Low-x and forward physics at HERA and the LHC

Workshop on High-energy QCD and nucleon structure
7 March 2014 @ KEK Tokai campus
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Today’s subjects

Low-x: high-density quark matter
  (multi-)partons interact coherently/incoherently

1. Did we learn anything about unpolarised parton densities at the LHC?

2. Can we draw consistent picture on forward physics between HERA, Tevatron and the LHC?
   - Total cross sections
   - Diffractive scattering
   - Multi-parton interactions

3. Perturbative QCD at the LHC: personal selection
   - Multi-leg simulation, Fat jet
   - $\alpha_s$ at the TeV scale
HERA 1992-2007

- The only $e^\pm p$ collider, with the energy comparable to other $pp$ and heavy ion colliders
  - 27.5 GeV $e \times 920$ GeV $p$
  - Luminosity upgrade 2001-2003
  - 0.1 fb$^{-1}$/experiment before upgrade
  - 0.5 fb$^{-1}$ when finished
The LHC

- Run-I finished
  - at 7/8 TeV with > 25 fb\(^{-1}\)
  - \( L \gtrsim 7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \)
  - small amount of data at 900 GeV, 2.76 TeV
  - Pb-Pb and p-Pb runs

- Restarting run-II in 2015
  - \( \sim 13 \) TeV CMS energy
  - \( L > (1.\times) \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
  - Further upgrade in 2019 and 2023 (SLHC) with \( L \gtrsim 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
Parton densities at HERA and the LHC
Parton densities at low-\(x\) by \(ep\) collisions

- Rapid increase in
  \[ F_2(x, Q^2) = e^2 x (q(x) + \bar{q}(x)) \]
  towards low-\(x\)

\[
x \approx p_{\text{parton}}/p_{\text{proton}}
\]
\[
Q^2 = -(p'_e - p_e)^2
\]

\(\gamma\)
\(e\)
\(e'\)
\(F_2(x, Q^2)\)
\(Q^2 \approx \frac{1}{\lambda^2}\)
rest of the proton
scattered quark

Quark density decreasing at high-\(x\) with \(Q^2\)
Improvement in low-x region

- With charm data $F_2^{cc}(x, Q^2)$
  - Charm quarks are mostly produced from gluons

Gluons are better constrained at middle x ($10^{-3} < x < 10^{-1.5}$)

Low-x and forward physics at HERA and the LHC
NC/CC data and high-\(x\) pdfs

- NC/CC high-\(Q^2\) data analysis finalised
- Combination of H1 and ZEUS data

PDF from HERA (without fixed target) but without these data

Charged current \(e^-p\)

Neutral current \(e^\pm p\)

Give constraint also to valence quarks
Improvement in high-x regime

- Valence: better constrained, especially the shape
  - N.B. it does not use fixed target data
- Glue larger uncertainty
  - 10 vs 14 parameter fit
LHC forward jets

- Jet production is sensitive to parton densities
  - Forward jet: low-x gluons

\[
\int L \, dt = 0.20 \, \text{pb}^{-1}
\]
\[
\rho = \frac{\sigma_{\text{jet}}^{2.76 \, \text{TeV}}}{\sigma_{\text{jet}}^{3.7 \, \text{TeV}}}
\]

\[\text{anti-}\kappa_T \, R = 0.6\]

- Data with statistical uncertainty
- Systematic uncertainties
  - NLO pQCD
  - non-pert. corr. (CT10, \(\mu = p_T^{\text{max}}\))
  - POWHEG \(\otimes\) PYTHIA
tune AUET2B
(CT10, \(\mu = p_T^{\text{Born}}\))
  - POWHEG \(\otimes\) PYTHIA
tune Perugia 2011
(CT10, \(\mu = p_T^{\text{Born}}\))

Forward cross sections are slightly lower than NLO

Jets in \(3.2 \leq |\eta| < 4.7\), vs NLO
Combined HERA+LHC fit on PDF

Reducing mid – high-\(x\) gluons also reducing low-\(x\) gluons

Improved description on very forward jets

LHC data constrains gluon density!
Strange quark from W/Z at the LHC

- No valence contribution for strange quark (perhaps)
  - No largely asymmetric configuration
  - Z production through Drell-Yan (annihilation) occurs more in central rapidity if $s, \bar{s}(x)$ are larger

Data shows slight excess in central rapidity
Strange from W+charm production

- Sensitive to strange quarks
- Slight enhancement on $c$ over $\bar{c}$

$s \rightarrow W^- + c$
$d \rightarrow W^- + c$

(Cabbibo-suppressed)

$s \rightarrow W^+ + \bar{c}$

MSTW off (assuming $\bar{s}/\bar{d} \sim 0.5$)

CT10 ~ OK

NNPDF (collider only) overshoots

ATLAS WZ feedback: consistent!

Another evidence: strange not suppressed
Top quark cross section and pdf

- Top mass is hard to define (pole, $\overline{MS}$ ...) and measure
- An idea is to fix mass (or $\alpha_s$) by measuring top cross section

Low-$x$ and forward physics at HERA and the LHC

ATLAS-CONF-2013-099

Cross section depends on $m_t$ because of kinematics change in generators used for experimental correction

Top quark prediction: some uncertainty from PDF

CMS, PLB 728(2014)496
Total cross sections
Diffraction
Other multi-parton phenomena
**pp total cross sections**

- TOTEM is equipped with double-arm spectrometer (Roman Pot)
- Total cross section is derived from forward elastic scattering through optical theorem

Rising slowly:
- No indication of saturation (unitarity)
- No indication of rapid increase (parton-like)
**pp elastic cross sections**

- Roman pot inserted very close to the beam, reaching to $|t| = 5 \times 10^{-3}$ GeV$^2$
- $t \sim -p_T^2$ of recoil proton (for elastic)

**TOTEM collaboration, EPL 101 (2013) 21002**

- Clear diffractive dip
- $e^{-B|t|}$ behaviour:
  - Large B value: very soft scattering
  - ‘Shrinkage’ continues

Hadrons becoming larger with $\sqrt{s}$
High-energy hadron collisions and the `Pomeron`

- The slow rise is often attributed to the Pomeron trajectory
  - \( \alpha(t) = \alpha_0 - \alpha' t = 1 + \epsilon - \alpha' t \)
  - Often parameterised like: \( \alpha_0: \sim 1.08, \alpha' \sim 0.25 \text{ GeV}^{-2} \)
    (Donnachie and Landshoff’s universal Pomeron)
  - Elastic cross section
    \[
    \frac{d\sigma_{el}}{dt} \sim \frac{1}{s^2} |A|^2 \sim \left( \frac{s}{s_0} \right)^{2\alpha(t) - 2}
    \]
  - Total cross section through optical theorem:
    \[
    \sigma_{tot}^2 \approx 16\pi \frac{d\sigma_{el}}{dt} \bigg|_{t=0} \rightarrow \sigma_{tot}(s) = \sigma_0 \left( \frac{s}{s_0} \right)^{\alpha_0 - 1}
    \]

Does diffraction also be described by the Pomeron trajectory?
Diffraction in $ep$ collisions: issues

- Diffraction at HERA:
  - photon dissociates into small mass ($X$)
  - proton stays intact
  or proton dissociates into small mass ($Y$)
- Standard view:
  - Pomeron ($\mathbb{P}$) emitted from proton, which is scattered off by a photon
  DIS of the Pomeron
- Pomeron or 2-gluon ?
  - If 2 gluons, the exchanged intermediate state is no longer a particle:
    left and right vertices talks each other (factorisation breaking)
Is Pomeron a “particle”?

- Check if the cross section can be factorised into:
  - the Pomeron flux $f_{pP}(x_P, t)$ and
  - the upper part $F_2^{pP}(\beta, Q^2)$
- This holds pretty well: cross section shape in $x_P$ is independent of $\beta$ and $Q^2$

Pomeron is not quite perturbative 2-gluon
Scaling violation analysis for $g(\beta, Q^2)$ in DPDF

- Positive scaling violation in almost all $\beta$ values
  - Quarks dynamically produced through gluons
  - The exchanged object is still gluon-rich
LRG events by detectors at the LHC

Interaction Point

Diffractive dijet candidate at 7 TeV

`fragmented proton’

Single diffraction  Double diffraction

Low-x and forward physics at HERA and the LHC
Double diffraction by TOTEM

- T1 and T2 telescopes to tag proton dissociation system
  - T2 to tag the system X/Y
  - T1 veto for rapidity gap

**Main sample**

<table>
<thead>
<tr>
<th>Subcategories</th>
<th>$I_{\text{track}}$</th>
<th>$D_{1\text{track}}$</th>
<th>$D_{2\text{track}}$</th>
<th>$D_{1\text{track}}$</th>
<th>$D_{2\text{track}}$</th>
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<tbody>
<tr>
<td>Visible</td>
<td>$131 \pm 22$</td>
<td>$58 \pm 14$</td>
<td>$20 \pm 8$</td>
<td>$31 \pm 5$</td>
<td>$34 \pm 5$</td>
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<td>$\eta_{\text{min}}$</td>
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<td>$65 \pm 20$</td>
<td>$12 \pm 5$</td>
<td>$26 \pm 5$</td>
<td>$27 \pm 5$</td>
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<tr>
<td><em>PYTHIA</em> $\eta_{\text{min}}$</td>
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<td>$70$</td>
<td>$17$</td>
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<td><em>PHOJET</em> $\eta_{\text{min}}$</td>
<td>$101$</td>
<td>$44$</td>
<td>$12$</td>
<td>$23$</td>
<td>$23$</td>
</tr>
</tbody>
</table>

Somewhere between two models

Next: $t$-dependence

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Low-x and forward physics at HERA and the LHC
Events with LRG: ATLAS and CMS

- $\alpha_0$ extracted from cross section dependence with rapidity gap $\Delta \eta$
  - triple-Pomeron formula:
    $$\frac{d\sigma}{d\xi_X} \propto s^{-1+\epsilon} \xi_X^{-\left(1+\epsilon+2\alpha't\right)}$$
    $$\xi_X = \frac{M_X^2}{s} \quad \text{(longitudinal momentum fraction of the diffractive exchange)}$$
  - $\Delta \eta \simeq -\ln \xi_X$
    $\rightarrow$ cross section rise by $\sim (\Delta \eta)^{\epsilon}$
  - DL universal Pomeron: $\alpha(0) = 1.08$
Multi-parton interaction at the LHC

• $\sigma_{\text{parton}} > \sigma_{\text{inelastic}}$
  at high $\sqrt{s}$ and low $p_T$
  – multiple parton collision in one crossing
    of nucleon is unavoidable
  – Observed in Tevatron, many evidences at HERA

• Double-parton interaction cross section is expressed as:
  \[
  \sigma_{\text{DPI}}(A, B) = \frac{\sigma_A \cdot \sigma_B}{\sigma_{\text{eff}}}
  \]
  – $\sigma_A$, $\sigma_B$ : cross sections of the two interactions,
    which often increase with $\sqrt{s}$ because of
    increasing number of partons
  – $\sigma_{\text{eff}}$ : effective overlapping area of partons from two nucleons
    in collision.
    Smaller the $\sigma_{\text{eff}}$, more squeezed the partons, thus higher $\sigma_{\text{DPI}}$
DPI in $W + 2$jets

- DPI dijet tend to be back-to-back
- Generic $W+2$jets: $W$ balances to 2 jets

$\nu_1 \nu_2 j_1 j_2$
Diffraction and rescattering in pp

aka absorption, survival probability ...

• Diffractive cross sections in pp can be calculated using factorisation assumption

\[
\frac{d\sigma}{d\xi dt} = \sum_i \int dx_1 dx_2 d\hat{t} f(\xi, t) f_p(x_1, \mu) f_p(x_2, \mu) \frac{d\hat{\sigma}(\hat{s}, \hat{t})}{d\hat{t}}
\]

• Rescattering may destroy diffractive condition (large rapidity gap) ⇒ suppression on diffraction

• CMS survival probability: \( S = 0.08 \pm 0.04 \) (NLO rescaled, proton dissociation subtracted)

Diffraction, but different “Pomeron flux”
Selection from
Hard pQCD results at the LHC
Z+jets, W+b-jets

- Good agreement with NLO and multi-leg MCs for light jets, with some deviation
- b-quark: slight excess, but consistent with simulation
Boosted objects and subjets

Hadronic decay of a top quark

\[ m_{jj} \text{ for } t \to Wb, W \to qq \]

- Jet substructure adopted to tag heavy objects

ATLAS, JHEP 1301 (2013) 116

Top mass reconstruction for searching \( t\bar{t} \) resonance

Nhan Tran, LP2013

CMS-PAS-B2G-13-001

CMS Preliminary, \( \sqrt{s} = 8 \text{ TeV}, 19.6 \text{ fb}^{-1} \)

\[ m_{\text{DATA}} = 84.3 \pm 0.3 \text{ GeV/c}^2 \]
\[ m_{\text{MC}} = 83.7 \pm 0.2 \text{ GeV/c}^2 \]
Single W/Z + Etmiss
Dark matter search

• Hadronic W/Z decay:
  Boosted object to reconstruct mass

• Sensitivity to:
  – D5 (vector) spin independent
  – D9 (tensor) spin dependent

![Graph showing cross-section vs. mass for dark matter search]

World best limit!!
$\alpha_s$ at TeV scale

- Renormalisation Group Equation may change the slope if there is new physics in the strong sector

The data will be extended to higher $Q$ in 14TeV run


Low-x and forward physics at HERA and the LHC
Summary

• LHC starts to constrain PDF
  – With interaction with HERA, where last piece of data are under careful analysis
  – Essential ingredients for discovery

• Investigating “Pomeron-related” phenomena at the LHC:
  – General feature can be understood in the framework of Pomeron exchange
  – Details are to be investigated

• pQCD quite advanced at the LHC
  – New tool: jet substructure
  – Indirect investigation of quark sector in very high-$p_T$ regime by measuring $\alpha_s$
Low-$x \approx$ forward

- Protons almost unperturbed after small-$x$ partons taken out
- Small-$x$ partons are pretty “backward”
  - **Large rapidity gap (LRG)**
    between the small-$x$ parton and most forward particle
B-slope of leading baryons at HERA

- Proton: flat at $b \sim 7 \text{ GeV}^{-2}$ ($\sigma \propto e^{-bp_T^2}$)
  - Larger than the proton size
  - The vertex is somewhat soft = peripheral but not too soft either (unlike elastic $pp$)

Protons from inelastic scattering with $x_L = \frac{p_L}{p}$

$p_L$: proton longitudinal momentum in the final state

$p$: incoming proton’s momentum