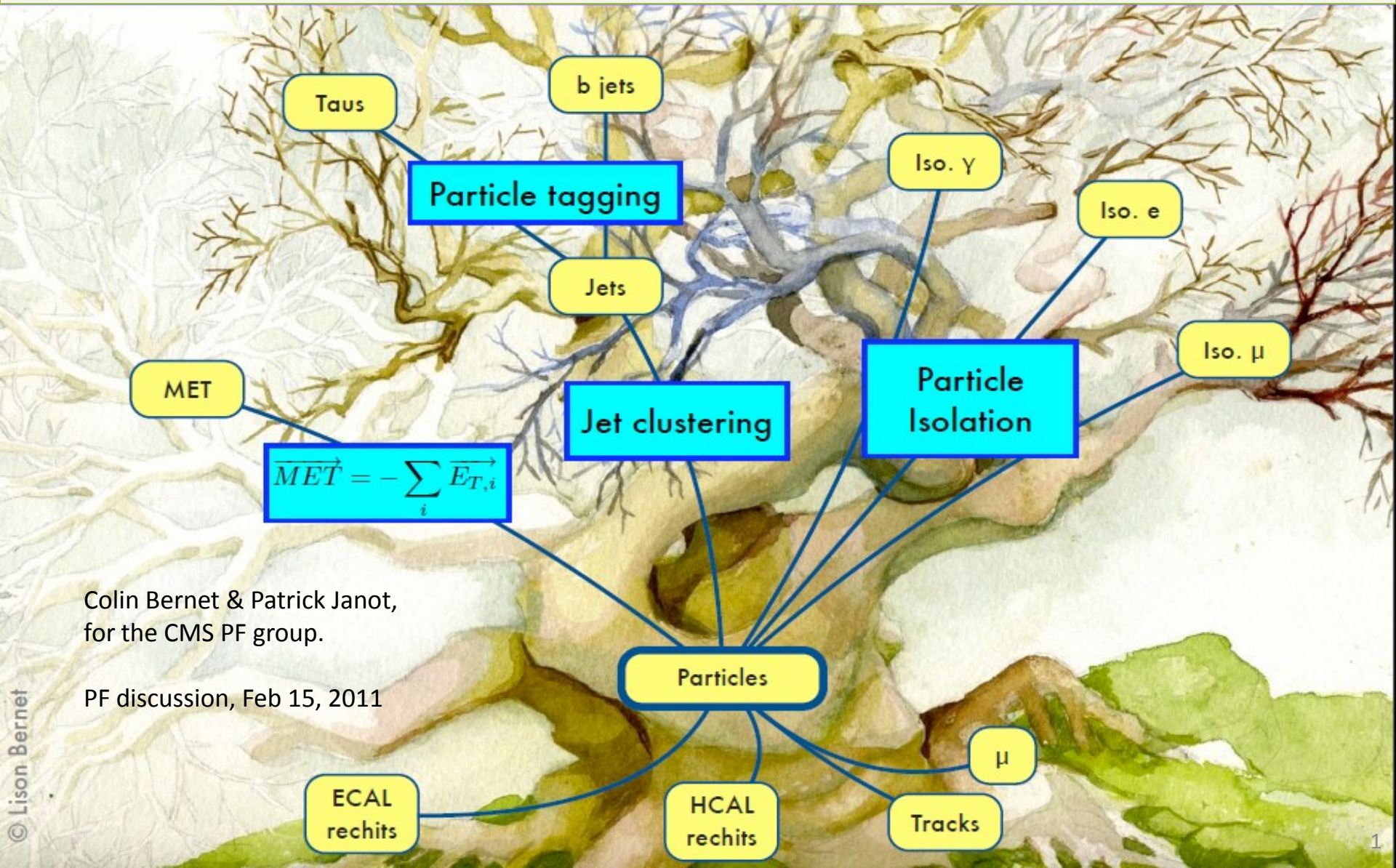
Energy Flow in CMS ;-P

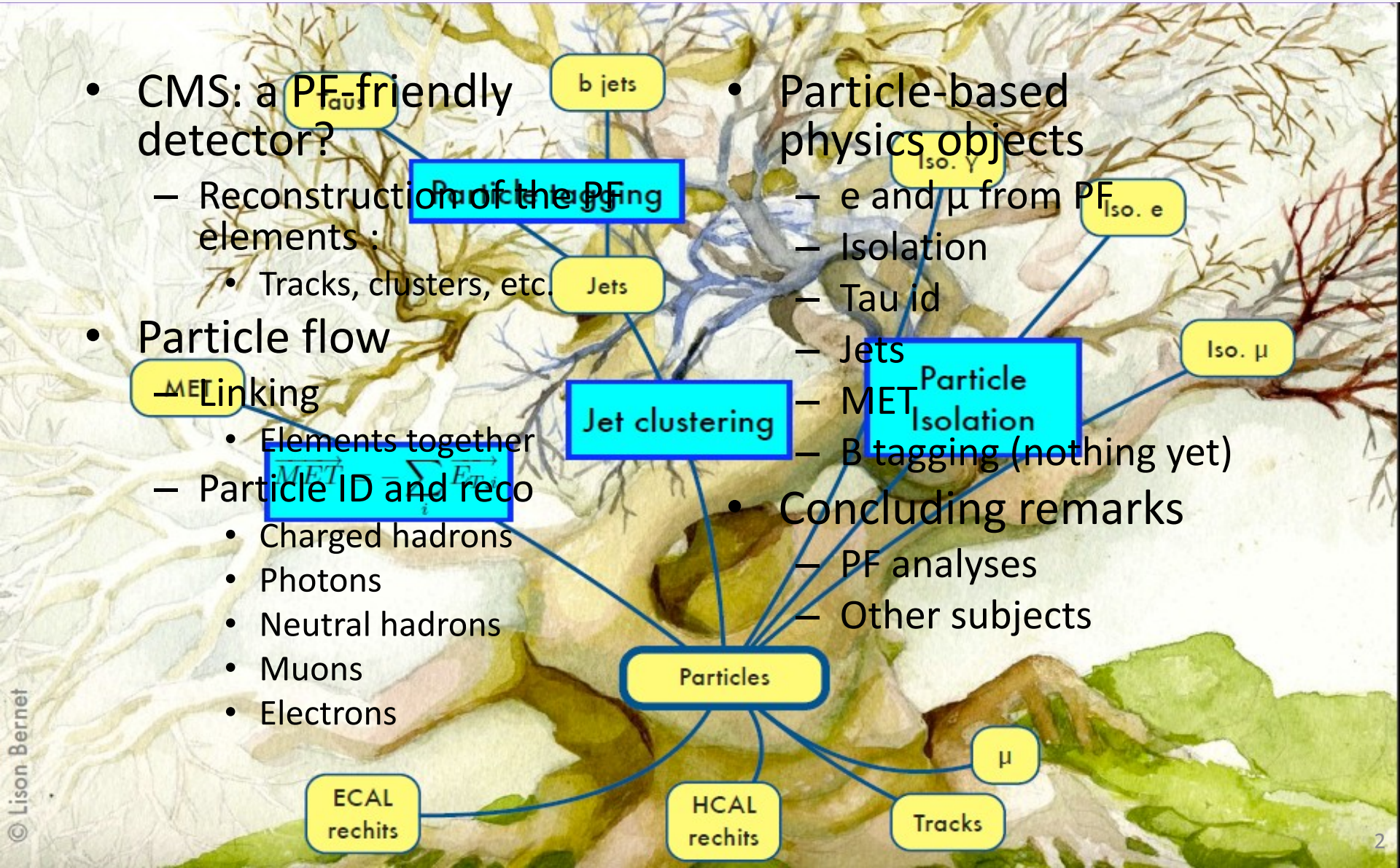


Colin Bernet & Patrick Janot,
for the CMS PF group.

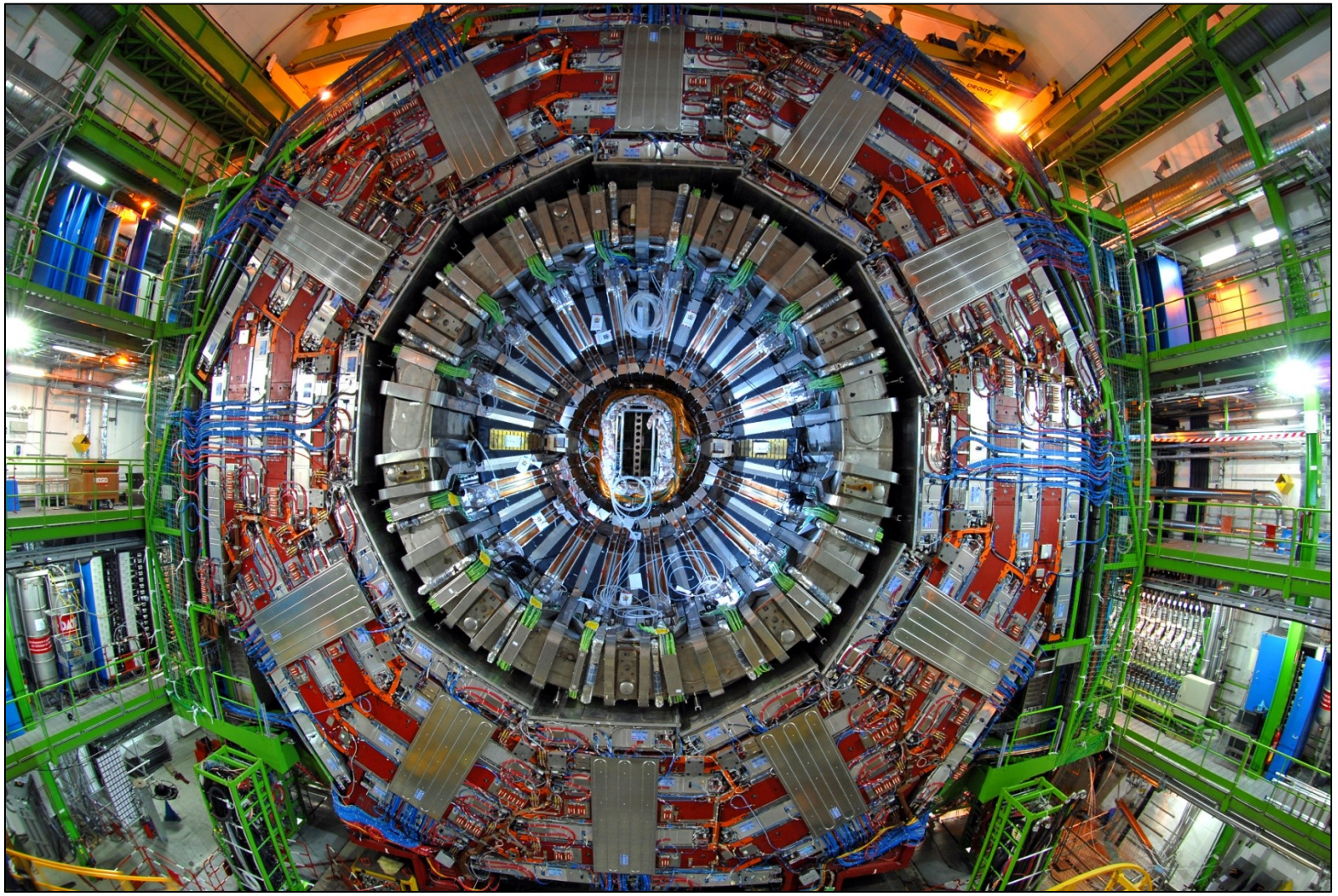
PF discussion, Feb 15, 2011

Outline

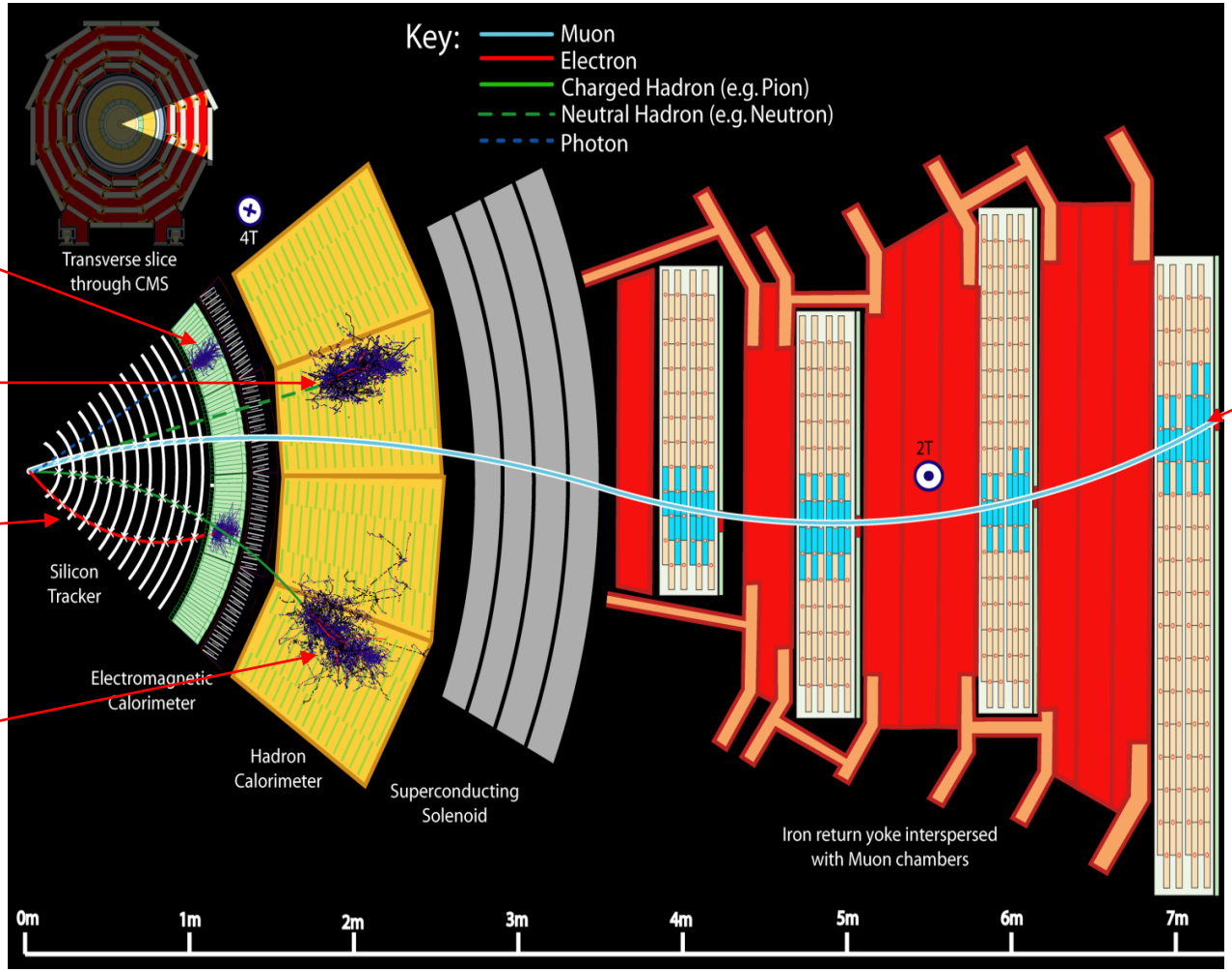
- CMS: a PF-friendly detector?
  - Reconstruction of the PF elements :
    - Tracks, clusters, etc.
- Particle flow
  - Linking
    - Elements together
  - Particle ID and reco
    - Charged hadrons
    - Photons
    - Neutral hadrons
    - Muons
    - Electrons
- Particle-based physics objects
  - e and μ from PF
  - Isolation
  - Tau id
  - Jets
  - MET
  - B tagging (nothing yet)
- Concluding remarks
  - PF analyses
  - Other subjects



CMS : a PF friendly detector?



Looks like we can do it ;-)



γ

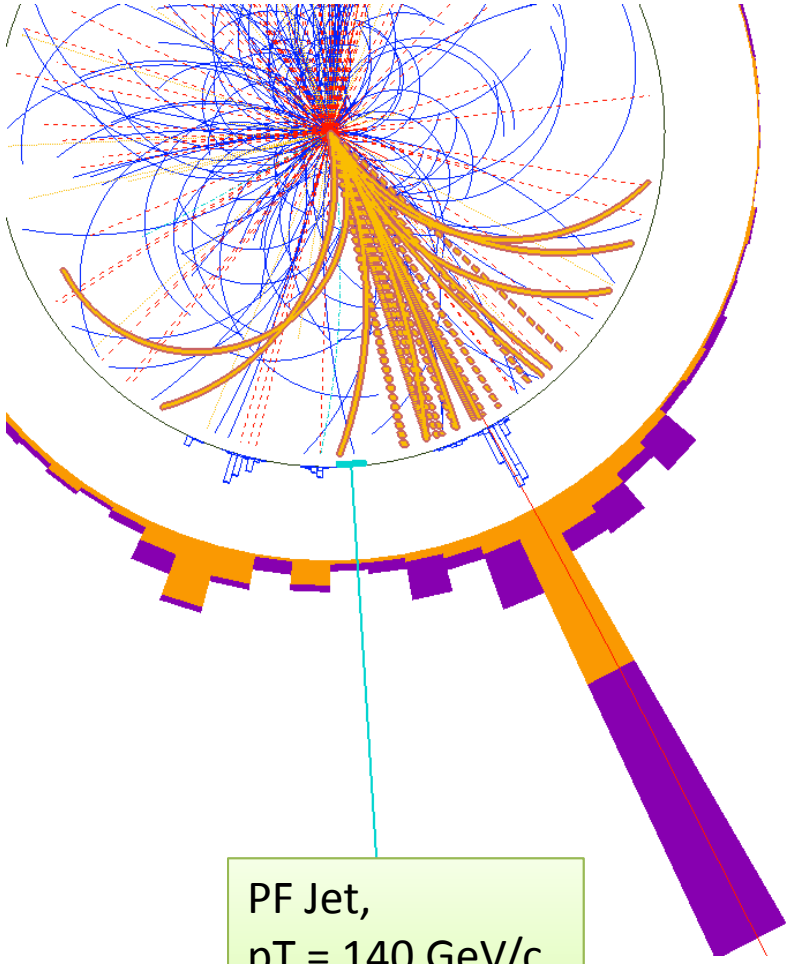
h^0

e

$h^{\pm}$

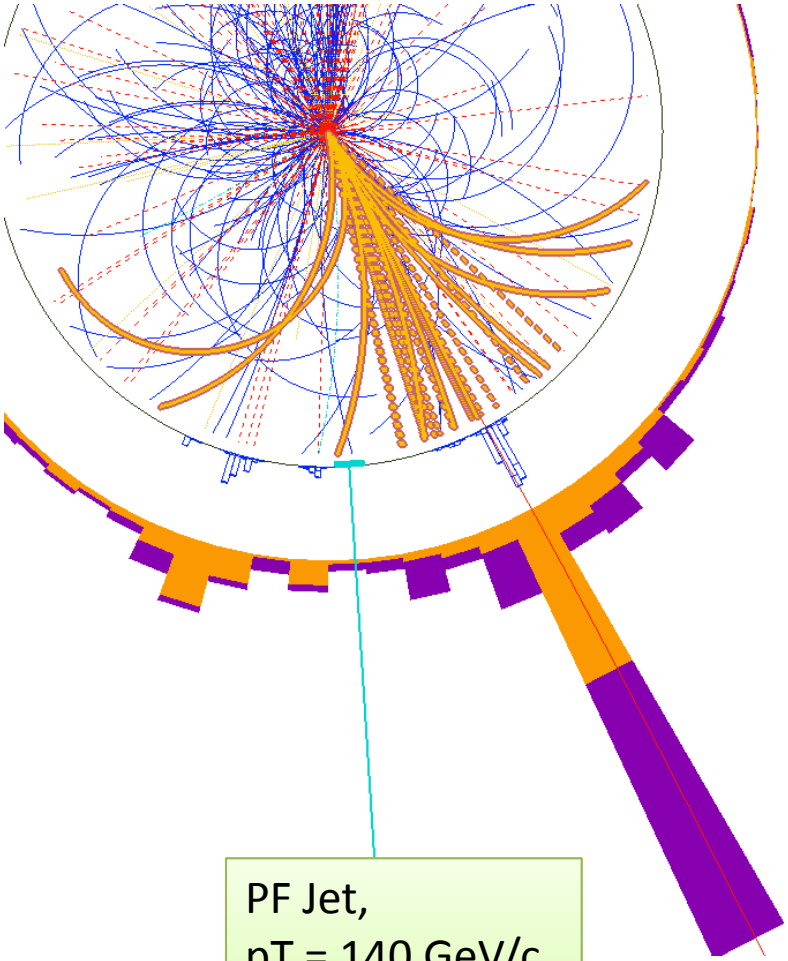
μ

Recipe for a good particle flow



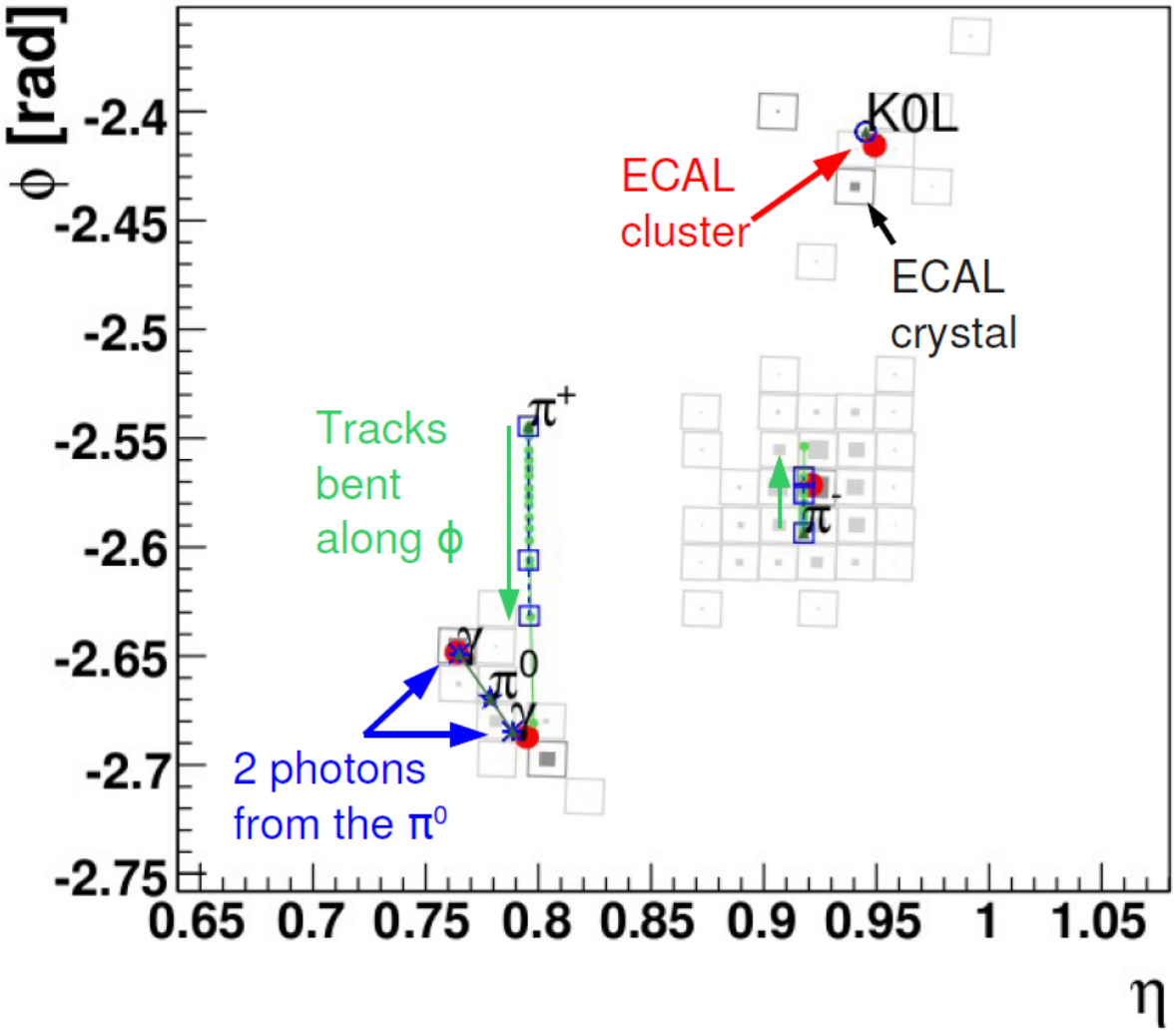
- Separate neutrals from charged hadrons
  - Field integral (BxR)
  - Calorimeter granularity
- Efficient tracking
- Minimize material before calorimeters
- Clever algorithm to compensate for detector imperfections

Neutral/charged separation (1)
Field Integral



- Strong magnetic field: 3.8 T
- ECAL radius 1.29 m
- BxR = 4.9 T.m
  - ALEPH: 1.5x1.8 = 2.7 T.m
  - ATLAS: 2.0x1.2 = 2.4 T.m
  - CDF: 1.5x1.5 = 2.25 T.m
  - DO: 2.0x0.8 = 1.6 T.m

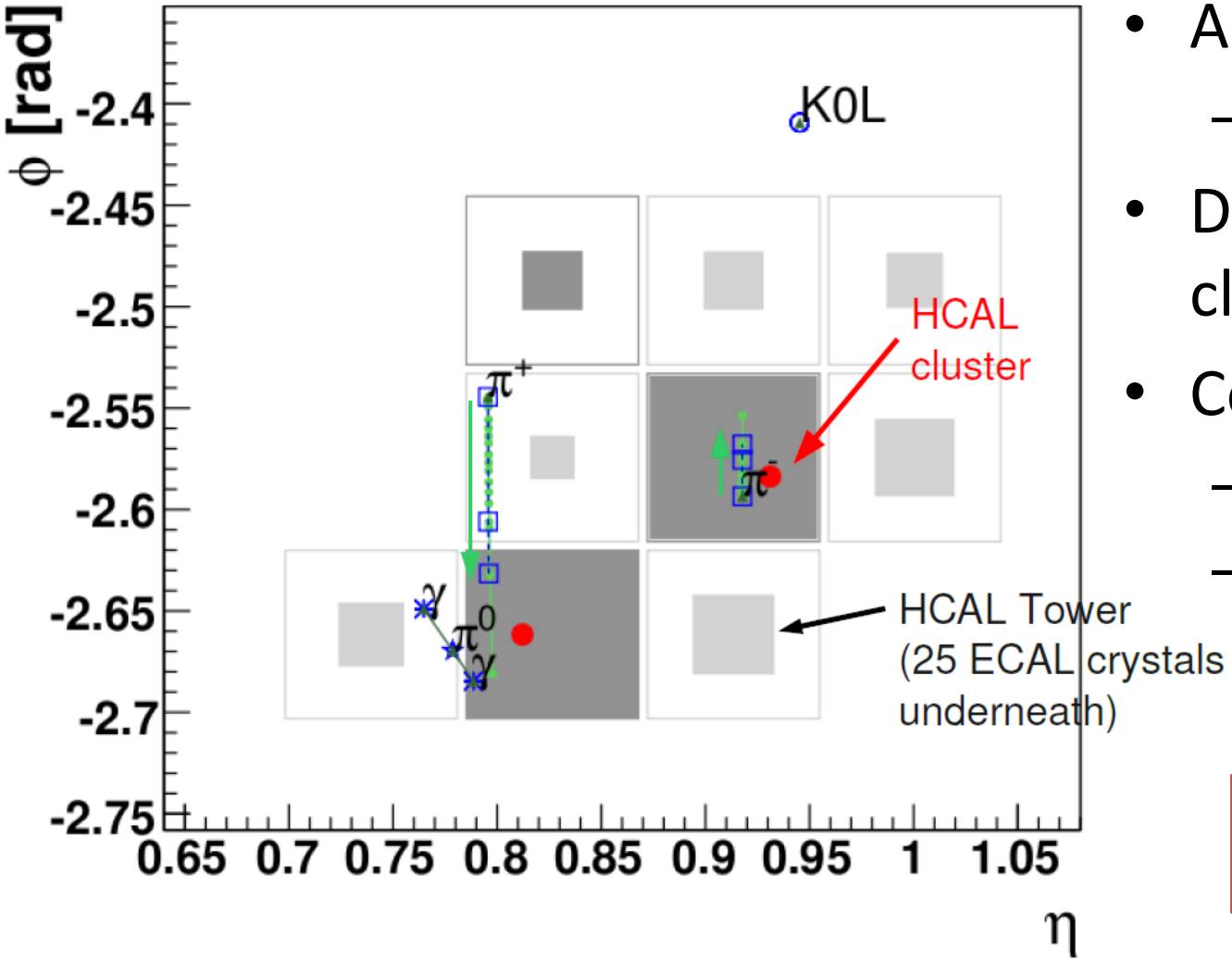
Neutral/charged separation (1)
ECAL granularity



- A typical jet
  - pT = 50 GeV/c
- Details about clustering follow
- Cell size:
  - 0.017x0.017

Good!

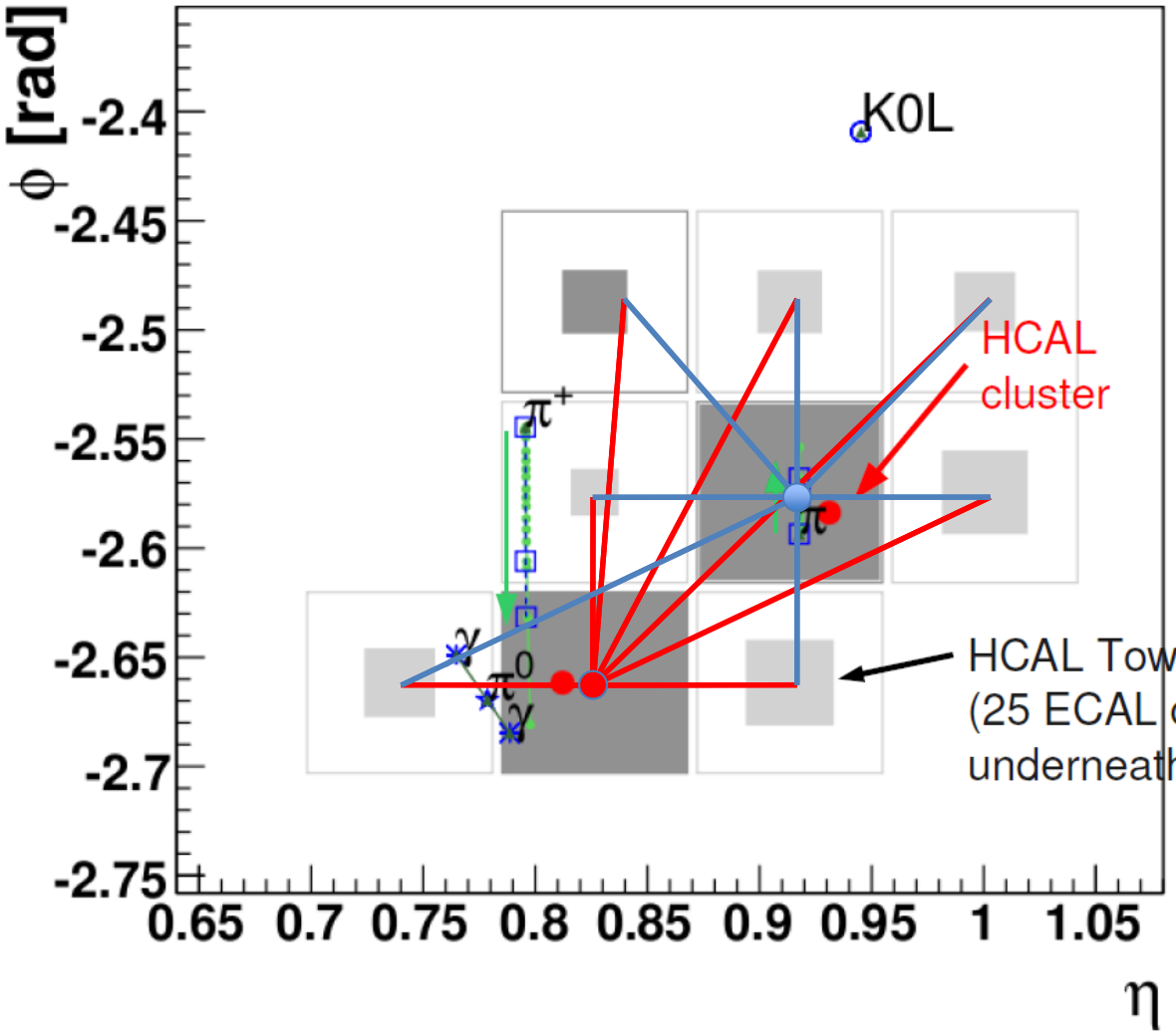
Neutral/charged separation (1)
HCAL granularity



- A typical jet
  - pT = 50 GeV/c
- Details about clustering follow
- Cell size:
  - 0.085x0.085
  - 5 ECAL crystals

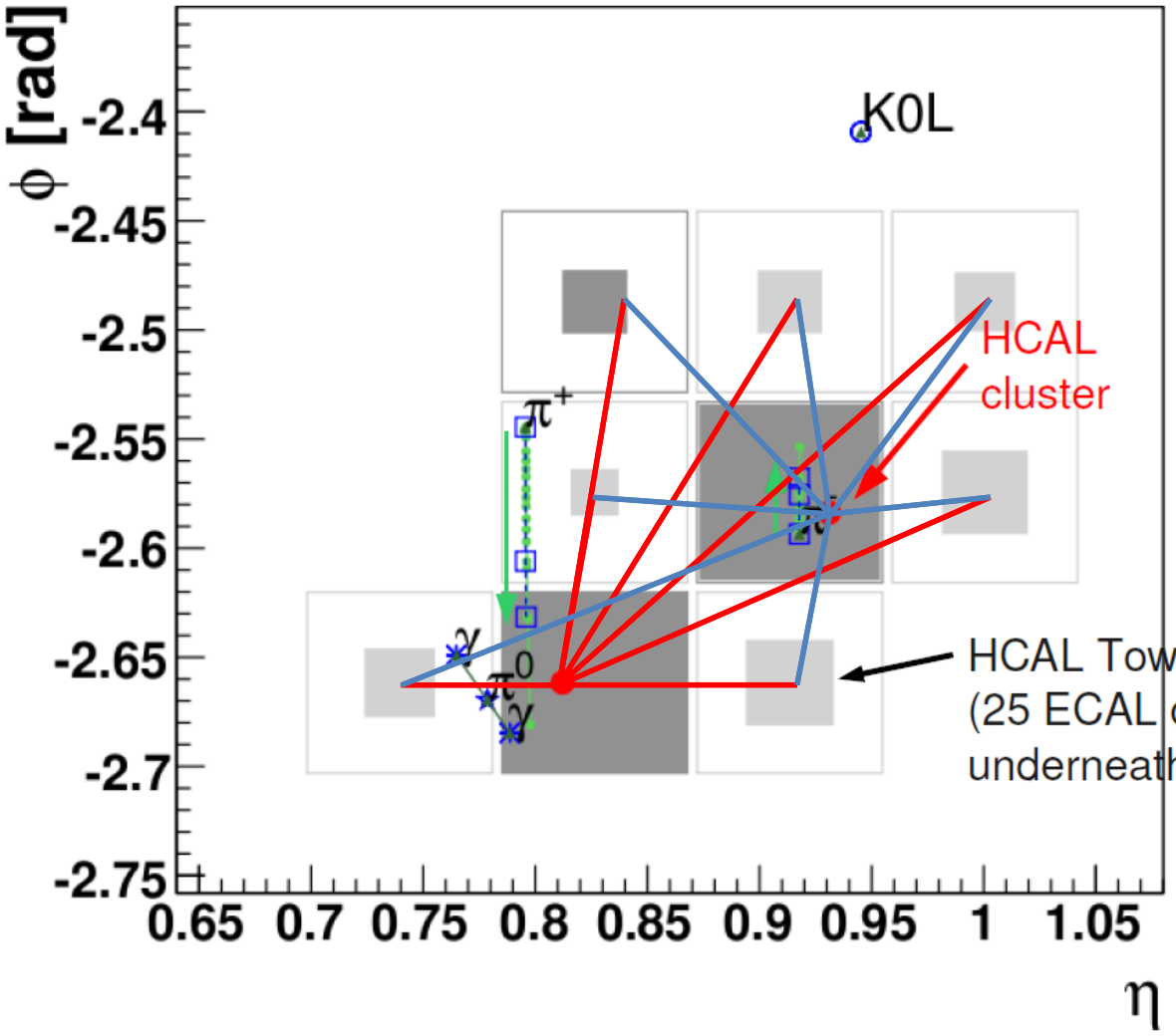
Bad…

PF Clustering, HCAL



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

PF Clustering, HCAL



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- Iterative, energy sharing
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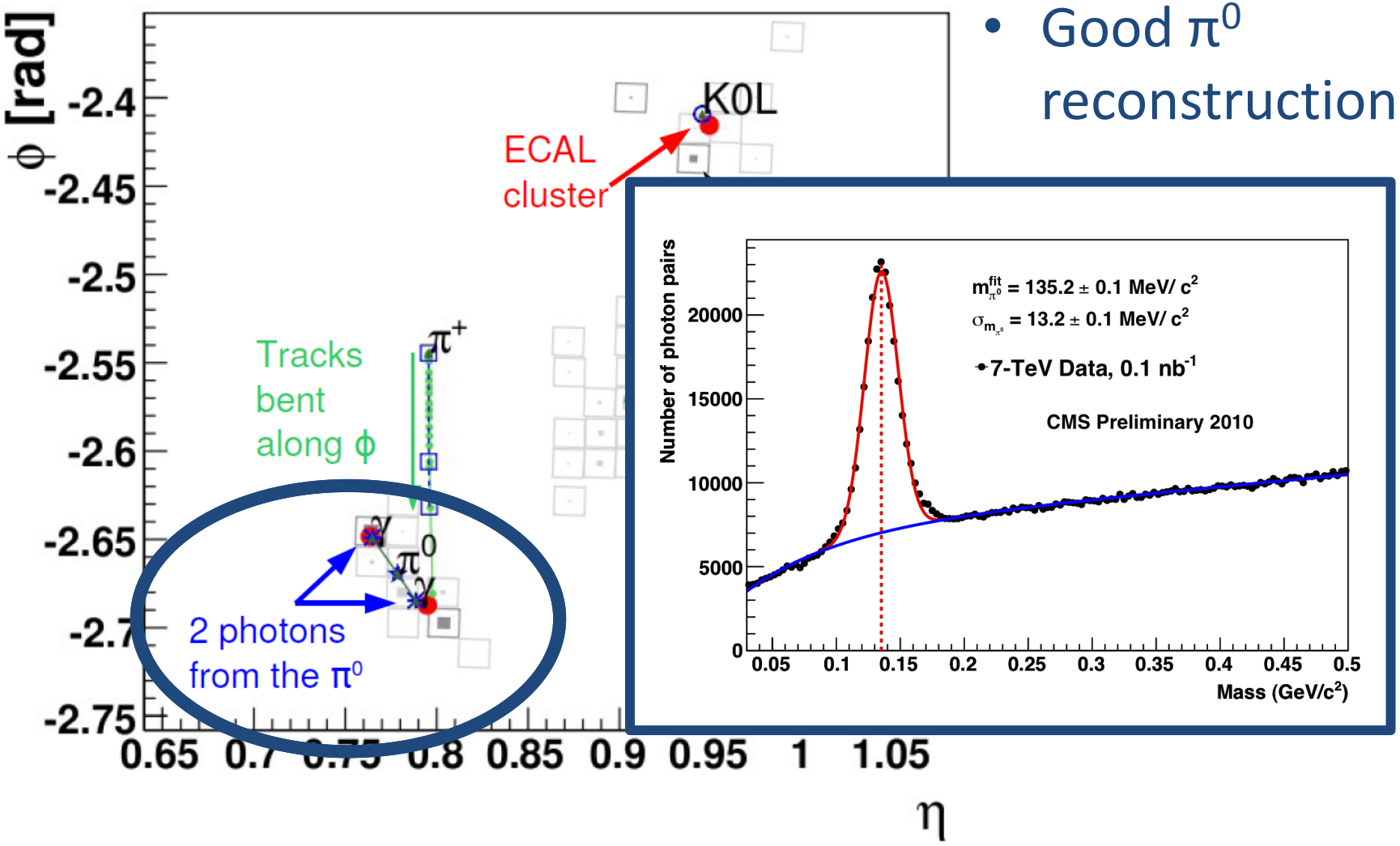
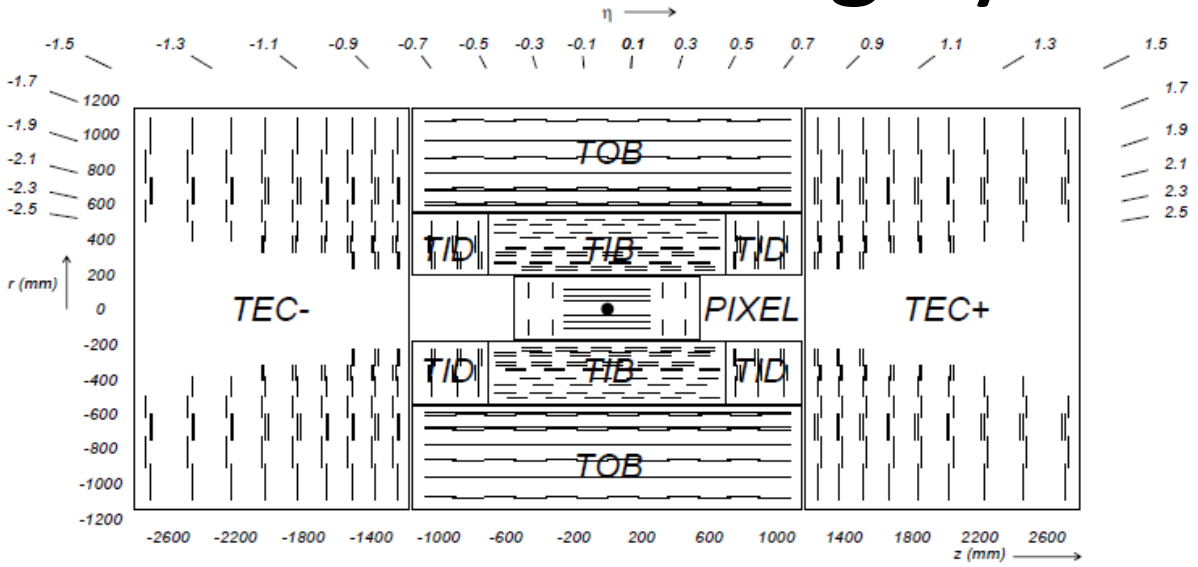
  - HCAL : E > 0.8 GeV

PF Clustering, ECAL

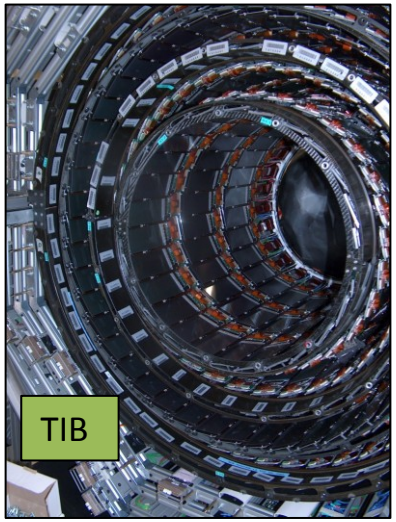
- Good π^0 reconstruction

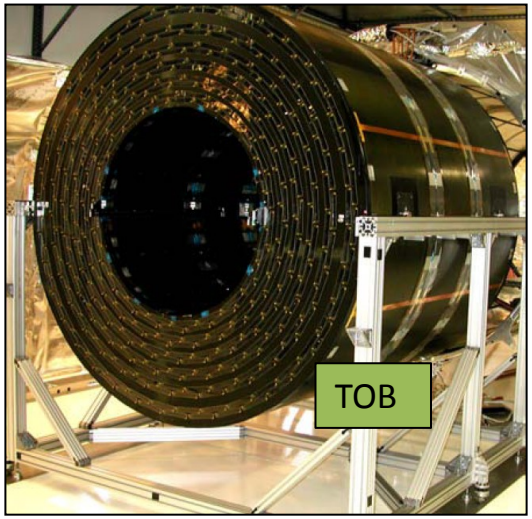


Tracking System

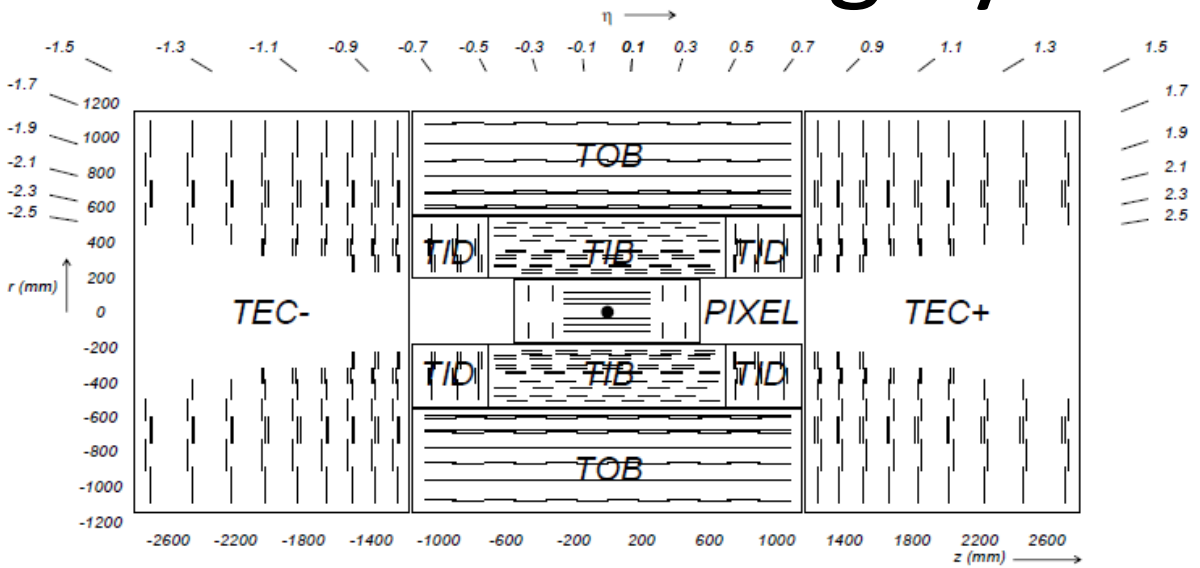


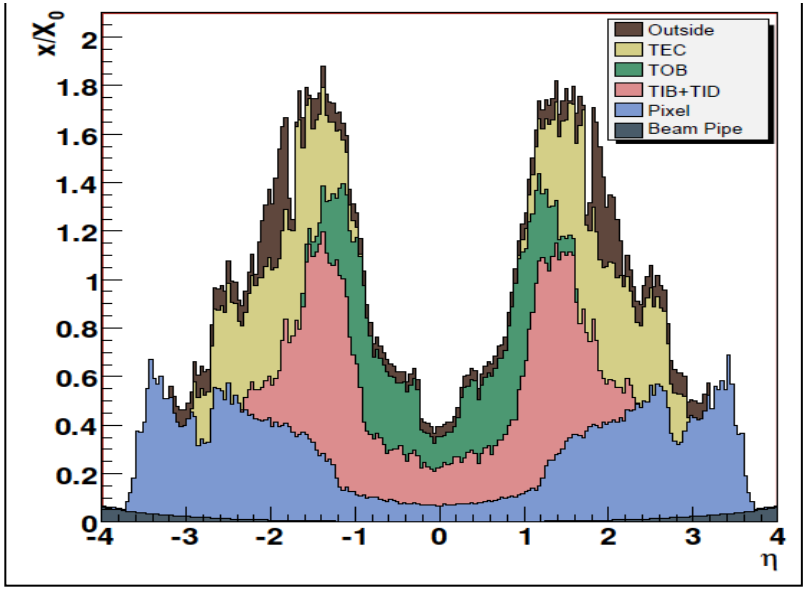
- Huge silicon tracker
- Hermetic
- Highly efficient, in principle





Tracking System

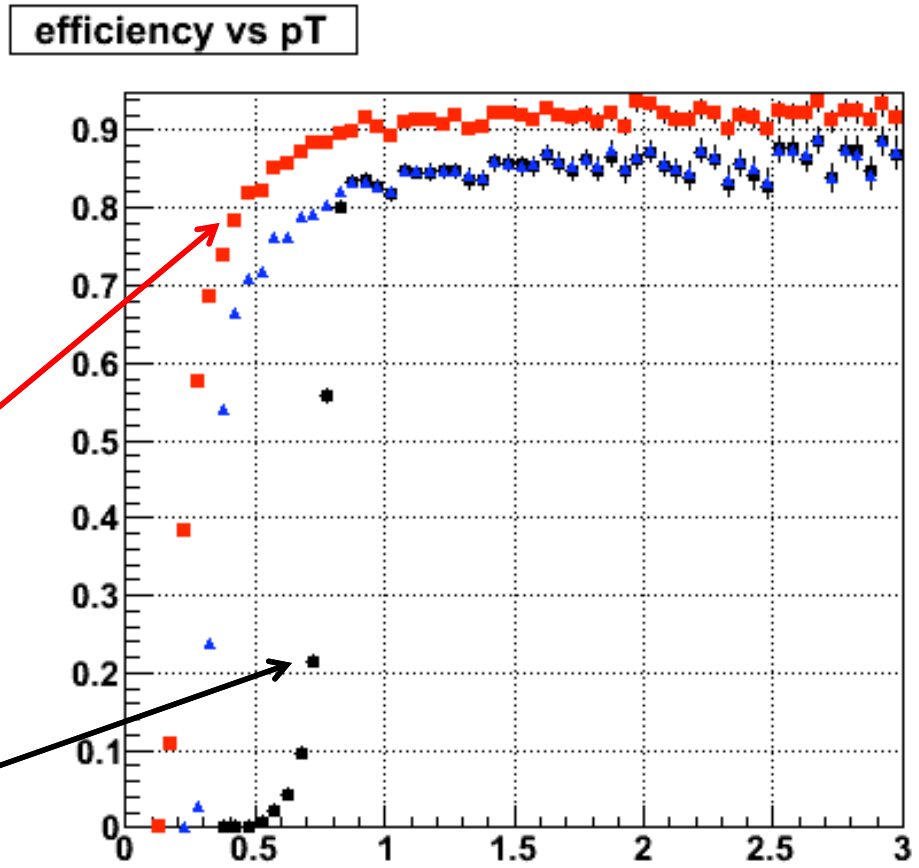




- Huge silicon tracker
- Hermetic
- Highly efficient, in principle…
- But up to 1.8 X0
  - Nuclear interactions
  - γ conversions
  - e- brems

Iterative Tracking (1/2)

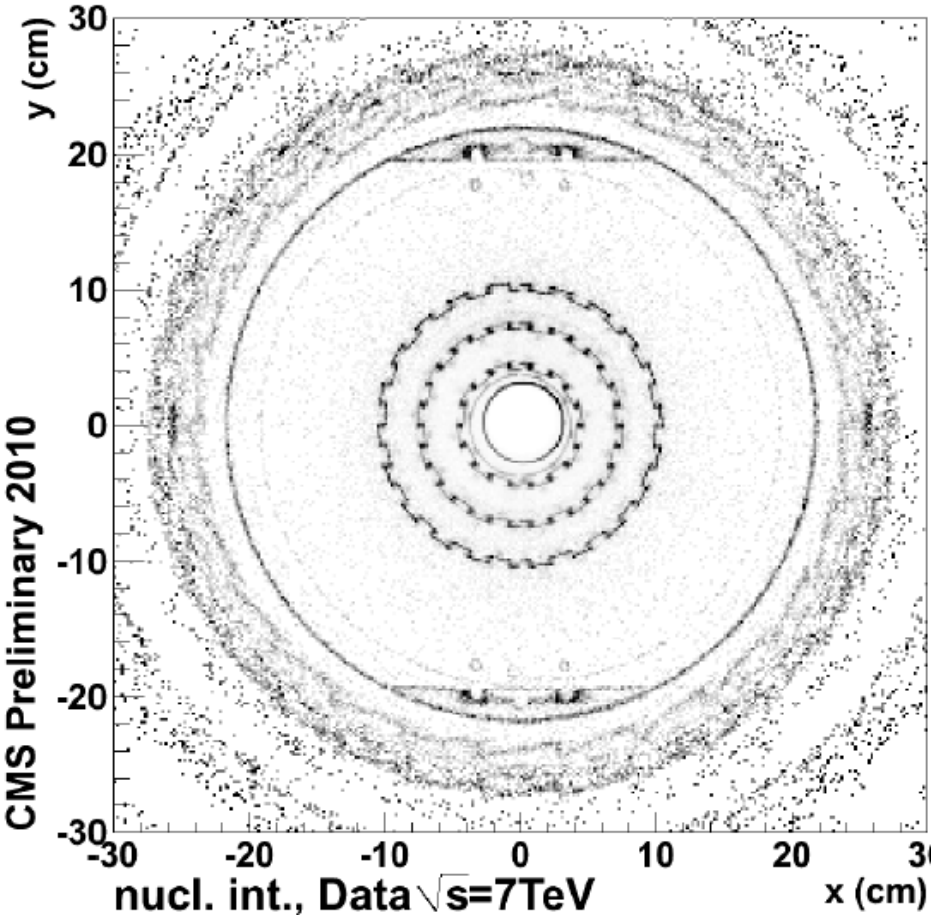
- Developed for PF, now standard
- At each iteration:
  - Reconstruct a set of tracks
  - Remove track hits
  - Relax constraints
- Fast (~10 s / event)
- Iterative tracking:
  - 1-2 % fake rate
- Old “CTF” tracking:
  - 20 % fake rate



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



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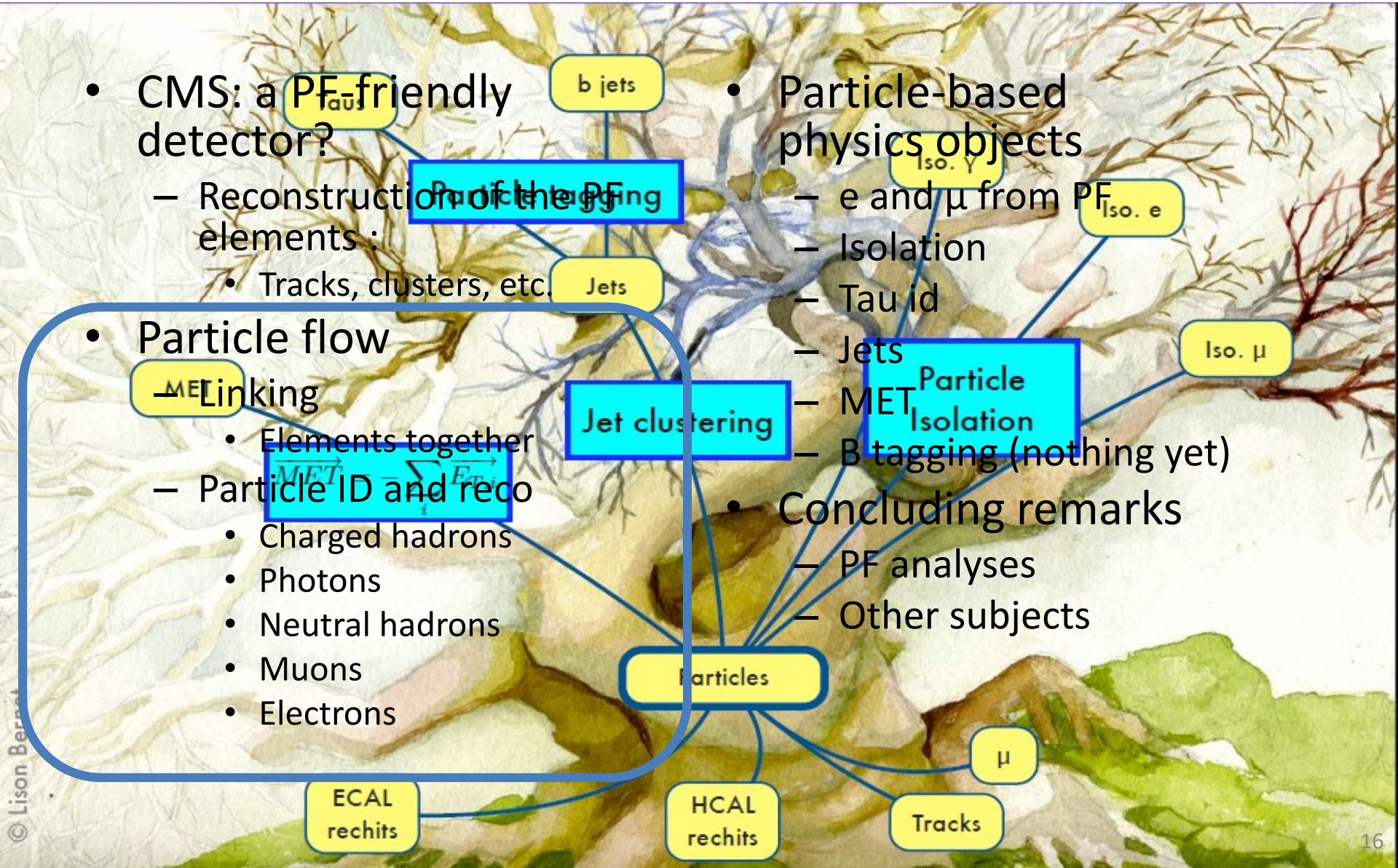
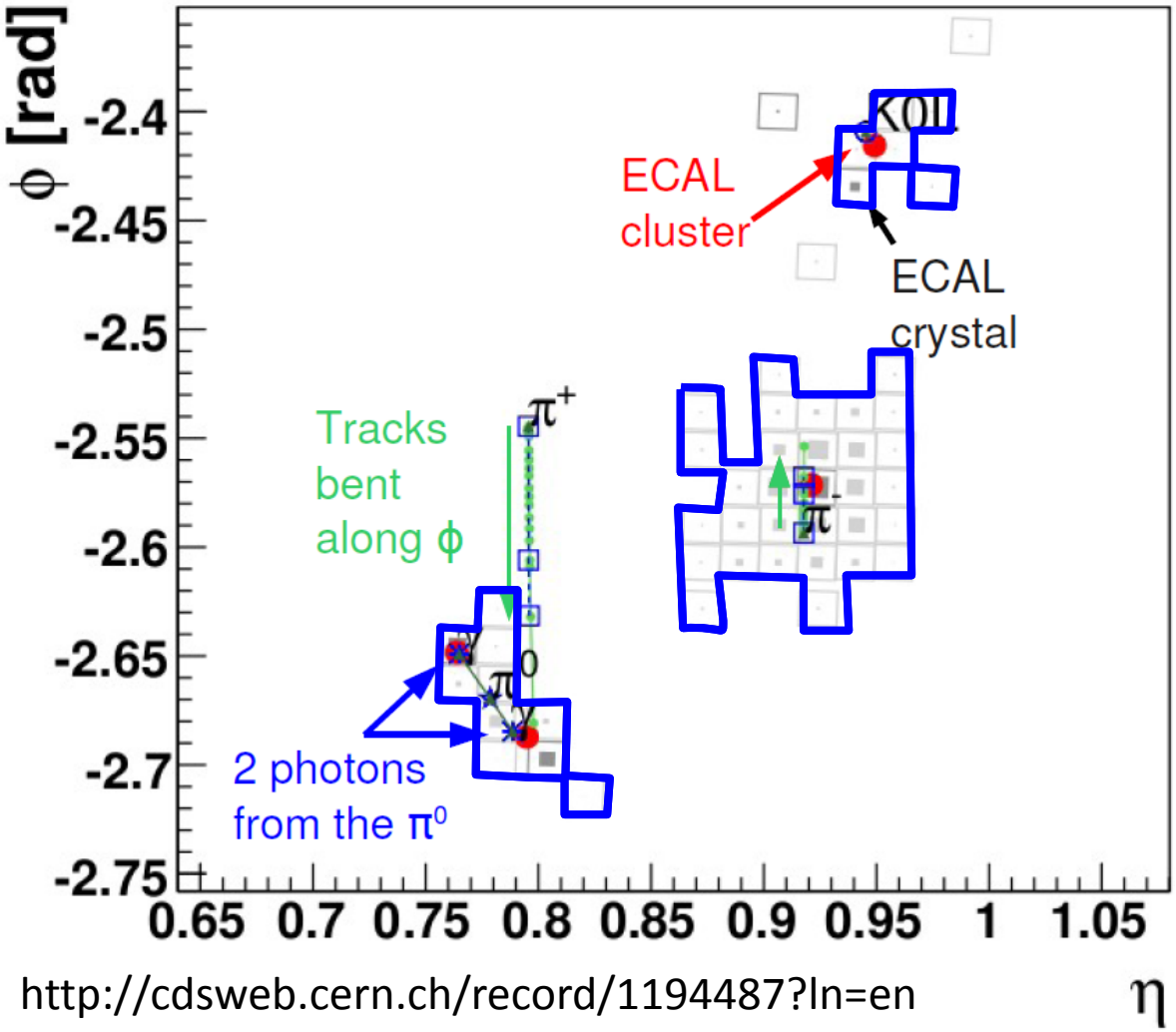


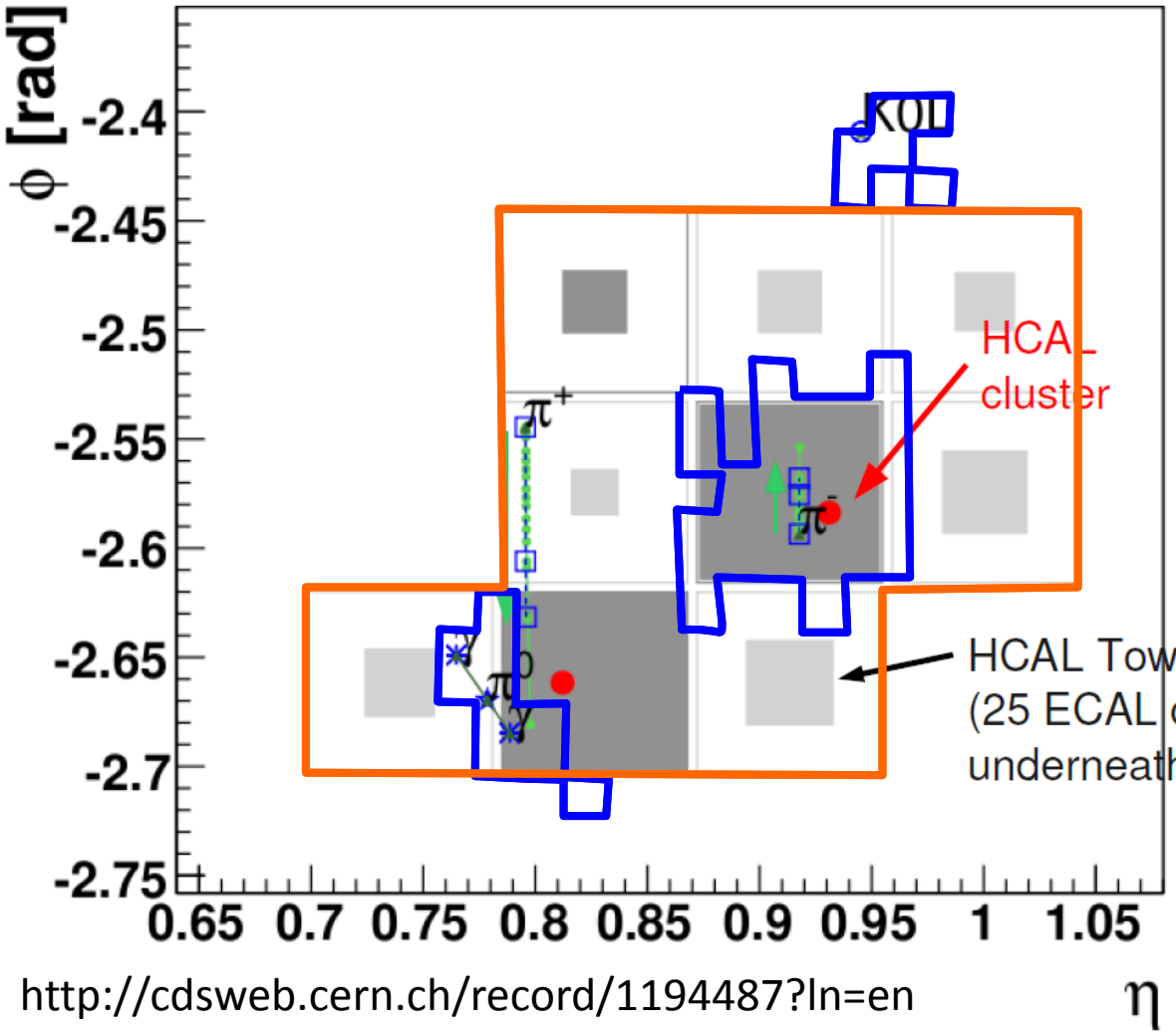
Linking – ECAL view



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

- Track impact within cluster boundaries
  → track & cluster linked

Linking – HCAL view

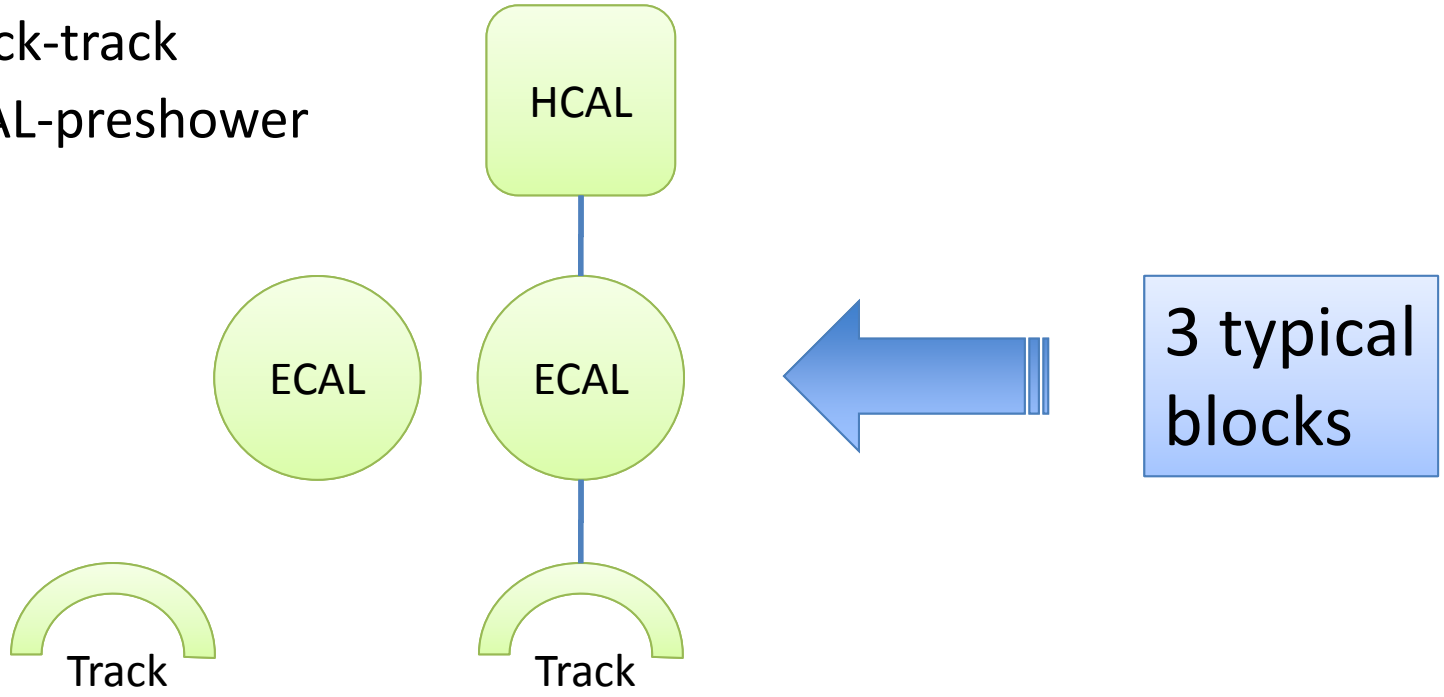


http://cdsweb.cern.ch/record/1194487?ln=en

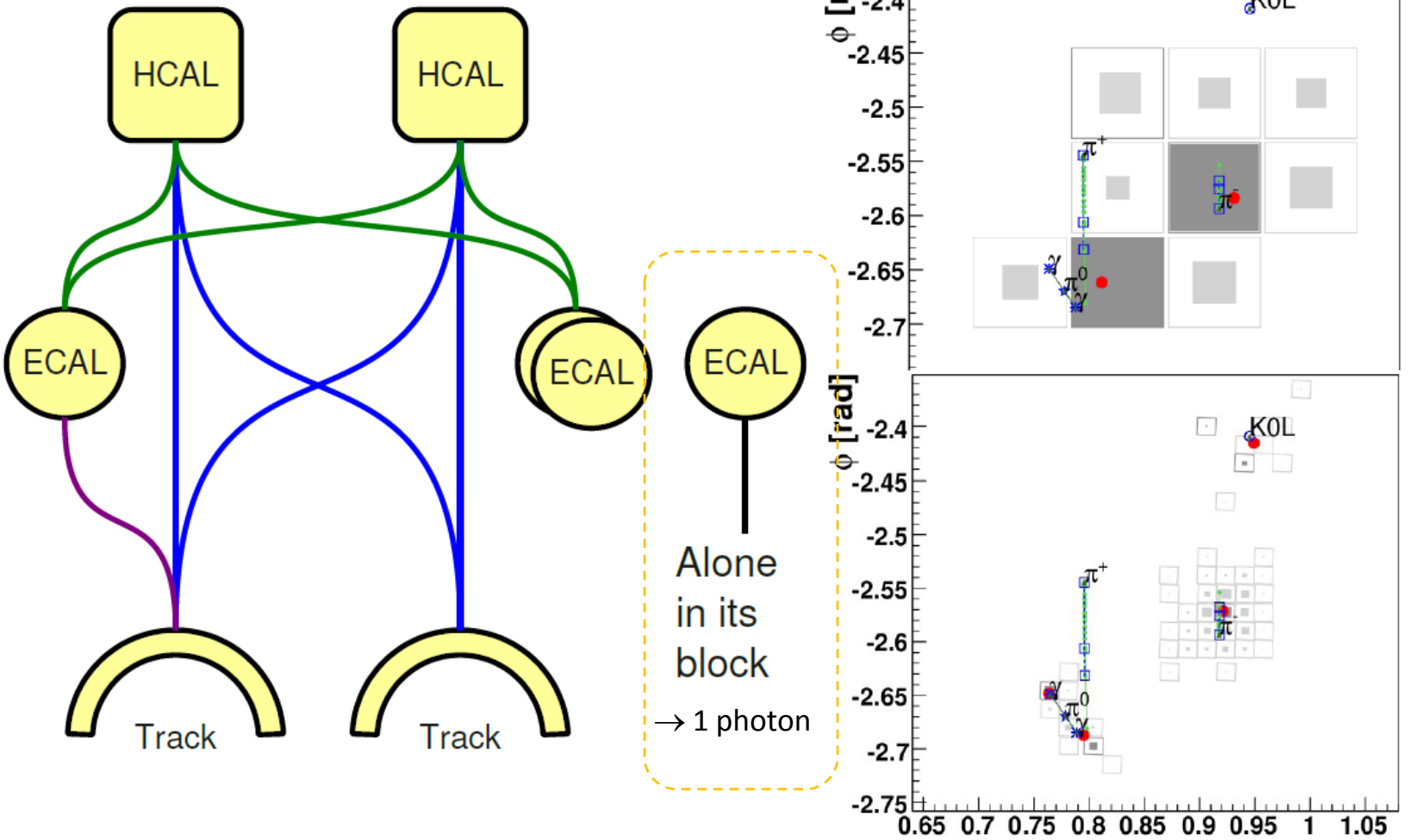
- Track impact within cluster boundaries
  → track & cluster linked
- Clusters overlapping
  → clusters linked

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”



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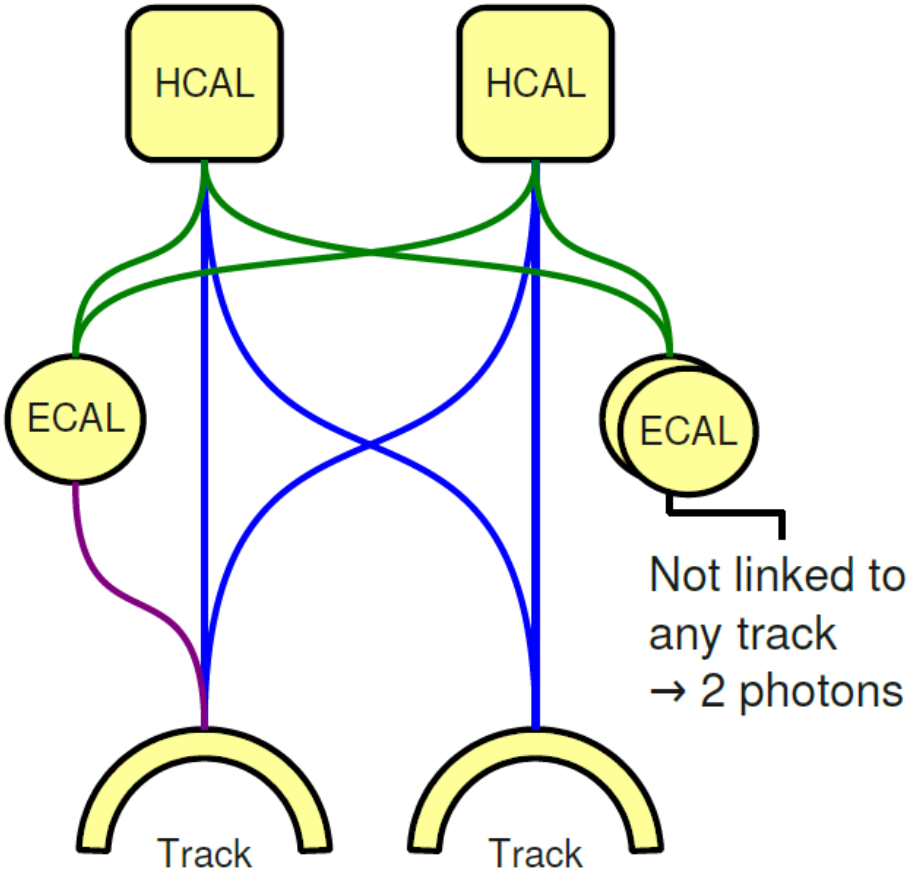
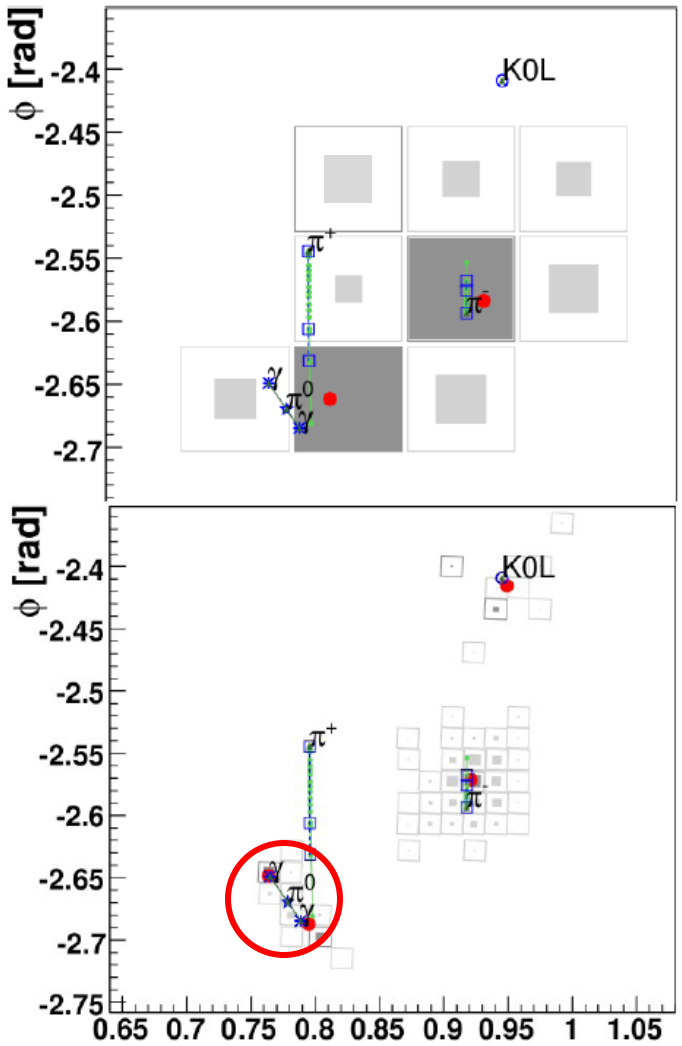
Photons





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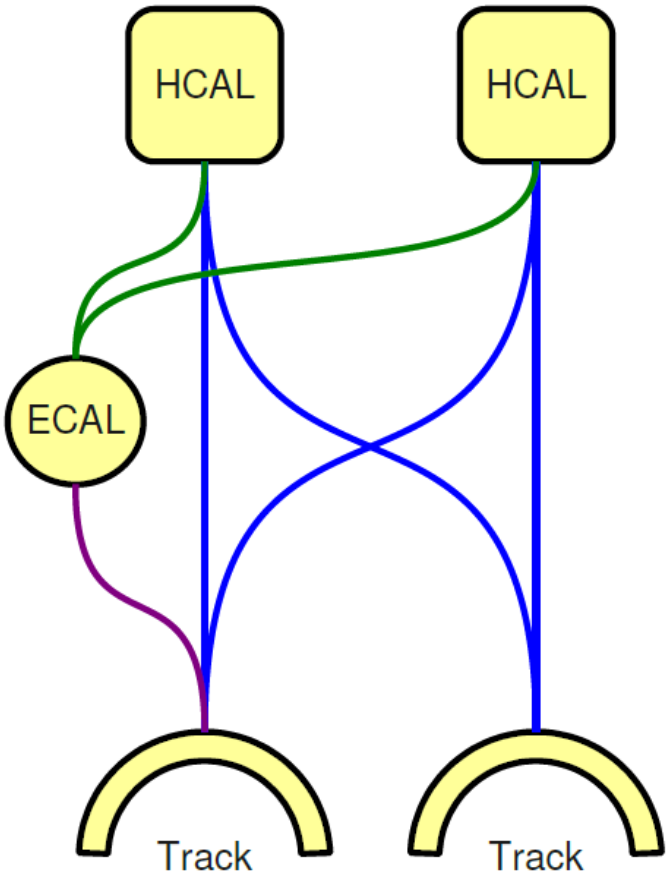
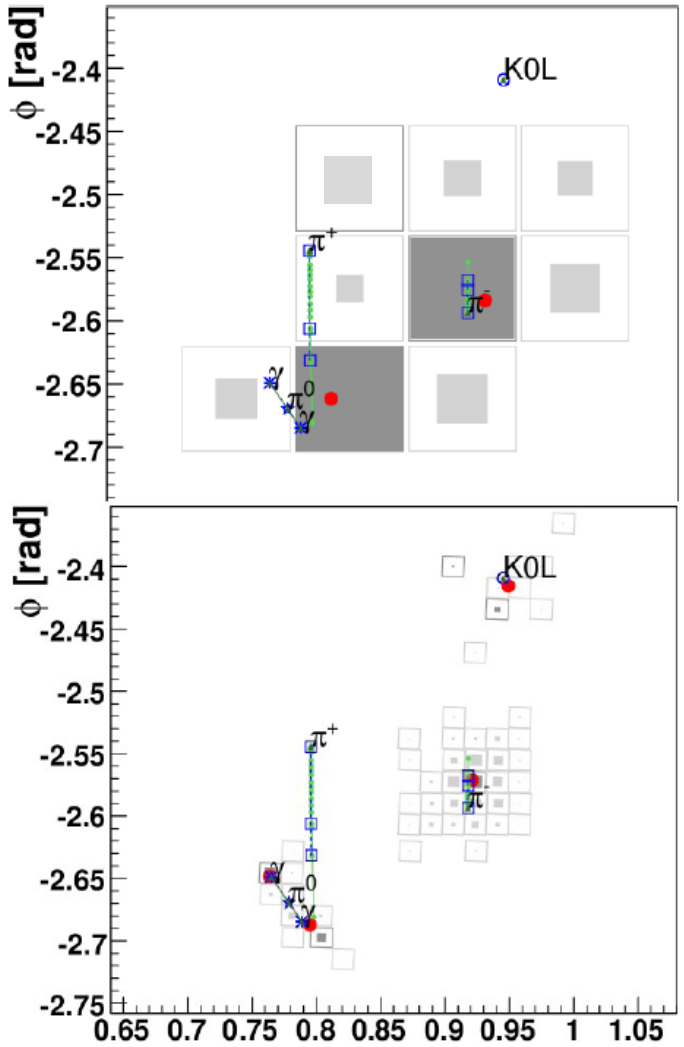
Photons





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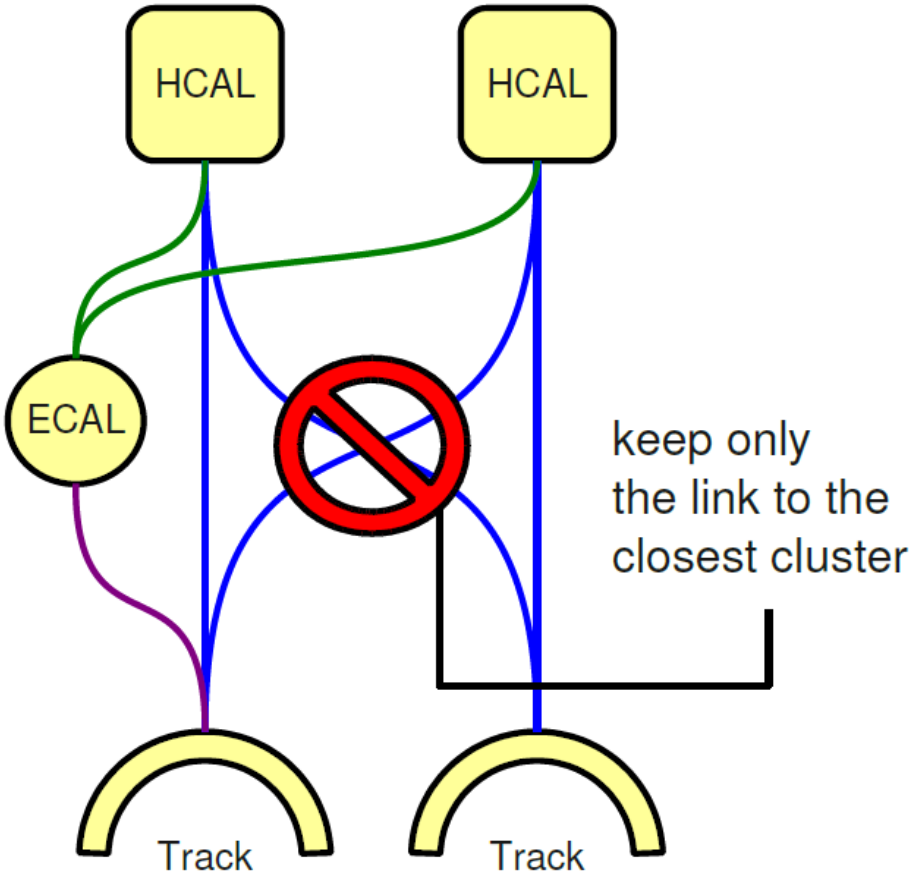
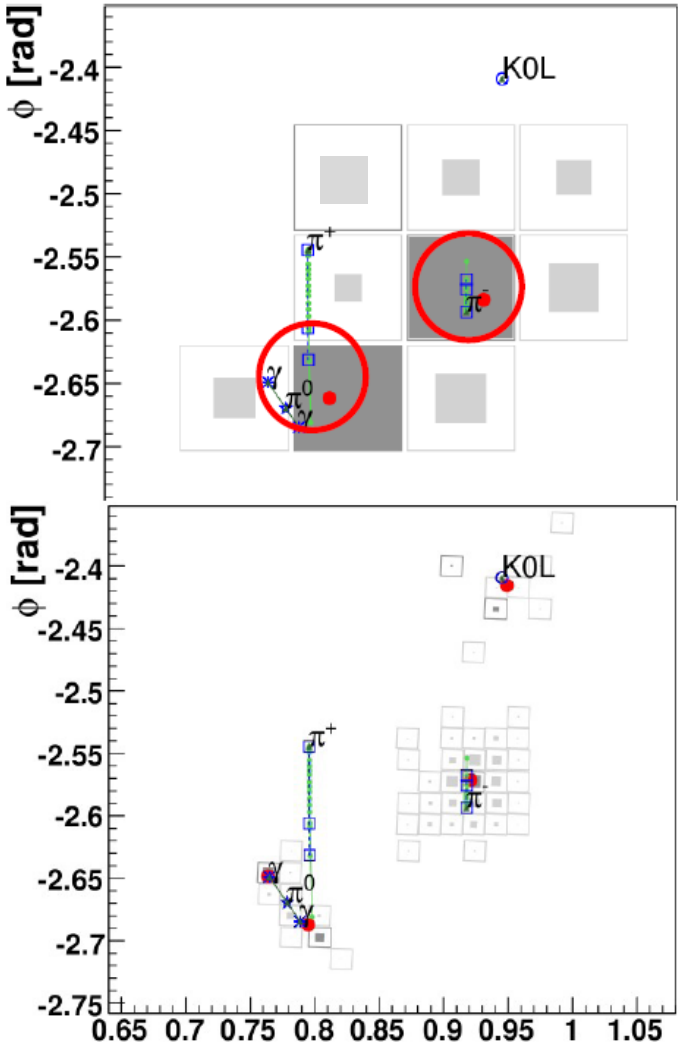
Block simplification





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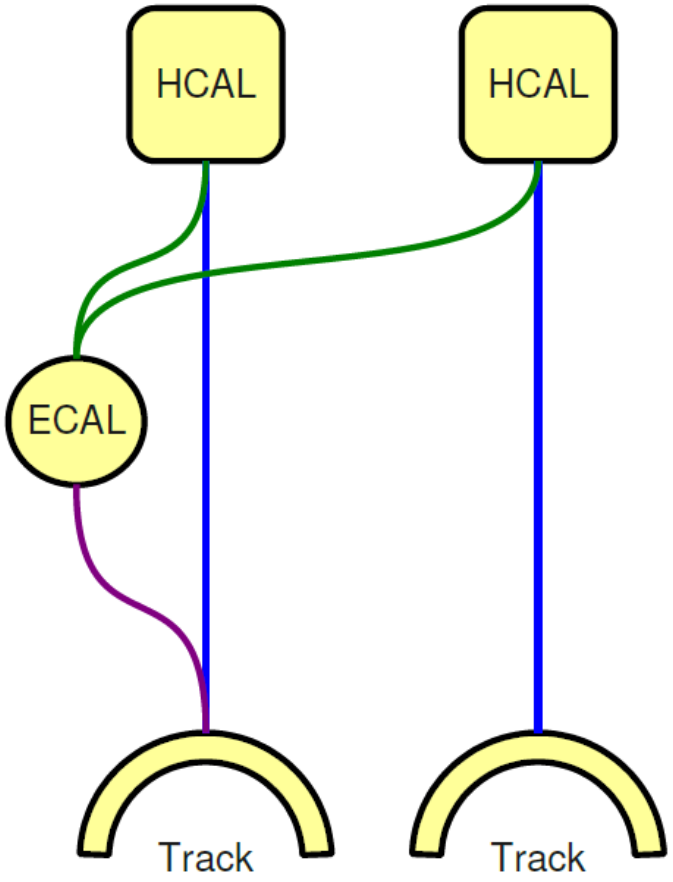

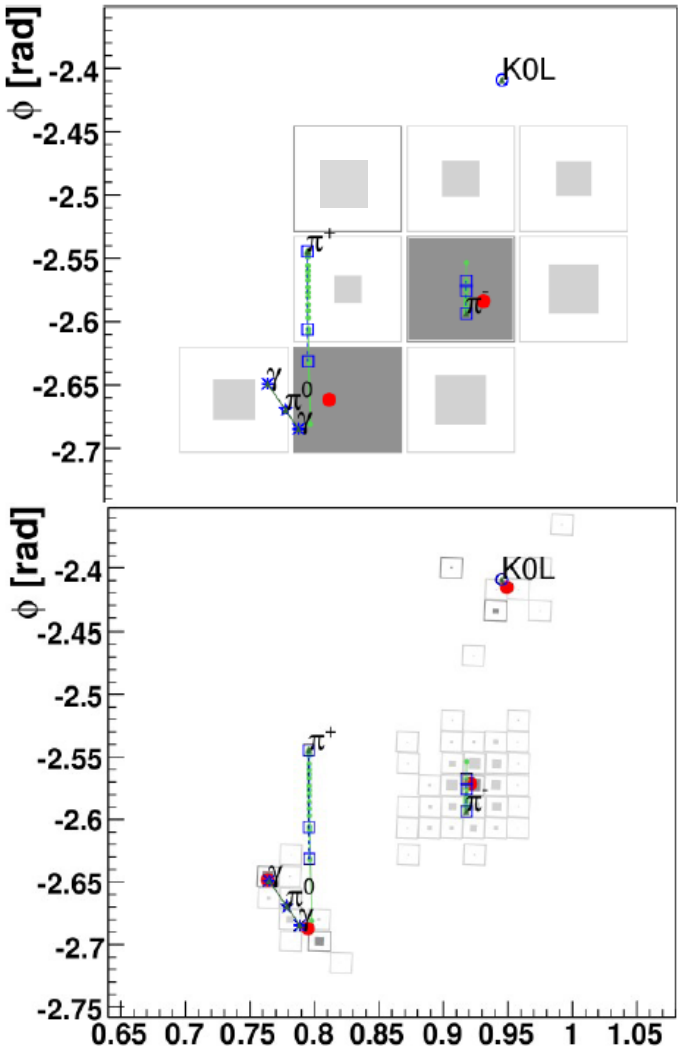

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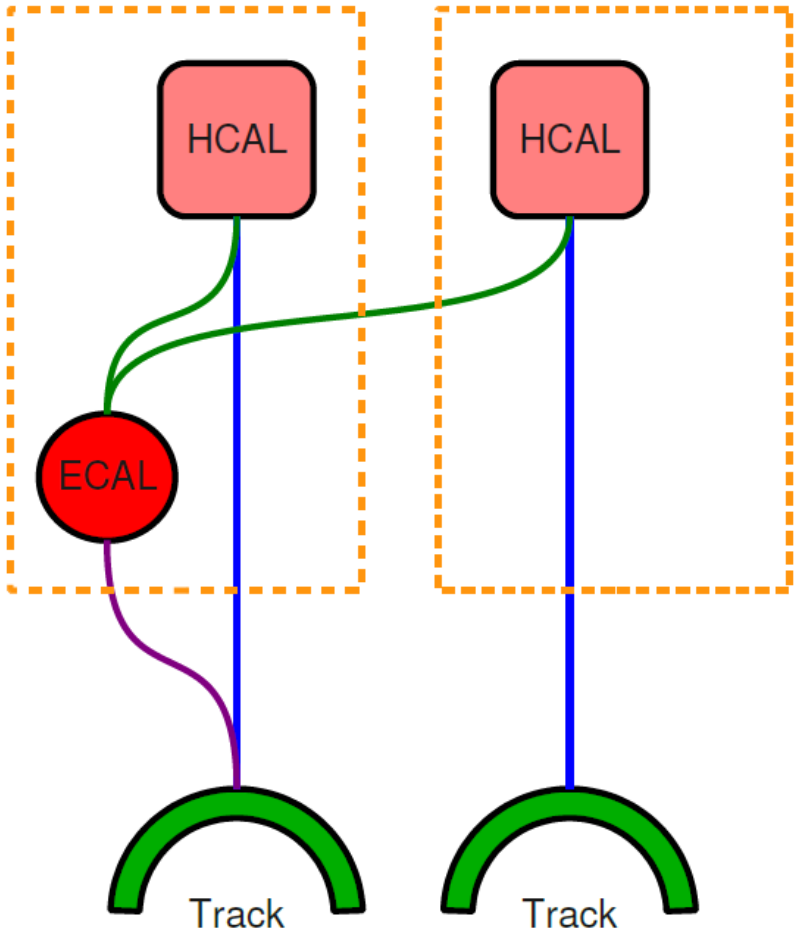
Charged hadrons, overlapping neutrals



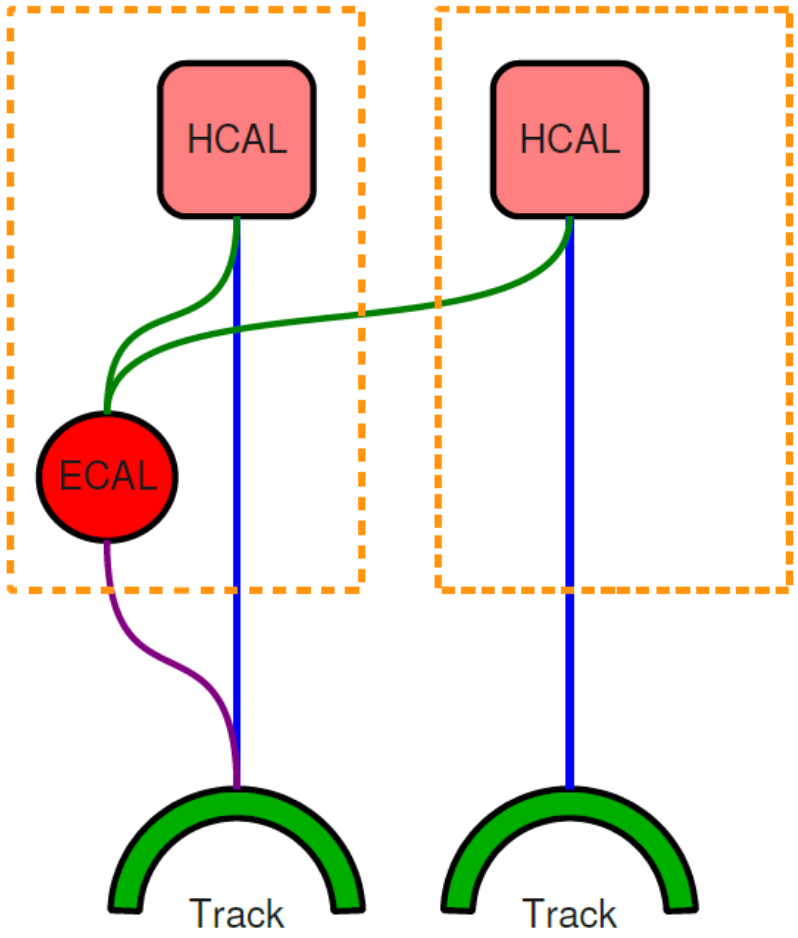
- For each HCAL cluster, compare:
  - Sum of track momenta p
  - Calorimeter energy E
    - Linked to the tracks
    - Calibrated for hadrons

$$E = a + bE_{ECAL} + cE_{HCAL}$$

- E and p compatible
  - Charged hadrons
- E > p + 120% √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 ≈ p

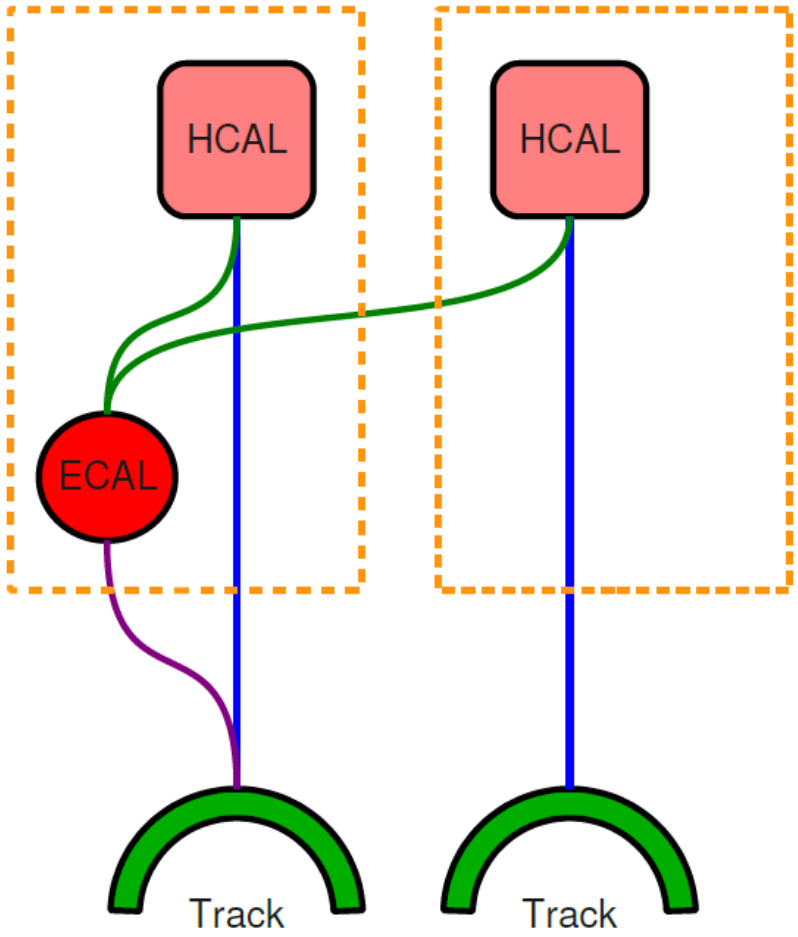


- Charged hadron energy from a fit of p_i and E
  - i = 1, .. , Ntracks
  - Calorimeter and track resolution accounted for
- Makes the best use of the tracker and calorimeters
  - Tracker measurement at low pT
  - Converges to calorimeter measurement at high E

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

$$E = a + bE_{ECAL} + cE_{HCAL}$$

Charged+neutrals: E > p

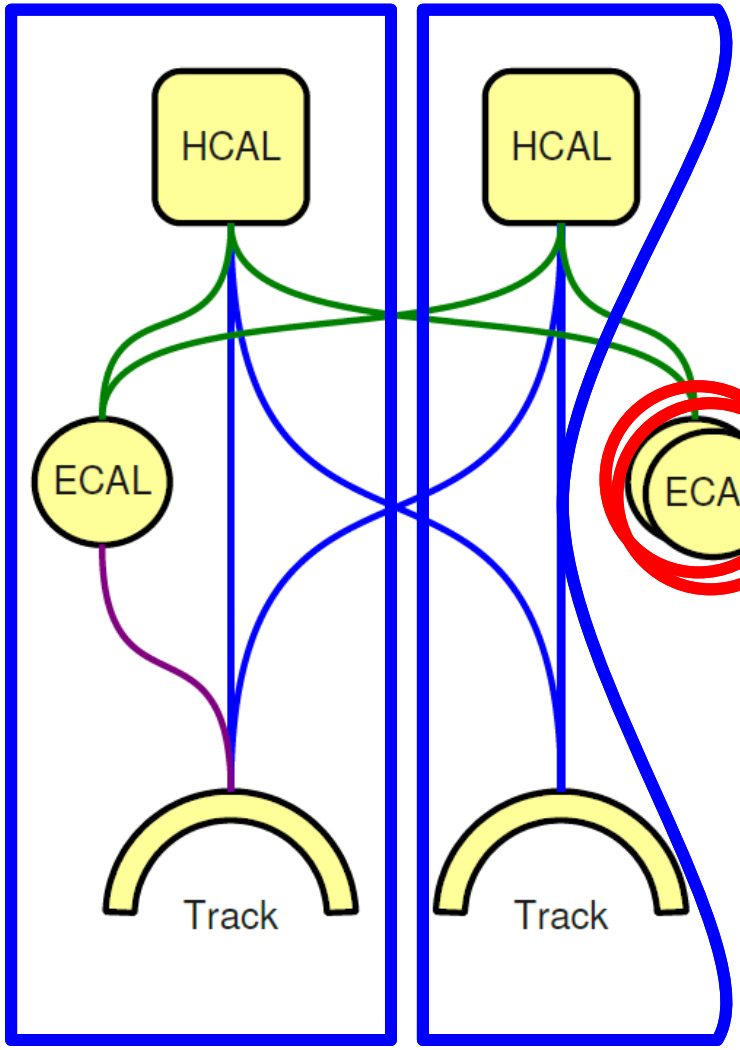


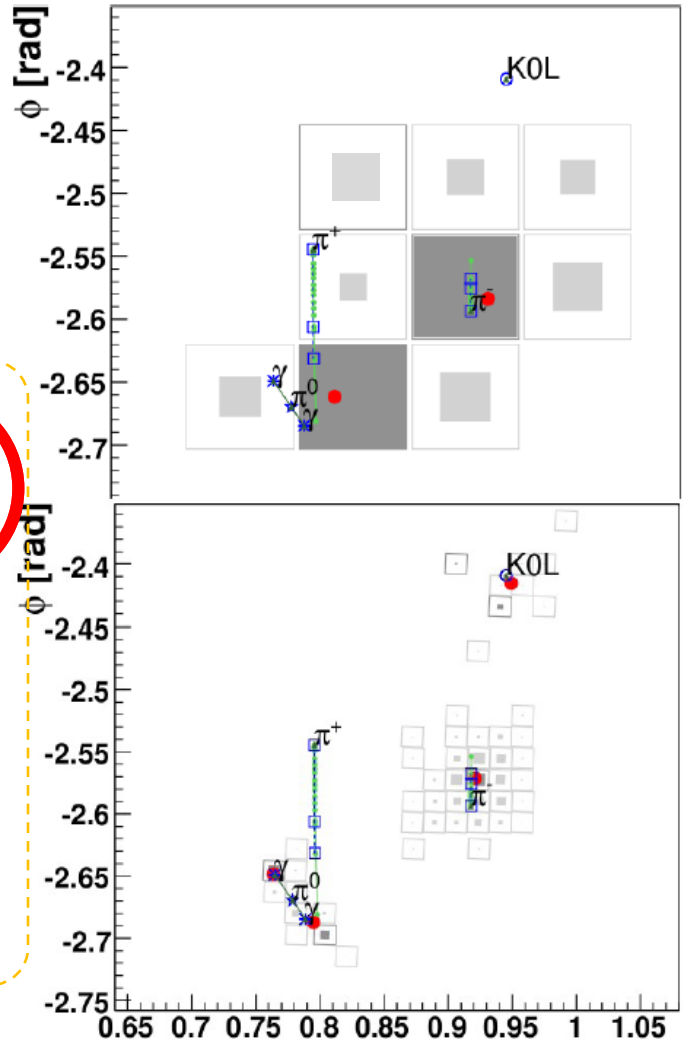
- Significant excess of energy in the calorimeters:
  $E > p + 120\% \sqrt{E}$
- Charged hadrons [p_i]
- Neutrals:
  - E from ECAL or HCAL only:
    - HCAL → h^0 [E – p]
    - ECAL → γ [E_{ECAL} – p/b]
  - E from ECAL and HCAL:
    - E-p > E_{ECAL} ?
      - γ [E_{ECAL}]
      - h^0 with the rest
  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

Always give precedence to photons

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

2 charged hadrons, 3 photons



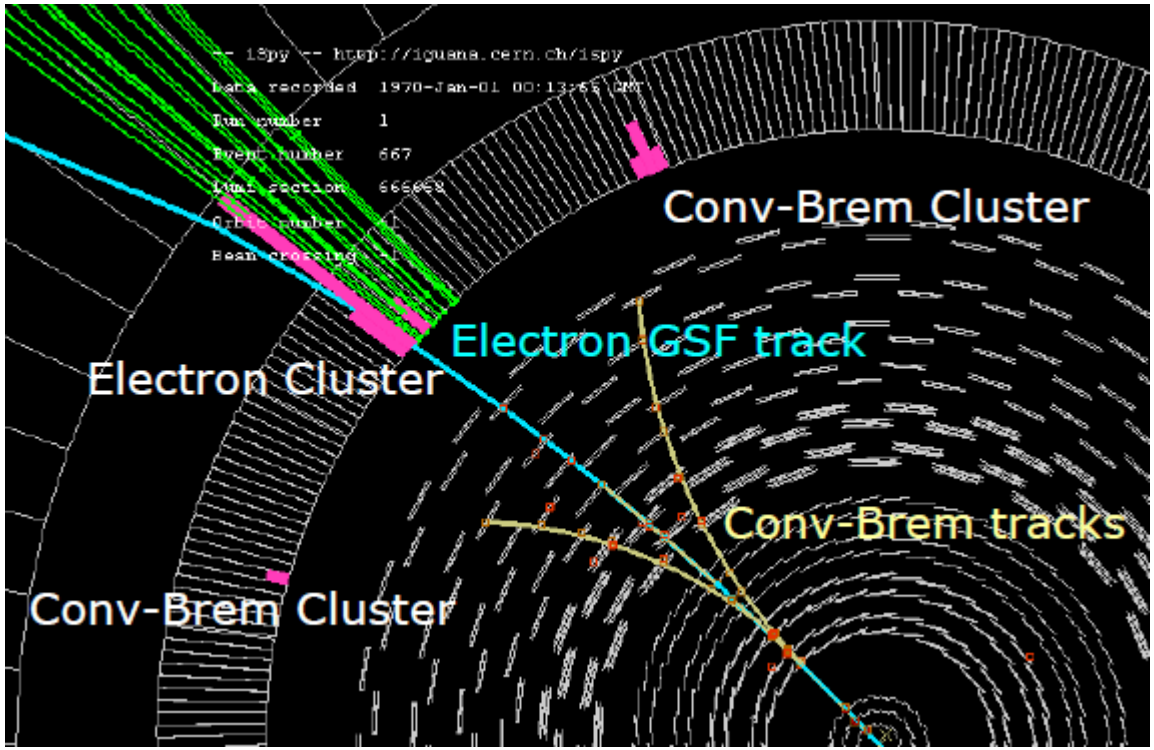


http://cdsweb.cern.ch/record/1194487?ln=en

Electrons

2. Tangents to the track are used to collect brem photons

3. Brems convert. Secondary electrons reconstructed and collected



4. ECAL "super-cluster" also used to collect energy in case of an isolated electron

1. Reconstruction of non-isolated electrons starts from the tracker

http://cdsweb.cern.ch/record/1279347?ln=en

Muons (1/2)

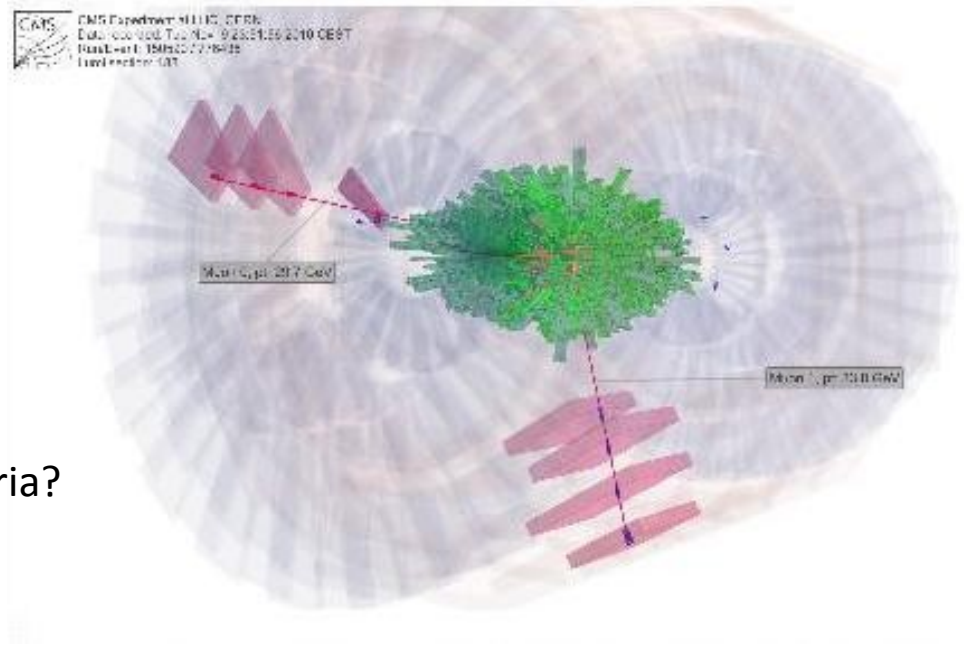
- In a jet:
  - Need high efficiency:
    Lost muon
    → linked calorimeter energy double-counted
  - Need low fake rate
    Fake muon
    → linked calorimeter energy lost
- high efficiency &
  low fake rate to avoid tails

- 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 muon and neutrals linked to the muon.

http://cdsweb.cern.ch/record/1279347?ln=en

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 << p ?
      - Loose muon ID criteria?
        - » Yes → take it
      - Else not a muon
- W analysis:
  - 5% higher efficiency at same fake rate.



Z→μμ (PbPb)

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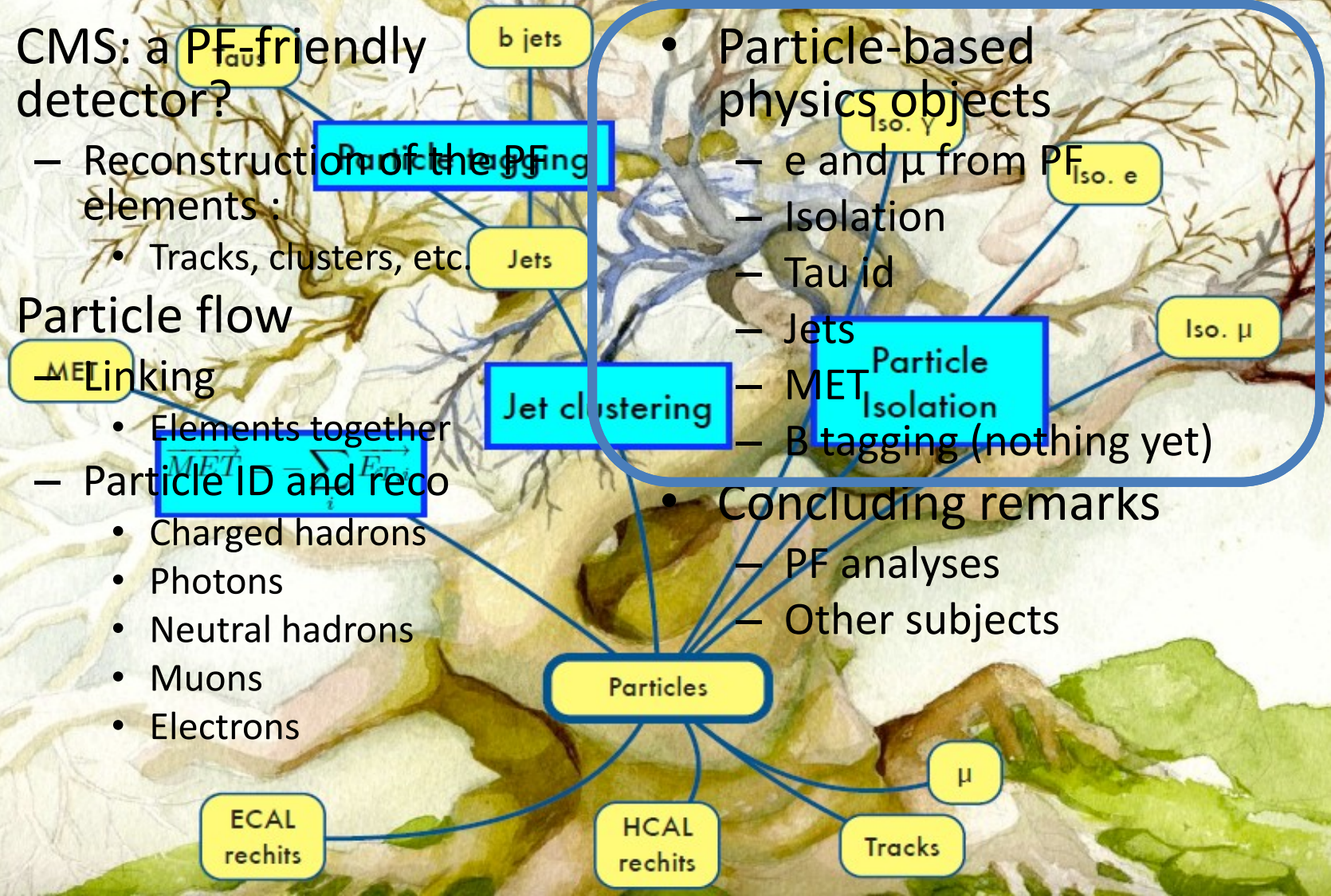
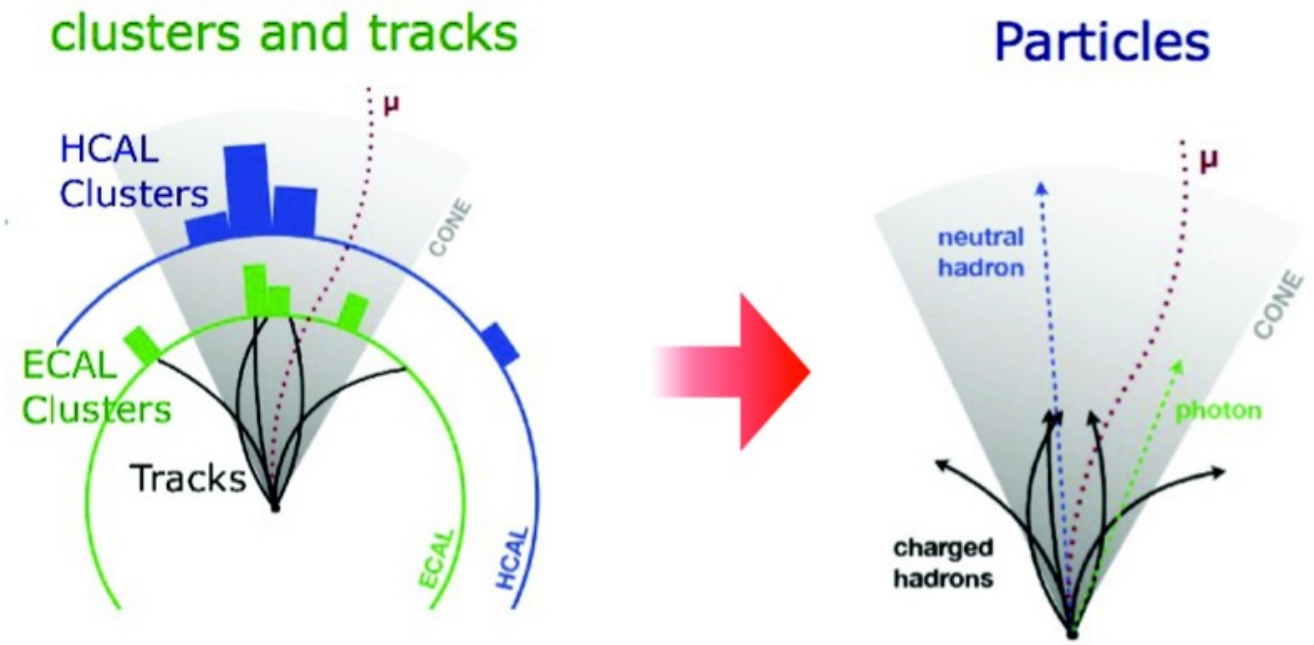


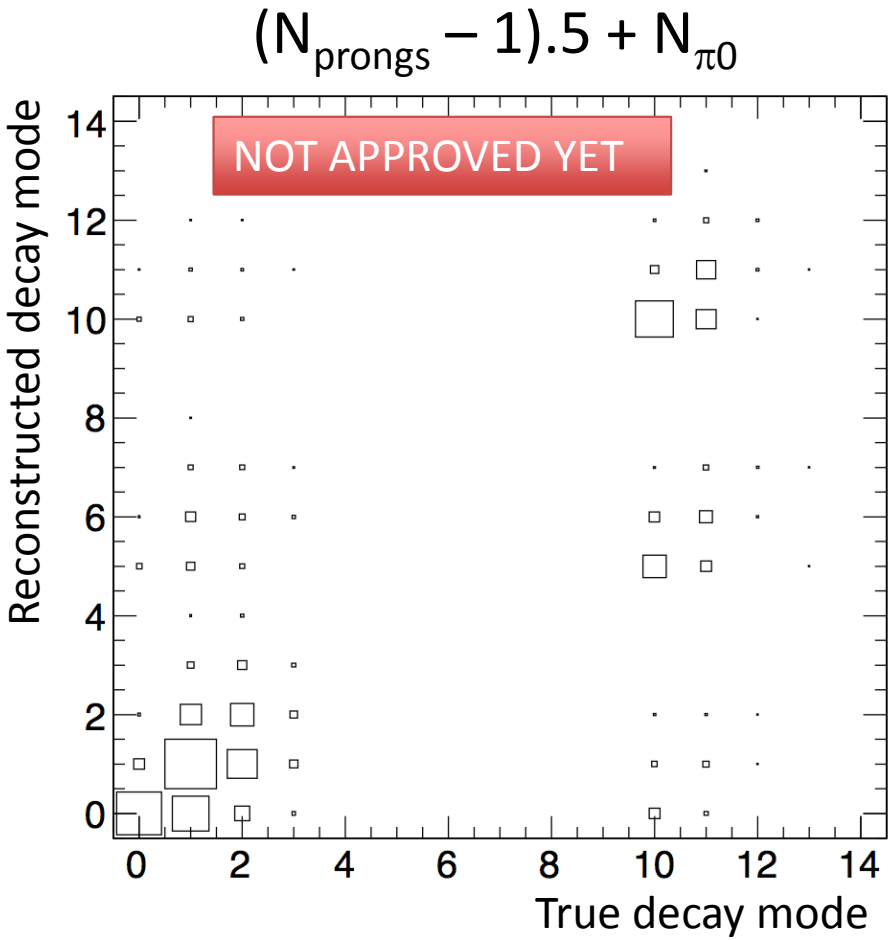
Particle-based isolation

- Used for e, μ, τ
- No double-counting of particle energy deposits in different sub-detectors

- Direct correspondence with GEN-level isolation
- Few % gain in efficiency at same background rate

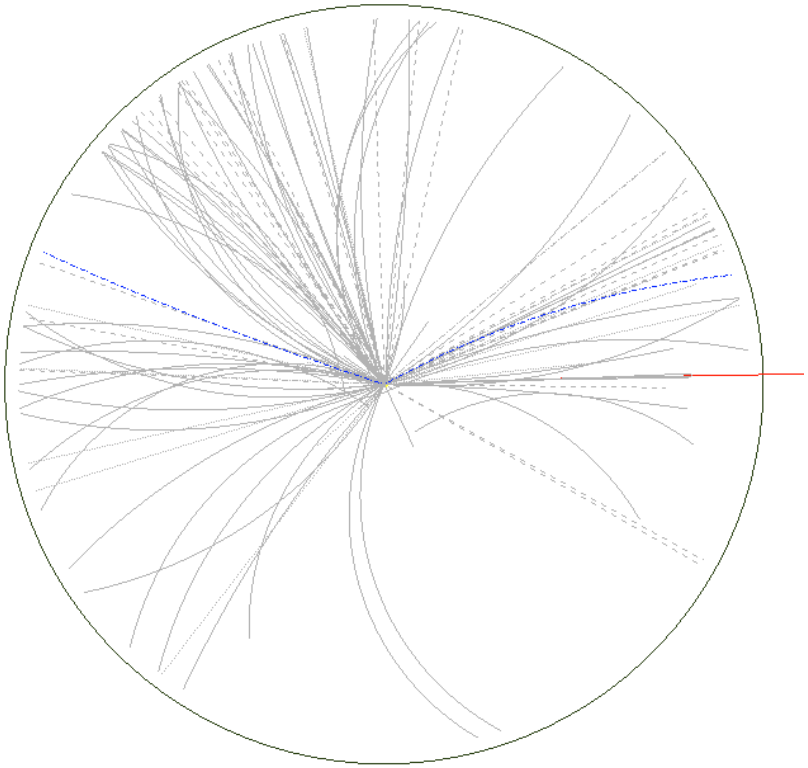


Tau identification



- Using:
  - Particle-based isolation
  - Tau constituents, which are resolved
- 5 times better energy resolution
- 3 times lower fake rate at same efficiency

Reconstructed Particles



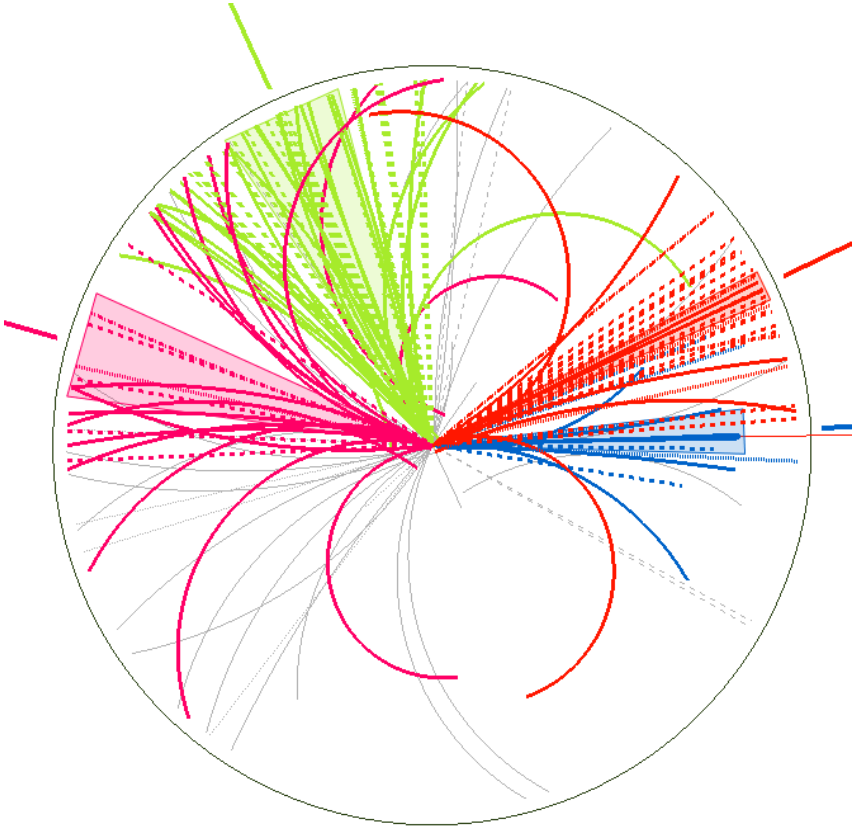
An event recorded in 2010

NOT APPROVED YET

- Solid: charged hadrons
- Dashed: photons
- Dotted: neutral hadrons
- Blue: electrons

- Coming next:
  - Jets
  - MET

Particle Jets

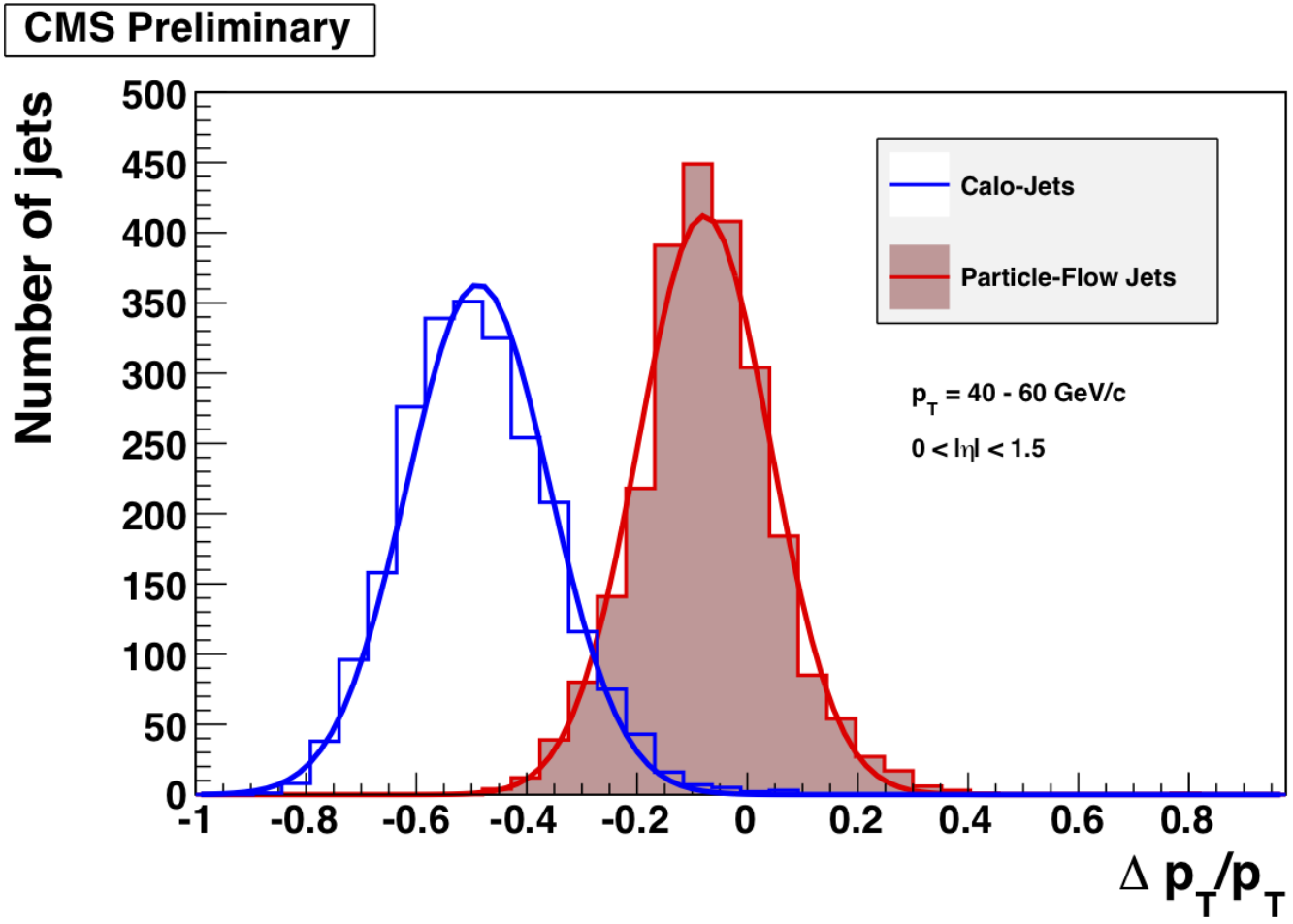


An event recorded in 2010

NOT APPROVED YET

- Showing jets with pT > 50 GeV/c

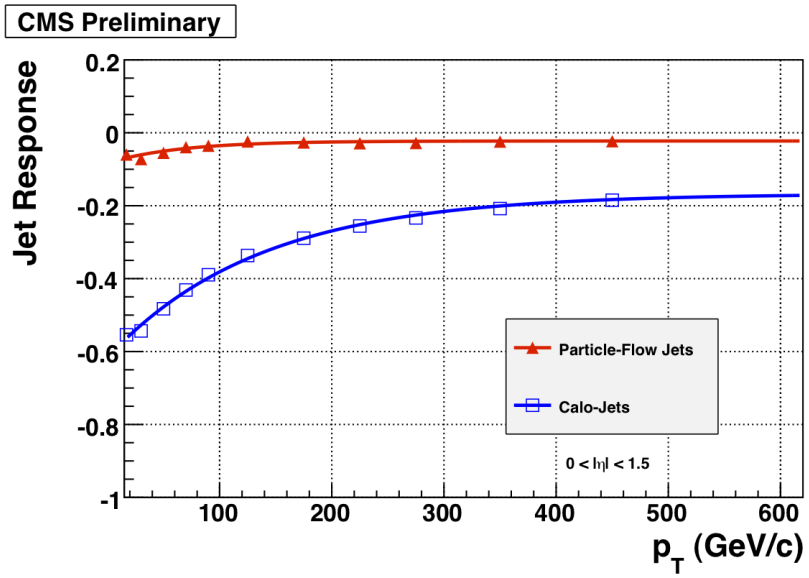
Jet pT Response and Resolution



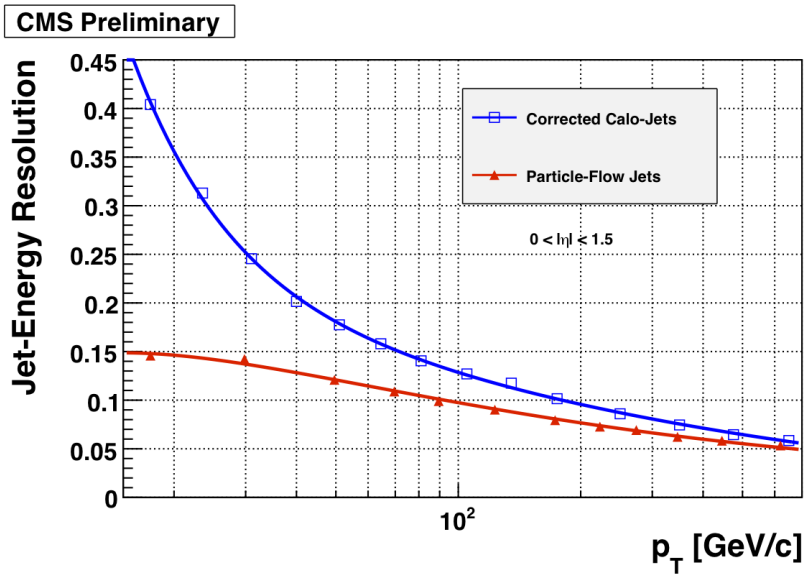
http://cdsweb.cern.ch/record/1194487?ln=en

Jet pT Response and Resolution

Response



Resolution for *corrected* jets



Energy correction: $f(\eta, p_T)$ → brings response to 1

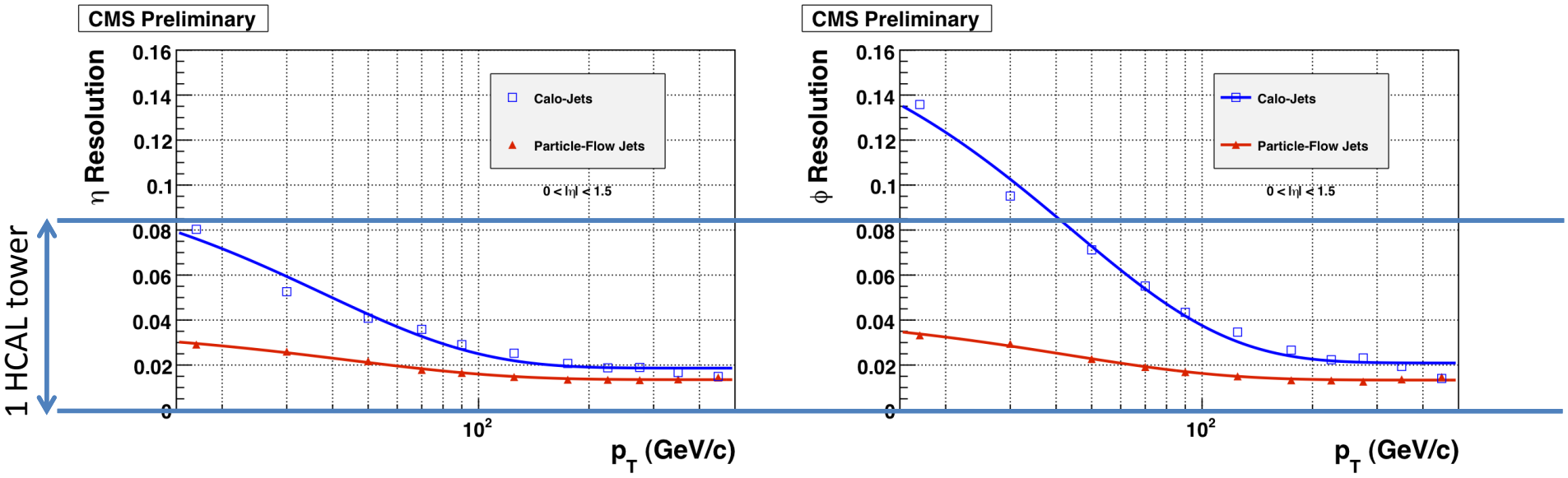
Adding a dependence on jet contents does not bring anything

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

Jet η and ϕ Resolution

η

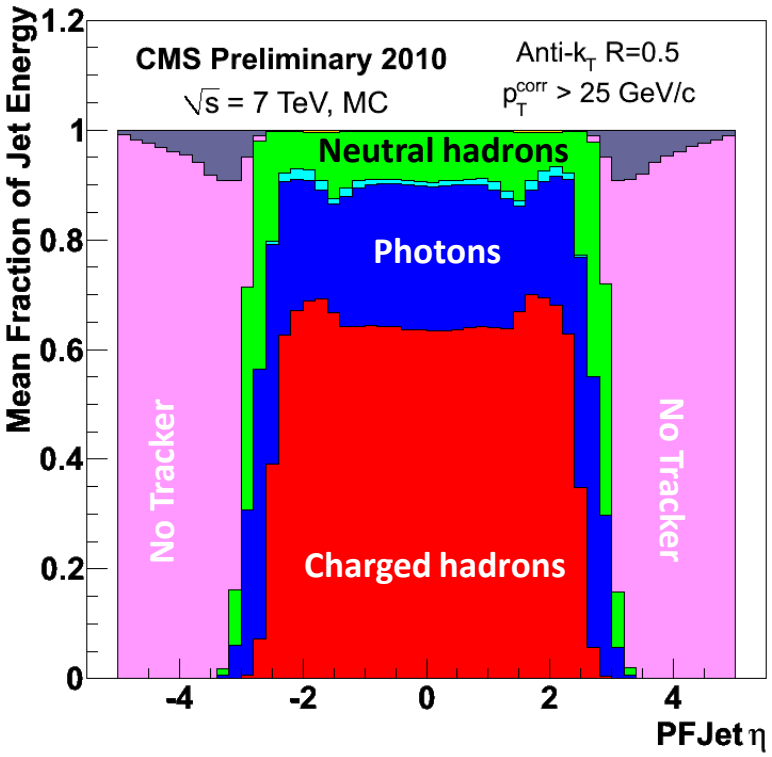
ϕ



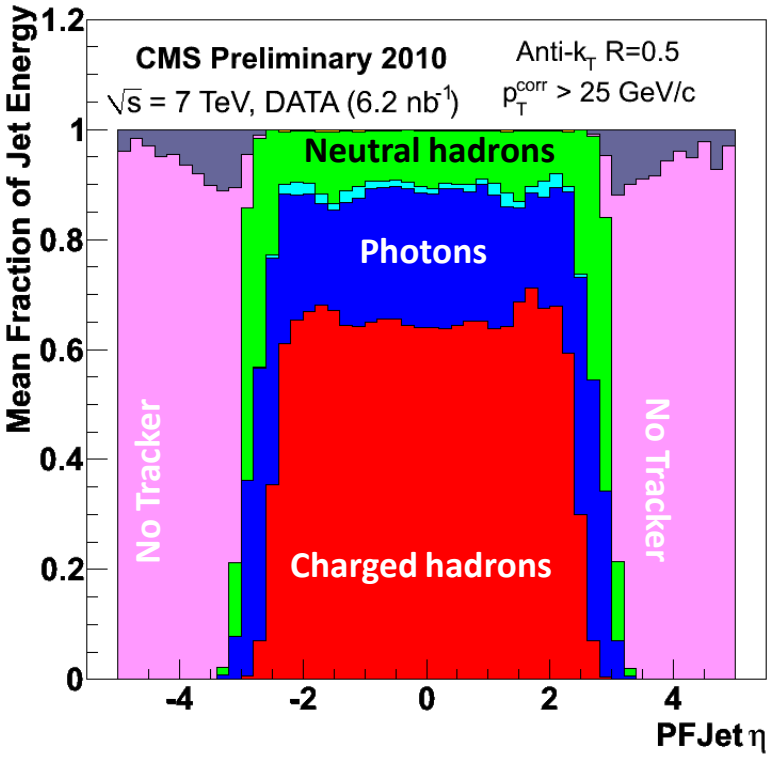
http://cdsweb.cern.ch/record/1194487?ln=en

Jet Composition

Simulation

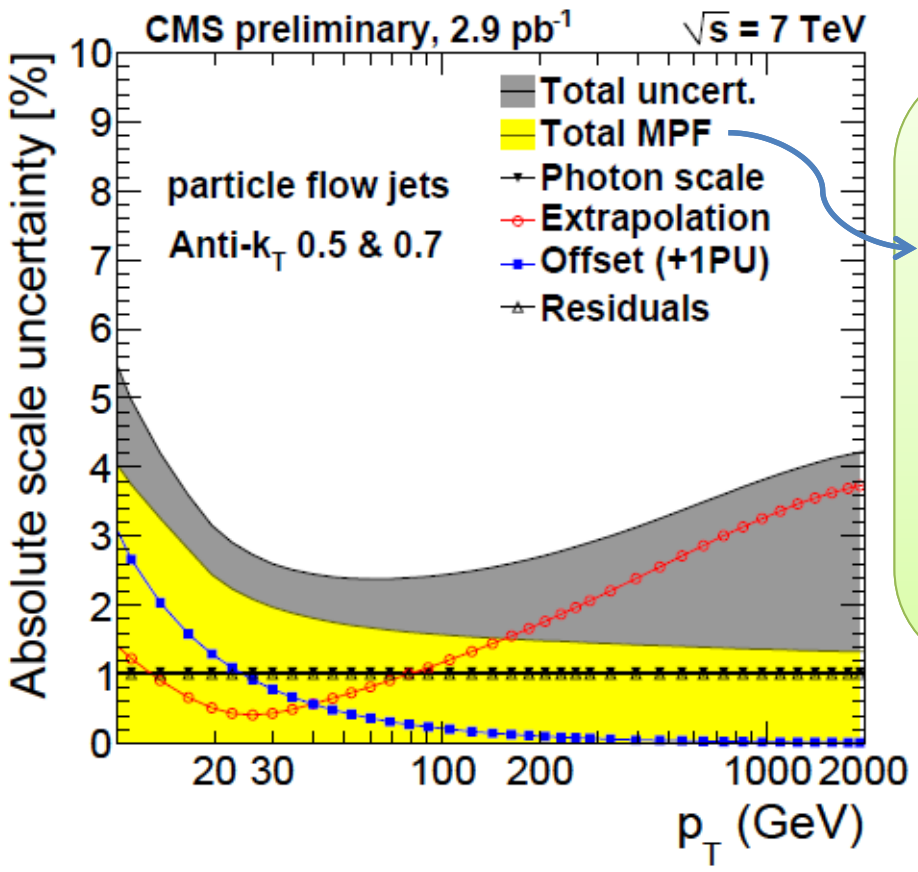


Data



http://cdsweb.cern.ch/record/1279341?ln=en

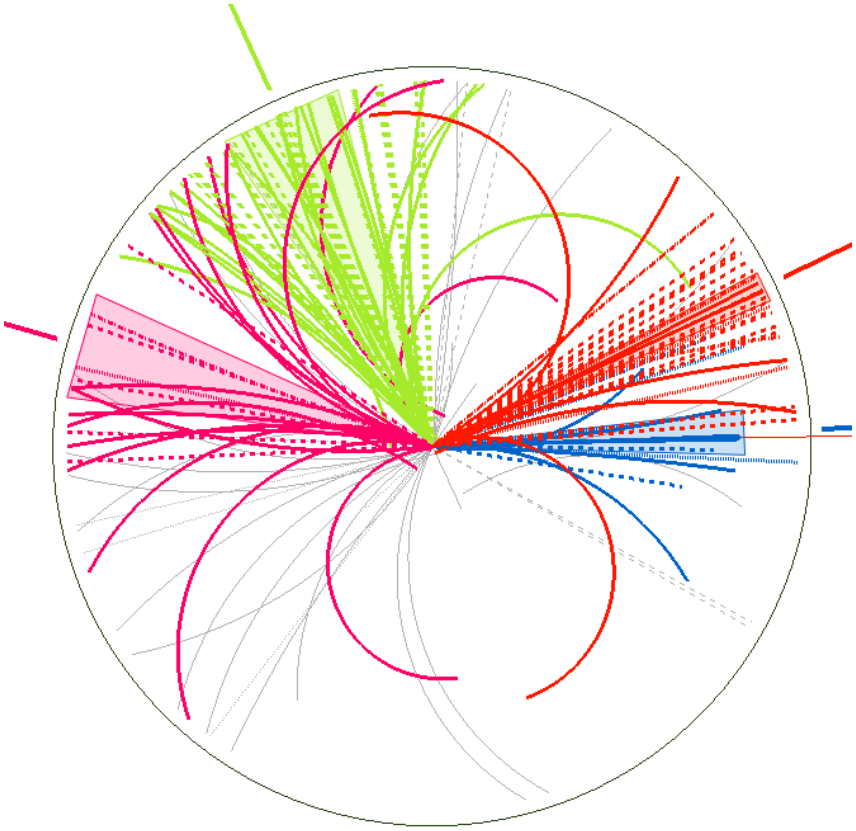
Jet Energy Scale Uncertainty



- γ+jet events
- Total MPF Includes:
  - Flavour uncertainty
  - Parton correction
  - Proton fragments
  - …
- Would be 10% for calorimetric jets
- Done with 3 pb-1
  - Current stat error ~ 2%

http://cdsweb.cern.ch/record/1308178?ln=en

Missing Transverse Momentum



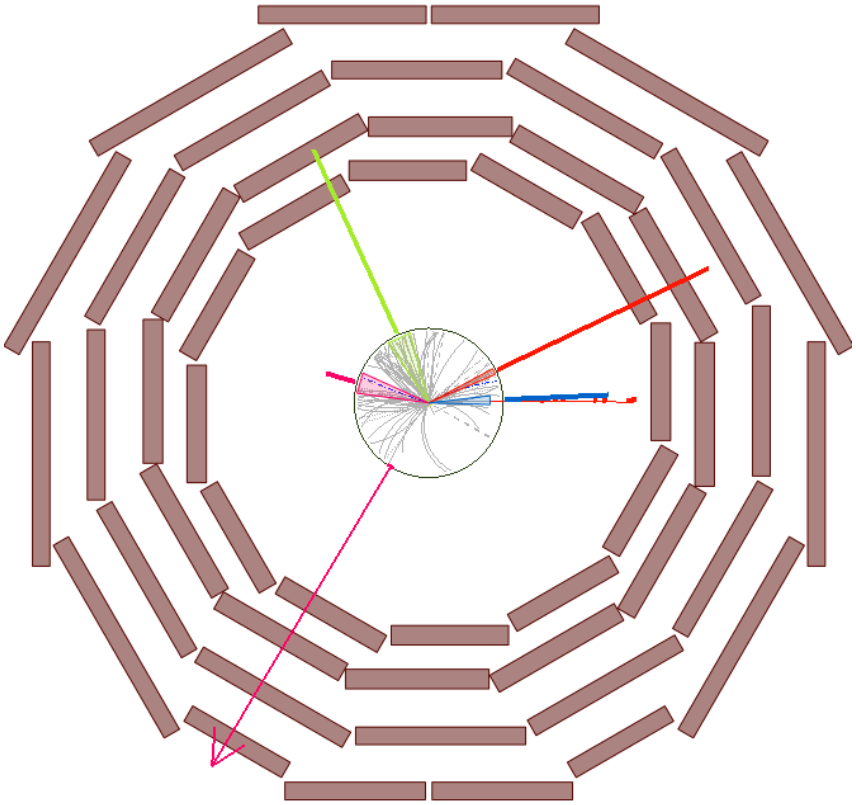
$$\vec{E}_T^{\text{miss}} = -\sum_{\text{All particles}} \vec{p}_T$$

- Simple, compared to calorimeter MET:

$$\vec{E}_T^{miss} = -\sum_{i=1}^{N_{\text{Towers}}} \vec{E}_{\text{T}}^{\,i} - \sum_{i=1}^{N_{\text{muons}}} \vec{E}_{\text{T}}^{\,i} - \sum_{i=1}^{N_{\text{Jets}}} \left(\vec{E}_{\text{T,corr}}^{\,i} - \vec{E}_{\text{T,raw}}^{\,i} \right) - \alpha \sum_{i=1}^{N_{\text{Unclustered towers}}} \vec{E}_{\text{T}}^{\,i}$$

An event recorded in 2010 NOT APPROVED YET

Missing Transverse Momentum



MET

$$\vec{E}_T^{\text{miss}} = -\sum_{\text{All particles}} \vec{p}_T$$

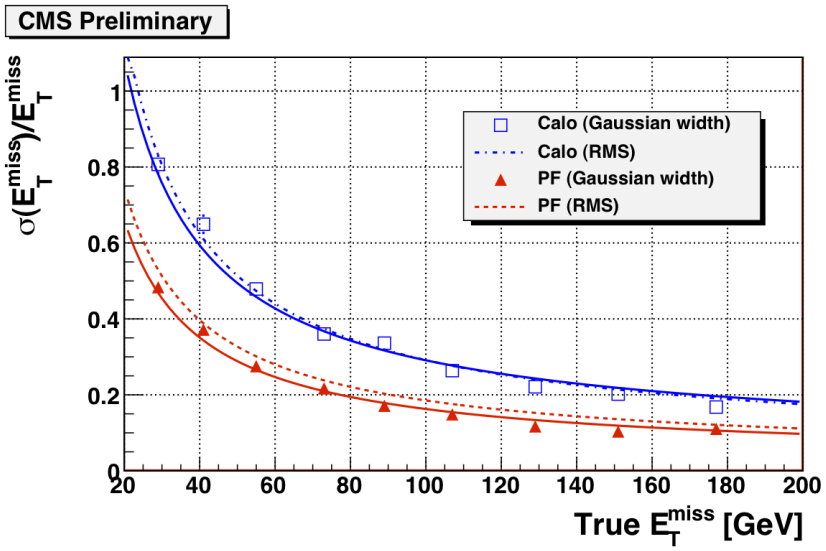
- Simple, compared to calorimeter MET:

$$\vec{E}_T^{miss} = -\sum_{i=1}^{N_{\text{Towers}}} \vec{E}_{\text{T}}^{\,i} - \sum_{i=1}^{N_{\text{muons}}} \vec{E}_{\text{T}}^{\,i} - \sum_{i=1}^{N_{\text{Jets}}} \left(\vec{E}_{\text{T,corr}}^{\,i} - \vec{E}_{\text{T,raw}}^{\,i} \right) - \alpha \sum_{i=1}^{N_{\text{Unclustered towers}}} \vec{E}_{\text{T}}^{\,i}$$

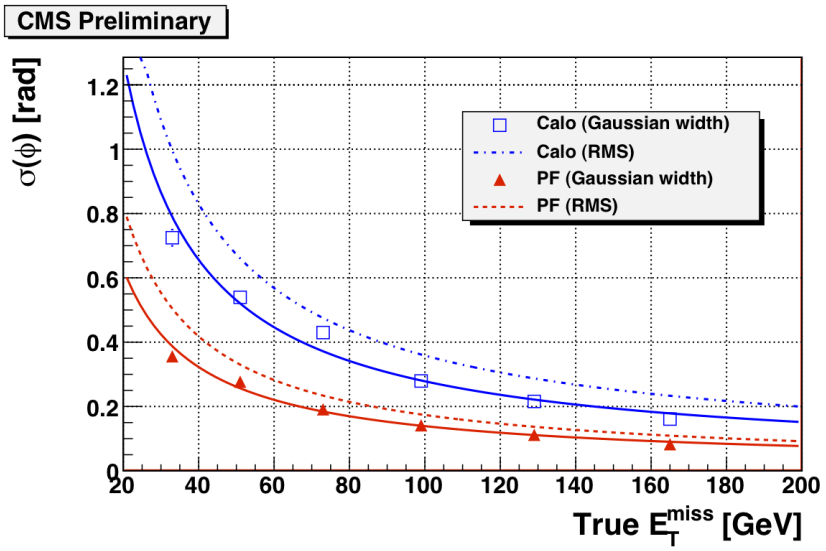
An event recorded in 2010 NOT APPROVED YET

MET resolution (ttbar, simulation)

MET resolution

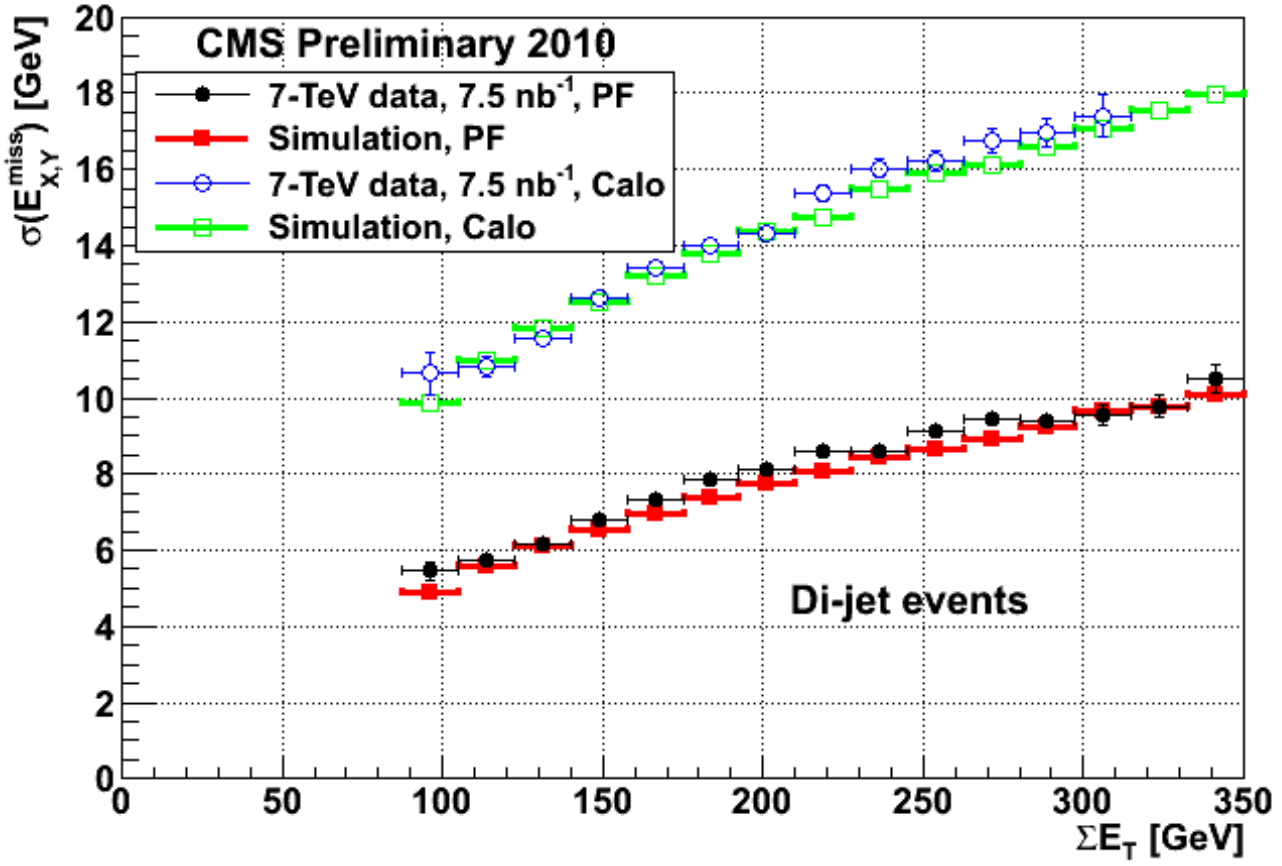


MET phi resolution



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

MET resolution (di-jets, data)



$$\frac{55\%}{\sqrt{\Sigma E_T}}$$

http://cdsweb.cern.ch/record/1279341?ln=en

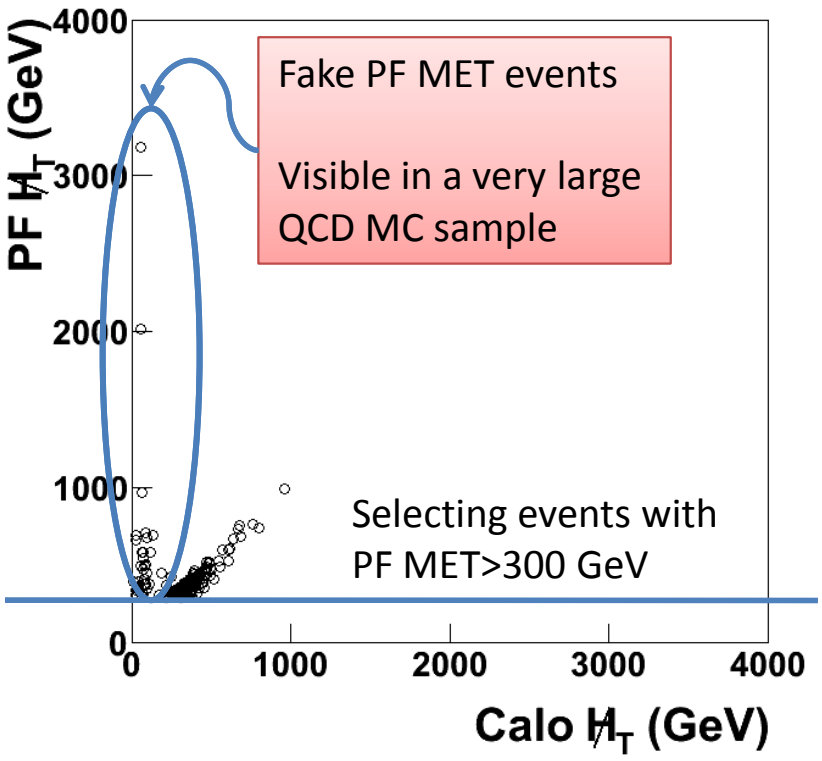
Fake MET

- SUSY searches with Jets + MET :
  - MET resolution in QCD events important
  - Fake MET crucial!

    Rare but large MET mismeasurements

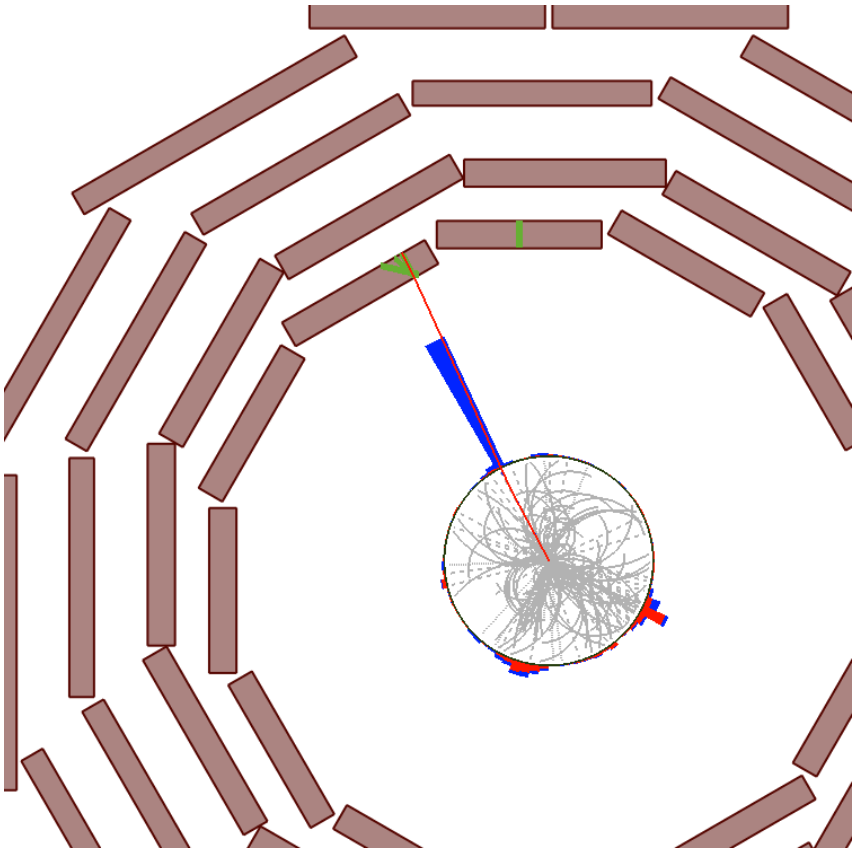
    + large QCD cross-section

    = Sizeable contribution from QCD in signal region



NOT APPROVED YET

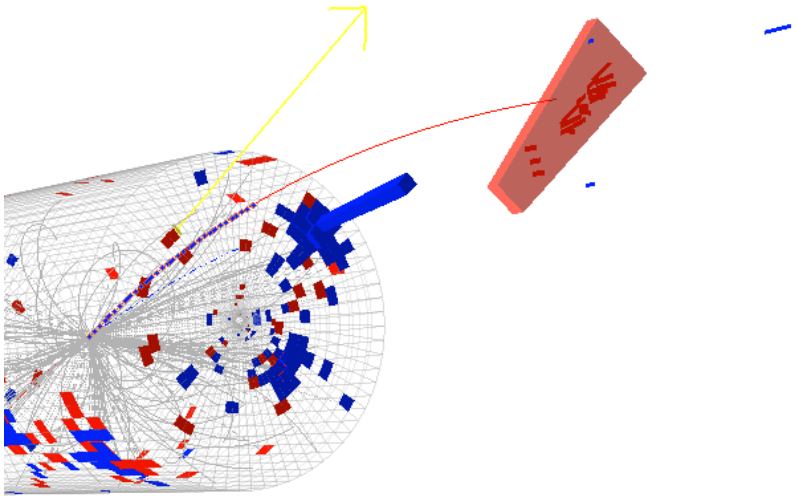
Fake MET



- Fake, high pT muons from jet punch-through
  - Up to 12 TeV/c
- Can easily be identified
- Removed from analysis, PF algo corrected

NOT APPROVED YET

Fake MET



Muon with p_T = 1.6 GeV/c
steals 1.3 TeV of HCAL energy…

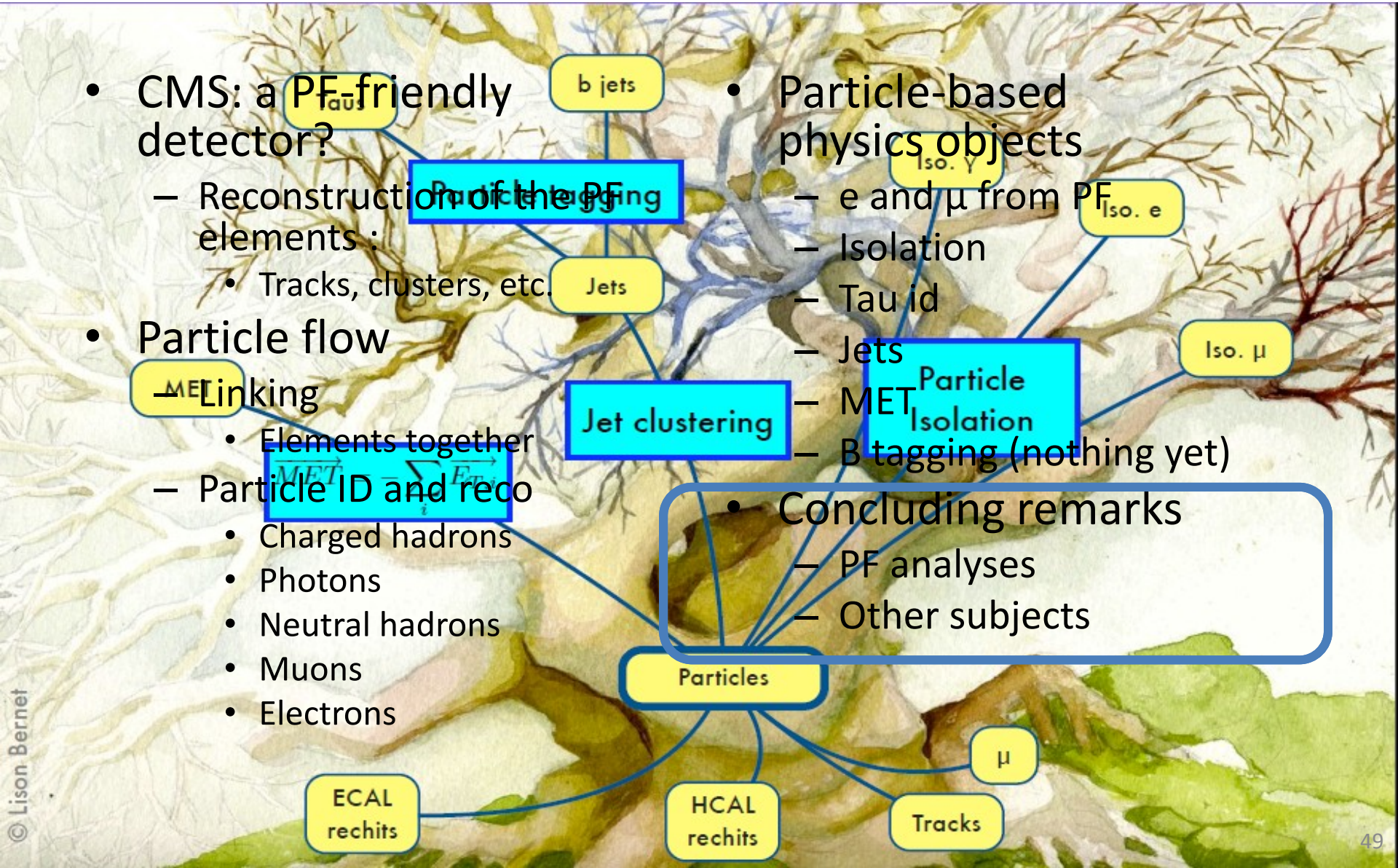
- Fake low p_T muons from jet punch-through, Isolated
- Isolated muons allowed to collect an arbitrary large amount of energy E from the calorimeter
  - Account for possible brems
- PF algo corrected: Limit $E \leq p_T$

- After corrections, N (PF tail) expected in 35 pb-1: 0.002

NOT APPROVED YET

Outline

- CMS: a PF-friendly detector?
  - Reconstruction of the PF elements :
    - Tracks, clusters, etc.
- Particle flow
  - Linking
    - Elements together
  - Particle ID and reco
    - Charged hadrons
    - Photons
    - Neutral hadrons
    - Muons
    - Electrons
- Particle-based physics objects
  - e and μ from PF
  - Isolation
  - Tau id
  - Jets
  - MET
  - B tagging (nothing yet)
- Concluding remarks
  - PF analyses
  - Other subjects



Concluding remarks

- Particle flow now used for almost all physics objects in CMS
  - Jets, MET, tau ID, leptons, isolation
- Nothing yet for:
  - b tagging, photons
- Other interesting subjects:
  - PF at HLT
  - PF analysis tools:
    - GEN → PF conversion
    - Reco at analysis level
  - Pile-up, noise, …

- Full PF analyses:
  - Long range particle correlations ("ridge")
  - **Z / H → ττ**
  - **W / Z + jets**
  - **Top cross-section measurements**
  - **Fully hadronic SUSY search**
  - **Search for di-jet resonances**
  - Jet quenching in heavy-ion collisions

More info in Patrick's lecture @ EDIT:

http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=96989