SM and jet measurements at the LHC

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**Part I – jet characteristics**
1) Introduction to ATLAS and the LHC
2) Jet reconstruction and performance
3) Inclusive jet measurements

**Part II – event structure**
4) Multi-jet final states
5) Vector boson production (with/without jets)
6) What to expect from 2011
The LHC in 2010

- 45 pb\(^{-1}\) of data taken in total.
- Average number of interactions per bunch crossing was about 3.5 for the final runs.
- The plan is to take at least 1 fb\(^{-1}\) of data in 2011 at \(\sqrt{s}=7\) TeV.
  - Likely that the luminosity will be higher than this, possibly even increase in energy to 8-9 TeV (under discussion)
The ATLAS detector – a general multipurpose detector

Muon Spectrometer (|\(\eta\)|<2.7): air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to \(E_\mu \sim 1\) TeV

3-level trigger reducing the rate from 40 MHz to \(~200\) Hz

EM calorimeter: Pb-LAr Accordion
e/\gamma trigger, identification and measurement
E-resolution: \(\sigma/E \sim 10%/\sqrt{E}\)

HAD calorimetry (|\(\eta\)|<5): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing \(E_T\)
E-resolution: \(\sigma/E \sim 50%/\sqrt{E} \oplus 0.03\)

Inner Detector (|\(\eta\)|<2.5, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing, e/\pi separation
Momentum resolution:
\(\sigma/p_T \sim 3.8 \times 10^{-4} p_T\) (GeV) \(\oplus 0.015\)

Length: \(~46\) m
Radius: \(~12\) m
Weight: \(~7000\) tons
\(~10^8\) electronic channels
3000 km of cables
<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Number of Channels</th>
<th>Approximate Operational Fraction</th>
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</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>80 M</td>
<td>97.3%</td>
</tr>
<tr>
<td>SCT Silicon Strips</td>
<td>6.3 M</td>
<td>99.2%</td>
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<tr>
<td>TRT Transition Radiation Tracker</td>
<td>350 k</td>
<td>97.1%</td>
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<tr>
<td>LAr EM Calorimeter</td>
<td>170 k</td>
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<td>Tile calorimeter</td>
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<tr>
<td>Forward LAr calorimeter</td>
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<tr>
<td>LVL1 Muon RPC trigger</td>
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<td>99.5%</td>
</tr>
<tr>
<td>LVL1 Muon TGC trigger</td>
<td>320 k</td>
<td>100%</td>
</tr>
<tr>
<td>MDT Muon Drift Tubes</td>
<td>350 k</td>
<td>99.5%</td>
</tr>
<tr>
<td>CSC Cathode Strip Chambers</td>
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<tr>
<td>RPC Barrel Muon Chambers</td>
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<tr>
<td>TGC Endcap Muon Chambers</td>
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<td>98.4%</td>
</tr>
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</table>
Jets at ATLAS: reconstruction and performance in 2010
The ATLAS calorimeter
The anti-
\( k_T \) algorithm

- Default algorithm for studying jets at both ATLAS and CMS.
- For each object, ‘i’, and each pair of objects, ‘ij’, define the merging parameters:
  \[
  d_{ij} = \min(k_{T_i}^{-2}, k_{T_j}^{-2}) \frac{(\Delta R)_{ij}^2}{R^2}
  \]
  \[
  d_{iB} = k_{T_i}^{-2}
  \]
  where
  \[
  (\Delta R)_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2
  \]
- If \( d_{ij} \) is smallest, merge objects ‘i’ and ‘j’
- If \( d_{iB} \) is smallest, define object ‘i’ as a jet and remove from the list.
- Repeat procedure until no objects remaining.
- Algorithm is both infra-red and collinear safe.
- Generally produces jets of definite size

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Jet inputs

- Topo-clusters are 3D objects:
  - Clustering across many layers of calorimeter
  - Seed cell identified by $|E| > 4\sigma$ initiates the cluster
  - Neighbour cells iteratively added to cluster if $|E| > 2\sigma$
  - Ring of Guard cells added ($|E| > 0\sigma$)

- Towers are constructed by using cells that are aligned along a given $\eta$-$\phi$ direction
  - 6400 towers in ATLAS,
  - Noise suppressed towers are those constructed from cells that belong to topo-clusters
Default jet energy scale calibration and uncertainty

• The default calibration scheme currently corrects EM-scale jets.
• Response, $R$, of a jet in the calorimeter is studied for jets in PYTHIA:
  \[ p_T^{EM} = R(p_T^{true}, \eta) \ p_T^{true} \]
• Response parameterized and inverted to give the jet energy scale (JES) correction
• Using the MC derived response introduces uncertainty due to:
  – Detector simulation (e.g. geometry, dead material, noise, hadronic shower models...)
  – Event generator modeling (hadronization, parton shower and underlying event)
The problem with forward jets

- The relative response as a function of pseudo-rapidity is measured in-situ:
  - Dijet events selected
  - ISR/FSR suppressed by selecting back-to-back jets ($|\Delta \phi| > 2.6$) and cutting on third jet $p_T$
  - Asymmetry of dijets measured to give the relative response

- Data and MC do not agree well in the forward region! Could be:
  - Detector simulation problem (should calibrate).
  - A physics modeling problem (should not calibrate)
The difference between ‘quark’ and ‘gluon’ jets

• Jets studied so far include jets originating from both hard gluons and hard quarks in the MC:
  – jets from gluons typically softer and soft particles typically deposit less energy

• This causes a problem if the sample of jets we are looking at do not have the same mixture of quarks/gluons as the inclusive MC sample
  – Additional uncertainty needed that is analysis specific (no ‘one calibration fits all’ approach)
The problem of near-by jets

• The jet calibration was calculated for jets that are well separated from any other jet activity
• Response is much lower in jets if there are ‘nearby’ jets
• Additional uncertainty in multi-jet analyses
  – depends on the topology of the event in question.
How good is this calibration? – current ATLAS view

- Validation of the energy scale was performed with the single hadron response, measuring the $E/p$ for charged particles. Little deviation between data and MC.
- Propagating this uncertainty to the jet-level [using pseudo-experiments], yields a much smaller intrinsic uncertainty than the default MC-based approach.
The measurement of the production cross-section of VBF Higgs is crucial to the extraction of the Higgs couplings. Dominant uncertainty from JES.
- The CSC study assumed 7% (15%) JES uncertainty for central (forward) jets.
- We already have that precision!

The measurement of the top-quark mass in semi-leptonic and hadronic channels is dominated by JES
- 0.7GeV uncertainty per percent JES uncertainty.
- A long way to go for top-studies.
How good is this calibration? – comparison with CMS

- The CMS basic jet energy scale is smaller than the current ATLAS one in the central region
  - This makes sense, as they have used 2.9pb⁻¹ of data and photon-jet balancing to get an in-situ handle on the JES. The ATLAS JES will be similar.
- In the forward region, the CMS uncertainty is MUCH smaller than the ATLAS one.
  - MC/data discrepancy is calibrated away after extrapolating the discrepancy to $p_{T,3}=0$
  - This assumes that the discrepancy is NOT due to physics effects. ATLAS does not attempt to claim this yet.
How good is this calibration? – comparison with D0

- It shouldn’t come as a surprise that the JES at D0 is better than that at ATLAS and CMS.

- Central uncertainty determined by photon-jet balance to be <2% for jets in the central region.

- Uncertainty grows to about 4% by |η|~3

- The ATLAS/CMS goal of a 1% uncertainty in the JES is realistic (at least for central jets)

7 years of work! 1.2%
Inclusive jet measurements at ATLAS
Inclusive jet measurements – the benefits

- Key observable in particle physics
  - previously measured in $e^+e^-$, ep, pp and $p\bar{p}$ colliders

- The inclusive measurement is an ideal stepping stone to more complicated jet topologies.
  - Simplest possible jet measurement
  - NLO prediction known for over 20 years, with small uncertainty

- Once the inclusive jet measurement has been made to high accuracy, can use to
  - provide precise measurement of $\alpha_s$
  - determine the structure of the proton (PDF fits)
  - study BSM physics (see talk by C.Issever)
Event selection

- Anti-$k_T$ algorithm used with $R=0.4$ and $R=0.6$ and compared to QCD calculations
  - Different soft physics effects for different jet radii
- Inclusive cross-section measured as a function of jet $p_T$ and $y$ for all jets with $p_T>60\text{GeV}$ and $|y|<2.8$
  - All jets in region of central jet-trigger plateau
  - No forward jets (MC/data JES discrepancy)
- Dijet cross-section measured as a function of $m_{jj}$ and $\chi=\exp(|y_1-y_2|)$
  - Leading jet satisfies $p_T>60\text{GeV}$ and $|y|<2.8$
  - Second jet satisfies $p_T>30\text{GeV}$ and $|y|<2.8$
  - High purity and efficiency of jet reconstruction for both jets
  - Stability of NLO improved by asymmetric cuts

Also:
1) Vertex required with 5+ tracks
2) Jets cleaned to remove jets from ‘noise’ and poorly reconstructed regions of detector
Unfolding detector effects

- Bin-by-bin unfolding to remove effect of detector inefficiencies and resolutions.
- Unfolding factor \( \frac{\sigma_{\text{truth}}}{\sigma_{\text{reco}}} \) determined using PYTHIA 6, uncertainty on this evaluated by (i) using different generators (ii) changing the resolution (iii) changing the shape of the input distributions.
- Typically 5% (or less) uncertainty in unfolding factors.
Inclusive jets: comparison to LO event generators

- Shape is well described by the LO 2-> 2 matrix element + parton shower approach
- Cross-sections determined at leading order – normalization required to get the MC to match the data
Inclusive jets: comparison with NLO predictions

- NLO prediction at parton-level from NLOJet++ using CTEQ6.6 PDF (checked with JETRAD)
- Soft (non-perturbative) corrections applied to parton level predictions to allow comparison to data
Comparison with NLO predictions, in a bit more detail

Approximately 5% uncertainty in NLO theory, compared to 30% experimental uncertainty - this is JES dominated, should be able to drastically improve on this in the near future
Dijet mass distributions

**ATLAS**
- anti-\(k_t\) jets, \(R = 0.6\)
- \(\sqrt{s} = 7\) TeV, \(\int L dt = 17\) nb\(^{-1}\)
- \(2.1 < |y|_{\text{max}} < 2.8\) (\(\times 10^5\))
- \(1.2 < |y|_{\text{max}} < 2.1\) (\(\times 10^4\))
- \(0.8 < |y|_{\text{max}} < 1.2\) (\(\times 10^3\))
- \(0.3 < |y|_{\text{max}} < 0.8\) (\(\times 10^2\))
- \(|y|_{\text{max}} < 0.3\) (\(\times 10^1\))

**Systematic uncertainties**

\[ \frac{d^2\sigma}{dm_{12} dm_{\text{max}}} \text{[pb/GeV]} \]

\[ m_{12} \text{[GeV]} \]

\[ \text{Data / Theory} \]

\[ m_{12} \text{[GeV]} \]

\[ \text{NLO pQCD (CTEQ 6.6)} \times \text{Non-pert. corr.} \]
Dijet angular distributions

\[ \frac{d^2\sigma}{d\phi d\theta} [\text{pb/GeV}] \]

- \( m_{12} < 520 \text{ GeV} \)
- \( 520 < m_{12} < 800 \text{ GeV} \)
- \( 0.8 < m_{12} < 1.2 \text{ TeV} \)

\[ \frac{\text{Data}}{\text{Theory}} \]

- Systematic uncertainties
- NLO pQCD (CTEQ 6.6) × Non-pert. corr.

\[ \sqrt{s} = 7 \text{ TeV}, \int L dt = 17 \text{ nb}^{-1} \]
Inclusive jet cross-section comparison with POWHEG

- POWHEG-Box recently implemented dijet production (published in arXiv:1012.3380)
- NLO matrix element interfaced to PYTHIA/HERWIG to benefit from parton shower, hadronization and underlying event.
  - Allows out-of-box particle level comparison (shown above)
- But, for the experiments, POWHEG could be used to
  - improve the uncertainty in the unfolding corrections
  - Reduce physics modeling dependence of JES determination using dijet balancing
The measurement of jets in a collider experiment

1) A lot of work is needed to calibrate the energy of jets in a collider experiment to the accuracy required for precision measurements.
2) The current public ATLAS (CMS) uncertainty is about 7% (4%) for central jets and is improving steadily through in-situ measurements.

The inclusive jet cross-section measurement

1) The simplest measurement of jet production at the LHC - a stepping stone to the more complicated, exclusive final states discussed in the next lecture.
2) Dominated by JES uncertainty (>30%)
3) NLO predictions accurate to about 5% in the inclusive single jet measurement
Event with dijet mass, $m_{jj}=3.1\text{TeV}$ – the SM at unprecedented energies
Extras
Status of the CMS detectors

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<th>MUON-CSC</th>
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<th>MUON-RPC</th>
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<th>HCAL ENDCAP</th>
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<th>ECAL BARREL</th>
<th>ECAL ENDCAP</th>
<th>PRE-SHOWER</th>
<th>STRIP TRACKER</th>
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<tr>
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<td>99.3</td>
<td>98.9</td>
<td>99.8</td>
<td>98.1</td>
<td>98.2</td>
</tr>
</tbody>
</table>
The limitations of the inclusive jet measurements

• Low statistics: measurement performed with less than $1/1000^{th}$ of the current available data.

• Conservative JES estimate – results in experimental uncertainty 6x larger than NLO uncertainty

• Covers a limited $p_T$ range ($60<p_T<500\text{GeV}$) and low rapidity range ($|y|<2.5$).

• Future extensions (probably for the winter conferences):
  – Improved JES on its way!
  – Full dataset of 2010, allowing larger $p_T$ and $m_{jj}$ to be probed
  – As well as probing smaller $p_T$ (as low as 20GeV) and larger $|y|$ (up to 4.5)