Factorization and factorization breaking in non-diffractive scattering at HERA

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- When Should Factorization Apply?
- Tests of Factorization
  - Parton Densities: Can NLO QCD fits describe $e\bar{p}$, $\gamma p$ and $p\bar{p}$?
  - Fragmentation Functions: Compare NC DIS (Breit frame) and $e^+e^-$
- Factorization Breaking
  - Underlying event studies in tagged photoproduction
  - Forward Neutron Production
- Sketch of the Dipole Model of DIS
- Conclusions
When Should Factorization Apply?

- Incident particles have high momentum
  - Hadrons are Lorentz contracted along the direction of flight, so the interaction time is decreased.
  - Interactions internal to hadrons are time dilated, so the lifetime of the partonic state is increased.
  - Long distance interactions of partons within the hadron can be neglected during the (short-distance) hard interaction, so the partons can be treated as free particles.
  - The partons can be assigned a fraction $x$ of the hadron's longitudinal momentum. The momentum distribution of parton species $i$ within hadron $H$ in $x$ can be described by a universal parton density $f_{i/H}(x)$ with $0 < x < 1$.

- The density of partons should not be too high, so that the collision can be described by a single hard scattering
Factorized Cross Sections

- The Neutral Current DIS cross section can be factored into a sum over quark densities and a hard scattering cross section

\[
\frac{d^2\sigma(ep)}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4}(1 + (1 - y)^2) \sum_i e_i^2 f_{i/p}(x, Q^2)
\]

- The direct \(\gamma p\) cross section can be written

\[
\sigma_{\text{dir}}(ep \rightarrow e + N\text{jets} + X) = \int_{\Omega} f_{\gamma/e}(y, Q^2) \sum_i f_{i/p}(x, \mu^2) d\hat{\sigma}(\gamma i \rightarrow N\text{jets})
\]

- The resolved \(\gamma p\) cross section can be written

\[
\sigma_{\text{res}}(ep \rightarrow e + N\text{jets} + X) = \int_{\Omega} f_{\gamma/e}(y, Q^2) \sum_{ij} f_{i/p}(x, \mu_p^2) f_{j/\gamma}(x, \mu^2) d\hat{\sigma}(ij \rightarrow N\text{jets})
\]
Factorization in the Final State

- After the hard scatter, hadron formation occurs over a much longer time scale, so it can be described independently of the hard process, again by a universal function $g_{H/i}(z)$ which gives the density in $z$, the fraction of the parton momentum carried by the hadron for hadrons of species $H$ produced in the fragmentation of parton species $i$. 
ZEUS NLO QCD Fit Compared to ZEUS NC DIS Data

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CTEQ61 Compared to CDF Jet Data

CTEQ61 also gives an excellent description of the HERA DIS data
ZEUS NLO QCD Fit Compared to Direct Photoproduction Data

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The data lies above the NLO QCD calculations, especially at high $E_T$. 

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Resolved Photoproduction Data Compared to NLO Predictions

CTEQ5M1 parton densities for the proton

The hatched theory error band includes:
- Renormalization and factorization scales $\mu$ varying between $E_T/4$ and $E_T$
- Hadronization uncertainty
- $\alpha_s(M_Z) = 0.116 \pm 0.003$

High $E_T$ excess especially pronounced for forward jets
NC DIS Breit Frame Current Region Scaled Momentum Spectra

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\[ q = (0, 0, 0, -Q) \] is the virtual photon momentum.

Max momentum of particles in the current region is \( Q/2 \)

For particle with momentum \( p \),
\[ x_p = 2p/Q \]
Open Symbols are $e^+e^-$ multiplicities (divided by 2) plotted at $Q^2 = s$.

$Q^2$ variation = scaling violation

$e^+e^-$ and NC DIS data agree well.

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Parameterize the $\ln(1/x_p)$ distribution with mean $l$ and width $w$ as a distorted Gaussian in $\delta = (\ln(1/x_p) - l)/w$:

$$f(\delta) = \exp\left(\frac{k}{8} - \frac{s\delta}{2} - \frac{(2+k)\delta^2}{4} + \frac{s\delta^3}{6} + \frac{k\delta^4}{24}\right)$$

$e^+e^-$ and NC DIS data agree well.
Event Characteristics for Tagged Photoproduction

$Q^2 < 0.01 \text{GeV}^2$

Tagged electron with $8 < E'_e < 20 \text{GeV}$

$0.25 < y < 0.7$

$150 < W < 251 \text{GeV}$

Better description using simulations with multiple interactions (PHOJET, PYTHIA mia)

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Tagged Photoproduction Underlying Event $E_T$ density vs. $x_\gamma$

Require 2 jets with $E_{T,jet} > 7$ GeV and $-2.5 < \eta^* < 0.5$.

$x_{\gamma}^{jets}$ is the fraction of the photon's longitudinal momentum carried by the dijet system:

$$x_{\gamma}^{jets} = \frac{(E - P_z)_{jet1} + (E - P_z)_{jet2}}{(E - P_z)_{\gamma}}$$

Plot shows the $(\eta, \phi)$ $E_T$ density in the central region $|\eta^*| < 1$ excluding cones of radius 1.3 centered on the 2 highest $E_T$ jets.

Low $x_{\gamma}^{jets}$ (resolved) $\gamma p$ interactions have $\sim 2 \times$ as much $E_T$ density as direct $\gamma p$. 

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Photoproduction $E_T$ Spectrum Compared to NLO QCD

H1 inclusive jet photoproduction

- $\frac{d\sigma_{ep}}{dE_T^{jet}}$ [nb/GeV]
- $1 + \delta_{hadr} = (1 + \delta_{frag})(1 + \delta_{ue})$
- $1 + \delta_{frag}$ corrects for fragmentation.

The underlying event correction $1 + \delta_{ue}$ is defined as the ratio of cross sections with and without a simulated underlying event which was tuned to describe the energy flow between jets.
Forward Neutron Production in DIS and $\gamma P$

**ZEUS**

For $Q^2 > 4$ GeV$^2$
- $0.1 < Q^2 < 0.74$ GeV$^2$
- $Q^2 < 0.02$ GeV$^2$

Probability of producing a neutron is about 1/2 that observed in $pp$ collisions at the ISR.

$\gamma P$ collisions are 20-30% less likely to produce a neutron compared to NC DIS, although no $Q^2$ dependence is observed for $Q^2 > 4$. 

$x_L = P_n / P_p$

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Forward Neutron Production in DIS and $\gamma^P$

**ZEUS**

$\rho = \frac{1}{\sigma_{\text{tot}}^{\text{P}} \frac{d\sigma_{\text{tot}}^{\text{P}}}{dx_L}} \frac{1}{\sigma_{\text{DET}}^{\text{DIS}} \frac{d\sigma_{\text{DET}}^{\text{DIS}}}{dx_L}}$

**H1 data**

- Small $\gamma = \text{High } Q^2$, No Rescatter, $n$ detected
- Large $\gamma = \text{Low } Q^2 \rightarrow \text{Rescatter.}$

$r_{n\pi}$ smaller at lower $x_L \rightarrow \text{Rescatter}$

The Optical Theorem relates the amplitude for elastic $\gamma^*p$ scattering (no cut) to the inclusive $\gamma^*p$ cross section (with the cut). The total cross section is a sum of all diagrams with all possible Pomeron (gluon ladder) exchanges. Diagram (a) above right gives the leading term to the diffractive cross section.

Dipole Model of Deep Inelastic Scattering

The $\gamma^* p$ cross section for $k$-cut Pomerons vs. impact parameter $b$ is

$$\frac{d\sigma_k}{d^2b} = \frac{\Omega(b)^k}{k!} \exp(-\Omega(b)),$$

where

$$\Omega = \frac{\pi^2}{N_C} r^2 \alpha_s(\mu^2) x g(x, \mu^2) T(b)$$

is the Opacity written in terms of the dipole radius $r$, the gluon density $x g(x, \mu^2)$ and the transverse shape of the proton $T(b)$.

To get the total cross section, $F_2$, average the dipole cross sections over the photon wave function $\psi(r, z)$ and integrate over the impact parameter

$$F_2^k = \frac{Q^2}{4\pi^2 \alpha_{em}} \int d^2r \int \frac{dz}{4\pi} \psi^* \psi \int d^2b \frac{d\sigma_k}{d^2b}.$$

Contributions to $F_2$ from $k$-cut Pomerons (H.Kowalski).

Fraction of $F_2$ due to single Pomeron exchange, multiple Pomeron exchange, and diffraction.

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Conclusions

- Factorization holds very well in non-diffractive interactions of protons with point-like photons

- Universal parton densities can describe $ep$, direct $\gamma p$, and hard $p\bar{p}$ interactions

- Fragmentation functions measured in DIS are quite compatible with those measured in $e^+e^-$. 
Conclusions

- In resolved photoproduction, which is a hadron-hadron collision, multiple-interaction models describe the data better than LO models without multiple interactions.
  - The underlying event produces about twice as much $E_T$ in resolved photoproduction compared to direct
  - Resolved $\gamma p$ cross sections exceed NLO QCD predictions, at high $E_T$
  - HERA experiments should measure event shapes and energy flow in $\gamma p$ more systematically, instead of focusing entirely on jets

- The probability to produce a forward neutron is process dependent, highest in $pp$ collisions, and lowest in $\gamma p$ interactions.

- The dipole model relates the cross section for multiple gluon exchange to the diffractive cross section. Even at the relatively high $Q^2$ of 40 GeV$^2$, the model predicts that multiple gluon exchange makes up 6-8% of the DIS cross section.