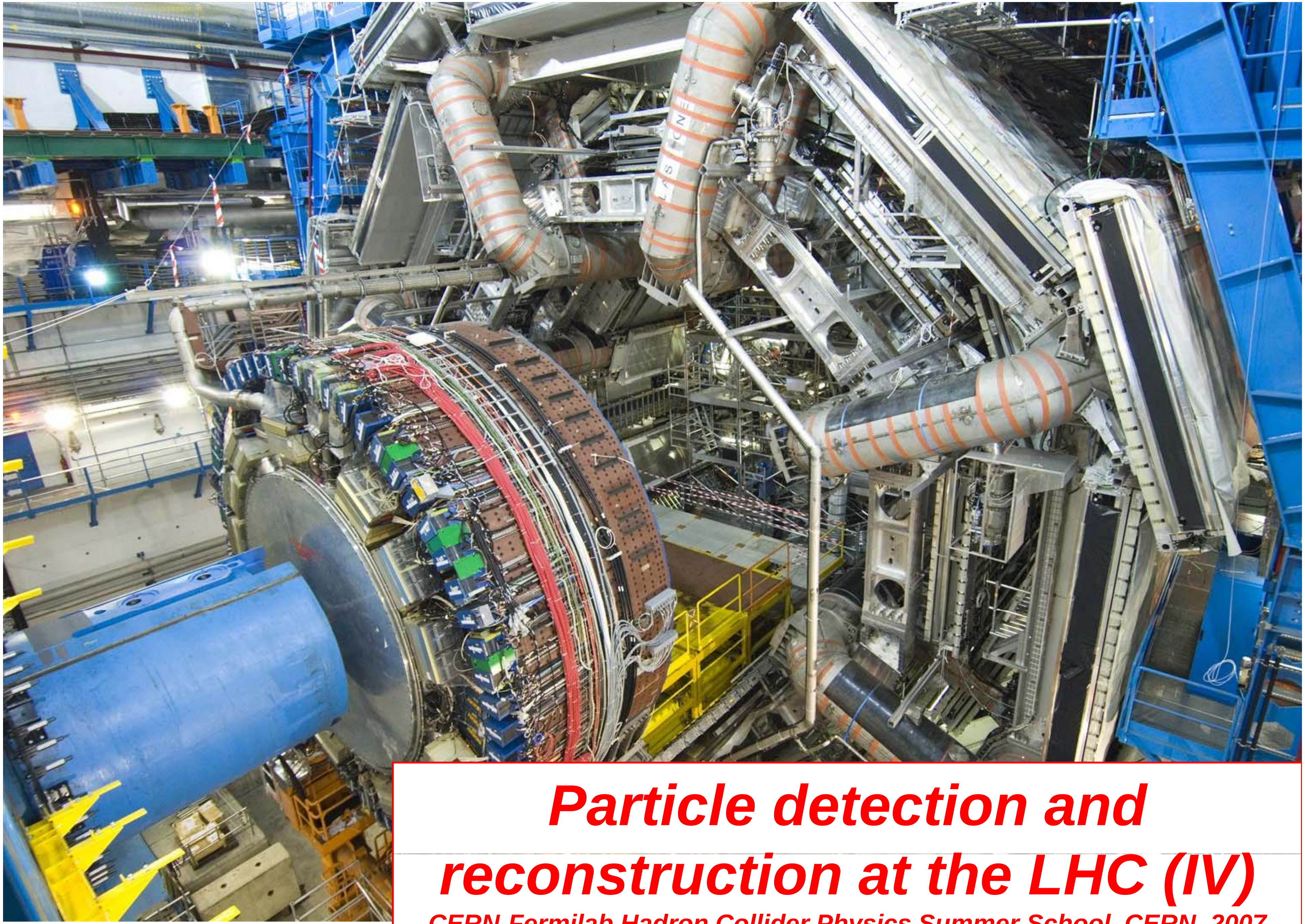


Particle detection and reconstruction at the LHC (IV)

CERN-Fermilab Hadron Collider Physics Summer School, CERN, 2007

11th to 14th of August 2007 (D. Froidevaux, CERN)

Particle detection and reconstruction at the LHC (and Tevatron)

Lecture 1

- Historical introduction: from UA1/UA2 to ATLAS/CMS

Lecture 2

- Experimental environment and main design choices of ATLAS and CMS

Lecture 3

- Global performance overview, electrons and photons (and particle-ID in ALICE/LHCb)

Lecture 4

- Muons and hadronic jets

Acknowledgments

- Material from HCP conferences (in particular for Tevatron)
- Special thanks to O. Kortner, M. Lefebvre, P. Loch and P. Sphicas

Electrons and photons in ATLAS/CMS: conclusions

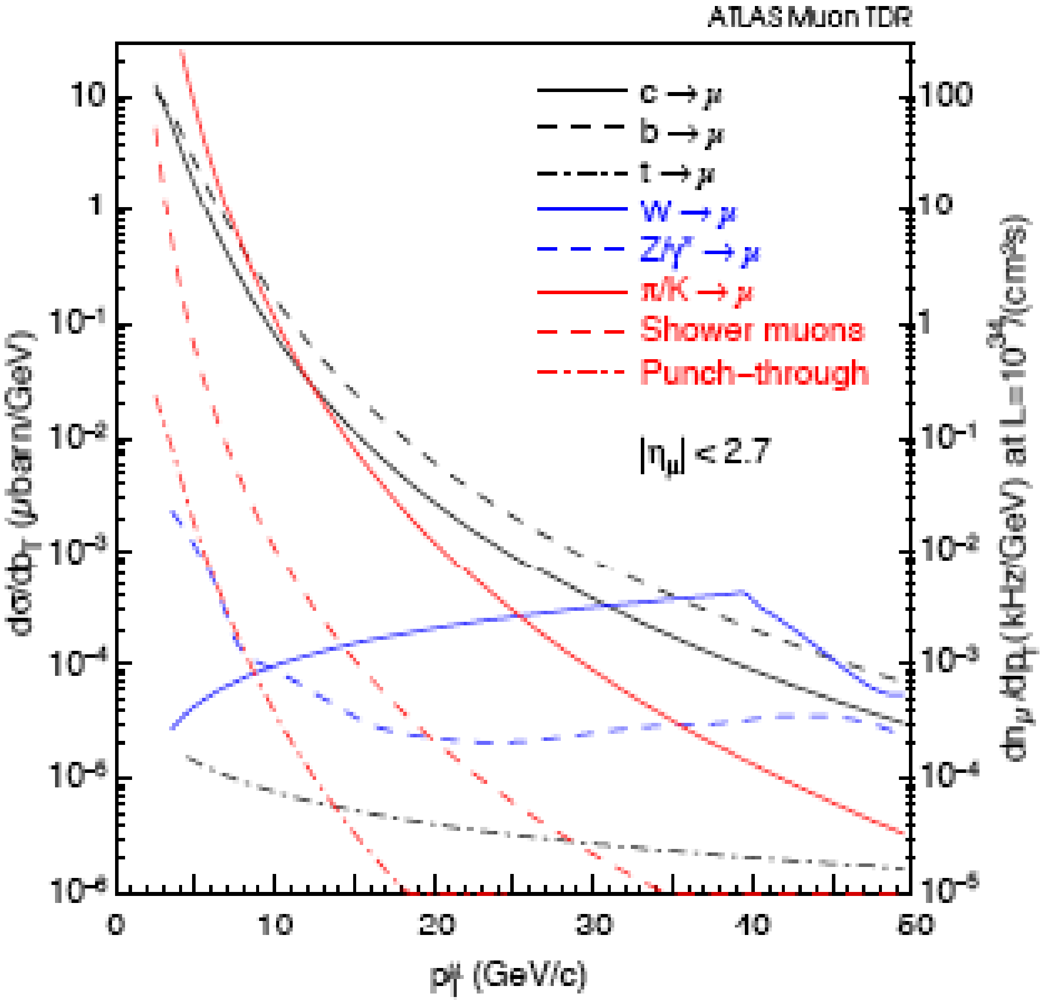
Electron/photon ID in ATLAS and CMS will be a challenging and exciting task (harsher environment than at Tevatron, larger QCD backgrounds, more material in trackers)

But LHC detectors are better in many respects! Software is on its way to meet the challenge!

Huge effort in terms of understanding performance of detectors as installed ahead of us (calibration of calorimeters and alignment of trackers, material effects)

ATLAS/CMS: muon measurements and identification

Inclusive muon cross sections



Remember which are primordial tasks of muon systems:

1. **Trigger on high-p_T single muons and muon pairs**
2. **Identify muons**
3. **Measure muon momenta independently of tracker**

What is expected composition of muon L1 trigger at ~ 10 GeV?

1. **About 50% heavy flavours**
2. **About 50% π/K decays**

Most muons are real but also non-isolated and embedded in jets with

ATLAS/CMS: muon spectrometer parameters

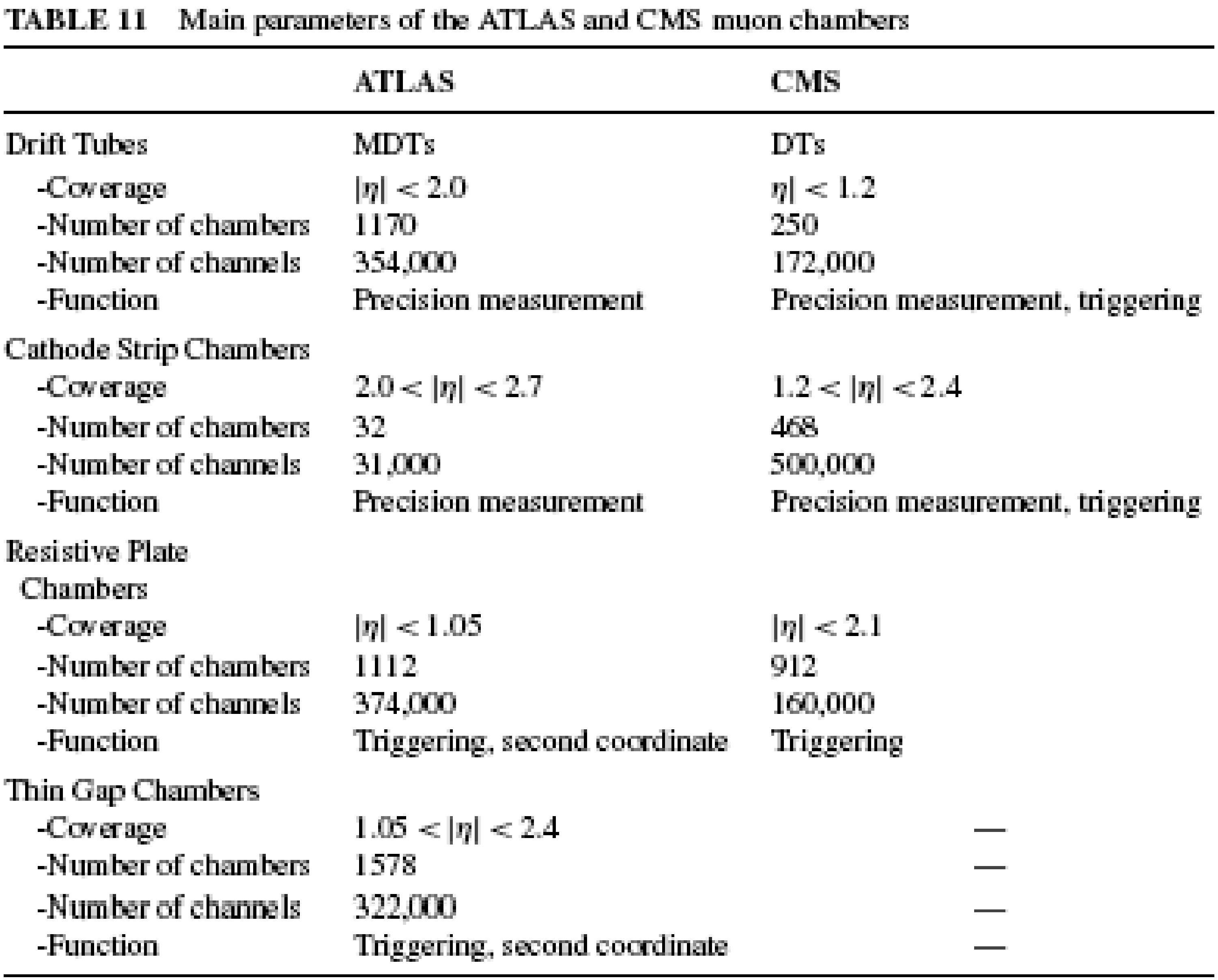
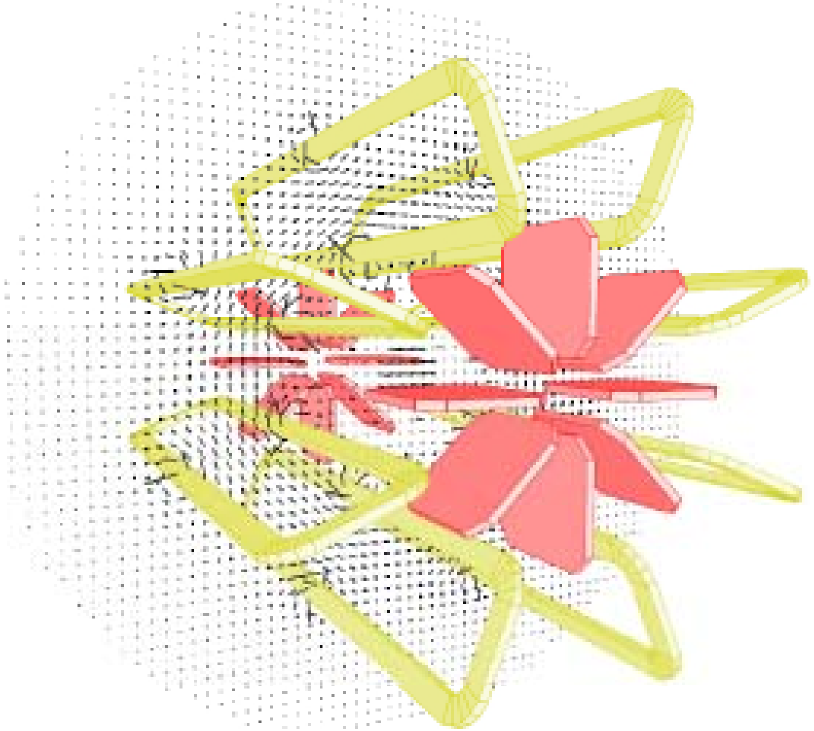


TABLE 11 Main parameters of the ATLAS and CMS muon chambers

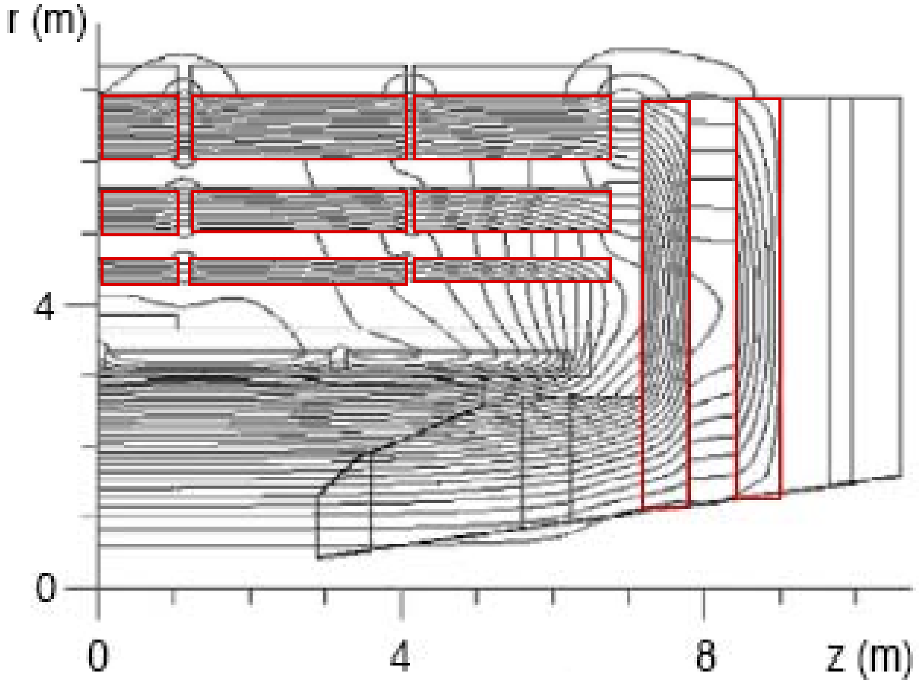
	ATLAS	CMS
Drift Tubes	MDTs	DTs
-Coverage	$\|\eta\| < 2.0$	$\eta\| < 1.2$
-Number of chambers	1170	250
-Number of channels	354,000	172,000
-Function	Precision measurement	Precision measurement, triggering
Cathode Strip Chambers		
-Coverage	$2.0 < \|\eta\| < 2.7$	$1.2 < \|\eta\| < 2.4$
-Number of chambers	32	468
-Number of channels	31,000	500,000
-Function	Precision measurement	Precision measurement, triggering
Resistive Plate Chambers		
-Coverage	$\|\eta\| < 1.05$	$\|\eta\| < 2.1$
-Number of chambers	1112	912
-Number of channels	374,000	160,000
-Function	Triggering, second coordinate	Triggering
Thin Gap Chambers		
-Coverage	$1.05 < \|\eta\| < 2.4$	—
-Number of chambers	1578	—
-Number of channels	322,000	—
-Function	Triggering, second coordinate	—

ATLAS/CMS: muon measurements and identification

ATLAS Air-Core Toroid



Iron Return Yoke of CMS Solenoid



- Limited impact on resolution from MS
- B-field highly non-uniform and rapidly varying (has to be measured!)
- Some difficult regions for acceptance (z = 0 and feet)
- Transverse momentum resolution

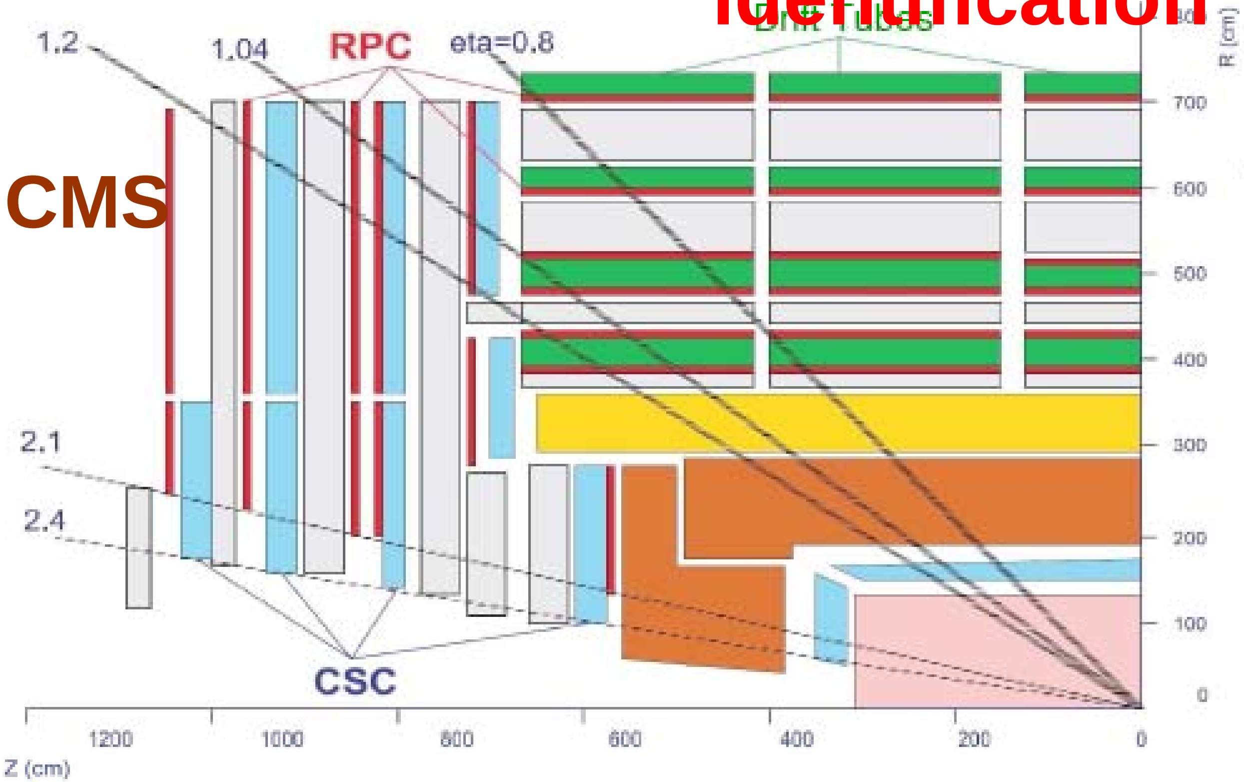
- Resolution severely limited by MS
- Very uniform B-field in central region

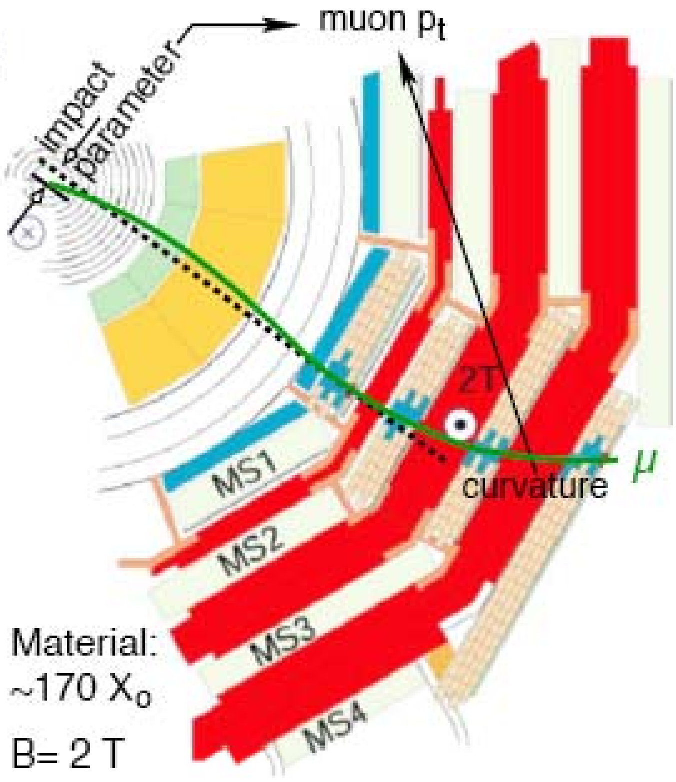
- Excellent geometrical acceptance

- Transverse momentum resolution degrades significantly at large η

ATLAS/CMS: muon measurements and identification

CMS

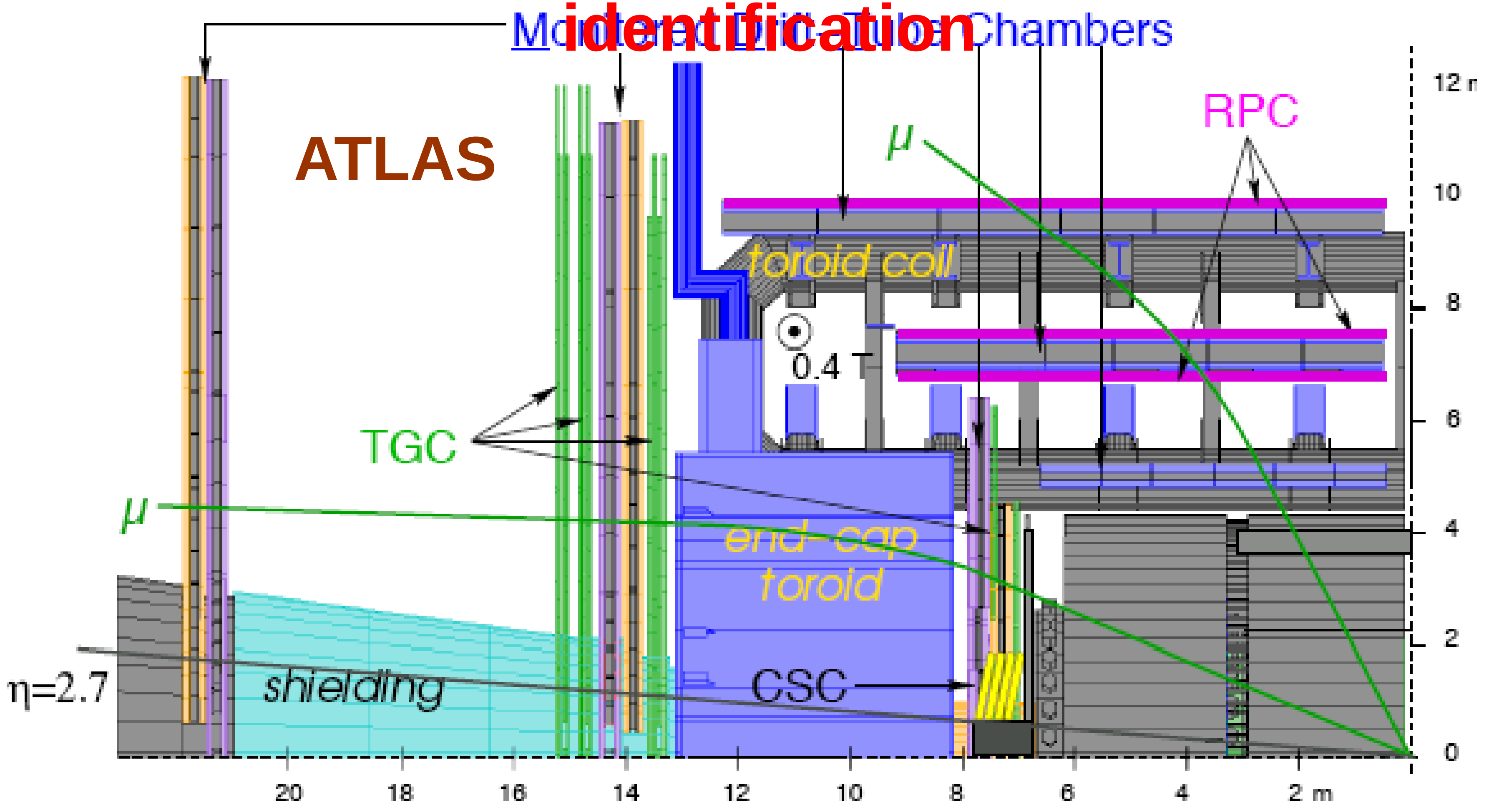




CMS muon spectrometer

- Superior combined momentum resolution in central region
- Limited stand-alone resolution and trigger (at very high luminosities) due to multiple scattering in iron
- Degraded overall resolution in the forward regions ($|\eta| > 2.0$) where solenoid bending power becomes insufficient

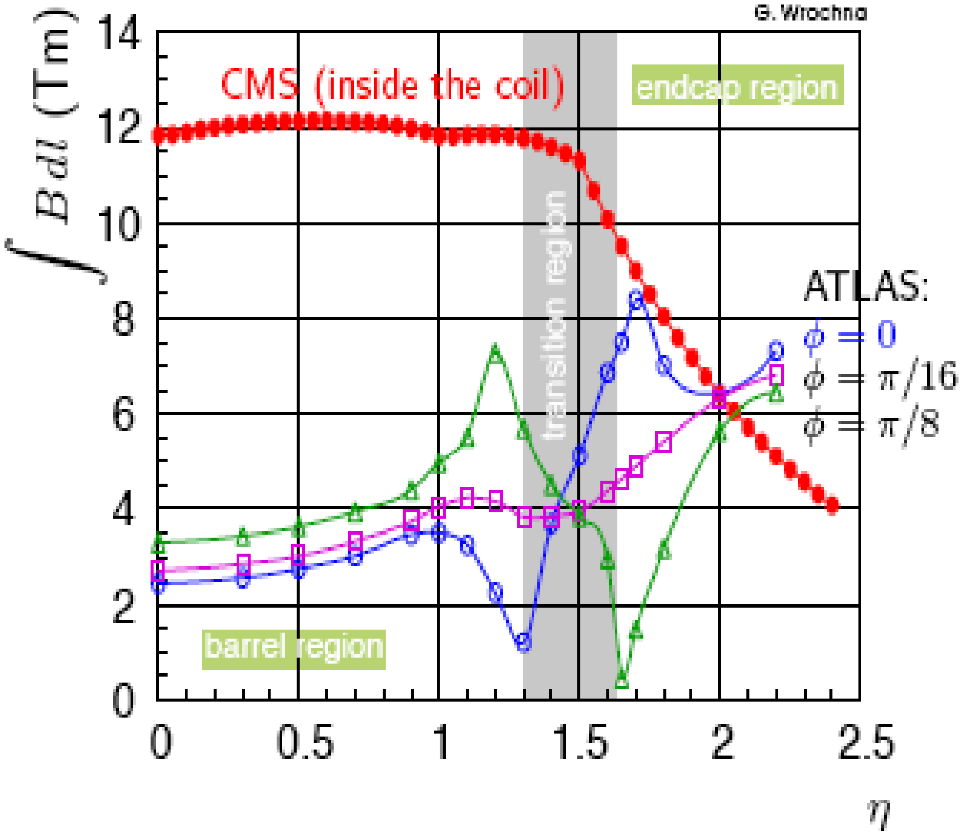
ATLAS/CMS: muon measurements and identification



ATLAS muon spectrometer

- **Excellent stand-alone capabilities and coverage in open geometry**
- **Complicated geometry and field configuration (large fluctuations in acceptance and performance over full potential η x ϕ coverage (|η| < 2.7)**

ATLAS/CMS: muon measurements and identification



Barrel: ≈ 5× higher bending power in CMS, **but** ≈ 14× larger multiple scattering.

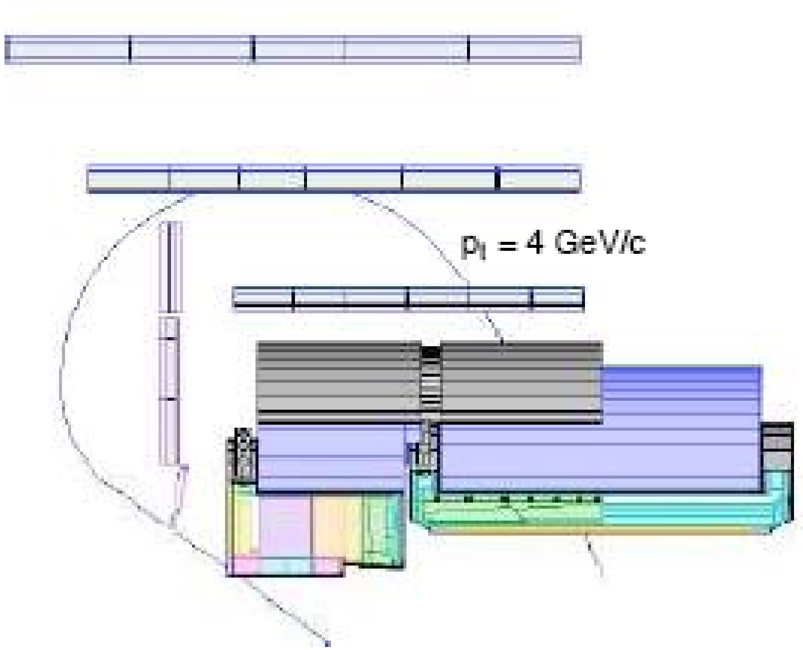
→ ≈ 3× worse p_t resolution in CMS.

Endcap: similar bending powers, ≈ 10× large multiple scattering.

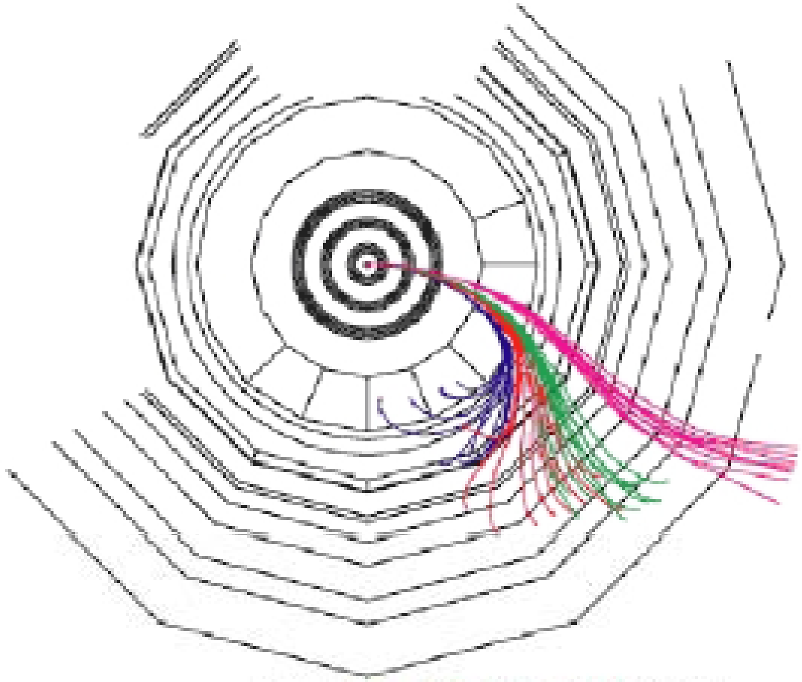
→ ≈ 5× worse p_t resolution in CMS.

ATLAS/CMS: low-p_T muons

ATLAS



CMS

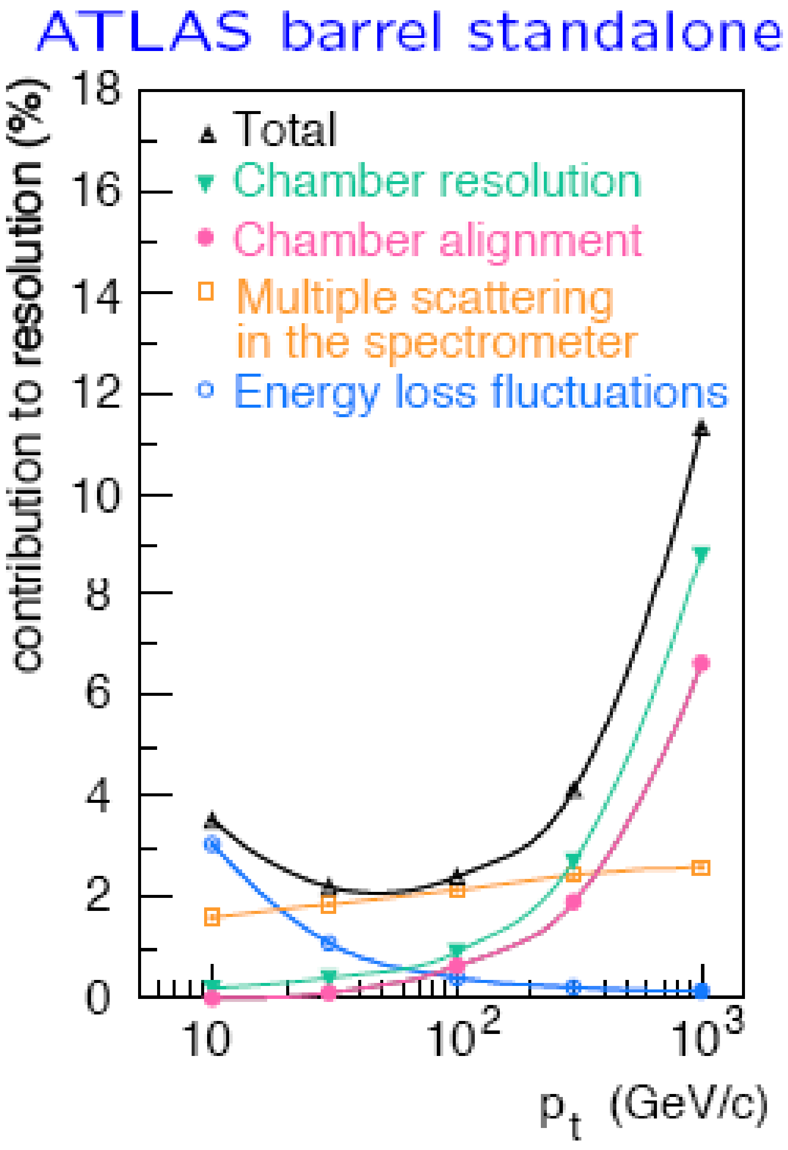


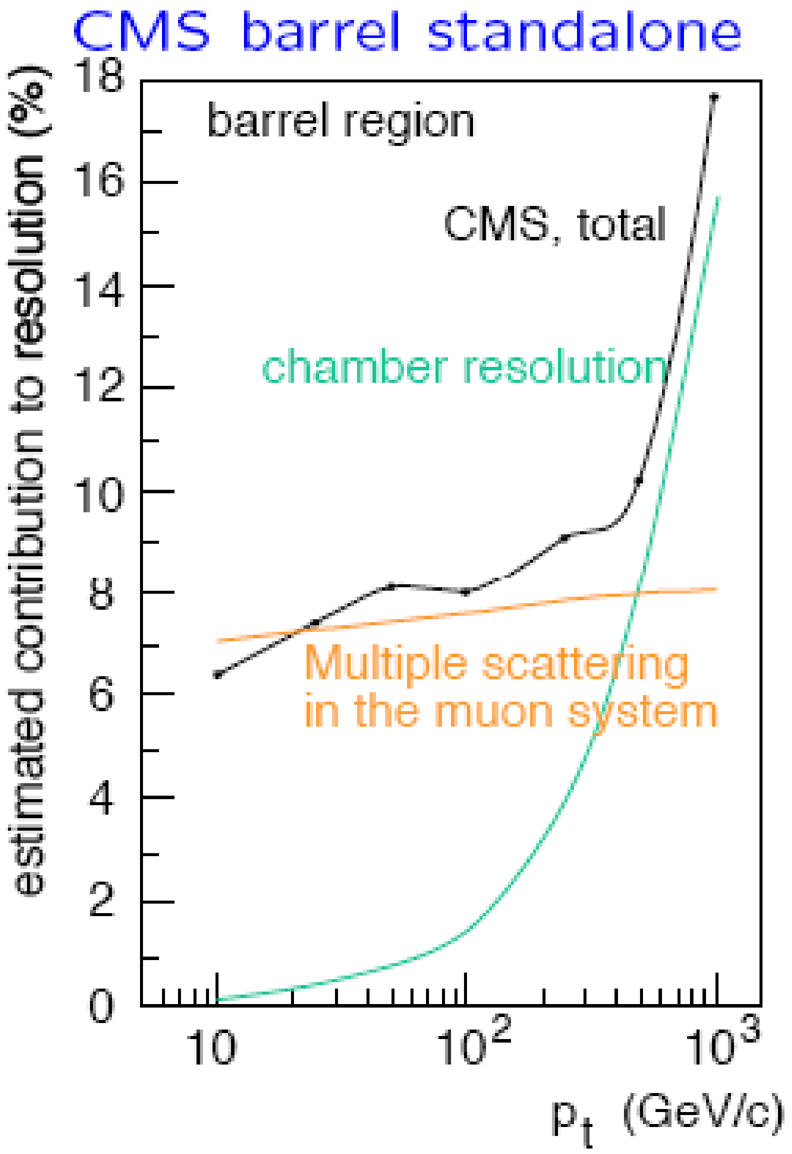
p_t = 3.5, 4.0, 4.5, 6.0 GeV

Requirements for muon identification and reconstruction at low p_T

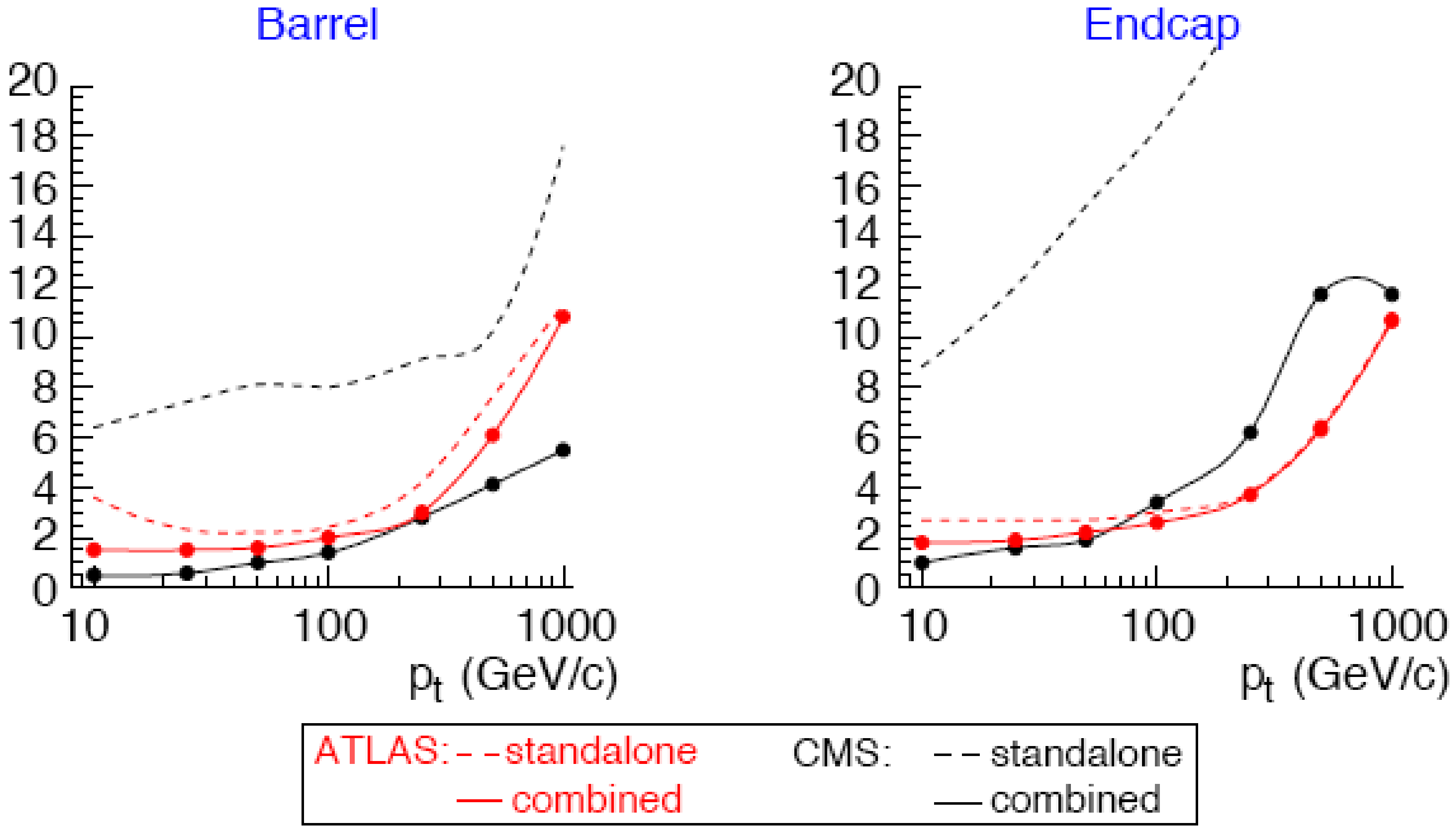
- **Identify track stub in first layer of muon system**
- **Check for minimum ionising signals in last layers of hadron calorimeter**
- **Match as precisely as feasible (within limitations due to large MS and energy loss in calorimetry) measured track in inner detector with track stub in muon system**

ATLAS/CMS: muon measurements and





ATLAS/CMS: muon measurements and



ATLAS/CMS: L1 trigger rates at L = 2 10^{33}

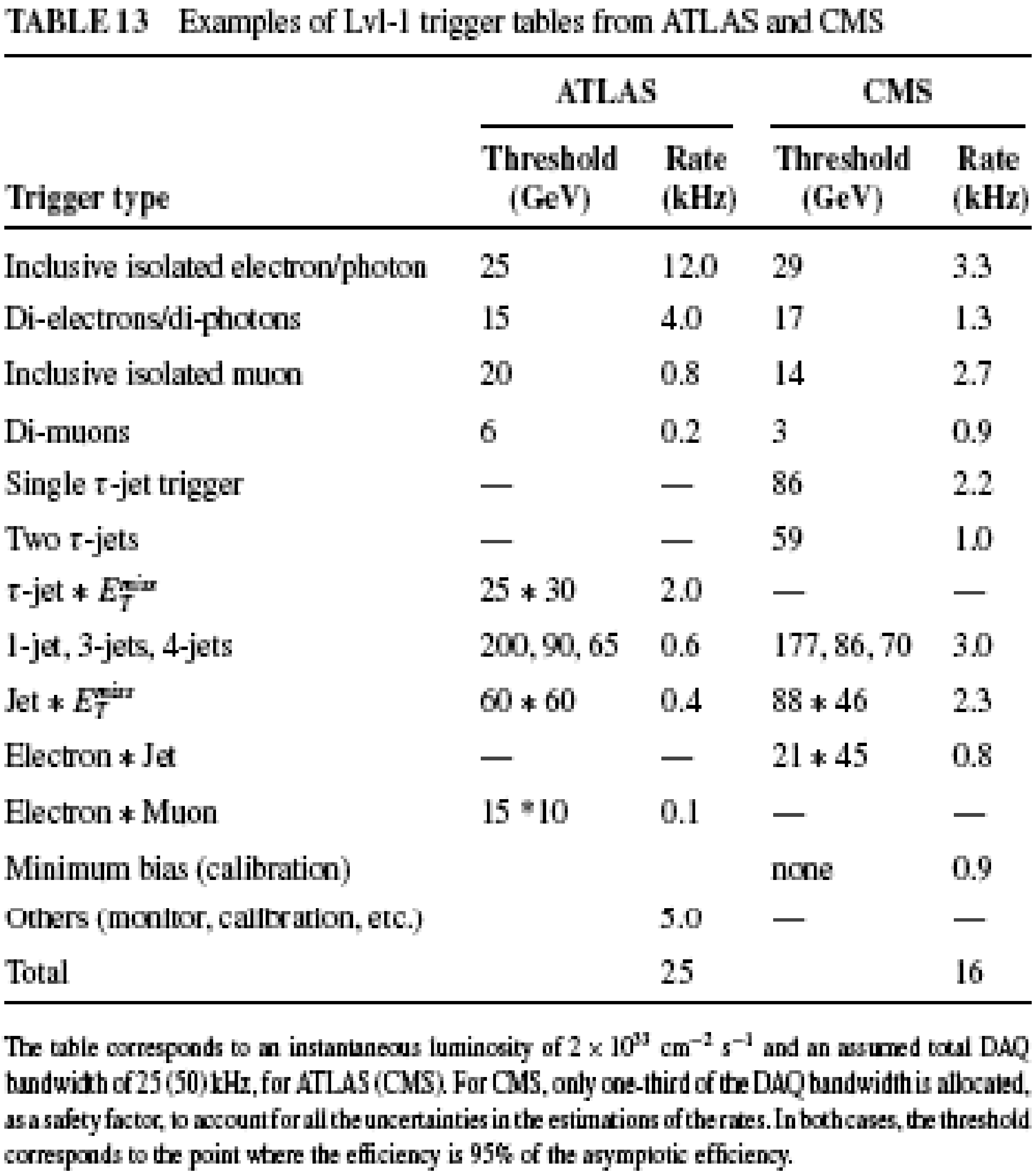


TABLE 13 Examples of Lvl-1 trigger tables from ATLAS and CMS

	ATLAS		CMS	
Trigger type	Threshold (GeV)	Rate (kHz)	Threshold (GeV)	Rate (kHz)
Inclusive isolated electron/photon	25	12.0	29	3.3
Di-electrons/di-photons	15	4.0	17	1.3
Inclusive isolated muon	20	0.8	14	2.7
Di-muons	6	0.2	3	0.9
Single τ-jet trigger	—	—	86	2.2
Two τ-jets	—	—	59	1.0
τ-jet $*$ E_T^{miss}	25 $*$ 30	2.0	—	—
1-jet, 3-jets, 4-jets	200, 90, 65	0.6	177, 86, 70	3.0
Jet $*$ E_T^{miss}	60 $*$ 60	0.4	88 $*$ 46	2.3
Electron $*$ Jet	—	—	21 $*$ 45	0.8
Electron $*$ Muon	15 *10	0.1	—	—
Minimum bias (calibration)			none	0.9
Others (monitor, calibration, etc.)		5.0	—	—
Total		25		16

The table corresponds to an instantaneous luminosity of 2×10^{33} cm^{-2} s^{-1} and an assumed total DAQ bandwidth of 25 (50) kHz, for ATLAS (CMS). For CMS, only one-third of the DAQ bandwidth is allocated, as a safety factor, to account for all the uncertainties in the estimations of the rates. In both cases, the threshold corresponds to the point where the efficiency is 95% of the asymptotic efficiency.

A few words about trigger

L1 runs from calo and muons only (unlike CDF/D0!)

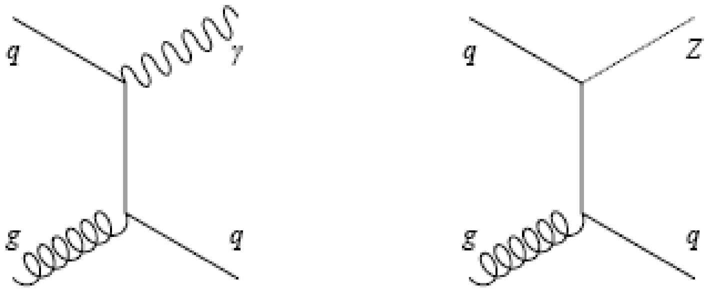
Jet trigger thresholds defined by luminosity and multiplicity

Muon and electron trigger thresholds defined by physics (heavy flavours and W/Z)

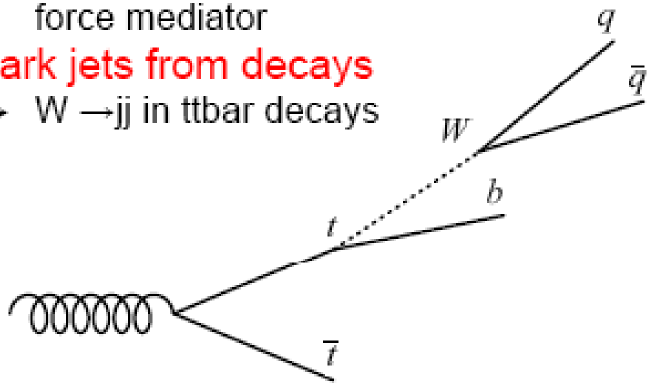
Hadronic τ and E_T^{miss} trigger thresholds defined by physics only when combined topologically with other trigger (e.g. τ x E_T^{miss} for W to τ and lepton x τ for Z/H to $\tau\tau$

LHC environment: jet signatures

- ☐ Jets at LHC
  - ❖ gluon jets from parton scattering
    - ➢ mostly in (lower Pt) QCD 2→2 processes
  - ❖ quark jets from parton scattering
    - ➢ high end Pt in QCD 2→2 processes
    - ➢ dominant prompt photon channel, Z+jet, …

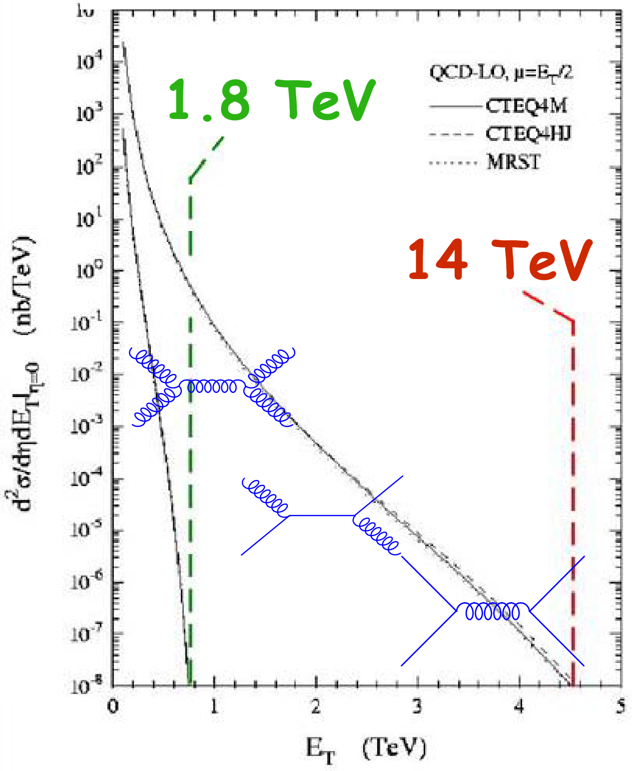


    - ➢ final state in extra dimension models with graviton force mediator
  - ❖ quark jets from decays
    - ➢ W →jj in ttbar decays



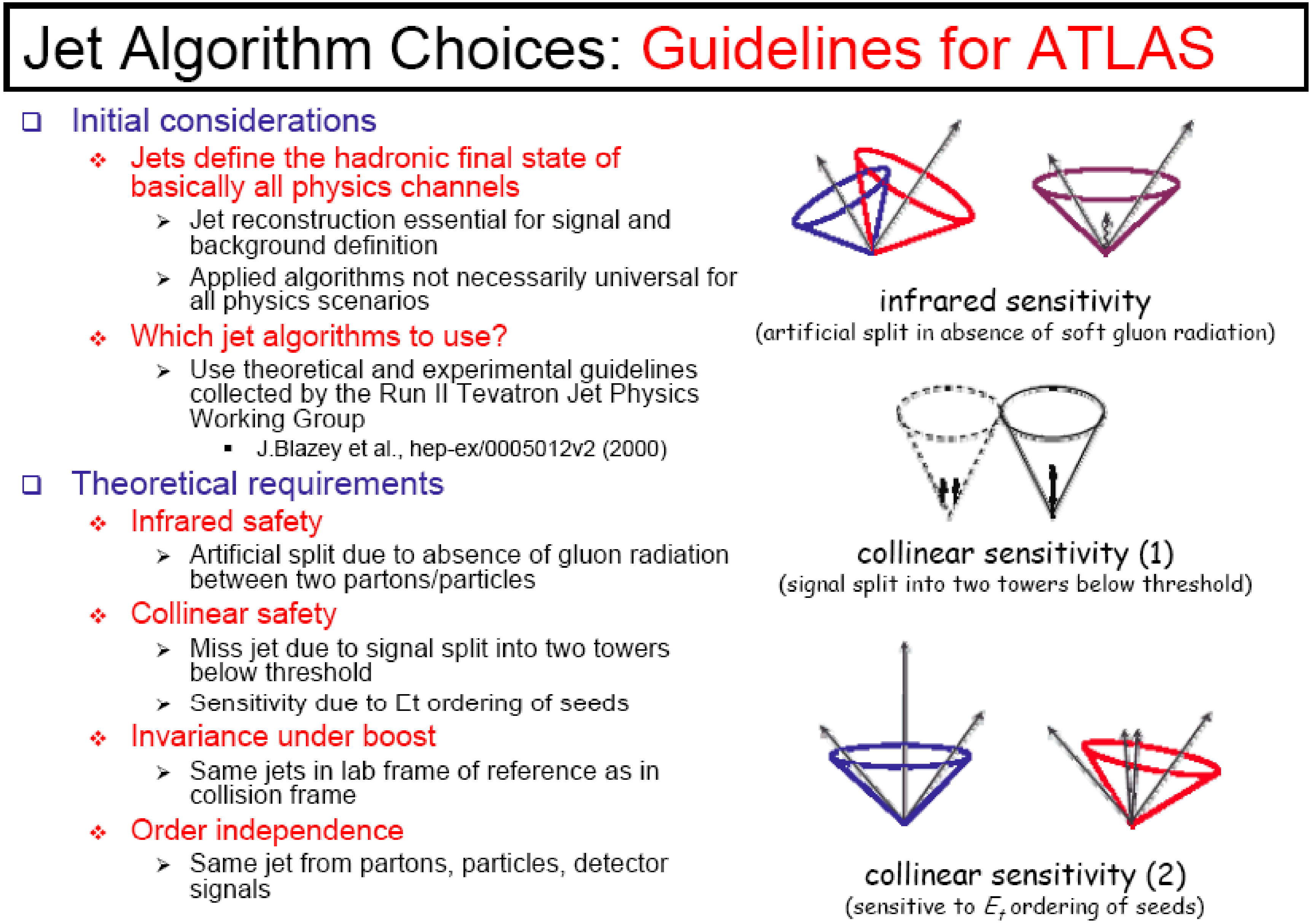
    - ➢ end of long decay chains in SUSY and exotic (ultra-heavy) particle production, like leptoquarks

Inclusive jet cross-section



Multitude of "jet flavours" generated in *pp* collisions at LHC
→ expect corresponding variety of jet shapes with (possibly) specific calibrations!

LHC environment: jet signatures



Jet Algorithm Choices: Guidelines for ATLAS

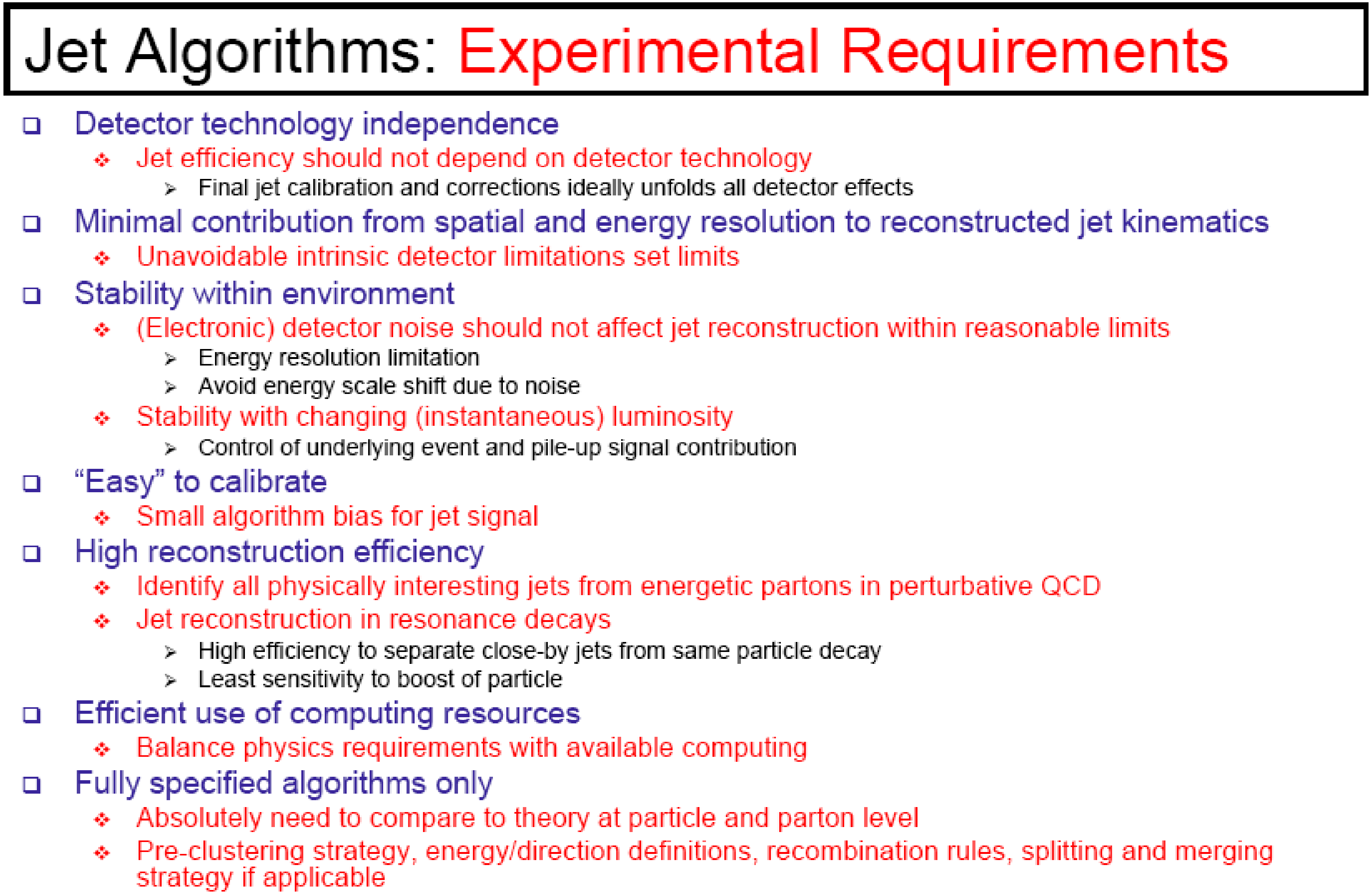
- ❑ Initial considerations
  - Jets define the hadronic final state of basically all physics channels
    - Jet reconstruction essential for signal and background definition
    - Applied algorithms not necessarily universal for all physics scenarios
  - Which jet algorithms to use?
    - Use theoretical and experimental guidelines collected by the Run II Tevatron Jet Physics Working Group
      - J.Blazey et al., hep-ex/0005012v2 (2000)
- ❑ Theoretical requirements
  - Infrared safety
    - Artificial split due to absence of gluon radiation between two partons/particles
  - Collinear safety
    - Miss jet due to signal split into two towers below threshold
    - Sensitivity due to Et ordering of seeds
  - Invariance under boost
    - Same jets in lab frame of reference as in collision frame
  - Order independence
    - Same jet from partons, particles, detector signals

infrared sensitivity
(artificial split in absence of soft gluon radiation)

collinear sensitivity (1)
(signal split into two towers below threshold)

collinear sensitivity (2)
(sensitive to E_t ordering of seeds)

LHC environment: jet signatures



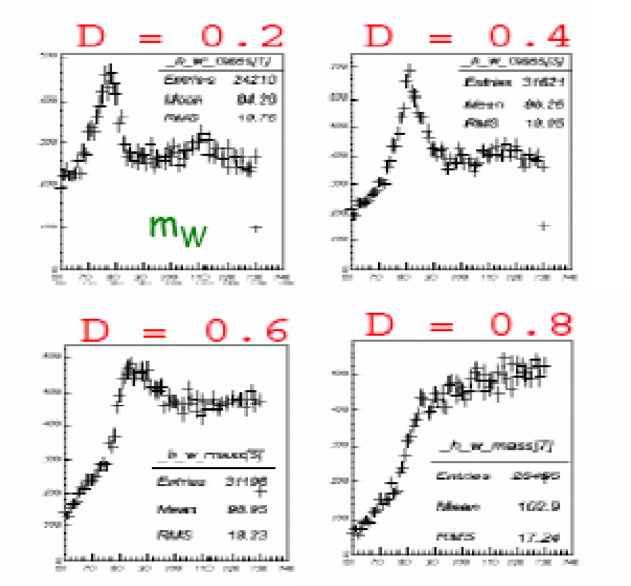
Jet Algorithms: Experimental Requirements

- Detector technology independence
  - Jet efficiency should not depend on detector technology
    - Final jet calibration and corrections ideally unfolds all detector effects
- Minimal contribution from spatial and energy resolution to reconstructed jet kinematics
  - Unavoidable intrinsic detector limitations set limits
- Stability within environment
  - (Electronic) detector noise should not affect jet reconstruction within reasonable limits
    - Energy resolution limitation
    - Avoid energy scale shift due to noise
  - Stability with changing (instantaneous) luminosity
    - Control of underlying event and pile-up signal contribution
- "Easy" to calibrate
  - Small algorithm bias for jet signal
- High reconstruction efficiency
  - Identify all physically interesting jets from energetic partons in perturbative QCD
  - Jet reconstruction in resonance decays
    - High efficiency to separate close-by jets from same particle decay
    - Least sensitivity to boost of particle
- Efficient use of computing resources
  - Balance physics requirements with available computing
- Fully specified algorithms only
  - Absolutely need to compare to theory at particle and parton level
  - Pre-clustering strategy, energy/direction definitions, recombination rules, splitting and merging strategy if applicable

LHC environment: jet signatures

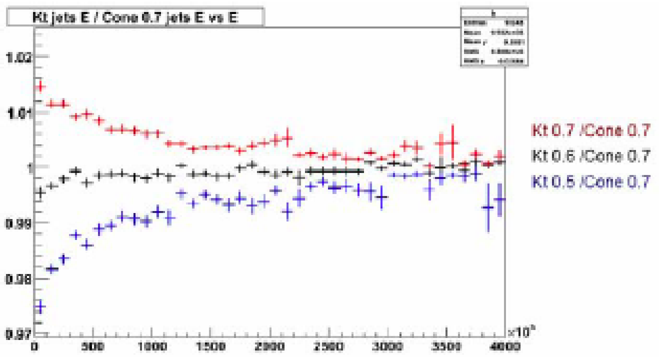
Jet Finders in ATLAS: Algorithm Parameters

- Adjust parameters to physics needs
  - Mass spectroscopy W →jj in ttbar needs narrow jets
    - Generally narrow jets preferred in busy final states like SUSY
    - Increased resolution power for final state composition
  - QCD jet cross section measurement prefers wider jets
    - Important to capture all energy from the scattered parton
- Common configuration
  - ATLAS, CMS, theory
    - J.Huston is driving this
  - Likely candidate two-pass mid-point
    - Chosen on the base of least objections
    - Some concerns about properties (esp. infrared safety)
    - Second pass should reduce problem with missing signal



N.Godbhane, JetRec Phone Conf. June 2006

Algorithm	Cone Size R	Distance D	Clients
Seeded Cone	0.4	🟩	W mass spectroscopy, top physics
Kt	🟩	0.4	
Seeded Cone	0.7	🟩	QCD, jet cross-sections
Kt	🟩	0.6	

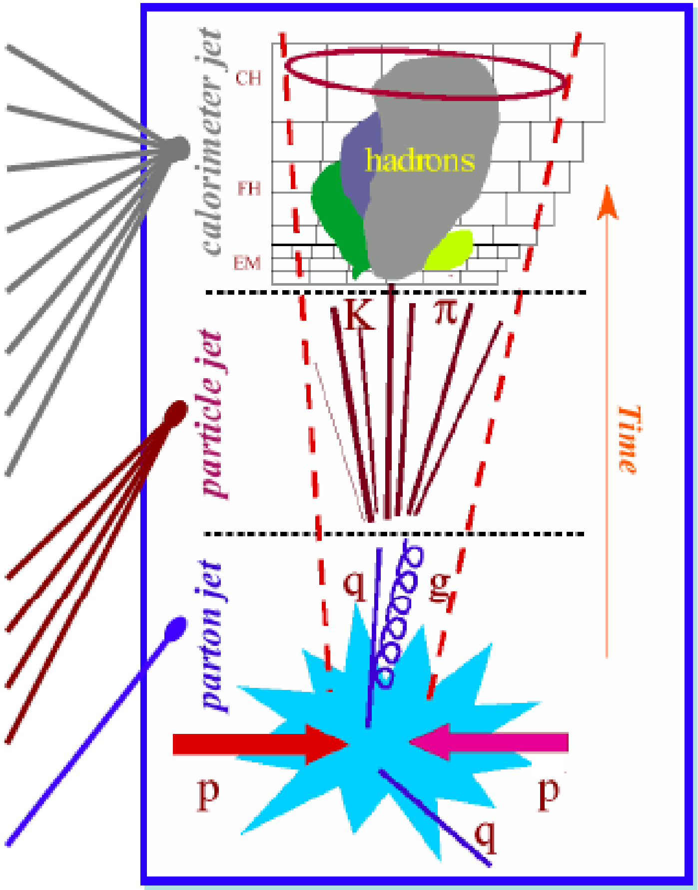


P.-A. Delsart, JetRec Phone Conf. June 28, 2006

LHC environment: jet signatures

Jet reconstruction and calibration strategy

❑ Contributions to the jet signal:



longitudinal energy leakage
detector signal inefficiencies (dead channels, HV…)
pile-up noise from (off-time) bunch crossings
electronic noise
calo signal definition (clustering, noise suppression ,…)
dead material losses (front, cracks, transitions…)
detector response characteristics (e/h ≠ 1)
jet reconstruction algorithm efficiency

jet reconstruction algorithm efficiency
added tracks from in-time (same trigger) pile-up event
added tracks from underlying event
lost soft tracks due to magnetic field

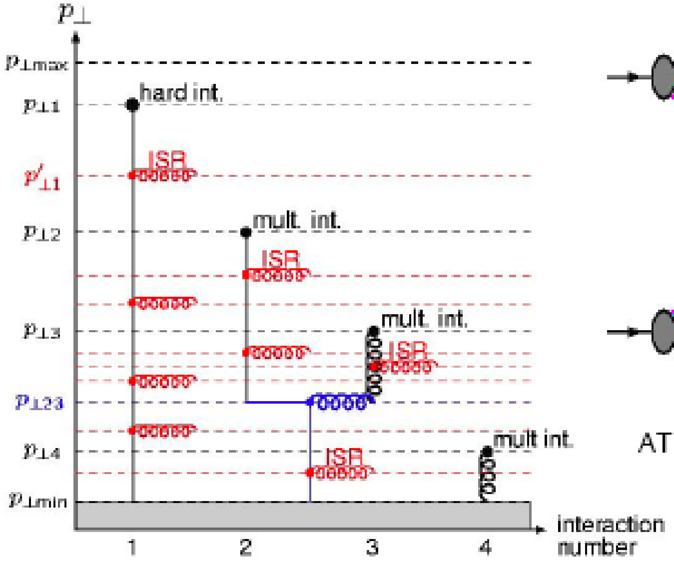
physics reaction of interest (parton level)

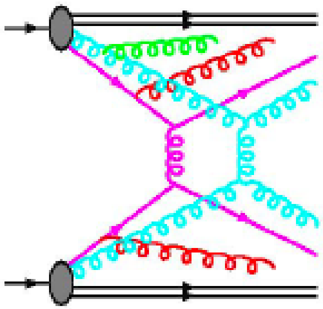
❑ Try to address reconstruction and calibration through different levels of factorization

LHC environment: underlying event

- Distortion of hadronic final state signals (1)
  - Underlying event
    - collisions of partons from both p remnants
      - in-time collisions produce (soft) particles
      - some correlation with hard scatter
      - generates Et flow “perpendicular” to hard scatter → experimental estimates?
    - background to jet and missing Et signals
      - Et balanced → distorts missing Et resolution
      - generates Et flow around hard scatter → signal shift (up) for jets
      - fake jets not related to hard scatter
      - Et flow in transverse region in QCD 2→2 processes estimates activity

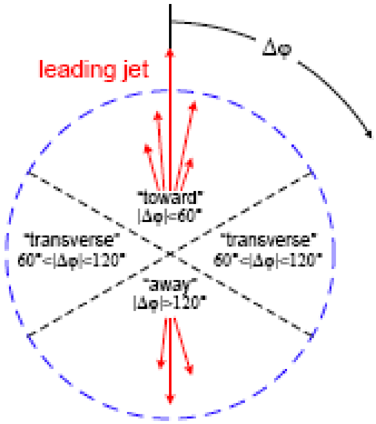
Interleaved Multiple Interactions

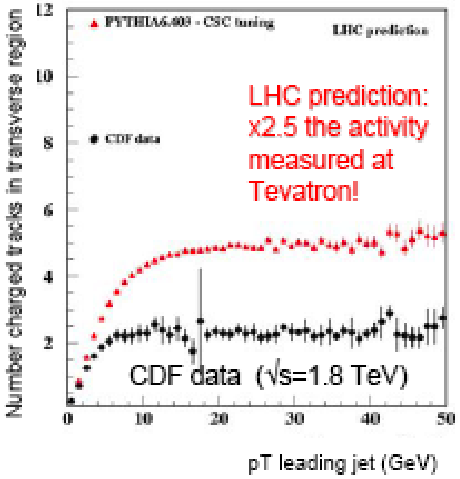




A.Moraes, ATLAS-UK SM Mtg Sept. 2005

CDF data: Phys.Rev, D, 65 (2002)



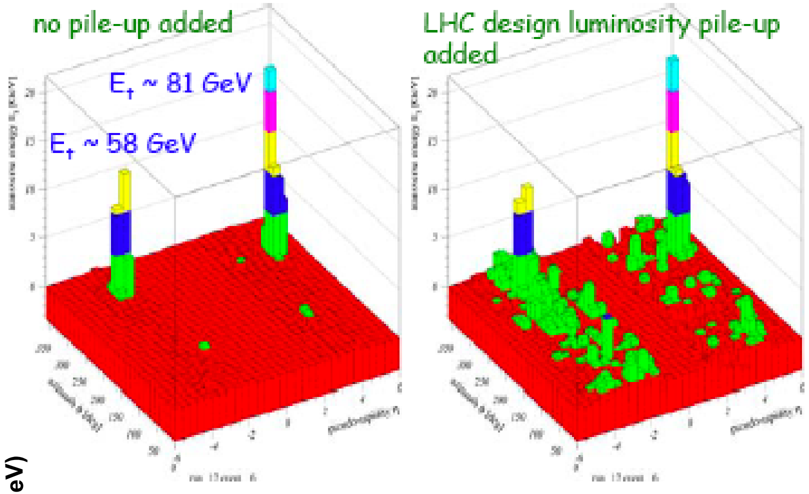


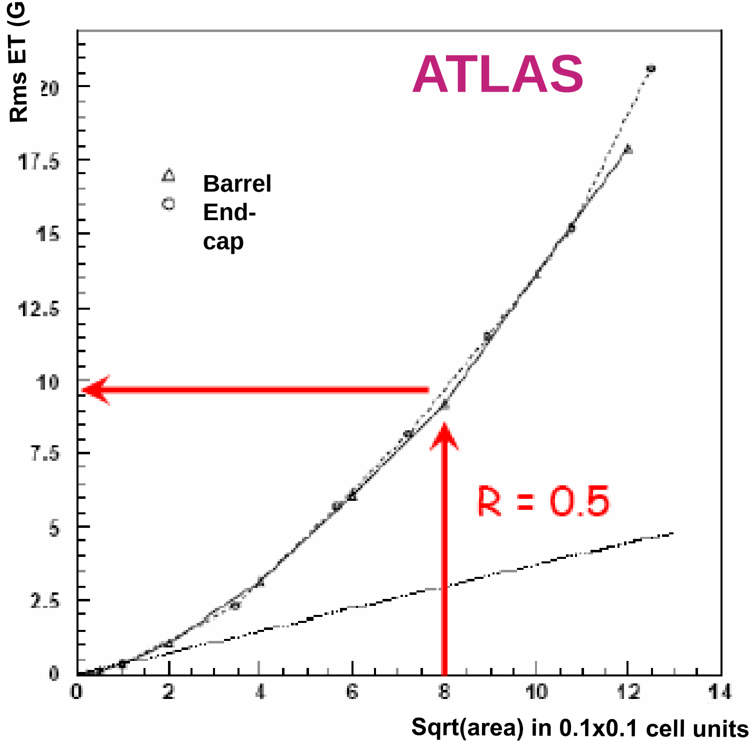
LHC prediction: x2.5 the activity measured at Tevatron!

A.Moraes, HERA-LHC Workshop, DESY, March 2007

LHC environment: pile-up

- Distortion of hadronic final states (2)
  - Pile-up
    - Minimum/zero bias (MB) collisions
      - same (non-perturbative) QCD dynamics as UE
      - no correlation with hard scatter
    - Depends on instantaneous luminosity
      - average ~25 statistically independent collisions/bunch crossing @ 10^{34}, 2.5 @10^{33}, 0.025 @ 10^{31}cm^{-2}s^{-1}…
    - Jet signals
      - signal bias ~ jet area;
      - signal fluctuations ~10 GeV RMS (Et) for R=0.5 cone jets @ 10^{34}cm^{-2}s^{-1}
    - Missing Et
      - signal bias depending on calculation strategy
      - major resolution contribution



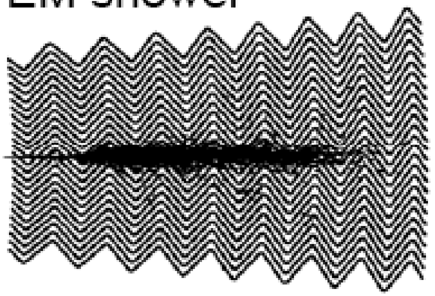


P. Savard et al, ATLAS-CAL-NO 084/1996

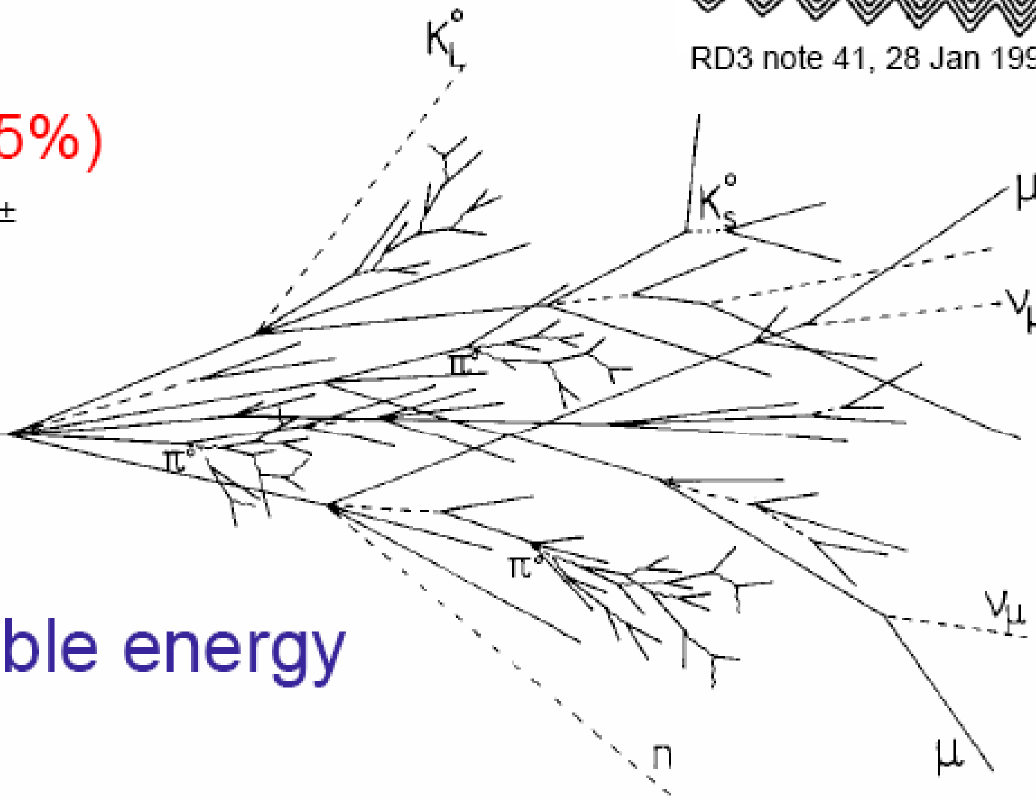
Jet reconstruction: hadronic showers

- ❑ More complex than EM showers
  - visible EM O(50%)
    - $e^{\pm}$, γ, $\pi^{o}\to\gamma\gamma$
  - visible non-EM O(25%)
    - ionization of $\pi^{\pm}$, p, $\mu^{\pm}$
  - invisible O(25%)
    - nuclear break-up
    - nuclear excitation
  - escaped O(2%)
- ❑ Only part of the visible energy is sampled

EM shower



RD3 note 41, 28 Jan 1993



Grupen, Particle Detectors

Jet reconstruction: hadronic showers

- Each component fraction depends on energy
  - visible non-EM fraction decreases with *E*
  - pion (and jets) response non linear with *E*

$$\text{"}\pi/\text{e"} = 1-(1-\text{h/e})\left(\frac{E}{E_0}\right)^{m-1}$$

$0.80 \le m \le 0.85$
$E_0 \approx 1$ GeV for $\pi^{\pm}$
$E_0 \approx 2.6$ GeV for p

  - in ATLAS, e/h > 1 for each sub-detector
    - "e" is the intrinsic response to visible EM
    - "h" is the intrinsic response to visible non-EM
    - invisible energy is the main source of e/h > 1
- Large fluctuations of each component fraction
  - non-compensation amplifies fluctuations
- Hadronic calibration attempts to
  - provide some degree of software compensation
  - account for the invisible and escaped energy

ATLAS/CMS: calorimeter response to pions

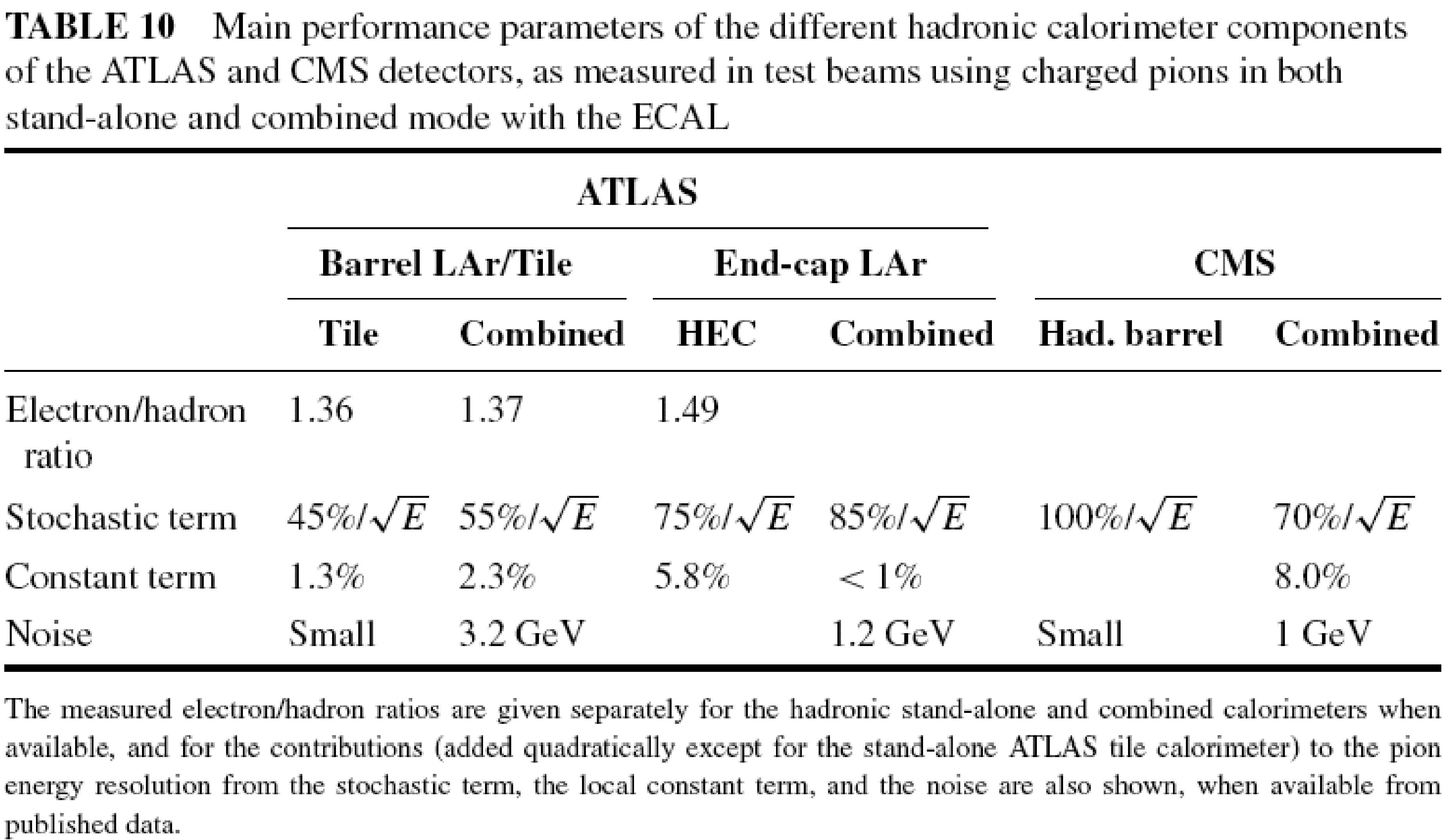


TABLE 10 Main performance parameters of the different hadronic calorimeter components of the ATLAS and CMS detectors, as measured in test beams using charged pions in both stand-alone and combined mode with the ECAL

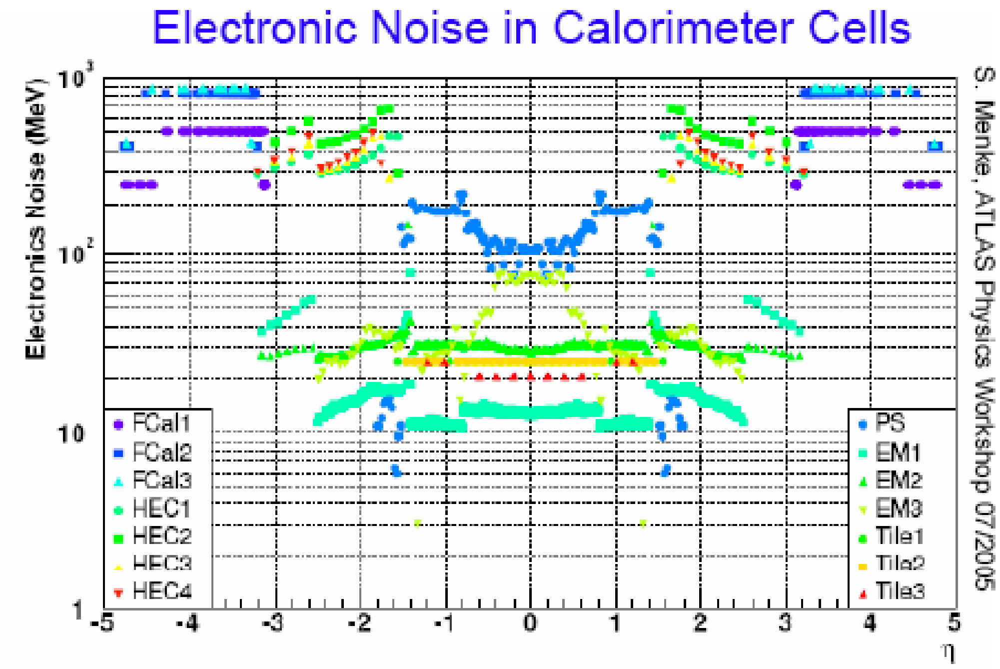
	ATLAS				**CMS**	
	Barrel LAr/Tile		**End-cap LAr**			
	Tile	**Combined**	**HEC**	**Combined**	**Had. barrel**	**Combined**
Electron/hadron ratio	1.36	1.37	1.49			
Stochastic term	$45\%/\sqrt{E}$	$55\%/\sqrt{E}$	$75\%/\sqrt{E}$	$85\%/\sqrt{E}$	$100\%/\sqrt{E}$	$70\%/\sqrt{E}$
Constant term	1.3%	2.3%	5.8%	$< 1\%$		8.0%
Noise	Small	3.2 GeV		1.2 GeV	Small	1 GeV

The measured electron/hadron ratios are given separately for the hadronic stand-alone and combined calorimeters when available, and for the contributions (added quadratically except for the stand-alone ATLAS tile calorimeter) to the pion energy resolution from the stochastic term, the local constant term, and the noise are also shown, when available from published data.

Huge effort in test-beams to measure performance of overall calorimetry with single particles and tune MC tools: not completed!

Jet reconstruction: noise (incoherent) in

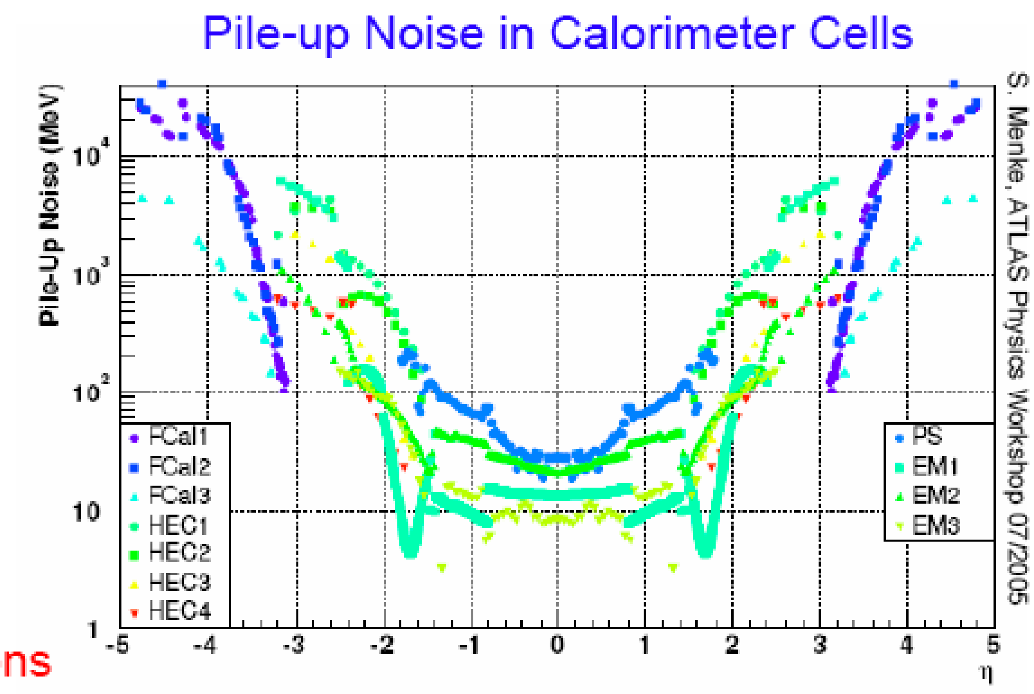
- ❑ Electronic noise
  - ❖ unavoidable basic fluctuation on top of each calorimeter cell signal, typically close to Gaussian (symmetric)



  - ❖ ranges from ~10 MeV (central region) to ~850 MeV (forward) per cell
  - ❖ independent of physics collision environment
  - ❖ coherent noise contribution in cells generated in the calorimeter and/or in the readout electronics typically much smaller than incoherent cell electronic noise
    - ➢ “fake” pile-up noise avoided

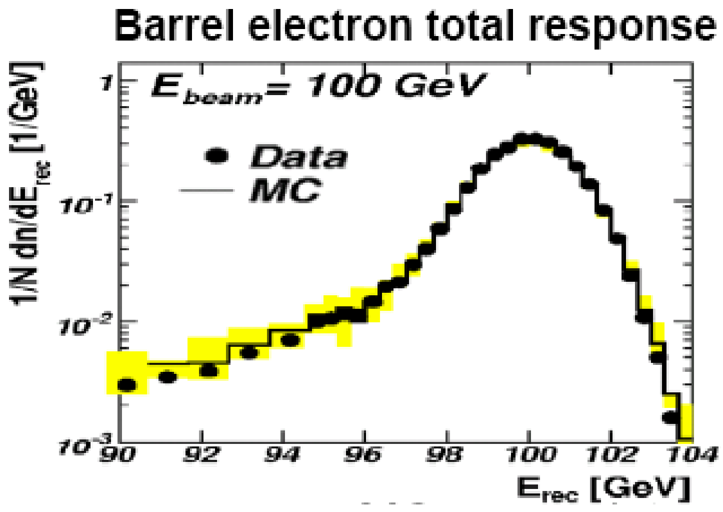
Jet reconstruction: noise (coherent) in

- Pile-up noise
  - Generated by (many) minimum bias events (MB) in physics collisions → depends on instantaneous luminosity (see earlier discussion)
  - illuminates basically the whole calorimeter
  - Major contribution to out-of-time signal history due to calorimeter shaping functions (total of ~625 MB/triggered event affect the signal @ $10^{34}cm^{-2}s^{-1}$)
    - slow charge collection in LAr calorimeters (~500ns) versus high collision frequency (25ns bunch crossing to bunch crossing) generates signal history in detector
  - Introduces asymmetric cell signal fluctuations from ~10 MeV (RMS, central region) up to ~4 GeV (RMS, forward) similar to coherent noise
    - "real" showers generated by particles in pile-up event introduce cell signal correlation leading to (large) coherent signal fluctuations

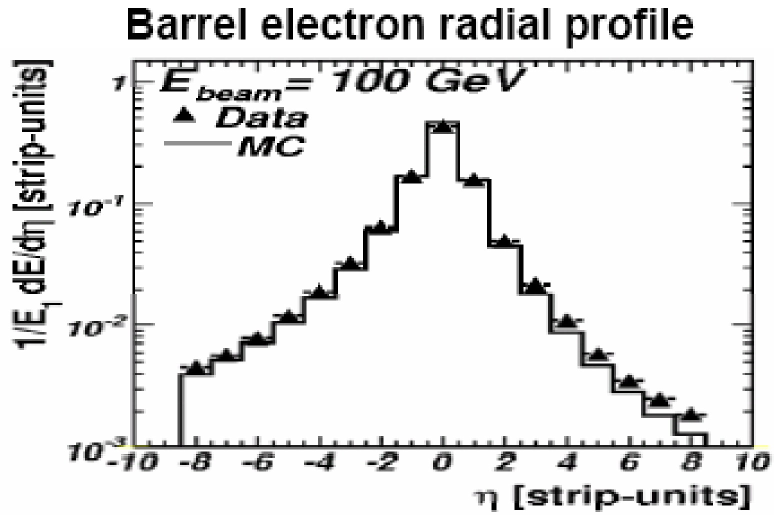


Validation of G4 with test-beam data (ATLAS)

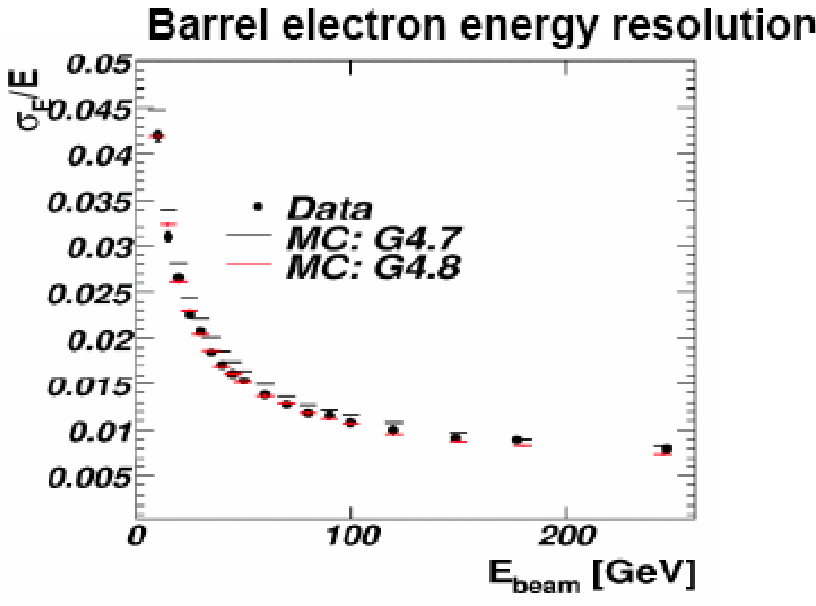
Response to EM showers for LAr barrel EM and LAr hadronic end-c



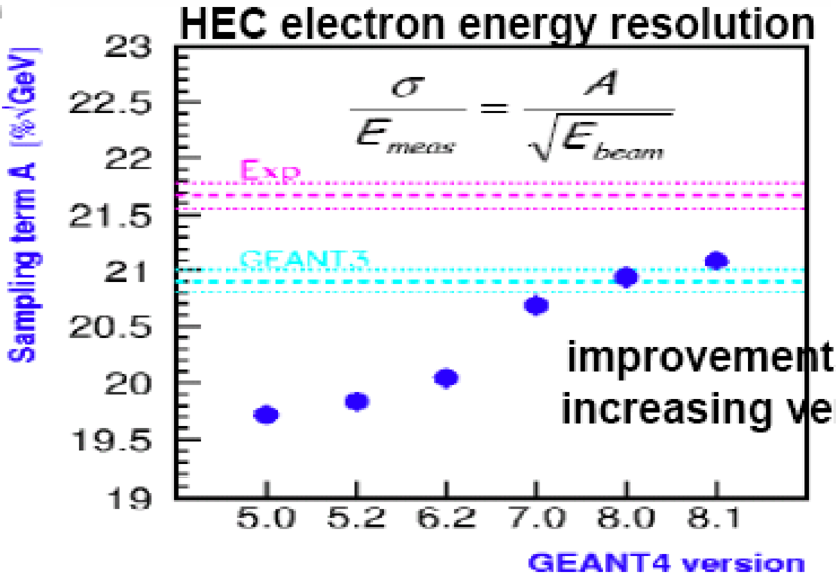
Barrel electron total response



Barrel electron radial profile



Barrel electron energy resolution



HEC electron energy resolution

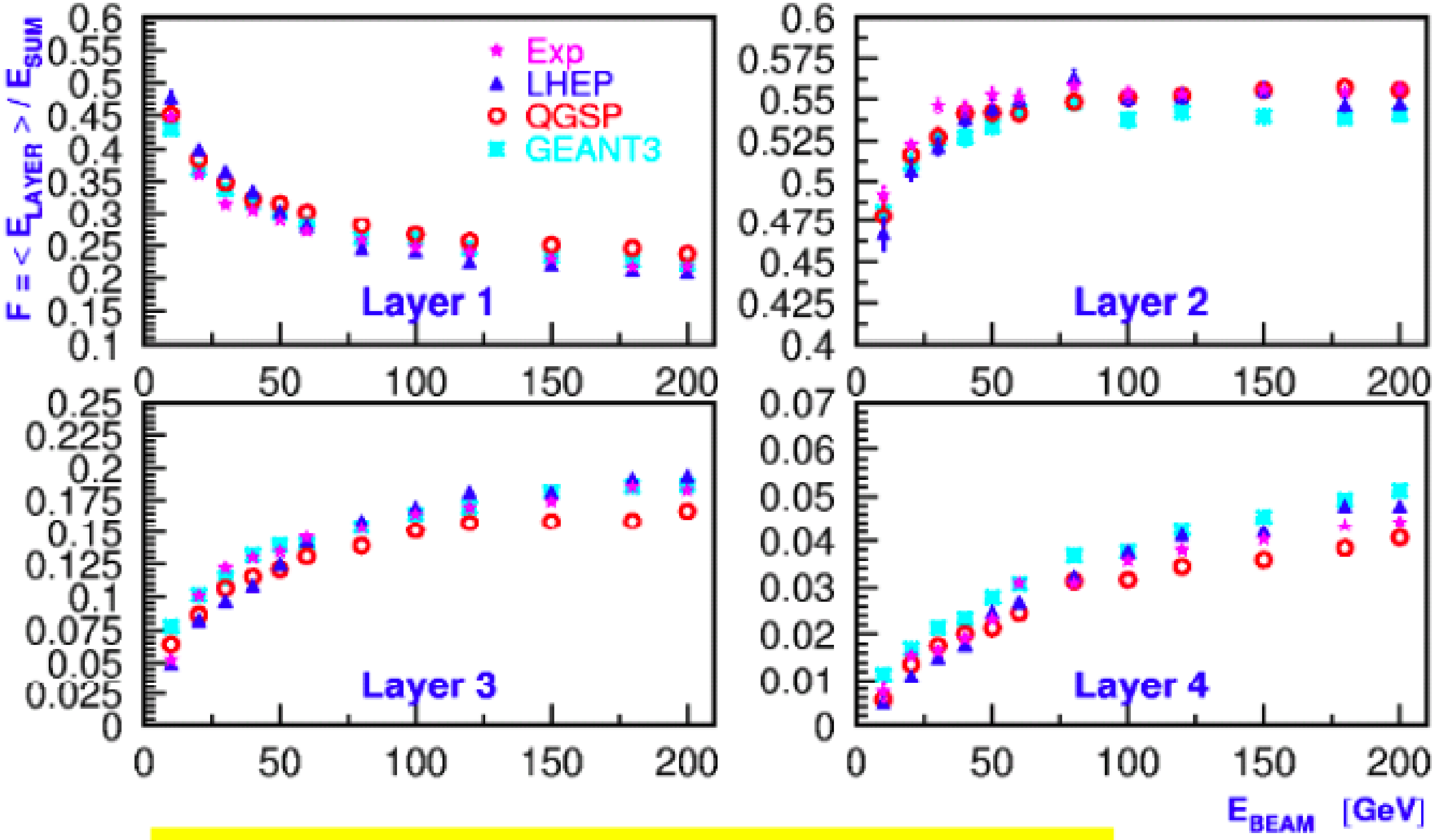
improvements with increasing version#

Validation of G4 with test-beam data (ATLAS)

Response to pion showers for LAr hadronic end-cap

pion longitudinal fractions in HEC longitudinal layers

Long. Layers: 1.5/2.9/3.0/2.8 interaction length



Largest energy in layer 2
Hadronic shower penetrates deeper as energy increases

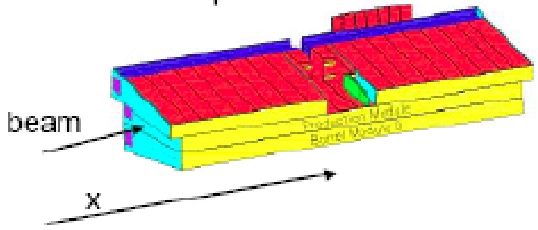
G4.81

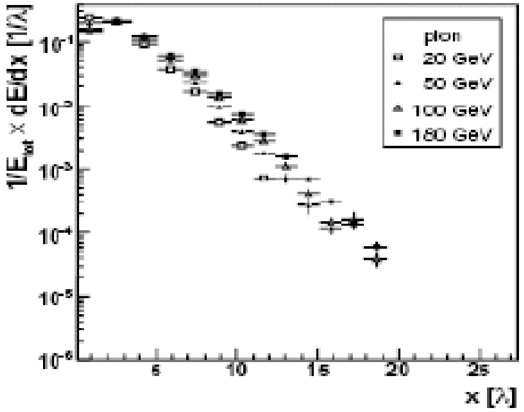
Validation of G4 with test-beam data (ATLAS)

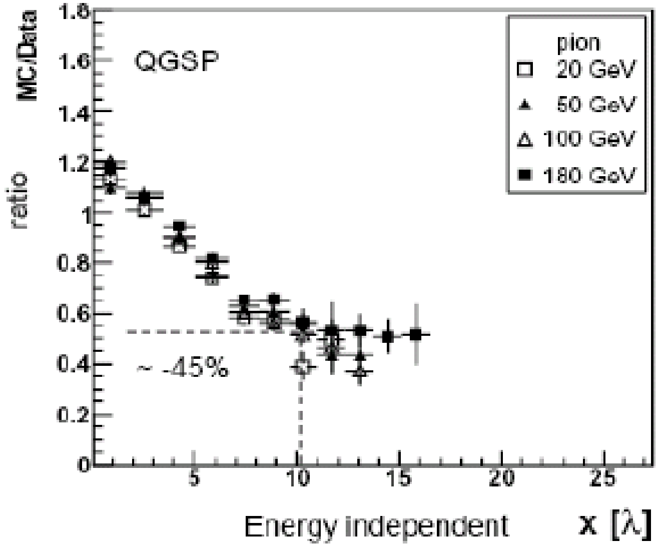
Response to pion showers for hadronic tile calorimeter (parallel to

Atlas Tile: Pion Shower Profile

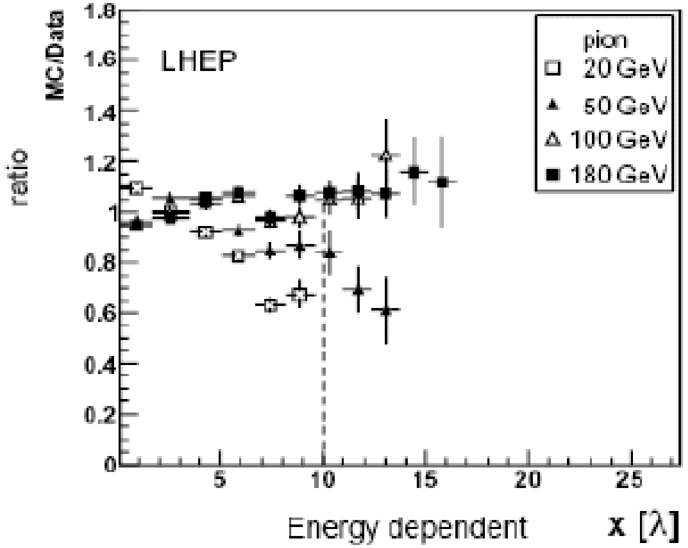
Special TB set-up:







Energy independent

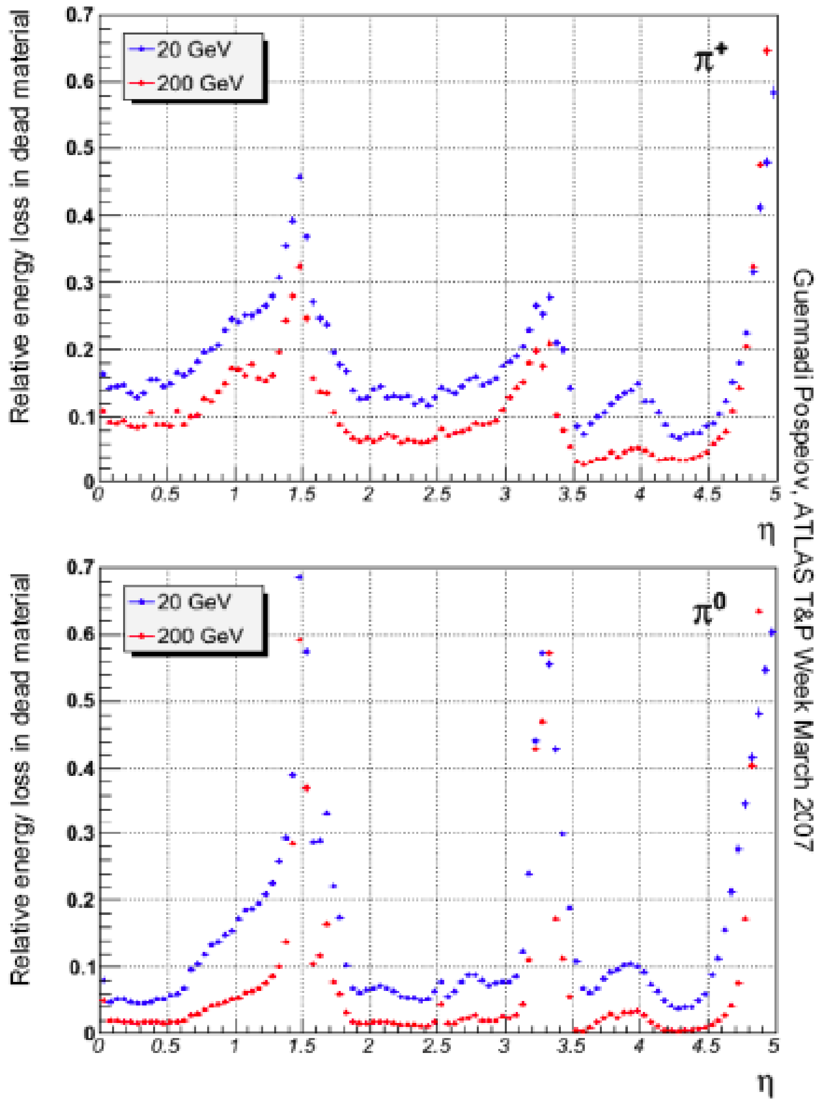


Energy dependent

- QGSP predicts too short showers.
- LHEP describes shower profile at high energies quite well.

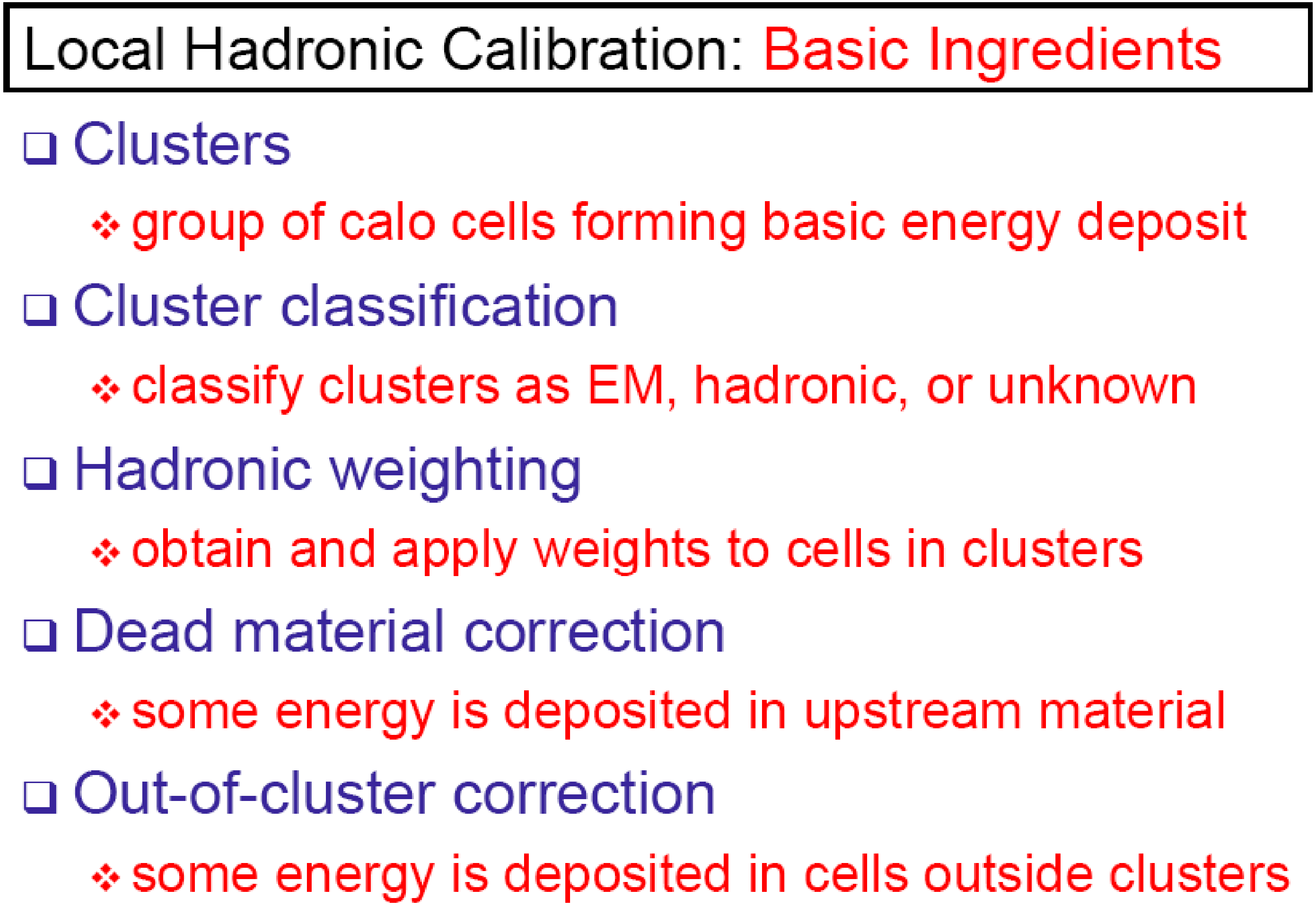
Jet reconstruction: dead material and cracks in ATLAS

- ❑ Dead material
  - Energy losses not directly measurable
    - Signal distribution in vicinity can help
  - Introduces need for signal corrections up to O(10%)
    - Exclusive use of signal features
    - Corrections depend on electromagnetic or hadronic energy deposit
  - Major contributions
    - Upstream materials
    - Material between LArG and Tile (central)
- ❑ Cracks
  - dominant sources for signal losses
    - $|\eta| \approx 1.4\text{-}1.5$
    - $|\eta| \approx 3.2$
  - Clearly affects detection efficiency for particles and jets
    - already in trigger!
    - Hard to recover jet reconstruction inefficiencies
  - Generate fake missing Et contribution
    - Topology dependence of missing Et reconstruction quality



Guennadi Pospelov, ATLAS T&P Week March 2007

Jet reconstruction: calibrated energy clusters in

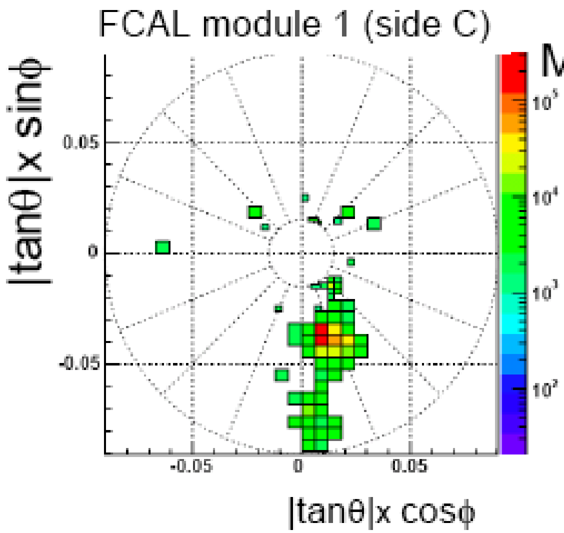


Local Hadronic Calibration: Basic Ingredients

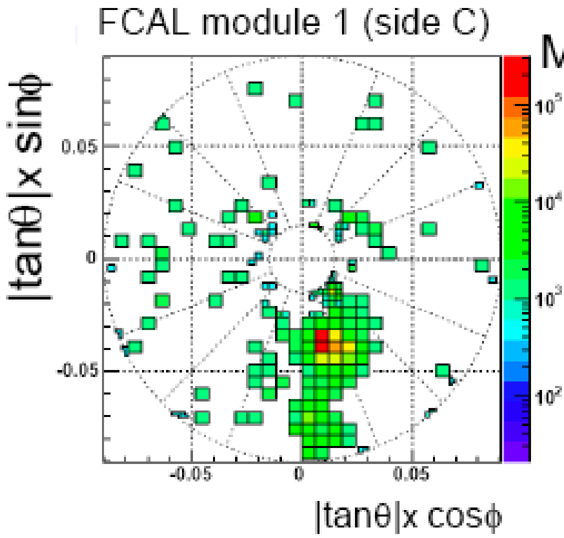
- ☐ Clusters
  - group of calo cells forming basic energy deposit
- ☐ Cluster classification
  - classify clusters as EM, hadronic, or unknown
- ☐ Hadronic weighting
  - obtain and apply weights to cells in clusters
- ☐ Dead material correction
  - some energy is deposited in upstream material
- ☐ Out-of-cluster correction
  - some energy is deposited in cells outside clusters

Jet reconstruction: calibrated energy clusters in

Sven Menke

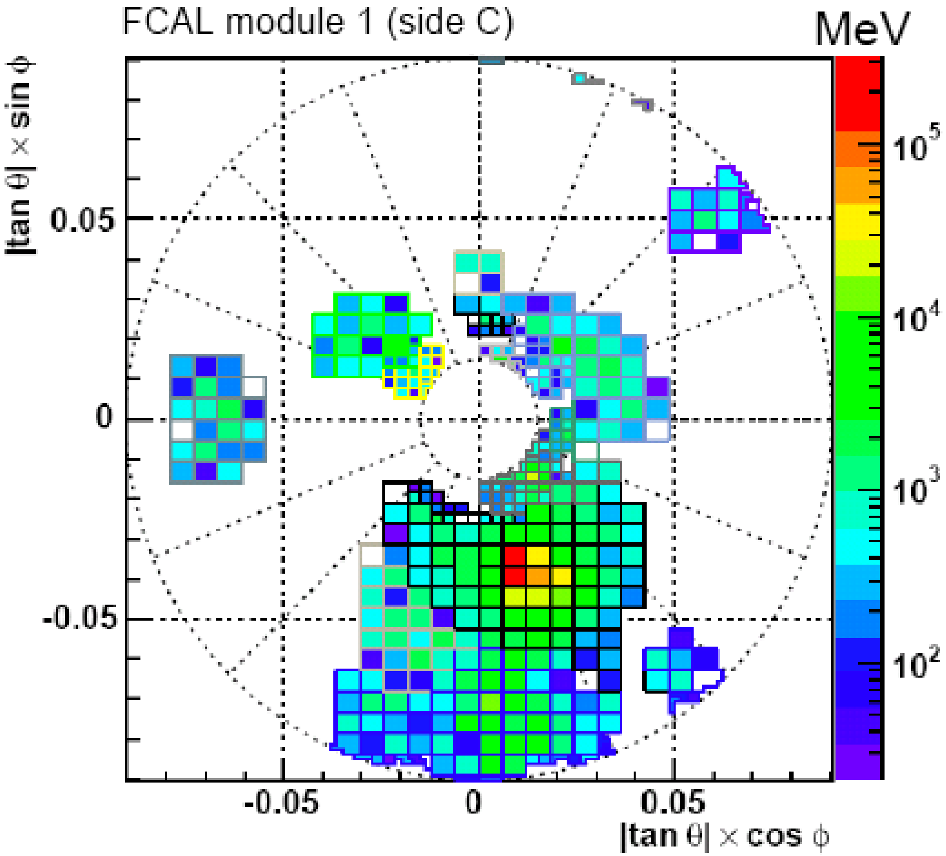


cells with $|E_{cell}|>4\sigma_{noise}$



cells with $|E_{cell}|>2\sigma_{noise}$

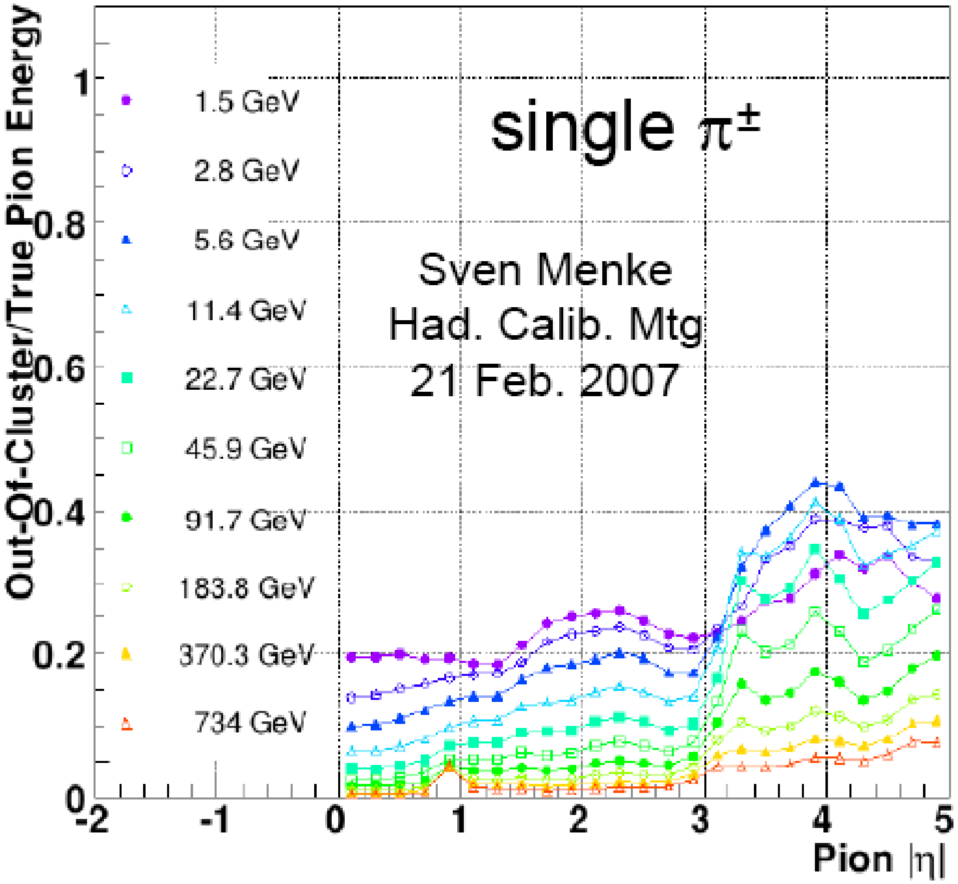
- ❑ Topological clustering
  - 4,2,0 clusters in FCal
    - jets with p_T > 50 GeV



Jet reconstruction: calibrated energy clusters in

Local Hadronic Calibration: Out-of-cluster Correction

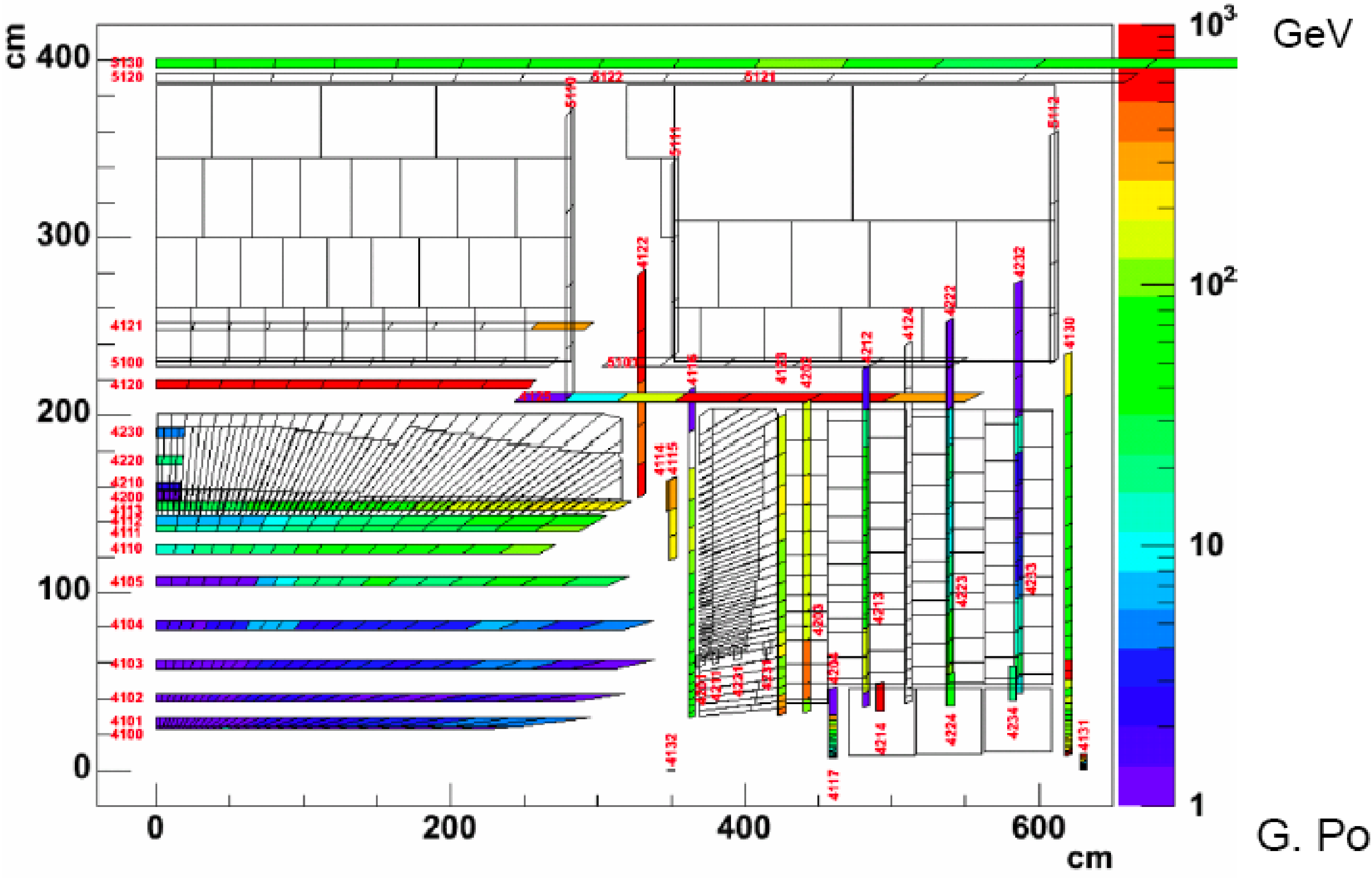
- Consider a cluster produced by a single pion
  - some energy is deposited in nearby cells not part of the cluster
    - use calib hits
- Correction factor is $\left(1+\frac{E_{OOC}}{E_{cluster}}\right)$
- Keep lookup table from $\pi^{\pm}$
  - $|\eta|$, E, λ bins



Jet reconstruction: calibrated energy clusters in

Local Hadronic Calibration: Dead Material Corrections

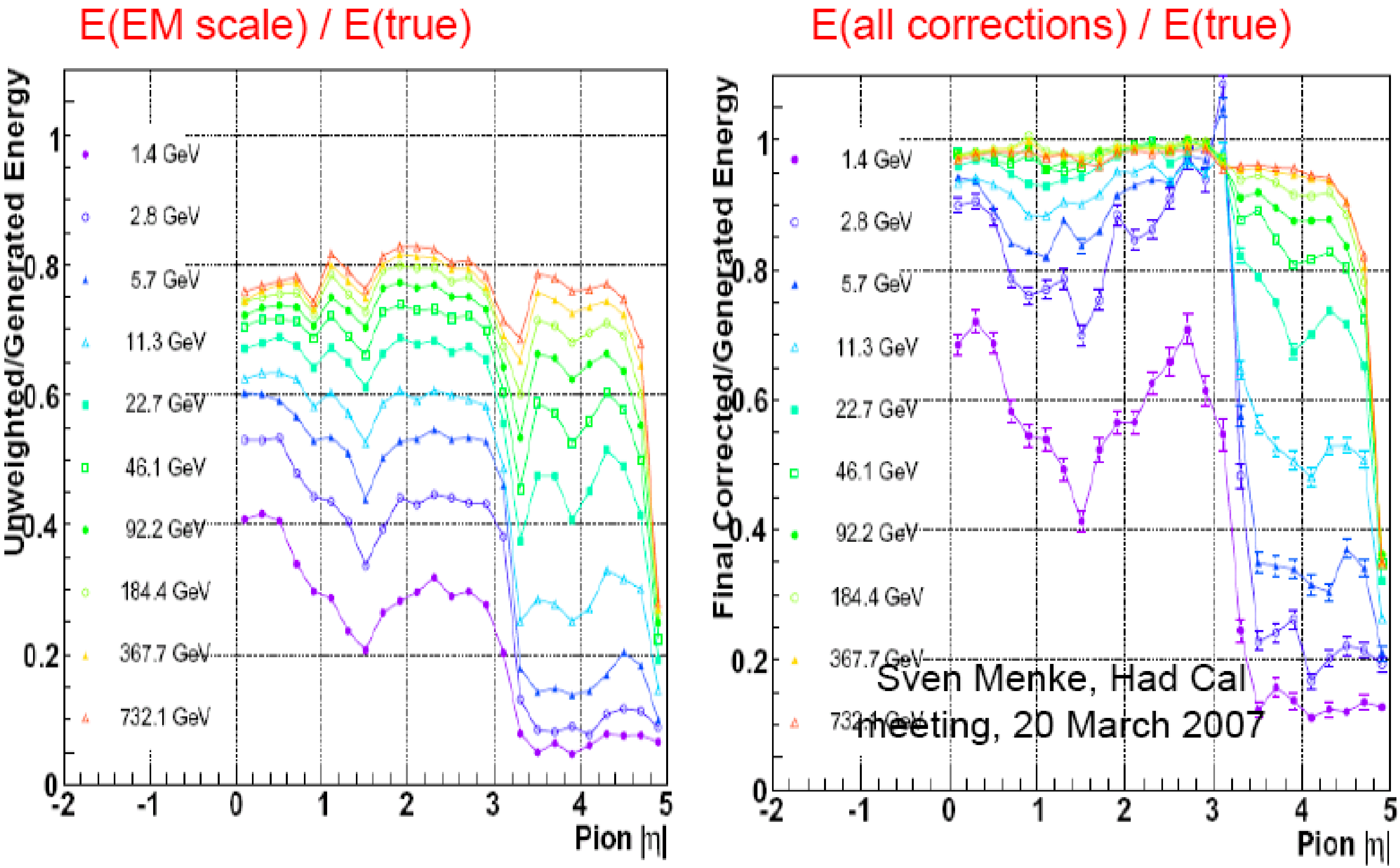
- Average energy in dead material deposited by 500 GeV single pion showers
- Generated flat in $|\eta| < 5$. Energy summed in phi in this plot.



G. Pospelov

Jet reconstruction: calibrated energy clusters in ATLAS

- Performance on single charged pions


E(EM scale) / E(true)

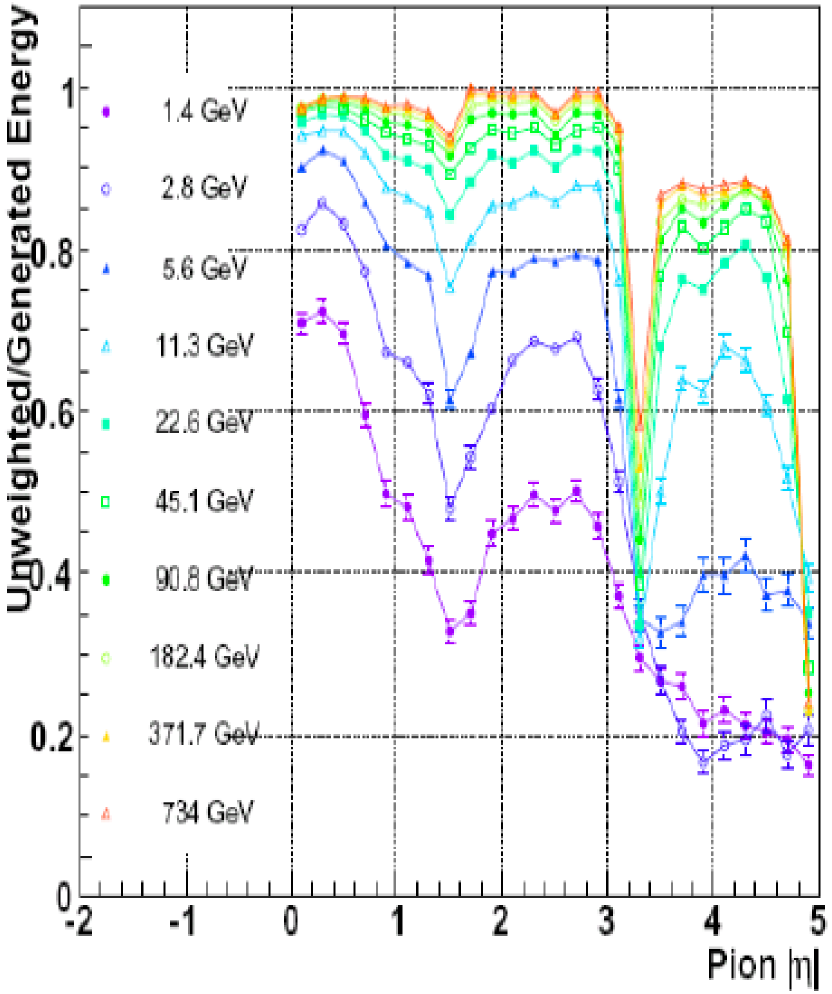
E(all corrections) / E(true)

Sven Menke, Had Cal meeting, 20 March 2007

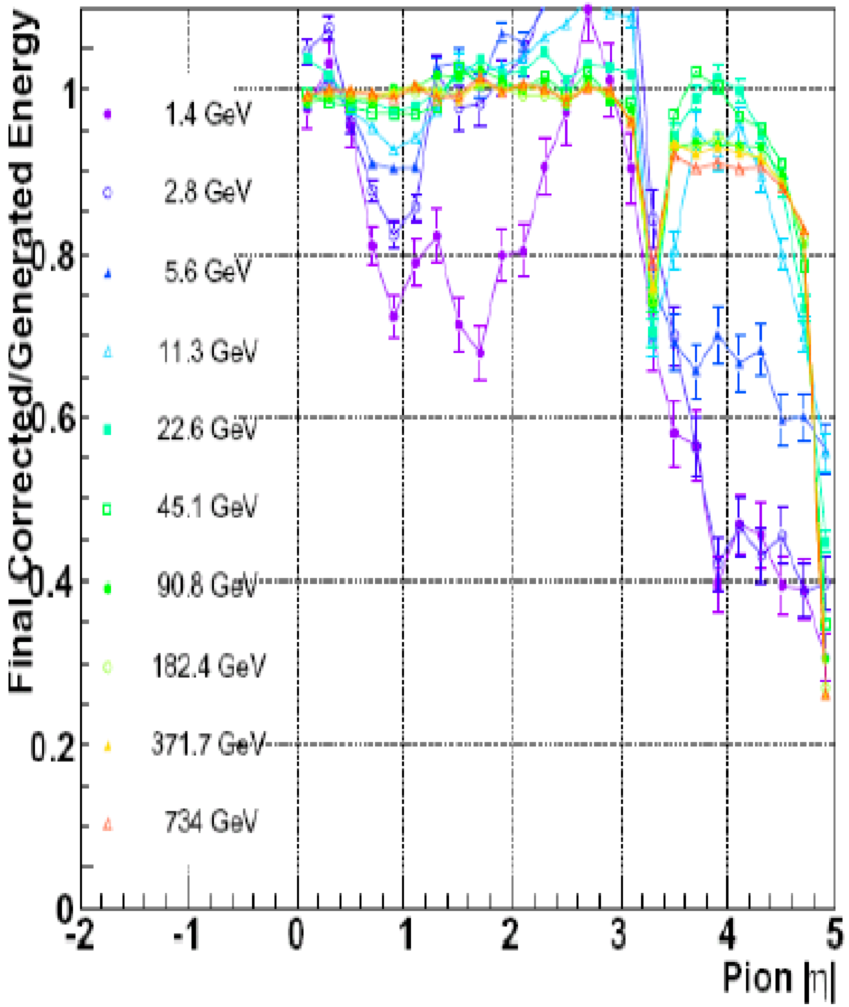
Jet reconstruction: calibrated energy clusters in ATLAS

- Performance on single neutral pions

E(EM scale) / E(true)



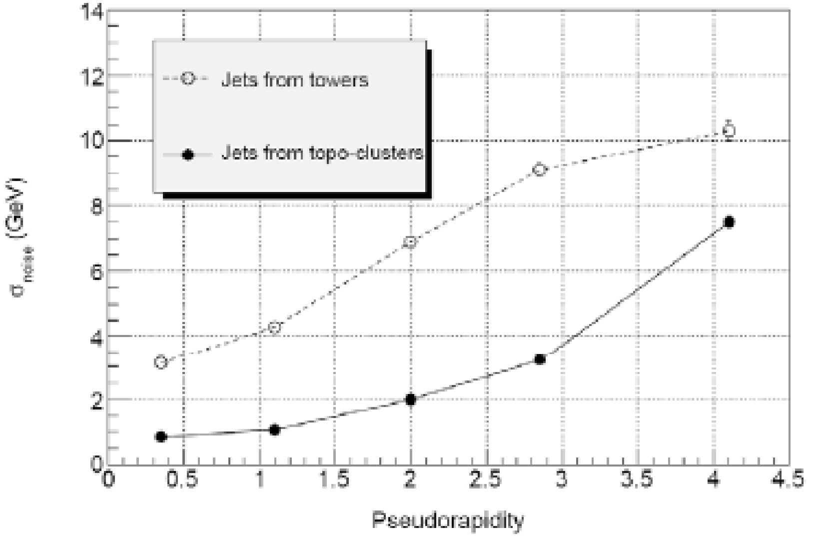
E(all corrections) / E(true)

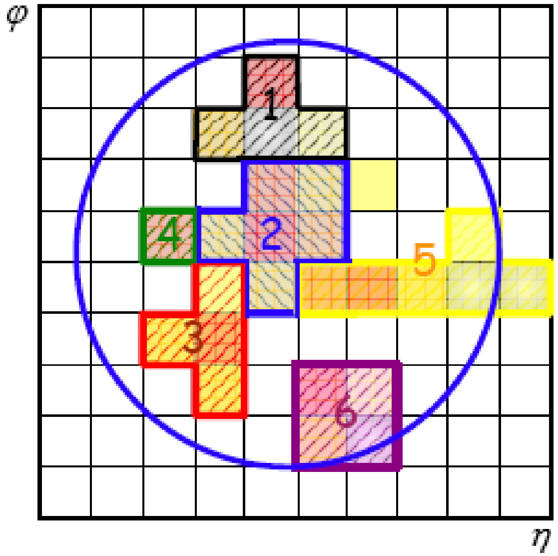


Jet reconstruction: impact of new scheme in ATLAS

- Noise in jets
  - Only electronic noise studied so far
    - Need to understand the effect in pile-up scenario
  - clear indication of significant improvement
    - Expect due to “active” noise suppression in calorimeter signal
    - Much smaller number of cells contributing to jet signal

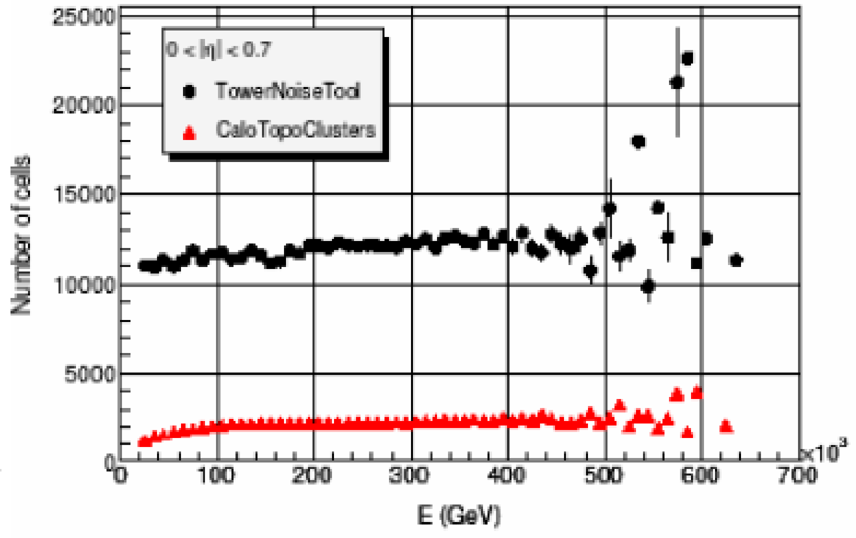
Noise in Calorimeter Jets vs Jet Rapidity





3rd Hadronic Calibration Workshop, Milan, Italy, 26-27

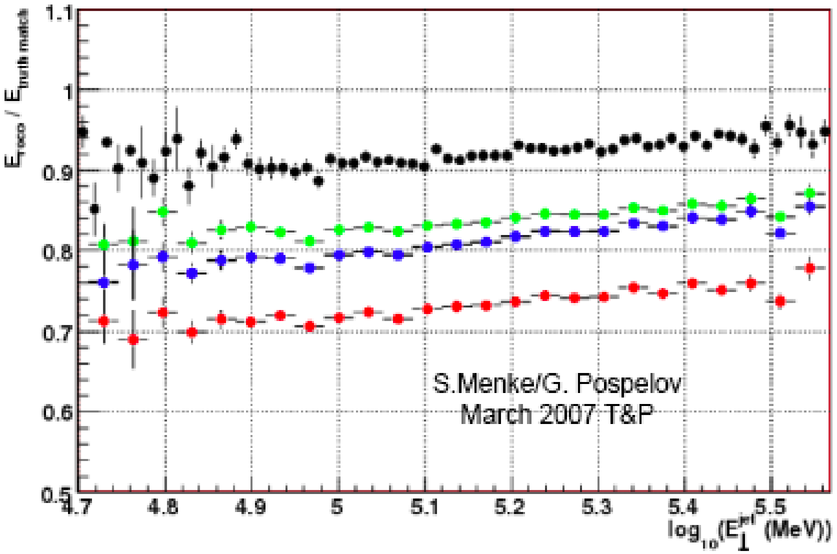
Number Cells in Calorimeter Jets vs Jet Energy

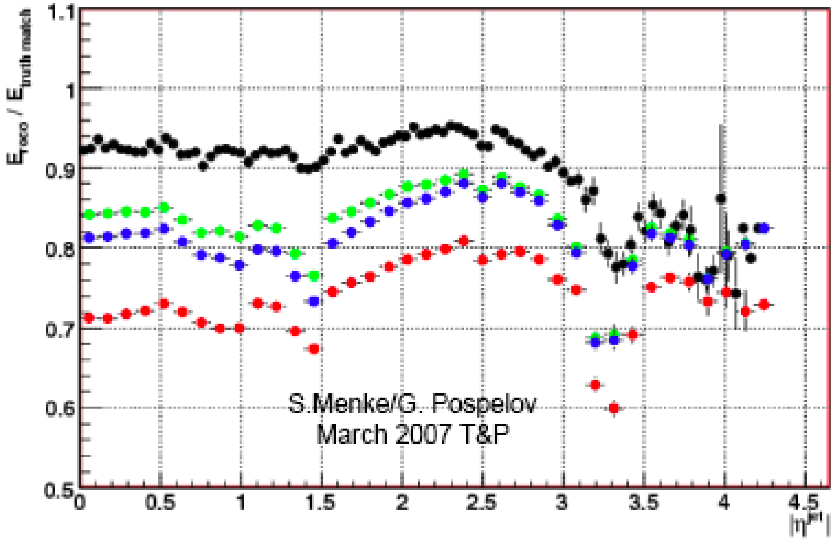


I.Vivarelli, Calorimeter Calibration Workshop, September 2006

Jet reconstruction: impact of new scheme in ATLAS

- Apply local hadronic calibration to jets
  - QCD di-jets
    - C4 sample
  - Flat response in Et within +/- 2%
    - ~50-400 GeV range
  - Rapidity dependence ok up to |η|≈2.7
    - likely em scale calibration problem in FCal
    - Dead material correction in
- Indicators
  - All calibrations and corrections derived from single particle signals alone
    - no jet context bias at all
  - Achieved high level of factorization (!!)
    - classification, weighting, dead material and out-of-cluster corrections are mutually independent derived and applied
    - all energy scale dependent observables used in look-up or parametrized functions are calculated on the electromagnetic energy scale
  - Still missing
    - calibrations for electromagnetic clusters
    - jet context driven energy scale corrections
      - Dead material losses impossible to correct at cluster level
      - Jet algorithm efficiency corrections like out-of-cone





Jets in ATLAS/CMS: conclusions

Jets are the most abundantly produced objects at the LHC and need therefore to be understood to the best of our ability for a variety of physics tasks on our to-do list over the next ten years:

- **QCD processes are interesting per se**
- **QCD corrections to SM EW processes are very large and do not always converge for specific exclusive final states as one puts in more and more higher-order processes**
- **Jets (in particular b-jets) are often amongst the decay products of both SM (top) and new physics processes**

Major and exciting effort in terms of understanding performance of calorimetry, software (energy-flow algorithms, optimisation of Etmiss calculations) ahead of us (calibration of calorimeters and alignment of trackers,