Jets and E_T^{miss} at the LHC

Role of Jets in LHC Physics

- Jet multiplicity and E_T distribution:
  QCD, SUSY...
- Reconstruction of resonances:
  $W \rightarrow jj$, $t \rightarrow bW$, $Z \rightarrow b\bar{b}$, $Z' \rightarrow jj$...
- Central jet veto & forward jet tagging

Role of E_T^{miss} in LHC Physics

- Missing E_T = important signal for new physics
- Used in invariant mass recontruction in decays involving neutrinos: $A/H \rightarrow \tau\tau$...

- Jets and E_T^{miss} will be used in offline analysis but also in the trigger
- Experimental conditions will change:
  low luminosity ⇔ high luminosity
- Emphasis will be sometime on controlling energy scale, efficiency for reconstructing low p_T jets, or good two-jet separation in boosted decays, …

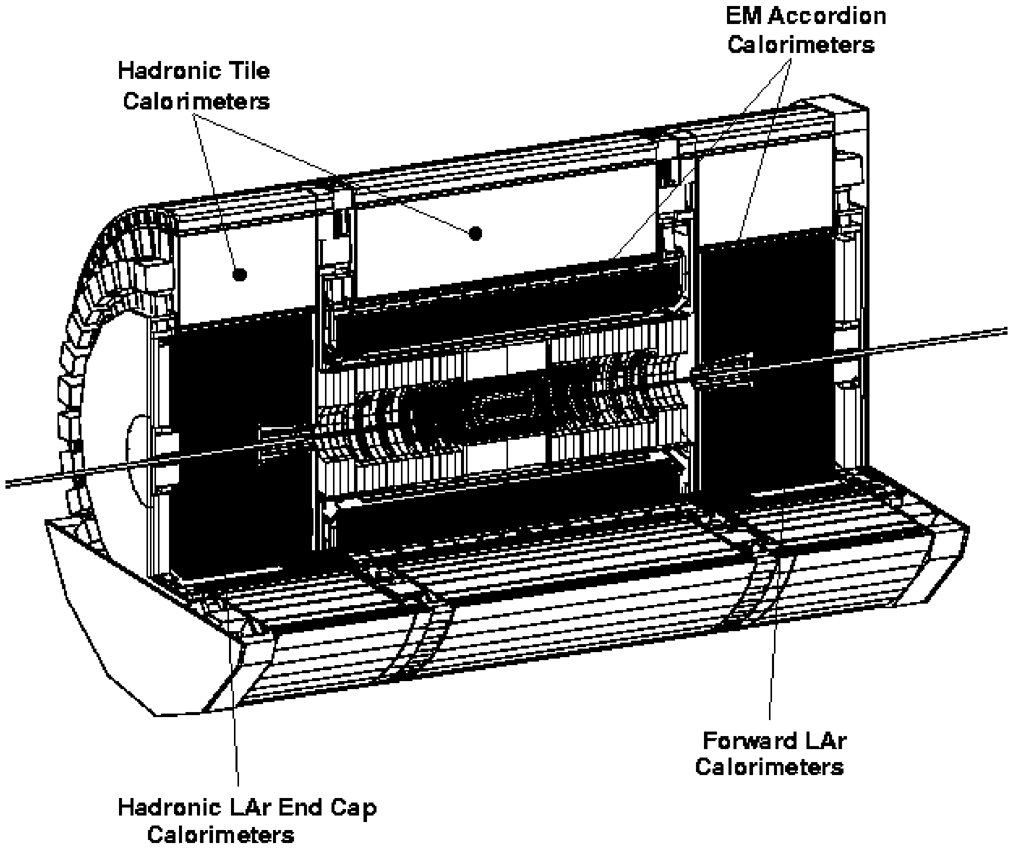
Jets and E_T^{miss} at the LHC

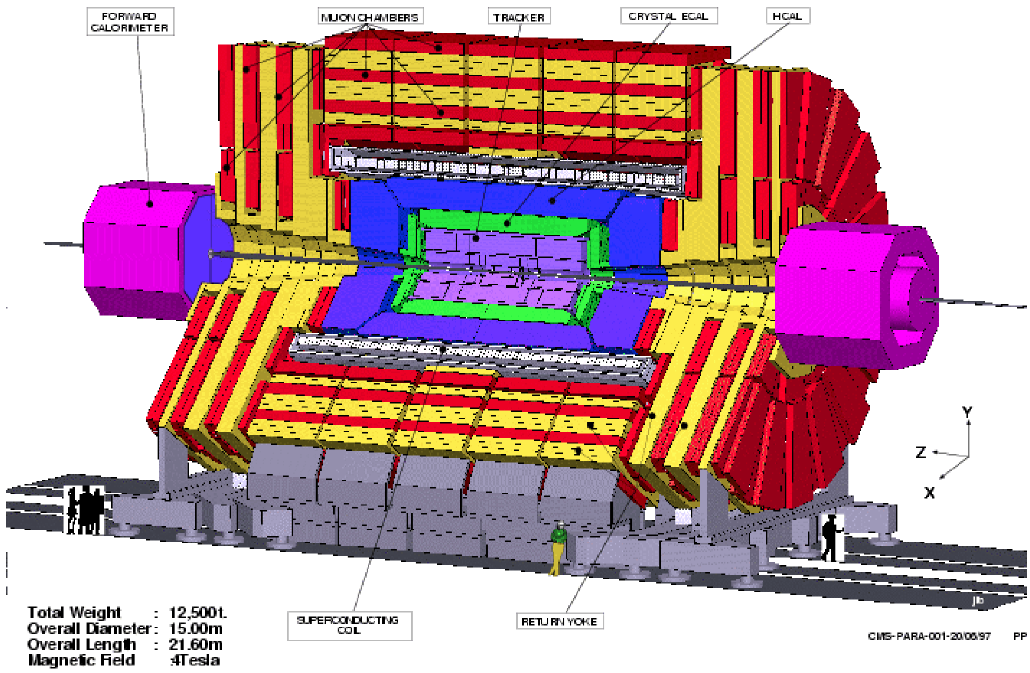
Outline

- ATLAS and CMS calorimetry
- Jet: reconstruction, algorithms, reconstruction of resonances, trigger
- τ jet reconstruction, trigger
- E_T^{miss} reconstruction and trigger
- Forward jet tagging, low p_T jet veto

Presentation on behalf of ATLAS & CMS collaborations

Jets and E_T^{miss} at the LHC





ATLAS and CMS calorimetry

Requirements on Calorimetry

- Good η coverage: up to about $|\eta|=5$
  for $E_T$miss resolution, forward jet tagging

- Hermiticity: non pointing "cracks"
  to avoid tails from badly reconstructed jets

- Thickness: avoid tails in energy deposit for high energy pions: >~ 9 λ_{int}
  to reduce punch-through in muon detector

- Granularity: adapted to hadron shower size
  $\Delta\eta x \Delta\varphi=0.087x0.087$ CMS
  $\Delta\eta x \Delta\varphi=0.1x0.1$ ATLAS

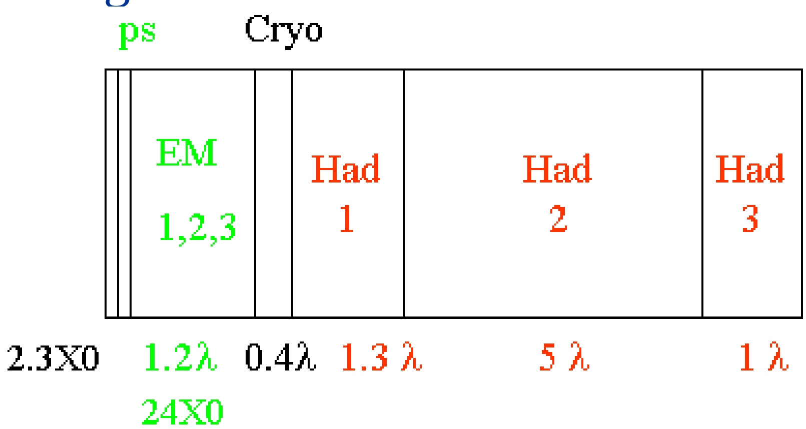
- Longitudinal segmentation:
  EM calo + optimized segmentation of hadronic compartment

ATLAS and CMS calorimetry

- Longitudinal segmentation:

ATLAS:

barrel



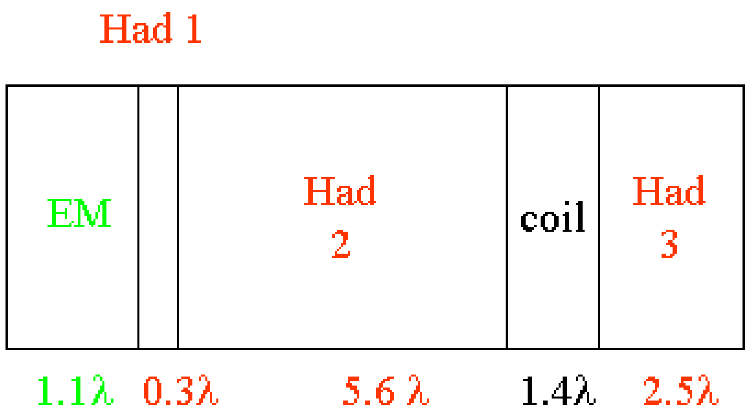
EM: Pb/LAr

HAD: Sc/Fe (barrel); Cu/Lar (endcap)

Forward: Cu/LAr + W/LAr

CMS:

barrel



EM: PbWO4 Crystals

HAD: (Sc/Cu) (barrel,endcap)

Forward: Fe+quarz fibers

ATLAS and CMS calorimetry

CMS and ATLAS: EM and HAD compartments both

non-compensated calorimeters

CMS: HAD $e/h \cong 1.4$; $e/h(EM) >> e/h(HAD)$

ATLAS: HAD $e/h \cong 1.35$; $e/h(EM) >> e/h(HAD)$

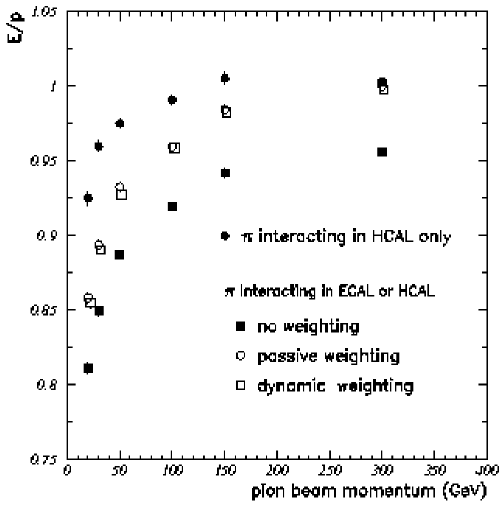
CMS

Non-linearity 15%

20-300GeV pions

EM calibrated at EM scale

HAD had scale pions 50 GeV



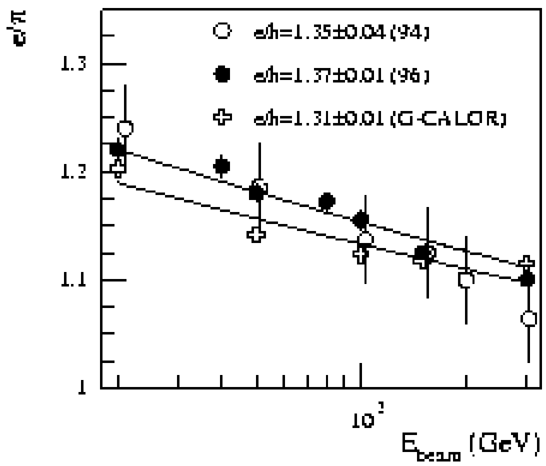
ATLAS

Non-linearity 12%

20-300GeV pions

EM and HAD

Calibrated at EM scale



resolution, linearity depend on algorithm for energy reconstruction

CMS: $E_{tot} = E_{EM} + \alpha \times H_1 + H_2 + H_3$ $\sigma_E/E = 122\%/\sqrt{E} \oplus 5\%$

ATLAS: $E_{tot} = \alpha \times E_{EM} + \beta \times E_{EM}^2 + \gamma \times E_{HAD} + \delta \times \sqrt{(E_{HAD1} * E_{EM3})}$

$\sigma_E/E = 50\%/\sqrt{E} \oplus 3.4\% \oplus 1./E$ noise cut at 2σ cone dR=0.3

Jet Reconstruction

From parton to reconstructed jet

- Factors related to physics
  - Fragmentation
  - Initial State Radiation, Final State Radiation
  - Underlying Event
  - Minimum bias (ATLAS high luminosity)

    0.5 GeV in tower $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$

    3.5 GeV (14 GeV) in cone of dR=0.4 (0.7)

    (el. noise included)

- Factors related to detector performance
  - Electronic noise

    ATLAS: 200 MeV in tower $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$

    0.7 GeV (1.4 GeV) in cone of dR=0.4 (0.7)

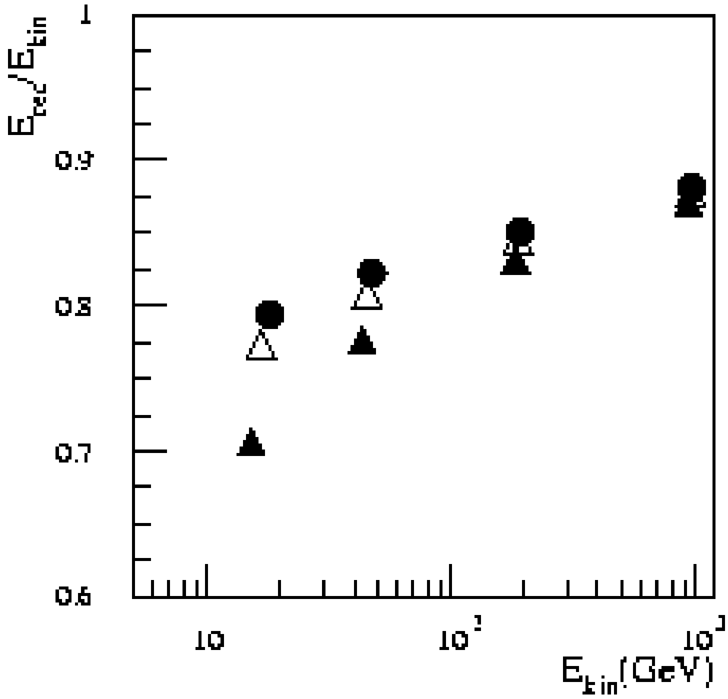
    CMS: 150 MeV in tower $\Delta\eta \times \Delta\varphi = 0.087 \times 0.087$
  - Magnetic field:

    p_T cutoff: 0.5 GeV ATLAS, 0.9GeV CMS
  - Different response to neutral and charged component (non-linearity)
  - Lateral shower size, granularity (out of cone loss, two-jet separation, τ jet identification)
  - Dead material and cracks
  - Longitudinal leakage (very high p_T jets)

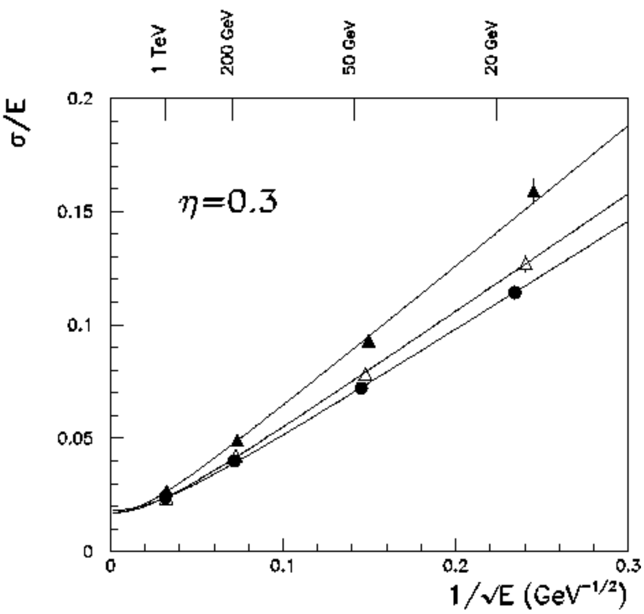
Jet Reconstruction

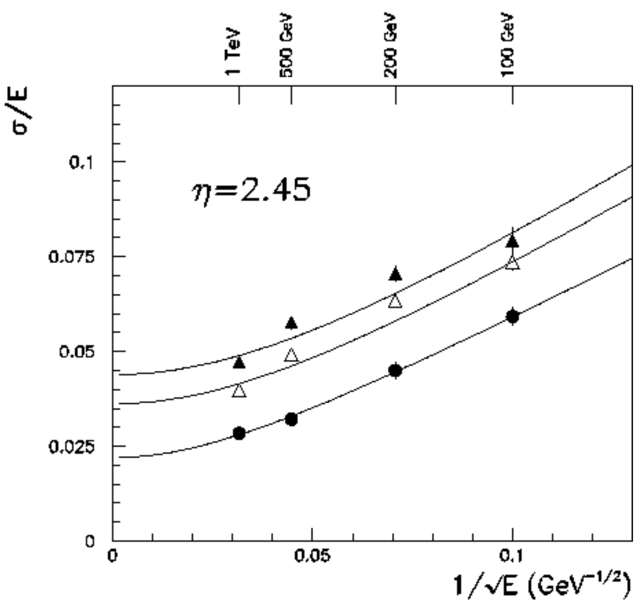
Different response to neutral and charged component of jet

- ● Total energy in calo
- △ Cone dR=0.7
- ▲ Cone dR=0.4



Calorimeter resolution (w.r.t particle energy in cone)





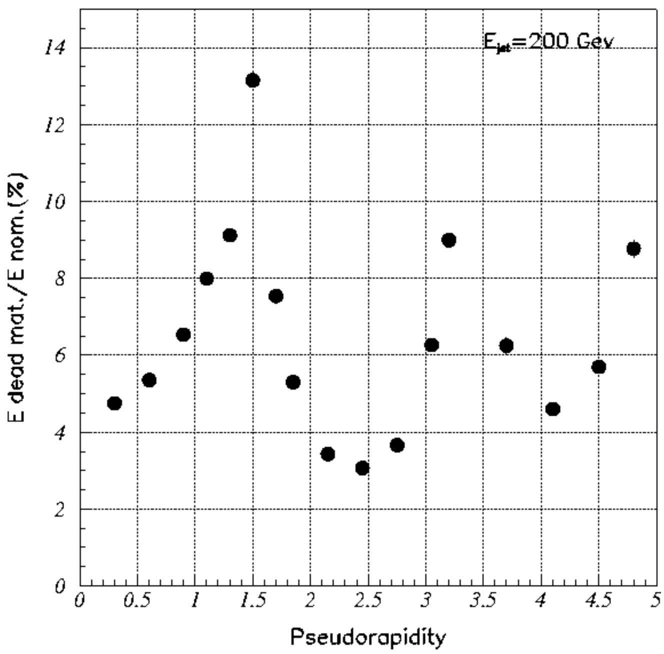
$\sigma_E/E=62\%/\sqrt{E}\oplus1.5\%$ $\sigma_E/E=68\%/\sqrt{E}\oplus4.4\%$

for dR=0.4

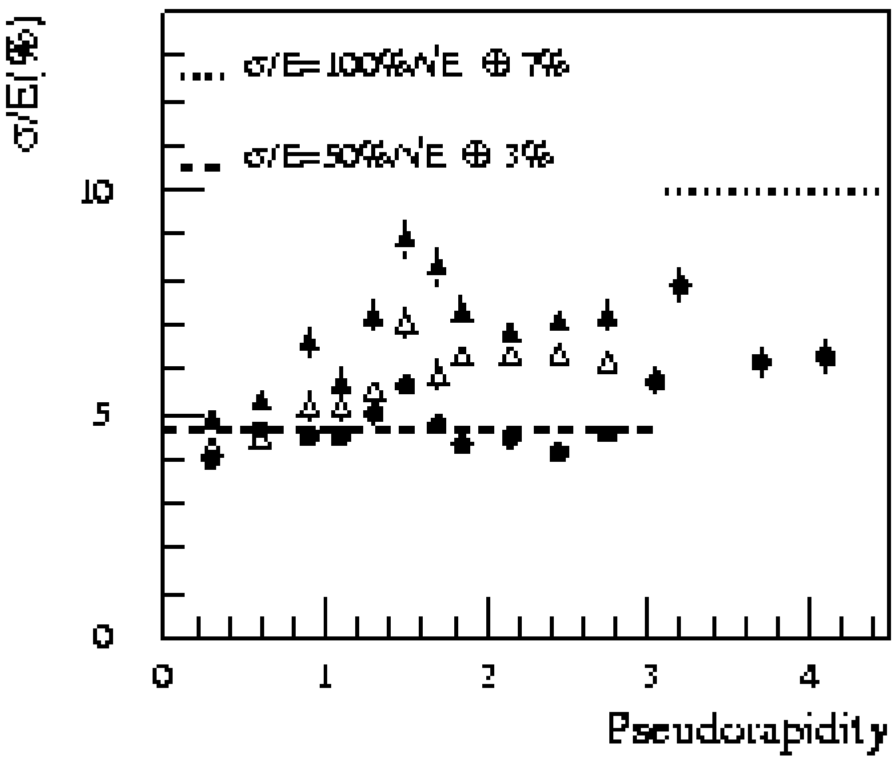
Jet Reconstruction

Dead material

and cracks



Resolution jets E=200 GeV



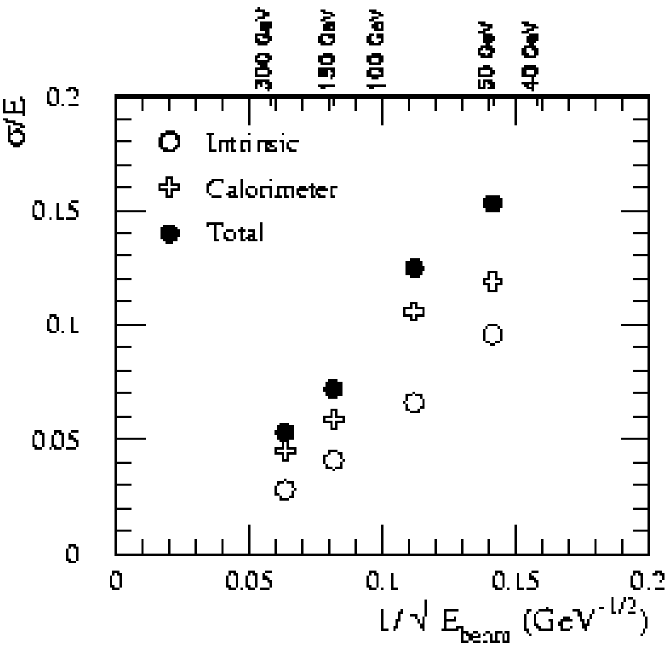
Jet Reconstruction

Contribution to resolution
from “cone size”,
fragmentation
magnetic field

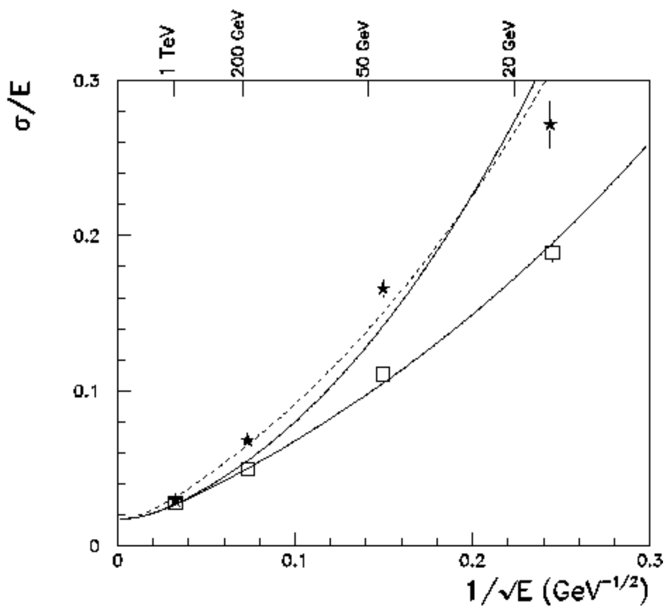
$\oplus$

contribution from
ISR,FSR,
underlying event

example of fixed cone
Z^0+jet events



Minimum bias
dR=0.4



$\sigma_E/E=62\%/\sqrt{E}\oplus 1.5\% \oplus 4.7/E$ min.bias + el.noise

(1.7 el.noise only)

Jet Algorithms

- Jet algorithms: two basic approaches, many possible variant
  - Cone algorithm: seed + cone

    iteration of cone direction, jet overlap & energy sharing,...
  - Clustering algorithm (QCD inspired):

    pairing of "particles" (calorimeter towers) starting from "closest" particles

    stop at fixed jet multiplicity or a certain "size" ...

- different energy bias vs ET for different algorithms

  from physics

  pile-up introduces a luminosity dependent bias

  Å

  experimental effects: detector non-linearity, shower size effects depend on particle composition and size of jet

- Choice of algorithm will depend on physics channel and luminosity conditions

  some examples:

  QCD jet multiplicity study at low luminosity or

  high p_T $W \rightarrow jj$ reconstruction

- Jet energy calibration will be a complex issue because of the combination of physics + detector effects.

  In-situ physics processes like Z^0+jet, $W \rightarrow jj$

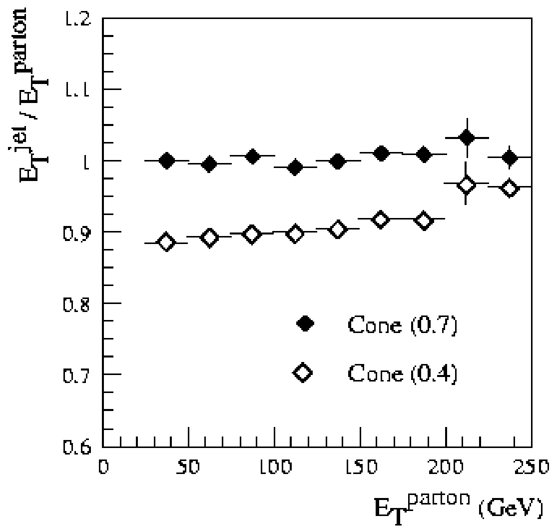
Jet Algorithms

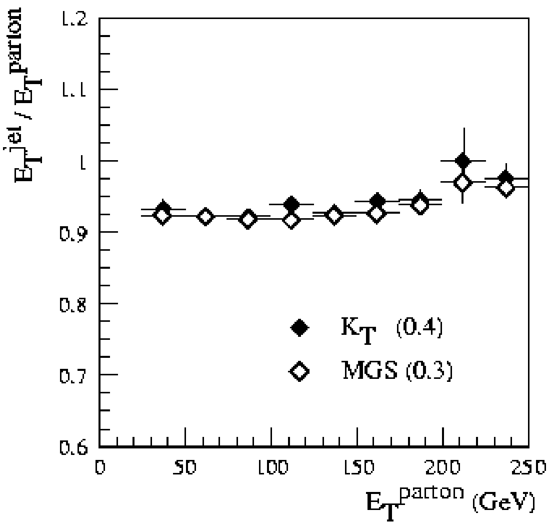
different energy bias vs ET for different algorithms

different at low and high luminosity

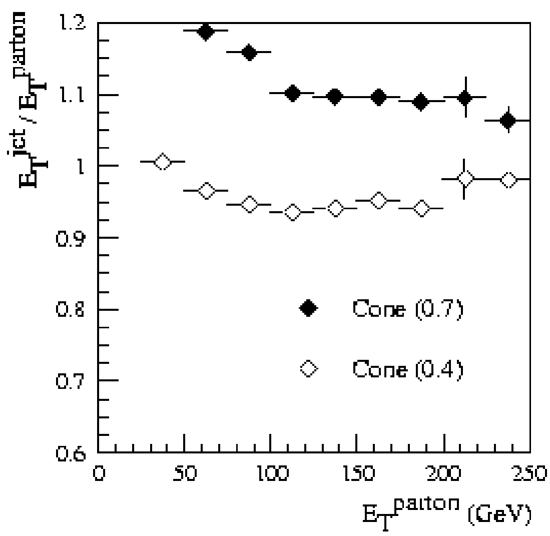
Particle level study with W(jj)+j events

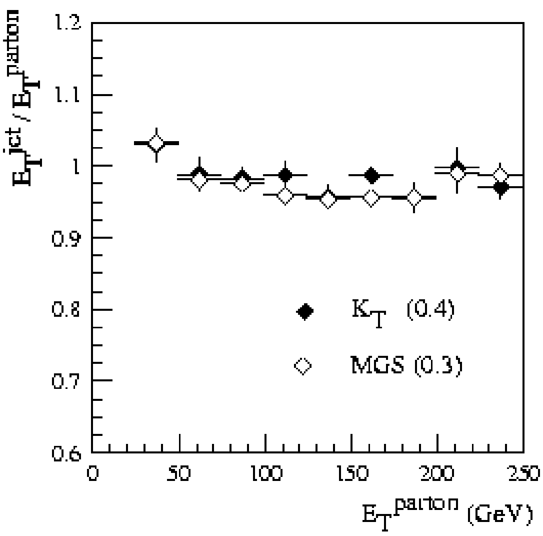
No minimum bias added





High luminosity pile-up





Reconstruction of resonances

ATLAS: mid p_T W: ~120-150 GeV

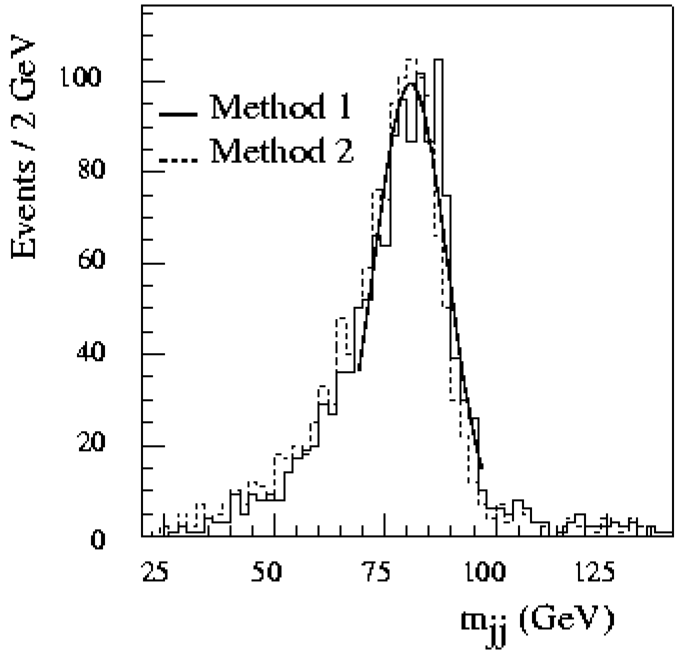
Resolution ~8 GeV

(high luminosity ~13 GeV)

Tail:

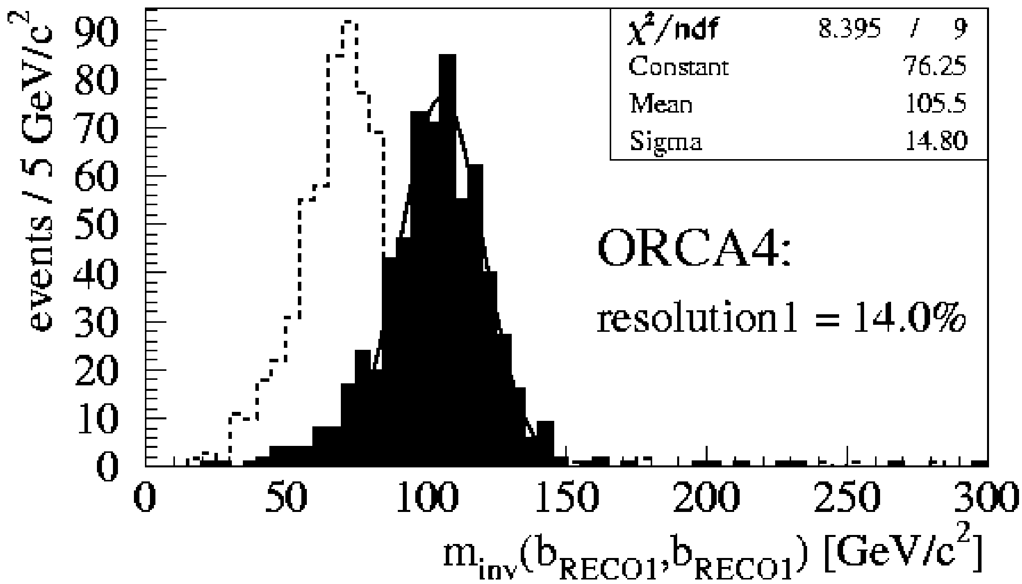
bias in jet direction

due to jet overlap



CMS: H(110 GeV)→$b\bar{b}$ Resolution ~14 GeV

High luminosity



Jet Trigger

low p_T jet cross-section $d\sigma/dp_T \sim 1/p_T^3$

sharpness of efficiency curve is important

not to be dominated by lower p_T jets

LvL1:

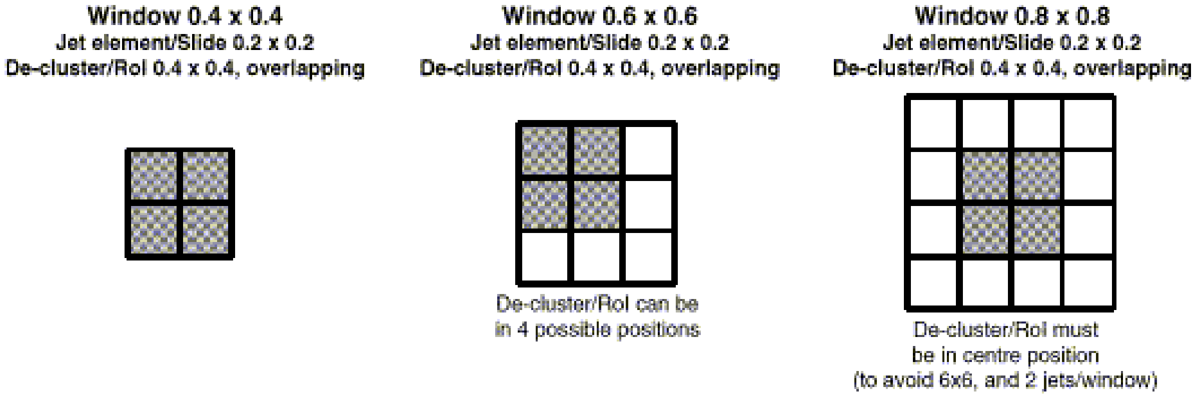
ATLAS: 2x2 cluster (0.2x0.2) moved by 0.2 ⇒ local maximum

E_T jet measured in window (2x2; 3x3; 4x4)

programmable, optimum = f (E_T,luminosity)

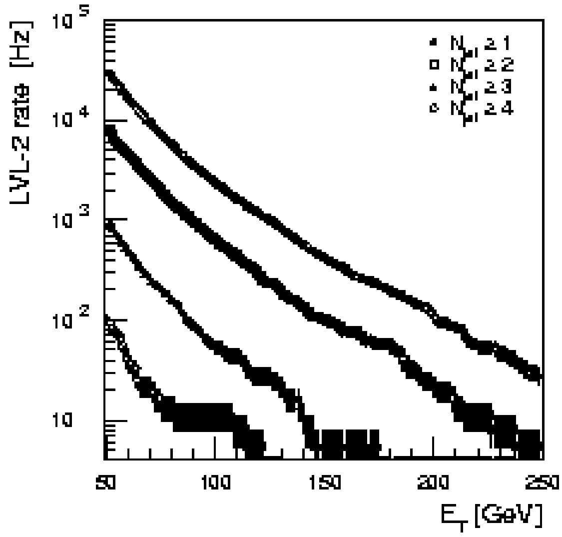
CMS: 4x4 cluster (0.348x0.348) moved by 0.348 ⇒ local max.

E_T jet measured in window 12x12



LvL2: apply jet algorithm in window 1.0x1.0

improved calibration



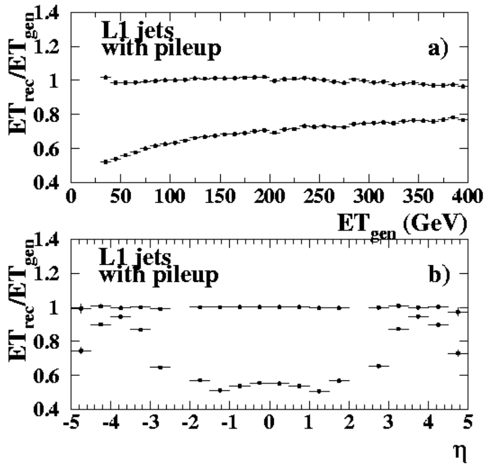
To achieve final 25 Hz

1j 360 GeV

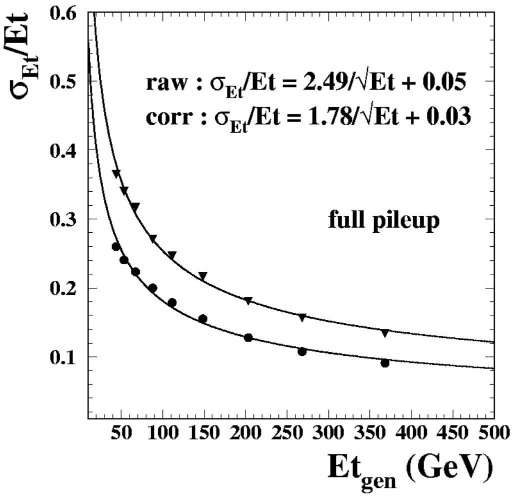
3j 150 GeV

4j 100 GeV

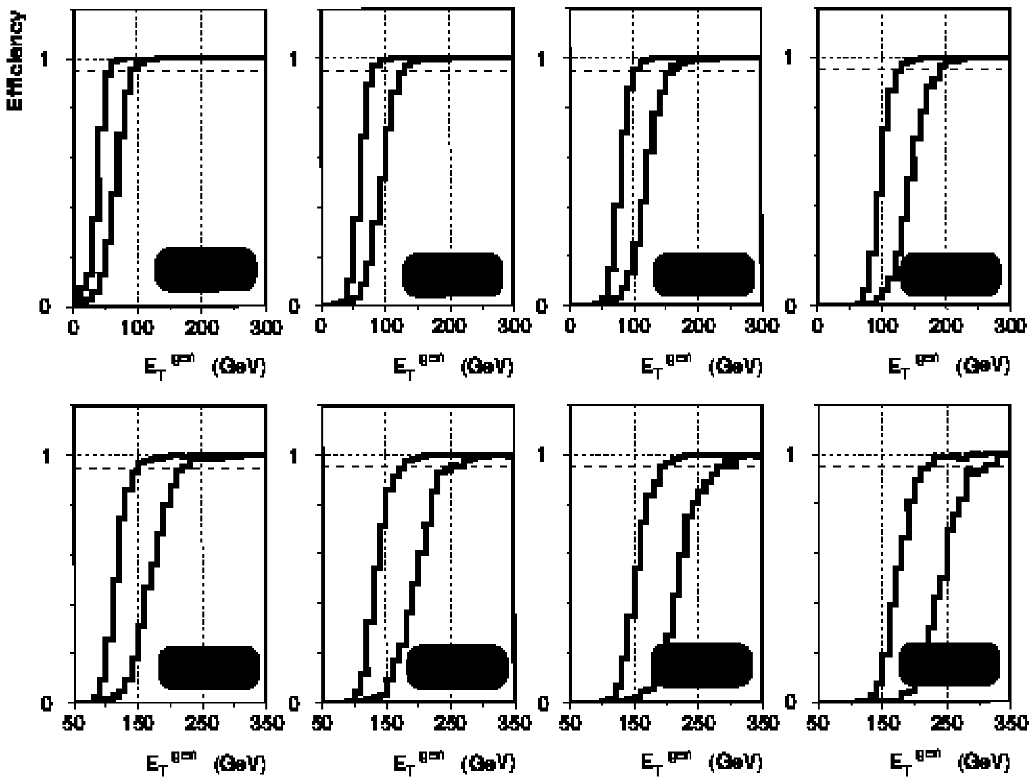
Jet Trigger: CMS Level1



L1 Jets Resolution, |η|<5



L1 jets efficiency curves for various E_T thresholds
with / without jet energy corrections



τ jets: A/H →ττ (Z →ττ), W →τυ

τ jet identification:

Narrow, isolated jet associated to 1 (3) track(s)

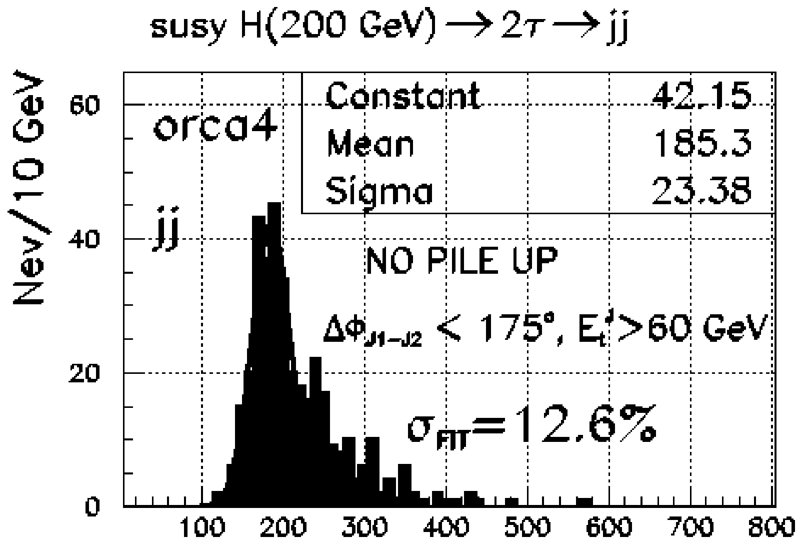
ATLAS: QCD jet rejection ≈ 100 for τ efficiency ≈ 50%

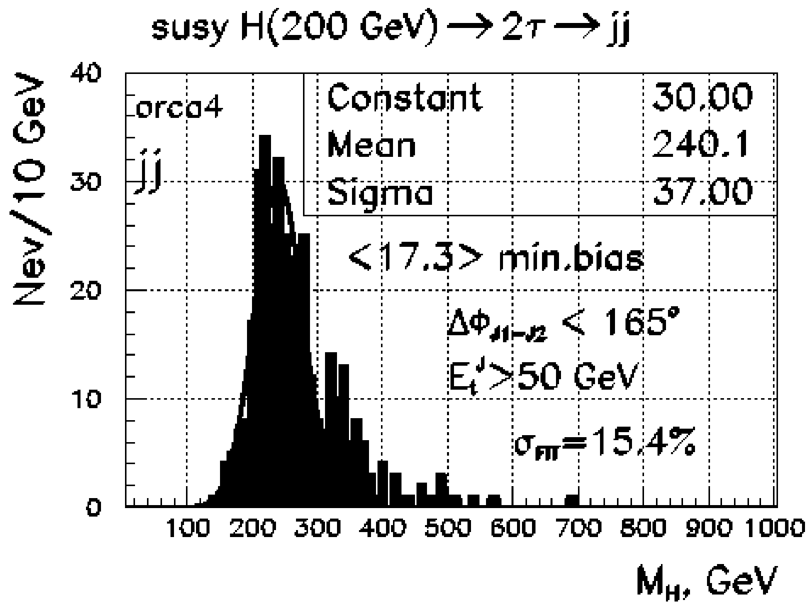
Final state with τ jet:

τ direction from decay products + $p_T$miss vector

CMS

offline





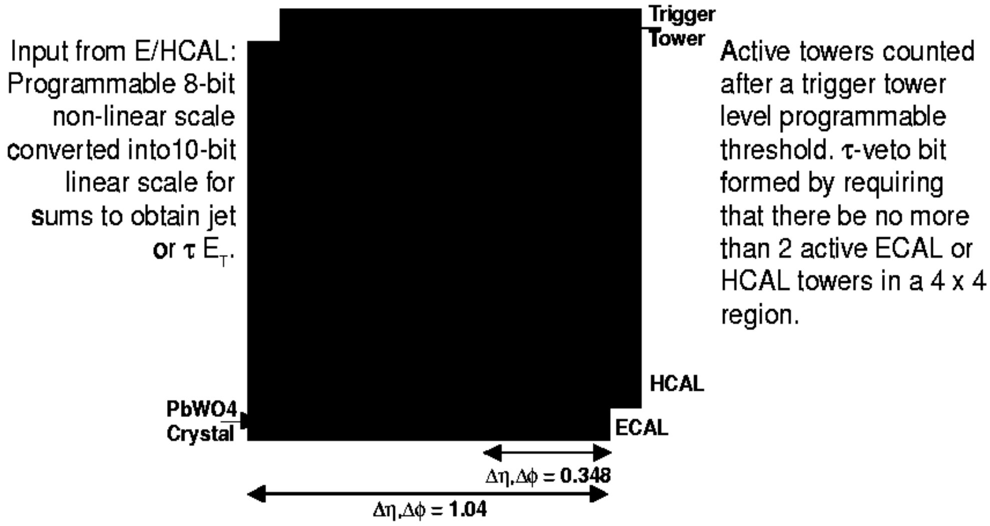
τ jets: A/H $\rightarrow\tau\tau$ (Z $\rightarrow\tau\tau$), W $\rightarrow\tau\upsilon$

- ATLAS: single τ+E_t^{miss} (low p_T W $\rightarrow\tau\upsilon$)
- CMS: single, double τ trigger (A/H $\rightarrow\tau\tau$)

Example: CMS trigger chain (High Luminosity)

LvL1: 4kHz for **1 t** (p_T>80 GeV); **2 t** (p_T>50 GeV);

Efficiency:
H 200GeV
64%
H 500 GeV
81%



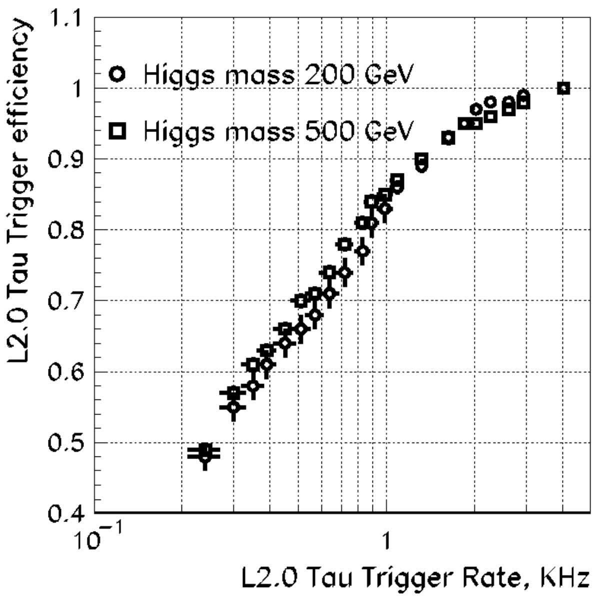
LvL2: 450 Hz for efficiency ~ 65%

- Reconstruct LvL1 jet:

iterative cone dR=0.6

- Isolation in EM:

E_TEM(R<0.4)
- E_TEM(R<0.13)<5.3 GeV



LvL3: one isolated track reconstructed in Pixel detetctor (under study)

E_T^{miss} Reconstruction

- p_T^{miss} vector for invariant mass reconstruction: $A/H \to \tau\tau$ ... $\Rightarrow$ resolution important
- Large E_T^{miss} = signature for new physics (SUSY,...) $\to$ minimize tails from fake E_T^{miss} from instrumental effects like "cracks" (badly measured jets)

$p_{X,Y}^{miss}$ reconstructed from the cell (tower) energies

Important factors (ATLAS study with $A/H \to \tau\tau$)

- Calorimeter coverage: needs coverage up to $|\eta|\approx 5$

  Particle level $\sigma(p_{X,Y}^{miss})$ 2.3 GeV ↗ 8.3 GeV $|\eta|\approx 5$ ↘ $|\eta|\approx 3$

- Calorimeter resolution: contribution depends on $|\eta|$

  P. L. $\sigma(p_{X,Y}^{miss})$ 2.3 GeV ↗ 8.3 GeV (fully simulated)
  barrel (5 GeV) endcap (4 GeV) forward (3 GeV)
  because $\langle E_T \rangle$ decreases

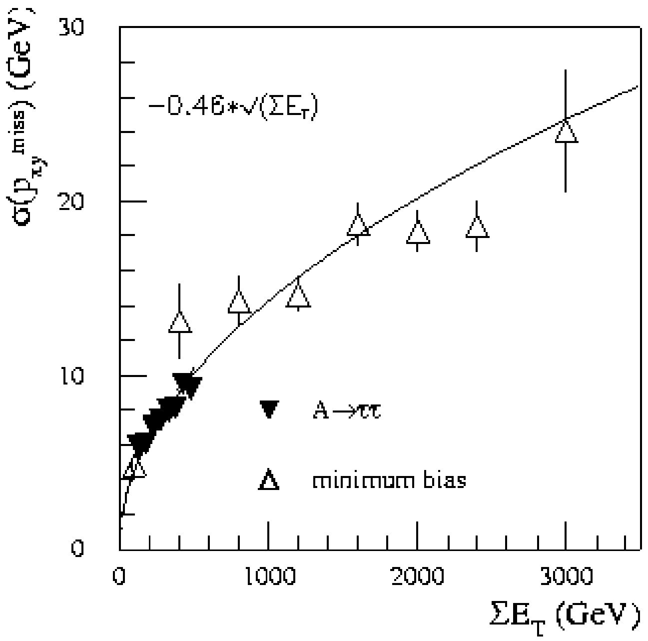
- Calorimeter calibration: important to correct for non-compensation (low p_T particles)

- Electronic noise: 200 MeV in tower 0.1X0.1

  1.5 σ cut on noise : $\sigma(p_{X,Y}^{miss})$ 8.3 GeV ↗ 9 GeV

E_T^{miss} Reconstruction

$\sigma(p_{X,Y}^{miss})$ versus total transverse energy in the calorimeters

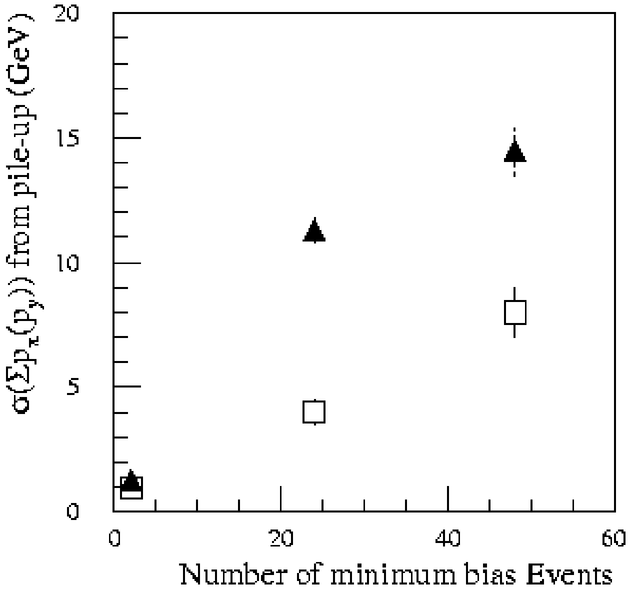


Contribution to $\sigma(p_{X,Y}^{miss})$ from min.bias events

E_T tower cut > 1 GeV

▲ total

☐ Fcal alone



E_T^{miss} trigger

- CMS: LvL1 uses 4x4 towers ($\Delta\eta x \Delta\varphi$=0.348x0.348)
  Least significant bit : 1 GeV E_T
- ATLAS: LvL1 uses 2x2 towers ($\Delta\eta x \Delta\varphi$=0.2x0.2)
  Least significant bit : 1 GeV E_T
  ADCsaturation @ 256 GeV

- LvL3: recalculate E_T^{miss} with fine granularity, better calibration constants

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- E_T^{miss} trigger used in conjunction with jet and tau trigger
- inclusive E_T^{miss} : cut determined by bandwitdh allocated to that trigger

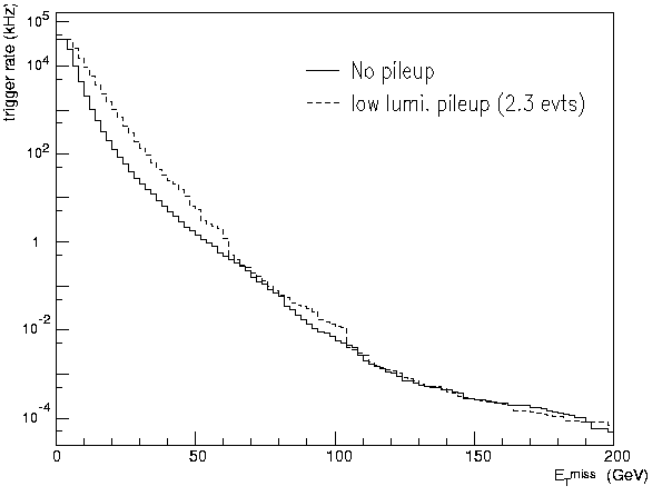
E_T^{miss} Reconstruction

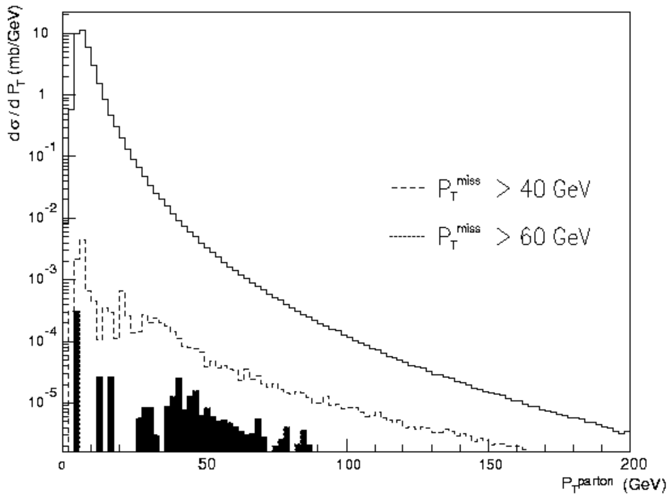
LvL1 inclusive E_T^{miss} rate dominated by QCD dijet + pile-up

Low luminosity

E_t^{miss} < 60 GeV min.bias increases rate by factor 5

E_t^{miss} > 100 GeV min.bias has no effect

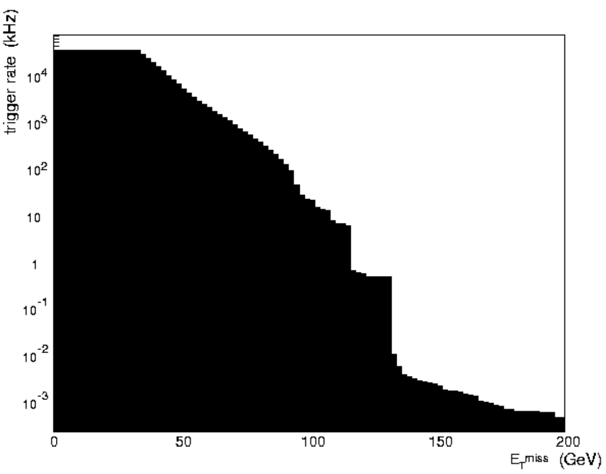


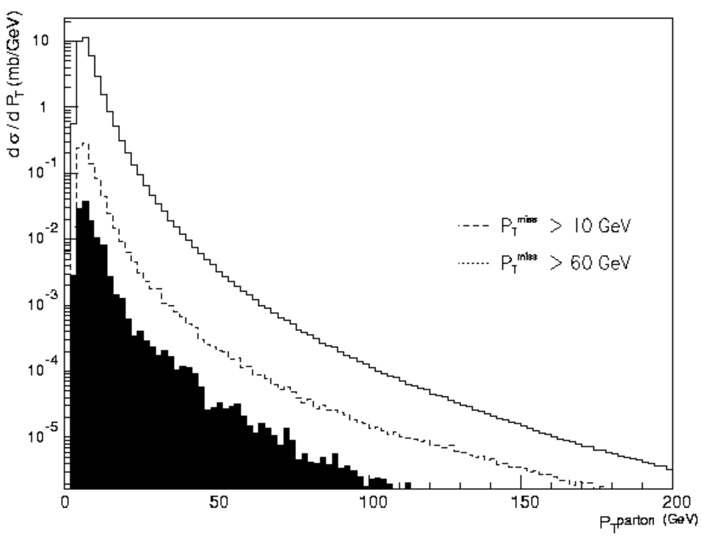


High luminosity

Rate increases by a factor 10^3 at 100GeV

10 at 200 GeV

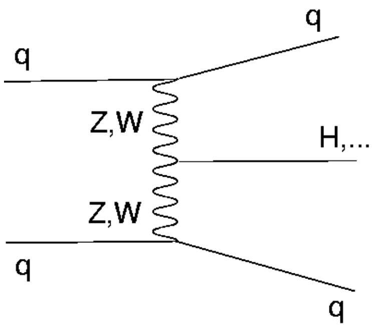


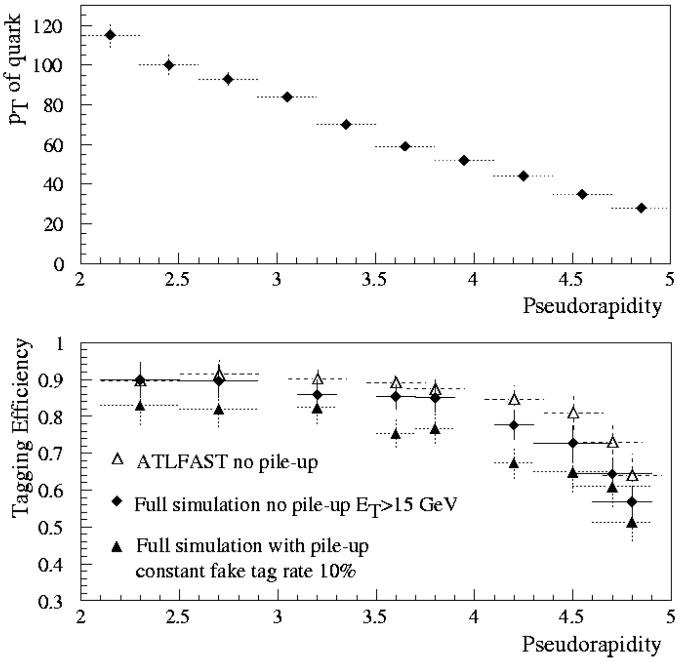


Forward jet tagging, low p_T jet veto

- Forward jet tagging

To select boson fusion processes



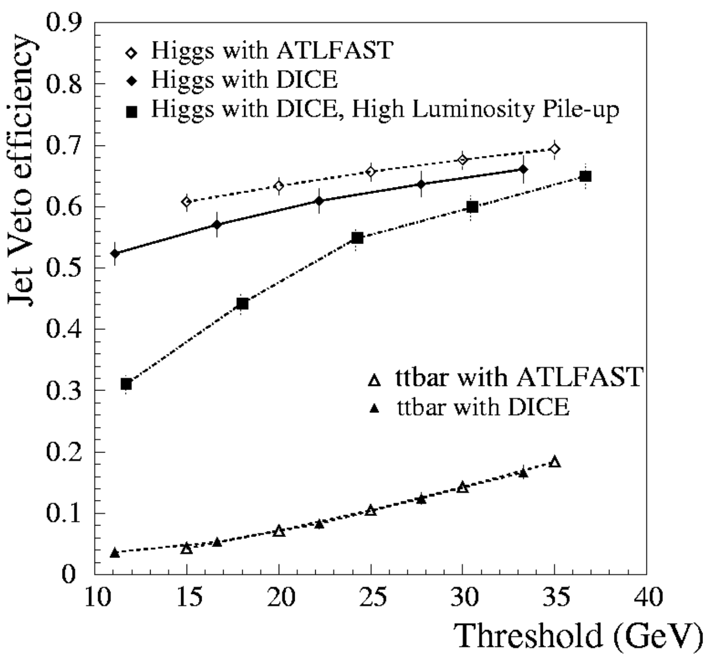


- Low pT jet veto

To reject background,

From multijet events

Usually $t\bar{t}$



Conclusions

A lot of interesting physics with jets, τ-jets and p_T^{miss}

Jet energy calibration will be a challenging and crucial task

- There are physics and experimental effects at play
- They depend on the algorithm, the luminosity conditions ...
- Jet trigger: trigger rate dominated by sharpness of threshold curves

t-jets are identified as narrow and isolated jets with 1(3) pointing tracks. They can be triggered on.

- Resonances decay to $\tau\tau$ are reconstructed combining τ-jets with p_T^{miss} vector

E_T^{miss} is reconstructed with good precision thank's to the good coverage and hermiticity of the detectors.

- Calorimeter calibration important
- High luminosity pile-up deteriorates the resolution significantly