LHC: from detector commissioning to first physics

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The LHC machine

Energy: $\sqrt{s}$=14 TeV

LEP tunnel: 27 Km circumference

1232 Superconducting dipoles, field 8.33 T

Luminosity:

- peak$\sim 10^{33}$ cm^{-2}s^{-1} - initial "low luminosity"

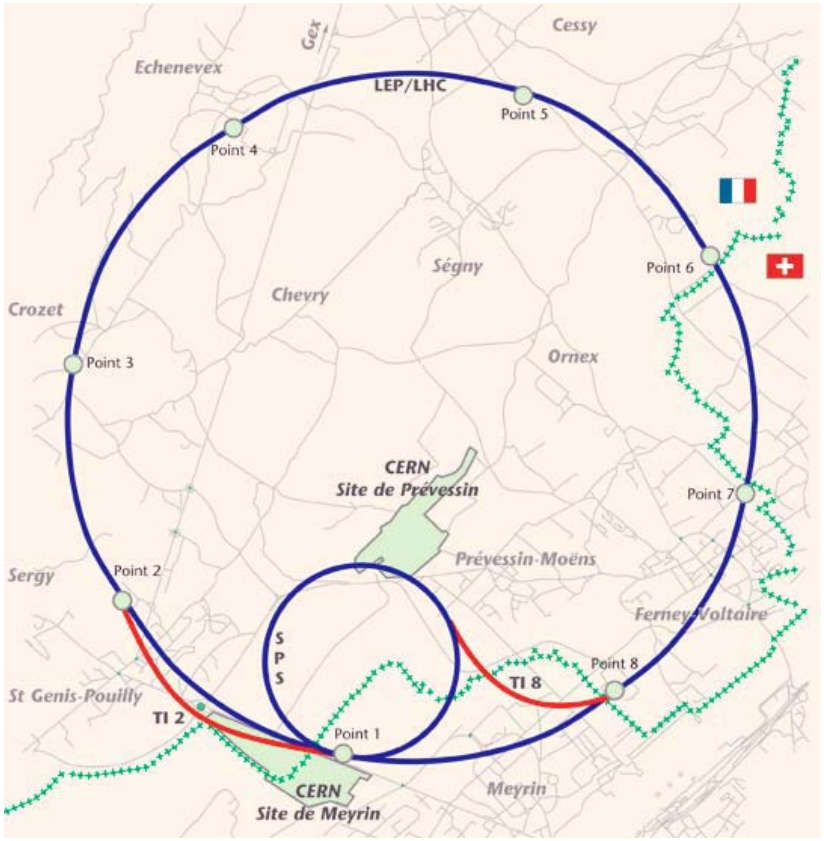
$$\int \mathcal{L} \mathrm{dt} = 10 \ \mathrm{f}b^{-1} \ \mathrm{per\ year}$$

- peak$\sim 10^{34}$ cm^{-2}s^{-1} - design "high luminosity"

$$\int \mathcal{L} \mathrm{dt} = 100 \ \mathrm{f}b^{-1} \ \mathrm{per\ year}$$

2808 bunches, 1.15×10^{11} protons per bunch

Inter-bunch space: 25 ns $\Rightarrow\sim 23$ inelastic interactions per crossing at full luminosity



Eight sectors

Point 1: ATLAS General purpose

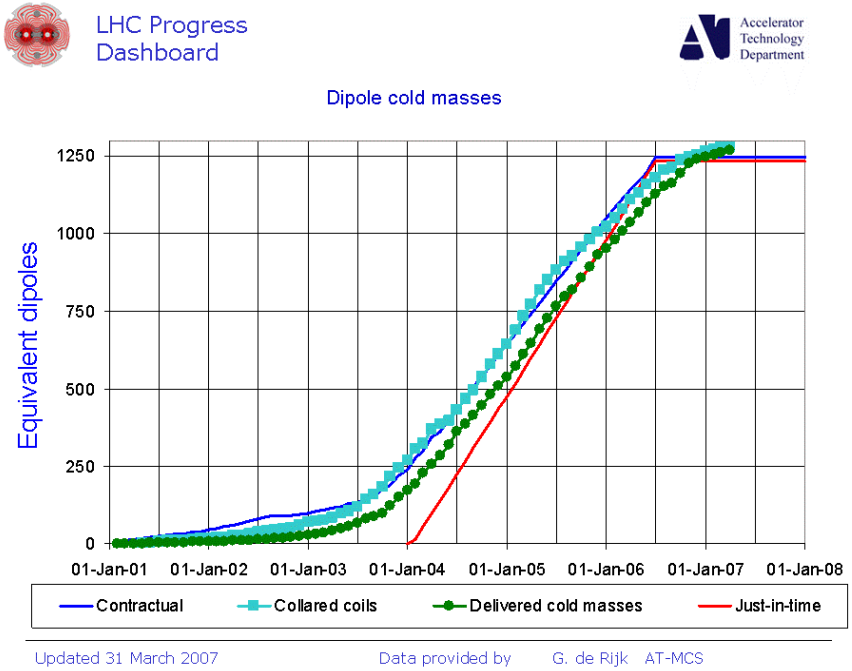
Point 2: ALICE Heavy ions

Point 5: CMS General purpose

Point 8: LHCb B-physics

Spectacular achievements

26 April 2007: last superconducting magnet lowered into the LHC tunnel

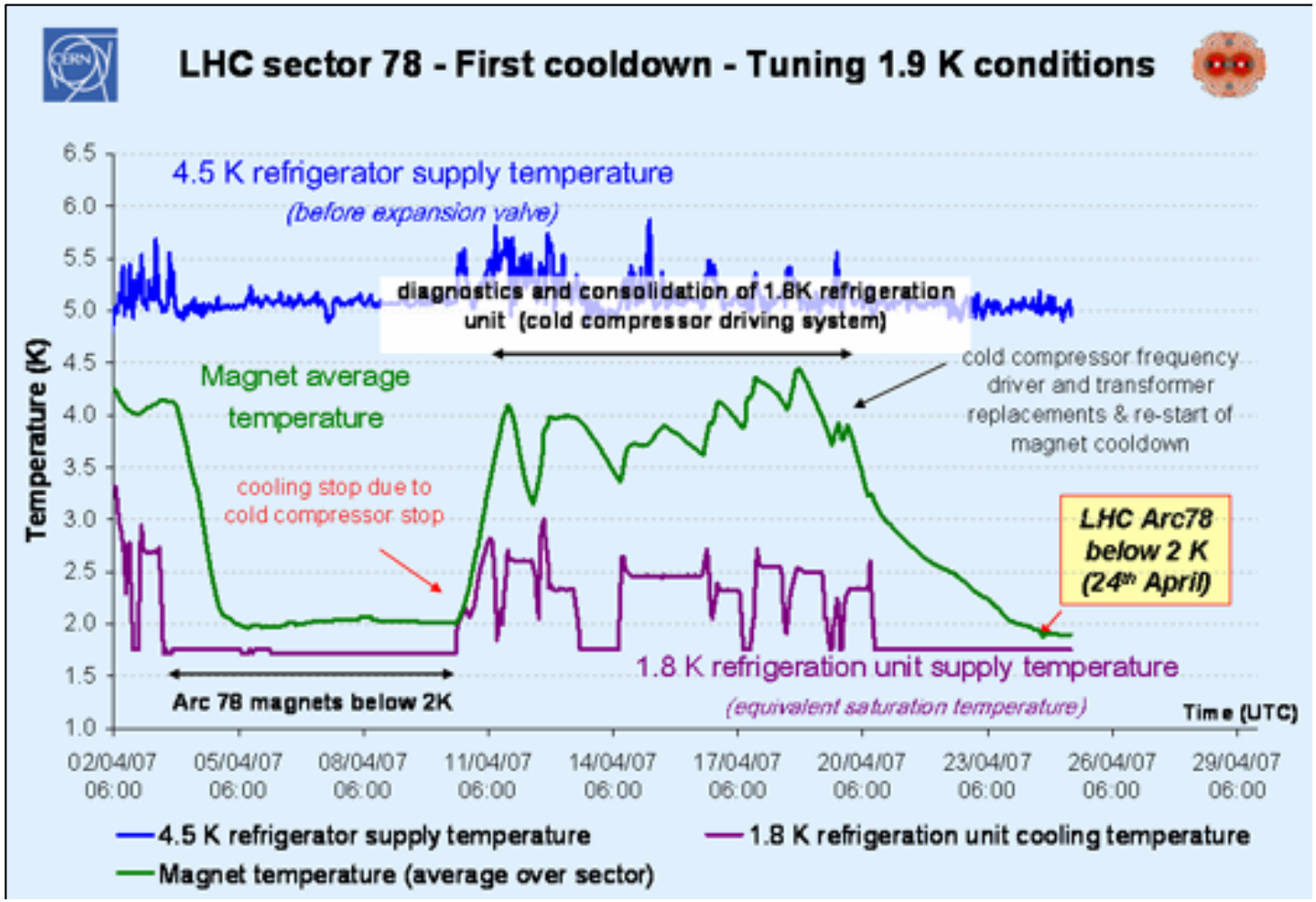


Once magnets installed they need to be interconnected (1700 interconnections)

Work well advanced, six magnet sectors fully interconnected, remaining ones almost done



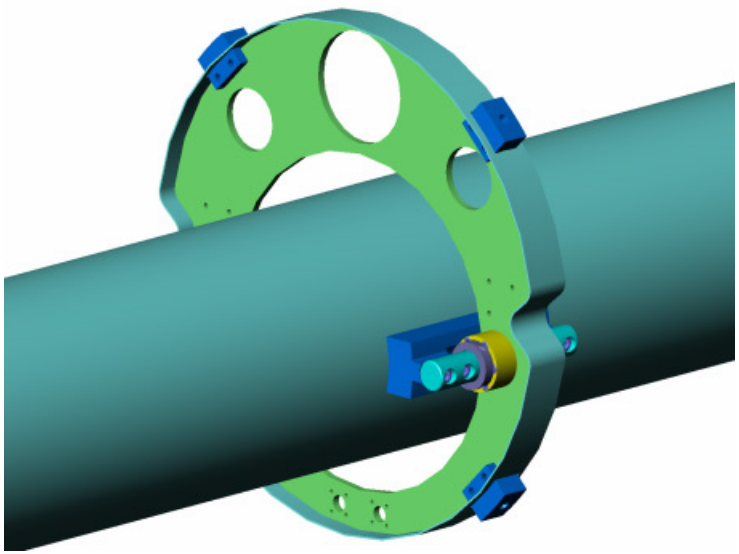
5 April: Sector 7-8, one eight of the LHC ring, 3.3 Km in length, cooled down to 1,9 Kelvin, after two months of commissioning work

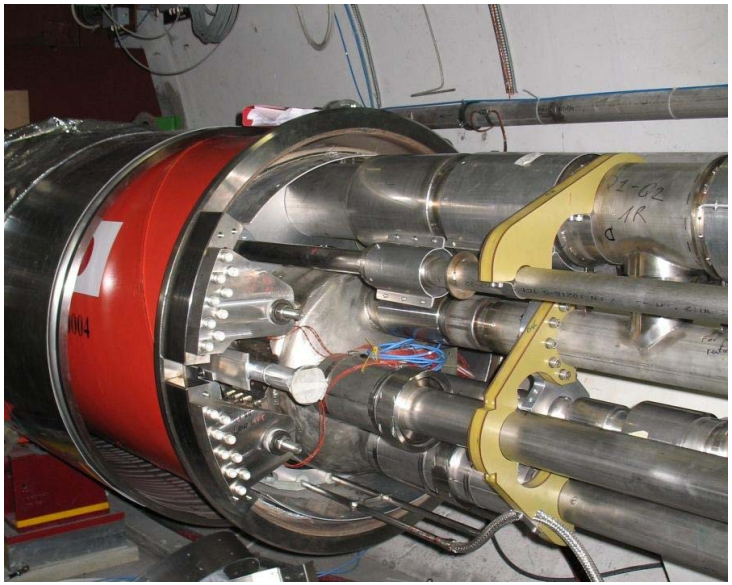


.. and work for mastering problems of a very complex system

27 March: high pressure test of an "inner triplet" of quadrupoles in the LHC tunnel.

Longitudinal forces applied during the test caused a magnet to move, leading to break of support system.





Solution found: strengthen support with longitudinal support rods attached with brackets to cold mass and cryostat outer wall

Impact of repair on schedule minimised by isolating faulty triplets for commissioning of first sectors

Addditional warm-up/cooldown cycles required for testing after repairs

RF bellows in the 1700 interconnections

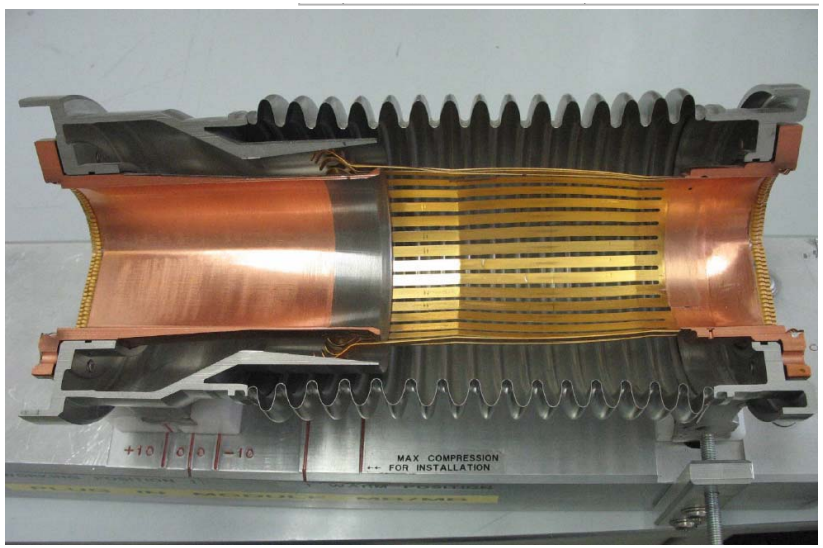
Buckled fingers into beam aperture found in sector 7-8 (5 cases)

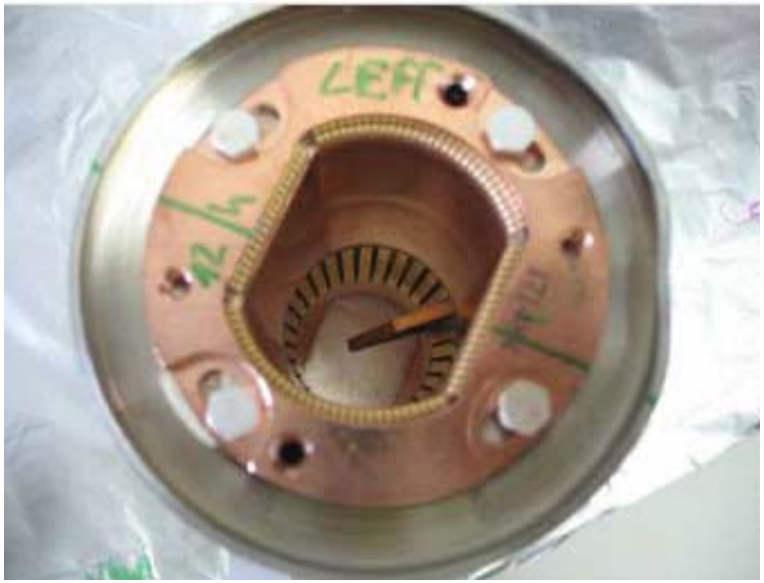
Problem found to happen during warm-up of sector

Diagnostic methods for verification of a clear aperture developed

Faulty fingers replaced

Investigation underway to ascertain causes understand how to prevent further damage





Some slowing down of the interconnection work because of this problem

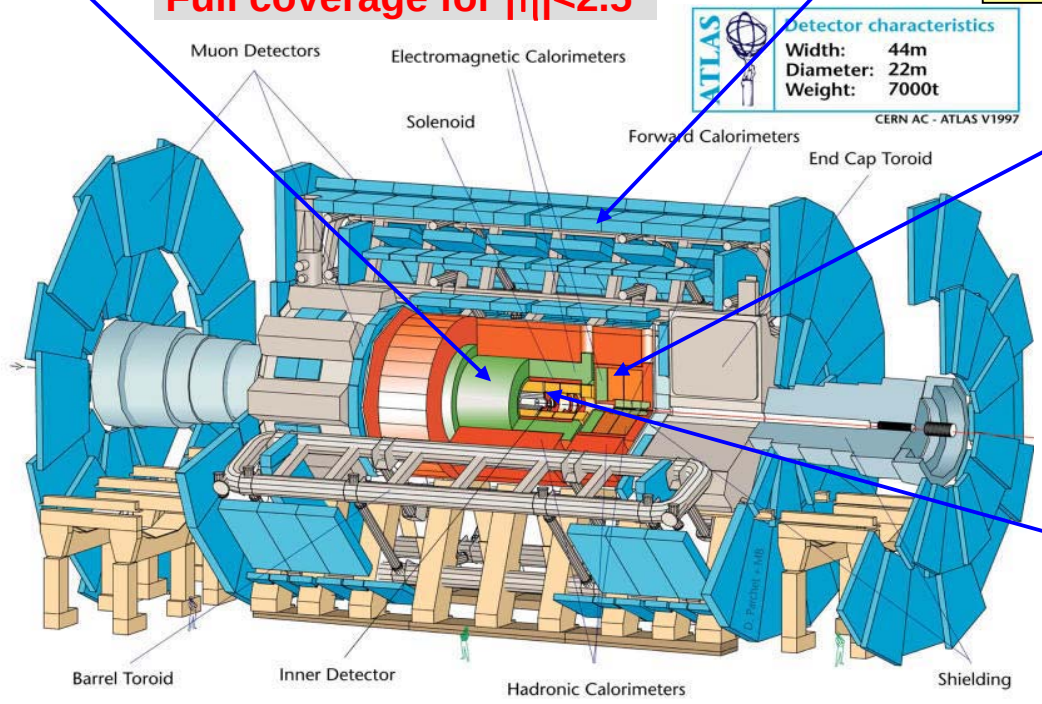
ATLAS detector

EM Calorimeters, $\sigma/E \approx 10\%/\sqrt{E(GeV)} \oplus 0.7\%$

excellent electron/photon identification

Good *E* resolution (e.g., $H \to \gamma\gamma$)

Full coverage for $|\eta|<2.5$



Precision Muon Spectrometer,

$\sigma/p_T \approx 10\%$ at 1 TeV/c

Fast response for trigger

Good *p* resolution

(e.g., $A/Z' \to \mu\mu$, $H \to 4\mu$)

Hadron Calorimeters,

$\sigma/E \approx 50\% / \sqrt{E(GeV)} \oplus 3\%$

Good jet and E_T miss performance

(e.g., $H \to \tau\tau$)

Inner Detector:

Si Pixel and strips (SCT) &

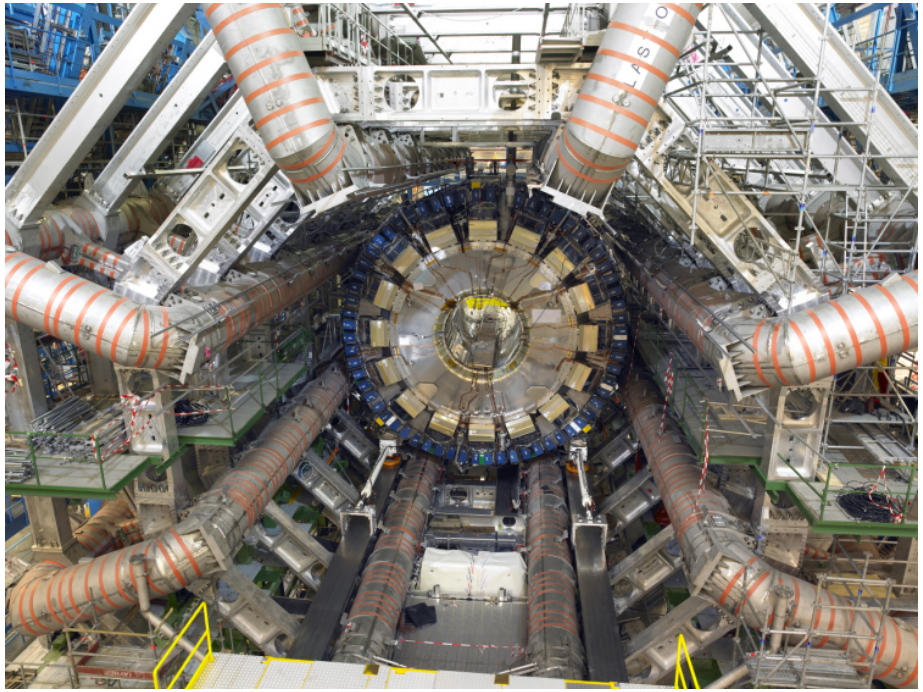
Transition radiation tracker (TRT)

$\sigma/p_T \approx 5 \times 10^{-4}\ p_T \oplus 0.001$

Good impact parameter res.

$\sigma(d_0)=15\mu m$@20GeV (e.g. $H \to bb$)

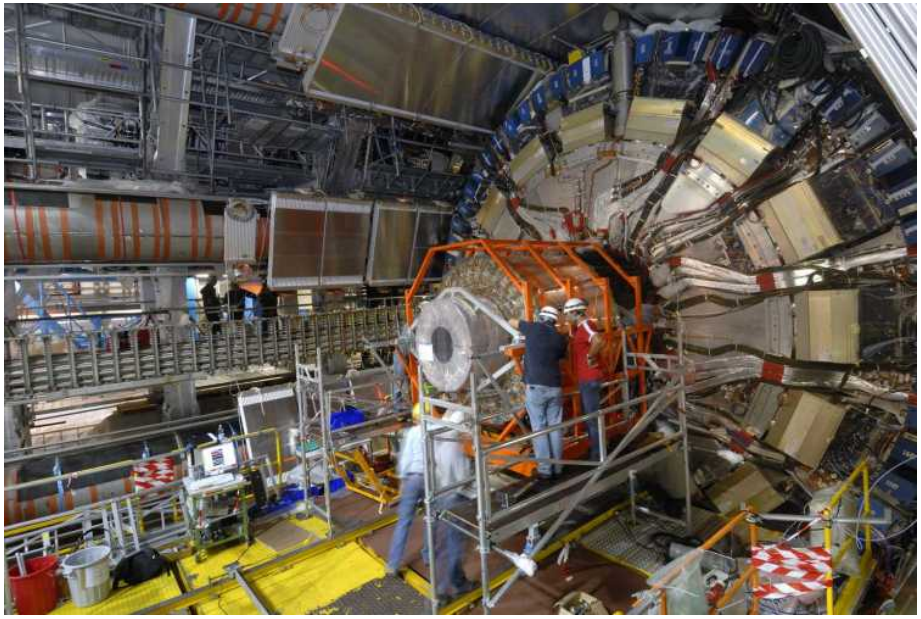
Magnets: solenoid (Inner Detector) 2T, air-core toroids (Muon Spectrometer) ~0.5T



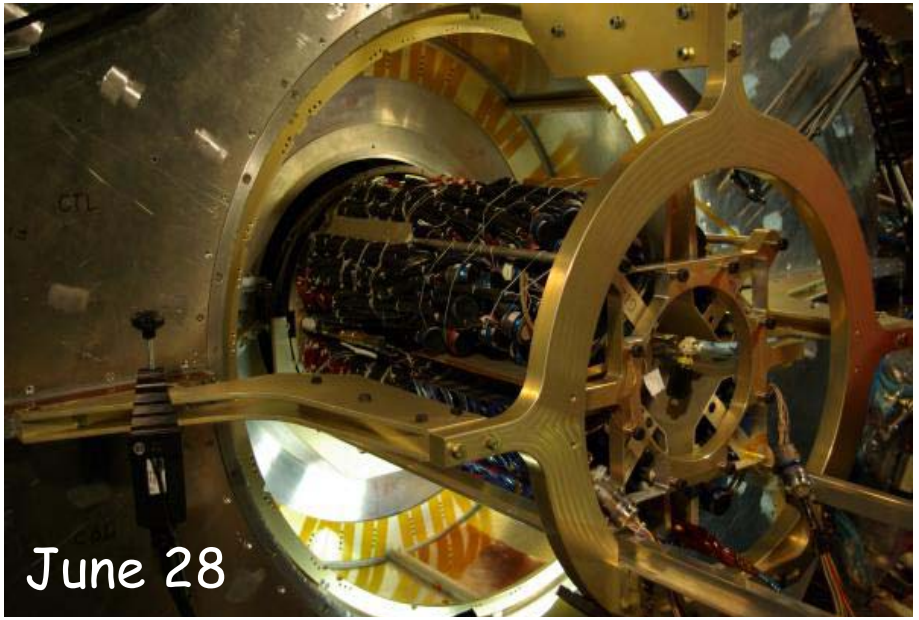
The calorimeters and the solenoid are installed at their nominal position inside the barrel toroid magnet.

Insertion of the inner detector into the solenoid

The barrel toroid is almost fully equipped with the muon chambers

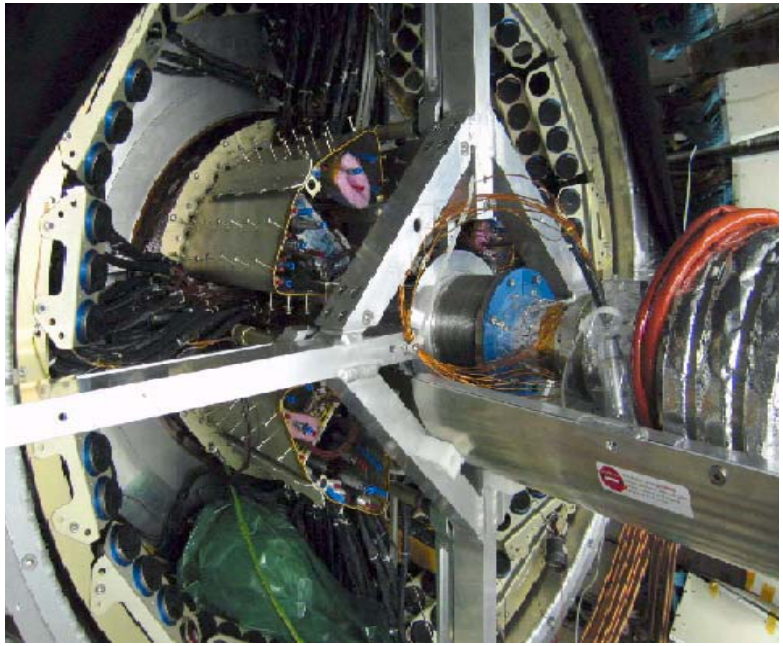


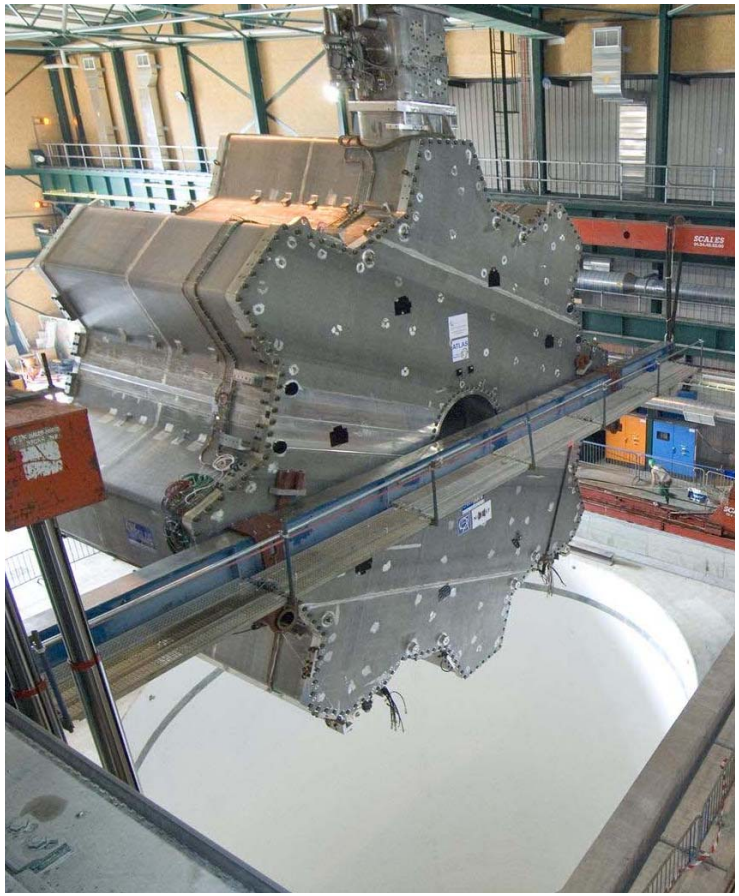


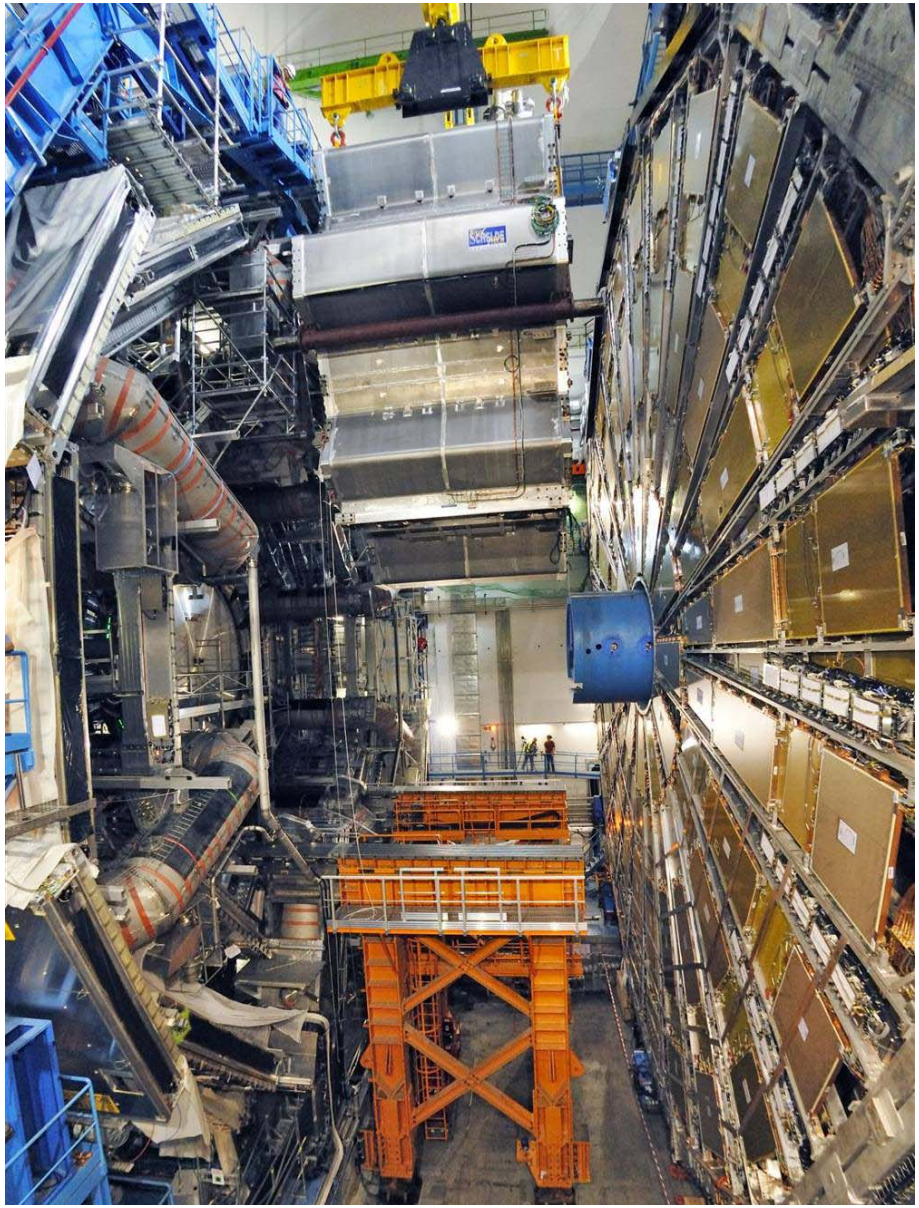


Pixel detector successfully installed

After installation, positioning phase completed, and test of cables on first patch panel



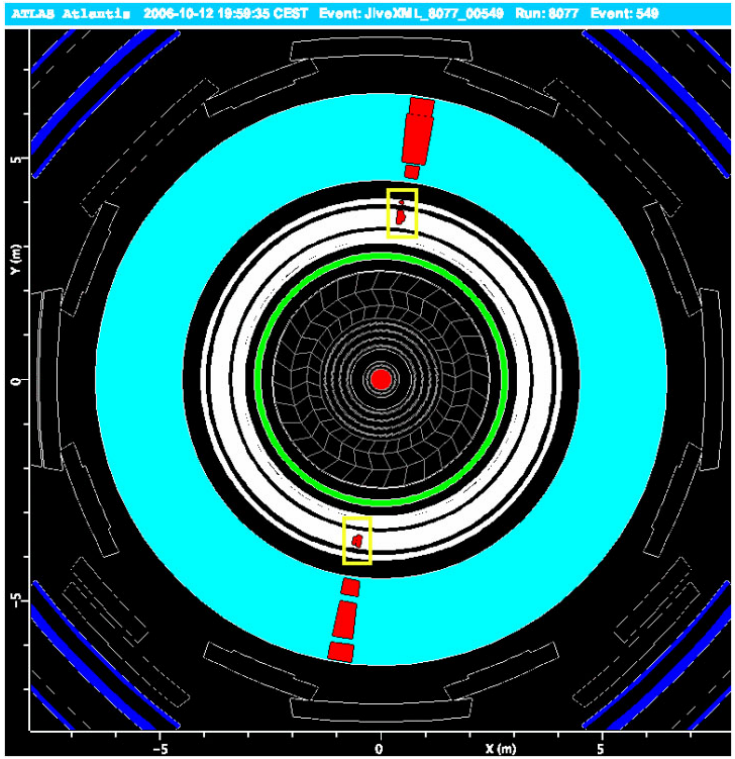




Both end cap toroids now lowered into the pit

The barrel toroid was ramped to full field

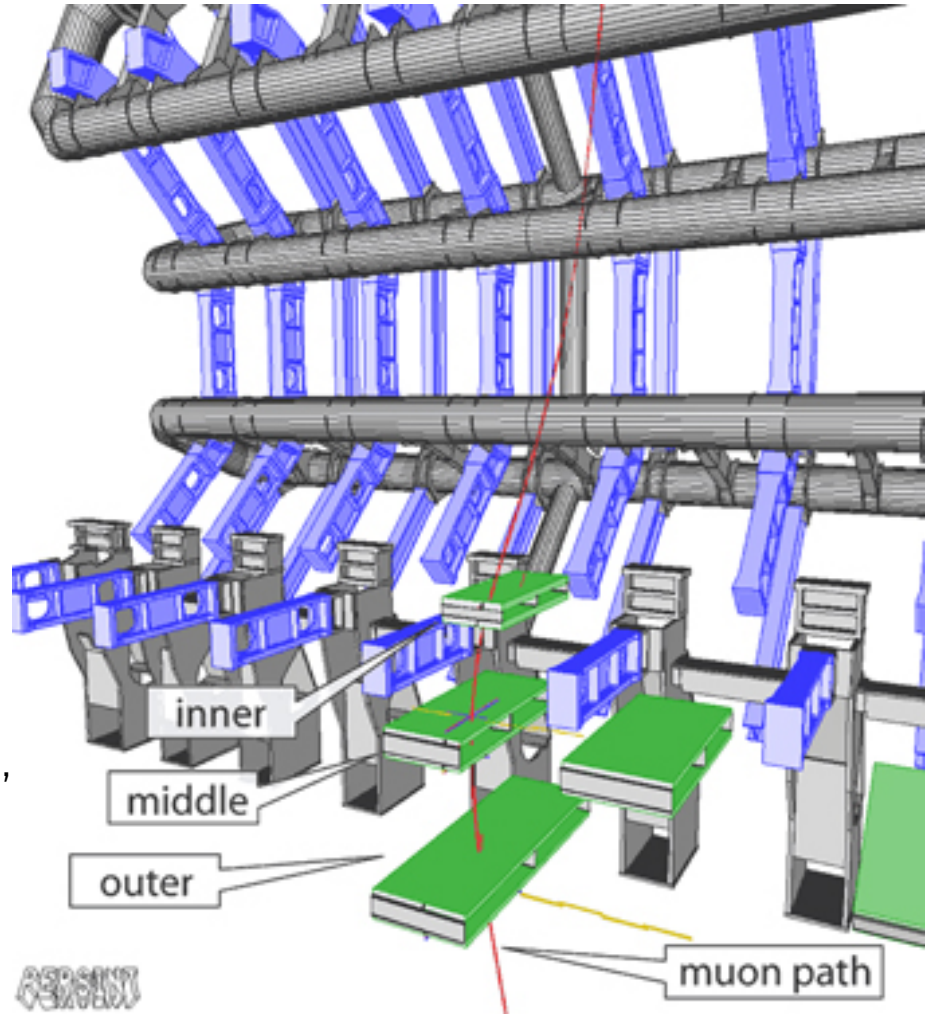
And the first cosmic muons curved by the toroidal field are detected by the muon chambers



The system is being commissioned:

Cosmic rays are being observed in the calorimeters,

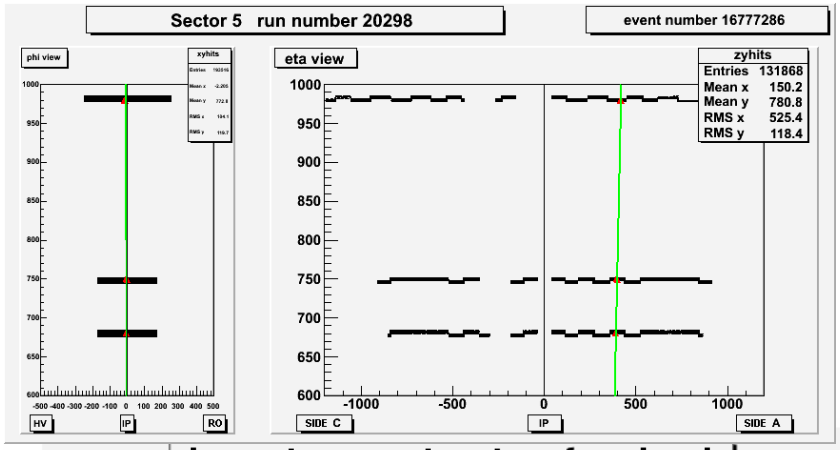
in the inner detector and in the muon system.

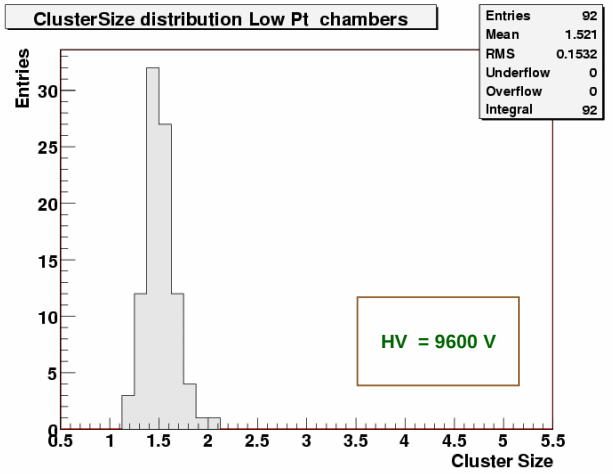


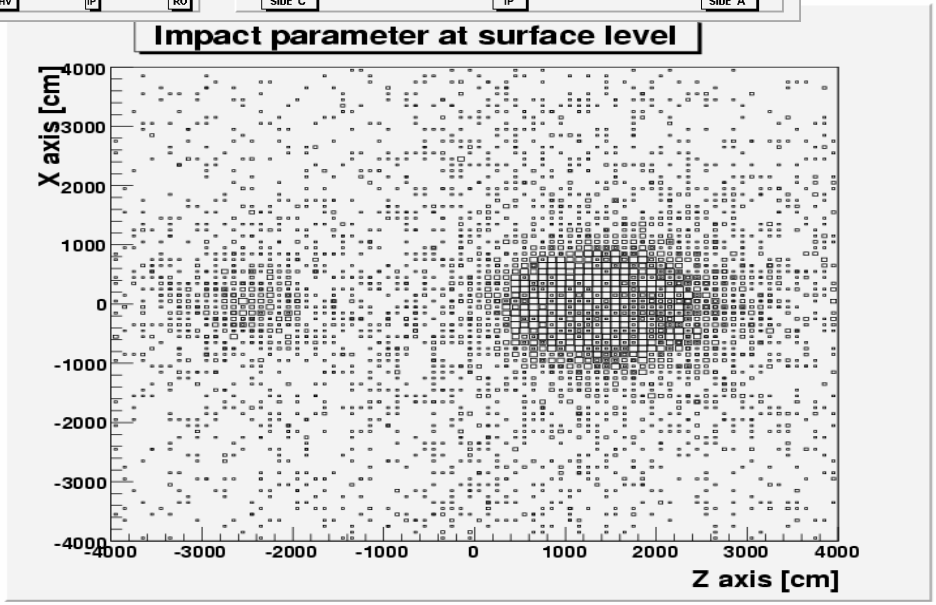
ATLAS Preliminary

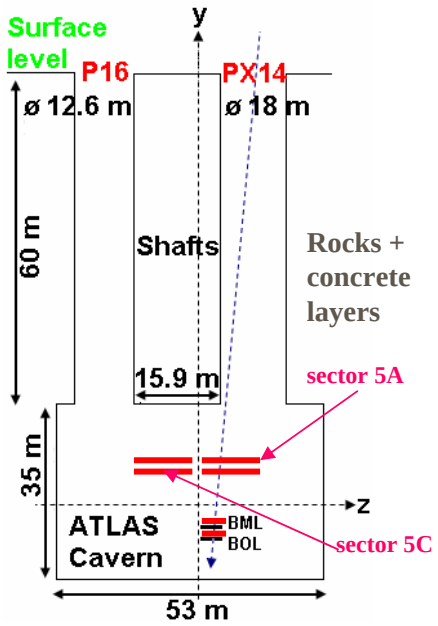
RPC Sector 5

RPC standalone track reconstruction









A few examples of required performance:

- Lepton measurement: $p_T \sim \mathrm{GeV} \rightarrow 5\mathrm{TeV}$ ($b \rightarrow lX$, W', Z')
- Mass Resolution (m~ 100 GeV):

  $\sim 1\%$ $(H \rightarrow \gamma\gamma, 4l)$

  $\sim 10\%$ $(W \rightarrow jj,\ H \rightarrow bb)$

- Calorimeter coverage: $|\eta| < 5$ (E_T^{miss}, forward jet tag)
- Particle identification :

  $\epsilon_b \sim 50\%$ $R_j \sim 100$ $(H \rightarrow bb$, SUSY)

  $\epsilon_\tau \sim 50\%$ $R_j \sim 100$ $(A/H \rightarrow \tau\tau)$

  $\epsilon_\gamma \sim 80\%$ $R_j \sim 10^3$ $(H \rightarrow \gamma\gamma)$

  $\epsilon_e > 50\%$ $R_j \sim 10^5$

- Trigger: 40 MHz$\rightarrow$ 100 Hz reduction

Commissioning scenarios

We need to address a very difficult problem:

- Complex detector with tens of millions of channels and many different subsystems
- Ambitious performance goals, based on complex algorithms involving the combined performance of all subdetector systems

Large amount of work (and time) required to control detector at desired level

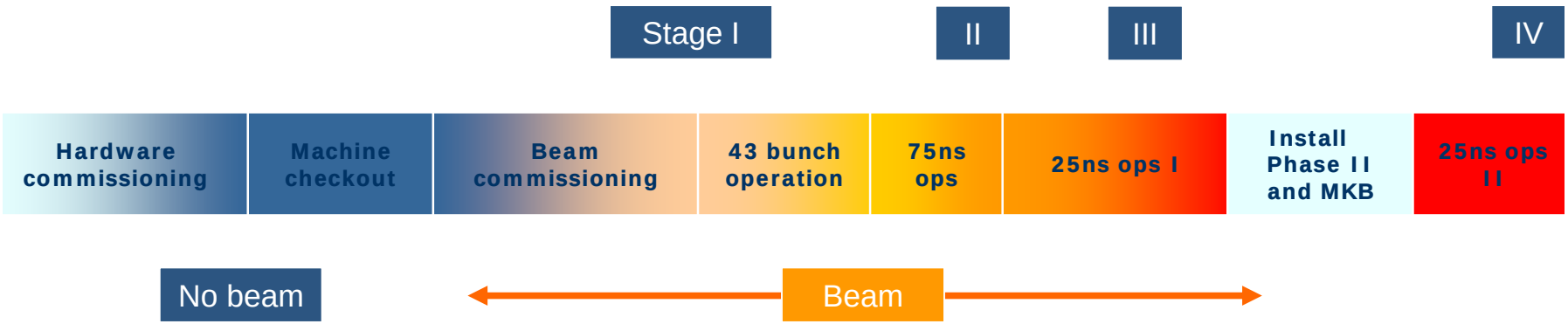
Need however to be ready to optimally exploit the very first LHC data

Final understanding of detectors only with real collisions in LHC environment

Develop strategy to exploit time from now to collisions to achieve detector understanding adequate to fully take advantage of data from the first day

Main variables: readiness of detectors, time before LHC is running at full steam, building up of integrated luminosity

Staged commissioning plan for protons (R. Bailey)



I. Pilot physics run
- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Expected performance ~10^{31} cm^{-2} s^{-1} at ~1 event/crossing
- Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
- Performance limit 10^{32} cm^{-2} s^{-1} (event pileup)

II. 75ns operation
- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Expected performance ~10^{32} cm^{-2} s^{-1} at ~1 event/crossing
- Push squeeze and crossing angle
- Performance limit 10^{33} cm^{-2} s^{-1} (event pileup)

III. 25ns operation I
- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal
- Performance limit 2 10^{33} cm^{-2} s^{-1}

IV. 25ns operation II
- Push towards nominal performance

Need to map this to dates and time

General schedule (W. Scandale, 17/09)

- Engineering run originally foreseen at end 2007 now precluded by delays in installation and equipment commissioning.
- 450 GeV operation now part of normal setting up procedure for beam commissioning to high-energy
- General schedule has been reassessed, accounting for inner triplet repairs and their impact on sector commissioning
  - All technical systems commissioned to 7 TeV operation, and machine closed April 2008
  - Beam commissioning starts May 2008
  - First collisions at 14 TeV c.m. July 2008
  - Pilot run pushed to 156 bunches for reaching 10^{32} $cm^{-2}s^{-1}$ by end 2008
- No provision in success-oriented schedule for major mishaps, e.g. additional warm-up/cooldown of sectors

For 2008 maximum achieve Stage I: integrated luminosity (guess) < 100 pb^{-1}

Based on this information develop start-up strategy

- Last few years: extensive test-beam activities with final detector components
  - Standalone Detector test beams: Basic calibration of calorimeter modules, test of electronics and alignment procedures
  - ATLAS combined test-beam of full slice of detector: test in real life particle ID algorithms, procedures of inter-detector alignment, validation of detailed simulation
- Now, extending up to most of 2007:
  - Cosmics data taking: Study detector timing and alignment.

    Have $\sim$ 0.5 Hz of Through-going muons passing near origin

    Can study EM calorimeter response variations versus η to 0.5%

    May achieve statistical precision on alignment of 10μm in part of Pixels/SCT

    May achieve 30-40 μm alignment precision for muon chambers within $\pm 60^{\circ}$ to vertical

- From first injections: beam-halo and beam-gas interactions. More specialised alignment work

  Alignment and calibration for detector sectors (End Caps) for which cosmic geometry not adequate

- First 14 TeV interactions:
  - Understand and calibrate detector and trigger in situ using well-known physics samples:
    - $Z \to ee, \mu\mu$: tracker, ECAL, muons system
    - $tt \to b\ell\nu bjj$: Jets scale, b-tag performance, $\not\!\!E_T$
  - Understand basic SM physics at 14 TeV: first checks of MonteCarlo
    - jets and W, Z cross-section top mass and cross-section
    - Event features: Min. bias, jet distributions, PDF constraints
  - Prepare road to discovery: background to discovery from tt, W/Z + jets.

Physics with early data

Realistic approach: assume low selection efficiency for interesting events

Process	$\sigma \times BR$		Events selected for 100 pb^{-1}
$W \to \ell\nu$	20 nb	$\sim 20\%$	~ 400000
$Z \to \mu\mu$	2 nb	$\sim 20\%$	~ 40000
$\bar{t}t$ (semileptonic)	370 pb	$\sim 1.5\%$	< 1000

Jets and minimum bias statistics only limited by allocated trigger bandwidth

Already in autumn 2008 probably enough statistics for physics studies

It is mandatory to demonstrate that we understand LHC physics through SM measurement before going for discovery physics

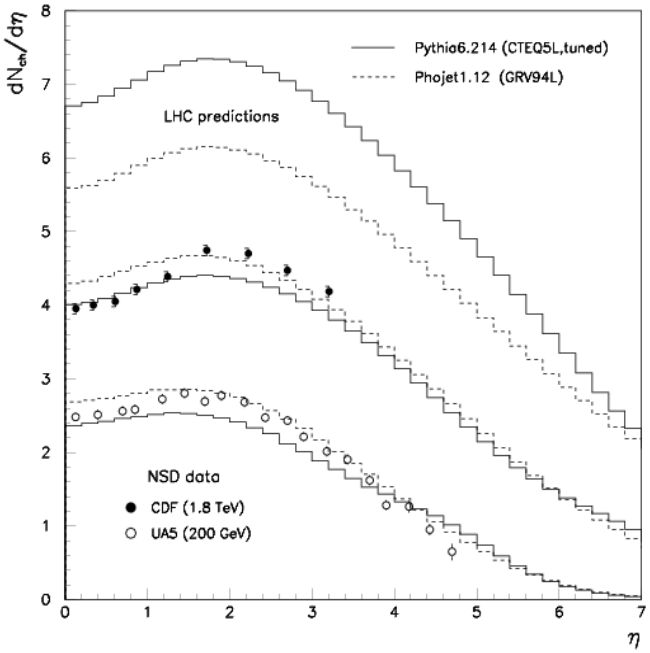
Nobody will believe we have an excess in a channel with $\not\!\!E_T$+leptons+jets if we can not show that we can perform measurements on jets, W, Z, top

Show today plans for some early measurements which will probably be the first physics publications from the LHC

Minimum bias and Underlying Event studies

Hadronic interactions:

- Hard processes (high p_T): well described by PQCD
- Soft interactions (low p_T): require non-perturbative phenomenological models:
  - Minimum bias: non single-diffractive events: $\sigma \sim 60 - 70$ mb
  - Underlying event: everything except two outgoing hard scattered jets



Large uncertainty in prediction of track multiplicity when extrapolating from Tevatron data

First physics available at the LHC

Interesting *per se*

Modeling of minimum bias pile-up and underlying event necessary tool for high P_T physics

Measuring minimum bias with early data (ATLAS preliminary)

Number of charged tracks N_{ch} as a function of η $(dN_{ch}/d\eta)$ and p_T $(dN_{ch}/d\eta)$

On fully simulated events compare reconstructed to generated distributions

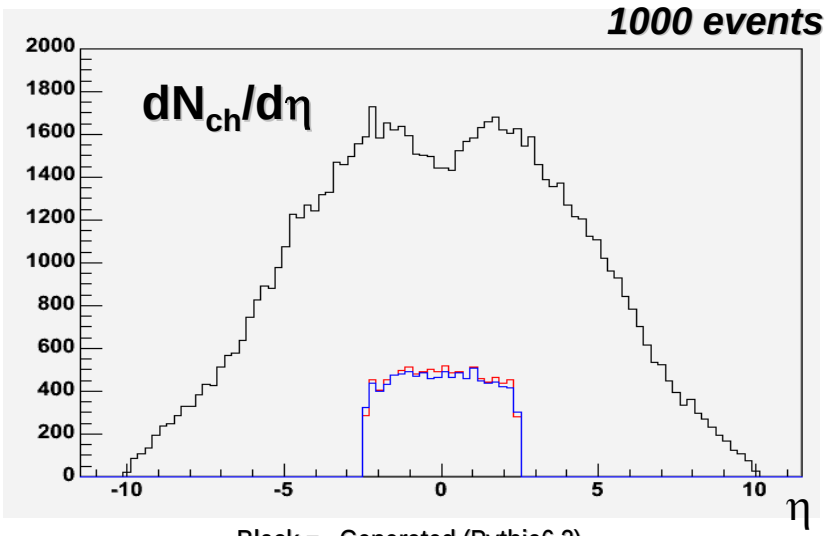
Very few events required

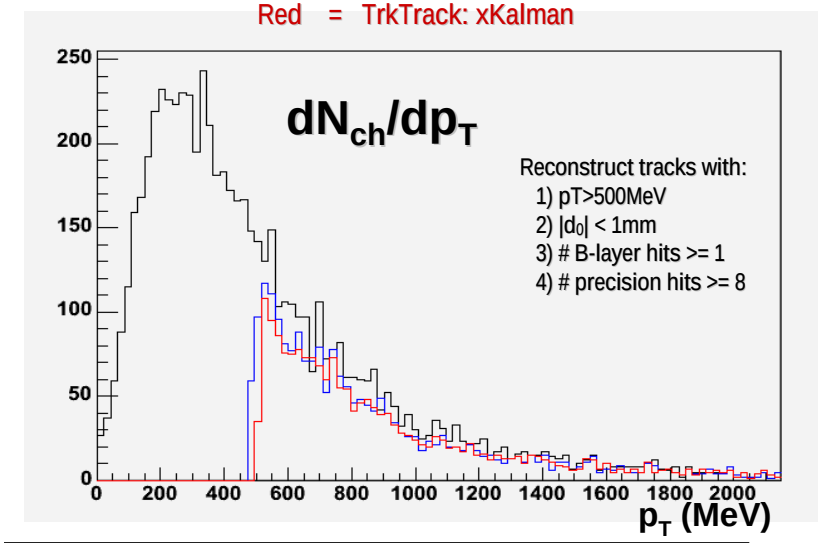
Only a fraction of tracks reconstructed:

- Limited rapidity coverage
- Can only reconstruct track p_T with good efficiency down to ~500 MeV

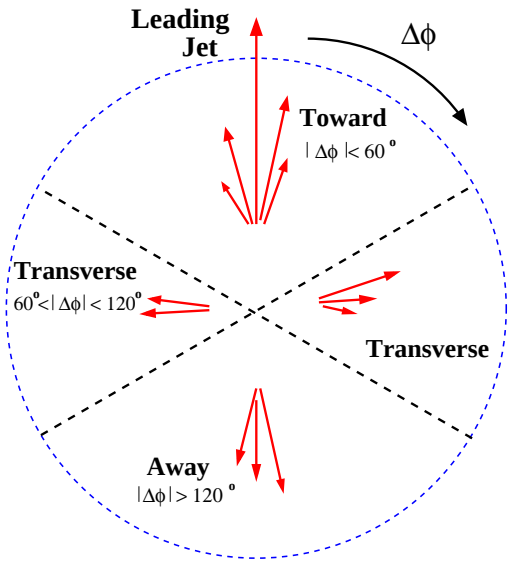
Need to apply correction factor from MonteCarlo to subtract minimum bias: systematic uncertainty

Explore extending tracking down to lower p_T, lots of work in CSC notes





Measuring Underlying Event at the LHC



Perform measurement by looking at tracks in the "transverse" region with respect to jet activity

On fully simulated events compare reconstructed and generated multiplicity

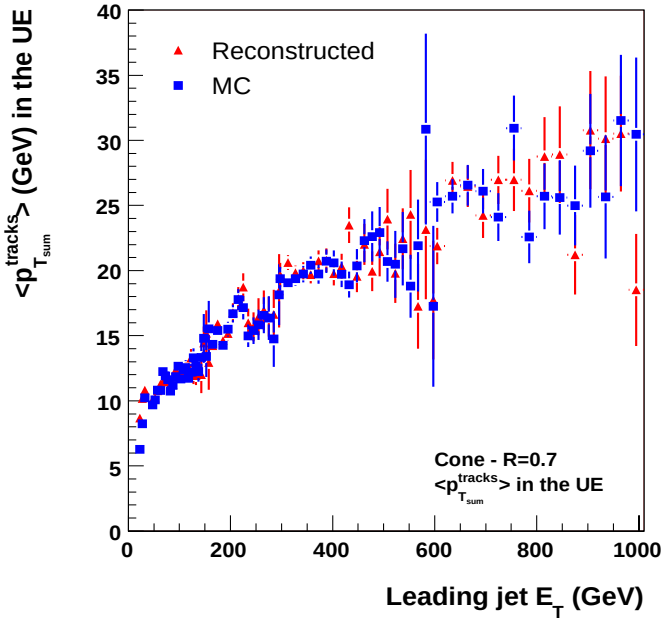
Select:

$N_{jet} > 1 \quad p_T^{jet} > 10 \text{ GeV} \quad |\eta_{jet}| < 2.5$

$p_T^{track} > 1.0 \text{ GeV} \quad |\eta_{track}| < 2.5$

Good agreement reconstructed/generated

Can use to tune MonteCarlo

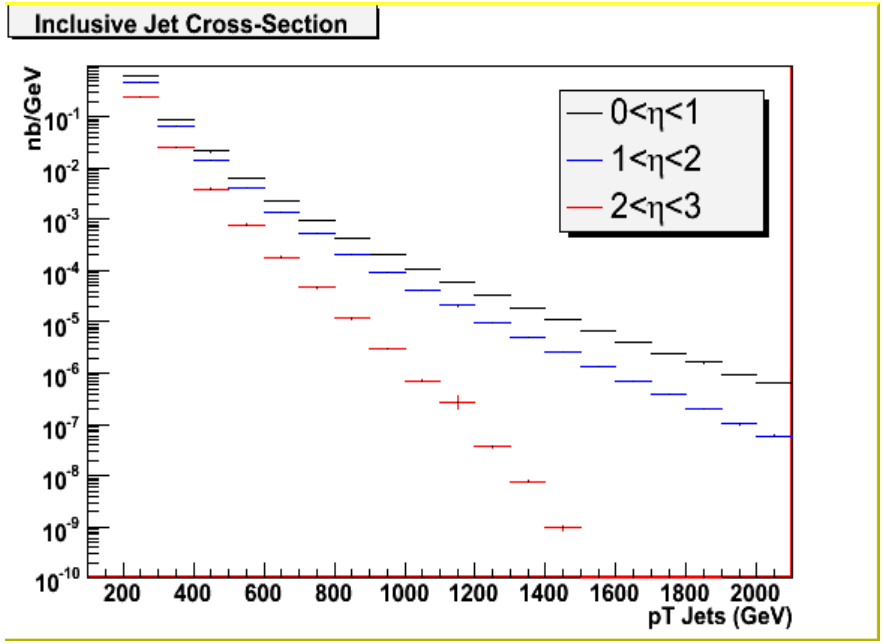


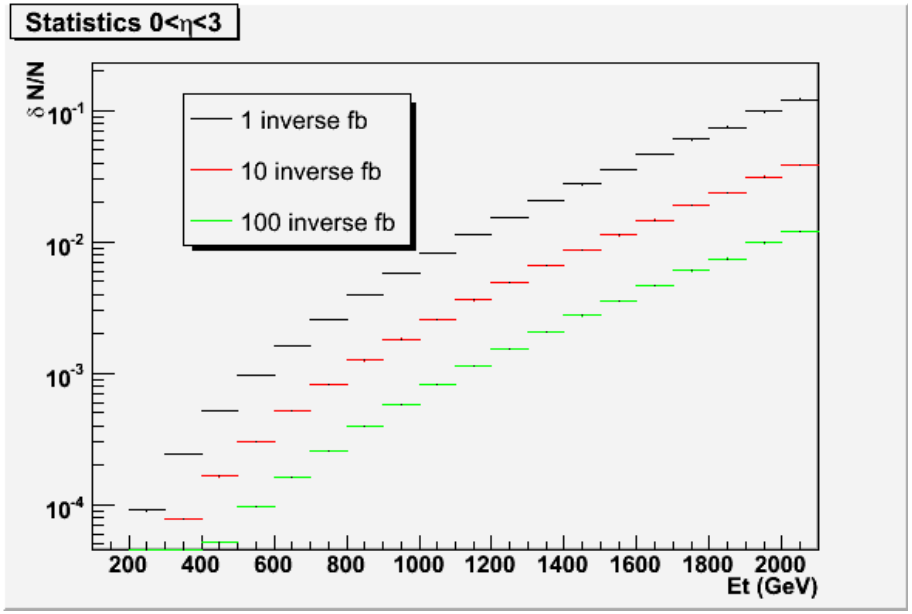
Inclusive Jet cross-section measurement

Concerns all events containing jets, the bulk of high p_T events at the LHC

Show preliminary investigation of ATLAS Glasgow group assessing relative weight of possible error sources

Study based on the NLOJET++ calculation (Z. Nagy)





Statistical error

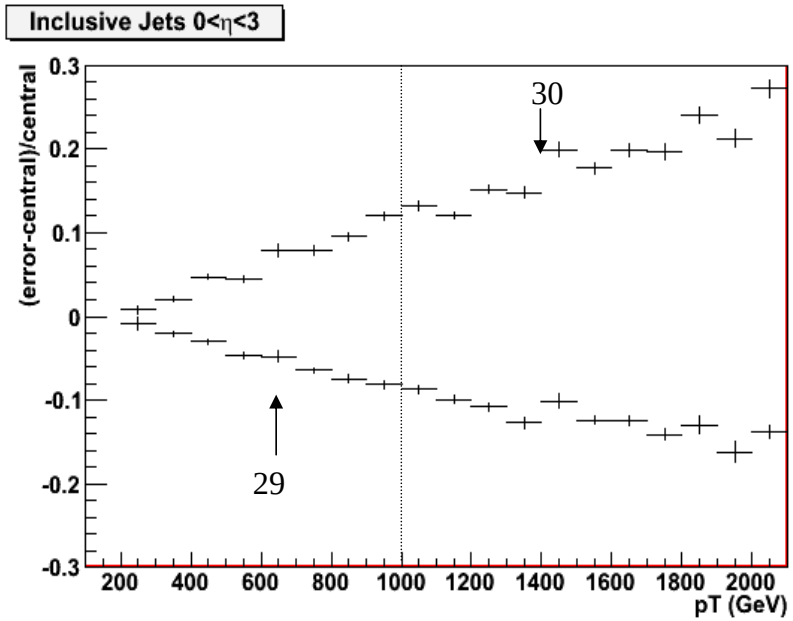
Naive estimate: take error as $\sqrt{N}$, with N number of events for a given integrated luminosity

Plot relative error $\sqrt{N}/N$

For 1 fb^{-1} 1% error for $P_T(jet) \sim 1$ TeV

For 100 pb^{-1} 1% error for $P_T(jet) \sim 0.8$ TeV

Theoretical uncertainties



Use LHAPDF error estimate

Study relative change of NLOJET X-S for the extreme sets of the CTEQ6 PDF

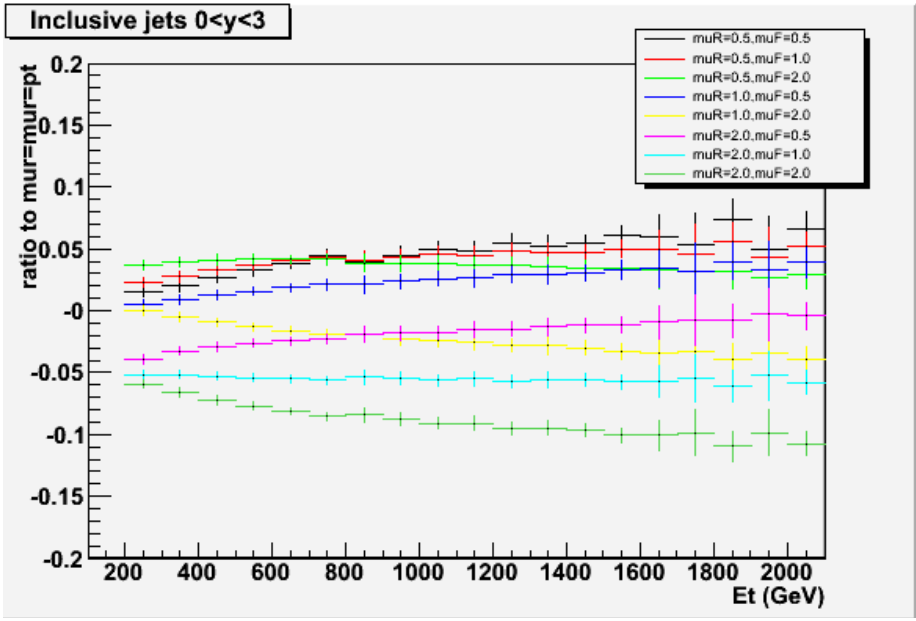
For a jet p_T of 1 TeV errors are approx 10 to 15%

Dominated by high-x gluon uncertainty

Vary renormalisation (μ_R) and factorisation scale (μ_F) between $0.5E_T$ and $2E_T$

Relatively small variation due to use of NLO cross-sections

Uncertainty of 5 to 10% on inclusive jet cross-section for jet p_T of 1 TeV

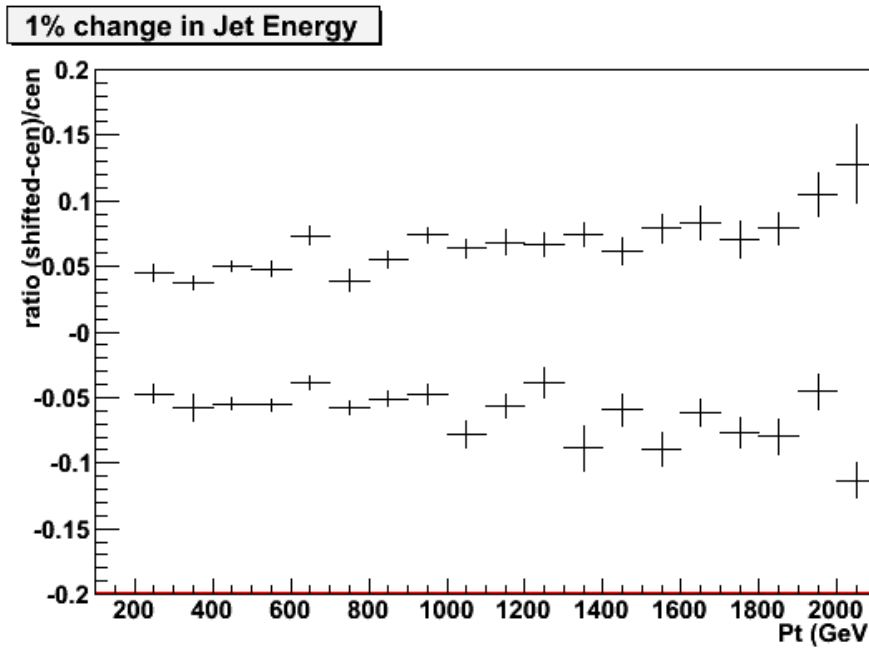


Experimental errors

Many possible sources of experimental errors:

- Jet energy scale,
- Linearity of calo response
- Jet resolution, UE subtraction, trigger efficiency....
- Luminosity determination

Focus on jet energy scale, dominant in Tevatron analyses



Uncertainty on jet scale of 1% yields error on σ(jet) X-s of 6%

Uncertainty on jet scale of 5% yields error on jet σ(jet) of 30%

Jet scale must be known to $\sim 1\%$ in the TeV region: $\Rightarrow$ control of linearity to carry to high energy scale established at 100 GeV.

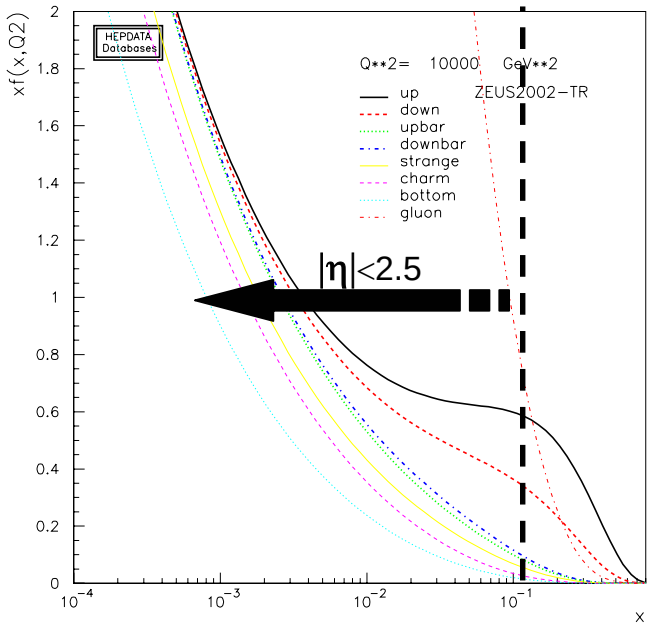
Requires studies of many control samples: tt, γ+jets, Z+jets,... likely to be the dominant factor in determining the time of publication

Studies of W and Z production

W and Z production cross-section precisely predicted by QCD

Measuring them is one of first basic physics checks at the LHC

Eventually can be used as a luminosity measuring device if theoretical and experimental uncertainties down to $\sim$3%



Main theoretical uncertainty: PDF parametrisation

For W and Z production at the LHC:

- Dominant sea-sea parton interactions at low x
- At $Q^2 = M_Z^2$ sea distributions driven by gluon
- Low x gluon has large uncertainty

Studying W and Z production can increase our knowledge of gluon SF

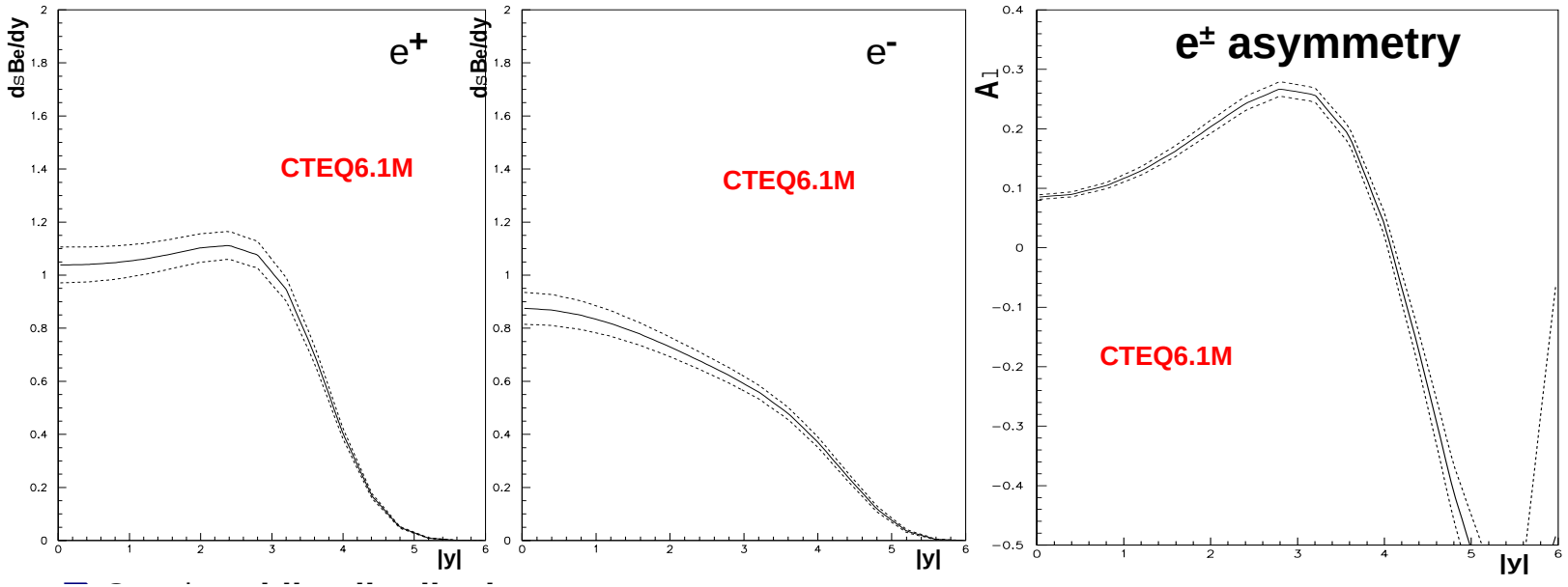
Show study performed by ATLAS Oxford group

Rapidity distributions

Shape of W y distributions particularly sensitive to PDF errors:

At y=0 total W PDF uncertainty order 8-10%, sum of uncertainty of single PDF (5-8%) and spread among paramtrisations (4-5%)

Observe lepton from W decays: sensitivity to gluon parameters similar to the W

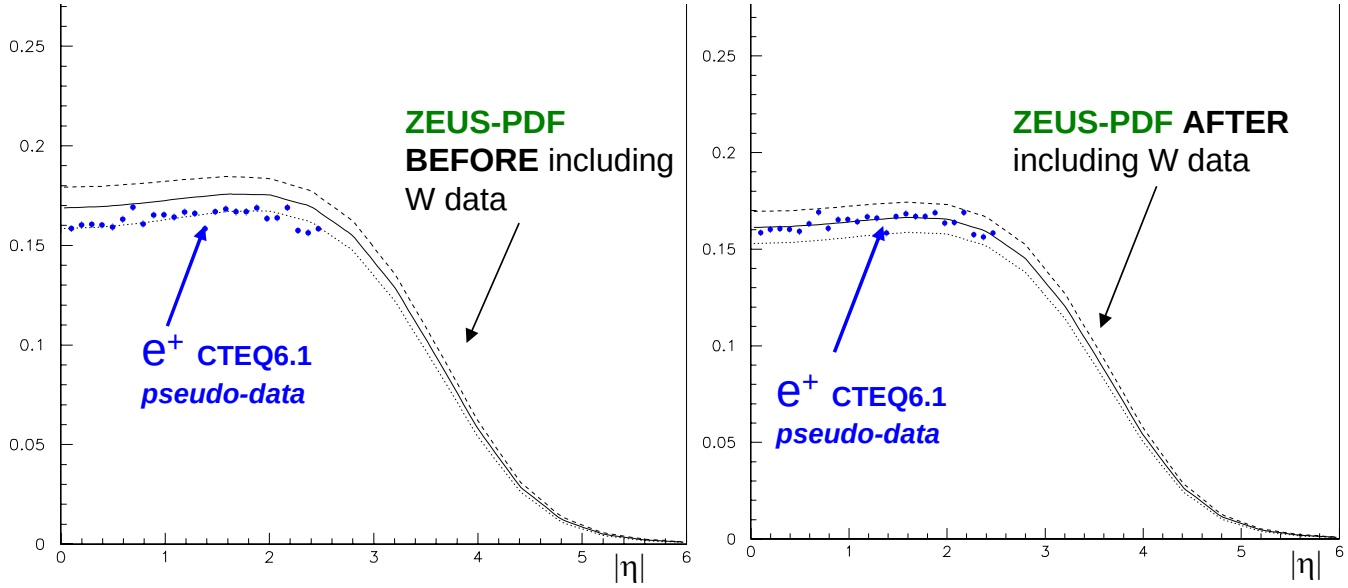


Uncertainties mostly canceled if asymmetry considered: SM benchmark

PDF constraining potential of ATLAS

Exercise: generate 1M ATLAS pseudo-data (ATLFAST) with CTEQ6.1 PDF's, correct back for acceptance effects, and include in ZEUS PDF fit

Statistics corresponds to $\sim$100-200 pb^{-1}



To simulate experimental uncertainties impose a 4% random error on data points

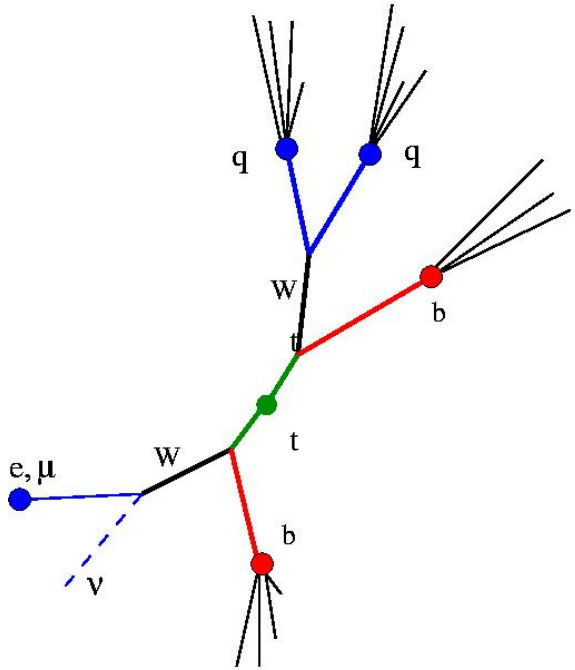
Low-x gluon distribution determined by shape parameter λ ($xg(x) \sim x^{-\lambda}$)

Observe 35% error reduction λ when ATLAS pseudo-data included in fit

Early top physics in ATLAS

Top production is ideal laboratory for initial studies

Very high cross-section at the LHC: $\sigma_{\bar{t}t} = 830$ pb



Semi-leptonic signature: $\bar{t}t \rightarrow b\ell\nu bqq$:

Easy to trigger on and to extract

involves many detector signatures:

lepton-id, $\not\!\!E_T$, Jet reconstruction and

calibration, b-tagging

Three main aspects of early top studies:

- Initial measurements of mass, σ_{tt}, possible deviations due to new physics
- Use as a calibration tool
- Learn how to control top as a background

Commissioning scenarios

Several months to achieve pixel alignment necessary for nominal b-tagging

Study separation of sample of top events from background without b-tagging

- Use high multiplicity in final state
- hard p_T cuts to clean sample and minimize contribution of additional jets

Even with a 5% selection efficiency still have $\sim$10 events/hour at 10^{33}

Full simulation study by the ATLAS NIKHEF group

Jet assignment:

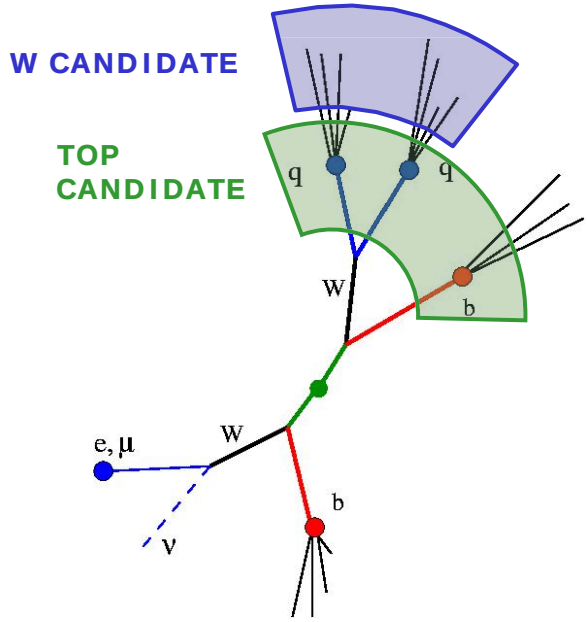
Hadronic top:

Three jets with highest $\Sigma \vec{p}_T$ as top decay products

W boson:

Two jets in hadronic top with highest momentum

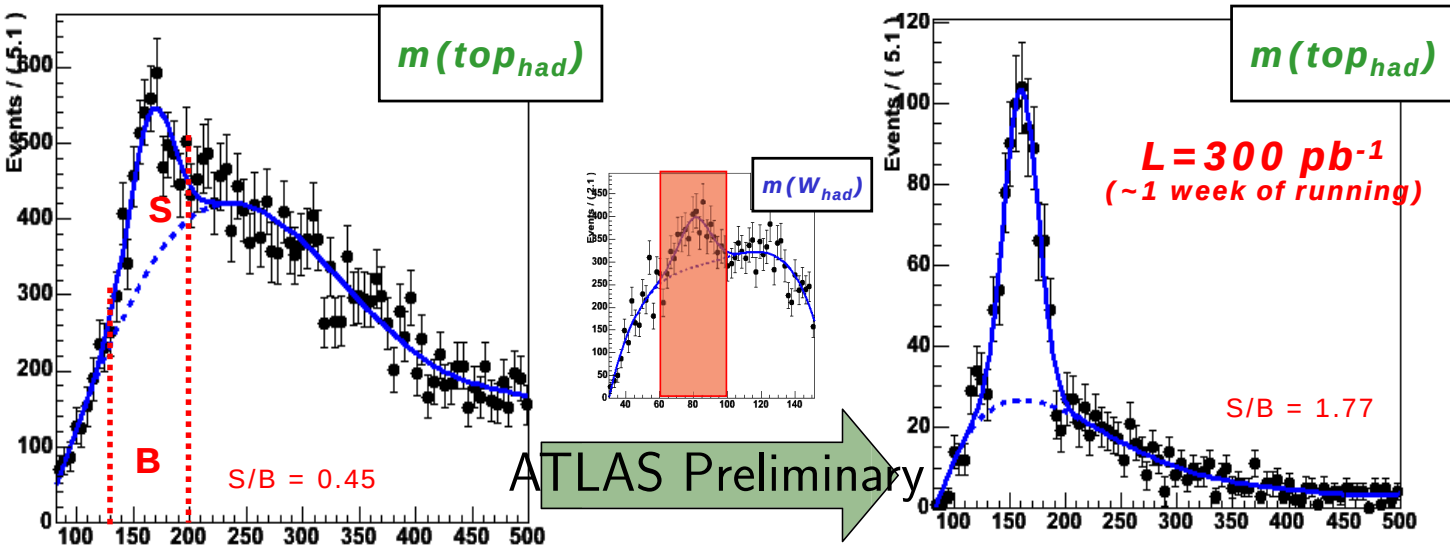
in reconstructed jjj C.M. frame



Signal + W+jets background

Exploit correlation between $m(top_{had})$ and $m(W_{had})$ to clean top signal

Show $m(top_{had})$ only for events with $|m(jj) - m(W)| < 10$ GeV



A clear top signal can be observed even at low statistics

Expect a statistical error on cross-section between 5 and 10%, depending on cuts

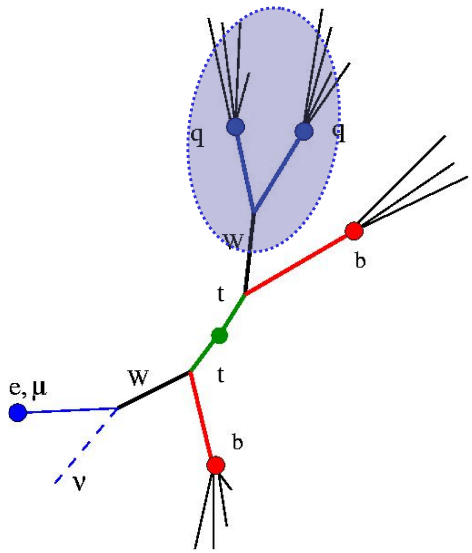
Error on $m(top)$ already dominated by systematic effects

Using ttbar events: jet energy scale from W

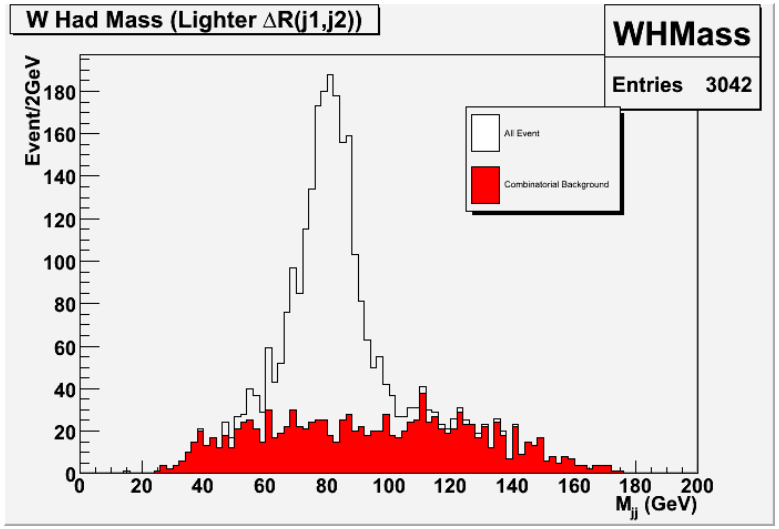
Exercise on ATLAS full simulation

Use top semileptonic decay: select two light jets from W decay, and calibrate to W mass

Selection with 1 or 2 b tags Typically 3000(6000) W/fb^{-1} for 2(1) b-tag, $\epsilon_{btag} = 60\%$



ATLAS Preliminary



W mass distribution ATLAS full sim, 500 pb^{-1}.

Using both b-tagging and kinematic constraints achieve purity of 80-90%

Cover jet energies from 40 to 400 GeV

Use a naive jet scaling method for equating the peak position to the nominal W mass

Expect to achieve a 1% calibration level with 1 fb^{-1}

Early discovery

Conditions for new physics to be visible in first LHC year (max 1 fb^{-1})

- Cross-section O(100 fb) for leptonic signatures
- Small SM backgrounds
- Clear kinematic signature (peak, edge). No need for counting experiment
- Signature visible also with not completely understood detector

Well studied and well motivated candidates:

- High mass resonances decaying into two leptons
- ets+$\not\!\!E_T$ (+ Multilepton) SUSY signals

  Probably two-leptons with correlated-flavour edge is easiest signal

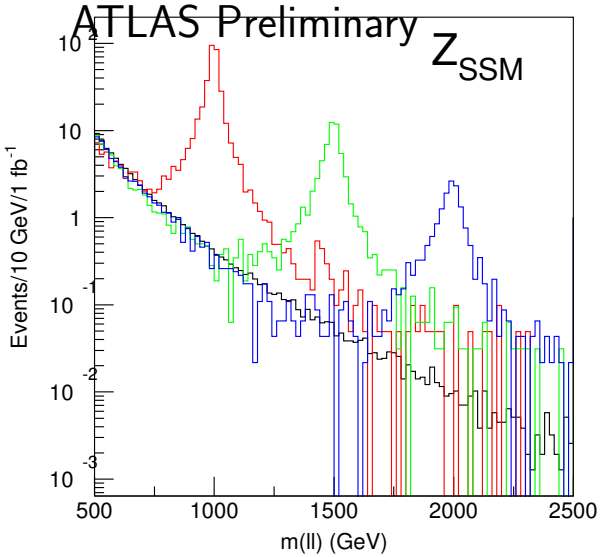
Key experimental issue: detector performance when calibration and alignment not perfectly understood

For reliable answers need in simulation detector geometry as-installed, material distortions and residual miscalibratio/misalignment effects

Incorporating now in ATLAS all this info from having most of the detector installed in the pit, and early commissioning studies

Z' statistics

Consider "Sequential" Z', same couplings as Standard Model



Drell-Yan background $\sim$ 2 orders of magnitude lower than signal in peak

Other backgrounds much smaller

Natural width Γ: $\Gamma/M \sim 0.03$

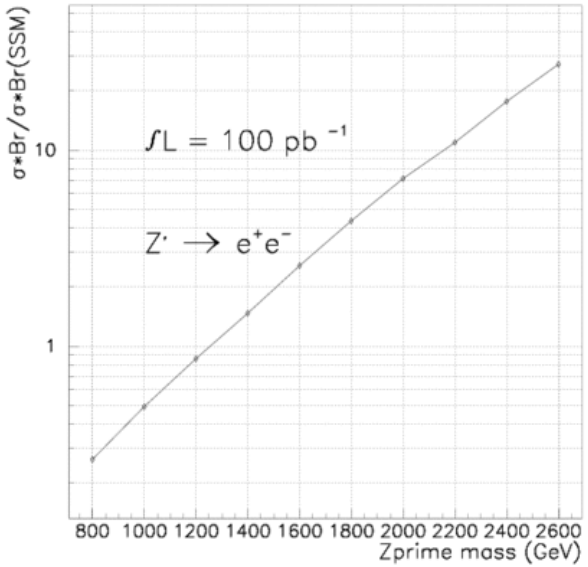
For $M_Z = 1$ TeV, 275 events in signal peak ($\pm 2\Gamma$) for 1 fb^{-1}. 2.5 events from Drell-Yan

ATLAS analysis with nominal performance:

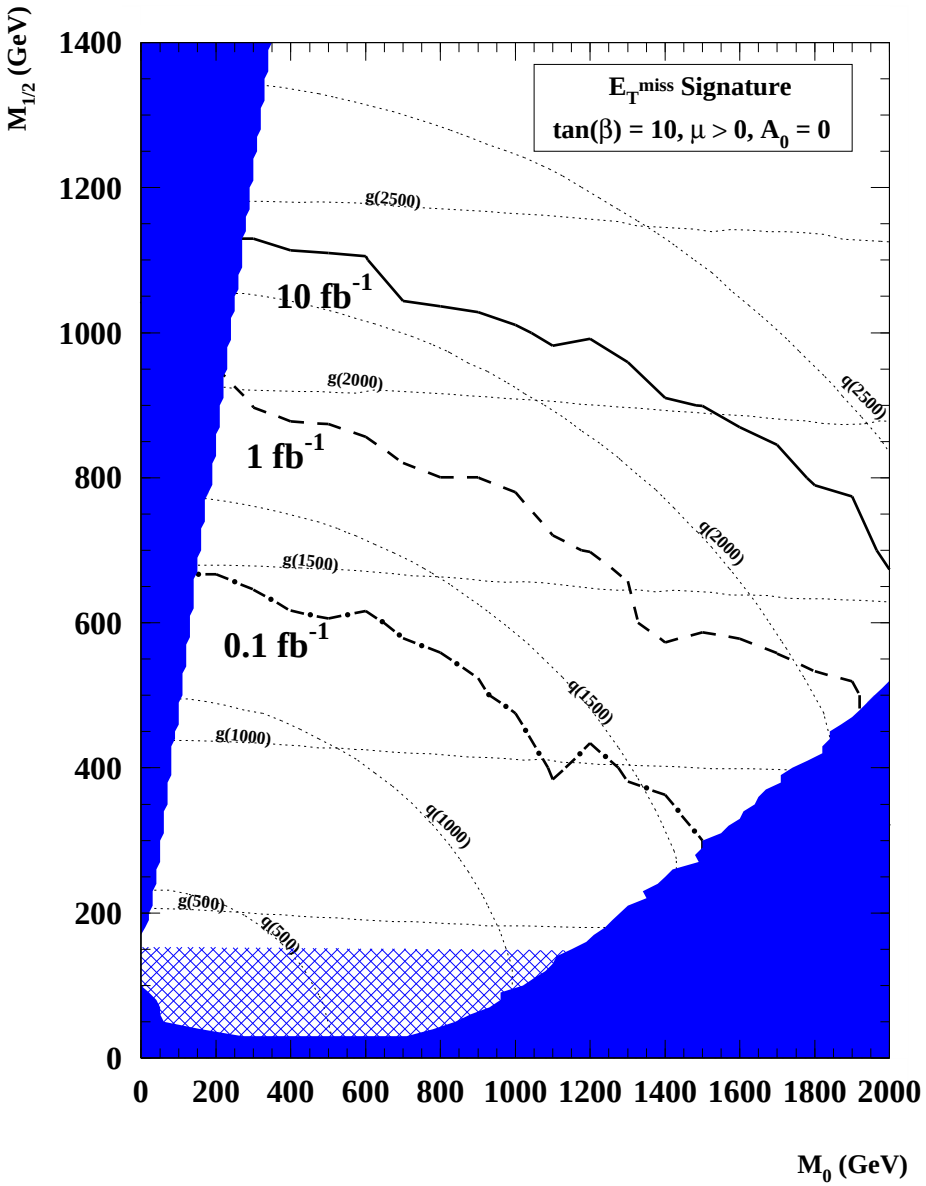
Instrumental peak width $\sim$ 0.7% dominated by constant term of EM resolution $<<$ natural width

Worst-case constant term at run start: 2%

For 100 pb^{-1} and SSM couplings, 5σ reach up to ~ 1300 GeV



Discovery reach as a function of luminosity



$\sim$100 pb^{-1}: few days of running

$\sim$1 fb^{-1}: first run (1-2 months)

$\sim$10 fb^{-1}: first year at 10^{33}cm^{-2}s^{-1}

Fast discovery from signal statistics, BUT

Before we discover SUSY we need to:

- Understand early detector performance:

  $\not\!\!E_T$ tails, lepton id, jet scale

- Collect sufficient statistics of SM control samples:

  W, Z+jets, $\bar{t}t$

Two main background classes:

- Instrumental $\not\!\!E_T$
- Real $\not\!\!E_T$ from neutrinos

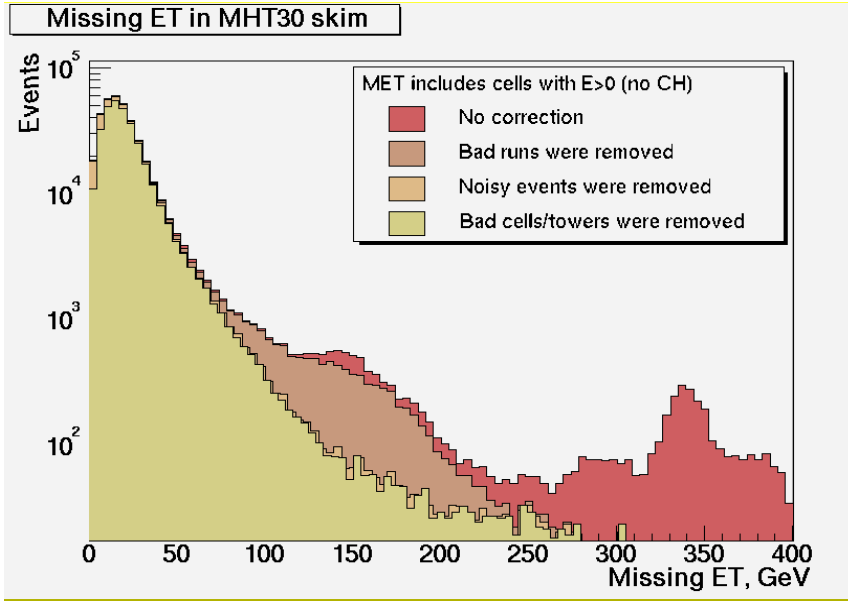
Instrumental backgrounds to $\not\!\!E_T$+ jets analysis

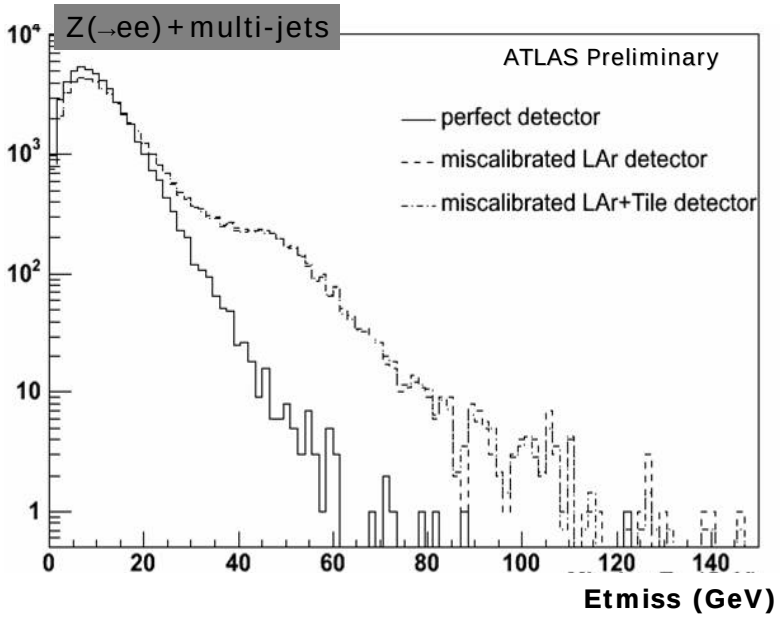
$\not\!\!E_T$ from mismeasured multi-jet events:

Populated by detector and machine problems

Example of $\not\!\!E_T$ cleaning in D0

- Reject runs with detector malfunctioning
- Reject events with noise in the detector
- Remove bad cells





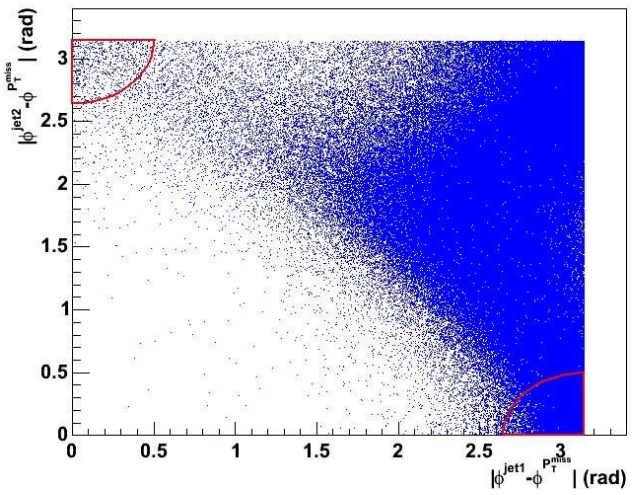
ATLAS example: assume a few HV channels dead in calorimeters. Tools being prepared to monitor and correct event-by-event

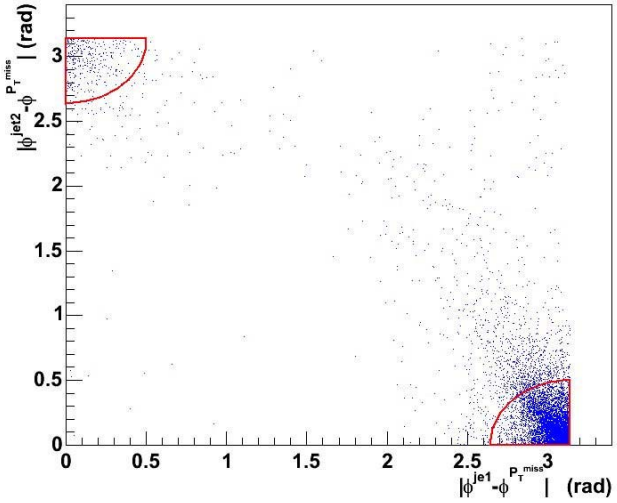
Lot of work in front of us to identify all sources of $\not\!\!E_T$ from detector and machine problems

When this is done, it is only the start of the work!

Instrumental background 2: cracks, response fluctuations

Next step is rejection of topologies which likely to yield instrumental





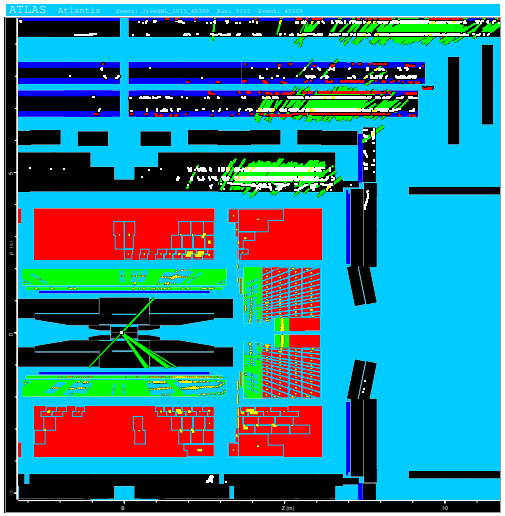
CMS:

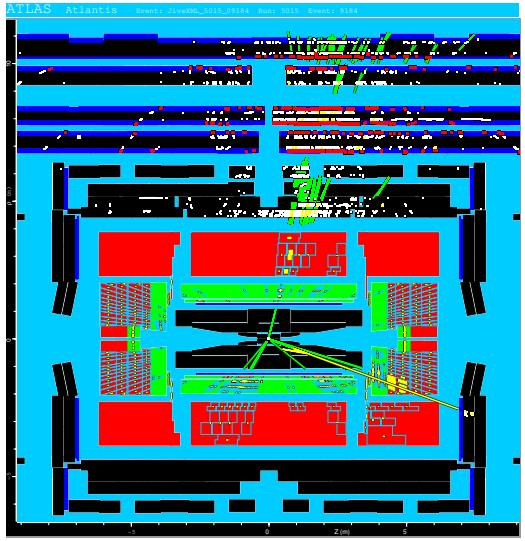
$|\phi^{jet2} - \phi^{\not{E}_T}|$ vs.

$|\phi^{jet1} - \phi^{\not{E}_T}|$

Left: Signal

Right: QCD





ATLAS:

Reject events with high multiplicity in muon chambers from jets in crack or jet punch-through

Data-driven estimate of instrumental background

Once sample cleaned fom "obvious" topologies need to estimate residual backgrounds

MonteCarlo estimate of QCD background very difficult: dealing with non-gaussian response tails

⇒ Data-driven estimate (ATLAS preliminary)

1: Measure jet smearing function:

- Select events with:

$\not\!\!E_T > 60$ GeV, $\Delta\phi(\not\!\!E_T, jet) < 0.1$

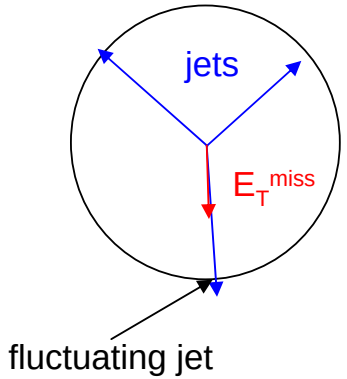
- Estimate true E_T of jet closest to $\not\!\!E_T$ as:

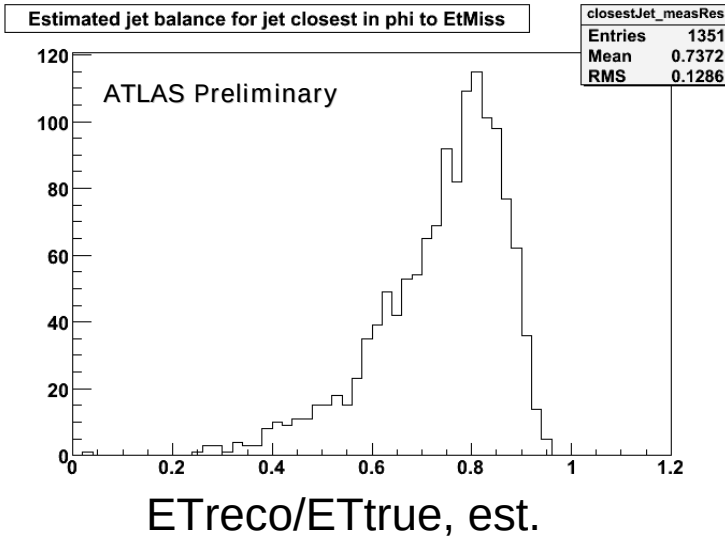
$E_T^{true} = p_T^{reco} + \not\!\!E_T$

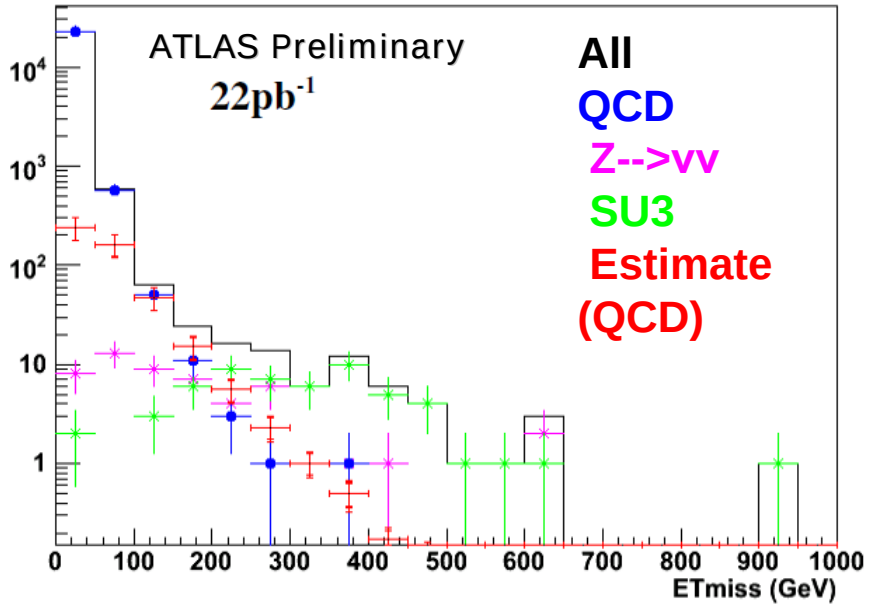
2: Take low $\not\!\!E_T$ jet events and smear jets with measured smearing function

3: Normalize to data

QCD $\not\!\!E_T$ tail nicely reproduced







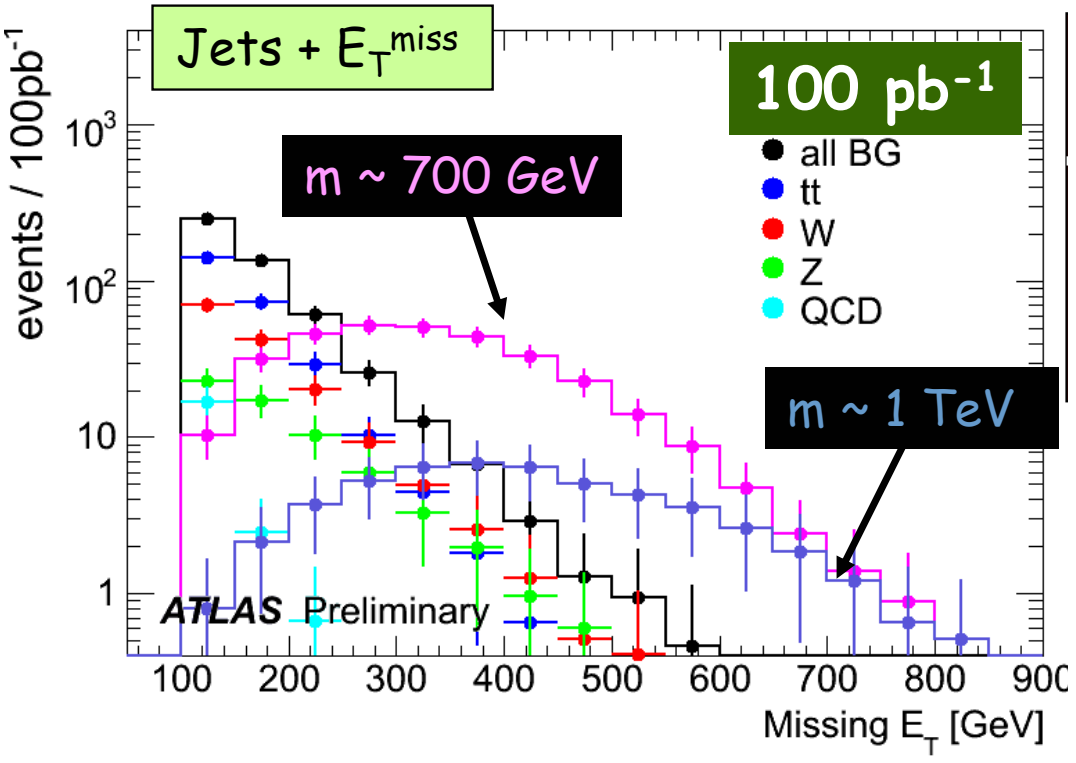
Control of $\not\!\!E_T$ from Standard Model processes

Real $\not\!\!E_T$ from ν production in SM:

SUSY selection:

- $\not\!\!E_T > 100$ GeV
- At least 1 jet with $p_T > 100$ GeV
- At least 4 jets with $p_T > 50$ GeV

Plot $M_{\text{eff}} = \Sigma_{i=1}^{4} |p_{T(jet_i)}| + E_T^{\text{miss}}$



Comparable contributions from: • $\bar{t}t$+jets • W+jets • Z+jets

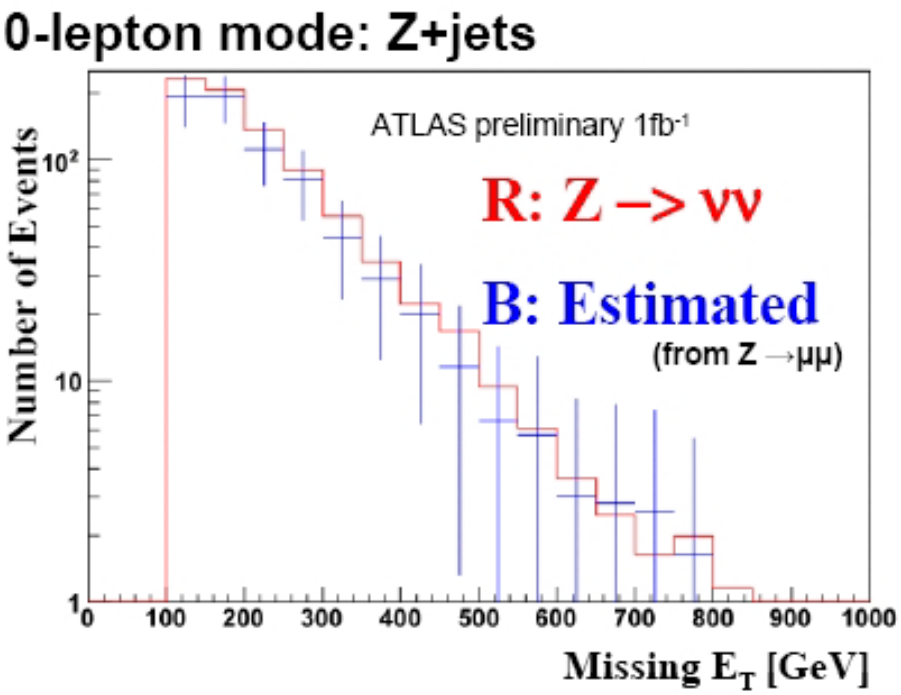
Counting experiment: need precise estimate of background processes in signal region

Complex multi-body final states: can not rely on MonteCarlo alone. Need both data and MonteCarlo

The simplest case: $Z \rightarrow \nu\nu +$ jets

Select a sample of $Z \rightarrow \mu\mu$+multijets from data

Same cuts as for SUSY analysis (4 jets+Etmiss), throw away μ's and calculate $\not{p}_T$ of events from μ momenta (normalized to 1 fb^{-1})



Main problem is correct normalisation and shape distortion from $Z \rightarrow \mu\mu$ selection

Need to correct for:

- Efficiency for μ (experimental)
- Acceptance of $\mu^+\mu^-$ pairs (MonteCarlo)

Combination of data and MonteCarlo needed for firm estimate

Good prediction of background shape, but large statistical error

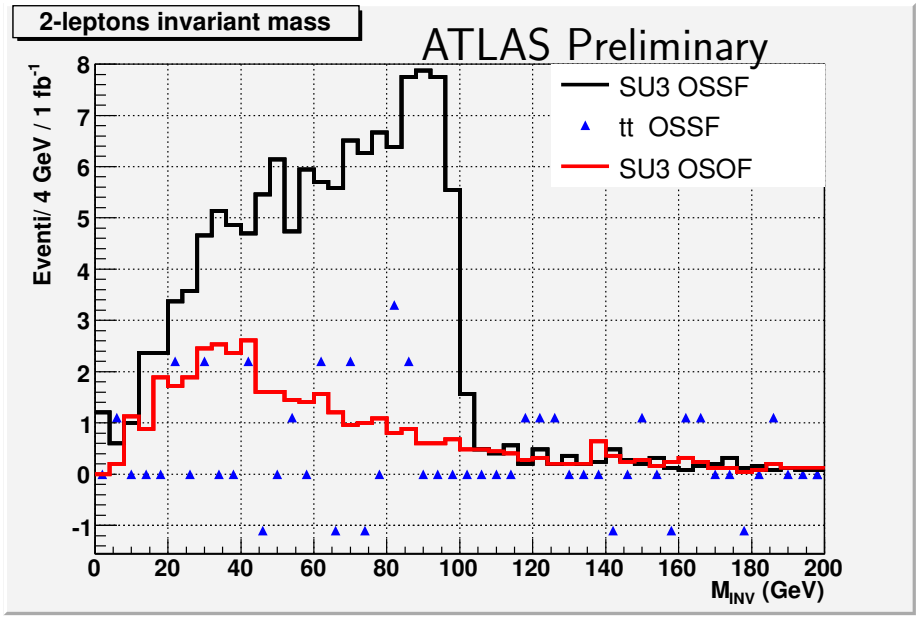
Additional techniques such as using $W \rightarrow e\nu$ or using MC only for shapes under study to improve statistical power

2-leptons + $\not{E}_T$ + jets inclusive search

Significantly lower reach than other channels, but also lower backgrounds

Different topologies, corresponding to different SM background sources

- Opposite-Sign Same-Flavour (OSSF)
- Opposite-Sign Opposite-Flavour (OSOF)
- Same-Sign Same-flavour (SSSF)
- Same-sign Opposite-Flavour (SSOF)



OS-OF can show flavour-correlated signal.

$$\tilde{q}_L \rightarrow \tilde{\chi}_2^0 \quad q$$
$$\hookrightarrow \tilde{\ell}^{\pm}_{R(L)} \quad \ell^{\mp}$$
$$\hookrightarrow \tilde{\chi}_1^0 \quad \ell^{\pm}$$

Only $Z/\gamma \rightarrow e^+e^-, \mu^+\mu^-$ has same-flavour leptons, strongly reduced by $\not{E}_T$+jets requirement

Background dominated by $\bar{t}t$, can be exactly flavour-subtracted

Clear kinematic signature: if we are lucky best chance for early discovery

Conclusions

Both the LHC machine and the two big detectors are nearing completion

LHC startup will require a long period of development and understanding for both machine and detectors

Detailed commissioning plan for detectors: plan to achieve baseline 'reasonable' calibration and alignment before collisions using cosmics and machine development periods

As soon as interactions at 14 TeV happen, interesting physics available in data

Parallel processes of using data to further 'technical' detector understanding and to perform benchmark SM physics measurements

Goal is to arrive at high statistics (few fb^{-1}) data-taking ready to go for early discovery physics