Prospects for precise electroweak physics at LHC

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At tree level in the SM 3 parameters are sufficient to predict the EW sector: $G_F$, $\alpha$, $\sin(\Theta_W)$.

Precision EW physics look for deviations from this, introduced via:

- **Loops:**

\[ M_{W,\text{tree}}^2 = \pi \sqrt{2} \frac{\alpha}{G_F} \left( 1 - \sqrt{1 - \frac{4\pi\alpha}{\sqrt{2}G_FM_Z^2}} \right)^{-1} \]

\[ G_F = \frac{\pi\alpha}{\sqrt{2M_W^2\sin^2\theta_W}} \cdot \frac{1}{1 - \Delta r} \]

\[ \Delta r = \Delta r^t + \Delta r^H \]

\[ \Delta r^t \approx \frac{3G_Fm_t^2}{8\sqrt{2}\pi^2} \left( \frac{\cos^2\theta_W}{\sin^2\theta_W} \right) \]

\[ \Delta r^H \approx \frac{11G_FM_W^2}{24\sqrt{2}\pi^2} \left( \ln \left( \frac{M_H^2}{M_W^2} \right) - \frac{5}{6} \right) \]

- **Couplings** that differ from standard model predictions. E.g.

Check SM & search for new physics via modifications of $M_W$, $m_t$ and $M_H$ relations & couplings.
Electroweak characteristics at LHC

In general:

- Cross-sections increase with $\sqrt{s}$
- Expected instantaneous luminosity $10^{33}$ cm$^{-2}$s$^{-1}$
  (for most electroweak measurements)
- Many analyses benefit from large statistics (14 TeV):
  - **Top** - Cross section: ~800 pb.
    → 0.8 M events in 1 fb$^{-1}$.
    → 7.5 K (5 K) semileptonic for 1 b-tag (2 b-tag).
  - **Single Top** – Cross sections 1/3 of ttbar
  - **W** - NNLO Cross section: 40 nb (e+\(\mu\))
    → ~6 M reconstructed events in 1 fb$^{-1}$(e+\(\mu\)).
  - **DiBoson** Cross sections in the range 15-450 pb
    → 1–1000 observed events in 1 fb$^{-1}$.
  - **Forward-Backward asymmetry**
    → Based on Z sample ~200 K selected in 1 fb$^{-1}$.
top pair: production & decay

Production:

- All hadronic
  - Huge background
  - Complicated combinatorics
  - 350,000 events in 1 fb⁻¹

- All leptonic
  - Low background
  - Simple combinatorics
  - 50,000 events in 1 fb⁻¹

- Semi leptonic
  - Comprimise
  - 250,000 events in 1 fb⁻¹

- e+jets 15%
- μ+jets 15%
- τ+jets 15%
- all jets 44%
- dileptons 9%
Selecting jets for the W hypothesis:
After requiring $|M_{jj} - M_W| < 30\text{GeV}$, minimize \textit{in situ}:

$$
\chi^2 = \frac{(M_{jj}(\alpha_{E_1}, \alpha_{E_2}) - M_{PDG}^W)^2}{(\Gamma_{PDG}^W)^2} + \frac{(E_{j1}(1 - \alpha_{E_1}))^2}{\sigma_1^2} + \frac{(E_{j2}(1 - \alpha_{E_2}))^2}{\sigma_2^2}
$$

In each event:
- Additional cut: $M_{jj}$ in mass window of $\pm 2\Gamma_{MW} = 4.2\text{GeV}$
- Fitted with Gaussian + 3$^{\text{rd}}$ order pol.
- Result: $M_{t^\text{op}} = 175 \pm 0.2_{(\text{stat})} \text{GeV} \ (1\text{fb}^{-1})$.
- Precision given by jet scale accuracy

### Light jet energy scale
0.2 GeV/%

### b jet energy scale
0.7 GeV/%

### ISR/FSR
\approx 0.3 GeV

### b quark fragmentation
\leq 0.1 GeV

### Background
negligible

### Method
0.1 - 0.2 GeV

Result: $M_{t^\text{op}} = 175 \pm 0.2_{(\text{stat})} \pm 1_{(\text{sys})} \text{GeV}$ with 1 fb$^{-1}$.

### Systematic uncertainty

#### Hadronic top decay
(avoid $\nu$-reco)
top mass: leptonic and hadronic channels

**Leptonic channel**
- Kinematical reconstruction
- Clean signal: S/B=12
- Main systematics: JES, Kinematical hypothesis

**Hadronic channel**
- Using likelihood techniques on masses and angles to define pairing.
- Main systematics: QCD background, JES, ISR/FSR

Result with 1fb$^{-1}$:

**Leptonic channel**

$M_{\text{top}} = 178.5 \pm 1.5^{\text{(stat)}} \pm 4.2^{\text{(sys)}} \text{GeV}$

**Hadronic channel**

$M_{\text{top}} = 175.0 \pm 0.6^{\text{(stat)}} \pm 4.2^{\text{(sys)}} \text{GeV}$
W mass: Characteristics at LHC

### Production:

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+\nu_e$</td>
<td>$10.75 \pm 0.13%$</td>
</tr>
<tr>
<td>$\mu^+\nu_\mu$</td>
<td>$10.57 \pm 0.15%$</td>
</tr>
<tr>
<td>$\tau^+\nu_\tau$</td>
<td>$11.25 \pm 0.20%$</td>
</tr>
<tr>
<td>$q\bar{q}'$</td>
<td>$67.60 \pm 0.27%$</td>
</tr>
</tbody>
</table>

For precision measurements only the $W \rightarrow e\nu$ & $W \rightarrow \mu\nu$ channels are useful.

### Observables: lepton $p_t$ & $M_t$. Systematics differ

### Precision measurements requires extremely good measurement/knowledge of:

**Systematics:**
- Lepton energy scale & linearity
- Missing Et calibration
- Backgrounds

**Theoretical sources:**
- PDF
- FSR (effects the lepton directly)
- $y(W)$, $p_t(W)$, and ISR (effects the lepton though the W)

**Enviromental sources:**
- Underlying event
- Pileup
- Beam crossing angle

Most calibration performed on well-known Z events
**W mass: Template fitting**

**GENERAL IDEA:**

![A set of lepton pt distributions corresponding to different input values of MW.](image)

**Step 1:** Validate method of handling det. effects
- Fit $E_{\text{rec}}/E_{\text{truth}}$
- Smear truth according to fit parameters
- Check that smeared truth matches reco

**Step 2:** Calibrate on Z events
- Scale
- Technique works √

**Step 3:** Transport to W events

15pb⁻¹: $M_W = 80.466 \pm 110\text{(stat)} \pm 114\text{(exp)} \pm 25\text{(PDF)}$ MeV
W mass: Long term perspectives

Best fit corresponds to: \( \alpha = 0.9958 \pm 0.0003 \), \( \sigma = 0.0207 \pm 0.0003 \) for 200pb\(^{-1}\)

Since the impact on the W mass measurement goes like:

\[
\frac{\partial M_W}{\partial \text{rel} \alpha_L} \sim 800 \text{ MeV/\%} \quad \frac{\partial M_W}{\partial \text{rel} \sigma_L} = 0.8 \text{ MeV/\%}
\]

the error estimated on the W mass from scale and resolution uncertainty is (at 10fb\(^{-1}\)):

\[
\delta M(\alpha) = \frac{\delta \alpha}{\alpha} \cdot \frac{\partial M}{\partial \text{rel} \alpha} \sqrt{\frac{\chi^2_{\text{sample}}}{\chi^2_{\text{final}}}} = 0.0003 \cdot 0.9952 \cdot 800 \text{ MeV/\%} \cdot \sqrt{\frac{200 \text{ pb}^{-1}}{10 \text{ fb}^{-1}}} \approx 4 \text{ MeV}
\]

\[
\delta M(\sigma) = \frac{\delta \sigma}{\sigma} \cdot \frac{\partial M}{\partial \text{rel} \sigma} \sqrt{\frac{\chi^2_{\text{sample}}}{\chi^2_{\text{final}}}} = 0.0003 \cdot 0.0207 \cdot 0.8 \text{ MeV/\%} \cdot \sqrt{\frac{200 \text{ pb}^{-1}}{10 \text{ fb}^{-1}}} \approx 1 \text{ MeV}
\]

**LONG TERM PERSPECTIVES:** Energy dependent lepton scale and resolution

- Scale

- Resolution

Seems possible to get a relative precision of \( 2 \times 10^{-5} \) for the scale and \( 2 \times 10^{-3} \) for resolution.
**W mass: Breakdown of systematics (10 fb$^{-1}$)**

<table>
<thead>
<tr>
<th>Sys unc.</th>
<th>Method of evaluation</th>
<th>Error [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\not{q}$W rapidity</td>
<td>Using the strong correlation between $Z$ and W rapidity + LHC improvement</td>
<td>1</td>
</tr>
<tr>
<td>W width</td>
<td>Templates study + Assume W width uncertainty reduced with LHC</td>
<td>0.5</td>
</tr>
<tr>
<td>W $p_t$</td>
<td>From $Z$ (+Drell Yan), exploiting the lever arm induced by the large $Z$ width.</td>
<td>3</td>
</tr>
<tr>
<td>QED</td>
<td>PHOTOS study + Assume existence of high precision event generators</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Scale &amp; lin.</td>
<td>From energy dependent calibration using $Z$ events</td>
<td>4</td>
</tr>
<tr>
<td>Resolution</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Tag and probe</td>
<td>4.5(e), 1(\mu)</td>
</tr>
<tr>
<td>$W \rightarrow \tau \nu$</td>
<td>Template</td>
<td>2</td>
</tr>
<tr>
<td>$Z \rightarrow \ell(\ell)$</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>$Z \rightarrow \tau \tau$</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>QCD</td>
<td>Tevatron extrapolation</td>
<td>0.5</td>
</tr>
<tr>
<td>Pileup&amp;U.E.</td>
<td>Assuming 2% precision in hadronic energy flow</td>
<td>1(e), 0(\mu)</td>
</tr>
<tr>
<td>BeamCross.</td>
<td>Generator study</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>~7(e), 6(\mu)</td>
</tr>
</tbody>
</table>
Triple gauge bosons couplings (TGC): Characteristics at LHC

- Cross sections typically 10 times higher than Tevatron
  ⇒ tens to hundreds events in the first fb⁻¹.
- Trilinear gauge boson couplings measured:
  - Directly from ZW, WW & ZZ cross sections
  - Boson $p_t$
  - Production angle
- Charged TGC: WWZ & WWγ: allowed in SM
  ⇒ Study WW ($\sigma=112$pb) & WZ ($\sigma=48$pb) processes
- Neutral TGC: ZZZ, ZZγ & Zγγ: forbidden in SM tree level
  ⇒ Study ZZ processes
- Modelled by 5 independent CP conserving couplings that don't break gauge invariance
- Complementary to direct searches for new physics
  In fact background to Higgs and beyond SM physics
Triple gauge bosons: WZ selection

Z selection
- Reconstruct ee or μμ pair with: 50 GeV < M_{ll} < 120 GeV
- Veto additional Z candidates

W reconstruction
- Associate 3rd lepton the W decay
- Require neutrino indirectly so that M_T(W) > 50 GeV

5σ observation with less than 350pb⁻¹.
Expect observation of all di-boson processes with less than 1fb⁻¹.
Forward-backward asymmetry

In pp→Z/\gamma→ee events, electroweak neutral current violates parity and leads to an asymmetry in the polar emission angle of the electron in the ee-restframe:

$$
\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta} = \frac{3}{8} N_c [1 + \frac{4}{3} A_{FB} \cos \theta + \cos^2 \theta]
$$

Can be used to determine $\sin^2 \Theta_{eff}$. Important for SM fit.

Measurement assumption: the quark directions equals that of the Z boost.

Counting problem

Prospects of measuring $\sin^2 \Theta_{eff}$ with a stat precision of $10^{-4}$ with 100fb$^{-1}$

Comparable systematic error dominated by PDF uncertainty ($\sim 2 \cdot 10^{-4}$)
Conclusions

- At LHC the challenge of precision electroweak measurements is a challenge of reducing syst.
- In the absence of unforeseen complications:
  - $\delta M_{\text{top}} = 1$ GeV & $\delta M_W = 7$ MeV seem reachable with $10\,\text{fb}^{-1}$ (after many years of hard work)
  - Measure anomalous TGC deviation from zero at the percent level
  - $\sin^2 \Theta_{\text{eff}}$ measured at the $10^{-4}$ level
  - Direct measurement of $V_{tb}$ at the ~few % level.
- The electroweak section of the Standard Model will be even more constrained than presently.
- Useful not only for cross checking the model, but also to constrain extensions to the Standard Model
Backup slides: references

- **W mass measurement**
  - ATLAS CSC note: CERN-OPEN-2008-020
  - CMS Note 2006-061
  - ATL-PHY-PUB-2006-007

- **Top mass measurement**
  - ATLAS CSC note: CERN-OPEN-2008-020
  - CMS Note 2006-066
  - CMS Note 2006-077

- **Forward backward asymmetry**
  - ATLAS CSC note: CERN-OPEN-2008-020

- **Triple gauge couplings**
  - ATLAS CSC note: CERN-OPEN-2008-020
  - CMS PAS EWK-08-003

- **Single Top**
  - ATLAS CSC note: CERN-OPEN-2008-020
Backup slides: detectors

B field: 2 T solenoid + 4T toroid

- Inner tracker: $|\eta|$ coverage
  - $\sigma(p_T)/p_T$ at $p_T=100$ GeV
    - 2.5
    - 3.8%

- EM calorimeter: $|\eta|$ coverage
  - $\sigma(E)/E$
    - 3.2
    - 9%/√E + 0.5%

- HAD calorimeter: $|\eta|$ coverage
  - $\sigma(E)/E$ (EM+HAD combined)
    - 4.9
    - 70%/√E + 3.3%

- Muon system: $|\eta|$ coverage
  - $\sigma(p_T)/p_T$ at $p_T=1$ TeV
    - 2.7
    - 7%

3.8 T solenoid

- Inner tracker: $|\eta|$ coverage
  - 2.5
  - 1.5%

- EM calorimeter: $|\eta|$ coverage
  - $\sigma(E)/E$
    - 3.0
    - 3%/√E + 0.25%

- HAD calorimeter: $|\eta|$ coverage
  - $\sigma(E)/E$ (EM+HAD combined)
    - 5.2
    - 70%/√E + 8%

- Muon system: $|\eta|$ coverage
  - 2.4
  - 5%
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Systematic Uncertainty</th>
<th>Effect on $M_{\text{top}}$</th>
<th>Method of Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light jet energy scale</td>
<td>0.2 GeV/%</td>
<td>Multiplying jet momenta by scaling factors ⇒ linear dependence of $M_{\text{top}}$. Reduced due to the W mass constraint. Prospects of 1% precision with 1 fb$^{-1}$</td>
</tr>
<tr>
<td>b jet energy scale</td>
<td>0.7 GeV/%</td>
<td>Same procedure. Will ultimately be determined from Z+jets, but in the beginning from the light JES + MC correction modelling the difference in the scales.</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>≈0.3 GeV</td>
<td>Estimated from shifts in $M_{\text{top}}$ in AcerMC ttbar samples with varying ISR, FSR parameters as well as $\Lambda$(QCD).</td>
</tr>
<tr>
<td>b quark fragmentation</td>
<td>≤0.1 GeV</td>
<td>Varieng the Peterson parameter within its uncertainty</td>
</tr>
<tr>
<td>Background</td>
<td>negligible</td>
<td>Shape will be measured from data – variations of the size have no notable effect.</td>
</tr>
</tbody>
</table>
W mass: Impact of scale and resolution

Figure 5: Left: bias on $m_W$, $m_W^{\text{fit}} - m_W^{\text{true}}$, as a function of the relative bias on $\alpha$, $\delta \alpha = (\alpha^{\text{fit}} - \alpha^{\text{true}})/\alpha^{\text{true}}$. Right: bias on $m_W$ as function of the resolution bias, $\delta \sigma = (\sigma^{\text{fit}} - \sigma^{\text{true}})/\sigma^{\text{true}}$. A linear dependence is observed in each case, with $\partial m_W/\partial_{\text{rel}} \alpha = 800 \text{ MeV}/\%$ and $\partial m_W/\partial_{\text{rel}} \sigma = 0.8 \text{ MeV}/\%$. 
Differentiate in energy (i.e. consider lepton energy bins i, j).

Fit for every pair configuration (i,j):

- \( M_{ij}^2 = E_i E_j (1 - \cos \theta) \); \( (1 + \beta_{ij})^2 M_{ij}^2 = (1 + \alpha_i) E_i (1 + \alpha_j) E_j (1 - \cos \theta) \)
- \( \Rightarrow \beta_{ij} \sim (\alpha_i + \alpha_j)/2 \); \( \sigma_{ij}^2/M^2 = \sigma_i^2/E_i^2 + \sigma_j^2/E_j^2 \); write this for all \( (i,j) \)
- and solve the linear system (least squares) to get the \( \alpha_i \) and \( \sigma_i^2 \)
Templates from Z events: Scaled observable method
- using lepton $p_t$ as observable
- Remove randomly 1 e from $Z \rightarrow ee$
- Rescale the observable: $X_V = p_t / M_V$
- Weight by $R(V) = \frac{d\sigma^W}{dX_W} / \frac{d\sigma^Z}{dX_Z}$, $X_V = \frac{p_t^e}{M_V}$, $V = W, Z$
- Which depends on theory, selection and det effects
- Apply W selection on Z events using the scale.
  e.g. Missing $E_t > 29 \text{ GeV} \times \frac{M_W}{M_Z}$

Results: $\pm 40^{(\text{stat})} \pm 40^{(\text{exp})} \pm 40^{(\text{theory})} \text{ MeV with } 1\text{fb}^{-1}$

Templates from Z events: Morphing
- Using $M_t$ as observable
- Scaling the Z event rather than the observable

Results: $\pm 40^{(\text{stat})} \pm 64^{(\text{exp})} \pm 20^{(\text{theory})} \text{ MeV with } 1\text{fb}^{-1}$

Template fitting – calibrate using Z templates: next slides
Limit on anomalous TGC (95%CL) for WWZ assuming $\Delta \kappa_Z = g_Z^1$. Systematics errors included.
With 2M \((10^{23} \text{ cm}^2 \text{s}^{-1} \text{ at } 14\text{TeV})\) events produced per year, measurements of the individual contributions to the single top cross section seem feasible.

Comparison with SM predictions provides a crucial test (sensitive to W' or charged Higgs).

Direct measurement of \(V_{tb}\) at the \(~\text{few } \%\) level.

Complex analysis: Huge \(t\bar{t}b\) and \(W+\text{jets}\) bkg. Require good knowledge of JES and well-understood b-tagging tools.

\(\Rightarrow\) Use likelihood or BDT techniques

3\(\sigma\) evidence achievable with a few \(\text{fb}^{-1}\) and 20\(\%\) precision on cross section with 10\(\text{fb}^{-1}\).