Summary of Recent ATLAS Standard Model Measurements

Alison Lister
(University of British Columbia)
LHC

- 27km circumference
- 4 collisions points
- 7 experiments
- CM energy
  - 2010-2011: 7 TeV
  - 2012: 8 TeV
  - 2015: 13 TeV
  - 2016: 13/14 TeV?

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ATLAS @ LHC

25 m

46 m
Wednesday 3rd June 2015: Officially back in business!

**PROTON PHYSICS: STABLE BEAMS**

- **Energy:** 6500 GeV
- **I(B1):** $2.92 \times 10^{11}$
- **I(B2):** $2.91 \times 10^{11}$

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**FBCT Intensity and Beam Energy**

**Instantaneous Luminosity**

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**BIS status and SMP flags**

- **B1**
  - Link Status of Beam Permits: false
  - Global Beam Permit: true
- **B2**
  - Link Status of Beam Permits: false
  - Global Beam Permit: true
One of our first 13 TeV events

First Stable Beams at 13 TeV
New detector layer (Insertable B Layer)
New detector layer (Insertable B Layer)

Yep! It’s really there

Already aligning it
To our Run 1 measurements...
The Standard Model of particle physics

The known...

Quarks

- u
- c
- t
- d
- s
- b

Forces

- Z
- γ
- W
- g

Leptons

- e
- μ
- τ
- ν_e
- ν_μ
- ν_τ

The unknown...

- Dark Energy?
  - 68%
- Dark Matter?
  - 27%
- Atoms
  - 5%

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The Problem:

\[ m_{H^2} = m_{\text{bare}}^2 + \Delta m_{H^2} \]

\[ \Delta m_{H^2} \sim \frac{3}{8\pi^2} y_t^2 \Lambda^2 \]

If \( \Lambda \sim \text{Plank scale} \):

\[ m_{H^2} \sim \Delta m_{H^2} \times 10^{-32} \]

Possible Solutions:

A) SM only low energy effective theory

i.e. \( \Lambda \ll \text{Plank} \)

If \( \Lambda \sim \text{TeV} \):

\[ \Delta m_{H^2} \sim O(m_{H^2}) \]

B) Add new particles (e.g. SUSY, top partners)

Loops cancel
Trying to poke holes in the model...
Hadron colliders... not so easy

- Matrix element (hard)
- Parton Shower
- Multiple interactions
- Fragmentation and hadronisation
- QED radiation

Sherpa picture
How far we have come
A few selected topics

- Jets
- Photons
- W/Z+jets
- Multi-boson
- Top
- Constraining PDFs

Many many interesting un-covered topics!

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
Photon Production

**Inclusive Di-photon**

\[ \int L \, dt = 4.6 \, \text{fb}^{-1} \]

\[ |\eta^\gamma| < 1.37 \]

**ATLAS**

- Data 2011 (s=7 TeV)
- PYTHIA (MRST 2007 LO)
- HERWIG (MRST 2007 LO)
- NLO (Jetphox) CT10
- Total uncertainty
- Scale uncertainty
- NLO (Jetphox) MSTW2008nlo

**Graphs**

- Plot showing the distribution of di-photon production in ATLAS
- Comparison of data with theoretical predictions

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JHEP 02 (2013) 086
Ratio: $W$+jets / $Z$+jets

ATLAS
anti-$k_t$ jets, $R=0.4$,
$p_T > 30$ GeV, $|y| < 4.4$

$\frac{(W\to l\nu)/(Z\to l\ell\bar{l})}{(W\to l\nu)/(Z\to l\ell\bar{l})}$ + jets
- Data, $\sqrt{s}=7$ TeV, 4.6 $fb^{-1}$
- $W$+jets
- $Z$+jets
- ALPGEN+HERWIG
- SHERPA

MC / Data NLO / Data

Now, from observation to precision measurements at LHC
● First observed at LEP, Tevatron
➔ Diboson final states: $gg$, $Wg$, $Zg$, $WW$, $WZ$, $ZZ$

In SM: only charged TGCs ($Wg$, $WW$, $WZ$)
Quartic Gauge Coupling

Vector boson scattering: Direct probe of EWSB mechanism

\[ A(W_L W_L \rightarrow W_L W_L) \propto \frac{g_W^2}{v^2} \left[ -s - t + \frac{s^2}{s - m_H^2} + \frac{t^2}{t - m_H^2} \right] \]

- 3 bosons production
- Vector Boson Scattering
  - Probed via:
    - Direct probe of the nature of the EWSB mechanism
    - First evidences with 8 TeV LHC data
- gg exclusive production
- Vector Boson Scattering: Direct probe of EWSB mechanism
- First evidence!

\[ W^+ g g \rightarrow W^+ \gamma \gamma \rightarrow e^+ n \gamma \gamma \]

Inclusive and exclusive cross sections

\[ \sigma_{\text{incl.}} \left[ \text{fb} \right] \quad \sigma_{\text{MCDFM}} \left[ \text{fb} \right] \]

<table>
<thead>
<tr>
<th>Inclusive (( N_{\text{jet}} \geq 0 ))</th>
<th>( \sigma_{\text{ fid}} )</th>
<th>( \sigma_{\text{MCDFM}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu \nu \gamma \gamma )</td>
<td>7.1 \pm 1.3 (stat.) \pm 1.5 (syst.) \pm 0.2 (lumi.)</td>
<td></td>
</tr>
<tr>
<td>( e\nu \gamma \gamma )</td>
<td>4.3 \pm 1.8 (stat.) \pm 1.9 (syst.) \pm 0.2 (lumi.)</td>
<td>2.90 \pm 0.16</td>
</tr>
<tr>
<td>( \ell \nu \gamma \gamma )</td>
<td>6.1 \pm 1.1 (stat.) \pm 1.2 (syst.) \pm 0.2 (lumi.)</td>
<td></td>
</tr>
</tbody>
</table>

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

Data: electron channel (\( N_{\text{jets}} \geq 0 \))
Quartic Gauge Coupling

vector boson scattering

First evidence! 3.6 sigmas

ATLAS: $\sigma^{\text{fid}} = 1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})$ fb

Predicted: $0.95 \pm 0.06$ fb

ATLAS

Data 2012

20.3 fb$^{-1}$, $\sqrt{s} = 8$ TeV

$m_{jj} > 500$ GeV

95% CL intervals

ATLAS

CMS

ATLAS $W^+W^-jj$, $\sqrt{s} = 7$ TeV

$4.6$ fb$^{-1}$, $\Lambda_{FF} = \infty$

CMS $W^+W^-jj$, $\sqrt{s} = 7$ TeV

$4.9$ fb$^{-1}$, $\Lambda_{FF} = \infty$

ATLAS $W^+W^-jj$, $\sqrt{s} = 7$ TeV

$4.6$ fb$^{-1}$, $\Lambda_{FF} = \infty$

CMS $W^+W^-jj$, $\sqrt{s} = 7$ TeV

$5.0$ fb$^{-1}$, $\Lambda_{FF} = \infty$

ATLAS $W^+W^\ast jj$, $\sqrt{s} = 7$ TeV

$4.6$ fb$^{-1}$, $\Lambda_{FF} = \infty$

CMS $W^+W^\ast jj$, $\sqrt{s} = 7$ TeV

$5.0$ fb$^{-1}$, $\Lambda_{FF} = \infty$

D0 comb., $\sqrt{s} = 1.96$ TeV

$8.6$ fb$^{-1}$, $\Lambda_{FF} = 2$ TeV

LEP comb.

$0.7$ fb$^{-1}$, $\Lambda_{FF} = \infty$

95% CL Limits
Let's take a short break...
4.3 The SM phase diagram in terms of Higgs and top masses

The two most important parameters that determine the various EW phases of the SM are the Higgs and top-quark masses. In fig. 3 we update the phase diagram given in ref. [4] with our improved calculation of the evolution of the Higgs quartic coupling. The regions of stability, metastability, and instability of the EW vacuum are shown both for a broad range of $M_h$ and $M_t$, and after zooming into the region corresponding to the measured values. The uncertainty from $\alpha_3$ and from theoretical errors are indicated by the dashed lines and the colour shading along the borders. Also shown are contour lines of the instability scale $\ast_I$.

As previously noticed in ref. [4], the measured values of $M_h$ and $M_t$ appear to be rather special, in the sense that they place the SM vacuum in a near-critical condition, at the border between stability and metastability. In the neighbourhood of the measured values of $M_h$ and $M_t$, the stability condition is well approximated by

$$M_h > 129.6 \pm 2.0 \text{ GeV}.$$  

The quoted uncertainty comes only from higher order perturbative corrections. Other non-perturbative factors also play a role, and can be included in the calculation. 

The Fate of our universe

- Stability
- Meta-stability
- Instability

arXiv:1307.3536
ATLAS+CMS Preliminary $m_{\text{top}}$ summary, $\sqrt{s}$ = 7-8 TeV  TOPLHCWG

<table>
<thead>
<tr>
<th></th>
<th>Total uncertainty</th>
<th>$m_{\text{top}}$ ± tot. (stat⊕JSF⊕bJSF ± syst)</th>
<th>$\sqrt{s}$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, l+jets (*)</td>
<td></td>
<td>172.31 ± 1.55 (0.75 ± 1.35)</td>
<td>7 TeV</td>
<td>[1]</td>
</tr>
<tr>
<td>ATLAS, dilepton (*)</td>
<td></td>
<td>173.09 ± 1.63 (0.64 ± 1.50)</td>
<td>7 TeV</td>
<td>[2]</td>
</tr>
<tr>
<td>CMS, l+jets</td>
<td></td>
<td>173.49 ± 1.06 (0.43 ± 0.97)</td>
<td>7 TeV</td>
<td>[3]</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td></td>
<td>172.50 ± 1.52 (0.43 ± 1.46)</td>
<td>7 TeV</td>
<td>[4]</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td></td>
<td>173.49 ± 1.41 (0.69 ± 1.23)</td>
<td>7 TeV</td>
<td>[5]</td>
</tr>
<tr>
<td>LHC comb. (Sep 2013)</td>
<td></td>
<td>173.29 ± 0.95 (0.35 ± 0.88)</td>
<td>7 TeV</td>
<td>[6]</td>
</tr>
<tr>
<td>World comb. (Mar 2014)</td>
<td></td>
<td>173.34 ± 0.76 (0.36 ± 0.67)</td>
<td>1.96-7 TeV</td>
<td>[7]</td>
</tr>
<tr>
<td>ATLAS, l+jets</td>
<td></td>
<td>172.33 ± 1.27 (0.75 ± 1.02)</td>
<td>7 TeV</td>
<td>[8]</td>
</tr>
<tr>
<td>ATLAS, dilepton</td>
<td></td>
<td>173.79 ± 1.41 (0.54 ± 1.30)</td>
<td>7 TeV</td>
<td>[8]</td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td></td>
<td>175.1 ± 1.8 (1.4 ± 1.2)</td>
<td>7 TeV</td>
<td>[9]</td>
</tr>
<tr>
<td>ATLAS, single top</td>
<td></td>
<td>172.2 ± 2.1 (0.7 ± 2.0)</td>
<td>8 TeV</td>
<td>[10]</td>
</tr>
<tr>
<td>ATLAS comb. (Mar 2015)</td>
<td></td>
<td>172.99 ± 0.91 (0.48 ± 0.78)</td>
<td>7 TeV</td>
<td>[8]</td>
</tr>
<tr>
<td>CMS, l+jets</td>
<td></td>
<td>172.04 ± 0.75 (0.18 ± 0.74)</td>
<td>8 TeV</td>
<td>[11]</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td></td>
<td>172.47 ± 1.41 (0.17 ± 1.40)</td>
<td>8 TeV</td>
<td>[12]</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td></td>
<td>172.08 ± 0.89 (0.37 ± 0.80)</td>
<td>8 TeV</td>
<td>[11]</td>
</tr>
<tr>
<td>CMS comb. (Sep 2014)</td>
<td></td>
<td>172.38 ± 0.65 (0.14 ± 0.64)</td>
<td>7+8 TeV</td>
<td>[11]</td>
</tr>
</tbody>
</table>

(*) Superseded by results shown below the line.

Measurement precision ~ 0.65 GeV (0.38%)
\[ m_{\text{top}} = 172.99 \pm 0.48(\text{stat}) \pm 0.78(\text{syst}) \text{ GeV} \]

Understanding Systematics is key

arXiv:1503.05427
$m_{\text{top}} = 172.9^{+2.5}_{-2.6}$ GeV

$\Delta m_{\text{top}} \sim 2$ GeV

$m_{\text{top}} = 173.7\pm1.5\text{(stat.)} \pm1.4\text{(syst.)}^{+1.0}_{-0.5}\text{(theo.)}$ GeV

$\sqrt{s_{ttj}}$ : invariant mass of ttj system

$m_0$ : arbitrary mass parameter, 170 GeV


ATLAS-CONF-2014-053
\[ \Delta \sigma_{\text{the}} \sim 5.4\% \]
\[ \Delta \sigma_{\text{exp}} \sim 3.9\% \]
Unfolding: Parton vs Particle

ATLAS Preliminary
20.3 fb⁻¹, 1s = 8 TeV

MC / Data

Particle top-jet candidate $p_T$ [GeV]

Particle

Data
ALPGEN + HERWIG
MC@NLO + HERWIG
POWHEG + HERWIG
POWHEG + PYTHIA

Parton

Data

$\frac{d^2\sigma}{d^2p_T}$ [fb/GeV²]

$\frac{d\sigma}{dp_T}$ [fb/GeV]

$\frac{d\sigma}{dp_T}$ [fb/GeV]

$\frac{d\sigma}{dp_T}$ [fb/GeV]

Events / GeV

Data / MC

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Unfolding: Parton vs Particle

- Parton vs Particle

Easier to calculate

Closer to what we measure

Reco

What we measure

ATLAS-CONF-2014-057
Tails (New Physics?)

**ATLAS** $1s = 7\text{ TeV}, 4.6\text{ fb}^{-1}$

- **Data**
- **stat. @ syst. uncert.**
- **POWHEG+PYTHIA**
- **POWHEG+HERWIG**
- **POWHEG(HERAPDF)+PYTHIA**
- **MC@NLO+HERWIG**

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**Post-fit**

**Expected/Data**

- **Data**
- **SM tt**
- **SM W+jets**
- **Other SM**
- **g_{kk} 2.0\text{ TeV, 15.3\%}**
- **g_{kk} 0.8\text{ TeV, 15.3\%}**

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**Reco**

**ATLAS** $1s = 8\text{ TeV}, 20.3\text{ fb}^{-1}$

- **Data**
- **SM tt**
- **SM W+jets**
- **Other SM**
- **g_{kk} 2.0\text{ TeV, 15.3\%}**
- **g_{kk} 0.8\text{ TeV, 15.3\%}**
Evidence for both $ttZ$ ($3.1\sigma$) and $ttW$($3.1\sigma$) production!
**Top Spin Correlation**

\[ A_{\text{helicity}} = 0.38 \pm 0.04 \]

\[ f_{\text{SM}} = 1.20 \pm 0.05 \text{(stat)} \pm 0.13 \text{(syst)} \]

![Graph showing data and fit results](image)

Single Top t-channel
PDFs from LHC data

- **W,Z**: light quarks at low and high $x$
- **Top**: gluon at high $x$, and $u,d,b$ quarks
- **Jets**: gluon at medium $x$
- **W+c**: $s$-quark at medium $x$
Outlook

• Many high precision SM measurements performed in Run 1
• Many more Run 1 results still to come
  • Difficult measurements, often systematics dominated
• Already looking into Run2 data
  • Hoping for the unknown
  • Expecting lots of hard work ahead over many years

\[ \sigma_{\text{ttbar}} = 831.76 \pm 35.06 \text{ pb} \]

arXiv:1112.5675