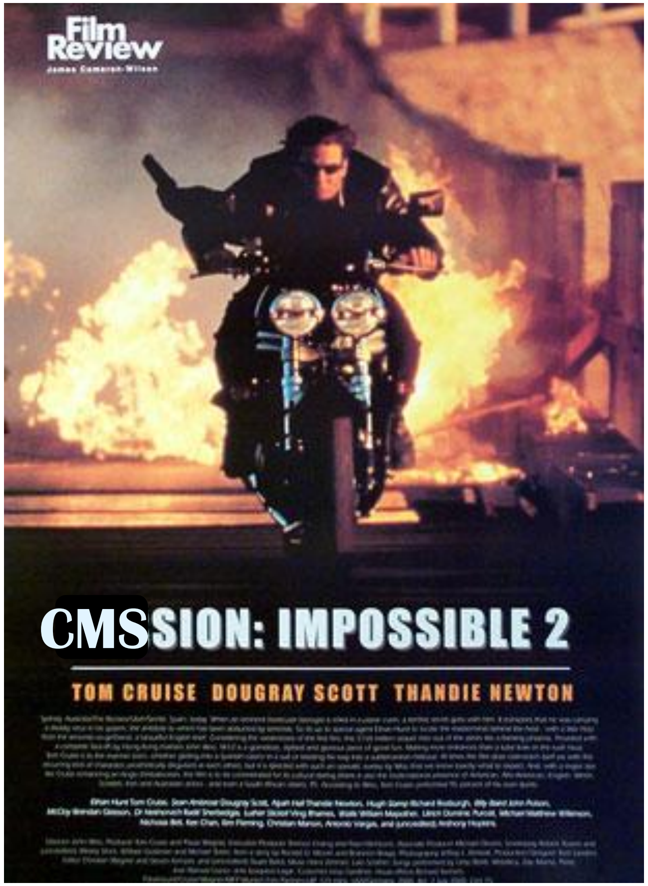
Particle-Flow Event Reconstruction from LEP to LHC

- Outline
  - Introduction : Basics of Particle-Flow Event Reconstruction
  - First Lecture : Second Lecture :

Intermezzo :

Lessons Learned ?

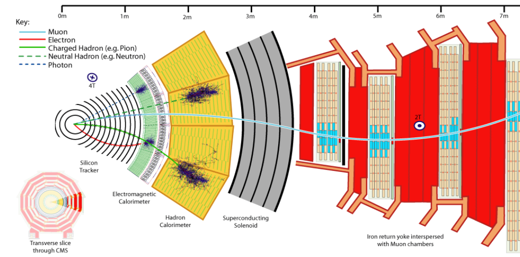
Exercises…



Basics of Particle-Flow Event Reconstruction (I)

- What is Particle-Flow Event Reconstruction ?
  - A better name could actually be

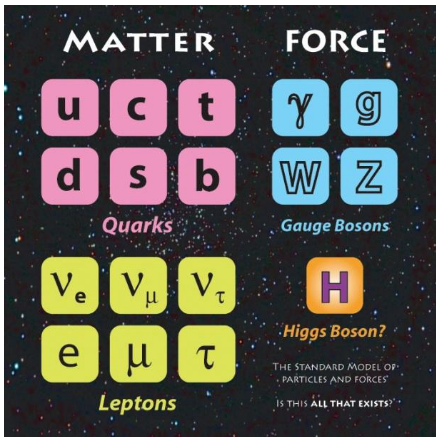
    "PARTICLE FOLLOW RECONSTRUCTION"



  - Made easier by a smart detector design, carefully thought ahead of time
    - To be able to follow individually each particle arising from a collision
      - → In their journey through the various sub-detectors
    - To be able to identify each particle
      - → With their characteristic interaction in the various sub-detectors
    - To be able to measure the origin, direction, energy, charge of each particle
      - → With an optimal combination of the measurements of all sub-detectors
      - → With a decent accuracy (See later for the definition of "decent")
    - Towards a global event description with a complete list of particles
      - → As if it came directly from a Monte Carlo event generator

Basics of Particle-Flow Event Reconstruction (2)

- What particles are to be followed ?
  - Ideally : build a detector to follow all the standard model (SM) particles
    - By definition, any exotic particle decays to SM particles (+ dark matter)

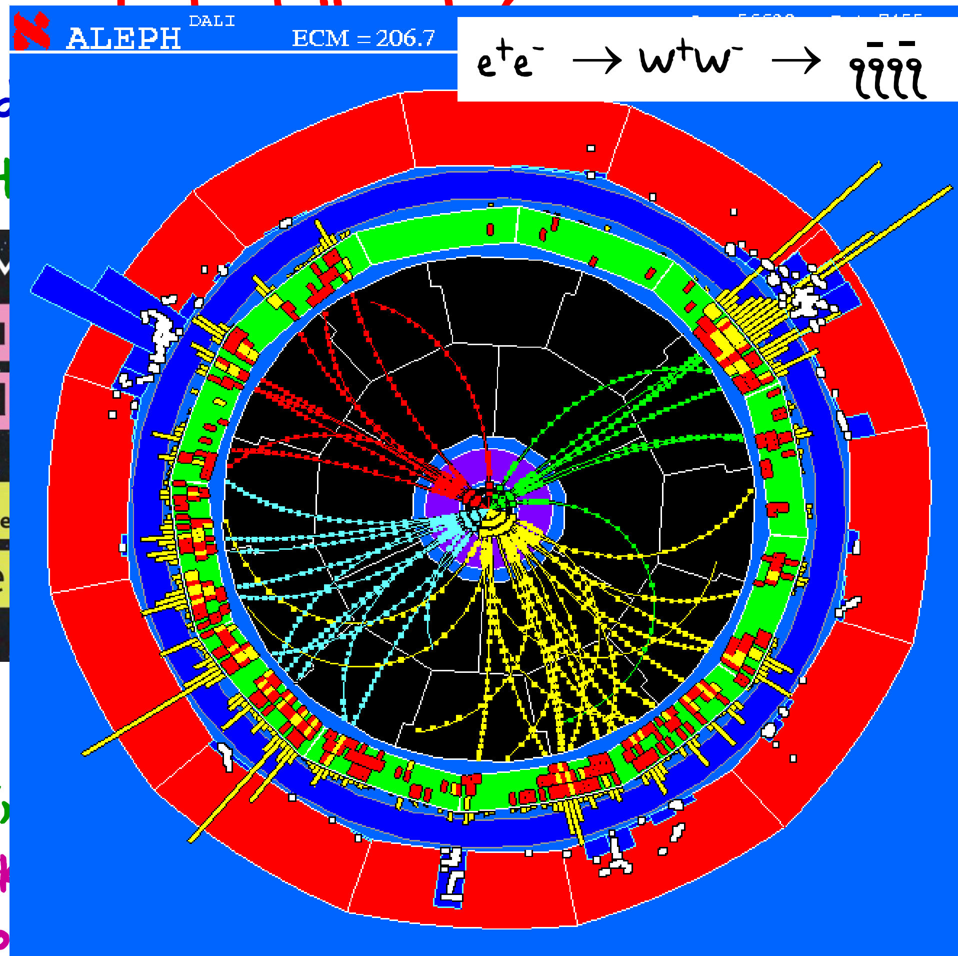


+

  - Not quite …
    - Only e, γ, ν stable, and $\mu \to e\nu_e\nu_\mu$ but $\beta\gamma c\tau \sim 6$ Km/GeV, quasi stable
      - → Quarks and gluons hadronize to give jets of hadrons, τ, W, Z decay to leptons and quarks, and H decay to pairs of every other particles

Basics of Particle-Flow Event Reconstruction (2)

- What particles …
  - Ideally : build … SM) particles
    - By definit… (+ dark matter)



  - Not quite …
    - Only e, γ, … /GeV, quasi stable
      - → Quark… τ, W, Z decay to lepto… ther particles

Basics of Particle-Flow Event Reconstruction (2)

- What particles

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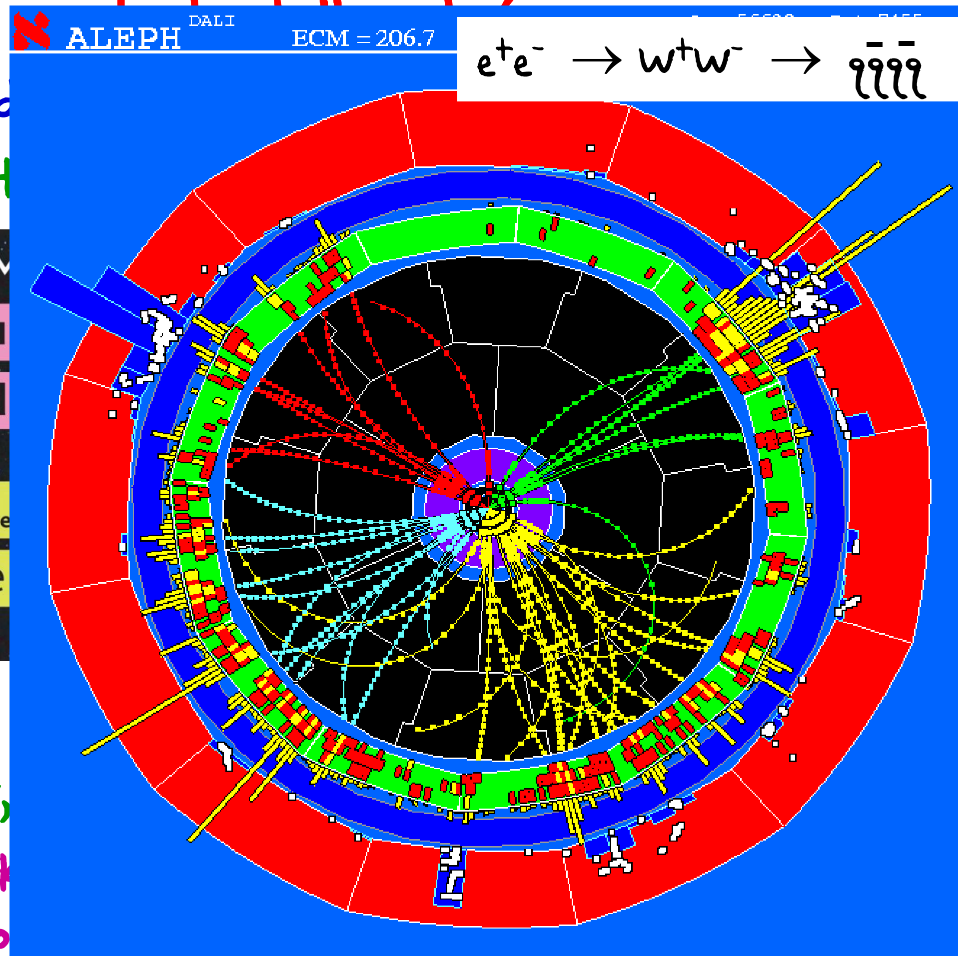


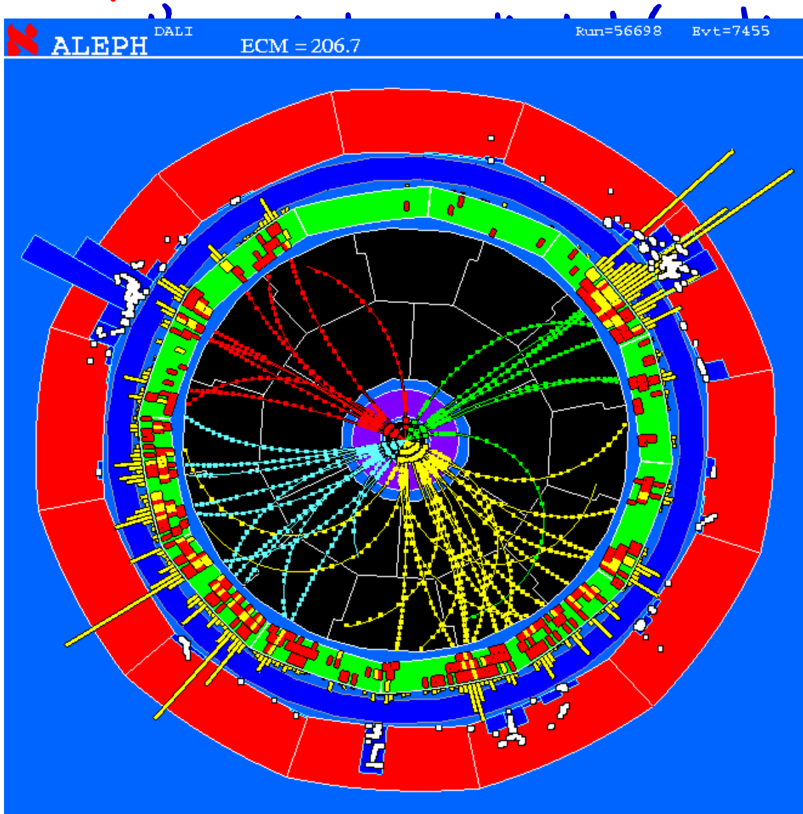
  - Not quite …
    - Only e, γ, ... /GeV, quasi stable
      - → Quark ... τ, W, Z decay to lepto ... ng
  - Therefore : Follow electrons, muons, photons, stable hadrons, neutrinos and 
    - And identify/reconstruct them individually, to go back to SM particles

Basics of Particle-Flow Event Reconstruction (3)

- Why bother with individual particle reconstruction ?
  - It's seemingly complicated (combination, optimization, ...)
    - People usually like simple criteria for identification, reconstruction, ...
  - It requires an excellent knowledge of all sub-detectors of an experiment
    - People usually have the knowledge of the sub-detector they built
  - It requires to think ahead of time of the detector design, and of the interplay between sub-detectors
    - People usually optimize the design of "their" sub-detector, with at best one primary goal in mind
      - → e.g., b tagging for vertex detector, tracks for tracker, isolated photons and isolated electrons for ECAL, jets for HCAL, ...
    - But with multiple technical/practical/financial constraints
      - → which often take the precedence on the primary goal

Basics of Particle-Flow Event Reconstruction (3)

- why bother with individual particle reconstruction ?



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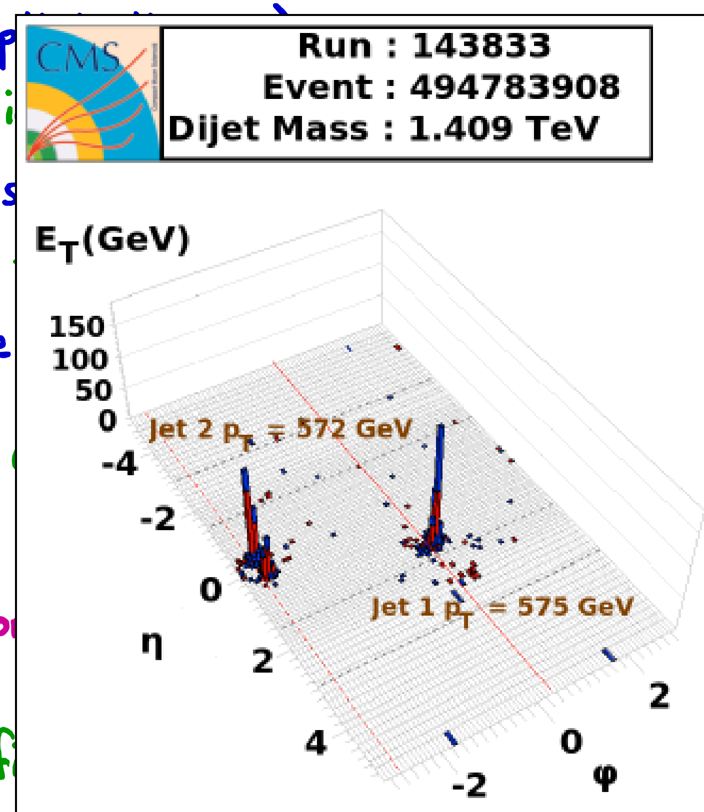


→ which often take the precedence on the primary goal

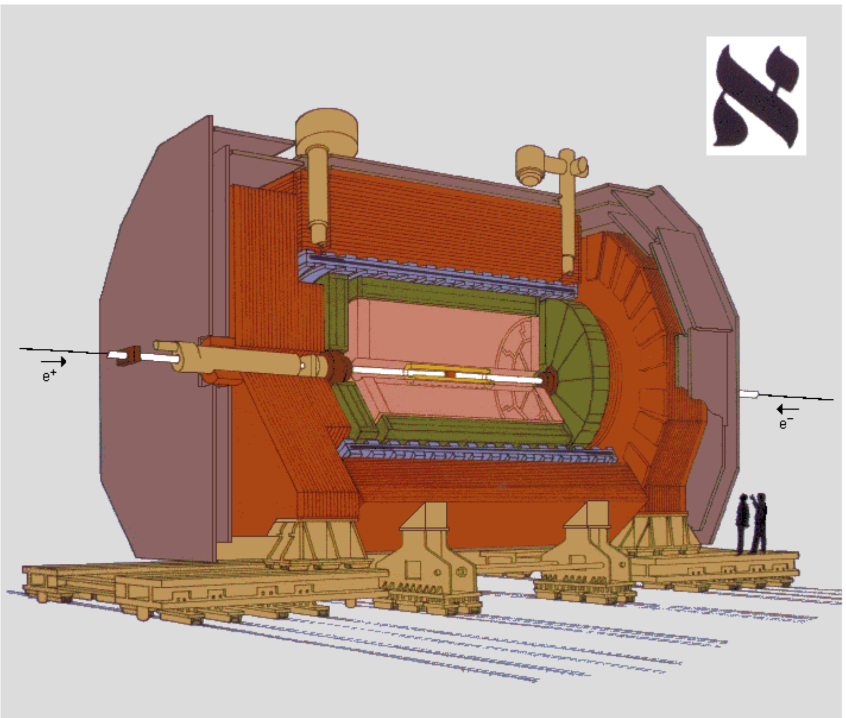
- There are easier/faster ways to reconstruct "physics objects" (e.g., jets…)
  - e.g., purely tracker-based, or purely calorimeter-based

Basics of Particle-Flow Event Reconstruction (4)

- So, indeed ... why bother ?
  - Philosophical answer
    - A list of particles is the closest one can get from the actual collision
      - → Giving a complete and fully consistent view of the event
      - → Making reconstructed events very similar to generated events
      - → Greatly simplifies the analysis design process, for any final state
  - Practical answer
    - Each sub-detector response depends on the particle type. After identification of a particle, their combination
      - → Returns the best energy, direction, (mass) determination for each type
      - → Gives in turn the optimal response for jets, photons and leptons
      - → Is expected to improve the performance of any data analysis
  - Financial answer : detector are expensive, thus make optimal use of them !
  - Question : is the improvement with respect to easier approaches worth it ?

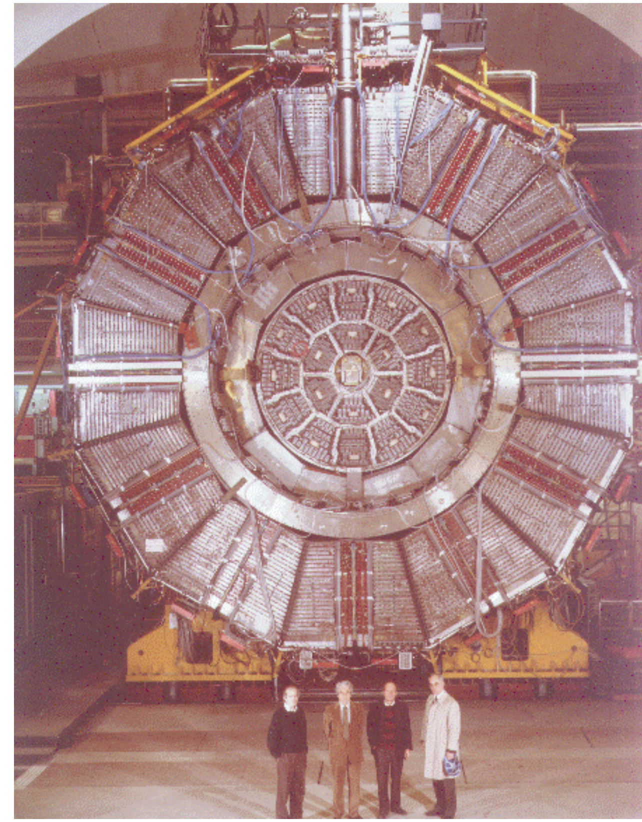
A detector thought for Particle Flow : ALEPH

- ALEPH is not very different from the standard HEP detector



The ALEPH Detector

- Vertex Detector
- Inner Tracking Chamber
- Time Projection Chamber
- Electromagnetic Calorimeter
- Superconducting Magnet Coil
- Hadron Calorimeter
- Muon Chambers
- Luminosity Monitors



- Tracking, hermetic EM and HAD calorimetry, muon chambers, large axial B field
  - So, what is so special about the design of this detector ?

A detector thought for Particle Flow : ALEPH

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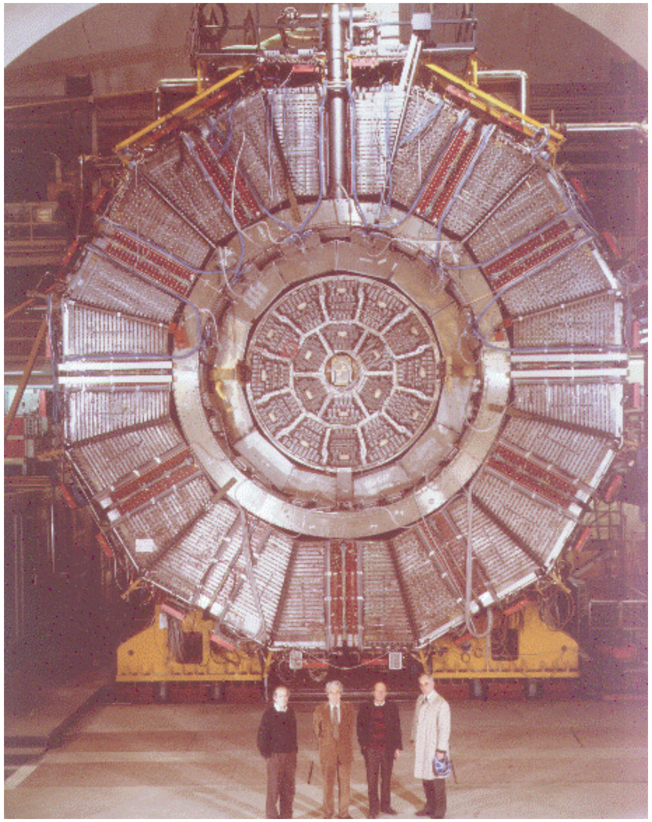
The ALEPH Detector

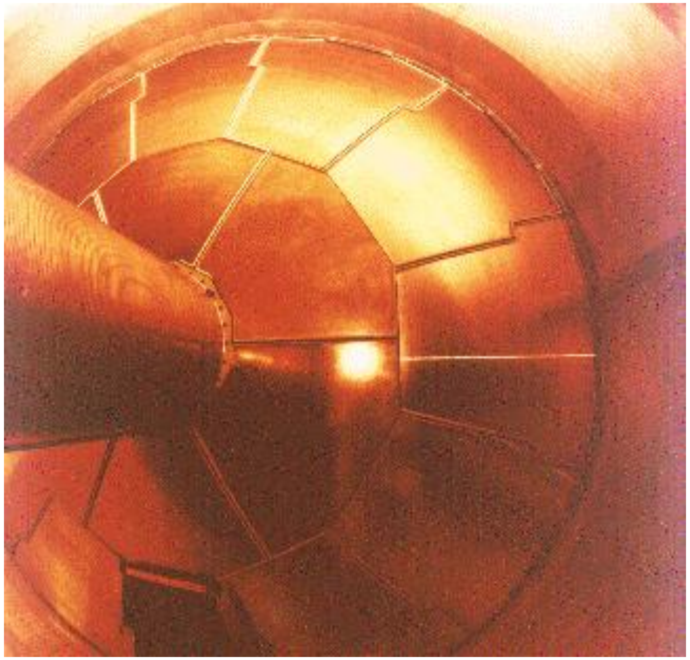


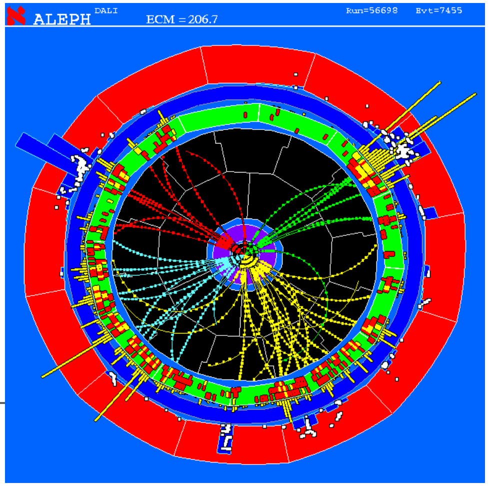
- ◆ Tracking, hermetic EM and HAD calorimetry, muon chambers, large axial B field
  - So, what is so special about the design of this detector ?

A tracker thought for Particle Flow (I)

- ALEPH choice : a Time Projection Chamber
  - Large volume mostly empty (filled with gas)
    - 1% X_0, non destructive
  - 21 three-dimensional measurements up to R=1.80m
    - No track-to-track ambiguity
    - 100% tracking efficiency, even in jets
      - → Even if originating far from main IP
    - $\sigma(1/p_T) = 6.10^{-4}$ GeV^{-1} , no charge flip
      - → Almost perfect in the LEP p_T range
    - No fake track, hence no fake energy reconstructed
      - → All hits are displayed in this figure !
  - Event charged-particle energy reconstructed perfectly
    - Origin, energy, direction, charge, but yet no ID.
      - → (some e/π separation below 5 GeV, dE/dx)

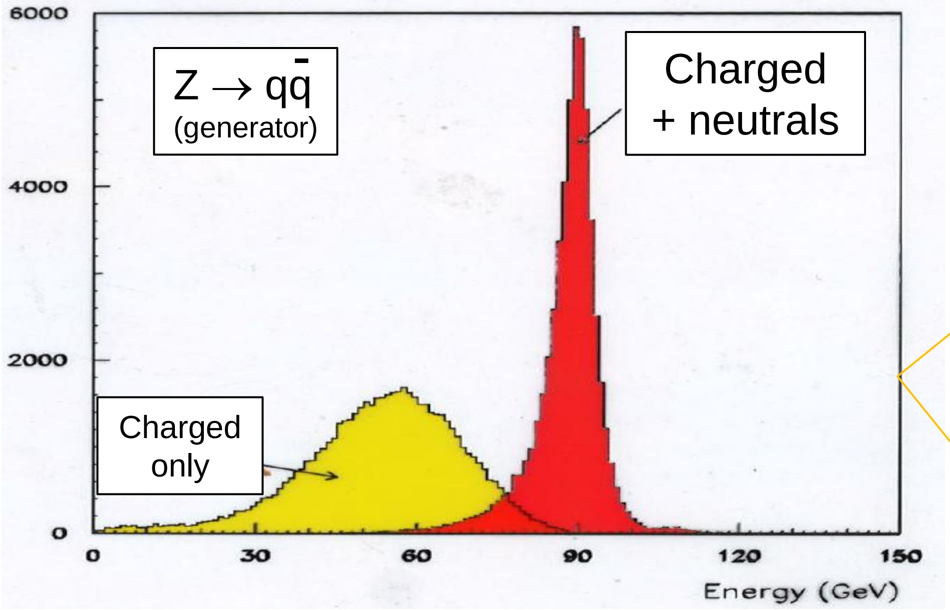
B Field 1.5T





A tracker thought for Particle Flow (2)

- Is that perfection enough ?
  - Not really ...
    - In a hadronic Z decay, charged particles ($\pi^\pm$, $K^\pm$, p, $\bar{p}$, $e^\pm$, $\mu^\pm$) carry 65% of the total energy
      → with a broad distribution (from 0 to 100%)
    - Back to almost 100% if neutral particles are identified perfectly

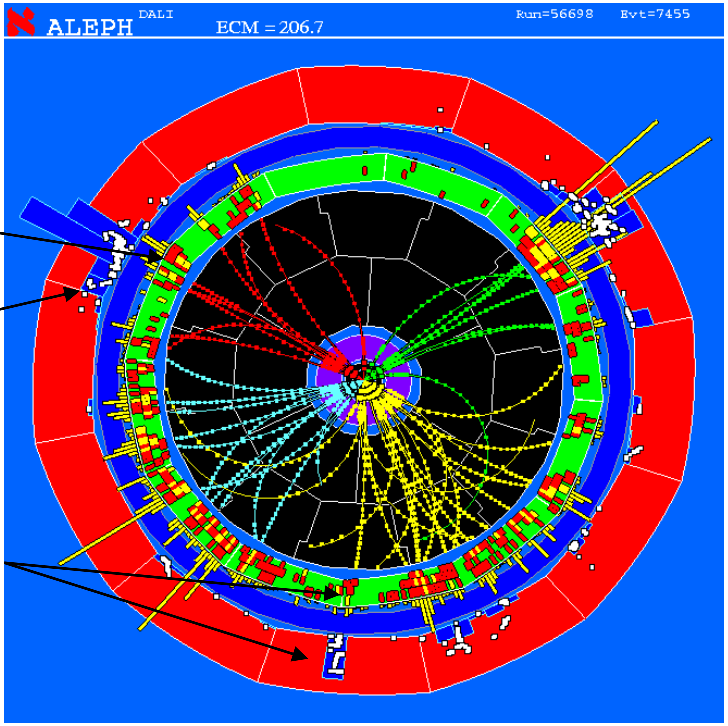


A proof of principle for particle flow reco

→ Calorimeter resolution and acceptance taken into account

A calorimetry thought for Particle Flow ? (1)

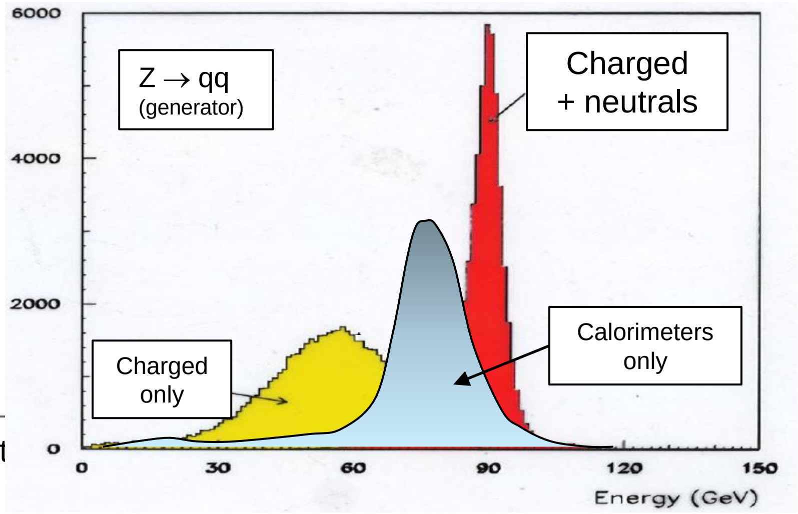
- Remember our famous e+e- → WW event
  - Neutrals as energy deposits in the calorimeters
    - 25% are photons (mostly from π^0 decay)
      - → Detected in ECAL
    - 10% are neutral hadrons (K^0_L, n, $\bar{n}$, ...)
      - → Detected in ECAL and HCAL
    - But 65% are charged particles
      - → Electrons in ECAL, Muons in HCAL
      - → Charged hadrons in ECAL and HCAL



- Weapons to identify what is what
  - Large B field + large tracking volume
    - separate charged from neutrals, and charged from charged
  - Calorimetry fine (3D) segmentation + small Moliere radius ("isolate" all deposits)
  - No/little material in front of calorimetry (one particle = one deposit)

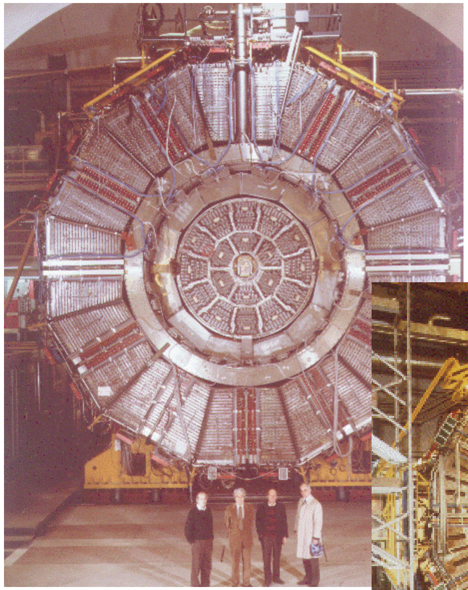
A calorimetry thought for Particle Flow ? (2)

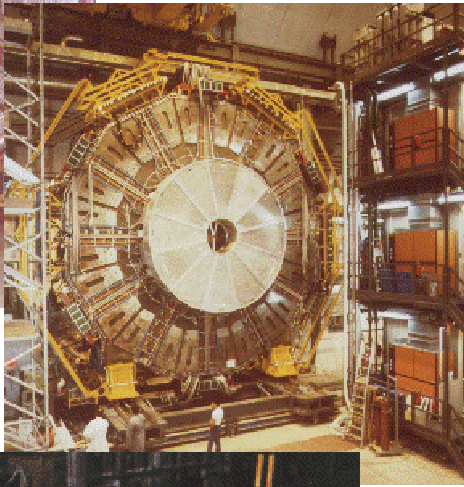
- Why not using calorimeters only ?
  - Worse energy resolution for charged hadrons (100%/√E vs perfect) and worse direction determination for charged hadrons (magnetic field)
    - Affects 65% of the event energy in hadronic final states
  - Muons are just minimum ionizing particles
    - Energy information is lost, so need anyway to use tracking
  - ECAL response for charged/neutral hadrons is smaller than for photons/electrons
    - A large fraction of the energy is not underestimated
  - Low momentum charged particles do not reach calorimeters
    - Their energy is lost
  - No particle list
  - For Z hadronic decays
    - Reconstruct 72 ± 10 GeV
    - Need a posteriori corrections

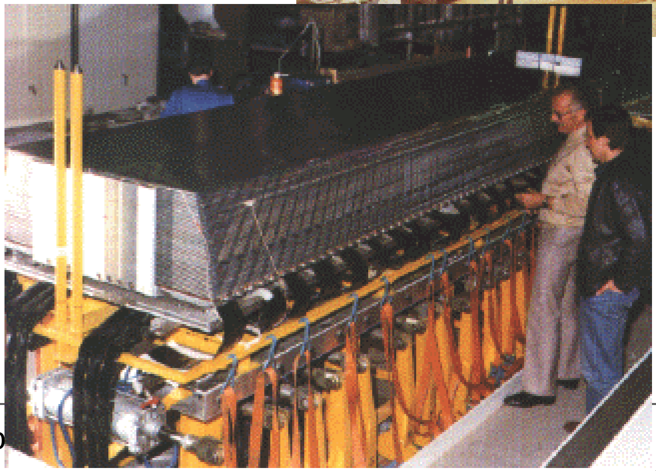


An EM calorimetry thought for Particle Flow (1)

- The ECAL, for electrons and photons
  - 36 modules (12 in barrel and 12/end-cap)
  - For each module: $R_M = 1.5$ cm
    - 45 planes of lead / wire chamber
    - Total thickness 22 X_0
    - Transverse segmentation of 3x3 cm
    - Longitudinal segmentation 4/9/9 X_0
    - 75000 x 3 cathode readout "towers"
    - Each of the 45 wire planes is readout too
  - Main characteristics
    - Hermeticity
    - 3D fine granularity
    - Redundancy
    - Simplicity

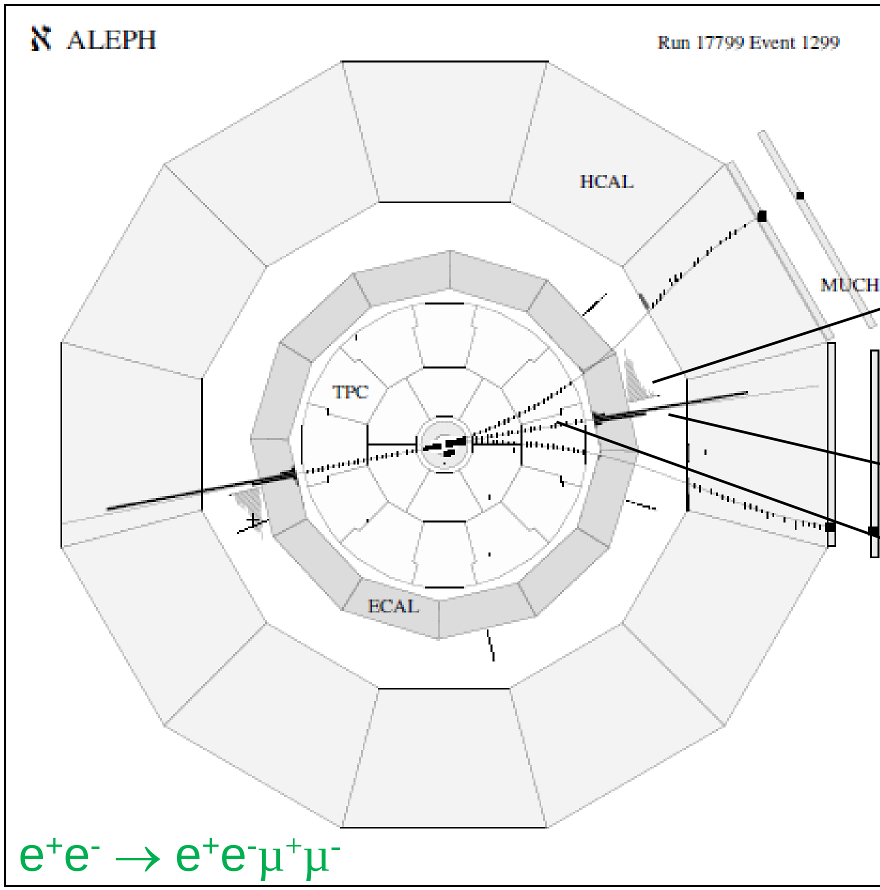


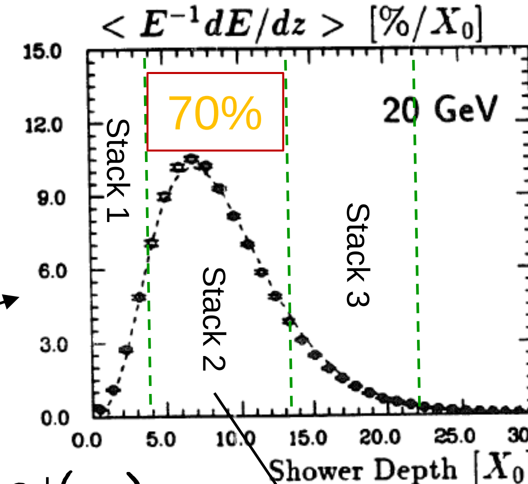


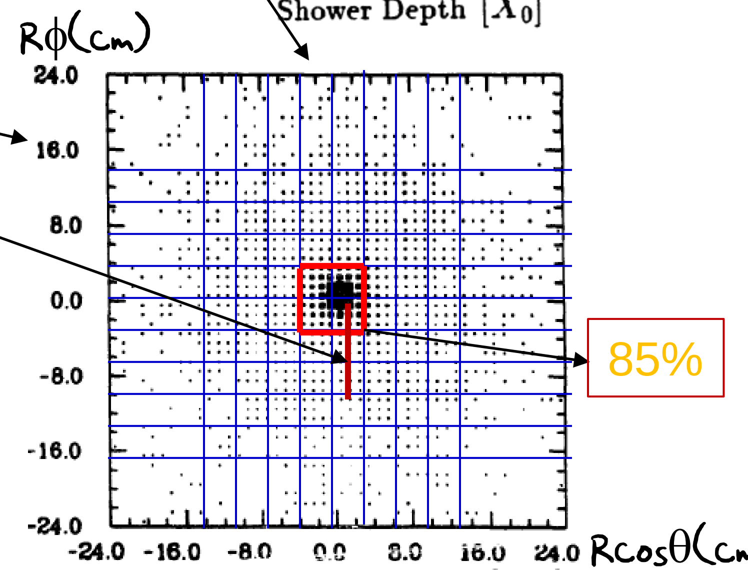


An EM calorimetry thought for Particle Flow (2)

- How do electromagnetic showers look like in this ECAL ?

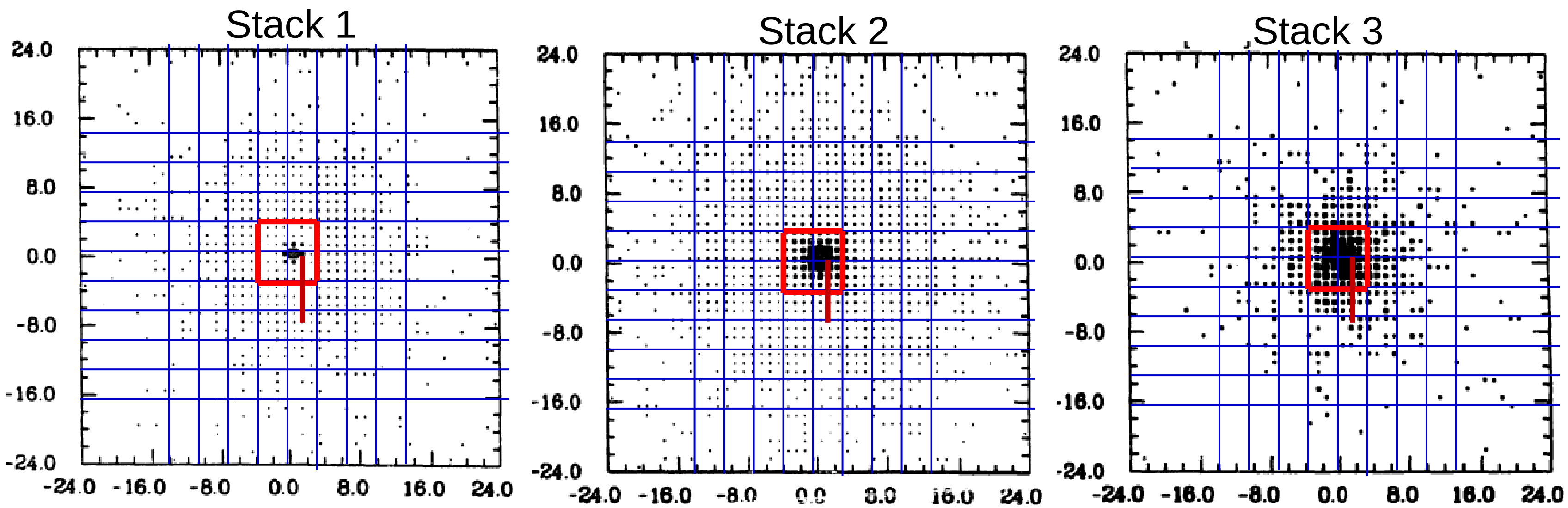






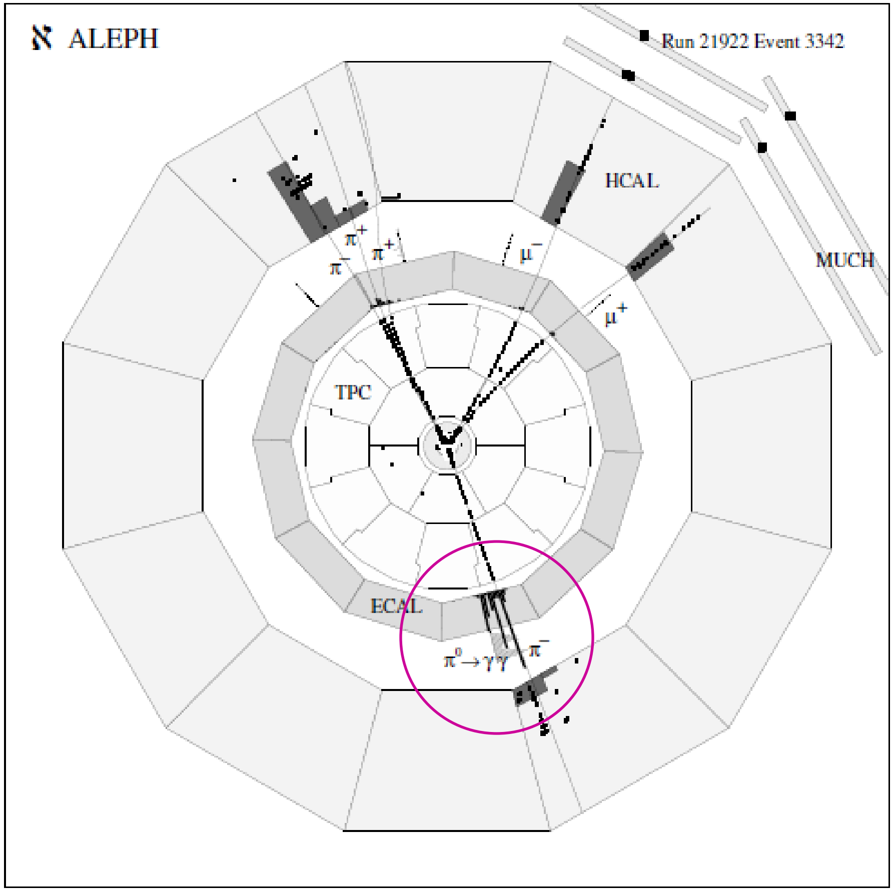
An EM calorimetry thought for Particle Flow (3)

- EM energy deposits (γ, $e^\pm$) are reconstructed as follows
  - Seed with a cell in stack 2 with E_2>30 MeV, and larger than its 8 neighbours
  - Correlate with a cell in stack 1 and/or in stack 3 with $E_{1,3}$>15 MeV
  - Estimate the energy from the four central towers E_4 (and divide by 0.85)
  - Call it photon if the closest track extrapolation is > 2cm away from barycentre
  - Otherwise, test E_4/p , $\Sigma E_i x_i / E_4$, dE/dx against the electron hypothesis
    - and call it either electron or charged hadron



An EM calorimetry thought for Particle Flow (4)

- Efficiency for photons (E>250MeV) in jets and tau decays > 95%
  - And 100% in isolation



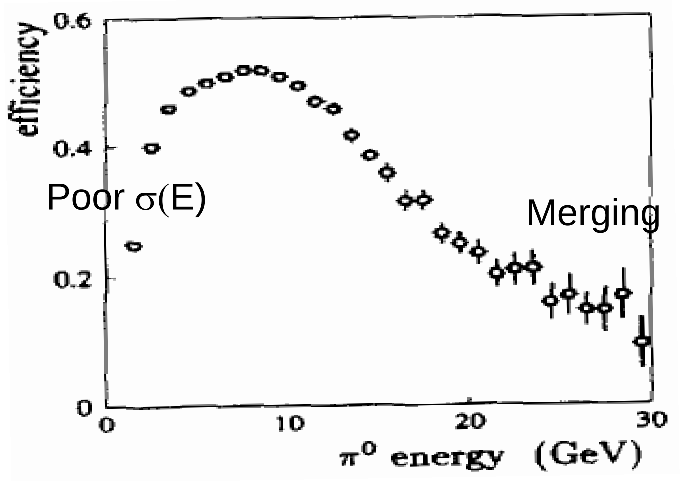
Example : $e^+e^- \rightarrow \tau^+\tau^-\mu^+\mu^-$

$\tau^- \rightarrow \rho^-\nu_\tau \rightarrow \pi^-\pi^0\nu_\tau \rightarrow \pi^-\gamma\gamma\nu_\tau$

$\tau^+ \rightarrow \pi^+\pi^+\pi^-\nu_\tau$

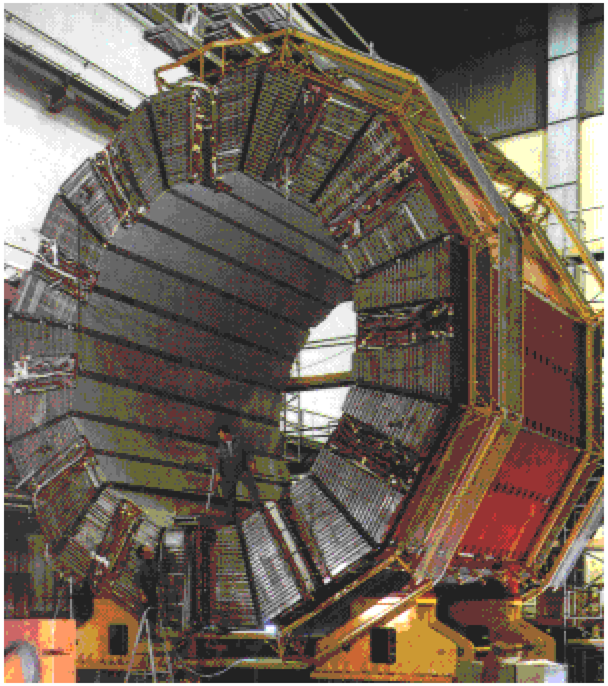
ECAL granularity performance:

π^0's can even be resolved in jets (mostly irrelevant for PF purposes)



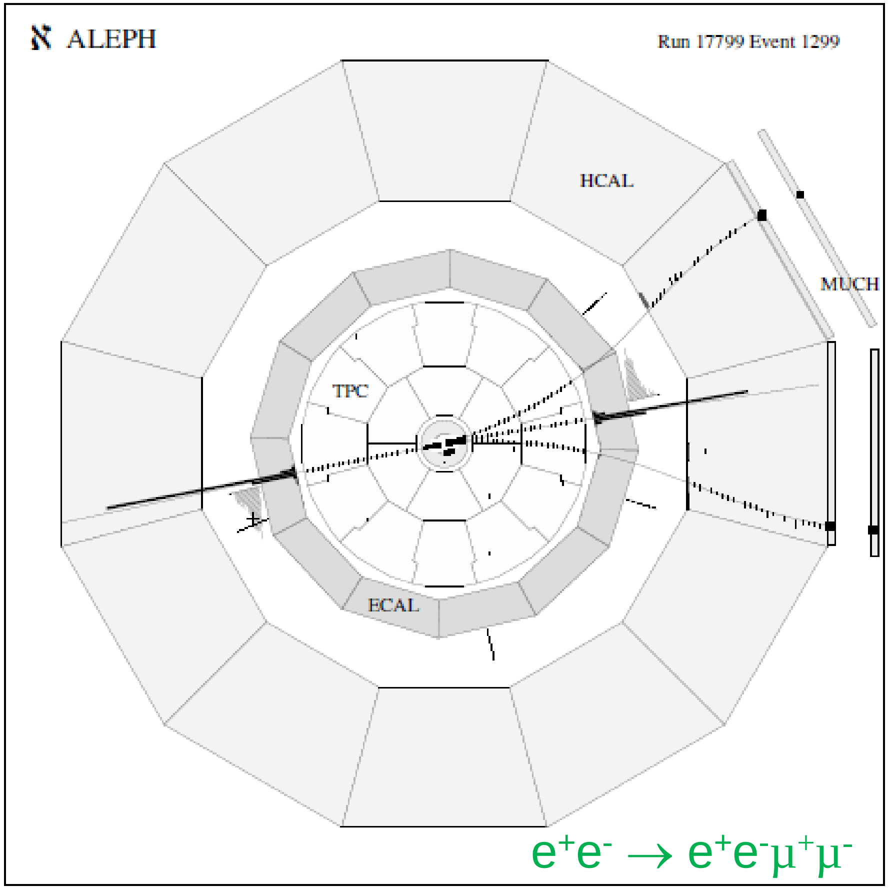
A HAD calorimetry thought for Particle Flow ? (1)

- The HCAL for charged/neutral hadrons, … and muons
  - 36 modules (24 in barrel, 6/end-cap)
  - Placed behind the magnet coil
    - Hadrons lose some energy in the coil
  - For each module
    - 23 planes of 5cm iron / drift streamer tubes
    - Total thickness 7.2 λ_0's
    - Cathode readout, transverse size 15cm x 15cm
      - → But no longitudinal segmentation
    - Digital individual drift tube readout (Yes/No)
      - → But only 2D granularity
  - Seems not particularly optimal for hadron/hadron separation
    - We'll see that in a couple slides
  - What about muons ?



A HAD calorimetry thought for Particle Flow ? (2)

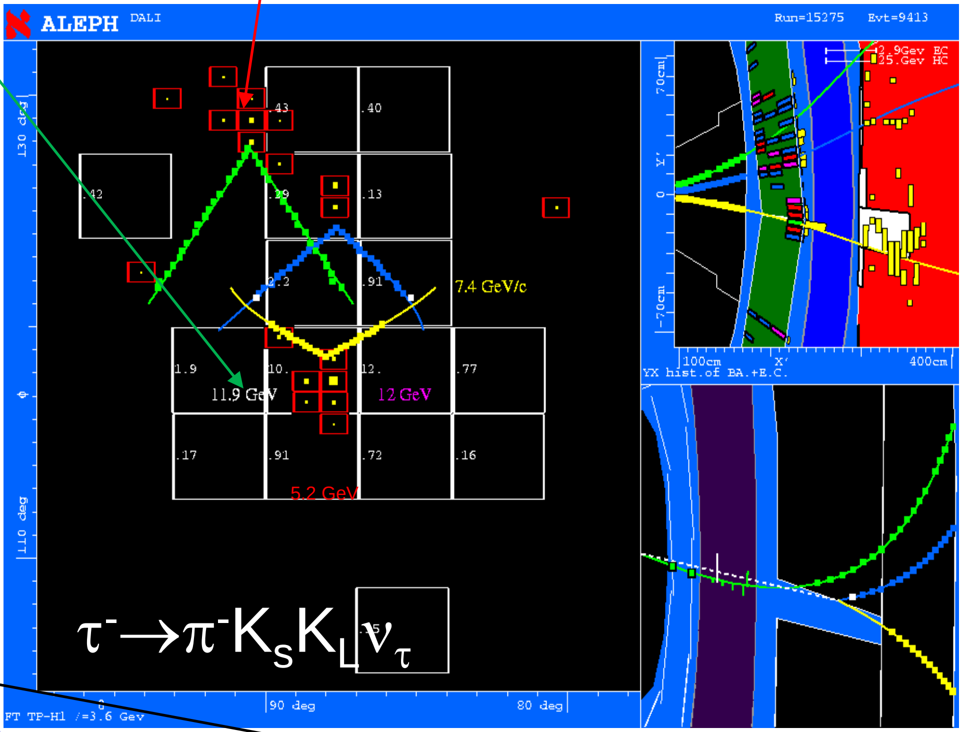
- Muon tracking in HCAL
  - Remember our ee$\mu\mu$ event
    - Drift tubes used to track muons
      - → All the way to mu-chambers
    - "Energy" measured : 3-5 GeV
      - → About 300 MeV/layer (mip)
      - → Easily link-able to the track
    - Unambiguous identification
      - → width, penetration depth, μCH
      - → 95% identification efficiency
    - Almost no difference in jets
      - → 0.5% fake rate (decays)



- Summary so far : γ's, e's, μ's (tracks + calo energies) well identified
  - Thanks to 3D (2D) segmentation of tracker, ECAL, HCAL (+ B field)

A HAD calorimetry thought for Particle Flow ? (3)

- We are left with charged and neutral hadrons
  - i.e., with several sets of tracks remaining after e and μ identification
    - Possibly linked to one HCAL cluster and ECAL cluster(s)
      - → Unlinked HCAL clusters give rise to a neutral hadron
- In this particular event:
  - Three charged particles
  - Each linked to an ECAL cluster
  - Two linked to one HCAL cluster
  - All identified as charged hadron
    - with $E = p_{Track}$
  - But clear excess of Calo energy
    - 5, 25 GeV in ECAL, HCAL
    - 7.4 and 4.8 GeV in Tracker
  - Signs the presence of a neutral hadron



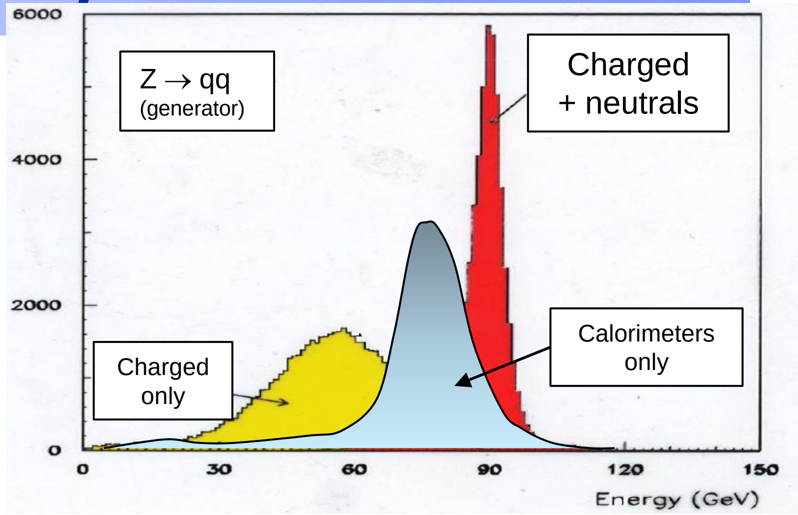
Note the $K_S \to \pi^+\pi^-$ decay

A HAD calorimetry thought for Particle Flow ? (4)

- Determination of the neutral hadron energy
  - HCAL cluster without a track pointing to it
    - $E_{\text{Neutral Hadron}} = E_{\text{HCAL cluster}}$
      - → Keep if $E_{\text{Neutral Hadron}} > 500$ MeV
  - HCAL cluster with one or more tracks pointing to it
    - $E_{\text{Neutral Hadron}} = E_{\text{HCAL cluster}} + c_{e/\pi}\Sigma E_{\text{ECAL cluster}} - \Sigma p_{\text{Track}}$
      - → with $c_{e/\pi} = 1.30$ (ratio of electron to pion response in ECAL)
      - → Keep if $E_{\text{Neutral Hadron}} > 100\% \sqrt{\Sigma p\text{Track}}$
        i.e., if larger than 1σ of the expected hadron shower fluctuations
- The HCAL of ALEPH could have been more carefully designed
  - Only 50% efficiency (and 50% purity) for neutral hadrons
    - Better granularity, better material, would have helped (more expensive)
      - → Could the 2D granularity of the streamer tubes have been exploited ?
    - The HCAL could have been put inside the magnet (more expensive)

Does it work as initially designed for ? (I)

- Remember the ideal projection
  - In hadronic Z decays, the energy is shared
    - 65% are charged particles.
      - → with perfect energy resolution
    - 25% are photons. For single photons:
      - → $\sigma(E_\gamma) = 20\%\sqrt{E_\gamma}$
    - 10% are neutral hadrons. For single hadrons
      - → $\sigma(E_{Had}) = 100\%\sqrt{E_{Had}}$



  - The total energy resolution, if all particles were ideally identified, would be

$$\sigma(E_{tot}) = \left[\sum_{tracks} \sigma^2(p_{track}) + \sum_{photons} \left(0.20\sqrt{E_\gamma}\right)^2 + \sum_{\substack{neutral\\hadrons}} \left(1.00\sqrt{E_{had}}\right)^2 \right]^{1/2}$$

$$= \left[0 + 0.04 \times 0.25 E_{tot} + 1.00 \times 0.10 E_{tot}\right]^{1/2}$$

$$= [0 + 0.01 + 0.10]^{1/2}\sqrt{E_{tot}} = 33\%\sqrt{E_{tot}} = 3.1\,\mathrm{GeV}$$ (For $E_{tot} = m_Z$)

Charged hadrons

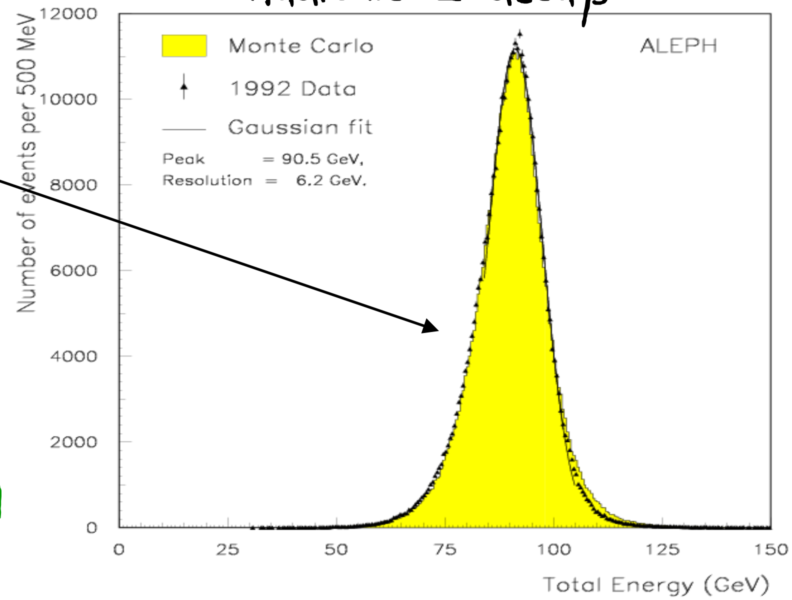
Photons

Neutral hadrons

Does it work as initially designed for ? (2)

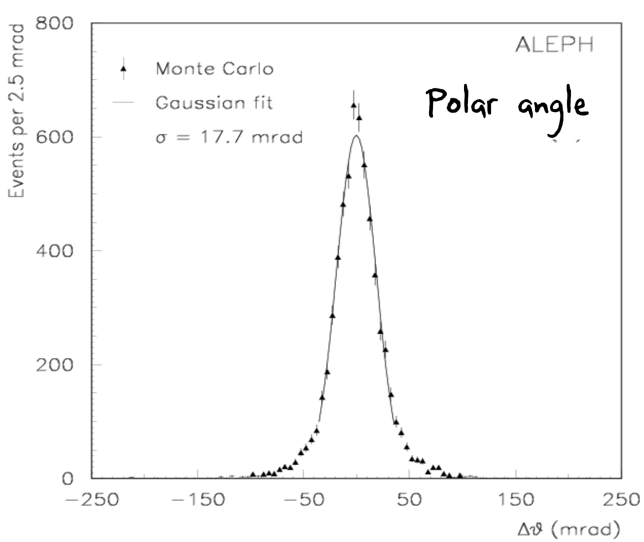
- Not quite for the energy resolution …
  - Measured resolution twice as large:
    - $E_{tot} = 90.5 \pm 6.2$ GeV
  - But remember with calorimeters only:
    - $E_{tot} = 72 \pm 13$ GeV
- Reasons for the difference ?
  - Neutral hadron energy losses
    - e.g., neutral hadron shower in the coil
    - e.g, unresolved neutral hadron shower
  - Neutral hadron energy double couting
    - e.g., charged hadron shower upwards fluctuation, interaction in the coil
      - → giving rise to a fake neutral hadron
- Could have been alleviated with a better HCAL design
  - And maybe with an optimal use of streamer tubes (was tried, not hard enough)?

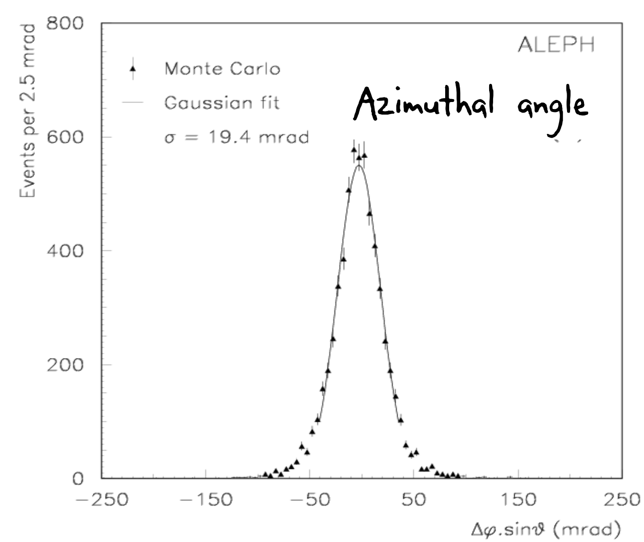
Hadronic Z decays



Does it work as initially designed for ? (3)

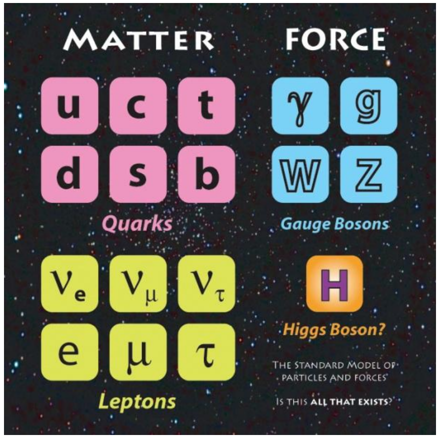
- But very much so for the quark angular resolution
  - Performance on hadronic Z decays (cont'd)
    - Jet angular resolutions (with respect to parton) of about 18 mrad
      - → Would have been 13 mrad with an ideal detector
      - → Was 64 mrad with tracks only, and 100 mrad with calos only
    - Made a breakthrough in b-tagging efficiency, in particular
      - → By a better determination of track impact parameter wrt the jet axis





Does it work as initially designed for ? (4)

- And what about the very initial and very ambitious aim ?
  - i.e., identify all standard model particles and possibly dark matter particle ?



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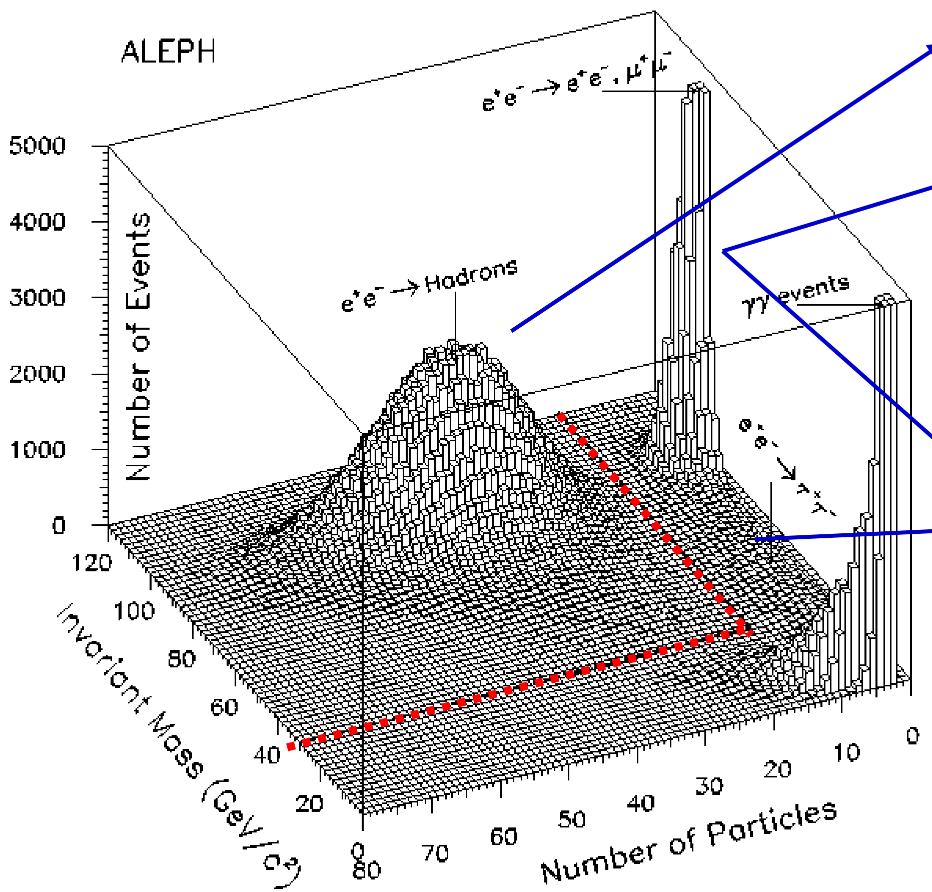
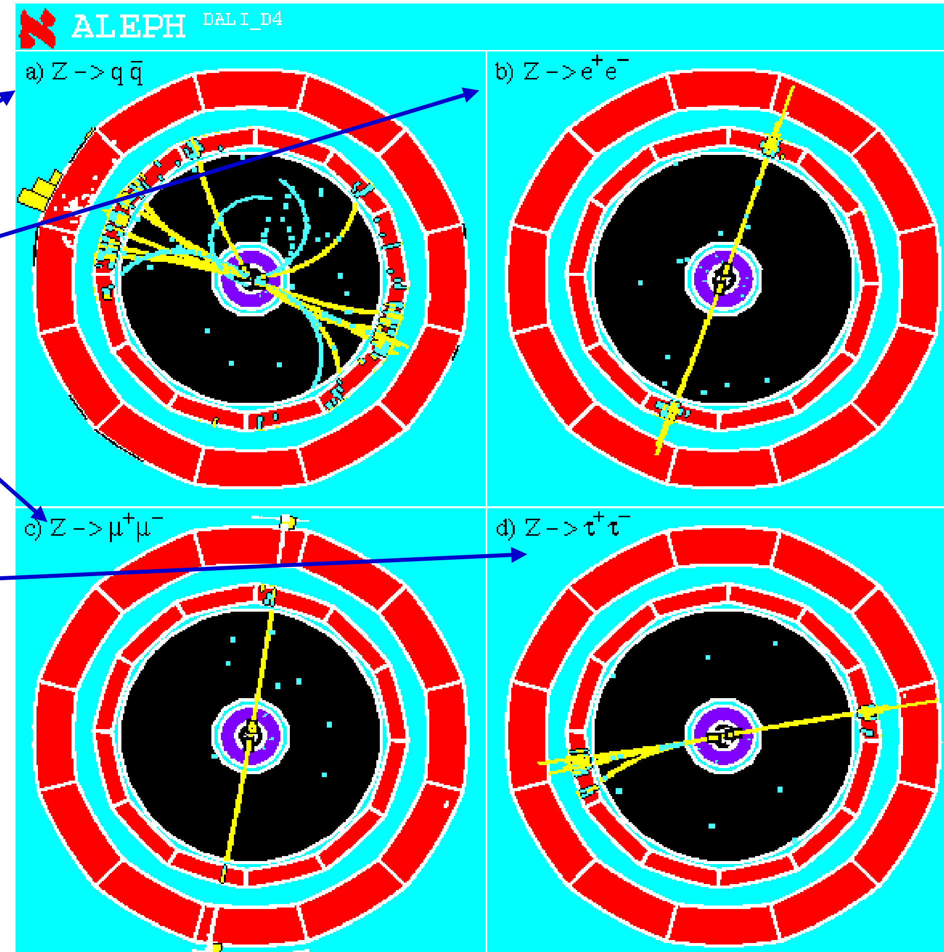
  - We already went through a lot here
    - Electrons
    - Muons
    - Photons
    - Taus
    - Quark and gluons (jets)

Does it work as initially designed for ? (5)

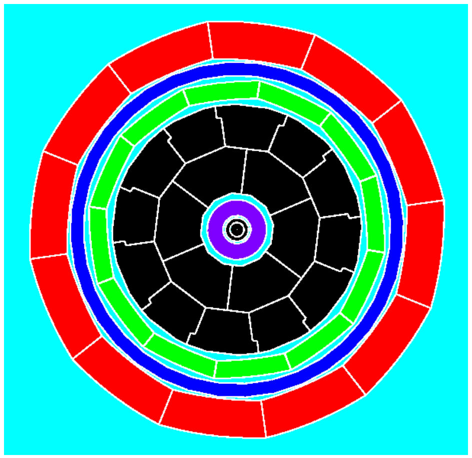
- Identification of Z (or W, H) through decay products
  - M > 30 GeV/c², N > 15 particles – 99.6% efficient for hadronic Z decays

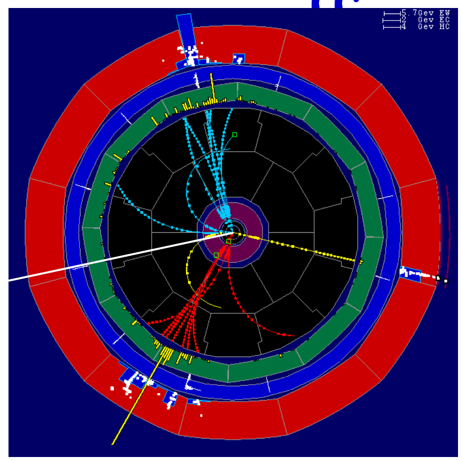


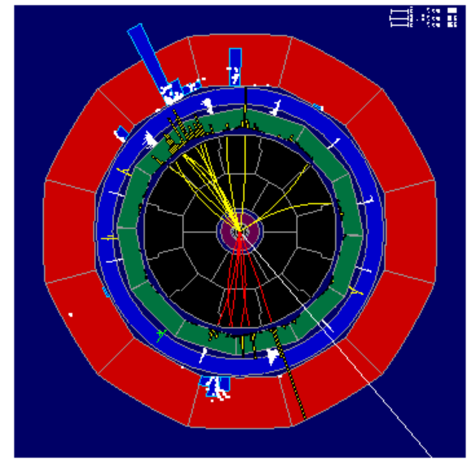


Does it work as initially designed for ? (6)

- And what about neutrinos ?
  - $Z \rightarrow \nu\bar{\nu}$ $\qquad$ $WW \rightarrow q\bar{q}\mu\nu$ $\qquad$ $HZ \rightarrow b\bar{b}\nu\bar{\nu}$







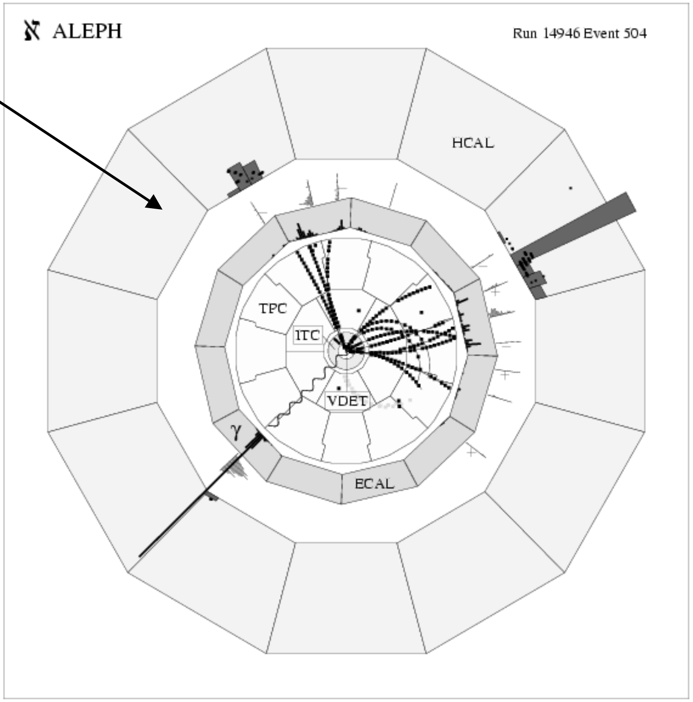
  - First event not detectable (no trigger), but neutrinos in the other two are !
    - From energy-momentum conservation: $\vec{p}_\nu = -\sum_{\text{particles}} \vec{p}_i$ and $E_\nu = \sqrt{s} - \sum_{\text{particles}} E_i$

→ Hence the importance of measuring well the energy/direction of all particles in the event. Particle-Flow reconstruction is the tool for ν's

→ The same statement holds true for 

Does it work as initially designed for ? (7)

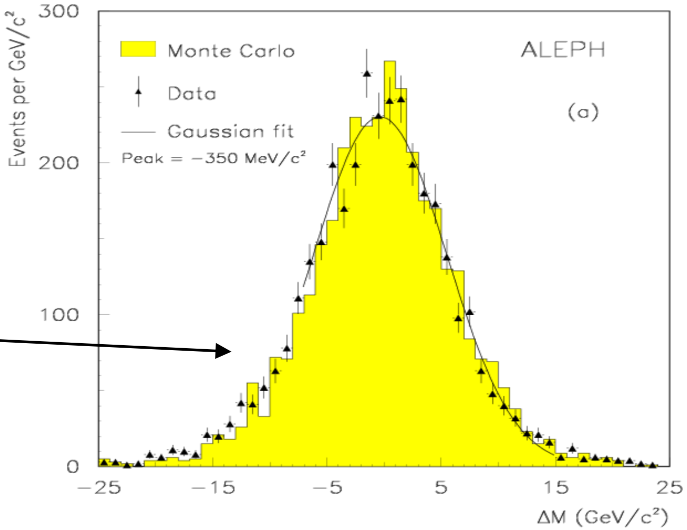
- Are neutrinos (or any kind of missing energy) well measured ?
  - Difficult to know, as neutrinos are not directly detected, but ...
    - Can use $e^+e^- \to q\bar{q}\gamma$ events, and fake a neutrino by "removing" the photon
      - → And the energy of the neutrino is known in that case !



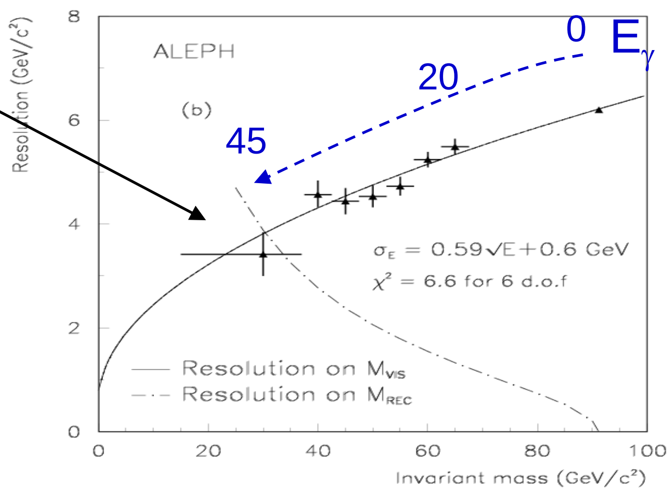
- Exercise
  - Establish that $$E_\gamma^{\text{recoil}} = \frac{s - m_{\text{had}}^2}{2\sqrt{s}}$$
  - One can now compare
    - E_γ(measured) and E_γ(recoil)
  - Or equivalently
    - m_{had}(measured) and m_{had}(recoil)
      - → The latter determined from $E\gamma$
  - And establish the detector calibration for ν

Does it work as initially designed for ? (8)

- Particle-Flow calibration with $q\bar{q}\gamma$ events
  - Determine the hadronic mass
    - With particle flow: m_{had}(measured)
    - As recoiling to the photon: m_{had}(recoil)
  - Plot the difference ΔM
    - Compatible with 0, establishes calibration



  - Determine the mass resolution
    - As a function of E_γ (i.e., of m_{had})
      - → $E_\gamma = 0$ means $Z \to q\bar{q}$
    - Result
      - → $\sigma(m) = 59\%\sqrt{m}$ or $\sigma(E) = 59\%\sqrt{E}$
      - → To be compared to 33% ideally



Is it ready for physics analysis ? (I)

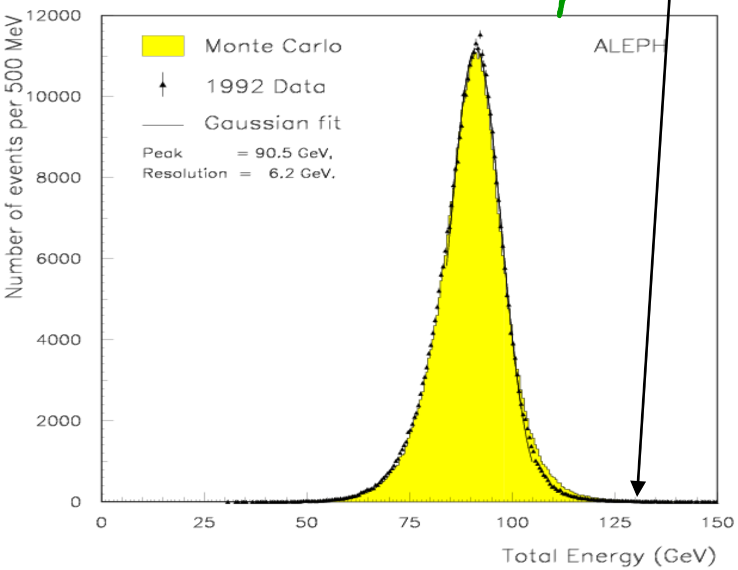
- Core resolution vs tails : The devil is in the details
  - Particle-Flow reconstruction is a beautiful intellectual construction
    - With a superior core resolution and larger efficiencies for almost everything
      - → Jet energy and direction, jet-jet invariant mass, missing energy, b tagging, tau selection, etc...
      - → which a priori helps to separate different processes
  - But it might be subject to more reconstruction failures than simpler methods
    - Because it uses all sub-detectors of the experiments and needs a refined algorithm to put all pieces together
      - → Again, the (apparent) simplicity of the detector design is essential here.

        The simpler the detector, the simpler the algorithm ...
    - Pure tracking methods are not sensitive to calorimeter noise
    - Pure calorimetric methods are not sensitive to track-cluster link efficiency
  - Tails may therefore develop in various distributions (e.g., jet energy or direction)
    - Which may become a showstopper when looking for rare events

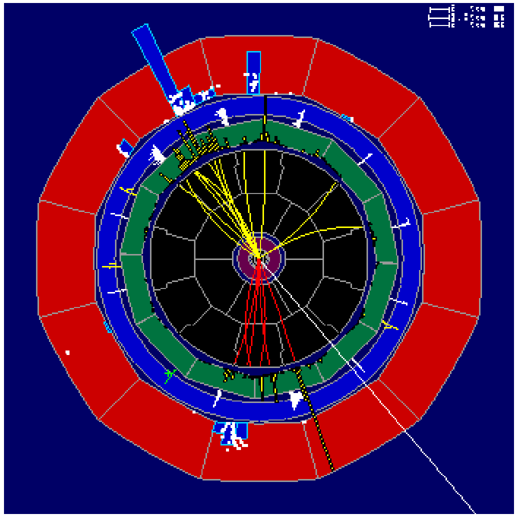
Is it ready for physics analysis ? (2)

- Strategy, in the simulation and in the data (the best MC is the data)
  - 1) study events in the far tails, with a specific physics analysis
  - 2) fix the problem (if any – after all, in the data, it might be New Physics!)
  - 3) Go to 1) until no obvious problem remain
- More specifically, look here … and here

Hadronic Z decays



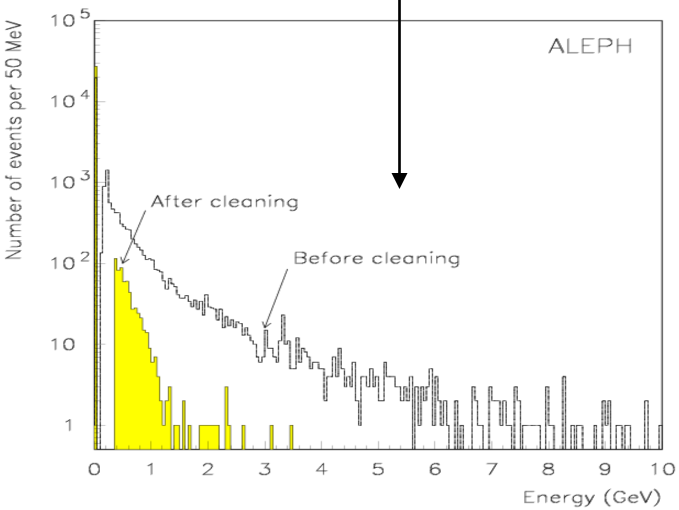
$HZ \to b\bar{b}\nu\bar{\nu}$



- Iterative process that improves the reliability, and ultimately the core resolution

Is it ready for physics analysis ? (3)

- Example : calorimeter noise (electronics, sparks, radioactive decays)
  - Typically creates high energy tails, fake particles in the list
    - Easily identified thanks to the redundancy of the calorimeter measurements
      - → Pads vs wires in ECAL, towers vs drift tubes in HCAL
    - Noise cleaning requires compatibility between the measurements
      - → Check effectiveness of the criterion on randomly triggered events and on Z hadronic decays (large tail must disappear)
      - → Check over-cleaning in the $H\nu\bar{\nu}$ search (in MC, or in the first data)
- Repeat the exercise with $H\nu\bar{\nu}$ candidates
  - Track-cluster link failure
  - Particle identification failure
  - PF Algorithm bugs
  - Unforeseen configurations
    - With stubbornness and pragmatism



Is it ready for physics analysis ? (4)

- First analysis done in ALEPH with particle flow : $H\nu\bar{\nu}$ search
  - Two acoplanar jets, accompanied with missing energy (from the neutrinos)
    - LEP started in July 1989, delivered 25K Z in 1989
      - → Used to develop and "tune" the algorithm
    - Particle-Flow algorithm written between January and April 1990
    - Algorithm and analysis first presented in May 1990, with 100K Z
    - Outperformed other analyses in ALEPH (tracks only) by a factor 2
    - Took the leadership in Higgs boson search until the end of LEP
- At that point, particle-flow reconstruction
  - Became the standard way of doing physics analysis in ALEPH
    - For precision measurements
    - For searches for Higgs boson and new particles
    - Almost 400 publications that use PF reconstruction

Lessons learned [?] (1)

- Particle Flow is potentially a very powerful event reconstruction
  - With possibly benefits in any physics analysis, if several conditions are met
- The detector better be designed with particle flow in mind
  - Overall simplicity of the design (over the full 4π solid angle)
    - Combination of all sub-detector information in PF algorithm
  - 3D granularity for all sub-detectors
    - ALL : Tracker, calorimeters, muon detectors, towards efficiency and purity
    - Good energy resolution is a bonus, but not crucial. Granularity comes first.
  - Large magnetic field (and large tracking volume)
    - To measure charged particle momenta and separate their energy deposits
  - Little material in front of the calorimeters
    - Must think of tracker, coil, services, ...
  - Redundancy of the measurements
    - To fight against fake, noise, ...

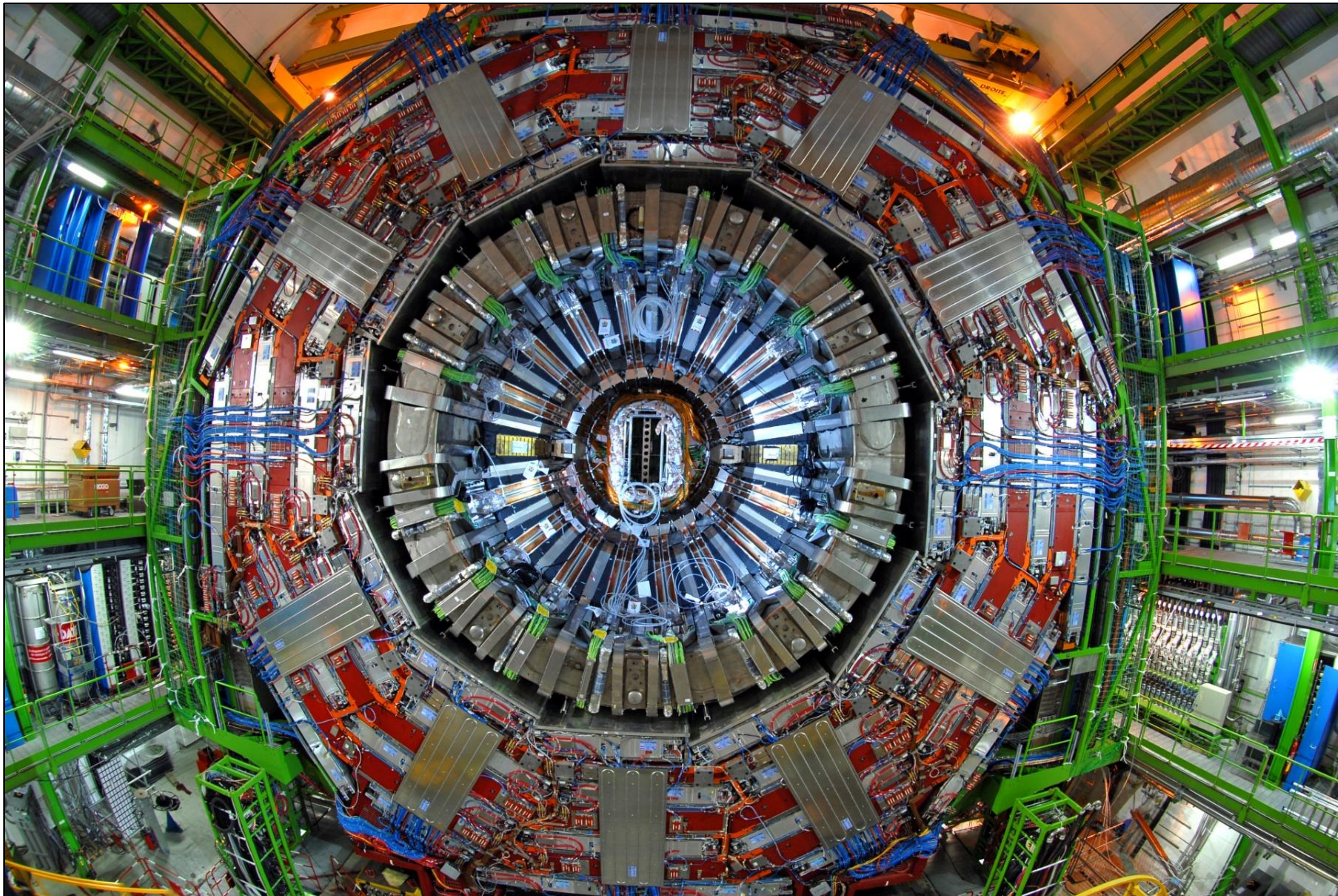
Lessons learned [?] (2)

- The algorithm development is also quite demanding
  - It requires an excellent Knowledge of all sub-detectors
    - Towards the optimal use of the information
      - → for particle identification, reconstruction, and for "cleaning"
  - It requires an excellent Knowledge of particle/detector interaction theory
    - Towards the understanding and handling of "special" cases
  - It requires a specific developer profile
    - Stubbornness
      - → There are no problems, there are only solutions
    - Pragmatism
      - → Each special case is indeed special and requires specific treatment
  - It requires to be developed for/with a physics analysis, possibly with data
    - Towards performance improvement with superior motivation
      - → And natural finding/solving of "special" cases

Lessons learned [?] (3)

- Exercise (1)
  - Study the design of other experiments : DELPHI, OPAL, L3, and ATLAS
  - Answer the following questions
    - Was/is a particle-flow event reconstruction developed ?
    - If yes, was/is its performance significantly better than simpler methods ?
    - Was/is it used in physics analyses ?
    - With the help of slides 35/36, find the reason(s) for the answers above.
- Exercise (2) and hint for Exercise (1)
  - Another method, now called "energy flow", combines tracking and calorimeters
    - It opens a road around each track (momentum p) extrapolation
    - It either masks the calorimeter energy measured in this road, replaced by p
    - Or it replaces the charged-hadron expected energy by p
  - Did/do the above experiments use this method ? If yes, why ?
  - Explain why, in ALEPH, the performance was poorer than PF (σ_E > 10GeV)

A detector not designed for Particle Flow: CMS (1)



A detector not designed for Particle Flow: CMS (2)

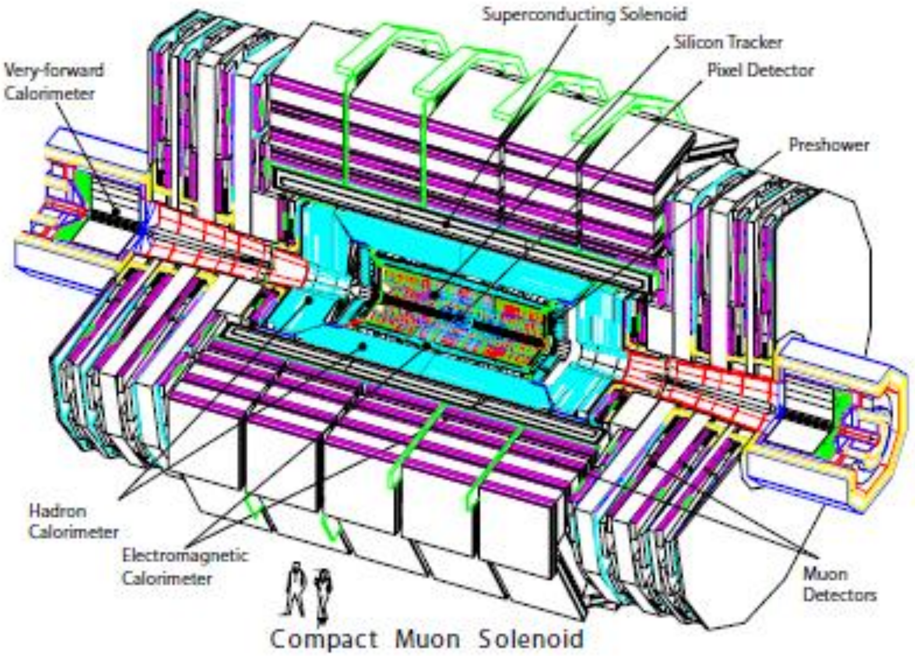
- Original/official list of design requirements

  - Good muon identification and momentum resolution over a wide range of momenta and angles, good dimuon mass resolution ($\approx 1\%$ at 100 GeV), and the ability to determine unambiguously the charge of muons with $p < 1$ TeV;
  - Good charged-particle momentum resolution and reconstruction efficiency in the inner tracker. Efficient triggering and offline tagging of τ's and b-jets, requiring pixel detectors close to the interaction region;
  - Good electromagnetic energy resolution, good diphoton and dielectron mass resolution ($\approx 1\%$ at 100 GeV), wide geometric coverage, π^0 rejection, and efficient photon and lepton isolation at high luminosities;
  - Good missing-transverse-energy and dijet-mass resolution, requiring hadron calorimeters with a large hermetic geometric coverage and with fine lateral segmentation.

  - Particle Flow reconstruction was not part of this list
    - Although some of the requirements might be useful towards particle flow

A detector not designed for Particle Flow: CMS (3)

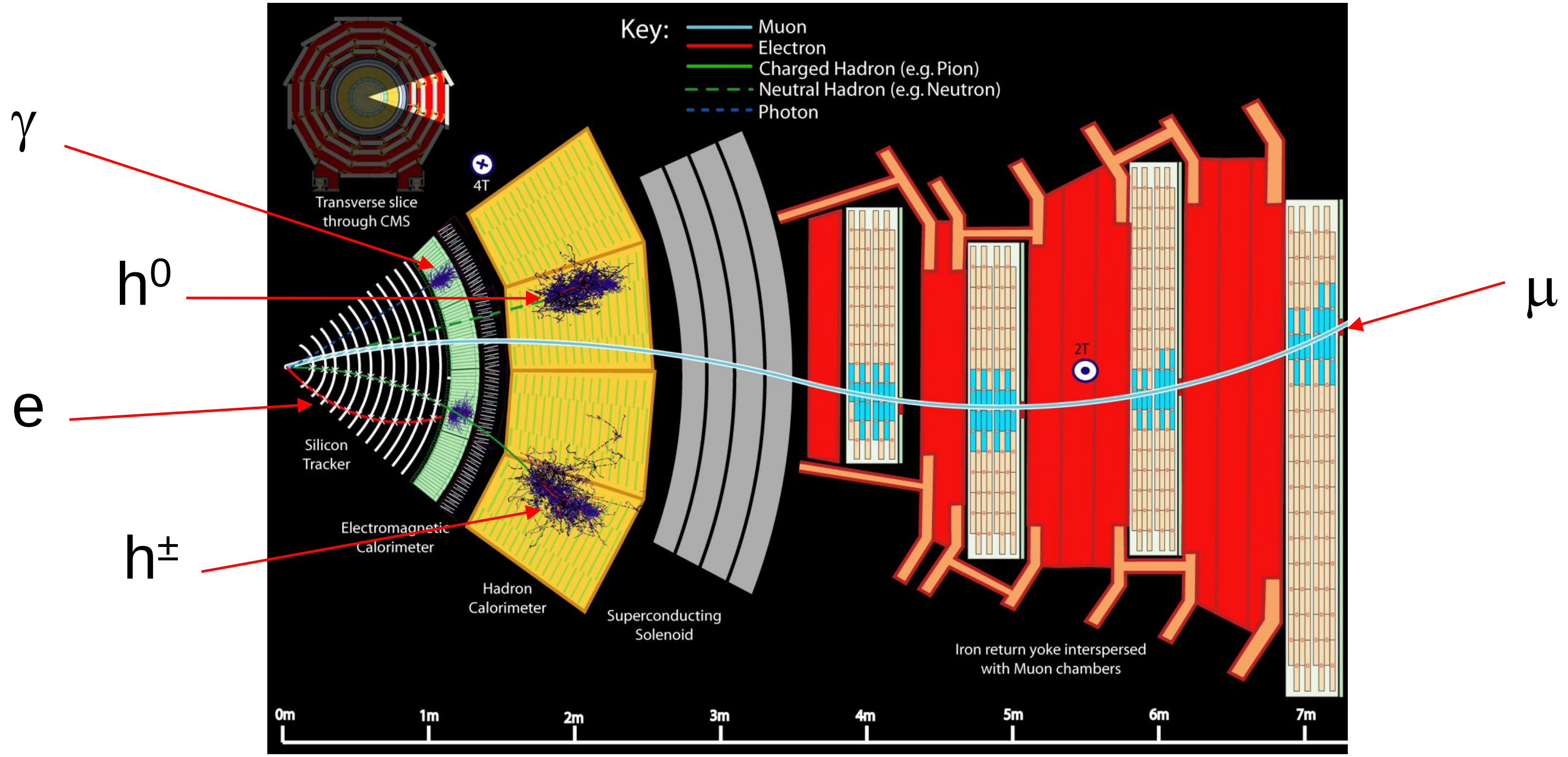
- Let's check the main criteria for a PF-friendly detector
  - Simplicity
  - Hermeticity
  - Magnetic Field
  - Granularity
  - Material
  - Redundancy



?

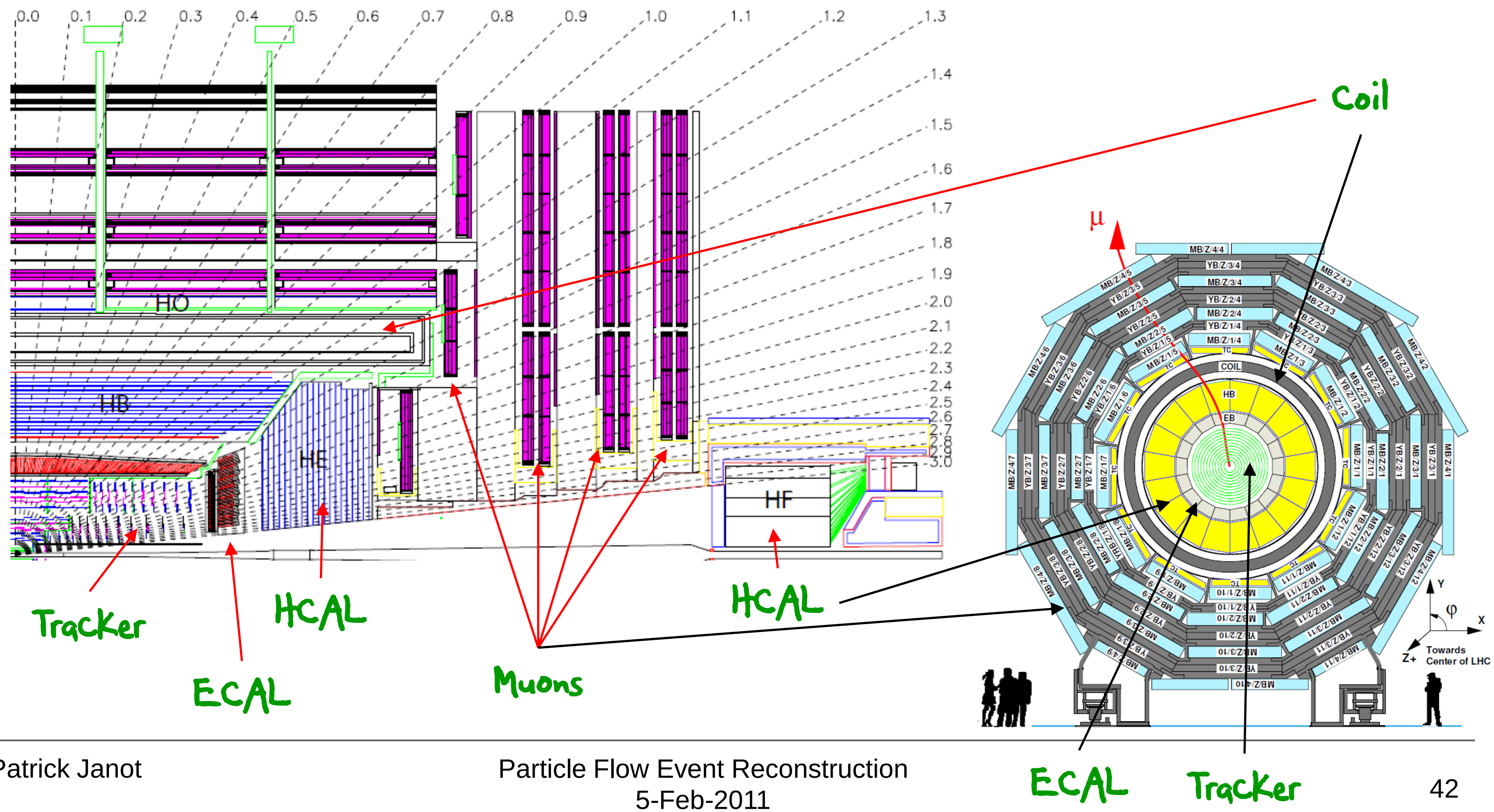
Simplicity

- The design looks "simple" : tracker, ECAL, HCAL, Muon chambers, B Field
  - Difficult to say at first glance that CMS was not designed for PF
    - It even seems able to follow each type of stable particles
      - → Photon, electrons, muons, charged hadrons, neutral hadrons



Hermeticity

- The detector is hermetic
  - Calorimetry up to $|\eta| = 5.1$, tracking up to $|\eta| = 2.5$, muons up to $|\eta| = 2.4$

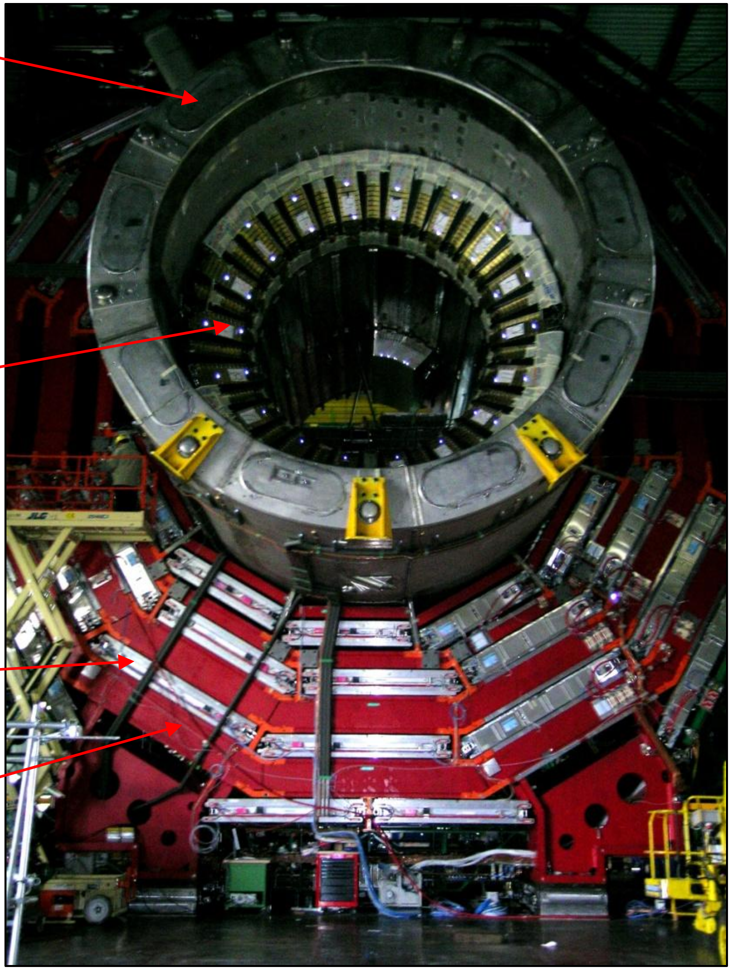


Large magnetic field

- The magnetic field is large indeed
  - Superconducting magnet
    - Length 12.50m
    - Diameter 6.30m
  - Designed to deliver 4 T
    - Operated routinely at 3.8 T
    - A bonus over ALEPH
  - Note : Outside the HCAL !
    - Another bonus over ALEPH
      - → See slides about Material

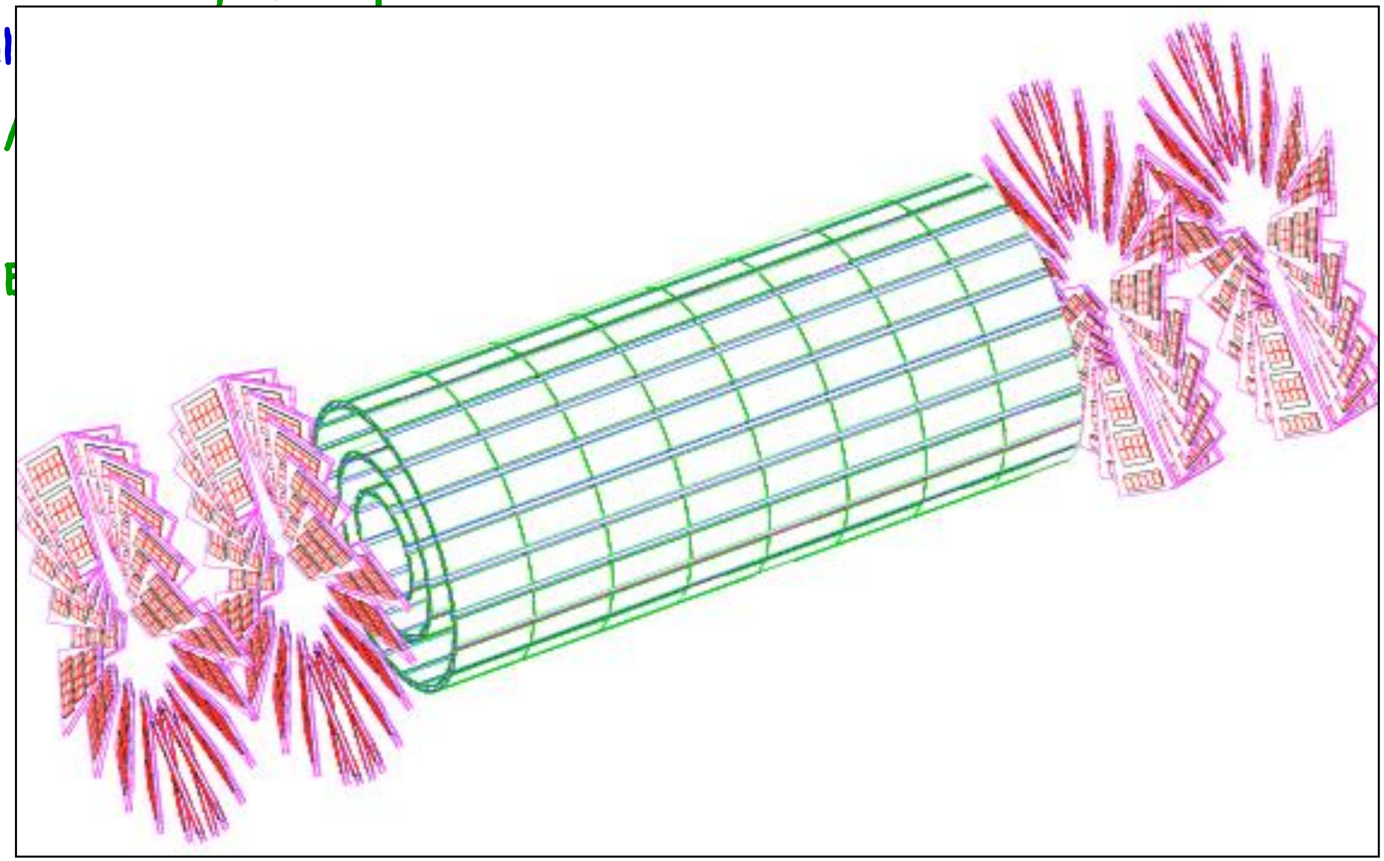
Muons

Iron return yoke



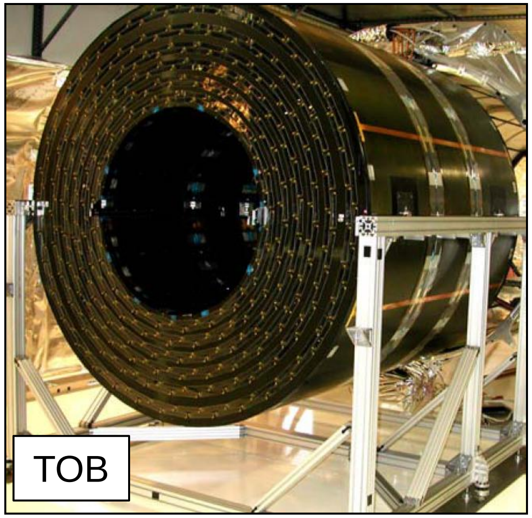
3D Granularity (1)

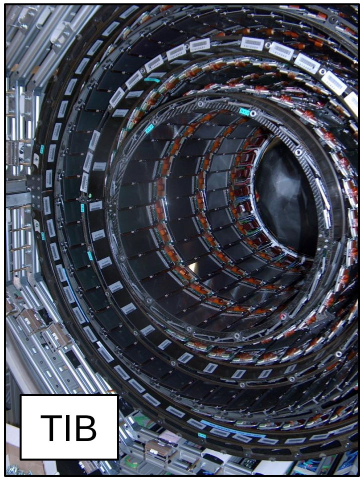
- The tracker consists of
  - A pixel detector with full 3D granularity, surrounding the beam pipe
    - 3 barrel layers, 2 pixel disks
  - A sil
    - /
    - E

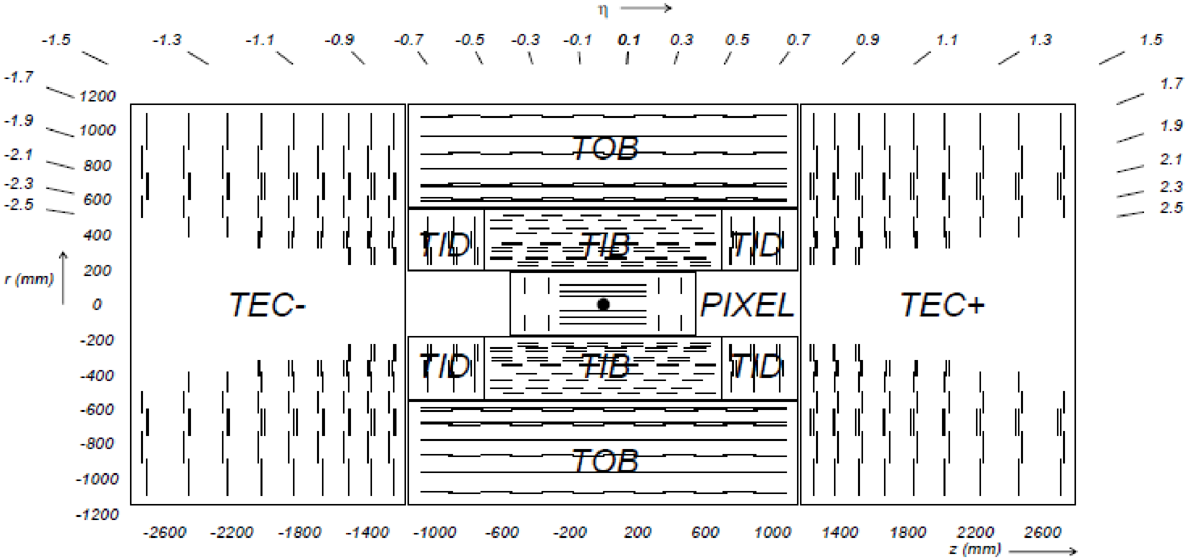


3D Granularity (2)

- The tracker consists of
  - A pixel detector with full 3D granularity
    - 3 barrel layers, 2 pixel disks
  - A silicon-strip tracker with 3D-ish granularity
    - A few double sided layers
      - → TIB 1,2; TOB 1,2; TID 1,2; TEC 1,2,5
    - Expect slightly more ambiguities than in ALEPH
      - → Fake tracks ?



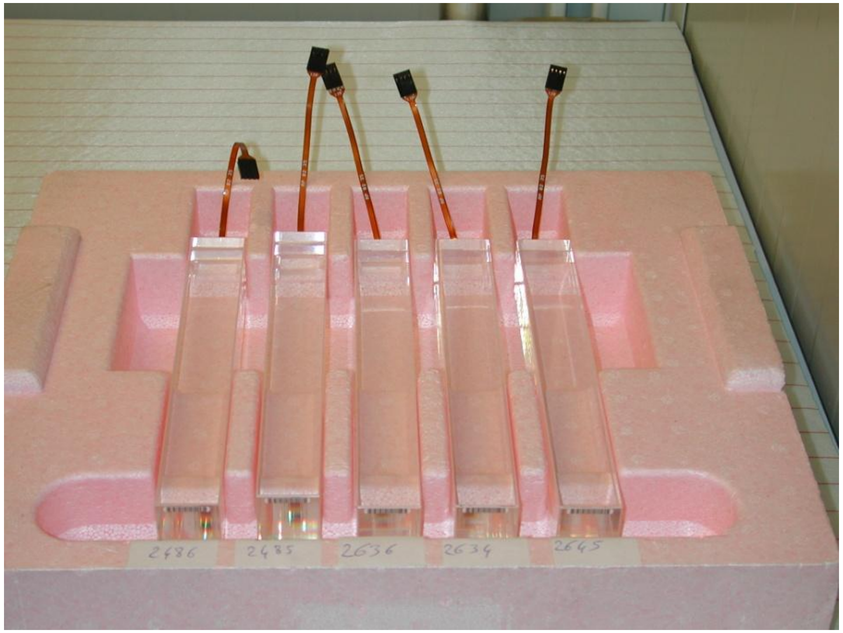




Note the large tracking volume as well

3D Granularity (3)

- The ECAL consists of
  - 75,848 crystals of $PbWO_4$
    - (75K towers in ALEPH)
  - with transverse size 2.2 x2.2 cm
    - (ALEPH : 3 x 3 cm)
  - Moliere radius 2.2 cm
    - (ALEPH 1.6 cm)
  - Radiation Lengths : 25.8 X_0
    - (ALEPH : 22X_0)



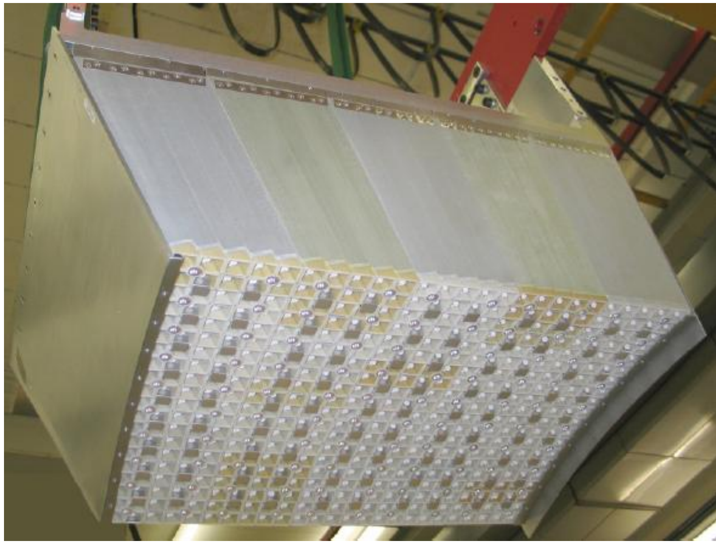
- Transverse granularity very similar to that of ALEPH
  - But no longitudinal segmentation : photon/electron ID slightly less pure/efficient
    - (3 segmentation in depth in ALEPH + 45 wire planes/module)
- Excellent energy resolution due to the homogenous material

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.30\%)^2,$$

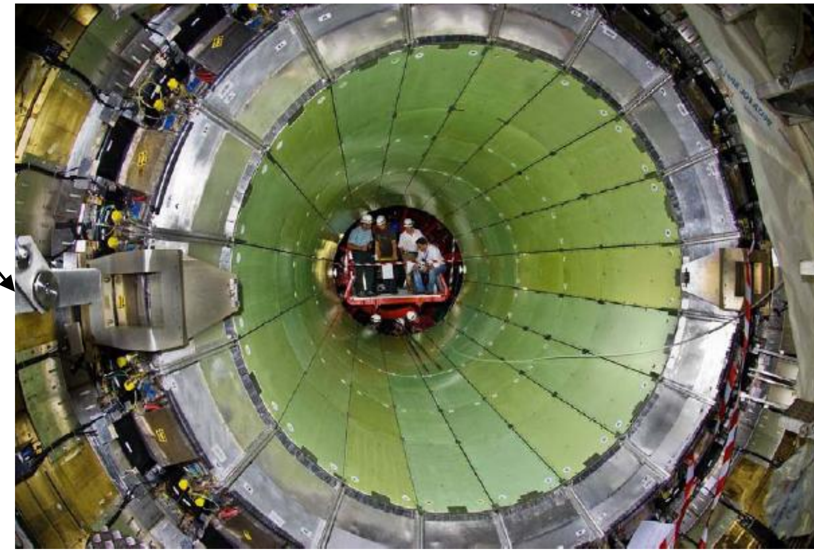
(ALEPH: 20%/√E, but non essential)

3D Granularity (4)

- ECAL crystals arranged towards quasi hermetic coverage



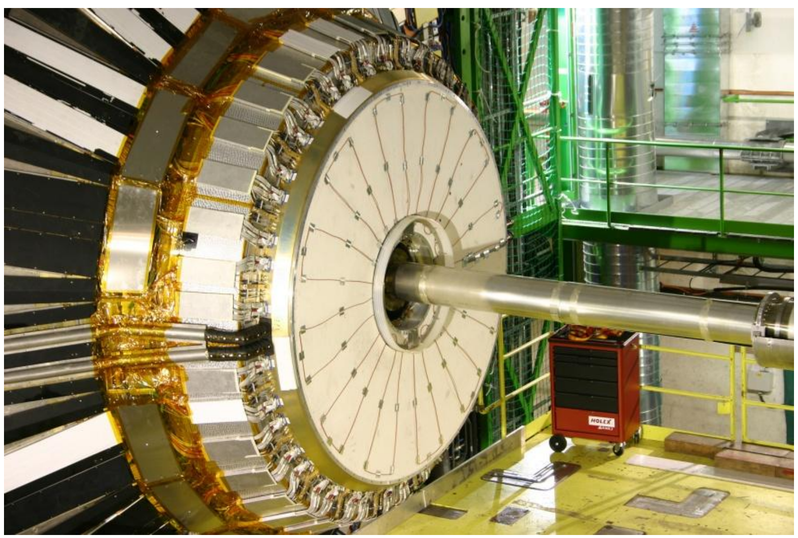
Barrel

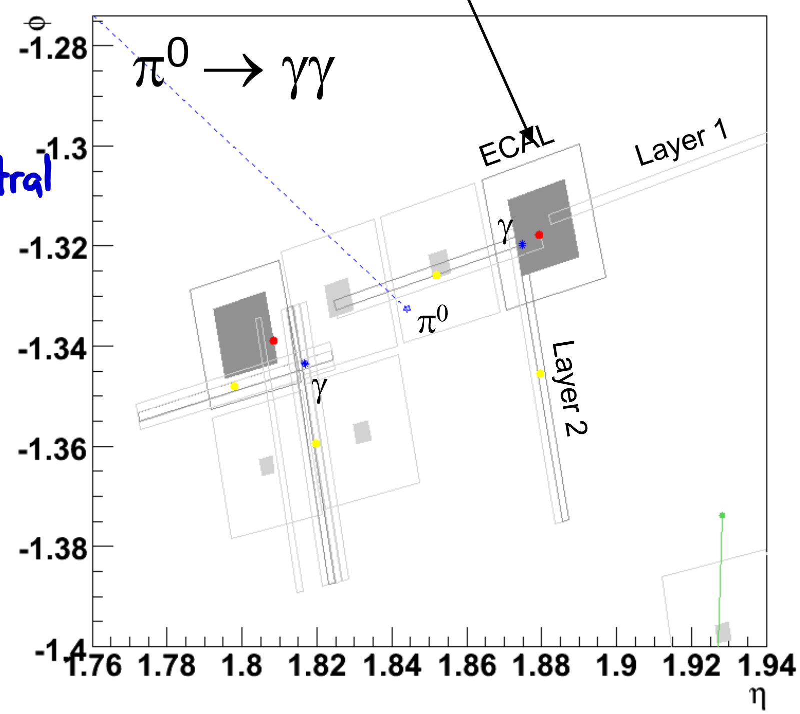


End-caps

3D Granularity (5)

- End-caps covered by a preshower detector
  - With two layers of Lead + Silicon Strips (6 cm long, 2mm wide, $3X_0$)
    - Increase transverse granularity in the end-cap region
    - Add a modest level of longitudinal segmentation
    - Adds complexity
    - Worsens energy resolution
  - Overall outcome turned out to be neutral

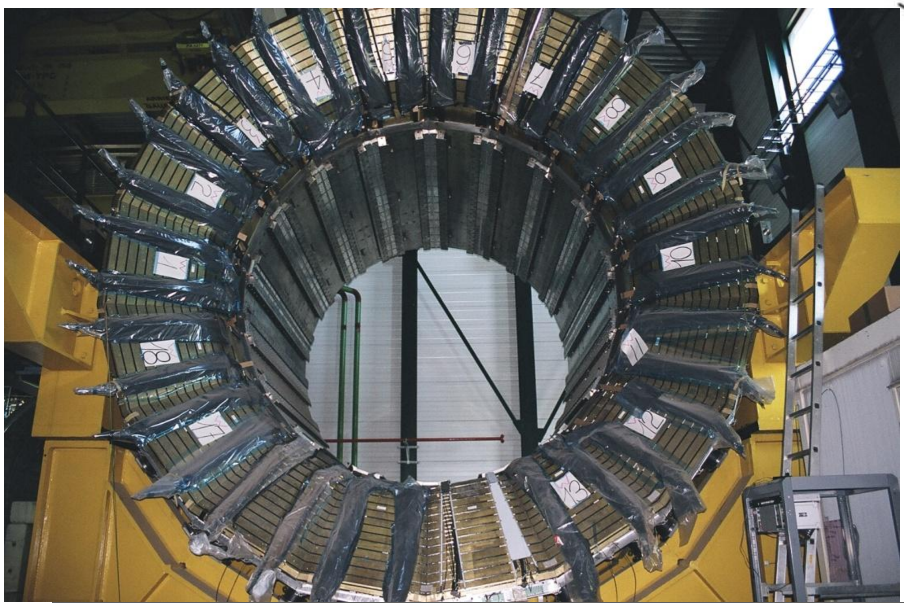


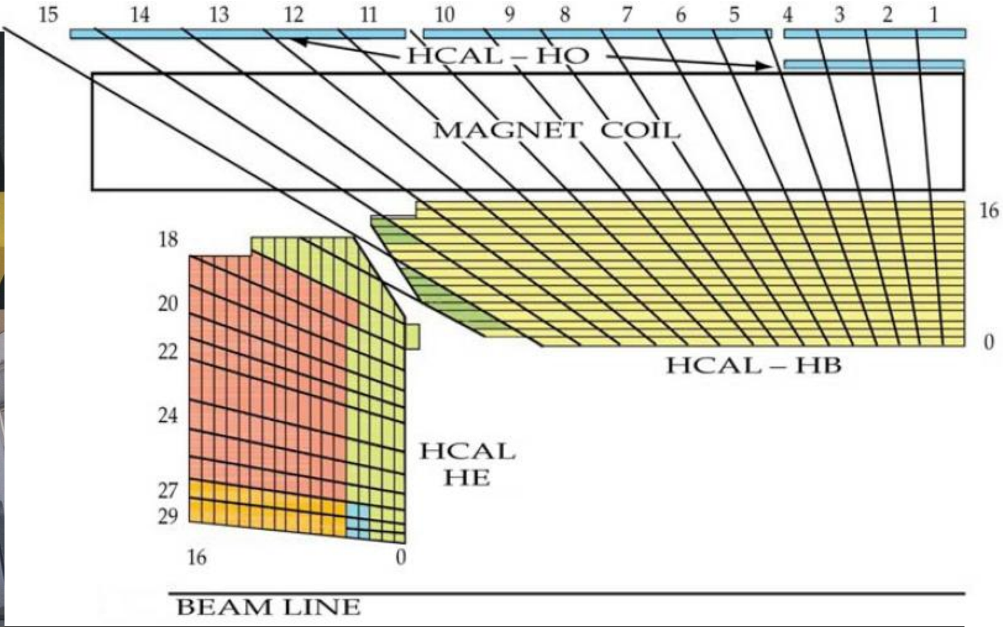


Better γ/π^0 separation ?
(electron pre-Id)

3D Granularity (6)

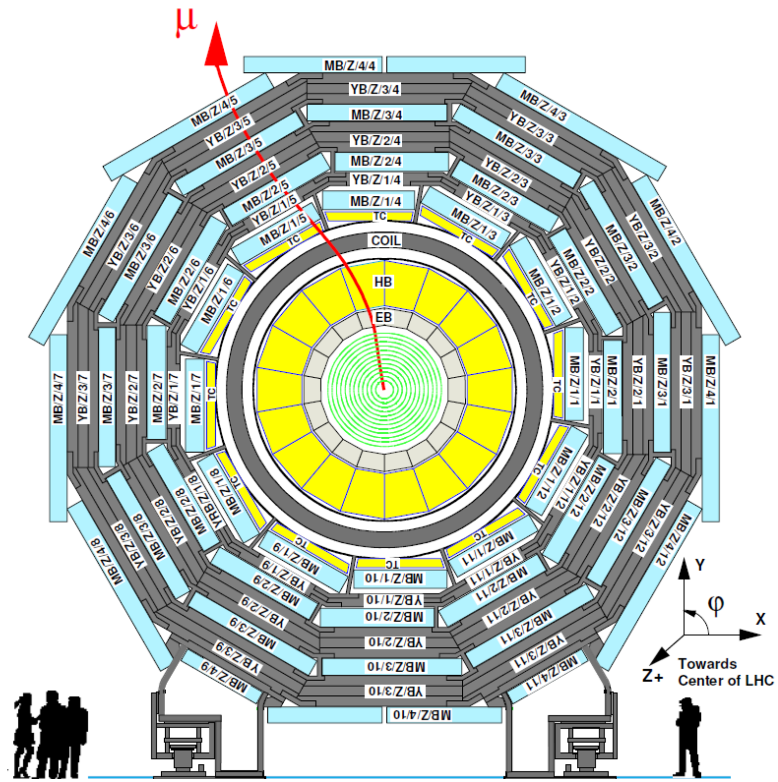
- The HCAL consists of
  - A sandwich of 16 plates of brass and scintillator tiles, from 5.5 to 10 λ_0 — Thin !
    - Read out into towers of transverse size 10 x 10 cm
      - → Similar transverse granularity to that of ALEPH
    - No longitudinal segmentation in the barrel (except HO), 2 depths in endcaps
      - → Similar to ALEPH for hadrons, but no layer-by-layer readout for muons





3D Granularity (7)

- ... but extensive 3D muon tracking behind the coil
  - For example, in the barrel ($|\eta| < 1.2$)
    - 4 muon stations, the first 3 with
      - → 8 layers of drift tubes
        - 4 for the $r\phi$ coordinate
        - 4 for the z coordinate
    - And the fourth with only $r\phi$
      - → For the momentum resolution
  - Similar design in end-caps ($|\eta| < 2.4$)
    - But cathode-strip chambers instead
      - → with anode wire measurements for z
- Muons should not be a problem
  - But watch out HCAL thickness
    - Energetic pion punch-through likely

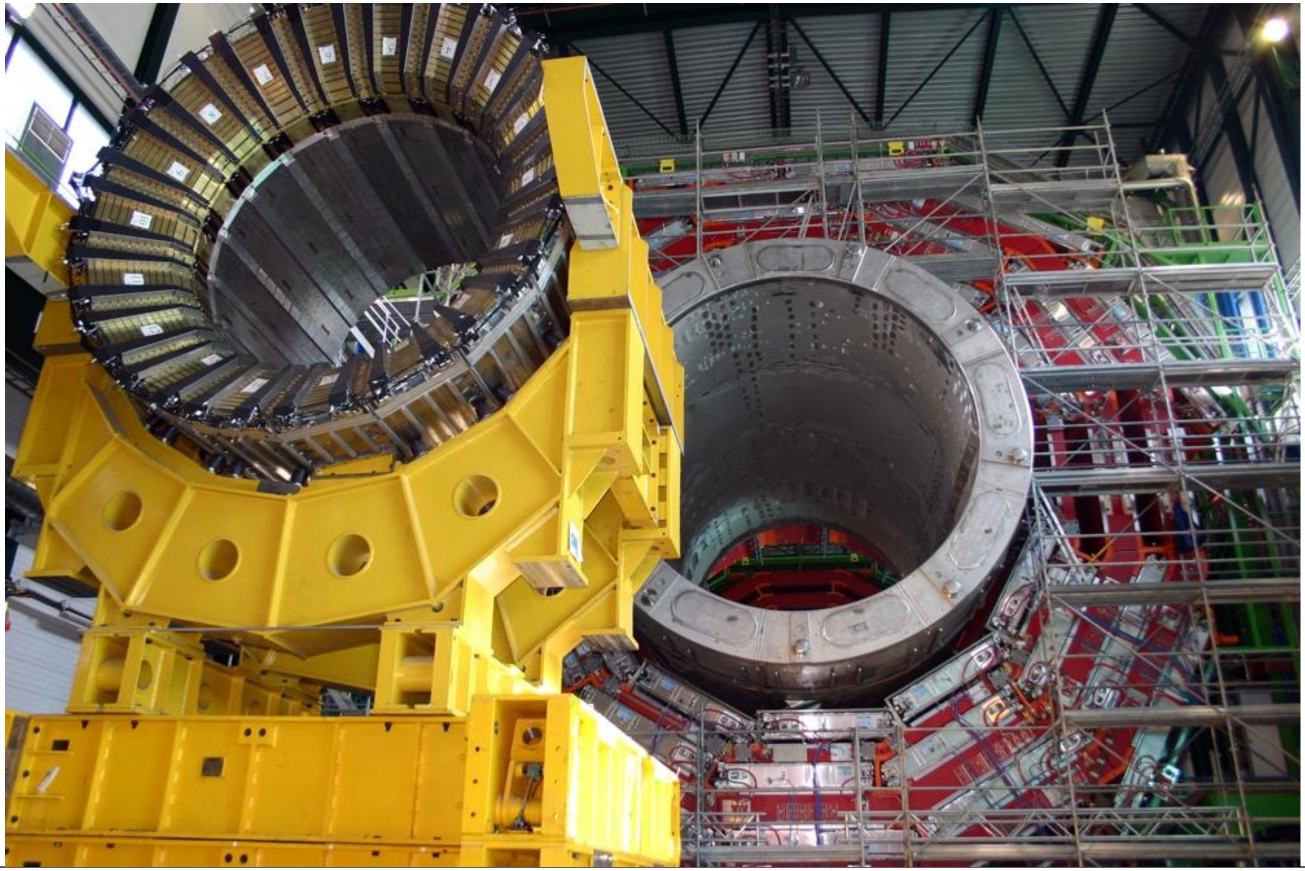


Redundancy : tough luck !

- That one is easy
  - There is essentially no redundancy for the energy measurements
    - Neither in the ECAL (only the crystal light is collected)
    - Nor in the HCAL (only the scintillator light is collected)
  - Calorimeter cleaning might be challenging
    - And CMS calorimeters turned out to be more noisy than ALEPH's ...
    - Need to use isolation and timing of the signals to disentangle with noise
      - → Careful with overcleaning !
  - Particle identification might be complicated by the absence of redundancy
    - But let's see how it comes out.

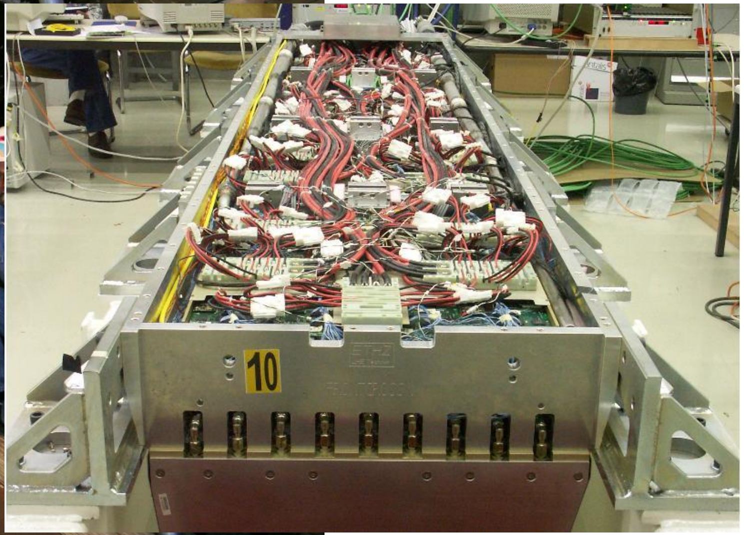
Material Budget (I)

- As we already mentioned : the coil is behind the HCAL
  - One λ_0 less in front of HCAL with respect to ALEPH
    - Less neutral hadrons lost, less charged hadrons showering



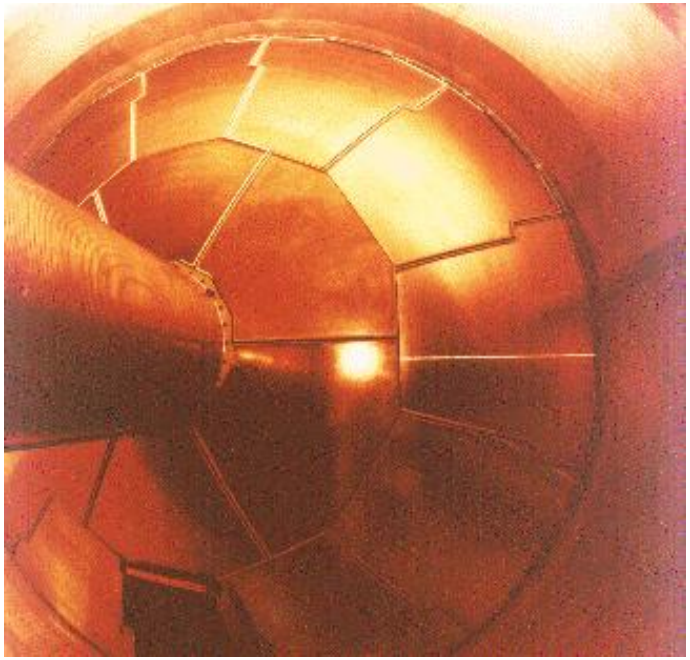
Material budget (2)

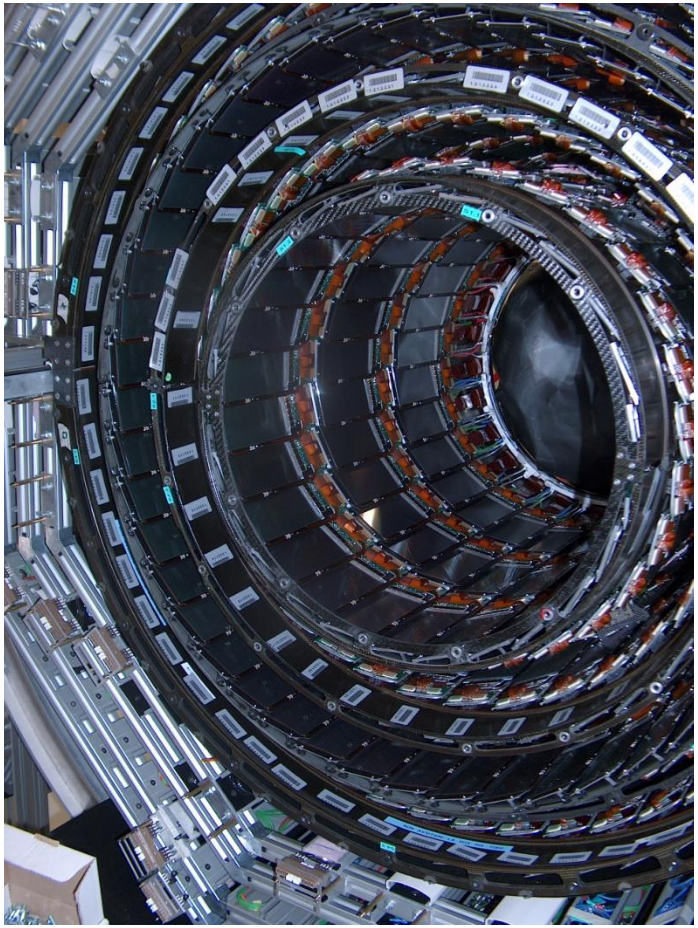
- But ECAL services ($0.5\lambda_0$) between ECAL and HCAL
  - Mostly back to ALEPH situation … It was too good to be true !



Material budget (3)

- The tracker is not a TPC (too slow for LHC), but a silicon tracker
  - Remember the TPC [mostly empty] ? .... And here we are now [mostly full] !



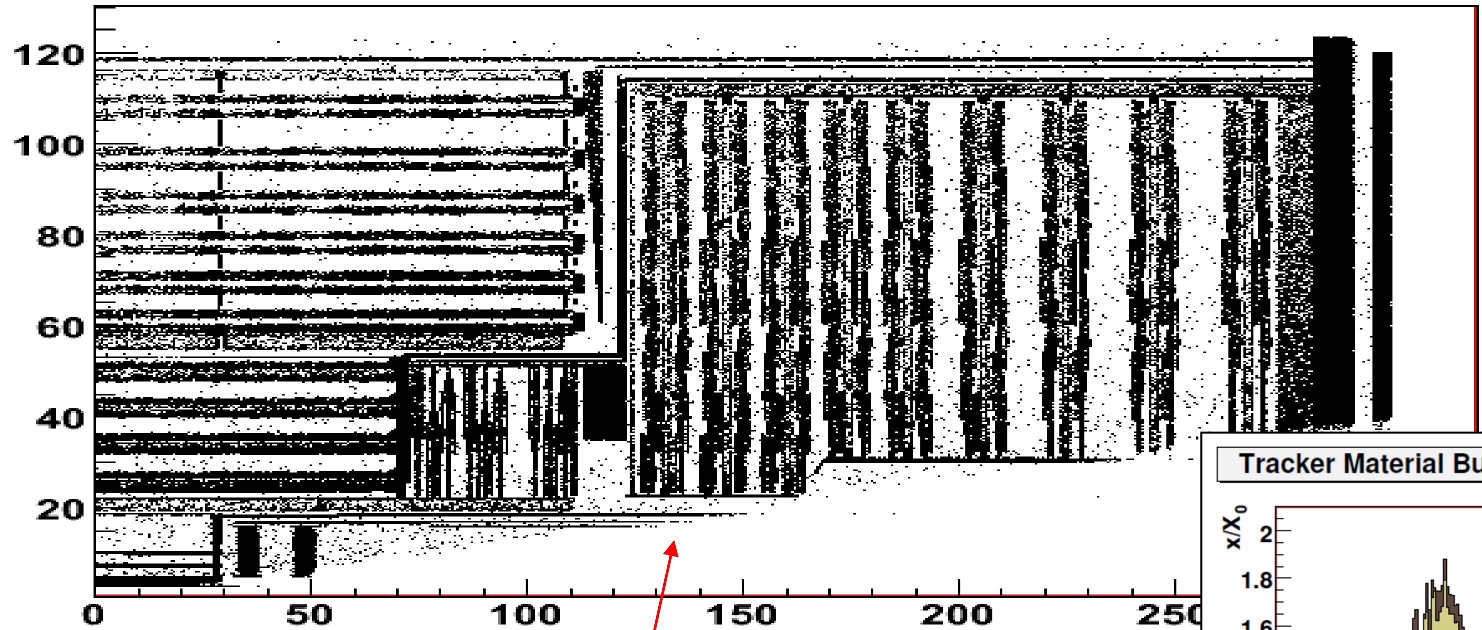


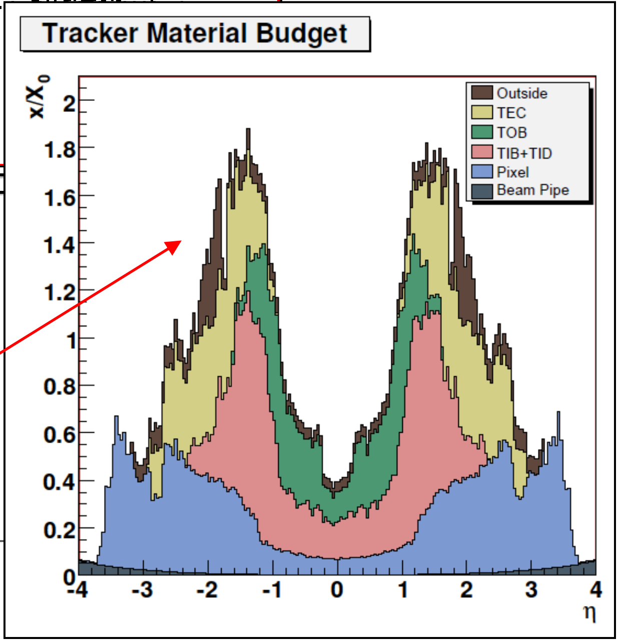
- The CMS tracker looks very thick

Material budget (4)

- … And it is thick indeed !

Full Tracker radiography (MC information)





- Vertices of converted single photons (100k photons)
  - Services account for 90% of the material
  - From $0.5X_0$ up to $2X_0$ in the tracker !
    - → (was predicted to be $0.8X_0$ in 2000)

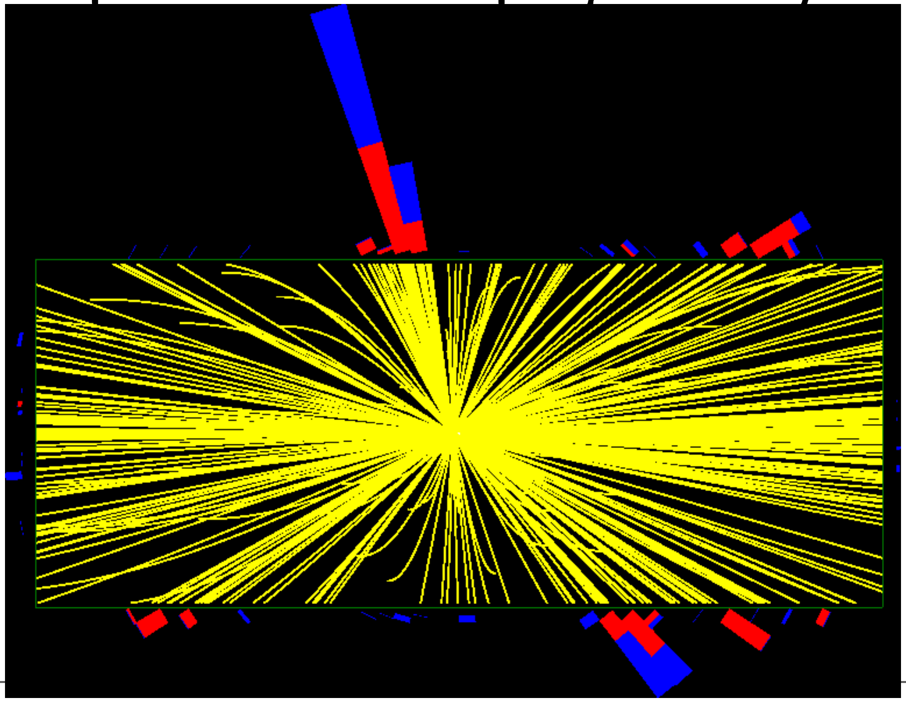
CMS design and Particle Flow : Summary

- Situation so far, when compared to ALEPH
  - Simplicity : OK
    - (despite the presence of the pre-shower ?)
  - Hermeticity : OK
    - (did not talk of the forward HCAL, no tracker there)
  - Large magnetic field : OK
    - Actually much larger than ALEPH, may compensate granularity
  - 3D granularity : almost OK
    - Less tracker measurements, not all 3D; No ECAL longitudinal segmentation
    - Note: much better E resolution in ECAL; slightly worse in HCAL (120%/$\sqrt{E}$)
- So far so good – and even quite promising – but …
  - No redundancy whatsoever
  - Tracker material might be a killer for particle-flow reconstruction
    - Note: what is the need of a pre-shower after $2X_0$ in the tracker ?

Overall CMS environment (I)

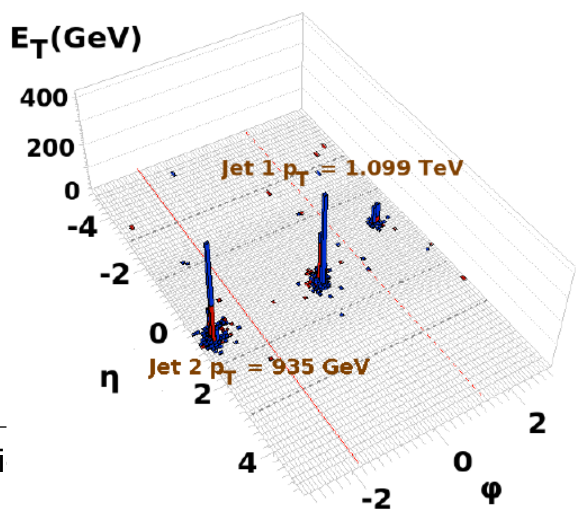
- Two major differences with ALEPH
  - The LHC is a pp collider (and from time to time a PbPb collider)
    - Much larger particle multiplicity in the final state than at LEP
      - → Not mentioning pile-up collisions, which enhance the problem

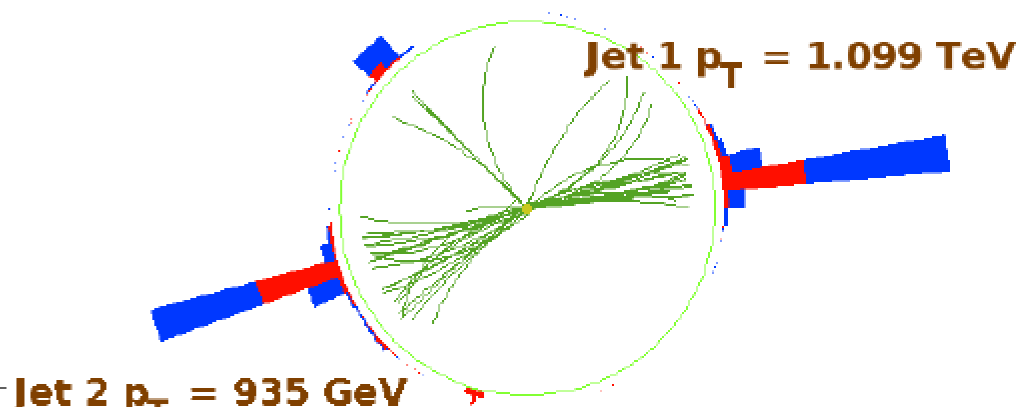
        More confusion is possible, although granularity is mostly adequate to keep the detector occupancy low enough



Overall CMS environment (2)

- Two major differences with ALEPH (cont'd)
  - Energy spectrum for reconstructed particles from 200 MeV to 5 TeV
    - Was 100 MeV to 100 GeV at LEP
  - For jets with very large p_T, charged and neutrals are less separated
    - Separation becomes smaller than detector segmentation at one point;
    - Particle identification becomes less efficient; momenta less well measured;
    - The PF performance converges (for jets) to a pure calo determination ?
      - → Given the B field, the Σp_T at which this happens is probably large
      - → There are always low p_T particles in jets, for which PF will help anyway



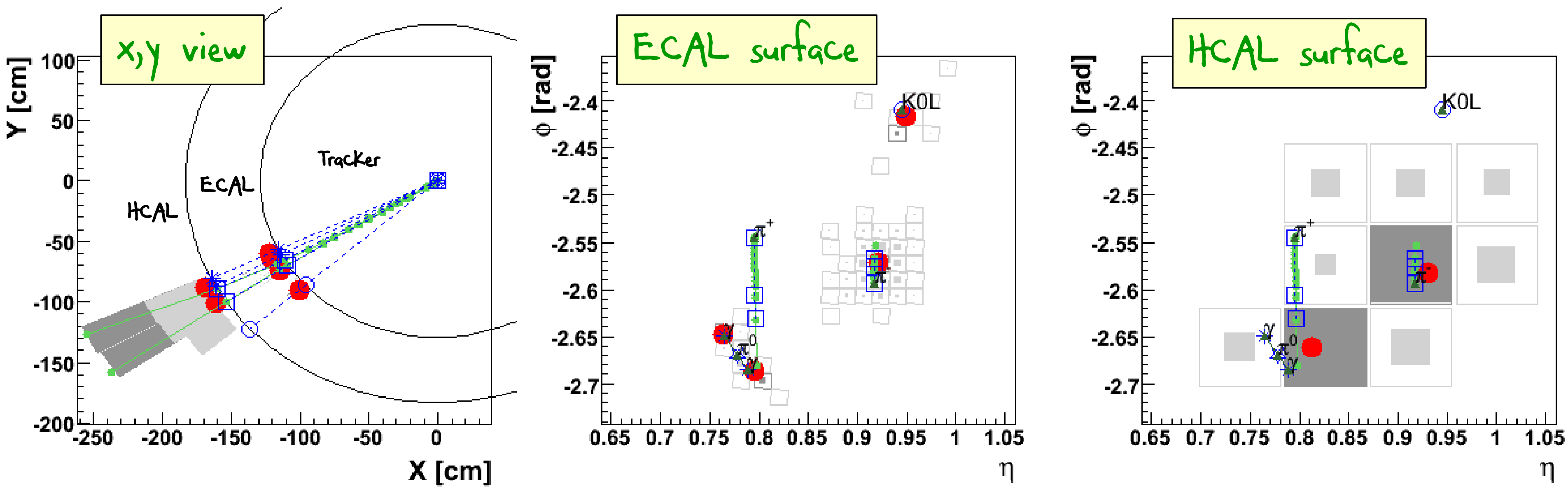


Back to 2005 : Checking CMS basic promises (I)

- Pre-requisite for particle-flow reconstruction
  - Reconstruct (some) charge particle tracks for charged hadrons
    - Seeded with at least two hits in the pixel detector
      - → Originating from the beam axis within tight tolerances
    - Pattern recognition with a combinatorial Kalmann-Filter track finder
      - → Request at least 8 hits and $p_T > 1$ GeV/c
  - Reconstruct clusters in the ECAL and HCAL, for photons and hadrons
    - Seeded by cells above a given energy threshold
      - → 230 MeV in ECAL, 1 GeV in HCAL
    - Surrounded by 4 direct neighbouring cells with smaller energies
      - → Optimal use of the available granularity (better than ALEPH for HCAL)
    - There might be several seeds/sub-clusters in a given "topological" cluster
      - → Share the cell energies among the sub-clusters (according to $d_{seed,cell}$)
  - Ignore electrons and muons for the time being (for pedagogical purposes)

Back to 2005 : Checking CMS basic promises (2)

- First fully simulated jet, p_T = 100 GeV (Tracker thickness < $1X_0$)
  - Four particles : π^+, π^-, π^0 and K^0_L



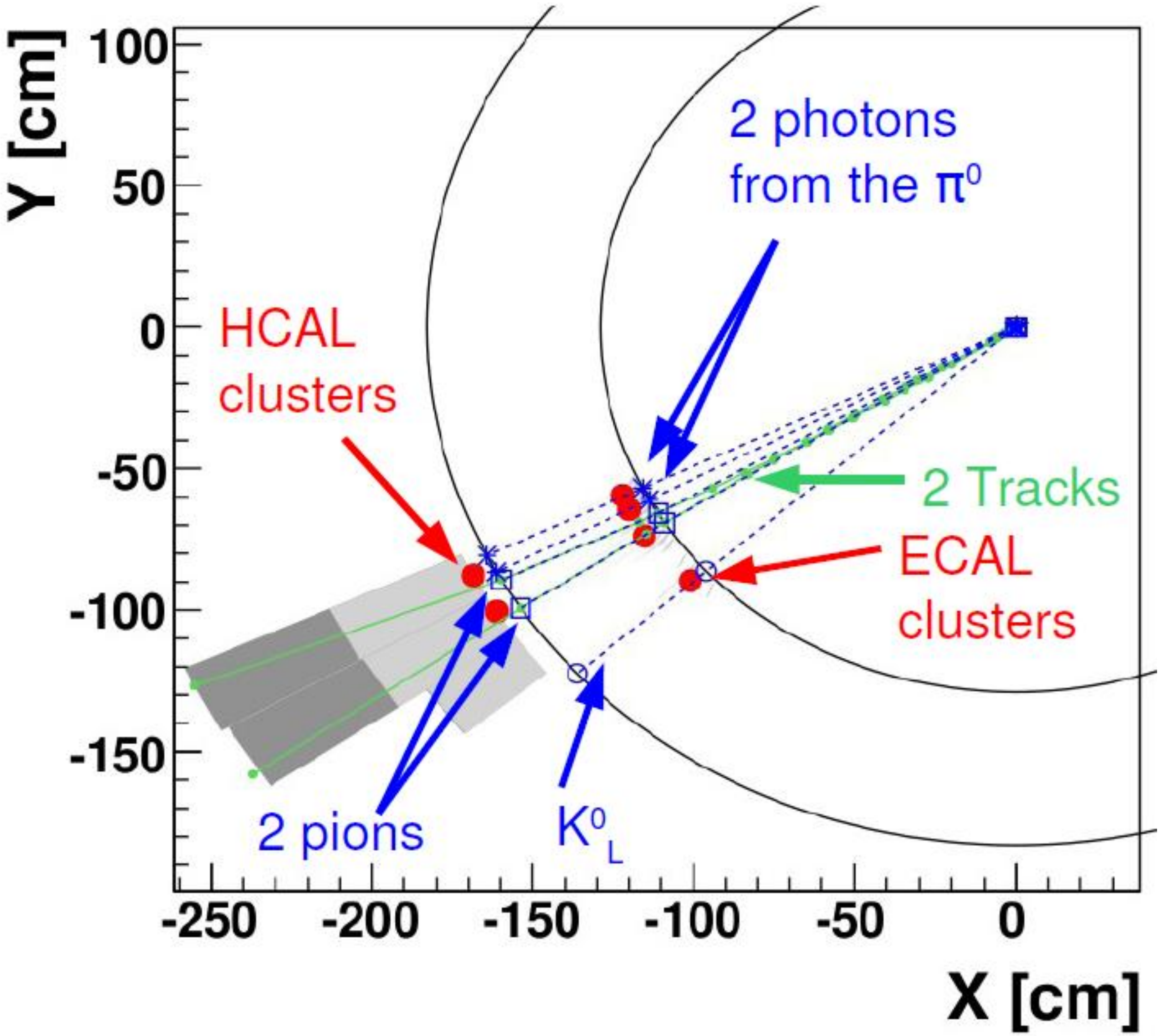
True particles in blue, Tracks and tracker hits in green

Cluster seeds in dark grey, cluster position in red, other cluster cells in light gray

- From this sole jet, PF feasibility with CMS was declared
  - Simplicity, magnetic field and granularity appeared to be adequate indeed.

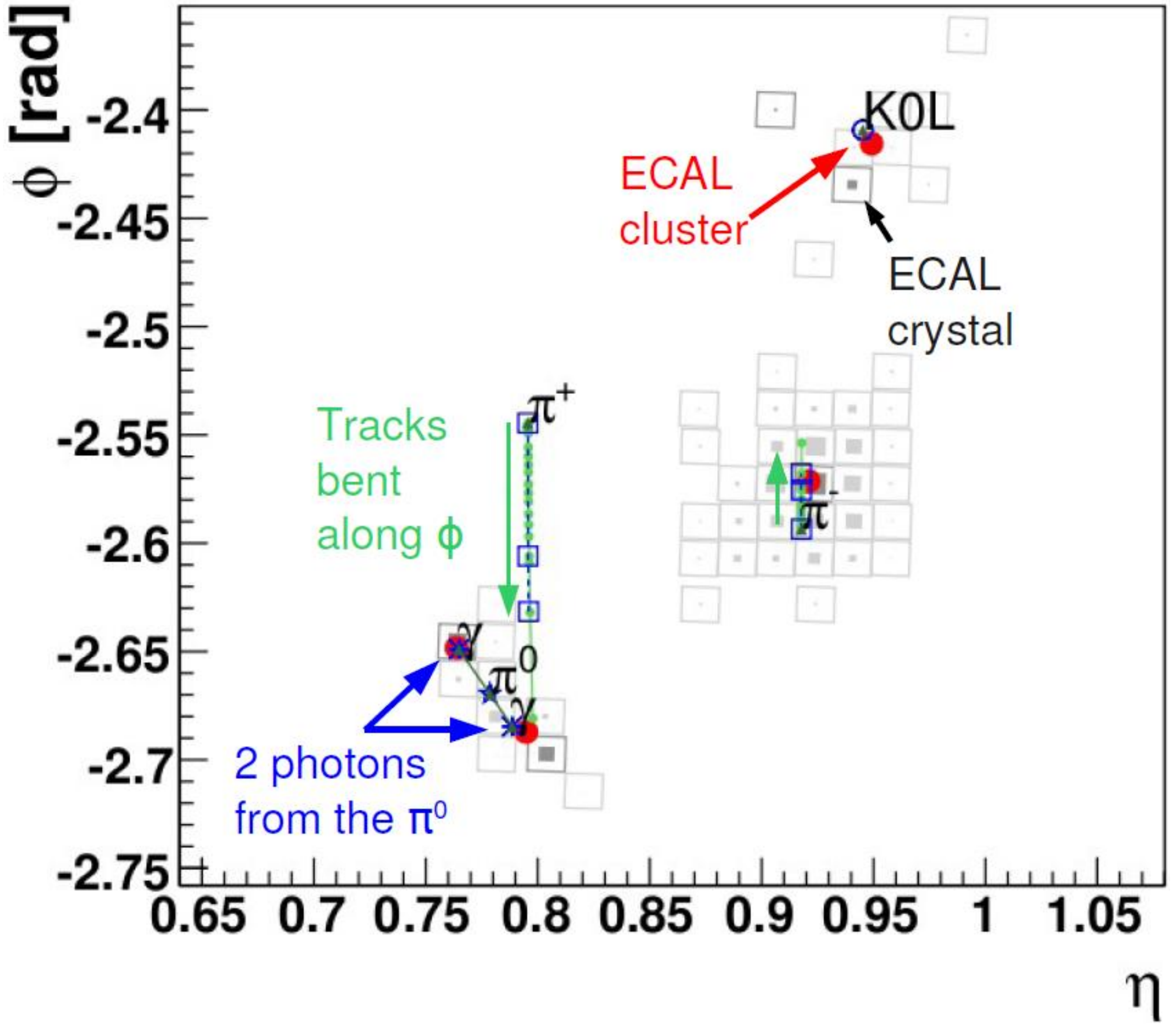
Back to 2005 : Checking CMS basic promises (3)

- The x,y (or r,φ) view in more details



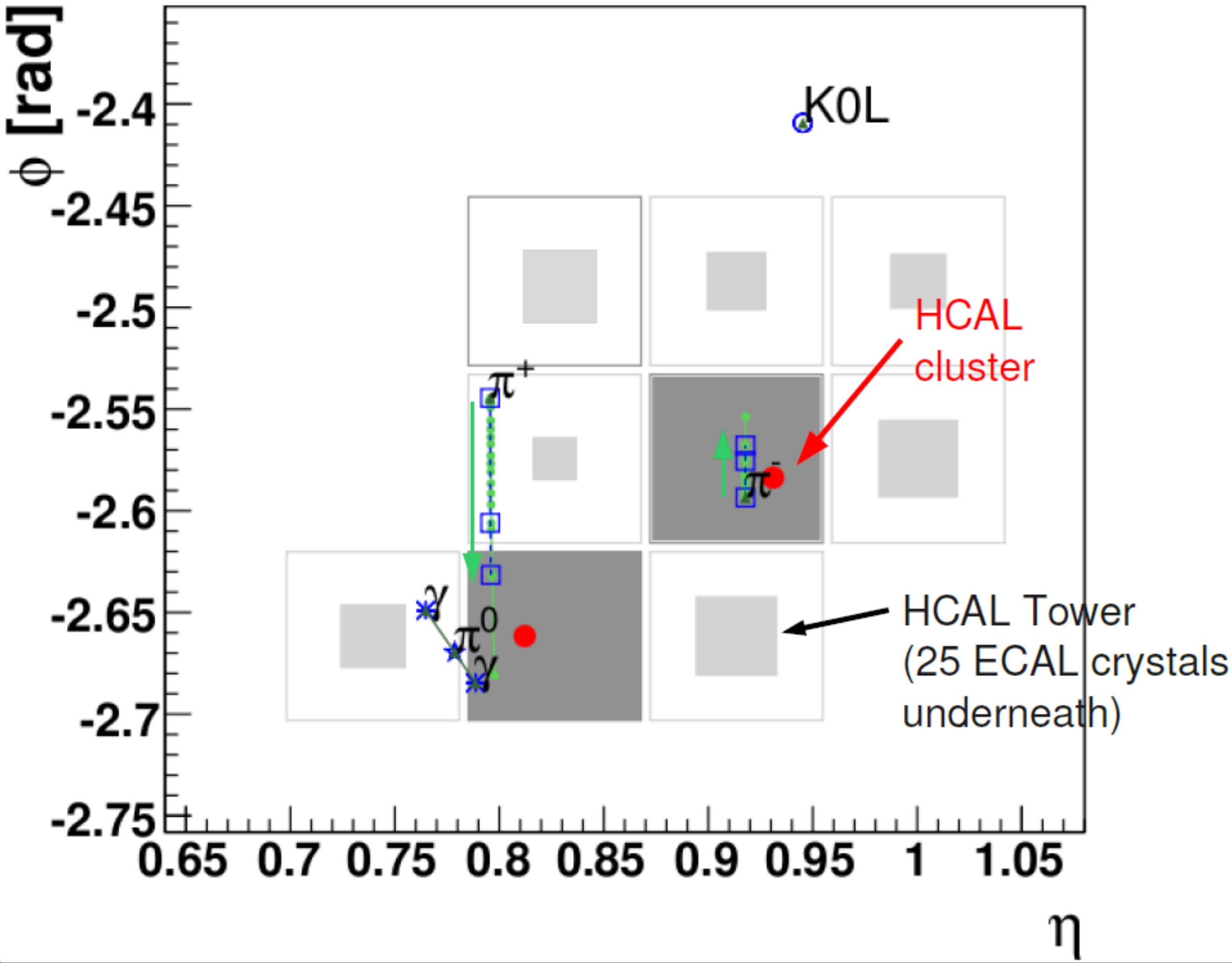
Back to 2005 : Checking CMS basic promises (4)

- The ECAL surface (η,φ) view in more details



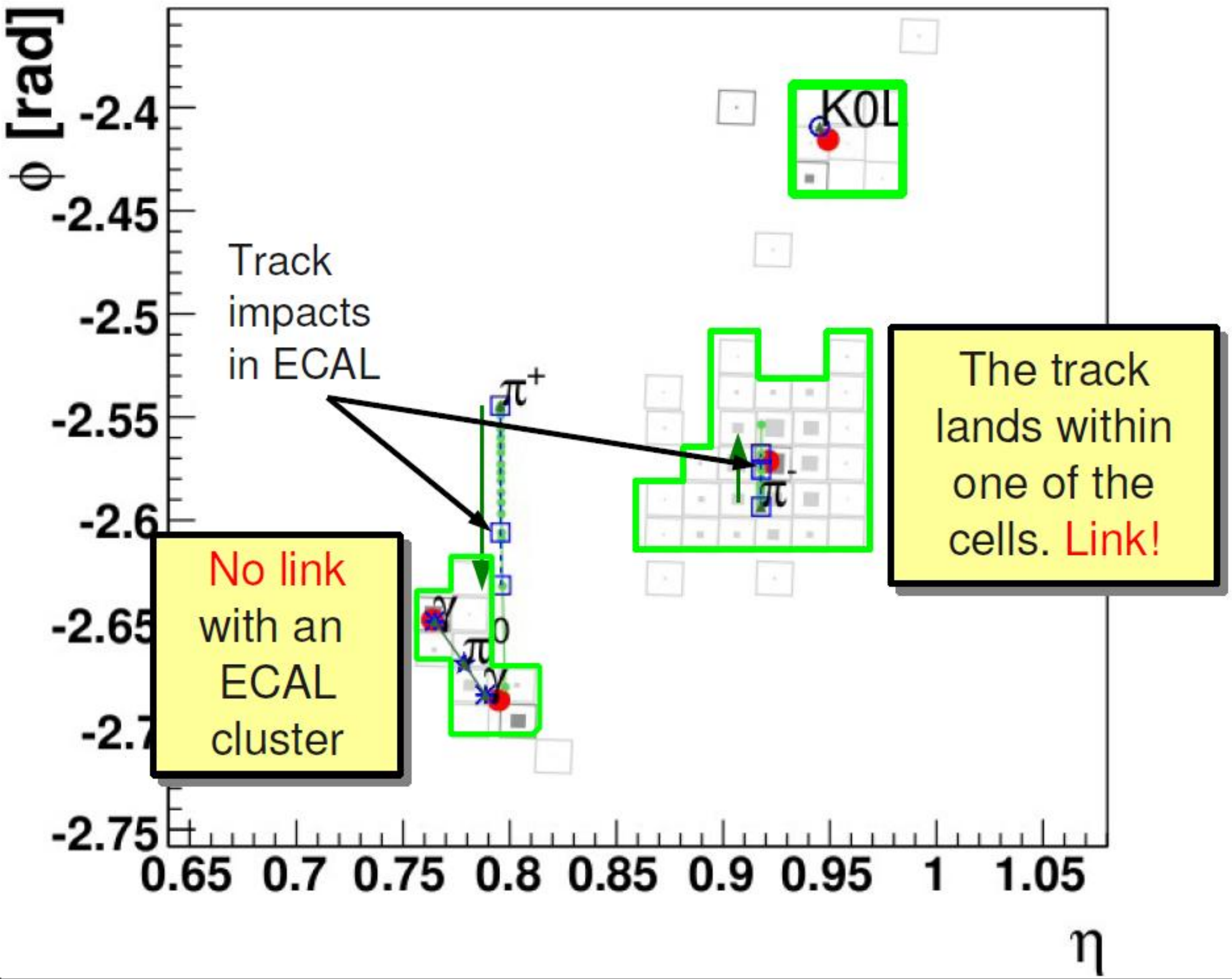
Back to 2005 : Checking CMS basic promises (5)

- The HCAL surface view (η,ϕ) in more details



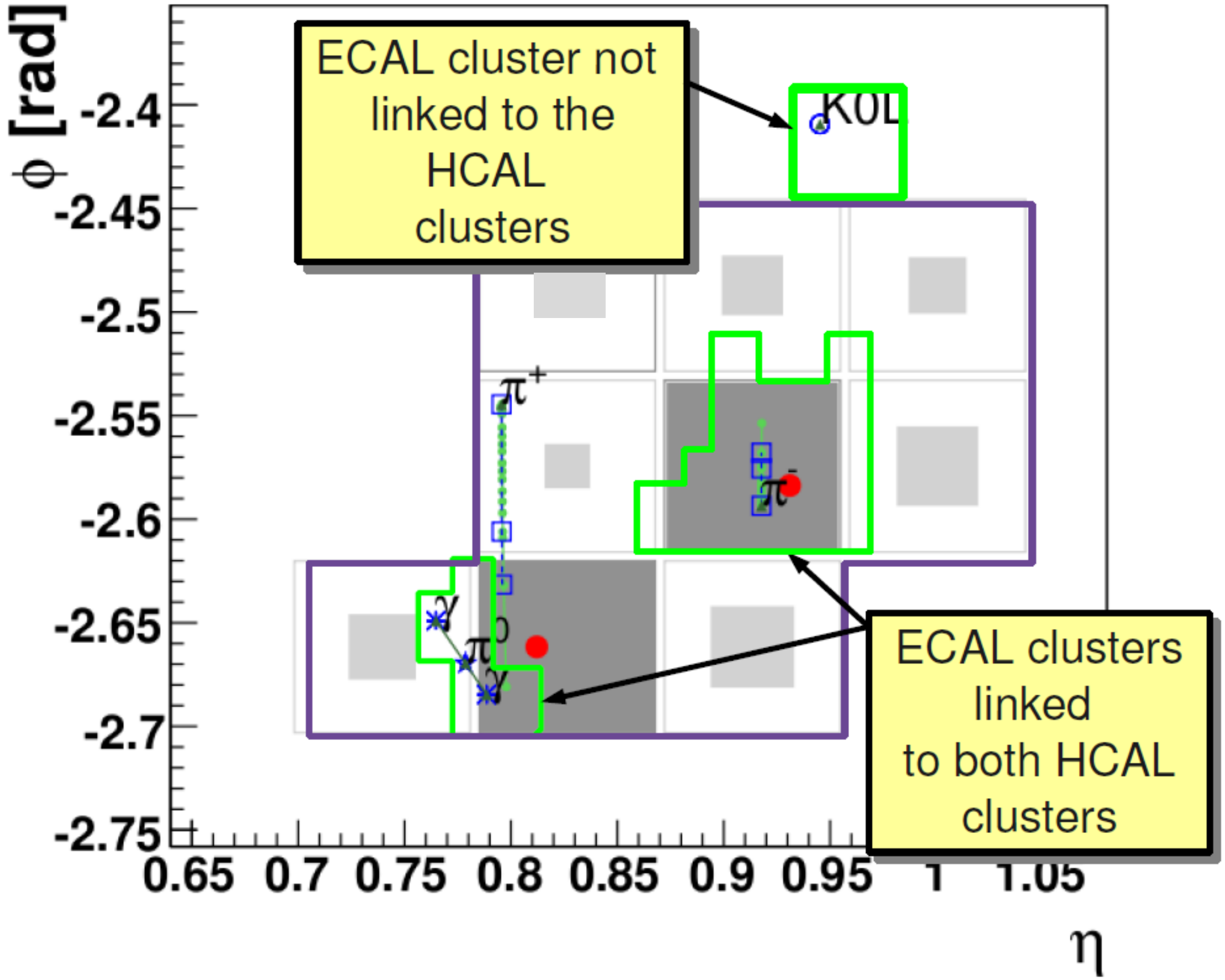
Back to 2005 : checking CMS basic promises (6)

- Track – ECAL cluster link



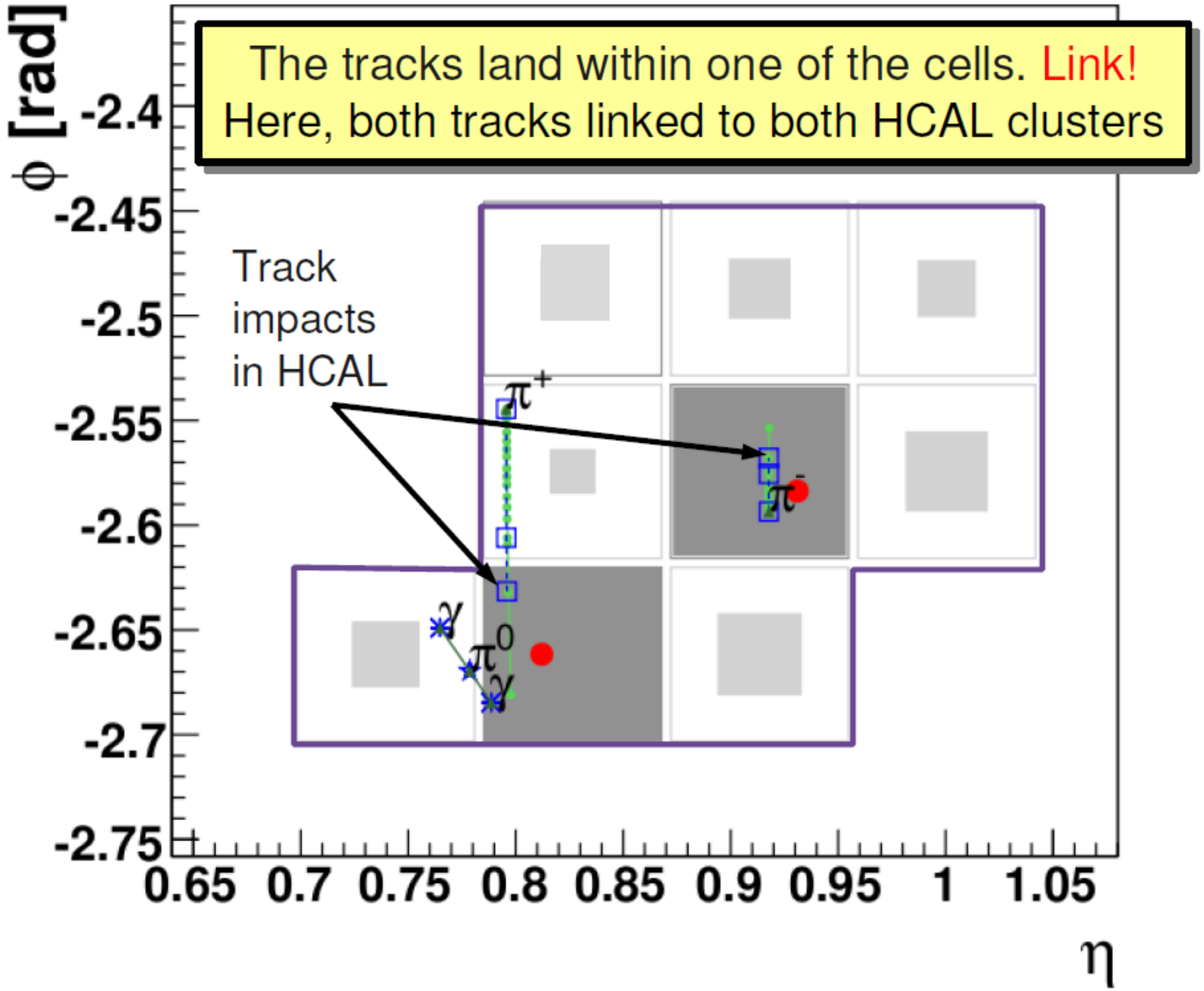
Back to 2005 : Checking CMS basic promises (7)

- ECAL cluster – HCAL cluster link



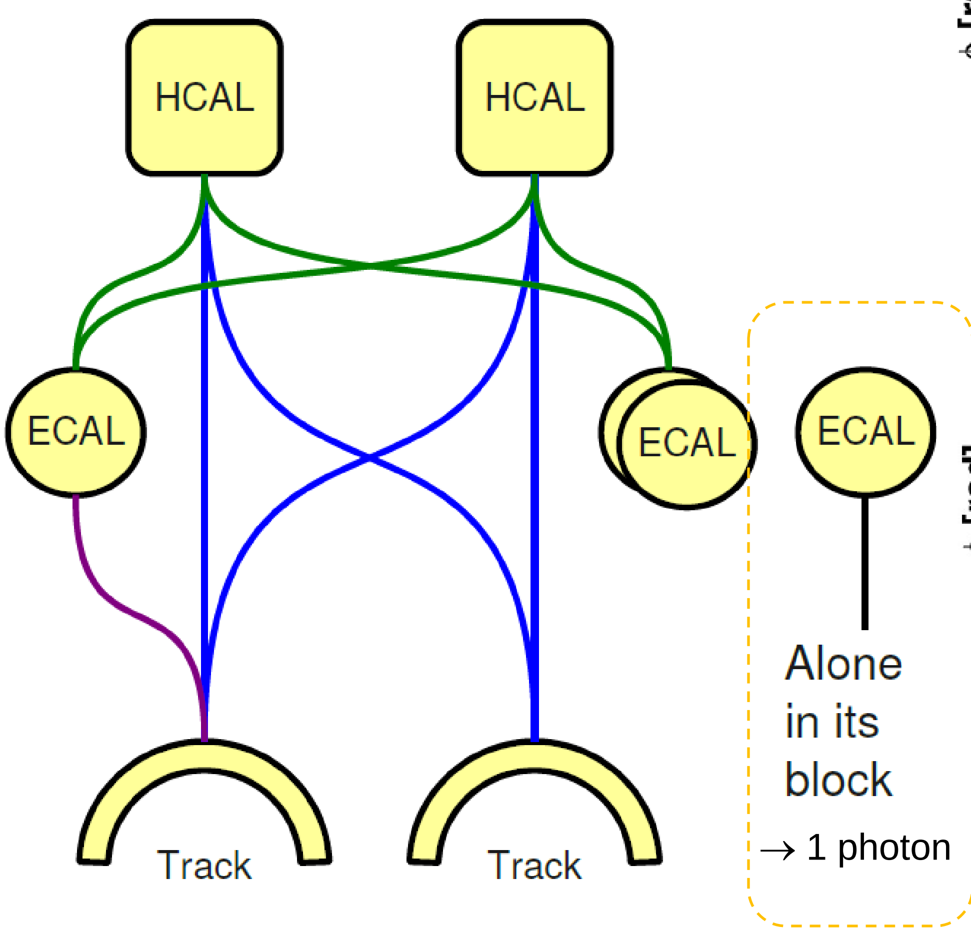
Back to 2005 : Checking CMS basic promises (8)

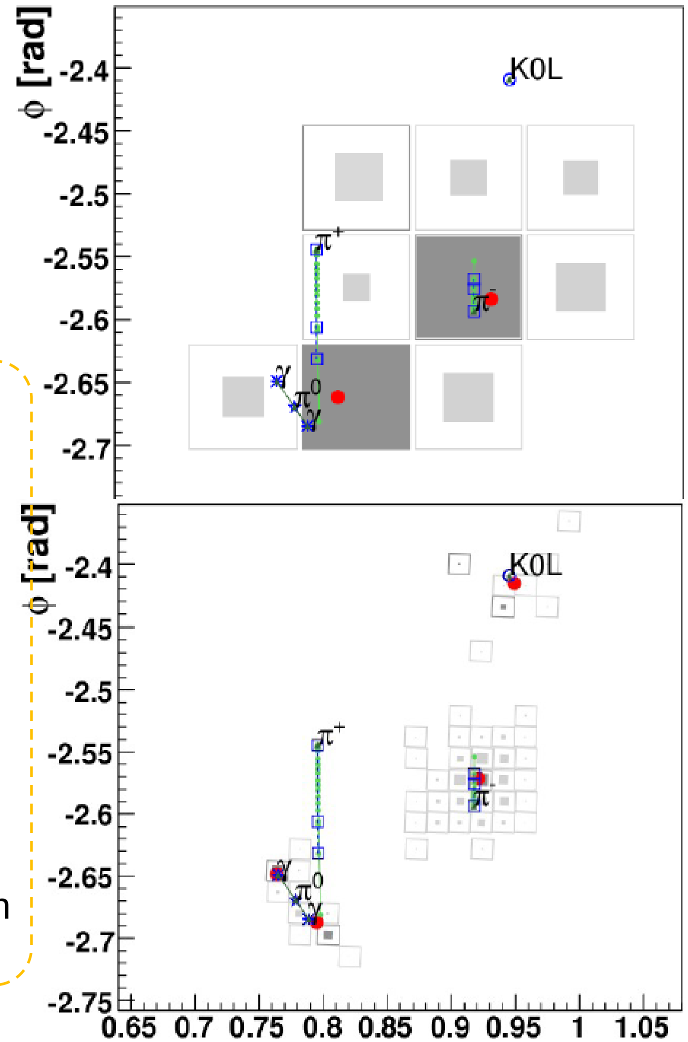
- Track – HCAL cluster link



Back to 2005 : Checking CMS basic promises (9)

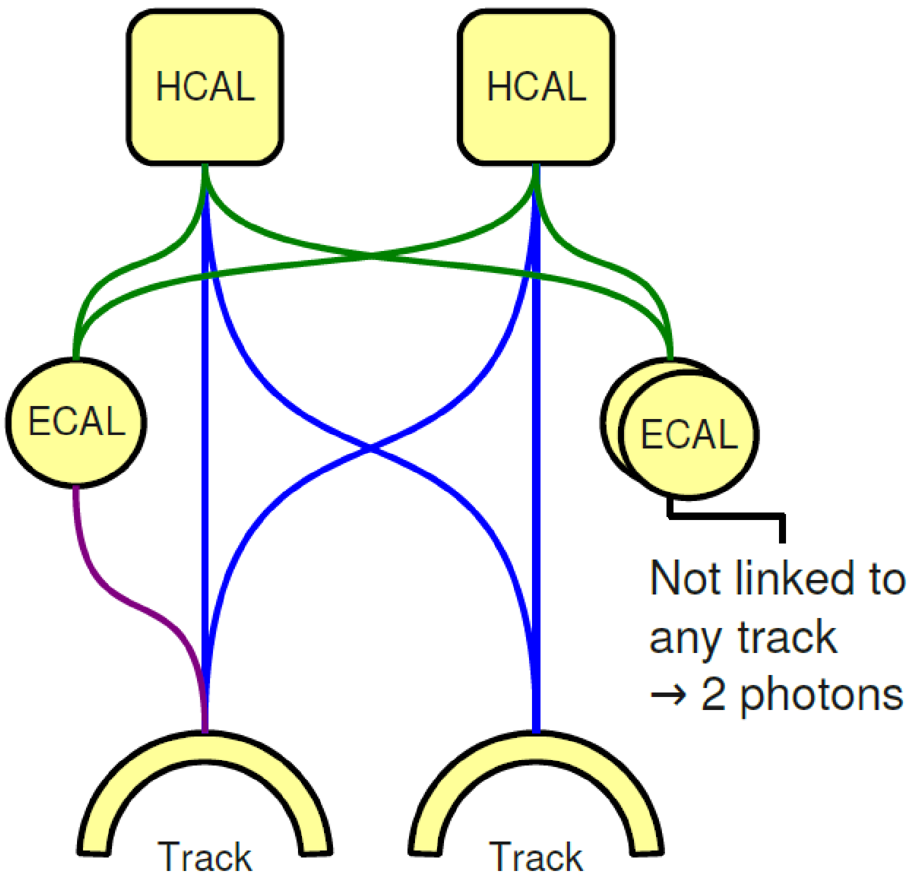
- Build "blocks" of elements linked to each other

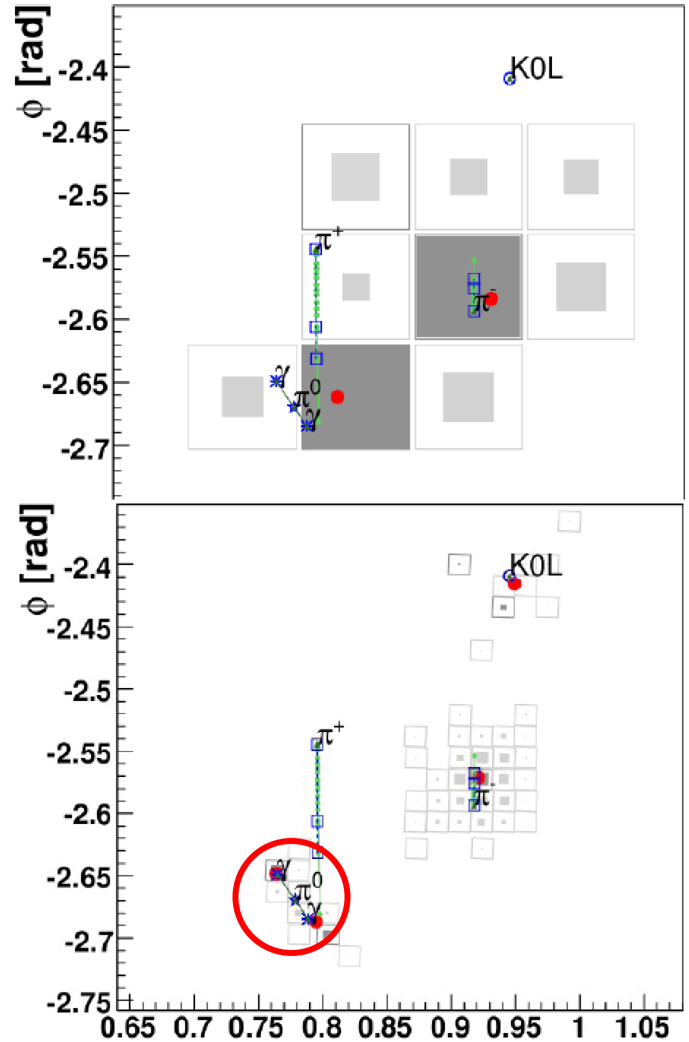




Back to 2005 : Checking CMS basic promises (10)

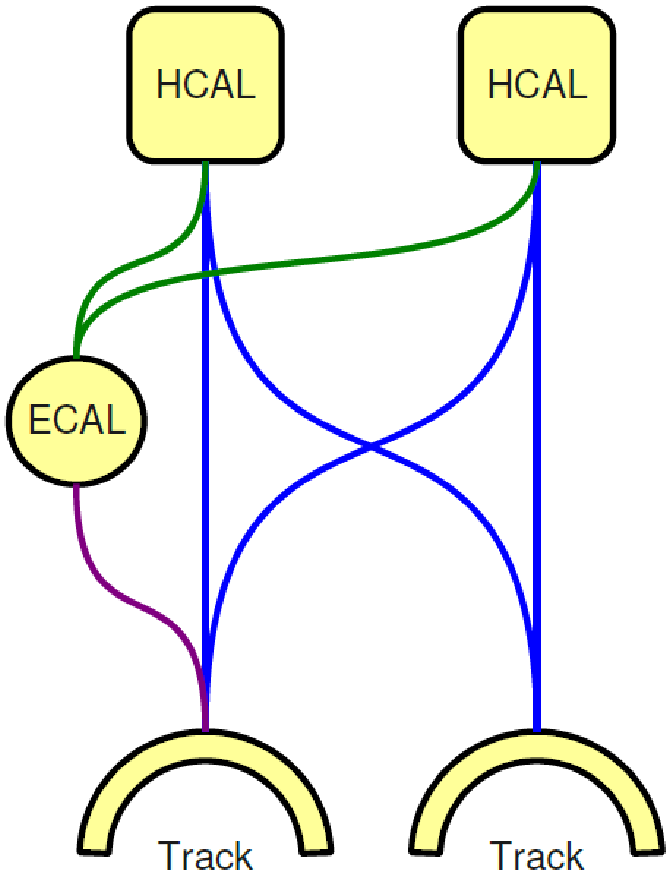
- Find isolated photons in the blocks

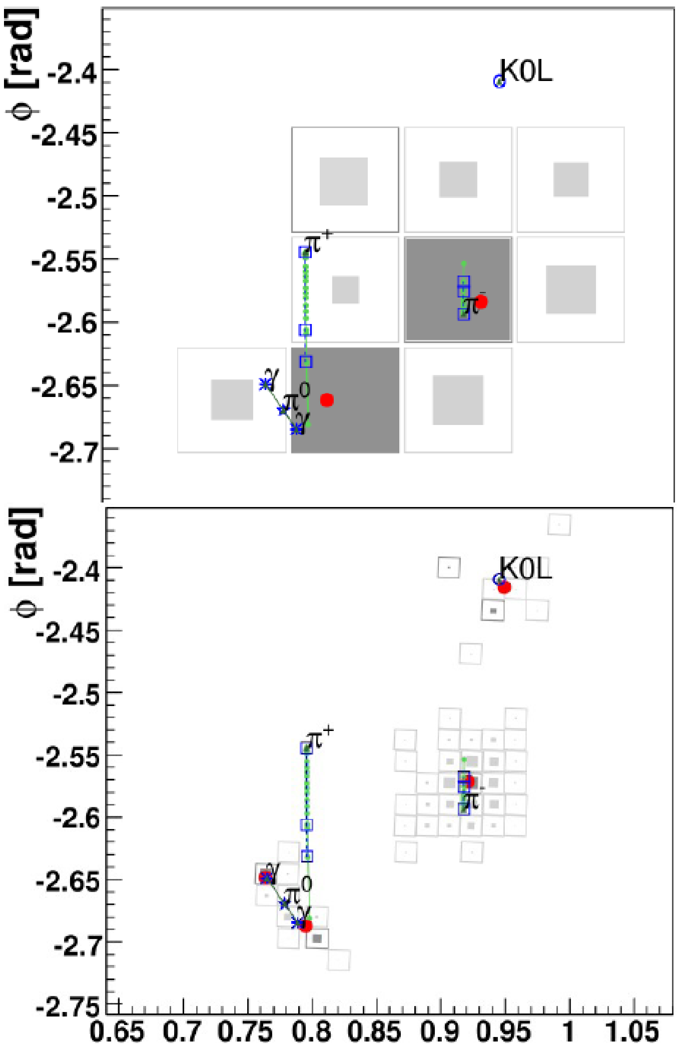




Back to 2005 : Checking CMS basic promises (II)

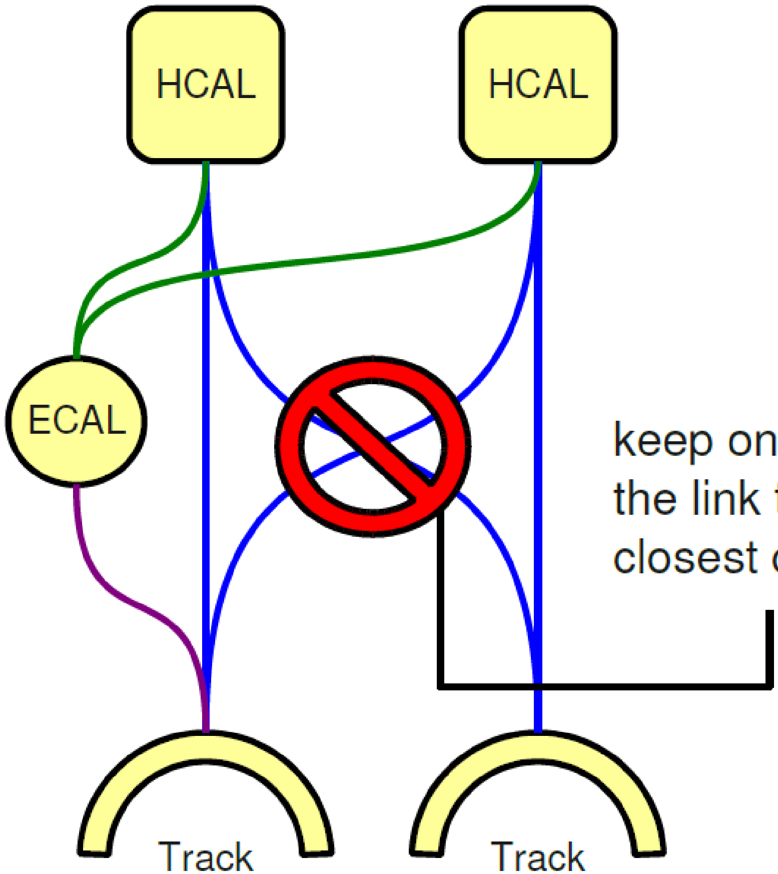
- Simplified block (1st step)



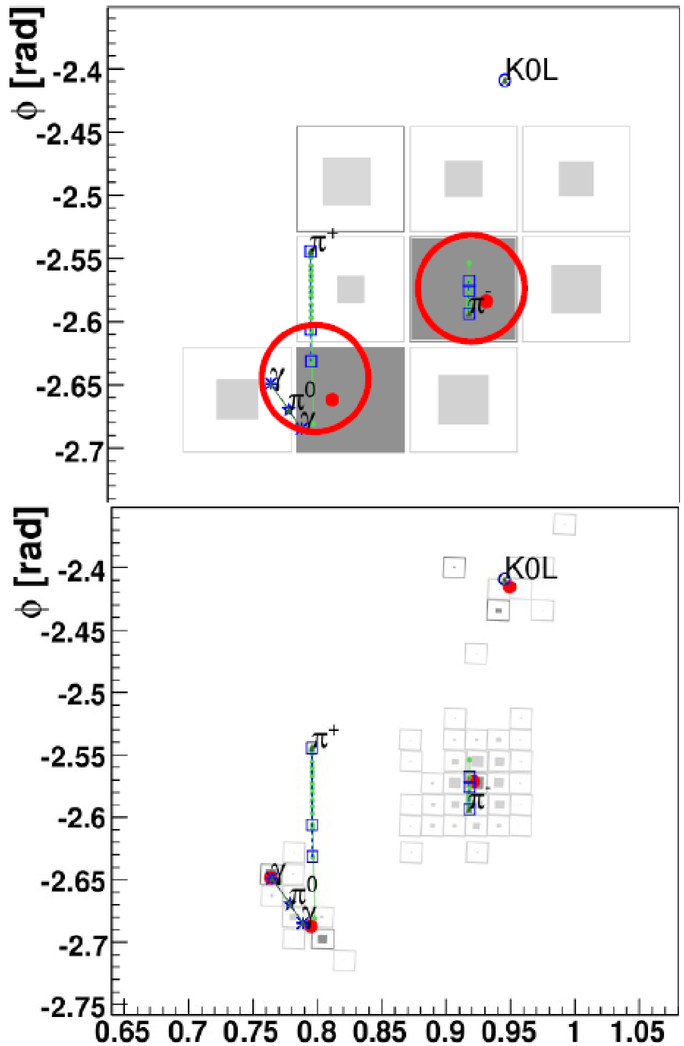


Back to 2005 : Checking CMS basic promises (12)

- Optimize the use of HCAL granularity

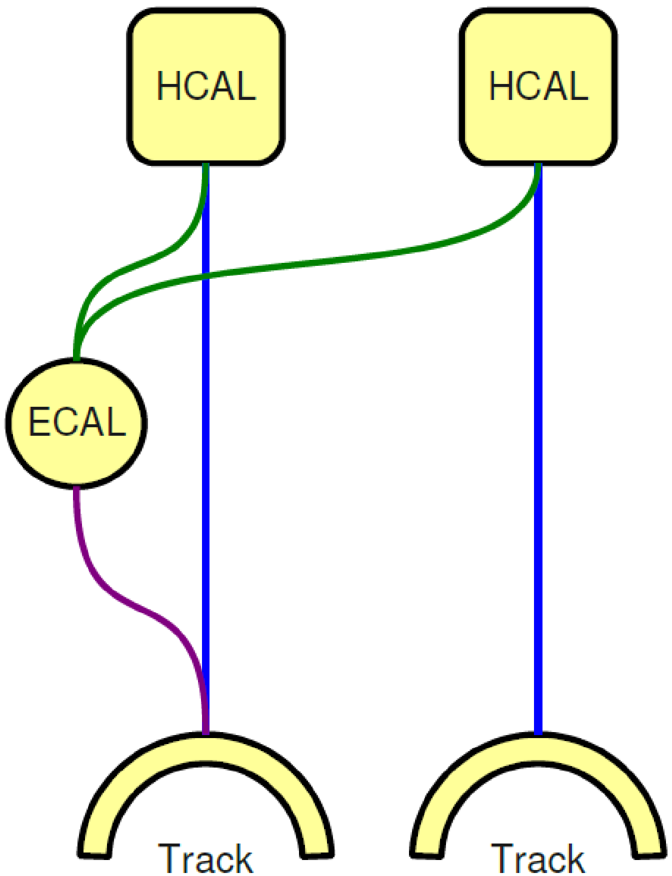


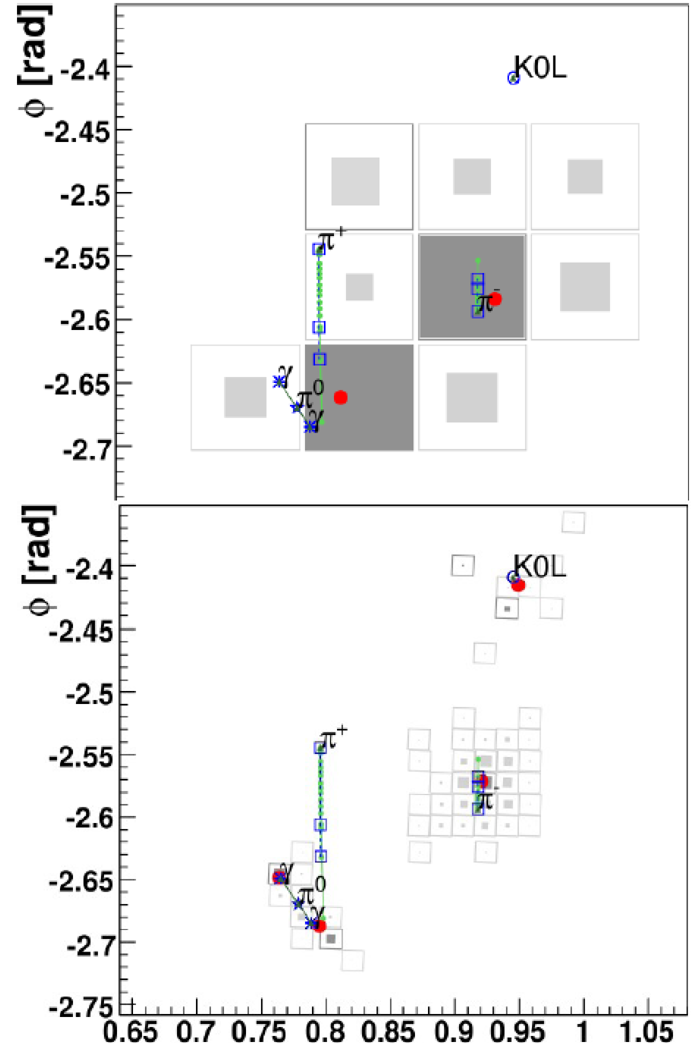
keep only the link to the closest cluster



Back to 2005 : Checking CMS basic promises (13)

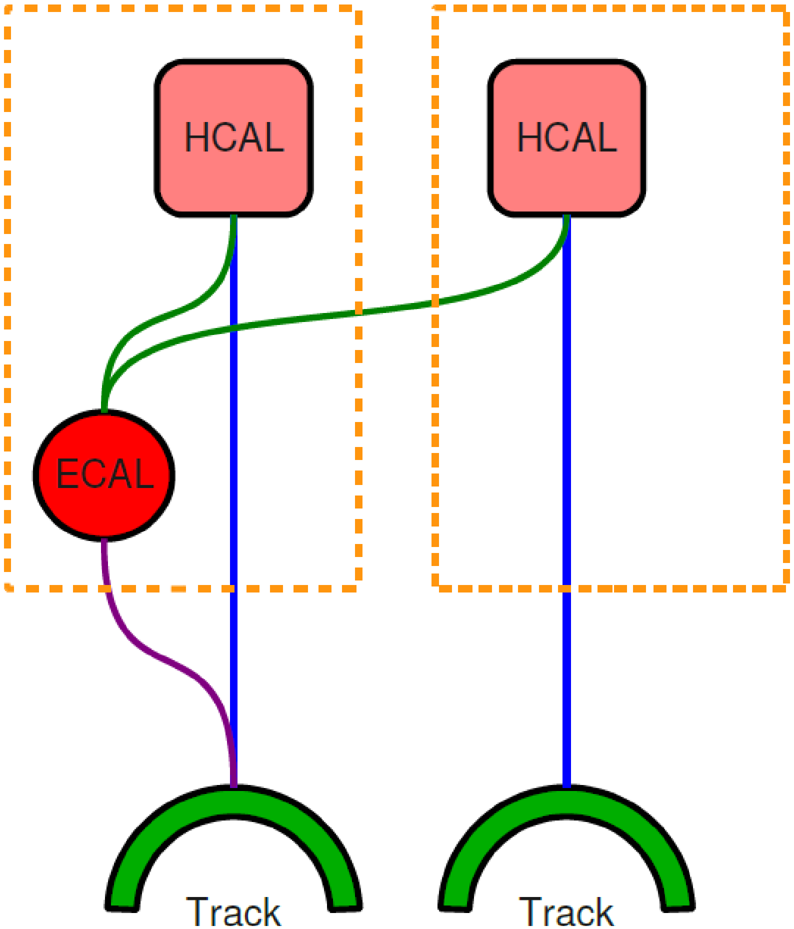
- Further simplified block (2nd step) : blocks are usually very small !





Back to 2005 : Checking CMS basic promises (14)

- Find charged hadrons, and merged photons / neutral hadrons



For each HCAL cluster, compare :

- The sum of the track momenta p
- The sum of the cluster energies E
  - Linked to the tracks
  - In ECAL and in HCAL
  - ("Hadron Calibrated" (see later)

If p and E are compatible

- Charged hadrons only (1 per track)

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

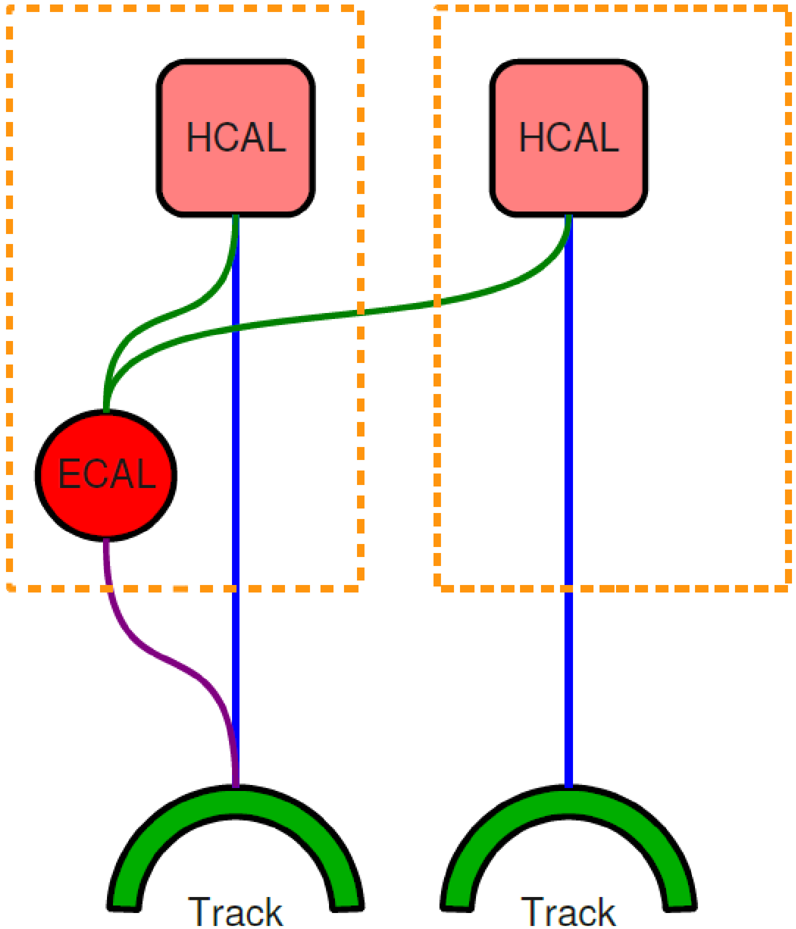
- Charged hadrons + photon/neutral hadrons

If $E \ll p$

- Something odd going on… Needs attention (doesn't happen often)

Back to 2005 : Checking CMS basic promises (15)

- … and determine their energies



If p and E are compatible

  Fit of p_i and E according to σ_{E,p_i}

  Charged hadrons : p_i at small $p_{T,i}$

  Converges to p = E at high E

If E is in significant excess of p

  Charged hadrons : p_i

  If E is from HCAL or ECAL only

    HCAL : Neutral hadron (E-p)

    ECAL : Photon (E_{ECAL}-p)

  If E is from ECAL and HCAL

    If (E-p) > E_{ECAL}

    Photon(E_{ECAL}) + neutral hadron

    otherwise

    Photon : (E-p)/b

(Always give precedence to photons in ECAL)

Back to 2005 : Checking CMS basic promises (16)

- In our famous first simulated jet ever :
  - Four particles generated : π^+, π^-, π^0 and K^0_L
  - Five particles reconstructed :
    - Two oppositely-charged hadrons (π^+ and π^-)
    - Three photons
      - → Two from the π^0 decay and one from the K^0_L energy deposit
    - No neutral hadron
      - → Because for each of the two tracks, E was compatible with p
  - Note : the precedence given to photon identification in ECAL
    - May underestimate the ECAL energy deposits of neutral hadrons
      - → But the neutral hadron energy deposited in ECAL corresponds to

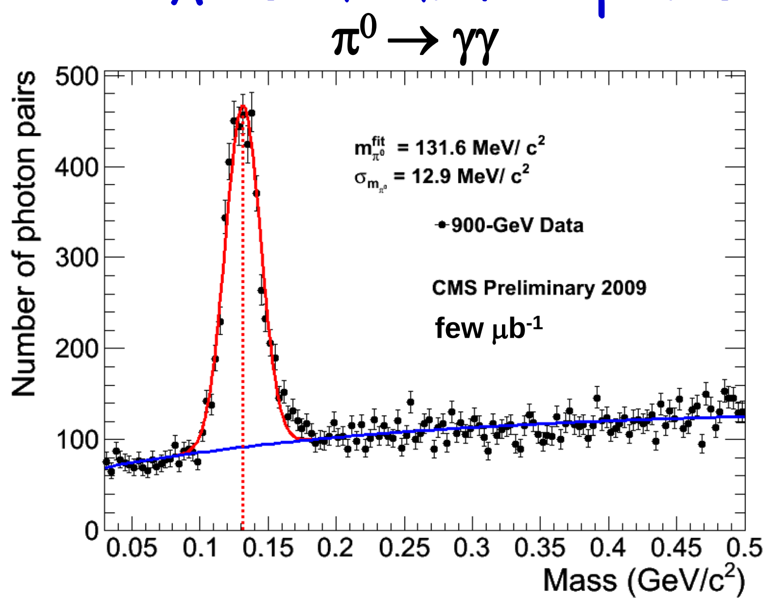
        10% neutral hadron x 30% ECAL fraction = 3% of event energy

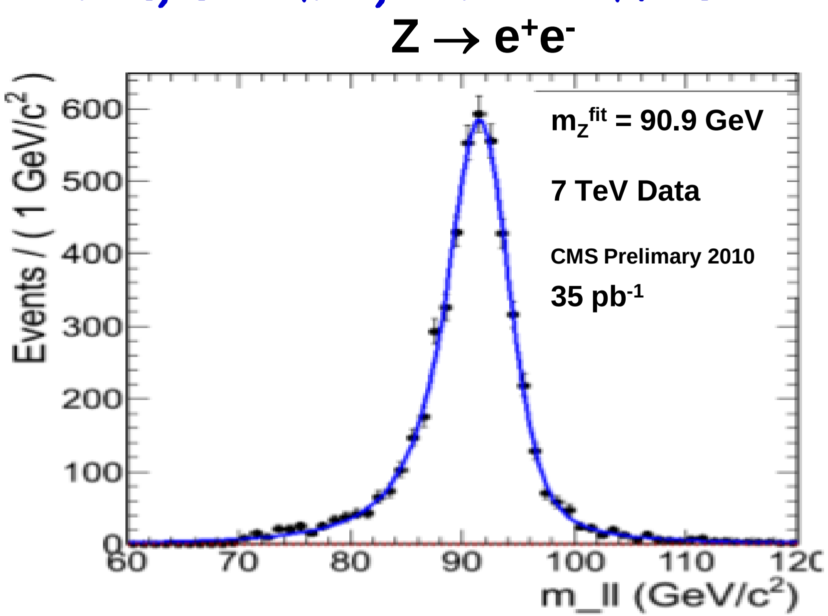
        May lose <0.5% of the event energy from this identification choice

        (was the same in ALEPH)

A few subtleties : the devil is in the details (I)

- Calibration of ECAL and HCAL energies for charged hadrons
  - ECAL is calibrated for photons (and electrons, see later), not for hadrons





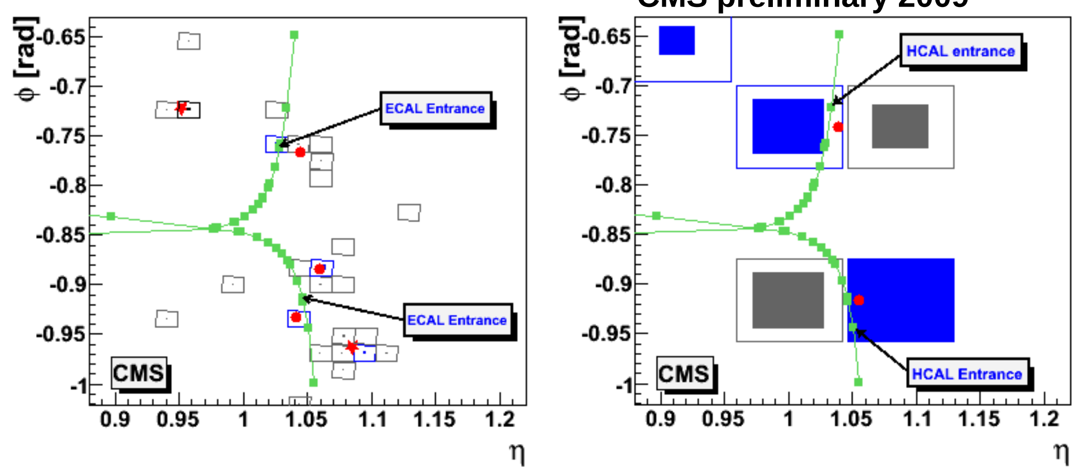
  - HCAL is calibrated for 50 GeV charged pions at normal incidence
    - Test-beam calibration done without ECAL/Services in front of HCAL
  - Hence, when a charged hadron (p) interacts with the calorimeters
    - $E_{ECAL} + E_{HCAL}$ does not equal p (in general significantly smaller)

A few subtleties : the devil is in the details (2)

- Calibration of ECAL and HCAL energies for charged hadrons (cont'd)
  - To optimize merged neutral hadron identification, need to calibrate $E_{ECAL,HCAL}$ as
    - $E = a + b(p,\eta)\, E_{ECAL} + c(p,\eta)\, E_{HCAL}$
      - → Compensates for ECAL response and also for HCAL nonlinearities (!)
  - Charged hadrons and photons (90% event energy) insensitive to this calibration
    - Only the neutral hadron identification efficiency is
      - → Calorimeter calibration for hadrons is a second order effect for PF
  - Use ("isolated") tracks in minimum bias events for a, b and c determination

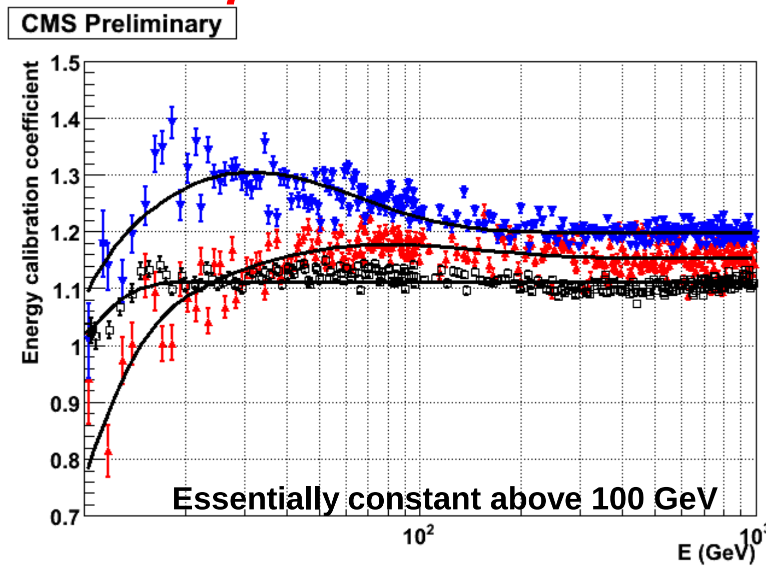
Granularity Helps !
- One HCAL in the block
- One Track in the block
- High-quality fit
- Fit a, b, c
  - → As function of p
  - → As function of η

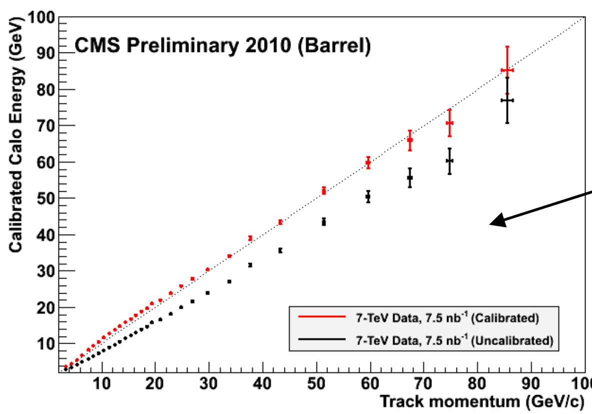
CMS preliminary 2009



A few subtleties : the devil is in the details (3)

- Calibration of ECAL and HCAL energies for charged hadrons (cont'd)
  - Coefficients obtained from simulation
    - Blue : b(E,0)
    - Black : c(E,0) / HCAL only
    - Red : c(E,0) / ECAL + HCAL
    - a = threshold correction (couple GeV)
  - Can be applied directly on data
    - But can be /are obtained from data
      - → Seem fine all the way to 150 GeV

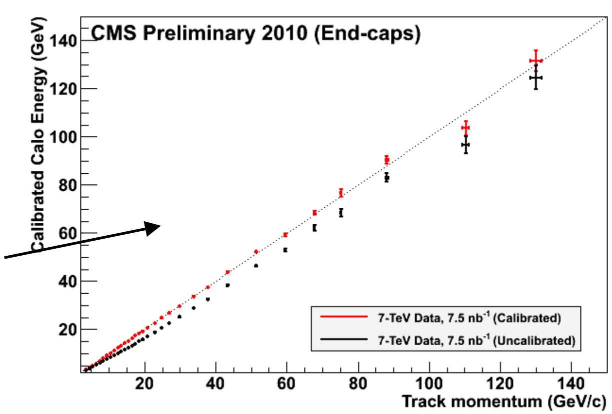




Only 7.5 nb^{-1} data

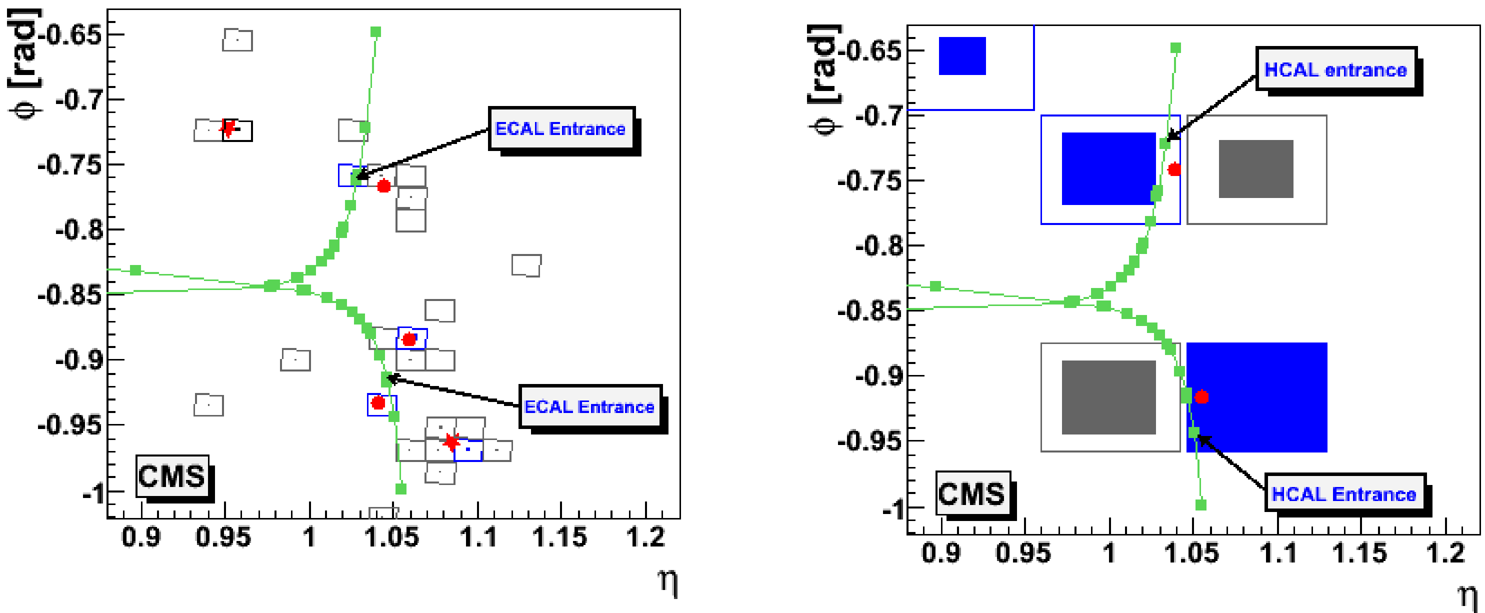
350K tracks in barrel

1.7M tracks in end-caps



A few subtleties : the devil is in the details (4)

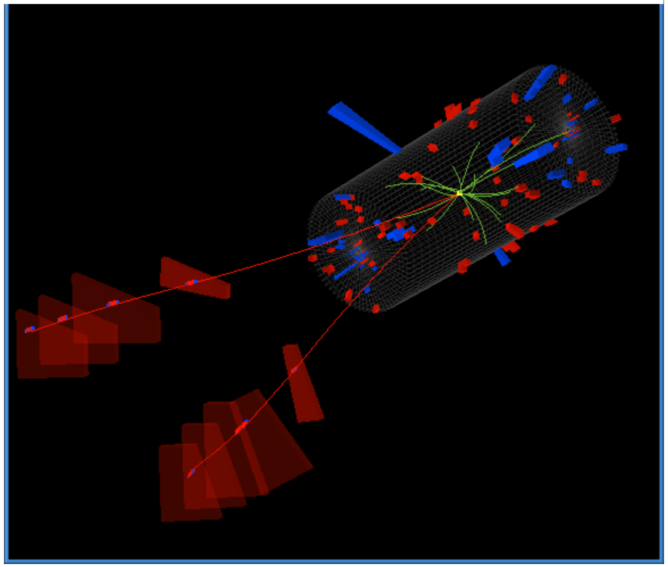
- Calibration of ECAL and HCAL energies for charged hadrons (cont'd)



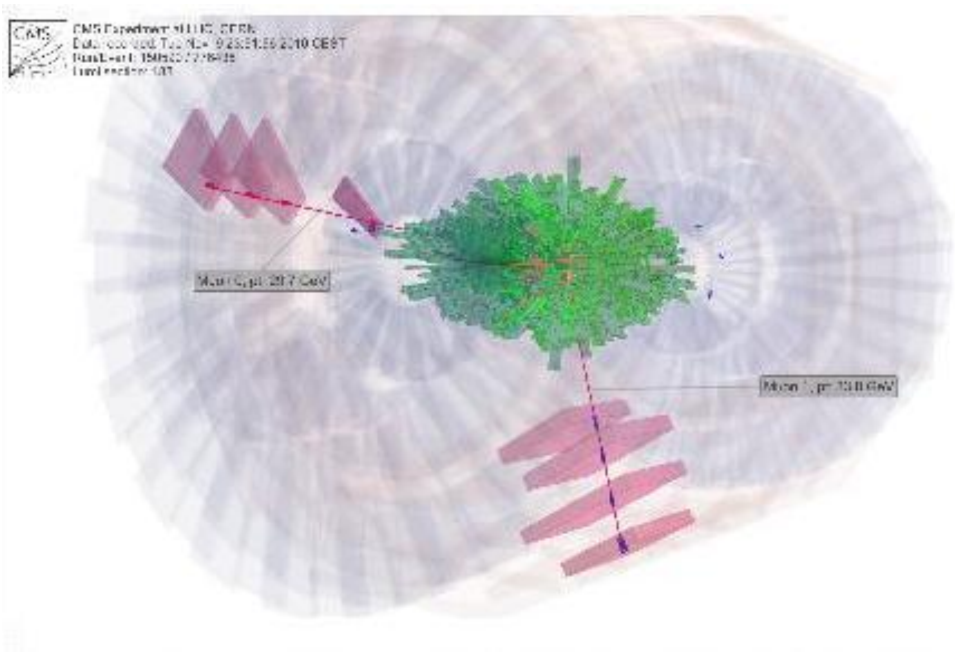
- Track pointing "downwards"
  - p = 14.64 GeV/c, E_{ECAL} = 1.87 GeV, E_{HCAL} = 7.35 GeV, E_{CALIB} = 14.33 GeV
- Track pointing "upwards"
  - p = 10.94 GeV/c, E_{ECAL} = 0.98 GeV, E_{HCAL} = 6.77 GeV, E_{CALIB} = 9.19GeV
- Gives two charged hadrons of 14.64 GeV and 10.94 GeV in the particle list.

A few subtleties : the devil is in the details (5)

- Cases E << p
  - Arise from muons, in the majority of the cases
    - Muon reconstruction and identification is rather easy in CMS
      - → Even in a very busy environment



$J/\psi \to \mu\mu$ (pp)



$Z \to \mu\mu$ (PbPb)

A few subtleties : the devil is in the details (6)

- Cases with E << p : Muons (cont'd)
  - Muon reconstruction/identification requires
    - A high-quality track in the silicon tracker
    - A high-quality track in the muon system
    - A global fit with a good χ^2
  - Typically very efficient (95% in the muon system acceptance) and 99.5% pure
    - As in ALEPH, these muon tracks are removed from the block
      - → Before the charged hadrons, photons, neutral hadron treatment
  - The remaining 5% lead to E << p cases
    - A much looser muon identification is used in this configuration
      - → Isolated tracks (not likely to be a hadron)
      - → Tracker track only (plus a few hits in the muon system)
      - → Poor-quality tracker track (but good fit in the muon system)
    - Typical particle-flow attitude: use all detectors to improve particle ID/Reco

A few subtleties : the devil is in the details (7)

- Cases where $E \ll p$: Fake tracks, p mis-measurements
  - Despite the tight selection for charge particle tracks (reminder)
    - Seeded with at least two hits in the pixel detector
      - → Originating from the beam axis within tight tolerances
    - Pattern recognition with a combinatorial Kalmann-Filter track finder
      - → Request at least 8 hits and $p_T > 0.9$ GeV/c
    - Leading to only 85% efficiency for primary charged pions (see just after)
  - The 3D-ish granularity of the tracker leads to ambiguities
    - Hits wrongly associated to tracks
    - Confusion in the pattern recognition
      - → Leading to fake tracks with a 1-2% rate
      - → Leading to incorrect momentum determination
    - Typically create high-momentum tracks
      - → The problem increases with the charge multiplicity, i.e., with jet p_T

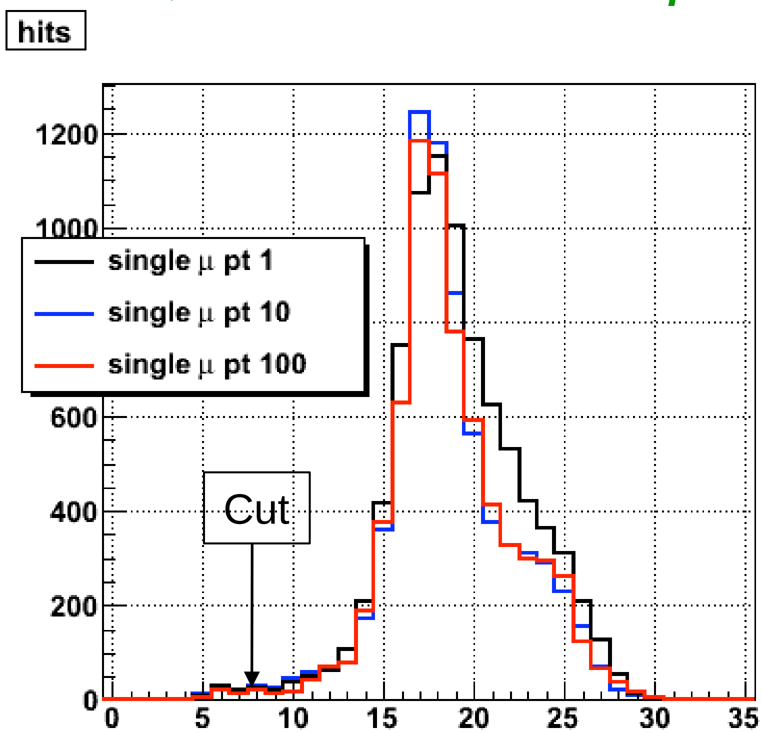
A few subtleties : the devil is in the details (8)

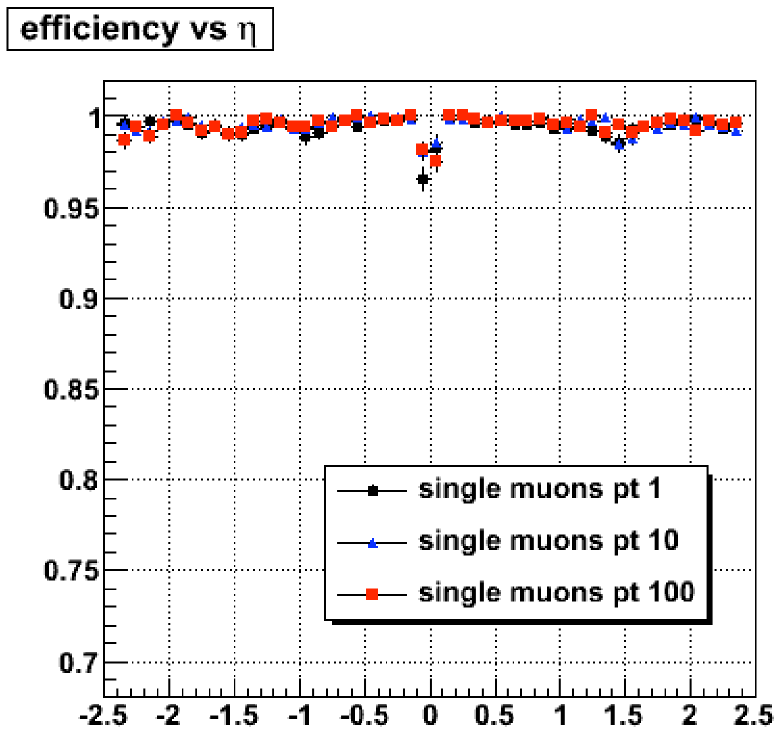
- Cases where $E << p$: Fake tracks, p mis-measurements (cont'd)
  - The problem of fake tracks was solved in the following way
    - Reject tracks obviously fake (bad quality fit, missing hits along the track)
    - For each block, rank the remaining tracks according to $\sigma_{fit}(p_T)$
      - → In the very few blocks with more than one track (few %)
      - → For the very few tracks with $\sigma_{fit}(p_T) > 1$ GeV (0.1%)
      - → Remove the worse tracks until E compatible with p

        The "last" track is simply rescaled to make $p = E$
      - → 0.001 % of the tracks concerned by this procedure
    - Note : for these (small) blocks, the energy is given by the sole calorimeters
      - → But photon identification (and energy determination) still holds
      - → Individual charged particle multiplicity and momenta are still available
      - → Momentum direction mostly from tracking and ECAL
    - Typical particle-flow attitude : use the redundancy of all measurements.

A few subtleties : the devil is in the details (9)

- A tracking efficiency of 85% : why ?
  - Silicon detectors are very efficient in finding hits (>99%)
    - As seen with simulated single muons (confirmed with data)

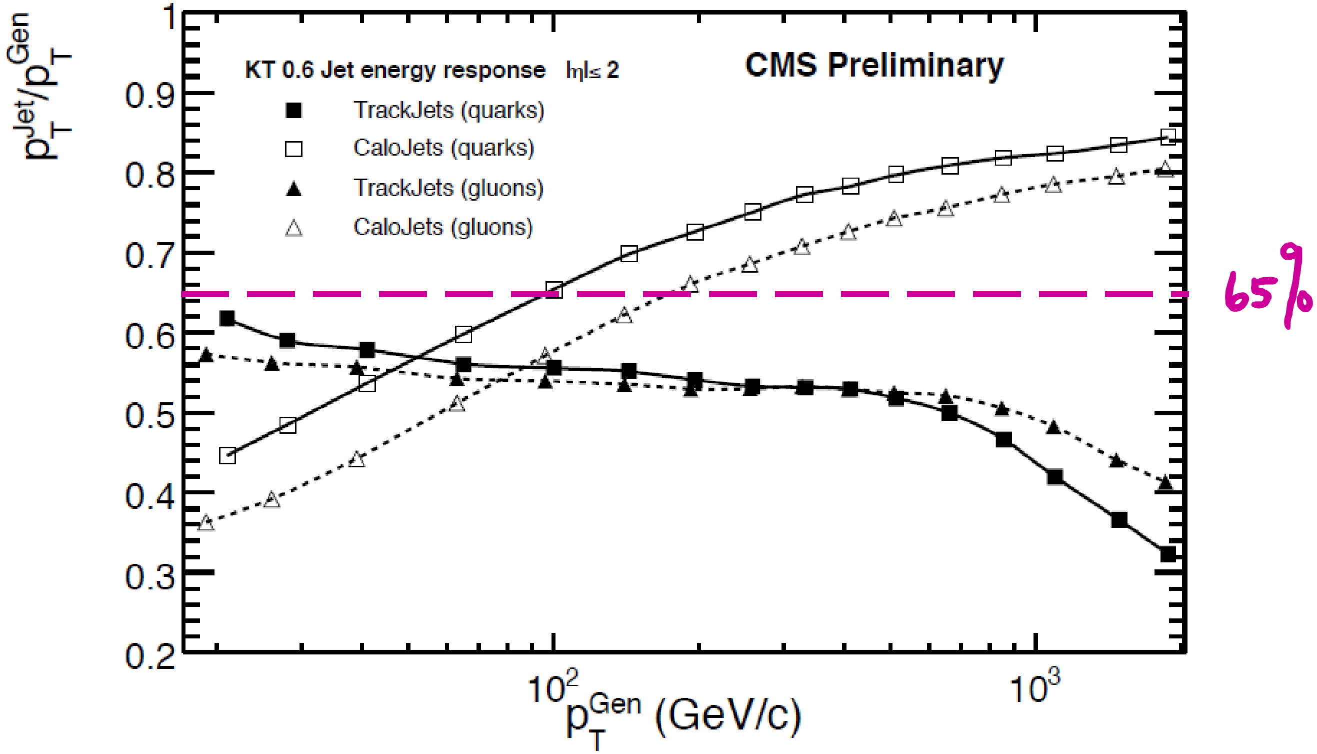




    - Only slights drops of efficiency in the pixel detector cracks and overlaps

A few subtleties : the devil is in the details (10)

- A tracking efficiency of 85% : why ? (cont'd)
  - Question : Is it due to large occupancy in jets ?
    - Hence large overlap between tracks ?



  - Answer : not for p_T up to 800 GeV/c, where this effect starts to show up

A few subtleties : the devil is in the details (II)

- A tracking efficiency of 85% : why ? (cont'd)
  - Remember : About $2X_0$, or $0.4\ \lambda_0$, of material in the tracker
    - About 20% of the hadrons interact in the tracker material
      - → Sometimes in a spectacular manner

A single K^0_L (270 GeV) interacting in the tracker after 15 cm:

Blue : true particles

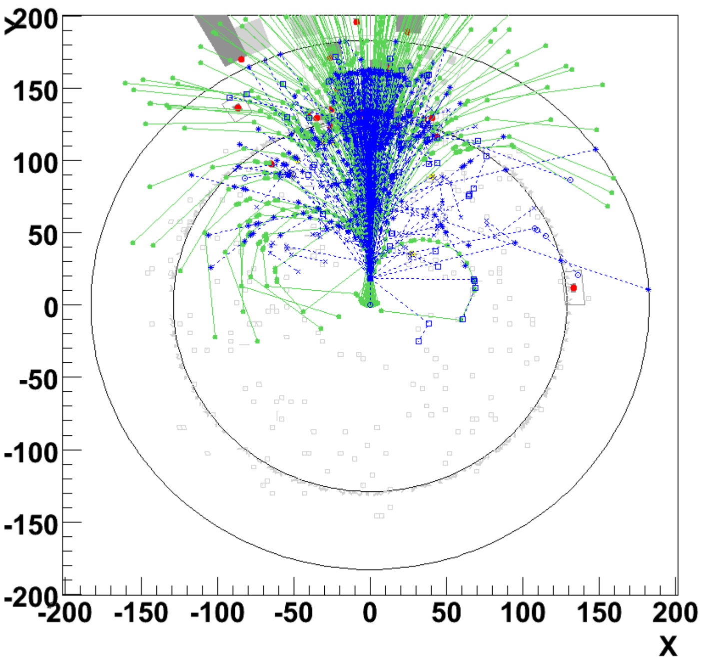
Green : reconstructed tracks

(well, not yet)

→ what happens to these tracks ?

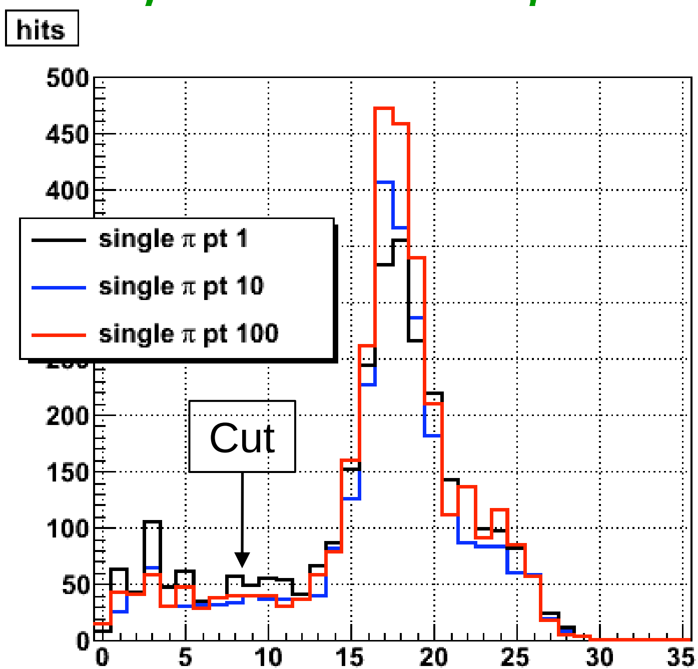
Not enough hits on the primary

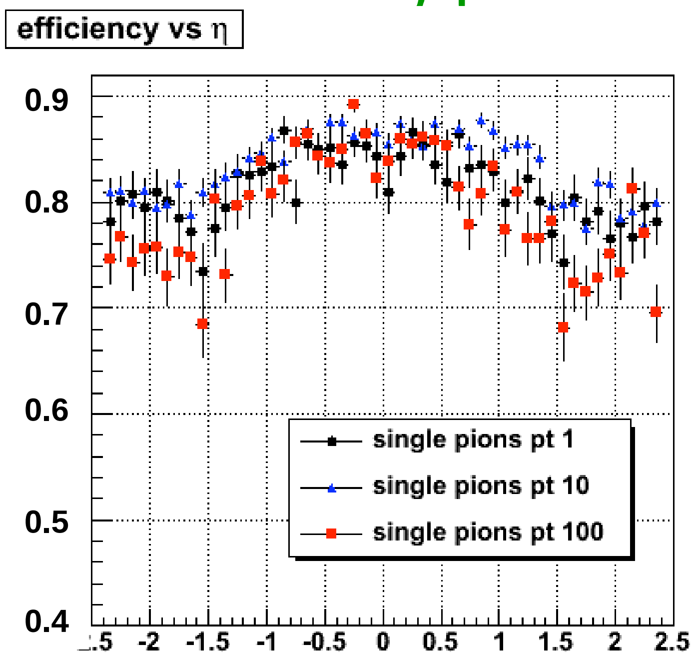
Bad origin for the secondaries



A few subtleties : the devil is in the details (12)

- A tracking efficiency of 85% : why ? (cont'd)
  - Indeed, for single pions :
    - Large loss of efficiency due to short tracks from interacting pions





    - With a $n_{Hit} > 5$ cut, the fake rate jumps to about 20%, not manageable.
  - Can one increase the tracking efficiency without increasing the fake rate ?

A few subtleties : the devil is in the details (13)

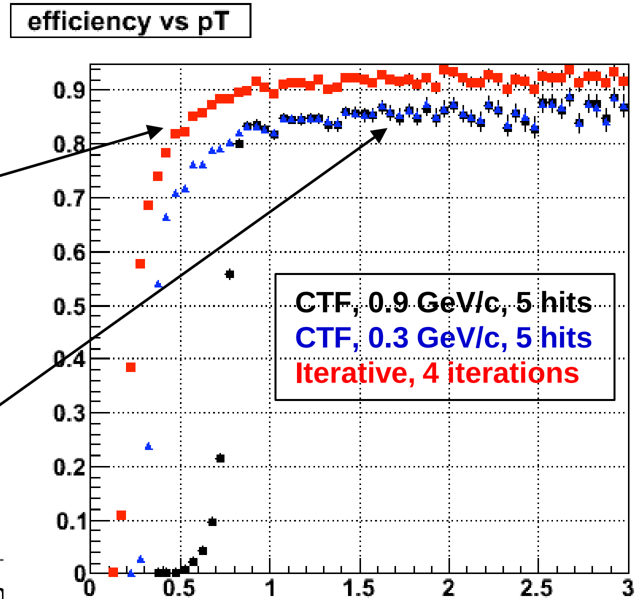
- Increasing the tracking efficiency : Iterative tracking
  - Fake tracks come from wrong combinatorial hit association
    - Reduce the number of hits fed to the combinatorial track finder ?
  - 1. Start from a very pure seeding
    - e.g., 3 pixel hits, very tight origin constraint, p_T > 0.9 GeV/c
      - → 75% efficiency, less than 1% fake rate
  - 2. Reconstruct the corresponding tracks (≥3 hits) and "remove" the hits used
    - 40% of the hits in the tracker are removed in this first iteration
  - 3. With the 60% remaining hits, try a looser seeding
    - e.g., 2 pixel hits, very tight origin constraint, p_T > 0.9 GeV/c
      - → Adds 15% efficiency, but still less than 1% fake rate

        Because the combinatorial possibilities are much less
  - 4. Reconstruct the corresponding tracks (≥3 hits) and "remove" the hits used
    - 10% of the hits are further removed in this second iteration

A few subtleties : the devil is in the details (14)

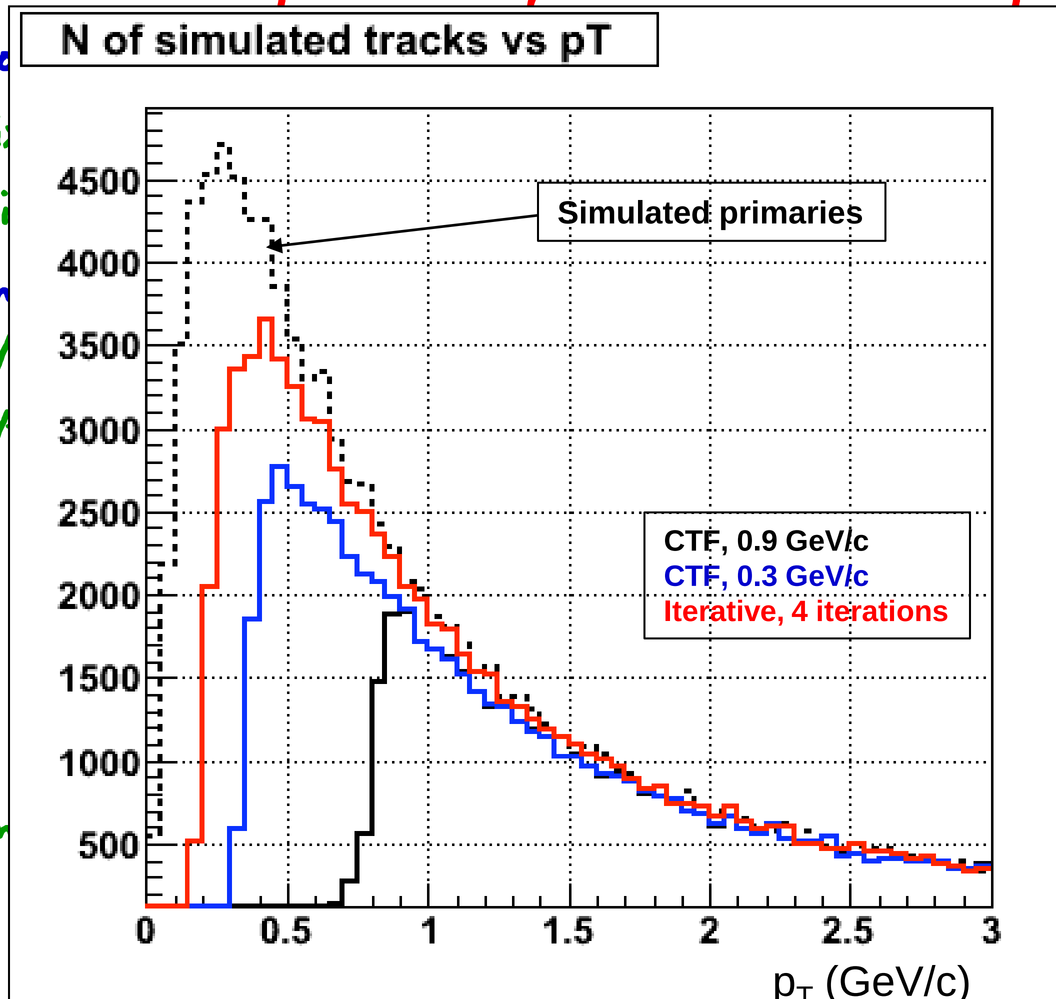
- Increasing the tracking efficiency : Iterative tracking (cont'd)
  - And so on with more iterations :
    - Third iteration : 3 pixel hits, tight origin constraint, $p_T > 0.2$ GeV/c
    - Fourth iteration : 2 pixel hits, looser origin constraint, $p_T > 0.3$ GeV/c
  - And even try to catch secondary tracks (interactions, conversions, decays ...)
    - Fifth : TIB/TID seeding, loose origin constraint, $p_T > 0.5$ GeV/c
    - Sixth : TOB/TEC seeding, very loose origin constraint, $p_T > 0.8$ GeV/c
  - After 4 iterations
    - 93% efficiency, 1-2% fake rate
    - Down to very low momentum

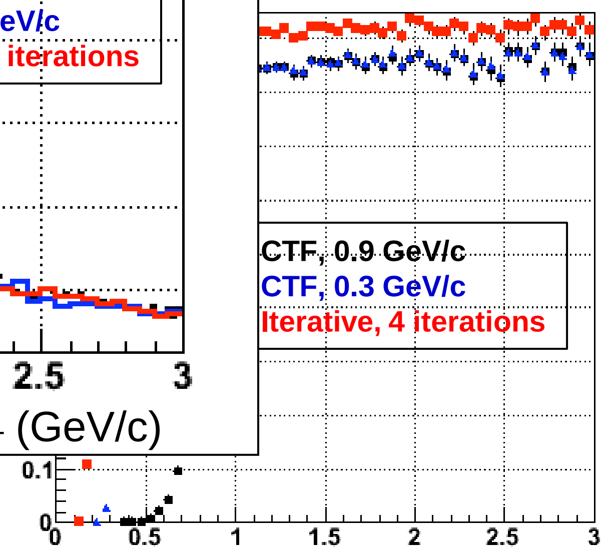
85% efficiency, 20% fake rate



A few subtleties : the devil is in the details (14)

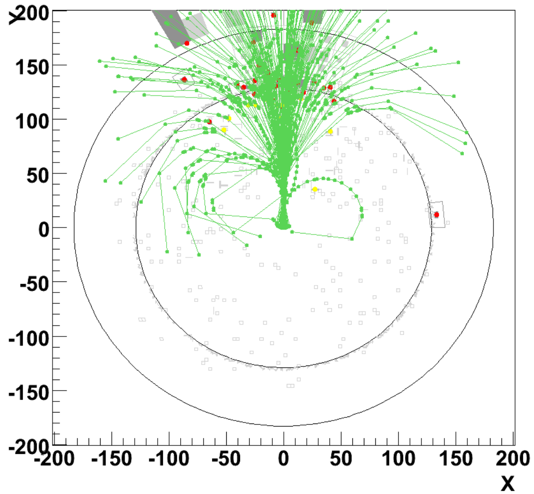
- Increasing the tracking efficiency : Iterative tracking (cont'd)
  - And so o
    - 3 pi
    - 2 pi
  - And even … ons, decays …)
    - TIB/
    - TOB/ … eV/c
  - After 4
    - 93%
    - Down





A few subtleties : the devil is in the details (15)

- Increasing the tracking efficiency : Iterative tracking (cont'd)
  - Nuclear interactions, photon conversions, decays in flight :



Many tracks reconstructed

with TIB/TID and TOB/TEC seeding

Small fake rate dealt with by PF protections

  - Next problem : avoid double counting from primary vs secondaries
    - Create a "link by vertex" between primary and secondaries

      → And chose the best energy determination

      Most likely the primary if more than 5-6 hits, secondaries otherwise
  - Typical particle-flow attitude : reconstruct/identify as many particles as possible !

A ... (15)

- Inc
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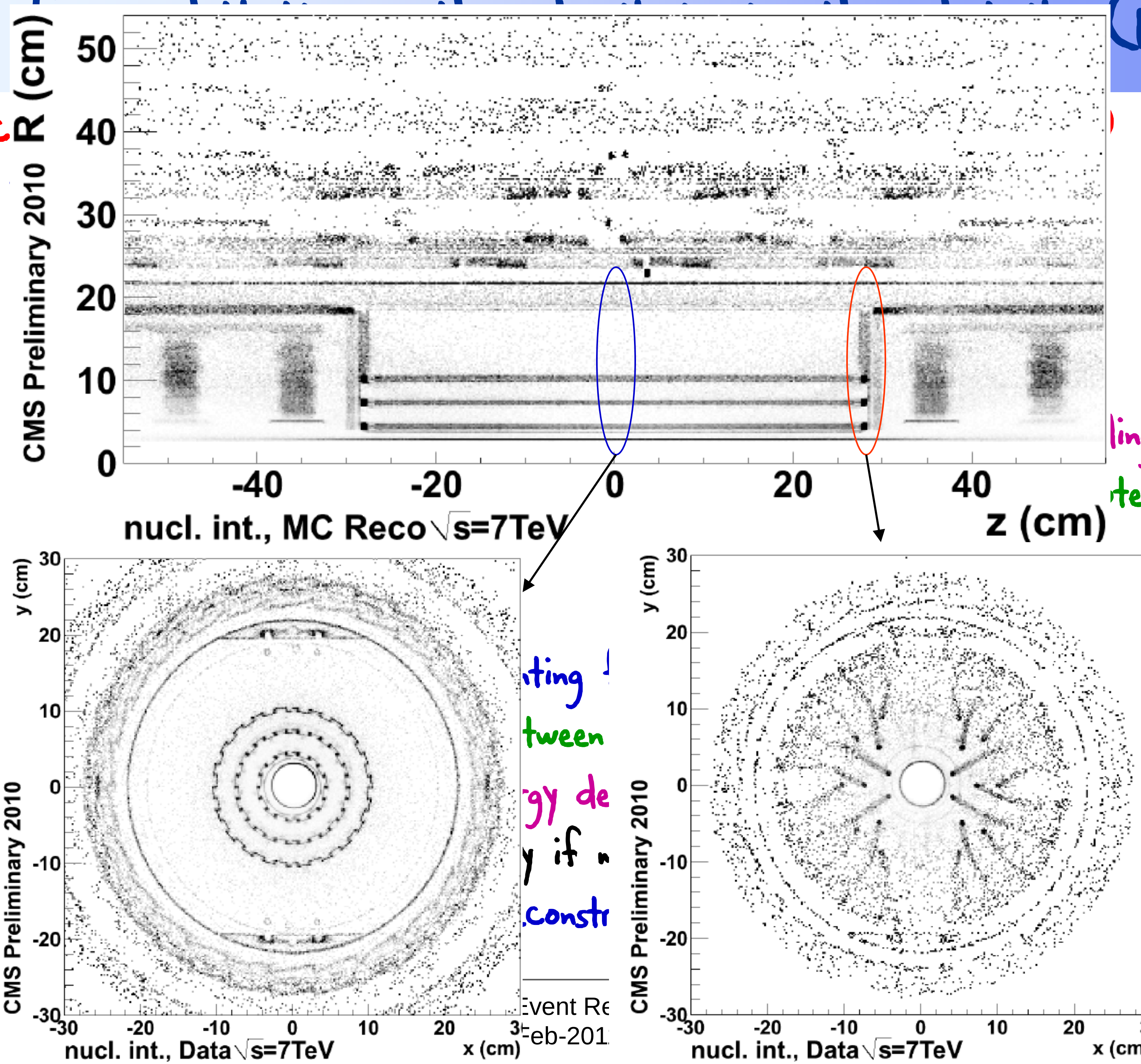
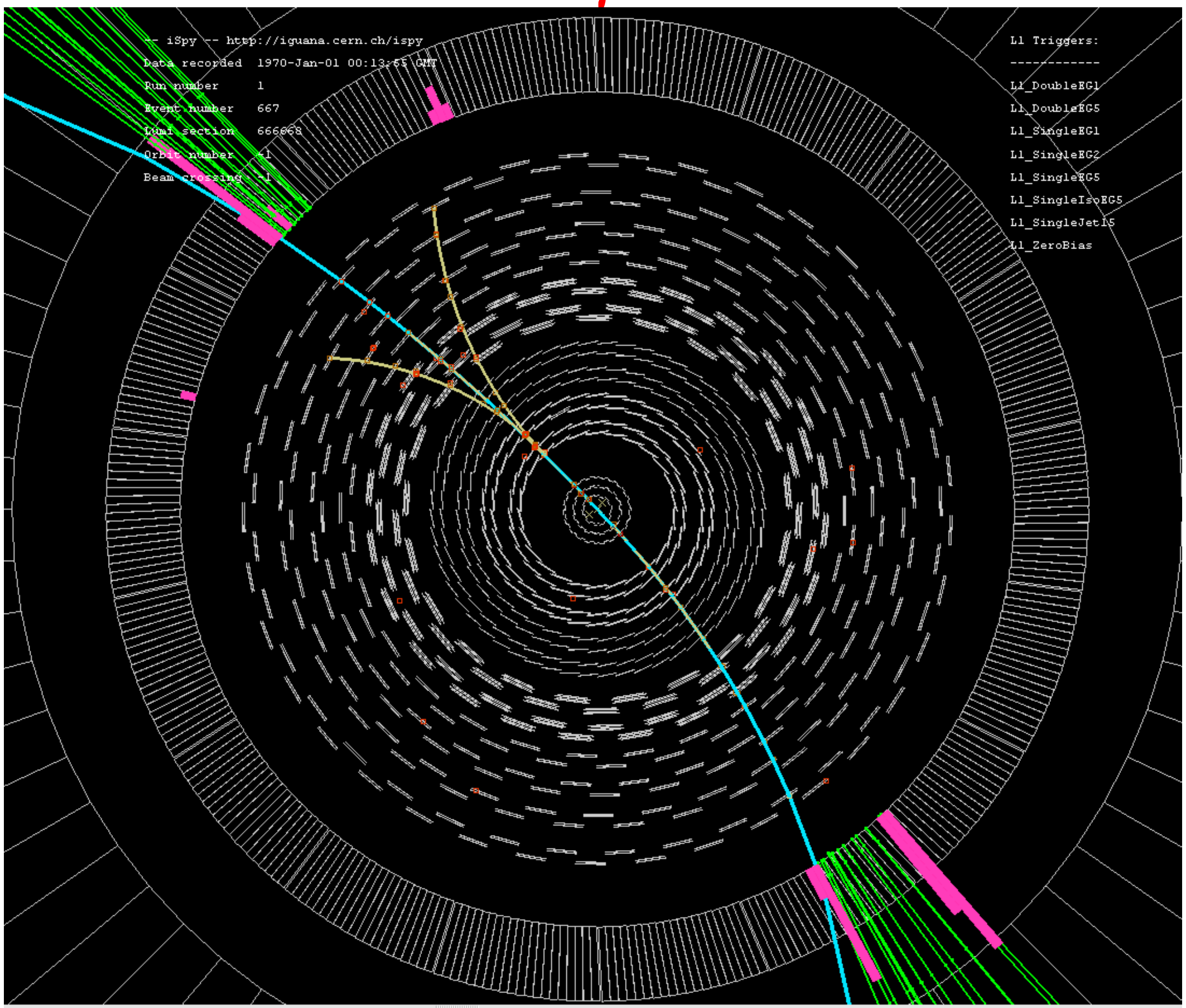
  - ossible !



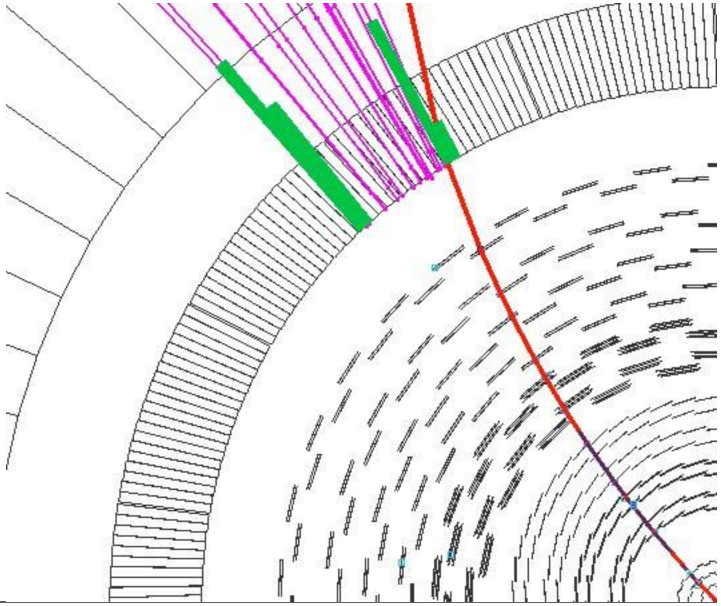
A few subtleties : the devil is in the details (16)

- And what about electrons ? They radiate, and the brem γ's convert !



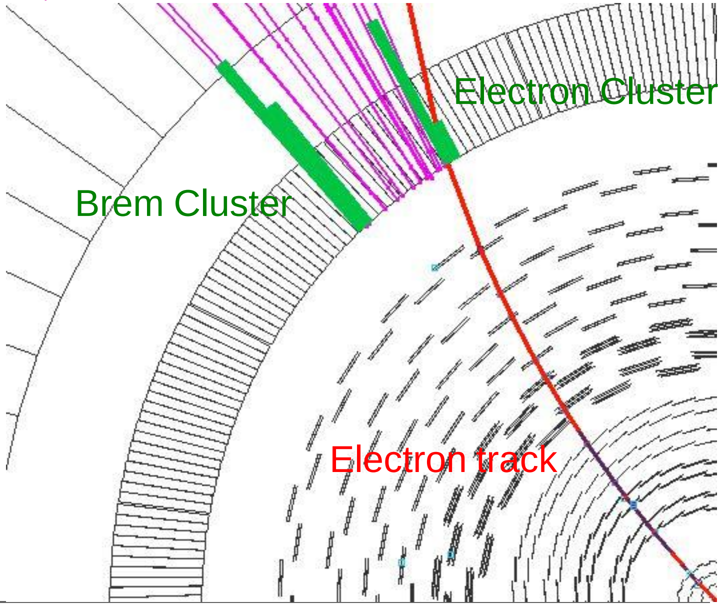
A few subtleties : the devil is in the details (Π)

- Electrons : Tracking
  - Because they radiate, many electrons would have failed the N_{hits} > 8 cut
    - The Kalman filter pattern recognition quickly gives up
  - The iterative tracking was initially meant at solving this issue for PF
    - Tracks with at least 3 hits are used as seed
    - Use a Gaussian-Sum filter to follow the electron track all the way to ECAL
  - Issue : GSF tracking is slow
    - Use it only for pre-identified tracks
      - → Small number of hits
      - → or : Poor quality fit
      - → or : p/E_{ECAL} not far from unity
      - → Linked to pre-shower hits
    - Concerns only 5% of the tracks
      - → with 95% efficiency on electrons



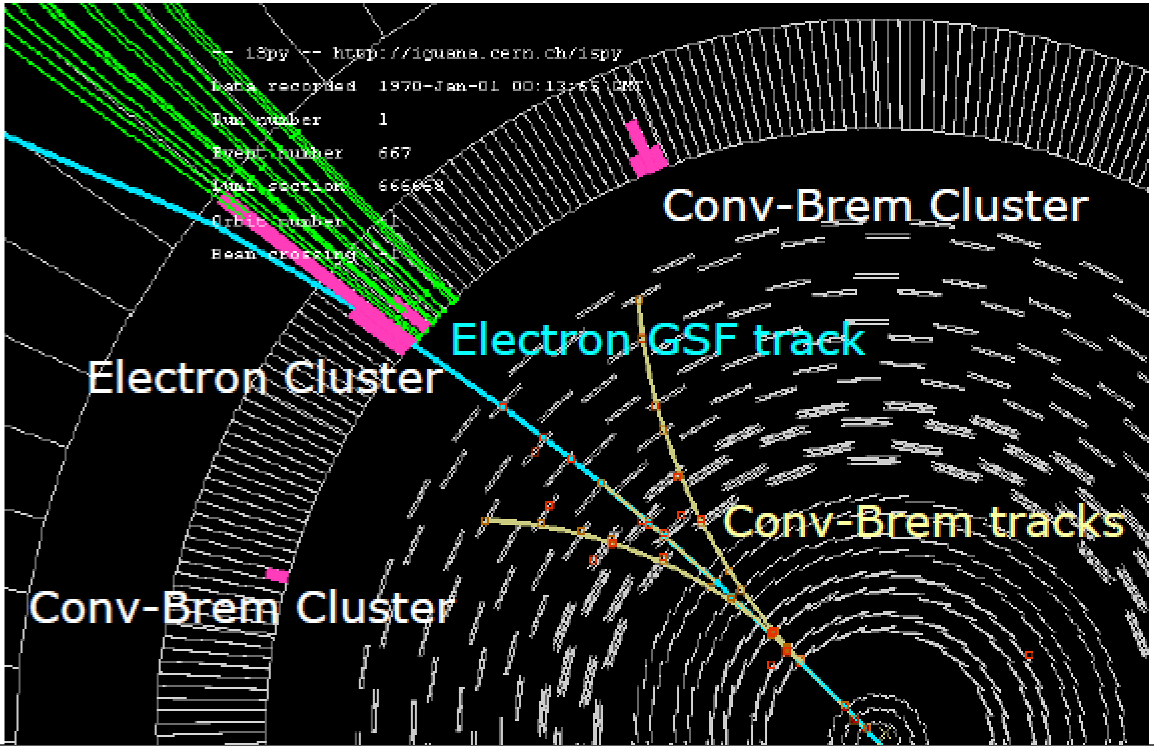
A few subtleties : the devil is in the details (18)

- Electrons : Recovering the Bremsstralhung photons
  - If nothing is done, radiated photon energy is counted twice
    - Once from the electron initial momentum, p_{IN}
    - Twice from the energy from corresponding ECAL cluster(s), E_{BREM}
  - Create a new type of track – ECAL cluster link
    - The link "by tangent"
      - → Purple lines are tangents to the GSF track
        Starting from each tracker layer
      - → If the tangent points to a cluster
        Link the cluster to the track
      - → Another handle (not used) :
        Compatibility between Ecluster
        and ΔP along the GSF track



A few subtleties : the devil is in the details (19)

- Electrons : Recovering the converted Bremsstrahlung photons
  - Tracks recovered by the 5th and 6th step of the iterative tracking
    - Linked by vertex to the original electron tracks
    - Linked to ECAL clusters in a classical way
      - → And added to the block …

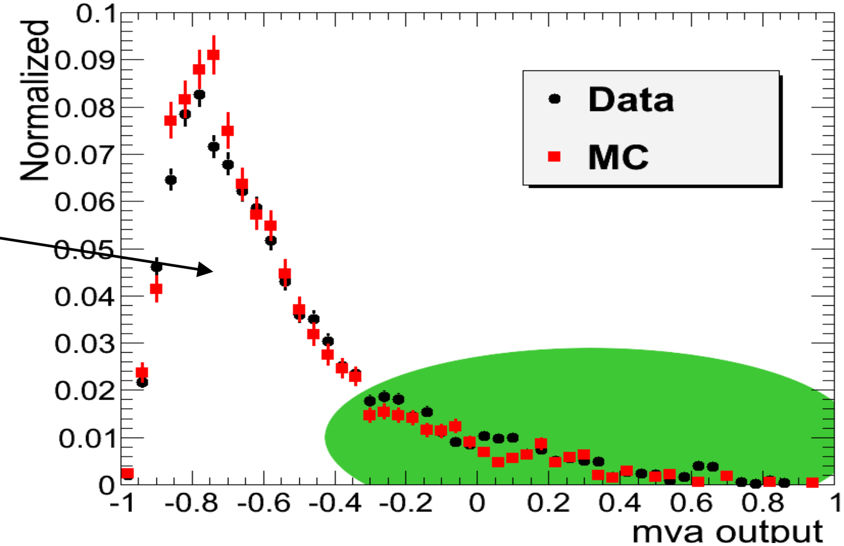


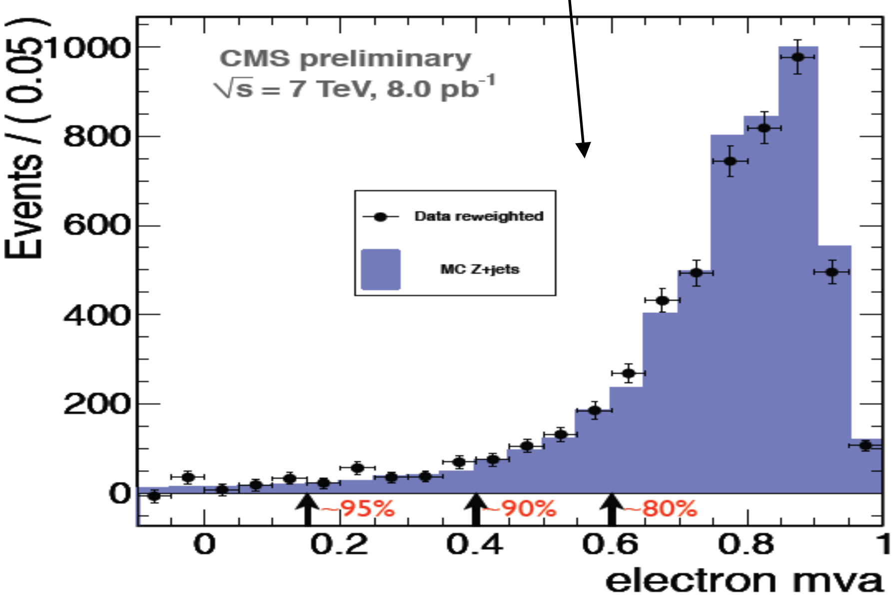
A few subtleties : the devil is in the details (20)

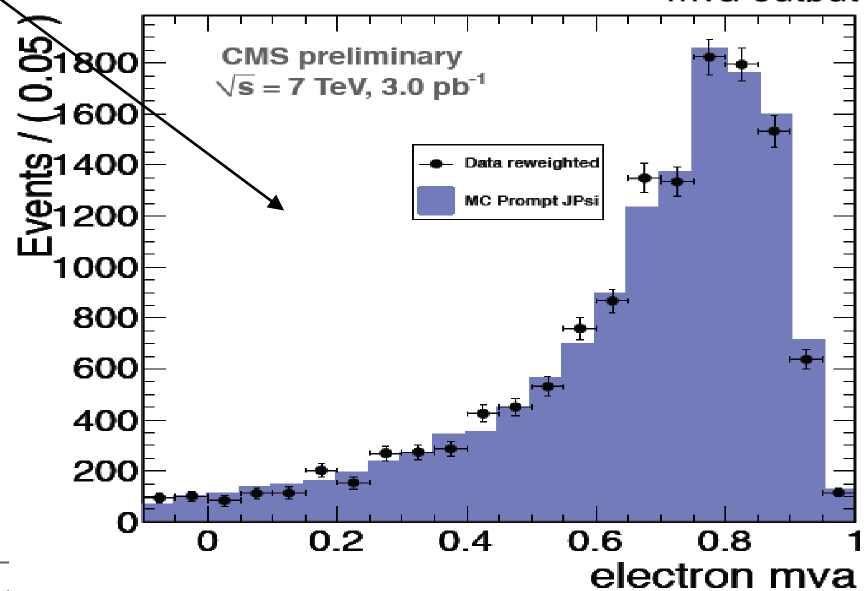
- Electrons : Identification
  - Use the tracker as a preshower !
    - Number of hits of the KF tracks
    - Energy loss along the GSF track : $p_{IN} - p_{OUT}$
    - Number of Bremsstrahlung photons associated to the track
    - Comparison of E_{BREM} and P_{IN}-P_{OUT}
    - Comparison of $E_{ELECTRON} + E_{BREM}$ and p_{IN}
    - …
  - Plus some calorimeter-only quantities
    - Shower width along η
    - Linked HCAL energy
    - …
  - And combine in a boosted decision tree (could be any MVA tool)
    - 70-80% efficiency in jets, 95% for isolated electrons

A few subtleties : the devil is in the details (21)

- Electrons : Identification, cont'd
  - It works with data as in simulation !
    - $K^0_S \to \pi^+\pi^-$
    - $J/\psi \to e^+e^-$
    - $Z \to e^+e^-$

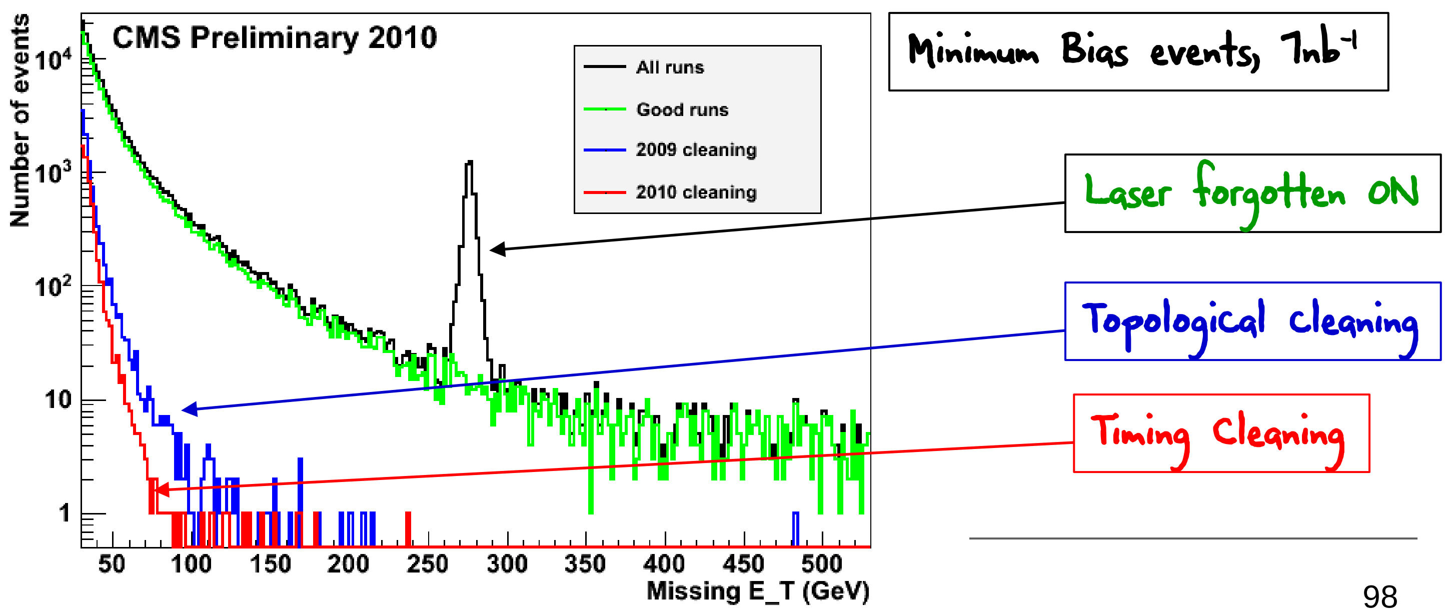






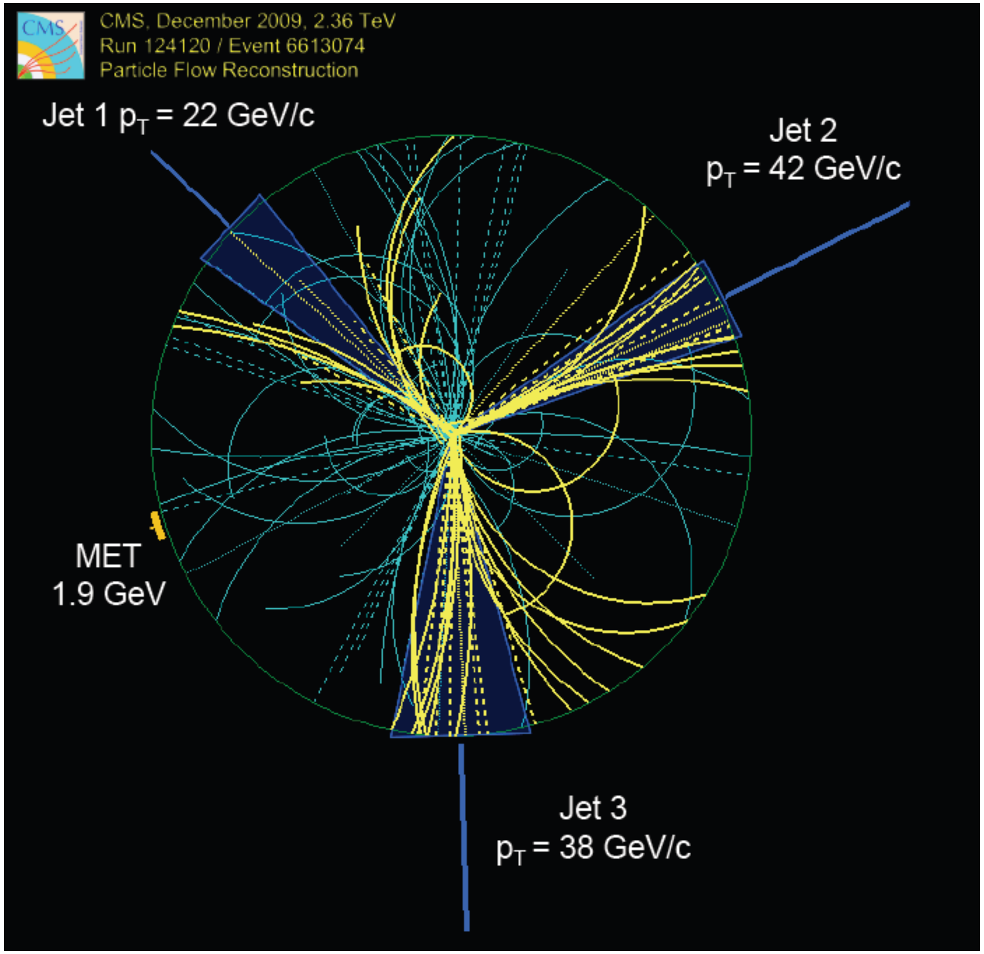
A few subtleties : the devil is in the details (22)

- The tracker material was the cause of most devilish details
  - The lack of redundancy was also a high price to pay for calorimeter cleaning
    - Needed to use information on timing, pulse shape, isolation, … to get rid of
      - → ECAL spikes (due to slow neutrons hitting APD's)
      - → HF spikes (due to Cerenkov light from hadron-shower muons in PMT's)
      - → HCAL spikes (due to ion feedback in HPD's)
  - But efficient cleaning could be achieved (so far) – without over-cleaning.



Particle-Flow performance in CMS (I)

- We now have a list of particles to work with
  - Charged hadrons, photons, neutral hadrons, (electrons, muons) :



- An event at $\sqrt{s}$=2.36 TeV

Full lines : charged hadrons
Dashed lines : photons
Dotted lines : neutral hadrons

- Jets with p_T > 20 GeV/c

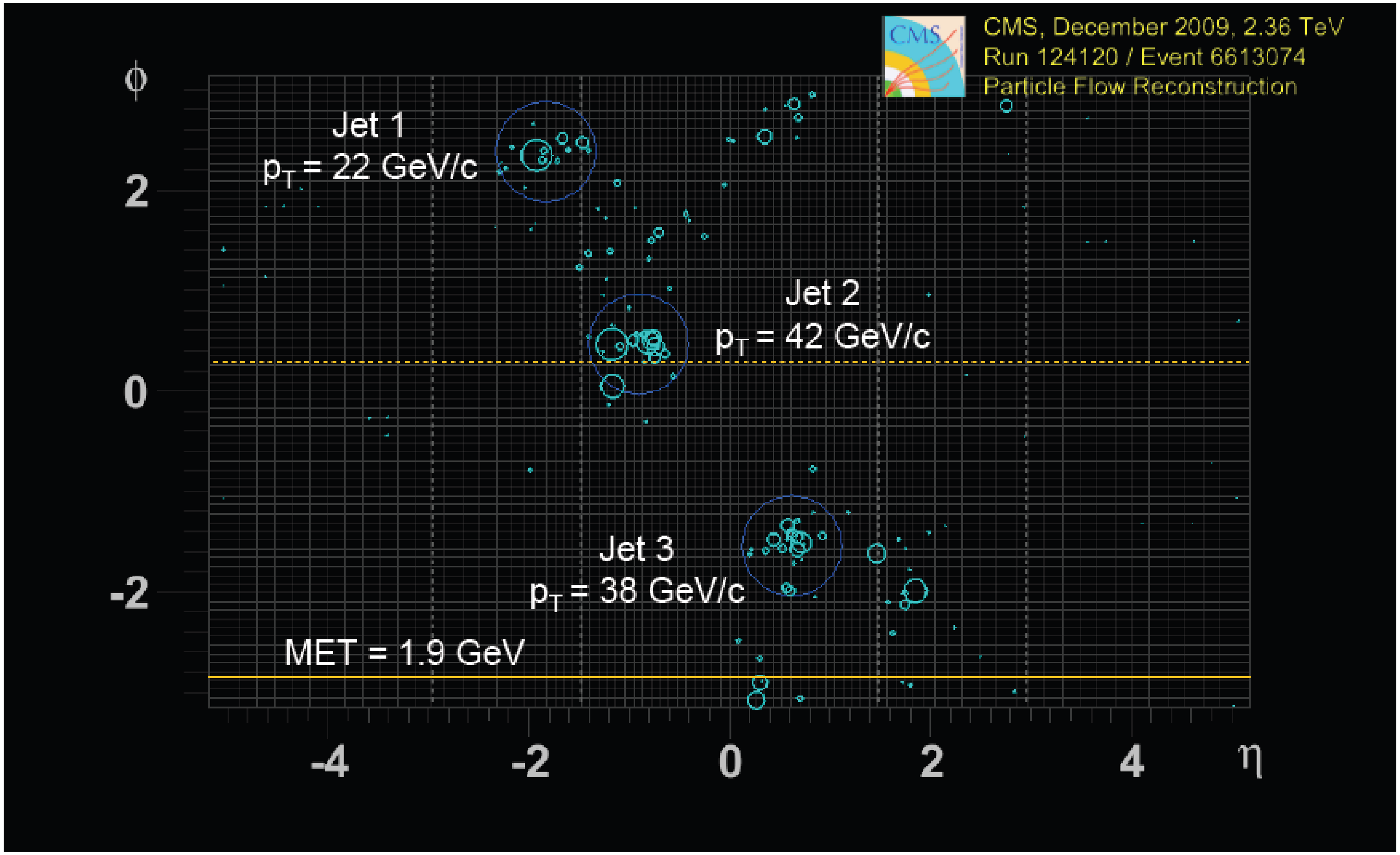
Yellow lines : Jet constituents
Blue areas : Jet "cone"

- Tastes like generated particles

But reconstructed particles, really

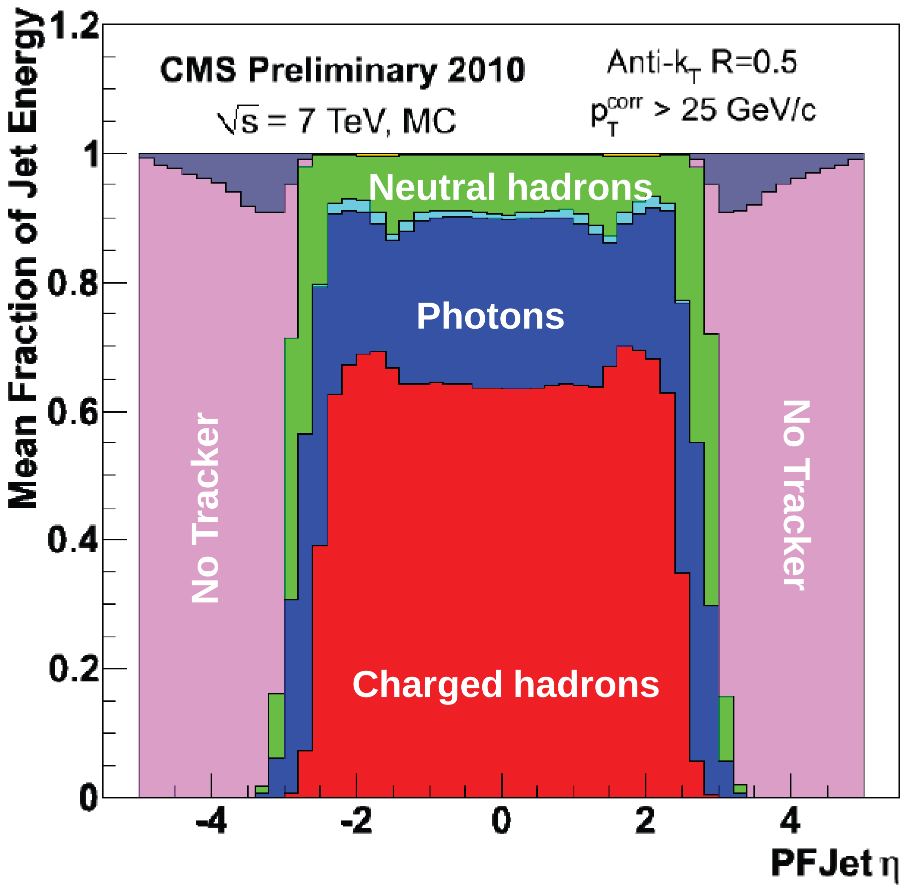
Particle-Flow performance in CMS (2)

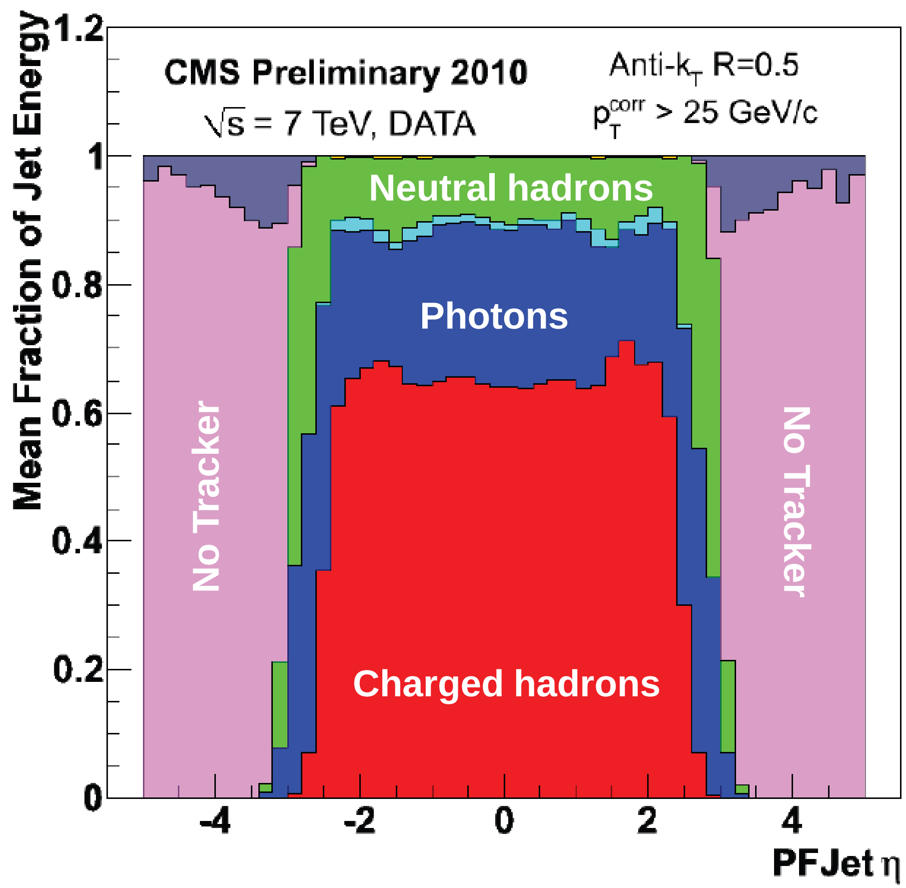
- We now have a list of particles to work with (cont'd)
  - With optimal particle-to-particle granularity + collimated jets at the lowest p_T's



Particle-Flow performance in CMS (3)

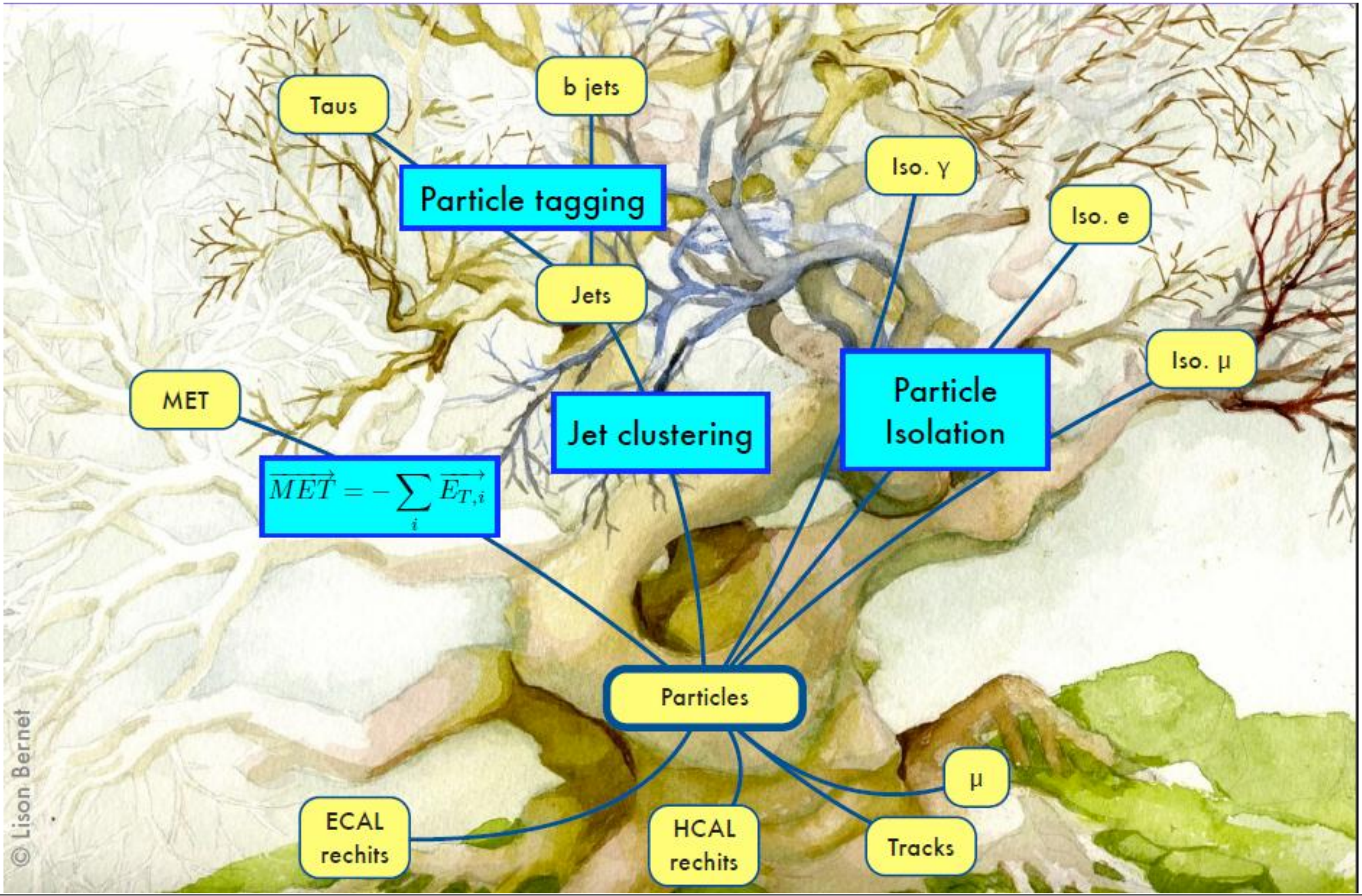
- We now have a list of particles to work with (cont'd)
  - With the expected fractions in jets (65% $h^{\pm}$, 25% γ and 10% h^0)
    - What is data, what is simulation ?





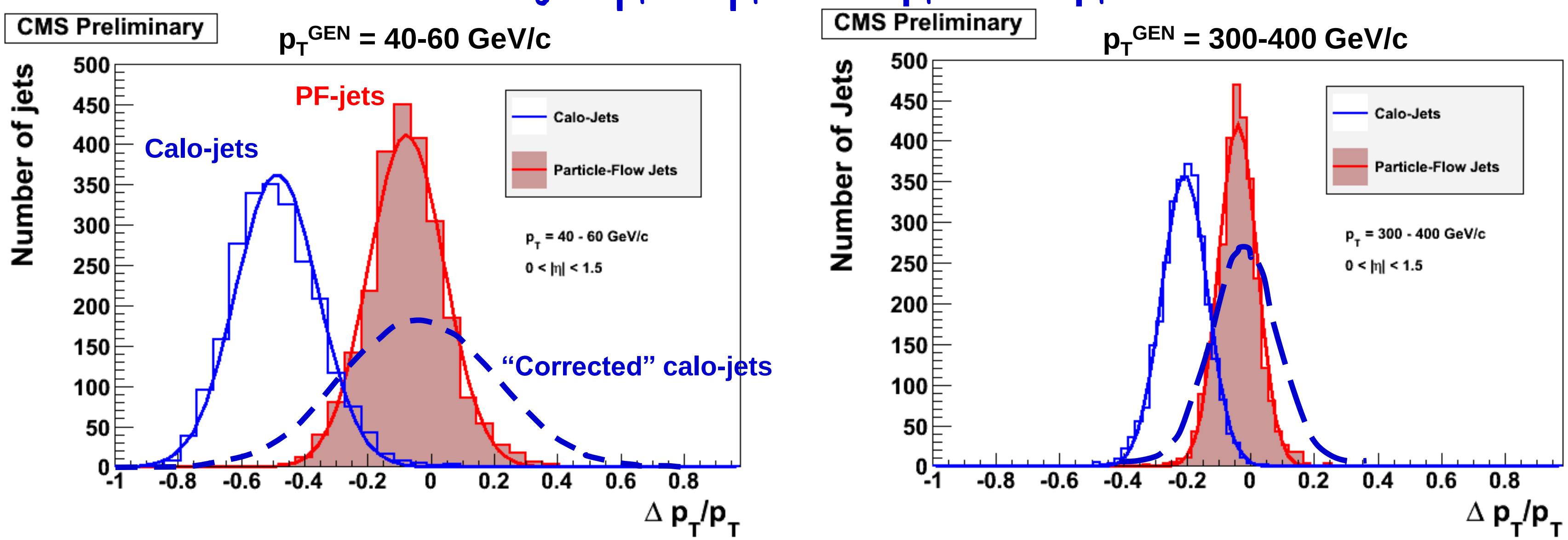
Particle-Flow performance in CMS (4)

- Physics objects from the global event description with particles



Particle-Flow performance in CMS (5)

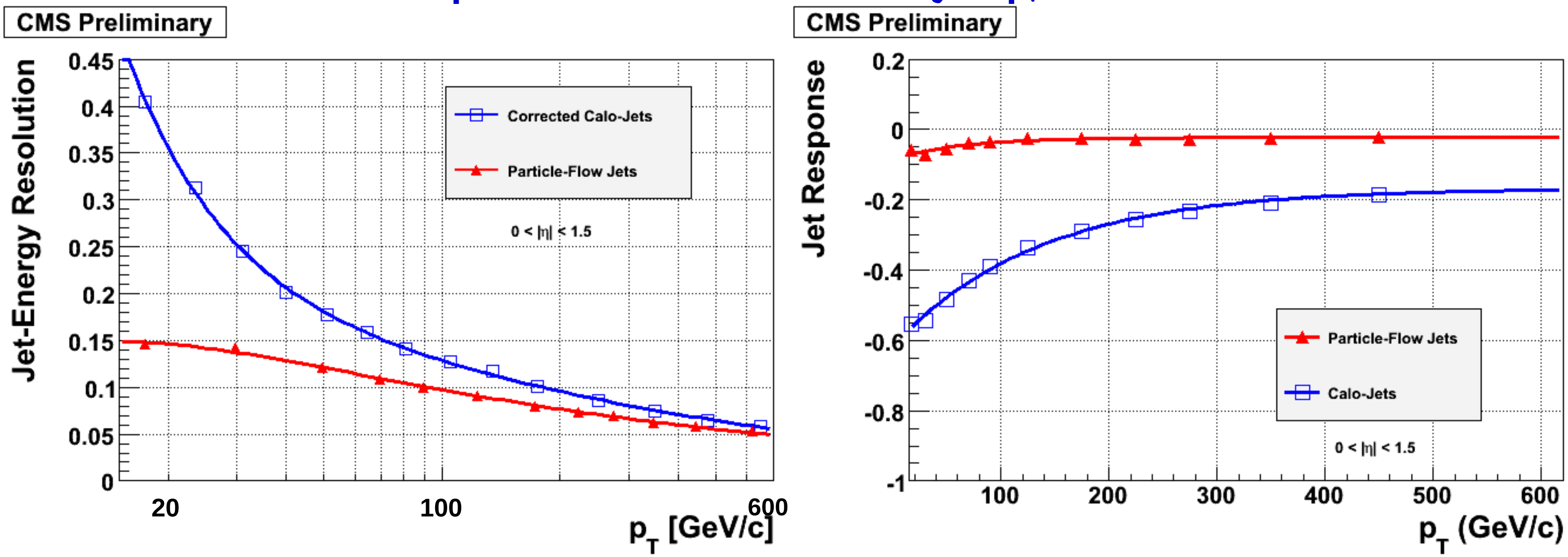
- Expected performance for jets
  - Reconstruction of the jet p_T : $(p_T^{RECO} - p_T^{GEN}) / p_T^{GEN}$



- Comparison with calorimetric jets
  - → Response larger than 95% of the original jet energy
  - → Almost no need for a posteriori corrections (systematic uncertainties!)
  - → Much better energy resolution
  - → Similar Gaussian behaviour despite the large number of sub-detectors used

Particle-Flow performance in CMS (6)

- Expected performance for jets (cont'd)
  - Resolution and response as a function of the jet p_T :



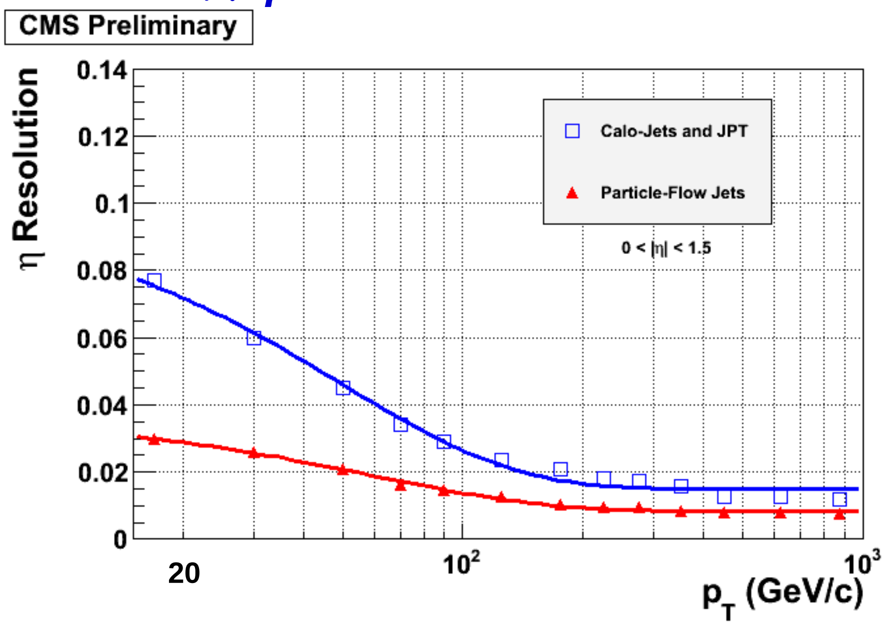
- Better resolution even at large p_T's, where calorimeters are well behaved
- Linear response, between 95% and 97% of the true jet energy

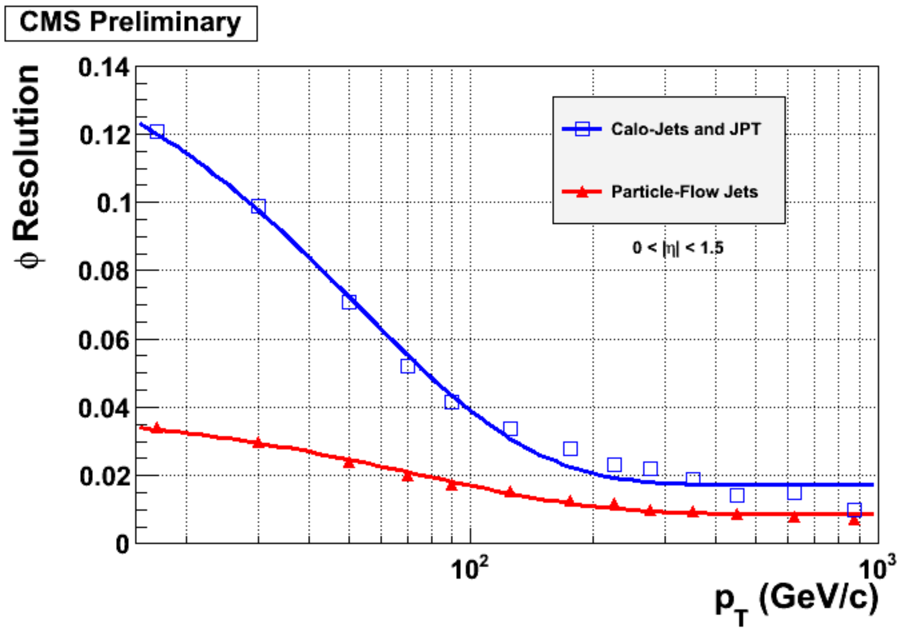
→ No need for large, non-linear, corrections, down to p_T = 10 GeV/c

(Calo nonlinearities : Magnetic field, thresholds, photons, muons, ...)

Particle-Flow performance in CMS (7)

- Expected performance for jets (cont'd)
  - Angular resolution



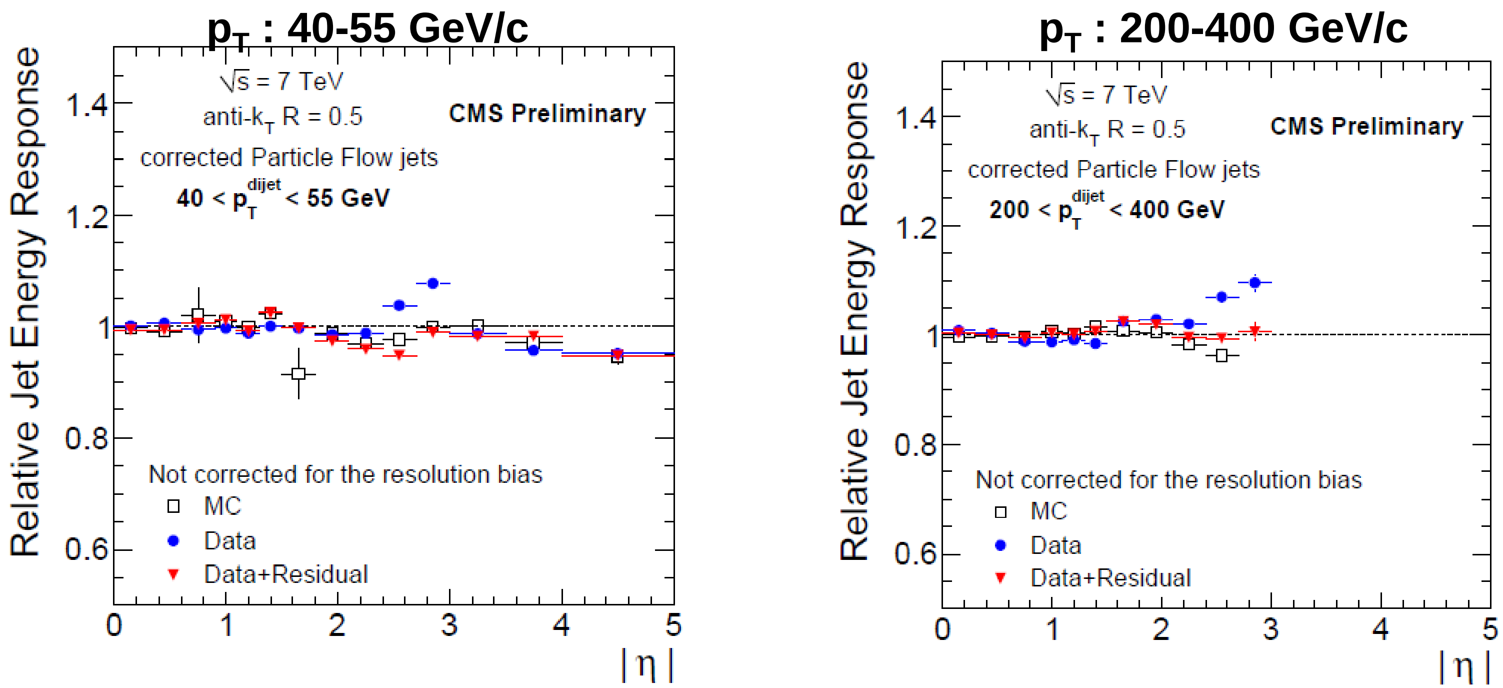


- A factor of 2.0 to 4.0 improvement in ϕ (B Field degrades calo jets)
- A factor of 1.5 to 3.0 improvement in η (tracker and ECAL granularity)

→ Large improvements expected in jet-jet mass resolution
with both improvements in jet energies and jet directions

Particle-Flow performance in CMS (8)

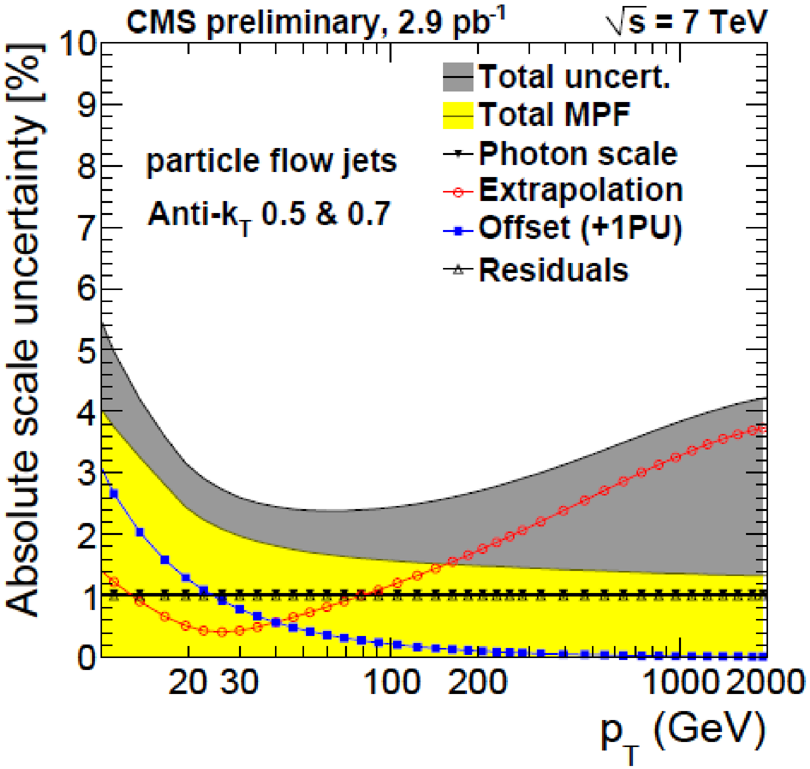
- **Measured jet response in data**
  - From γ+jet events (as in ALEPH) : use the γ p_T to predict the jet p_T



- Impressive agreement between data and simulation
- Slight HCAL end-cap over-calibration, visible only beyond tracker acceptance
  - → Being calibrated away for 2011 data taking

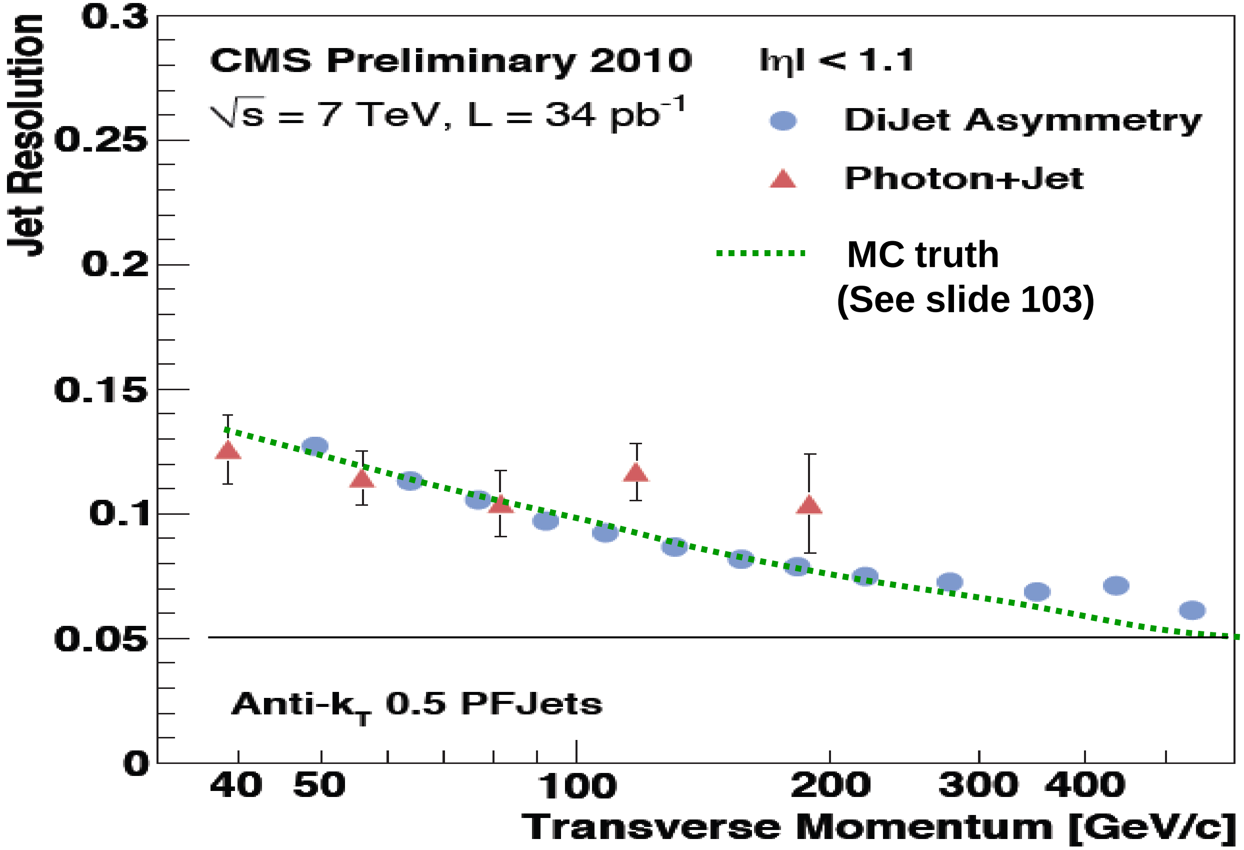
Particle-Flow performance in CMS (9)

- Systematic uncertainty on the jet energy scale (JES)
  - From data : ECAL scale known to 1% (π^0, Z). HCAL scale known to 5%
    - With 25% γ and 10% h^0, the ultimate JES uncertainty is about 1%
  - With γ+jet events, including
    - Flavour uncertainty
    - Photon scale
    - Method uncertainty
    - Statistical uncertainty
    - Extrapolation uncertainty
  - About 3% JES uncertainty for PF jets
    - With only 3 pb^{-1} of data
    - Would be 10% for calorimetric jets



Particle-Flow performance in CMS (10)

- Measured jet resolution in data
  - Still with γ+jet events, but also with di-jet events (p_T imbalance)



Particle-Flow performance in CMS (II)

- Expected performance for Missing Transverse Energy, MET
  - Aimed at measuring the p_T of neutrinos or 
    - MET from particle flow is very intuitive (from p_T conservation):
      - → Sum over all particles from particle flow reconstruction

$$MET = -\sum_{i=1}^{N_{\text{Particles}}} \vec{E}_{\mathrm{T}}^{i}$$

→ The importance of having all particles reconstructed appears clearly

Down to the smallest possible p_T

with the best possible energy determination

- Another important variable, SET, measures the overall activity in the event

$$SET = \sum_{i=1}^{N_{\text{Particles}}} E_{\mathrm{T}}^{i}$$

Particle-Flow performance in CMS (12)

- Expected performance for Missing Transverse Energy , MET (cont'd)
  - Aimed at measuring the p_T of neutrinos or 
    - MET from calorimetry-alone is, instead, a complicated beast :

→ Raw MET :

Sum over all calo towers

$$MET = -\sum_{i=1}^{N_{\text{Towers}}} \vec{E}_{\text{T}}^{\,i}$$

→ Corrected for muons :

Muon-corrected MET

$$-\sum_{i=1}^{N_{\text{muons}}} \vec{E}_{\text{T}}^{\,i}$$

→ Corrected for jet response :

Type-I corrected MET

$$-\sum_{i=1}^{N_{\text{Jets}}} \left(\vec{E}_{\text{T,corr}}^{\,i} - \vec{E}_{\text{T,raw}}^{\,i} \right)$$

→ Corrected for un-clustered energy response

Type-II corrected MET

$$-\alpha \sum_{i=1}^{N_{\text{Unclustered Towers}}} \vec{E}_{\text{T}}^{\,i}$$

Particle-Flow performance in CMS (13)

- Expected performance for Missing Transverse Energy, MET (cont'd)
  - Aimed at measuring the p_T of neutrinos or 
    - MET from calorimetry-alone can also be corrected for tracks :
      - → Raw MET :

        Sum over all calo towers

        $$MET = -\sum_{i=1}^{N_{\text{Towers}}} \vec{E}_{\text{T}}^{\,i}$$

      - → Corrected for muons :

        Muon-corrected MET

        $$-\sum_{i=1}^{N_{\text{muons}}} \vec{E}_{\text{T}}^{\,i}$$

      - → Corrected for track expected response in a calorimetric road :

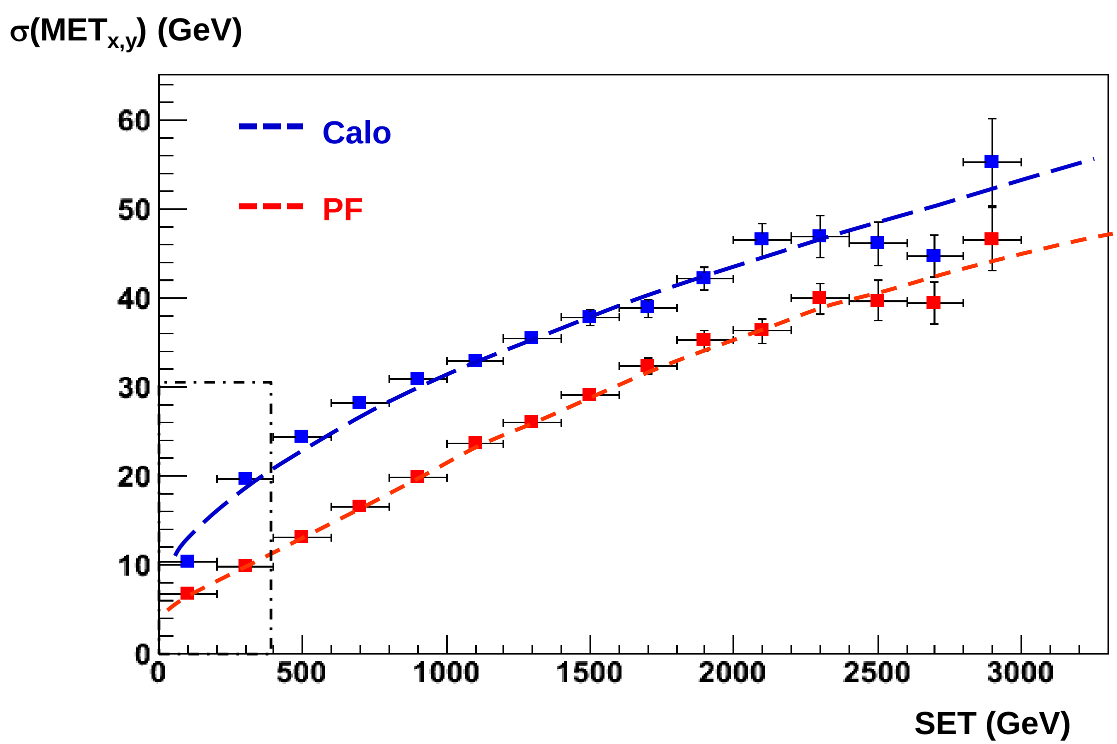
        Track-corrected MET

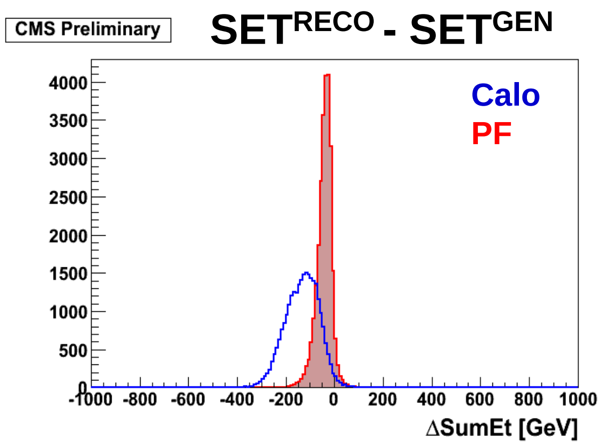
        $$-\sum_{i=1}^{N_{\text{Tracks}}} \left(\vec{p}_{\text{T}}^{\,i} - \vec{E}_{\text{T,expected}}^{\,i}\right)$$

    - … which gives an "Energy-Flow" type of MET
      - → An intermediate step, if one is too shy to go to full Particle Flow

Particle-Flow performance in CMS (14)

- Expected MET resolution for multi-jet events
  - No MET expected in these events (no neutrinos) :
    - $\sigma(MET_{x,y})$ is the resolution to measure 0



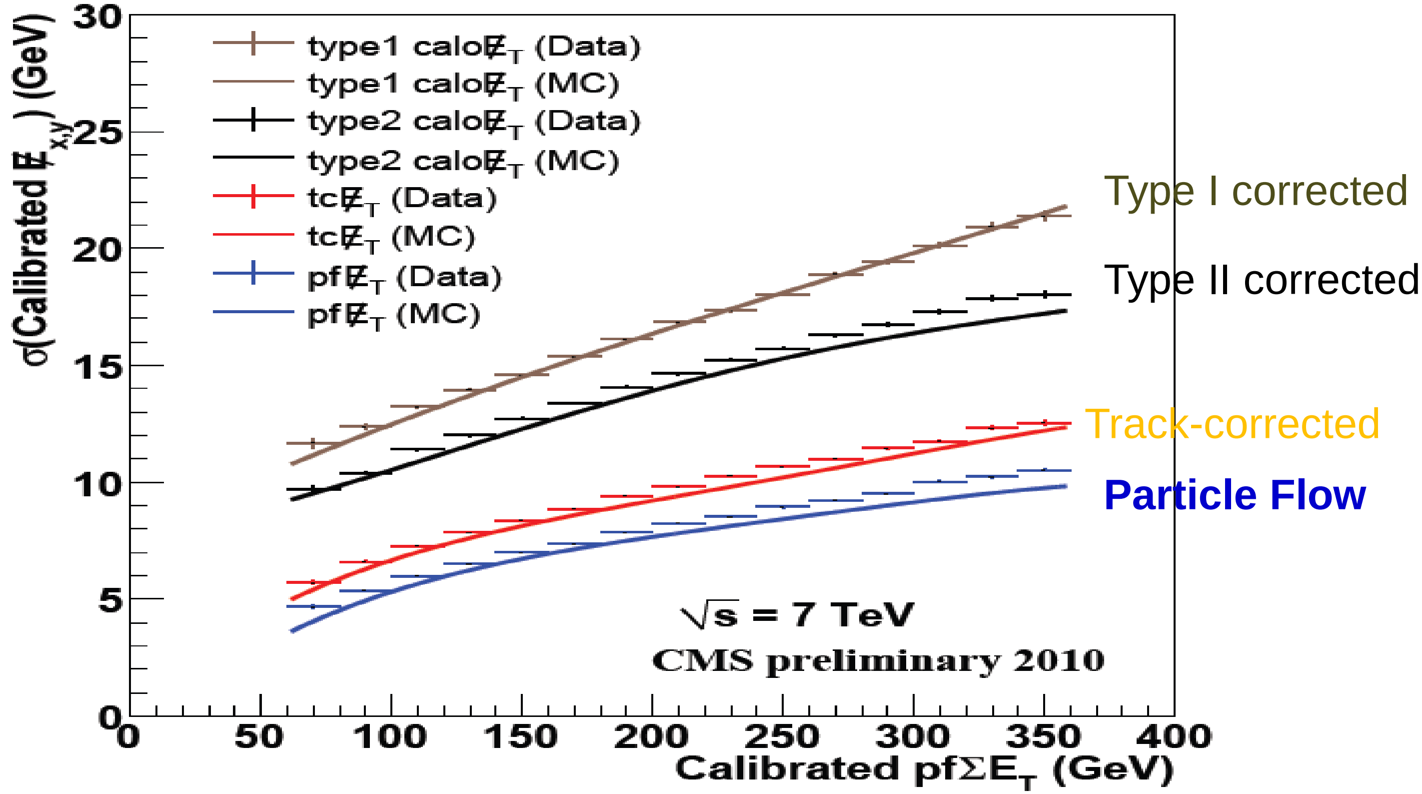


- Improved resolution by a factor > 2 all the way to SET = 1 TeV

→ Significant expected improvement up to the largest SET values

Particle-Flow performance in CMS (15)

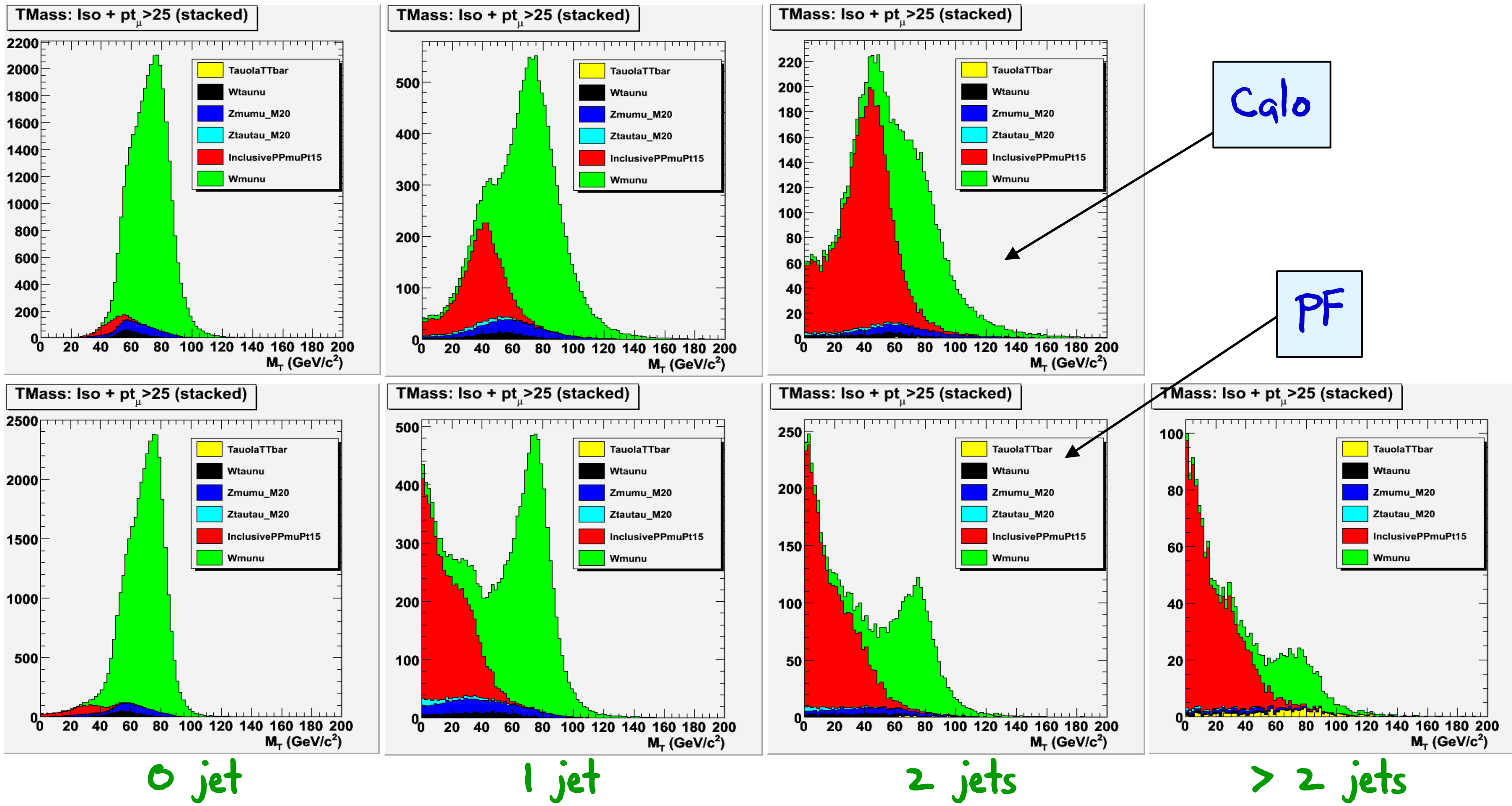
- Measured MET resolution for multi-jet events
  - Factor of 2 improvement confirmed with data, on both x,y components



- Residual disagreement with simulation will disappear with HCAL calibration

Particle-Flow performance in CMS (16)

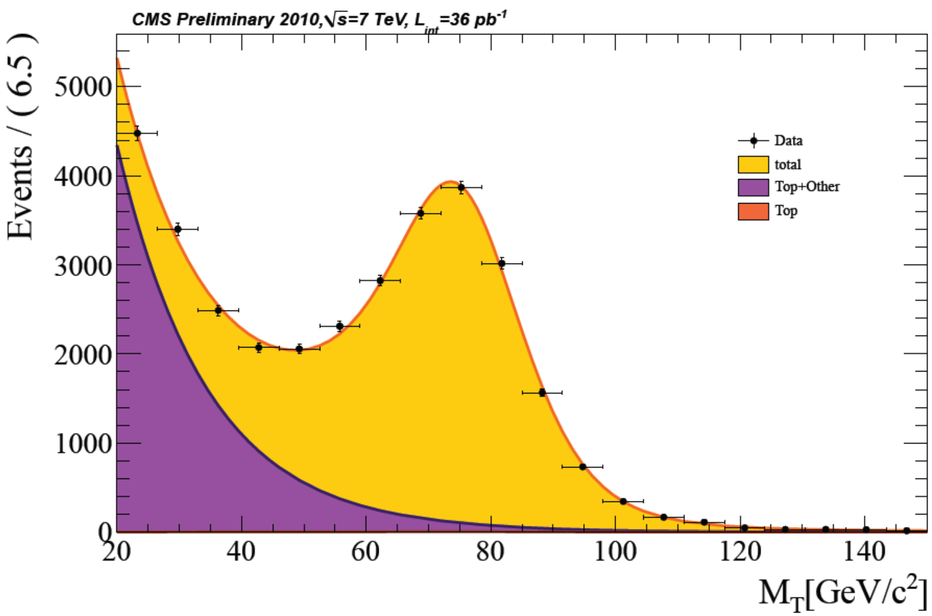
- Expected MET resolution for events with missing energy
  - W + jets events, with W → μν : Transverse mass made with $p_T(\mu)$ and MET



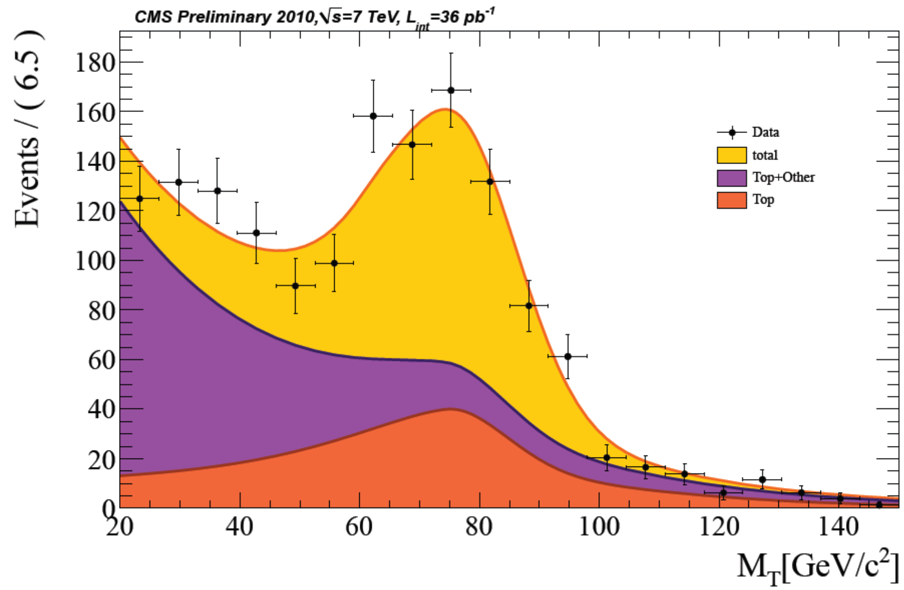
Particle-Flow performance in CMS (Π)

- Measured MET resolution for events with missing energy
  - W + jets events, with W → μν : Transverse mass made with $p_T(\mu)$ and MET

W + one jet



W + three jets



- Missing energy resolution and response for neutrino confirmed
  - → Both for events without and events with missing energy

Particle-Flow performance in CMS (18)

- CMS was (by chance) almost designed for particle-flow reconstruction
  - Hermeticity, Simplicity, Granularity, Magnetic Field [Slide 35]
    - Found to be just adequate
      - → Even if one could have done better (tracker, HCAL)
  - Material : External constraints led to a (very) thick tracker [Slide 35]
    - Caused a lot of work for years to deal with it
      - → Photon conversions, Electron Bremsstrahlung, Hadron nuclear interactions
  - Redundancy : No energy measurement redundancy in the calorimeters [Slide 35]
    - Source of continuous nightmares for calorimeter cleaning
  - But there was a handful of enthusiastic and knowledgeable people [Slide 36]
    - who believed in the success of the project from first principles
    - And who completed it in about four years of ceaseless work
      - → (Remember : four months in ALEPH, because of the thoughtful design)
  - Particle Flow is now used in most CMS physics analyses

Bad/suboptimal design is not the worse enemy !

- People are worse …
  - Religious war from calorimeter experts / users (50% of the CMS collaboration)
    - "Particle Flow never worked at a hadron collider" 2007
    - "Particle Flow is too complicated – calorimeters are simple" 2008
    - "It may work on simulation, but it won't work on data" 2009
    - "It may work on data, but it does not bring much …" 2010
  - Religious war from tracking experts / users (50% of the CMS collaboration)
    - "Iterative tracking is hopeless is such an environment" 2006
    - "It may work for electrons, but what else do we need it for?" 2007
    - "It works, but it does not bring that much" 2008
  - Iterative tracking has become the official CMS tracking 2009
  - Particle Flow is now used in most analyses in CMS 2011
    - But still people think it's magic inside

Concluding remark

- Extracts from Richard Wigmans' lecture on Monday, Jan. 31st
  - A number of religious statements, typical of a calorimeter expert
    - "Calorimeter granularity brings only confusion"
    - "The fact that 65% of the energy is perfectly measured in tracker is irrelevant"
    - "GEANT4 has never predicted anything correctly concerning hadron calorimetry"
    - "Advocates of particle-flow reconstruction use phony statistics"
      - → "Because they are not happy of the results"

- Conclusion
  - Once you have convinced yourself that you have a good idea
    - Based on scientific observations (first principles, feasibility study, ...)
      - → Don't let experts (of something else) Kill your enthusiasm !

Just think, move forward, and FOLLOW YOUR DREAMS