Standard Model physics with the ATLAS early data

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on behalf of
the ATLAS Collaboration

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**The Large Hadron Collider (LHC)**

- **Diameter**: 25 m
- **Barrel toroid length**: 26 m
- **End-cap end-wall chamber span**: 46 m
- **Overall weight**: 7000 tons

**Calorimetry (|η| < 5)**
- EM: Pb-LAr
- HAD: Fe/scintillator (central), Cu/W-LAr (fwd)

**Tracking (|η| < 2.5, B=2T)**
- Si pixels and strips
- TRD (e/π separation)

**LHC Collider Parameters**

- **pp collision cm**: 14 TeV (x7 Tevatron)
- **25 ns bunch spacing**
- **1.1 10^{11} proton/bunch**
- **Design lumi**: 10^{34} cm^{-2}s^{-1} (10 nb^{-1}s^{-1})
- **Physics/year**: ≈ 100 days

**Luminosity**

- **100 fb^{-1}/year**: ≈ 20 int./x-ing (2009)
- **Low lumi**: ≈ 10^{33} cm^{-2}s^{-1} (1 nb^{-1}s^{-1})
  - **10 fb^{-1}/year**: ≈ 2 int./x-ing (2008)
- **Initial lumi**: < 10^{32} cm^{-2}s^{-1} (0.1 nb^{-1}s^{-1})
  - **100-300 pb^{-1}??**; (2007)
What's on the menu:

✓ LHC: a parton accelerator. Understand and constrain PDF's
  o W, Z as standard candles for luminosity monitoring.
✓ LHC as top factory (tt x-section nearly a nb!):
  ✓ m_t – crucial constraint on SM Higgs,
  ✓ top spin physics (production and decay),
  ✓ single top,
  o top charge,
  o FCNC in top decays (t->qZ->qll, t->qγ, t->qg),
  o hadronic top decays (t->Wb, W->2jets) very useful for
    in situ JES calibration (W mass!). Also useful for b-tagging
    calibration!
  o W mass measurement (systematics very challenging)
  o D.Y.: lepton pair spectrum up to high masses. Z
    resonance – mostly calibration, but also sensitive to new
    physics.
  o B-physics: prospects depend largely on the actual LHC
    operation and the length of low lumi period (B_s oscillations
    and CP violation, B rare decays, b-baryon physics)
  o QCD.

and many more...
Acknowledgements

I’d like to thank the ATLAS Standard Model Group and the Top Group for the wide choice of the analysis material. Special thanks go to:


whose work directly contributed to this presentation.
At the TeV scale, uncertainties in cross section predictions for new physics are dominated by high-x gluon uncertainty.

At the EW scale (i.e., W and Z masses), theoretical predictions are dominated by low-x gluon uncertainty.

The $Q^2$ dependence of $f(x,Q^2)$ is parameterised and fitted to data. Done by various groups: CTEQ, MRST, ZEUS, Alekhin etc.

Rate=$e_{\exp} \times \int dx_1 dx_2 \sigma_{ab->x} (x_1 x_2 S = Q^2) f_a(x_1,Q^2) f_b(x_2,Q^2) \times \int Ldt$
just an example -> single W± Productions (standard candles at LHC)

\[ \bar{u}d \rightarrow W^+ \rightarrow e^+ \nu \]
\[ d\bar{u} \rightarrow W^- \rightarrow e^- \bar{\nu} \]

Uncertainties dominated by PDFs

NNLO corrections small ~ few% NNLO residual scale dependence < 1%

Error on the low-x gluon shape parameter \( \lambda \), \( xg(x) \sim x^{-\lambda} \) can be significantly reduced (35%) with just 100 pb\(^{-1}\) of data. (4% exp. systematic and no Luminosity measurement assumed!)
(Work in progress)

Due to the clean signal and very good control of theoretical predictions W± and Z production in their leptonic decays may prove to be one of the most reliable (parton) luminosity monitors.
\(\bar{t}t\) production at the LHC

LHC will be a top factory!

X-section determination limited by the luminosity and detector systematics.

\[\hat{s} = Sx_1x_2\]

\[x_1x_2 \geq \frac{4m_t^2}{\hat{s}} \approx 6 \times 10^{-4}\]

(Tevatron: \(\geq 3 \times 10^{-2}\))

LHC: \(\sigma_{tt} \approx 830\) pb

Tev: \(\sigma_{tt} \approx 6.7\) pb

\(\times 100\)

LHC Low L \(10^{33}\) cm\(^{-2}\)s\(^{-1}\)

Tevatron \(10^{32}\)

Prod Rate \(\times 1000\)

S/B way higher!
Status of summer 2005 (hep-ex/0511027):

Top quark mass = 172.7 ± 2.9 GeV

\[ m_W = 80.410 ± 0.032 \text{ GeV} \]

\[ m_H = 91^{+45}_{-32} \text{ GeV/c}^2 \]

\[ m_H < 186 \text{ GeV/c}^2 \quad @ \text{95\% CL (theory incl.)} \]

\[ \chi^2 \text{ contribution: } \Delta m_W \sim 0.007 \times \Delta m_t \]

LHC goal: \[ \Delta m_t \sim 1 \text{ GeV/c}^2 \]

Hope to go down to \[ \delta m_W \sim 0.015 \text{ GeV} \text{ @LHC} \]

Only logarithmic dependence
Single lepton $t\bar{t}$ event selection

- Isolated lepton $P_T > 20$ GeV
- $E_T^{\text{miss}} > 20$ GeV
- 4 jets with $E_T > 40$ GeV, $|\eta| < 2.5$
- $>1$ b-jet ($\varepsilon_b \approx 50\%$, $\varepsilon_{uds} \approx 10^{-3}$, $\varepsilon_c \approx 10^{-2}$)
- BKG < 2% W/Z+jets, WW/ZZ/WZ

Efficiency: $\approx 1\%-2\%$

Golden plated channel (BR=30%)
- Clean trigger from isolated lepton
- Allows for in situ light jet energy scale calibration
- Reconstruction starts with the W (different ways to pair the right jets)
- Important to tag the b-jets!
  Largely cleans the sample and helps jet assignment.
top mass reconstruction

1 Hadronic top:
Three jets with highest vector-sum $p_T$ as the decay products of the top

2 W boson:
Two jets in hadronic top with highest momentum in reconstructed $jjj$ C.M. frame.

Hadron side No b-tag
$L=300 \text{ pb}^{-1}$

$W$ CANDIDATE

$TOP$ CANDIDATE

$TOP$ CANDIDATE

$W$ CANDIDATE

$m(top_{had})$

$m(W_{had})$

$m(top_{had})$
### Mass Measurement Systematics

#### Statistical error for 10 fb\(^{-1}\) : 0.05 GeV/c\(^2\)

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Hadronic top (\delta M_{\text{top}}) (GeV/c(^2))</th>
<th>Kinematic fit (\delta M_{\text{top}}) (GeV/c(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light jet energy scale (1 %)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>b-jet energy scale (1 %)</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>b-quark fragmentation</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>ISR</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>FSR</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Combinatorial background</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td>1.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Statistical error (10 fb(^{-1}))</td>
<td>0.05</td>
<td>0.1</td>
</tr>
</tbody>
</table>

In situ calibration possible e.g.: \(m_t = \langle m_{jjb} - m_{jj} \rangle - M_W\) (PDG)

**Background mostly combinatorial**
top mass reconstruction – other channels

- **di-lepton events**
  - efficiency = 6.5 % → 20 000 events @ 10 fb⁻¹
  - \( \delta m_{\text{stat}} = 0.04 \text{ GeV/c}^2 \)

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>( \delta M_{\text{top}} ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistic &amp; reconstruction method</td>
<td>0.3</td>
</tr>
<tr>
<td>b–jet energy scale</td>
<td>0.6</td>
</tr>
<tr>
<td>b–quark frag.</td>
<td>0.7</td>
</tr>
<tr>
<td>ISR</td>
<td>0.1</td>
</tr>
<tr>
<td>FSR</td>
<td>0.6</td>
</tr>
<tr>
<td>Parton distribution function</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.7</strong></td>
</tr>
</tbody>
</table>

- **fully hadronic events**
  - efficiency = 0.08 % → 3300 events @ 10 fb⁻¹
  - \( \delta m_{\text{stat}} = 0.18 \text{ GeV/c}^2 \)

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>( \delta m_{\text{top}} ) (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light jet energy scale</td>
<td>0.8</td>
</tr>
<tr>
<td>b-jet energy scale</td>
<td>0.7</td>
</tr>
<tr>
<td>b–quark fragmentation</td>
<td>0.3</td>
</tr>
<tr>
<td>ISR</td>
<td>0.4</td>
</tr>
<tr>
<td>FSR</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>3</strong></td>
</tr>
</tbody>
</table>
W polarization in top decay

- Top decay: predominantly source of longitudinal W's
  - Polarization depends only on $M_t$ and $M_W$ (LO)

<table>
<thead>
<tr>
<th></th>
<th>Longitudinal $W^+$ ($F_0$)</th>
<th>Left-handed $W^+$ ($F_L$)</th>
<th>Right-handed $W^+$ ($F_R$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Model (M$_{top}$=175 GeV)</td>
<td>0.703 ($\frac{M_t^2}{M_t^2 + 2M_W^2}$)</td>
<td>0.297 ($\frac{2M_W^2}{M_t^2 + 2M_W^2}$)</td>
<td>0.000</td>
</tr>
<tr>
<td>NLO</td>
<td>0.695</td>
<td>0.304</td>
<td>0.001</td>
</tr>
</tbody>
</table>

- Sensitive to EWSB
- Test of V-A structure

- All 3 components in angular distribution of lepton in W rest frame:

$$\frac{1}{N} \frac{dN}{d\cos \Psi} = \frac{3}{2} \left[ F_0 \left( \frac{\sin \Psi}{\sqrt{2}} \right)^2 + F_L \left( \frac{1-\cos \Psi}{2} \right)^2 + F_R \left( \frac{1+\cos \Psi}{2} \right)^2 \right]$$

- Angle between:
  - lepton in W rest frame and
  - W in top rest frame
W helicity results

Results for 10 fb\(^{-1}\), fast simulation:

<table>
<thead>
<tr>
<th></th>
<th>SM values</th>
<th>(F_0)</th>
<th>(F_R)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(0.703)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>± Stat</td>
<td>(\pm 0.004)</td>
<td>(\pm 0.003)</td>
<td></td>
</tr>
<tr>
<td>± Syst</td>
<td>(\pm 0.016)</td>
<td>(\pm 0.012)</td>
<td></td>
</tr>
</tbody>
</table>

From W polarization, deduce sensitivity to tWb anomalous couplings → model independent approach, i.e. effective Lagrangian
**$\bar{t}t$ spin correlation**

- Tops not polarized in pairs, but **correlations** between spins
  - Like-helicity pairs more abundant in LHC

$$A = \frac{\sigma(t_{L} \bar{t}_{L}) + \sigma(t_{L} \bar{t}_{R}) - \sigma(t_{L} \bar{t}_{R}) - \sigma(t_{R} \bar{t}_{L})}{\sigma(t_{L} \bar{t}_{L}) + \sigma(t_{R} \bar{t}_{R}) + \sigma(t_{L} \bar{t}_{R}) + \sigma(t_{R} \bar{t}_{L})} \neq 0$$

$$A_{D} = A_{X} + A_{Y} + A_{Z}$$

≈equivalent; Sensitive to BSM production mechanisms

- Measure angular distributions of daughter lepton in top rest frames

$$\frac{1}{N} \frac{d^{2}N}{d (\cos \theta_{1}) d (\cos \theta_{2})} = \frac{1}{4} \left( 1 - A \alpha_{1} \alpha_{2} \cos \theta_{1} \cos \theta_{2} \right)$$

**Angle between t(t) and spin analysers**

$$\frac{1}{N} \frac{dN}{d \cos \Phi} = \frac{1}{2} \left( 1 - A_{D} \alpha_{1} \alpha_{2} \cos \Phi \right)$$

**Angle between spin analysers**

ref: hep-ex/0303092

$\alpha=1$ for charged lepton from t ( $d\sigma/d\cos\theta$→(t-$m_{t}$s).l b.v )

$gg\rightarrow$tt ($^{1}S_{0}$) 90%

$qq\rightarrow$tt ($^{3}S_{1}$) 10%
Spin correlation results

Results with fast simulation of detector (10 fb⁻¹):

<table>
<thead>
<tr>
<th>SM values</th>
<th>A</th>
<th>A_D</th>
<th>A¹</th>
<th>A_D¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.33</td>
<td>-0.24</td>
<td>0.42</td>
<td>-0.29</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative errors</th>
<th>ΔA/A</th>
<th>ΔA_D/A_D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>semi + dileptonic</td>
<td>3%</td>
</tr>
<tr>
<td>Systematic</td>
<td>semi + dileptonic</td>
<td>5%</td>
</tr>
</tbody>
</table>

Precision dominated by systematics

Sensitivity to new physics:

Any deviation from SM prediction might sign the presence of tt production through a new mechanism.

A heavy spin-0 (Higgs ?), new vector particle or spin-2 (KK graviton ?)

Tevatron: Expect ≈40% @ 2 fb⁻¹

ref: hep-ex/0508061
Single top production (1)

Three production mechanisms:

- Wg fusion: $245\pm27$ pb
  
  S. Willenbrock et al., Phys.Rev.D56, 5919

- Wt: $62.2^{+16.6}_{-3.7}$ pb
  
  A. Belyaev, E. Boos, Phys.Rev.D63, 034012

- W*: $10.2\pm0.7$ pb
  
  M. Smith et al., Phys.Rev.D54, 8696

NLO already available for Wg fusion ($\pm9$ pb) and Wt.

- Main Background [$\propto BR(W \rightarrow \ell \nu)$, $\ell = e, \mu$]:
  - $tt$: $\sigma = 833$ pb
  - $Wbb$: $\sigma = 300$ pb
  - $Wjj$: $\sigma = 18 \cdot 10^3$ pb

Main uncertainty due to:
- choice of $b, g$ PDF's, (dominates by far!)
- the renormalisation scale $\mu$
- $m_t$

**Tevatron:**
- Wg fusion: $2.1$ pb ± 5%
- Wt: $0.1$ pb ± 10%
- W*: $0.9$ pb ± 5%

**Two orders of magnitude smaller!**
Single top production (2)

Physics motivation:

- Tevatron will have hard time to establish the 5σ-evidence with the 2 fb\(^{-1}\) of data
- LHC will see it immediately
- Allows direct determination of \(|V_{tb}|^2 - O(\%)\) \(\prec\) PDF limited
- Test of V-A nature of the Wtb vertex \(P \approx 100\%\) \(\{\) Wg and Wt channels \(\}
- Anomalous couplings, FCNC (gu-\(\rightarrow\)t)
- Charged Higgs bosons (2HDM), extra gauge bosons W', (extra dim KK, etc.) - increase of the total x-section
- Possibility of seeing heavy resonances in the s-channel tb final system (starting from \(\approx 30\) fb\(^{-1}\))
- Interest in measuring x-sections of the three channels separately! Experimentally challenging!
  High backgrounds. Strongly dependent on detector performance.
Summary

- I hope I’ve convinced you there is lots of interesting and relevant physics within the SM @ LHC, often giving possibility of insight into BSM phenomena.
- Many can be explored to full extent in the first years of the LHC operation. Systematics dominate in most cases.
- Theoretical predictions very often are limited by the PDF uncertainties. The latter can be substantially reduced using very first LHC data.
- There is much more I haven’t covered!
- Lots of excitement ahead of us even before we start seeing directly Higgs or “new physics”.
PDF constraining potential of ATLAS

Effect of including the ATLAS W Rapidity “pseudo-data” in global PDF Fits: how much can we reduce the PDF errors when LHC is up and running?

Simulate real experimental conditions:

Generate 1M “data” (≈100 pb⁻¹) sample with CTEQ6.1 PDF through ATLFAST detector simulation and then include this pseudo-data (with imposed 4% error) in the global ZEUS PDF fit (with Det.->Gen. level correction). Central value of ZEUS-PDF prediction shifts and uncertainty is reduced:

\[
\lambda_{\text{BEFORE}} = -0.199 \pm 0.046 \\
\lambda_{\text{AFTER}} = -0.181 \pm 0.030 
\]

35% error reduction

In ZEUS-PDF fit the e± Normalisation left free => no assumption on Luminosity measurement!
FIG. 4. Differential cross section for $t\bar{t}$ production as a function of the $t\bar{t}$ invariant mass for the LHC with center of mass energy 14 TeV, decomposed into LR+RL and LL+RR in the zero momentum frame of the $t\bar{t}$ pair for both $q\bar{q}$ and $gg$ components.

FIG. 6. The solid curve is the fraction of those $t\bar{t}$ pairs at the LHC (14 TeV) with an invariant mass below $M_{t\bar{t}}$ which have helicities LL+RR. The dashed curve is the fraction of the total cross section with an invariant mass below $M_{t\bar{t}}$. 

(G.Mahlon, S.Parke hep-ph/9512264)