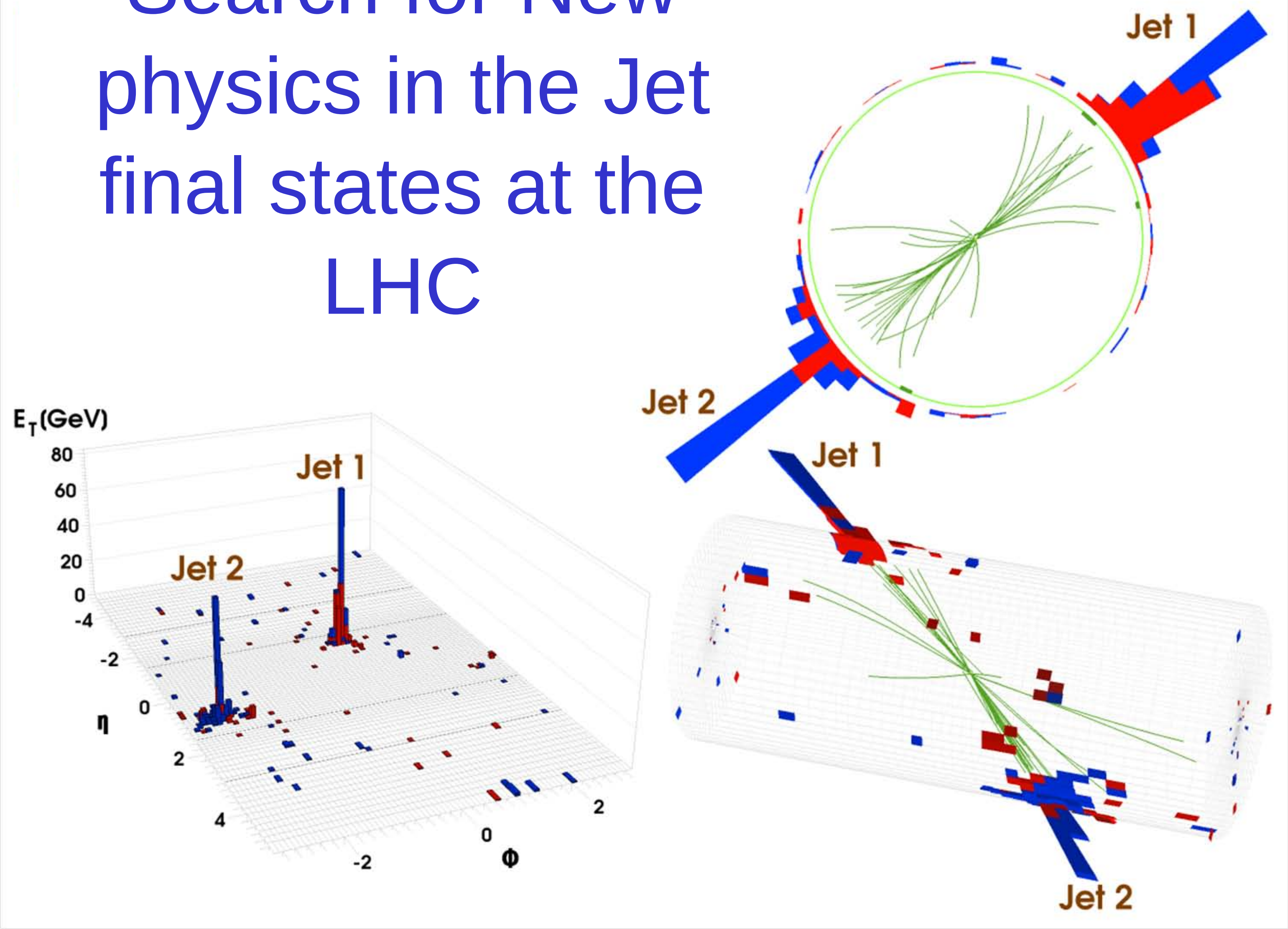
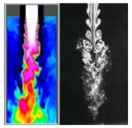
Maxime Gouzevitch

Search for New physics in the Jet final states at the LHC



1) Jets in LHC physics

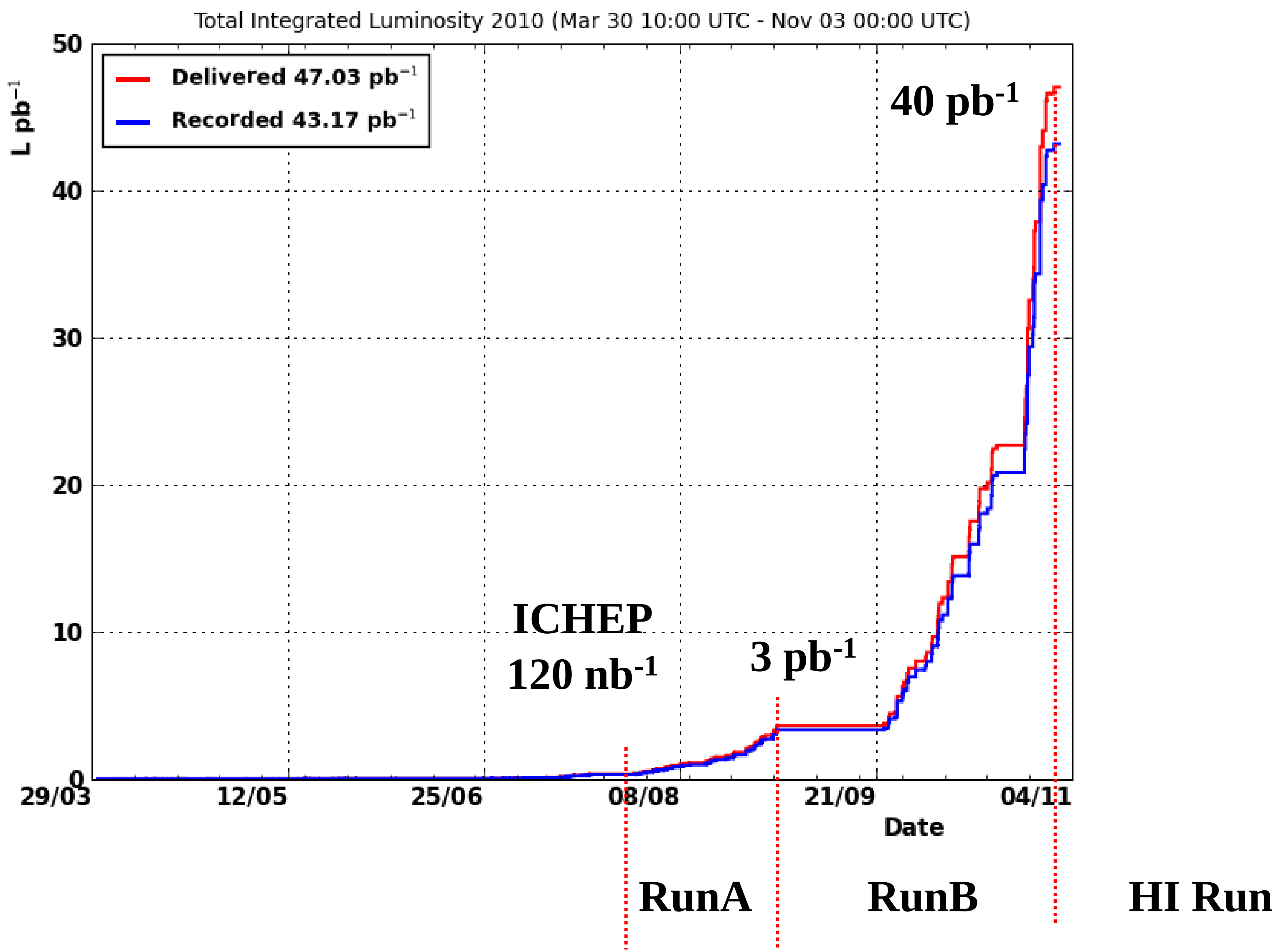


Jets reconstruction in CMS:
Jets production overwhelming at LHC energies:
Commissioning in Min-Bias just after the photons and charged hadrons.

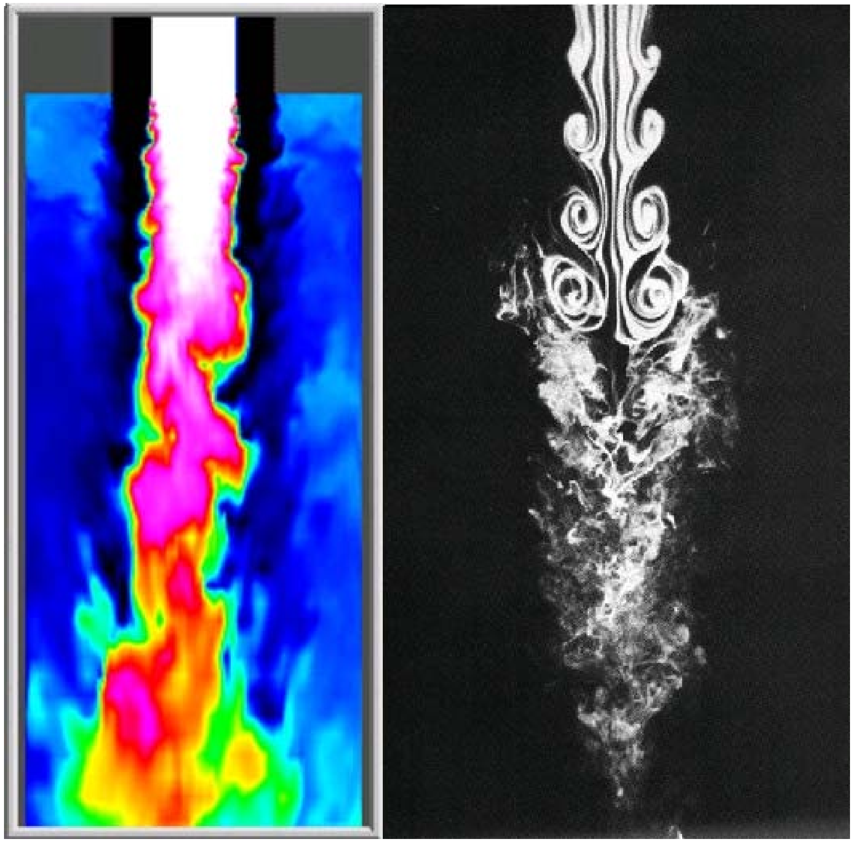
- Particle Flow in CMS.

- Testing ("rediscover") QCD at large scales:
  - This is a simple and robust observable:
  - No need for complicated isolation/identification studies.
  - Acceptance going up to $\eta = 5$.
- Exploring new domains:
  - Well adapted for search of new physics coupling to q,g with first data.
- Jets that you don't see.

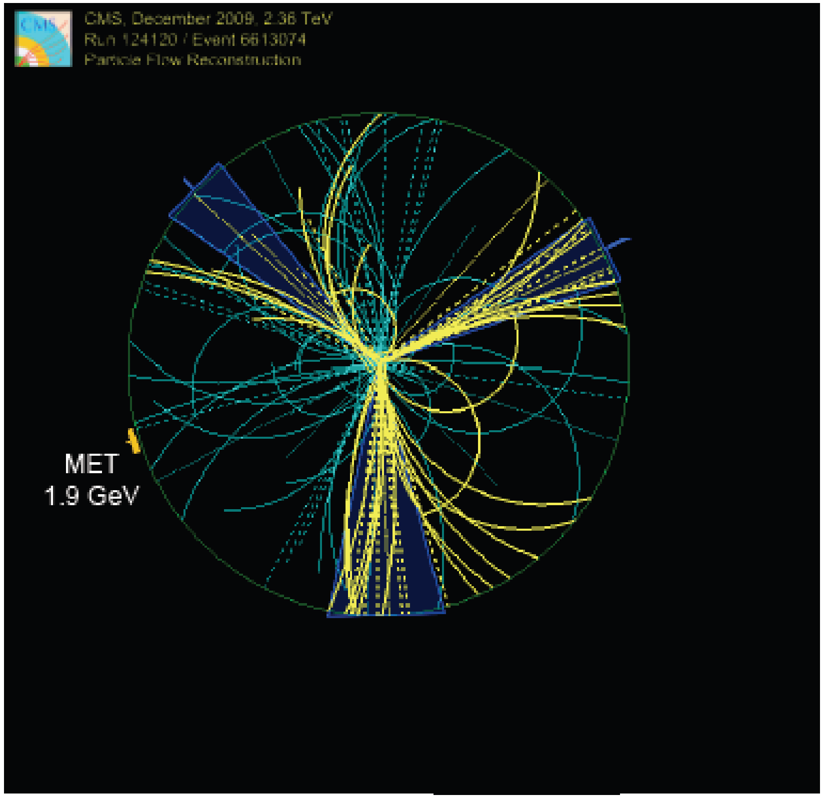
CHRONOLOGY


Total Integrated Luminosity 2010 (Mar 30 10:00 UTC - Nov 03 00:00 UTC)
Delivered 47.03 pb⁻¹
Recorded 43.17 pb⁻¹
L pb⁻¹
50
40
30
20
10
0
29/03
12/05
25/06
08/08
21/09
04/11
Date
40 pb-1
ICHEP
120 nb-1
3 pb-1
RunA
RunB
HI Run

Jets reconstruction in CMS



1.1) 2 word about algorithms

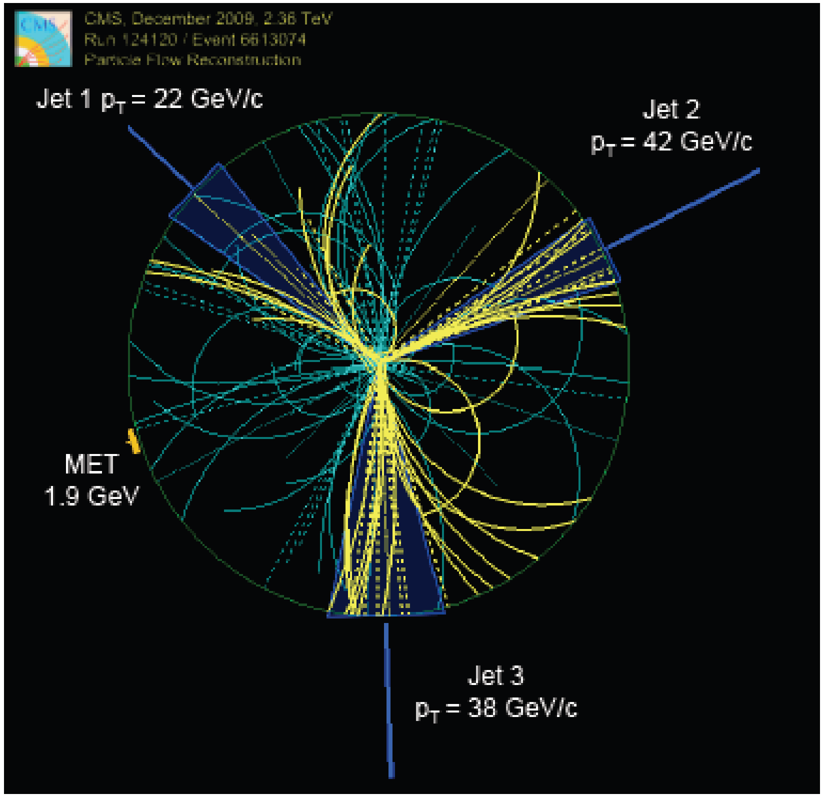


A jet is something that happens in high energy events:

a collimated bunch of hadrons flying roughly in the same direction

Often you don't need a fancy algorithm to 'see' the jets

1.1) 2 word about algorithms



A jet is something that happens in high energy events:

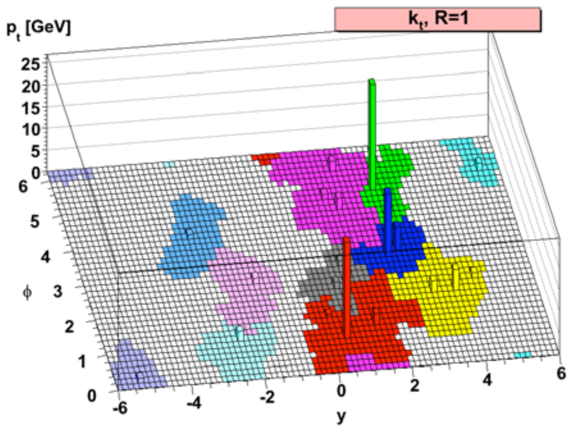
a collimated bunch of hadrons flying roughly in the same direction

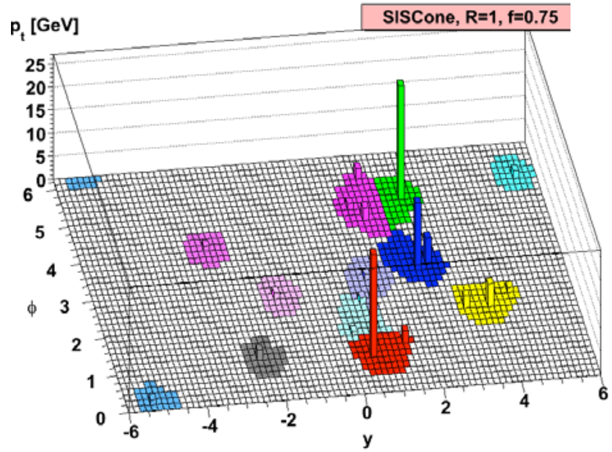
Often you don't need a fancy algorithm to 'see' the jets

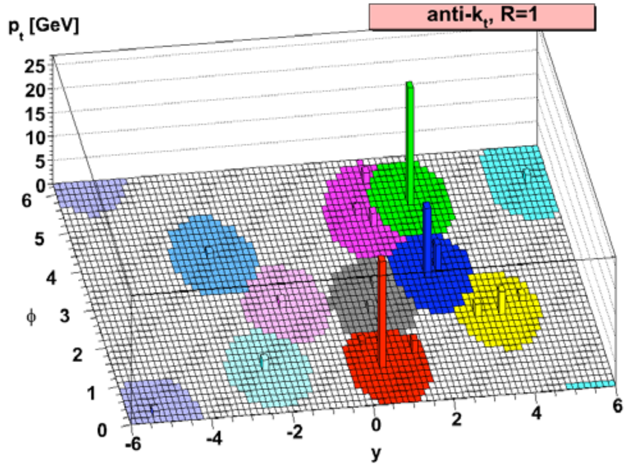
But you do to give them a **precise** and **quantitative** meaning

1.2) 1 word about algorithms: 3 golden boys

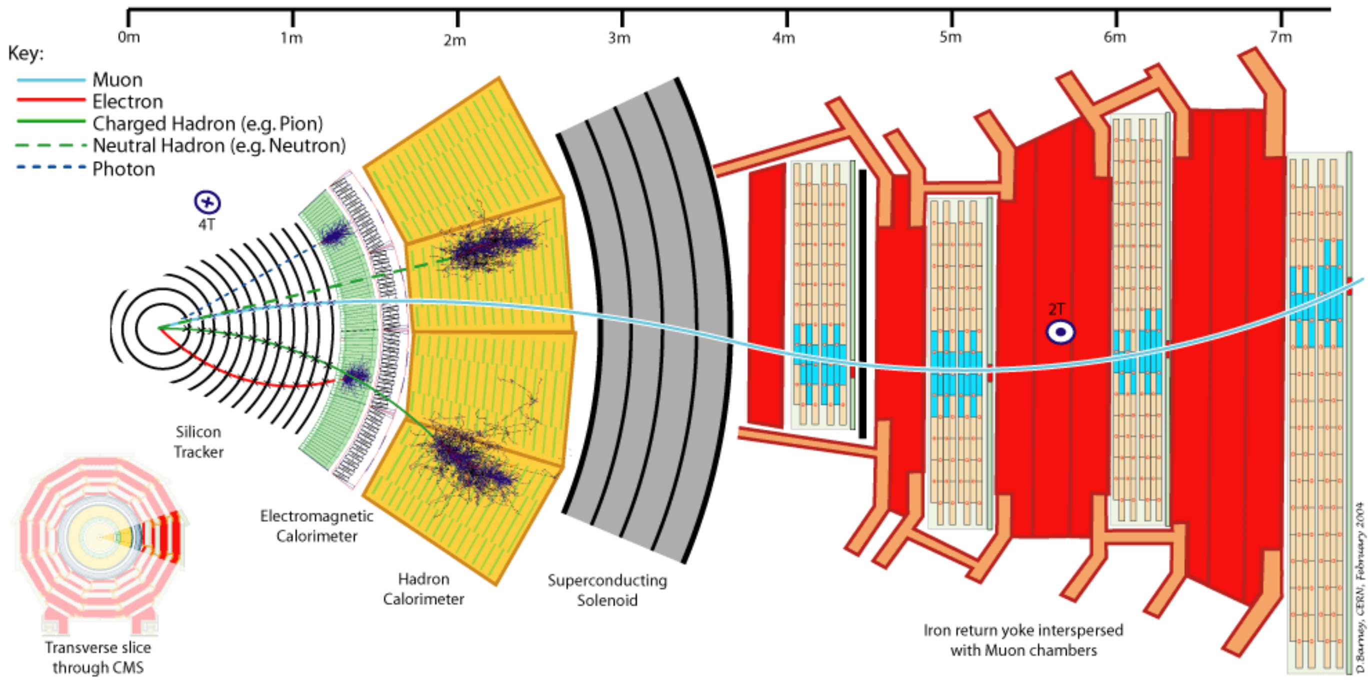
- In the LHC world it was decided to:
  - Use only(mainly) Infrared/Colinera safe algorithms.
  - Maintain different algorithm adapted to different needs.
  - 3 Golden boys: k_T, anti-k_T and Sis-cone.





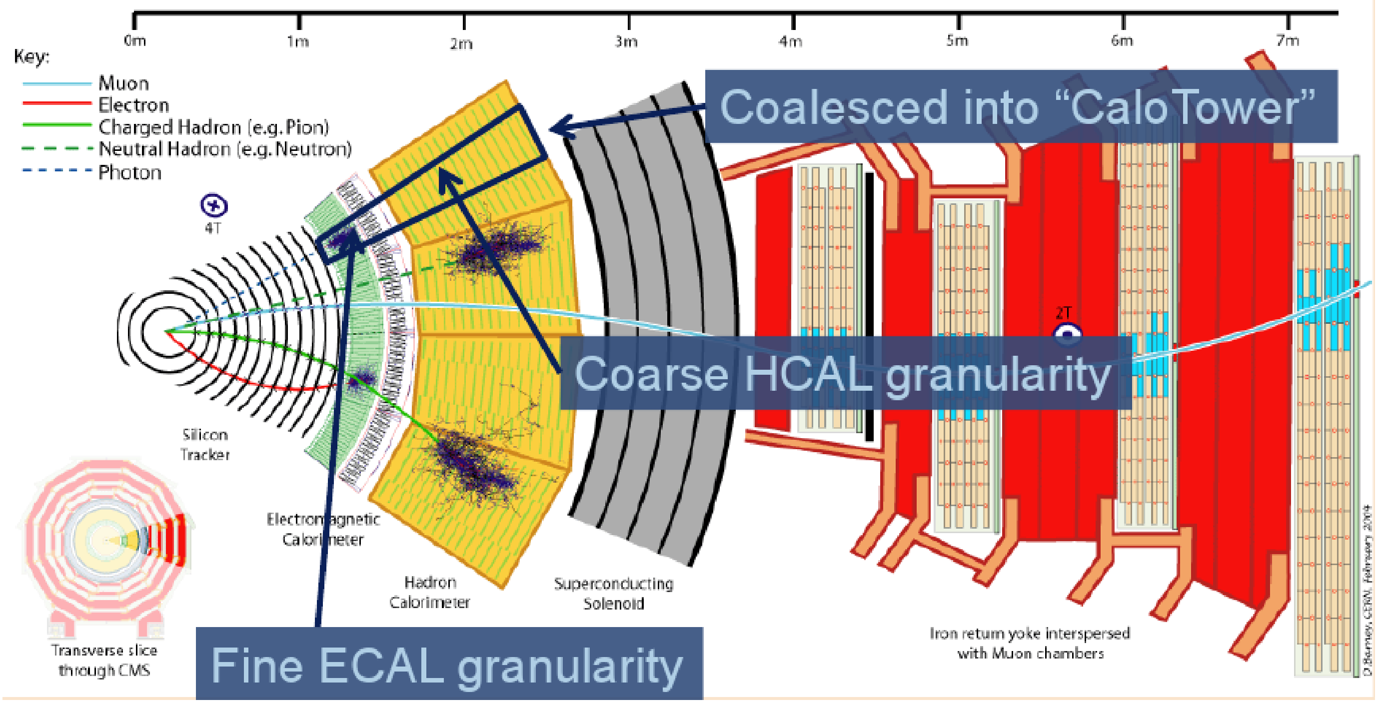


2) Jet reconstruction in CMS: 3 types



Bunch of standard algos:
(anti-)k_T, SisCone, R=0.5, 0.7

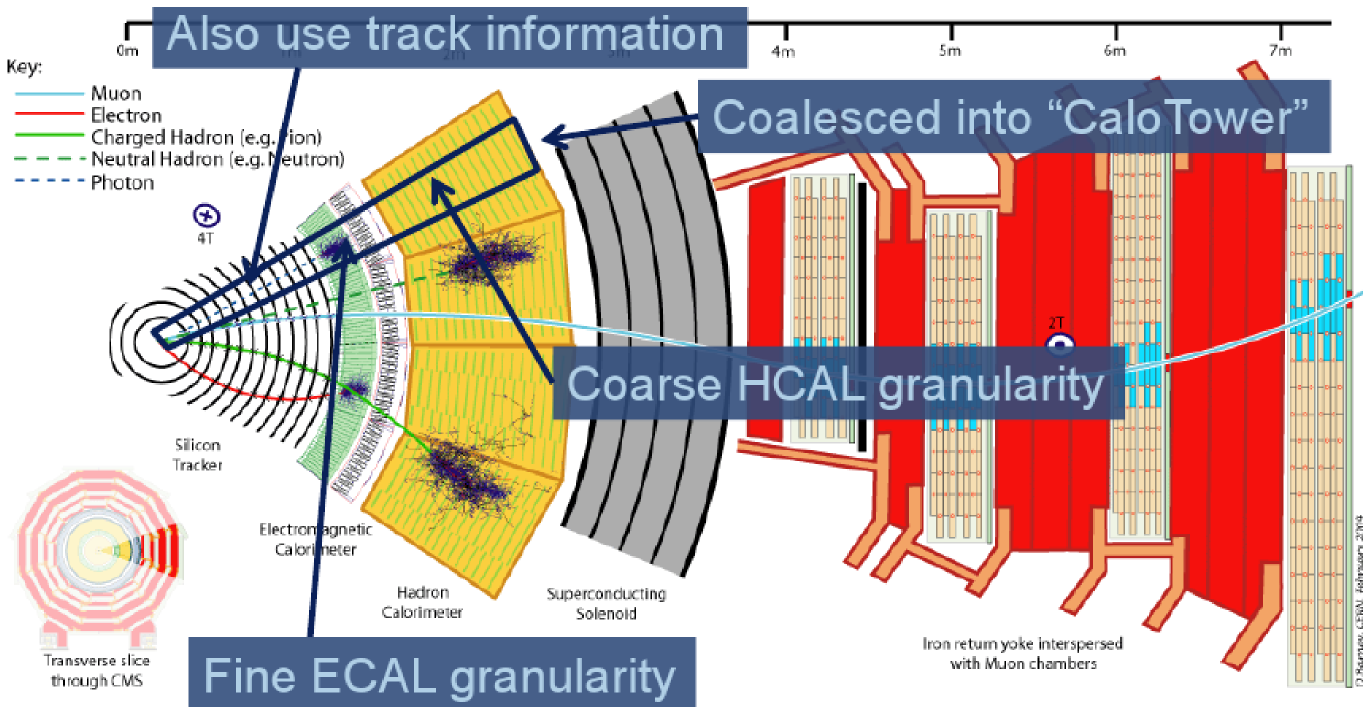
2) Jet reconstruction in CMS: 3 strategies



Calorimeter jets

Bunch of standard algos:
(anti-)k_T, SisCone, R=0.5, 0.7

2) Jet reconstruction in CMS: 3 strategies



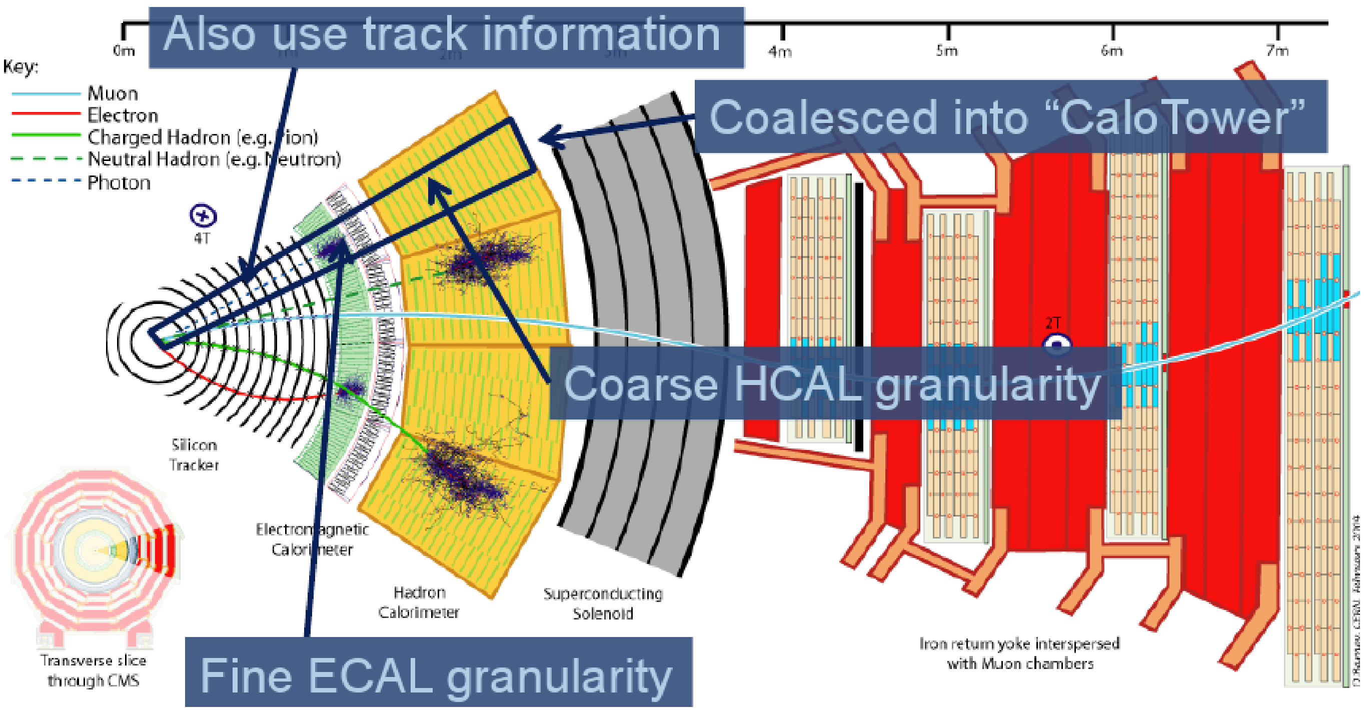
Calorimeter jets

Jet + Track jets (JPT)

replace calo towers
by tracks when matched.
Resolution of tracks ~1%

Bunch of standard algos:
(anti-)k_T, SisCone, R=0.5, 0.7

2) Jet reconstruction in CMS: 3 strategies



Calorimeter jets

Jet + Track jets (JPT)

replace calo towers
by tracks when matched.
Resolution of tracks ~1%

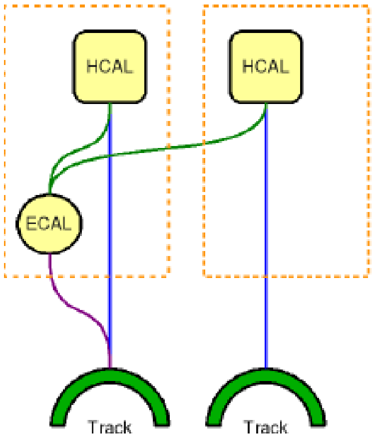
Particle Flow jets

- use a coherent combination all detectors to reconstruct and identify particles.

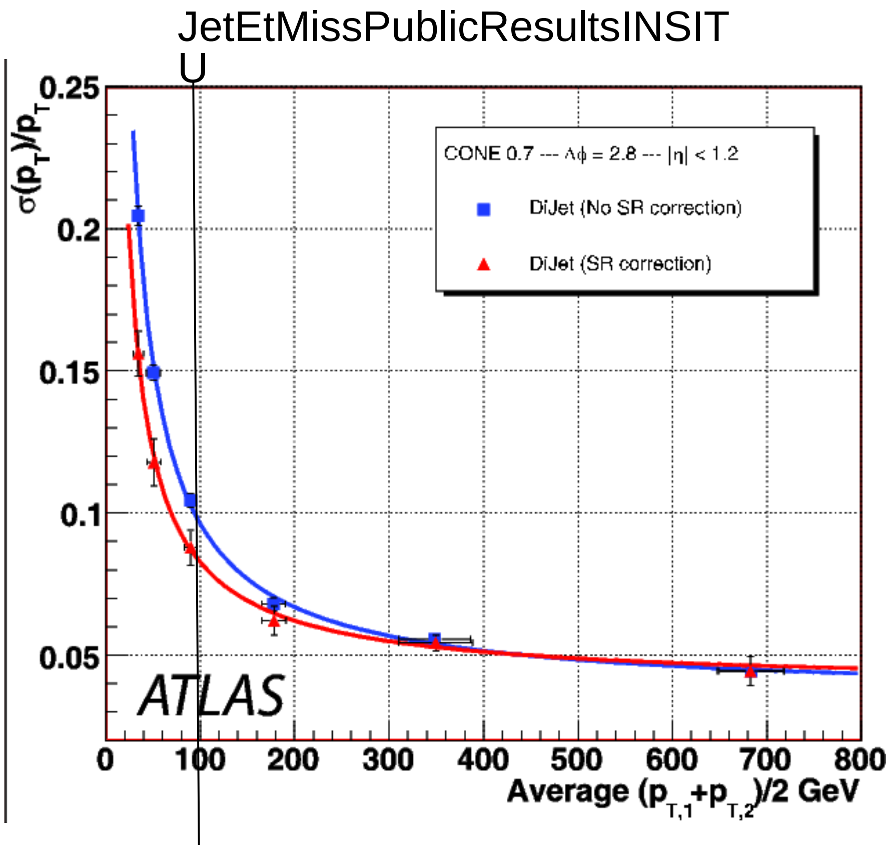
- compute jets out of those particles.

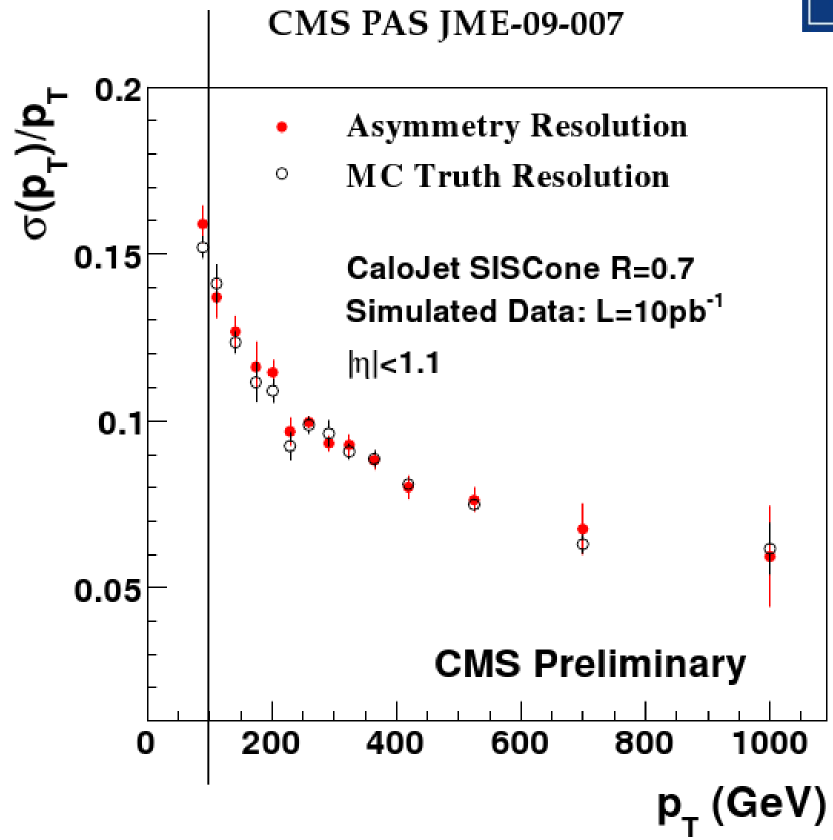
Bunch of standard algos:
(anti-)k_T, SisCone, R=0.5, 0.7

Some words about the Particle Flow algorithm at CMS



1) Initial motivation to do complicated things?





- Calorimeter jet resolution at 100 GeV
  Atlas - 8%, CMS – 14% (intrinsically limited)

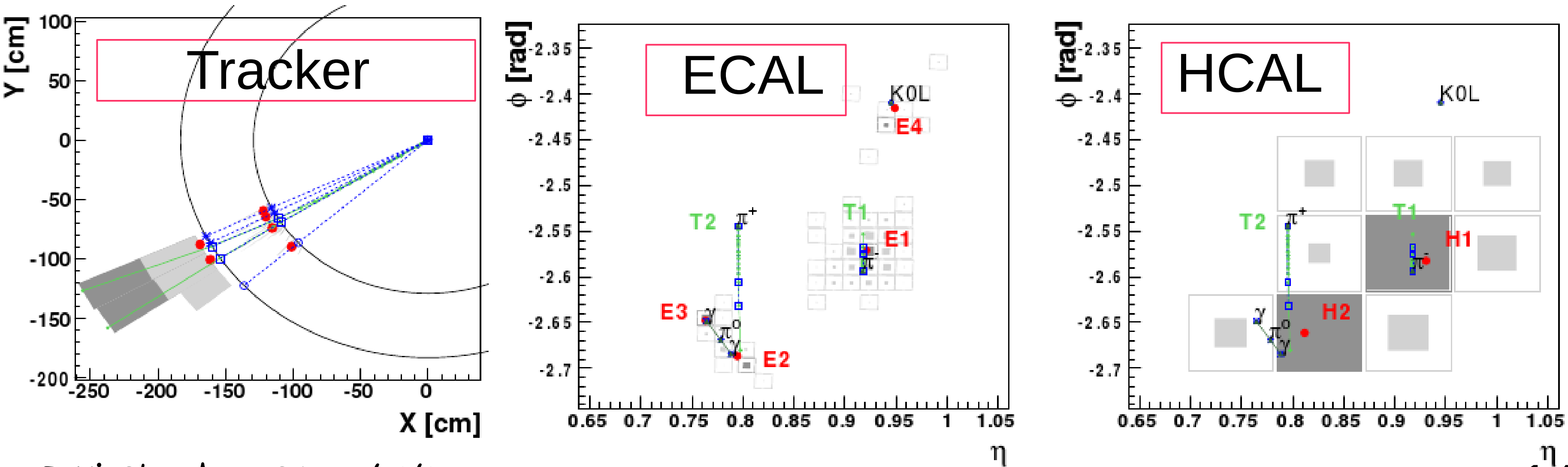
- Calibration factors for jet energy scale 30% at 100 GeV in CMS

1) Particle Flow algorithm

1) The basic ingredients
- Charged tracks: iterative tracking algorithm.
- Calorimeter clusters.
- Muons: standard Muon finder in CMS.
- Electrons: Tracker driven and Calo driven finders

2) Are linked together by an approach distance into Blocks.

3) Block are parsed into particle candidates.



2.1) Particles identification in a block: LEPTONS

➔ **μ:** are removed with deposed calo energy: muons with a Muon chambers track and possibly a tracker track.

➔ **e:** are removed.

2.2) Particles identification in a block: HARDONS, PHOTONS

P_{trk} - total track momentum
E_{calo}- total calibrated ECAL+HCAL energy

- $E_{calo} \sim P_{trk}$: charged hadrons (p^+, π^+, K^+...) are computed with momentum averaged from P_{trk} and ECAL.

- $E_{calo} >> P_{trk}$: photons (γ) and neutral hadrons (n, K^0, Λ^0...) created in addition to charged hadrons.

- $E_{calo} << P_{trk}$: presence of fake tracks, nuclear interactions, lost calo clusters. A cleaning is done. Then compare again E_{calo} and P_{trk}.

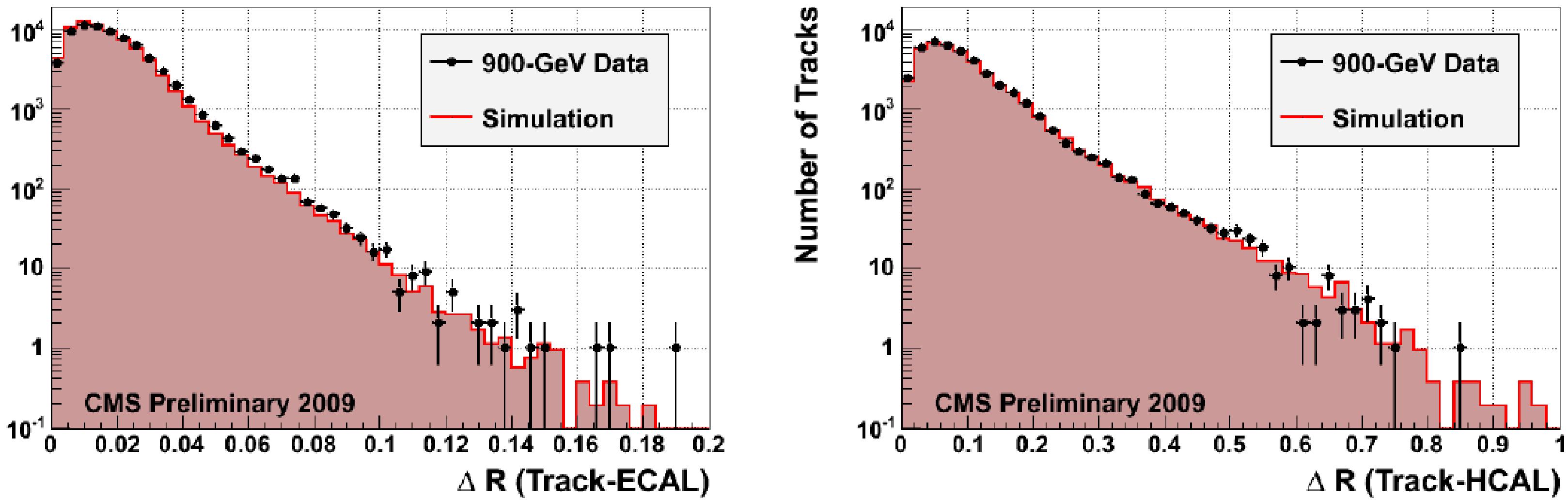
3.1) Validation of Pflow objects in Min Bias

- First data: low occupancy of the detector. Good environment to test Particle Flow parameters

ECAL
Cell 0.02

CMS-PAS-PFT-10-001

HCAL
Cell 0.1

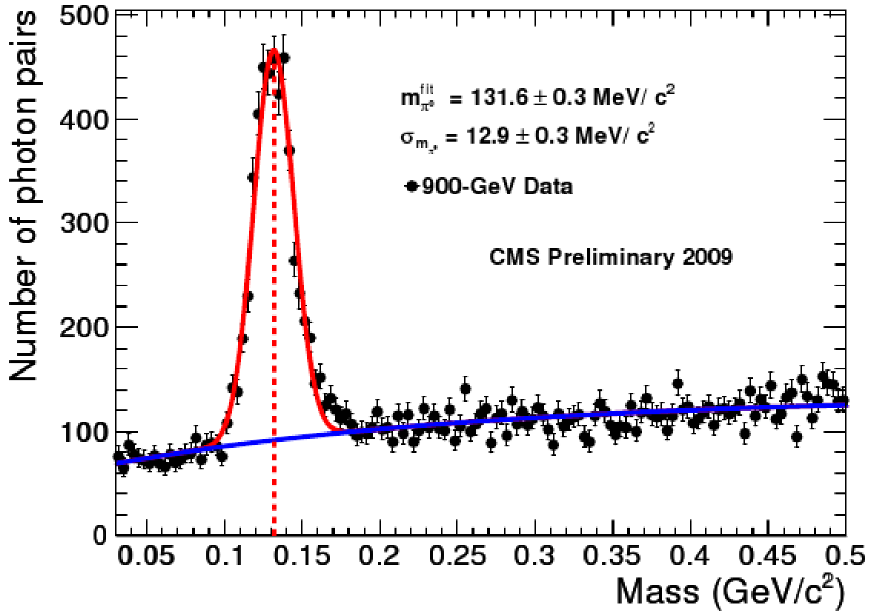


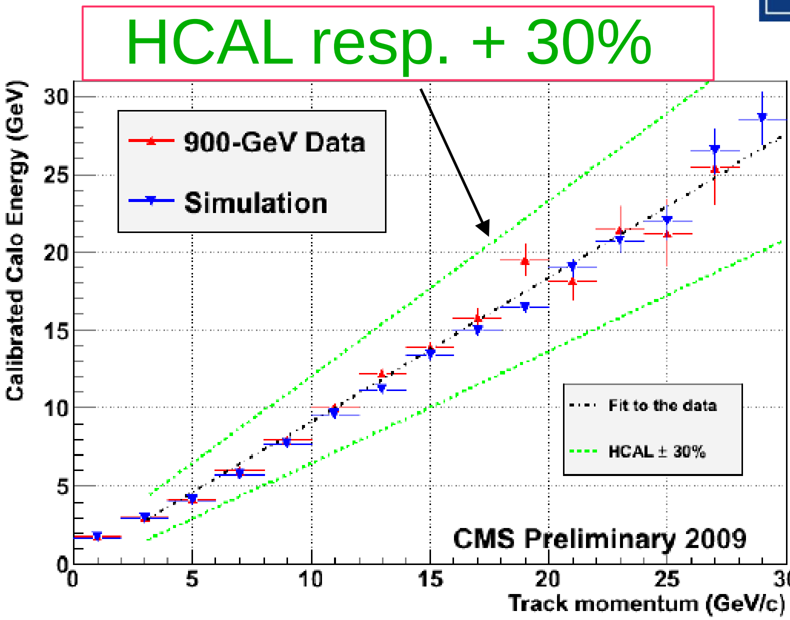
- Track extrapolated to the shower maximum in ECAL/HCAL.

- Track-Cluster linked if track within cluster+1 cell (fluctuations).

3.2) Validation of Pflow objects in Min Bias

CMS-PAS-PFT-10-001





- $\pi \rightarrow \gamma\gamma$

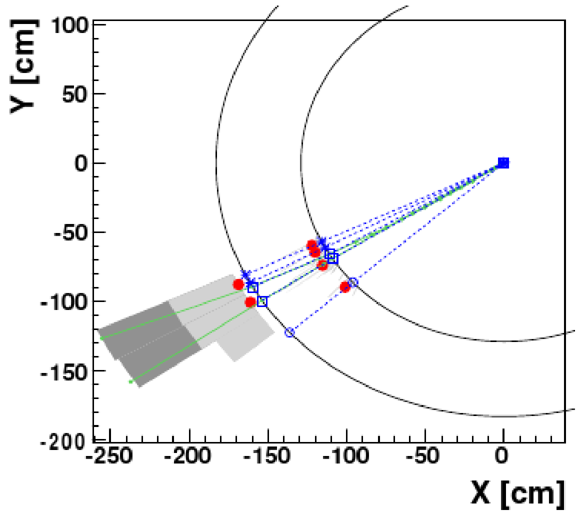
- Agreement within 2% (World average: 135 MeV) with word average. Typical level of control of the ECAL response.

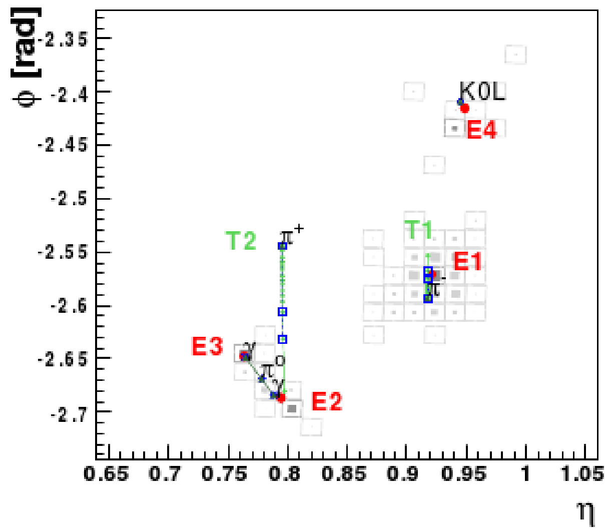
- In first data few overlaps: charged/neutral particles.

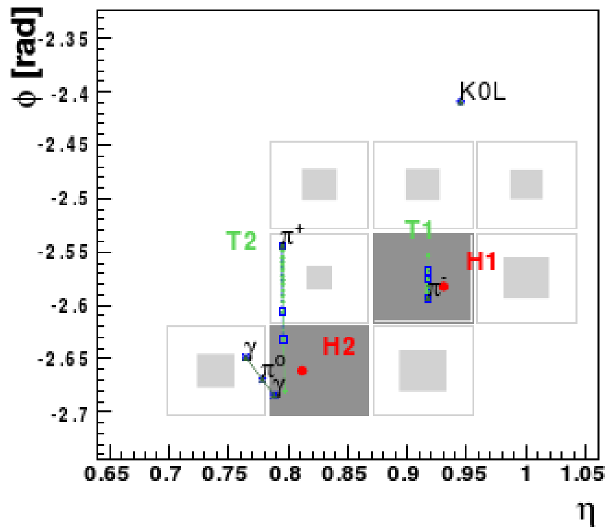
- Good agreement: $P_{trk} \sim E_{calo}$

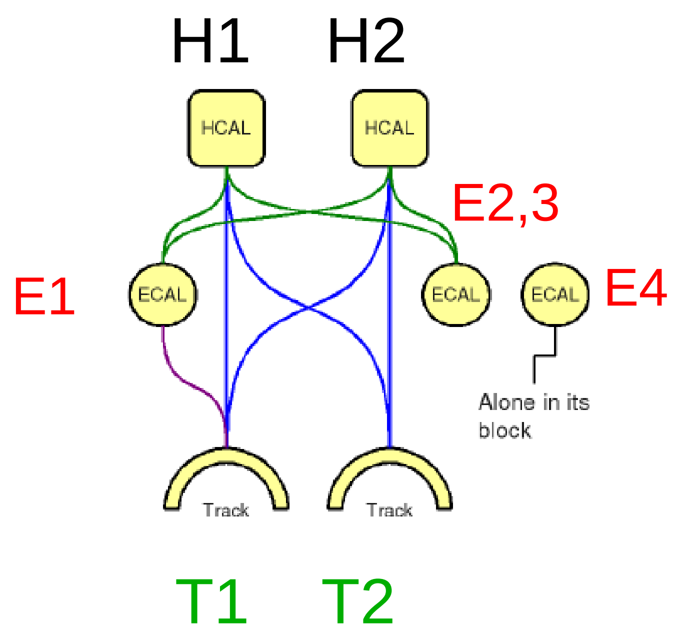
- Good control of HCAL response

4) Back to our example









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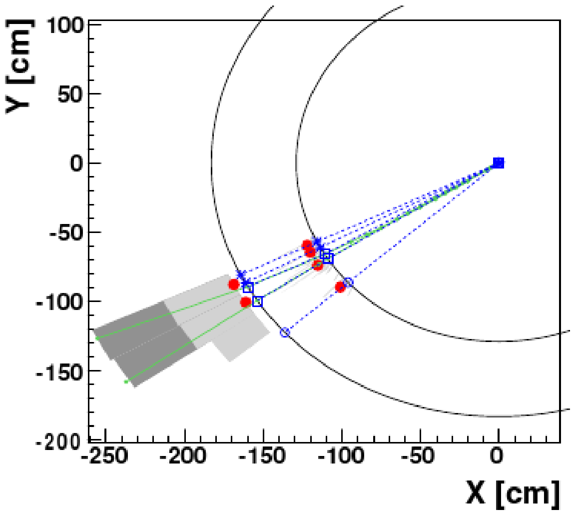

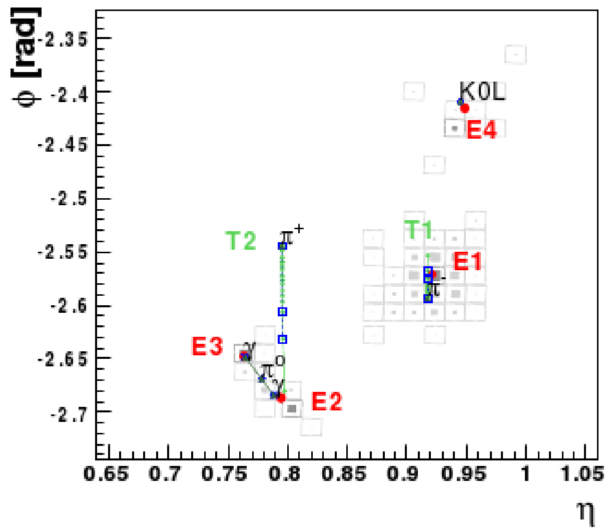

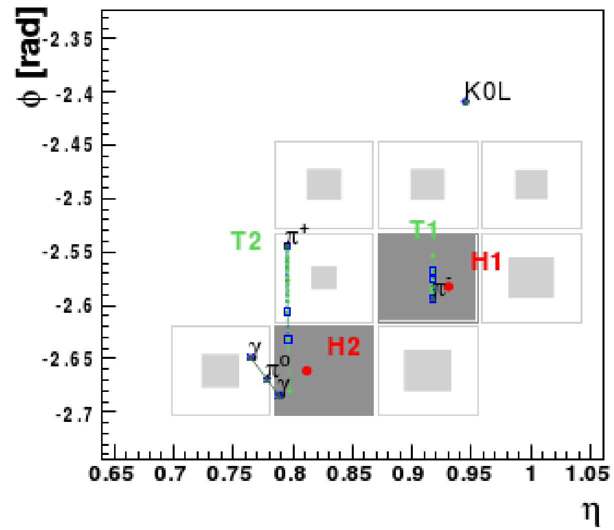

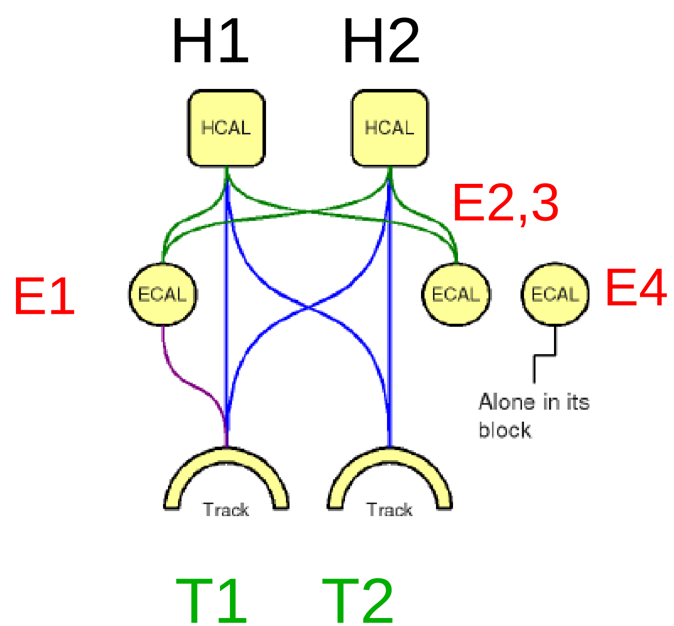

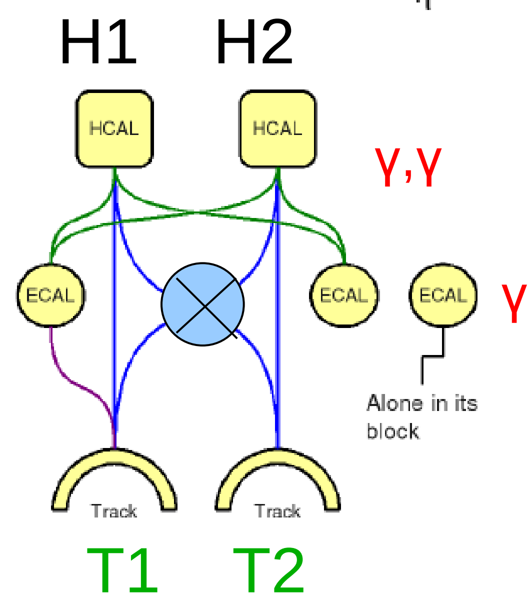

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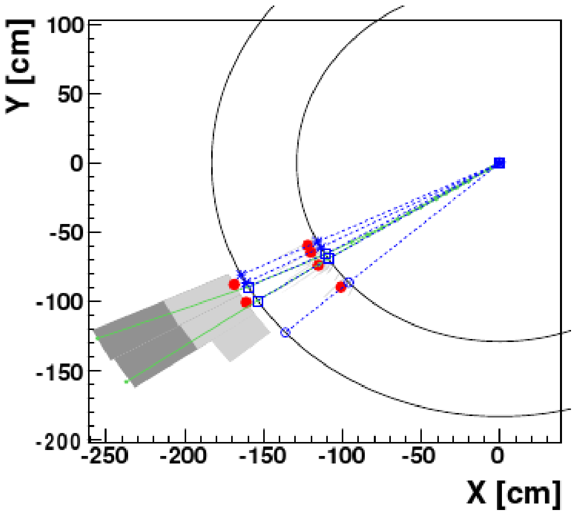
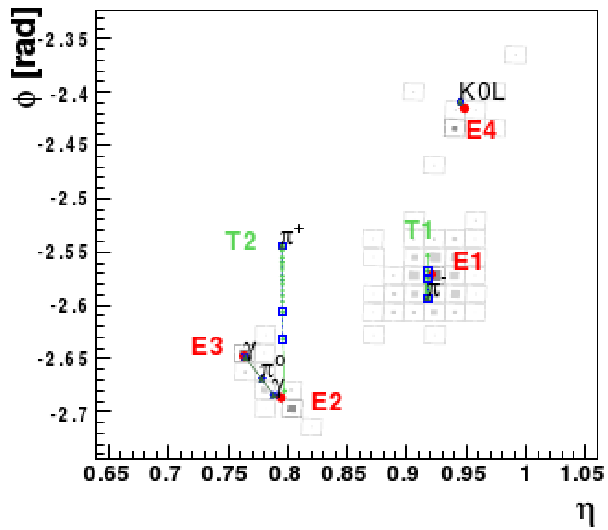
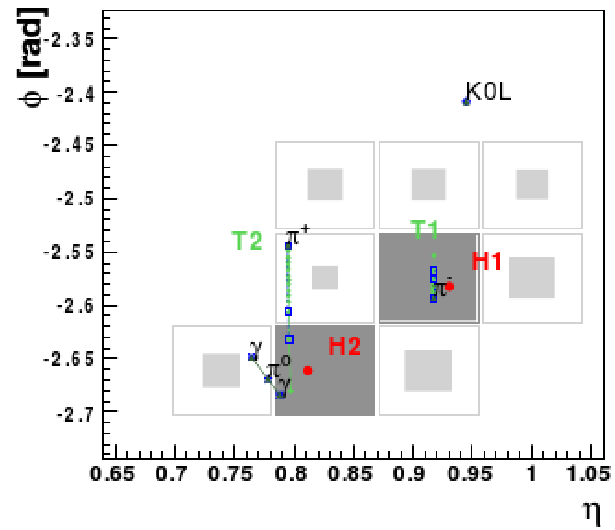
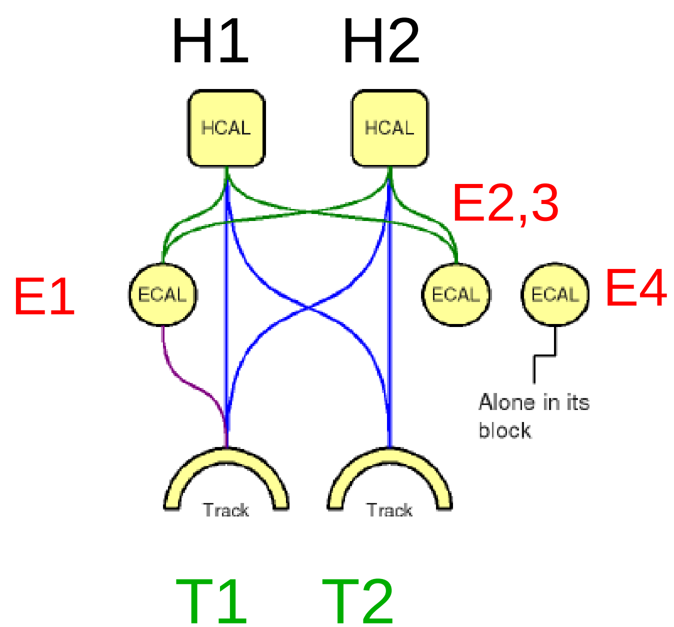
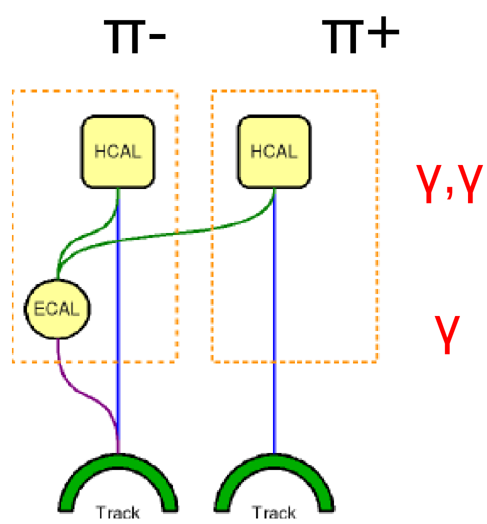








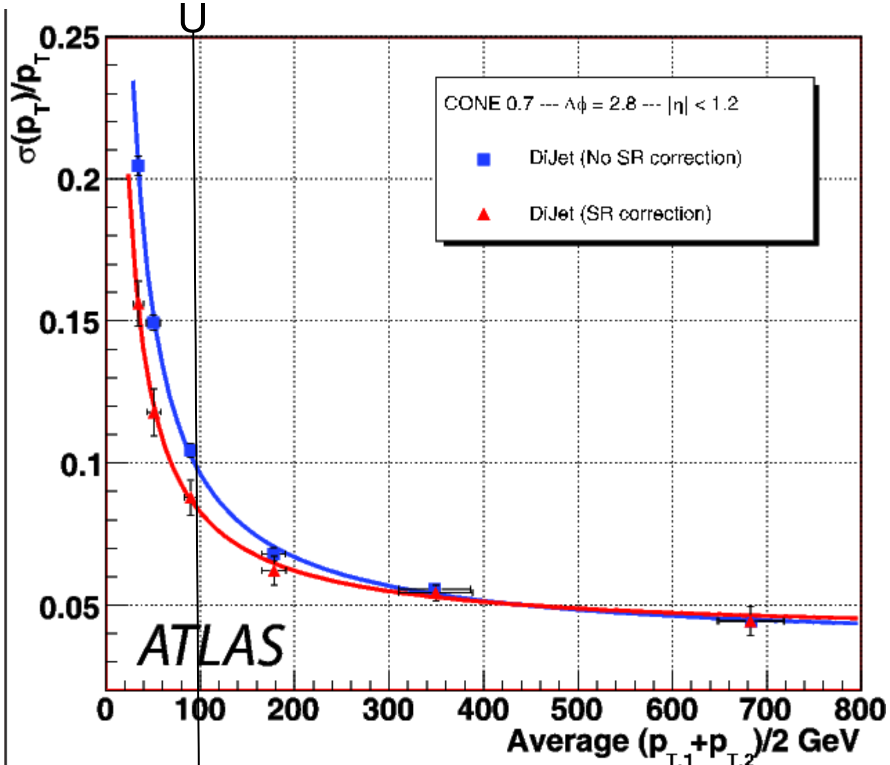


Generated jet (p_T = 65 GeV):
$\pi^-, \pi^+, \pi^0(\gamma+\gamma), K^0$

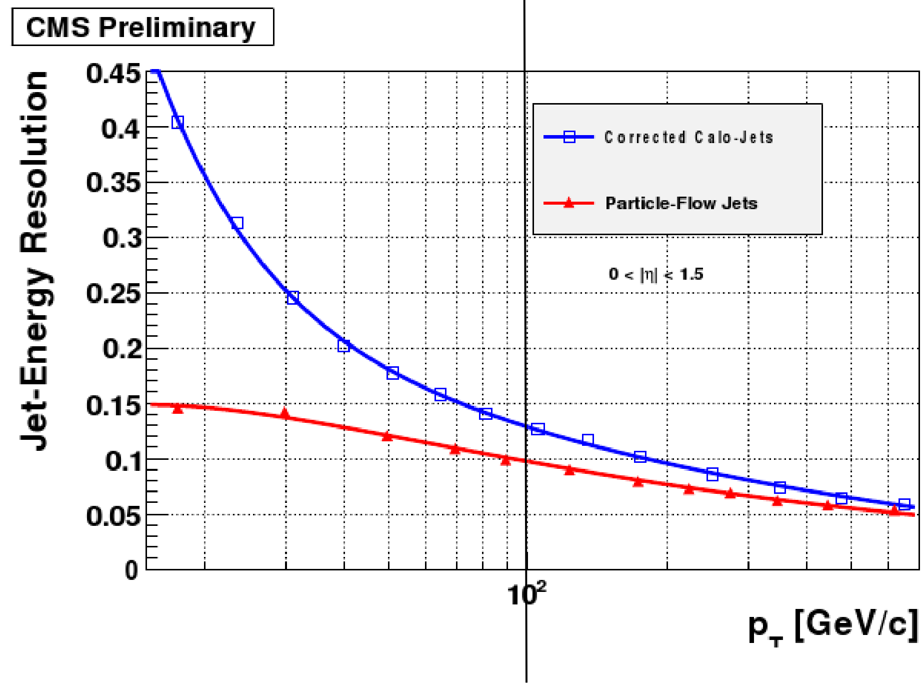
Reconstructed jet (?????):
$\pi^-, \pi^+, \gamma+\gamma, \gamma$

5) Are we happy?

JetEtMissPublicResultsINSIT U



CMS-PAS-PFT-09-001



- Calorimeter jet resolution at 100 GeV

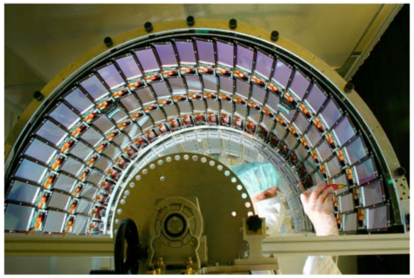
  Atlas - 8%, CMS PFlow - 9%

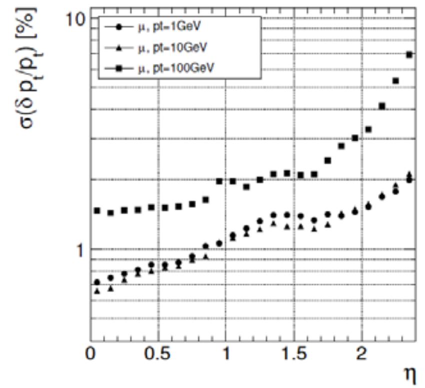
Calibration factors for jet energy scale 5% at 100 GeV in PFlow.

Jets calibration and related systematic

1.1) Single particle response

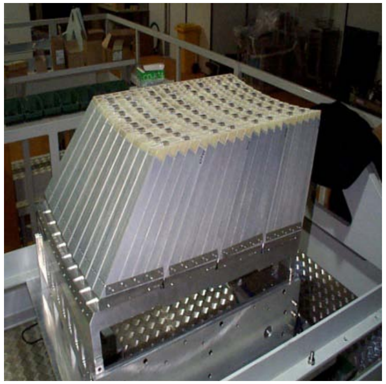
- Full Si tracking system: ~1% resolution for **μ±** below 100 GeV. Slightly worse but comparable for **π±**.

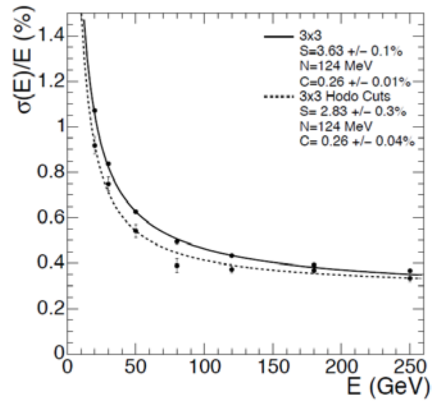




- ECAL (PbWO4): ~1% resolution on **e±** and **γ**.

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2,$$





1.2) Single particle response

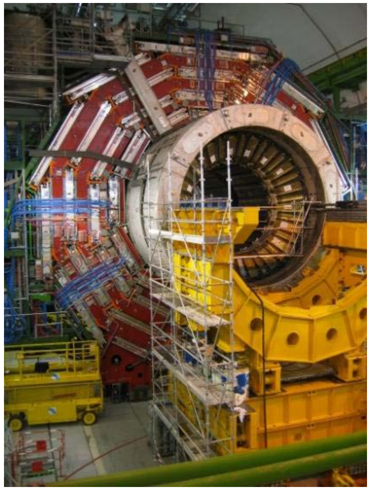
- HCAL (Cu + Tiles/fiber)

  Response = 1 for 50 GeV $\pi\pm$.

  Then propagated to all modules by radiation sources.

  Sim. Tuned using e/ π beam.

  Resolution for $\pi\pm$: **120% /$\sqrt{E}$ + 6.9%**

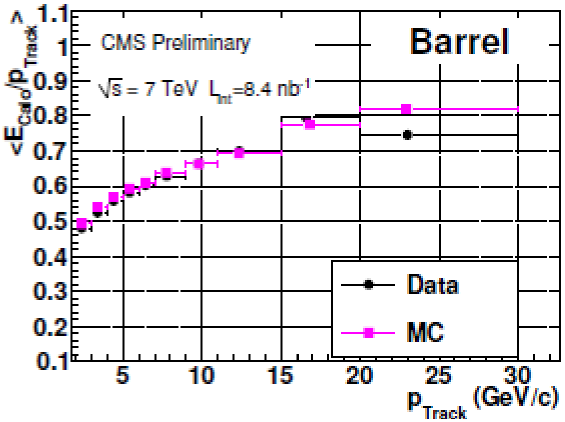


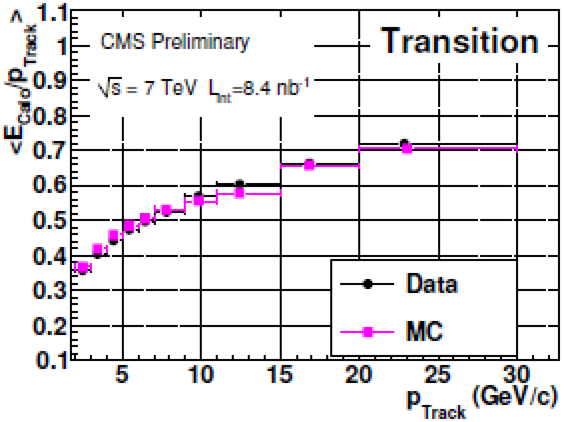
HCAL non compensation

e/h different for ECAL and HCAL (not so significant for Atlas)

Significant NON LINEARITY in response.

Dependence on simulation: 5-8% difference Data/MC

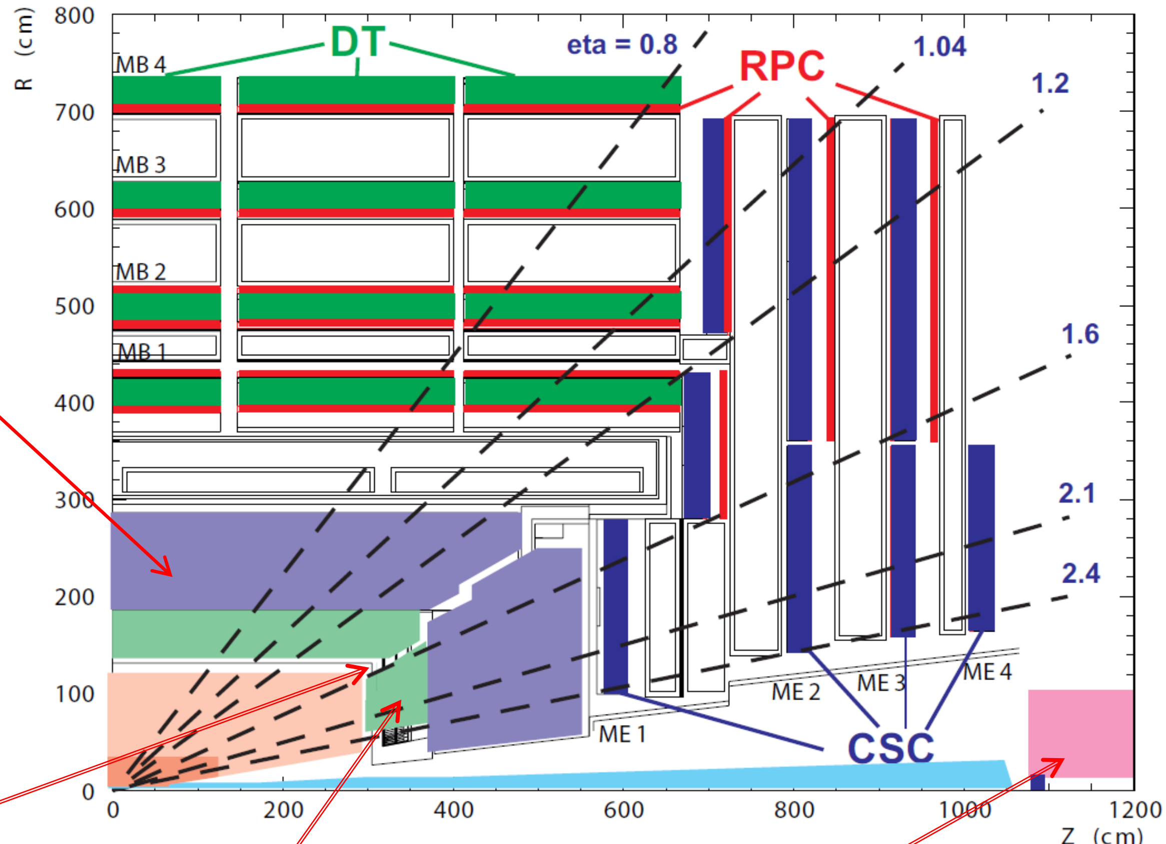




CMS-PAS-JME-10-008

2) Jet energy correction: what for

The jet energy correction is designed to correct for material/acceptance effects and HCAL non linearity



BARREL |η|<1.3:

Uniform in ELAC, HCAL and Tracker

INTERMEDIATE 1.4<|η|<1.6: Crack with Energy loss

ENDCAP

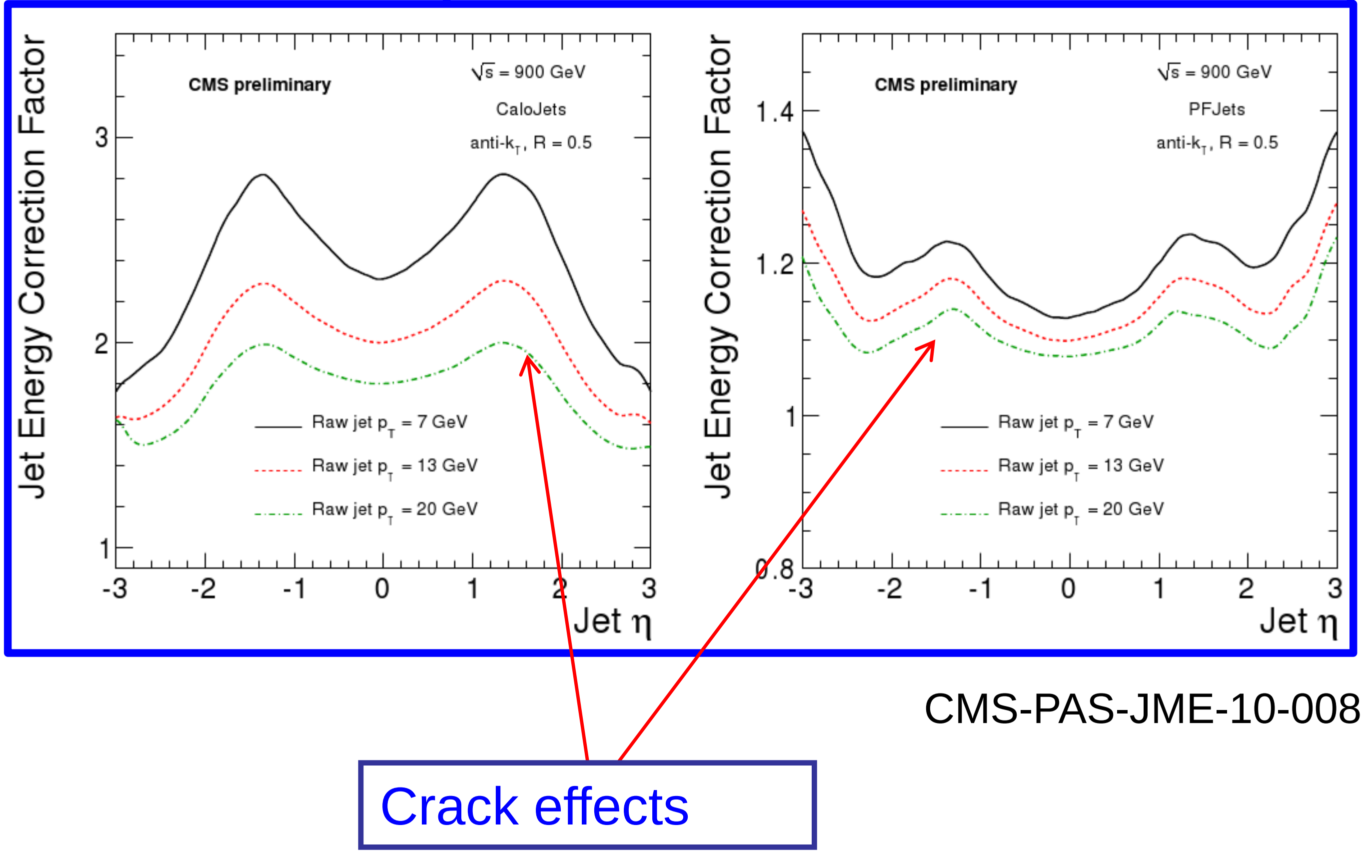
FORWARD: no tracker, HF – Pb/fiber

2) Jet energy correction: how

- 2 step calibration procedure: Reco to Gen (stable hadrons)
  - Relative in η to equalize the response wrt to the barrel (|η| < 1.3)
  - Absolute in p_T

$$p_\mu^{cor} = C(p_T, \eta) \times P_\mu$$

$$C(p_T, \eta) = \mathrm{Rel}(\eta, p_T) \times \mathrm{Abs}(p_T \times \mathrm{Rel}(\eta, p_T))$$



CMS-PAS-JME-10-008

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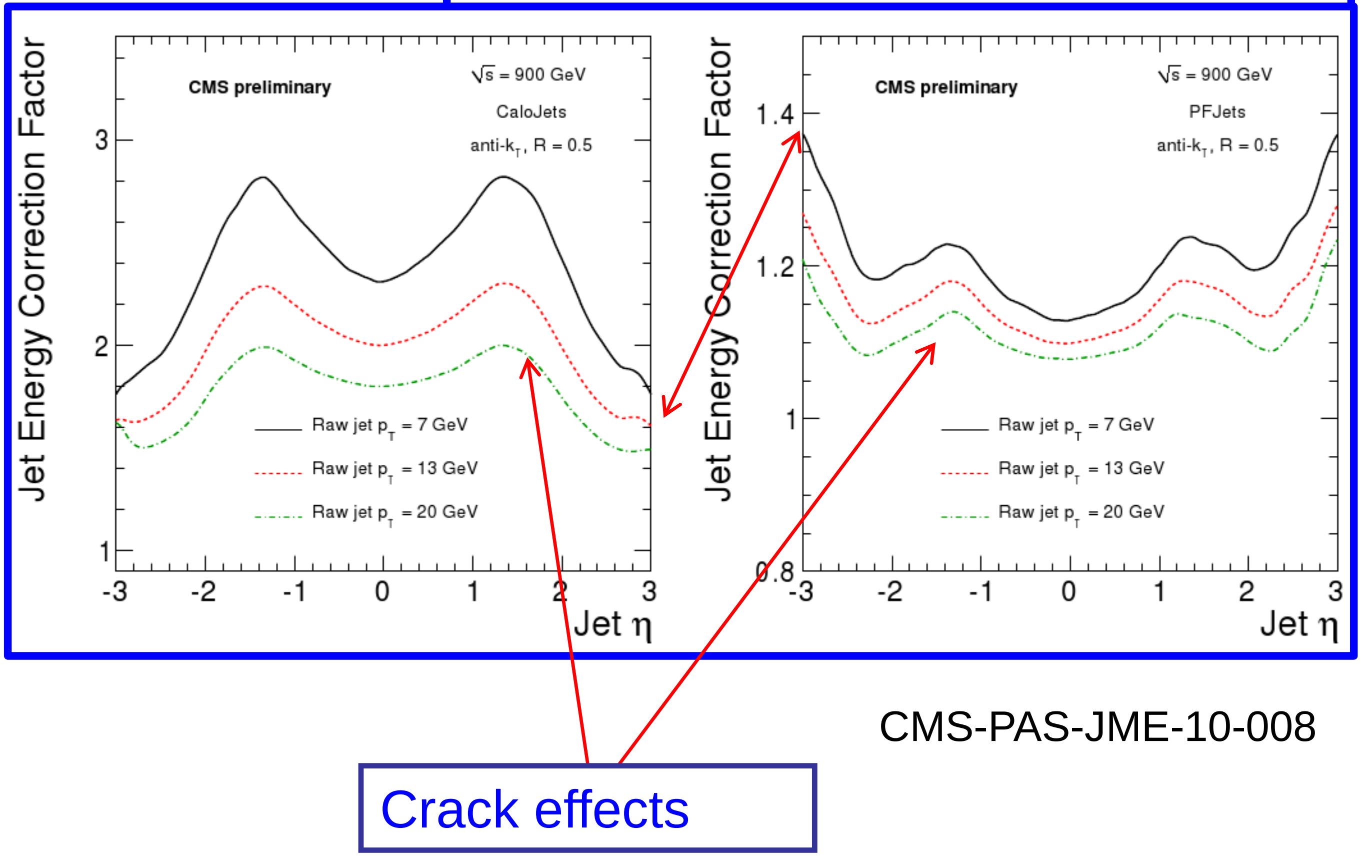
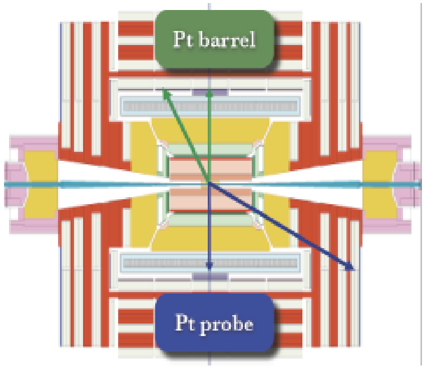
$$C(p_T, \eta) = \mathrm{Rel}(\eta, p_T) \times \mathrm{Abs}(p_T \times \mathrm{Rel}(\eta, p_T))$$



CMS-PAS-JME-10-008

3) Jet energy correction: Is it enough?

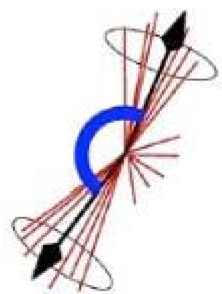
- In fact this is 90-100% of what is necessary: 5-10% uncertainty on jet energy scale (comparable to Atlas: ATLAS-CONF-2010-056). Let's continue our way!
- Calibration is done using MC. But single particle response is slightly different between data/MC. Let's add residual corrections using jet p_T.

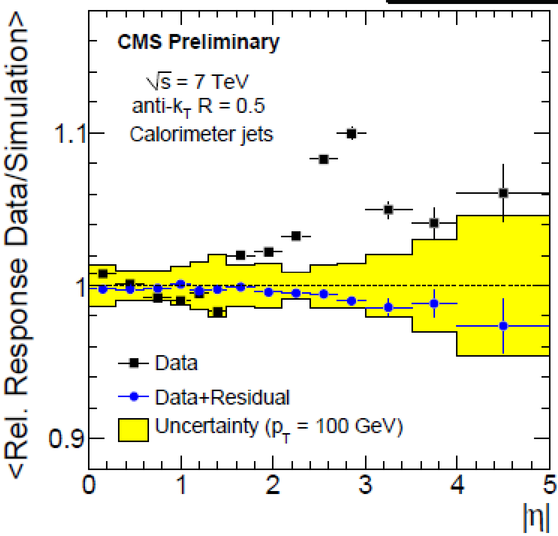


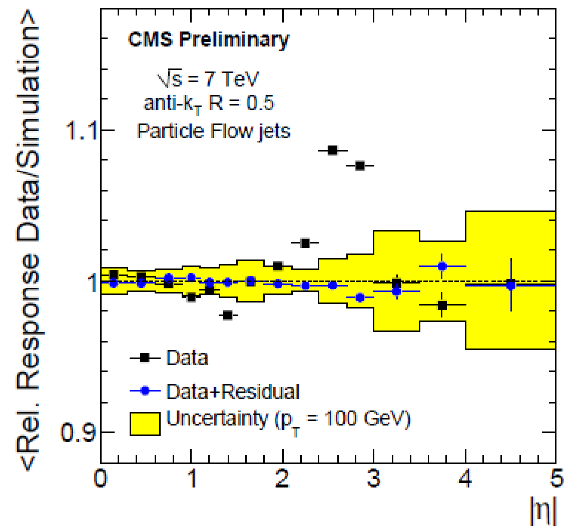
$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

$$B = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{dijet}}$$

$$r = \frac{2 + \langle B \rangle}{2 - \langle B \rangle} \qquad r_{th} = \langle \frac{p_T^{probe}}{p_T^{barrel}} \rangle$$





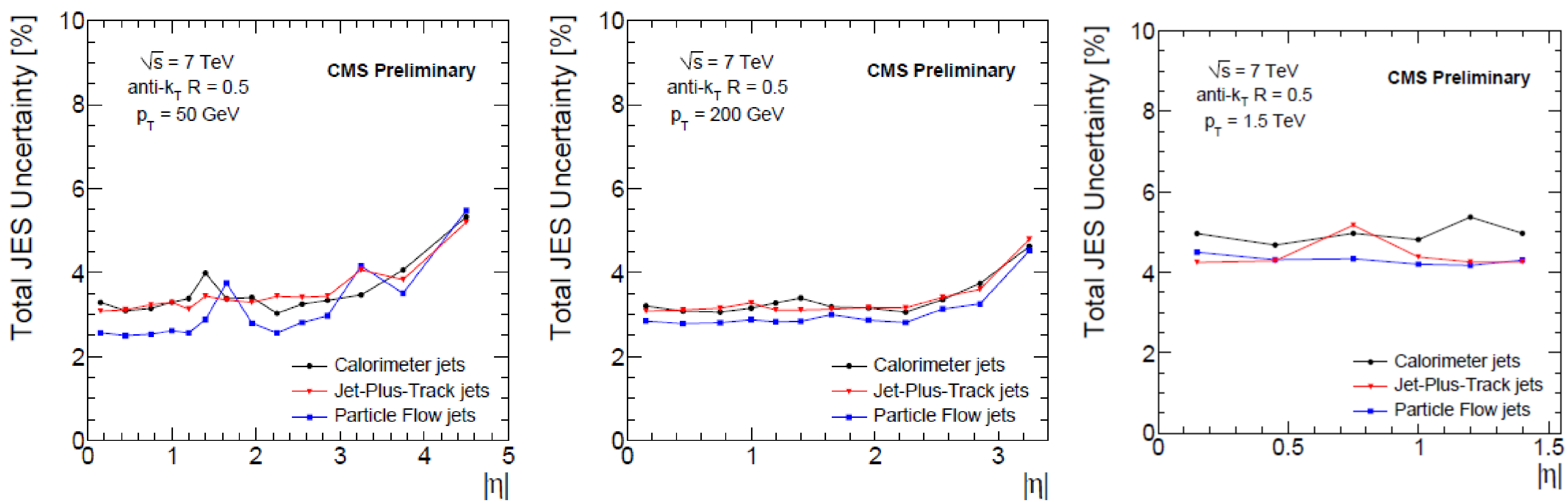


Selected to be back-to-back in φ

CMS-PAS-JME-10-010

3) Jet energy correction: And now Is it enough?

- Our total uncertainty is now 3% for PF jets and 5% for Calo jets (H1 in 2005 after 12 years of operation 2%!). But we can still do better:
  - Flavor dependant corrections (g radiate more than b and more than u,d).



CMS-PAS-JME-10-010

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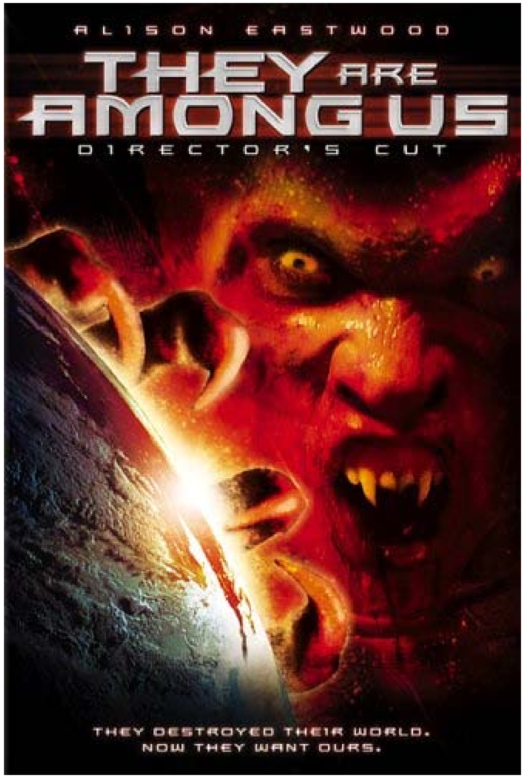
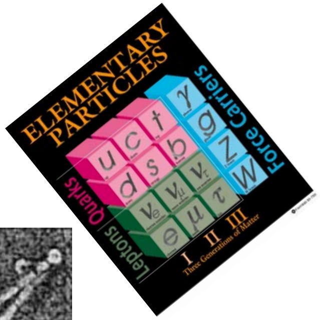
  - Flavor dependant corrections (g radiate more than b and more than u,d).
    - Pile Up corrections : they are increasing, they are among us! At L = $2*10^{32}$ cm^{-2} s^{-1} ~2 Pile-up / event.
      - UE corrections using jet Area (CMS-PAS-QCD-10-005) especially important in Heavy Ions collisions.



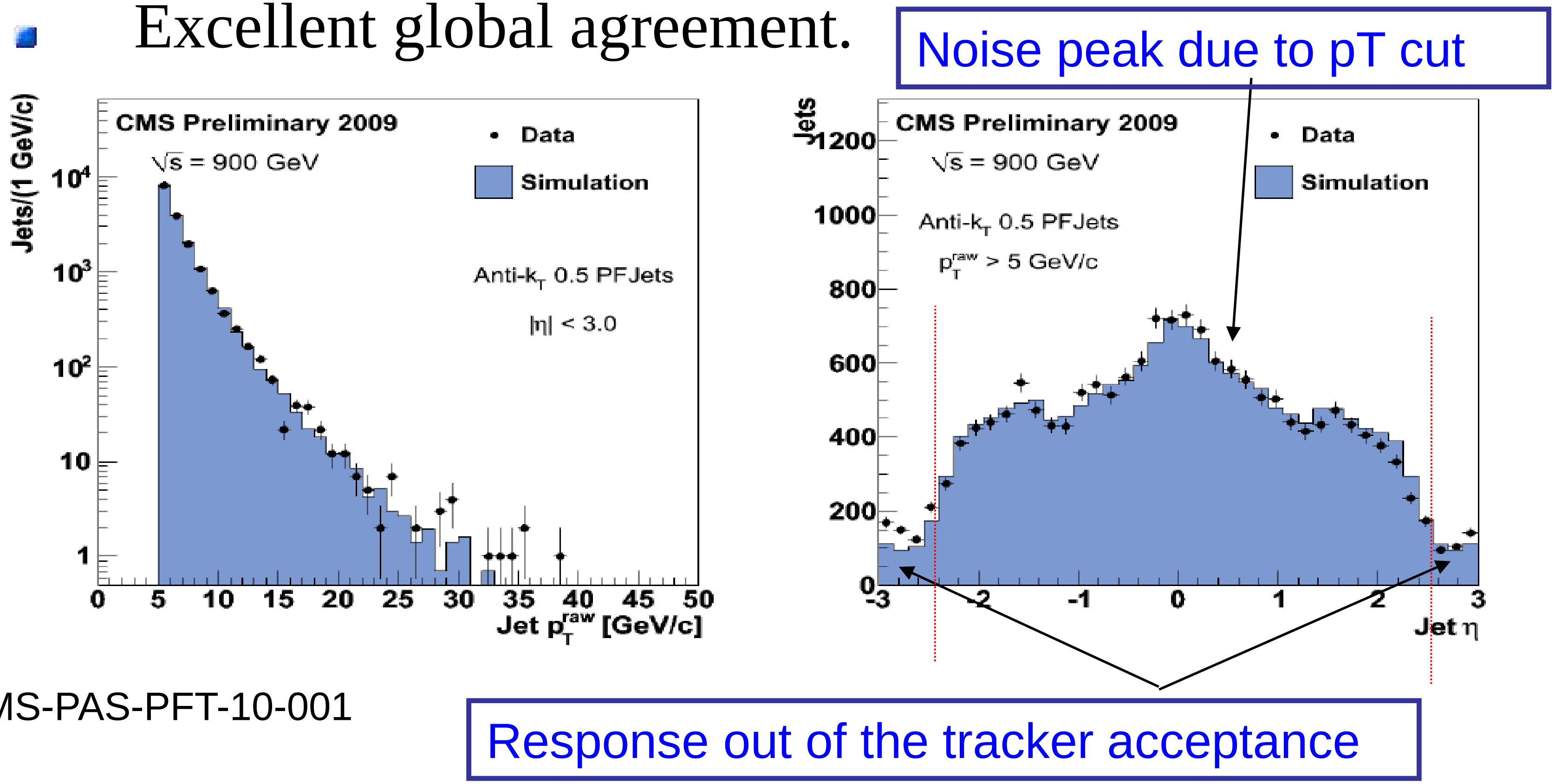
QCD
MARE NOSTRUM

- The LHC rediscover the Standard model and retest the pQCD at large energy scale $\mu = p_T$ up to and above the Tevatron region.
- In this part I would concentrate on PF Jets since they was proved to produce better results.



2.1) Commissioning of low p_T jets (0.9 - 7 GeV)

- The first minimum bias data was used to validate the jets :
  - No quality cut and down p_T > 5 GeV.
  - AK5 used as reference algorithm for validation
  - Lowest p_T jets sensitive to the experimental effects (noise...).
  - Excellent global agreement.

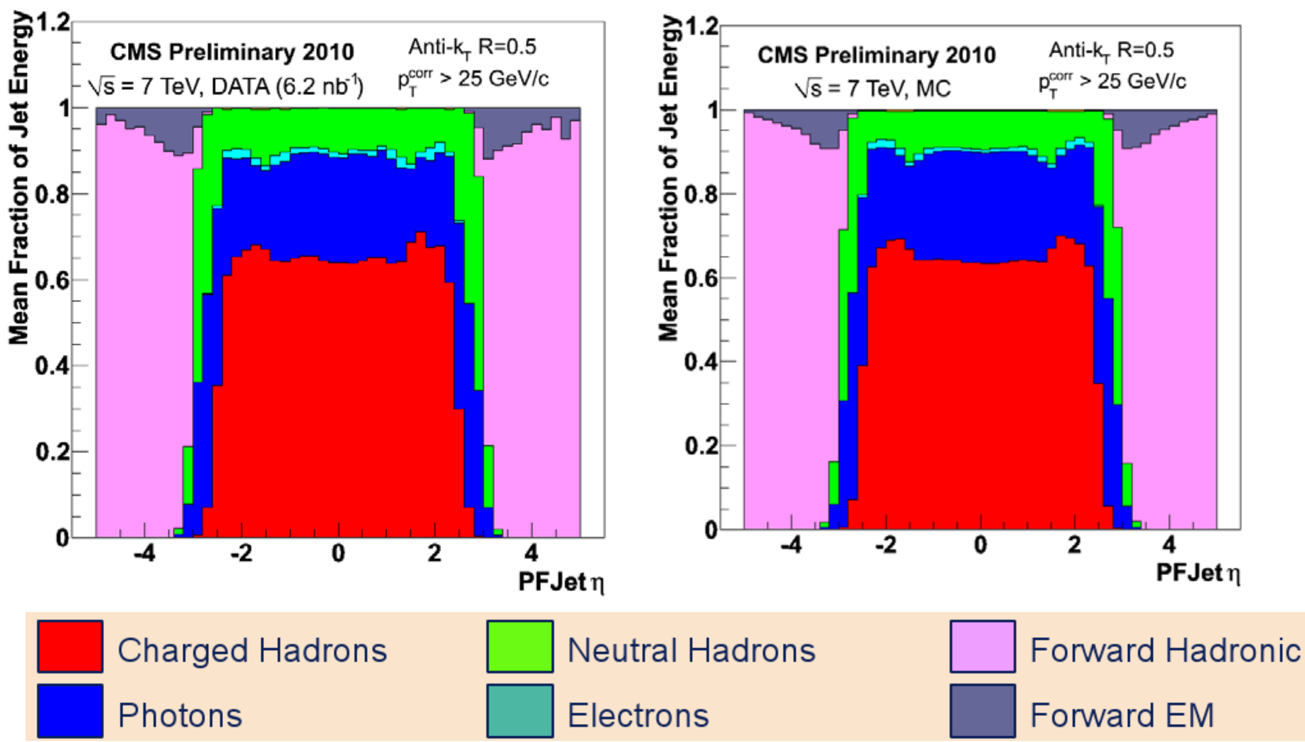


CMS-PAS-PFT-10-001

2.2) Commissioning of low p_T jets (0.9 - 7 TeV)

In addition a dedicated study shows a good description of the internal structure of jets. This result is updated at 7 TeV:

- Different species for PF jets (see below).
- For PF jets recover the composition of Gen jets.

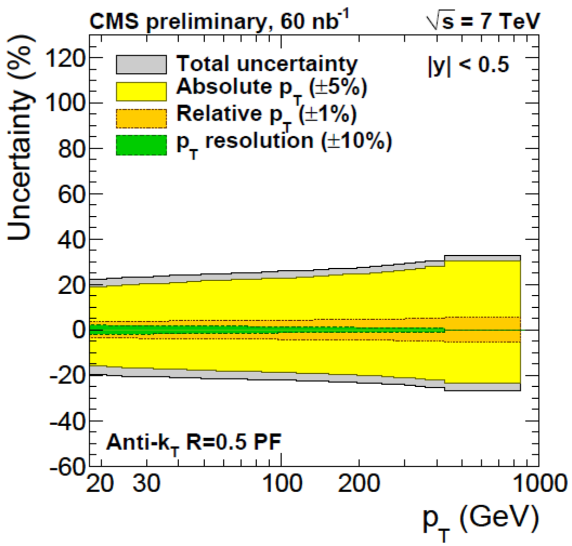


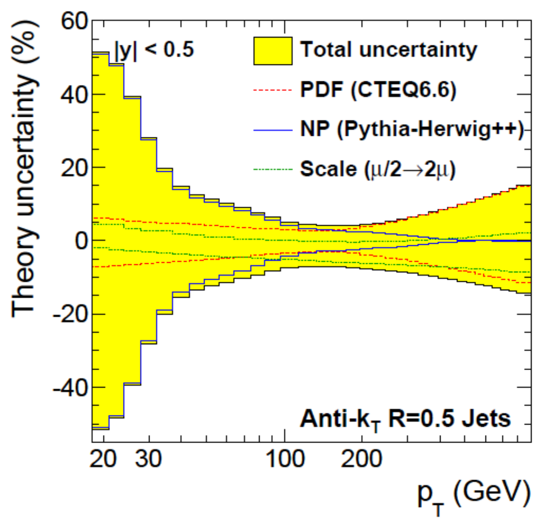
CMS-PAS-PFT-10-002

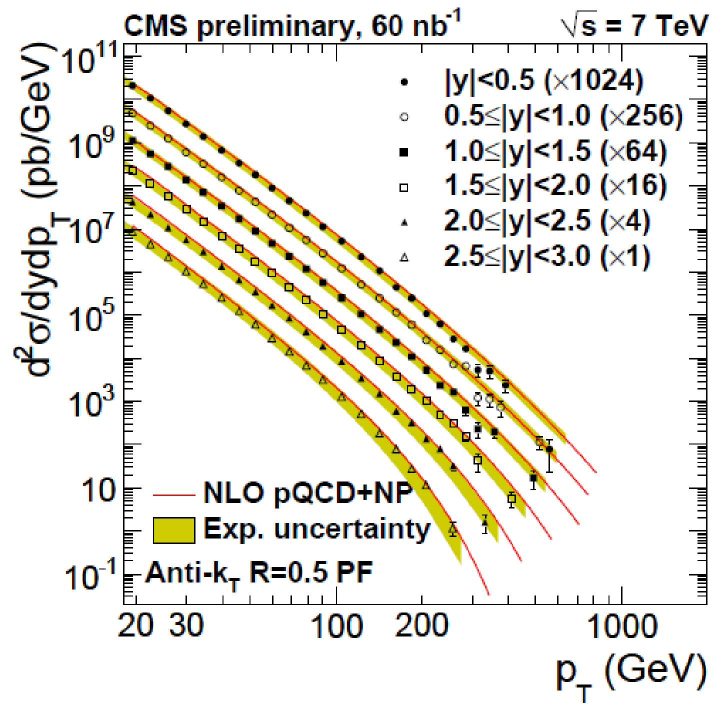
3) Sacred cow: inclusive jets spectrum

- The spectrum where jets are counted instead of events.
- Preliminary results from CMS based on 60 nb-1 for ICHEP. Precise measurement using 35 pb-1 is incoming.
- Compared to QCD NLO (NLOJET/FastNLO) + hadronic corrections from Pythia/Herwig. PDF = CTEQ 6.6

$$\frac{d^2\sigma}{dp_T dy} = \frac{C_{res}}{\mathcal{L}\cdot\epsilon}\cdot\frac{N_{jets}}{\Delta p_T\cdot\Delta y}$$

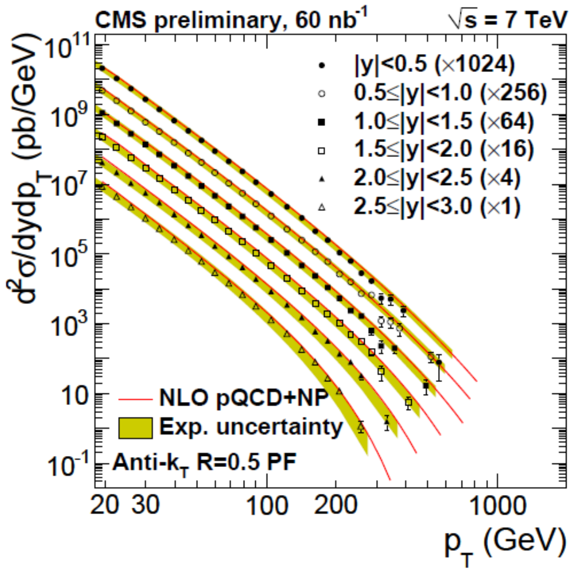




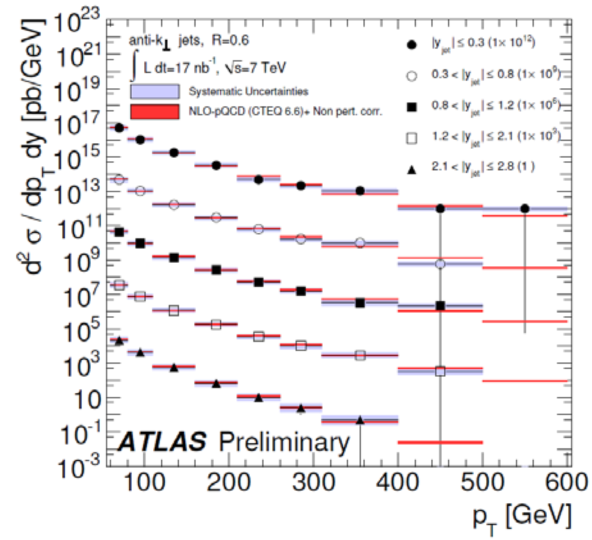


CMS-PAS-QCD-10-011

3) Sacred cow: inclusive jets spectrum

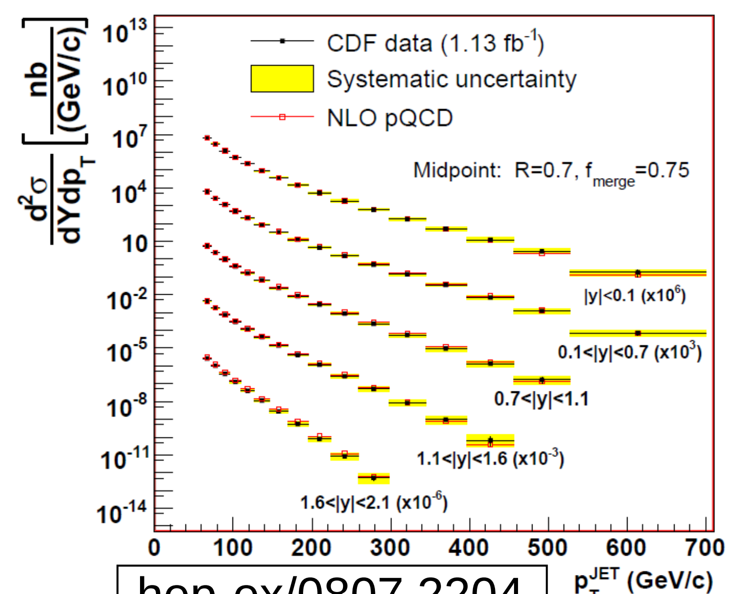


CMS-PAS-QCD-10-011



ATLAS-CONF-2010-050

- NLO QCD perfectly working @ TeV.
- LHC reaches the domain of Tevatron even with first nb^{-1}.



hep-ex/0807.2204

AGE OF EXPLORATIONS FROM QCD to EXOTICA

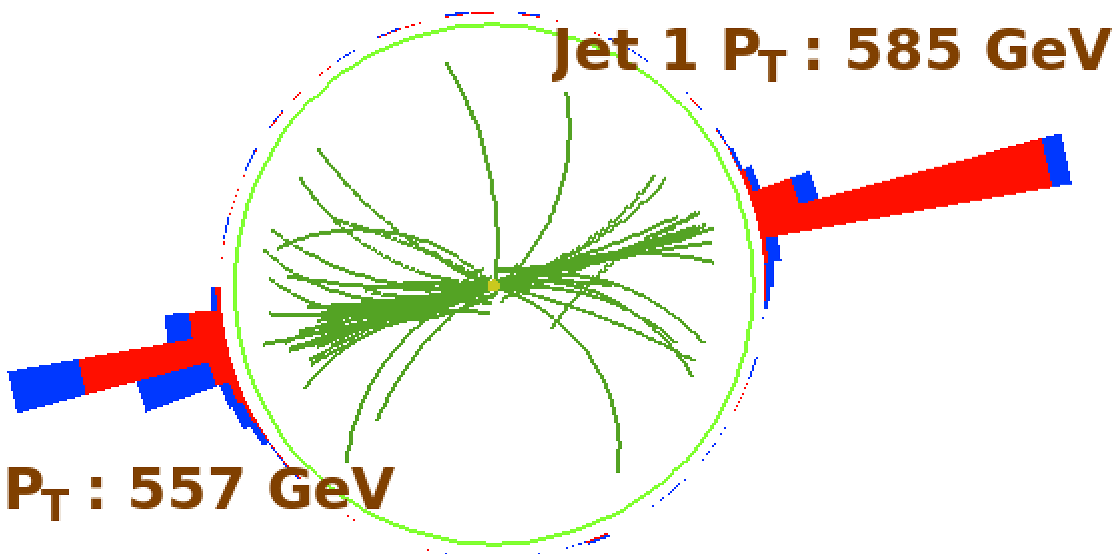
1) Exploring new area

- The exploration process is always the same:
  we measure the QCD spectrum (or standard model for other benchmarks)

- The excess with respect to NLO QCD:
  bumps, deviations at large energy scale (pT, Mass), excess in angular distributions is an indication that the cost of the new continent is not far away…

2) Dijet production

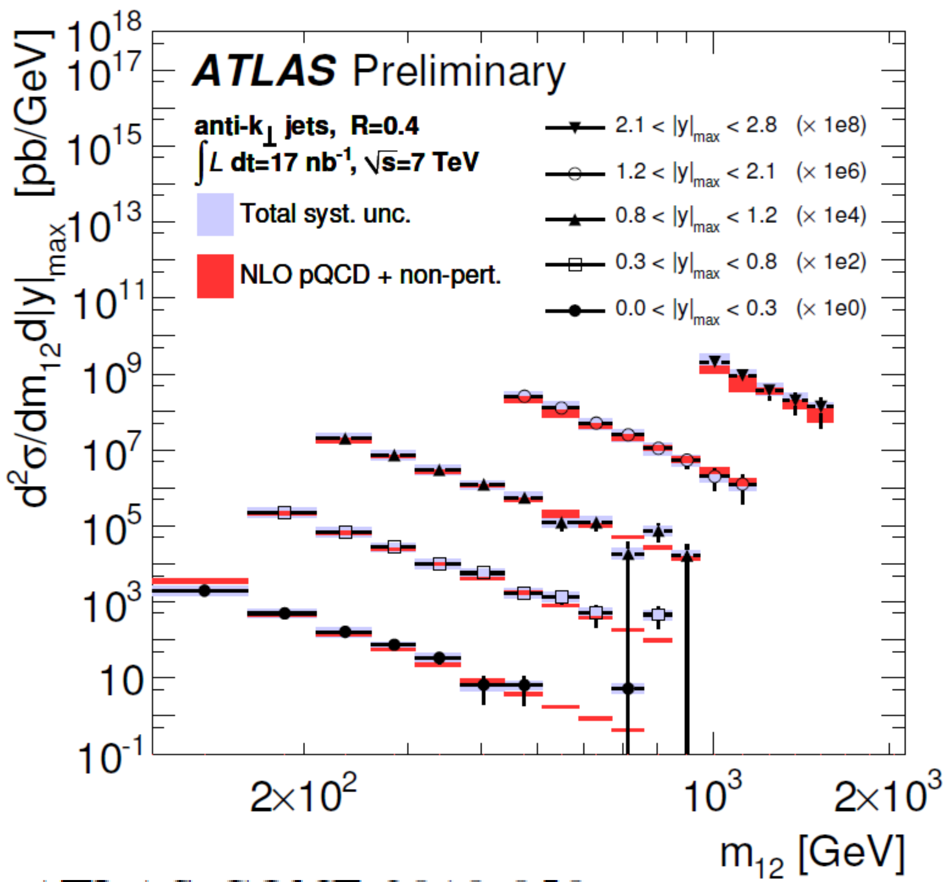
Run : 138919
Event : 32253996
Dijet Mass : 2.130 TeV



$$M_{12} \sim 2p_T\,(1+\Delta\eta^2/8)$$

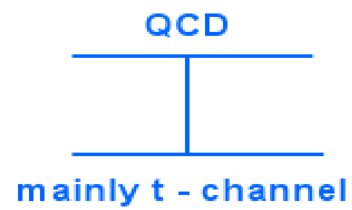
3) Dijet invariant mass spectrum

- QCD Dijet mass spectrum produced for ICHEP by Atlas (not yet available for CMS)
- QCD pairs produced mainly at large $\eta \rightarrow$ large M_{12} at a given p_T.



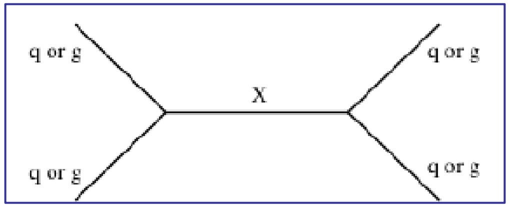
ATLAS-CONF-2010-050

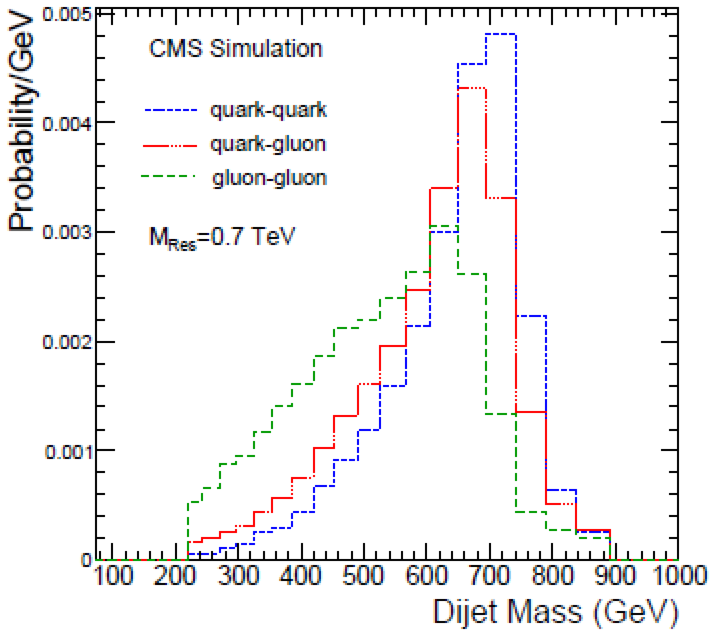
$M_{12} \sim 2p_T\,(1+\Delta\eta^2/8)$



4.1) Exotic resonances decaying into jets

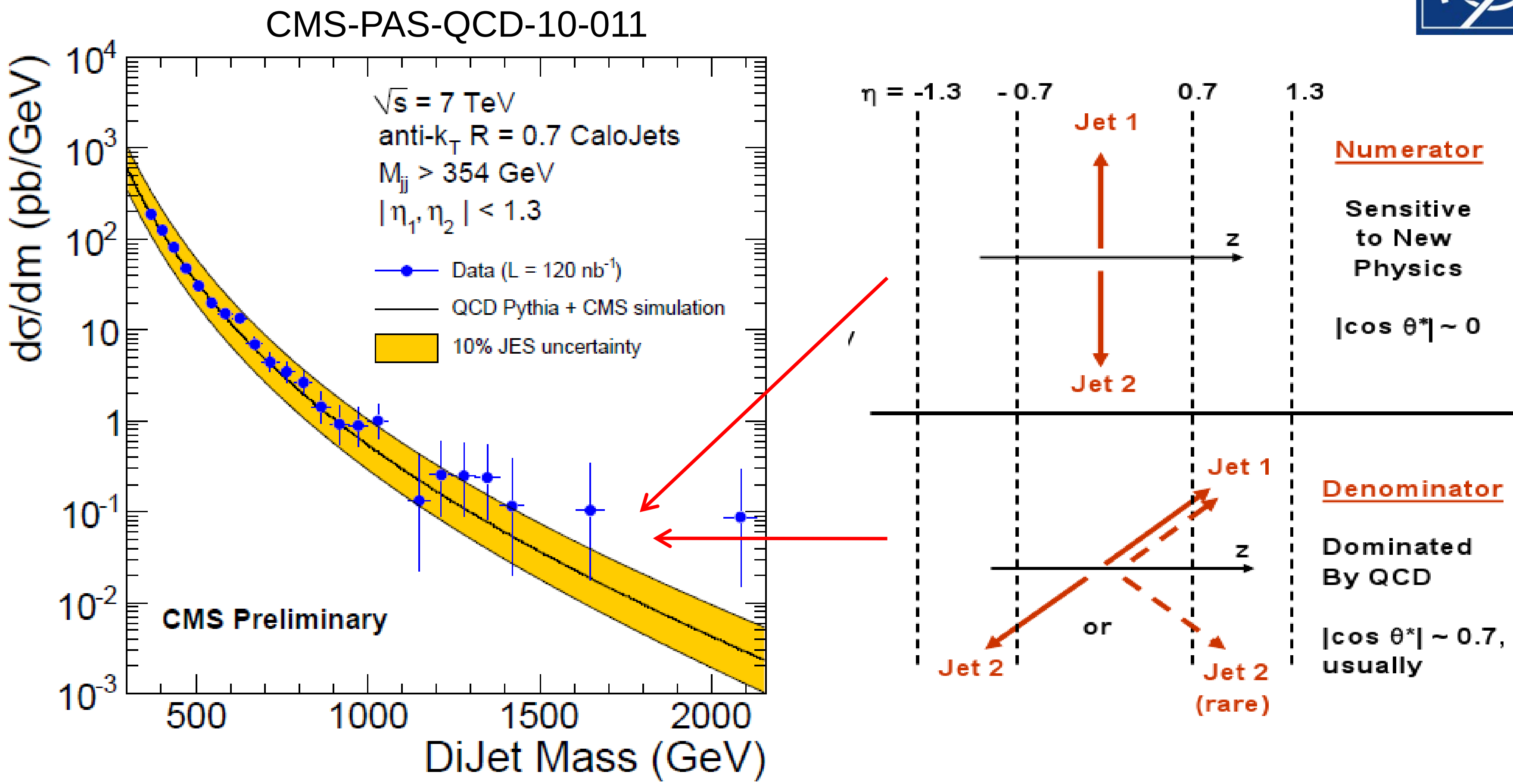
- Many theories predict heavy resonances coupling to q, g
  → Excited quarks, GUT - Z', R&S, Gluinos etc...
- We can project all theories on a small sample of final states: qq, qg, gg
  For example: FS(R&S Grav.) = xqq+ygg





CMS-PAS-EXO-10-001

4.2) Tail of the mass shape

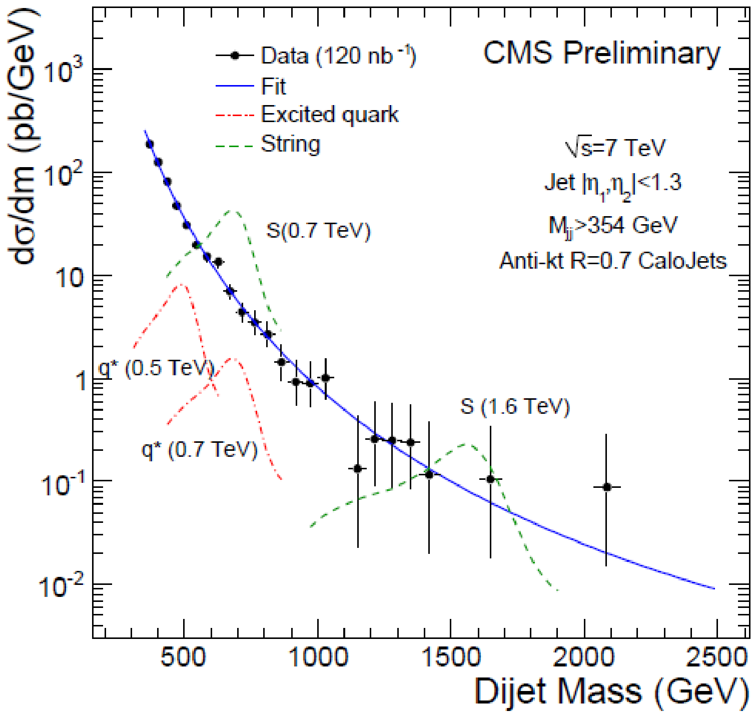


1) Take only jets with small η to enhance the sensitivity to new physics.

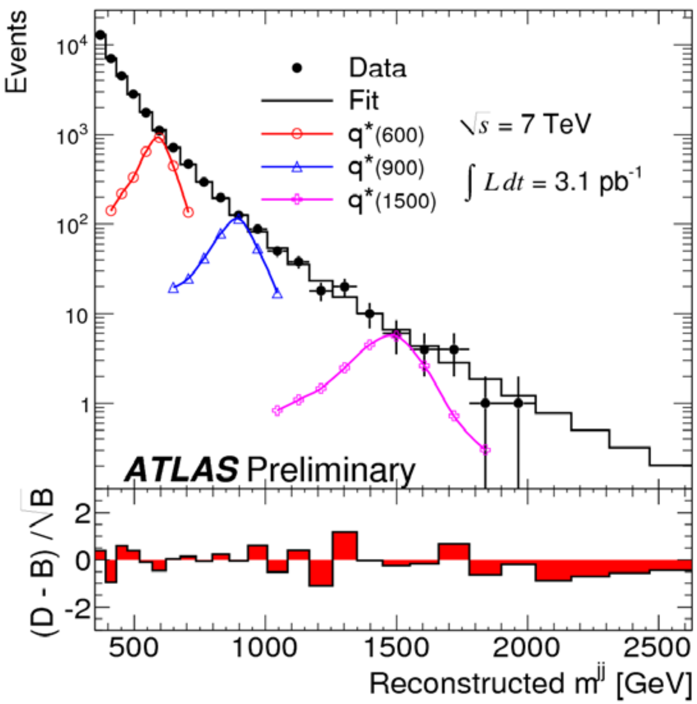
2) Suggested also for ongoing analysis to cut on $|\Delta\eta|<1.3$.

4.3) Tail of the mass shape

CMS-PAS-QCD-10-011



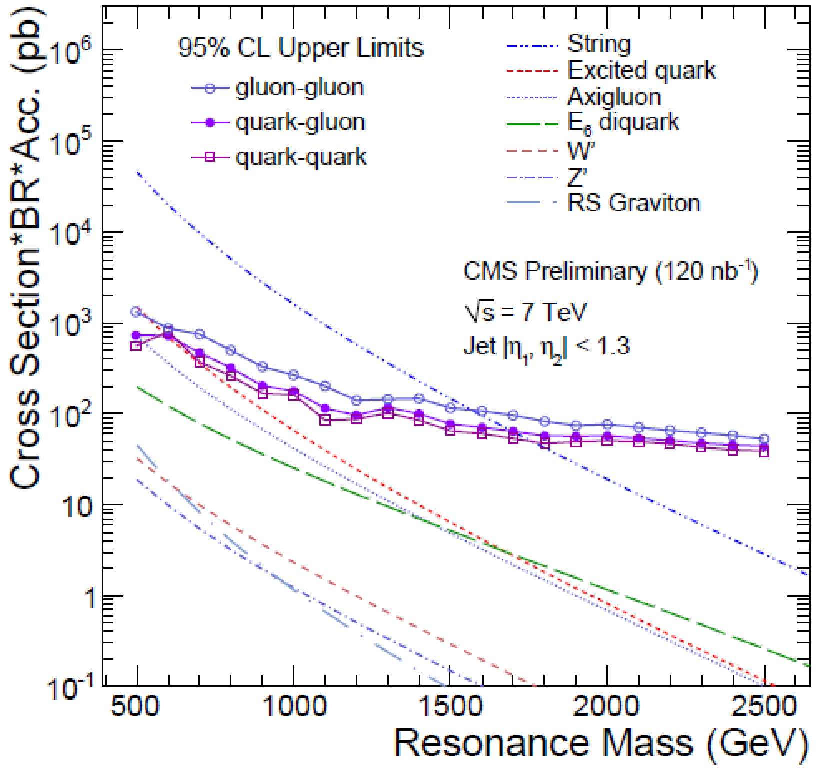
ATLAS-CONF-2010-093



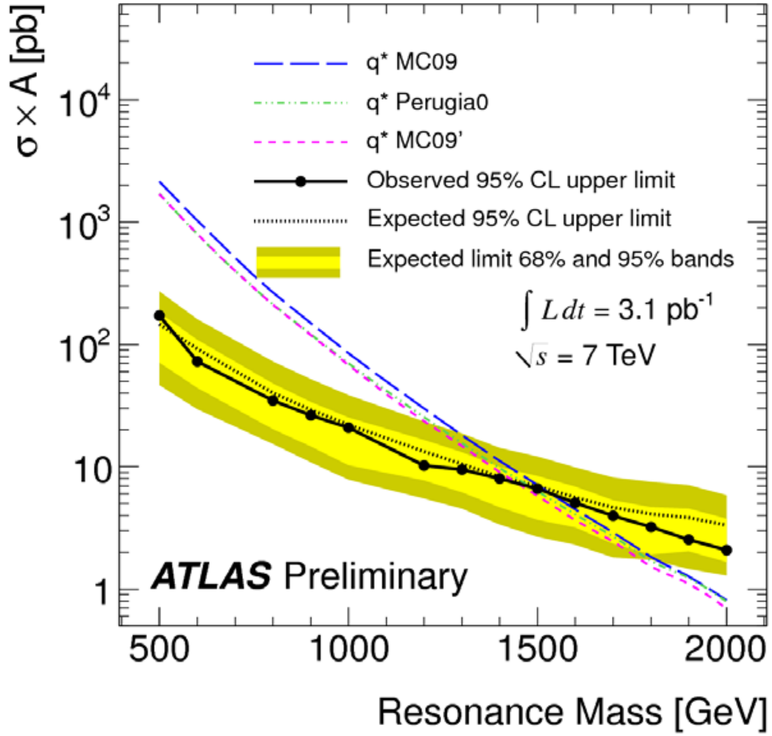
Both collaborations update regularly the search in the tail of Dijet Mass spectrum.

4.4) Tail of the mass shape

ATLAS-CONF-2010-093



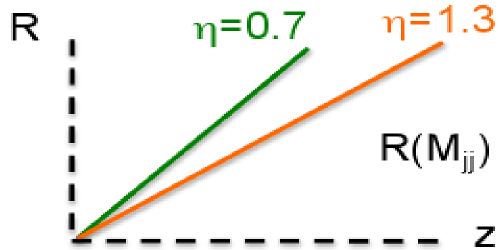
ATLAS-CONF-2010-093



1) Uncertainties dominated by Jet Energy scale everywhere.

2) At large Mass statistics of of course limiting parameter.

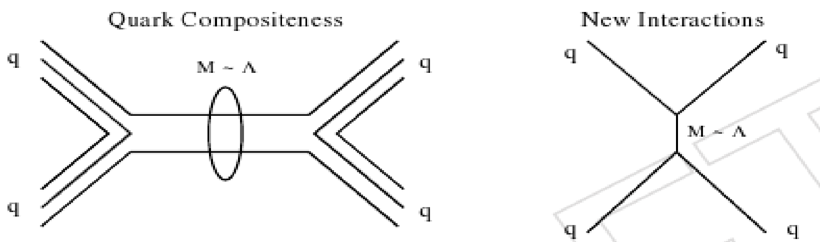
5) Dijet centrality ratio

- 

Di-jet ratio

$$R(M_{jj}) = \frac{N(\,|\eta_{j1,j2}| < 0.7\,)}{N(\,0.7 < |\eta_{j1,j2}| < 1.3\,)}$$

- Cancel many systematic.
  Less sensitive to mass shapes, but more sensitive to Contact Interactions.

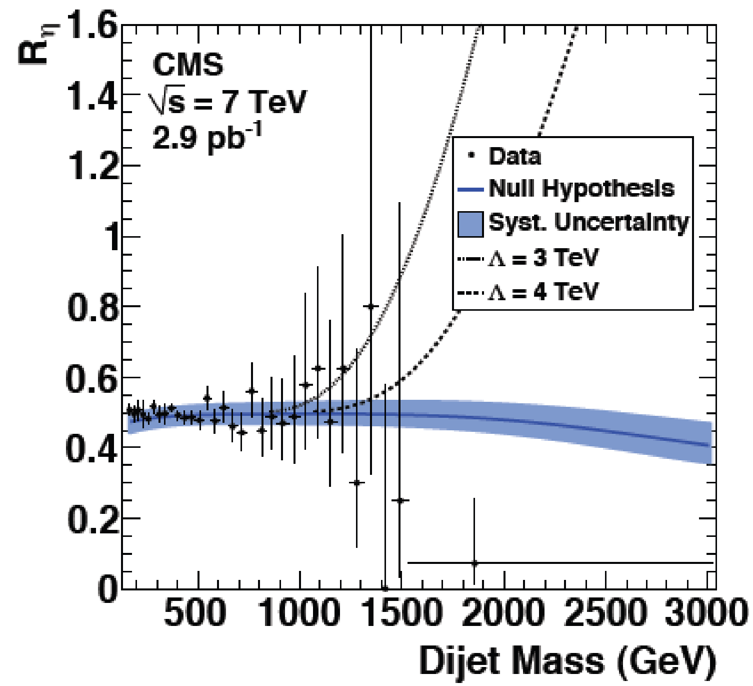


- For example CMS exclude for

$$L_{qq} = (\pm 2\pi/\Lambda^2)(\bar{q}_L \gamma^\mu q_L)(\bar{q}_L \gamma_\mu q_L)$$

Λ = 2.9 TeV (3.4 TeV for Atlas)

CMS PAPER EXO-10-002



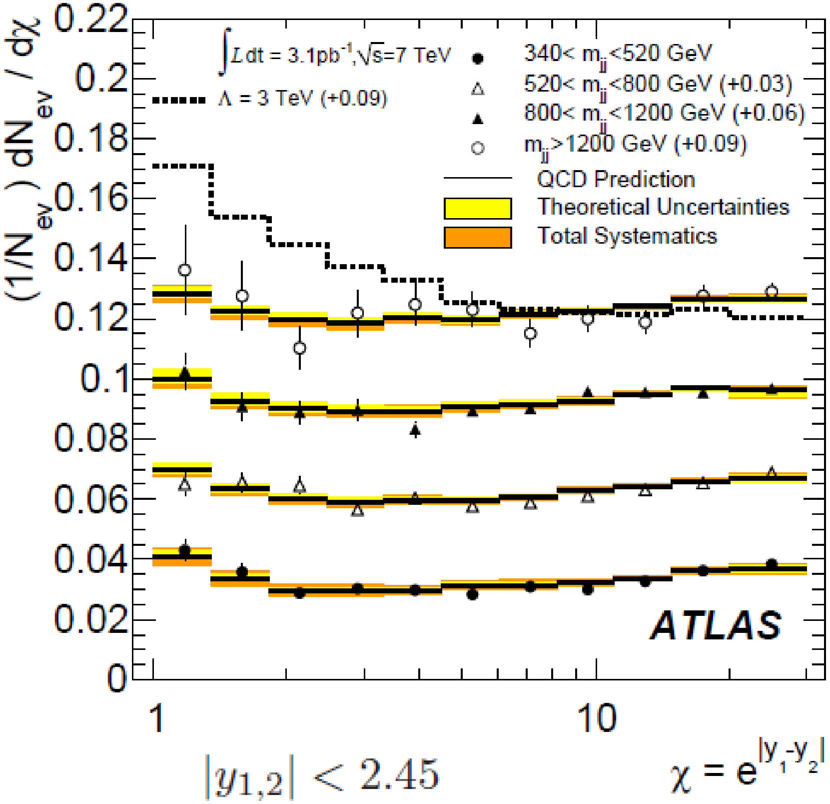
6) Dijet Angular distribution

- This observable instead of looking maximal Mass at small |η|, looks at a given Mass to an excess in small |η|, |Δη| region.

$$\chi = \exp(|y_1 - y_2|) \approx \frac{1 + cos\theta^*}{1 - \cos\theta^*}$$

- QCD is like Rutherford scattering $dN/d\cos\theta^* \propto 1/\sin^4(\theta^*/2)$
  Thus: dN/dχ = cst (LO).
- While new physics points at small χ and large Mass.

arXiv:1009.5069v1



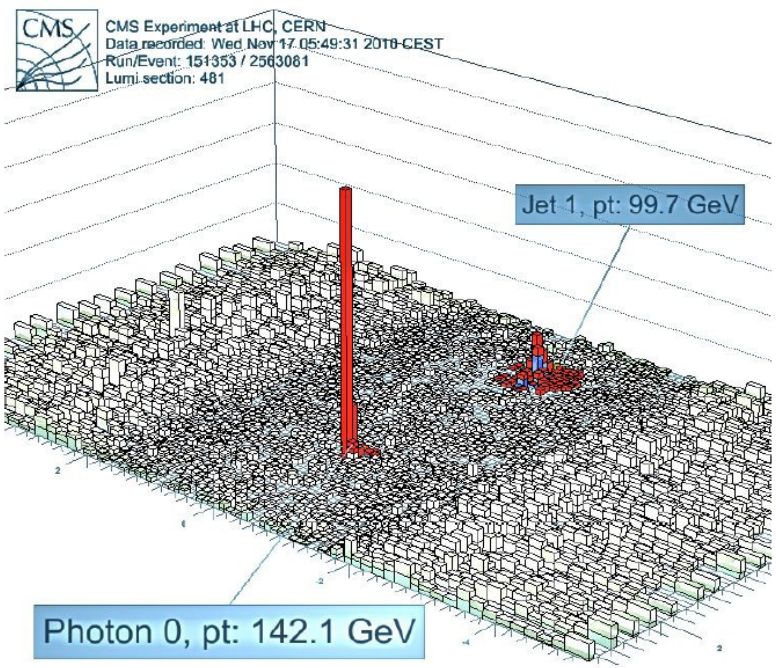
$|y_{1,2}| < 2.45$

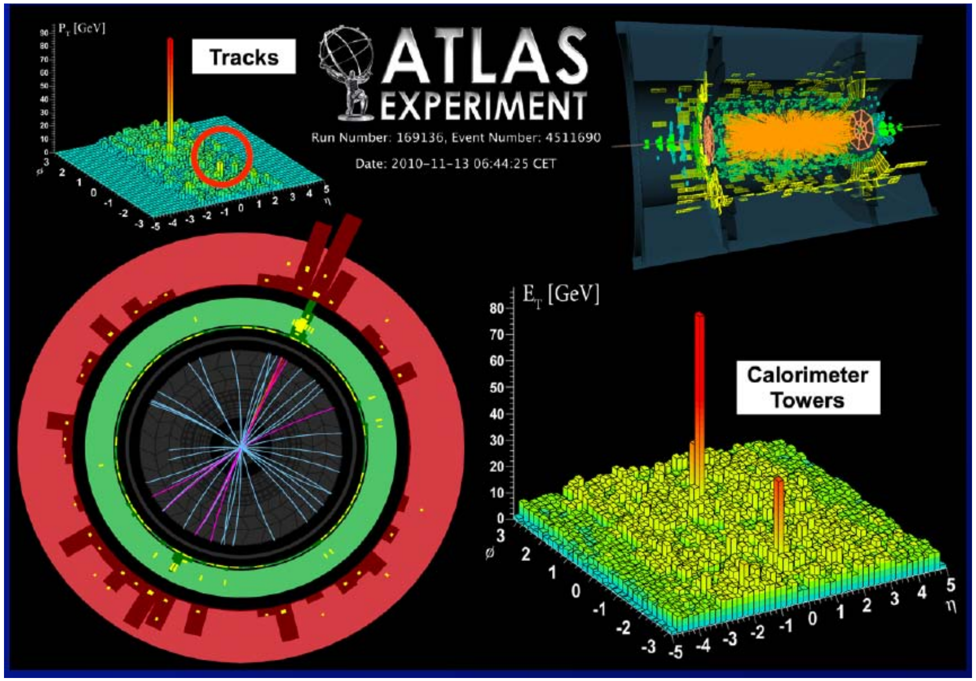
- Atlas exclude CI with Λ=3.4 TeV
- CMS results are not yet public, expected in winter.

Cachez-moi ce jet que je ne serais voir!

Acte 1

Of course I cannot leave without showing for those who missed the yesterday seminar the famous jets lost in the Big Band soup:

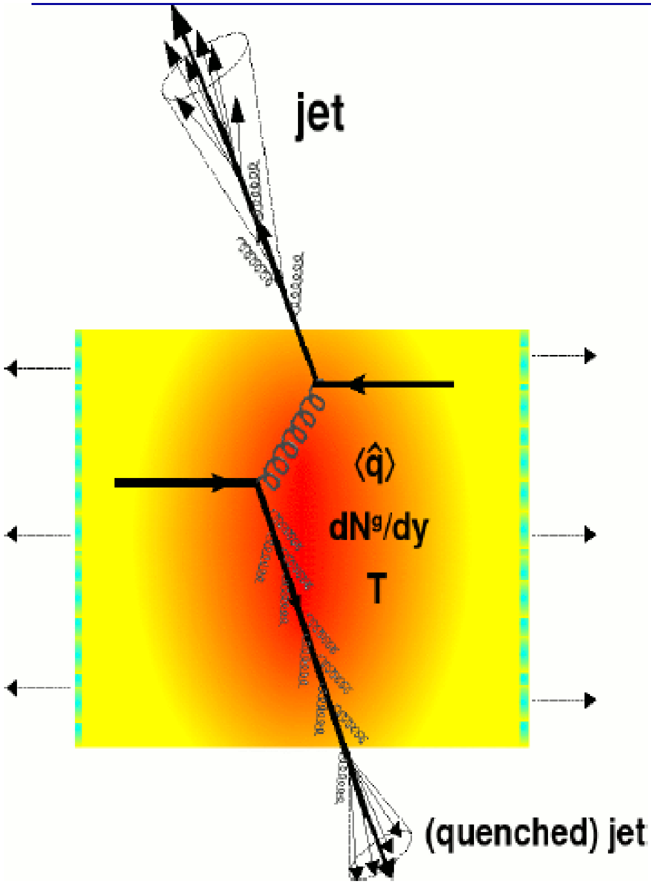




http://indico.cern.ch/conferenceDisplay.py?confId=114939

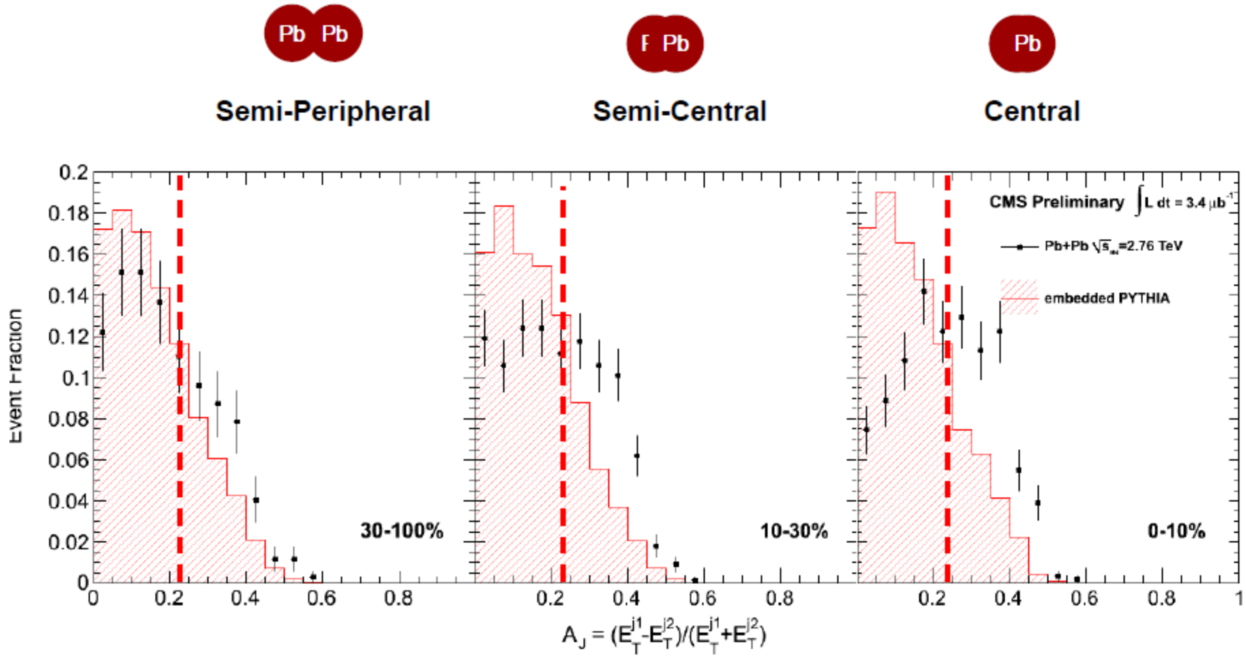
Acte 2

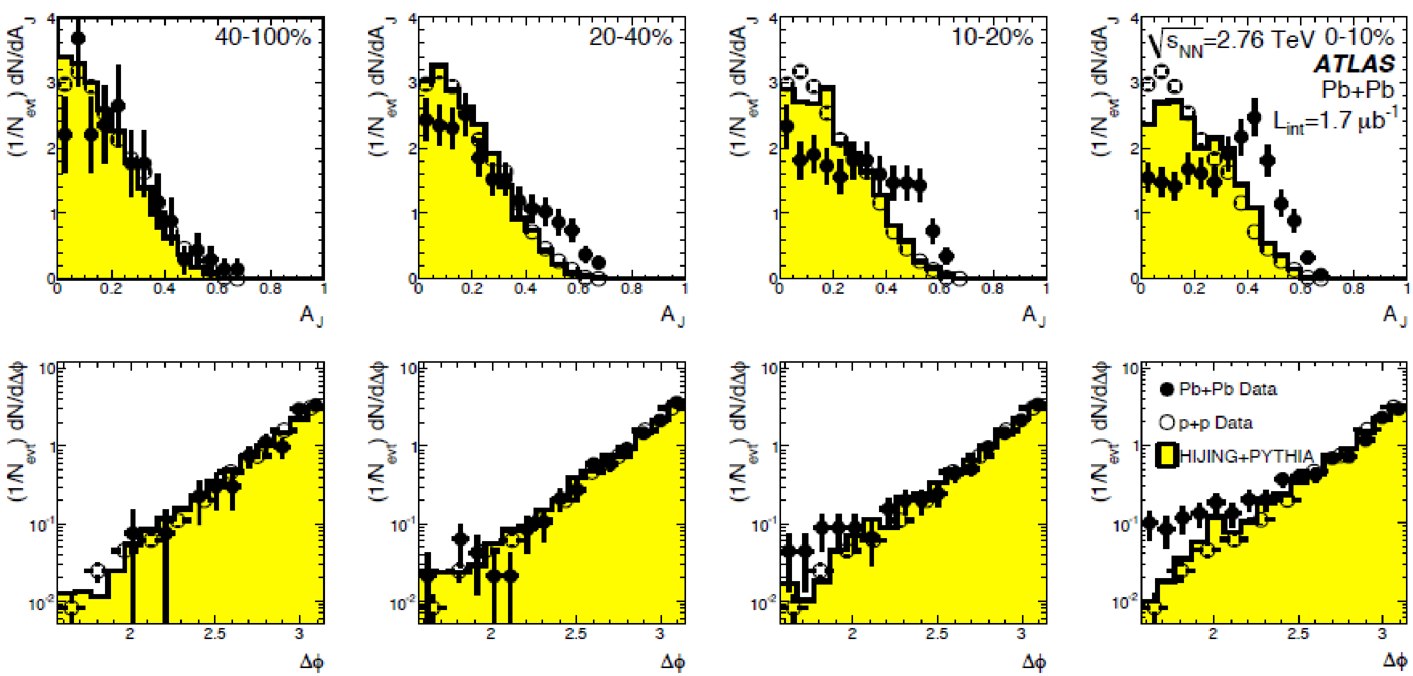
Of course I cannot leave without showing for those who missed the yesterday seminar the famous jets lost in the Big Band soup:



- **Strong quenching effects were observed in single particle spectra and particle correlations**
- **Direct jet reconstruction possible but very difficult**

Acte 3


Pb Pb
Semi-Peripheral
Semi-Central
Pb
Central
CMS Preliminary ∫L dt = 3.4 μb⁻¹
Pb+Pb √s_NN=2.76 TeV
embedded PYTHIA
Event Fraction
30-100%
10-30%
0-10%
A_J = (E_T^j1-E_T^j2)/(E_T^j1+E_T^j2)


40-100%
20-40%
10-20%
√s_NN=2.76 TeV 0-10%
ATLAS
Pb+Pb
L_int=1.7 μb⁻¹
(1/N_evt) dN/dA_J
A_J
(1/N_evt) dN/dΔφ
Δφ
Pb+Pb Data
p+p Data
HIJING+PYTHIA

SUMMARY

1) The jets observable was promising and kept it promises.

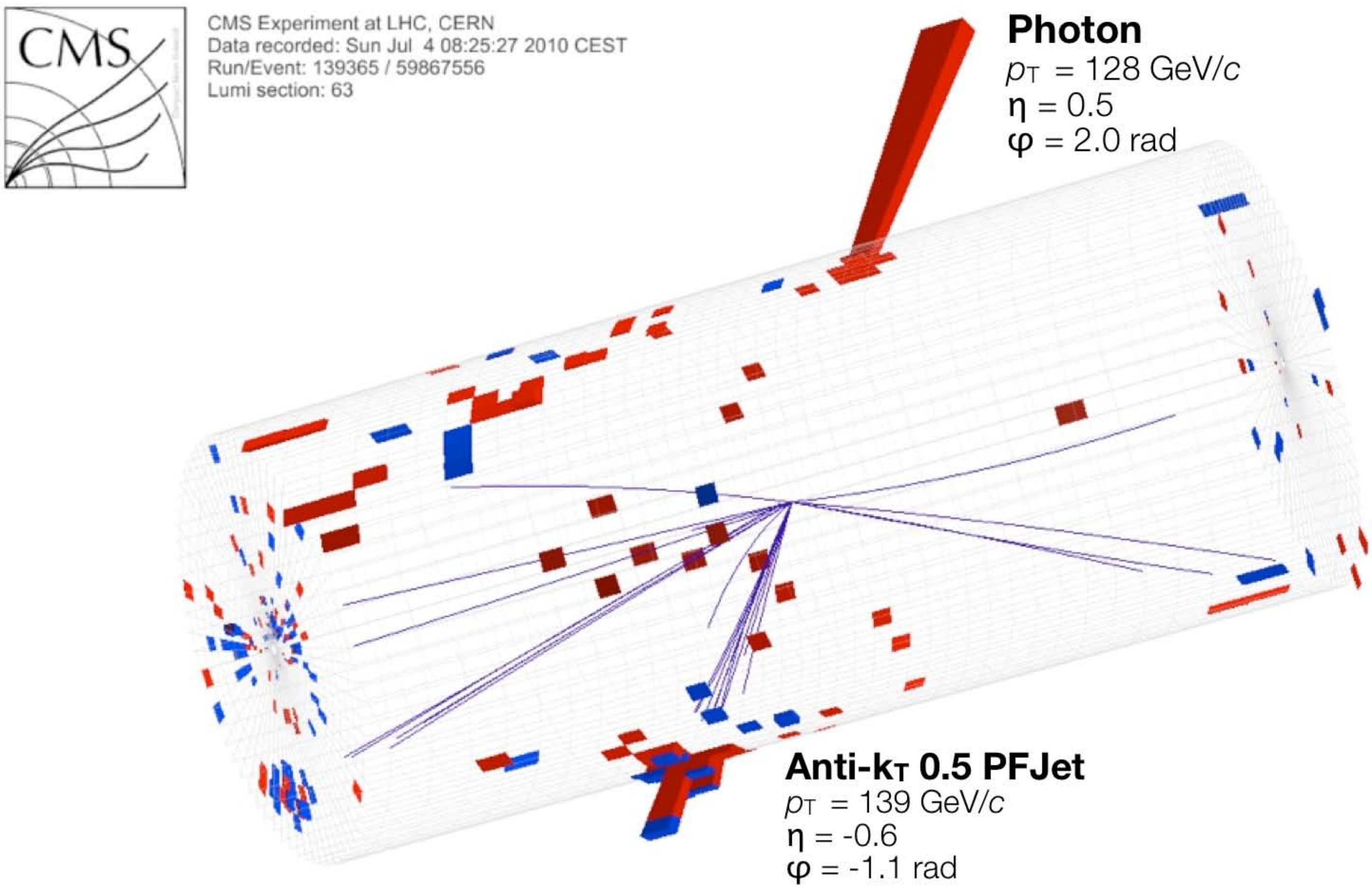
2) Impressive level of control over the jet energy scale: theoretical progress, detector quality, experimentalist experience, available time to develop calibration procedures.

3) Jets stays one of the sacred cows of search for new physics at the same level than photons, electrons and muons. Unfortunatelynothing was happened within the 2010 run ☹, even if the exclusion domain of different theories was pushed away with respect to the Tevatron.

4) Stay in touch for 2011.

BACKUP

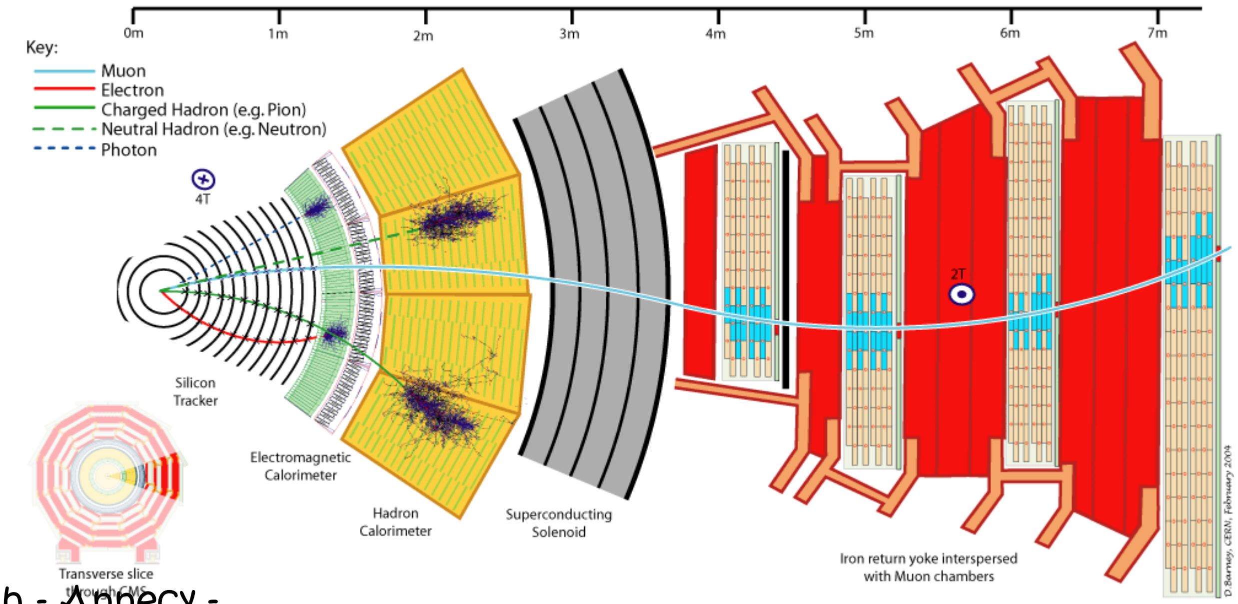
1) Dijet invariant mass spectrum



2.3) Basic ingredients: muons

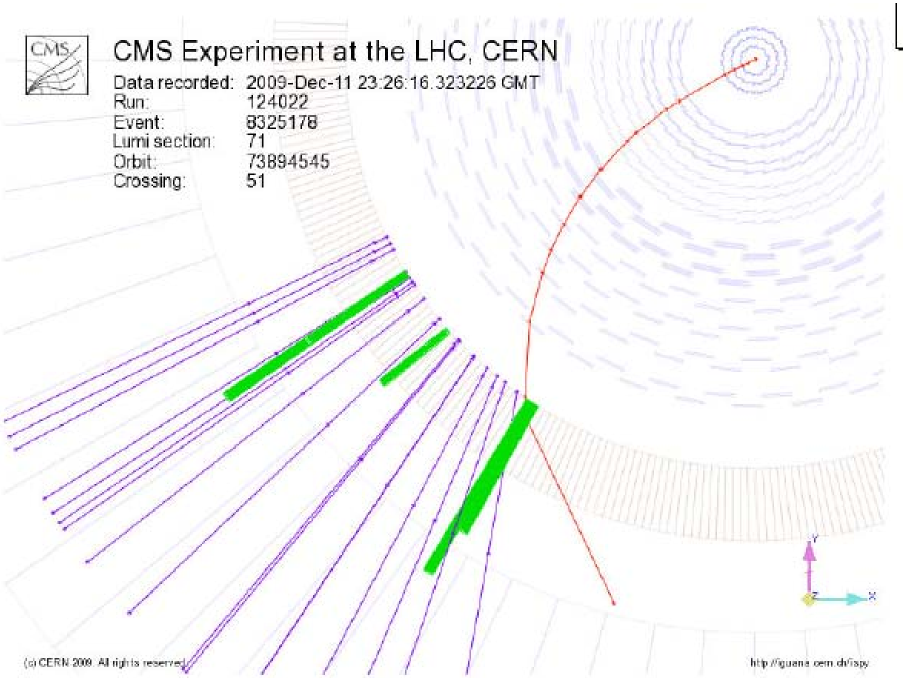
➔ Muons can be seeded :

- From muon chambers (more high p_T)
- From tracker (more low p_T)
- The tracker tracks and muon chamber tracks may be matched or not

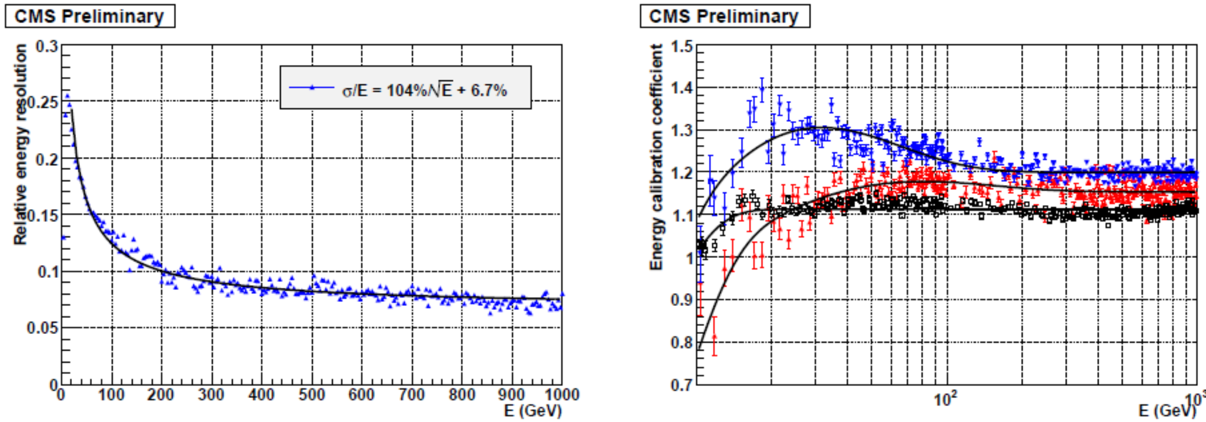


2.4) Basic ingredients: electons

➔ Special electron tracking
- Standard tracking fail to reconstruct all electon track
- Sudden change of curvature due to Bremsstrahlung photons
- Electron tracks include ECAL clusters from potential photons



5) PF Clusters Calibration



(a) (b)

Figure 2: Energy resolution σ/E as a function of the true hadron energy E (a). Calibration coefficients as a function of E (b), for hadrons depositing energy in HCAL barrel only (open squares), and for hadrons depositing energy in both ECAL and HCAL barrel, for ECAL (downward triangles) and HCAL (upward triangles). The smooth curves are obtained with a fit of the data points to *ad-hoc* functions of E, used in the particle-flow algorithm.

$$E_{\text{calib}} = a + b(E, \eta)E_{\text{ECAL}} + c(E, \eta)E_{\text{HCAL}}$$