Electroweak Precision Measurements

8 TeV Measurements
High Mass Drell-Yan Cross Sections
New 3D Drell-Yan Cross Sections
Systematic Uncertainties
13 TeV Plans
The Standard Model

Standard Model Total Production Cross Section Measurements

**ATLAS** Preliminary
Run 1,2 $\sqrt{s} = 7$, 8, 13 TeV

Probing EW and QCD sector of Standard Model over 12 orders of magnitude!

$\sigma \sim 10^{-3}$ pb at $m=1$ TeV

Eram Rizvi
Collider Cross Talk, CERN - 13th July 2017
Drell—Yan & Photon Induced Dilepton Production

\[ \sqrt{s} = 13 \text{ TeV} \]

- **Total NLO Cross Section**
- **Z Contribution**
- **\( \gamma^* \) Contribution**
- **Z/\( \gamma^* \) Interference (Modulus)**

\[ \sigma (Q, m) \]

Measure single + double + triple differential cross sections:

\[ \frac{d\sigma}{dm_{\ell\ell}} \quad \frac{d^2\sigma}{dm_{\ell\ell}dy_{\ell\ell}} \quad \frac{d^3\sigma}{dm_{\ell\ell}dy_{\ell\ell}d\cos \theta^*} \]

Measurements access range of

\[ x > 4 \times 10^{-4} \]
\[ 46 \leq m \leq 1500 \text{ GeV} \]

\[ Q^2 [\text{GeV}^2] \]

Drell—Yan cross section falls nine decades for \( m=100 \text{ GeV} \rightarrow 1000 \text{ GeV} \)

Off-shell production dominated by \( \gamma^* \) terms

Sensitive to high \( x \) antiquarks

\[ x_{1,2} = \frac{M_{\gamma^*}}{8 \text{TeV}} \]
\[ Q = M \]

High Mass Drell-Yan Phase Space

\[ M = \text{1 TeV} \]
\[ M = \text{100 GeV} \]

**ATLAS**

**CMS**

**LHCb**

**HERA**
General models of new physics SM Lagrangian extended by dimension 6 operators
They describe new physics appearing at scale \( m > \sqrt{s} \)
- new EW vector bosons
- new EW fermions
- EW compositeness

Effective field theory (EFT) attempts to encapsulate this
For DY production 4 propagator form-factors introduced:
\( S, T, Y, W \)
- \( Y \) and \( W \) increase with \( \sqrt{s} \)
- \( S \) and \( T \) do not grow with \( \sqrt{s} \)

LHC data can help constrain \( Y \) & \( W \)

Current constraints based on neutral current HMDY 8 TeV data
⇒ Cannot yet compete with LEP

https://arxiv.org/abs/1609.08157
Run-I Measurements from ATLAS

\[
\frac{d\sigma}{dm_{ll}} \quad \frac{d^2\sigma}{dm_{ll}dy_{ll}} \quad \frac{d^3\sigma}{dm_{ll}dy_{ll}d\cos\theta^*}
\]

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High mass DY 8 TeV
Neutral current - e & \(\mu\) channels
116 < \(m\) < 1500 GeV

publication: JHEP 08 (2016) 009

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On-shell DY 8 TeV
Neutral current - e & \(\mu\) channels
46 < \(m\) < 200 GeV
Extended to high \(y\) with FCAL analysis
preliminary public plots
Expect arXiv submission ~ August

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Complete 2012 data set analysed

\[ \int L \, dt = 20.2 \text{ fb}^{-1} \]

Centre of mass energy \(\sqrt{s} = 8\) TeV

Previous measurement (arXiv:1305.4192) used
5 fb\(^{-1}\)
\(\sqrt{s} = 7\) TeV
electron channel only
This analysis increases precision by factor 3!
### High Mass $Z/\gamma^*$ Selection

#### Muon Selection

- Good quality detector status (all sub-systems on)
- muon trigger fired (matched to lepton)
- $\geq 2$ good quality muons
- muon $|\eta| < 2.4$
- muon $p_T > 30$ GeV
- longitudinal impact parameter $|z_0| < 10$ mm
- isolated muon $\sum p_{T,i}^{(\Delta R=0.2)}/p_T^{\mu} < 0.12$
  - $p_T$ sum of tracks within a cone size $\Delta R=0.2$ is less than 12% of muon $p_T$
- opposite charge
- one muon has $p_T > 40$ GeV

#### Electron Selection

- Good quality detector status (all sub-systems on)
- electron trigger fired (matched to lepton)
- $\geq 2$ good quality “tight” electrons
- electron $|\eta| < 2.47$ excl. $1.37 < |\eta| < 1.52$
- electron $E_T > 30$ GeV
- isolated electron $\sum E_{T,i}^{(\Delta R=0.4)} < 0.022 \times E_T + 5$ GeV
  - $E_T$ sum of calo energy within a cone size $\Delta R=0.4$ is less than 2% of electron $E_T$ with $E_T$ scaled offset
- one electron has $p_T > 40$ GeV
- $|\Delta\eta_{ee}| < 3.5$ to suppress multijet background

### Fiducial Cross Section Definition

- lepton $p_T > 30$ GeV & $p_T > 40$ GeV
- lepton $|\eta| < 2.5$
- $116 < m_{ll} < 1500$ GeV
- Unfolding to Born level lepton kinematics (dressed level available as a correction factor)

Electron + muon cross sections combined account for 35 correlated systematic uncertainties improved result for both statistical & systematic precision
High Mass $Z/\gamma^*$ Cross Sections $\sqrt{s} = 8$ TeV

- Theory = NNLO pQCD $\otimes$ NLO EW + PI
- data precision better than theory uncertainty over most of the phase space $\rightarrow$ measurements can constrain theory
- theory generally in agreement with data
- Measurement accuracy systematically limited for $m < 400$ GeV

At low m observe large spread of predictions from different PDFs compared to experimental accuracy $\Rightarrow$ large potential to constrain PDFs
Cross sections are measured with 1% precision at $m \sim 200$ GeV (each channel)

Bin-to-bin correlated systematics can be further constrained by combining channels

For larger $m$ combination reduces $\sqrt{N}$ statistical error

Stat error dominates at large $m$ reaching $\sim 20\%$
Muon channel

| $m_{\mu\mu}$ | $|y_{\mu\mu}|$ | $\frac{\Delta^2 \sigma}{\Delta m_{\mu\mu} \Delta y_{\mu\mu}}$ [pb/GeV] | $\delta^{\text{stat}}$ [%] | $\delta^{\text{sys}}$ [%] | $\delta^{\text{tot}}$ [%] | $\delta_{\text{trig}}^{\text{cor}}$ [%] | $\delta_{\text{reco}}^{\text{cor}}$ [%] | $\delta_{\text{MSres}}^{\text{cor}}$ [%] | $\delta_{\text{Dres}}^{\text{cor}}$ [%] | $\delta_{\text{Eres}}^{\text{cor}}$ [%] | $\delta_{\text{iso}}^{\text{cor}}$ [%] | $\delta_{\text{unc}}^{\text{cor}}$ [%] | $\delta_{\text{top}}^{\text{cor}}$ [%] | $\delta_{\text{diboson}}^{\text{cor}}$ [%] | $\delta_{\text{bgMC}}^{\text{cor}}$ [%] | $\delta_{\text{mult}}^{\text{cor}}$ [%] | $\delta_{\text{unc}}^{\text{cor}}$ [%] | $\delta_{\text{unc}}^{\text{cor}}$ [%] | $k_{\text{dressed}}$ |
|----------|---------|-----------------|-------------|-------------|-------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 300–500  | 0.0–0.4 | $3.72 \times 10^{-4}$ | 4.0 | 2.9 | 4.9 | -0.1 | -0.6 | 0.2 | 0.1 | -0.2 | -0.2 | -2.2 | -0.8 | 0.7 | -0.5 | 1.2 | 0.2 | 1.036 |
| 300–500  | 0.4–0.8 | $3.28 \times 10^{-4}$ | 4.1 | 2.5 | 4.8 | -0.1 | -0.6 | -0.2 | -0.1 | -0.3 | -0.2 | -1.9 | -0.7 | 0.8 | -0.4 | 0.7 | 0.2 | 1.036 |
| 300–500  | 0.8–1.2 | $3.09 \times 10^{-4}$ | 4.0 | 1.6 | 4.2 | -0.1 | -0.6 | 0.1 | -0.1 | -0.3 | -0.2 | -1.1 | -0.5 | 0.6 | -0.1 | 0.2 | 0.2 | 1.034 |
| 300–500  | 1.2–1.6 | $2.51 \times 10^{-4}$ | 4.1 | 1.1 | 4.2 | -0.1 | -0.6 | 0.0 | 0.1 | -0.3 | -0.2 | -0.5 | -0.3 | 0.5 | -0.1 | 0.0 | 0.3 | 1.035 |
| 300–500  | 1.6–2.0 | $1.29 \times 10^{-4}$ | 5.7 | 1.2 | 5.8 | -0.1 | -0.8 | -0.2 | -0.1 | -0.3 | -0.2 | -0.2 | -0.3 | 0.6 | 0.0 | 0.0 | 0.4 | 1.040 |
| 300–500  | 2.0–2.4 | $3.93 \times 10^{-5}$ | 11.2 | 1.9 | 11.4 | -0.1 | -1.0 | -0.3 | -0.1 | -0.5 | -0.2 | -0.1 | -0.1 | 0.7 | 0.0 | 0.0 | 1.3 | 1.037 |

- Muon trigger uncertainty required effort to reduce to 0.1% (was dominant sys)
- Muon reco uncertainty could be reduced in future
- Top +diboson b/g: dilepton filtered mass-binned samples needed
- MC signal stats not a problem

Electron channel

| $m_{ee}$ | $|y_{ee}|$ | $\frac{\Delta^2 \sigma_{\text{dressed}}}{\Delta m_{ee} \Delta y_{ee}}$ [pb/GeV] | $\delta^{\text{stat}}$ [%] | $\delta^{\text{sys}}$ [%] | $\delta^{\text{tot}}$ [%] | $\delta_{\text{trig}}^{\text{cor}}$ [%] | $\delta_{\text{reco}}^{\text{cor}}$ [%] | $\delta_{\text{Eres}}^{\text{cor}}$ [%] | $\delta_{\text{iso}}^{\text{cor}}$ [%] | $\delta_{\text{unc}}^{\text{cor}}$ [%] | $\delta_{\text{unc}}^{\text{cor}}$ [%] | $\delta_{\text{unc}}^{\text{cor}}$ [%] | $\delta_{\text{unc}}^{\text{cor}}$ [%] | $\delta_{\text{unc}}^{\text{cor}}$ [%] | $\delta_{\text{unc}}^{\text{cor}}$ [%] | $\delta_{\text{unc}}^{\text{cor}}$ [%] | $\delta_{\text{unc}}^{\text{cor}}$ [%] | $k_{\text{dressed}}$ |
|----------|-------|-----------------|-------------|-------------|-------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 300–500  | 0.0–0.4 | $3.23 \times 10^{-4}$ | 4.6 | 3.3 | 5.7 | -0.1 | 0.2 | -0.2 | -0.8 | -0.1 | 0.4 | 0.1 | 0.9 | -1.8 | 0.6 | -2.2 | -0.8 | 0.8 | 0.3 | 1.080 |
| 300–500  | 0.4–0.8 | $3.34 \times 10^{-4}$ | 4.3 | 2.8 | 5.1 | -0.1 | 0.2 | -0.2 | -0.8 | -0.1 | 0.4 | 0.1 | 1.4 | -1.1 | 0.6 | -1.6 | -0.7 | 0.7 | 0.3 | 1.072 |
| 300–500  | 0.8–1.2 | $3.16 \times 10^{-4}$ | 4.3 | 2.8 | 5.2 | -0.1 | 0.2 | -0.2 | -0.8 | -0.1 | 0.4 | 0.2 | 2.0 | -0.9 | 0.5 | -1.1 | -0.6 | 0.7 | 0.3 | 1.058 |
| 300–500  | 1.2–1.6 | $2.30 \times 10^{-4}$ | 4.9 | 2.9 | 5.7 | -0.1 | 0.2 | -0.2 | -0.8 | -0.1 | 0.4 | 0.1 | 2.0 | -1.6 | 0.5 | -0.6 | -0.4 | 0.6 | 0.4 | 1.053 |
| 300–500  | 1.6–2.0 | $1.31 \times 10^{-4}$ | 6.5 | 3.2 | 7.3 | -0.1 | 0.2 | -0.4 | -0.9 | -0.2 | 0.4 | 0.2 | 2.8 | -0.3 | 0.4 | -0.2 | -0.2 | 0.5 | 0.6 | 1.047 |
| 300–500  | 2.0–2.4 | $3.62 \times 10^{-5}$ | 11.5 | 3.5 | 12.0 | -0.1 | 0.2 | -0.6 | -1.0 | -0.2 | 0.4 | 0.4 | 2.5 | -1.3 | 1.0 | 0.0 | -0.1 | 0.8 | 0.9 | 1.046 |

- Energy scale - dominant systematic
leptonic decay angle in Collins-Soper frame

\[
\cos \theta^* = \frac{p_{Z,\ell\ell}}{m_{\ell\ell} |p_{Z,\ell\ell}|} \frac{p_1^+ p_2^- - p_1^- p_2^+}{\sqrt{m_{\ell\ell}^2 + p_{T,\ell\ell}^2}}
\]

\[
\frac{d^3 \sigma}{dm_{\ell\ell} dy_{\ell\ell} d \cos \theta^*} = \frac{\pi \alpha^2}{3 m_{\ell\ell} s} \sum_q P_q \left[ f_q(x_1, Q^2) f_{\bar{q}}(x_2, Q^2) + (q \leftrightarrow \bar{q}) \right]
\]

pure $\gamma^*$

\[
P_q = e_i^2 e_q^2 (1 + \cos^2 \theta^*)
\]

interference $Z/\gamma^*$

\[
+ e_i e_q \frac{2 m_{\ell\ell}^2 (m_{\ell\ell}^2 - m_Z^2)}{\sin^2 \theta_W \cos^2 \theta_W [ (m_{\ell\ell}^2 - m_Z^2)^2 + \Gamma_Z^2 m_Z^2 ]} [v_\ell v_q (1 + \cos^2 \theta^*) + 2 a_\ell a_q \cos \theta^*]
\]

pure $Z$

\[
+ \frac{m_{\ell\ell}^4}{\sin^4 \theta_W \cos^4 \theta_W [ (m_{\ell\ell}^2 - m_Z^2)^2 + \Gamma_Z^2 m_Z^2 ]} [(a_\ell^2 + v_\ell^2)(a_q^2 + v_q^2)(1 + \cos^2 \theta^*) + 8 a_\ell v_\ell a_q v_q \cos \theta^*]
\]

\[
A_{FB} = \frac{d^3 \sigma(\cos \theta^* > 0) - d^3 \sigma(\cos \theta^* < 0)}{d^3 \sigma(\cos \theta^* > 0) + d^3 \sigma(\cos \theta^* < 0)}
\]

forward = $\cos \theta^* > 0$

backward = $\cos \theta^* < 0$

Asymmetry

Sensitive to $\sin^2 \theta_W$
Previous measurement of $\sin^2 \theta_W$ limited by PDF uncertainty

JHEP09(2015)049

$5 \text{ fb}^{-1}$

$\sqrt{s} = 7 \text{ TeV}$

ATLAS measurement of $\sin^2 \theta_W$ limited by PDF uncertainty

<table>
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<th>Uncertainty source</th>
<th>CC electrons $[10^{-4}]$</th>
<th>CF electrons $[10^{-4}]$</th>
<th>Muons $[10^{-4}]$</th>
<th>Combined $[10^{-4}]$</th>
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<tr>
<td>Muon energy scale</td>
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<tr>
<td>Other sources</td>
<td>1</td>
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<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
y spectrum shapes changes dramatically for $m_W \neq m_Z$ different Z and $\gamma^*$ couplings

cos $\theta^*$ spectrum has sensitivity to gluon PDF via gq terms
**Muon Selection**
- Good quality detector status (all sub-systems on)
- muon trigger fired (matched to lepton)
- \( \geq 2 \) good quality muons
- muon \( |\eta| < 2.4 \)
- muon \( p_T > 20 \) GeV
- longitudinal impact parameter \( |z_0| < 10 \) mm
- isolated muon \( \sum p_{T,i}'(\Delta R=0.2)/p_{T\mu} < 0.12 \)
  - \( p_T \) sum of tracks within a cone size \( \Delta R=0.2 \) is less than 12\% of muon \( p_T \)
- opposite charge

**Central Electron Selection**
- Good quality detector status (all sub-systems on)
- electron trigger fired (matched to lepton)
- \( \geq 2 \) good quality “medium” electrons
- electron \( |\eta| < 2.4 \) excl. \( 1.37 < |\eta| < 1.52 \)
- electron \( E_T > 20 \) GeV

**Fiducial Cross Section Definition**
- lepton \( p_T > 20 \) GeV
- lepton \( |\eta| < 2.5 \)
- \( 46 < m_\parallel < 200 \) GeV
- Unfolding to Born level lepton kinematics
  (dressed level available as a correction factor)

**High Rapidity Electron Selection**
- Good quality detector status (all sub-systems on)
- electron trigger fired (matched to lepton)
- 1 good quality “tight” central electron
  - electron \( |\eta| < 2.47 \) excl. \( 1.37 < |\eta| < 1.52 \)
  - electron \( E_T > 25 \) GeV
- 1 good quality “tight” forward electron
  - electron \( 2.5 < |\eta| < 4.9 \) excl. \( 3.0 < |\eta| < 3.4 \)
  - electron \( E_T > 20 \) GeV

**Fiducial Cross Section Definition**
- lepton \( p_T > 25 \) GeV & lepton \( |\eta| < 2.5 \)
- lepton \( p_T > 25 \) GeV & lepton \( 2.5 < |\eta| < 4.9 \)
- \( 66 < m_\parallel < 150 \) GeV
- Unfolding to Born level lepton kinematics
  (dressed level available as a correction factor)
**Central Rapidity Channel**

\[
\begin{align*}
    m_{ll} & = [46, 66, 80, 91, 102, 116, 150, 200] \text{ GeV} & 7 \text{ bins} \\
    |y_{ll}| & = [0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4] & 12 \text{ bins} \\
    \cos \theta^* & = [-1.0, -0.7, -0.4, 0.0, 0.4, 0.7, 1.0] & 6 \text{ bins}
\end{align*}
\]

Total bins = 504

x 2 channels

measure in electron + muon channels
check for consistency of channels
combine both measurements
account for ~200 correlated systematic errors
improved result for both statistical & systematic precision

**High Rapidity Channel**

\[
\begin{align*}
    m_{ll} & = [66, 80, 91, 102, 116, 150] \text{ GeV} & 5 \text{ bins} \\
    |y_{ll}| & = [1.2, 1.6, 2.0, 2.4, 2.8, 3.6] & 6 \text{ bins} \\
    \cos \theta^* & = [-1.0, -0.7, -0.4, 0.0, 0.4, 0.7, 1.0] & 6 \text{ bins}
\end{align*}
\]

Total bins = 150
The figure shows distributions of invariant mass for the region $12000 < m < 20000$ with entries / 2 GeV. The panels below each plot show the ratio of data to expectation. The error bars represent the data statistical uncertainty, the data (solid points), and the expectation (stacked histogram) are shown after the complete selection. The lower shaded band represents the statistical uncertainty on the expectation.

Entries / 2 GeV

Simulation describes data well.
Already good precision achieved for run-II!
Need to ensure phase-space corners are well covered e.g.
boosted Zs access high pT lepton efficiencies
For run-I lepton pT ~ 200 GeV
For run-II we should reach lepton pT ~ 400 GeV

**Electron Channel**
Energy scale dominates error at large \(|\cos \theta^*|\) → ~3%
efficiency error also large at at large \(\cos \theta^*\) (even at small \(|y|\)) → ~2-3%

**Muon Channel**
In peak region at \(m\sim m_Z\)
momentum scale dominates sys error → ~0.6%
compared to 0.8% stat error
Tracking misalignments ~ 1.7% cf stat error 2% at small \(\cos \theta^*\) or large \(y\)

**High Rapidity Electron Channel**
Energy scale / resolution dominates error at large \(|\cos \theta^*|\) & \(y\)
→ ~5% compared to ~3% stat error

Combination of channels constrains correlated systematic uncertainties

Improved precision for combined central channels
Central rapidity electron & muon combined result
Large forward-backward asymmetry at low mass, decreasing to ~zero at $m_\| \sim m_Z$

Upper plots: shaded regions highlight equal $|\cos \theta^*|$
Data precision reaches ~0.5% for $m_\parallel \sim m_Z$

**Good agreement with Powheg based predictions incl. NNLO/NLO k-factor (and Z polarisation correction)**
Triple-differential $Z/\gamma^* \times$ Cross Sections $\sqrt{s} = 8\,\text{TeV}$

High y region has greatest sensitivity to $\sin^2\theta_W$ and PDFs
High y analysis shows much larger asymmetry

$\frac{d^3\sigma}{dm_\ell\ell\,|y_\ell\ell|\,d\cos\theta^*}$

High rapidity channel
Showing selected bins
Forward-Backward Asymmetry

Central rapidity channel

\[
A_{FB} = \frac{d^3 \sigma (\cos \theta^* > 0) - d^3 \sigma (\cos \theta^* < 0)}{d^3 \sigma (\cos \theta^* > 0) + d^3 \sigma (\cos \theta^* < 0)}
\]

Note: \(A_{FB}\) derived from unfolded cross section measurements

Asymmetry increases with |\(y|\)

Due to better determination of initial quark

(high |\(y|\) access higher x valence PDF)
Forward-Backward Asymmetry

High rapidity channel

For $A_{FB}$ measurements uncorrelated sources dominate:
data stats are factor 2 larger than MC stat / multijet unc / bg MC stats
correlated sources ~ factor 10 smaller
Summary - I

- Measurement of DY cross section at $\sqrt{s} = 8$ TeV presented
- High mass phase space $116 < m < 1500$ GeV
- Precision of 1% attained at low m
- Data compatible with NNLO pQCD $\otimes$ NLO EW
- Measurements are sensitive to PDFs

New measurement of DY cross section at $\sqrt{s} = 8$ TeV shown
- on-shell analysis covers phase space $46 < m < 200$ GeV
- triple-differential cross sections determined
- Precision of 0.5% attained at $m = m_Z$
- Data compatible with NNLO pQCD $\otimes$ NLO EW
- Data to be published in ~3-4 weeks
- Plan to extract $\sin^2 \theta_W$ in follow-up paper ~ 6 months
LHC Schedule to 2035

* actual schedule slipped by 1 year
  e.g. LS3 starts 2023

Large increases in intensity
Requires significant changes to LHC magnets
Higher intensity means faster degradation of experiments

√s=7 TeV
\( L \sim 5 \text{ fb}^{-1} \)

√s=8 TeV
\( L \sim 20 \text{ fb}^{-1} \)

√s=13 TeV
\( L \sim 120 \text{ fb}^{-1} \)

√s=14 TeV ?
\( L \sim 300 \text{ fb}^{-1} \)

√s=14 TeV ?
\( L \sim 3000 \text{ fb}^{-1} \)

Peak LHC Intensity
\( L = \text{Total amount of data collected} \)

\( \sqrt{s}=7 \text{ TeV} \quad L \sim 5 \text{ fb}^{-1} \)

\( \sqrt{s}=8 \text{ TeV} \quad L \sim 20 \text{ fb}^{-1} \)

\( \sqrt{s}=13 \text{ TeV} \quad L \sim 120 \text{ fb}^{-1} \)

\( \sqrt{s}=14 \text{ TeV} \quad L \sim 300 \text{ fb}^{-1} \)

\( \sqrt{s}=14 \text{ TeV} \quad L \sim 3000 \text{ fb}^{-1} \)

LS = Long Shutdown for repairs and upgrades

We are here!

run 1

run 2

run 3

High Lumi Upgrade
High Mass W/Z/γ* Production at $\sqrt{s} = 13$ TeV

Three measurement regimes:

- $m_{\mu\mu} < m_Z$ – low muon $p_T$ / low x partons
- $m_{\mu\mu} = m_Z$ – ultra-high precision
- $m_{\mu\mu} > m_Z$ – high muon $p_T$ / new physics / high x partons

- At large $Q$ $\sigma(W^+) > \sigma(W^-) >= \sigma(\gamma^*)$ by ~ factor 2
- Run-II total $\int L \sim 120$ fb$^{-1}$
- Lumi ~ 4-5 times larger than Run-I
- Factor >2 larger cross section at 13 TeV ⇒ order of magnitude more data

High mass DY reaches high x region
Factor 5 higher x than on-shell Z at 8 TeV
At $M=300-500$ can achieve ~ 2% precision for $|y| < 1$
Stringent constraints on $Y$ & $W$ from LEP
100 fb$^{-1}$ of NC data $Z/\gamma^* \rightarrow l^+l^-$ reaches LEP precision
20 fb$^{-1}$ of CC data $W \rightarrow l\nu$ surpasses LEP by factor 4!

Discussions with Andrea / Riccardo et al
Request for unfolded cross sections
Additional gains in NC channel measuring decay angles
$\cos \theta^*$
$y_\parallel$
$m_\parallel$
$\rightarrow$ triple differential cross sections

Started analysis of high mass DY cross sections
in run-II @ $\sqrt{s}=13$ TeV

Simultaneous measurement in NC & CC channels

https://arxiv.org/abs/1609.08157
Run-I precision measurements gained excellent knowledge of ATLAS detector and performance
Improved our calibration methods
Will allow us to improve detector modelling
Now have experience of highly differential measurements with leptonic decay angles
Extend measurement using FCAL to high $|y|$  
Aim to now extend the precision region at higher m
Measure lepton decay angle also at high m $p_{T,\mu}$ vs $m_T$

**Questions:**

Neutral current channel
- exclude PI contribution?
- which angular variables?
- measure $A_{FB}$ at high m?
- can we constrain $W$ better with new 3D data?

Charged current channel
- is ratio of $W^+/W^-$ useful?
- measure lepton charge asymmetry vs $\eta$
- measure $m_T$ for increasing lepton $p_T$
  control migration = wide $m_T$ bins

Missing $E_T$ resolution is largest problem in $W^\pm$ channels
Large migrations off-peak
Good correlation of lepton $p_T$ with $m_T$
Better resolution for lepton $\rightarrow$ measure $m_T$ for increasing lepton $p_T$ cut
### MC Samples

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<th>Process</th>
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<th>Parton shower</th>
<th>Generator PDF</th>
<th>Model parameters (&quot;Tune&quot;)</th>
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<td>CT10</td>
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<td>PYTHIA 8.170</td>
<td>MRST2004qed</td>
<td>4C [68]</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>POWHEG</td>
<td>PYTHIA 6.427.2</td>
<td>CT10</td>
<td>AUET2 [69]</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>MC@NLO 4.06</td>
<td>HERWIG 6.520</td>
<td>CT10</td>
<td>AUET2</td>
</tr>
<tr>
<td>$Wt$</td>
<td>MC@NLO 4.06</td>
<td>HERWIG 6.520</td>
<td>CT10</td>
<td>AUET2</td>
</tr>
<tr>
<td>Diboson</td>
<td>HERWIG 6.520</td>
<td>HERWIG 6.520</td>
<td>CTEQ6L1</td>
<td>AUET2</td>
</tr>
</tbody>
</table>

- **Drell—Yan signal simulated at NLO in matrix element with PS** cross section is scaled to mass dependent NNLO calculation (FEWZ) includes final state photon emission (photos) (for cross checks MC@NLO is also used) 25 — 1000 x data statistics simulated

- **Photon Induced cross section available at LO only in pythia** 20 — 6000 x data statistics simulated

- **Top production simulated at NLO and renormalised to NNLO+NNLL prediction** 5 x data luminosity

- **Diboson production channels simulated at LO with herwig** 40 — 50,000 x data statistics simulated
Several sources of so-called "electroweak" backgrounds yielding isolated dileptons:

DY → tau production modes found to be negligible contribution

**top background**
up to 9% contribution top background
estimated from MC
validated with eμ dilepton selection
validated with two MC generators

**diboson background**
up to 2% contribution
estimated from MC

- **diboson (WW)**
- **diboson (WZ)**
- **diboson (ZZ)**
**Multijet Backgrounds**

**Multijet Background**
Multijet production dominates cross section at LHC
Also large W+jets cross section
contributes to background via:
- leptonic meson decays
- misidentification of hadron jet as calorimeter electron
soft leptons produced typically
contributing processes involve complex hadronisation simulation
⇒ use data to estimate this background

**Muon Channel**
use same sign dimuons as proxy for multijet b/g

<table>
<thead>
<tr>
<th>dimuon pairs</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>isolated</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>opposite sign</td>
<td>non-isolated opposite sign</td>
<td>isolated same sign</td>
</tr>
</tbody>
</table>

\[
\frac{N_A}{N_B} = \frac{N_C}{N_D}
\]

assume ratio of same sign to opp sign pairs is same in isolated and in non-isolated region
<1% contribution in muon channel

**Electron Channel**
use matrix method:

\[
\begin{pmatrix}
N_{TT} \\
N_{TL} \\
N_{LT} \\
N_{LL}
\end{pmatrix}
\begin{pmatrix}
r_1r_2 \\
r_1(1-r_2) \\
(1-r_1)r_2 \\
(1-r_1)(1-r_2)
\end{pmatrix}
\begin{pmatrix}
r_1f_2 \\
r_1(1-f_2) \\
(1-r_1)f_2 \\
(1-r_1)(1-f_2)
\end{pmatrix}
\begin{pmatrix}
f_1r_2 \\
f_1(1-r_2) \\
(1-f_1)r_2 \\
(1-f_1)(1-r_2)
\end{pmatrix}
\begin{pmatrix}
f_1f_2 \\
f_1(1-f_2) \\
(1-f_1)f_2 \\
(1-f_1)(1-f_2)
\end{pmatrix}
\begin{pmatrix}
N_{RR} \\
N_{RF} \\
N_{FR} \\
N_{FF}
\end{pmatrix}
\]

Depends on:
\[
f = \text{fake rate probability (estimated from dijet data)}
\]
\[
r = \text{real electron efficiency (estimated from MC)}
\]

~4% contribution in electron channel
Simulation provides good description of electron data to better than 5%
Simulation provides good description of muon data to better than 5%

\[ m > 116 \text{ GeV} \]

\[ m > 300 \text{ GeV} \]

\[ \eta_\mu \]

\[ pT,\mu \]

\[ pT,\mu \]

\( \Rightarrow \) can use MC simulation to unfold for detector resolution to Born level kinematics
Cross Section

\[ \frac{d^2\sigma}{dm_{\ell\ell} dy_{\ell\ell}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{C_{DY} L_{\text{int}}} \cdot \frac{1}{\Delta m_{\ell\ell} 2\Delta y_{\ell\ell}} \]

- Bin purities typically \( \geq 85\% \) (and \( \geq 75\% \) everywhere)
- \( C_{DY} \) includes small extrapolations to reach common fiducial phase space:
  - muon: \( |\eta| < 2.4 \rightarrow |\eta| < 2.5 \)
  - electron: \( |\eta| < 2.47 \) excl. \( 1.37 < |\eta| < 1.52 \) \( \rightarrow |\eta| < 2.5 \)
  - electron: \( |\Delta\eta_{ee}| < 3.5 \rightarrow |\Delta\eta_{ee}| < \infty \) (for \( dmd|y| \) cross section only)

Combination

Combine electron & muon channel measurements in averaging procedure
Minimise difference between measurements
Taking correlated uncertainties into account

\[ \chi^2_{tot}(m, b) = \sum_i \frac{[\mu^i - m^i(1 - \sum_j \gamma^i_j b_j)]^2}{\delta_{i,\text{stat}}^2 m^i(1 - \sum_j \gamma^i_j b_j) + (\delta_{i,\text{unc}} m^i)^2} + \sum_j b_j^2 \]

- Bin-to-bin correlated error sources \( j = 35 \) including
  - lepton trigger, ID, isolation efficiencies
  - lepton scale and resolution uncertainties
  - background contributions
  - etc.

- \( \mu^i \) = measurement
- \( m^i \) = averaged value
- \( \gamma^i_j \) = correlated sys uncertainty on point \( i \) from error source \( j \)
- \( b_j \) = systematic error source strength
- Nuisance parameter left free in fit but constrained to no extra degrees of freedom due to additional constraint
Combination of Electron & Muon Channels

Cross sections are measured with 1% precision at low $m$ (each channel)

Measurement accuracy systematically limited for $m < 400$ GeV

Bin-to-bin correlated systematics can be further constrained by combining channels

For larger $m$ combination reduces $\sqrt{N}$ statistical error

Stat error dominates at large $m$ reaching ~20%

Excellent agreement between channels over full range

$$\chi^2/\text{ndf} = 14.2 / 12 = 1.19$$

all nuisance parameters < 1 standard deviation
Combination of Electron & Muon Channels

- No large pulls between the measurement channels
- Combination $\chi^2/\text{ndf} = 53.1 / 48 = 1.11$
Combination of Electron & Muon Channels

\[
\frac{d^2\sigma}{dm_\ell\ell d|\Delta\eta_\ell\ell|}
\]

116 GeV < m < 150 GeV

150 GeV < m < 200 GeV

200 GeV < m < 300 GeV

300 GeV < m < 500 GeV

500 GeV < m < 1500 GeV

combination \(\chi^2/\text{ndf} = 59.3 / 47 = 1.26\)
Combined Differential Cross Sections

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

- MMHT2014 with 68% CL (PDF + $\alpha_s$) + scale + PI unc.
- MMHT2014 w/o PI corrections

Comparison of predictions from different PDF sets and theoretical uncertainties.

The error bars represent the statistical uncertainty. The inner shaded band represents the absolute dilepton rapidity differential in invariant mass.

Figure 7.

$\frac{d^2\sigma}{dm_\ell^2d|y_\ell^2|}$ data/theory ratio

PI contribution increases with $m$ and decreasing $|y_\ell^2|$

PDF uncertainties calc’d for each PDF scaled to 68% CL

ABM12 uncertainty smaller than MMHT

CT14, NNPDF3.0 uncertainty larger than MMHT

HERAPDF2.0 uncertainty much larger than MMHT

Compatibility of data to predictions with other PDFs tested with $\chi^2$ function

|       | $m_\ell$ | $|y_\ell^2|$ | $|\Delta\eta_\ell^2|$ |
|-------|---------|-------------|---------------------|
| MMHT2014 | 18.2/12 | 59.3/48    | 62.8/47            |
| CT14   | 16.0/12 | 51.0/48    | 61.3/47            |
| NNPDF3.0 | 20.0/12 | 57.6/48    | 62.1/47            |
| HERAPDF2.0 | 15.1/12 | 55.5/48    | 60.8/47            |
| ABM12  | 14.1/12 | 57.9/48    | 53.5/47            |

All data & theory correlated errors treated as nuisance parameters e.g. PDF eigenvectors (incl. for NNPDF)

Data in agreement with predictions:

$\chi^2$ probability at worst ~6%

Eram Rizvi
Collider Cross Talk, CERN - 13th July 2017
The combined data.

The pull of the electron (red) and muon (blue) channel measurements with respect to the shaded band represents the total measurement uncertainty (excluding the luminosity uncertainty). The shaded band represents the systematic uncertainty on the combined cross sections, and the outer error bars represent the statistical uncertainty. The inner error bars display the combined 68% confidence level (CL) PDF and the uncertainty band on the left side displays the combined 68% confidence level (CL) PDF and the PI uncertainty.

The ratio of theoretical NNLO pQCD and NLO EW calculations to the combined differential cross section as a function of invariant mass $m_{ll}$.

PDF uncertainty is dominated by PI piece at large $|\Delta\eta_{ll}|$.

PI contribution increases with $m$ and $|\Delta\eta_{ll}|$.

Similar conclusions here:
- At low $m$ spread of PDFs is larger than data accuracy.
- PDF uncertainty is dominated by PI piece at large $|\Delta\eta_{ll}|$. 

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Figure 10: The combined Born-level fiducial cross sections $d^3 \sigma$. The kinematic region is shown in the legend. The data are shown as solid ($\cos \theta^* > 0$) and open ($\cos \theta^* < 0$) symbols and the prediction from Powheg including NNLO QCD and NLO EW factors is shown as the solid line. The lower panels shows the ratio of the prediction to the measurement. The error bars represent the statistical uncertainties of the data, and the shaded band shows the total experimental uncertainty. The contribution to the uncertainty of the luminosity measurement is excluded. The cross-hatched band indicates the PDF uncertainty on the predictions.
Classic problem: how to constrain PDFs at high $x$ for BSM searches?

Measure cross sections at high rapidity

FCAL forward electrons $\rightarrow$ PDF sensitivity up to $x=1$ at $m=500$ GeV

$Q^2$ (GeV$^2$)

$y = 6 \quad 4 \quad 2 \quad 0 \quad 2 \quad 4 \quad 6$

$M = 10 \text{ GeV}$

$M = 100 \text{ GeV}$

$M = 500 \text{ GeV}$

$M = 10 \text{ TeV}$

$M = 10 \text{ TeV}$
Neutral current
Cross section enhancement > factor 5 at large $m_{ll}$
Similar for charged current

Charged current
First measurement off-shell high $m_T$ $W^\pm$ production
Analogous to neutral current $Z/\gamma^*$ measurement