SM physics at the LHC: relevance, challenges and prospects

Département de physique nucléaire et corpusculaire,
Université de Genève
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Michelangelo L. Mangano
TH Unit, Physics Department, CERN
michelangelo.mangano@cern.ch
Key outcomes of 3 yrs at the LHC: 1

1: The Higgs signal has been detected through sharp mass peaks in several channels.

II: Its production and decay rates are consistent with the SM expectation, at the +/- 20% level. ....
Key outcomes of 3 yrs at the LHC: I

I: The Higgs signal has been detected through sharp mass peaks in several channels

II: Its production and decay rates are consistent with the SM expectation, at the $\pm 20\%$ level ......

.... how far can we push the accuracy of these tests, and probe the mechanism of EWSB ?
Key outcomes of 3 yrs at the LHC: 2

No sign of BSM, in all places the experiments have looked .....
Key outcomes of 3 yrs at the LHC: 2

No sign of BSM, in all places the experiments have looked ..... 

.... how to access regions of parameters of BSM models where the sensitivity is low?
Key outcomes of 3 yrs at the LHC: 3

The theoretical description of high-$Q^2$ processes at the LHC is very good ....
Key outcomes of 3 yrs at the LHC: 3

The theoretical description of high-$Q^2$ processes at the LHC is very good ....

.... but must and can be improved
SM studies at the LHC:

- improve and validate our ability to model final states and make predictions, increasing the potential for precise measurements and for more sensitive BSM searches

- provide opportunities for the exploration of new and complex dynamical regimes of the SM, both in the QCD and EW sectors

- feed back into the HEP community valuable and often unique knowledge
LHCf: Very forward energy flow

"Measurement of zero degree single photon energy spectra for $\sqrt{s} = 7$ TeV proton-proton collisions at LHC"
PLB 703 (2011) 128
Impact on modeling of HECR showers: first assessment

$\pi^0$ spectrum and air shower

$\pi^0$ spectrum at $E_{\text{lab}} = 10^{17}\text{eV}$

- Artificial modification of meson spectra (in agreement with differences between models)
- $\Delta<X_{\text{max}}(p-Fe)> \sim 100 \text{ g/cm}^2$
- Effect to air shower $\sim 30 \text{ g/cm}^2$

Alessia Tricomi  
Results from LHCf  

Longitudinal AS development

$<X_{\text{max}}>_\text{EPOSv1.99} = 718 \text{ g/cm}^2$

$<X_{\text{max}}>_\text{QGSJET01} = 689 \text{ g/cm}^2$

AUGER, ICRC 2011
Open challenge:

To prove that the underlying mechanisms of multiparticle production at high energy are understood, in addition to being simply properly modeled.
Back to large $Q^2$ ....
Current challenges for the field: precision

Ex: Future precision in the determination of Higgs coupling ratios

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<thead>
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<tbody>
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<td>[6,9]</td>
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<td>[2,5]</td>
<td>[2,7]</td>
<td>2,3</td>
<td>N/a</td>
<td>[7,10]</td>
<td>[5,6]</td>
<td>[6,7]</td>
<td>[6,9]</td>
<td>[29,30]</td>
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<tr>
<td></td>
<td>CMS</td>
<td>[2,5]</td>
<td>[2,5]</td>
<td>2,3</td>
<td>[3,5]</td>
<td>[2,4]</td>
<td>[3,5]</td>
<td>[6,8]</td>
<td>[7,8]</td>
<td>[12,12]</td>
<td></td>
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</tr>
</tbody>
</table>

Table 1. Estimated precision on the measurements of ratios of Higgs boson couplings. These values are obtained at √s = 14 TeV using an integrated dataset of 300 fb⁻¹ at LHC, and 3000 fb⁻¹ at HL-LHC. Numbers in brackets are % uncertainties on couplings for [no theory uncertainty, current theory uncertainty] in the case of ATLAS and for [Scenario2, Scenario1] in the case of CMS.

CMS Scenario 1: same systematics as 2012 (TH and EXP)
CMS Scenario 2: half the TH syst, and scale with 1/sqrt(L) the EXP syst

Note: assume no invisible Higgs decay contributing to the Higgs width

Note: results of scenario 2 @ 3000/fb are overall as powerful as LC@500GeV !!
### Current challenges for the field: precision

#### Theoretical uncertainties on production rates (Higgs XS WG, arXiv:1101.0593)

<table>
<thead>
<tr>
<th>Process</th>
<th>$\delta$(pert. theory)</th>
<th>$\delta$(PDF, $\alpha_s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg\rightarrow H$</td>
<td>± 10 %</td>
<td>± 7%</td>
</tr>
<tr>
<td>VBF ($WW\rightarrow H$)</td>
<td>± 1 %</td>
<td>± 2%</td>
</tr>
<tr>
<td>$qq\rightarrow WH$</td>
<td>± 0.5 %</td>
<td>± 4%</td>
</tr>
<tr>
<td>$(qq,gg)\rightarrow ZH$</td>
<td>± 2 %</td>
<td>± 4%</td>
</tr>
<tr>
<td>$(qq,gg)\rightarrow ttH$</td>
<td>± 8 %</td>
<td>± 9%</td>
</tr>
</tbody>
</table>

**Improve with higher-loop calculations:**
- $gg\rightarrow H$ @ NNNLO
- $ttH$ @ NNLO

**Improve with dedicated QCD measurements, and appropriate calculations:**
Example: Large-pt production of gauge bosons as a probe of gluon PDF in the region of relevance to $gg \rightarrow H$ production

S.Malik and G.Watt, arXiv:1304.2424

⇒ excellent motivation to undertake the calculation of $d\sigma/dp_T(V)$ at NNLO !!
Current challenges for the field:
accurate description of final states

- to properly model experimental selection cuts
- to properly model the separation between signals and background
- to improve the sensitivity to rare and “stealthy” final states in BSM searches

Ex. jet veto efficiency, required to reduce bg’s to $H \rightarrow WW^*$

Banfi, Monni, Salam, Zanderighi, arXiv:1206.4998
Goals of the SM LHC programme

- Precise determination of fundamental SM parameters:
  - $m(\text{top}), m(W), \alpha_s, \sin^2\theta_W, \text{CKM}$
  - Higgs properties
- Determination of the PDFs
- Validation of the reliability/precision/uncertainties of the modeling of SM dynamics (QCD and EW), for applications to:
  - the measurements above
  - the search for new phenomena, through deviations from established SM behaviour

Means:

- Precise measurement of ancillary quantities, necessary to
  - improve the inputs of theory calculations
  - validate the theoretical precision and systematics
- This includes what may otherwise be considered as “and now what?” measurements, whose key purpose is to build confidence in the theoretical modeling, for applications to the precision physics programme and to the searches
Opportunities opened by LHC data

- High statistics and superior experimental precision
- Access to small rates:
  - rare final states (multijets, associated production of multiple EW and QCD objects)
  - high-energy final states (highest pt jets, highest mass DY, ....)
  - VBF final states
- EW radiative corrections:
  - impact on EW observables (V, VV production - V=W,Z)
  - impact on QCD observables (jet cross sections)
- New probes of PDFs:
  - large-x gluons (jet, top production)
  - heavy quarks (γQ, ZQ, WQ associated production)
- Correlations:
  - ratios of cross sections for different processes
  - ratios of cross sections at 7 vs 8 vs 14 TeV
Example: Jet cross section

Rates span 10 orders of magnitude!
Example: Jet cross section

Theory: absolute prediction for both shape and normalization

Agreement to within 20% (over 10 orders of magnitude!)
Residual discrepancy consistent with PDF and perturbative NLO uncertainties
Example: $Z + \text{jets}$

ATLAS

\[ \int dt \cdot d^2p_T \cdot d^2y \cdot d^2z = 4.6 \text{ fb} \]

\[ a_T, N_{\text{jet}} = 0.4 \]

\[ p_T > 30 \text{ GeV}, |y| < 4.4 \]

Data 2011 (56 = 7 \text{ TeV})

ALPGEN

SHERPA

MC@NLO

BLACKHAT + SHERPA

MC@NLO + SHERPA

MC@NLO + SHERPA
Example: Jet fragmentation function

ATLAS, arXiv:1109.5816

- jet shapes
- $pt_{rel}$ spectra
- $\langle N_{ch} \rangle$ and $z$ distributions,
- ....
Constraints on quark contact interactions

\[ \chi = \frac{1 + |\cos \theta^*|}{1 - |\cos \theta^*|} \]

Quarks appear pointlike even at the distances probed by the LHC
Inclusive jet cross section at NNLO


NNLO/NLO ~ 1.2

NNLO scale systematics ~ few % ...
- does this survive if $\mu_F \neq \mu_R$?

Notice that NNLO outside the NLO scale-variation band

At this level of precision, there are other things one should start considering.
E.g. non-perturbative systematics and EW corrections
Impact of EW radiative corrections, example:
Jet+MET spectrum from \((Z\rightarrow\nu\nu)+\text{jet}\): corrections due to pure EW and pure EM corrections

Unless EW corrections are included in the calculations, we might end up removing possible differences between data and QCD predictions for the \(Z\) pt spectrum by retuning the QCD MCs!

How does one convince himself that possible deviations of this size from the QCD expectation are indeed the result of EW corrections? E.g. compare \(Z\) pt, \(W\) pt and \(\gamma\) pt (different EW effects)

Denner, Dittmaier, Kasprzik, Mück, arxiv:1211.5078v2
$W$ production, in events with high-$E_T$ jets

- Substantial increase of $W$ production at large energy: over 10% of high-$E_T$ events have a $W$ or $Z$ in them!

- It would be interesting to go after these $W$ and $Z$s, and verify their production properties

- Dotdashes: $\sigma(jj)$ in the denominator replaced by $\sigma(jj, \text{no } gg \rightarrow gg)$
Multi-gauge boson production:

$\text{WWW} \rightarrow 3\text{lept's}$

$\sigma(W) = 100 \text{ nb}$

$\sigma(WW) = 50 \text{ pb}$ \hspace{1cm} $\sigma(WW) / \sigma(W) = 0.5 \times 10^{-3}$

$\sigma(WWWW) = 60 \text{ fb}$ \hspace{1cm} $\sigma(WWWW) / \sigma(WW) = 10^{-3}$

$\sigma(WWWW \rightarrow 3 \ell) = 0.7 \text{ fb} \Rightarrow 20 \text{ events/30 fb}^{-1}$ \hspace{1cm} $\ell = e, \mu$

$\text{ZWW} \rightarrow 4\text{lept's}$

$\sigma(Z) = 30 \text{ nb}$

$\sigma(ZW) = 20 \text{ pb}$ \hspace{1cm} $\sigma(ZW) / \sigma(Z) \sim 10^{-3}$

$\sigma(ZWWW) = 50 \text{ fb}$ \hspace{1cm} $\sigma(ZWWW) / \sigma(ZW) \sim 2 \times 10^{-3}$

$\sigma(ZWWW \rightarrow 4 \ell) = 0.15 \text{ fb} \Rightarrow 5 \text{ events/30 fb}^{-1}$ \hspace{1cm} $\ell = e, \mu$

$\frac{\sigma(W)}{\sigma(Z)} \sim 3$

$\frac{\sigma(WW)}{\sigma(ZW)} \sim 2.5$

$\frac{\sigma(WWWW)}{\sigma(ZWWW)} \sim 1.2$

Ratio determined by couplings to quarks, u/d PDF

Ratio determined by couplings among W/Z, SU(2) invariance
Multi-gauge boson production:
**ttZ → WWZ → 4lept’s**

\[
\sigma(Ztt) = 100 \text{ fb} = 40_{(uubar+dubar)} \text{ fb} + 60_{(gg)} \text{ fb} = 100 \text{ fb}
\]

The gg part is directly proportional to the ttZ coupling. **First** “direct” measurement (indirect: virtual corrections to Z self-energy)

\[
\text{fb}^{-1}
\]

**ttW → 3 W →3lept’s**

\[
\sigma(Wtt) = 110 \text{ fb}
\]

Notice \(\sigma(Wtt) \sim \sigma(Ztt)\), while typically \(\sigma(W) \sim 3 \sigma(Z)\). The reason is that Wtt cannot have a gg production channel!!

\[
\text{fb}^{-1}
\]

\[
\sigma(Wtt) \times B(W \rightarrow \ell) \times B(tt \rightarrow \ell''') = 1.2 \text{ fb} \Rightarrow 40 \text{ events/30 fb} \quad \ell = e, \mu
\]

\[
\sigma(Wtt) / \sigma(tt) = 0.7 \times 10^{-3}
\]
Precise determinations of the self-couplings of EW gauge bosons

5 parameters describing weak and EM dipole and quadrupole moments of gauge bosons. The SM predicts their value with accuracies at the level of $10^{-3}$, which is therefore the goal of the required experimental precision.

<table>
<thead>
<tr>
<th>Coupling</th>
<th>14 TeV 100 fb$^{-1}$</th>
<th>14 TeV 1000 fb$^{-1}$</th>
<th>28 TeV 100 fb$^{-1}$</th>
<th>28 TeV 1000 fb$^{-1}$</th>
<th>LC 500 fb$^{-1}$, 500 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_\gamma$</td>
<td>0.0014</td>
<td>0.0006</td>
<td>0.0008</td>
<td>0.0002</td>
<td>0.0014</td>
</tr>
<tr>
<td>$\lambda_Z$</td>
<td>0.0028</td>
<td>0.0018</td>
<td>0.0023</td>
<td>0.009</td>
<td>0.0013</td>
</tr>
<tr>
<td>$\Delta \kappa_\gamma$</td>
<td>0.034</td>
<td>0.020</td>
<td>0.027</td>
<td>0.013</td>
<td>0.0010</td>
</tr>
<tr>
<td>$\Delta \kappa_Z$</td>
<td>0.040</td>
<td>0.034</td>
<td>0.036</td>
<td>0.013</td>
<td>0.0016</td>
</tr>
<tr>
<td>$g_{Z_1}^+$</td>
<td>0.0038</td>
<td>0.0024</td>
<td>0.0023</td>
<td>0.0007</td>
<td>0.0050</td>
</tr>
</tbody>
</table>

(LO rates, CTEQ5M, $k \sim 1.5$ expected for these final states)

<table>
<thead>
<tr>
<th>Process</th>
<th>$N(m_H = 120 \text{ GeV})$</th>
<th>$N(m_H = 200 \text{ GeV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WWW$</td>
<td>2600</td>
<td>7100</td>
</tr>
<tr>
<td>$WWZ$</td>
<td>1100</td>
<td>2000</td>
</tr>
<tr>
<td>$ZZW$</td>
<td>36</td>
<td>130</td>
</tr>
<tr>
<td>$ZZZ$</td>
<td>7</td>
<td>33</td>
</tr>
<tr>
<td>$WWWW$</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>$WWWZ$</td>
<td>0.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>
Examples of open issues
D0 results

\[ \gamma + b \]

\[ \gamma + c \]
Similar trend in cdf and D0: an excess in both c and b.

However, if we look at the ratios c/b:

Are the CDF and D0 results consistent with each other?
\[ R_{gg} = \frac{\sigma(c)}{\sigma(b)} \sim 4 \times \frac{f(c)}{f(b)} \sim 4 \frac{\log(p_T/m_c)}{\log(p_T/m_b)} \]

\[ R_{qq} = \frac{\sigma(c)}{\sigma(b)} \sim \frac{\log(p_T/m_c)}{\log(p_T/m_b)} = \frac{1}{4} R_{gg} \]
Tevatron

\[ \frac{d\sigma}{dp_t} \gamma \]
\[ |\eta_\gamma| < 1, |\eta_{\text{jet}}| < 1.5 \]

\[(gg+qqbar) \rightarrow cc\gamma\]

\[gg \rightarrow cc\gamma\]

LHC

\[ \frac{d\sigma}{dp_t} \gamma \]
\[ |\eta_\gamma| < 2.5, |\eta_{\text{jet}}| < 2.5 \]

\[(gg+qqbar) \rightarrow cc\gamma\]

\[gg \rightarrow cc\gamma\]
Thus $\gamma c$ production at large $p_T$ at the LHC is more sensitive to the charm PDF than at the Tevatron, where gluon splitting has a major role at large $p_T$. 
Ancillary handles: D* in jets, fragmentation function

PHYSICAL REVIEW D 85, 052005 (2012)
CMS, Z+b jets, arXiv:1310.1349v1: rate and correlations OK to ~20%

Would be nice to see a complete comparative study of Z+c, Z +b, γ+c, γ+b at the LHC !!
Towards experimental constraints on Higgs production dynamics ....

To put it in perspective, W/Z physics started like this ......, from a score of events:
There is enough to start plotting $p_t(H)$, $N_{\text{jet}}$ distribution in $H$ production, etc.

~15 signal events, $S/B \sim 1$
p_T(H): qq → qq H vs gg → H

- \( p_T(\text{peak}) \approx 60 \text{ GeV} \)
- Large size of EW corrections

\( gg \rightarrow H \) at \( p_T > m_{\text{top}} \) resolves the inside of the production triangle, an alternative probe to its components

- \( p_T(\text{peak}) \approx 10 \text{ GeV} \)
8TeV/7TeV and 14TeV/8TeV cross section ratios: the ultimate precision

MLM and J.Rojo, arXiv:1206.3557

\[ R_{E_2/E_1}(X) \equiv \frac{\sigma(X, E_2)}{\sigma(X, E_1)} \]

- TH: reduce “scale uncertainties”
- TH: reduce parameters’ systematics: PDF, \( m_{\text{top}} \), \( \alpha_s \), .... at \( E_1 \) and \( E_2 \) are fully correlated
- TH: reduce MC modeling uncertainties
- EXP: reduce syst’s from acceptance, efficiency, JES, ....

\[ R_{E_2/E_1}(X, Y) \equiv \frac{\sigma(X, E_2)/\sigma(Y, E_2)}{\sigma(X, E_1)/\sigma(Y, E_1)} \equiv \frac{R_{E_2/E_1}(X)}{R_{E_2/E_1}(Y)} \]

- TH: possible further reduction in scale and PDF syst’s
- EXP: no luminosity uncertainty
- EXP: possible further reduction in acc, eff, JES syst’s (e.g. \( X,Y=W^+,W^- \))

Following results obtained using best available TH predictions: NLO, NNLO, NNLL resummation when available
### Diboson cross section ratios

<table>
<thead>
<tr>
<th>8 over 7 TeV</th>
<th>$R_{\text{th, npdf}}$</th>
<th>$\delta_{\text{PDF}}$ (%)</th>
<th>$\delta_{\text{scales}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW$</td>
<td>1.223</td>
<td>$\pm 0.1$</td>
<td>$-0.4 - 0.2$</td>
</tr>
<tr>
<td>$gg \rightarrow WW$</td>
<td>1.330</td>
<td>$\pm 0.2$</td>
<td>$-0.0 - 0.0$</td>
</tr>
<tr>
<td>$WW/W$</td>
<td>1.057</td>
<td>$\pm 0.1$</td>
<td>$-0.3 - 0.2$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>1.209</td>
<td>$\pm 0.4$</td>
<td>$-1.2 - 0.4$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>1.165</td>
<td>$\pm 0.4$</td>
<td>$-0.6 - 1.1$</td>
</tr>
<tr>
<td>$gg \rightarrow ZZ$</td>
<td>1.218</td>
<td>$\pm 1.2$</td>
<td>$-0.0 - 0.0$</td>
</tr>
<tr>
<td>$ZZ/Z$</td>
<td>1.000</td>
<td>$\pm 0.4$</td>
<td>$-0.5 - 1.1$</td>
</tr>
<tr>
<td>$WW/WZ$</td>
<td>1.012</td>
<td>$\pm 0.4$</td>
<td>$-0.2 - 1.0$</td>
</tr>
<tr>
<td>$WW/ZZ$</td>
<td>1.050</td>
<td>$\pm 0.4$</td>
<td>$-0.9 - 0.7$</td>
</tr>
<tr>
<td>$WZ/ZZ$</td>
<td>1.038</td>
<td>$\pm 0.5$</td>
<td>$-1.7 - 0.4$</td>
</tr>
</tbody>
</table>
**14 TeV / 8 TeV: NNPDF results**

<table>
<thead>
<tr>
<th>CrossSection</th>
<th>( r^{\text{th,nnPDF}} )</th>
<th>( \delta_{\text{PDF}}(%) )</th>
<th>( \delta_{\alpha_s}(%) )</th>
<th>( \delta_{\text{scales}}(%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t}/Z )</td>
<td>2.121</td>
<td>1.01</td>
<td>-0.84 - 0.75</td>
<td>0.42 - 1.10</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>3.901</td>
<td>0.84</td>
<td>-0.51 - 0.66</td>
<td>0.38 - 1.07</td>
</tr>
<tr>
<td>( Z )</td>
<td>1.839</td>
<td>0.37</td>
<td>-0.10 - 0.34</td>
<td>0.28 - 0.18</td>
</tr>
<tr>
<td>( W^+ )</td>
<td>1.749</td>
<td>0.41</td>
<td>-0.03 - 0.27</td>
<td>0.31 - 0.18</td>
</tr>
<tr>
<td>( W^- )</td>
<td>1.859</td>
<td>0.39</td>
<td>-0.08 - 0.26</td>
<td>0.32 - 0.13</td>
</tr>
<tr>
<td>( W^+/W^- )</td>
<td>0.941</td>
<td>0.28</td>
<td>0.00 - 0.05</td>
<td>0.00 - 0.04</td>
</tr>
<tr>
<td>( W/Z )</td>
<td>0.976</td>
<td>0.09</td>
<td>-0.07 - 0.04</td>
<td>0.04 - 0.02</td>
</tr>
<tr>
<td>( ggH )</td>
<td>2.564</td>
<td>0.36</td>
<td>-0.10 - 0.09</td>
<td>0.89 - 0.98</td>
</tr>
<tr>
<td>( ggH/t\bar{t} )</td>
<td>0.657</td>
<td>0.75</td>
<td>-0.56 - 0.41</td>
<td>1.38 - 1.05</td>
</tr>
<tr>
<td>( \bar{t}t(M_{tt} \geq 1\text{TeV}) )</td>
<td>8.215</td>
<td>2.09</td>
<td>0.00 - 0.00</td>
<td>1.61 - 2.06</td>
</tr>
<tr>
<td>( \bar{t}t(M_{tt} \geq 2\text{TeV}) )</td>
<td>24.776</td>
<td>6.07</td>
<td>0.00 - 0.00</td>
<td>3.05 - 1.07</td>
</tr>
<tr>
<td>( \sigma_{\text{jet}}(p_T \geq 1\text{TeV}) )</td>
<td>15.235</td>
<td>1.72</td>
<td>0.00 - 0.00</td>
<td>2.31 - 2.19</td>
</tr>
<tr>
<td>( \sigma_{\text{jet}}(p_T \geq 2\text{TeV}) )</td>
<td>181.193</td>
<td>6.75</td>
<td>0.00 - 0.00</td>
<td>3.66 - 5.76</td>
</tr>
</tbody>
</table>

- \( \delta < 10^{-2} \) in \( W^\pm \) ratios: absolute calibration of 14 vs 8 TeV lumi
- \( \delta \sim 10^{-2} \) in \( \sigma(\bar{t}t) \) ratios
- \( \delta_{\text{scale}} < \delta_{\text{PDF}} \) at large \( p_T^{\text{jet}} \) and \( M_{tt} \): constraints on PDFs

**14 TeV / 8 TeV: NNPDF vs MSTW vs ABKM**

<table>
<thead>
<tr>
<th>Ratio</th>
<th>( r^{\text{th,nnPDF}} )</th>
<th>( \delta_{\text{PDF}}(%) )</th>
<th>( \Delta_{\text{mstw}}(%) )</th>
<th>( r^{\text{th,abkm}} )</th>
<th>( \delta_{\text{ABKM}}(%) )</th>
<th>( \Delta_{\text{abkm}}(%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{t}t/Z )</td>
<td>2.121</td>
<td>1.01</td>
<td>0.95</td>
<td>0.93</td>
<td>2.213</td>
<td>1.87</td>
</tr>
<tr>
<td>( \bar{t}t )</td>
<td>3.901</td>
<td>0.84</td>
<td>3.874</td>
<td>0.91</td>
<td>4.103</td>
<td>1.87</td>
</tr>
<tr>
<td>( Z )</td>
<td>1.839</td>
<td>0.37</td>
<td>1.838</td>
<td>0.41</td>
<td>1.855</td>
<td>0.34</td>
</tr>
<tr>
<td>( W^+ )</td>
<td>1.749</td>
<td>0.41</td>
<td>1.749</td>
<td>0.49</td>
<td>0.03</td>
<td>1.879</td>
</tr>
<tr>
<td>( W^- )</td>
<td>1.859</td>
<td>0.39</td>
<td>1.854</td>
<td>0.42</td>
<td>0.21</td>
<td>1.879</td>
</tr>
<tr>
<td>( W^+/W^- )</td>
<td>0.941</td>
<td>0.28</td>
<td>0.943</td>
<td>0.19</td>
<td>-0.19</td>
<td>0.940</td>
</tr>
<tr>
<td>( W/Z )</td>
<td>0.976</td>
<td>0.09</td>
<td>0.976</td>
<td>0.10</td>
<td>0.03</td>
<td>0.977</td>
</tr>
<tr>
<td>( ggH )</td>
<td>2.564</td>
<td>0.36</td>
<td>2.572</td>
<td>0.57</td>
<td>-0.30</td>
<td>2.644</td>
</tr>
<tr>
<td>( ggH/t\bar{t} )</td>
<td>0.657</td>
<td>0.75</td>
<td>0.000</td>
<td>0.00</td>
<td>0.00</td>
<td>0.000</td>
</tr>
<tr>
<td>( \bar{t}t(M_{tt} \geq 1\text{TeV}) )</td>
<td>8.215</td>
<td>2.09</td>
<td>7.985</td>
<td>2.02</td>
<td>3.12</td>
<td>8.970</td>
</tr>
<tr>
<td>( \bar{t}t(M_{tt} \geq 2\text{TeV}) )</td>
<td>24.776</td>
<td>6.07</td>
<td>23.328</td>
<td>4.32</td>
<td>6.05</td>
<td>23.328</td>
</tr>
<tr>
<td>( \sigma_{\text{jet}}(p_T \geq 1\text{TeV}) )</td>
<td>15.235</td>
<td>1.72</td>
<td>15.193</td>
<td>1.62</td>
<td>-1.33</td>
<td>14.823</td>
</tr>
<tr>
<td>( \sigma_{\text{jet}}(p_T \geq 2\text{TeV}) )</td>
<td>181.193</td>
<td>6.75</td>
<td>191.208</td>
<td>3.34</td>
<td>-6.52</td>
<td>174.672</td>
</tr>
</tbody>
</table>

- Several examples of 3-4\( \sigma \) discrepancies between predictions of different PDF sets, even in the case of \( W \) and \( Z \) rates
Inclusion of $m_H$ in EW fits greatly tightens correlation between $m_W$ and $m_{\text{top}}$ introducing perhaps a slight tension?

New EW fit results, including $m_{\text{Higgs}}$:

$m_{\text{top}} = 175.8^{+2.7}_{-2.4}$ GeV

$m_W = 80395 \pm 11$ MeV

Continued improvement in the direct determination of $m_W$ and $m_{\text{top}}$ remains a high priority
Tension released in the MSSM:

S. Heinemeyer et al, arXiv:1311.1663v1
Tevatron combined $W$ mass: $M_W = 80387 \pm 16$ MeV
Tevatron+LEP2 combined $W$ mass: $M_W = 80385 \pm 15$ MeV

## Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>D0</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton energy scale/resn/modelling</td>
<td>17</td>
<td>7</td>
</tr>
<tr>
<td>Hadronic recoil energy scale and resolution</td>
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<td>6</td>
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<tr>
<td>Backgrounds</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Parton distributions</td>
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<td>10</td>
</tr>
<tr>
<td>QED radiation</td>
<td>7</td>
<td>4</td>
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<tr>
<td>$p_T(W)$ model</td>
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<td>5</td>
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<tr>
<td>Total systematic uncertainty</td>
<td>22</td>
<td>15</td>
</tr>
<tr>
<td>$W$-boson statistics</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>26 MeV</td>
<td>19 MeV</td>
</tr>
</tbody>
</table>

90% of $M_W$ information is in transverse mass
Predictions for PDF-induced TH syst at the LHC


**Theory syst:**

\[ \Delta m_W \approx \pm 8 \text{ MeV} \]

- This uncertainty should be further reduced, to be confident that it’s negligible in the context of a measurement with a total systematics of less than \( \pm 20 \text{ MeV} \).

- These systematics should be validated through dedicated measurements: can one extract at the same time PDF and \( m_W \) from the fit of the relevant distributions (e.g. \( pt(e) \))?

- There remain issues raised by Krasny et al, Eur. Phys. J. C 69, 379 (2010) which are not fully addressed by this study (e.g. the impact of the charm mass in using \( pt(Z) \) to model \( pt(W) \).
There is still room to further constrain PDF distributions relevant for W/Z production properties.

Questions:
- How do we convince ourselves that we are actually fitting the PDFs, and not missing higher-order QCD or EW effects in the matrix elements?
- Would this have an impact in the extraction of $m_W$?
Top quark mass

Tevatron combination:
\[ m_{\text{top}} = 173.20 \pm 0.51 \text{ (stat)} \pm 0.71 \text{ (syst)} = 173.20 \pm 0.87 \text{ GeV} \]

LHC combination:
\[ m_{\text{top}} = 173.29 \pm 0.23 \text{ (stat)} \pm 0.92 \text{ (syst)} = 173.29 \pm 0.95 \text{ GeV} \]
If $\Gamma_{\text{top}}$ were < 1 GeV, top would hadronize before decaying. Same as b-quark.

But $\Gamma_{\text{top}}$ is > 1 GeV, top decays before hadronizing. Extra antiquarks must be added to the top-quark decay final state in order to produce the physical state whose mass will be measured.

As a result, $M_{\text{exp}}$ is not equal to $m_{\text{pole}}$, and will vary in each event, depending on the way the event has evolved.

The top mass extracted in hadron collisions is not well defined below a precision of $O(\Gamma_{\text{top}})$~ 1 GeV.
1. Hard Process
1. Hard Process
2. Shower evolution
1. Hard Process
2. Shower evolution
3. Gluon splitting
1. Hard Process
2. Shower evolution
3. Gluon splitting

4. Formation of “even” clusters and cluster decay to hadrons
1. Hard Process
2. Shower evolution
3. Gluon splitting

4. Formation of “even” clusters and cluster decay to hadrons
5. Formation of “odd” cluster
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6. Decay of “odd” clusters, if large cluster mass, and decays to hadrons
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Controlled by perturbative shower evolution, mostly insensitive to hadronization modeling
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Out-of-cone radiation, controlled by perturbative shower evolution, minimally sensitive to hadronization modeling
Controlled by perturbative shower evolution, mostly insensitive to hadronization modeling

Partly shower evolution, partly color reconnection, ambiguous paternity

Out-of-cone radiation, controlled by perturbative shower evolution, minimally sensitive to hadronization modeling
A good way to assess the relevance of these effects and the reliability of the MC modeling is to monitor the dependence of the reconstructed $m_{top}$ on the production environment. E.g.

- $m_{top}$ vs $pt$

- $pp \rightarrow t \bar{t}$ implies that hadronization of top decay products differs from hadronization of $t$-bar decay products $\Rightarrow m_t$ vs $m_{t\bar{t}}$ at the LHC
probes possible hadronization systematics

- $q \bar{q} \rightarrow t \bar{t}$ vs $gg \rightarrow t \bar{t}$ $\Rightarrow m_{top}(Tevatron)$ vs $m_{top}(LHC)$ is a probe of hadronization systematics

- ditto for $m_{top}$ from single top events
First studies of kinematical dependence of top mass reconstruction, CMS

Dependence of Top Mass on Event Kinematics

First top mass measurement binned in kinematic observables.
Additional validation for the top mass measurements.
With the current precision, no mis-modelling effect due to
- color reconnection, ISR/FSR, b-quark kinematics, difference between pole or MS masses.

\[ \Delta m_t = m_{t^{\text{had}}} - m_{\bar{t}^{\text{had}}} = -272 \pm 196 \text{ (stat)} \pm 122 \text{ (syst.)} \text{ MeV} \]
Pole vs MSbar masses

\[ m_{pole} = \bar{m} \times \left[ 1 + g_1 \frac{\bar{\alpha}}{\pi} + g_2 \left( \frac{\bar{\alpha}}{\pi} \right)^2 + g_3 \left( \frac{\bar{\alpha}}{\pi} \right)^3 \right] \]

where

\[ \bar{m} = m_{MS} \left( m_{MS} \right) \]
\[ \bar{\alpha} = \alpha(\bar{m}) \]
\[ g_1 = \frac{4}{3} \]
\[ g_2 = 13.4434 - 1.0414 \sum_k \left( 1 - \frac{4}{3} \frac{m_k}{\bar{m}} \right) \]
\[ g_3 = 0.6527 n_l^2 - 26.655 n_l + 190.595 \]

In the range \( m_{top} = 171 \text{ – } 175 \text{ GeV}, \) \( \alpha_S \) is \( \sim \)constant, and, using the 3-loop expression above,

\[ m_{pole} = \bar{m} \times [1 + 0.047 + 0.010 + 0.003] = 1.060 \times \bar{m} \]

showing an excellent convergence. In comparison, the expansion for the bottom quark mass behaves very poorly:

\[ m_{pole}^b = \bar{m}^b \times [1 + 0.09 + 0.05 + 0.04] \]

Assuming that after the 3rd order the perturbative expansion of \( m_{pole} \) vs \( m_{MS} \) start diverging, the smallest term of the series, which gives the size of the uncertainty in the resummation of the asymptotic series, is of \( O(0.003 \times m) \), namely \( O(500 \text{ MeV}) \), consistent with \( \Lambda_{QCD} \)

This same \( O(\alpha_S^3) \) term gives also:

\[ \bar{m}^{(3\text{-loop})} - \bar{m}^{(2\text{-loop})} = 0.49 \text{ GeV} \]
Meson vs hvy-Q masses

Heavy meson \(\implies\) (point-like color source) + (light antiquark cloud): properties of “light-quark” cloud are independent of \(m_Q\) for \(m_Q \to \infty\)

\[
m_M = m_Q + \bar{\Lambda} - \frac{\lambda_1 + 3\lambda_2}{2m_Q}
\]

\[
m_{M^*} = m_Q + \bar{\Lambda} - \frac{\lambda_1 - \lambda_2}{2m_Q}
\]

where \(\bar{\Lambda}, \lambda_1, \lambda_2\) are independent of \(m_Q\)

From the spectroscopy of the B-meson system:

\[
m(B^*) - m(B) = 2 \frac{\lambda_2}{m_b} \Rightarrow \lambda_2 \sim 0.15 \text{ GeV}^2
\]

QCD sum rules: \(\lambda_1 \sim 1 \text{ GeV}^2\)

QCD sum rules: \(\Lambda = 0.5 \pm 0.07 \text{ GeV}\)

thus corrections of \(O(\lambda_{1,2}/m_{\text{top}})\) are of \(O(\text{few MeV})\) and totally negligible

\[
\langle M| h_Q (iD)^2 h_Q |M\rangle = -\lambda_1 \text{tr}\{ \overline{\mathcal{M}} \mathcal{M} \} = 2M \lambda_1,
\]

\[
\langle M| h_Q s_{\alpha\beta} G^{\alpha\beta} h_Q |M\rangle = -\lambda_2(\mu) \text{tr}\{ i\sigma_{\alpha\beta} \overline{\mathcal{M}} s^{\alpha\beta} \mathcal{M} \} = 2d_M M \lambda_2(\mu),
\]

\(d_{M^*} = -1, \ d_M = 3\)

See e.g. Falk and Neubert, arXiv:hep-ph/9209268v1
Separation between $m_Q$ and $\Lambda$ is however ambiguous:
renormalon ambiguity on the pole mass:

$$
\delta m_{\text{pole}} = \frac{C_F}{2N_f|\beta_0|} e^{-C/2} m(\mu = m) \exp \left( \frac{1}{2N_f \beta_0 \alpha(m)} \right)
= \frac{C_F}{2N_f|\beta_0|} e^{-C/2} \Lambda_{QCD} \left( \ln \frac{m^2}{\Lambda_{QCD}^2} \right)^{\beta_1/(2\beta_0)} ,
$$

where $\beta_1 = -1/(4\pi N_f)^2 \times (102 - 38N_f / 3)$ is the second coefficient of the $\beta$-function.

$\delta m_{\text{pole}} = 270$ MeV for $m_{\text{top}}$.

This is smaller than the difference between MSbar masses obtained using the 3-loop or 2-loop MSbar vs pole mass conversion.

It would be very interesting to have a 4-loop calculation of MSbar vs $m_{\text{pole}}$, to check the rate of convergence of the series, and improve the estimate of the $m_{\text{pole}}$ ambiguity for the top.

Bigi et al, 1994
The region possibly sensitive to IR effects, $v^2 M_{\text{top}} < 10$ GeV, or $v<0.25$, contributes only $10^{-3}$ of the total rate. Uncertainties of the order of 100% in the description of this region only change the extraction of $M_{\text{top}}$ from the total rate at the level of 30 MeV.
The impact of Coulomb corrections (which first appear at NLO) is confined to values of \( v \) that contribute very little to the total cross section.

\[ \frac{\sigma(vm_{top} < x)}{\sigma_{tot}} \]

⇒ no evidence that the relation between \( m_{pole}(top) \) and total \( tt \) cross section in \( pp(\bar{p}) \) collisions is subject to the same IR problems that enter as main systematics in the extraction of \( m_{top} \) from the threshold scan in \( e^+e^- \)
All in all I believe that it is correct to assume that MC mass parameter is interpreted as $m_{\text{pole}}$.

We are left with the ambiguity intrinsic in the definition of $m_{\text{pole}}$, thus at the level of $\sim 250$-$500$ MeV (uncertainty to be reduced by a future $O(\alpha_s^4)$ calculation of $m_{\text{pole}}$ vs $m_{\text{MS}}$).
**$B_s \rightarrow \mu^+\mu^-$**

(LHCb+CMS) :  $B(B_s \rightarrow \mu^+\mu^-) = (2.9\pm0.7) \times 10^{-9}$

Intrinsic TH uncertainty below 1%, after recent calculation of 3-loop NNLO QCD and 2-loop NLO EW effects:

Uncertainty dominated by $f_{B_s}$ (lattice)

⇒ November 2013:

(Theory) :  $B(B_s \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$
Concluding remarks

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- The Higgs is there ... but where is everyone else ??
Concluding remarks
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• These improvements will come not only from progress in theoretical calculations, but will need to rely on a robust programme of experimental validation
• SM measurements are thus a flagship component of the LHC physics, and in particular a crucial and indispensable part of a successful BSM programme.