W/Z and Top Precision Measurement at ATLAS and CMS

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on behalf of the ATLAS & CMS Collaborations

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LHC

• 2010: 0.04 fb⁻¹
  • 7 TeV
  • Commissioning

• 2011: ~6 fb⁻¹
  • 7 TeV
  • Exploring the limits

• 2012: ~23 fb⁻¹
  • 8 TeV
  • Production

World highest energy particle collider
ATLAS Detector

ATLAS coped very well with the remarkable collider performance during the 2011-2012 runs:
• 23.3 fb⁻¹ delivered in 2012; 21.7 fb⁻¹ recorded.
• Operational efficiency ~93%.
• High reconstruction efficiency, even in presence of pileup.
Same for CMS, success of detector operations crucial to physics output:

- Overall operational efficiency ~93% and increased over time.
- Coped very well for the challenges of 2012 pileup.
- Order ~250 papers from CMS and ATLAS, each.
This paid off

Full 2011-2012 dataset

- Discovery of a new Higgs-like particle.
- Studies of this particle continues.
- The 2011-2012 runs were successful also for many other reasons...
• ATLAS and CMS collected an unprecedented amount of data at an hadron collider. Both at a center-of-mass energy of 7 and 8 TeV.
• Analyses moved from initial W and Z inclusive cross-sections to extensive and detailed studies of diboson, tt and single top production spanning more than 4 order of magnitude in production cross-section.
Top quark physics
Top Quark Pair Cross Section: 7 TeV

- \( t\bar{t} \) production dominated by gluon fusion at the LHC (~90%).
- State of the art theoretical calculations have uncertainties ~3%:

<table>
<thead>
<tr>
<th>Collider</th>
<th>( \sigma_{\text{tot}} ) [pb]</th>
<th>scales [pb]</th>
<th>pdf [pb]</th>
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<tr>
<td>Tevatron</td>
<td>7.164</td>
<td>+0.110(1.5%)</td>
<td>+0.169(2.4%)</td>
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<td>−0.200(2.8%)</td>
<td>−0.122(1.7%)</td>
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<td>LHC 7 TeV</td>
<td>172.0</td>
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<td>+4.7(2.7%)</td>
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<td>−5.8(3.4%)</td>
<td>−4.8(2.8%)</td>
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<td>LHC 8 TeV</td>
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<td>+6.2(2.5%)</td>
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<td>−8.4(3.4%)</td>
<td>−6.4(2.6%)</td>
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<td>LHC 14 TeV</td>
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<td></td>
<td></td>
<td>−33.9(3.6%)</td>
<td>−17.8(1.9%)</td>
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</table>

**ATLAS Preliminary**

Data 2011, \( \sqrt{s} = 7 \text{ TeV} \)

Channel & Lumi.

- Single lepton: 0.70 fb\(^{-1}\)
- Dilepton: 0.70 fb\(^{-1}\)
- All hadronic: 1.02 fb\(^{-1}\)
- Combination: 0.70 fb\(^{-1}\)

\( \sigma_{\text{tot}} \) [pb] graph:

- Single lepton, b → Xμν: 165 ± 2 ± 17 ± 3 pb
- \( \tau_{\text{had}} \) + jets: 1.67 fb\(^{-1}\)
- \( \tau_{\text{had}} \) + lepton: 2.05 fb\(^{-1}\)
- All hadronic: 4.7 fb\(^{-1}\)

- LHC Combination: \( \sigma_{\text{tt}} = 173.3 ± 10.1 \text{ pb} \)

**CMS Preliminary, \( \sqrt{s} = 7 \text{ TeV} \)**

- CMS e/\( \mu \)+jets: 164 ± 3 ± 12 ± 7 pb
- CMS \( \tau \)+jets: 156 ± 12 ± 33 ± 3 pb
- CMS dilepton (ee,\( \mu \mu \),\( \tau \tau \)): 162 ± 2 ± 5 ± 4 pb
- CMS dilepton (ee,\( \mu \mu \)): 143 ± 14 ± 22 ± 3 pb
- CMS all-hadronic: 136 ± 20 ± 40 ± 8 pb

**NNLO+NNLL: arXiv:1303.6254**

Future measurements using all available data at LHC.

**ATLAS-CONF-2012-134**

CMS PAS TOP-12-003
Top Quark Pair Cross Section: 8 TeV

\[ \sigma_{\bar{t}t} = 241 \pm 2 \text{ (stat.)} \pm 31 \text{ (syst.)} \pm 9 \text{ (lumi.)} \text{ pb.} \]

- Inclusive cross section at 7 and 8 TeV are consistent across channels (and experiments).
- Experimental uncertainty approaching theoretical precision.
Top Quark Mass

Measurement performed in several channels

Top-antitop mass difference measured at CMS:

$$\Delta m_t = -272 \pm 196 \text{ (stat.)} \pm 122 \text{ (syst.)} \text{ MeV}$$

CMS PAS TOP-12-031

Uncertainties dominated by systematics:

- Jet and b-jet energy scale.
- ISR and FSR.
- $t\bar{t}$ generator model
- Test pQCD in differential distributions in lepton + jets and dilepton channel.
- Measurement unfolded and extrapolated to full phase space.
- NLO calculation describes data satisfactorily.
**tt + jets**: jet multiplicity in tt dilepton (CMS) and l+jet (ATLAS) final states:

- Test QCD radiation
- Constraints various ISR/FSR models, and generator configurations.

**tt+bb**: Ratio of light flavor to b-flavored jets (dilepton final state):

- Important background for ttH searches

\[
\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)} = 3.6 \pm 1.1_{\text{stat}} \pm 0.9_{\text{syst}}\%
\]
Top Production Charge Asymmetry I

- Top quark pair production has a small asymmetry under charge conjugation predicted by the SM.
- New Physics may lead to enhancements of this effect.
- Tensions between theoretical predictions and measurements of forward-backward asymmetry at the Tevatron.

**Tevatron:** forward-backward asymmetry
- Asymmetric initial state correlates top quark to proton direction

**LHC:** Charge asymmetry
- Top is correlated to valence quark
- $A_c$ diluted by large gg component

$A_{FB}^{ii} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$

$A_c = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)}$
Top Production Charge Asymmetry II

ATLAS-CONF-2012-057

$A_T^{\text{C}} = 0.057 \pm 0.024 \text{ (stat.)} \pm 0.015 \text{ (syst.)}$

Theory (MC@NLO): $A_T^{\text{C}} = 0.006 \pm 0.002$

$A_C = 0.004 \pm 0.010 \text{ (stat.)} \pm 0.011 \text{ (syst.)}$

$A_T^{\text{thy}} = 0.015 \pm 0.0006$  Kühn, Rodrigo arXiv:1209.6830

Both experiments measured the asymmetry in dilepton and l+jet channels. LHC measurements are consistent with theoretical predictions within uncertainties. More data needed.
t-channel single top cross section measurements are limited by systematics, i.e. precision measurements:
- Jet energy scale
- b-tagging
- ISR/FSR and signal generator

Both ATLAS and CMS measured for the first time the $Wt$ production cross section: in agreement with the theoretical expectations.

CMS update with 13 fb$^{-1}$:

\[
\sigma_{t,\text{top}} = 49.9 \pm 1.9 \text{(stat.)} \pm 8.9 \text{(syst.)} \text{ pb} \\
\sigma_{t,\text{anti-top}} = 28.3 \pm 2.4 \text{(stat.)} \pm 4.9 \text{(syst.)} \text{ pb} \\
R_{t,\text{ch.}} = 1.76 \pm 0.15 \text{(stat.)} \pm 0.22 \text{(syst.)}
\]
In the SM at LO couplings of the $Wtb$ vertex reduce to $V_L = 1$ and $V_R = g_{RL} = 0$.

\[ \mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} b\gamma^\mu (V_L P_L + V_R P_R) tW^- - \frac{g}{\sqrt{2}} b\frac{i\sigma^{\mu\nu} q_v}{m_W} (g_L P_L + g_R P_R) tW^- + h.c. \]

- Top quark in $t$-channel is highly polarized.
- $A_{FB}^N$: forward-backward asymmetry with respect to the normal to the plain defined by the W momentum and the top polarization. Probes $\text{Im}(g_R)$.
- Non-zero $A_{FB}^N$ means asymmetry in the Wtb vertex that is not expected in the SM.
- Similarly, W-boson helicity fractions ($F_L$, $F_R$ and $F_0$) are predicted by SM.

$A_{FB}^N = 0.031 \pm 0.065 \text{ (stat.)} ^{+0.029}_{-0.031} \text{ (syst.)}$

$\text{Im}(g_R)$ in $[-0.20, 0.30]$ at 95% CL (assuming top polarization $P = 0.9$)

In agreement with SM prediction

$F_L^{\text{Comb.}} = 0.293 \pm 0.069 \text{ (stat.)} \pm 0.030 \text{ (syst.)}$

$F_R^{\text{Comb.}} = 0.713 \pm 0.114 \text{ (stat.)} \pm 0.023 \text{ (syst.)}$

$F_0^{\text{Comb.}} = -0.006 \pm 0.057 \text{ (stat.)} \pm 0.027 \text{ (syst.)}$
LHC Combination of several measurements.

- All measurements utilize $\cos(\theta^*)$
  - $\theta^*$ is the angle between the momentum direction of the charged lepton from the W-boson decay and the reversed momentum direction of the b-quark from top decay; both boosted in the W-boson rest frame.

- Agreement with theoretical predictions
W and Z Physics
• ATLAS and CMS measured W and Z inclusive cross sections and many related properties both at 7 and 8 TeV.
• SM predictions are found in very good agreement with what seen in the data.
• The huge amount of data allows to measure and test processes with low cross section and/or significant backgrounds: we will focus on these.
Probing events with more than 6 jets.

Nice agreement with NLO predictions (available up to ≥4 jets)

Jet multiplicity generally reproduced by LO ME matched to Parton Shower.

The impressive amount of events allows precision measurements of V+jets: crucial tests of event kinematics are now feasible.

- Angular correlations
- Jet pT, HT, etc...
**Z+jet Δφ Correlations**

**CMS, $\sqrt{s} = 7$ TeV, $L = 5.0$ fb$^{-1}$**

$Z/\gamma \rightarrow l^+l^-, p_T^Z > 0$ GeV, $N_{\text{jets}} \geq 3$

- Data
- **MADGRAPH**
- SHERPA
- POWHEG (Z+1j)
- PYTHIA6 (Z2)

$1/\sigma \frac{d\sigma}{d(\Delta \phi)}$ [1/ rad]

- $\Delta \phi(Z, j_1)$
- $\Delta \phi(Z, j_2)$
- $\Delta \phi(Z, j_3)$

$Z + \geq 3$-jets

- $\Delta \phi(Z, J_i)$
- $\Delta \phi(Z, j_i)$

- $\Delta \phi(j_1, j_2)$
- $\Delta \phi(j_1, j_3)$
- $\Delta \phi(j_2, j_3)$

- $\Delta \phi(j_i, J_j)$

- $\Delta \phi(j_i, j_j)$

- $\Delta \phi(j_i, j_j)$

**Observations:**

- Powheg NLO Z+1 jet matched to PS reproduces $\geq 3$ jet dynamics very well.
- The same applies to ME+PS Sherpa and Madgraph.
- Pythia not meant to reproduce data, but shown for completeness.
• Leading jet $p_T$ nicely reproduced by NLO calculations.
• Monte Carlo does not properly reproduce highly boosted events: important for searches.

$S_T = \Sigma P_T \text{ (jets)}$
• ME + parton shower programs reasonably reproduce $Z$ rapidity.
• They do not reproduce the rapidity difference: data in slightly better agreement with Sherpa.
$\sigma(W+c\text{-jet})$ sensitive to **strange content of the proton.**

- $c$-jet are selected through **charm meson reconstruction**
- **Very high $W+c$ purity: 80-90%**

**Fig. 10:** Comparison of the theoretical predictions for $\sigma(W+c)$ computed with MCFM and several sets of PDFs with the average of the experimental measurements. The top plot shows the predictions for a $p_T$ threshold of the lepton from the $W$ decay of $\l > 25 \text{ GeV}$ and the bottom plot presents the predictions for $p_T(l) > 35 \text{ GeV}$. 

- $W \rightarrow l\nu$ ($l = \mu$)
- $E_T(\text{jet}) > 25 \text{ GeV}$
- $p_T(l) > 25 \text{ GeV}$

First differential measurement of lepton pseudorapidity

**$s/d$ ratio**, measured using inclusive $W$ and $Z$ boson sample, also in agreement with CT10 (NLO)
The rate of hard double-parton interactions (DPI) is measured in the \(W + 2\) jets (\(W + 2j\)) channel with the ATLAS experiment. The kinematics of the jet system is used to extract the fraction of DPI events out of all \(W + 2j\) final states. The DPI-fraction is used to compute \(\sigma_{\text{eff}}\), a supposedly process-independent parameter related to the transverse size of the proton.

\[
f_{\text{DP}}^{(D)} = 0.08 \pm 0.01 \text{ (stat.)} \pm 0.02 \text{ (sys.)}
\]

\[
\sigma_{\text{eff}} = 15 \pm 3 \text{ (stat.)} \pm 3 \text{ (sys.) mb}
\]

\(W + 2\)jets DPI modeling in Alpgen+Herwig+Jimmy and Sherpa is found in agreement with data.
W+b-jet 7 TeV

- Separate sample into W+jet dominated signal with at least 2 jets and top dominated control sample with at least 4 jets
- Require exactly 1 b-tag (compare 2 tagging algorithms). Fit to multivariate b-tag output
- Correct for hadronization to allow comparisons with NLO QCD

- Also, first b-jet pT differential measurement.
- Some tension with NLO prediction at high b-jet pT.
W+2 b-jets 7 TeV

- Separate sample into W+jet dominated signal with at least 2 jets and top dominated control sample with at least 4 jets
- Require exactly 2 b-tags: complementary to the ATLAS result. Correct for hadronization to allow comparisons with NLO QCD.

\[ \sigma(pp \rightarrow W + b\bar{b}, p_T^b > 25 \text{ GeV}, |\eta^b| < 2.4) \times B(W \rightarrow \mu\nu, p_T^\mu > 25 \text{ GeV}, |\eta^\mu| < 2.1) = 0.53 \pm 0.05 \text{ (stat.)} \pm 0.09 \text{ (syst.)} \pm 0.06 \text{ (theo.)} \pm 0.01 \text{ (lum.)} \text{ pb.} \]

Very good agreement with NLO prediction (MCFM): \[ 0.52 \pm 0.03 \text{ pb} \]
ZZ Cross Section

ATLAS at 8 TeV: ATLAS-CONF-2013-020
\[ \sigma^{\text{tot}}_{ZZ} = 7.1^{+0.5}_{-0.4}\text{(stat.)} \pm 0.3\text{(syst.)} \pm 0.2\text{(lumi.) pb.} \]

Compared to MCFM prediction: \[ 7.2^{+0.3}_{-0.2} \text{ pb} \]

CMS at 8 TeV: arXiv:1301.4698
\[ \sigma(pp \to ZZ) = 8.4 \pm 1.0\text{ (stat.)} \pm 0.7\text{ (syst.)} \pm 0.4\text{ (lum.) pb.} \]

Compared to MCFM prediction: \[ 7.7 \pm 0.4 \text{ pb} \]

Measured cross sections agree with the SM prediction
- NB: “total” cross section depends on the Z mass window

Measurement precisions are statistics-limited
- Leading systematic errors is the lepton identification efficiency
ATLAS-CONF-2013-021

ATLAS at 8 TeV:

\[ \sigma_{\text{WZ}}^{\text{tot}} = 20.3^{+0.8}_{-0.7} \text{(stat.)} +1.2_{-1.1} \text{(syst.)} +0.7_{-0.6} \text{(lumi.) lb} \]

Compared to MCFM prediction:

\[ 20.3 \pm 0.8 \text{ pb} \]

CMS at 8 TeV:

\[ \sigma(pp \rightarrow W^+W^-) = 69.9 \pm 2.8 \text{ (stat.)} \pm 5.6 \text{ (syst.)} \pm 3.1 \text{ (lum.) lb} \]

Compared to MCFM prediction:

\[ 57.3^{+2.4}_{-1.6} \text{ pb} \]

arXiv:1301.4698

WZ cross sections agree with the SM prediction

WW slightly larger than prediction.
Triple Gauge Couplings

**WWV (V = Z/γ) couplings** □ WW and WZ (also Wγ)
- 5 parameters: \( \Delta g_1^Z (\equiv g_1^Z - 1) \), \( \Delta \kappa_Z (\equiv \kappa_Z - 1) \), \( \Delta \kappa_\gamma (\equiv \kappa_\gamma - 1) \), \( \lambda_Z \), \( \lambda_\gamma \)

**ZZV (V = Z/γ) couplings** □ ZZ (also Zγ)
- 4 parameters: \( f_4^Z \), \( f_4^\gamma \), \( f_5^Z \), \( f_5^\gamma \)

Parameters in red are zero in the SM

**Effects of aTGCs increase with**
- Increase sensitivity by binning in, or selecting the upper tail of
- Observables: \( m_{ZZ} \) (for ZZ), \( p_T \) of Z (for WZ or ZZ), \( p_T \) of leading lepton (for WW)
- Also used: \( p_T \) of di-jet in WW/WZ → ℓνjj
### Triple Gauge Couplings

#### TGCs consistent with the SM

- Four of the WWZ and WWγ couplings are constrained by LHC, Tevatron, and LEP to $O(0.05)$
  - Caveat: LEP scenario is used to relate $\Delta \kappa_Z$ to $\Delta \kappa_\gamma$, $\lambda_Z$ to $\lambda_\gamma$
  - $\Delta \kappa_\gamma$ remains less precise
- $ZZZ$ and $ZZ\gamma$ couplings are constrained by the LHC results to $O(0.01)$

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#### WWZ couplings

<table>
<thead>
<tr>
<th>$\Delta \kappa_Z$</th>
<th>WW</th>
<th>$-0.043 - 0.043$ fb$^{-1}$</th>
<th>CMS Limits</th>
<th>ATLAS Limits</th>
<th>LEP Combination</th>
<th>D0 Limit</th>
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<td></td>
<td>WW</td>
<td>$-0.043 - 0.033$ fb$^{-1}$</td>
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<td>LEP Combination</td>
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<td>$\lambda_Z$</td>
<td>WW</td>
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<td>WW</td>
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<td>WZ</td>
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<td>D0 Combination</td>
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<td>$\Delta g_1^Z$</td>
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<td>ATLAS Limits</td>
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<td>WZ</td>
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<td>LEP Combination</td>
<td>D0 Limit</td>
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#### WWγ couplings

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<td>$\lambda_\gamma$</td>
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Conclusions

- ATLAS and CMS did not just rediscover the Standard Model.

- New measurements are probing observables at an unprecedented level of accuracy and in unexplored phase space regions.

- Data consistent with the Standard Model (up to now).

- Big data samples of what were considered rare processes until 2 years ago are now available.

- In many cases we are already limited by systematic uncertainties: precision era.

- We need to learn as much as possible from the available data sets and be prepared for the 13 TeV runs.