Precision pQCD at HERA

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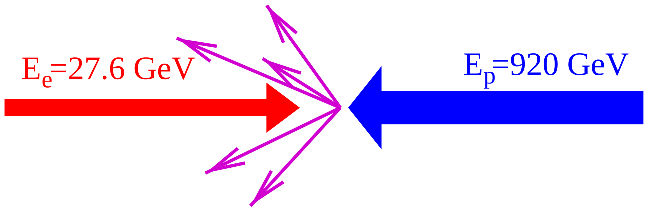
H1 Collaboration

- Introduction
- Structure functions
- α_s and the gluon density
- Jet Cross Sections
- Heavy flavour production
- Summary

The HERA ep Collider

HERA at DESY in Hamburg:

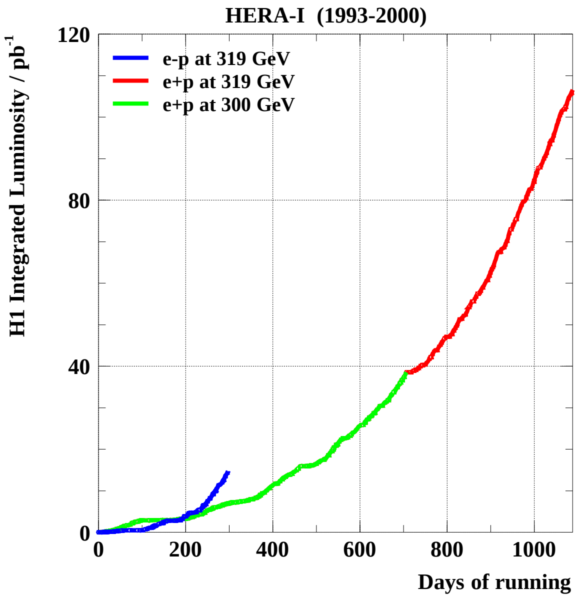
6.3 km circumference



4 interaction regions / experiments:

- H1, ZEUS: ep collisions at $\sqrt{s} = 320$ GeV
- HERMES, HERA-B: fixed target e or p

HERA-I: 1992-2000

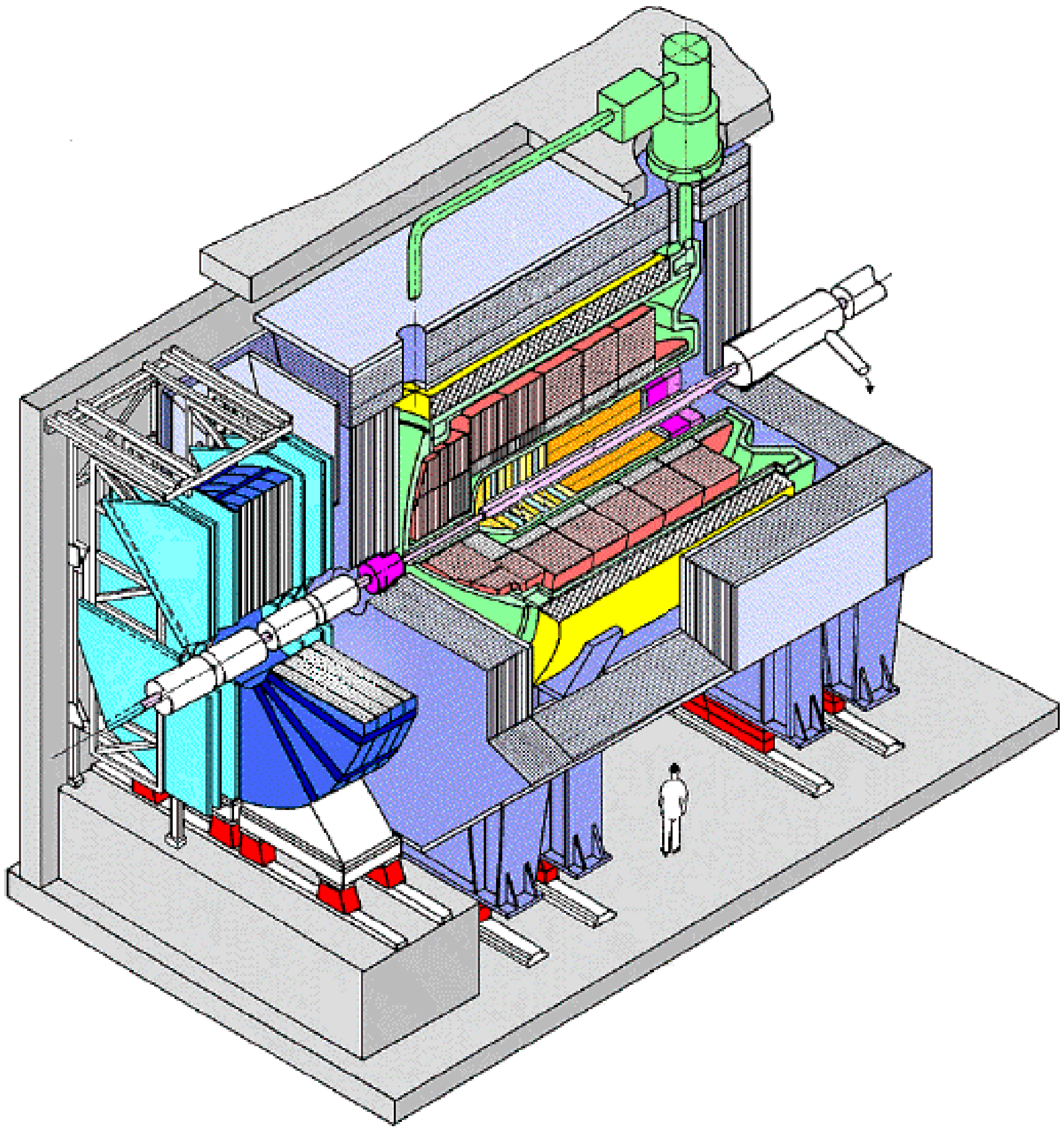


$120\ \mathrm{pb}^{-1}$ on tape per experiment

HERA-II: 2001-2006

- Major upgrade of machine (luminosity) and experiments
- Goal: $1\ \mathrm{fb}^{-1}$ until 2006
- Just started ...

The H1 Detector

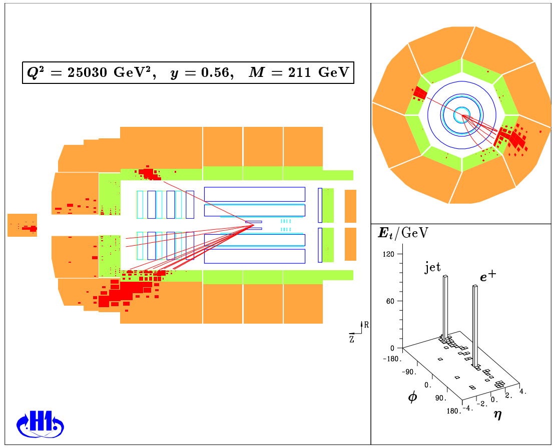


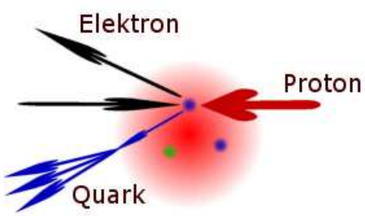
- Standard 4π state of the art detector
- Similar to LEP / TEVATRON experiments
- Asymmetric configuration
- Collaboration of 400 physicists / 12 countries

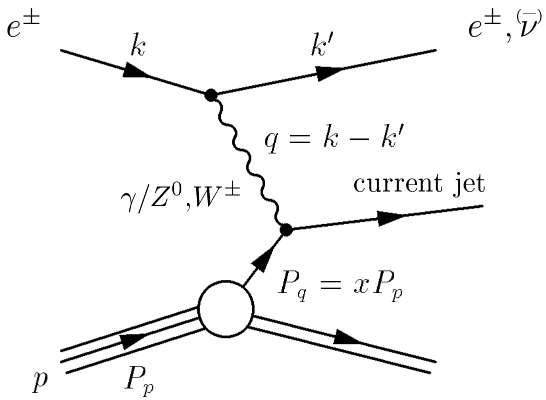
Physics Program:

- QCD studies (Structure functions, Jets, heavy flavours, diffraction)
- Electroweak physics
- Search for new physics (e.g. Leptoquarks, SUSY, substructure, ...)

Deep-Inelastic Scattering (DIS)







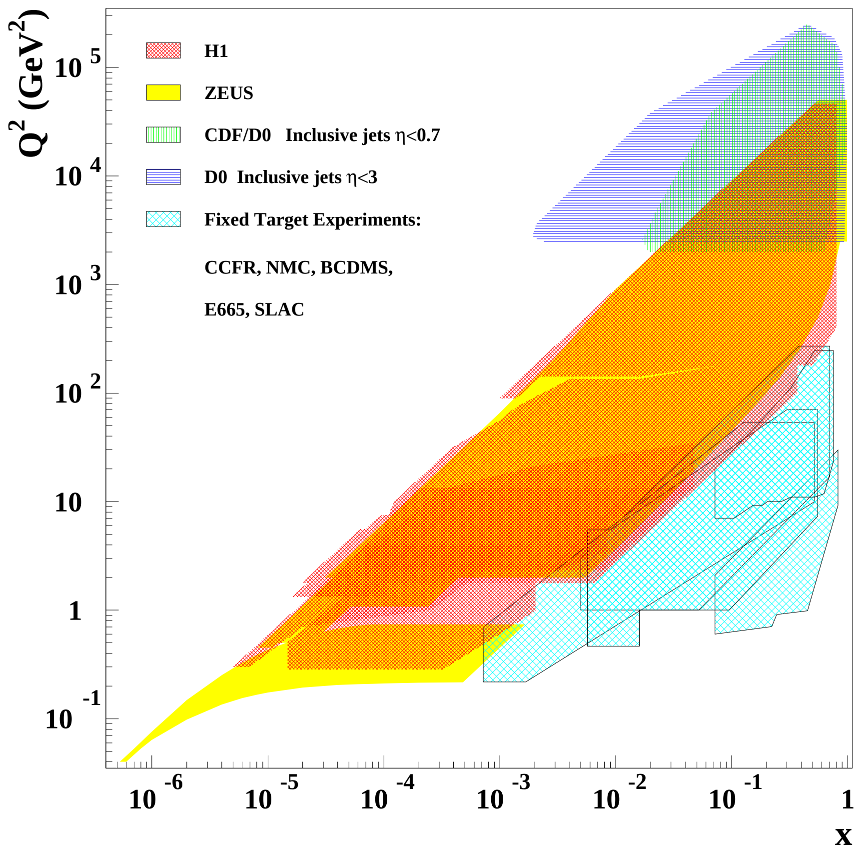
$$Q^2 = -q^2 = (k - k')^2$$

Photon virtuality

$$x = \frac{-q^2}{2P \cdot q} \quad (0 < x < 1)$$

Parton momentum fraction "Bjorken-x"

Kinematic plane (x, Q^2)



- Due to large CM energy: kinematic range much extended w.r.t. fixed target expts.

Structure Function $F_2(x, Q^2)$

The neutral current (NC) cross section

$$\frac{d^2\sigma^{\rm NC}}{dx\ dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left(Y_+F_2 - y^2F_L \pm Y_-xF_3\right)$$

where

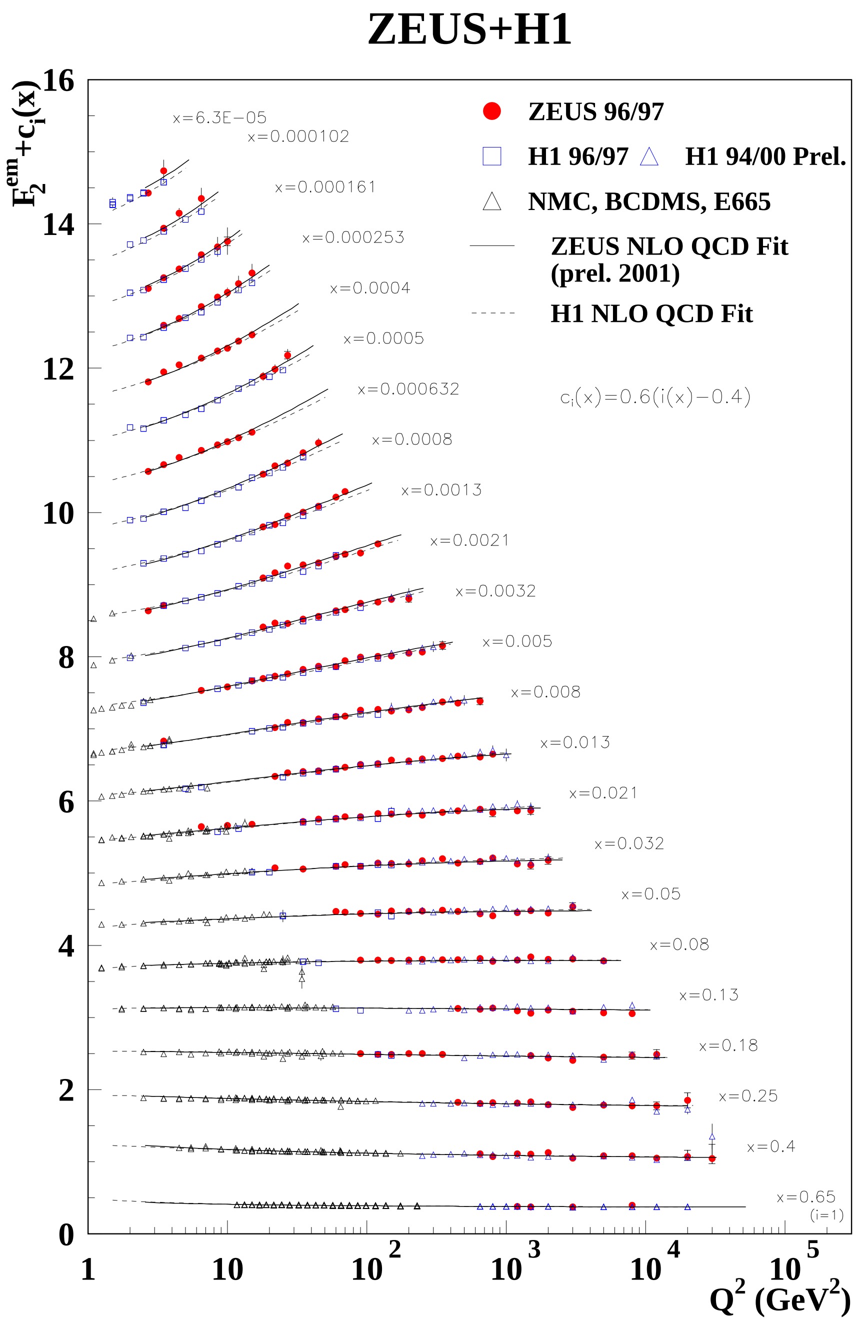
$$y = Q^2/xs \qquad Y_\pm = 1 \pm (1-y)^2$$

is related to the structure functions:

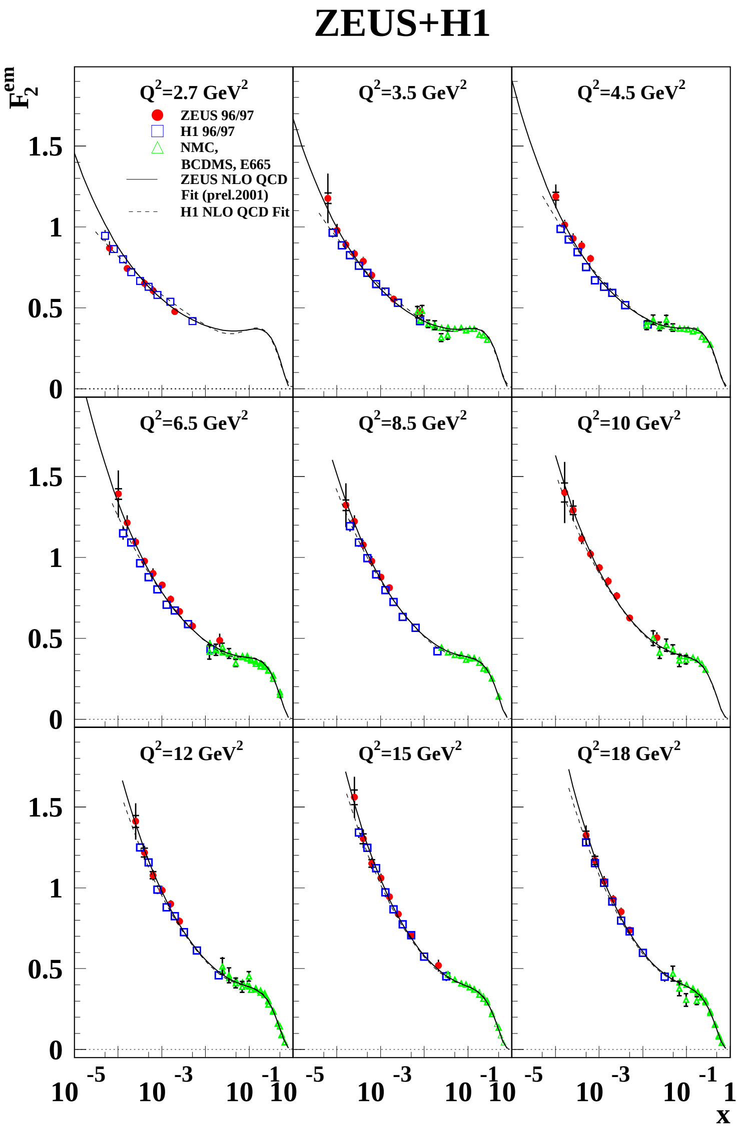
- F_2
- F_L (longitudinal part)
- xF_3 (parity violating, small for $Q^2 < M_Z^2$)

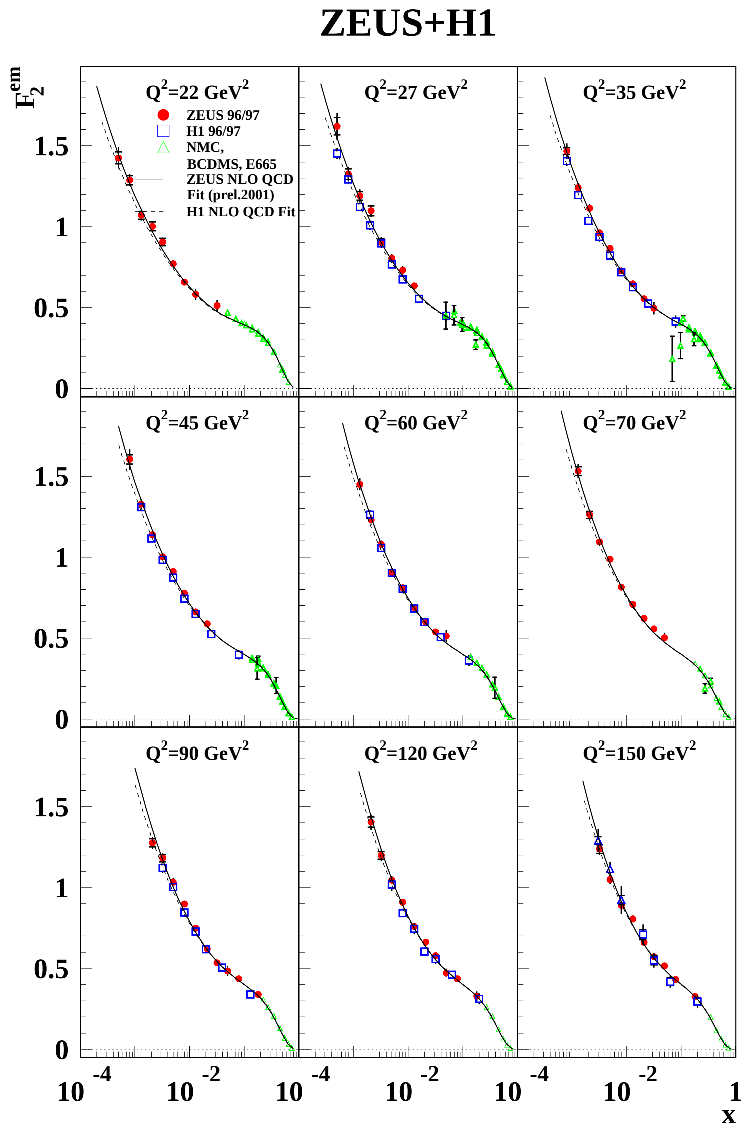
Exp. precision $2 - 3\%$!

[low-x scaling violations: $g \longrightarrow q\bar{q}$ splitting]



x dependence of $F_2(x, Q^2)$





Strong low-x rise discovered at HERA; driven by gluon distribution

NLO DGLAP QCD Fits

QCD Factorization:

$$F_2 = \sum_i \int_x^1 d\xi f_i(\xi, Q^2, \alpha_s)\, \hat{\sigma}(x/\xi, Q^2, \alpha_s)$$

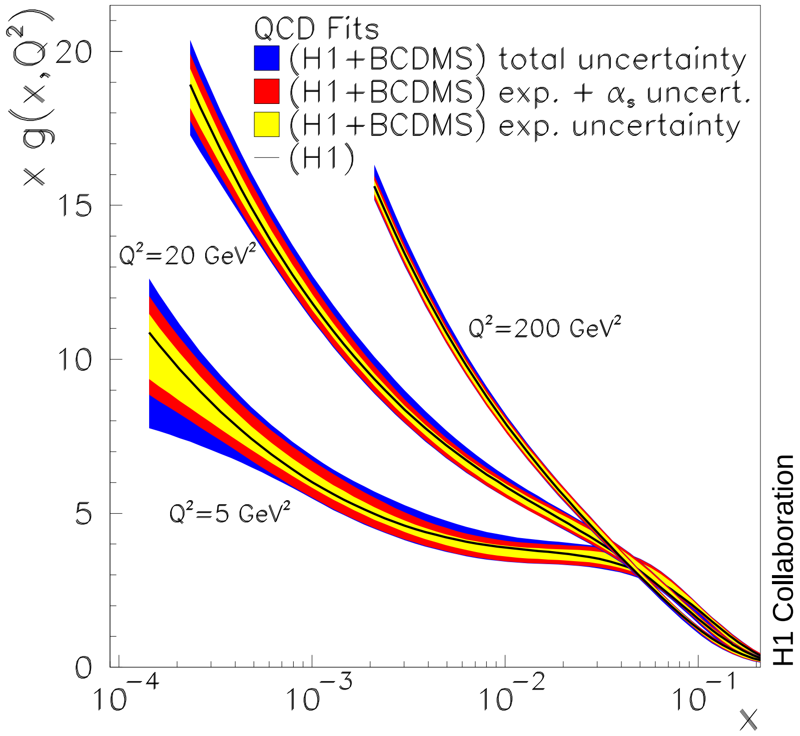
Short range $\hat{\sigma}$ and pdf's

pdf's evolve with DGLAP
(known to NLO for $\sigma_{incl.}$)

Data constrain pdf's at Q_0^2 (here $4\ \mathrm{GeV}^2$)

- Include BCDMS fixed target data
- Heavy quarks in massive scheme (PGF)
- Careful treatment of correlated systematic uncertainties (Pascaud,Zomer)

Gluon density $g(x, Q^2)$



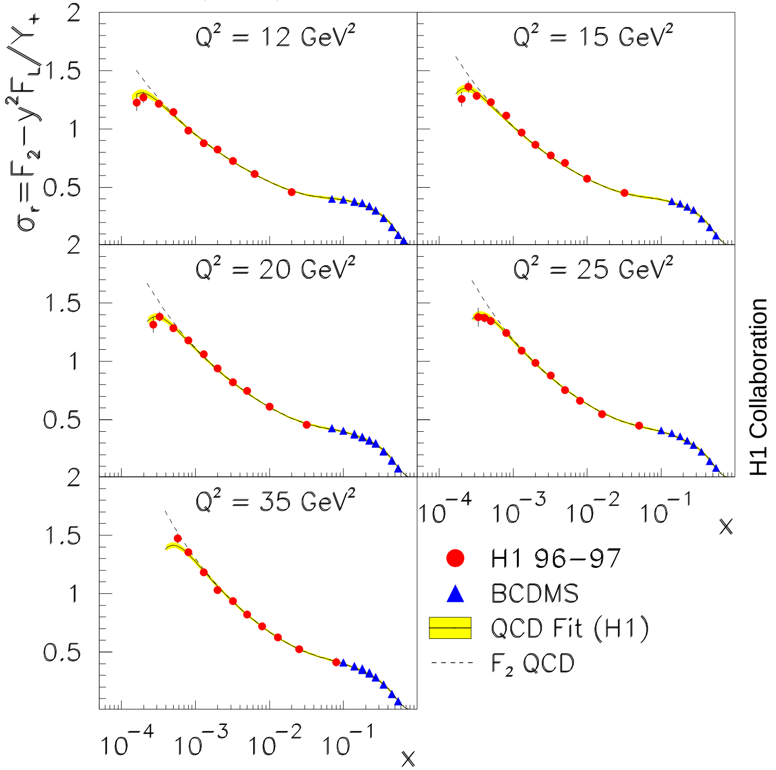
Precise down to $x = 10^{-4}$!

$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0017\ (\mathrm{exp.})\ ^{+0.0009}_{-0.0005}\ (\mathrm{model})\ \pm 0.0050\ (\mathrm{QCD})$$

Exp. error: World average precision (0.118 ± 0.003, S.Bethke)!
Dominating: Theory error (missing higher orders)
Theory error: reduce to ~ 0.001 at NNLO (soon!) $\Rightarrow$ High precision QCD !

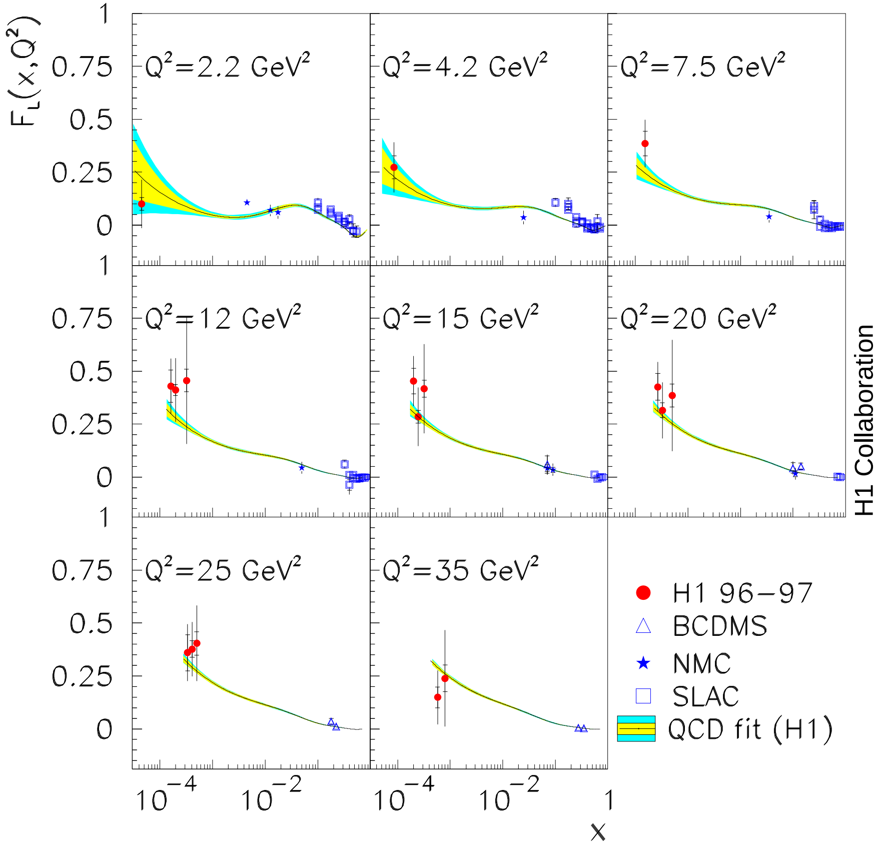
Longitudinal Structure Function F_L

Cross section at highest y,
i.e. smallest $x(Q^2)$: effect of F_L:



[difficult measurement at lowest E'_e]

F_L extraction through 'extrapolation' or 'derivative' method:

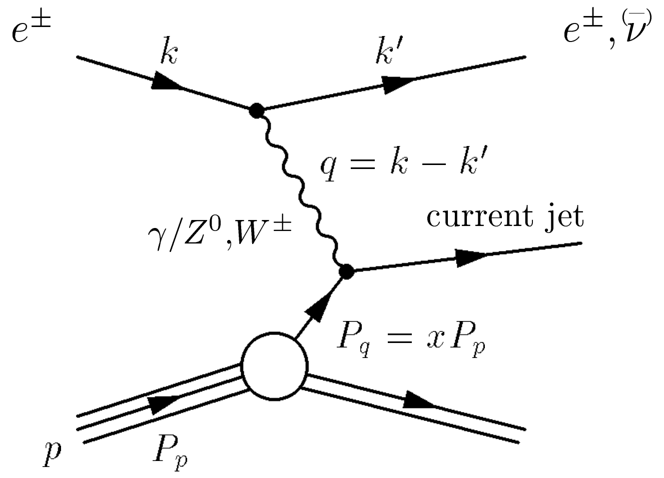


At NLO QCD, the leading twist longitudinal structure function F_L^D is predicted:

$$F_L^D \sim \frac{\alpha_s}{2\pi}\left[C_q^L \otimes F_2^D + C_g^L \otimes \sum_i e_i^2\, z g^D(z, Q^2)\right]$$

$\Rightarrow$ Consistency with QCD fit result is important cross check of data and theory !

High Q^2 NC and CC Cross Sections

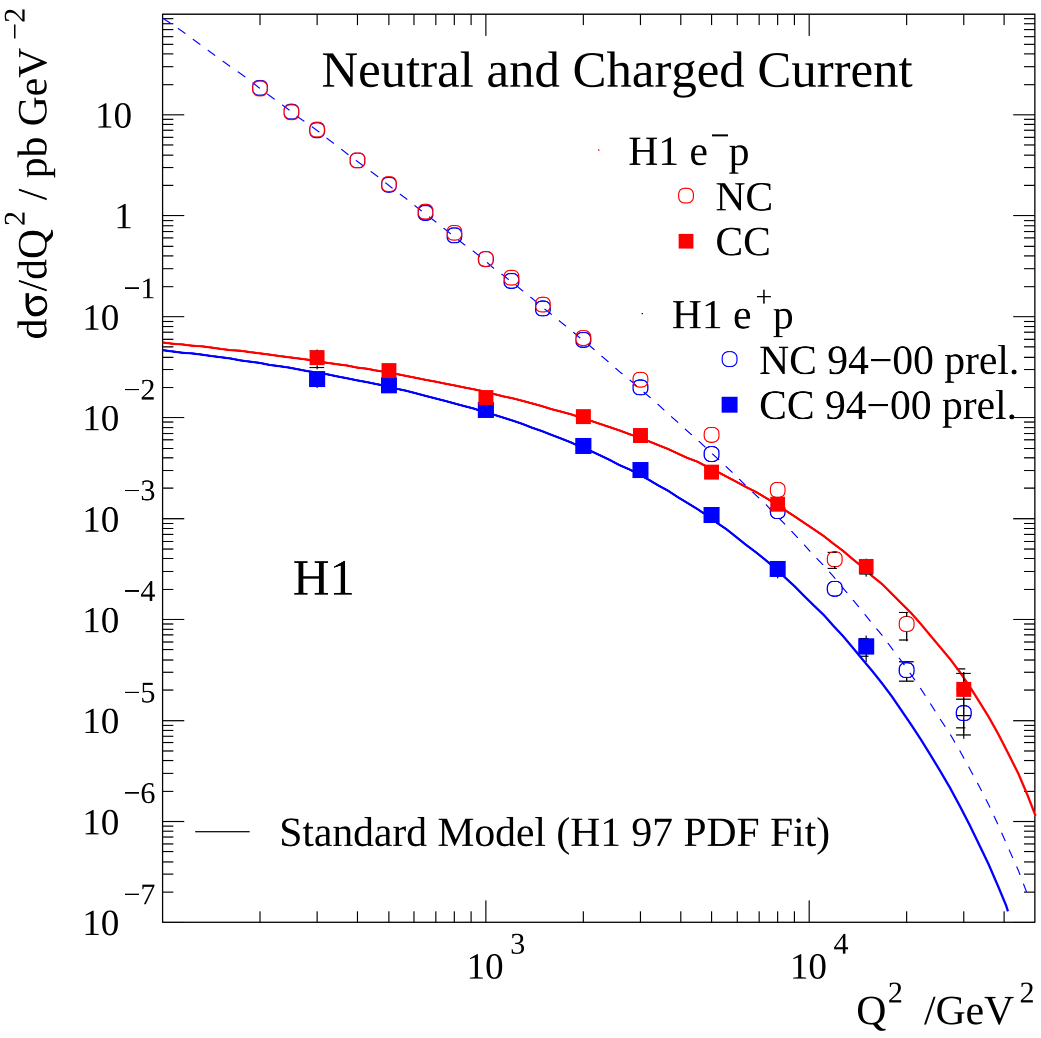


– Neutral Current NC (γ^* or Z^0):
$ep \rightarrow e'X$
– Chared Current CC ($W^\pm$):
$ep \rightarrow \nu_e X$

$W^\pm$ propagator:

$$\frac{d\sigma^{\rm CC}}{dxdQ^2} = \frac{G_F^2}{2\pi x}\left(\frac{Q^2}{Q^2+M_W^2}\right)^2 \sigma_r^{CC}$$

e^+p and e^-p scattering sensitive to d_v, u_v at high x



Success of DGLAP QCD over 7 orders of magnitude!

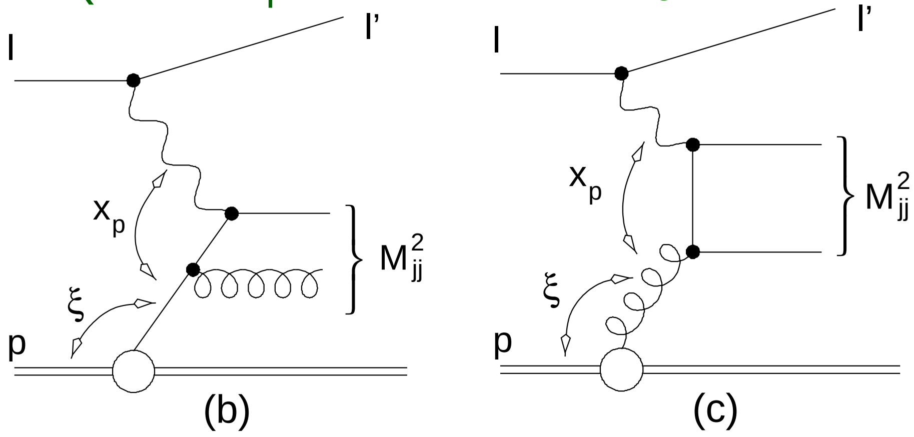
At highest Q^2 sensitivity to BSM physics (Leptoquarks, substructure etc.)

Jet Cross Sections in DIS

Leading order QCD processes:

QCD-Compton

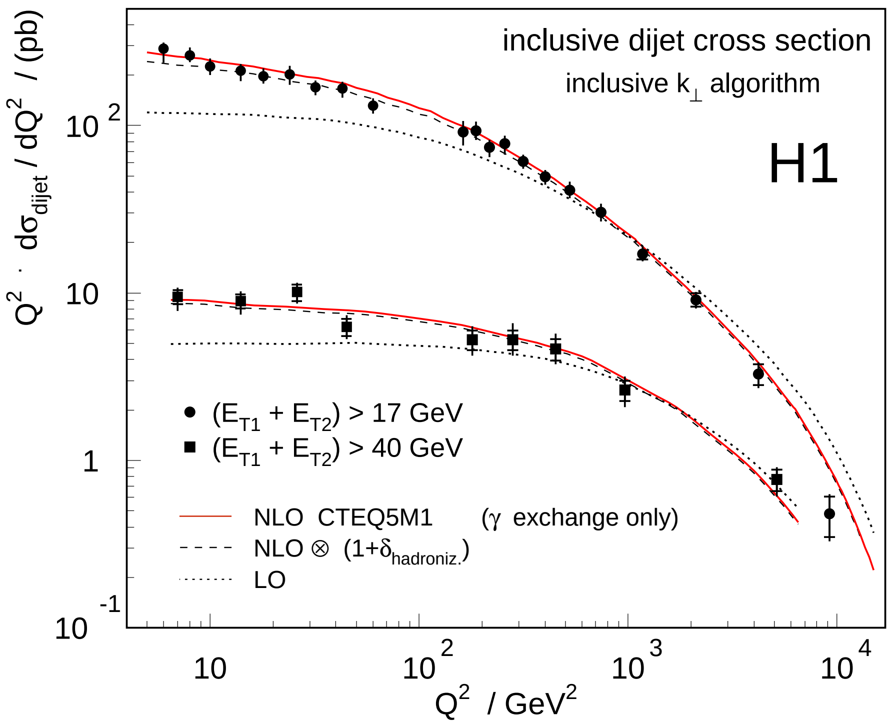
Photon-Gluon-Fusion



[dominates high Q^2] [dominates low Q^2]

- Sensitive to α_s and $g(x, Q^2)$
- In DIS have two scales: E_T and Q^2
- Jets searched for using invariant k_T algorithm (small hadronization corrections)
- Comparison with NLO QCD calculations tests pQCD

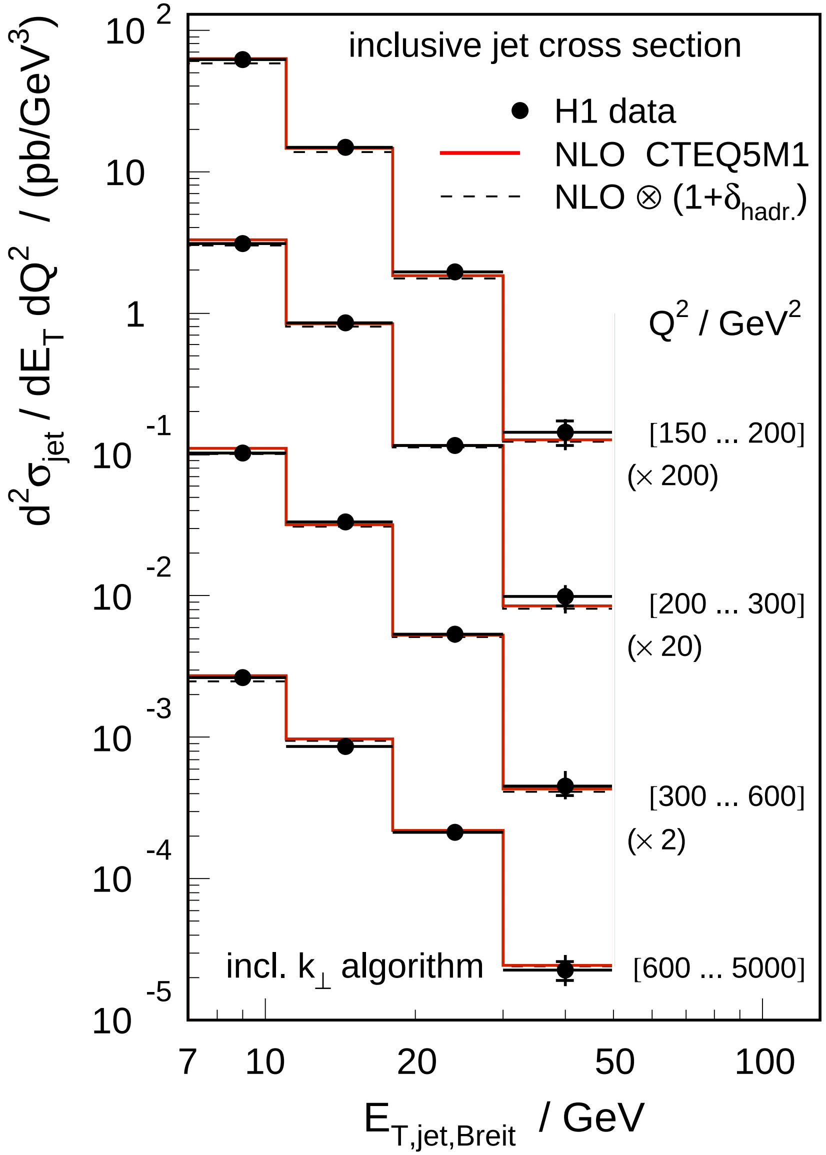
Dijet Cross Section:



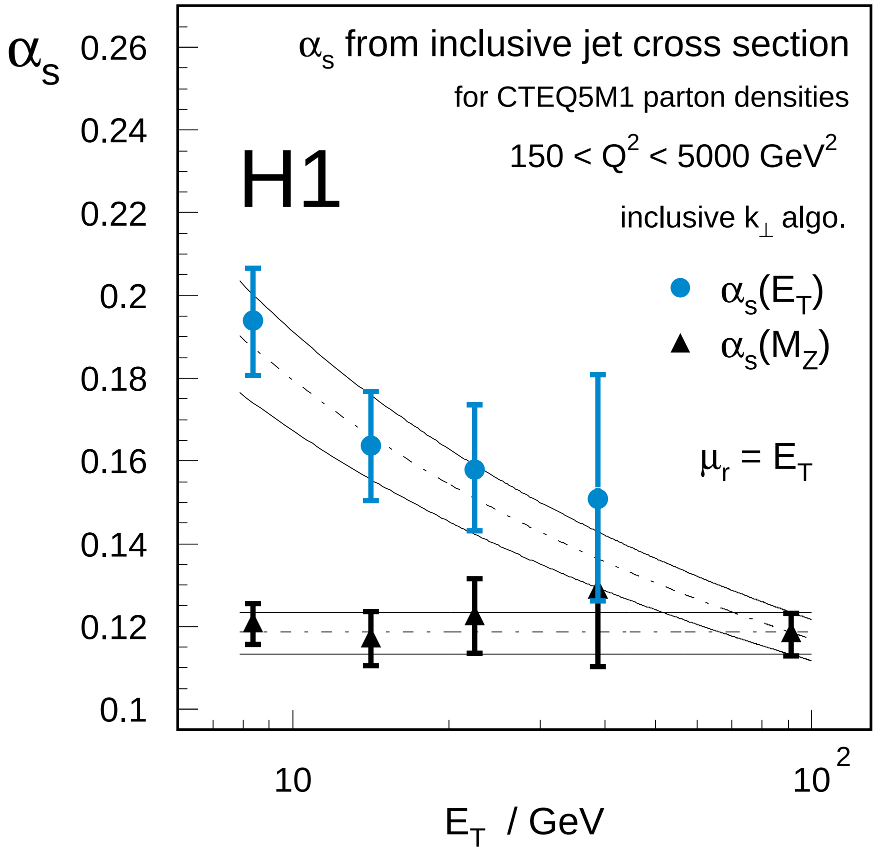
- NLO corrections small for $Q^2 > 200\ \mathrm{GeV}^2$
- Good agreement with NLO QCD

Inclusive Jet Cross Section and α_s

Double differential $\sigma_{jet}(E_T, Q^2)$:



- Good description by NLO QCD enables to Determine $\alpha_s(E_T)$

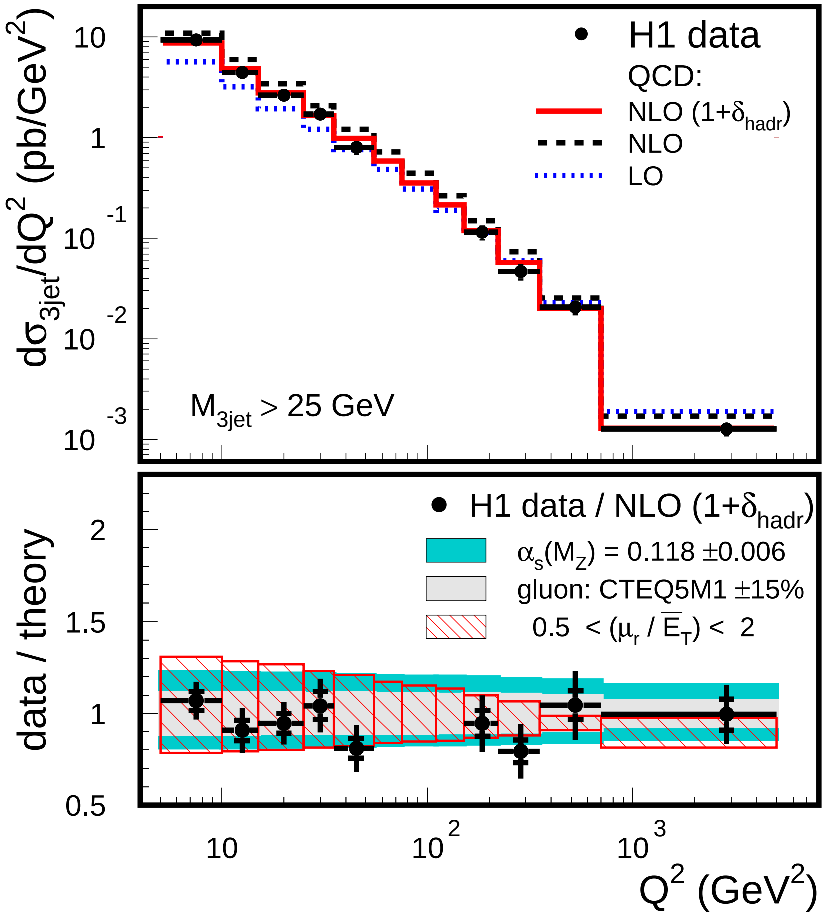


$\Rightarrow$ Consistent with RGE !

3-Jet Cross Section in DIS (first measurement)

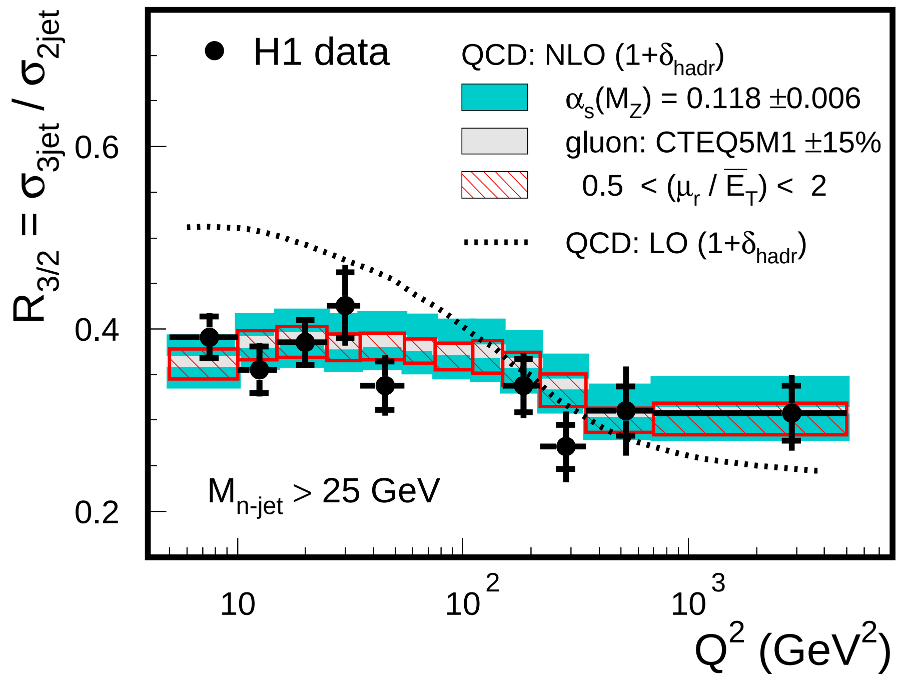
Reminder: for 3-Jet events:
LO is $\mathcal{O}(\alpha_s^2)$, NLO is $\mathcal{O}(\alpha_s^3)$

NLO Calculations recently made available



Well described by NLO (not by LO) !

Ratio 3-jet / 2-jet cross section:



– Word average $\alpha_s = 0.118$
– exp. / pdf uncertainties cancel !

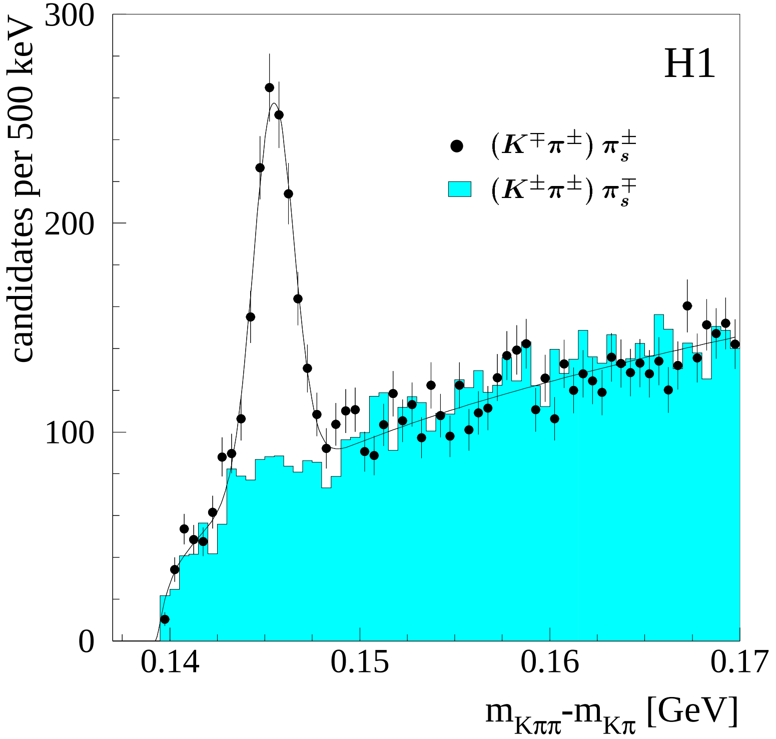
Strong sensitivity to α_s !

[Very interesting with more stats. (HERA-II)]

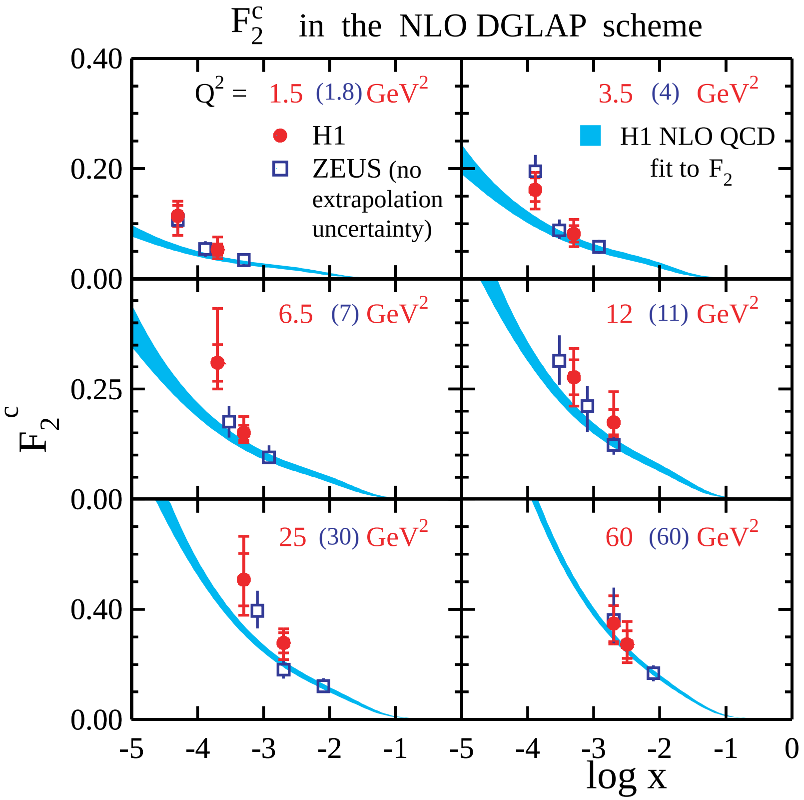
Heavy flavours: Charm and the gluon

Main production mechanism:
PGF: $\gamma p \longrightarrow c\bar{c}$

– Direct sensitivity to $g(x, Q^2)$
– Selection of charm events via $D^* \longrightarrow K\pi\pi$



Extraction of charm contribution to F_2:



N.B. large extrapolation to full phase space due to p_T, η cuts on D^*

Comparison with QCD fit to F_2:
Is there a problem at small x?

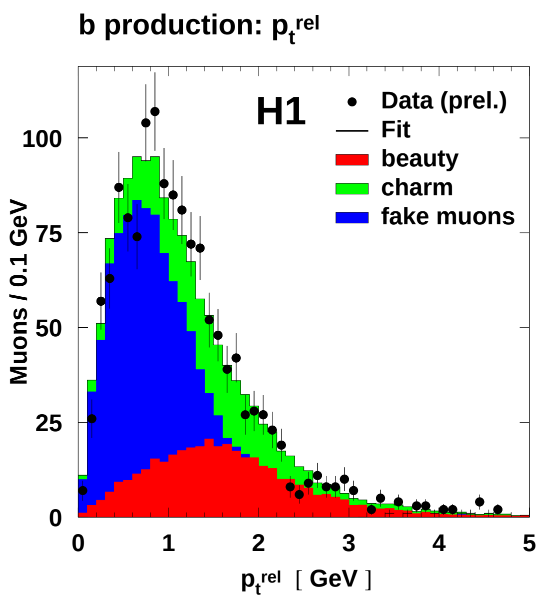
Open Beauty Production - The b puzzle

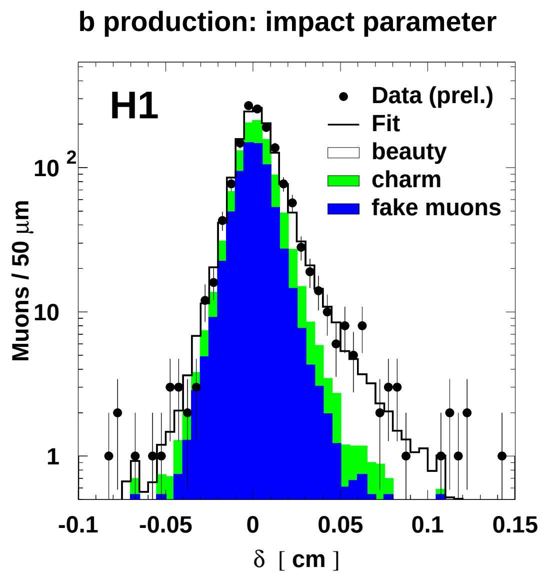
Production: PGF ($\gamma^* g \longrightarrow b\bar{b}$)

Use semi-leptonic decay of b hadron:
dijets + high p_T lepton

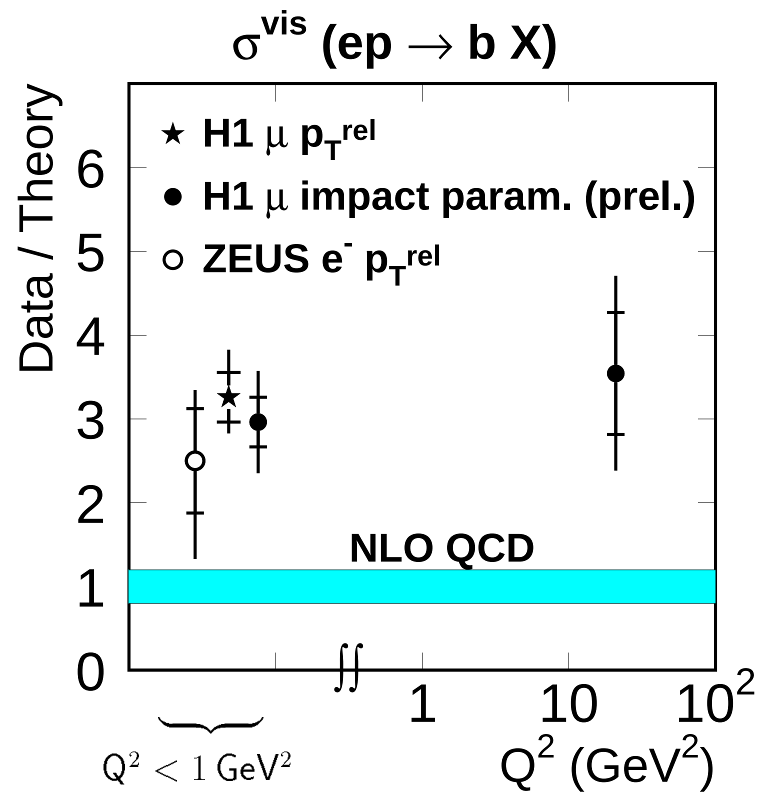
b tagging:

- Mass tag: high $p_{T,rel}$ of lepton w.r.t. jet
- Lifetime tag: impact parameter analysis (silicon tracking)





b cross sections compared with NLO QCD:



$\longrightarrow$ Data factor 2-3 above NLO !

Similar observations made at LEP and TEVATRON.

Missing higher orders or ... ?

Conclusions

[Disclaimer: this was just a small fraction of HERA QCD results]

- The HERA accelerator and the H1 and ZEUS experiments are a leading QCD facility
- High precision data over very large kinematic range accumulated
- Precise determination of strong coupling α_s challenges theoretical calculations (NNLO)
- Precise measurements of proton structure (quark and gluon densities) are vital to test QCD itself, but also to nail down the SM background in searches for new physics at TEVATRON and LHC
- Precision pQCD tests using Jet and heavy flavour cross sections
- Looking forward to HERA-II