Precision tests of the SM at the LHC with the ATLAS and CMS detectors

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for the ATLAS and CMS Collaborations

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9-14 June 2019
Introduction

• Precise EW measurements + theoretical calculations successfully predicted top quark & Higgs boson masses

• Provide critical test of SM consistency and constrain allowed New Physics parameters

• EW gauge & Higgs sector described by 4 parameters: $\alpha, G_F, m_Z, m_H$

• Other parameters predicted by theory $\rightarrow$ over-constrained

• Ultimate aim: direct precision measurements of EW mixing angle ($\pm 10^{-4}$) and W boson mass ($\pm 10$ MeV), competitive with global fit uncertainties

• Need excellent understanding of experimental and pdf uncertainties

• Rich program of Z/W measurements: $Z \rightarrow ll$ angular coefficients, $A_{fb}$, W charge asymmetry, $Z/W p_T$, differential cross-sections…

• Gauge boson self-interactions studied via EW $Z/W+jj$ and $VV(V)$ production (not discussed today)

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EW Fit | World average
--- | ---
$\sin^2 \theta_W$ | $0.23153 \pm 0.00006 \quad 0.23152 \pm 0.00016$
$m_W [GeV]$ | $80.354 \pm 0.007 \quad 80.379 \pm 0.013$
On the menu today

- Top mass
- W mass
- Effective weak mixing angle, $\sin^2\theta_{\text{eff}}$
- Higgs mass (➔ next talk)

- Differential Z/W xsections
- Z angular coefficients, $A_i$
- Z forward-backward asymmetry, $A_{FB}$
- W charge asymmetry

Selection from a rich harvest
The experiments

G. Pásztor: SM precision tests
At a glance...

Standard Model Production Cross Section Measurements

**ATLAS** Preliminary
Run 1,2 $\sqrt{s} =$ 5,7,8,13 TeV

- **LHC pp $\sqrt{s} =$ 5 TeV**
  - Data 0.025 fb$^{-1}$

- **LHC pp $\sqrt{s} =$ 7 TeV**
  - Data 4.5 - 4.9 fb$^{-1}$

- **LHC pp $\sqrt{s} =$ 8 TeV**
  - Data 20.2 - 20.3 fb$^{-1}$

- **LHC pp $\sqrt{s} =$ 13 TeV**
  - Data 3.2 - 79.8 fb$^{-1}$

Tihany, 10 June 2019

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Top quark and W boson mass
Top quark mass

- SM self-consistency
  - Corrections to EW parameters
- Stability of EW vacuum
- Direct measurement from reconstructed decay products → compare to MC → interpret as pole mass
- Indirect measurements from cross-section or differential distributions → either pole mass or running mass from MS scheme

**ATLAS Preliminary**

May 2019

<table>
<thead>
<tr>
<th>ATLAS: Preliminary</th>
<th>Top quark pole mass determinations compared to direct measurement</th>
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<tbody>
<tr>
<td>NNLO+NNLL: $t\bar{t}$ inclusive PDF4LHC, 7 TeV 2014</td>
<td>171.4 ± 2.6</td>
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<tr>
<td>NNLO+NNLL: $t\bar{t}$ inclusive PDF4LHC, 8 TeV 2014</td>
<td>174.1 ± 2.7</td>
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<tr>
<td>NNLO+NNLL: $t\bar{t}$ inclusive PDF4LHC, 7-8 TeV 2014</td>
<td>172.9 ± 2.6</td>
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<tr>
<td>NLO: $t\bar{t}+1$ jet, 7 TeV 2015</td>
<td>173.7$^{+2.3}_{-2.1}$</td>
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<tr>
<td>NLO: $t\bar{t}$ leptonic differential, 8 TeV 2017</td>
<td>173.2 ± 1.6</td>
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<tr>
<td>NLO: $t\bar{t}+1$ jet, 8 TeV 2019</td>
<td>171.1$^{+1.2}_{-1.1}$</td>
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<tr>
<td>Direct reconstruction 2018</td>
<td>$\delta m_t / m_t = 0.28%$</td>
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<td>172.69 ± 0.48</td>
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**CMS**

May 2019

<table>
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<tr>
<th>CMS Run 1 legacy</th>
<th>PRD 93 (2016) 072004</th>
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<tr>
<td>Dilepton</td>
<td>172.82 ± 0.19 ± 1.22 GeV</td>
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<td>All-jets</td>
<td>172.32 ± 0.25 ± 0.59 GeV</td>
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<tr>
<td>Lepton+jets</td>
<td>172.35 ± 0.16 ± 0.48 GeV</td>
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**ATL-PHYS-PUB-2019-020**

$|m_{pole}|$ [GeV] vs $m_t$ [GeV]
W boson mass

- Based on 4.5 fb\(^{-1}\) W → ev, \(\mu\nu\) data @ 7 TeV
- Experimental challenge: lepton and hadronic recoil calibration
- Multijet background from template fits
- Dominant uncertainty from physics modelling
- Template fit to \(p_T^l\) and \(m_T\)
  - \(p_T^l\) sensitive to \(p_T^W\) modelling
  - \(m_T\) sensitive to hadronic recoil \(u_T\)
- Templates from Powheg+Pythia8, reweighted to best theoretical model
  - \(d\sigma/d\eta\), W polarisation from DYNNLO
  - \(d\sigma/dp_T\) from Pythia8, AZ tune
- Z events heavily used for calibration and validation
**W boson mass**

\[ m_W = 80370 \pm 7(\text{stat.}) \pm 11(\text{exp. syst.}) \pm 14 (\text{mod. syst.}) \text{ MeV} = 80370 \pm 19 \text{ MeV} \]

**QCD uncertainty:** \( p_T^W \) distribution, extrapolation from Z to W; aim direct measurement at low PU

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**Combined categories**

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<tbody>
<tr>
<td>( m_{T-p_T} ), ( W^\pm, e-\mu )</td>
<td>80369.5</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>
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</table>
W boson mass at HL-LHC with upgraded detector

- Optimal MET reconstruction
  - Low detector occupancy
  - Extended pseudorapidity coverage
- Improved PDF
  - Possibility of new DIS data
Weak mixing angle (Z angular coefficients and $A_{FB}$)
Lepton ($\ell^-$) angular distributions in boson ($\ell\ell$) restframe ($\theta^*, \varphi^*$: polar, azimuth $\varphi$)

\[
\frac{d^2\sigma}{d\cos\theta^* d\varphi^*} \propto \left[ (1 + \cos^2 \theta^*) + A_0 \frac{1}{2} (1 - 3 \cos^2 \theta^*) + A_1 \sin(2\theta^*) \cos \varphi^* + A_2 \frac{1}{2} \sin^2 \theta^* \cos(2\varphi^*) + A_3 \sin \theta^* \cos \varphi^* + A_4 \cos \theta^* + A_5 \sin^2 \theta^* \sin(2\varphi^*) + A_6 \sin(2\theta^*) \sin \varphi^* + A_7 \sin \theta^* \sin \varphi^* \right].
\]

Forward – backward asymmetry due to $A_4$ term:

\[
A_{FB} = \frac{3}{8} A_4 = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}
\]

with $\sigma_{F(B)}$ total xsec for $\cos \theta > 0$ ($\cos \theta < 0$)

- Related to V-A structure of $\ell$ couplings
- $A_{FB}$ depends on $m_{\ell\ell}$, $\sin^2 \theta_W$, quark flavour
- Precise measurement around $m_Z \rightarrow \sin^2 \theta_W$, $u, d$ weak couplings
- Deviation from SM could arise from new neutral gauge bosons, quark-lepton compositeness, SUSY particles, extra dimensions…
- Collins-Soper (CS) frame to reduce uncertainty due to the incoming quarks’ $p_T$
Weak mixing angle and forward-backward asymmetry

- HO corrections modify the LO relations
- Introduce effective mixing angle: $v_f/a_f = 1 - 4|Q_f| \sin^2 \theta_{\text{eff}}^f$
- Fit measured $A_{FB}$
- $\sin^2 \theta_{\text{eff}}^\ell = 0.23101 \pm 0.00036 \text{ (stat)} \pm 0.00018 \text{ (syst)} \pm 0.00016 \text{ (theo)} \pm 0.00031 \text{ (pdf)}$
  
  $= 0.23101 \pm 0.00053$

\[
\sin^2 \theta_{\text{eff}}^f = k_l \sin^2 \theta_w \\
\text{from HO calculations}
\]

\[
\]

\[
m_{ee} \text{ (GeV)}
\]

\[
m_{ll} \text{ (GeV)}
\]

\[
\]

\[
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\]
Weak mixing angle and $A_4$ angular coefficient

- Fold $P_i(\cos \theta_{CS}, \phi_{CS})$ angular distributions to detector level
- Fit reconstructed $\cos \theta_{CS}$, $\phi_{CS}$, $m_\perp$, $y_\perp$ distributions in born-level $m_\perp$, $y_\perp$ bins
- Extract $A_4$ in full decay lepton phase space, dominated by statistical uncertainties
- Infer $\sin^2 \theta^f_{\text{eff}}$, dominated by QCD and PDF uncertainties
- $\sin^2 \theta^l_{\text{eff}} = 0.23140 \pm 0.00021 \text{ (stat.)} \pm 0.00024 \text{ (PDF)} \pm 0.00016 \text{ (syst.)}$

\[ = 0.23140 \pm 0.00036 \]

- LEP-1 and SLD: $Z$-pole
- LEP-1 and SLD: $A_{FB}^{0, b}$
- SLD: $A_1$
- Tevatron
- LHCb: 7+8 TeV
- CMS: 8 TeV
- ATLAS: 7 TeV
- ATLAS: $ee_{CC} + \mu\mu_{CC}$
- ATLAS: $ee_{CF}$
- ATLAS: 8 TeV
$Z/\gamma^*$ and W differential cross-sections
Drell-Yan cross-section measurements

- Test of higher-order EW and QCD predictions
- Sensitive to resummation techniques
- Constrains parton distribution functions
- Needed for precise EW measurements \((m_W, \sin^2\theta_W)\)
  - \(m_W\) from fit to lepton \(p_T\) distribution
  - Precise \(Z\) measurements to obtain prediction for \(W\) \(p_T\)

\[
\frac{d\sigma(W)}{dp_T} = \left[ \frac{d\sigma(W)}{dp_T} \right]_{\text{theory}} \times \left[ \frac{d\sigma(Z)}{dp_T} \right]_{\text{measured}}
\]

For \(Z \rightarrow \mu\mu\) (ee):
- \(p_T^l > 22\) (30), 10 GeV, \(|\eta^l| < 2.4\) (2.5)
- Corrected for FSR (dressed leptons)
- Good agreement with FEWZ (NNLO QCD + NLO EW) with NNPDF3.0
- At high \(m_\|\) photon-induced contributions tested with FEWZ + LUXqed

\(\gamma^*/Z \rightarrow e^+e^-, \mu^+\mu^-\)

CMS-PAS-SMP-17-010
Z boson $p_T @ 13$ TeV

- Fiducial selection (leptons after FSR)
- Normalised xsection: <0.5% uncertainty for $p_T^{ll} < 50$ GeV
- Compared to fixed-order, resummed and parton shower predictions
  - FO: Z at NNLO QCD (FEWZ) and Z+j at NNLO QCD (ZjNNLO). LO EW
  - Resummed (NNLL): Geneva, Resbos
  - PS: MadGraph5_aMC@NLO (0,1,2j at NLO, FxFx), Powheg (NLO), Powheg+MiNLO (0,1j at NLO)
Z boson rapidity and $\phi^* \sim p_T^Z / m_\ell$
W differential cross-sections and charge asymmetry @ 8 TeV

- Proton’s uud valence quark content → more $W^+$ produce $u\bar{d} \rightarrow W^+ \hspace{1em} d\bar{u} \rightarrow W^-$

- Charge asymmetry: 

\[ A(\eta) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \]

\[ \sigma^\pm = \frac{d\sigma}{d\eta}(pp \rightarrow W^\pm + X \rightarrow \mu^\pm \nu + X) \]

- $A$ constrains $u(x)/d(x)$ pdf ratio for Bjorken $x = 0.001 - 0.1$
- Luminosity uncertainty (1.9%) dominates, sum of other sources $\sim 1$-1.5%
- Compared to DYNLO with different PDF sets
- With $\sim 1\%$ precision can discriminate among PDF sets

**Fiducial selection** (Born-level):
- $p_T^\mu, p_T^\nu > 25$ GeV
- $|\eta^\mu| < 2.4$
- $m_T > 40$ GeV
Luminosity calibration

- Dominant systematic error for precision cross-section measurements with well-controlled systematics (leptonic Z, W, top decays): \( N_{\text{Events}} = \sigma \int L \)
- Preliminary calibration in Run 2: 2-2.5% / year
- 1% would make it subdominant in most cases
- Need to keep in mind for Phase 2 detector upgrades
Total production cross-section measurements

\[ \frac{pp}{X} \rightarrow X \]

\[ \frac{pp}{W} \rightarrow W \]

\[ \frac{pp}{Z/\gamma^*} \rightarrow Z/\gamma^* \]

+ new W, Z results at 2.76 TeV

\[ \frac{pp}{t\bar{t}} \rightarrow t\bar{t} \]

\[ \frac{pp}{tq} \rightarrow tq \]

\[ \frac{pp}{H} \rightarrow H \]

\[ \frac{pp}{WW} \rightarrow WW \]

\[ \frac{pp}{WZ} \rightarrow WZ \]

\[ \frac{pp}{ZZ} \rightarrow ZZ \]

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

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ATL-PHYS-PUB-2019-010

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7 TeV, 20 \( \mu \text{b}^{-1} \), Nat. Commun. 2, 463 (2011)
8 TeV, 500 \( \mu \text{b}^{-1} \), Phys. Lett. B761 158 (2016)
13 TeV, 60 \( \mu \text{b}^{-1} \), Phys. Rev. Lett. 117 182002 (2016)

7 TeV, 25 \( \mu \text{b}^{-1} \), Eur. Phys. J. C79 (2019) 128 (for Z/W)
7 TeV, 4.6 \( \mu \text{b}^{-1} \), Eur. Phys. J. C77 (2017) 367 (for Z/W)
8 TeV, 20.2 \( \mu \text{b}^{-1} \), JHEP 02, 117 (2017) (for Z)
13 TeV, 81 \( \mu \text{b}^{-1} \), PLB 759 (2016) 601 (for W)
13 TeV, 3.2 \( \mu \text{b}^{-1} \), JHEP 02, 117 (2017) (for Z)

7 TeV, 4.6 \( \mu \text{b}^{-1} \), Eur. Phys. J. C74:3109 (2014)
8 TeV, 20.3 \( \mu \text{b}^{-1} \), Eur. Phys. J. C74:3109 (2014)
13 TeV, 3.2 \( \mu \text{b}^{-1} \), Phys. Lett. B 761 (2016)

7 TeV, 4.6 \( \mu \text{b}^{-1} \), PRD 90, 112006 (2014)
8 TeV, 20.3 \( \mu \text{b}^{-1} \), Eur. Phys. J. C 77 (2017) 531
13 TeV, 3.2 \( \mu \text{b}^{-1} \), JHEP 1704 (2017) 086

7 TeV, 4.5 \( \mu \text{b}^{-1} \), Eur. Phys. J. C76 (2016) 6
8 TeV, 20.3 \( \mu \text{b}^{-1} \), Eur. Phys. J. C76 (2016) 6
13 TeV, 36.1 \( \mu \text{b}^{-1} \), Phys. Lett. B 786 (2018) 114

7 TeV, 4.6 \( \mu \text{b}^{-1} \), PRD 87, 112001 (2013)
8 TeV, 20.3 \( \mu \text{b}^{-1} \), JHEP 09 029 (2016)
13 TeV, 3.2 \( \mu \text{b}^{-1} \), Phys. Lett. B 773 (2017) 354

7 TeV, 4.6 \( \mu \text{b}^{-1} \), Eur. Phys. J. C (2012) 72:2173
8 TeV, 20.3 \( \mu \text{b}^{-1} \), PRD 93, 092004 (2016)
13 TeV, 36.1 \( \mu \text{b}^{-1} \), arXiv:1902.05759

7 TeV, 4.6 \( \mu \text{b}^{-1} \), JHEP 03, 128 (2013)
8 TeV, 20.3 \( \mu \text{b}^{-1} \), JHEP 01, 099 (2017)
13 TeV, 36.1 \( \mu \text{b}^{-1} \), Phys. Rev. D 97 (2018) 032005
Summary

- LHC became a precision machine
  - $\sigma(m_W) = 18$ MeV @ 7 TeV ATLAS
  - $\sigma(\sin^2\theta_{\text{eff}}) \sim 0.0004$ @ 8 TeV ATLAS, CMS
- Individual experiments approach precision of LEP/SLD and Tevatron combined
- PDF uncertainty important
- Many results on diboson production, VBF, VBS (not covered here)
  - Constraints on triple and quartic gauge couplings

http://gfitter.desy.de/Standard_Model/CMSPublic/PhysicsResultsCombined

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