# The CMS Particle Flow Algorithm

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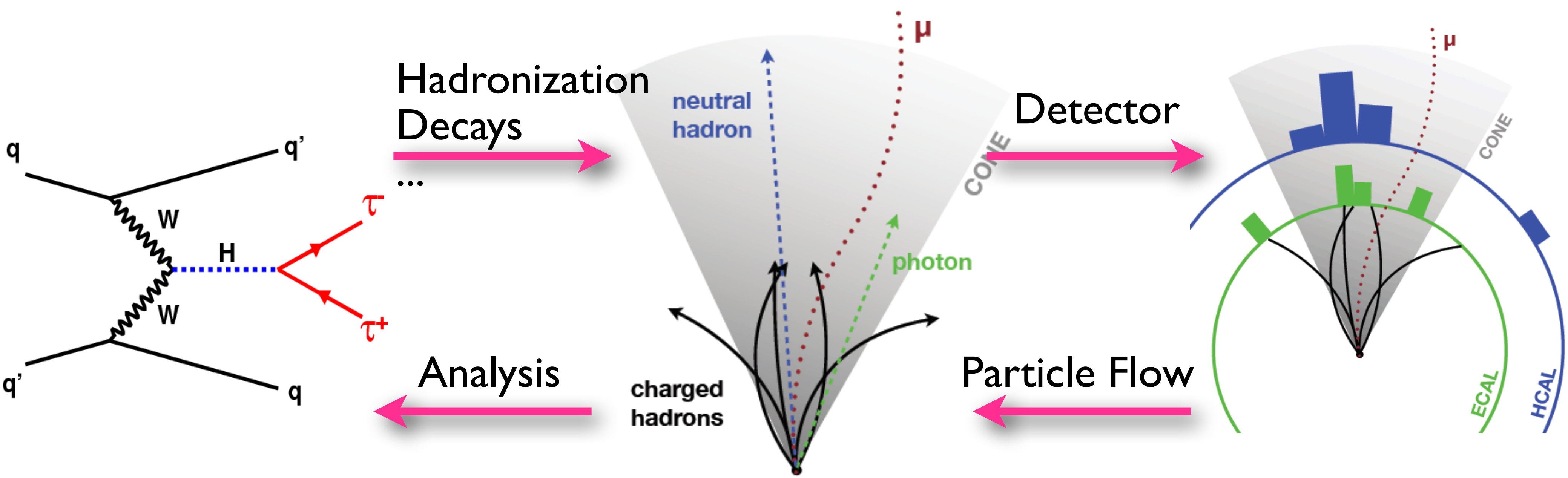
on behalf of the CMS collaboration

Including material from:
CMS-PAS-PFT-10-002
CMS-PAS-PFT-10-003
CMS-PAS-PFT-09-001
CMS-DP-2012/012
CMS-PAS-JME-12-002

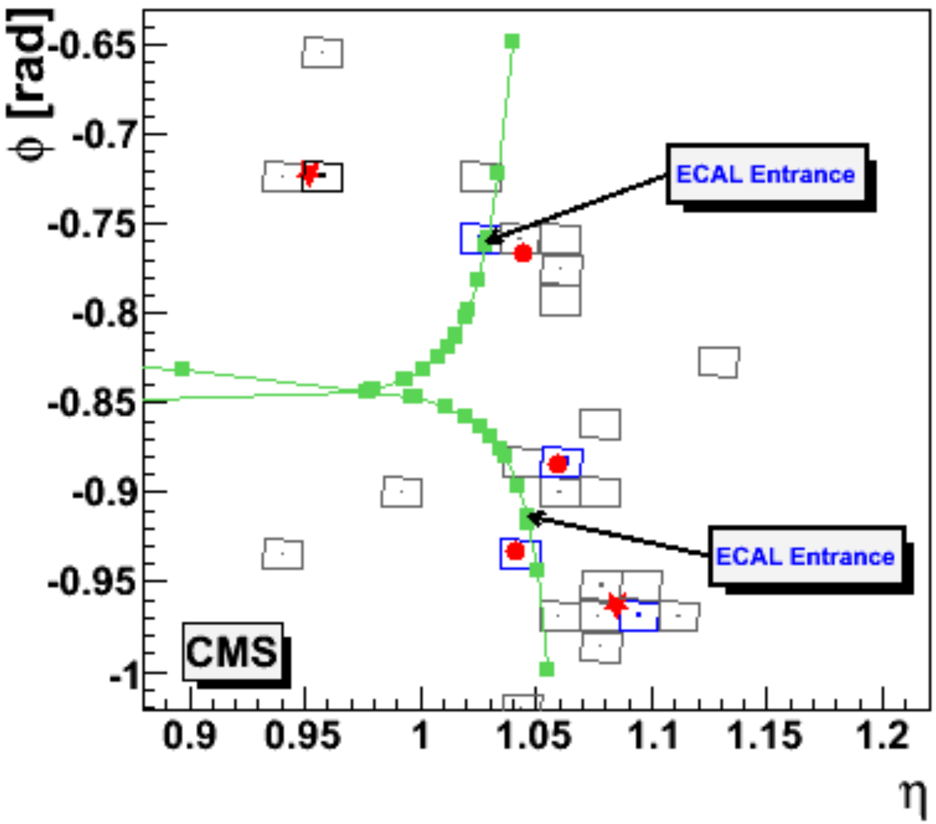
# Overview : the Particle Flow algorithm



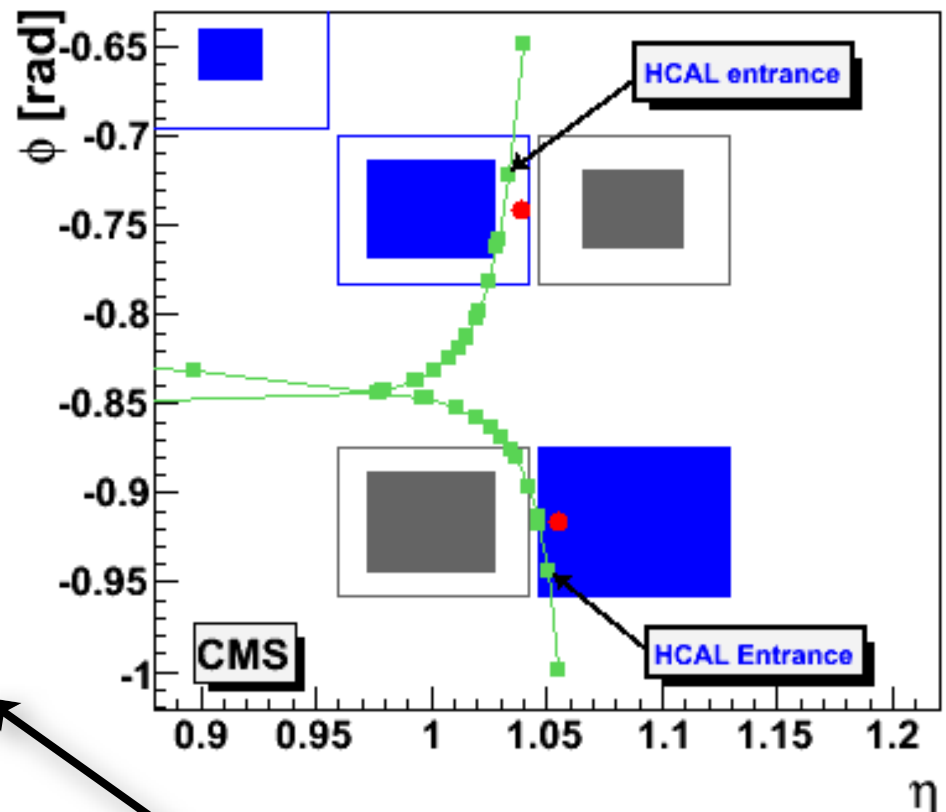

The list of individual particles is then used to build jets, to determine the missing transverse energy, to reconstruct and identify taus from their decay products, to tag b jets ...

# Track-cluster link

ECAL surface



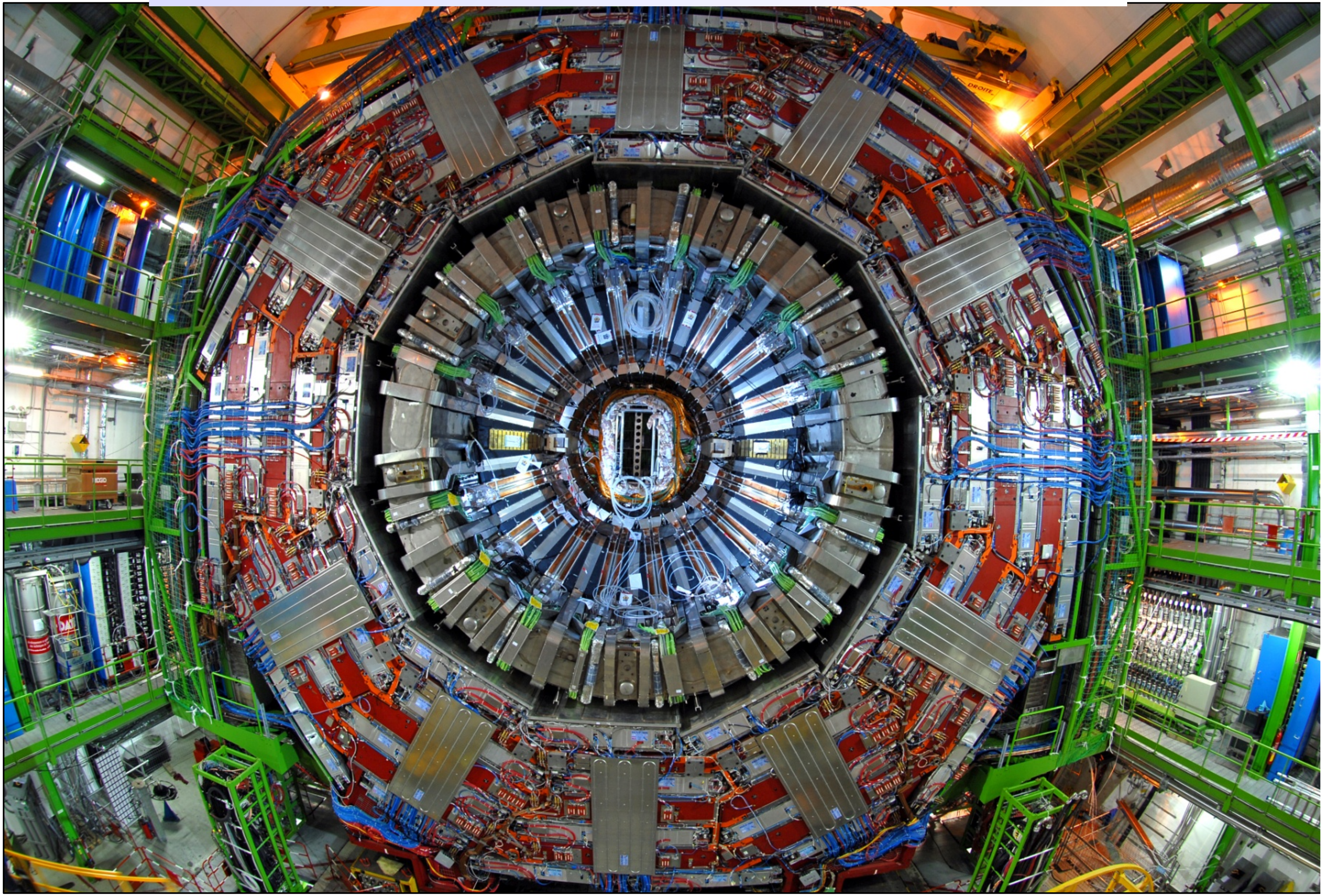

HCAL surface



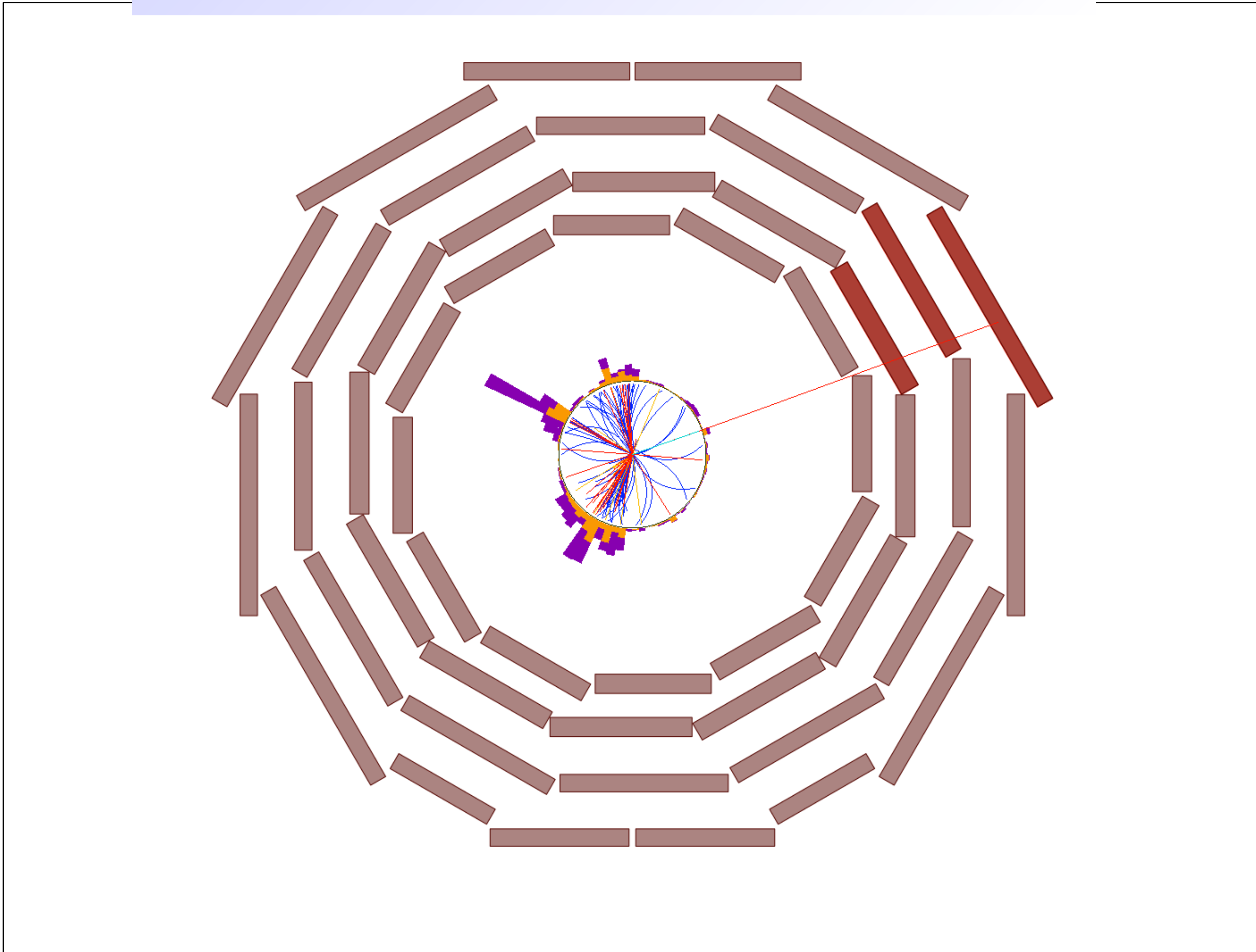

★ Two photons (ECAL clusters not linked to a track) plus a $\pi^+$ and $\pi^-$

Major role of the clustering algorithm !

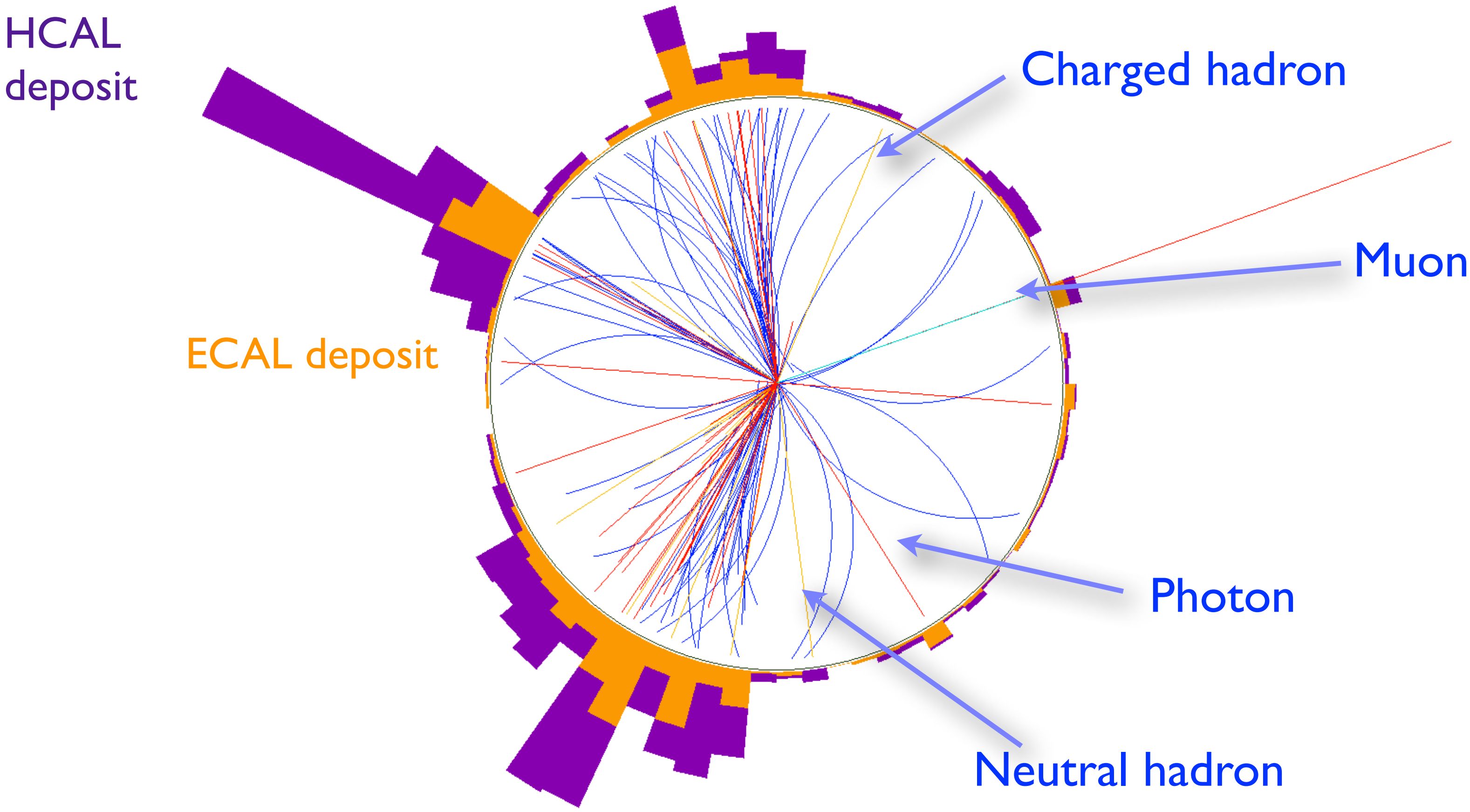
# The CMS detector



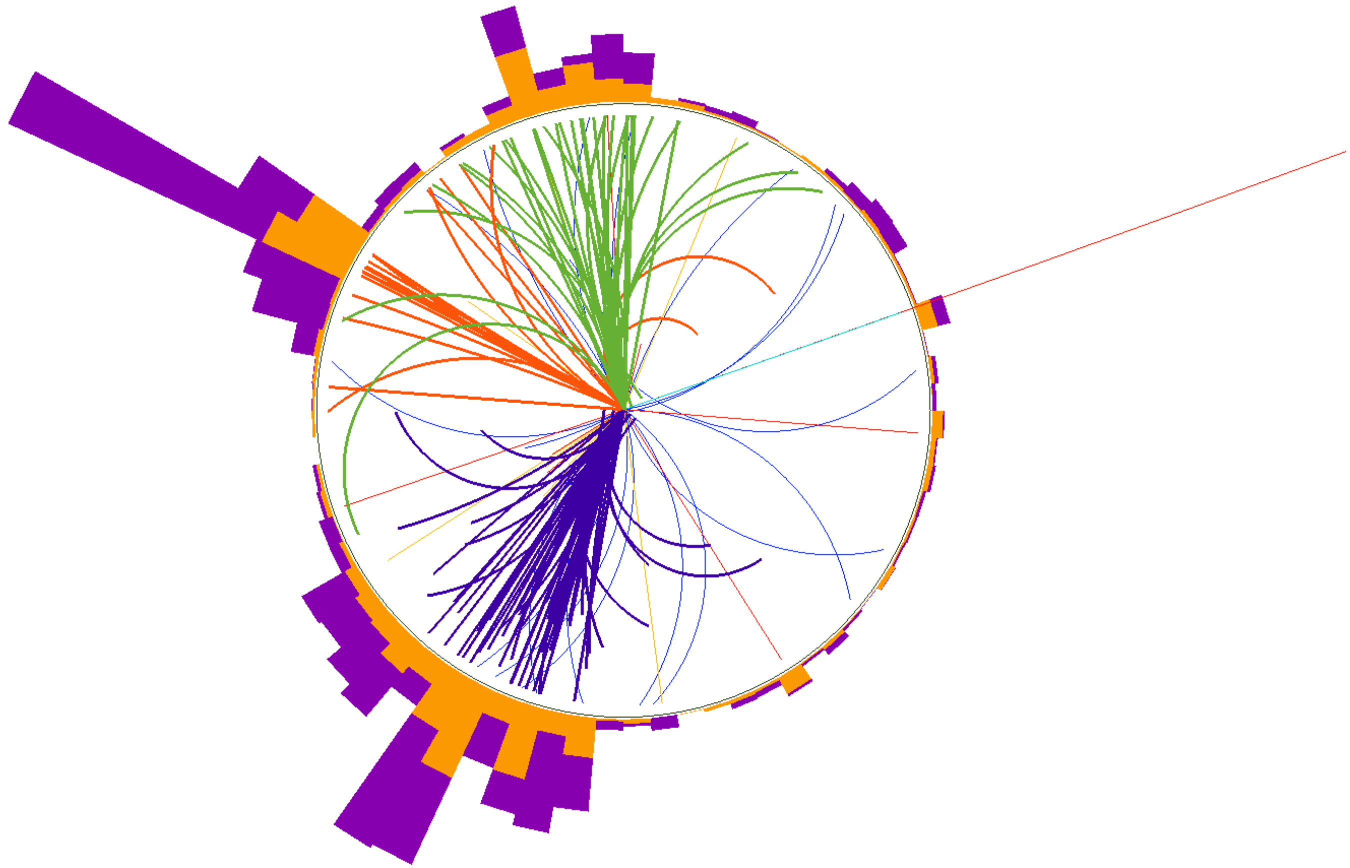
# The CMS detector



# Zooming in

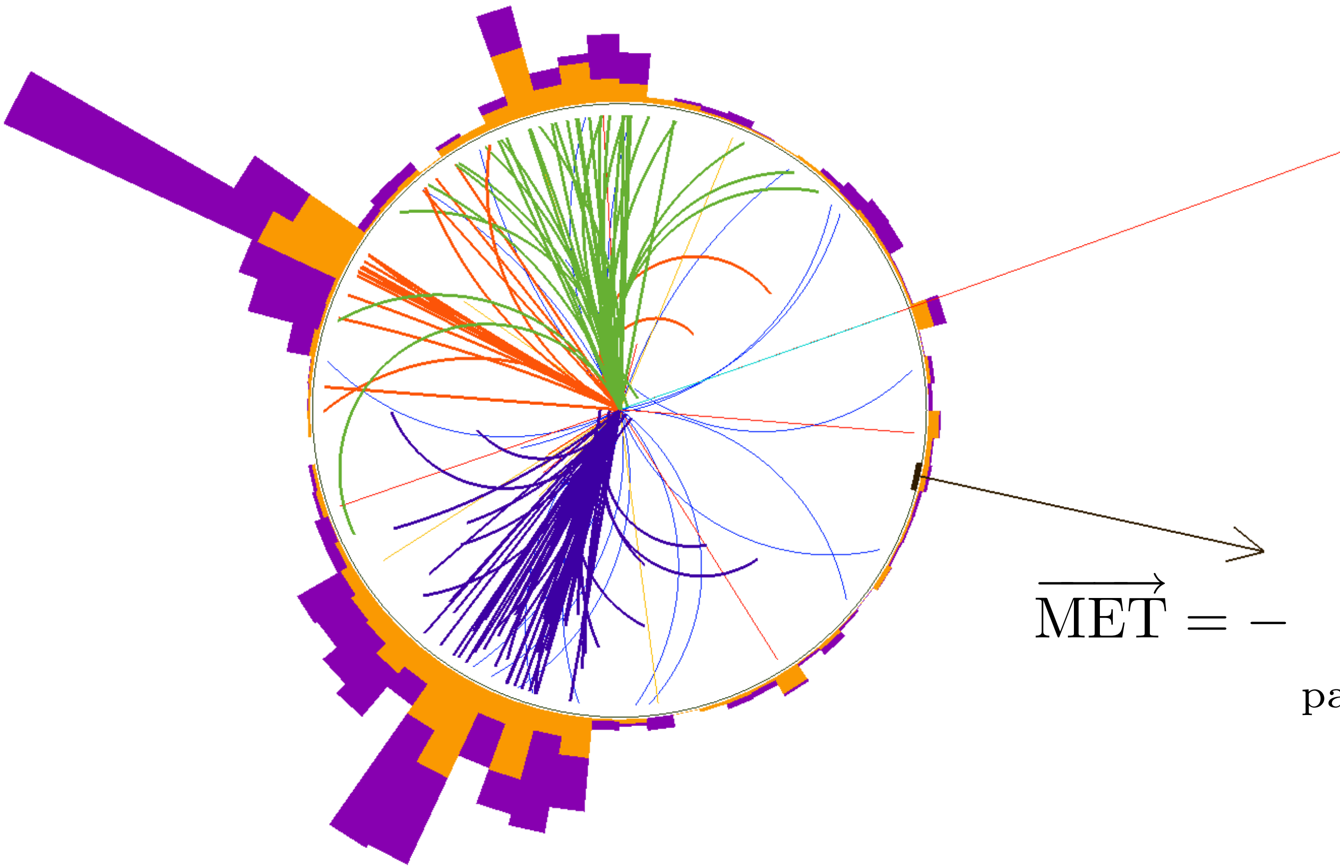

HCAL
deposit
ECAL deposit
Charged hadron
Muon
Photon
Neutral hadron

# Particle jets



# Missing transverse momentum

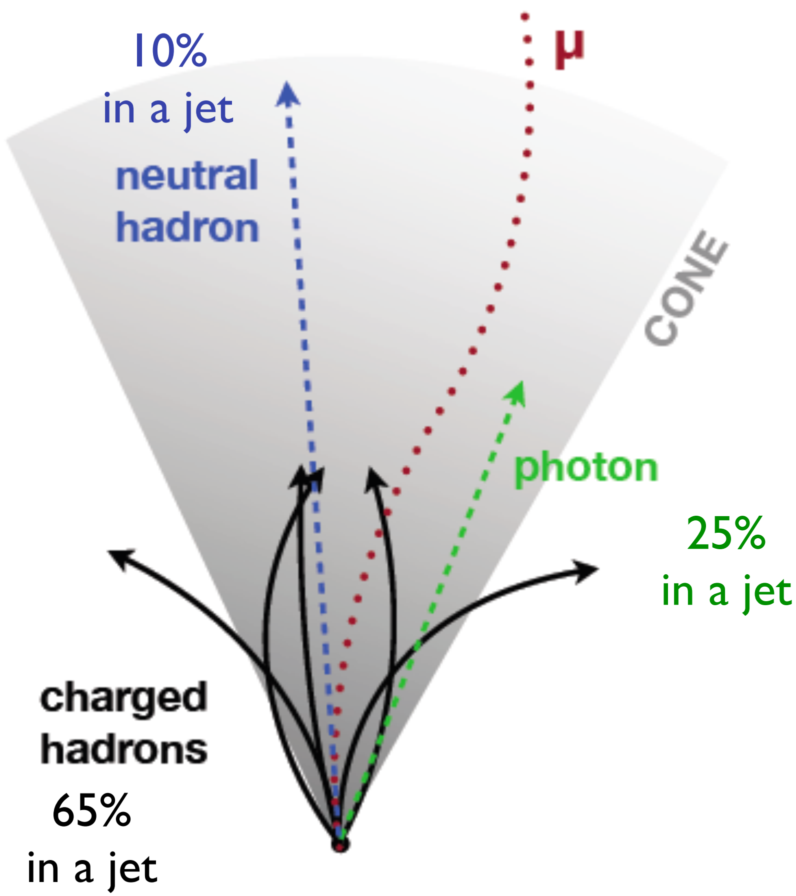
and not "energy" !



$$\overrightarrow{\mathrm{MET}} = -\sum_{\mathrm{particles}} \vec{p}_{\mathrm{T}}$$

For the first time at a hadron collider !

# Expectations for the jet energy response & resolution




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

Even in high-pT jets, the average $p_T$ of the stable particles remains usually soft

As a result, 90% of the energy is measured with a high precision:

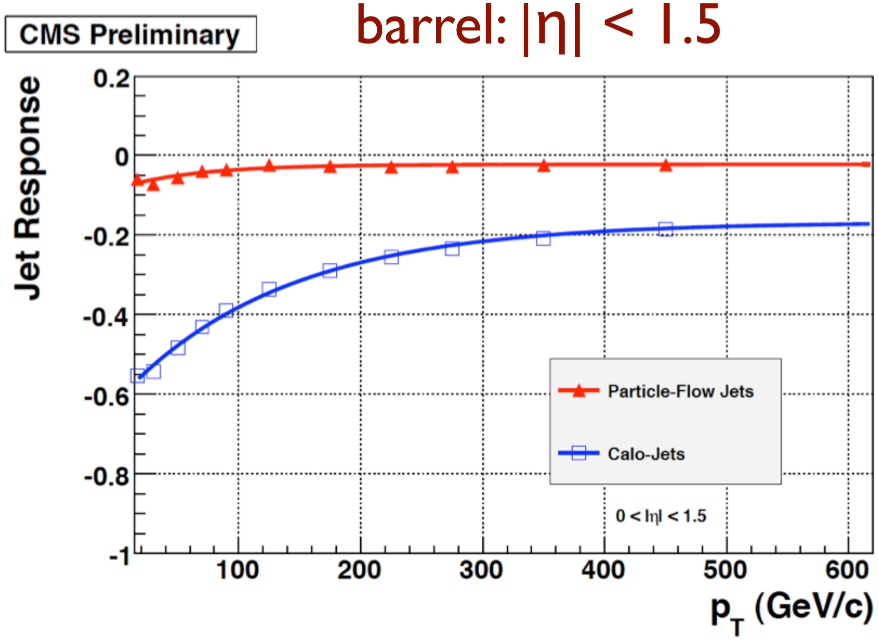
- Tracking: resolution < 1%
- Photons: $2.7\%/\sqrt{E} \oplus 0.5\%$ barrel
  $5.7\%/\sqrt{E} \oplus 0.5\%$ endcaps

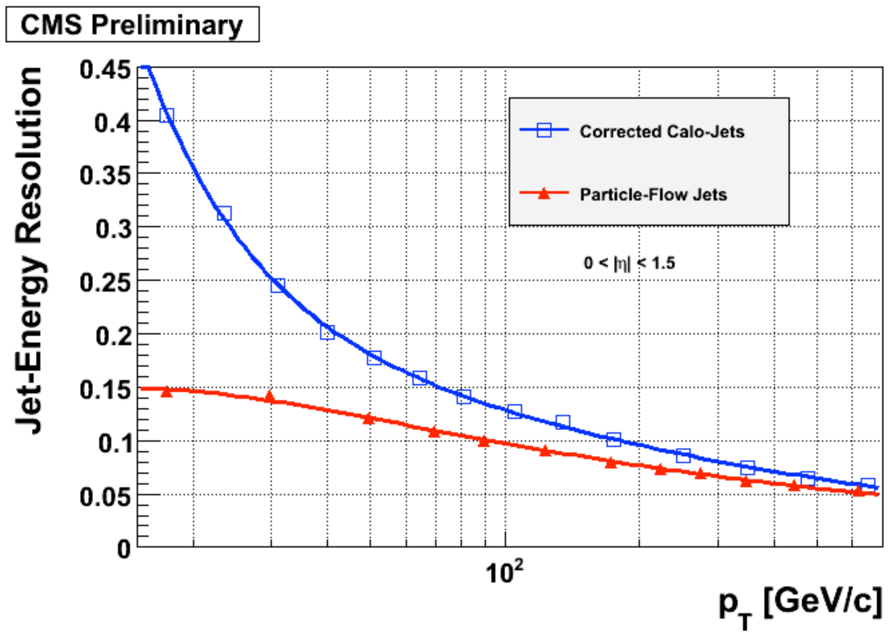
The remaining 10% are measured with the HCAL resolution

- Hadrons: $120\% / \sqrt{E}$

# Jet energy response & resolution

simulated QCD-multijets events
barrel: $|\eta| < 1.5$



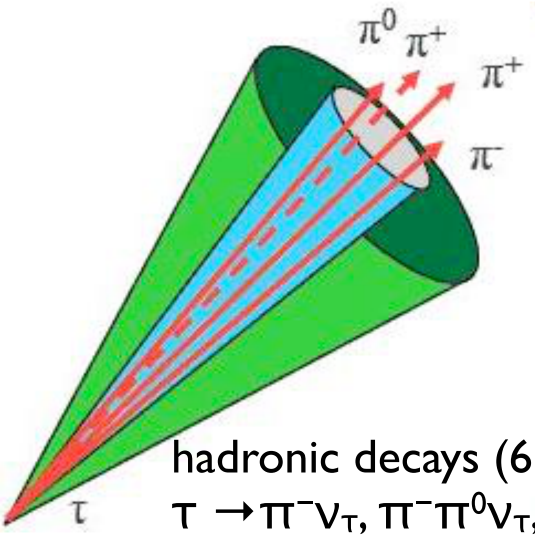

95-97% of the $p_T$ reconstructed, over the whole range

Very large improvement at low $p_T$, thanks to the tracks

Not mentioning:

- the gain in angular resolution (factor 2-3)
- much reduced dependency on the jet parton flavour (< 2% for jets $p_T$ > 20 GeV) instead of ~10%

# Tau lepton reconstruction

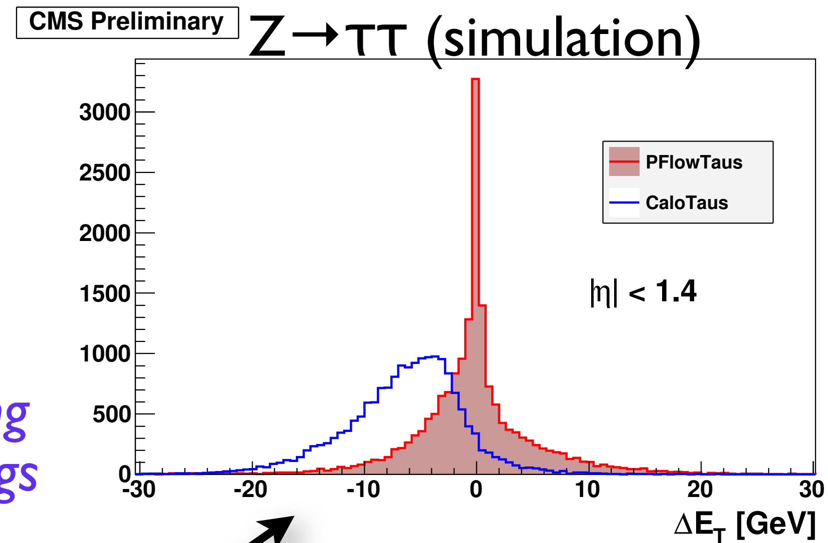


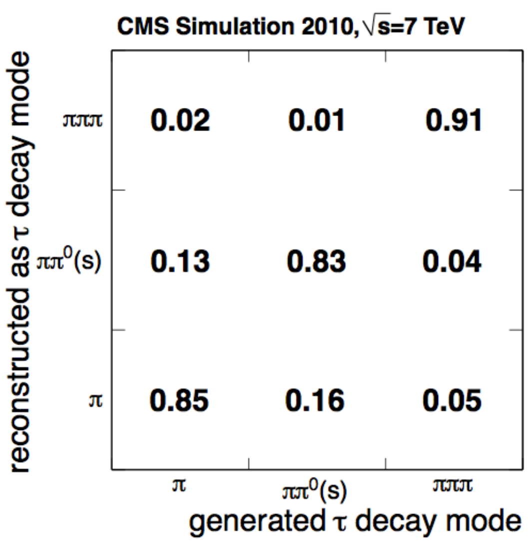

hadronic decays (65%)

$\tau \rightarrow \pi^- \nu_\tau,\ \pi^- \pi^0 \nu_\tau,\ \pi^-\ (n\pi^0) \nu_\tau$ *1-prong*

$\tau \rightarrow \pi^+ \pi^- \pi^- (n\pi^0)\ \nu_\tau$ *3-prongs*

(Reconstructed - simulated) visible energy

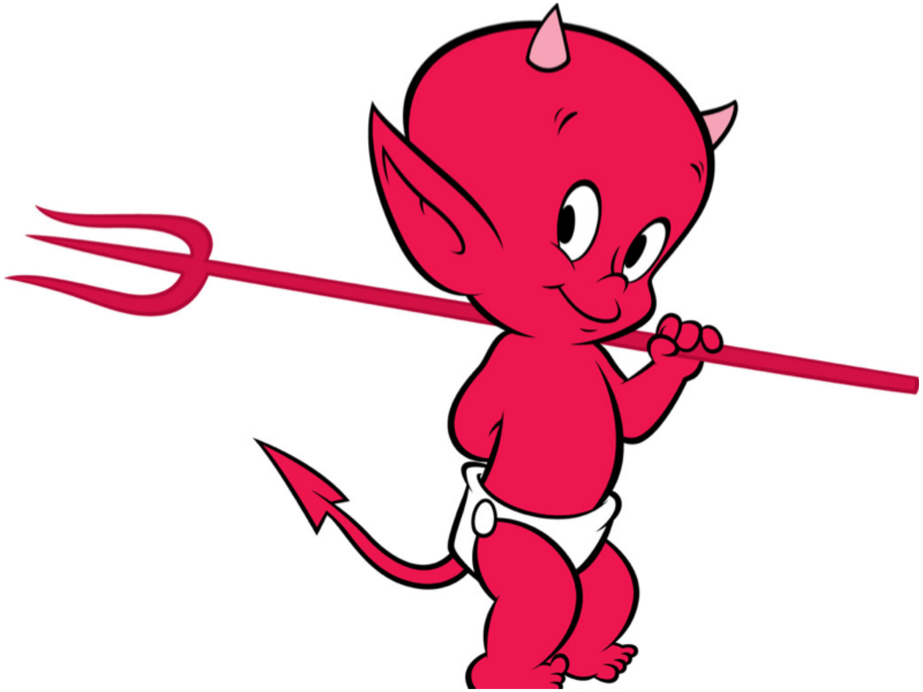



- Immediate and important benefit of using self-calibrated particles
- Access to the τ-decay channel

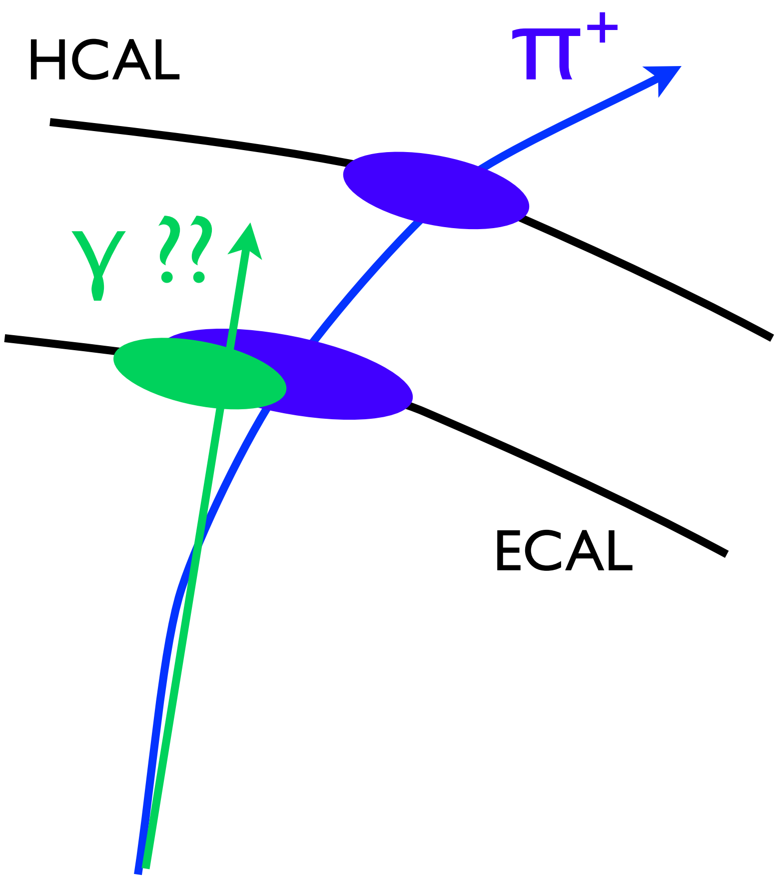
*More in Phil's talk just after...*

# A bit more into the details



# Charged hadrons, overlapping neutrals

*How to deal with neutrals overlapping with charged hadrons ?*
→ *exploit redundancy !*




For each HCAL cluster, compare:

- Sum of track momenta p
- Calorimeter energy E
  - Linked to the tracks
  - Calibrated for hadrons
    $a(E)E_{ECAL}+b(E)E_{HCAL}+\text{offset}$

E and p compatible

- Charged hadrons

$E > p + 120\% \sqrt{p}$

- Charged hadrons + Photon / neutral hadron

Precedence is given to photons as they are more abundant than neutral hadrons

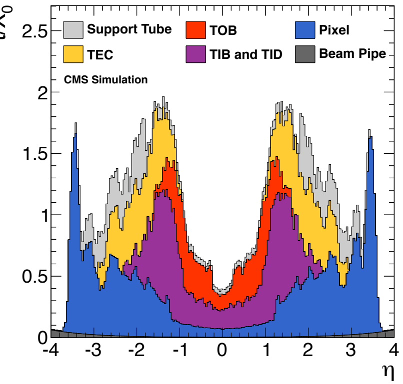
$E \ll p$

- Need attention …
  Rare: muon, fake track

# Electrons

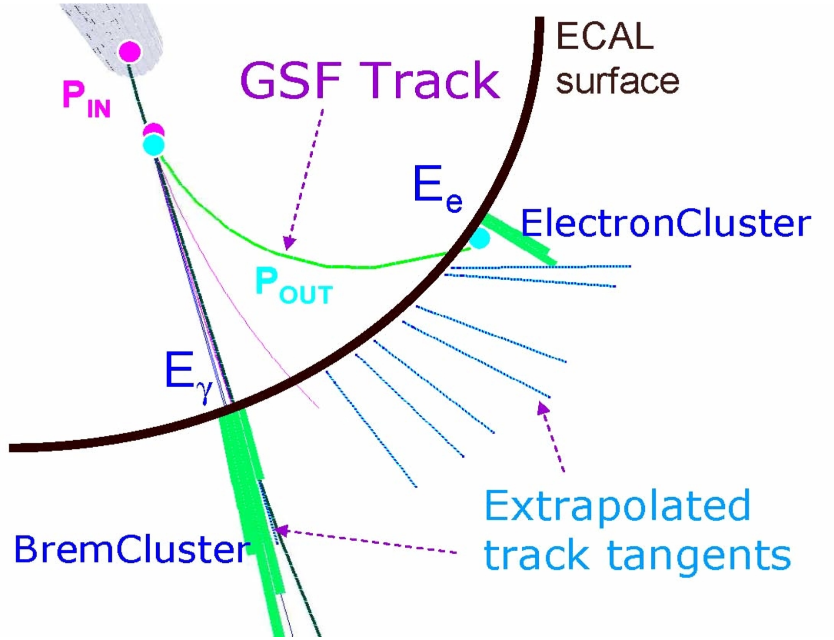
The PFlow needs to reconstruct all the electrons isolated or not, at all $p_T$s

- if not identified, the energy of a Bremsstrahlung photon cluster is counted twice
- in a jet, the electron should not swallow the entire jet




*Material: up to $2X_0$ in front of the ECAL*

*Magnetic field: 3.8T*




The electron track reconstruction is able to follow the electron up to the ECAL entrance, a Gaussian Sum Filter fit is then carried out

For each tracker layer where most of the material is located: mimic a Brem emission (tangent straight-line extrapolation)

Catch the electron cluster with a helix extrapolation from the outermost state of the track

Then, specific procedures to identify clusters from converted Brems

Finally, a loose electron-ID is applied

# Commissioning

The commissioning started with the first min-bias events at 900 GeV
It continued with the first collisions at 2.36 TeV and finally at 7 TeV

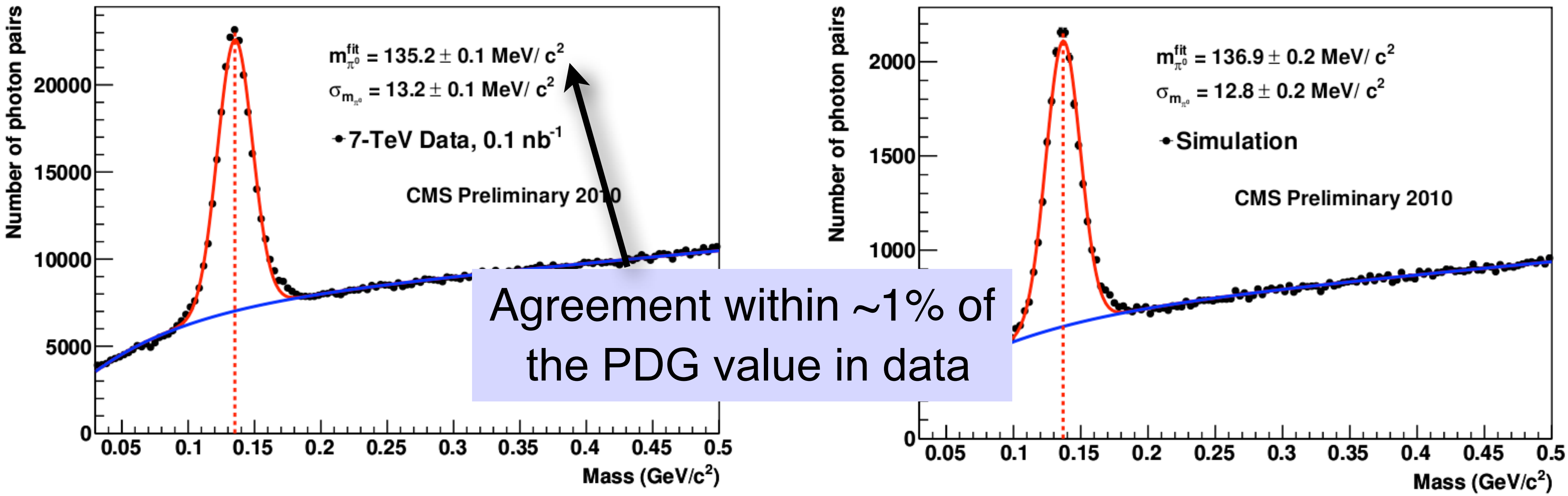
As a result, most of the plots shown hereafter are ~ 3 years old

Many recent results on Jets & MET have been shown in Chayanit's talk on Monday

but I couldn't resist in showing more recent results as well

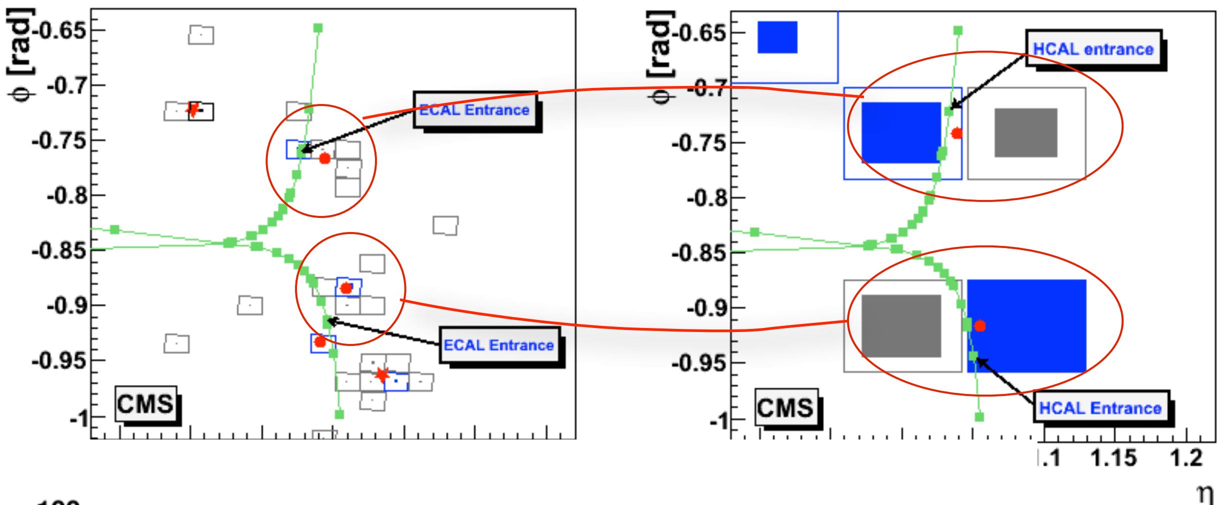
# Photons

Commissioning with $\pi^0 \rightarrow \gamma\gamma$ in 2010

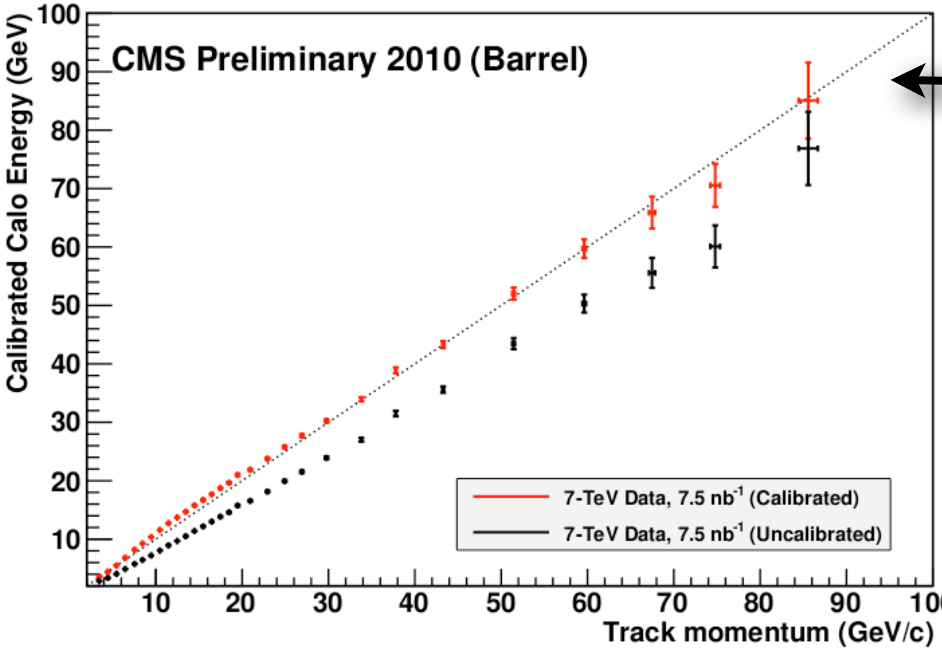



Demonstrates the suitability of the absolute ECAL calibration
(has improved since as shown in Maria's & Marc's talks on Monday)

# Calorimeter response to hadrons




Obtained with charged hadrons

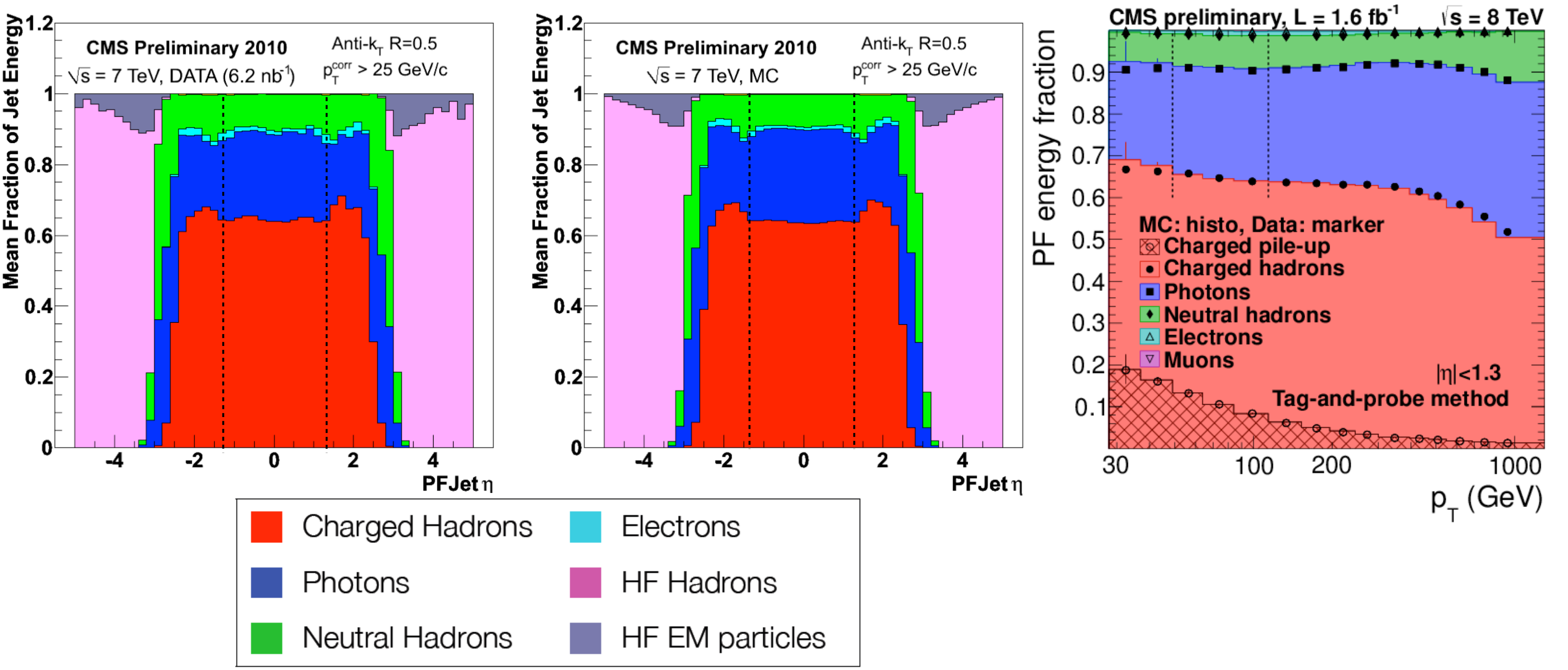



Calorimeter response is important for neutral hadrons

The calorimeter response to hadrons is well simulated.
The hadron response in the calorimeters is adequate at the 5% level (2010 result)
(similar agreement in the end-caps)

Currently around 2%

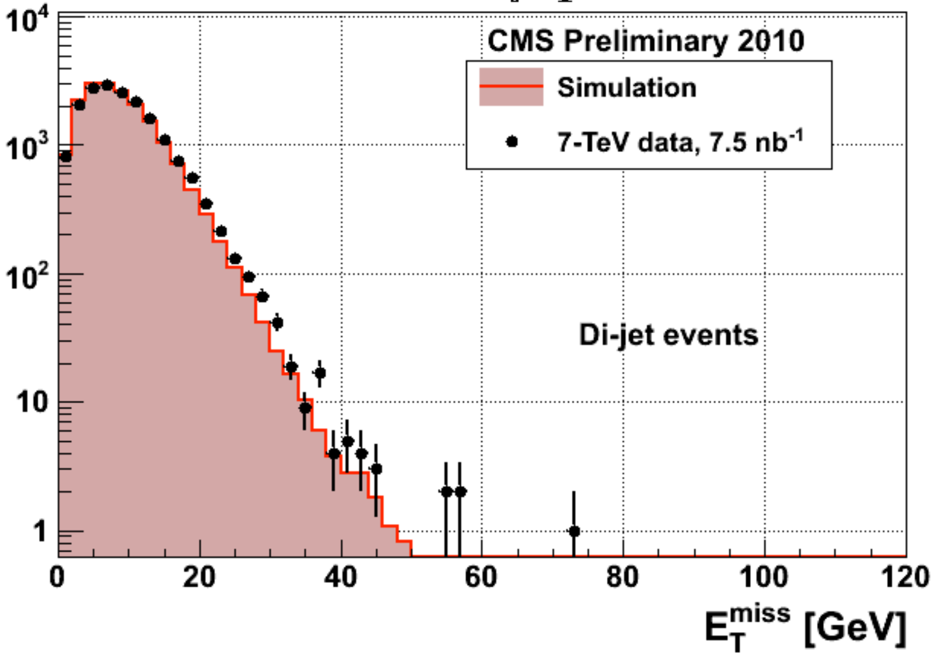
# Jet composition

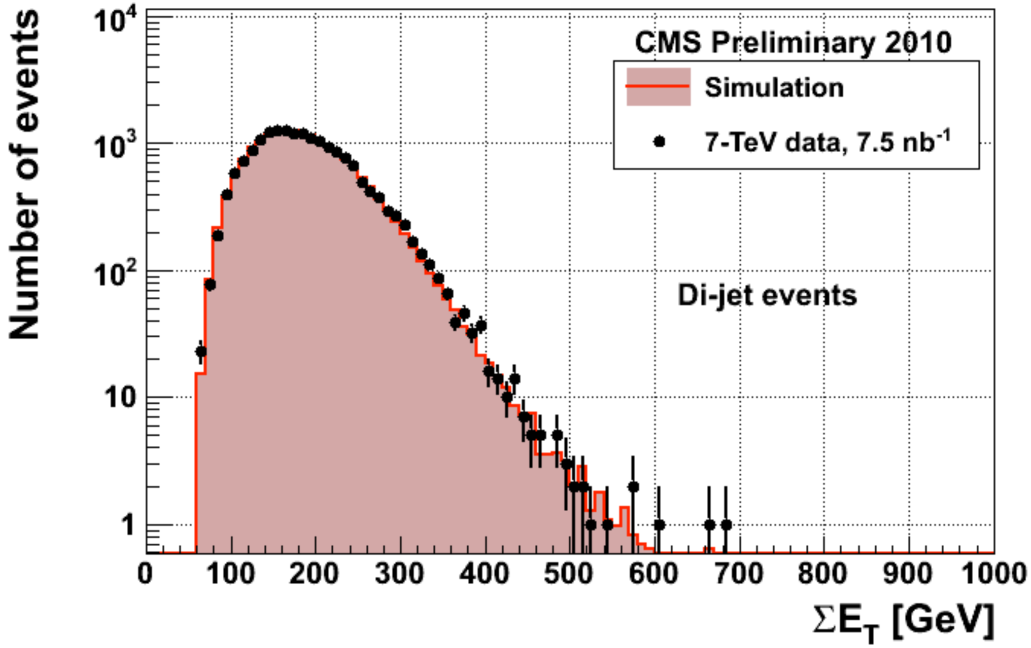



The agreement of the first days is confirmed with high statistics, even in presence of pile-up

# Missing transverse momentum

$$\overrightarrow{E_T^{miss}} = -\sum_{i=1}^{N_{particles}} \overrightarrow{E_T}^i$$




Agreement over 3 orders of magnitude for the $E_T^{miss}$

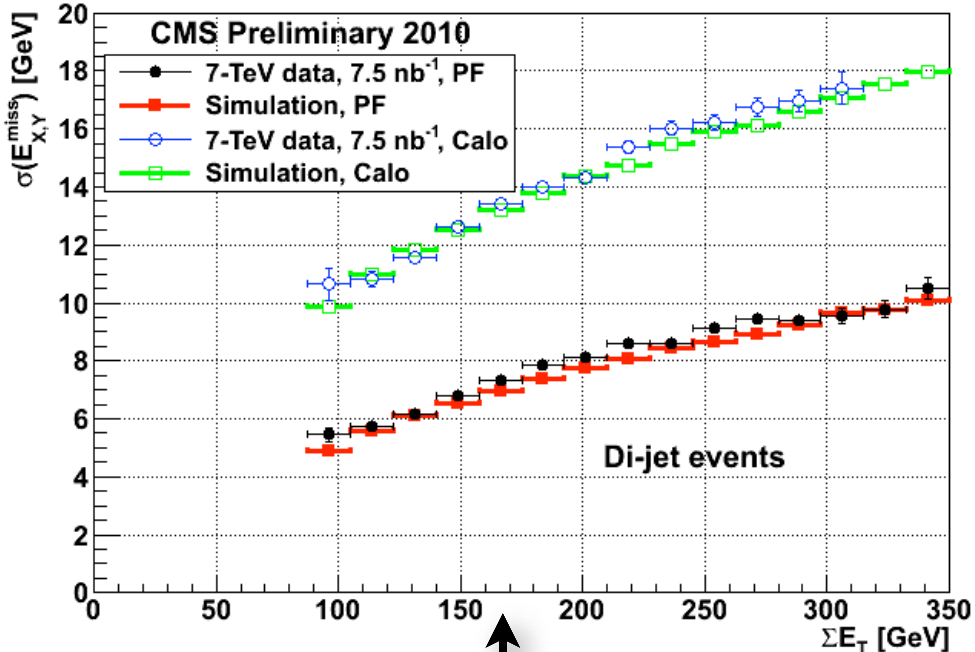
Even more challenging: the scalar sum of the particle $p_T$ were no cancellation can occur !

All together, a remarkable agreement is obtained on these quantities known to be difficult to reproduce at hadron colliders

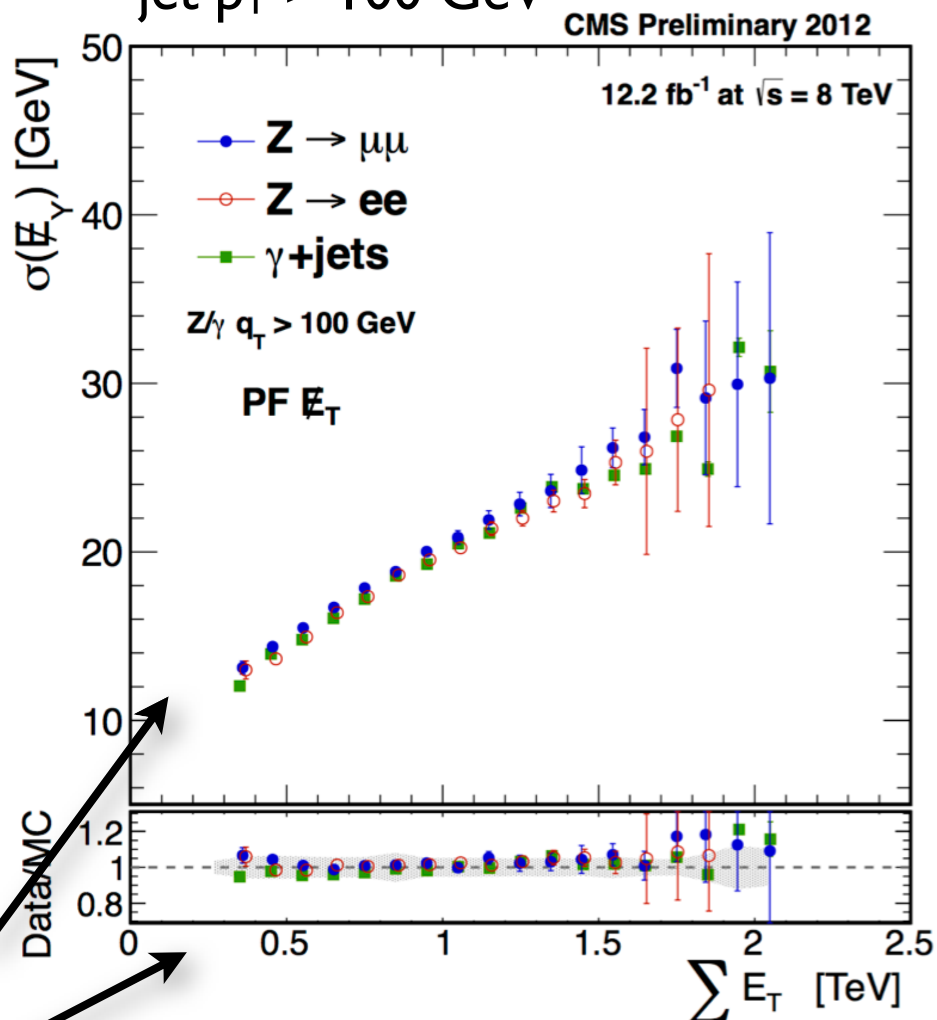
- robustness of the algorithm
- precise simulation of the detectors

# Missing transverse momentum resolution

jet $p_T$ > 20 GeV




jet $p_T$ > 100 GeV



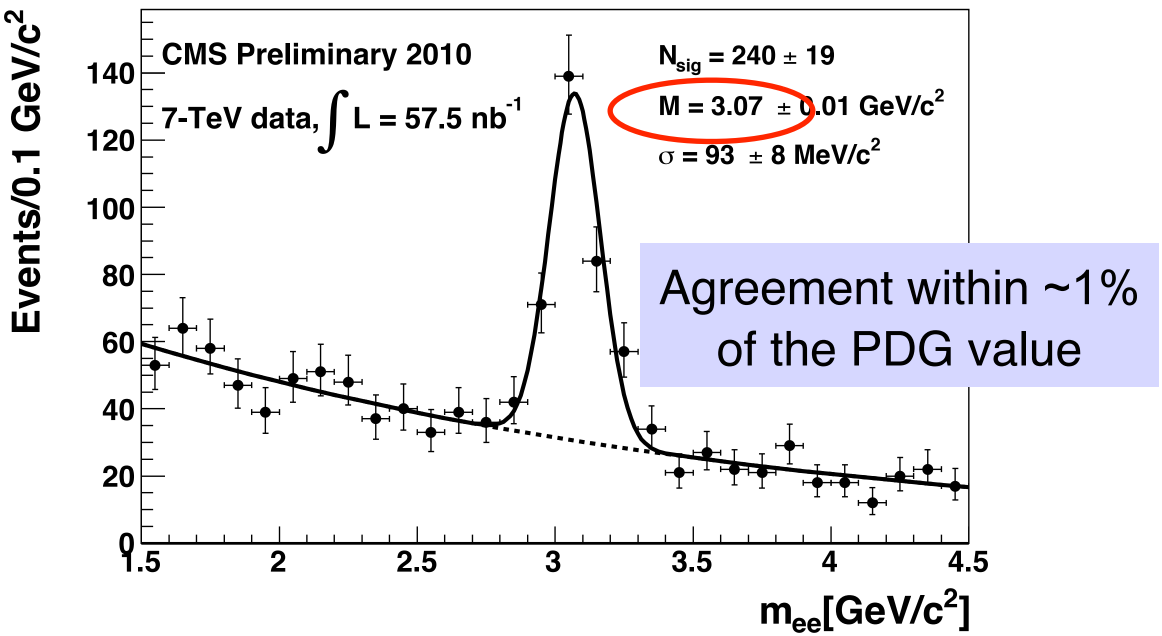

The $E_T^{miss}$ resolution is improved by a factor of ~2 wrt. the calorimeter-based $E_T^{miss}$

Nowadays, boosted Z's and γ+jets are used, the data/simulation agreement is impressive

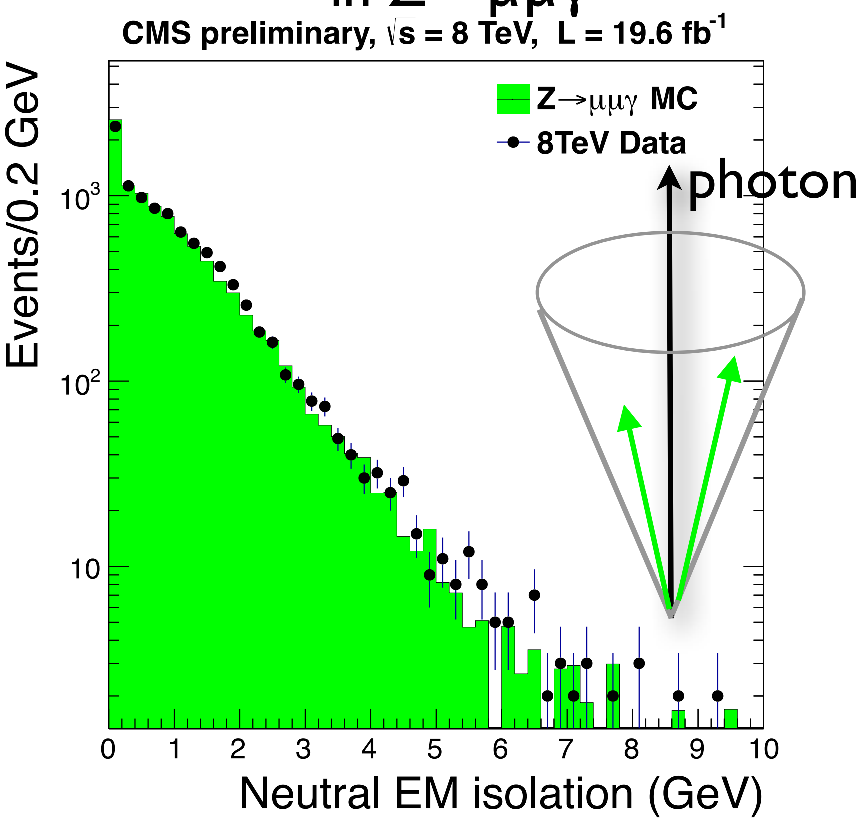
# Electrons & Photons

*From 2010 ....* *to* *...2013*

J/Ψ→ee




Photon isolation around photons in Z→μμγ




With a simple selection a nice J/Ψ→ee peak is obtained

With large statistics, rare and clean events can be used to carry out the detailed performance studies required by the high precision analyses done nowadays

# Effects on physics analyses

**Jets**

- energy resolution / 2
- angular resolution / 3
- Flavour dependence of response / 3
- Systematic error on JES / 2
- « electron in jet » b tagging
- quark-gluon jet tagging

**MET**

- resolution / 2
- less tails

**τ**

- jet fake rate / 3 @ same eff.
- energy resolution / 4
- decay mode

**Electrons**

- down to pT = 3 GeV
- in jets

**μ**

- 4% more efficient ID @ same bkg rate
- better momentum assignment at high $p_T$

**e, μ, τ, γ isolation**

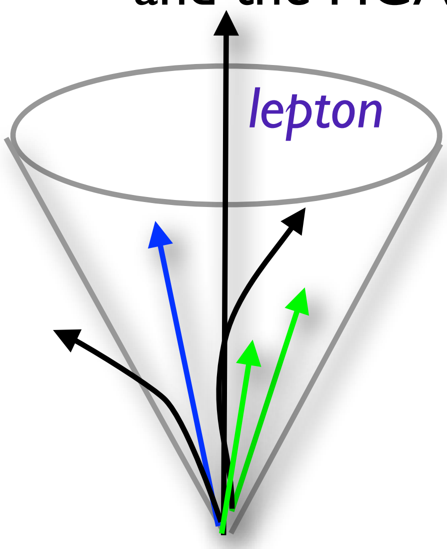
- improved performance, pile-up control

**Physics analyses**

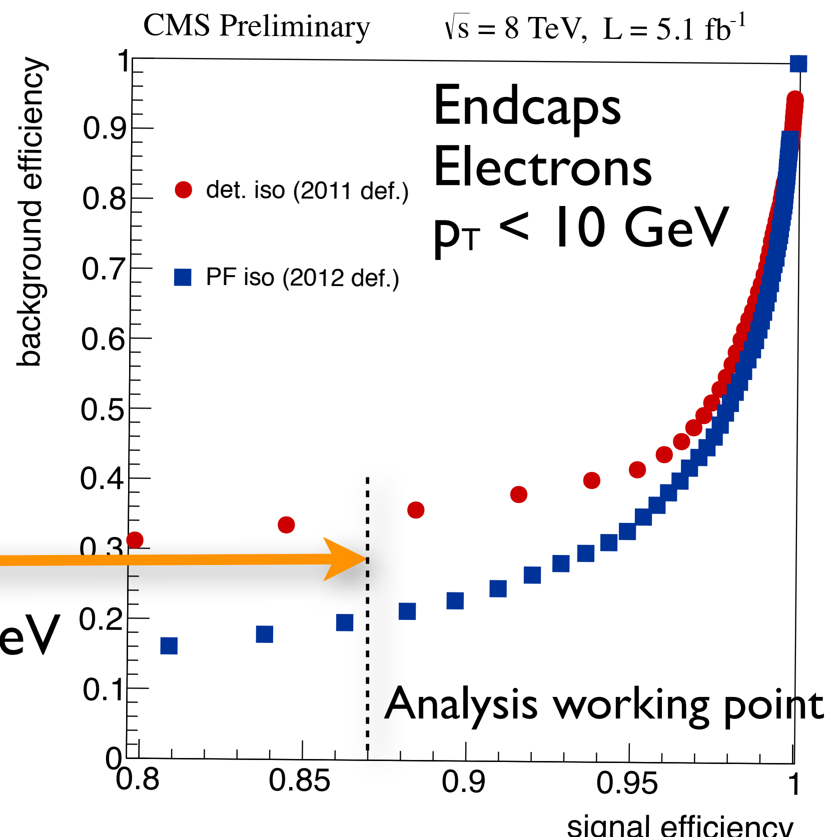
- Better trigger for jets, MET, taus (PF@HLT)
- FSR photon recovery in HZZ
- embedding in $H\rightarrow\tau\tau$
- jet substructure

# PF isolation

The "classic" method to compute the lepton/photon isolation was to sum the energy deposits in the tracker, the ECAL and the HCAL



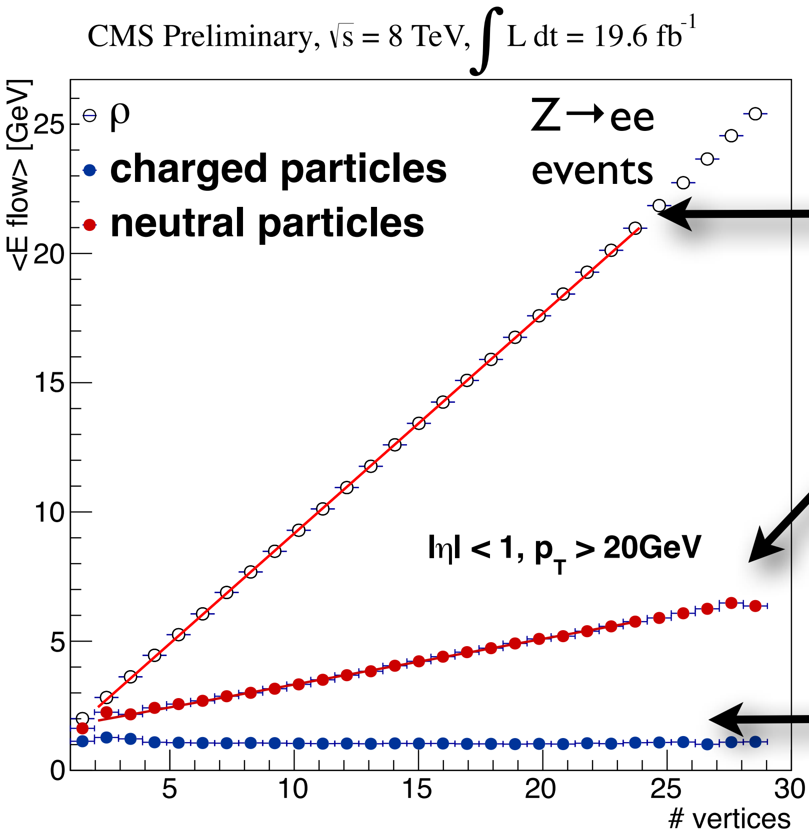

Background efficiency divided by a factor of 2
Similar gain for $p_T$ < 20 GeV




With the Particle Flow it is natural to use the reconstructed particles, to compute the momentum carried by charged hadrons/photons/neutral hadrons in a cone centered on the lepton/photon

- The object footprint is automatically removed by the PF
- No double counting of track and calorimeter energy deposits for charged particles

# Lepton/Photon isolation : pile-up mitigation

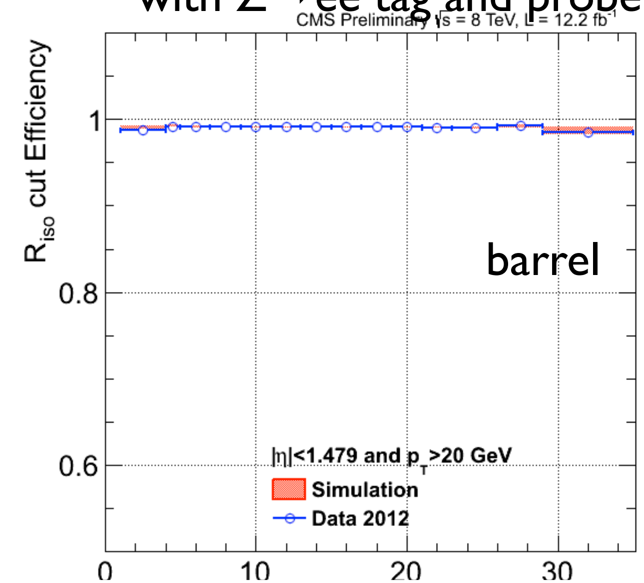


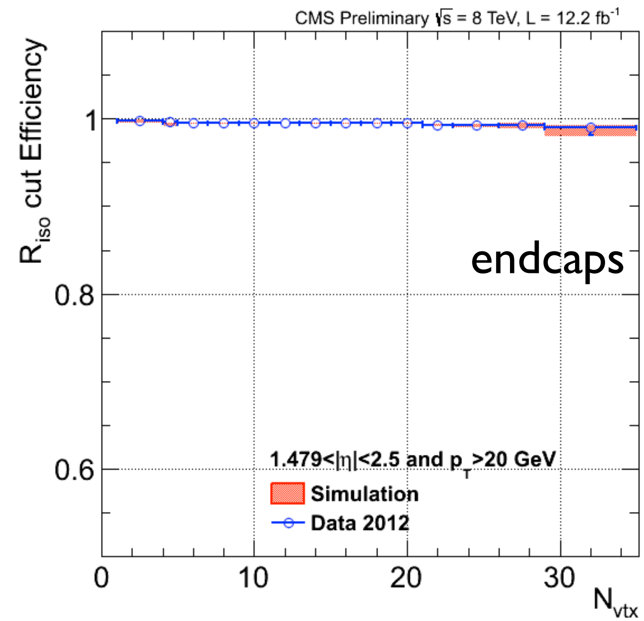

average event energy density (fastjet)

Neutral particles around leptons

Charged hadrons (required to come from the primary vertex) around leptons

Isolation efficiency measurement with Z→ee tag and probe



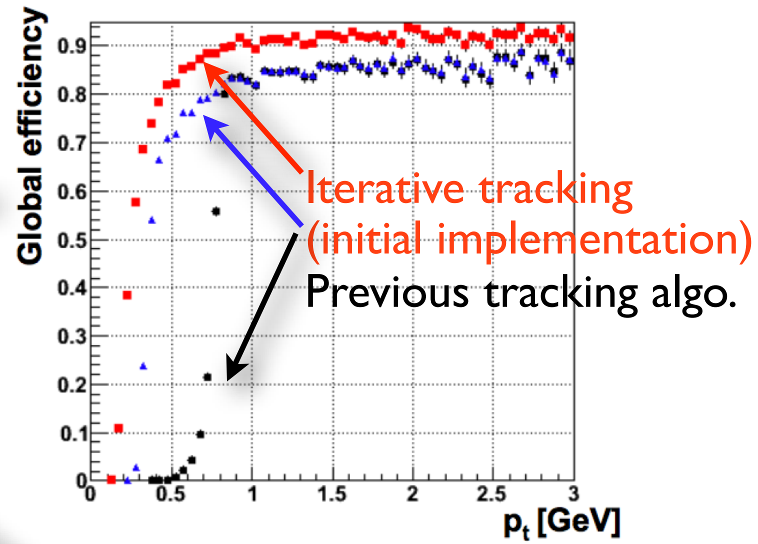



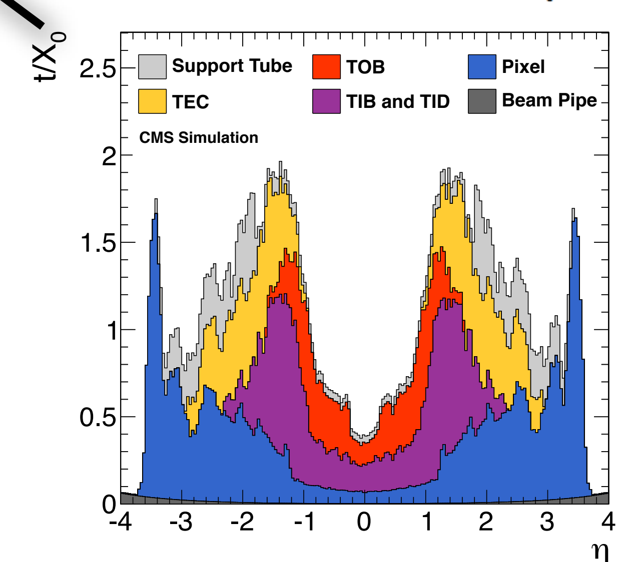

- No correction needed for the charged hadrons (vertex constraint)
- For the neutrals: the PU contribution in the cone is estimated (proportional to the energy density) and subtracted

# Ingredients for a good Particle Flow

CMS: 4.9 T.m (x~2 existing and past detectors)

- Separate neutrals *from* charged hadrons
  - Field integral (BxR)
  - Calorimeter granularity
- Efficient tracking
- Minimize material before calorimeters
- Clever algorithm to compensate for detector imperfections



# Conclusion

The Particle Flow algorithm has been deployed in CMS and is currently used in most of the analyses

The concept is simple, the implementation required some work...

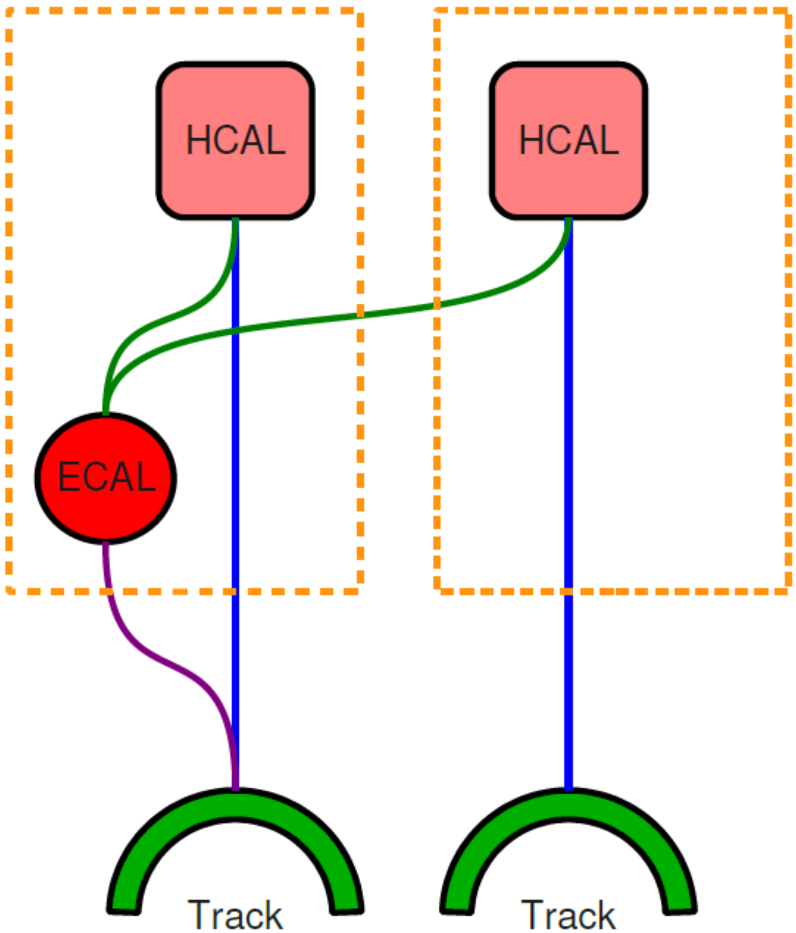
It has significantly improved the performance on jets, MET, taus, lepton isolation..

The PF has not only proven to work well with high PU, it is now considered as the only way to preserve or even hopefully improve the performance of CMS for the next rounds of data-taking
→Global Event Description

It is likely that many applications of the GED have not been invented or tried yet but the next talk will show was has already been done !

# Backup

# Charged+neutrals: E > p




Significant excess of energy in the calorimeters:

$E > p + 120\% \sqrt{E}$

Charged hadrons [ $p_i$ ]

Neutrals:

E from ECAL or HCAL only:

| | | |
|---|---|---|
| HCAL | $h^0$ | [ E – p ] |
| ECAL | γ | [ $E_{ECAL}$ – p/b ] |

E from ECAL and HCAL:

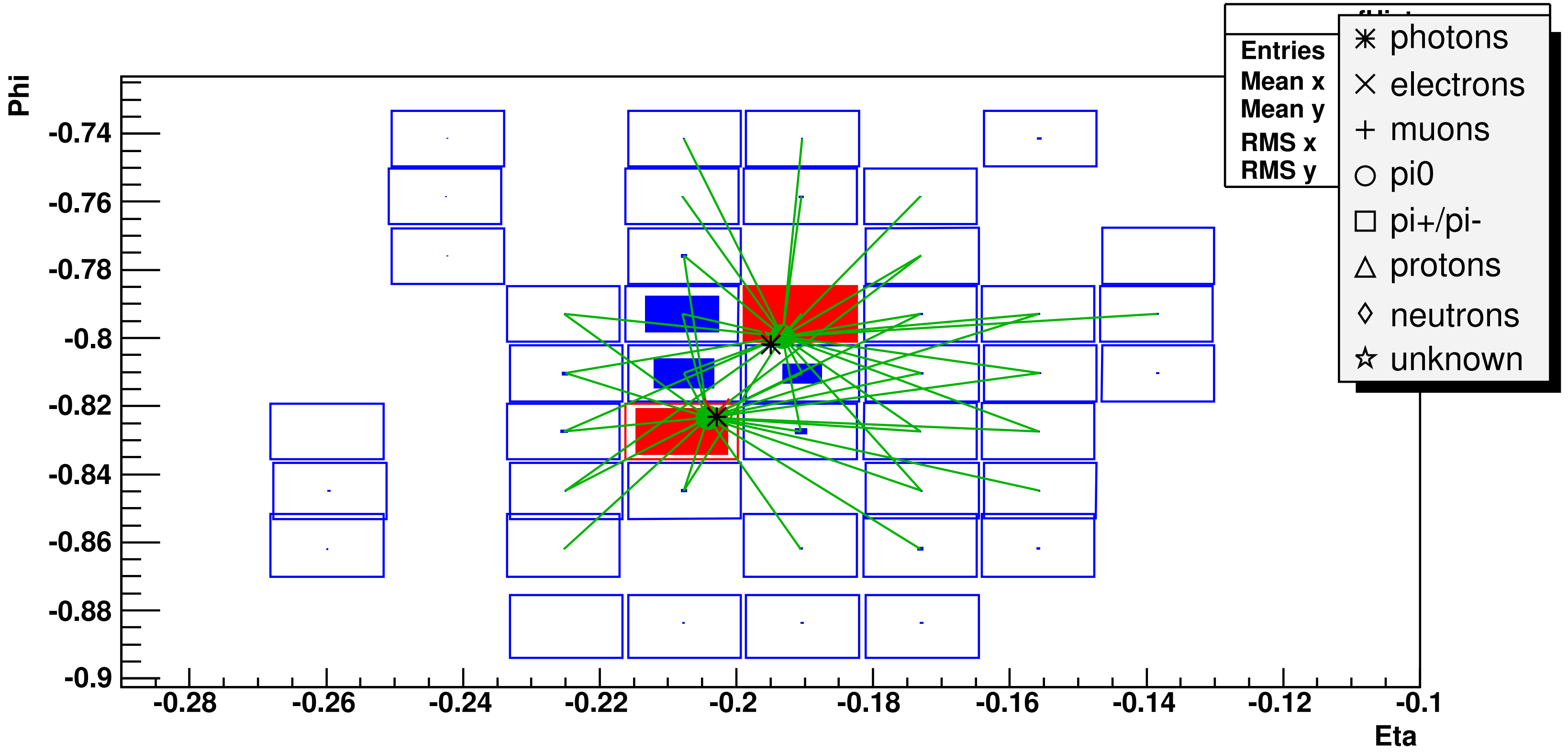
$E\text{-}p > E_{ECAL}$ ?

| | |
|---|---|
| γ | [ $E_{ECAL}$ ] |
| $h^0$ | with the rest |

Else:

| | |
|---|---|
| γ | [ (E – p) / b ] |

# Clustering



Entries
Mean x
Mean y
RMS x
RMS y
photons
electrons
muons
pi0
pi+/pi-
protons
neutrons
unknown
Phi
-0.74
-0.76
-0.78
-0.8
-0.82
-0.84
-0.86
-0.88
-0.9
-0.28
-0.26
-0.24
-0.22
-0.2
-0.18
-0.16
-0.14
-0.12
-0.1
Eta