Progress in QCD studies for high-sensitivity Electroweak, Higgs and BSM measurements

Jan Kretzschmar, University of Liverpool
on behalf of the ATLAS & CMS collaborations

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16.4.2018
2017 was another record year for the LHC: 50 fb$^{-1}$ delivered to ATLAS and CMS.

Run 2 concluding in 2018: expecting up to 60 fb$^{-1}$ data.

High luminosity comes with large pileup, maximum levelled to $\mu = 60$.

Additional low-$\mu$ data with $\sqrt{s} = 5$ and 13 TeV.

Two independent $Z \rightarrow \mu\mu$ candidates in one bunch crossing.
A wealth of results...

Electroweak precision with $W$ and $Z$ bosons and Multi-boson interactions

News from the Higgs boson

Selected search results
EW precision with $W$, $Z$ bosons

- Large numbers of $W \to \ell \nu$ and $Z/\gamma^* \to \ell\ell$ allow $m_W$ and $\sin^2 \theta_W$ measurement with small statistical uncertainties (e.g. $10^9$ $W$s)
  - Test of SM consistency
  - $m_W$ measurement at hadron colliders has surpassed LEP, key-role in EW fit
  - $\sin^2 \theta_W$ from $A_{FB}$ in $Z/\gamma^* \to \ell\ell$ on the way to tie with (discrepant) $e^+e^-$ measurements

- Significant challenge to control QCD-related theoretical uncertainties
Measurement of $m_W$ at LHC

Result dominated by analysis of lepton $p_T$-spectrum with large QCD uncertainties

- PDF uncertainties on light-quark sea decomposition from $u, d, s$ ($cs \rightarrow W$ fraction) as well as valence-shape uncertainty (polarisation effects): $W^+ - W^-$
- Modelling of small $W$-boson $p_T$ with significant uncertainties and NNLO+NNLL predictions using $W/Z$-ratio in disagreement with data: $u_\parallel$
- Fundamental improvements?

<table>
<thead>
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<td>$W^+$</td>
<td>8.9</td>
<td>6.6</td>
<td>8.2</td>
<td>3.1</td>
<td>5.5</td>
<td>8.4</td>
<td>5.4</td>
<td>14.6</td>
<td>23.4</td>
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<tr>
<td>$W^-$</td>
<td>9.7</td>
<td>7.2</td>
<td>7.8</td>
<td>3.3</td>
<td>6.6</td>
<td>8.3</td>
<td>5.3</td>
<td>13.6</td>
<td>23.4</td>
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<tr>
<td>$W^{\pm}$</td>
<td>6.8</td>
<td>6.6</td>
<td>6.4</td>
<td>2.9</td>
<td>4.5</td>
<td>8.3</td>
<td>5.5</td>
<td>9.2</td>
<td>18.5</td>
</tr>
</tbody>
</table>

Jan Kretzschmar, 16.4.2018

PDF constraints from $W, Z$ data

- Precise differential $W, Z$ data can constrain PDFs, especially the strange-quark density
- ATLAS-epWZ16 fit fixed-order NNLO QCD + NLO EW: theory uncertainty dominant

- Differences between predictions at fixed-order and with boson $p_T, \nu$ resummation $\sim 0.5\%$ effect similar to experimental precision — ensure predictions in PDF fits consistent with application to parton shower MCs to extract results
**W low-\(p_T,W\) spectrum**

- Significant uncertainty on \(m_W\)
- Direct differential measurement in low \(p_T,W\) region a significant challenge — unlike for \(Z/\gamma^* \rightarrow \ell\ell\)
- Low-pileup data taken in 2017:
  - 250 \(\text{pb}^{-1}@5\) TeV, 150 – 300 \(\text{pb}^{-1}@13\) TeV, should allow direct measurement in \(\sim 5\) GeV \(p_T,W\)-bins to \(\sim 1\%\)
- Significant uncertainty on $m_W$
- Direct differential measurement in low $p_{T,W}$ region a significant challenge — unlike for $Z/\gamma^* \rightarrow \ell\ell$
- Low-pileup data taken in 2017: 250 pb$^{-1}$@5 TeV, 150 – 300 pb$^{-1}$@13 TeV, should allow direct measurement in $\sim 5$ GeV $p_{T,W}$-bins to $\sim 1\%$
Simultaneous measurement as function of dilepton mass $m_{ll}$ and rapidity $y_{ll}$ and $\cos \theta^*$ in Collins–Soper frame

Sensitive to PDFs as well as $\sin^2 \theta_W$ through forward-backward asymmetry $A_{FB}$
Simultaneous measurement as function of dilepton mass $m_{\ell\ell}$ and rapidity $y_{\ell\ell}$ and $\cos \theta^*$ in Collins–Soper frame

Sensitive to PDFs as well as $\sin^2 \theta_W$ through forward-backward asymmetry $A_{FB}$
Valence-quark shape determines the “dilution” of $A_{FB}$ and is a significant uncertainty.

In-situ constraint using the $m_{\ell\ell}$–$y_{\ell\ell}$ dependence by factor $\sim 2$.

Differences between PDFs similar to NNPDF3.0 uncertainty.

Final result: $\sin^2 \theta_{\text{eff}}^{\text{lept}} = 0.23101 \pm 0.00036(\text{stat}) \pm 0.00018(\text{syst}) \pm 0.00016(\text{theory}) \pm 0.00030(\text{pdf})$.
Reaching “ultimate” precision of $\Delta \sin^2 \theta_W \sim 10 \cdot 10^{-5}$ and $\Delta m_W \sim 5$ MeV relies on improvements in PDFs.

$pp$ data: extended acceptance (LHCb and HL-LHC detectors) and ancillary measurements expected to provide some improvements, however this relies on well-understood PDF correlations and theoretical uncertainties.

Progress in theory calculations, e.g. NNLO $Z+\text{jets}$ for angular correlations.

DIS $ep$ data: LHeC would provide needed factor of $5-10$ in PDF improvement.
Boson production through electroweak interaction with high mass dijet system, no colour flow in central region – Vector Boson Fusion

Detailed studies possible in $Zjj$ final state:

- large background from strongly produced $Zjj$ not well described by many MCs — dedicated control region

**Electroweak**

\[
\begin{align*}
\text{Data Stat.} & \oplus \text{Syst.} \\
\text{MC / Data} & \\
\text{MC / Data} & \\
\text{MC / Data} & \\
\end{align*}
\]

**Strong**

\[
\begin{align*}
\text{Data Stat.} & \oplus \text{Syst.} \\
\text{MC / Data} & \\
\text{MC / Data} & \\
\text{MC / Data} & \\
\end{align*}
\]
Boson production through electroweak interaction with high mass dijet system, no colour flow in central region – Vector Boson Fusion

Detailed studies possible in $Zjj$ final state:
- large background from strongly produced $Zjj$ not well described by many MCs — dedicated control region
- MadGraph5_aMC@NLO FxFx NLO up to $Z + 3$jets in better agreement with data
- Challenge to describe radiation into the “rapidity gap”
- ATLAS: $\sigma_{EW}^{\ell\ell jj} = 119 \pm 16^{(\text{stat})} \pm 20^{(\text{syst})}$ fb
- CMS: $\sigma_{EW}^{\ell\ell jj} = 552 \pm 19^{(\text{stat})} \pm 55^{(\text{syst})}$ fb

(different phase spaces in ATLAS and CMS, esp. $m_{jj}$)

Electroweak

$$W^+ W^- Z$$

$$q' q q'$$

$$\mu^+, e^+ \mu^-, e^-$$

Strong

$$Z$$

$$q' q q$$

$$\mu^+, e^+ \mu^-, e^-$$
• Large NNLO corrections necessary to describe the data
• Fully differential NNLO predictions a milestone to provide precision predictions, needed for future Higgs searches and measurements and search for anomalous triple gauge boson couplings
- Electroweak production of massive dibosons sensitive to quartic couplings and existence of Higgs boson
- $ZZ(4\ell)jj$ channel: fully reconstructed, low statistics
- Golden channel with smallest strong-production background: same sign $W^\pm W^\pm (2\ell^\pm 2\nu)jj$ production
  – evidence in Run 1, first observation with Run 2 data
Studies of the Higgs Boson

- Diverse production modes and decays – lots to explore!
- Do the rates agree with SM predictions? How far did we get w.r.t. Run 1 measurements?

![Diagram of Higgs production modes and decays](image)

- "ggF" production: $49 \, \text{pb}$, $3.8 \, \text{pb}$, $2.2 \, \text{pb}$, $0.51 \, \text{pb}$
- "VBF" production: $q \rightarrow V \rightarrow H$
- "VH" production: $q \rightarrow V \rightarrow H$
- "ttH" production: $t \rightarrow t \rightarrow H$

Higgs BR:
- $\text{bb: 58.4\%}$
- $\text{WW: 21.4\%}$
- $\text{gg: 8.2\%}$
- $\text{ττ: 6.3\%}$
- $\text{ZZ: 2.6\%}$
- $\text{γγ: 0.2\%}$
- $\text{CC: 2.9\%}$
- $\text{YV: 0.2\%}$

A. Tuna @ Moriond 2018
Studies of the Higgs Boson

- Diverse production modes and decays – lots to explore!
- Do the rates agree with SM predictions? How far did we get w.r.t. Run 1 measurements?

Global $\mu$ summarises how stringently SM is tested, full Run 1 combination:

$$\mu = \sigma_{\text{meas}}/\sigma_{\text{SM}} = 1.09^{+0.11}_{-0.10} = 1.09 \pm 0.07(\text{stat}) \pm 0.04(\text{expt}) \pm 0.03(\text{thbgd})^{+0.07}_{-0.06}(\text{thsig})$$

In Run 2 more emphasis on model-independent results such as differential cross sections to disentangle experimental results and predictions and their uncertainties
**$H \to \gamma\gamma$ and $H \to 4\ell$**

- High-resolution channels with good $S/B$, but low BR profit most easily from large Run 2 datasets
- Results on 2015+2016 data compatible with SM, precision on overall $\mu$ still dominated by statistical uncertainties
  - $4\ell$: $\Delta\mu \approx 20\%$ per experiment
  - $\gamma\gamma$: $\Delta\mu \approx 15\%$ per experiment
High-resolution channels with good $S/B$, but low $BR$ profit most easily from large Run 2 datasets

Results on 2015+2016 data compatible with SM, precision on overall $\mu$ still dominated by statistical uncertainties

- $4\ell$: $\Delta\mu \approx 20\%$ per experiment
- $\gamma\gamma$: $\Delta\mu \approx 15\%$ per experiment

$H \to \gamma\gamma$ and $H \to 4\ell$

CMS $H \to 4\ell$

$\mu = 1.05^{+0.15}_{-0.14} (\text{stat})^{+0.10}_{-0.08} (\text{sys})$

ATLAS $H \to \gamma\gamma$

$\mu = 0.99 \pm 0.12 (\text{stat})^{+0.06}_{-0.05} (\text{exp})^{+0.07}_{-0.05} (\text{theo})$

<table>
<thead>
<tr>
<th>Uncertainty Group</th>
<th>$\sigma_{\mu}^{\text{syst.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory (QCD)</td>
<td>0.041</td>
</tr>
<tr>
<td>Theory ($B(H \to \gamma\gamma)$)</td>
<td>0.028</td>
</tr>
<tr>
<td>Theory (PDF+$\alpha_S$)</td>
<td>0.021</td>
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<tr>
<td>Theory (UE/PS)</td>
<td>0.026</td>
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<tr>
<td>Luminosity</td>
<td>0.031</td>
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<tr>
<td>Experimental (yield)</td>
<td>0.017</td>
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<tr>
<td>Experimental (migrations)</td>
<td>0.015</td>
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<tr>
<td>Mass resolution</td>
<td>0.029</td>
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<tr>
<td>Mass scale</td>
<td>0.006</td>
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<tr>
<td>Background shape</td>
<td>0.027</td>
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</tbody>
</table>
Event samples are further categorised / binned to

- access different production modes $ggH$, VBF, $VH$ and $t\bar{t}H$

- Challenge to describe $ggH$ contribution in VBF categories — “strong” vs. “EW” $Hjj$

- In contrast: $ep \rightarrow H$ is pure VBF, $ep(WW) \rightarrow \nu Hj$ and $ep(ZZ) \rightarrow eHj$
Event samples are further categorised / binned to

▸ access different production modes $ggH$, VBF, $VH$ and $t\bar{t}H$

▸ measure distributions within a production mode, e.g. $ggH$ with 0 jets, 1 jet and $p_T^{H} < 60$ GeV, ... – “simplified template cross sections” (STXS)
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- measure distributions within a production mode, e.g. $ggH$ with 0 jets, 1 jet and $p_T < 60$ GeV, ... – “simplified template cross sections” (STXS)
- measure phase-space regions enriched in production modes

![ATLAS Simulation](https://example.com/atlas_simulation.png)
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- measure distributions within a production mode, e.g. $ggH$ with 0 jets, 1 jet and $p_T^H < 60$ GeV, ... – “simplified template cross sections” (STXS)
- measure phase-space regions enriched in production modes
- measure “inclusive” differential distributions (summing over production modes)

\[ H \rightarrow 4\ell \text{ and } H \rightarrow \gamma\gamma \]
Evidence for the most abundant decay mode using $ZH$ and $WH$ production by both ATLAS and CMS: $3.5 \& 3.8\sigma$

Small $S/B$ and complex background composition:

- systematic uncertainties dominate
- significant corrections applied to many background processes such as $V + b$ and $t\bar{t}$
- challenge for the future, see also talk by Vieri Candelise on $V+HF$

### CMS Background normalisation factors

<table>
<thead>
<tr>
<th>Process</th>
<th>0-lepton</th>
<th>1-lepton</th>
<th>2-lepton low-$p_T$(V)</th>
<th>2-lepton high-$p_T$(V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W0b</td>
<td>1.14 ± 0.07</td>
<td>1.14 ± 0.07</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>W1b</td>
<td>1.66 ± 0.12</td>
<td>1.66 ± 0.12</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>W2b</td>
<td>1.49 ± 0.12</td>
<td>1.49 ± 0.12</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Z0b</td>
<td>1.03 ± 0.07</td>
<td>—</td>
<td>1.01 ± 0.06</td>
<td>1.02 ± 0.06</td>
</tr>
<tr>
<td>Z1b</td>
<td>1.28 ± 0.17</td>
<td>—</td>
<td>0.98 ± 0.06</td>
<td>1.02 ± 0.11</td>
</tr>
<tr>
<td>Z2b</td>
<td>1.61 ± 0.10</td>
<td>—</td>
<td>1.09 ± 0.07</td>
<td>1.28 ± 0.09</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0.78 ± 0.05</td>
<td>0.91 ± 0.03</td>
<td>1.00 ± 0.03</td>
<td>1.04 ± 0.05</td>
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### Source of uncertainty

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\sigma_\mu$</th>
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<tr>
<td>Total</td>
<td>0.39</td>
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<tr>
<td>Statistical</td>
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<tr>
<td>Systematic</td>
<td>0.31</td>
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<tr>
<td>Experimental uncertainties</td>
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<tr>
<td>Jets</td>
<td>0.03</td>
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<tr>
<td>$E_{miss}$</td>
<td>0.03</td>
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<tr>
<td>Leptons</td>
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<tr>
<td>$b$-tagging</td>
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<tr>
<td>$b$-jets</td>
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<tr>
<td>$c$-jets</td>
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<tr>
<td>light jets</td>
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<td>extrapolation</td>
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<td>Pile-up</td>
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<td>Luminosity</td>
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<td>Theoretical and modelling uncertainties</td>
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<td>Signal</td>
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<td>Floating normalisations</td>
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<tr>
<td>$Z +$ jets</td>
<td>0.07</td>
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<tr>
<td>$W +$ jets</td>
<td>0.07</td>
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<tr>
<td>$t\bar{t}$</td>
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<tr>
<td>Single top quark</td>
<td>0.08</td>
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<tr>
<td>Diboson</td>
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<tr>
<td>Multijet</td>
<td>0.02</td>
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<tr>
<td>MC statistical</td>
<td>0.13</td>
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</table>
Complex analyses with backgrounds from $WW$, $t\bar{t}$, $Z+\text{jets}$, and lepton “fakes” – control regions

Significant theoretical and experimental unc.

Total unc. $\sim 15\%$, sensitivity to $ggH$ and VBF
Very complex final states: many jets, several $b$-tagged, often isolated $e$, $\mu$ or $\tau$ leptons

Many analyses targeting different $H$ decays: $\gamma\gamma$, $ZZ^*$, $WW^*$, $\tau^+\tau^-$, $b\bar{b}$

Combination in ATLAS: 4.2(3.8)$\sigma$ observed (expected)

Combination in CMS: 5.2(4.2)$\sigma$ observed (expected) — Observation of $t\bar{t}H$ production!

Observed rate in agreement with SM expectation

\[ \text{Observed rate} \text{ in agreement with SM expectation} \]
“Multi-leptons”

- Analysis of final states with 2 same-charge or 3, 4 leptons ($e, \mu, \tau_{\text{had}}$) from $H \rightarrow WW^*, ZZ^*, \tau^+\tau^-$ decays have largest sensitivity

- Combination of 7(6) categories gives observed significance of $4.2(3.2)\sigma$ in ATLAS (CMS)
Largest rate, but large and difficult backgrounds, combinatorics tackled by multivariate methods (BDT, MEM, DNN)

Heavy-flavour production in association with $t\bar{t}$ events simulated through parton shower with large uncertainties, which are constrained with various control regions

Reweighting / uncertainty using dedicated Sherpa $t\bar{t} + b\bar{b}$ four-flavour scheme NLO calculation
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Reweighting / uncertainty using dedicated Sherpa \( t\bar{t} + b\bar{b} \) four-flavour scheme NLO calculation

### CMS uncertainties

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>±( \Delta \mu ) (observed)</th>
<th>±( \Delta \mu ) (expected)</th>
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</thead>
<tbody>
<tr>
<td>Total experimental</td>
<td>+0.15/−0.16</td>
<td>+0.19/−0.17</td>
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<tr>
<td>( b ) tagging</td>
<td>+0.11/−0.14</td>
<td>+0.12/−0.11</td>
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<tr>
<td>jet energy scale and resolution</td>
<td>+0.06/−0.07</td>
<td>+0.13/−0.11</td>
</tr>
<tr>
<td>Total theory</td>
<td>+0.28/−0.29</td>
<td>+0.32/−0.29</td>
</tr>
<tr>
<td>( t\bar{t}+hf ) cross section and parton shower</td>
<td>+0.24/−0.28</td>
<td>+0.28/−0.28</td>
</tr>
<tr>
<td>Size of the simulated samples</td>
<td>+0.14/−0.15</td>
<td>+0.16/−0.16</td>
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<tr>
<td>Total systematic</td>
<td>+0.38/−0.38</td>
<td>+0.45/−0.42</td>
</tr>
<tr>
<td>Statistical</td>
<td>+0.24/−0.24</td>
<td>+0.27/−0.27</td>
</tr>
<tr>
<td>Total</td>
<td>+0.45/−0.45</td>
<td>+0.53/−0.49</td>
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</table>

### ATLAS uncertainties

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>( \Delta \mu )</th>
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<tbody>
<tr>
<td>( tt + \geq 1b ) modeling</td>
<td>+0.46/−0.46</td>
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<tr>
<td>Background-model stat. unc.</td>
<td>+0.29/−0.31</td>
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<tr>
<td>( b )-tagging efficiency and mis-tag rates</td>
<td>+0.16/−0.16</td>
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<tr>
<td>Jet energy scale and resolution</td>
<td>+0.14/−0.14</td>
</tr>
<tr>
<td>( ttH ) modeling</td>
<td>+0.22/−0.05</td>
</tr>
<tr>
<td>( tt + \geq 1c ) modeling</td>
<td>+0.09/−0.11</td>
</tr>
<tr>
<td>JVT, pileup modeling</td>
<td>+0.03/−0.05</td>
</tr>
<tr>
<td>Other background modeling</td>
<td>+0.08/−0.08</td>
</tr>
<tr>
<td>( tt + ) light modeling</td>
<td>+0.06/−0.03</td>
</tr>
<tr>
<td>Luminosity</td>
<td>+0.03/−0.02</td>
</tr>
<tr>
<td>Light lepton (( e, \mu )) id., isolation, trigger</td>
<td>+0.03/−0.04</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>+0.57/−0.54</td>
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<tr>
<td>( tt + \geq 1b ) normalization</td>
<td>+0.09/−0.10</td>
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<tr>
<td>( tt + \geq 1c ) normalization</td>
<td>+0.02/−0.03</td>
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<tr>
<td>Intrinsic statistical uncertainty</td>
<td>+0.21/−0.20</td>
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<tr>
<td>Total statistical uncertainty</td>
<td>+0.29/−0.29</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>+0.64/−0.61</td>
</tr>
</tbody>
</table>
 Searches

- Spoiler alert: no physics beyond SM discovered so far by ATLAS or CMS
- Wealth of data and new experimental approaches to leave no stone unturned!
- Classic bump-hunts with more data: first 2017 data results in ee channel targeting high mass – no signal, extending $Z'_{SSM}$ limit from 4.5 TeV to 4.7 TeV

[Graph showing data and limits]

Jan Kretzschmar, 16.4.2018
New physics may hide at low mass with small coupling, but di-jet data at $m_{jj} \lesssim 1$ TeV typically not recorded at full luminosity.

- Analysis of calorimeter trigger level objects allows higher rate
- High $p_T$ $Z'$ candidates with ISR jet
- Covering large phase space from $m_{Z'} \sim 50$ GeV to kinematic limit – no significant excess so far

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**Dijet searches**

- ATLAS
  - $\sqrt{s}=13$ TeV, 29.3 fb$^{-1}$
  - $|y^*| < 0.6$

![ATLAS Event Plot](image)

**CMS**

- Data
- Total SM pred.
- $W(qq)+$jets ($\times 3$)
- $Z(qq)+$jets ($\times 3$)
- Multijet pred.
- $(t\bar{t})(qq)+$jets ($\times 3$)
- $Z'(qq), g=0.17, m_{Z'}=135$ GeV

- $p_T \geq 700-800$ GeV
- $m_{SD}$ (GeV)

![CMS Event Plot](image)

35.9 fb$^{-1}$ (13 TeV)
Dijet searches

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- High $p_T$ $Z'$ candidates with ISR jet
- Covering large phase space from $m_{Z'} \sim 50$ GeV to kinematic limit – no significant excess so far

![Graph showing $Z'$ mass (GeV) vs. coupling, $g$, with observed and expected limits.](image)
Mono-jet searches

- Target pair-production of (invisible) Dark Matter production with a high-$p_T$ ISR jet
- Main backgrounds are $Z(\nu\nu)+\text{jets}$ and $W(\ell\nu)+\text{jets}$ – challenge to describe these accurately with predictions up to NNLO QCD + nNLO EW
- Ratios of $V+\text{jets}$ predictions in agreement with theory predictions beyond 1 TeV
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- Main backgrounds are $Z(\nu\nu)+$jets and $W(\ell\nu)+$jets – challenge to describe these accurately with predictions up to NNLO QCD + nNLO EW
- Ratios of $V+$jets predictions in agreement with theory predictions beyond 1 TeV

![Graphs showing data and predictions for monojet searches](image-url)
**Multijet searches**

- Several BSM scenarios, e.g. R-parity violating SUSY, lead to spectacular signatures with many high-$p_T$ jets.
- Example: Selection of events with at least 4 large-$R = 1.0$ jets with $p_T > 200$ GeV, $M_J^\Sigma$ is sum of large-$R$-jet masses.
- MC simulation describes data qualitatively, background predictions in SRs built with data-driven method.
- Pushing exclusion gluino $\tilde{g}$ to masses of $\sim 2$ TeV.

![Graphical representation of ATLAS data and MC simulation results.](image-url)
Conclusion

- Deluge of LHC data used in diverse way to test our understanding of the SM – 36 fb$^{-1}$ Run-2 data
- Single $W$, $Z$ bosons: < 1% precision – constraining parameters of the EW sector of the SM such as $m_W$ and $\sin^2 \theta_W$
- Multiboson and VBF studies reach the $\sim 5 - 10\%$ level, VBS $W^\pm W^\pm$ observation
- Significant progress in studies of the Higgs boson:
  - Test of SM predictions reaching $\sim 15\%$ level, differential 20 – 30% precision per bin
  - New evidence / observation for $H \to b\bar{b}$ decay and $t\bar{t}H$ production
- Searches for phenomena beyond the SM leaving no stone unturned
- Uncertainties in QCD predictions, PDFs and MC modelling remain a challenge:
  - Advances in QCD calculations at/beyond NLO and MC simulation crucial
  - PDF and $\alpha_S$ uncertainties: future limitation that cannot be overcome using only $pp$ data
- What will the full Run-2 data bring?
Conclusion

- Deluge of LHC data used in diverse way to test our understanding of the SM – $36\text{ fb}^{-1}$ Run-2 data
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Jan Kretzschmar, 16.4.2018
EW precision with $W$, $Z$ bosons

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**Figure 1:**
- Left panel: Plot of $\Delta \chi^2$ vs. $M_W$ [GeV] with $G$ fit results.
  - SM fit w/o $M_H$ measurements.
  - SM fit w/o $M_H$ and $M_t$ measurements.
- Right panel: Plot of $\Delta \chi^2$ vs. $\sin^2(\theta_{\text{eff}})$.
  - SM fit w/o measurements sensitive to $\sin^2(\theta_{\text{eff}})$.
  - SM fit w/o measurements sensitive to $\sin^2(\theta_{\text{eff}})$ and $M_H$ measurements.

**References:**
- LEP [arXiv:1302.3415]
- Tevatron [arXiv:1204.0042]
- ATLAS [EPJC 78, 110 (2018)]

Jan Kretzschmar, 16.4.2018
Multi-differential $Z/\gamma^* \rightarrow \ell\ell$ [JHEP 12 (2017) 059, CMS-PAS-SMP-16-007]
Multi-differential $Z/\gamma^* \to \ell\ell$ [JHEP 12 (2017) 059, CMS-PAS-SMP-16-007]
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**CMS Preliminary**

18.8 fb$^{-1}$ (8 TeV)

$A_{FB}$

$\left| \mathbb{Y}_{\mu\mu} \right| < 0.4$
$0.4 \leq \left| \mathbb{Y}_{\mu\mu} \right| < 0.8$
$0.8 \leq \left| \mathbb{Y}_{\mu\mu} \right| < 1.2$
$1.2 \leq \left| \mathbb{Y}_{\mu\mu} \right| < 1.6$
$1.6 \leq \left| \mathbb{Y}_{\mu\mu} \right| < 2.0$
$2.0 \leq \left| \mathbb{Y}_{\mu\mu} \right| < 2.4$

Data - Fit

Data
Fit

$\mathbb{M}_{\mu\mu}$ (GeV)

$\mathbb{M}_{\mu\mu}$ (GeV)

Jan Kretzschmar, 16.4.2018
\sin^2 \theta_W

\begin{align*}
\sin^2 \theta_{\text{eff}} & \approx 0.229 \\
0.23 & \leq \sin^2 \theta_{\text{eff}} \leq 0.232
\end{align*}

<table>
<thead>
<tr>
<th>CMS Preliminary</th>
<th>18.8 fb^{-1} (8 TeV)</th>
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<tbody>
<tr>
<td>CT10</td>
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<tr>
<td>NNPDF(1000)</td>
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<td>MMHT</td>
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<td>CT14</td>
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<td>NNPDF(100)</td>
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Jan Kretzschmar, 16.4.2018
LHC $m_W$ with LHeC PDFs

- Generator-level study of PDF uncertainty following methodology of ATL-PHYS-PUB-2014-015 ($p_T^\ell$ spectrum only, no categorisation or optimisation)
- Using PDFs as expected to be extracted from LHeC NC and CC cross-section data reduces uncertainty reduced from $10 \sim 20$ MeV level to $\sim 2.5$ MeV – factor $4 \sim 10$
- Precision PDFs will allow experimental categories to be used to constrain other effects than PDFs
- Similar improvement can be expected in PDF-related uncertainty on $\sin^2 \theta_W$ extraction from $pp$ data

<table>
<thead>
<tr>
<th></th>
<th>CT10nlo</th>
<th>MSTW2008CPdeutnlo</th>
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<tr>
<td>$W^+$</td>
<td>+18 -22</td>
<td>+11 -10</td>
<td>+8 -10</td>
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<tr>
<td>$W^-$</td>
<td>+18 -23</td>
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<td>+8 -9</td>
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<tr>
<td>$W^\pm$</td>
<td>+14 -18</td>
<td>+7 -7</td>
<td>+6 -5</td>
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</tbody>
</table>

ATL-PHYS-PUB-2014-015

Gluon density - high $p_T$ $Z$ and $\gamma$

- $Z \rightarrow \ell\ell$ and isolated $\gamma$ measurable to $0.5 \sim 2\%$ precision at high $p_T$ – information on $qg$ luminosity

- NNLO corrections recently completed: large improvement on scale uncertainty, but also large correction, NNLO needed to fit the data with good $\chi^2$
The basic experimental set ups for accelerator particle physics:

- no initial hadron (….LEP, ILC, CLIC)
- 1 hadron (….HERA, LHeC)
- 2 hadrons (Tevatron, LHC, FCC)

The pdf are defined in DIS
The theory of inclusive DIS is crystal clear
Thru the factorization “theorem” the pdf’s and $\alpha_s$ determine the hadron collider rates

We often hear the statement that all the relevant info on pdf’s can directly be obtained from the LHC without need of the LHeC

Not really true. Certainly not at the same level of precision

- Deep theoretical questions e.g. on non-perturbative effects and factorization breaking in $pp$ – do not want to fold these into PDFs
- Illustrate limitations from limited PDF accuracy and issues we’re facing in extracting PDFs from $pp/p\bar{p}$ data
Combination

Parameter value

-1 -0.5 0 0.5 1 1.5 2 2.5 3 3.5 4

\( \mu^{\gamma\gamma} \)
\( \mu^{ZZ} \)
\( \mu^{WW} \)
\( \mu^{\tau\tau} \)
\( \mu^{bb} \)

Parameter value

0 0.5 1 1.5 2 2.5

\( \mu^{\gamma\gamma} \)
\( \mu^{ZZ} \)
\( \mu^{WW} \)
\( \mu^{\tau\tau} \)
\( \mu^{bb} \)

**ATLAS and CMS**

**LHC Run 1**

- **ATLAS+CMS**
- **ATLAS**
- **CMS**
- \( \pm 1\sigma \)
- \( \pm 2\sigma \)

**CMS Preliminary**

35.9 fb\(^{-1}\) (13 TeV)

- **Observed**
- \( \pm 1\sigma \) (stat\.+sys.)
- \( \pm 1\sigma \) (sys.)
- \( \pm 2\sigma \)
$H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$

**ATLAS**

$H \rightarrow ZZ^* \rightarrow 4l$

$\sqrt{s}=13$ TeV, 36.1 fb$^{-1}$

$H \rightarrow \gamma\gamma$, $m_H=125.09$ GeV

- If $|y| < 2.5$
- Reduced Stage 1
- ATLAS

### Expected SM
- Observed: Stat + Sys
- SM Prediction

### Measured $\sigma \times B$

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma B$ (fb)</th>
<th>$(\sigma B)_{SM}$ (fb)</th>
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<tbody>
<tr>
<td>$ggF-0j$</td>
<td>$880^{+240}_{-210}$</td>
<td>$730 \pm 50$</td>
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<tr>
<td>$ggF-1j-p_T^{HH}$-Low</td>
<td>$80^{+150}_{-140}$</td>
<td>$170 \pm 25$</td>
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<tr>
<td>$ggF-1j-p_T^{HH}$-Med</td>
<td>$160^{+110}_{-90}$</td>
<td>$120 \pm 20$</td>
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<tr>
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<td>$30^{+50}_{-40}$</td>
<td>$24 \pm 5$</td>
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<tr>
<td>$ggF-2j$</td>
<td>$200^{+160}_{-140}$</td>
<td>$140 \pm 30$</td>
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<tr>
<td>$VBF-p_T^{H}$-Low</td>
<td>$260^{+180}_{-150}$</td>
<td>$88.6 \pm 2.7$</td>
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<td>$VBF-p_T^{H}$-High</td>
<td>$60^{+50}_{-40}$</td>
<td>$4.2 \pm 0.2$</td>
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<td>$VH$-Had</td>
<td>$&lt; 200$ (95% CL)</td>
<td>$36.2^{+1.9}_{-3.3}$</td>
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<tr>
<td>$VH$-Lep</td>
<td>$&lt; 180$ (95% CL)</td>
<td>$16.6^{+0.8}_{-1.4}$</td>
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<tr>
<td>$ttH$</td>
<td>$&lt; 110$ (95% CL)</td>
<td>$15.4^{+1.1}_{-1.6}$</td>
</tr>
</tbody>
</table>

Jan Kretzschmar, 16.4.2018
$H \rightarrow \gamma\gamma$ and $H \rightarrow 4\ell$

**ATLAS Preliminary**

13 TeV, 36.1 fb$^{-1}$

$\gamma\gamma \rightarrow ZZ, H \rightarrow H$

$N_{\text{jets}} \geq 1$ $N_{\text{jets}} \geq 2$ $N_{\text{jets}} \geq 3$

**Theory/Data**

0.4 0.6 0.8 1 1.2 1.4 1.6

$\sigma [\text{pb}]$

0 5 10 15 20 25 30 35 40 45 50

Combined

NNLOPS (@N$^3$LO) + XH

SCETlib + MCFM8 + XH

XH = VBF+WH+ZH+ttH+bbH

JVE + XH

MG5 (@N$^3$LO) + XH

STWZ + XH

XH = VBF+WH+ZH+ttH+bbH

Hy/$\sigma$ $d\sigma$/$d|y^H|$