Selected Experimental Results from DIS 2005: XIIIth Workshop on Deep Inelastic Scattering in Madison, Wisconsin, April 27 – May 1

Wesley H. Smith
University of Wisconsin – Madison
Seminar at Northwestern University
May 23, 2005
Thanks to Working Group Organizers

Structure Functions & Low x
- Jianwei Qiu
- Un-Ki Yang
- Jo Cole

Diffraction & Vector Mesons:
- Valery Khoze
- Xavier Janssen
- Marta Ruspa

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- C.-P. Yuan
- Beate Heinemann
- Alex Tapper

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- Steve Maxfield
- Claudia Glasman

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- Gennaro Corcella
- Andy Mehta
- Massimo Corradi

Spin Physics:
- Krishna Kumar
- Pasquale Di Nezza
- Marco Stratmann

Future of DIS:
- Uta Stoesslein
- Dave Soper

and especially to conference summary from Allen Caldwell and the 271 participants who gave 240 talks
**F₂ & Fₐ measurements at Low Q²**

(E. Lobodzinska/A. Petrukhin) (H1)

- Precision low Q² F₂ measurements
- Number of different methods
- Extension into the higher x region - overlap with fixed target data
- Close to completing HERA-I structure function programme
Recent Progress on PDFs – MRST

- Discussion of impact on LHC physics: W & Z cross sections; also jet cross sections
- General move towards NNLO PDFs - expect this to become the standard
- But note the impact on certain distributions:
PDFs from ZEUS data

- Addition of NC DIS jet data and direct-enriched dijet photoproduction data to ZEUS PDF fit
- Improves gluon density uncertainties at moderate $x$
- Also allows precise $\alpha_S$ determination from ZEUS data alone:
  \[ \alpha_S = 0.1183 \pm 0.0058 \]
- Comparison to Bethke 2004:
  \[ \alpha_S = 0.1182 \pm 0.0027 \]
Polarized NC/CC Cross Sections at HERA

- ZEUS(NC/CC) by A. Tapper, H1(CC) by A. Nikiforov

**Well described by the SM**

**Test with more data**

at very high $Q^2$

- precise PDFs at high $x$
High $Q^2$ CC & NC DIS w/polarized leptons

Consistent with standard model

CC cross sections

$e^- p \rightarrow \nu X$
- $P_e = -0.25$ (prel.)
- $P_e = 0$
- $P_e = 0.33$ (prel.)

$e^+ p \rightarrow \overline{\nu} X$
- $P_e = -0.40$ (prel.)
- $P_e = 0$

$Q^2 > 400 \text{ GeV}^2$

$y < 0.9$

H1 PDF 2000

ZEUS

$03-04 P = -32\%$ (prel.) / $99-00 P = 0$

$04 P = -40\%$ (prel.) / $99-00 P = 0$

$03-04 P = -32\%$ (prel.) / $04 P = -40\%$ (prel.)

$\sigma_{CC} (\text{pb})$

$P + 32\% / P = 0$

$P - 40\% / P = 0$

$\frac{d\sigma}{dQ^2}$ ratio

$Z\overline{EUS}$
Mixing angle from parity violating Moller scattering (SLAC 158)

\[ \sin^2 \theta_{\text{eff}} = 0.2397 \pm 0.0010 \pm 0.0008 \]

* Limit on \( \Lambda_{\text{LL}} \sim 7 \) or 16 TeV
* Limit on SO(10) \( Z' \sim 1.0 \) TeV
* Limit on lepton flavor violating coupling \( \sim 0.01G_F \)

**Limit on SO(10) \( Z' \sim 1.0 \) TeV**

\[ \sin^2 \theta_{w}^{\text{MS}}(M_Z) = 0.2292 \pm 0.0019 \]

\[ \sin^2 \theta_{w}^{\text{MS}}(M_Z) = 0.2361 \pm 0.0017 \]

\[ \sin^2 \theta_{w}^{\text{MS}}(M_Z) = 0.2330 \pm 0.0014 \]

\[ \sin^2 \theta_{w}^{\text{MS}}(M_Z) = 0.2312 \pm 0.0002 \]

**hep-ex/0504049**
Final NuTeV diff. cross sections ($E_\nu = 20-360$ GeV, $x = 0.01 - 0.7$)

- $F_2$, $xF_3$ are finalized too.

NuTeV $F_2$, $xF_3$ at $x = 0.65$ are 20% higher than CCFR, 10–15% higher than charged lepton data.

Improved calibration of B-field, calorimeter, MC model: explain 11%.

Higher $F_2$: < 5% nuclear effect at $x = 0.65$? need to be understood before NuTeV high-x data can be used in the global PDFs analysis.

CHORUS (lead) data can resolve, and future MINOS/Minerva.

nucl. corr at $x=0.65$: 0.85

M. Tzanov
W charge asymmetry at Tevatron

Run II CDF measurements with higher Et cut to prove d/u at higher x
Would be interesting how the PDF with nucl. Corr (d/u->0.2) compare with the CDF data
Big improvement with direct W asymmetry measurement is expected.
Dedicated efforts to measure \( d/u \) at high \( x \) from JLab

Measure SF of nearly on-shell neutron by detecting slow spectator proton in semi-inclusive \( ed \rightarrow epX \) reaction: JLab CLAS++, BONUS exp. (almost scattering off free nucleon) — S. Kuhn

Parity violation in DIS on \(^1\text{H}\): very sensitive to \( d/u \) — P.A. Souder

\[
A_{PV} = \frac{G_F Q^2}{\sqrt{2} \pi \alpha} \left[ a(x) + f(y)b(x) \right] \quad a(x) = \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}
\]
New treatment of smearing. Correlation matrix:
- removes systematic correlations
- introduces statistical correlations

First Moments Calculation

<table>
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<tr>
<th>Exp.</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$x$ range</th>
<th>Target</th>
<th>Moment</th>
<th>HERMES Moment</th>
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<td>0.03-0.7</td>
<td>p</td>
<td>$0.128\pm0.006$</td>
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<td>SMC</td>
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<td>d</td>
<td>$0.043\pm0.007$</td>
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<tr>
<td>E143</td>
<td>5</td>
<td>0.03-0.8</td>
<td>d</td>
<td>$0.043\pm0.003$</td>
<td>$0.0433\pm0.0013$</td>
</tr>
</tbody>
</table>
Extended x-range with higher accuracy. COMPASS systematically > SMC at low-x.
Spin Structure at high $x$

Precision measurements at high $x$ for:
$A_1^n, \Delta u/u, \Delta d/d, A_2^n, g_1^n, g_2^n, A_1^p, A_1^d, g_2^n, \ldots$
Sometimes statistical errors improved by 1 order of magnitude

> 0
Direct measurement of $\Delta G/G$ via open charm production has still too few events.

Measurement of $\Delta G/G$ via high $P_t$ hadrons more powerful but model dependent

$$A_{||} = R_{pgf} \langle \hat{a}_{pgf} \rangle \frac{\Delta G}{G} + \langle \text{background asymmetry} \rangle$$

2002+2003 data, $Q^2 < 1 \text{ GeV}^2$

$$\frac{\Delta G}{G} = 0.024 \pm 0.089\text{(stat.)} \pm 0.057\text{(syst.)}.$$  

- either $\Delta G$ is small,
- either $\Delta G/G$ has to cross 0 around $x_G = 0.1$. 
• Uncertainty still large \( \left( P^2 \sqrt{L} \right) \).
• Dramatic improvement by lumi and beam polarization (~70%) 

New silicon VTX will increase the x range coverage for \( \Delta G \)
Strange Pentaquark H1 and ZEUS

Observation of $\Theta^+$

ZEUS Collaboration: S. Chekanov et al.

- Kinematics range
  \[ Q^2 > 20 GeV^2 \]
  \[ P_T(\Theta^+) > 0.5 GeV, |\eta(\Theta^+)| < 1.5 \]
- A signal with $\sim 4.6 \sigma$ statistical significance was observed at
  \[ M = 1521.5 \pm 1.5(stat) \pm 2.8(syst) \text{MeV} \]
- Gaussian width $6.1 \pm 1.5 \text{MeV}$
  (experimental resolution $\sim 2 \text{MeV}$)

...but is there really a contradiction?

no significant signal in the interesting mass range 1.52 to 1.54 GeV
Both ZEUS & H1 have taken a closer look...

- Published already
  - Non-observation of $\Xi^-$ in $\Xi\pi$
  - Observation of $\Theta^+ \rightarrow K^0_s p$
  - $\sigma(ep \rightarrow e\Theta + X) : 125 \pm 27^{+36}_{-28} (stat) pb$

Goal of new ZEUS studies
- Look at various kinematics regions
  - Understand the production mechanism?
- check statistical sensitivity to established states

$\Theta^+$ May favor proton-remnant fragmentation origin
- Production rate is higher at forward region than rear region
- Production rate is higher for particle than for anti-particle
  - however the statistics is too small to make strong conclusion
H1: extraction of upper limit for $\theta^+$ cross section

Comparison with ZEUS:

low-momentum dE/dx selection
$20 < Q^2 < 100 \text{ GeV}^2$
$0.1 < y < 0.6$

$M=1.52 \text{ GeV} \quad \sigma_{U.L.} \sim 100 \text{ pb}^*$

ZEUS observation:
$Q^2 > 20 \text{ GeV}^2$, $0.04 < y < 0.95$, $p_T > 0.5$, $|\eta| < 1.5$

$\sigma(ep\rightarrow e^- + X\rightarrow eK^0pX) = 125 \pm 27(\text{stat}) +36 -28 (\text{syst.}) \text{ pb (prel.)}$

$\sigma_{U.L.} \sim 100 \text{ pb}$ not in contradiction with ZEUS measured cross section

$^*$ at $M=1.522 \text{ GeV}$ assuming a resolution of 5 (8) MeV

$\sigma_{U.L.} = 89.6 (116.3) \text{ pb}$
Charm Pentaquark at HERA

Karin Daum / Yehuda Eisenburg

Seen by H1...

DIS: $1 \text{ GeV}^2 < Q^2 < 100 \text{ GeV}^2$

Photoproduction: $Q^2 < 1 \text{ GeV}^2$

H1 Preliminary:

$$R_{\text{cor}}(D^*p(3100)/D^*) = 1.59 \pm 0.33\%_{-0.45\%}^{+0.33\%}$$

...but negative results (in different processes) from ALEPH, FOCUS, CDF, BELLE

...and ZEUS same process
Precision Measurements of $\alpha_S$ 

Claudia Glasman

- Review of $\alpha_S$ determinations from H1 and ZEUS experiments.
- Evaluation of HERA averages of $\alpha_S(M_Z)$ and scale dependence of $\alpha_S$.

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Most precise determinations used in averages

Experimental uncertainties: $\sim 3\%$

Theoretical uncertainties: $\sim 4\%$ (jet cross sections and NLO QCD fits)$
$\sim 8\%$ (internal structure of jets)
More on $\alpha_s$

- Averaging must take proper account of correlations in e.g.
  - Energy-scale uncertainties, PDFs, hadronisation corrections, terms beyond NLO

$$\alpha_s(M_Z) = 0.1186 \pm 0.0011 \text{ (exp.)} \pm 0.0050 \text{ (th.)}$$

Experimental uncertainty: $\sim 0.9\%$

Theoretical uncertainty: $\sim 4\%$

Combined running of $\alpha_s$ using correlation method for data at similar $E_T$... Next steps will need NNLO
Brian Davies

- Run II has \(~0.7 \text{ fb}^{-1}\) (~half being analysed here)
- Increased beam energy \(\Rightarrow\) extended \(p_T\) reach promising sensitivity to gluon at high \(x\)
- New cone algorithm IR safe
- Dominant experimental systematic from jet energy scale (~5%) – still understanding new detector components
- Also looking at flavour tagging of jets with \(\mu\)s (vertex tagging to come) and \(\phi\) decorrelations
Jet measurements at CDF

Rick Field

• Now using $k_T$ algorithm

Data at the “hadron level”!

NLO parton level theory corrected to the “hadron level”!

Correction factors applied to NLO theory!
Jet Production at High $Q^2$ (H1)

Thomas Kluge

- Measure 2- and 3-jet cross sections at high $Q^2$ - $150 < Q^2 < 15000$ GeV$^2$

- Use to make $\alpha_s$ determination

Highest bin needs electroweak corrections from Z exchange. Not used
Extract $\alpha_s$ from 3 jet/2 jet (H1)

- Measure cross section ratio $R_{3/2}$
- Reduced experimental and theory uncertainties (e.g. $\mu_R$ dependence reduced to ~5%)

$\alpha_s(m_Z) = 0.1175 \pm 0.0017 \pm 0.005 \pm 0.0068$ (stat. + syst. + theo.)
Jeff Standage

New measurement with 1999/2000 ZEUS data

• Data points consistent with NLO prediction within the uncertainties.

• This measurement is directly sensitive to value of $\alpha_s(M_Z)$ and the scale dependence of $\alpha_s$.

• Consistent with NLO predicted $\sim 10\%$ increase in cross-section
Event shapes from ZEUS

- Choose IR- and collinear-safe event shape variables.
- Compare with NLO + power corrections \((\text{Dokshitzer, Webber})\) (+ resummation for differential distributions)

Adam Everett

\[ \frac{1}{n} \frac{dn}{dF} \]

Momentum out of plane

\[ K_{\text{out}} = \sum_{i} |\vec{p}_i| \]

Higher order process
Calculations LO for this
No fits performed up to now

First comparison with \(\text{LO+NLL+PC}\) is shown
- \(\alpha_s(M_Z) = 0.118\)
- \(\alpha_0 = 0.52\)

Waiting on generalized resummation program

ZEUS 98-00 (82.2 pb\(^{-1}\))
\(Q^2 > 100\ \text{GeV}^2\)

\(\alpha_0 \approx 0.45 - 0.5\)
Measurement of Forward Jet Production at low $x$ in DIS (H1)

Albert Knutsson

Large $x_{Bj}$, $Q^2$ and $p_t^2$ ⇒ NLO describes data

Smaller $x_{Bj}$, $Q^2$ and $p_t^2$ ⇒ NLO insufficient

'forward' jet $x = \frac{E_{\text{jet}}}{E_{\text{proton}}} = \text{large}$

$x_{Bj}$ small

evolution from large to small $x$
Inclusive Forward Jet production in DIS (ZEUS)

- Average hadronisation correction obtained with LEPTO and ARIADNE
- Proton PDF CTEQ5D
- NLO predictions lower than data but within theoretical uncertainties (except very low $x_{Bj}$)
- Theory has too large uncertainty
- No disagreement with NLO DGLAP has been observed for forward jets

Different way of estimating scale uncertainty?
Charged multiplicity distributions (ZEUS)

Breit Frame analysis of multiplicities

Careful look at: current region in B.F. ≡ one $e^+e^-$ hemisphere

No migrations: $E_{\text{Breit}} = \sqrt{Q^2}/2$

With migrations: $E_{\text{Breit}} < \sqrt{Q^2}/2$

Photon region in HCM mostly target region in BF

- Measurement in current region of the Breit frame shows similar dependence to $e^+e^-$ if $2E_{\text{current}}$ is used as the scale
- The same dependence is observed for the photon region of the HCM frame vs. W.
Events with a $D^*$ and $\geq 1$ jet ($E_T > 6\text{GeV}$)

$D^*$-jet and “other”-jet distribution

Consistent with NLO massive (FMNR) and Massless calculations
Dijet correlations, directly sensitive to NLO corrections

FMNR too low at large $p_T^j$ and low $\Delta \phi$

Need higher orders or matching with PS
H1 Charm + jet photoproduction

$D^*$ and “other”-jet $P_T > 3\text{GeV}$ (tagged PhP)

$\Delta_\phi$ not well reproduce by massive and massless NLO
CDF b-jets

- **Jet algorithm**: JetClu with $R_{\text{cone}} = 0.7$
- **Kinematical range**
  - 2 b-jets within $|\eta| < 1.2$
  - $E_T^{1\text{st} \text{b-jet}} > 30 \text{ GeV}$, $E_T^{2\text{nd} \text{b-jet}} > 20 \text{ GeV}$
- **Data sample**: $65 \text{ pb}^{-1}$
  - Jet 20 only (prescaled trigger)
- **Comparison to MC@NLO $\oplus$ JIMMY**
  - Default JIMMY  
  - Small MC sample
$F_2^{qar{q}}$ from H1, ZEUS vs. NLO

$F_2^{CC}$ vs $Q^2$

$F_2^{bb}$ vs $Q^2$

H1 PRELIMINARY
H1, ZEUS $F_{2}^{qar{q}}$ vs. NNLO (MRST)

$F_{2}^{car{c}}$ vs $Q^2$

H1 Preliminary

$F_{2}^{bar{b}}$ vs $Q^2$

H1 Preliminary

Wesley Smith, U. Wisconsin, May 23, 2005
\[ \nu N \rightarrow \mu^{-} c (\rightarrow \mu^{+}) X \]

Signed selected beam, look at \( s(x) \) and \( \bar{s}(x) \) independently.

Complete data sample (20 times previous results)

LO analysis, extract \( S^{-} = \int dx \ x (s(x) - \bar{s}(x)) \)

Strange asymmetry compatible with zero

\[ S^{-} = 0.0068 \] required to explain \( \sin^{2} \theta_{W} \) anomaly
Z + (b-jet) from DØ

N. Parua

$p\bar{p} \rightarrow Z + b$ production sensitive to b-pdf

180 pb$^{-1}$ of Run-II data $\sim 5000$ $Z(\rightarrow l^+l^-)$+jet

require a secondary vertex significance $> 7$

$$\frac{\sigma(Z+bjets)}{\sigma(Z+jets)} = 0.021 \pm 0.004\text{(stat.)}^{+0.002}_{-0.003}\text{(syst.)}$$

Theory: $0.018 \pm 0.004$ (NLO+CTEQ6)
$H1$ vs ZEUS $b$: $\mu +$ dijet photoprod.

**Graphs:**
- Left: $d\sigma/d\eta_{\mu}$ vs $\eta_{\mu}$
  - $ep \rightarrow e\mu X \rightarrow e\mu j j X$
  - $Q^2 < 1 \text{ GeV}^2$
  - $0.2 < y < 0.8$
  - $p_t^{\mu} > 2.5 \text{ GeV}$
  - $p_t^{\mu \mu (\gamma)} > 7(6) \text{ GeV}$
  - $|\eta^{\mu \mu}| < 2.5$

- Right: $d\sigma/dp_t^{\mu}$ vs $p_t^{\mu}$ [GeV]
  - $-0.55 < \eta^{\mu} < 1.1$
  - $-1.6 < \eta^{\mu} < 2.3$

**Legend:**
- **H1**: Red circles
- **ZEUS**: Blue triangles
- **NLO QCD $\otimes$ Had**: Yellow area

**Key Points:**
- **Good agreement** $H1$ vs ZEUS
- **ZEUS**: No excess at low $p_t^{\mu}$
H1 vs ZEUS b: $\mu + \text{jet}$ in DIS

![Graph showing data and theoretical predictions for H1 and ZEUS for $\mu + \text{jet}$ in DIS.](image)

**H1**
- Data points
- NLO QCD × Had
- NLO QCD

**ZEUS**
- ZEUS 99-00
- NLO QCD (HVQDIS)

\[0.05 < y < 0.7\]
\[-0.9 < \eta^* < 1.3, \ p_T > 2 \text{ GeV}\]
\[-1.6 < \eta^* < -0.9, \ p_T > 2 \text{ GeV}\]
\[E_T^{\text{jet}} > 6 \text{ GeV}, \ -2 < \eta^{\text{jet}} < 2.5\]

\[\Rightarrow \text{Good agreement}\]
Summary of HERA b-physics

- H1: $\gamma p: \sigma_{vis}(jj\mu X)$, $p_t^{rel}$ Impact Parameter
- H1: DIS: $\sigma_{vis}(ej\mu X)$, $p_t^{rel}$ Impact Parameter
- H1: $F_2^{bb}$ (high $Q^2$) Impact Parameter
- H1 Prel.: $F_2^{bb}$ (low $Q^2$) Impact Parameter
- H1 Prel.: $\gamma p$: dijet Impact Parameter
- H1: $D^{*}\mu$ Correlations
- ZEUS: $\gamma p: \sigma_{vis}(jj\mu X)$, $p_t^{rel}$
- ZEUS: DIS: $\sigma_{vis}(ej\mu X)$, $p_t$
- ZEUS Prel.: $D^{*}\mu$ Correlations
- ZEUS Prel. mu–mucorr.

QCD NLO (massive)
HERA: 10% of low-x DIS events are diffractive

\[ Q^2 = \text{virtuality of photon} = (4\text{-momentum exchanged at } e \text{ vertex})^2 \]

\[ t = (4\text{-momentum exchanged at } p \text{ vertex})^2 \]

typically: \(|t| < 1 \text{ GeV}^2\)

\[ W = \text{invariant mass of } \gamma-p \text{ system} \]

\[ M_X = \text{invariant mass of } \gamma-IP \text{ system} \]

\[ x_{IP} = \text{fraction of proton's momentum taken by } IP \]

\[ \beta = \text{Bjorken's variable for the } IP \]

\[ = \text{fraction of } IP \text{ momentum carried by struck quark} \]

\[ = x/x_{IP} \]

Probe structure of color singlet exchange \( \rightarrow F_2^D \)

M.Kapishin, Inclusive diffraction at HERA
Diffractive structure function

- Precise data
- Wide kinematic coverage

- $M_x$: higher $\beta$ region
- LPS: higher $x_{IP}$ region
Scaling violation of $F_2^{D(3)}$

Inclusive data

- Positive scaling violations to highest $\beta$
  → lot of gluons
Regge factorization assumed by P. Newmann, F.-P. Schilling, P Laycock

Observations:
- Singlet similar at low $Q^2$, evolving differently to higher $Q^2$
- Gluon factor $\sim 2$
  smaller than H1 gluon

Reminder that data comparisons revealed differences
- at low $M_X$ (high $\beta$)
  Most of those points are not included in the fit
- in the $Q^2$ dependences
  Different $Q^2$ evolution means different gluon

→ Observed differences in the data explain the differences in the extracted pdfs
Now both CDF and D0 have roman pots and are actively pursuing broad diffractive physics program.

- FPD being calibrated and working as planned.
- Level 1 FPD triggers being commissioned (new data samples).
- Comparing measurements with FPD tag vs. Gap tag yields new insight into processes.
Gap survival probability

\[ S = \frac{S_{1\text{-gap}/0\text{-gap}}}{S_{2\text{-gap}/1\text{-gap}}} \]

\[ S_{1\text{-gap}/0\text{-gap}} (1800 \text{ GeV}) \approx 0.23 \]

\[ S_{2\text{-gap}/1\text{-gap}} (630 \text{ GeV}) \approx 0.29 \]

Results similar to predictions by:
Gotsman-Levin-Maor
Kaidalov-Khoze-Martin-Ryskin
Soft color interactions

Wesley Smith, U. Wisconsin, May 23, 2005
Attractive Higgs studies at LHC

Much larger cross section

Exclusive DPE dijet production

Exclusive low-mass states

Vacuum quantum numbers!
Vector Meson Production

\[ e + p \rightarrow e + VM \ (= \rho, \omega, \phi, J/\psi, \ldots) \ (\text{or} \ \gamma) + p \]

**Regge Theory**

- Soft Pomeron exchange
  - \( \sigma \propto \left( \frac{W}{W_0} \right)^4 (\alpha_{IP}(t) - 1) \)
  - \( \alpha_{IP}(t) = 1.08 - 0.25|t| \)
  - Works for light VM

**pQCD Models**

- Exchange of \( \geq 2 \) gluons
  - \( \sigma \propto (xG(x, K^2))^2 \)
  - Steep rise of \( xG(x, K^2) \)
  - Requires hard scale: \( Q^2, m_q, t \)
Elastic J/Ψ Production

New Photoproduction data at high W

\[ \langle Q^2 \rangle = 0.05 \text{ GeV}^2 \]

- Steep rise with W
- \( \delta \) constant with \( Q^2 \)

\[ \alpha(t) = \alpha_0 + \alpha' t \]

Photoproduction:
\[ \alpha' = (0.164 \pm 0.028 \pm 0.030) \text{ GeV}^{-2} \]

Electroproduction:
\[ \alpha' = (0.019 \pm 0.139 \pm 0.076) \text{ GeV}^{-2} \]

Similar trajectories
\( \rho^0 \) and \( J/\psi \) at high \( |t| \)

Higher Order exchange

\[ Q^2 < 0.01 \text{ GeV}^2 \]
\[ 1.5 < |t| < 10 \text{ GeV}^2 \]
\[ 75 < W < 95 \text{ GeV} \]
\[ M_Y < 5 \text{ GeV} \]

BFKL based model describes \( t \) dependence

Sums perturbative series in \( \alpha_s \)

\Rightarrow \text{Effective gluon ladder ("QCD Pomeron")}

Can be described by BFKL evolution at low \( x \)

\[ Q^2 \sim 0 \text{ GeV}^2 \]
\[ 1 < |t| < 20 \text{ GeV}^2 \]
\[ 50 < W < 150 \text{ GeV} \]
\[ M_Y < 30 \text{ GeV} \]
First $t$ measurement

Fix model normalisation

Sensitivity to GPD parametrisation?
Future of DIS

Key measurements:

- Hadron structure – JLAB, MINERvA, COMPASS+ fixed target at CERN. Require large statistics – need subtle correlations, differences of cross sections, multiply differential cross sections → wavefunctions!

- Small-x physics – LHC, eRHIC (eLIC), ILC, eLHC. Luminosity requirement modest. However, need optimized (forward) detectors, high energies.

- Spin – eRHIC (eLIC). Requires large luminosity, high energy to reach small-x glue.
Future DIS at JLab

12 GeV CEBAF

- Add 5 cryomodules
- 20 cryomodules
- CHL-2
- Add arc
- Enhance equipment in existing halls
- Upgrade magnets and power supplies
- Add Hall D (and beam line)

Wesley Smith, U. Wisconsin, May 23, 2005
CEBAF operation @ 6 GeV has provided results with unprecedented precision on structure functions and form factors (including strangeness).

Upcoming years will highlight precision hypernuclear studies, standard model tests and . . .

The Upgrade to 12 GeV is essential to provide access to new kinematic regions and will:

• determine with extreme precision the spin and flavour structure of the nucleon in the valence region
• provide a totally new and complete view of the nucleon structure access to quark angular momentum
• finally (after > 30 years) determine the origin of the EMC effect
• test our understanding of quark confinement
• and much much more . . .
eRHIC vs. Other DIS Facilities

New kinematic region for polarized DIS
\( E_e = 10 \text{ GeV (≈5–12 GeV variable)} \)
\( E_p = 250 \text{ GeV (≈50–250 GeV variable)} \)
\( E_A = 100 \text{ GeV/nucleon} \)
\( \sqrt{s_{ep}} = 30–100 \text{ GeV} \)

Kinematic reach of eRHIC:

- \( X = 10^{-4} \rightarrow 0.7 \) (\( Q^2 > 1 \text{ GeV}^2 \))
- \( Q^2 = 0 \rightarrow 10^4 \text{ GeV}^2 \)

Polarization of e,p and He beams at least
\( \sim 70\% \) or better

Heavy ions of ALL species at RHIC

Luminosity Goal:
- \( L(ep) \sim 10^{33–34} \text{ cm}^{-2} \text{ sec}^{-1} \)

Optimized detector design will make a big difference in the physics which can be accessed. Towards Bjorken’s FAD.

- Variable beam energy
- P-U ion beams
- Light ion polarization
- Huge luminosity
**ILC & eLHC**

**ILC:** high energy, so in principle $e^+e^-$ gives access to small-$x$. However, low rates, need forward detectors. Better is $e\gamma$, but likely staged.

**eLHC:** extends HERA physics by 1 order of magnitude in $x$. Time scale and cost acceptable?

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**Table 1: Beam Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Electrons</th>
<th>Protons</th>
</tr>
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<tbody>
<tr>
<td>beam energy</td>
<td>$E_b$</td>
<td>75 GeV</td>
<td>7 TeV</td>
</tr>
<tr>
<td>bunch population</td>
<td>$N_0$</td>
<td>$4 \times 10^9$</td>
<td>$6.5 \times 10^{13}$</td>
</tr>
<tr>
<td>rms bunch length</td>
<td>$\sigma_z$</td>
<td>35 $\mu$m</td>
<td>12.4 m</td>
</tr>
<tr>
<td>(Gaussian)</td>
<td></td>
<td></td>
<td>(uniform)</td>
</tr>
<tr>
<td>bunch spacing</td>
<td>$L_{\text{sp}}$</td>
<td>0.66 ns</td>
<td>N/A</td>
</tr>
<tr>
<td>number of bunches</td>
<td>$n_0$</td>
<td>154</td>
<td>1</td>
</tr>
<tr>
<td>effective line</td>
<td>$\lambda$</td>
<td>$2.0 \times$</td>
<td>$2.1 \times$</td>
</tr>
<tr>
<td>density</td>
<td>$10^{19}$ m$^{-1}$</td>
<td>$10^{12}$ m$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>IP beta function</td>
<td>$\beta_{z,y}$</td>
<td>0.25 m</td>
<td>0.25 m</td>
</tr>
<tr>
<td>spot size at IP</td>
<td>$\sigma_{z,y}$</td>
<td>11 $\mu$m</td>
<td>11 $\mu$m</td>
</tr>
<tr>
<td>full interaction length</td>
<td>$d_{IR}$</td>
<td>2 m</td>
<td>N/A</td>
</tr>
<tr>
<td>norm. rms emittances</td>
<td>$\gamma_{x,y}$</td>
<td>73 $\mu$m</td>
<td>3.75 $\mu$m</td>
</tr>
<tr>
<td>collision frequency</td>
<td>$f_{\text{coll}}$</td>
<td>100 Hz</td>
<td>N/A</td>
</tr>
<tr>
<td>luminosity</td>
<td>$L$</td>
<td>$1.1 \times 10^{31}$ cm$^{-2}$s$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>beam-beam tune shift</td>
<td>$\xi_{x,y}$</td>
<td>N/A</td>
<td>0.004</td>
</tr>
</tbody>
</table>

*perhaps higher with TESLA cavities*  
*(L. Gladilin et al., hep-ph/0504008)*

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**Figure 1:** Bunch filling patterns in LHC and CLIC for the nominal LHC (left) and with an LHC superbunch (right).
Conclusions

Structure Functions:

- HERA-I program $\Rightarrow$ new precision PDFs, HERA-II data & NNLO will improve
- Additional data from NuTeV, SLAC 158, TeVatron

Spin Physics

- Polarized SF now from JLab, RHIC, COMPASS (Gluon Polarization)
- Many fascinating other results not covered here

Hadronic Final States:

- Pentaquarks seen by some and not by others...
- Jet measurements precisely determine $\alpha_S$ & check NLO

Heavy Flavors

- Improved understanding of jets and heavy quarks
- NLO (NNLO) explains $F_2$ for c (b) quarks

Diffraction:

- Moving towards consistent picture of inclusive diffractive DIS
- VM & DVCS constrain the generalized parton distributions

Future of DIS:

- Many opportunities: 12 GeV CEBAF, eRHIC, LHC, ILC, eLHC....