Standard Model Physics with ATLAS and CMS

F. Petrucci
Universita’ Roma Tre & INFN

On behalf of the ATLAS and CMS Collaborations
Outline

LHC was built as a discovery machine
- Target: find the Higgs and any new physics beyond the Standard Model (SM);

- Key issues to be addressed before any discovery is possible:
  - Understanding of the detectors;
  - SM processes W,Z,t (benchmark processes)

1. Introduction
2. Inclusive Z and W cross sections measurements
3. W mass measurements
4. Top quark mass measurements
5. Summary
LHC design parameters: pp collisions at $\sqrt{s}=14\text{TeV}$
$L=10^{34}\text{ cm}^{-2}\text{s}^{-1}$

**Startup scenario:**
- Machine cold by September -> first collisions late in October
- Beam physics running during winter 2009- autumn 2010
- start with 450 GeV up to 5 TeV per beam;
- goal: integrate $\sim 200 \text{ pb}^{-1}$
Introduction

Standard Model physics - motivations:
- EW parameters: $m_{\text{top}}$, $m_W$, $\Gamma_W$, $\sin^2\theta_W$ and couplings -> SM precision test and consistency
- Direct sensitivity to new physics (e.g. rare top decays .. )
- High precision cross sections to test QCD predictions
- Constraints on Parton density functions
- Measure background to many physics channels

All these measurements foreseen at the LHC.

$W/Z$ and top production sections, $W$ mass , Top mass

### Cross section

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [TeV]</th>
<th>Cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$W \rightarrow l\nu$</strong></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>20.5 nb</td>
</tr>
<tr>
<td>10</td>
<td>14.3 nb</td>
</tr>
<tr>
<td><strong>$Z \rightarrow ll$</strong></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>2.02 nb</td>
</tr>
<tr>
<td>10</td>
<td>1.35 nb</td>
</tr>
<tr>
<td><strong>$t\bar{t}$</strong></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>833 pb</td>
</tr>
<tr>
<td>10</td>
<td>396 pb</td>
</tr>
</tbody>
</table>

- $Z,W \sim 6$ times larger than at Tevatron
- $t\bar{t}$ bar $\sim 100$ times than Tevatron
Introduction

Motivation (II):
Clean processes with large and well predicted cross-sections -> “standard candles” for:

- MC tuning;
- calibration and alignments;
- Electron/Muon/Jets/Missing E_T energy scales and resolutions;
- Lepton identification/triggering efficiencies;

Tag & probe method: muon example
Z and W inclusive cross-sections
Z→ee,μμ events selections

Z→μμ
- trigger: single muon HLT
- Hits from Tracker + Muon Chambers
- 2 high $p_T$ muons ($p_T>20.0$ GeV, $|\eta|<2.0$)
- Opposite charge sign
- Track Isolation ($\Sigma p_T<3$ GeV, $\Delta R<0.3$)
- $M_{\mu,\mu}>40$ GeV

Z→ee
- trigger: One electron, $p_T>10$ GeV
- 2 EM clusters ($E_T>15$ GeV, $|\eta|<2.4$)
- Loose electron identification criteria
- isolation ($\Sigma E_T/E_T^e<0.2$, $\Delta R<0.45$)

- Use only robust cuts:
  - common vertex and impact parameter not included.
- Background estimation from sidebands and/or simultaneous fit to signal & background.
  - A low background sample, in particular in the muon case.
W events selections

W->ev
- Trigger: Single Isolated electron HLT
- A high $E_T$ electron ($E_T>$30.0 GeV, $|\eta|<$2.5)
- Track Isolation (no tracks $p_T>$1.5 GeV in $\Delta R<$0.6)
- ECAL isolation ($\Sigma E_T/E_T^e<$ 0.02; $\Delta R<$0.3)
- HCAL isolation ($\Sigma E_T/E_T^e<$ 0.10; 0.15<$\Delta R<$0.3)
- tight electron Identification;
- Reject events with 2nd electron having $E_T>$20.0 GeV.

W->$\mu$\nu
- trigger: One muon, $p_T>$20 GeV
- A high $p_T$ muon ($p_T>$25.0 GeV, $|\eta|<$2.5)
- isolation ($\Sigma E <$ 5 GeV, $\Delta R<$0.4)
- ETMiss > 25 GeV
- $M_T >$ 40 GeV

Electron final state:
- major bck are jet final state events;
- CMS: obtained from a data sample passing electron selection with isolation criteria inverted
- ATLAS: bkg shape obtained from a “$\gamma$+jets” sample (same selection but no ID track).

Muon final state: Z->$\mu$\mu, W->$\tau$\nu major bkg. Estimated from MC (well understood).
Z and W cross-sections

\[ \sigma_{W(Z)} \times BR(W(Z) \rightarrow \text{leptons}) = \frac{N_{W(Z)}^{\text{obs}} - B_{W(Z)}}{\varepsilon_{W(Z)} \cdot A_{W(Z)} \int \mathcal{L} dt} \]

\[ \frac{\delta \sigma}{\sigma} = \frac{\delta N \oplus \delta B}{N - B} \oplus \frac{\delta \varepsilon}{\varepsilon} \oplus \frac{\delta A}{A} \oplus \frac{\delta \mathcal{L}}{\mathcal{L}} \]

CMS expectation for 10 pb\(^{-1}\)
\[ \Delta \sigma/\sigma(\text{pp} \rightarrow Z+X \rightarrow \mu\mu+X) = 0.13 \text{ (stat)} \pm 2.3 \text{ (syst)} \% \]
\[ \Delta \sigma/\sigma(\text{pp} \rightarrow W+X \rightarrow \mu+X) = 0.04 \text{ (stat)} \pm 3.3 \text{ (syst)} \% \]
- Identification/reconstruction efficiency: \(-1\%\) from data
- Backgrounds: \(5\%\) (e)
- Theory (including acceptance) \(-2\%\) (PDFs, ISR)

ATLAS expectation for 50 pb\(^{-1}\)
\[ \Delta \sigma/\sigma(\text{pp} \rightarrow Z+X \rightarrow \mu\mu+X) = 0.20 \text{ (stat)} \pm 2.4 \text{ (syst)} \% \]
\[ \Delta \sigma/\sigma(\text{pp} \rightarrow W+X \rightarrow e+X) = 0.04 \text{ (stat)} \pm 2.5 \text{ (syst)} \% \]
- Identification/reconstruction efficiency: \(2-3\%\)
- Backgrounds: \(<1\%\) (muons)
- Theory (including acceptance) \(-2\%\) (PDFs, ISR)

On a longer timescale:

CMS expectation for 1 fb\(^{-1}\)
\[ \Delta \sigma/\sigma(\text{pp} \rightarrow Z+X \rightarrow \mu\mu+X) = 0.13 \text{ (stat)} \pm 2.3 \text{ (syst)} \% \]
\[ \Delta \sigma/\sigma(\text{pp} \rightarrow W+X \rightarrow \mu+X) = 0.04 \text{ (stat)} \pm 3.3 \text{ (syst)} \% \]
- Eff unc. \(<1\%\) with data-driven methods
- Background reduced with selections

ATLAS expectation for 1 fb\(^{-1}\)
\[ \Delta \sigma/\sigma(\text{pp} \rightarrow Z+X \rightarrow ee+X) = 0.20 \text{ (stat)} \pm 2.4 \text{ (syst)} \% \]
\[ \Delta \sigma/\sigma(\text{pp} \rightarrow W+X \rightarrow e+X) = 0.04 \text{ (stat)} \pm 2.5 \text{ (syst)} \% \]
W MASS
**W mass measurements**

$m_W$: fundamental parameter of the theory linked to $m_{\text{top}}$ and $M_H$.
- $m_W$ and $m_{\text{top}}$ need to be measured with highest precision
- LHC can improve current world average ($m_W = 80399 \pm 25$ MeV)

1. Select W candidate events (as in previous analysis).
2. Use the two best observables that are sensitive to the W mass:
   - $p_t(m_W)$
   - $M_T(m_W)$

3. Build templates distributions $p_t(m_W)$ and $M_T(m_W)$;
4. Fit the templates to data -> find $m_W$.

Z events are crucial:
1) Building the templates;
2) lepton energy scale, energy resolution; differential reconstruction efficiency

$$m_T^W = \sqrt{2 p_T^e p_T^\nu (1 - \cos \Delta\phi)}$$
**W mass measurements**

Build templates:

**ATLAS:**
- Generate the $p_T$ and $M_T$ distributions
- Get energy and momentum scales, resolutions and MET response from Z events

**CMS:**
Transformation event by event
(Kinematic transformation):
1) Rescale lepton momentum in Z rest-frame by $m_W/m_Z$;
2) remove one lepton (simulate neutrino);
3) boost back to detector frame.

| Uncertainties on $m_W$ [MeV] for 15 pb$^{-1}$ (ATLAS). |
|-----------------|-----------------|-----------------|-----------------|
|                | $p_T(e)$ (MeV)  | $p_T(\mu)$ (MeV) | $M_T(e)$ (MeV) | $M_T(\mu)$ (MeV) |
| Statistical    | 120             | 106             | 61             | 57             |
| Experimental   | 114             | 114             | 230            | 230            |
| Theo (PDF)     | 25              | 25              | 25             | 25             |
| TOTAL          | 167             | 158             | 239            | 238            |

Not competitive with current experiments.
The analysis performed with 15pb$^{-1}$ is intended as a study to set the method and to understand what can be done with very early data.

| Uncertainties on $m_W$ [MeV] for the scaled $M_T(\mu)$ method (CMS) |
|-----------------|-----------------|-----------------|
|                 | 1 fb$^{-1}$     | 10 fb$^{-1}$    |
| Statistical     | 40              | 15              |
| Experimental    | 64              | <30             |
| Theo (PDF)      | 20              | 10              |
TOP QUARK
Top Quark physics

- Top quark events Contain all relevant signatures: $(e, \mu, \text{jet}, E_{\text{miss}}, b\text{-jet}) \rightarrow$ a milestone in physics commissioning
- LHC will be a “top factory” \(\sigma_{\text{tt}} \sim 830\text{pb} (~\times 100 \text{ TeVatron})\)

Decay: \(\text{BR}(t \rightarrow Wb) \sim 100\%\)
- “all jets”:
  - High BR
  - Full event reconstruction
  - High BKG and combinatorics
- “dilepton”:
  - Low BR
  - Final state difficult to reconstruct
  - Lower bkg and combinatorics
- “lepton+jets”: golden channel

**Backgrounds:**
- \(W+\text{jets}\) (dominant)
- \(Z+\text{jets}\) (\(Z \rightarrow \ell\ell\))
- \(t\text{t}\text{bar}\) in other channels
- Single top events
- QCD Multijet \(\rightarrow\) fake leptons and MET
  - Very large cross section + tiny efficiency \(\rightarrow\) Very difficult to simulate (data driven methods needed!)
  - Smaller than \(W+\text{jet}\) estimate.
Top Quark pair production (10pb\(^{-1}\))

**CMS muon channel selection cuts:**

- One muon \(p_T>30\) GeV, \(|\eta|<2.1\) (loose)
- Isolation: \(E_{\text{calo}}^{\text{iso}} < 1\) GeV and \(dR_{\mu-jet} > 0.3\)
- at least 4 jets; \(|\eta|<2.4\), \(E_T>65,40,40,40\) GeV
- no b-tagging

- For 10 pb\(^{-1}\): 128/90 signal/background
- Overall selection efficiency (including acceptance): 10.3%.
- Shapes of the W/Z+jets bck from simulation
  (Normalizations by comparison with a control sample at low jet multiplicities.)

![Graphs showing event distributions](image)
Top quark mass measurement

Standard cuts $|\eta|<2.5$:
- 1 isolated lepton $p_T>20(25)$ GeV for $\mu$ (e)
- Missing $E_T>20$ GeV (reduces QCD bkg)
- at least 4 jets $p_T>40$ GeV
- two b-tagged jets

\begin{itemize}
  \item Jet Energy Scale main source of systematic uncertainties (reduced with rescaling)
  \item b-jets JES initially modelled from light JES, complemented with $Z+(b$-jet) data
\end{itemize}

With JES=1\% and using b-tagging
$\Delta m_{\text{top}}=0.3$ GeV (stat.) $\pm 1$ GeV (syst.)

\begin{itemize}
  \item m_{\text{top}}=174.8 \pm 0.3$ GeV
  \item $\chi^2$ minimization method
\end{itemize}

\begin{itemize}
  \item m_{\text{top}}=175.2 \pm 0.5$ GeV
  \item No b-tagging
  \item Geometrical method with rescaling
\end{itemize}

\begin{itemize}
  \item Systematic uncertainty $|\eta|<2.5$
  \item 1 b-tagged jet
  \item No b-tagging
\end{itemize}

\begin{itemize}
  \item Light jet energy scale $0.3$ GeV/\% $0.4$ GeV/\%
  \item b jet energy scale $0.7$ GeV/\% $0.7$ GeV/\%
  \item ISR/FSR $\approx 0.4$ GeV $\approx 0.4$ GeV
  \item b quark fragmentation $\leq 0.1$ GeV $\leq 0.1$ GeV
  \item Background $< 1$ GeV $1$ GeV
\end{itemize}
Summary

- The LHC will start providing collisions late October this year;
- First steps: understand detector response and establish SM signatures;
- A strategy for the measurement of $W/Z$ cross sections has been developed also for early data;
  - Simple & Robust selections for electrons & muons to cope with the imperfections in calibration and alignment of the detectors;
- $W$ mass and top mass require a detailed detector understanding and will come at a later stage;
- Tag & Probe (applied on $Z$ events) will provide the selection, reconstruction & trigger efficiencies from data;
- Some methods to estimate QCD background from data were also developed.

I covered only few aspects. For more details:

- CMS "Physics Analysis Summaries“
  (https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults)
- ATLAS “Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics”
  (http://arxiv.org/abs/0901.0512)

Many thanks to the colleagues of the ATLAS and CMS collaborators (in particular the SM and Top WG Conveeners) and to the conference organizers.
BACKUP SLIDES
Cross sections

<table>
<thead>
<tr>
<th>PROCESS</th>
<th>Xsec(nb)</th>
<th>Tevatron</th>
<th>CSC</th>
<th>10 TeV</th>
<th>14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td></td>
<td>7.153</td>
<td></td>
<td>40.065</td>
<td>57.881</td>
</tr>
<tr>
<td>Z-\rightarrow ll (BR=3.36%)</td>
<td>0.240</td>
<td>2.020</td>
<td>1.346</td>
<td>1.945</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>25.032</td>
<td>132.671</td>
<td>188.919</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W-\rightarrow lv (BR=10.8%)</td>
<td>2.574</td>
<td>20.500</td>
<td>14.328</td>
<td>20.402</td>
<td></td>
</tr>
<tr>
<td>W^+</td>
<td>11.920</td>
<td>77.524</td>
<td>108.859</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W^+-\rightarrow lv (BR=10.8%)</td>
<td>1.287</td>
<td>8.372</td>
<td>11.756</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W^-</td>
<td>11.920</td>
<td>55.147</td>
<td>80.060</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W^-\rightarrow lv (BR=10.8%)</td>
<td>1.287</td>
<td>5.956</td>
<td>8.646</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tt</td>
<td>7.112 pb</td>
<td>0.833</td>
<td>0.396</td>
<td>0.876</td>
<td></td>
</tr>
<tr>
<td>t^+W^- + t^-W^+</td>
<td>0.138 pb</td>
<td>0.066</td>
<td>0.028</td>
<td>0.061</td>
<td></td>
</tr>
<tr>
<td>t^+q + t^-q (t channel)</td>
<td>2.050 pb</td>
<td>0.246</td>
<td>0.134</td>
<td>0.250</td>
<td></td>
</tr>
<tr>
<td>t^+b + t^-b (s channel)</td>
<td>0.942 pb</td>
<td>0.011</td>
<td>0.071</td>
<td>0.011</td>
<td></td>
</tr>
</tbody>
</table>

Notes:

Cross sections at NNLO

CSC: value used for ATLAS CSC notes, Z: m_{ll}>60 GeV
### L=50 pb$^{-1}$

<table>
<thead>
<tr>
<th>Process</th>
<th>$N \times 10^4$</th>
<th>$B \times 10^4$</th>
<th>$A \times \varepsilon$</th>
<th>$\delta A/A$</th>
<th>$\delta\varepsilon/\varepsilon$</th>
<th>$\sigma$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow ev$</td>
<td>22.67 ± 0.04</td>
<td>0.61 ± 0.92</td>
<td>0.215</td>
<td>0.023</td>
<td>0.02</td>
<td>20520 ± 40 ± 1060</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>30.04 ± 0.05</td>
<td>2.01 ± 0.12</td>
<td>0.273</td>
<td>0.023</td>
<td>0.02</td>
<td>20530 ± 40 ± 630</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>2.71 ± 0.02</td>
<td>0.23 ± 0.04</td>
<td>0.246</td>
<td>0.023</td>
<td>0.03</td>
<td>2016 ± 16 ± 83</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>2.57 ± 0.02</td>
<td>0.010 ± 0.002</td>
<td>0.254</td>
<td>0.023</td>
<td>0.03</td>
<td>2016 ± 16 ± 76</td>
</tr>
</tbody>
</table>

### L=1 fb$^{-1}$

<table>
<thead>
<tr>
<th>Process</th>
<th>$N \times 10^5$</th>
<th>$B \times 10^5$</th>
<th>$A \times \varepsilon$</th>
<th>$\delta A/A$</th>
<th>$\delta\varepsilon/\varepsilon$</th>
<th>$\sigma$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow ev$</td>
<td>45.34 ± 0.02</td>
<td>1.22 ± 0.41</td>
<td>0.215</td>
<td>0.023</td>
<td>0.004</td>
<td>20520 ± 9 ± 516</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>60.08 ± 0.02</td>
<td>4.02 ± 0.05</td>
<td>0.273</td>
<td>0.023</td>
<td>0.004</td>
<td>20535 ± 7 ± 480</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>5.42 ± 0.01</td>
<td>0.46 ± 0.02</td>
<td>0.246</td>
<td>0.023</td>
<td>0.007</td>
<td>2016 ± 4 ± 49</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>5.14 ± 0.01</td>
<td>0.02 ± 0.001</td>
<td>0.254</td>
<td>0.023</td>
<td>0.007</td>
<td>2016 ± 4 ± 49</td>
</tr>
</tbody>
</table>
Tracker

$|\eta|<2.5$ coverage
$\sigma / p_T \approx 5 \cdot 10^{-5} p_T \oplus 0.01 [\text{GeV}]$

$|\eta|<2.6$ coverage
$\sigma / p_T \approx 1.5 \cdot 10^{-5} p_T \oplus 0.005$

EM Calorimeter

$|\eta|<4.9$ coverage
$\sigma / E \approx 10\% / \sqrt{E} \ [\text{GeV}]$

$|\eta|<4.9$ coverage
$\sigma / E \approx 2 - 5\% / \sqrt{E}$

HAD Calorimeter

$|\eta|<4.9$ coverage
$\sigma / E \approx 50\% / \sqrt{E} \oplus 0.03 [\text{GeV}]$

$|\eta|<4.9$ coverage
$\sigma / E \approx 100\% / \sqrt{E} \oplus 0.05$

Muon Spectrometer

$|\eta|<2.7$ coverage, 1TeV muons:
$\sigma / p_T \approx 0.07 \ (\text{standalone})$

$|\eta|<2.6$ coverage, 1TeV muon:
$\sigma / p_T \approx 0.10 \ (\text{standalone})$
<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>INNER TRACKER</td>
<td>Silicon pixels + strips TRT → particle ID (e/π) B=2T $\sigma/p_T \sim 4 \times 10^{-4} p_T \oplus 0.01$</td>
<td>Silicon pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$</td>
</tr>
<tr>
<td>EM CALO</td>
<td>Pb-liquid argon $\sigma/E \sim 10%/E$ Uniform longitudinal segmentation</td>
<td>PbWO$_4$ crystals $\sigma/E \sim 2.5%\sqrt{E}$ no longitudinal segmentation</td>
</tr>
<tr>
<td>HAD CALO</td>
<td>Fe-scint. + Cu-liquid argon $\sigma/E \sim 50%/E \oplus 0.03$</td>
<td>Cu-scint. (&gt; 5.8 l +catcher) $\sigma/E \sim 100%/E \oplus 0.05$</td>
</tr>
<tr>
<td>MUON SYSTEM</td>
<td>Air-core toroids $\sigma/p_T \sim 10%$ at 1 TeV standalone</td>
<td>Fe $\rightarrow \sigma/p_T \sim 5%$ at 1 TeV combining with tracker</td>
</tr>
<tr>
<td>MAGNETS</td>
<td>Inner tracker in solenoid (2T) Calorimeters in field-free region Muon system in air-core toroids</td>
<td>Solenoid 4T Calorimeters inside the field</td>
</tr>
</tbody>
</table>
Examples of additional cuts in top selection

- **Cut C2**: the invariant mass of the hadronic $W$ boson and the $b$-jet associated to the leptonic $W$ boson must be greater than 200 GeV.

- **Cut C3**: the invariant mass of the lepton and the $b$-jet associated to the leptonic $W$ boson must be lower than 160 GeV.