Performance of the (S)LHC for Jets and Missing E_t

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This Talk

- Introduction to Hadronic Final States at the LHC;
- Jet Calibration and Reconstruction;
- Missing Et Reconstruction;
- Measurement Challenge: Pile-up from Minimum Bias Events;
- Jets at S(uper)LHC;
- Conclusions;

"Disclaimers"

- all plots shown are based on simulations and have to be looked at with care!
- this talk is heavily biased towards ATLAS studies, due to lack of time for a more careful preparation – apologies to my CMS and ALICE/LHCb colleagues!

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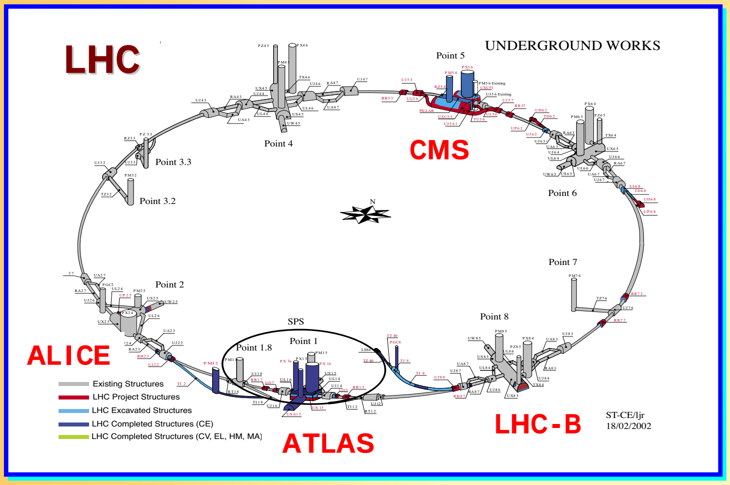
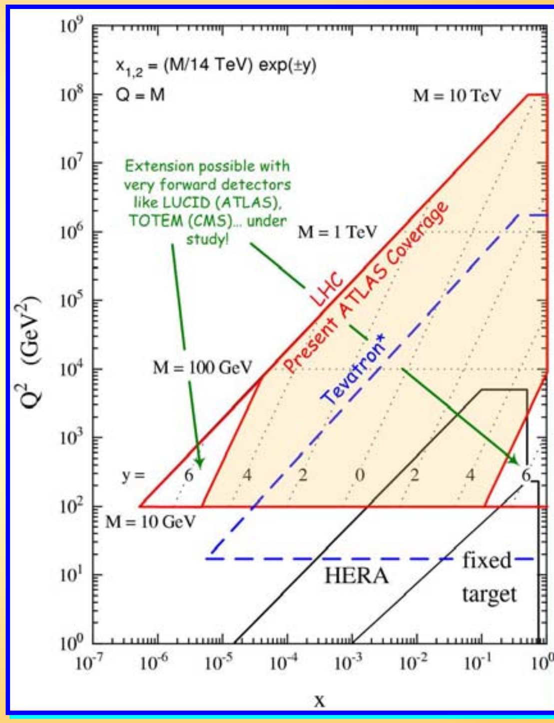
The Large Hadron Collider (LHC) @ CERN:





W. Stirling, LHCC Workshop “Theory of LHC Processes” (1998)
*annotation from J. Huston, Talk @ ATLAS Standard Model WG Meeting (Feb. 2004)

- pp collider with $\sqrt{s} = 14\,\mathrm{TeV}$, located in the LEP tunnel at CERN, Geneva, Switzerland;
- initial L=~2×10^{33} cm^{-2}s^{-1} (Λ = 20 fb^{-1}), design ~10^{34} cm^{-2}s^{-1} (Λ = 100 fb^{-1}), upgrade 10^{35} cm^{-2}s^{-1} (Λ = 1000 fb^{-1});
- bunch crossings every 25 ns (40 MHz);

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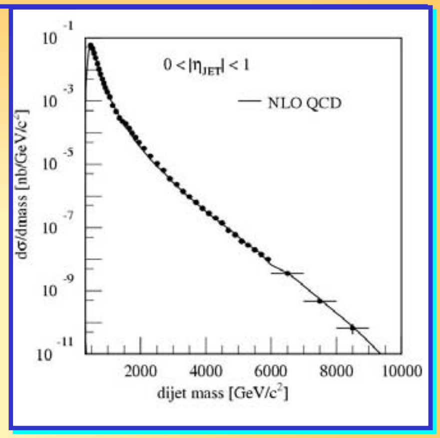
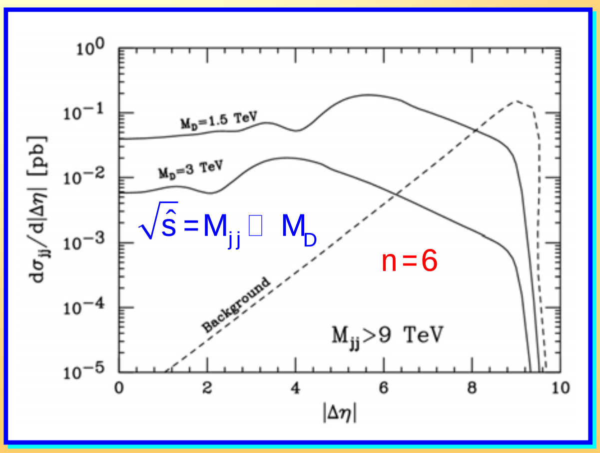
Hadronic Final States at LHC



- important source for gluon jets is Standard Model physics: extensive kinematic reach accesses (pertubative) QCD cross sections in so far unexplored kinematic domains;
- also important jet signatures in Higgs (forward jet tagging, central jets from b's and W decays) and SUSY (quark jets);
- missing transverse energy generated in Standard Model Higgs decays H → lvlv, lvjj, lvjj, vvvv;
- other important source for missing E_t are SUSY/MSSM Higgs decays like A → ττ → ℓℓvvvv, ℓhvvv, hhvv;
- SUSY extensions and exotics or extra dimensions usually produce final states with (lots of) jets and significant missing E_t;



G.F.Giudice, R.Rattazzi, J.D.Wells, hep-ph/0112161

di-jet separation $|\Delta\eta|$ for a model with a large number n of (flat) extra dimensions, indicating graviton exchange contributions to the (very small) cross-section

Physics Requirements for Jet and Missing E_t Measurements

- hadronic final state reconstruction requirements are stringent and often exceed what has been achieved in running experiments at Tevatron and HERA, for example;
- top reconstruction in ttbar events requires jet energy scale error of <1% absolute (immensely challenging!);
- jets need to be tagged to highest possible rapidities (~5) to enhance Higgs signal-to-background ratio in WW scattering production (order 10% or all Higgs over expected mass range);
- good missing E_t resolution also requires largest possible rapidity coverage;
- SUSY final state reconstruction also requires excellent hadronic calibration at a level of 1%;

Interesting:

• increasing particle detection from $|\eta|<3$ to $|\eta|<5$ improves mass resolution for a light MSSM Higgs (M_A = 150 GeV) from 8 to 2 GeV;
• yet, quality requirements to forward particle measurements are relaxed → most missing E_t is produced in the central region!

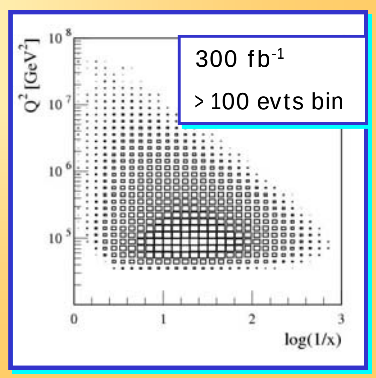
Required Energy Resolution

$$\sigma/E = \begin{Bmatrix} 50\%/\sqrt{E(\mathrm{GeV})} \oplus 3\% \text{ for } |\eta| < 3 \\ 100\%/\sqrt{E(\mathrm{GeV})} \oplus 6\% \text{ for } |\eta| > 3 \end{Bmatrix}$$

ATLAS requirements for hadronic (jet) energy resolution
ATLAS Detector & Physics TDR CERN/LHCC/99-14/15

- hadronic (or jet) energy resolution is an important ingredient to the measurement error at LHC, even though we are very quickly dominated by systematics due to high event rate;
- nevertheless, one of the first distributions we have to understand are the QCD backgrounds to discovery physics channels and the parton distribution functions (PDFs) in yet uncovered kinematics regimes → inclusive jet cross-section measurement (next slide);
- best illumination of kinematic region for PDF constraints, measuring the strong coupling at high mass scales, and detecting compositeness (probably more long term measurements) require good jet energy resolution as well;

$d\sigma/dQ^2 d(\log(1/x))$



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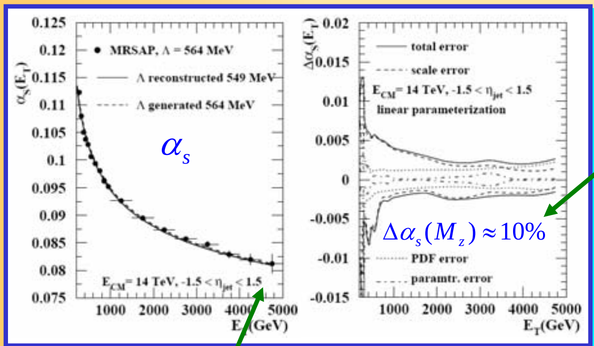
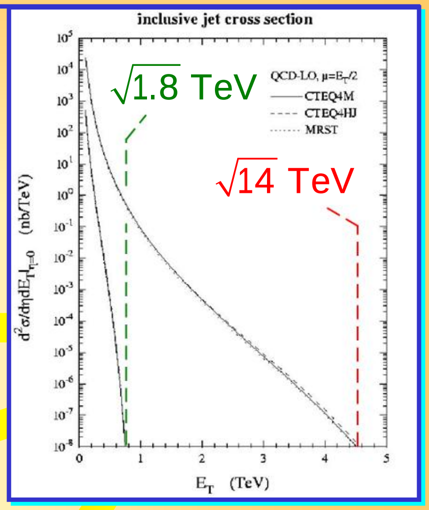
From the Inclusive Jet Cross-Section:

Strong Coupling

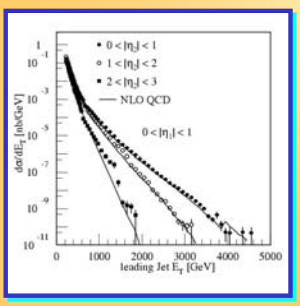


test of QCD at very small scale ($\alpha_s \approx 0.08$)

just from cross-section, can be improved by 3/2 jet ratio, but no competition for LEP/HERA!

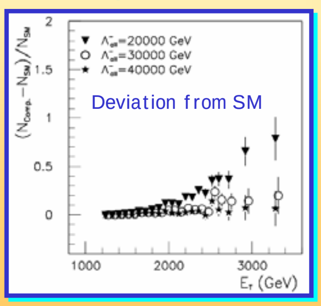


PDFs



di-jet cross section and properties (E_t,η_1,η_2) constrain parton distribution function

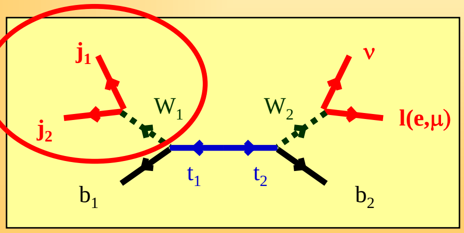
Compositeness



sensitivity to compositeness scale Λ up to 40 TeV @ 300 fb^{-1} (all quarks are composites)

Other Jet Features at LHC:

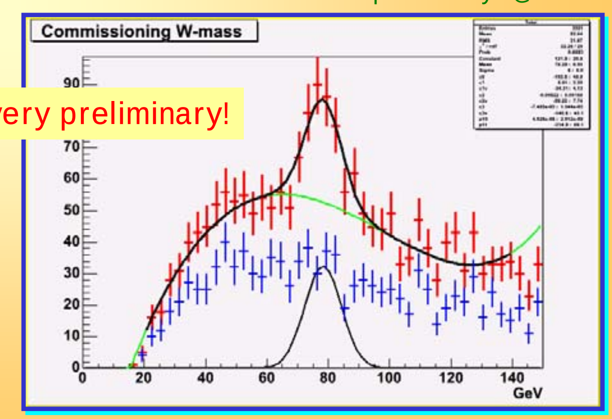
- ❖ statistical errors are small → systematic uncertainties from jet algorithm, jet energy scale (mostly linearity of calorimeter response), and control of contributions from underlying event and pile-up dominate the total hadronic energy scale error rather quickly!
- ❖ several "calibration channels" for jets ($W \to jj$, $Z+jj$) available with high statistics → ~1% systematic error on energy scale possible;
- ❖ calibration measurements can be done in initial low luminosity running to minimize effects from pile-up events;



Process		σ (nb)	Evts/year (Λ=10 fb^{-1})
W ev		15	~10^8
Z $e^+ e^-$		1.5	~10^7
tt		0.8	~10^7
Inclusive Jet Production	p_t > 200 GeV	100	~10^9
	p_t > 1 TeV	0.1	~10^6
	p_t > 2 TeV	10^{-4}	~10^3
	p_t > 3 TeV	1.3×10^{-6}	~10

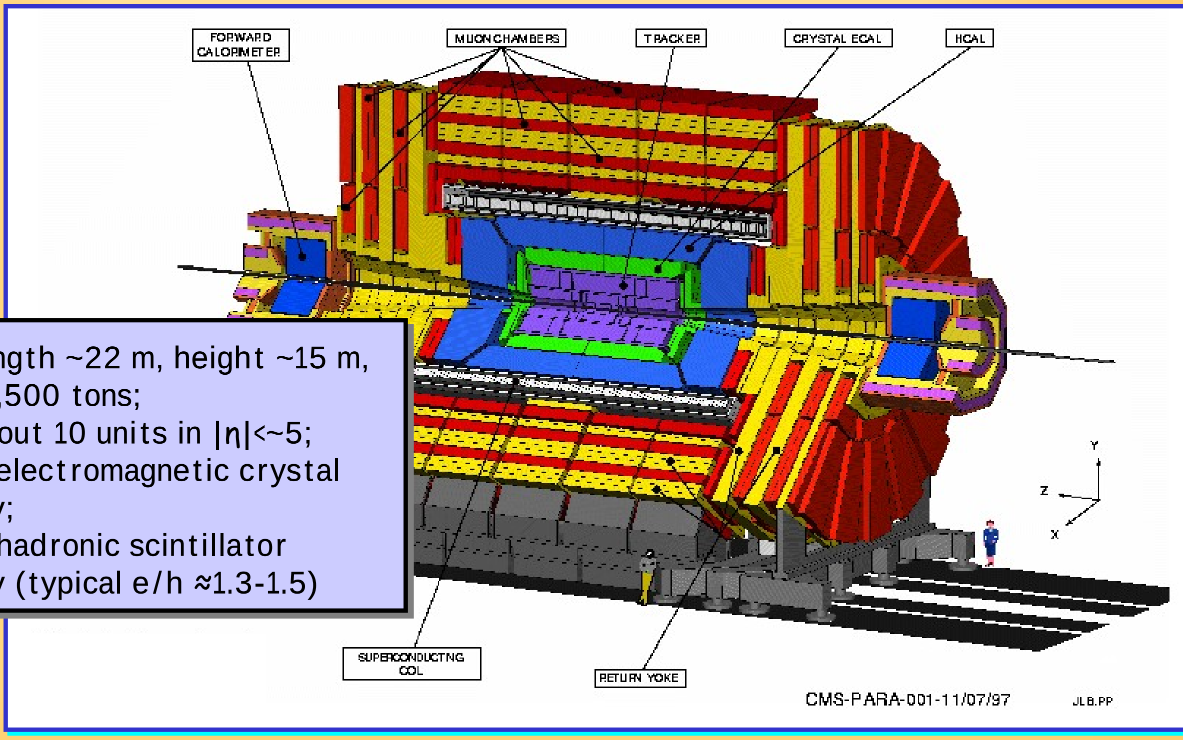
30 pb^{-1} ~4 days @ 10^{33}

very preliminary!



D. Pallin, ATLAS Calorimeter Calibration Workshop, Slowakia, Dec. 2004

The CMS Detector at LHC



- overall length ~22 m, height ~15 m, weight ~12,500 tons;
- covers about 10 units in $|\eta|<\sim 5$;
- features electromagnetic crystal calorimetry;
- features hadronic scintillator calorimetry (typical e/h ≈1.3-1.5)

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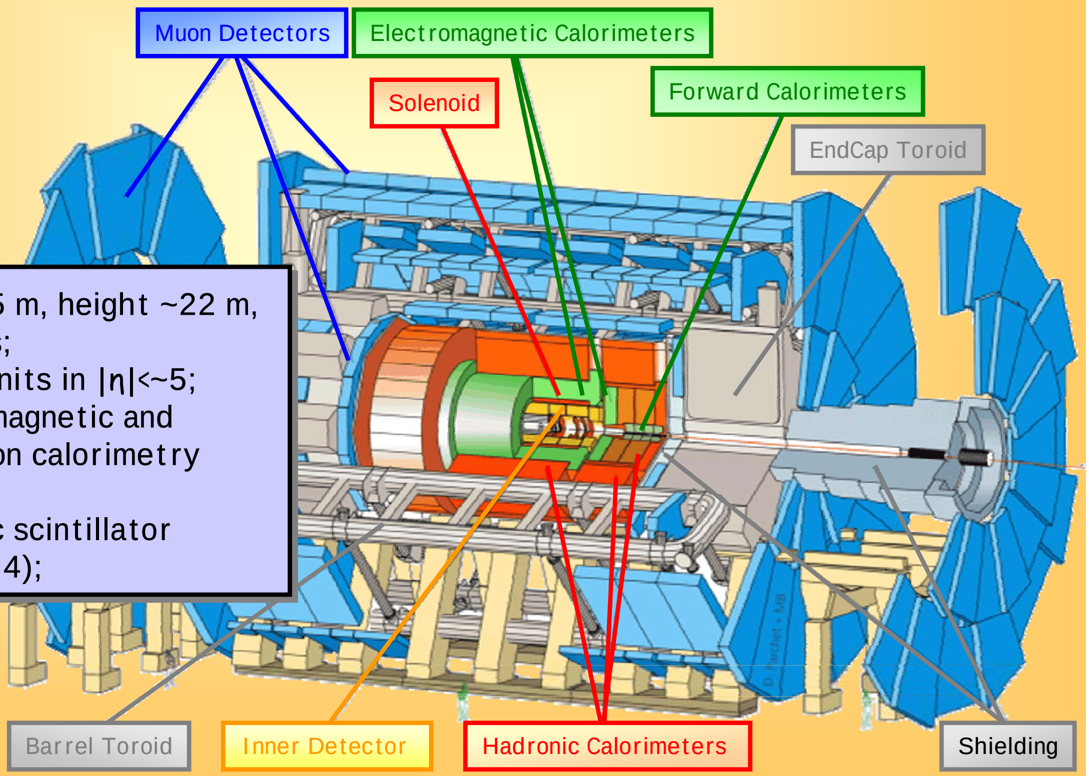
The ATLAS Detector at LHC



- overall length ~45 m, height ~22 m, weight ~7,000 tons;
- covers about 10 units in $|\eta|<\sim5$;
- features electromagnetic and hadronic liquid argon calorimetry ($e/h\approx1.4$);
- features hadronic scintillator calorimetry ($e/h\approx1.4$);

Ingredients to Jet Reconstruction in the Calorimeters

longitudinal energy leakage

detector signal inefficiencies (dead channels, HV…)

pile-up noise from (off-time) bunch crossings

electronic noise

signal definition (clustering, noise suppression algos,…)

dead material losses (front, cracks, transitions…)

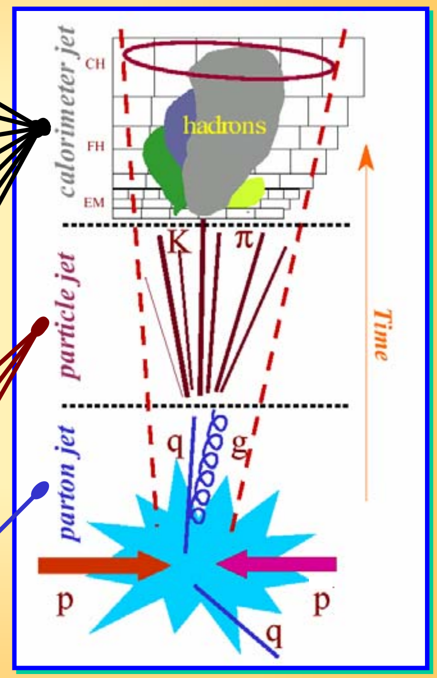
detector response characteristics (e/h ≠ 1)

added tracks from in-time (same trigger) pile-up event

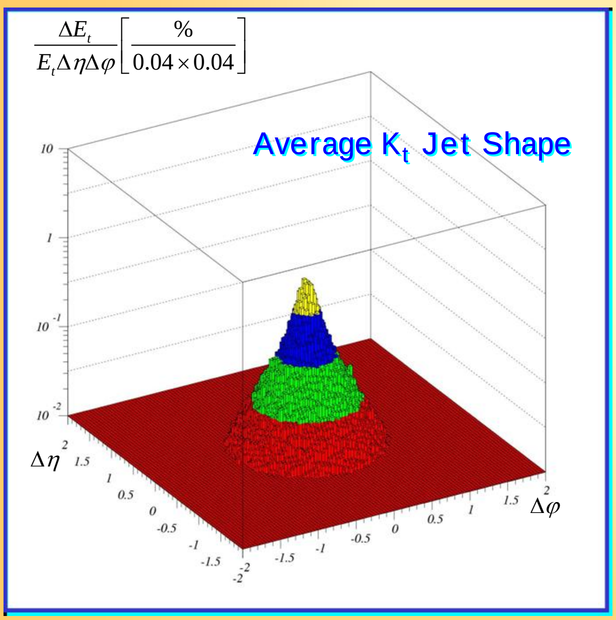
added tracks from underlying event

lost soft tracks due to magnetic field

physics reaction of interest (parton level)



Jet Reconstruction in ATLAS



❖ typically use K_t or (seeded) cone with full four-momentum recombination → Tevatron Run I experience and Run II application;

❖ large number of calorimeter cells (~200,000 in ATLAS) requires pre-clustering in towers ($\Delta\eta\times\Delta\varphi$ = 0.1×0.1) or clusters (3-d energy blobs), especially for K_t;

❖ split and merge algorithms (cut-off 50%) are applied for cone jets to avoid infrared divergen-cies;

❖ input are calorimeter cell signals on the electromagnetic energy scale (now from detailed Geant4 simulations of physics and/or calibration events, with or without noise and pile-up added, later experiment);

❖ reference is typically closest particle jet in simulations build with the same jet algorithm;

Jet Calibration in ATLAS

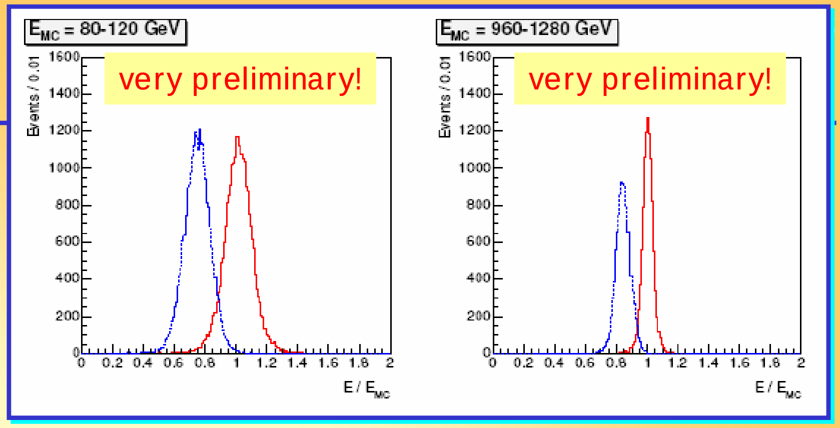
- present day principle approach: absorb all detector and algorithm inefficiencies in one step within a given jet context (cone, K_t) → compensate for everything in one calibration function*;
- function choice is motivated by the H1-style software cell signal weighting, which gives a larger weight to a low density cell signal and a smaller (limit is 1) weight to high density cell signals to achieve statistical signal compensation for $e/h \neq 1$;
- the reasoning behind this approach is the idea that electromagnetic energy deposits typically generated higher signal densities than hadronic deposits;
- functions are typically fitted to cell signals in a given calorimeter jet in a given calibration sample (QCD 2-jets) and built with a given jet algorithm (seeded cone R=0.7), with the normalization defined by the particle jet nearest in space to this jet;
- alternative ansatz uses additional variable like the jet energy itself (iterative approach);

*the context is needed as isolated cell signals in a non-compensating calorimeter have no information about their origin – only including neighbours can establish a hypothesis (electromagnetic or hadronic);

ILC-LHC Session
Snowmass 2005
August 23, 2005
Slide 14

ATLAS Jet Calibration

- several schemes under study, most developed scenario is based on fitting cell signal weights in jets in fully simulated QCD di-jet events -> motivated by H1 signal weighting technique;
- clearly only possible in MC -> fitting of weights requires choosing truth reference (particle level jets found with the same algorithm, particles pointing into direction of calorimeter jet…) , but calibration to particle level certainly a good idea!



F. Paige, ATLAS Jet/EtMiss Working Meeting 2/2/2005

cone jet signal linearity in QCD di-jet events (ΔR = 0.7) in the ATLAS calorimeters ($|\eta|<3$)

calibrated jets

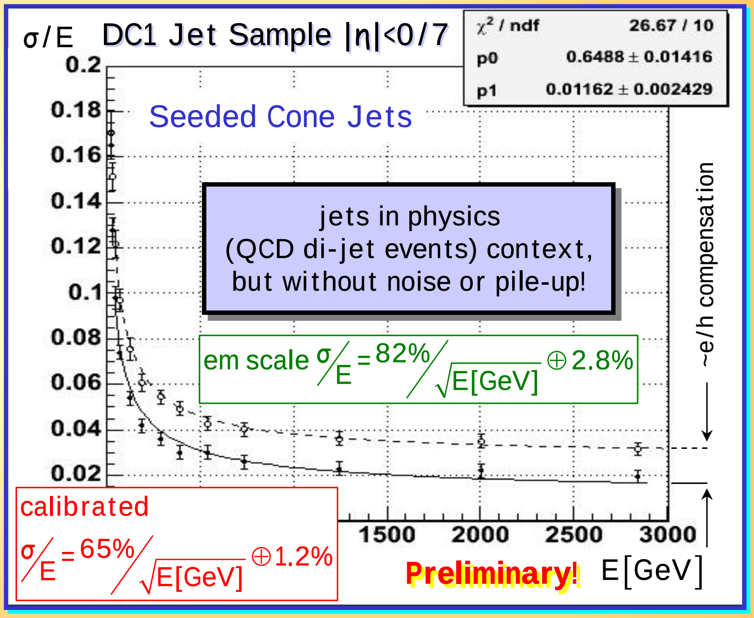
uncalibrated (em scale) jets

S. Pahdi, ATLAS Jet/EtMiss Working Meeting 2/2/2005

Jet Energy Resolution in ATLAS

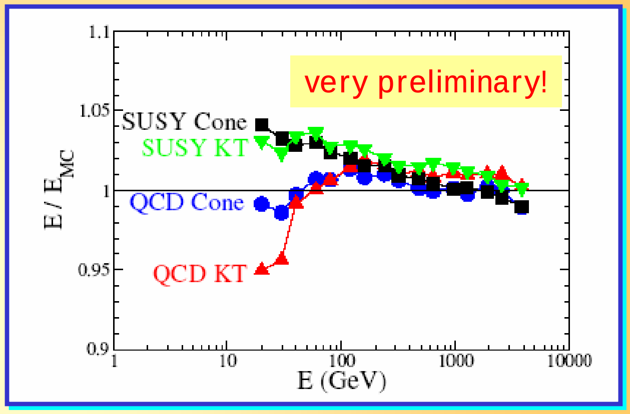
- clear indication of compensation by using cell weights;
- clustering fluctuations (also in the reference particle jet!) not unfolded in this study;

C. Rhoda, I. Vivarelli, ATLAS Software Workshop 09/2004

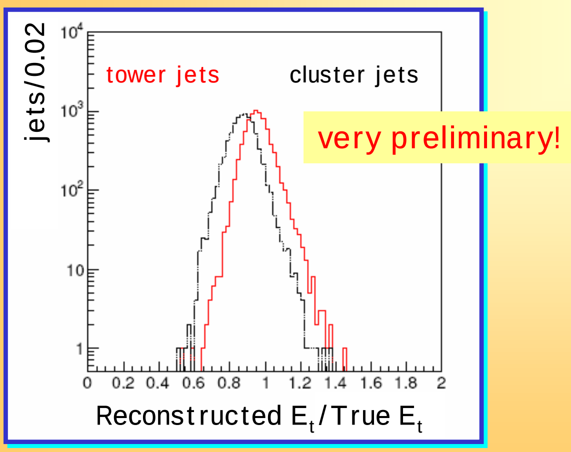


Jet Calibration Biases

- dependencies on event environment and jet algorithm not addressed by "all-inclusive" approach;
- also, change of calorimeter signal definition leads to mis-calibration (order 5%);



F. Paige, ATLAS Jet/EtMiss Working Meeting 02/02/2005

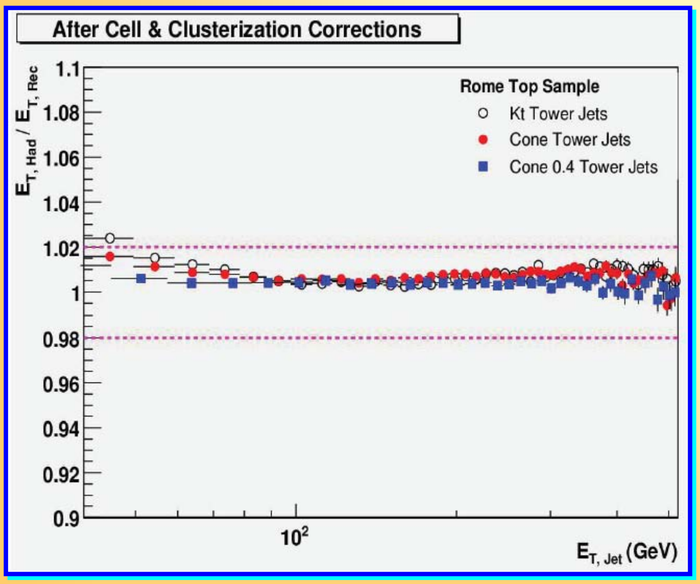


F. Paige, ATLAS Software Workshop 09/2004

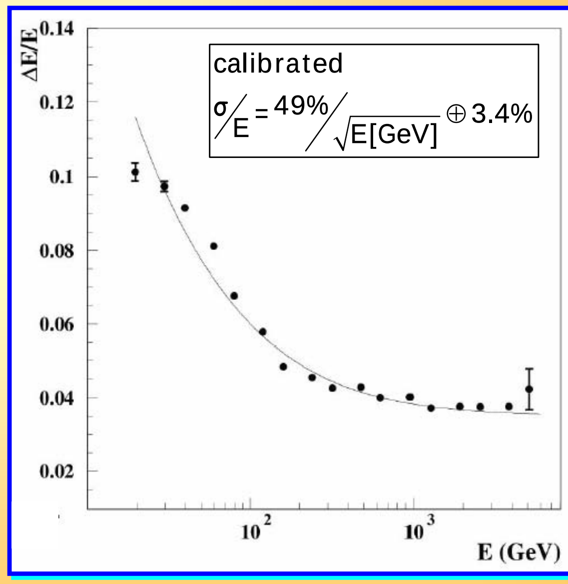
- further development still uses cell weighting approach, but tries to factorize some of the contributions to the jet signal, especially the clustering dependency (see next slide);

Improved Cell Level Jet Calibration

- "factorization" of cell corrections (signal weights to compensate $e/h \neq 1$), clusterization corrections, and crack corrections;



S. Padhi, ATLAS Physics Workshop 07/2005



S. Padhi, ATLAS Physics Workshop 07/2005

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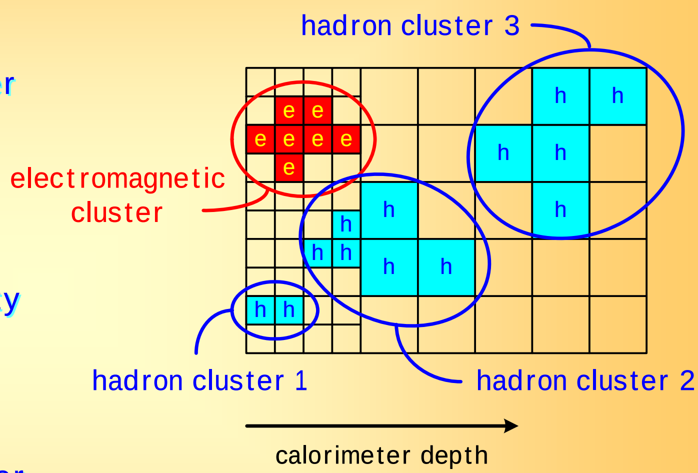
New Approach in ATLAS: Local Hadronic Cluster Calibration

- use the 3-d nearest neighbour topological cell clusters as a basic calorimeter signal;
- move the cell level calibration, basically intended to compensate e/h ≠ 1, from the jet context to the cluster context → expect more sensitivity of cluster shapes to nature of energy deposit;
- classify each cluster according to its shape and location as "electromagnetic" or "hadronic" (possibly one or two hadronic classifications!);
- apply the best calibration function to each cluster, depending on its classification and possibly cluster (shape) and/or signal variables;
- apply dead material and crack corrections at cluster level, too → (nearly) all detector effects are calibrated out or corrected before jet finding, or missing E_t calculation → common basic hadronic signal for both!!



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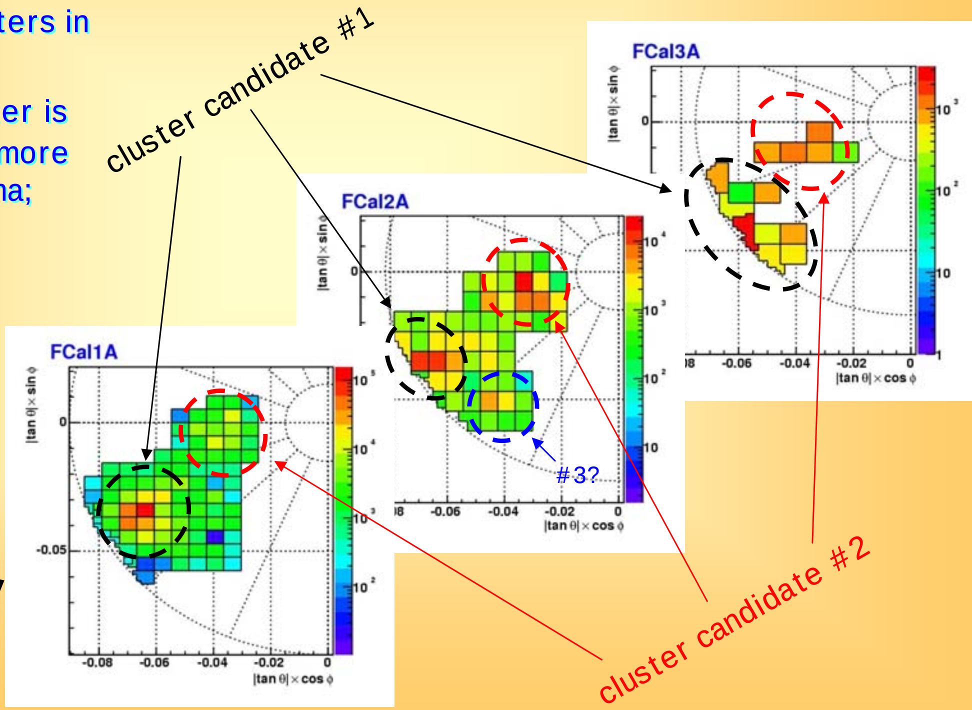
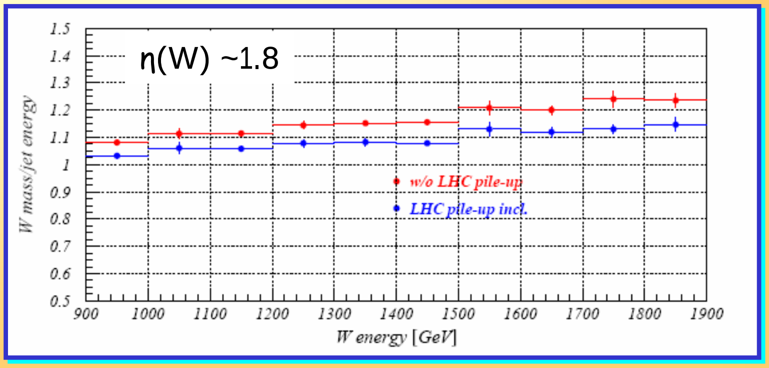
Clusters in Jets

- jets are typically build out of order(10) clusters in ATLAS at least;
- a topological cluster is split when there are more than one signal maxima;



Final Jet Calibration

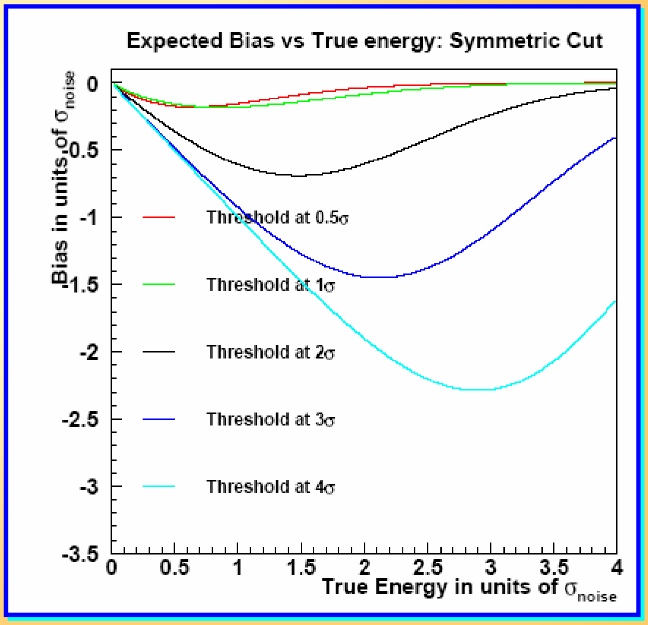
- using fully calibrated and corrected clusters in jet finding reduces the problem of jet calibration to the understanding of the contributions from the jet algorithm inefficiencies, the underlying events, and the overall event topology possibly including pile-up;
- W → jj can help to estimate these final corrections, but are mostly found in a very specific ttbar topology (bias ?), and with special jets (no color link to rest of event); also, there are kinematical limits on the effectiveness of this calibration signal – order(3%) more likely than 1% today;
- other channels like Z+jet(s) or photon+jet(s) can help, but good understanding of initial and final state radiation needed;



P. Savard, P. Loch, CALOR97

Missing Transverse Momentum Reconstruction

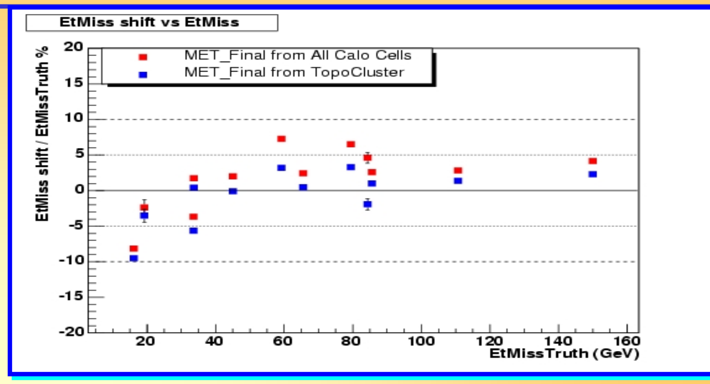
- best missing E_t calculation is using calibrated cell signals and all cells with true signal;
- in a real detector this calculation is very sensitive to electronic noise (at least) – typically 70-90% of all cells in ATLAS have no true or significant signals;
- symmetric or asymmetric cell noise cuts reduce the fluctuations significantly, but introduce a bias (shift off 0) due to this cut;
- topological clustering imposes a noise cut, but lets cells survive based in the signal in their neighbours → less bias, yet near optimal suppression of incoherent (electronics) noise;



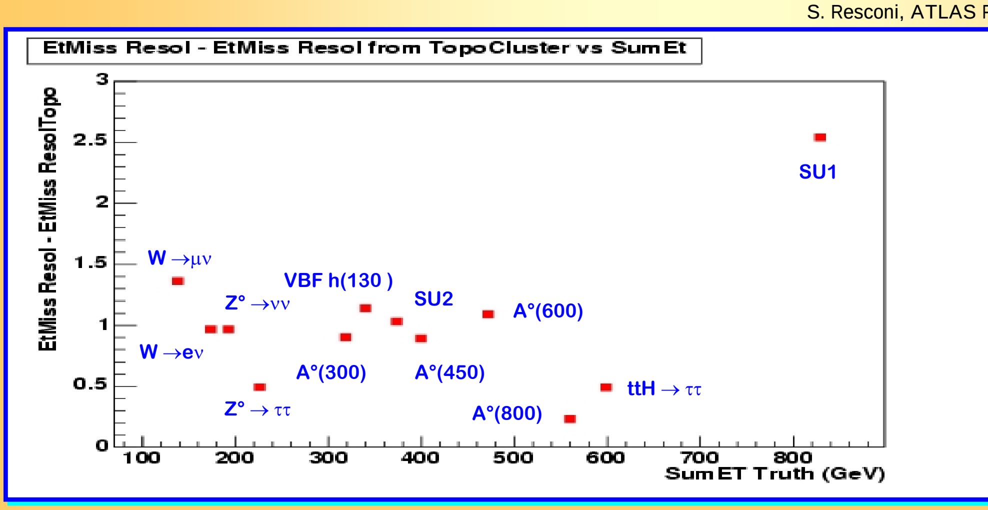
K. Cranmer, in talk by S. Menke, ATLAS Physics Workshop 07/2005

Missing Et Reconstruction

- calculating missing E_t from topological clusters brings a small improvement in the bias;



S. Resconi, ATLAS Physics Workshop 07/2005



S. Resconi, ATLAS Physics Workshop 07/2005

- calculating missing E_t from topological clusters improves the missing Et resolution for many physics channels;

$$\sigma_{ExMiss} \approx 47\% \cdot \sqrt{\sum |E_{t,i}|}$$

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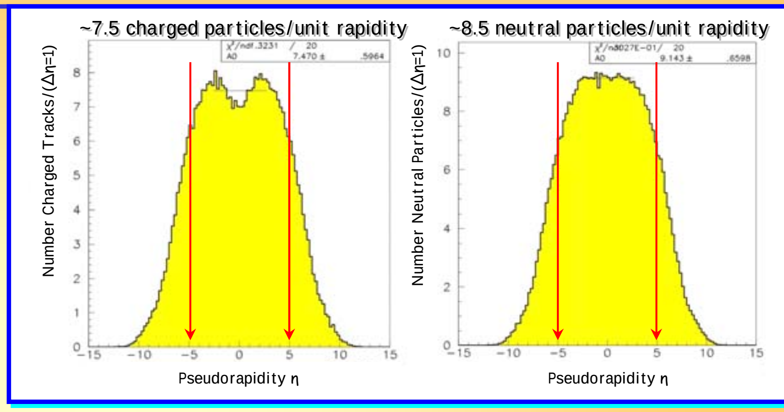
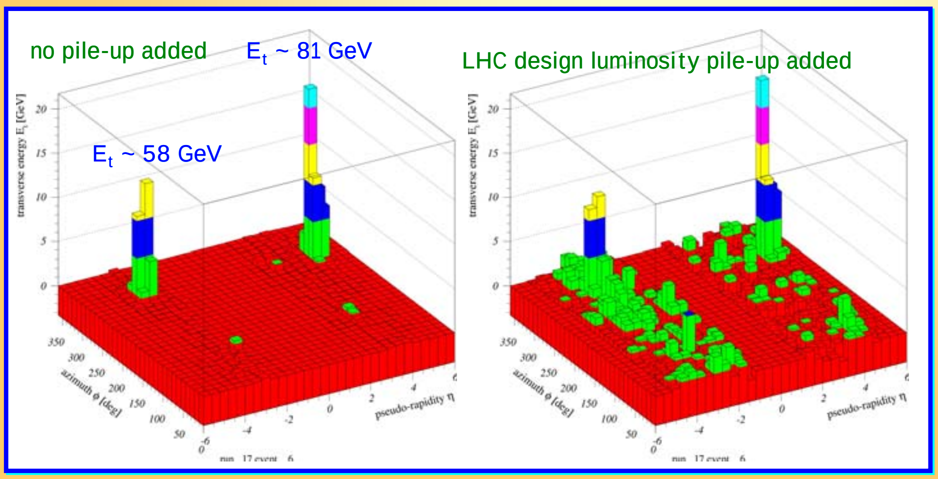
Pile-Up

- high lumi, large $\sigma_{incl} \approx 80$ mb -> ~23 min bias events/bunch crossing, with ~75 charged tracks/event within typical detector acceptance $|\eta|<5$ at 10^{34} cm^{-2}s^{-1};



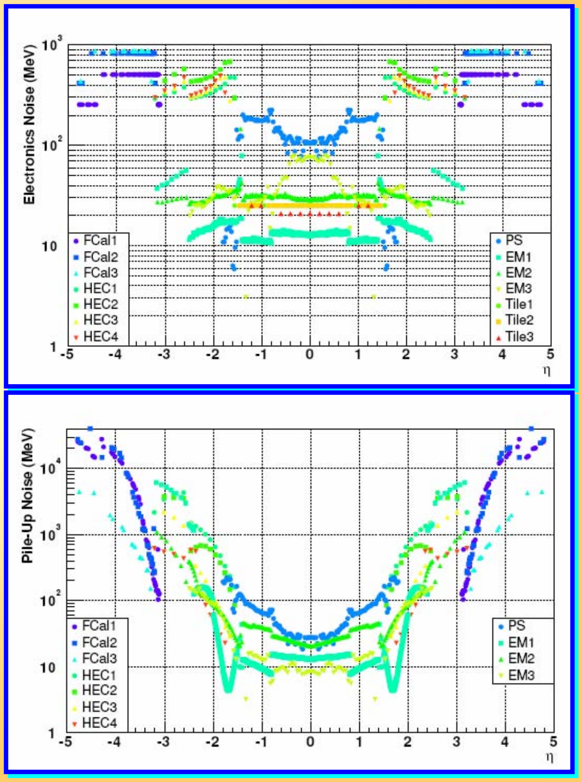
ATLAS Calorimeter Performance Technical Design Report CERN/LHCC 96-40



- effect of pile-up depends on detector technology and readout electronics - long bi-polar shaping functions in ATLAS calorimeters lead to out-of-time contributions with negative signals;

Pile-Up vs Electronic Noise in Calorimeter Cells

- cell signal fluctuations introduced by pile-up dominate wrt electronics noise in the ATLAS endcap calorimeters, but are comparable to, or less than, electronic noise in the central calorimeters;
- pile-up fluctuations in a given cell are not Gaussian due to the lateral and longitudinal coupling of signals in neighbouring cells introduced by the showers in minimum bias events;
- still, pile-up RMS in each cell (a function of the instantaneous luminosity) can be used to define the significance of the cell signal to first order;
- still more detailed studies are needed to understand the structure (mini-jets, etc…) in the pile-up events, and to find a measure for the instantaneous lumi for each triggered event (correlation between forward energy flow and pile-up ?);



S. Menke, ATLAS Physics Workshop 07/2005

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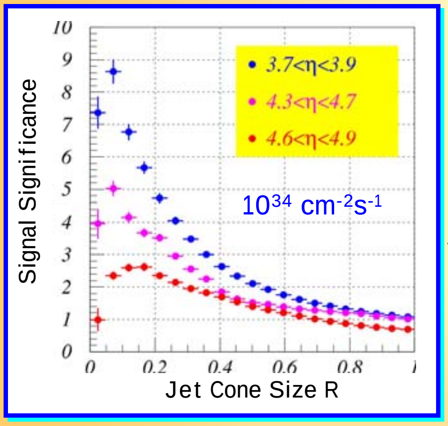
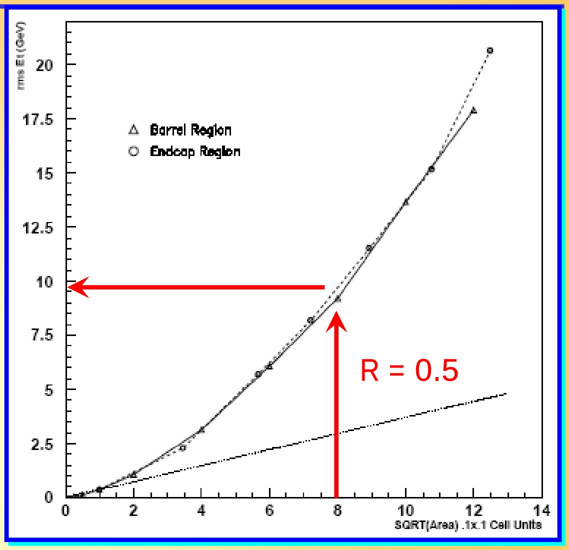
Pile-Up in Jets

- typically around 10 GeV E_t signal fluctuations in jet cone of R = 0.5 at design luminosity;
- this finding is rather independent of η;



P.Loch & P.Savard, CALOR97



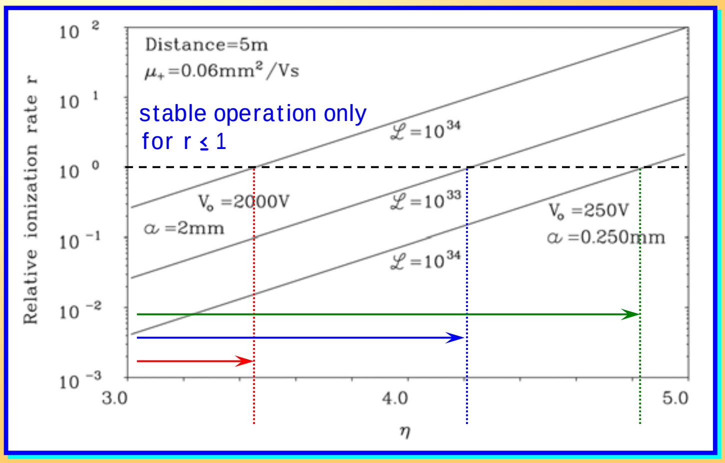
P. Savard et al., ATLAS-CAL-NO 084/1996

Forward tag jets in Higgs production have average E_t of 30-50 GeV only (descreasing with increasing η)

- forward jet detection is non-trivial (low significance of signal even in smallest jet cone);
- further studies needed to understand pile-up contributions to other jet finders;

Jets in SLHC

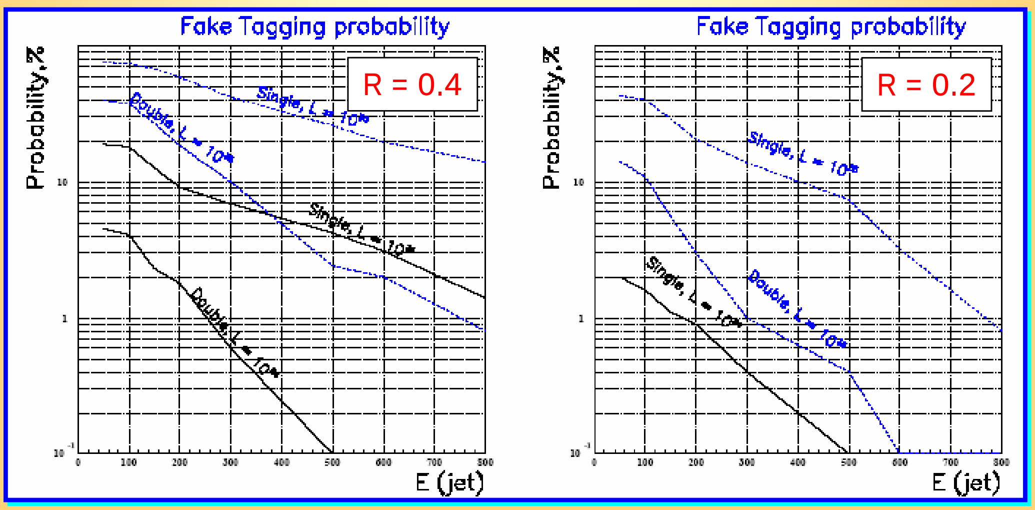
- several upgrade scenarios have been discussed - increase of luminosity by 10, doubling of energy at present design lumi, doubiling of energy and increase of lumi by 10;
- due to technical constraints from the LHC machine, increasing the energy above 7.54 TeV/beam is only possible by replacing (all) beam elements (not really an option);
- lumi only upgrade somewhat more obvious – mainly changing cavities only;
- even that is challenging for the ATLAS calorimeters (space charge effects etc.);
- some ongoing studies to understand the benefits for physics versus the impact on the detectors and machine;



J.P.Rutherfoord, Scientific Note SN-ATLAS-2001-003

Jets Performance Degradation

- major problem is increase of pile-up activity (23 events/crossing to 230 events per crossing);
- pile-up signal fluctuations in jet cone increase by ~sqrt(10) to more than 30 GeV → performance degradation e/jet separation, b-jet tagging, Higgs tagging…



Conclusions

- In general we expect the jet and missing E_t performance at the LHC to meet most physics requirements, with some challenges remaining for the jet energy scale error;
- Further improvements are depending on a significant increase of the prediction power of hadronic shower models in Geant4 – continuing focus on validation using testbeam data;
- A new hadronic calibration model in ATLAS using local cluster calibration for jets and missing Et looks very promising and should be available end of this year;
- We still miss systematic evaluations of jet shapes and topologies in the presence of pile-up;