CMS experiment at LHC

Topics relevant for B-physics

Kajari Mazumdar

TIFR, Mumbai

E-mail: mazumdar@tifr.res.in

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Prologue

- Got the notice to give this talk pretty late.
- Keeping the broad spectrum of the audience, will discuss some basic aspects of CMS experiment at LHC.

✓ Introduction to proton-proton collisions

✓ Rudimentary discussion about CMS detector and its performance.

Will not cover:

❑ Specific B-physics results from CMS → *Talk by Nairit Sur*

❑ Not even the other physics achievement of CMS experiment → *several talks in CKM conference*

❑ As well as future potential in years to come.

Apologies to the experts and the senior students.

THE LARGE HADRON COLLIDER

LHC Operations: mainly p-p collisions, but also Pb-Pb and p-Pb collisions

Run1: 2009 – 2013

pp collisions at various centre-of-mass energies

√s = 900 GeV, 2.76 TeV in 2009, 7 TeV (in 2010, 2011), 8 TeV (in 2012)

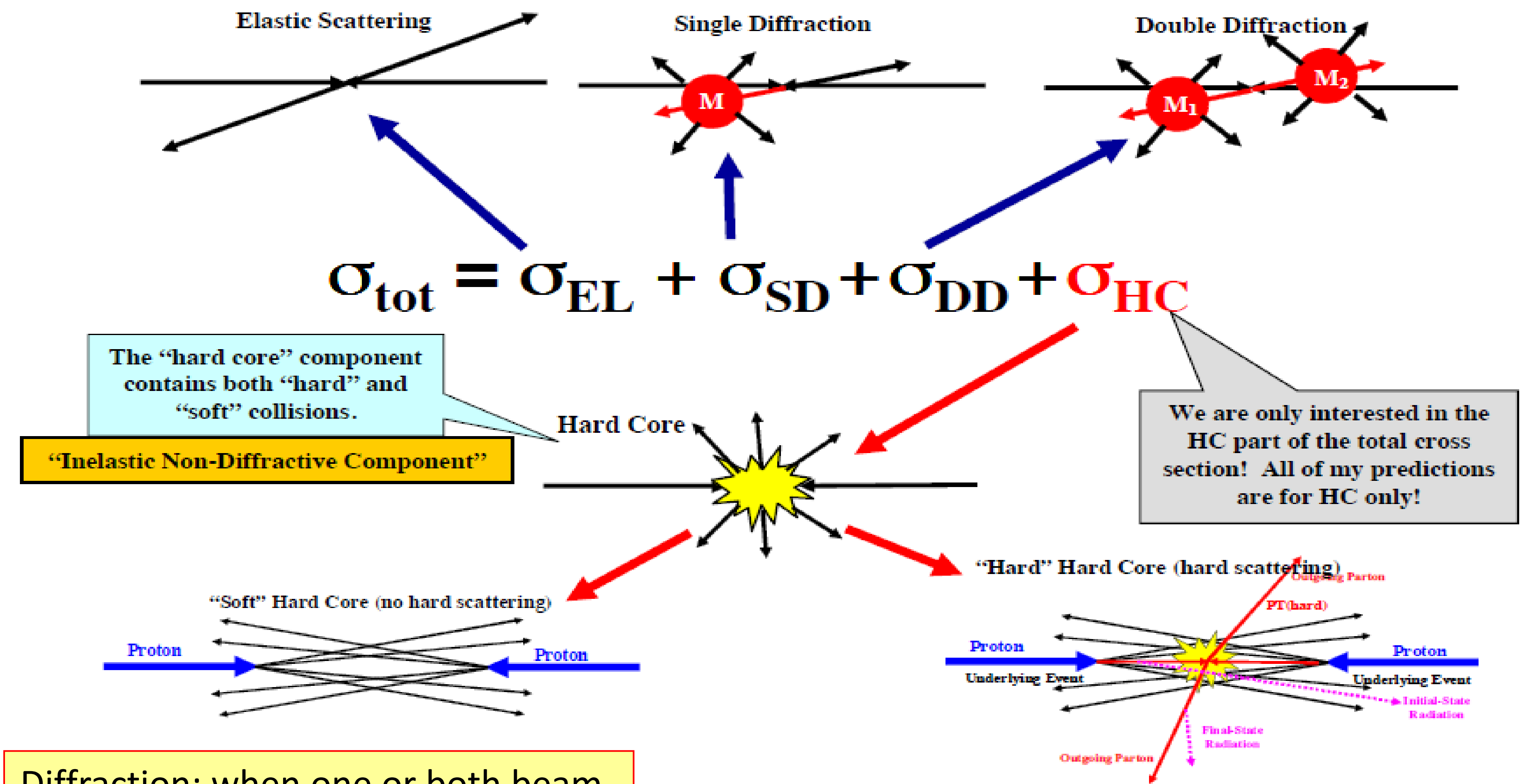
Run2: 2015-2018

pp collisions at √s = 13 TeV, p-Pb collisions at 5 and 8 TeV

→ expect > 100/fb per experiment, already delivered ~ 40/fb

Excellent performance: best operated, best monitored, best understood machine!

collision of 2 protons

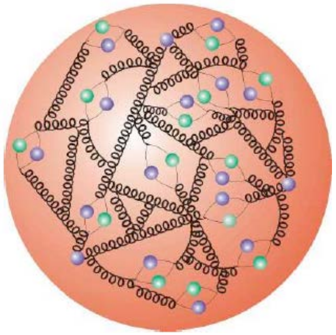


Diffraction: when one or both beam particles go to high mass state.

Diffractive events have much less charged multiplicity compared to non-diffractive collision

We are interested in non-single diffractive events

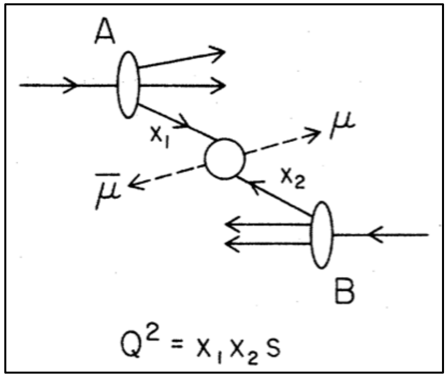
The composition of proton



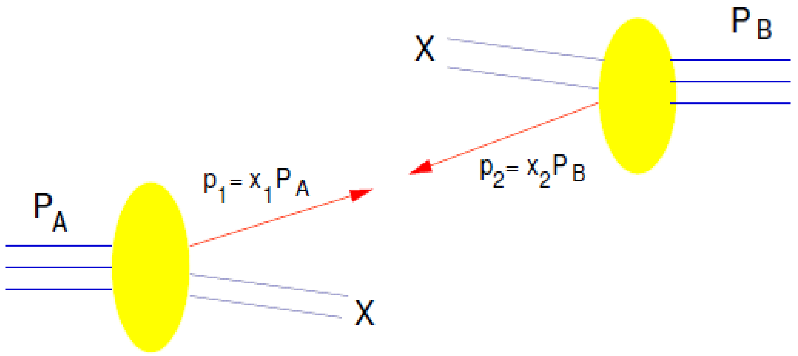
- It is not a simple object → do not take part directly in fundamental interactions.
- Consists of valence quarks, gluons, sea-quarks, sea-antiquarks; → partons.
- Exact mixture of partons depends on energy scale of the interaction: Q^2 and Bjorken x variable: fraction of proton longitudinal momentum carried by the parton involved in the interaction
- Each constituent of proton carries only a fraction of the proton's energy

→effective energy for a given sub-process ($Q = \sqrt{s'}$) is less than the CM energy $\sqrt{s}$

→ the inelasticity of the event varies .



proton-proton hard collision



Centre-of-mass energy: $2E_b = \sqrt{s}$
Sub-process energy : $\sqrt{s'}$
$s' = s\, x_1\, x_2$
$x_i = p_i^z / E_b$ → Bjorken x
E_b = beam energy

- Sub-process energy could be, in principle, from few MeV to few TeV.

- Most of the collisions are mundane and the physics is understood !
- only 1 in 10^7 events /sec are stored to be looked into carefully.

- $M = \sqrt{x_1 x_2 s}$
- rapidity $y = \frac{1}{2} \ln \frac{x_1}{x_2}$

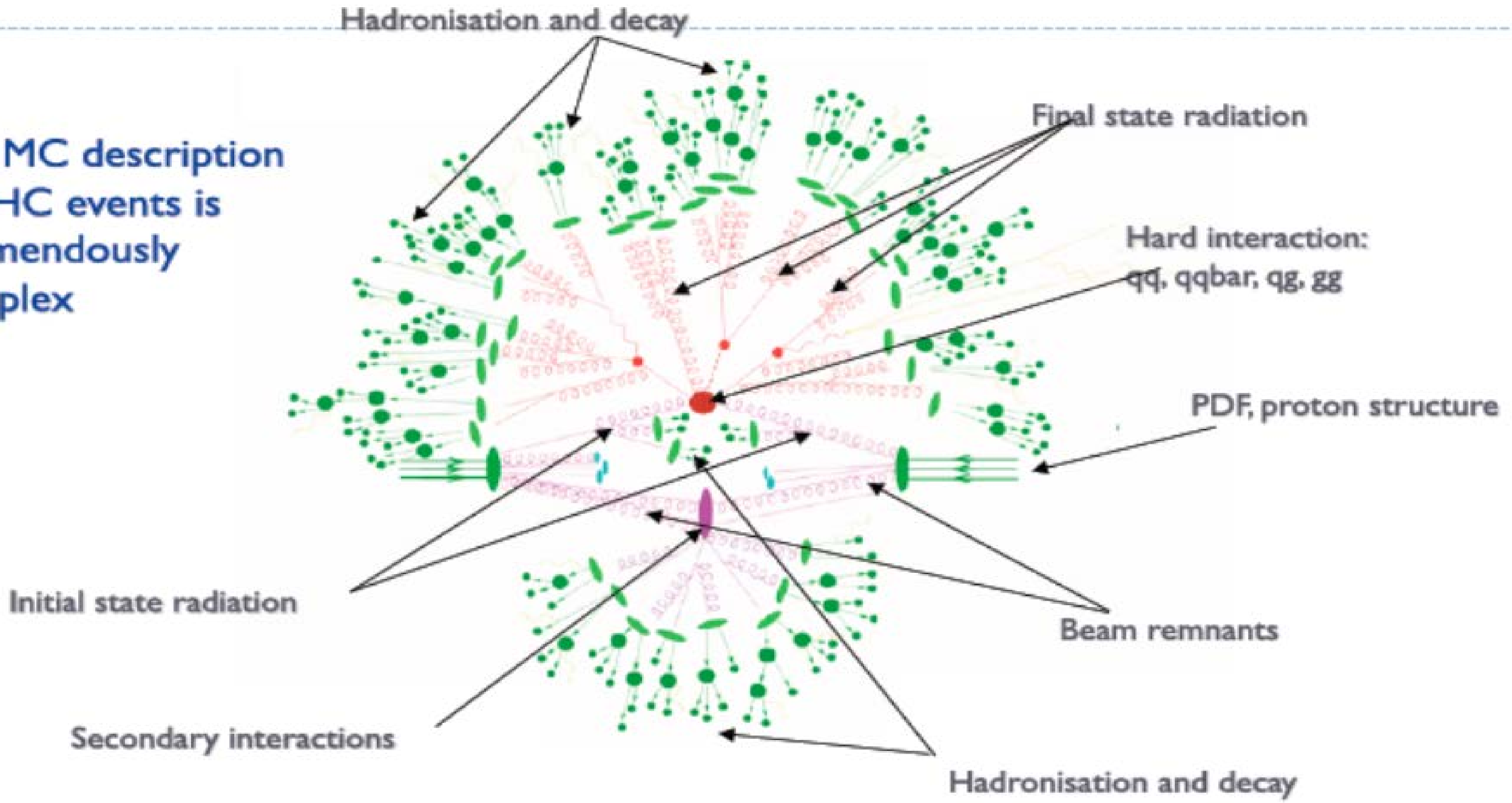
pseudorapidity $\equiv \eta \equiv \ln \tan \frac{\theta}{2}$
$=$ rapidity for massless objects

→ possibility of producing various new particles of different masses.
→ eg. Higgs of any mass within the allowed range could be produced at LHC!

Roughly, acceptance for jets $|\eta| < 5$
for e, μ, γ $|\eta| < 2.5$

Note: if $x_1 \neq x_2$ there is a longitudinal boost in the system.

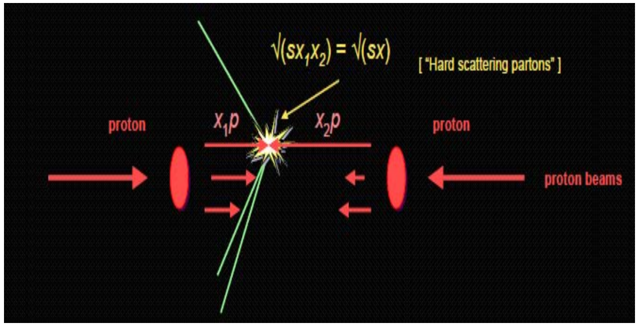
Cartoon of an inelastic event in LHC



The MC description of LHC events is tremendously complex

When the two oppositely moving proton bunches collide (every 25 ns), there are **more than one collision recorded as a single event in the detector**
➔ **event pile up, to be taken care of during offline analysis.**

Dissecting the proton-proton collision



$$\sigma_{pp} = \sum_{i,j\in\{q,g\}} \int dx_1 dx_2 f_i(x_1) f_j(x_2) \hat{\sigma}_{ij\to X}(s_{ij} = x_1 x_2 s_{pp})$$

Theoretical calculations for the hard scatter use perturbative method:

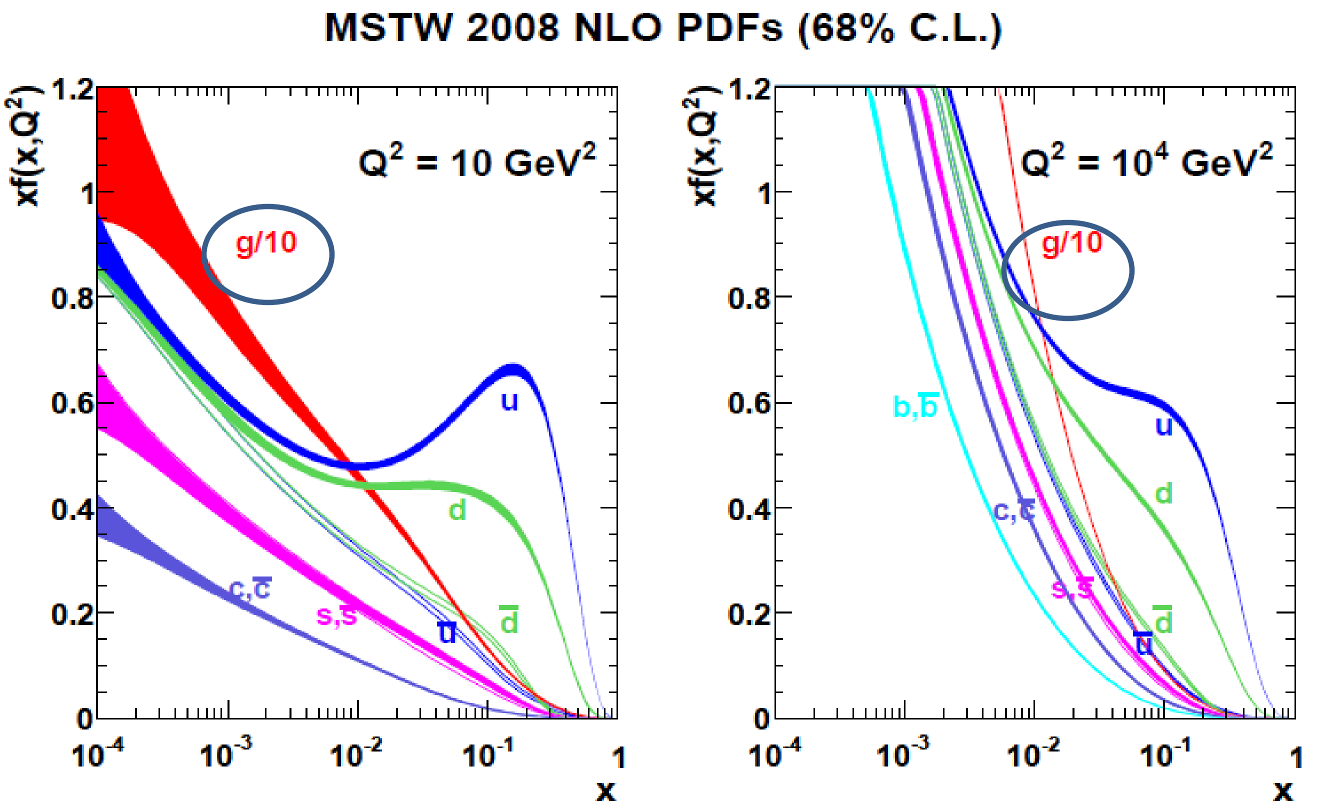
- upto a given (fixed) order
- possible since hard scatter matrix element can be separated out from the parton density function ➔ factorization
- value of strong coupling constant is large ➔ contributions from higher order processes must be taken into account
- calculations are complicated.

✓ Soft interaction cannot be described by perturbative QCD.

✓ Need models which involve parameters ➔ must be tuned using data.

✓ There are also soft interactions among the rest of constituents (spectators) simultaneous to the hard scatter.

Parton Density Function

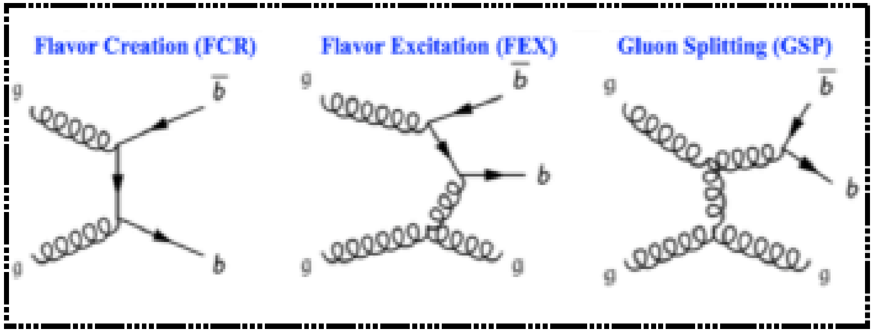


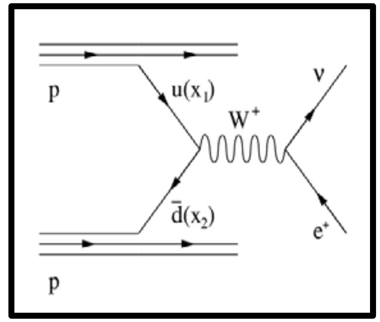
- **Gluon density increases significantly with Q^2**

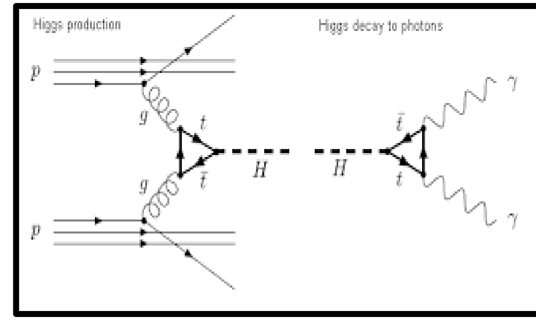
➔ Many interesting physics processes at LHC have gluon(s) in the initial state.

- The study of PDFs is a very active field
- There are several other PDFs in the market
- NNPDF set is doing the best in describing LHC data.

Some of the interesting hard scatter processes







Inclusive b-bbar production

$u\bar{d} \rightarrow W^{+} \rightarrow \ell^{+}\nu_{\ell}$

gg-H → 2 γ

- B hadrons are produced with only moderate transverse momentum.
- Their decay to leptons and photons have limited acceptance in CMS experiment which is designed for ding "high pT" physics.

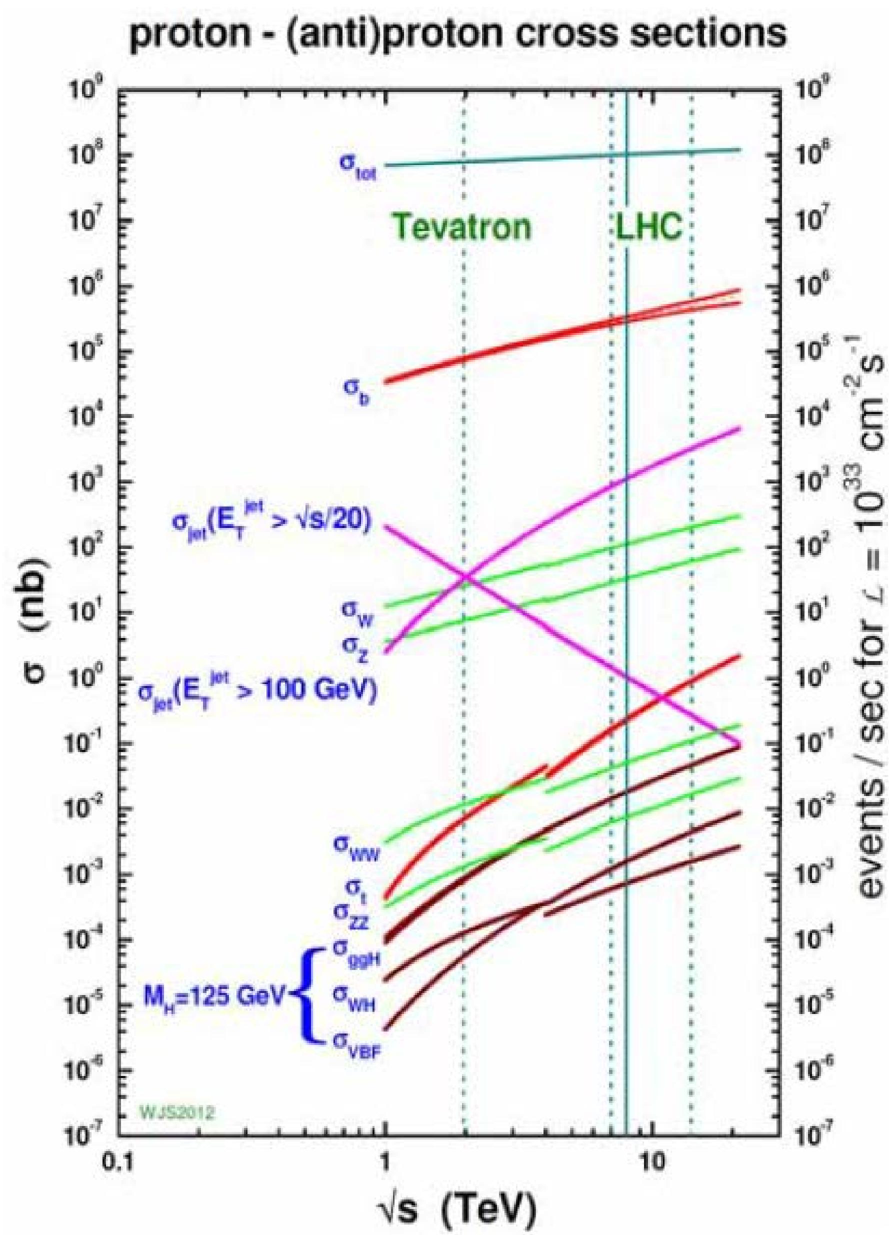
- The leptons from semileptonic decays of hadrons are surrounded by other particles, as opposed to the cases from W, Z decays.

➔ apply "isolation" criteria to pick up letons from W,Z

Tackling the backgrounds is the art of data analysis at LHC.

Example: landmark analysis: Higgs particle discovery in 2012

Cross sections in proton-proton collisions



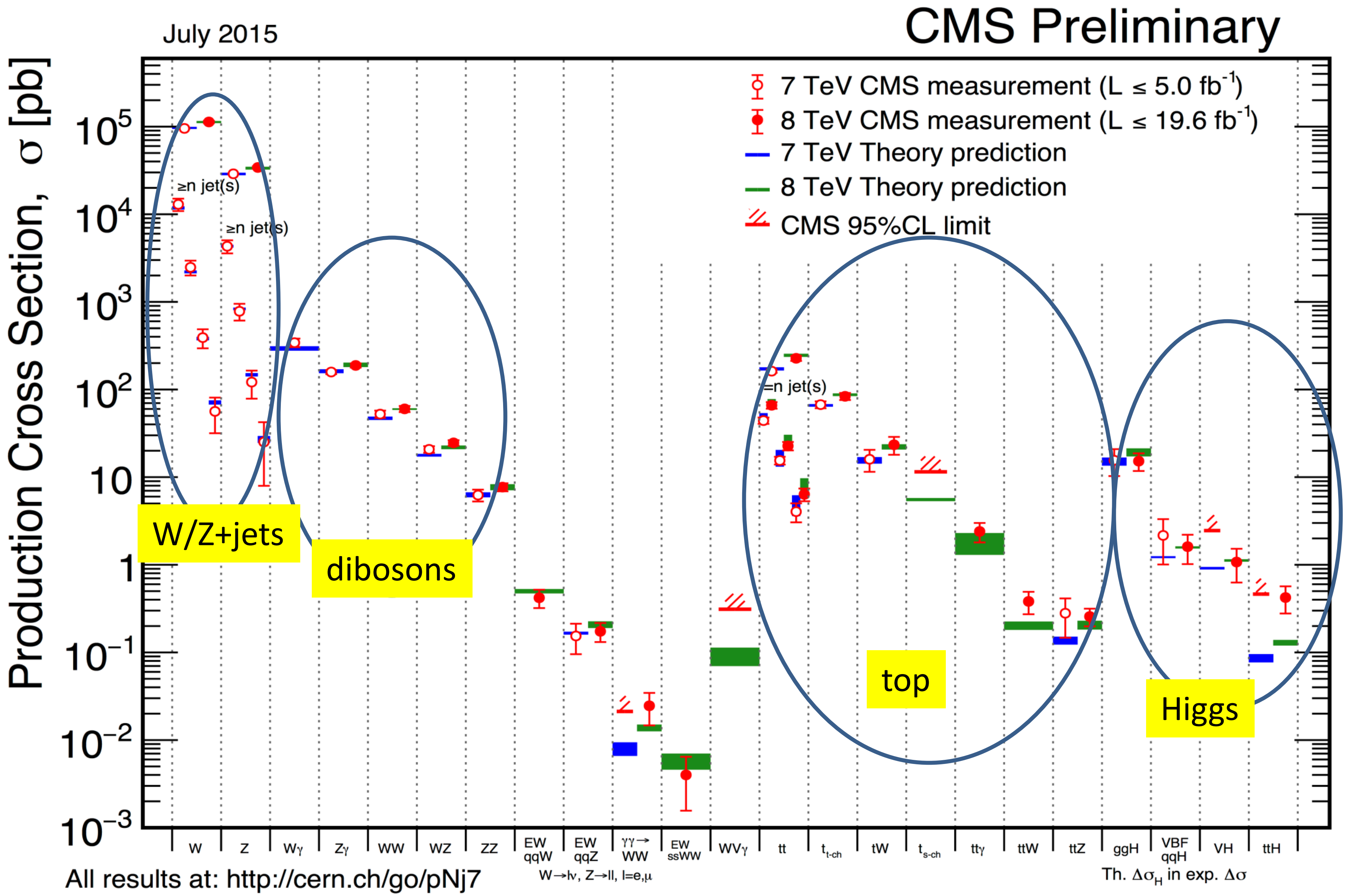
For $\sqrt{s}$ = 7 TeV

- Total 110 mb
  - elastic: 40 mb
  - inelastic: 60 mb
  - diffraction: 12 mb
- **bottom-quark pair ~ 0.4 mb**
- Top-quark pair: 160 pb $(10^{-12}$ b)
- W, and Z: 100 nb and 30 nb
- 125 GeV Higgs boson: 20 pb

  (10^{-10} lower rate than total)

With increase in energy relative rates of different processes have changed.

Cross section measurements over many orders of magnitude



Heavy flavour programme of CMS

1. Understand the underlying QCD processes
   - ➢ Measurement of standard quarkonia spectrum, polarization and heavy flavour production: differential and total cross sections.
   - ➢ Search for new exotic quarkonia states and new heavy baryons.

2. Test of Standard Model with high precision measurements.
   - ➢ measurement of decay rates, lifetimes, CP phase of B-hadrons.

3. Look for new physics in the loop
   - ➢ rare decays: $B_{d,s} \rightarrow \mu\mu$, $B \rightarrow K^* \mu\mu$ etc.

4. A large fraction of b-hadrons have low transverse momentum
   $\rightarrow$ event acceptance within the detector and the efficiency for identification is low

Future: utilize high luminosity and large production rate
$B_s \rightarrow J/\Psi\ \phi$, $B_{d,s} \rightarrow \mu\mu$, $\tau \rightarrow \mu\mu\mu$, $B_s \rightarrow \phi\phi$

Experimental issues for B-physics programme

1. Charged particle tracking in pixel layer and Si-strip detectors

➔ Long lifetime and large mass reconstruction

➔ Measurement of transverse momentum (p_T)

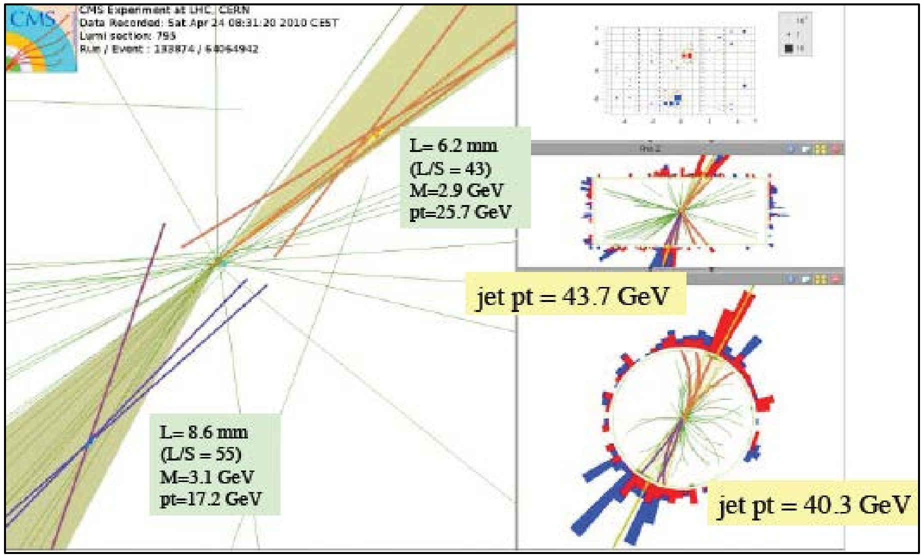
➔ Primary and secondary vertex reconstruction

2. Muon measurements: 3 different sub-detector types

➔ Muon identification

➔ Muon p_T measurement

➔ Semileptonic decays



3. Event reconstruction:

Particle Flow algorithm

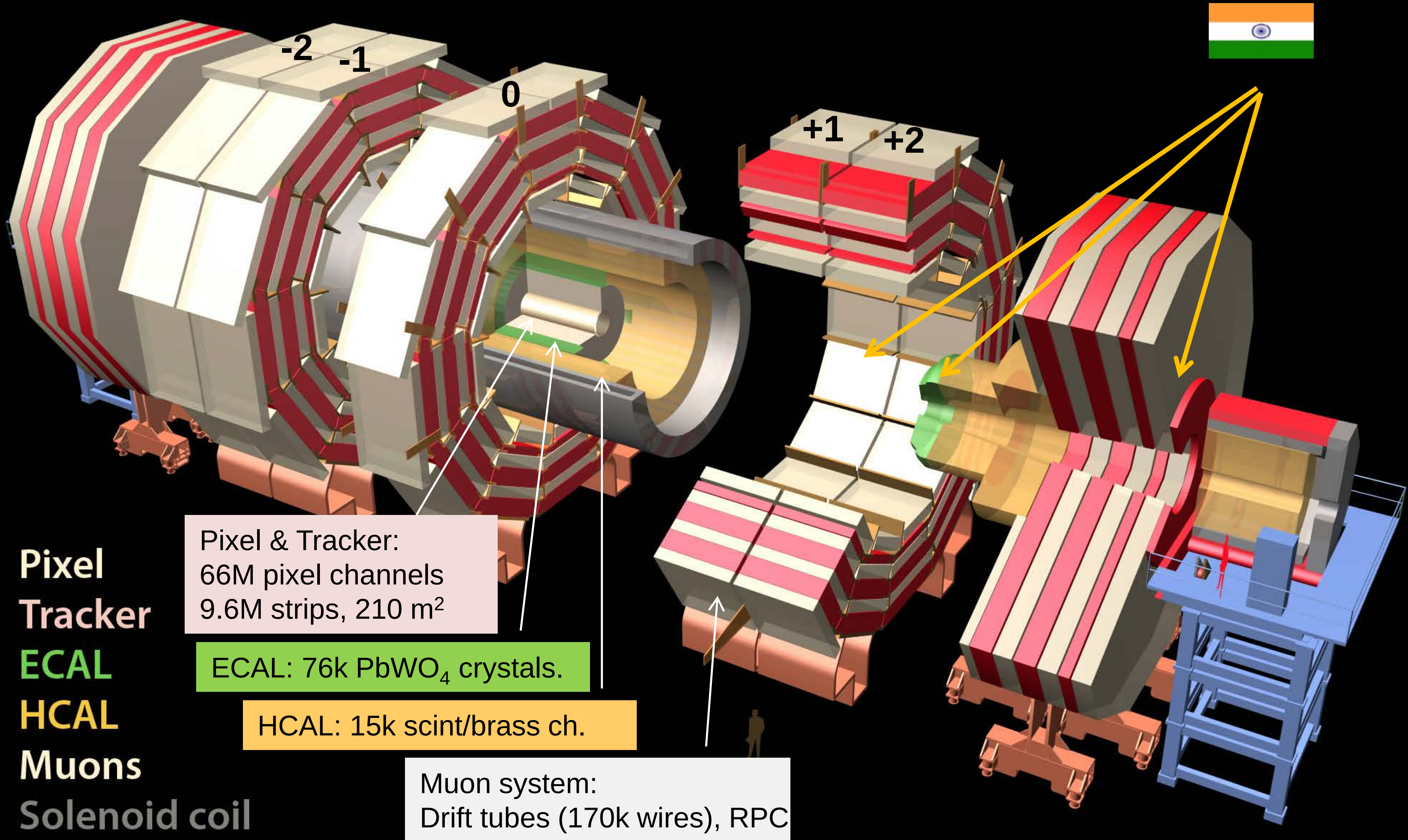
4. Minimum bias and inclusive

single jet triggers

How does CMS experiment work?

The CMS Detector

India 's contributions



Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

Pixel & Tracker:
66M pixel channels
9.6M strips, 210 m^2

ECAL: 76k $PbWO_4$ crystals.

HCAL: 15k scint/brass ch.

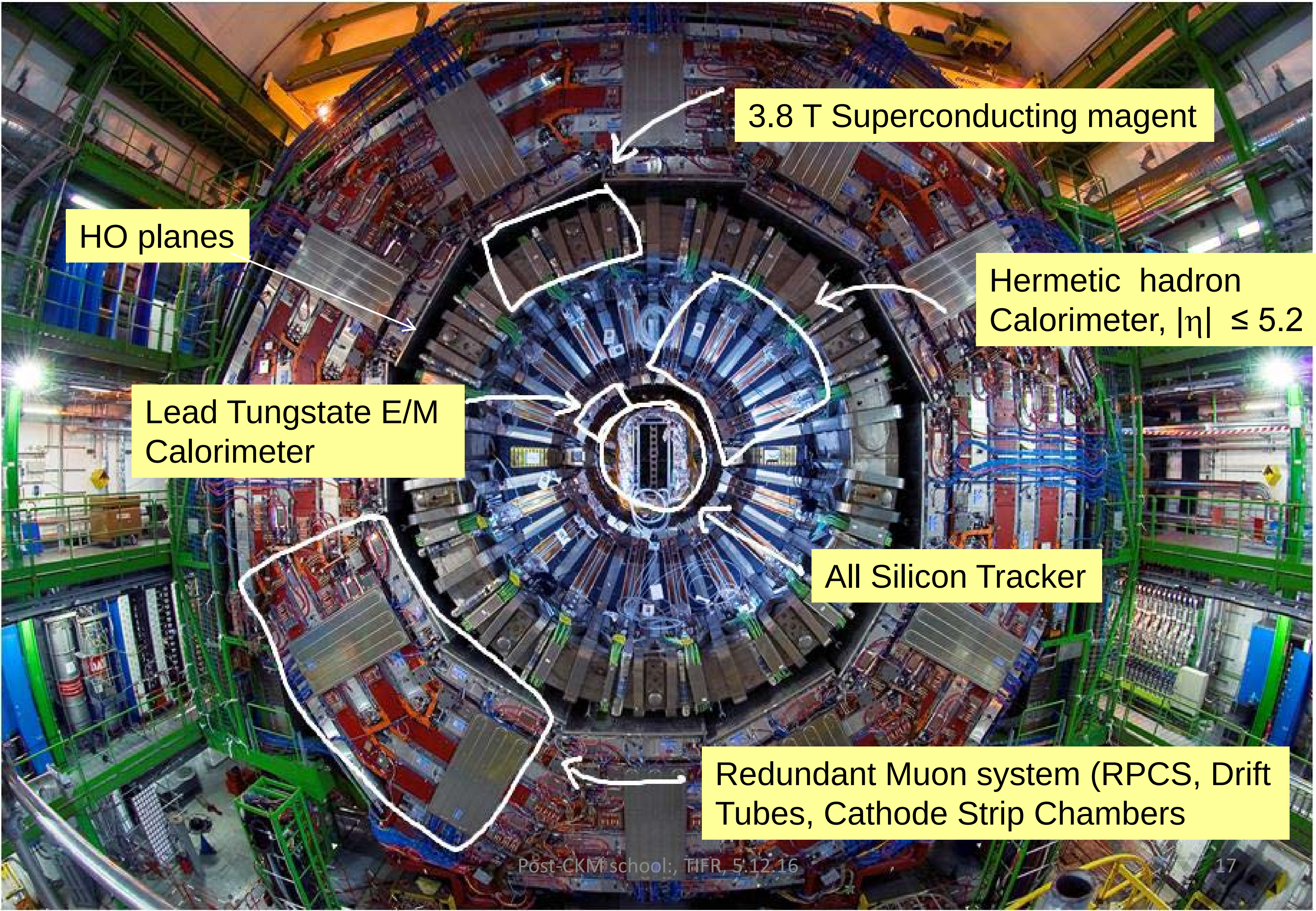
Muon system:
Drift tubes (170k wires), RPC
Cathode Strip Ch.(200k wires

Total weight 12500 t, Overall diameter 15 m, Overall length 21.6 m, Magnetic field 4 Tesla

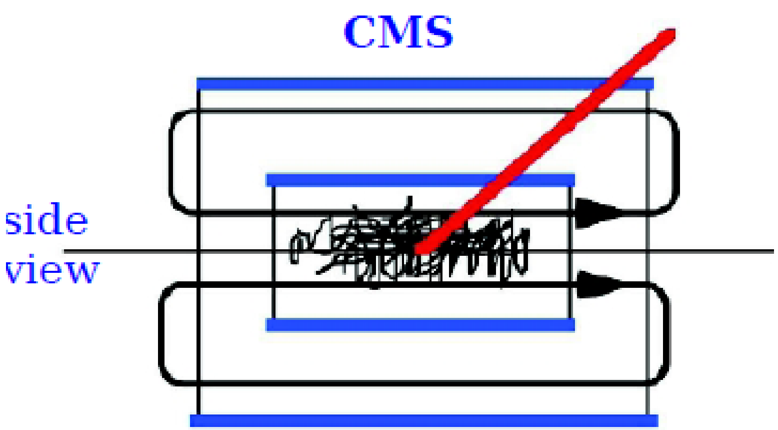
Some facts about CMS experiment

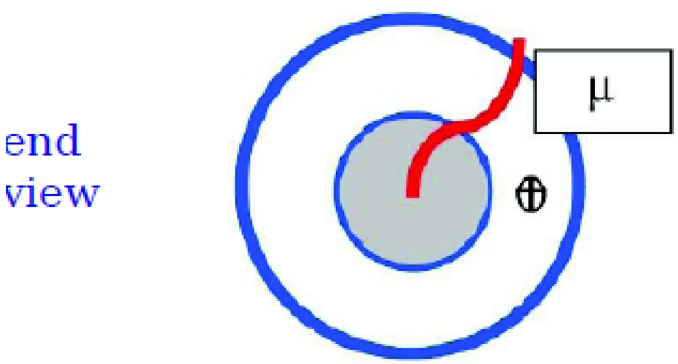
- Huge detector: ~ 40m in length, 15m in radius, weighing 12.5 kTon
- The magnetic field= 3.8 Tesla ~ 10^5 times earth's field
- Silicon-based tracking detector at the core.
  total area ~ size of swimming pool for Olympic games
- 80 thousand scintillator crystals (96% metal by mass), supported by 0.4 mm thick glass/carbon fibre structure.
- Brass used as absorbing material came from dismantled artillery shells of Russian warships.
- 1 sec. running of the experiment produces data volume ~ 10K encyclopedia Britannica.
- Data production in CMS ~ 1 Mb/event, ~ 600M events/sec.

ρ–ϕ view of Detector

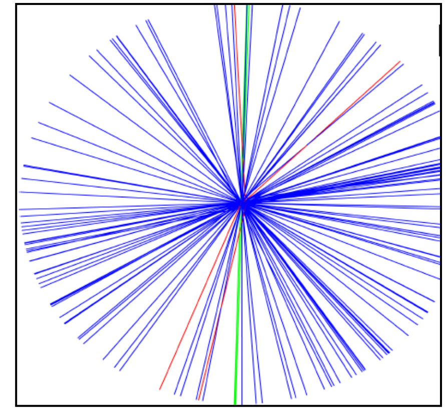


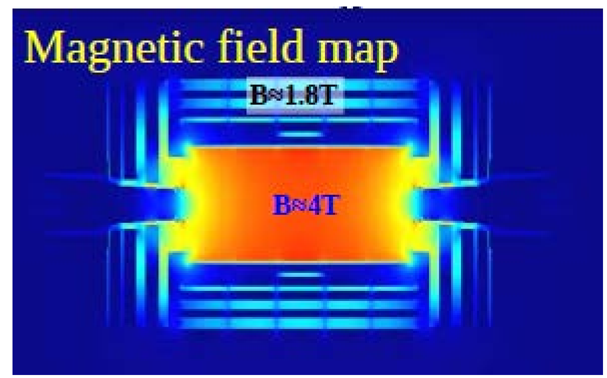
Effect of magnetic field in CMS



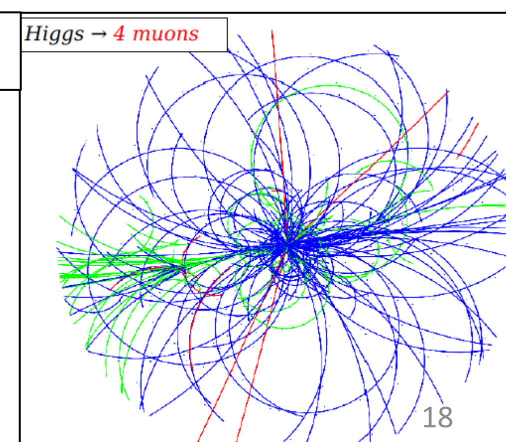


Simulation
Higgs → *4 muons*
Magnetic filed B =0



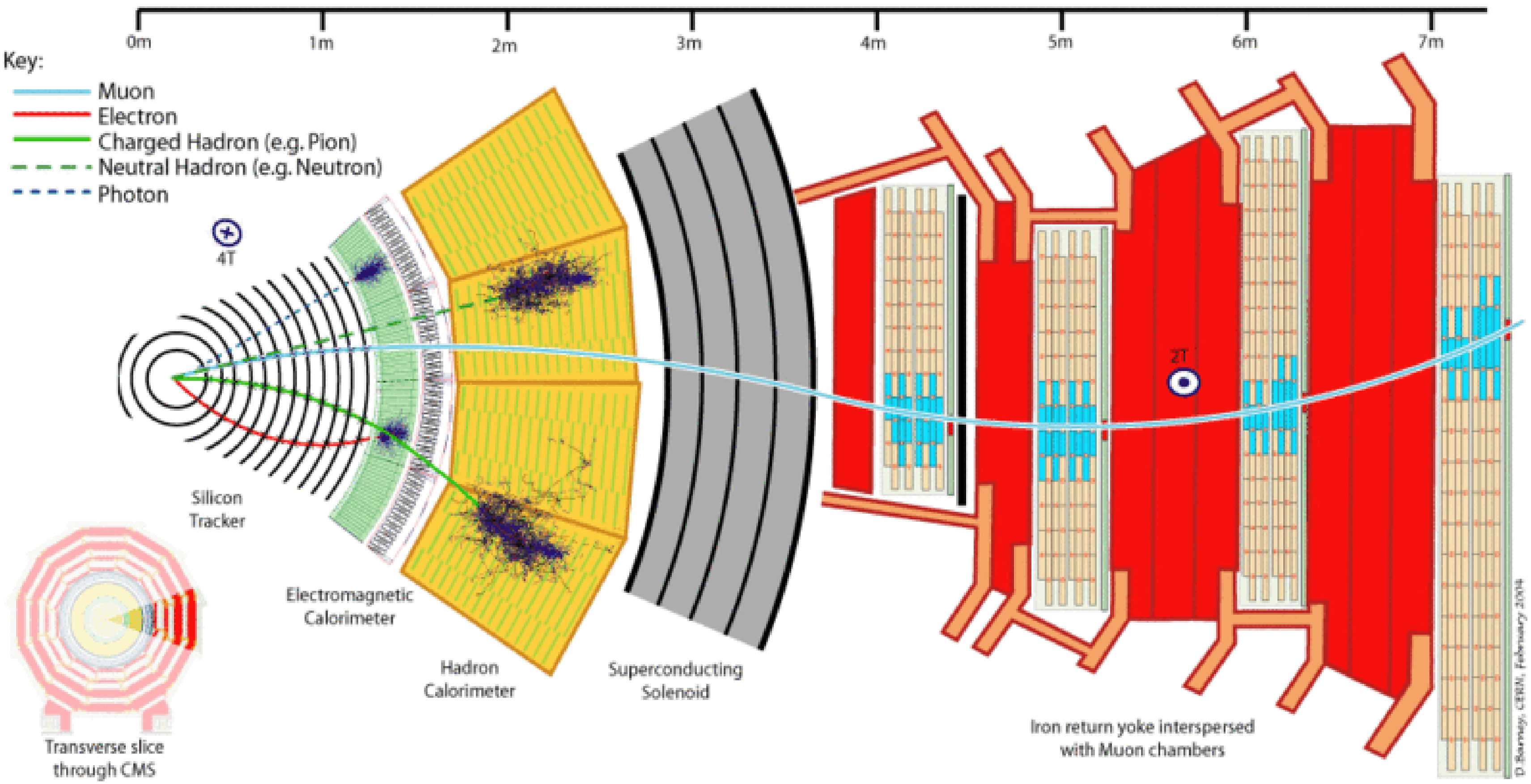


Magnetic filed B = 4T



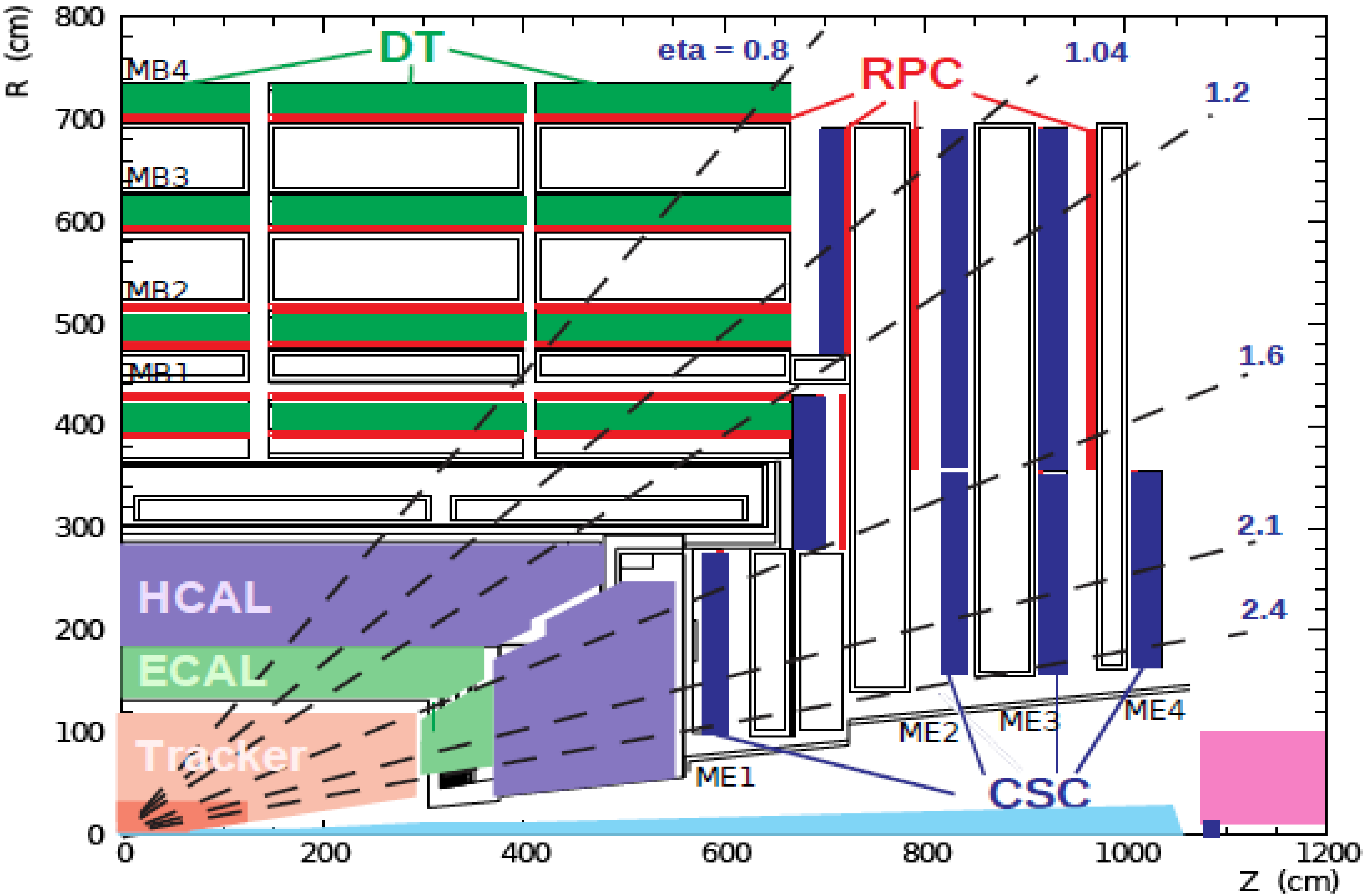
Effect of magnetic field along beam direction:
low energy particles loop away along field direction

A slice of the CMS detector

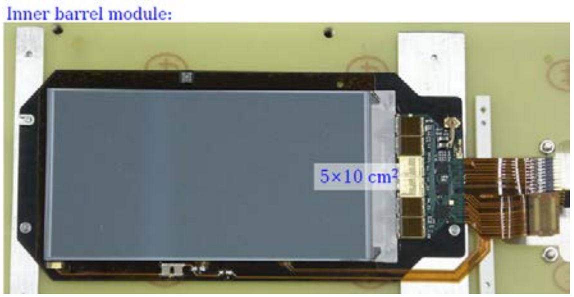


- Principle of measurement: the particle must interact with the detector material and an effect of the interaction must be measured.
- The detector can only "see" **γ, e$^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, n, p, K !**.

One quadrant of CMS detector : Longitudinal layout



CMS Silicon Tracker

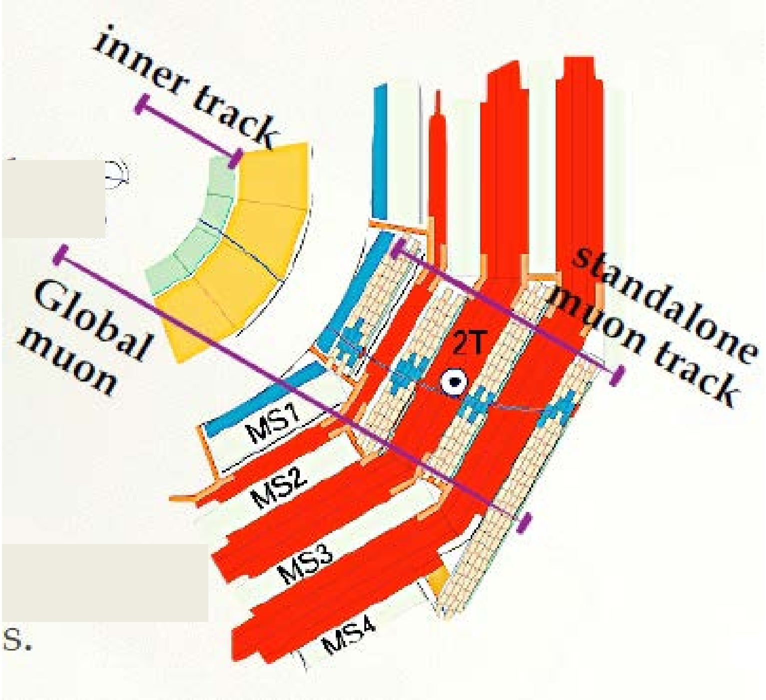


- 3 barrel layers of 100 X150 μm pixels
  (66M eletcrnics readout channel in total)
- 10 barrel layers of 180 μm strips (9.6 M channels)

Excellent track and momentum resolution at low p_T
Excellent vertex reconstruction and impact parameter measurement

➔ p_T threshold ~ 100 MeV/c, $|\eta|\leq 2.4$
Eff. > 80% for pions, p_T=250 MeV/c

Muon reconstruction in CMS



Muon subsystem:

- 3 different technologies
- Large coverage upto $|\eta| < 2.4$

Reconstruction algorithm uses

1. only muon system: standalone muon
2. Tracker muon: using tacks only
3. Global muon: muon AND tracker systems

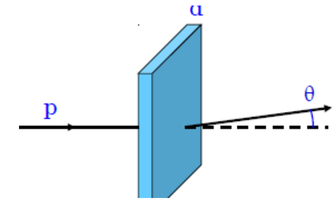
Good dimuon mass resolution:

0.6 to 1.5 % , depending on the region of detector

Excellent muon identification:

- fake rate < 0.1% for π, K , < 0.05% for proton
- use multivariate analysis method for identification of B → $\mu\mu$

Momentum resolution in CMS



Momentum resolution
$$\frac{\sigma_{p_t}}{p_t} \sim \frac{\sigma_x}{\sqrt{N}} \frac{p_t}{BL^2} \oplus \frac{\sqrt{d/X_0}}{BL}$$

Multiple scattering

$$\langle\theta\rangle[rad] \approx \frac{0.014}{p[GeV/c]}\sqrt{d/X_0}$$

Silicon detectors:
σ_x ~ 10-20 μm

X_0=9.4 cm for Si
18.8 for C

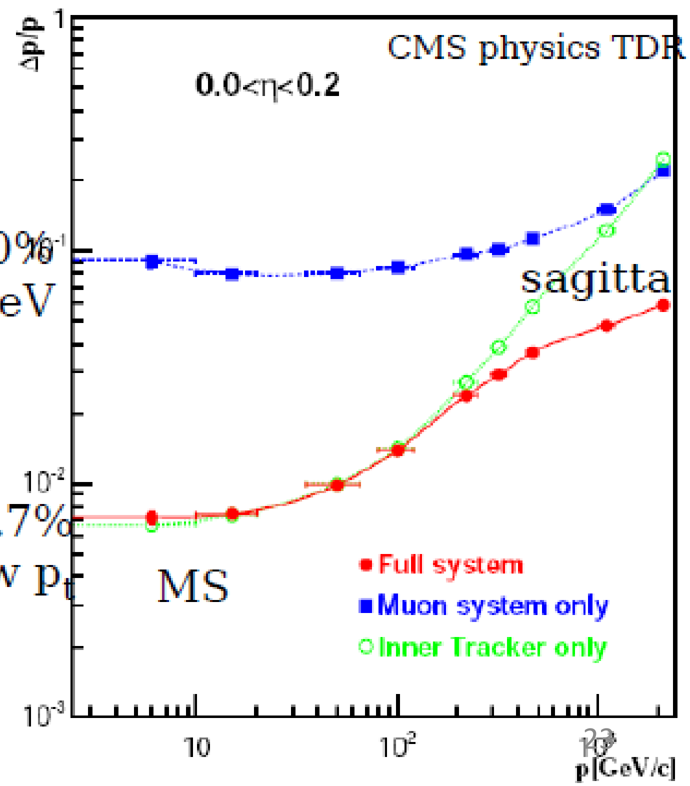
Sagitta measurement

p_t [GeV/c] = 0.3 R [m] B [T]

Tracking detector plays crucial role in momentum measurement for most of the physics at LHC.

10% at 1000 GeV

0.7% at low p_t



Particle identification in CMS

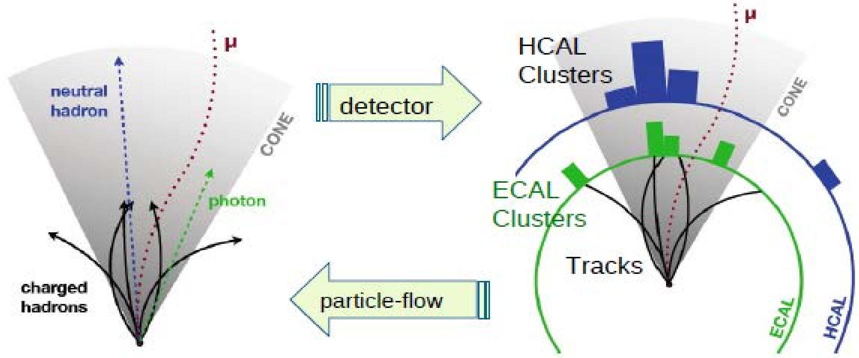
Objects are reconstructed using information from different detector subsystems combined in a particle flow algorithm.

✓ Measure the position and energy-momentum with high resolution

- There is no dedicated identifier for π , K particles
- Electrons radiate via brehmmsstrahlung
- Electron may convert to e+e- pairs in the tracker
- Jet energy is composed of charged/neutral hadrons (65% and 10%) as well as photons (25%) → both calorimeter and tracker info are exploited.
- Estimation of missing transverse energy requires full event reconstruction .

➢ CMS experiment was designed meticulously for study of hard collisions
➢ Serving well even for softer ones

Essentials of Particle Flow reconstruction

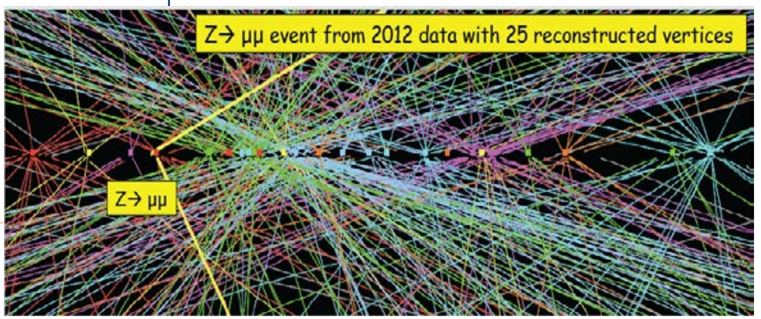


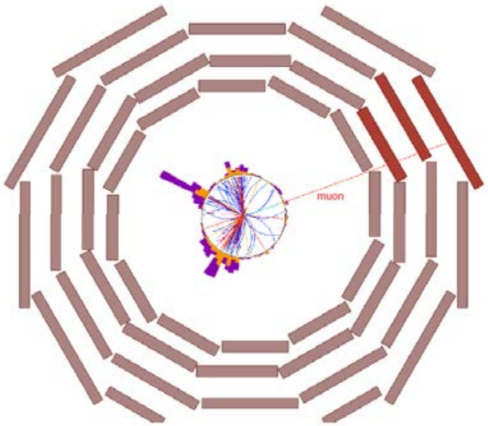
Link well measured tracks with clusters of energy deposits in calorimeter

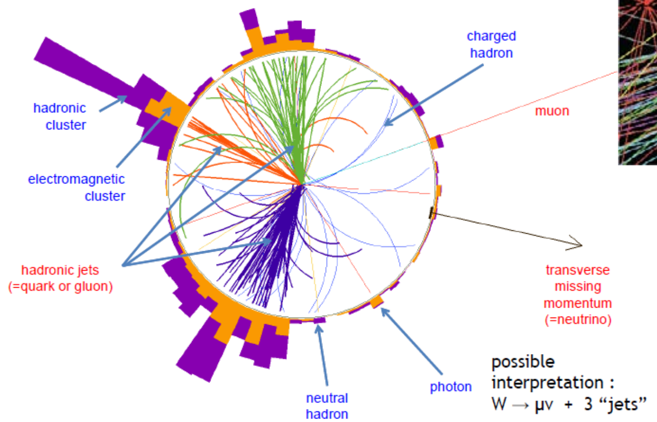
- Prepare a list of all the final state particles.
- Build jets to determine missing transverse energy.

➔ significant improvement in jet energy resolution.

- Identify tau from the decay products
- Tag b-jets







Fantastic Detector Performance

electrons

scale known to 0.5%

muons

scale known to better than 1.0%

photons

scale known to better than 1.0%

taus

identified with ~70% efficiency and ~5% fake rate

(b-)jets

scale known to 1%-5% (p_T and η dep.)

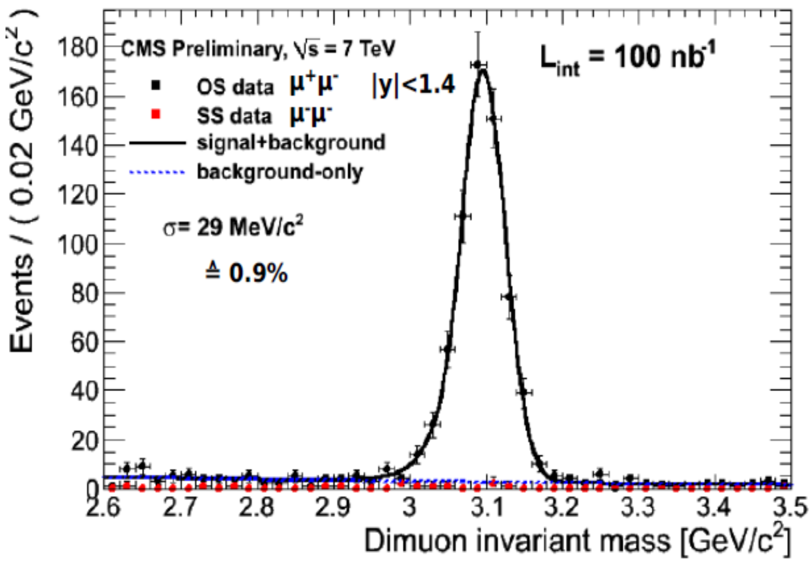
Missing transverse energy

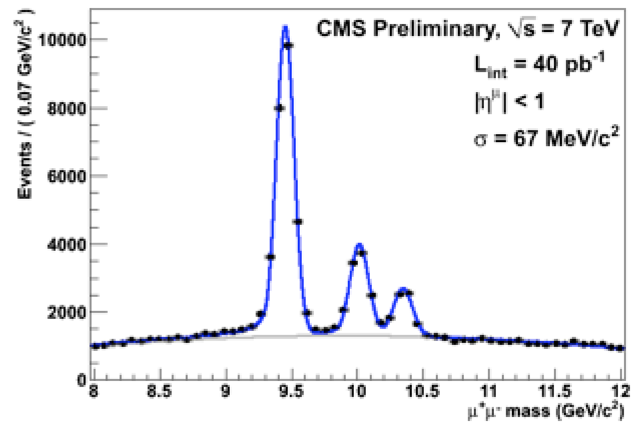
MET

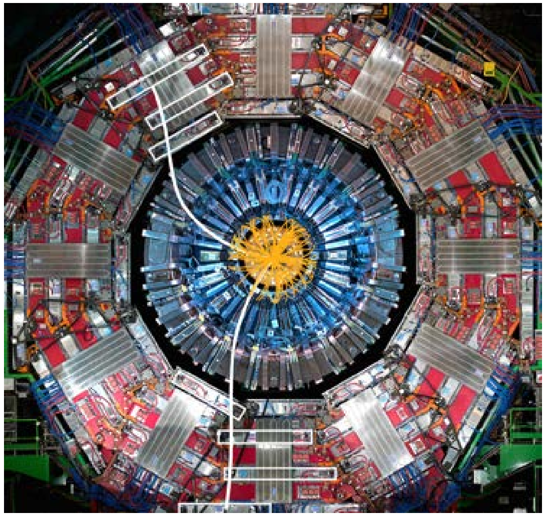
Nice agreement with simulation

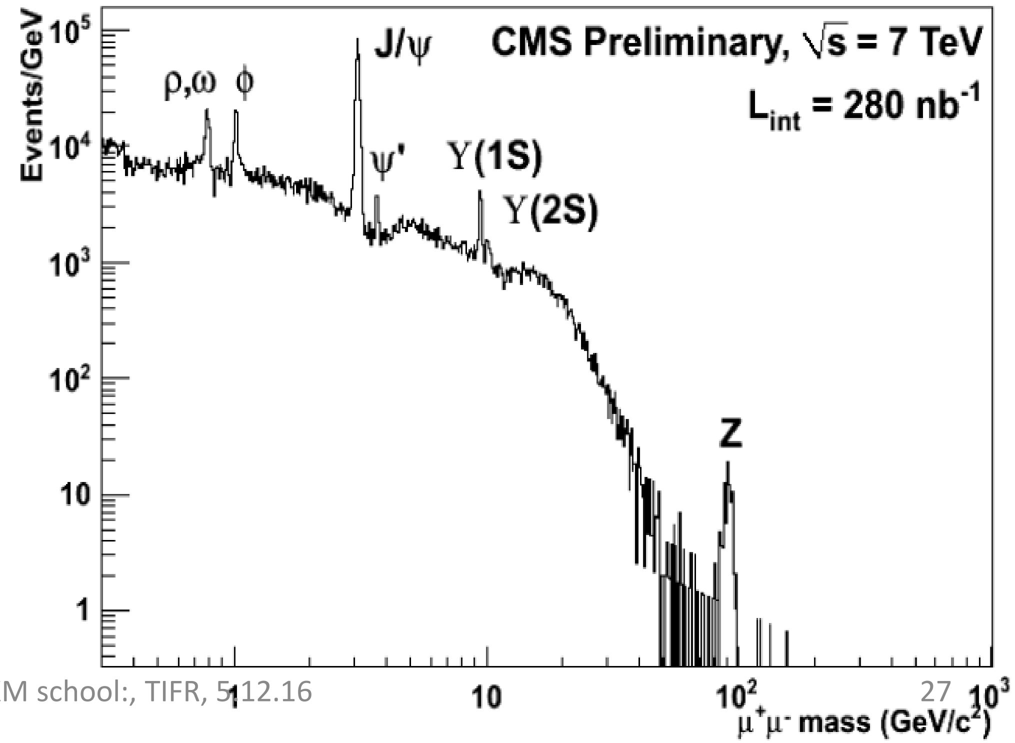
Deep understanding of impact of PU

CMS mass resolution

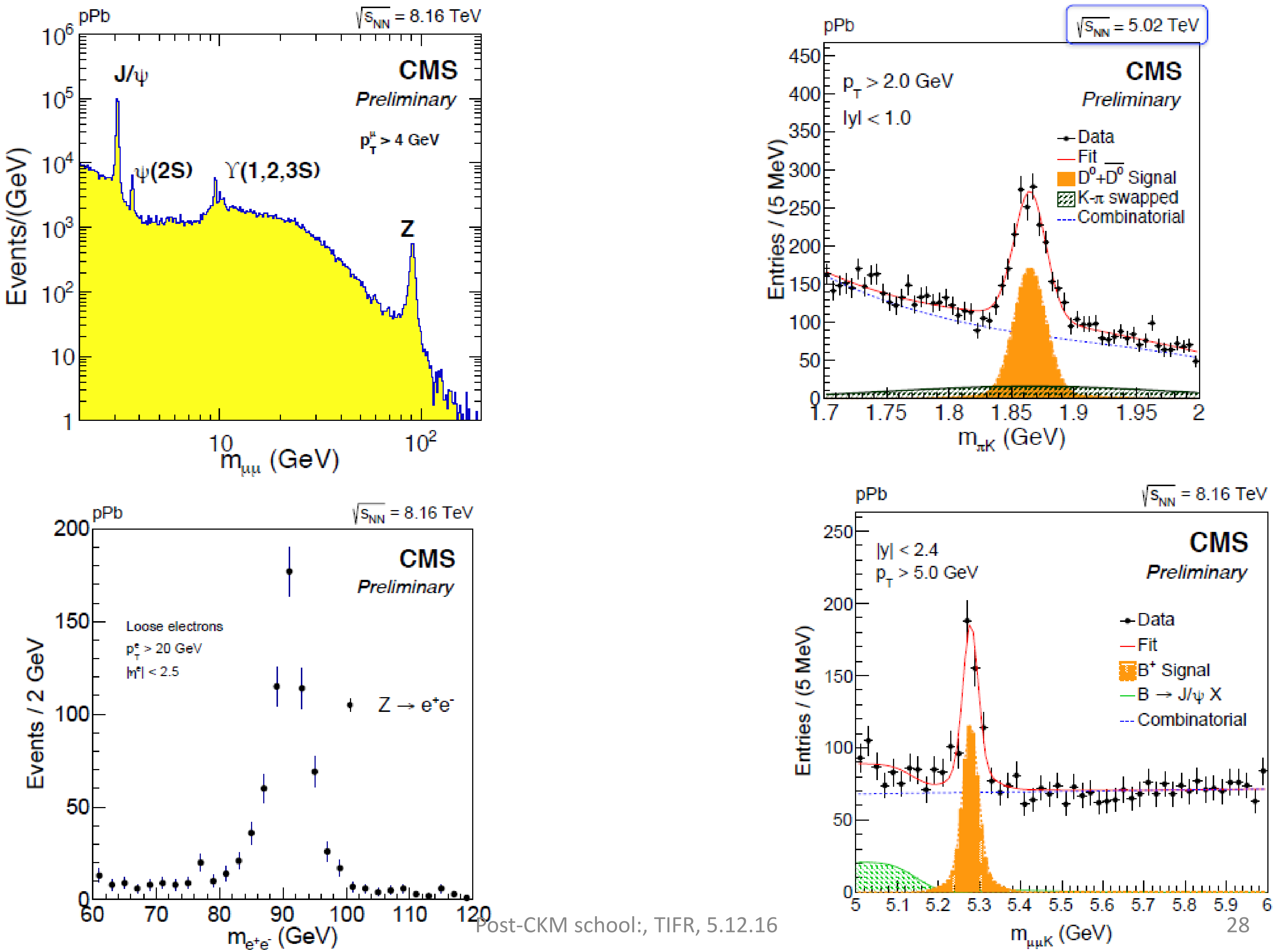




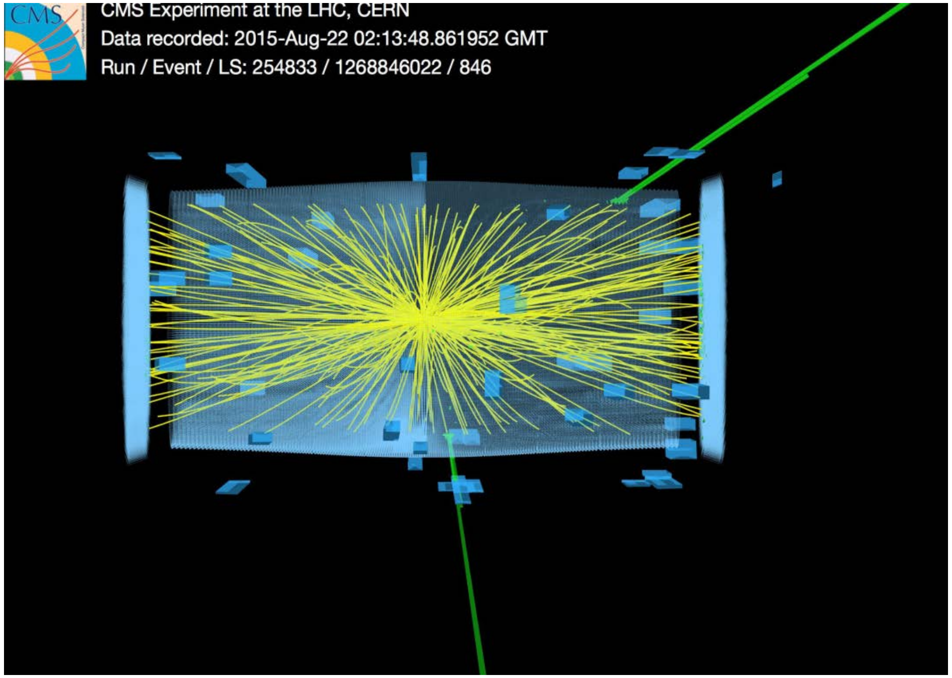




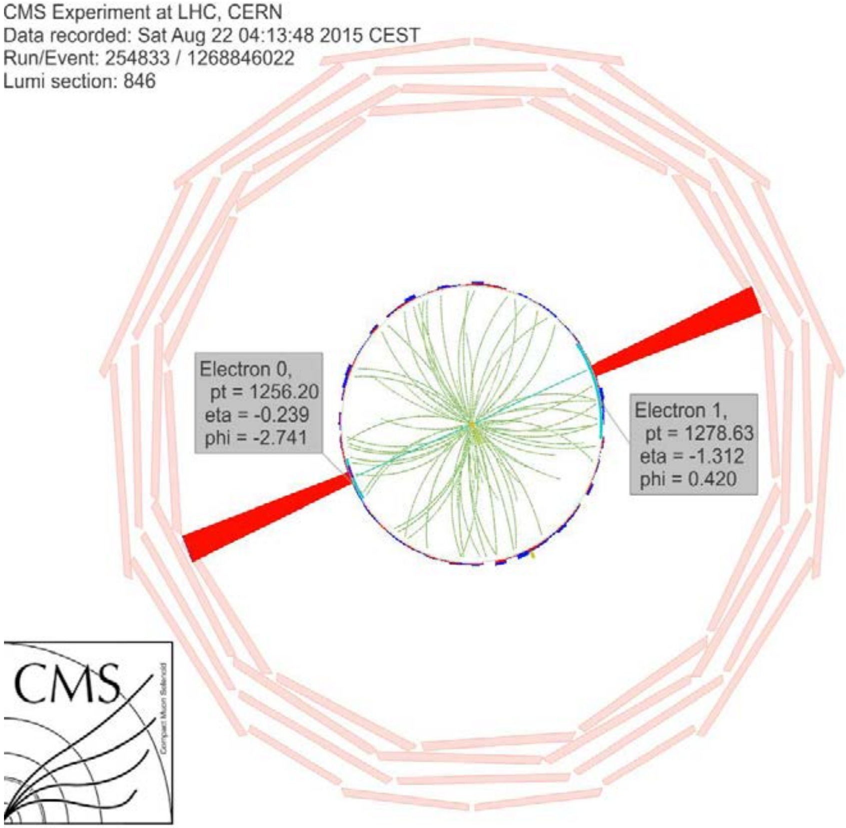
Performance in CMS in heavy ion run

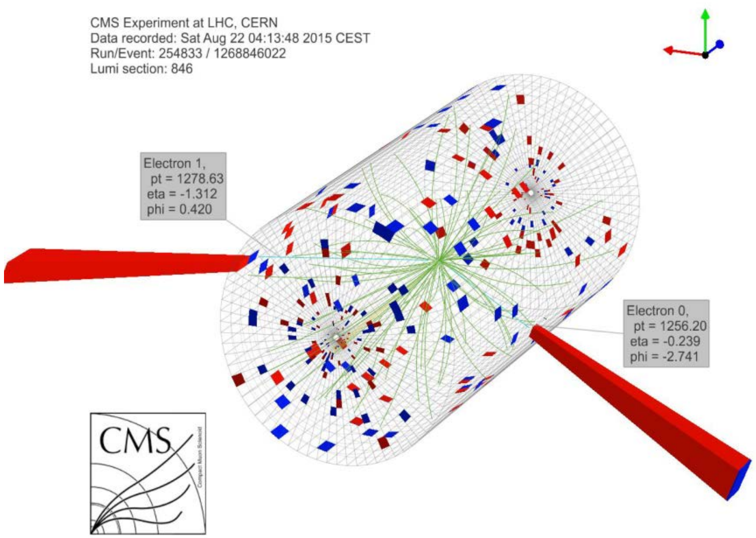


Performance for very hard scatter events

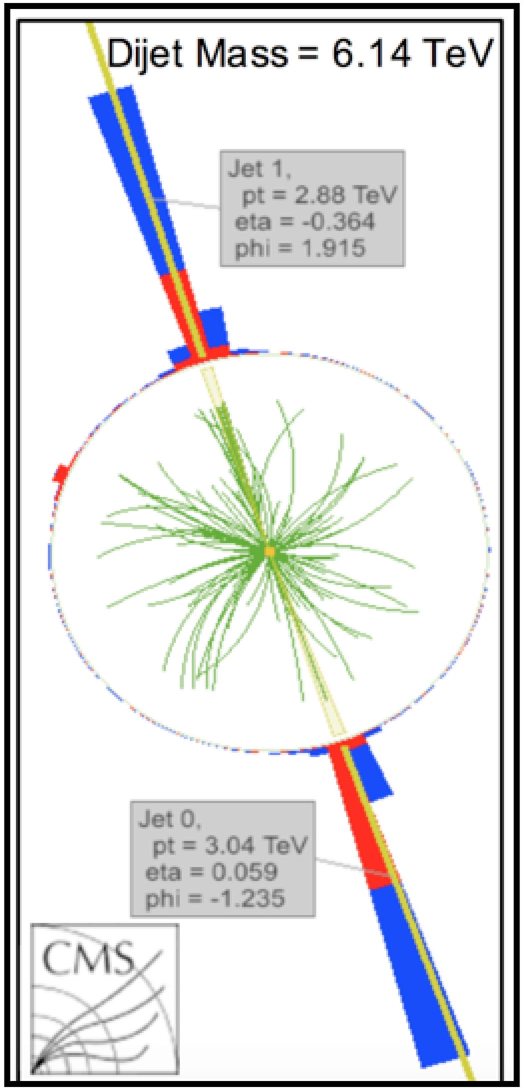


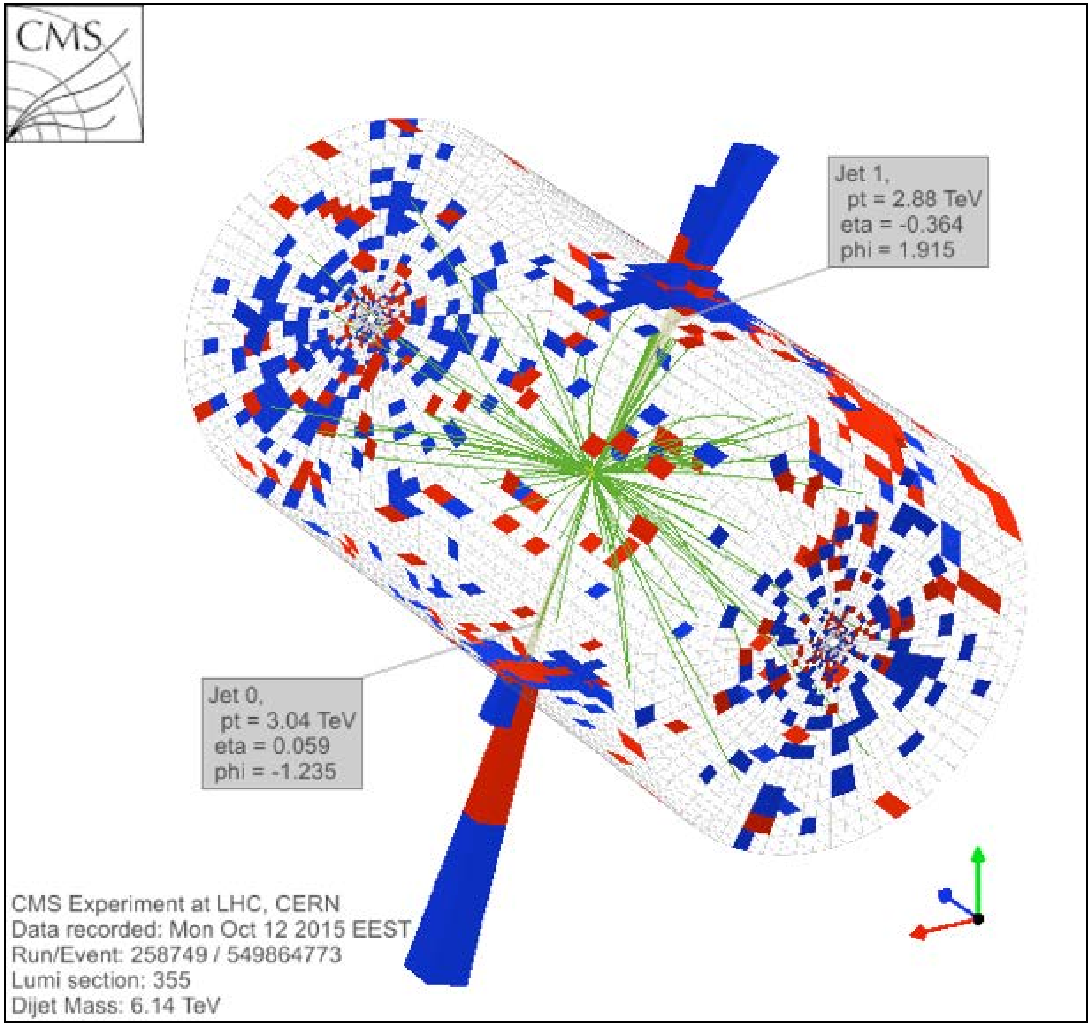
e+e- pair with invariant mass 2.9 TeV



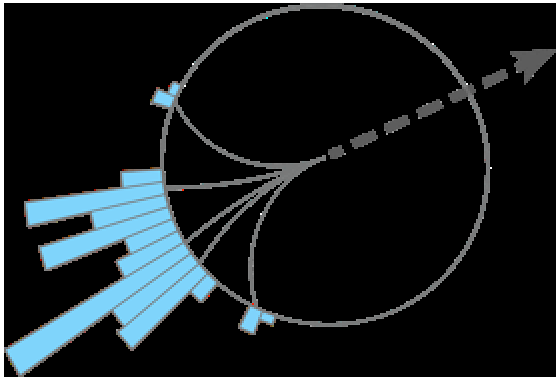


High mass dijet event



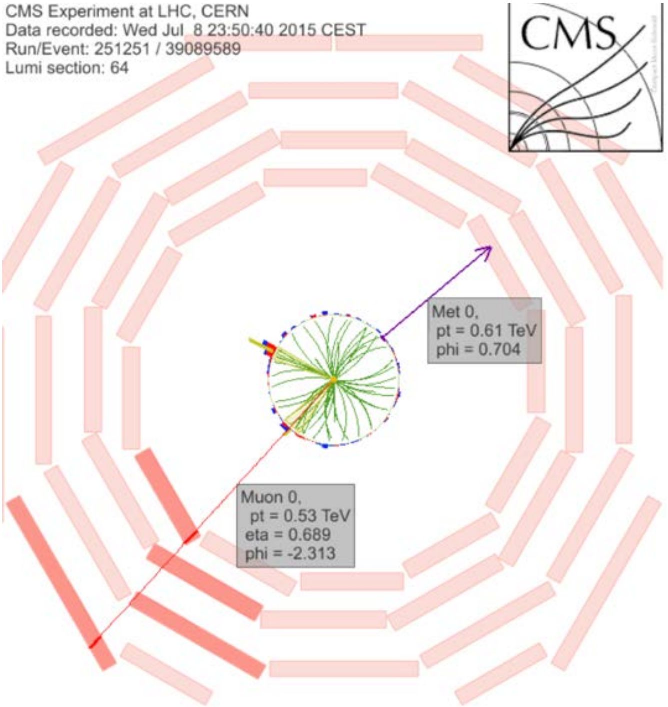


Muon+ missing E_T event



$\Delta\phi$ (μ-MET) = 3.0

m_T = 1.1 TeV



- Transverse momentum (defined in the plane perpendicular to the beam direction) in the initial state ~0.

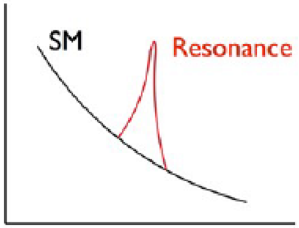
- Momentum imbalance can be due to: neutrinos and other undetectable particle, eg., dark matter, graviton,..

How do we search for resonances?

Mathematical description: relativistic Breit-Wigner distribution

$$\left|\frac{1}{s-m^2+im\Gamma}\right|^2 = \frac{1}{(s-m^2)^2+m^2\Gamma^2}$$

mass, **m**
width, **Γ**=1/τ

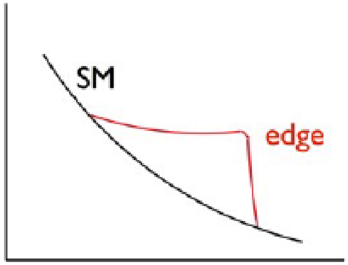


- Experimentally: *Bump Hunt*
- Peak in reconstructed mass spectrum of daughter particles.
- Narrow resonance: width determined by (Gaussian) detector resolution

- If not all the final state particles are detected, estimate transverse mass.
- End point is at true mass.

W' → l ν ⇒ $M_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{\text{miss}} \cdot (1-\cos\Delta\phi_{\ell,\nu})}$

$$M_T^2 = (E_{T,1}+E_{T,2})^2 - (\vec{p}_{T,1}+\vec{p}_{T,2})^2 \xrightarrow{m_1 \sim m_2 \to 0} 2E_{T,1}E_{T,2}(1-\cos\phi)$$



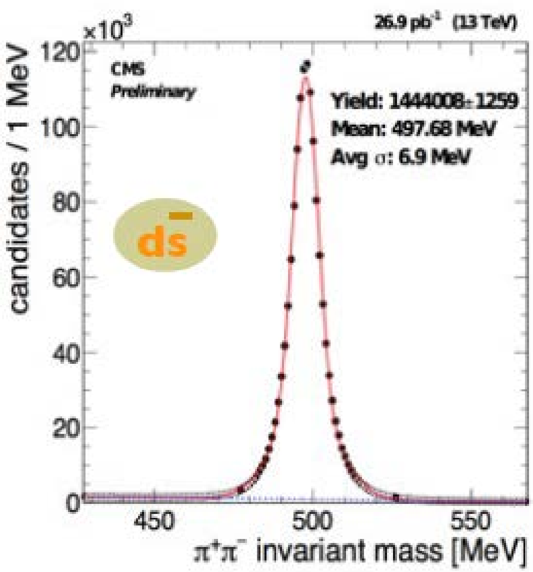
Low mass resonances can be, within the realm of QCD or due to New Physics :
→hadrons, heavy flavour, quarkonia, B-physics,
→ exotic hadronic states, rare decays of heavy flavours

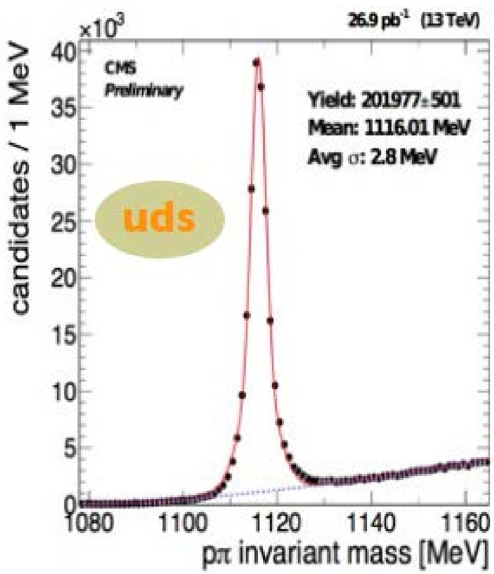
Low mass resonance searches

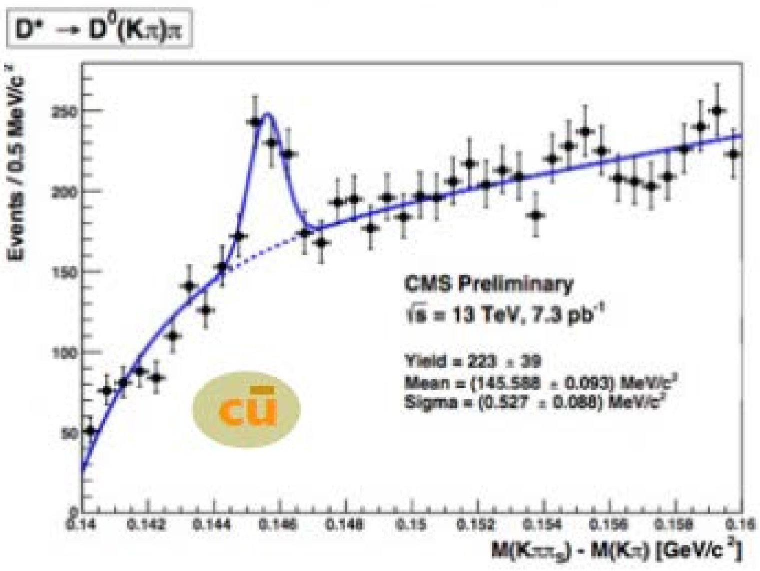
- Low momentum, stable (cτ >10 cm) charged hadrons :

→ reconstructed in the tracker

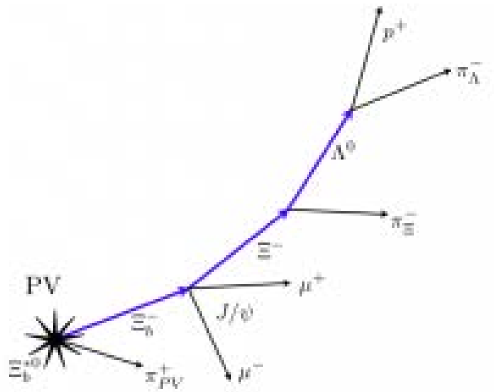
→ subsequently used to reconstruct other unstable particles.

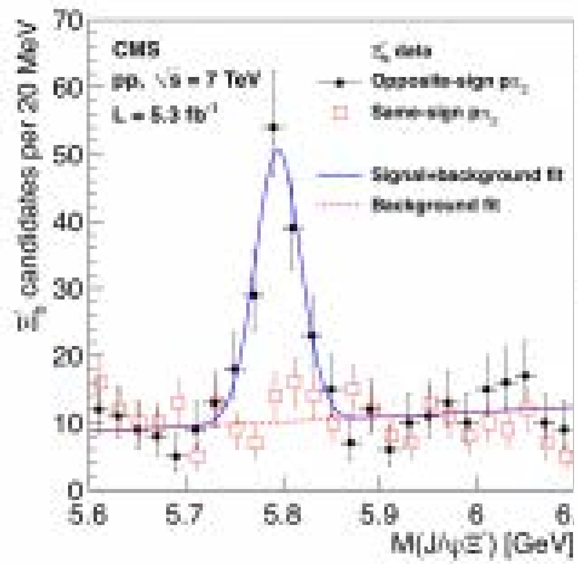


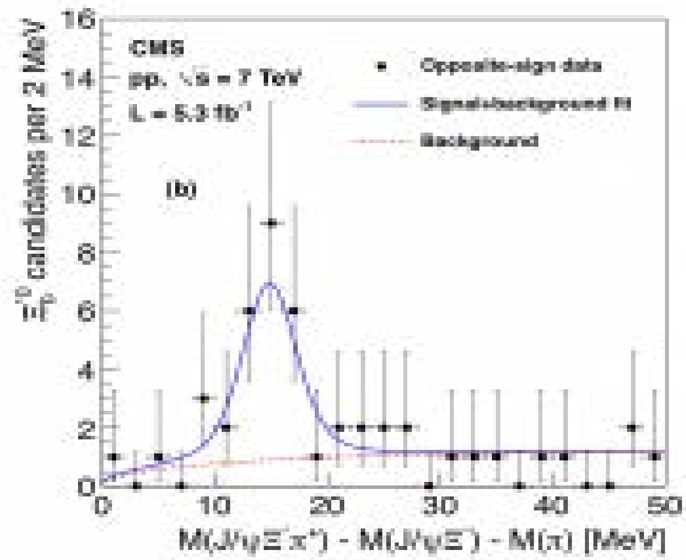




Observation of new baryon Ξ_b^0







$Q = M(J/\psi\Xi^-\pi^+) - M(J/\psi\Xi^-) - M(\pi)$

$\Xi^{*}{}_b^0 \rightarrow \Xi_b^- \pi^+$, (this first pion is "prompt), followed by the subsequent decay:

$\Xi_b^- \rightarrow J/\psi\ \Xi^-$ followed by:

$J/\psi \rightarrow \mu^+\mu^-$ and $\Xi^- \rightarrow \Lambda^0\pi^-$ and finally:

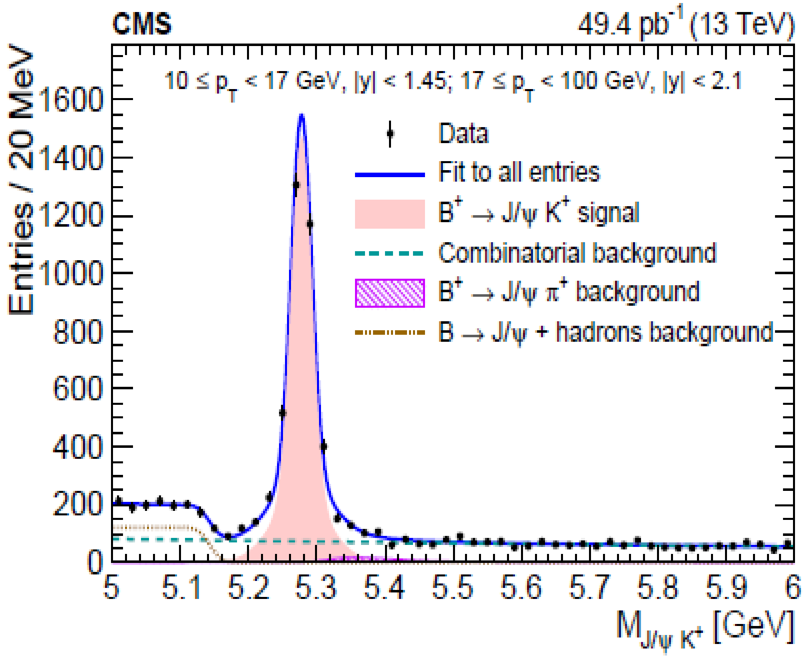
$\Lambda^0 \rightarrow p^+\pi^-$.

$c\tau(\Lambda^0)$ = 78.9 mm, $c\tau(\Xi^-)$ = 49.1 mm and $c\tau(\Xi_b^-)$ = 0.47 mm

Mass: 5945.0 ± 2.8 MeV, $J^P = 3/2^+$

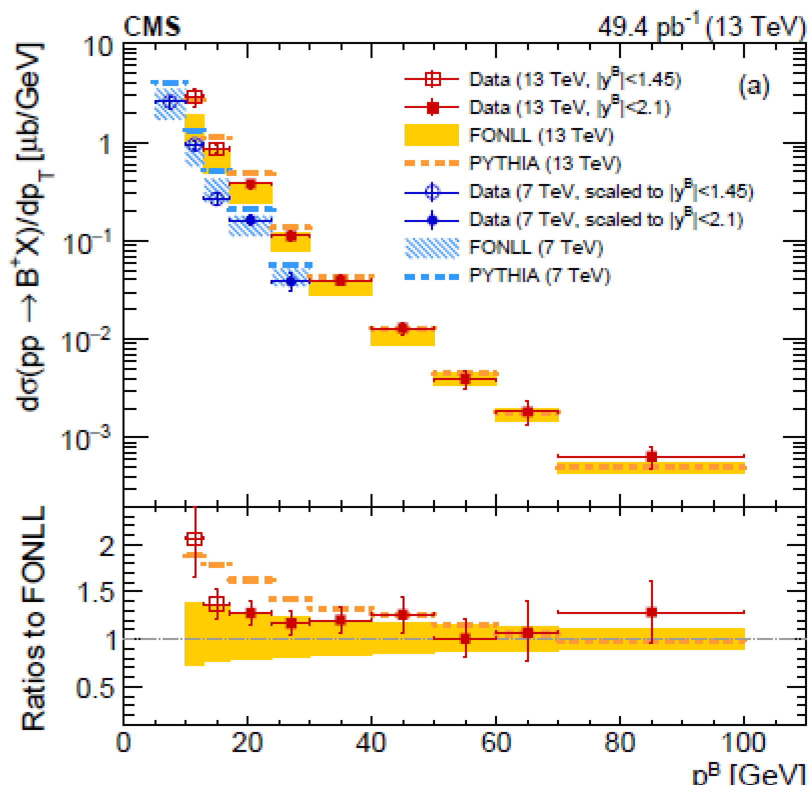
First new baryon observed at LHC with > 5 σ significance

Total and differential inclusive B production rates at 13 TeV



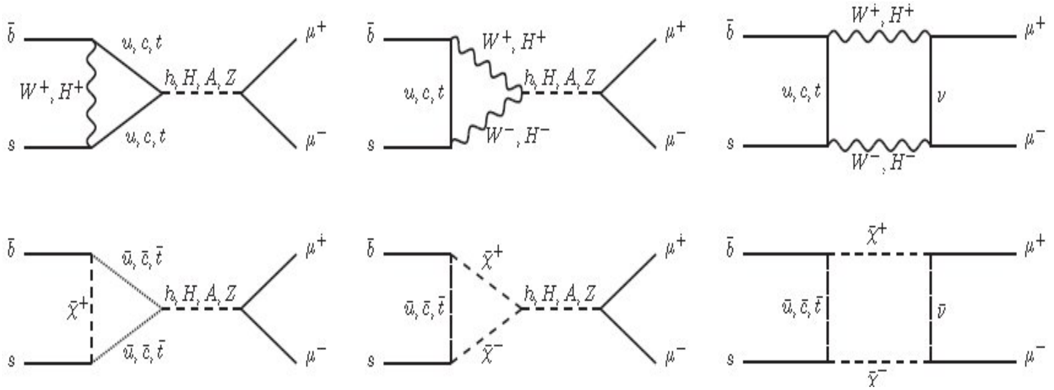
$$\frac{d\sigma(pp \to B^+X)}{dp_T^B} = \frac{n_{sig}(p_T^B)}{2\,A(p_T^B)\,\epsilon(p_T^B)\,\mathcal{B}\,\mathcal{L}\,\Delta p_T^B},$$

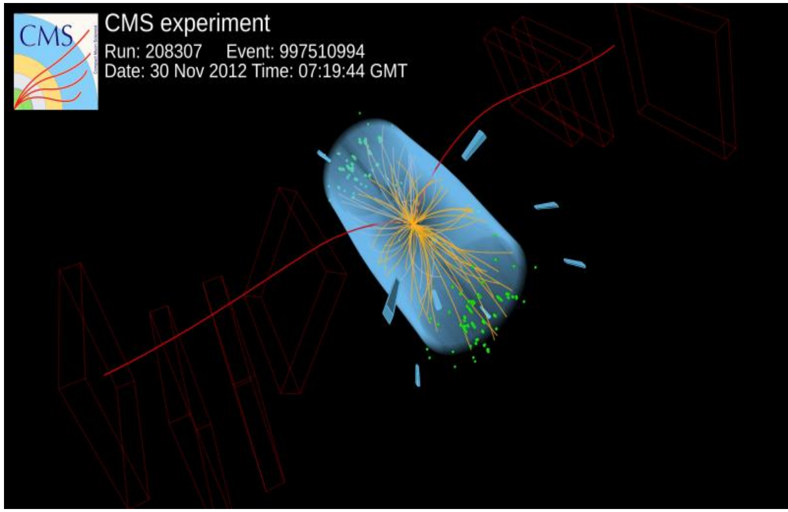
n_{sig}	$A\epsilon$ [%]	σ [μb]
$3477\,^{+86}_{-84}$	3.9 ± 0.5	$14.9 \pm 0.4 \pm 2.0 \pm 0.4$



Searching for new physics through indirect evidence

Flagship measurement: $B^0_s \rightarrow \mu^+\mu^-$





Standard model prediction for branching ratio : $3.2 \pm 0.2 * 10^{-9}$

Run1 result from LHC experiments (CMS and LHCb):

$Br\ (B^0_s \rightarrow \mu^+\mu^-) = 3.0\ ^{+1.0}_{-0.9} * 10^{-9}$,

@ 95% CL $Br\ (B_d^0 \rightarrow \mu^+\mu^-) < 1.1 * 10^{-9}$

Wrapping up

- CMS is a great experiment → could hardly cover various aspects.
- Though it was not planned originally, CMS experiment has produced fantastic physics in the domain of heavy flavours.

- LHC is going to be here for next 2 decades.
- LHC has delivered till now only few % of total anticipated data volume.
- There is lot of opportunity for doing excellent B-physics with CMS detector

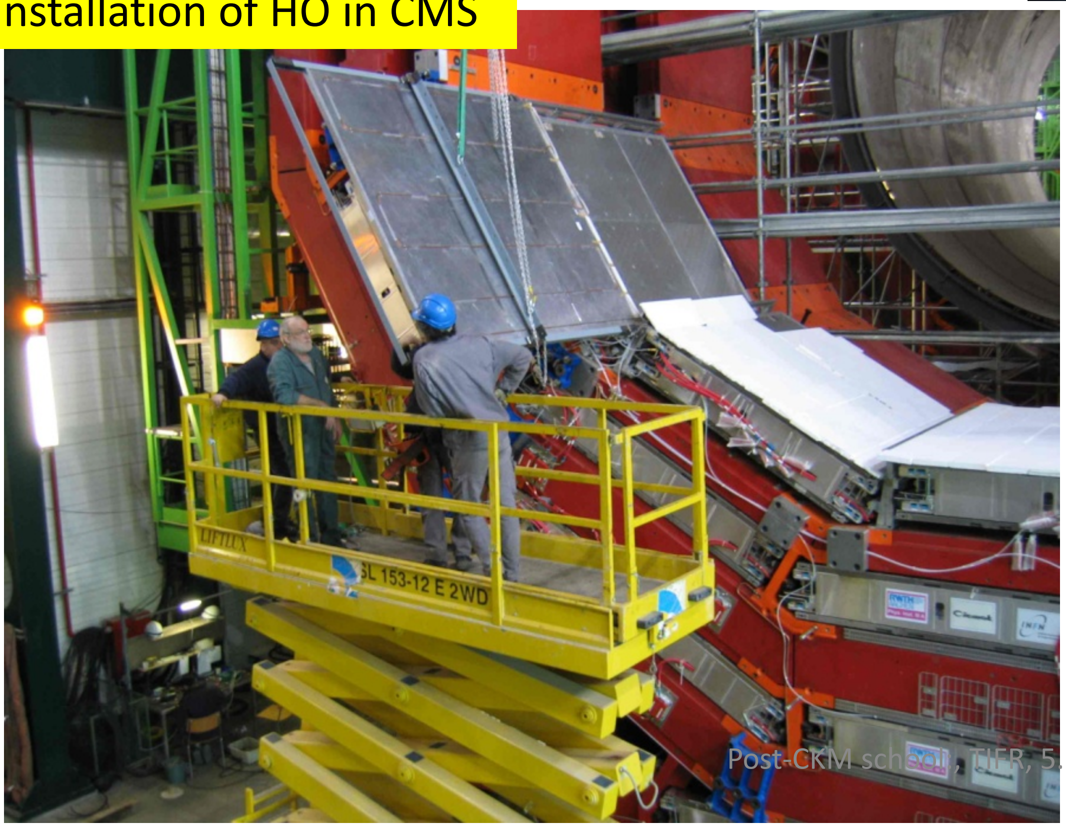
- **Join hands and stay tuned for exciting results from CMS.**

Backup

Indian effort in Hadron Outer Calorimeter detector:
Participation from TIFR and Panjab University
Plastic scintillator+ fibre readout:
about 450 modules, covering 100 m^2

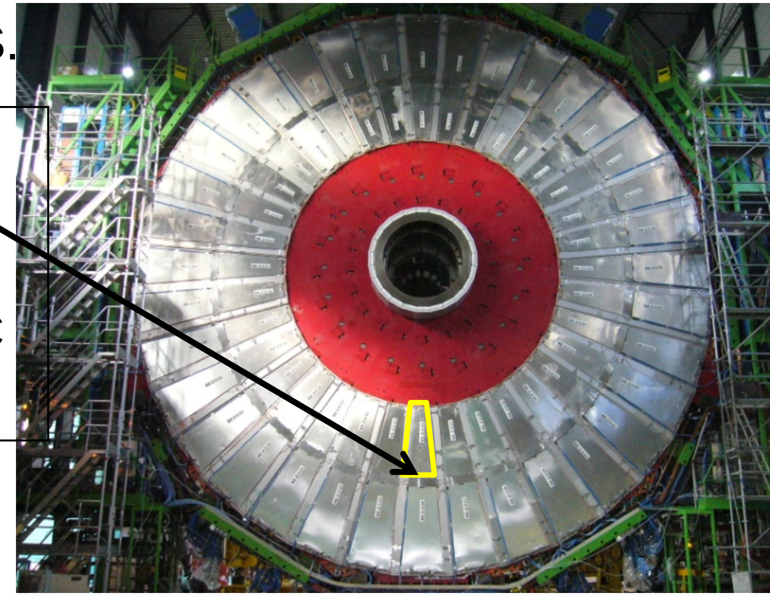
Upgrade of photo detector→Silicon Photo Multiplier
2200 units
Development of farmware for fabrication of
readout board, quality control

Installation of HO in CMS



Resistive Plate Chambers

RPC detectors improves physics with muons in CMS.



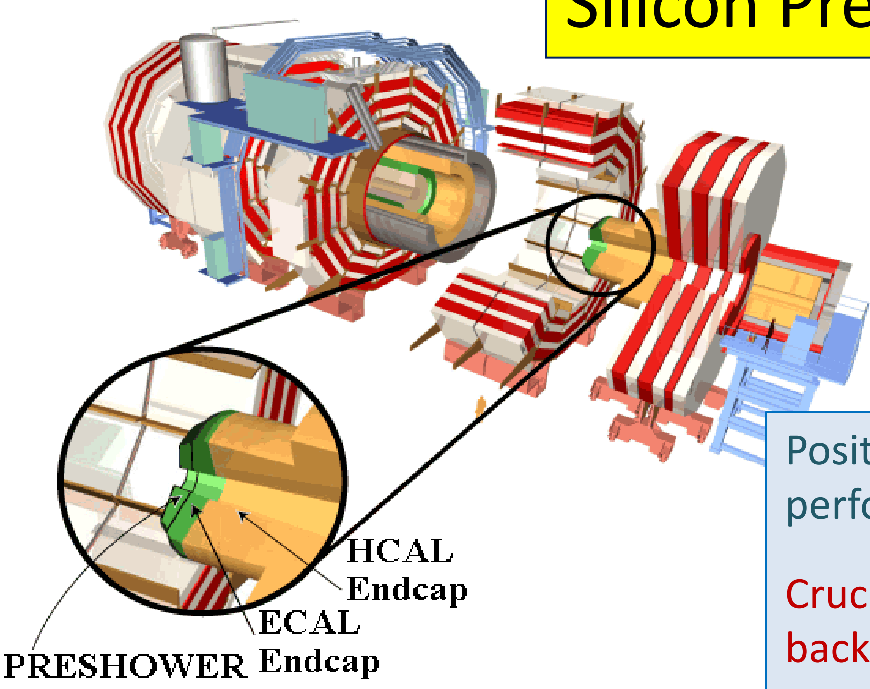
Total 200 chambers :
50 chambers made in BARC, Chandigarh
+ cooling accessories for 200 chambers

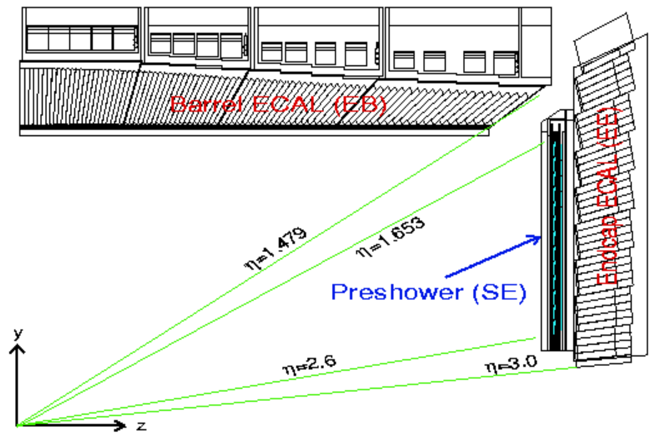
Common technical specification and protocols + QC

Database for production and tests.

Plexiglass spacers for guiding co-axial cables

Silicon Preshower





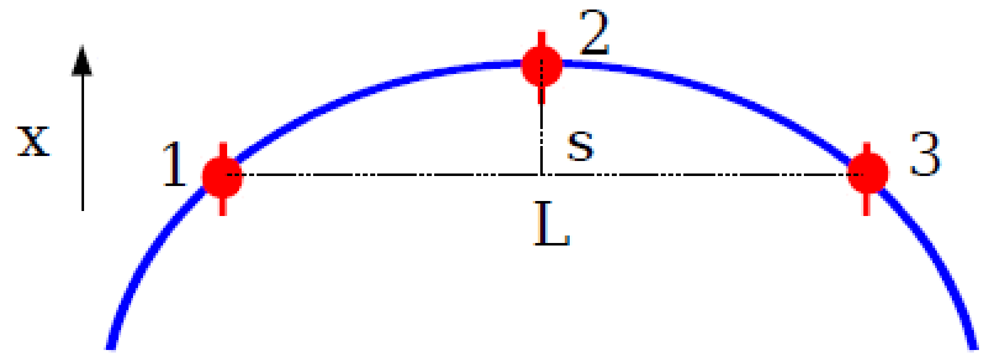
Position sensitive silicon preshower in endcap enhances performance of electromagnetic calorimetry in CMS.

Crucial for Higgs → 2 photon decay, to differentiate from background processes mimicking same final state.

Participation from BARC+ Delhi University

- Fabrication at industry at Bangalore with close supervision of physicists, engineers.
- Characterization studies.
- India supplied 1500 silicon strip detectors out of total 4200 covering an area of about 17 m^2
- Detector: 32 strips with a pitch of 1.8mm and are of 63 mm x 63 mm
- First ever construction of large area silicon detectors in the country.
- High quality of detectors comparable to international suppliers.

Momentum resolution



Sagitta: $s = x_2 - \frac{x_1 + x_3}{2}$

Error propagation: $\sigma_s^2 = \sigma_2^2 + \sigma_1^2/4 + \sigma_3^2/4$ (usually Gaussian)

All σ equal: $\sigma_s = \sqrt{3/2}\,\sigma_x$ $\qquad p_t = qBL^2/8s$

$\Rightarrow \sigma_{p_t}/p_t = \sigma_s/s = \sqrt{96}\,\sigma_x\, p_t/qBL^2$ (always non-Gaussian)

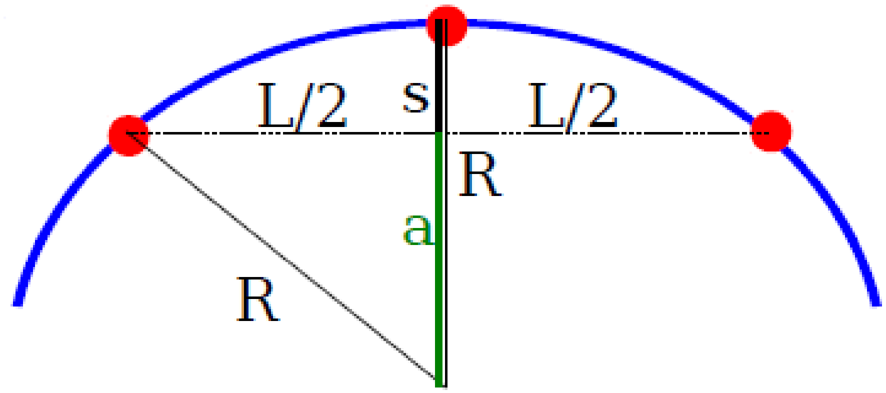
N equidistant measurements: $\sigma_{p_t}/p_t = \sqrt{720/(N+4)}\,\sigma_x\, p_t/qBL^2$

(Glückstern 1964)

Note: $\sigma_{p_t}/p_t \sim p_t$ worse resolution at high p_t.

$\sigma_{p_t}/p_t \sim \sigma_x/BL^2$ want large, precise tracker, strong field.

Sagitta measurement



1. Pythagoras: $a^2 + L^2/4 = R^2$

$\Rightarrow a = R\sqrt{1 - L^2/4R^2}$

Taylor: $\sqrt{1-x} \approx 1 - x/2$

$\Rightarrow a \approx R(1 - L^2/8R^2)$

2. Sagitta: $s = R - a$, insert a

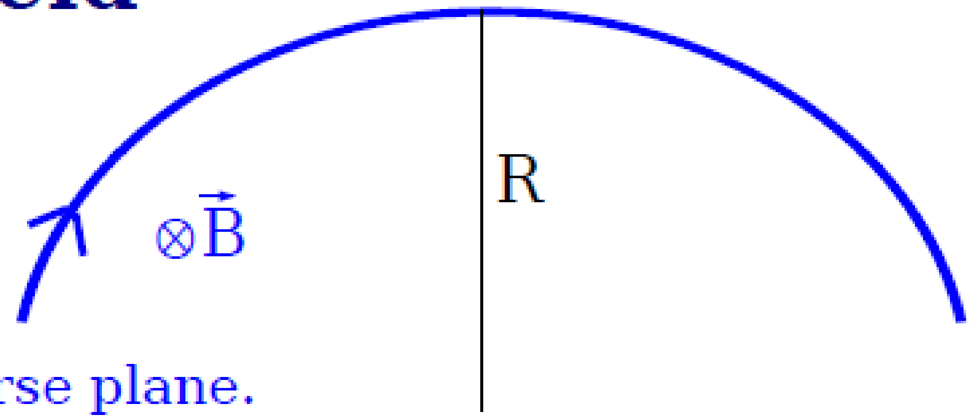
$$\Rightarrow \boxed{s = L^2/8R}$$

$$\Rightarrow p_t = qBL^2/8s$$

CMS: B = 3.8 T, L = 1 m

P_t [GeV/c]	s [cm]
100	0.15
10	1.50
1	15.00

Charged particles in a magnetic field



Lorentz Force:

$$\vec{F}_L = q\,\vec{v} \times \vec{B}$$

For B = constant:
circular motion in the transverse plane.
Equation of motion:
Lorentz force balanced by centrifugal force: $q\,v_t\,B = m\,v_t^2/R$

$p_t = m\,v_t \quad \Rightarrow \boxed{p_t = qRB}$ also holds relativistically.

$$\boxed{cp_t\,[GeV] = 0.3\,R\,[m]\,B\,[T]}$$

for q = e

CMS: B = 3.8 T

p_t [GeV/c]	R [m]
100	87.72
10	8.77
1	0.88

Low p_t tracks curl up
inside the tracker if 2R < L

Tracking detector in CMS

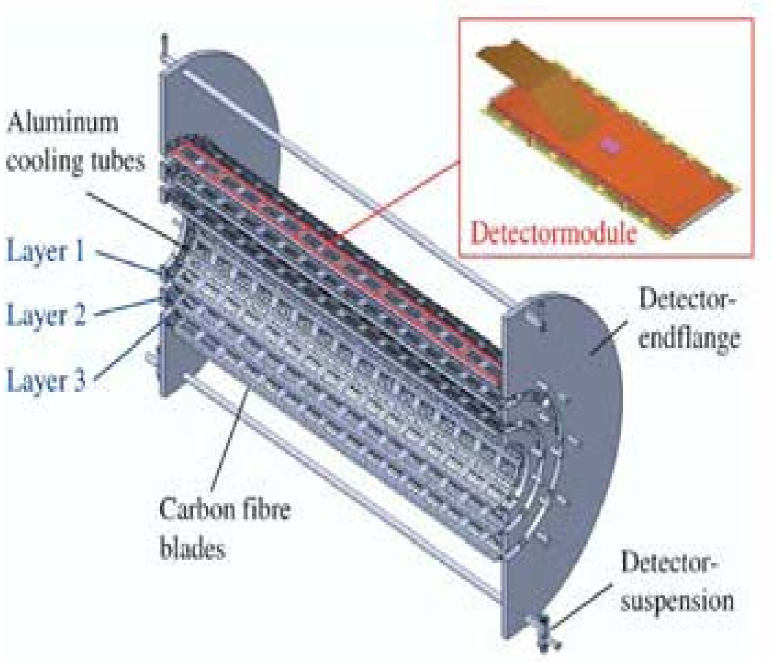
World's largest silicon detector, at -10^0 C

- 1440 silicon pixel + 15148 silicon strip detectors (SST) , $|\eta| \leq 2.5$
- Impact parameter resolution : 100 μm
- transverse momentum resolution: 0.7% for 1 GeV/c charged particles

Pixels: three 53.3 cm long barrel layers at radii 4.4, 7.3, 10.2 cm.
+ 2 forward disks between 6-15 cm. , at z = 34.5, 46.5 cm

ST: total 205 m^2 , 55 cm long, 10 layers
between 22 to 110 cm from beam.
Precision in alignment for particle trajectories in bending plane : 3-4 μm

A new pixel detector with 4 layers to be installed soon.

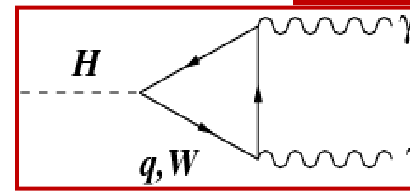


Higgs decaying to a pair of photons

- Simple and clean signature: final state with 2 energetic photons.

- Narrow peak to be identified on top of huge continuously falling background in the invariant mass distribution.

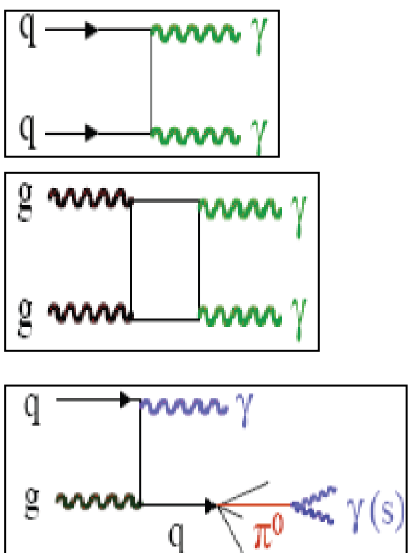
signal

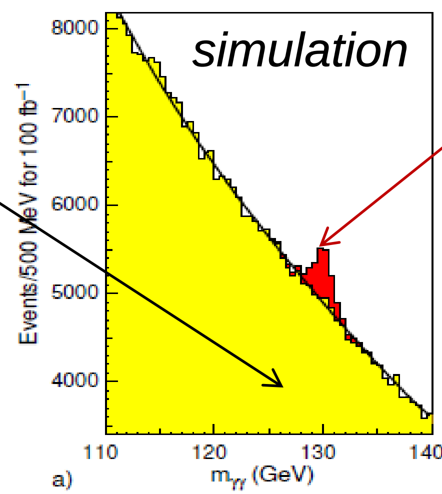


$m^2_{\gamma\gamma} = 2\, E_1\, E_2\, (1-\cos\alpha)$

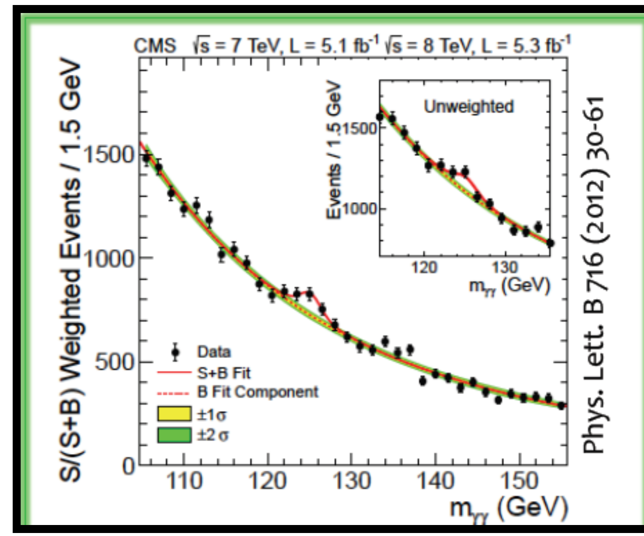
Accurate measurements of individual energy and angle between 2 γ s.

Main backgrounds





Run1 data



H → 2 photons

$m^2_{\gamma\gamma} = 2\,E_1\,E_2\,(1-\cos\alpha)$

Crucial → measurement s of individual energy and angle between 2 γ s.

- Photon reconstruction from clusters in electromagnetic calorimeter cells
- Recovery of conversion in inner detector
- Identification of isolated photons
- Calibration of photon energy
- Thorough understanding of the background

The calorimeter material chosen to have low radiation length and Moliere radius.
→ compact detector with good energy, position, and angular resolutions.
→ excellent mass resolution ~1%

- 75,000 crystals: 24 X 2 X 2 cm^3
- Compact inorganic, scintillators. transparent but 96% metal by mass, supported by 0.4 mm thick glass/carbon fibre structure.