The road to discovery at the LHC

The case of CMS

Filip Moortgat (ETH Zurich)

or

?

Disclaimer

This presentation contains many slides that I have shamelessly stolen from my CMS colleagues. Many thanks to all!

Road to discovery

So you want to discover new physics ….

Start with:

1) Build a powerful accelerator (energy and luminosity)
2) Build high performance detectors

Once this is done:

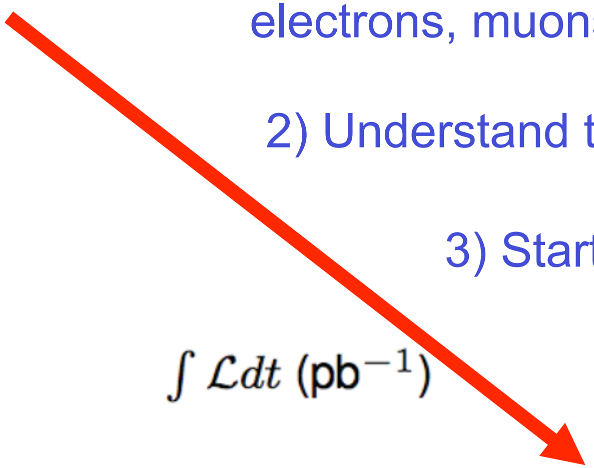
The roadmap:

1) Understand basic physics objects:
   electrons, muons, jets, b's, tau's, MET

2) Understand the Standard Model (QCD, W, Z, top)

3) Start looking for anomalies … anywhere …

4) Interprete signals, measure properties

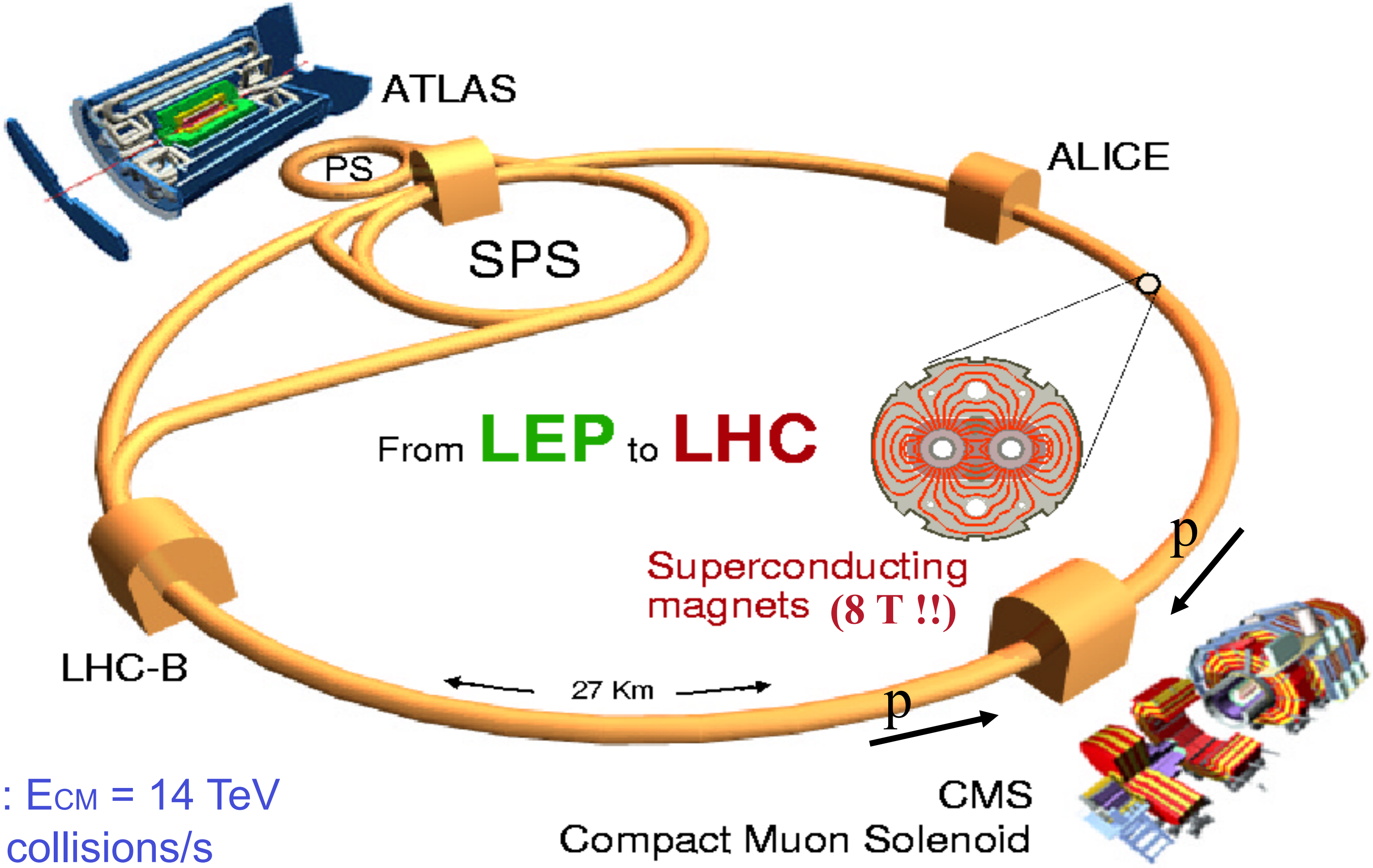


$\int \mathcal{L}dt\ (\mathrm{pb}^{-1})$

Why LHC?

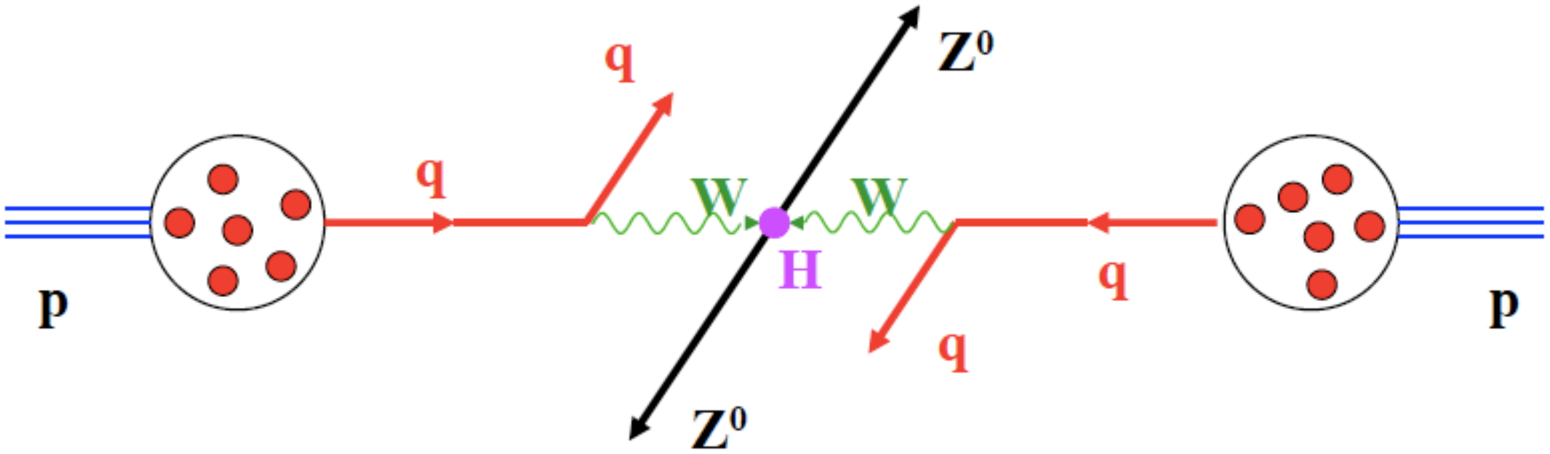
- LEP not enough energy for new physics (limited due to synchrotron radiation)
- upgrade: either larger R or larger m (since $-\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4$)
- so: 1) keep LEP tunnel and go to protons (large m) or
  2) go to a linear collider (large R)
- decided to do 1) first

The LHC Collider



Goal: E_{CM} = 14 TeV
40M collisions/s
inst. lumi: 10^{34} cm^{-2}s^{-1}

Motivation



M_H ~ 1000 GeV

$E_W \geq 500$ GeV

$E_q \geq 1000$ GeV (1 TeV)

$E_p \geq 6000$ GeV (6 TeV)

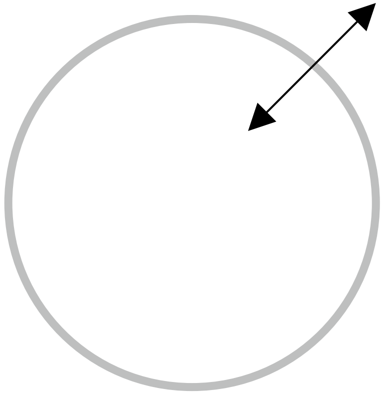
→ Proton Proton Collider with $E_p \geq 7$ TeV

LHC location

LHC energy

Simple calculation:

require that the magnetic field compensates the centrifugal acceleration:

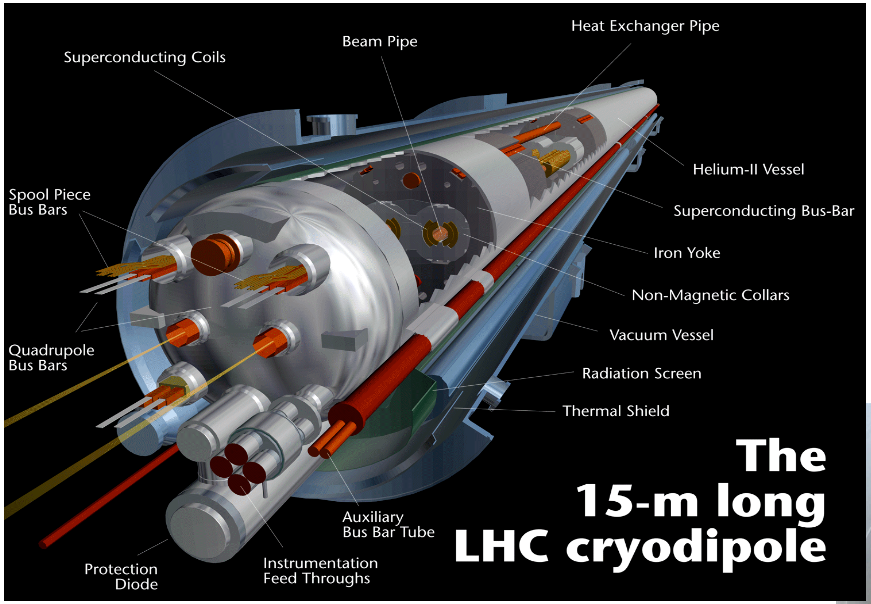


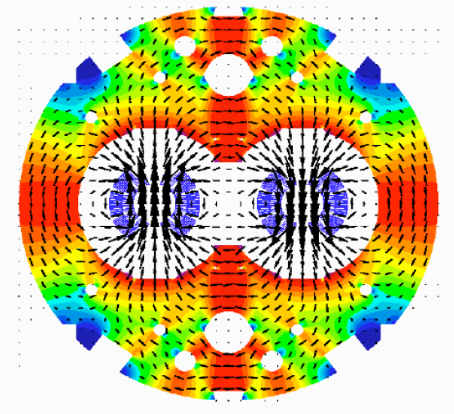
$$F = m\frac{v^2}{R} \quad \leftrightarrow \quad F = qvB$$

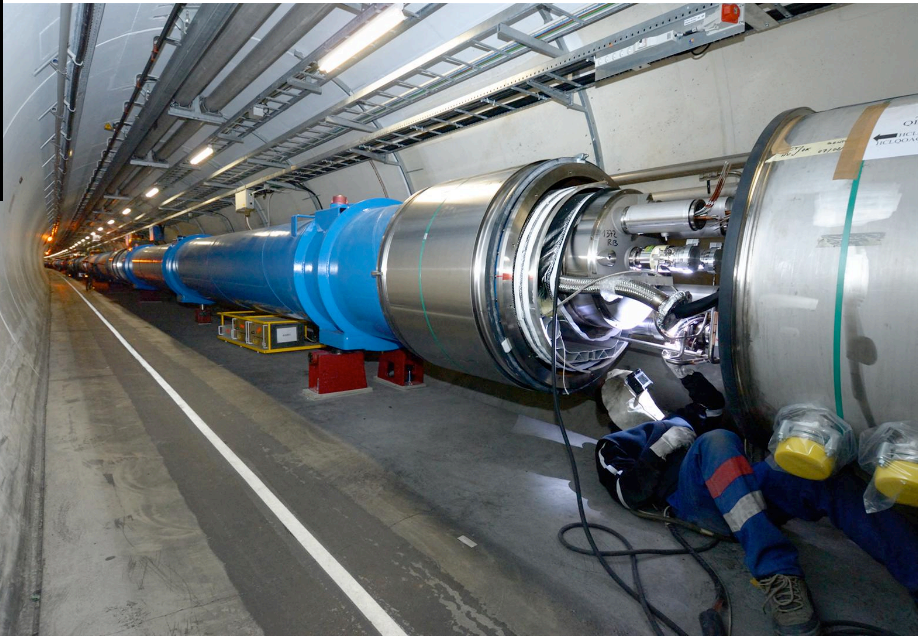
$$\Leftrightarrow$$

$$E\,[\mathrm{TeV}] = 0.84\,B\,[\mathrm{T}]$$

Accelerator challenges





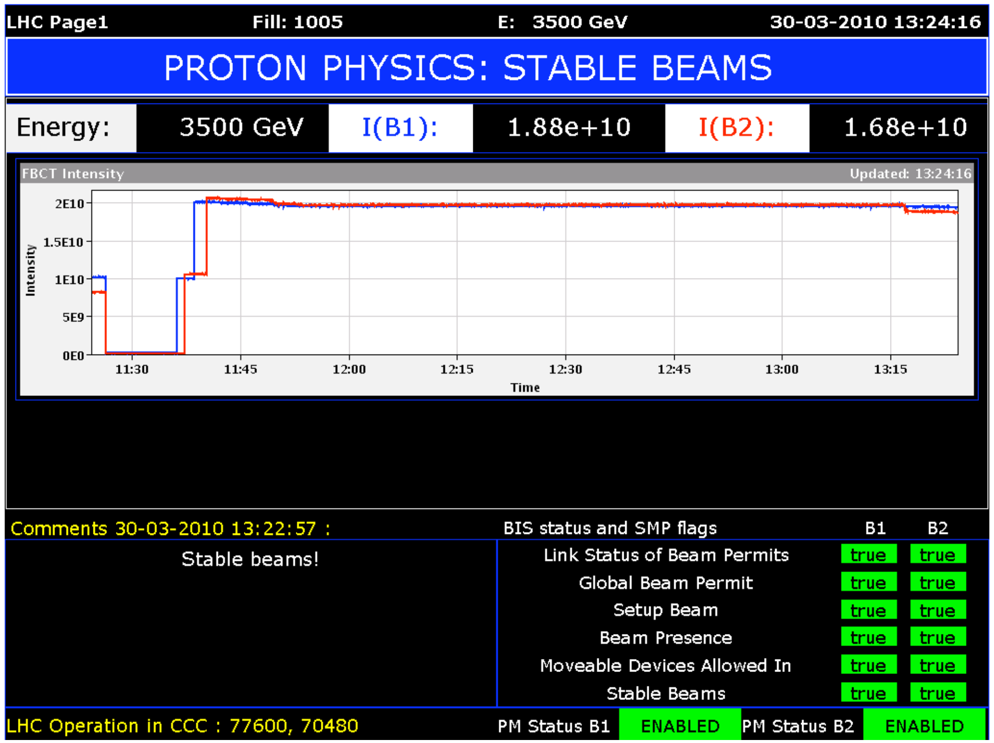


LHC magnets are cooled with pressurized superfluid helium.

The LHC startup

First collisions at 900 GeV : 23 November 2009
First collisions at 7 TeV : 30 March 2010

30 March 2010 at 12:58



LHC Page1 Fill: 1005 E: 3500 GeV 30-03-2010 13:24:16

PROTON PHYSICS: STABLE BEAMS

Energy:	3500 GeV	I(B1):	1.88e+10	I(B2):	1.68e+10

Comments 30-03-2010 13:22:57 :

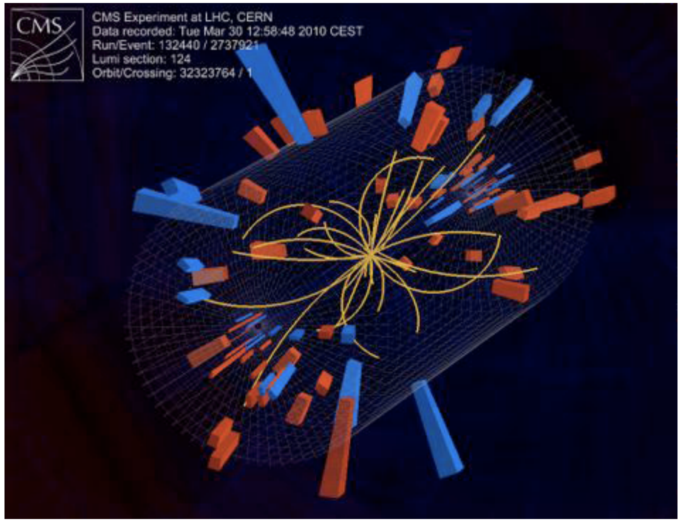
Stable beams!

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

LHC Operation in CCC : 77600, 70480

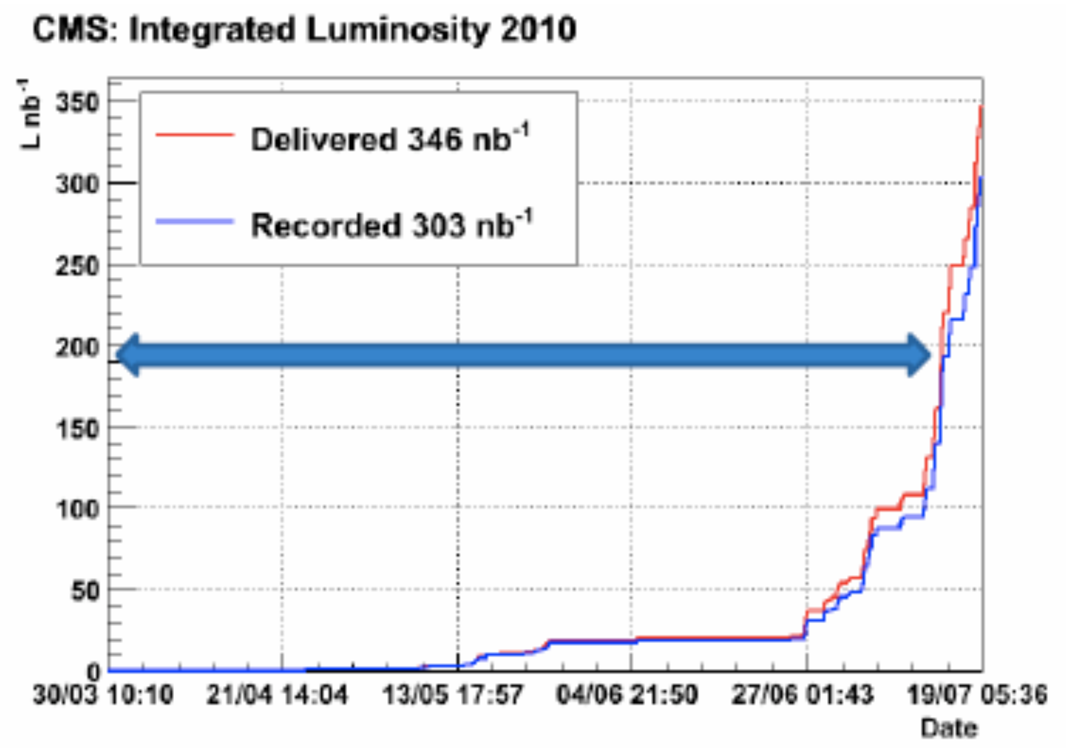
PM Status B1 ENABLED PM Status B2 ENABLED

One of the first 7 TeV collisions:



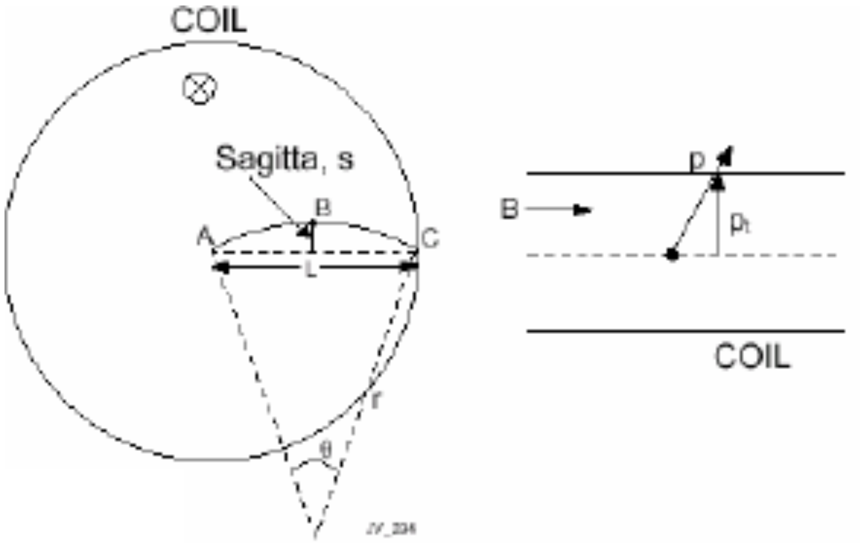
LHC timeline: 2010-2011: 1 fb^{-1} collisions at E_{cm}= 7 TeV
from 2013 onwards: collisions at E_{cm}~ 14 TeV

Luminosity delivered



Overall data taking efficiency: ~ 89%

Momentum measurement

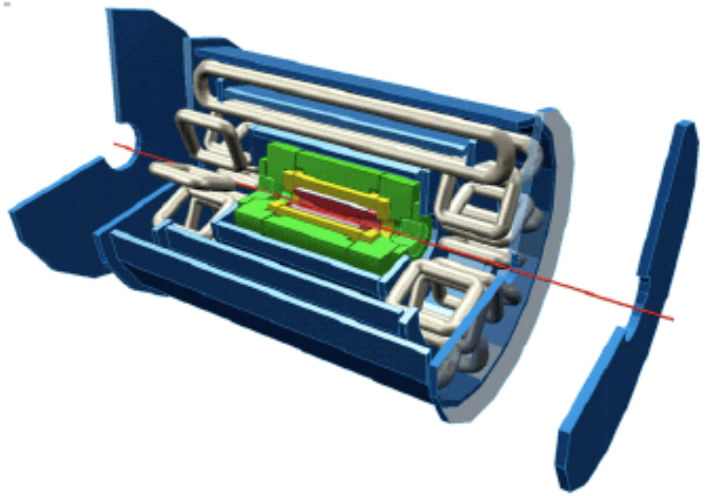


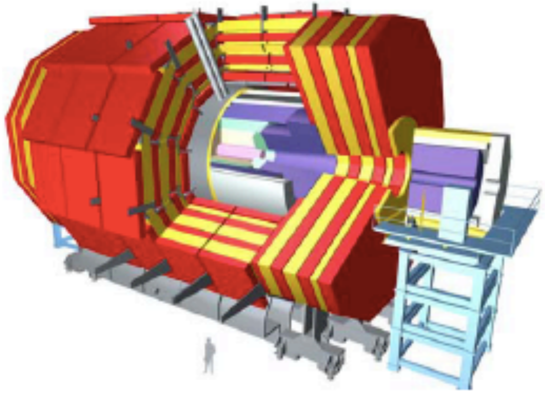
Need high BL^2 and good tracking resolution

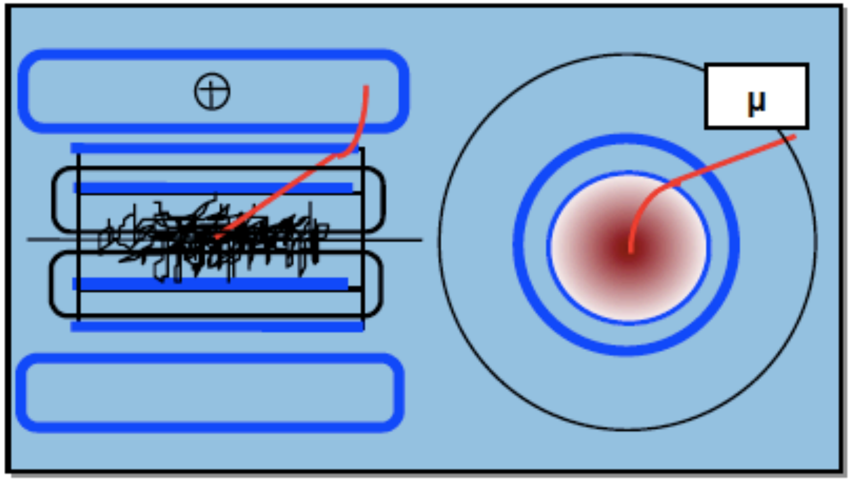
General purpose expts

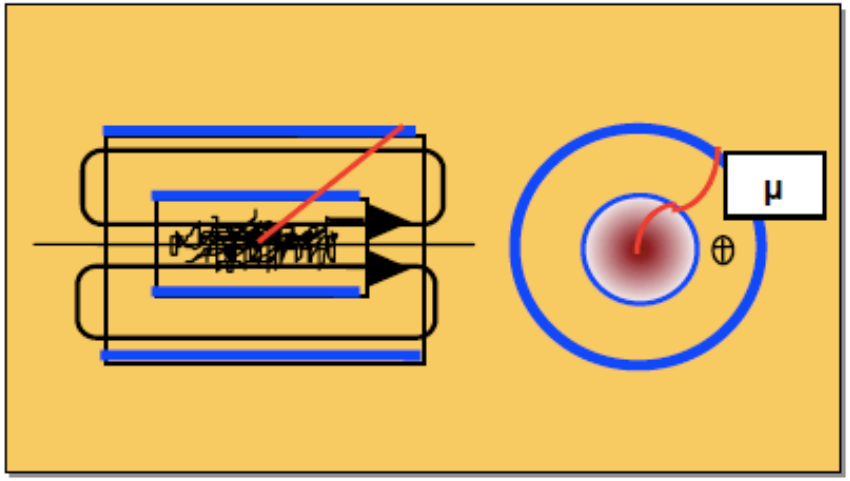
ATLAS A Toroidal LHC ApparatuS

CMS Compact Muon Solenoid









CMS design criteria

Very good muon identification and momentum measurement
Trigger efficiently and measure sign of TeV muons dp/p < 10%

High energy resolution electromagnetic calorimetry
Energy resolution ~ 0.5% @ E_T ~ 50 GeV

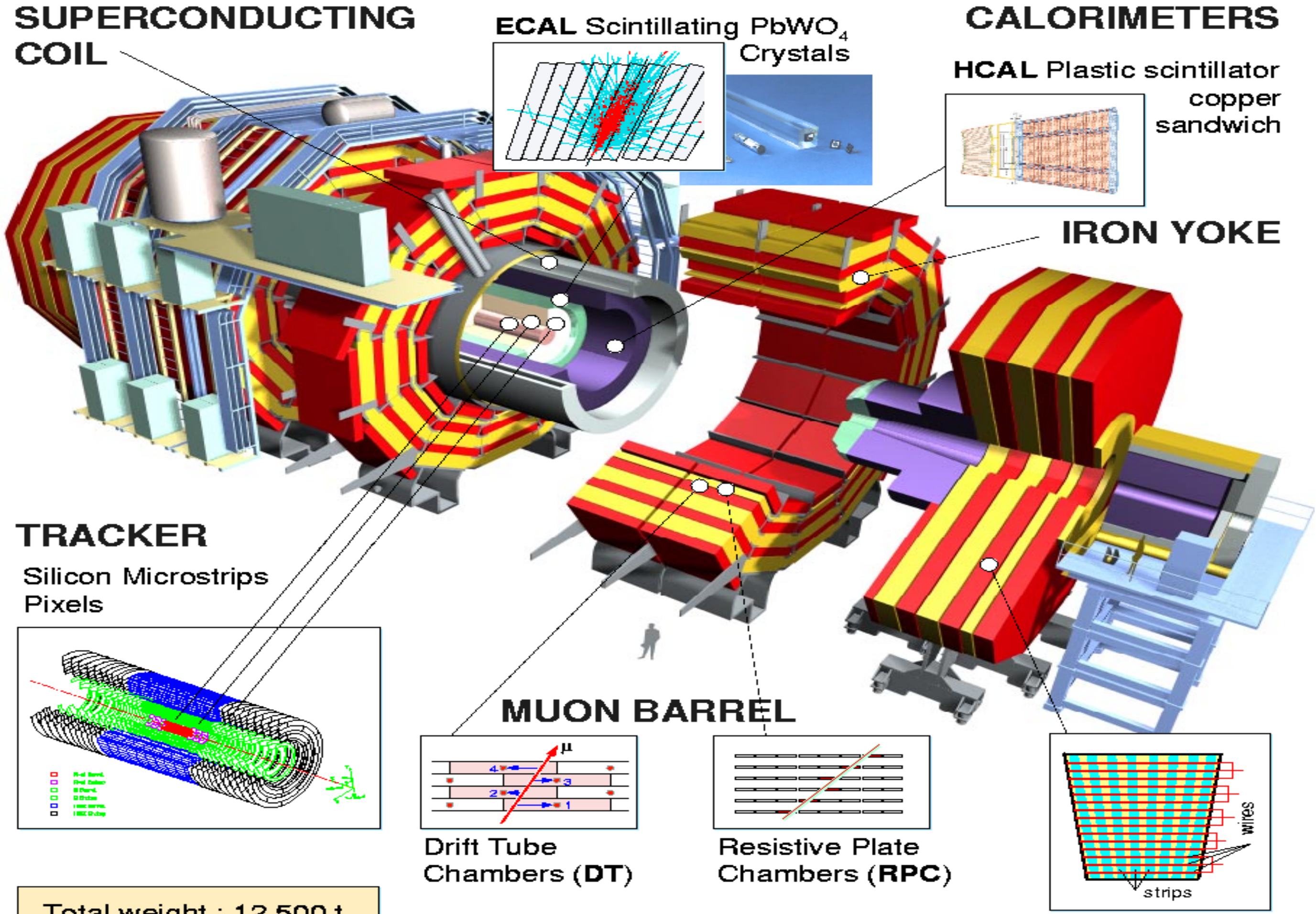
Powerful inner tracking systems
Momentum resolution a factor 10 better than at LEP

Hermetic calorimetry
Good missing E_T resolution

(Affordable detector)

Transparency from the early 90's

The Compact Muon Solenoid



SUPERCONDUCTING COIL

ECAL Scintillating $PbWO_4$ Crystals

CALORIMETERS

HCAL Plastic scintillator copper sandwich

IRON YOKE

TRACKER

Silicon Microstrips
Pixels

MUON BARREL

Drift Tube Chambers (**DT**)

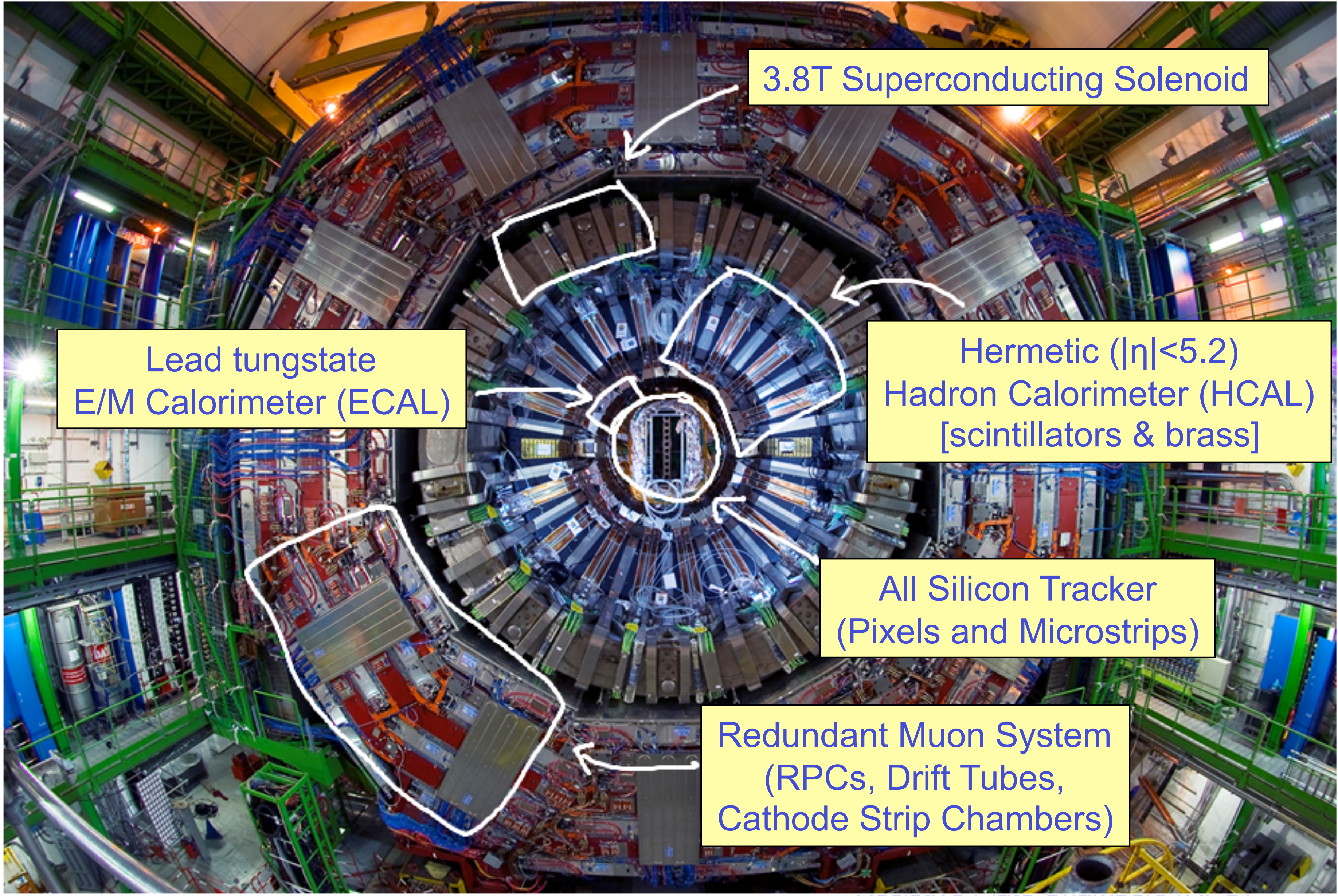
Resistive Plate Chambers (**RPC**)

MUON ENDCAPS

Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

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

The CMS detector



3.8T Superconducting Solenoid

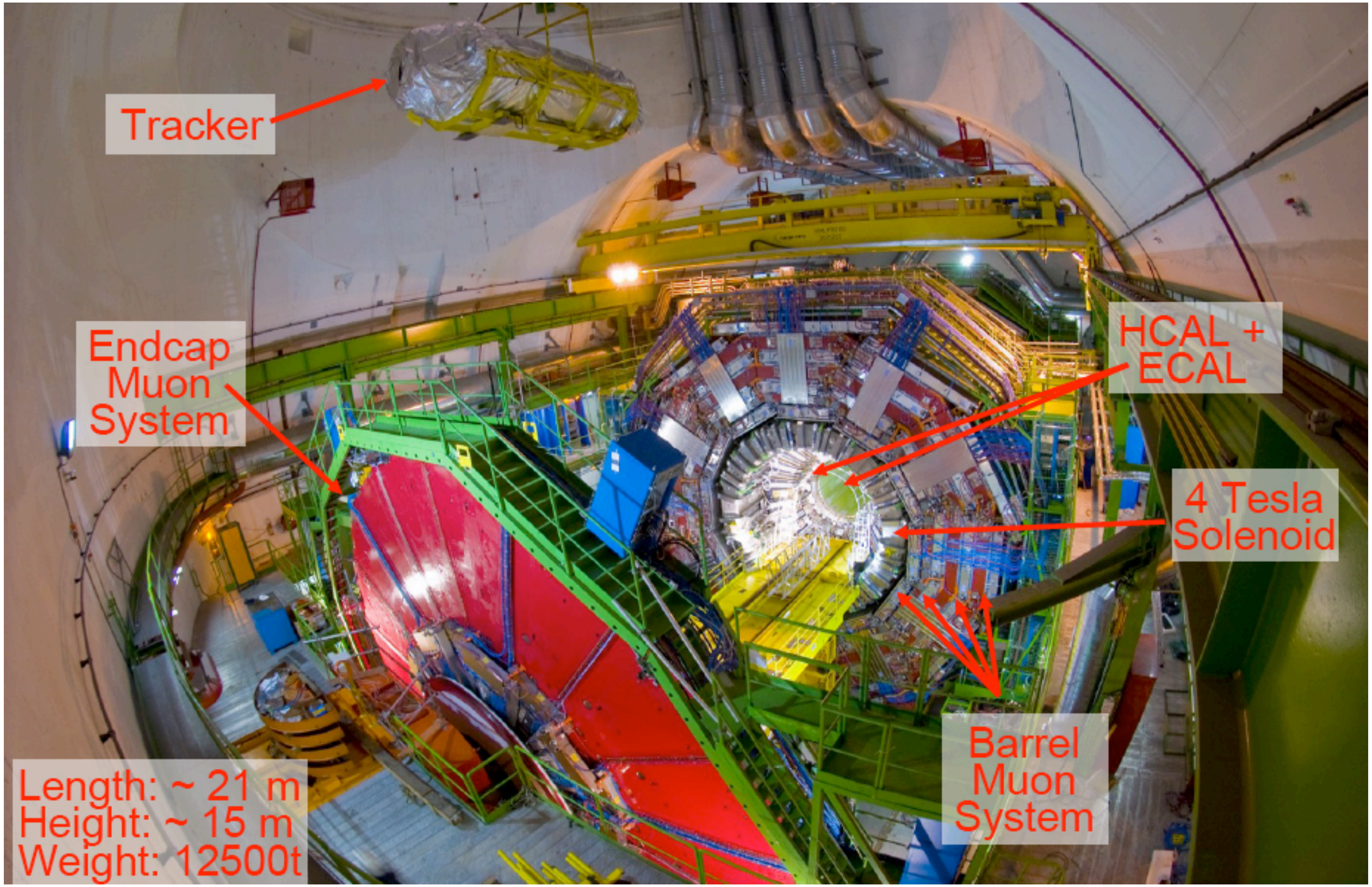
Lead tungstate E/M Calorimeter (ECAL)

Hermetic (|η|<5.2) Hadron Calorimeter (HCAL) [scintillators & brass]

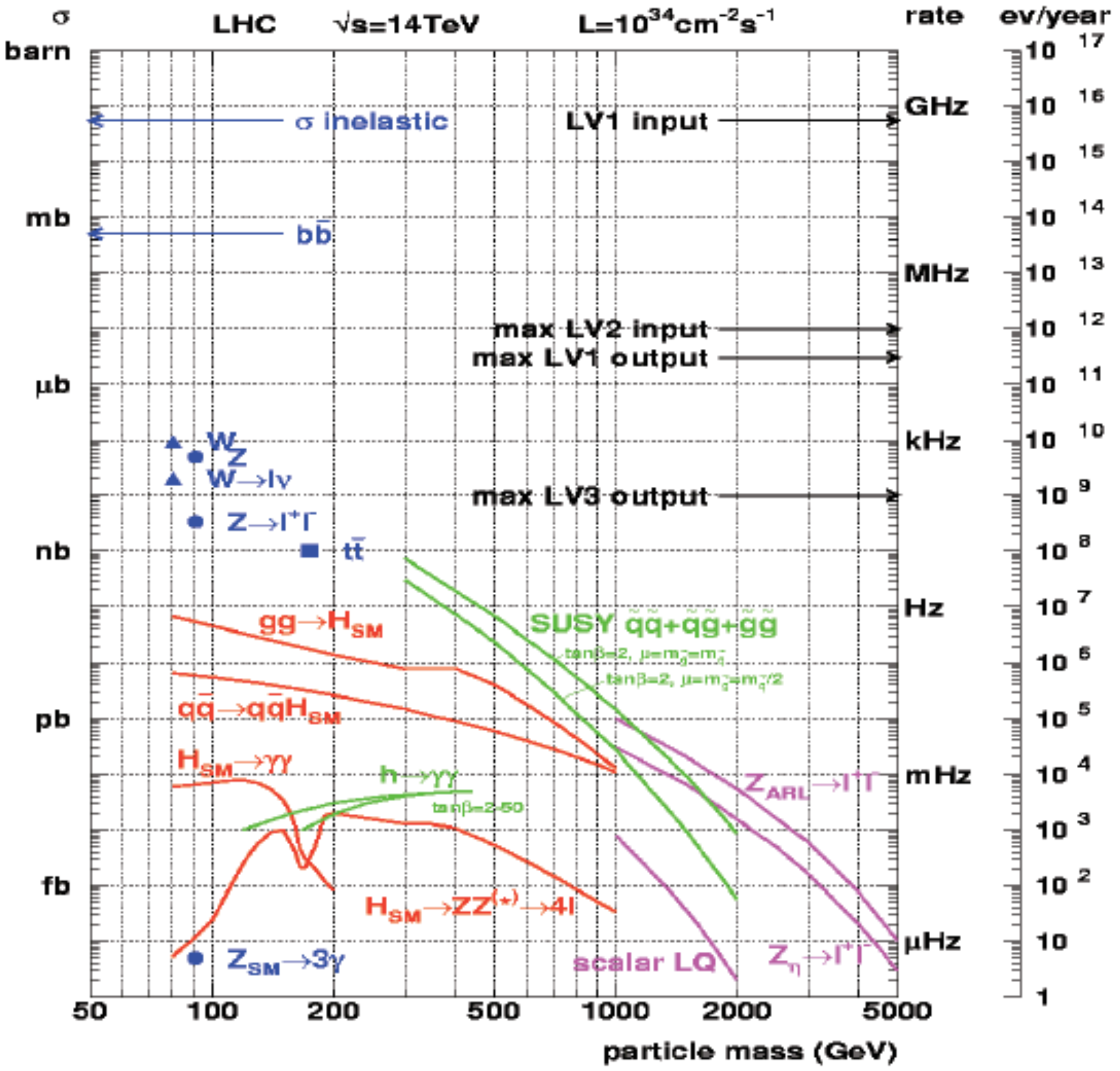
All Silicon Tracker (Pixels and Microstrips)

Redundant Muon System (RPCs, Drift Tubes, Cathode Strip Chambers)

Assembling


Tracker
Endcap Muon System
HCAL + ECAL
4 Tesla Solenoid
Barrel Muon System
Length: ~ 21 m
Height: ~ 15 m
Weight: 12500t

Trigger



"Well known"processes, don't need to keep all of them …

New Physics!!
This we want to keep!!

Event selection at the LHC

Per year, the LHC will provide about 10^{16} *pp* collisions.

An observation of ~ 10 events could be a discovery of new physics.

→ One has to find these 10 events among 10^{16} non-interesting ones!!

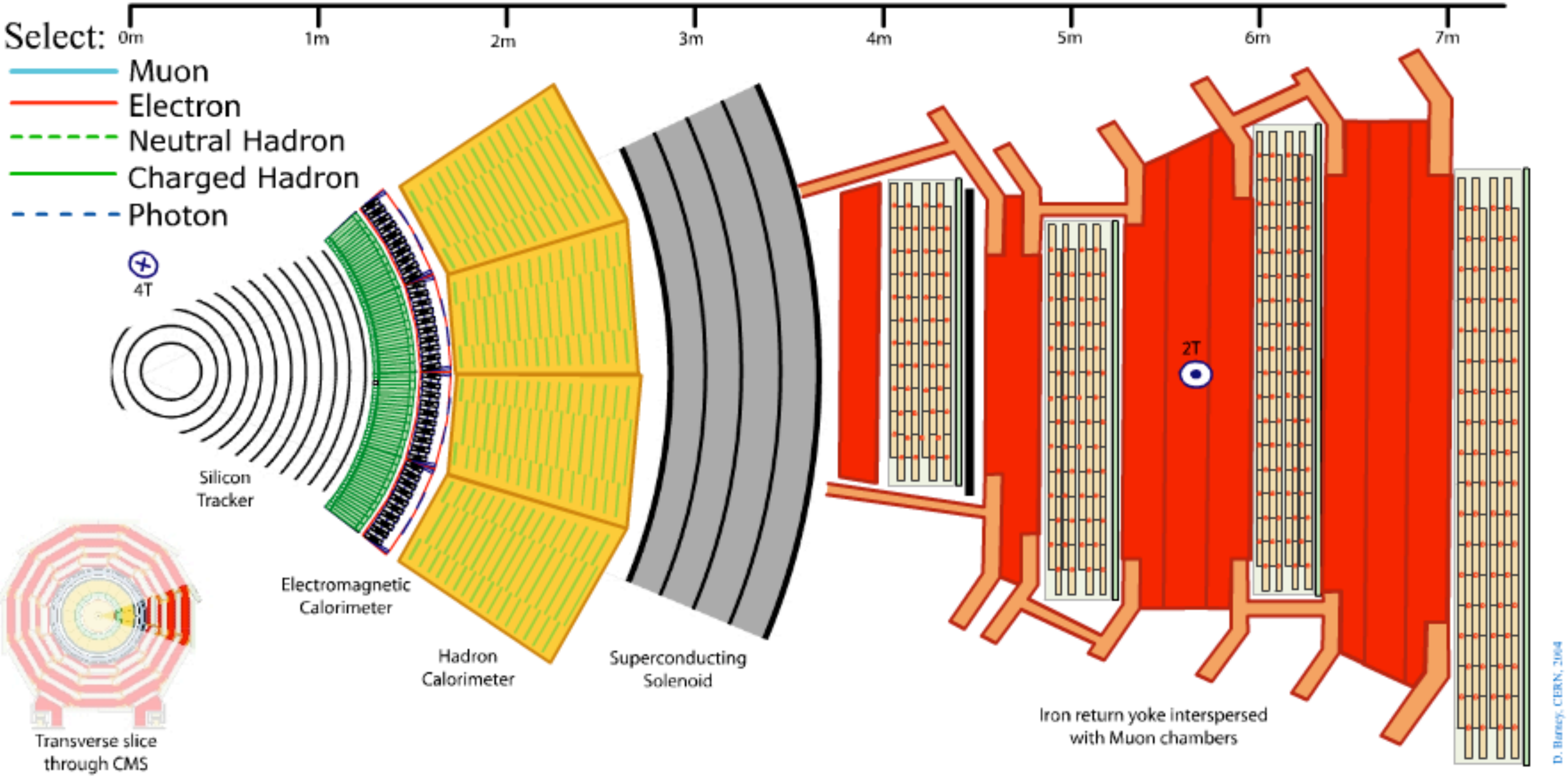
Searching for a needle in a hay stack?

- typical needle: 5 mm^3
- typical haystack: 50 m^3

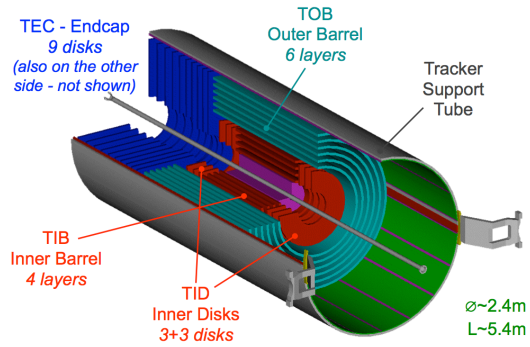
→ needle : haystack = 1 : 10^{10}

→ Looking for new physics at the LHC is like looking for a needle in 100000 haystacks …

CMS


Select:
Muon
Electron
Neutral Hadron
Charged Hadron
Photon
0m
1m
2m
3m
4m
5m
6m
7m
4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D. Barney, CERN, 2004

CMS Tracker

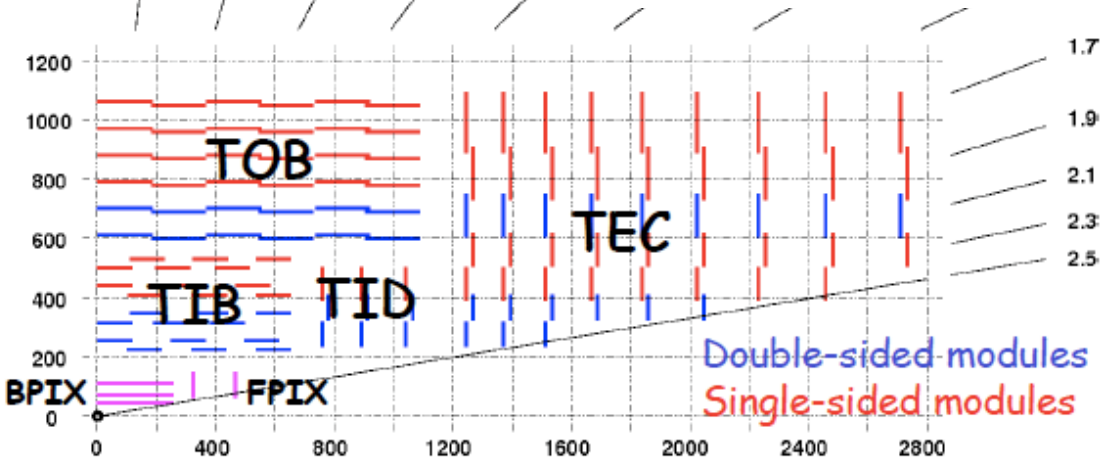


The largest silicon tracking detector ever built!

- must provide low occupancy for LHC high luminosity
- high-precision tracking for heavy flavour identification
- coverage up to $|\eta| < 2.5$

Strips

- 9.3M channels
- ~ 200 m^2 sensor area
- 10 barrel layers
- 9 (+3) endcap disks

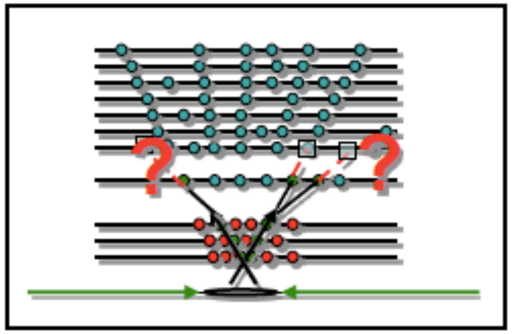


Pixels

- 66M channels
- ~ 1.1 m^2 sensor area
- 3 barrel layers
- 2 endcap disks
- innermost layer at r = 4.3 cm

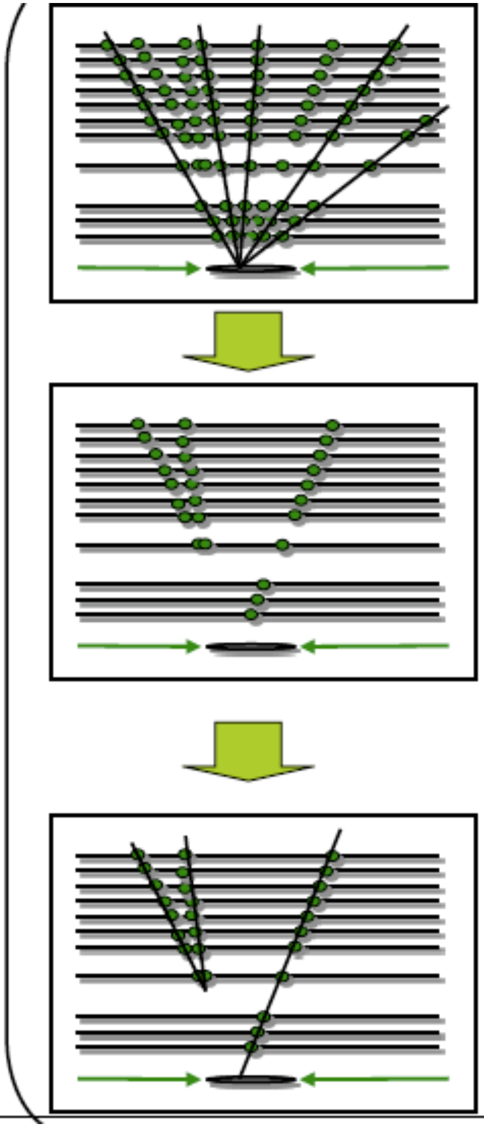
Operational fractions
strips: 98.1%
pixels: 98.3%

Tracking



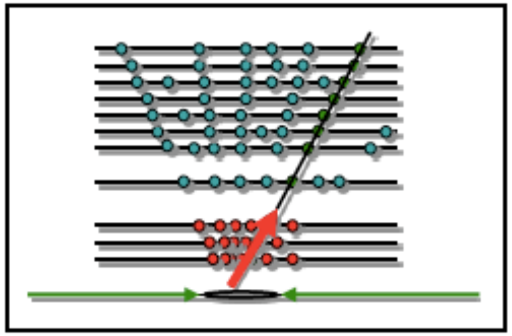
Seeding starts from innermost pixel layers.

Inside-out trajectory building



Iterative tracking with hits-removal

(6 iterations like this)

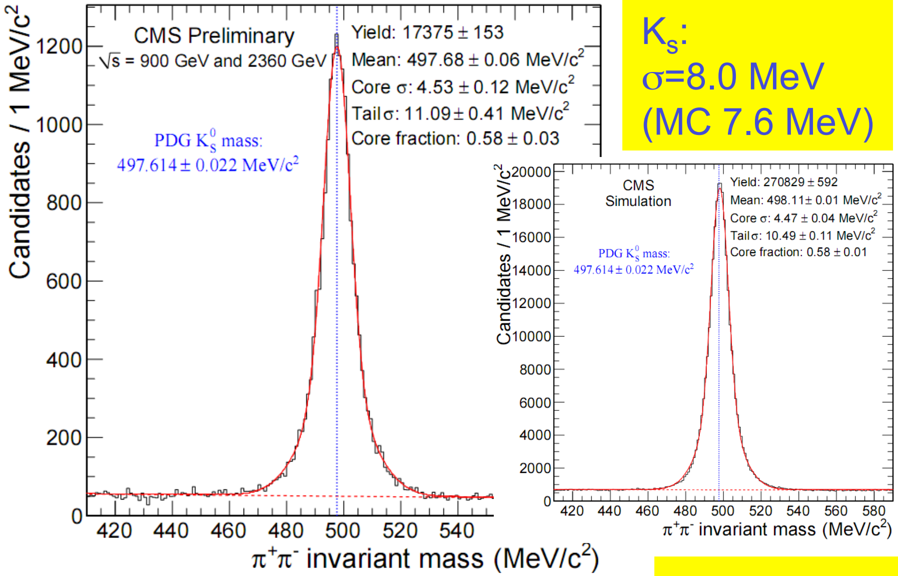


Final fit using **Kalman Filter/Smoother**.

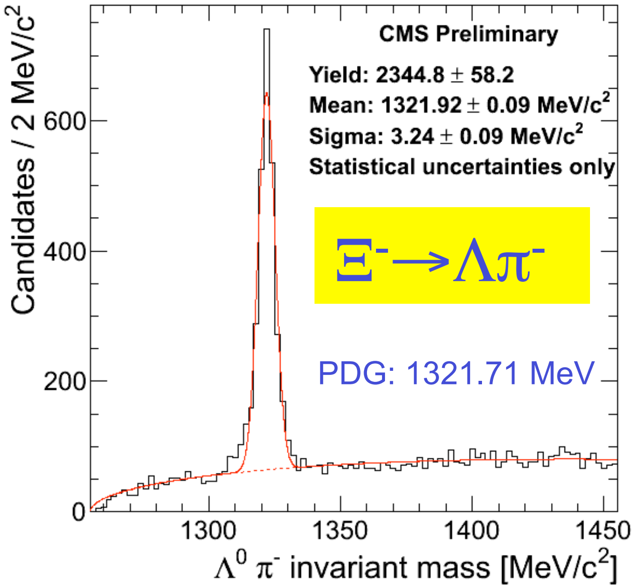
Parameters propagated through magnetic field inhomogeneities using **Runge-Kutta propagator**

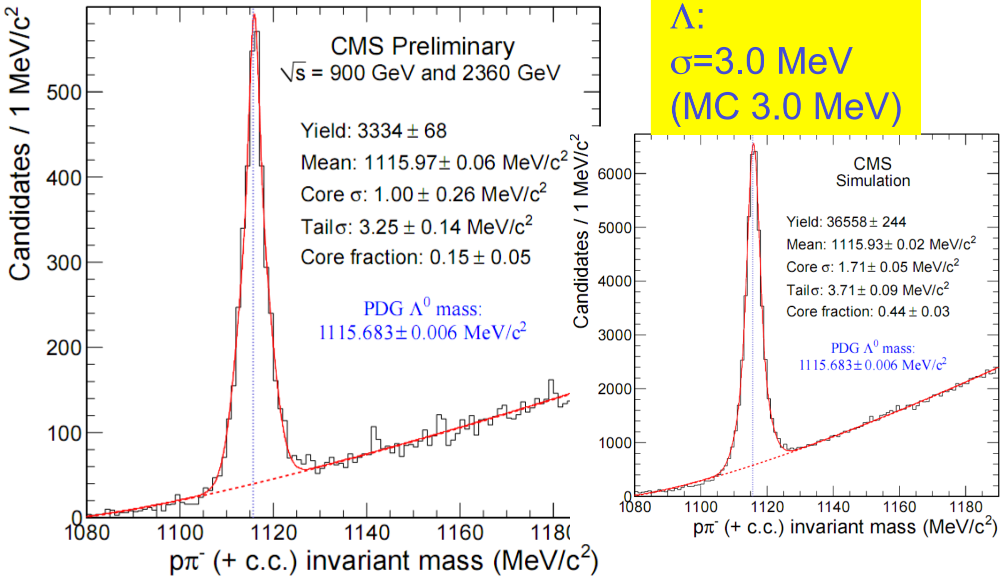
Track Parameters (q/p,eta,phi,dz,d0)

Tracking works

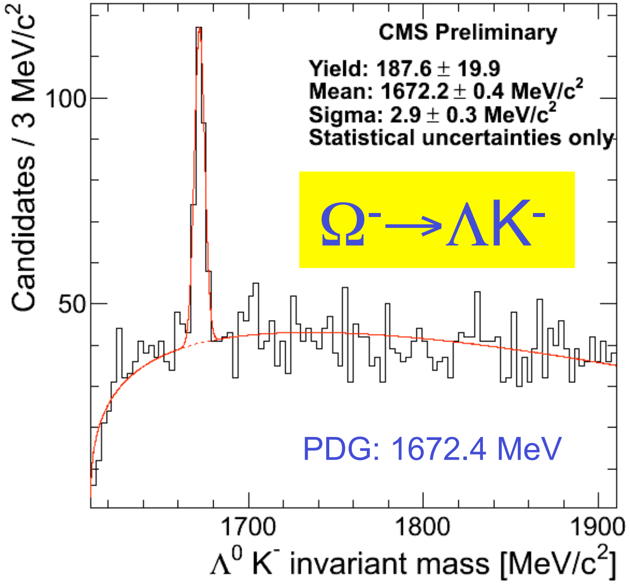


K_s:
σ=8.0 MeV
(MC 7.6 MeV)





Λ:
σ=3.0 MeV
(MC 3.0 MeV)

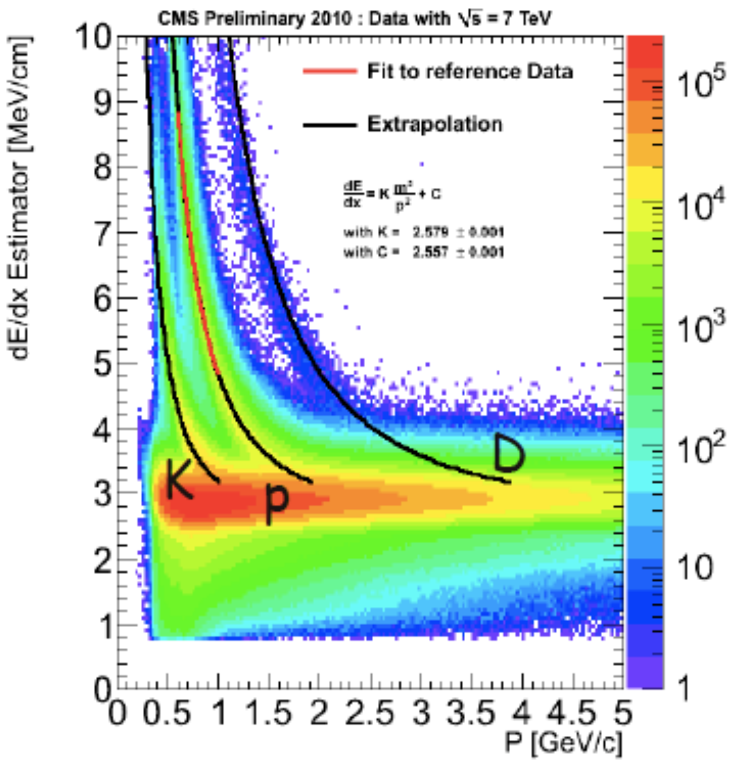


PID with tracker

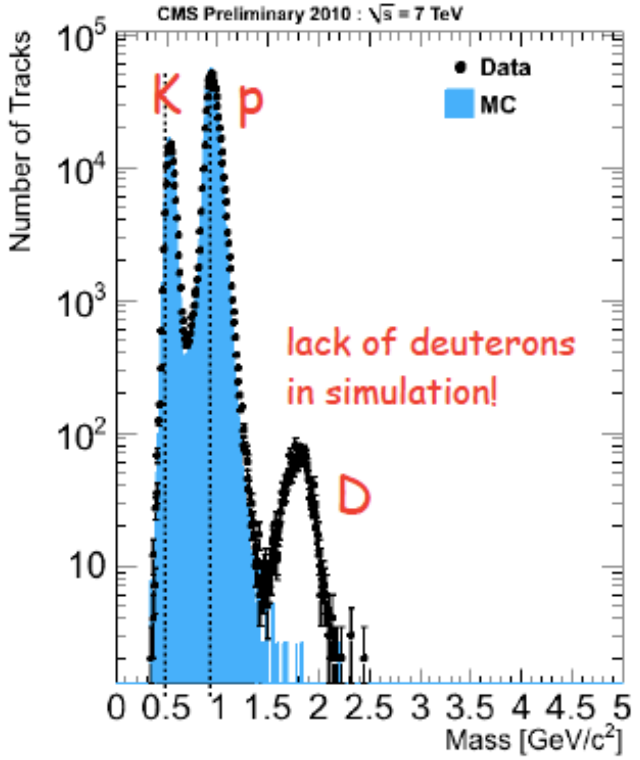
Particle identification using the strips

- all strip readout channels were calibrated to uniform energy response using particles

energy loss estimation dE/dx allows particle identification with the strip tracker

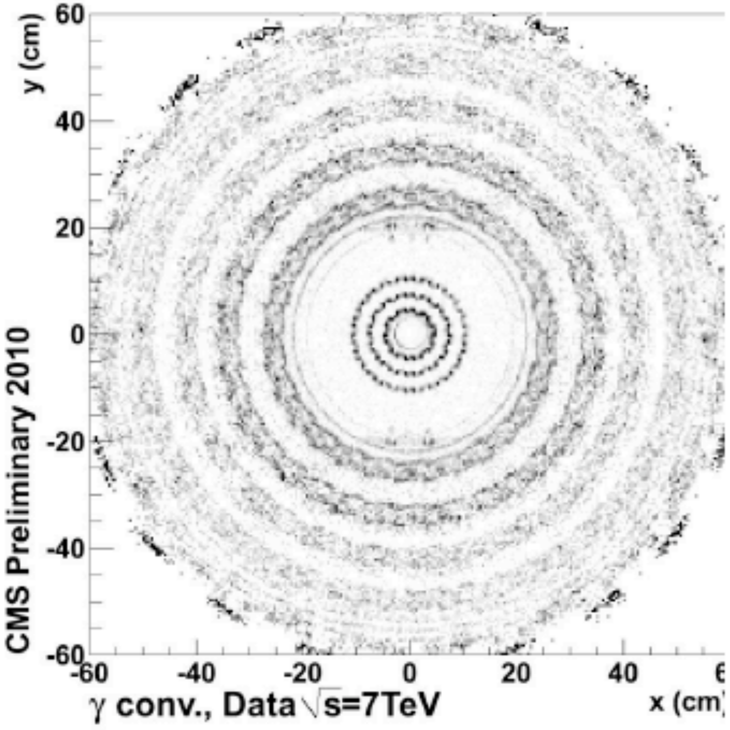


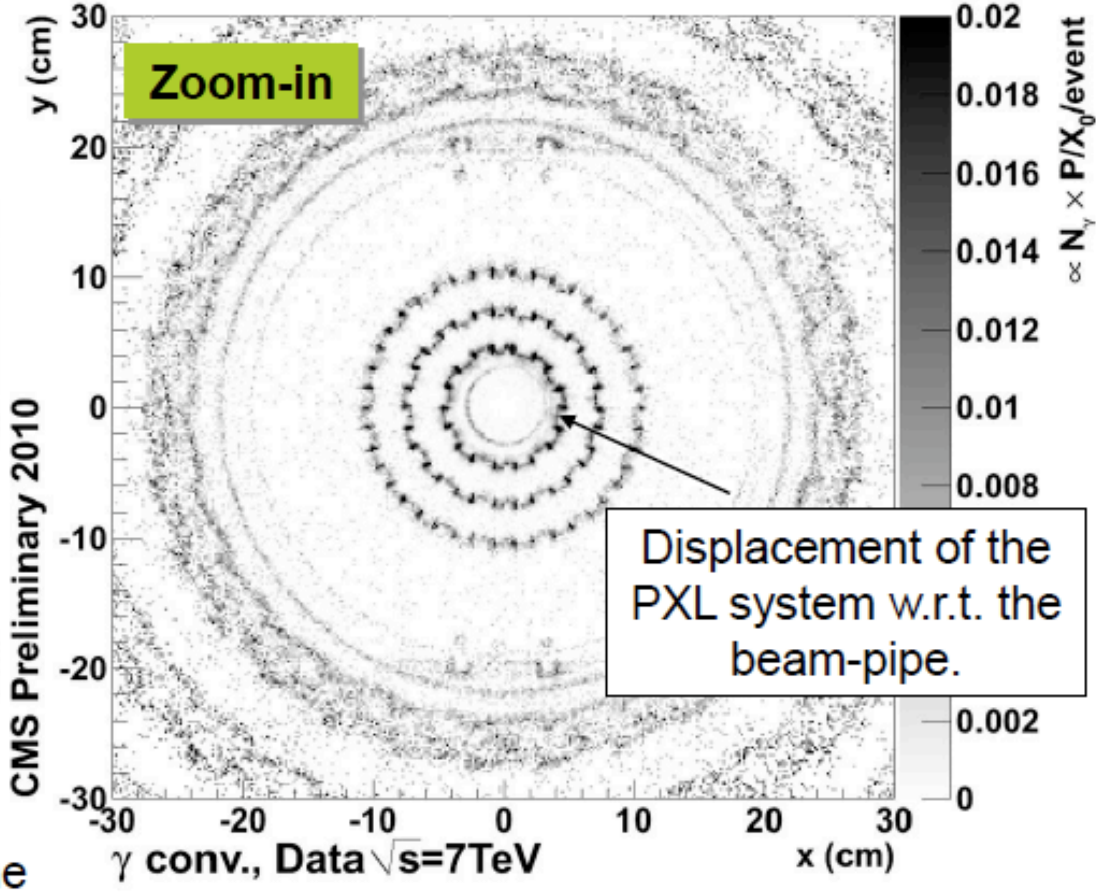
mass estimation from good tracks with dE/dx > 5MeV/cm



lack of deuterons in simulation!

Material budget

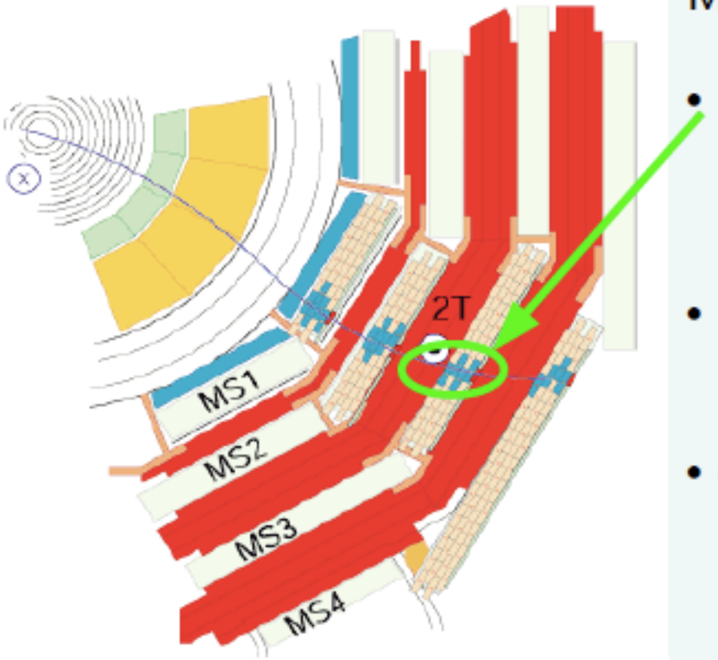




Displacement of the PXL system w.r.t. the beam-pipe.

Results corrected according to the expected photon flux and conversion reconstruction efficiency.

Muon reconstruction

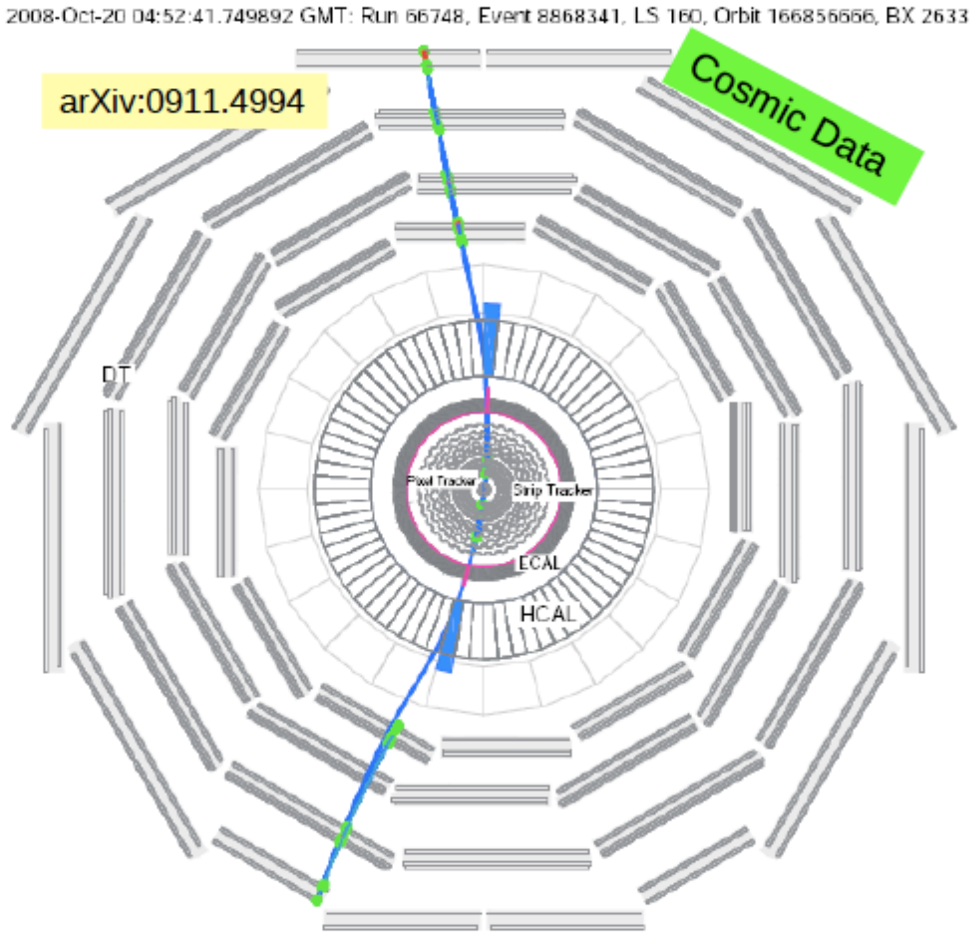


Muon reconstruction in 3 stages

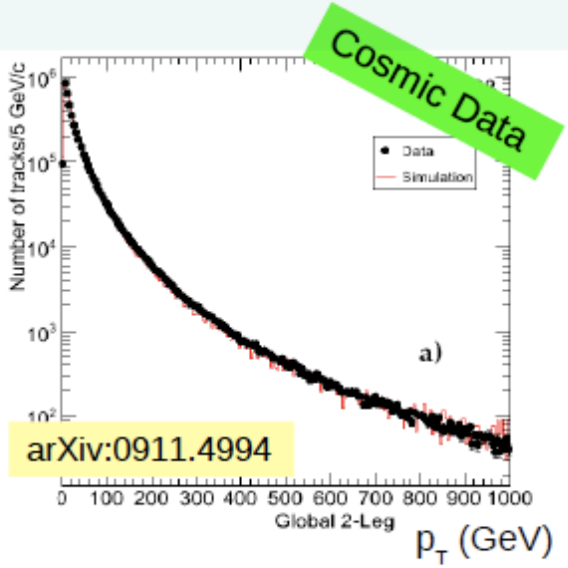
- **Local muon** reconstruction
  - Hits are reconstructed in subdetectors (CSC, DT and RPC)
  - Make track segments from hits
- **Standalone muon** reconstruction
  - Combine track segments in Kalman Filter
  - Builds muon trajectory in muon system
- **Global muon** reconstruction
  - Combines silicon tracker information with muon system
  - Build global muon trajectory

Cosmic muons

Event display of a cosmic muon track with magnetic field of 3.8 Tesla

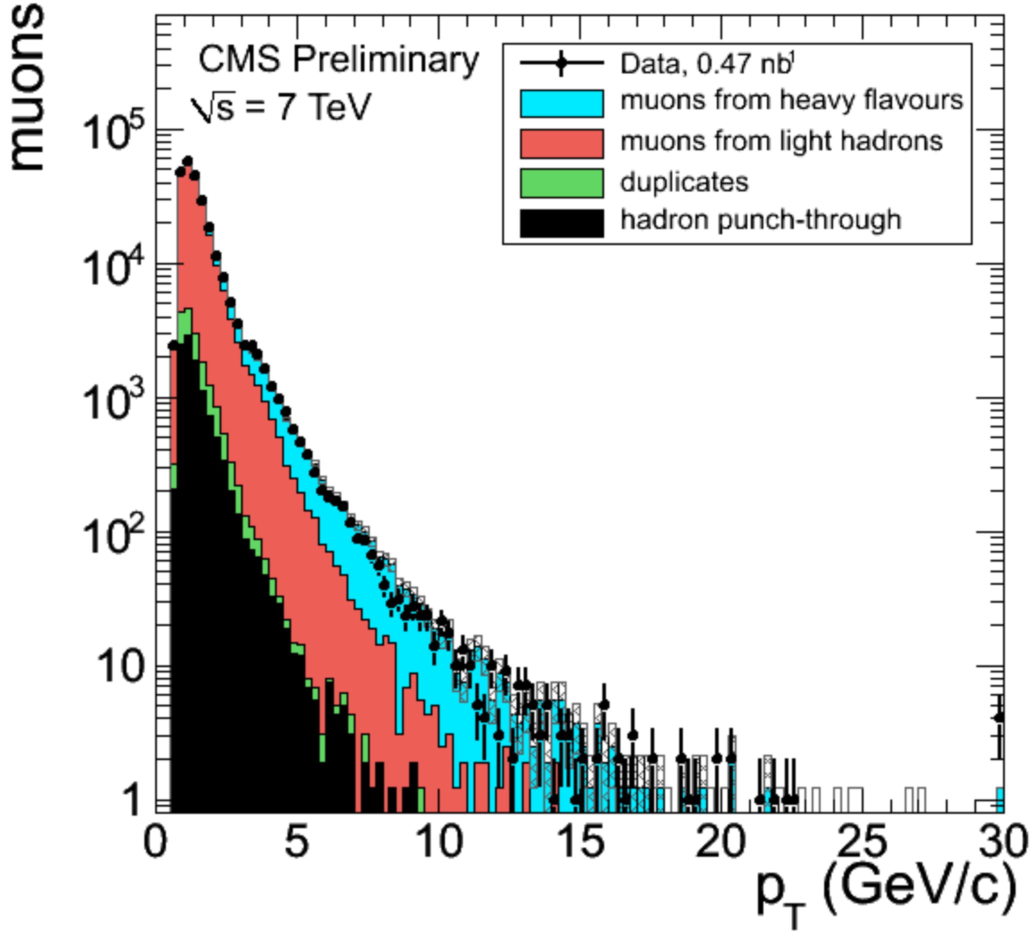


- Comparison between dedicated MC simulation and data
- Muon required to pass closely by the nominal interaction point
- “2-leg” muon: reconstructed 2 tracks in the opposite hemispheres to mimic collision muons



First muons

Soft muons



Data collected with a minimum bias trigger

compared to

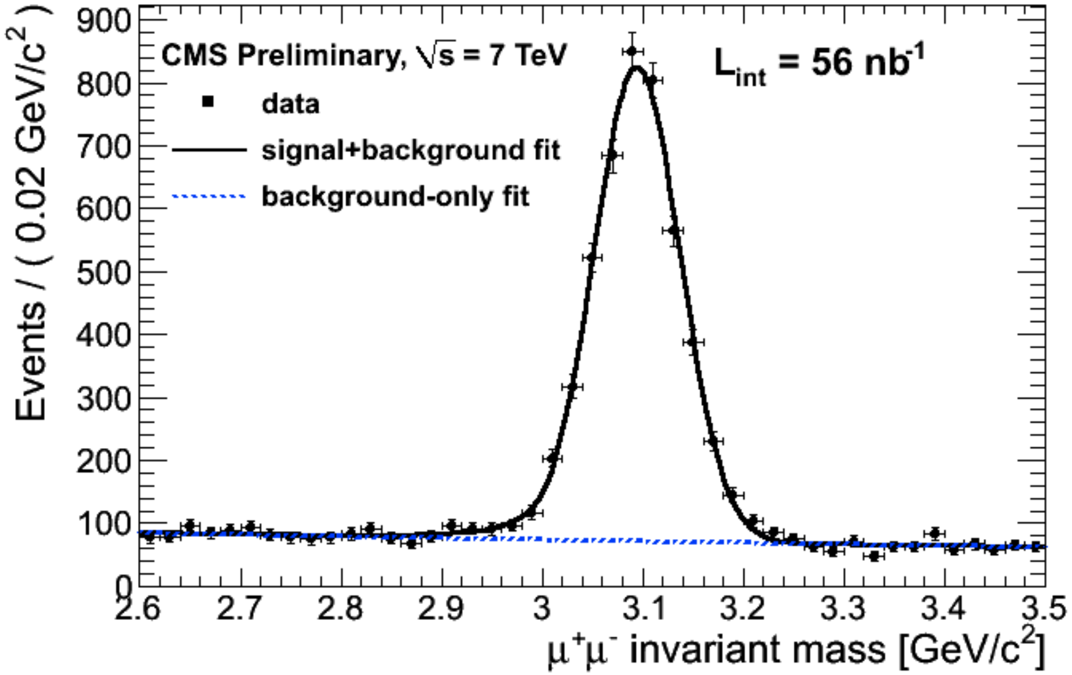
Simulation of minbias events; muons separated according to their origin:

- **84% from π/K decays**
- **9% from b/c decays**
- **4.4% from hadron punch-through**

J/psi

Mean from data = 3.092±0.001 GeV

PDG mass = 3.096±0.000011 GeV

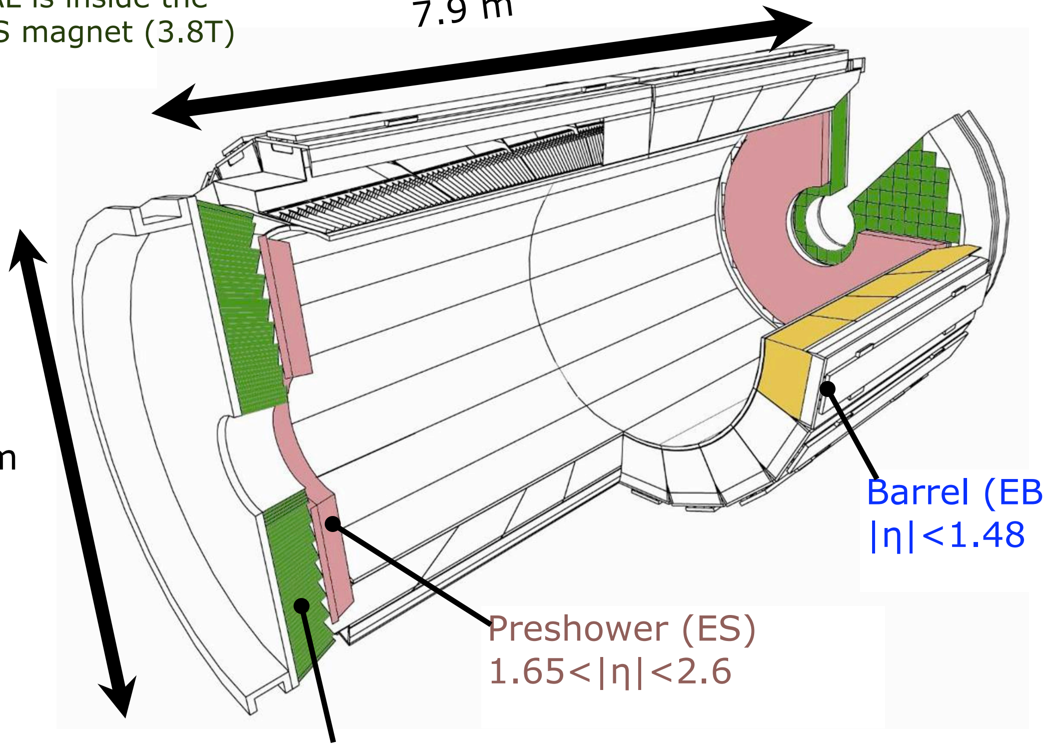


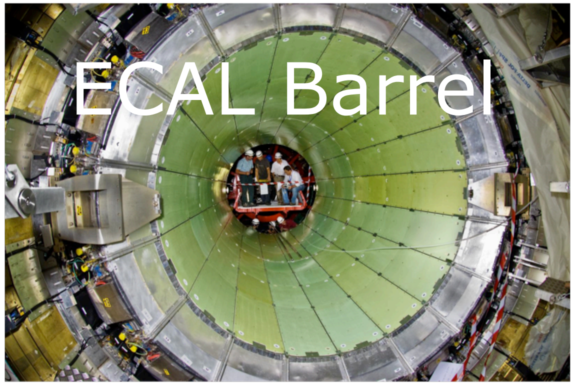
→ Data driven muon efficiency determination (tag&probe)

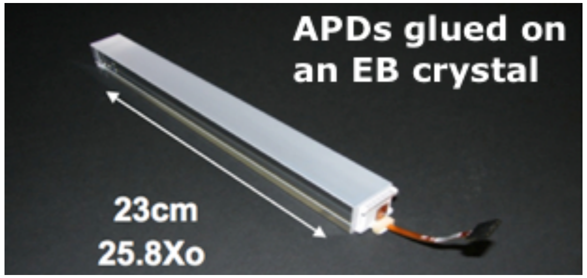
Electromagnetic calorimeter

CMS ECAL constists of 75848 $PbWO_4$ crystals

ECAL is inside the
CMS magnet (3.8T)



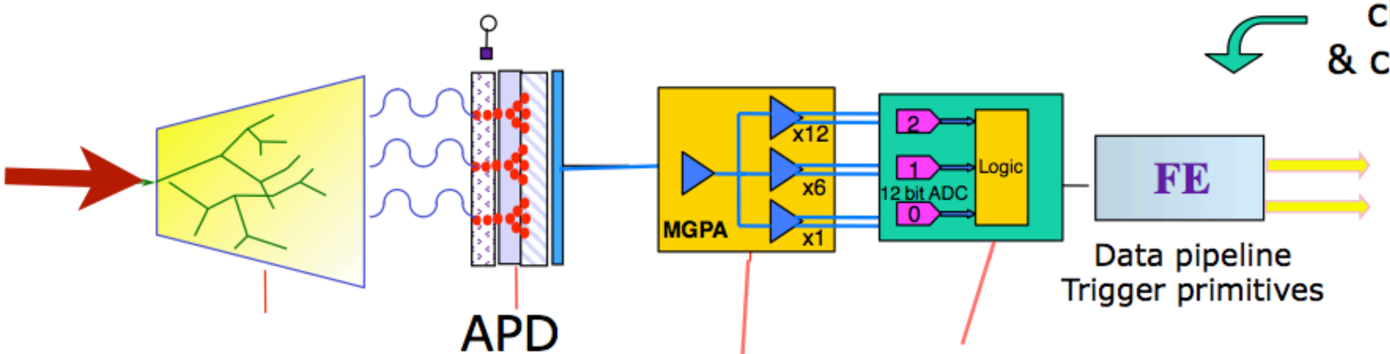




optimized by design for
H→γγ and H→ZZ→4e

Outstanding energy resolution:
ΔE/E < 0.5 % for unconverted γ
@ E>100 GeV (testbeam result)

ECAL energy reconstruction chain



clock
& control

Trigger
DAQ

100m optical
data link
800 Mbit/s
to counting
room

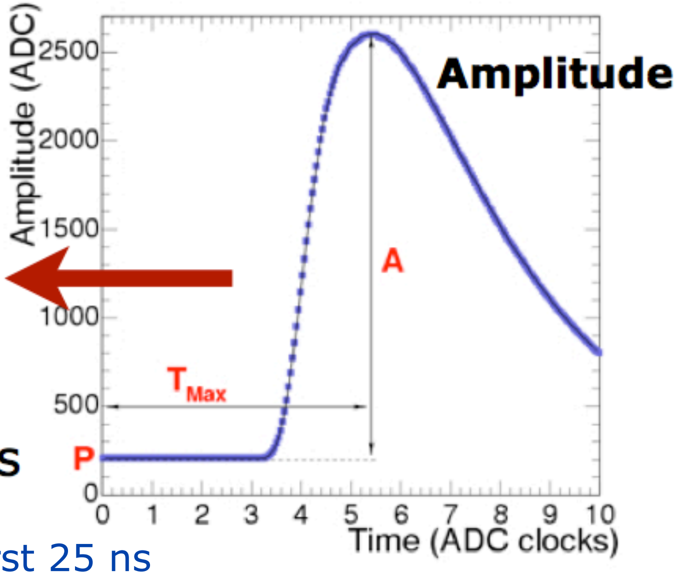
PbWO4
crystal

APD
(VPT)

Multi Gain
(1x,6x,12x)
Preamplifier

Multi channel
12-bit ADC
40MHz

Data pipeline
Trigger primitives



The energy of the shower is reco'ed in clusters of channels (5x5 in TB)

$$E = G * \sum c_i A_i \longleftarrow \hat{A} = \sum_{i=1}^{N} w_i S_i$$

Global ADCtoGeV scale

intercalibration

weights

- ~80% of the scintillation light is collected in the first 25 ns
- dynamic range 25 MeV to 2 TeV

Electron reconstruction

Energy clustering to recover bremsstrahlung

- **Superclusters** are built by collecting clusters of crystals within in φ window

Electron seeding two complementary algorithms

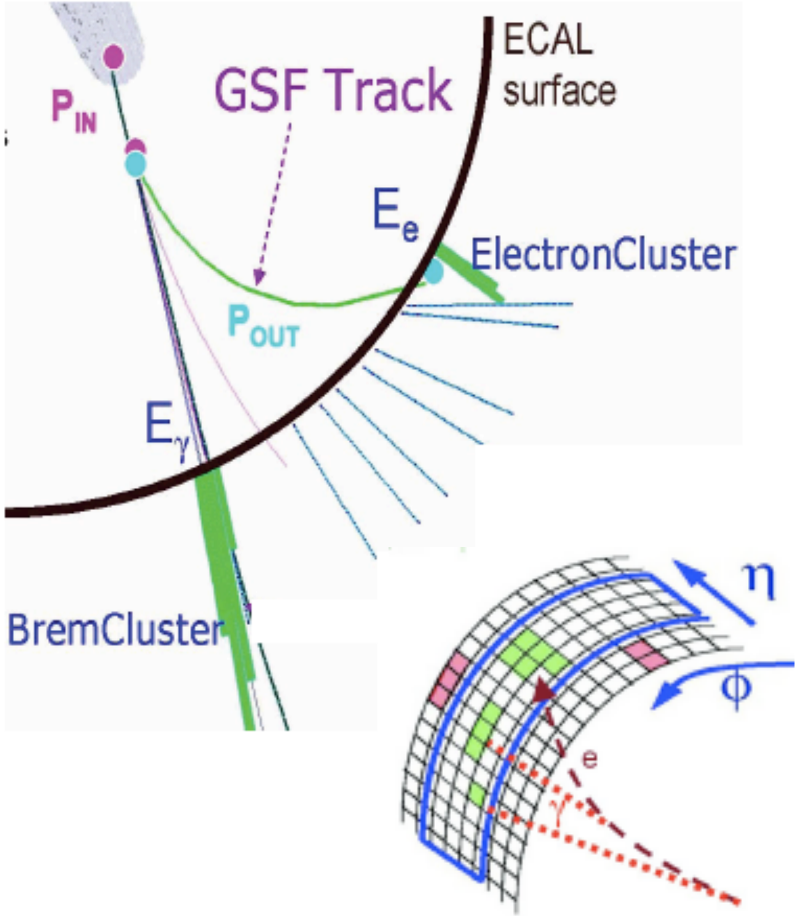
- Start from ECAL superclusters and search for compatible hits in the tracker inner layers (ECAL driven)
- Start from tracks (Tracker driven)

Electrons tracking

- Bremsstrahlung energy loss modeled with a mixture of Gaussians (Gaussian Sum Filter)

Electrons preselection

- Track Supercluster position matching cuts
- Multivariate analysis

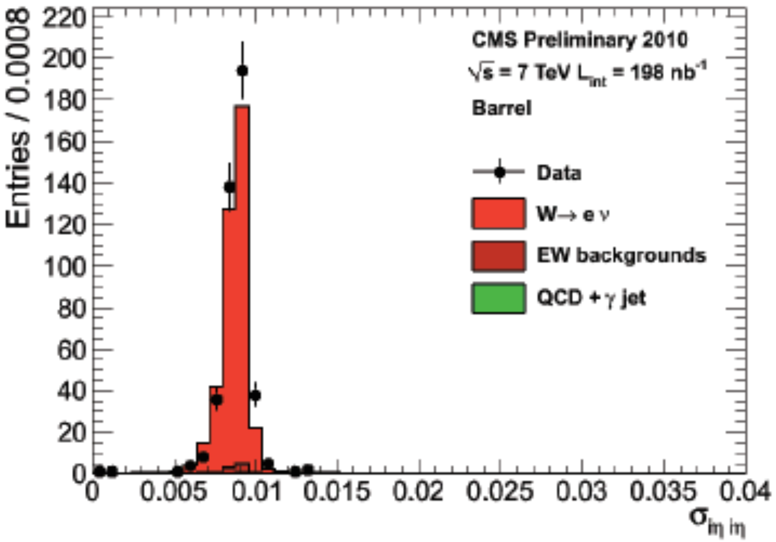


Electron ID

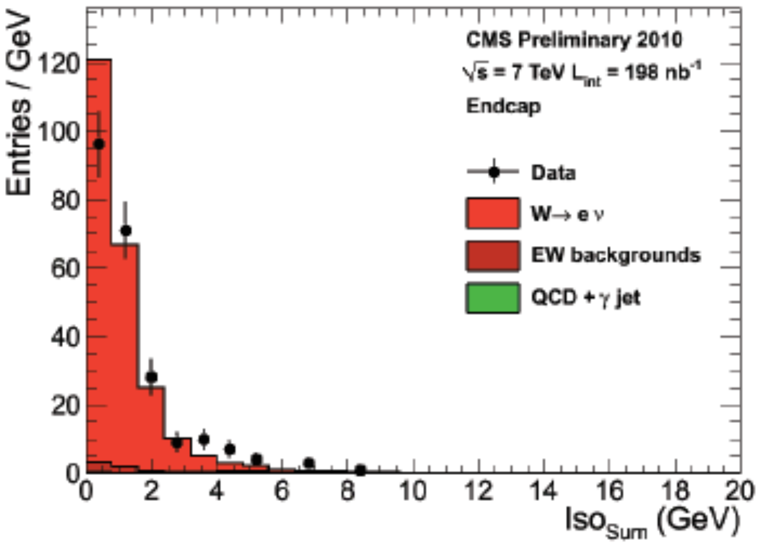
Examples of discriminating variables:

- supercluster shower spread in η ($\sigma_{i\eta i\eta}$)
- electron isolation
  - combined ECAL/Tracker/HCAL isolations
  - removal of the electron footprint in each detectors

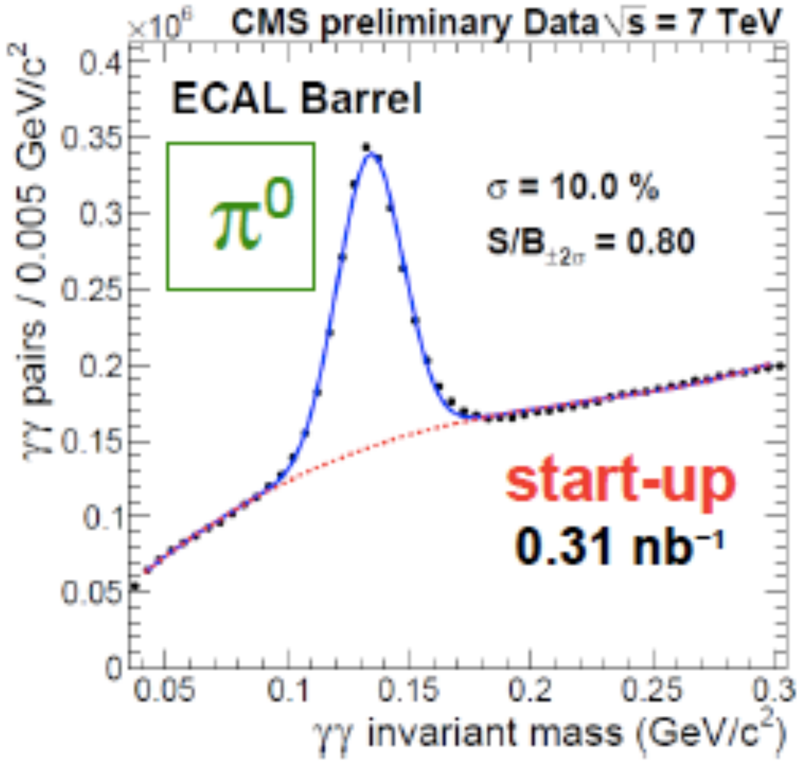
ECAL barrel

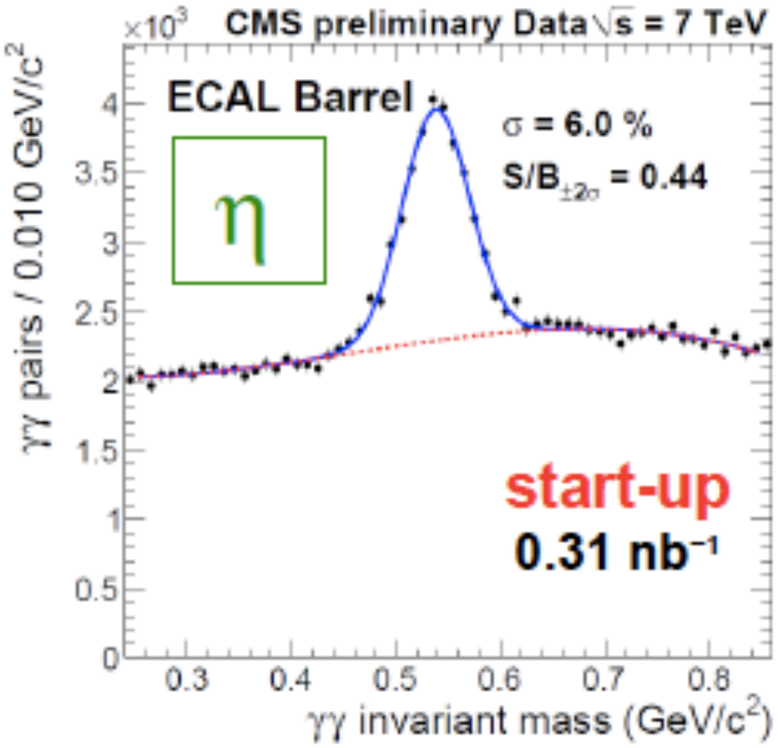


ECAL endcap



ECAL commissioning

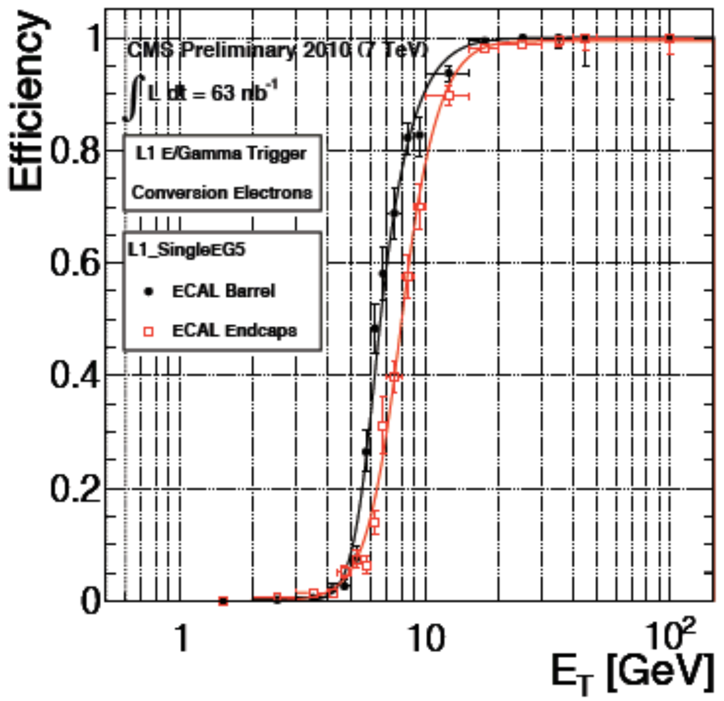




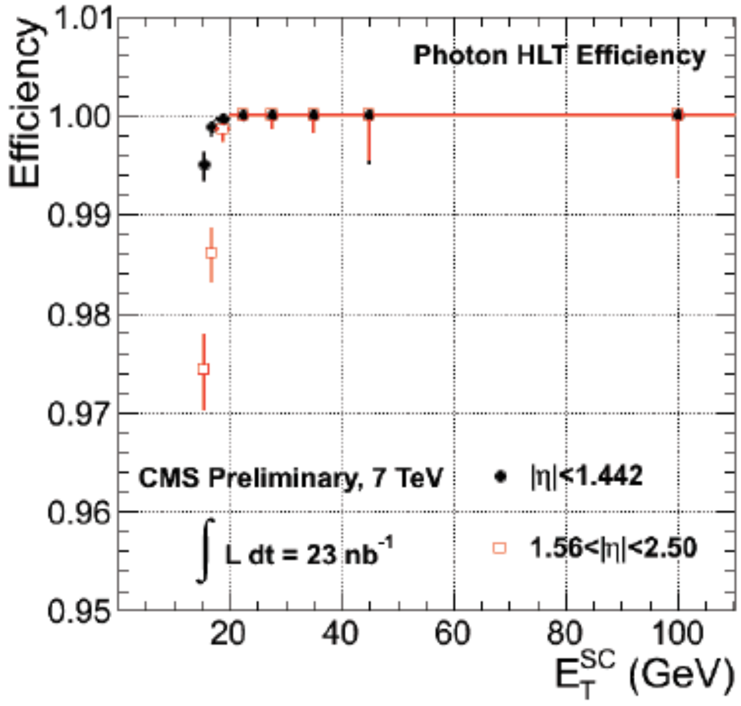
Electron Trigger Efficiency

Events filtered online in two steps: Level1 (hardware) High Level Trigger (software)

Trigger efficiencies has been measured on Minimum Bias data



The Level1trigger efficiency for a nominal 5 GeV threshold



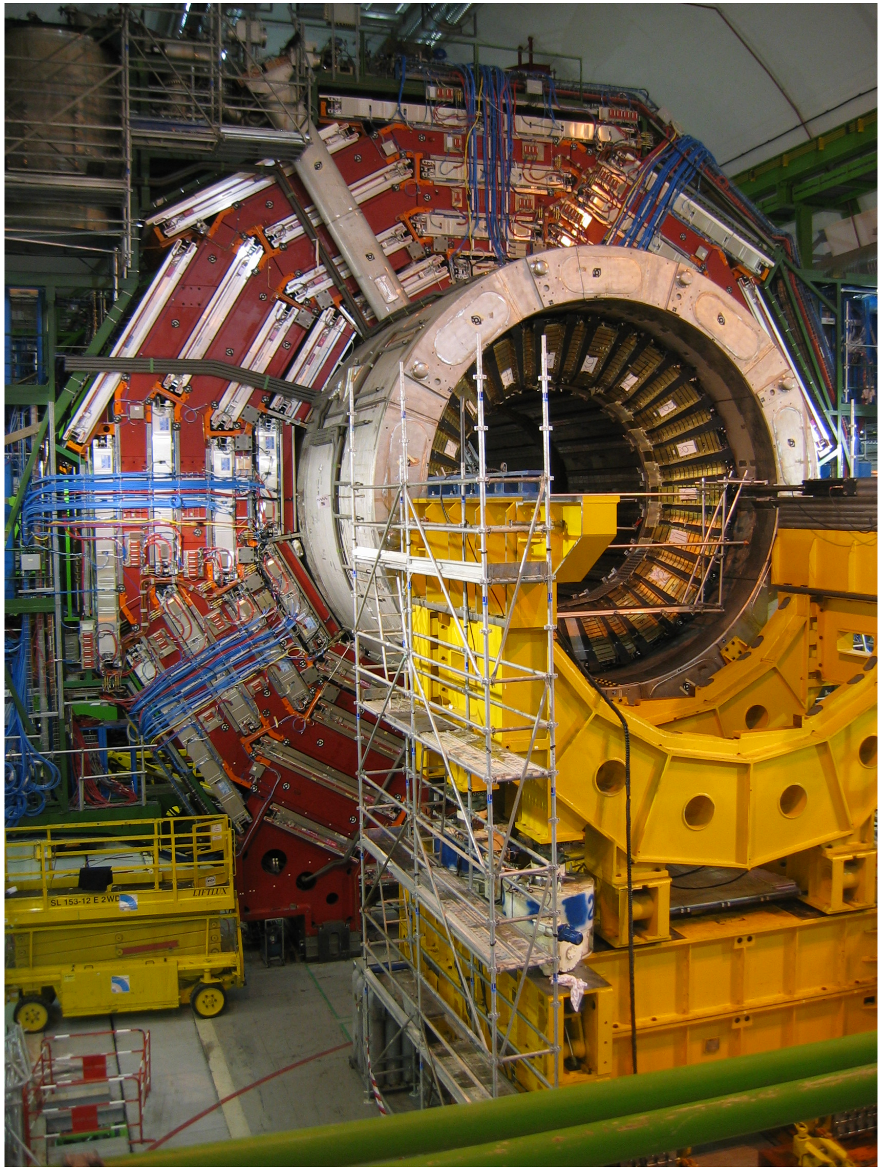
The HLT efficiency for nominal 15 GeV threshold

Minimum Bias Data

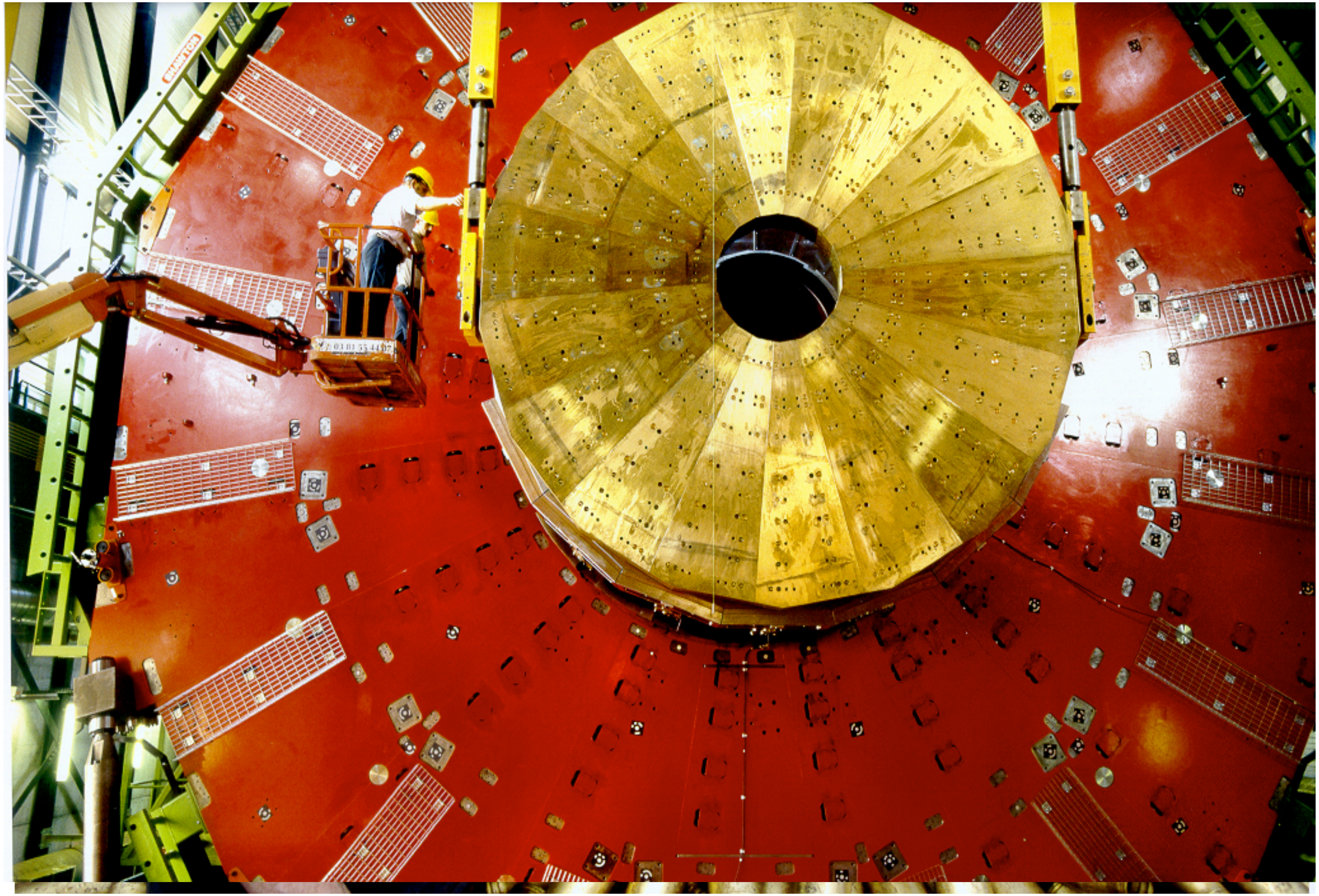
Electrons in the ECAL barrel (black dots), electrons in the ECAL endcaps (red empty squares)

HCAL

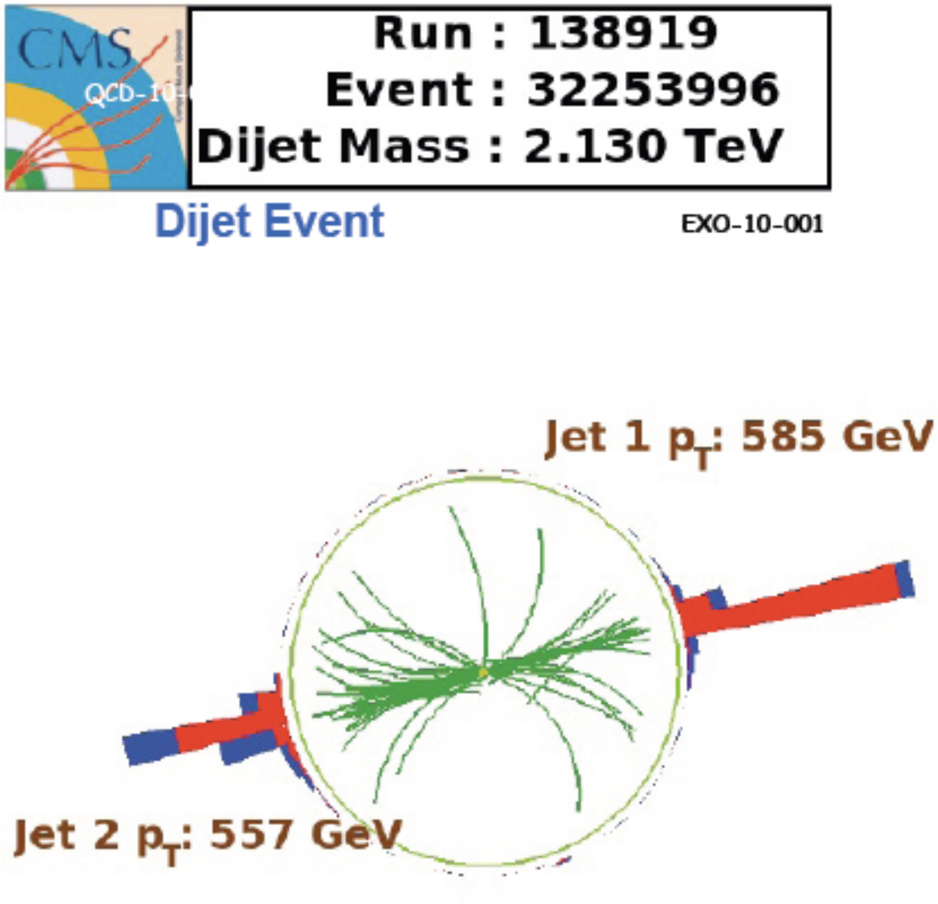
- Hadronic calorimeter, HCAL:
  - Barrel (HB): Brass + Scintillators
    - $\Delta\eta \times \Delta\varphi = 0.087 \times 0.087$
  - Barrel tail catcher (HO): Scintillators
  - Endcap (HE): Brass + Scintillators
    - $\Delta\eta \times \Delta\varphi = 0.087 \times 0.087 \ldots 0.35 \times 0.087$
  - Forward (HF): Steel + quartz fibre (Čerenkov)
    - $\Delta\eta \times \Delta\varphi = 0.349 \times (0.175 \text{ or } 0.35)$
  - > 99.75% working channels (100% in HB/HE/HF)

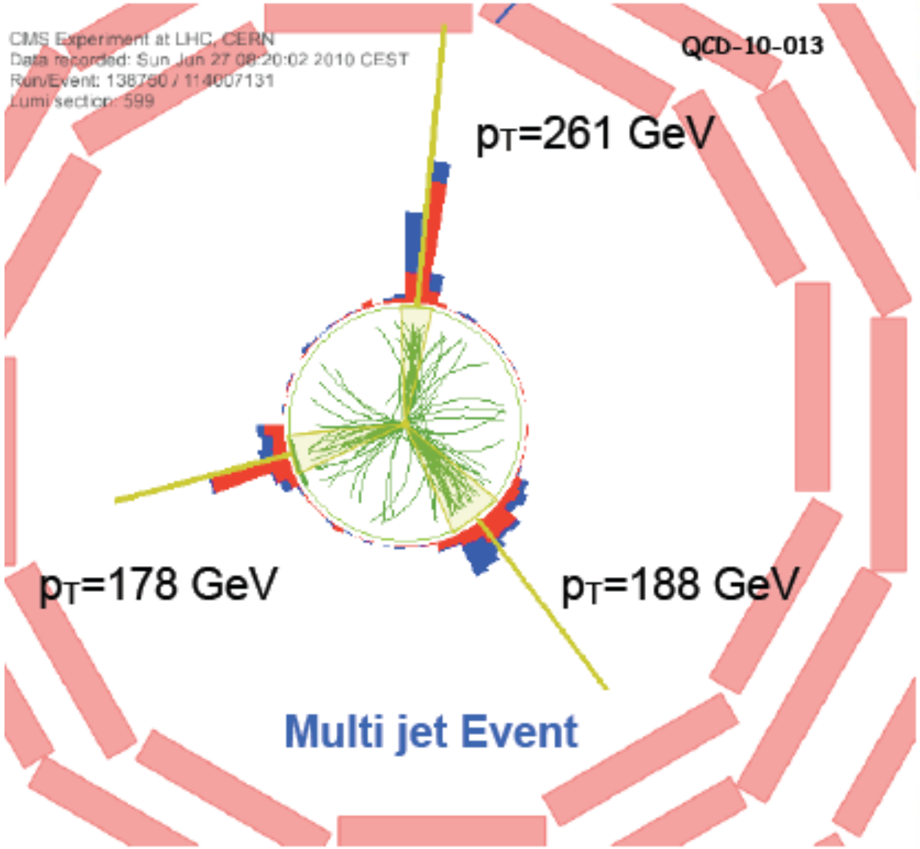


Swords to Ploughshares !



Jets


CMS
QCD-10-
Run : 138919
Event : 32253996
Dijet Mass : 2.130 TeV
Dijet Event
EXO-10-001
Jet 1 p_T: 585 GeV
Jet 2 p_T: 557 GeV

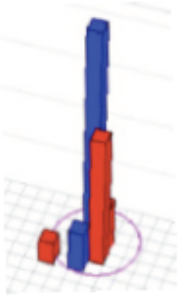

CMS Experiment at LHC, CERN
Data recorded: Sun Jun 27 08:20:02 2010 CEST
Run/Event: 138750 / 114007131
Lumi section: 599
QCD-10-013
p_T=261 GeV
p_T=178 GeV
p_T=188 GeV
Multi jet Event

Jet reconstruction

4 types:

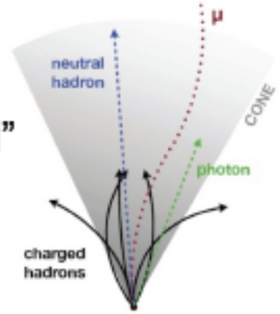
Calorimeter Jets

Jets clustered from ECAL and HCAL deposits (Calo Towers)



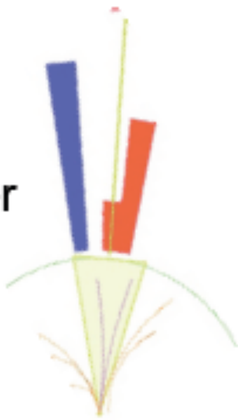
Particle Flow Jets (PF)

Cluster Particle Flow objects: Unique list of calibrated particles "a la Generator Level"
=> optimal combination of information across all CMS subdetector



Jet-Plus-Track Jets (JPT)

Correct calorimeter jets with tracking information:
=> Subtract average calorimeter response and replace it with the track measurement



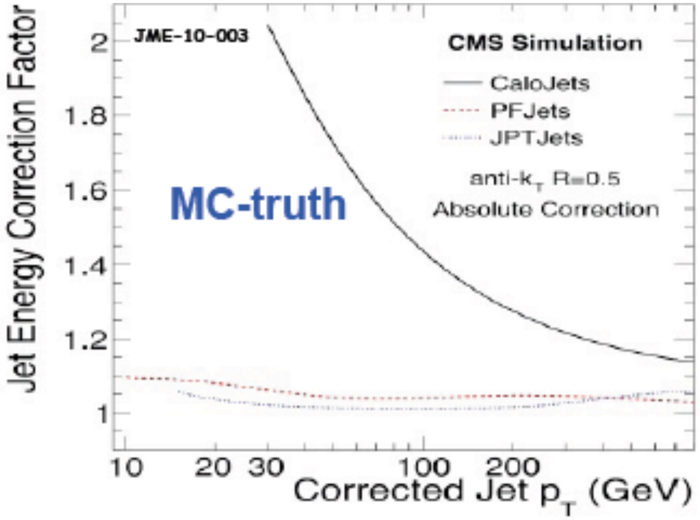
Track Jets

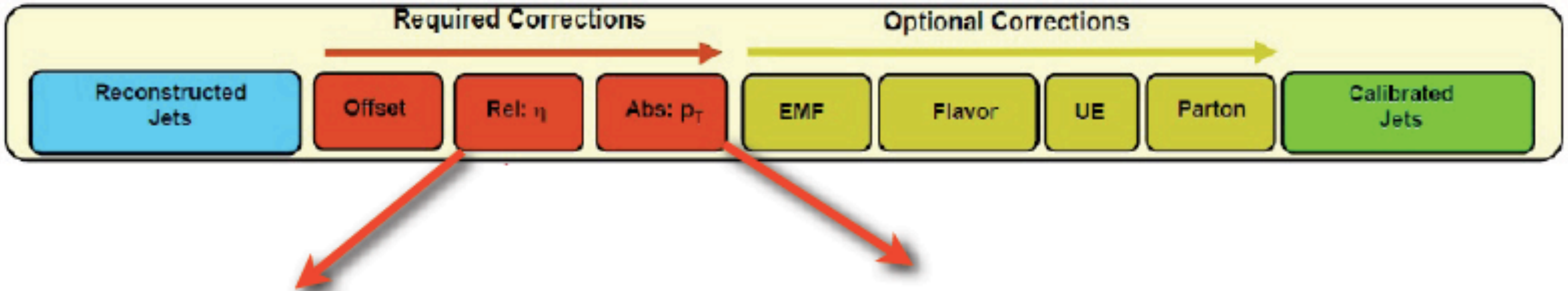
Reconstructed from tracks of charged particles
=> completely independent from calorimetric jet measurements, excellent angular resolutions

Jet Energy Corrections

Factorized approach with 2 strategies:
MC-truth JEC and In-situ JEC

- Majority of CMS physics analyses currently use MC-truth JEC
- MC corrections are derived from Pythia QCD dijet MC events.
- In-situ JEC sub-corrections will replace MC-truth corrections when available



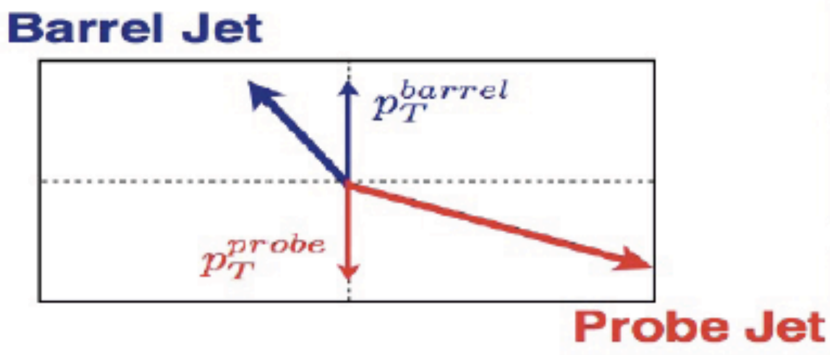


Relative:
correct to uniform calorimeter response in η
In-situ method:
Dijet p_T balance

Absolute:
correct absolut energy scale
In-situ method:
Photon+jet p_T balance

Relative corrections (eta)

Di-jet Pt balance:



$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

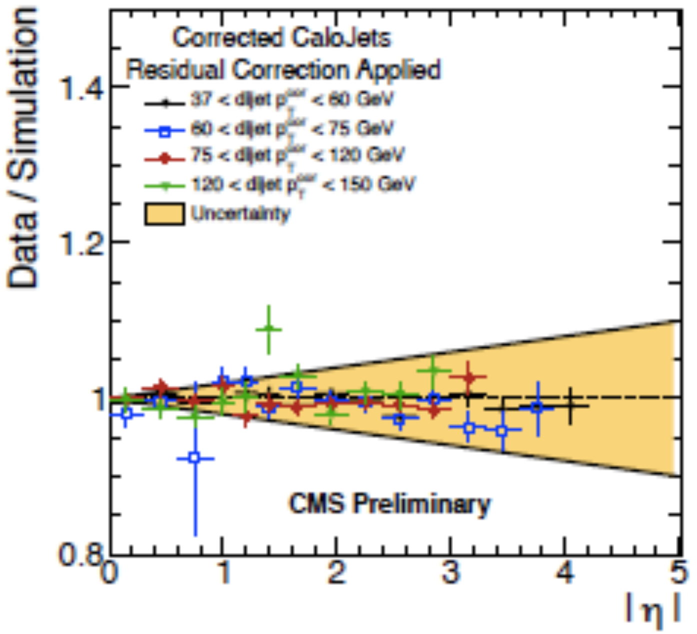
$$B = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{dijet}}$$

$$r = \frac{2 + < B >}{2 - < B >}$$

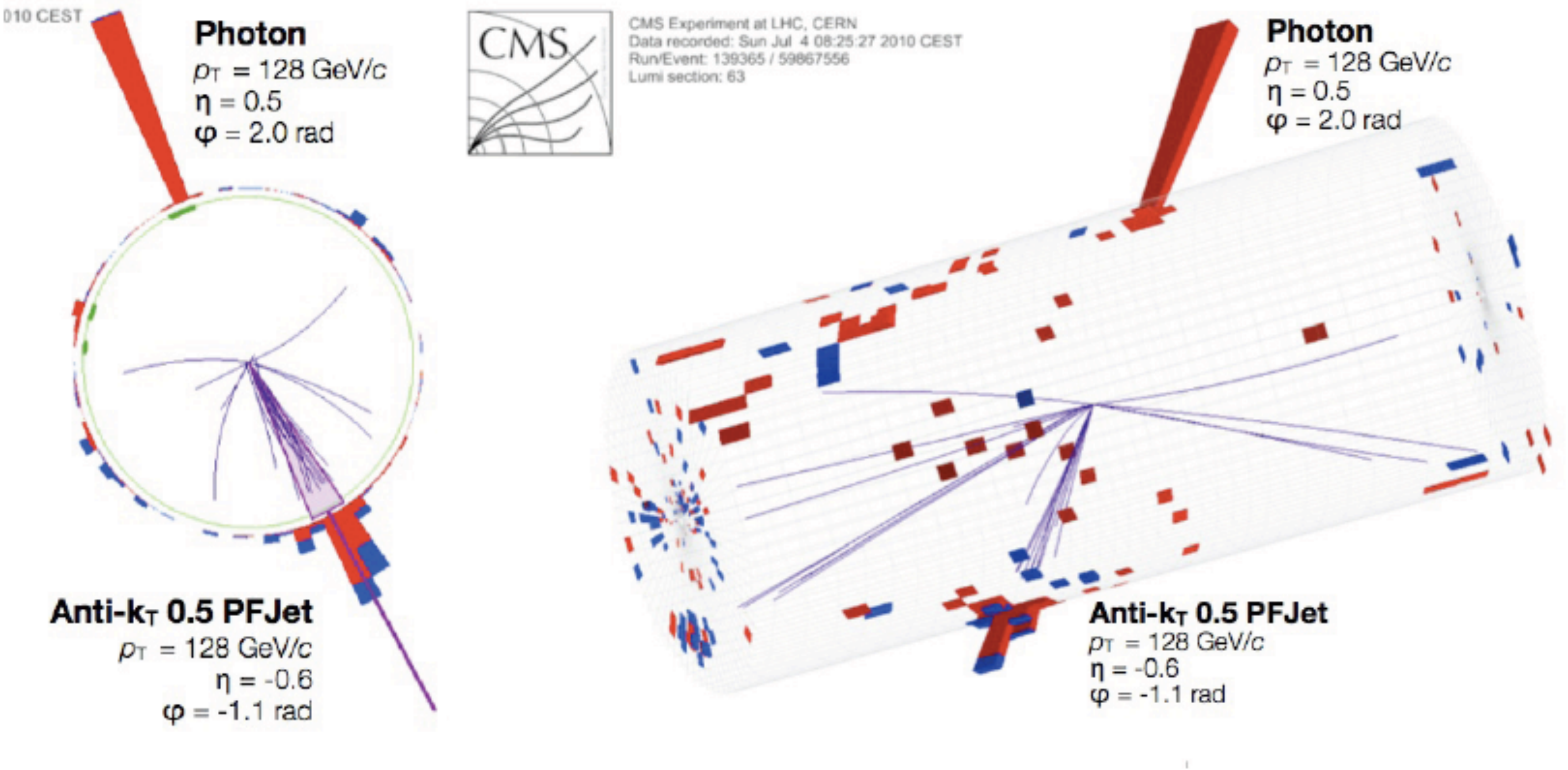
r :=relative response in a given bin

- Require at least 2 jets, one jet in the barrel region |η|<1.3
- Azimuthal separation ΔΦ > 2.7
- Third jet veto p_T^{3rd}/p_T dijet < 0.2

=> Measure distributions of balance variable B in representative (p_T dijet, |η|) bins for all jet types

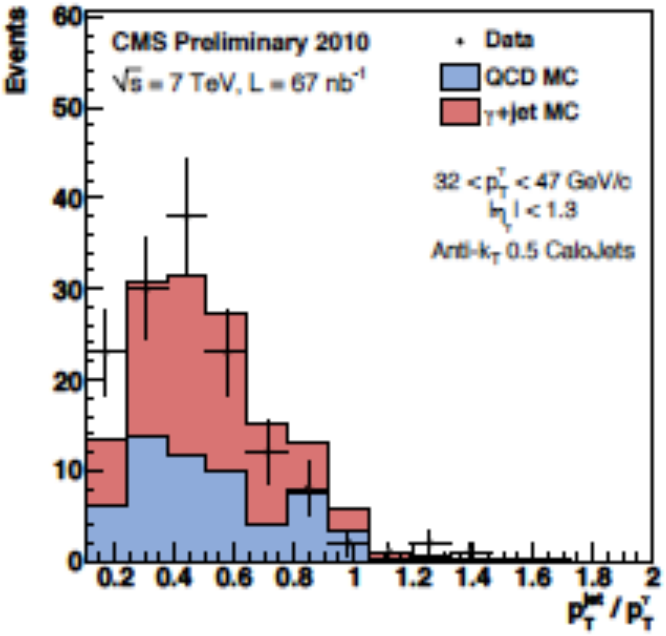


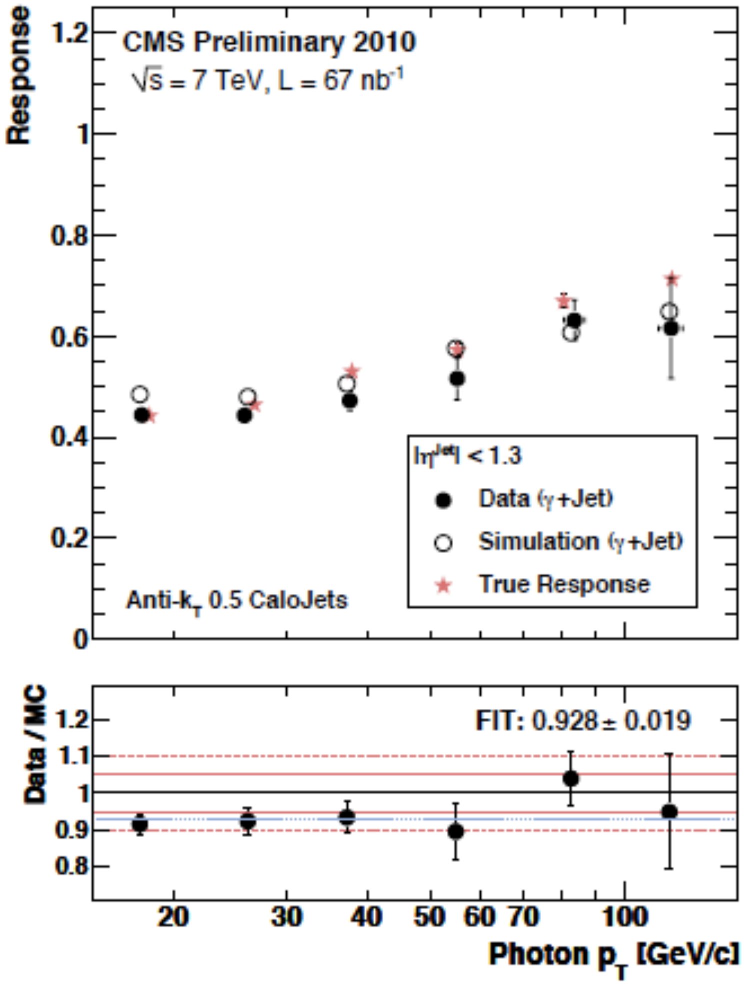
Absolute scale



Absolute scale

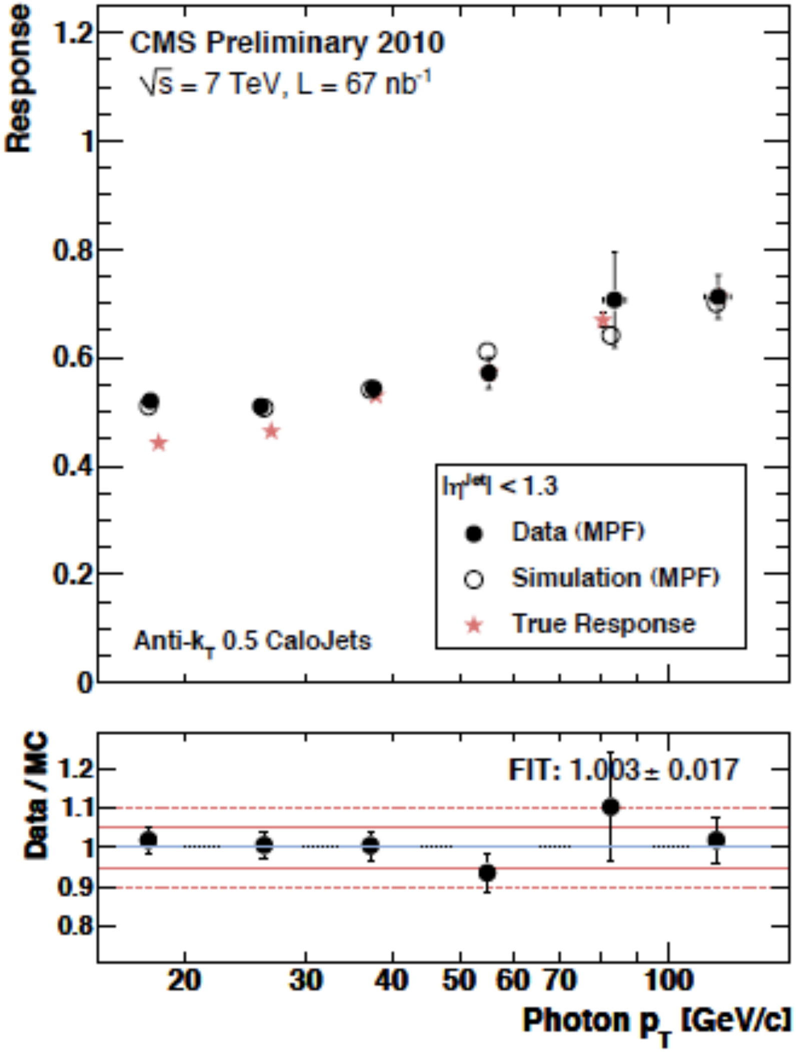
Photon balancing:





Absolute scale

MPF method:



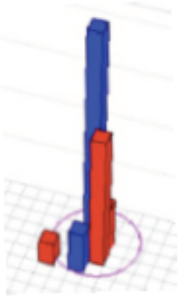
→ JES uncertainty: 10%

Jet reconstruction

4 types:

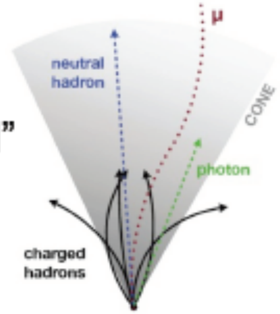
Calorimeter Jets

Jets clustered from ECAL and HCAL deposits (Calo Towers)



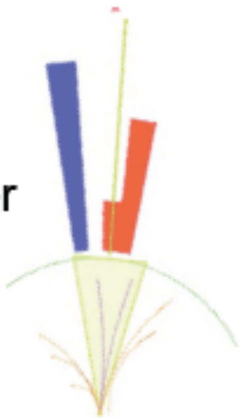
Particle Flow Jets (PF)

Cluster Particle Flow objects: Unique list of calibrated particles "a la Generator Level"
=> optimal combination of information across all CMS subdetector



Jet-Plus-Track Jets (JPT)

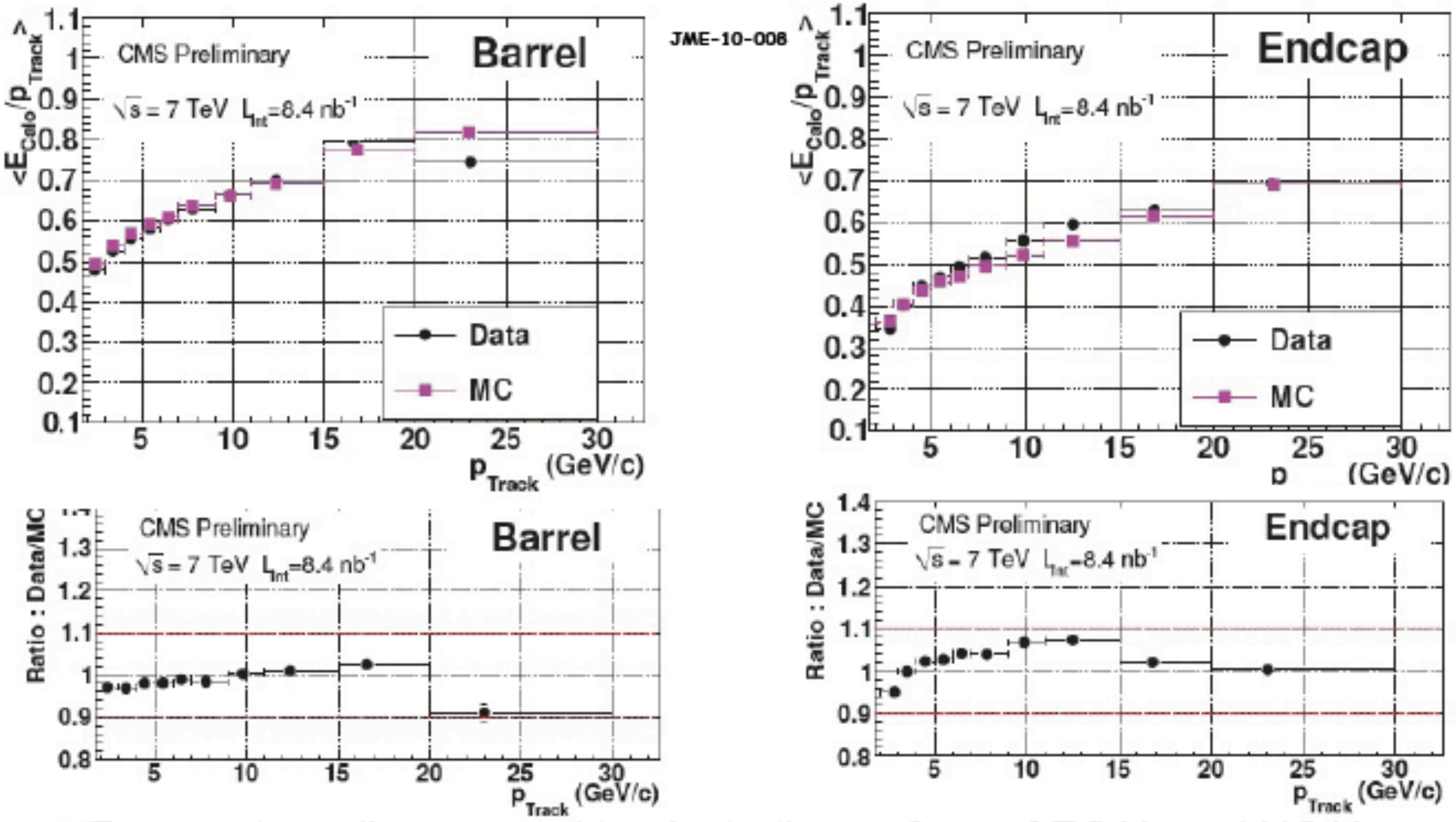
Correct calorimeter jets with tracking information:
=> Subtract average calorimeter response and replace it with the track measurement



Track Jets

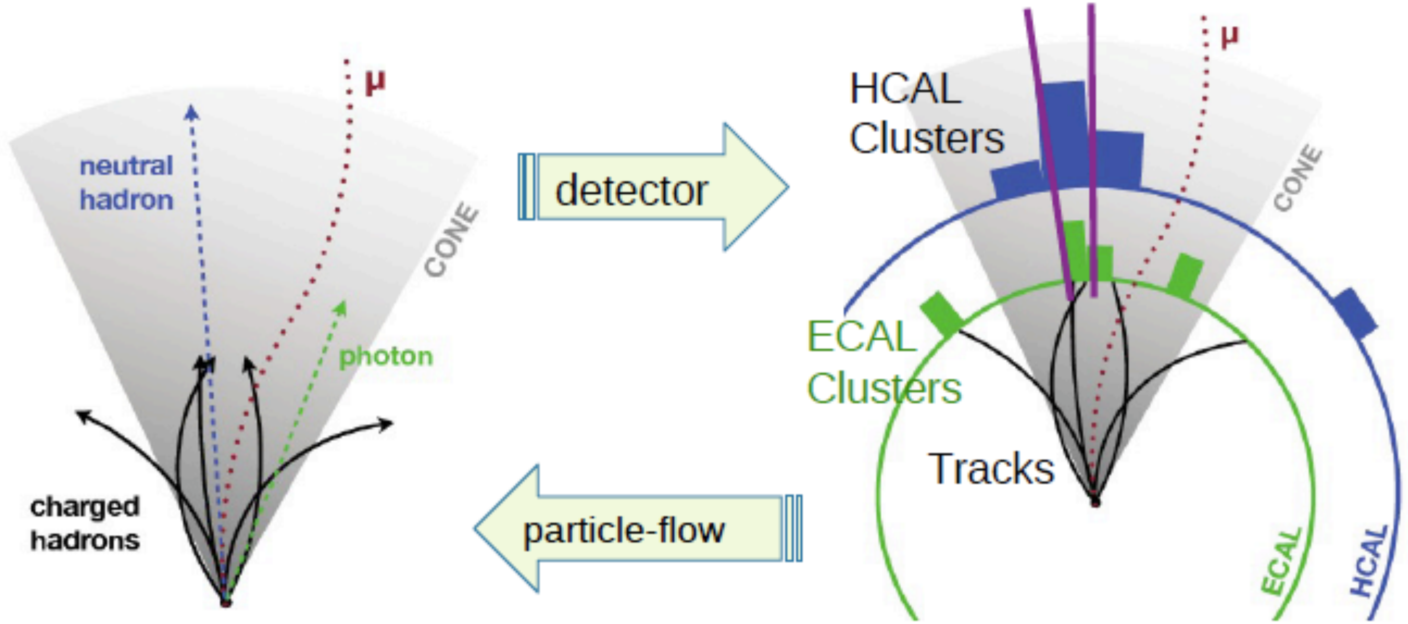
Reconstructed from tracks of charged particles
=> completely independent from calorimetric jet measurements, excellent angular resolutions

Single particle response



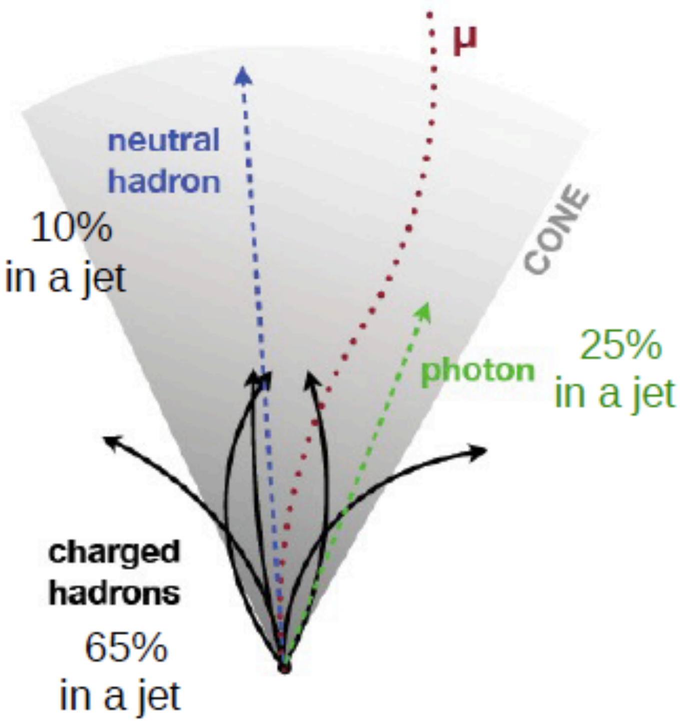
- Propagate well measured tracks to the surface of ECAL and HCAL

Particle Flow



The list of individual particles is then used to build jets, to determine the missing transverse energy, to reconstruct and identify taus from their decay products, to tag b jets …

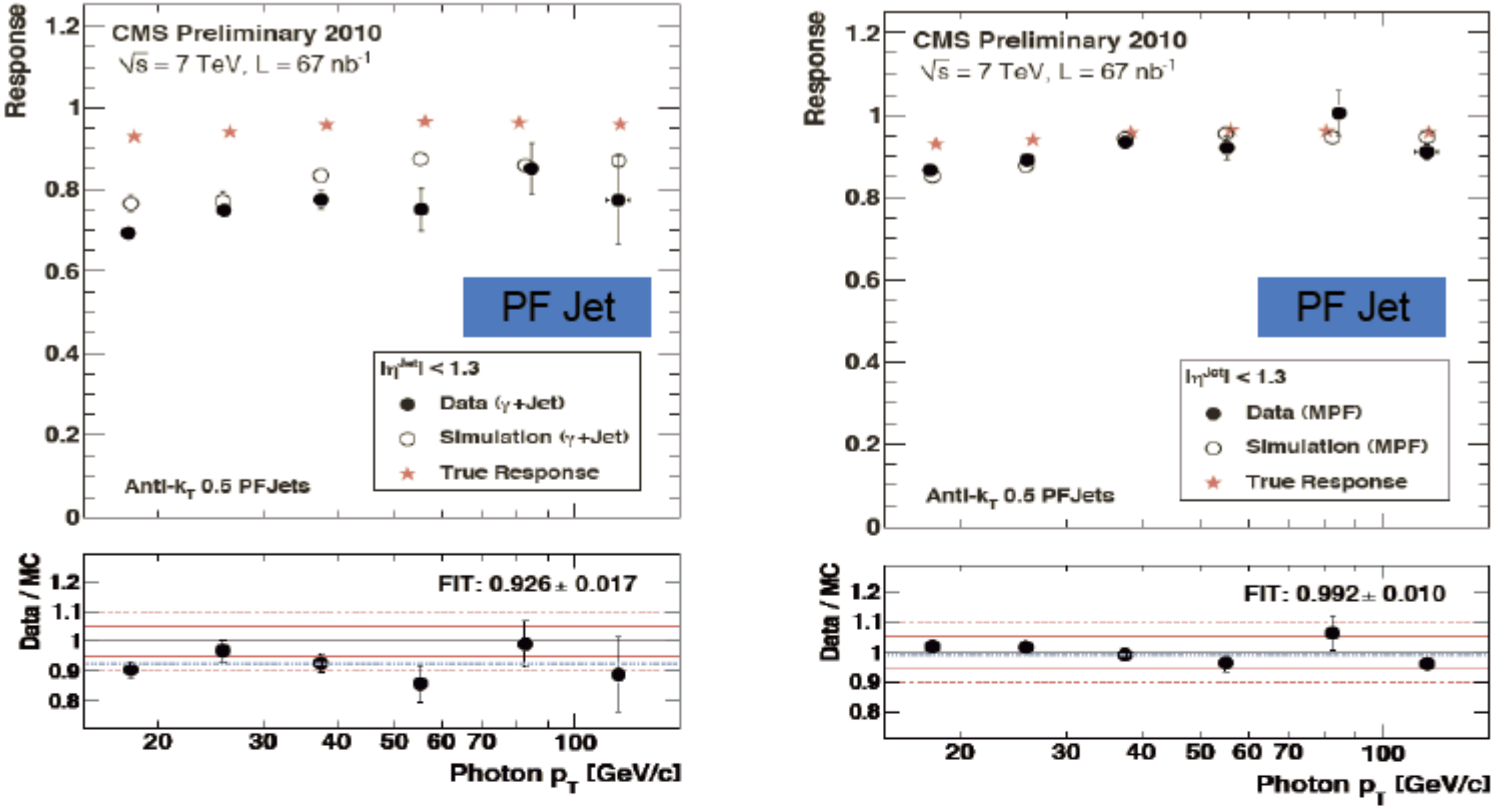
Particle Flow jets



Even for a jet of p_T = 500 GeV/c
the average p_T of the stable particles
is of around 10 GeV/c

~90% of the jet energy is carried
out by charged-hadrons and photons

Absolute scale

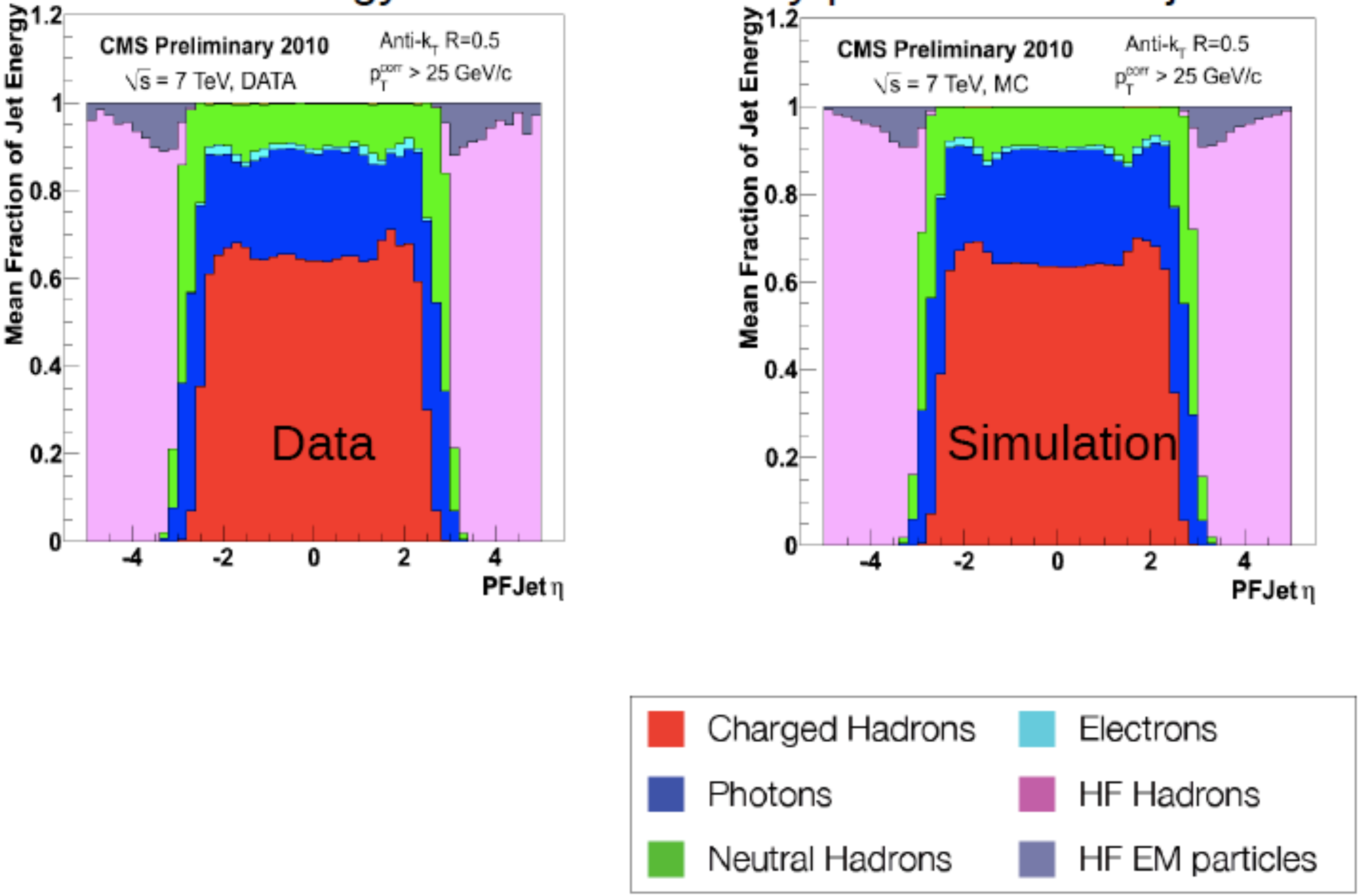


=> Mostly good agreement when same method applied to MC and Data

→ JES uncertainty : 5%

PF jet composition

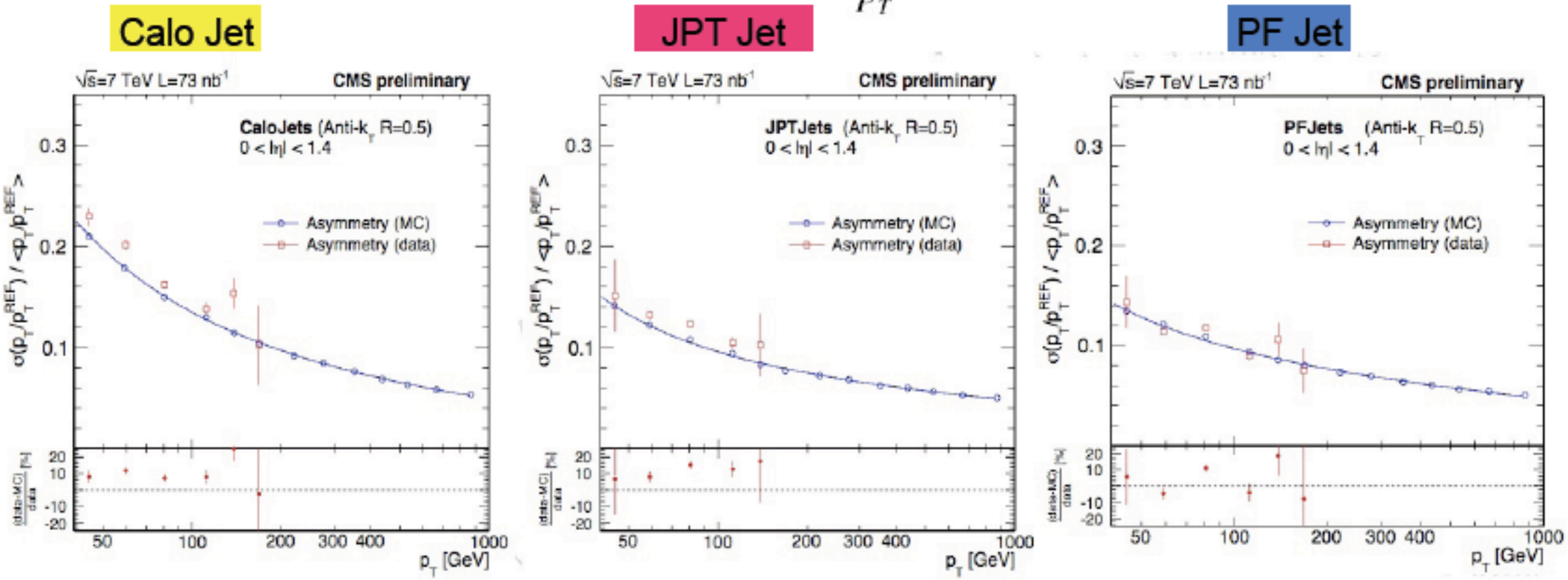
Jet energy fraction carried by particles within jets



Jet energy resolution

Dijet Asymmetry method (In Situ)

- Define pT asymmetry of the two leading jets in back-to-back dijet events: $A = \frac{p_T^{jet1} - p_T^{jet2}}{p_T^{jet1} + p_T^{jet2}}$
- For approximately equal value of the jet p_T's: $\frac{\sigma(p_T)}{p_T} = \sqrt{2}\,\sigma_A$



- Full chain of Dijet Asymmetry method applied to data and MC dijet events to extract jet p_T resolutions

=> Observed data/MC agreement within ~10%.

JER (2)

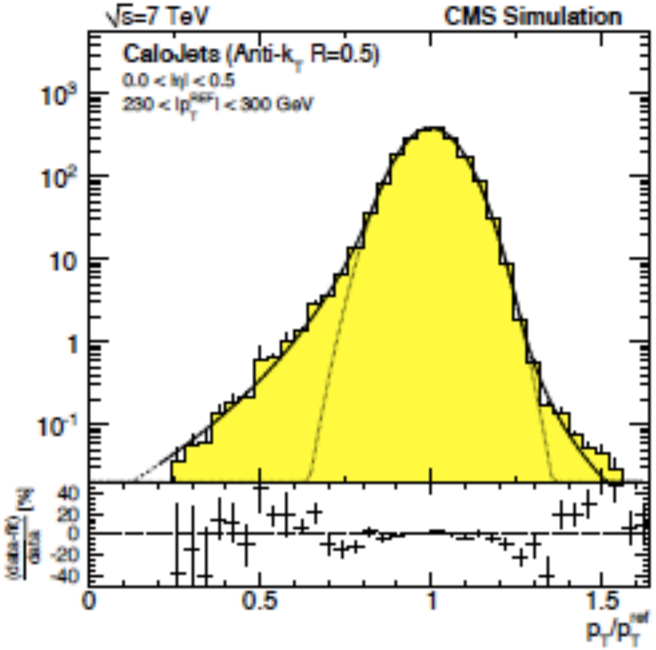


Figure 16: Distribution of calorimeter jet response, p_T / p_T^{REF}, in MC simulation for a particular $|\eta|$ and p_T^{REF} range. Example of fit with Gaussian and double-sided Crystal Ball are shown. The residuals in percent with respect to the latter are shown at the bottom.

Jet Identification

Calo and JPT:

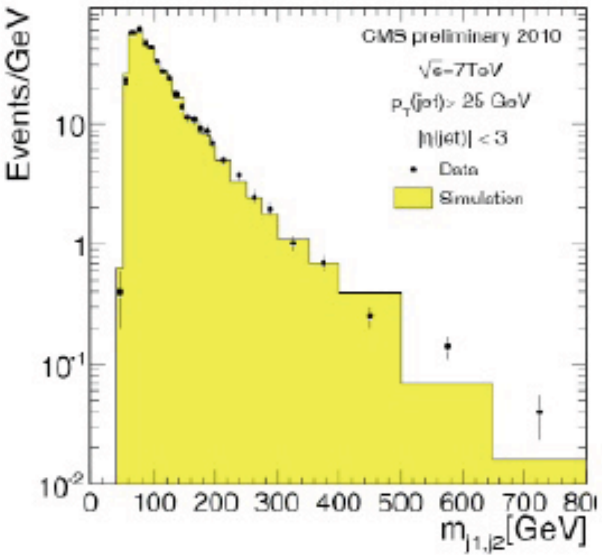
variable	$\|\eta\|$	loose
EMF	< 2.6	> 0.01
n_{hits}^{90}	-	> 1
f_{HPD}	-	< 0.98

Particle Flow:

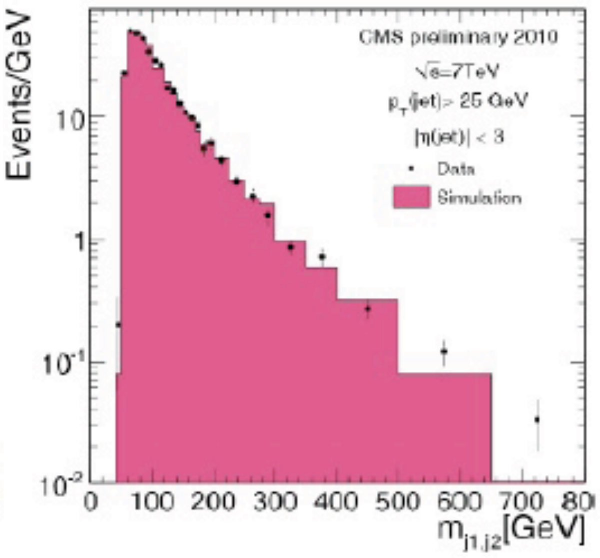
variable	$\|\eta\|$	loose
CHF	< 2.4	> 0.0
NHF	-	< 1.0
CEF	-	< 1.0
NEF	-	< 1.0

Di-jet mass

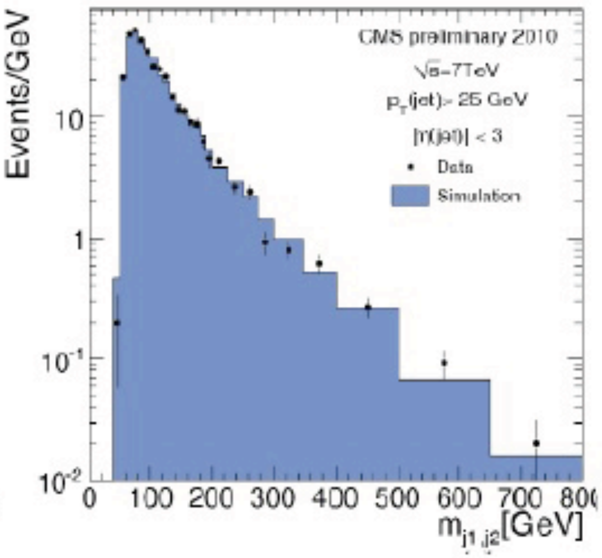
Calo jets



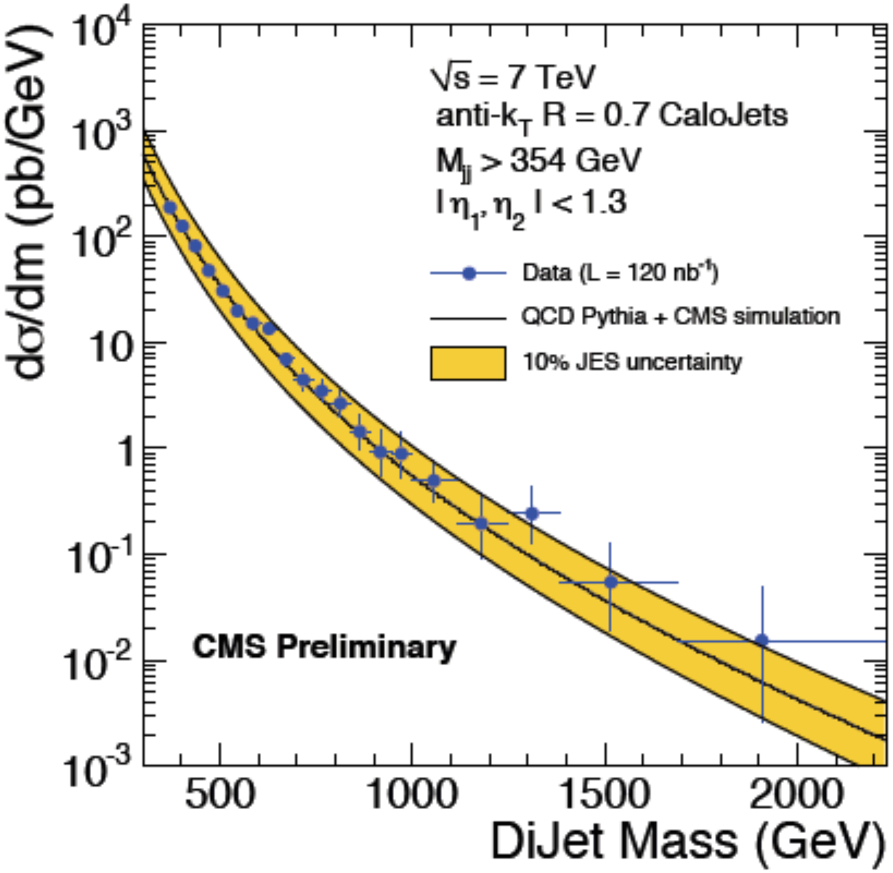
JPT jets



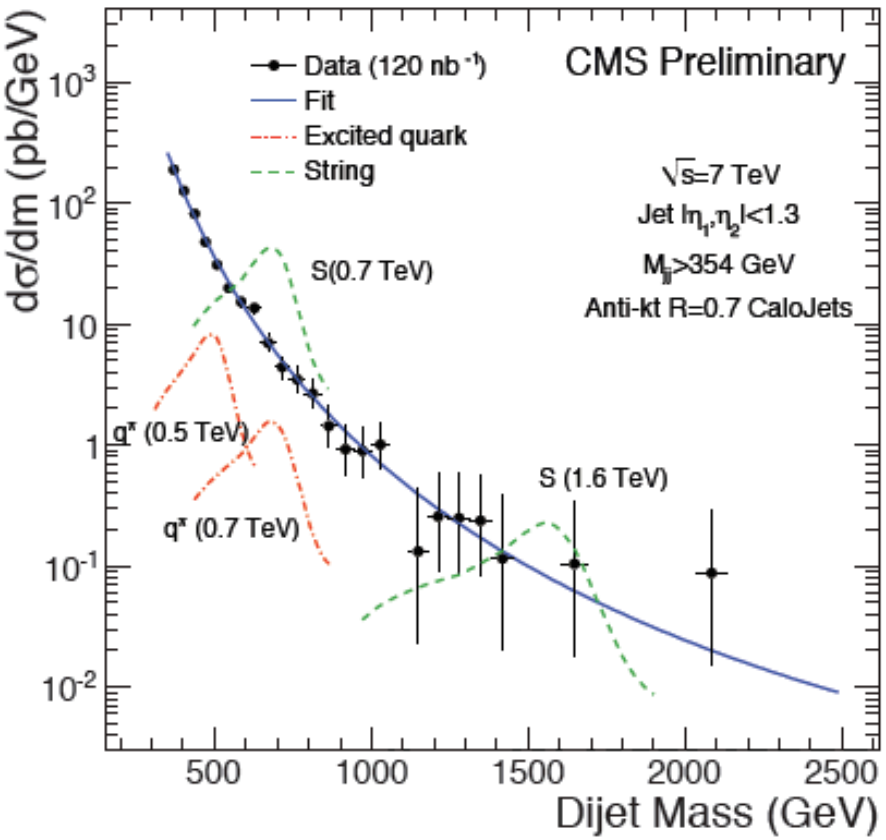
PF jets



Di-jet mass



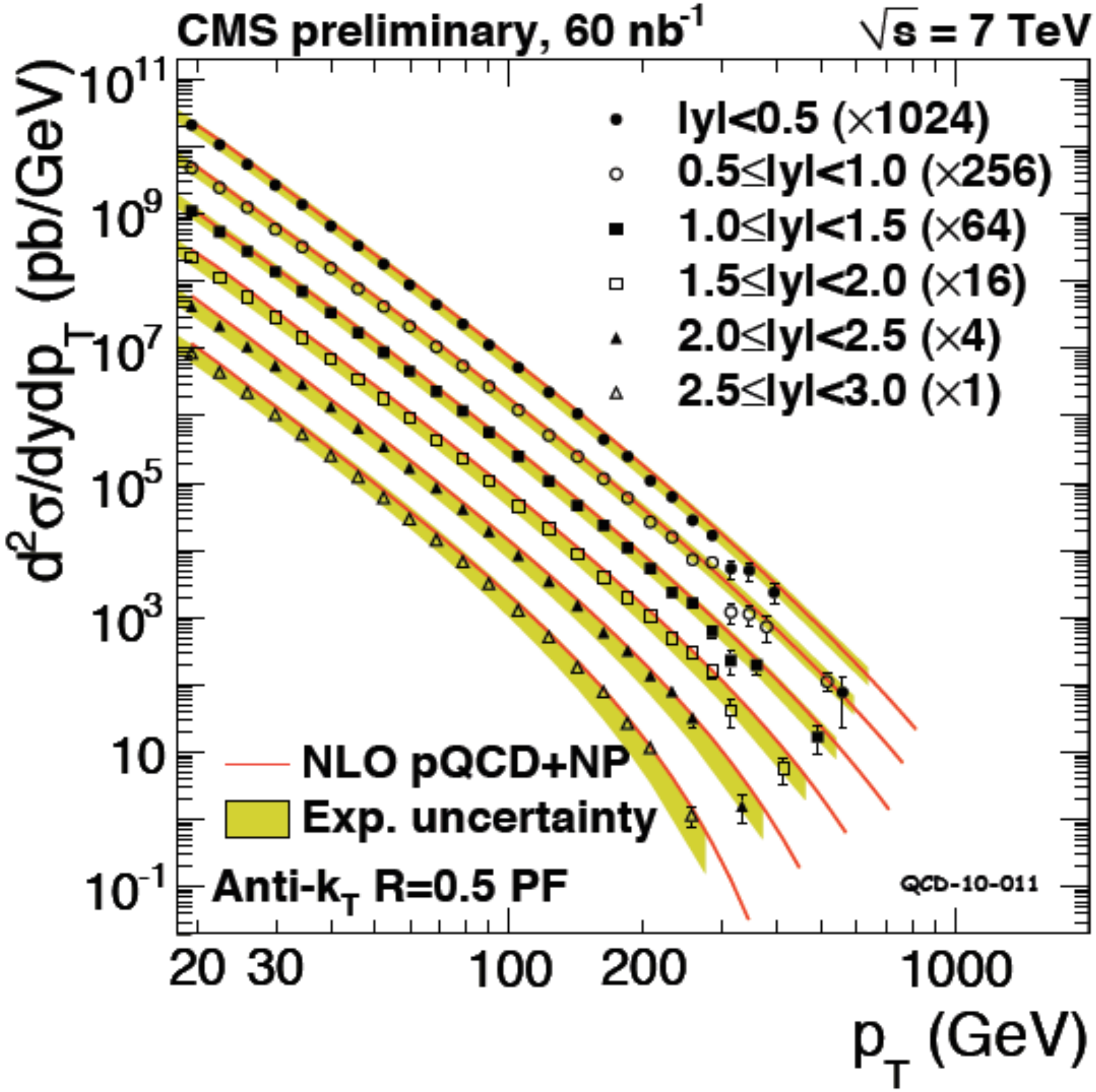
dσ/dm (pb/GeV)
DiJet Mass (GeV)
√s = 7 TeV
anti-k$_T$ R = 0.7 CaloJets
M$_{jj}$ > 354 GeV
I η$_1$, η$_2$ I < 1.3
Data (L = 120 nb^{-1})
QCD Pythia + CMS simulation
10% JES uncertainty
CMS Preliminary
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
500
1000
1500
2000



dσ/dm (pb/GeV)
Dijet Mass (GeV)
Data (120 nb^{-1})
Fit
Excited quark
String
CMS Preliminary
√s=7 TeV
Jet Iη$_1$,η$_2$I<1.3
M$_{jj}$>354 GeV
Anti-kt R=0.7 CaloJets
S(0.7 TeV)
q* (0.5 TeV)
q* (0.7 TeV)
S (1.6 TeV)
10^3
10^2
10
1
10^{-1}
10^{-2}
500
1000
1500
2000
2500

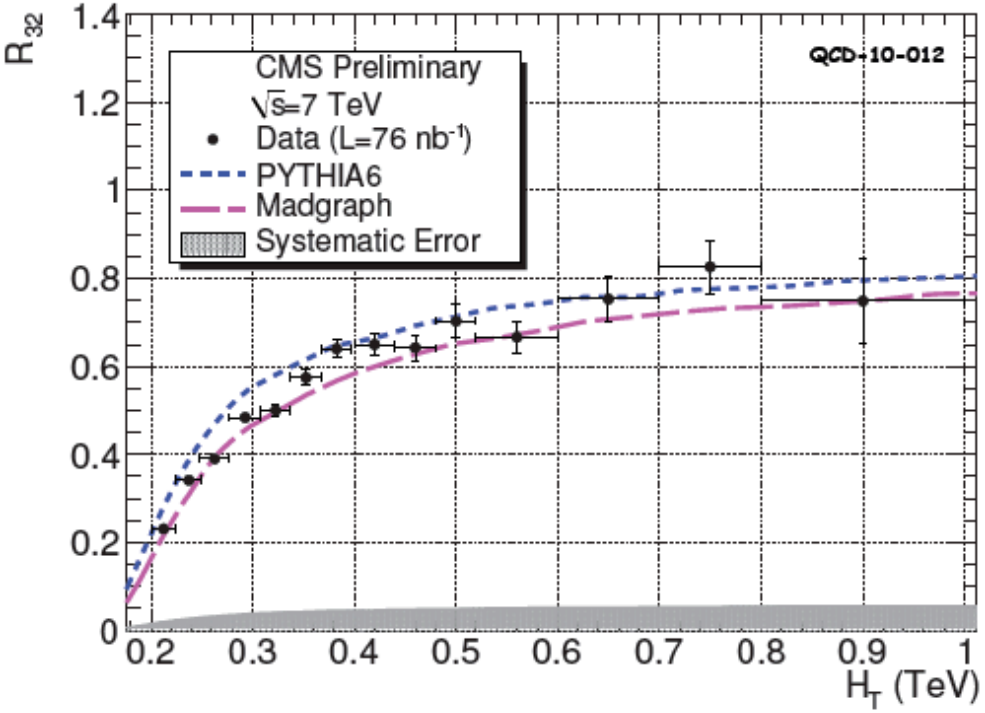
Inclusive jet cross section

- Inclusive jet p_T spectra are in good agreement with NLO theory for all reconstruction types
- Past Tevatron published (0.7 fb^{-1}) record of 624 GeV jet at high p_T
- Extending below TeV's 50 GeV at low p_T thanks to novel reconstruction methods (Particle Flow)



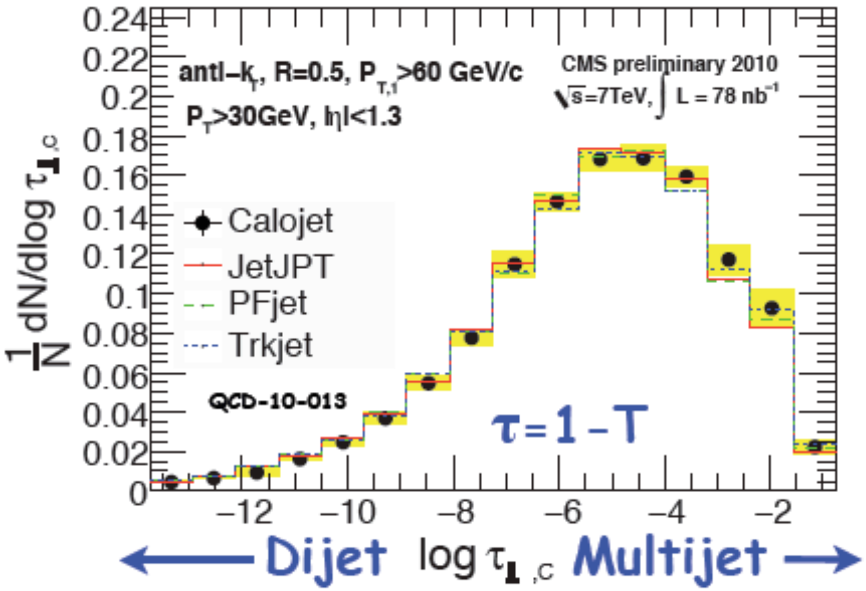
3/2 jet ratio

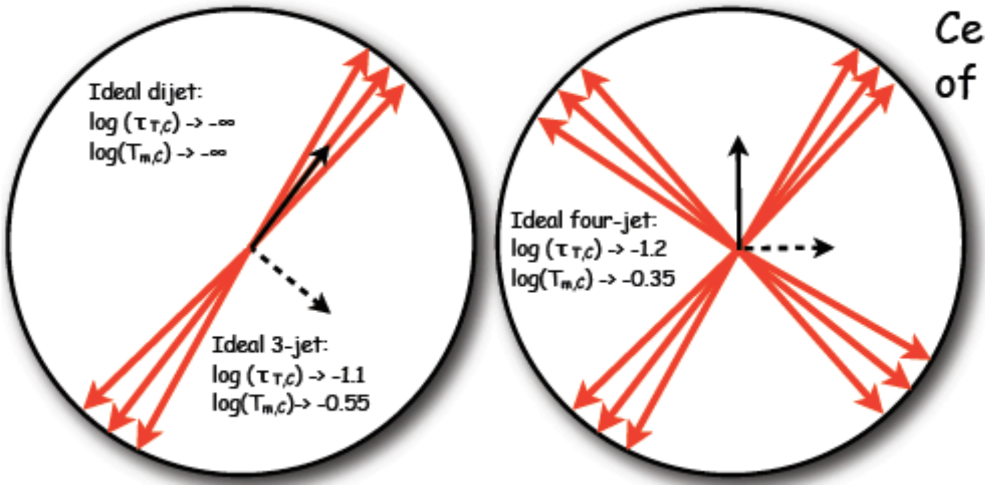
- Starting from inclusive jets and dijets, multiple ratio measurements are performed to reduce or cancel JEC and luminosity uncertainties
- Ratio of inclusive 2-jet and inclusive 3-jet cross sections is a good example; $p_{T,}$jet > 50 GeV, $|y| < 2.5$, $R_{32} = (d\sigma_3/dH_T) / (d\sigma_2/dH_T)$
- Good agreement found with Pythia and Madgraph within uncertainties



Hadronic Event Shapes

- Event shapes provide geometric information about energy flow in hadronic events
- Essential for tuning parton shower and non-perturbative components of Monte Carlo event generators
- Event shapes are robust against choice of jet reconstruction, as well as JEC and JER uncertainties





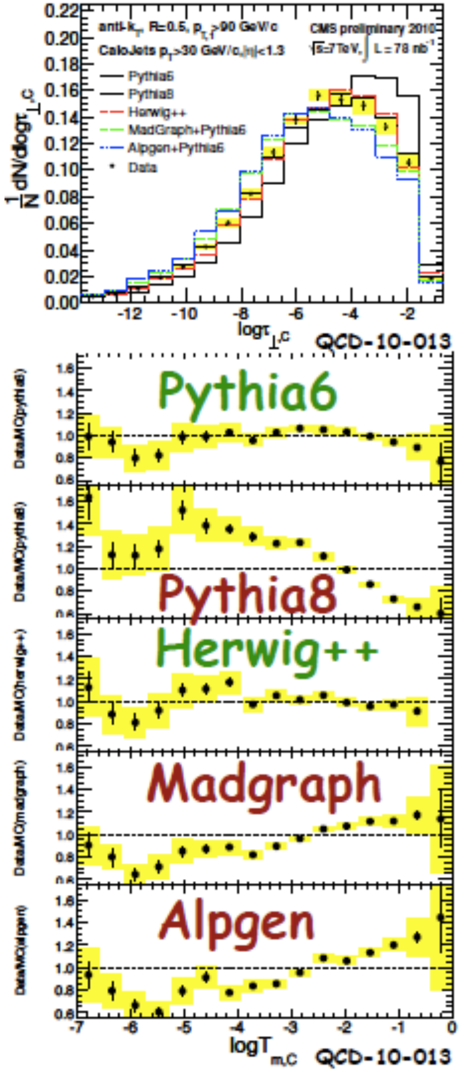
Central transverse thrust: maximum of projection on a transverse axis

$$T_{\perp,\mathcal{C}} \equiv \max_{\vec{n}_T} \frac{\sum_{i\in\mathcal{C}} |\vec{p}_{\perp,i}\cdot\vec{n}_T|}{\sum_{i\in\mathcal{C}} p_{\perp,i}}$$

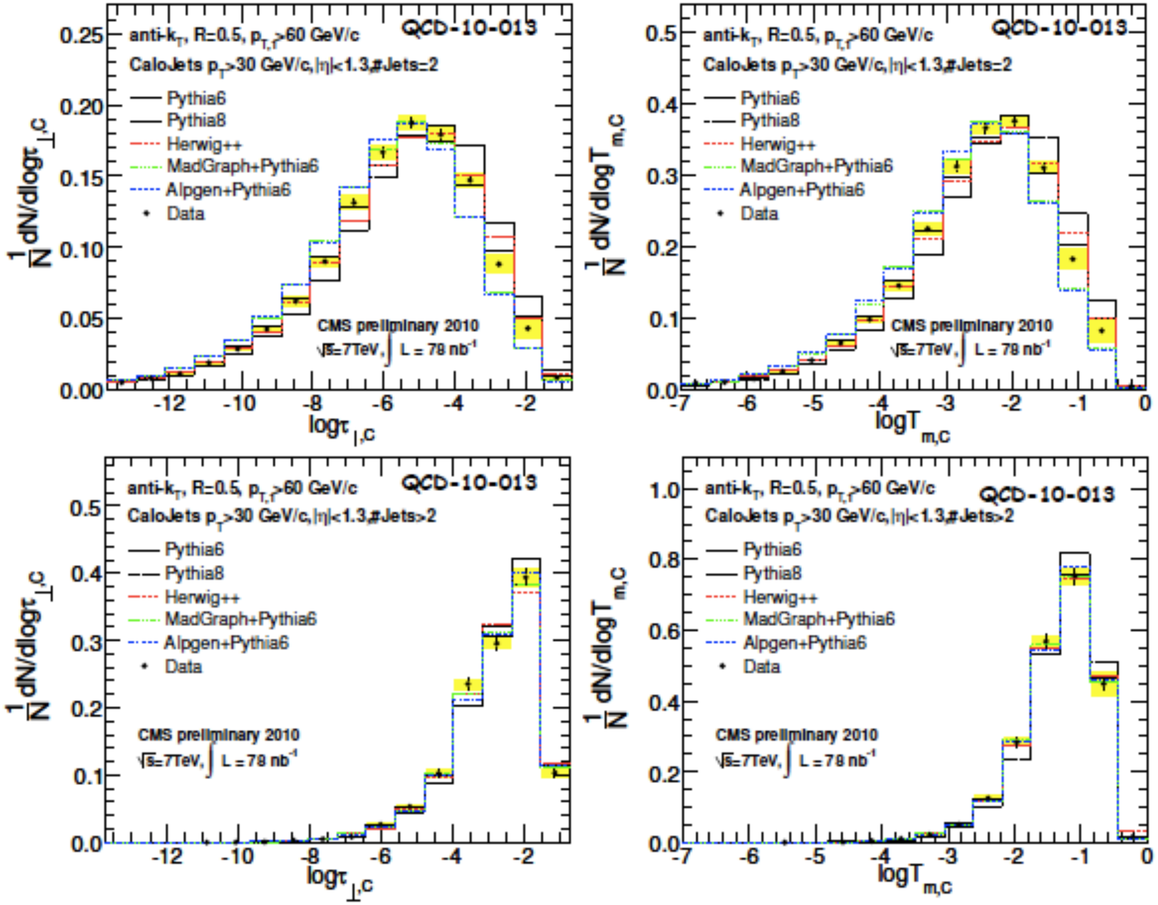
Central thrust minor: projection out of the plane of beam axis and transverse axis n_T

$$T_{m,\mathcal{C}} \equiv \frac{\sum_{i\in\mathcal{C}} |\vec{p}_{\perp,i}\times\vec{n}_{T,\mathcal{C}}|}{\sum_{i\in\mathcal{C}} p_{\perp,i}}$$

Event Shapes (2)

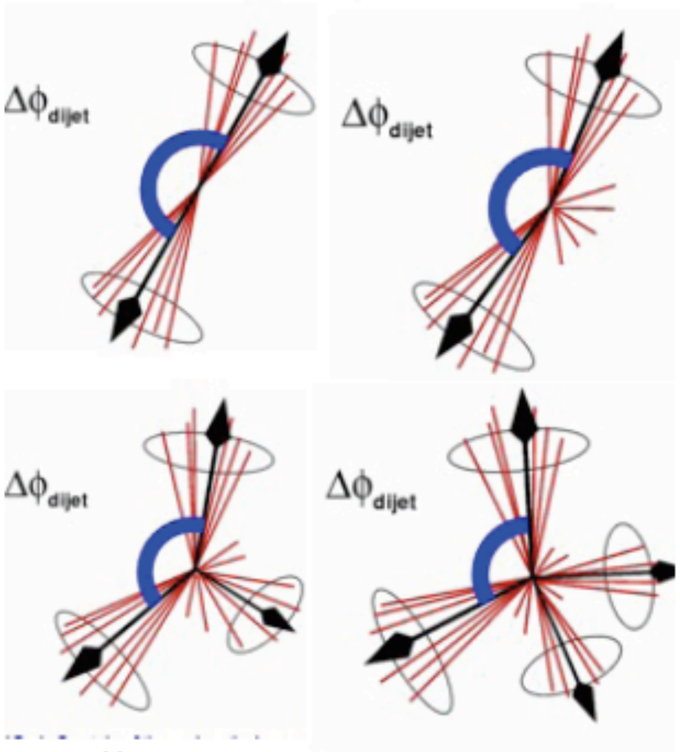


Pythia 6 and Herwig++ agree with data within uncertainties; Alpgen and Madgraph overestimate fraction of back-to-back dijets, and Pythia 8 underestimates it; similar at all p_T

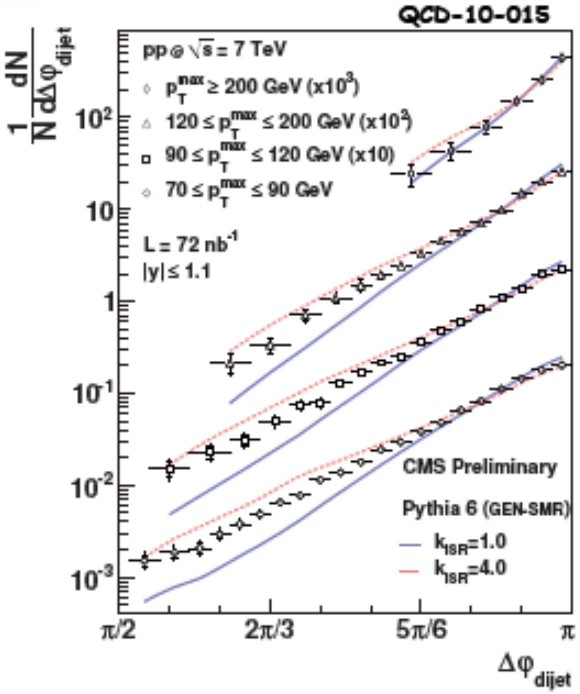


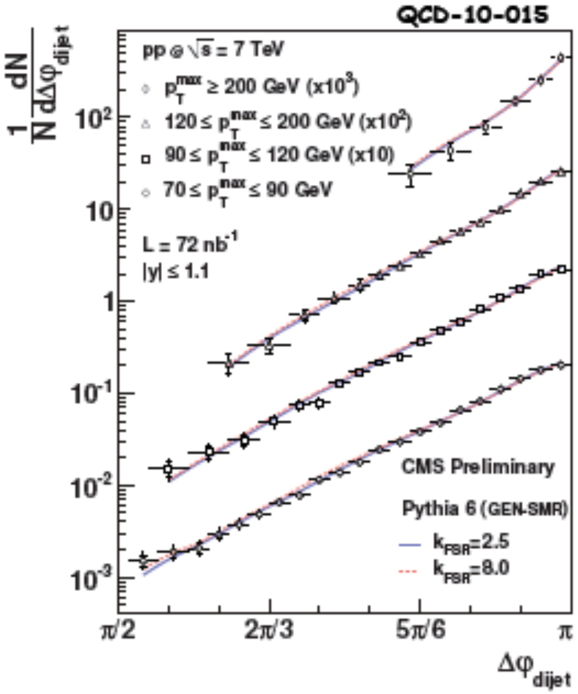
Azimuthal decorrelation

- Azimuthal decorrelations was the first QCD measurement from D0 Run II: little sensitivity to JEC and luminosity, but much to perturbative radiation
- Observable is very sensitive to initial state radiation (k_{ISR}=PARP(67)), but shows little sensitivity to final state radiation (k_{FSR}=PARP(71))
- Good agreement between data and Pythia default tune (k_{ISR}=2.5, k_{FSR}=4.0)



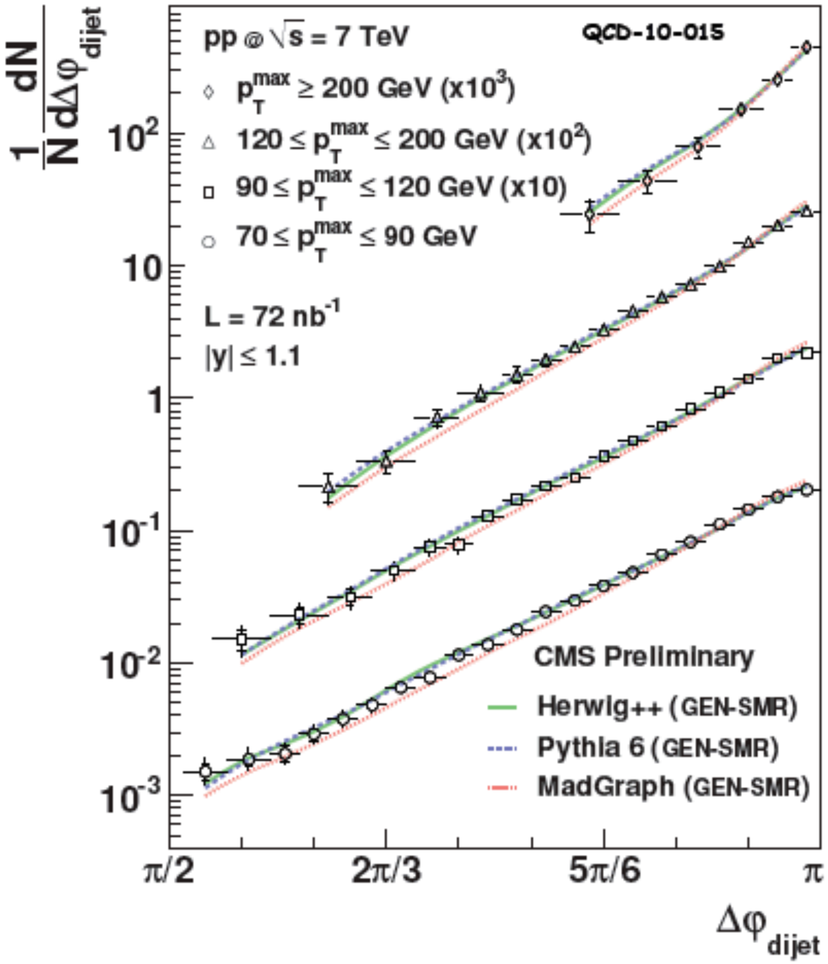
graphics: D0

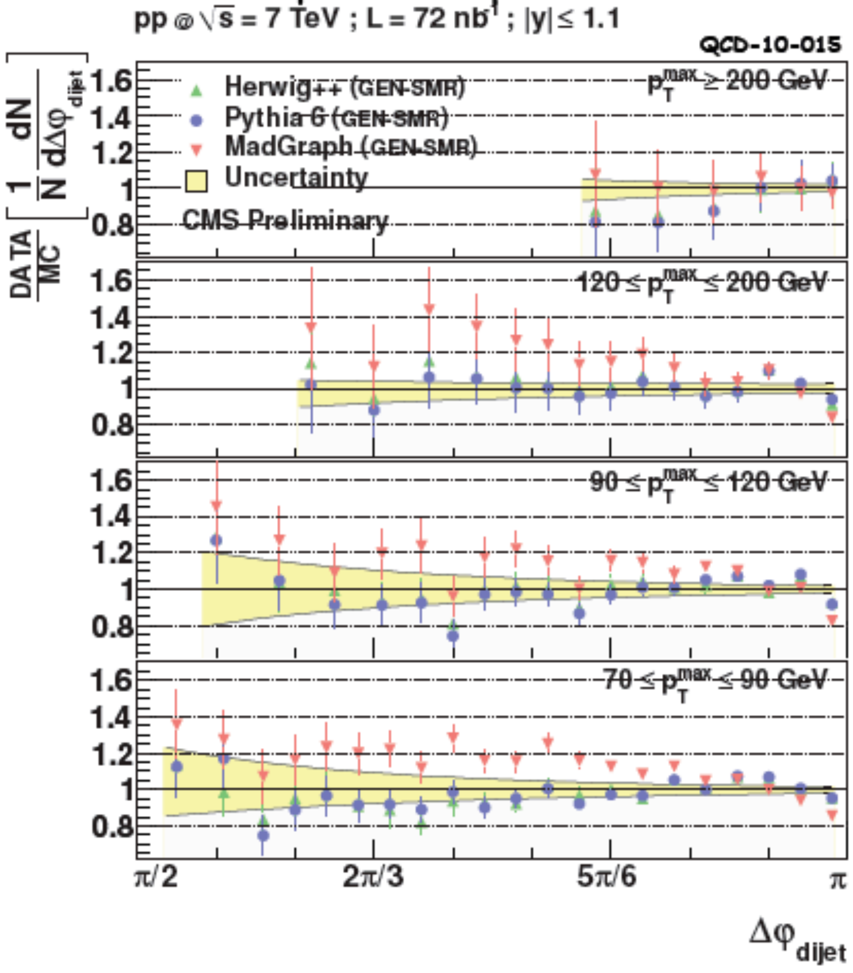




Azimuthal decorrelation (2)

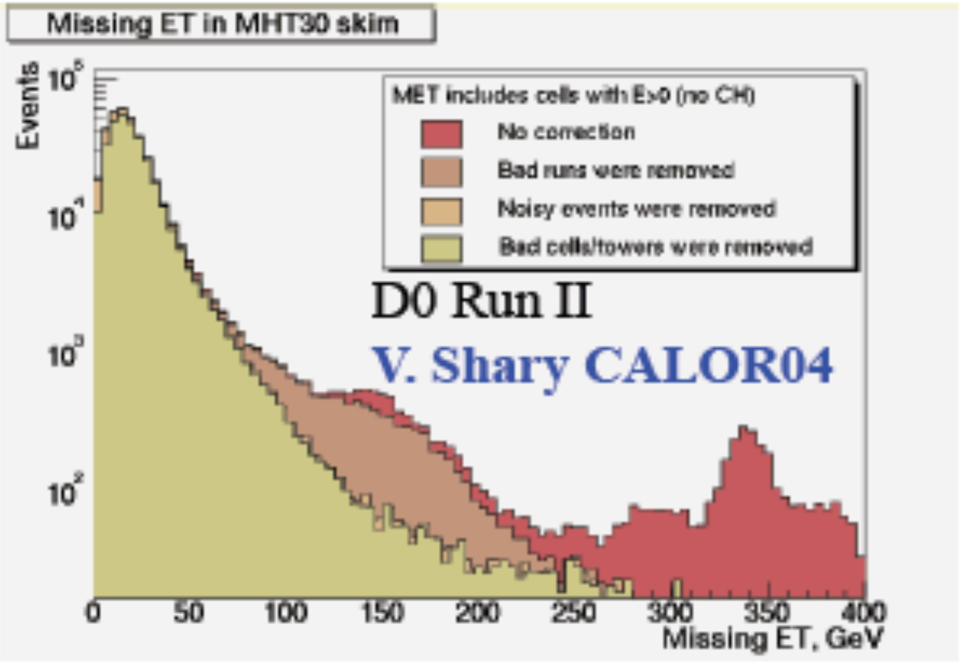
- Comparisons between data and different models show good agreement with Pythia and Herwig, but less agreement with MadGraph at low p_T





MET

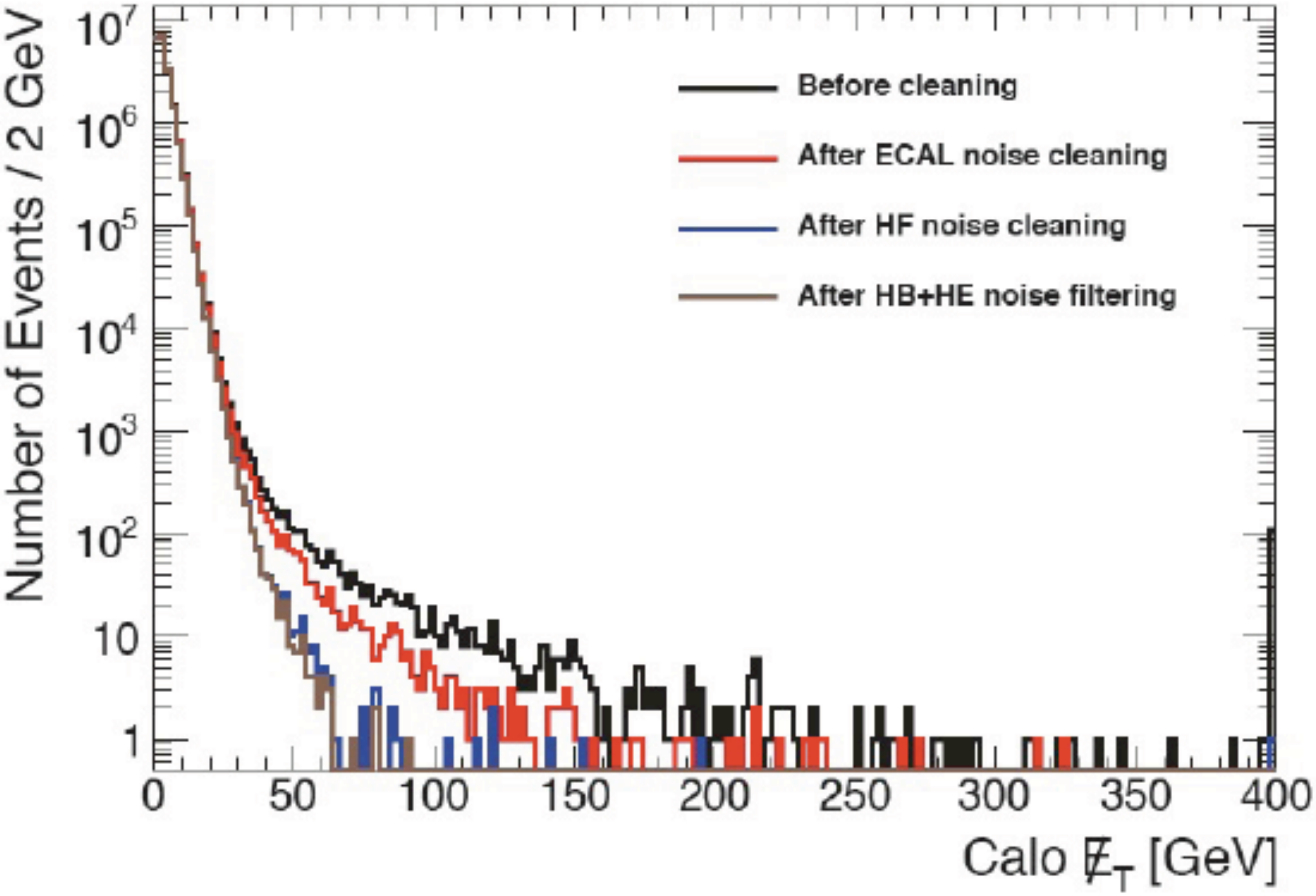
Our expectations from Tevatron:



Sources of instrumental noise:

* readout discharge
* electronics noise
* beam halo muons
* cosmics, …

MET reconstruction



HCAL anomalies

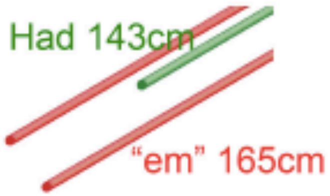
"Known unknowns"

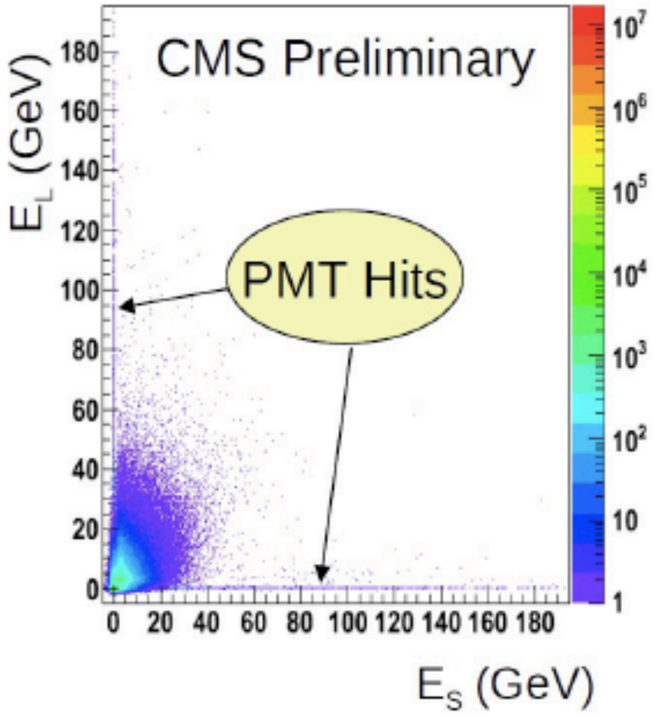
HCAL barrel - endcap

- **origin**: ion feedback, noise & discharges in HPDs
- **characteristic**: Random, ~ 10-20 Hz (E>20 GeV). .
- **filtering**: topology + timing

HCAL forward

- **origin**: Čerenkov light by particles going through PMT glass
- Appear mostly in one channel in time with collisions
- **filtering**: based on energy sharing between long and short fibers + timing





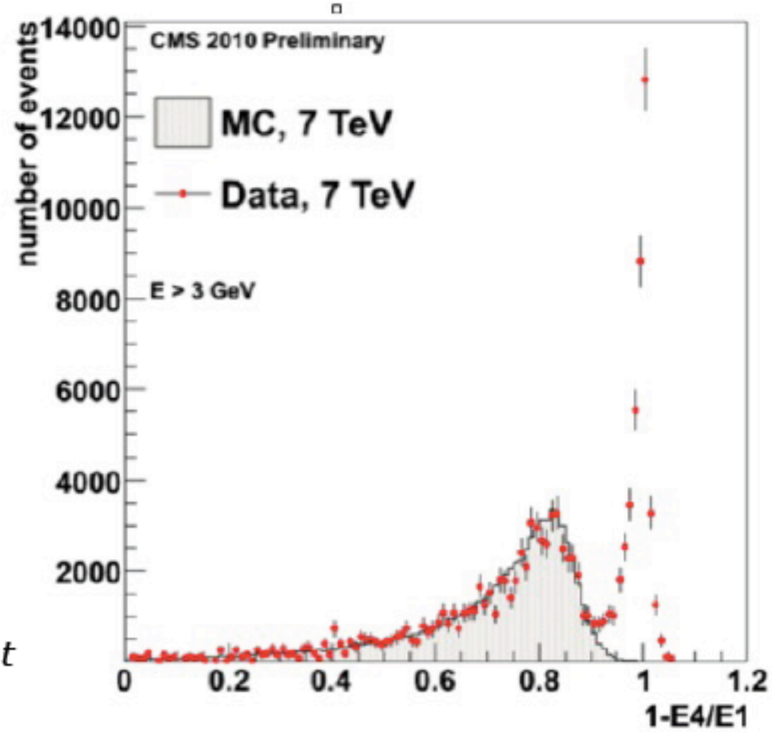
ECAL anomalies

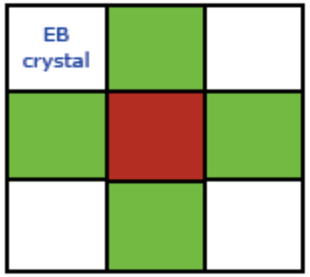
“Unknown unknowns”

In a small fraction of collision data we observe anomalous signals in ECAL:

- distinct pulse shape
- different timing
- single crystal energy deposit
- uniformly distributed in EB
- not seen in EE (VPTs readout)

Origin: highly ionizing particles in the APDs

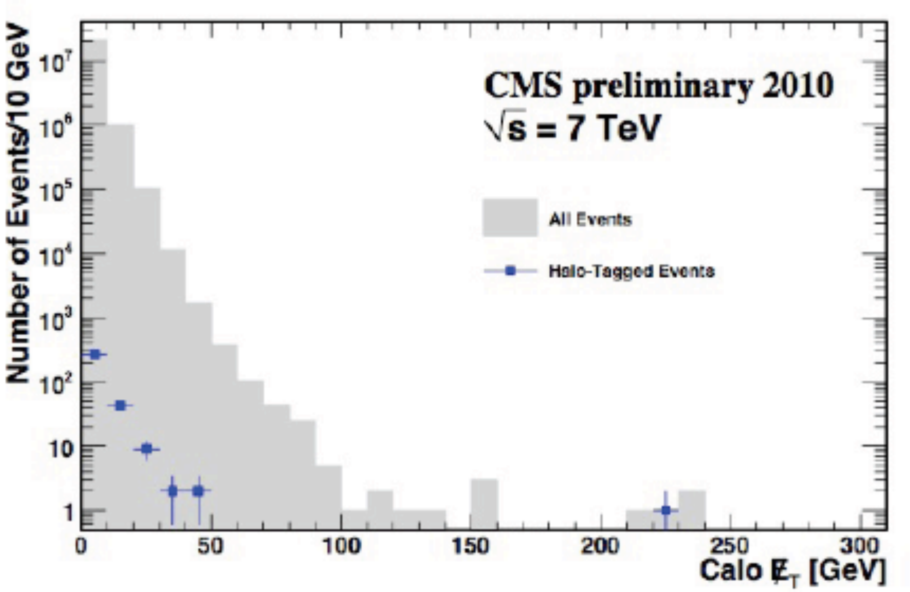


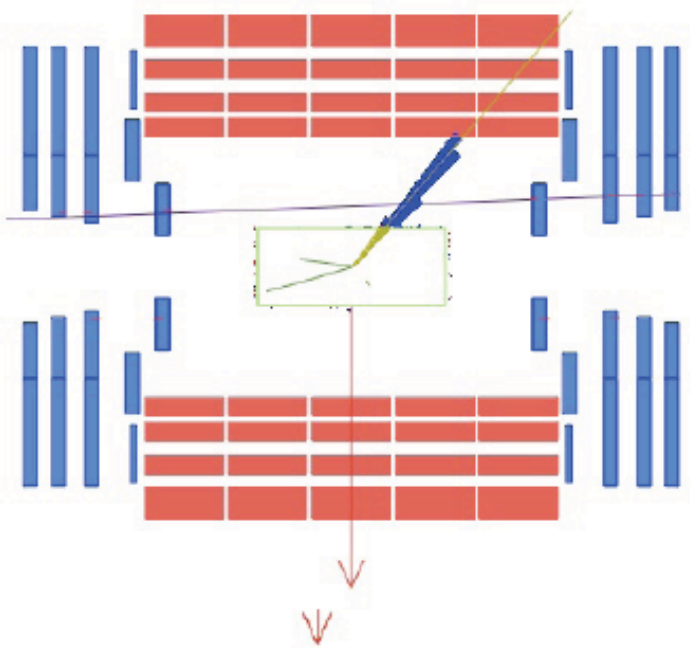


pulse shape exhibits faster rising time and is *inconsistent* with the signal shape from scintillation

Easily identified and removed by a quality selection (e.g. an energy ratio **E4**/**E1**). Timing and pulse shape discriminants could also be deployed to tag these signals.

Beam halo muons





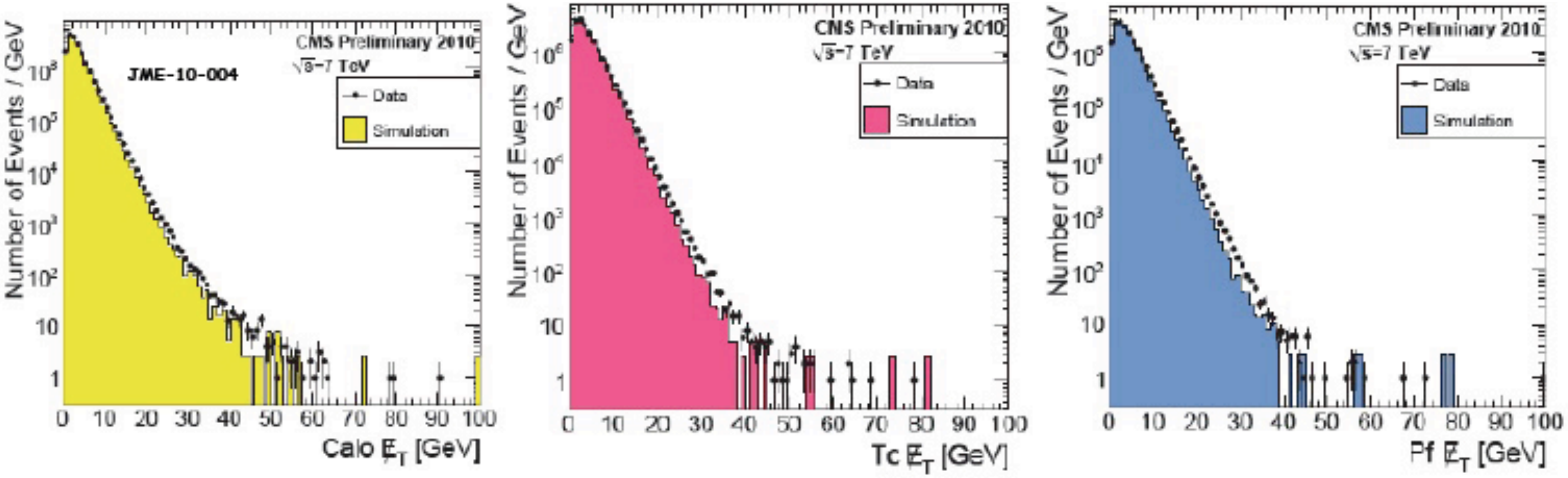
CaloMET for events before the beam-halo fitler is applied and for beam-halo tagged events in minimum-bias or jet 15 trigger events

Beam-halo tagged events with highest CaloMET (224 GeV)

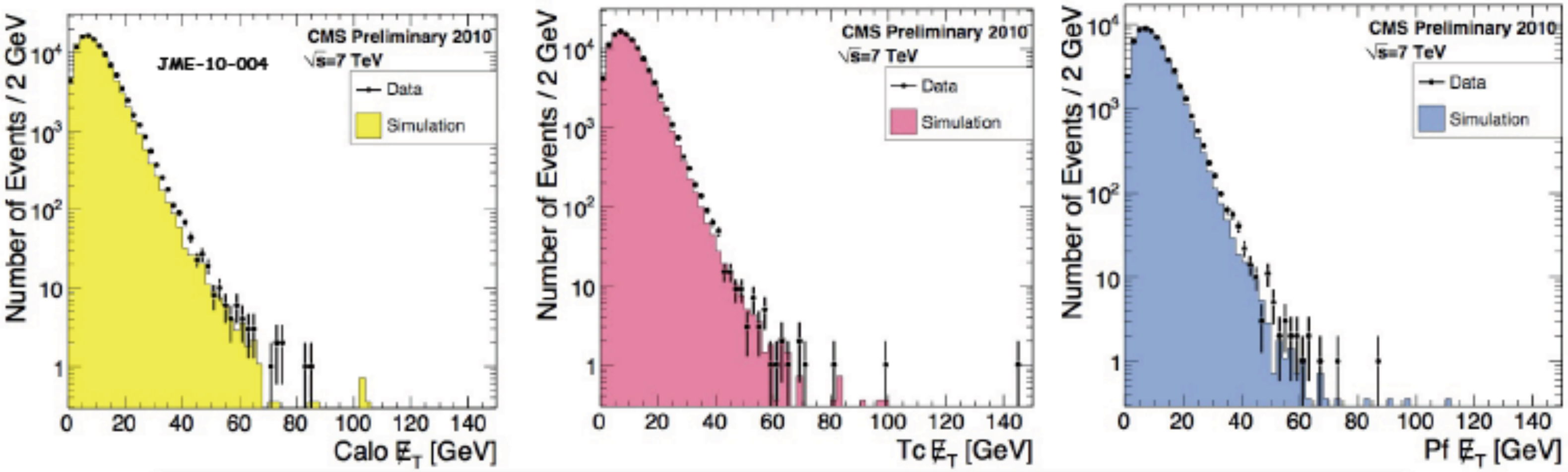
Beam halo does not significantly affect MET generally; however, it can cause high MET in an event.

MET performance

Min Bias: **Calo MET** **JPT MET** **PF MET**



Dijet events with corr. $p_T^{1,2}>25$ GeV, $|\eta_{1,2}|<3$:



Sum ET

Status in March/April 2010:

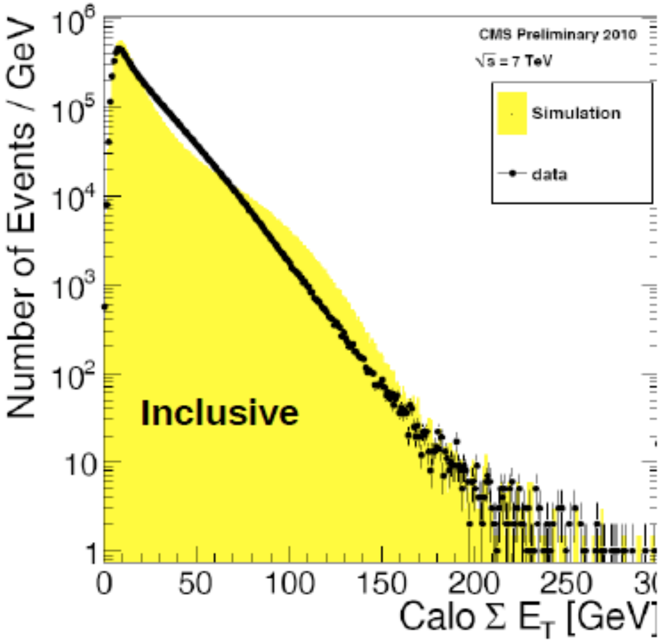


Figure: Data vs MC: Calo ΣE_T

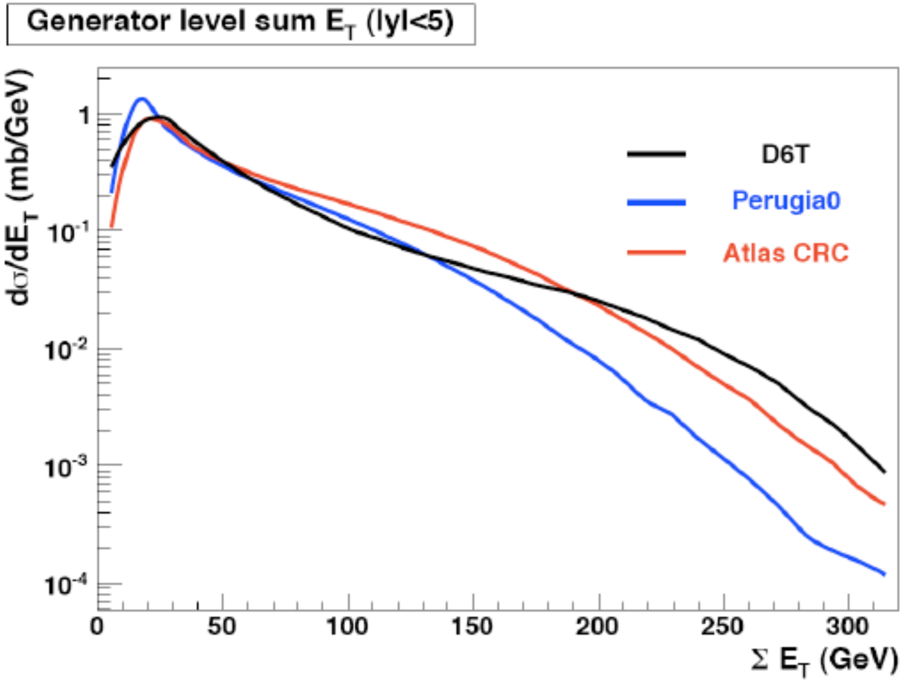


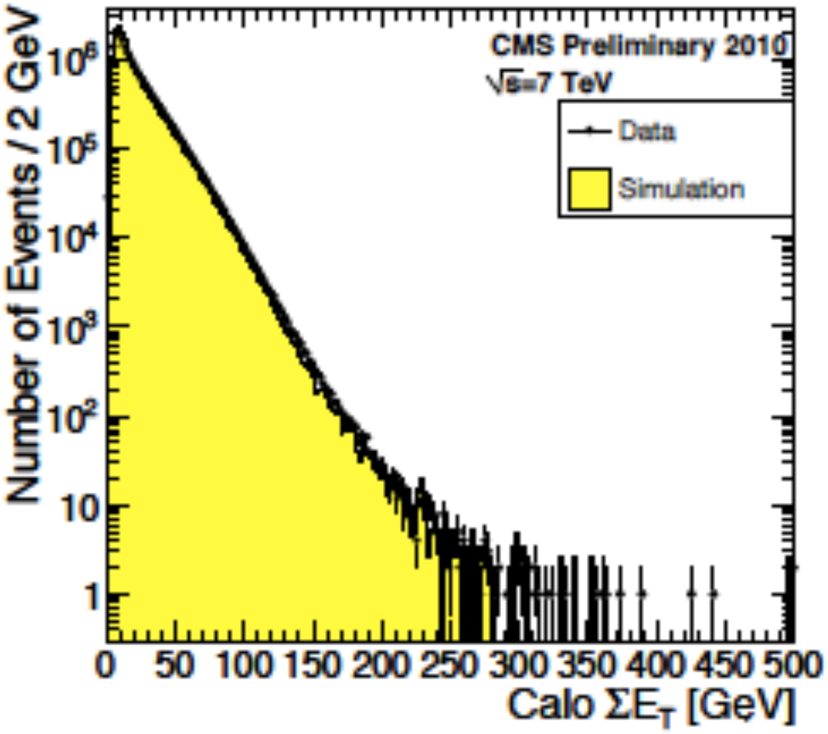
Figure: ΣE_T with different PYTHIA6 tunes

- Disagreement in SumE_T seen for all MET reco methods
- SumE_T very dependent on Pythia tunes as shown by right plot

SumET (2)

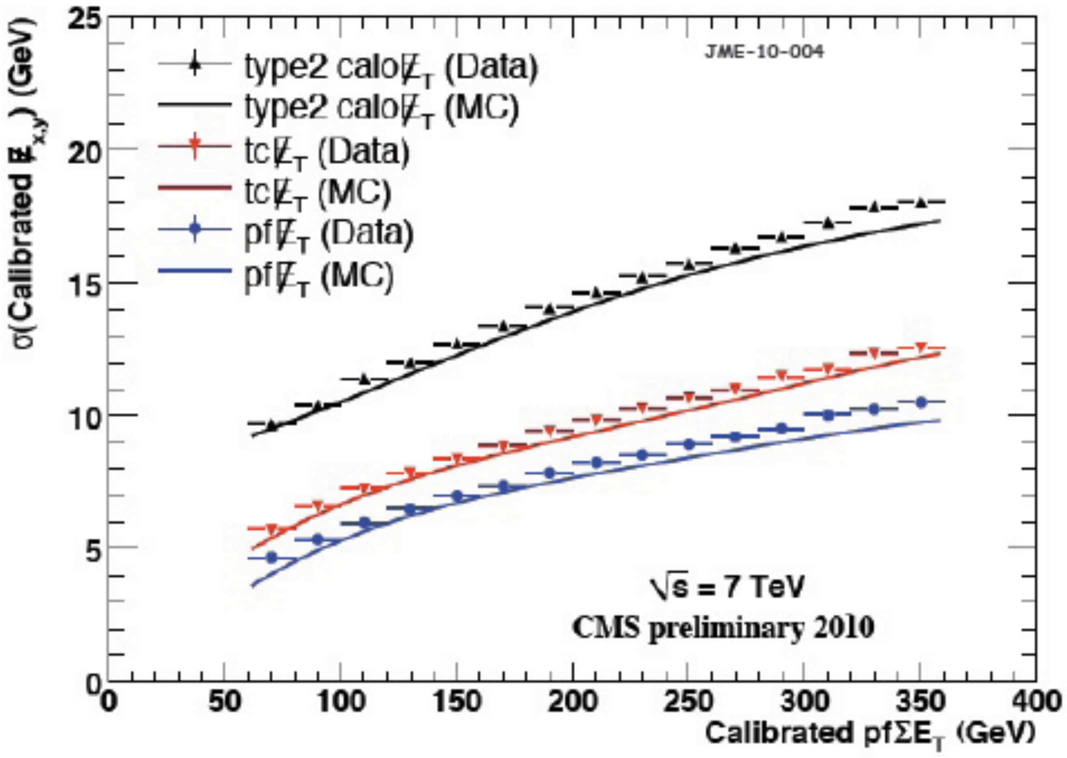
July 2010

Using PYTHIA8:



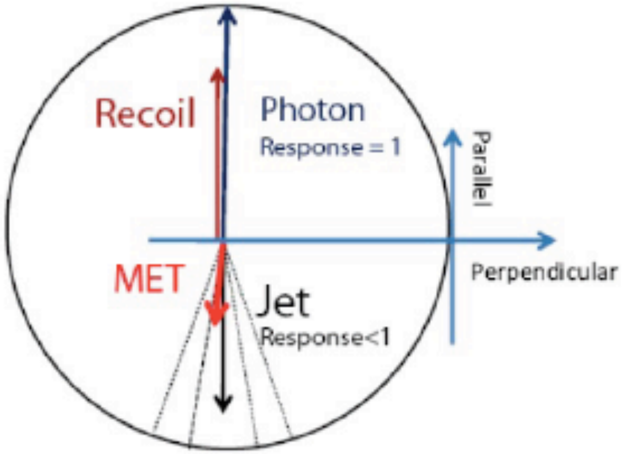
(b) calo$\sum E_T$ distribution

MET resolution



- PF SumE$_T$ is calibrated to generator level Sum E$_T$

- Observed MET sigma is scaled by the MET scale obtained from photon+jets MC events:



=> PF MET has the best resolution.
Tc MET also shows significant impovement w.r.t. the calorimeter-only MET

Fit Gaussian:

Calo MET

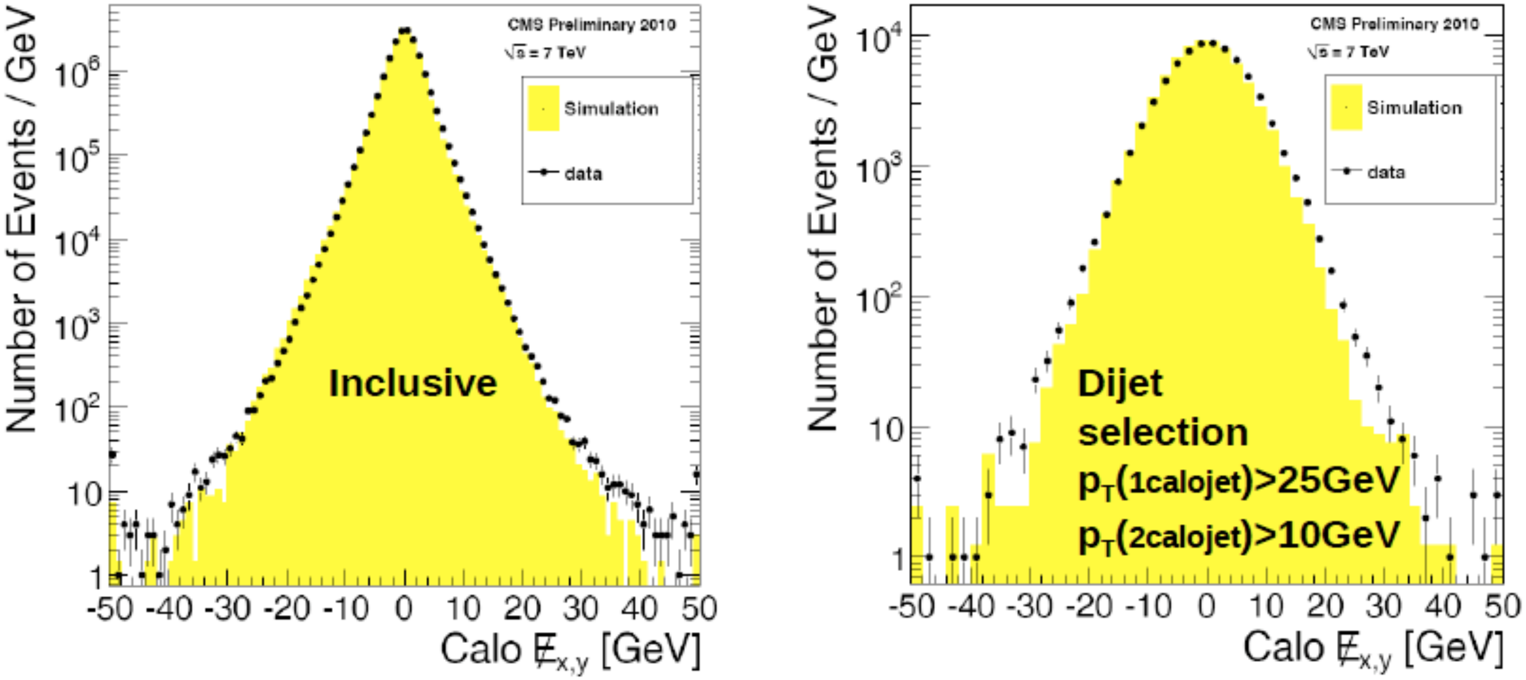
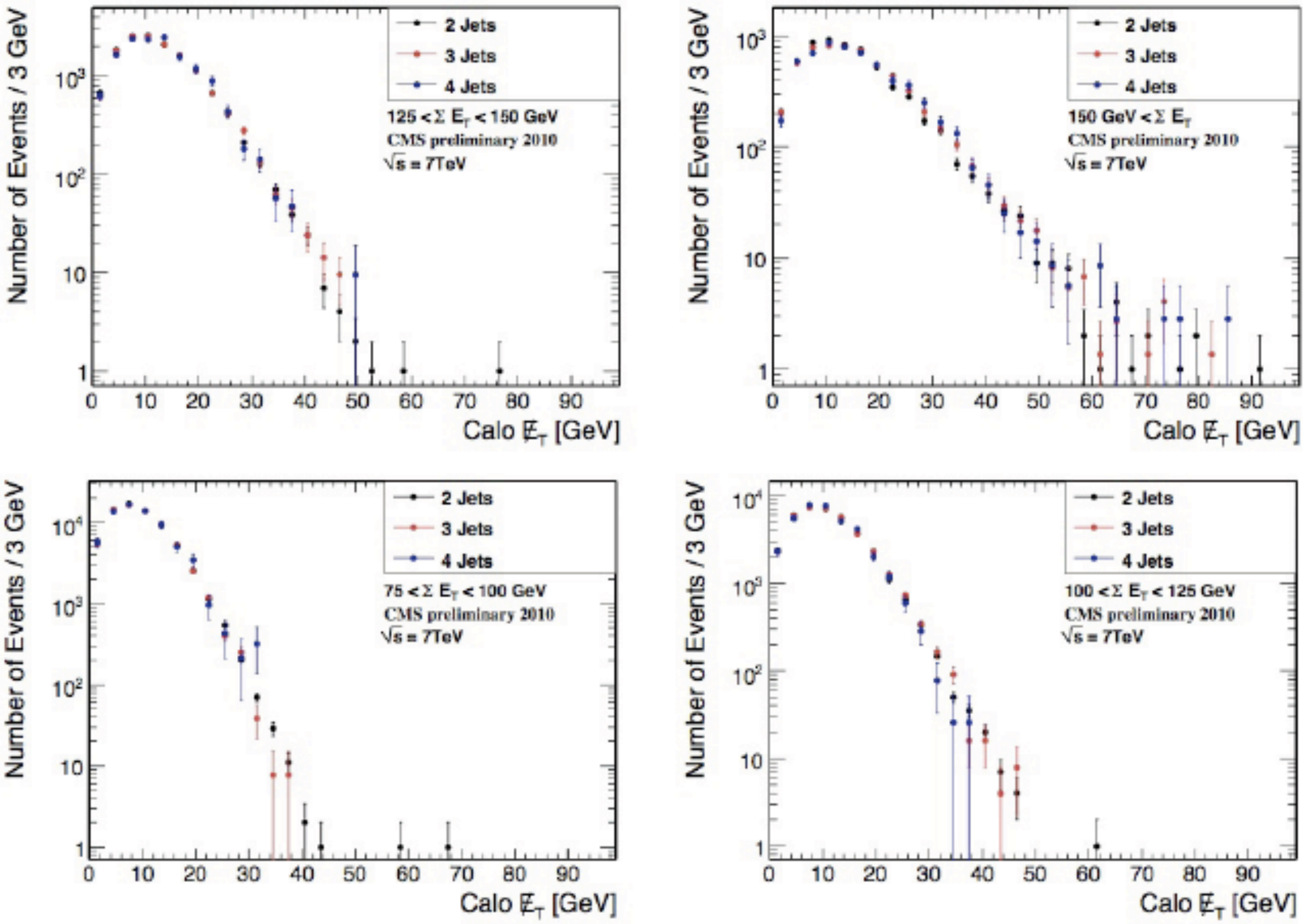


Figure: Data vs MC: Calo $\not{E}_x$, $\not{E}_y$ distributions

MET in multijets

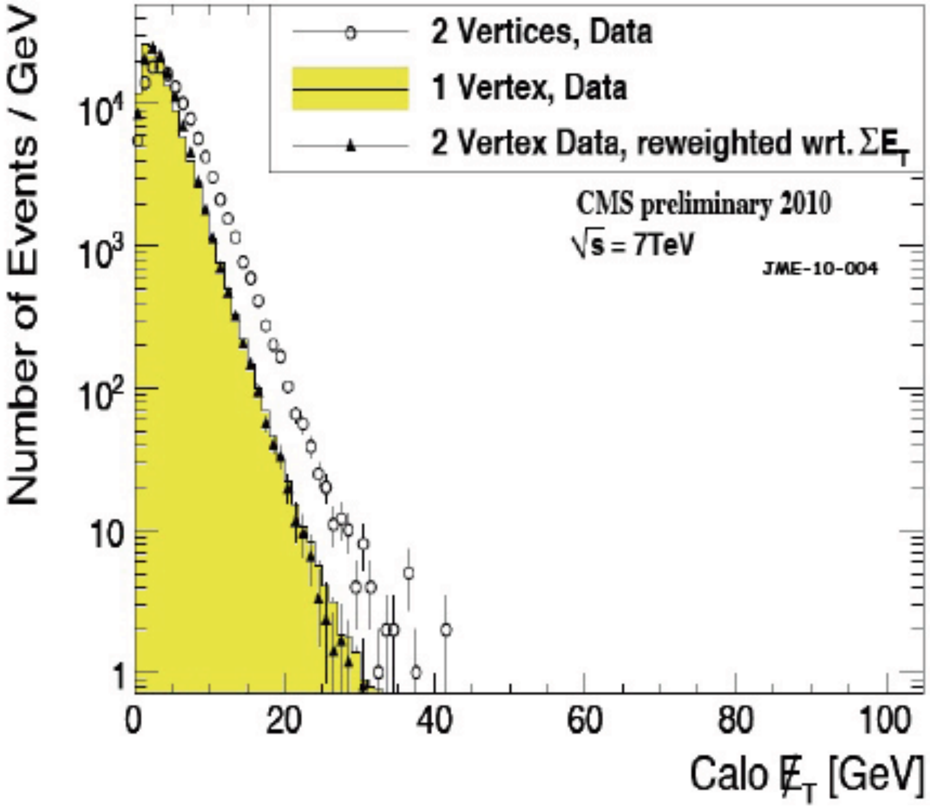


- Uncorrected Calo MET in jet events for different SumE_T ranges
- Different jet multiplicity bins (jets w/p_T>20 GeV, |η|<3)

=> MET distribution "primarily" controlled by SumE_T, and not jet multiplicities

MET in pile-up conditions

Study of MET distribution in 1-and 2-vertex events in minimum-bias events



- MET distributions wider in 2-vertex events
- Reweight 2 vertex events so that the SumE$_T$ distribution matches that of the 1 vertex events
- After reweighting, MET distribution agree between 1-vertex and 2-vertex events

=> Widening of MET distribution in 2-vertex events due to transverse energy increase in events