Particle Flow in CMS (and ATLAS)

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For the CMS and ATLAS Collaborations

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Outline

The CMS particle flow algorithm:
charged hadrons, photons, neutral hadrons, electrons, *(muons)*

Performance:
Jets, Taus, *(MET, Leptons)*

The ATLAS algorithm:
Principles, Jet performance, Comparison with CMS

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Particle-flow reconstruction and global event description with the CMS detector

The CMS collaboration

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ABSTRACT: The CMS apparatus was identified, a few years before the start of the LHC operation at CERN, to feature properties well suited to particle-flow (PF) reconstruction: a highly-segmented tracker, a fine-grained electromagnetic calorimeter, a hermetic hadron calorimeter, a strong magnetic field, and an excellent muon spectrometer. A fully-fledged PF reconstruction algorithm tuned to the CMS detector was therefore developed and has been consistently used in physics analyses for the first time at a hadron collider. For each collision, the comprehensive list of final-state particles identified and reconstructed by the algorithm provides a global event description that leads to unprecedented CMS performance for jet and hadronic τ decay reconstruction, missing transverse momentum determination, and electron and muon identification. This approach also allows particles from pileup interactions to be identified and enables efficient pileup mitigation methods. The data collected by CMS at a centre-of-mass energy of 8 TeV show excellent agreement with the simulation and confirm the superior PF performance at least up to an average of 20 pileup interactions.

KEYWORDS: Large detector systems for particle and astroparticle physics; Particle identification methods

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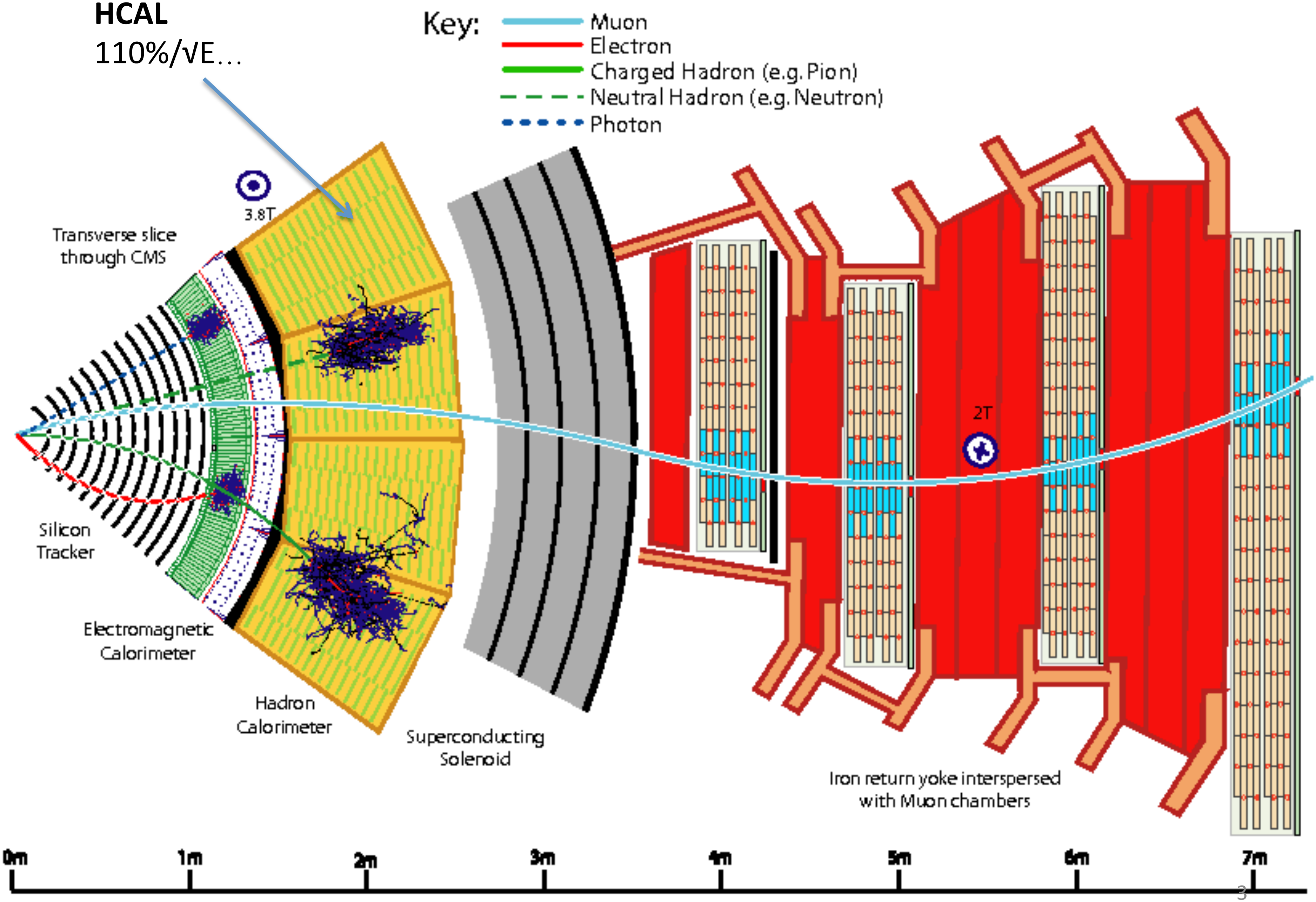
arxiv:1706.04965

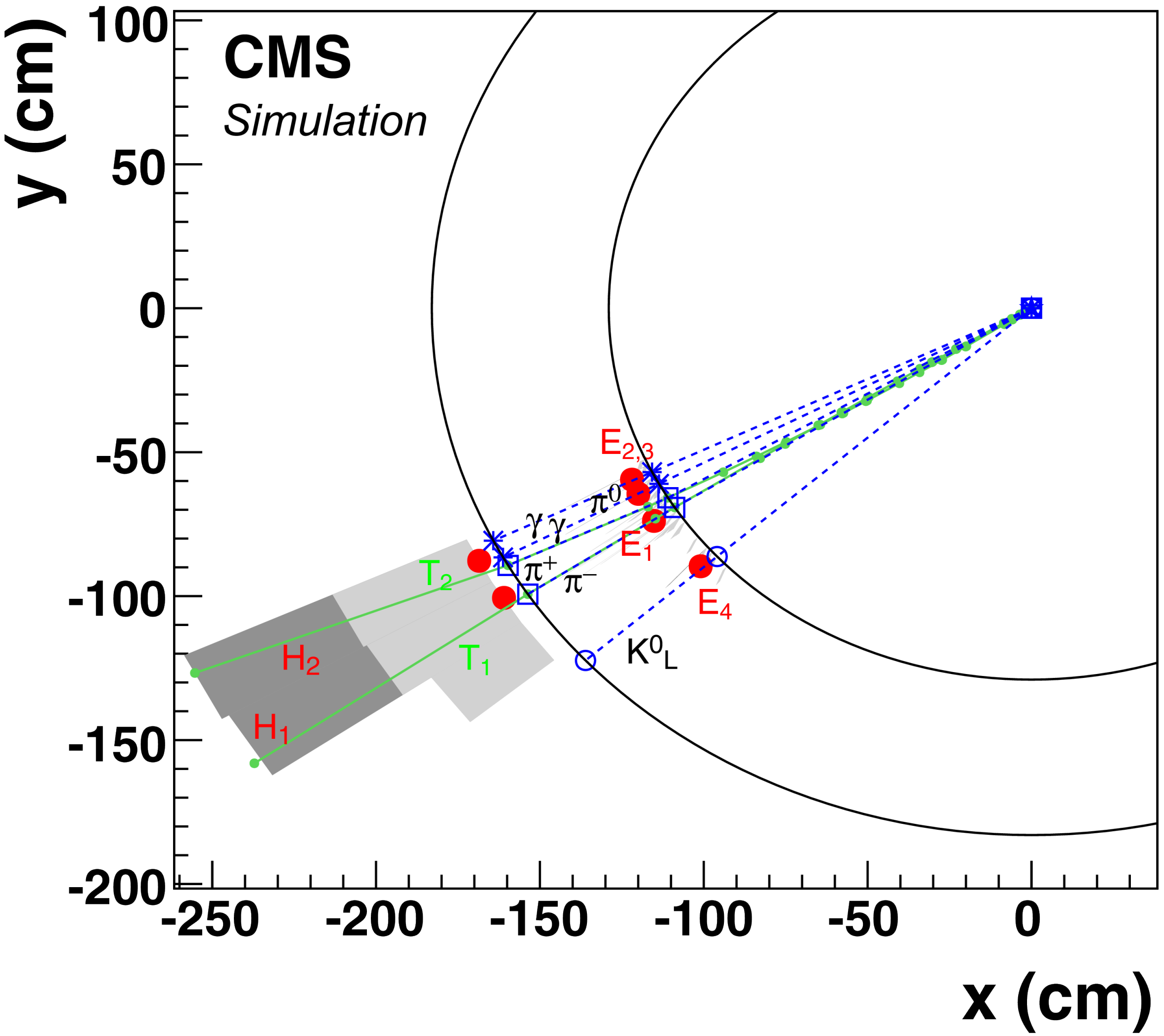
HCAL

110%/√E…



Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
3.8T
Transverse slice through CMS
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0m
1m
2m
3m
4m
5m
6m
7m

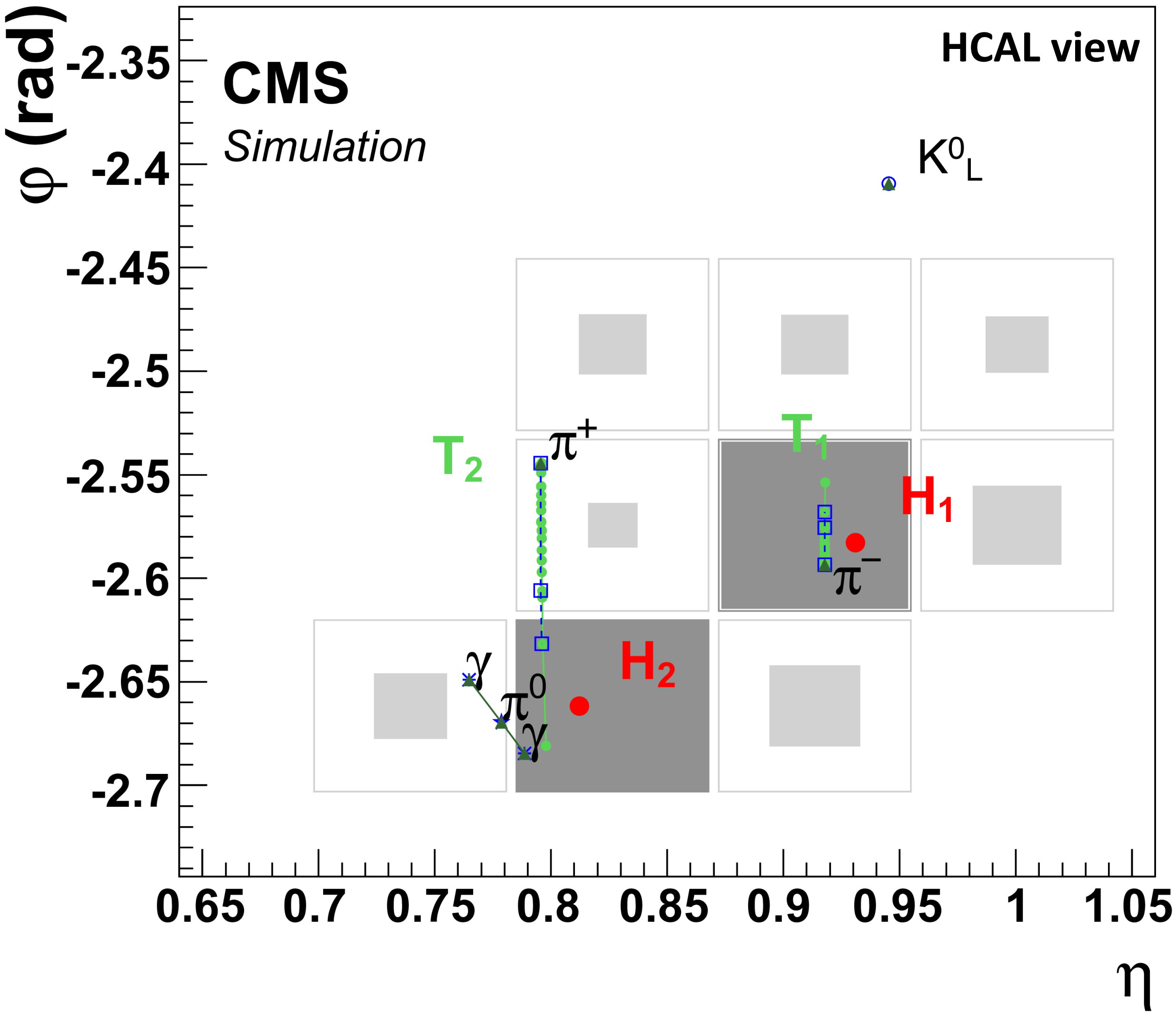
A Simple Jet



pT = 65 GeV
only 5 particles

Illustrate:
- calo clustering
- particle flow

Calorimeter Clustering

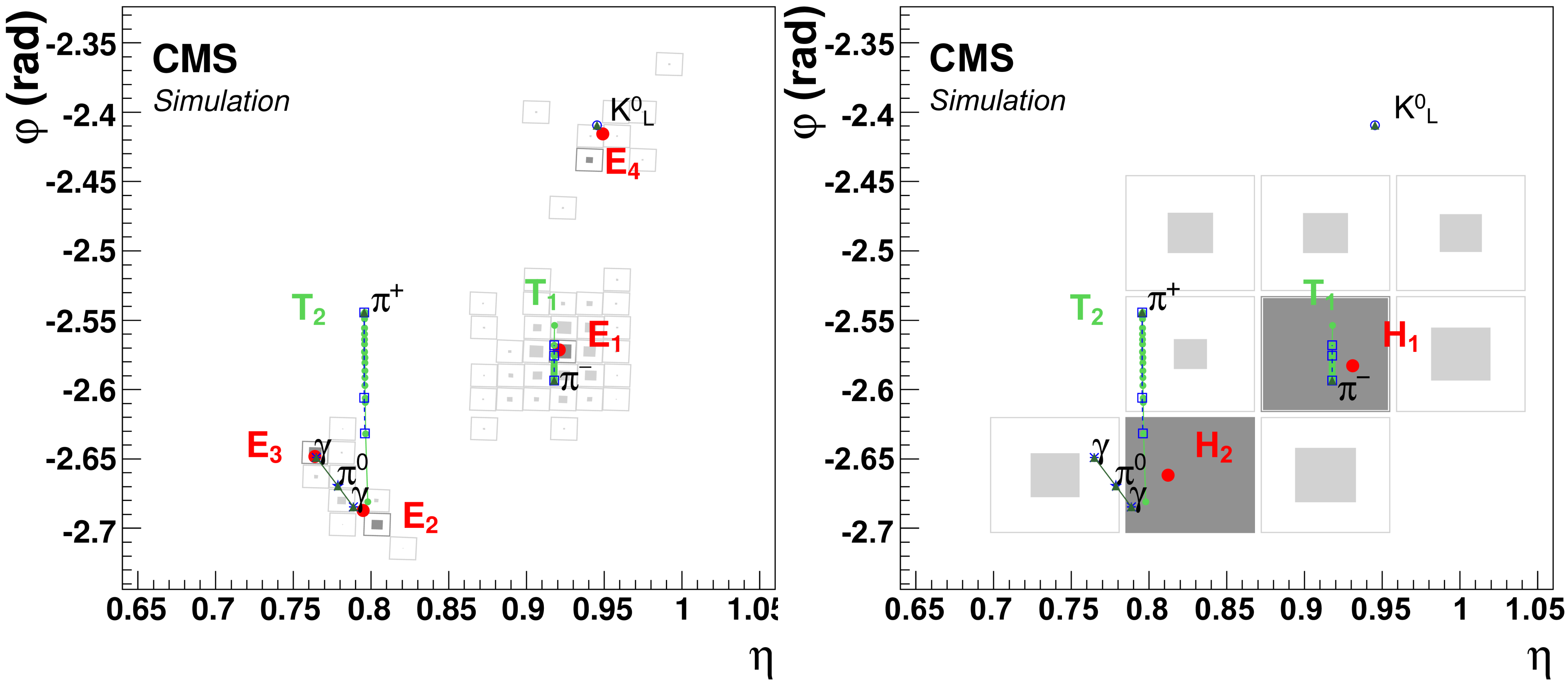


Seeds
- local energy maxima

Connected cells

Share energy
- iteratively
- assuming Gaussian shower profile

Particle Flow

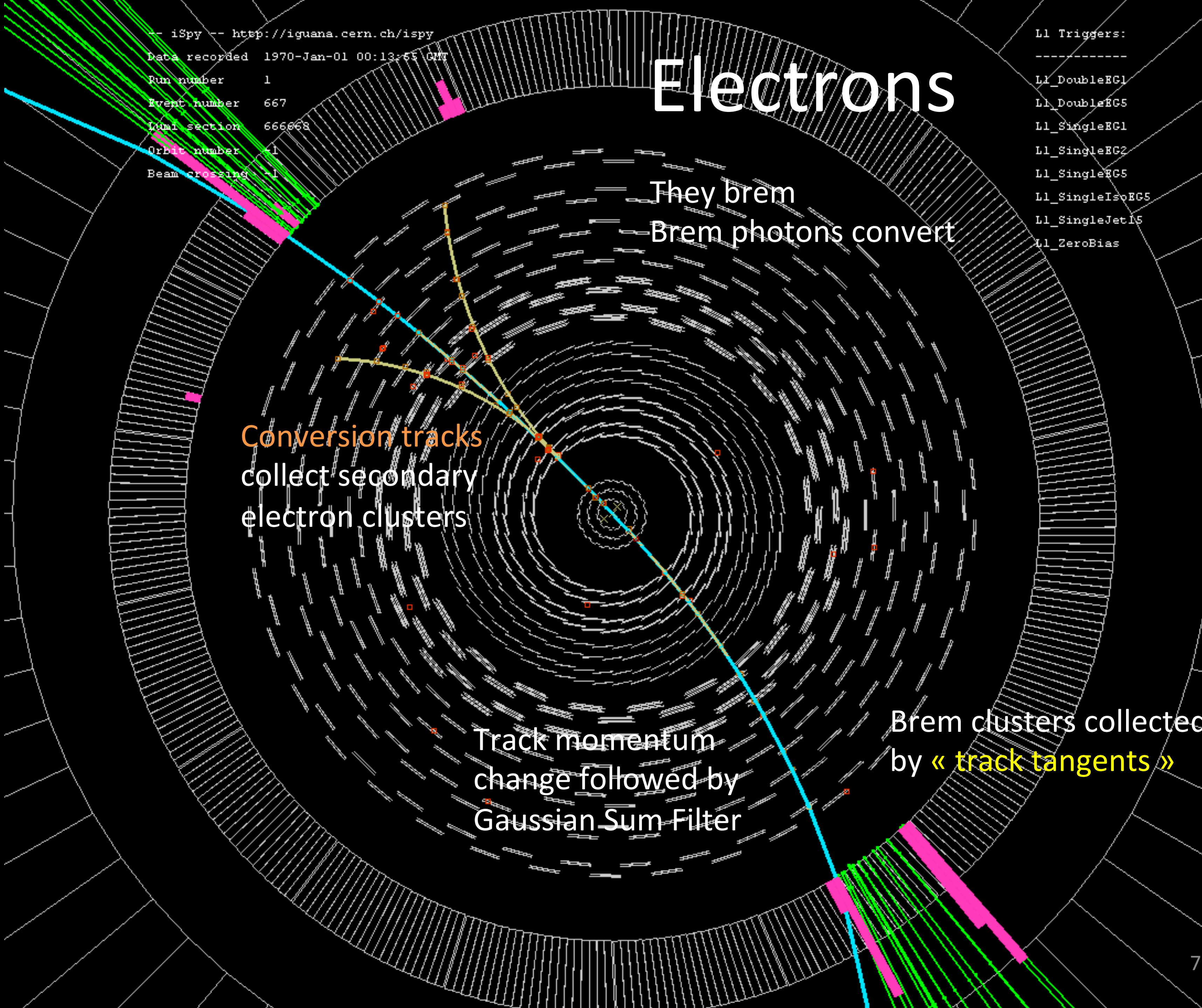


Clusters not linked to a track → photon (ECAL) or neutral hadron (HCAL)

Tracks → charged hadrons

- compatible energy in calos: energy from a fit of track and cluster measurements
- excess: additional neutrals
- deficit: muon, fake track

Electrons

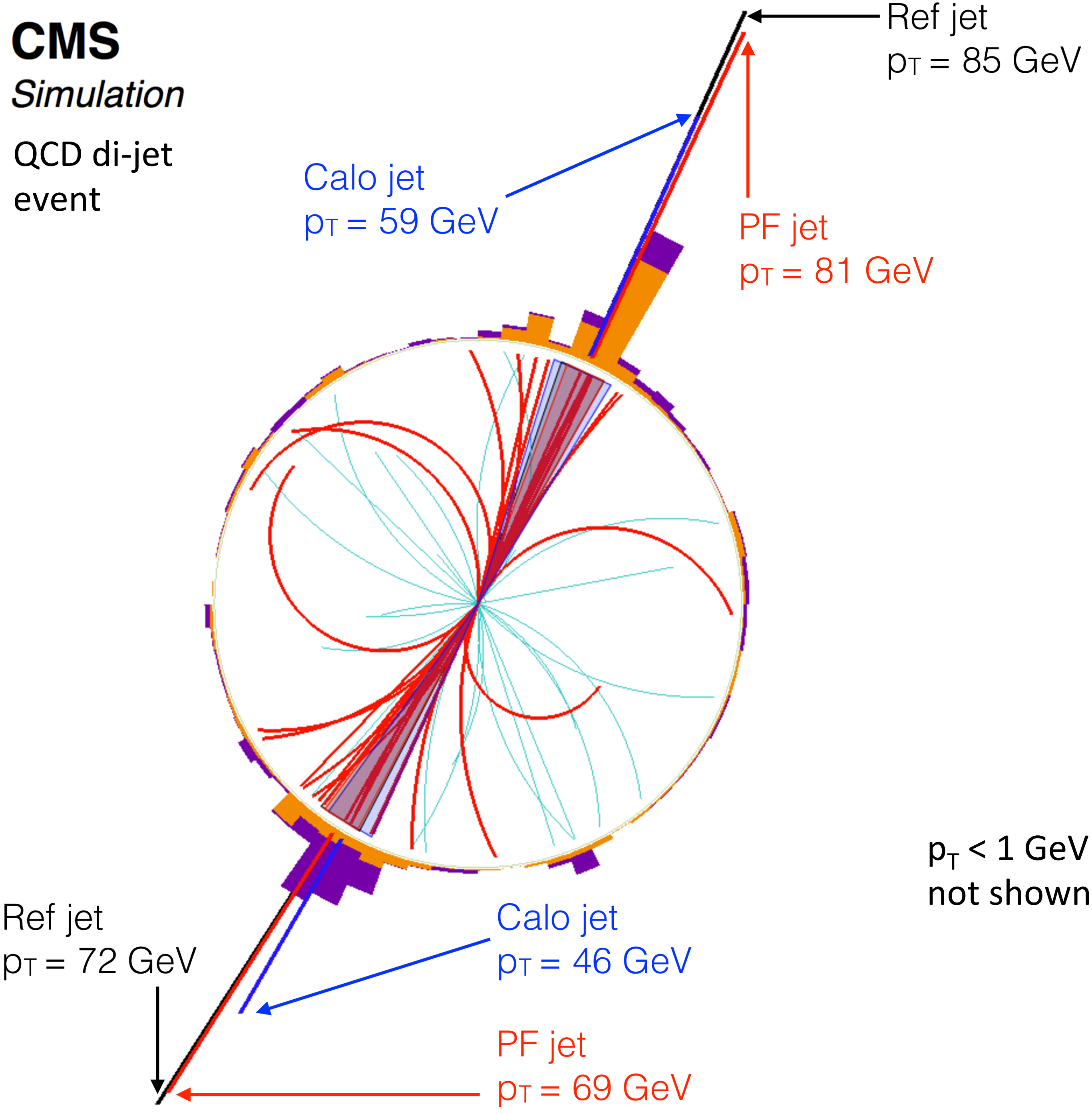


They brem
Brem photons convert

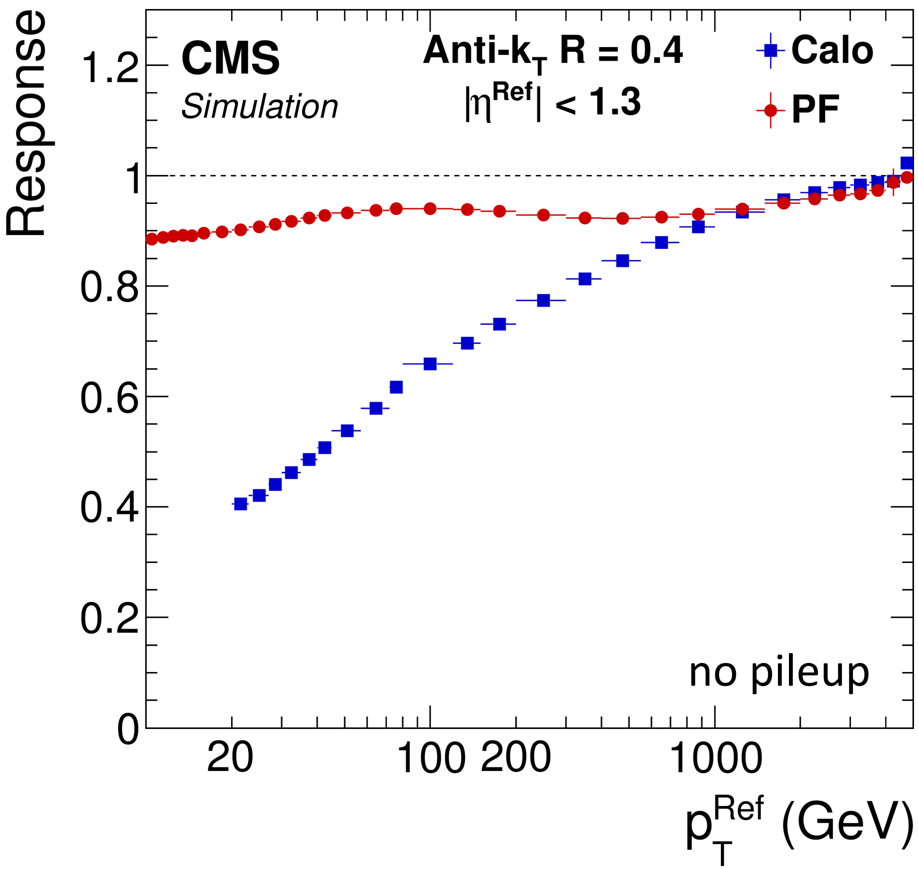
Conversion tracks collect secondary electron clusters

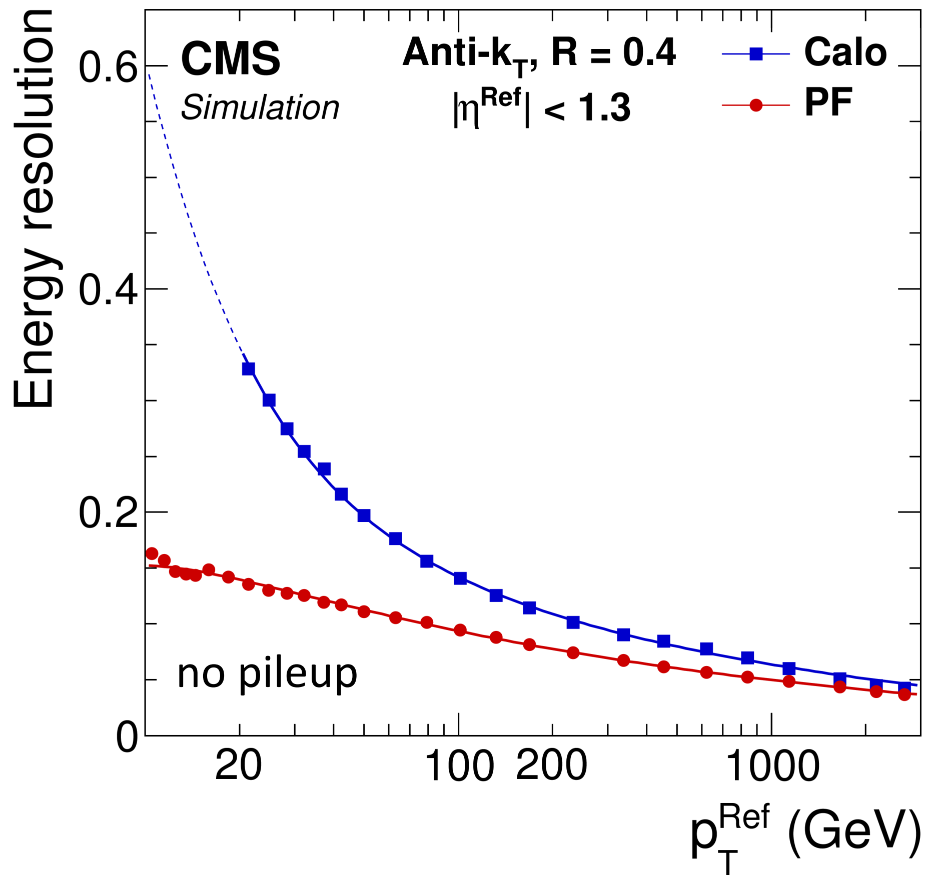
Track momentum change followed by Gaussian Sum Filter

Brem clusters collected by « track tangents »


CMS
Simulation
QCD di-jet event
Calo jet $p_T = 59$ GeV
Ref jet $p_T = 85$ GeV
PF jet $p_T = 81$ GeV
Ref jet $p_T = 72$ GeV
Calo jet $p_T = 46$ GeV
PF jet $p_T = 69$ GeV
$p_T < 1$ GeV not shown

Jet Response and Resolution

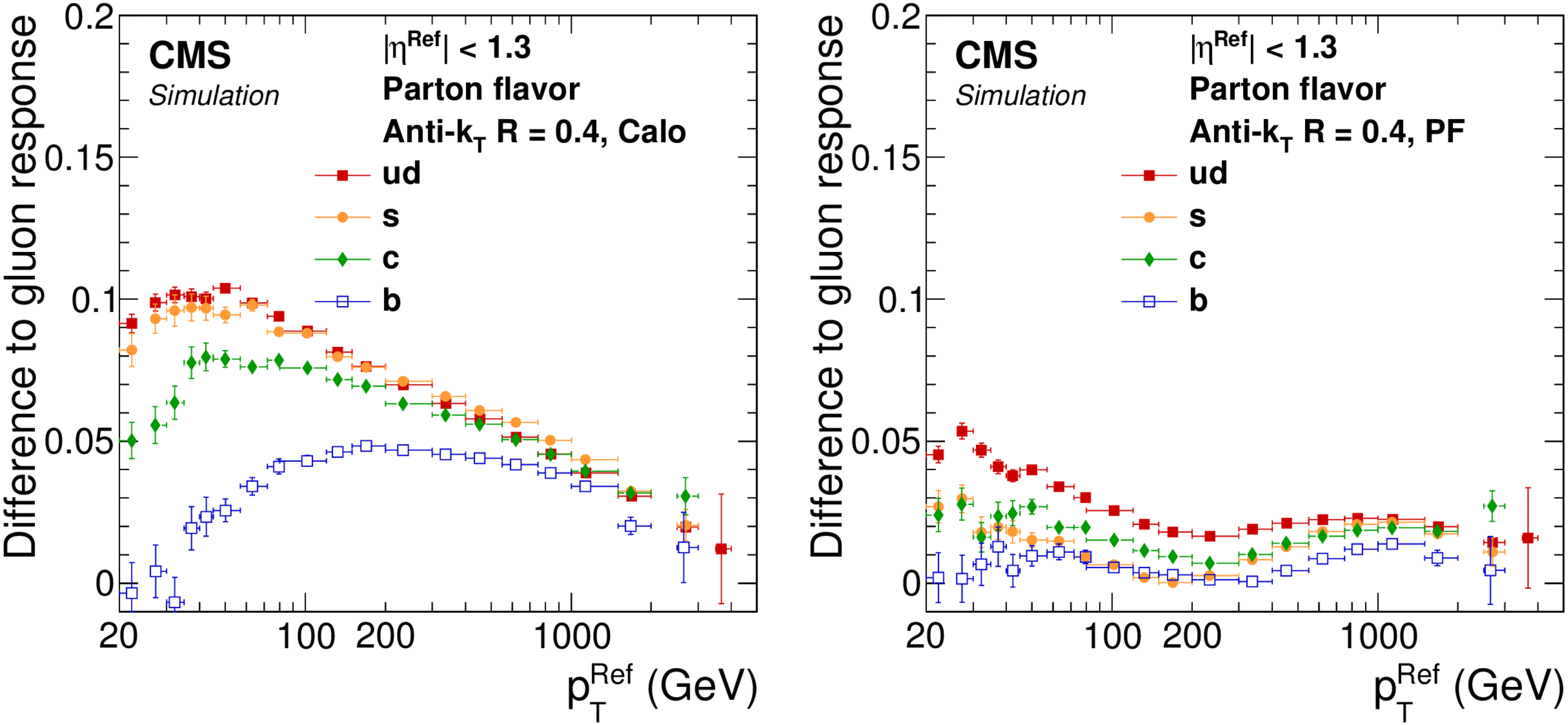




Response closer to unity
~linear

Resolution always better than for calo jets:
- PF works when particles are close
- charged hadron energy from fit of track and cluster measurements

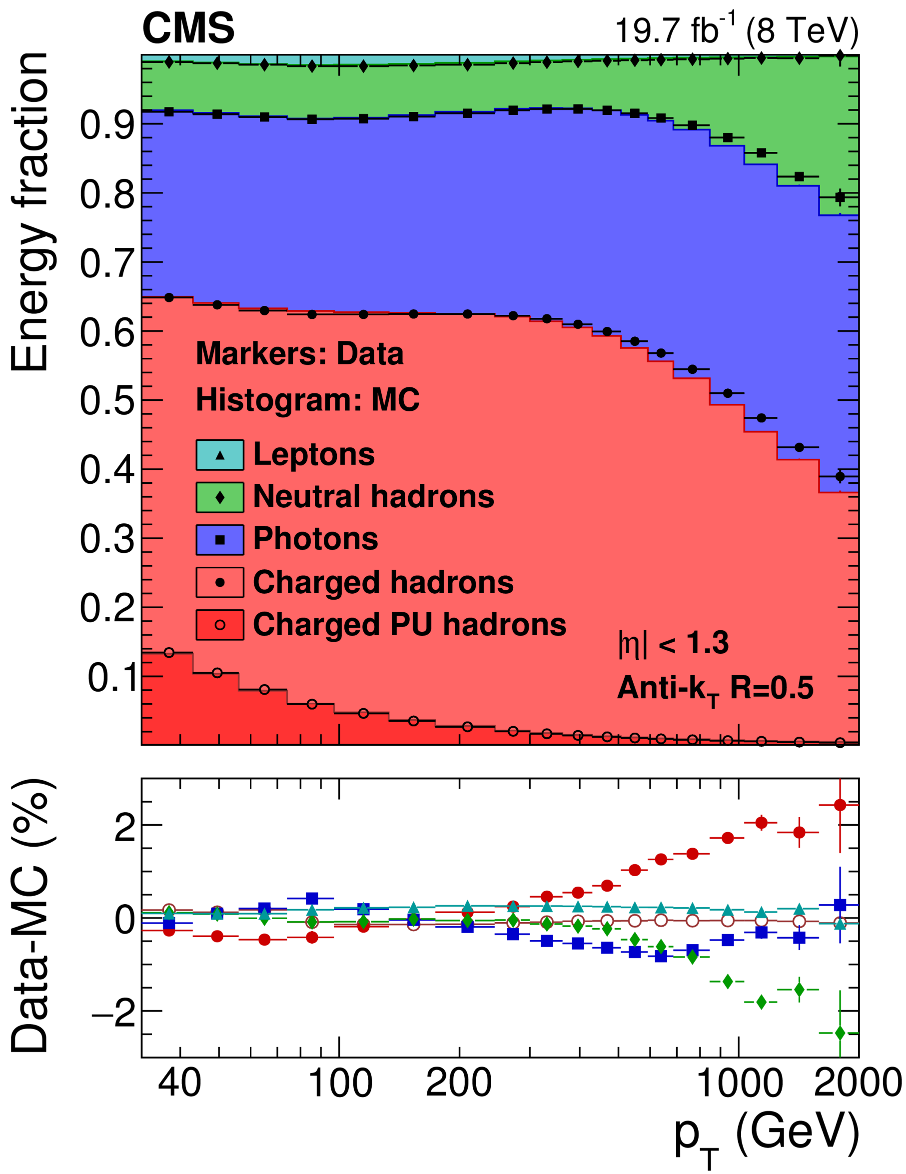
Response for different flavours

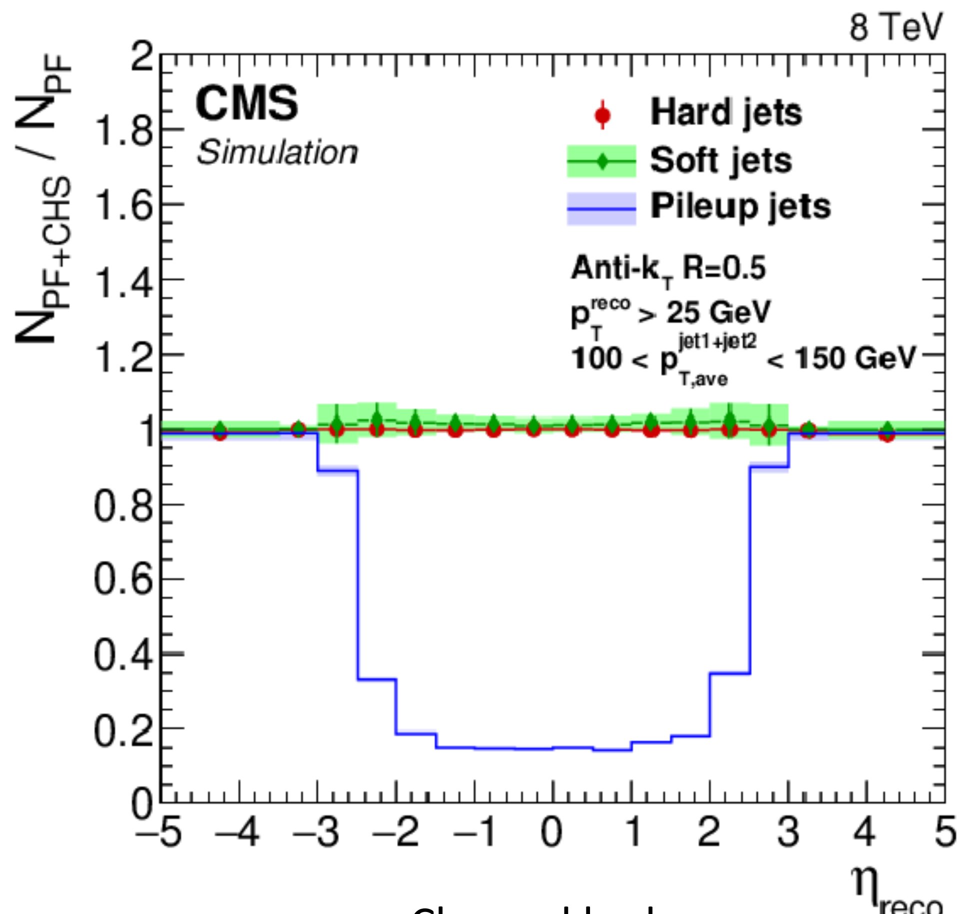


Sensitivity of the response to the parton flavour reduced

→ Jet energy scale systematic uncertainty reduced

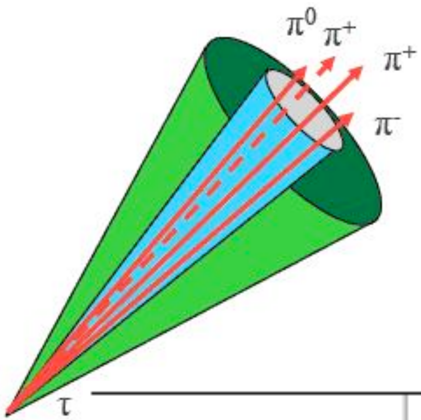
Jet Composition, Pileup



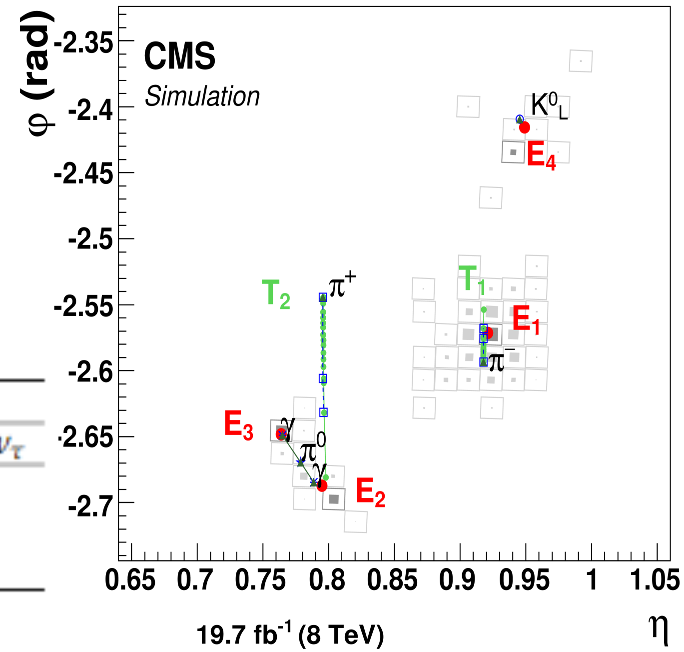


Charged hadrons
from pileup vertices
removed before jet clustering

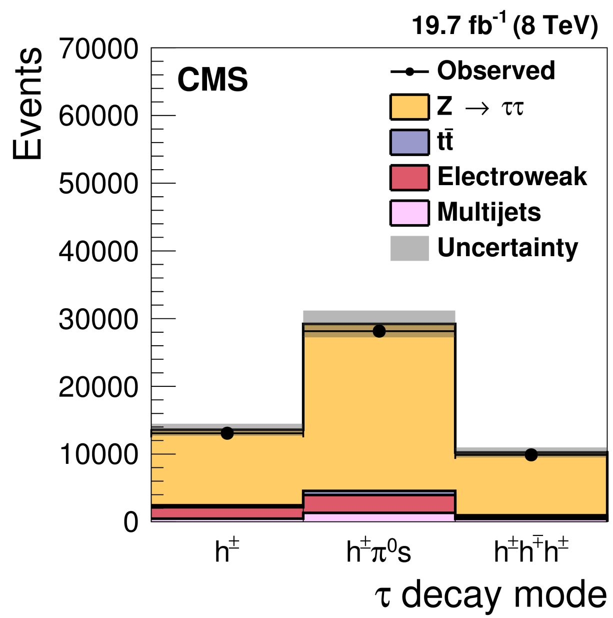
Tau Reconstruction & Identification

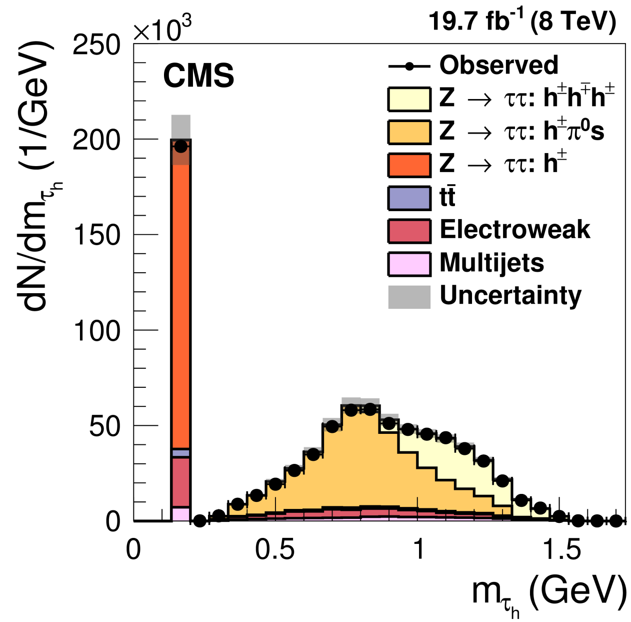


1 or 3 $\pi^{\pm}$
photons from π^0

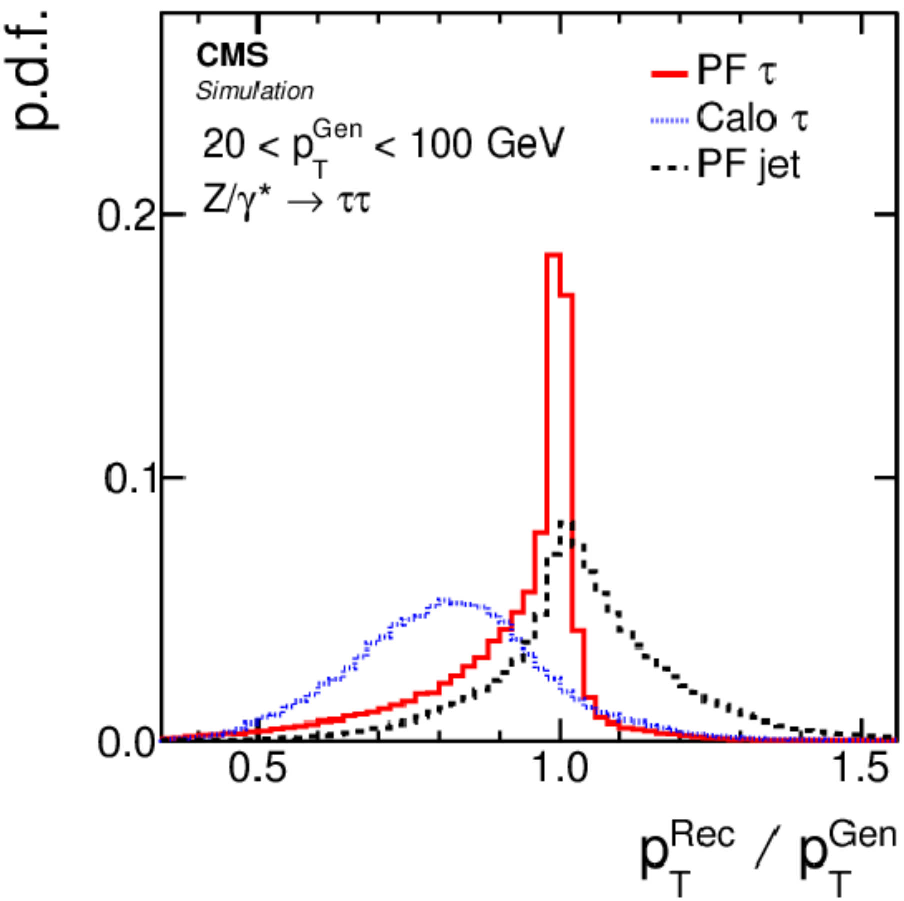


Reconstructed	Generated: $\tau^- \to h^- \nu_\tau$	$\tau^- \to h^- \geq 1\pi^0 \nu_\tau$	$\tau^- \to h^- h^+ h^- \nu_\tau$
$\tau^- \to h^- \nu_\tau$	0.89	0.16	0.01
$\tau^- \to h^- \geq 1\pi^0 \nu_\tau$	0.11	0.83	0.02
$\tau^- \to h^- h^+ h^- \nu_\tau$	0.00	0.01	0.97

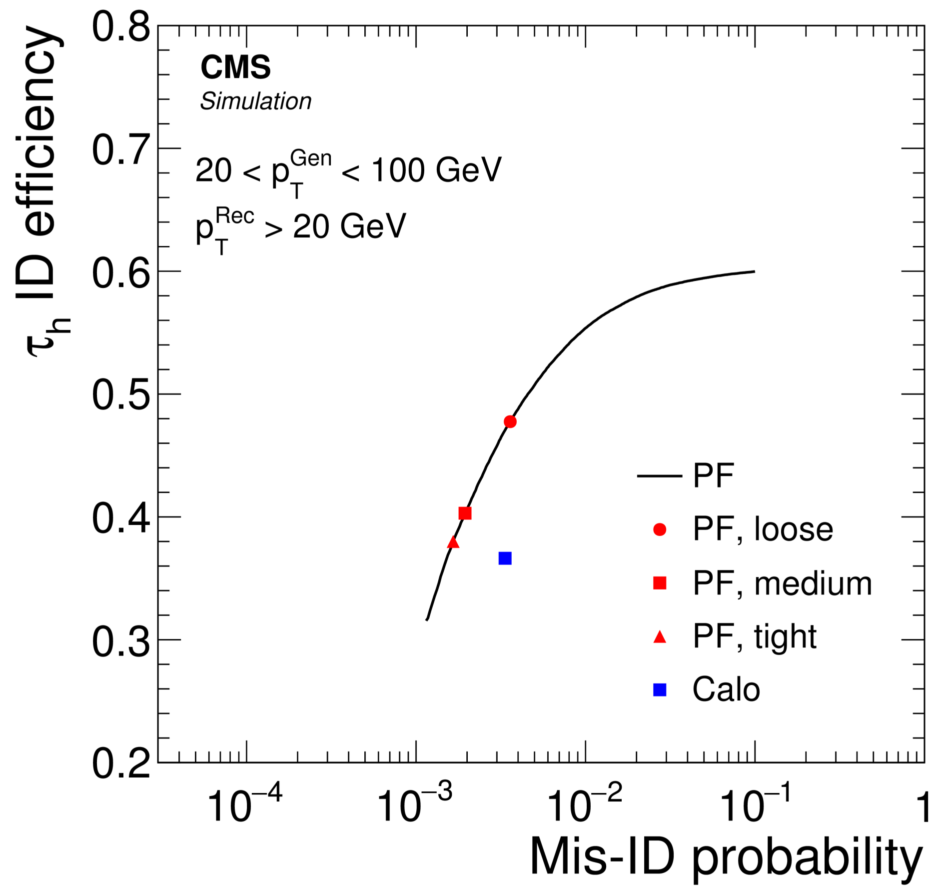




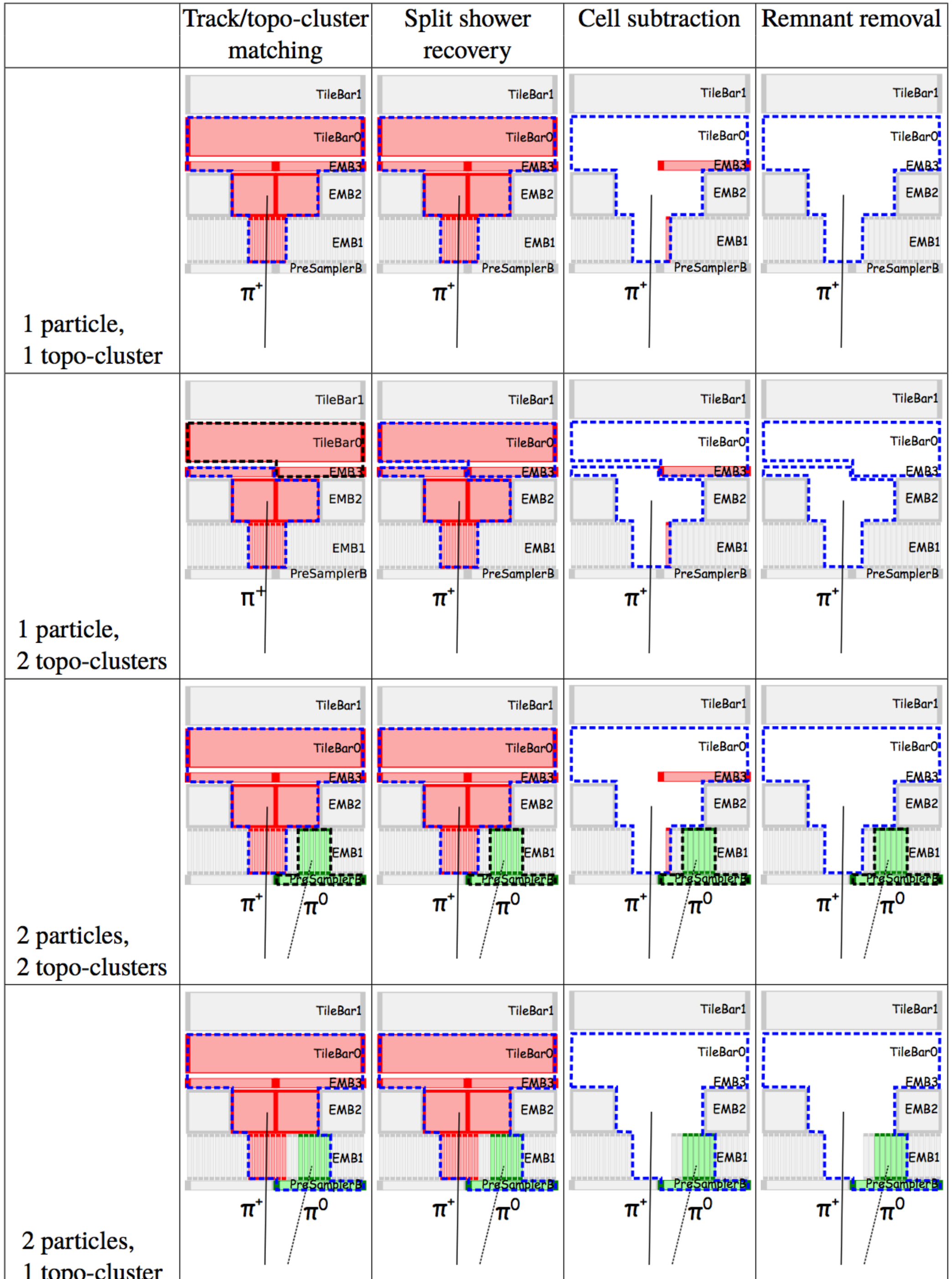
Tau Reconstruction & Identification



p_T resolution



identification performance

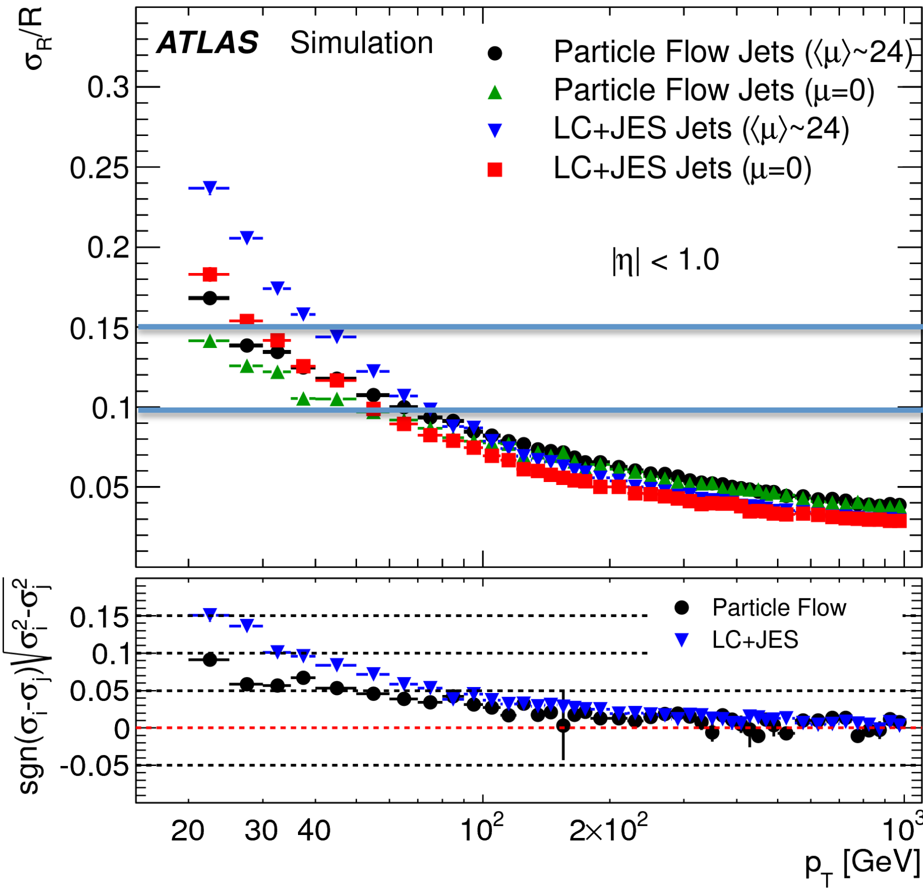


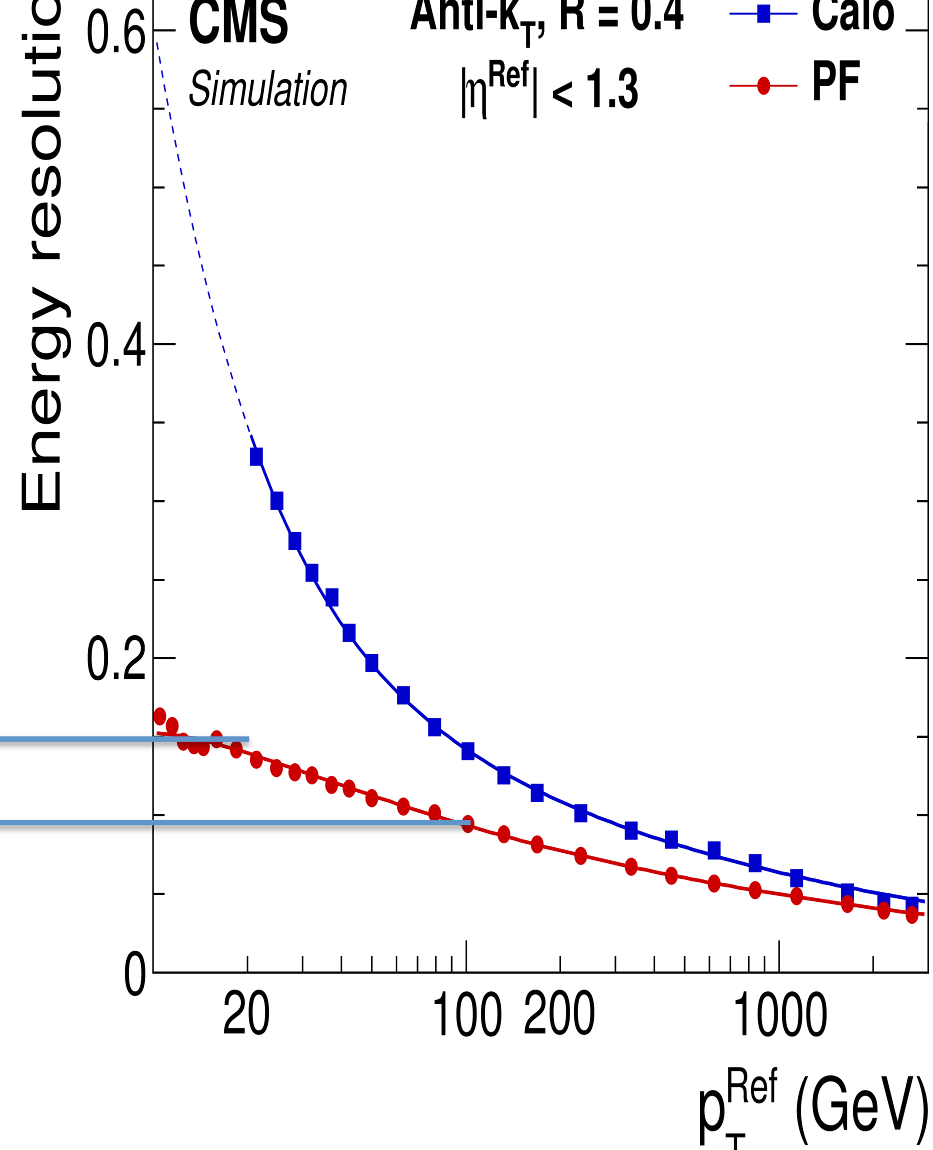
PF in ATLAS

- Not an attempt to identify all particles
- But: use the tracker to improve jets and MET
- Main idea:
  - subtract expected hadron energy deposit from topo clusters
  - jets and MET from tracks and (modified) topo clusters

arxiv:1703.10485

Jet Resolution





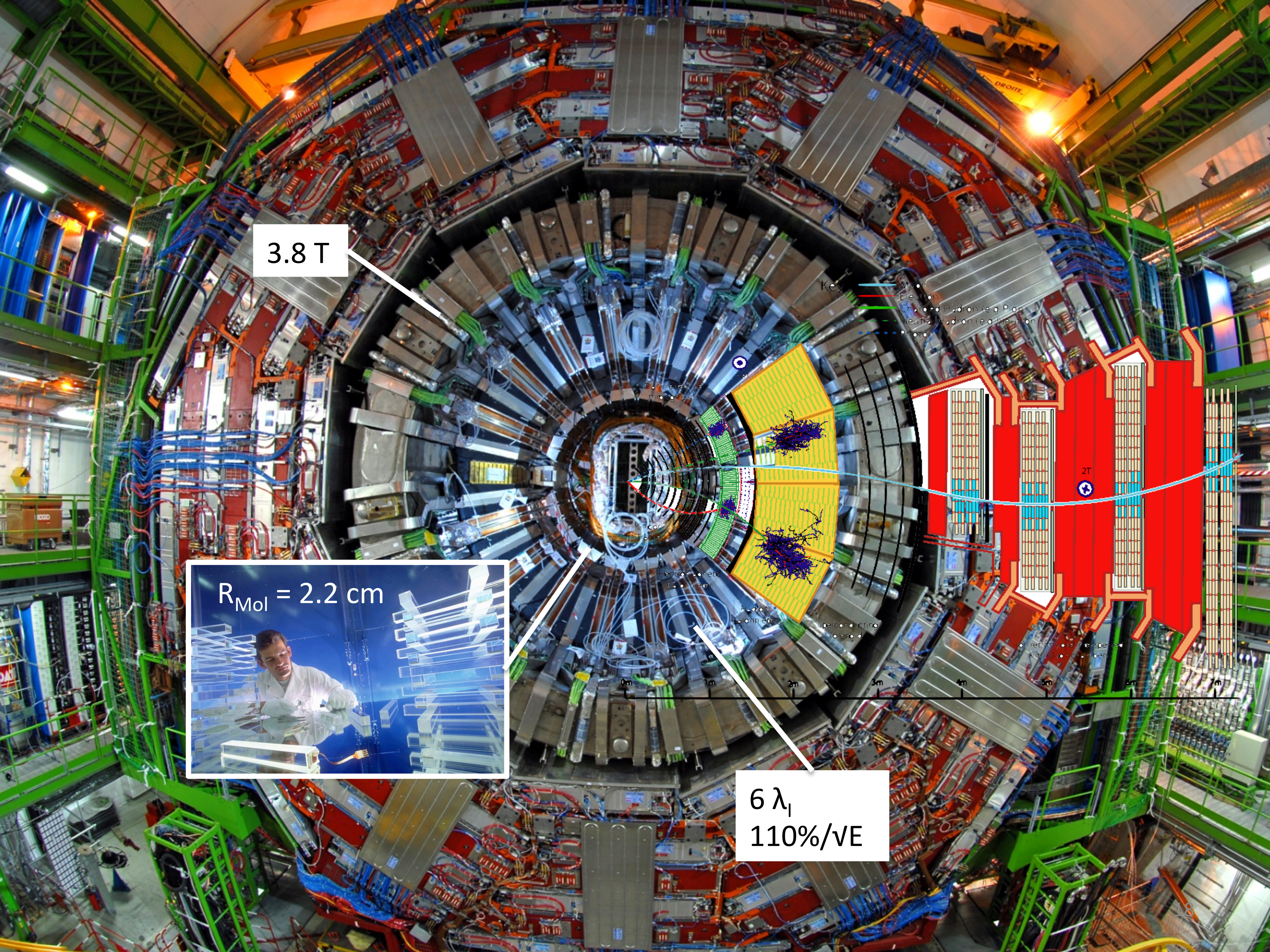
Same jet energy resolution!

arxiv:1703.10485

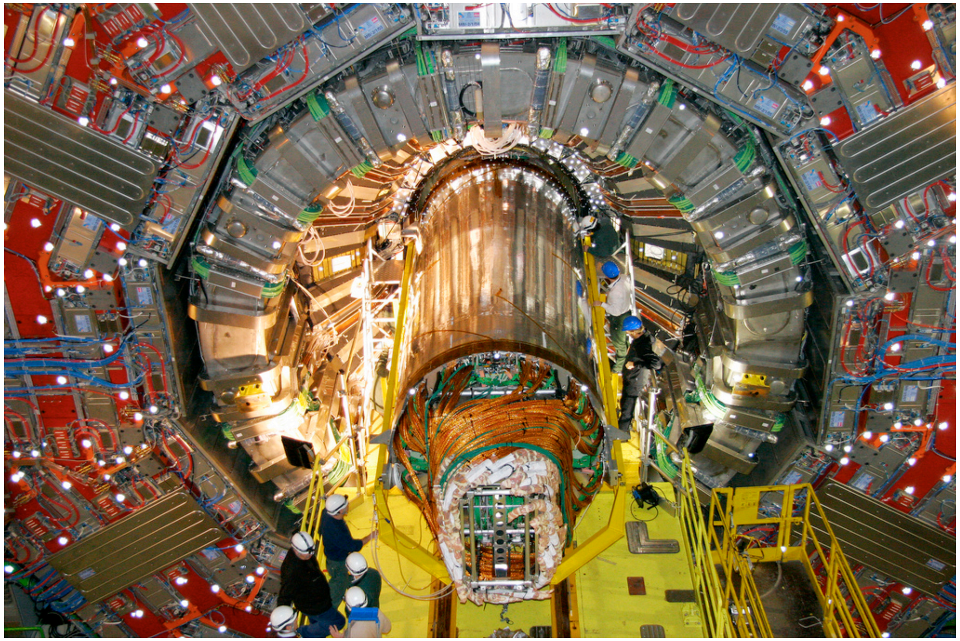
Conclusion

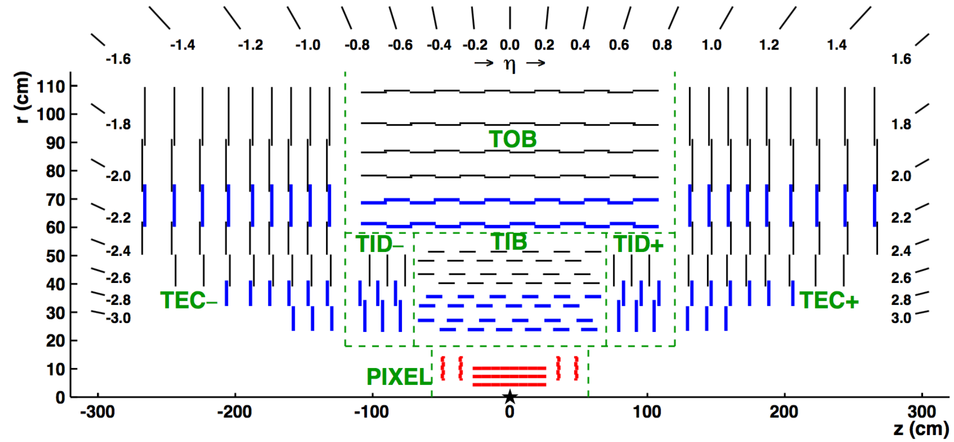
- **PF is the foundation of >99% of CMS analyses**
  - all physics objects come from PF
  - global, high-res view of the final state particles (e.g. control underlying event − colour reconnection)
- **> 50 000 lines of code**
  - to deal with the gory « details » :
    - fake tracks, muons, e/γ, secondary interactions, noise, …
- **Algorithm unchanged since 2009**
  - 0 → 45 pileup collisions
- **What now?**
  - PF in ATLAS! Jet resolution now the same as in CMS
  - HL-LHC data: big challenge. PF is needed to deal with PU
  - Trending: deep learning on PF particles
    - e.g. tau ID, MET reconstruction, boosted top tagging, ..

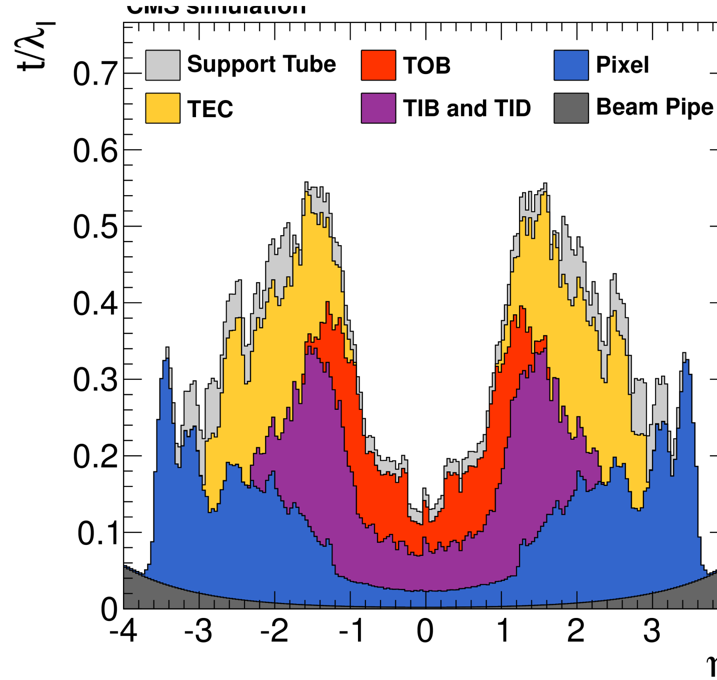
Backup


3.8 T
R_{Mol} = 2.2 cm
6 λ_I
110%/√E

The CMS Tracker: Big! (and Thick)



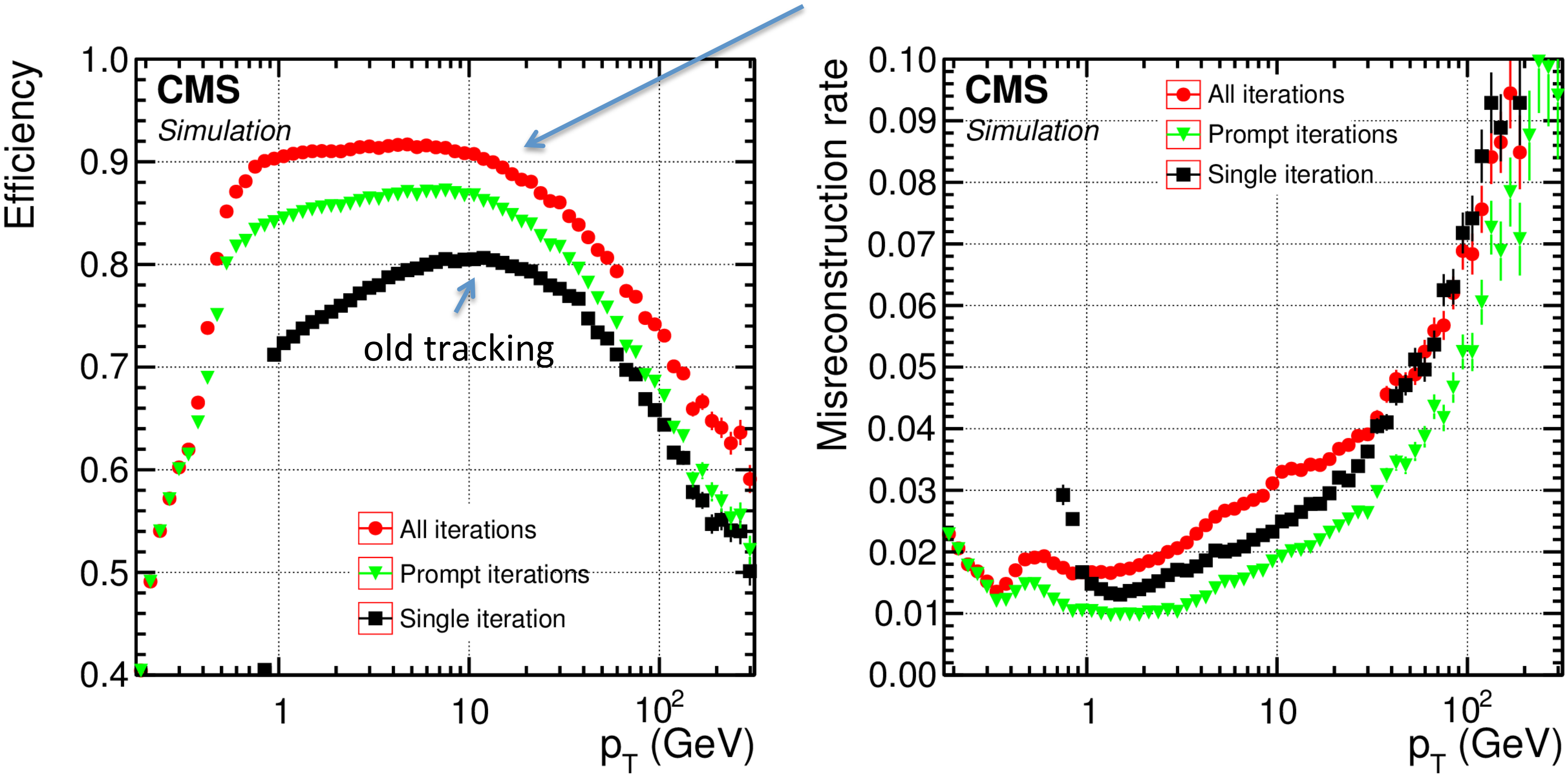




Hadrons: nuclear interactions

e/γ: bremsstrahlung, conversions

Iterative tracking



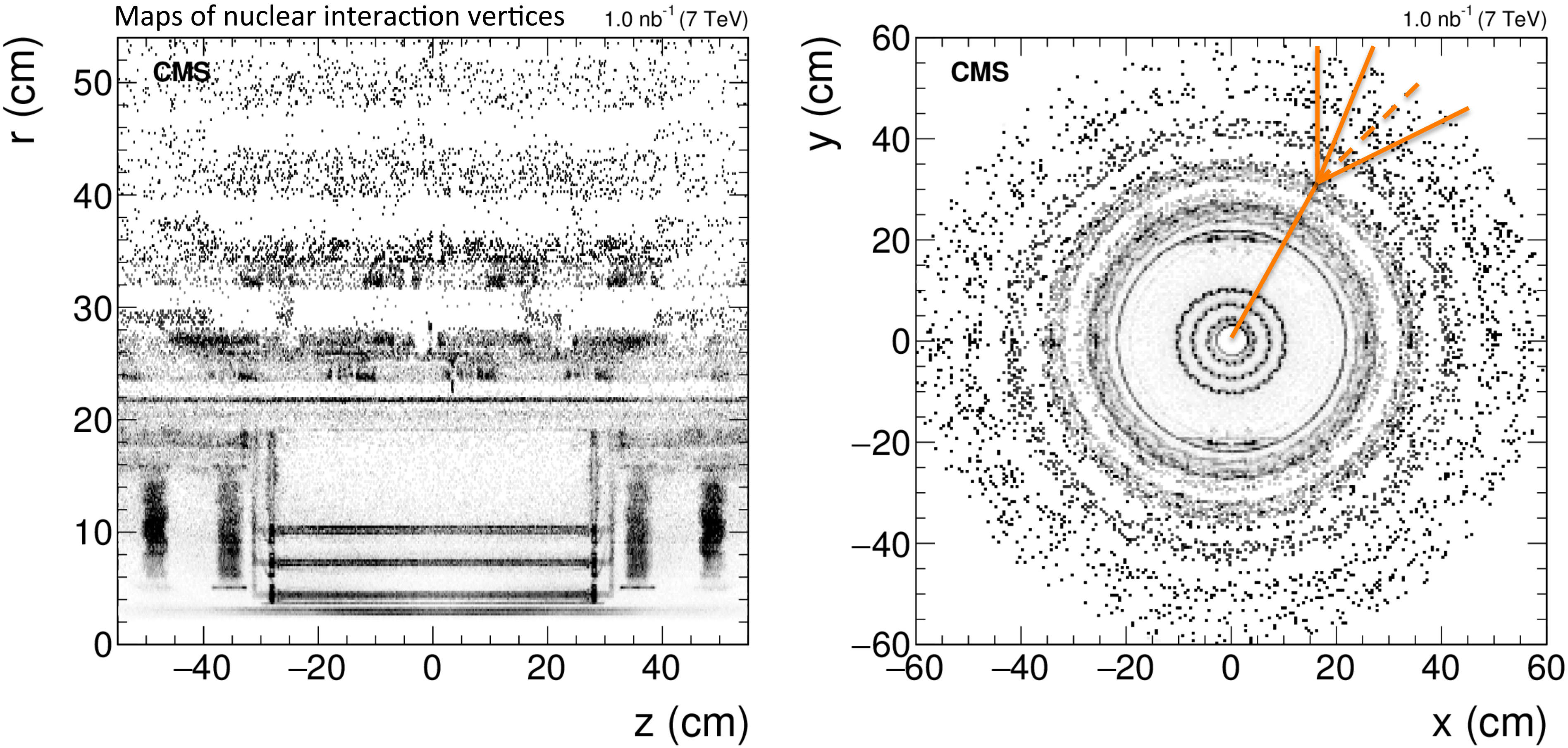
10 iterations:

1- Reconstruct easy tracks

2- Remove their hits

3- Reconstruct more difficult tracks

Nuclear Interactions



- Secondary vertices reconstructed from displaced tracks (+ 0 or 1 incoming track)
- Secondary charged particles reconstructed by PF → single charged hadron
- Secondary neutrals reconstructed by PF as usual
- Incoming track if any is discarded

Particle Flow and Jets @HLT

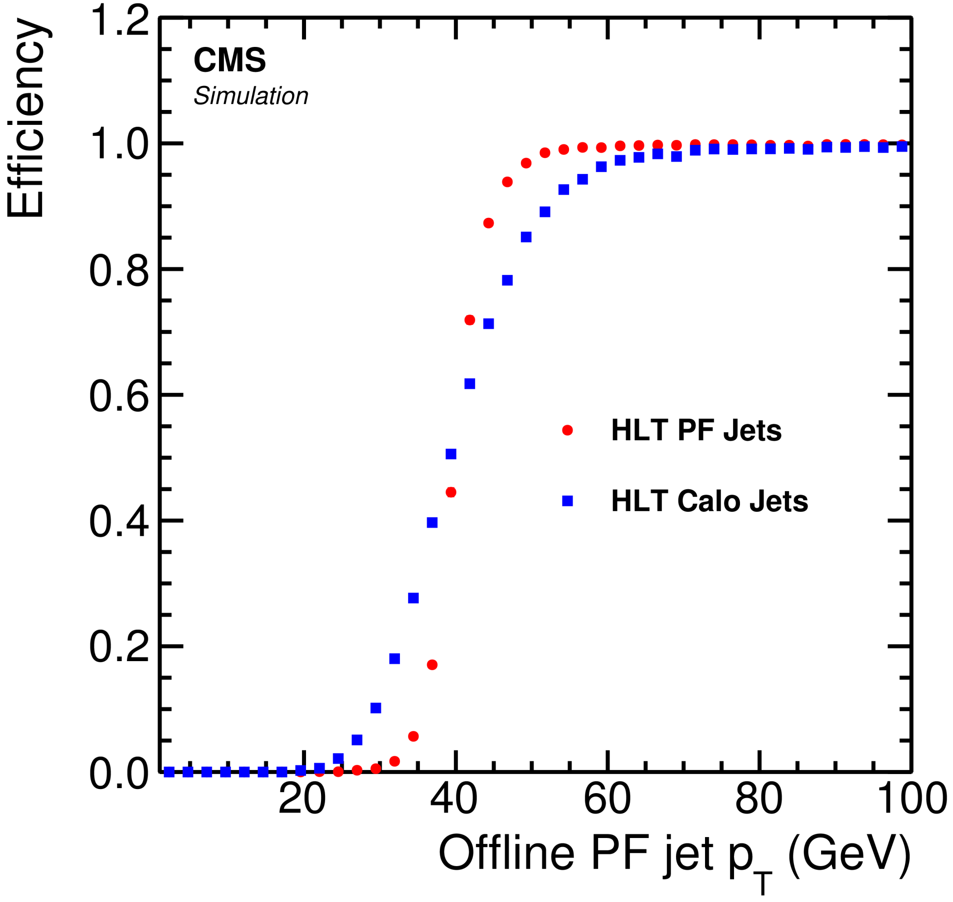
In the High-Level trigger, timing is crucial! (~140 ms / evt)

	Tracking	PF
Offline	600 ms	70 ms
HLT	60 ms	30 ms

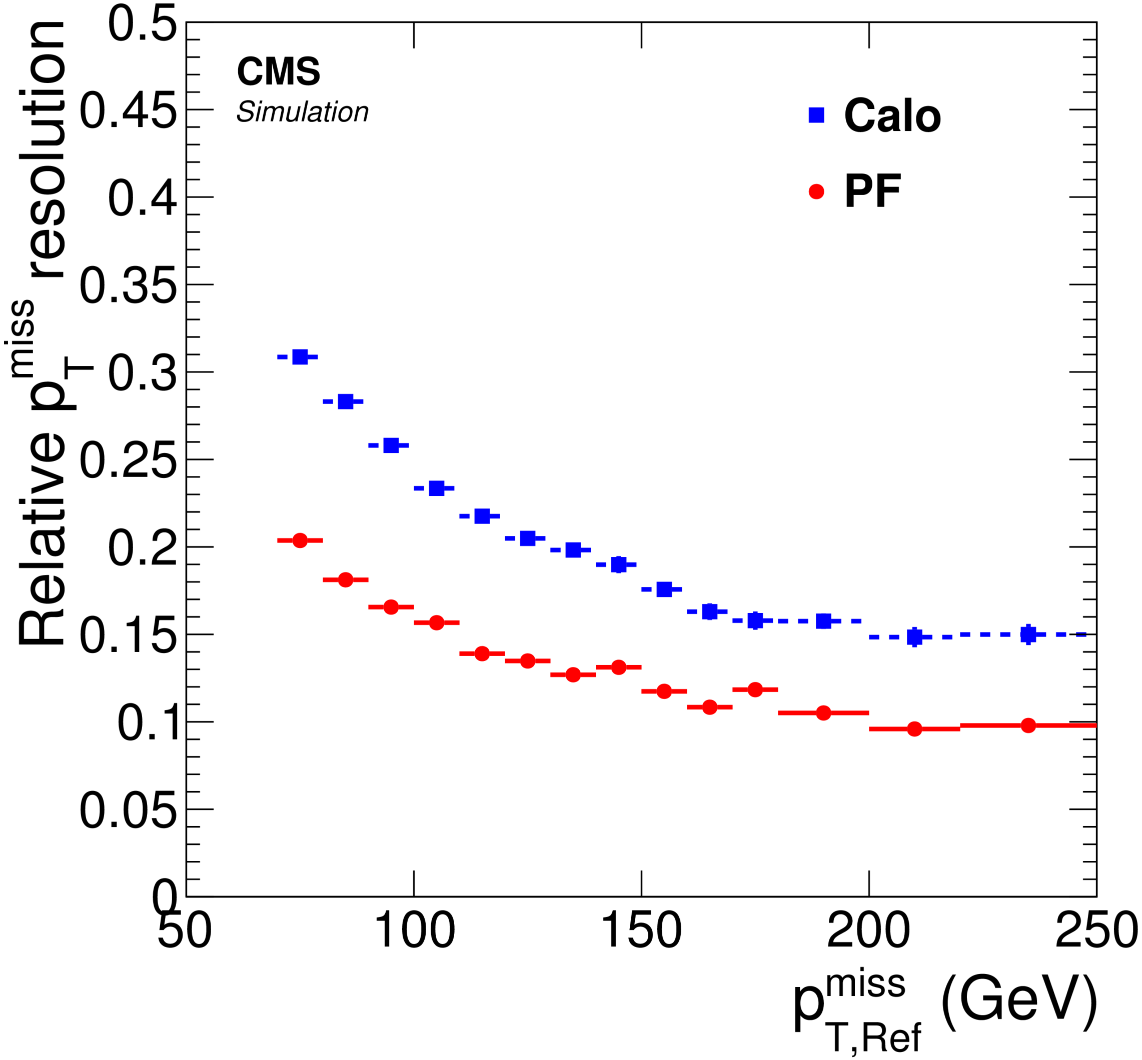
no pileup, assuming tracking and PF are performed for every event

Fraction of total time at HLT @45 pileup:

	Tracking	PF
HLT	< 20%	< 10 %

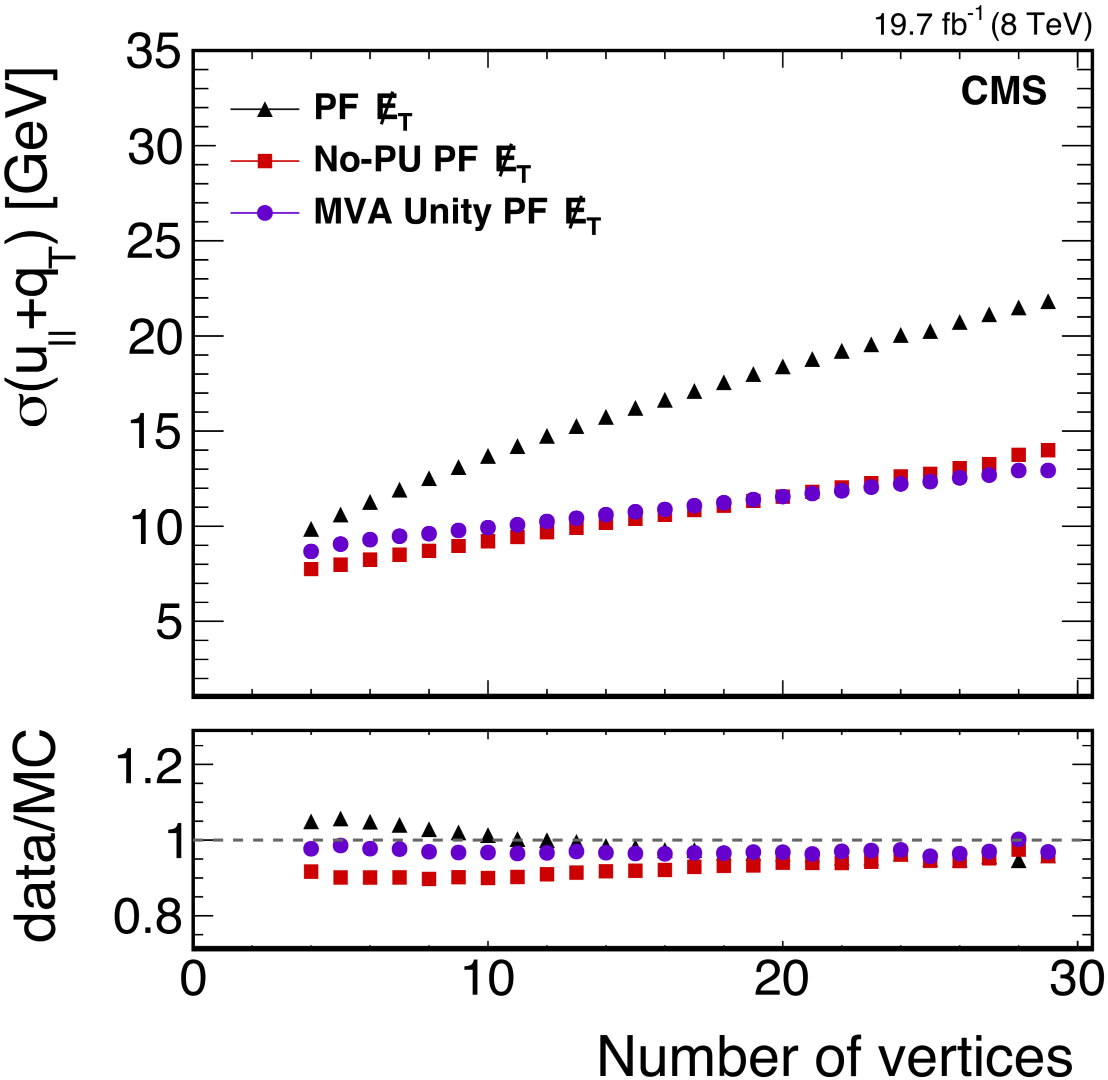


MET



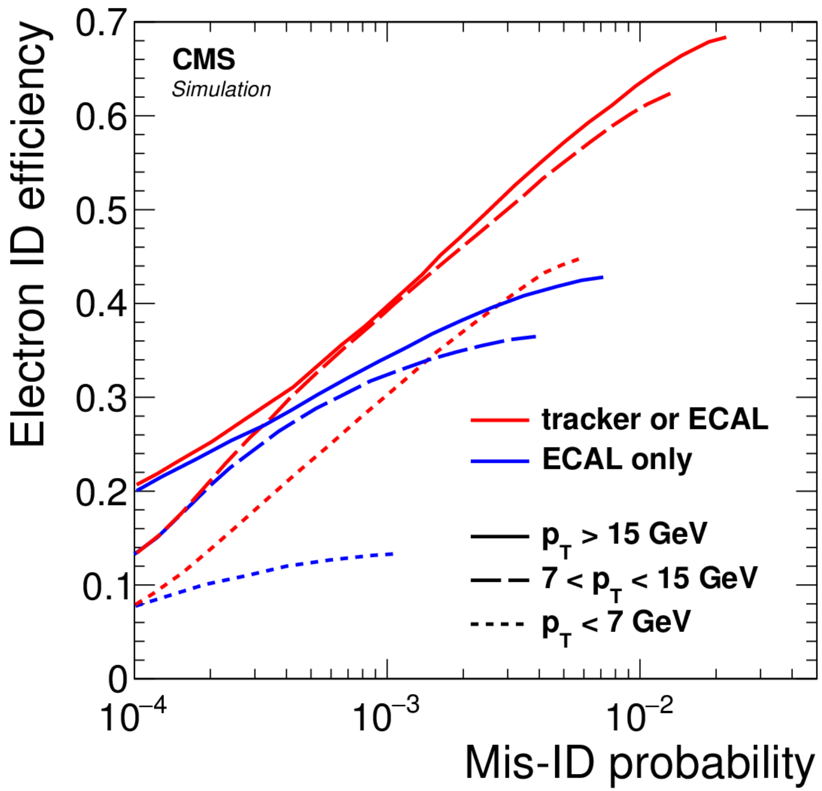
CMS
Simulation
Calo
PF
Relative p_T^{miss} resolution
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
50
100
150
200
250
$p_{T,Ref}^{miss}$ (GeV)

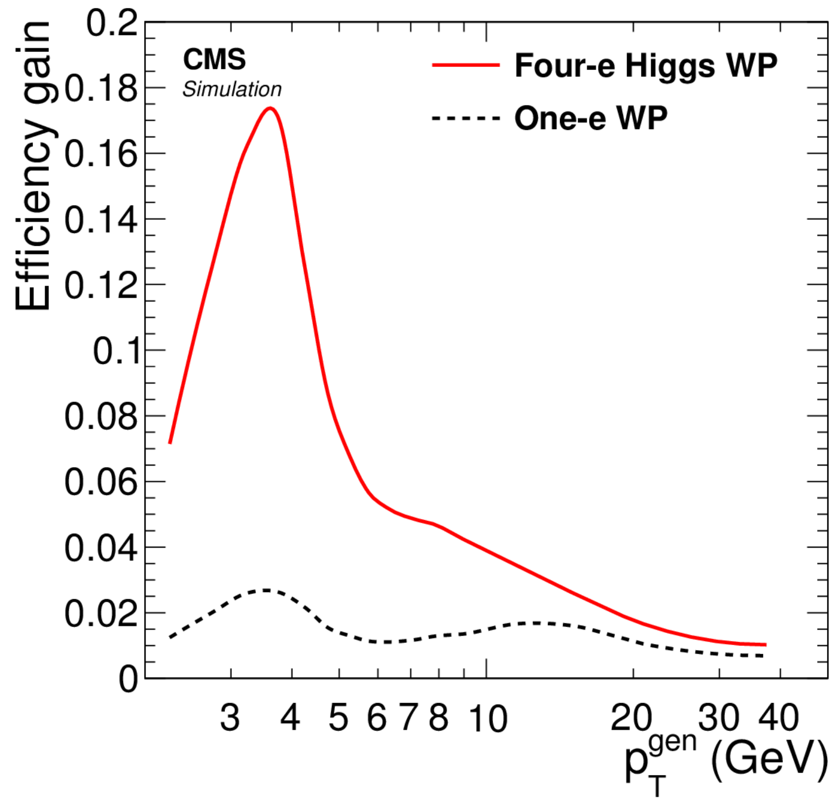
MVA MET



19.7 fb^{-1} (8 TeV)
CMS
PF E_T
No-PU PF E_T
MVA Unity PF E_T
$\sigma(u_{||}+q_T)$ [GeV]
35
30
25
20
15
10
5
data/MC
1.2
1
0.8
0
10
20
30
Number of vertices

Electrons





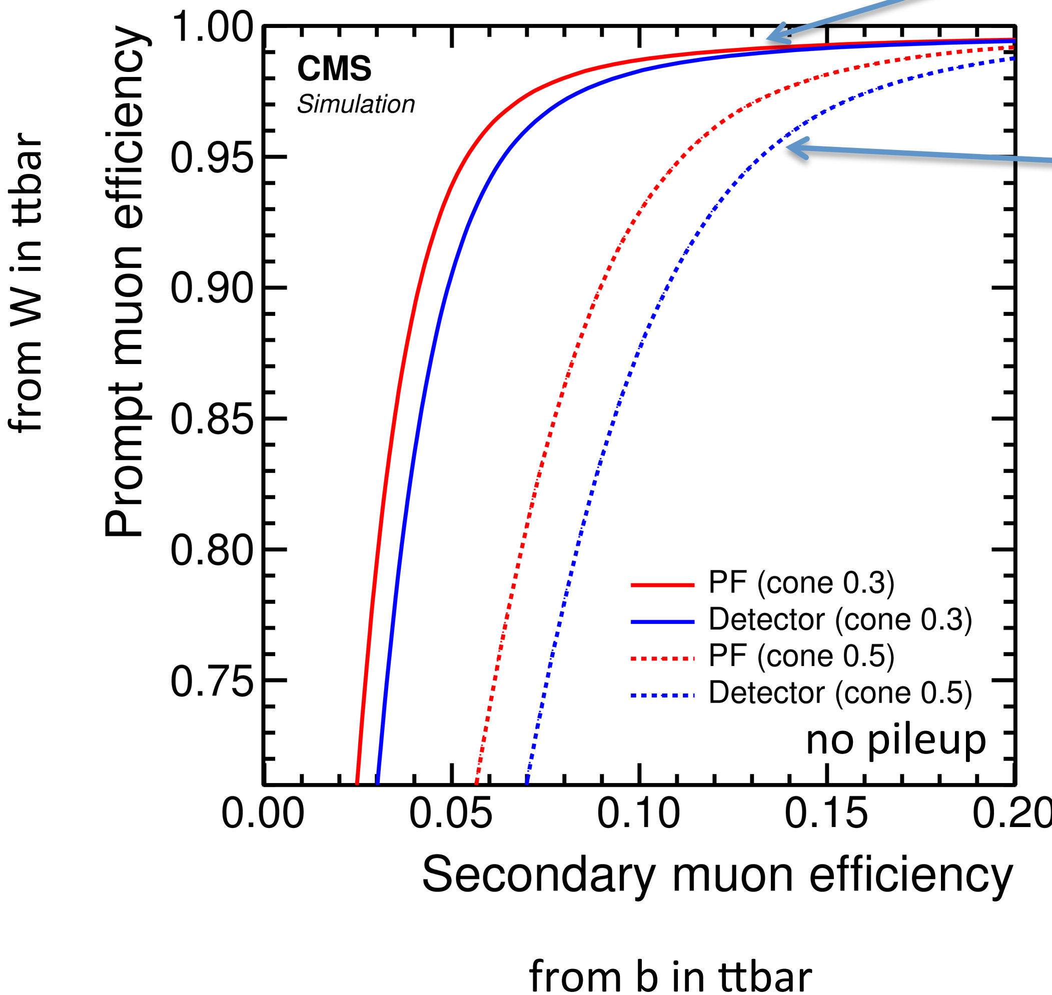
Electrons in jets
b tagging with electrons possible

Prompt electrons
Big efficiency gains at low pT:
+7% more H→ZZ→4e events

Isolation

$$I_{\mathrm{PF}} = \frac{1}{p_{\mathrm{T}}} \left(\sum_{\mathrm{h}^{\pm}} p_{\mathrm{T}}^{\mathrm{h}^{\pm}} + \sum_{\gamma} p_{\mathrm{T}}^{\gamma} + \sum_{\mathrm{h}^{0}} p_{\mathrm{T}}^{\mathrm{h}^{0}} \right)$$

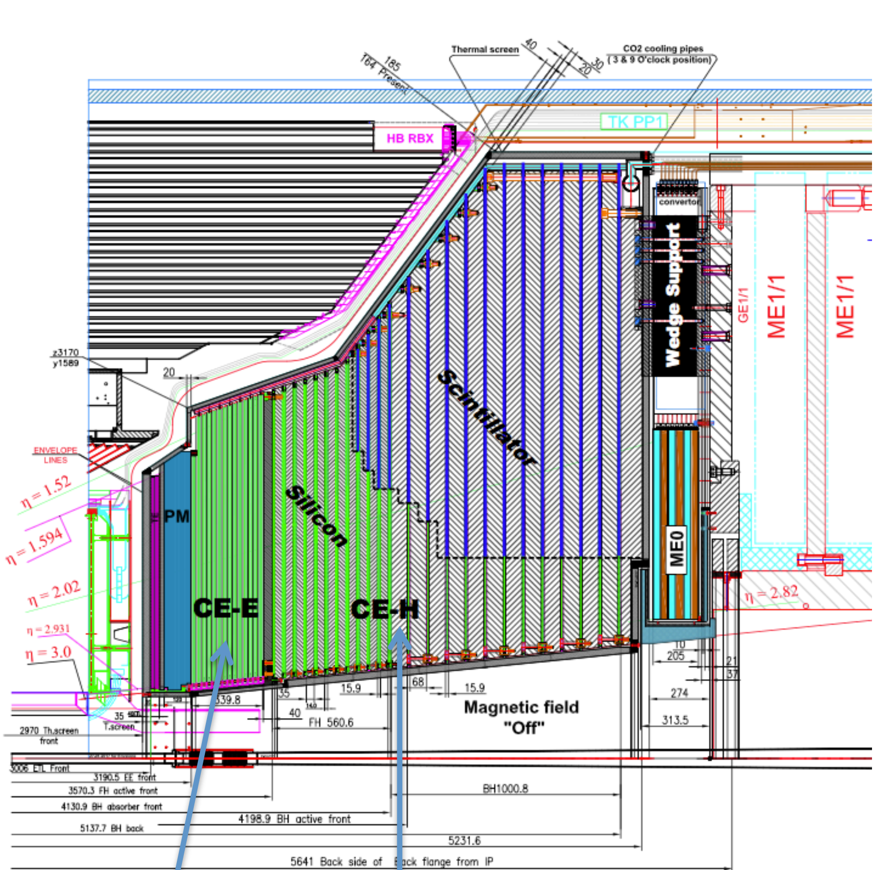
$$I_{\mathrm{det}} = \frac{1}{p_{\mathrm{T}}} \left(\sum_{\mathrm{tracks}} p_{\mathrm{T}}^{\mathrm{track}} + \sum_{\mathrm{ECAL}} E_{\mathrm{T}}^{\mathrm{ECAL}} + \sum_{\mathrm{HCAL}} E_{\mathrm{T}}^{\mathrm{HCAL}} \right)$$

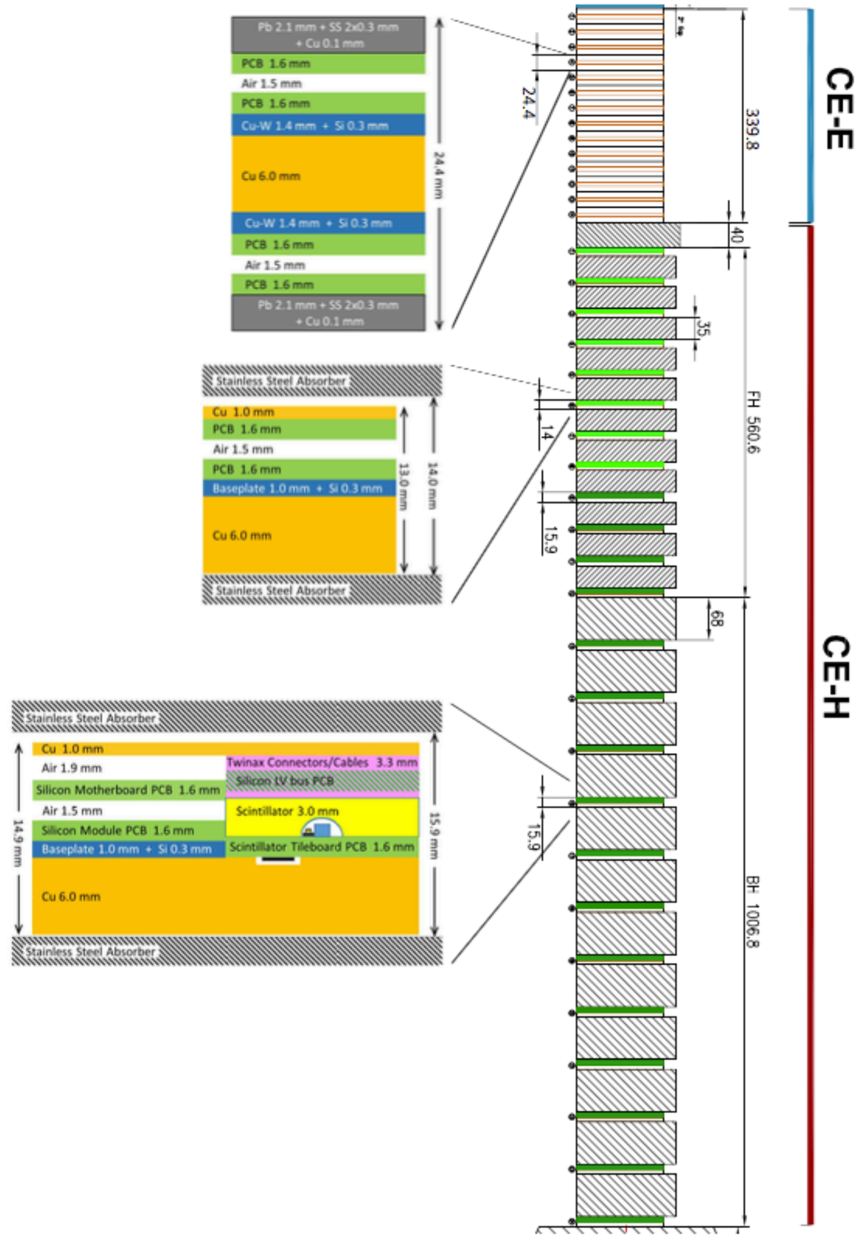


Detector-based isolation:

- Charged-hadron energy double counted
- Cannot easily remove pileup calorimeter deposits

The CMS HGCAL

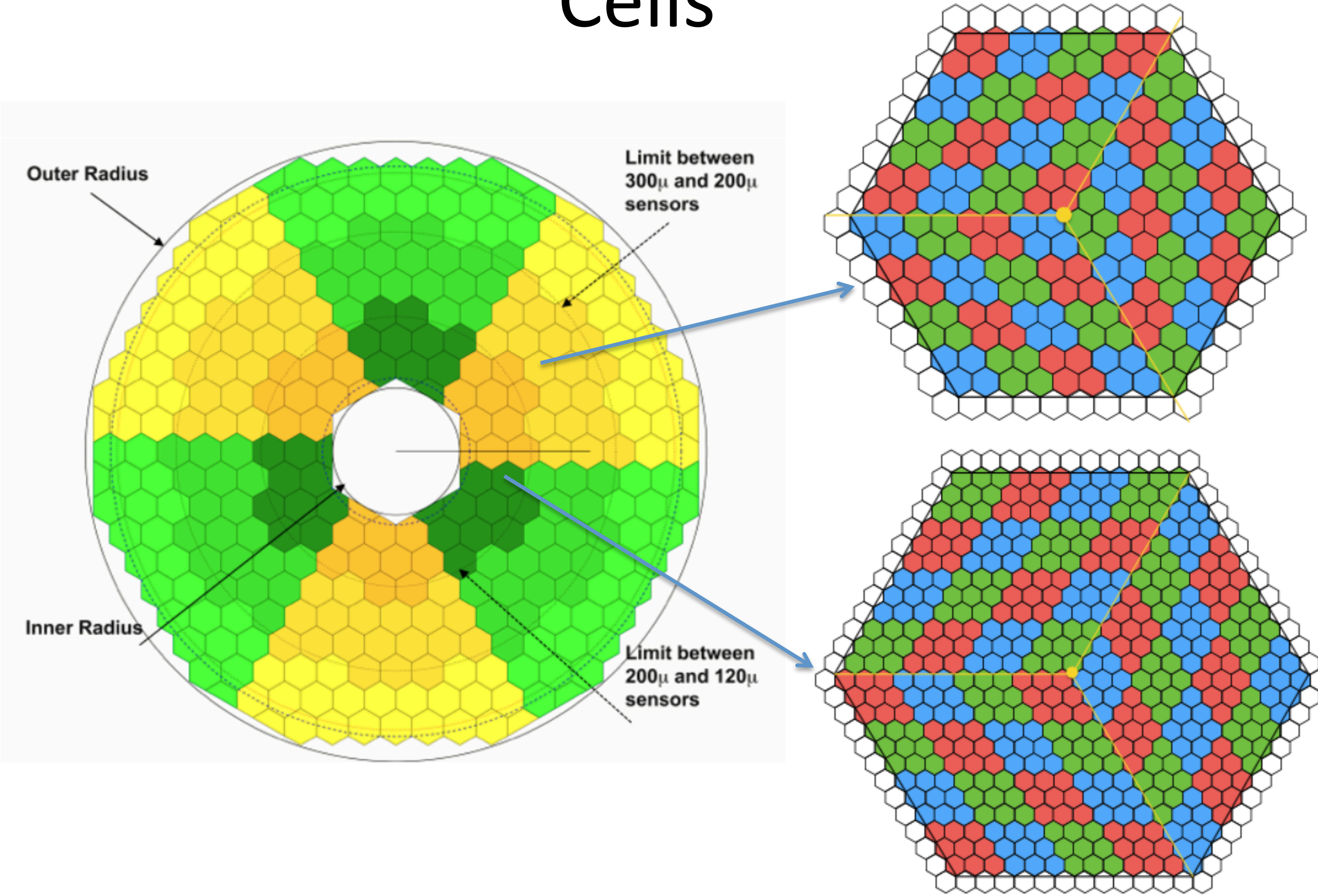




28 layers
$26\ X_0$
$1.7\ \lambda_I$

$9\ \lambda_I$

Cells



Outer Radius
Limit between 300μ and 200μ sensors
Inner Radius
Limit between 200μ and 120μ sensors

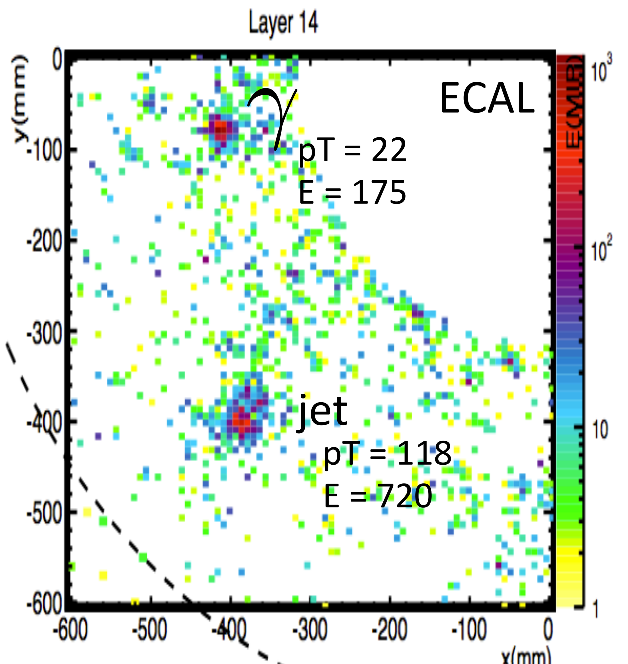
HGCAL

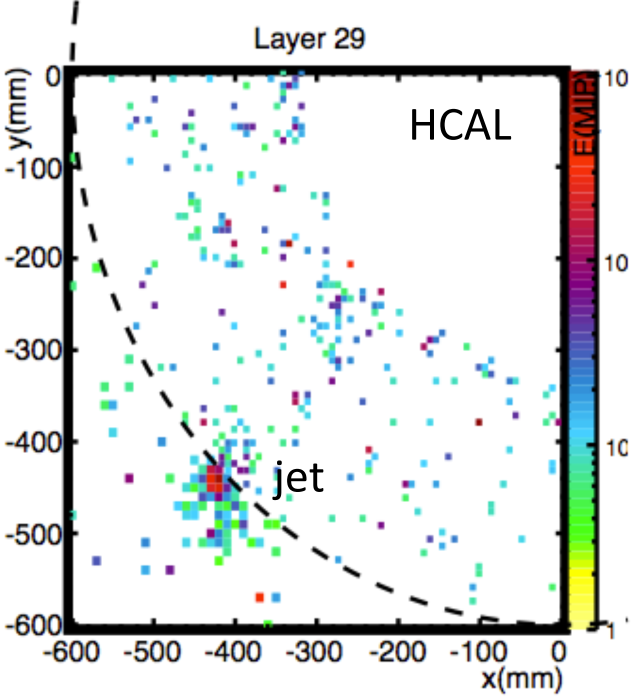
https://cds.cern.ch/record/2293646?ln=fr

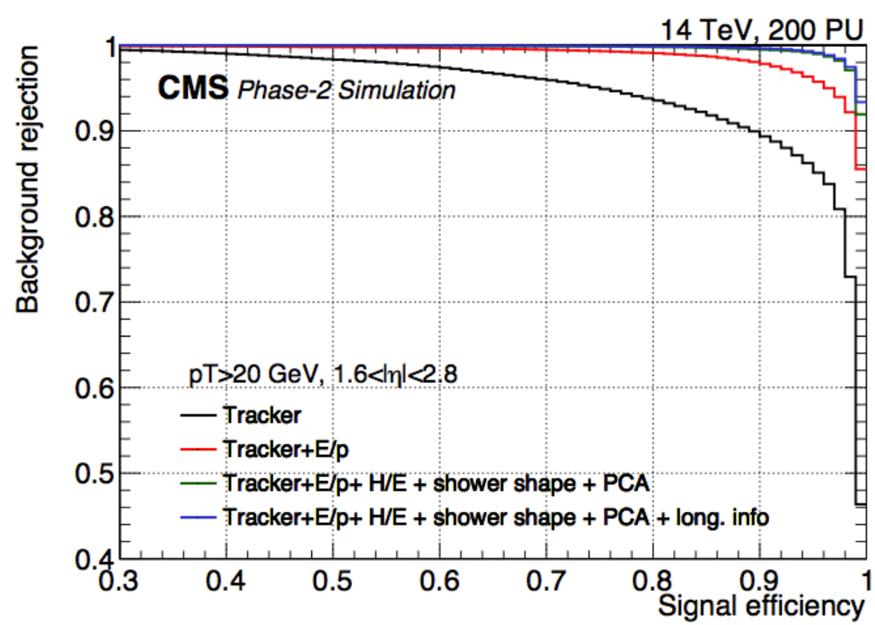
200 pileup collisions / beam crossing
Boosted jets
Pandora and Arbor:
- aggregate many unrelated hits

Tried a different approach:
- fast 2D clustering in each layer
- projective association into 3D clusters
- works only for electrons so far

Setting up a full PF algo will take time and effort

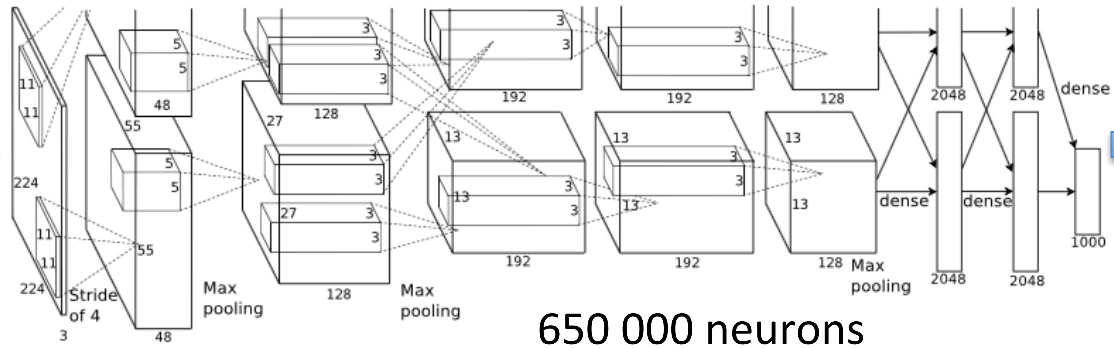






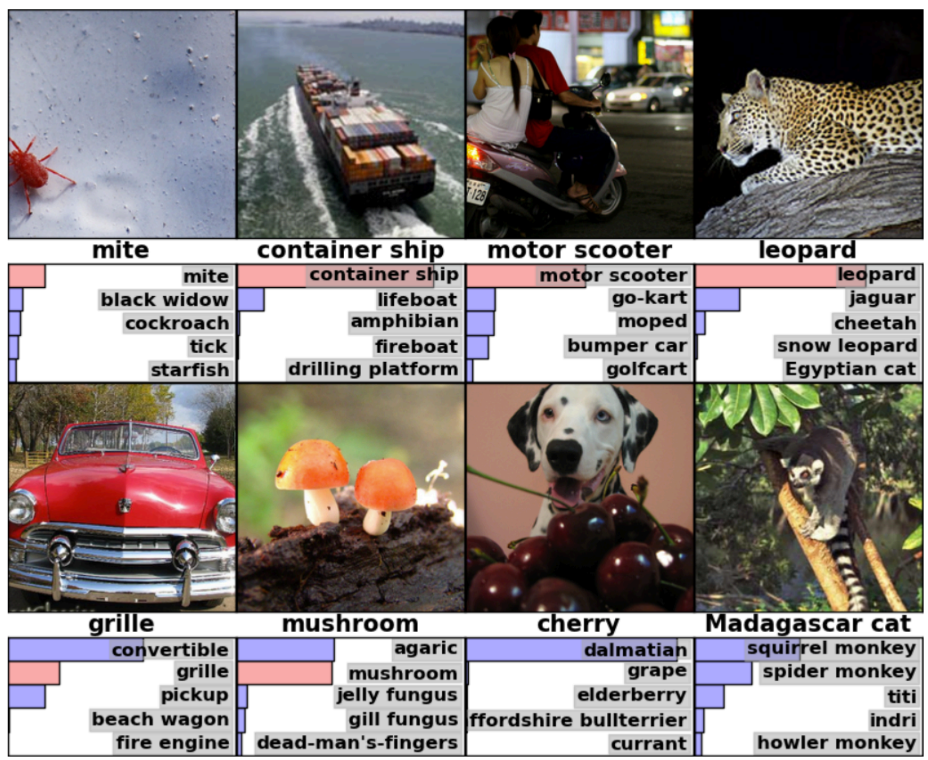
Deep Learning

Input:
raw image
(color levels
for each pixel)



650 000 neurons

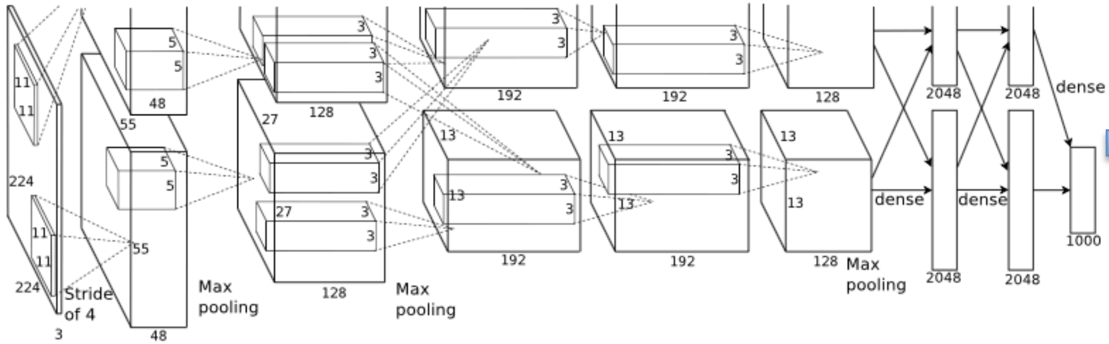
Output:
score for
each
category



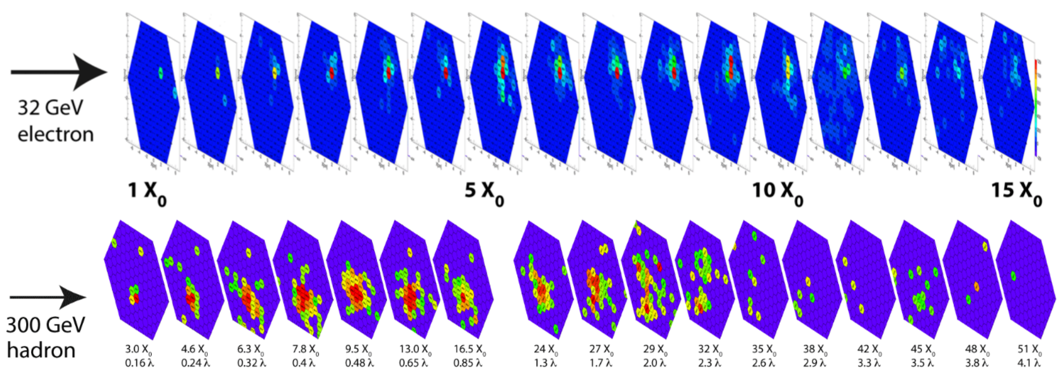
[AlexNet]

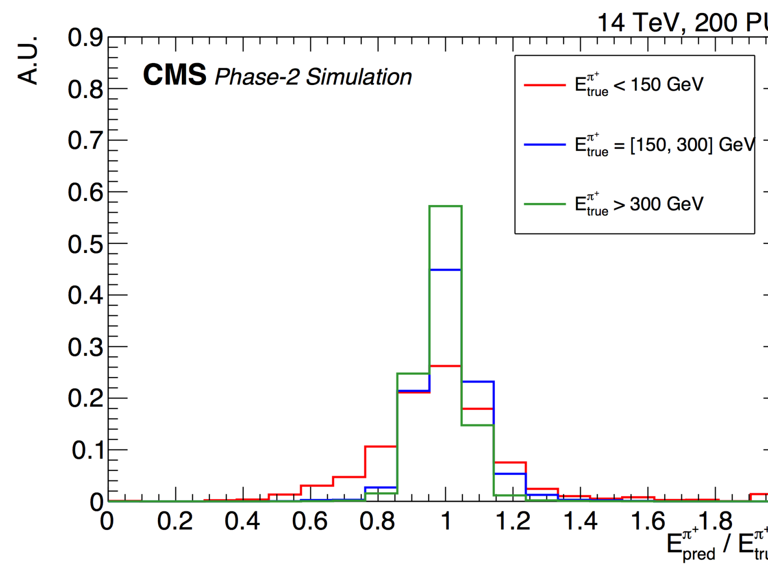
Deep Learning for HGCAL reconstruction

Input:
raw image



Output:
shower
energy

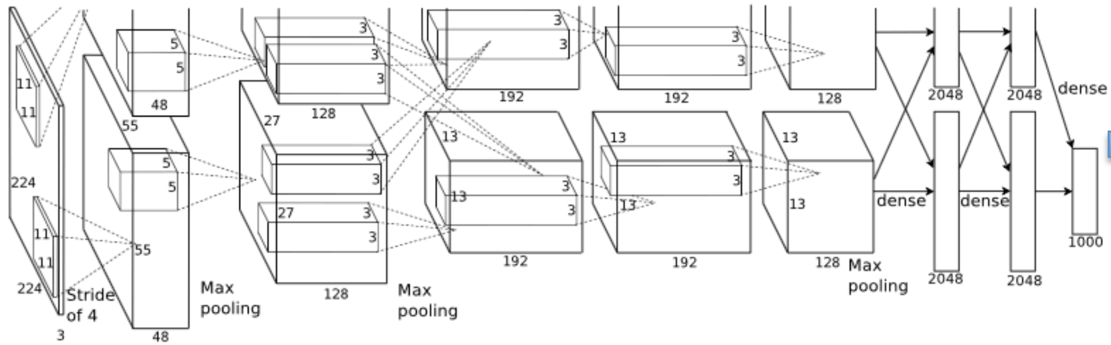




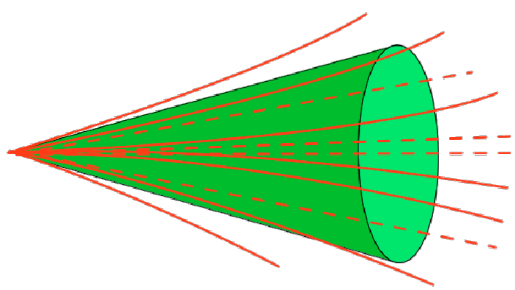
Deep Learning on PF output

Input:
raw jet
(e.g. 1st 100 particles in jet)

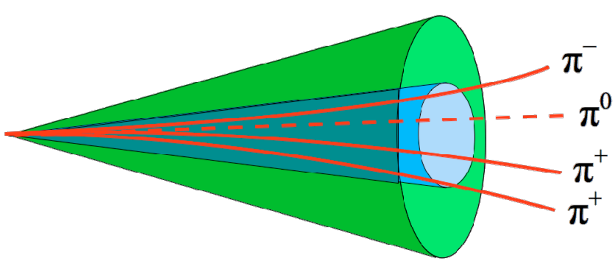
or other collection of particles



Output:
score for each category
or
regression value



jet of hadrons



e.g. :
- τ identification
- b jet tagging
- jet energy correction
- MET

Our advantage:
Monte Carlo Simulation
- large number of events
- we know the truth (NN target)