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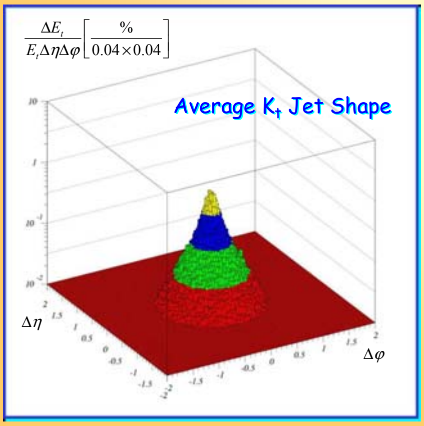
QCD and Hadronic Calibration at LHC



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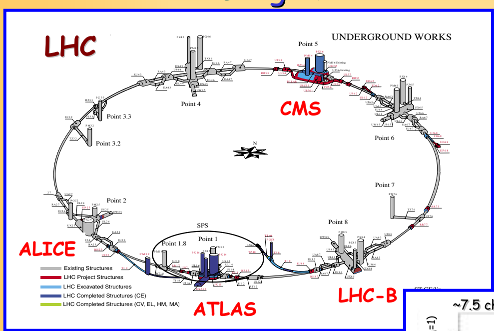
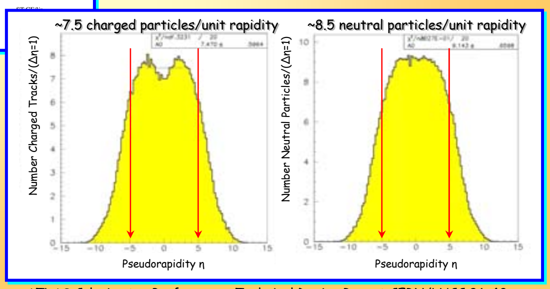
The Large Hadron Collider (LHC) @ CERN:



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



- high lumi, large $\sigma_{incl} \approx 80$ mb -> ~23 min bias events/bunch crossing, with ~75 charged tracks/event within typical detector acceptance $|\eta|<5$;
- mass reach more than 5 TeV;

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

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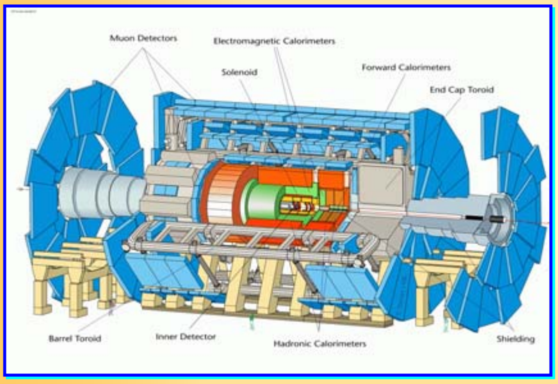
The ATLAS Detector



Length ~45 m, height ~22 m, weight ~7000 tons

Clear ATLAS bias in this talk!

- Inner Detector (2T solenoid, $|\eta|<2.5$):
  $\sigma_{p_t}/p_t \approx 0.05\%/\text{GeV} \times p_t \oplus 1\%$
- Calorimetry:
  * electromagnetic, $|\eta|<3.2$
    $\sigma_E/E \approx 10\%\sqrt{\text{GeV}}/\sqrt{E} \oplus 0\%$
  * hadronic (central, $|\eta|<1.7$)
    $\sigma_E/E \approx 50\%\sqrt{\text{GeV}}/\sqrt{E} \oplus 3\%$
  * hadronic (endcaps, $1.7<|\eta|<3.2$)
    $\sigma_E/E \approx 60\%\sqrt{\text{GeV}}/\sqrt{E} \oplus 3\%$
  * hadronic (forward, $3.2<|\eta|<4.9$)
    $\sigma_E/E \approx 100\%\sqrt{\text{GeV}}/\sqrt{E} \oplus 5\%$
- Muon system (~4T toroid, $|\eta|<2.7$):
  $\sigma_{p_t}/p_t \approx 10\%$ for $p_t(\mu) \approx 1$ TeV/c

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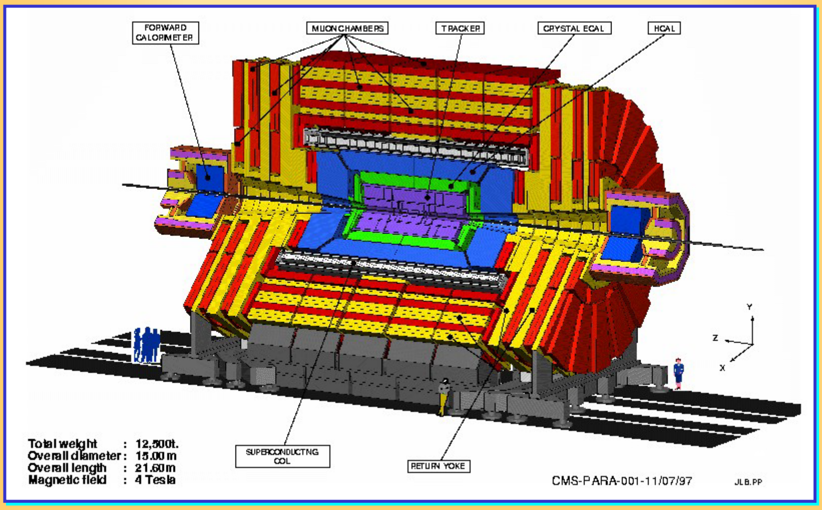
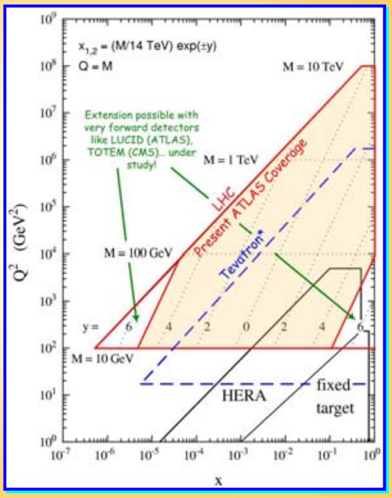
The CMS Detector



QCD at LHC

- nearly all LHC physics is connected to the interaction of quarks and gluons -> QCD provides the underlying dynamics for basically everything!
- large event rate reduces statistical errors quickly and allows precision measurements of Standard Model cross sections over a yet unexplored kinematic regime;
- access to quark and gluon structure functions, strong coupling at high momentum transfers, compositeness scales…
- QCD provides background for nearly all searches (direct photon production for low mass Higgs, multi-jet production for SUSY…);
- (non-pertubative) QCD determines shapes and rates for minimum bias events -> important limitation on precision measurements at design luminosity!



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

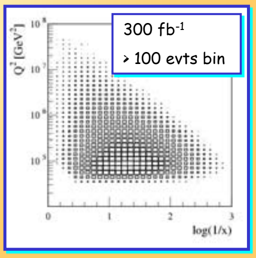
Jet Physics at LHC

- jet cross section measurements allow tests of pertubative QCD in unexplored kinematic regions;
- statistical errors are small -> systematic uncertainties from jet algorithm & trigger efficiency, jet energy scale (mostly linearity of calorimeter response), contributions from underlying event and pile-up, and luminosity (~5%);

Process		σ (nb)	Evts/year (Λ=10 fb^{-1})
$W \to e\nu$		15	~10^8
$Z \to e^+ e^-$		1.5	~10^7
$t\bar{t}$		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

- several "calibration channels" for jets (W->jj, Z+jj) available with high statistics -> ~1% systematic error on energy scale possible (see comments later!);
- measurements best done in initial low luminosity running to minimize effects from pile-up events;
- ATLAS measures jets with $\sigma_E/E \approx 50(60)\%/\sqrt{E(GeV)} \oplus 1.5(3)\%$ in the central (endcap) calorimeters (example);

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



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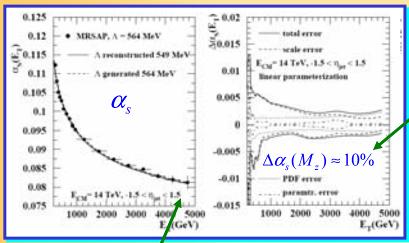
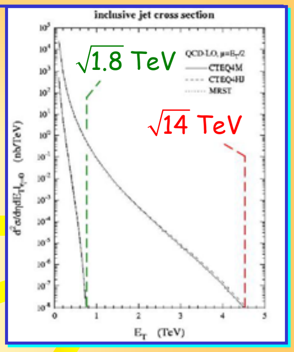
From the Inclusive Jet Cross-Section:

Strong Coupling

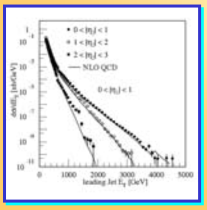


just from cross-section, can be improved by 3/2 jet ratio, but no competition for LEP/HERA!

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

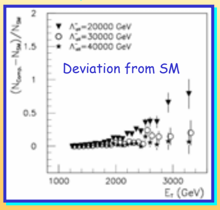


PDFs



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)

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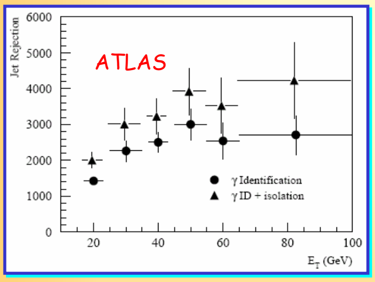
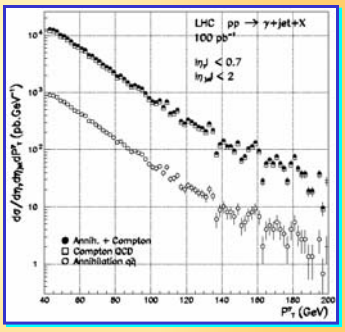
Exclusive Final State: Direct Photon Production

- interesting: major contribution to direct photon production ($qg \rightarrow \gamma q$, QCD Compton) provides access to gluon density function (requires good knowledge of α_s);
- needs good photon/jet separation -> highly granular calorimeters used;





- irreducible background from jets with leading π^0, expected total systematics 10-22% (mostly from $xG(x)$ parametrization uncertainties);
- also Drell-Yan processes (no final state QCD radiation!) help to constrain the proton structure at $Q^2 \approx m_{\ell\ell}^2$

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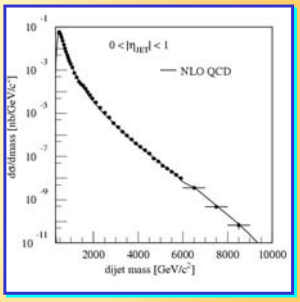
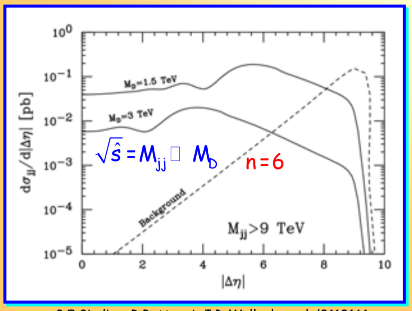
QCD as Background

- QCD provides background signals for almost all new signals expected at LHC: Higgs (di-photon production), SUSY (multi-jet events), exotics (large transverse momentum jets, high mass systems) -> need to understand QCD production mechanisms over a large kinematic range;
- especially high mass reach of the (QCD) di-jet system and the large coverage |η|<5 of ATLAS & CMS (w/o TOTEM) allows to study models with widely separated jets in very heavy hadronic final states;





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

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

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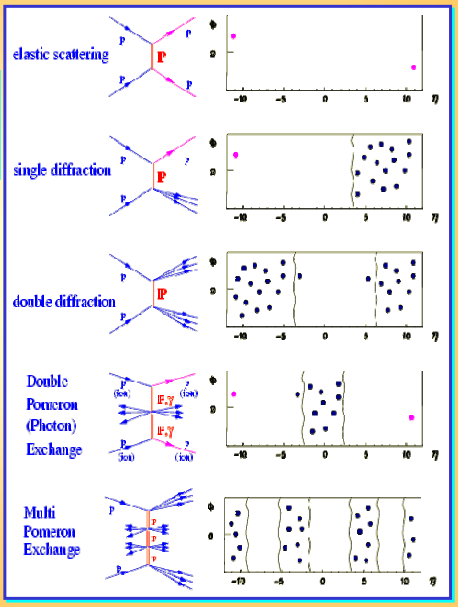
Rapidity Gap Physics

A. de Roeck, "Future of Forward Physics at LHC", Manchester, Dec. 2004

- very forward detectors help with lumi measurement (ATLAS focus in LUCID), diffractive pp scattering (CMS focus in TOTEM), and event-by-event pile-up suppression (correlation between forward and central region central region pile-up events increases with forward coverage – subject to studies ?);
- QCD interest in diffractive physics potential probably driven by structure functions (low-x dynamics, BFKL/CCFM evluation, parton saturation…) and min bias dynamics;



A. de Roeck, "Future of Forward Physics at LHC", Manchester, Dec. 2004

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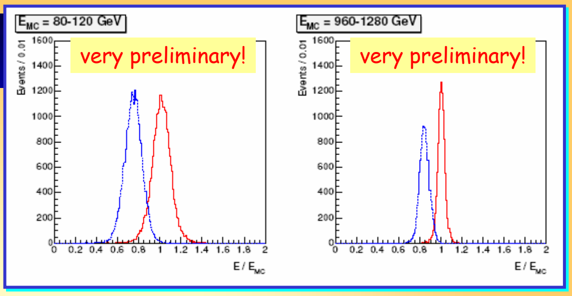
Hadronic Calibration

- depending on physics, requirements on hadronic calibration (jet energy scale error and resolution, missing transverse energy scale and resolution) can be stringent: typically 0.5% for top mass, O(1%) for QCD jet physics and jets in SUSY events…
- this is by no means easy to achieve - running experiments at Tevatron, HERA at best 1% systematics for selected physics, typically "few" % in less hostile environments than LHC!
- typical contribution to hadronic final state reconstruction:
  - ❖ detector effects – both ATLAS and CMS feature non-compensating calorimeters with typical e/h = 1.3-1.6;
  - ❖ control of physics environment contribution (underlying event) to fully reconstructed final state objects like jets;
  - ❖ suppression of pile-up contribution (~23 in-time minimum bias events on average, + signal history from previous bunch crossings, ATLAS) to these objects and global event measurements like missing transverse energy;
  - ❖ suppression of incoherent and coherent thermal noise in calorimeters;
  - ❖ general detector inefficiencies (dead material);
  - ❖ algorithm biases especially in jet finding;
  - ❖ …
- some observations, ideas, and strategies to address these challenges (this is really ATLAS only!);

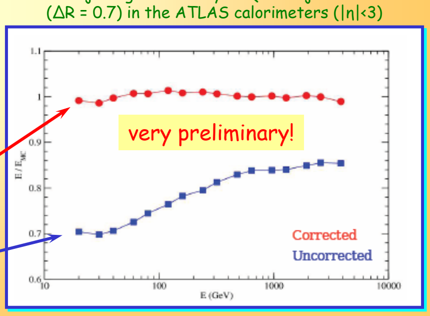
ATLAS Jet Calibration



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

- 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!

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



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

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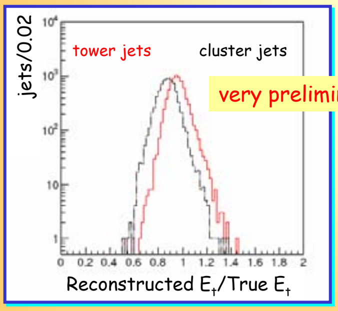
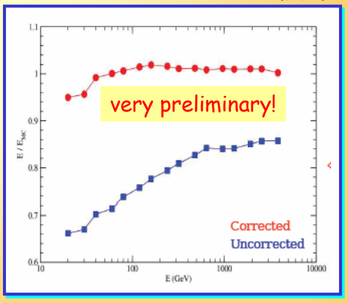
Some Limitations & Inefficiencies

- ansatz attempts to calibrate out several inefficiencies at the same time: detector effects (e/h ≠ 1, leakage, cracks,…), jet algorithm (only fitted for cone with ΔR = 0.7, intrinsically corrects for out-of-cone losses), contributions from underlying physics in QCD di-jet events, truth definition/jet matching, calorimeter signal definition…



F. Paige, ATLAS Software Workshop 09/2004

Kt jet signal linearity in QCD di-jet events in the ATLAS calorimeters (|η|<3)



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

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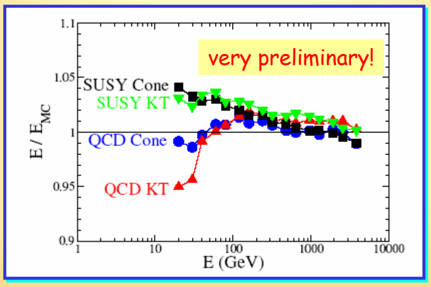
Event Topology Dependencies

- clear topology dependencies observed in SUSY events when applying QCD cone jet fitted calibration -> reasons manifold, possibly including different underlying event dynamics in generators (Herwig vs Pythia), different jet fragmentation (harder jets in SUSY) -> no quantitative analysis, no conclusion yet!



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

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Jet Calibration Normalization

- particle level clustering effects clearly contribute to fluctuations in the truth reference for the calibration -> inefficient jet finding in both signal spaces, jet matching;
- can be unfolded by special simulation (pre-selection of particles within QCD di-jet events);
- physics provides calibration events with mass constraints in hadronic W decays or events with well calibrated electromagnetic systems balancing the hadronic final state (Z+jets, direct photon production) in transverse energy -> in-situ calibration;
- but care is required: not obvious to extract universal jet calibration from these very specific final states, clearly limits in control of systematics (ISR/FSR, physics environment, isolation of electromagnetic signals/jets…);
- also change of normalization base -> particle to parton level;

TeV4 LHC Workshop
February 3-5, 2005 at Brookhaven National Laboratory
QCD and Hadronic Calibration at LHC

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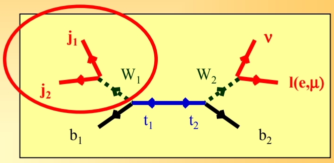
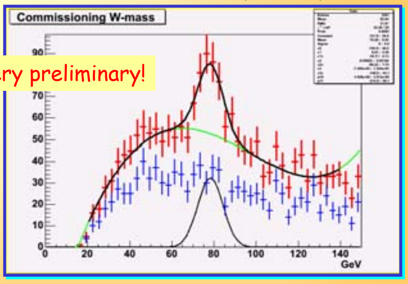
W->jj calibration

- reasonable rate (few 10ks with b-tagging) in ttbar events;
- small background when using b-tagging, basically only combinatorics to be considered (event itself is quite busy, though -> accidental signal contributions to jets…);
- precision of absolute jet calibration limited to 3% of O(3 fb^{-1});

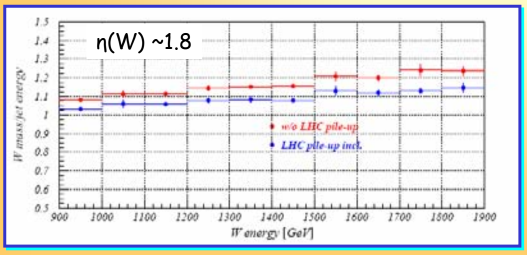


30 pb^{-1} ~4 days @ 10^{33}

very preliminary!



D. Pallin, Dec. 2004



P. Savard, P. Loch, CALOR97

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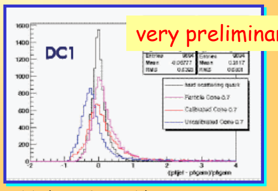
Direct Photons/Z+jet(s)

- Pt balance between electromagnetic and hadronic final state can constrain hadronic/jet energy scale;
- some concerns about background (jet fluctuates into π^0 or charge exchange) but not clear (to me!) why these events should not be usable for calibration purposes (missing transverse energy more critical);
- connects jet energy scale to parton level (photon), allows estimate of showering effects, for example;
- available at high statistics to probe the whole detector;
- mixes physics and algorithm effects with response -> strong cone size dependence observed;
- present status of studies indicates problem at low Pt < 60 GeV -> ongoing studies in ATLAS (C. Deluca, M. Bosman);



C. Deluca, ATLAS Calorimeter Calibration Workshop, Dec. 2004

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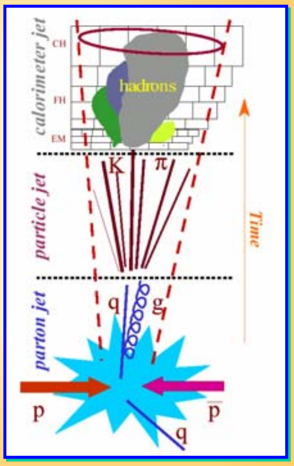
Under Study Today: Local Hadronic Calibration

- all discussed methods are clearly sensitive to calibration event topology (extrapolation to all events not completely clear) and tend to mix detector signal characteristics, acceptance, and physics environment;
- also, jet calibration is not calibration of the full hadronic final state -> missing Et should probably not be biased by jet reconstruction (too many algorithms and parameters with different calibrations, hard to control variable space);
- unfolding the detector effects (non-compensation, dead materials) first may help the situation considerably, especially in controlling systematics related to the calorimeters -> local calibration;
- basic idea: calibrated cell clusters are the calorimeter final state, with clusters generated by electrons and photons calibrated differently than hadronic clusters -> requires some granularity;
- important: no jet context (missing Et, e.g.);



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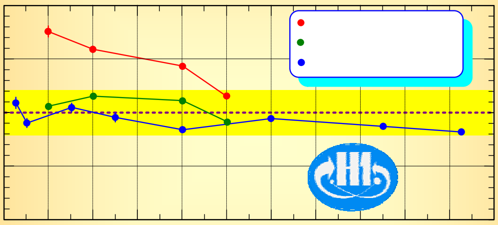
Cluster Based Calibration

- principle approach has been used before (H1) -> cluster classification important step towards compensation;

P. Loch, Diss. 4/92



- clustering helps with noise suppression (first hints in ATLAS calorimeters);
- missing Et can be calculated without jet context;
- jets still need to be corrected for physics environment, algorithms etc. -> more analysis responsibility, detector effects unfolded as much as possible!
- benchmarking with testbeam possible!

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Conclusions

- LHC allows precision tests of QCD in yet unexplored kinematic domains, including but not limited to constraints on PDFs in (high Q^2,low x), strong coupling at very small distances, and limits of compositeness;
- Other large cross-section QCD channels not discussed in this talk, mainly W/Z and heavy quark production, provide measurements of masses and couplings;
- Good understanding of soft (non-pertubative) QCD required to understand contributions from the underlying (hard initial/final state radiation, proton remnants) and minimum bias ("pile-up", non-single diffractive) events at high luminosity;
- Hadronic final state calibration challenging, but several approaches under study -> particular interest in stable calibration with reasonable control of environmental contribution, especially from pile-up;