Forward and Low-x Physics

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Inspiration for this talk...

**MPI @ LHC 2013**
- Antwerp, December 2-6
- [http://www.ua.ac.be/mpi13](http://www.ua.ac.be/mpi13)

**Low x mini workshop**
- DESY, February 18-19
- [https://indico.desy.de/conferenceDisplay.py?ovw=True&confId=9415](https://indico.desy.de/conferenceDisplay.py?ovw=True&confId=9415)
- focus on recent observations related to BFKL

Many discussions with Hannes Jung, Francesco Hautmann, Krzysztof Kutak, Albert Knutsson, ... *(thanks!!)*

I apologise for my (unavoidably) biased and limited view on the world...
Mistakes and misunderstandings are my own!
Introduction
Going forward on the kinematic plane

Forward production of particles/jets

- collision of a low and high $x$ parton

\[ x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y} \]

- collision of 2 low $x$ partons + QCD evolution

› forward physics $\equiv$ low $x$ physics
QCD description of hadronic scattering

Fixed-order perturbation theory and collinear factorization

- factorisation of weak and strong coupling dynamics:

\[ \sigma_{pp} = f_i^A(x_1, \mu^2) \otimes \hat{\sigma}(i + j \rightarrow X) \otimes f_j^B(x_2, \mu^2) \]

matrix element @ LO, NLO, ...

- collinear factorisation: PDFs do not depend on parton transverse momentum \( k_T \Rightarrow \) also \( X \) must be collinear with the incoming protons (at LO)
- leading twist: a single parton is picked from the proton
- valid for hard momentum scales and hadrons consisting of a dilute set of partons

\[ f(x, Q^2) \text{ determined by } f(x_0 > x, \ Q_0^2 < Q^2) \]

\[ \text{ Parton Density Functions (PDFs) with evolution driven by DGLAP equations: } \]

\[ \text{ works well for inclusive cross sections!} \]
The interest in low $x$ physics

$x$ low, $Q^2$ not too high:

- **partonic $k_T$** may become important!
  - are (perturbative) parton showers enough to describe this?
  - or does one need something more? $k_T$-dependent parton densities?

**Large parton densities at low $x$**

- dense regime is expected to lead to new physics: **saturation**
  - this will happen at perturbative scales!

See talks by
- H. Jung (WG1, Tue. p.m.)
- S. Dooling (WG2, Wed. p.m.)
- A. Szczurek (WG2, Thu. a.m.)
Parton evolution schemes

**DGLAP**
- Valid for medium to large $x$, large $Q^2$
- Contributions leading in $\log(Q^2)$
- Parton showers strongly ordered with increasing $k_T$

**BFKL**
- Valid for low $x$, medium $Q^2$
- Re-summation of $\log(1/x)$ terms to all orders in $\alpha_S$
- Parton showers exhibit random walk in $k_T$
  $\Rightarrow$ diffusion of $k_T$ towards small $x$
- BFKL naturally incorporates unintegrated PDFs!
Saturation

**HERA: proton becomes increasingly densely packed!**

- Parton densities from HERA exhibit a strong rise towards low $x$ and fixed $Q^2$
  $\Rightarrow$ this will eventually violate unitarity
- **Non-linear evolution** must eventually become relevant and parton densities must saturate
- Parton recombinations will lead to non-linear terms in evolution equations
- Note: $Q^2$ is still large and the coupling is still weak
  $\Rightarrow$ parton level understanding of dense limit of QCD
- Saturation scale: defined by packing factor $\sim 1$

$$\frac{\text{density}}{\text{unit transverse area}} \sim 1 \quad \Rightarrow \quad \frac{xg(x, Q_s^2)}{Q_s^2} \sim 1 \quad \Rightarrow \quad Q_s^2 \sim Q_0^2 \left( \frac{1}{x} \right)^\lambda$$

See talks by
- K. Kutak (WG2, Wed. p.m.)
- G. Beuf (WG2, Wed. p.m.)
- Y. Mulian (WG2, Wed. p.m.)
QCD phase diagram

What is the interplay between re-summation (BFKL) and non-linear effects?
Multiple parton interactions

Partonic cross section exceeds inelastic cross section!

\[
\frac{d\sigma}{dp_T^2} = \frac{8\pi \alpha_S^2(p_T^2)}{9p_T^4} \quad \text{diverges for } p_T \to 0!
\]

Two-fold solution (in PYTHIA...):

- introduce a cut-off parameter

\[
\frac{d\sigma}{dp_T^2} = \frac{8\pi \alpha_S^2(p_{T,0}^2 + p_T^2)}{9(p_{T,0}^2 + p_T^2)^2}
\]

which is energy-independent

\[
p_{T,0}(\sqrt{s}) = p_{T,0}(\sqrt{s_0}) \cdot \left(\frac{\sqrt{s}}{\sqrt{s_0}}\right)^\epsilon
\]

- 1 proton interaction ($\sigma_{\text{tot}}$) can contain several ($n$) parton interactions ($\sigma_{\text{int}}$)

\[
\langle n \rangle(p_{T,\text{min}}) = \frac{\sigma_{\text{int}}(p_{T,\text{min}})}{\sigma_{\text{tot}}}
\]

⇒ more MPI activity is predicted for smaller values of $p_{T,0}$ and $\epsilon$

At very small $p_T$ the exchanged gluon can no longer resolve the individual colour charges

- effective coupling decreases
- cross section suppressed
Search for BFKL effects
Inclusive to exclusive dijet ratio

Consider dijet production with pT > 35 GeV/c

- Exclusive dijet sample: exactly one pair of jets in the event
- Inclusive dijet sample: at least one pair of jets in the event; each pair-wise combination of jets enters the sample
- Mueller-Navelet dijet sample: most forward/backward jet pair enters the sample

Define ratios

\[ R^{\text{incl}} = \frac{\sigma^{\text{incl}}}{\sigma^{\text{excl}}} \]
\[ R^{\text{MN}} = \frac{\sigma^{\text{MN}}}{\sigma^{\text{excl}}} \]

- Reduced influence of parton distribution function
- Particularly sensitive to parton radiation patterns
- BFKL evolution predicts a strong increase of the ratios with increasing rapidity separation between the jets
Inclusive to exclusive dijet ratio

- Ratios increase with \( \Delta y \) due to increased phase space for extra radiation
- PYTHIA agrees with the data; HERWIG overestimates the measured ratios at medium and large rapidity separations
- BFKL-motivated models, CASCADE and HEJ, strongly overestimate the data (note: large dijet mass in exclusive sample enforces high \( x \), but no valence contribution in these models...)

![Graphs showing inclusive to exclusive dijet ratio](image.png)
Gap fraction vs. rapidity separation

- selection of most forward/back +veto 3rd jet with $p_T$ above $(p_{T1}+p_{T2})/2$
- gap fraction ~ inverse of inclusive/exclusive ratio
- well described by POWHEG+PYTHIA or HERWIG; HEJ undershoots data

» no sign for BFKL effects
Mueller-Navelet dijet decorrelation

BFKL predicts azimuthal angle de-correlations with increasing jet separations

- Measure average cosines (Fourier coefficients in an expansion of the $\Delta \phi$ distribution)

$$\langle \cos(n(\pi - \Delta \phi)) \rangle$$

- For back-to-back jets $\langle \cos \rangle = 1$
- BFKL predicts an increasing number of partons with increasing rapidity interval between MN jets $\Rightarrow \langle \cos \rangle < 1$

- Average cosines reflect properties of BFKL evolution equation, absent in DGLAP
- Ratios of average cosines further suppress DGLAP contributions

Experimental analysis

- Select events with at least two jets with $p_T > 35$ GeV and $|y| < 4.7$
- MN jet pair is the pair of jets with the largest rapidity separation
Mueller-Navelet dijet decorrelation

$\Delta \phi$ distribution

- Decorrelation increases with rapidity separation
- DGLAP models (especially HERWIG) give reasonable description of data
- BFKL-inspired CASCADE model predicts too strong decorrelations
Mueller-Navelet dijet decorrelation

Average cosines vs. rapidity separation

- Well described by DGLAP models...

See talks by
- G. Safronov (WG2+4, Wed. a.m.)
- P. Cipriano (WG2, Wed. p.m.)
Why does DGLAP work at low $x$?

“BFKL must be the correct theory of low $x$ QCD!”

However...

- It is already known for a long time that NLO corrections to BFKL tame the growth of the parton density towards low $x$.
- Running of $\alpha_S$ became relevant when BFKL went NLO.
- A BFKL chain with running coupling favours an initial piece with limited $k_T$, followed by a $k_T$-ordered rise to high virtuality.
- For small $x$ and large $Q^2$, the result can be well described by a DGLAP chain, starting with a tuned input at low $k_T$. 

[G. Gustafson]
MN dijet decorrelations

NLL calculation by Szymanowski, Wallon, Ducloué

- NLL BFKL kernel
- NLO impact factors
- Brodsky-Lepage-Mackenzie procedure to fix scale for $\alpha_S$

See talk by
- B. Ducloué (WG2+4, Wed. a.m.)

› this implementation of BFKL describes data nicely!
(Personal) summary of BFKL discussion

No sign for BFKL in experimental data...
  • are we looking at the right observables?

“State of the art” BFKL resembles DGLAP: coincidence?
  • probably not, to infinite order, both should give the same answer
  • both are being fudged until they describe the data
    • DGLAP needs $k_T$ from parton showers, multi-parton interactions, angular ordering
    • BFKL needs NLO/NLL corrections...

Is the whole BFKL/DGLAP debate obsolete in view of higher order, multi-leg matrix calculations?

▷ Still, at high energy, BFKL must be the right theory for low $x$ QCD ...
Saturation
Reminder: saturation of $F_2$

- DIS cross section levels off when decreasing $Q^2$ to photoproduction limit
- expected from saturation (e.g. as in dipole models)
- but $Q^2$ is very small, is this non-perturbative?
- many studies of $F_2$ exist based on saturation-inspired model and are being applied to new observables

See talks by
- A. Rezaeian (WG2, Tue. a.m.)
- T. Szumlak (WG2, Tue. p.m.)
- P. Kotko (WG2, Wed. p.m.)
Integrated $p_T$ spectrum

Measurement proposed in Grebenyuk et al. (arXiv:1209.6265)

- leading jet $p_T$ spectrum in limited rapidity range ($|\eta| < 2.5$)

$$\sigma(p_{T\text{ min}}) = \int_{p_{T\text{ min}}} d^2p_T \int_\infty^\infty dy \frac{d^2\sigma}{dp_T^2 dy}$$

- integrate above $p_{T\text{ min}} \Rightarrow$ should approach $\sigma_{\text{inel}}$ for $p_{T\text{ min}} \to 0$

- by using the leading jet, one is less sensitive to MPI

- in principle should be sensitive
  - regularisation of $\sigma_{\text{int}}$
  - saturation of parton density

› reminiscent of saturation in $F_2$!
Integrated $p_T$ spectrum

**CMS measurement with leading charged particles**

- cross section integrated from minimal pT of leading track and scaled to $\sigma_{\text{inel}}$
- generally well described by PYTHIA
- but large sensitivity to MC tunes
- observe turnover at ~ a few GeV

- What about forward leading tracks/jets (low x!)

- Can this be described by PDFs with saturation?

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See talk by
- A. Knutsson (WG2, Wed. p.m.)
Multi-parton interactions
The underlying event

The Underlying Event (UE) is everything except the hard scattering (ME)

Multi-parton interactions (MPI) are well established in the description of the underlying event

- Most convincing argument is high multiplicity observed in hadronic collisions → this is very difficult to explain without MPI

Understanding the UE is crucial for precision measurements of the SM and for the search for new physics, but its dynamics is not well understood

- Phenomenological models involve parameters which must be tuned to data
Quantitative analysis of UE

Study of the UE activity as function of the hard scale in the event

- divide $\phi$ phase space to separate the UE from the hard scatter
  - “Toward” and “Away” capture the hard scatter
  - “Transmax” captures MPI and parton showers
  - “Transmin” captures the MPI
- look at particle densities, energies in the transverse region
- As function of the hard scatter $p_T$ scale: leading jets, Drell-Yan

› enables detailed tuning of models!

See talks by
- A. Minaenko (WG2+4, Wed. a.m.)
- T. Frueboes (WG2+4, Wed. a.m.)
Double parton scattering

What if more than one MPI is a “hard” parton scattering?

- cross section for a generic DPS process

\[ \sigma_{AB} = \frac{m}{2} \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}} \]

with \( \sigma_{\text{eff}} \sim \sigma_{\text{inel}} \)

- \( \sigma_{\text{eff}} < \sigma_{\text{inel}} \) means an enhanced DPS cross section (correlated production of A and B)

- \( \sigma_{\text{eff}} \) should be roughly process and energy independent

However, many effects are neglected in \( \sigma_{\text{eff}} \)

- factorisation of double pdf?
- correlation in momentum fraction, spin/colour/flavour?
- perturbative splitting of single parton can also lead to DPS...
Double Parton Scattering

Double (hard) parton scattering (DPS) must occur at the LHC!

- Large parton density at small $x$
- High rate processes (such as dijet production)

E.g. measurement of DPS in $W$+jets final states

- SPS production of $W$+jets is an irreducible background
- Exploit differences in kinematics to extract DPS fraction
  - $\Delta \phi$: azimuthal separation between jets: DPS gives back-to-back jets
    \[
    \Delta_{\phi}^{rel} = \frac{|\vec{p}_T(j1) + \vec{p}_T(j2)|}{|\vec{p}_T(j1)| + |\vec{p}_T(j2)|} \quad p_T \text{ balance between jets: DPS peaks at zero}
    \]
  - $\Delta S = \arccos \left( \frac{\vec{p}_T(\mu, E_T^{miss}) \cdot \vec{p}_T(j1,j2)}{|\vec{p}_T(\mu, E_T^{miss})| \cdot |\vec{p}_T(j1,j2)|} \right)$
    azimuthal angle between $W$ and dijet: DPS gives flat distribution
Double Parton Scattering

W + at least 2 jets (pT > 20 GeV/c and |η| < 2)

- PYTHIA8 does not describe data and would need a large DPS fraction
- MADGRAPH+PYTHIA reproduces data well and needs MPI to describe the normalization
- $\sigma_{\text{eff}}$ is extracted by fitting SPS and DPS templates to data
- important to get a good definition of the SPS background!
- determination of DPS fraction relies on de-correlation between final state systems... where did we hear that before??

See talks by
- A. Grebenyuk (WG2+4, Wed. a.m.)
- R. Maciula (WG2+4, Wed. a.m.)
Rivet/professor tuning

Alternative way to obtain $\sigma_{\text{eff}}$

- retune models (e.g. MadGraph+PYTHIA) to DPS observables in data

\[ \sigma_{\text{eff}} = 21.3^{+1.2}_{-1.6} \text{ mb} \quad \rightarrow \sigma_{\text{eff}} \text{ (Tune 4C)} \sim 30.2 \text{ mb} \]

- tension appears between tunes for soft UE and hard DPS...
MPI & Diffraction

Can MPI explain the rapidity gap survival probability?

- the idea: if a diffractive interaction occurs, the gap may be destroyed by additional partonic interactions
- numbers roughly agree: 10-20% of events have more than 1 MPI
  $\Rightarrow$ survival factor $\sim 10\%$
- awaits detailed simulation and comparison to data...
- caveat: survival of the proton is a soft (long time scale) process; how can this depend on (semi-) hard (short time scale) MPIs?
- idea could be rephrased as reduced survival probability in case of multiple partonic interactions
Summary

‣ Forward and low $x$ processes are the area where the conventional (collinear) QCD description of hadronic scattering is challenged

‣ Many (related) effects are expected and/or observed
  • alternative QCD shower dynamics
  • saturation of parton densities
  • multi-parton interaction and hard double parton scattering

‣ Interpretation of measurements is often difficult and real deviations from standard description are sometimes surprisingly hard to find

‣ Forward and low $x$ QCD is a vibrant field with many experimental and theoretical ideas and discussion