Electroweak physics at the LHC with ATLAS

Arthur M. Moraes
University of Sheffield, UK
(on behalf of the ATLAS collaboration)
Outline

- LHC and ATLAS.
- **W mass** measurement
- Improvements in the measurements of the mass of the top quark ($m_t$).
- $A_{FB}$ asymmetry in dilepton production: $\sin^2\theta_{\text{eff, lept}}(M_Z^2)$.
- EW single top quark production: direct measurement of $V_{tb}$.
- Triple gauge boson couplings (TGC).
- Conclusion.
LHC (Large Hadron Collider):

- **p-p collisions at** $\sqrt{s} = 14$ TeV

- **bunch crossing every** 25 ns (40 MHz)

  - **low-luminosity:** $L \approx 2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ ($L \approx 20$ fb$^{-1}$/year)
  
  - **high-luminosity:** $L \approx 10^{34}$ cm$^{-2}$s$^{-1}$ ($L \approx 100$ fb$^{-1}$/year)

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$ (nb)</th>
<th>Events/year ($L = 10$ fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \to e\nu$</td>
<td>15</td>
<td>$\sim 10^8$</td>
</tr>
<tr>
<td>$Z \to e^+ e^-$</td>
<td>1.5</td>
<td>$\sim 10^7$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0.8</td>
<td>$\sim 10^7$</td>
</tr>
<tr>
<td>Inclusive jets $p_T &gt; 200$ GeV</td>
<td>100</td>
<td>$\sim 10^9$</td>
</tr>
</tbody>
</table>

- **W, Z, top, b, ... factory!**

- **Large statistics → small statistical error!**

- **Huge discovery potential for new physics:** Higgs and Supersymmetry.

A. M. Moraes
ATLAS: A Toroidal LHC AparatuS

- Multi-purpose detector
  coverage up to $|\eta|=5$;
design to operate at $L=10^{34}\text{cm}^{-2}\text{s}^{-1}$

- Inner Detector (tracker)
  Si pixel & strip detectors + TRT;
  2 T magnetic field;
  coverage up to $|\eta|<2.5$.

- Calorimetry
  highly granular LAr EM calorimeter
  ($|\eta|<3.2$);
  hadron calorimeter – scintillator tile
  ($|\eta|<4.9$).

- Muon Spectrometer
  air-core toroid system
  ($|\eta|<2.7$).

Lepton energy scale: precision of 0.02% ($Z\rightarrow ll$)
Jet energy scale: precision of 1% ($W\rightarrow jj; Z\rightarrow ll + \text{jets}$)
Absolute luminosity: precision $\leq 5\%$ (machine, optical theorem, rate of known processes)
W mass measurement

- W mass is one of the fundamental parameters of the SM ($\alpha_{\text{QED}}, G_F, \sin \theta_W$)

$$M_W = \frac{\pi \alpha}{\sqrt{G_F} \sqrt{2} \sin \theta_W (1 - \Delta R)}$$

- Precise measurements will constrain the mass of the SM Higgs or the $h$ boson of the MSSM;
- At the time of the LHC start-up the W mass will be known with a precision of about 30 MeV (LEP2 + Tevatron)
- Equal weights in a $\chi^2$ test:
  $$\Delta M_W \approx 0.7 \times 10^{-2} \Delta m_t$$

At the LHC $\Delta m_t \sim 2$ GeV

$M_W$ should be known with a precision of about 15 MeV (combining $e/\mu$ and CMS data).

(achievable during the low-luminosity phase at ATLAS)

- constrains $M_H$ to $\sim 25\%$

$M_W = 80.446 \pm 0.040$ GeV (LEP2 – PDG)
W mass measurement

Sources of uncertainty:

- **Statistical uncertainty**: < 2 MeV for $\mathcal{L} \approx 10$ fb$^{-1}$

  \[ pp \rightarrow W + X \]

  \[ W \rightarrow l \nu \]

  $\sigma = 30$ nb ($l=e, \mu$)

  3x10$^8$ events ($\mathcal{L} \approx 10$ fb$^{-1}$)

- **Systematic error**
  a) physics: $W$ $p_t$ spectrum, structure functions,
      $W$ width, radiative decays and background.
  b) detector performance: lepton scale, energy/momentum resolution and response to recoil.

- Lepton energy and momentum scale:
  ~0.1% at Tevatron
  ~0.02% at LHC – ATLAS (tuned to $Z \rightarrow l^+l^-$, $l=e, \mu$)

- p.d.f.’s & radiative corrections: improve theoretical calculations!

➢ Detector resolution + pile-up will smear significantly the transverse mass distribution.
(method limited to the low-luminosity phase!)
Top mass

- Together with $M_W$, $m_t$ helps to constrain the SM Higgs mass. 
  \[ m_t = 175.3 \pm 4.4 \text{ GeV} \] (global fit – PDG)

- $t\bar{t}$ production is expected to be the main background to new physics processes: production and decay of Higgs bosons and SUSY particles.

- Precision measurements in the top sector are important to get more clues on the origin of the fermion mass hierarchy.

- Top events will be used to calibrate the calorimeter jet scale ($W \rightarrow jj$ from $t \rightarrow bW$).

\[ \sigma_{NLO} (pp \rightarrow t\bar{t}) = 833 \text{ pb at LHC} \]

\[ gg \rightarrow t\bar{t} (\sim 90\%) \quad (\sim 7 \text{ pb at Tevatron}) \]

\[ q\bar{q} \rightarrow t\bar{t} (\sim 10\%) \]

Best channel for $m_t$ measurement will be $t\bar{t} \rightarrow WWbb \rightarrow (l\nu)(jj)bb$  (m$_t$ = m$_{jjb}$)

$\Delta m_t = 2 \text{ GeV}$

- $\Delta m_t$ at LHC will be dominated by systematic errors!
  - Jet energy scale:
    - $\sim 3\%$ at Tevatron
    - $\sim 1\%$ at LHC – ATLAS (including $W \rightarrow jj$ from $t \rightarrow bW$)
  - Final state gluon radiation ($\sim 1\%$)

### $t\bar{t}$ leptonic decays ($t \rightarrow bW$)

| Single lepton: $W \rightarrow l\nu, W \rightarrow jj$ | 2.5 x $10^6$ events |
| 4.9% | (400,000 events) |

\[ L \approx 10 \text{ fb}^{-1} \]

A. M. Moraes
Determination of $\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z^2)$

- $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ is one of the fundamental parameters of the SM!

- Precise determination will constrain the Higgs mass and check consistency of the SM.

- $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ will be determined at the LHC by measuring $A_{FB}$ in dilepton production near the Z pole.

$$A_{FB} = b \{ a - \sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z^2) \}$$

$a$ and $b$ calculated to NLO in QED and QCD.

- Main systematic effect: uncertainty on the p.d.f.'s, lepton acceptance (~0.1%), radiative correction calculations.

$$\sin^2 \theta_{\text{eff}}^{\text{lept}}(M_Z^2) = 0.23126 \pm 1.7 \times 10^{-4} \text{ (global fit PDG)}$$

Can be further improved: combine channels/experiments.

A. M. Moraes

EW physics at ATLAS

APS April 8, 2003
**EW single top quark production** (not yet observed!)

![Diagram showing EW single top quark production processes](image)

- **W-gluon fusion** \( \sigma_{Wg} \approx 250 \text{ pb} 

- For each process: \( \sigma \propto |V_{tb}|^2 \)

- **Probe the** \( t-W-b \) vertex

- **Directly measurement** (only) of the CKM matrix element \( V_{tb} \) at ATLAS (assumes **CKM unitarity**)

- **New physics**: heavy vector boson \( W' \)

- **Source of** high polarized tops!

- **Background**: \( t\bar{t}, Wb\bar{b}, Wjj \)

- **Systematic errors**: b-jet tagging, luminosity (\( \Delta \mathcal{L} \approx 5 - 10\% \)), **theoretical** (dominate \( V_{tb} \) measurements!).

**Table**

<table>
<thead>
<tr>
<th>Process</th>
<th>S/B</th>
<th>S/\sqrt{B}</th>
<th>( \Delta V_{tb}/V_{tb} ) – statistical</th>
<th>( \Delta V_{tb}/V_{tb} ) – theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W-gluon )</td>
<td>4.9</td>
<td>239</td>
<td>0.51%</td>
<td>7.5%</td>
</tr>
<tr>
<td>( Wt )</td>
<td>0.24</td>
<td>25</td>
<td>2.2%</td>
<td>9.5%</td>
</tr>
<tr>
<td>( W* )</td>
<td>0.55</td>
<td>22</td>
<td>2.8%</td>
<td>3.8%</td>
</tr>
</tbody>
</table>

\( \mathcal{L} = 30 \text{ fb}^{-1} \)

**A. M. Moraes**
Triple gauge boson couplings

- TGC of the type $WW\gamma$ or $WWZ$ provides a direct test of the non-Abelian structure of the SM (EW symmetry breaking).

- It may also indicate hints of new physics: new processes are expected to give anomalous contributions to the TGC.

- New physics could show up as deviations of these parameters from their SM values.

- This sector of the SM is often described by 5 parameters: $g_1^Z$, $\kappa_\gamma$, $\kappa_Z$, $\lambda_\gamma$ and $\lambda_\gamma$, (SM values are equal to $g_1^Z = \kappa_\gamma = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_\gamma = 0$, at the tree level).

- Anomalous contribution to TGC is enhanced at high $\sqrt{s}$ (increase of production cross-section).

A. M. Moraes
• Variables:
  \( W_\gamma \): \((m_{W\gamma}, |\eta_\gamma^*|)\) and \((p_T^\gamma, \theta^*)\) sensitive to high-energy behaviour: \(m_{WV}, p_T^V\)
  \( WZ \): \((m_{WZ}, |\eta_Z^*|)\) and \((p_T^Z, \theta^*)\) sensitive to angular information: \(|\eta_V^*|, \theta^*\)

• SM: vanishing helicity at low \(|\eta|\)
  Non-standard TGC: partially eliminates `zero radiation'

**Systematic uncertainties:**

• At the LHC, sensitivity to TGC is a combination of the very high energy and high luminosity.
• Uncertainties arising from low \(p_T\) background will be quite small: anomalous TGC signature will be found at high \(p_T\).
• Theoretical uncertainties: p.d.f.'s & higher order corrections

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Statistical (at 95% C.L.)</th>
<th>Systematic (at 95% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta g_1^Z )</td>
<td>-0.0064 + 0.010</td>
<td>±0.0058</td>
</tr>
<tr>
<td>( \Delta \kappa_Z )</td>
<td>-0.10 + 0.12</td>
<td>±0.024</td>
</tr>
<tr>
<td>( \lambda_Z )</td>
<td>-0.0065 + 0.0066</td>
<td>-0.0032 + 0.0031</td>
</tr>
<tr>
<td>( \Delta \kappa_\gamma )</td>
<td>-0.073 + 0.076</td>
<td>-0.015 + 0.0076</td>
</tr>
<tr>
<td>( \lambda_\gamma )</td>
<td>±0.0033</td>
<td>±0.0012</td>
</tr>
</tbody>
</table>

\( L = 30 \text{ fb}^{-1} \)

Using max-Likelihood fit to \(m_{WV} \otimes |\eta_V^*|\)
Conclusions:

- LHC will allow precision measurements: unexplored kinematic regions, high-statistics (W, Z, b, t factory);
- ATLAS: valuable precision measurements of SM parameters;
- W mass can be measured with a precision of 15 MeV (combinig e/μ and ATLAS + CMS);
- Top mass: ~ 2 GeV (combined with $\Delta m_W$~15 MeV, constrains $M_H$ to ~ 25%);
- $\sin^2\theta_{\text{eff}}^{\text{lept}}(M_Z^2)$ can be determined with statistical precision of $1.4\times10^{-4}$ (competitive to lepton collider measurements!)
- EW single top production: direct measurement of $V_{tb}$; measurement of top polarization ($Wg$ with statistical precision of ~ 1.6%);
- Sensitivity to anomalous TGC’s: indicative of new physics!