The Proton Structure from HERA and the Tevatron

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Topics

- F_2, F_L, $F_2^{c\bar{c}}$
- High Q^2 Neutral & Charged Current Cross Sections
- Gluon Momentum Density
- Inclusive Jet Cross Section at all η and Dijet Mass
- Ratio of Jet Cross Sections at Different $\sqrt{s}$
- BFKL vs DGLAP

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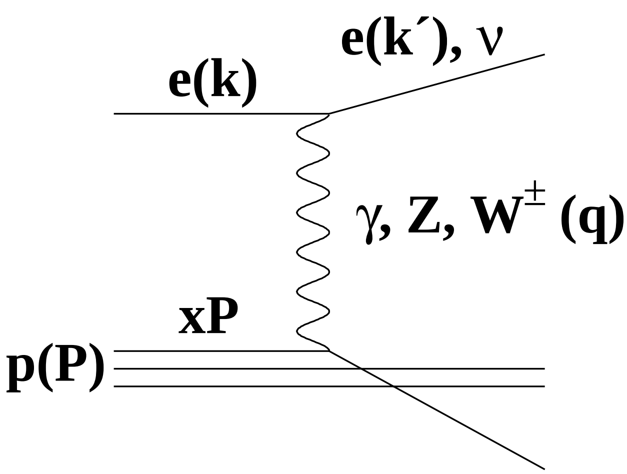
Some History

- powerful tool: Deep Inelastic Scattering of leptons off protons
- if virtual γ carries "large" 4-momentum transfer,
  it can probe internal p structure
- Structure Functions scale with momentum transfer,
  similarly to e scattering off μ
  $\Rightarrow$ *pointlike constituents* of p
- 30 years of DIS experiments $\rightarrow$
  impressive understanding of p structure
- complimentary: $p\bar{p}$ collisions
- p structure understanding crucial for (new) physics
  in current and future colliders

Deep Inelastic Scattering at HERA



$Q^2 = -q^2 = -(k - k')^2$

(4-momentum transfer)^2

$x = Q^2/(2P \cdot q)$

parton momentum fraction

$y = P \cdot q/(P \cdot k)$

fractional energy transfer

$$\frac{d^2\sigma^{NC}(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2^{NC}(x,Q^2) - y^2 F_L^{NC}(x,Q^2) \mp Y_- xF_3^{NC}(x,Q^2)\right]$$

$$F_2^{NC}(x,Q^2) = \sum_{i=1}^{n_f} A_i\, x\,[q_i(x,Q^2) + \bar{q}_i(x,Q^2)]$$

$$xF_3^{NC}(x,Q^2) = \sum_{i=1}^{n_f} B_i\, x\,[q_i(x,Q^2) - \bar{q}_i(x,Q^2)]$$

A_i, B_i: electroweak quark couplings

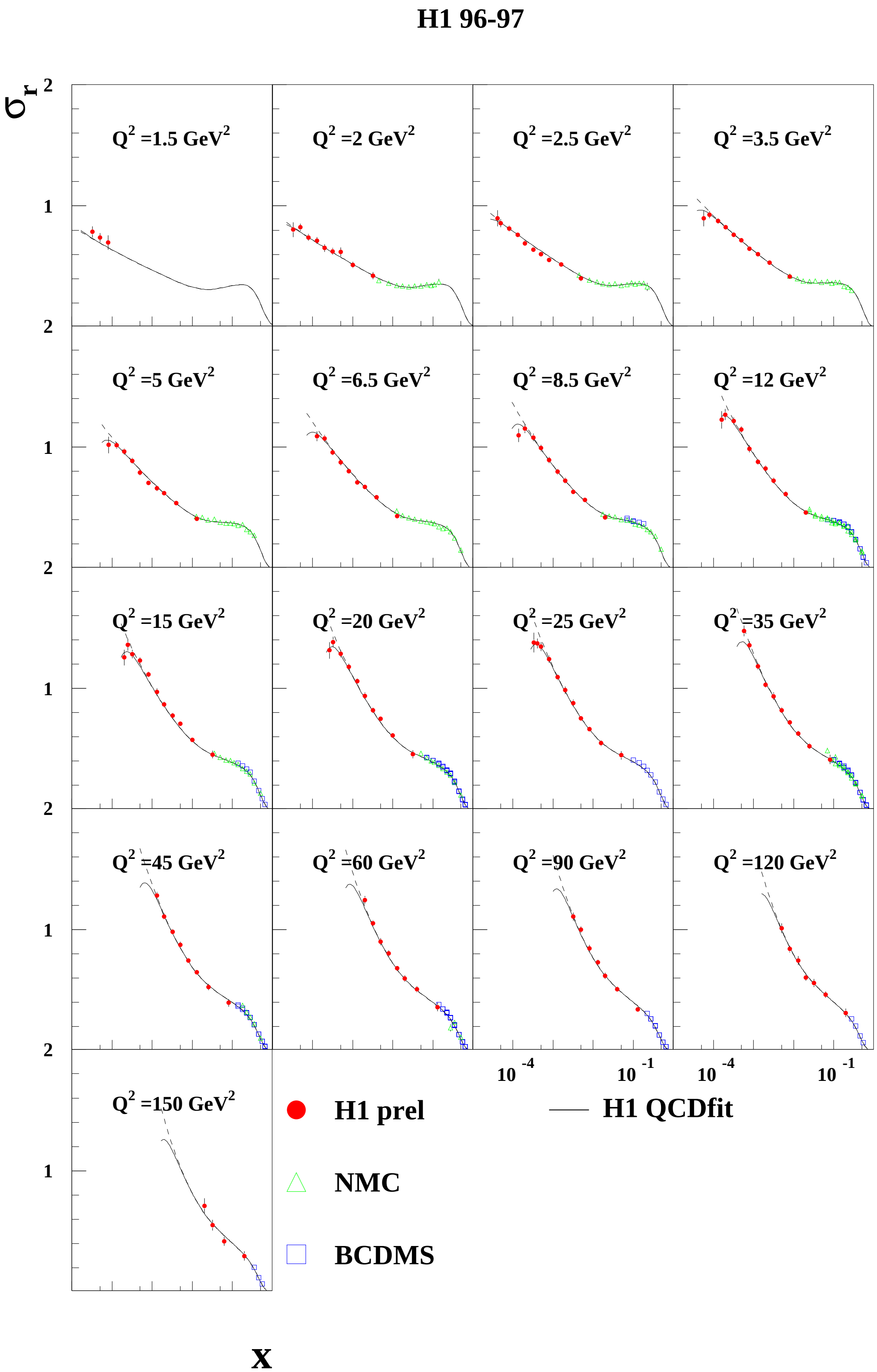
$xq(x,Q^2), x\bar{q}(x,Q^2)$: momentum distributions of (anti)quarks

$F_L(x,Q^2)$: longitudinal S.F. (zero at LO, a few % at NLO)

$Y_{\pm} = 1 \pm (1-y)^2$

Cross Section at Moderate Q^2

$$\sigma_r(x,Q^2) = \frac{d^2\sigma}{dx dQ^2} \cdot \frac{xQ^4}{2\pi\alpha^2} \cdot \frac{1}{Y_+} = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$



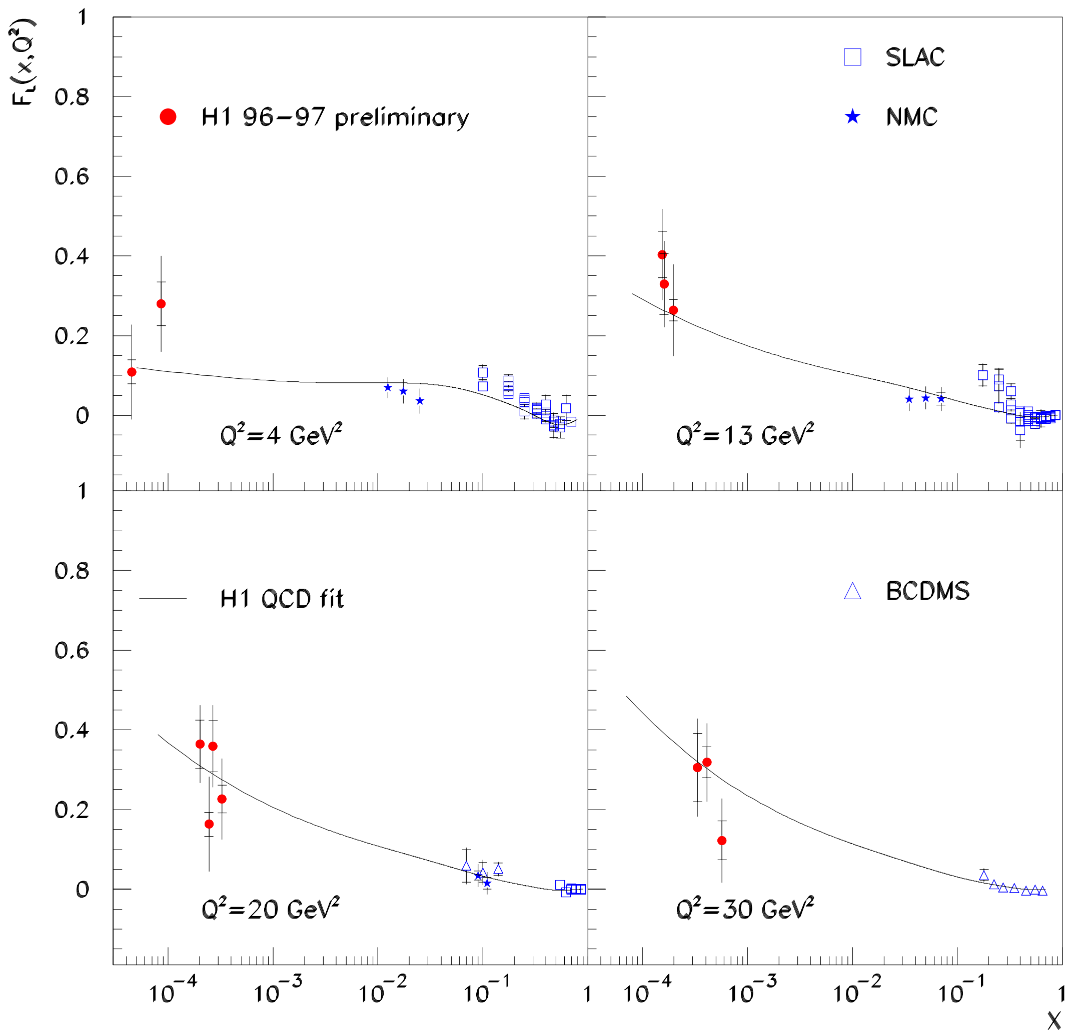
σ_r rise with decreasing x persists down to $Q^2 \approx 1$ GeV^2

pQCD describes the data at $Q^2 \geq 1$ GeV^2

$F_L(x, Q^2)$

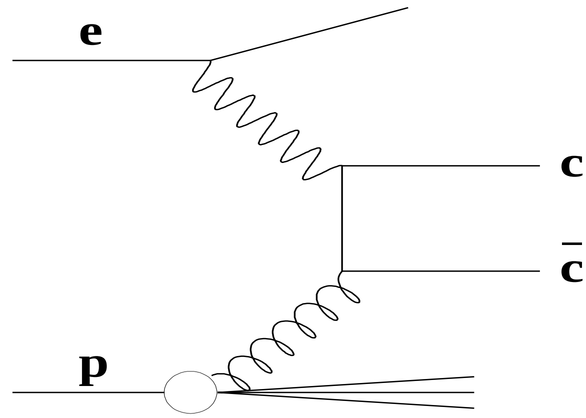
$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} \cdot \{[1 + (1 - y)^2]F_2(x, Q^2) - y^2 F_L(x, Q^2)\}$$

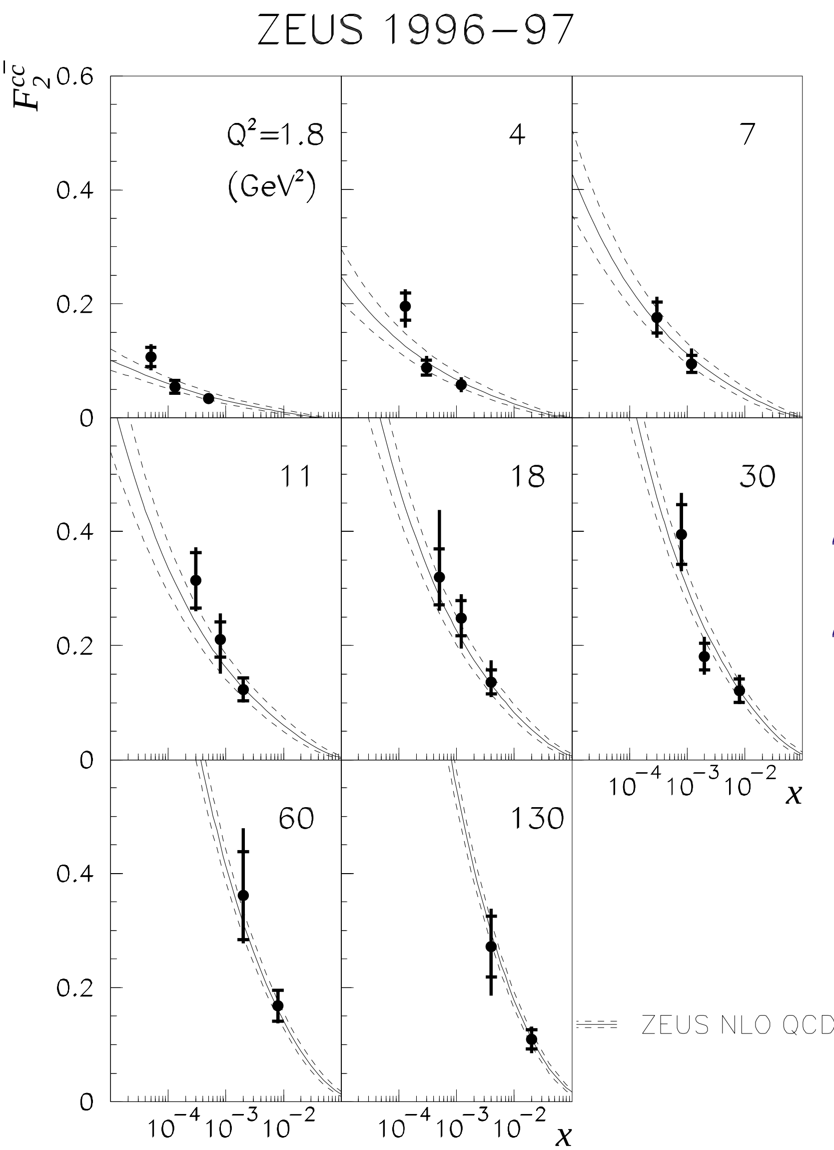
- at high y, $[1 + (1 - y)^2]$ and y^2 comparable
- QCD fit to F_2 at low y $\rightarrow$ extract PDF's $\rightarrow$ evolve in Q^2 $\rightarrow$ predict F_2 at high y
- subtract F_2 from $d^2\sigma/dxdQ^2$



$F_2^{c\bar{c}}(x, Q^2)$

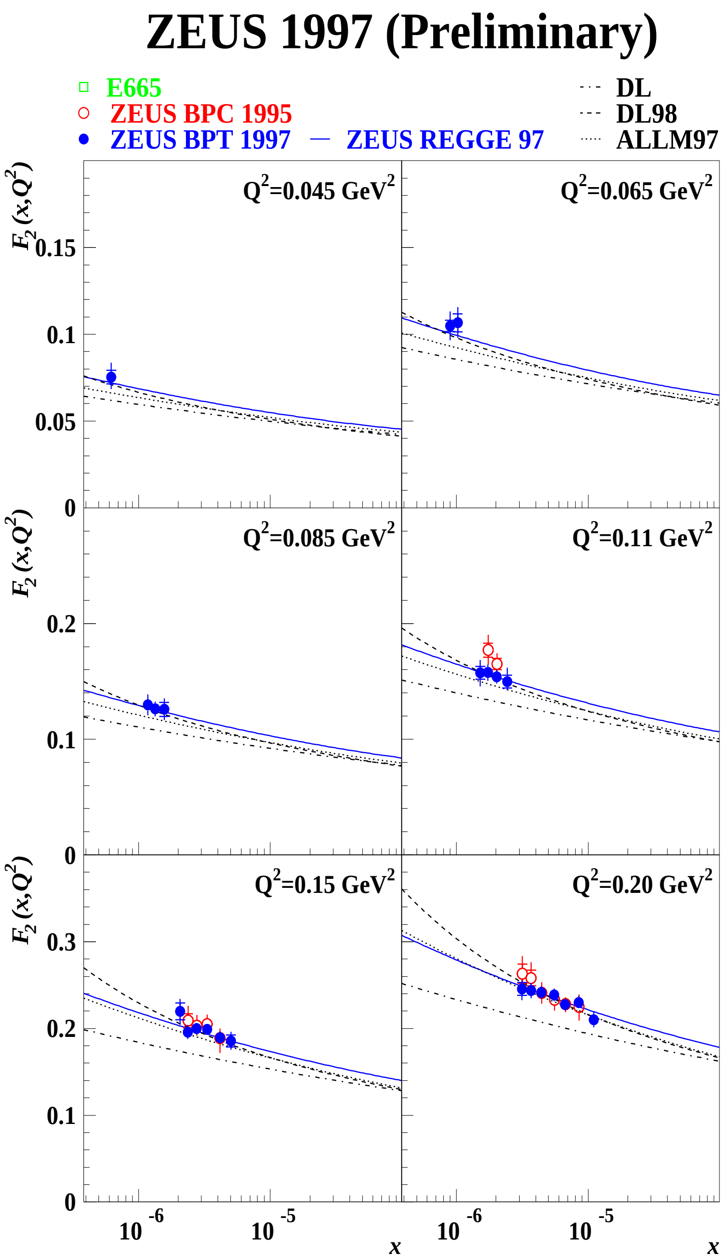
Boson-Gluon Fusion

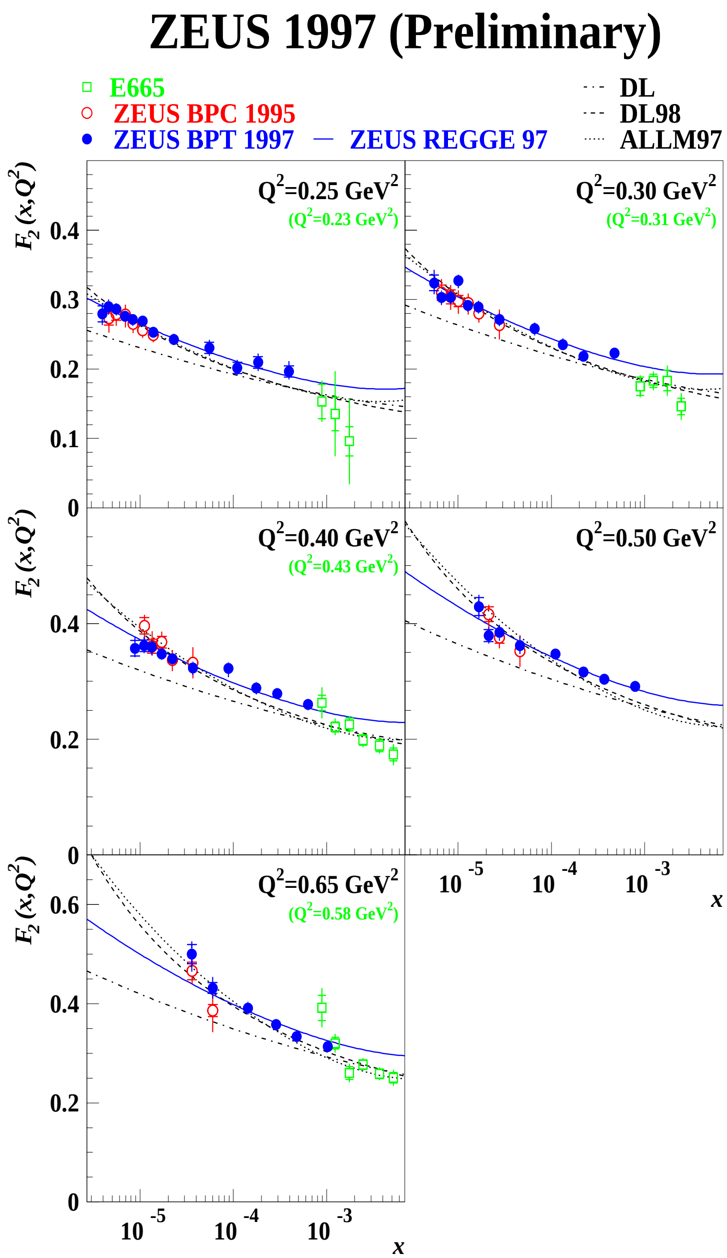




- $F_2^{c\bar{c}} \uparrow$ when $x \downarrow$ faster than F_2 (gluonic origin of c)
- $F_2^{c\bar{c}}/F_2$ is $\sim$10% at $Q^2 = 1.8$ GeV^2 $\sim$30% at $Q^2 = 130$ GeV^2 for $10^{-4} < x < 10^{-3}$

$F_2(x, Q^2)$ at very low Q^2

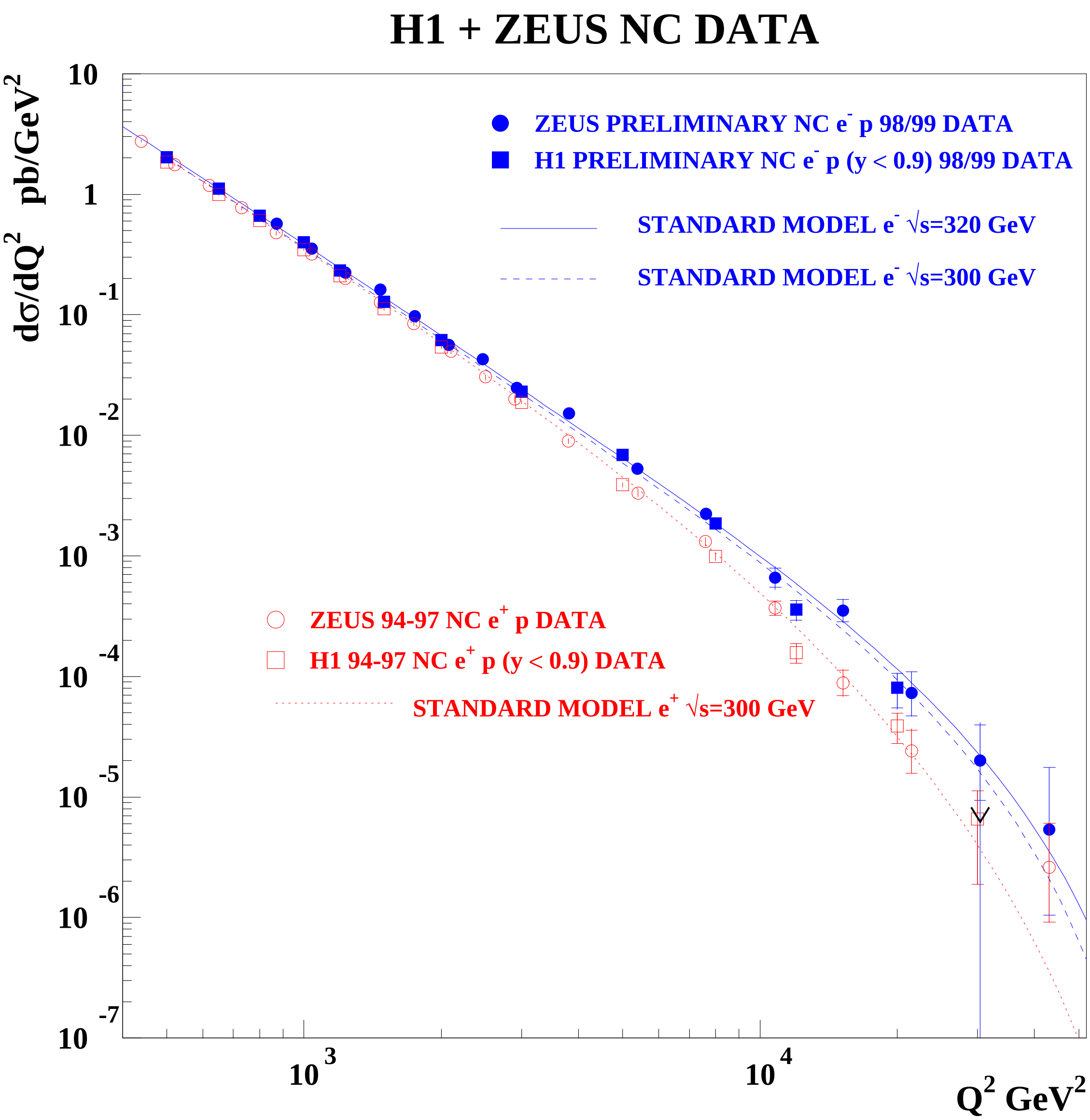




- F_2 still rises at $Q^2 \approx 0.1$ GeV^2

High Q^2 Neutral Current

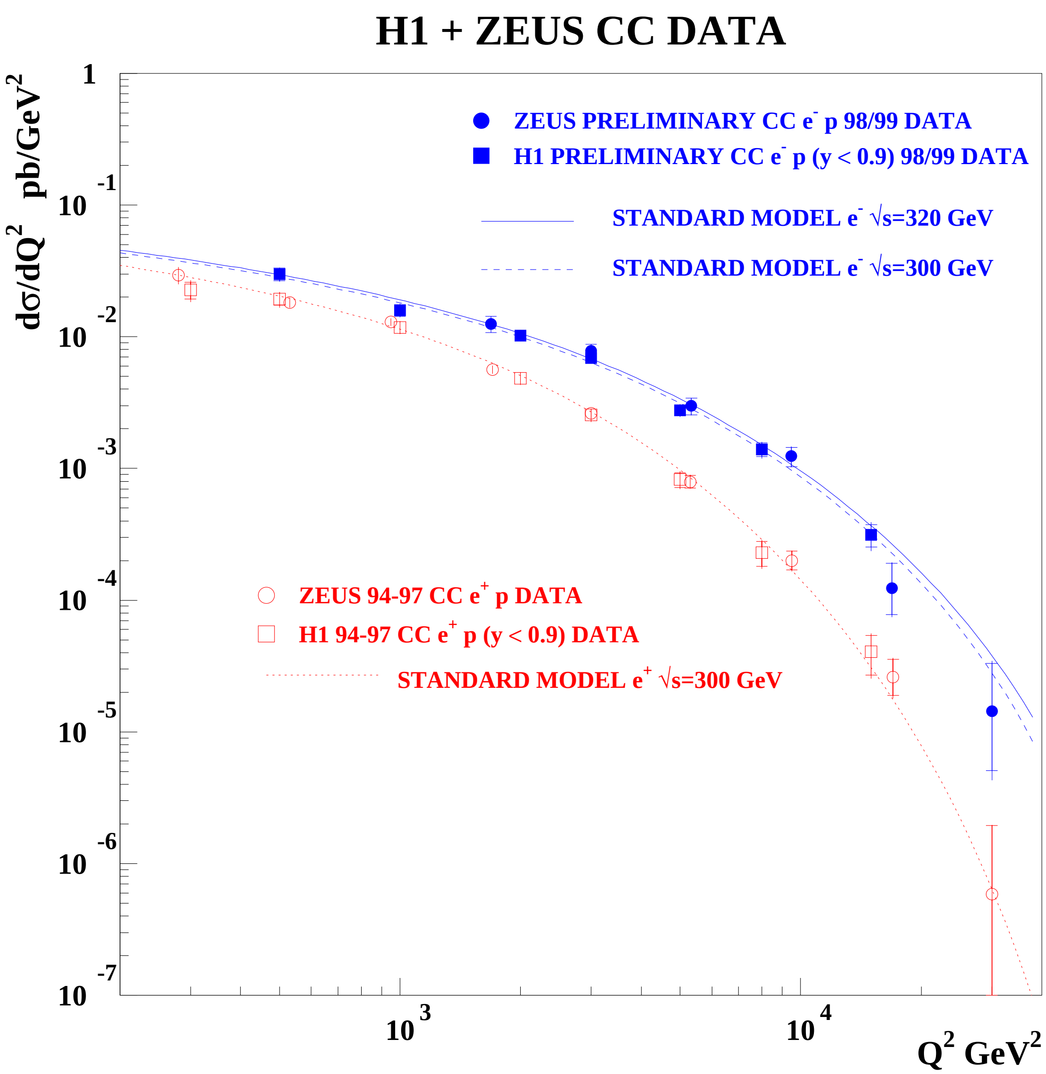
$$\frac{d^2\sigma^{NC}(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+F_2(x,Q^2) - y^2F_L(x,Q^2) \mp Y_- xF_3(x,Q^2)]$$



- SM predictions agree with data
- Parity-violating contribution from Z exchange visible for $Q^2 \geq M_Z^2$

High Q^2 Charged Current

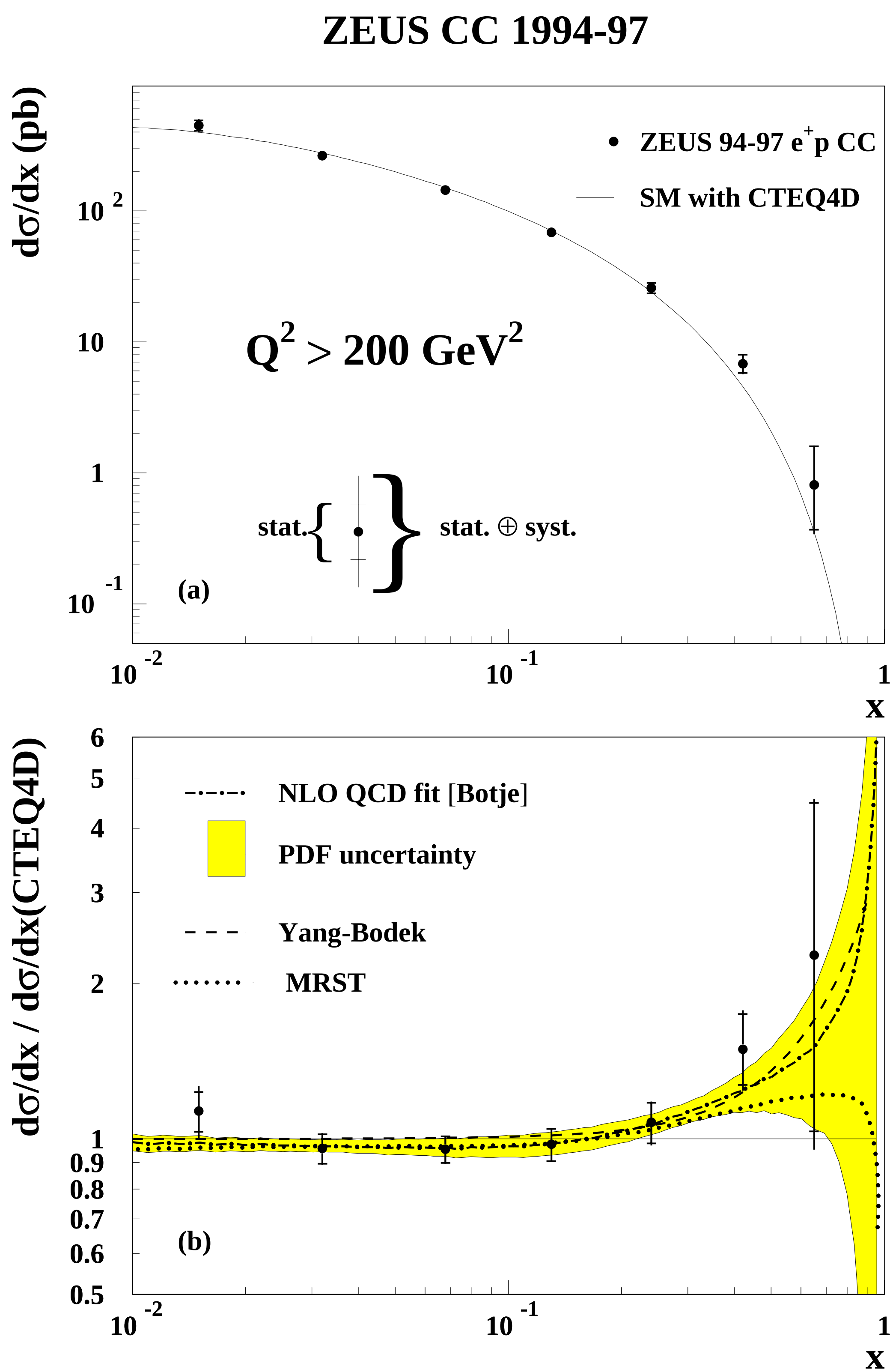
$$\frac{d^2\sigma^{CC}(e^{\pm}p)}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \begin{matrix}[\bar{u}+\bar{c}+(1-y^2)(d+s)] \\ [u+c+(1-y^2)(\bar{d}+\bar{s})]\end{matrix}$$



- SM predictions agree with data
- e^-p dominated by u, e^+p dominated by $(1-y)^2 d$
- $M_W = 80.8^{+4.9}_{-4.5}(stat)^{+5.0}_{-4.3}(syst)^{+1.4}_{-1.3}(PDF)$ GeV

  agrees w/ direct determination of M_W at Tevatron

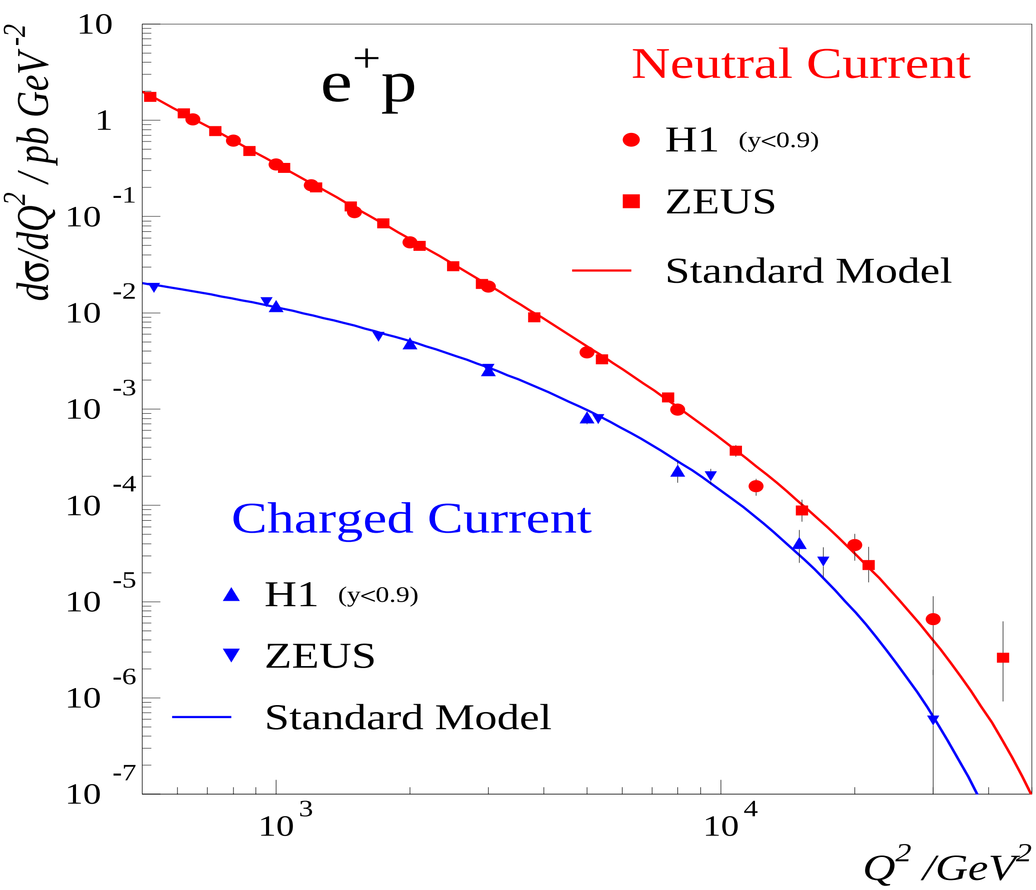
High Q^2 CC (and the d/u ratio)



High Q^2 NC and CC (from e^+p)

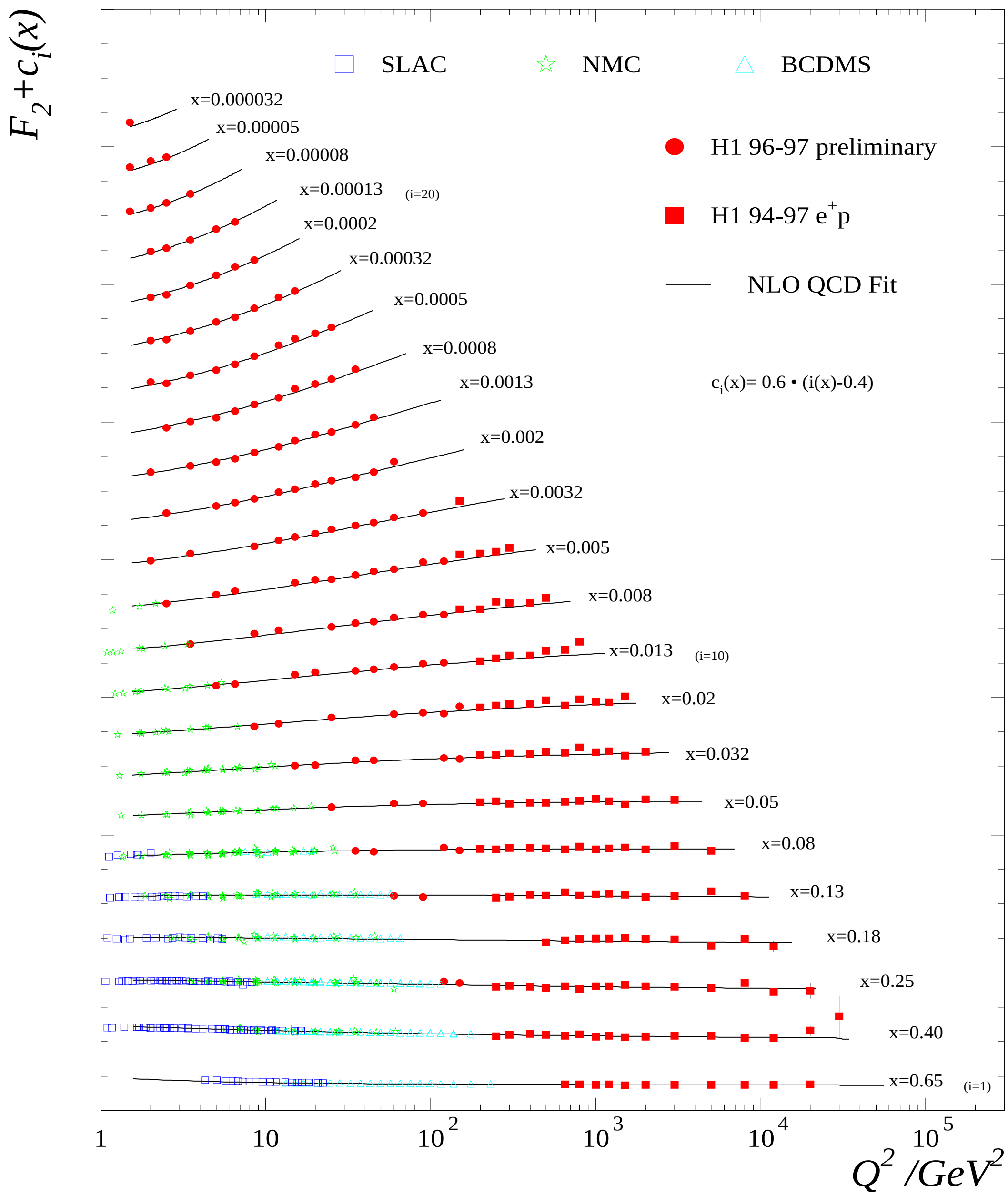
$$\frac{d^2\sigma(e^+p)}{dxdQ^2} = \mathcal{P}\left[Y_+F_2(x,Q^2) - y^2F_L(x,Q^2) - Y\_xF_3(x,Q^2)\right]$$

$$\mathcal{P}^{NC} = \frac{2\pi\alpha^2}{xQ^4}, \qquad \mathcal{P}^{NC} = \frac{G_F^2}{4\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2$$



- EM force stronger than weak for $Q^2 < M_W^2, M_Z^2$
- EM & Weak forces comparable for $Q^2 \geq M_W^2, M_Z^2$

$F_2(x, Q^2)$: Scaling Violations

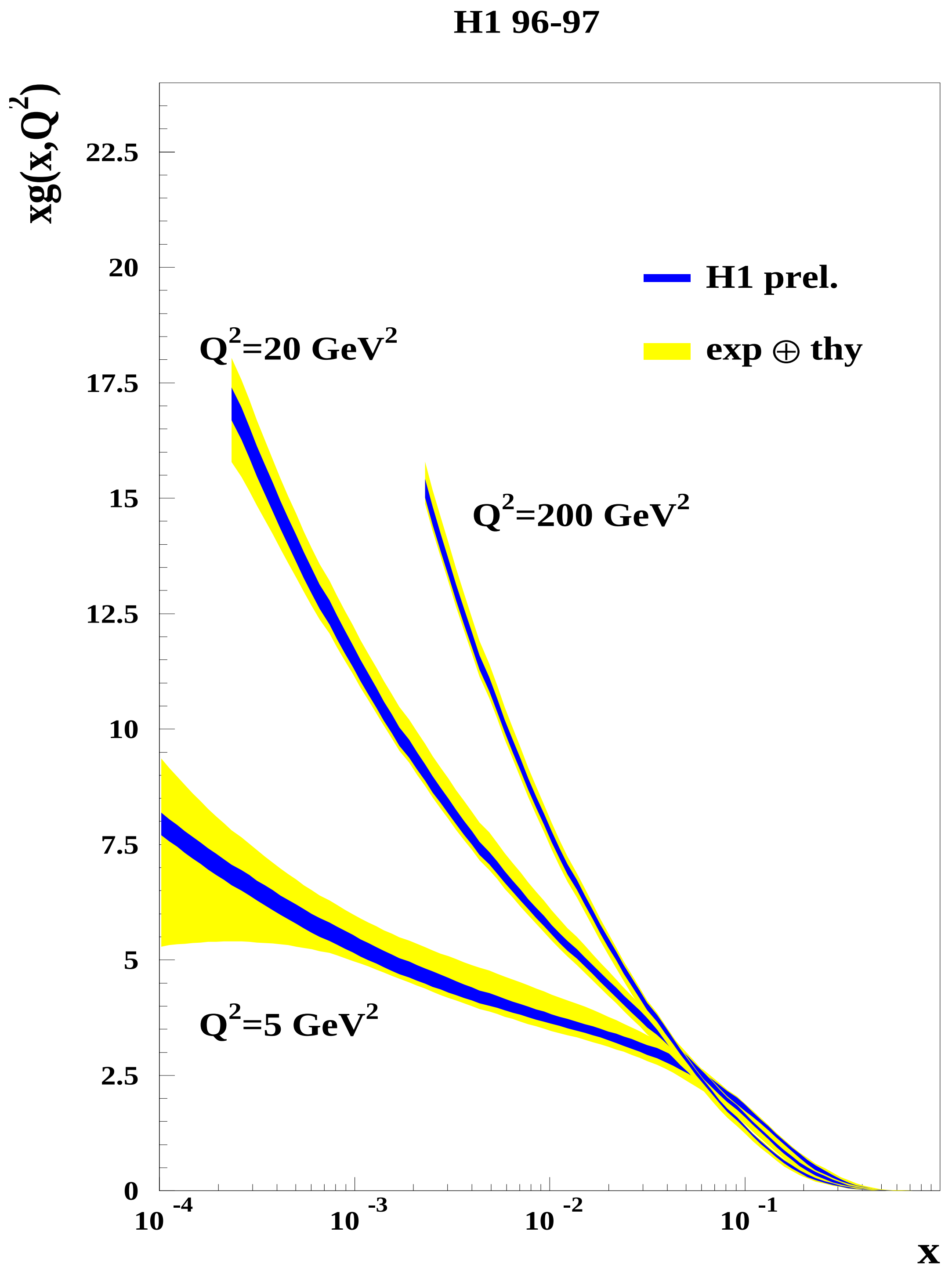


- due to quark-gluon interactions, $\propto \alpha_s \log Q^2$
- as $Q^2 \uparrow$: gluons and sea quarks $\Rightarrow$ more partons of smaller x
- Large scaling violations described by NLO DGLAP

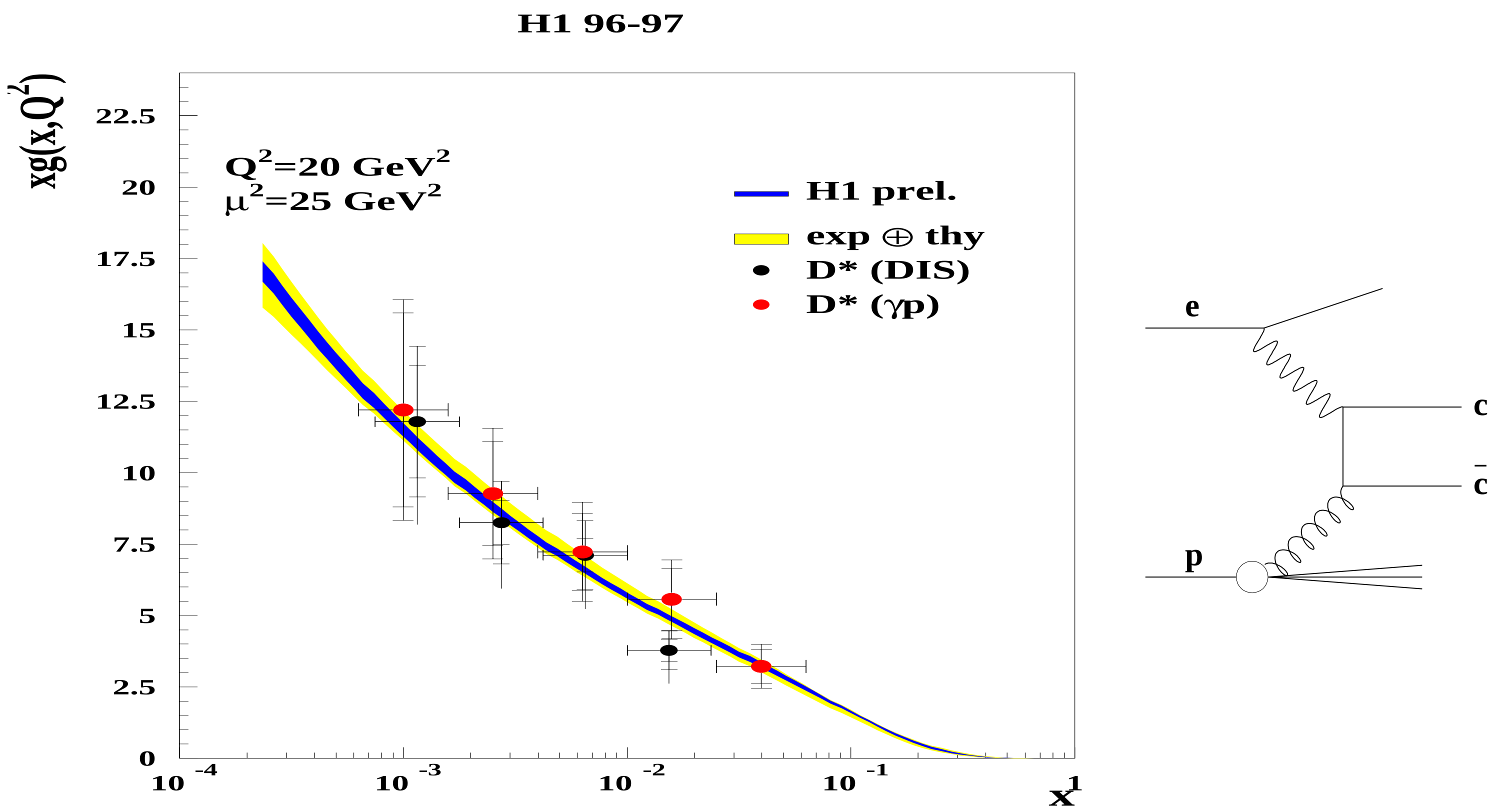
  for $3 \cdot 10^{-5} < x < 0.65$ and $1 < Q^2 < 3 \cdot 10^4$ GeV^2

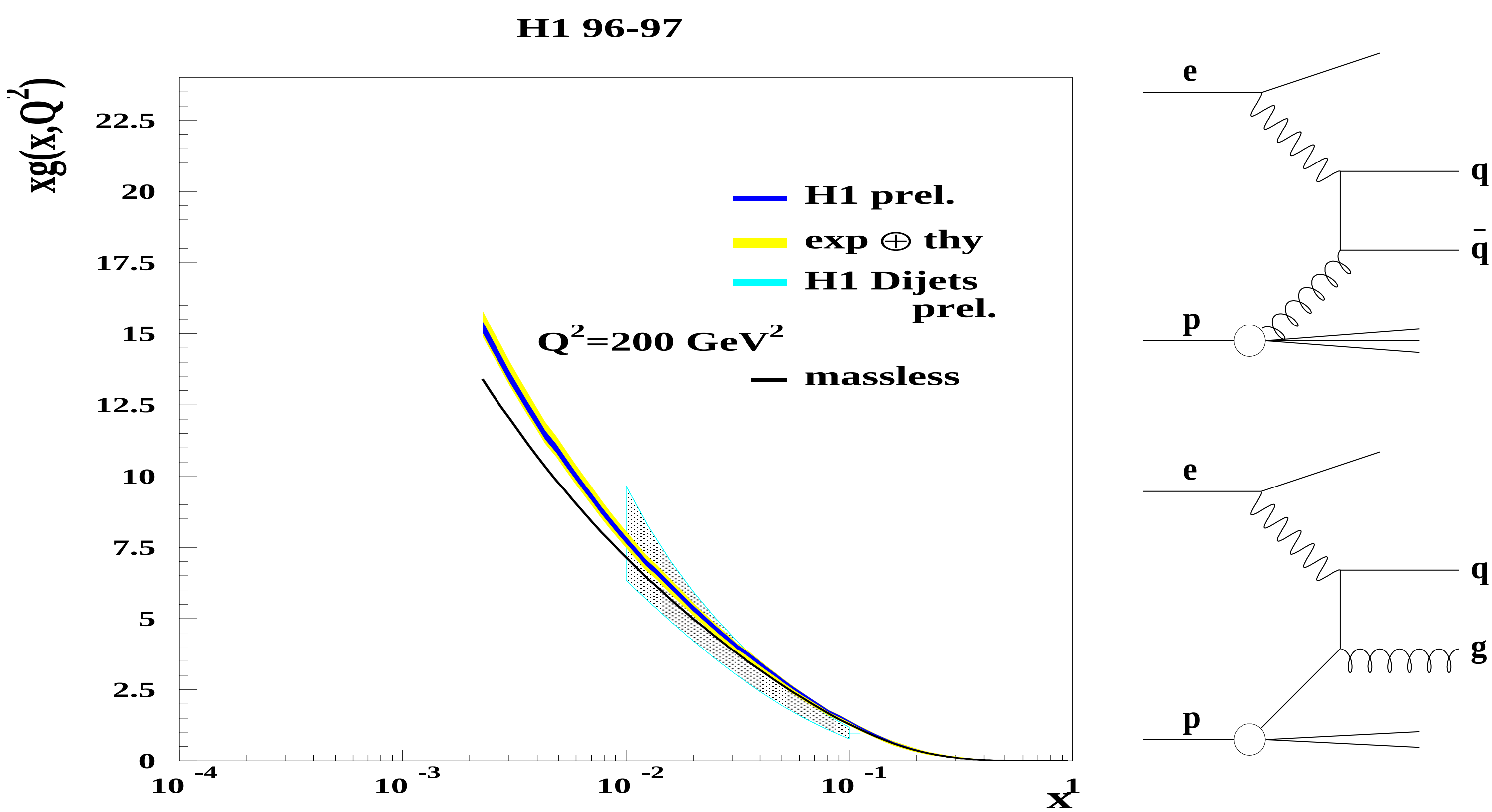
$xg(x,Q^2)$ from F_2 Scaling Violations

extract $xg(x,Q^2)$ from $dF_2/d\ln Q^2$



$xg(x, Q^2)$ from $F_2^{c\bar{c}}$ and Dijets

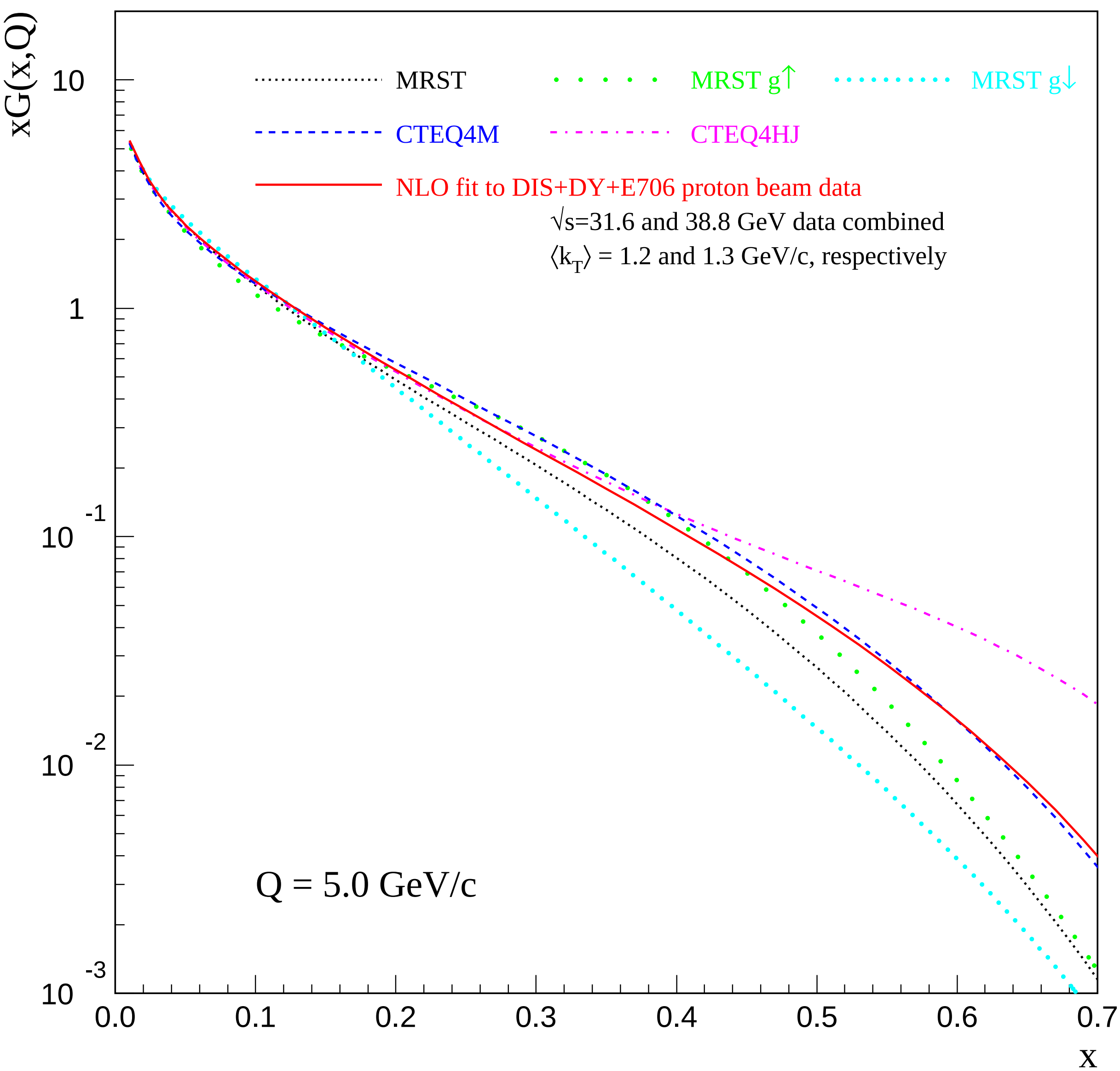




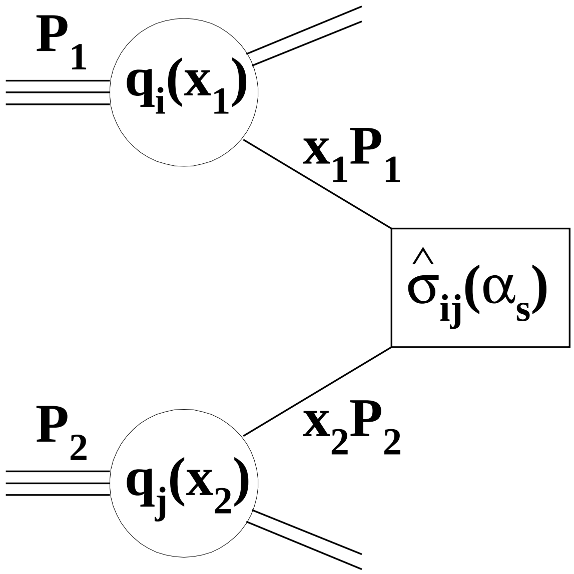
$xg(x, Q^2)$ at high x

MRST: direct photons from WA70,
range of k_T corrections from E706

CTEQ: inclusive jets from Tevatron



Jet Physics in $p\bar{p}$ collisions



$q_{i,j}$: parton densities

$\hat{\sigma}_{ij}$: partonic cross section

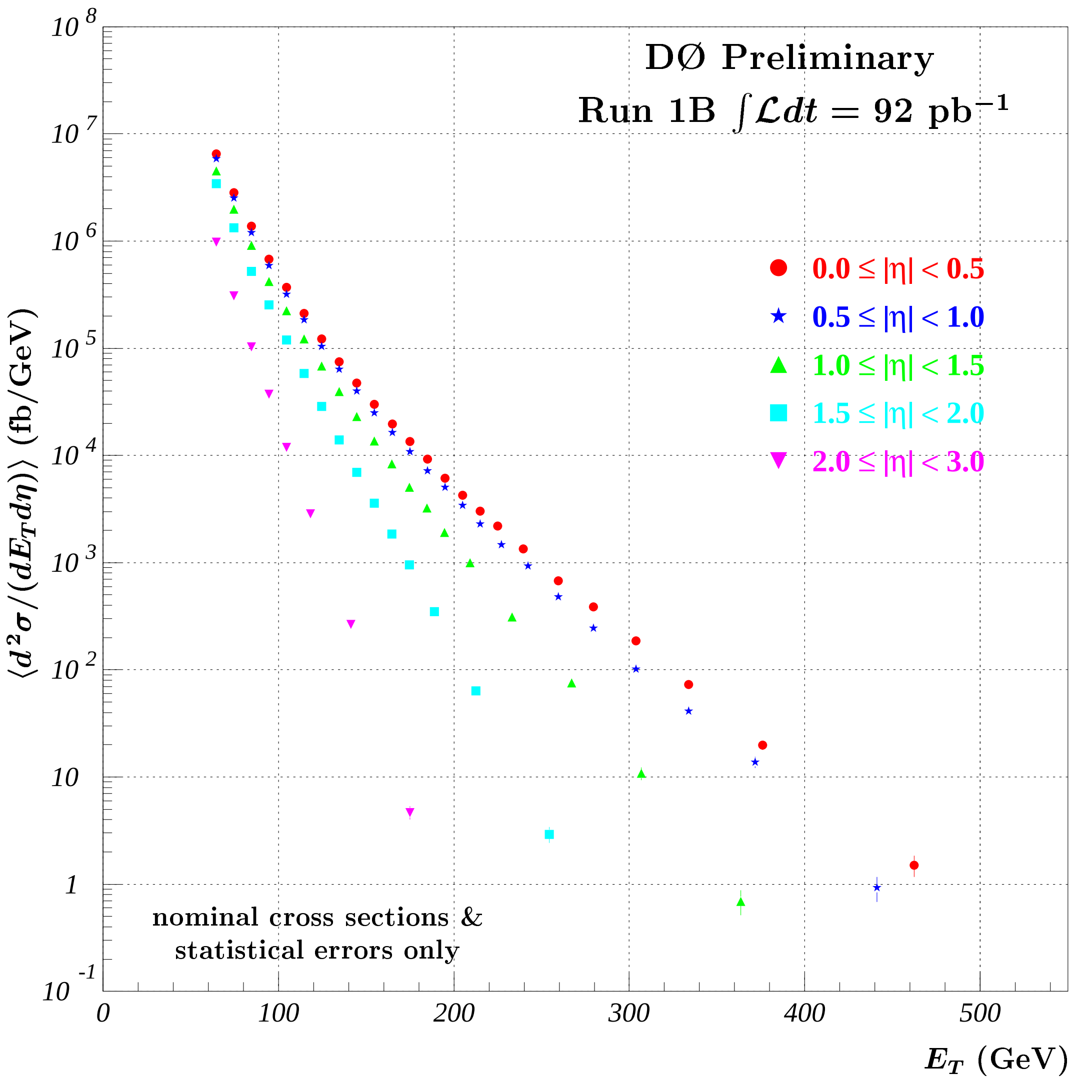
$\hat{\sigma}_{ij}(x_1\mathrm{P}_1, x_2\mathrm{P}_2, Q^2, \mu_F^2, \mu_R^2)$

- Q: characteristic scale of the hard scattering
- Factorization scale μ_F: separates long- from short-distance
- Renormalization scale μ_R: to avoid divergent integrals in $\hat{\sigma}$
- scheme: $\mu_F = \mu_R = Q$
- Q of order jet-E_T

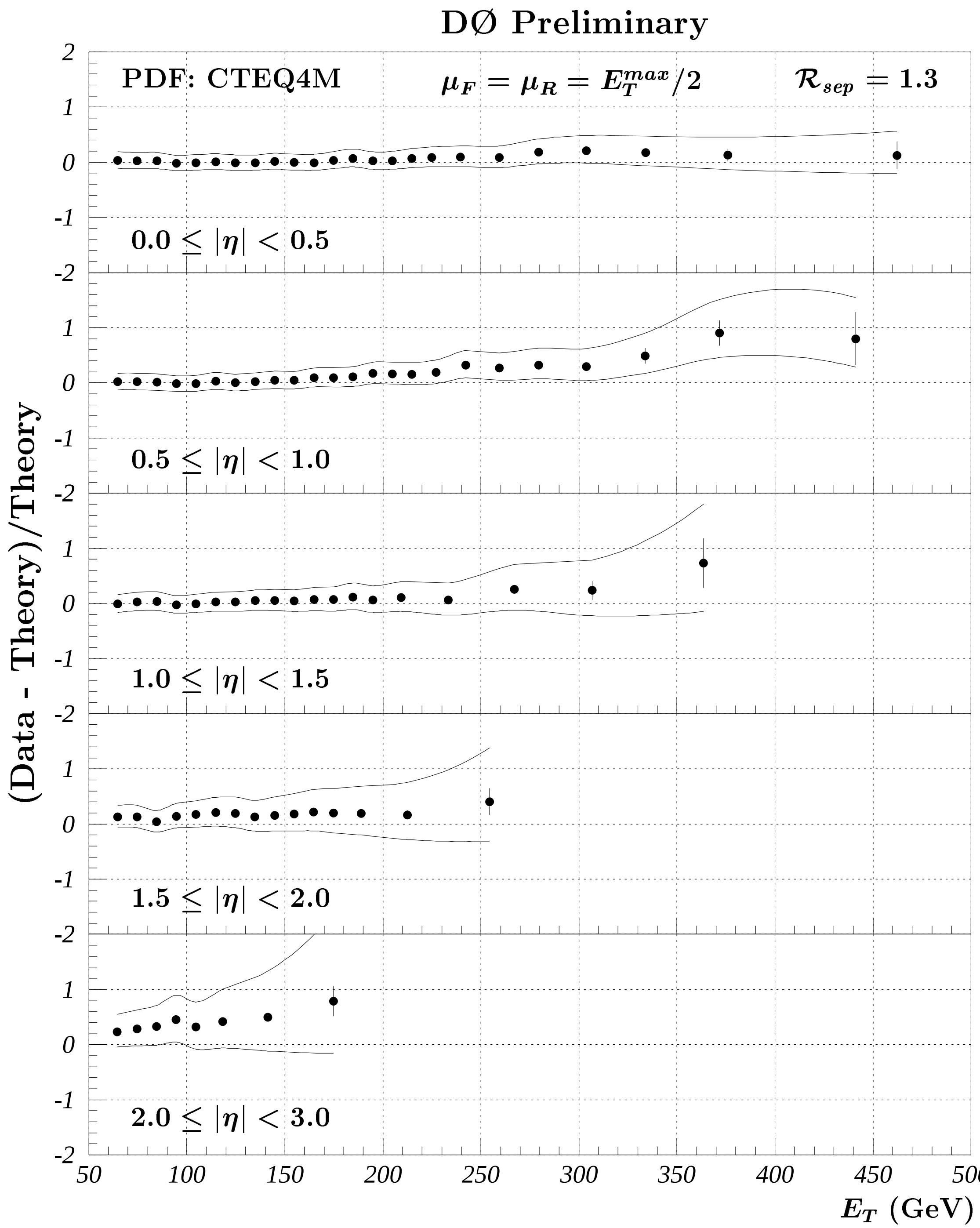
- probe perturbative QCD (hard scattering)
- test and use in PDF's
- search for quark substructure

Inclusive Jet Cross Section

- open question at high jet E_T's
- new measurement at all rapidities $\Rightarrow$ better discriminating power:
  - 4x data points
  - correlations (χ^2)
  - forward $\eta \Rightarrow$ higher x

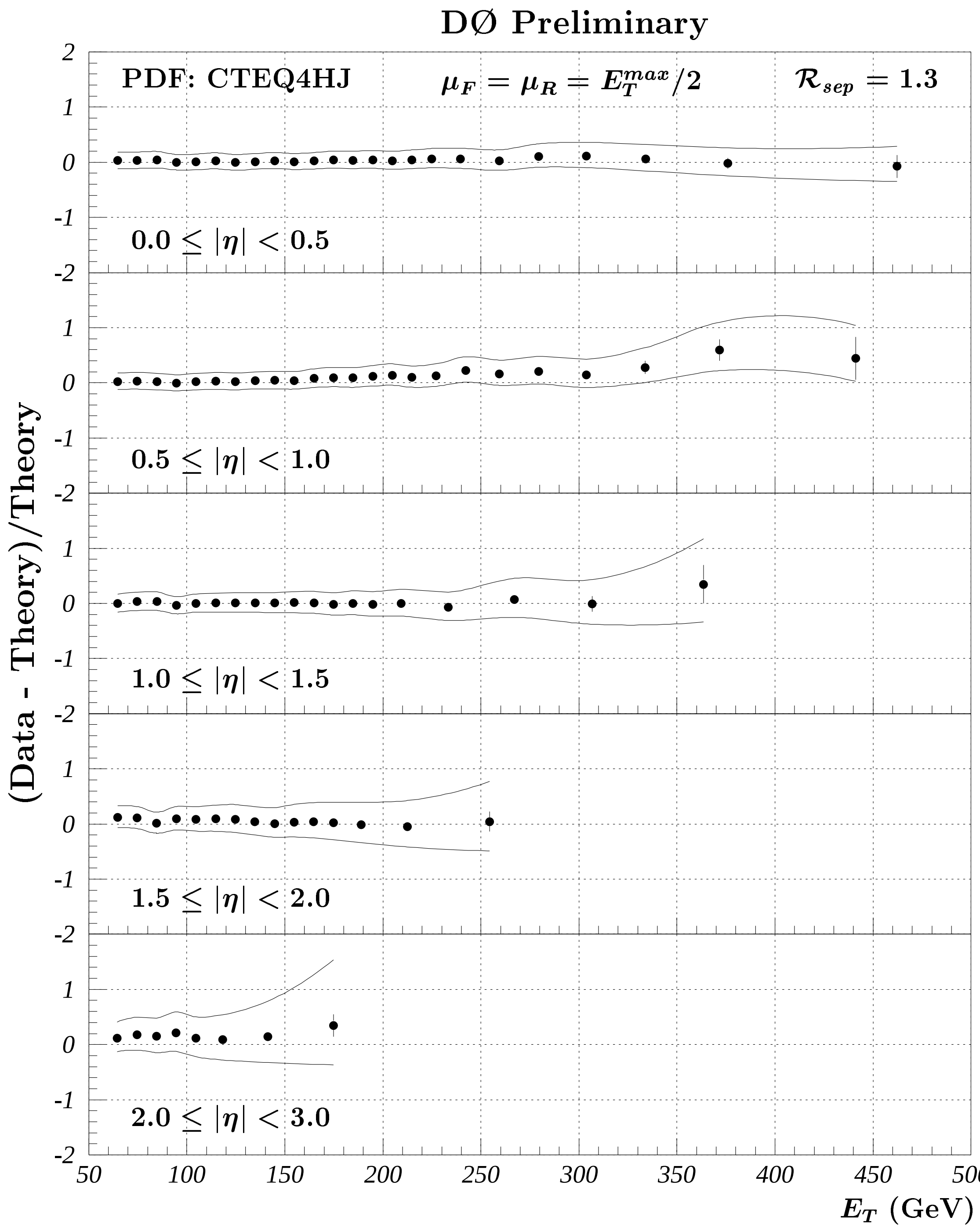


Inclusive Jet Cross Section at All Rapidities



- NLO QCD describes the data over seven orders of magnitude
- trend at higher E_T's?

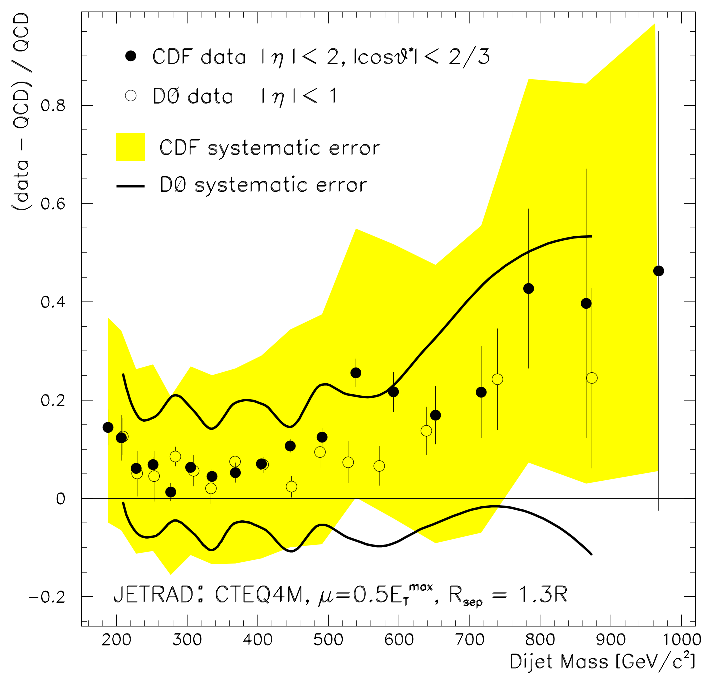
Inclusive Jet Cross Section at All Rapidities

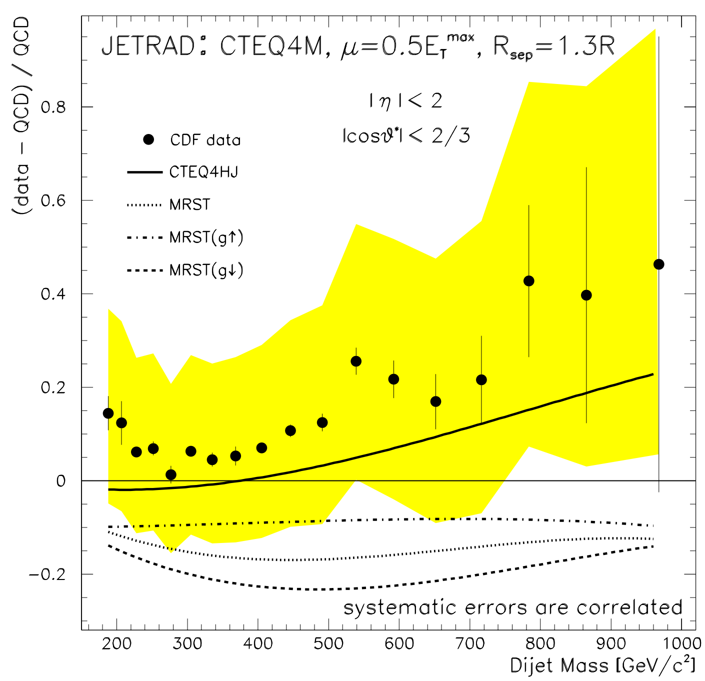


- enhanced gluon at higher x or other effects?
- what about prompt photon data? (k_T, resummation)

Dijet Mass

$$M \equiv \sqrt{(E_1+E_2)^2-(\vec{P}_1+\vec{P}_2)^2} = \sqrt{2E_{T_1}E_{T_1}[\cosh(\Delta\eta)-\cos(\Delta\phi)]}$$

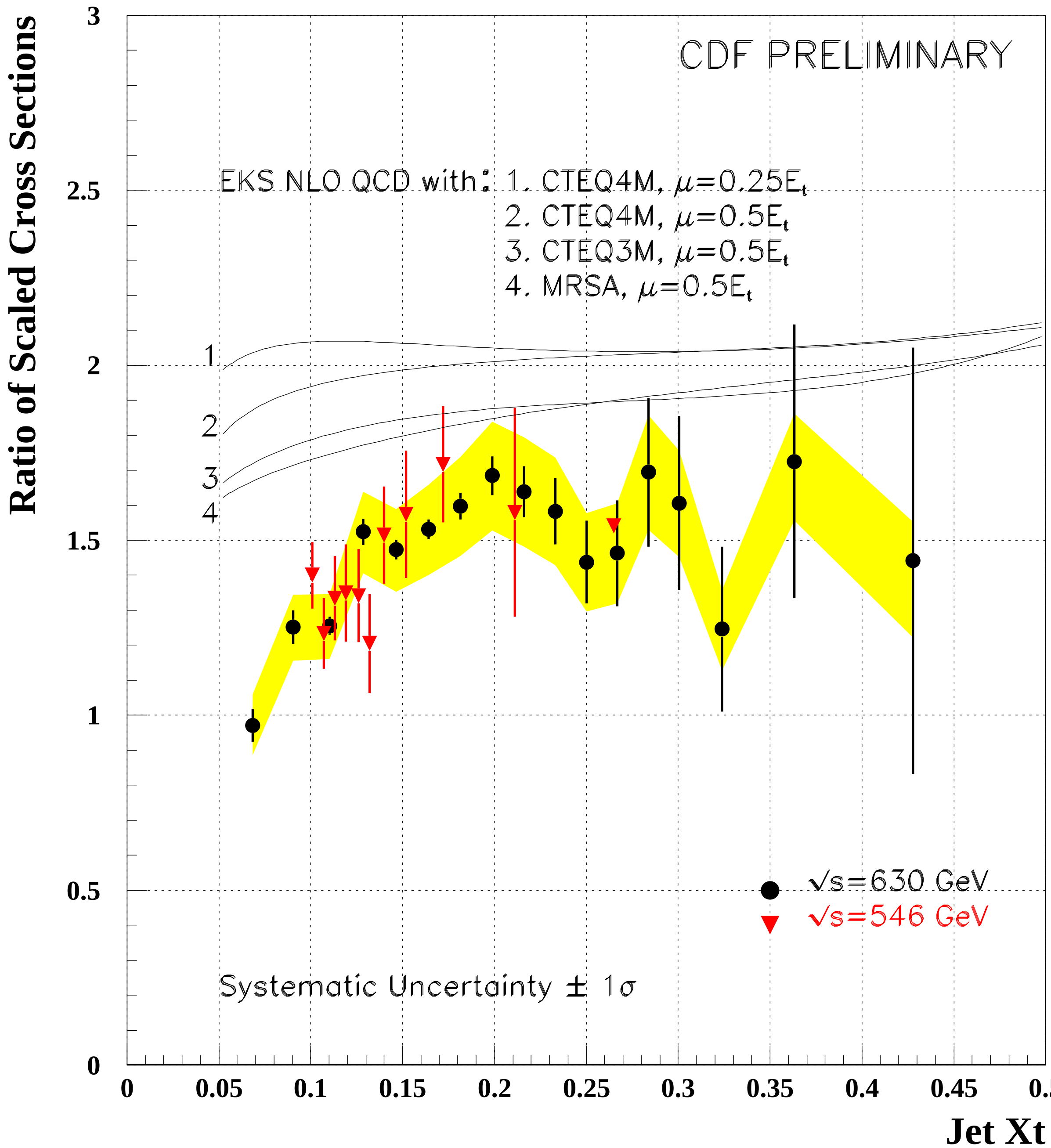




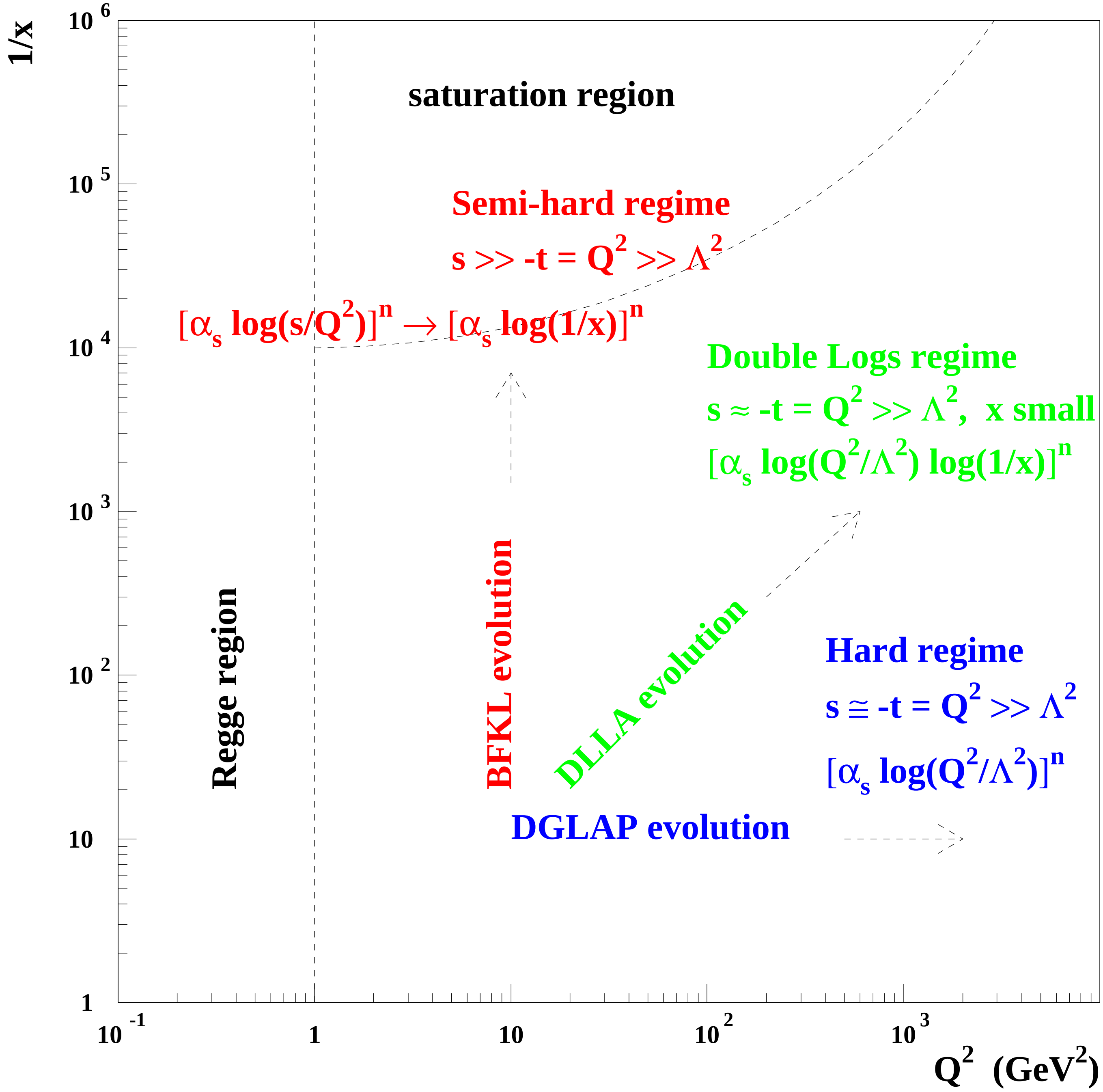
Ratio of Inclusive Jet Cross Sections at $\sqrt{s} = 1800$ and 630 GeV

Scaling violations: at intermediate/high $x_T = 2E_T/\sqrt{s}$,

cross section should decrease with $(Q^2)\ \sqrt{s}$



DGLAP vs BFKL



Dijets at Large Rapidity Intervals

- for $\Lambda_{QCD} \ll Q \ll \sqrt{s} \Rightarrow$ large $\ln(s/Q^2)$ in σ_{dijet}
- $\hat{s} = x_1 x_2 s \Rightarrow$ for large $x_i \Rightarrow$ large $\ln(\hat{s}/Q^2) \approx \Delta\eta$ in $\hat{\sigma}$
- use BFKL to sum all powers of $(\alpha_s \Delta\eta) \Rightarrow$

$$\hat{\sigma} \sim \frac{e^{(\alpha_{\rm BFKL}-1)\Delta\eta}}{\sqrt{\alpha_s \Delta\eta}} \quad \text{with} \quad \alpha_{\rm BFKL} = 1 + \frac{4\ln 2\, {\rm N_c}\, \alpha_{\rm s}}{\pi} \simeq 1.5$$

- PDF's steeply falling at large $x \Rightarrow$

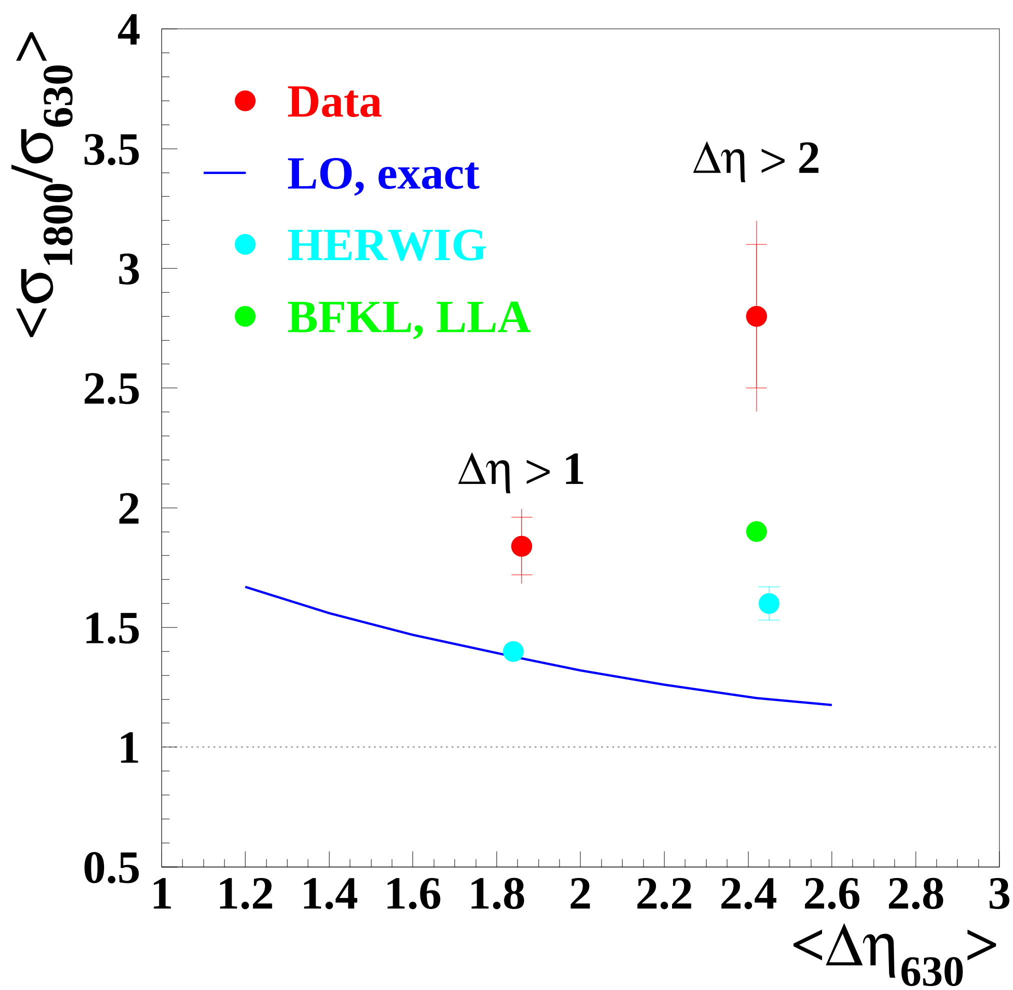
  not possible to see exponential growth in σ_{dijet}

- take ratio at $\sqrt{s_A} = 1800$ GeV, $\sqrt{s_B} = 630$ GeV
- fix x_1, x_2, $Q^2 \Rightarrow$ PDF's cancel $\Rightarrow$

$$R = \frac{\sigma(x_1, x_2, Q^2, s_A)}{\sigma(x_1, x_2, Q^2, s_B)} = \frac{e^{(\alpha_{\rm BFKL}-1)(\Delta\eta_A - \Delta\eta_B)}}{\sqrt{\Delta\eta_A/\Delta\eta_B}}$$

- rise with $\Delta\eta \Rightarrow$ rise with s
- extract an effective value for $\alpha_{\rm BFKL}$

Dijets at Large $\Delta\eta$ (cont'd)



- R increases with $\Delta\eta \Leftrightarrow \sqrt{s}$:

  for $\Delta\eta > 2 \Rightarrow <\Delta\eta_{630}>= 2.4$ and $<\Delta\eta_{1800}>= 4.6$

$$<\sigma_{1800}/\sigma_{630}>= 2.8 \pm 0.3\,(\text{stat}) \pm 0.3\,(\text{syst})$$

- effective BFKL intercept:

$$\alpha_{\text{BFKL}}(20\,\text{GeV}) = 1.65 \pm 0.05\,(\text{stat}) \pm 0.05\,(\text{syst})$$

- difference in σ between different $\sqrt{s}$ ($\Delta\eta$) increases w/ $\Delta\eta$

Summary

- proton structure function measured
  for $0.04 < Q^2 < 3 \cdot 10^4$ GeV^2 and $6 \cdot 10^{-7} < x < 0.65$
- DGLAP evolution describes data down to $Q^2 \sim 1$ GeV^2
- c content of proton 10-30%
- d/u ratio uncertainty at high x
- high Q^2 CC and NC data agree with SM predictions
- $xg(x, Q^2)$ well constrained at low-x,
  but large uncertainties at high-x
- jet cross section from $p\bar{p}$ at forward $\eta \Rightarrow$ gluon at high-x
- sign of BFKL evolution at dijets with large $\Delta\eta$ in $p\bar{p}$
- await increased L, high Q^2 at HERA and
  high E_T jets at Tevatron Run II !