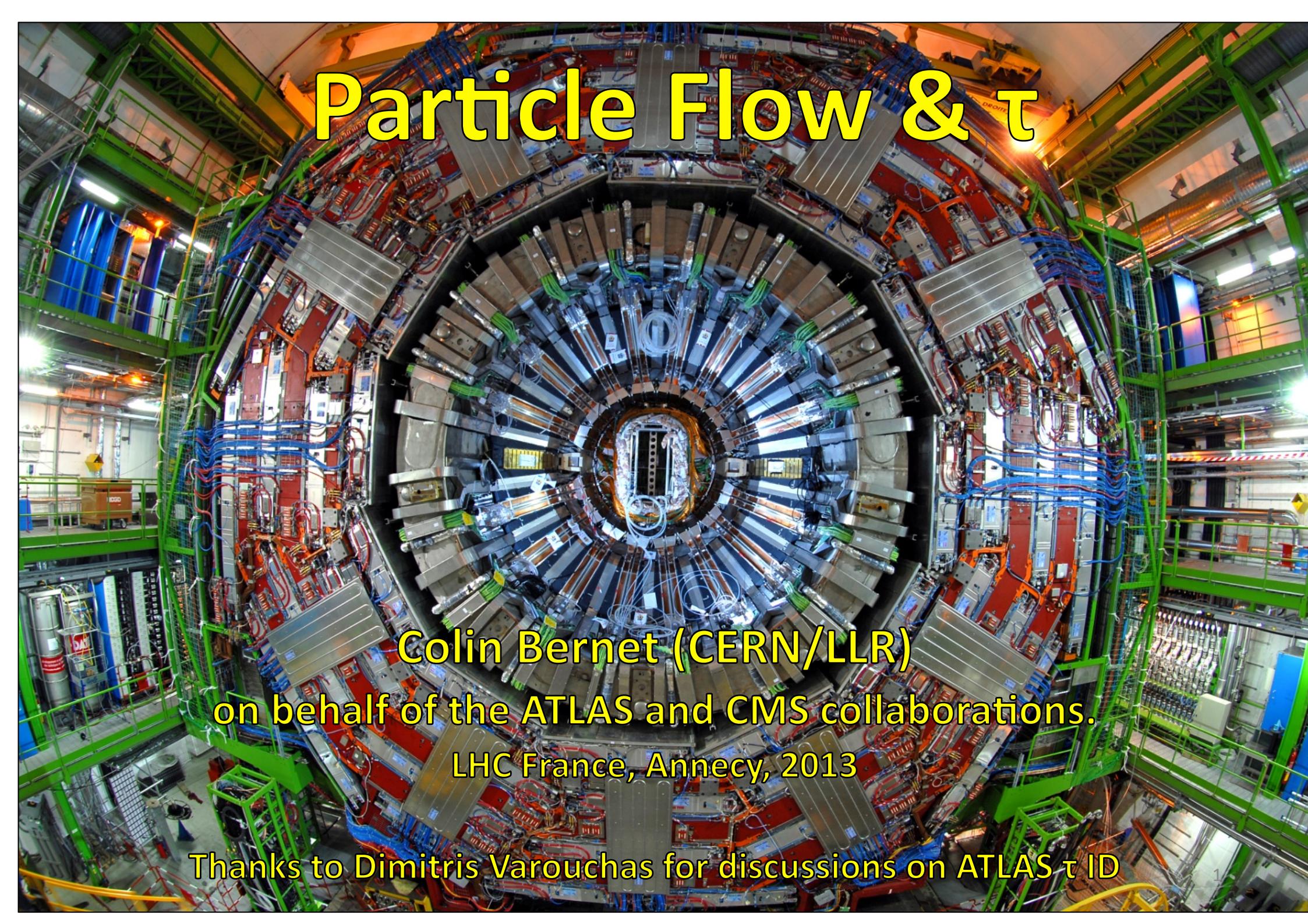
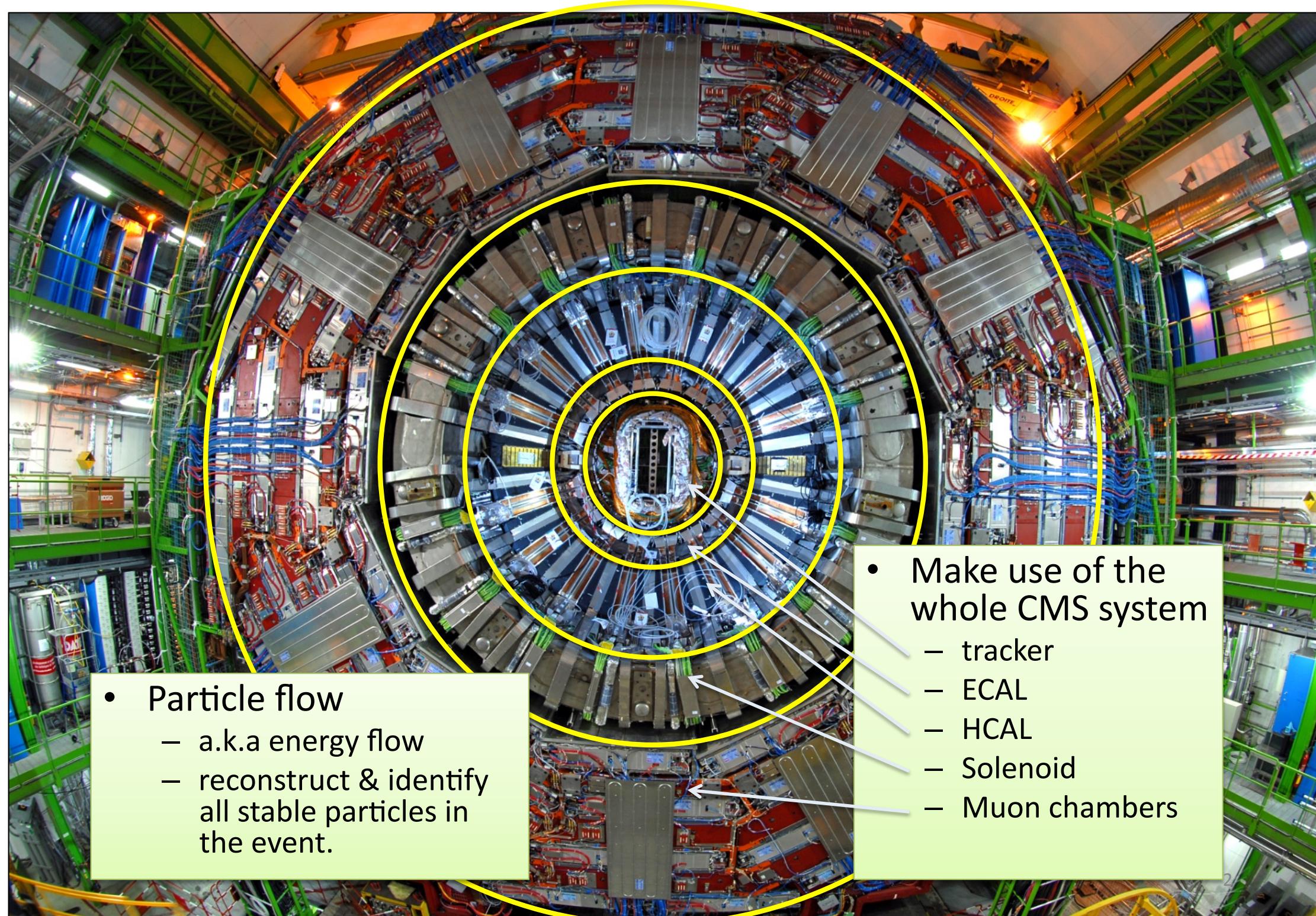


# Particle Flow & $\tau$



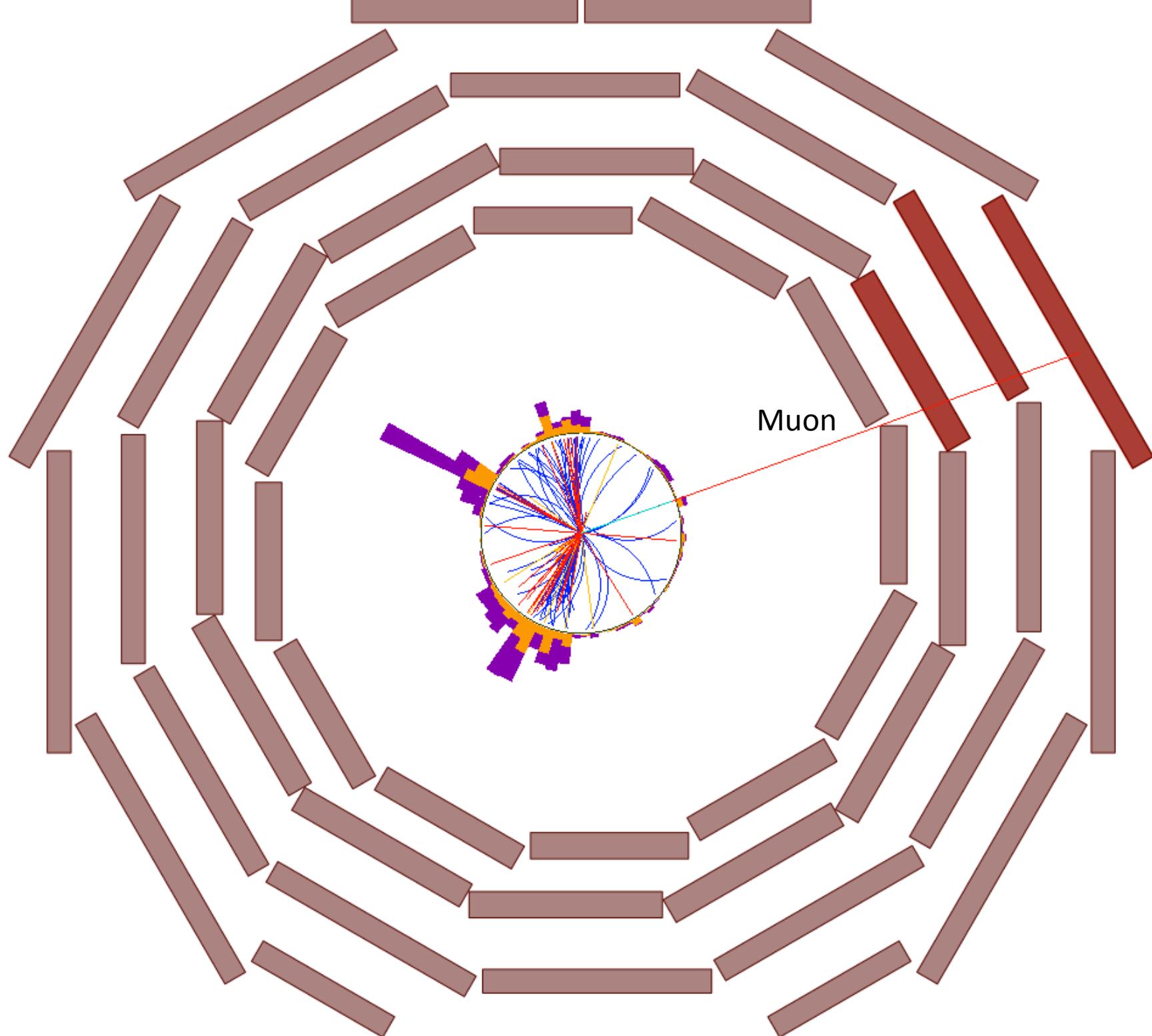
Colin Bernet (CERN/LLR)  
on behalf of the ATLAS and CMS collaborations.  
LHC France, Annecy, 2013

Thanks to Dimitris Varouchas for discussions on ATLAS  $\tau$  ID

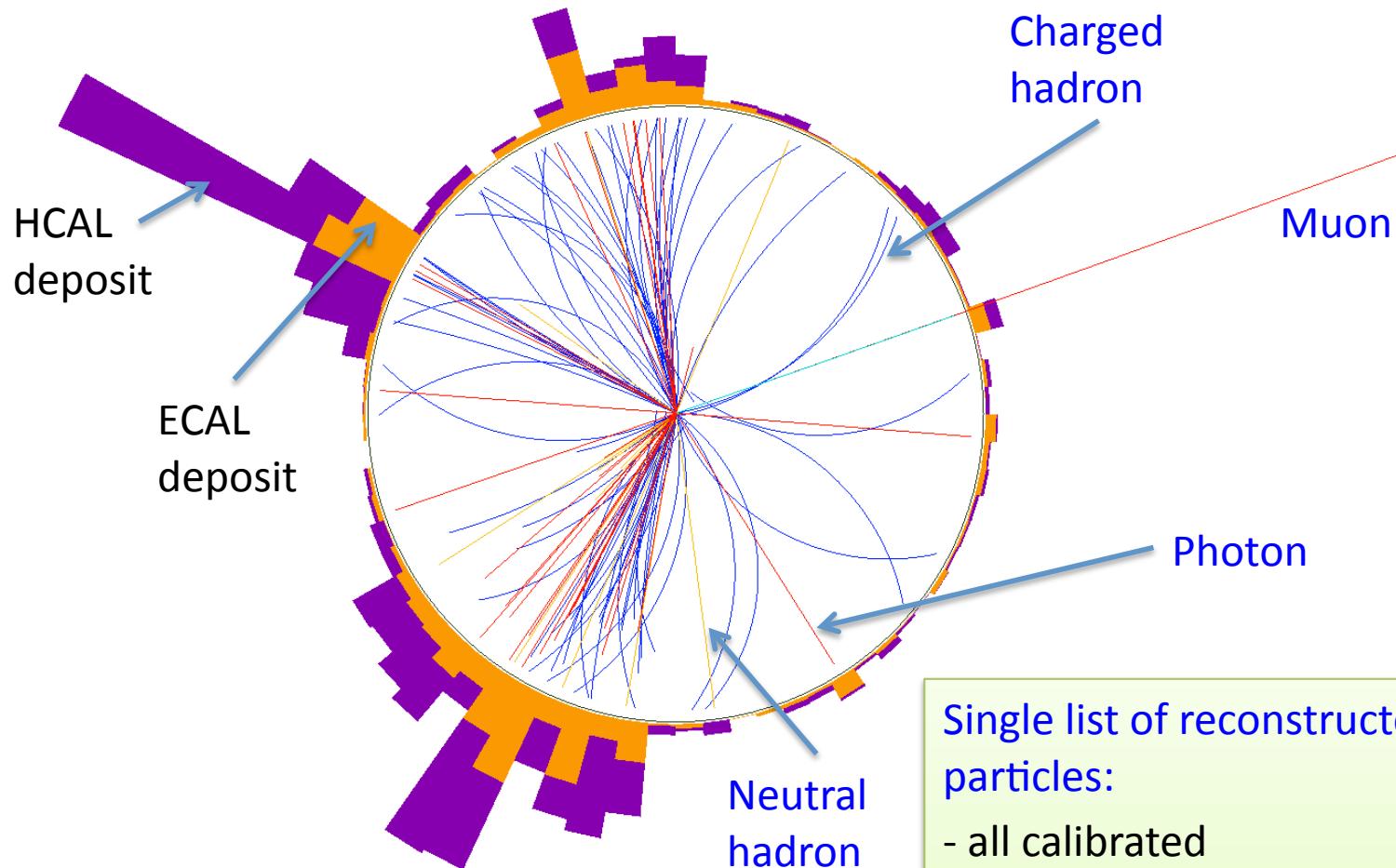


- Particle flow
  - a.k.a energy flow
  - reconstruct & identify all stable particles in the event.

- Make use of the whole CMS system
  - tracker
  - ECAL
  - HCAL
  - Solenoid
  - Muon chambers

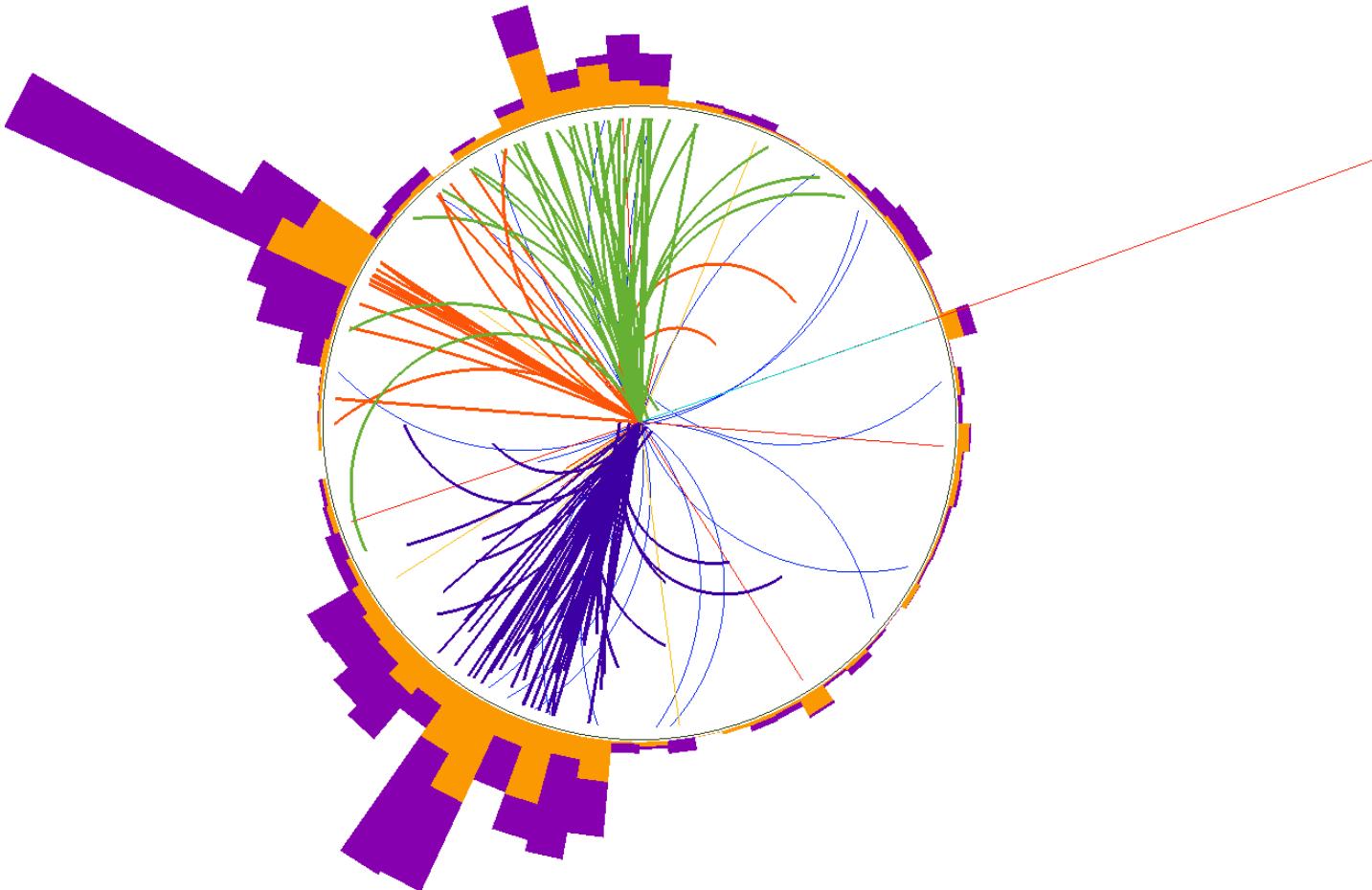


# Zoom



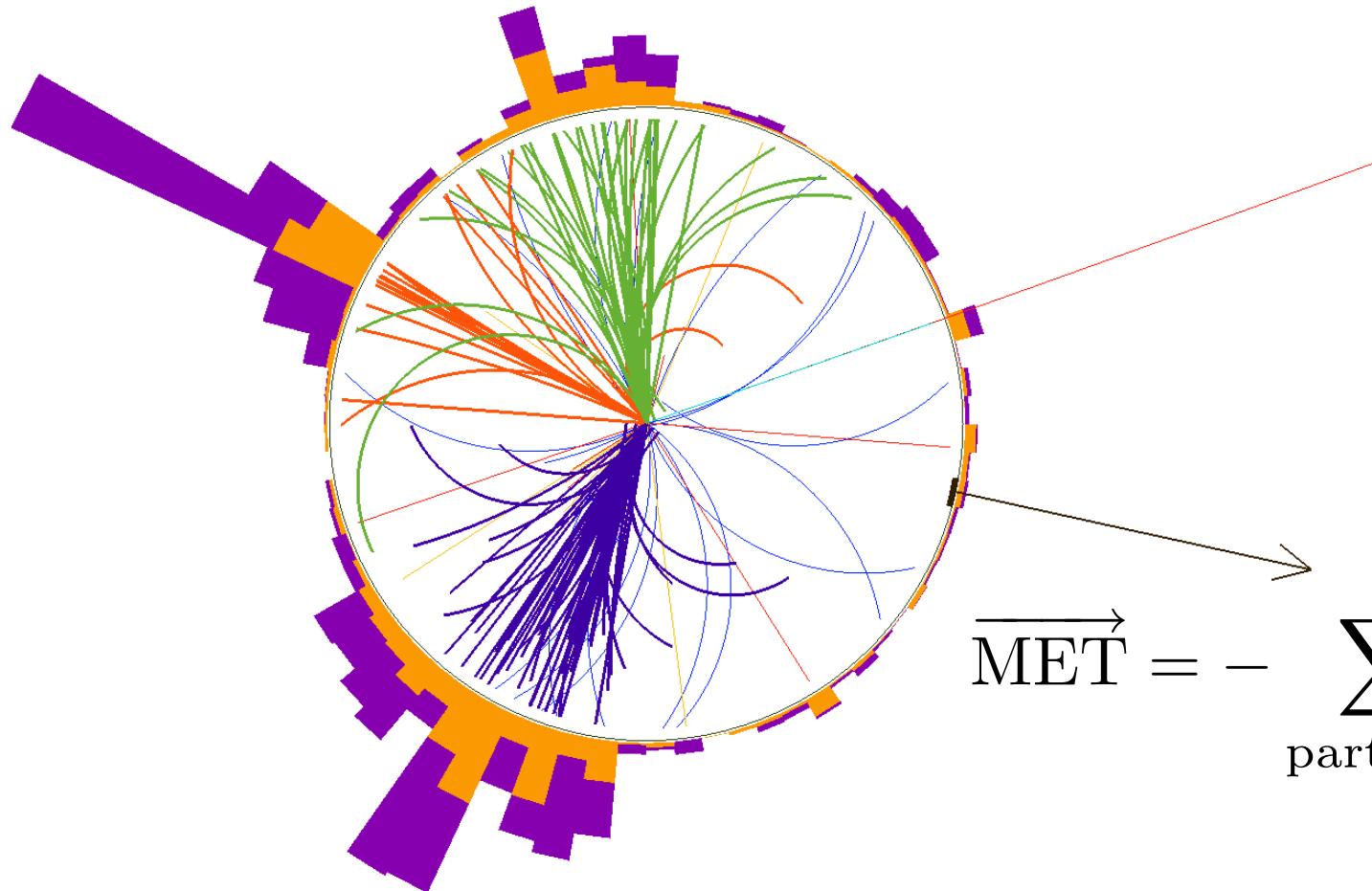
Single list of reconstructed particles:  
- all calibrated  
- used to build high-level objects in a consistent way (global event description)

# Particle Jets



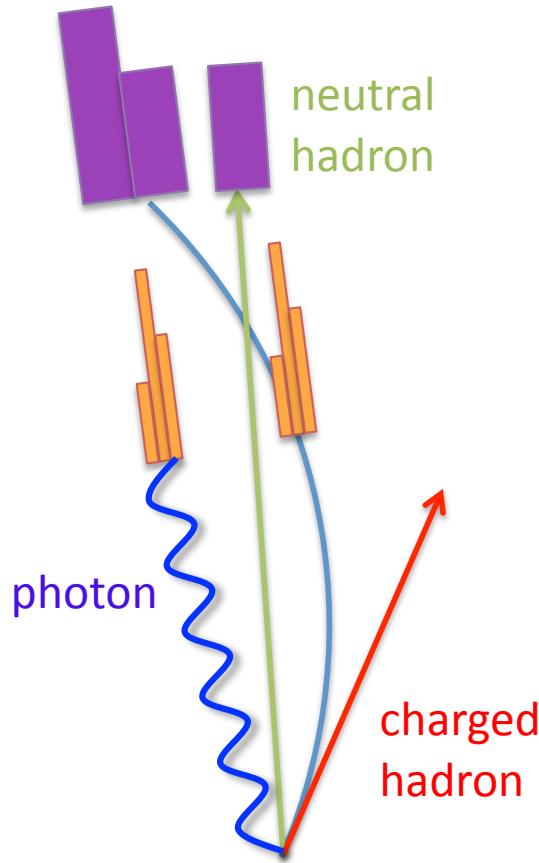
For the first time in a hadron collider experiment

# Missing Transverse Energy Momentum



For the first time in a hadron collider experiment

# Why Particle Flow?



- Calorimeter jet:
  - $E = E_{HCAL} + E_{ECAL}$
  - $\sigma(E) \sim$  calo resolution to hadron energy:  $120\% / \sqrt{E}$
  - direction biased ( $B = 3.8\text{ T}$ )
- Particle flow jet:
  - **65% charged hadrons**
    - $\sigma(pT)/pT \sim 1\%$
    - direction measured at vertex
  - **25% photons**
    - $\sigma(E)/E \sim 1\% / \sqrt{E}$
    - good direction resolution
  - **10% neutral hadrons**
    - $\sigma(E)/E \sim 120\% / \sqrt{E}$
  - **Need to resolve the energy deposits from the neutral particles...**

Better performance expected, at least on jet and MET reconstruction

# Particle Flow: How?

PF

Particle Flow  
algorithm,  
1 year old,  
2006

# Particle Flow: How?

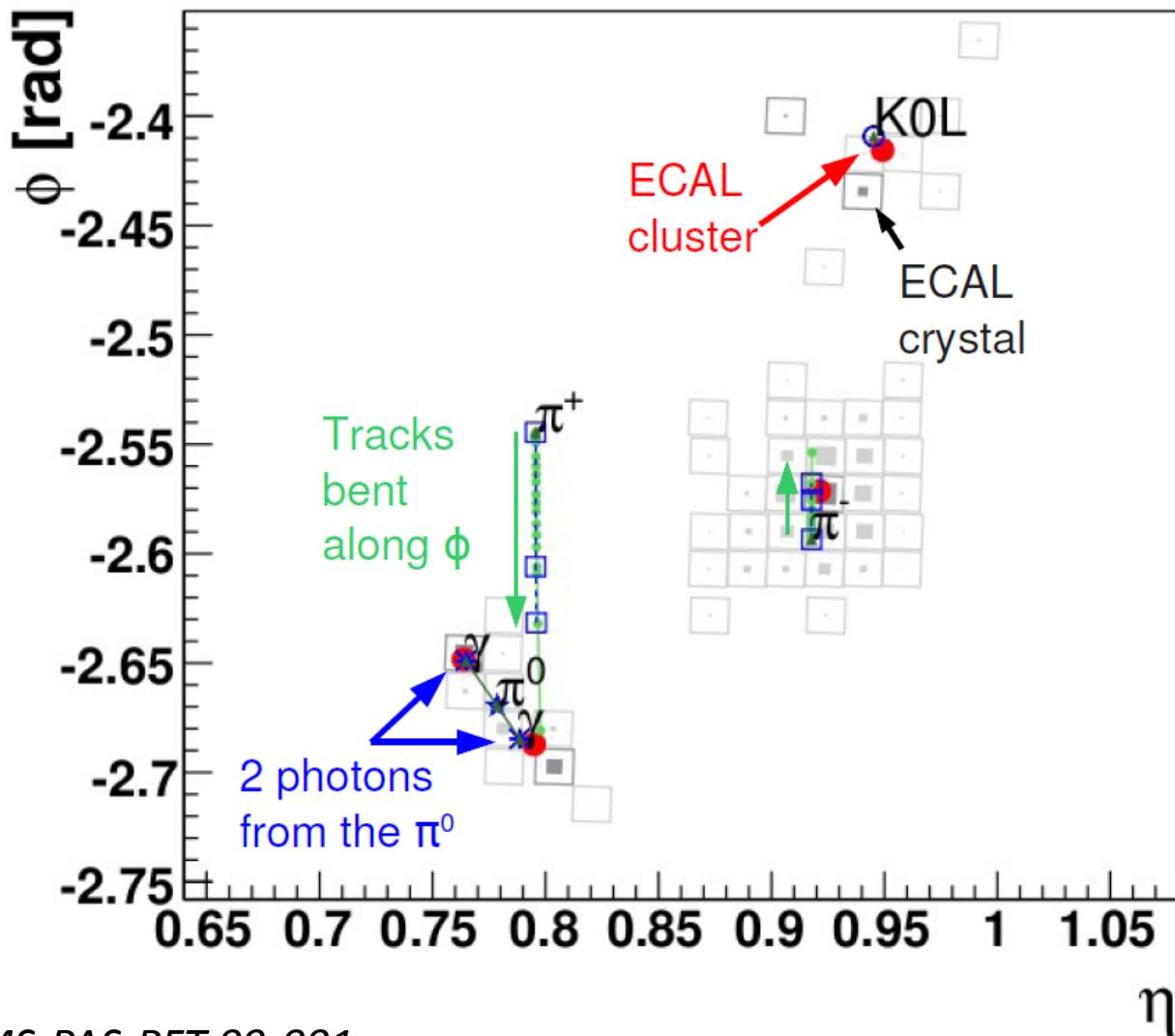
PF

Particle Flow  
algorithm,  
1 year old,  
2006



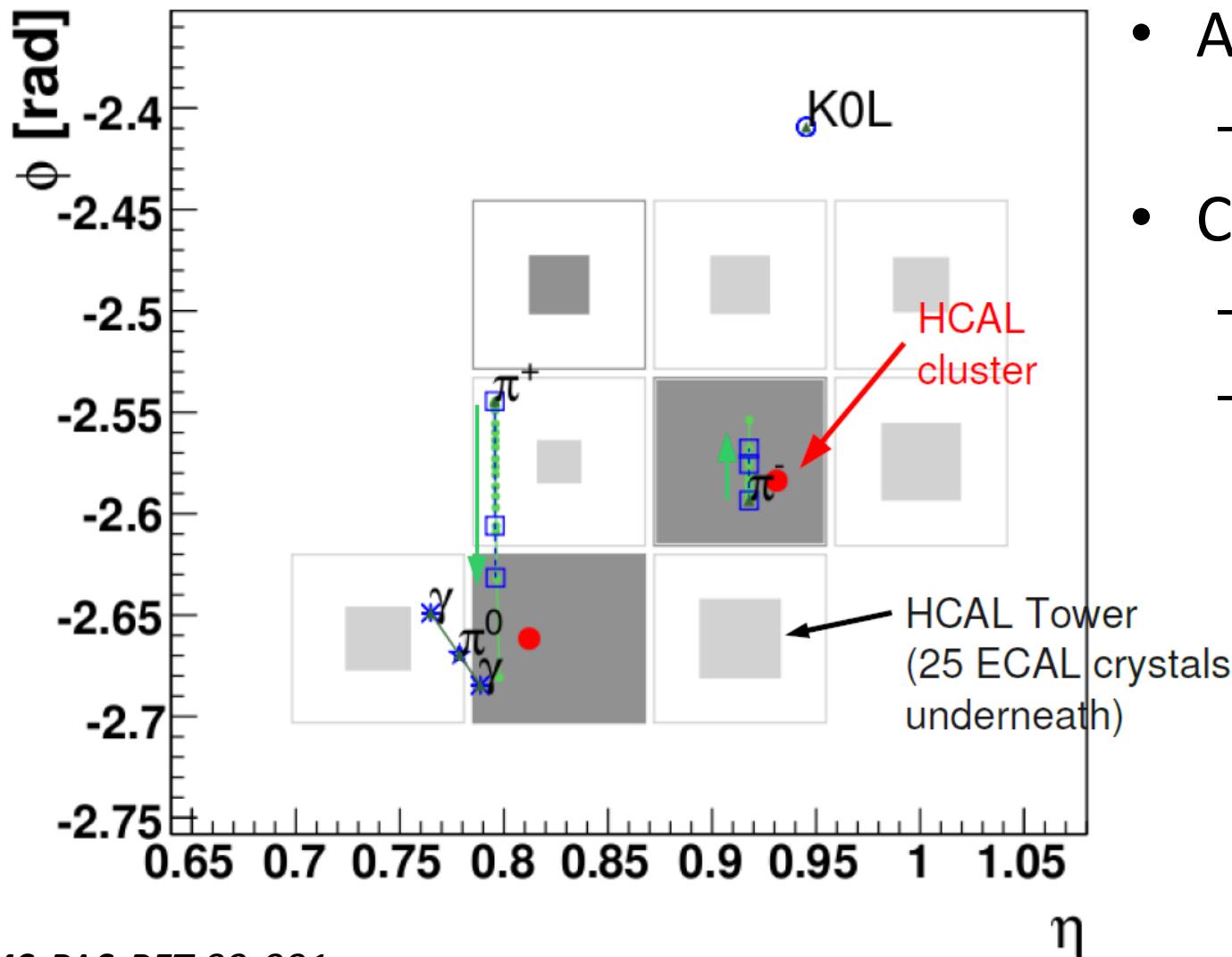
Particle Flow  
algorithm,  
Nowadays

# ECAL Surface

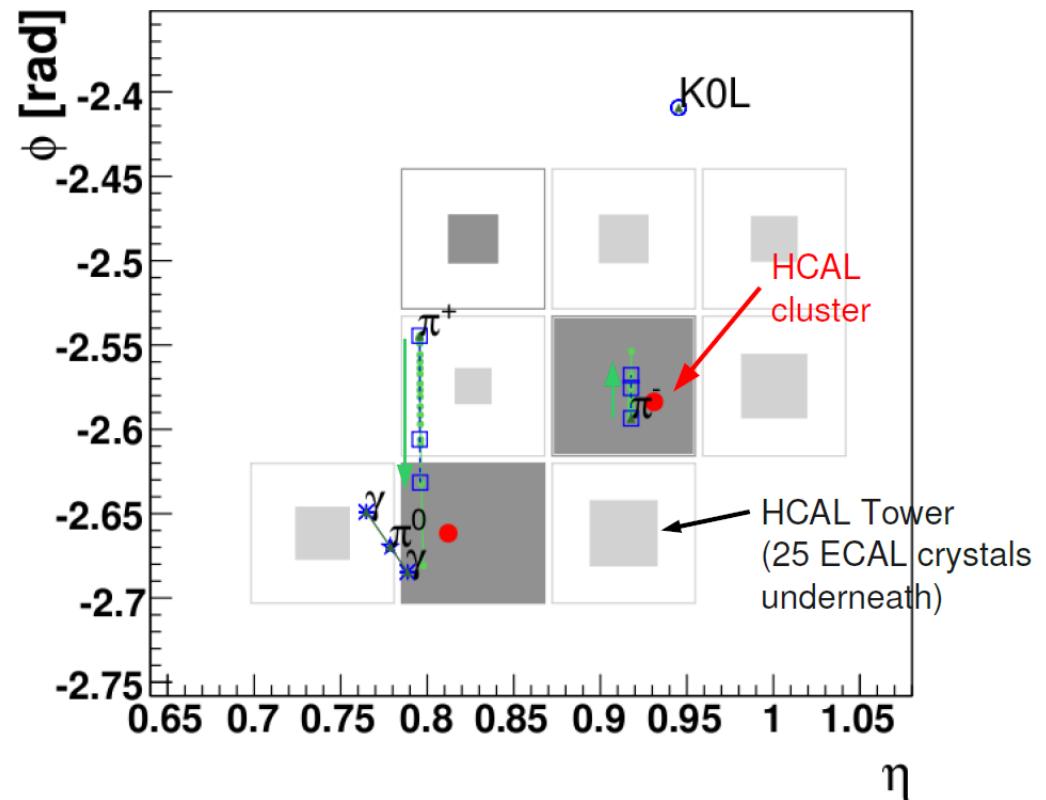
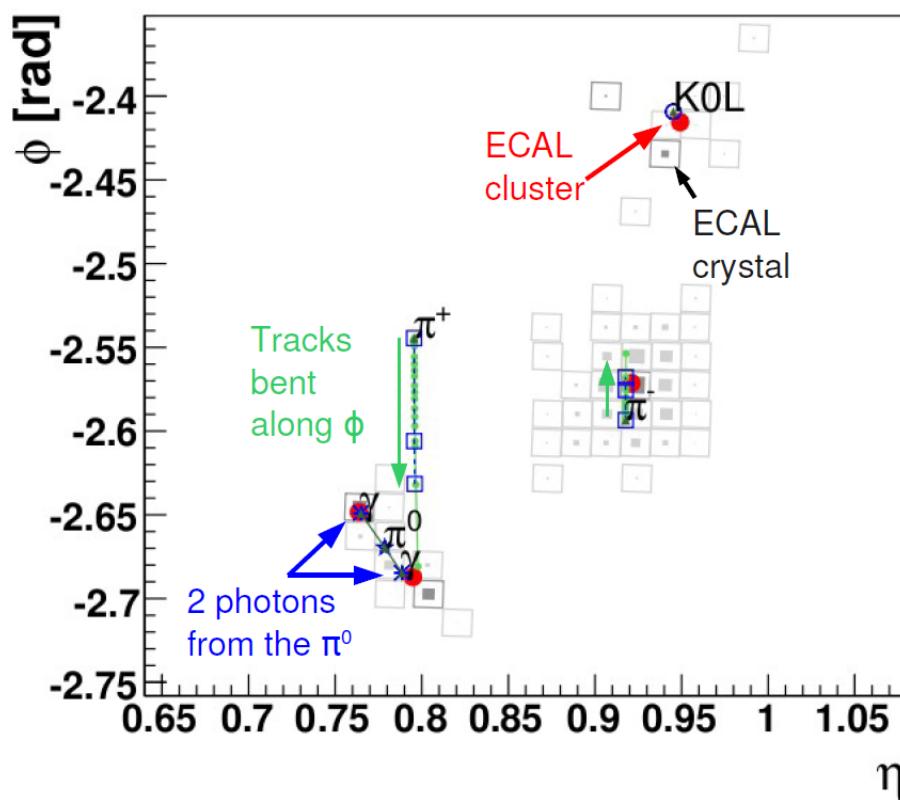


- A typical jet
  - $pT = 50 \text{ GeV}/c$
- Cell size:
  - $0.017 \times 0.017$

# HCAL Surface



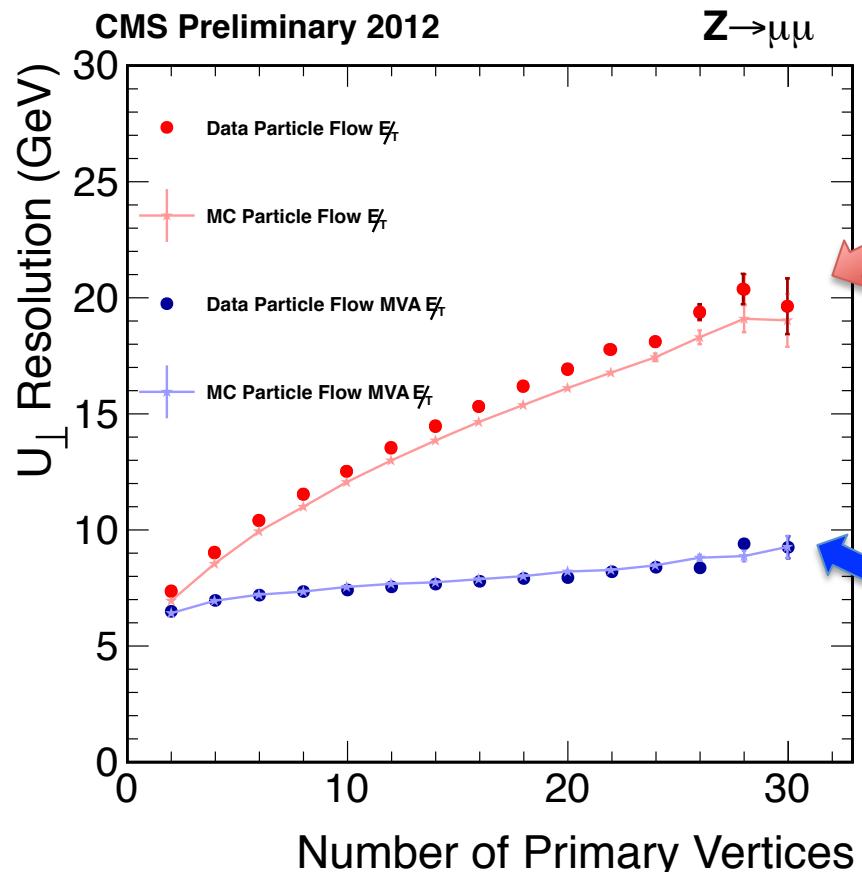
# 2 charged hadrons, 3 photons



# Effects of particle flow in CMS

- **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 / 3
  - smallest tails
- **$\tau$** 
  - jet fake rate / 3 @ same eff.
  - energy resolution / 4
- **Electrons**
  - down to  $pT = 3 \text{ GeV}$
  - in jets
- **$\mu$** 
  - 4% more efficient ID @ same bkgd rate
  - better momentum assignment at high  $pT$
- **$e, \mu, \tau, \gamma$  isolation**
  - pile-up control
- **Physics analyses**
  - Better trigger for jets, MET, taus (PF@HLT)
  - e.g:
    - FSR photon recovery in  $H \rightarrow ZZ$
    - embedding in  $H \rightarrow \tau\tau$
    - jet substructure

# Multivariate MET



several kinds of particle-flow MET:

MET  
from all  
particles

MET  
from  
pileup  
particles

MET  
from  
primary  
vertex  
particles

etc.

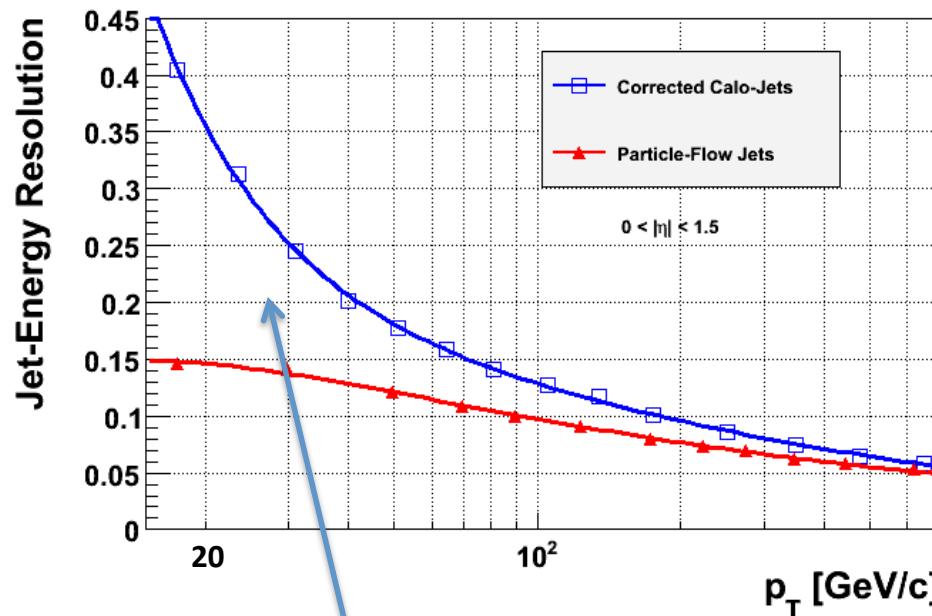
Multivariate MET  
estimation

Almost insensitive to pile-up

# Jets : Energy Resolution & Response

QCD simulation

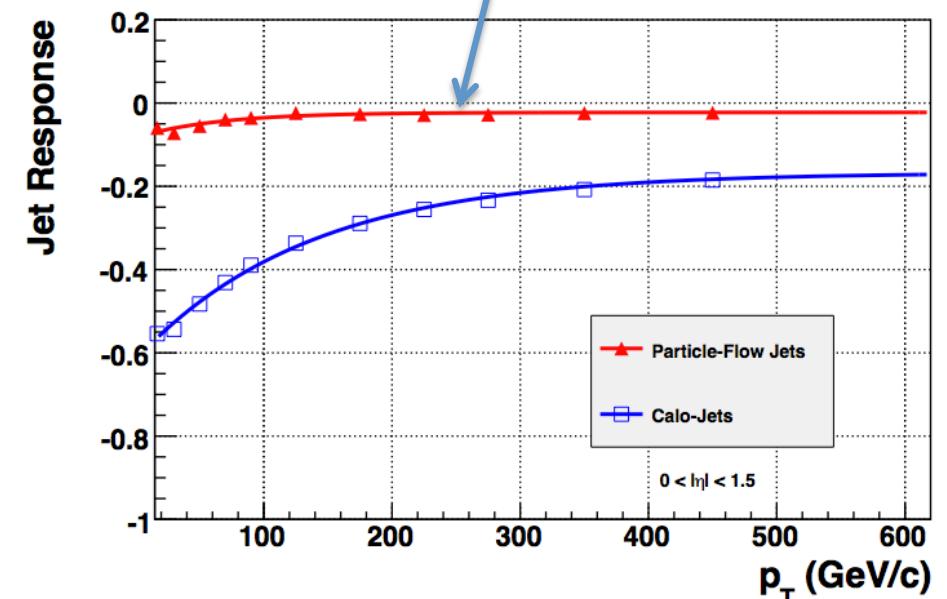
CMS Preliminary



Large improvement  
at low  $p_T$

The jet particles were calibrated  
→ response close to 1 before  
any jet energy correction

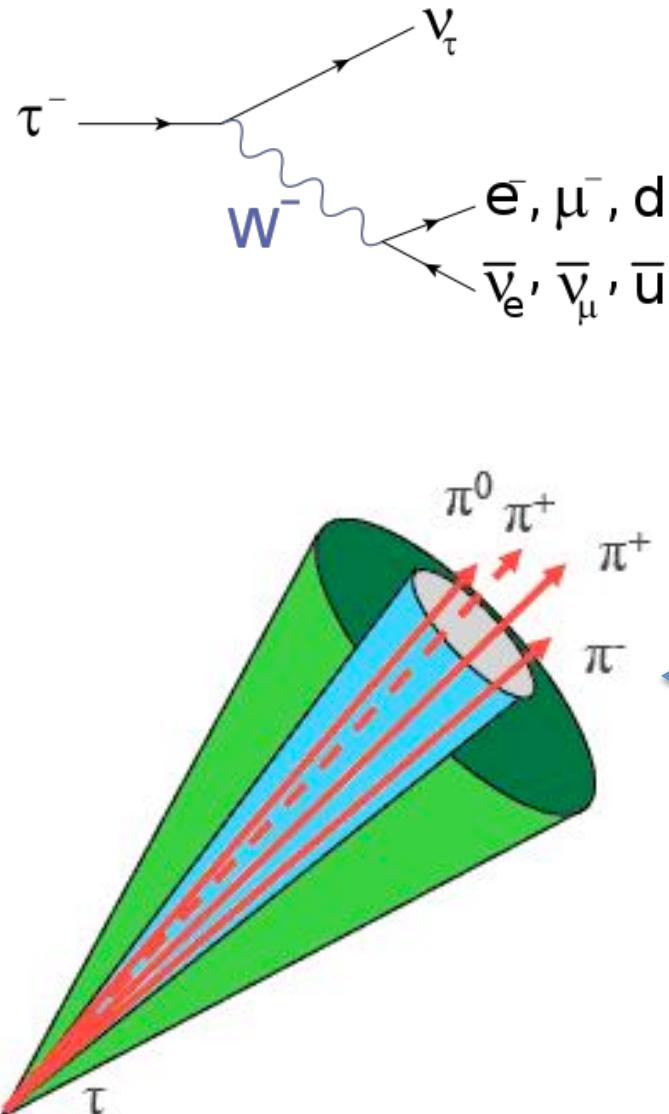
CMS Preliminary



CMS-PAS-PFT-09-001

CMS-PAS-PFT-10-002

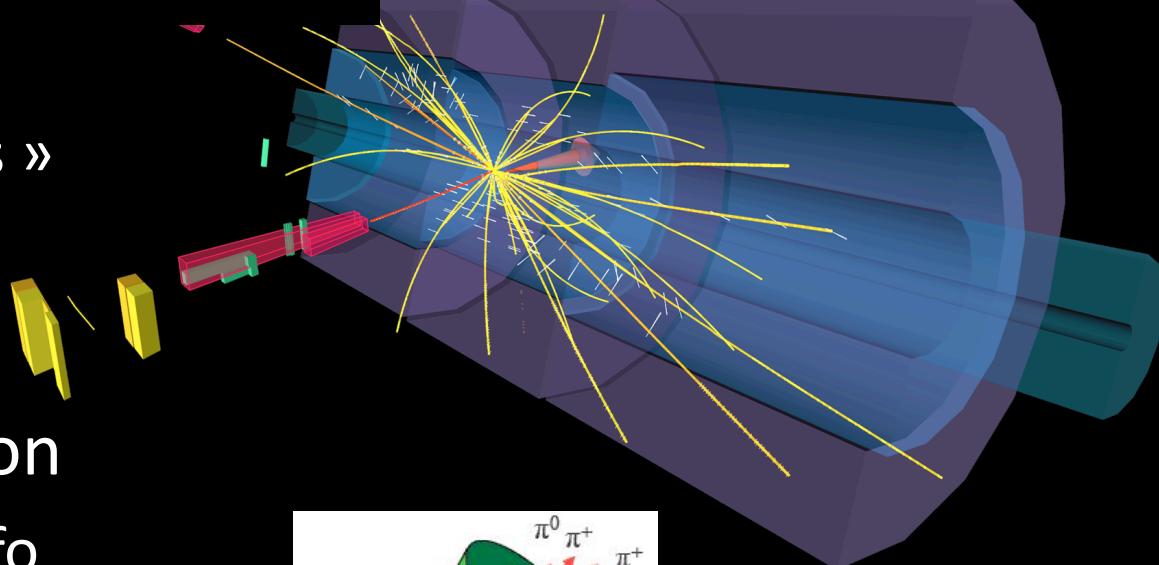
# The $\tau$ lepton



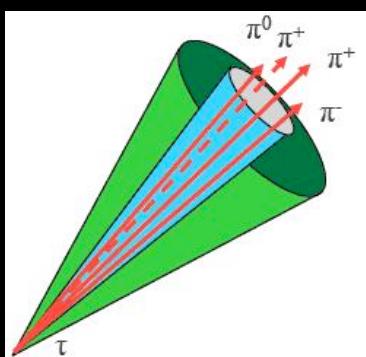
- $m = 1.78 \text{ GeV}$ 
  - Largest Higgs-lepton coupling!
- $c\tau = 90 \mu\text{m}$
- Branching ratios:
  - 65%  $\tau^\pm \rightarrow \tau_{\text{had}}^\pm \nu_\tau$ 
    - 75%,  $\tau^\pm \rightarrow 1\pi^\pm + [\pi^0('s)] + \nu_\tau$  (**1 prong**)
    - 23%,  $\tau^\pm \rightarrow 3\pi^\pm + [\pi^0('s)] + \nu_\tau$  (**3 prongs**)
  - 35%  $\tau^\pm \rightarrow l^\pm \nu_l \nu_\tau$
- Narrow “jet” with only a few particles, typically isolated

- Seed jet built from calo clusters  $\Delta R < 0.4$ 
  - $\tau$  momentum from clusters with  $\Delta R < 0.2$

- Associate tracks
  - with  $\Delta R < 0.2$
  - 1 or 3 « prongs »

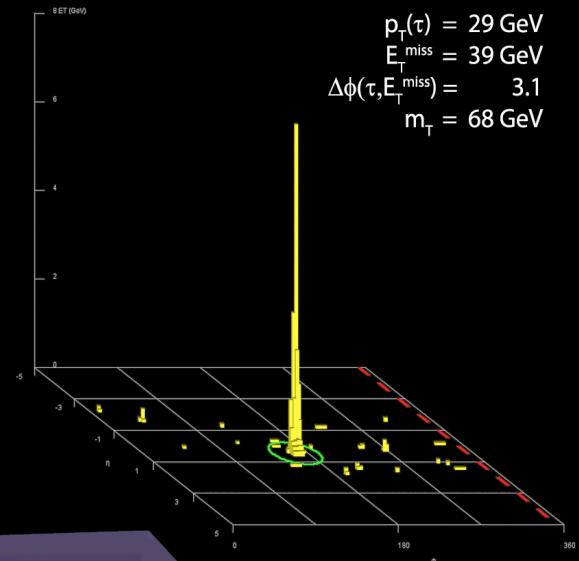


- MVA jet rejection
  - calo & track info
    - e.g. track isolation, jet energy profile, etc.

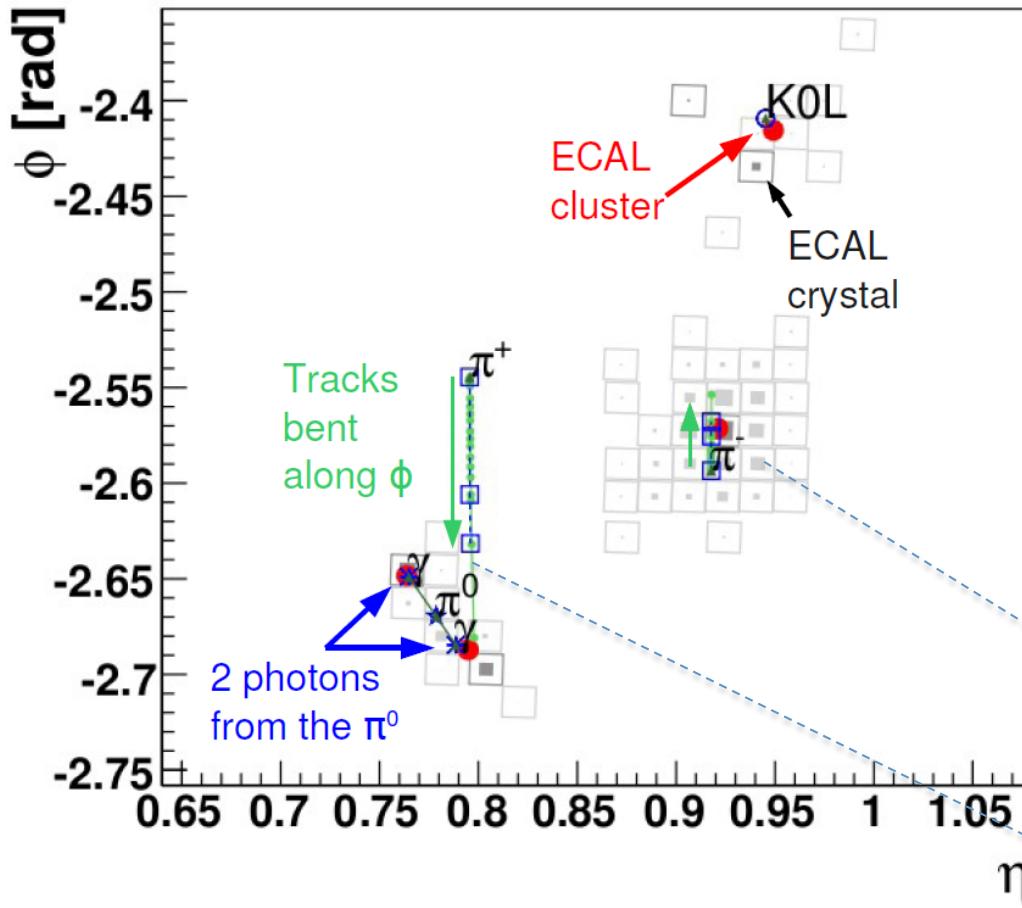


Run 155697, Event 6769403  
Time 2010-05-24, 17:38 CEST

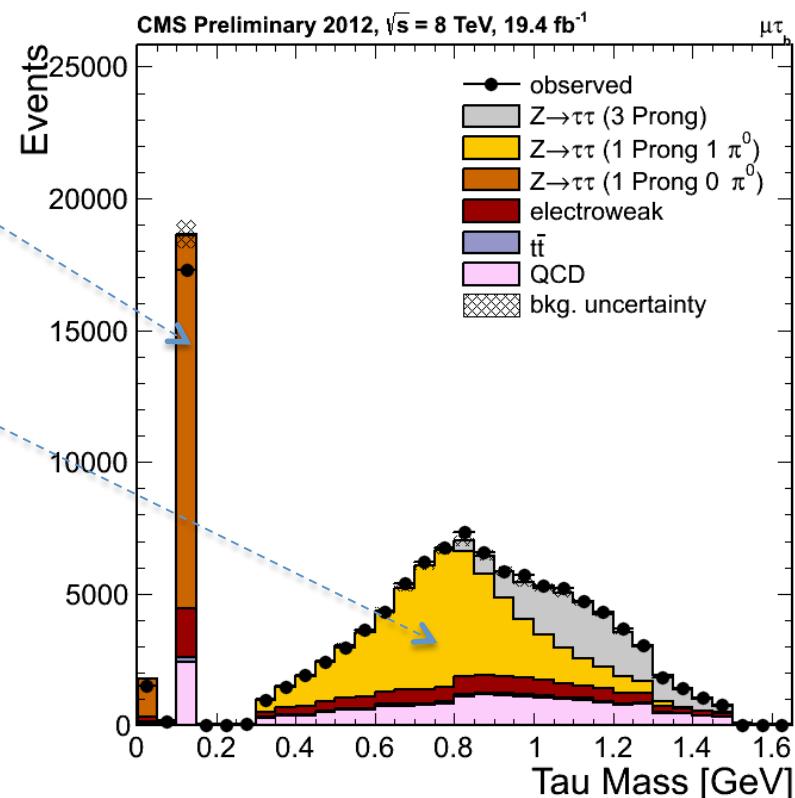
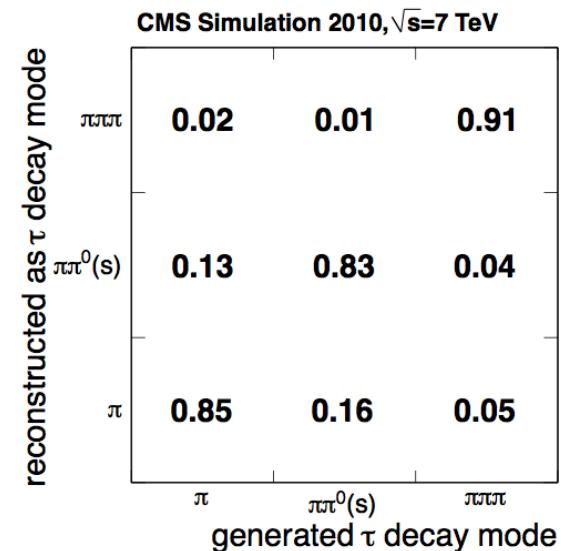
$W \rightarrow \tau v$  candidate in  
7 TeV collisions



# $\tau$ Reco & ID in CMS

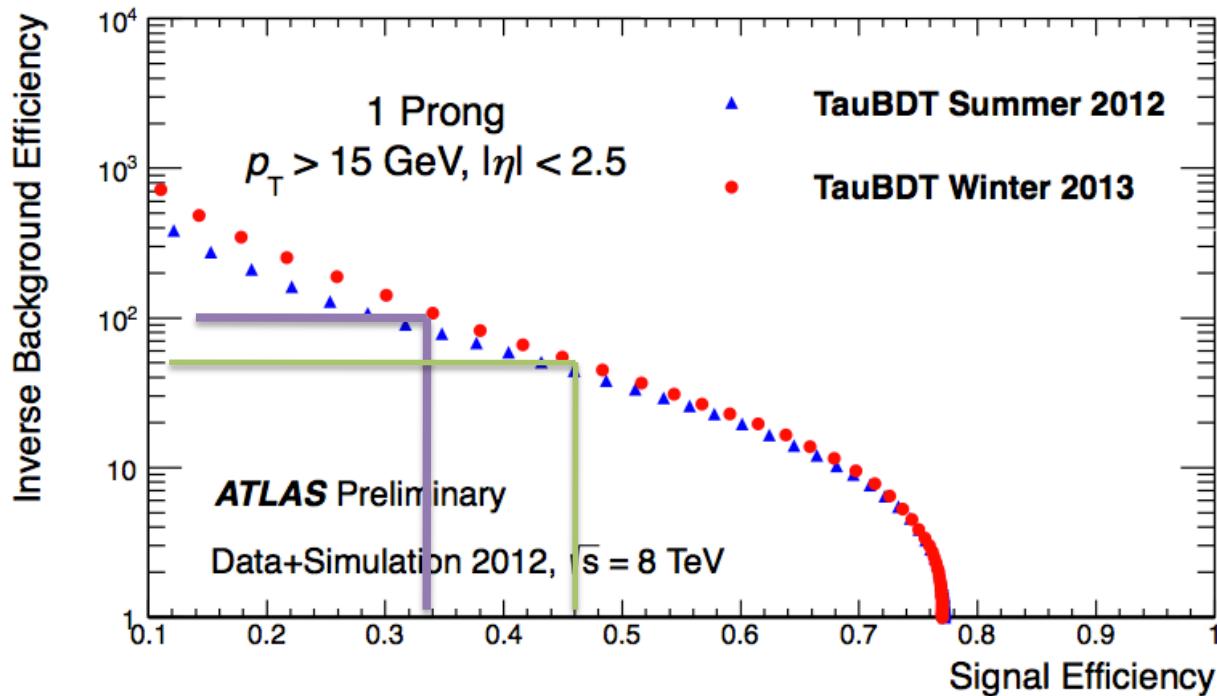


- Select decay particles according to decay mode
- Isolation w/r to other particles

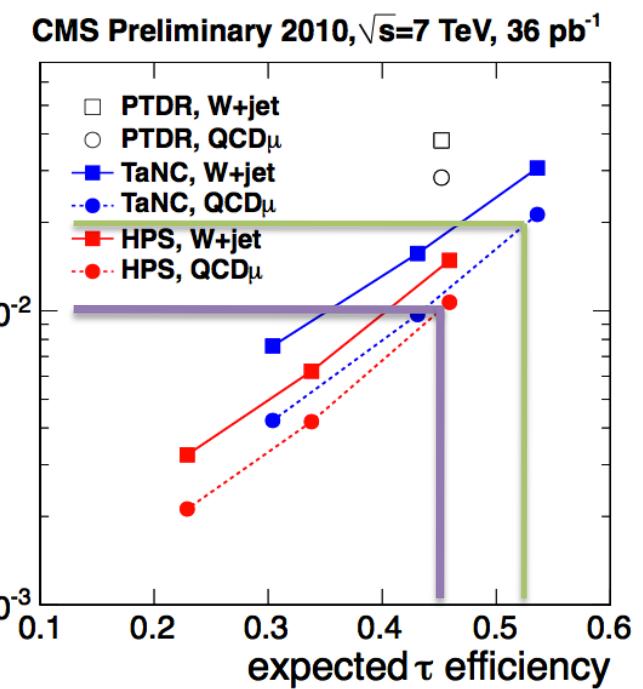


# $\tau$ ID performance

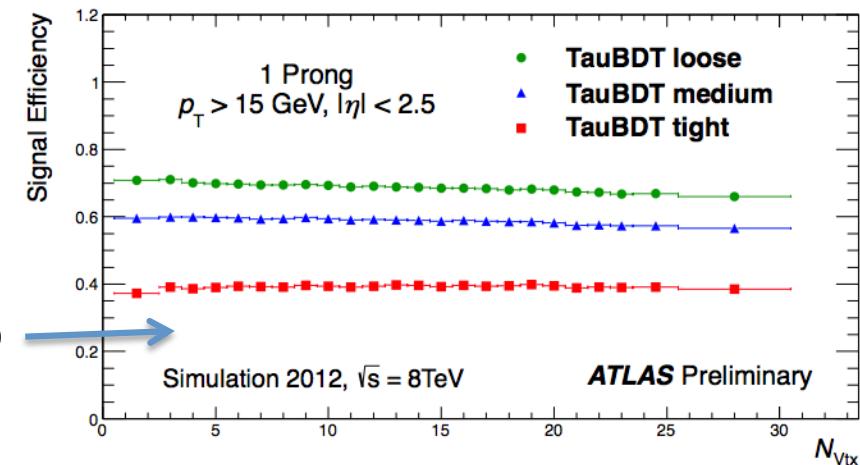
ATLAS



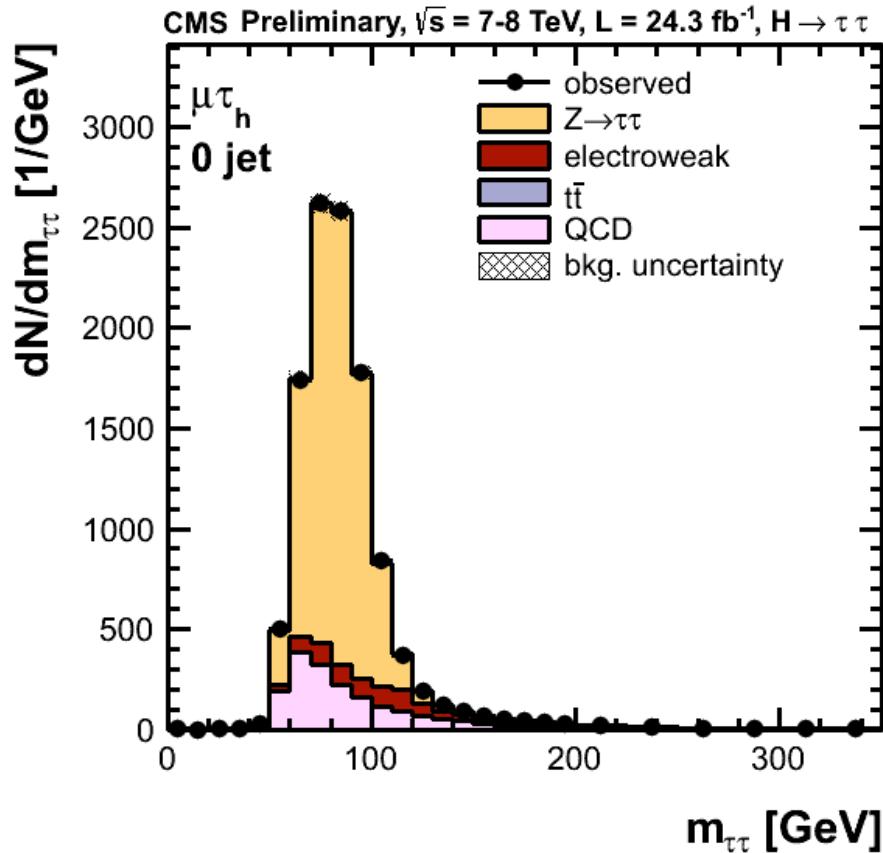
CMS (HPS)



- ATLAS and CMS  
(apple to apple comparison difficult!)
  - 40% efficiency at 1% fake rate
  - 50% efficiency at 2% fake rate
- Efficiency (and fake rate) flat vs pileup



# $\tau$ Energy Scale

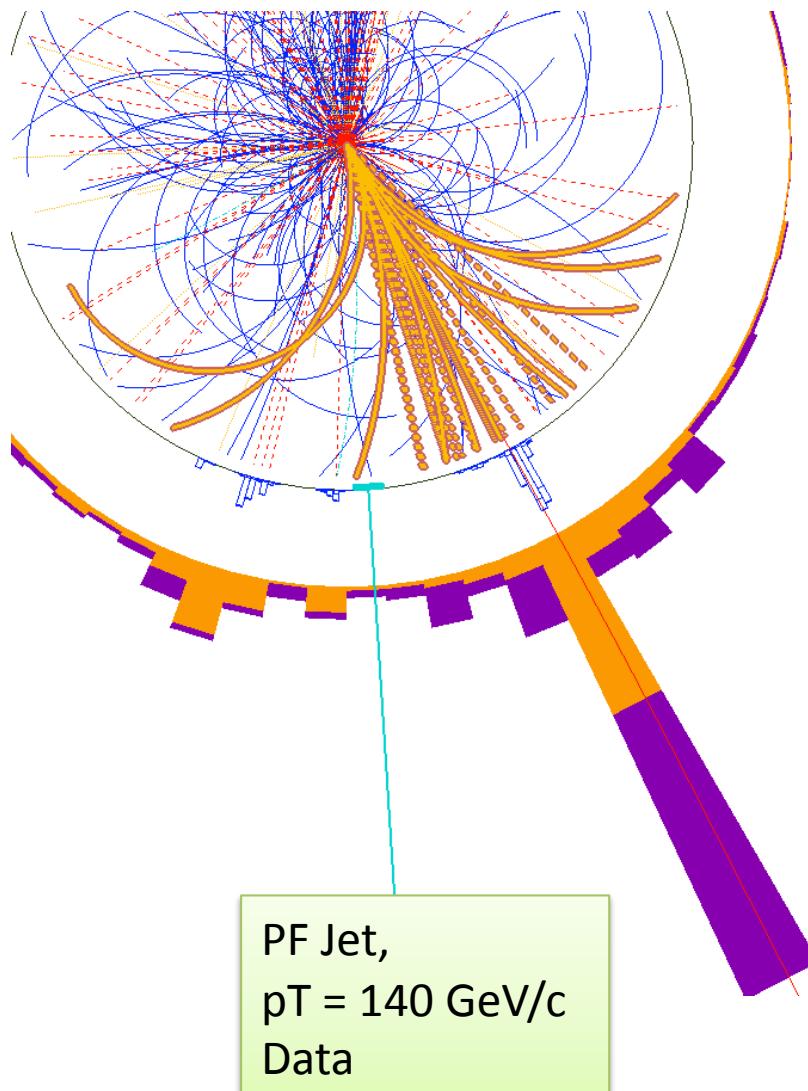


- In the past (low int. lumi.)
  - fit mass of  $\tau$  visible decay products (CMS)
  - single-particle response modification (ATLAS)  
 $\rightarrow \tau$  E scale uncertainty = 3%
- Future (now)
  - fit mass of  $\tau$  visible decay products (CMS)
  - fit mass of the  $\mu\tau$  system  
 $\rightarrow \tau$  E scale uncertainty  $\leq 1\%$ ?

# Summary

- Particle flow used in almost all analyses in CMS
  - Now competitive with ATLAS on jets, MET
- Excellent tau performance in ATLAS and CMS
  - See taus (& PF) in action, e.g. tomorrow:  
Arun Nayak,  $H \rightarrow \tau\tau$  in ATLAS & CMS

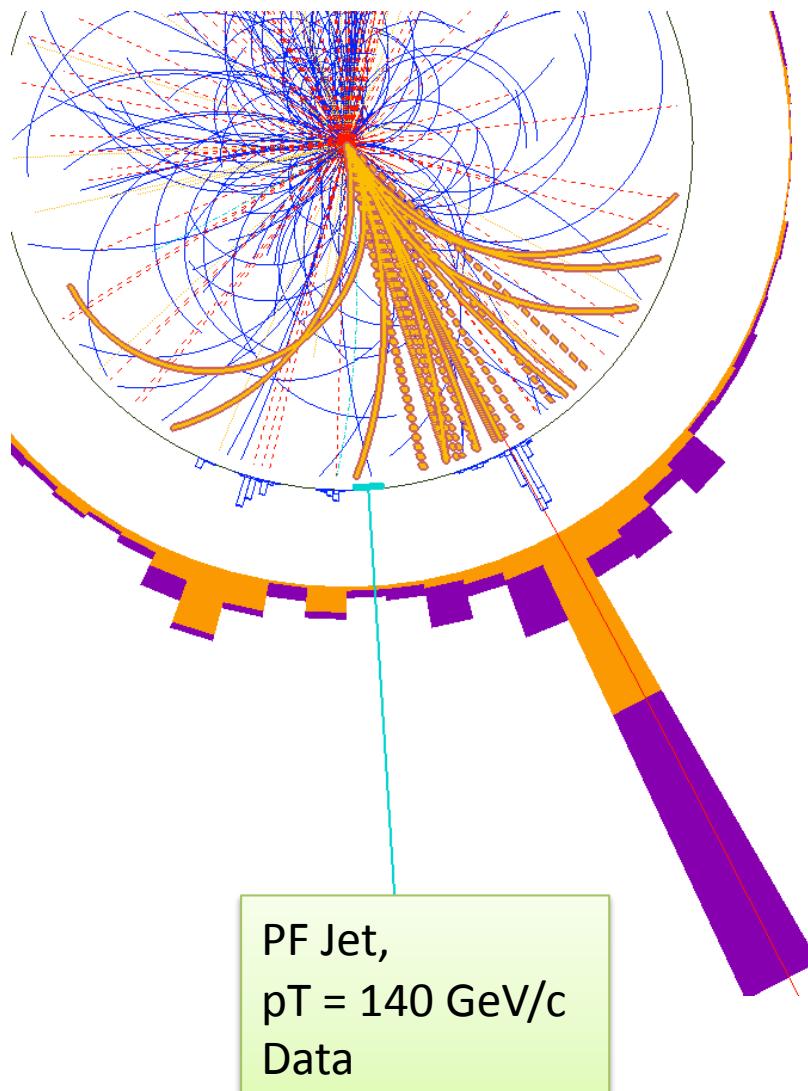
# Recipe for a good particle flow



- Separate neutrals from charged hadrons
  - Field integral ( $B \times R$ )
  - Calorimeter granularity
- Efficient tracking
- Minimize material before calorimeters
- Clever algorithm to compensate for detector imperfections

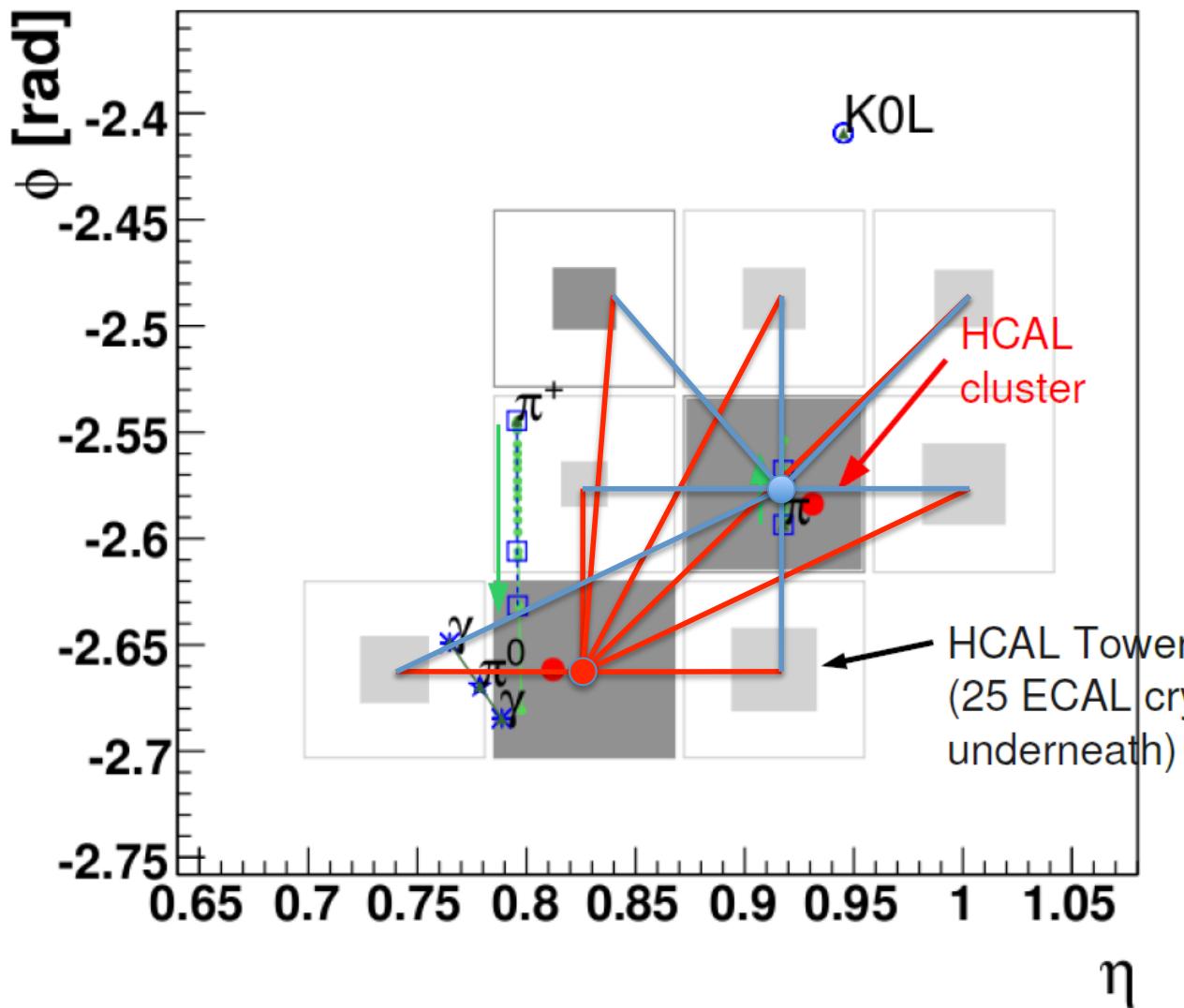
# Neutral/charged separation (1)

## Field Integral



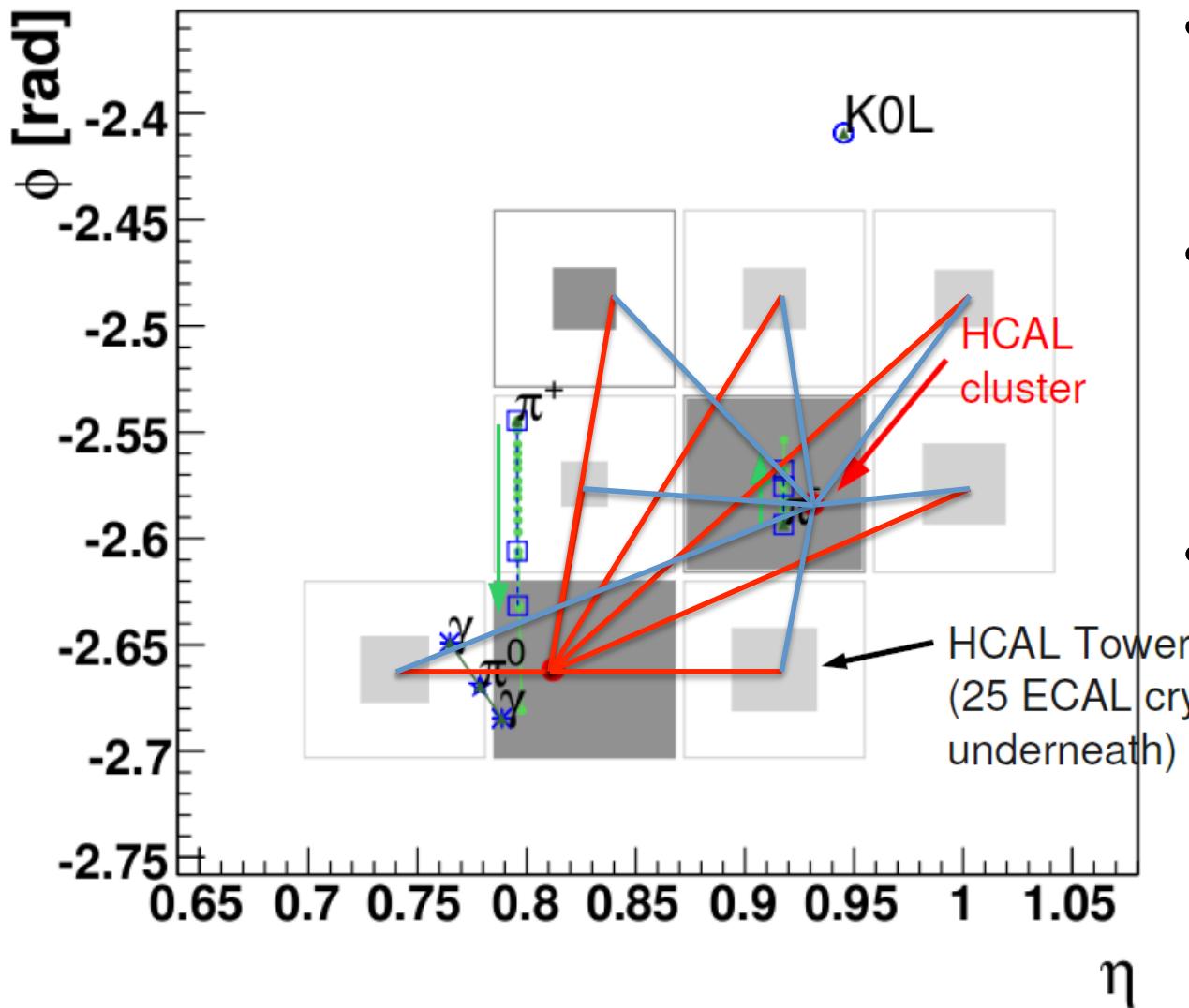
- Strong magnetic field: 3.8 T
- ECAL radius 1.29 m
- $B \times R = 4.9 \text{ T.m}$ 
  - ALEPH:  $1.5 \times 1.8 = 2.7 \text{ T.m}$
  - ATLAS:  $2.0 \times 1.2 = 2.4 \text{ T.m}$
  - CDF:  $1.5 \times 1.5 = 2.25 \text{ T.m}$
  - DO:  $2.0 \times 0.8 = 1.6 \text{ T.m}$

# PF Clustering, HCAL



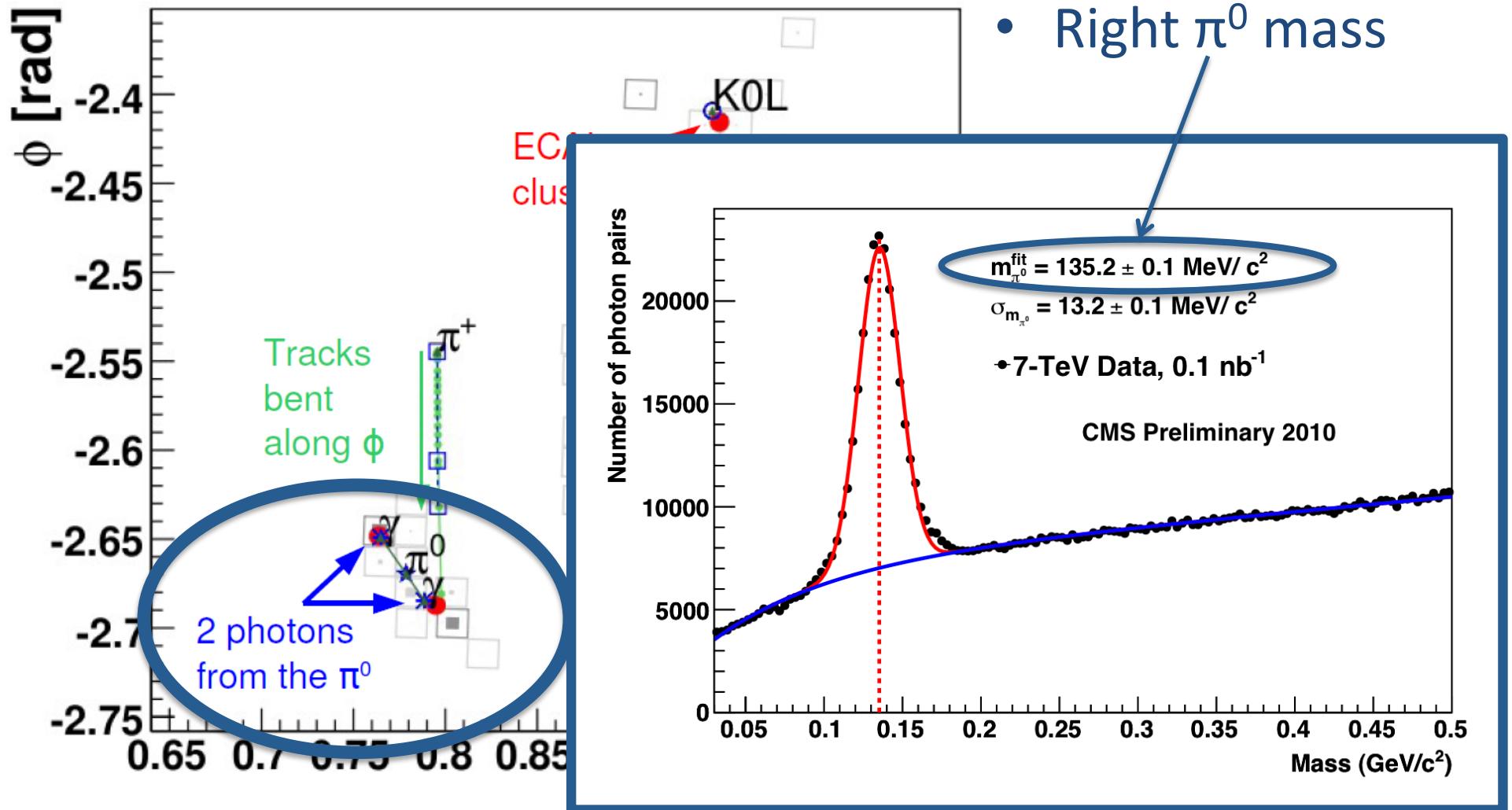
- Used in:
  - ECAL, HCAL, preshower
- Iterative, energy sharing
  - Gaussian shower profile with fixed  $\sigma$
- Seed thresholds
  - ECAL :  $E > 0.23$  GeV
  - HCAL :  $E > 0.8$  GeV

# PF Clustering, HCAL



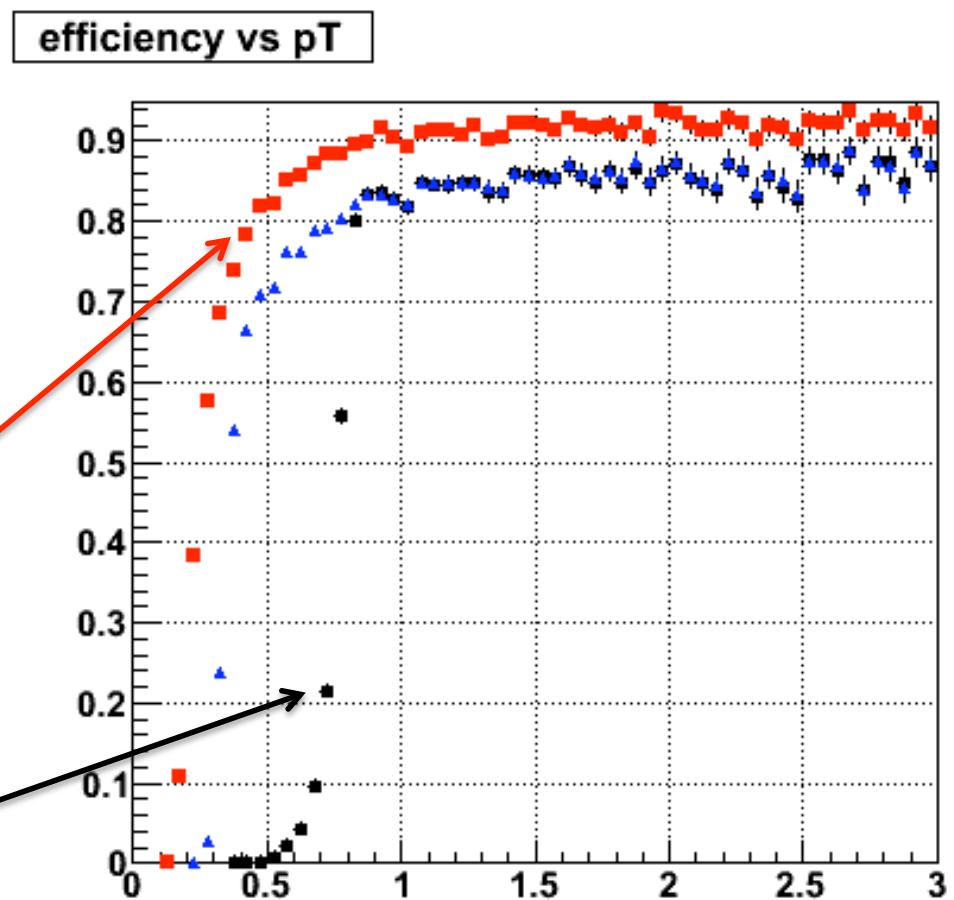
- Used in:
  - ECAL, HCAL, preshower
- Iterative, energy sharing
  - Gaussian shower profile with fixed  $\sigma$
- Seed thresholds
  - ECAL :  $E > 0.23 \text{ GeV}$
  - HCAL :  $E > 0.8 \text{ GeV}$

# PF Clustering, ECAL - Validation



# Iterative Tracking (1/2)

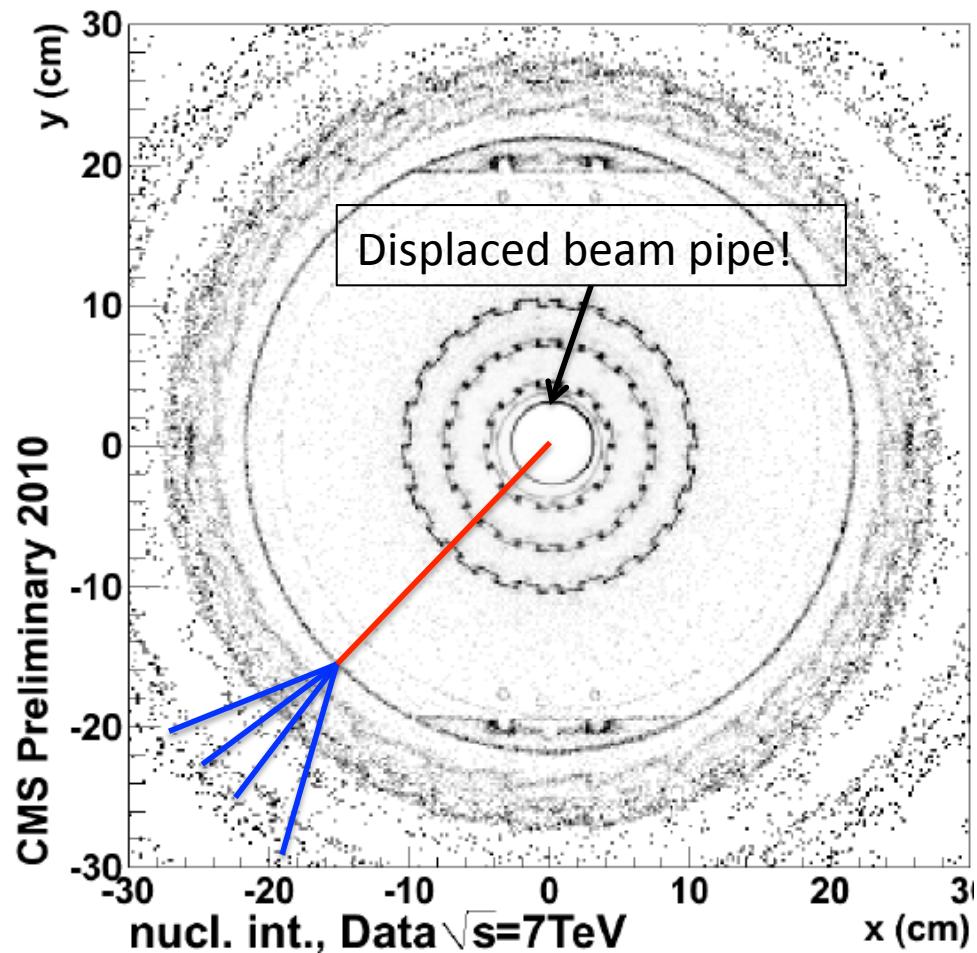
- Developed for PF, now standard
- At each iteration:
  - Reconstruct a set of tracks
  - Remove track hits
  - Relax constraints
- Fast ( $\sim 10$  s / event)
- Iterative tracking:
  - 1-2 % fake rate
- Old “CTF” tracking:
  - 20 % fake rate



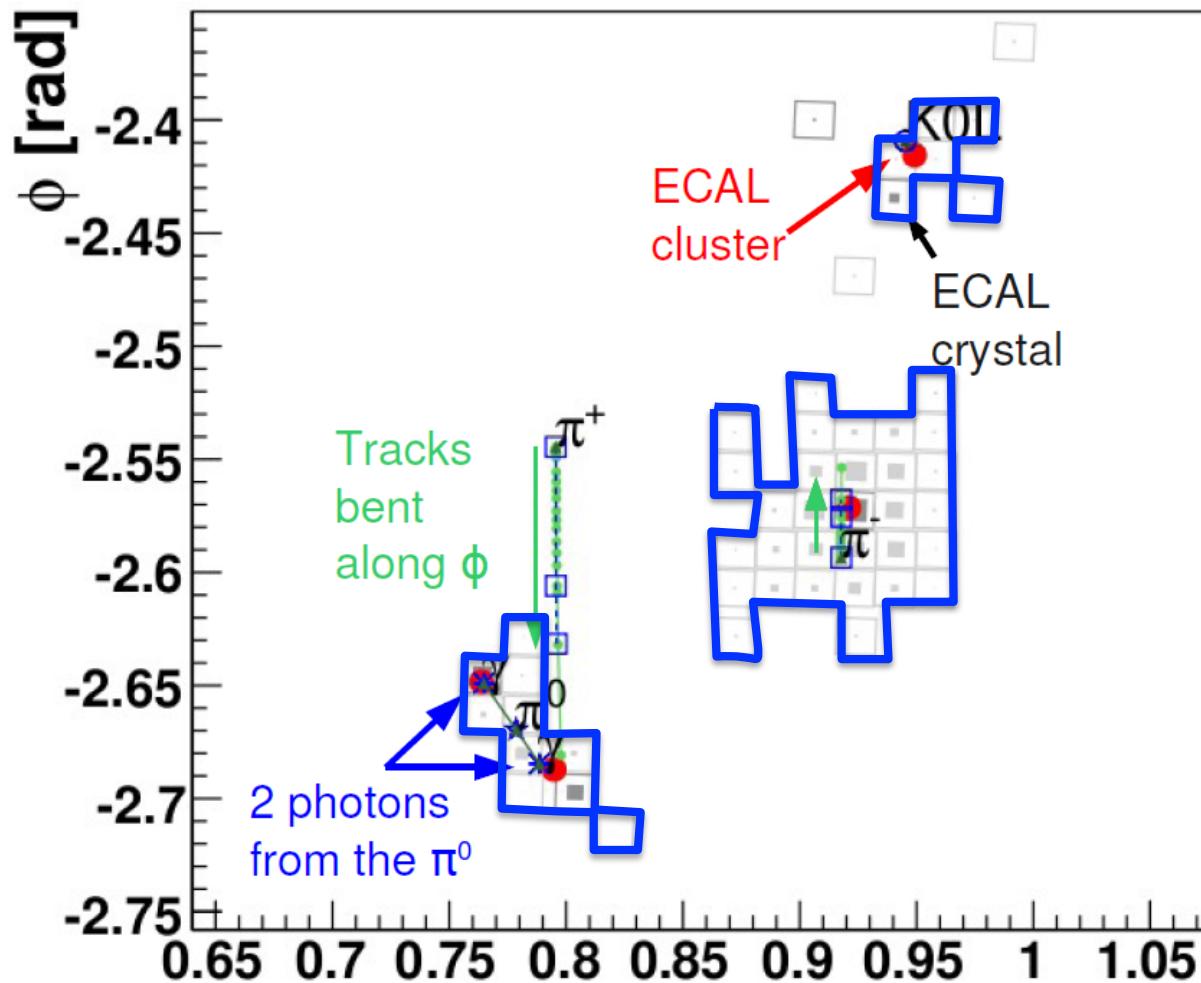
# Iterative Tracking (2/2)

- Efficient also for secondary tracks
- Secondary tracks used in PF:
  - Charged hadrons from nuclear interactions
    - No double-counting of the primary track momentum
  - Conversion electrons
    - Converted brems from electrons (cf electron slide later)

Nuclear interaction vertices

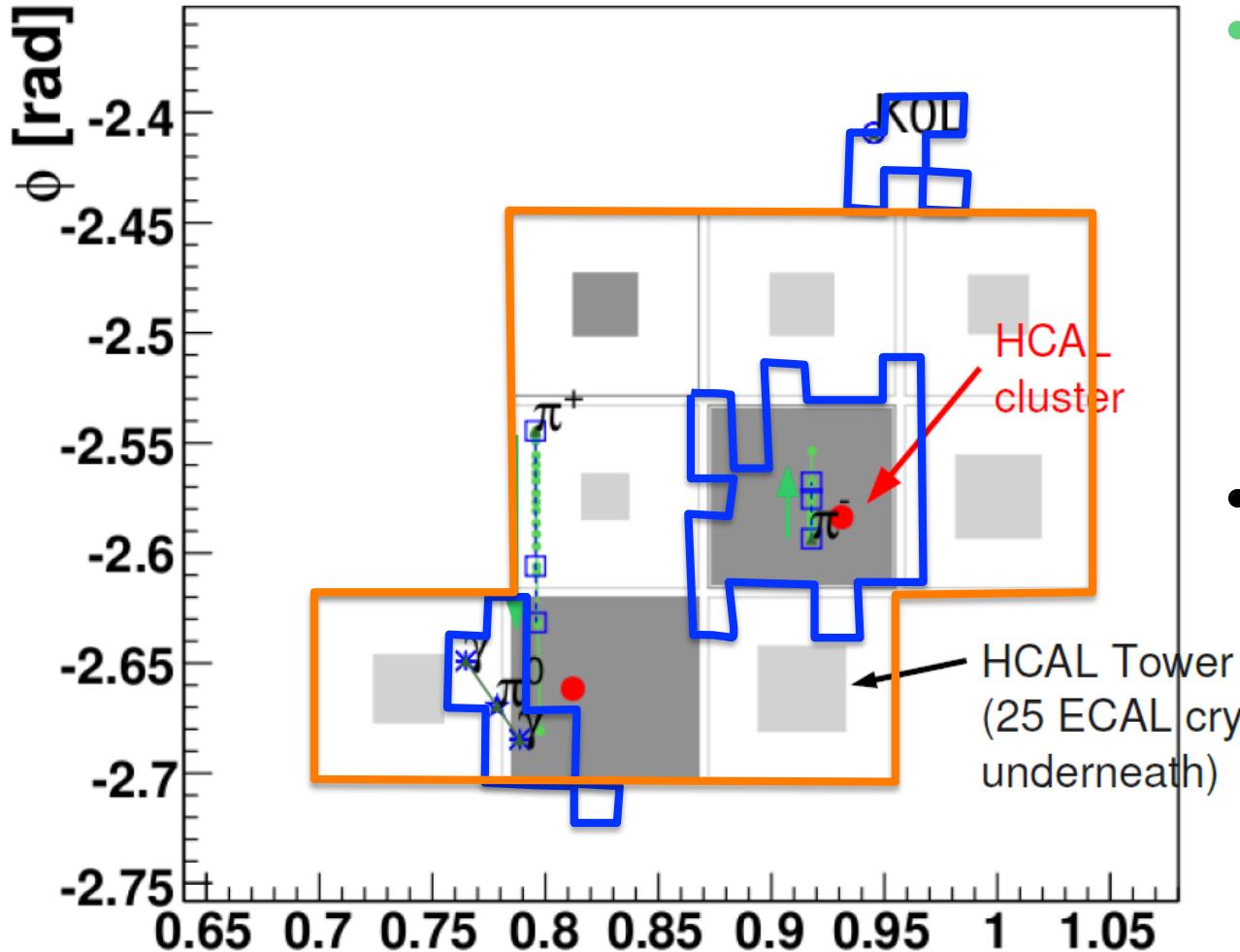


# Linking – ECAL view



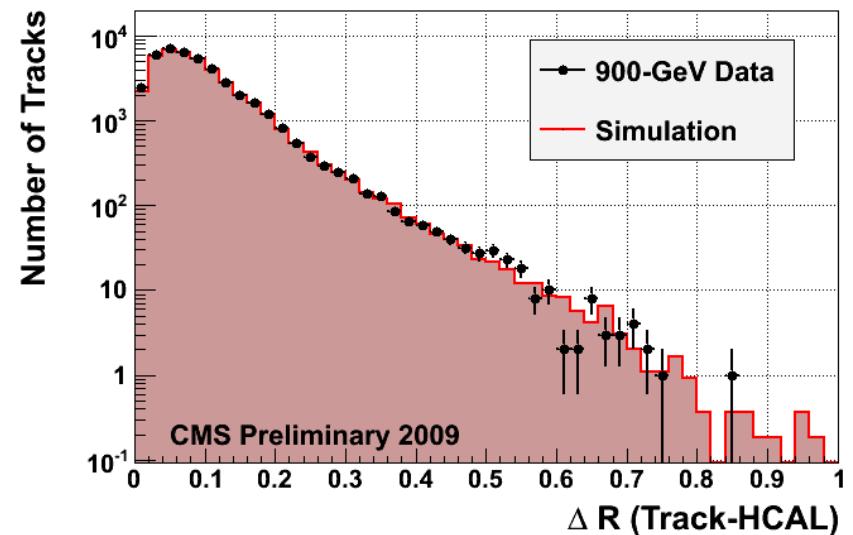
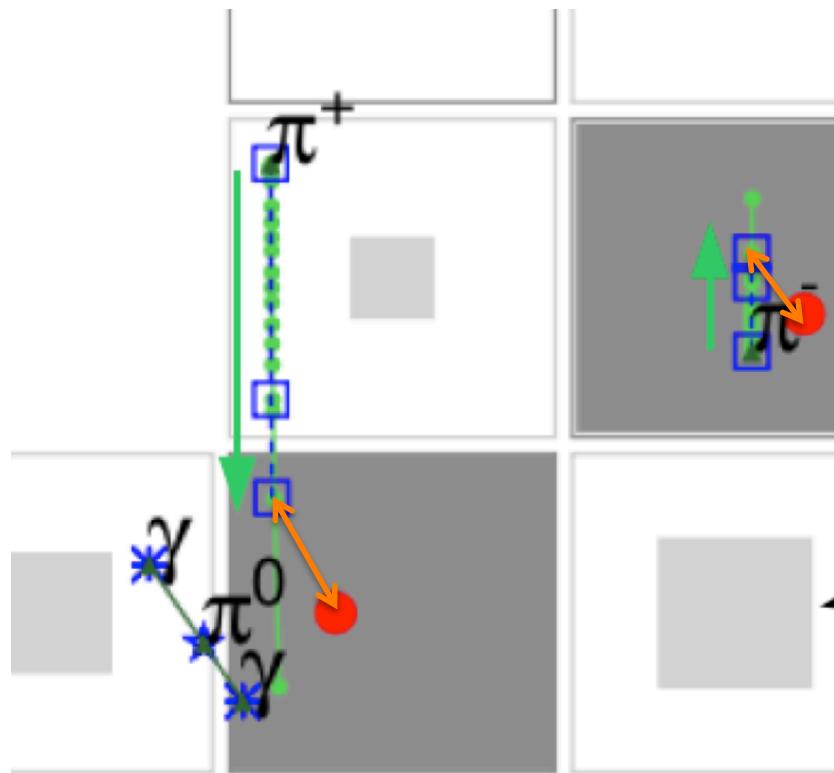
- Track impact within cluster boundaries  
→ track & cluster linked

# Linking – HCAL view



- Track impact within cluster boundaries → track & cluster linked
- Clusters overlapping → clusters linked

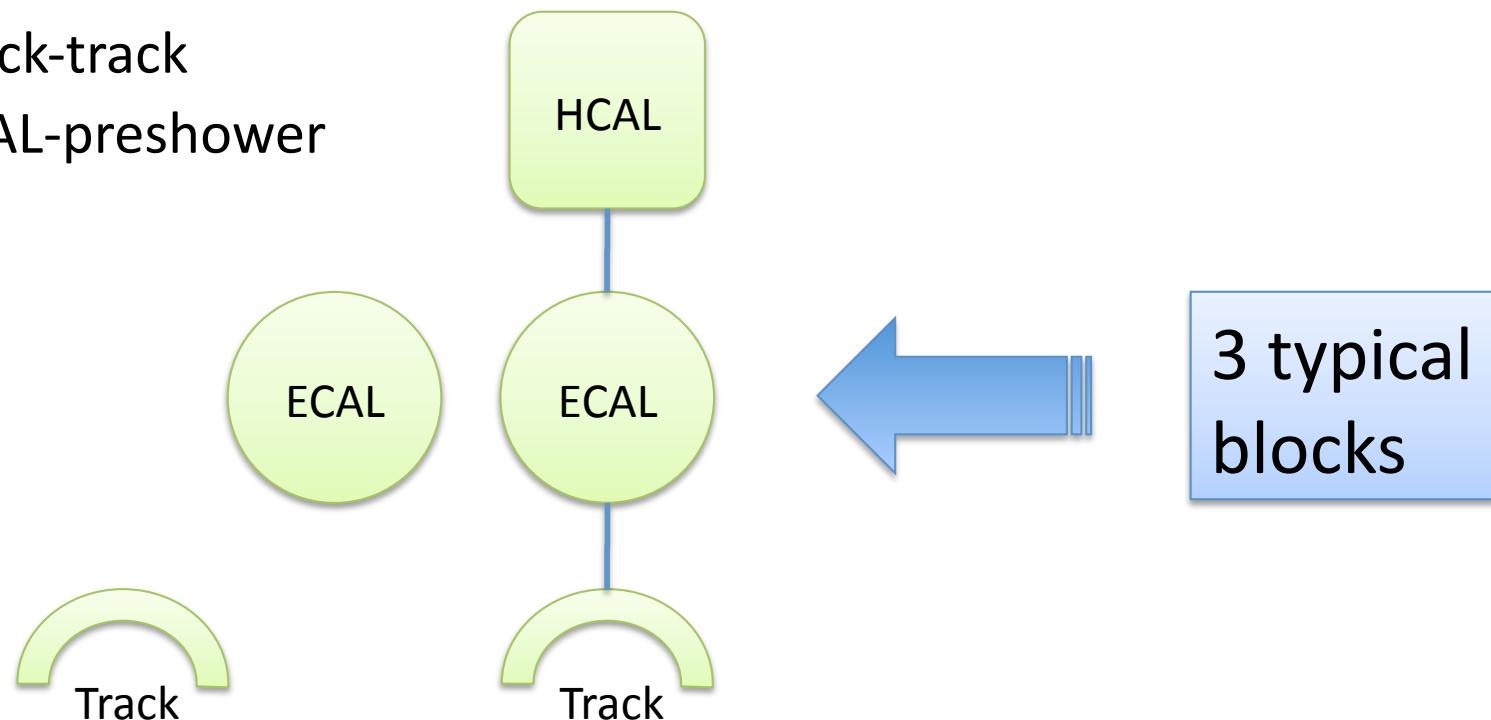
# Link Validation



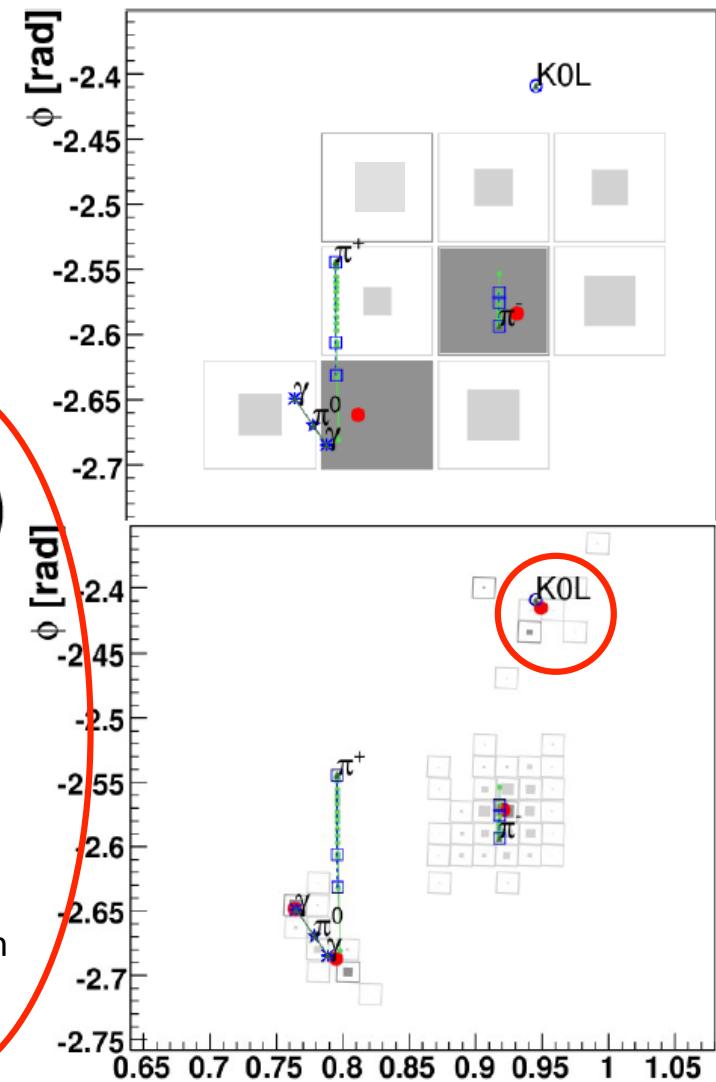
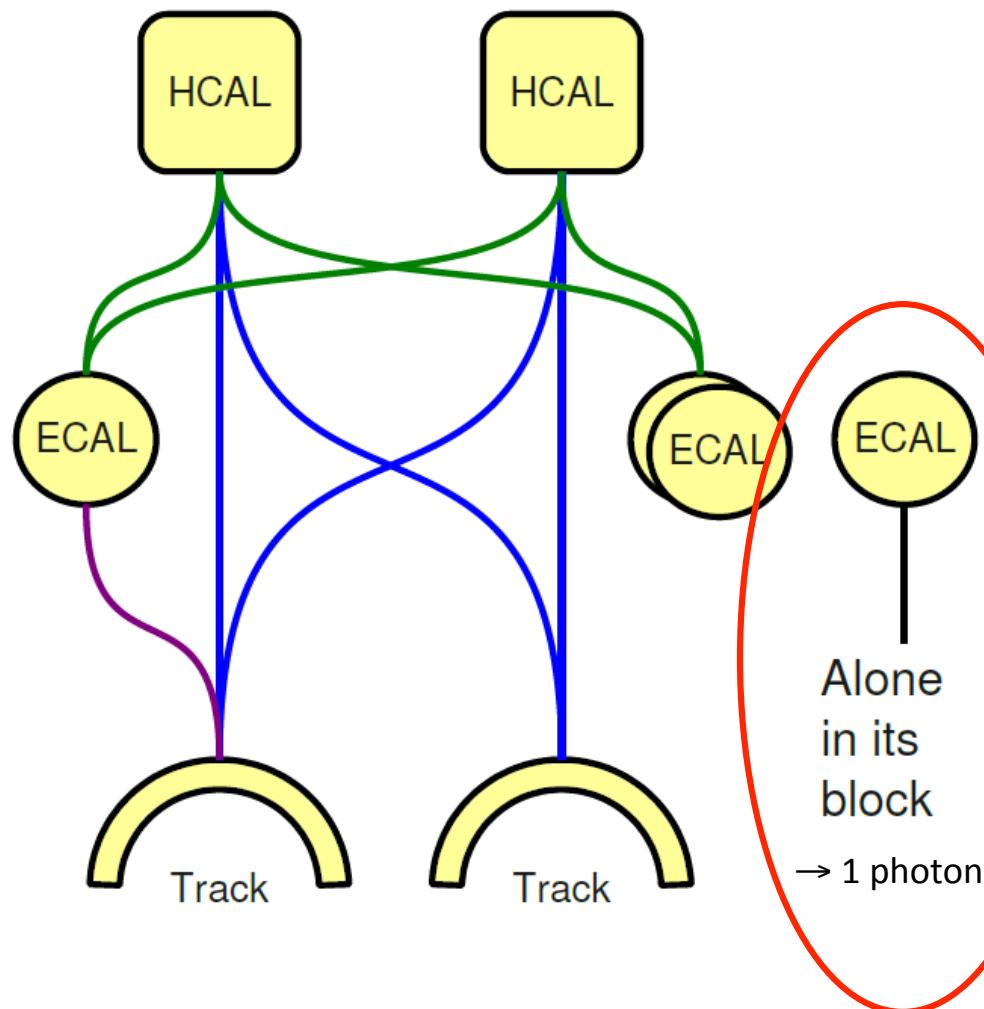
Distance between:  
- the track impact and  
- the closest HCAL cluster

# Links and blocks

- Links:
  - Track-ECAL
  - Track-HCAL
  - ECAL-HCAL
  - Track-track
  - ECAL-preshower
- The block building rule:
  - 2 linked PF elements are put in the same blocks

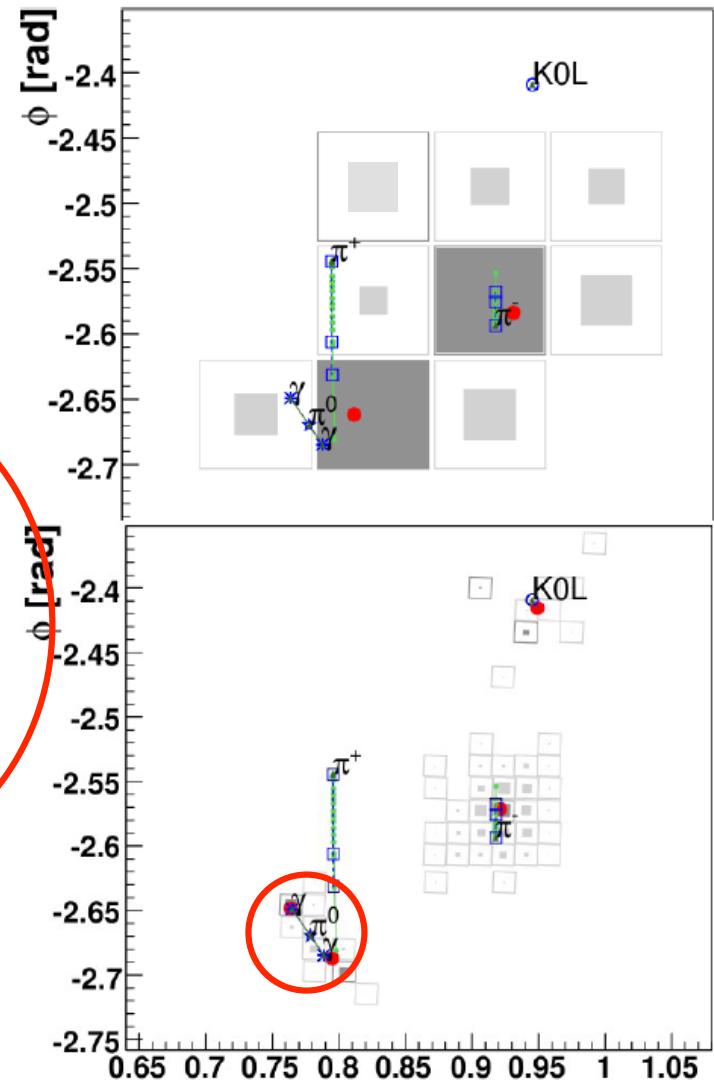
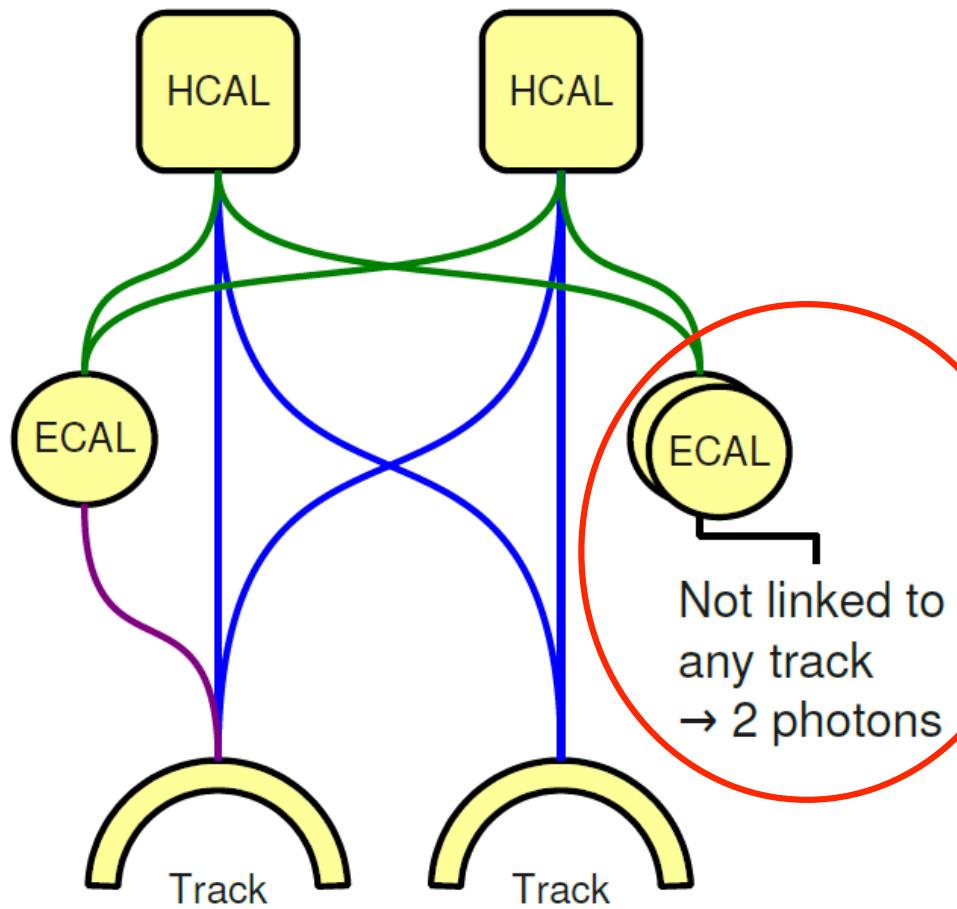


# Result: 2 PF “Blocks”

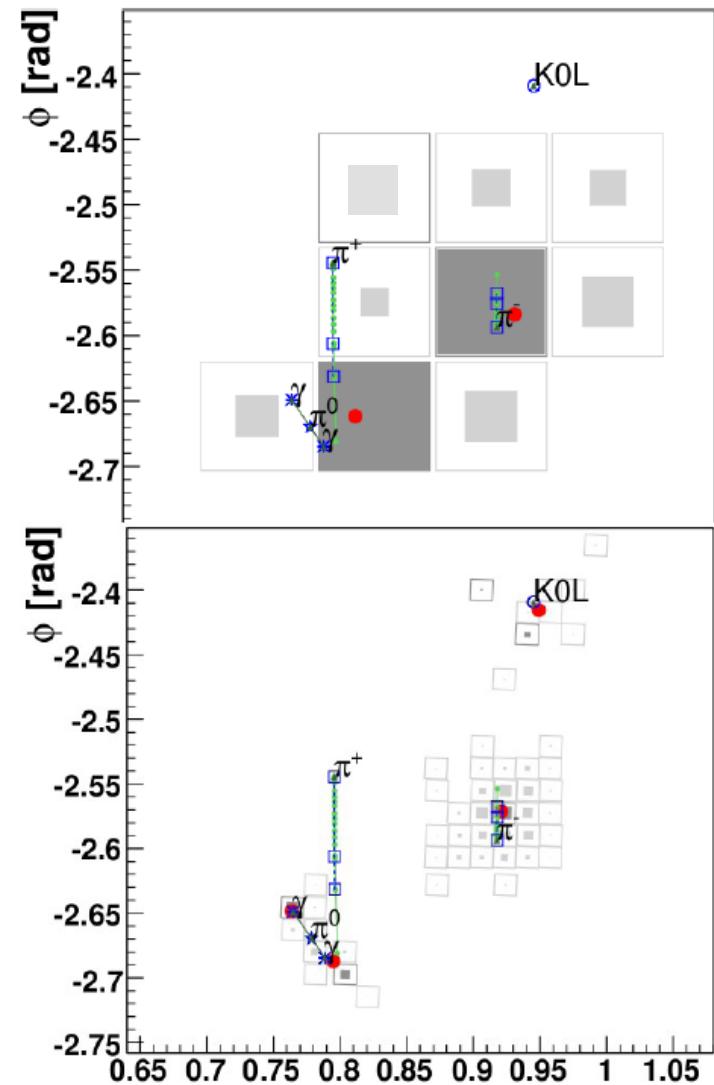
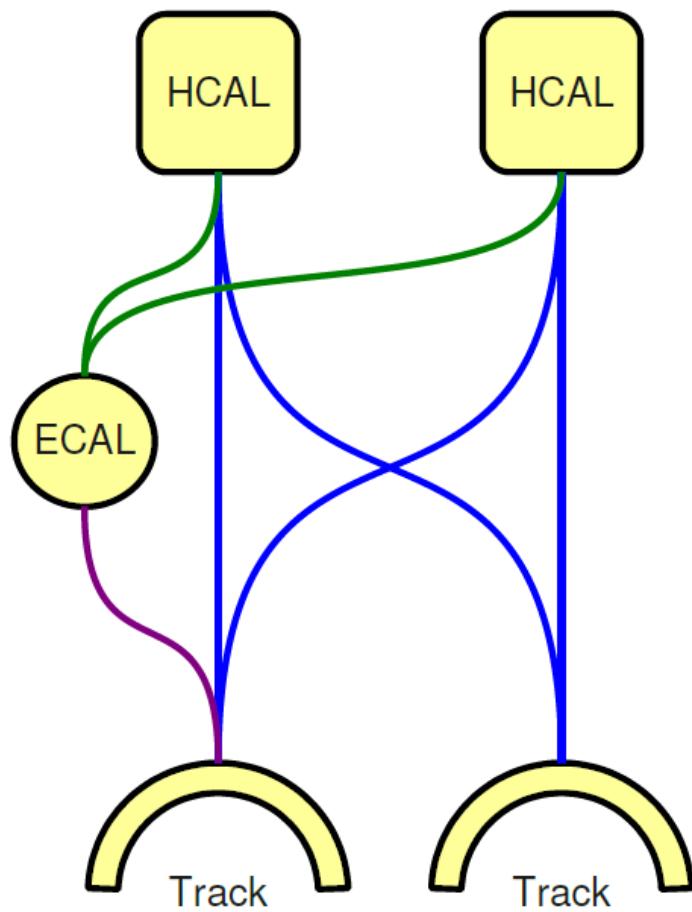


<http://cdsweb.cern.ch/record/1194487?ln=en>

# Photons

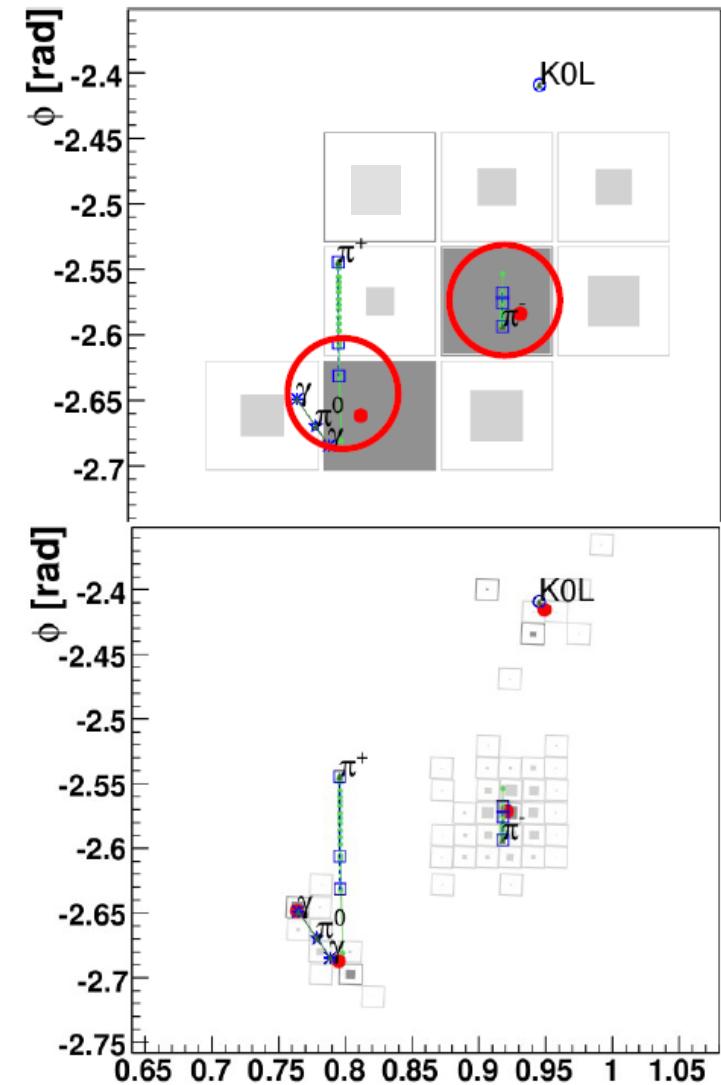
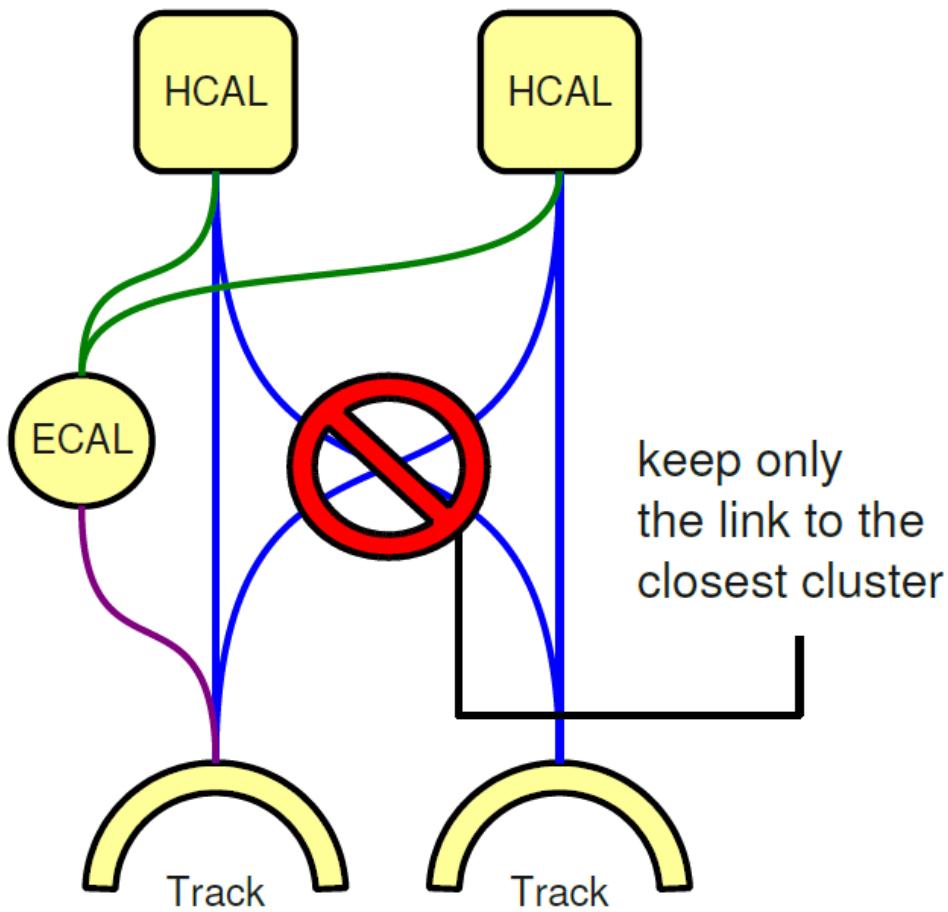


# Photons

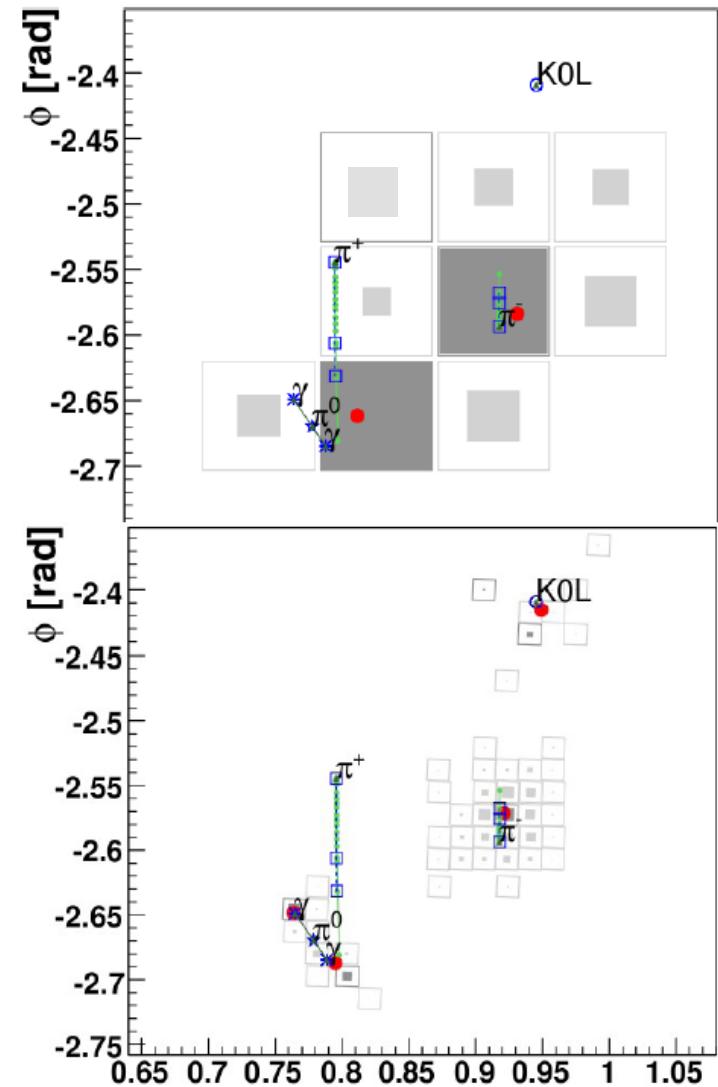
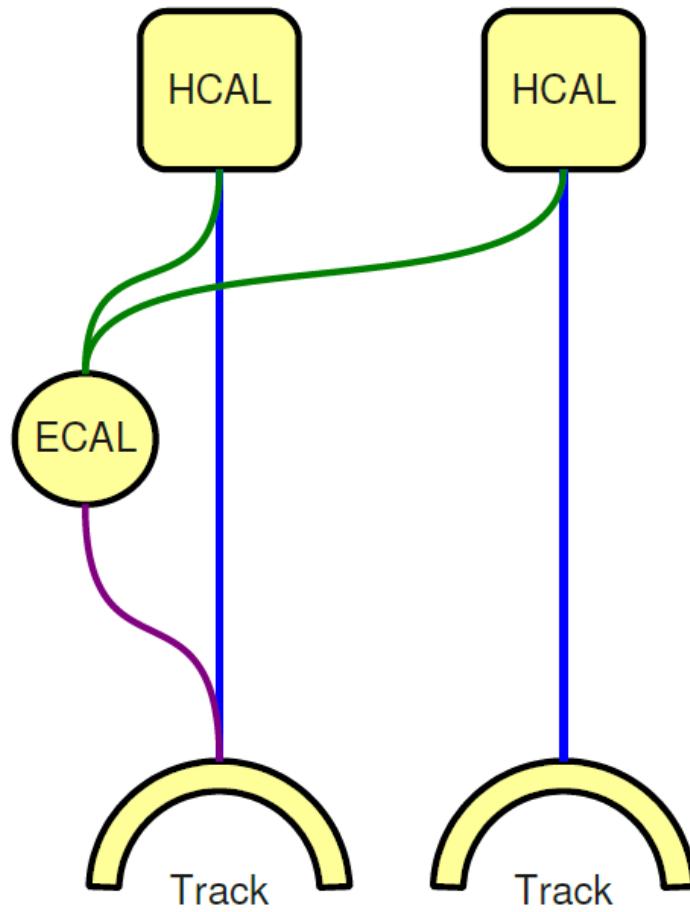


<http://cdsweb.cern.ch/record/1194487?ln=en>

# Block simplification

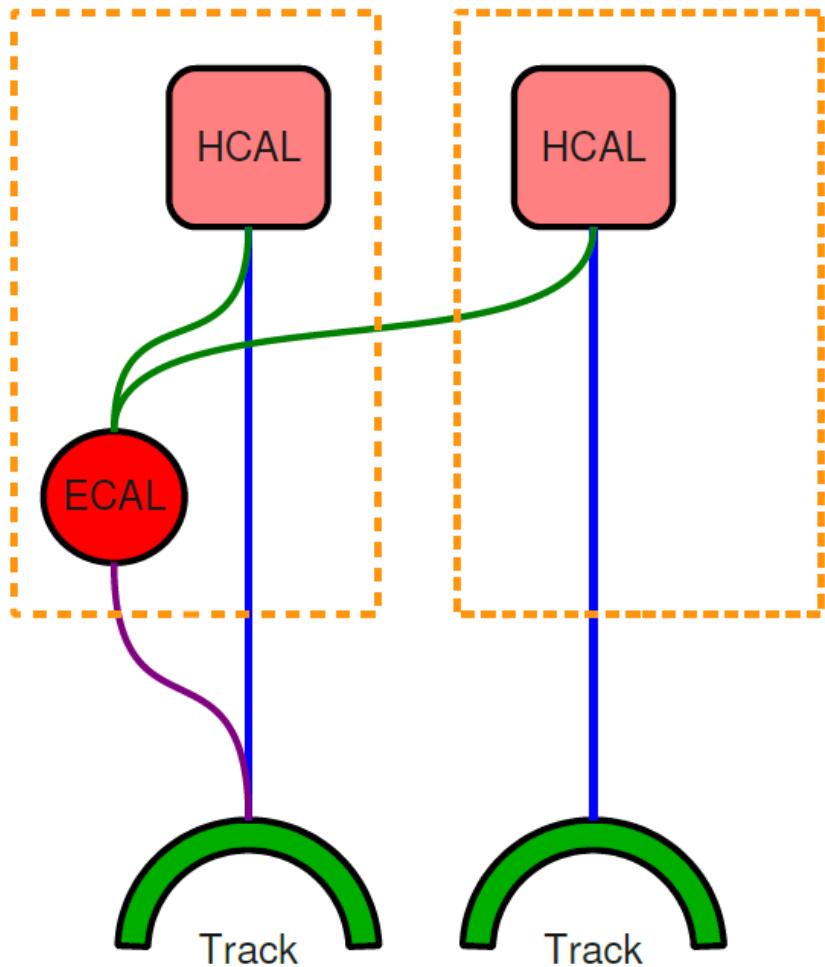


# Block simplification



<http://cdsweb.cern.ch/record/1194487?ln=en>

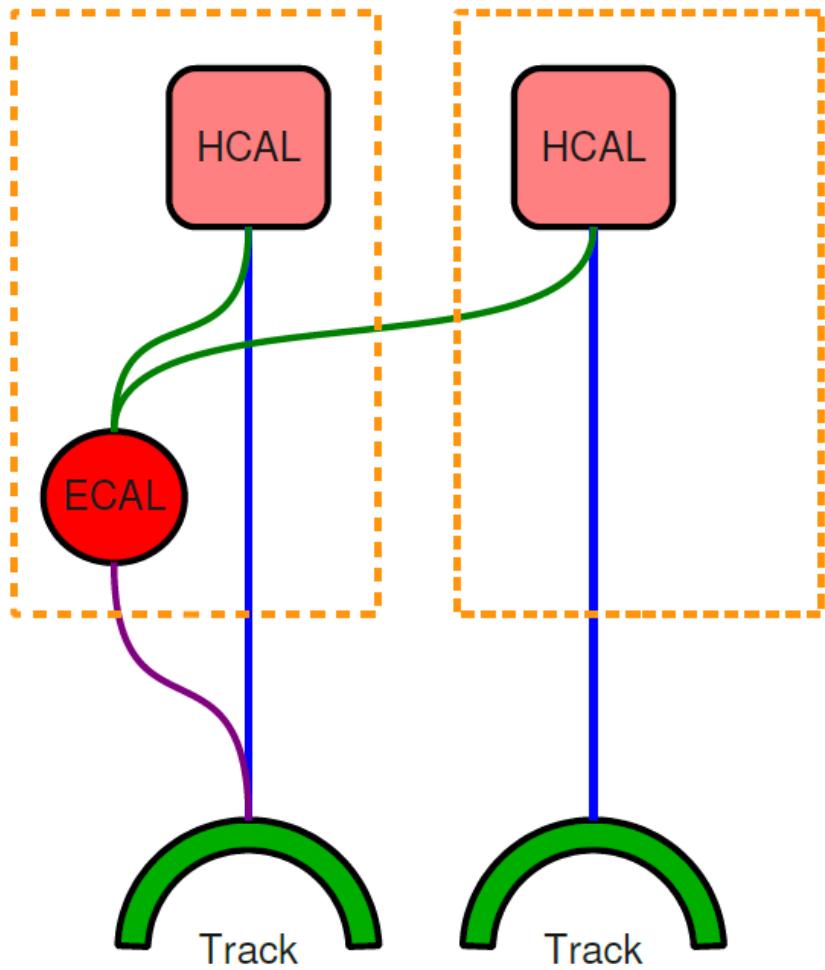
# Charged hadrons, overlapping neutrals



- For each HCAL cluster, compare:
  - Sum of track momenta  $p$
  - Calorimeter energy  $E$ 
    - Linked to the tracks
    - Calibrated for hadrons
- $E$  and  $p$  compatible
  - Charged hadrons
- $E > p + 120\% \sqrt{p}$ 
  - Charged hadrons +
  - Photon / neutral hadron
- $E < p$ 
  - Need attention ...
  - Rare: muon, fake track

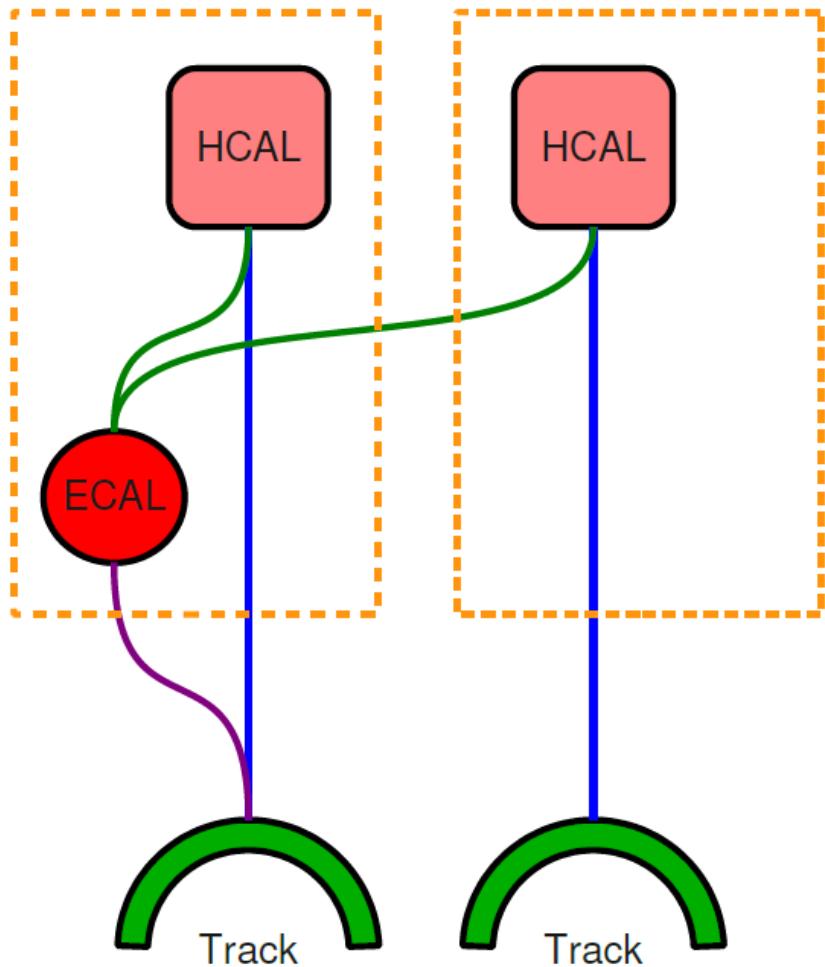
<http://cdsweb.cern.ch/record/1194487?ln=en>

# Charged+neutrals: $E \approx p$



- Charged hadron energy from a fit of  $p_i$  and  $E$ 
  - $i = 1, \dots, N_{\text{tracks}}$
  - Calorimeter and track resolution accounted for
- Makes the best use of the tracker and calorimeters
  - Tracker measurement at low  $pT$
  - Converges to calorimeter measurement at high  $E$

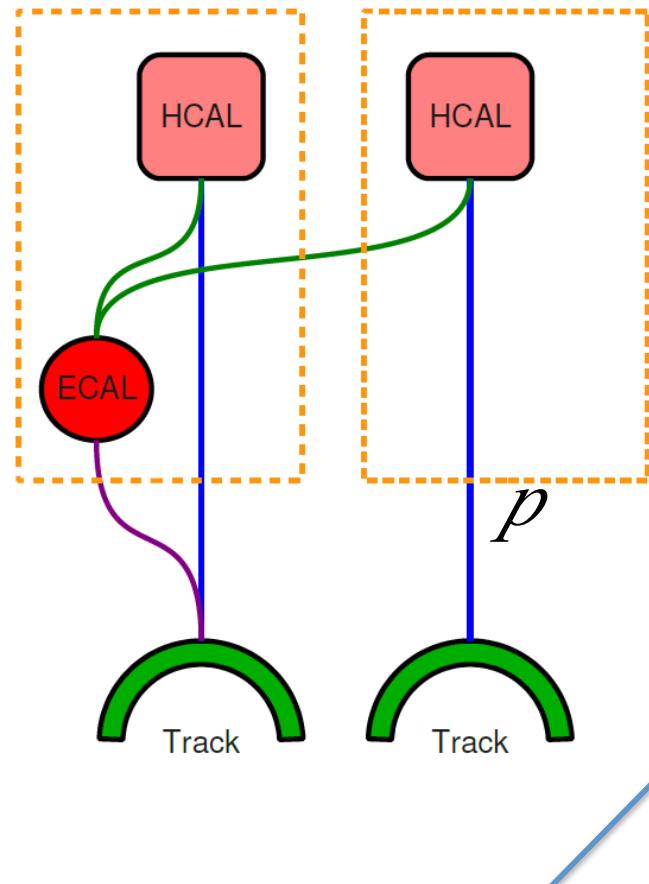
# Charged+neutrals: $E > p$



- Significant excess of energy in the calorimeters:  
 $E > p + 120\% \sqrt{E}$
- Charged hadrons [  $p_i$  ]
- Neutrals:
  - $E$  from ECAL or HCAL only:
    - HCAL  $\rightarrow h^0$  [  $E - p$  ]
    - ECAL  $\rightarrow \gamma$  [  $E_{ECAL} - p/b$  ]
  - $E$  from ECAL and HCAL:
    - $E - p > E_{ECAL}$  ?
      - $\gamma$  [  $E_{ECAL}$  ] with the rest
      - $h^0$
    - Else:
      - $\gamma$  [  $(E - p) / b$  ]

*Always give precedence to photons*

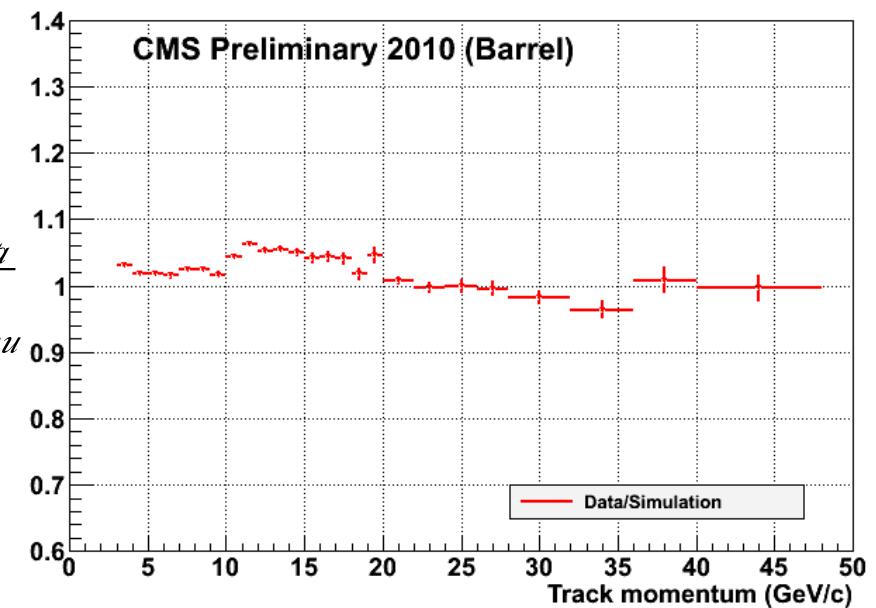
# Validation of the calibration



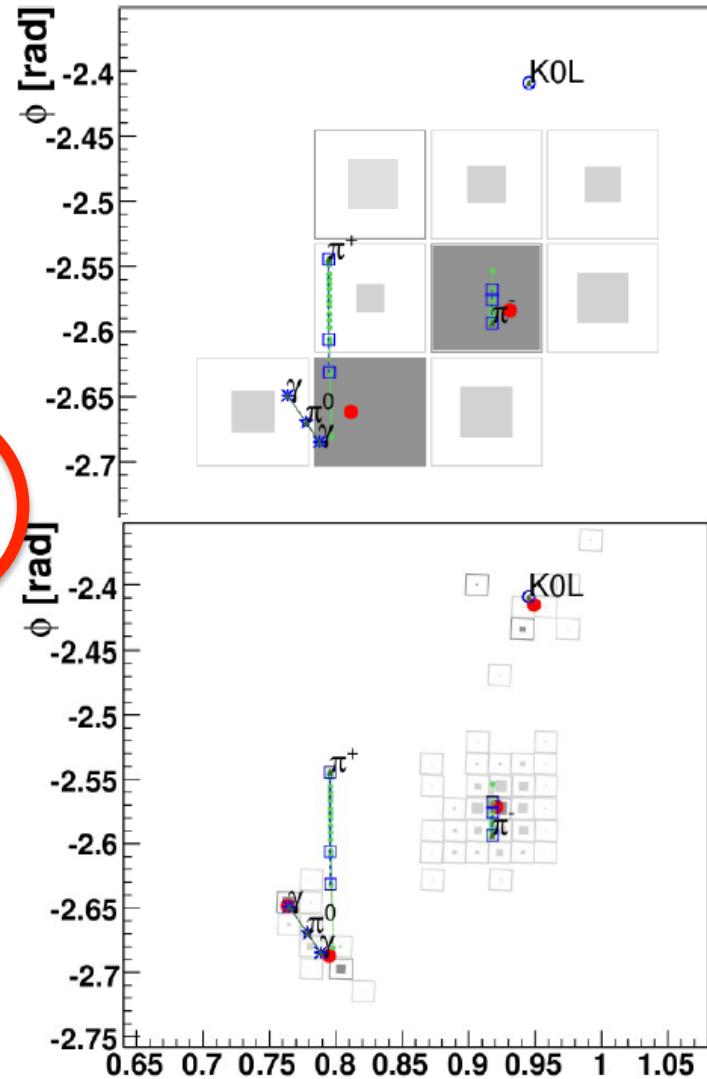
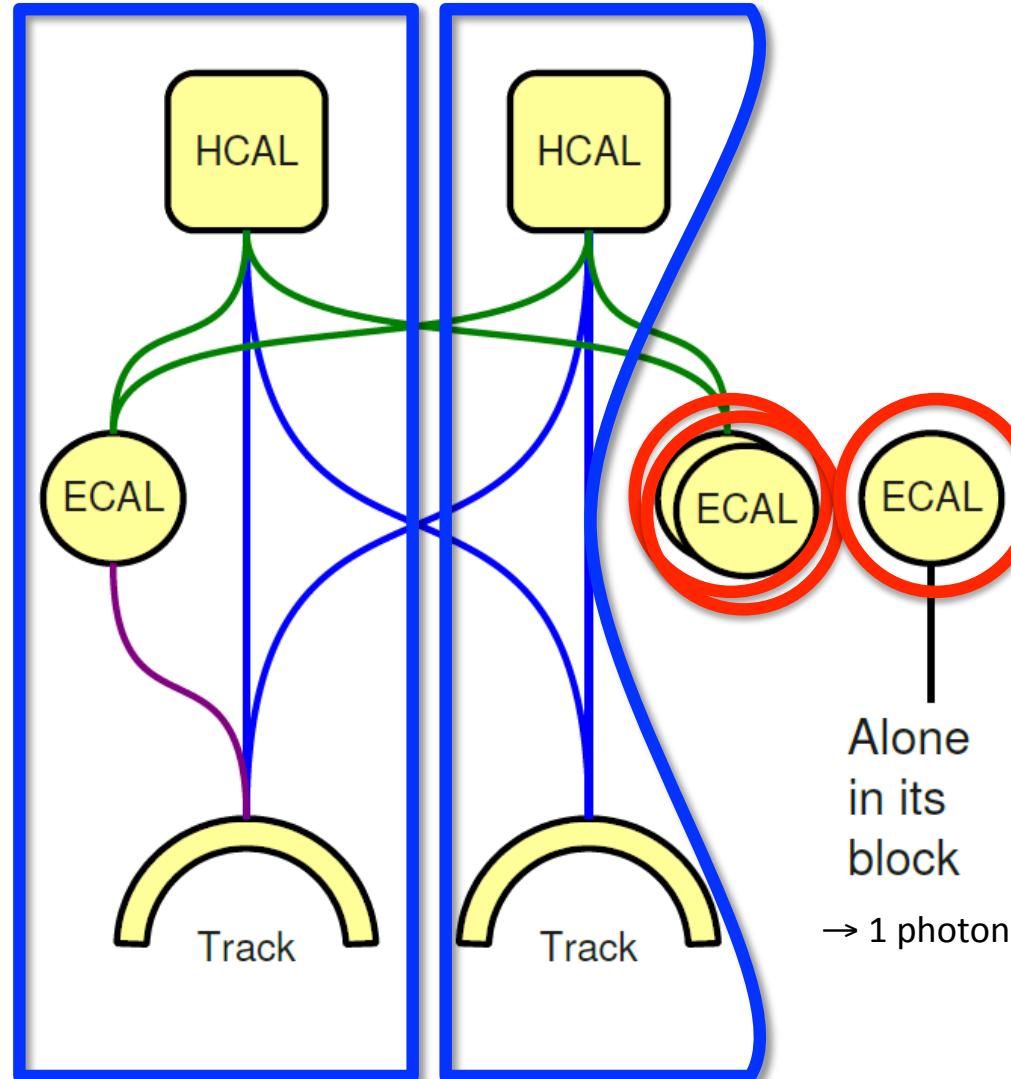
$$E = \alpha + bE_{ECAL} + cE_{HCAL}$$

$$\frac{(E/p)_{data}}{(E/p)_{simu}}$$

Ratio of the calorimeter response  
between data and Monte-Carlo

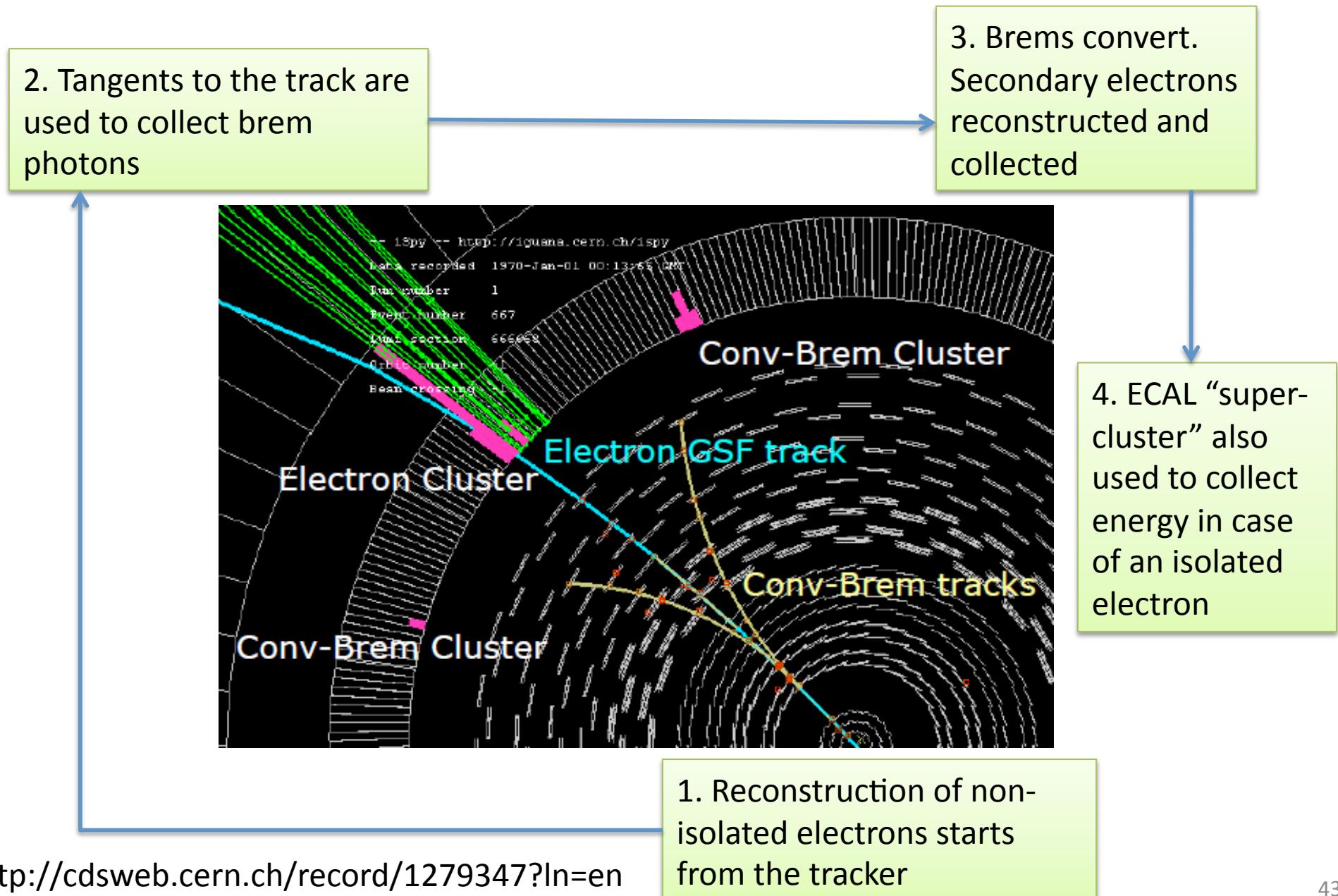


# 2 charged hadrons, 3 photons



<http://cdsweb.cern.ch/record/1194487?ln=en>

# Electrons



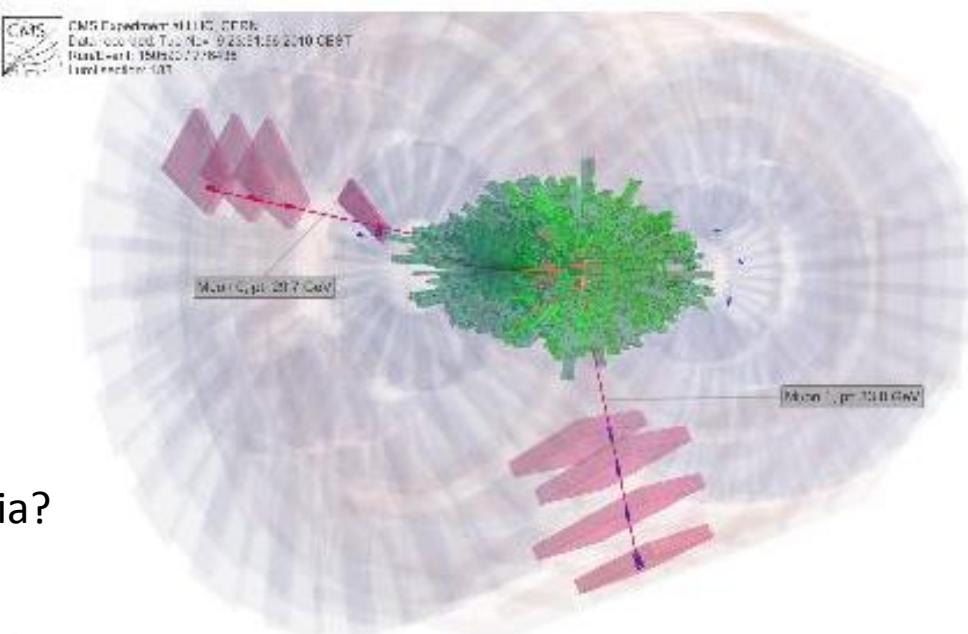
# Muons (1/2)

- In a jet:
  - Need high efficiency:  
Lost muon  
→ linked calorimeter  
energy lost
  - Need low fake rate  
Fake muon  
→ linked calorimeter  
energy double-counted
- high efficiency &  
low fake rate to avoid  
tails
- Isolated:
  - Need very high efficiency  
Not to bias analyses
    - Muon ID cuts applied at  
analysis stage
  - Fake rate not important
    - Low probability for a jet with  
only a fake muon and  
neutrals linked to the muon  
→ MET not affected by fakes

# Muons (2/2)

- 3 steps, starting from a very loose muon
  - Isolated?
    - Yes → take it
  - Else:
    - Tight muon ID criteria?
      - Yes → take it
    - Else  $E \ll p$ ?
      - Loose muon ID criteria?
        - » Yes → take it
      - Else not a muon

- $H \rightarrow ZZ \rightarrow 4\mu$  analysis:
  - 10% higher efficiency, background rate smaller



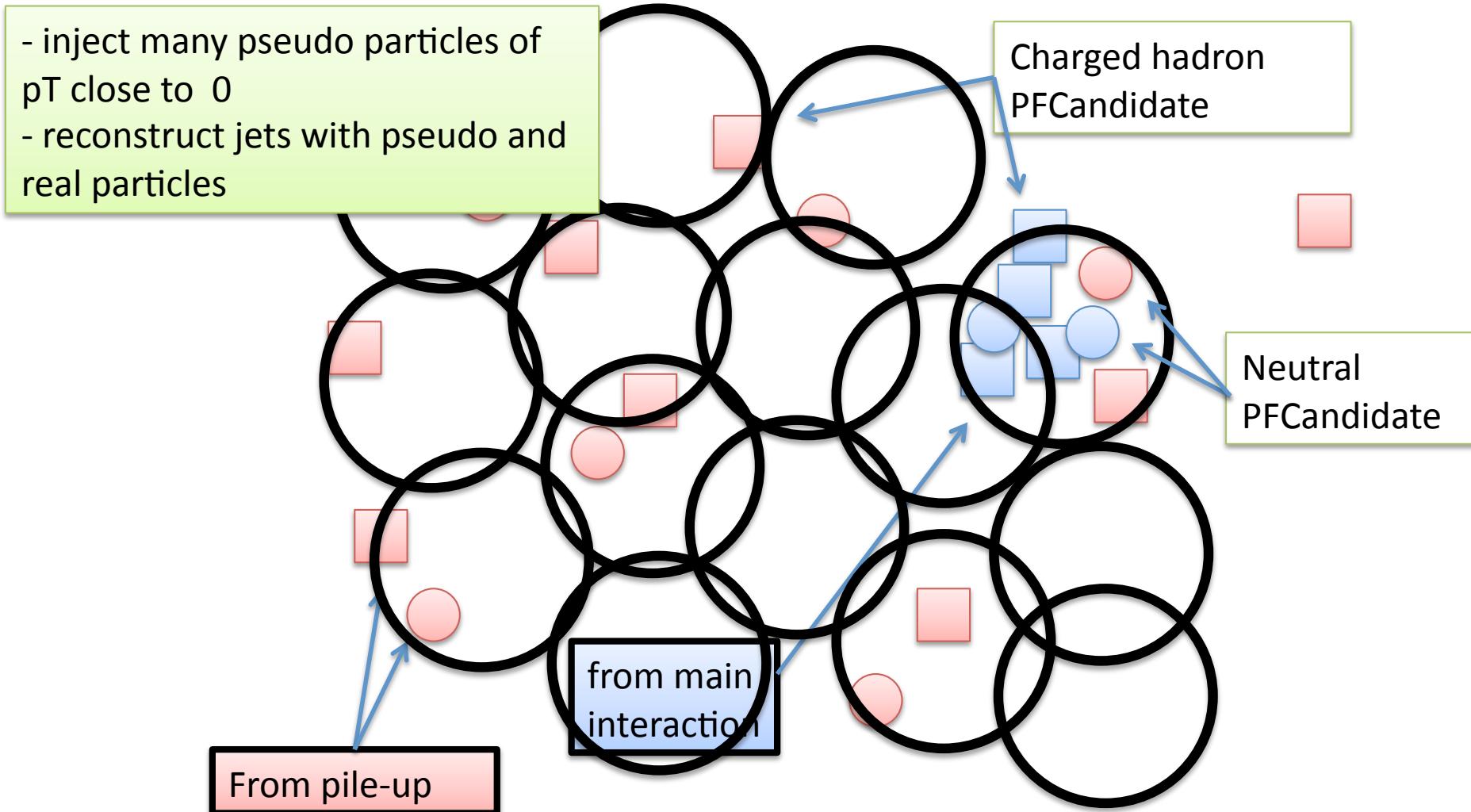
$Z \rightarrow \mu\mu$  (PbPb)

## - The CMS Particle Flow Algorithm

### - Performance

- Jets
- MET
- Tau ID
- ...

# How is the pile-up density estimated?



# How is the pile-up density estimated?

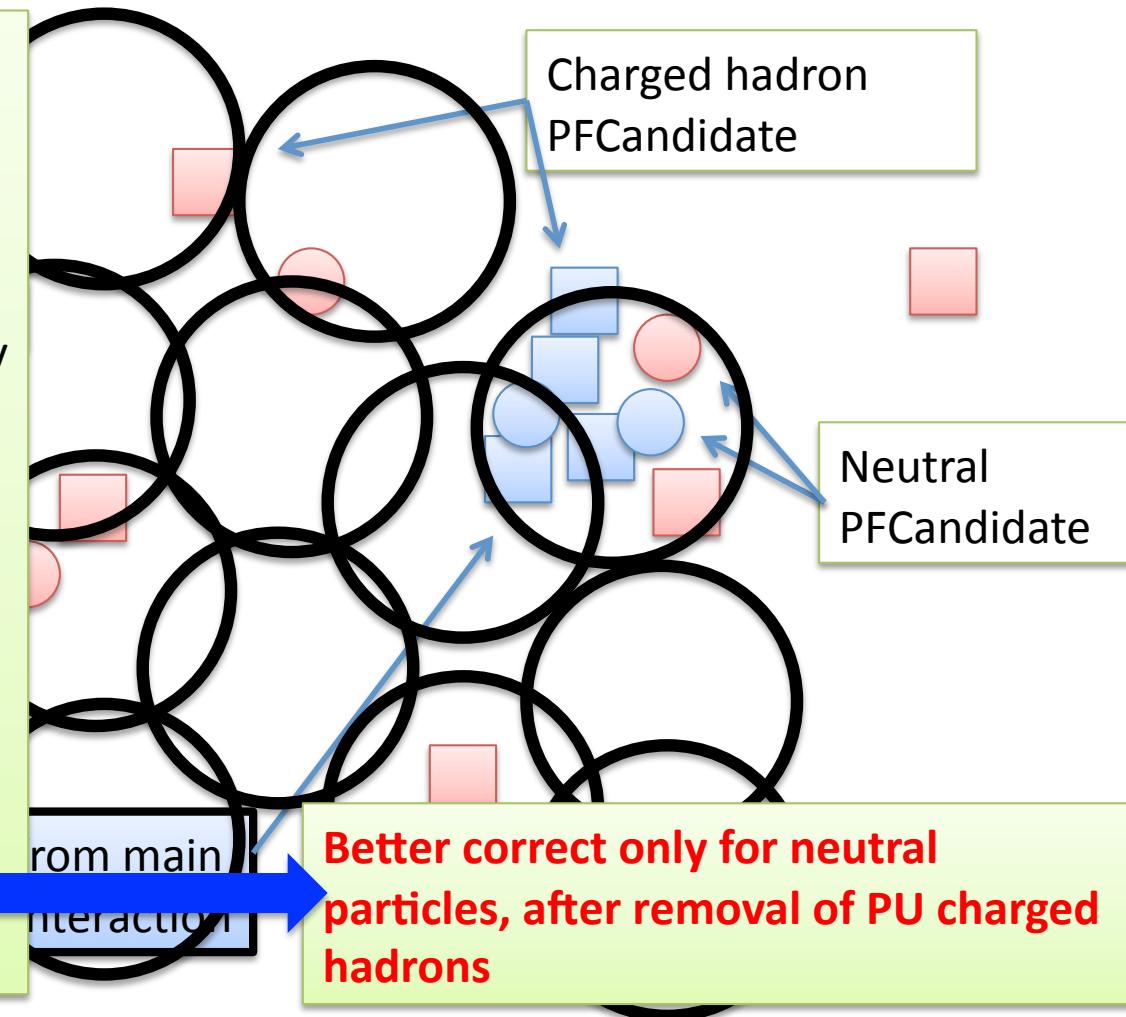
- inject many pseudo particles of pT close to 0
- reconstruct jets with pseudo and real particles
- compute pT density in each jet
- take the median of the pT density distribution

→ not sensitive to hard objects

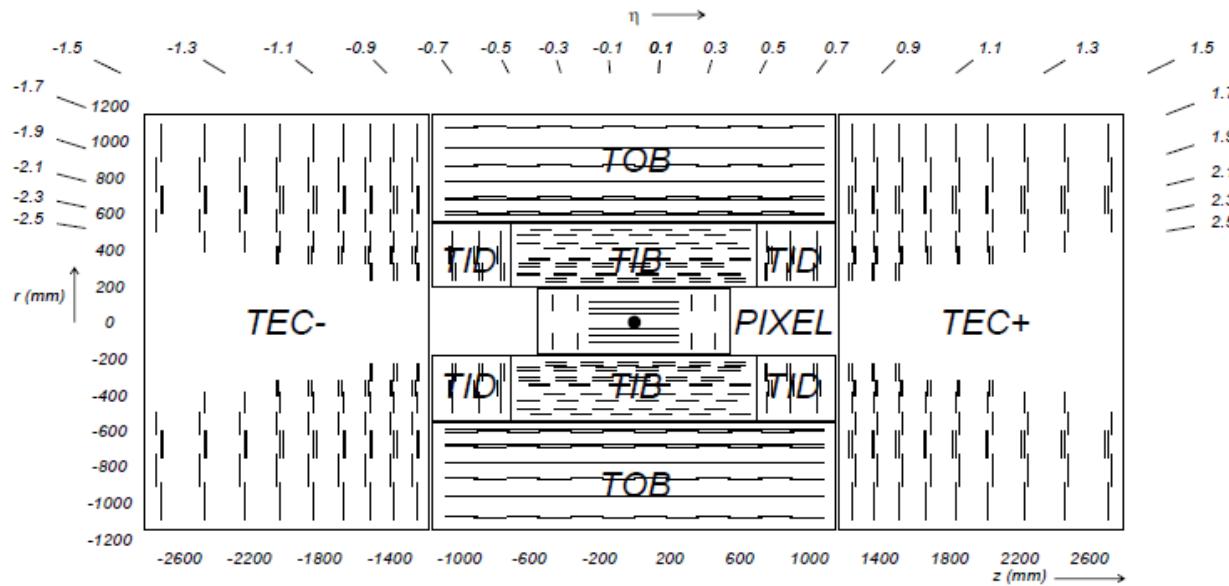
- from primary interaction (good, done for that)
- from pile-up (bad)

If a pile-up jet contaminates a good jet, PU contribution very underestimated

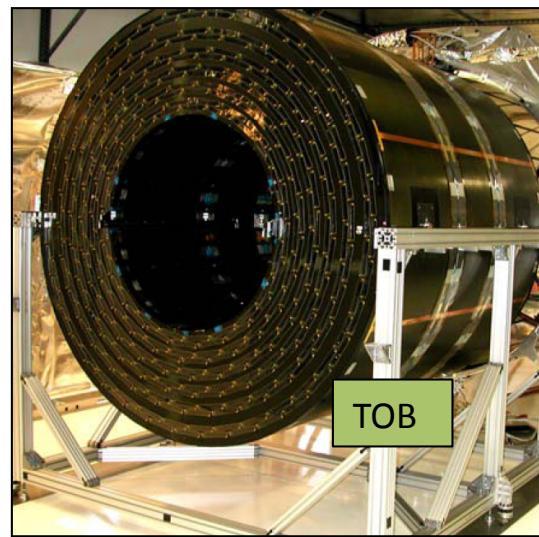
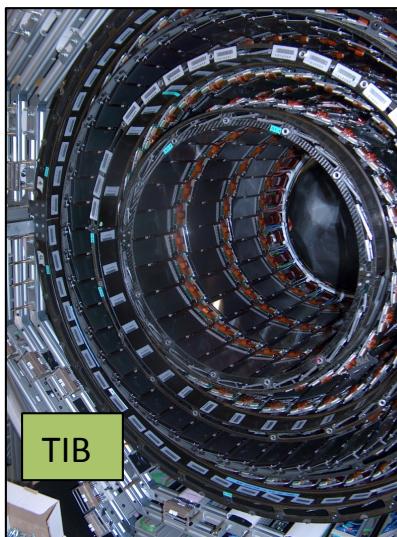
From pile-up



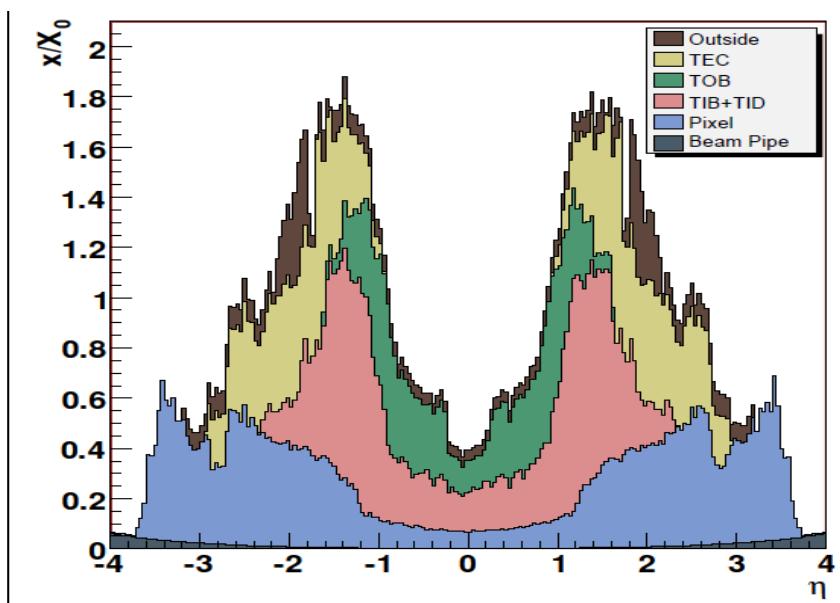
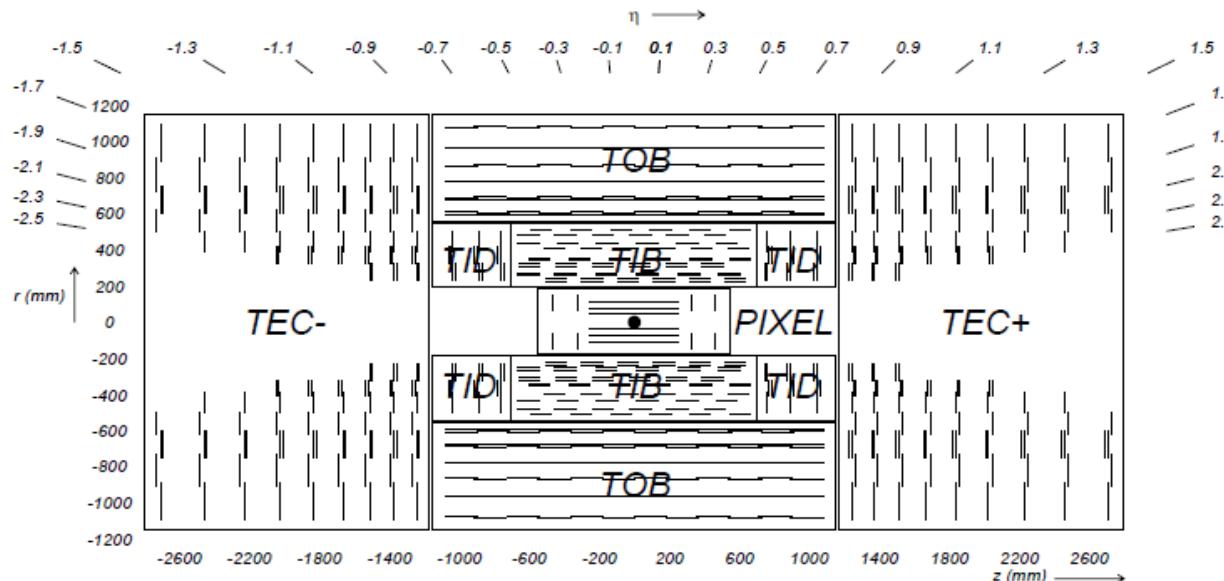
# Tracking System



- Huge silicon tracker
- Hermetic
- Highly efficient, in principle...



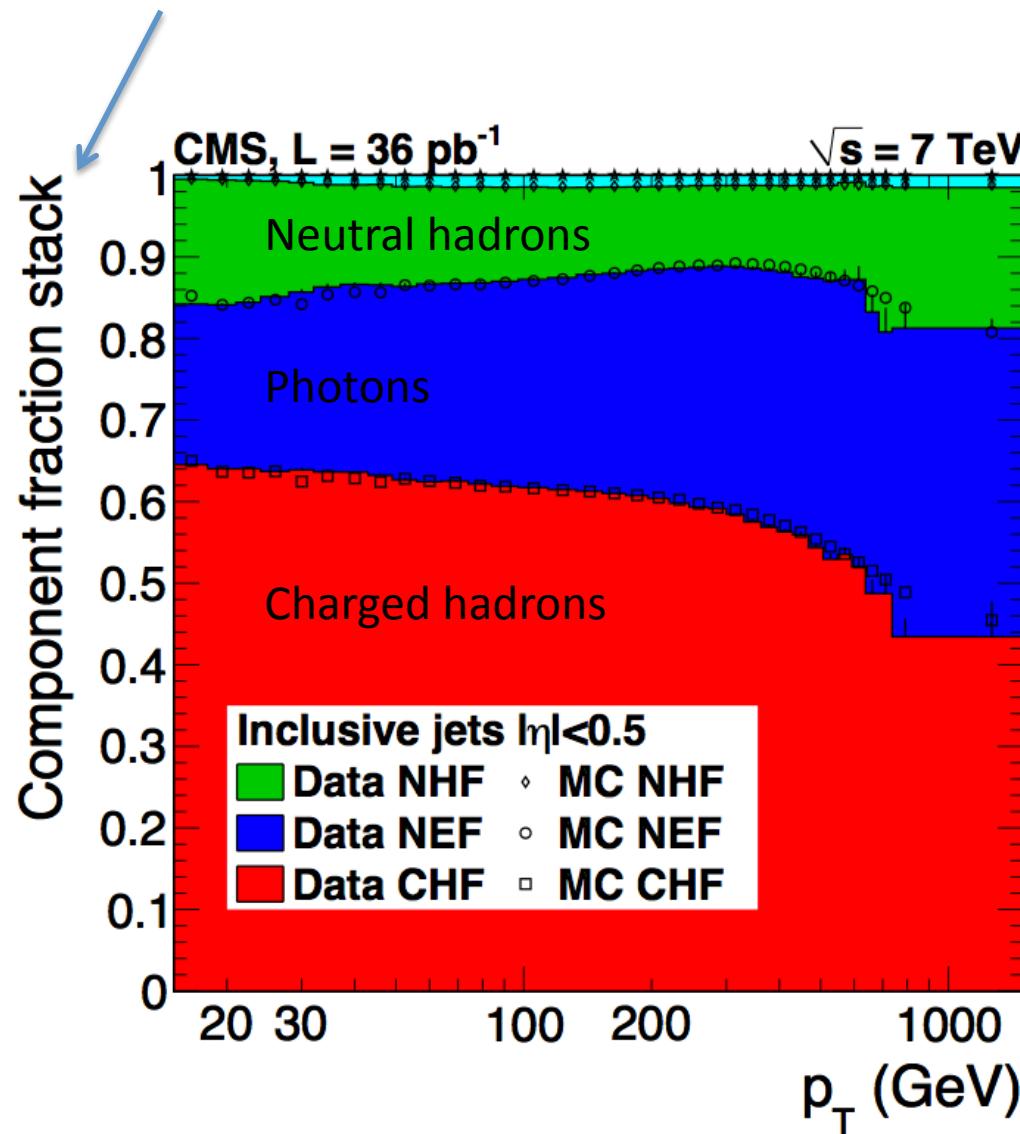
# Tracking System



- Huge silicon tracker
- Hermetic
- Highly efficient, in principle...
- But up to 1.8  $X_0$ 
  - Nuclear interactions
  - $\gamma$  conversions
  - e- brems

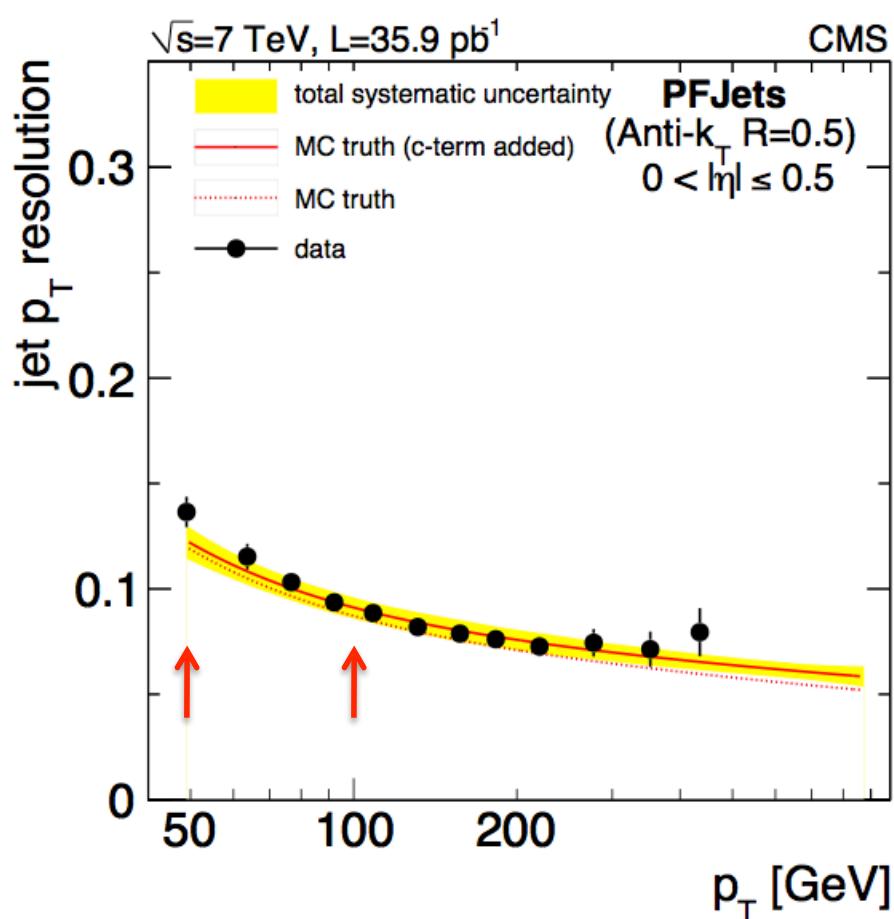
Fraction of the jet energy carried by the various types of particles

# Jets : Particle Content



- Data and MC agree at the % level
- Jet energy distributed as expected
- Drop in track reconstruction  $\epsilon$  in high  $p_T$  jets  
→ charged hadrons reconstructed as:
  - photons
  - neutral hadrons

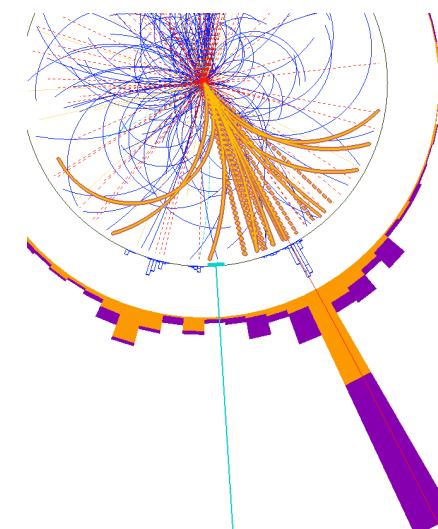
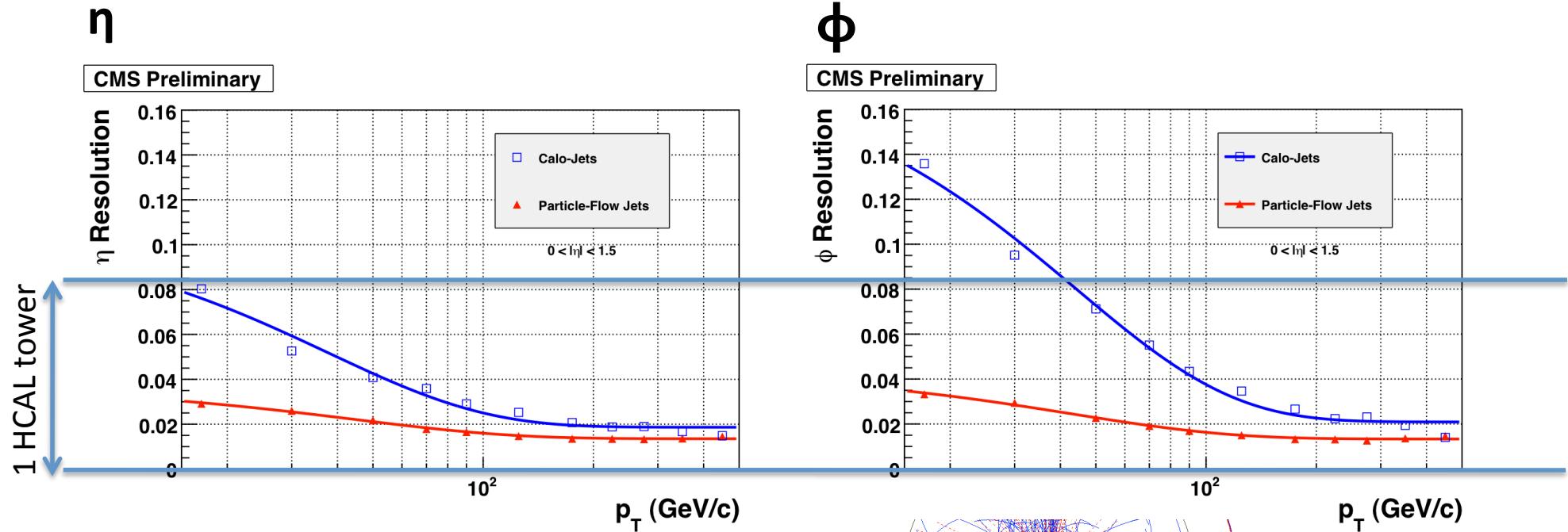
# Jets : Energy Resolution (data)



- Resolution measured using di-jet and gamma + jet events

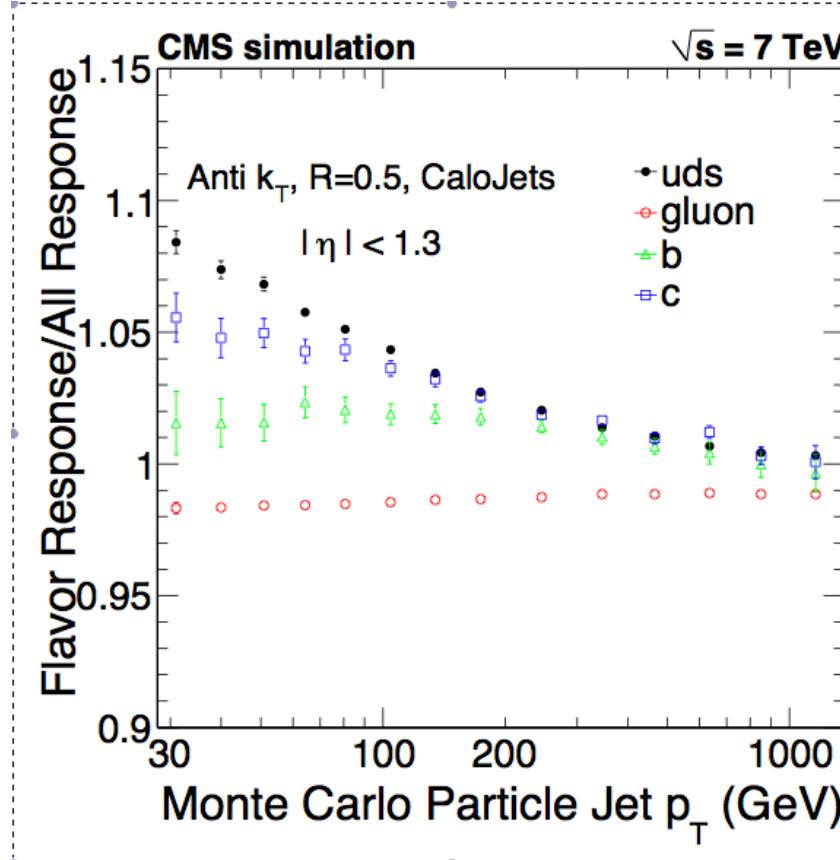
PF jet resolution validated with the data

# Jets : $\eta$ and $\phi$ Resolution

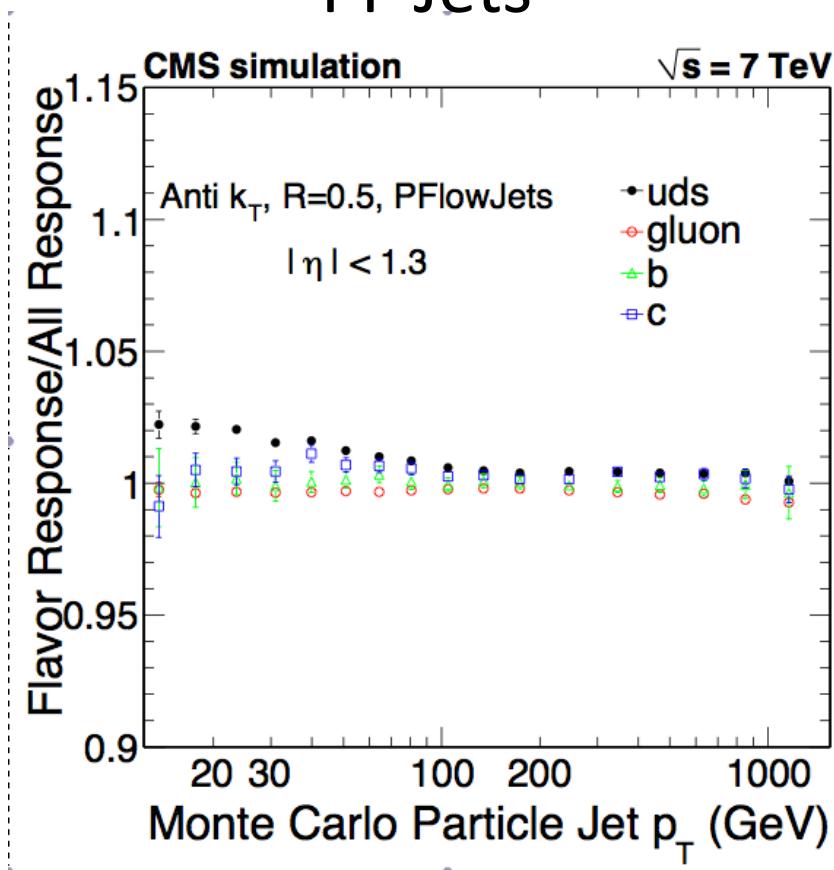


# Jet Response: Flavour Sensitivity

Calo Jets



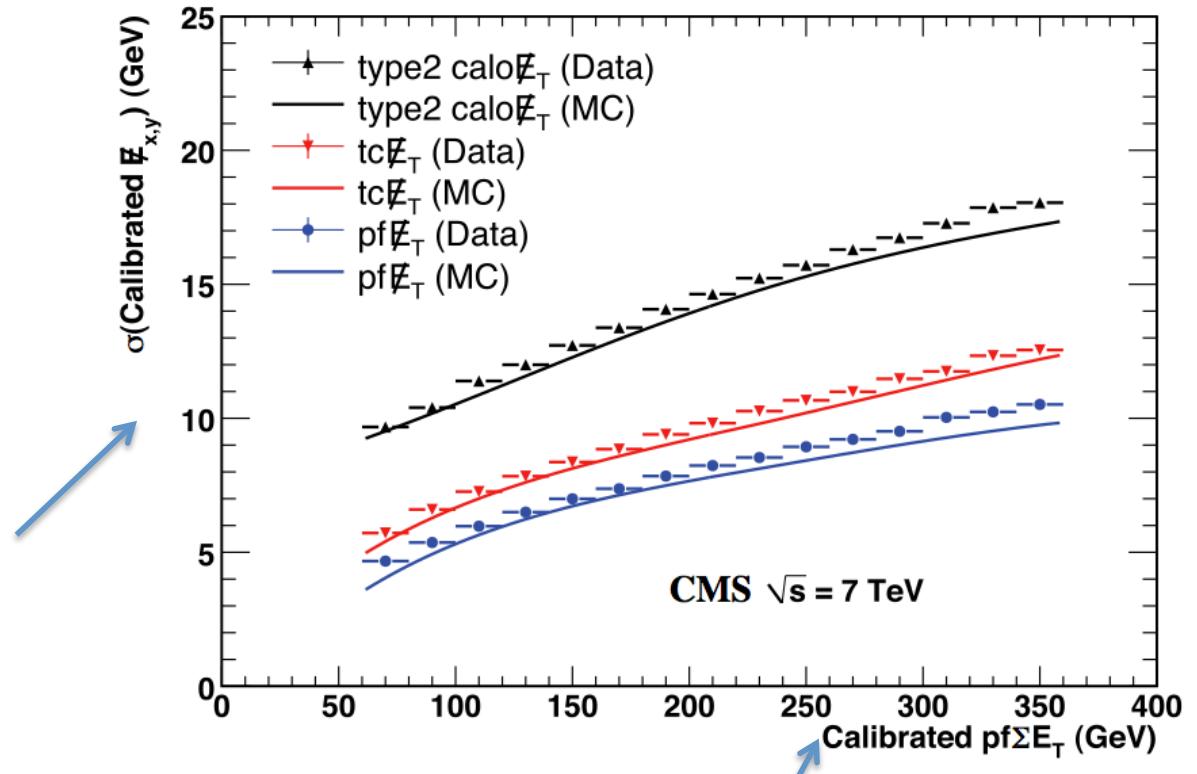
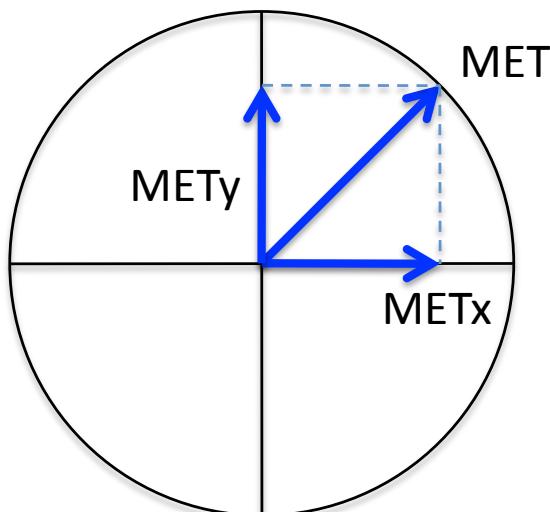
PF Jets



PF jet response almost independent from the flavour of the jet-initiating parton  
In particular: same response for gluon and b jets

# MET in multijet events

- MET residual distribution non Gaussian:
  - true MET = 0
  - reconstructed MET > 0
- MET<sub>x</sub> and MET<sub>y</sub> distribution Gaussian
  - can define and plot  $\sigma$

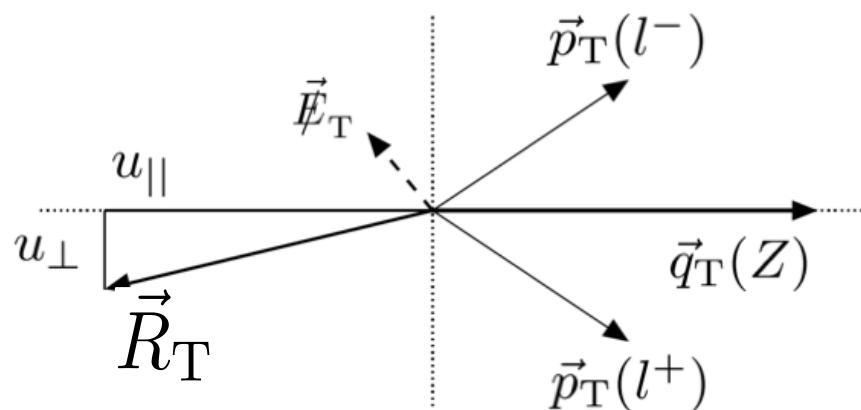


Scalar sum of the particle flow particles pT

Factor 2 gain in resolution  
Confirmed in the data

# MVA MET (1/2)

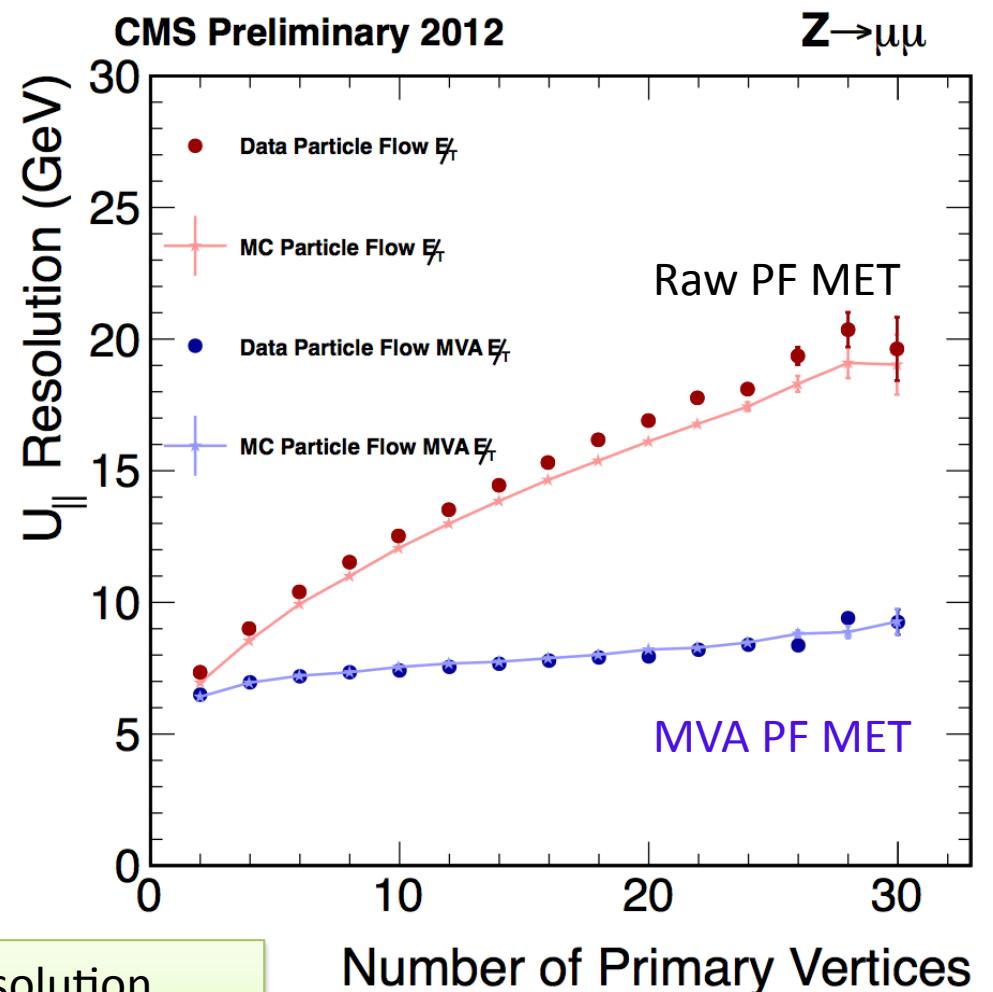
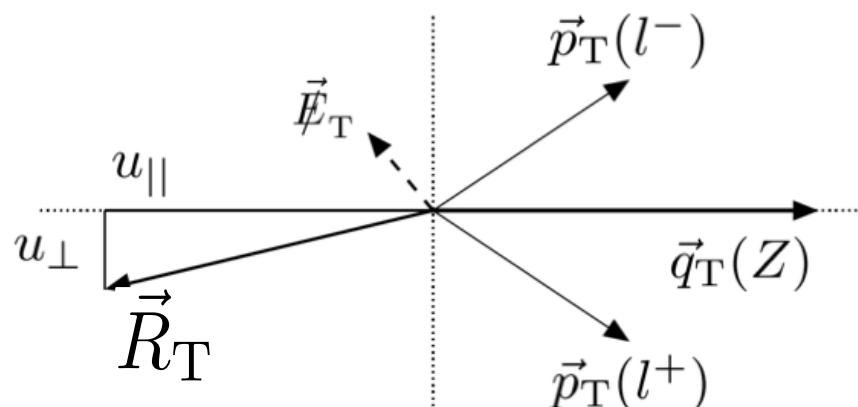
- Hadronic recoil to a boson (e.g. a Z)



- Multivariate regression
  - Correction to the recoil
  - Inputs:  $\vec{R}_T$ ,  $\sum E_T$  for:
    - All particles
    - $h^{\pm}$  from primary vertex (PV)
    - $h^{\pm}$  from PV and neutrals in jets from PV
    - $h^{\pm}$  from PU vertices and neutrals in jets from PU vertices.

# MVA MET (2/2)

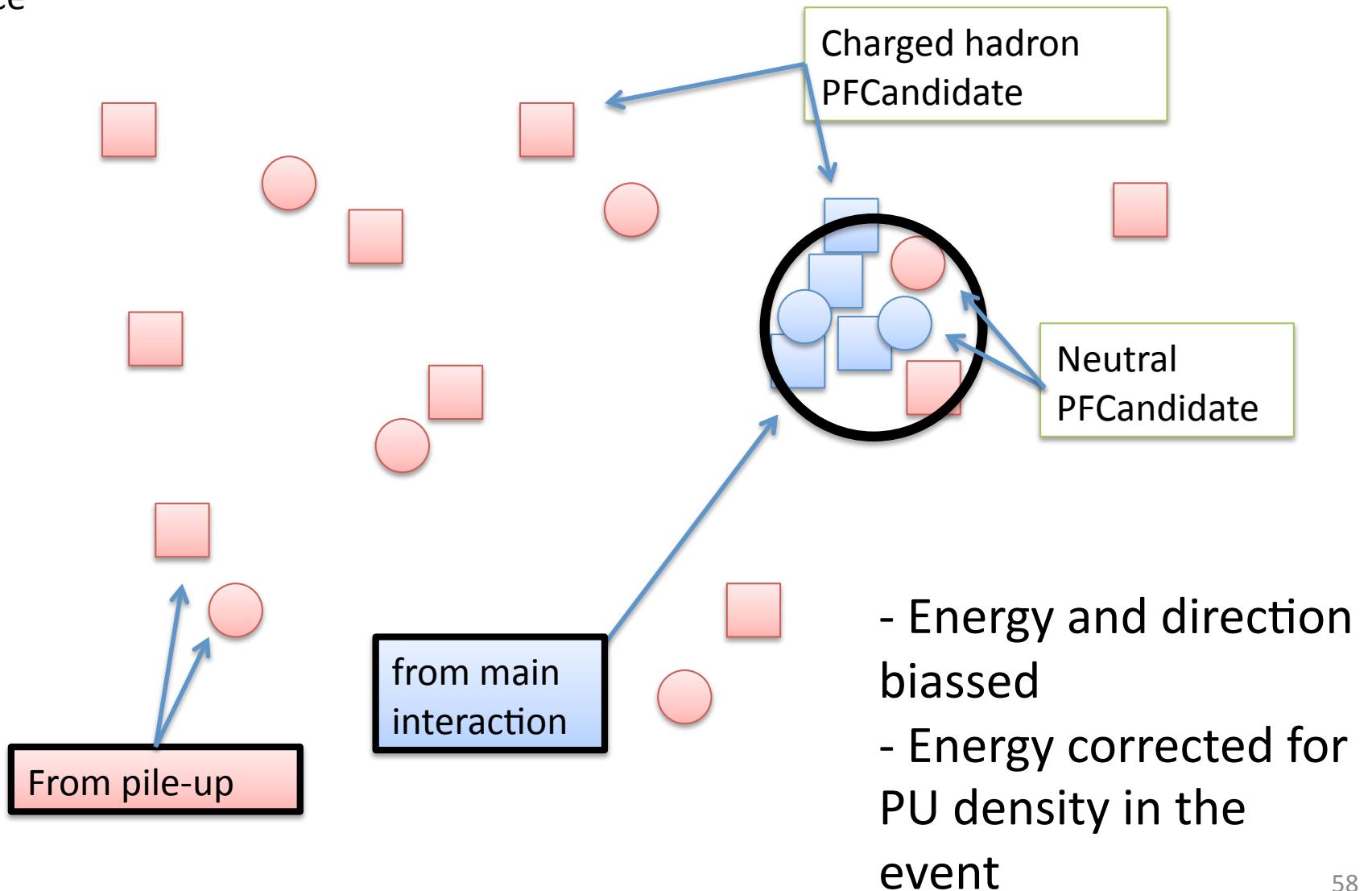
- Hadronic recoil to a boson (e.g. a Z)



Factor 2 gain in resolution  
Confirmed in the data

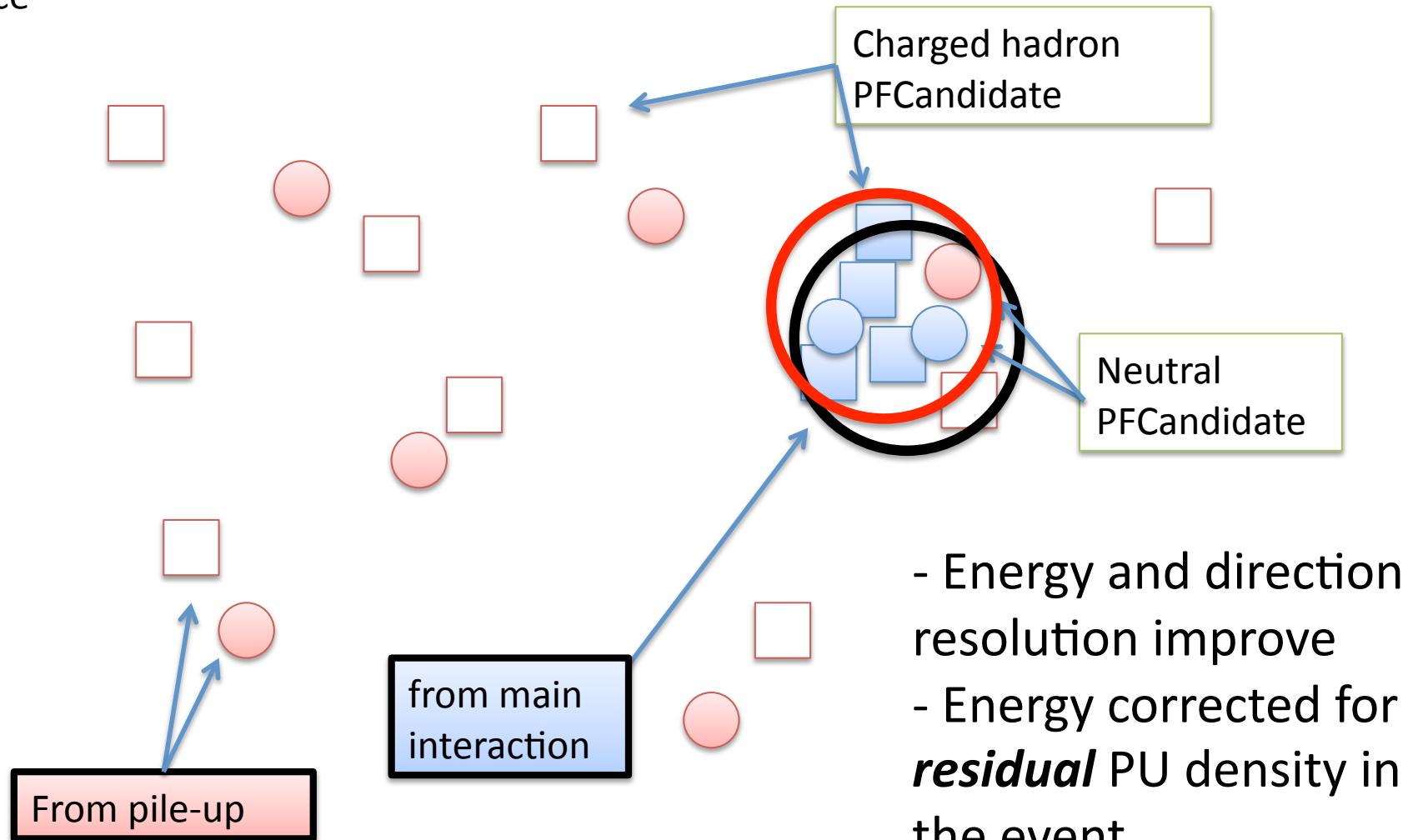
# All particles, raw jet

In the tracker  
acceptance

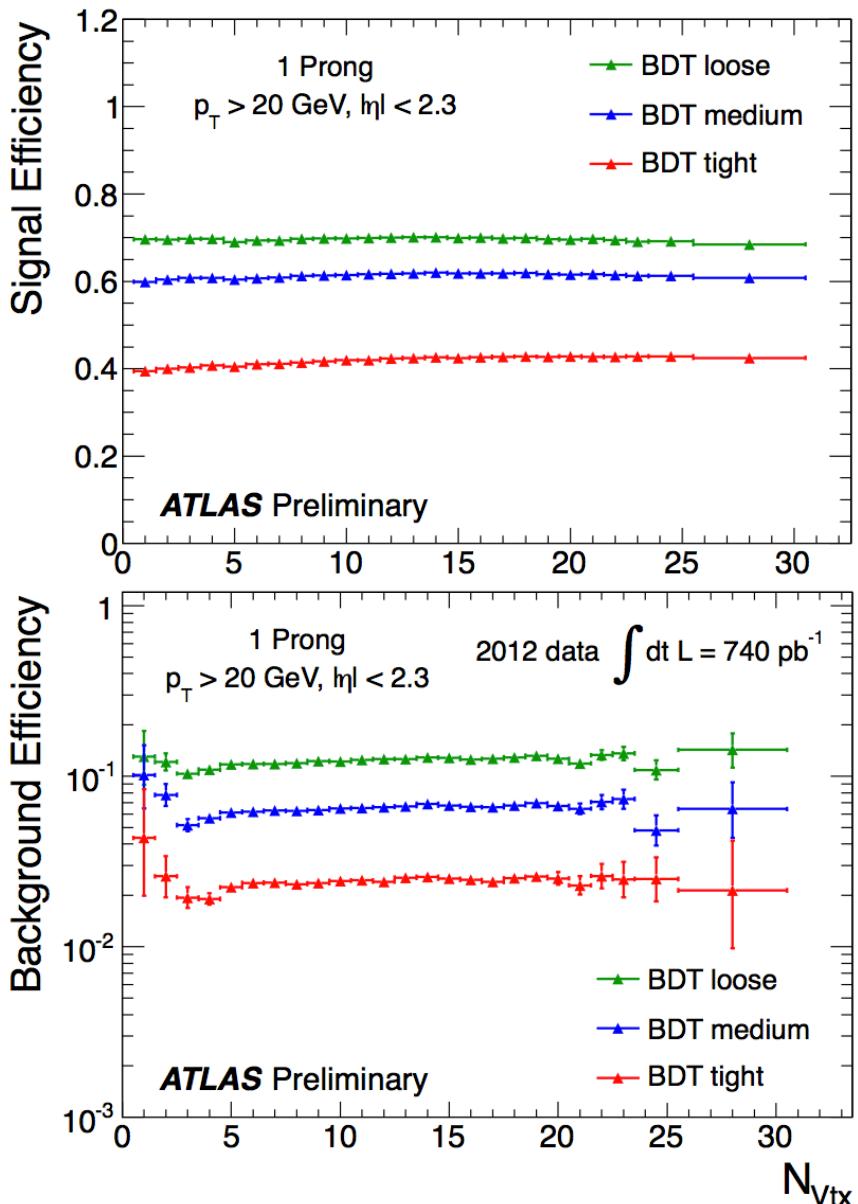


# PU charged hadron removal, CHS jet

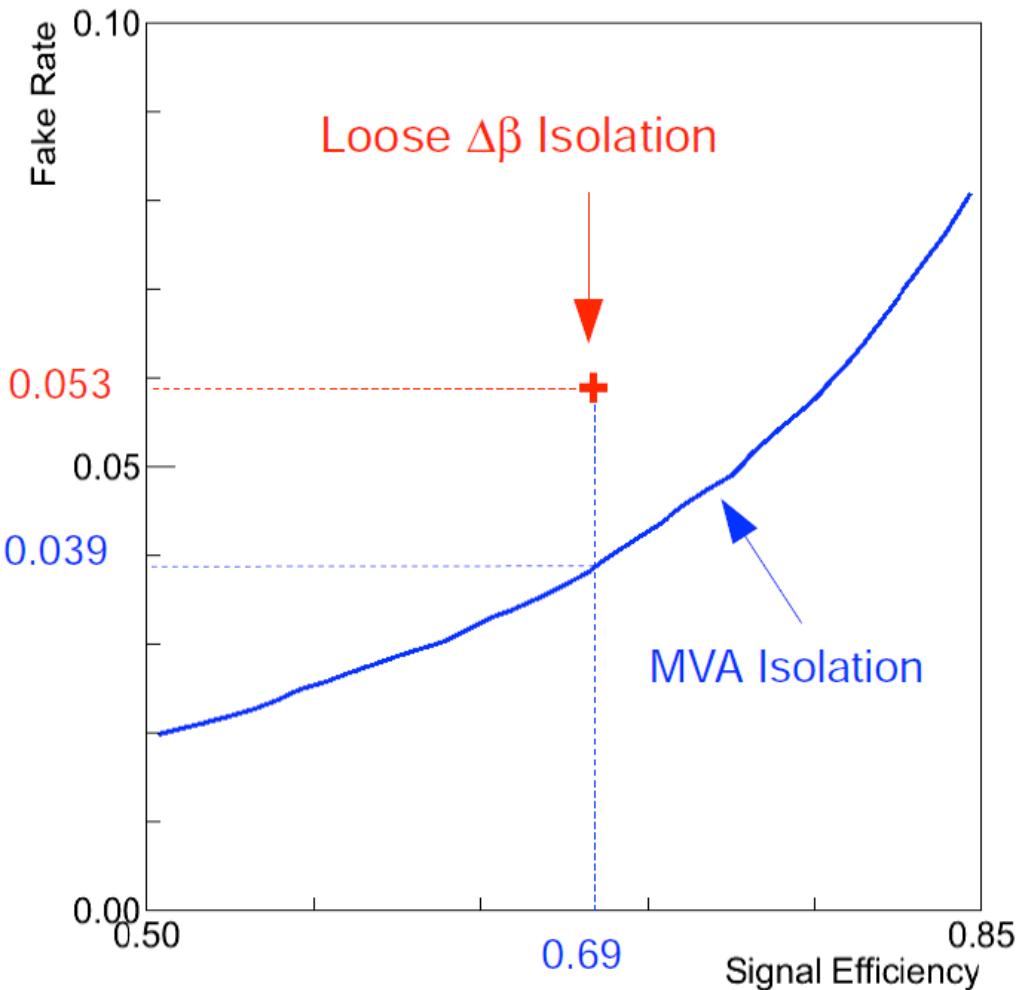
In the tracker  
acceptance



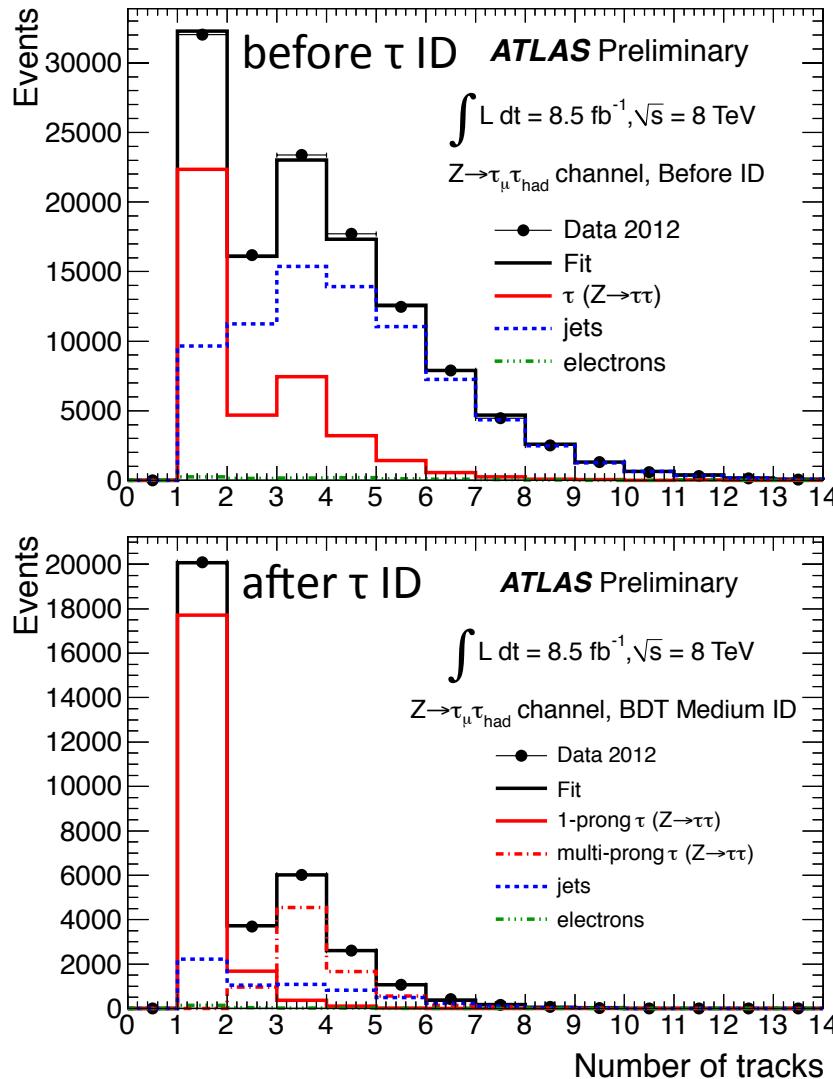
# $\tau$ ID Efficiency and Fake Rate



- Performance in ATLAS:
  - Efficiency ~60%
  - Fake rate ~5%
- Both flat vs pileup
- Similar performance in CMS



# $\tau$ ID Efficiency Measurement



- Tag & Probe
- $Z \rightarrow \tau\tau \rightarrow \mu\tau$  events
  - ATLAS also uses  $W \rightarrow \tau$  events
- Fit tau track multiplicity
  - signal template from sim.
  - bgd template from same-sign
  - ATLAS and CMS also fit the  $\mu\tau$  mass distribution
- Systematic uncertainty on  $\tau$  ID efficiency:  $\sim 5\%$

[twiki.cern.ch/twiki/bin/view/AtlasPublic/TauPublicCollisionPlots](http://twiki.cern.ch/twiki/bin/view/AtlasPublic/TauPublicCollisionPlots)

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