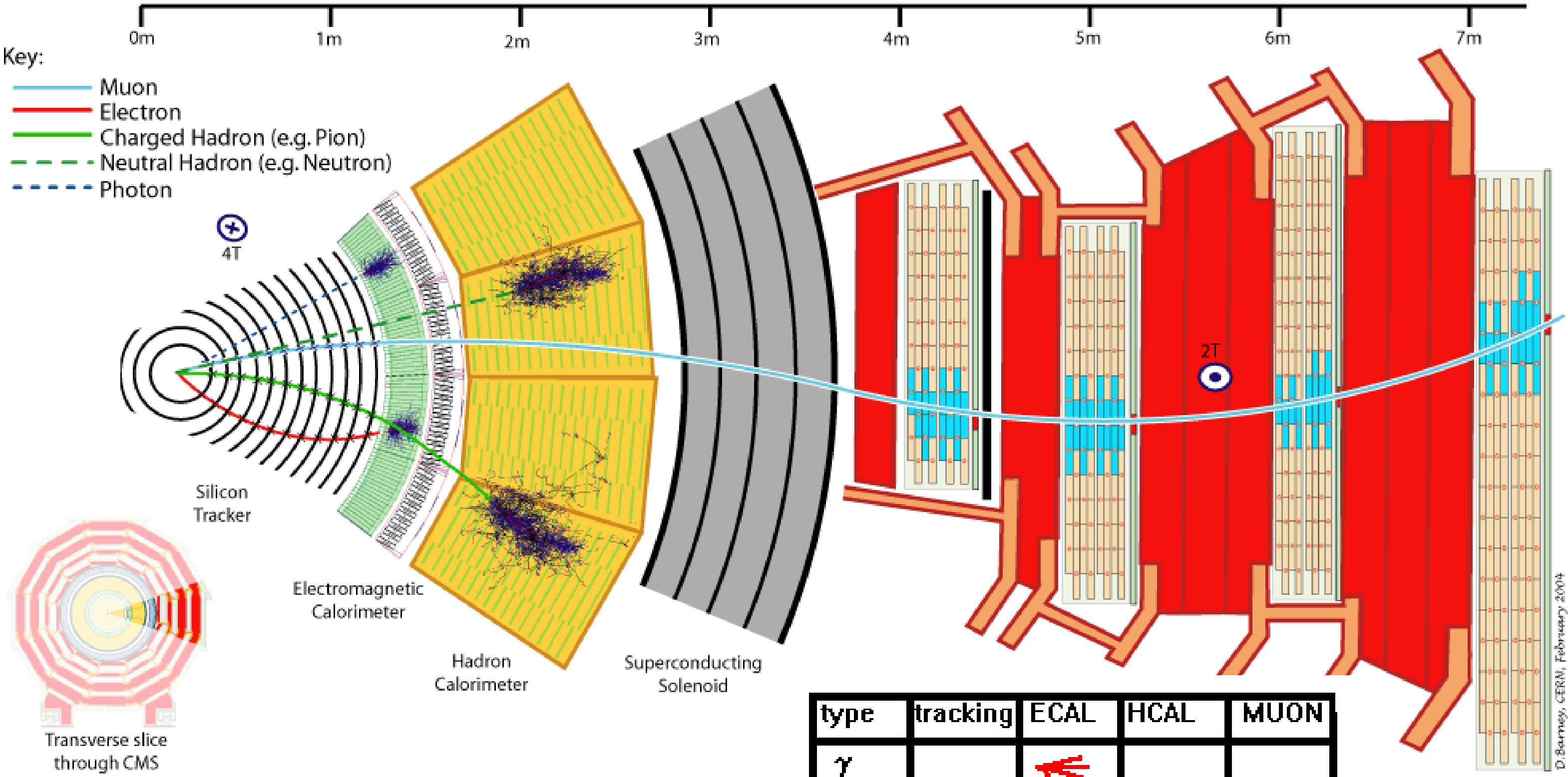
CMS Design Features

- Very large solenoid – 6m diameter x 13 m long
- Tracking and calorimetry fits inside the solenoid
  - particles measured before they pass through the solenoid coil and cryostat, which would degrade their resolution
- Very strong field – 3.8 T
  - Excellent momentum resolution
  - Coils up soft charged particles
- Tracking chambers in the return iron track and identify muons
  - This makes the system very compact
  - Weight of CMS is dominated by all the steel and is 14,000 Tonnes
- A lead tungstate crystal calorimeter (~76K crystals) for photon and electron reconstruction
- Hadron calorimeters for jet and missing E_t reconstruction (provides coverage to $\eta\sim5$)

- Charged Particle Tracking is based on all-silicon components
  - A silicon pixel detector out to radius ~ 20 cm
  - A silicon microstrip detector from there out to 1.1 m
  - Small pitch gives CMS excellent charged particle tracking and primary and secondary reconstruction
  - High segmentation results in very low occupancy
  - Silicon detectors are very radiation hard

Muon momentum is measured in the muon system but the best resolution comes from associating a silicon track, which has excellent momentum resolution ,with the muon track and doing a full fit. Challenge is to do this with high pileup → fine pitch→ low occupancy, MAJOR DIFFERENCE BETWEEN ATLAS AND CMS. It is why CMS is "compact"

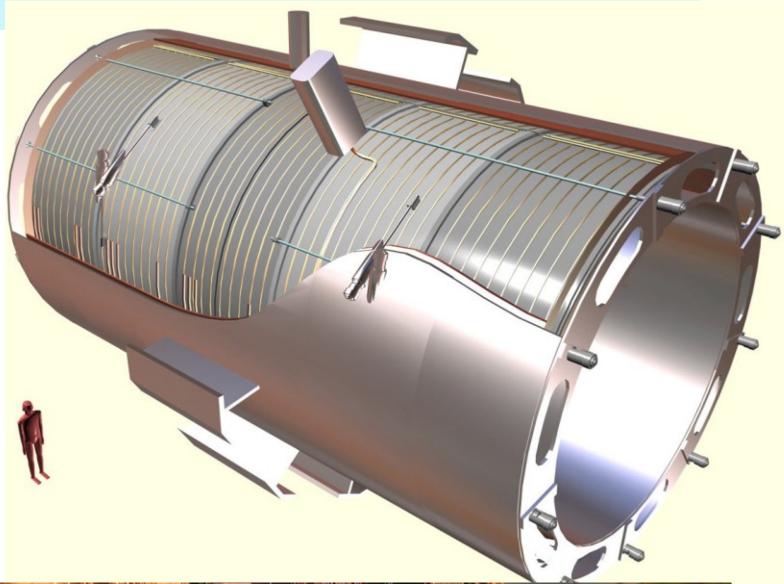
CMS Slice

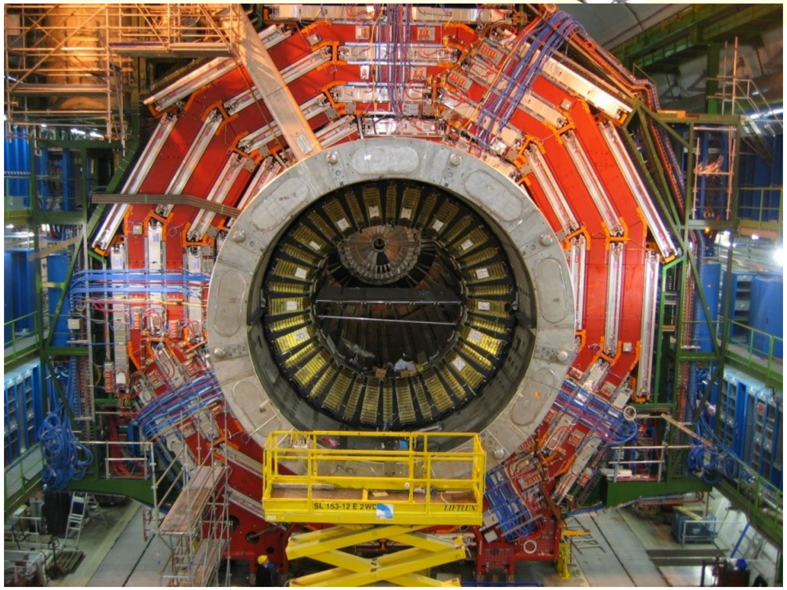


type	tracking	ECAL	HCAL	MUON
γ				
e				
μ				
Jet				
Et miss				

CMS Solenoid

- Solenoid has the features described above
  - **Large acceptance in the most promising region**
  - **Bends charged particles, allowing tracker to measure the transverse momentum. Optimal for measuring P_t in central region**
- **3.8 T magnet at 4^{o} K**
- **6 m diameter and 12.5 m long (largest ever built)**
- **220 t (including 6 t of NbTi)**
- **Stores 2.7 GJ — equivalent to 1300 lbs of TNT**

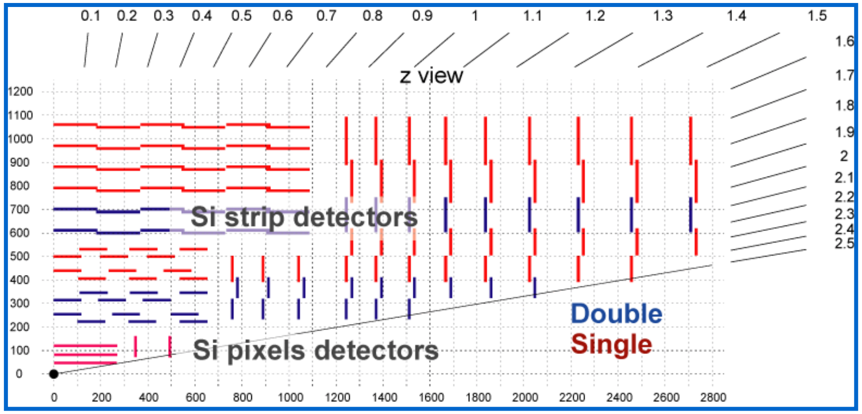




CMS Tracker

- **All silicon tracker**
  - **3 layers of 100x150 μm^2 pixels: radii = 4.4cm, 7.3 cm, 10.3 cm**
    - **Precision vertex – primary and secondary – reconstruction**
    - **“seeds” the pattern recognition**
  - **10 layers of silicon strips with ~100 μm pitch, from r =25 cm to 110 cm**
    - **Measures the momentum**
    - **Precision matching of charged tracks to calorimeters and muon detectors**
    - **Four layers are “double sided” – two back to back ladders with an azimuthal and small angle stereo view**
- **Entire system at -10^{o}C which improves radiation tolerance by a factor of 100 compared to 25^{o}C**

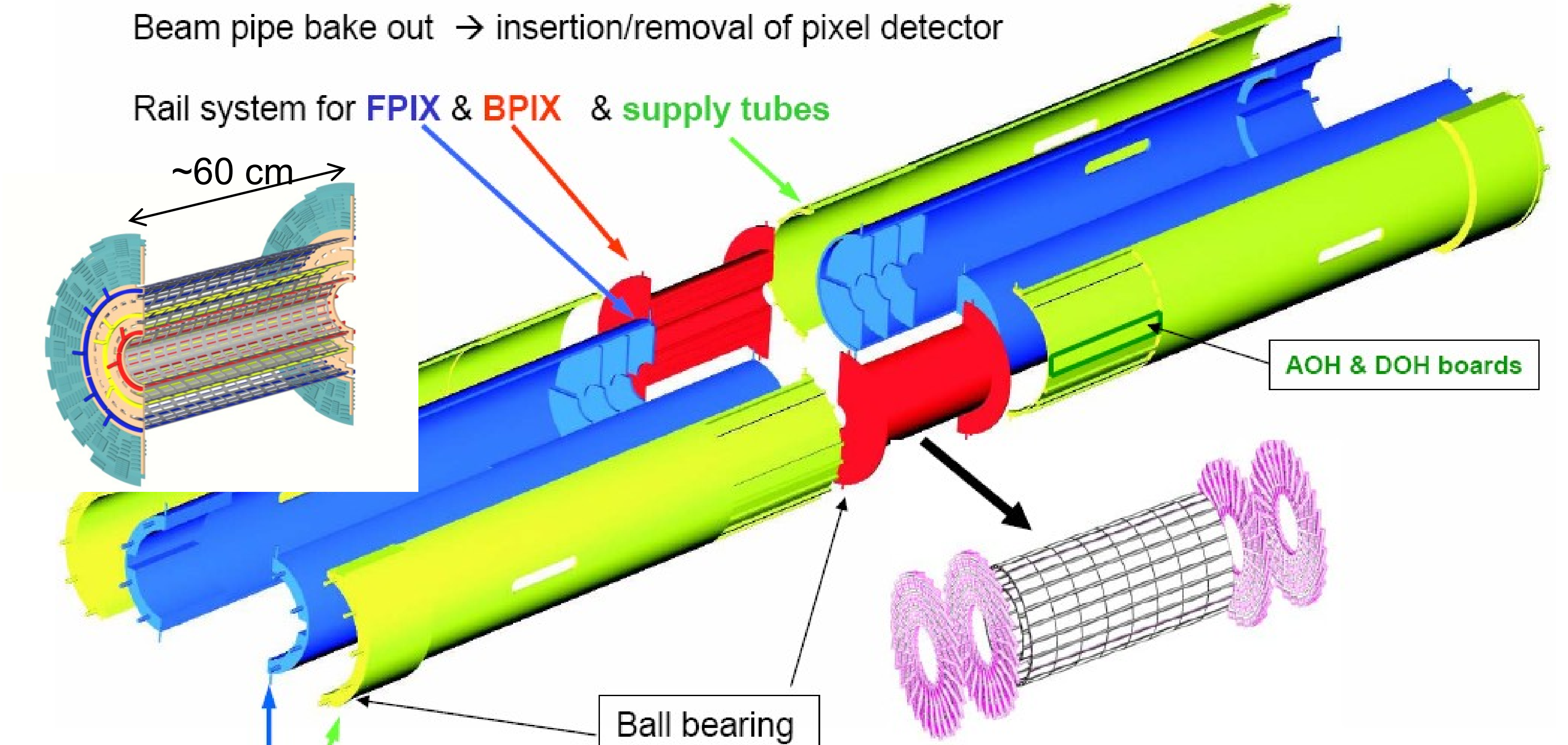
68M pixels and 10M strips produces low occupancy. Detector can function well in high pileup environment



The CMS Pixel System

Beam pipe bake out → insertion/removal of pixel detector

Rail system for **FPIX** & **BPIX** & **supply tubes**



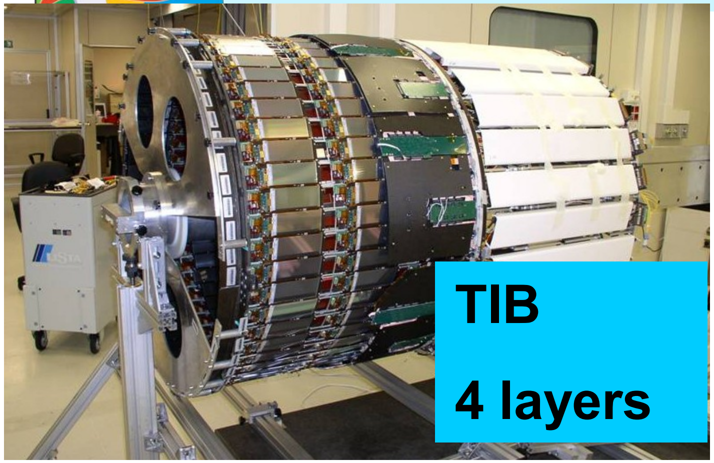
AOH & DOH boards

Ball bearing rollers

Supply tube:
power, cooling & optical links
Pigtails of power cables

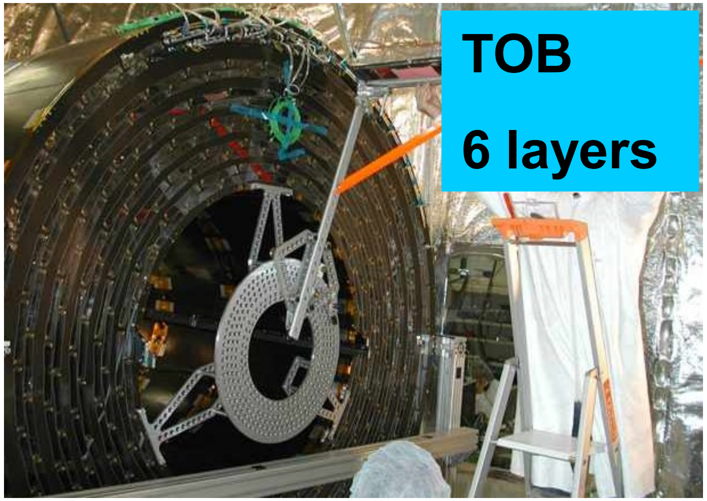
BPIX (3 Layers)	**FPIX** (2 Disk)
672 Modules	96 Blades
96 Halfmodules	672 Plaquettes
11520 ROC	4320 ROC

Completed Tracker



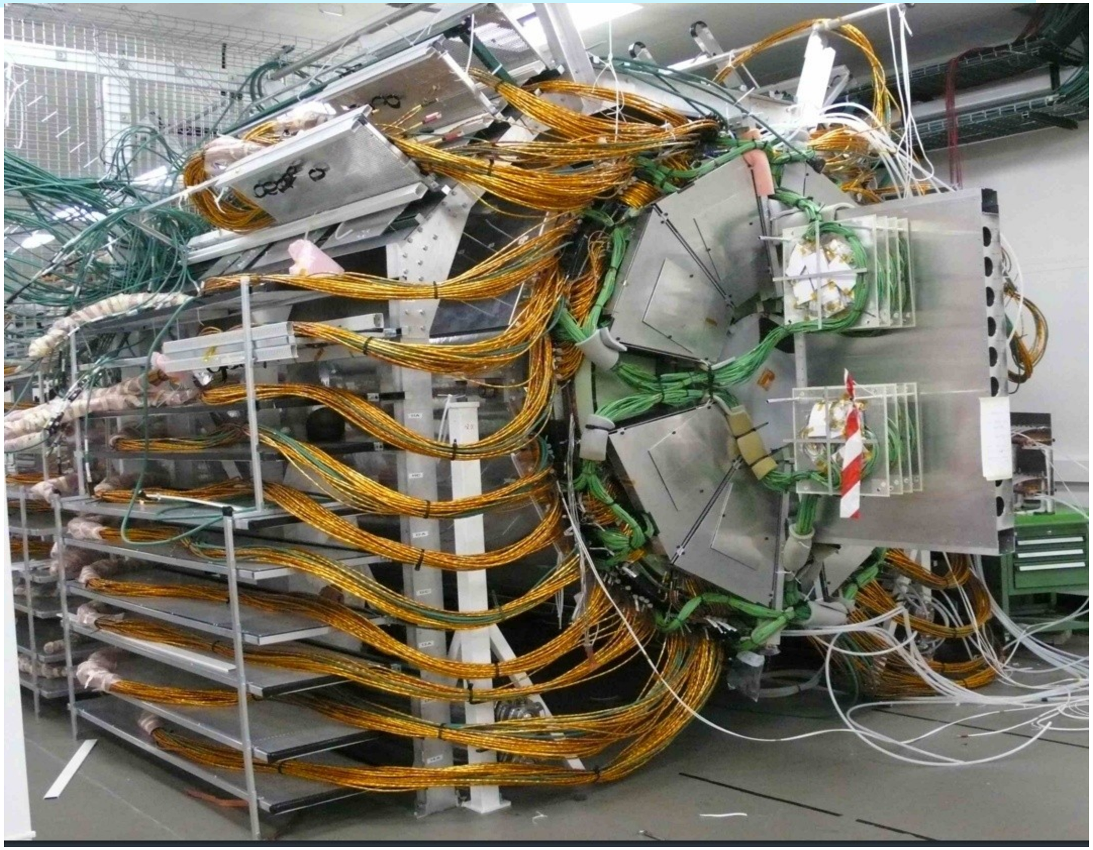
TIB

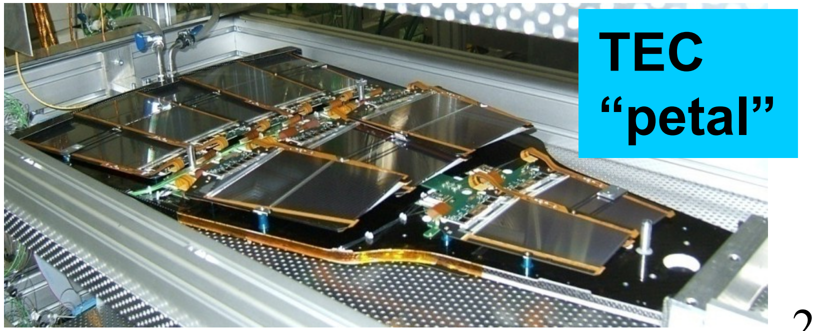
4 layers



TOB

6 layers





TEC
"petal"

2300 square feet of silicon!!!!!
detectors, 11 million strips

Tracking System Performance

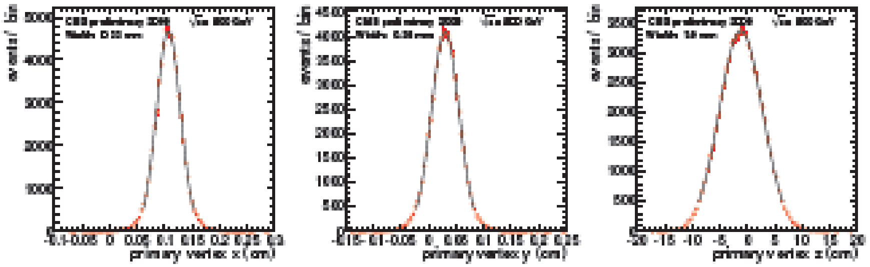
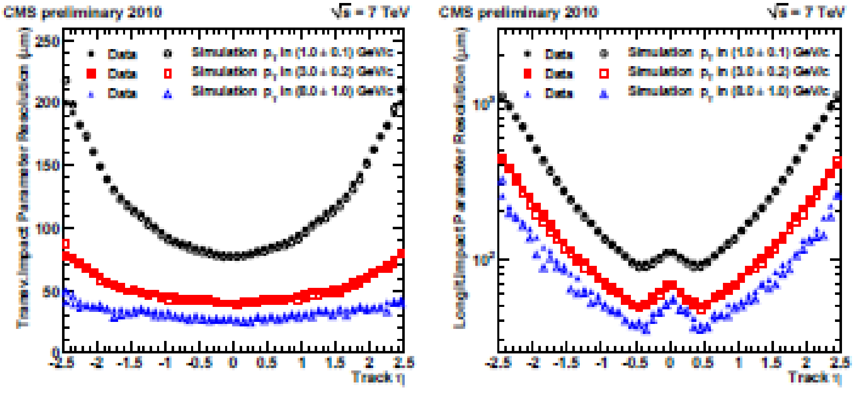
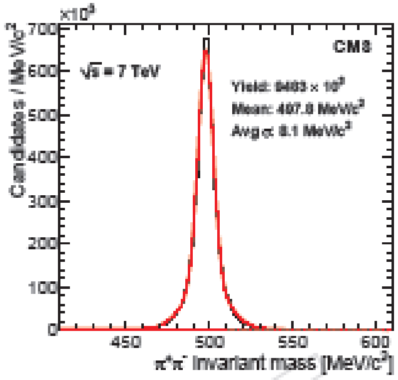


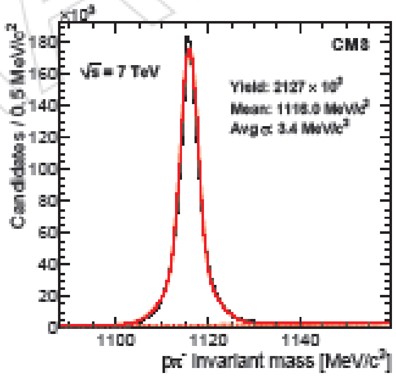
Figure 2: Primary vertex distributions from a single run.



(a) (b)

Figure 7: Measured resolution of the track transverse (a) and longitudinal (b) impact parameter as a function of the track η for transverse momenta in $1.0 \pm 0.1\,\mathrm{GeV}/c$ (circles), in $3.0 \pm 0.2\,\mathrm{GeV}/c$ (squares) and in $8.0 \pm 1.0\,\mathrm{GeV}/c$ (triangles). Filled and open symbols correspond to results from data and simulation, respectively.



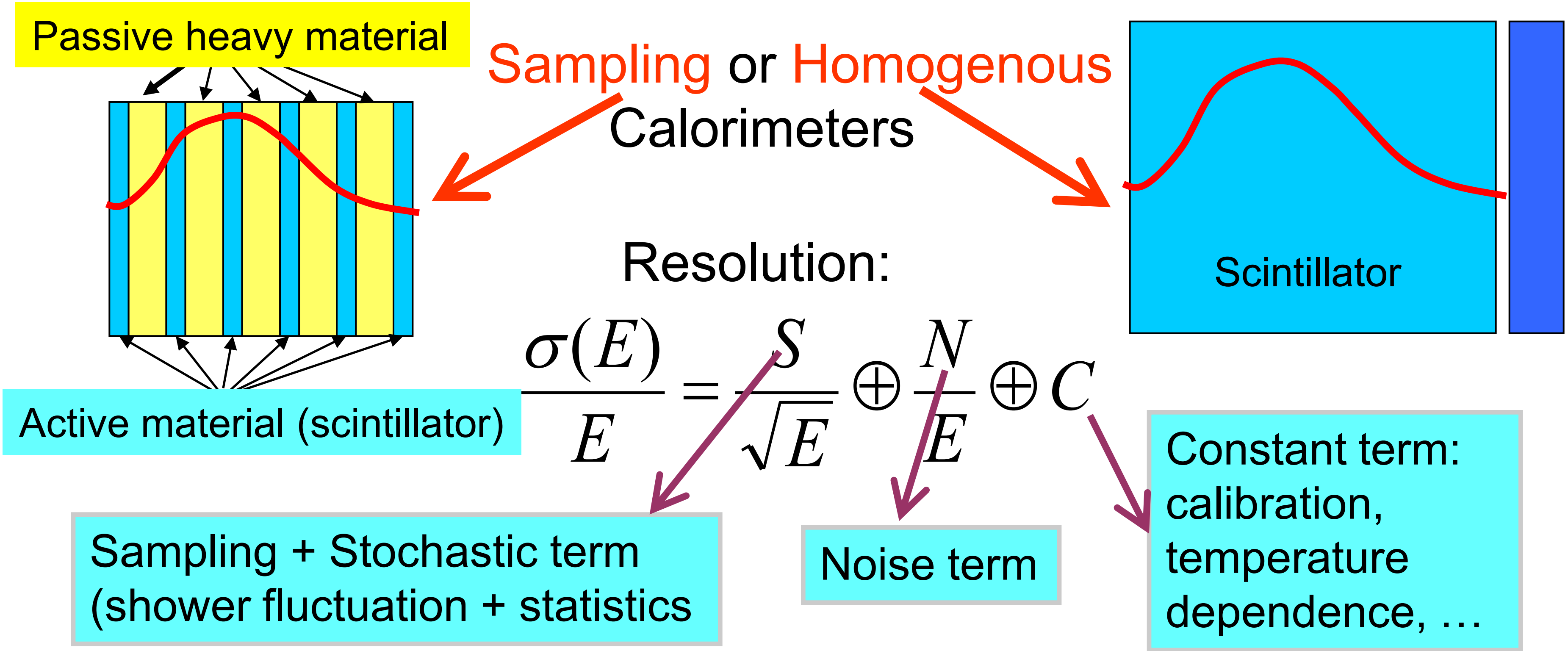


$$\langle \text{Impactparameter} \rangle_{b-jet} \approx \frac{1}{2} \times \pi \times c\tau_{b-hadron} \approx 700\mu\text{m}$$

<impact parameter> > resolution

Calorimetry

- Particles shower in calorimeter creating other particles which shower and so on until no more energy is left
- The created charged particles release energy which can be collected and is proportional to the original particle energy



Passive heavy material

Sampling or Homogenous Calorimeters

Active material (scintillator)

Resolution:

$$\frac{\sigma(E)}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C$$

Sampling + Stochastic term (shower fluctuation + statistics)

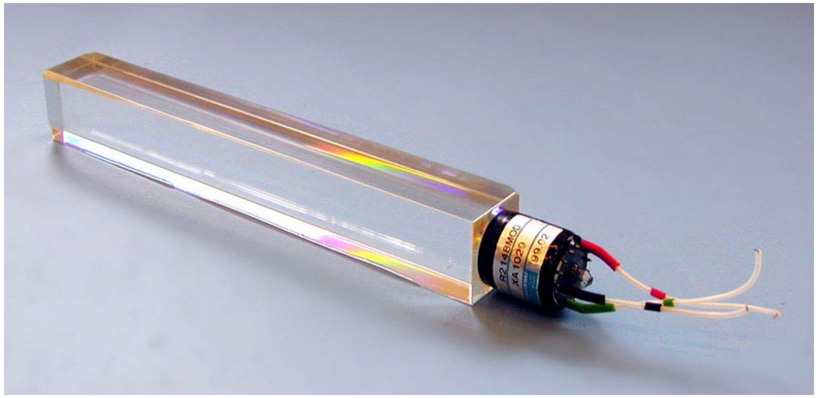
Noise term

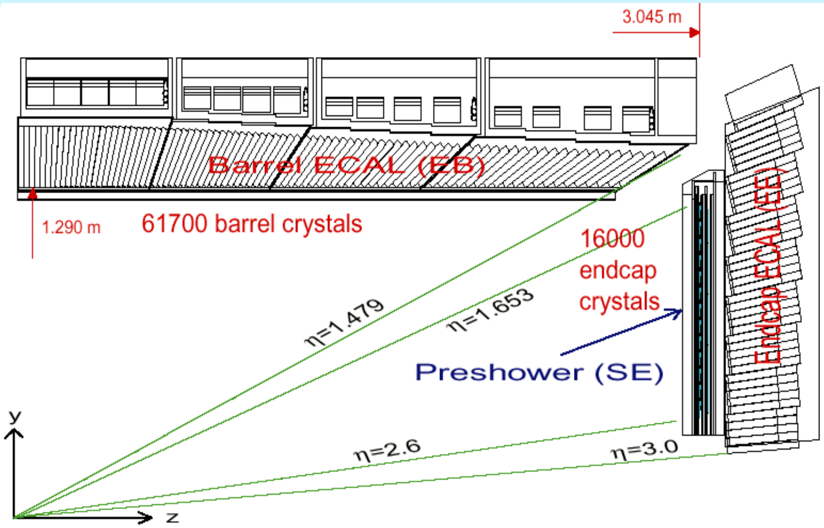
Constant term: calibration, temperature dependence, …

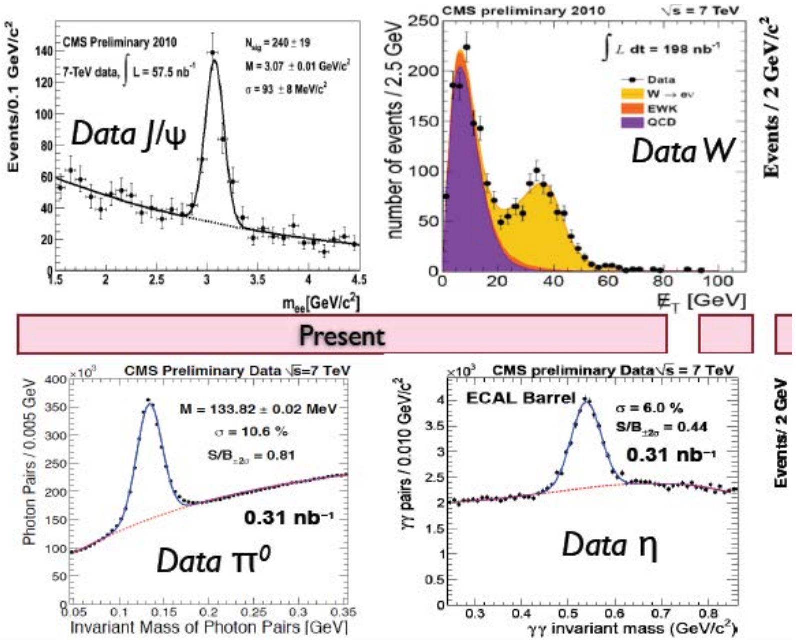
CMS ECAL

- Photons and electrons shower in high Z material
- Homogenous calorimeter
- Lead tungstate ($PbWO_4$) crystals: 2.3 x 2.3 x 23 cm^3
  - ~76,000 crystals
- Radiation hard, dense, and fast
- Magnetic field and radiation require novel electronics APD and VPT

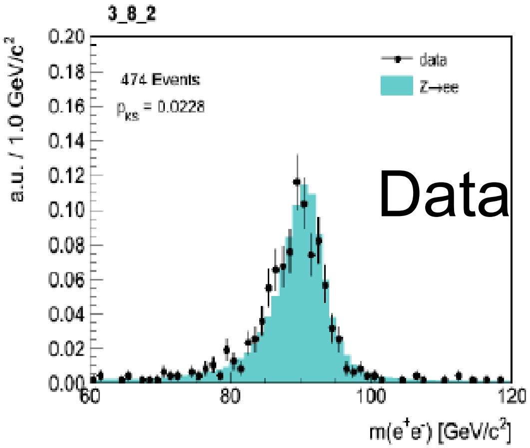
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{\approx 2.5\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.3\%)^2$$

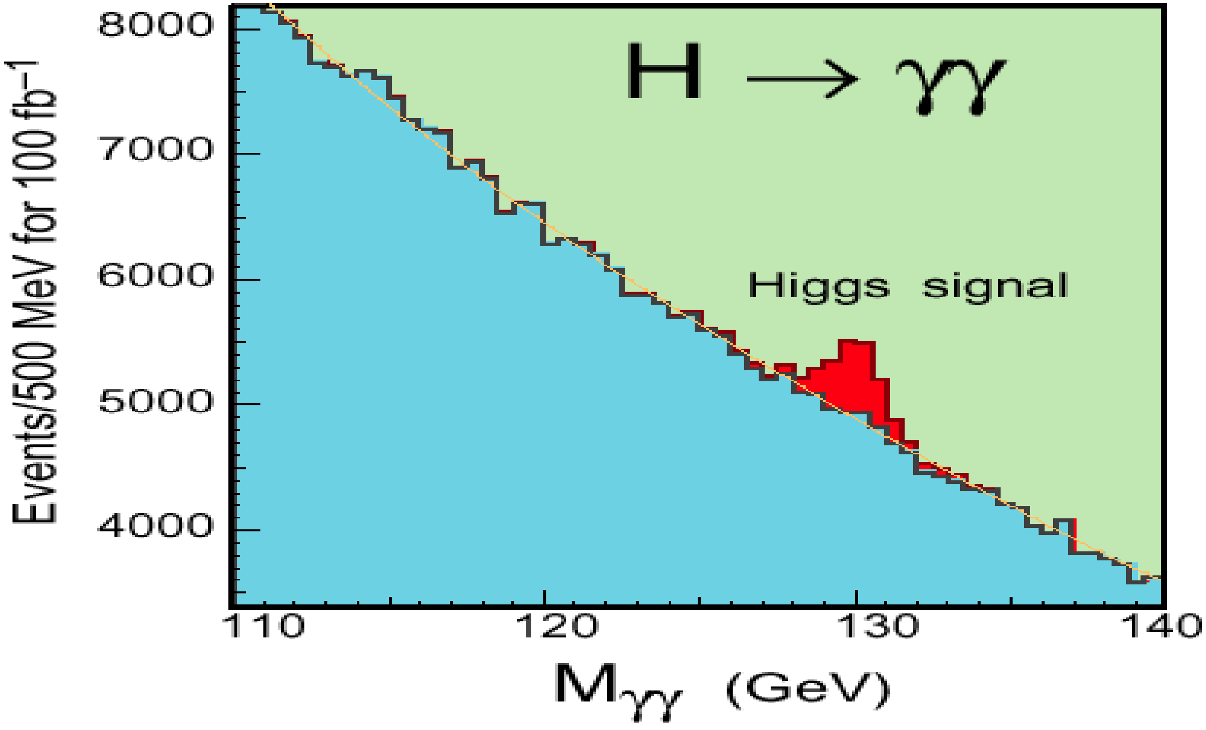


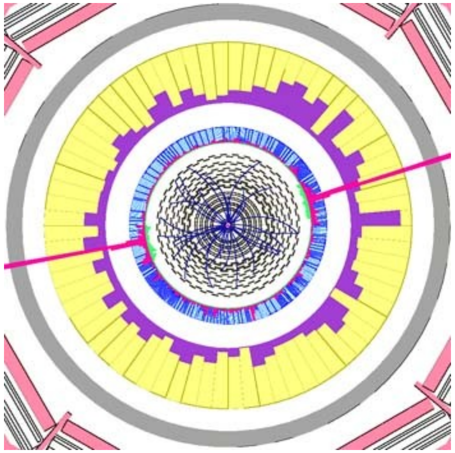




Higgs to 2 photons ($H \rightarrow \gamma\gamma$)





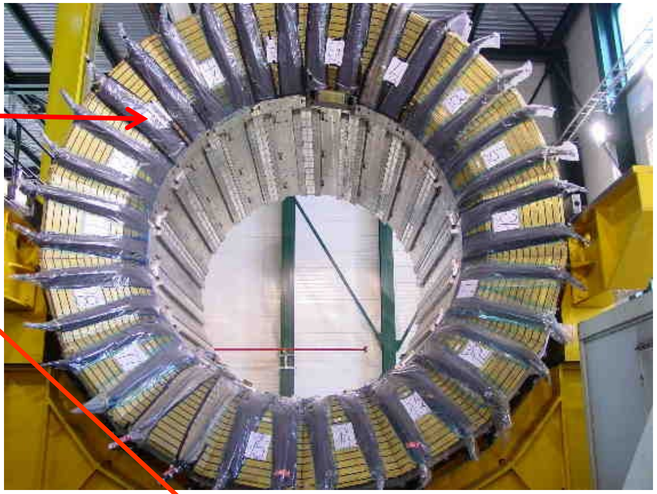


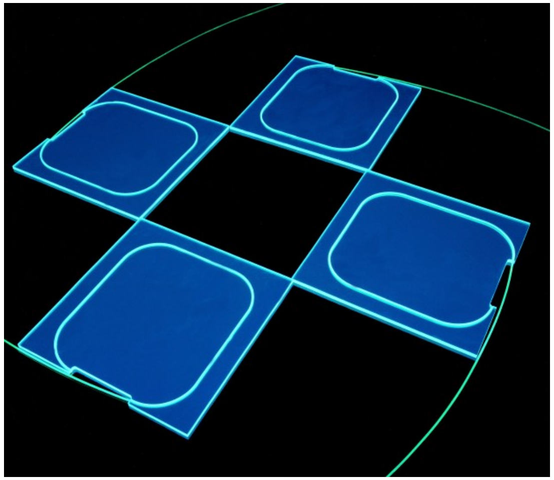
Simulated $H \rightarrow \gamma\gamma$ with M_H=120 GeV as observed in the CMS detector

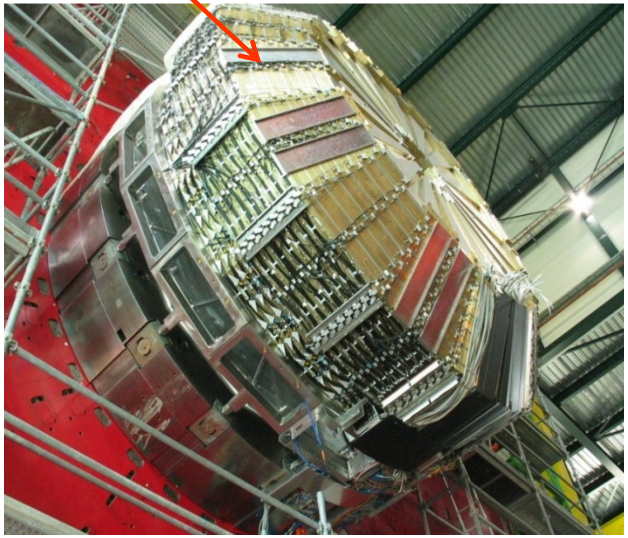
Excellent calorimeter provides ~1 GeV mass resolution which allows a peak to be seen

CMS HCAL

- Sampling calorimeter
- Brass absorber from Russian artillery shells (non-magnetic)
- Scintillating tiles with wavelength shifting (WLS) fiber
- WLS fiber is fed into a hybrid photo-diode (HPD) for light yield measurement
- Tower size is $\Delta\eta\Delta\phi$=0.087x0.087

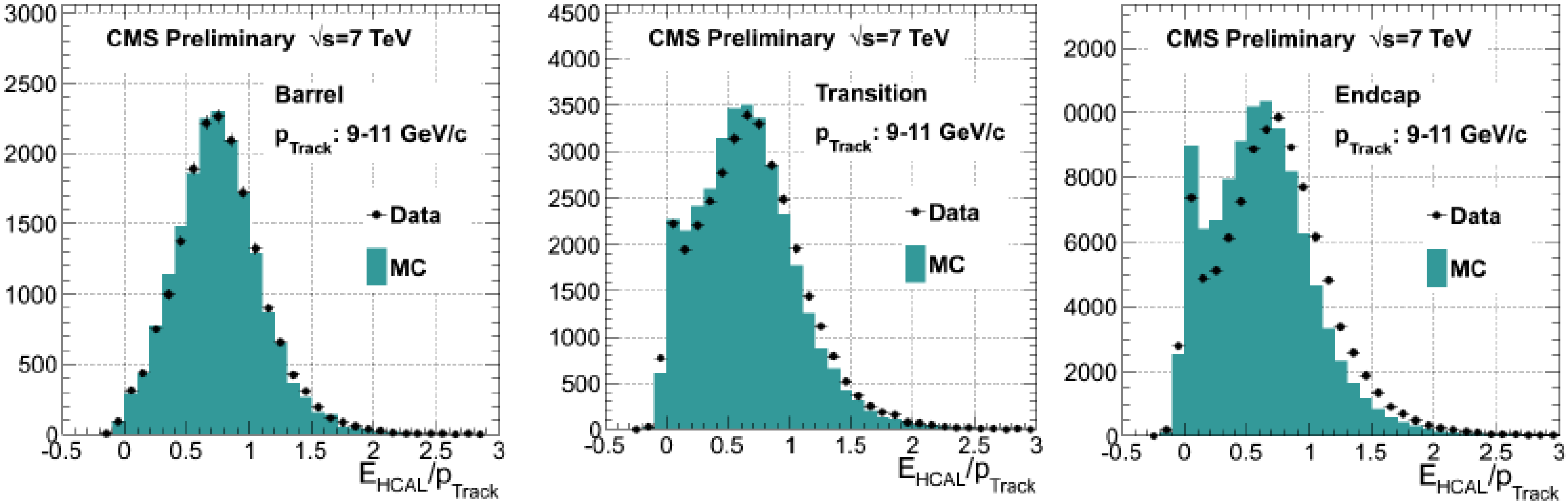




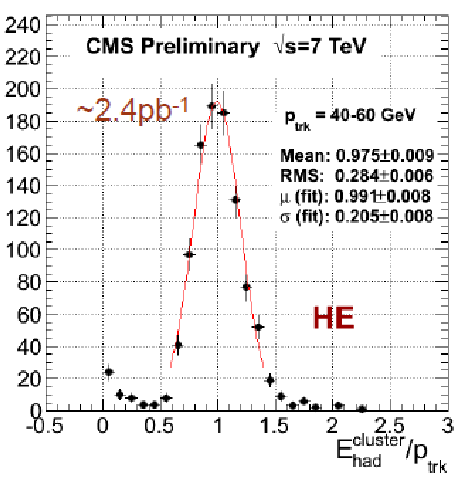


Hadron Calorimeter Performance

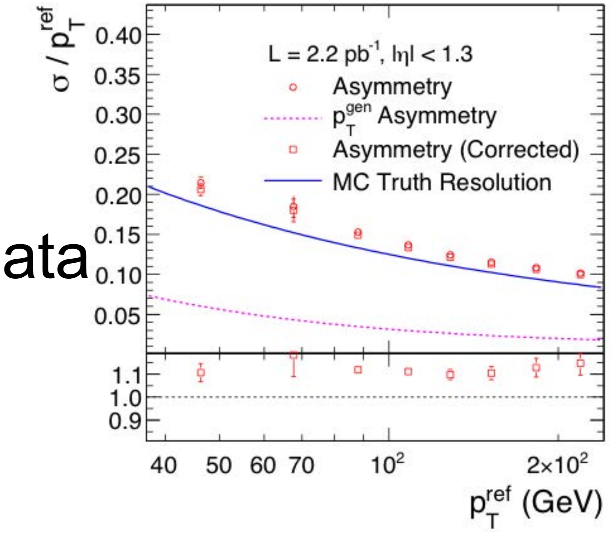
Comparisons of MinBias data and MC



Isolated track trigger (after bias removal)



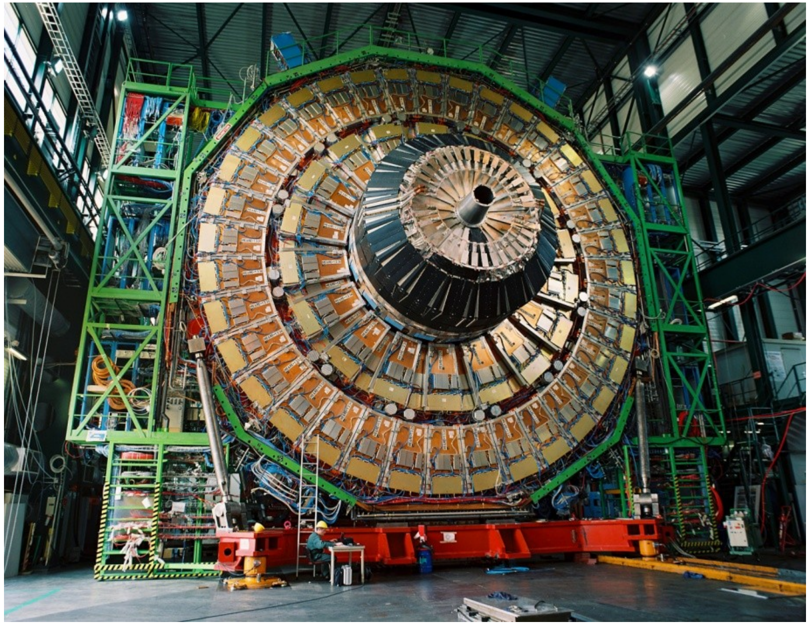
Data

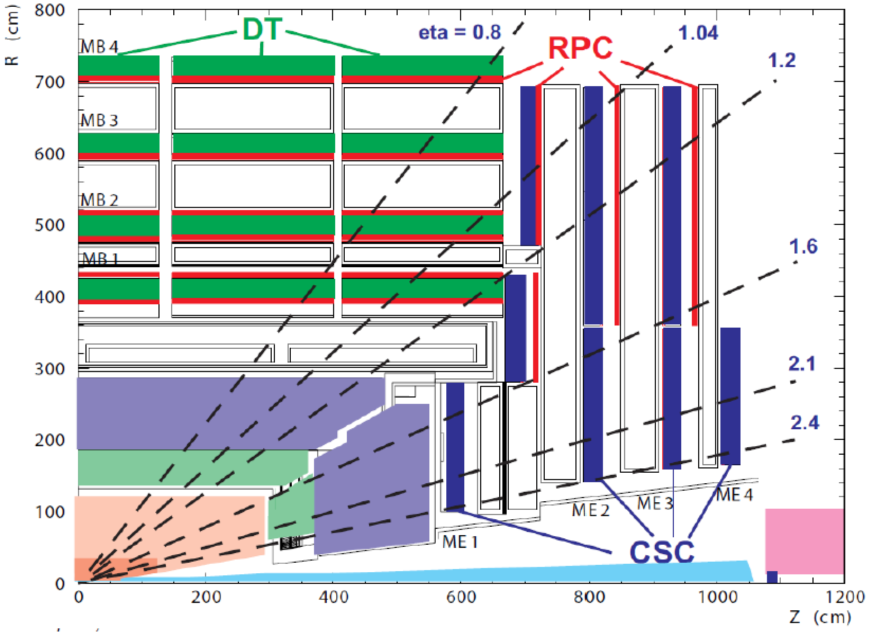


$$\frac{\sigma}{E} \sim \frac{100-150\%}{\sqrt{E}}$$

Muon systems

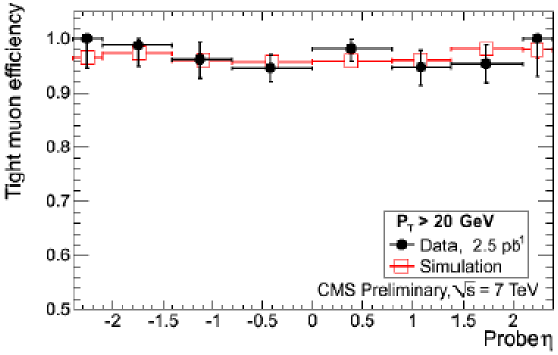
- Muons interact less than other charged particles
  - Place detectors after material and what comes through is a muon
- Add B field and tracking to find momentum at trigger level and link with main tracker
- 14000 t of iron absorber and solenoid flux return
- Three tracking technologies: Drift Tube, Resistive Plate Chamber, and Cathode Strip Chamber
  - Each pseudorapidity interval is covered by two of these subsystems

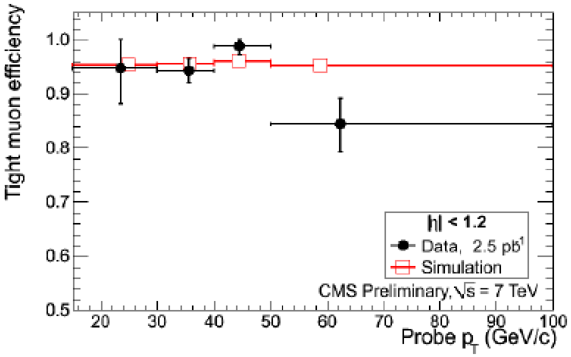


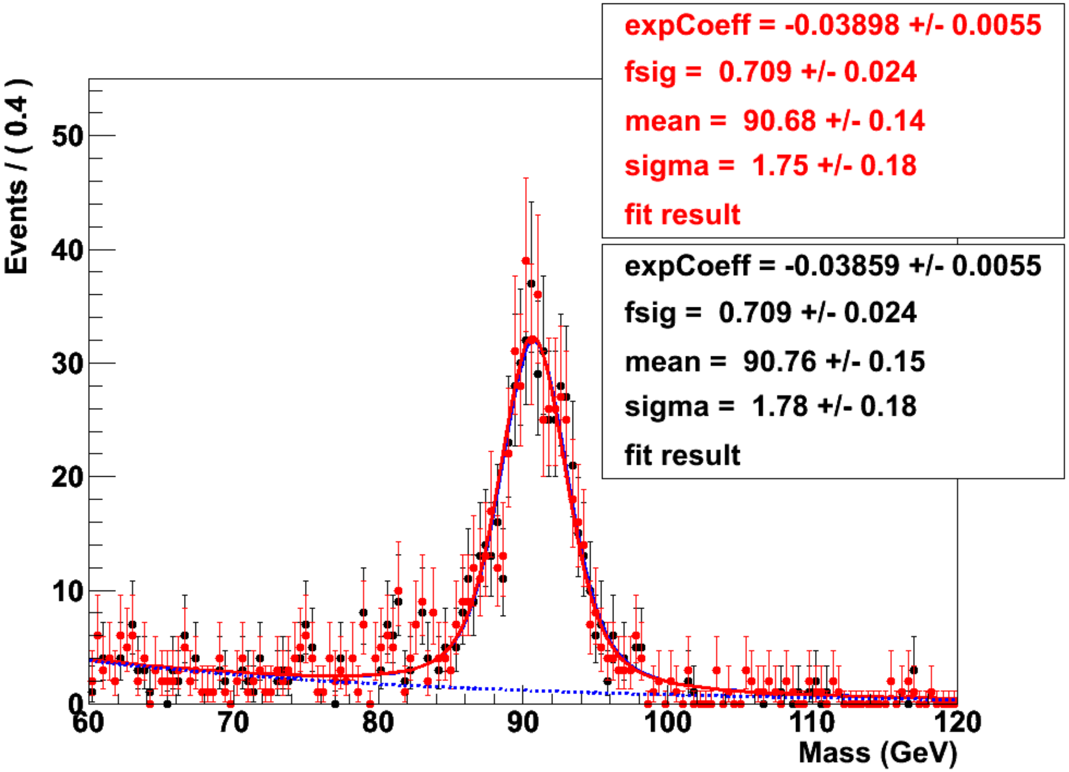


Muon System Performance

- **Tracker Muon (TM): silicon track with at least one matched muon segment**
- **Standalone muon (STA): fits to hits and segments in muon system alone**
- **Global Muon (GLB): combined fit to tracker and muon hits**
- **Tight muons: global plus tracker plus other**







Triggering and data acquisition

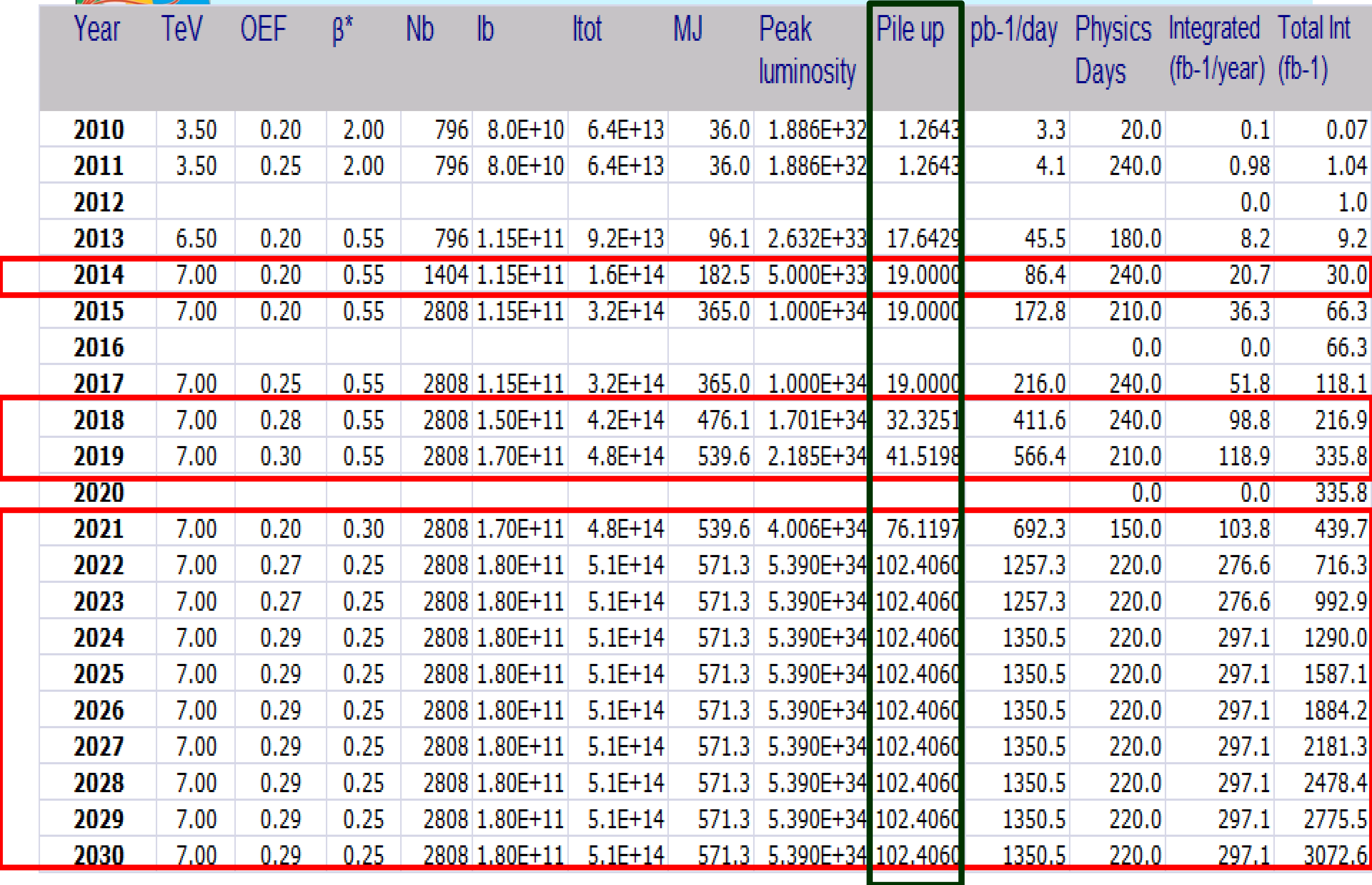
The problem

- 40 MHz of beam crossings, with a average of ~20 interactions/crossing means that there are nearly 1 billion events/ second
- Beam crossings generate ~1 MB of data or 40 Terabytes/s
- Restricted to ~200 Hz of events = 200 MB/s = 20 TB/day = 2 Petabyte per year
- Need to reject 99.9998% of events in quasi real time

The solution

- Hardware trigger finds jets, electrons, muons, and missing E_T and rejects 99.8% of events in 3 μs
- Surviving 100 KB/s of events fed into ~1000 CPU farm where events are reconstructed and 0.1% kept

The Future: Luminosity Predictions



Year	TeV	OEF	β*	Nb	Ib	Itot	MJ	Peak luminosity	Pile up	pb-1/day	Physics Days	Integrated (fb-1/year)	Total Int (fb-1)
2010	3.50	0.20	2.00	796	8.0E+10	6.4E+13	36.0	1.886E+32	1.2643	3.3	20.0	0.1	0.07
2011	3.50	0.25	2.00	796	8.0E+10	6.4E+13	36.0	1.886E+32	1.2643	4.1	240.0	0.98	1.04
2012												0.0	1.0
2013	6.50	0.20	0.55	796	1.15E+11	9.2E+13	96.1	2.632E+33	17.6429	45.5	180.0	8.2	9.2
2014	7.00	0.20	0.55	1404	1.15E+11	1.6E+14	182.5	5.000E+33	19.0000	86.4	240.0	20.7	30.0
2015	7.00	0.20	0.55	2808	1.15E+11	3.2E+14	365.0	1.000E+34	19.0000	172.8	210.0	36.3	66.3
2016											0.0	0.0	66.3
2017	7.00	0.25	0.55	2808	1.15E+11	3.2E+14	365.0	1.000E+34	19.0000	216.0	240.0	51.8	118.1
2018	7.00	0.28	0.55	2808	1.50E+11	4.2E+14	476.1	1.701E+34	32.3251	411.6	240.0	98.8	216.9
2019	7.00	0.30	0.55	2808	1.70E+11	4.8E+14	539.6	2.185E+34	41.5198	566.4	210.0	118.9	335.8
2020											0.0	0.0	335.8
2021	7.00	0.20	0.30	2808	1.70E+11	4.8E+14	539.6	4.006E+34	76.1197	692.3	150.0	103.8	439.7
2022	7.00	0.27	0.25	2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1257.3	220.0	276.6	716.3
2023	7.00	0.27	0.25	2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1257.3	220.0	276.6	992.9
2024	7.00	0.29	0.25	2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	1290.0
2025	7.00	0.29	0.25	2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	1587.1
2026	7.00	0.29	0.25	2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	1884.2
2027	7.00	0.29	0.25	2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	2181.3
2028	7.00	0.29	0.25	2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	2478.4
2029	7.00	0.29	0.25	2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	2775.5
2030	7.00	0.29	0.25	2808	1.80E+11	5.1E+14	571.3	5.390E+34	102.4060	1350.5	220.0	297.1	3072.6

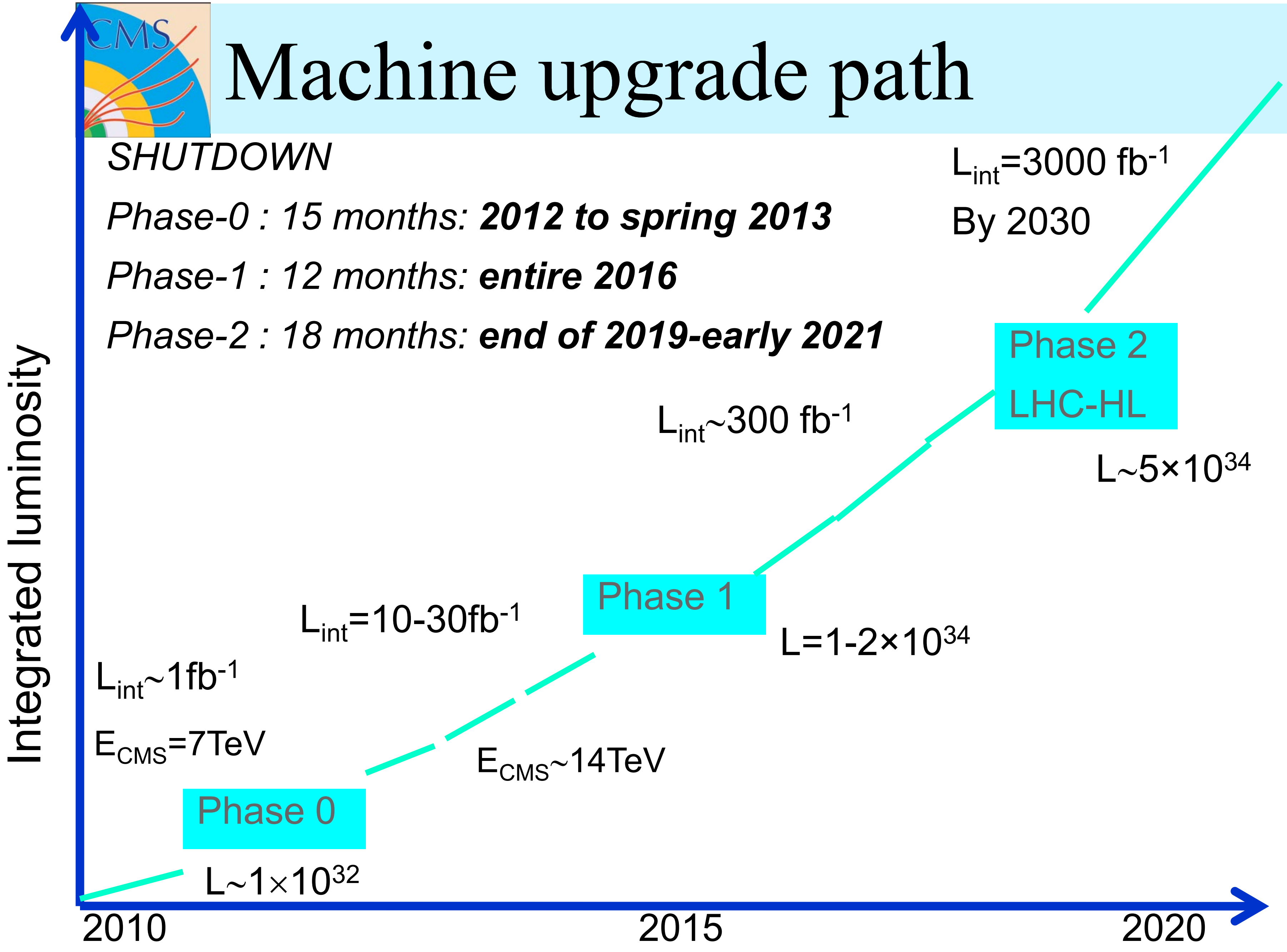
Machine upgrade path

SHUTDOWN

Phase-0 : 15 months: ***2012 to spring 2013***

Phase-1 : 12 months: ***entire 2016***

Phase-2 : 18 months: ***end of 2019-early 2021***



Integrated luminosity

L_{int}=3000 fb^{-1}
By 2030

Phase 2
LHC-HL

$L \sim 5 \times 10^{34}$

$L_{int} \sim 300\ fb^{-1}$

Phase 1

$L=1\text{-}2 \times 10^{34}$

L_{int}=10-30fb^{-1}

$L_{int} \sim 1fb^{-1}$

E_{CMS}=7TeV

$E_{CMS} \sim 14$TeV

Phase 0

$L \sim 1 \times 10^{32}$

2010
2015
2020

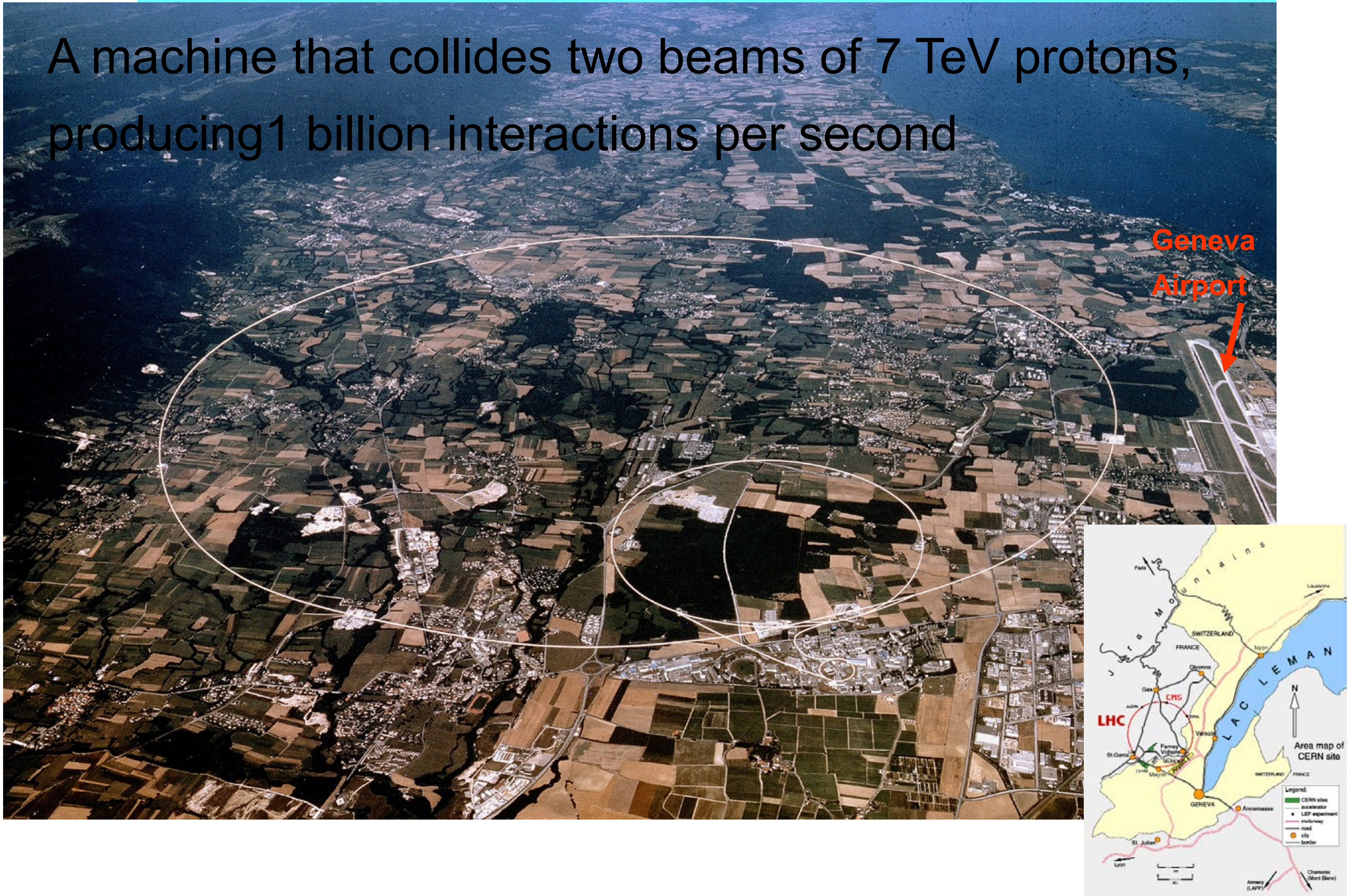
Detector Issues for Phase 1

- **Maintain the CMS detector physics performance expected for $L=10^{34}$ cm^{-2} s^{-1} at higher luminosity and pileup**
  - **By the end of Phase 1 already 40 (80) interactions/crossing at $L=2\times10^{34}$ cm^{-2} s^{-1} and 25 (50) ns bunch crossing**
- **In Phase 1 the main concern is the increase in $L_{\text{Instantaneous}}$**
  - Trigger performance degradation
    - Upgrades to the muon system and the hadron calorimeters aim to preserve the Level 1 trigger capability by providing it with more and higher quality inputs.
  - Decreases capability to discriminate electrons from jets
    - Implement longitudinal segmentation in hadronic calorimeter
  - Dead time
    - Severe data losses in the inner pixel layer
    - Radiation damage will lead to efficiency and poor position resolution in the inner pixel layer
- **In phase 2 radiation damage and increase in $L_{\text{instantaneous}}$ lead to more serious issues.**

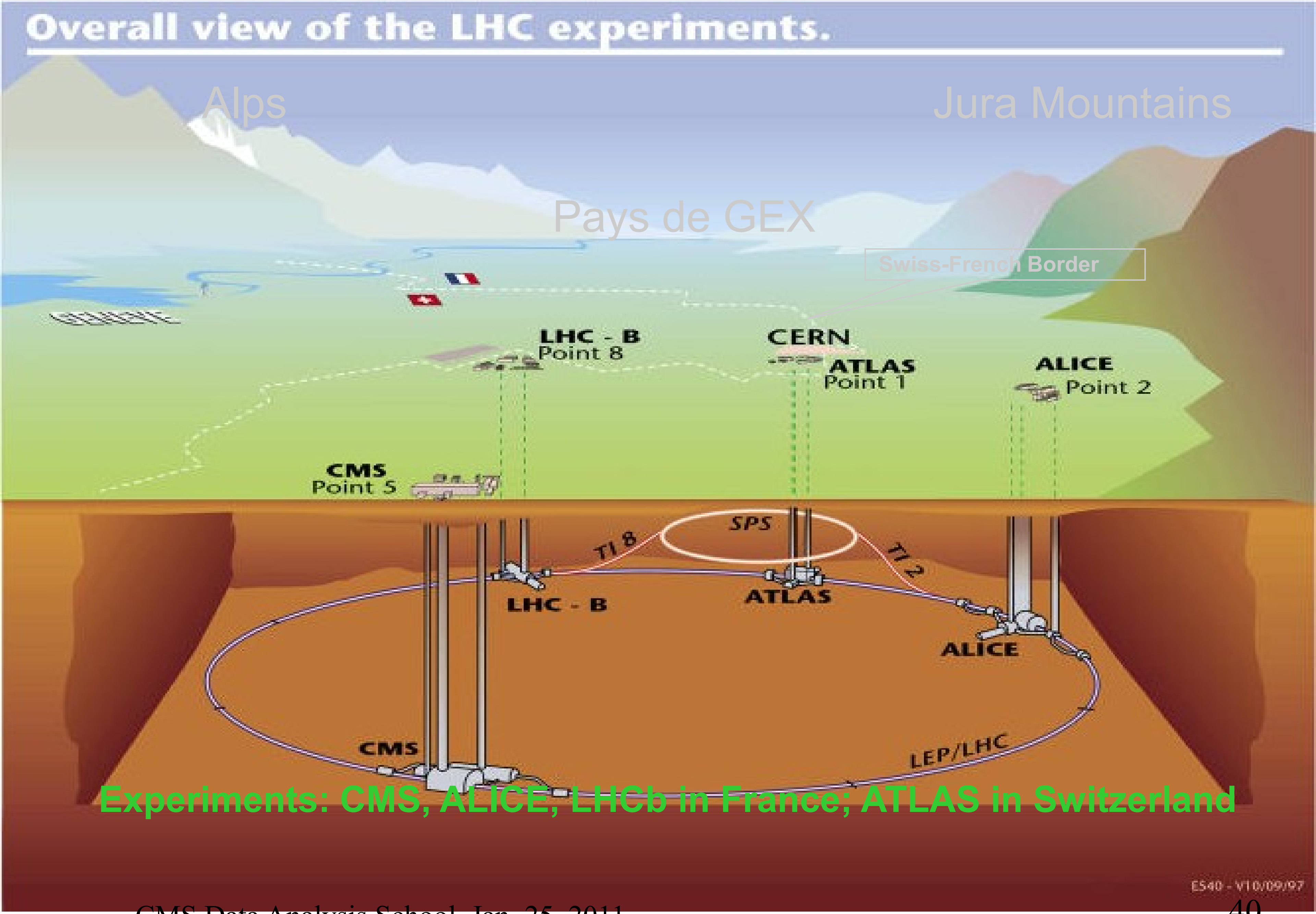
Summary

- LHC is the first machine capable of exploring the whole range of phenomena up to ~1 TeV
- CMS is superbly designed to find how nature behaves at the Terascale
  - what is responsible for electroweak symmetry breaking (Higgs or other?) which is the final piece of the Standard Model
  - find something (SUSY, other?) around 1 TeV to take care of some of the problems with the SM (and which might also be the elusive dark matter)
  - Opening a new energy frontier can also bring lots of surprises,
    - Maybe we can even learn something about gravity
- In the next two years we might see some of the answers coming out!!!!!!

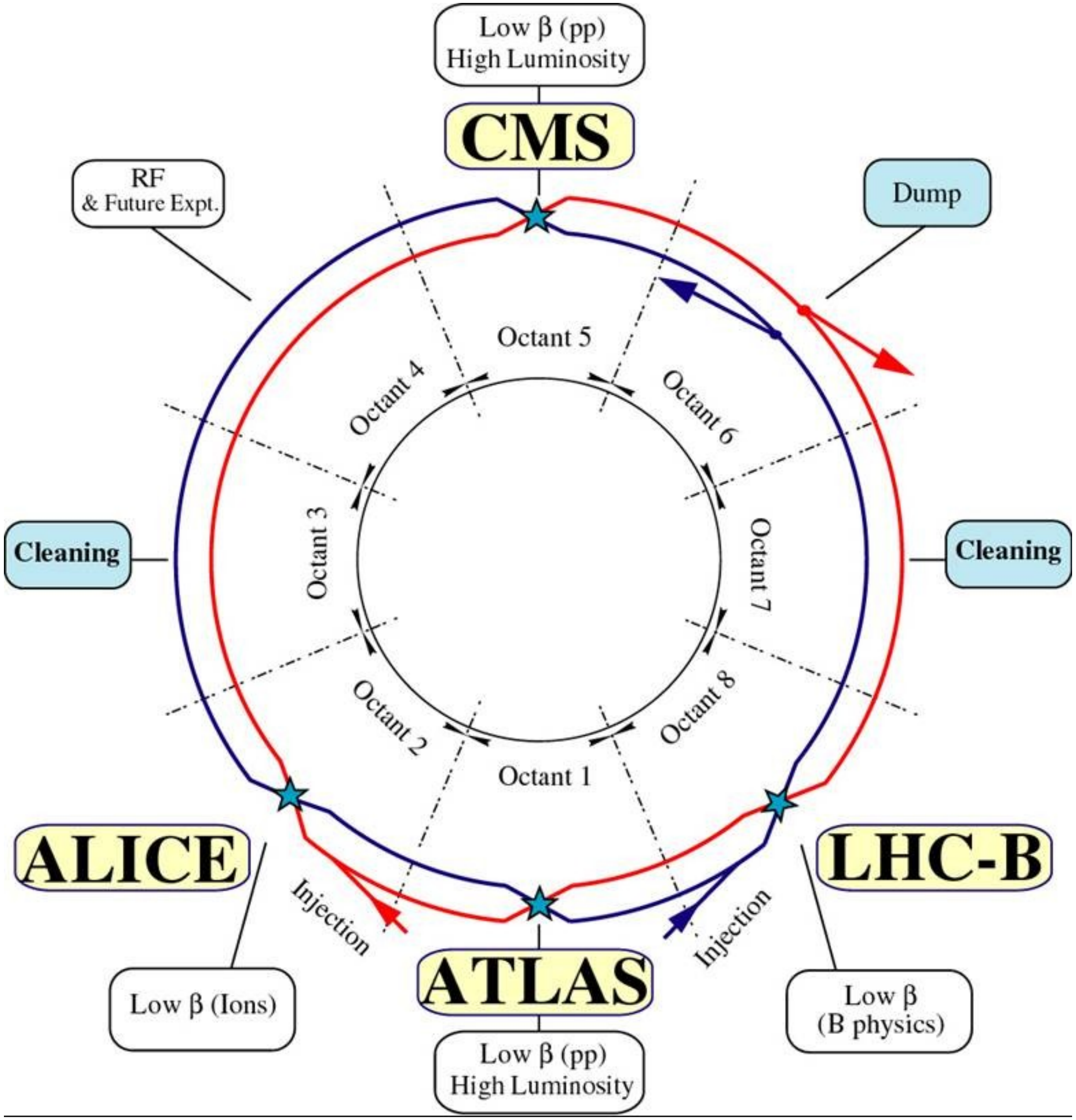
A machine that collides two beams of 7 TeV protons, producing1 billion interactions per second



Overall view of the LHC experiments.

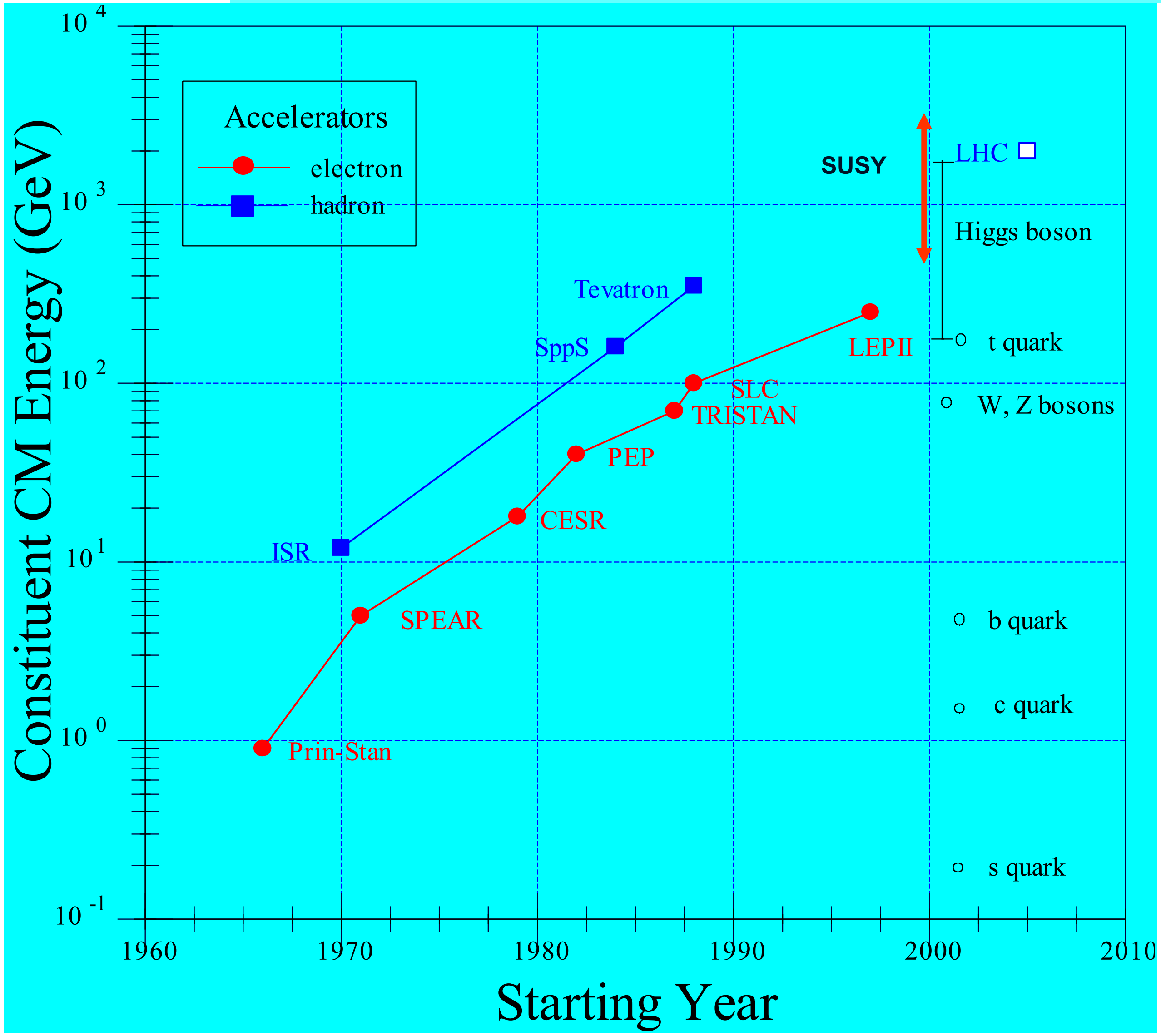


Experiments: CMS, ALICE, LHCb in France; ATLAS in Switzerland

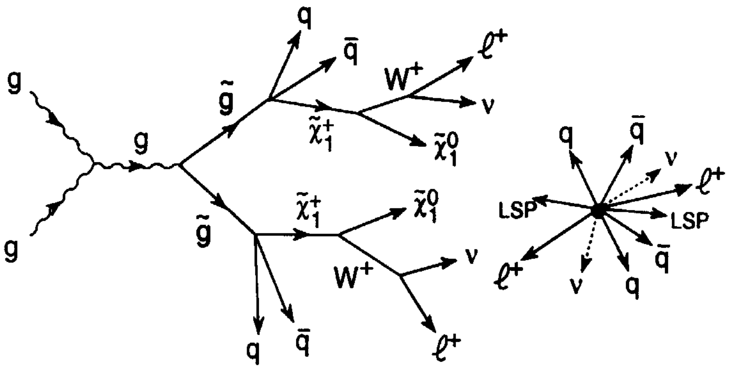

Low β (pp)
High Luminosity
CMS
RF
& Future Expt.
Dump
Octant 5
Octant 4
Octant 6
Octant 3
Octant 7
Cleaning
Cleaning
Octant 2
Octant 8
Octant 1
ALICE
LHC-B
Injection
Injection
ATLAS
Low β (Ions)
Low β
(B physics)
Low β (pp)
High Luminosity

- Tunnel (originally built for “Large Electron-Positron” Collider –LEP)
  - Circumference: 26.659km
  - Tilt: 1.4^{o} (122m)
- Number of magnets
  - Main dipoles: 1232
    - Magnetic field: 8.33 Tesla (@7 TeV)
    - Two beam tubes and coils with opposite fields to guide two counter-circulating proton the beams
  - Main quadrupoles: 858
  - Correction magnets: 6208
  - Total magnets: ~9300
- Operating temperature: 1.9^{o}K
  - Helium is superfluid
- RF cavities: 8/beam at 5.5MV/m @ 400..8 MHz
- Revolution frequency: 11.2455 KHz
- Power consumption: ~120MW

- Injection
  - From SPS (Super Proton Synchrotron)
  - 450 GeV/c
- Energy in each proton beam (peak) 7 TeV
  - Stored energy in each beam is 350 MJ (Tevatron ~2MJ)
  - Current in each beam: 0.5 A
- Expected luminosity
  - 10^{34}/cm^2-s (achieved after a few years of running)
- Beams are bunched; bunch spacing is 25 ns
  - Protons/bunch at peak luminosity: 1×10^{11}.
  - Spot size: ~10-30 μm
  - β^*= ~30cm
- At design luminosity 20 minimum bias events per beam crossing
  - One billion collisions/second
  - Thousands of particles produced per beam crossing – a major detector challenge to sort out 20 interactions

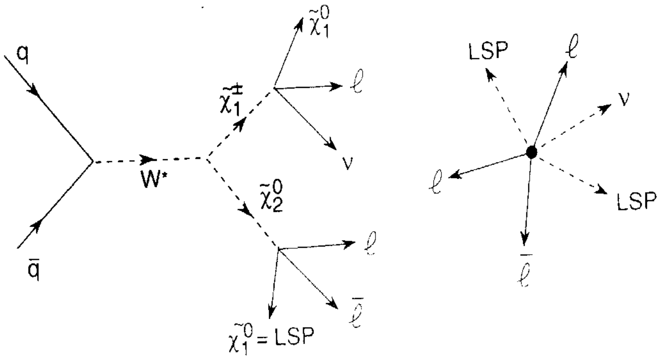


High enough energy to produce the particles of interest



Production: Gluons collide to make Gluinos

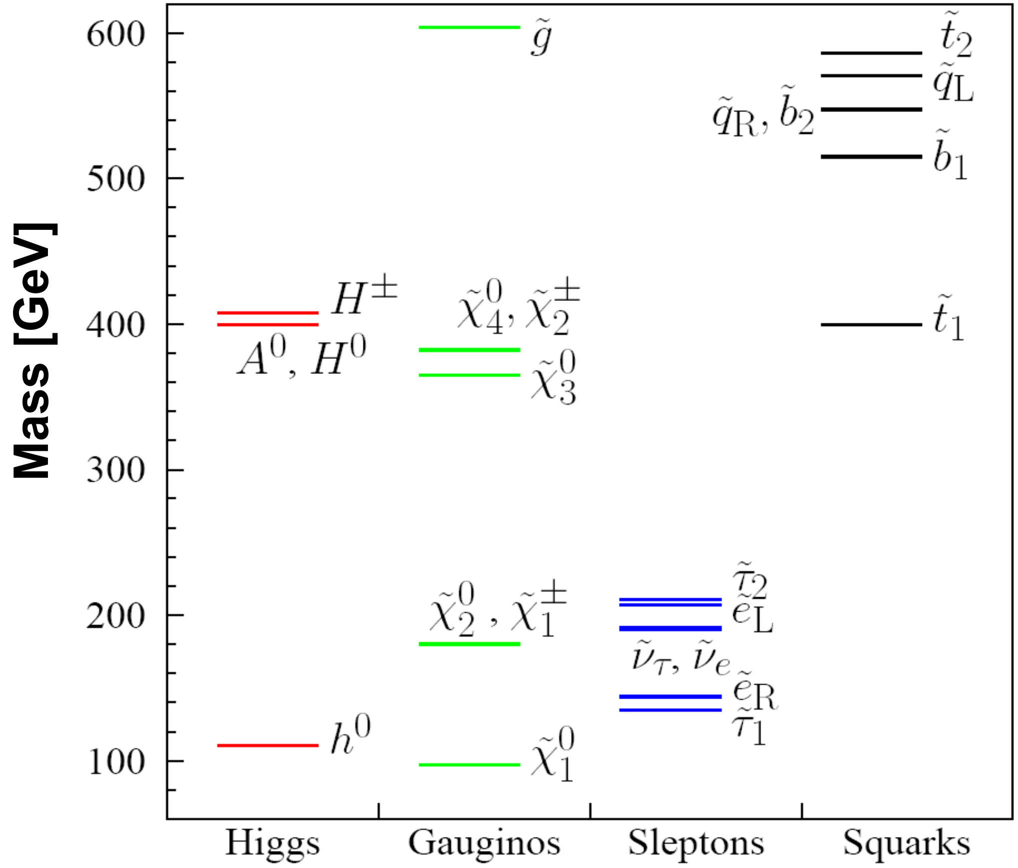
Decay: Cascade to quarks, leptons, LSP



Production: q anti-q collide to make Gaugino pair

Decay: Cascade to leptons plus neutrino plus LSP

Many more examples! In fact, so many that if SUSY is discovered, sorting it all out will be quite difficult.



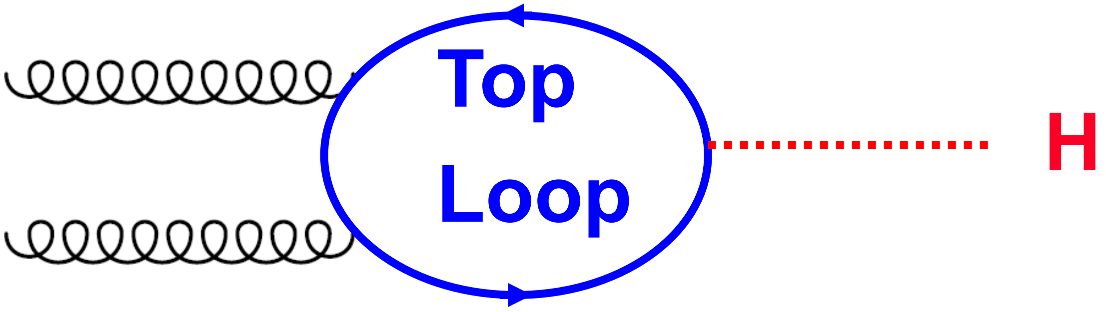
Why SUSY? Indications:

- **GUT Mass scale, unification**
- **Improved Weak mixing angle prediction**
- **p decay rate**
- **Neutrino mass (seesaw)**
- **Mass hierarchy – Planck/EW**
- **Dark matter candidate**
- **String connections**

A whole new spectrum waiting at a few hundred GeV?

Lightest Supersymmetric Particle (LSP), if stable, is a galactic Dark Matter candidate.

- If the coupling to the Higgs field is what gives particles mass, then heavier particles have stronger couplings to the Higgs.
- The heaviest particle we know, the top quark, then provides a virtual path to making the Higgs:
- Two gluons collide, make a virtual top-antitop pair, which then annihilates into a Higgs.



- The enclosure was finished very late - only became available in Oct 2007
- Large pieces, weighing as much as 2000 Tons, were assembled above ground and lowered down a shaft to the hall 100m below ground using a massive crane

YouTube - CMS YB0 Lowering.flv

Last Updated: Wednesday, 28 February 2007, 13:49 GMT

'It's like stepping on to a film set'

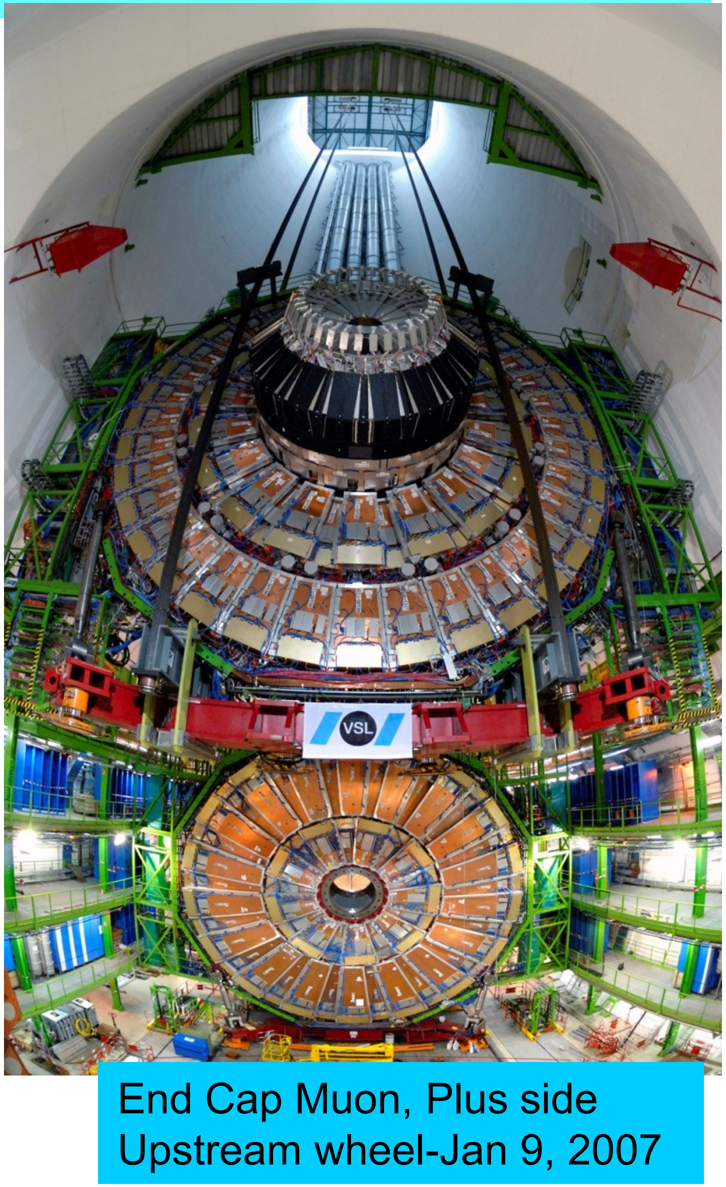
Construction of the Large Hadron Collidor, a giant underground particle accelerator, is reaching a major milestone as a key piece of machinery is lowered into the ground. BBC News Science Correspondent David Shukman reports from the scene.

It's like stepping onto the set of a James Bond film.

Or possibly something involving Austin Powers.

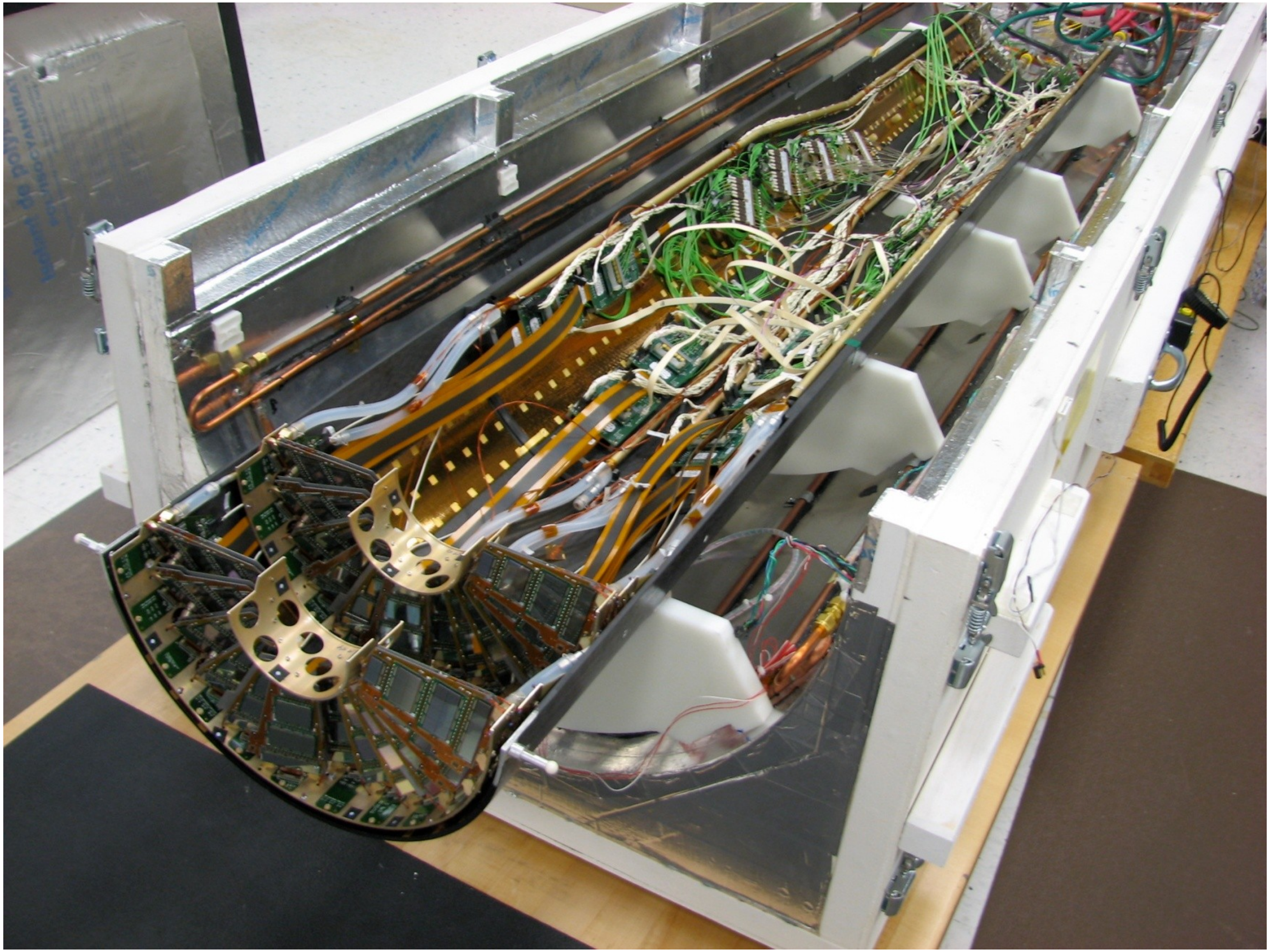
Everything here is on a vast scale; many tens of thousands of cables woven together, silicon sensors by the thousand, towering shapes of steel, impossibly complicated engineering and science.

YB0 is the biggest and most impressive element of the CMS



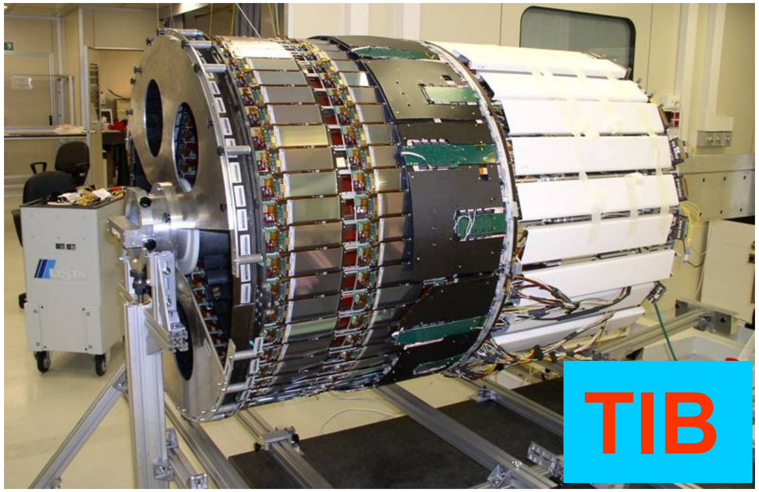
End Cap Muon, Plus side Upstream wheel-Jan 9, 2007

A Half-cylinder of the Forward Pixels



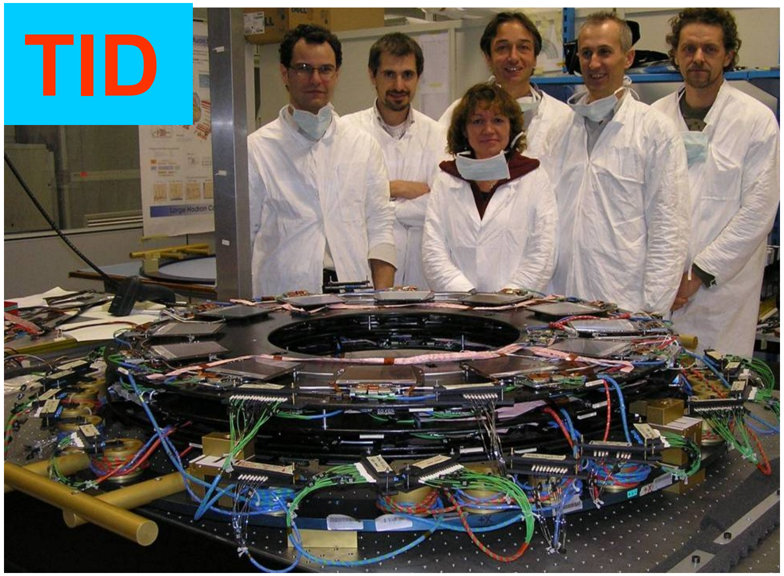
CMS Silicon Strip Detectors

2300 square feet of silicon detectors, 11 million strips



TIB

TEC

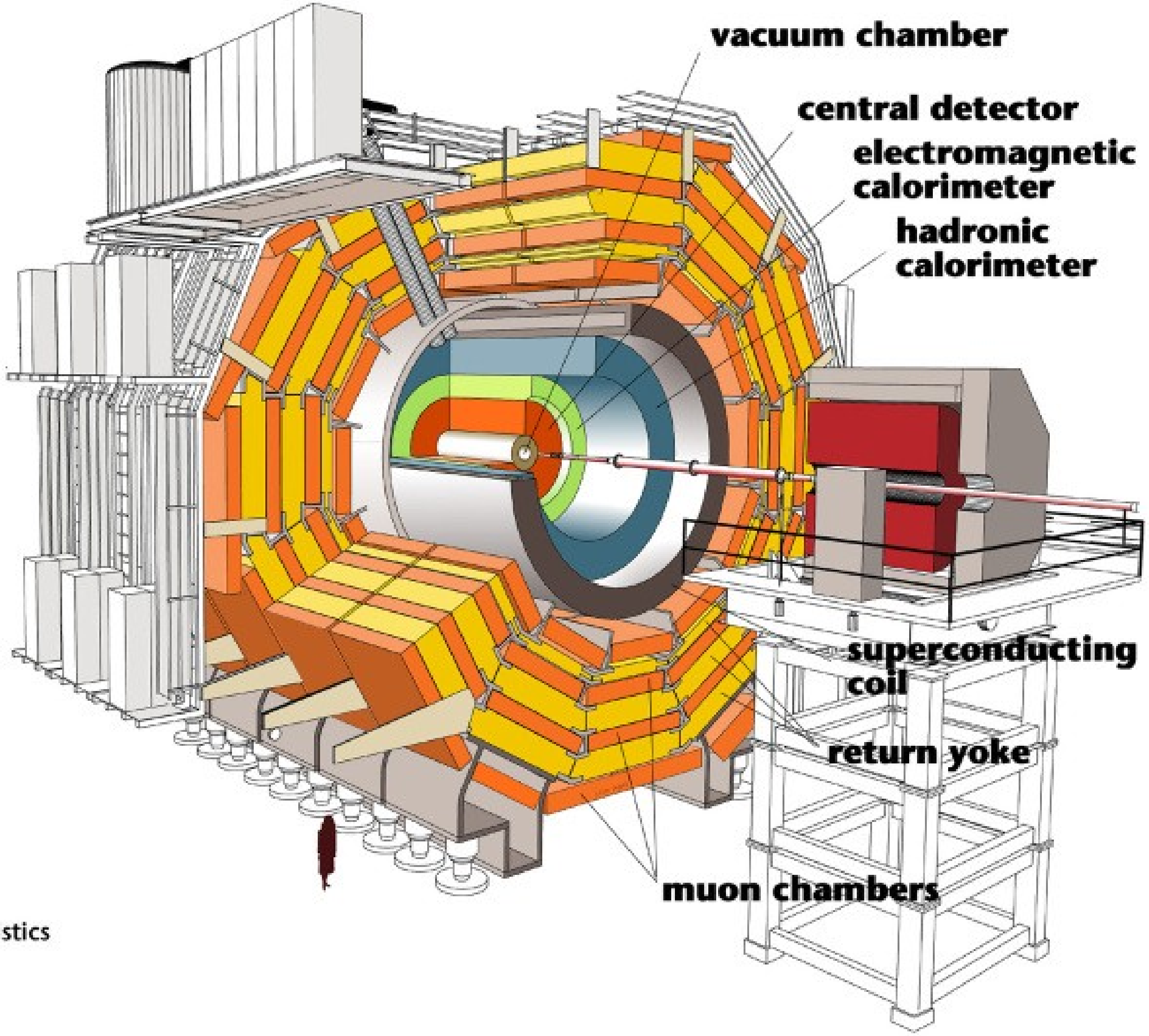


TID

TOB

Tight Muon Requirement

- GlobalMuonPromptTight
- Tracker Muon
- $|d_{xy}| < 2$mm
- pixel hits>0, tracker hits>10
- global $\chi^2 < 10$
- μ hits>0
- ≥ 2 muon valid stations



Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

Production Kinematics - 2

The Y_B that we effectively use is the one that takes the particle from the frame where $P_L=0$ to the lab

“Transverse Mass”

$$\begin{pmatrix} E+P_L \\ E-P_L \end{pmatrix} = \begin{pmatrix} e^{y_B} & 0 \\ 0 & e^{-y_B} \end{pmatrix} \begin{pmatrix} \sqrt{M^2+P_T^2} \\ \sqrt{M^2+P_T^2} \end{pmatrix} \longrightarrow \frac{d^3p}{E} = \frac{1}{2} d\varphi \, dP_T^2 \, dy$$

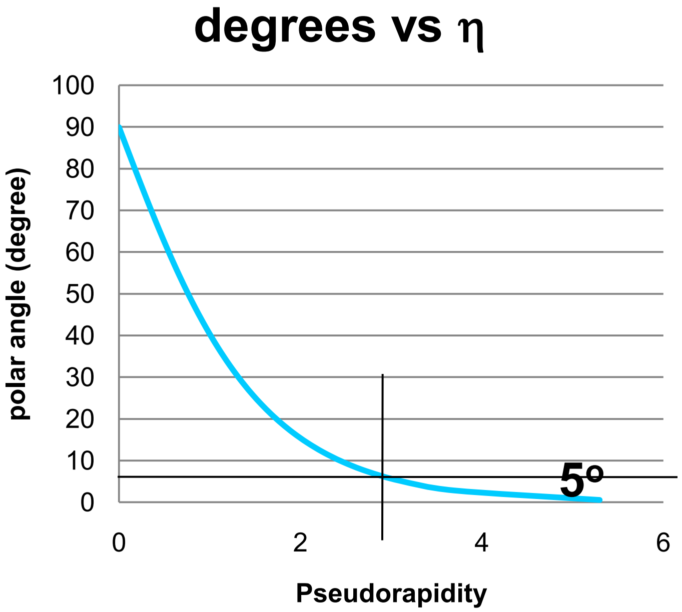
Since $y' = y + Y_B$, span of a object $\Delta y = y_1 - y_2$ is independent of CM motion of the 2 colliding partons →central to definition of a “jet”

For relativistic particles, $\beta \sim 1$, the momentum drops out, only depends on angle. Called pseudorapidity, η.

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

Relation to parton momentum fractions:

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


degrees vs η

Detector should focus on measuring P_t, η (polar angle), azimuthal angle, ϕ