QCD results from colliders

2007 Aspen Winter Conference

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Outline:

Parton Density Functions & Structure Functions
Jets & Measurements of $\alpha_s$
Multijets, Inclusive Jets, W + Jets, Dijets
Prompt Photons
Diffraction

This talk is available on:
HERA Parton Densities

QCD evolution

Zeus and H1 DGLAP analyses of HERA-I (130 pb$^{-1}$) and fixed target) data:

→ H1 2000 PDFs
→ ZEUS-S PDFs

HERA PDFs essential for LHC
Jets at HERA constrain gluon distribution

First fit using HERA incl and jets data
- HERA-I inclusive cross sects
- Inclusive jet cross sects in NC DIS
- Dijet cross sects in photo-production

Data from one Experiment only:
- Syst unc. well understood
- No fixed target unc.
- Valence quarks from high-$Q^2$ NC and CC cross sections

Jet data help to constrain the gluon and $\alpha_s$:
- Reduction of gluon unc. by $\sim$ factor 2 for $0.01 < x < 0.4$
- Precise determination of $\alpha_s$
Measurement of $F_L$ at HERA

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[ Y_+ F_2(x, Q^2) - y^2 F_L(x, Q^2) \right]$$

$$Y_+ = \left( 1 + (1 - y)^2 \right)$$

$$F_L = \left( \frac{Q^2}{4\pi^2\alpha} \right) \sigma_L$$

$$F_L = \frac{\alpha_s}{4\pi} x^2 \int \frac{dz}{z^3} \left[ \frac{16}{3} F_2 + 8 \sum e_q^2 (1 - x/z) z g \right]$$

- Directly connected to the gluon distribution dominant at low-$x$.
- Predictions are still very uncertain.

- Need to measure cross sections at same $x, Q^2$ and different $y$.
- To change $y = Q^2/xs$, HERA changes $s$ by lowering $E_p$ to 460 GeV.
- The price in integrated luminosity is a factor of $4 \rightarrow 10$ pb$^{-1}$ requires 3 months.
HERA Charged Current Scattering: sensitive to u, d valence at high $Q^2$

\[
\frac{d\sigma}{dQ^2 dx}^{\text{unpol CC}} = \frac{G_F}{2\pi} \left( \frac{M_W^2}{M_W^2 + Q^2} \right)^2 \left[ \bar{u}_i(Q^2, x) + (1 - y)^2 d_i(Q^2, x) \right]
\]

more e$^-$ data: 16 pb$^{-1}$ → 122 pb$^{-1}$

Central values unchanged

Uncertainty on $u_V$ reduced

HERA-I: 130 pb$^{-1}$, HERA-II: 350 pb$^{-1}$ with e$^\pm$ polarization so far -- stops June 30.
Neutral Currents vs. lepton charge: $x F_3$ on $\gamma Z$ interference flips sign when $e^+ \rightarrow e^-$

$\rightarrow$ Add all $e^+ p$ (and $e^- p$) data, correct for residual pol. $\rightarrow$

$$x F_3^{\gamma Z} = \frac{Y_+}{2k a_{q} Y_{-}} \cdot (\sigma^+ - \sigma^-) \simeq \frac{x}{3} [2u_v + d_v]$$

$\rightarrow$ Add to the knowledge of valence quarks at lower $x$
Electroweak tests: Charged current vs $P_e$

- Demonstrates absence of RH charged currents
  - $M(W_R) > \sim 180-208$ GeV with current precision

Polarized electron-proton scattering at HERA
Aspen Winter Conference: Experimental QCD

Electroweak tests: Neutral currents vs $P_e$

Use prelim. H1 and ZEUS $e^\pm p$ data from 2003-2005

$A^\pm = \frac{2}{P_R - P_L} \cdot \frac{\sigma^+(P_R) - \sigma^-(P_L)}{\sigma^+(P_R) + \sigma^-(P_L)} \approx \mp k\alpha_e \frac{F_2^{\gamma Z}}{F_2}$

$\sim$ Parity violating $\alpha_e \mathcal{U}_q$ terms

H1 & ZEUS combined data

First observation of parity viol. in NC $e^\pm p$ data at $R < 10^{-18}$ m
High $p_T$ jets at the Tevatron

In 2005: CDF published both central cone and $k_T$ jets with 400pb$^{-1}$
Now: new preliminary results with full rapidity coverage for 1fb$^{-1}$

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Midpoint Searchcone Algorithm

CDF Run II Preliminary

Data corrected to the hadron level
Systematic uncertainty
NLO: EKS CTEQ 6.1M $\mu = p_T^{JET}/2$, $R_{gap} = 1.3$
Midpoint $R_{cone} = 0.7$, $f_{merge} = 0.75$

$\int L = 1.04$ fb$^{-1}$

$|y|<0.1$ (x10$^6$)
$0.1<|y|<0.7$ (x10$^3$)
$0.7<|y|<1.1$
$1.1<|y|<1.6$ (x10$^3$)
$1.6<|y|<2.1$ (x10$^6$)

CDF Run II Preliminary

$K$, $D=0.7$
Data
Systematic uncertainties
NLO: JETRAD CTEQ 6.1M
Corrected to hadron level
$\mu_H = \mu_F = \max_p p_T^{JET} / 2 = \mu_0$
PDF uncertainties

$|y^{JET}|<0.1$ ($\times 10^6$)
$0.1<|y^{JET}|<0.7$ ($\times 10^3$)
$0.7<|y^{JET}|<1.1$
$1.1<|y^{JET}|<1.6$ ($\times 10^3$)
$1.6<|y^{JET}|<2.1$ ($\times 10^6$)

$k_T$ Algorithm

$p_T^{JET}$ [GeV/c]
### Tevatron Inclusive Jets: cone & $k_T$

**Data are well-described by NLO pQCD**

Experimental Uncertainties: Smaller than PDF Uncertainties!!

(only shown for $k_T$ Algorithm)

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**CDF Run II Preliminary**

$\int L = 1.04 \text{ fb}^{-1}$

| $|y|<0.1$ | $0.1<|y|<0.7$ | $0.7<|y|<1.1$ | $1.1<|y|<1.6$ | $1.6<|y|<2.1$ |
|---|---|---|---|---|
| $p_T^{\text{jet}}$ | Data (parton level) / NLO pQCD | Systematic uncertainty | Systematic uncertainty including hadronization and UE |

**Midpoint Searchcone Algorithm**

**$k_T$ Algorithm**

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Inclusive Jet Cross Section

Compare to NLO pQCD + 2-loop Threshold Corrections (Kidonakis, Owens)

→ Sensitive to PDFs!! -- esp. Gluon!
These measurements will provide additional constraints for the gluon distribution at middle $x$; and give a measurement of $\alpha_S$. 

Jet energy scale uncertainty of 1%
charm contribution to $F_2$

c massive

$\rightarrow$ test/constrain gluon density

or

c massless

$(Q^2 >> m_c^2)$

$\rightarrow$ obtain virtual charm content (charm PDF) of proton
**Beauty contribution to $F_2$**

- First measurement of $F_2^{bb}$
- First NNLO calculation
- Data in agreement with NLO and NNLO
- Checks $b$ PDF for LHC:

$$Q^2 \gg m_b^2$$
Probing the b PDF with $Z+b$-jet at Tevatron

$Z^0 + b$ jet:

Fit of Mass at Secondary Vertex

$\sqrt{s}=1.96$ TeV, $L \sim 335$ pb$^{-1}$

$E_T^\text{jet}>20$ GeV

$|\eta^\text{jet}|<1.5$

CDF: $N_{\text{data}}=101$

$N_{\text{MC}}=99$

$N_{\text{light}}=30 \pm 12$

$N_{\text{c}}=23 \pm 19$

$N_{\text{b}}=46 \pm 15$

CDF: 2.4$\pm$0.7(stat) $\pm$0.5(sys) %

D0: 2.1$\pm$0.4(stat) $\pm$0.3-0.2(sys) %

NLO: 1.8$\pm$0.4 % (CTEQ6)

\textbf{OK}
can Tevatron results be used for LHC?

Are PDFs measured thus far applicable?

Does DGLAP QCD evolution work sufficiently to extrapolate?

Need to take care of low-x effects:

- saturation
- multiple interactions

BFKL vs. DGLAP

→ study at HERA
Evolution & Resummation

DGLAP

Evolution & resummation in powers of $\ln Q^2$

$Q^2 \gg k_{T,n}^2 \gg \ldots \gg k_{T,2}^2 \gg k_{T,1}^2$

The DGLAP gluon cascade is strongly ordered in $k_T$ and ordered in $x$

BFKL

Evolution & resummation in powers of $\ln(1/x)$

$x_1 \gg x_2 \gg \ldots \gg x_n \gg x$

The BFKL is only strongly ordered in $x$

$\leftarrow$ Expect more energetic jets in forward region

• **DGLAP** (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) is expected to break down at low $x$ and $Q^2$ region (LEPTO, DISENT)

• **BFKL** (Balitsky-Fadin-Kuraev-Lipatov) can be applicable at low $x$ (~ARIADNE)

• **CCFM** (Ciafaloni-Catani-Fiorani-Marchesini) describes an evolution in both $Q^2$ and $x$ and approaches BFKL at low $x$ and DGLAP at high $Q^2$; angular ordering (CASCADE)
ZEUS Forward Jets

Measurement extended to 2<\eta_{jet}<3.5

- CASCADE set1 disagrees with all cross sections
- CASCADE set2 (with non-singular terms) is in a good agreement with data in \(Q^2\) and \(E_{T,\text{jet}}\) but fails to reproduce the shapes of \(x_{Bj}\) and \(\eta_{jet}\)
- CDM (ARIADNE) gives a good description of data in all measured cross sections
- LEPTO underestimates data by a factor of 2
H1 forward jets

Forward JET: $\theta_{jet} < 20^\circ$ and $x_{jet} = E^*_jet / E_P > 0.035$

LO is suppressed by kinematics,
NLO is a factor of 2 too low, Cascade somewhat better
Multijets in photoproduction: 3-jet & 4-jet events from ZEUS

Test pQCD at higher order of $\alpha_S$
- NLO calculations for $O(\alpha\alpha_S^2)$: 3 jets
- 4 jets measure $O(\alpha\alpha_S^3)$

Test of MC models (LO+PS) & Multiple Parton interactions
- MPIs and Multi-jet HFS will be abundant at the LHC

Test of parton showers (LLA) used to simulate multi-jet states in (LO ME+PS) Monte Carlos.

What’s new:
- $7.5 \times$ more lumi than existing 3-jet photoproduction results.
- 3-jets studied in more inclusive phase-space region.
- No published 4-jet photoproduction results by ZEUS or H1 yet.
ZEUS 3-jet photoproduction

- Cross sections peak at $x_\gamma^{\text{obs}} \approx 0.9$, and are kinematically suppressed at low $x_\gamma^{\text{obs}}$.
- MC predicts peaks partly due to direct (LO definition) but significant resolved PHP contributions.
- MCs without MPIs fail to describe low $x_\gamma^{\text{obs}}$ region at low $M_{3j}$ - MC requires additional component.
- MC predicts MPIs augment low $x_\gamma^{\text{obs}}$ but don’t affect high $x_\gamma^{\text{obs}}$ - are MPIs the missing component?
- PYTHIA MPI model predicts excessive contribution - HERWIG+MPI describes $x_\gamma^{\text{obs}}$ very well.
again, cross sections peak at $x^\gamma_{\text{obs}} \approx 0.9$ and low $x^\gamma_{\text{obs}}$ kinematically suppressed... BUT...

...smaller direct contribution and less suppression even though four-jet HFS more tightly constrained.

MCs predict that differences at low $x^\gamma_{\text{obs}}$ are due to larger missing component/more MPIs... BUT...

...high $x^\gamma_{\text{obs}}$ region is insensitive to MPIs so not the sole reason for larger resolved contribution.

resolved processes have more complex colour structure - generate multi-jet states more efficiently.
Study parton dynamics with DIS multijets at HERA

three jet events

four jets:

or need unordered gluon radiation?

2 forward jets

2 Jets emerging from the hard subprocess

Jets initiated by radiated gluons

O(\(\alpha_s^3\)) ("NLO")
much better than
O(\(\alpha_s^2\)) ("LO")
but not perfect

need NNLO?

NLO: not available!
=> use LO+PS
Color Dipole Model OK
(DJANGOH: CDM: \(k_T\) unordered gluons)
DGLAP parton shower fails
(Rapgap: \(k_T\) ordered parton showers & resolved photon component)

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Cross Section for Restricted W Phase Space

→ Avoid Model-Dependent Acceptance Corr.

Shape-Comparison with LO Alpgen+PYTHIA: Reasonable Agreement!
Z+n Jets

Smaller \( \sigma \) than (W+Jets) but cleaner exp. signature

Data are described by:
- MCFM: NLO for Z+jet, Z+2-jet
- Madgraph: ME+PS (Z+ \( \leq 3 \) parton) tree-level + PYTHIA parton shower
- ALPGEN (LO ME) (\( p_T \) Dependence)

D0 preliminary (340pb-1)
Dijet Azimuthal Decorrelation

Compare with theory:

- LO has Limitation \(>2\pi/3\) & Divergence towards \(\pi\)
- NLO is very good – down to \(\pi/2\) & better towards \(\pi\)

... still: resummation needed
Compare with theory:

- HERWIG is perfect “out-the-box”
- PYTHIA too low in tail but can tune

- SHERPA (ME+PS+CKKW match) good \( \Delta \phi_{\text{dijet}} \) (rad)
- ALPGEN (LO ME) looks good – but low efficiency \( \rightarrow \) large stat. fluct.

\[ D\bar{O} \]
- \( p_T^{\text{max}} > 180 \text{ GeV} \) \((\times 8000)\)
- \( 130 < p_T^{\text{max}} < 180 \text{ GeV} \) \((\times 400)\)
- \( 100 < p_T^{\text{max}} < 130 \text{ GeV} \) \((\times 20)\)
- \( 75 < p_T^{\text{max}} < 100 \text{ GeV} \)

\[ 1/\sigma_{\text{dijet}} \, d\sigma_{\text{dijet}} / d\Delta \phi_{\text{dijet}} \]

\( \Delta \phi_{\text{dijet}} \) (rad)
DIS Event Shapes

Use power corrections to correct for non-perturbative effects in infrared and collinear safe event shape variable, $F$:

$$\tau = 1 - T_\gamma \quad \text{with} \quad T_\gamma = \frac{\sum_h |\vec{p}_{z,h}|}{\sum_h |\vec{p}_h|}$$

$$\tau_C = 1 - T_C \quad \text{- thrust along the axis maximising } T \quad \text{(like in } e^+e^-)$$

$$B = \frac{\sum_h |\vec{p}_{z,h}|}{2 \sum_h |\vec{p}_h|} \quad \text{- Jet Broadening}$$

$$\rho = \frac{(\sum_h F_{h')^2} - (\sum_h \vec{p}_h)^2}{(2 \sum_h |\vec{p}_h|)^2} \quad \text{- Jet inv. mass}$$

$$C = \frac{3}{2} \frac{\sum_{h,h'} |\vec{p}_h||\vec{p}_{h'}| \sin^2 \theta_{h,h'}}{(\sum_h |\vec{p}_h|)^2} \quad \text{ - Collinear & infrared safe combination of sphericity eigenvalues}$$

\[ \alpha_0 = \text{Universal "non-perturbative parameter"} \]

\[ \alpha_S (M_Z) = 0.1198 \pm 0.0013 \text{(exp)} \pm 0.0056 \text{(th)} \]

\[ \alpha_0 = 0.476 \pm 0.008 \text{(exp)} \pm 0.018 \text{(th)} \]

Extracted values of \( \alpha_S \) are in good agreement with world average (shown as yellow band)
Precise measurement of $\alpha_S$ at HERA, error dominated by theory
Running measured from jets and event shapes in a single experiment
New world measurement incl. HERA Jets: $\alpha_S = 0.1189 \pm 0.0010$ (hep-ex/0606035)
Direct photons directly probe hard scattering dynamics:

\[ \frac{d^2\sigma}{dp_T\,dy} \]

Isolated Photon Cross Sect.

\[ |y| < 0.9 \]

\[ L = 326 \text{ pb}^{-1} \]

PDF sensitivity requires:

- Reduced exp. uncertainties – dominated by purity uncertainty
- Improved theory (resummation / NNLO)

Data/theory (NLO: JETPHOX): good agreement over 23<p_T<300GeV

\[ \begin{align*}
\text{ratio of data to theory (JETPHOX)} \\
\text{CTEQ8.1M PDF uncertainty} \\
\text{scale dependence} \\
(\mu_R=\mu_F=\mu_F=p_T^2) \text{ and } 2\mu_T^2)
\end{align*} \]
Di-Photon Cross Section


- Pseudorapidity < 0.9
- Photon $p_T$ > 13 & 14 GeV

**DIPHOX:**
- NLO prompt di-photons
- NLO fragmentation (1 or 2 $\gamma$)
- NNLO $gg \rightarrow \gamma\gamma$ diagram

**ResBos:**
- NLO prompt di-photons
- LO fragmentation contribution
- Resummed initial state gluon radiation (important for $q_T$)

**PYTHIA** (increased by factor 2)
**Di-Photon Cross Section**

Additional measurement for $\Delta\phi$ (gamma-gamma) $< \pi/2$
(open markers) compared to DIPHOX

**NLO fragmentation contribution**
- only in DIPHOX
  $\rightarrow$ at high $q_T$, low $\Delta\phi$, low mass

**Resummed initial-state gluon radiation**
- only in ResBos
  $\rightarrow$ at low $q_T$

**Important:**
Combined Calculation with
NLO Fragmentation
& Initial State Resummation

Statistical fluctuations: much larger
data set soon - 1 fb$^{-1}$
Inclusive Prompt $\gamma$ at HERA:
effective quark to photon fragmentation fn.

Prediction for prompt $\gamma$
in ep DIS: Gehrmann et al.  
(hep-ph/0601073,0604030)
LO($\alpha^3$) calculation with
lepton radiation (LL), quark
radiation (QQ - incl.
non-perturb. frag. function
based on ALEPH data)
& interference (QL):

LL dominates at small $\eta$
QQ dominates at large $\eta$
Reasonable description of data
Photoproduced Prompt $\gamma + \text{Jet}$

**Photon Kinematics $E_T^\gamma$ (GeV)**

- $0.2 \leq \gamma_{J\beta} \leq 0.8$
- $Q^2 < 1 \text{ GeV}^2$

**Jet Kinematics $E_T^\text{Jet}$ (GeV)**

- $6.0 \leq E_T^\text{Jet} \leq 17.0 \text{ GeV}$
- $-1.6 \leq \eta^\text{Jet} \leq 2.4$

Underestimate data:

<table>
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<th>Program</th>
<th>Value</th>
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<tr>
<td>KZ</td>
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<td>PYTHIA</td>
<td>19.98 pb</td>
</tr>
<tr>
<td>HERWIG</td>
<td>13.54 pb</td>
</tr>
</tbody>
</table>

$\sigma(e^+p \rightarrow e^+ + \text{prompt } \gamma + \text{jet} + X) = 33.1 \pm 3.0 \text{ (stat.)} \pm 4.6 \text{ (syst.) \text{ pb}}$

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Aspen Winter Conference: Experimental QCD - 35
Color Non-Singlet and Singlet Exchange in Photoproduction

**Color Non-Singlet Exchange:**
- Final state partons color connected
- Space between final state partons filled with final state particles
  - No Gap between jets

**Color Singlet Exchange:**
- Final state partons not color connected
- Space btw final state partons empty
  - Rapidity Gap between jets--measure $E_T^{\text{Gap}}$
Evidence for Color Singlet

Inclusive dijet gap cross section vs. $E_T^{\text{Gap}}$ for Herwig (x 3.3) & Pythia (x 1.8) with & w/o color-singlet exchange.

MCs w/o color-singlet do not describe data in two lowest $E_T^{\text{Gap}}$ bins.

Color-singlet needed for best fit to data is $\sim$3-4% of total inclusive dijet gap cross section for $E_T^{\text{Gap}}$ from 0 - 12 GeV.

Indicates variation in gap probability (i.e. survival) from Tevatron-like low $x_{\gamma}$ to pointlike DIS at $x_{\gamma} = 1$. 

Fraction of events with less than 1 GeV in gap between jets vs. fraction of photon energy participating in hard scatter.
Diffractive DIS & Factorization

\[
\sigma^D (\gamma^* p \rightarrow Xp) = \sum_{\text{parton}_i} f_i^D (x, Q^2, x_{IP}, t) \cdot \sigma^{\gamma^*i} (x, Q^2)
\]

- universal hard scattering cross section (same as in inclusive DIS)
- Diffractive Parton Distribution Function \( \Rightarrow \) obey DGLAP, universal for diffractive \( ep \) DIS (inclusive, Dijets, Charm)

- Extract DPDFs from QCD
  fit to inclusive diffractive DIS

- Test DPDFs in diffractive Final States (Boson Gluon Fusion)

\( x_{IP} \) - momentum fraction of proton carried by color singlet exchange
\( Z_{IP} \) - momentum fraction of color singlet carried by parton entering hard sub-process
\( \beta \) - momentum fraction of color singlet carried by struck quark

Assumption:
proton vertex
factorization:
shape of
diffractive
PDFs
independent
of \( x_{IP} \) and \( t \)
(needed?)
DPDFs from Inclusive Diff DIS

Fit DPDFs ($\beta$ & $Q^2$ dependences) using NLO QCD.

~70% gluons

Integrated over $z$
Inclusive DPDFs at high $z$

- Gluon DPDF $\rightarrow$ from positive scaling violations $\rightarrow$ larger uncertainty

Slope $B$: $\sigma_r^D = A + B \ln Q^2$

- At high momentum fraction QCD evolution is driven by quark radiation $\rightarrow$ no sensitivity to gluon DPDF

• Fit constrains quark singlet DPDF and gluon DPDF at low $z$
Add Diff. Dijets to DPDF fit

Obtain better constraint on high z gluon

Both datasets well described by combined fit

Caveat: Gap survival (reinteractions)
Test factorization: diffr. charm

DIS & Direct Photo.

Resolved Photo.

x_γ = 1 dominates

0 < x_γ < 1 small fraction (~10%)

DIS: D* & H1 Lifetime method data consistent with NLO QCD

Photoprod: D* data consistent with NLO QCD within scale error
Inclusive Diffraction at CDF

Use high $p_T$ jets to measure Diffractive Structure Function, $F_{jj}^D$

$\xi = P_{pomeron}/P_{proton}$

$\beta = P_{parton}/P_{Pomeron}$

No $Q^2$ dependence (100 < $Q^2$ < 10000 GeV$^2$)

Diffractive SF ~ proton SF

$\xi = \frac{P_{pomeron}}{P_{proton}}$

$\beta = \frac{P_{parton}}{P_{Pomeron}}$

$R(x_Bj) of \frac{\sigma_{jj}(SD)}{\sigma_{jj}(ND)} = \frac{F_{jj}^D(x_Bj, Q^2)}{F_{jj}(x_Bj, Q^2)}$ (LO QCD)

Data

Known Proton PDF

Slope of $d\sigma/dt$ indep. of $Q^2$ in SD dijets:
QCD Mediated Dijet Production

Strategy: • select DPE dijets: $\bar{p} + p \rightarrow \bar{p} + X (\geq 2\text{jets}+\ldots) + \text{gap}$

• examine the dijet mass fraction $R_{jj}$

$R_{jj} = \frac{M_{jj}}{M_X}$

Exclusive QCD: DPEMC

Inclusive QCD: ExHuME

Similar to central exclusive Higgs production

ExHuME based on Khoze, Martin, Ryskin calculation used for Higgs

CDF Run II Preliminary

$F_{excl} = 15.0 \pm 1.2\%$ (stat. only)

$3.6 < |\eta_{\text{gap}}| < 5.9$

$E_{T,\text{jet}2} > 10 \text{ GeV}$

$E_{T,\text{jet}3} < 5 \text{ GeV}$

Study tail→
Jet data constrains gluon & PDFs at high-x & $\alpha_s$

- Final HERA PDFs should improve by 50% from inclusive measurements, jets, cross-sections, NNLO fits, etc.

Improved measurements of heavy flavor PDFs

QCD evolution has been studied at lower x

- Region over which DGLAP works is extended, but may need BFKL
- Better understanding of extrapolation of PDFs to the LHC

Multijets measure higher order pQCD processes

- Need theoretical calculations to higher order

Multiple Parton Interactions are important

NLO QCD describes new jet data & prompt $\gamma$ well.

Diffractive DIS factorizes into DPDF + hard scatter $\sigma$

- Consistent with NLO QCD
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