Overview of Standard Model Measurements at ATLAS

Will Buttinger
On Behalf of the ATLAS Collaboration
Why Standard Model measurements are important

1. Calibrate our Predictions
   - Constrain phenomenological models of strong interaction (parton showers etc)
   - Compare/Improve Parton Distribution Functions (PDFs)
   - Measure fundamental parameters (e.g. coupling constants, mixing angles)
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3. Test the Standard Model
   - Precision tests of latest perturbative QCD calculations
     • These are also often the main backgrounds in BSM searches
   - Test Electroweak interactions
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Other talks at this conference

- Overview of Recent ATLAS results, Fares Djama
- Precision measurements of Standard Model parameters and Review of Drell-Yan and vector boson plus jets measurements with the ATLAS detector, Noemi Calace
- Measurements of Multi-boson production, Trilinear and Quartic Gauge Couplings with the ATLAS detector, Maurice Becker
- Recent results on soft QCD topics, and jet and photon production from ATLAS, Roger Jones
Soft QCD

- Test Parton Showers
- Test/tune models of Underlying Event: Multiple Parton Interactions, ISR, FSR, photon emission/absorption
- Test theorems on, e.g., C.o.M energy dependence of total pp cross-section
1. Latest Minimum bias results
2. “Large Photon Collider”

Soft QCD

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• Minimum bias studies: e.g. charged particle multiplicity per interaction
  – Measurements from events with a single primary vertex (at least 3 tracks)
• Compare different generators (with different parton showers) and different tunes
• Minimum bias studies: e.g. charged particle multiplicity per interaction
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![Graph showing minimum bias studies](attachment:image.png)
• Minimum bias studies: e.g. charged particle multiplicity per interaction
  – Measurements from events with a single primary vertex (at least 3 tracks)
• Compare different generators (with different parton showers) and different tunes
  – EPOS model (implementation of parton-based Gribov-Regge theory) with its LHC tune best describes data (except at high eta)
• Observe Gamma-gamma collisions from exclusive dilepton events
  – Pure QED hard scatter: easily calculable

signal

(some of the) backgrounds
- Data consistent with model that includes corrections for reabsorption of photons into proton (protons have finite size .. Suppresses emission of photons)


- Observe Gamma-gamma collisions from exclusive dilepton events
  - Pure QED hard scatter: easily calculable
Categories of SM Measurement at ATLAS

**Minimum bias: track multiplicities**

**Total cross-section with ALFA detectors**

**Photon-photon collisions**

**Underlying event in jet events**

### Soft QCD

- Test Parton Showers
- Test/tune models of Underlying Event: Multiple Parton Interactions, ISR, FSR, photon emission/absorption
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### Jet Physics

- Calibrate jet reconstruction
- Test perturbative QCD, multi-leg generators
- Test PDFs and parton showers
- Measure strong coupling constant
- Heavy resonance searches
Categories of SM Measurement at ATLAS

Minimum bias: track multiplicities

Total cross-section with ALFA detectors

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1. Inclusive jet Cross-section at 7 and 13 TeV
2. 3 and 4-jet cross-sections (7 and 8 TeV, respectively)
3. Measurement of strong coupling constant
   - Test PDFs and parton showers
   - Measure strong coupling constant
   - Heavy resonance searches

Photon-photon collisions

Underlying event in jet events

Inclusive jet Cross-section at 7 and 13 TeV

3 and 4-jet cross-sections (7 and 8 TeV, respectively)

Measurement of strong coupling constant

Test PDFs and parton showers

Measure strong coupling constant

Heavy resonance searches
Jet Physics – Inclusive jet Cross-section (October 2014)

- Compare data NLO QCD calculation (NLOJET++) with different PDFs: CT10, MSTW08, NNPDF2.1, HERAPDF1.5, ABM11
- Can also compare different underlying event tunes

Overview of ATLAS SM Measurements

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Jet Physics – Inclusive jet Cross-section (July 2015)

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Overview of ATLAS SM Measurements

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Overview of ATLAS SM Measurements


ATLAS

\[ |Y^*| = |y_1 - y_2| + |y_2 - y_3| + |y_1 - y_3| \]

NLO QCD @CT 10
\( \times \) non-pert. corr

\( |Y^*| < 2 \times (x10^2) \)
\( 2<|Y^*| < 4 \times (x10^1) \)
\( 4<|Y^*| < 6 \times (x10^2) \)
\( 6<|Y^*| < 8 \times (x10^3) \)
\( 8<|Y^*| < 10 \times (x10^4) \)

3-jet Cross-section

4-jet Cross-section

Modelling is dominant uncertainty at low \( H_T \)

\( \bar{s} = 8 \text{ TeV}, 95 \text{ pb}^{-1} \) - 20.3 fb^{-1}

Relative uncertainty

Total experimental systematic uncertainty
JES+JER uncertainty
Unfolding uncertainty
Statistical uncertainty

Scalar sum of jet \( p_T \)

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ATLAS Preliminary
\( \bar{s} = 8 \text{ TeV} \)
\( \alpha_s \) from \( E_T - E_T \) Correlations  \( \text{arxiv: 1508.01579} \)

- Plot azimuthal angle between every pair of jets, weighting the pair by \( E_{T1} E_{T2} / (\Sigma E_T)^2 \)

\[ \text{Distribution sensitive to value of } \alpha_s \]
\( \alpha_s \) from \( E_T - E_T \) Correlations  

- Plot azimuthal angle between every pair of jets, weighting the pair by \( E_{T1} \cdot E_{T2} / (\Sigma E_T)^2 \)

\[ \alpha_s(m_Z) = 0.1173 \pm 0.0010 (\text{exp.})^{+0.0065}_{-0.0026} (\text{theory}) \]

Theory uncertainty (mostly scale uncert) dominates over experimental

Overview of ATLAS SM Measurements

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Categories of SM Measurement at ATLAS

Soft QCD
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- Calibrate lepton/photon reconstruction
- Probe QCD by measuring boson kinematics
- Test PDFs
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**Minimum bias: track multiplicities**
- Total cross-section with ALFA detectors
- Photon-photon collisions
- Underlying event in jet events

**Inclusive, 2, 3, 4 jet cross-sections**
- $\alpha_s$ measurement
- DGLAP vs BFKL resummations
- Limits on contact interactions

**1. 13 TeV W,Z cross-sections**
**2. 8 and 13 TeV cross-section ratios**
**3. Probing proton PDFs with Z +bjets and W+cjets**
- Calibrate lepton/photon reconstruction
- Probe QCD by measuring boson kinematics
- Test PDFs

Overview of ATLAS SM Measurements
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Boson Production – Z and W cross-sections (Aug. 2015)

- Already have preliminary measurement at 13TeV
  - Red line is the measured cross-section. Black points are the predictions

Cross-sections as a function of centre of mass energy

ATLAS-CONF-2015-039
• Calculate ratios of cross-sections: cancels uncertainties!
  – For example: the dominant lumi uncertainty from the previous slide

• Calculated “R-jets” in run-1 (7 TeV): ratio of W+jets to Z+jets cross-sections

W+jets cross-section (EPJC 2015, 75:82)
Boson Production – Cross-section ratios (Aug 2014.)

- Calculate ratios of cross-sections: cancels uncertainties!
  - For example: the dominant lumi uncertainty from the previous slide

- Calculated “R-jets” in run-1 (7 TeV): ratio of W+jets to Z+jets cross-sections

Overview of ATLAS SM Measurements

The discrepancies in these results are being compared by theorists to their latest calculations.
• Calculate ratios of cross-sections: cancels uncertainties!
  – For example: the dominant lumi uncertainty from the previous slide

Cross-section ratios at 13 TeV (ATLAS-CONF-2015-039)

• See significant differences between predictions from different PDFs
  – this measurement will be useful for improving the predictions, once we have reduced the remaining systematic uncertainties
Boson Production – Z + bjets

- Probe b-quark contribution to PDF: 4-flavour number scheme (4FNS) vs 5FNS
- Also tests NLO (MCFM, aMC@NLO) vs multileg LO generators (Sherpa, Alpgen)

Present with (5FNS) and without (4FNS) b-quark PDF

Requires 5FNS
• Probe b-quark contribution to PDF: 4-flavour number scheme (4FNS) vs 5FNS
• Also tests NLO (MCFM, aMC@NLO) vs multileg LO generators (Sherpa, Alpgen)
Boson Production – Z + bjets / W + cjets (February 2014)

- Probe b-quark contribution to PDF: 4-flavour number scheme (4FNS) vs 5FNS
- Also tests NLO (MCFM, aMC@NLO) vs multileg LO generators (Sherpa, Alpgen)

Do a similar analysis with W +cjets (or D mesons) ...

Tests s-quark PDF

PDFs without strange suppression

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Categories of SM Measurement at ATLAS

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Jet Physics
- Calibrate jet reconstruction
- Test perturbative QCD, multi-leg generators
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- Heavy resonance searches

Electroweak physics
- Test electroweak gauge structure
- Measure cross-sections and compare to MC: Backgrounds to many BSM searches
- Search for anomalous couplings / New Physics!
- Weinberg angle measurement

W/Z/γ Boson Production
- Calibrate lepton/photon reconstruction
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Categories of SM Measurement at ATLAS

**Minimum bias:** track multiplicities

**Total cross-section with ALFA detectors**

Photon-photon collisions

Underlying event in jet events

**Soft QCD**

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**W/Z/γ Boson Production**

- Calibrate lepton/photon reconstruction
- Probe QCD by measuring boson kinematics
- Test PDFs

1. Vector Boson Fusion
2. Vector Boson Scattering
3. WWγγ Quartic Coupling
4. A Diboson excess
5. Weinberg angle measurement
6. 4l differential cross-section

**Inclusive, 2, 3, 4 jet cross-sections**

\[ \alpha_s \text{ measurement} \]

DGLAP vs BFKL resummations

Limits on contact interactions

**Z+bjets**

Z+Jet cross section

W+cjets

W+Jet cross section

“R-jets” cross-section ratio

Inclusive W, Z cross-sections

Diphoton cross-section

**Z+bjets**

Z+Jet cross section

W+cjets

W+Jet cross section

“R-jets” cross-section ratio

Inclusive W, Z cross-sections

Diphoton cross-section
Bosons and dibosons

DIBOSONS ARE BACKGROUND TO MANY BSM SEARCHES
**Overview of ATLAS SM Measurements**

- **Bosons and dibosons**

_DIBOSONS ARE BACKGROUNDS TO MANY BSM SEARCHES_

_ALSO MEASURE RARE SM PROCESSES .. _
Bosons and dibosons

**DIBOSONS ARE BACKGROUNDS TO MANY BSM SEARCHES**

**Vector Boson Fusion**

Also measure rare SM processes ..
Electroweak – Feynman diagrams

• Bosons and dibosons

DIBOSONS ARE BACKGROUNDS TO MANY BSM SEARCHES

Vector Boson Fusion

Vector Boson Scattering

ALSO MEASURE RARE SM PROCESSES ..
Electroweak – Feynman diagrams

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DIBOSONS ARE BACKGROUNDS TO MANY BSM SEARCHES

Also measure rare SM processes ..

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**Vector Boson Fusion**

VBF is only 1% of inclusive $Zjj$ cross-section

$\frac{1}{\Delta \phi} \frac{d\sigma}{dm_{jj}}$

- Data (2012)
- Sherpa $Zjj$ (QCD + EW)
- Sherpa $Zjj$ (QCD)
- Powheg $Zjj$ (QCD + EW)
- Powheg $Zjj$ (QCD)

**ATLAS**

$\int L dt = 20.3 \text{ fb}^{-1}$

$t\bar{s} = 8 \text{ TeV}$

Baseline region

Overview of ATLAS SM Measurements

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**Vector Boson Fusion**

VBF is only 1% of inclusive Zjj cross-section

**W^±W^± Vector Boson Scattering**

Distinguish EW VBS ($\alpha_{EW}^4$) from strong production ($\alpha_s^2\alpha_{EW}^2$)

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Electroweak – Evidence of rare SM process (May 2014)

Overview of ATLAS SM Measurements

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Electroweak – Evidence of rare SM process (March 2015)

**Vector Boson Fusion**

VBF is only 1% of inclusive Zjj cross-section

**W±W± Vector Boson Scattering**

Distinguish EW VBS ($\alpha_{EW}^4$) from strong production ($\alpha_s^2\alpha_{EW}^2$)

**WWγγ quartic coupling**

Electroweak – Limits on anomalous triple/quartic couplings

• Plethora of parameters of generic extensions of SM Lagrangian term to incorporate anomalous electroweak couplings

<table>
<thead>
<tr>
<th>Coupling Parameters</th>
<th>Vertex</th>
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<tbody>
<tr>
<td>$\Delta g_1^Z$, $\Delta \kappa_Z$, $\lambda_Z$</td>
<td>WWZ</td>
</tr>
<tr>
<td>$\Delta \kappa_\gamma$, $\lambda_\gamma$</td>
<td>WW$\gamma$</td>
</tr>
<tr>
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<td>$\gamma Z Z$</td>
</tr>
<tr>
<td>$f_4^\gamma$, $f_5^\gamma$</td>
<td>$\gamma\gamma Z$</td>
</tr>
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<td>$h_3^Z$, $h_4^Z$</td>
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</tr>
<tr>
<td>$f_{T0}$, $f_{M2}$, $f_{M3}$</td>
<td>$WW\gamma\gamma$</td>
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- World-leading limits on anomalous electroweak couplings
Overview of ATLAS SM Measurements

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19 of 22
**Overview of ATLAS SM Measurements**

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**Excess in WW cross-section observed at 7 and 8 TeV**

**Current understanding of excess**

- The analyses feature a jet veto, to exclude QCD background
- Ongoing work to assess impact of jet veto on theoretical predictions (theorists suggest resumptions in 0-jet phase space may be significant)

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**Semi-leptonic (W+jj)**

**Vector Boson Fusion**

**Same Sign WW**

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**Table**: Summary of current cross-section measurements and theoretical predictions for WW, WZ, ZZ, γγ, Wγ, Zγ, WW+WZ, WZ+WW, W±W±jj, W±γγ, and WW±jj. The figures show the observed and theoretical values for LHC pp at √s = 7 and 8 TeV, with theoretical predictions from various sources such as PRD 85, 072004 (2012), PRD 87, 112003 (2013), and JHEP 01, 049 (2015).
Electroweak – Weinberg mixing angle (March 2015)

- Asymmetry of lepton direction (wrt initial state quarks) in Z decay is dependent on the Weinberg angle, $\theta_W$

$$\frac{d\sigma}{d(cos \theta)} = \frac{4\pi\alpha^2}{3\hat{s}} \left[ \frac{3}{8} A(1 + \cos^2 \theta) + B \cos \theta \right]$$

- Measure forward-backward asymmetry to infer $B$, hence measure $\theta_W$ at $M_Z$ scale
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\[ \frac{d\sigma}{d(\cos \theta)} = \frac{4\pi\alpha^2}{3\hat{s}} \left[ \frac{3}{8} A(1 + \cos^2 \theta) + B \cos \theta \right] \]

- Measure forward-backward asymmetry to infer $B$, hence measure $\theta_W$ at $M_Z$ scale

\[ \text{Asymmetry coefficient, } B, \text{ depends on } \theta_W \text{ (and } \hat{s} = m_l^2) \]

\[ \text{Angle between incoming quark and outgoing lepton} \]

ArXiv:1503.03709
Electroweak – differential distributions “lineshape” (July 2015)

- ATLAS produces many differential distributions of diboson fiducial cross-sections
- A new result (ATLAS-CONF-2015-031) is the differential 4l distribution. Contributions from:

![Diagrams of ATLAS processes](image)

Single $Z$  
$ZZ$  
$H \rightarrow ZZ$

**Overview of ATLAS SM Measurements**

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Electroweak – differential distributions “lineshape” (July 2015)

- ATLAS produces many differential distributions of diboson fiducial cross-sections
- A new result (ATLAS-CONF-2015-031) is the differential 4l distribution. Contributions from:
  - Only have gg->ZZ->4l prediction at LO
    - Extract gg k-factor from fit to $m_{4l} > 180$ GeV data

$\mu_{gg} = 2.4 \pm 1.0 \text{ (stat.)} \pm 0.5 \text{ (syst.)} \pm 0.8 \text{ (theory)}$
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22 of 22

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Jet Physics

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- Heavy resonance searches

Jet Physics

- Observation of VBF and VBS
- Forward-backward asymmetry
- Anomalous Triple/Quartic Gauge Coupling Limits
- Randall-Sundrum Graviton Search
- Diboson production cross-sections
- Inclusive 4l line-shape

W/Z/y Boson Production

- Calibrate lepton/photon reconstruction
- Probe QCD by measuring boson kinematics
- Test PDFs

Electroweak physics

- Test electroweak gauge structure
- Measure cross-sections and compare to MC: Backgrounds to many BSM searches
- Search for anomalous couplings / New Physics!
- Weinberg angle measurement
**Summary**

- ATLAS Standard Model Measurements test the latest theoretical calculations and phenomenological models of strong force interactions
- Measurements of fundamental SM parameters
- Measurement of SM processes essential for BSM searches: SM processes are the main backgrounds to many of these searches
- Probes the Electroweak gauge structure: use measurements to set limits on anomalous electroweak couplings
- Measurements at 13TeV already underway!

**https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults**
The rest is backup of old versions of slides
• Compare dijet cross-section prediction (NLOJET++) with different PDFs
  – Again, all PDFs describe data well, except ABM11
Jet Physics – Dijet cross-section

• Compare dijet cross-section prediction (NLOJET++) with different PDFs
  – Again, all PDFs describe data well, except ABM11

• Look for dijet resonances: set limits on energy scale of contact interactions
Jet Physics – Inclusive jet Cross-section

- Compare data NLO QCD calculation (NLOJET++) with different PDFs: CT10, MSTW08, NNPDF2.1, HERAPDF1.5, ABM11
- Also can compare tunes of the parton shower + underlying event

\[ \int L \, dt = 4.5 \, \text{fb}^{-1}, \, \ell s = 7 \, \text{TeV} \]

\[ \frac{d^2\sigma}{dp_T \, dy} \, \text{[pb/GeV]} \]

\[ p_T \, [\text{GeV}] \]

\[ \text{ATLAS} \]

- \(|y| < 0.5 \times 10^3\)
- \(0.5 \leq |y| < 1.0 \times 10^3\)
- \(1.0 \leq |y| < 1.5 \times 10^3\)
- \(1.5 \leq |y| < 2.0 \times 10^3\)
- \(2.0 \leq |y| < 2.5 \times 10^3\)
- \(2.5 \leq |y| < 3.0 \times 10^3\)

\[ \text{NLOJET+ (CT10)} \times \text{Non-pert. corr.} \times \text{EW corr.} \]

\[ \text{Systematic uncertainties} \]

\[ \text{POWHEG+PYTHIA} \]

\[ \mu_c = \mu_R = \rho_T^{\text{gen}} \]

\[ \text{Perugia 2011} \times \text{EW corr.} \]

\[ \text{AUGEST} \times \text{EW corr.} \]

\[ \text{NLOJET+ (CT10)} \times \text{Non-pert. corr.} \times \text{EW corr.} \]

\[ \text{Theory} \times \text{data} \]

\[ \text{JHEP02 (2015)} \, 153 \]
Jet Physics – More with jets

\( \alpha_s \) from \( E_T - E_T \) Correlations  

- Plot azimuthal angle between every pair of jets, weighting the events by \( E_{T1} * E_{T2} / (\Sigma E_T)^2 \)

**Combined result:**  \( \alpha_s(m_Z) = 0.1173 \pm 0.0010 \text{(exp.)}^{+0.0065}_{-0.0026} \text{(theory)} \)

Jet Vetoes and Azimuthal Decorrelation

- Rapidity gap Jet veto and azimuthal angle decorrelation: large eta separation of jets – phase space where most sensitive to pQCD resummation schemes (BFKL vs DGLAP)
  - Both schemes have strengths and weaknesses in different regions of the phase space
Excess in $WW$ cross-section observed at 7 and 8 TeV

**CMS-SMP-14-016**: Accounts for Higgs “background” contribution (8%) [ATLAS already did] and corrections due to jet veto / 1-jet restrictions. Measured $\sigma_{WW}=60.1 \pm 4.8$ pb