Electroweak physics measurements at the LHC for the Atlas and CMS collaborations

Mass of the top quark
Mass of the W boson
**Introduction**

- In SM, masses of top quark, W boson and Higgs boson are related through radiative corrections:

- Precise measurements of $M_{\text{top}}$ and $M_{W}$ allow
  - Consistency check of SM
  - Give hints of new physics
  - Constraint the mass of SM Higgs boson

- Up to date values:
  - $M_{\text{top}} = 172.6 \pm 0.8 \text{ (stat.) } \pm 1.1 \text{ (syst.) GeV}$
  - $M_{W} = 80.398 \pm 0.025 \text{ GeV}$
  - $M_{H} = 87^{+36}_{-27} \text{ GeV} \& M_{H} < 160 (190) \text{ GeV}$

- LHC = 10 days $\Leftrightarrow 1 \text{ fb}^{-1}$, 1 year $\Leftrightarrow 10 \text{ fb}^{-1}$

  Challenge = **systematics uncertainties**

- Outline
  - Top quark mass measurements at LHC
  - W boson mass measurement at LHC
  - Conclusion
Top pairs at LHC

High center of mass energy
14 TeV
High cross section
833 pb (NLO)
High luminosity
$10^{33}$ to $10^{34}$ cm$^2$s$^{-1}$
A lot of events
800 000 top pairs (1 fb$^{-1}$)

But very complex events

Many different objects:
• Light jets
• $b$ jets
• Missing $E_t$
• Leptons

Many sources of uncertainty:
• Jet Energy Scale (JES)
• ISR/FSR
• Backgrounds
• Combinatorial background
• $b$ fragmentation…
Top pairs: decays

Top Pair Branching Fractions

- "alljets" 44%
- \(\tau+\text{jets}\) 15%
- \(\mu+\text{jets}\) 15%
- \(e+\text{jets}\) 15%

**Low background**
- Low combinatorics
- Small BR
- \(\approx 50,000\) evts for 1 fb\(^{-1}\)
- Final state difficult to reconstruct

**Enormous background**
- Huge combinatorics
- 10 ways to combine 6 jets
- High BR
- \(\approx 350,000\) for 1 fb\(^{-1}\)
- Possible to reconstruct the whole event

**Good compromise**
- \(\approx 250,000\) evts for 1 fb\(^{-1}\)
Top mass: semileptonic channel (1/5)

250 000 events for 1 fb$^{-1}$ with $S/B \approx 10^{-5}$ prior to any cut and selection

- Event selection
  - One and only one isolated lepton inside acceptance ($|\eta| < 2.5$, $p_T > 20$ GeV ($\mu$) or $p_T > 25$ GeV (e))
  - Missing $E_T > 20$ GeV
  - At least 4 jets with $p_T > 40$ GeV
  - Among them exactly 2 which are b-tagged

- Backgrounds
  - Single top and ttbar fully hadronic (isolation) & dileptonic (1 lepton only)
  - W+jets (b-tagging) and Z+jets
  - Di bosons (low cross section)
  - QCD (missing $E_T$, lepton $p_T$)

- After lepton cuts QCD negligible and top all jets reduced by 2/3
Top mass: semileptonic channel (2/5)

- $W$ hadronic side, choice and *in situ* rescaling
  After selection of pairs in a mass range
determined on 2 light jets events

\[
\chi^2 = \frac{(M_{jj} - M_W^{PDG})^2}{\Gamma_W^2} + \frac{(E_{j1}(1 - \alpha_1))^2}{\sigma_1^2} + \frac{(E_{j2}(1 - \alpha_2))^2}{\sigma_2^2}
\]

- Efficiency: $\varepsilon = 1.93\%$

- Pairing:
  Several methods: here $b$ closest to $W$

- Gaussian fit + polynomial

$M_{\text{top}} = 175.0 \pm 0.2$ GeV
$\sigma_{\text{top}} = 11.6 \pm 0.2$ GeV
Top mass: semileptonic channel (3/5)

Systematics

<table>
<thead>
<tr>
<th>Systematic uncertainty sources</th>
<th>Effect on $m_{\text{top}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light jet energy scale</td>
<td>0.2 GeV/%</td>
</tr>
<tr>
<td>b-jet energy scale</td>
<td>0.7 GeV/%</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>$\approx 0.3$ GeV</td>
</tr>
<tr>
<td>b fragmentation</td>
<td>$\leq 0.1$ GeV</td>
</tr>
<tr>
<td>Background</td>
<td>negligible</td>
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</tbody>
</table>

Most important source of uncertainty

- Light JES (reduced thanks to in situ rescaling, if it’s not done the slope $\Rightarrow 1$ GeV/%)
- b-jets energy scale

JES studies:

- This analysis: JES taken from rec./sim. differences
- Template method comparing reconstructed $jj$ invariant masses with smeared $W$s
  - Systematic uncertainties (combinatorial, template ingredients, top mass..) all below 0.5% $\Rightarrow 1\%$ for 1 fb$^{-1}$
- This analysis: b-jet energy scale obtained from MC correction factors

\[ M_{\text{top}} = 175.0 \pm 0.2 \text{ (stat.)} \pm 1 \text{ (syst.) GeV} \]
Top mass: semileptonic channel (4/5)

- Alternative analysis based on likelihoods:
  - Probability from selection \( P_{\text{sign}} \)
  - Probability from jet combination \( P_{\text{comb}} \)
  - Probability from kinematic fit forcing \( M_W \)
    - Fitting \( M_{\text{top}} \), probability from \( \chi^2 \)
    - Forcing \( M_{\text{top}} \), probability from mass scan

\[
\chi^2 \left( \{ \vec{p}_j \}, m_i \right) = \left( \frac{m_i - m_i^{\text{fit}}}{\sigma_{m_i}^{\text{fit}}} \right)^2
\]

Mass scan gives (1 fb\(^{-1}\), only \( \mu \) channel)

\( M_{\text{top}} = 172.42 \pm 0.66 \text{ GeV (stat)} \pm 1.13 \text{ (syst)} \)

Largest: JES for b jets
Top mass:
dileptonic & fully hadronic channels (1 fb⁻¹)

<table>
<thead>
<tr>
<th>Starting from</th>
<th>S/B ≈ 5 10⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection</td>
<td>S/B ≈ 7</td>
</tr>
<tr>
<td>Kinematical reconstruction of the event and pairing with likelihood (660 evts)</td>
<td>S/B ≈ 12 ε = 1.2%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Starting from</th>
<th>S/B &lt; 10⁻⁶</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection</td>
<td>S/B ≈ 1/9 ε = 2.7%</td>
</tr>
<tr>
<td>Likelihood on masses and angles to perform the pairing + top choice</td>
<td></td>
</tr>
</tbody>
</table>

\[ M_{\text{top}} = 178.5 \pm 1.5 \text{ (stat)} \pm 4.2 \text{ (syst)} \]

Syst.: JES, kinematical hypothesis

\[ M_{\text{top}} = 175 \pm 0.6 \text{ (stat.)} \pm 4.2 \text{ (syst.)} \]

Syst.: QCD background, JES, ISR/FSR
W mass at LHC

- NNLO cross section 20.5 nb per lepton channel
  \( W \rightarrow \ell \nu \) 3 000 000 evts selected per channel in 1 fb\(^{-1}\)
  10 times less Z i.e. 300 000 evts selected per channel

- 2 observables sensitive to the W mass:
  \( m_T \) and \( p_t(\text{lepton}) \)

- Template method

  A reconstructed distribution: lepton \( p_t \)

  A set of distributions characterized by a scale factor \( \alpha \)

  \( \chi^2 \) test as a function of \( \alpha \)

Simple and efficient but crucially relies on control of any effect distorting the test distribution
Effects distorting the test distributions:

- Experimental sources of uncertainty:
  - Lepton energy scale and linearity
  - Lepton energy resolution
  - Non gaussian tails of the energy distributions
  - Recoil scale and resolution
  - Reconstruction efficiency

- Theoretical sources:
  - Direct effect on lepton $p_t$: FSR
  - Effect on lepton $p_t$ via the $W$ distribution $y(W)$ et $p_t(W)$ : $\Gamma_W$, PDF, ISR

- Environmental sources:
  - Backgrounds, underlying event, pileup, beam crossing angle

To control these effects in the templates, rely on our great knowledge of the Z physics, either by creating the templates from the Z events or by calibrating the effects on the Z events.
Creation of templates from Z events

**Scaled observable method**
with lepton $p_t$ distribution in $W \rightarrow e\nu$ for 1 fb$^{-1}$

- Randomly remove 1 e in $Z \rightarrow ee$
- Rescaling of the observable $X_V = \frac{p_t}{M_V}$
- Weight by $R(X)$

$$R(X) = \frac{d\sigma^W}{dX_W} / \frac{d\sigma^Z}{dX_Z}, \quad X_V = \frac{p_t}{M_V}, \quad V = W, Z$$

$R(X)$ depend on theory and sel. & det. effects

- Apply $W$ selection on $Z$ events with scale e.g. Missing $E_T > 29$ GeV $\times \frac{M_W}{M_Z}$

Most common uncertainties cancel

**Morphing**
scaling the $Z$ event instead of scaling the observable
With $m_T$ $W \rightarrow \mu\nu$ for 1 fb$^{-1}$

**40 (stat.) $\oplus$ 40 (exp.) $\oplus$ 40 (theo.) MeV**

Dominated by lepton energy scale linearity

**40 (stat.) $\oplus$ 64 (exp.) $\oplus$ 20 (theo.) MeV**

Dominated by $E_T$ scale

N. Besson CEA Saclay
Calibrate templates with Z constraints

- First step: validate the modelisation of detector effects

Parameters we need to control:
energy scale $\alpha$, resolution $\sigma$, tails $\tau$

$30 < p_t < 40$
$0.4 < |\eta| < 0.5$ (a), $0.8 < |\eta| < 0.9$ (b),
$1.3 < |\eta| < 1.4$ (c), $1.9 < |\eta| < 2.0$ (d)

Smear the leptons according to shapes fitted on $E_{\text{rec}}/E_{\text{true}}$ distributions in bins in $|\eta|$ and $p_t$.

- Example: very early data $15 \text{ pb}^{-1}$, $W \rightarrow e\nu$, $p_t$ lepton
Selection and backgrounds
  - High $p_t$ isolated lepton, $\not{E}_T$, had. recoil $\varepsilon = 22\%$
  - Backgrounds $W$ to $\tau$, $Z$ to leptons, jet events
    - After selection 2.2% of evts are background
      mainly $W \rightarrow \tau\nu$

$\alpha = 0.9995 \pm 0.0012$
Second step: calibrate the parameters on $Z \rightarrow ee$ events

- Non gaussian tails
- Scale and resolution

With the low statistics, only average scale and resolution can be derived with a template method.
Third step: validate we can « transport » calibration from Z events to W events

Results 15pb⁻¹
- With $p_T$ lepton (electron channel)
  $\delta M_W = 110 \text{ (stat)} \oplus 114 \text{ (exp.)} \oplus 25 \text{ (PDF) MeV}$
  main systematic uncertainty: energy scale
- With $m_T$ (muon channel)
  $\delta M_W = 60 \text{ (stat)} \oplus 230 \text{ (exp.)} \oplus 25 \text{ (PDF) MeV}$
  main systematic uncertainty: recoil scale
Long term perspectives

- Extensive systematic studies. Examples:
  - Experimental sources of uncertainty:
    - Lepton energy scale and resolution, linearity
  - Theoretical sources:
    - $W$ distributions $y(W)$ and $p_t(W)$

- First example: energy dependent scale and resolution

For 10 fb⁻¹ control up to $2 \times 10^{-4}$: $\delta M_W (\alpha) \approx 4$ MeV and $\delta M_W (\sigma) \approx 1$ MeV
Second example: W distributions

- Transverse momentum
  Contribution from intrinsic $p_t$ of partons and ISR
  Final states $l^+l^-$ $p_t(l^+l^-)$ versus $m(l^+l^-)$ with a huge lever arm

- Rapidity
  Contribution from PDF
  For the moment
  $\delta M_W \approx 25$ MeV

  Strong correlation between $y_W$ and $y_Z$ with respect to PDF variations

  With 10 fb$^{-1}$ improvement by a factor 20
  $\Rightarrow \delta M_W \approx 3$ MeV
<table>
<thead>
<tr>
<th>Source</th>
<th>effect</th>
<th>$\delta m_W$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical model</td>
<td>$\Gamma_W$</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>$\gamma_W$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$\rho_{tw}$</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>QED radiation</td>
<td>$&lt;1$</td>
</tr>
<tr>
<td>Lepton measurement</td>
<td>linearity and scale</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>resolution</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>efficiency</td>
<td>4.5 ($e$); $&lt;1$ ($\mu$)</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>$W \rightarrow \tau\nu$</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>$Z \rightarrow l$ $(l)$</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>$Z \rightarrow \tau\tau$</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>jet events</td>
<td>0.5</td>
</tr>
<tr>
<td>Pile-up and UE</td>
<td></td>
<td>$&lt;1$ ($e$); $\sim0$ ($\mu$)</td>
</tr>
<tr>
<td>Beam crossing angle</td>
<td></td>
<td>$&lt;0.1$</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td></td>
<td>$\sim7$ ($e$); $6$ ($\mu$)</td>
</tr>
</tbody>
</table>

One channel and one study (can be done for $m_T$)
Conclusion

- The challenge will be clearly to reduce systematic uncertainties
- $\delta M_{\text{top}} \approx 1\text{GeV}$ and $\delta M_{\text{W}} \approx 7\text{ MeV}$ seem within reach
- With 10 fb$^{-1}$ and a lot of hard work we might go to

- Really eager to have data to work on!

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References

ATLAS

ATL-PHYS-PUB-2006-007
Determination of the absolute lepton scale using Z boson decays. Application to the measurement of $M_W$

Forthcoming “CSC” notes
Top quark mass measurement with ATLAS
Measurement of $W$ mass at ATLAS with early data

To be published
Re-evaluation of the LHC potential for the measurement of $M_W$

CMS

CMS note 2006/066
Top quark mass measurement in single leptonic ttbar events

CMS note 2006/077
Measurement of top-pair cross section and top-quark mass in the di-lepton and full-hadronic channels with CMS

CMS note 2006/061
Prospects for the precision measurement of the $W$ mass with the CMS detector at the LHC

LEPEWWG
http://lepewwg.web.cern.ch/LEPEWWG/