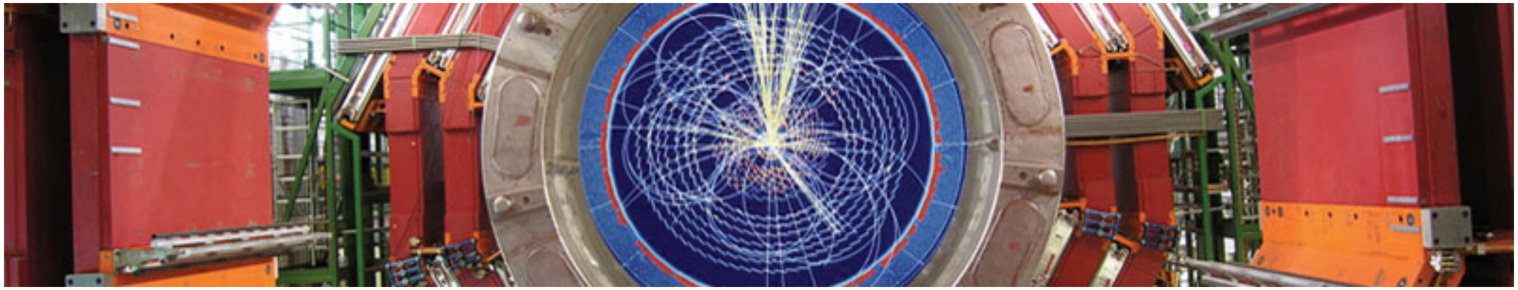
Introduction to the CMS Experiment

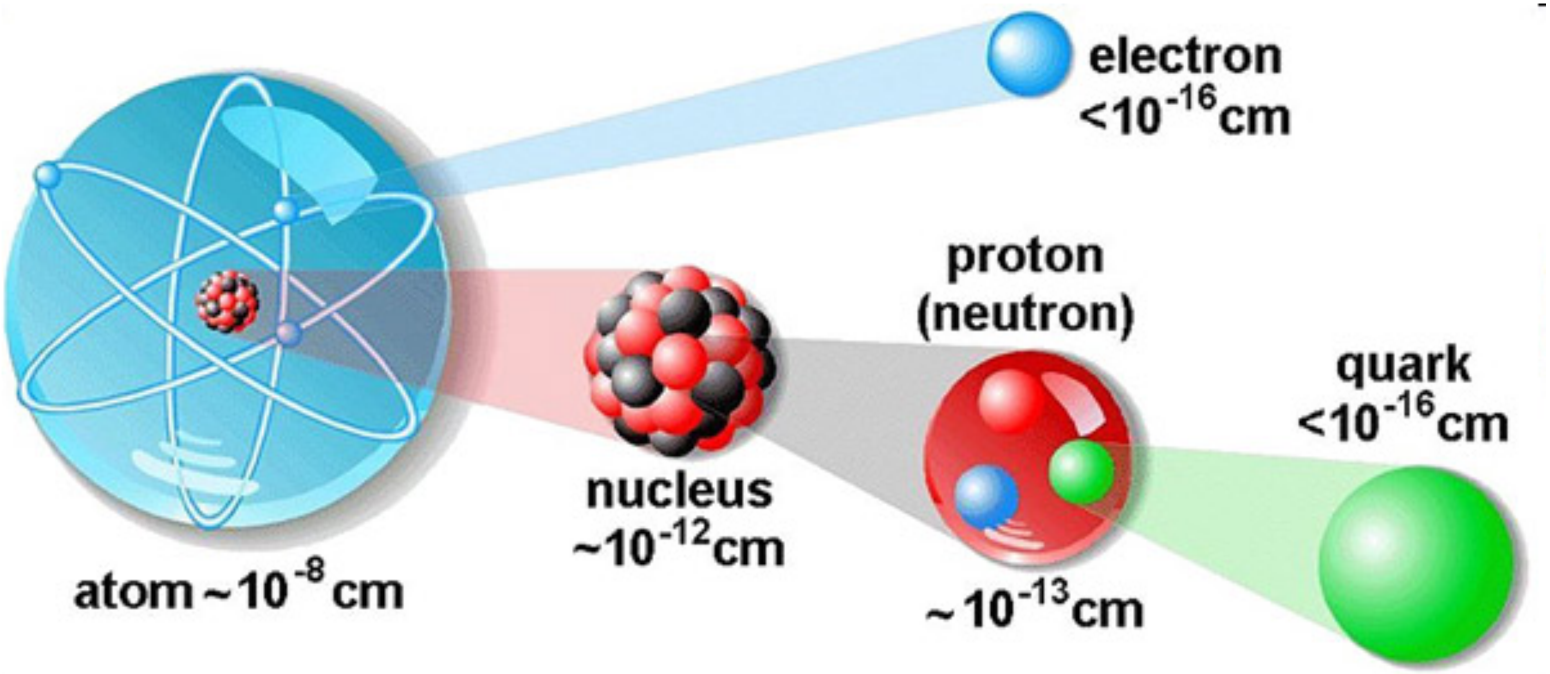


Hwidong Yoo
Seoul National University

Yonsei-Saga Workshop, December 22nd 2015

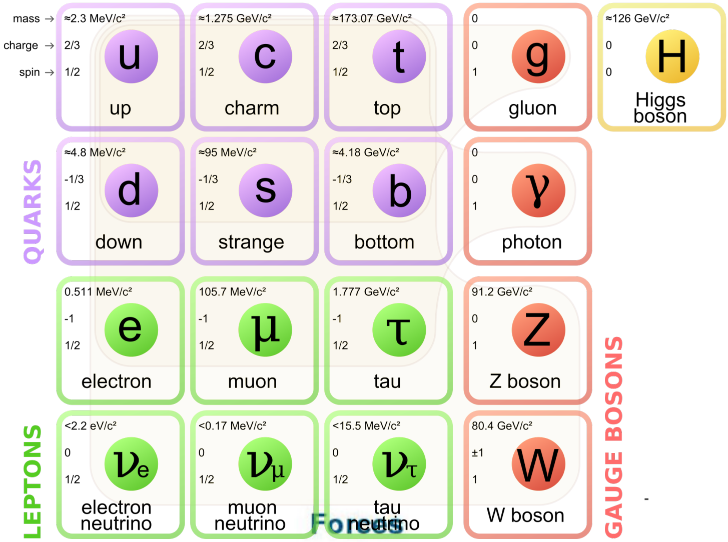
What is Particle Physics?

- Study the existence and interactions of particles, which are the constituents of what is usually referred as matter or radiation
- The most fundamental topic in physics

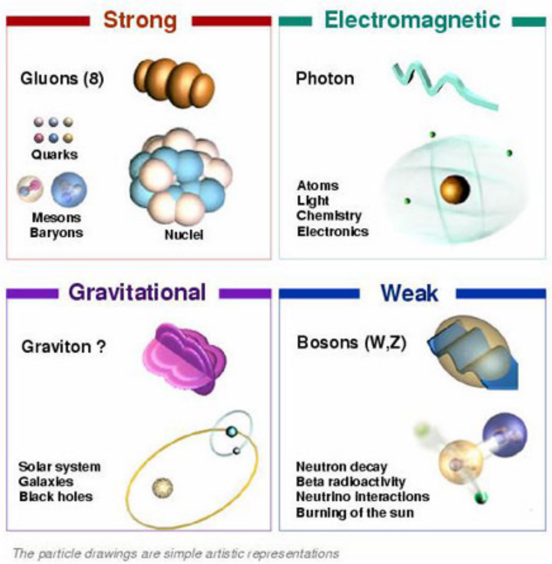


The Standard Model (SM)

- The SM is the current theory of fundamental particles and how they interact
- Forces
  - Strong force: (Gluons)
    - binds protons and neutrons to form nuclei
  - Electromagnetic force: (Photon)
    - binds electron and nuclei to form atoms
  - Weak force: (W & Z)
    - causes radioactivity
  - Gravitational force: (Graviton)
    - binds matter on large scales
- Higgs boson: explain why particles have a mass
- During last 3 decades, a lot of experimental observation support that the SM is correct



mass → charge → spin →	≈2.3 MeV/c² 2/3 1/2 u up	≈1.275 GeV/c² 2/3 1/2 c charm	≈173.07 GeV/c² 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c² 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c² -1/3 1/2 d down	≈95 MeV/c² -1/3 1/2 s strange	≈4.18 GeV/c² -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c² -1 1/2 e electron	105.7 MeV/c² -1 1/2 μ muon	1.777 GeV/c² -1 1/2 τ tau	91.2 GeV/c² 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c² 0 1/2 ν_e electron neutrino	<0.17 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino	80.4 GeV/c² ±1 1 W W boson	



We Need Something New!

- We are exploring the EWK symmetry breaking scale
- The SM does not correctly account for
  - Hierachy problem: fine-tuning required for Higgs mass at EWK scale
  - Dark matter: cosmological evidence. Can we produce the DM particles in the LHC?
  - Unification of forces: gauge coupling divergence at unification scale
  - … And the unexpected: probe unkno and unexpected territory!
- Therefore, the SM falls short of be a complete theory of fundamental interactions

A. Weiler

Beyond the Standard Model

Heavy gauge bosons

Extra dimension

Long-lived particles

RS Gravitons

Dark Matter

Supersymmetry

Excited fermions

Multijet resonances

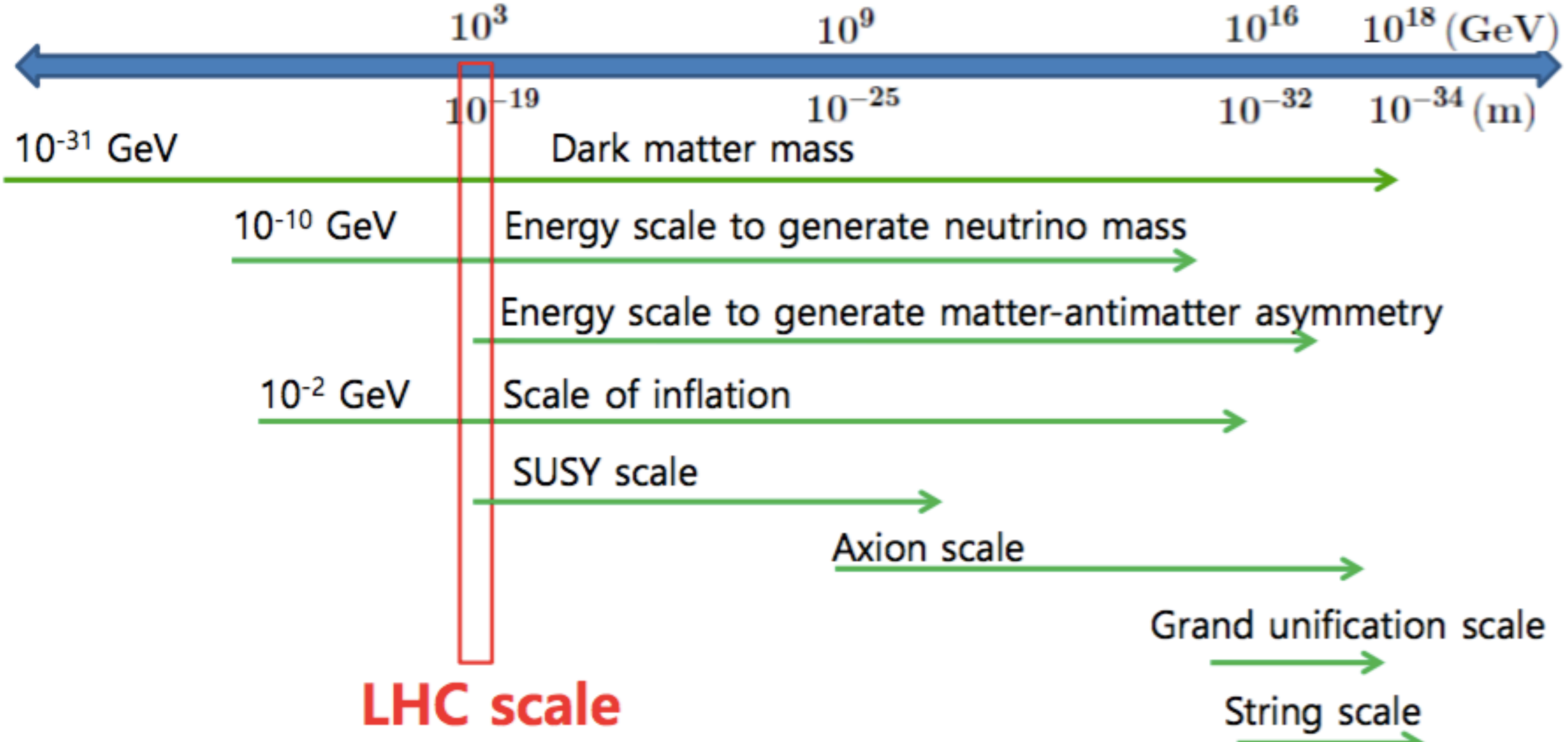
Leptoquarks

Compositeness

But we don't know yet "where they are"!

By Prof. KW Choi (IBS)

Unfortunately the scale of new physics is either inaccessibly high, or can be anywhere in a wide range.



10^{3} 10^{9} 10^{16} 10^{18} (GeV)

10^{-19} 10^{-25} 10^{-32} 10^{-34} (m)

10^{-31} GeV Dark matter mass

10^{-10} GeV Energy scale to generate neutrino mass

Energy scale to generate matter-antimatter asymmetry

10^{-2} GeV Scale of inflation

SUSY scale

Axion scale

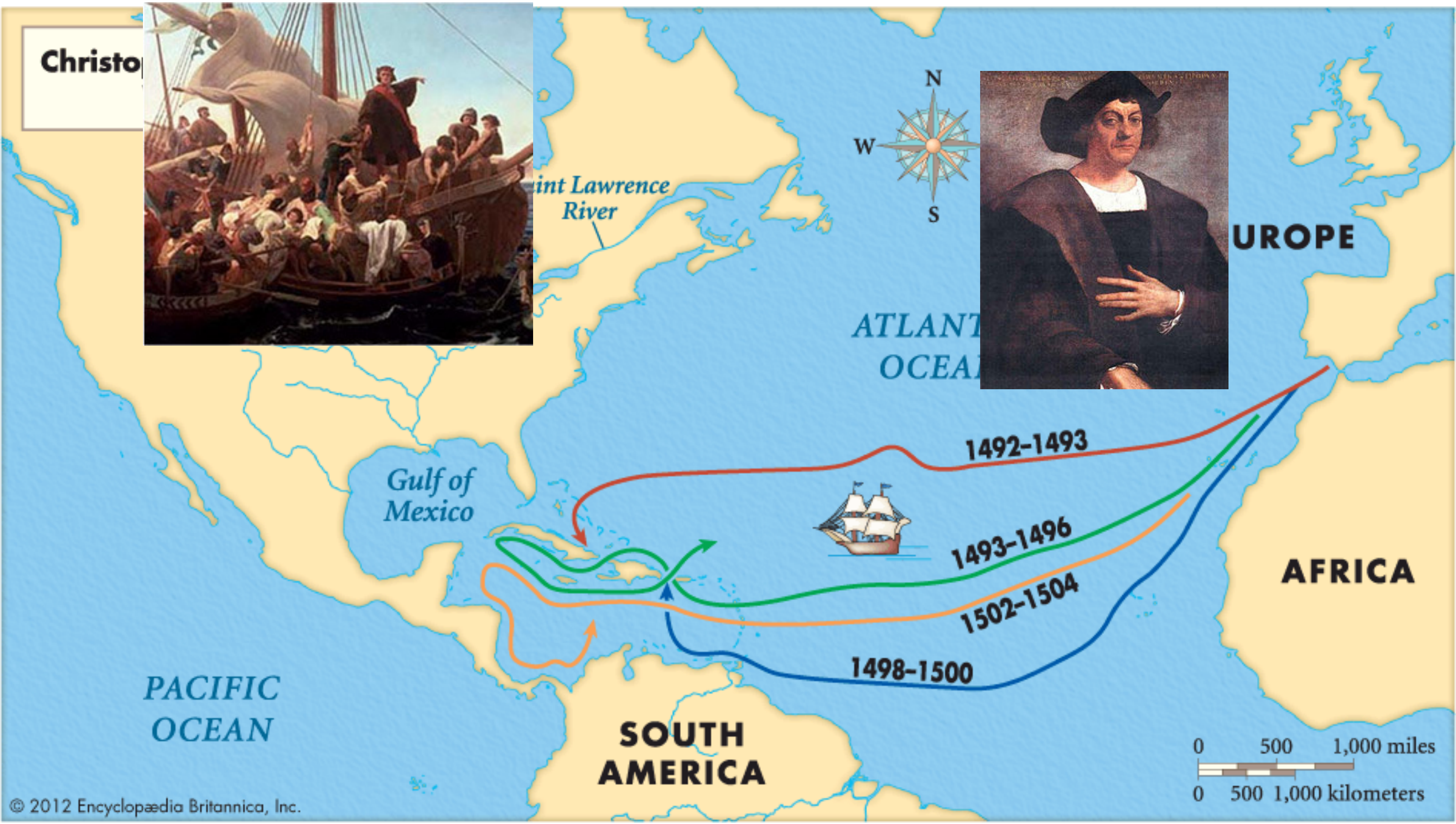
Grand unification scale

String scale

LHC scale

To discover new physics beyond the SM + GR, we need not only an ingenious plan & effort, but also a good fortune.

Where Should We Go?



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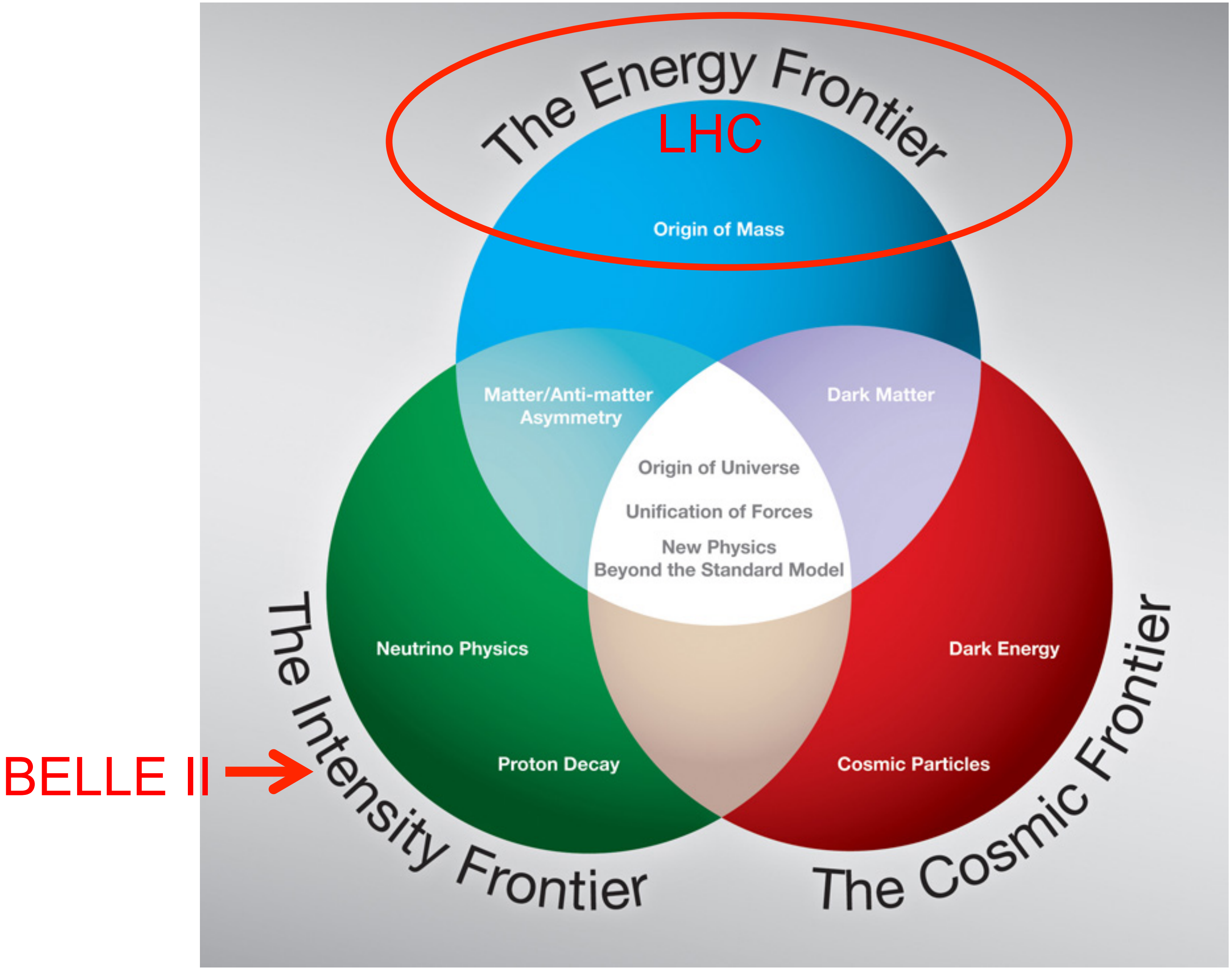
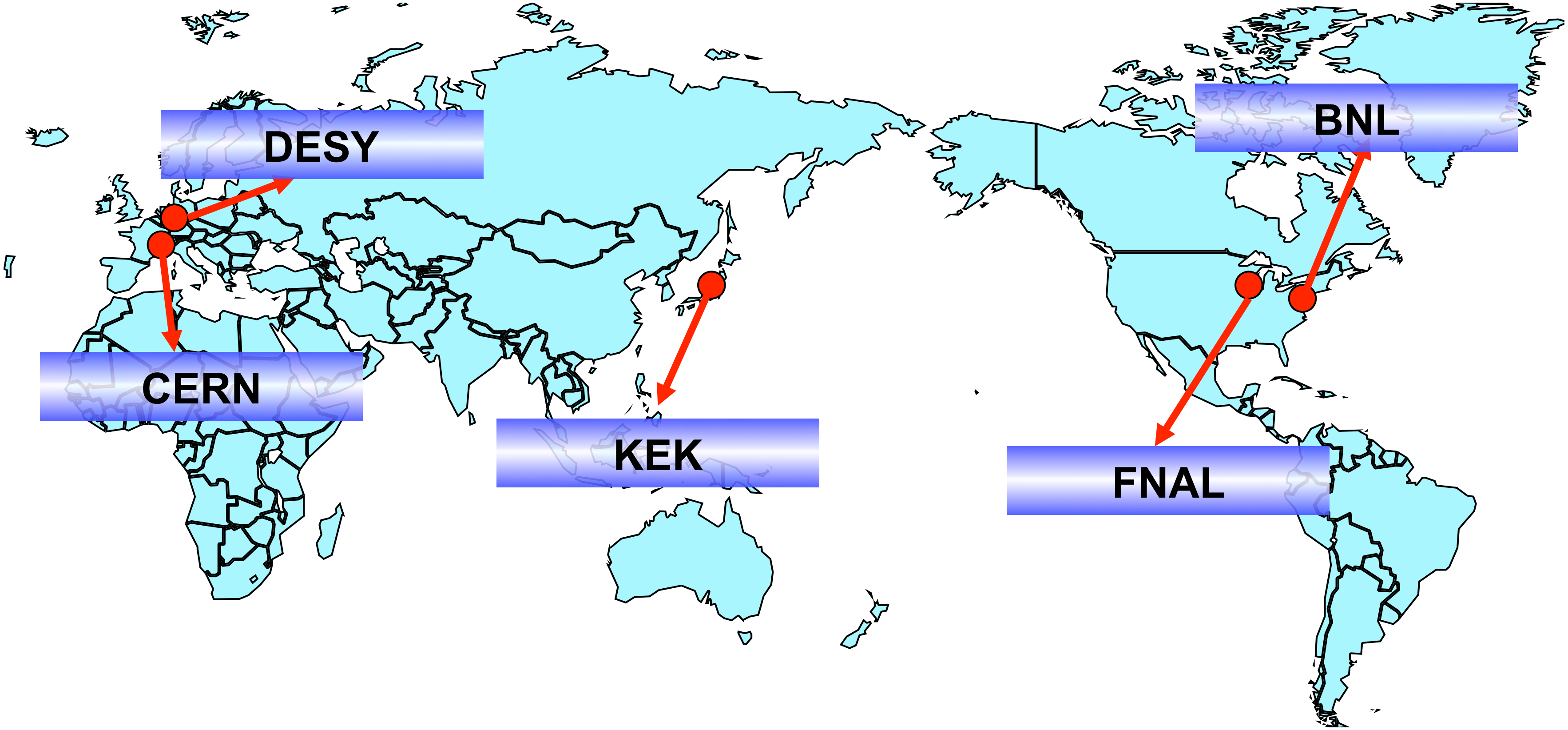
Experimental Approach



Particle Physics in the World



CERN was founded 1954: 12 European States

"Science for Peace"

Today: 20 Member States

~ 2300 staff
~ 1050 other paid personnel
> 11000 users

Budget (2012) ~1000 MCHF

Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, the Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

Candidate for Accession: Romania

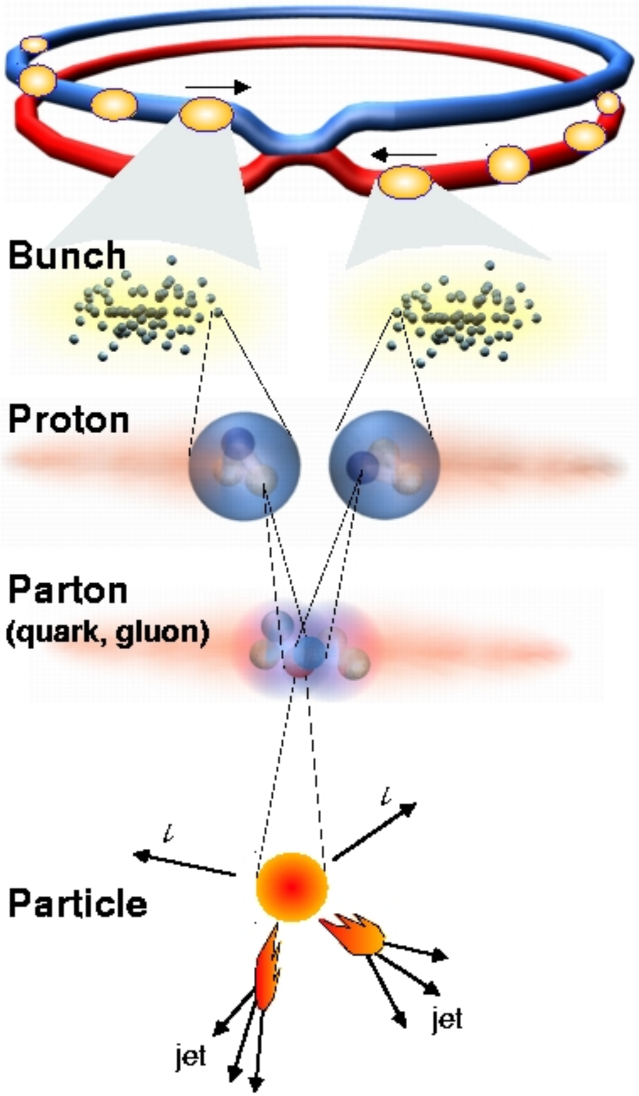
Associate Members in the Pre-Stage to Membership: Israel, Serbia

Applicant States: Cyprus, Slovenia, Turkey

Observers to Council: India, Japan, the Russian Federation, the United States of America, Turkey, the European Commission and UNESCO

CERN

Large Hadron Collider (LHC)

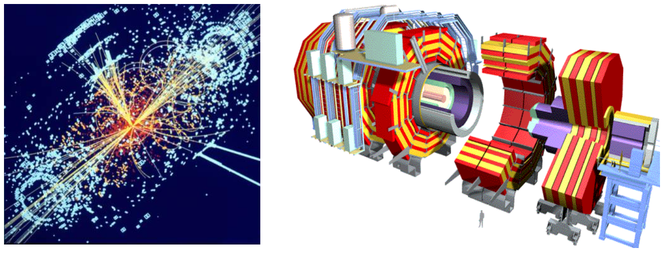


Proton- Proton Collision

Beam energy : 7,8 TeV
(13 TeV in 2015)
Luminosity : 10^{34} cm^{-2} s^{-1}
Data taking : > 2009

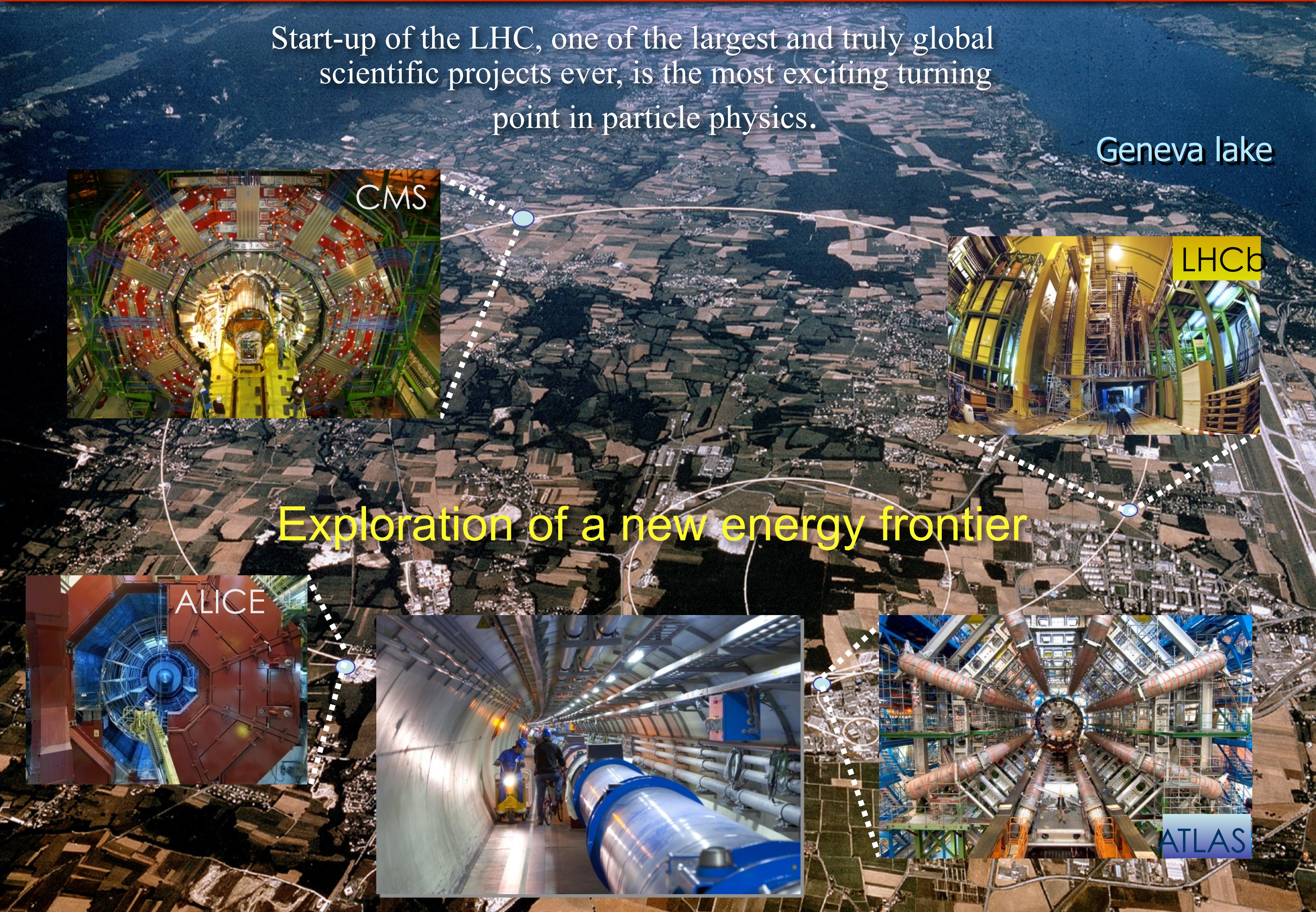
bunch-crossing rate: 40 MHz

~20 p-p collisions for each bunch-crossing
p-p collisions ≈ 10^9 evt/s (Hz)



Enter a New Era in Fundamental Science

Start-up of the LHC, one of the largest and truly global scientific projects ever, is the most exciting turning point in particle physics.



Exploration of a new energy frontier

LHC: History

30 years!

1982: First studies for the LHC project

1983: W, Z discovered at SPS ppbar collider

1989: LEP start

1994: Approval of the LHC by the CERN Council

1996: Final decision to start the LHC construction

2000: End of LEP operation

2002: Remove LEP equipments

2003: Start the LHC installation

2005: Start magnetic installation in LHC tunnel

2007: Installation complete

2008: Detector commissioning, succeed the first beam

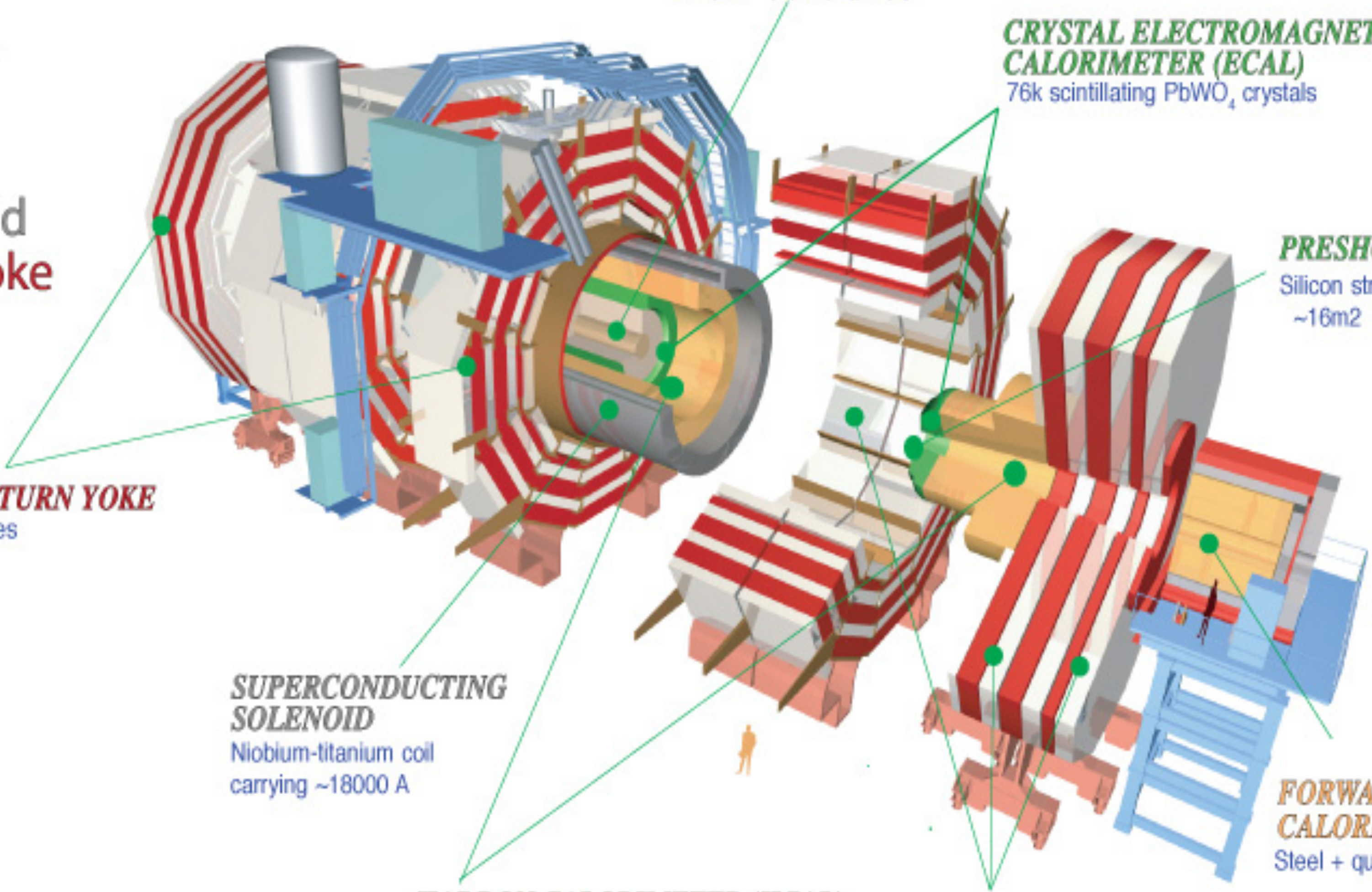
2009: succeed 900 GeV, 2.36 TeV collision

2012: data taking with 8 TeV collision (world highest)

2015: data taking with 13 TeV collision (world highest)

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



SILICON TRACKER
Pixels ($100 \times 150\ \mu m^2$)
~$1 m^2$ 66M channels
Microstrips (50-$100 \mu m$)
~$210 m^2$ 9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
76k scintillating $PbWO_4$ crystals

PRESHOWER
Silicon strips
~16m2 137k channels

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

FORWARD CALORIMETER
Steel + quartz fibres

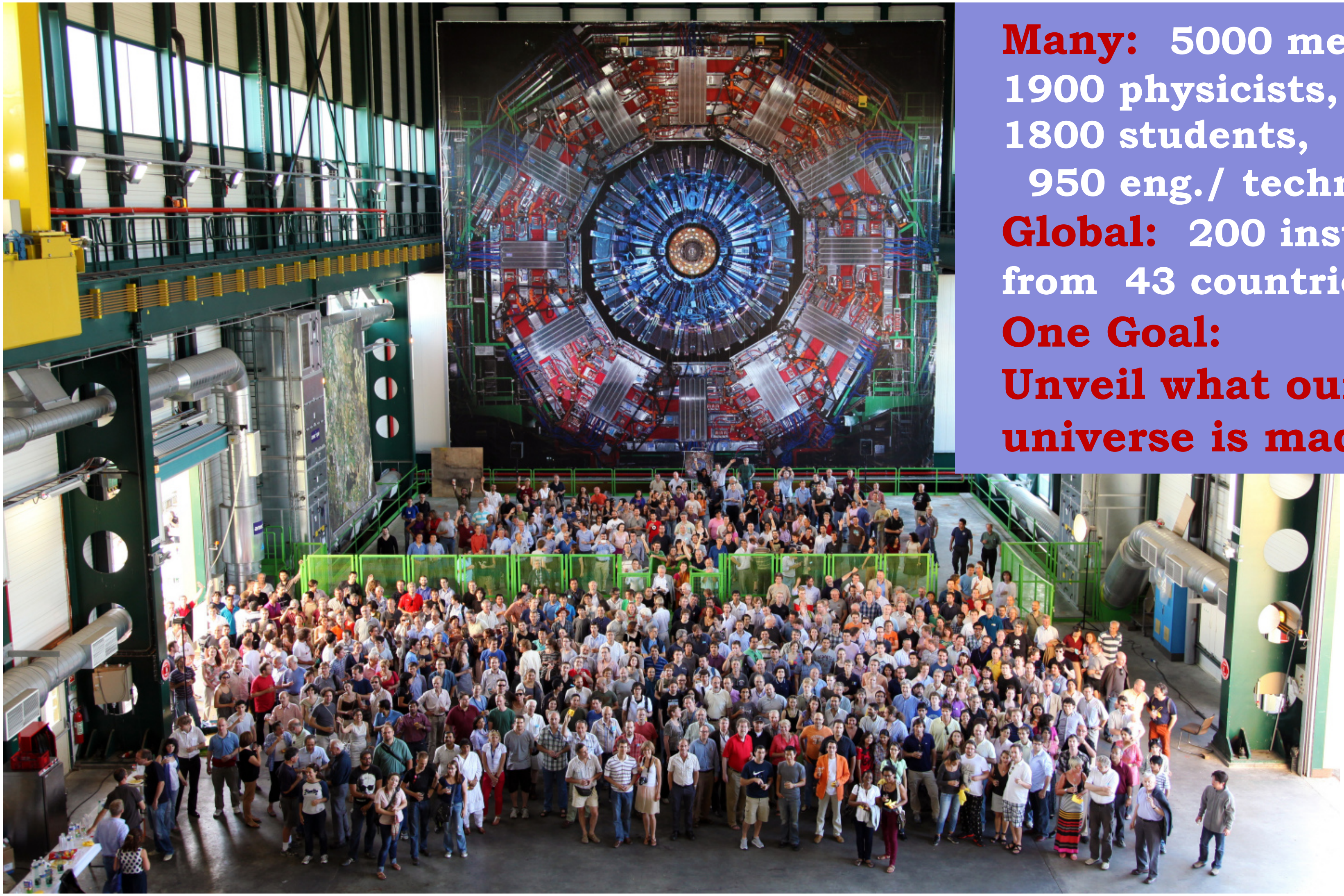
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator

MUON CHAMBERS
Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers

Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

Opening CMS Detector

The CMS Collaboration



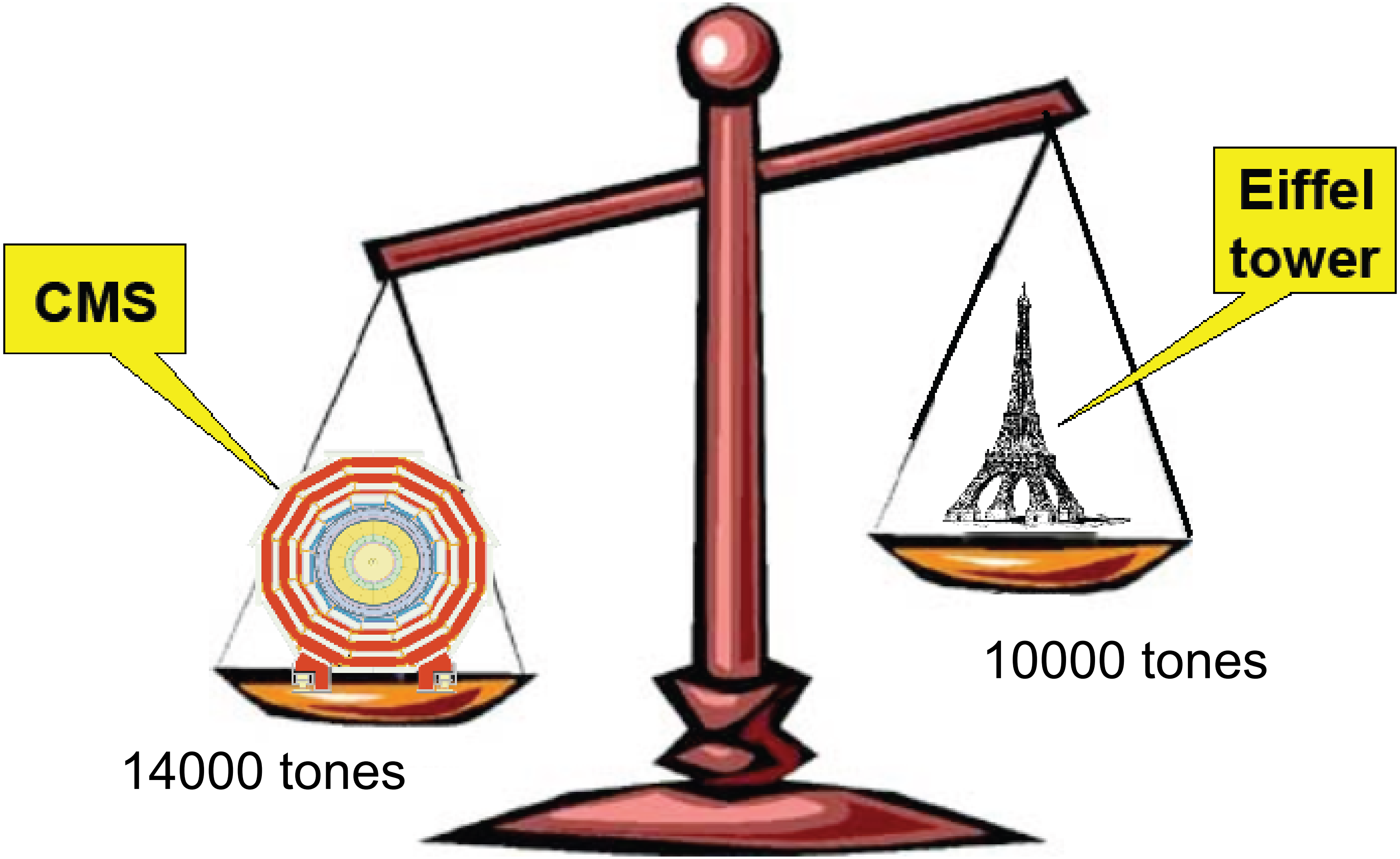
Many: 5000 members,
1900 physicists,
1800 students,
950 eng./ techn.

Global: 200 institutes
from 43 countries

One Goal:
Unveil what our universe is made of !

ATLAS and CMS in Berlin

Detector Mass in Perspective



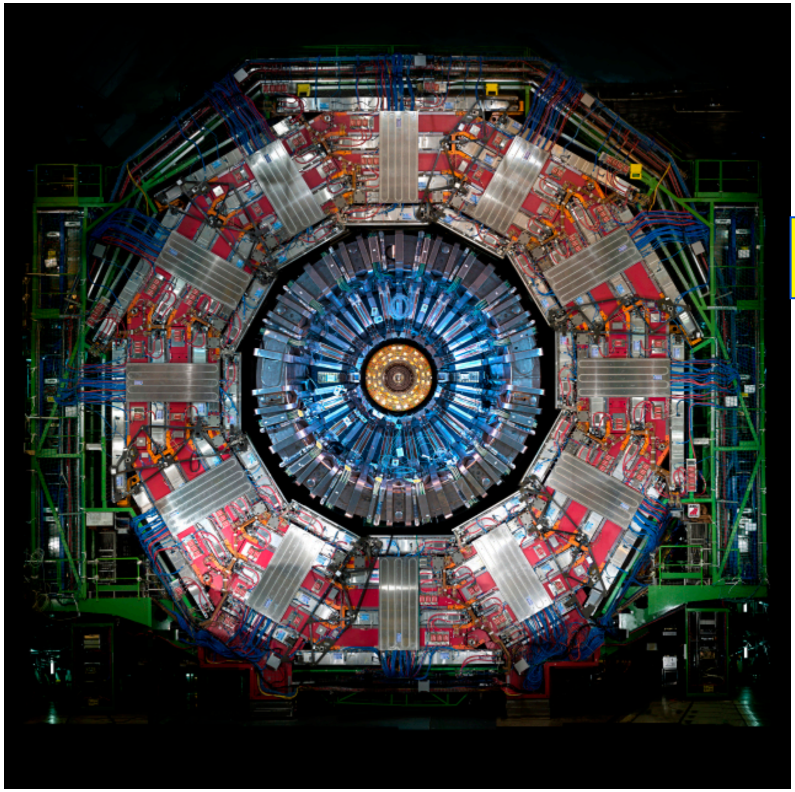
CMS

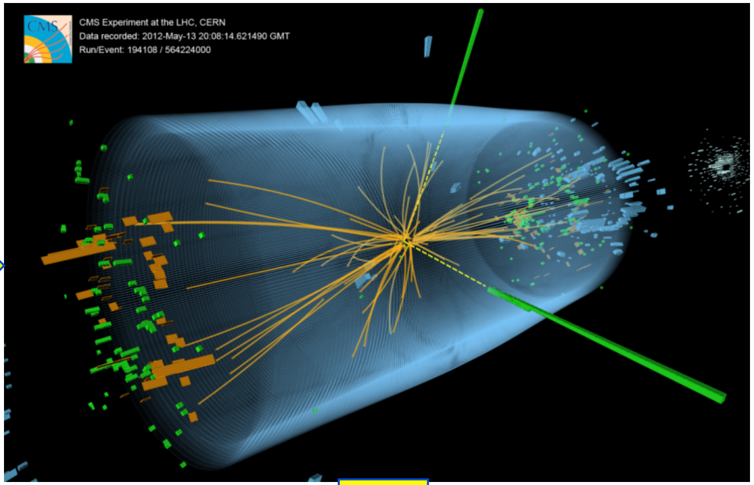
Eiffel tower

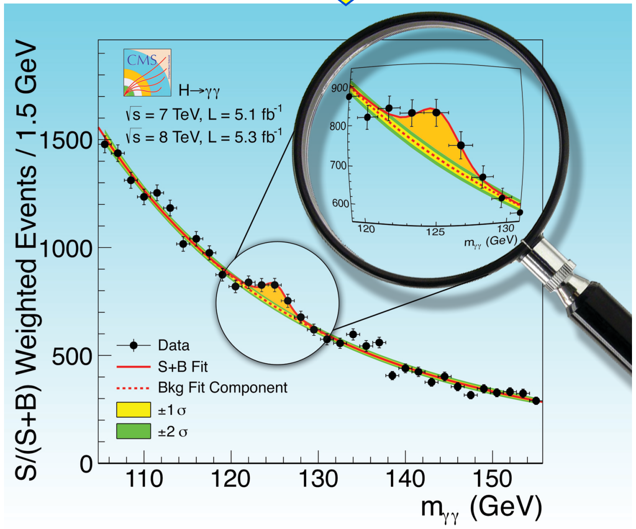
10000 tones

14000 tones

The CMS Detector







Detector Requirement

- Good Muon identification;good dimuon mass resolution (~1% at 100 GeV); distinguish charge at 1 TeV.
- Good momentum resolution for charged tracks. Efficient triggering and off-line tagging on τ and b-jets.
- Good EM energy resolution; good diphoton and dielectron mass resolution; wide geometrical coverage; π^0 rejection and efficient photon and lepton isolation
- Good missing-transverse-energy and dijet mass resolution

$\Rightarrow$ high-field solenoid, full-silicon-based inner tracking system and a homogenous scintillating-crystal-based electromagnetic calorimeter

CMS TDR (Technical Design Report)

http://cmsdoc.cern.ch/cms/cpt/tdr/

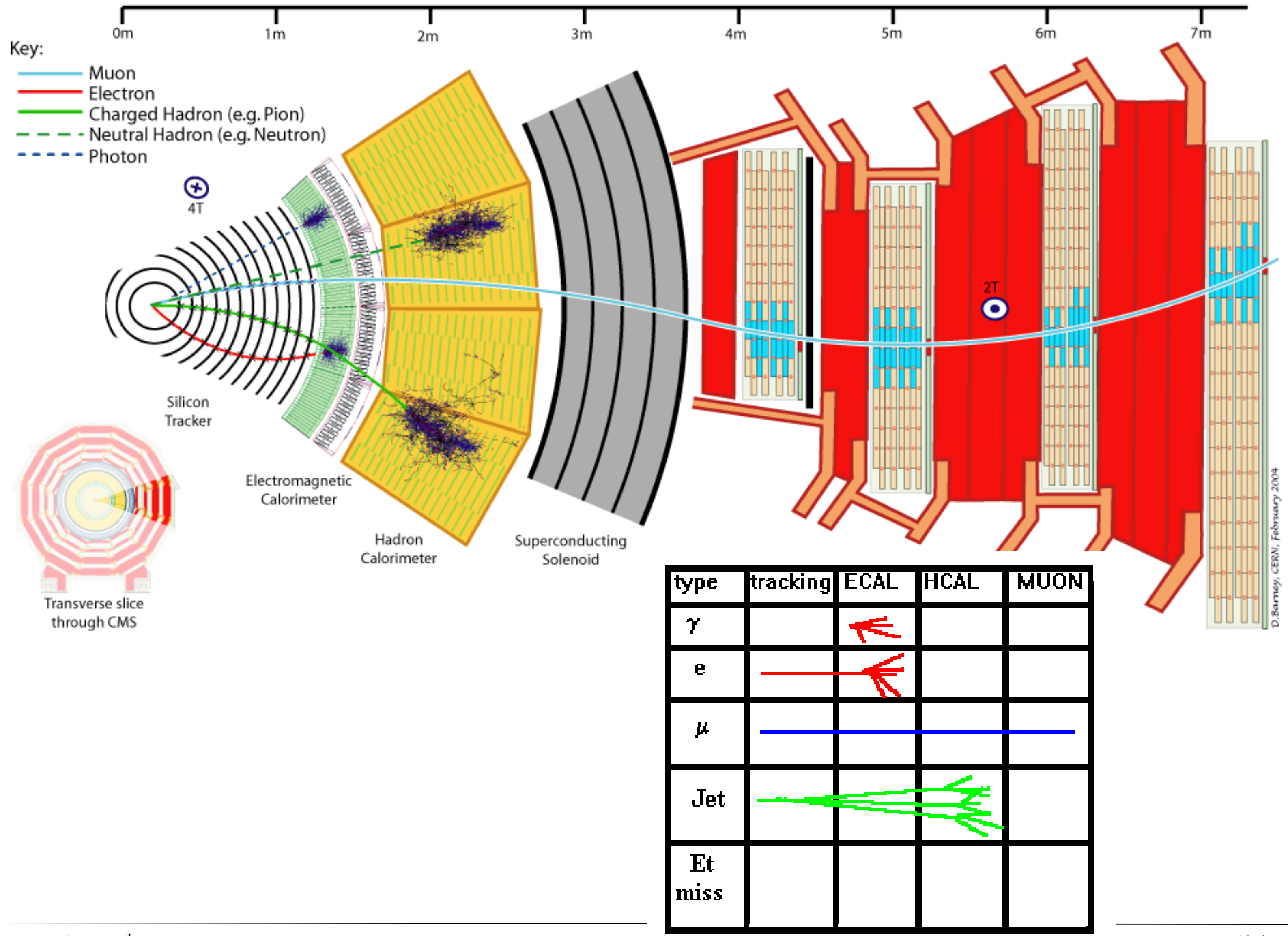
CMS Design Features

- 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 $\eta \sim 5$)

- 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 vertex reconstruction
  - Silicon detectors are very radiation hard

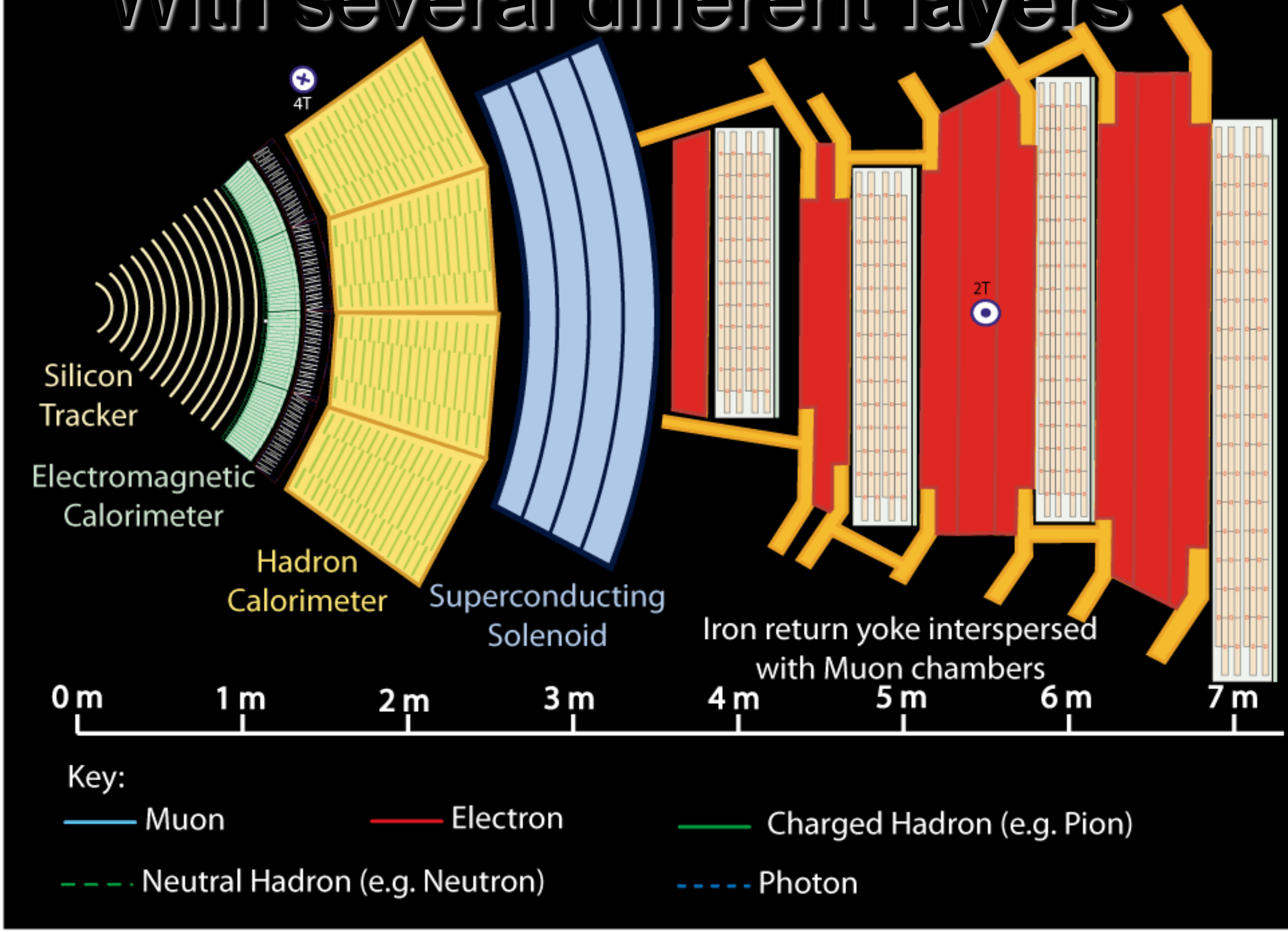
Muon momentum is measured in the muon system but the best resolution comes from associating a silicon track, which has excellent momentum resolution ,with the muon track and doing a full fit.

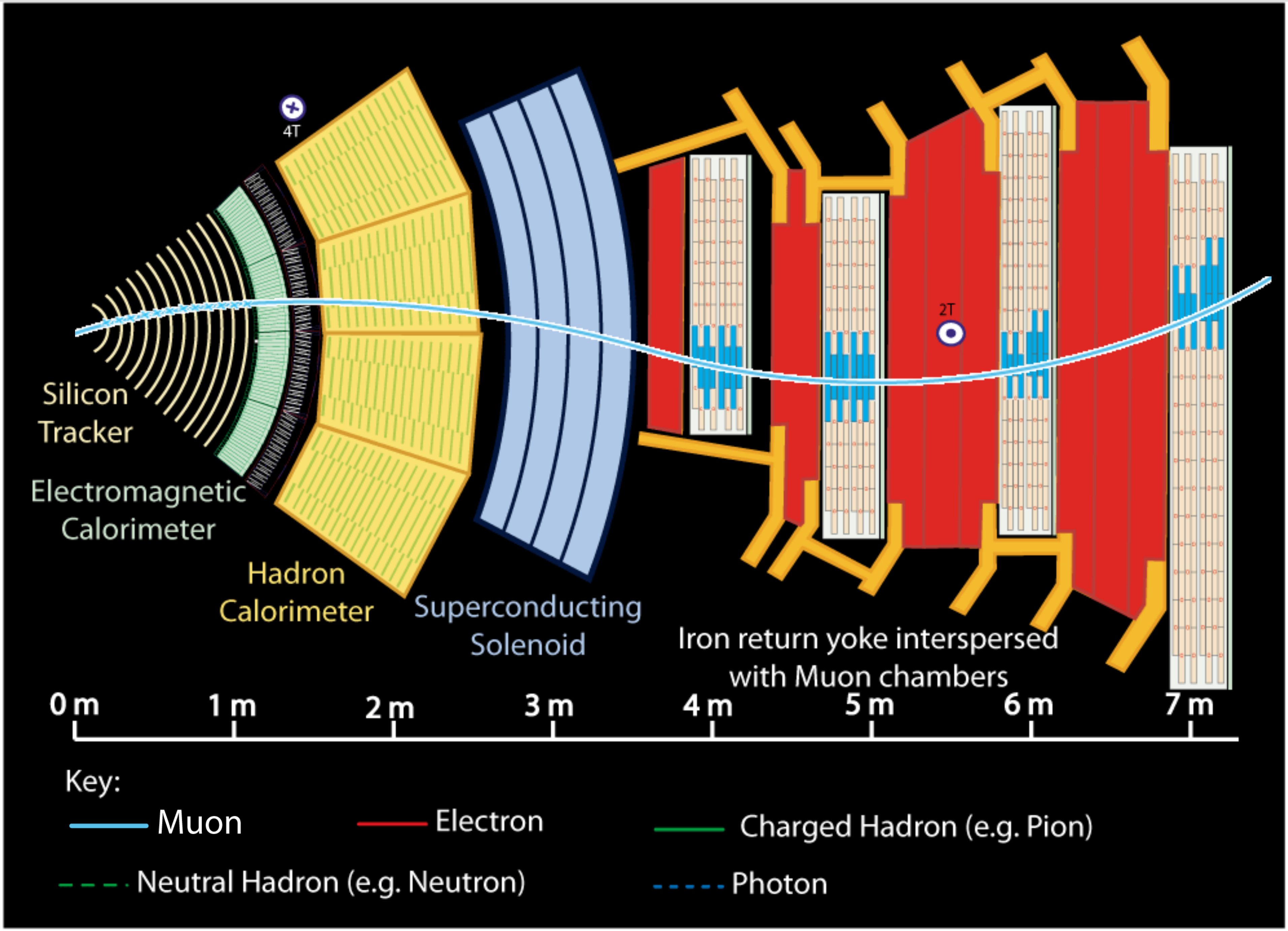
CMS Slice

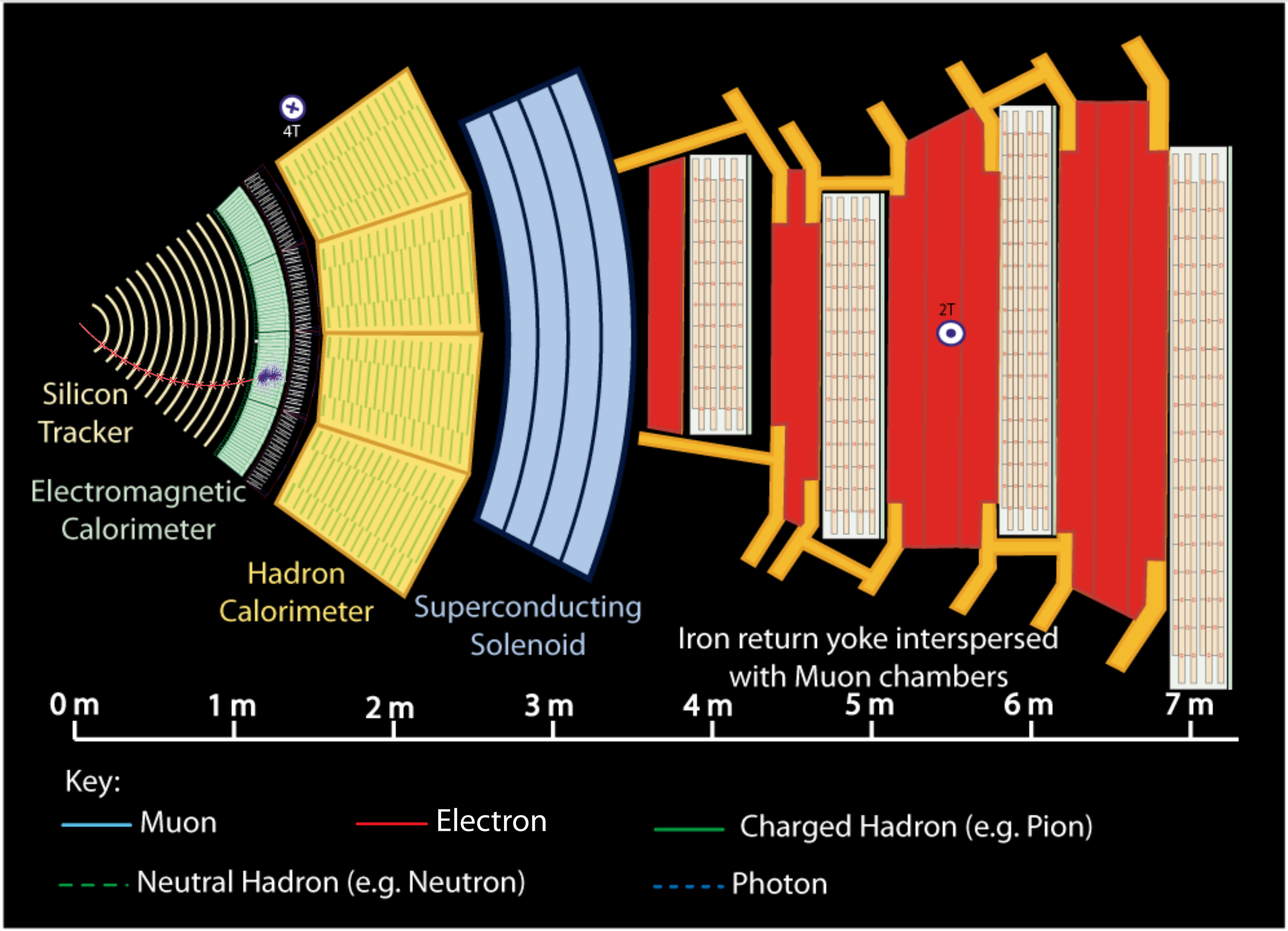


type	tracking	ECAL	HCAL	MUON
γ				
e				
μ				
Jet				
Et miss				

With several different layers




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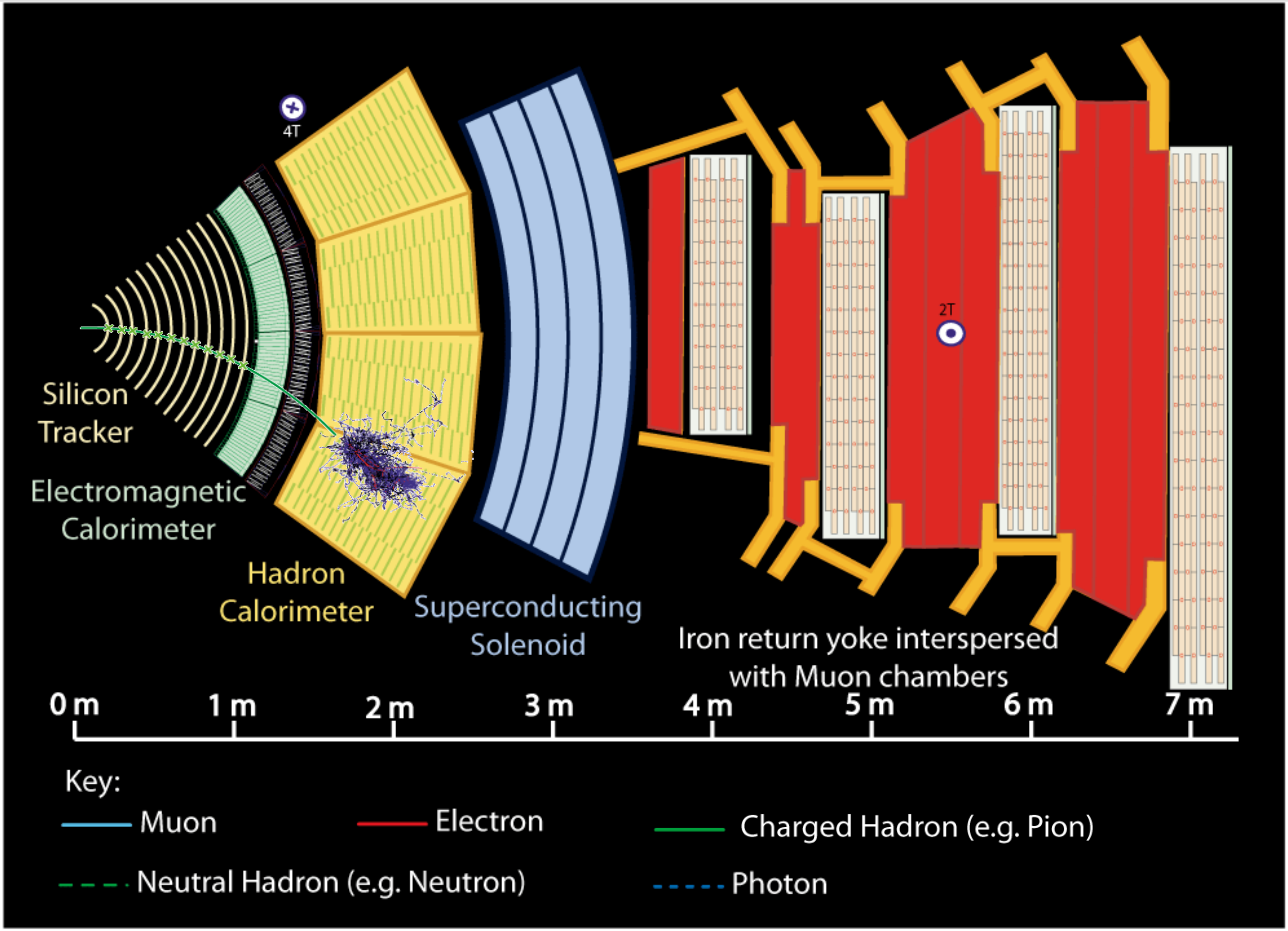
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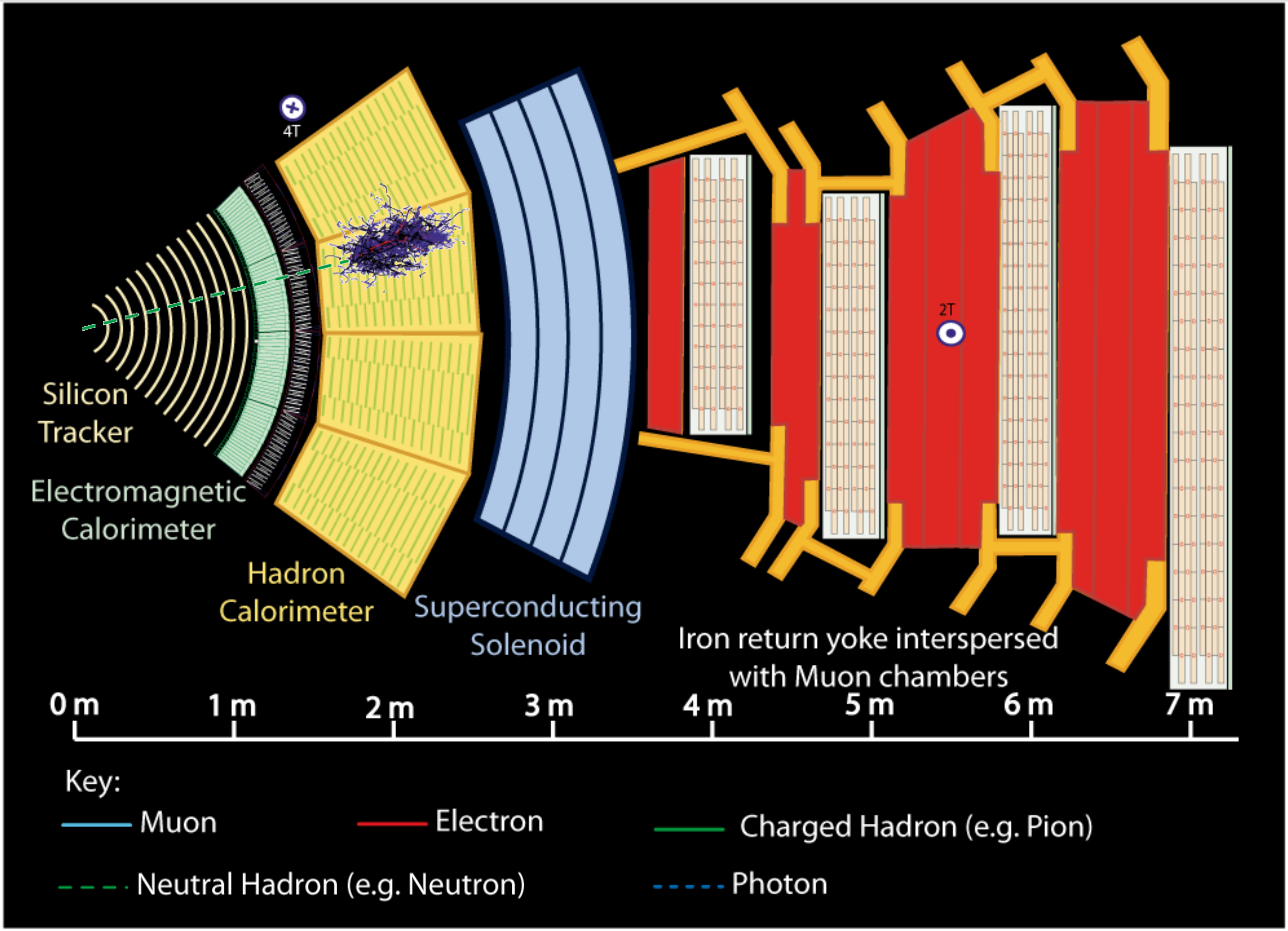
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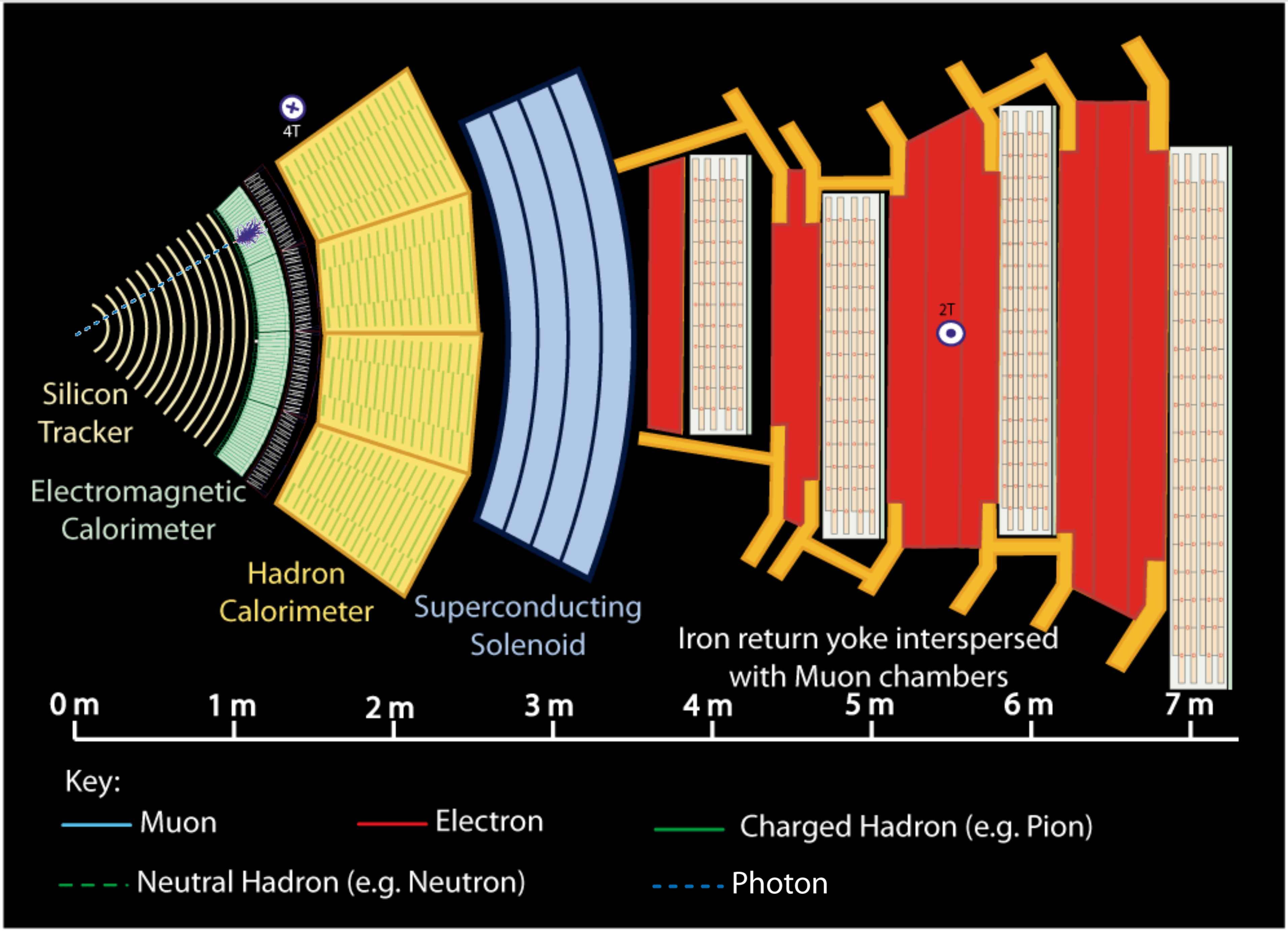
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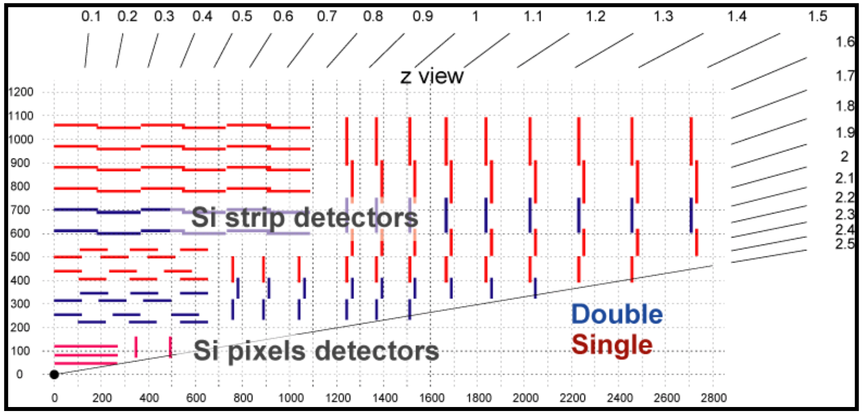
Neutral Hadron (e.g. Neutron)
Photon

Subsystem of CMS Detector

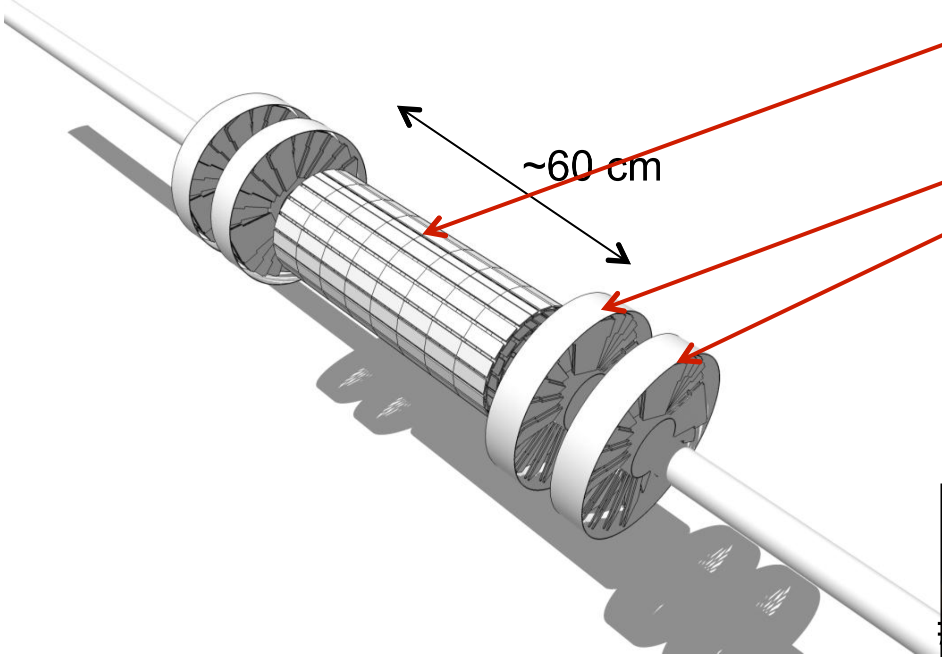
CMS Tracker

- **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 (pixels have lowest occupancy)
  - 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**

66M pixels and 10M strips produces low occupancy. Detector can function well in high pileup environment



The CMS Pixel System

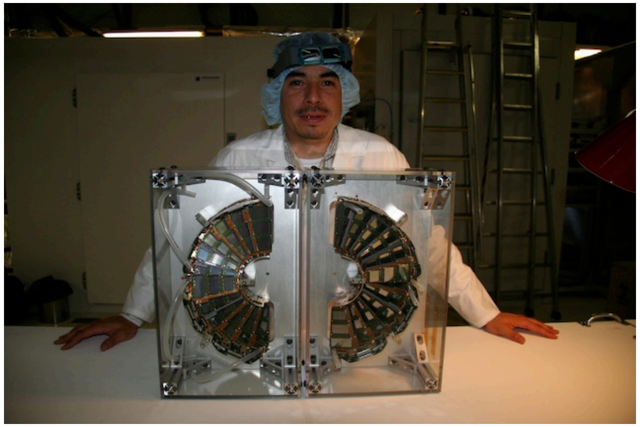


BPix (3 layers)	FPiX (2 disks each end)
672 modules	96 blades
+92 halfmodules	672 plaquettes
11520 ROCs	4320 ROCs

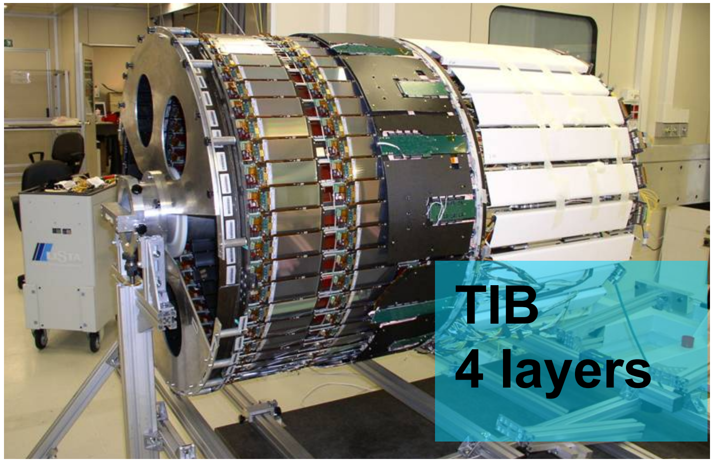
A Readout Chip (ROC) has 4160 pixels in an area of 8mm x 9 mm

Each pixel is 100μm x 150 μm.

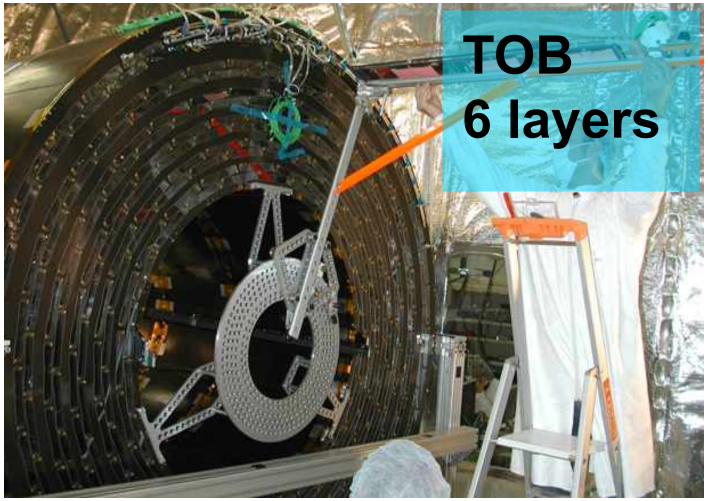
Total Pixels: 66M



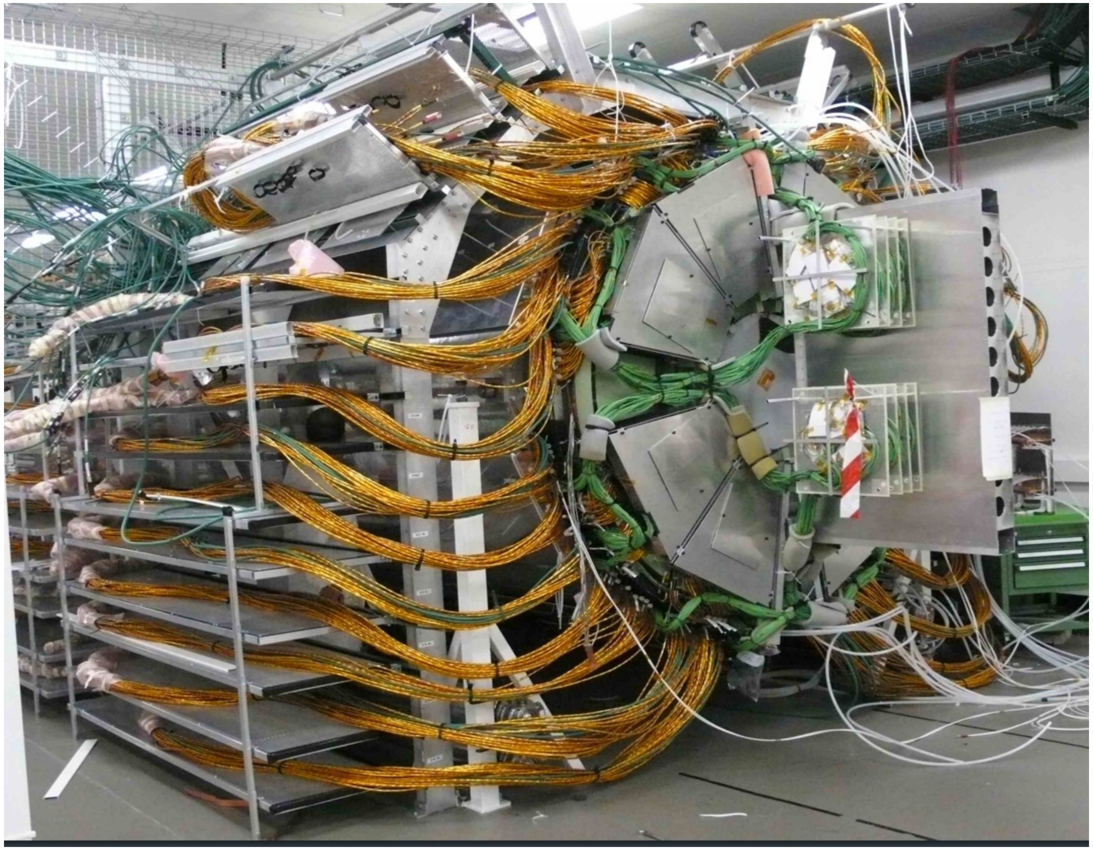
Completed Tracker



TIB
4 layers



TOB
6 layers



TEC
"petal"

2300 square feet of silicon!!!!!
detectors, >9 million strips

Tracking System Performance

- Can track charged particles from 100 MeV/c < P_T<1TeV/c
- Average efficiency for reconstructing charged particles with P_T>0.9 GeV/c is 95% (85%) in the barrel(endcap)
  - Main sources of inefficiency are due to hadron interactions
- For isolated muons, at P_T~100GeV, resolution in P_T is ~2.8%, in impact parameter ~10 μm transversely and 30 μm longitudinally
  - At 1 TeV/c, resolution in P_T is ~20% and depends on good alignment
- The primary vertex resolution for high P_T events of interest is ~10-12 μm in all three dimensions
  - Effective at vertexing even if the number of interactions/crossing is quite large (say 40 distributed over ~10cm)
  - Efficiency for finding vertices in minimum bias events is less, ~70%

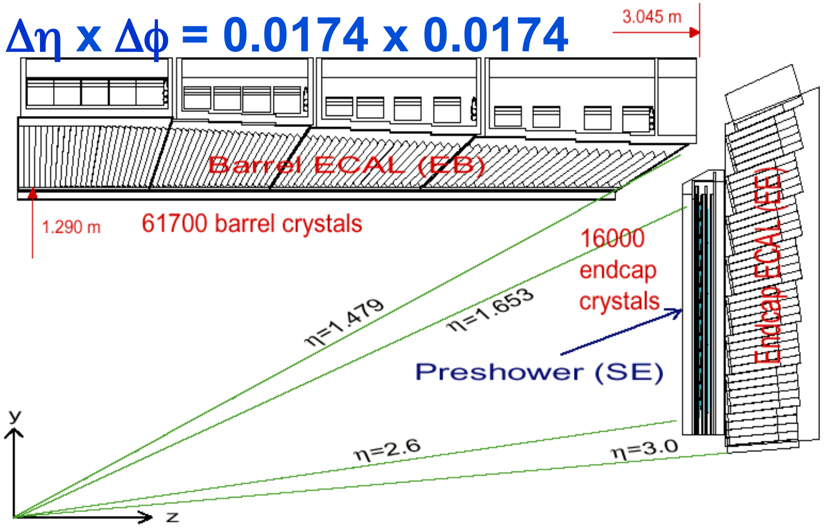
Many details of hit, cluster, track and vertex reconstruction and performance can be found in TRK-11-001

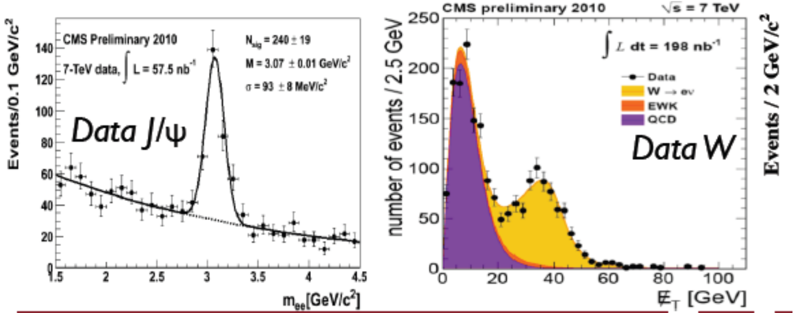
CMS ECAL

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

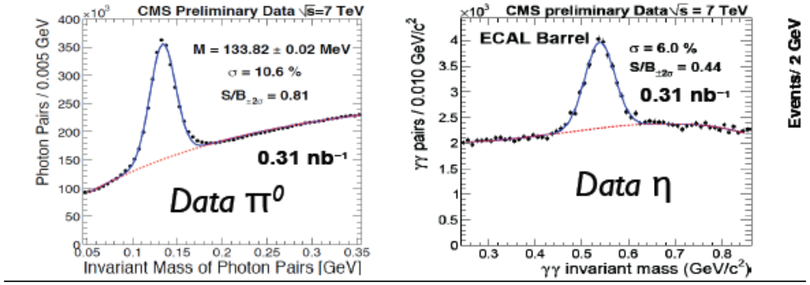
$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{12\%}{E}\right)^2 + (0.3\%)^2$$

$\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$

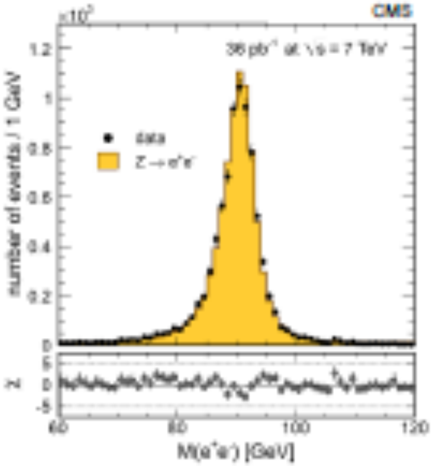


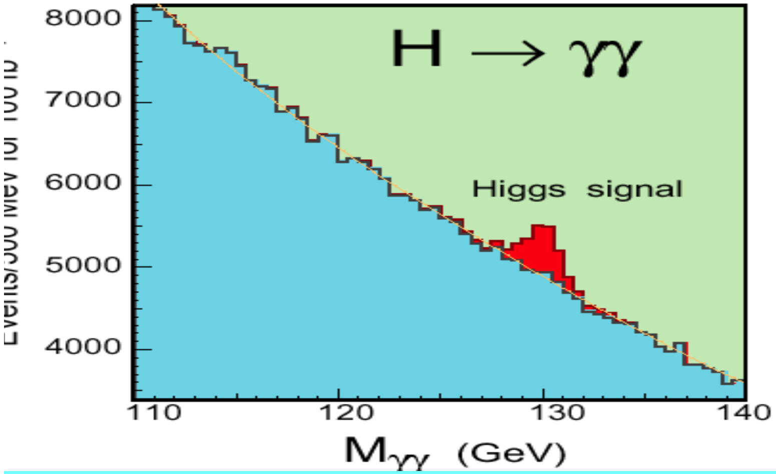


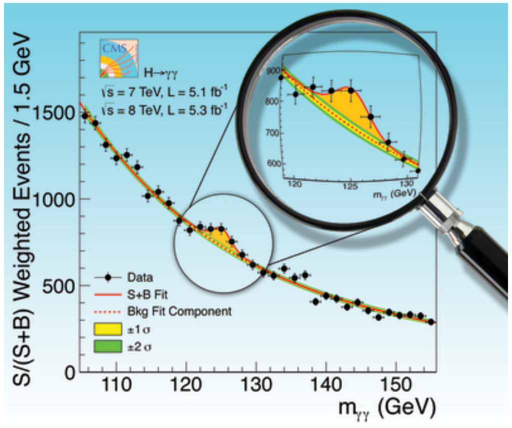
Present



Higgs to diphoton ($H \rightarrow \gamma\gamma$)





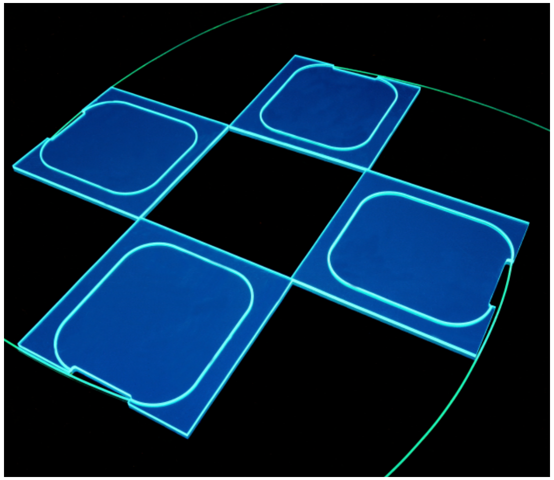


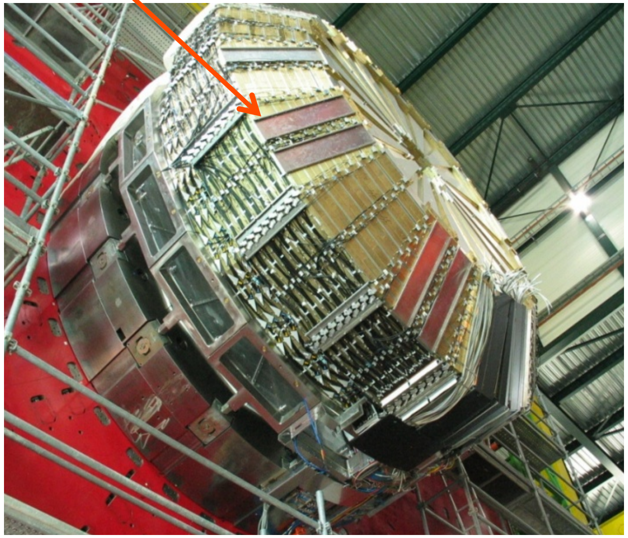
Simulated $H \rightarrow \gamma\gamma$ with M_H=130 GeV as observed in the CMS detector

- Tracker material in front of ECAL degrades resolution from ideal
- Actual performance: Calorimeter provides ~1 GeV mass resolution which allows a peak to be seen for the Higgs
  - $Z \rightarrow e^+e^-$ very similar to $H \rightarrow \gamma\gamma$.
    - $Z \rightarrow e+e^-$: barrel: 1.6%; endcap 2.6%
    - $H \rightarrow \gamma\gamma$: barrel 1.1−2.6%; endcap: 2.2-5%
- **Many details of electron and photon reconstruction are given in EGM-11-01**

CMS HCAL

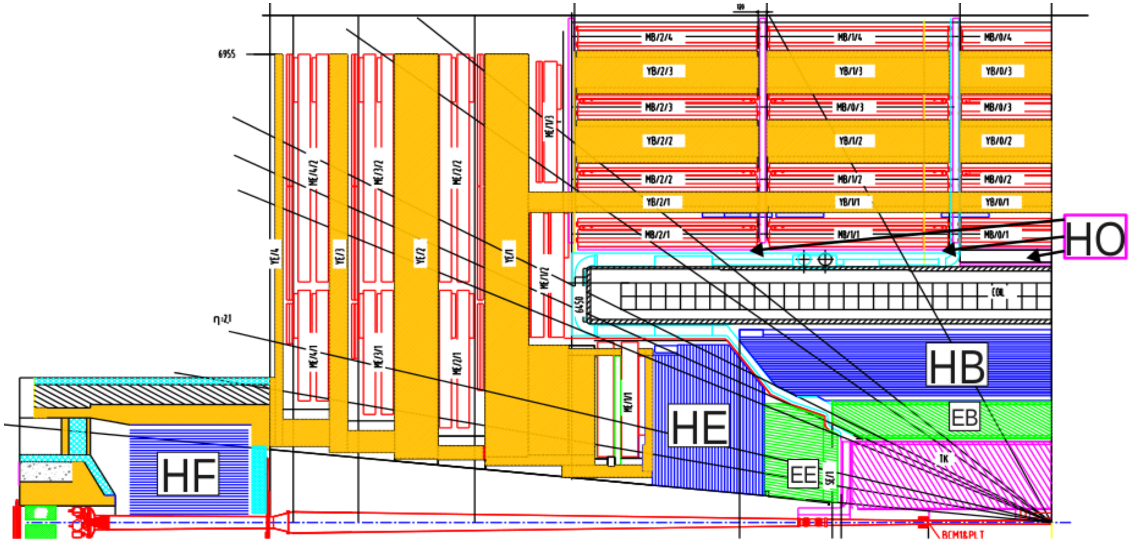
- Sampling calorimeter
- Brass absorber from Russian artillery shells (non-magnetic)
- Plastic scintillating tiles with wavelength shifting (WLS) fiber
- WLS fiber is fed into a **hybrid photo-diode** (HPD) for light yield measurement
- **Tower size is $\Delta\eta\Delta\phi$=0.087x0.087**





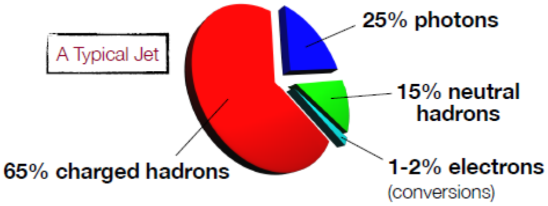
5X5 ECal crystals($\Delta\eta$ x $\Delta\phi$ = 0.0174 x 0.0174)→1 HCAL tower

Overview of Hadron Calorimetry



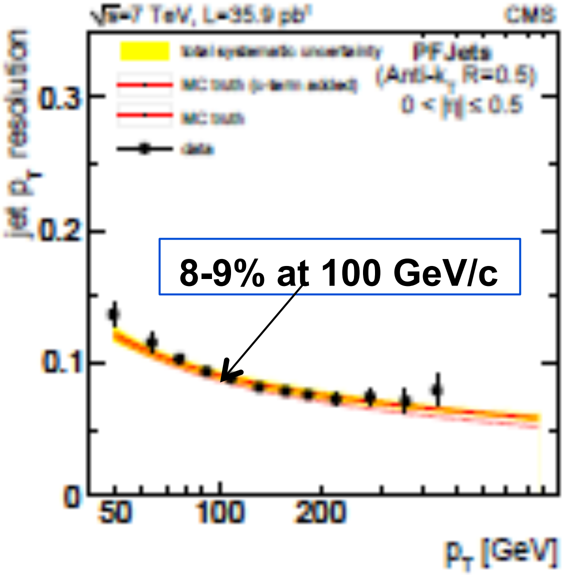
Hadron calorimeter resolution

$$\frac{\sigma_E}{E}(\%) \sim \frac{100-150\%}{\sqrt{E}}$$



Jet Resolution

$$\frac{\sigma_{P_T}}{P_T} = \frac{4}{P_T} \oplus \frac{0.2}{\sqrt{P_T}} \oplus 0.07 \text{ (all in GeV/c)}$$



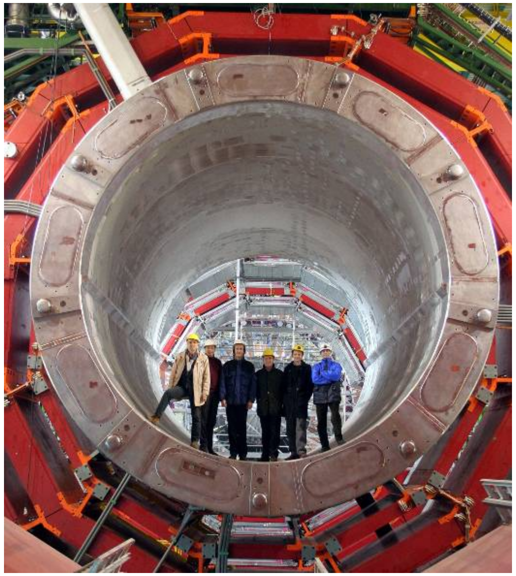
8-9% at 100 GeV/c

Jet measurements rely on ECAL and HCAL.The Level 1 trigger uses only information from them.

1) However, OFFLINE, since hadron calorimetry has lower resolution, a new technique to reconstruct jets, called **particle flow**, uses the charged tracks to get the charged hadron component of the hadronic shower, leaving only the neutral hadron component to be measured by HCAL. This improves that overall jet resolution

CMS Solenoid

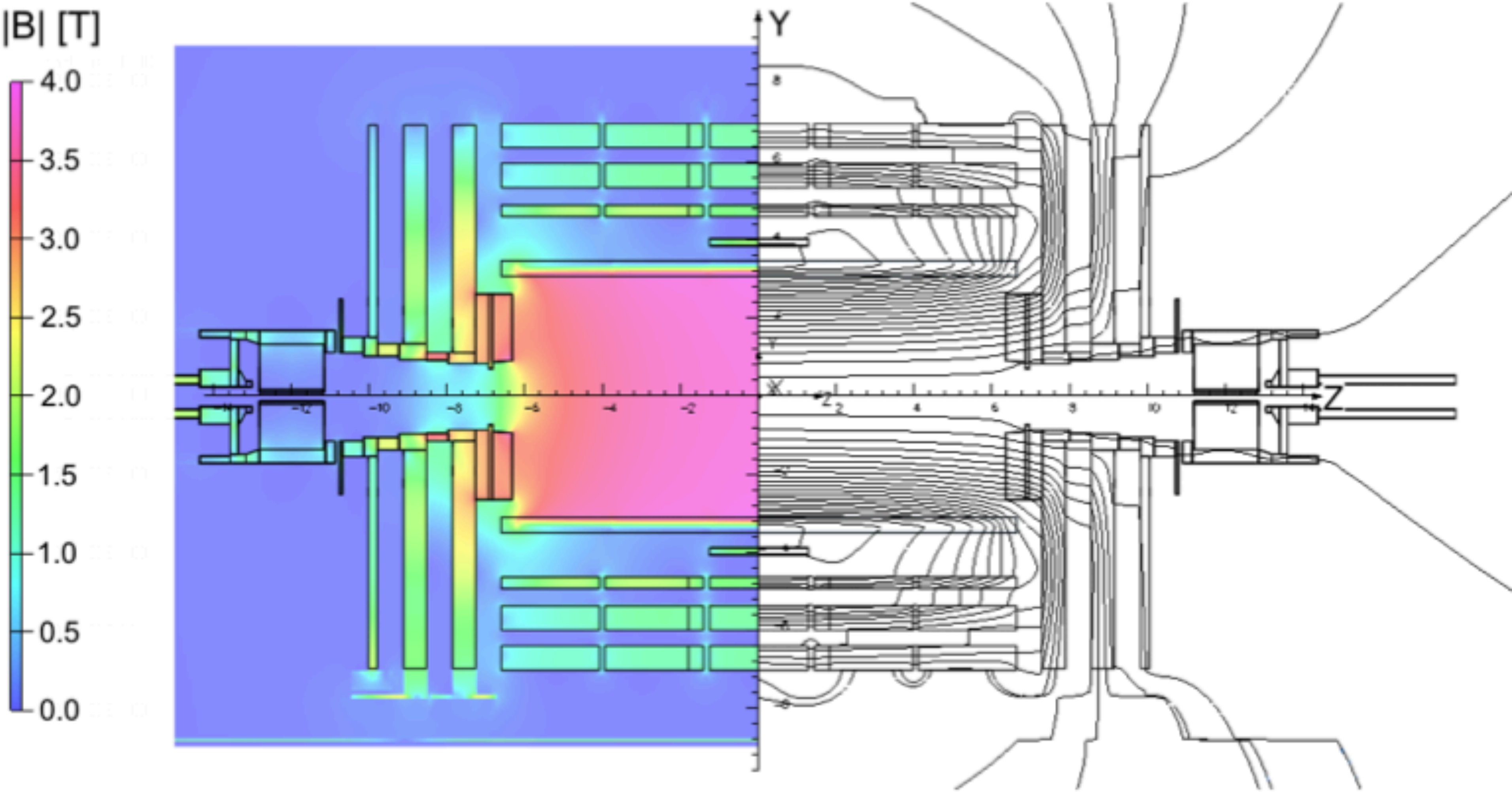
- The Solenoid has
  - **Large acceptance in central region**
    - **Optimal for measuring P_t in central region**
- **3.8 T magnet at 4^o K**
- **6 m diameter and 12.5 m long (largest ever built)**
  - **Room for all calorimetry inside**
- **220 t (including 6 t of NbTi)**
- **Stored energy 2.7 GJ — equivalent to 1300 lbs of TNT**



To have a very strong field you need a steel return(Amperes law BxL = μ_0 NI,. ➔ B = μ_0 NI/L , where L is the "effective" length of the flux line (length in "unsaturated" steel doesn't count)

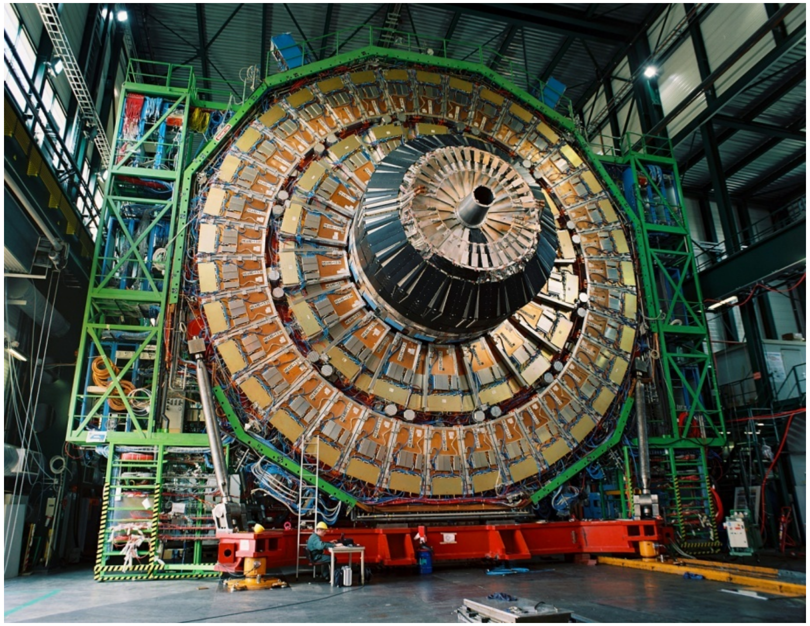
- **Good features of using steel flux return and measuring muon in it**
  - **good resolution for all charged particles**
  - **Muon detectors are well shielded and in low radiation field**
  - **Low B field outside of detector (good for electronics)**
- **Bad features of muons measuring in steel**
  - **Multiple scattering and radiation (bremsstrahlung) reduce resolution and cause measurement errors**
  - **Must be able to extrapolate muon track back to match track inside solenoid, to get good resolution**

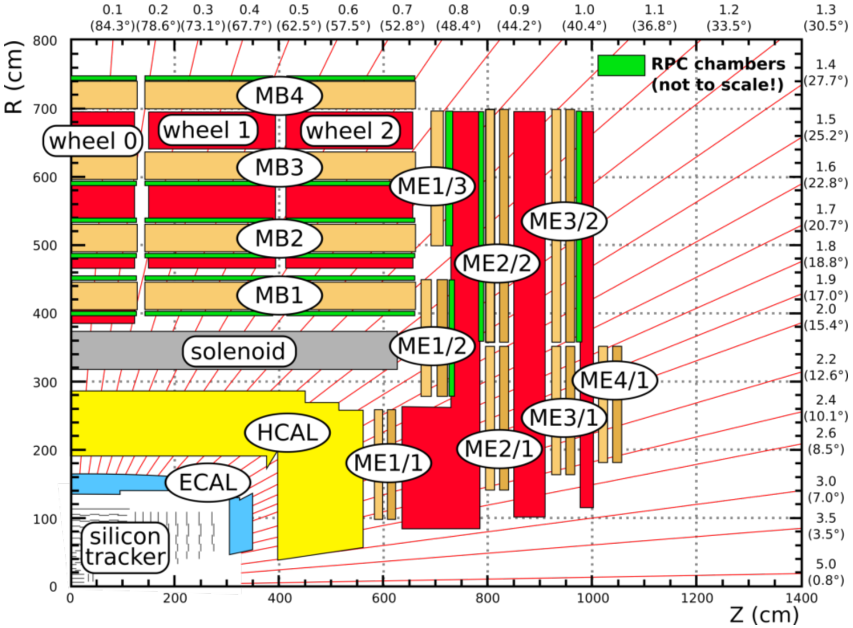
Magnetic Field



Muon Systems

- Muons interact less than other charged particles
  - Place detectors after material and what comes through is a muon candidate
- Use B field in steel and muon system tracking to find momentum at trigger level and link with main tracker
- 14000 tones of iron absorber and solenoid flux return
- **Three ionizing gas technologies: Drift Tube (Barrel), Resistive Plate Chamber (Barrel, Endcap), and Cathode Strip Chamber (Endcap)**
  - Each pseudorapidity interval is covered by two of these subsystems

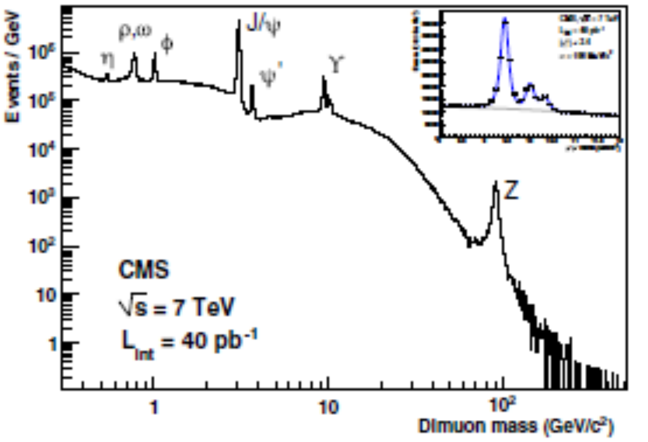




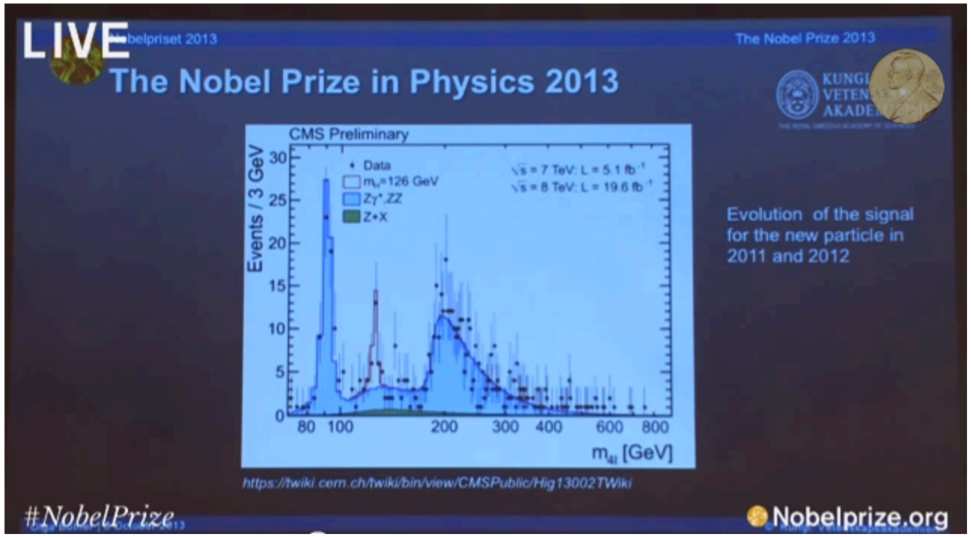
Muon System Performance

- **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 additional requirements**

Spatial Resolution” DT: 80-100μm; CSC: 40-150μm; RPC: 0.8-1.2cm
Efficiency: triggering (P_T>few GeV) >90%; reconstruction 95-98%
Muon misid: between a 1% and a fewx0.1% depending on cuts
P_T resolution: 1-6% (< 100 GeV/c), ~10-20% at 1 TeV/c, depending on η



Dimuons



The Nobel Prize in Physics 2013

Evolution of the signal for the new particle in 2011 and 2012

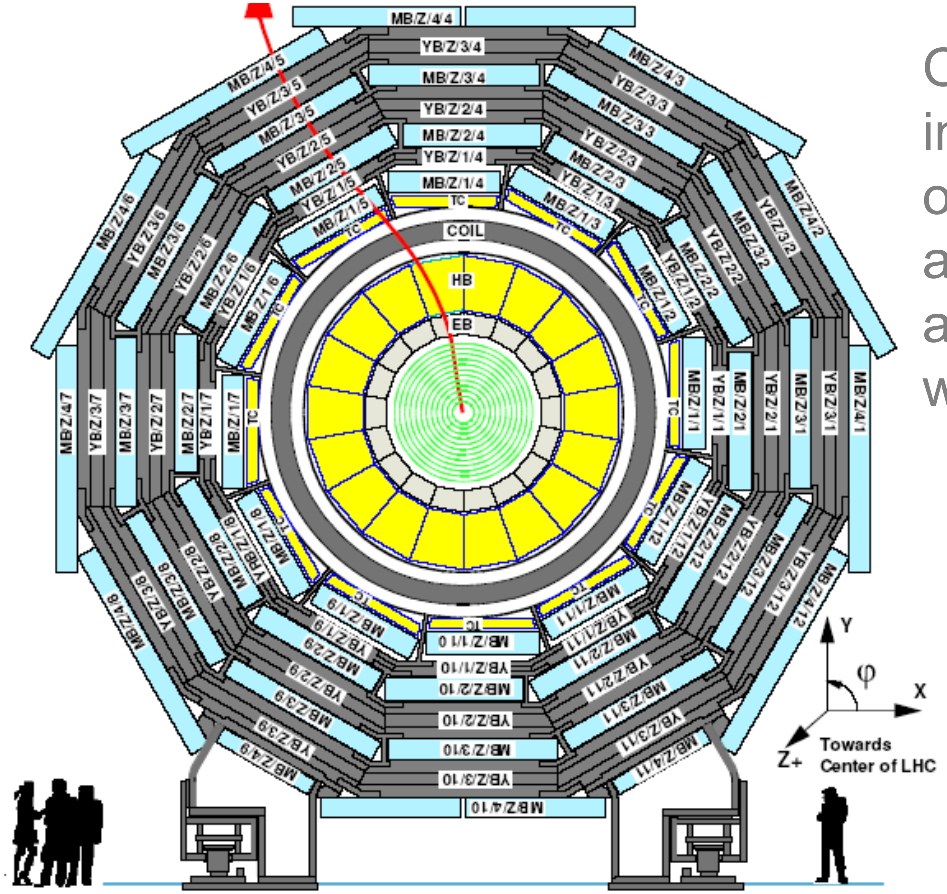
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13002TWiki

4leptons

Layout of Drift Tube (DT) Chambers

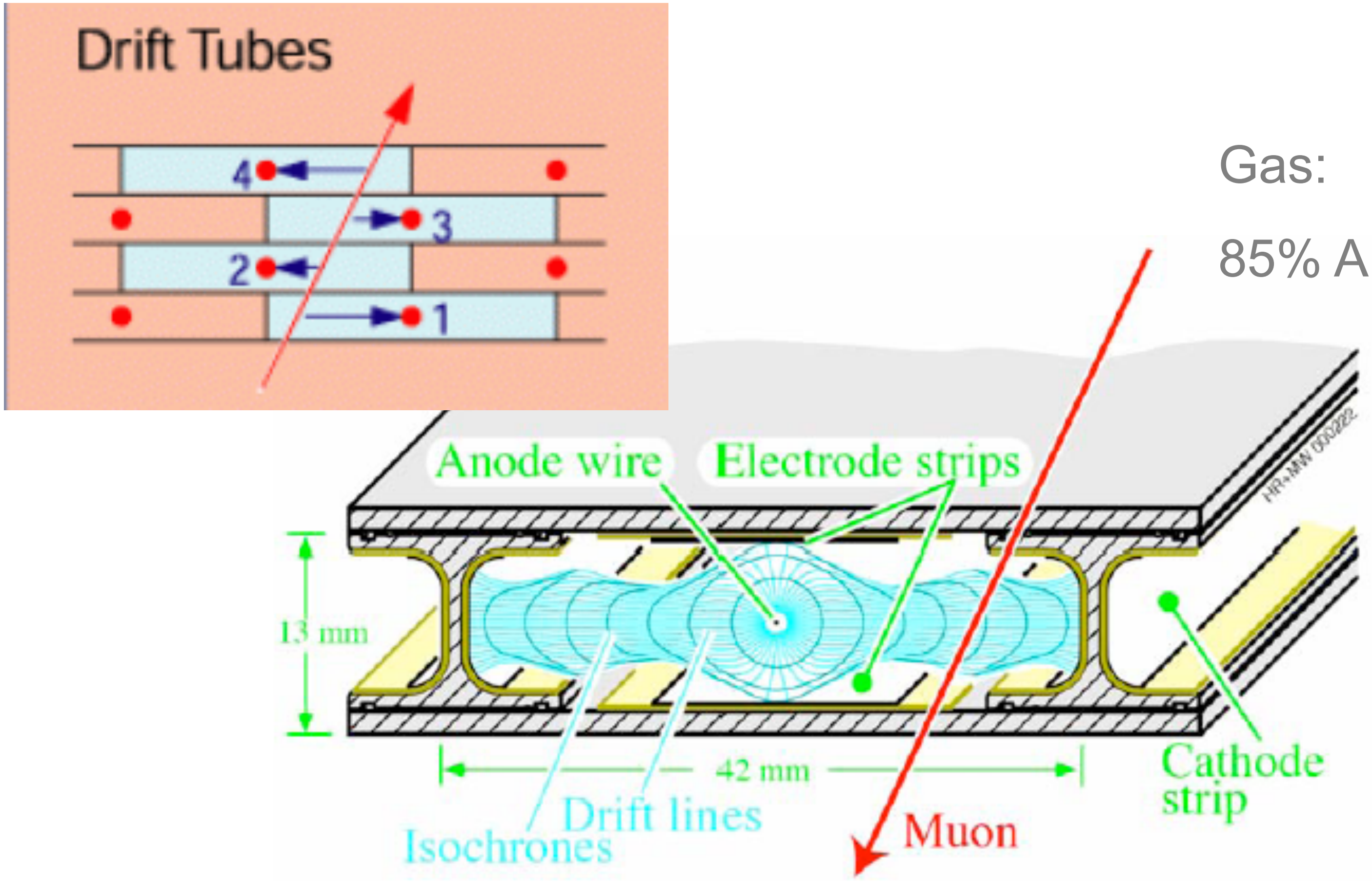
One of the five wheels.

60 chambers in the first three layers and 70 in the last.



One layer is inside the yoke, one is outside, and the other two are embedded within the york.

Sketch of DT Cell

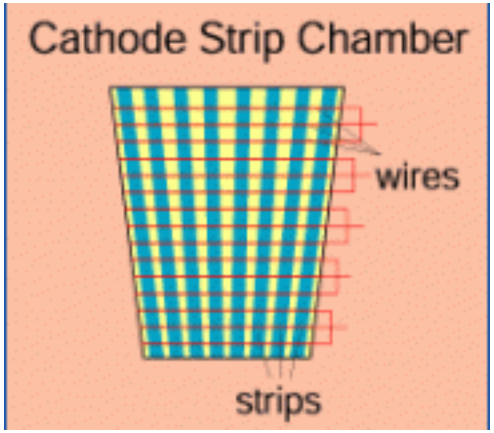


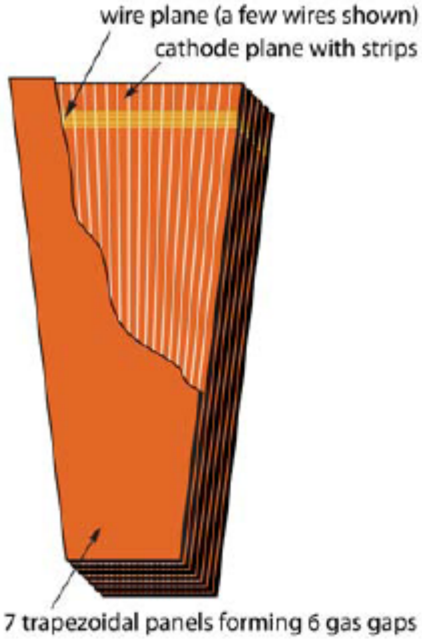
Gas:

85% Ar + 15% CO_2

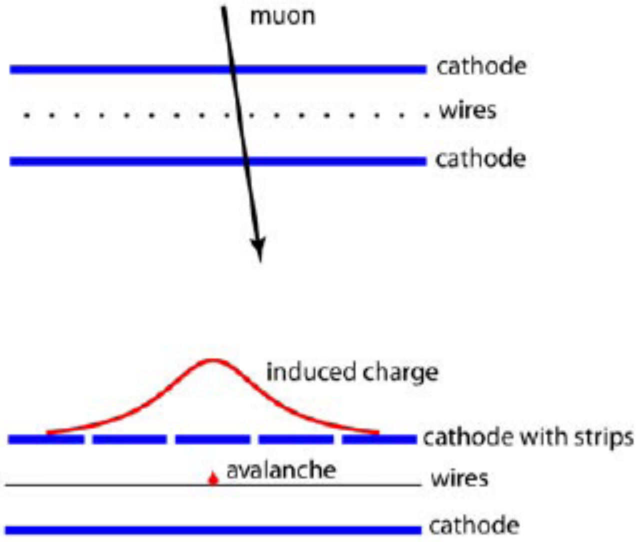
Top and bottom plates are grounded. The voltages applied to the electrode are +320V for wires, +1800 V for the strips and -1200 V for the cathode.

Cathode Strip Chambers (CSC)





HV: 3.5-3.9 kV



7 trapezoidal panels forming a 6 gas gaps.

Gas:

40% Ar + 50% CO_2 + 10% CF_4

Resistive Plate Chamber

Advantage: tagging the ionizing time much shorter than 25μs

⇒ good for triggers

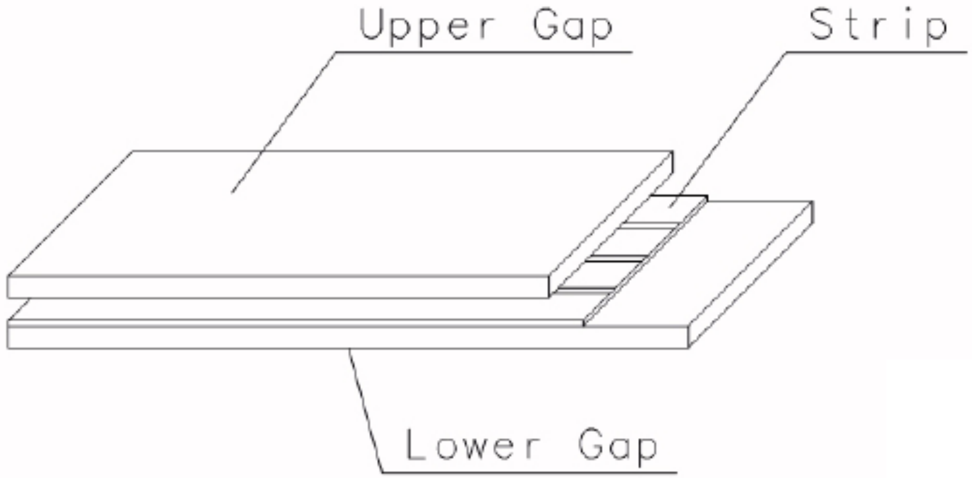
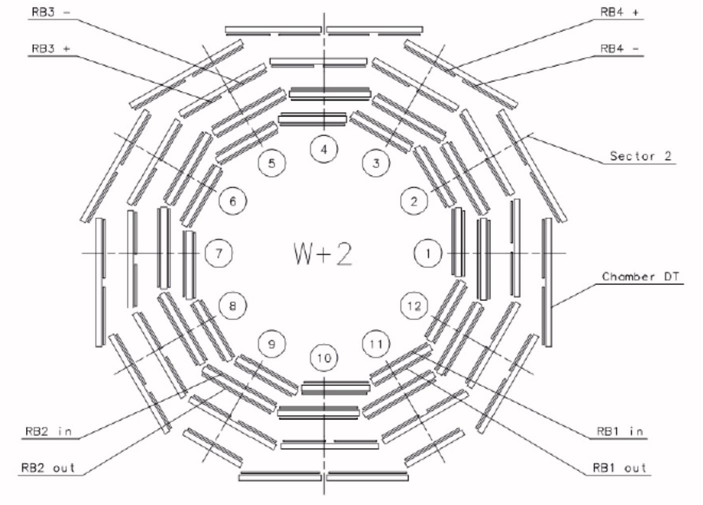
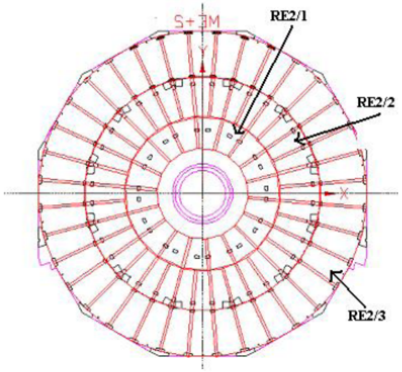
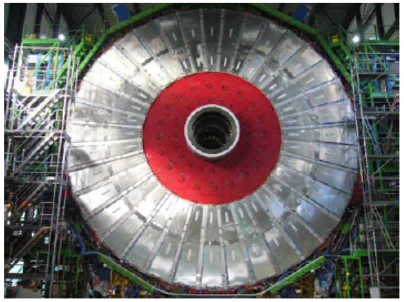


Figure 194: Layout of a double-gap RPC.







Gas:

96.2% $C_2H_2F_4$ +
3.5% C_2H_{10} + 0.3% SF_6

Triggering and Data Acquisition

The problem

- 40 MHz of beam crossings, with 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 ~300 Hz of events > 400 MB/s =>3-6 Petabyte per year (raw data)
- Need to reject 99.9998% of events in quasi real time

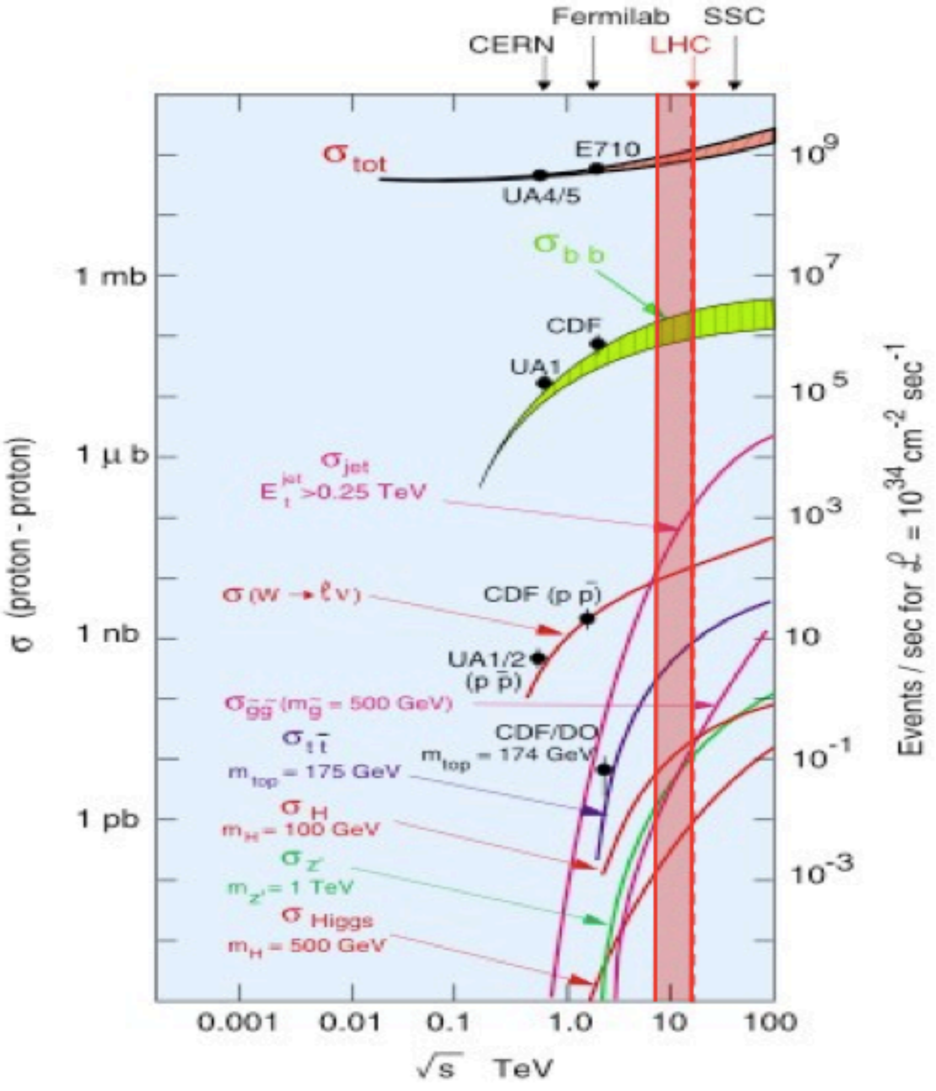
The solution

- **Level 1 (L1) Hardware trigger** finds jets, electrons, muons, and missing E_T using only calorimeters and muon detectors and rejects 99.8% of events in 3.2 μs
- **High Level Trigger (HLT):** Surviving 100 K Crossings/s of events fed into several thousand CPU core farm where events are reconstructed using full detector including tracking and 0.3-0.5% kept

The LHC: Setting the Scale

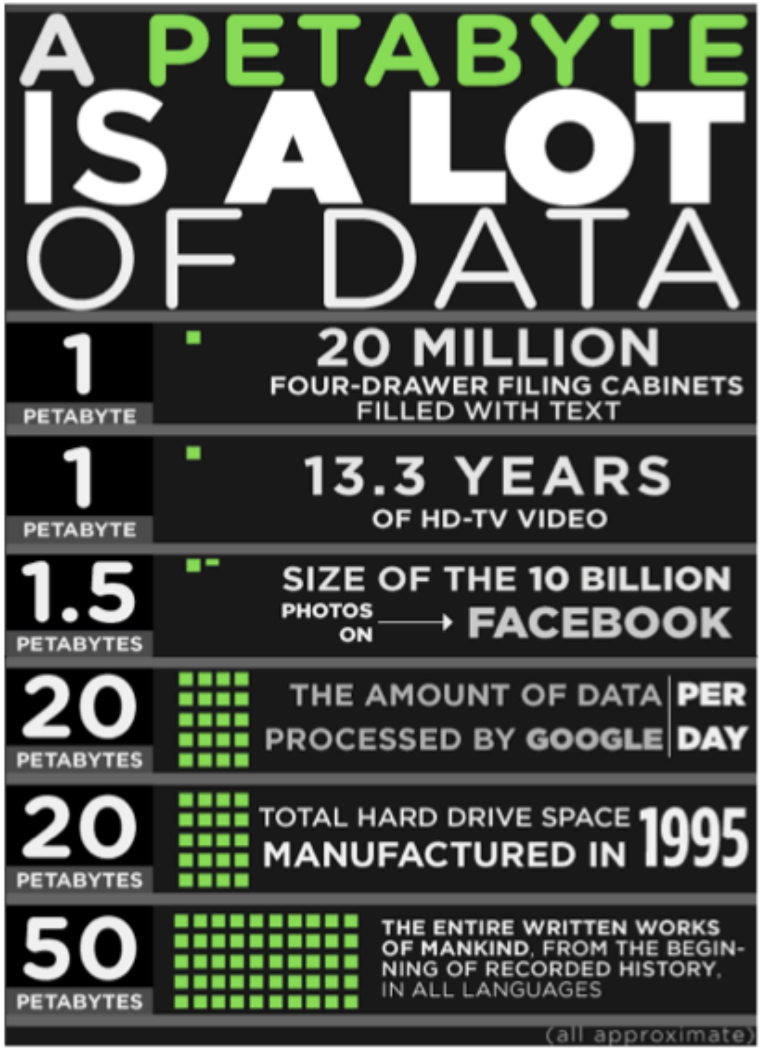
14 TeV, 10^{34} cm^{-2} sec^{-1}

Process	σ (nb)	Production rates (Hz)
Inelastic	10^8	10^9
$b\bar{b}$	5×10^5	5×10^6
$W \to \ell\nu$	15	150
$Z \to \ell\ell$	2	20
$t\bar{t}$	1	10
Z' (1 TeV)	0.05	0.5
$\tilde{g}\tilde{g}$ (1 TeV)	0.05	0.5
Higgs (100 GeV)	0.05	0.5
Higgs (500 GeV)	10^{-3}	10^{-2}



Keeping Events

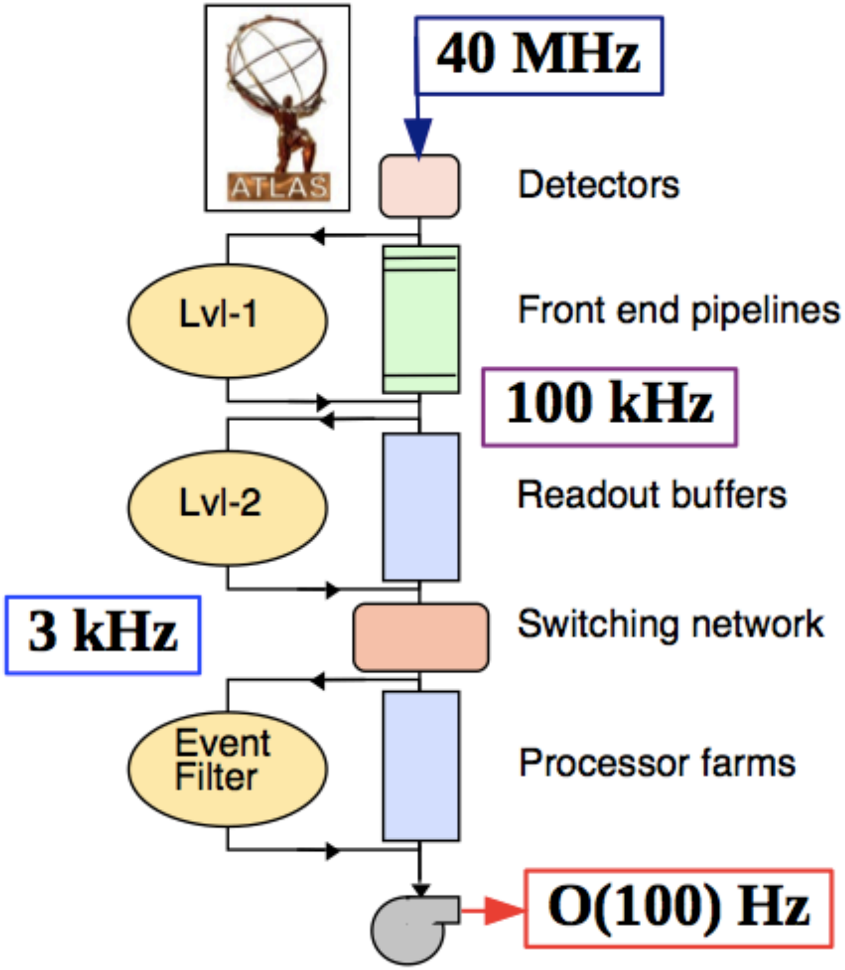
- We can't save everything!
  - Event size: about 1 MB
  - Event reconstruction time:
    - 30 sec – 1 minute
  - At a data rate of O(100 Hz)...
    - O(100) MB/sec
    - O(few) PB/year per experiment
  - Keeping every event
    - O(100000) PB/year
    - Too big to store
    - Too big to reconstruct
    - Too big to analyze

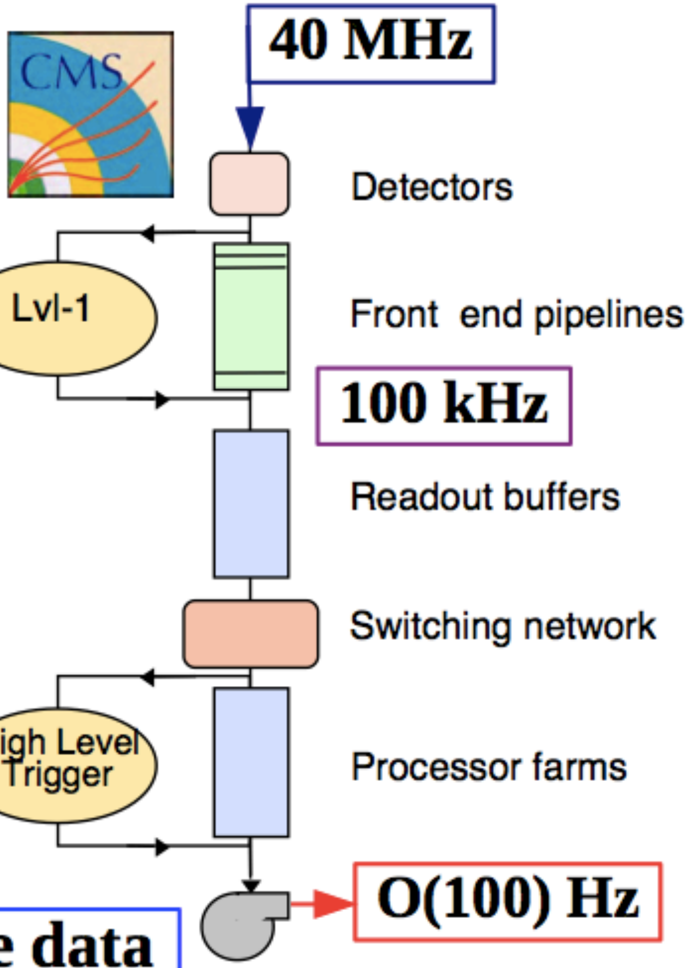


Trigger = Rejection

- Problem: We must analyze AND REJECT most LHC collisions prior to storage
- Solution: Trigger
    - Fast processing
    - High rejection factor: $10^4 – 10^5$
    - High efficiency for interesting physics
        - If events fail the trigger, we don't save them!
    - Flexible
    - Affordable
    - Redundant

Trigger Setup





Reduce the data volume in stages

Trigger Setup

- Level 1: Custom hardware and firmware
  - Reduces the rate from 40 MHz to 100 kHz
  - Advantage: speed
- Level 2: Computing farm (software)
  - Further reduces the rate to a few kHz
  - Reconstruct a region surrounding the L1 trigger object
  - Advantage: Further rejection, still relatively fast
- Level 3: Computing farm (software)
  - Store events passing final selection for offline analysis
  - Advantage: The best reconstruction

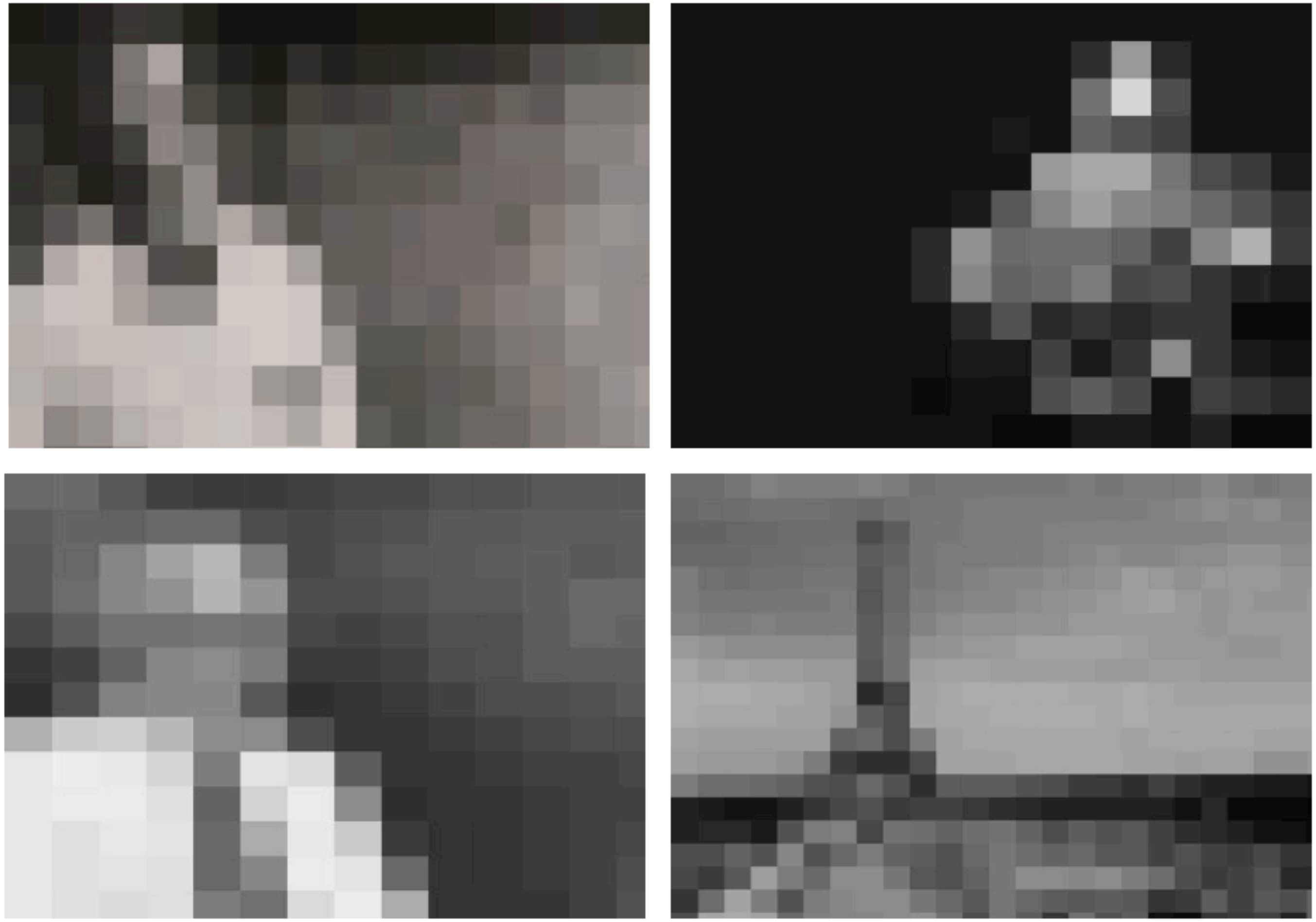
High Level Trigger

Trigger Example: Higgs

Higgs Selection
using the Trigger

Level 1:

Not all
information available,
coarse granularity

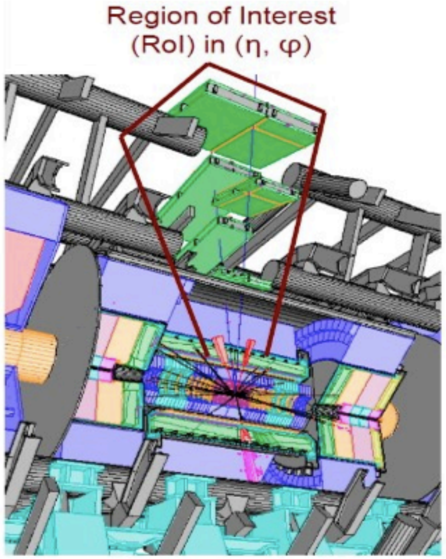


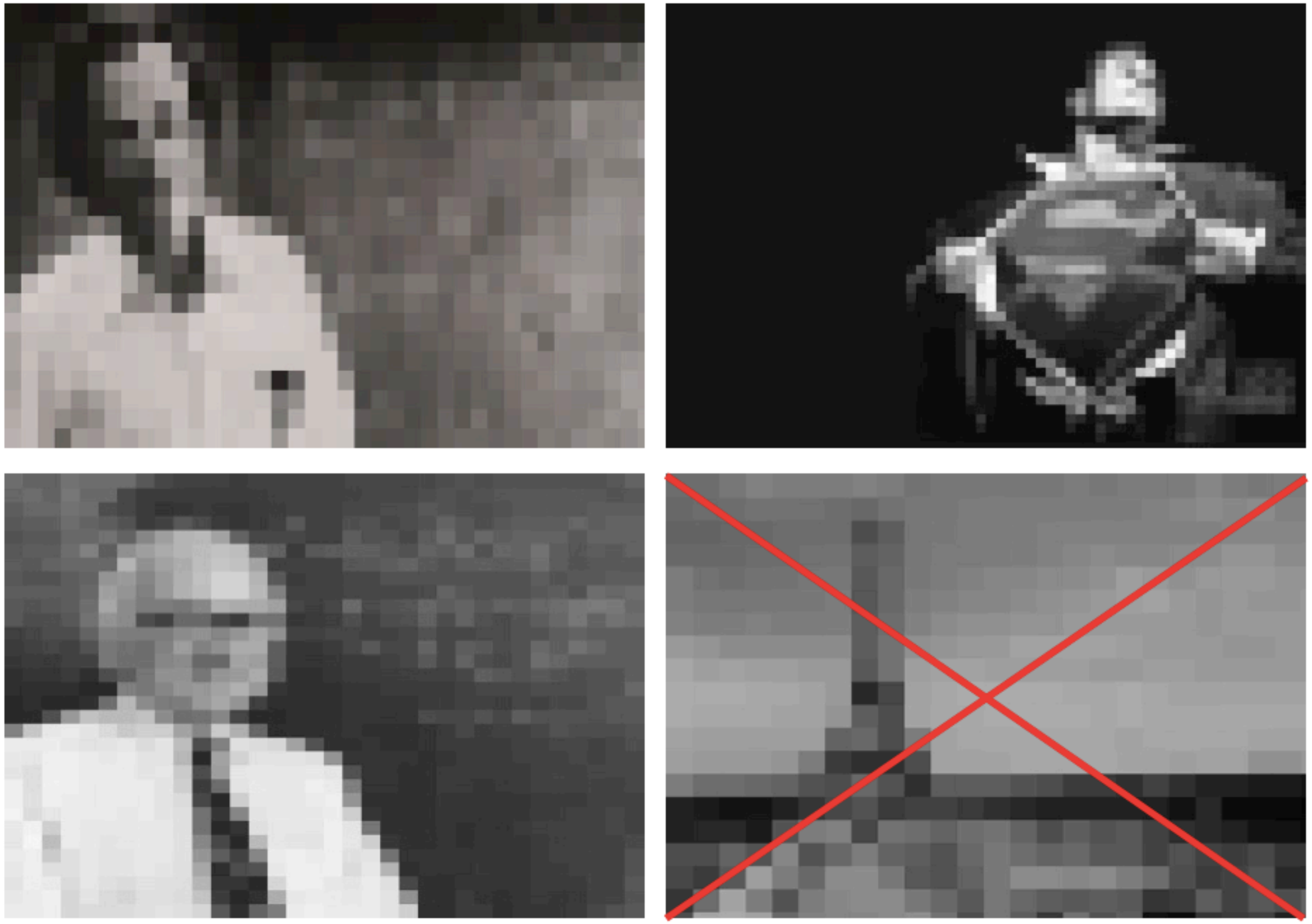
Trigger Example: Higgs

Higgs Selection using the Trigger

Level 2:

Improved reconstruction techniques, improved ability to reject events



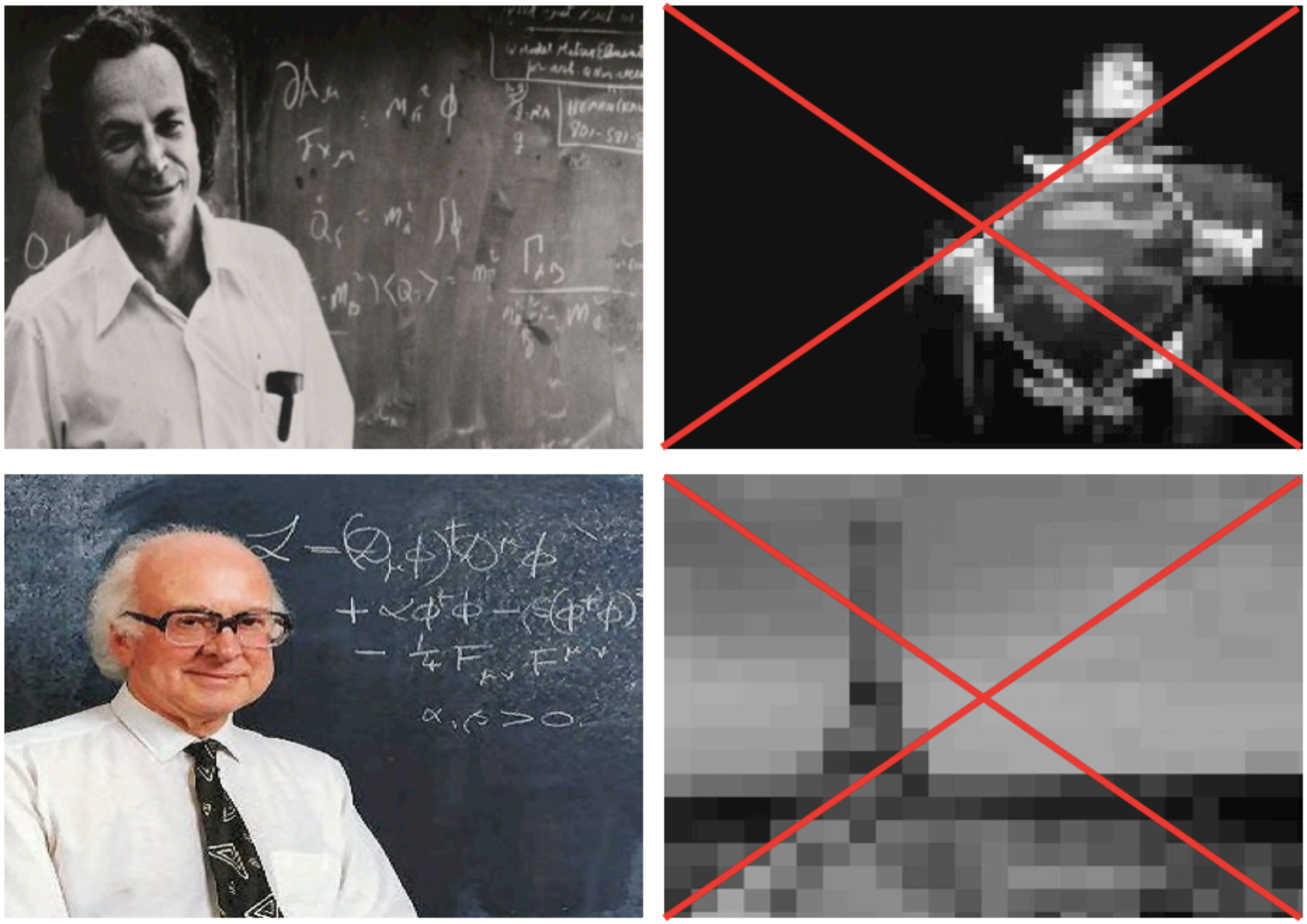


Trigger Example: Higgs

Higgs Selection using the Trigger

Level 3:

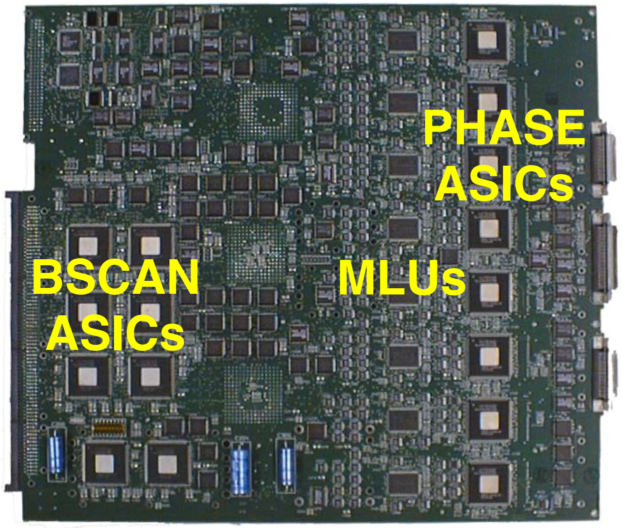
High quality reconstruction algorithms using information from all detectors



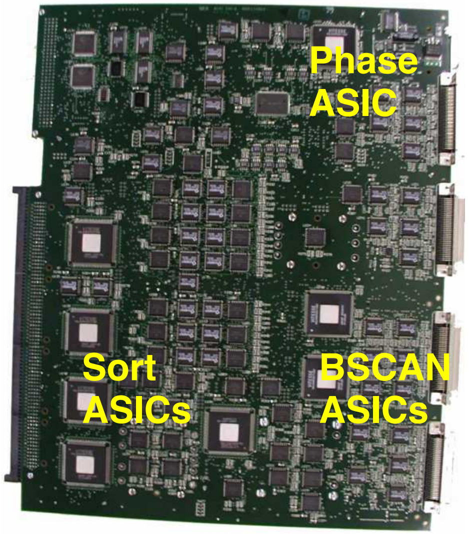
L1 Trigger

- Custom electronics designed to make very fast decisions
  - Application-Specified Integrated Circuits (ASICs)
  - Field Programmable Gate Arrays (FPGAs)
    - Possible to change algorithms after installation
- Must be able to cope with input rate of 40 MHz
  - Otherwise trigger wasting time (and money) as new events keep arriving
  - Event buffering is expensive, too
- L1 Trigger: Pipeline
  - Process many events at once
  - Parallel processing of different inputs as much as possible

Some L1 Hardware

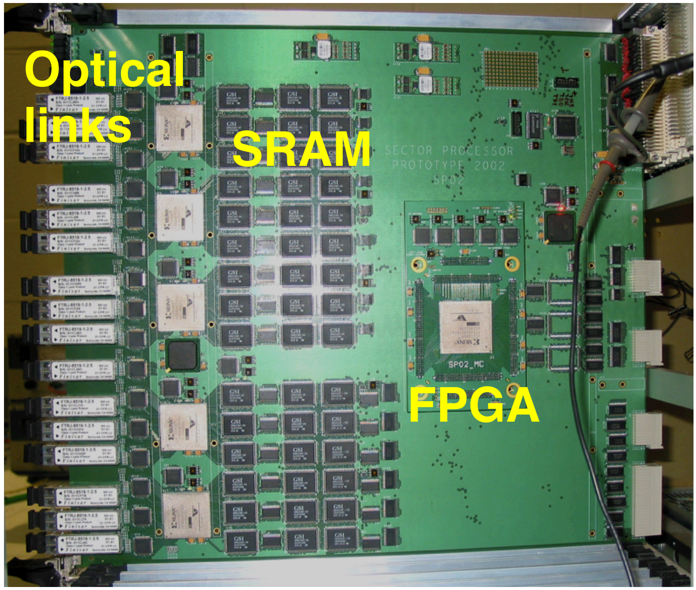


RCT Receiver card



RCT Jet/Summary card

RCT Electron isolation card

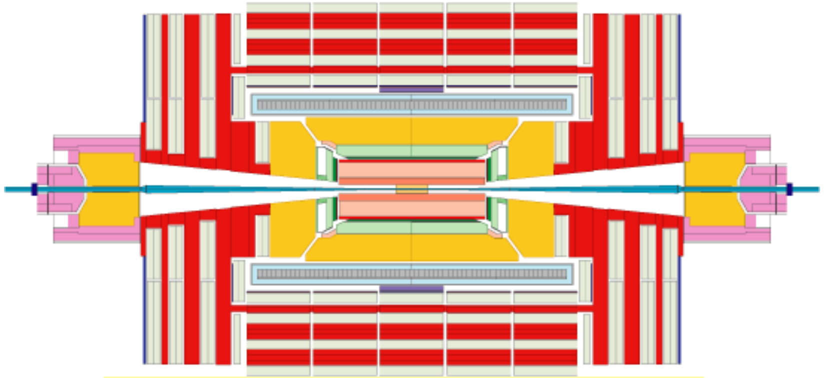


CSC Track-Finder

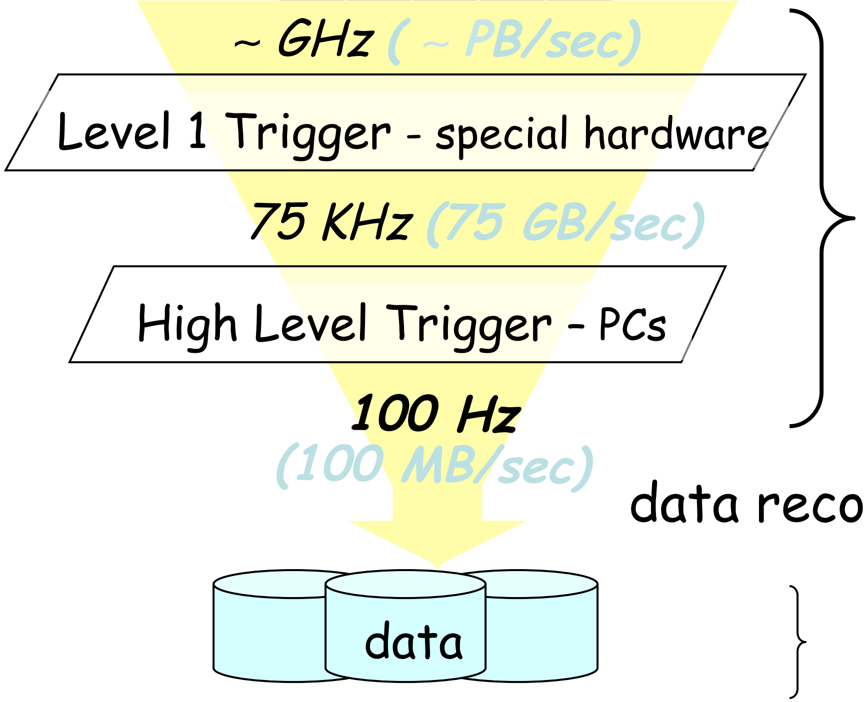
- **Custom ASICs**
- **Large FPGAs**
- **SRAM**
- **Gbit/s Optical links**
- **Dense boards**

CMS Trigger and Data Acquisition

Bunch crossing
40 MHz



1 event is ~ 1MB in size



~ GHz (~ PB/sec)

Level 1 Trigger - special hardware

75 KHz (75 GB/sec)

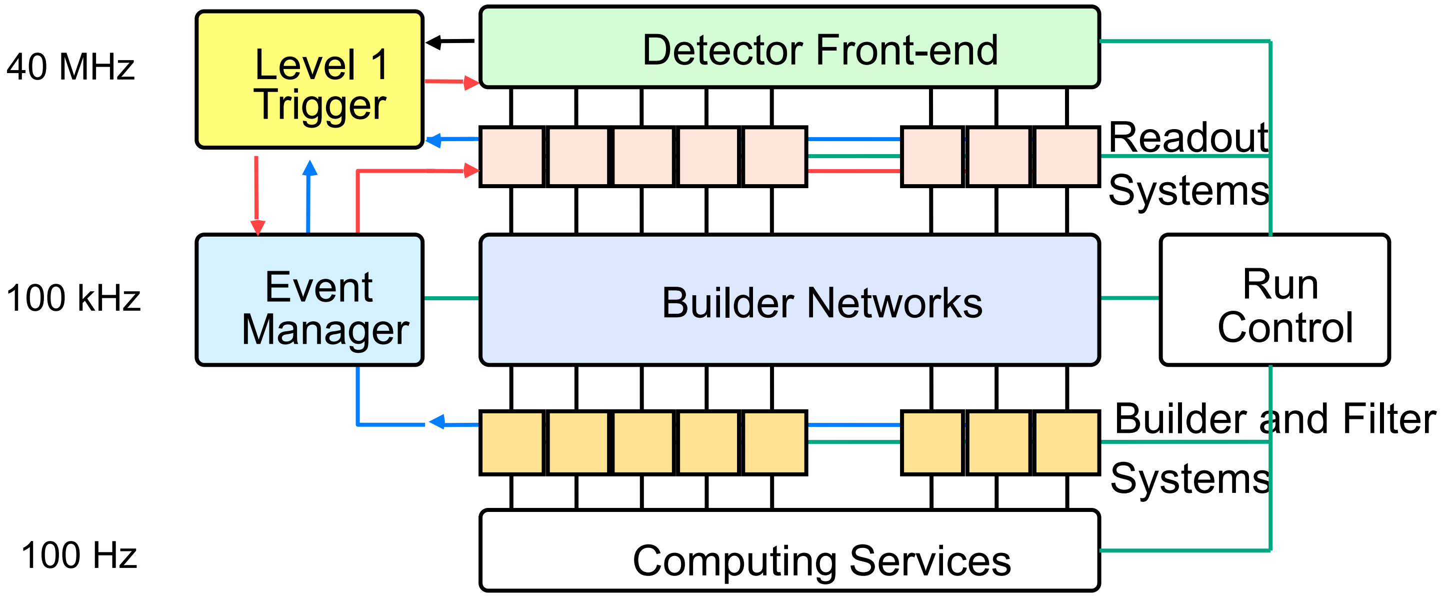
High Level Trigger - PCs

100 Hz
(100 MB/sec)

data recording

Offline analysis

Challenge of CMS DAQ



Large Data Volumes **(~100 Gbytes/s data flow, 20TB/day)**

- After Level 1 Trigger ~100 Gbytes/s (rate ~O(100) kHz) reach the event building **(2 stages, ~1600 computers).**
- HLT filter cluster select 1 out 1000. Max. rate to tape: ~O(100) Hz
  - ⇒ **The storage manager (stores and forwards) can sustain a 2GB/s traffic.**
  - ⇒ **Up to ~300 Mbytes/s sustained forwarded to the CERN T0. (>20TB/day).**

Object Reconstruction

How Can We Design a Detector?

- Heavy objects decay into “lighter objects”, which **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, the quarks and gluons, reveal themselves as collimated bursts of particles called “jets” so identifying and classifying jets and measuring their angles and energy is important
    - W’s, Z’s, top quarks, τ leptons, b and charm jets, while “fundamental,” in the SM, are unstable objects seen through decays into the lighter objects
  - Particles may leave the detector without interacting
    - Neutrinos are known SM particles that do that all the time
    - There may be NEW , possibly massive, weakly interacting particles that behave similarly
    - **These can be “detected” by observing missing transverse energy , a.k.a. “MET”,**

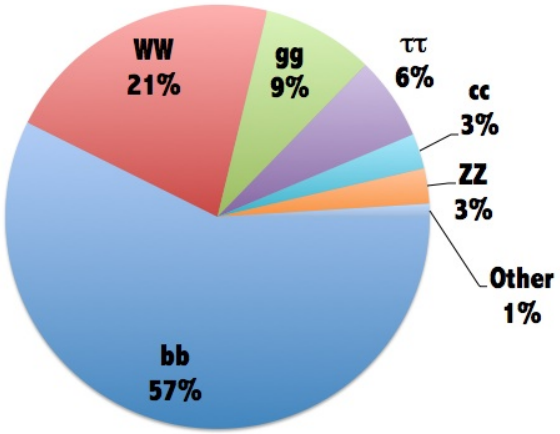
The Detector/Analysis Problem

- A “discovery” detector should be able to find and reconstruct all the objects of the SM and MET over as large a range of momenta and angles as possible to achieve the highest sensitivity to new particles/objects with masses from a few tens of GeV to very high mass (few TeV)
- Signals for new physics will emerge from
  - Combinations of these objects (mass bump or “excess” above background in some distribution)
  - New objects that are different from the “normal” ones
- Backgrounds come from similar combinations due to known physics, random combinations of objects, or either of the above with various misidentified objects due to detector limitations

Example: Our New Boson

- Search motivated by SM predictions for a “light Higgs”
  - The final states where the signal is seen have the rate expected for the decay modes of the “light Higgs”, which are predicted by the SM
  - They were seen in the “high resolution”, low rate, modes so far
- But in order for it to be “the Standard Model Higgs” , all the branching fractions must agree with predictions so **all the capabilities needed for the Higgs search will be needed also into the indefinite future (relevant to upgrades) to reach high precision in all modes**

Higgs decays at m_H=125GeV



- bb difficult due to large QCD dijet **background**
- WW and ττ have missing neutrinos→ poor mass resolution, but much progress
- ZZ and γγ will have best mass measurements

Physics Objects, e.g. SUSY

- **Search for top-squark pair production in the single-lepton final state in pp collisions at $\sqrt{s}$ = 8 TeV** single isolated electron or muon, jets, large missing transverse momentum, and large transverse mass.
- **Search for top squarks in R-parity-violating supersymmetry using three or more leptons and b-tagged jets**
- **Search for gluino mediated bottom- and top-squark production in multijet final states in pp collisions at 8 TeV large missing transverse energy, no isolated electron or muon, and at least three jets, with one or more identified as a bottom-quark jet.**
- **Search for physics beyond the standard model in events with *τ* leptons, jets, and large transverse momentum imbalance in pp collisions at *s*√= 7 TeV** one or more hadronically decaying tau leptons, highly energetic jets, and large transverse momentum imbalance.
- **Search for new physics in events with photons, jets, and missing transverse energy in pp collisions at *s*√ = 7 TeV**

Transverse Momentum

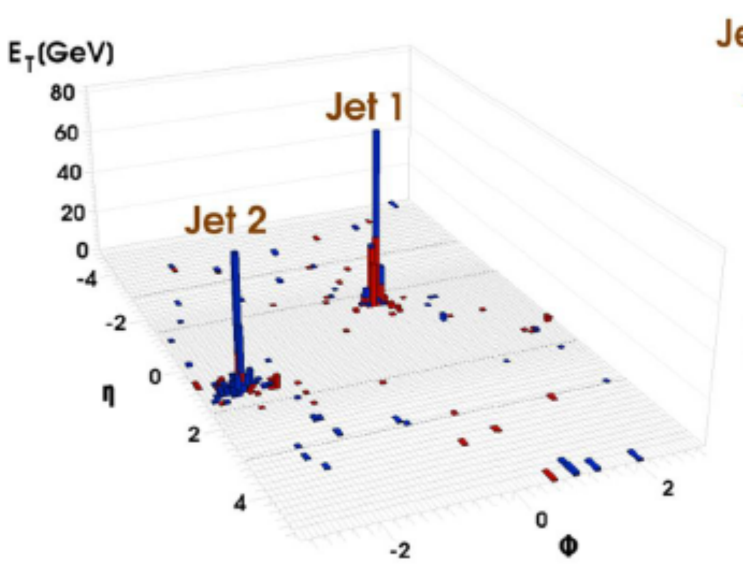
- There is little transverse momentum in the initial state of the protons
- Transverse momentum in the final state comes from
  - **The hard scattering process or**
  - **The decay of some heavy object made by the collision**
- **Transverse momentum is also invariant to a longitudinal boost**

Detector should measure well P_T, η (polar angle), ϕ (azimuthal angle)

How well do we have to measure **P_T**? Suppose an extreme case- a 2 TeV object decaying into two particles ($Z' \rightarrow \mu^+\mu^-$), then, P_T~1TeV/c x sin θ
Suppose we want P_T to ~10% in this extreme case

If $\sigma_{r\phi}$~ 50-100 μm, BL^2 must be around 3-4 T-m^2
For a tracker of 1m radius, you want a field of ~4T

Jet 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 in event

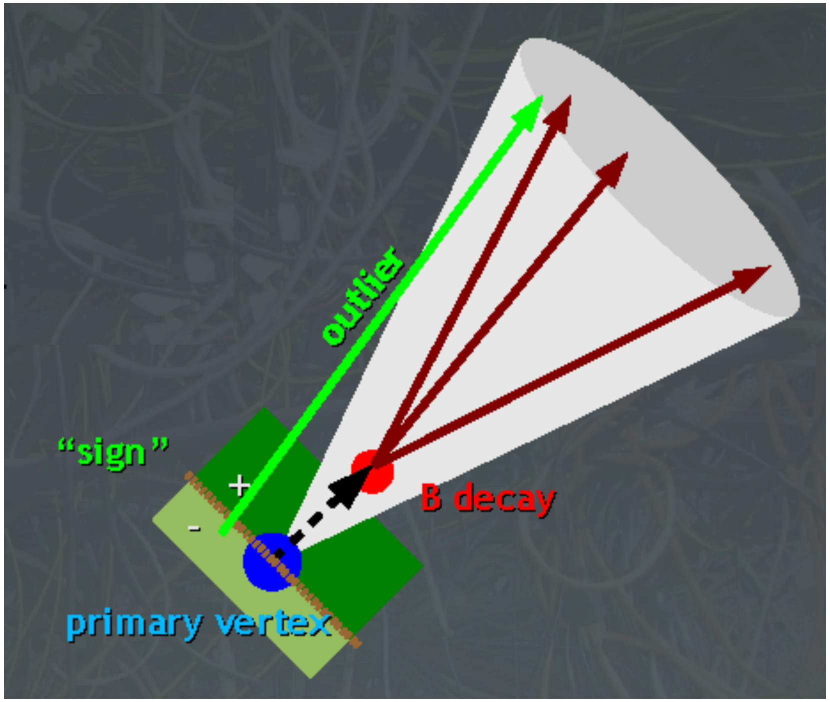
MET is the negative the vector sum of all the transverse components of observed energy including any muons. It Indicates the presence of weakly interacting particles, usually neutrinos, but possibly new exotic objects that interact only weakly.

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, weighted by their small angles. will not contribute much to the missing transverse energy

b-jet

Discriminants of b jets from light quark or gluon jets based on

- Long lifetime of b-hadrons in them
  - τ= 1.512 x 10^{-12} s, cτ = 455.4 μm
- High masses
- High fraction of semi-leptonic decays
  - ~10% e, μ (and from charm)
-



- **Methods for discrimination**
  - Impact parameter based
    - Track counting high efficiency
    - Track counting high purity
    - Jet probability
    - Jet B probability
  - Secondary vertices
    - Simple secondary vertex
    - Combined secondary vertex
  - Lepton based algorithms
    - Soft muon by $P_T$rel
    - Soft muon by IP significance
    - Soft electron
  - Combined algorithm
    - Combined MVA

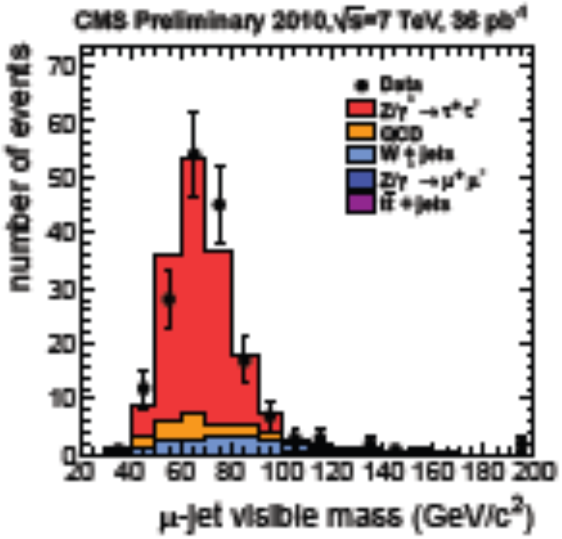
Tau (1)

- Tau leptons decay into
  - a charged lepton (μ or e) and its corresponding antineutrino; or
  - A tau neutrino and a hadronic state, which then typically decays into charged and neutral pions and kaons of relatively low multiplicity, sometimes with observable resonance behavior in the invariant mass of the hadrons
  - Isolated small clusters of hadrons at large P_T are tau letpon candidates and can be distinguished from gluon or quark jets which typically have much higher multiplicity
  - If the taus are produced in the signal in pairs the topology (e or μ) + hadrons is a powerful signature of the tau pair
  - The event topology also features
    - missing E_T from the neutrinos and
    - charged tracks which might have an observable impact parameter (useful? Not yet in CMS, but being worked on)

Tau (2)

- Tau lepton decay modes with hadrons in CMS. “h” can be either a pion or kaon. The collection of modes is called τ_h. A tau pair consists of
  - one leptonic decay into either electron or muon and neutrinos and one hadronic decay is called $e\,\tau_h$ or $\mu\,\tau_h$, respectively.
  - two leptonic decays resulting in the $e\mu$ final state

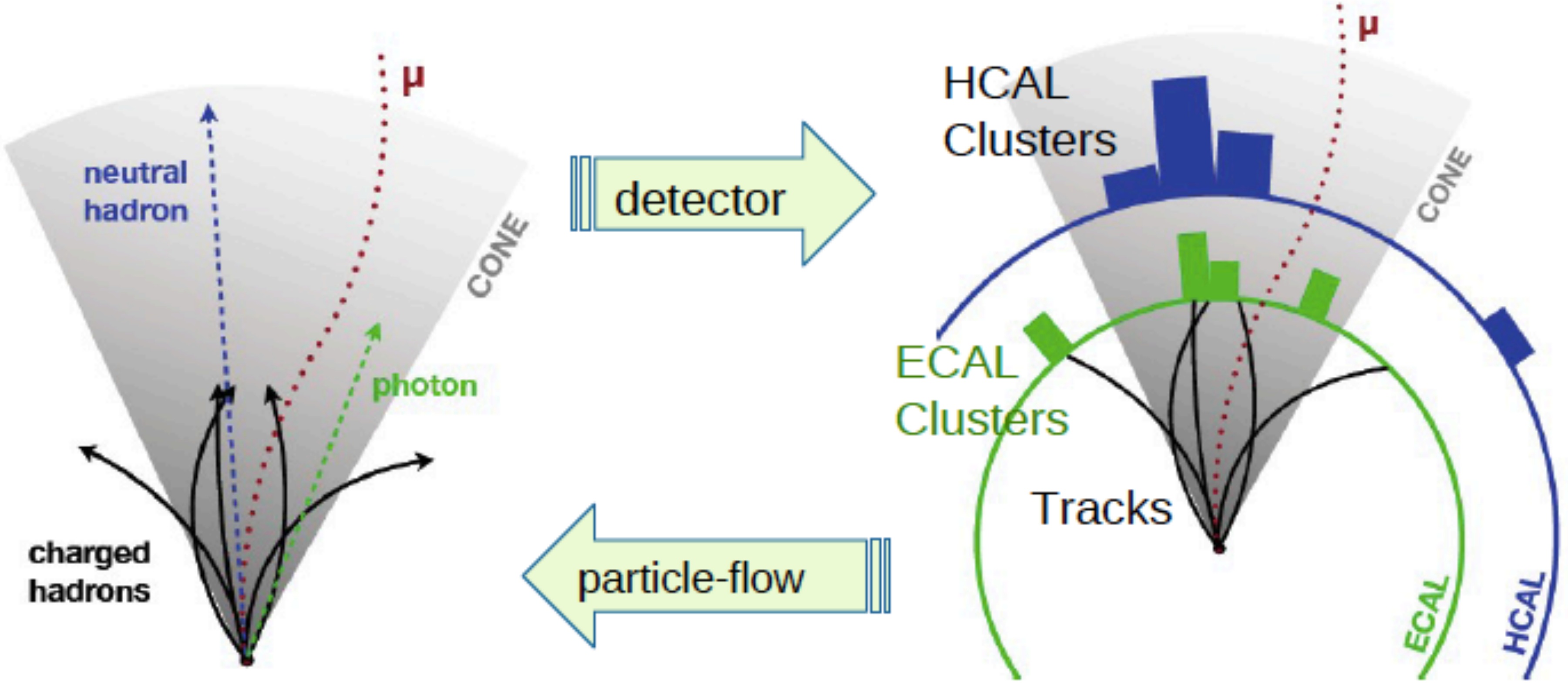
Decay mode	**Reson-ance**	**Mass (MeV/c^2)**	Branching Fraction (%)
$\tau^- \to h^- \nu_\tau$			11.6
$\tau^- \to h^- \pi^0 \nu_\tau$	ρ^-	770	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	a_1^-	1200	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	a_1^-	1200	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$			4.8



- Tau leptons are being used successfully as objects in the search for the SM model Higgs and for MSSM Higgs where their production would be enhanced
- Higgs→ $\tau^+\tau^-$ is the “easiest” measurement of its coupling to leptons

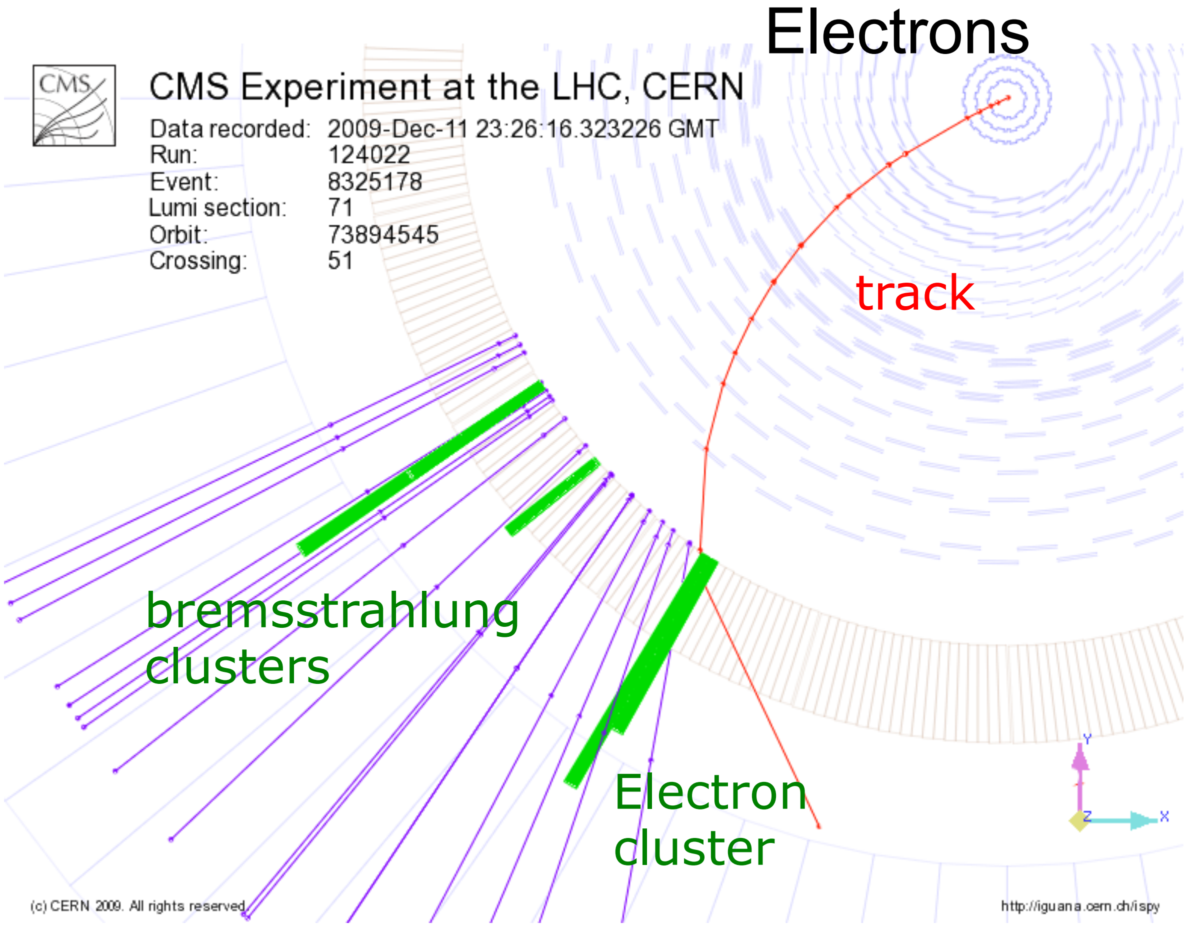
Overview: Particle Flow Algorithm

- The list of individual particles is used to build jets, to determine the MET, to reconstruction and identify taus from their decay products, to tag b-jets



Electron (1)

- Electrons radiate their energy in Bremsstrahlung photons.
- Photons convert in electron/positron pairs

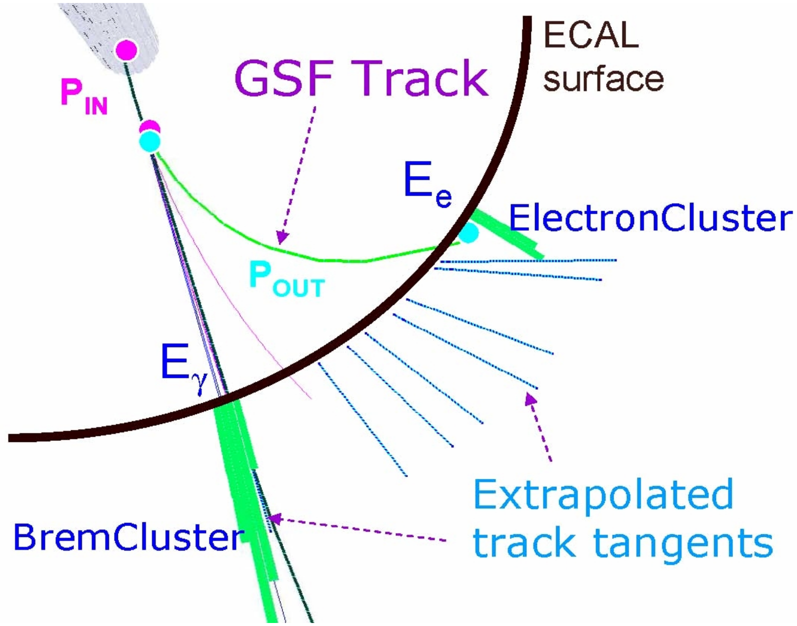

Electrons

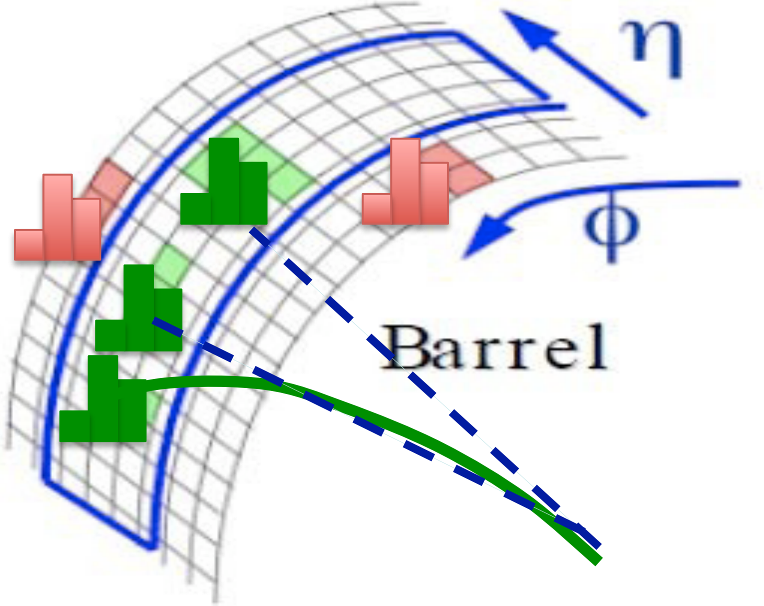
track

bremsstrahlung clusters

Electron cluster

Electron (2)





Properties of the electron tracking:
$P_{OUT}<P_{IN}$:
fbrem= $P_{IN}-P_{OUT}/P_{IN}$

… Pure tracking

Properties of the ECAL cluster-shapes:
η-width
ϕ-width

… Pure ECAL

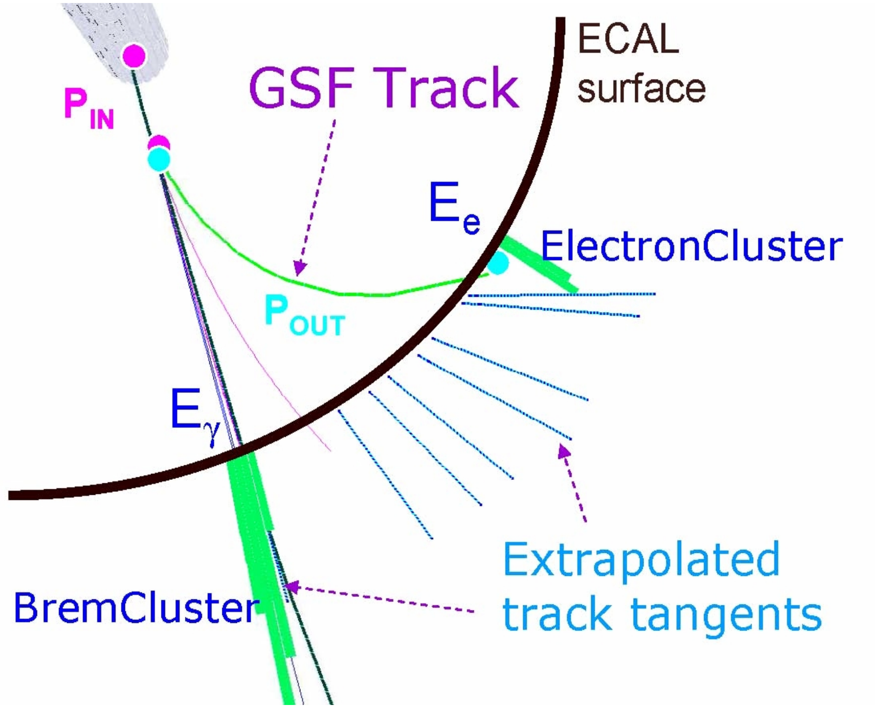
Matching between sub-detector:

1. energy matching
   - E_{TOT}/P_{IN}, E_{ele}/P_{OUT}
2. geometrical matching
   - $\Delta\eta_{IN}$, $\Delta\phi_{IN}$

…

Track-ECAL matching

Typical Variables used in Electron ID



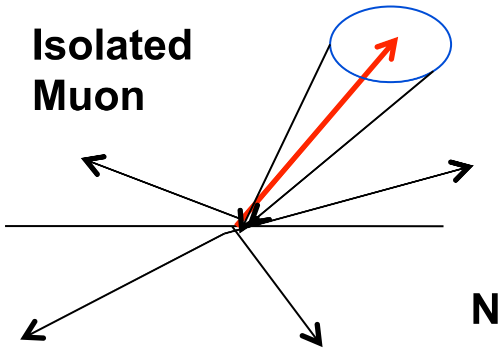
- ➢ Combining several variables is the typical optimization to be performed with a multivariate analysis (MVA).

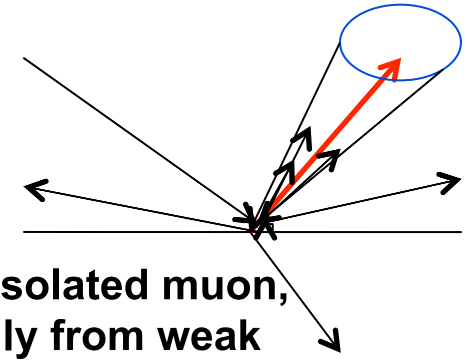
- ❖ Pure tracking observables
  1. P_{IN}-P_{OUT}/P_{IN} (GSF) = fbrem
  2. # hits KF
  3. χ^2 KF
  4. χ^2 GSF
- ❖ Pure ECAL observables
  1. Cluster shape in η direction $\sigma_{\iota\eta\iota\eta}$
  2. Cluster shape in ϕ direction $\sigma_{\iota\phi\iota\phi}$
  3. Cluster shape for circularity (E_{5x5}-E_{5x1})/E_{5x5}
  4. Cluster width in η
  5. Cluster width in ϕ
  6. R9
- ❖ Track-ECAL-HCAL-ES matching observables
  1. E_{Tot}/ P_{IN}
  2. E_{Ele}/ P_{OUT}
  3. $\Delta\eta_{OUT}$ (GsfTrackAtECAL-EleClus)
  4. $\Delta\eta_{IN}$ (GsfTrackAtVertex-Superclus)
  5. $\Delta\phi_{IN}$ (GsfTrackAtVertex-Superclus)
  6. H/E
  7. ES/E(Raw)
  8. 1/E – 1/p (p combination of gsfmean

Isolation

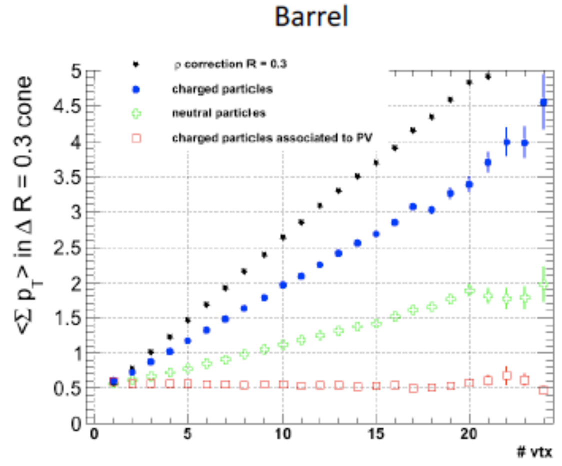
- Since hard processes produce large angles between the final state partons and the beam remnant jets stay close to the beam line, the objects we are interested in for our studies are usually well separated or **“isolated”** from other objects in the event
- Isolation is applied by drawing a cone around the object of interest in $\eta-\phi$ space; adding up the extra E_T in the cone (exclusive of the E_T of the candidate); and rejecting the object if the “extra E_T” is more than a certain fraction of the E_T of the candidate
- Example of isolation: discriminating an isolated muon from a W from a muon coming from the semileptonic decay inside a b-jet

Isolated Muon





Non-Isolated muon, usually from weak decay inside a jet

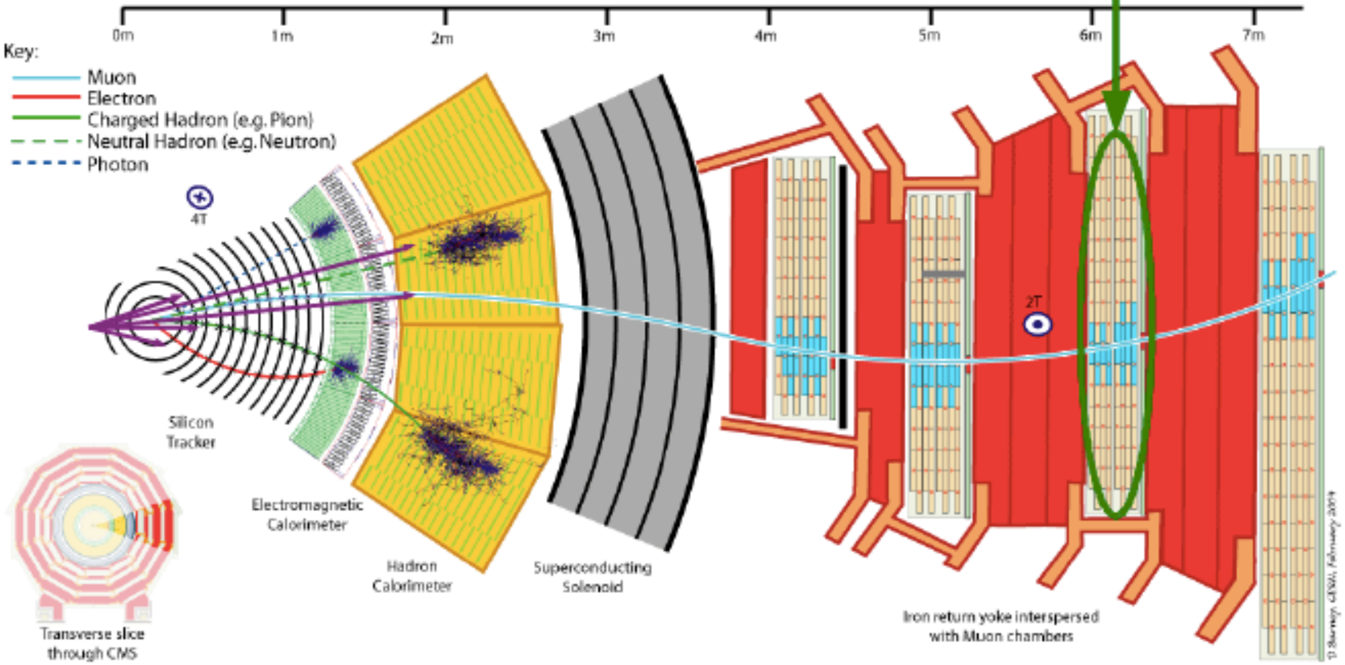


Impact of pileup on isolation

Overview of Muon Reconstruction

The muon reconstruction is divided into **three steps**

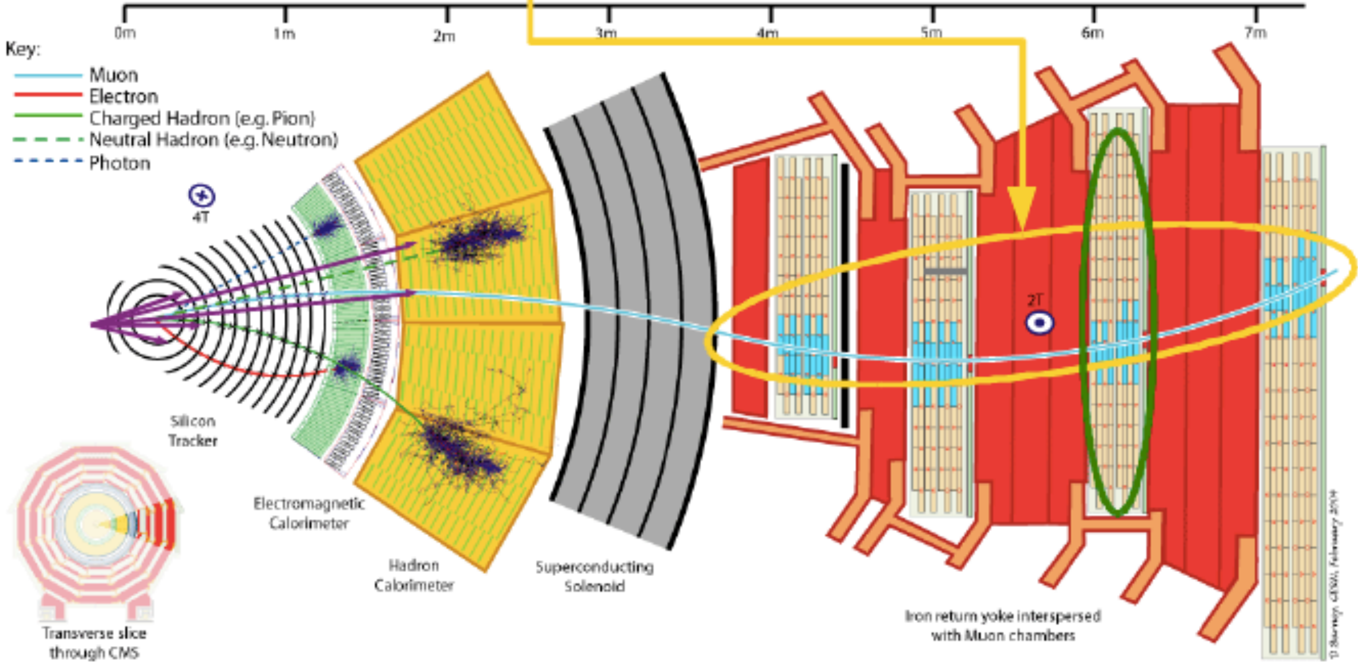
① Reconstruction of the **hits** and the **track segments** inside a chamber.



Overview of Muon Reconstruction

The muon reconstruction is divided into **three steps**

② Reconstruction of the **track** inside the **muon system**

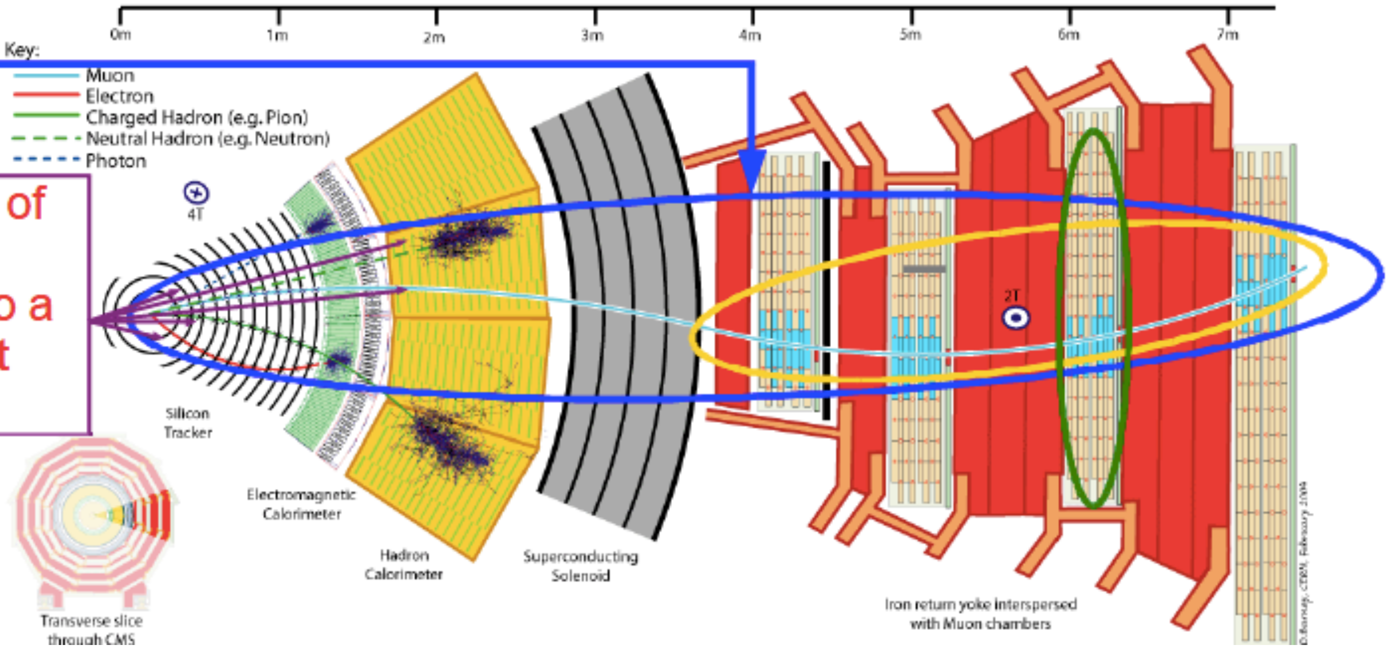


Overview of Muon Reconstruction

The muon reconstruction is divided into **three steps**

③ Combination of the information from the **tracker** *and* **the muon system** together

④ Interpretation of the muon candidate into a **Global Event Description**



Muon sources in pp collisions

Prompt muons
- Real muons (i.e. from boson decay)
- *Signature:* hits in tracker + hits in muon system + MIP deposit in calorimeter

Silicon volume decay
- Real muons from b/c decays (usually in jets) (=”muons from heavy flavour”)
- *Signature:* hits in tracker + hits in muon system + MIP deposit in calorimeter + not coming from the interaction point + non-isolated

- Real muons from kaon or pion (semilaptonic decay) (=”muons from light flavour”)
- *Signature:* hits in tracker + hits in muon system + MIP deposit in calorimeter + silicon/muon track segments could be “kinked”

Punch-through
- Fake muons (hits in the detector not made my muon but by some other particles)

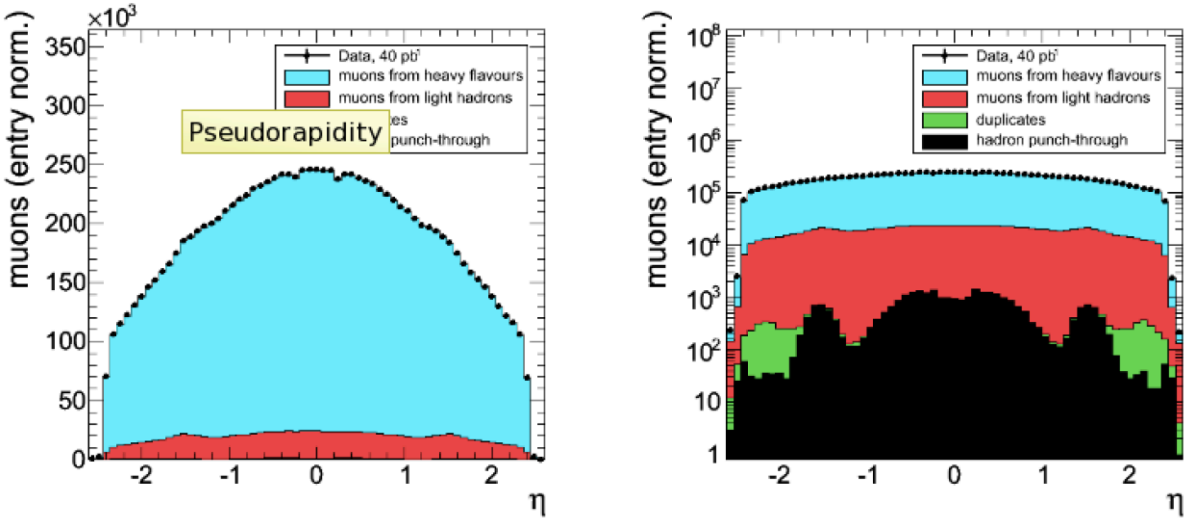
- Hadronic shower extending through muon system
- *Signature:* hits in tracker + hits in muon system (short track) + large disagreement in the momentum in tracker and muon system

- Non-muon that travels through the muon system
- *Signature:* hits in tracker + hits in muon system + non-MIP deposit in calorimeter + large disagreement in the momentum in tracker and muon system

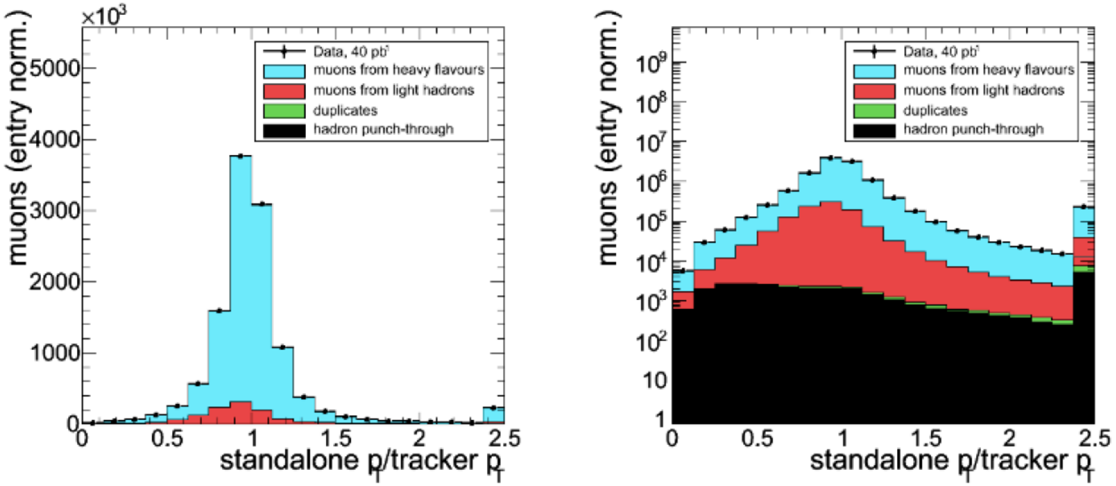
Calorimeter volume decay
- Real muons (coming from pion decay inside the CAL)
- *Signature:* hits in muon system + non-MIP deposit in calorimeter

Muons in Distributions (1)

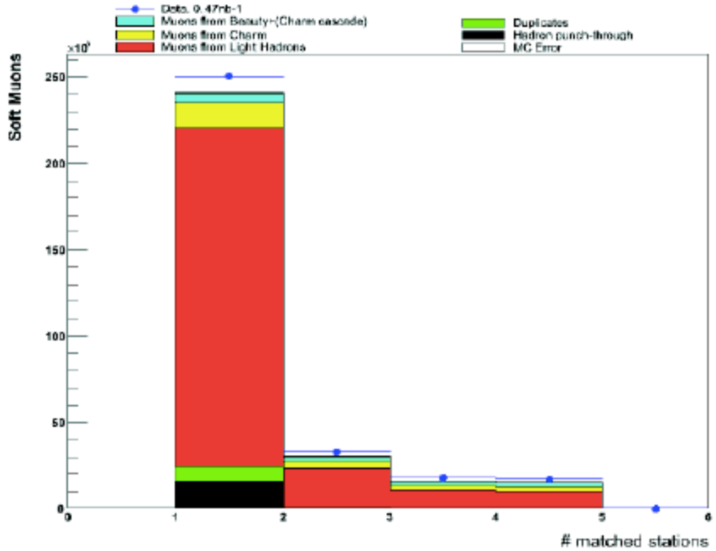
Pseudorapidity

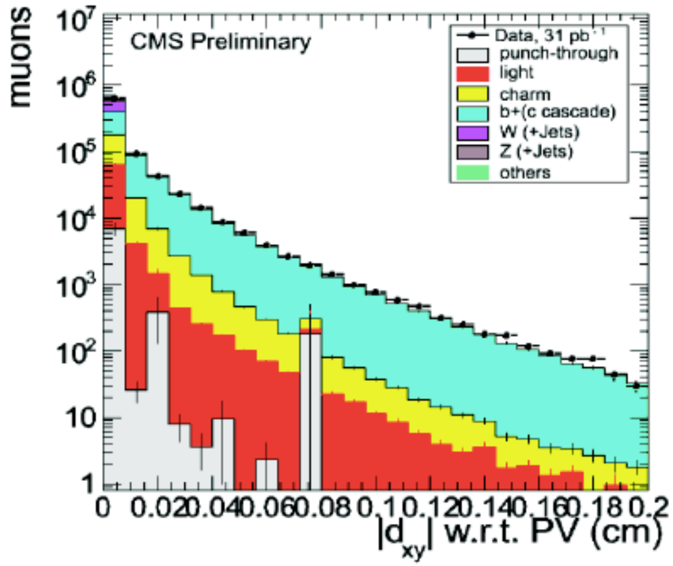


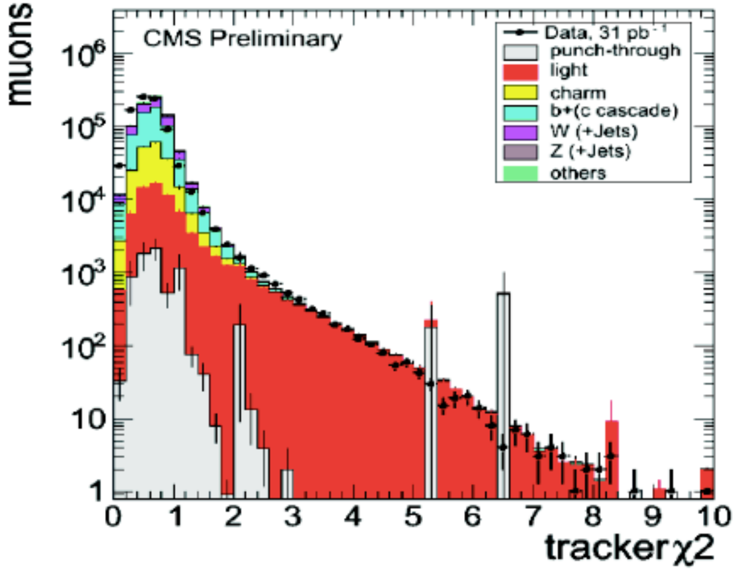
Ratio between standalone and tracker p_T

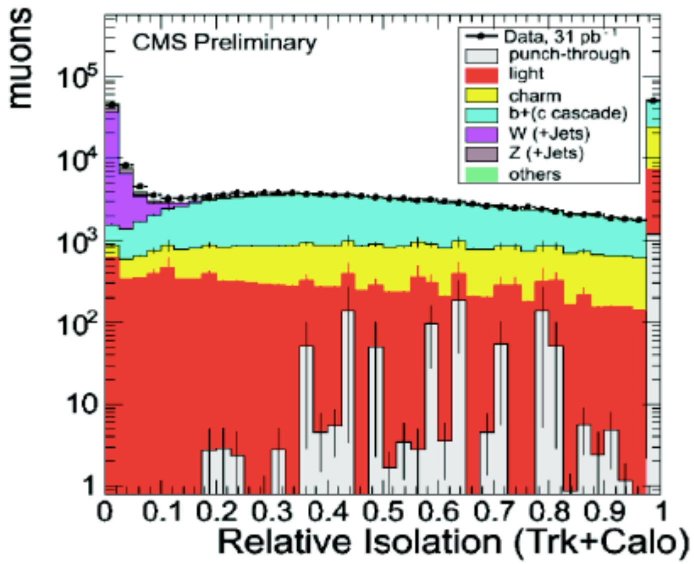


Muons in Distributions (2)









Standalone (STA) Muon

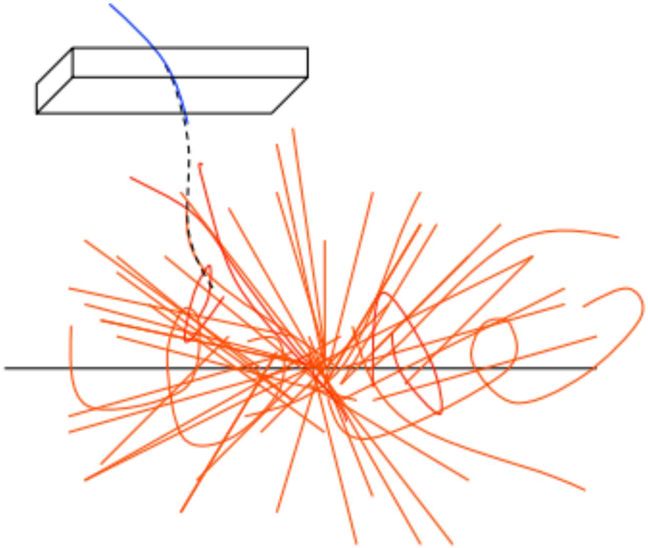
- "Local Reco" in each muon chamber separately
  - DT and CSC up to segments, RPC 2D hits
- "Seed" state estimation
  - From the local segments reconstruction for the offline reconstruction
  - From the L1 trigger in the online reconstruction
- Filtering
  - Propagation of the state to the next compatible layer of chamber
  - Looking for the measurements (segments/hit)
    - Pattern recongnition: choose of the most compatible (on chi2 basis)
    - Updating (filtering) of the state vector with the measurement if passes the chi2 cut
- Ghost suppression
- Extrapolation to the PCA and updating at vertex
  - Update of the track parameters
- Requirement for a track: two measurements (one from DT or CSC)

TK+Muon Reconstruction & ID

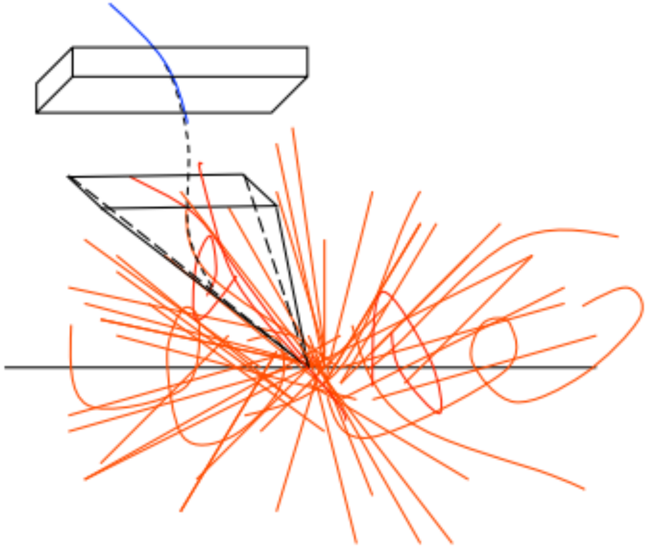
- Two complementary strategies: “Global Muon” (GLB) and “Tracker Muon” (TRK)
- GLB muon: the two track types (tracker, STA) are matched together using several compatibility variables (such as chi2, distance on a plan, dR)
  - A fit of all hits is performed to obtain a track crossing the whole CMS
- TRK muon: the tracker tracks are extrapolated in the muon system and compatible segments (on Pull(x) basis) are associated to them
  - No need to fit a track through a non-uniform magnetic field, accounting for large multiple scatteringand dE/dx
- The response from the two algorithms is then combined in a unique object that merge the information together, providing a coherent veiw of the muon candidate
  - Energy deposits in the calorimeters gets also associated, as such as isolation and ID variables are computed for a later usage in the analyses

Global Muons in a Sketch

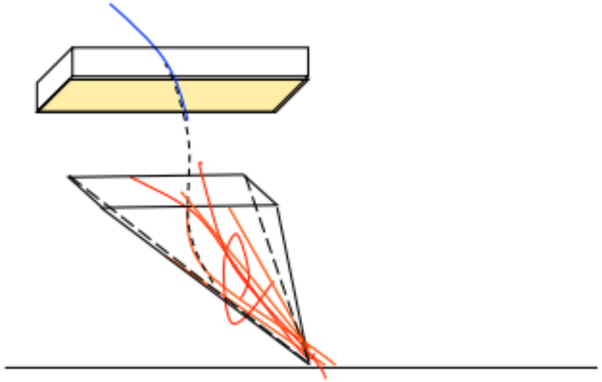
(1) Find StandAlone Muon



(2) Build a region of interest

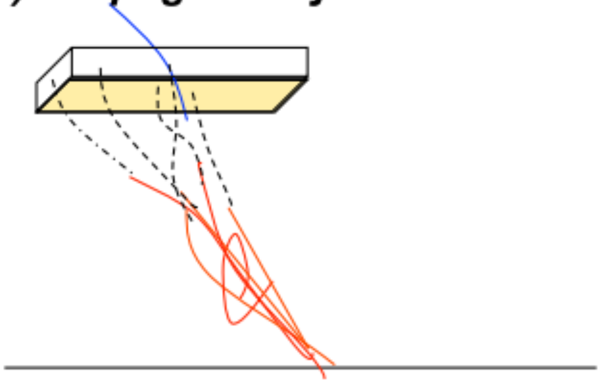


(3) Chose a common surface



(5) Compare parameters

(4) Propagate trajectories to surface

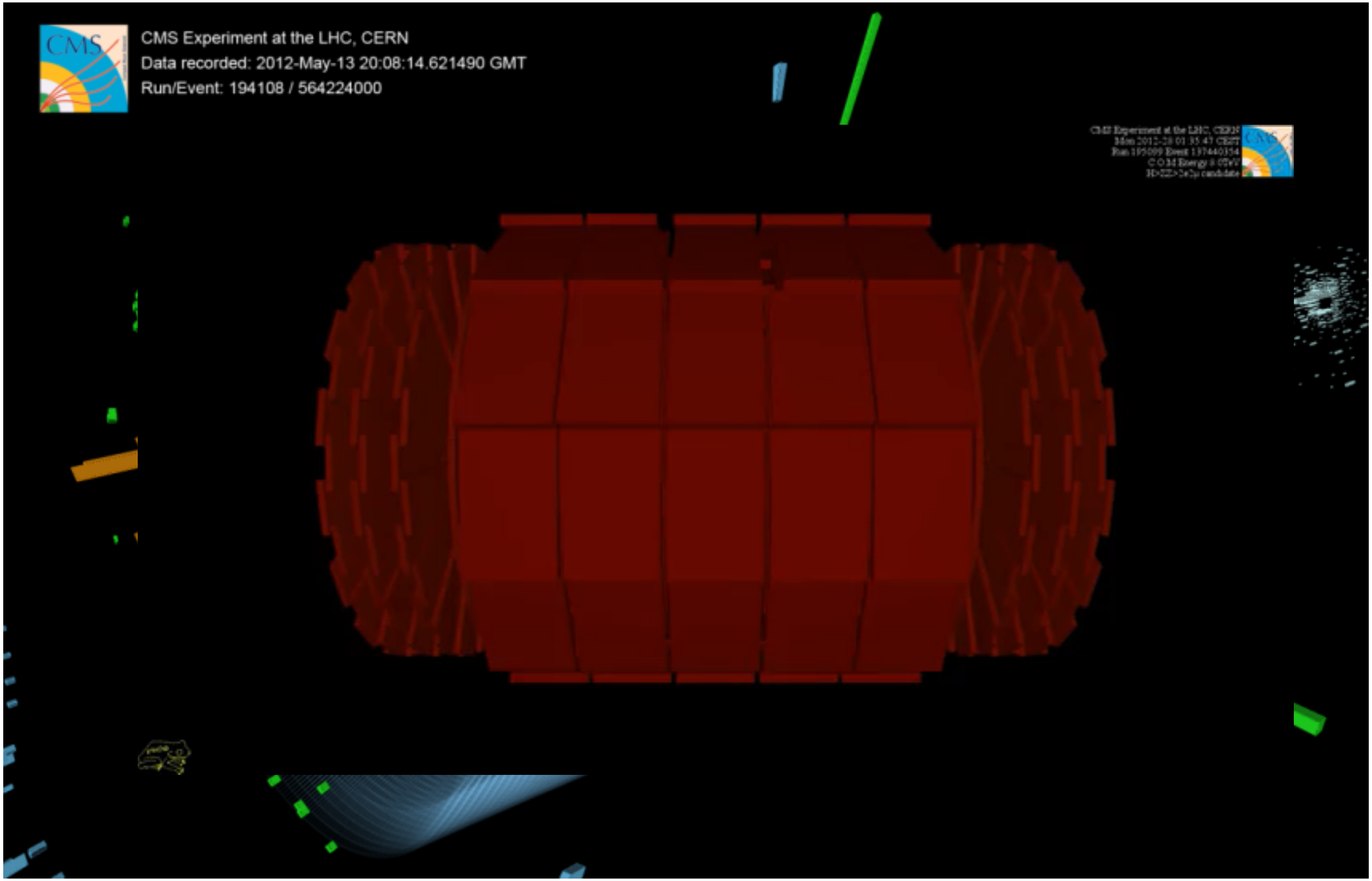


(6) Arbitration
-in case of more than 1 match

GLB Muon Refit

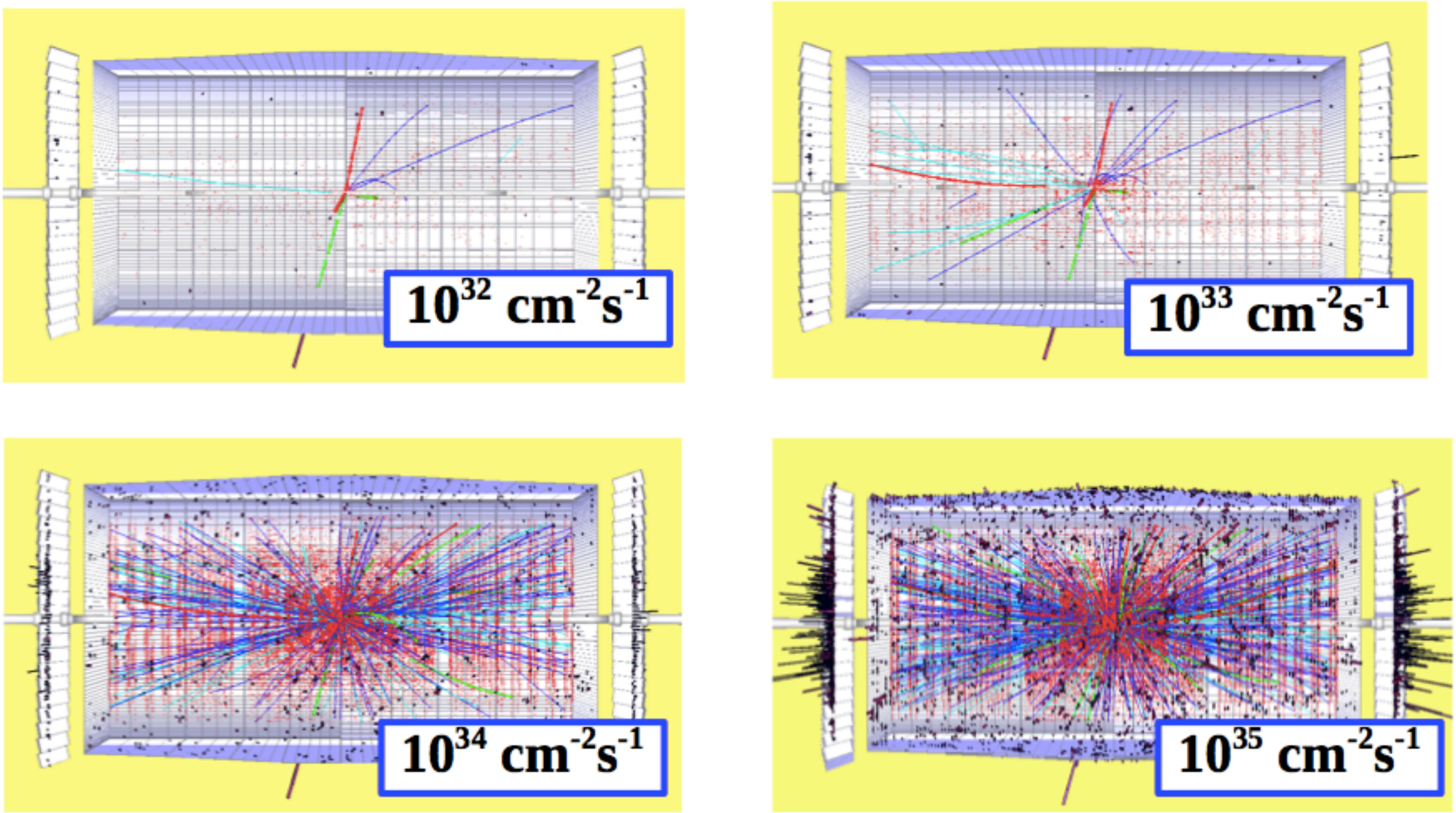
- After the muon track matching a complete track fit is performed for all compatible combinations
  - Fitting: inside-out
  - Smoothing: outside-in
  - Chi2 of global fit to decide on best match
- Finally the track parameters with their covariance matrix at innermost measurement is provided
  - Definite pt, eta, phi of muon
- The inclusion of all position measurements provided by the detector does not necessarily result in the best possible parameter estimation

Collision Data

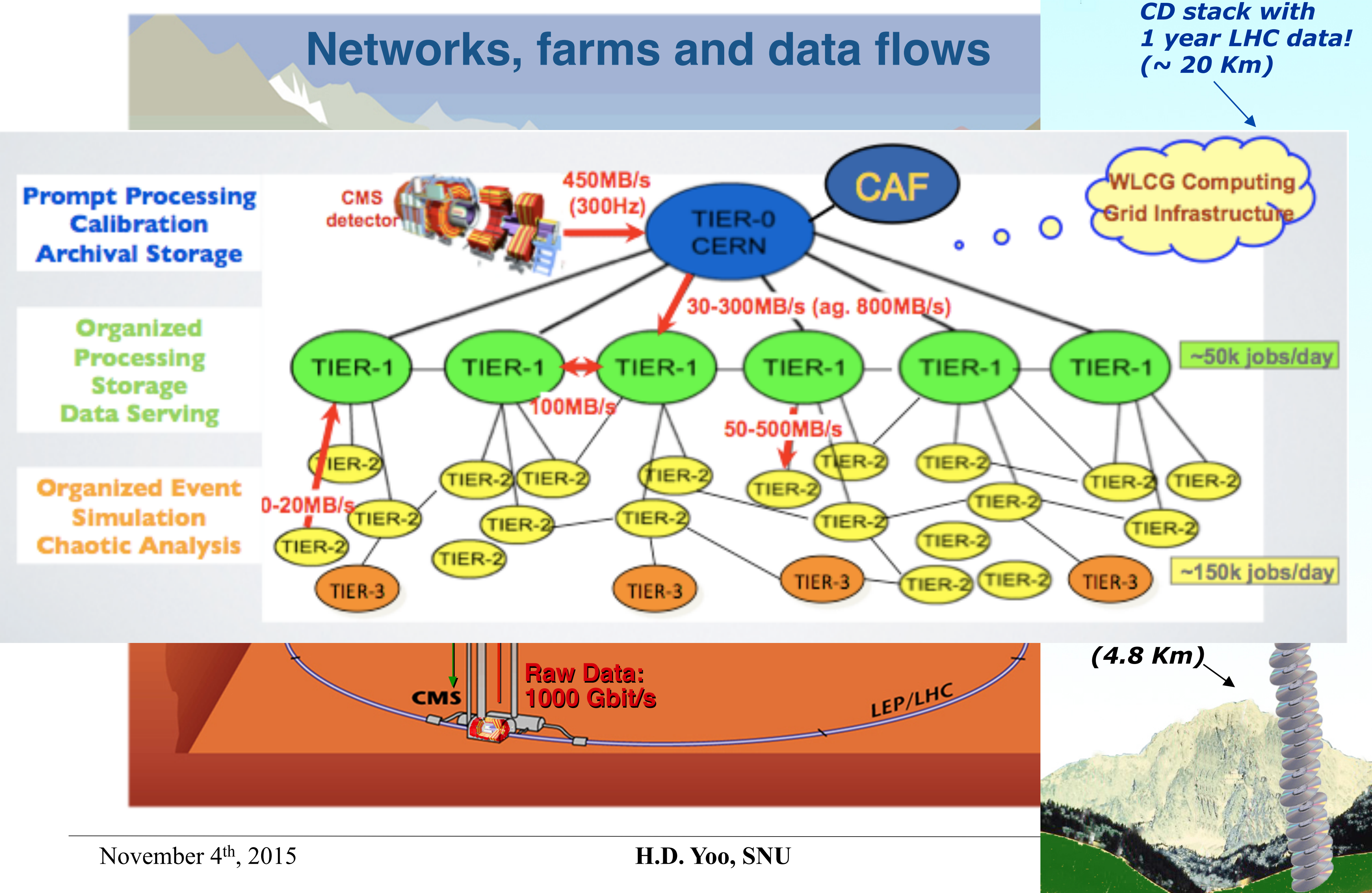


Pile Up

CMS Simulation: 300 GeV H→ZZ→eeμμ at various instantaneous luminosities



On the Tape (Grid)



Networks, farms and data flows

Playing in Particle Physics

Skills of an Exp. Particle Physicist

DATA ANALYSIS

Statistical Interpretation
Development of Methods
Data Mining

GENERAL

Problem Solving
Flexibility
Strong Motivation

INSTRUMENTATION

System Engineering
R&D and Prototyping
Assembly and Operation

COMPUTING

Data Management
Big Data
Grid and CLOUD

PARTICLE PHYSICS

In-depth Knowledge
Quantum Physics
Theoretical Calculations

COLLABORATION

Constructive Competition
International
Peer-Review system

SOFTWARE

Numerical Techniques
Algorithm Development
Multithreading
Parallel Computing

ELECTRONICS

Data Acquisition
Detector Front-End
Circuit Board Design

MANAGEMENT

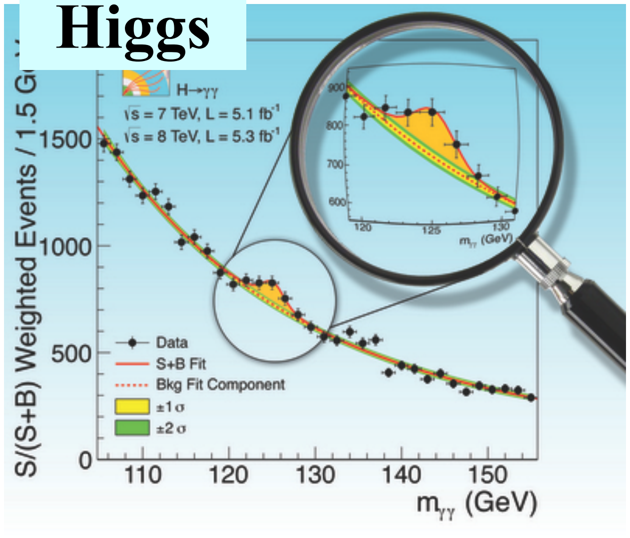
Supervision & Training
Strategic Planning
Crisis Management

COMMUNICATION

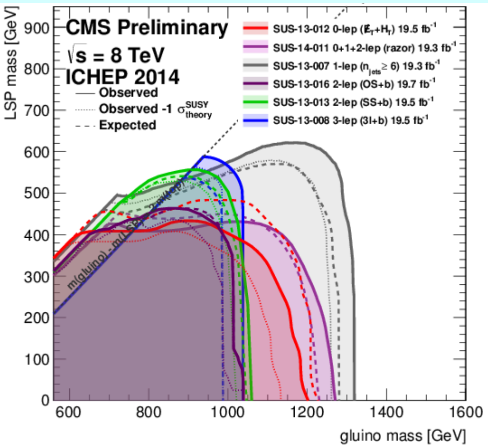
Teaching
Oral and Written
Defending Case

Physics at CMS

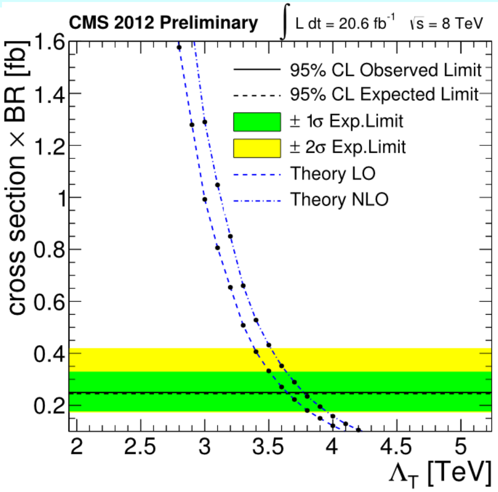
Higgs



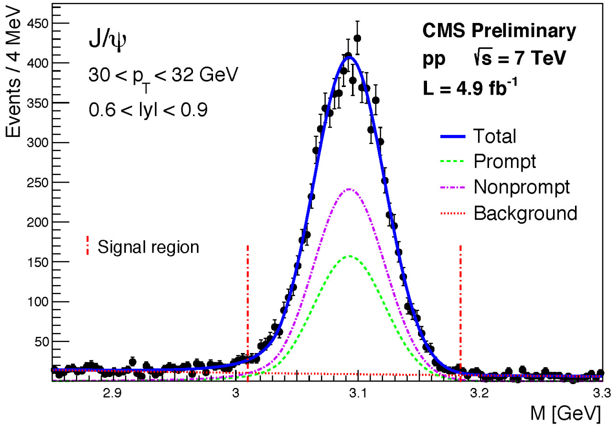
SuperSymmetry?



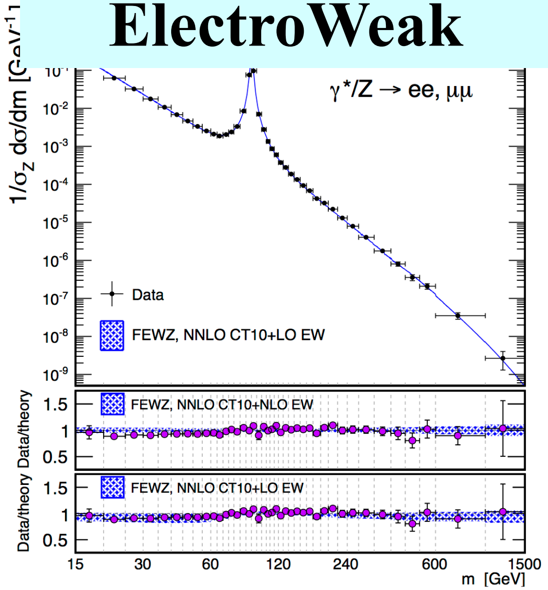
Extra Dimension?



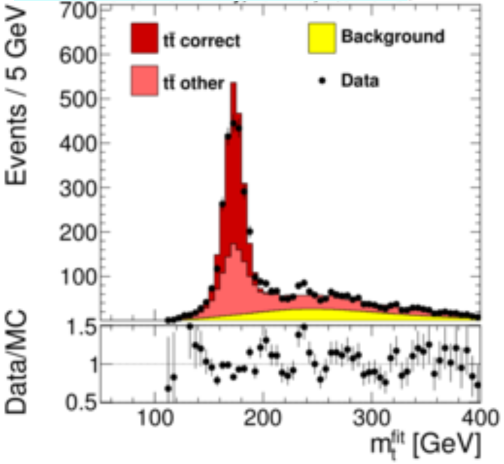
B-physics



ElectroWeak



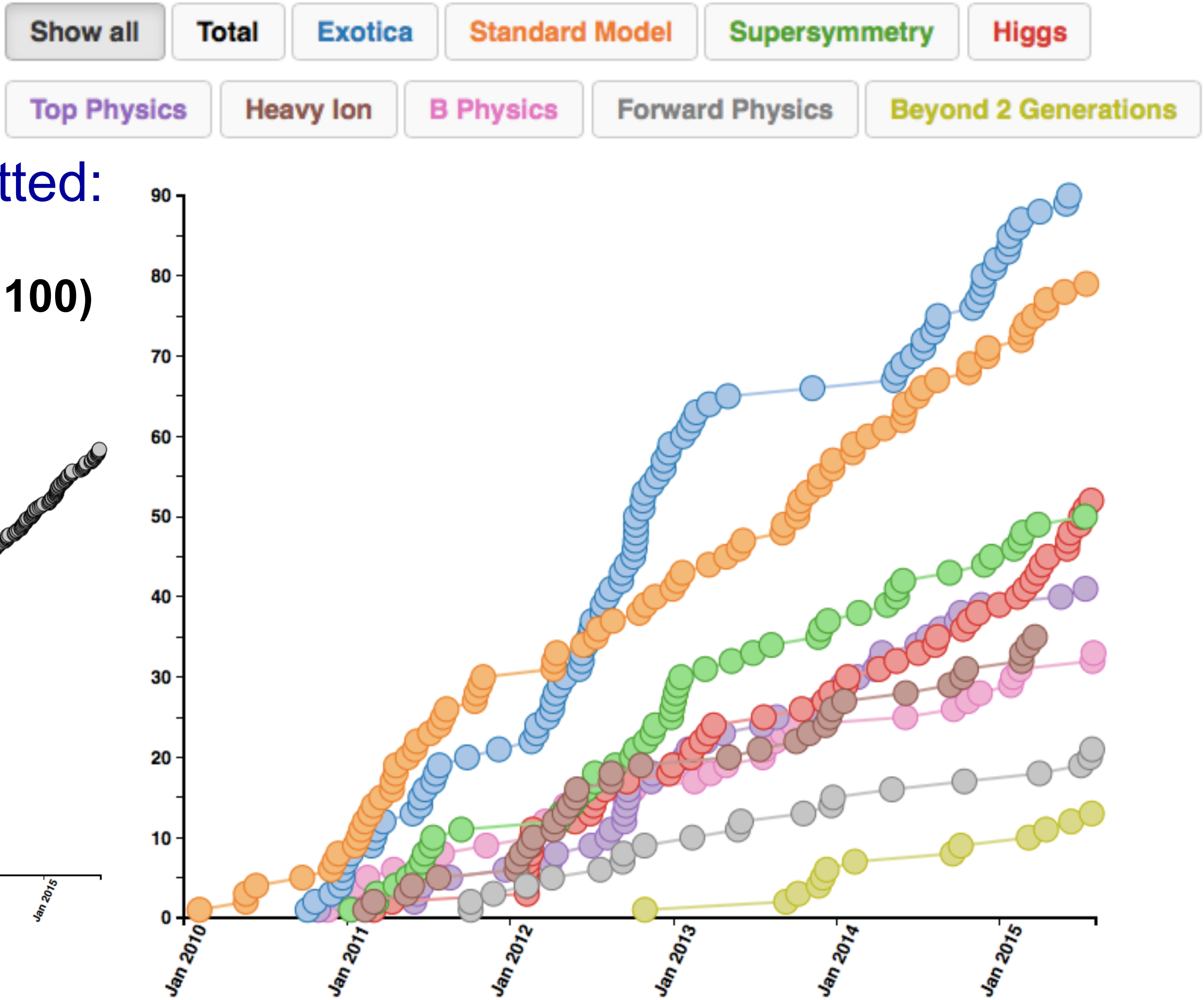
Top physics

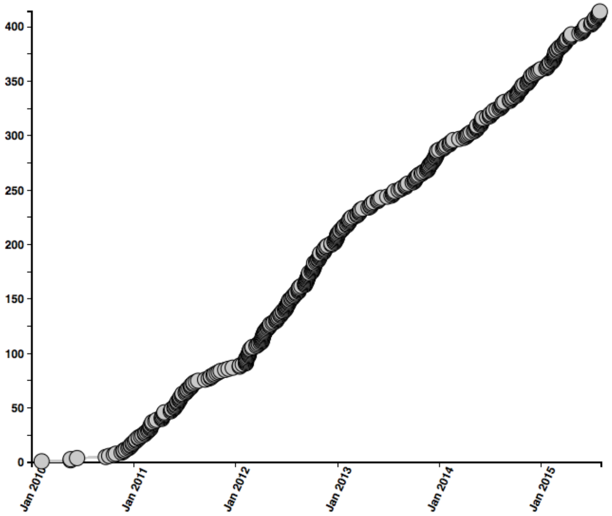


Run I Publication

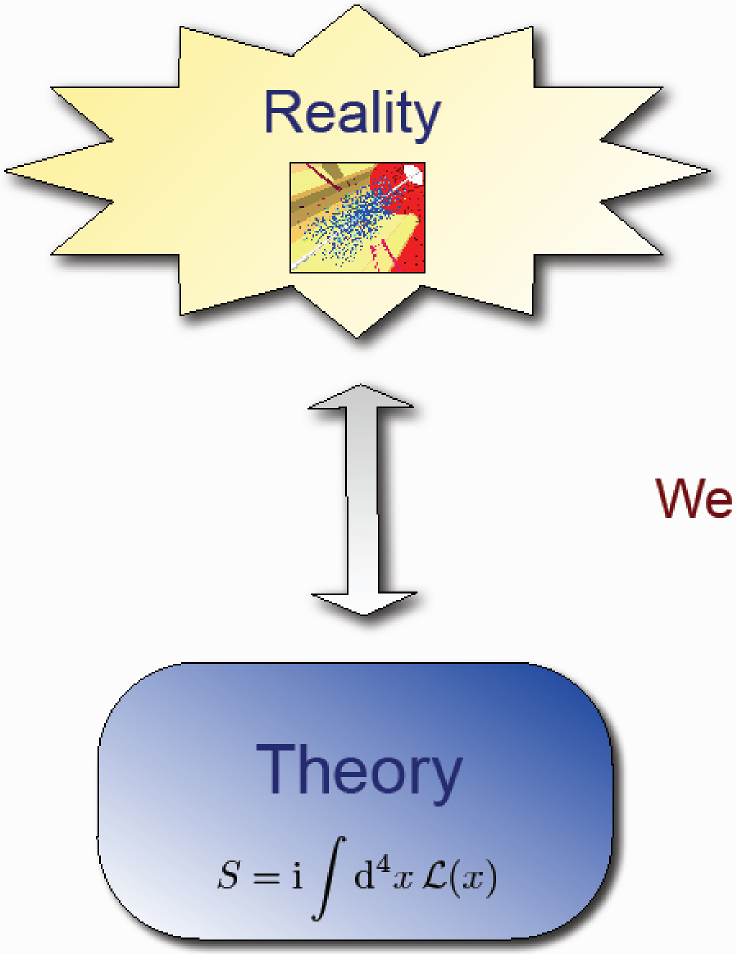
413 papers submitted:

In review process (> 100)





Our Task



Reality

Theory

$$S = \mathrm{i}\int \mathrm{d}^4x\,\mathcal{L}(x)$$

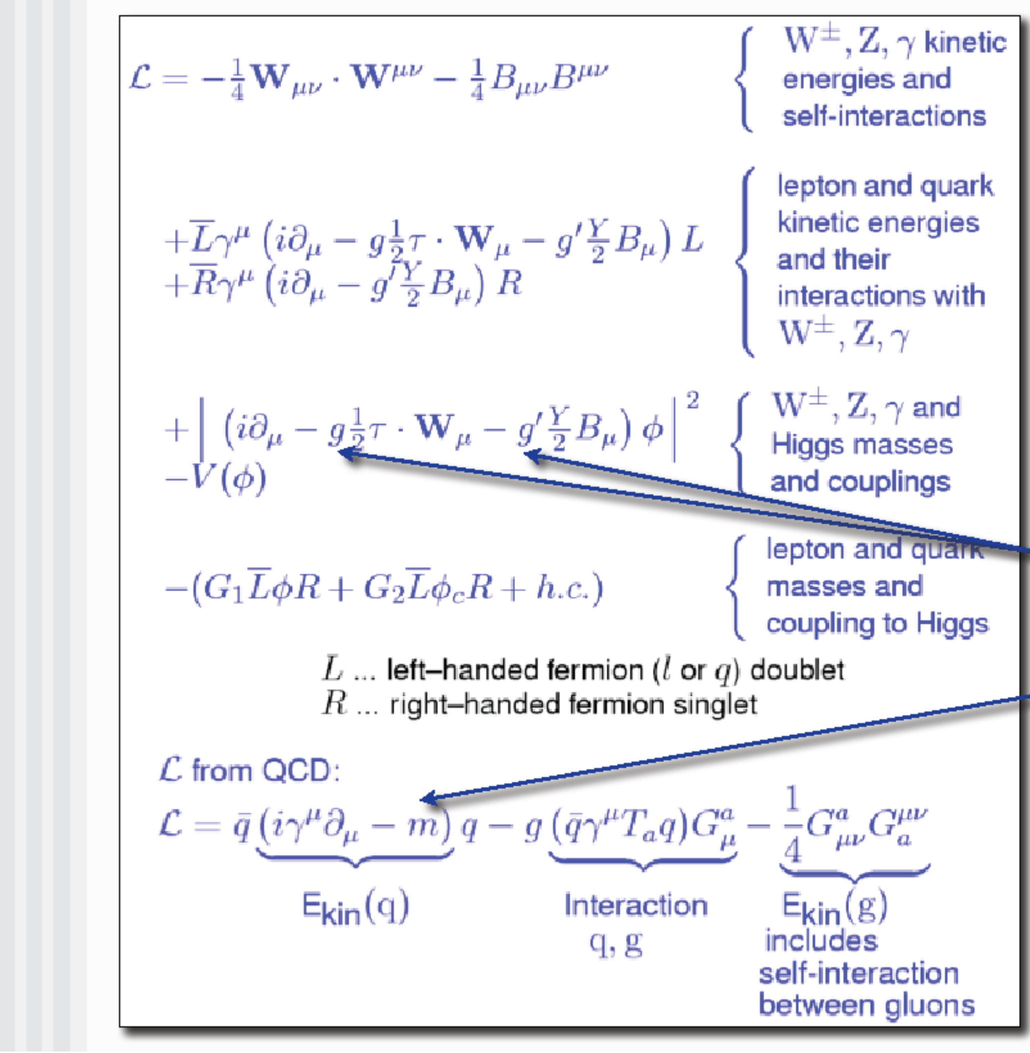
We use experiments to inquire about what "reality" (nature) does

We intend to fill this gap

The goal is to understand in the most general; that's usually also the simplest.

- A. Eddington

Theory



$$\mathcal{L} = -\tfrac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$W^\pm, Z, \gamma$ kinetic energies and self-interactions

$$+\bar{L}\gamma^\mu\left(i\partial_\mu - g\tfrac{1}{2}\tau\cdot\mathbf{W}_\mu - g'\tfrac{Y}{2}B_\mu\right)L$$
$$+\bar{R}\gamma^\mu\left(i\partial_\mu - g'\tfrac{Y}{2}B_\mu\right)R$$

lepton and quark kinetic energies and their interactions with $W^\pm, Z, \gamma$

$$+\left|\left(i\partial_\mu - g\tfrac{1}{2}\tau\cdot\mathbf{W}_\mu - g'\tfrac{Y}{2}B_\mu\right)\phi\right|^2$$
$$-V(\phi)$$

$W^\pm, Z, \gamma$ and Higgs masses and couplings

$$-(G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + h.c.)$$

lepton and quark masses and coupling to Higgs

L ... left–handed fermion (l or q) doublet
R ... right–handed fermion singlet

$\mathcal{L}$ from QCD:

$$\mathcal{L} = \bar{q}\underbrace{(i\gamma^\mu\partial_\mu - m)}_{E_{kin}(q)}q - g\underbrace{(\bar{q}\gamma^\mu T_a q)G^a_\mu}_{\text{Interaction } q,\, g} - \underbrace{\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a}_{E_{kin}(g)}$$

includes self-interaction between gluons

eg.
the Standard Model

has parameters

coupling constants

masses

predicts:
cross sections,
branching ratios,
lifetimes, ...

$$\begin{gathered}
\mathcal{L}_{SM} = -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left(\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \frac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M (H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-) - \\
\frac{1}{8}g^2\alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2) - \\
gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \\
\frac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\frac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\,(\frac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\frac{1}{4}g^2W^+_\mu W^-_\mu\,(H^2 + (\phi^0)^2 + 2\phi^+\phi^-) - \frac{1}{8}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu\,(H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-) - \\
\frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2s_w^2A_\mu A_\mu\phi^+\phi^- + \frac{1}{2}ig_s\,\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\frac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \frac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\frac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\frac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \\
\frac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \frac{g}{2}\frac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\frac{g}{2}\frac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \frac{ig}{2}\frac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \frac{ig}{2}\frac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5e^\lambda) - \frac{1}{4}\,\bar{\nu}_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat{\nu}_\kappa - \\
\frac{1}{4}\,\bar{\nu}_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat{\nu}_\kappa + \frac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_jC_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_jC_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \\
\frac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \\
\frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{G}^a\partial^2G^a + g_sf^{abc}\partial_\mu\bar{G}^aG^bg^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \\
\partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \\
\partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H\right) + \frac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) + \\
\frac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + \\
\frac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right).
\end{gathered}$$

- Lagrangi

$\mathcal{L} = \sqrt{g}($ $+ \psi\psi h)$

Einstein

Yukawa

Experiment

```
0x01e84c10:   0x01e8 0x8848 0x01e8 0x83d8 0x6c73 0x6f72 0x7400 0x0000
0x01e84c20:   0x0000 0x0019 0x0000 0x0000 0x01e8 0x4d08 0x01e8 0x5b7c
0x01e84c30:   0x01e8 0x87e8 0x01e8 0x8458 0x7061 0x636b 0x6167 0x6500
0x01e84c40:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c50:   0x01e8 0x8788 0x01e8 0x8498 0x7072 0x6f63 0x0000 0x0000
0x01e84c60:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c70:   0x01e8 0x8824 0x01e8 0x84d8 0x7265 0x6765 0x7870 0x0000
0x01e84c80:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c90:   0x01e8 0x8838 0x01e8 0x8518 0x7265 0x6773 0x7562 0x0000
0x01e84ca0:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84cb0:   0x01e8 0x8818 0x01e8 0x8558 0x7265 0x6e61 0x6d65 0x0000
0x01e84cc0:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84cd0:   0x01e8 0x8798 0x01e8 0x8598 0x7265 0x7475 0x726e 0x0000
0x01e84ce0:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84cf0:   0x01e8 0x87ec 0x01e8 0x85d8 0x7363 0x616e 0x0000 0x0000
0x01e84d00:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d10:   0x01e8 0x87e8 0x01e8 0x8618 0x7365 0x7400 0x0000 0x0000
0x01e84d20:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d30:   0x01e8 0x87a8 0x01e8 0x8658 0x7370 0x6c69 0x7400 0x0000
0x01e84d40:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d50:   0x01e8 0x8854 0x01e8 0x8698 0x7374 0x7269 0x6e67 0x0000
0x01e84d60:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d70:   0x01e8 0x875c 0x01e8 0x86d8 0x7375 0x6273 0x7400 0x0000
0x01e84d80:   0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d90:   0x01e8 0x87c0 0x01e8 0x8718 0x7377 0x6974 0x6368 0x0000
```

eg.

1/30th of an event in the BaBar detector

- get about 100 evts/sec

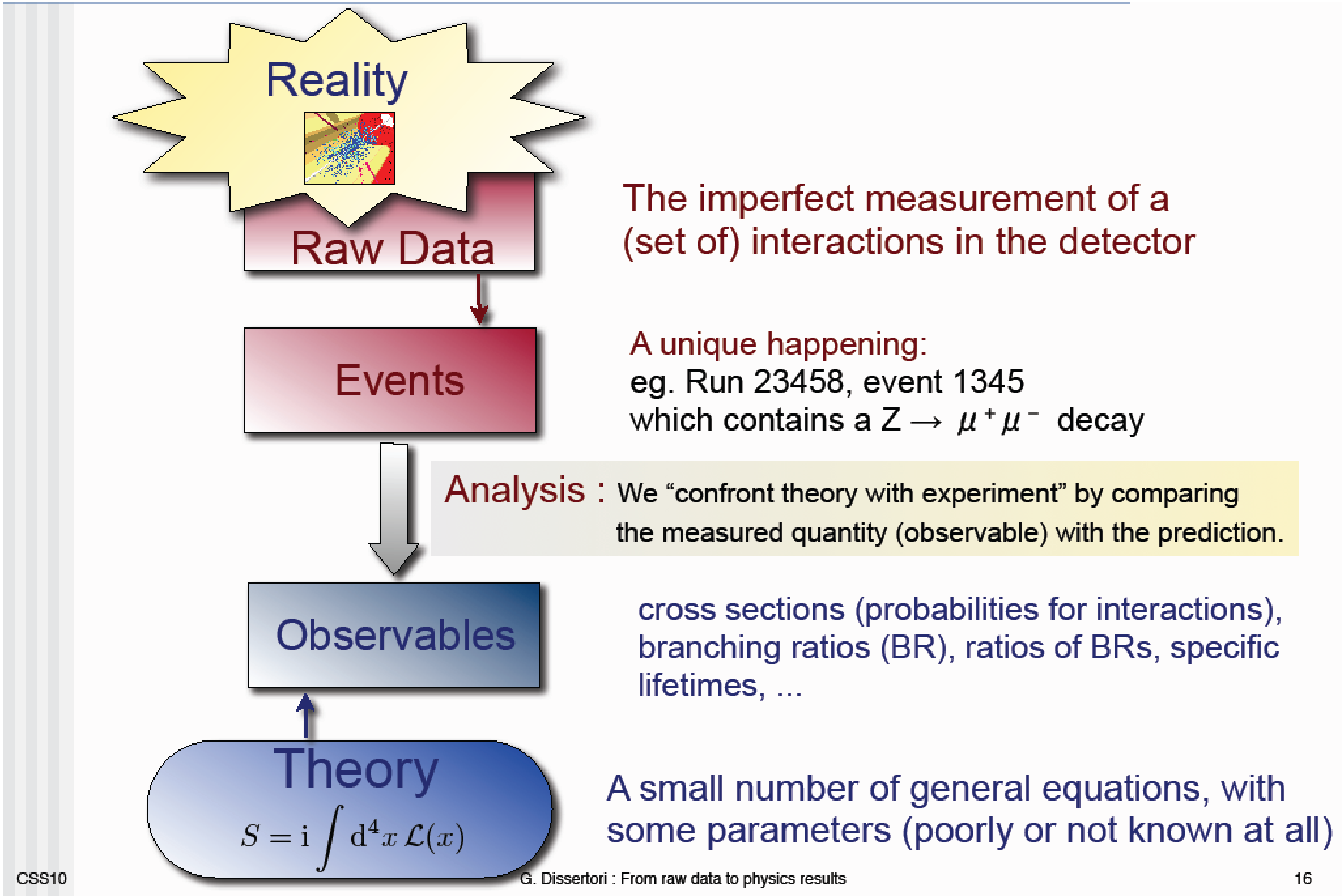
"Address" :

- which detector element took the reading

"Value(s)" :

- what the electronics wrote out

Making Connection



Reality

Raw Data

The imperfect measurement of a (set of) interactions in the detector

Events

A unique happening:
eg. Run 23458, event 1345
which contains a Z → $\mu^+\mu^-$ decay

Analysis : We “confront theory with experiment” by comparing the measured quantity (observable) with the prediction.

Observables

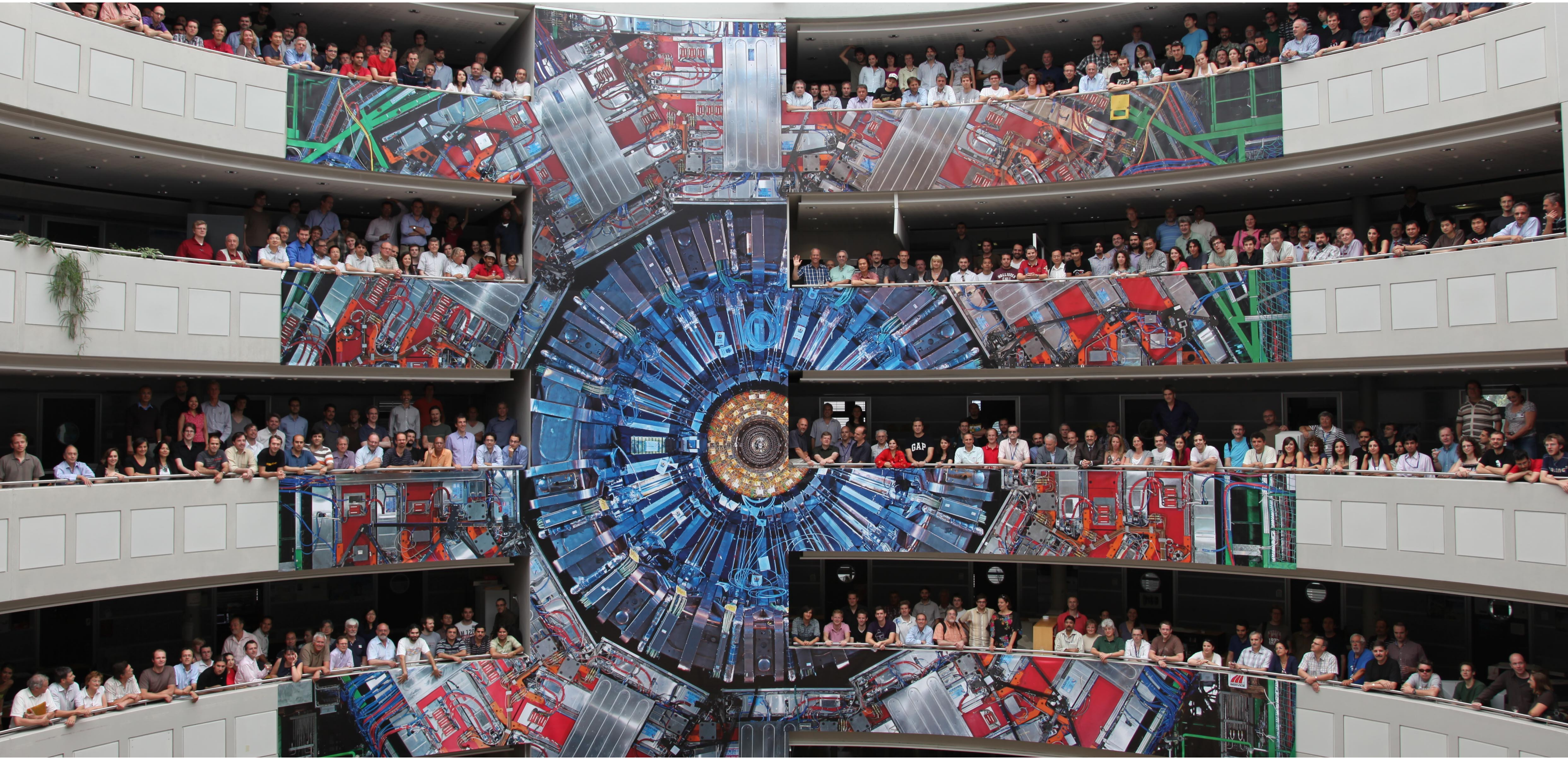
cross sections (probabilities for interactions), branching ratios (BR), ratios of BRs, specific lifetimes, ...

Theory

$$S = \mathrm{i}\int \mathrm{d}^4x\,\mathcal{L}(x)$$

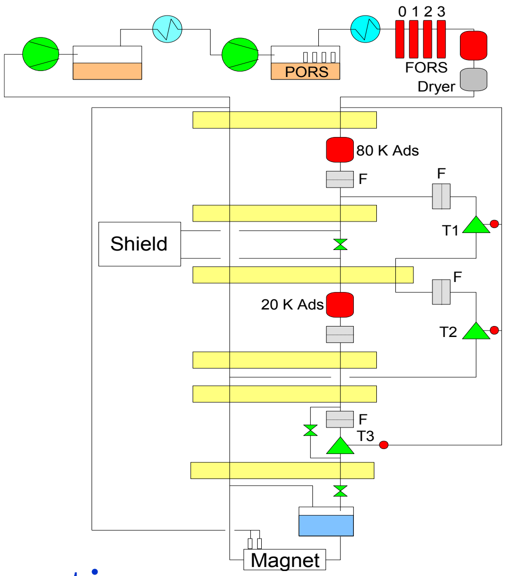
A small number of general equations, with some parameters (poorly or not known at all)

Thank You!



Back Up

Magnet Cryogenics



- The restart of the CMS magnet after LS1 was more complicated than anticipated due to problems with the cryogenic system in providing liquid Helium.
- Inefficiencies of the oil separation system of the compressors for the warm Helium required several interventions and delayed the start of routine operation of the cryogenic system.
- Currently the magnet can be operated, but the continuous up-time is still limited by the performance of the cryogenic system requiring more frequent maintenance than usual.
- A comprehensive program to re-establish its nominal performance is underway. These recovery activities for the cryogenic system will be synchronized with the accelerator schedule in order to run for adequately long periods.
- A consolidation and repair program is being organized for the next short technical stops and the long TS at the end of the year.

Naturalness problems:

If something is so small compared to its cousin,
putting big and small together requires a fine tuning.

A. Weiler

3 fine-tuning problems associated with the 3 scales and 2 angles:

* Cosmological constant problem:

Why $\Lambda_{DE}/M_{Planck} \sim 10^{-30}$ is so small?

* Gauge hierarchy problem:

Why $m_{higgs}/M_{Planck} \sim 10^{-16}$ is so small?

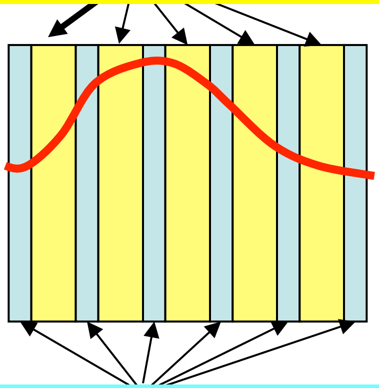
* Strong CP problem:

Why $\theta_{QCD} /\delta_{KM} < 10^{-10}$ is so small?

Calorimetry

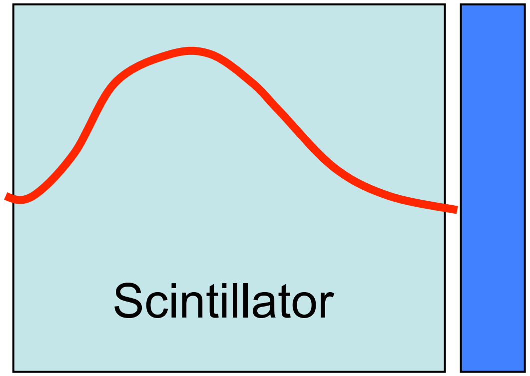
- **Particles shower in calorimeter creating other particles which shower and so on until no more energy is left**
- **The created charged particles produce light via scintillation or Cherenkov mechanisms which can be collected and is proportional to the original particle energy**

Passive heavy material



Active material (scintillator)

Sampling or Homogenous Calorimeters



Resolution:

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

Sampling + Stochastic term (shower fluctuation + statistics)

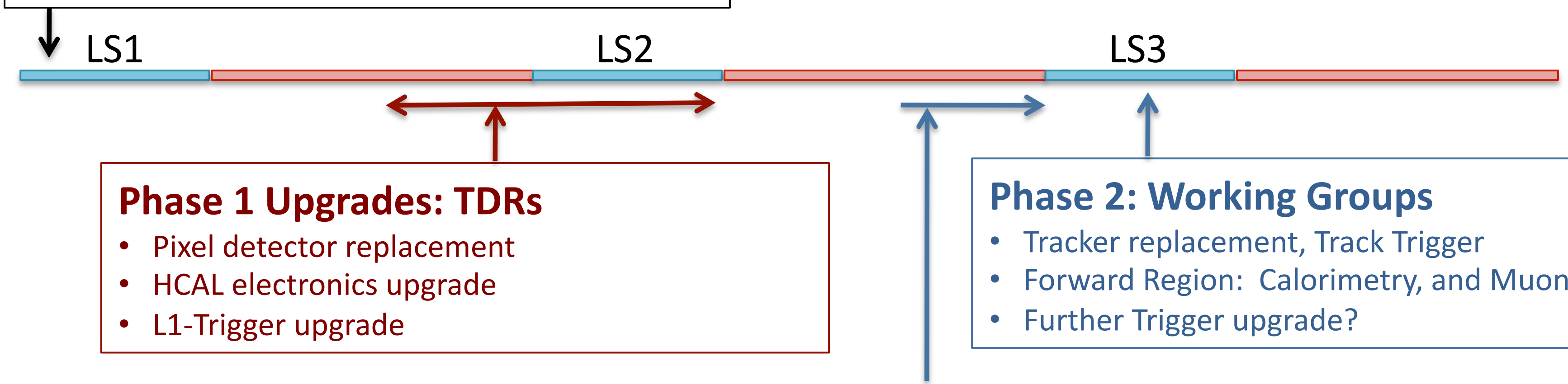
Noise term

Constant term: calibration, temperature dependence, …

CMS Upgrade Program

LS1 Projects: in production

- Completion of muon coverage (ME4)
- Improve muon operation (ME1), DT electronics
- Replace HCAL photo-detectors in HF (new PMTs) and HO (HPD→SiPM)



Phase 1 Upgrades: TDRs

- Pixel detector replacement
- HCAL electronics upgrade
- L1-Trigger upgrade

Phase 2: Working Groups

- Tracker replacement, Track Trigger
- Forward Region: Calorimetry, and Muons?
- Further Trigger upgrade?

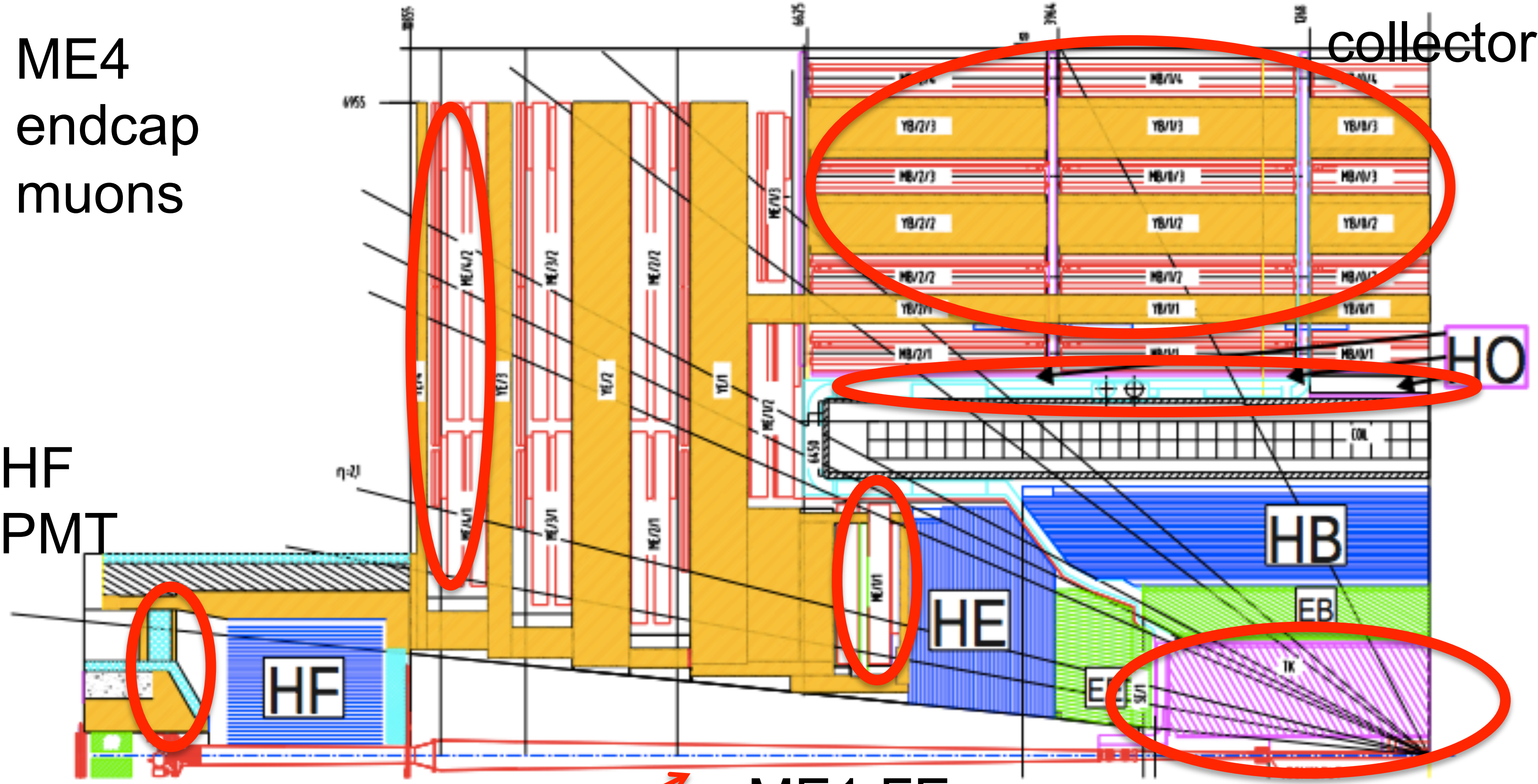
- Longevity → Phase 2
- Phase 2 Scope
- Targeted R&D program

2013

- Technical Proposal

2014

Detector Upgraded in LS1



ME4
endcap
muons

DT sector
collectors

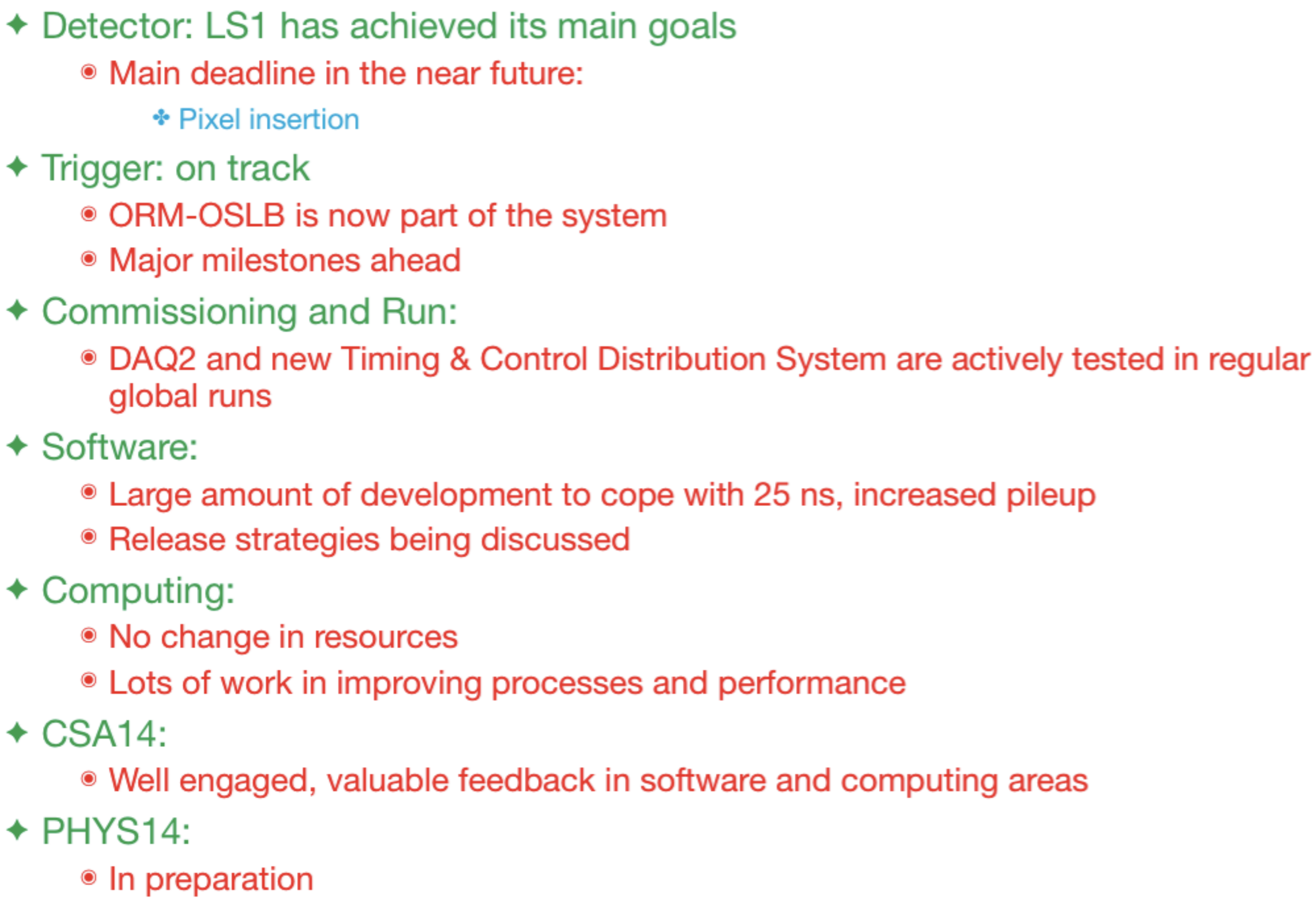
HF
PMT

New beampipe

ME1 FE
electronics

Cold trackrer
operation

LS1: Exercutive Summary



- Detector: LS1 has achieved its main goals
  - Main deadline in the near future:
    - Pixel insertion
- Trigger: on track
  - ORM-OSLB is now part of the system
  - Major milestones ahead
- Commissioning and Run:
  - DAQ2 and new Timing & Control Distribution System are actively tested in regular global runs
- Software:
  - Large amount of development to cope with 25 ns, increased pileup
  - Release strategies being discussed
- Computing:
  - No change in resources
  - Lots of work in improving processes and performance
- CSA14:
  - Well engaged, valuable feedback in software and computing areas
- PHYS14:
  - In preparation

LS1 Muon Upgrades

Trigger performance: significantly lower threshold for same rate

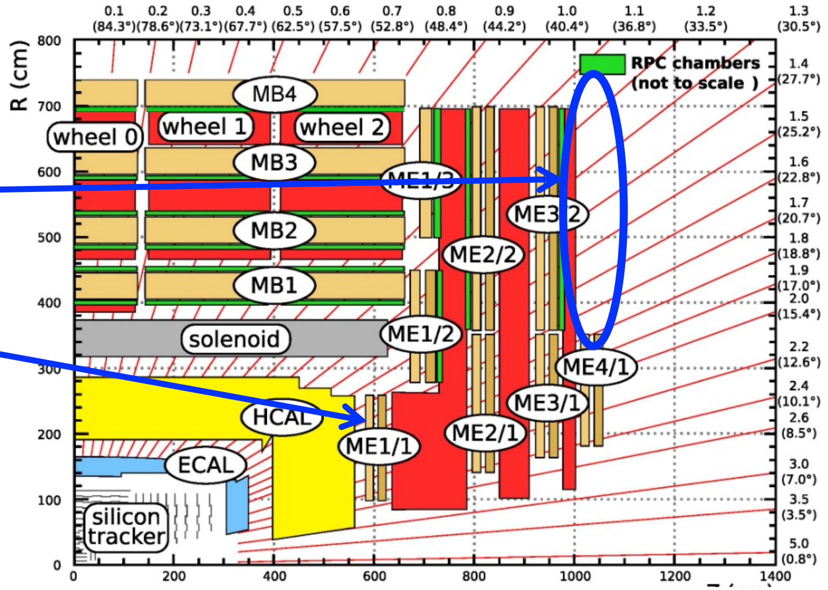
CSC and RPC: ME4/2 (1.25<|η|<1.8)

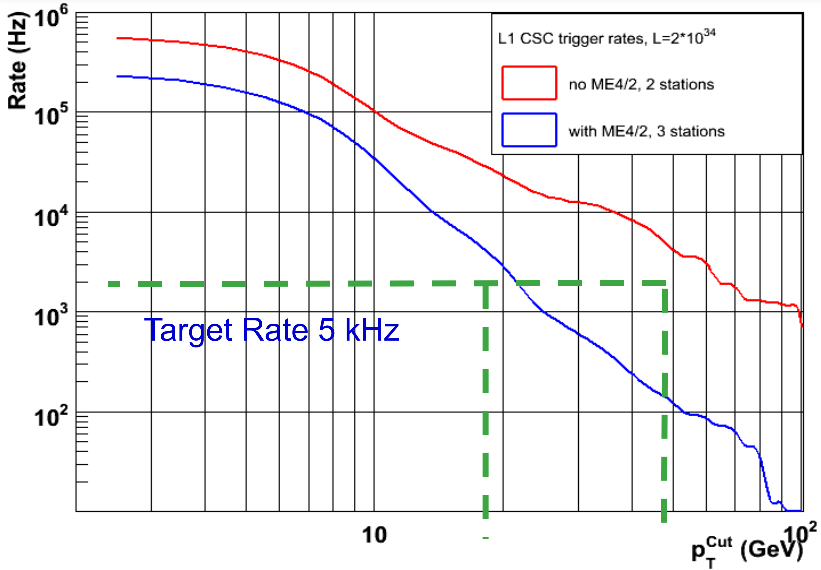
More hits, lower rates

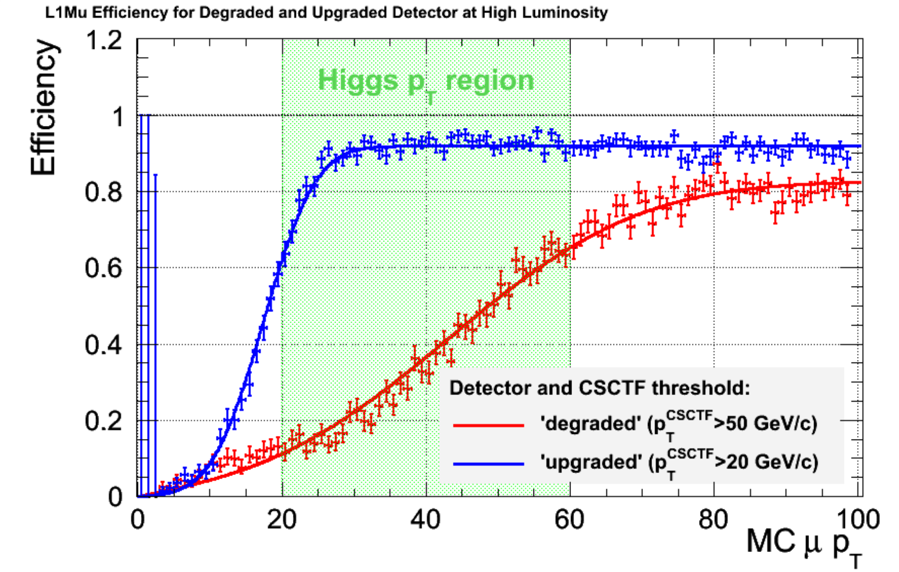
CSC: ME1/1 (2.1<|η|<2.4) new digital boards and trigger cards : higher strip granularity

Electronics reliability

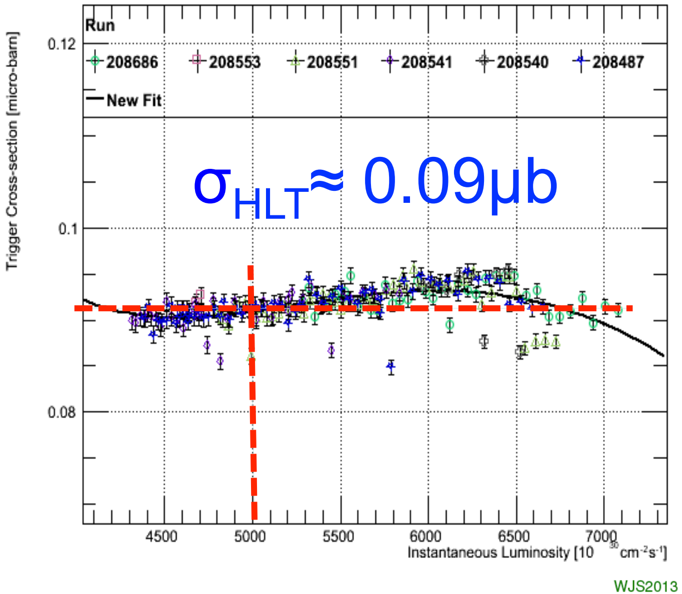
DT: new trigger readout board and relocation of sector collector from UXC55 to USC55 (new optical links)

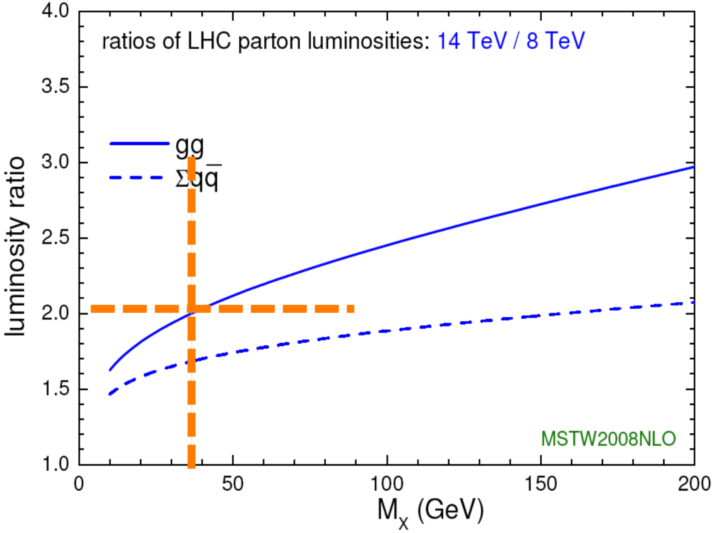






HLT: Challenges for 2015





- 2012: 8 TeV HLT σ ~0.09 μb
  - PU=25, small dependence on PU
- 8 TeV→ 14TeV ⇒ rates double
  - Average output rate of ~ 1.2kHz at $10^{34}cm^{-2}s^{-1}$ if menu untouched.
- To keep the present acceptance:
  - Improve HLT object reconstruction
    - Allowing tighter cuts
  - Reconsider strategies
    - More cross triggers
  - Will need more CPU
    - e.g. to extend PF usage
    - Particularly if PU <> grows above 25