Parton distributions at 14 TeV with ATLAS

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Outline

- LHC and ATLAS.
- Precision tests & measurements in unexplored kinematic region.
- Jet physics.
- Direct photon production (f_g(x), parton dynamics).
- Drell-Yan and W/Z production.
- Heavy quark production.
- Conclusions.
LHC (Large Hadron Collider):

- p-p collisions at $\sqrt{s} = 14\,\text{TeV}
- \text{bunch crossing every}\ 25\ \text{ns (40 MHz)}

- low-luminosity: $L \approx 2 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$
  ($\mathcal{L} \approx 20\ \text{fb}^{-1}/\text{year}$)
- high-luminosity: $L \approx 10^{34}\text{cm}^{-2}\text{s}^{-1}$
  ($\mathcal{L} \approx 100\ \text{fb}^{-1}/\text{year}$)

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$ (nb)</th>
<th>Events/year ($\mathcal{L} = 10\ \text{fb}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive $b\bar{b}$</td>
<td>$5 \times 10^5$</td>
<td>$\approx 10^{13}$</td>
</tr>
<tr>
<td>Inclusive jet $p_T &gt; 200,\text{GeV}$</td>
<td>100</td>
<td>$\approx 10^{10}$</td>
</tr>
<tr>
<td>Inclusive $t\bar{t}$</td>
<td>0.8</td>
<td>$\approx 10^{7}$</td>
</tr>
<tr>
<td>Inclusive jet $E_T &gt; 2,\text{TeV}$</td>
<td>$\approx 10^{-8}$</td>
<td>$\approx 10^{3}$</td>
</tr>
</tbody>
</table>

large statistics: small statistical error!

Production cross section and dynamics are largely controlled by QCD.

Mass reach ($E_T$) up to $\approx 5\,\text{TeV}$

Test QCD predictions and perform precision measurements.

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ATLAS: A Toroidal LHC AparatuS

- Multi-purpose detector
  coverage up to $|\eta| = 5$;
  design to operate at $L= 10^{34}$cm$^{-2}$s$^{-1}$

- Inner Detector (tracker)
  Si pixel & strip detectors + TRT;
  2 T magnetic field;
  coverage up to $|\eta| < 2.5$.

- Calorimetry
  highly granular LAr EM calorimeter
  ($|\eta| < 3.2$);
  hadron calorimeter – scintillator tile
  ($|\eta| < 4.9$).

- Muon Spectrometer
  air-core toroid system
  ($|\eta| < 2.7$).

Jet energy scale: precision of 1% ($W \rightarrow jj$; $Z (ll) +$ jets)

Absolute luminosity: precision $\leq 5\%$ (machine, optical
  theorem, rate of known processes)

Most of the QCD related measurements are expected to be performed during the “low-luminosity” stage.
LHC Parton Kinematics

- Essentially all physics at LHC are connected to the interactions of quarks and gluons (small & large transferred momentum).

- **This requires a solid understanding of QCD.**

- Accurate measurements of SM cross sections and QCD related processes at the LHC will further constrain the pdf’s.

- The kinematic acceptance of the LHC detectors allows a large range of $x$ and $Q^2$ to be probed (ATLAS coverage: $|\eta| < 5$).

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Jet physics

• Test of pQCD in an energy regime never probed! (probing the smallest distance scales at the LHC → huge cross-section!)

• The measurement of the jet production cross-section is sensitive both to the quark and gluon densities.

• The measurement of di-jets and their properties ($E_T$ and $\eta_{1,2}$) can be used to constrain p.d.f.’s.

  ➢ reconstruct $x_{1,2}$ & $Q^2$ of the hard scattering (LO):

$$x_{1,2} = \frac{E_T}{\sqrt{s}} (e^{\pm \eta_1} + e^{\pm \eta_2})$$

$$Q^2 \approx 2 E_T^2 \cosh^2 \eta^* (1 - \tanh \eta^*)$$

• Systematic errors: jet algorithm, calorimeter response (jet energy scale), jet trigger efficiency, luminosity (dominant uncertainty 5% -10%), the underlying event.

• At the LHC the statistical uncertainties on the jet cross-section will be small.

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LHC - ATLAS

$10^5 < Q^2 < 10^6$ GeV$^2$

$0.01 < x < 0.6$

• more studies are needed to quantify uncertainties;

• combined channels have also to be investigated!

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Direct photon production

- direct production of photons: information on gluon density in the proton, \( f_g(x) \). (requires good knowledge of \( \alpha_s \))

**Production mechanism:**

\[ qg \rightarrow \gamma q \quad \text{dominant (QCD Compton scattering)} \]

\[ q\bar{q} \rightarrow \gamma g \]

**Background:** mainly related to fragmentation (non-perturbative QCD)

**Isolation cut:** reduces background from fragmentation (\( \pi^0 \)) (cone isolation)

**ATLAS:** high granularity calorimeters (\( |\eta| < 3.2 \)) allow good background rejection.

**LHC**

\( p_T^\gamma > 40 \text{ GeV} \rightarrow Q^2 > 10^3 \text{ GeV}^2 \)

5. \( 10^{-4} < x < 0.2 \) (statistics)

**HERA**

\( Q^2 > 10^3 \text{ GeV}^2 \)

\( x > 0.01 \)
Drell-Yan processes
(e, \(\mu\) channels!)

- **W and Z production at the LHC**: huge statistical samples & clean experimental channel.

\[
\begin{align*}
W \text{ and } Z \text{ production:} \\
&\sim 10^5 \text{ events containing } W \ (p_T^W > 400 \text{ GeV}) \text{ for } \mathcal{L} = 30 \text{ fb}^{-1} \\
&\sim 10^4 \text{ events containing } Z \ (p_T^Z > 400 \text{ GeV}) \text{ for } \mathcal{L} = 30 \text{ fb}^{-1} \\
\text{LHC} & \quad Q^2 \approx 6 \ (8) \ 10^3 \text{ GeV}^2 \\
& \quad 3 \ 10^{-4} < x < 0.1 \quad (|\eta| > 2.5) \\
\text{HERA} & \quad Q^2 > 10^4 \text{ GeV}^2 \\
& \quad x > 0.1 \\
\text{DY production of muon pairs:} \\
& \quad m_{\mu\mu} > 400 \text{ GeV}: 10^4 \text{ events for } \mathcal{L} = 30 \text{ fb}^{-1} \quad Q^2 > 1.6 \ 10^5 \text{ GeV}^2 \\
& \quad (|\eta| > 2.5) \quad 2.3 \ 10^{-3} < x < 0.34
\end{align*}
\]

- **W^+ and W^- production**: different \(y^W\) distributions
  (differences in parton distributions leading to W production: \(u\) and \(d\))

- It can be used to constrain quark and anti-quark densities in the proton.

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Determination of $\sin^2\theta_{\text{eff}}^{\text{lept}}(M_Z^2)$

• $\sin^2\theta_{\text{eff}}^{\text{lept}}$ is one of the fundamental parameters of the SM (constrain the Higgs mass and check consistency of the SM)!

• Main systematic effect: uncertainty on the p.d.f.'s, lepton acceptance (~0.1%), radiative correction calculations.

• $\sin^2\theta_{\text{eff}}^{\text{lept}}$ will be determined at the LHC by measuring $A_{\text{FB}}$ in dilepton production near the Z pole.

\[ A_{\text{FB}} = b \{ a - \sin^2\theta_{\text{eff}}^{\text{lept}}(M_Z^2) \} \]

\[ a \text{ and } b \text{ calculated to NLO in QED and QCD.} \]

\[ \sigma( Z \rightarrow l^+l^-) \sim 1.5 \text{ nb} \text{ (for either e or } \mu) \]

\[ \sin^2\theta_{\text{eff}}^{\text{lept}}(M_Z^2) = 0.23126 \pm 1.7 \times 10^{-4} \text{ (global fit PDG)} \]

Can be further improved: combine channels/experiments.
**Heavy flavour production**

- The *dominant production* mechanism for heavy quarks (b and t) at the LHC is *gluon-gluon interaction*.

- Measurements of *heavy quark production* will provide constraints on the *gluon density*.

**c and b quarks**

- c and b can be measured by quark flavour tagged sub-sample of *photon-jet final states*;

- dominant production: \( c(b) g \rightarrow c(b) \gamma \)

- jet flavour is identified as a c or b jet by using *inclusive* high-\( p_T \) muons & b tagging

\[
\begin{array}{|c|c|c|}
\hline
\text{Process} & \sigma \text{ (nb)} & \text{Events/year} \quad (\mathcal{L} = 10 \text{ fb}^{-1}) \\
\hline
bb & 5 \times 10^5 & \sim 10^{12} \\
t\bar{t} & 0.8 & \sim 10^7 \\
\hline
\end{array}
\]

**LHC: Heavy quarks factory!**

\[
\begin{align*}
\text{Accepted } & \gamma + \text{jet}(\mu) \text{ events in } 10 \text{ fb}^{-1} \\
p_T^{\gamma} & > 40 \text{ GeV} \\
p_T^{\mu} & \sim 5 - 10 \text{ GeV} \\
0.001 & < x_c \ (x_b) < 0.1 \\
(\mathcal{L} = 10 \text{ fb}^{-1}) & \\
\end{align*}
\]

\text{muon spectrum of selected events}
Conclusions:

- LHC will probe QCD to unexplored kinematic limits;
- Jet studies (test of pQCD, constrain p.d.f.’s, physics studies);
- Prompt-photon production will lead to improved knowledge of $f_g(x)$ and parton dynamics;
- Drell-Yan processes will provide information that can be used to constrain quark and anti-quark densities ($W$ and $Z$ decays, muon pairs, $W^+$ and $W^-$ production);
- Heavy quark production (provide constraints for the gluon density & c and b densities).