High mass Drell-Yan measurements

Ultimate Precision at Hadron Colliders
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Introduction

• Measurement of the Drell-Yan production at high invariant masses (m_{ll}>116 GeV)
  • Sensitivity to PDFs at large x (current constraints are poor)
  • Some sensitivity to photon induced production (γγ->ll)
• Constraints on BSM physics
  • Resonant or broad modifications of the spectrum
LHC measurements

• High-mass neutral current Drell-Yan measurements at LHC
  • Clean experimental signature (electron and muon final states)

• ATLAS measurement at 8 TeV (integrated luminosity of 20.3 fb\(^{-1}\))
  • JHEP 08 (2016) 009
  • \(d\sigma/dM, d^2\sigma/dMd|Y|, d^2\sigma/dMd\eta ll\)
  • \(116 < M_{ll} < 1500\) GeV

• CMS measurement at 8 TeV (integrated luminosity of 19.7 fb\(^{-1}\))
  • \(d\sigma/dM, d^2\sigma/dMd|Y|\)

• CMS measurement at 13 TeV
  • arXiv:1812.10529, \(d\sigma/dM\)
  • Making use of 2015 dataset at 13 TeV (up to 2.8 fb\(^{-1}\))
  • \(M_{ll}<3000\) GeV
ATLAS/CMS measurements at 8 TeV

- High-mass neutral current Drell-Yan measurements at LHC
  - Measurements compared to NNLO pQCD predictions with FEWZ 3.1
Treatment of photon-induced contribution

- CMS subtracted photon-induced contribution
- ATLAS designed the analysis to be sensitive to photon-induced (PI)
  - Constraints on photon PDF derived (sensitivity far superseded by LUXQED)
  - Contribution reaches as much as ~15-20% in the high mass region
- Recent discussion within the LHC EW precision group on the treatment of the PI contribution in the future measurement
  - https://indico.cern.ch/event/864105/
Systematic uncertainties

- Data statistical uncertainties are dominant in Run-1 for very high masses
- Experimental systematic uncertainties are up to ~5%
  - Would be interesting to understand the differences in quoted systematic uncertainties between ATLAS and CMS for the future Run-2
- Multijet and $W + \text{jet}$ background systematic uncertainties dominate in electron channel
- Statistical component in some of the systematic uncertainties

### Sources

<table>
<thead>
<tr>
<th>Sources</th>
<th>$e^+e^-$</th>
<th>$\mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>2.9, 0.5, 0.7</td>
<td>1.0, 0.4, 1.8</td>
</tr>
<tr>
<td>Detector resolution</td>
<td>1.2, 5.4, 1.8</td>
<td>0.6, 1.8, 1.6</td>
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<tr>
<td>Background estimation</td>
<td>2.2, 0.1, 13.8</td>
<td>1.0, 0.1, 4.6</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>0.2, 2.4, 2.0</td>
<td>—</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>—</td>
<td>0.2, 1.7, 1.6</td>
</tr>
<tr>
<td>FSR simulation</td>
<td>0.4, 0.3, 0.3</td>
<td>0.4, 0.2, 0.5</td>
</tr>
<tr>
<td>Total experimental</td>
<td>3.7, 2.5, 14.0</td>
<td>1.6, 2.5, 5.4</td>
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<tr>
<td>Theoretical uncertainty</td>
<td>4.2, 1.6, 5.3</td>
<td>4.1, 1.6, 5.3</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.6, 2.6, 2.6</td>
<td>2.6, 2.6, 2.6</td>
</tr>
<tr>
<td>Total</td>
<td>6.3, 6.7, 15.3</td>
<td>5.1, 3.9, 8.0</td>
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</table>


arXiv: 1609.08157
High energy probes of EW sector

- High mass Drell-Yan measurements can indirectly probe heavy new physics
- Modification of the SM in self energies of vector bosons
  - Focus on oblique corrections: S, T, W, and Y
- W and Y modify the propagators off the pole
- W and Y modify the cross section by a factor that grows with energy as $q^2/mV$ (can be generated by dim-6 EFT operators)
  - Is the energy enhancement at hadron colliders sufficient to beat the precision at lepton colliders?
- Look at the “tails” of charged and neutral Drell-Yan lepton pairs

<table>
<thead>
<tr>
<th>universal form factor ($\mathcal{L}$)</th>
<th>contact operator ($\mathcal{L}'$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$</td>
<td>$-\frac{W}{4m_W^2}(D_\rho W_{\mu\nu})^2$</td>
</tr>
<tr>
<td>$Y$</td>
<td>$-\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$</td>
</tr>
</tbody>
</table>

$$
\begin{align*}
P_N &= \left[ \frac{1}{q^2} - \frac{t^2 W + Y}{m_Z^2} \frac{t(\hat{Y} + \hat{T}) c^2 + s^2 W - \hat{S}}{(c^2 - s^2)(q^2 - m_Z^2)} + \frac{t(Y - W)}{m_Z^2} \right] \\

P_C &= \frac{1 +((\hat{T} - W - t^2 Y) - 2t^2(\hat{S} - W - Y))/(1-t^2)}{(q^2 - m_W^2)} - \frac{W}{m_W^2},
\end{align*}
$$

arXiv: 1609.08157
Run-1 constraints

- Limits on W and Y from Run-1 neutral Drell-Yan measurements
- 95% exclusion contours obtained with ATLAS and CMS data in the W-Y plane
  - Already competitive with LEP constraints (gray region)
Charged current DY

- Measurements of high transverse mass W production can be used
  - Cross section measurements are not currently provided by ATLAS and CMS performed
  - The uncertainties can be estimated from W’ searches (where it appears as a background process)

![Graphs showing W' production and decay](image)

arXiv: 1606.03977

![Graphs showing W' production and decay](image)

arXiv: 1408.2745
13 TeV projections (HL-LHC)

- Projected limits on W and Y from 13 TeV Drell-Yan measurements
- For neutral DY: 2% correlated and 2% uncorrelated uncertainties assumed
- For charged DY: 5% correlated and 5% uncorrelated uncertainties assumed
  - 8 TeV “projection” is also shown (dotted)

arXiv: 1609.08157
13 TeV projections

• Which mass bins give us the sensitivity to Y and W
  • Mass bins below 1 TeV for $\sqrt{s}=8$ TeV and below 2 TeV for $\sqrt{s}=13$ TeV
  • Can we achieve ~1-2% experimental uncertainties at HL-LHC?
CMS 13 TeV measurement

- Measurement of the differential Drell-Yan cross section at 13 TeV
- arXiv:1812.10529, $d\sigma/dM$
- Dilepton invariant mass in the range 15 to 3000 GeV (leading lepton $p_T>$ 22 (30) GeV and sub-leading lepton $p_T > 10$ GeV)
Statistical uncertainties of ~1% up to 2 TeV possible with naive extrapolation

Upgraded detectors should maintain similar muon and electron performance (efficiency, momentum/energy scale)

Integrated luminosity uncertainty at HL-LHC. What can be achieved?

- Ideas of using Z counting and low pileup datasets (for absolute luminosity scale calibration) to achieve ~1-2% uncertainty:
  - arXiv:1806.02184
Upgraded muon detectors maintain good performance at high pileup and extend coverage to $|\eta| = 2.8$ for CMS e.g. (albeit with challenging situation for hardware trigger beyond 2.4)
Electron reconstruction/efficiency should be $\sim$ ok at high pileup

Some radiation and pileup related challenges for energy resolution
SM-EFT contributions

- SM-EFT contributions to charged and neutral DY
  - Consider all dim-6 operators contributing at leading order
  - NLO QCD corrections included (implemented in Powheg BOX V2)
    - Around ~30-40% in the highest bins
- Set bounds on effective operators using ATLAS and CMS searches
  - Angular distributions can be used to differentiate between different dim-6 operators

\[ m_T^W = \sqrt{2|p_T^f||p_T^\nu|(1 - \cos \Delta \phi_{\ell\nu})} . \]
PDF constraints at HL-LHC

- Sensitivity to PDFs at large $x$ (currently constraints are poor)
  - Poorly known large-$x$ sea quarks
  - Projected neutral DY data

$$x_{1,2} = \frac{m_{ll}}{\sqrt{s}} e^{\pm y_{ll}}.$$  

arXiv:1810.03633

- Perform a consistent SM+EFT/BSM fit with PDFs (talk by Shayan Iranipour last week)
Summary

- High mass DY measurements as high energy probe of BSM physics
- Electroweak precision tests in high energy DY processes
  - Surpassing the LEP sensitivity to universal parameters $W$ and $Y$
- Ultimate goal: Measurements of DY cross sections at dilepton masses of up to 2 TeV with $O(1)%$ uncertainty at HL-LHC
- Detailed measurements of high $m_T$ distributions of charged DY should be performed as well
- Full Run-2 ATLAS and CMS high mass neutral DY measurements still to come
  - Stay tuned...