Jet Production at HERA

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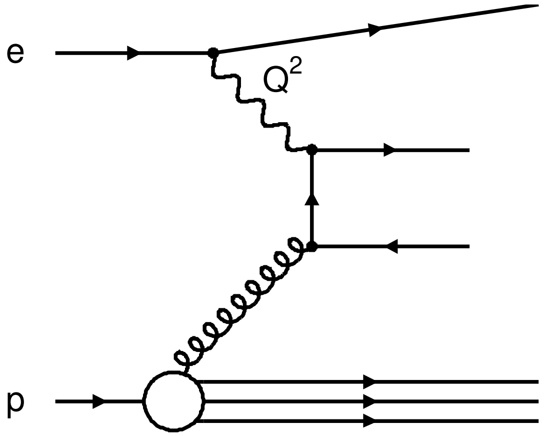
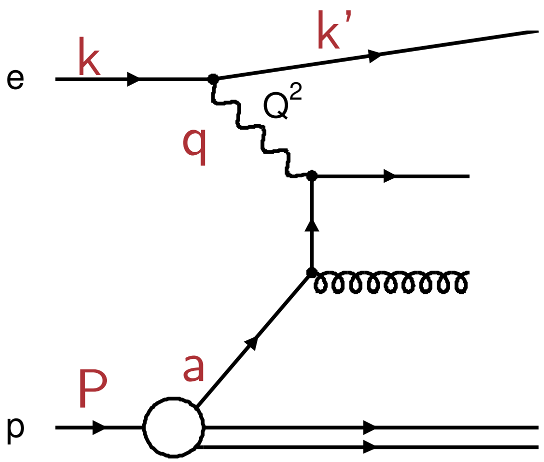
on behalf of the H1 and ZEUS Collaborations at HERA

Topics:

- Hard scales (α_s, proton and photon structure)
- Small scales (Limits of NLO pQCD)
- Substructure of jets
- Conclusions and Outlook

DIS Production mechanism of $eP \rightarrow e + jets$





HERA: $\sqrt{s} = 300 - 318$ GeV

– Negative squared four momentum transfer: $\mathbf{Q^2} = -(k - k')^2$

– momentum fraction carried by partons out of the proton $x_P = \frac{q \cdot a}{q \cdot P}$

σ_{eP} is convolution of short distance cross sections and proton-PDF:

$$\boxed{d\sigma_{eP} = P\text{-PDF}(x_P, \mu_f) \otimes d\hat{\sigma}_{e,i}(Q^2, \mu_f, \mu_r)}$$

and $d\hat{\sigma}_{e,i} = \sum_{n=1}^{\infty} \alpha_s^n(\mu_r) C_n(\mu_r)$

$\rightarrow$ extract α_s, pdfs?

Jet definition – invariant $k_\perp$ (Ellis/Soper)

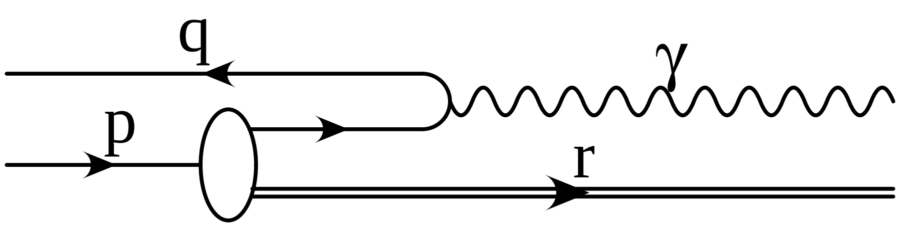
Advantages:

e.g. -smallest hadronization effects, no overlapping jets, small NLO corrections...

$\Rightarrow$ standard choice at HERA since 5 years

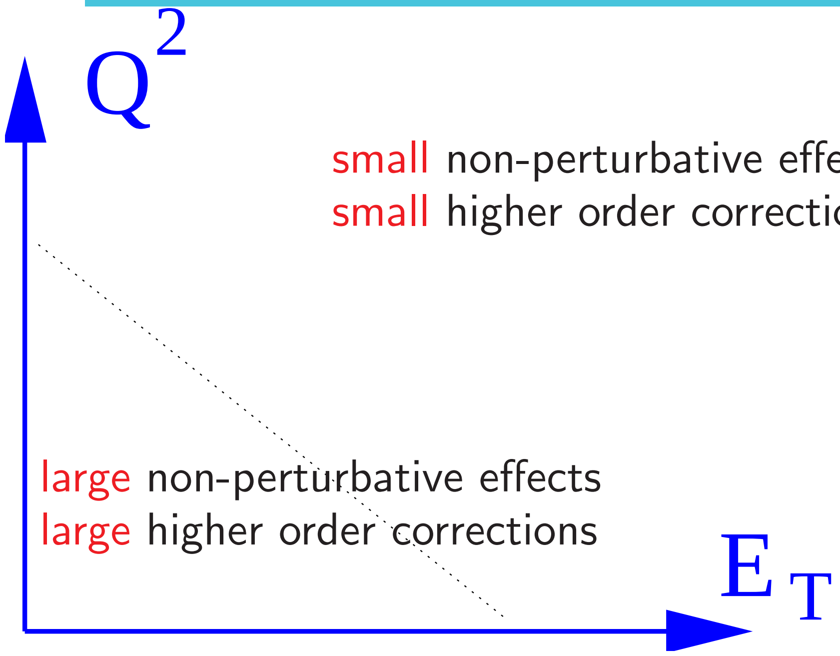
$\Rightarrow$ inclusive n-jet event: n-jets above E_T treshhold.

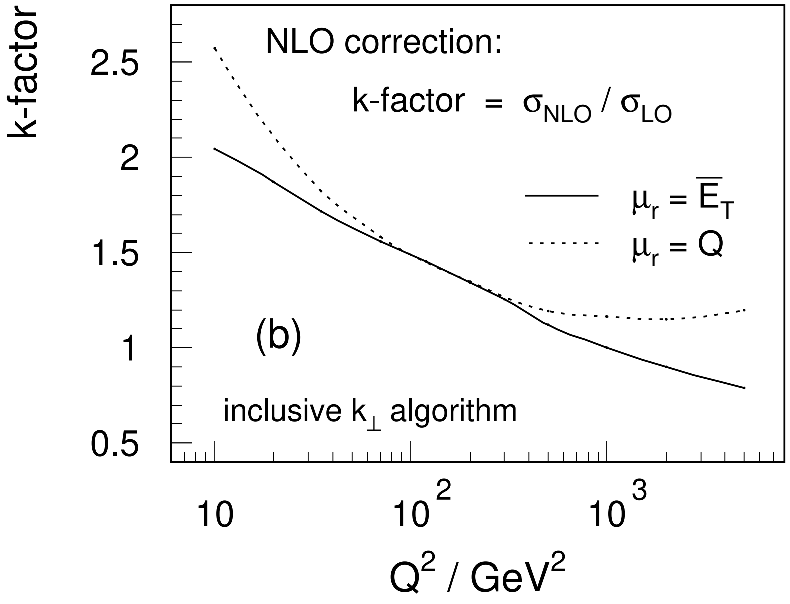
DIS: find jets in "Breit frame": $2xP + q = 0$



$\longrightarrow$ maximal separation between jet and beam remnant

A two scale problem

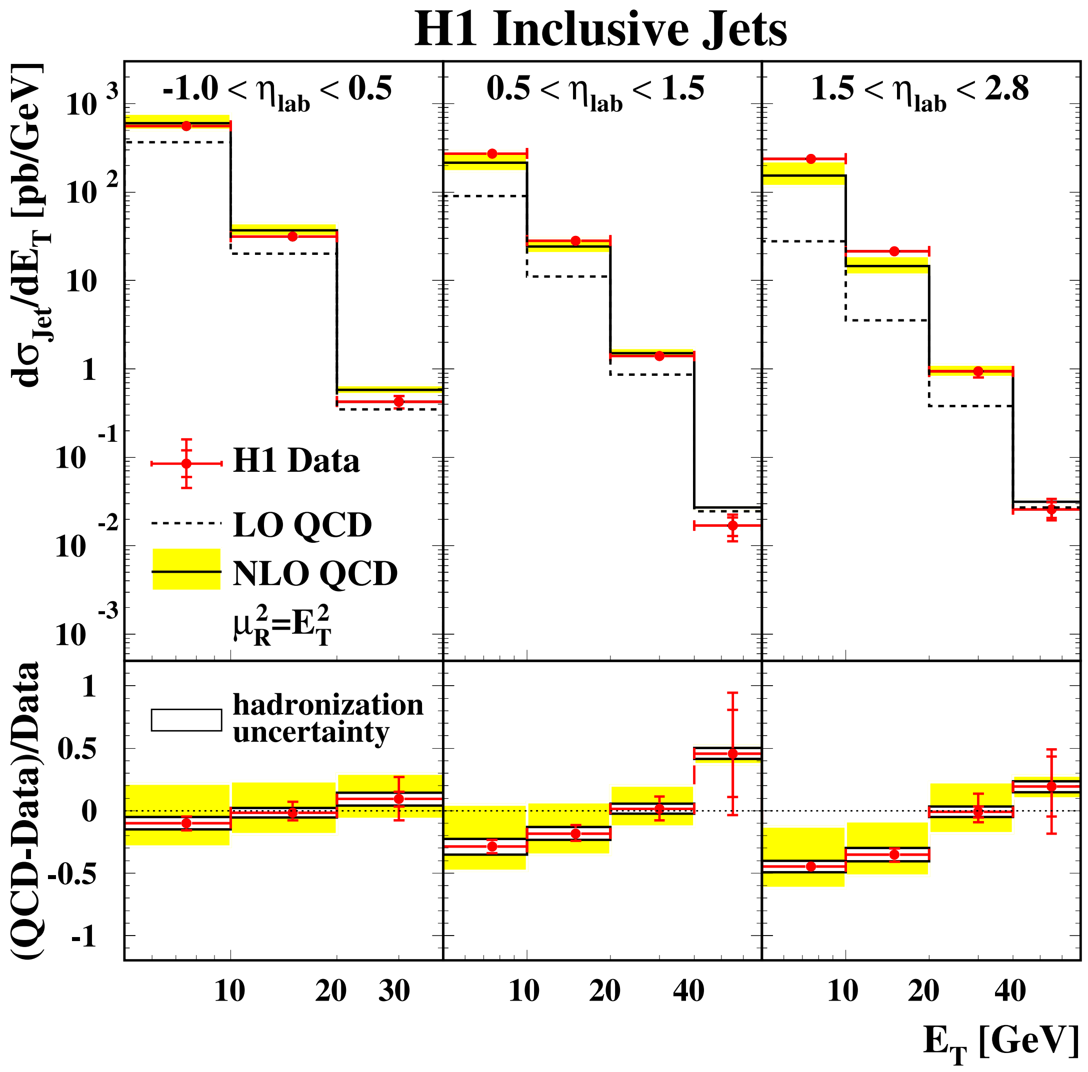




- At high E_T and/or Q^2 $\rightarrow$ quantitative tests of pQCD and possible extraction of α_s, proton and photon structure!
  $\rightarrow$ Additional and complementary information to $p\overline{p}$ and e^+e^- data

- At low Q^2, E_T $\rightarrow$ - low x - Higher orders? - test of non-perturbative physics (hadronization, Multiple Interactions, etc.)

Inclusive jets at low Q^2



Inclusive jets ⇒

Selection:

-5 $< Q^2 <$ 100 GeV^2

-jet $E_T >$ 5 GeV

-pseudorapidity $-1 < \eta < 2.8$

Theory:

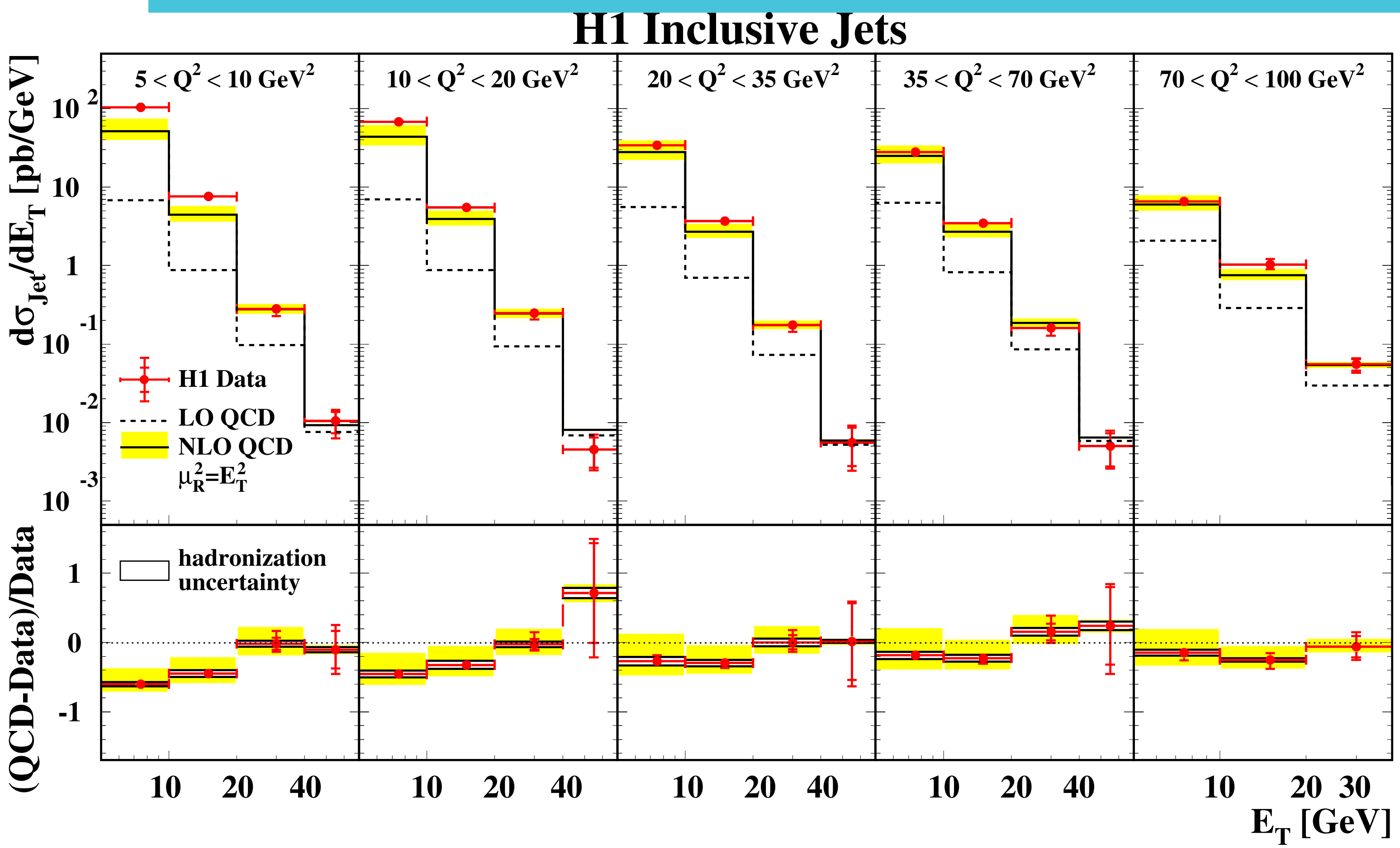
-renormalization scale: $\mu = E_T$

-theory uncertainty estimated by variation of scale by factor 2 (0.5)

-ratio NLO/LO goes up to 5!

NLO works, but discrepancies at low E_T and $\eta > 1.5$

Inclusive jets at low Q^2 in forward region

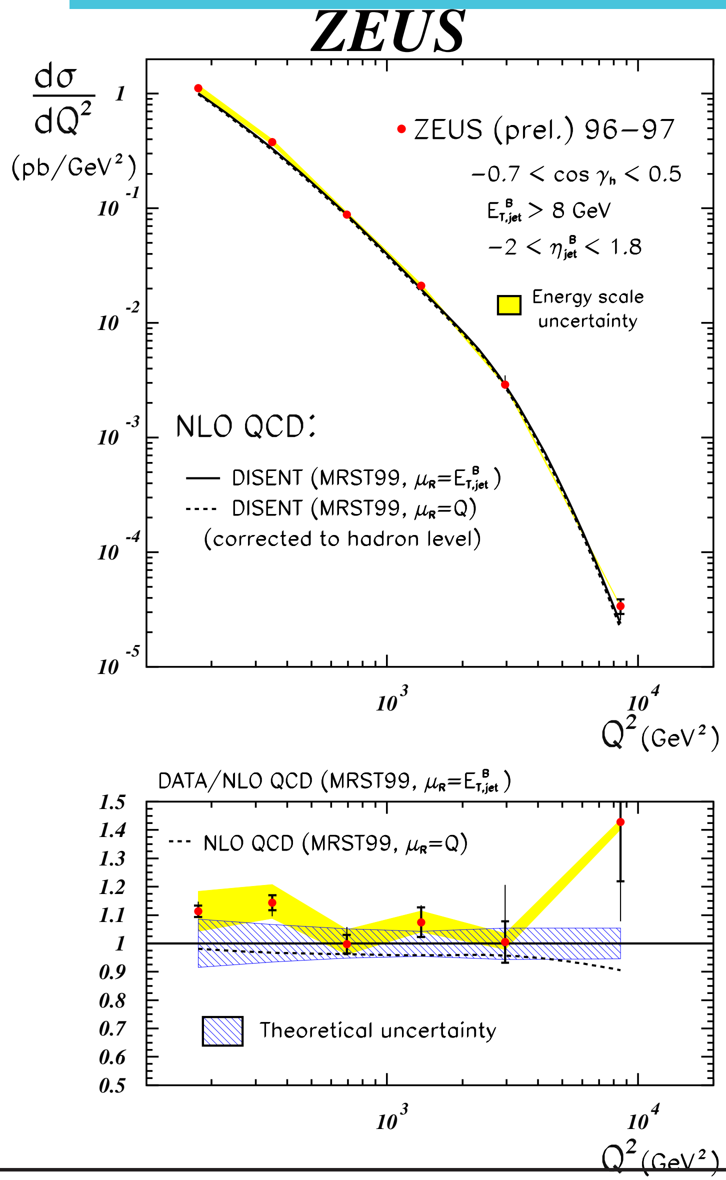


Now forward region only: $\eta > 1.5$!

$\longrightarrow$ data not described at low Q^2 and low E_T

DGLAP vs BFKL? Virtual photon needed? Or higher order calculations?

Jets at high Q^2



Selection:

-$Q^2 > 125$ GeV^2

-jet $E_T^B > 8$ GeV (Breit frame)

Physics:

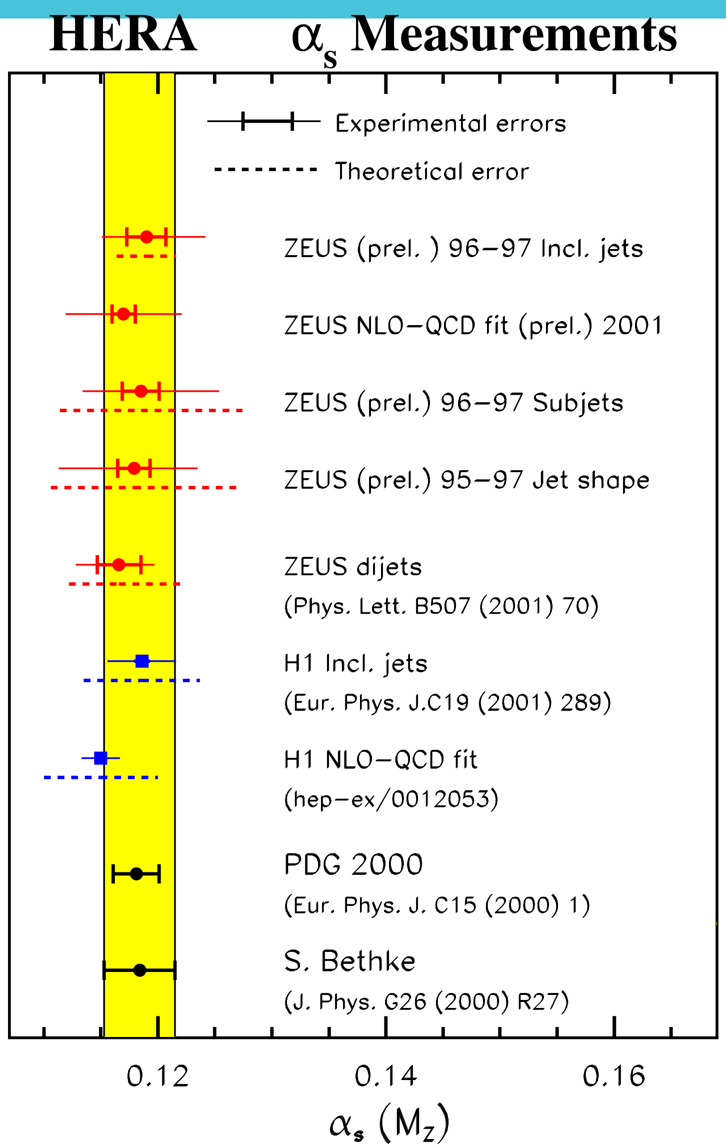
comparison with NLO pQCD

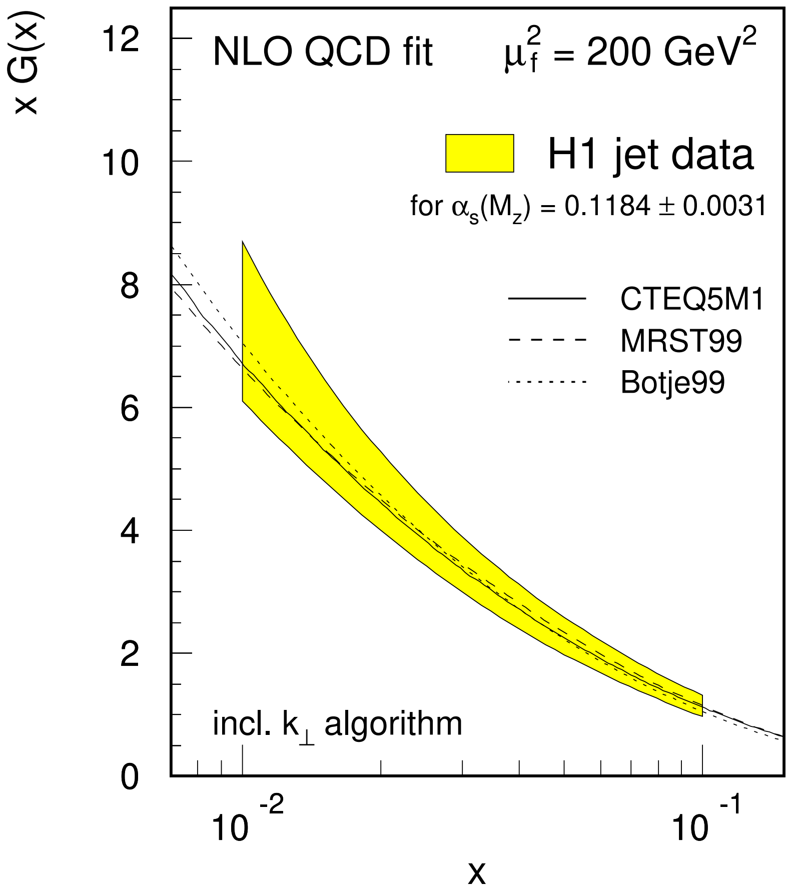
extract α_s

Data described by NLO pQCD at high Q^2

- small scale uncertainty
- small NLO/LO ratio

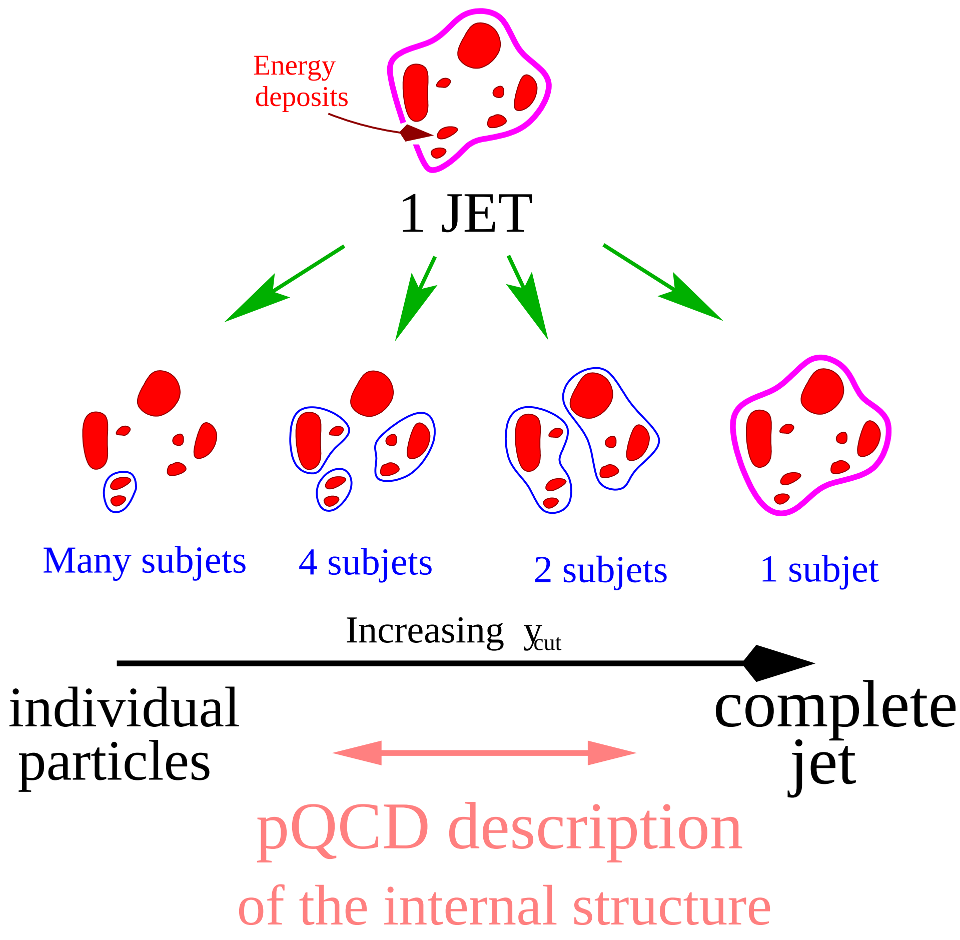
α_s and gluon density





$\longrightarrow$ direct determination of g from jets

Internal jet structure



Subjet Multiplicity:

repeating k_T algorithm with smaller resolution scale (merge until for every pair of particles i and j $d_{ij} > d_{cut}$ with $d_{cut} = y_{cut} E^2_{T,jet}$).

$$< n_{subjet} >= \frac{1}{N_{jet}} \sum_{1}^{N_{jet}} n_{subjet}$$

jets defined in lab. frame

$\longrightarrow$ up to 3 partons in a jet

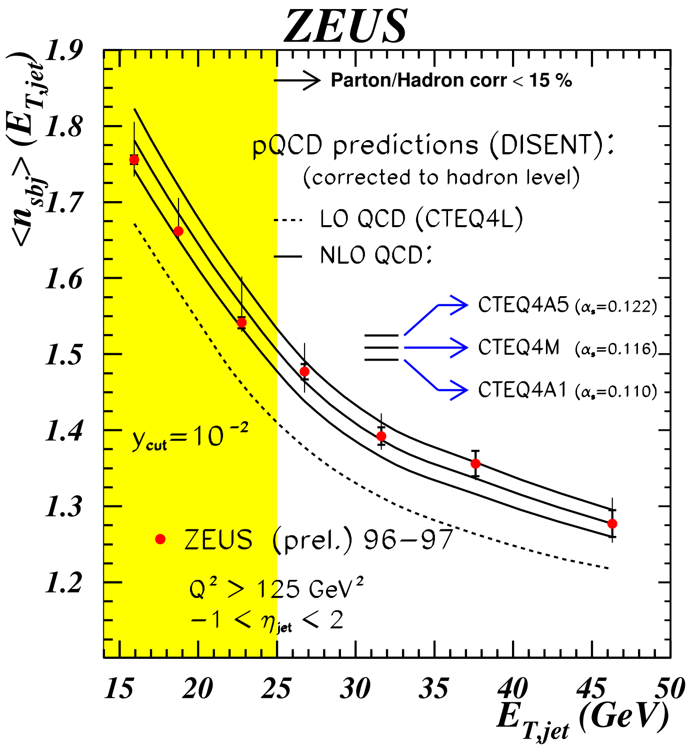
$\longrightarrow$ compare with NLO calculation!

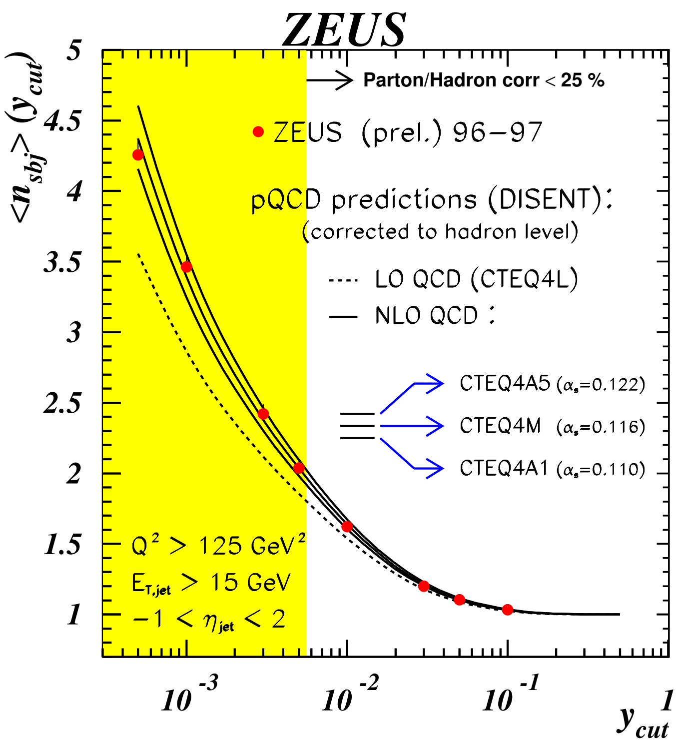
Selection:

$Q^2 >$ 125GeV^2

$E_T^L >$ 15 GeV

Internal jet structure

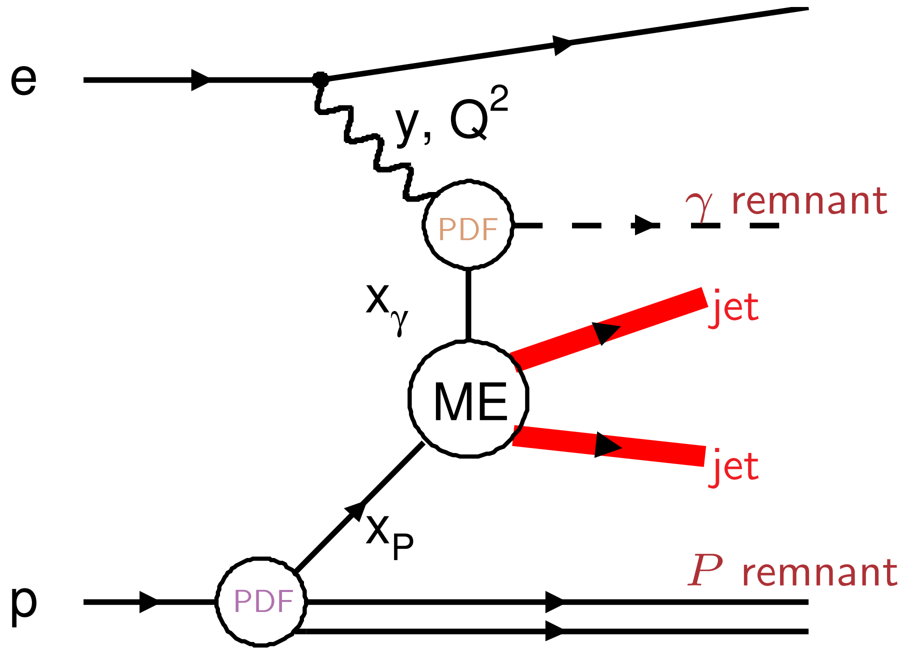




$\longrightarrow$ Jet structure described by NLO

$\longrightarrow$ Possible to derive α_s with jet structure in the well understood region

$\gamma^{(*)}P$ Production of jets



-$\mathbf{Q^2}$ photon virtuality ≈ 0
-$\mathbf{y}$ fraction of electron momentum carried by the photon
-$\mathbf{x_P}$ momentum fraction carried by partons out of the proton
-$\mathbf{x_\gamma}$ momentum fraction carried by partons out of the photon.

At small Q^2 photon may fluctuate into partons before hard scatter $\longrightarrow$ photon structure

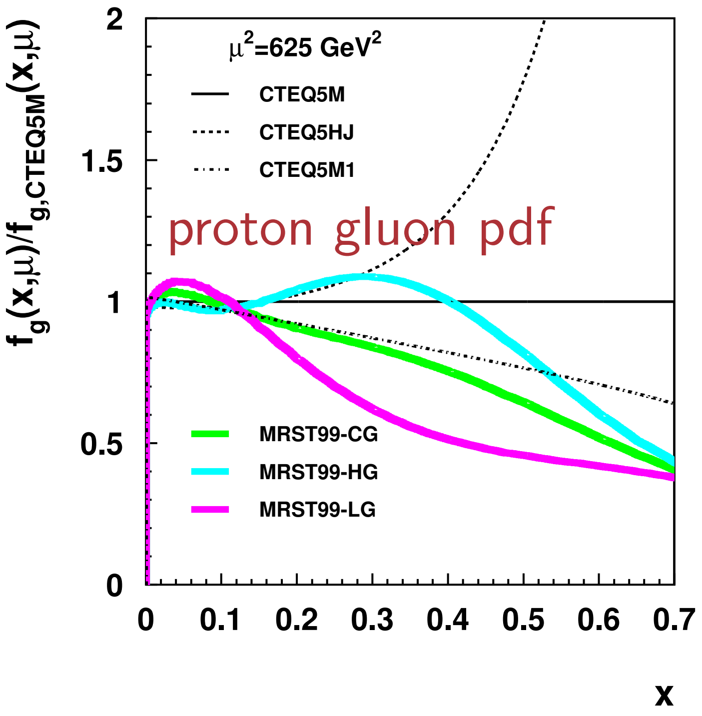
DIRECT: $\Rightarrow x_\gamma \approx 1$ $\gamma q \rightarrow qg$, $\gamma g \rightarrow q\overline{q}$
RESOLVED: $\Rightarrow x_\gamma < 1$ $qq \rightarrow qq$, ,$qq \rightarrow gg$ ..

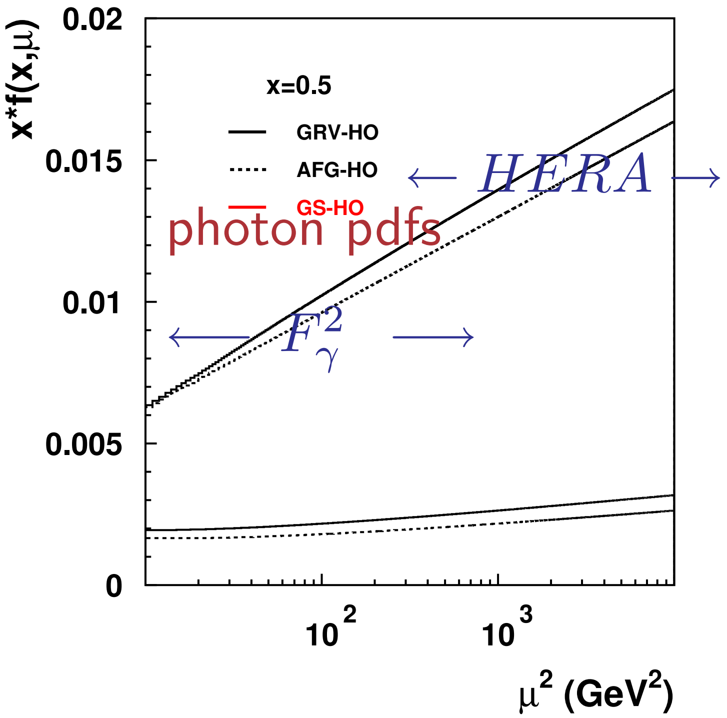
$E_T \longrightarrow$ hard scale μ!

σ_{eP} is convolution of short distance cross sections and PDFs:

$$\boxed{d\sigma_{eP} = \gamma\text{-flux}(y) \otimes \gamma\text{-PDF}(x_\gamma, \mu_f) \otimes P\text{-PDF}(x_P, \mu_f) \otimes d\sigma_{ij}(\mu_f, \mu_r)}$$

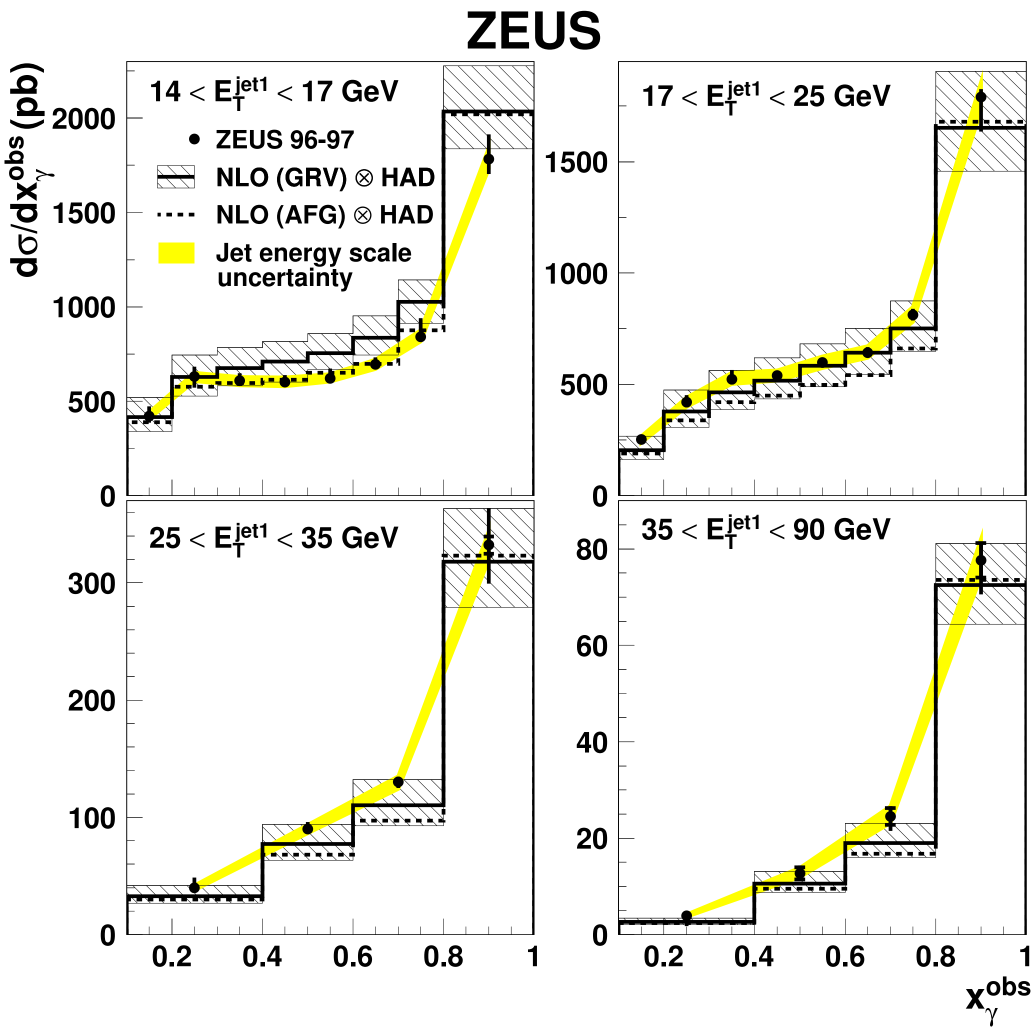
Jets at high E_T in γP ($Q^2 \approx 0$)





- high $E_T \longrightarrow$ small nonperturbative effects
- high $E_T \longrightarrow$ high x_γ, x_P at high scales $\mu^2 = E_T^2 \approx 400 - 6000$ GeV^2
- photoproduction data sensitive to photon and proton structure

Dijets at high E_T in γP



Exp. progress: jet energy scale uncertainty now $1-2\%$
$\rightarrow$ very precise data!

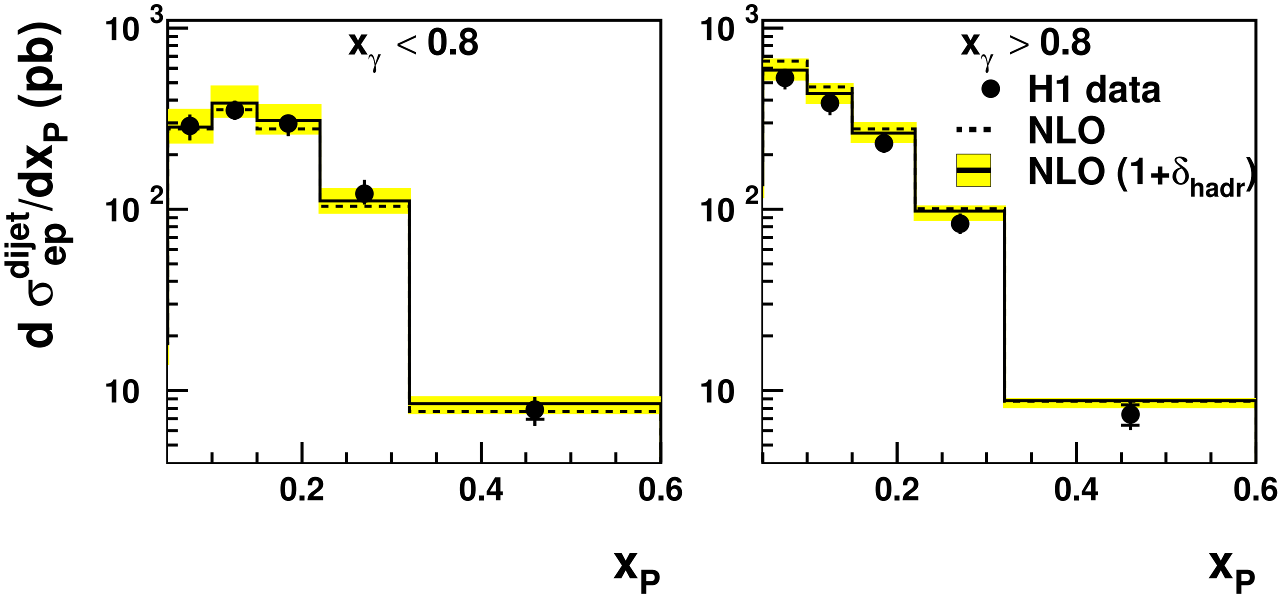
Dijet data: $d\sigma/dx_\gamma$

$\Rightarrow$ Data sensitive to photon PDF

exp. uncertainty $<$ theor. uncertainty

$\rightarrow$ constrain photon pdfs (quarks and gluon) !

Dijets at high E_T in γP



Dijet data: $d\sigma/dx_P$ $\longrightarrow$ **Data sensitive to proton gluon density**

$\Rightarrow$ $\approx 35\%$ gluon induced at $x_P \approx 0.4$

$x_P < 0.1$: $< 5\%$ difference between CTEQ5M and MRST (g↓,g↑)

$x_P > 0.1$: 15% difference between CTEQ5M and MRST (g↓,g↑)

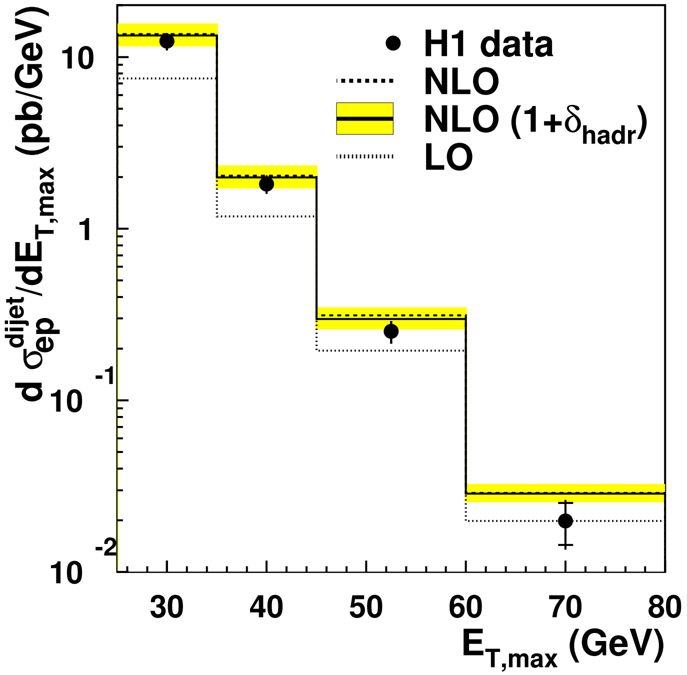
NLO scale uncertainty dominant effect

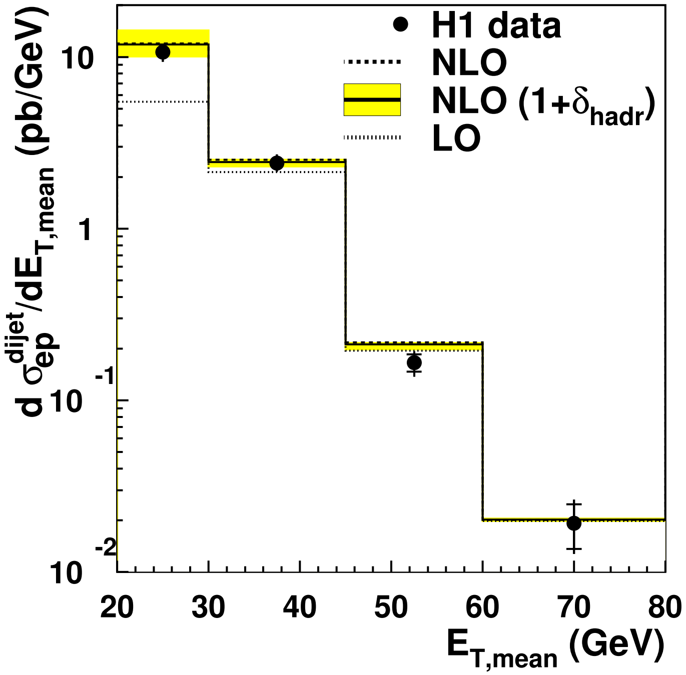
$\Rightarrow$ Very interesting in future

Dijets at high E_T in γP

$d\sigma/dE_T$: asymmetric jet cuts ($E_T^1 \neq E_T^2$) $\rightarrow E_T^1 > 25$ GeV, $E_T^2 > 15$ GeV

$\longrightarrow$ else NLO uncertainties due to IR-sensitive region of phase space





Good description up to $E_T \approx 70GeV$

$\longrightarrow$ Significant lower scale uncertainty for high $E_{T,mean}$ $\longrightarrow$ Choice for dijet E_T cuts important!

Summary and Outlook

- Shown is only a very small fraction of HERA jet physics! not shown:3-jets,4-jets in DIS and γP, charm jets, diffractive jets,virtual photon structure....
- Problems of pQCD at low scales (E_T, Q^2)
- NLO calculations and current PDF parameterizations are mostly compatible with high E_T and high Q^2 jet data ($\rightarrow \alpha_s$, gluon)
- Often: exp. uncertainty $<$ theor. uncertainty
- $\rightarrow$ Deeper understanding of jet physics requires theoretical progress!
- HERA2: Much more data to come $(30\times)$ $\rightarrow$ high E_T, high x