Calorimeters & Level-1 Trigger for the CMS Experiment @ LHC

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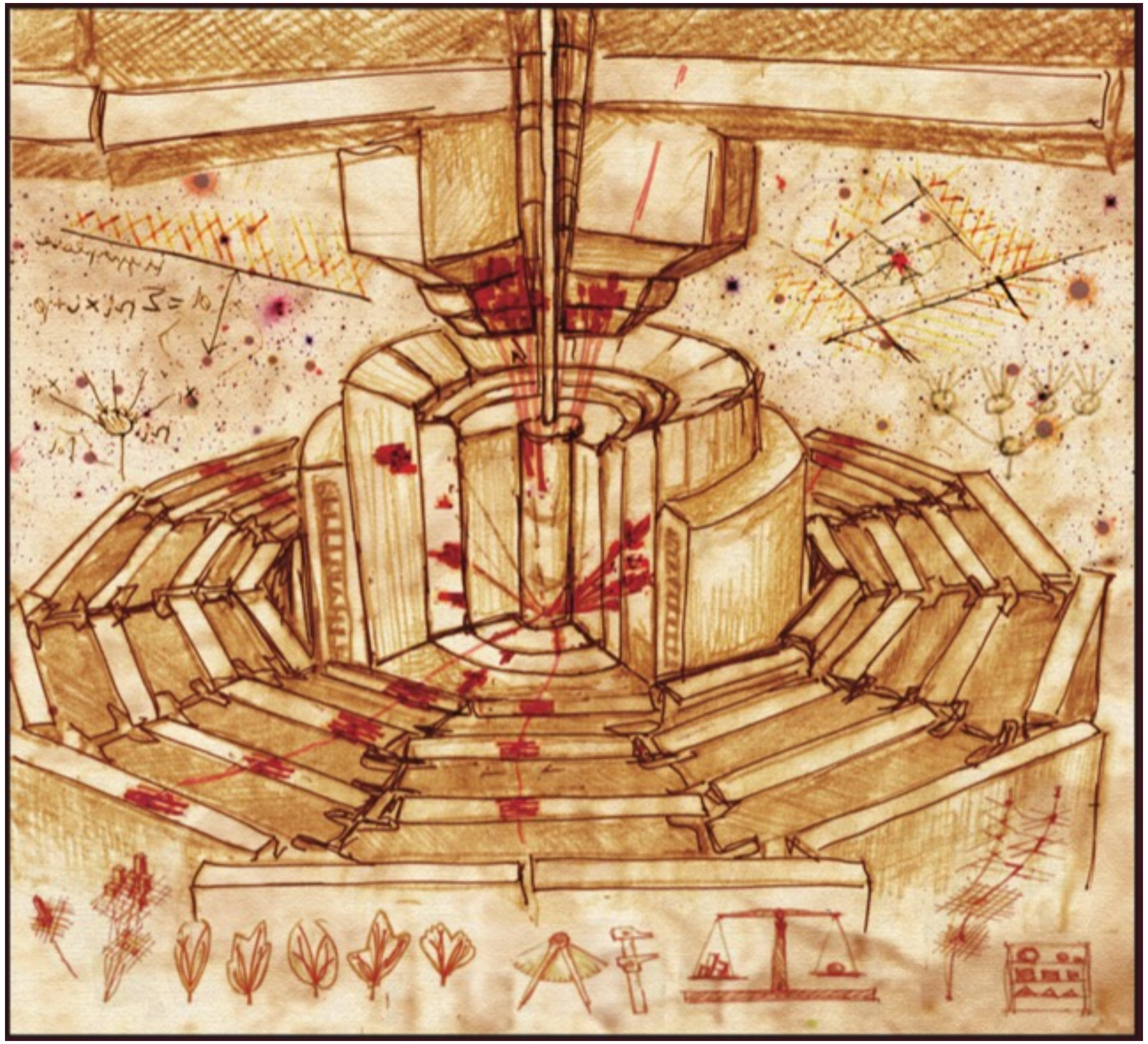
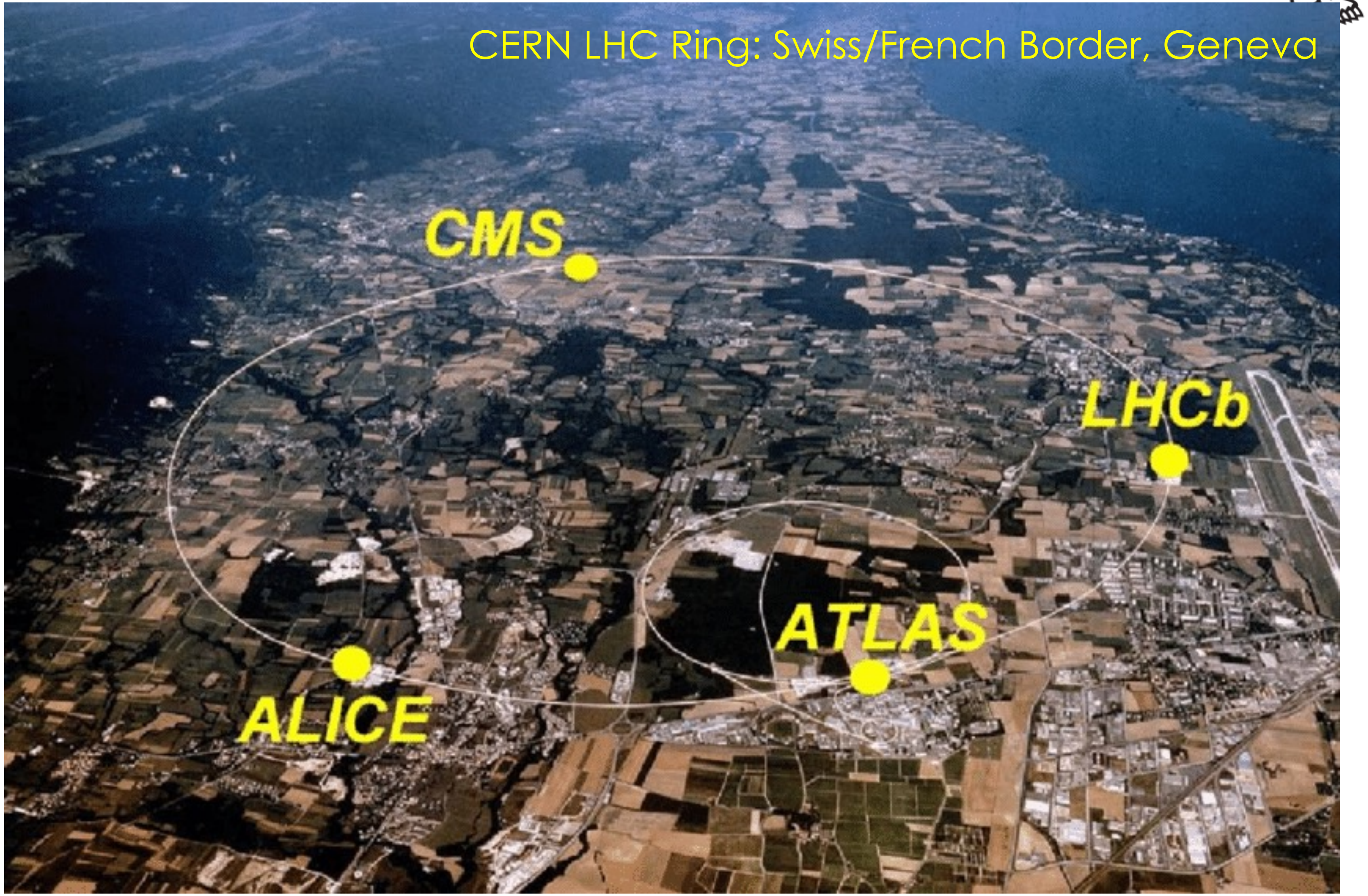


Large Hadron Collider

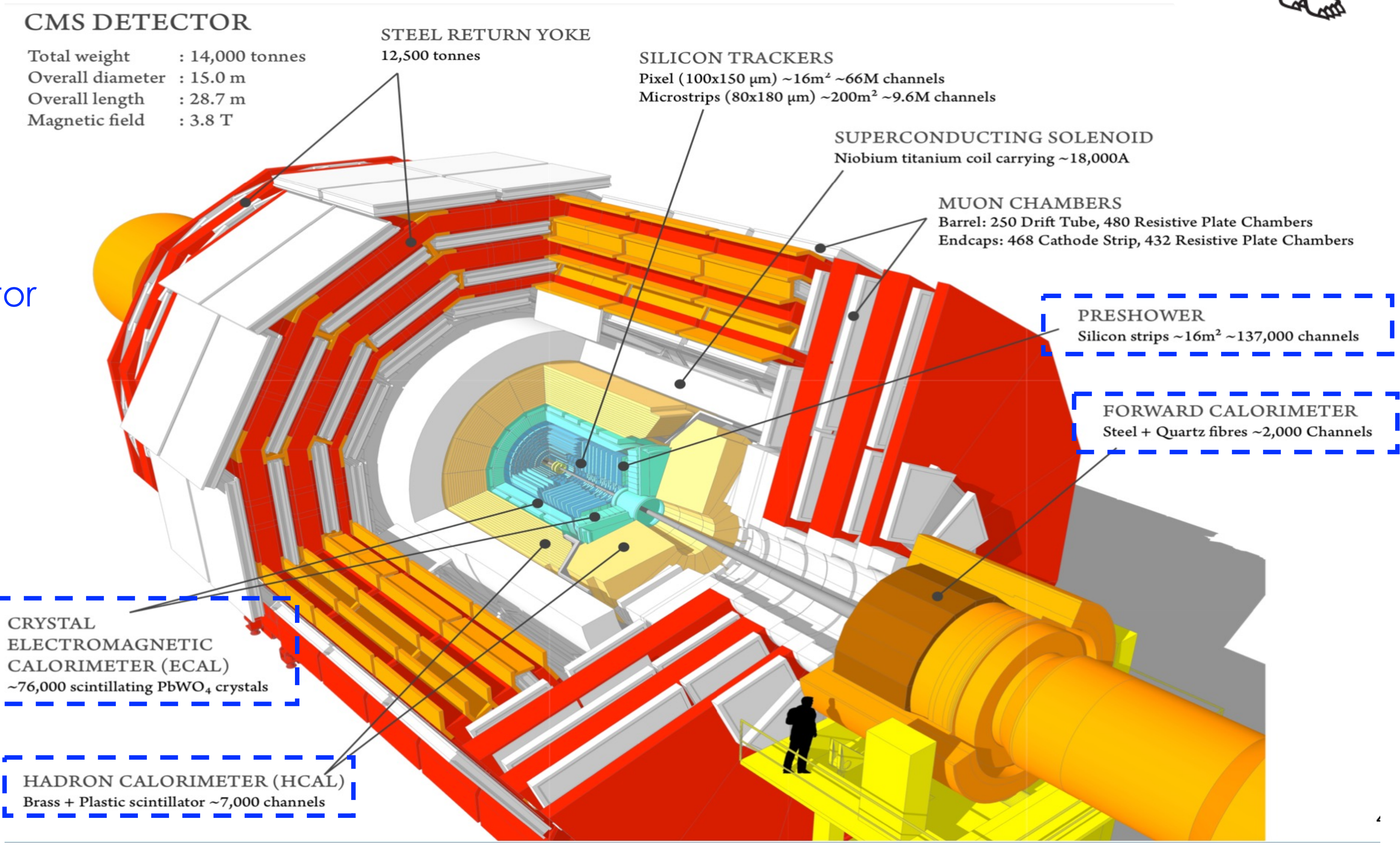
- 27km – circumference ring ~ 100m underground
- Collide protons and heavy Ions
- Two beams counter-rotate, interact at 4-points
- Collision Rate 40MHz
- Run-2: 2015-2018
- **Run-3: 2022 onwards**
- HL-LHC: 2028* onwards



The CMS Detector

General purpose dectector

Designed to observe any new physics phenomena that LHC might reveal



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

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Calorimeters

Calorimetry: Quantitative measurement of energy

One of the most important and powerful detector technique in experimental particle physics

Calorimetry

- Two main categories:
  - Electromagnetic calorimeters – $e^{\pm}$, γ
  - Hadron calorimeters - $\pi^{\pm}$, $p^{\pm}$, $K^{\pm}$, n, K^0_L

$\mu^{\pm}$ usually traverse the calorimeters losing small amounts of energy by ionisation

The 13 particle types above completely dominate the particles from high energy collisions reaching and interacting with the calorimeters

All other particles decay ~instantly, or in flight, usually within a few hundred microns from the collision, into one or more of the particles above

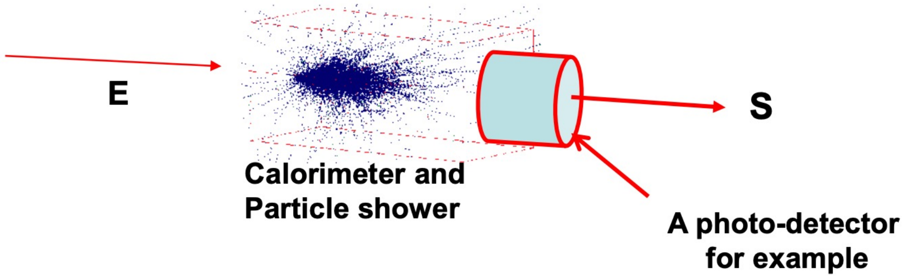
Neutrinos, aand neutralinos, remain undetected but with the hermetic calorimeters can be inferred from measurements of missing transverse energy in collider experiments

Calorimeters

- Designed to stop and fully contain their respective particles
    - "End of the road" for the incoming particle
- Measure:
    - **Energy** of incoming particles by total absorption in calorimeter
    - **Spatial location** of the energy deposit
    - (sometimes) **direction** of the incoming particle

Convert energy **E** of the incident paraticle into detector response **S**

$\mathbf{E} \propto \mathbf{S}$



Energy lost by the formation of electromagnetic or hadronic cascades/showers in the material of calorimeter

The charged particles ionize or excite the calorimeter medium

The ionization or excitation can give rise to
- The emission of visible photons, via scintillations
- The release of ionization electrons

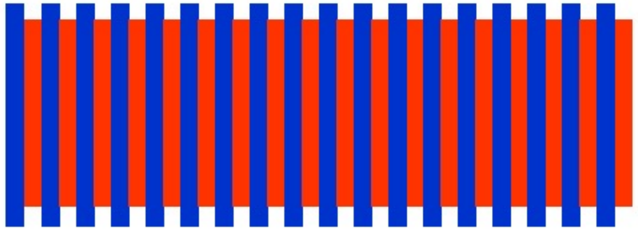
Photo-detectors or anodes/dynodes then detect these "quanta"

Calorimeter Design

Sampling calorimeters:

Layers of passive absorber (i.e. Pb or Cu) alternating with active detector layers such as plastic scintillator, liquid argon or silicon

- Only part of the energy is sampled
- Used for both e.m. and hadronic calorimeters
- Cost effective



Homogeneous calorimeters

Single medium, both absorber and detector

- Liquified Ar/Xe/Kr
- Organic liquid scintillators, large volumes
- Dense crystal scintillators: PbWO4, CsI(Tl), BGO and many others
- Lead loaded glass

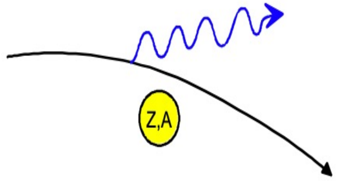
Almost entirely for electromagnetic calorimetry

Electromagnetic Interaction

e± Bremsstrahlung and photon pair production:

- Most important processes for energy loss by electrons/positrons/photons with energies above 1 GeV
  ⇒ Leads to an e.m. cascade of particles

Bremsstrahlung: Characterised by a 'radiation length', X_0, in the absorbing medium over which an electron loses, on average, 63.2% of its energy by bremsstrahlung



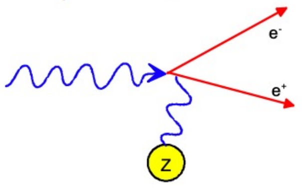
$$-\frac{dE}{dx} \propto \frac{Z^2 E}{m_e^2}$$

Using high Z materials for compact e.m. calorimetry

Due to the $1/m^2$ dependence for bremsstrahlung, muons only emit significant bremsstrahlung above ~1 TeV (m_μ ~ 210 m_e)

Pair production: Intensity of a photon beam entering calorimeter reduced to 1/e of the original intensity, $I = I_0 \exp(-7/9\ X/X_0)$.

$$E_\gamma \geq 2m_e c^2$$

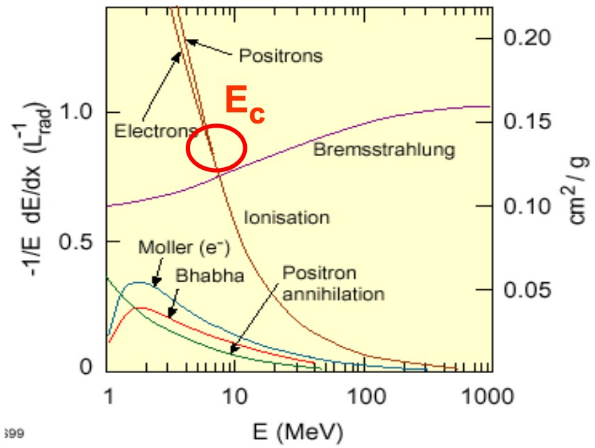


Below a certain crictical energy, **E_c**

- **Electrons** losses energy via ionisation
- Multiplication process runs out
  - Slow dec in # of particles in shower
  - Electrons/positrons are stopped

- **Photons** progressively lose energy by Compton scattering, converting electrons via photo-electic effect

Fractional Energy Loss by Electrons

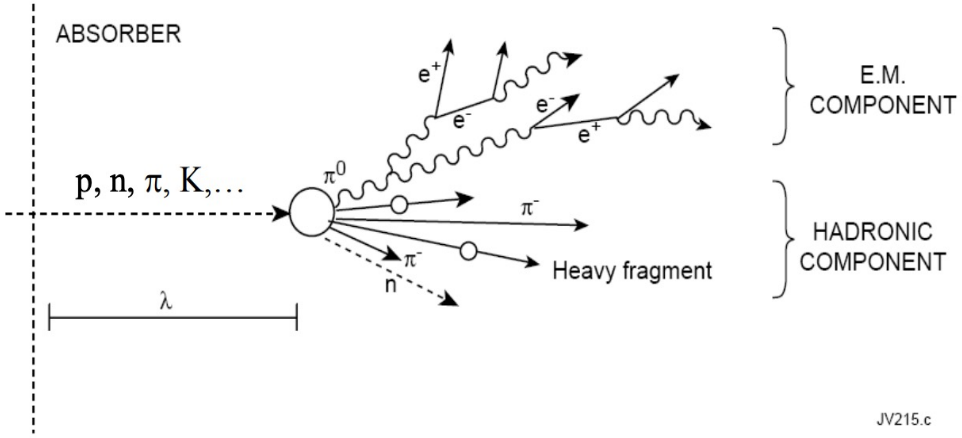


Hadronic Interations

Hadronic cascades much more complex than an electromagnetic cascade

- Shower development determined by the mean free path, λ_I , between inelastic collisions
- The nuclear interaction length is given by $\lambda I = A / (N_A.\sigma_{inel})$

High energy hadrons interact with nuclei producing secondary particles, mostly $\pi^{\pm}$ and π^0

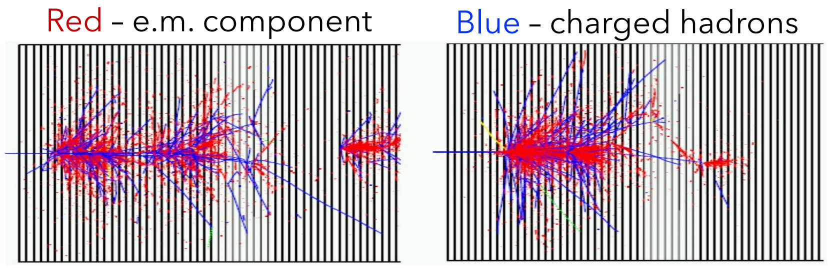


The neutral pions (π^0)quickly decay to two e.m. particles ($\gamma\gamma$) in ~10^{-16}s

Thus hadronic cascades have two distinct components:

- Hadronic (largely $\pi^{\pm}$, heavy fragments, excited nuclei) &
- Electromagnetic ($\gamma\gamma$)

This gives rise to a much more complex cascade development which limits the ultimate resolution possible for hadronic calorimetry

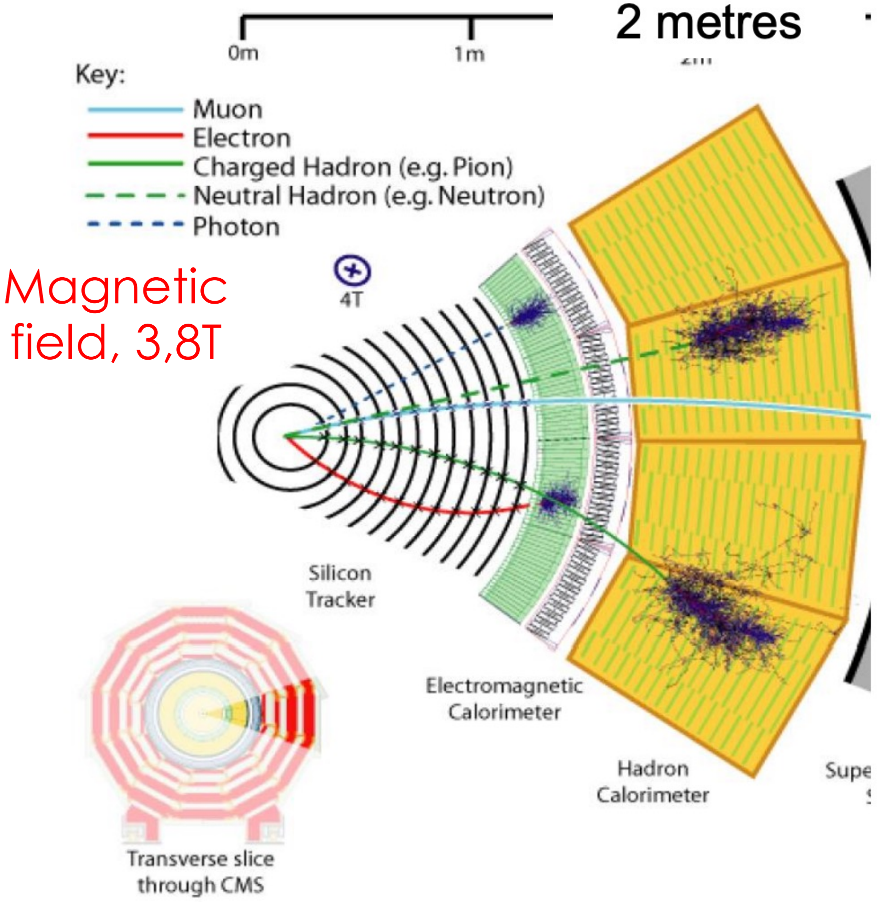

Red – e.m. component

Blue – charged hadrons

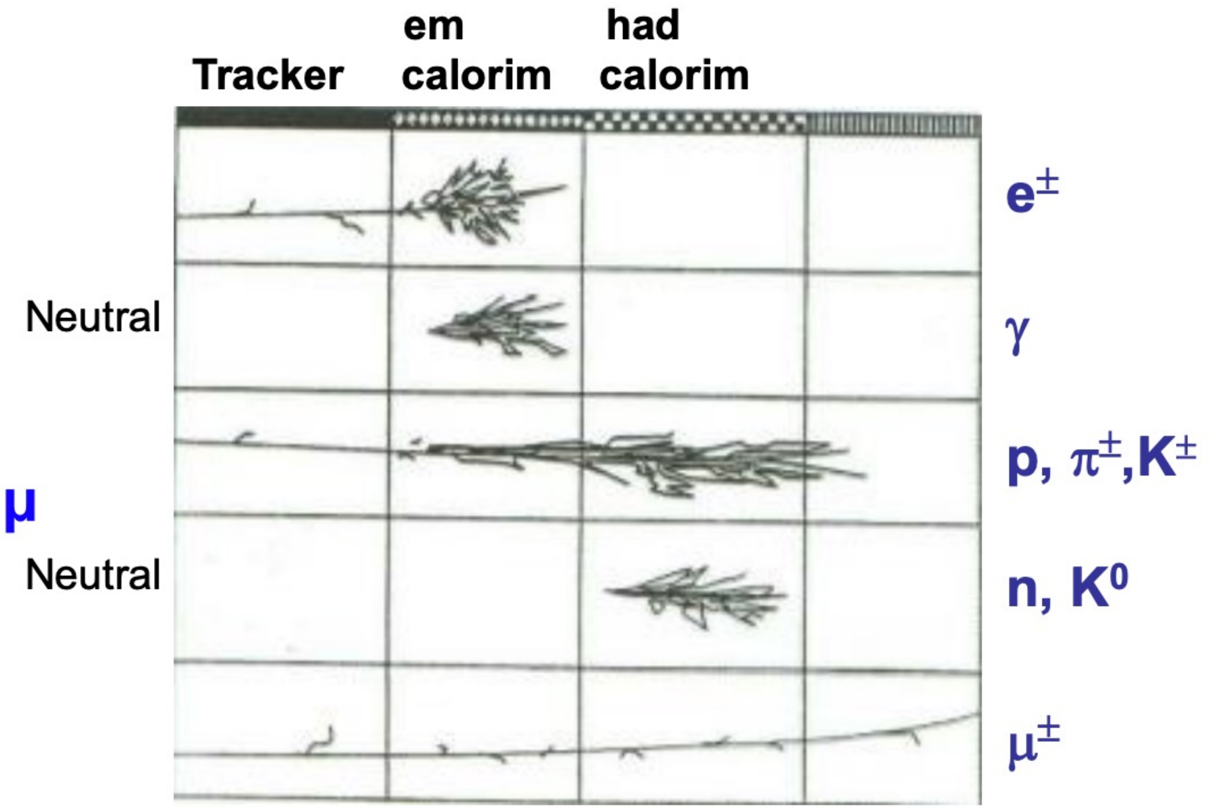
Unlike electromagnetic showers, hadron showers do not show a uniform deposition of energy throughout the detector medium

Calorimeters

Where you **STOP** is what you **ARE** !!!



Magnetic field, 3,8T



Get sign of the charged particles from the tracker

Tracker to be of minimum material to avoid losing particle energy before the calorimeters

CMS ECAL

ECAL is a homogeneous, high-granularity calorimeter

Compact & Radiation tolerant

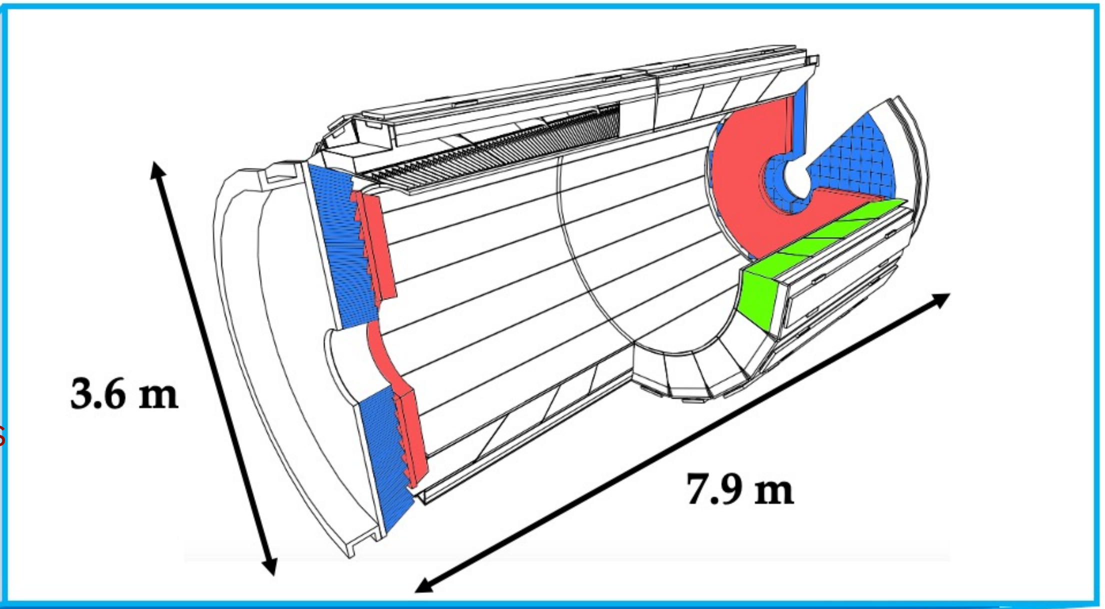
- Radiation Length, $X_0 = 0.89$ cm
- Moliere radius, $r_M = 2.19$ cm
- Density, $\rho = 8.28$ g/cm^3

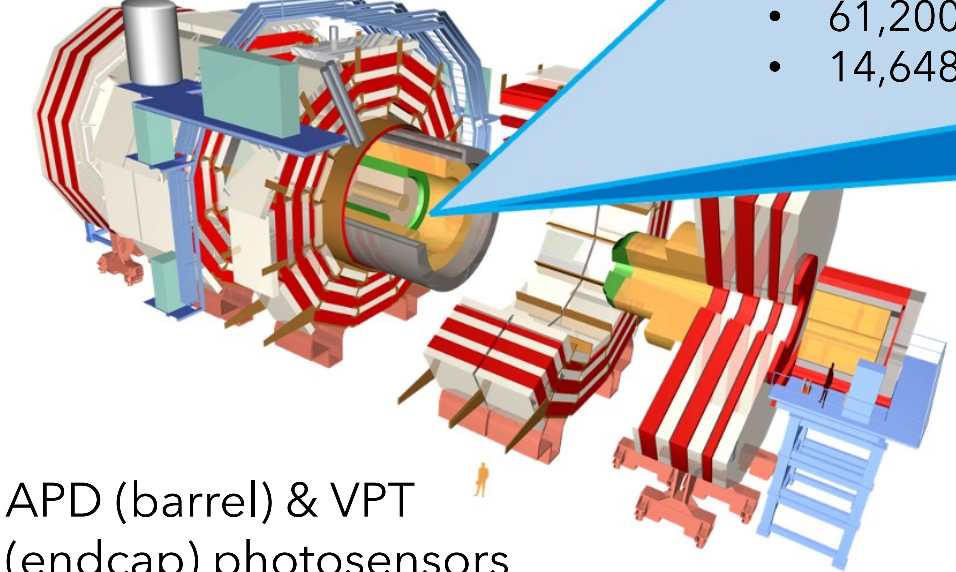
Fast Scintillation

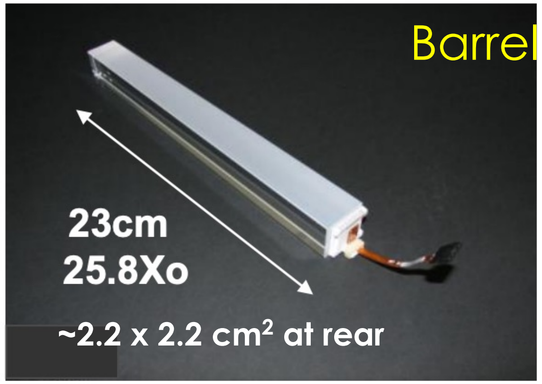
- Emission, $t_{75\%} = 25$ ns
- Light yield: 100γ/MeV
- Peak emission: ~430nm

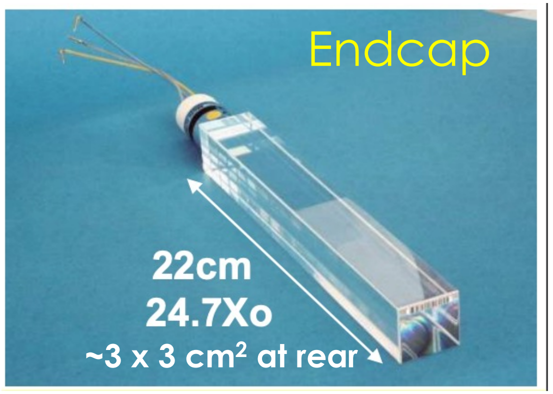
Lead tungstate crystals ($PbWO_4$)

- 61,200 in barrel
- 14,648 in endcaps









- APD (barrel) & VPT (endcap) photosensors

ECAL Performance

Energy resolution, where E is energy of incoming particle

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \quad \Rightarrow \quad \frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E} \oplus 0.3\%$$

a , stochastic term: Fluctuations in the number of signal generating processes, ie on the number of photo-electrons generated

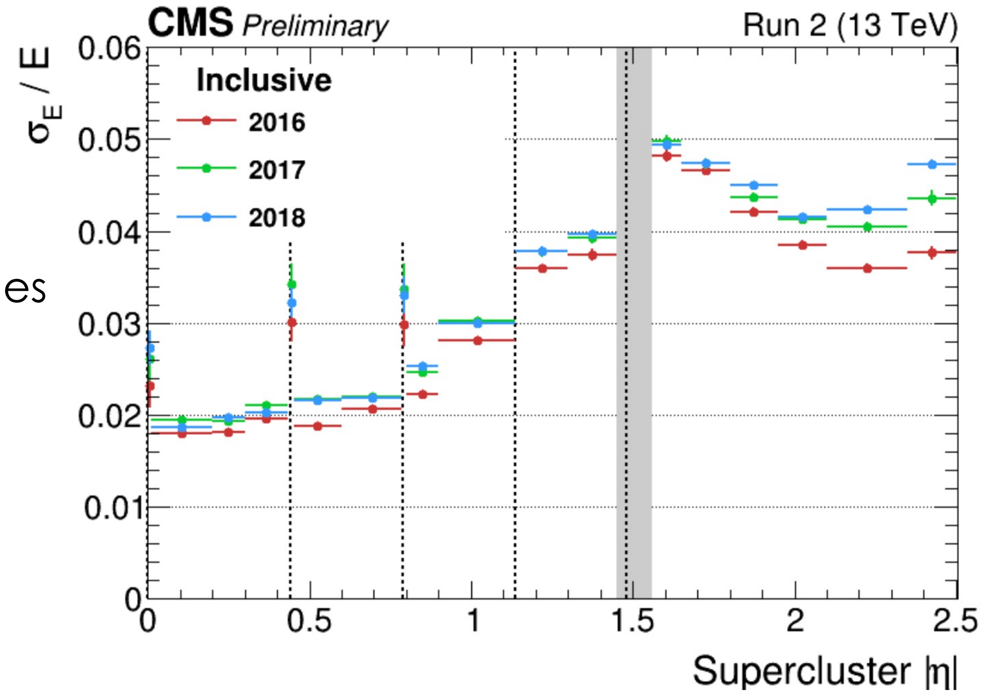
b , noise term: Noise in readout electronics 'pile-up' due to other particles from other collision events arriving close in time

c , constant term:

- Imperfections in calorimeter construction (dimension variations)
- Non-uniform detector response
- Channel to channel intercalibration errors
- Fluctuations in longitudinal energy containment
- Energy lost in dead material, before or in detector

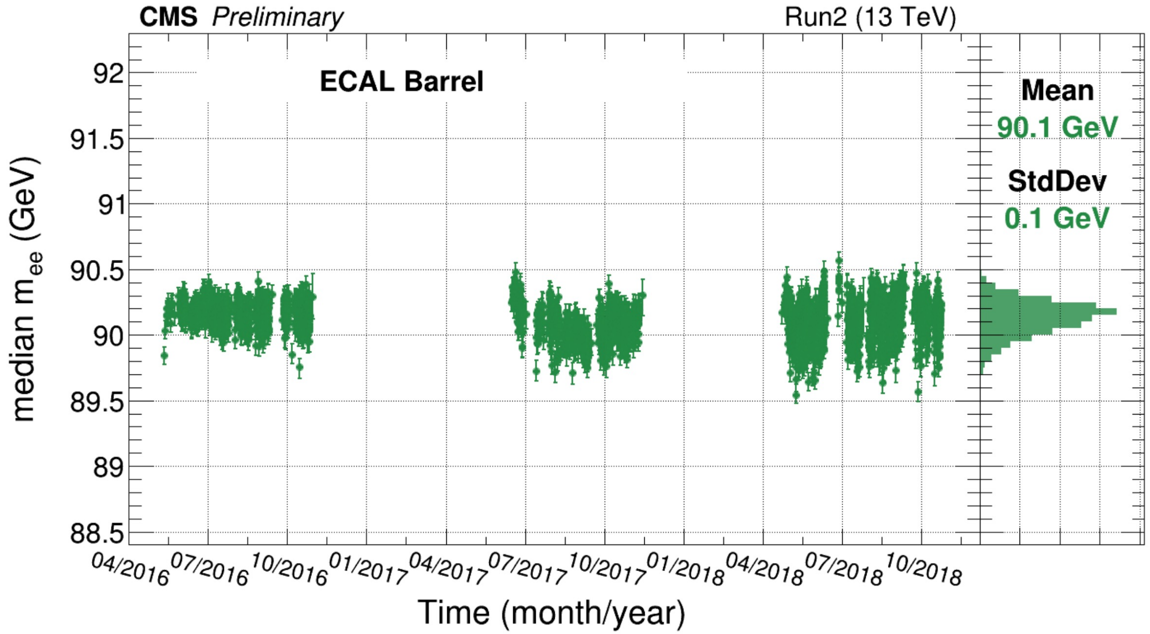
Crucial to have small constant term for good energy resolution at the highest particle energies

Excellent energy resolution

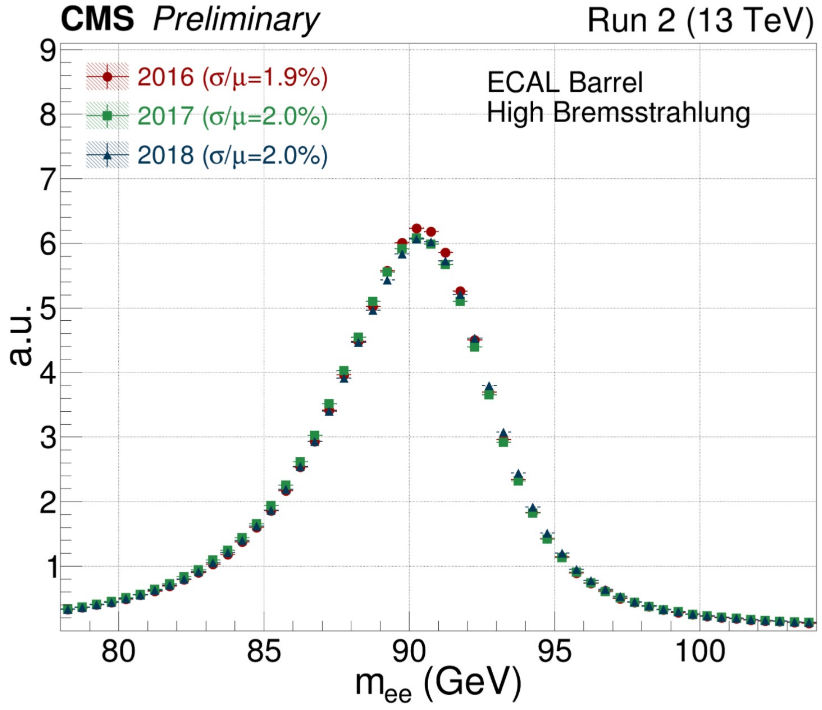


Electrons from Z → ee decays

ECAL Stability



Time stability of the di-electron invariant mass distribution for the full Run2 data-taking period using Z→ee

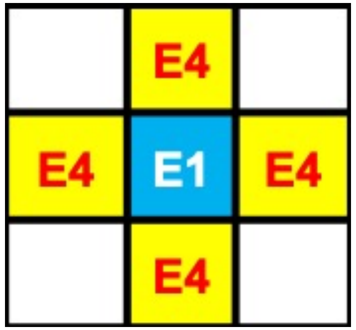


Invariant mass distribution comparing 2016, 2017, and 2018 data-taking period using Z→ee events with a refined re-calibration performed in 2019 for the full Run2 dataset.

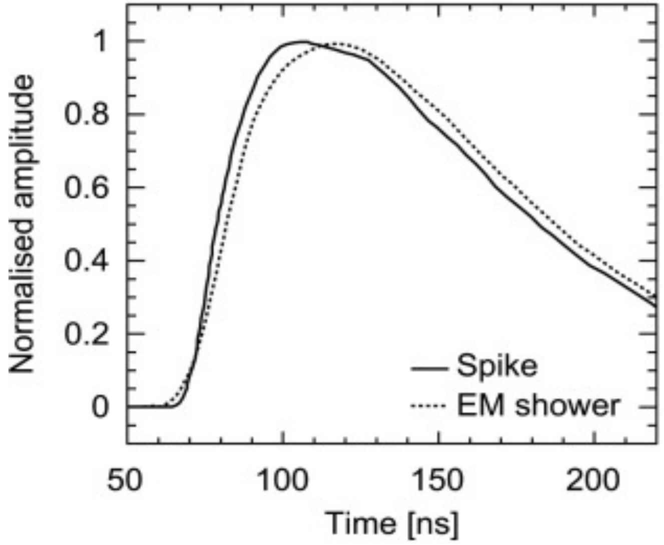
After contributing to the Higgs boson discovery in 2012, ECAL continues to be vital for **Higgs precision measurements** and for a vast number of **searches for rare Standard Model or beyond SM phenomena**

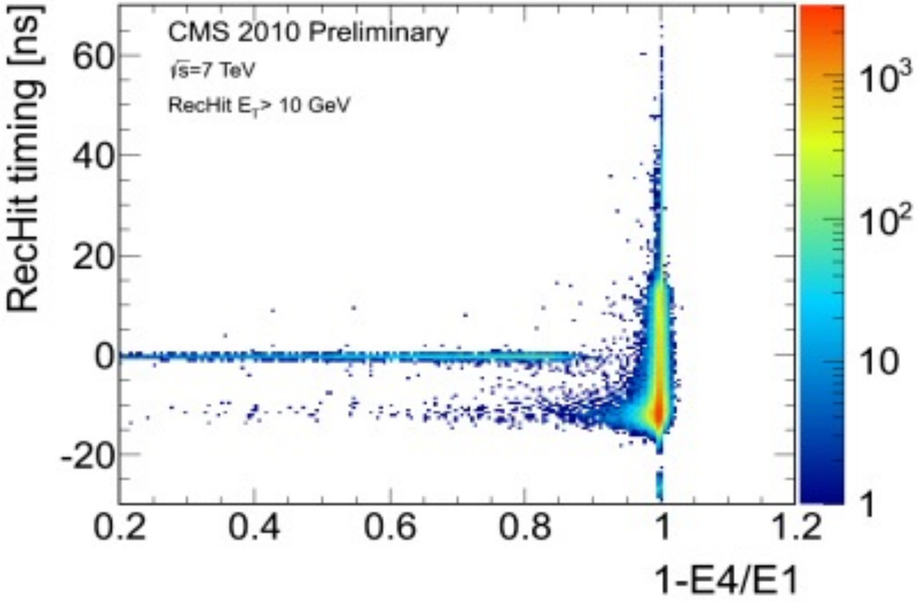
ECAL Spikes

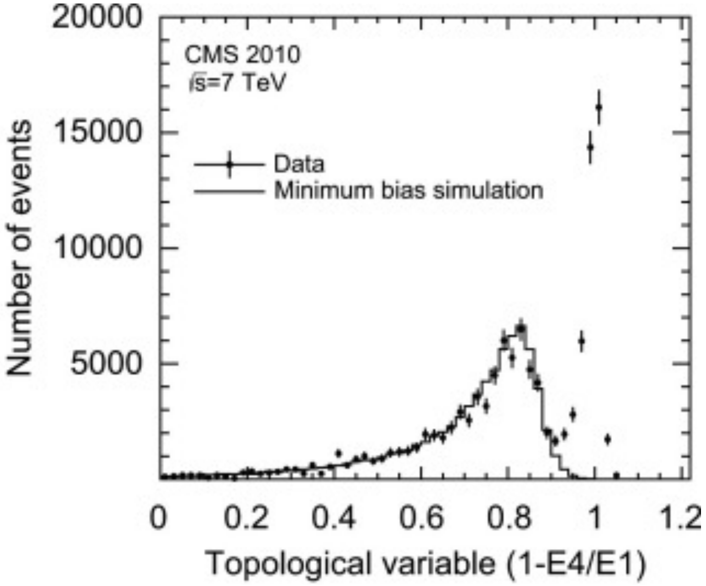
- Direct interactions with photodetectors
  - particularly in barrel APDs
- Different timing/energy distributions
- Use to reject offline



$$1 - \frac{E4}{E1}$$







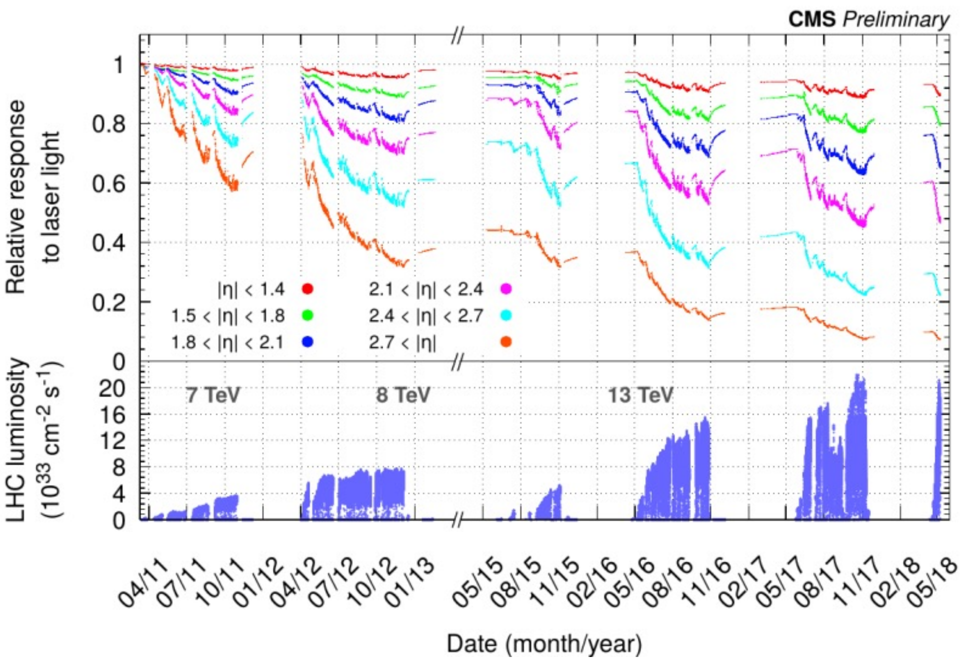
ECAL at High Luminosity LHC

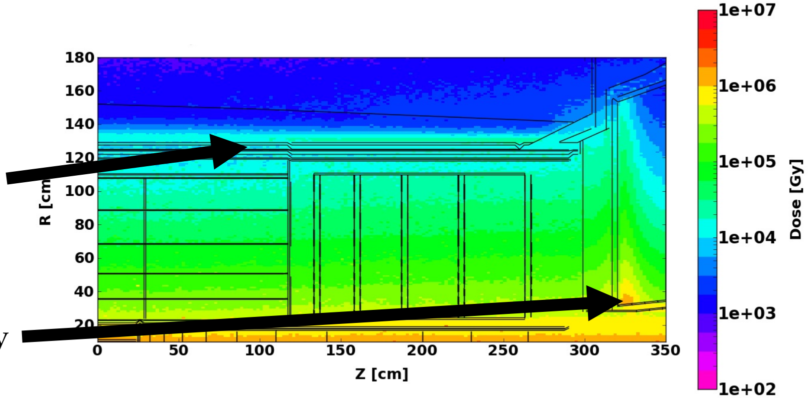
Crystal transparency has been measured regularly during data taking in Run-1 and 2 and accounted for specific corrections

Radiation-induced leakage current in the APD would make APD noise the dominant term in energy resolution at HL-LHC, in the current configuration

Affected by radiation damage:

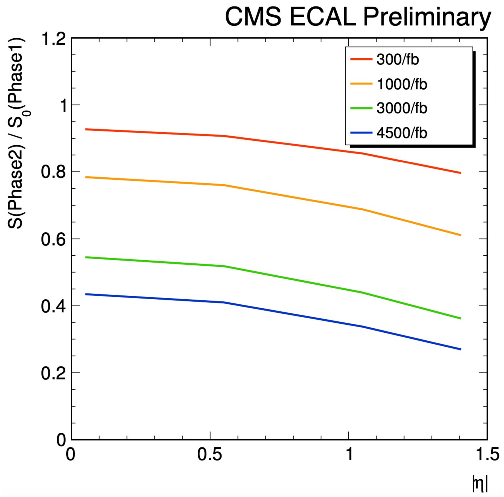
- EM damage recoverable at room temperature
- Hadron induced damage dominant at (HL-LHC) not recoverable





EB up to ~50 kGy

EE up to ~10^3 kGy



Expected signal loss in EB ($0 \leq |\eta| < 1.5$) from 55% to 70% at 3000 fb^{-1}

✓ Crystals in EB will still perform well

☐ EE will be fully replaced by HGCAL, a high granularity calorimeter, silicon and scintillator-based

CMS HCAL

Sampling calorimeter with hermetic coverage

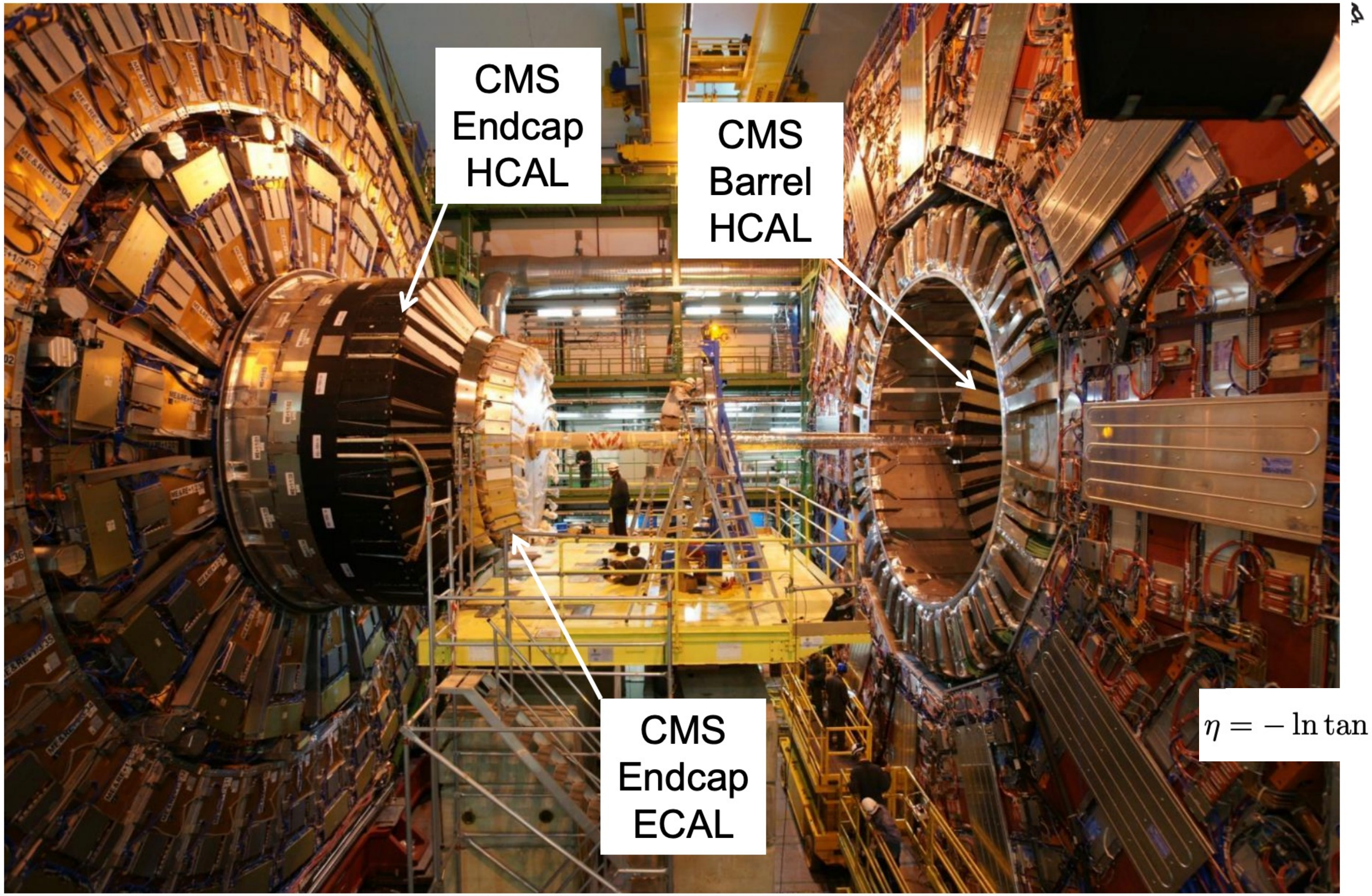
- Hadron Barrel (HB)
  - $|\eta| < 1.3$
- Hadron Outer (HO)
  - $|\eta| < 1.3$
- Hadron Endcap (HE)
  - $1.3 < |\eta| < 3$
- Hadron Forward (HF)
  - $3 < |\eta| < 5.2$

Resolution (HB/HE):

$$\frac{\sigma}{E} = \frac{115\%}{\sqrt{E}} \oplus 5.5\%$$

Resolution (HF):

$$\frac{\sigma}{E} = \frac{280\%}{\sqrt{E}} \oplus 11\%$$



$$\eta = -\ln\tan\frac{\vartheta}{2}$$

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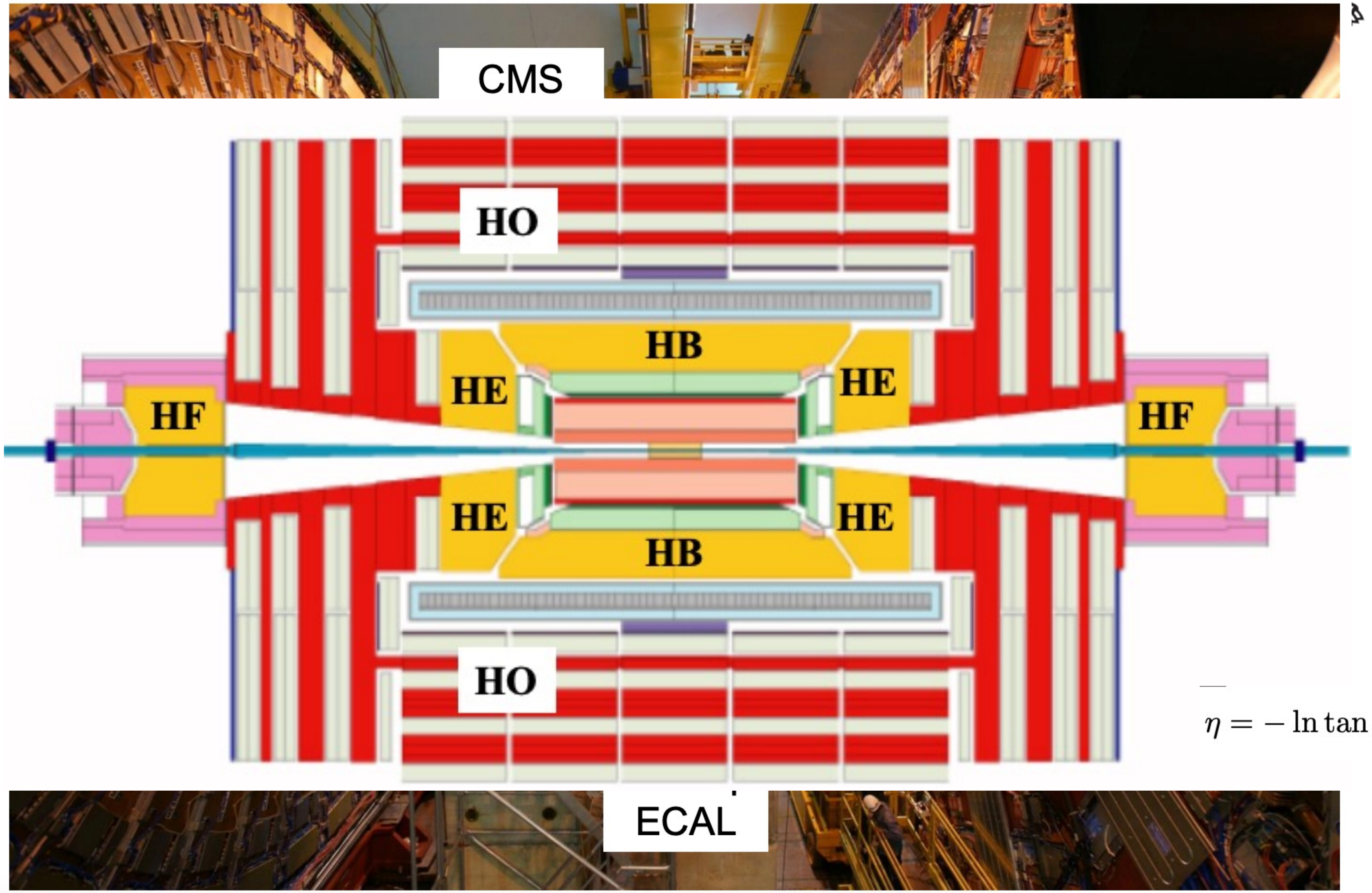
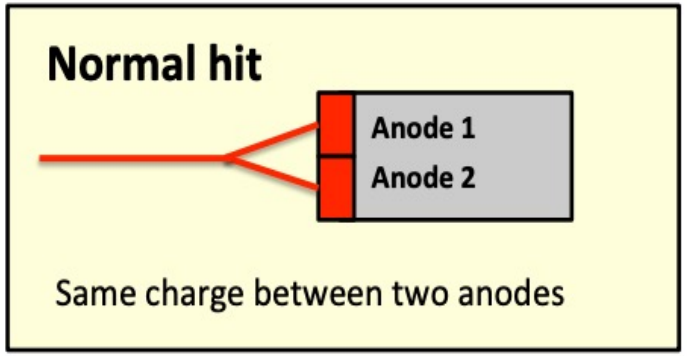


$$\eta = -\ln\tan\frac{\vartheta}{2}$$

CMS HCAL

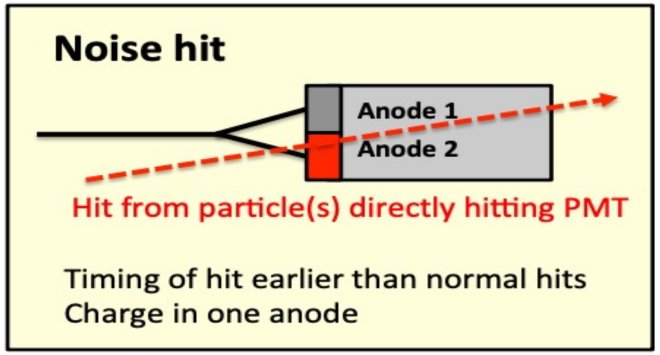
- HB & HE calorimeter: Over 1000 tons of brass plates interleaved with scintillator tiles
  - WLS Fibers transfer scintillation light to readout electronics
  - Readout with hybrid photodiodes (HPDs) and upgraded to SiPMs in HE.
- Forward (HF) Cherenkov detector
  - Steel plates embedded with quartz fibers
  - Readout with PMTs

In the HF, anomalous signals were produced by particles hitting the PMT windows. These PMT have been replaced with thinner window, multi-anode readout design, that mitigates this effect by a significant factor



Normal hit

Same charge between two anodes



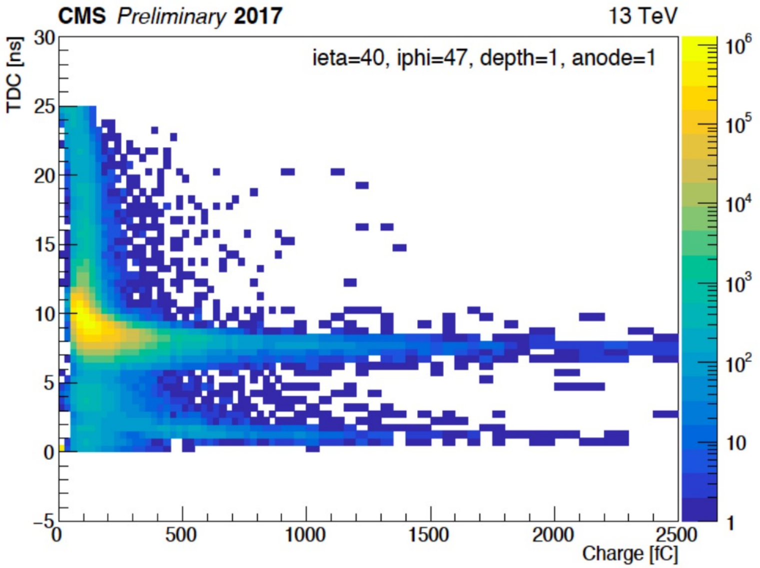
Noise hit

Hit from particle(s) directly hitting PMT

Timing of hit earlier than normal hits
Charge in one anode

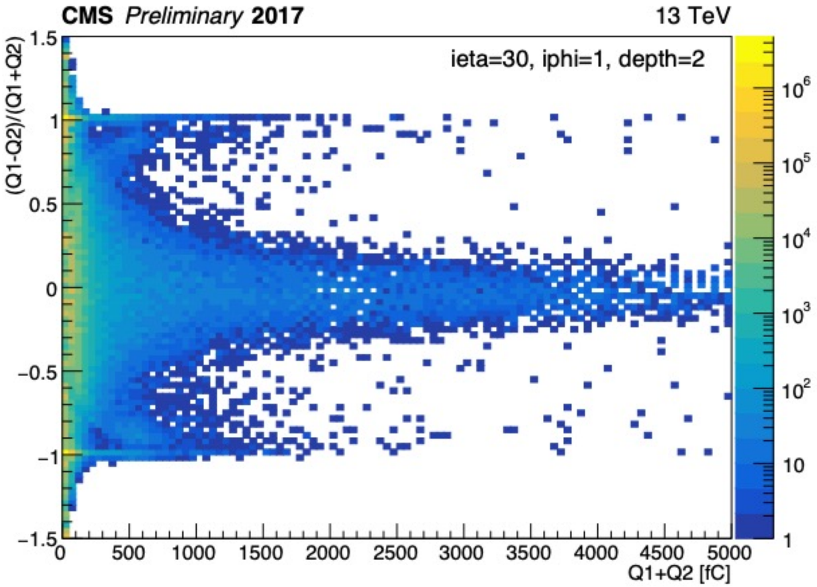
CMS HCAL

Time as measured by TDC vs anode charge in a given HF channel

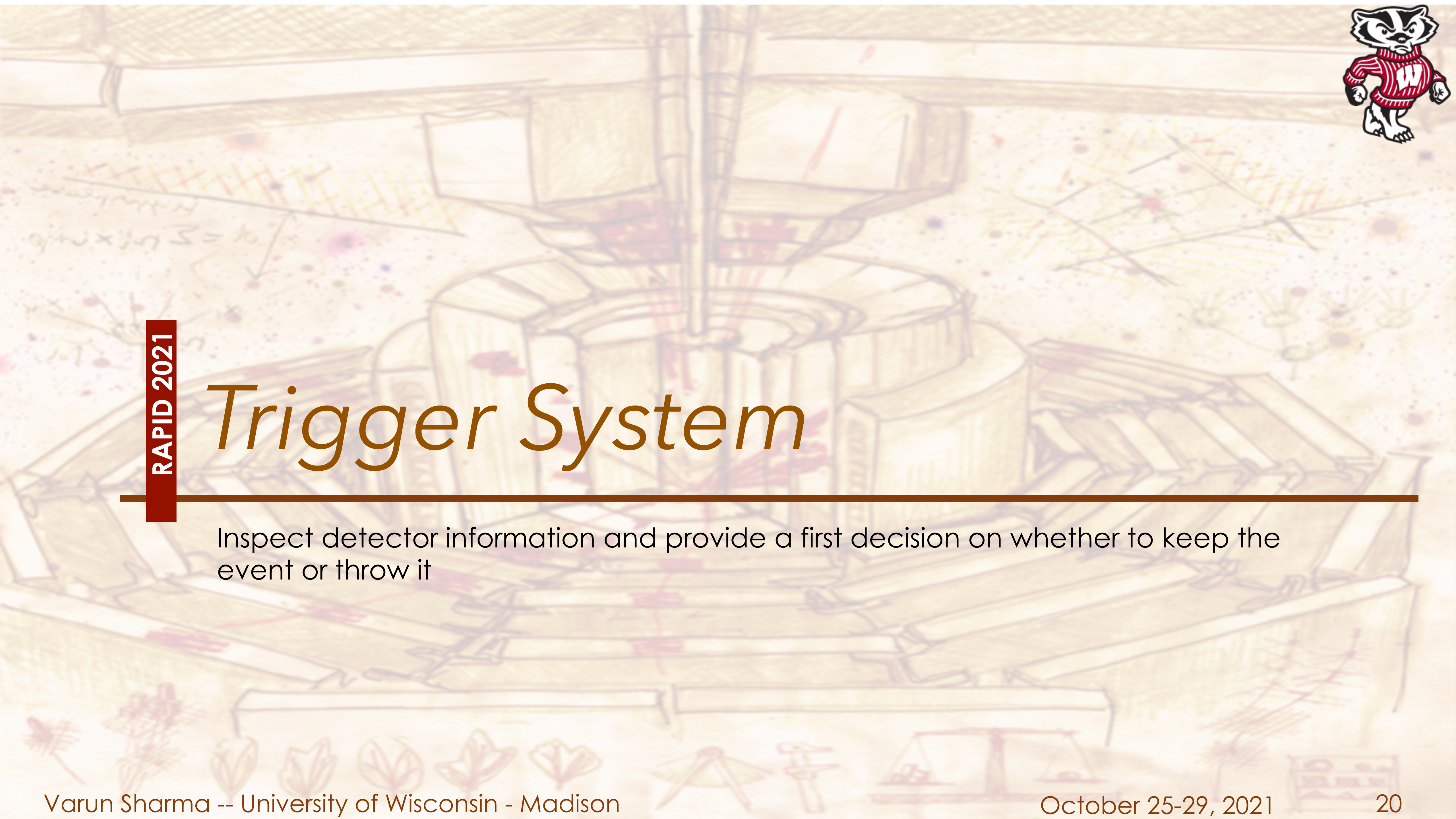


There is a contribution with low TDC values (< 5ns) that originate from particles hitting PMT. Normal hits are populated around 8 ns.

Charge asymmetry



Good separation can be observed between particles directly hitting the PMTs sitting at low time values, and hits from standard collision particles



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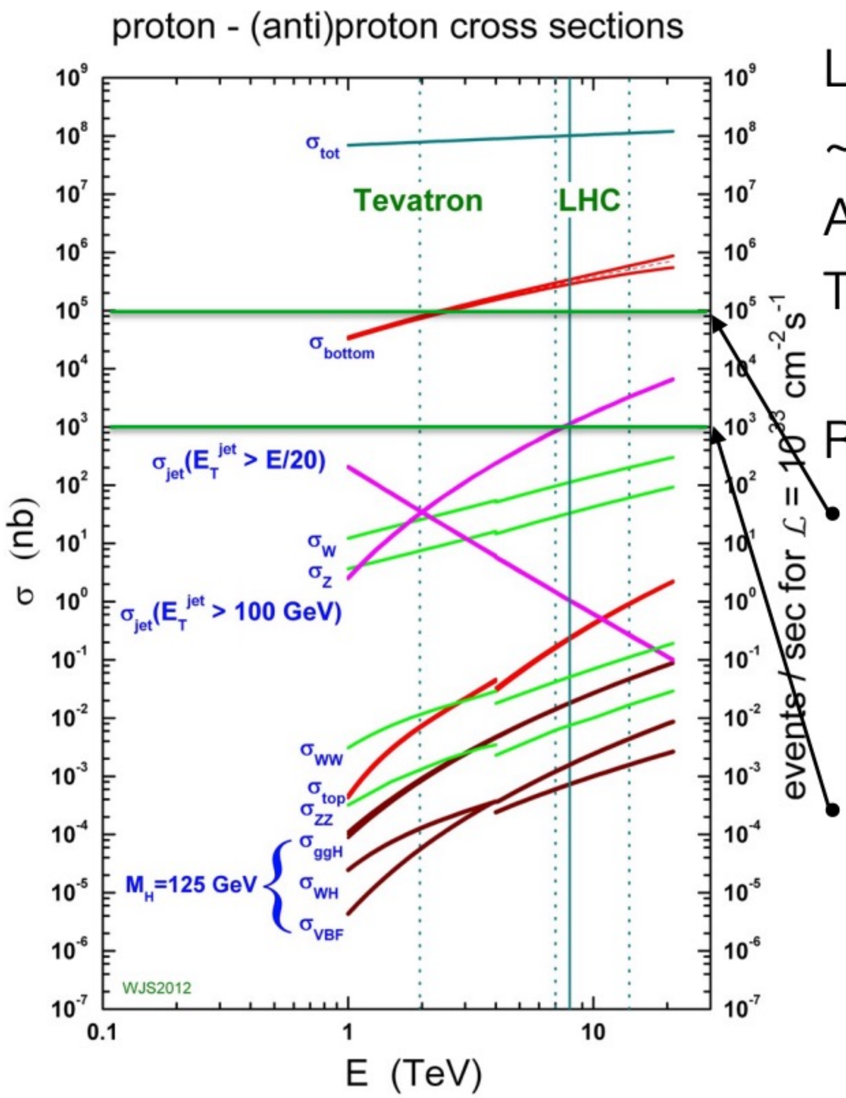
Trigger System

Inspect detector information and provide a first decision on whether to keep the event or throw it

Trigger System



LHC collides bunches of protons at 40MHz

~25 collisions per bunch ➞ GHz rate

At a Mb per event, CMS can record ~1kHz

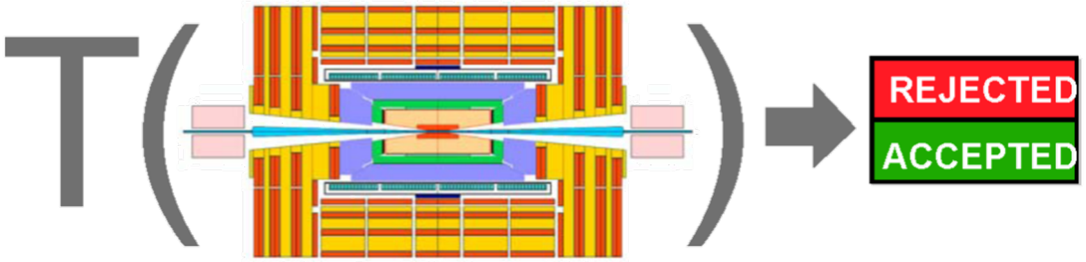
Trigger System decides what to keep

Rate reduction in two steps:

- Level-1 Trigger (40 MHz → 100kHz)
  - Custom hardware
  - Subset of detector information
  - Reduces rate to ~100kHz
- High-Level Trigger (100 kHz → 1 kHz)
  - Software, CPU-limited
  - Full detector information
  - Reduces rate to ~1kHz

Level-1 Trigger System

The trigger is a function of :



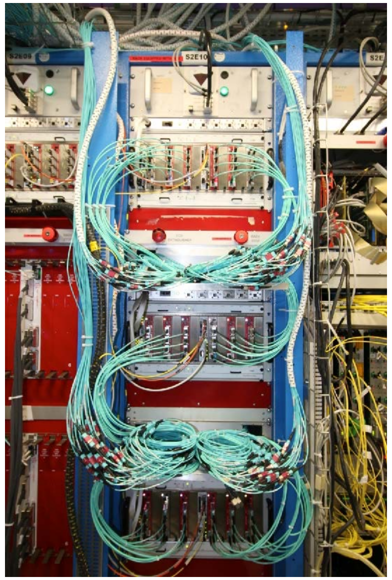
L1 Trigger receives simplified detector information from calorimeters and muon systems, and forms

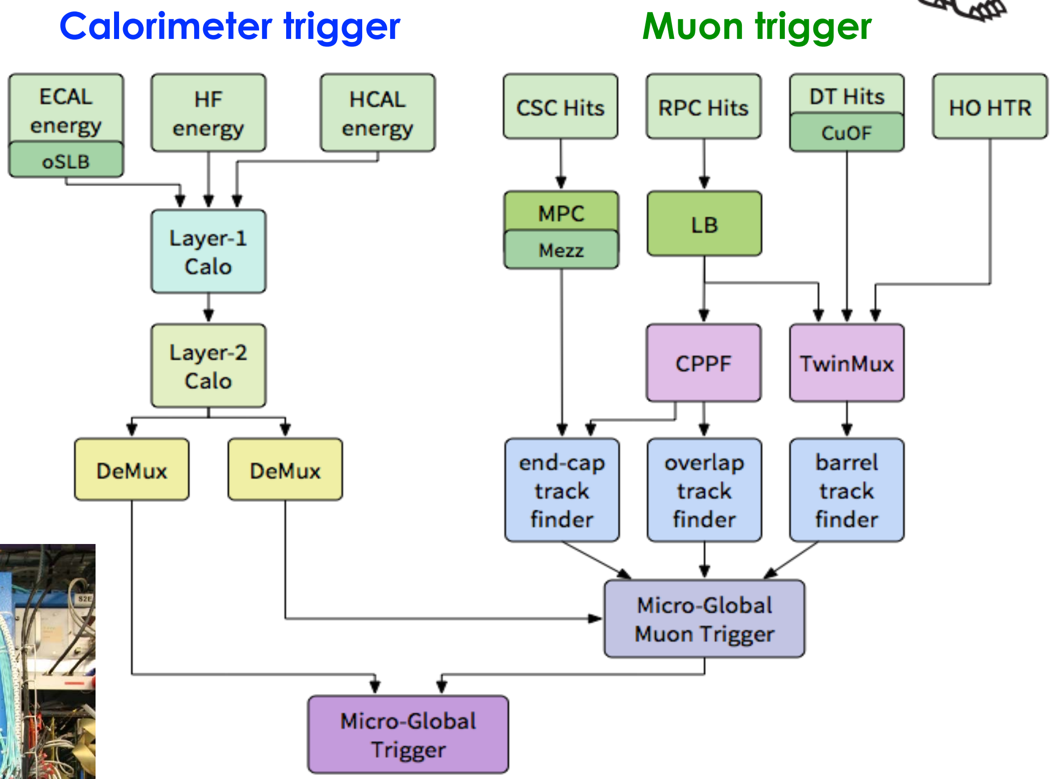
- EG candidates
- Jet candidates
- Missing energy estimates
- Muon candidates

L1 accept if objects pass

- Energy thresholds
- Coincidence
- Object topology

- Defined in ‘trigger menu’
- Once every 25ns
- Pipeline ~4μs long





Calorimeter trigger

ECAL energy
oSLB
HF energy
HCAL energy
Layer-1 Calo
Layer-2 Calo
DeMux
DeMux

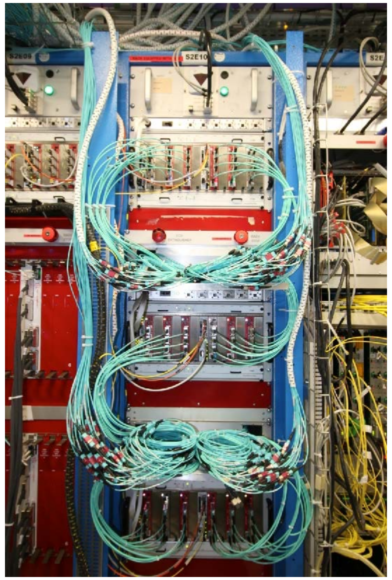
Muon trigger

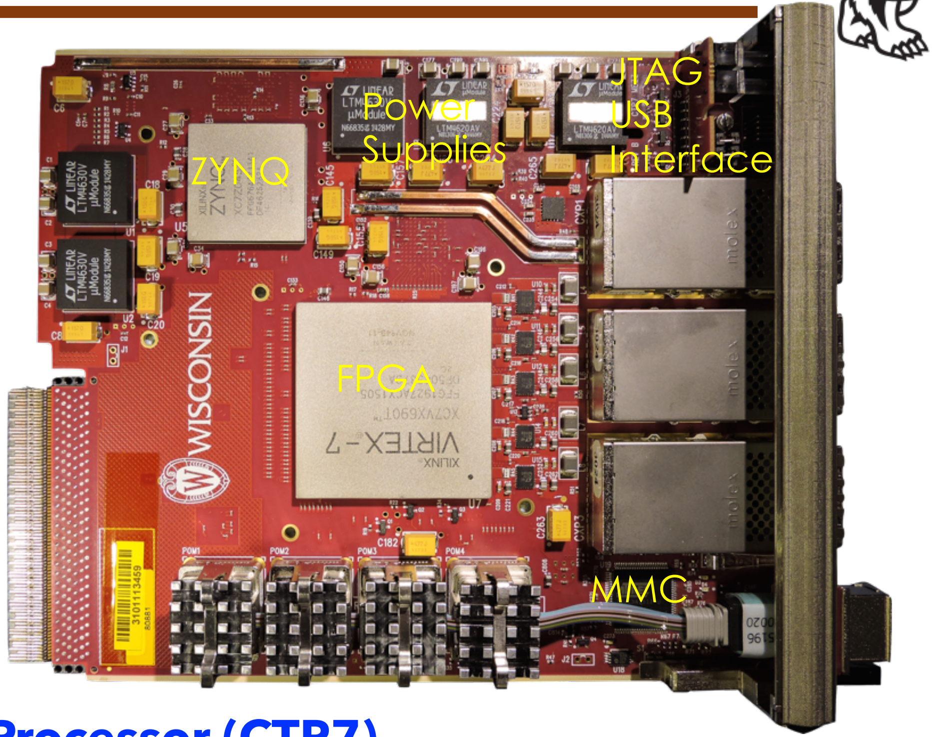
CSC Hits
RPC Hits
DT Hits
CuOF
HO HTR
MPC
Mezz
LB
CPPF
TwinMux
end-cap track finder
overlap track finder
barrel track finder
Micro-Global Muon Trigger
Micro-Global Trigger

FPGA based High-speed custom hardware

WHY FPGAs?

- Field Programmable Gate Arrays (FPGAs) give a huge amount of flexibility and are used in the LHC
- Design is specified by schematics or with a hardware language (HDL, Verilog)
- Revolutionised trigger systems since the logic (algorithms) do not need to be fixed when the board is produced
- Can change the algorithms running in hardware, in light of better detector understanding, even physics discoveries
- Traditionally difficult to program, requiring low-level languages e.g. VHDL, recently
- Huge progress in high-level language translation (Xilinix's HLS tool)





Calorimeter Trigger Processor (CTP7)

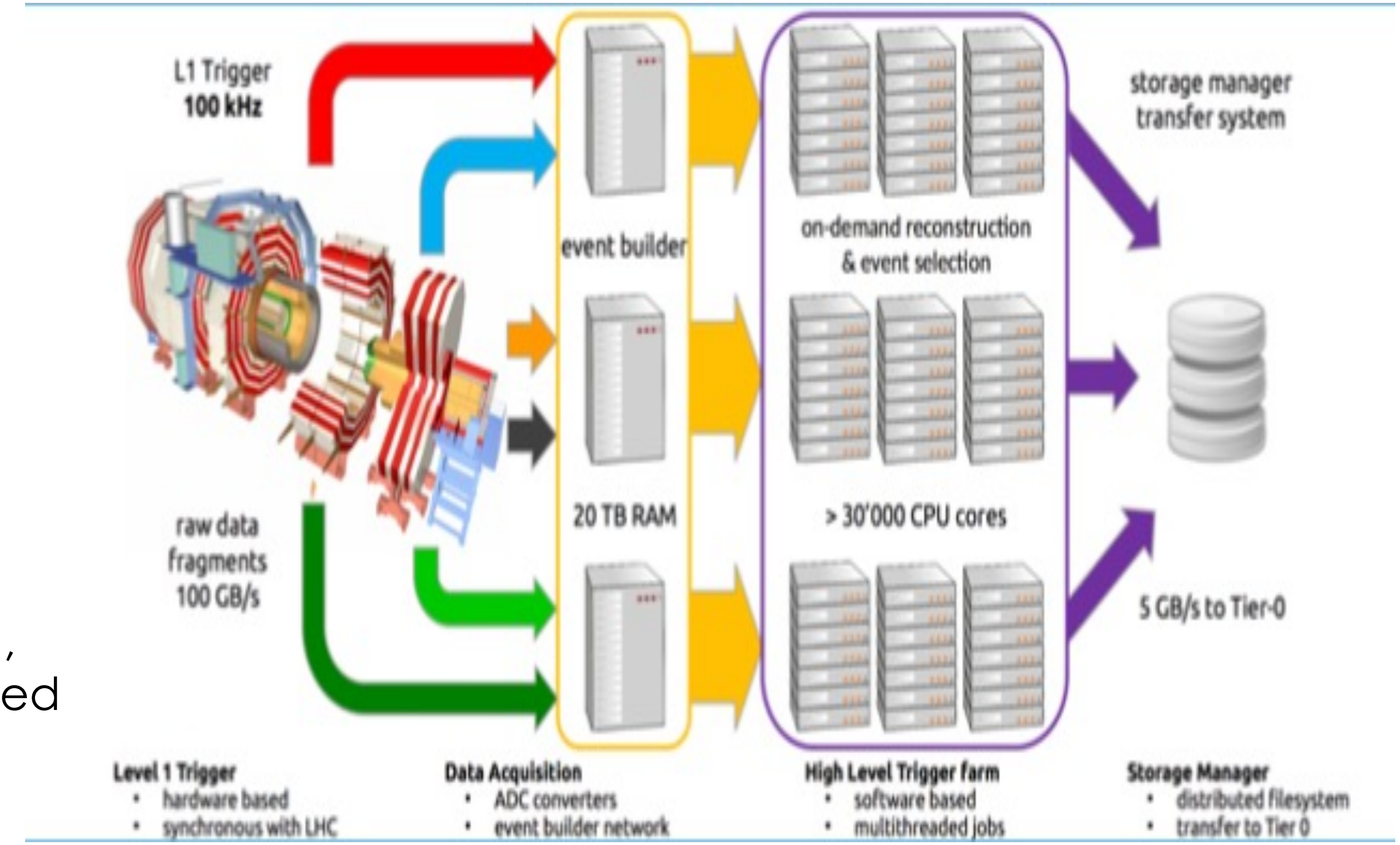
- mTCA Single Virtex 7 FPGA, 67 optical inputs, 48 outputs, 12 RX/TX backplane
- Virtex 7 allows 10 Gb/s link speed on 3 CXP (36 TX & 36 RX) and 4 MiniPODs (31 RX & 12 TX)
- ZYNQ processor running Xilinx PetaLinux for service tasks, including virtual JTAG cable

High Level Trigger

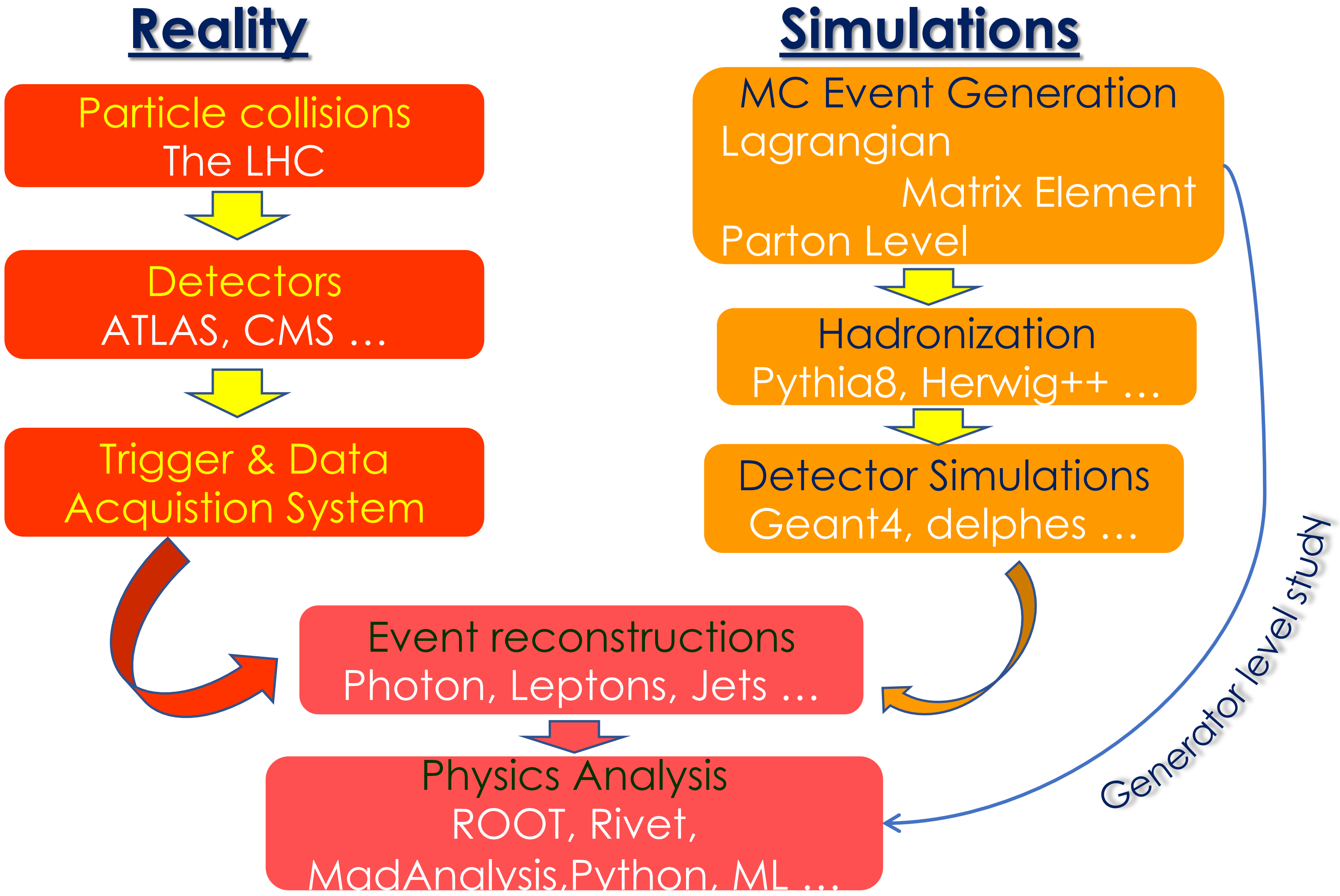
Dedicated computer farm

- Commodity hardware
- Receives full detector readout
- Software based information
- Subset of reconstruction algorithms
- Over 450 trigger paths in HLT menu
- On average event decisions must be made in **200 μs**

- For HLT accepts, raw data is processed, compressed and calibrations are applied
- Some raw data can be ‘parked’



Physics Analysis in nutshell



Reality

Particle collisions
The LHC

Detectors
ATLAS, CMS …

Trigger & Data
Acquistion System

Simulations

MC Event Generation
Lagrangian
Matrix Element
Parton Level

Hadronization
Pythia8, Herwig++ …

Detector Simulations
Geant4, delphes …

Generator level study

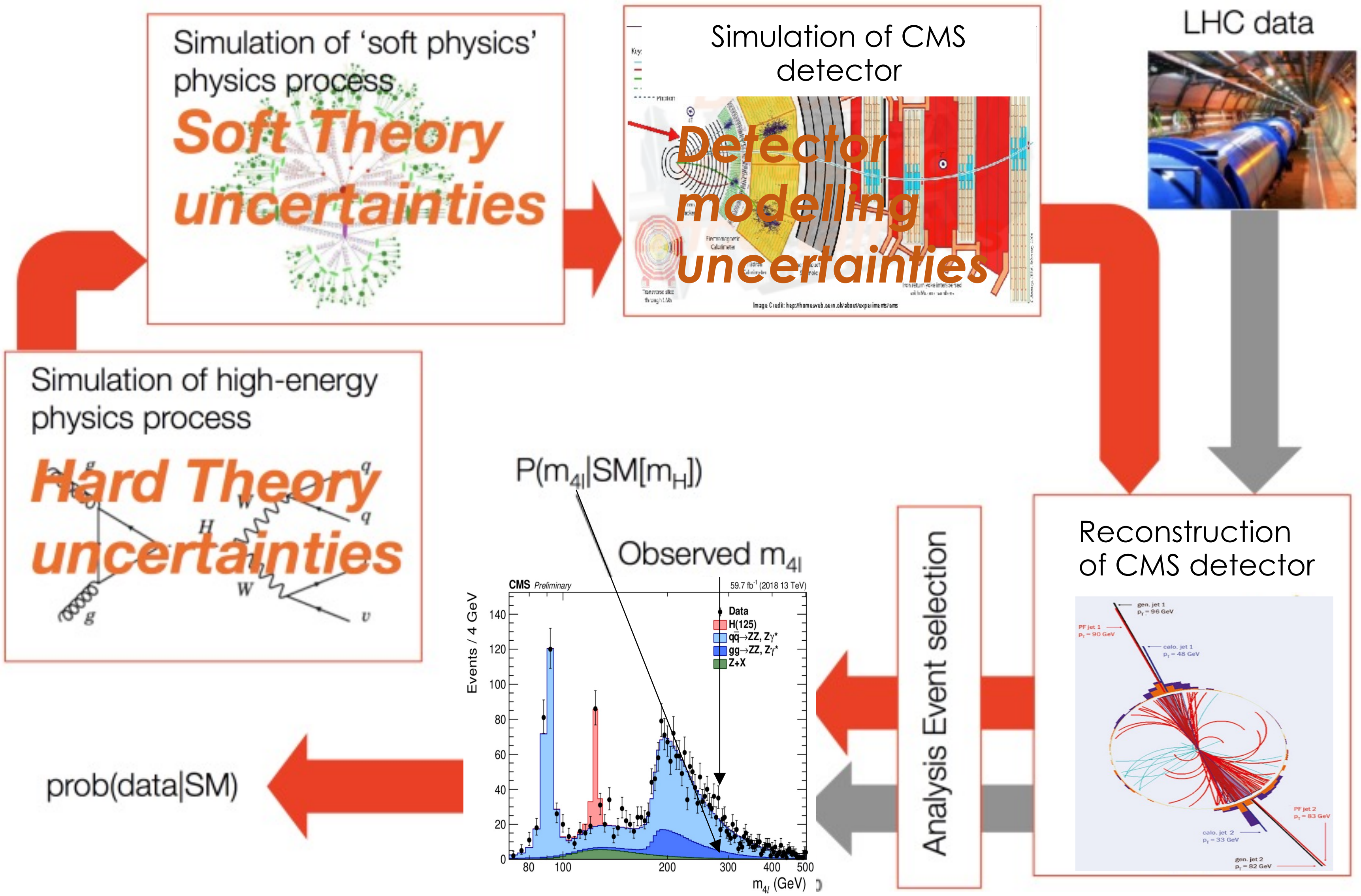
Event reconstructions
Photon, Leptons, Jets …

Physics Analysis
ROOT, Rivet,
MadAnalysis,Python, ML …

Never so
trivial in
reality!

New Physics = Data – Standard Model

An example



Simulation of 'soft physics' physics process

Soft Theory uncertainties

Simulation of CMS detector

Detector modelling uncertainties

LHC data

Simulation of high-energy physics process

Hard Theory uncertainties

Reconstruction of CMS detector

Analysis Event selection

$P(m_{4l}|SM[m_H])$

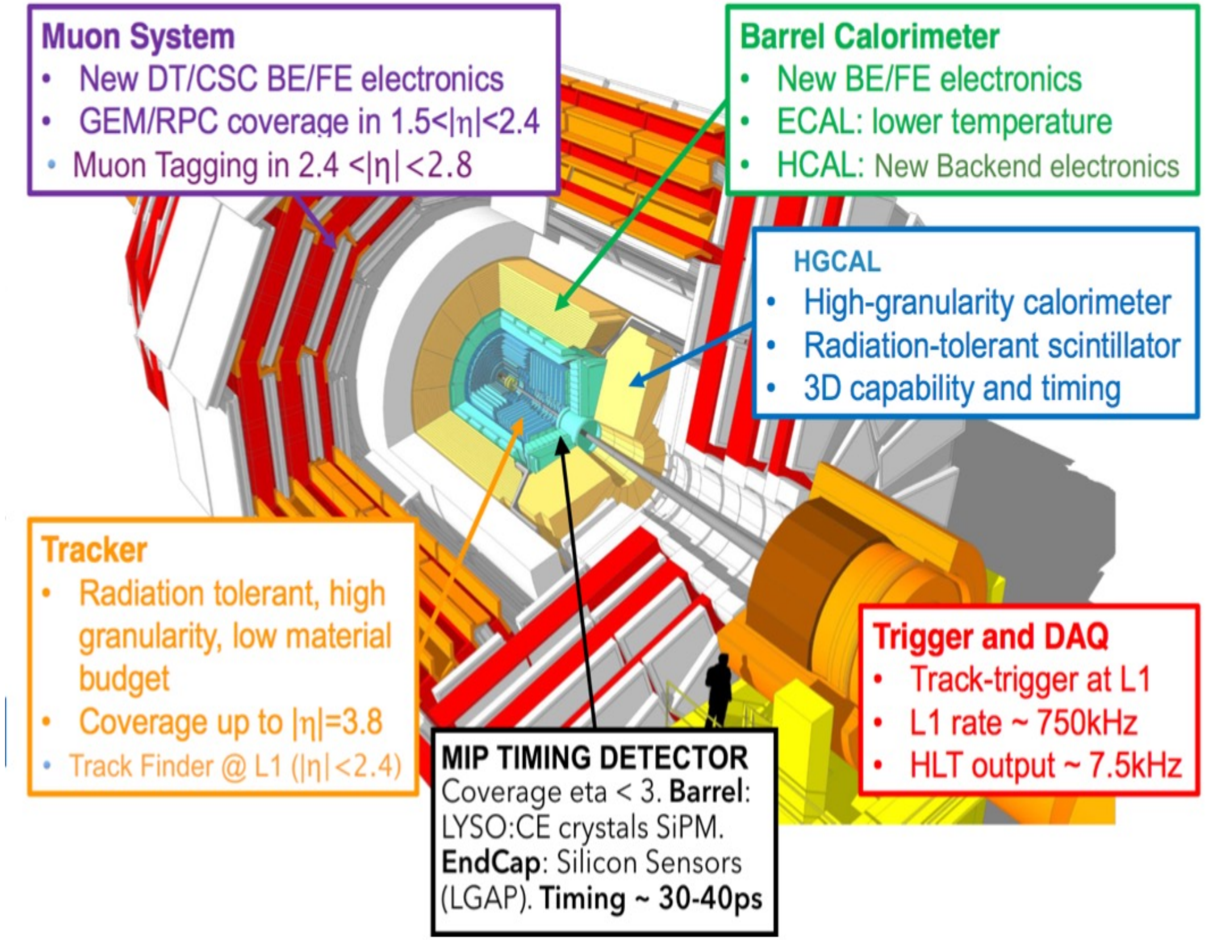
Observed m_{4l}

prob(data|SM)

THE CMS HL-LHC Upgrade

- ***Unprecedented opportunity to explore uncharted territory***
  - High precision measurements in SM
  - Improved characterization of Higgs Sector
  - Unravel the blind spots and unconventional signatures in BSM scenarios

- ***How to address***
  - ✓ Large data sample
  - ✓ Upgraded detector (extended coverage)
  - ✓ Advanced selection algorithms
  - ✓ Sophisticated triggers to select specific topologies such as VBS/VBF, rare B-meson decay, etc.
  - ✓ Scouting system



Muon System
- New DT/CSC BE/FE electronics
- GEM/RPC coverage in $1.5<|\eta|<2.4$
- Muon Tagging in $2.4 <|\eta|<2.8$

Barrel Calorimeter
- New BE/FE electronics
- ECAL: lower temperature
- HCAL: New Backend electronics

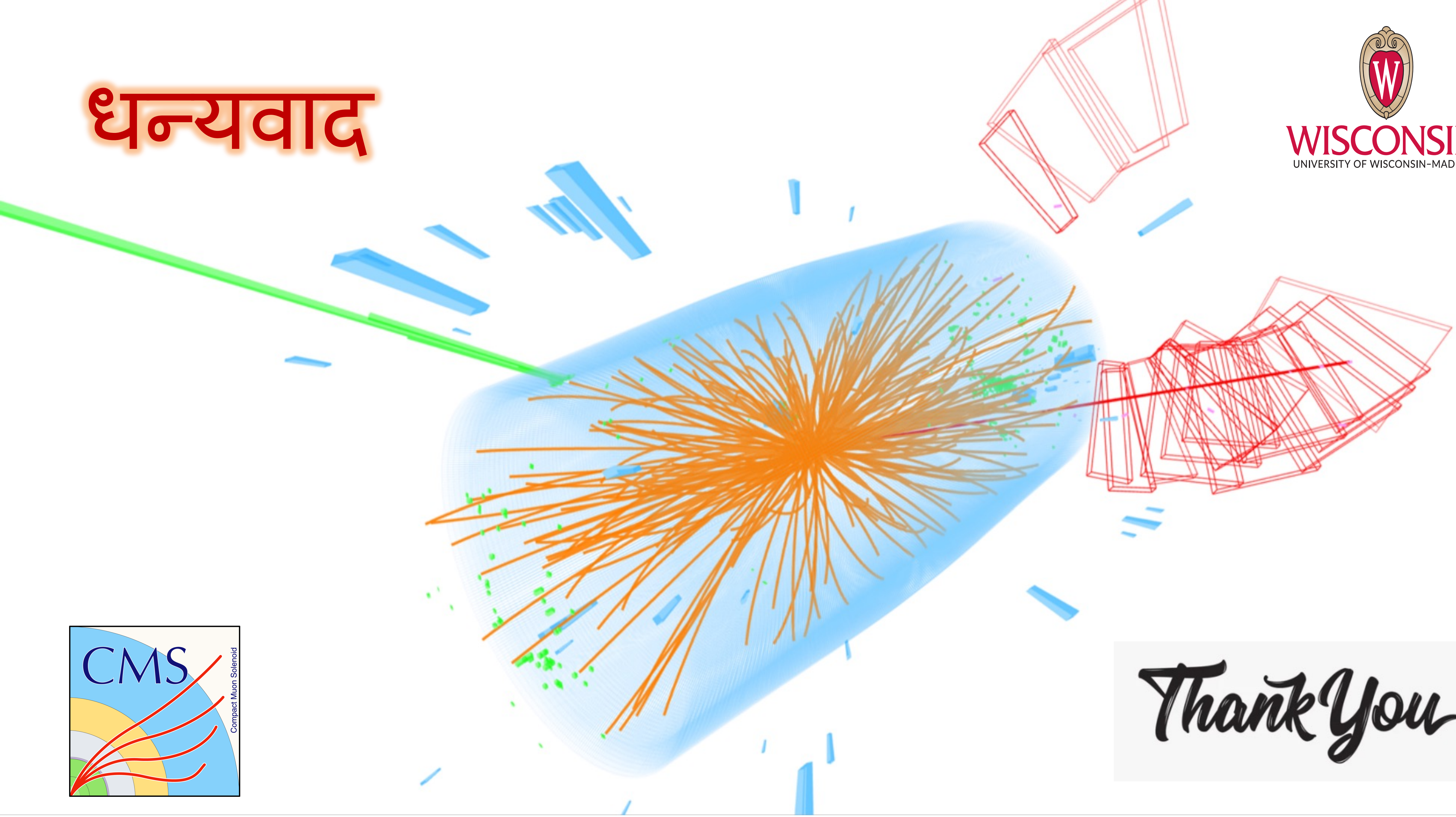
HGCAL
- High-granularity calorimeter
- Radiation-tolerant scintillator
- 3D capability and timing

Tracker
- Radiation tolerant, high granularity, low material budget
- Coverage up to $|\eta|=3.8$
- Track Finder @ L1 ($|\eta|<2.4$)

MIP TIMING DETECTOR
Coverage eta < 3. **Barrel**: LYSO:CE crystals SiPM. **EndCap**: Silicon Sensors (LGAP). **Timing ~ 30-40ps**

Trigger and DAQ
- Track-trigger at L1
- L1 rate ~ 750kHz
- HLT output ~ 7.5kHz

धन्यवाद



Thank You

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Additional material

Event Simulation: Proton Collision

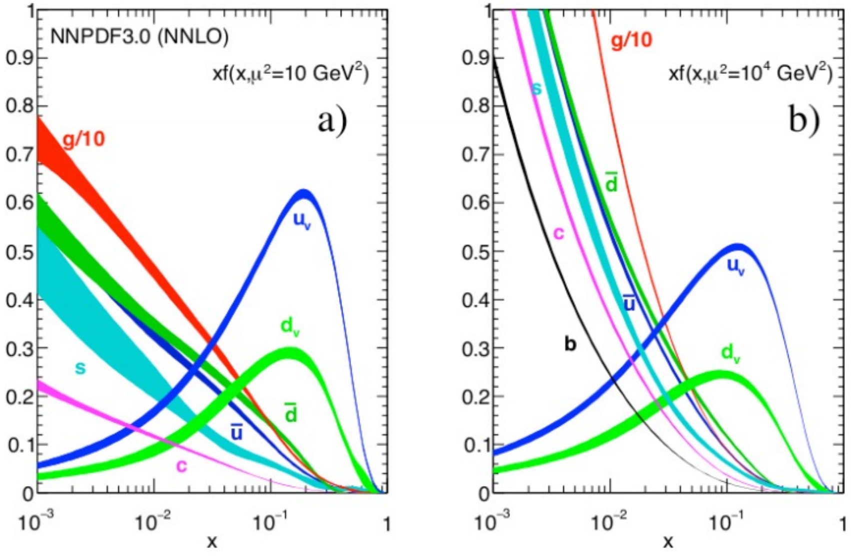
Factorization theorem: proton collision consists of

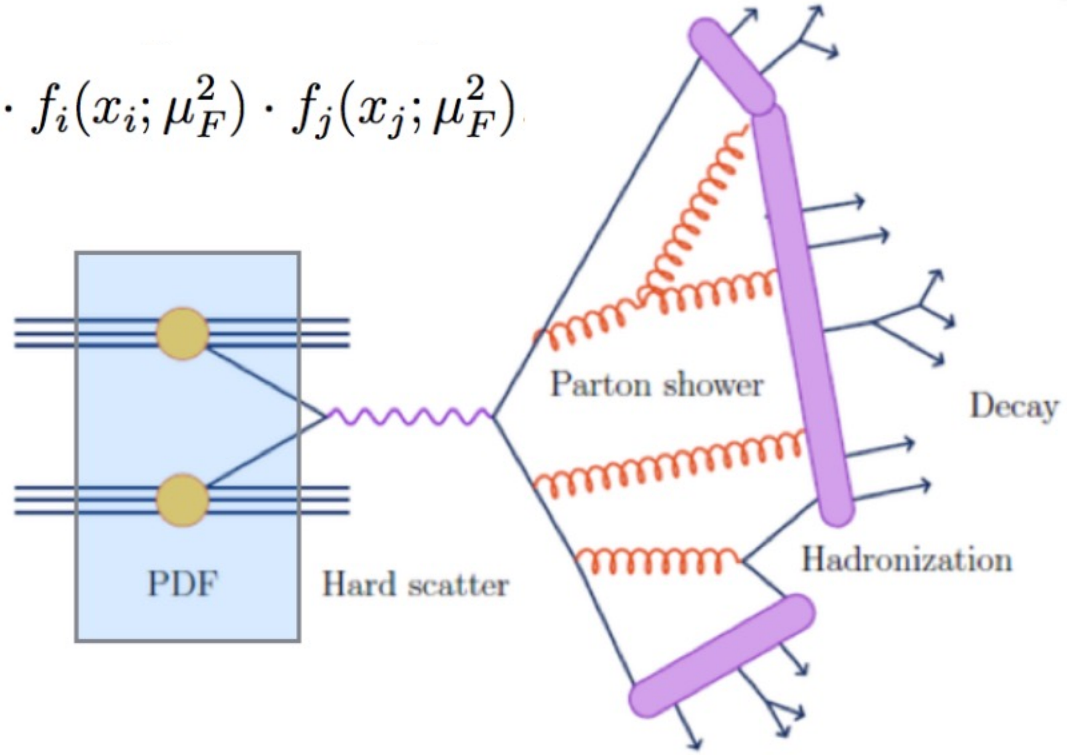
- Hard scatter (high-energy)
- Underlying event (low-energy)

Modern picture of a proton:

- Each parton (quark/gluon) contributes momentum fraction x with probability *f*, as resolved at factorization scale *μ*
- Cross section:

$$\sigma_{pp\to X} = \sum_{i,j}\int dx_i dx_j\, \sigma_{ij\to X}(x_i, x_j)\cdot f_i(x_i;\mu_F^2)\cdot f_j(x_j;\mu_F^2)$$

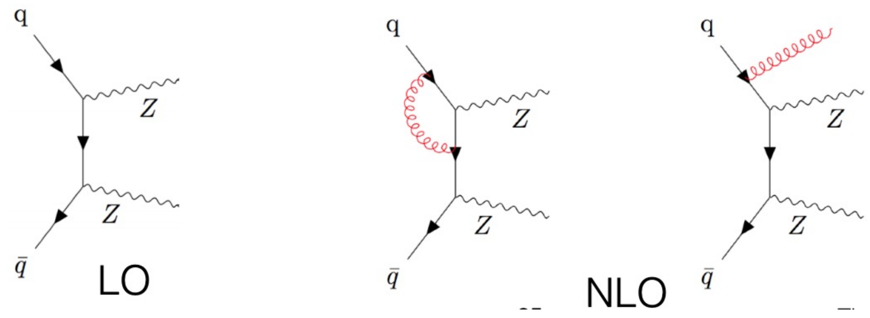




Hard Scatter, Hadronization & Detector Effects

Programs for hard scatter simulation

- MadGraph/aMC@NLO: Automated calculation of Feynman diagrams
- MCFM, PYTHIA, etc.
- These (mostly) provide predictions at Next-to Leading Order (NLO) in quantum chromodynamics (QCD) perturbation theory, eg.

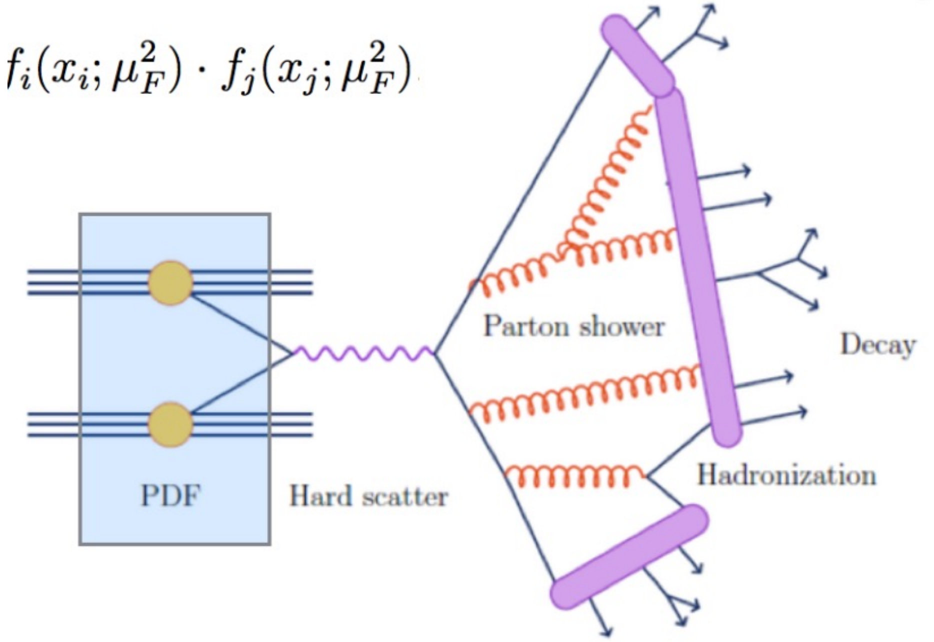


After the hard scatter simulation

- Pythia simulates
  - Parton Shower
  - Hadronization
  - Decay to stable particles

GEANT4

- Passage of stable particles through detector

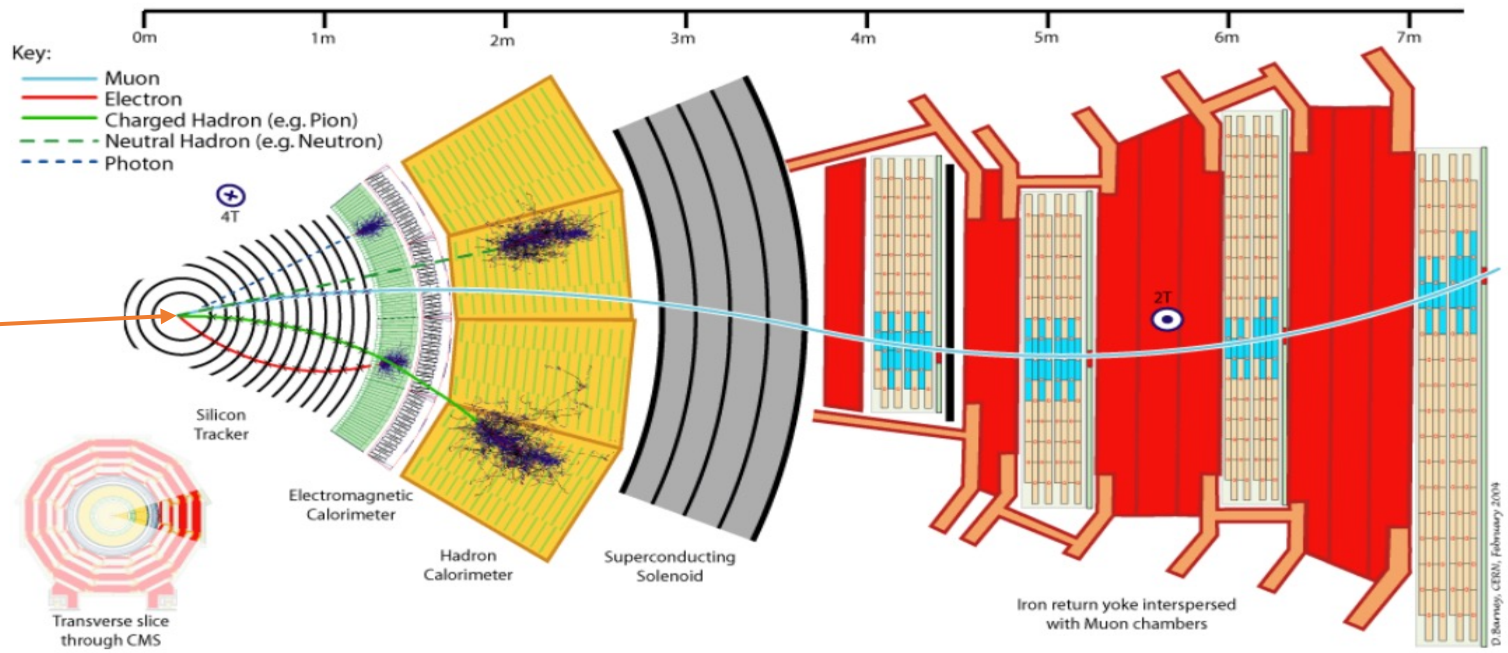


$$f_i(x_i;\mu_F^2)\cdot f_j(x_j;\mu_F^2)$$

Event Reconstruction

Particle Flow (PF) Reconstruction combines information from all detector components, building candidates in order of purity

- Muon system tracks are combined with inner tracker to make muon candidates
- ECAL & HCAL deposits are matched to tracker tracks to make electron & charged hadron candidates
- Remaining calorimeter energy is clustered to form photon candidates (ECAL) & neutral hadron candidates (HCAL)



Primary Vertex: the collision (vertex) from which our objects are linked

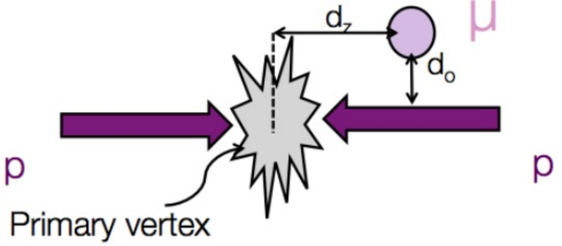
Muon Reconstruction

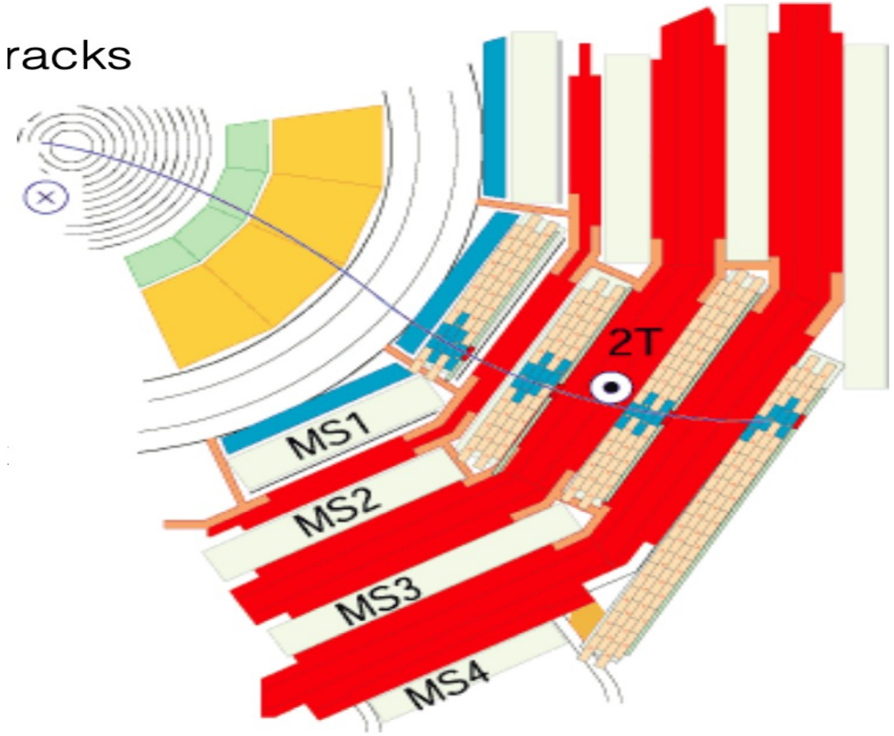
Categories of reconstructed muons:

- Standalone - tracks from segments in muon systems
  - 1% exclusive rate, very high cosmic muon acceptance
- Tracker - match inner detector tracks with one segment in muon system
  - High efficiency for low pT muons
- Global - match standalone muons with tracks
  - More information available
  - High purity

Muons in analysis

- Global reconstruction
- Require segments in at least 2 muon stations
- >5 tracker layers for pT measurement
- Distance of closest approach to primary vertex
  - Transverse < 0.2 mm
  - Longitudinal < 1 mm





Electron/Photon Reconstruction

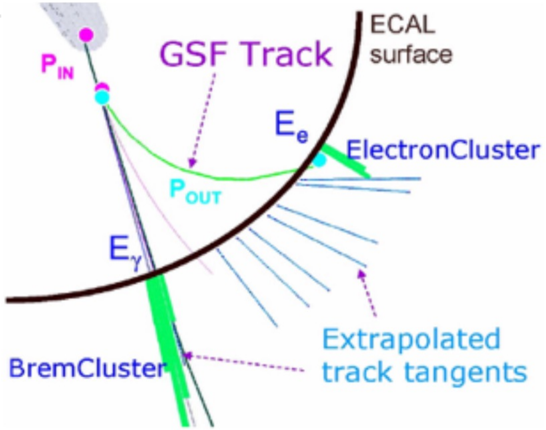
Electrons identified by combination of detectors

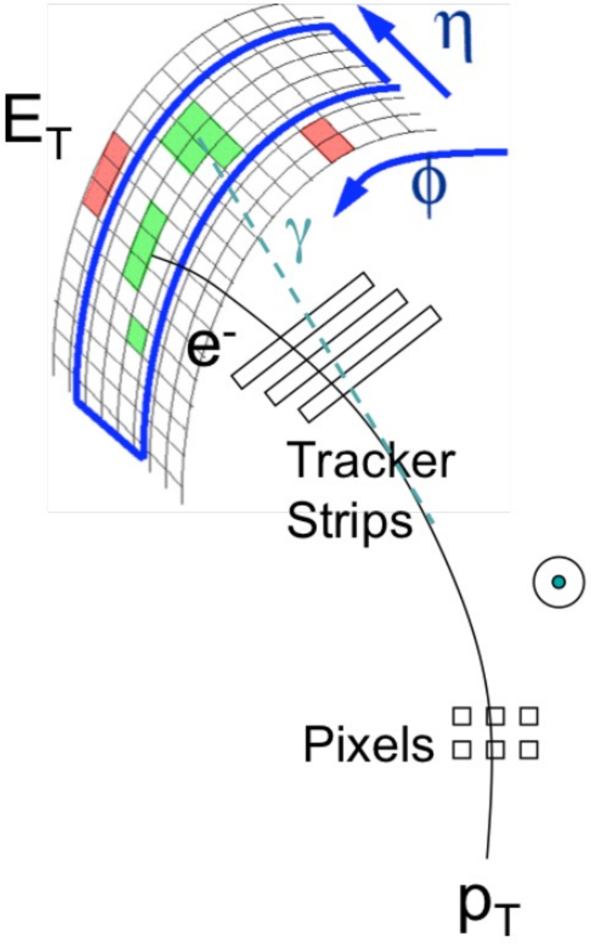
- Basic object called 'GSF electron'
- ECAL supercluster
- Gaussian-Sum Filter track reconstruction

Electron: match superclusters to track seeds
Photon: superclusters unmatched to track see

Electrons in analyses:

- Tracker
  - <2 missing track hits
  - Photon conversion vertex veto
- ECAL
  - Distance between cluster and track
  - ECAL energy to track momentum compatibility
  - Shower shape compatibility requirement
- HCAL
  - H/E cut for rejection of hadrons





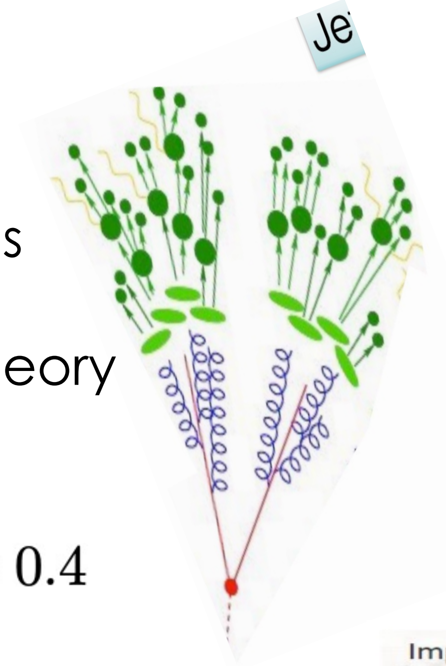
ECAL Barrel: $|\eta| < 1.479$

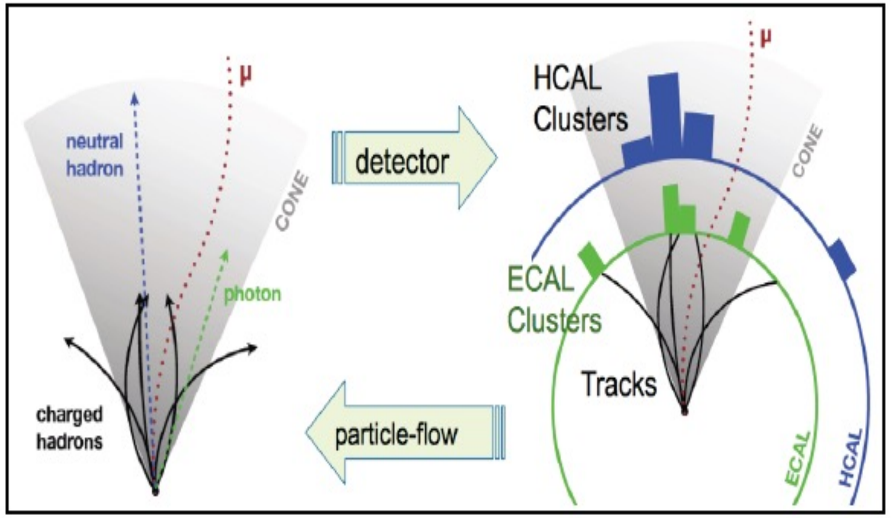
Jet Reconstruction

Quarks and gluons hadronized

- Showers of many particles formed
- Jet reconstruction algorithms:
    - Iteratively cluster nearby particles
    - Form macroscopic objects
    - Preserve ability to compare to theory
- In analysis, Anti-kT distance metric:

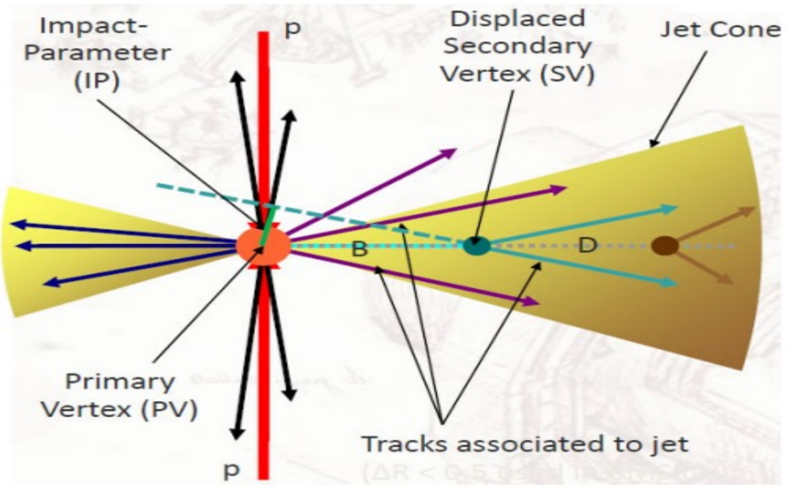
$$d_{ij} = \min\left(\frac{1}{k_{t,i}^2}, \frac{1}{k_{t,j}^2}\right)\frac{\Delta_{ij}^2}{R^2}, \quad R = 0.4$$





Jets from b quarks are distinctive

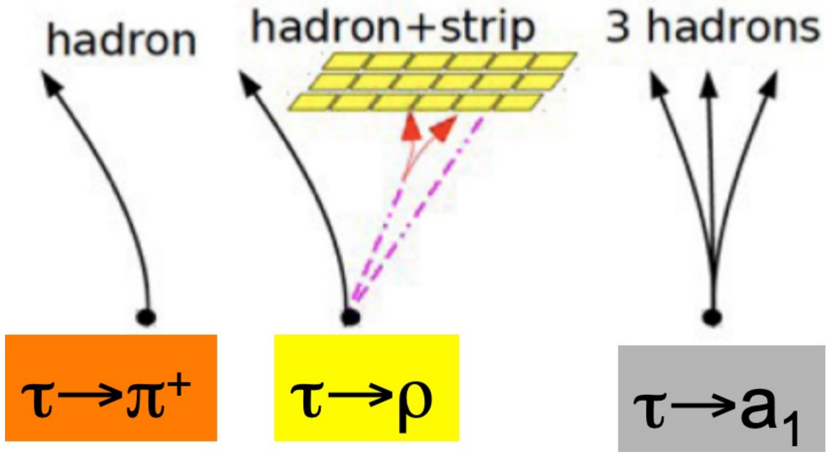
- Long-lived b hadrons form displaced vertex
- B-tagging identifies jets with displaced tracks

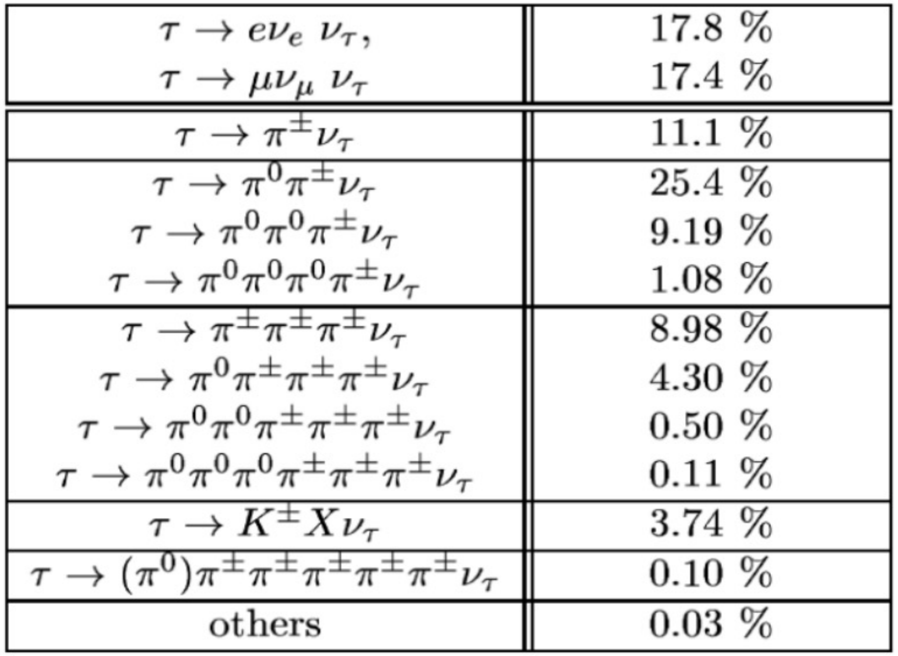


Hadronic Tau Reconstruction

- Hadron plus strips (HPS) algorithm used to reconstruct hadronic taus
- Hadronic taus are seeded from PF Jets with ΔR=0.4
- Hadronic decays are reconstructed from charged and neutral jet constituents in CMS's Particle Flow algorithm
    - 1-prong, 1-prong + π^0s, 3-prong

- Hadrons Plus Strips algorithm:
    - Can identify each hadronic decay mode
    - Exploits intermediate resonances ρ(770) and a1(126





$\tau \to e\nu_e\,\nu_\tau$, $\tau \to \mu\nu_\mu\,\nu_\tau$	17.8 % 17.4 %
$\tau \to \pi^\pm\nu_\tau$	11.1 %
$\tau \to \pi^0\pi^\pm\nu_\tau$	25.4 %
$\tau \to \pi^0\pi^0\pi^\pm\nu_\tau$	9.19 %
$\tau \to \pi^0\pi^0\pi^0\pi^\pm\nu_\tau$	1.08 %
$\tau \to \pi^\pm\pi^\pm\pi^\pm\nu_\tau$	8.98 %
$\tau \to \pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	4.30 %
$\tau \to \pi^0\pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	0.50 %
$\tau \to \pi^0\pi^0\pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	0.11 %
$\tau \to K^\pm X\nu_\tau$	3.74 %
$\tau \to (\pi^0)\pi^\pm\pi^\pm\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	0.10 %
others	0.03 %

Missing Transverse Momentum

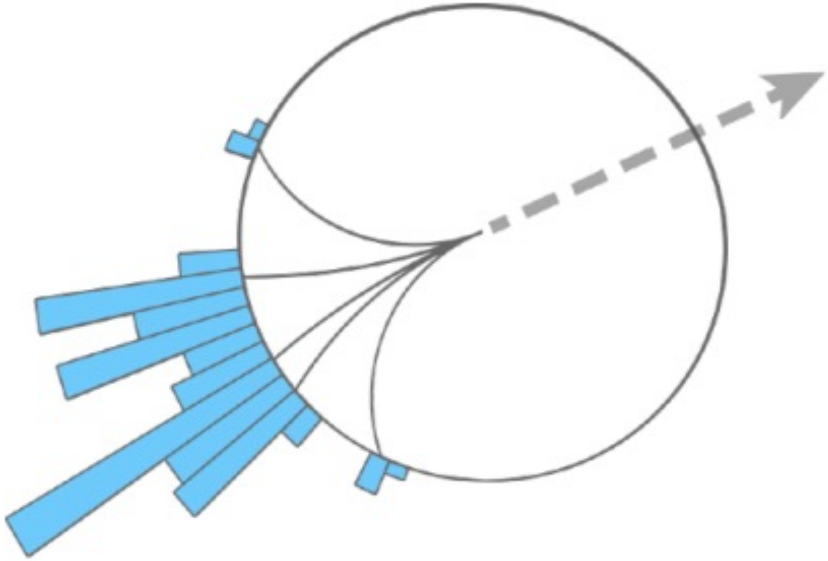
Missing Transverse Momentum (pTmiss)

Negative vector sum of transverse momentum from all reconstructed particles,

pTmiss in analysis,

- All particle-flow candidates summed
- Jet energy corrections are propagated
- Events with anomalous pTmiss removed
  - Noise in HCAL
  - Beam halo muons
  - Pathologies in reconstruction
  - ECAL crystal saturation

- Resolution: ~30 GeV



Usually results from neutrinos or other particles escaping undetected