QCD at colliders

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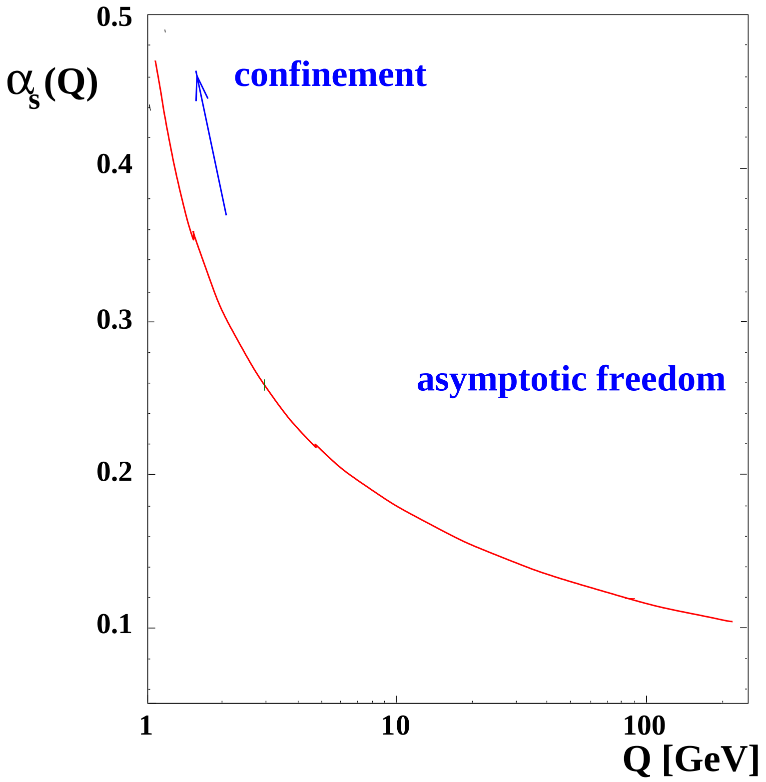
- **Introduction**
- **QCD at e^+e^- (LEP, SLD)**
- **QCD at ep (HERA)**
- **QCD at $p\bar{p}$ (Tevatron)**
- **Conclusions**

I. Introduction

QCD is a difficult (and vast) subject! ... because

- **QCD** is a theory of the interaction of quarks and gluons... but
- What we have in the laboratory are **hadrons**...and
- We don't understand yet how **QCD** makes **hadrons** out of quarks and gluons.

However, asymptotic freedom, allows us to make perturbative predictions of **QCD**, at high energies (colliders).



- Which needs (hopefully small) modifications from higher-order and non-perturbative effects.
- This talk will be about tests of perturbative QCD at colliders. Will try to assess the theoretical and experimental uncertainties. $\Rightarrow$

I. QCD at $\mathrm{e}^+\mathrm{e}^-$

Cartoon of our understanding of **QCD** $\Rightarrow$

- Stage 1: Fixed-order pQCD “Under control”
  - Typically calculated to Next-to-Leading-Order (NLO), i.e. $\mathcal{O}(\alpha_s^2)$. Sometimes to NNLO or beyond..
  - Depends on renormalization scale, μ_R. (dependence vanishes at all-orders).
- Stage 2: Higher-Order pQCD “More or less under control”
  - Resummation: For some observable $\mathcal{R}$ which is becoming small, one may be able to resum all terms proportional to $\alpha_s^n(\ln 1/\mathcal{R})^{n+1-l}$, $(n = 1..\infty)$.
    $l = 0$ is called Leading-Log (LL), $l = 1$, NLL, etc.
    Need to worry about “matching” with fixed-order pQCD.
  - QCD model: Parton Showers (PS) Monte Carlo implementation of HO parton branching in LL approximation.

- Stage 3: Hadronization "Only models"
  - The virtuality of the partons are below some cut-off, t_0, (typically a few times λ_{QCD}). $\Rightarrow$ non-perturbative regime.
  - Models, such as cluster fragmentation (HERWIG) or string fragmentation (ARIADNE) are very successful in describing the observed hadron spectra. (After tuning)
  - To have a confidence in the results we want

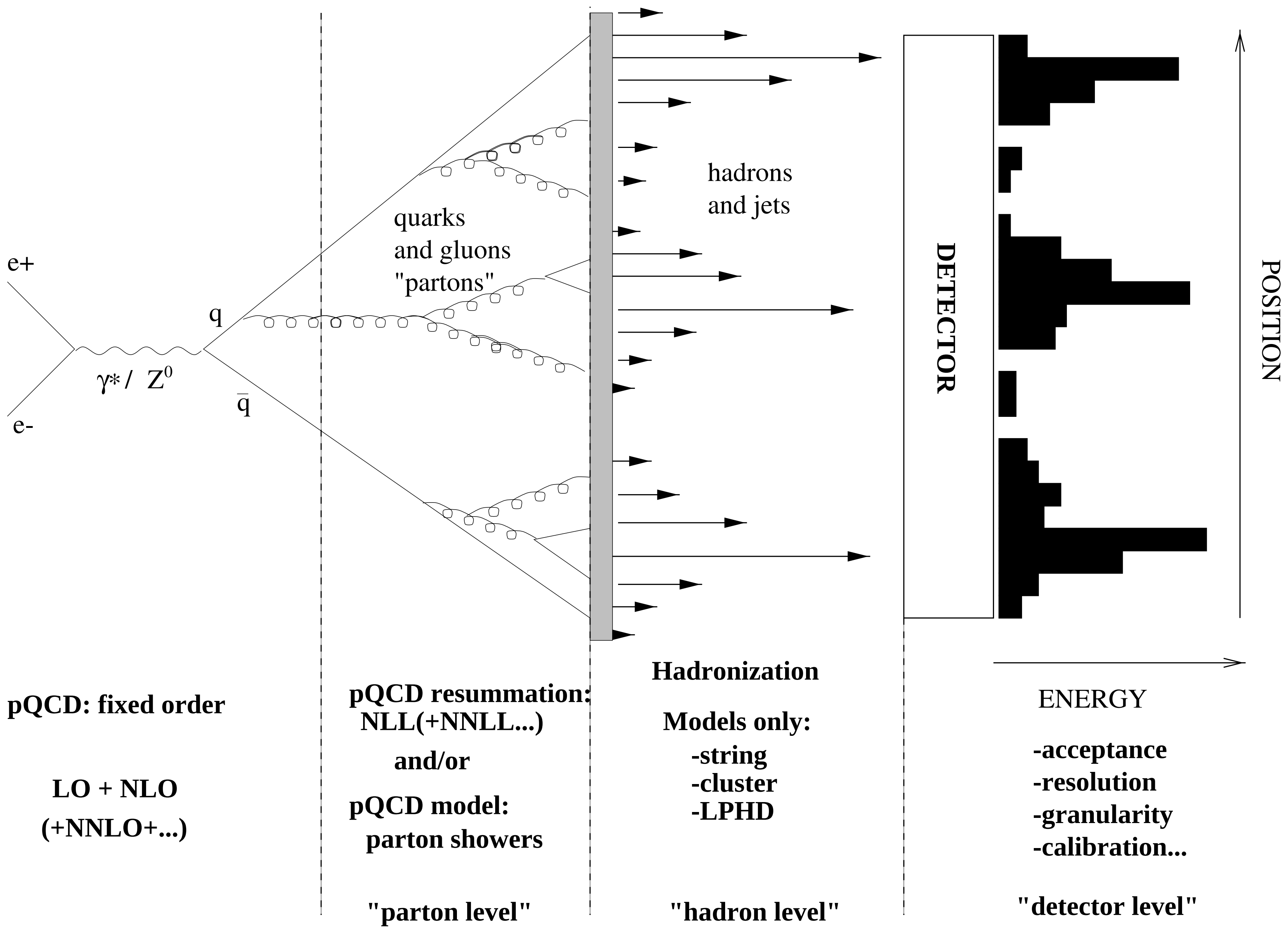
$$\text{hadronization corrections} = \frac{\text{``parton level''}}{\text{``hadron level''}}$$

    to be small (i.e ~ 1).

- Stage 4: Detector

Finally...

- The hadrons are measured in a detector with finite acceptance, resolution, granularity, etc.
- Note that a reliable comparison of data to pQCD requires a good description (by Monte Carlo) of the hadronic final state.



e+
e-
γ*/ Z0
q
q̄
quarks
and gluons
"partons"
hadrons
and jets
DETECTOR
POSITION
ENERGY
pQCD: fixed order
LO + NLO
(+NNLO+...)
pQCD resummation:
NLL(+NNLL...)
and/or
pQCD model:
parton showers
"parton level"
Hadronization
Models only:
-string
-cluster
-LPHD
"hadron level"
-acceptance
-resolution
-granularity
-calibration...
"detector level"

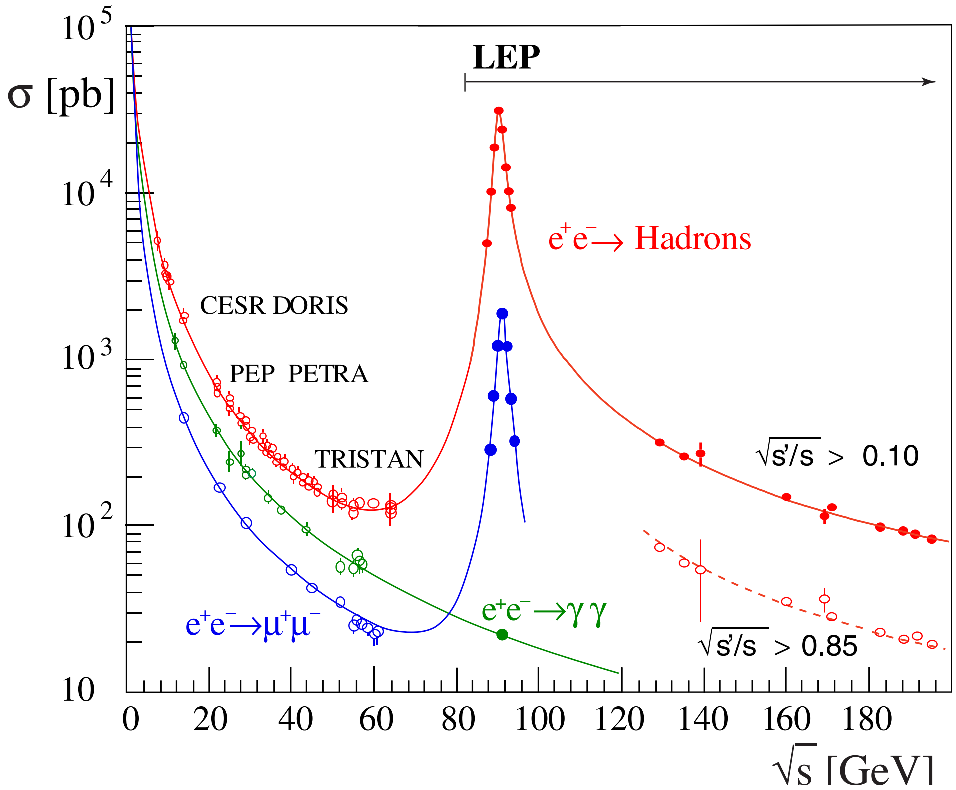
1. Total hadronic cross-section in $(\mathrm{e}^+\mathrm{e}^-)$

$$R_\gamma = \frac{e^+e^- \to \mathrm{hadrons}}{e^+e^- \to \mu^+\mu^-} \approx 3\sum_q Q_q^2$$

:one of the original signs of existence of quarks.

- Hadronization takes place at a late time scale ($\sim 1/\lambda_{QCD}$)

$\Rightarrow$ the total hadronic cross-section from qQCD only (+EW).



$$R_Z = \frac{\Gamma(Z \to \mathrm{hadrons})}{\Gamma(Z \to \mu^+\mu^-)} = R_0(1+\delta_{QCD})$$

$$\delta_{QCD} = 1.045(\frac{\alpha_s}{\pi}) + 0.94(\frac{\alpha_s}{\pi})^2 - 15(\frac{\alpha_s}{\pi})^3$$

$\Rightarrow$

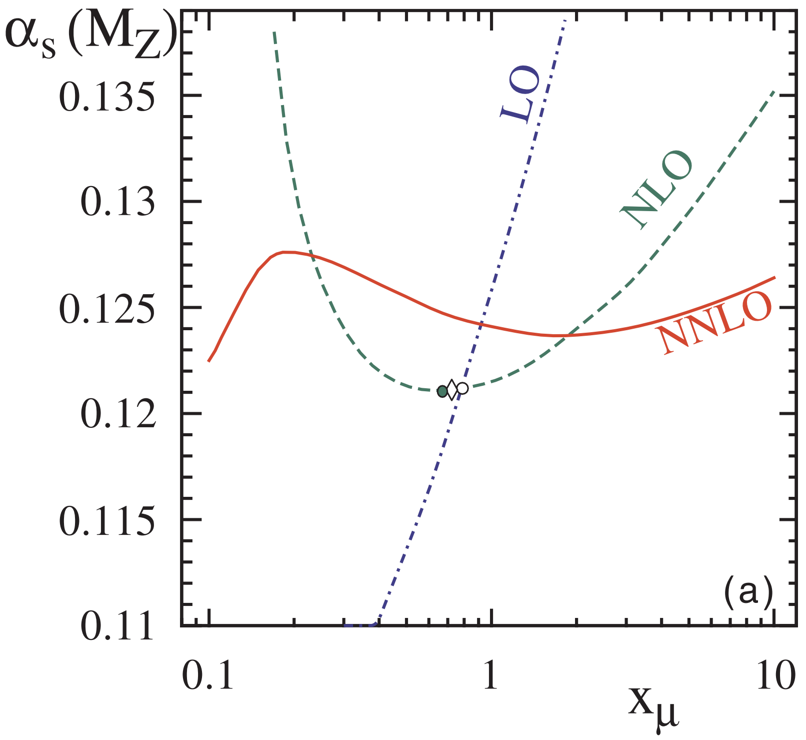
$$\alpha_s(M_Z) = 0.124 \pm 0.004(exp) \pm 0.002(M_H, M_t) \pm^{0.003}_{0.001} (QCD)$$

(S. Bethke *J. Phys.G26: R27,2000* from LEP combined values of R_Z)

Renormalization scale dependence

μ_R dependence of
$\alpha_s(M_Z)$
from R_Z $\Rightarrow$
(S. Bethke review)

$x_\mu = \mu_R / M_Z$



- pQCD calculations needs to have μ_R.
- Gets more stable with higher orders.
- Uncertainties from μ_R are usually assigned by varying x_μ: typically $0.5 \leftrightarrow 2.0$.
- No "proof" of what the right range of variation is.

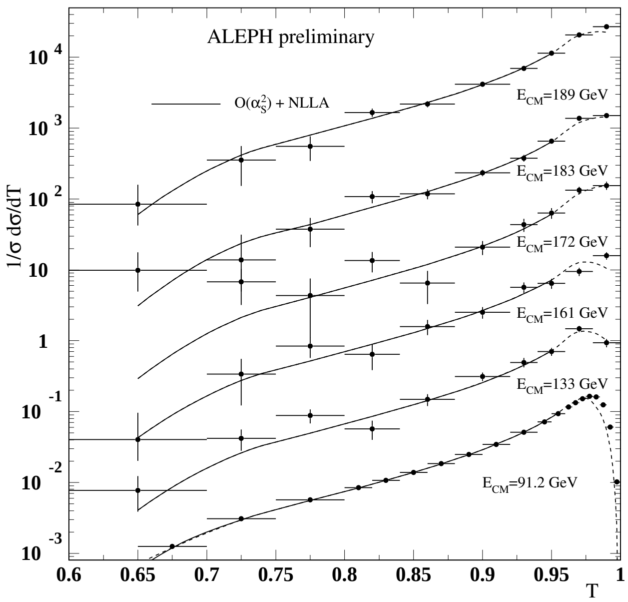
2. Event shapes in (e^+e^-)

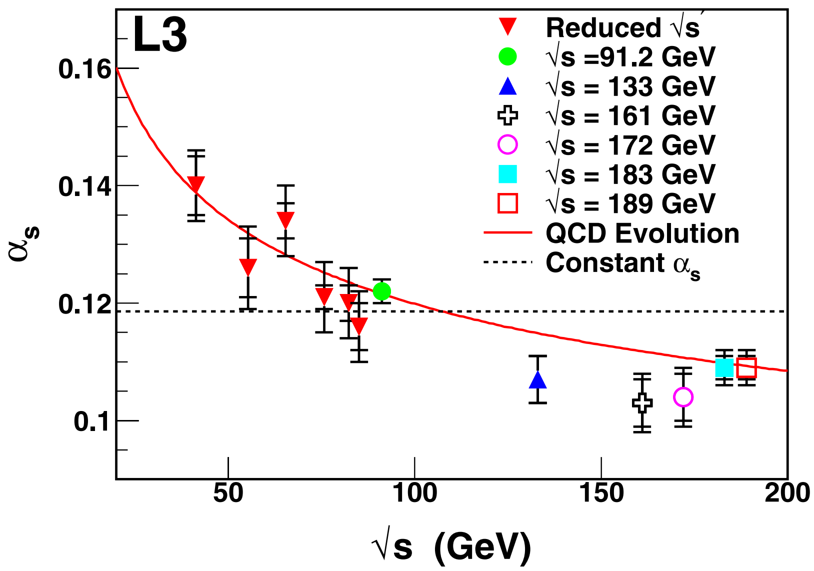
- "Infra-red safe" observables. Invariant under $\vec{p}_i \rightarrow \vec{p}_k + \vec{p}_l$. e.g.

Thrust, T

$$T = \max\left(\frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}\right)$$

T=1 **T=0.5**

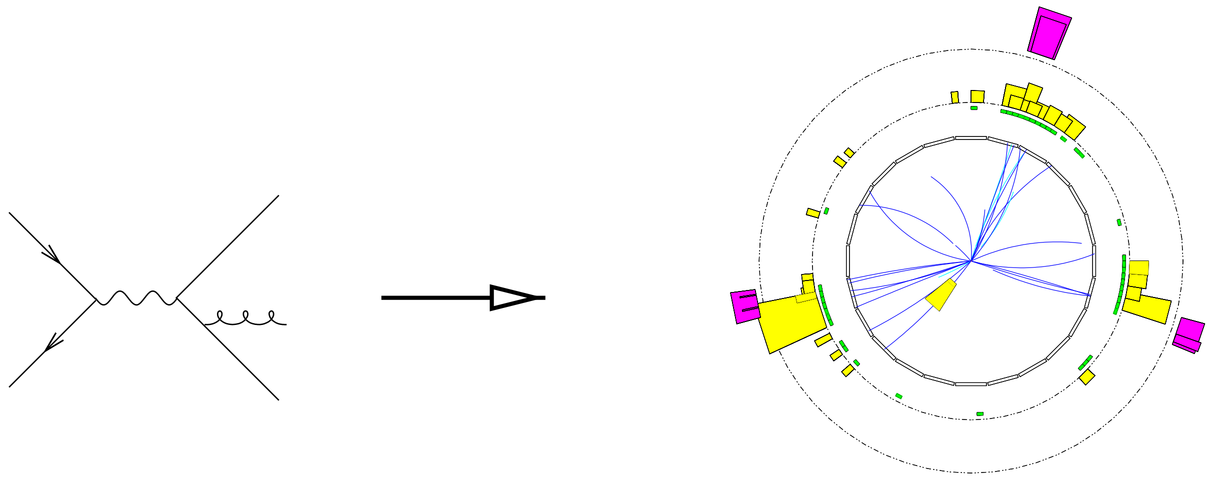




- Compare to $\mathcal{O}(\alpha_s^2)$ + NLLA corrected for hadronization using MC.
- α_s running!
- Another approach: power corrections $\rightarrow$ hadronization corrections "taken care" of by a universal non-pert. constant α_0. (not discussed here)

3. Jets

- Hadron jets are intuitively appealing:



- Definition of “jet algorithm” (i.e. an observable) which matches to pQCD calculations non-trivial.

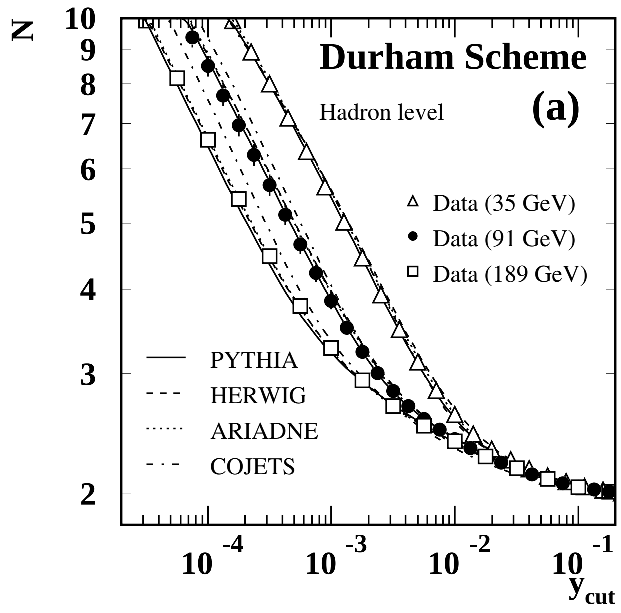
- Durham (k_T), Cambridge, Geneva algorithms.

- Clusters particles (or partons in theo.) using

a “resolution parameter”, y_{ij}. For Durham $\Rightarrow$

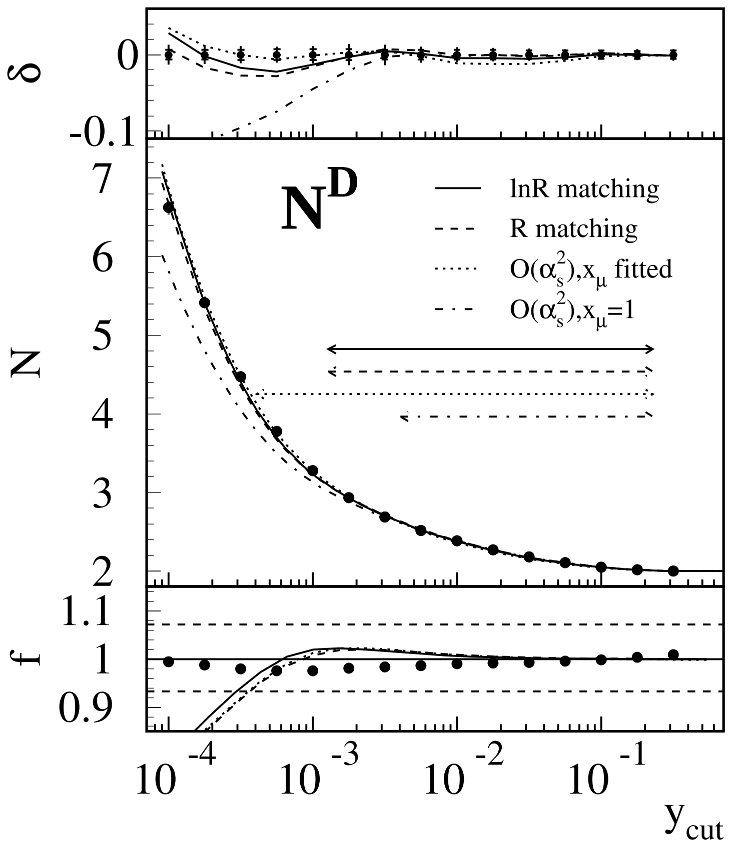
$$y_{ij} = \frac{\min(E_i^2, E_j^2)(1 - \cos(\theta_{ij}))}{s}, \; y_{ij} \geq y_{cut}$$

JADE-OPAL jet multiplicity, N

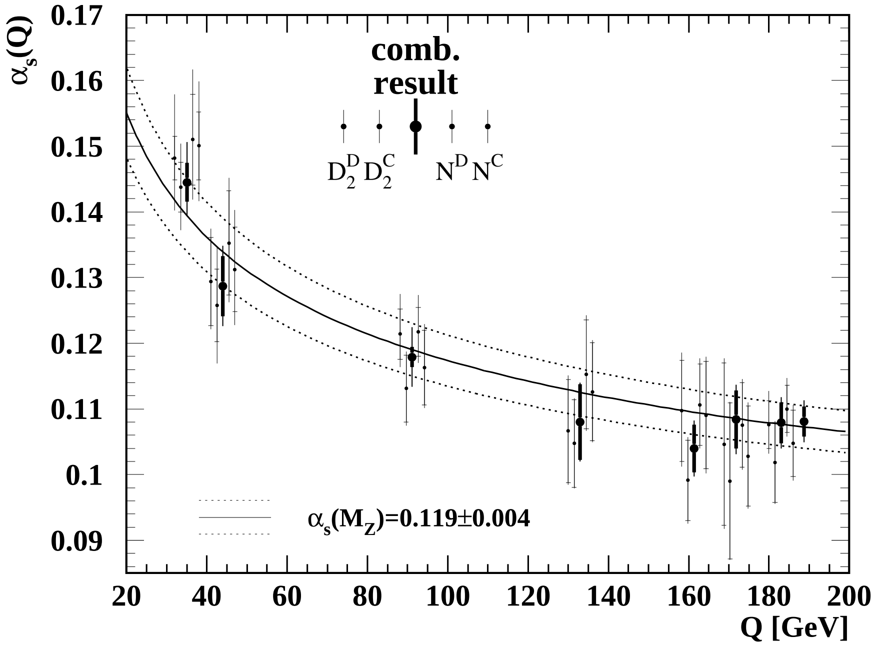


Jets from JADE-OPAL

189 GeV data compared to theory

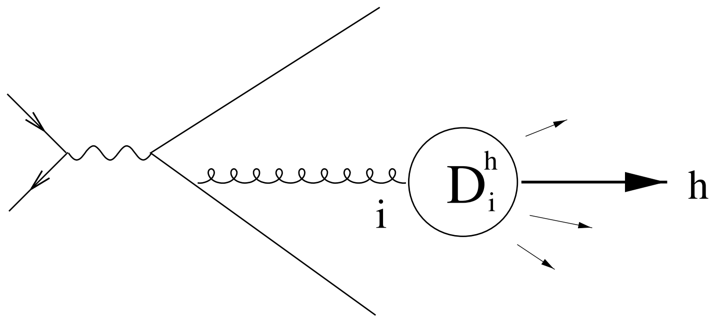


Running α_s from jets



4. Charged Multiplicities

QCD factorization



Single particle distribution of hadron, h, in $x_p = \frac{2|\vec{p}_h|}{\sqrt{s}}$:

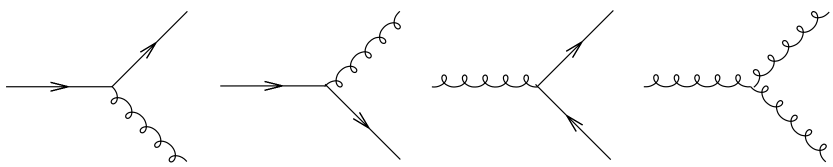
$$F^h(x, s) = C \otimes D^h$$

C are from pQCD calculations and D^h are (universal) fragmentation functions.

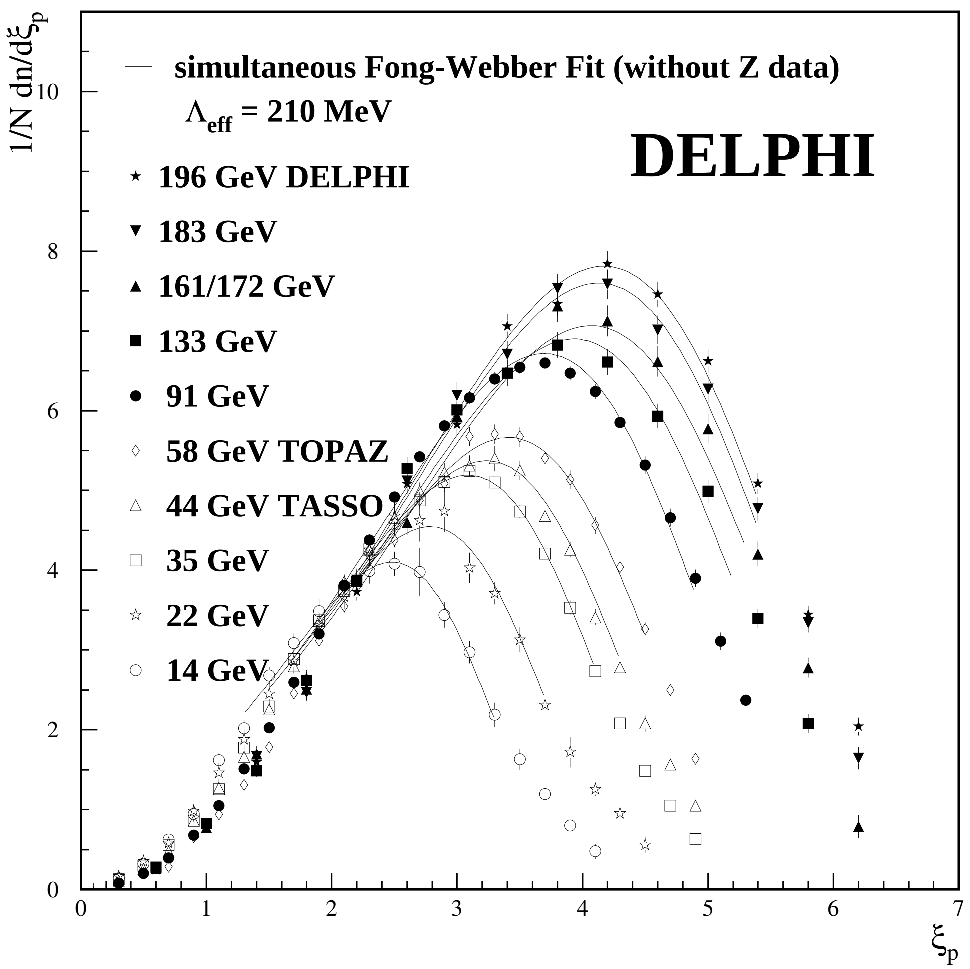
Fragmentation functions are non-perturbative but: It's "evolution" with s is predicted via pQCD (DGLAP equations).

$$\frac{\partial D^h}{\partial \ln s} = P \otimes D^h$$

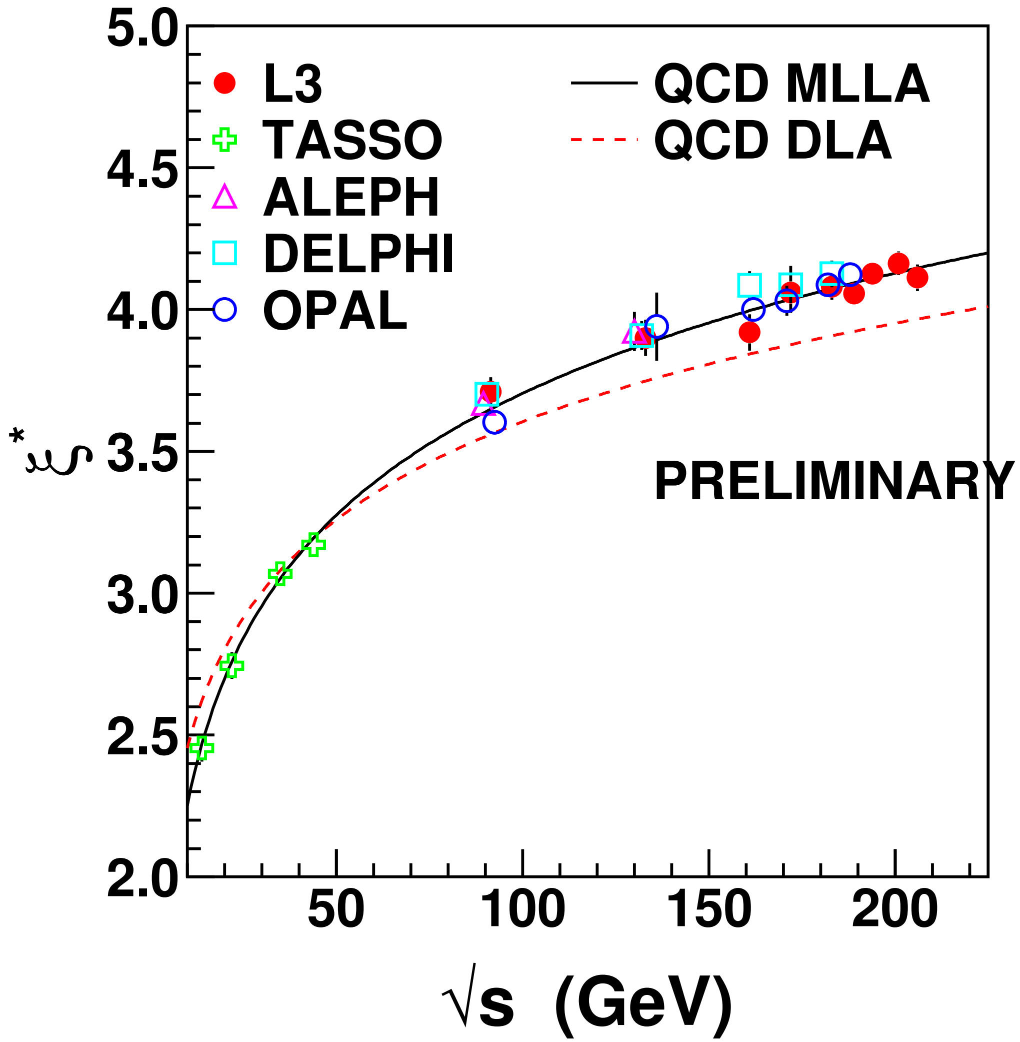
P are splitting functions which describe the probability of parton branching:



Evolution of charge particle spectra in $\xi = \ln 1/x_p$ and the peak of the spectra ξ^* $\Rightarrow$

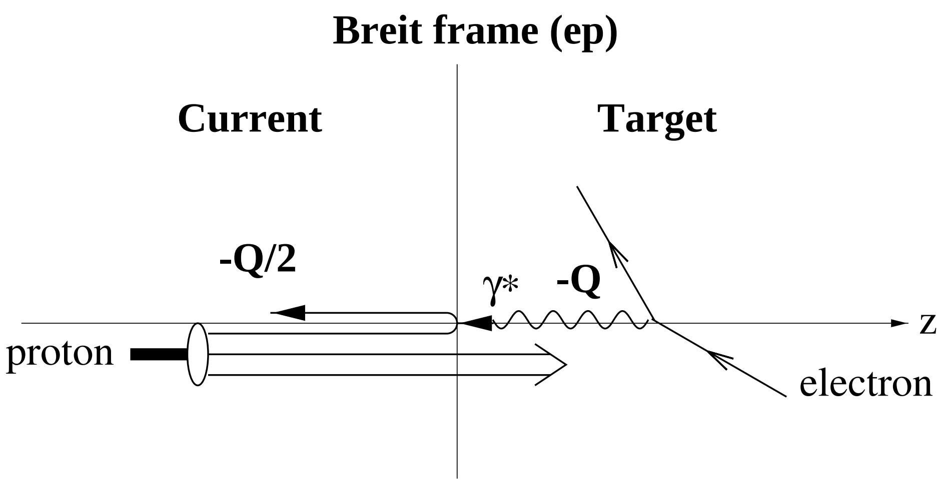


1/N dn/dξp
simultaneous Fong-Webber Fit (without Z data)
Λeff = 210 MeV
DELPHI
196 GeV DELPHI
183 GeV
161/172 GeV
133 GeV
91 GeV
58 GeV TOPAZ
44 GeV TASSO
35 GeV
22 GeV
14 GeV
ξp



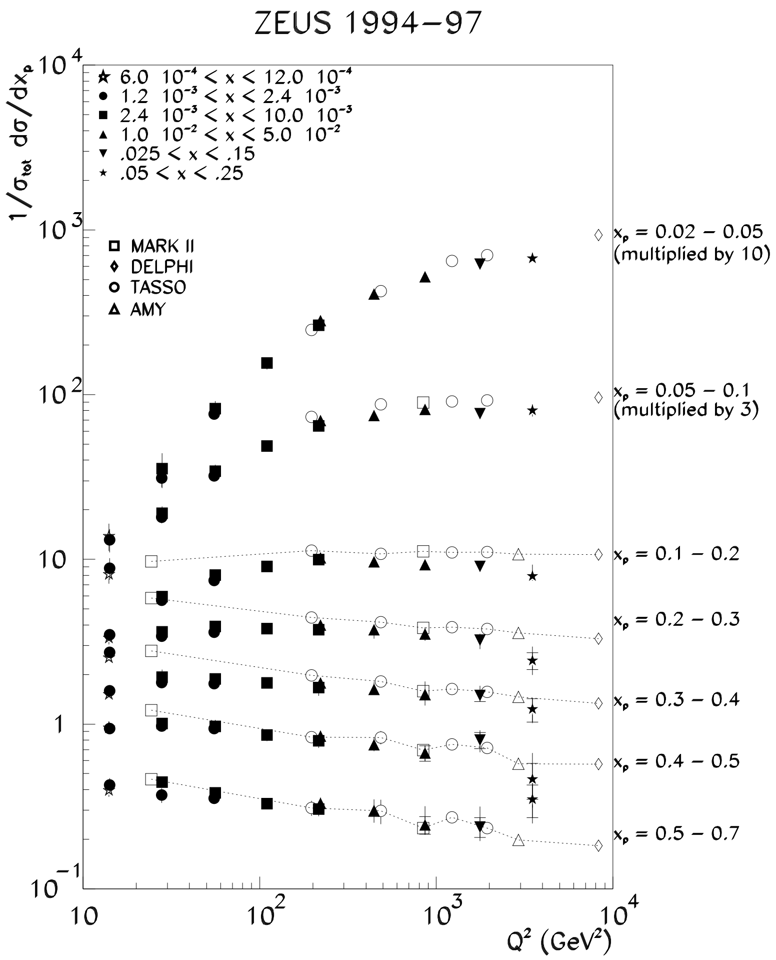
L3
TASSO
ALEPH
DELPHI
OPAL
QCD MLLA
QCD DLA
PRELIMINARY
ξ*
√s (GeV)

Fragmentation functions at ep



- The current hemisphere of ep is similar to half of e^+e^-!

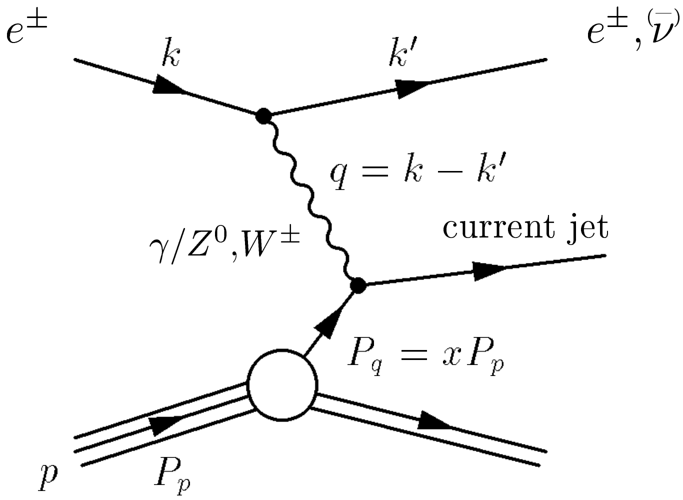
$x_p = 2|\vec{p}_h|/Q$.



- Universality of fragmentation functions!

III. QCD at HERA (ep)

1. Proton Structure Fcn and Parton Distributions



$Q^2 = -q^2$: virtuality (“size” of the probe)

x: mom. frac. of the struck parton (inf. mom. frame)

Factorization, i.e.:

$$\sigma_{DIS} \sim f_p(x) \otimes \hat{\sigma}$$

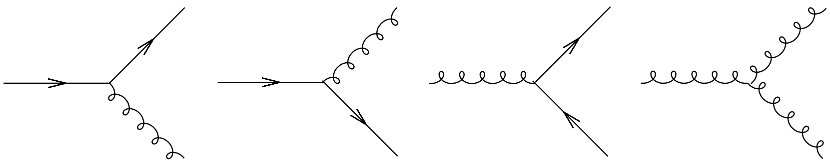
$f_p(x)$: (universal) parton densities of the proton.

$\hat{\sigma}$: partonic cross section. pQCD

GLAP evolution equation:

$$\frac{\partial f_p}{\partial \ln Q^2} \sim f_p \otimes P$$

Where P are the splitting fnc:



Neutral Current (γ, Z exchange) interaction

$$\frac{d\sigma^2_{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+ F_2 - y^2 F_L \mp Y_- xF_3)$$

$y = Q^2/xs$, the inelasticity parameter, $Y_\pm = (1 \pm (1-y)^2)$

F_2, F_L, and xF_3 are structure functions of the proton.

- F_L: longitudinal component, damped by y^2.
- xF_3: Small at $Q^2 \ll M_Z^2$,

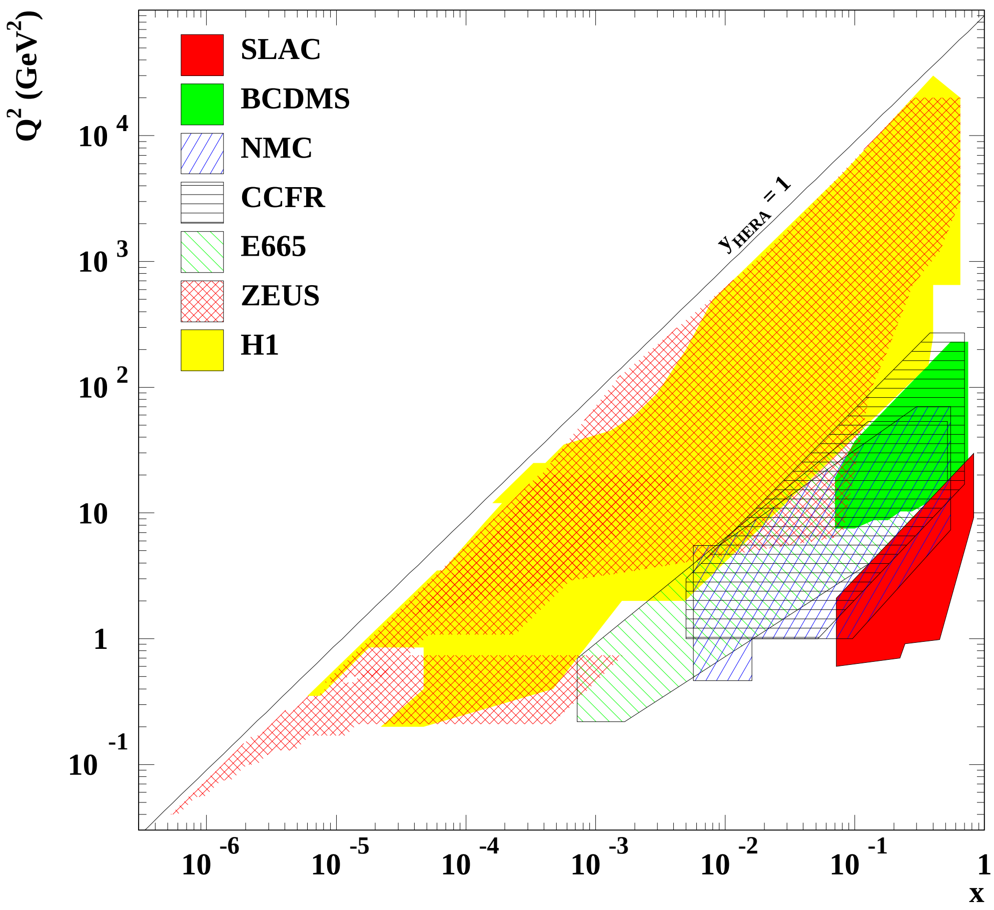
And (LO (or in DIS scheme..))

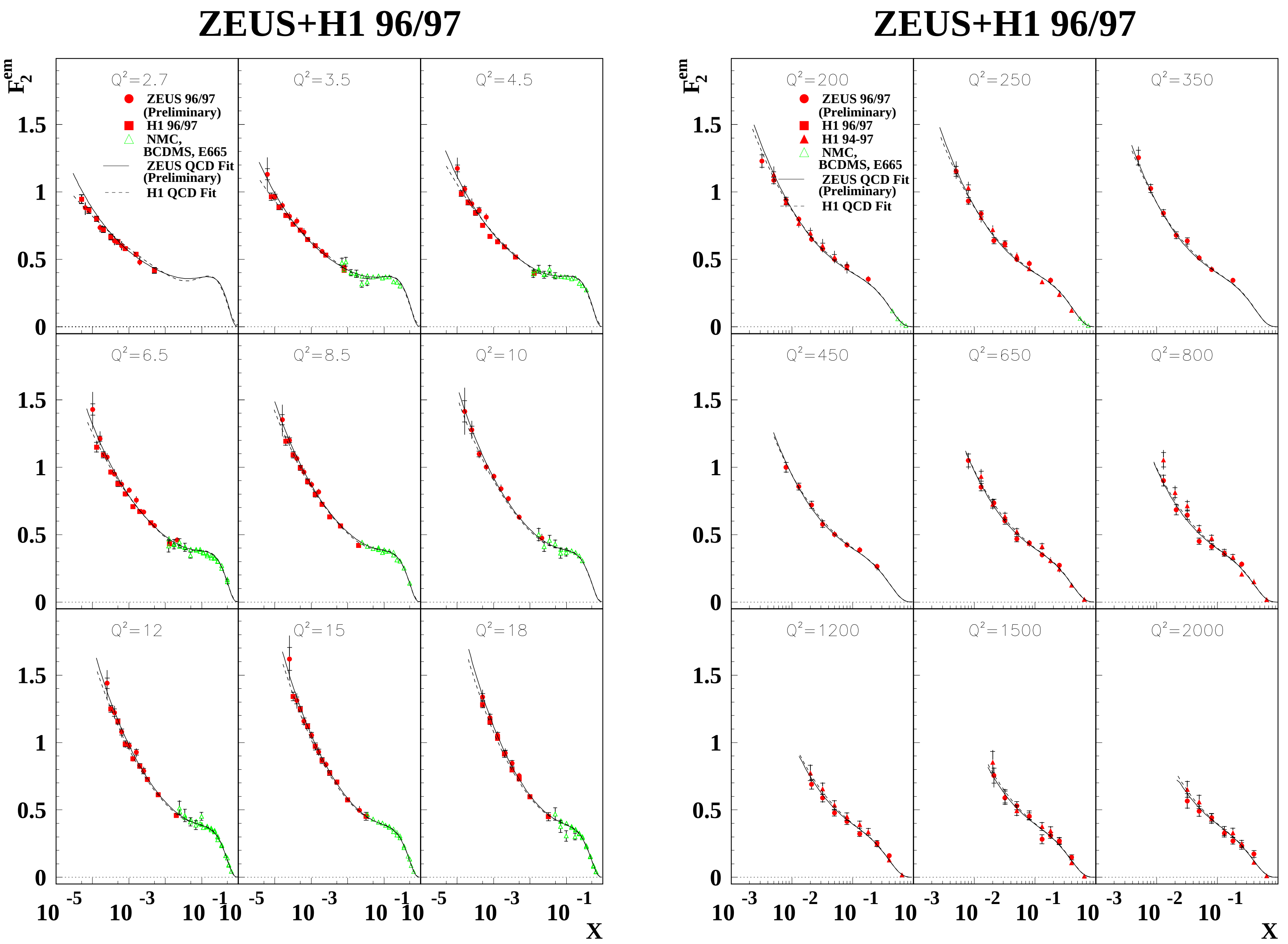
$F_2(x, Q^2) = x \sum_q e_q^2 (q(x, Q^2) + \bar{q}(x, Q^2))$

where q, $\bar{q}$ are quark, antiquark densities in the proton.

HERA ep collider: $\sqrt{s} \approx 300$ GeV $\Rightarrow$

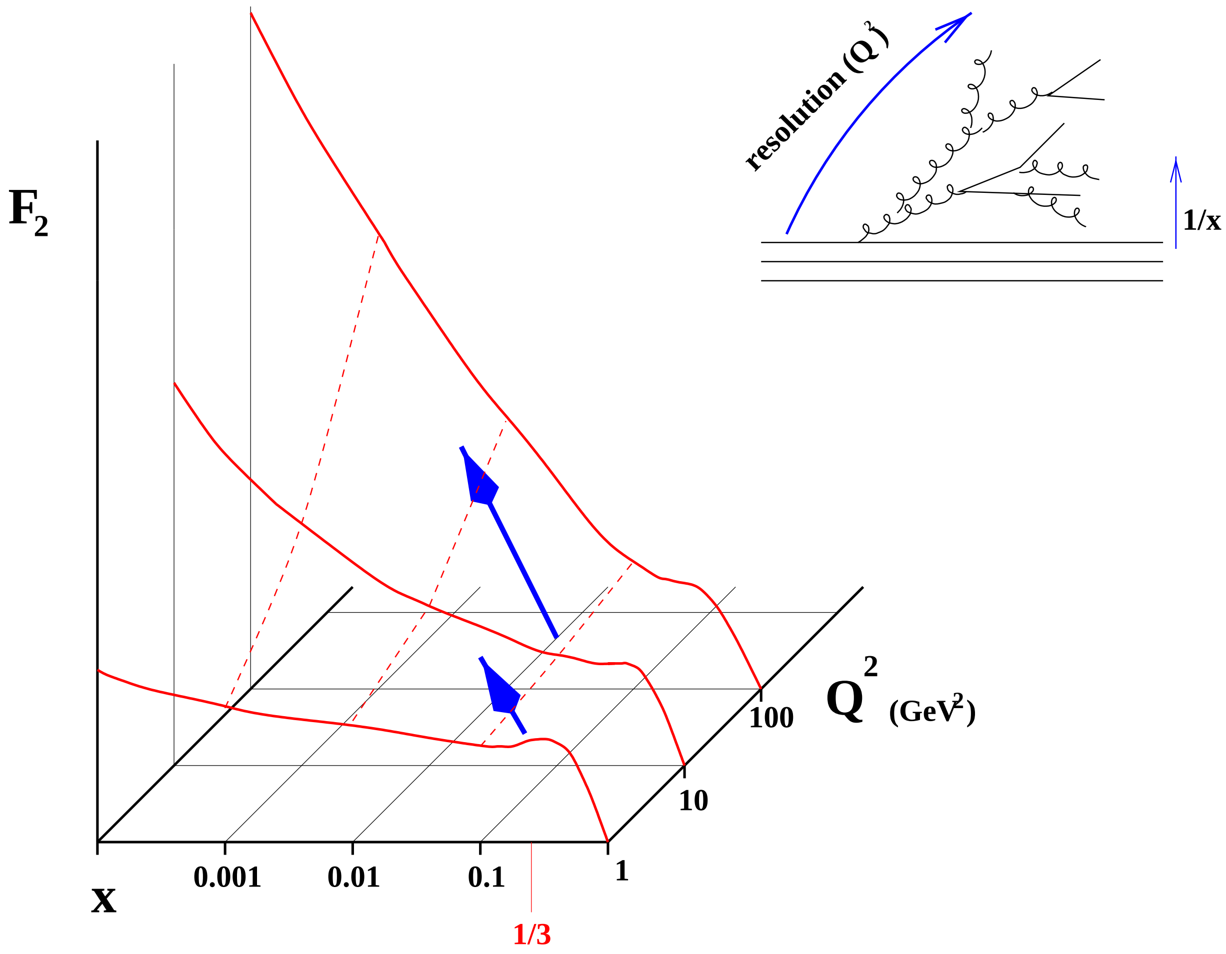
Q^2 and x can be varied over 6 orders of magnitude.





ZEUS+H1 96/97
ZEUS+H1 96/97
F_2^{em}
Q^2=2.7
Q^2=3.5
Q^2=4.5
Q^2=6.5
Q^2=8.5
Q^2=10
Q^2=12
Q^2=15
Q^2=18
Q^2=200
Q^2=250
Q^2=350
Q^2=450
Q^2=650
Q^2=800
Q^2=1200
Q^2=1500
Q^2=2000
ZEUS 96/97 (Preliminary)
H1 96/97
H1 94-97
NMC, BCDMS, E665
ZEUS QCD Fit (Preliminary)
H1 QCD Fit
X

Qualitative picture of DGLAP evolution:



- At smaller distances (large Q^2), more and more partons at low x are resolved.

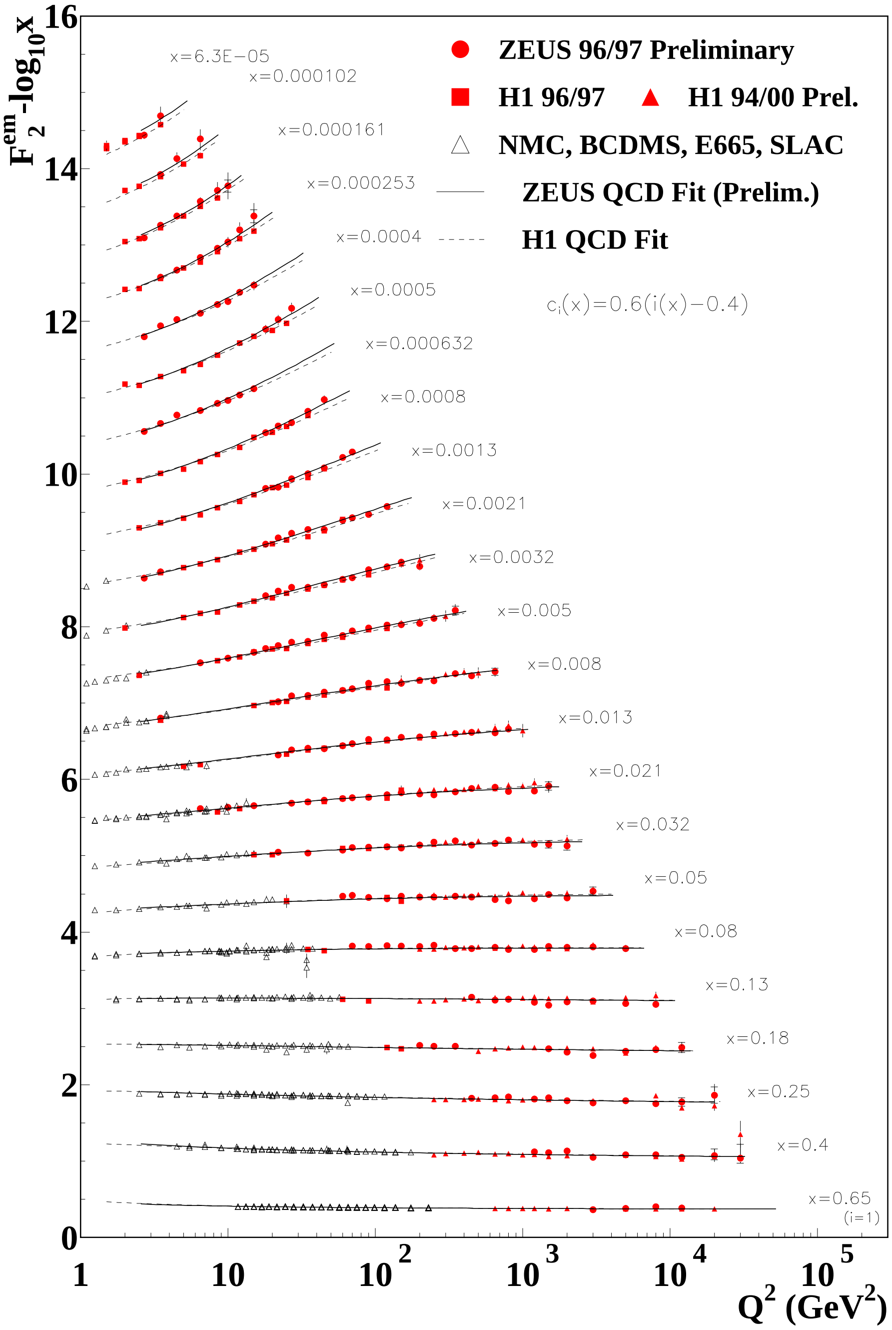
- Gluons "drive" the low x rise of $F_2 \sim x(q+\bar{q})$ at fixed Q^2.

$\Rightarrow$ The scaling violations (dotted line) reflect the gluon density.

In fact to LO in DGLAP at low x:

$$\frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_s x g$$

QCD DGLAP fit

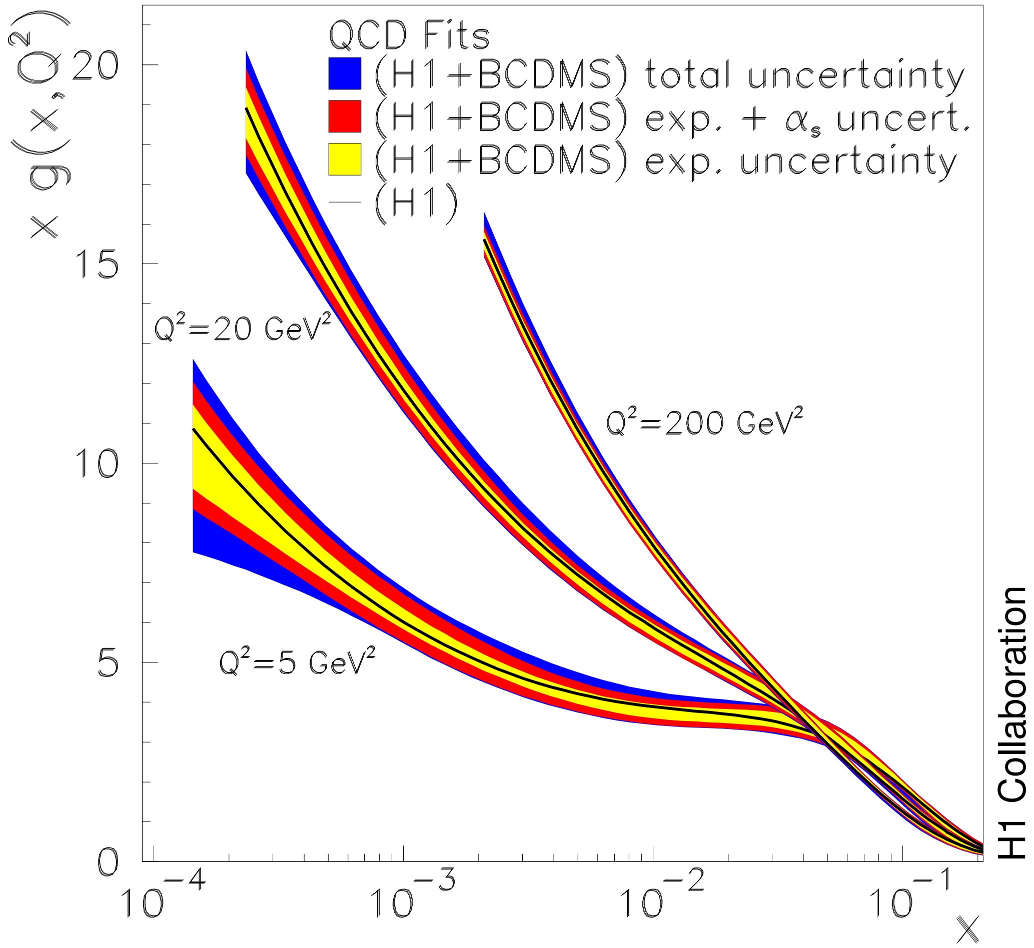


- Parametrize parton densities:

$$xq(x) = ax^b(1-x)^c[1+d\sqrt{x}+ex]$$

- Fit data for (a,b,c..): Example H1 fit (H1+BCDMS), 16 parameters including α_s. $\Rightarrow$

H1: NLO QCD DGLAP fit



- Gluon density is rising at low x. • •

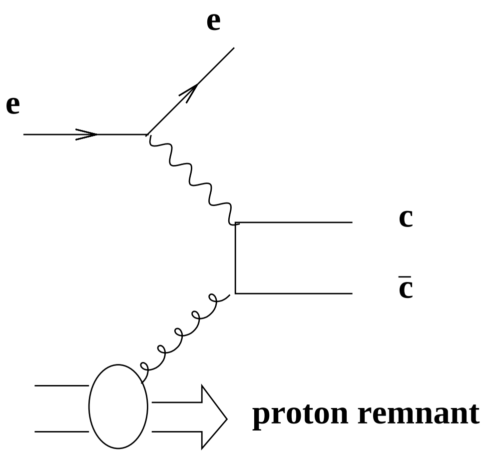
$$\alpha_s(M_Z) = 0.1150 \pm 0.0017(exp) \pm^{0.0009}_{0.0005} (\text{“}model\text{”})$$

- μ_R and μ_f uncertainties are large (~ 0.005) $\Rightarrow$ need NNLO.

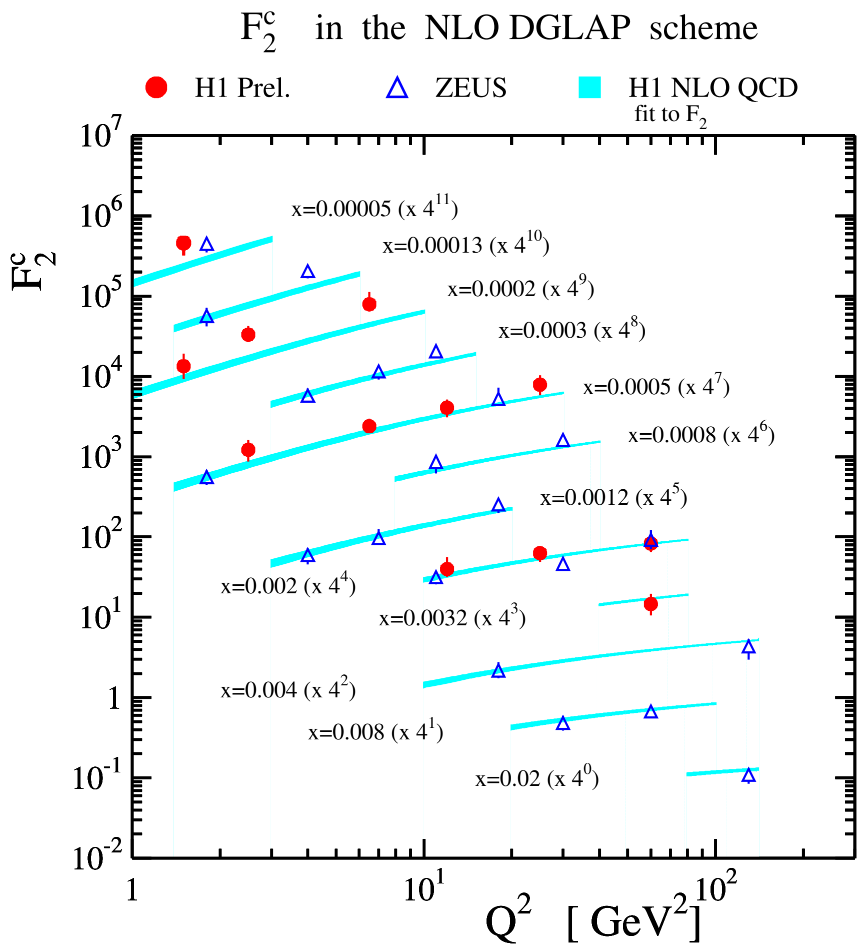
$\Rightarrow$ Note the x is small! What about $(\ln 1/x)$ terms?

$\Rightarrow$ H. Jungs talk.

Charm Production in DIS at HERA



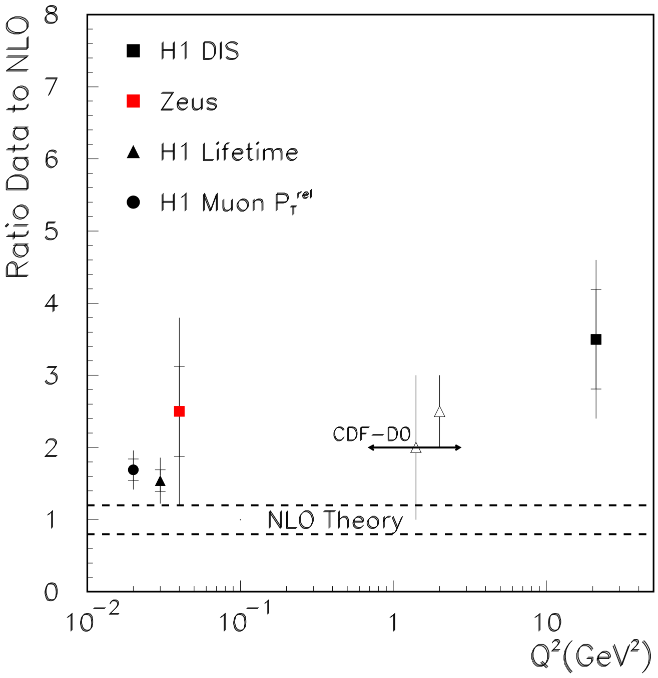
- Charm production is directly sensitive to the gluon!



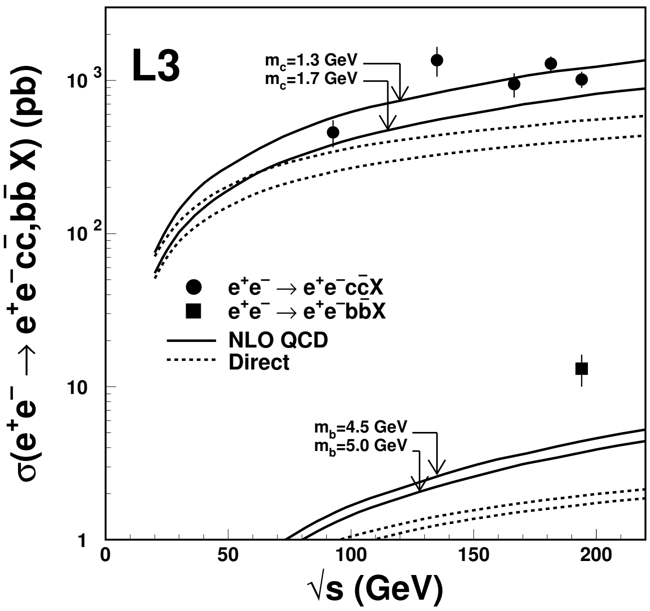
- Expressed in terms of F_2^c, the charm component of F_2
- Good agreement with expectations from the gluon from the NLO QCD fit! (or is it? See H. Jung talk)

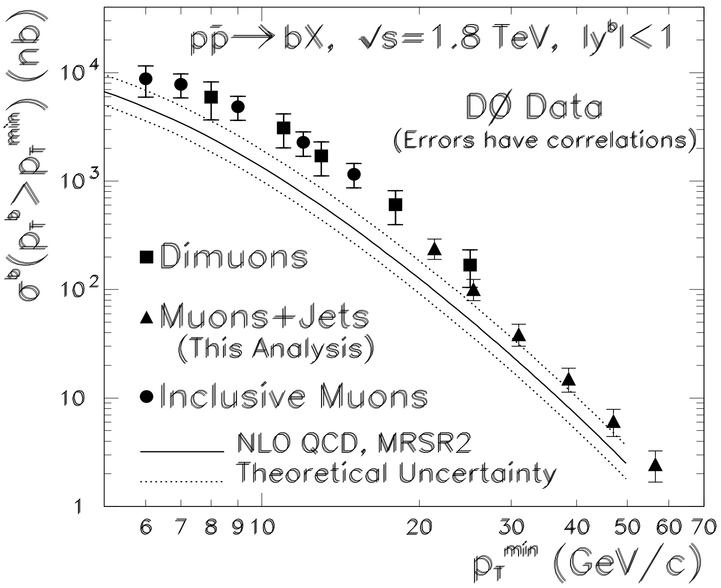
Beauty Production in ep, $\bar{p}p$ and $\gamma\gamma$

$$\frac{\sigma(ep\to b(\bar{b})e'X)_{data}}{\sigma(ep\to b(\bar{b})e'X)_{theory}}$$



$$\gamma\gamma \to c\bar{c}, b\bar{b}(L3)$$



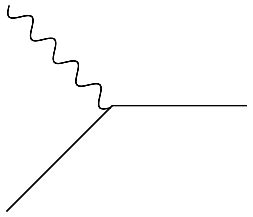


- Something wrong with the b calculations? (see H. Jung talk)

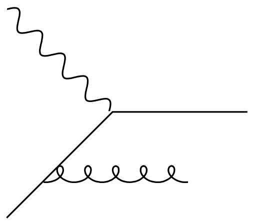
Structure function F_L

- F_L corresponds to absorption of longitudinally polarized virtual photon.

- Spin 1/2 quarks (with no transverse momentum) cannot absorb a longitudinally polarized boson.



LO: k_T=0, F_L=0



NLO: $k_T \neq 0$, $F_L \neq 0$

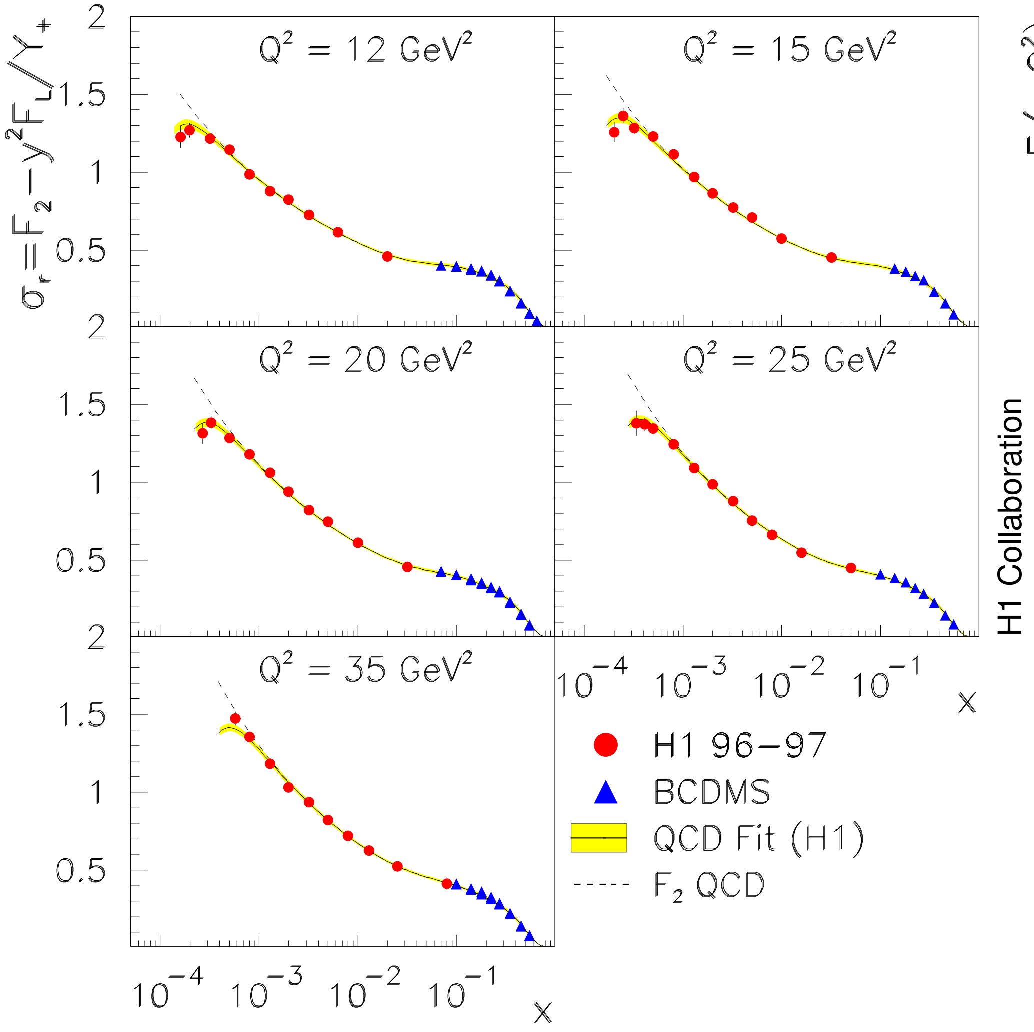
- At higher orders, quarks have transverse momentum (k_T), and therefore $F_L \neq 0$.

- F_L is related to the gluon density in the proton.

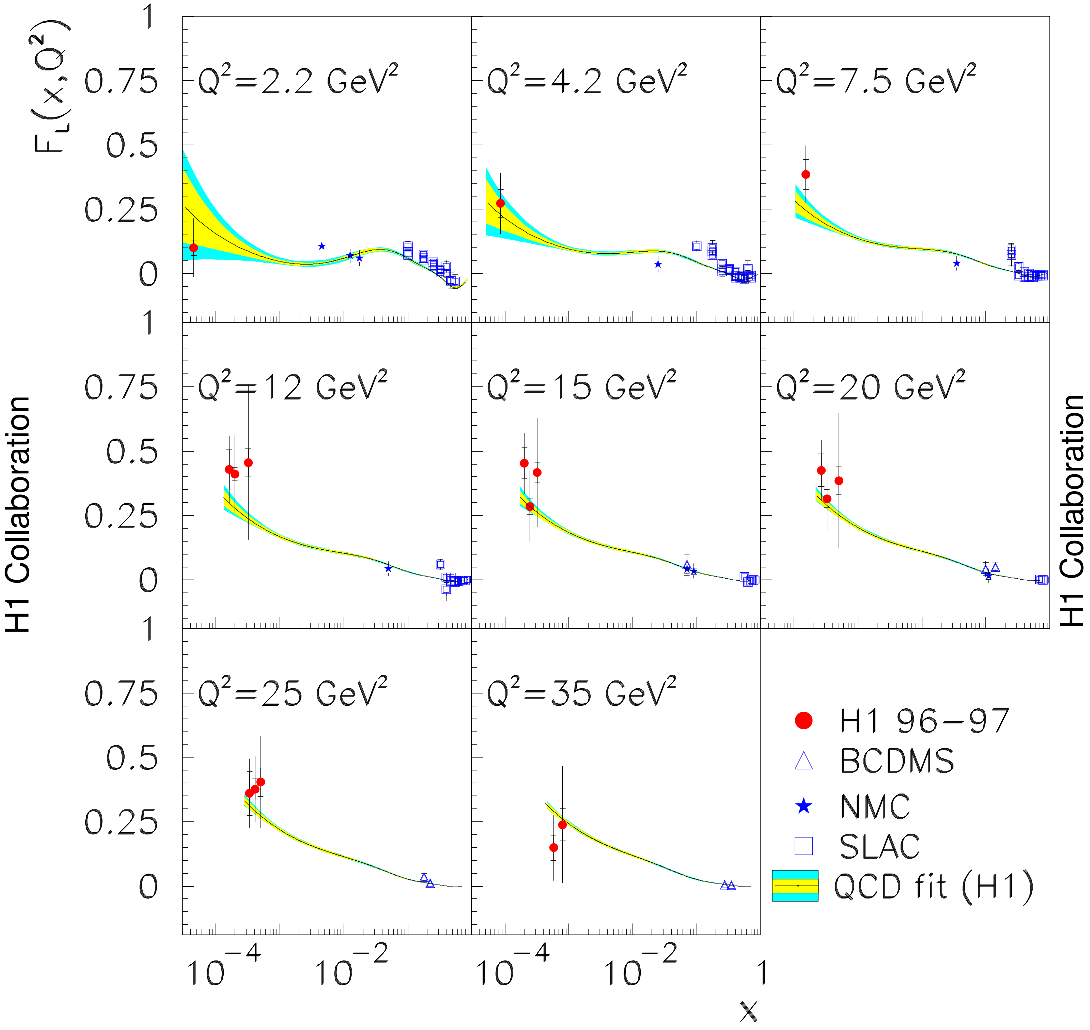
$$\frac{d\sigma^2}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+F_2 - y^2F_L \pm Y_-xF_3)$$

$y = Q^2/xs$: need to measure at different $\sqrt{s}$ to get F_L (or indeed F_2, in principle). This has not been done at HERA.

But...

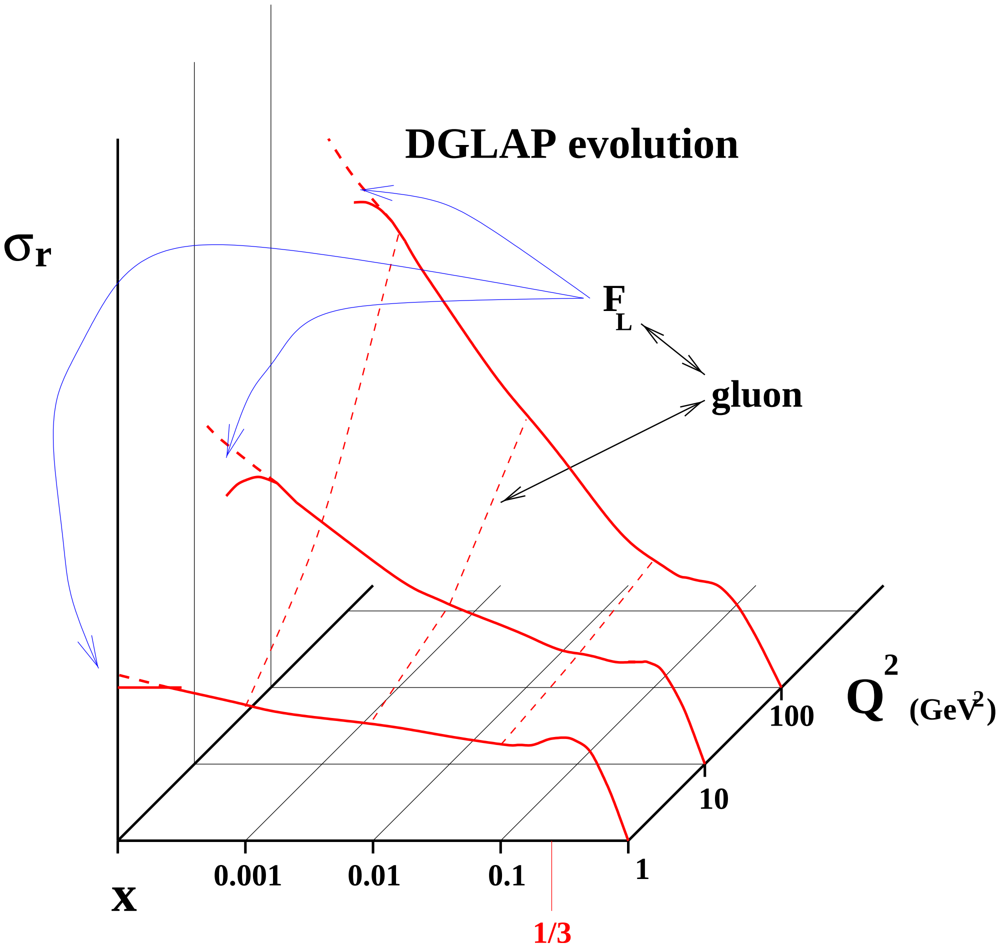


$\sigma_r = F_2 - y^2 F_L / Y_+$
Q^2 = 12 GeV^2
Q^2 = 15 GeV^2
Q^2 = 20 GeV^2
Q^2 = 25 GeV^2
Q^2 = 35 GeV^2
x
H1 96−97
BCDMS
QCD Fit (H1)
F_2 QCD
H1 Collaboration



$F_L(x,Q^2)$
Q^2=2.2 GeV^2
Q^2=4.2 GeV^2
Q^2=7.5 GeV^2
Q^2=12 GeV^2
Q^2=15 GeV^2
Q^2=20 GeV^2
Q^2=25 GeV^2
Q^2=35 GeV^2
x
H1 96−97
BCDMS
NMC
SLAC
QCD fit (H1)
H1 Collaboration

•DGLAP fit to the cross-section σ : F_L and the scaling violation of F_2 connected through the gluon.



• The fixed-target data on F_L comes from true measurements (i.e. from varying the cms energy).

• The F_L curves are the results of the H1 NLO QCD fit.

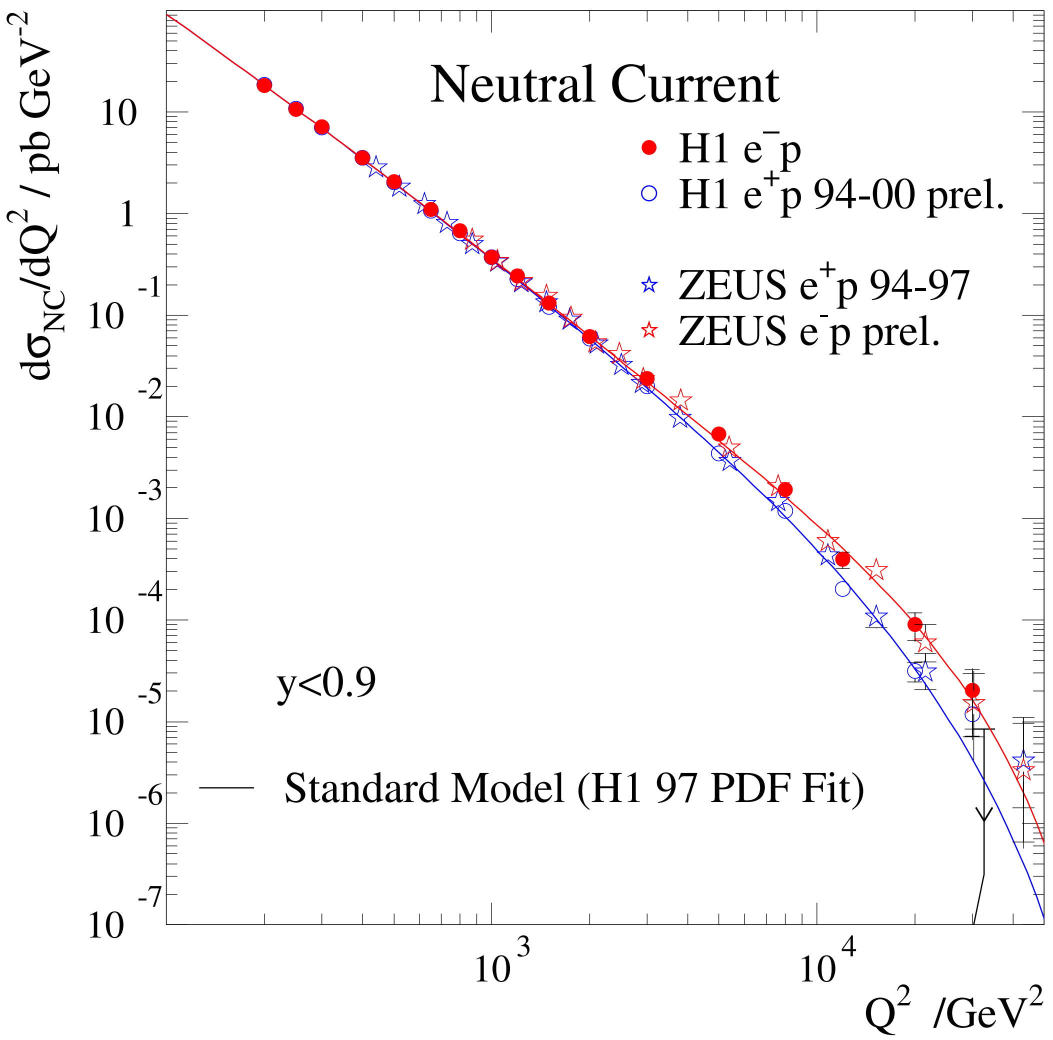
• The H1 F_L points are from F_2 extrapolation from lower y. Should give the same results as the fit.

• Consistency of DGLAP interpretation of the ep cross-section!

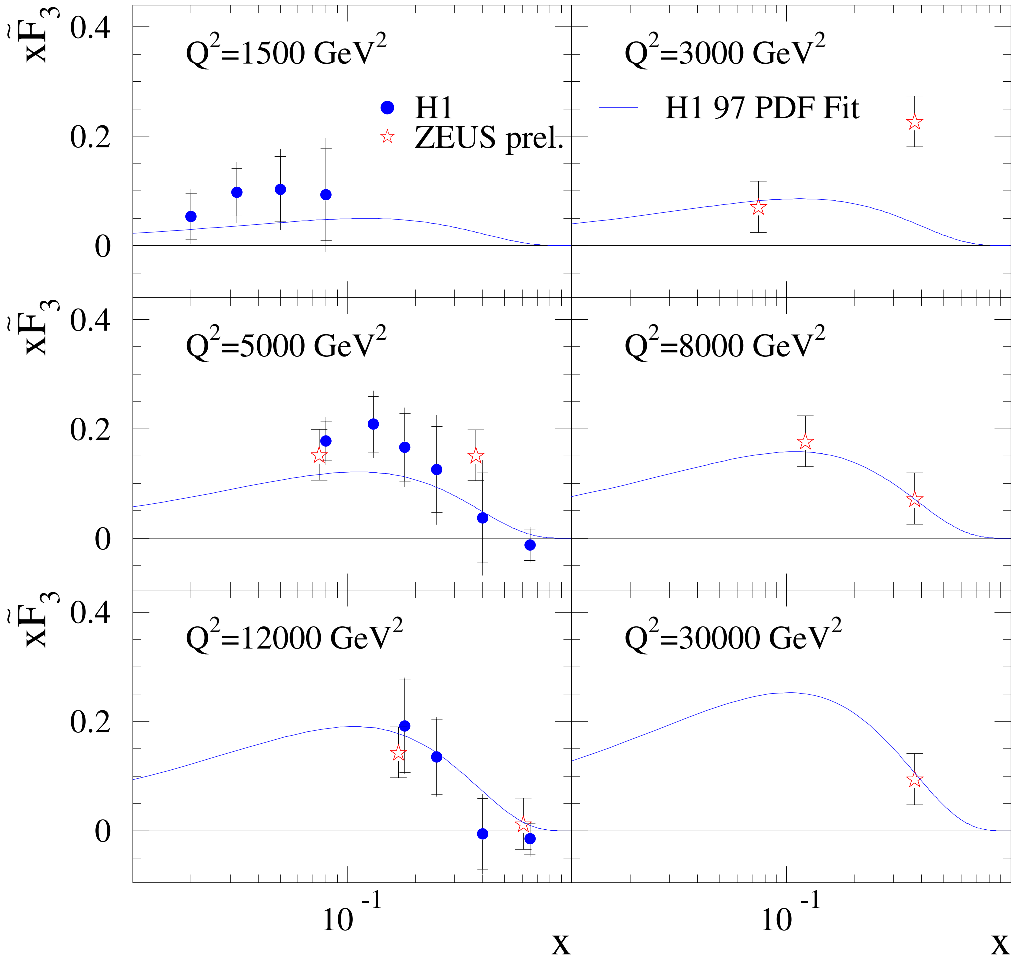
High Q^2 NC cross-section and xF_3

$$\sigma_{nc}(e^{\pm}p) \sim \frac{\alpha^2}{Q^4}[Y_+ F_2 \mp Y_- xF_3]$$

$$Y_{\pm} = 1 \pm (1-y)^2, xF_3 = \sum B(Q^2)(q - \bar{q})$$



xF_3 from HERA



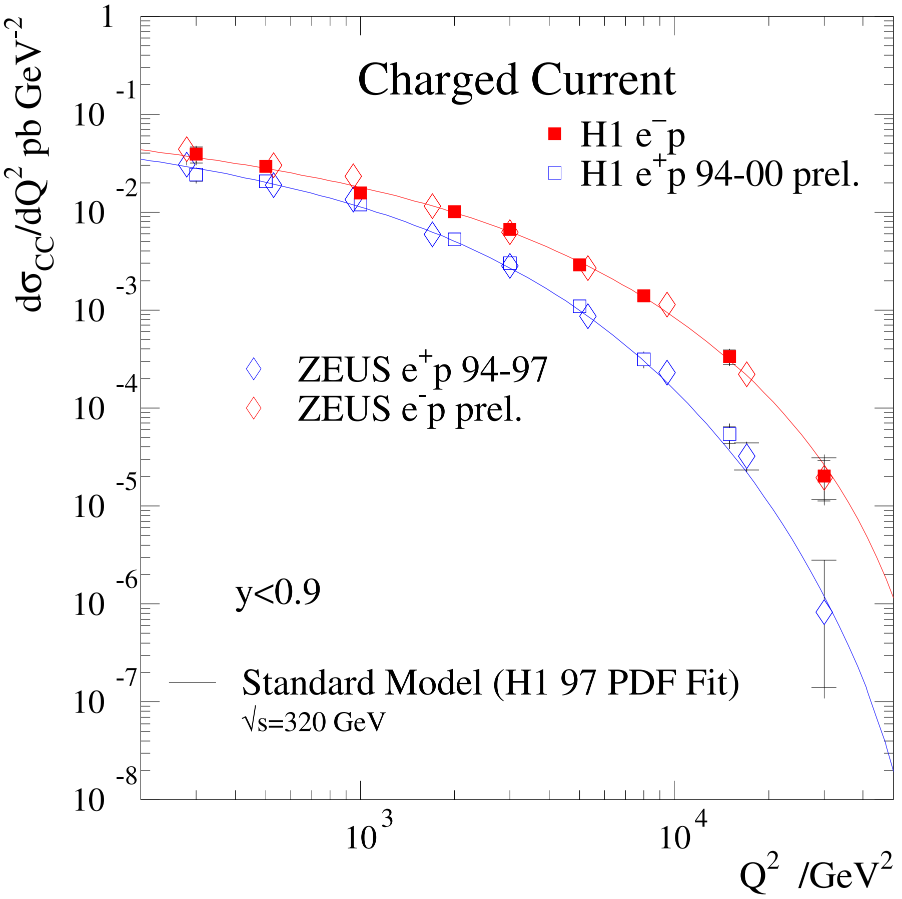
- First xF_3 measurement on protons, and at high Q^2.
- Agrees well with PDF's evolved from lower Q^2.
- Still statistics limited. $\Rightarrow$ pointing the way to a future measurement with high-luminosity HERA.

Charged current measurements from HERA

$$ep \to \nu X$$

$$\sigma_{cc}(e^+p) \sim G_F^2 \left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2 [(1-y)^2(d+s) + (\bar{u}+\bar{c})]$$

$$\sigma_{cc}(e^-p) \sim G_F^2 \left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2 [(1-y)^2(\bar{d}+\bar{s}) + (u+c)]$$



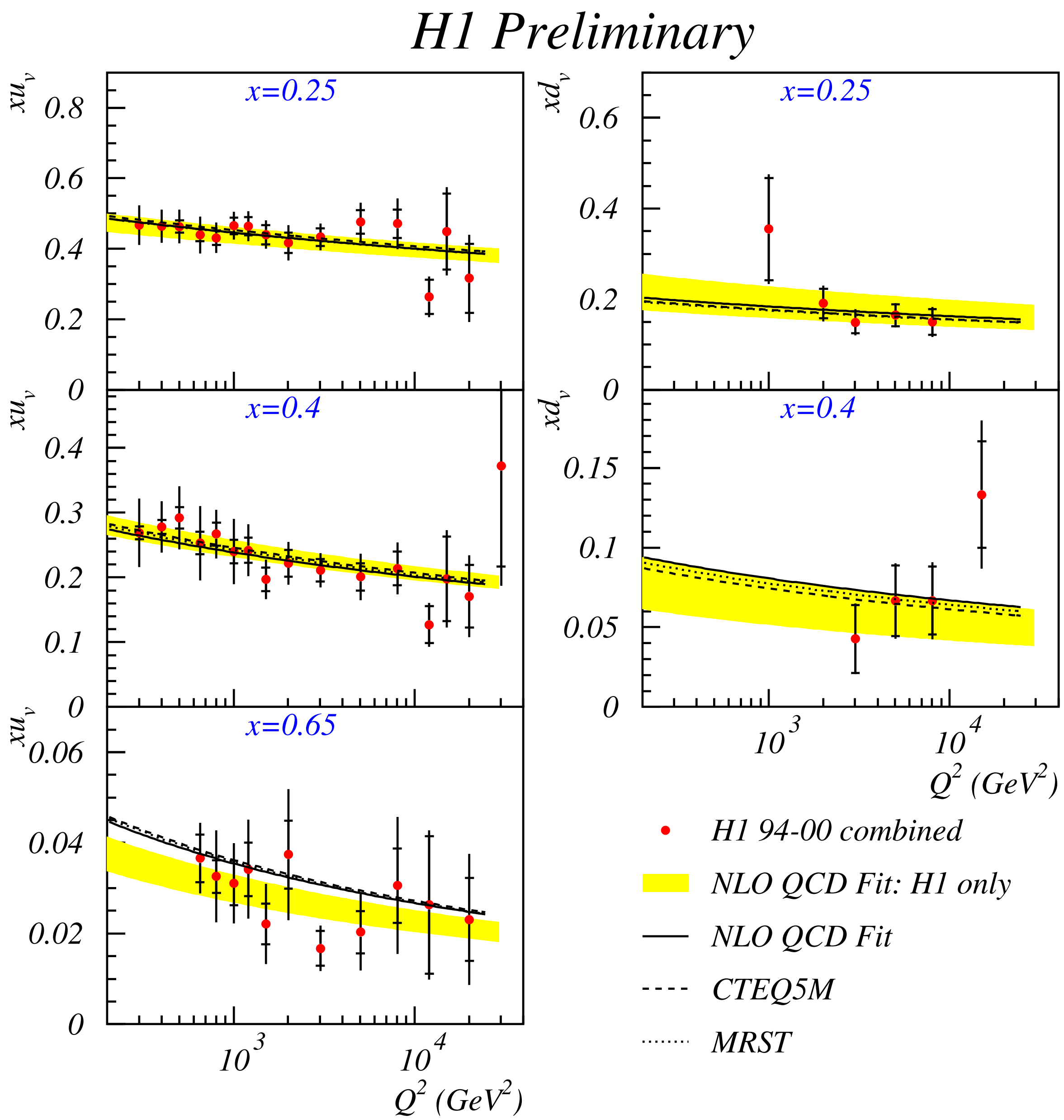
- Effect of the propagator mass (M_W)
- Difference in underlying quark distributions.

u and d densities from HERA

$\sigma_{cc}(e^+p)$ is mostly d at high x.

$\sigma_{cc}(e^-p)$ is mostly u at high x.

$\Rightarrow$ get u and d with minimal corrections from QCD fits.



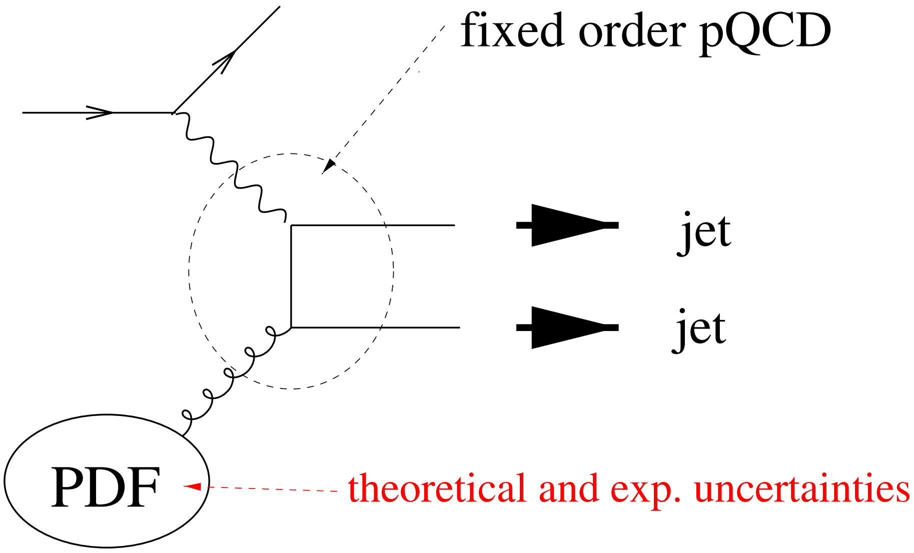
- Agrees well with PDF's evolved from lower Q^2.

Parton distribution functions and pQCD at ep

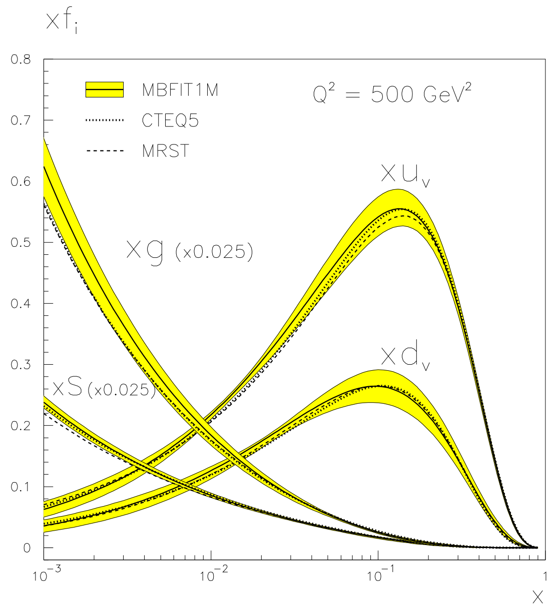
- Many of the pQCD studies discussed in e^+e^- can be done..

however..

Factorization structure of ep processes:

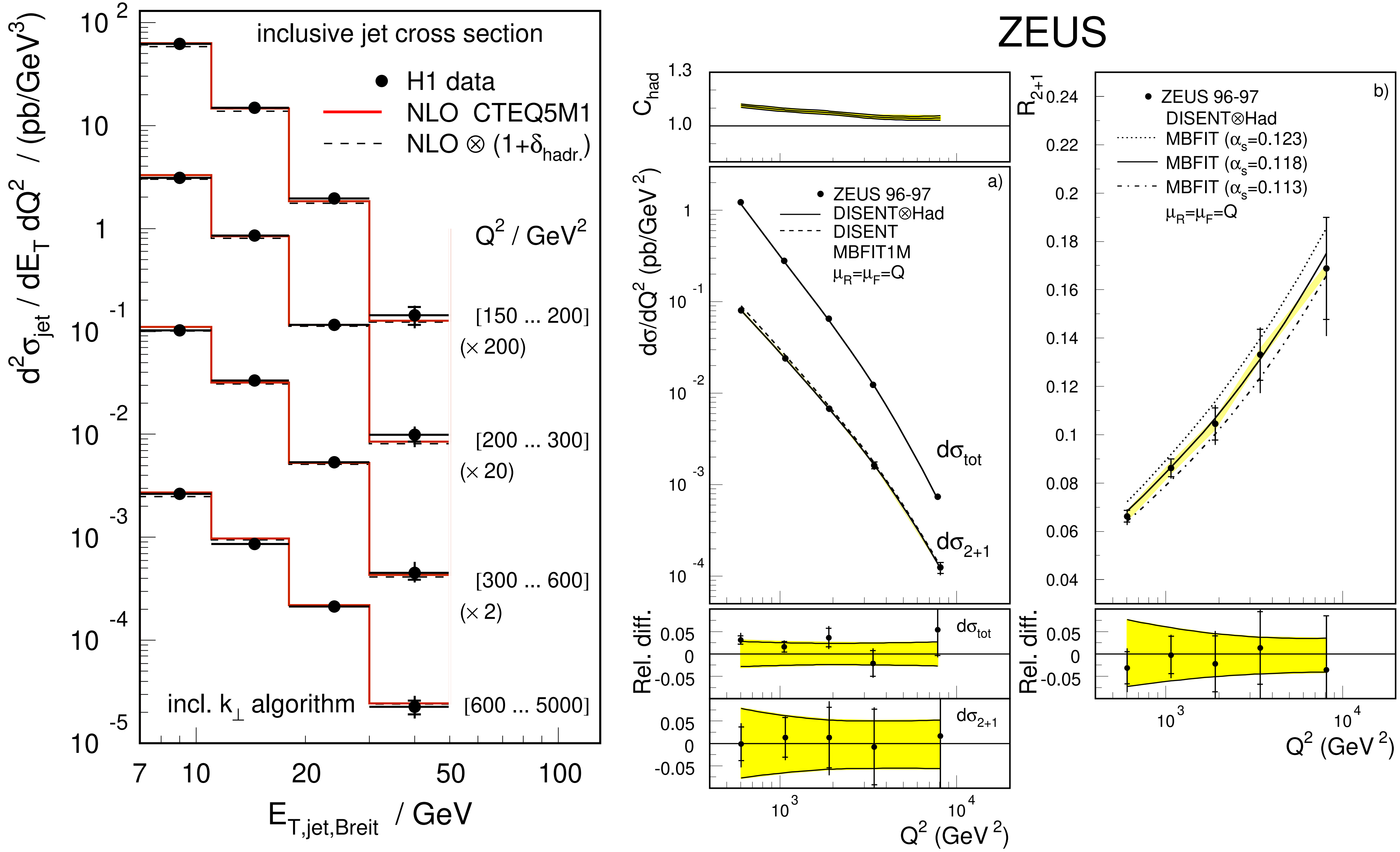


- The uncertainties in the experimentally determined PDF's must be carefully considered. (in addition to all others)



- Errors and correlations of PDF's now becoming available (M. Botje fits)

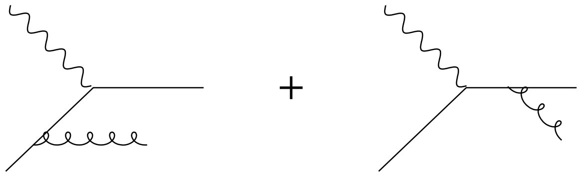
NLO QCD calculations of jet cross-sections in DIS $\Rightarrow$



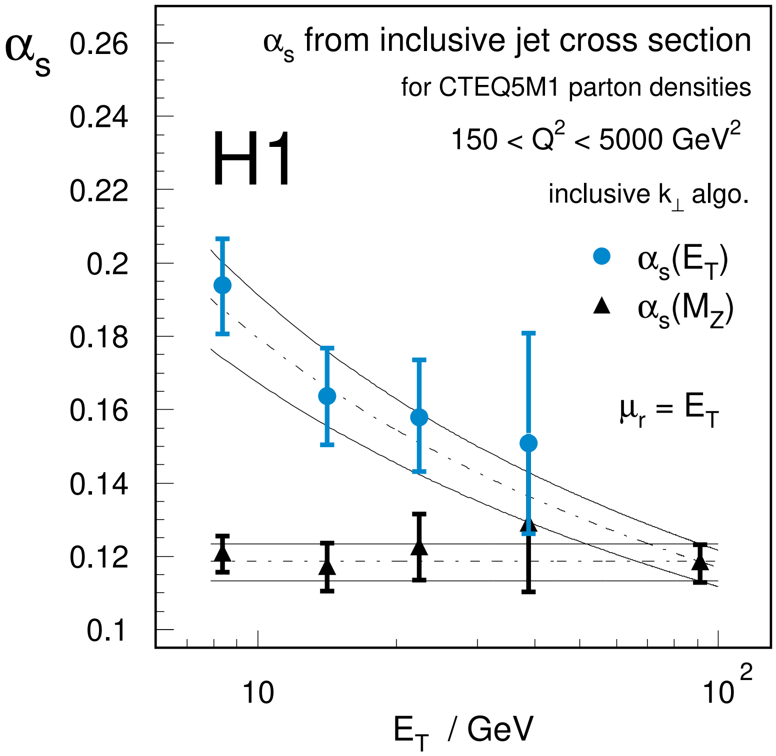
inclusive jet cross section
H1 data
NLO CTEQ5M1
NLO ⊗ (1+δhadr.)
Q2 / GeV2
[150 ... 200] (× 200)
[200 ... 300] (× 20)
[300 ... 600] (× 2)
[600 ... 5000]
incl. k⊥ algorithm
d2σjet / dET dQ2 / (pb/GeV3)
ET,jet,Breit / GeV
ZEUS
Chad
ZEUS 96-97
DISENT⊗Had
DISENT
MBFIT1M
μR=μF=Q
dσ/dQ2 (pb/GeV2)
dσtot
dσ2+1
Rel. diff.
Q2 (GeV2)
R2+1
MBFIT (αs=0.123)
MBFIT (αs=0.118)
MBFIT (αs=0.113)
a)
b)

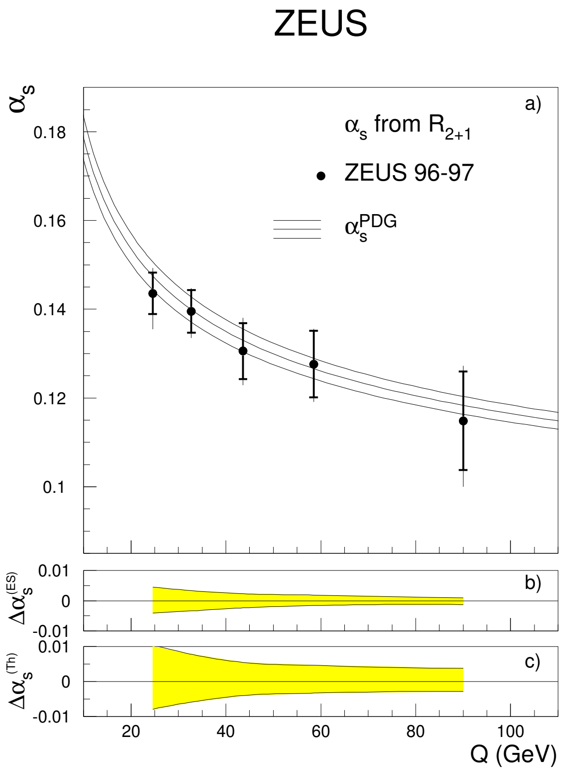
α_s from jets in DIS

- At high Q^2 QCDC dominates



- High x quark PDF, well-known.





H1 (inclusive jets):

$$\alpha_s(M_z) = 0.1186 \pm 0.0030(exp) \pm^{0.0039}_{0.0045} (th.) \pm^{0.0033}_{0.0023} (pdf)$$

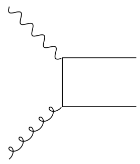
ZEUS (2jet/total ratio):

$$\alpha_s(M_z) = 0.1166 \pm 0.0019(stat) \pm^{0.0024}_{0.0033} (exp) \pm^{0.0057}_{0.0044} (th, pdf)$$

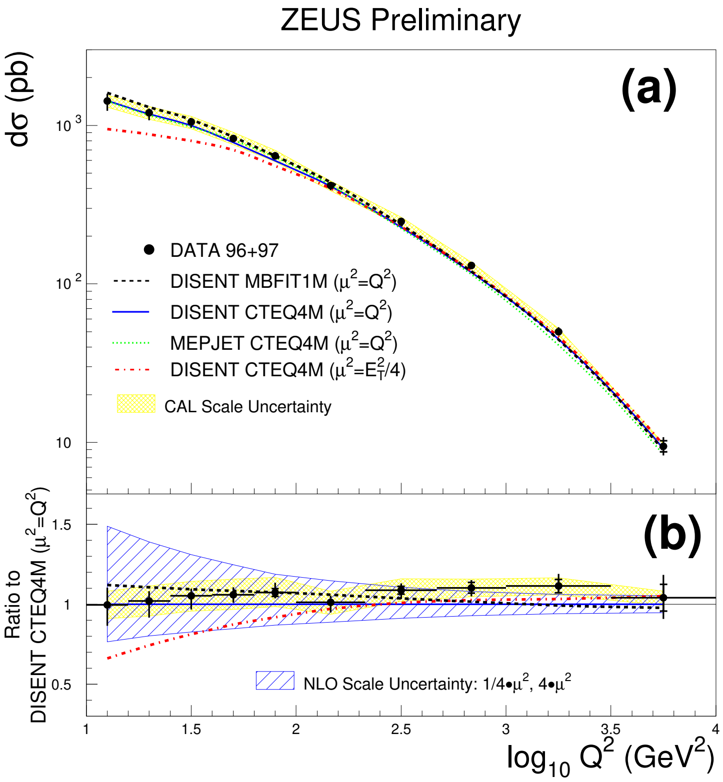
- Uncertainties from pdf, pdf α_s interplay taken into account.

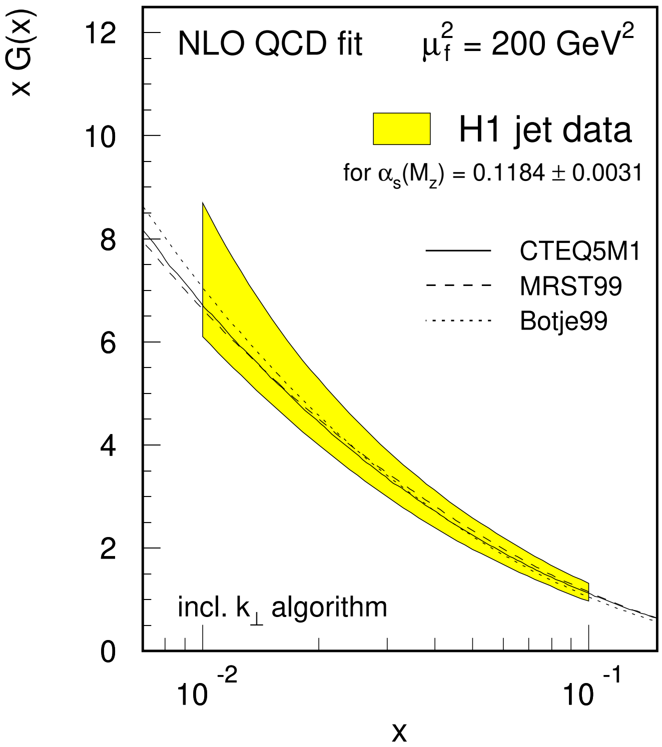
- Theory, exp. errors comparable.

Dijets in DIS: gluon sensitivity



- At lower Q^2, dijet cross-sections are mostly from photon-gluon fusion.

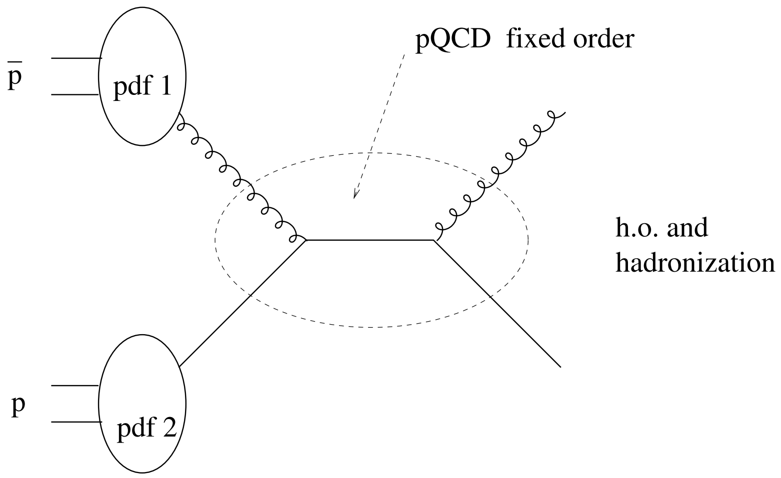




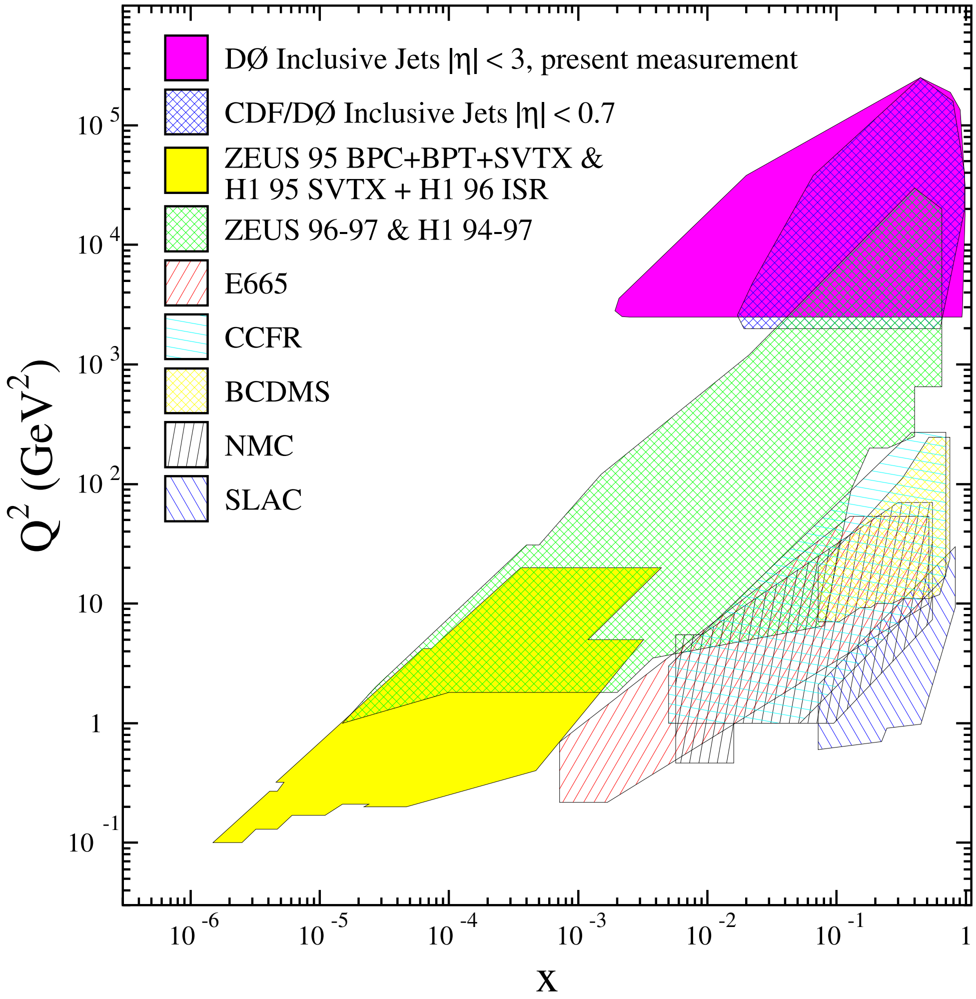
- Fix α_s and measure gluon?
- μ_R and μ_f uncertainties large in comparison to uncertainties in gluons.
- Needs theoretical input to proceed further.

I. QCD at $\bar{p}p$ (Tevatron)

- Factorization structure of pQCD at the Tevatron

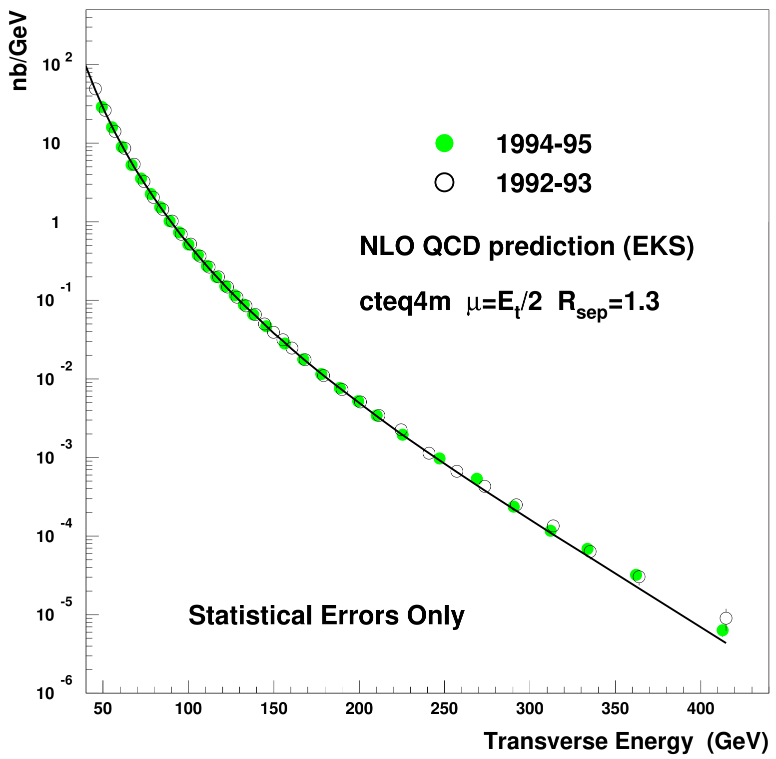


- Important to know uncertainties of PDF's

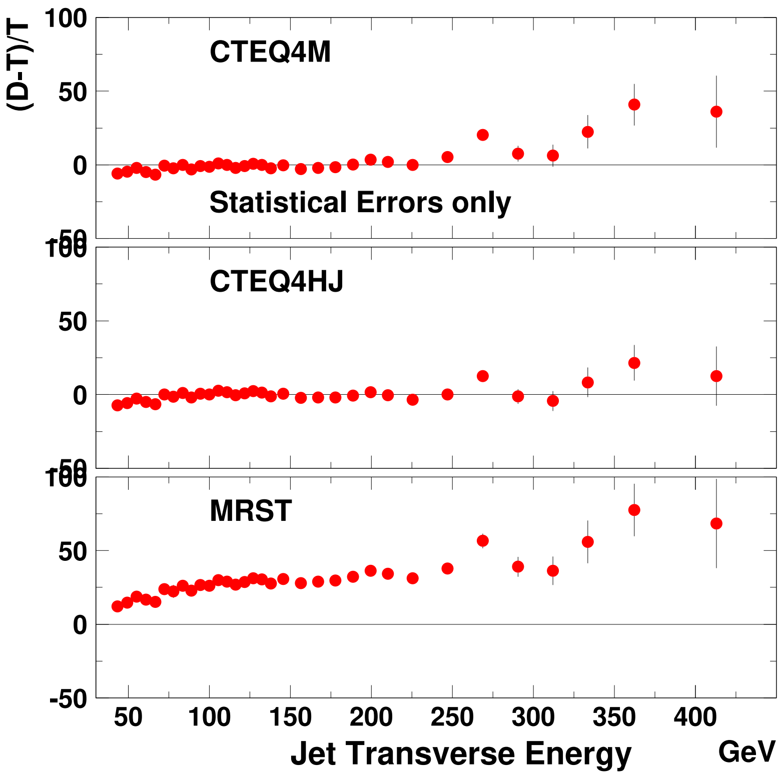


- Tevatron high E_T jets probe high x and high Q^2.

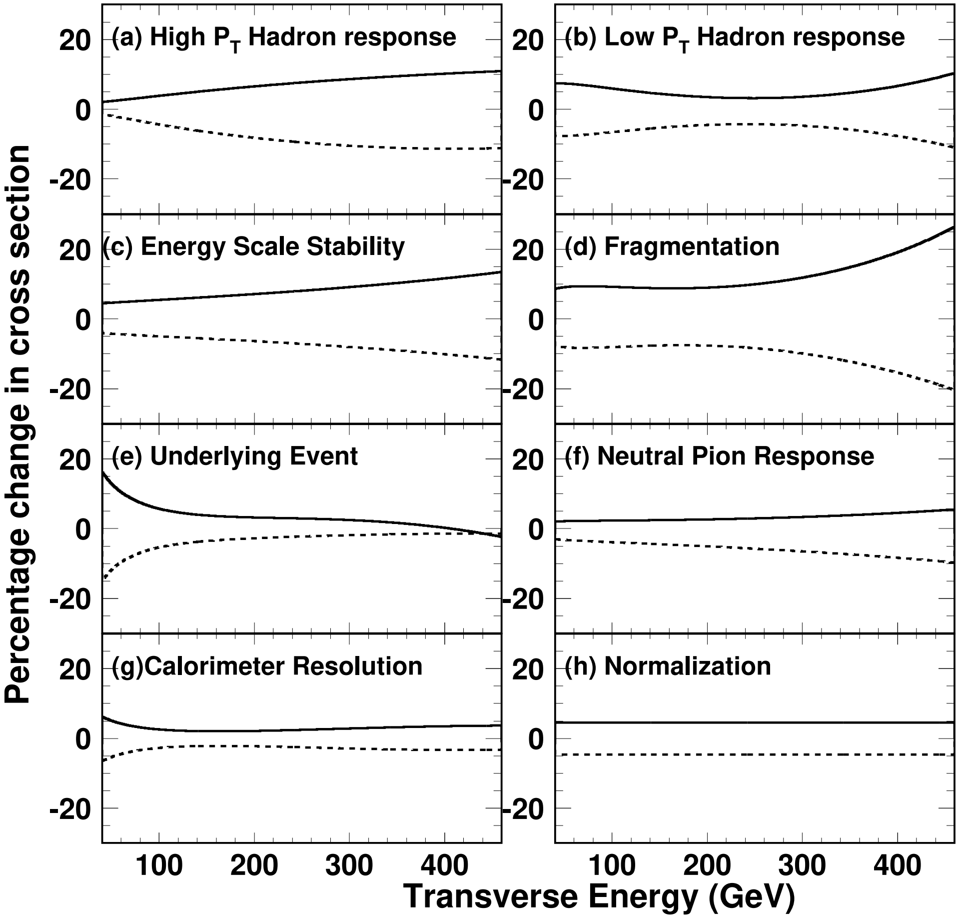
Inclusive jets at CDF: • Good agreement for many orders of magnitude (CDF at $\sqrt{s} = 1.8$ TeV):

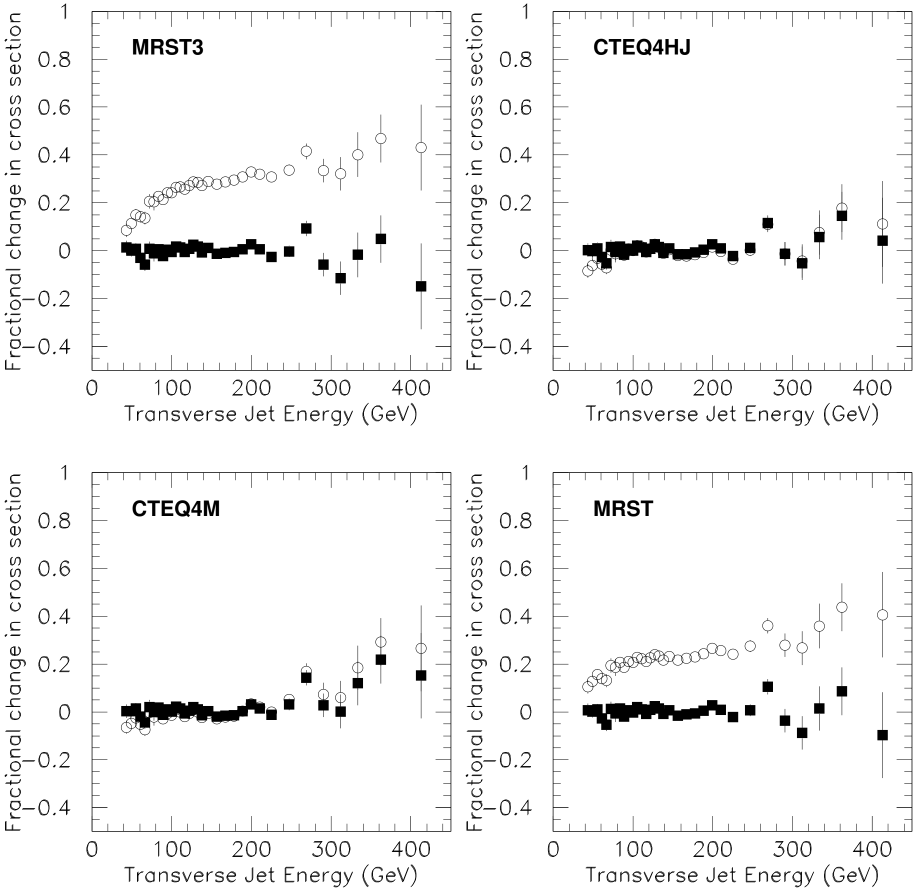


• Comparing closely with particular PDF sets:



However, experimental uncertainties cover the difference: $\Rightarrow$


(a) High P_T Hadron response
(b) Low P_T Hadron response
(c) Energy Scale Stability
(d) Fragmentation
(e) Underlying Event
(f) Neutral Pion Response
(g)Calorimeter Resolution
(h) Normalization
Percentage change in cross section
Transverse Energy (GeV)
20
0
-20
100
200
300
400

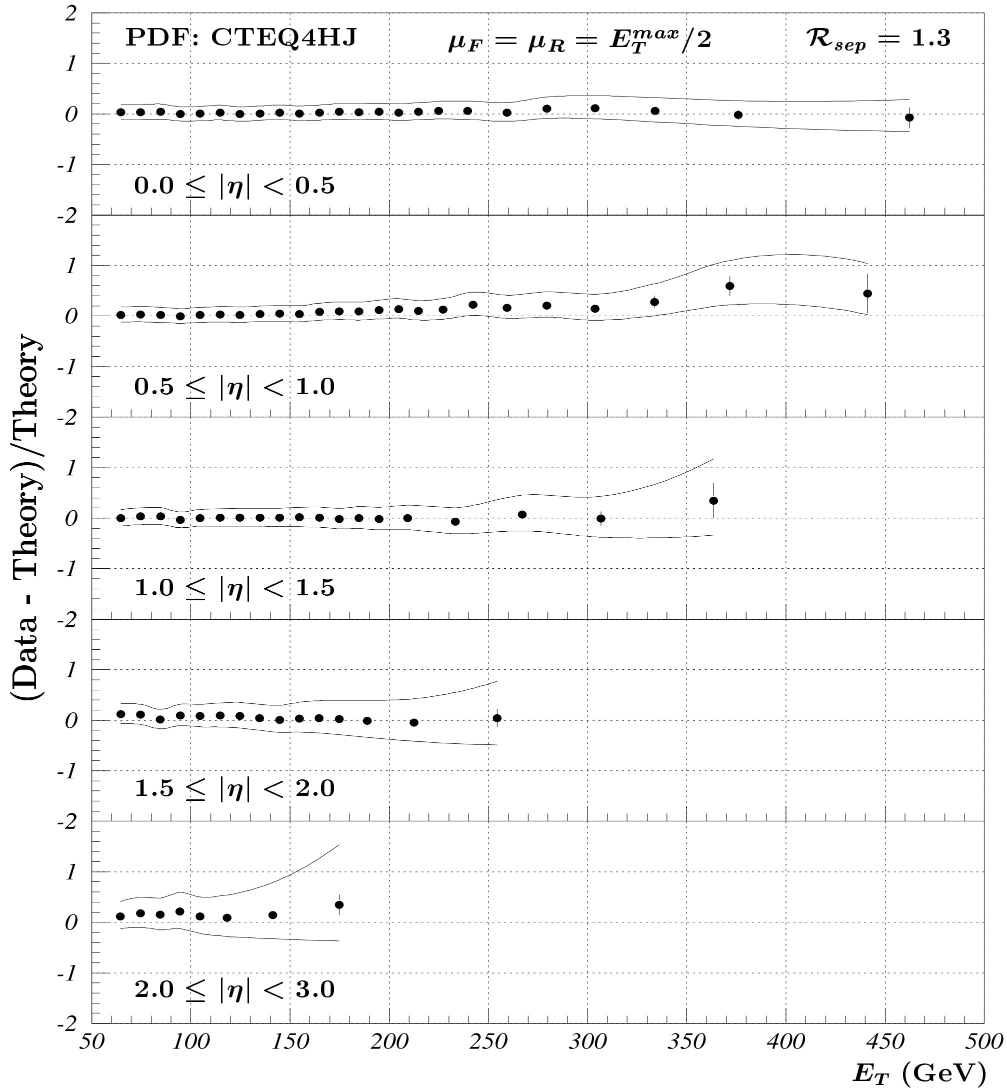

MRST3
CTEQ4HJ
CTEQ4M
MRST
Fractional change in cross section
Transverse Jet Energy (GeV)
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
0
100
200
300
400

Inclusive jets at D0: extending the kinematic reach:

- In LO, the fractional momenta, x_1 and x_2 are:

$$x_{12} = \frac{E_T}{\sqrt{s}}(e^{\pm\eta_1} + e^{\pm\eta_2})$$

$$\eta = -\ln(\tan(\theta/2))$$

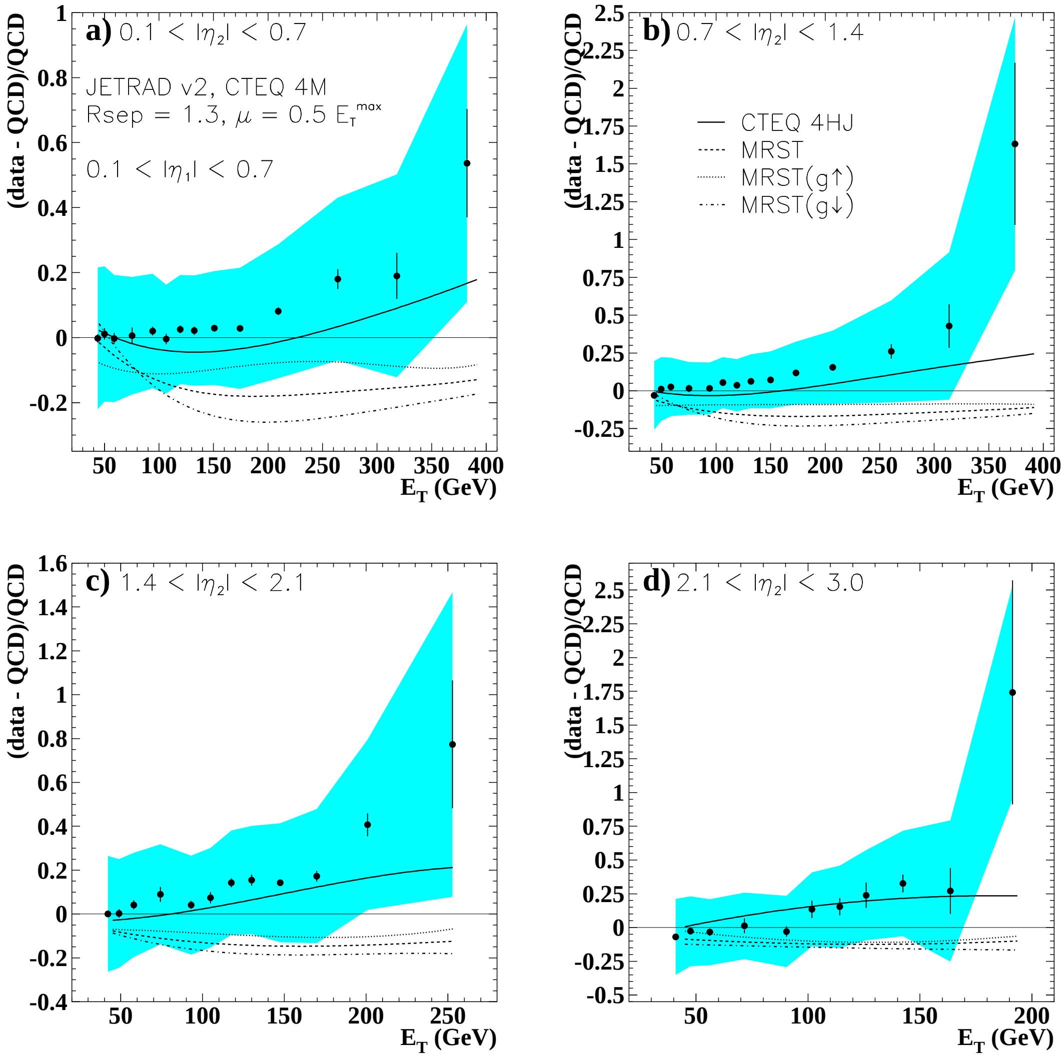


$|\eta|$ range extended from 0.7 to 3.0.

- Compatible with most standard PDF's.

Dijet studies at CDF:

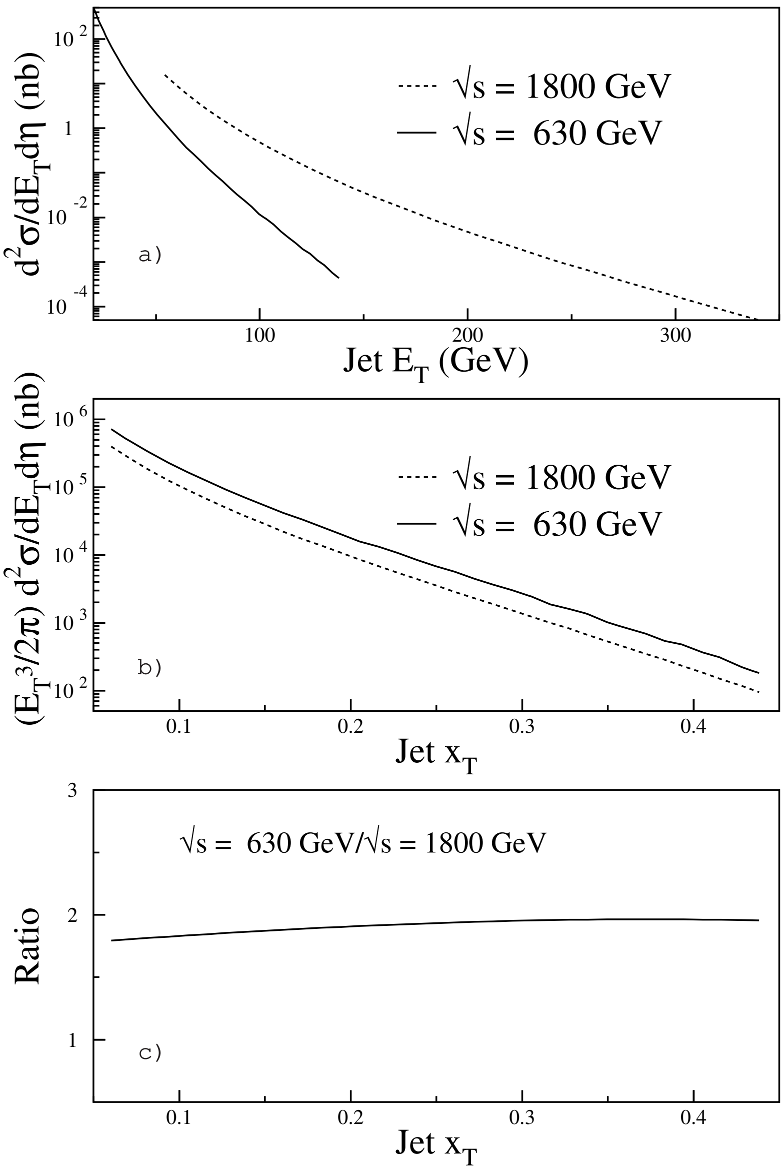
- Fix one jet at $0.1 < |\eta_1| < 0.7$. Bin in different $|\eta_2|$ ranges for the other jets.



- MRST, CTEQ4 pdf's give $\chi^2/dof = 2.5 - 4.5$.
- Can pdf's "retune" without causing problems elsewhere?

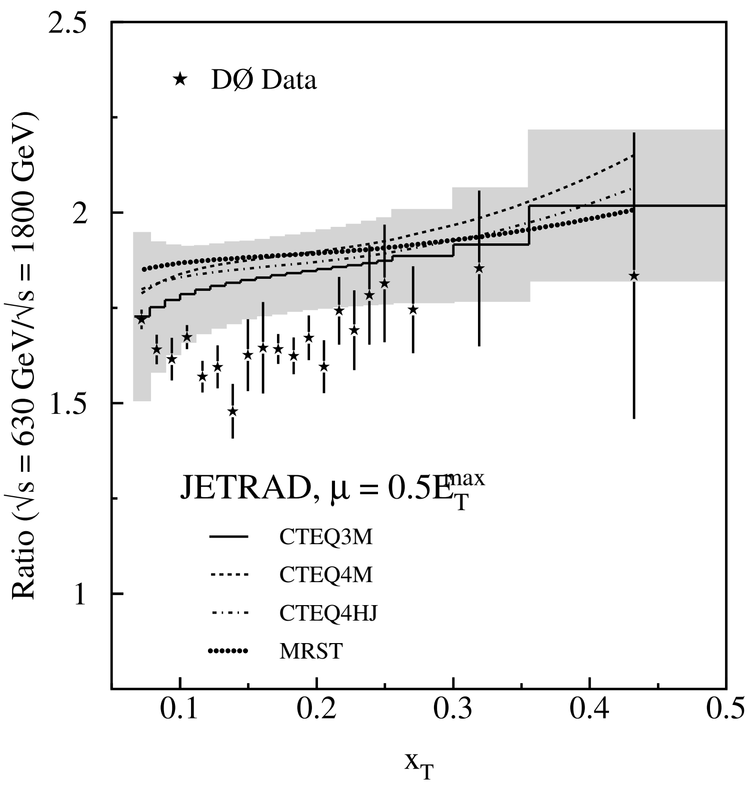
Jet cross-section ratio at $\sqrt{s}$ 1.8 and 0.63 TeV (D0)

$$x_T = 2E_T/\sqrt{s}$$

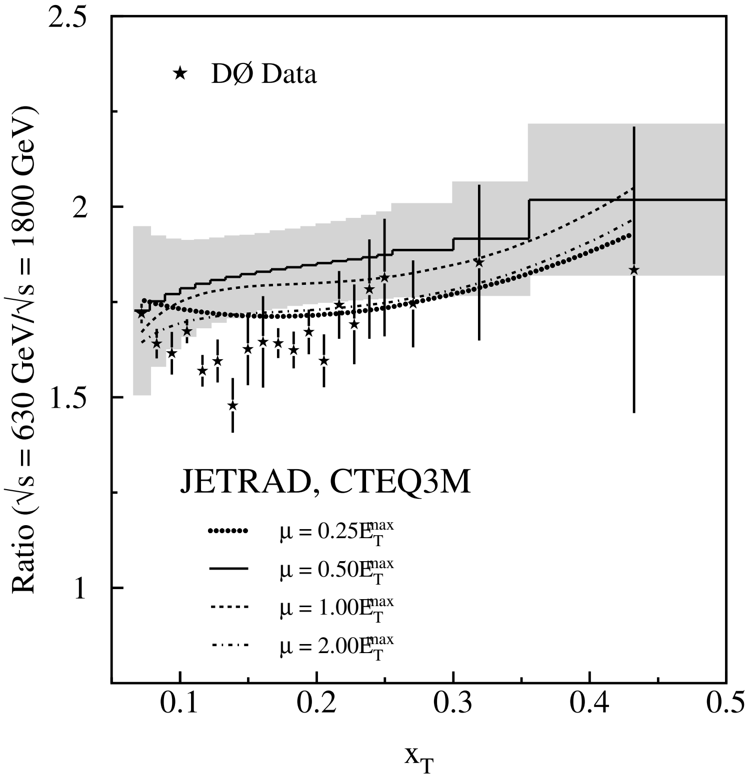


- Many experimental uncertainties cancel.
- PDF dependence cancel to a large degree.
- Other theoretical uncertainties (μ_R, etc.) also cancel to some extent.

Jet cross-section ratio at $\sqrt{s}$ 1.8 and 0.63 TeV (D0)



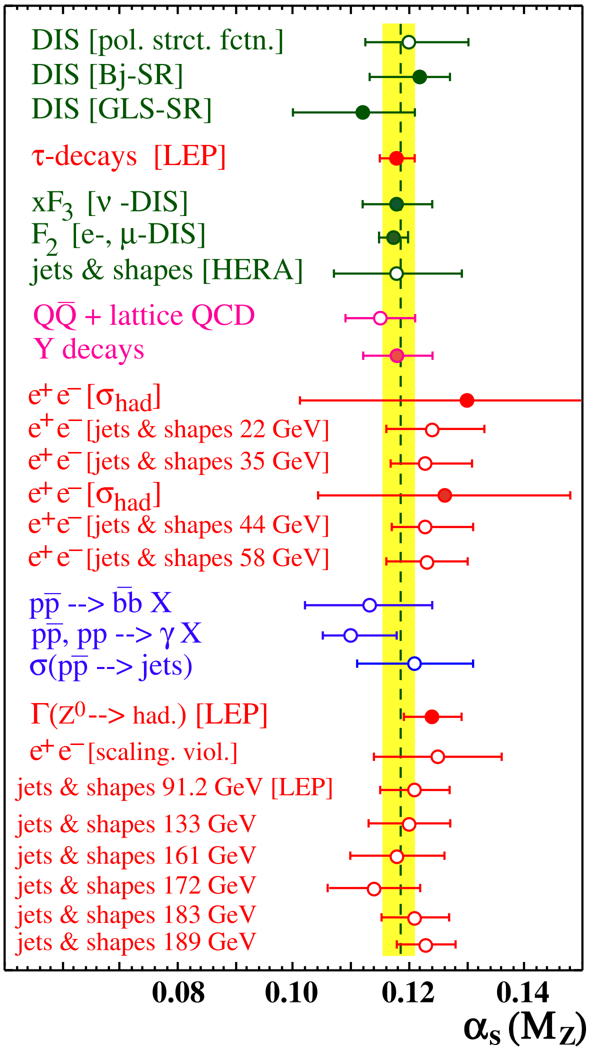
- The pQCD predictions consistently lie above data.



- Fairly extreme choice of $\mu_R = 0.25 E_T^{max}$ gives an acceptable χ^2.
- Still needs higher orders?

IV Conclusion

- Many other interesting(and important) QCD studies were not mentioned here.
- QCD is a diffcult theory to test (which make it intersting!)
- Many tests of pQCD at colliders. Precision is of order 5-20%.
- However, all give impressively consistent picture (eg S. Bethke review):



- In detail, many questions remain...
- More examination of QCD is needed and will continue!