Taller de Altas Energías

Bilbao 2011

PHYSICS WITH CMS - PART I

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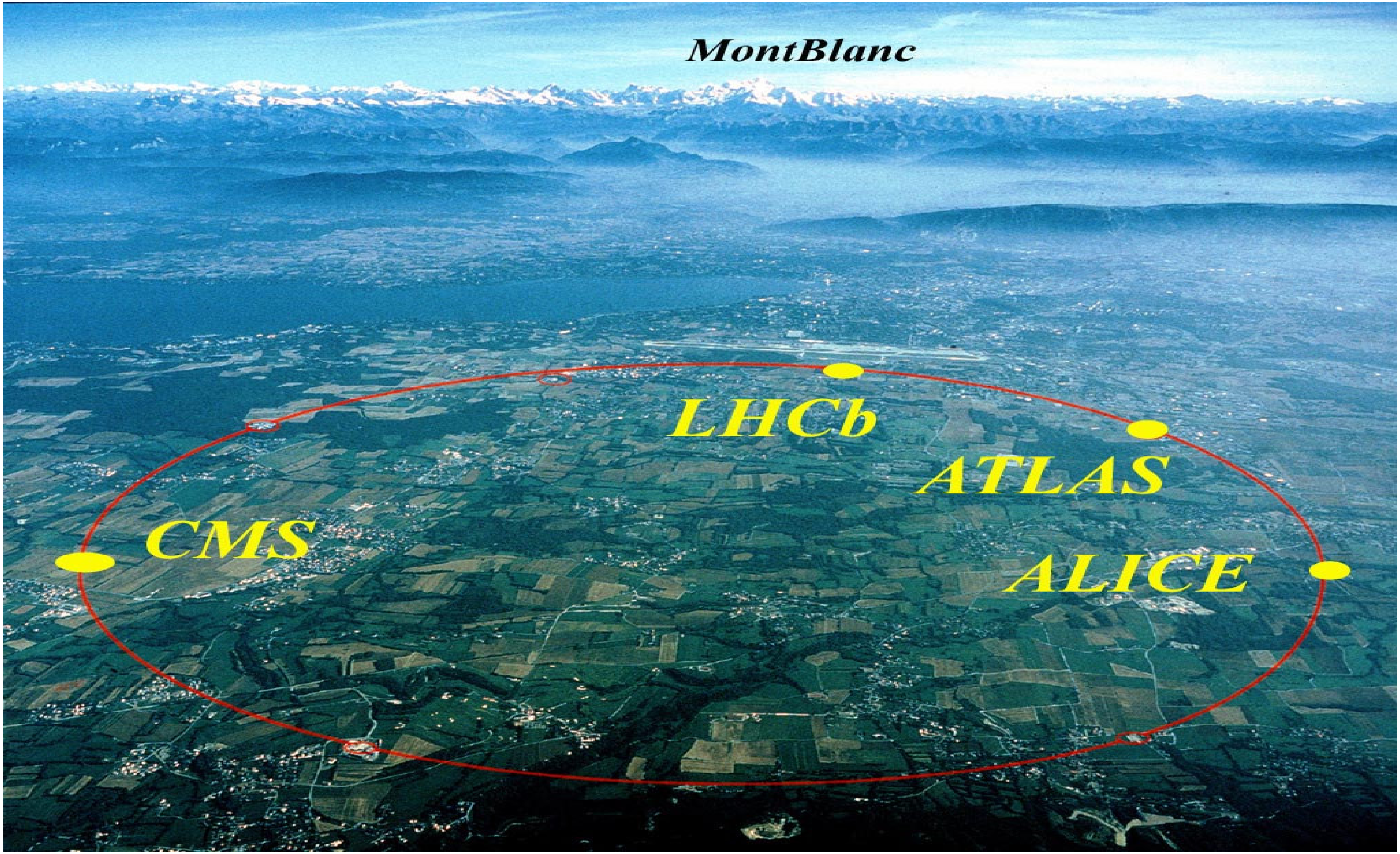
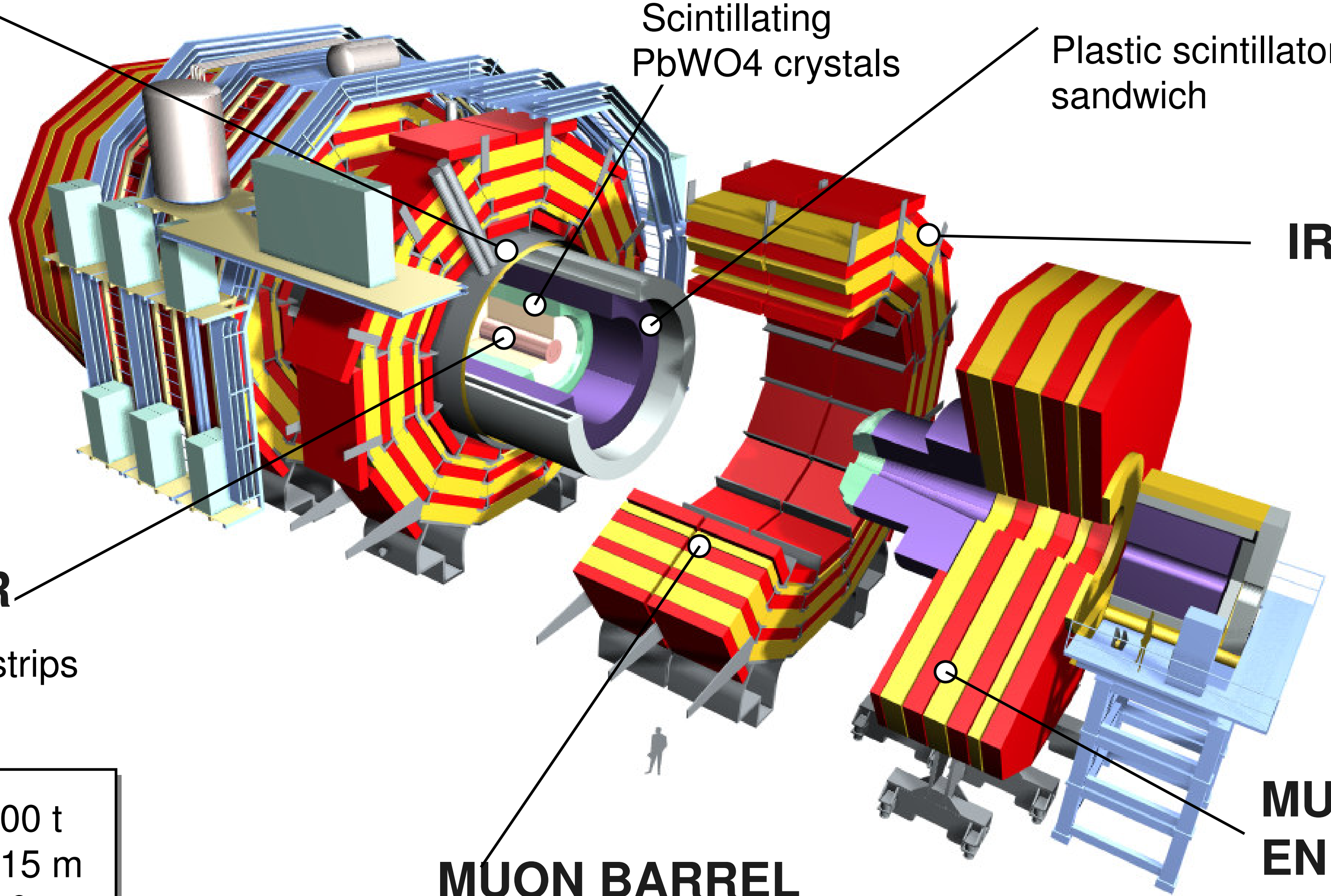
Universidad Autónoma de Madrid

CMS at the LHC

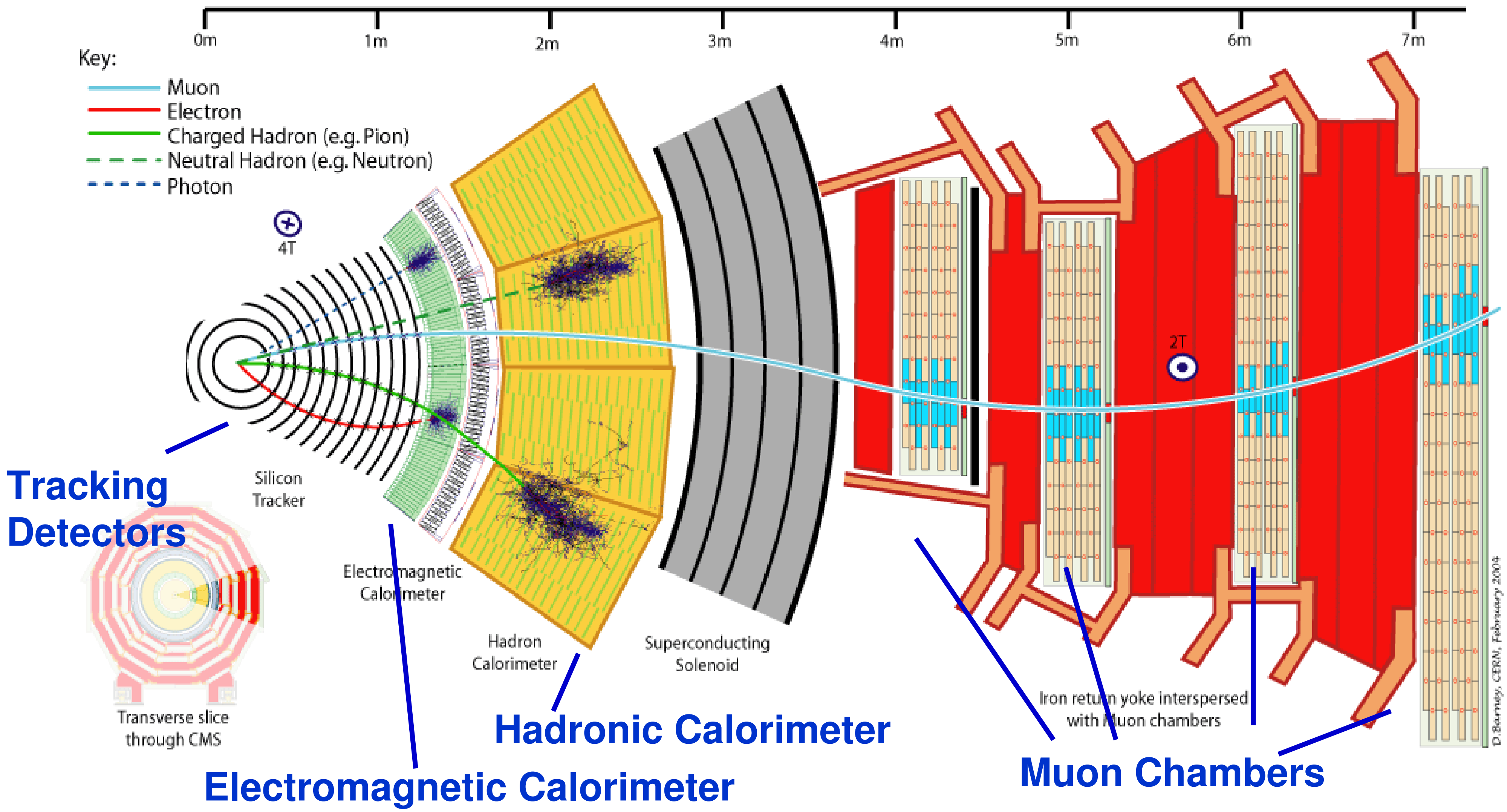


The Modular Design of CMS

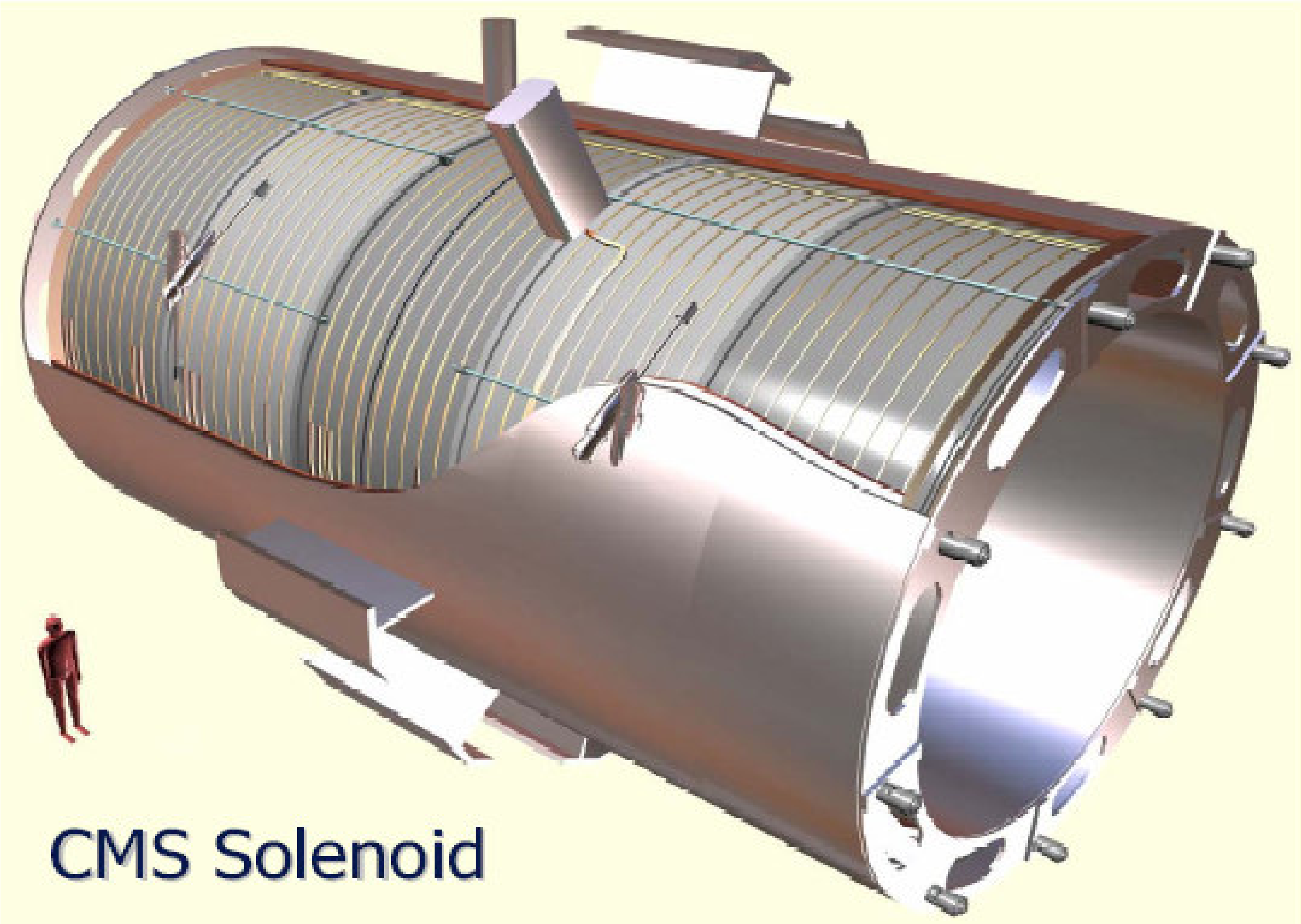


Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

CMS Detector Slice



CMS Superconducting Magnet



central magnetic field:
4 T

nominal current:
20'000 A

stored energy:
2.7 GJ

magnetic inductance:
14 T

weight of cold mass:
220 t

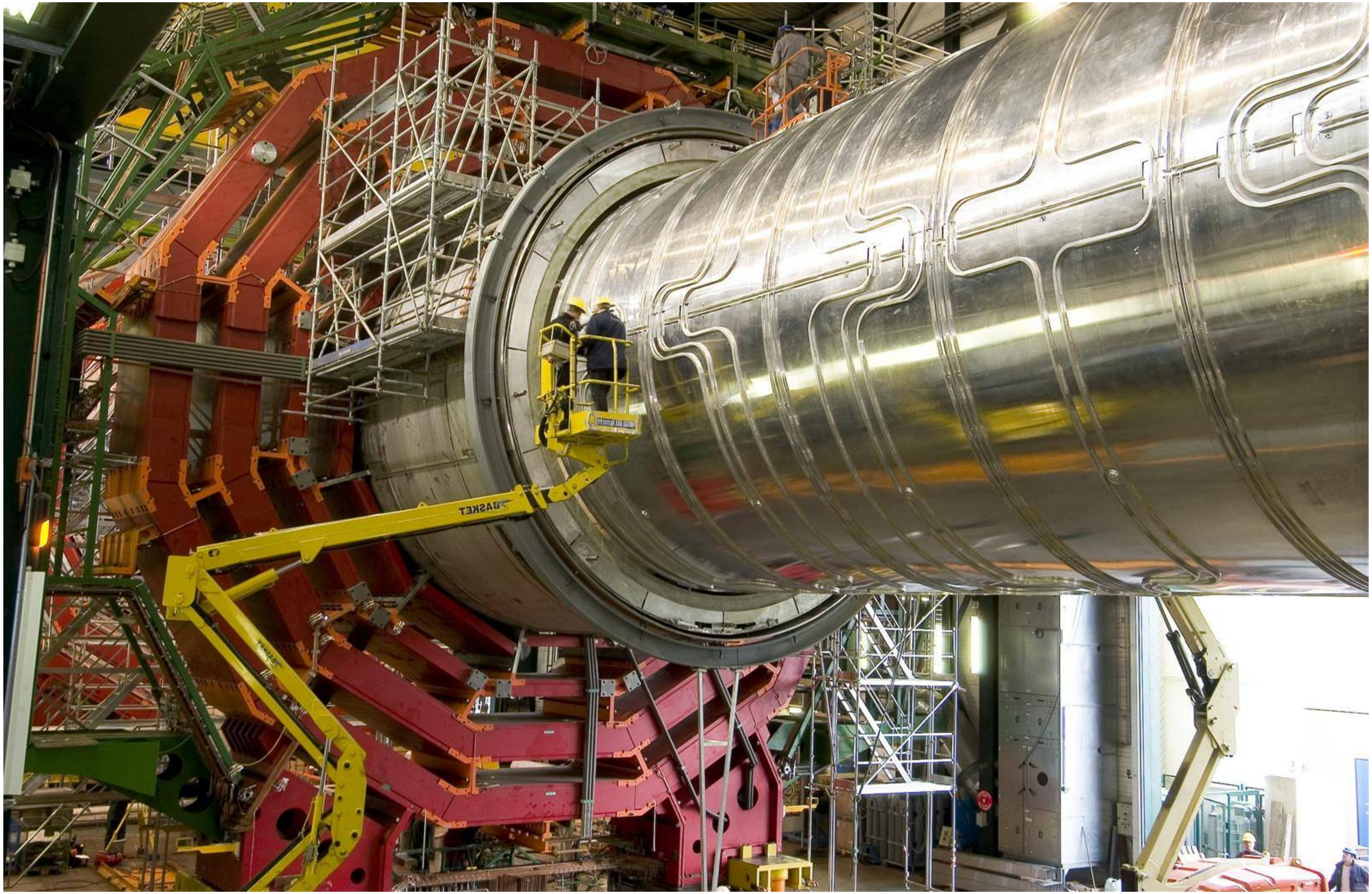
length:
12.5 m

diameter:
6 m

The strong magnetic field of 4 Tesla is a key feature of the CMS experiment.

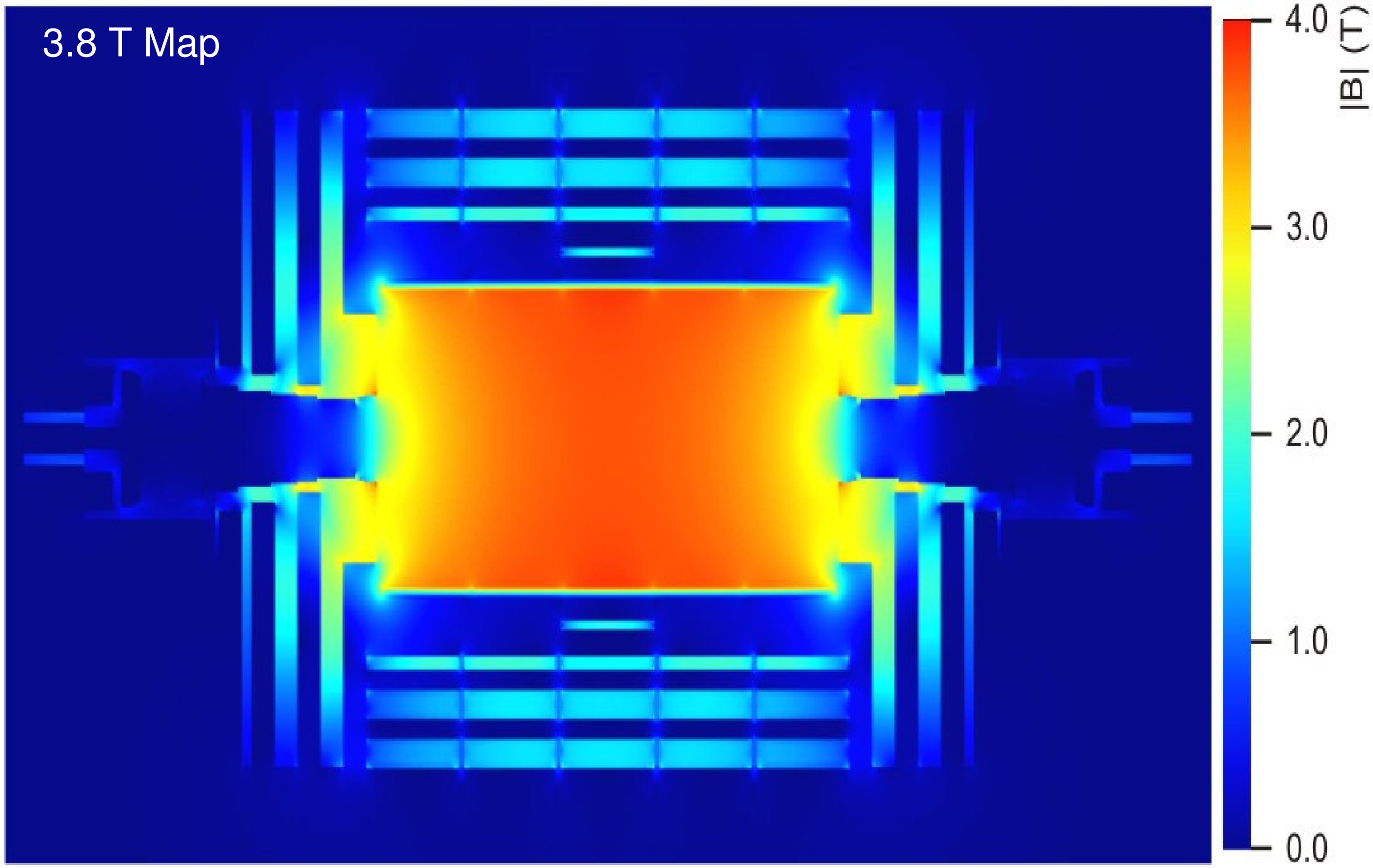
- Allows precise determination of charged particle momenta.
- Sweeps away background of low momentum charged particles before entering the calorimeter and muon detection systems.

CMS Superconducting Magnet

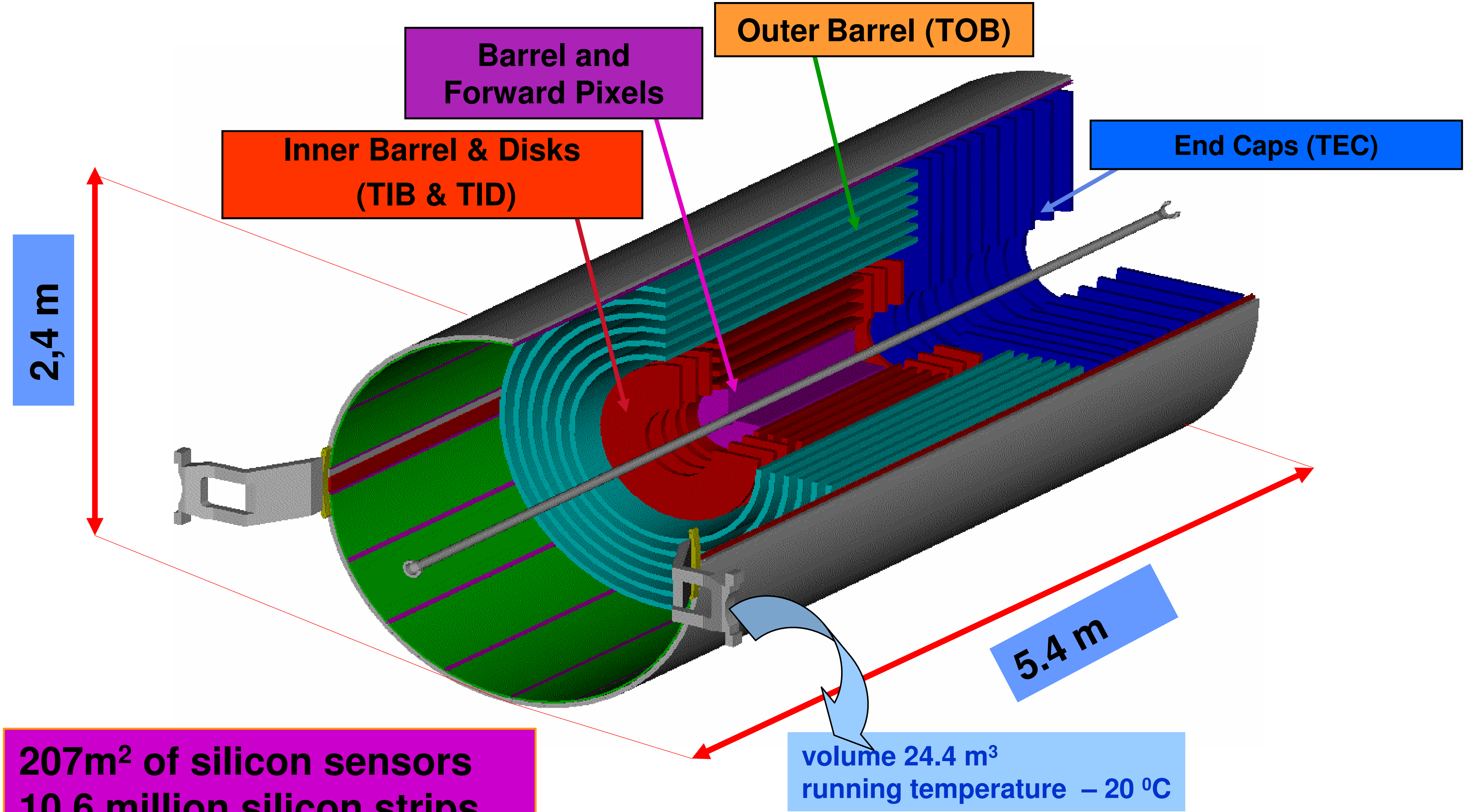


B-Field Mapping

- Magnetic field is 3.8 T inside the coil
- Around 2 T in the return yoke
- Field known with 0.1% (3%) accuracy in solenoid (return yoke).

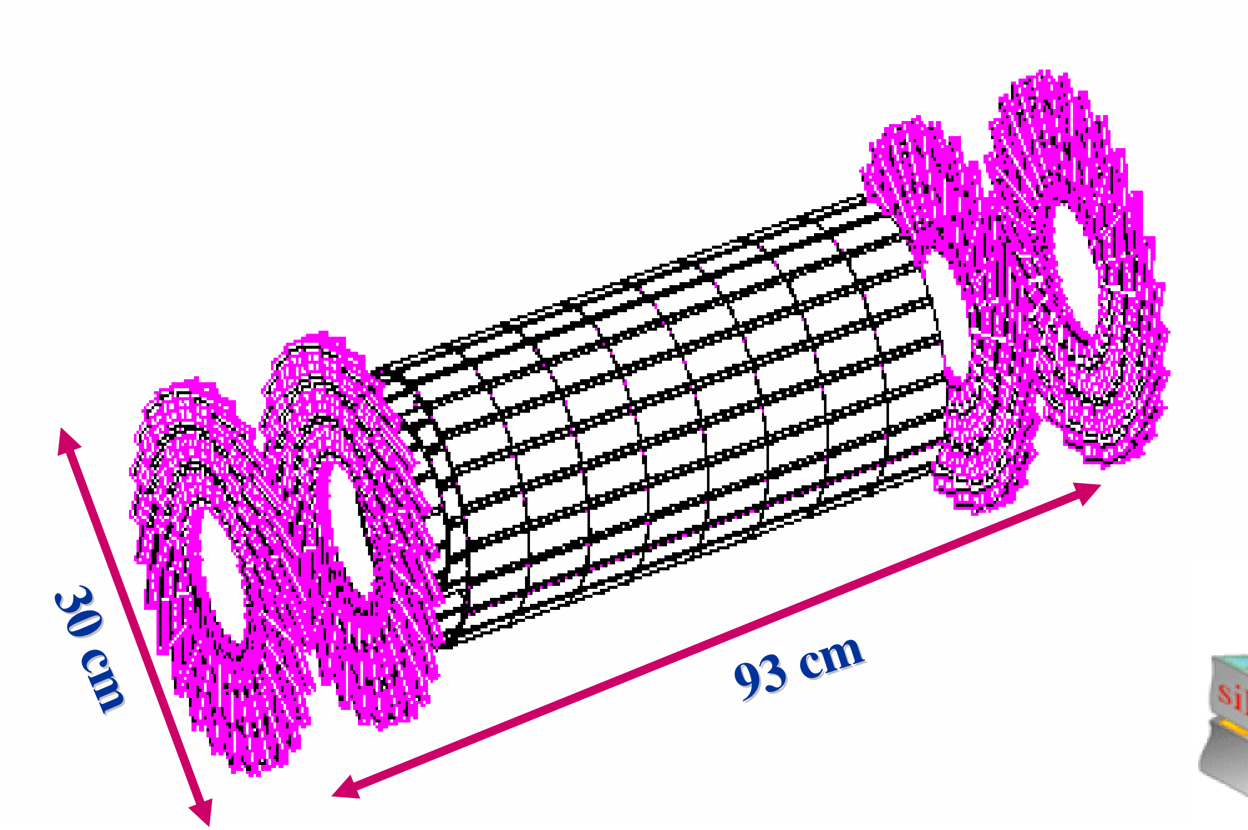


All Silicon Tracker



$207 m^2$ of silicon sensors
10.6 million silicon strips
65.9 million pixels ~ $1.1 m^2$

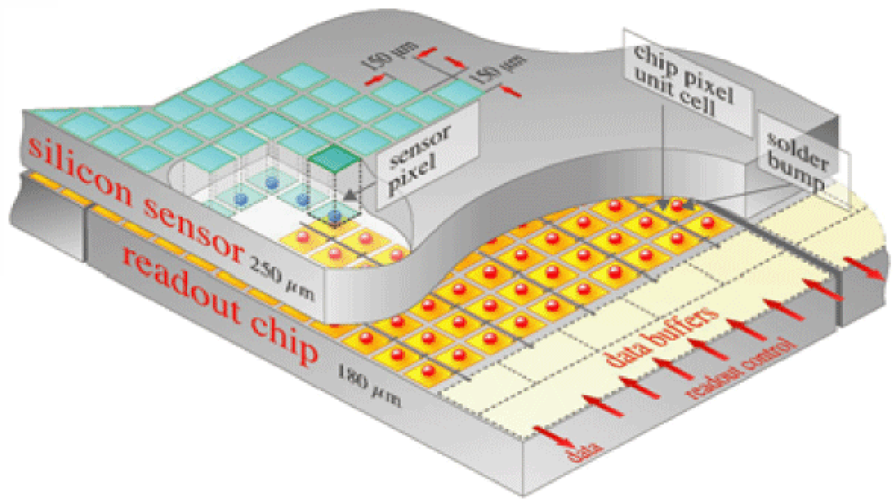
Pixel Detector



3 pixel layers in barrel
(4.3, 7.2, and 11.0 cm away from Interaction Point)

2 disks in each endcap

66 Million pixels, Area: 1.1 m^2



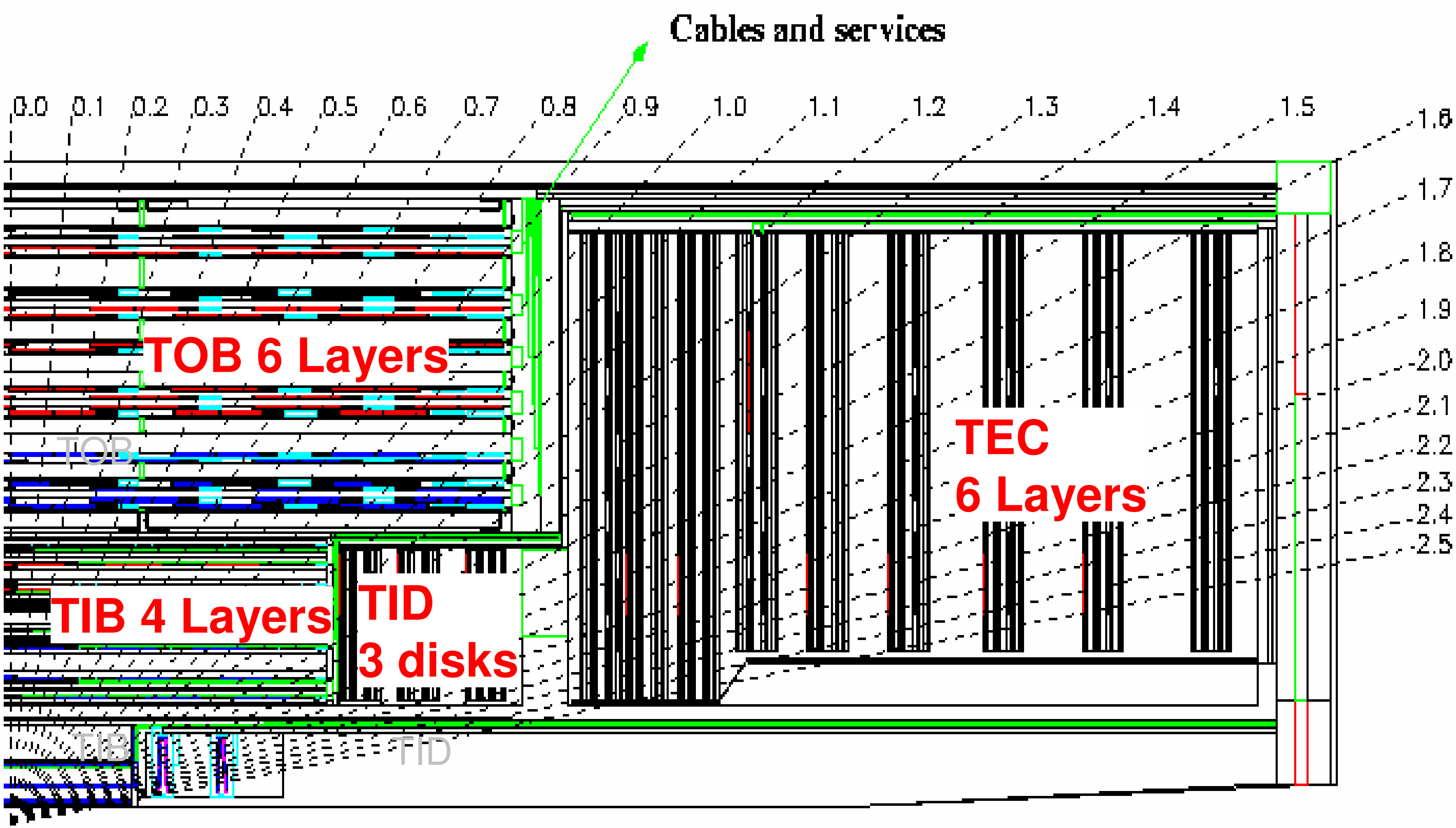
Cell size 100 x 150 microns

Spatial resolution 10 (Φ) – 20 (z) microns

(due to large Lorentz angle)

Average channel occupancy ~ 10^{-4} at high luminosity

Silicon Microstrip Tracker



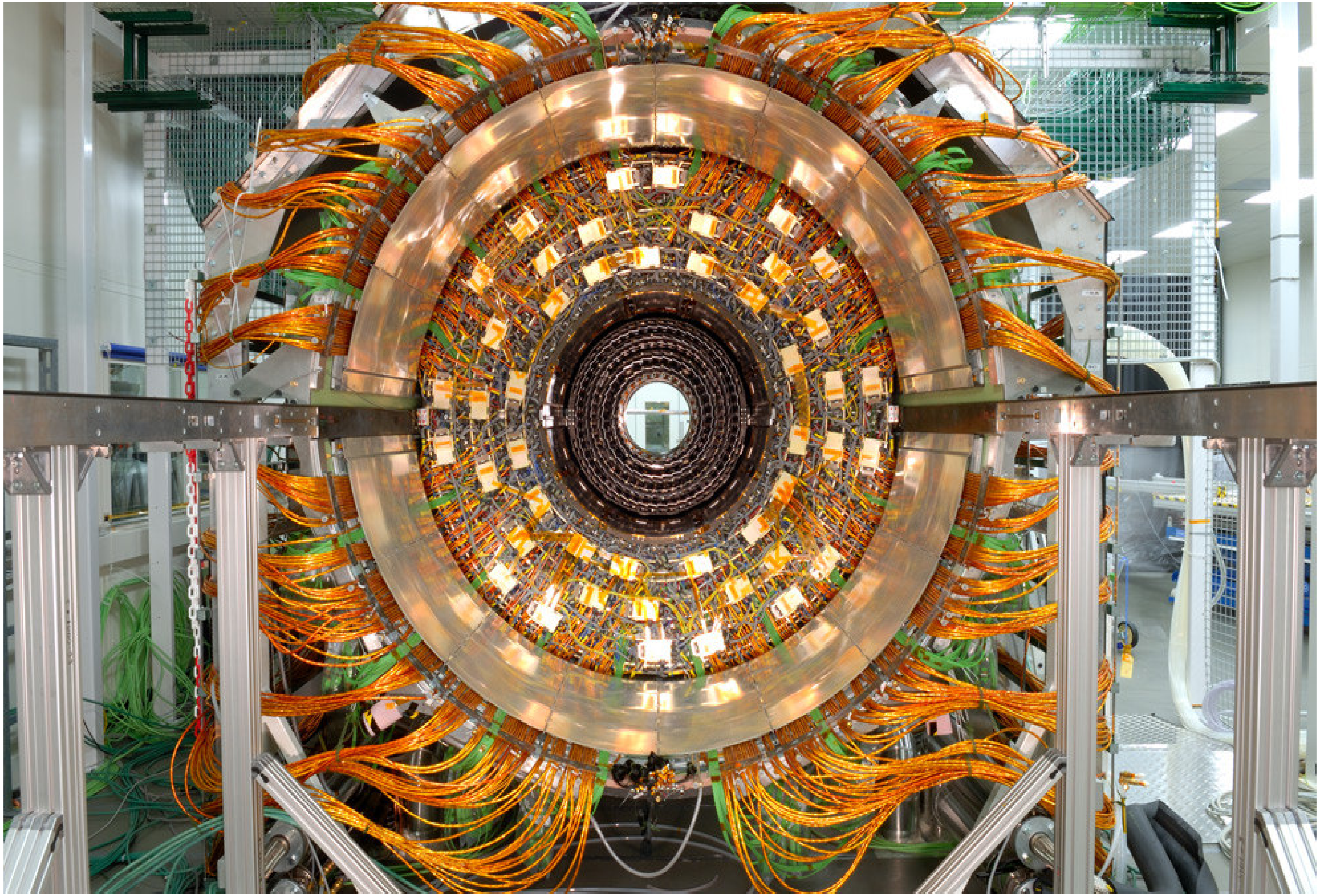
16000 modules of 27 different types

Pitch: 80 – 180 microns

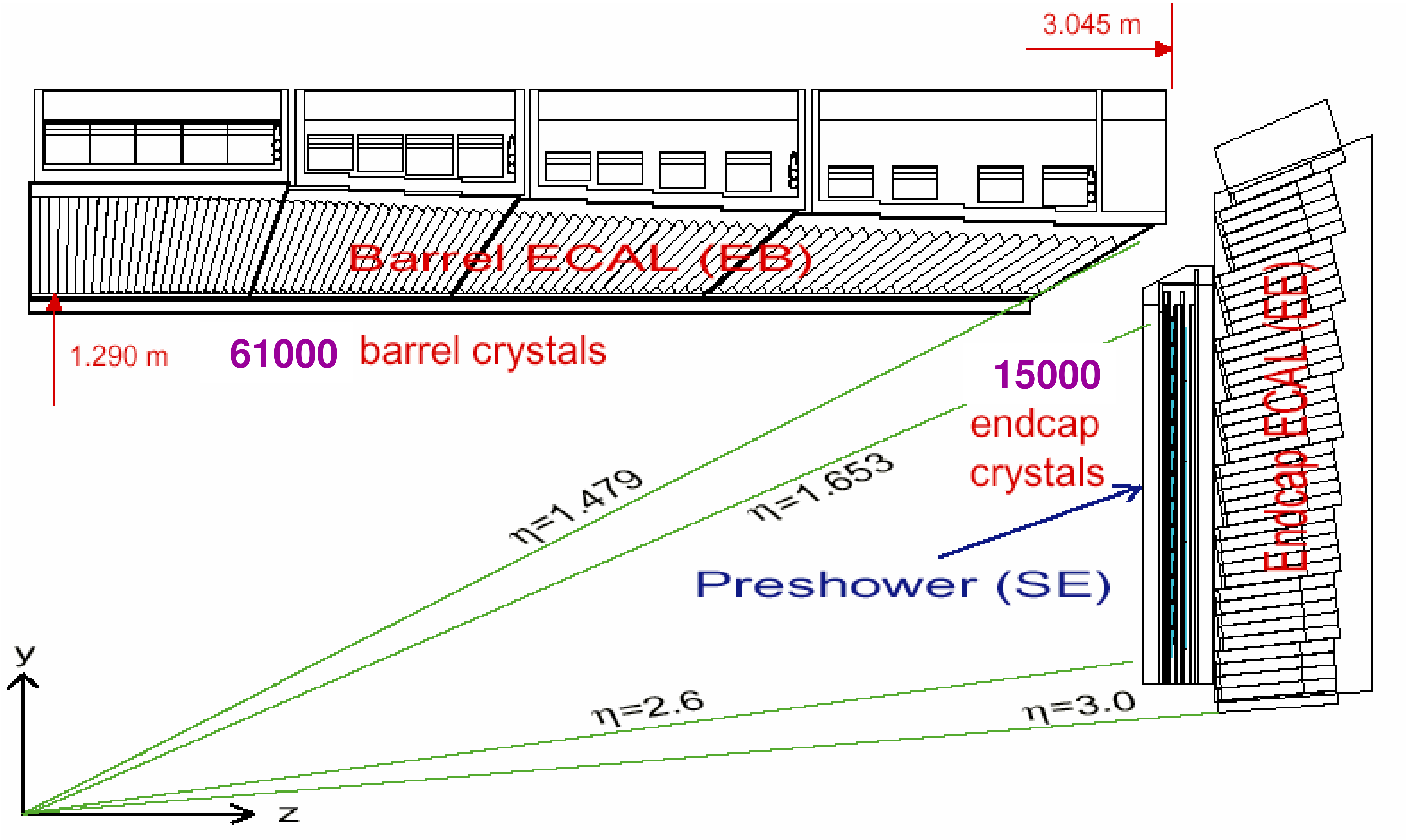
Hit resolution: 20 – 50 microns

Occupancy always below $10^{-2}/cm^2$

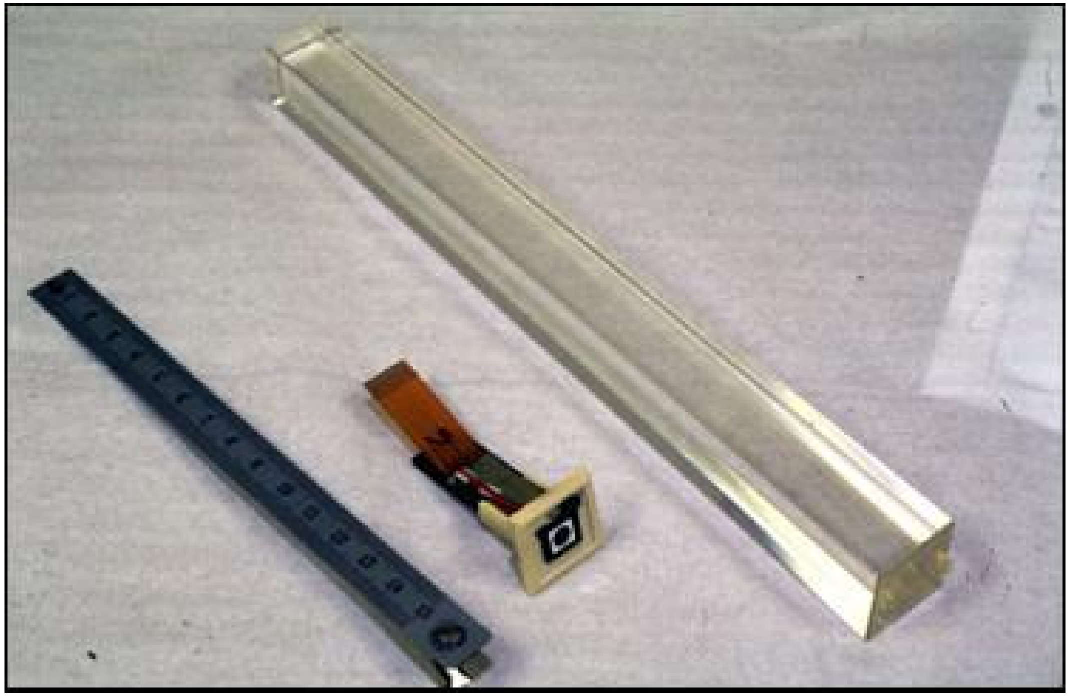
CMS Tracker



Electromagnetic Calorimeter



ECAL: PbWO4 Crystals



Characteristics of $PbWO_4$
$X_0 = 0.89cm$
$\rho = 8.28g/cm^3$
R_M (Molière radius) = 2.2cm

Barrel:

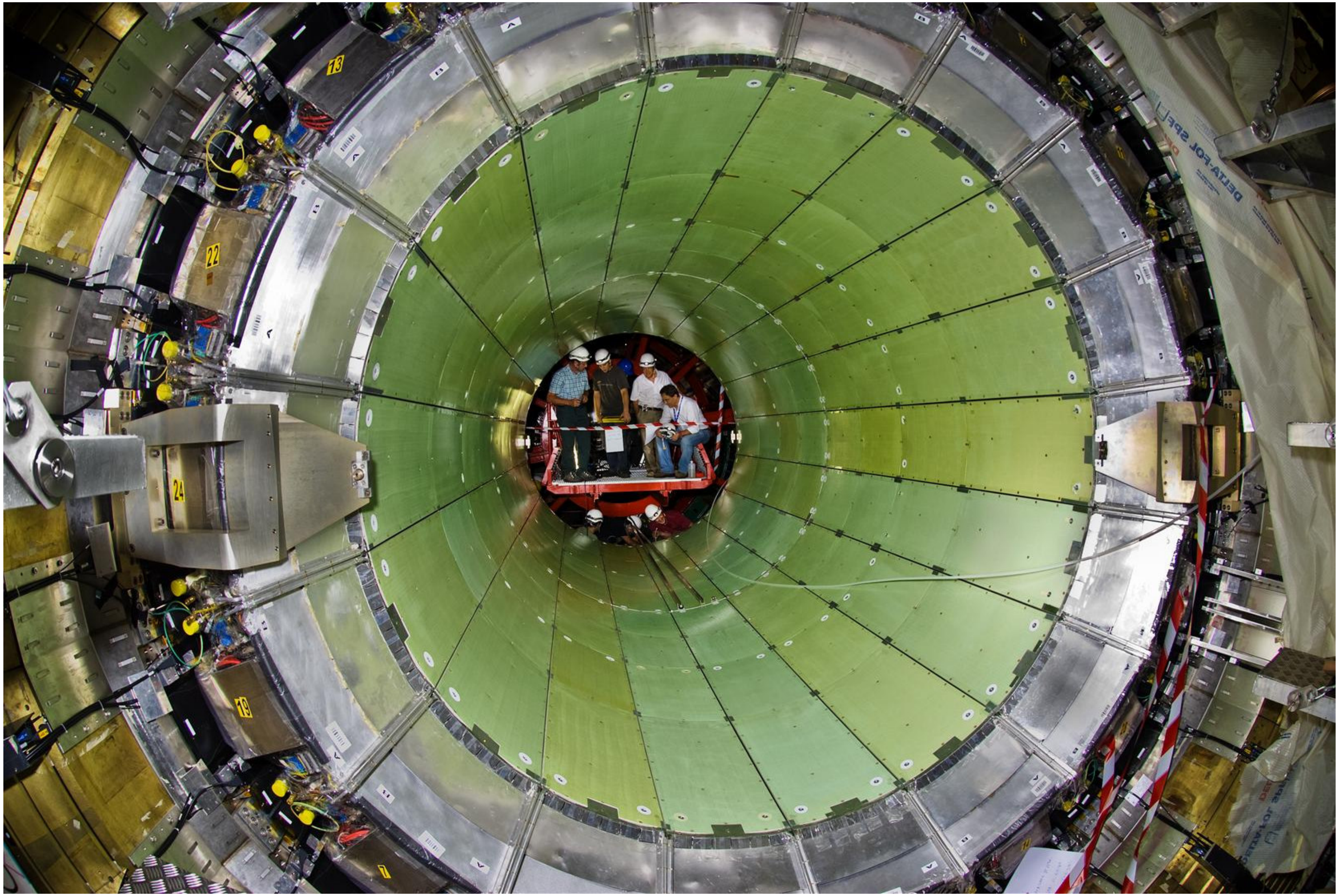
- $2.2 \times 2.2 \times 23\ cm^3$
- 17 crystal shapes
- 36 supermodules

Endcap:

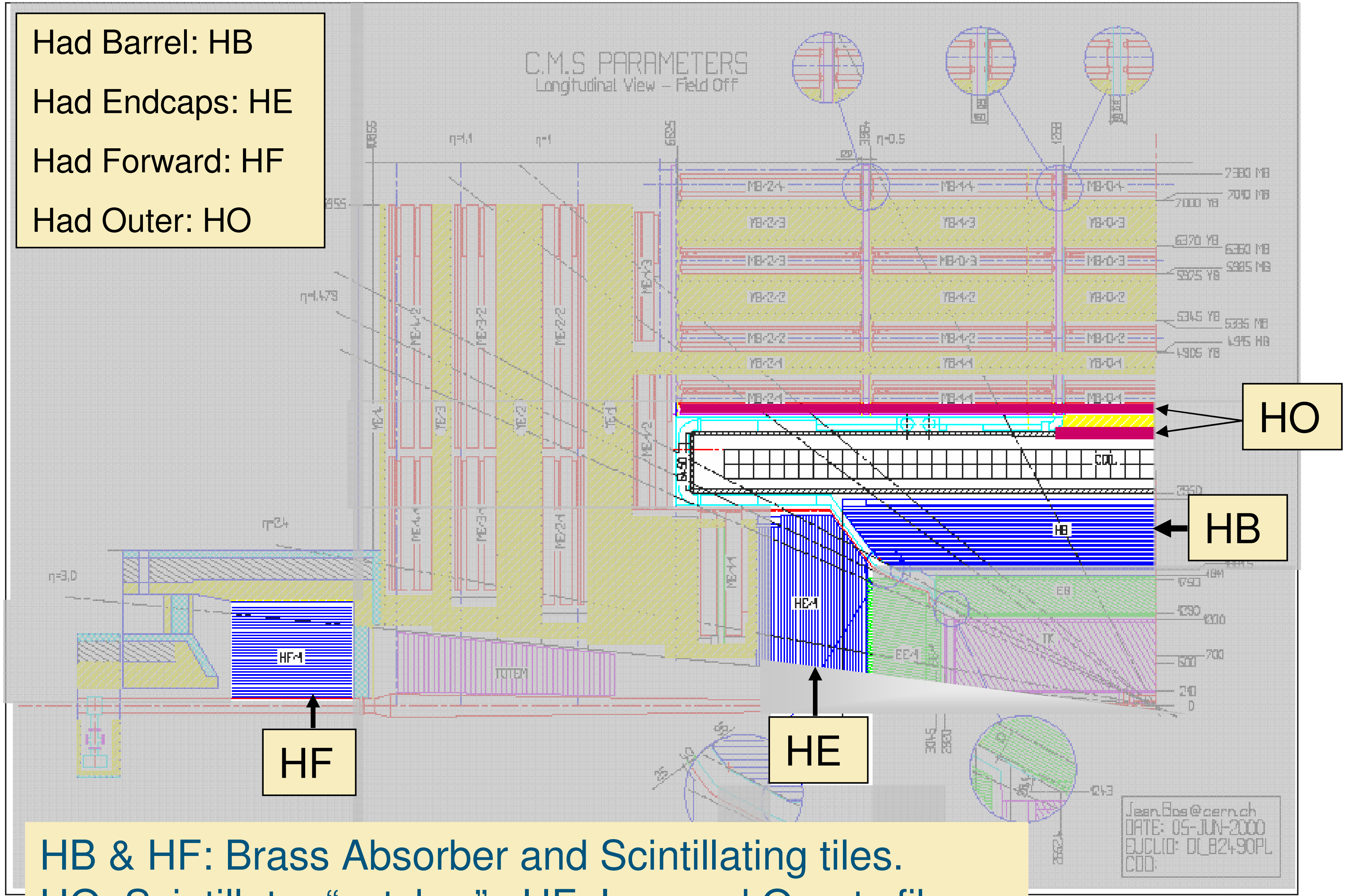
- $2.9 \times 2.9 \times 22\ cm^3$
- 1 crystal shape
- 4 Dees

- 80000 $PbWO_4$ crystals
- approx. 26 interaction lengths
- Energy resolution < 1%, (E>30 GeV)

CMS ECAL

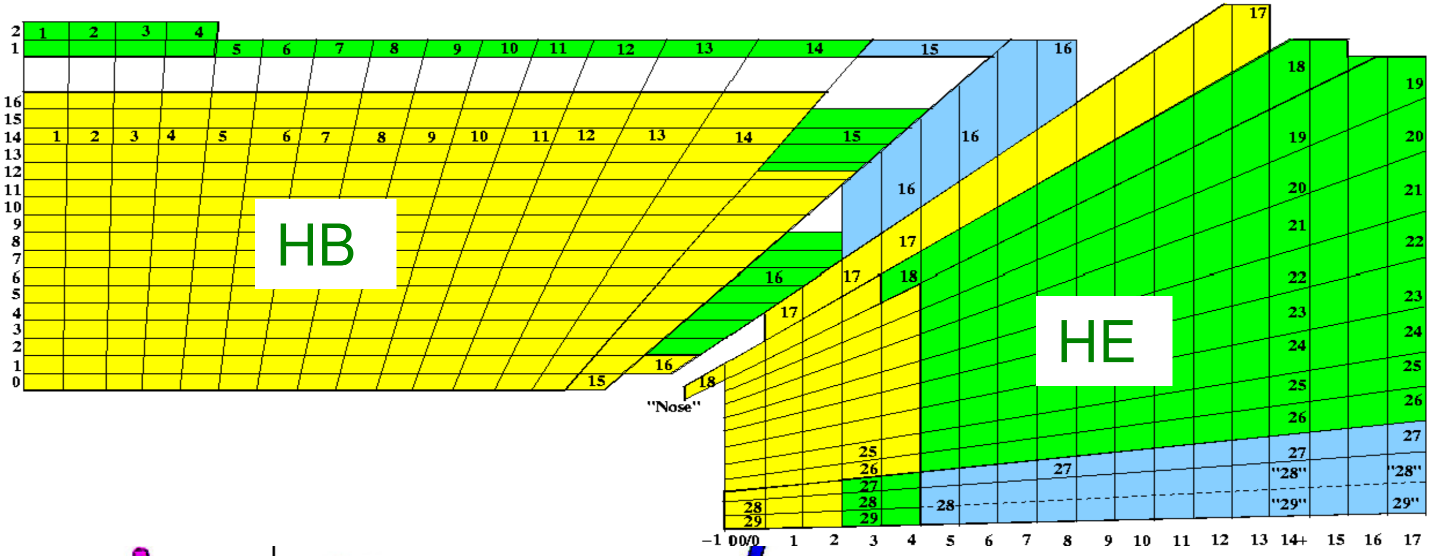


Hadronic Calorimeter



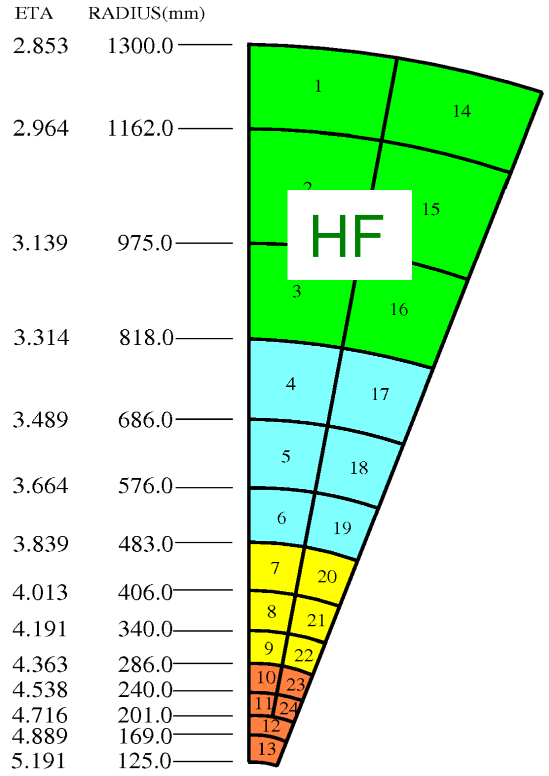
HB & HF: Brass Absorber and Scintillating tiles.
HO: Scintillator “catcher”. HF: Iron and Quartz fibers

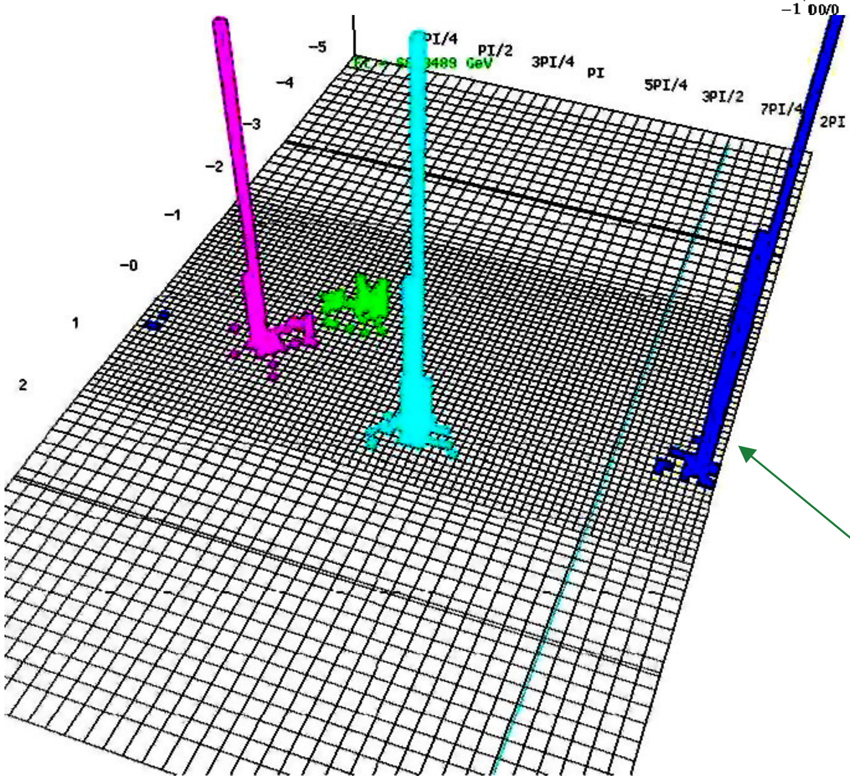
HCAL Segmentation and Coverage



HF: $3<|\eta|<5$

$\Delta\phi \times \Delta\eta = 0.17 \times 0.17$





HB: $|\eta|<1.3$

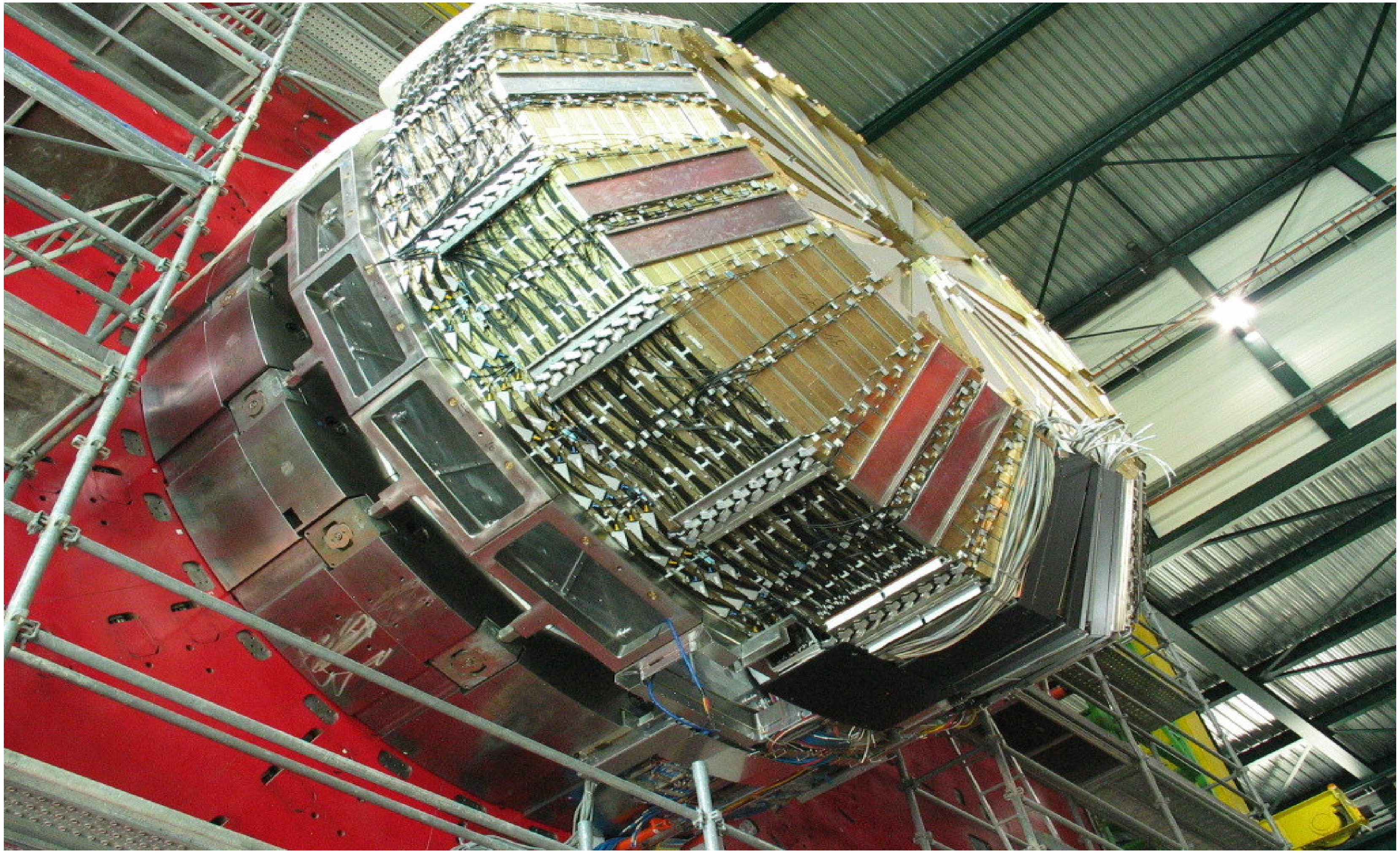
HE: $1.3<|\eta|<3$

HF: $3<|\eta|<5$

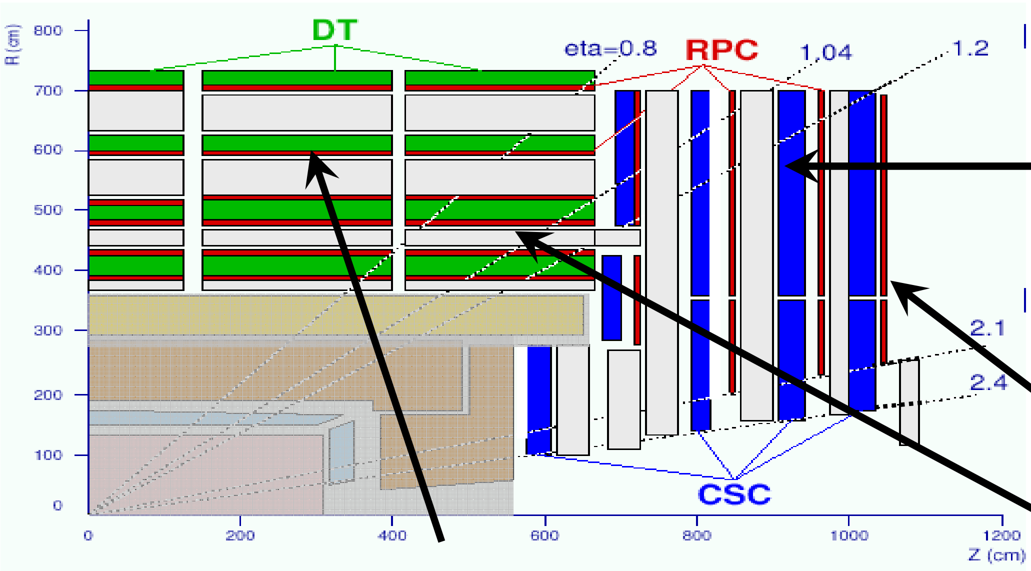
Very Fine Granularity:

$\Delta\phi \times \Delta\eta = 0.087 \times 0.087$ for $|\eta|<1.7$

CMS HCAL



Muon Detectors

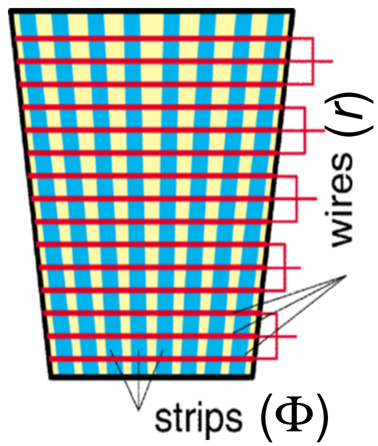


Cathode Strip Chambers:
4 endcap stations

10 or 20 deg in Φ

6 layers of chambers

75 – 150 µm in Φ
15 – 55 mm in r
4.5 ns in time



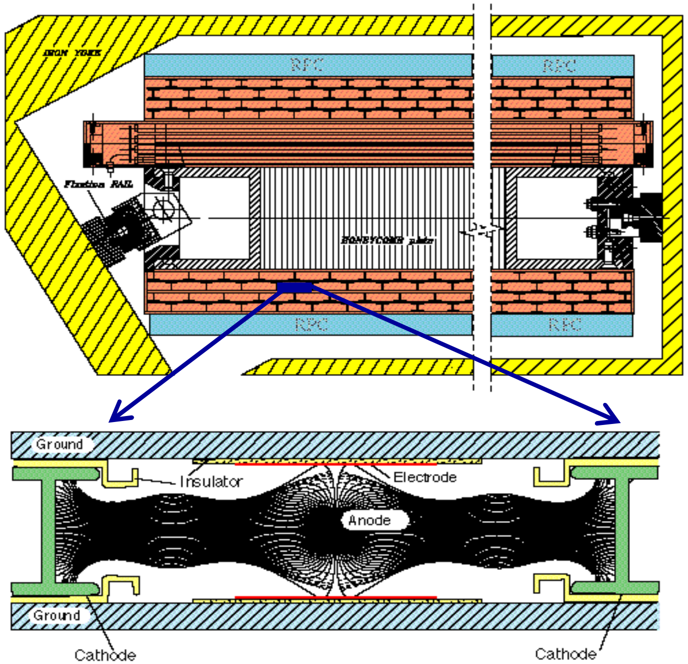
Drift Tubes: 4 barrel stations

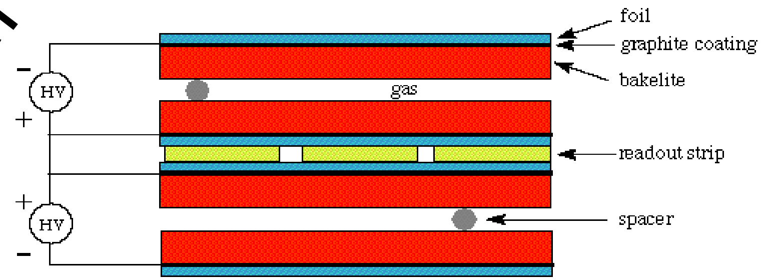
2 r-Φ superlayers

1 r-z superlayer

4 layers of cells

100 µm in Φ
150 µm in z
1 mrad in angle

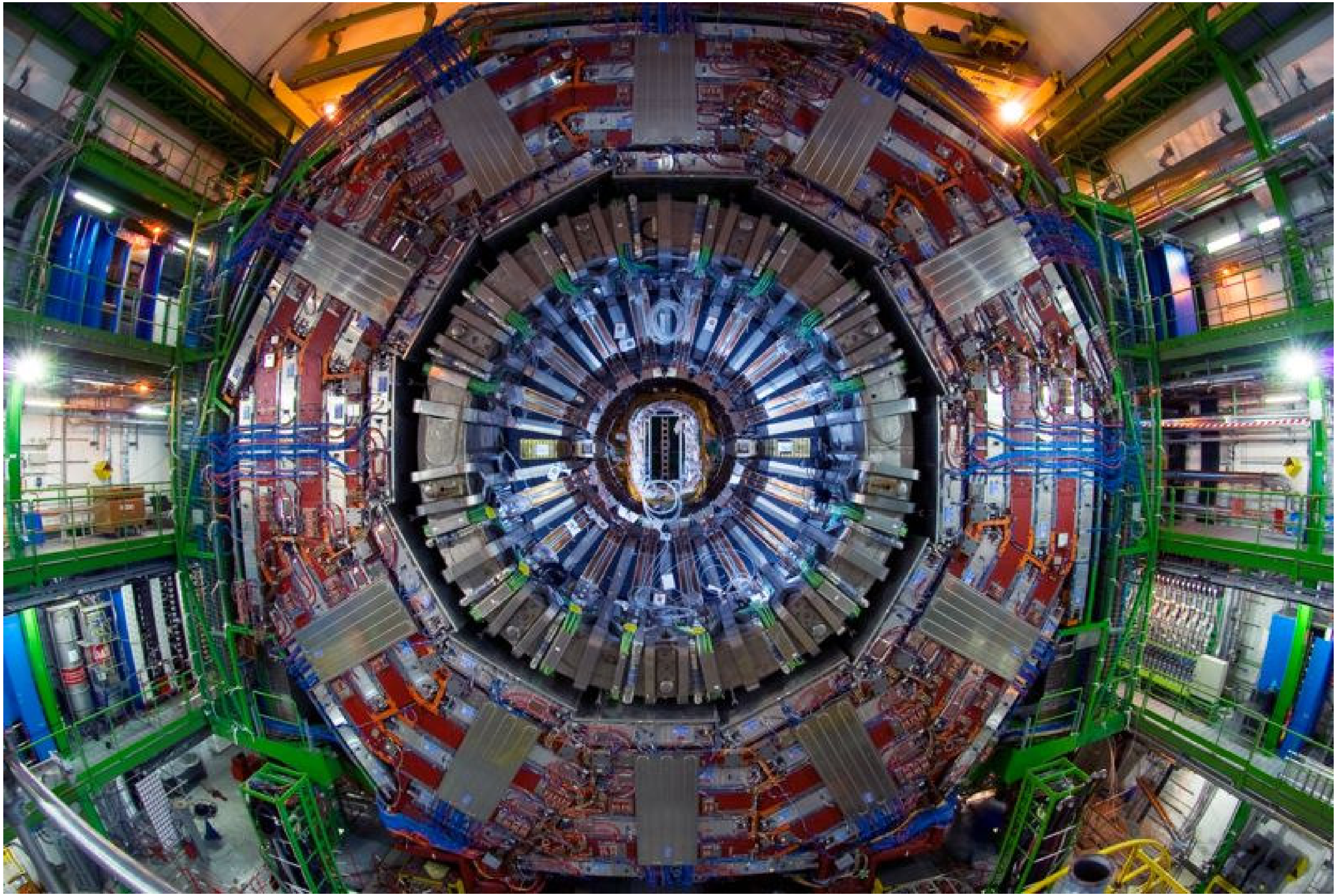




Resistive Plate Chambers
6 barrel layers;
4 endcap layers

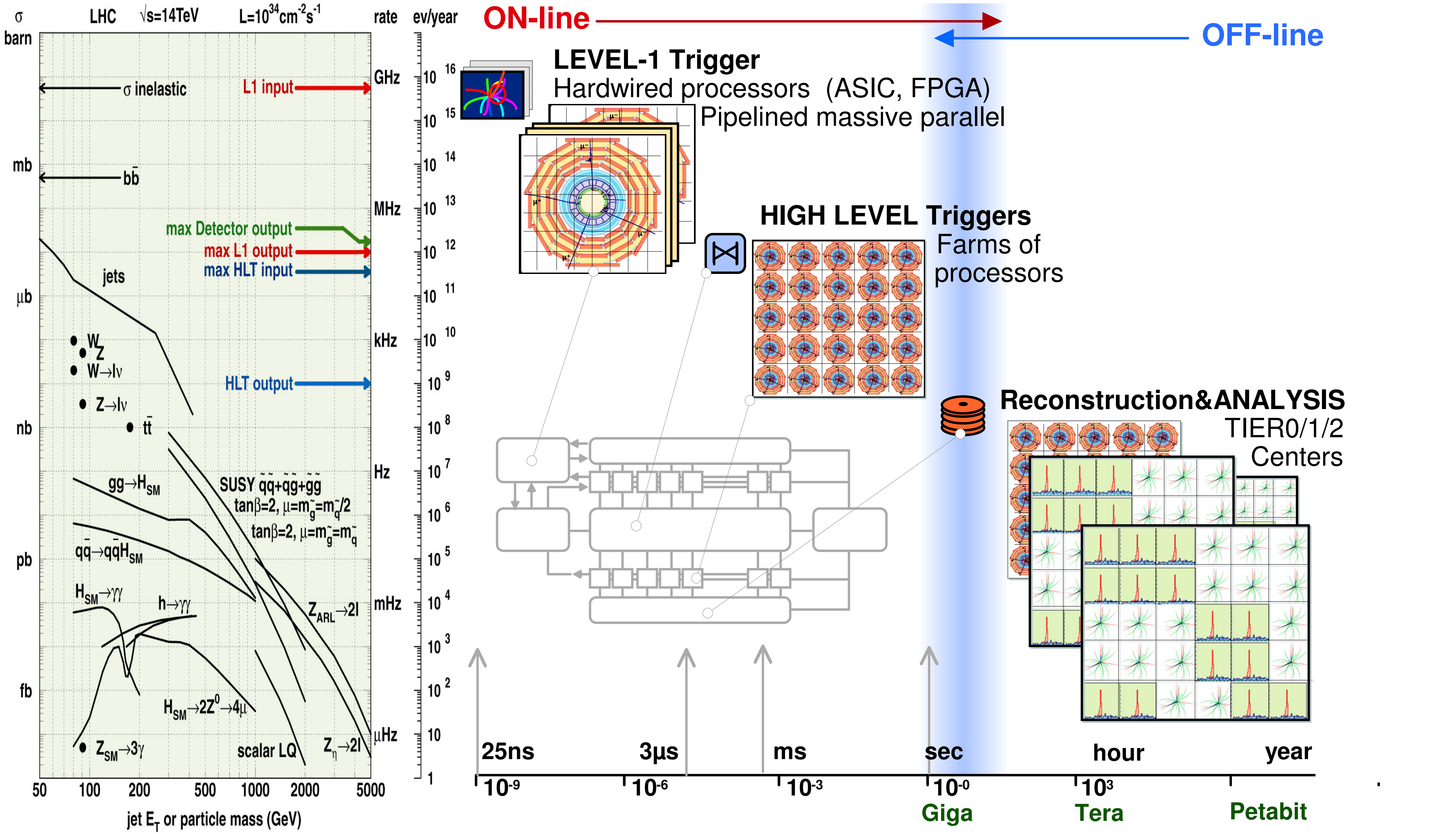
Time resolution < 3 ns

CMS Muon System

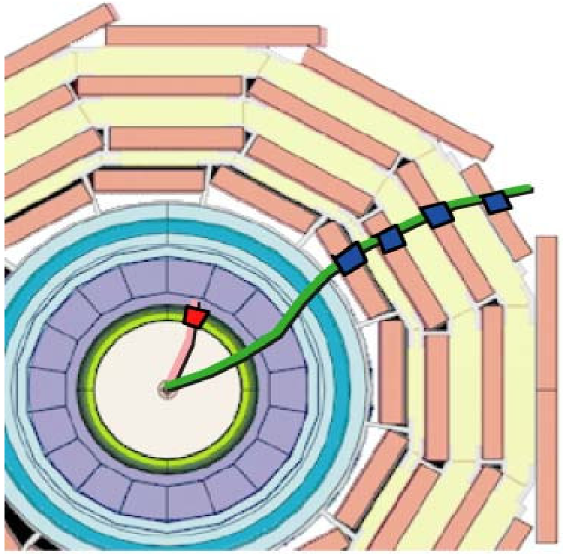


Final Closure

Physics Selection at LHC

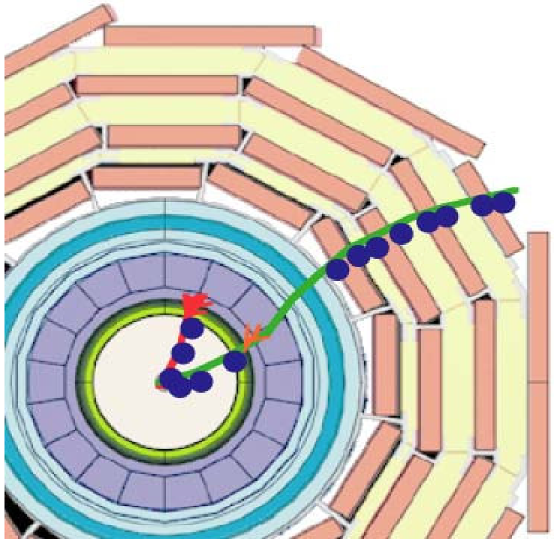


CMS Trigger Levels



Level-1 Trigger

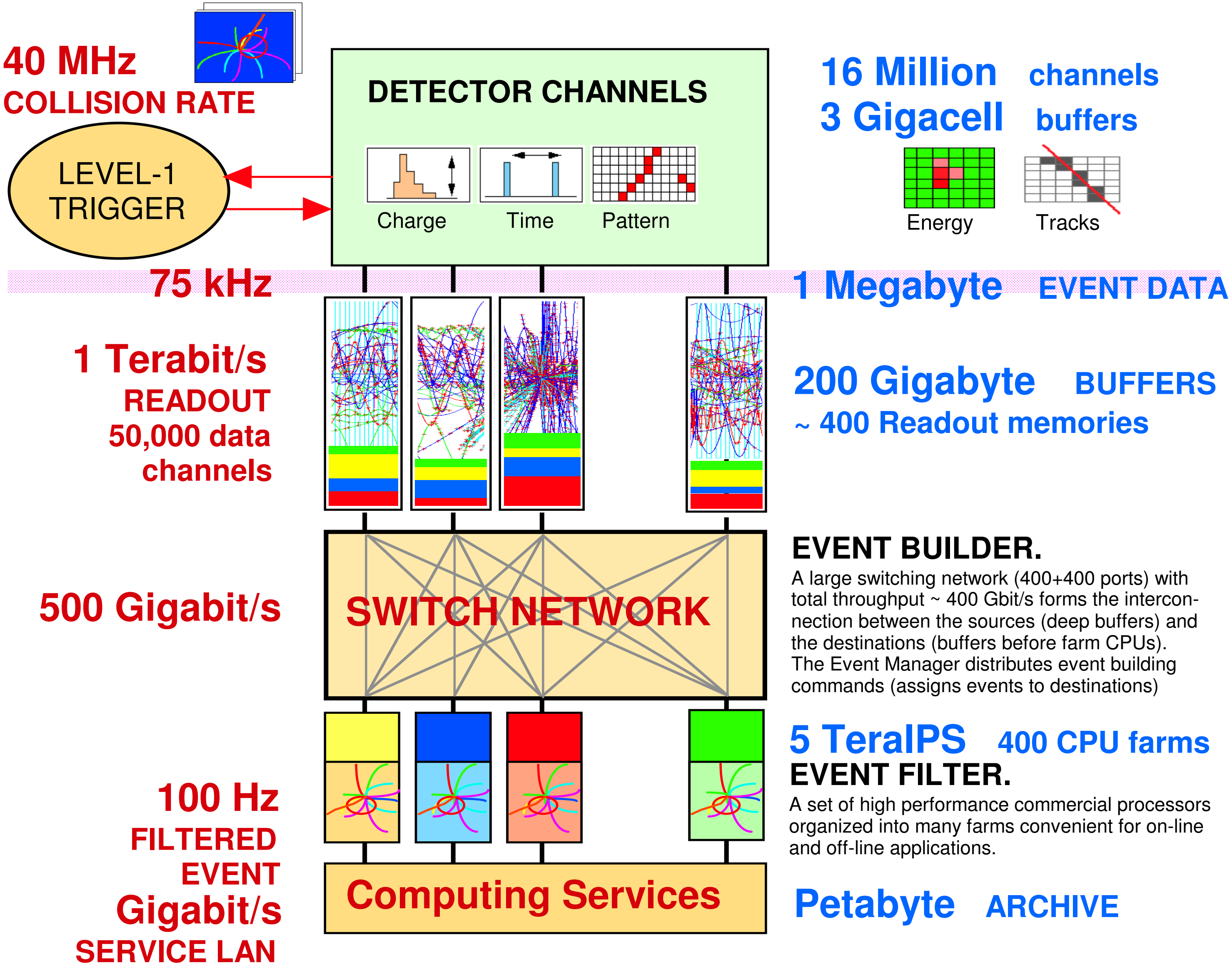
Macro.granular information from calorimeters and muon system (electron, muon, jets, $E_T^{missing}$)
Threshold and topology conditions possible
Latency: 3.2 µs
Input rate: 40 MHz; no dead time
Output rate: up to 100 kHz
Custom designed electronics system



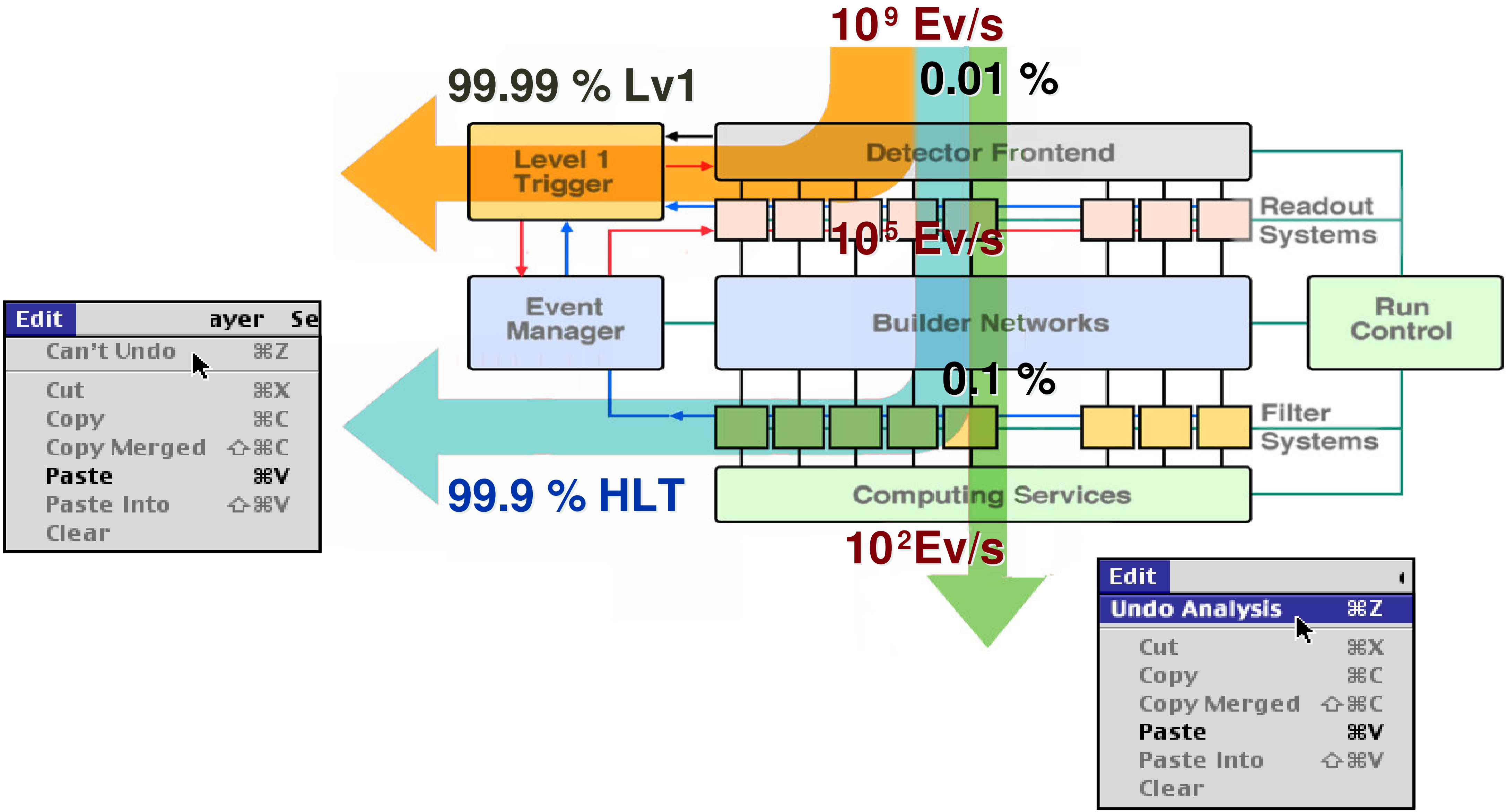
High Level Trigger (several steps)

More precise information from calorimeters, muon system, pixel detector and tracker
Thresholds, topology, mass, … criteria possible as well as matching with other detectors
Latency: between 10 ms and 1 s
Input rate: up to 100 kHz
Output (data acquisition) rate: approx. 100 Hz
Industrial processors and switching network

Online Selection Flow



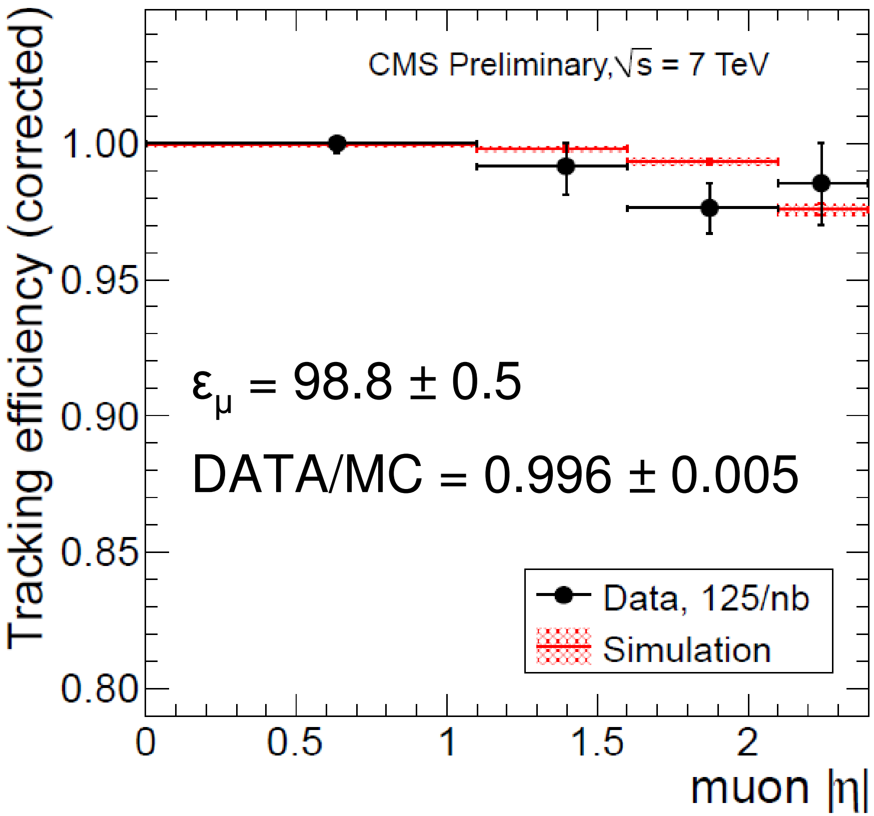
Physics Online Selection Summary



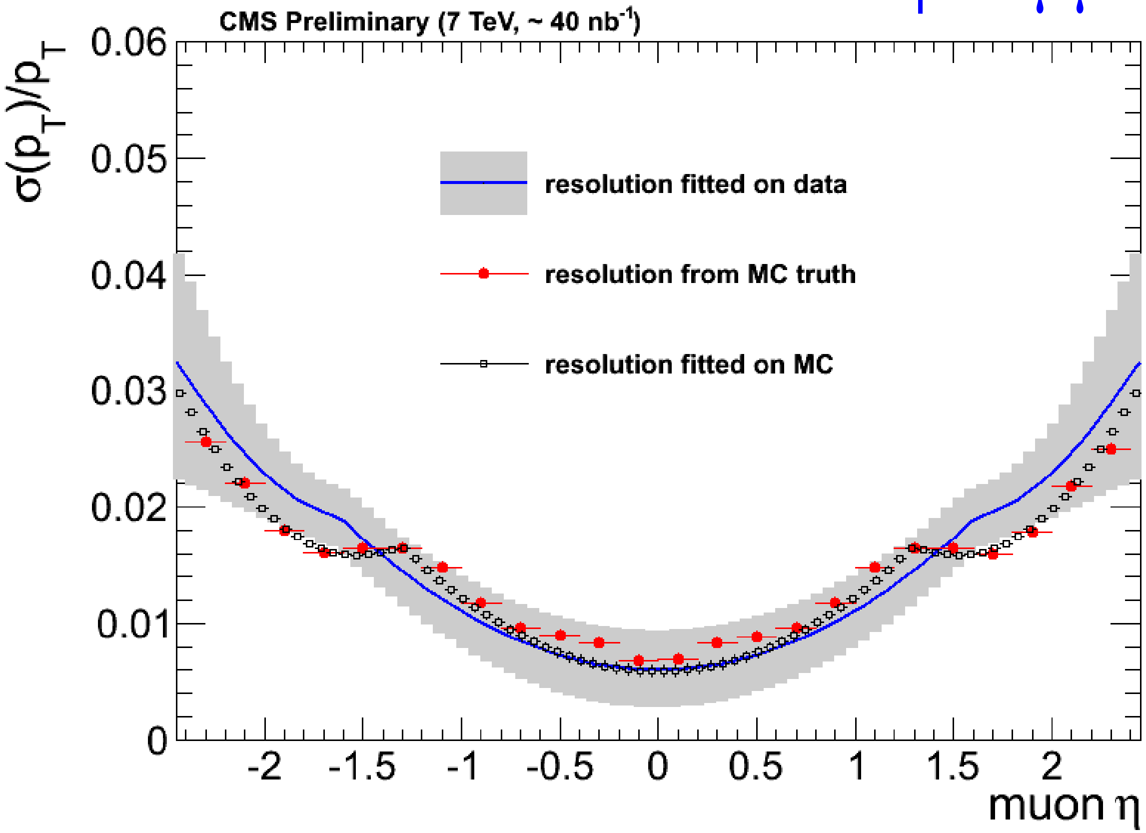
DETECTOR PERFORMANCE AND EXPERIMENTAL METHODS

Tracker Efficiency, Scale, Resolution

$J/\psi \to \mu\mu$

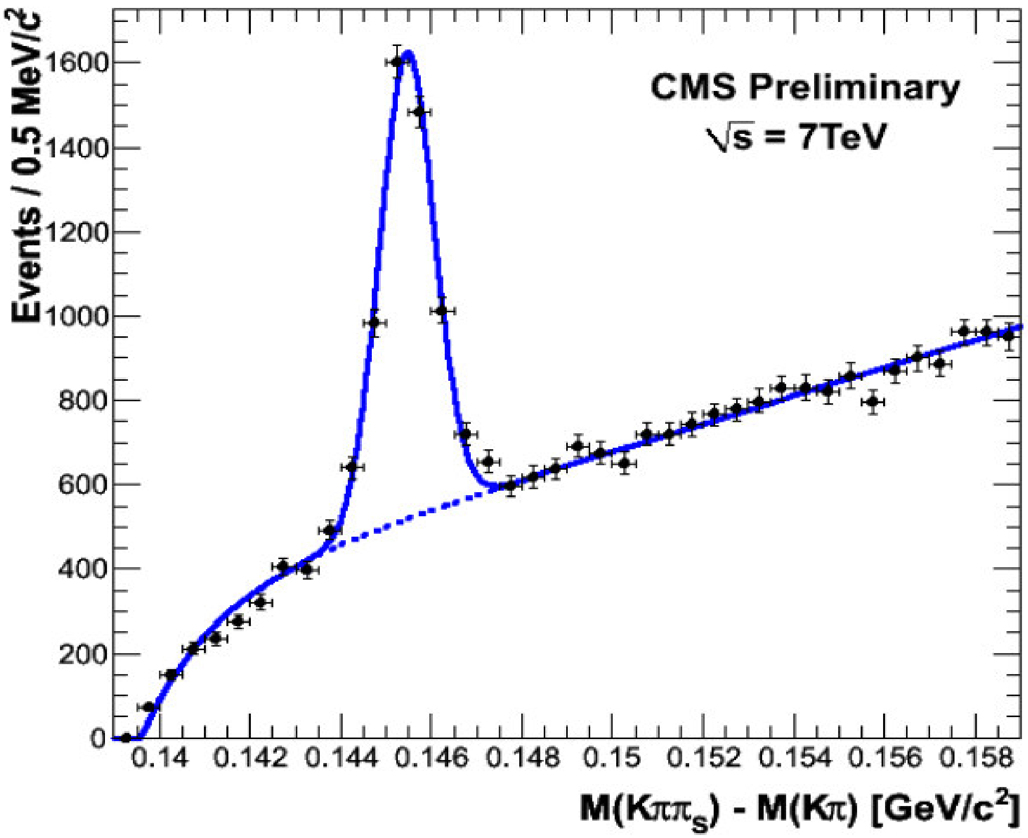


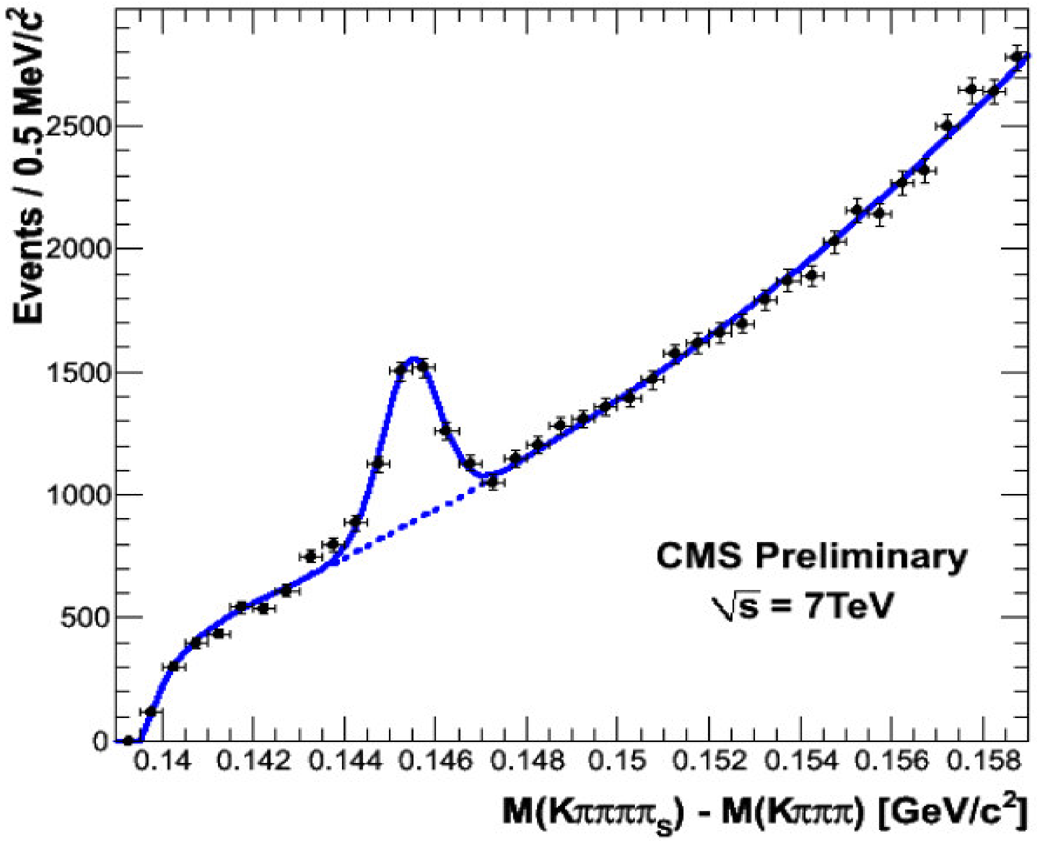
$J/\psi \to \mu\mu$



- Using low mass resonances.
- Measurement of track efficiencies: for instance, muon efficiency from J/ψ tag-and-probe.
- Validation of momentum scale and resolution; detailed comparison to MC provides information about possible sources of bias.

Pion Tracking Efficiency



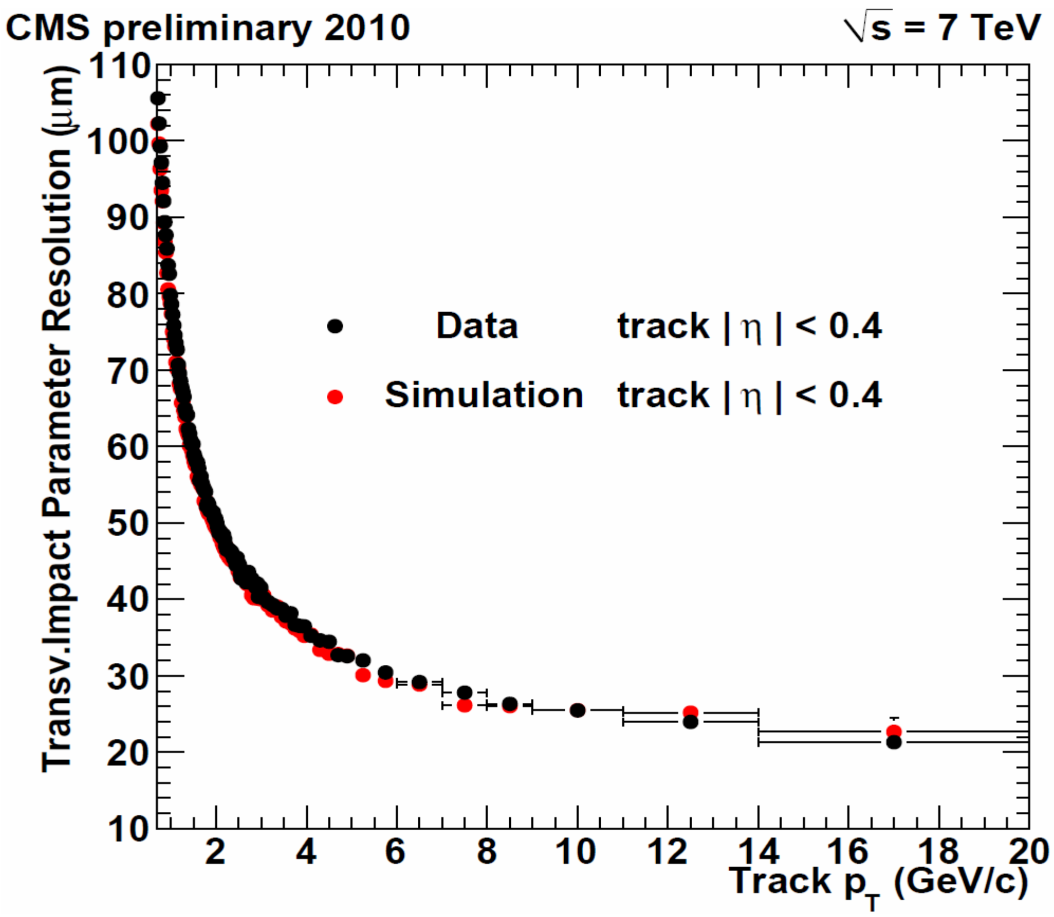


$D^{*+} \to D^0 \pi^+$, $\hookrightarrow K^- \pi^+$

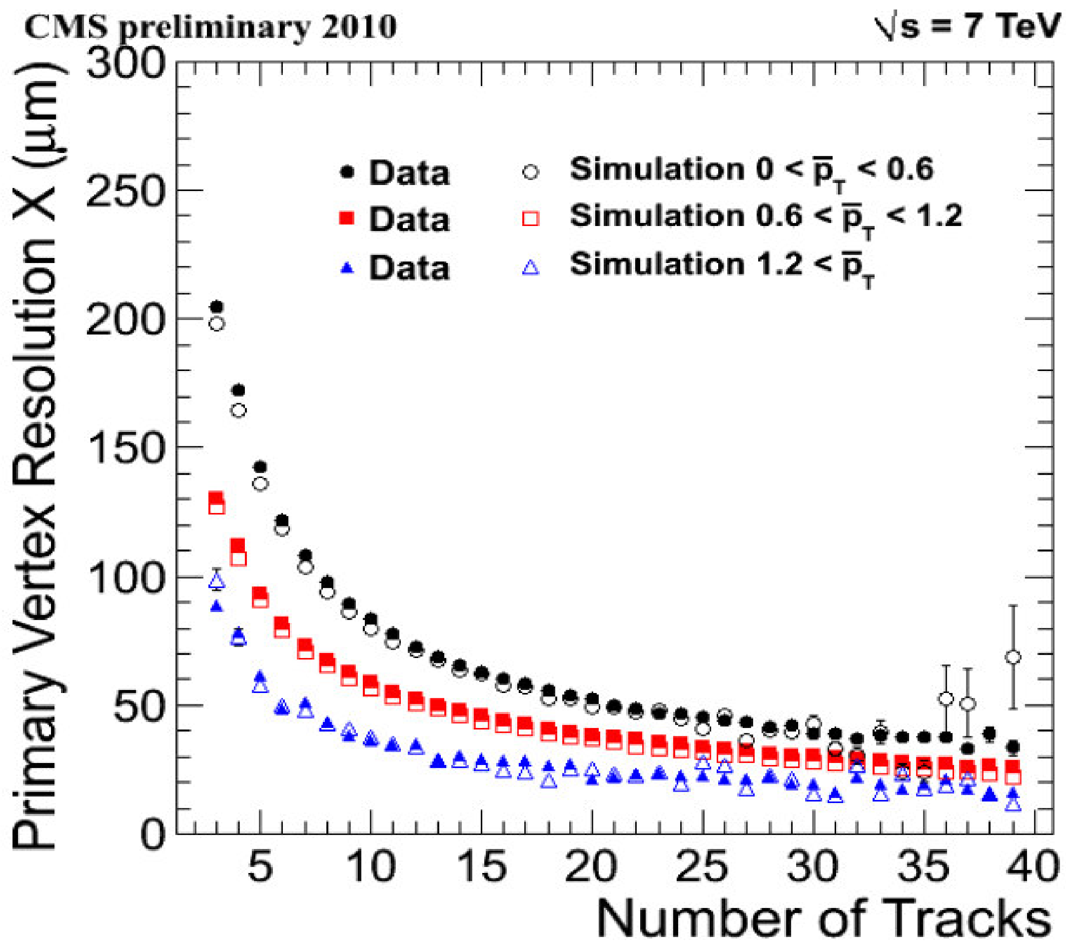
$D^{*+} \to D^0 \pi^+$, $\hookrightarrow K^- \pi^+ \pi^- \pi^+$

$$\mathcal{R} = \frac{N_{K3\pi}}{N_{K\pi}} \cdot \frac{\epsilon_{K\pi}}{\epsilon_{K3\pi}} \Rightarrow \frac{\epsilon_\pi^{\rm DATA}}{\epsilon_\pi^{\rm MC}} = \sqrt{\frac{\mathcal{R}}{\mathcal{R}_{\rm PDG}}} = 1.007 \pm 0.034_{\rm stat} \pm 0.014_{\rm syst} \pm 0.012_{\rm PDG}$$

Vertexing

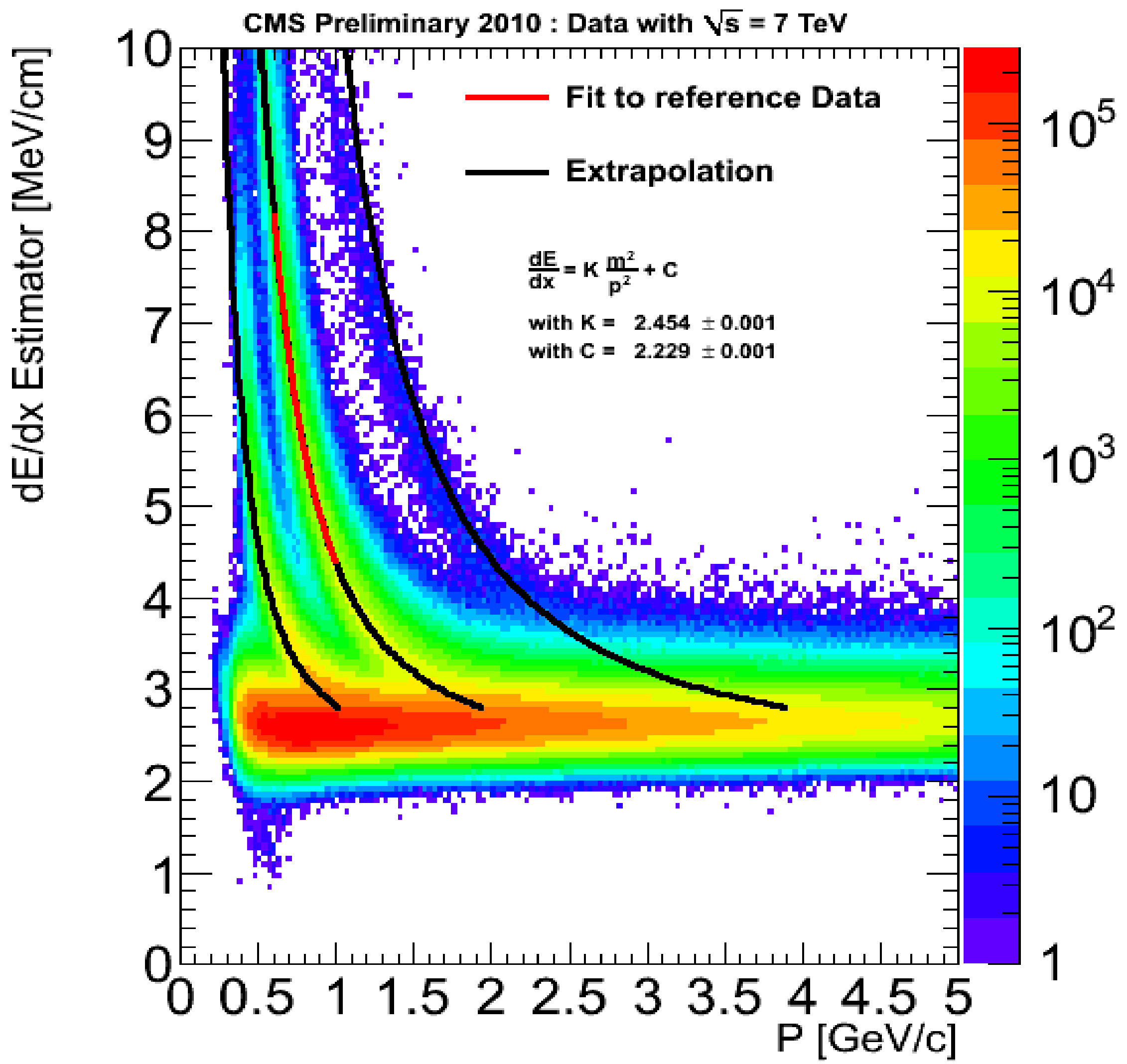


Track impact parameter resolution

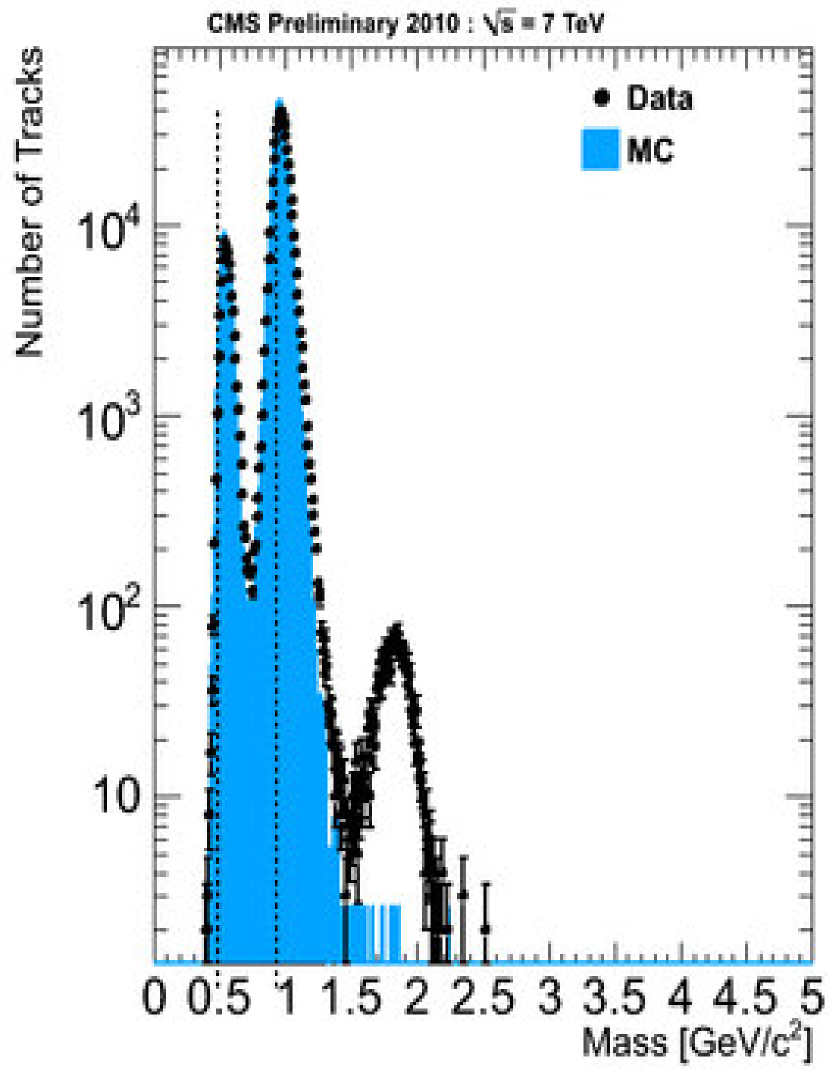


Primary vertex transverse resolution

Particle Id with dE/dx



Kaon, proton and deuteron bands well visible.



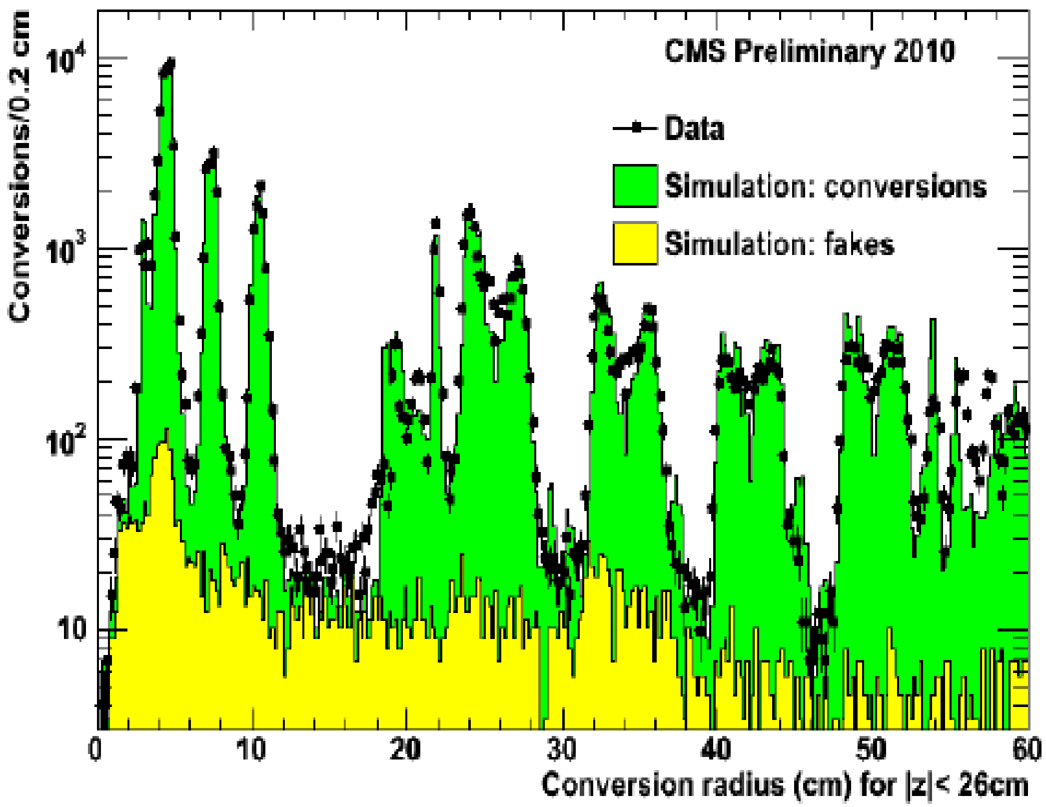
P < 2. GeV/c; dE/dx > 5. MeV/cm

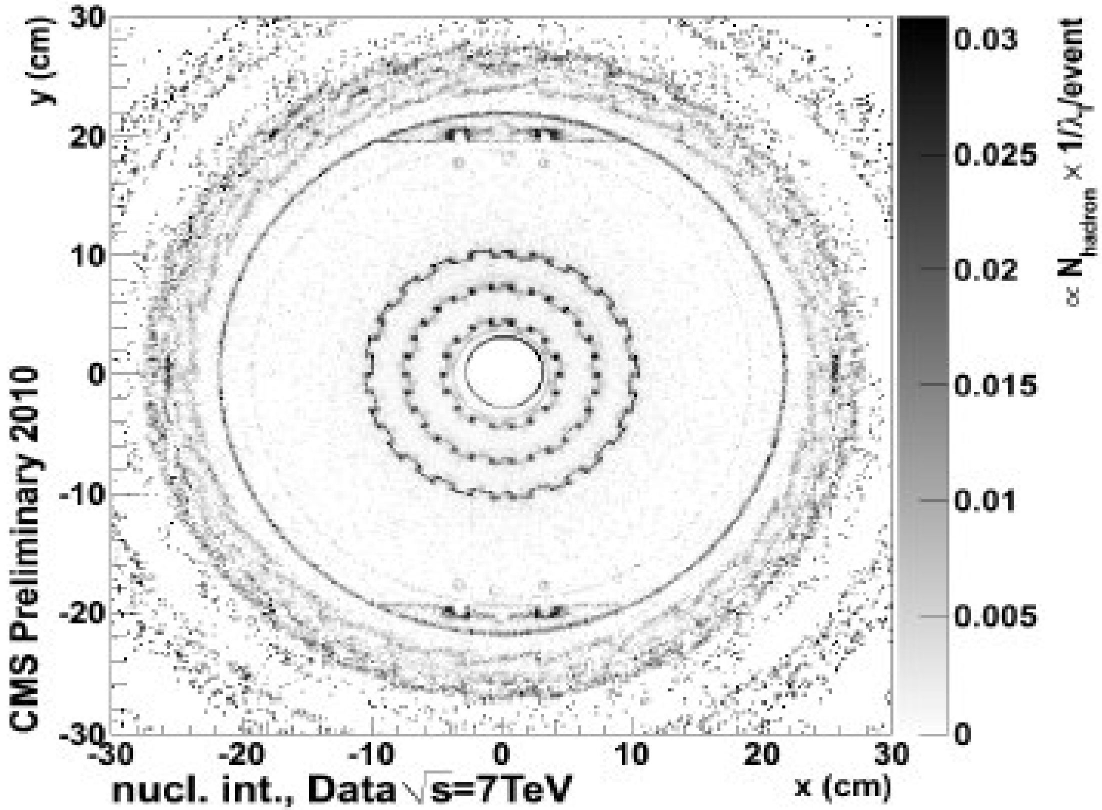
Tracker Material

Photon conversions: up to 1.8 X_0; 70% of photons convert. Vertex resolution: 2-5 mm.

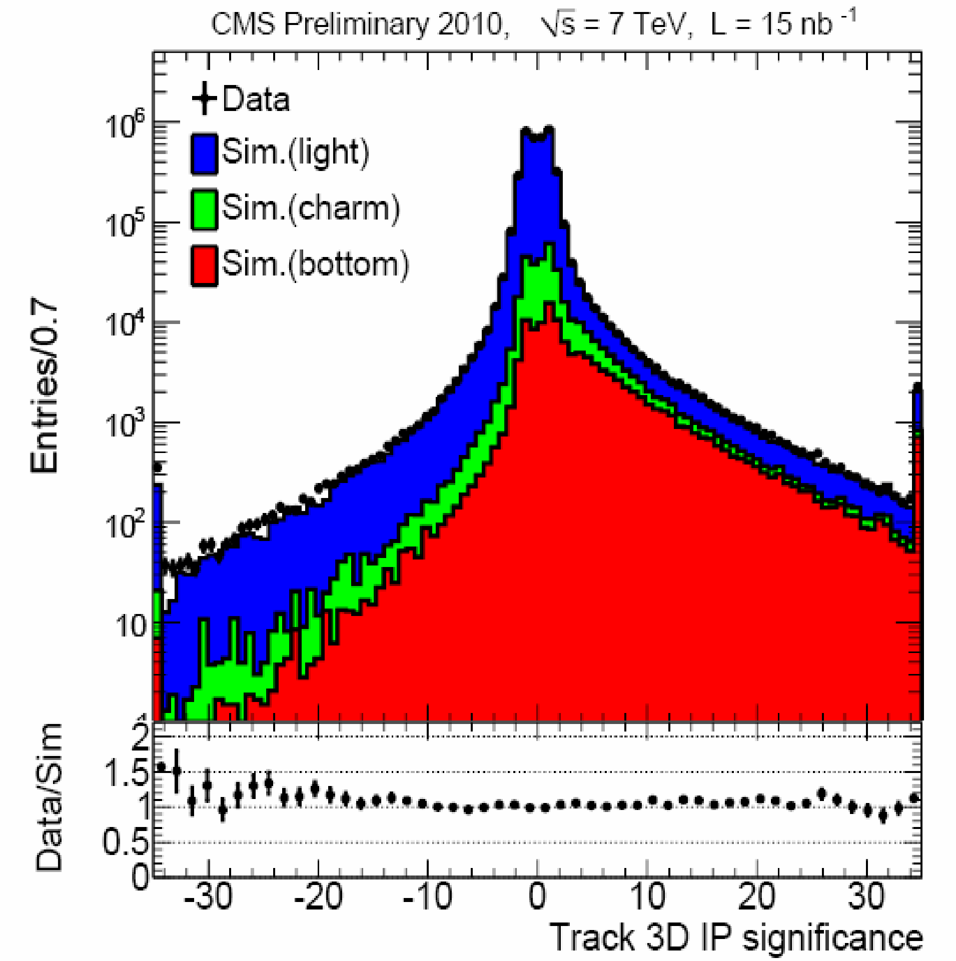
Nuclear interactions: 0.1 – 0.5 λ_I; 5% of charged pions interact. Vertex resolution: 0.1 mm.

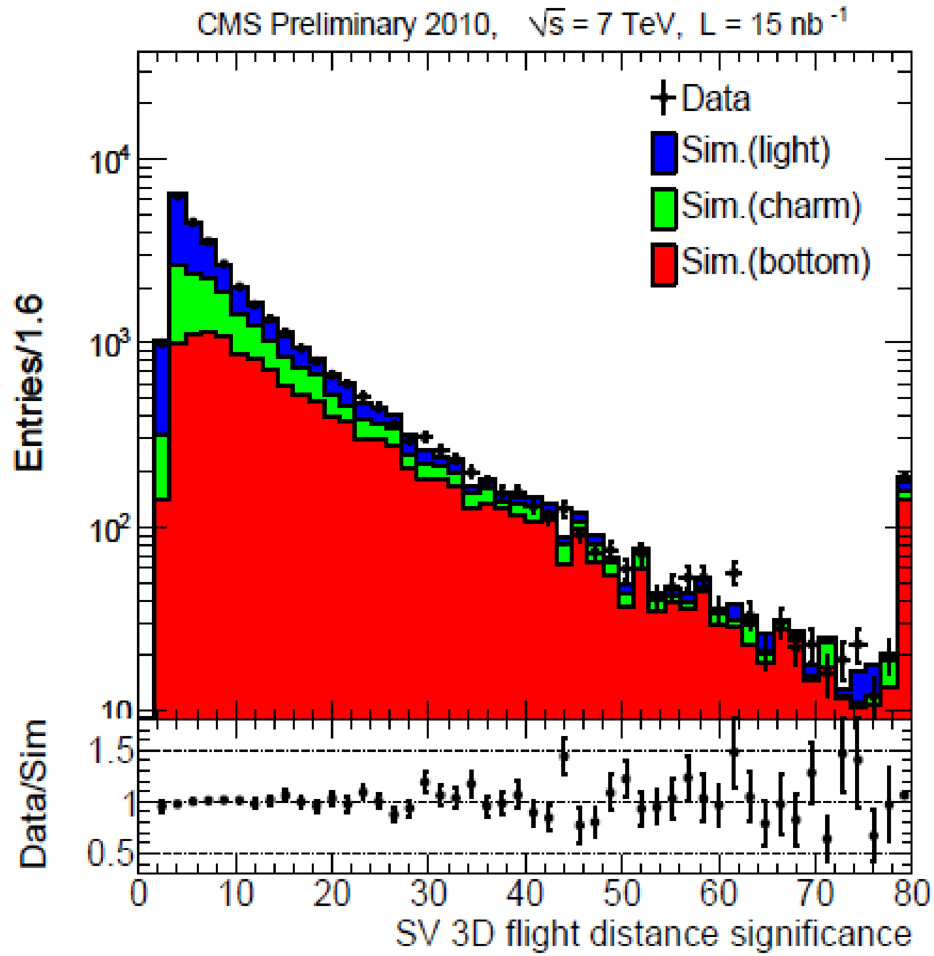
Particle “radiography”: tracker material known at 10% level.





B-tagging

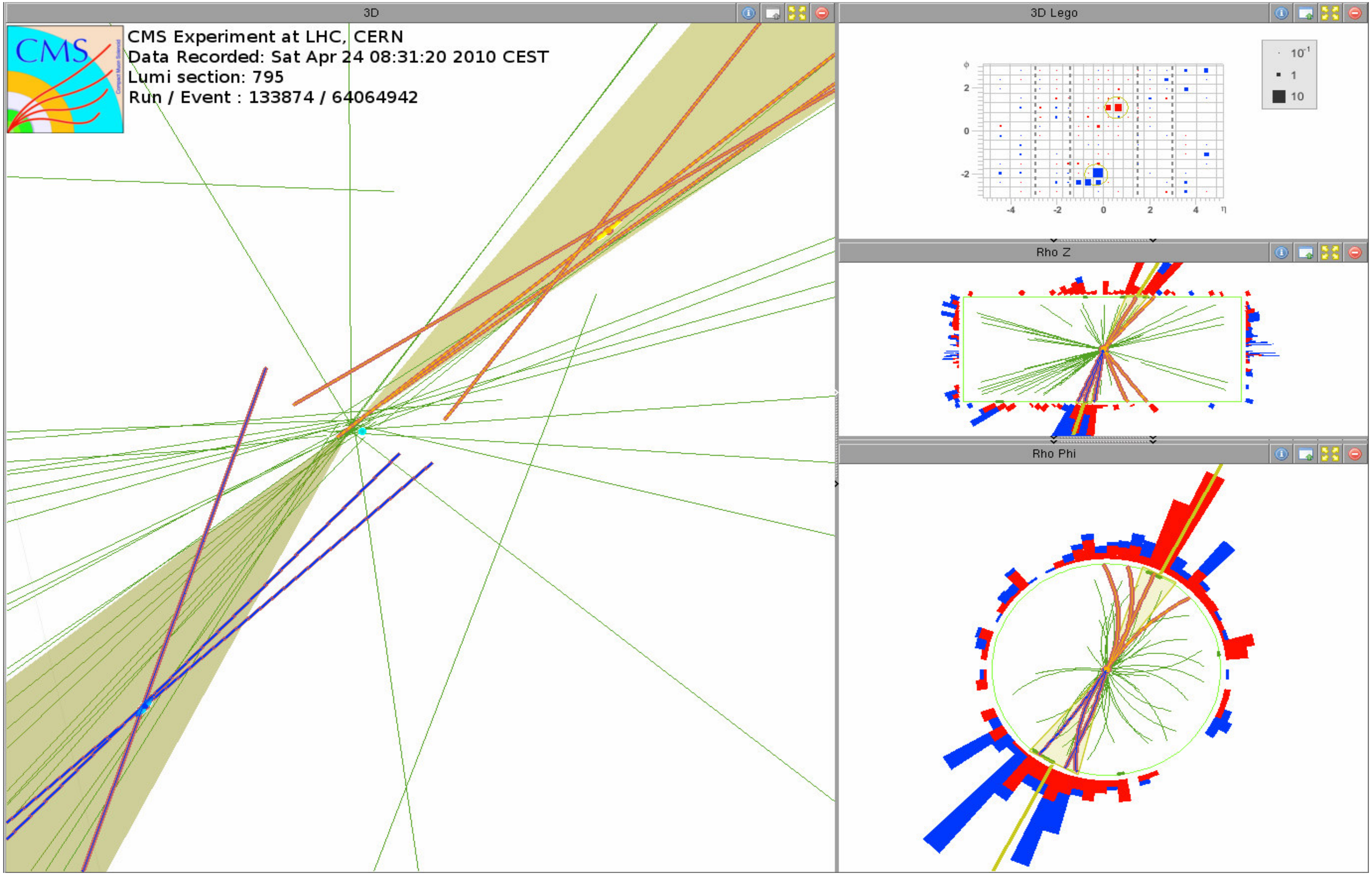




B-tagging algorithms:

- ❑ Track Counting (above some 3D impact parameter significance threshold), for high efficiency.
- ❑ 3D Secondary Vertex reconstruction, for high purity.

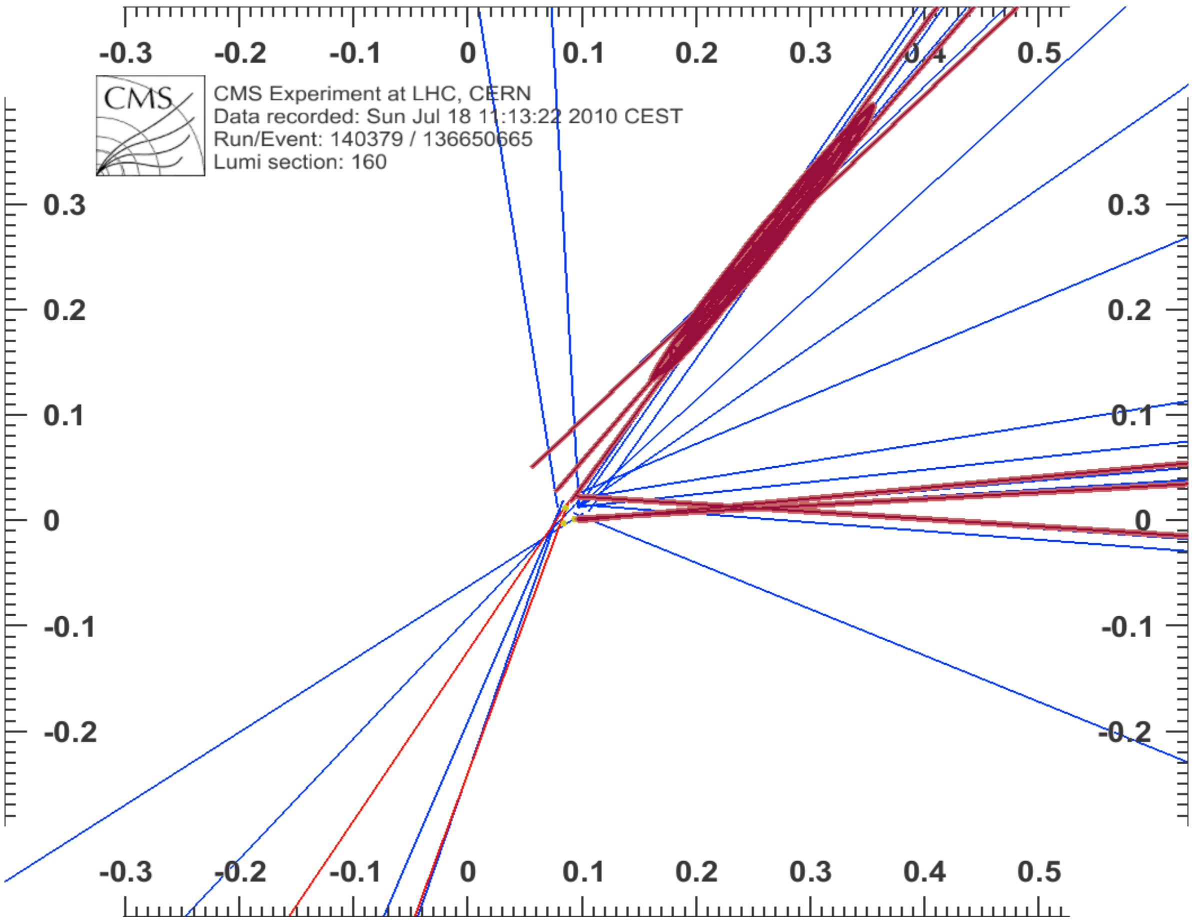
B-tagging

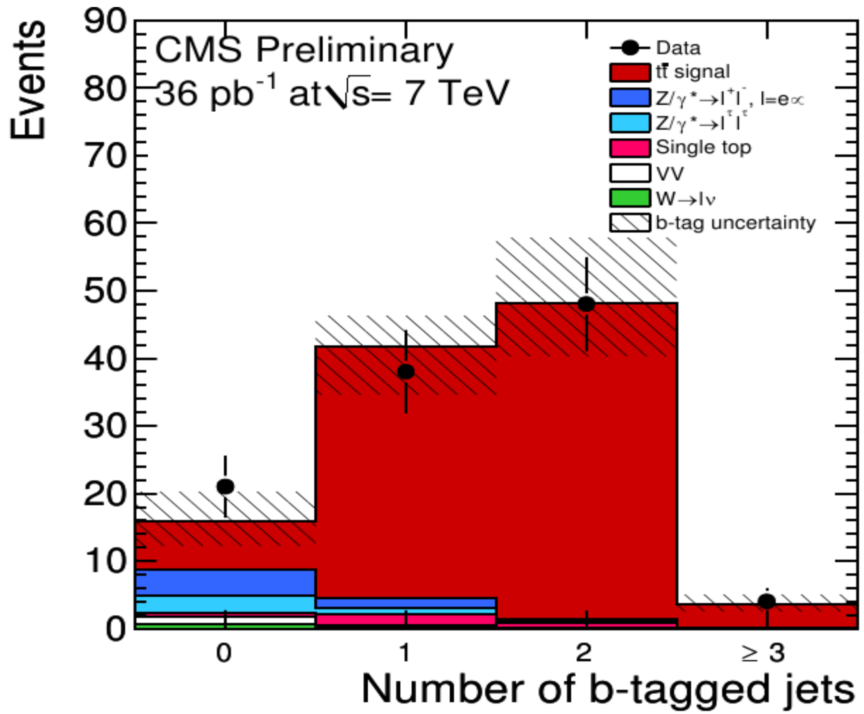

3D
CMS Experiment at LHC, CERN
Data Recorded: Sat Apr 24 08:31:20 2010 CEST
Lumi section: 795
Run / Event : 133874 / 64064942
3D Lego
Rho Z
Rho Phi

B-tagging in Top Events

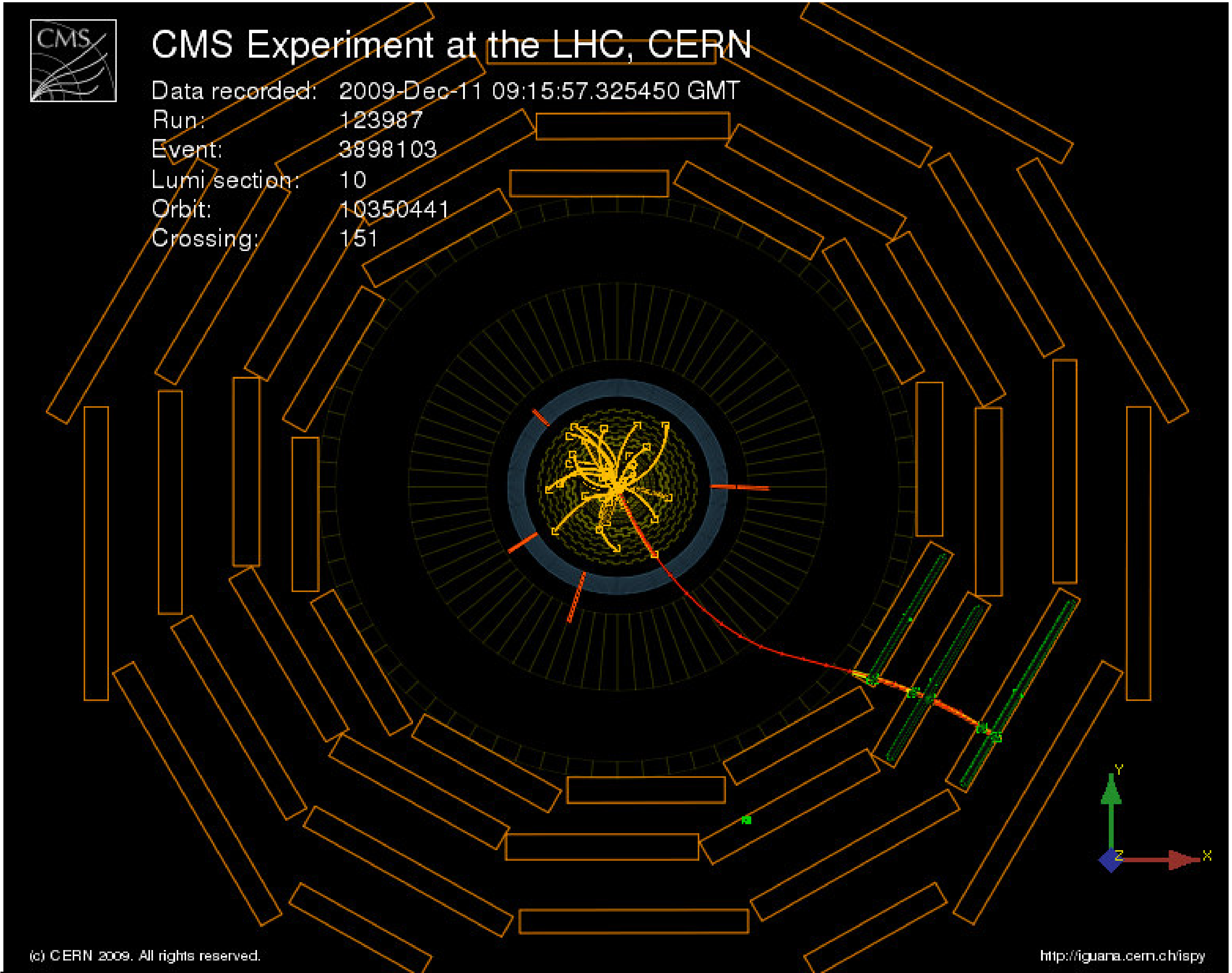
Top events are a high purity B-tagging test bench at the LHC.

$SF_b = 1.0 \pm 0.1$





Muons


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2009-Dec-11 09:15:57.325450 GMT
Run: 123987
Event: 3898103
Lumi section: 10
Orbit: 10350441
Crossing: 151
Y
X
Z
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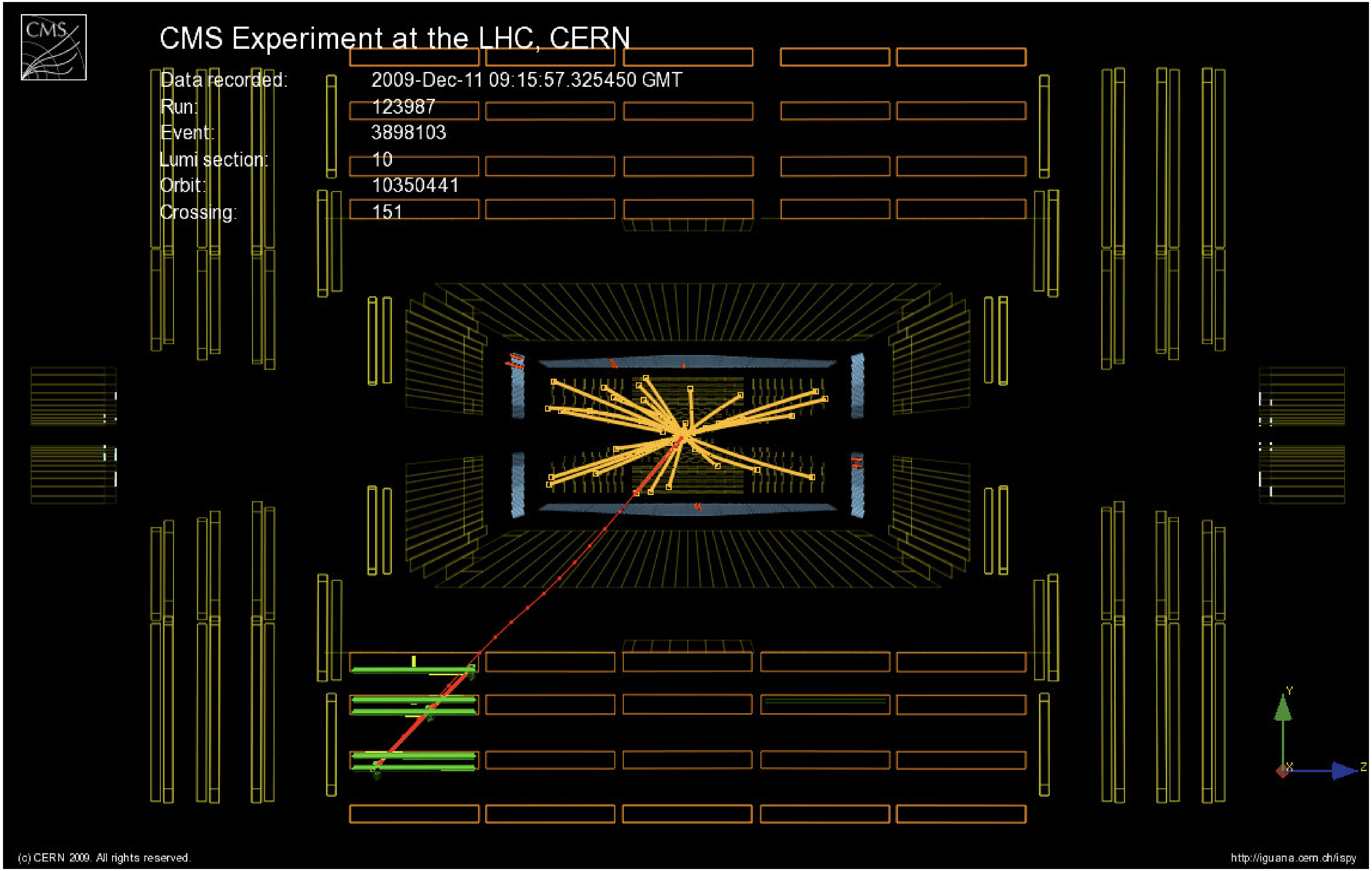
http://iguana.cern.ch/ispy

Muons


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2009-Dec-11 09:15:57.325450 GMT
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Y
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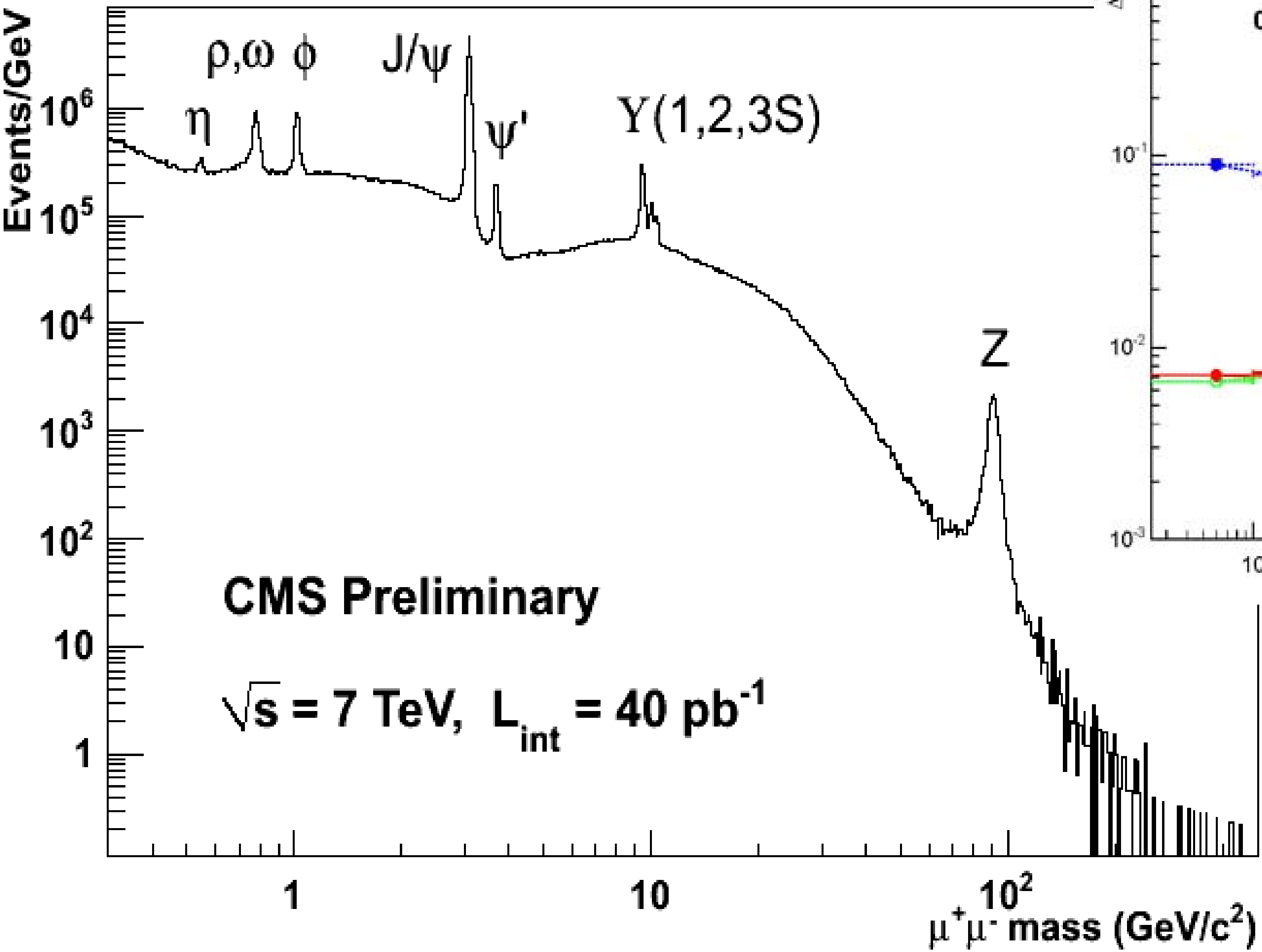
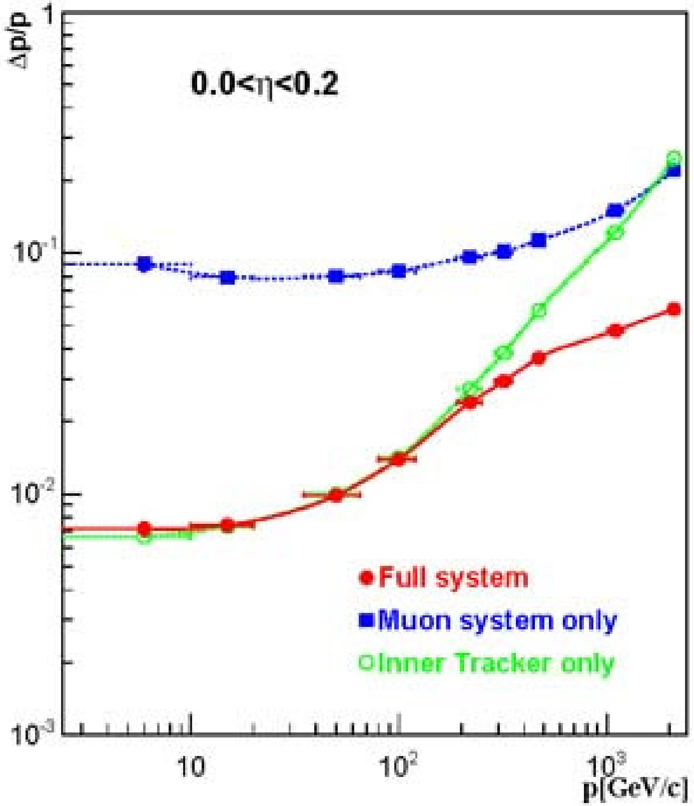
http://iguana.cern.ch/ispy

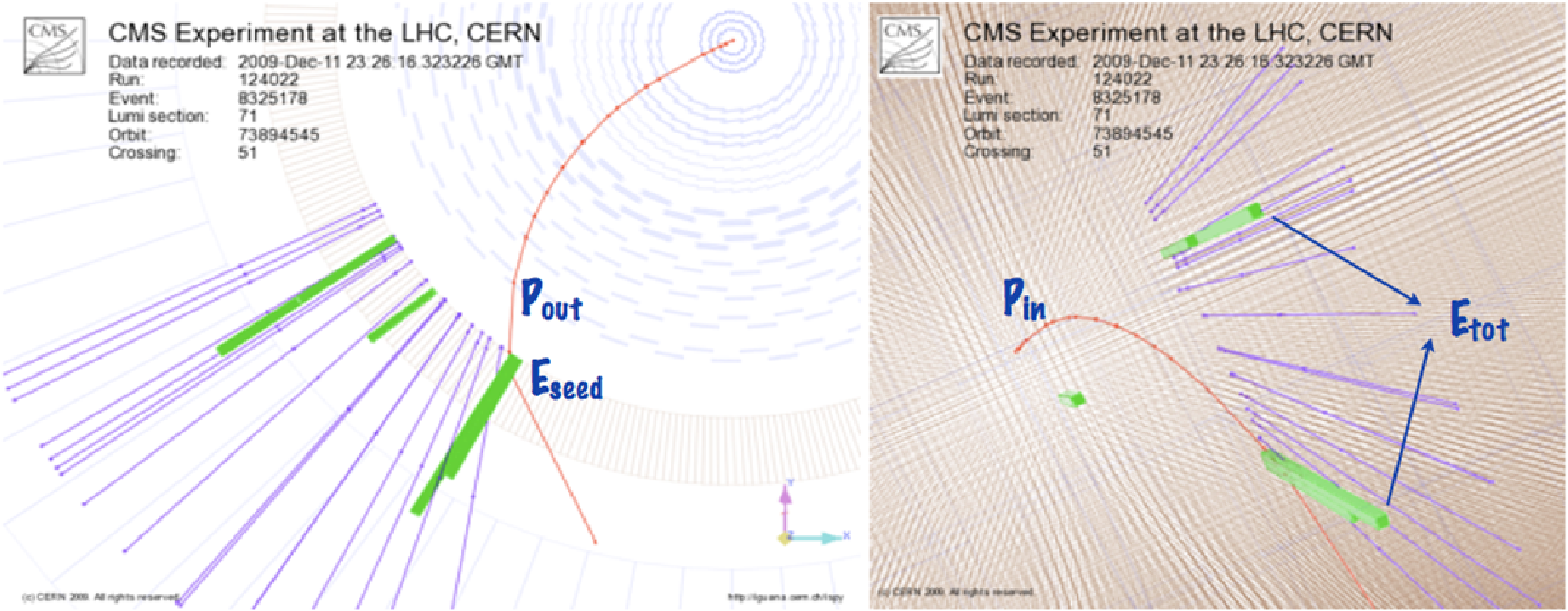
Muons


Events/GeV
η
ρ,ω
ϕ
J/ψ
ψ'
Υ(1,2,3S)
Z
CMS Preliminary
√s = 7 TeV, L_int = 40 pb^-1
μ+μ- mass (GeV/c²)


Δp/p
0.0<η<0.2
Full system
Muon system only
Inner Tracker only
p[GeV/c]

Electrons

900 GeV data

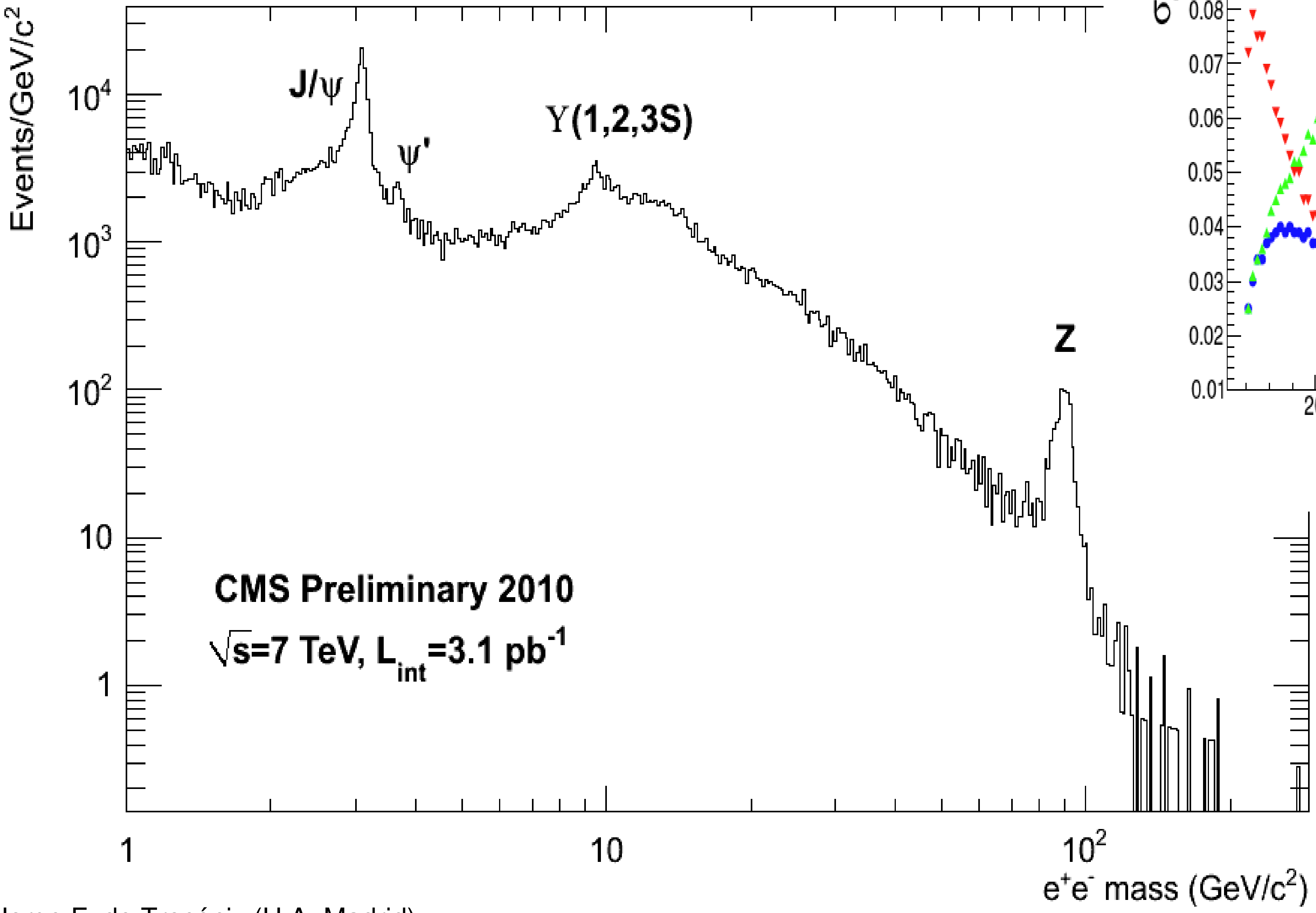


E_{seed} = 1.26 GeV,
P_{out} = 1.18 GeV/c:
E_{seed}/P_{out} = 1.07

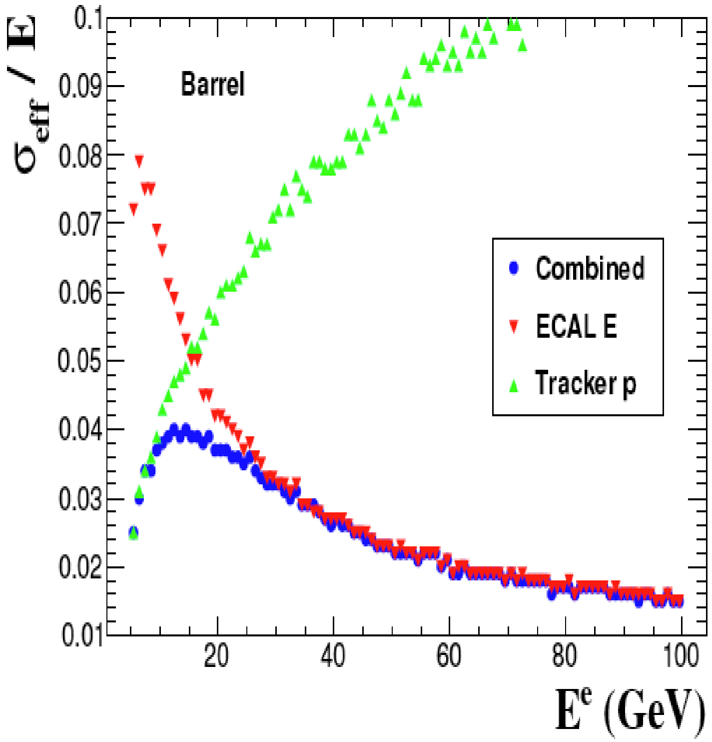
E_{tot} = 2.32,
P_{in} = 2.56 GeV/c:
E_{tot}/P_{in} = 0.91

E_{brem} = 1.06 GeV,
$P_{in}-P_{out}$ = 1.38 GeV/c

Electrons

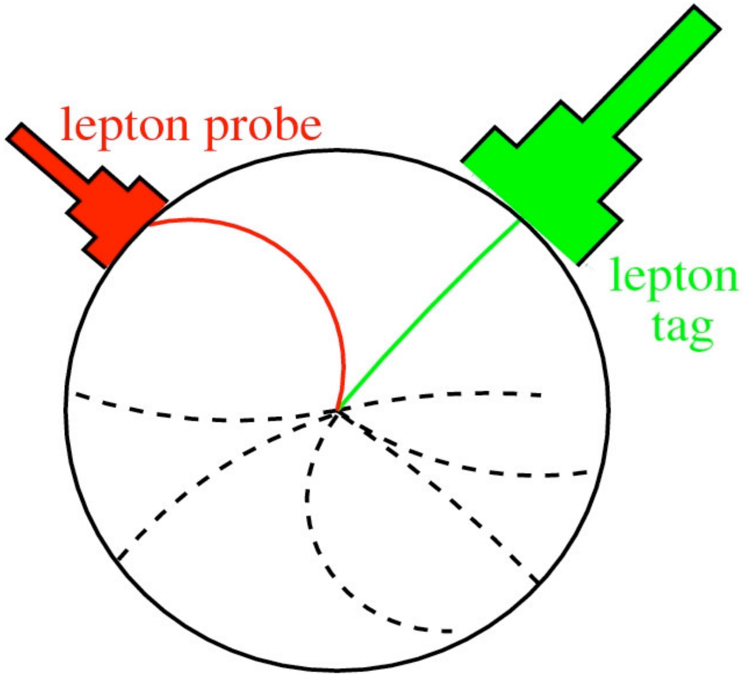


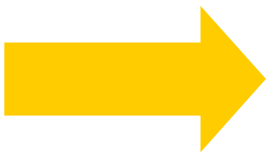
Events/GeV/c²
J/ψ
ψ'
Υ(1,2,3S)
Z
CMS Preliminary 2010
√s=7 TeV, L_int=3.1 pb⁻¹
e⁺e⁻ mass (GeV/c²)

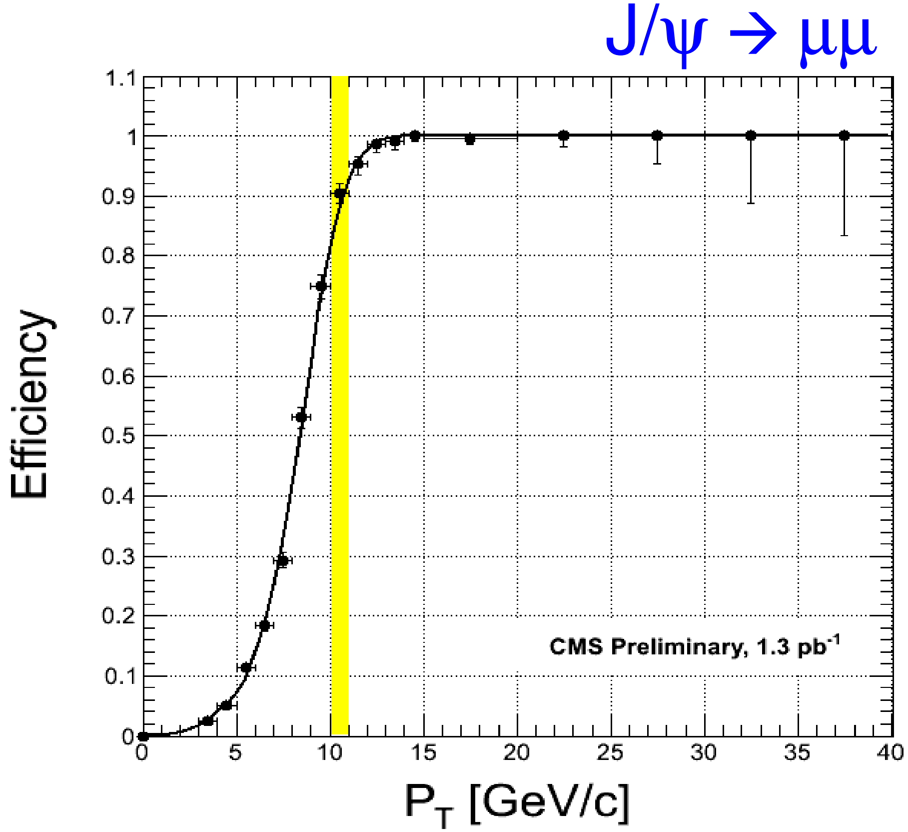


σ_eff / E
Barrel
Combined
ECAL E
Tracker p
E^e (GeV)

Efficiencies





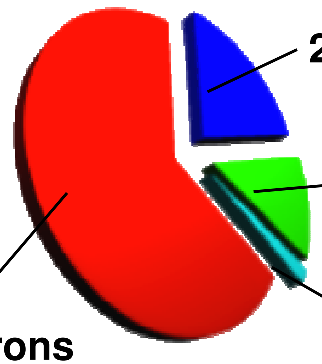


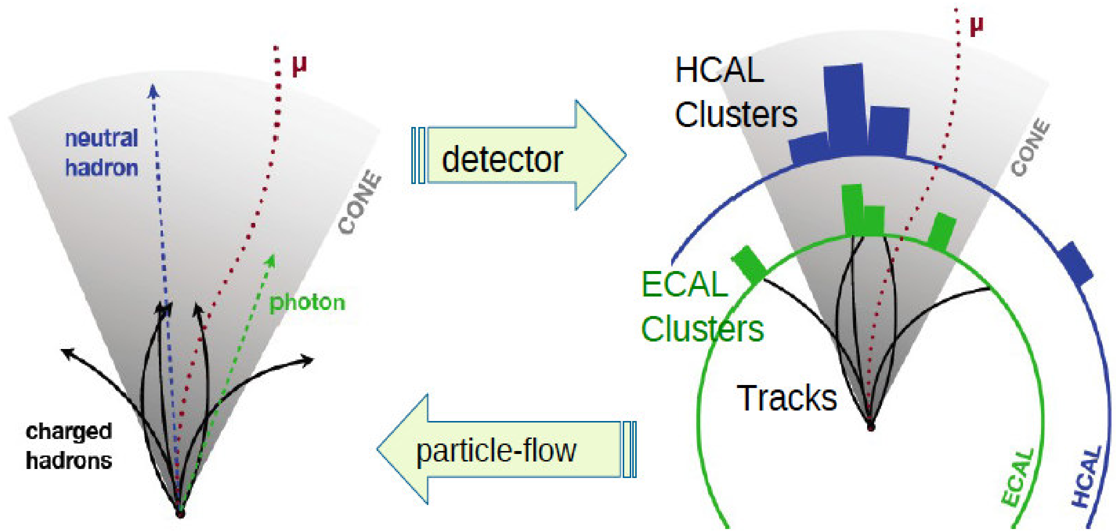
Tag-and-Probe method uses resonance decays: J/ψ, Z.

- One lepton satisfying tight selection criteria.
- The second lepton is used to measure trigger, isolation and reconstruction/id efficiencies, as a function of momentum and position.

Particle Flow

A Typical Jet

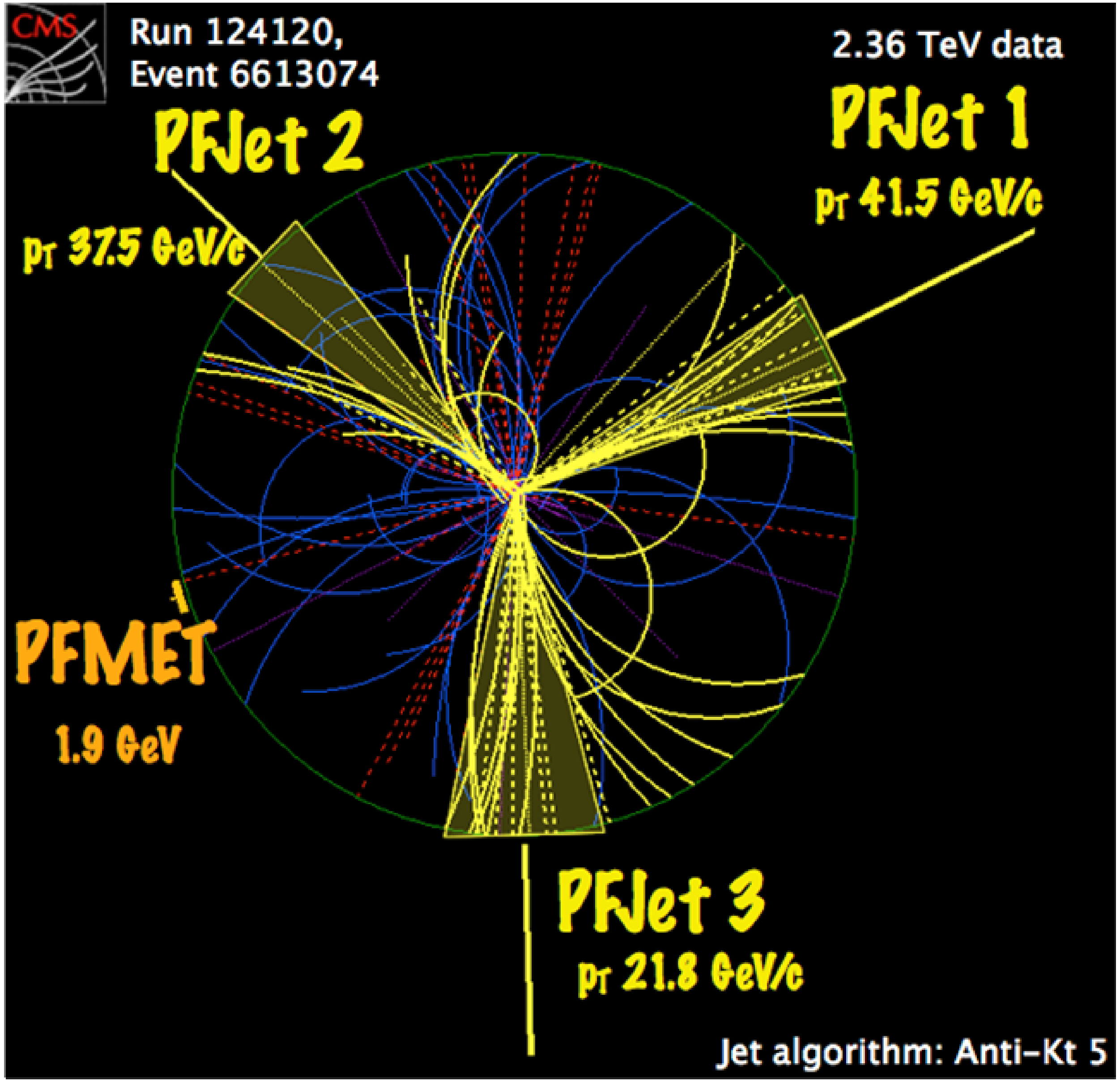




- Charged particles get well separated due to the huge tracker volume and the high magnetic field.
- Excellent tracking resolution, able to go to down to very low momenta.
- Excellent electromagnetic calorimeter with good granularity.
- In multijet events, only 10% of the energy corresponds to neutral (stable) hadrons.

Big improvement in energy resolution and tau identification using particle-flow techniques.

Particle Flow Event Reconstruction



PFJets with (uncorrected) p_T > 20 GeV/c

Particle inside the jet:

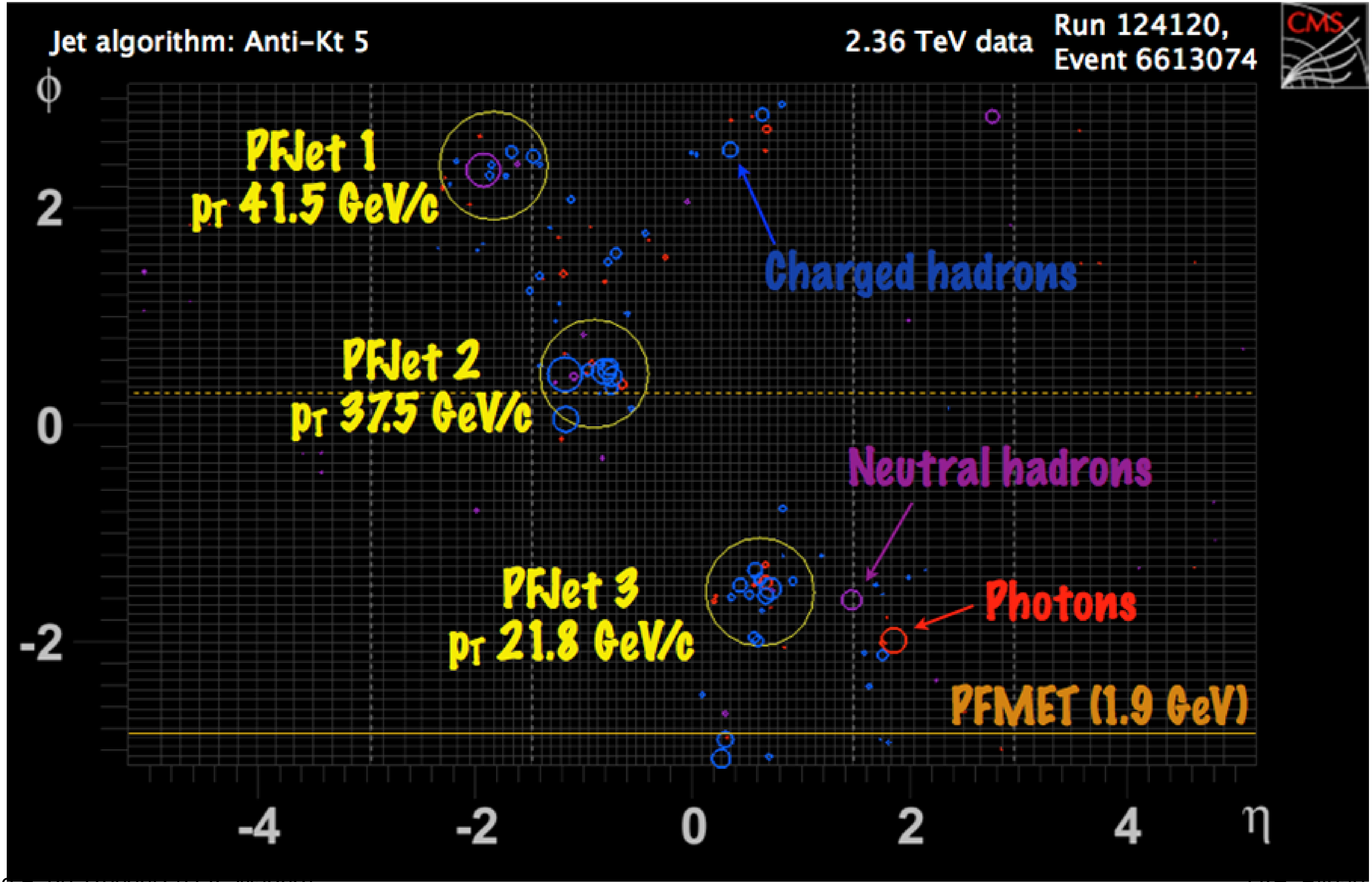
- Charged hadrons
- Photons
- Neutral hadrons

Particles outside the jet:

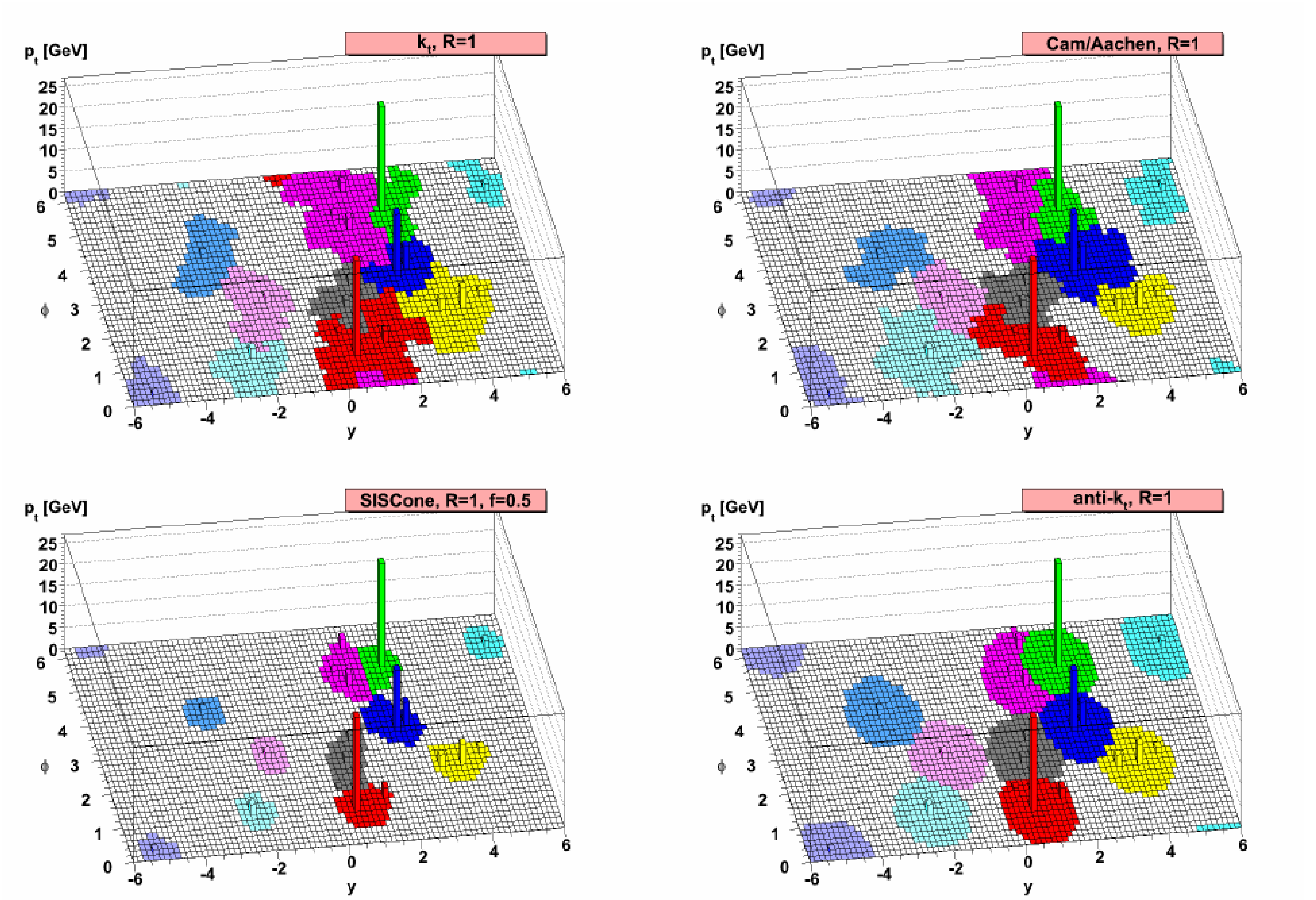
- Charged hadrons
- Photons
- Neutral hadrons

PFMET (1.9 GeV)

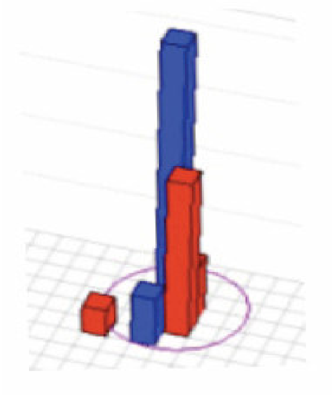
Particle Flow Event Reconstruction



Clustering Algorithms: Anti-k_T

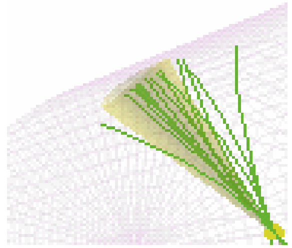


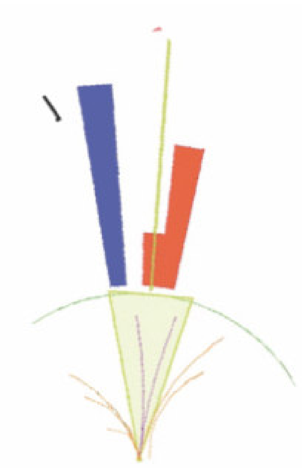
Detector Objects for Jet Clustering



Calorimeter Jets
clustered from
calorimeter towers

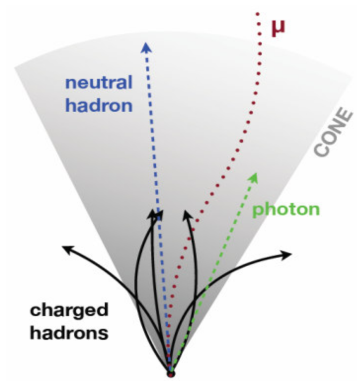
Track Jets
clustered from
tracks





Jet plus Tracks
correct Calorimeter Jets
using momentum of tracks

Particle Flow Jets
clustered from
identified particles
reconstructed
using all detector
components



Jet Reconstruction at CMS

1. Calorimeter Jets: calorimeter towers

PROS: simple, robust

CONS: worst resolution

2. Jet Plus Tracks: correct for tracks

PROS: improve resolution with tracks

CONS: seeded on calorimeter jets

3. Particle Flow: particle candidates

best resolution

used in most analyses

Jet Calibration

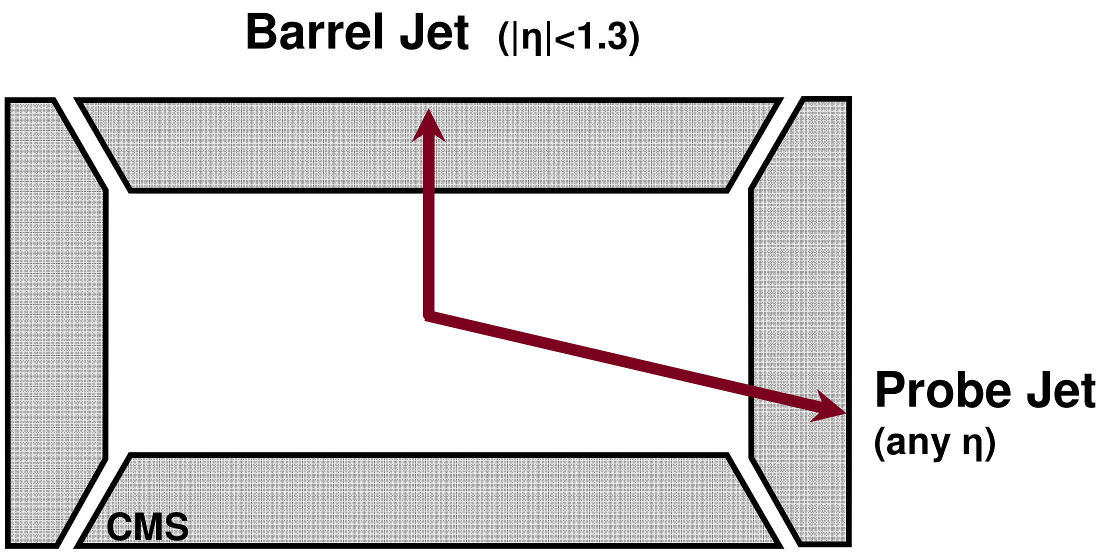
$$\text{Response} = \frac{\text{Reco Jet } p_T}{\text{True Jet } p_T}$$

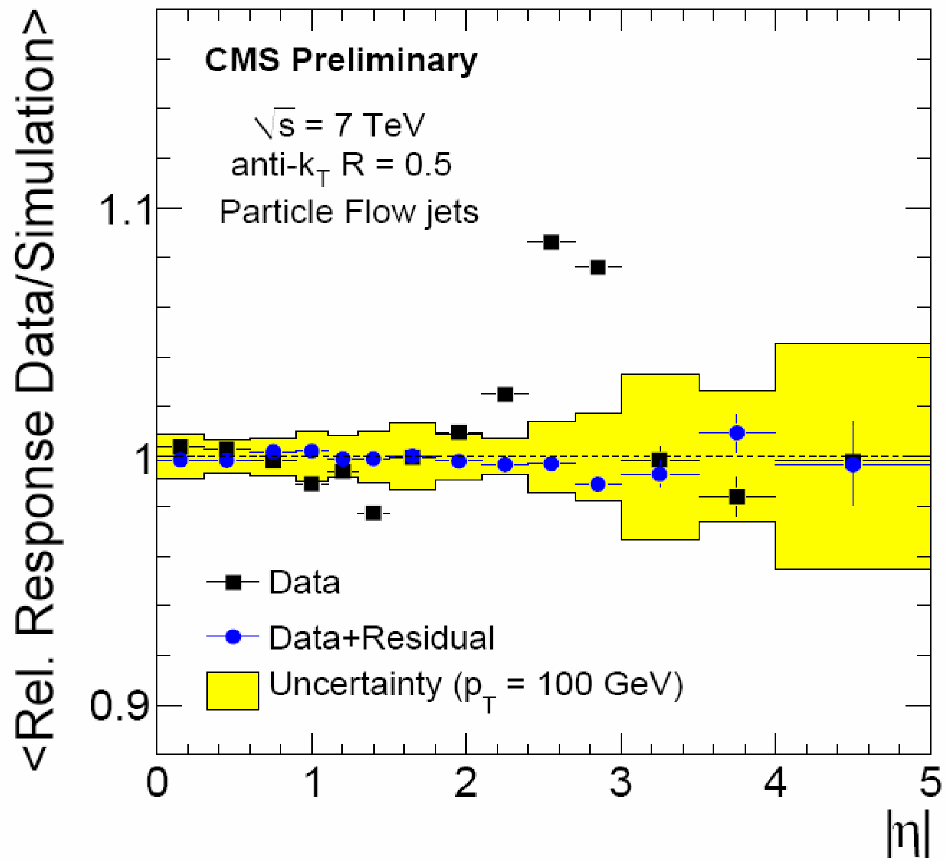
Physics Object

Raw Jet × Offset Correction (pile up) × Relative Response (vs. η) × Absolute Response (vs. p_T) = Calibrated Jet

Additional corrections (e.g. flavour) are analysis dependent

Jet Relative Response



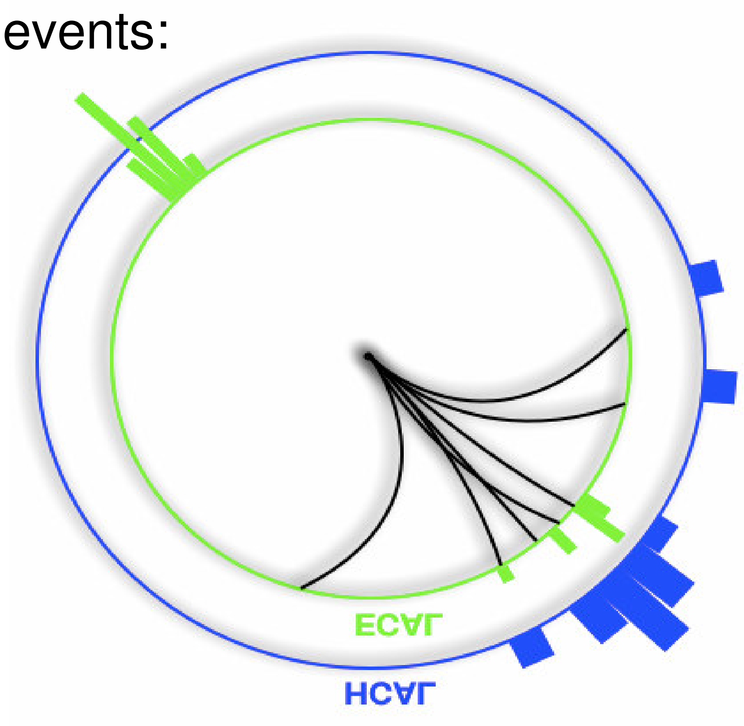


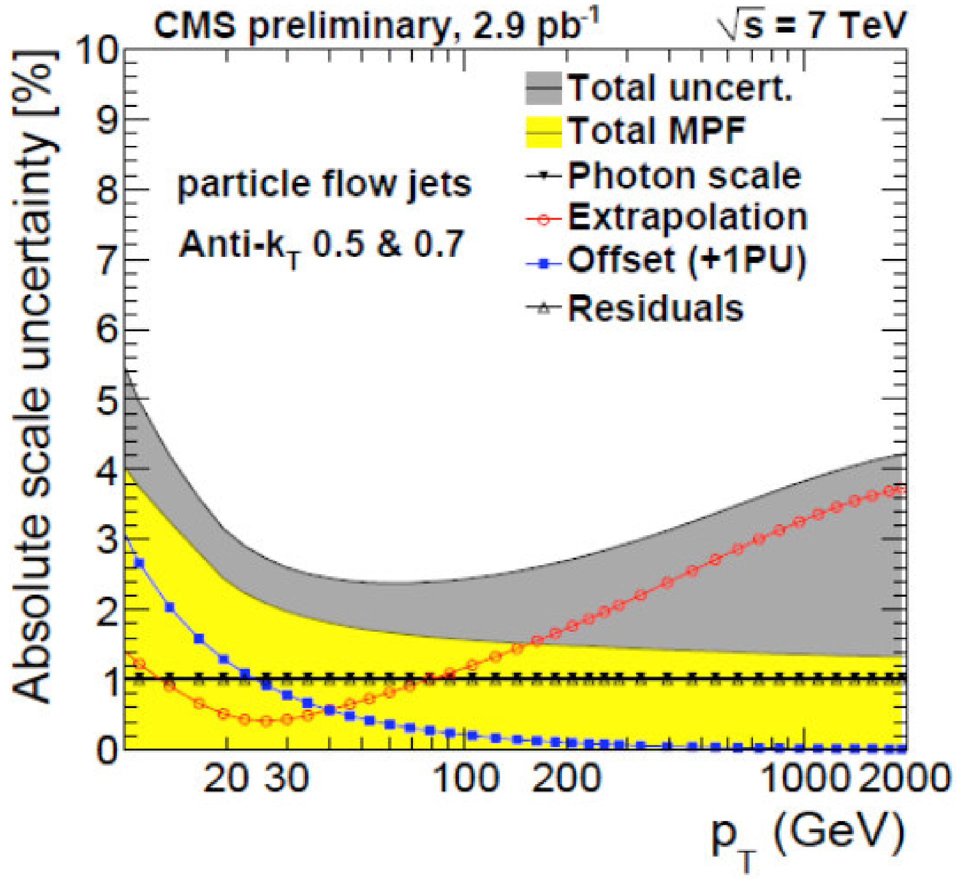
- Flaten jet response in η using di-jet p_T balance method.
  - Barrel calorimeter response as reference.

- Jet response uniformity as a function of η better than 1%.

Jet Absolute Response

γ+Jet events:





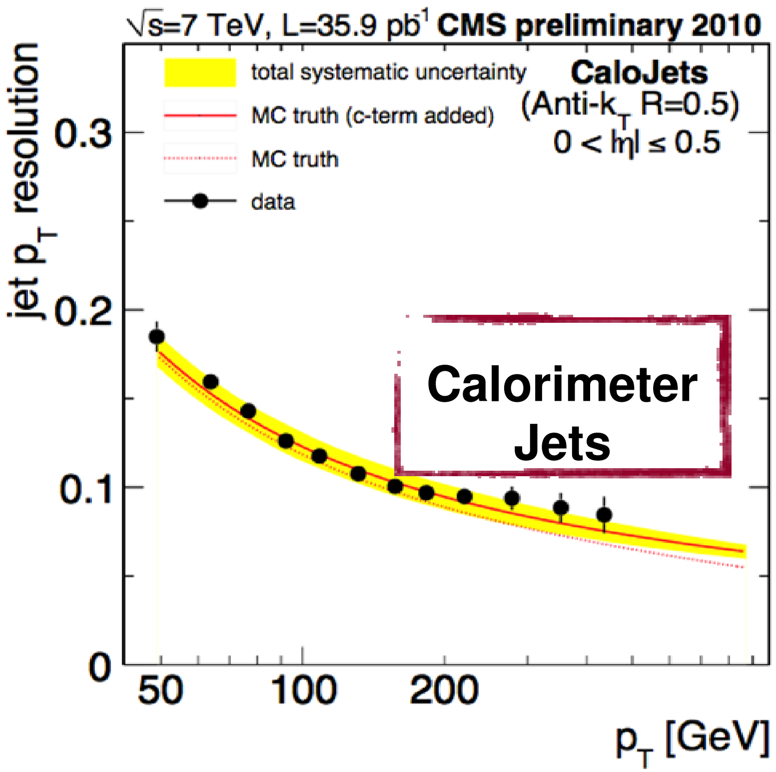
- ➢ Transverse plane balancing
  - ❑ Photon vs jet (p_T balance)
  - ❑ Photon vs missing E_T (MPF)

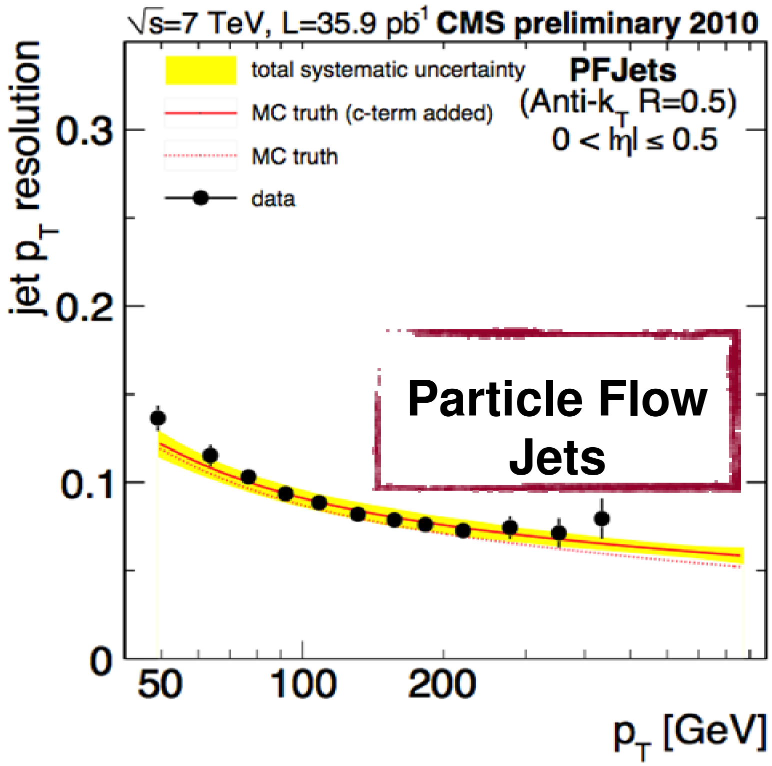
- ➢ Jet energy scale uncertainty: 3-5% over whole p_T range

Jet Resolution

- Dijet asymmetry method:

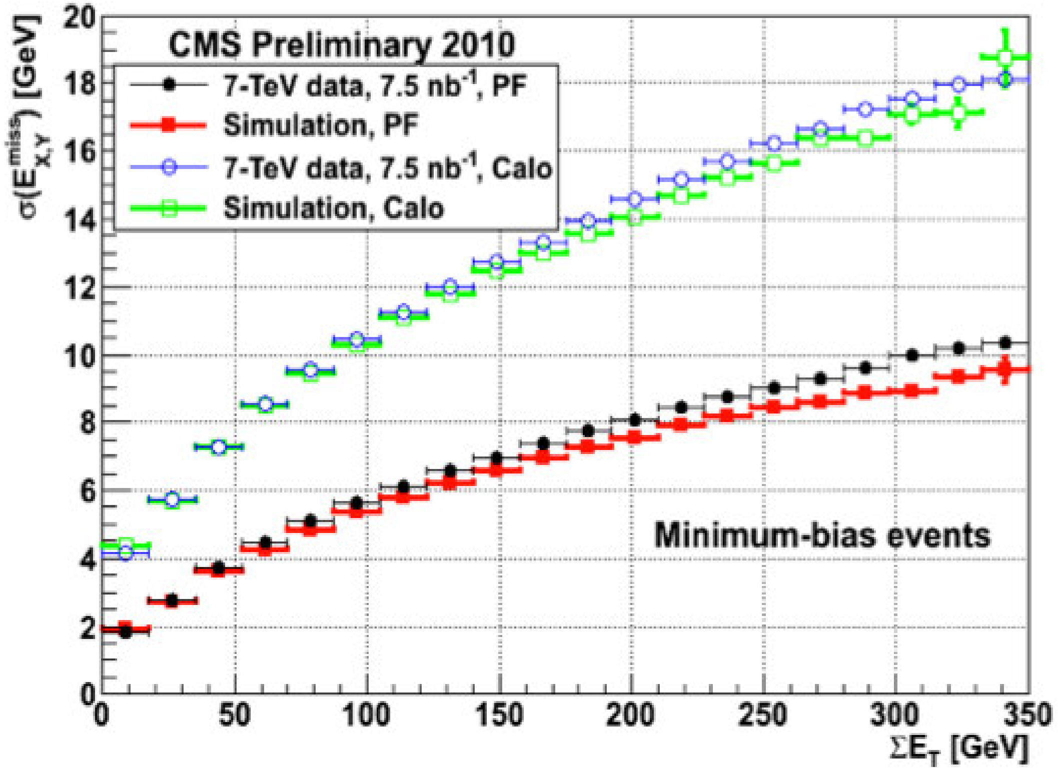
$$\mathcal{A} = \frac{p_T^{Jet1} - p_T^{Jet2}}{p_T^{Jet1} + p_T^{Jet2}} \longrightarrow \frac{\sigma(p_T)}{p_T} = \sqrt{2}\,\sigma_{\mathcal{A}}$$

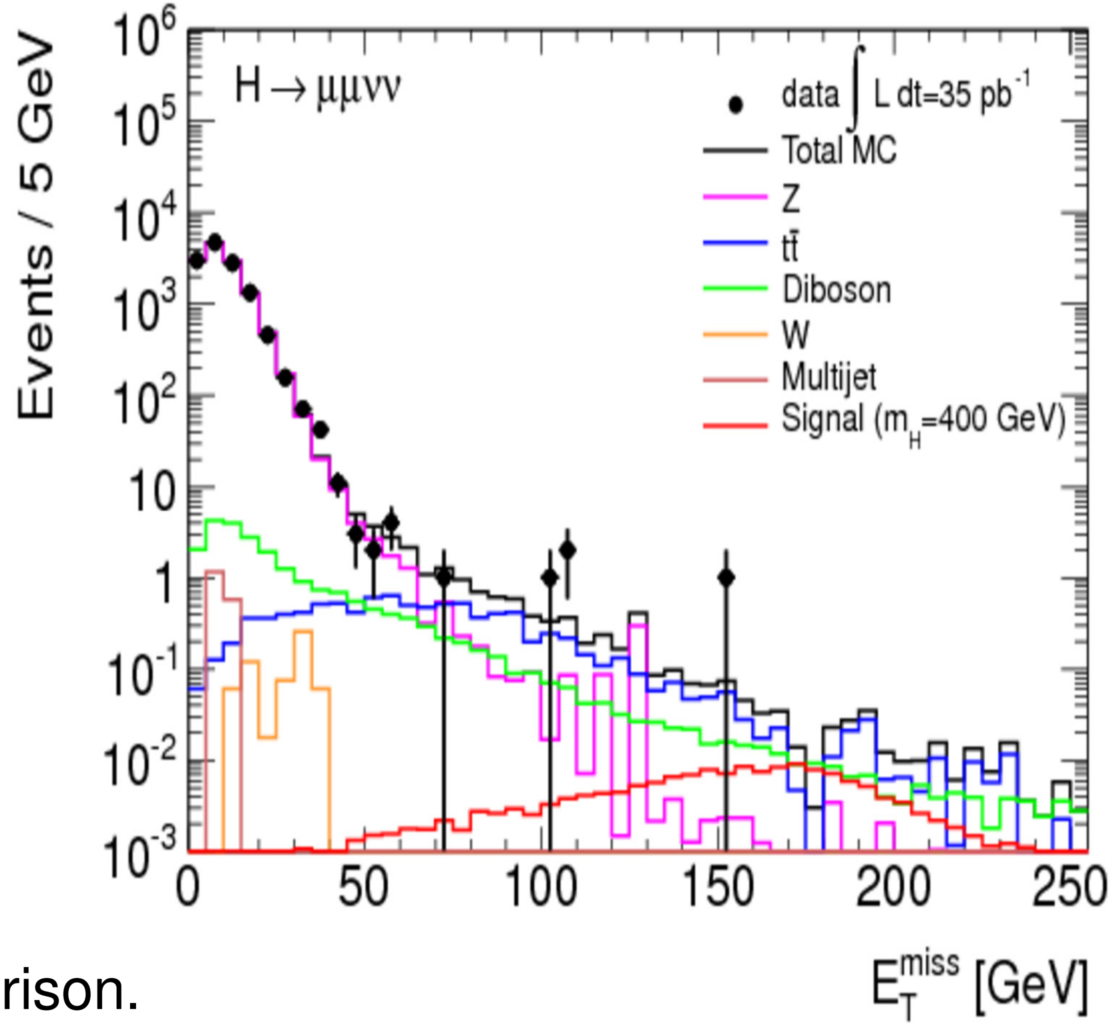




- Jet energy resolution:10% @ p_T = 100 GeV
- Jet position resolution in Φ and η: 0.01 @ p_T = 100 GeV

Missing Transverse Energy (MET)





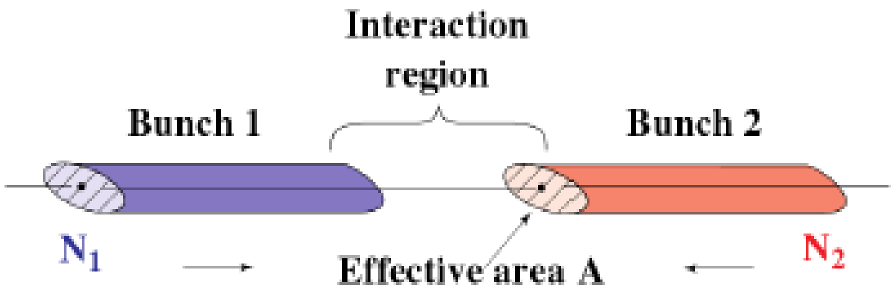
- ❑ Well calibrated: data vs. MC comparison.
- ❑ Big improvement in MET resolution using Particle Flow.
- ❑ Excellent performance for physics.

Luminosity

$$\mathcal{L} = N_1 N_2 f n_b \int \rho_1(x,y)\rho_2(x,y)dxdy$$

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{A_{eff}}$$

$$A_{eff} = 2\pi\sigma_x\sigma_y$$



- Intensities N_1,$N_{2,}$ measured by LHC beam current transformers.
- Shape and size of the interaction region, A_{eff}, measured via Van der Meer scans: relative variations or rate as a function of the transverse separation between beams.
- Rates measured in CMS using fraction of zero counts of HF and vertexing.

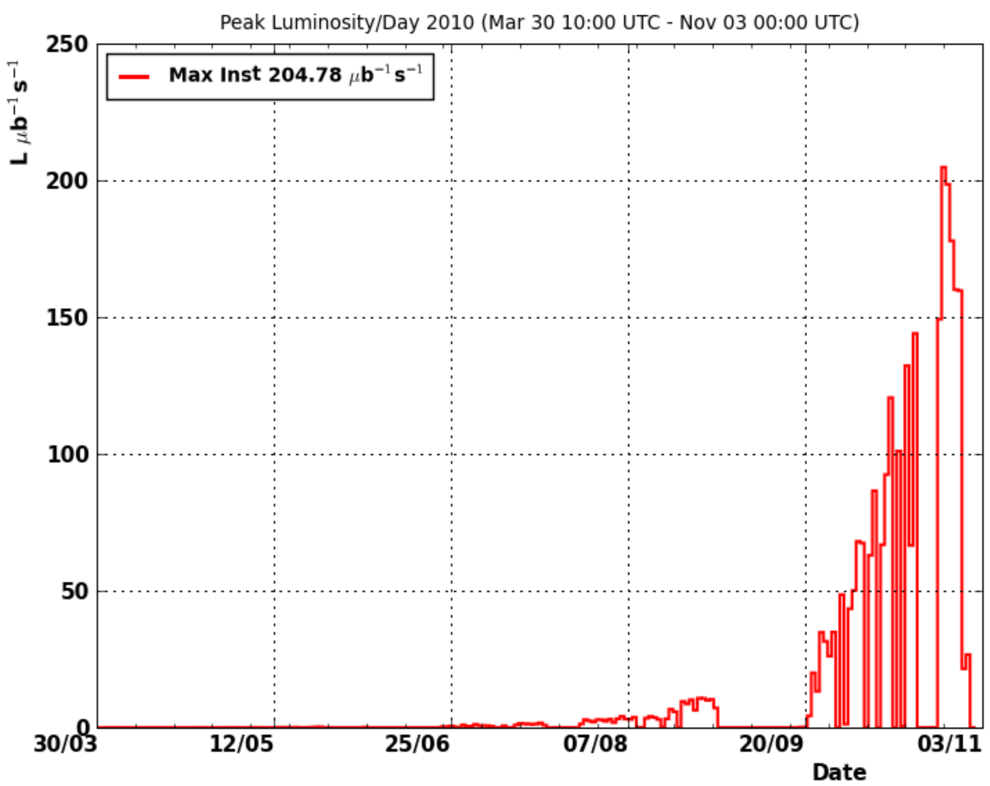
Systematic	Error (%)
Effective Area Determination	2.7
Beam Intensity	2.9
Sample Dependence	0.7
Total	**4.0**

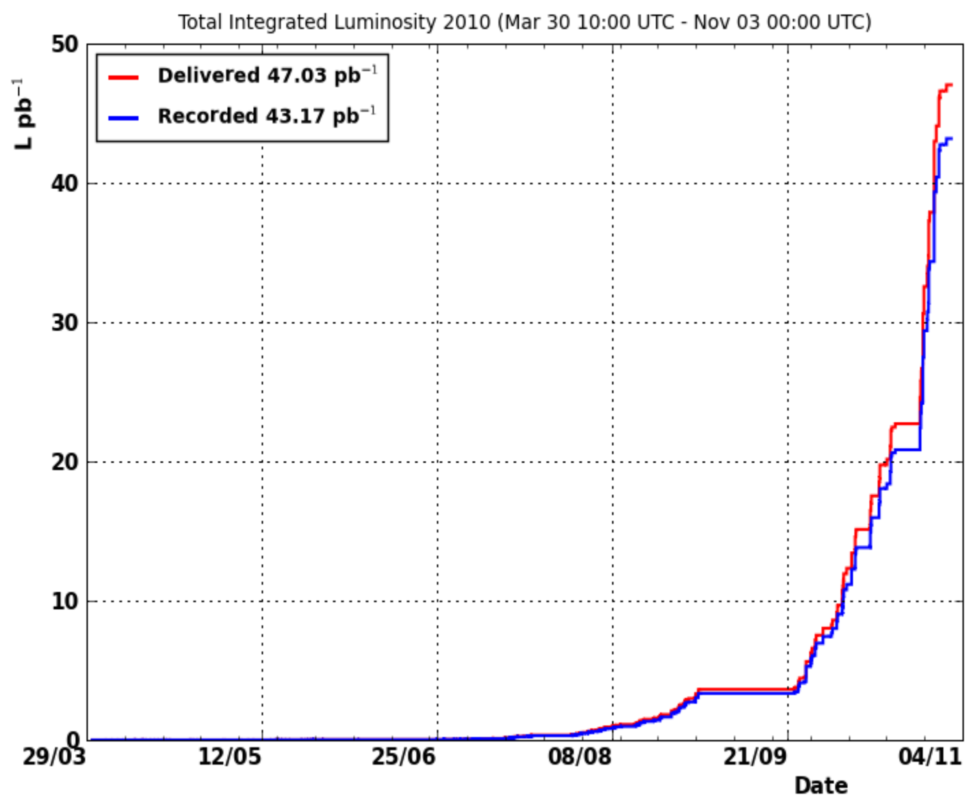
Uncertainty: 4%

Luminosity correction with respect to initial estimates: -0.7%

LHC/CMS Operation in 2010

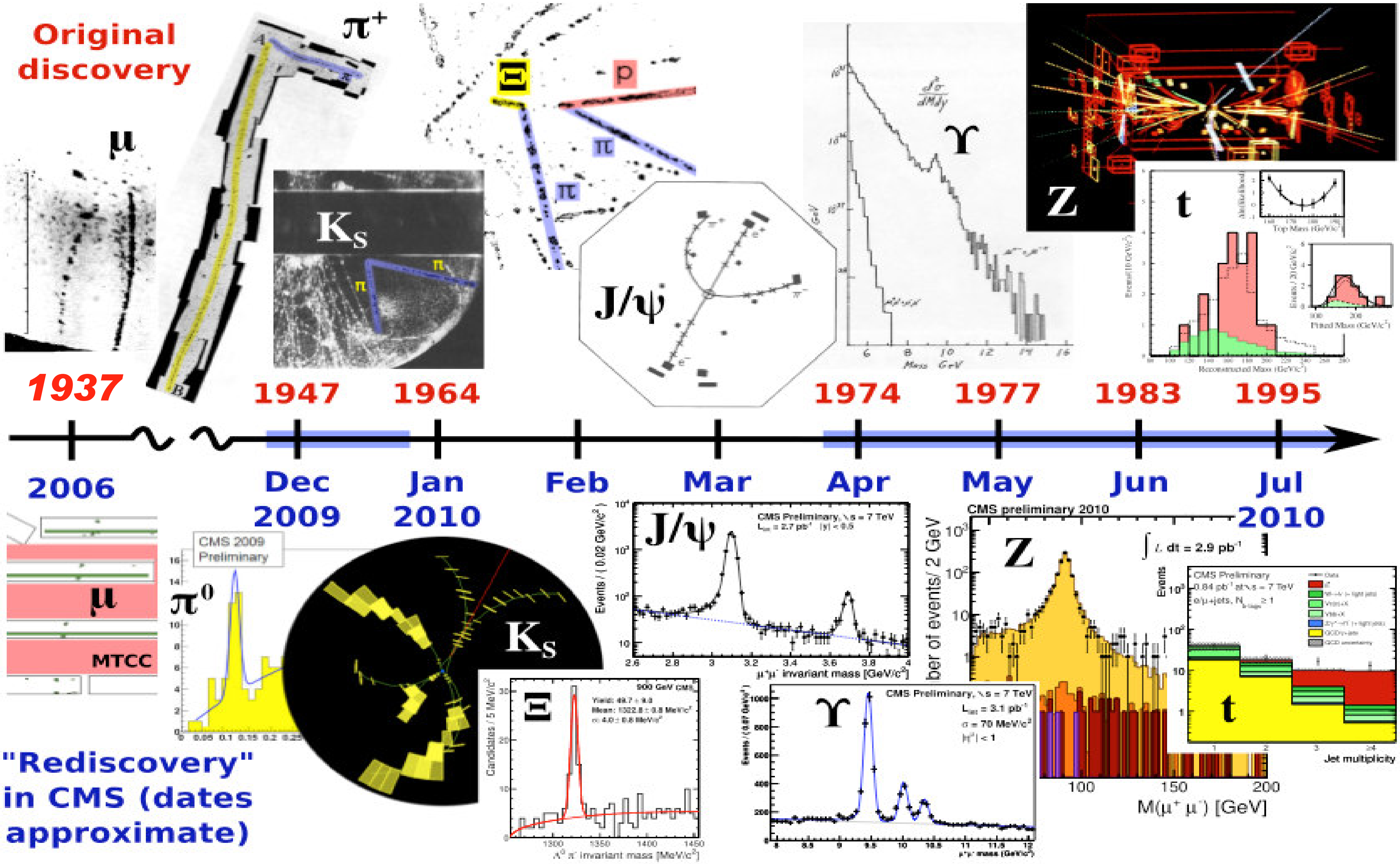
Integrated luminosity delivered to CMS **43 pb^{-1}**. Overall data taking efficiency **> 92%.** Efficiency with all subsystems good **~90%.**





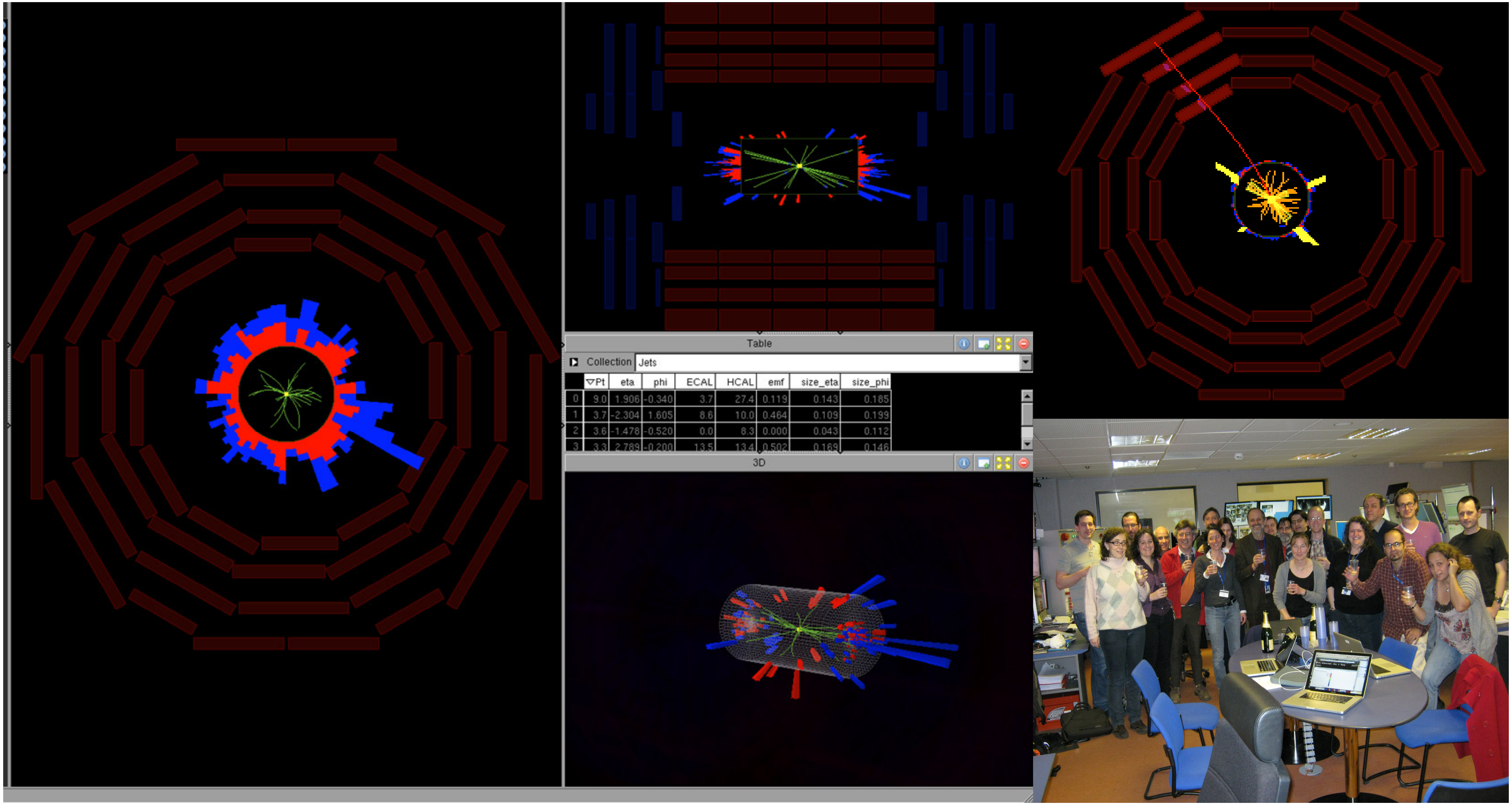
Results shown today based on 2010 data; use up to 40 pb^{-1} of integrated luminosity.

Rediscovering the SM in 2010



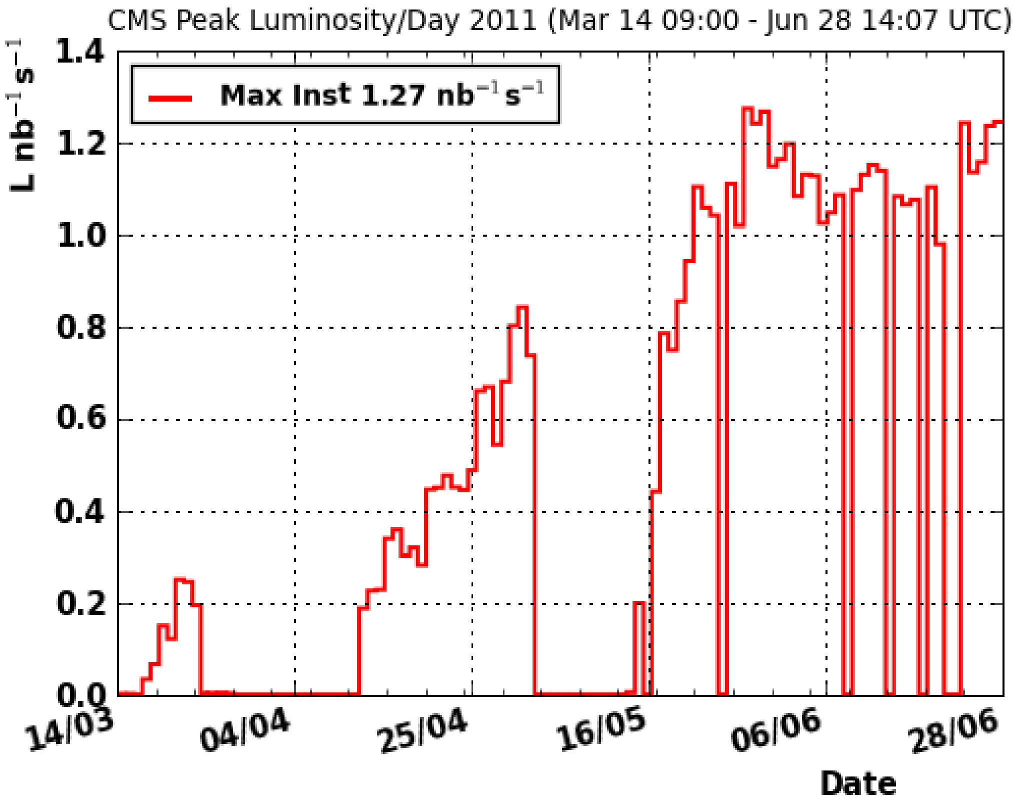
Start of 2011 Operation

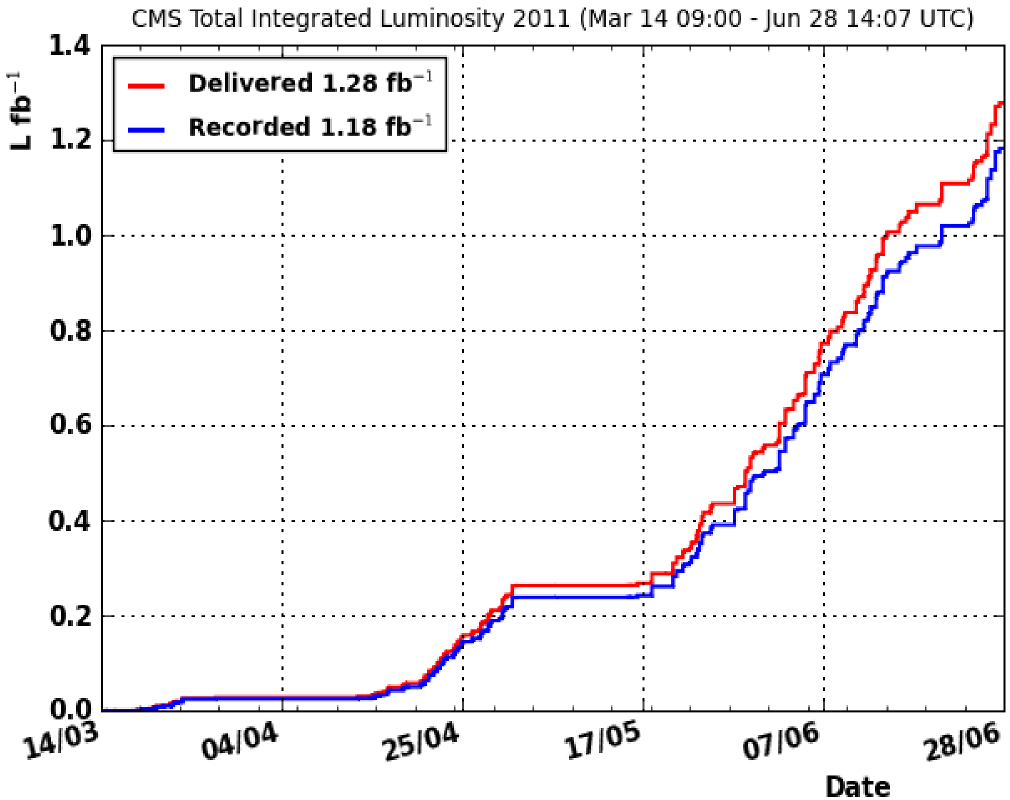
Sunday March 13, 18:20 Stable beams in LHC and CMS taking good data.



LHC/CMS Operation in 2011

Integrated luminosity delivered to CMS **> 1fb^{-1}**. Overall data taking efficiency **> 92%.**





The official goal for the whole 2011 has been achieved in less than 3 months. In terms of yearly goal we are virtually at ~1fb^{-1}/month. If the machine continues to make progress we might exceed 5 fb^{-1} by the end of the year.

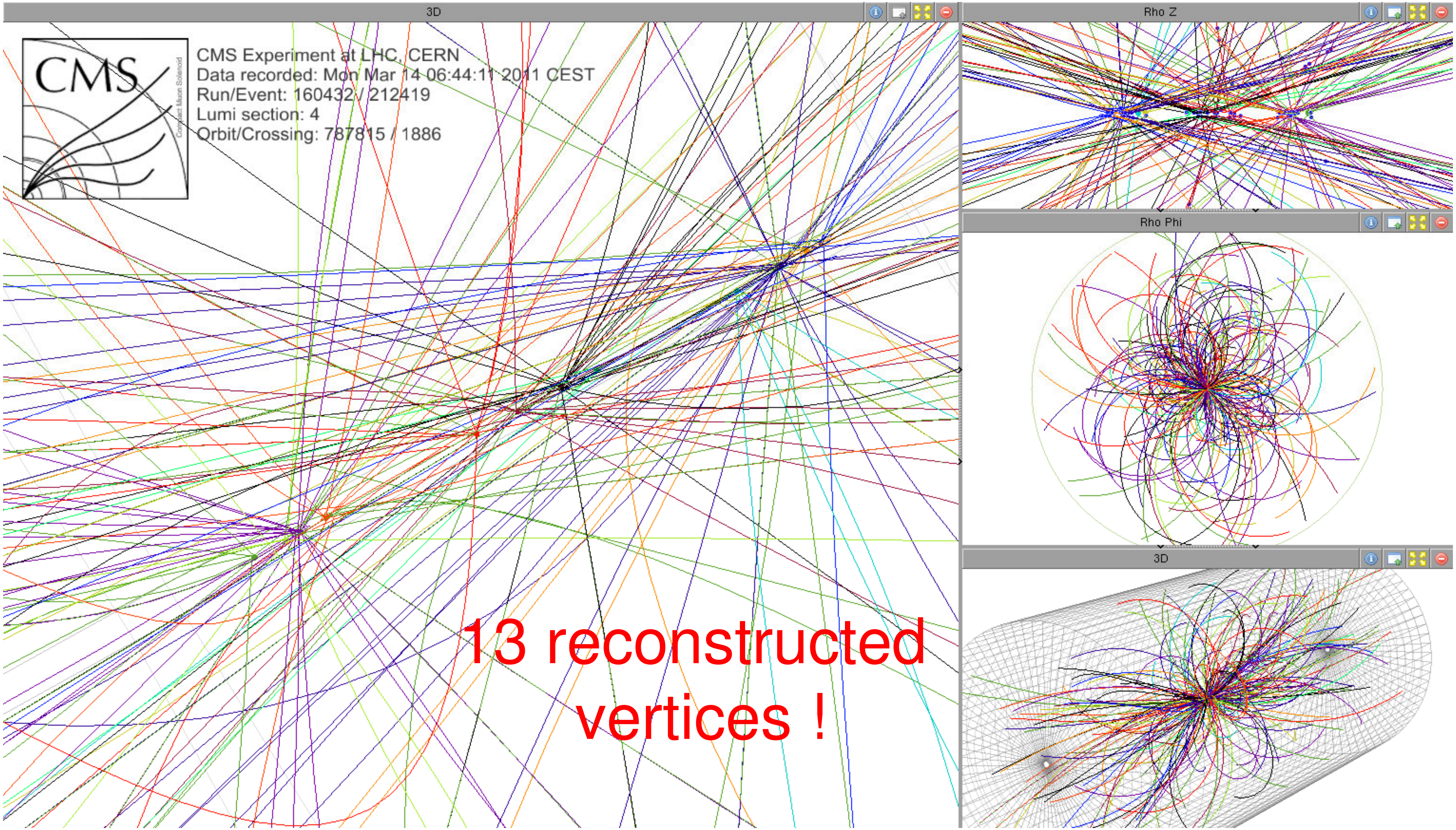
Example of CMS/LHC Current Conditions

- LHC Fill 1901; CMS Run 167898-913; 28/6/2011 2am to 2pm

- Beta-star: 1.50 m; Crossing angle: 120 µrad (H)
- Bunches: 1318; Bunch separation: 50 ns
- Luminous size: 26.8 µm (x), 24.3 µm (y), 63.3 mm (z)
- Current: 1.6E14 protons; Current per bunch: 1.2E11 protons
- Max Inst. Luminosity: 1.22E33 $cm^{-2}\ s^{-1}$; PU: ~6 collisions/BX
- Beam Energy: 3500 GeV

- Event size: 370 kB
- L1 Accept Rate: 50 kHz; Data to HLT: 1.8E4 MB/s
- HLT Accept Rate: 300 Hz; Data to tape: 110 MB/s
- Integrated luminosity: 44 pb^{-1}

Pileup


3D
CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Mar 14 06:44:11 2011 CEST
Run/Event: 160432 / 212419
Lumi section: 4
Orbit/Crossing: 787815 / 1886
Rho Z
Rho Phi
3D
13 reconstructed vertices !

Consequences of Pileup

$Z \rightarrow \mu\mu$

10 in-time + 10 out – of – time pileup