Some aspects of recent SM and Higgs results from ATLAS and CMS

• In this talk, I will attempt to discuss some aspects of recent SM and Higgs results of the ATLAS and CMS collaborations, highlighting wherever possible between the two experiments, the impact of the performance differences, of the different treatment of the modelling of important physics backgrounds, and of the theory uncertainties affecting the measurements in key example physics cases

• First measurement of $m_W$ at the LHC: quick overview of results
• Measurements of $\sin^2\theta_W$ at the LHC: recent results and prospects for EW precision measurements in runs 1-2 and beyond.
• Z VBF measurements in run 2 from ATLAS and CMS
• Higgs VBF measurements in run 2 from ATLAS and CMS
• New measurements in run 2 with high statistics: $H$ to $\gamma\gamma$ cross sections per production mode by ATLAS
Disclaimer

• There have been many new and interesting results from ATLAS and CMS over the summer in the SM and Higgs sectors covering the full 2015+2016 dataset at 13 TeV. There is no way I could cover them all and do justice to them in a 30’ talk, so I list the most important ones below (the full list can be found easily from the web)

• Measurement of vector boson scattering and constraints on anomalous quartic couplings from events with four leptons and two jets in proton–proton collisions at $\sqrt{s} = 13$ TeV (CMS, arXiv:1708.02812)
• Observation of electroweak production of same-sign W boson pairs in the two jet and two same-sign lepton final state in proton-proton collisions at $\sqrt{s}= 13$ TeV (CMS, arXiv:1709.05822)
• Measurements of differential cross sections and search for the electroweak production of two Z bosons in association with jets (CMS, CMS-PAS-SMP-16-019)
• $ZZ \rightarrow 4l$ cross-section measurements and search for anomalous triple gauge couplings in 13 TeV pp collisions with the ATLAS detector (arXiv:1709.07703)
• Evidence for the decay of the Higgs boson to bottom quarks (CMS, arXiv:1709.07497)
• Inclusive search for the standard model Higgs boson produced in pp collisions at $\sqrt{s} = 13$ TeV using $H\rightarrow bb$ decays (CMS, arXiv:1709.05543)
• Observation of the SM scalar boson decaying to a pair of $\tau\tau$ leptons with the CMS experiment at the LHC (arXiv:1708.00373)
• Measurements of Higgs boson properties in the diphoton decay channel with 36.1 fb$^{-1}$ pp collision data at the center-of-mass energy of 13 TeV with the ATLAS detector (ATLAS-CONF-2017-045)
• ATLAS-CONF-2017-045 Measurement of inclusive and differential cross sections in the $H\rightarrow ZZ^*\rightarrow 4\ell$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector (arXiv:1708.02810)
• Measurement of the Higgs boson coupling properties in the $H\rightarrow ZZ^*\rightarrow 4\ell$ decay channel at $\sqrt{s}= 13$ TeV with the ATLAS detector (ATLAS-CONF-2017-043)
Precision measurements in the EW/Higgs sectors at the LHC

• The word « precision » has different meanings in different areas (note that mass measurements are a special case) at the LHC today:
  • It means sub-percent precision in DY and in some aspects of flavour physics in LHCb
  • It means a few percent at best still for top physics
  • It means 10-40% for Higgs physics (eg couplings), at least for a while
  • It is not a surprise therefore that DY measurements are the most demanding in terms of theoretical accuracy (far more than Higgs!).
  • In a nutshell, there are two key difficulties we are confronted with:
    a) The lack of a MC generator tool for DY production which would include N...NLO+N...NLL QCD (and EW/QED) calculations, perfectly matched and merged to PS, with a UE model reproducing the data
    b) The complexity of dealing with a large number of sources of theoretical uncertainty which are not always reliable nor stable
Lepton and event selection for measurement of $m_W$

**Lepton selections**
- Muons: $|\eta| < 2.4$; isolated (track-based)
- Electrons: $0 < |\eta| < 1.2$ or $1.8 < |\eta| < 2.4$; isolated

**Kinematic requirements**
- $p_T > 30$ GeV  $p_T^{\text{miss}} > 30$ GeV
- $m_T > 60$ GeV  $u_T < 30$ GeV

**Measurement categories**:

| $|\eta_\ell|$ range | 0 – 0.8 | 0.8 – 1.4 | 1.4 – 2.0 | 2.0 – 2.4 | Inclusive |
|-------------------|---------|-----------|-----------|-----------|-----------|
| $W^+ \rightarrow \mu^+ \nu$ | 1 283 332 | 1 063 131 | 1 377 773 | 885 582 | 4 609 818 |
| $W^- \rightarrow \mu^- \bar{\nu}$ | 1 001 592 | 769 876 | 916 163 | 547 329 | 3 234 960 |

| $|\eta_\ell|$ range | 0 – 0.6 | 0.6 – 1.2 | 1.8 – 2.4 | Inclusive |
|-------------------|---------|-----------|-----------|-----------|
| $W^+ \rightarrow e^+ \nu$ | 1 233 960 | 1 207 136 | 956 620 | 3 397 716 |
| $W^- \rightarrow e^- \bar{\nu}$ | 969 170 | 908 327 | 610 028 | 2 487 525 |

7.8 M events

5.9 M events
Fit results for $m_W$

$m_W = 80.370 \pm 0.007 \text{ (stat.)} \pm 0.011 \text{ (exp. syst.)} \pm 0.014 \text{ (mod. syst.)} \text{ GeV}$

$= 80.370 \pm 0.019 \text{ GeV}$

$m_{W^+} - m_{W^-} = -29 \pm 13 \text{ (stat.)} \pm 7 \text{ (exp. syst.)} \pm 24 \text{ (mod. syst.)} \text{ MeV}$

$= -29 \pm 28 \text{ MeV}$
Relative importance of different measurements

• Measuring electrons AND muons provides a crucial set of closure constraints on the experimental systematic uncertainties. A number of experimental issues at the ~30-50 MeV level on $m_W$ were resolved in both channels thanks to this.

• Even though the weight of the $m_T$ measurement is much smaller than that of $p_T^\ell$, it plays an important role in the understanding of the theoretical modelling uncertainties on $p_T^W$.

<table>
<thead>
<tr>
<th>Combination</th>
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<td>$W^-$</td>
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</table>
Consistency of experimental results

![Graph showing consistency of experimental results for various experiments including ALEPH, DELPHI, L3, OPAL, CDF, D0, ATLAS W^+, ATLAS W^-, and ATLAS W^±. The graph plots m_W [MeV] on the x-axis and shows the range of measured values and uncertainties for each experiment.](image)
### Results in the various measurement categories

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</tbody>
</table>

**Strongly correlated\(|\eta|\) comb. $e \rightarrow \sim 15$ MeV $\mu \rightarrow \sim 11$ MeV**

**Fit ranges**: $32 < p_T < 45$ GeV and $66 < m_T < 99$ GeV, minimising total expected measurement uncertainty
Relation between top, Higgs and W masses

The measurements of the Higgs and top-quark masses are currently more precise than their indirect determination from the global fit of the electroweak observables.

Indirect determination of $m_W$ ($\pm 8$ MeV) is more precise than the experimental measurement.

Improving precision will not increase sensitivity to new physics.

Call for $\delta m_W < 10$ MeV.

The $W$ mass is nowadays the crucial measurement to improve the sensitivity of the global EW fits to new physics.
W-boson mass history

1983 CERN SPS – W discovery
UA1/UA2
\[ m_W = 81 \pm 5 \text{ GeV} \]

1992 UA2 (with \( m_Z \) from LEP)
\[ m_W = 80.35 \pm 0.37 \text{ GeV} \]

2013 LEP combined
\[ m_W = 80.376 \pm 0.033 \text{ GeV} \]

2013 Tevatron combined
\[ m_W = 80.387 \pm 0.016 \text{ GeV} \]

2017 LHC (ATLAS)
\[ m_W = 80.370 \pm 0.019 \text{ GeV} \]

Only four W-boson mass measurements in the last 7 years

Complex measurements which require O(5-7) years
TeVatron results/prospects and LHC prospects

**D0**  5.3 fb\(^{-1}\)  \(1.7 \times 10^6\) \(W \rightarrow e\nu\)

\[
M_W = 80.375 \pm 0.011 \text{ (stat.)} \pm 0.020 \text{ (syst.)} \text{ GeV}
\]
\[
= 80.375 \pm 0.023 \text{ GeV.}
\]

**CDF**  2.2 fb\(^{-1}\)  \(1.1 \times 10^6\) events, \(W \rightarrow e\nu, \mu\nu\)

\[
M_W = 80\,387 \pm 12 \text{ (stat)} \pm 15 \text{ (syst)} \text{ GeV}
\]
\[
= 80\,387 \pm 19 \text{ MeV/c}^2
\]

**Tevatron prospects:** full dataset (10 fb\(^{-1}\)) + end-cap \(W \rightarrow e\nu\) for D0 (?)

**W samples in ATLAS**  \((W \rightarrow e\nu, \mu\nu)\):

<table>
<thead>
<tr>
<th>Energy</th>
<th>(~4.5) fb(^{-1})</th>
<th>(~20.3) fb(^{-1})</th>
<th>(~30) fb(^{-1})</th>
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<tr>
<td>7 TeV</td>
<td>15\times10^6</td>
<td>80\times10^6</td>
<td>190\times10^6</td>
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<tr>
<td>8 TeV</td>
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<td></td>
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<tr>
<td>13 TeV</td>
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</tbody>
</table>

D. Froidevaux, CERN

ICPPA Conference, Moscow, 05/10/2017
W-boson mass measurements: Tevatron vs LHC

CDF: Tracker Linearity Cross-check & Combination

Final momentum calibration using the J/ψ, ϒ and Z bosons

Combined momentum scale correction:

\[ \Delta p/p = ( -1.29 \pm 0.07_{\text{independent}} \pm 0.05_{\text{QED}} \pm 0.02_{\text{align}} ) \times 10^{-3} \]

\[ \Delta M_W = 7 \text{ MeV} \]

Note: this paves the way to a precision measurement of m_Z at hadron colliders, can LHC do better than LEP?
Control of $p_T^W$ modelling: $u_{\parallel}^e$, $u_{\parallel}^\mu$

The region $u_{\parallel} < -10$ GeV is sensitive to the physics modelling of the soft part of the $p_T^W$ spectrum.

With a total of e.g. $\sim 0.8M$ $W$ to $\mu\nu$ decays, one can constrain modelling uncertainties to $\sim 10$ MeV.
Control of $p_T^W$ modelling: $u_\parallel^e$, $u_\parallel^\mu$

The $u_\parallel^l$ distribution is very sensitive to the underlying $p_T^W$ distribution, for $u_\parallel^l < 0$. This feature can be exploited, even in a high pile-up environment to verify the accuracy of the baseline model, and to compare to alternative (more state-of-the-art?) models.

Pythia 8 tuned to Z OK; DYRES, Powheg MiNLO disfavoured
Experimental interlude: cross-checks with Z events (ATLAS and CMS)
1. The CMS measurement is less precise statistically than the ATLAS one for muons for several reasons (only muons with $|\eta| < 0.9$ used in CMS, half of the sample used for the recoil calibration and the other half for the measurement).

2. The lepton calibration in ATLAS is more precise because it is based on the full run-1 dataset (7 and 8 TeV).

3. The recoil calibration in CMS appears more precise than the ATLAS one (particle flow versus 3D topological clusters) but the response of the recoil in CMS is $\sim 30\%$, to be compared to $\sim 70\%$ in ATLAS.

4. The efficiency systematics for CMS are much smaller (stats insufficient?)

### Cross-checks with Z events (ATLAS and CMS 7 TeV)

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<tr>
<th>Source of uncertainty (values in MeV for $m_T$ meas.)</th>
<th>CMS muons</th>
<th>ATLAS muons</th>
<th>ATLAS electrons</th>
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### Remarks

1. The CMS measurement is less precise statistically than the ATLAS one for muons for several reasons (only muons with $|\eta| < 0.9$ used in CMS, half of the sample used for the recoil calibration and the other half for the measurement).
2. The lepton calibration in ATLAS is more precise because it is based on the full run-1 dataset (7 and 8 TeV).
3. The recoil calibration in CMS appears more precise than the ATLAS one (particle flow versus 3D topological clusters) but the response of the recoil in CMS is $\sim 30\%$, to be compared to $\sim 70\%$ in ATLAS.
4. The efficiency systematics for CMS are much smaller (stats insufficient?)
Measurements of $\sin^2 \theta^\text{eff}_\text{lep}$: status before July 2017

The diagram shows measurements from various experiments:
- **LEP-1 and SLD: Z-pole**
- **LEP-1 and SLD: $A^0_{FB}$**
- **SLD: $A_t$**
- **CMS $\mu\mu$ 1 fb$^{-1}$**
- **ATLAS $ee+\mu\mu$ 5 fb$^{-1}$**
- **LHCb $\mu\mu$ 3 fb$^{-1}$**
- **CDF $\mu\mu$ 9 fb$^{-1}$**
- **CDF $ee$ 9 fb$^{-1}$**
- **CDF $ee+\mu\mu$ 9 fb$^{-1}$**
- **D0 $ee$ 10 fb$^{-1}$**

Each measurement is accompanied by its value and uncertainty. For example, the SLD measurement yields $0.23098\pm0.00026$. The graph plots the value of $\sin^2 \theta^\text{eff}_\text{lep}$ against different datasets, with the x-axis representing the range from 0.226 to 0.234.
Measurements of \(\sin^2\theta_{\text{lep}^{\text{eff}}}: \) dilution in \(\text{pp}\)

Asymmetry diluted by two effects:

- Larger for up-type quarks than down-type quarks (measuring a mixture)
- Mistakes in signing the direction of the incoming quark

Measured asymmetry is larger at high dilepton system rapidity:

- Value at Z-pole (main sensitivity to \(\sin^2\theta_{\text{lep}^{\text{eff}}})\) is only a few %

- Asymmetry prediction is sensitive to PDF uncertainties
Measurements of $\sin^2\theta_{\text{lep}}^{\text{eff}}$: new result by CMS

Standard $Z/\gamma^*\rightarrow ee$ and $\mu\mu$ event selections, very small background near Z peak

- Precise control of efficiency (in particular charge dependence and mis-assignment)
- Precise understanding of energy/momentum scale and resolution ($m_\parallel$ migrations)

- Not: CMS does not use central-forward electrons used in ATLAS measurement from 7 TeV data (higher sensitivity at high $y_Z$)
Measurements of $\sin^2\theta_{\text{lep}}^{\text{eff}}$ : new result by CMS

$\chi^2$ fit between data $A_{FB}$ distributions and prediction in 72 dilepton ($m_\ell\ell$, $y_\ell\ell$) bins

MC reweighted using event-by-event matrix elements to vary $\sin^2\theta_{\text{lep}}^{\text{eff}}$
Measurements of $\sin^2 \theta_{\text{lep eff}}$: new result by CMS

Largest uncertainty from data statistics

Systematic uncertainties

- Significant contribution from MC statistics, even after smoothing
- Selection efficiencies which are correlated between lepton charges cancel out
- Energy/momentum calibration performed using $Z \rightarrow ll$ samples
  ▲ Coherent treatment of uncertainties in calibration and asymmetry analyses

Theoretical uncertainties subdominant

- Various uncertainties in modelling of $Z/\gamma^* \ p_T$ spectrum including $Z+$jets
- PDF uncertainties accounted for separately

<table>
<thead>
<tr>
<th>channel</th>
<th>statistical uncertainty</th>
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<tbody>
<tr>
<td>muon</td>
<td>0.00044</td>
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<td>electron</td>
<td>0.00060</td>
</tr>
<tr>
<td>combined</td>
<td>0.00036</td>
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</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>muons</th>
<th>electrons</th>
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<tbody>
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<td>0.00015</td>
<td>0.00033</td>
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<tr>
<td>Lepton momentum calibration</td>
<td>0.00008</td>
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<td>Lepton selection efficiency</td>
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<td>0.00004</td>
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<td>Background subtraction</td>
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<td>0.00005</td>
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<td>Pileup modeling</td>
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<td>0.00002</td>
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<tr>
<td>Total</td>
<td>0.00018</td>
<td>0.00039</td>
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<table>
<thead>
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<th>model variation</th>
<th>Muons</th>
<th>Electrons</th>
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<tr>
<td>Dilepton $p_T$ reweighting</td>
<td>0.00003</td>
<td>0.00003</td>
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<td>QCD $\mu_{R/F}$ scale</td>
<td>0.00011</td>
<td>0.00013</td>
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<td>POWHEG MiNLO $Z+$j vs NLO $Z$ model</td>
<td>0.00009</td>
<td>0.00009</td>
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<td>FSR model (PHOTOS vs PYTHIA)</td>
<td>0.00003</td>
<td>0.00005</td>
</tr>
<tr>
<td>UE tune</td>
<td>0.00003</td>
<td>0.00004</td>
</tr>
<tr>
<td>Electroweak ($\sin^2 \theta_{\text{lep eff}} - \sin^2 \theta_{\text{eff}}^{u,d}$)</td>
<td>0.00001</td>
<td>0.00001</td>
</tr>
<tr>
<td>Total</td>
<td>0.00015</td>
<td>0.00017</td>
</tr>
</tbody>
</table>
Measurements of $\sin^2\theta_{\text{lep}}^{\text{eff}}$: new result by CMS

Large PDF uncertainties due to dilution and to u/d ratio valence quark uncertainties

But PDF uncertainties are largest away from Z-pole, small $\sin^2\theta_{\text{lep}}^{\text{eff}}$ sensitivity
Constrain PDF uncertainties using data

- NNPDF3.0 uncertainties expressed as 100 replicas to span the uncertainty
  - Typically take RMS to calculate uncertainty on an observable
  - C.f. quadrature sum of eigenvectors for other PDFs e.g. CT14 and MMHT

Weight the various replicas according to their $\chi^2$ compatibility with the data

$$w_i = \frac{e^{-\frac{\chi^2_{\text{min}}}{2}}}{\frac{1}{N} \sum_{i=1}^{N} e^{-\frac{\chi^2_{\text{min}}}{2}}}$$

- Final $\sin^2\theta^\text{eff}_{\text{lep}}$ from weighted average

Reduces PDF uncertainty by factor ~2

- Also for other PDFs

<table>
<thead>
<tr>
<th>Channel</th>
<th>without constraining PDFs</th>
<th>with constraining PDFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon</td>
<td>0.23125 ± 0.00054</td>
<td>0.23125 ± 0.00032</td>
</tr>
<tr>
<td>Electron</td>
<td>0.23054 ± 0.00064</td>
<td>0.23056 ± 0.00045</td>
</tr>
<tr>
<td>Combined</td>
<td>0.23102 ± 0.00057</td>
<td>0.23101 ± 0.00030</td>
</tr>
</tbody>
</table>
Measurements of $\sin^2\theta_{\text{lep eff}}$: new result by CMS

$$\sin^2\theta_{\text{lep eff}} = 0.23101 \pm 0.00052$$

Competitive with Tevatron results, despite quark direction dilution

Breakdown at hadron colliders

<table>
<thead>
<tr>
<th>Error ($10^{-3}$)</th>
<th>Stat</th>
<th>Syst</th>
<th>PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS 8 TeV</td>
<td>0.36</td>
<td>0.24</td>
<td>0.30</td>
</tr>
<tr>
<td>ATLAS 7 TeV</td>
<td>0.5</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>LHCb ($\mu\mu$ only)</td>
<td>0.73</td>
<td>0.52</td>
<td>&lt;0.56</td>
</tr>
<tr>
<td>D0 (ee only)</td>
<td>0.43</td>
<td>0.08</td>
<td>0.17</td>
</tr>
<tr>
<td>CDF</td>
<td>0.43</td>
<td>0.07</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Impressive progress in the last years from LHCb and CMS
Exploring phase-space in V+jet events

- Study of EW-production of V+jets is important to understand Higgs and BSM backgrounds.
- Higher stats than even more interesting diboson EW production

- **EW production** is roughly 10 times smaller than **QCD production**.
- **To enhance EW component to 15-40%**: large $\Delta y_{jj}$, $m_{jj}$, $p_T^{\text{jet}}$; lepton(s) in the central region or $p_T$ balance; low $n_{\text{jets}}$ in the gap region between leading jets.
ATLAS: QCD + EW Z+jets @ 13 TeV (3.2 fb⁻¹)

Analysis performed in EW-enriched and QCD-enriched regions. Fits to templates in the EW-enriched region to measure fiducial cross-section.

QCD Zjj simulated with Alpgen 2, Sherpa 2.2 and MG5_aMC, EW Zjj with Powheg;

Zjj QCD-enriched region

Data-derived correction factors to QCD Zjj templates before fitting QCD+EW Zjj in EW-enriched region.

Zjj QCD largely mismodelled by Sherpa 2.2 and MG5_aMC at high $m_{jj}$ in QCD enriched region;
Analysis performed in EW-enriched and QCD-enriched regions. Fits to templates in the EW-enriched region to measure fiducial cross-section.

Inclusive Zjj cross-sections measured in six different fiducial regions with varying EW Zjj fractions.
Multivariate analysis (BDT) used to separate QCD Zjj and EW Zjj signal.

- Discriminating variables: \( m_{jj}, \Delta \eta_{jj}, R(p_T^{\text{hard}}) \),

\[
R(p_T^{\text{hard}}) = \frac{\left| \vec{p}_{T1} + \vec{p}_{T2} + \vec{p}_{TZ} \right|}{\left| \vec{p}_{T1} + \vec{p}_{T2} + \vec{p}_{TZ} \right|} = \frac{|\vec{p}_T^{\text{hard}}|}{|\vec{p}_{T1} + \vec{p}_{T2} + \vec{p}_{TZ}|}
\]

Good agreement between data and MC predictions attained.

- **MG5_aMC@NLO:**
  - EW Zjj (LO)
  - QCD Zjj (NLO up to 3 j)
  - FxFx
  - QCD Zjj (LO up to 4j) MLM
Signal extraction:
Distribution of BDT discriminant used to extract cross-section.
Shown envelopes for dominant uncertainties: JES and QCD scales.
Simultaneous fit of EW and QCD component in the signal (high BDT) and control (low BDT) regions.

Studies on hadronic activity in gap region:
BDT > 0.92 => region with 50% EW Zjj

Gap veto efficiency: Fraction of events with a measured gap activity below a given threshold.
Data disfavour bgd only predictions; in reasonable agreement with presence of signal with both PS predictions.
Comparison between ATLAS and CMS Z VBF results

- ATLAS result: $\sigma_{\text{EW}}(Zjj) = 119 \pm 16 \pm 20 \text{ fb for } m_{jj} > 250 \text{ GeV}$

- CMS result: $\sigma_{\text{EW}}(Zjj) = 552 \pm 19 \pm 55 \text{ fb for } m_{jj} > 120 \text{ GeV}$

- How can the uncertainties be so much smaller in CMS than in ATLAS? Especially given the large variations in predictions of Zjj QCD contribution in VBF phase space between event generators.

- In ATLAS, there is a 13% residual uncertainty assigned to the modelling of the Zjj QCD background in the VBF phase space, once the control region has been used to rescale the predicted background. This uncertainty is assumed to be negligible in the CMS preliminary result.

- It remains to be seen which shape uncertainty from the fit of the whole BDT output distribution will finally be published by CMS. This could well be significantly larger than the only implemented shape uncertainty from theory to-date, namely through QCD scale variations and PDFs for both the signal and background processes.
From VBF Z to VBF Higgs production

• It is often said that the VBF Higgs boson production is very accurately known in pQCD. Well, a couple of years ago we have learned that this is not really true (see next slide)

• The VBF Higgs signal has the same kinematic properties as the Z VBF signal and the handles to suppress the background from QCD Hjj production are the same as for the Z: $m_{jj}$ and $|\eta|_{jj}$

• However, the statistics in the Higgs channels is totally inadequate to devise a control region for the ggF Hjj background.

• For the new measurements obtained recently in the 2015-2016 run-2 datasets by ATLAS and CMS, the only way to assess possible large mismodellings of the ggF signal in the VBF phase space is to enlarge considerably the corresponding theory uncertainties and to assess the magnitude of the impact on the VBF measurement (both in terms of bias and uncertainty)
Theory: issues with Higgs VBF predictions

The QCD corrections obtained in this approach are small (O(5%) NLO, O(3%) NNLO); it then seemed natural to assume that this size of QCD corrections will be indicative for the fiducial cross sections.

However, this assumption turns out to be incorrect and, in fact, one can get larger O(6-10%) corrections for fiducial (WBF cuts) cross sections and kinematic distributions. Often, the shape of those corrections seems rather different from both the NLO and/or parton shower predictions. The message -- again -- seems to be that fixed order computations are required beyond certain level of precision; approximate results may indicate their magnitude but not much beyond 1

WBF cuts

\[
p_{t1,2} > 25 \text{ GeV}, \quad |y_{j1,2}| < 4.5, \\
\Delta y_{j1,j2} = 4.5, \quad m_{j1,j2} > 600 \text{ GeV}, \\
y_{j1}y_{j2} < 0, \quad \Delta R > 0.4
\]

<table>
<thead>
<tr>
<th></th>
<th>(\sigma_{\text{nocuts}}) [pb]</th>
<th>(\sigma_{\text{VBF cuts}}) [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO</td>
<td>4.032_{-0.069}^{+0.057}</td>
<td>0.957_{-0.059}^{+0.066}</td>
</tr>
<tr>
<td>NLO</td>
<td>3.929_{-0.023}^{+0.024}</td>
<td>0.876_{-0.018}^{+0.008}</td>
</tr>
<tr>
<td>NNLO</td>
<td>3.888_{-0.012}^{+0.016}</td>
<td>0.826_{-0.014}^{+0.013}</td>
</tr>
</tbody>
</table>

Cacciari, Dreyer, Kalberg, Salam, Zanderighi

PA Conference, Moscow, 05/10/2017
Higgs coupling measurements: how is this done?

Mainly ggF

<table>
<thead>
<tr>
<th>Decay / Production</th>
<th>Untagged</th>
<th>VBF</th>
<th>VH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4\ell$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow 2\ell 2\nu$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td></td>
<td>Possible in run 2?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The green colour above means that ATLAS and CMS have combined these channels together in their joint publication for run-1.
- Other production channels such as $bbH$, $gg$ to $ZH$, $tH$ are included resp. in $ggF$, $ZH$ and $ttH$ since they are not accessible as specific channels (nor will they be in run 2).
- With much larger statistics, it would be interesting to measure specifically the signal strength or effective coupling squared for any of the above $i$ to $H$ to $f$ processes, where $i$ denotes the production and $f$ denotes the decay.
Coupling measurements: how is this done?

- Many different final discriminant distributions combined

- Purity varies between categories (especially for production modes)

- A total of $O(100)$ categories for each experiment are combined

\[
\begin{align*}
    n_{\text{signal}}(k) &= \mathcal{L}(k) \times \sum_i \sum_f \left\{ \sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}^f \right\}, \\
    &= \mathcal{L}(k) \times \sum_i \sum_f \mu_i \mu^f \left\{ \sigma_i^{\text{SM}} \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}_{\text{SM}}^f \right\}
\end{align*}
\]

$L$: integrated luminosity, $A$: acceptance, $E$: efficiency
From VBF Z to VBF Higgs production: H to ZZ

Improvements on overall precision ~ x2 wrt Run1
Starting to approach SM theory uncertainty (also improved!)
From VBF Z to VBF Higgs production: $H \to \gamma\gamma$

*Precision similar to $ZZ$, despite lower $S/B$*
Stage 1: designed for full Run 2 statistics

- Designed for full Run 2 statistics
- ~30 cross sections can be measured
- Each one is labelled as "production b" to avoid confusion with reconstructed event categories
- Defined at “truth particle-level"
- Division is in bins of $n_{\text{jets}}$ and in $p_T$ of H, Hjj, Vector boson-W/Z

Simplified Template Cross Sections (STXS)
For this analysis, we merge together low stats bins to 9 production bins:

- 5 ggF, 1 VBF, 1 VH-lep, 1 ttH, 1 BSM
**Hγγ reco category composition for prod modes**

**reco category**
- ttH, tH
  - 50-100%
- VH-lep, VH-MET
  - 70-80%
- VH-had
  - 25-40%
- VBF
  - 25-90%
- ggF
  - 80-97%

**selection**

**fraction of prod mode**

**ATLAS Preliminary**\( H \rightarrow \gamma \gamma, m_H = 125.09 \text{ GeV} \)

- **ttH**
- **VH-lep, VH-MET**
- **VH-had**
- **VBF**
- **ggF**

**N_s - expected Higgs boson events**

<table>
<thead>
<tr>
<th>Selection</th>
<th>Fraction of Prod Mode</th>
<th>ttH</th>
<th>VH-lep, VH-MET</th>
<th>VH-had</th>
<th>VBF</th>
<th>ggF</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 lep, 2 met</td>
<td>10-45%</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>5-45%</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>38</td>
<td>6-20%</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>70</td>
<td>6-50%</td>
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</tr>
<tr>
<td>1600</td>
<td>2-10% BSM ~20%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**BSM ~20%**

**Total:**

**1700**
**H\(\gamma\gamma\) STXS region purity per category**

**STXS regions (production bins)**

**ATLAS Preliminary** \(H \rightarrow \gamma \gamma, m_H = 125.09\) GeV

**Reconstruction event categories**

- VBF
- VBF + ggF
- VBF (VBF-like)

**VBF (VBF-like)**

**Reconstruction event categories**
Reduced Stage 1 production bins

**ggF**
- $= 0$-jet
- $= 1$-jet
- $\geq 2$-jet
  - $p_T^{jj} [0, 60]$
  - $p_T^{jj} [60, 120]$
  - $p_T^{jj} [120, 200]$
  - $p_T^{jj} [200, \infty]$

**VBF**
- $p_T^{jj} [0, 200]$

**VBF + VH -hadronic**
- $\geq 2$-jet VBF cuts
  - $p_T^{jj} [0, 25]$
  - $p_T^{jj} [25, \infty]$
- $\geq 2$-jet VH cuts
  - Rest

**VH -leptonic**
- $W \to l\nu$
  - $p_T^W [0, 150]$
- $Z \to l^+ l^- \nu\bar{\nu}$
  - $p_T^Z [0, 150]$

**BSM**
- $bbH$ merged with $ggF$

Bins with large correlations ($\geq 50\%$) have been merged.
From VBF Z to VBF Higgs production: H to $\gamma\gamma$

- The VBF measurement in this Higgs decay channel has a total expected uncertainty of ±0.45 with a ±0.12 contribution from the theory uncertainties, dominated by the uncertainty on the nominal ggF background.
- If instead, we assign a 100% (rather than 20-30%) uncertainty to the ggF background expected in the VBF phase space, then the signal theory uncertainty increases by ~ a factor of 2, while the total uncertainty increases only by 10%.
In conclusion, the results for VBF Higgs production are not affected much by possible large ggF theoretical uncertainties in VBF phase space, but they will be in the future unless experimental measurements directly constrain the theory (as has been shown for Z VBF production) and/or the theory itself improves.
Summary

• ATLAS and CMS are on track to improve the legacy measurements from LEP and TeVatron for some of the fundamental Standard Model parameters, such as $m_W$, $\sin^2\theta_W$ (and possibly $\Gamma_W$ and $m_Z$) thanks to the huge datasets provided by the LHC machine and to the extraordinary performance of the detectors. This in itself is a huge achievement!

• ATLAS and CMS are also on track to pursue the studies of the Higgs boson production and decay properties, patience is required here until as many Higgs bosons are recorded in each experiment as $Z$ bosons were recorded at 7 TeV six years ago.

• As for new physics, the decision here is in the hands of mother nature and even more patience may be required.
Back-up slides
Can we be reasonably certain that full calculation would fall within red bands below?
More importantly, how can we be sure that this would be the case after acceptance cuts, which eg for searches select only small fraction of events?
Measurement of W boson mass at hadron colliders

• This talk will provide an overview of the recently published measurement of $m_W$ by ATLAS, together with a comparison between the ATLAS and CMS experimental systematics based on Z events measured as if they were W decays

• First measurement of $m_W$ at the LHC: quick overview of results
• The main challenges at the LHC
  → historical interlude
• The modelling of $p_T^W$ and the issues related to using the Z as a reference
  → experimental interlude
• What next? Questions for theory

Important caveat: it is impossible to cover all the subtle points about measuring $m_W$ at the LHC (even in a 90’ seminar), so only a few topics will be covered here. See back-up slides for more details.
Lepton and event selection for measurement of $m_W$

Lepton selections
- Muons : $|\eta| < 2.4$; isolated (track-based)
- Electrons : $0 < |\eta| < 1.2$ or $1.8 < |\eta| < 2.4$; isolated

Kinematic requirements
- $p_T^l > 30$ GeV $\quad p_T^{\text{miss}} > 30$ GeV
- $m_T > 60$ GeV $\quad u_T < 30$ GeV

Measurement categories:

| $|\eta_\ell|$ range | 0 – 0.8 | 0.8 – 1.4 | 1.4 – 2.0 | 2.0 – 2.4 | Inclusive |
|-------------------|---------|-----------|-----------|-----------|-----------|
| $W^+ \rightarrow \mu^+\nu$ | 1 283 332 | 1 063 131 | 1 377 773 | 885 582 | 4 609 818 |
| $W^- \rightarrow \mu^-\bar{\nu}$ | 1 001 592 | 769 876 | 916 163 | 547 329 | 3 234 960 |

| $|\eta_\ell|$ range | 0 – 0.6 | 0.6 – 1.2 | 1.8 – 2.4 | Inclusive |
|-------------------|---------|-----------|-----------|-----------|
| $W^+ \rightarrow e^+\nu$ | 1 233 960 | 1 207 136 | 956 620 | 3 397 716 |
| $W^- \rightarrow e^-\bar{\nu}$ | 969 170 | 908 327 | 610 028 | 2 487 525 |

7.8 M events
5.9 M events
W-boson mass measurement at the LHC

A proton-proton collider is the most challenging environment to measure $m_W$, worse than $e^+e^-$ and also worse than proton-antiproton

In ppbar collisions, $W$ bosons are mostly produced in the same helicity state

In pp collisions, they are equally distributed between positive and negative helicity states

Further QCD complications:
- Heavy-flavour-initiated processes
- $W^+$, $W^-$ and $Z$ are produced by different light-flavour fractions
- Larger gluon-induced $W$ production

Large PDF-induced $W$-polarisation uncertainty affecting the lepton $p_T$ distribution

Very large $Z$ samples, available for detector calibration given the precisely known $Z$ mass $\rightarrow$ most of the measurement is then the transfer from $Z$ to $W$
PDF uncertainties in W mass measurement

In proton-antiproton collisions:
- Asymmetry of the W rapidity
- Same cross section for W^+ and W^-
- Valence-dominated production
- Very small ambiguity for the incoming partons: quark from proton, antiquark from antiproton
PDF uncertainties in $W$ mass measurement

In proton-proton collisions:
• Different cross section for $W^+$ and $W^-$
• Large ambiguity in the direction of the incoming quark
→ Will need to exploit difference between $W^+$ and $W^-$

https://arxiv.org/abs/1612.03016
Historical interlude: the 80’s in UA1/UA2 at the SppS
From the beginning, with the observation of two-jet dominance
and of $4 \ W \rightarrow \ e \nu$ and $8 \ Z \rightarrow \ e^+e^-$ decays

$$\sqrt{s} = 546 \ \text{GeV}, \ L \sim 10^{29} \ \text{cm}^{-2}\text{s}^{-1}$$

UA2 was perceived as large at the time:

♥ 10-12 institutes
♥ from 50 to 100 authors
♥ cost $\sim 10 \ \text{MCHF}$
♥ duration 1980 to 1990

Physics analysis was organised in two groups:

1. Electrons $\rightarrow$ electroweak
2. Jets $\rightarrow$ QCD

D. Froidevaux, CERN
Historical perspective: the 80’s in UA1/UA2 at the SppS

To the end, with first accurate measurements of the W/Z masses and the search for the top quark and for supersymmetry
Software design in UA2
Historical perspective: the 80’s in UA1/UA2 at the SppS

Software documentation in UA2
Historical perspective: the 80’s in UA1/UA2 at the SppS

First ever EW fits in UA2 before LEP turned on

From these events we measure the mass of the $Z^0$ boson to be:

$$M_Z = 91.9 \pm 1.3 \pm 1.4 \text{ GeV/c}^2$$

(2)

where the first error accounts for measurement errors and the second for the uncertainty on the overall energy scale.

The rms of this distribution is $2.6 \text{ GeV/c}^2$, consistent with the expected $Z^0$ width\(^{14}\) and with our experimental resolution of $\sim 3\%$.

Under the hypothesis of Breit-Wigner distribution we can place an upper limit on its full width

$$\Gamma < 11 \text{ GeV/c}^2 \quad (90\% \text{ CL})$$

(3)

corresponding to a maximum of $\sim 50$ different neutrino types in the universe\(^{15}\).

The standard SU(2) × U(1) electroweak model makes definite predictions on the $Z^0$ mass. Taking into account radiative corrections to $\alpha$ one finds\(^{14}\)

$$M_Z = 77 \rho^{-1/2} (\sin 2 \theta_W)^{-1} \text{ GeV/c}^2$$

(4)

where $\theta_W$ is the renormalised weak mixing angle defined by modified minimal subtraction, and $\rho$ is a parameter which is unity in the minimal model.

Assuming $\rho = 1$ we find

$$\sin^2 \theta_W = 0.227 \pm 0.009$$

(5)

However, we can also use the preliminary value of the W mass found in this experiment\(^{16}\)

$$M_W = 81.0 \pm 2.5 \pm 1.3 \text{ GeV/c}^2.$$ Using the formula\(^{14}\)

$$M_W = 38.5 (\sin \theta_W)^{-1} \text{ GeV/c}^2$$

(6)

we find $\sin^2 \theta_W = 0.226 \pm 0.014$, and using also Eq. (4) and our experimental value of $M_Z$ we obtain

$$\rho = 1.004 \pm 0.052$$

(7)
Most important results from 1987-1990 campaign with UA2:

- Precise measurement of $m_W/m_Z$
- Direct limit on top-quark mass ($m_{\text{top}} < 60 \text{ GeV}$)

**Transverse mass distribution for electron-neutrino pairs**

\[
\frac{m_W}{m_Z} = 0.8813 \pm 0.0036 \pm 0.0019
\]

Using the precise measurement of $m_Z$ (LEP):

\[
m_W = 80.35 \pm 0.33 \pm 0.17 \text{ GeV}
\]

Indirect limits on top-quark mass in the context of the Standard Model:

\[
m_{\text{top}} = 160^{+50}_{-60} \text{ GeV}
\]

(four years before the discovery of the top quark at Fermilab)
Historical perspective: first run at 7 TeV in 2010

First W/Z events seen in April-May 2010 were very exciting!
The measurement of $m_W$ at the LHC is extremely challenging and prone to many potential biases due to QCD effects.

These affect all aspects of the measurement: detector calibration, transfer of theory predictions tuned to data from $Z$ to $W$, PDF uncertainties, $W$ polarisation, modelling of $p_T^W$.

Need to design the measurement to be “as waterproof as possible” from the point of view of detector calibration and physics modelling.

At the same time, the challenge makes the measurement hugely interesting, and provides a great occasion to improve the understanding of the detector performance and of QCD beyond that achieved by any other measurement or search at the LHC.
Transverse momentum distribution

- Theoretically more advanced calculations were also attempted
  - DYRES (and other resummation codes: ResBos, CuTe)
  - Powheg MiNLO + Pythia8
- All predict a significantly harder $p_T^W$ spectrum for given $p_T^Z$ distribution:

  - This behaviour is disfavoured by data (see later); predictions discarded for now. As a result, no explicit uncertainty from missing fixed-order terms at $O(\alpha_s^2)$, but use data to place an upper bound on this effect.
Summary of QCD predictions and uncertainties

- **Baseline**
  - $d\sigma/dy, A_i(p_T,y)$: DYNNLO+CT10nnlo (fixed-order)
  - At given $y$, $d\sigma/dp_T$ is predicted using Pythia8 AZ

- **Uncertainties**
  - CT10nnlo uncertainties (synchronised in DYNNLO and Pythia) + envelope comparing CT10 to CT14 and MMHT. Strong anti-correlation of uncertainties for $W^+$ and $W^-$!
  - AZ tune uncertainty; parton shower PDF and factorization scale; heavy-quark mass effects
  - $A_i$ uncertainties from Z data; envelope for A2 discrepancy

<table>
<thead>
<tr>
<th>W-boson charge</th>
<th>$W^+$</th>
<th>$W^-$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic distribution</td>
<td>$p_T^\ell$</td>
<td>$m_T$</td>
<td>$p_T^\ell$</td>
</tr>
<tr>
<td>$\delta m_W$ [MeV]</td>
<td>13.1</td>
<td>14.9</td>
<td>12.0</td>
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<td>Fixed-order PDF uncertainty</td>
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<td>3.4</td>
<td>3.0</td>
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<td>AZ tune</td>
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<td>Charm-quark mass</td>
<td>5.0</td>
<td>6.9</td>
<td>5.0</td>
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<td>Parton shower $\mu_F$ with heavy-flavour decorrelation</td>
<td>3.6</td>
<td>4.0</td>
<td>2.6</td>
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<tr>
<td>Parton shower PDF uncertainty</td>
<td>5.8</td>
<td>5.3</td>
<td>5.8</td>
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<tr>
<td>Angular coefficients</td>
<td>15.9</td>
<td>18.1</td>
<td>14.8</td>
</tr>
</tbody>
</table>
Summary of QCD predictions and uncertainties

\[ \frac{d\sigma}{dp_1 dp_2} = \left( \frac{d\sigma(m)}{dm} \right) \left[ \frac{d\sigma(y)}{dy} \right] \left[ \frac{d\sigma(p_T, y)}{dp_T dy} \left( \frac{d\sigma(y)}{dy} \right)^{-1} \right] \left[ 1 + \cos^2 \theta + \sum_{i=0}^{7} A_i(p_T, y) P_i(\cos \theta, \phi) \right] \]

- **Baseline**
  - \( d\sigma/dy, A_i(p_T, y) \) : DYNNLO+CT10nnlo (fixed-order)
  - At given \( y \), \( d\sigma/dp_T \) is predicted using Pythia8 AZ

![Graph](image-url)
Measurement of angular coefficients in $Z(W)$ decays to leptons

What is measured?

Primary: Eight $A_i(p_T^Z)$
Secondary: Eight $A_i(p_T^Z, y^Z)$
... Integrated over $m^Z$

$$\frac{d^5\sigma}{dp_T^Z dy^Z dm^Z d\cos \theta d\phi} = \frac{3}{16\pi} \frac{d^3\sigma^{U+L}}{dp_T^Z dy^Z dm^Z} \times \{ (1 + \cos^2 \theta) + 1/2 A_0 (1 - 3 \cos^2 \theta) + A_1 \sin 2\theta \cos \phi \\
+ 1/2 A_2 \sin^2 \theta \cos 2\phi + A_3 \sin \theta \cos \phi + A_4 \cos \theta \\
+ A_5 \sin^2 \theta \sin 2\phi + A_6 \sin 2\theta \sin \phi + A_7 \sin \theta \sin \phi \}.$$
Measurement of angular coefficients in Z(W) decays to leptons

Comparisons to theory

- **$A_0$, $A_0 - A_2$**
  - Powheg completely mismodels $A_0$ (important for $m_W$ discussion)
  - Related to implementation of Sudakov form factors and cutoffs in $b$-quark mass
  - Fixed in Powheg+MiNLO
  - $A_0 - A_2$ (Lam-Tung) sensitive to higher order corrections
  - First ever observation of significant deviation from NNLO predictions
Prospects on measurements at 8 and 13 TeV

• Larger data samples allow (in principle) more precise calibrations of detector response, provided material, alignment, geometry, etc… are all well understood.

• However, these larger data samples come with higher pile-up, which deteriorates recoil resolution. This will compromise the $m_T$ measurement, and reduce our ability to control and validate modelling uncertainties through the recoil distributions.

• In order to benefit from the larger 8 and 13 TeV data samples, it is therefore crucial to improve the methodology used for the recoil calibration in order to mitigate pile-up effects as much as possible while preserving small systematics from extrapolation from Z to W.

• The single lepton triggers are also a concern, especially for the electrons, since the trigger turn-on curve extends in 2016 into the fit region, while this was not the case in 2011. The improved phase-1 calorimeter trigger for run 3 should solve this important concern for the run-2 data.
Prospects on physics modelling

• PDF uncertainties can be reduced by the inclusion in the fit of precise W, Z inclusive rapidity measurements with ATLAS/CMS run-1 data.

• $p_T^W$ uncertainties can be reduced by using higher-order predictions based on analytical resummation, and with fits to Z $p_T$ 8 TeV measurement, which is more precise than the 7 TeV measurement, and has low- and high-mass distributions which can constrain heavy-flavour-initiated production.

• Much work was already done on the two points above, and there are plans to update the 7 TeV ATLAS measurement with improved physics modelling tools and fits.

• Thanks to the precise measurements at 8 TeV, uncertainties on the angular coefficients are currently not a limiting factor. In the future, they can be reduced with more precise predictions and more precise measurements.

• For the physics modelling, ultimately, we need to perform precise and direct measurements of the W $p_T$, angular coefficients, and underlying event, either with dedicated low pile-up runs, or with new methodologies. This will remove the most difficult source of systematic uncertainty, which otherwise will remain a source of endless debate.
Questions to theory colleagues

• Can one really extrapolate from Z to W assuming certain cancellations of theory uncertainties (in particular the dreaded scale variations, where resummation needs to be added to the usual suspects)?

• Why are NNLO+NNLL calculations worse than simple parton shower when compared to data? Could this be due to oversimplication of ansatz assuming a sophisticated calculation of a single observable provides more accuracy than a model generating event-by-event kinematics of multiple soft gluon emission? Or is this mostly due an as yet poorly understood treatment of heavy flavours? These play an important role at the LHC, and the contributions are not at all the same for W (charm, strangeness) and Z (bottom).

• How can one solve the bottlenecks in the theory used by PDF fits? Scale variations, parton shower effects, etc

• Is there a way to extrapolate the discrepancies seen between NNLO QCD and data for the Z angular coefficients to the W boson? Presumably experiments need to do the W measurements themselves but the accuracy will always be worse than for Z bosons.
Control of $p_T^W$ modelling: $u_{\parallel}^e$, $u_{\parallel}^\mu$

**Muons**

**Electrons**
## Muon calibration: performance and results

![Graphs showing data, signal, and background distributions for muon calibration.](image)

| \(|\eta|\) range | Kinematic distribution | \(\delta m_W\) [MeV] |
|------------------|------------------------|----------------------|
| \([0.0, 0.8]\)   | \(p_T\) \(m_T\) \(p_T\) \(m_T\) \(p_T\) \(m_T\) \(p_T\) \(m_T\) \(p_T\) \(m_T\) | Combined \(p_T\) \(m_T\) |
| \([0.8, 1.4]\)   | \(8.9\) \(9.3\) \(14.2\) \(15.6\) | \(8.4\) \(8.8\) |
| \([1.4, 2.0]\)   | \(27.4\) \(29.2\) | \(111.0\) \(115.4\) |
| \([2.0, 2.4]\)   | \(111.0\) \(115.4\) | \(8.4\) \(8.8\) |
| **Combined**     | **8.4** \(8.8\) | **8.4** \(8.8\) |

- **Momentum scale**
- **Momentum resolution**
- **Sagitta bias**
- **Reconstruction and isolation efficiencies**
- **Trigger efficiency**

**Total**

<table>
<thead>
<tr>
<th>(p_T)</th>
<th>(m_T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.4</td>
<td>11.4</td>
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<td>16.9</td>
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<td>30.4</td>
<td>31.0</td>
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<tr>
<td>112.0</td>
<td>116.1</td>
</tr>
<tr>
<td>9.8</td>
<td>9.7</td>
</tr>
</tbody>
</table>
Electron calibration: performance and results

| $|\eta^\ell|$ range | [0.0, 0.6] | [0.6, 1.2] | [1.82, 2.4] | Combined |
|-------------------|-----------|-----------|------------|-----------|
| Kinematic distribution | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ | $p_T^\ell$ | $m_T$ |
| $\delta m_W$ [MeV] | | | | | | |
| Energy scale | 10.4 | 10.3 | 10.8 | 10.1 | 16.1 | 17.1 | 8.1 | 8.0 |
| Energy resolution | 5.0 | 6.0 | 7.3 | 6.7 | 10.4 | 15.5 | 3.5 | 5.5 |
| Energy linearity | 2.2 | 4.2 | 5.8 | 8.9 | 8.6 | 10.6 | 3.4 | 5.5 |
| Energy tails | 2.3 | 3.3 | 2.3 | 3.3 | 2.3 | 3.3 | 2.3 | 3.3 |
| Reconstruction efficiency | 10.5 | 8.8 | 9.9 | 7.8 | 14.5 | 11.0 | 7.2 | 6.0 |
| Identification efficiency | 10.4 | 7.7 | 11.7 | 8.8 | 16.7 | 12.1 | 7.3 | 5.6 |
| Trigger and isolation efficiencies | 0.2 | 0.5 | 0.3 | 0.5 | 2.0 | 2.2 | 0.8 | 0.9 |
| Charge mis-measurement | 0.2 | 0.2 | 0.2 | 0.2 | 1.5 | 1.5 | 0.1 | 0.1 |
| Total | 19.0 | 17.5 | 21.1 | 19.4 | 30.7 | 30.5 | 14.2 | 14.3 |
Recoil calibration: performance and results

![Graphs showing data and predictions for Z and W events.](image)

<table>
<thead>
<tr>
<th>Kinematic distribution</th>
<th>$W^+$</th>
<th>$W^-$</th>
<th>Combined</th>
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<tbody>
<tr>
<td>$\delta m_W$ [MeV]</td>
<td>$p_T^\ell$</td>
<td>$m_T$</td>
<td>$p_T^\ell$</td>
</tr>
<tr>
<td>$\langle \mu \rangle$ scale factor</td>
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<td>1.0</td>
<td>0.2</td>
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<tr>
<td>$\Sigma E_T$ correction</td>
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<td>12.2</td>
<td>1.1</td>
</tr>
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<td>Residual corrections (statistics)</td>
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<td>2.7</td>
<td>2.0</td>
</tr>
<tr>
<td>Residual corrections (interpolation)</td>
<td>1.4</td>
<td>3.1</td>
<td>1.4</td>
</tr>
<tr>
<td>Residual corrections ($Z \to W$ extrapolation)</td>
<td>0.2</td>
<td>5.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>2.6</td>
<td>14.2</td>
<td>2.7</td>
</tr>
</tbody>
</table>
Cross-checks with Z events

Z boson rapidity and $p_T$ distributions:

Good agreement. Error bars are statistical only.
Results are consistent with $m_Z$ within experimental uncertainties. Fitted values are a bit low on average, but they are all from the same events.
Post-fit distributions: lepton $p_T$

Electrons

Muons

Predictions set to the result of the combined $m_W$ fit to all distributions
Post-fit distributions: transverse mass $m_T$

**Electrons**

**Muons**

Predictions set to the result of the combined $m_W$ fit to all distributions
Fit results for $m_W$

Compatibility tests, performed before unblinding

$$\chi^2 / n_{dof} = 29 / 27$$
SM prediction for $m_W$ vs $m_t$,
assuming $m_H = 125.09 \pm 0.24$ GeV
$m_t = 172.84 \pm 0.70$ GeV

SM prediction for $m_W$, assuming
$m_H = 125.09 \pm 0.24$ GeV
$m_t = 172.84 \pm 0.70$ GeV
Other production channels such as $bbH$, $gg$ to $ZH$, $tH$ are included resp. in $ggF$, $ZH$ and $ttH$ since they are not accessible as specific channels (nor will they be in run 2).

With much larger statistics, it would be interesting to measure specifically the signal strength or effective coupling squared for any of the above $i$ to $H$ to $f$ processes, where $i$ denotes the production and $f$ denotes the decay.
Many different final discriminant distributions combined

Purity varies between categories (especially for production modes)

A total of $O(100)$ categories for each experiment are combined

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{ \sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}^f \right\},$$

$\mathcal{L}$: integrated luminosity, $A$: acceptance, $E$: efficiency
For this analysis, we merge together low stats bins to 9 production bins (this will be described later!):
Coupling measurements: how is this done?

<table>
<thead>
<tr>
<th>Channel</th>
<th>References for individual publications</th>
<th>ATLAS</th>
<th>CMS</th>
<th>Signal strength [μ]</th>
<th>Signal significance [σ]</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>ATLAS</td>
<td>CMS</td>
<td></td>
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<tr>
<td>$H \to γγ$</td>
<td>[51]</td>
<td>$1.15_{−0.25}^{+0.27}$</td>
<td>$1.12_{−0.23}^{+0.24}$</td>
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<tr>
<td></td>
<td></td>
<td>($0.24$)</td>
<td>($0.24$)</td>
<td>($0.22$)</td>
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</tr>
<tr>
<td>$H \to ZZ \to 4\ell$</td>
<td>[53]</td>
<td>$1.51_{−0.34}^{+0.39}$</td>
<td>$1.05_{−0.27}^{+0.32}$</td>
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<td>7.0</td>
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<tr>
<td></td>
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<td>($0.27$)</td>
<td>($0.31$)</td>
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<td>$H \to WW$</td>
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<td>$0.91_{−0.21}^{+0.24}$</td>
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<td>4.8</td>
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<td>($0.20$)</td>
<td>($0.23$)</td>
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<tr>
<td>$H \to ττ$</td>
<td>[58]</td>
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<td>($0.33$)</td>
<td>($0.31$)</td>
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<tr>
<td>$H \to bb$</td>
<td>[38]</td>
<td>$0.62_{−0.36}^{+0.37}$</td>
<td>$0.81_{−0.42}^{+0.45}$</td>
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<td></td>
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<td>($±3.6$)</td>
<td>($±3.5$)</td>
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<tr>
<td>$ttH$ production</td>
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<td>$2.9_{−0.9}^{+1.0}$</td>
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<td>3.6</td>
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<tr>
<td></td>
<td></td>
<td>($−0.66$)</td>
<td>($+0.88$)</td>
<td>($+0.80$)</td>
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</tbody>
</table>

(Section 5.2)
• Coupling measurements: how is this done?

- Purity varies between categories (especially for production modes)
- A total of O(100) categories for each experiment are combined

\[ n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{ \sigma_i \times A^f_i(k) \times \varepsilon^f_i(k) \times \text{BR}^f \right\} , \]

\[ = \mathcal{L}(k) \times \sum_i \sum_f \mu_i \mu^f \left\{ \sigma^\text{SM}_i \times A^f_i(k) \times \varepsilon^f_i(k) \times \text{BR}^f_{\text{SM}} \right\} \]

L: integrated luminosity, A: acceptance, E: efficiency

- Cannot measure \( \sigma_i, \text{BR}^f \) or \( \mu_i, \mu_f \) at the same time, need to measure ratios or make additional assumptions
- Measuring ratios is done through a generic parameterisation of the above yields or of \( \sigma_i \times \text{BR}^f \), such that there is no dependence on the inclusive theory cross section uncertainties (signal strength measurements) or such that one tests directly for deviations of the couplings of the Higgs boson from their SM values (\( \kappa \) framework)
- Additional assumptions in the narrow-width approximation allow measurements of production or decay signal strengths
- Additional assumptions about BSM physics (for example \( \text{BR}_{\text{BSM}} = 0 \)) allow measurements of absolute coupling strengths

\[ \Gamma_H = \frac{\kappa_H \cdot \Gamma^\text{SM}_H}{1 - \text{BR}_{\text{BSM}}} . \]
Simplified Template Cross Sections (STXS)

- **main ggF contributions**
- **VBF**
- **VH-leptonic**
- **VH-hadronic**

- $p_T^H, p_T^{j1} > 200$ GeV BSM

For this analysis, we merge together low stats bins to 9 production bins (this will be described later!):

- 5 ggF, 1 VBF, 1 VH-lep, 1 ttH, 1 BSM