

# Jet Cross Sections and $\alpha_s$ at HERA



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## Outline

1. Cross Sections Dependence on R
2. High- $E_T$  Dijet Photoproduction
3. Charged Current Multijets
4. Inclusive and Multijets Production
5.  $\alpha_s$  Extraction from Low and High  $Q^2$  Data

*Low X 2008, 6-10 July*  
*Kolimpari, Greece*

# Motivation

Jets physics is a powerful ground for:

- Testing of QCD predictions in DIS
- Providing new phenomena for very precision  $\alpha_s$  and PDF extraction
- Directly sensitive to  $\alpha_s$  and PDF  $\rightarrow$  constrain further gluon and parton densities in proton and photon



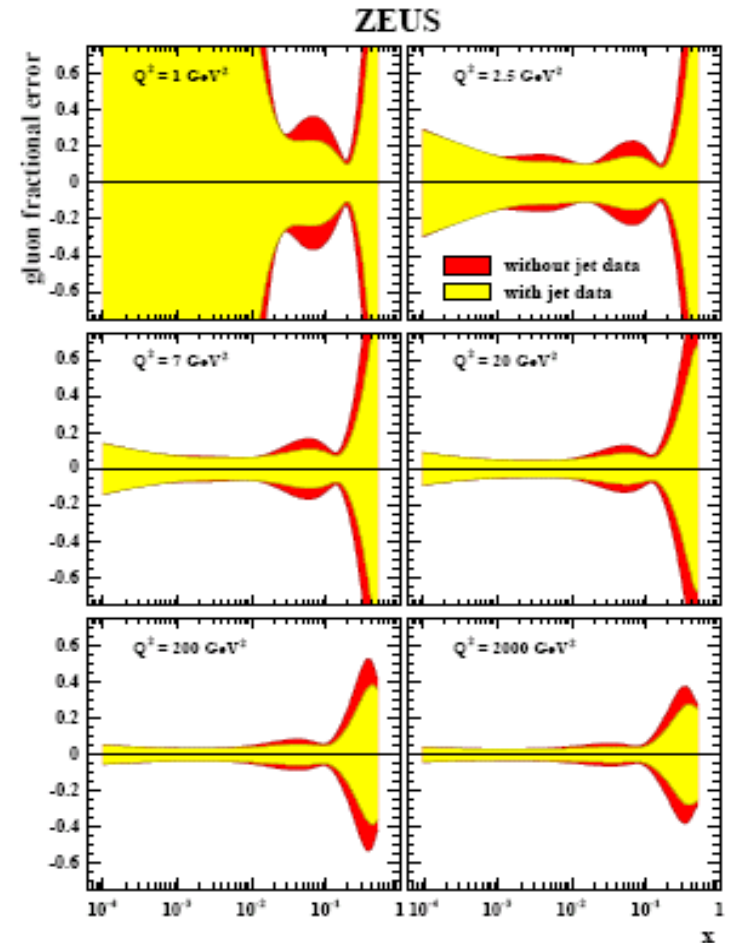
Inclusive jets:

High statistics

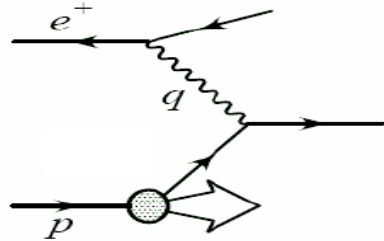
- IR safety
- Few non-perturbative complications

*High  $Q^2$* : small theoretical uncertainties  $\rightarrow$  precision extraction of  $\alpha_s$

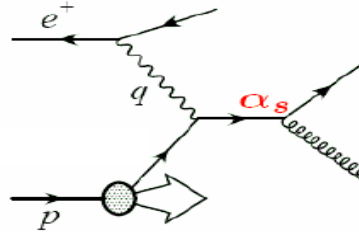
*Low  $Q^2$* : test of QCD, check how low in  $Q^2$  and  $P_T$  the theory can be used



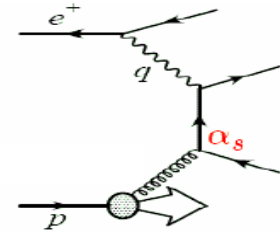
# NC Jet Production in DIS



Born Level

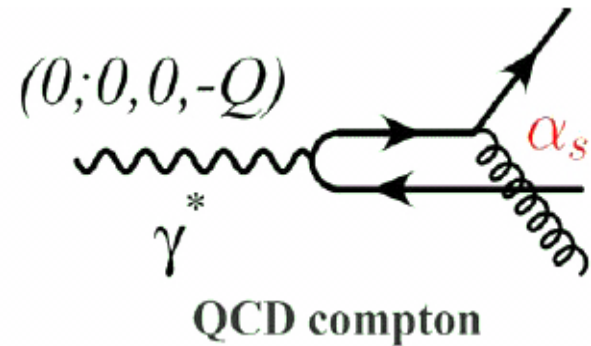
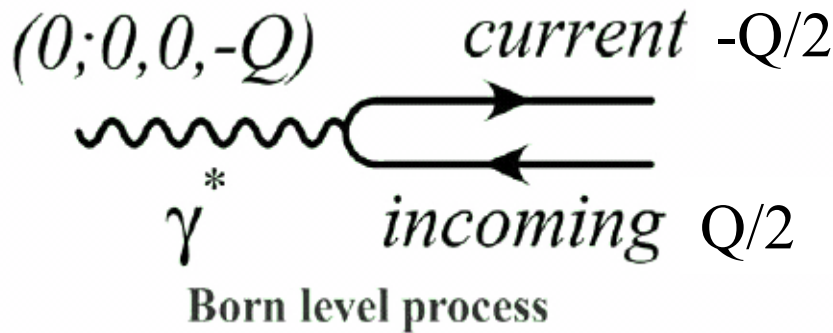


QCD Compton



Boson Gluon Fusion

## In Breit Frame



For jets with  $E_T (> 5 \text{ GeV})$

- Born level contribution is suppressed
- Jets well separated from the proton remnant ( $E_T = 0$ )

## Used Jet Finder:

### Longitudinal invariant inclusive $k_T$ algorithm

- infrared and collinear safe
- factorizable

“Merging” parameter  $R = 1.0$  (S.D.Ellis, D.E.Soper ...)

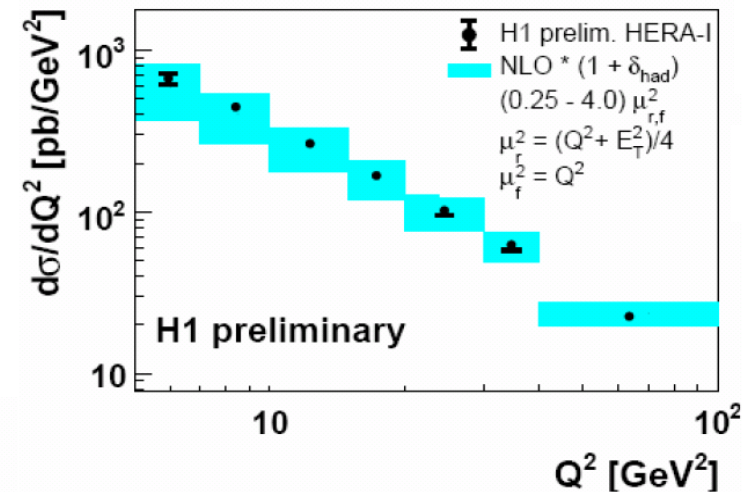
$$\mu_R = \sqrt{(Q^2 + E_T^2)}/2$$



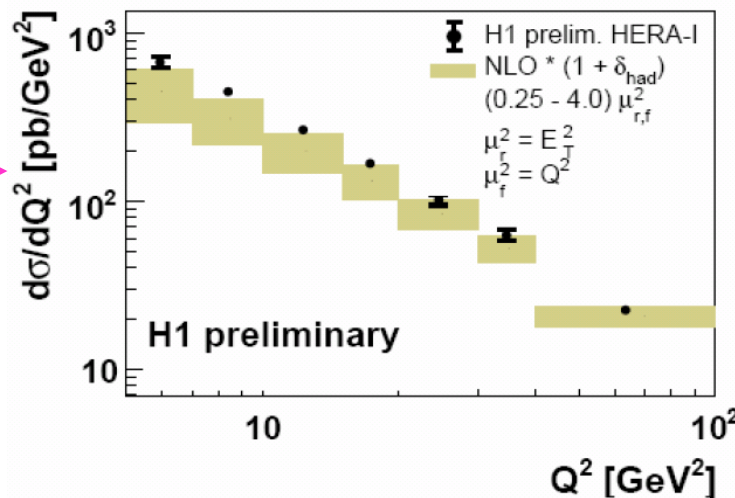
## Used Theoretical Models:

### NLOJET++ / FastNLO with

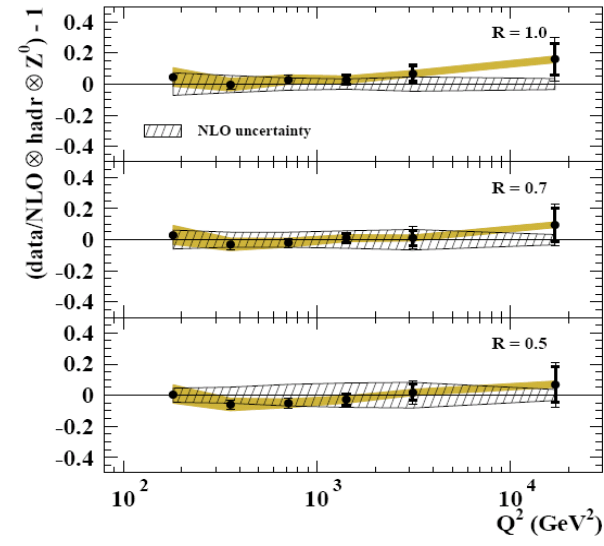
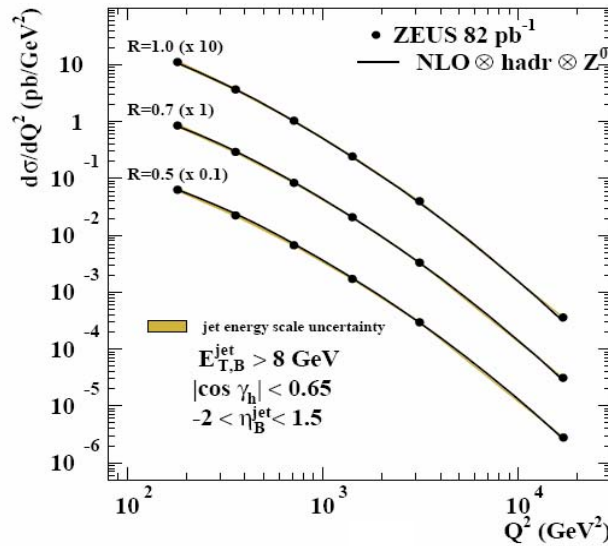
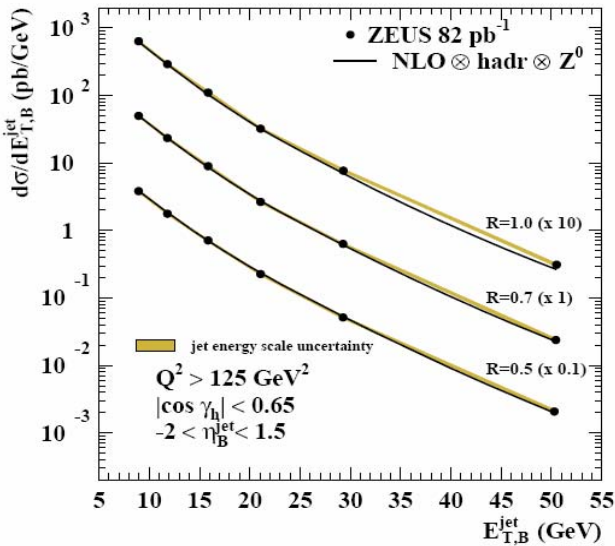
- PDF CTEQ65M
- $\mu_F = Q$
- $\mu_R = \sqrt{Q^2 + E_T^2}/2$  for inclusive jets
- $\mu_R = Q$  for 2 & 3- jets



$$\mu_R = E_T$$



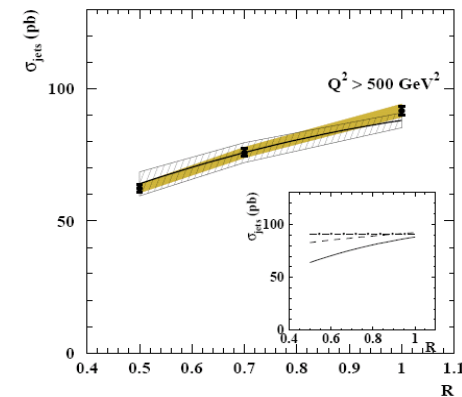
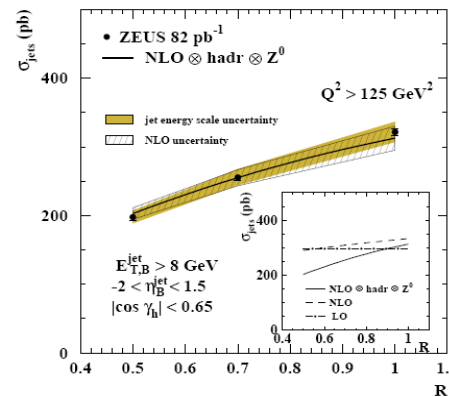
# Cross Section Dependence on R



Good agreement between data and NLO for  $R = 1, 0.7, 0.5$ .

Integrated cross section linearly depends vs.  $R \rightarrow R = 1$

• Integrated jet cross sections for the regions  $Q^2 > 125 \text{ GeV}^2$  and  $Q^2 > 500 \text{ GeV}^2$



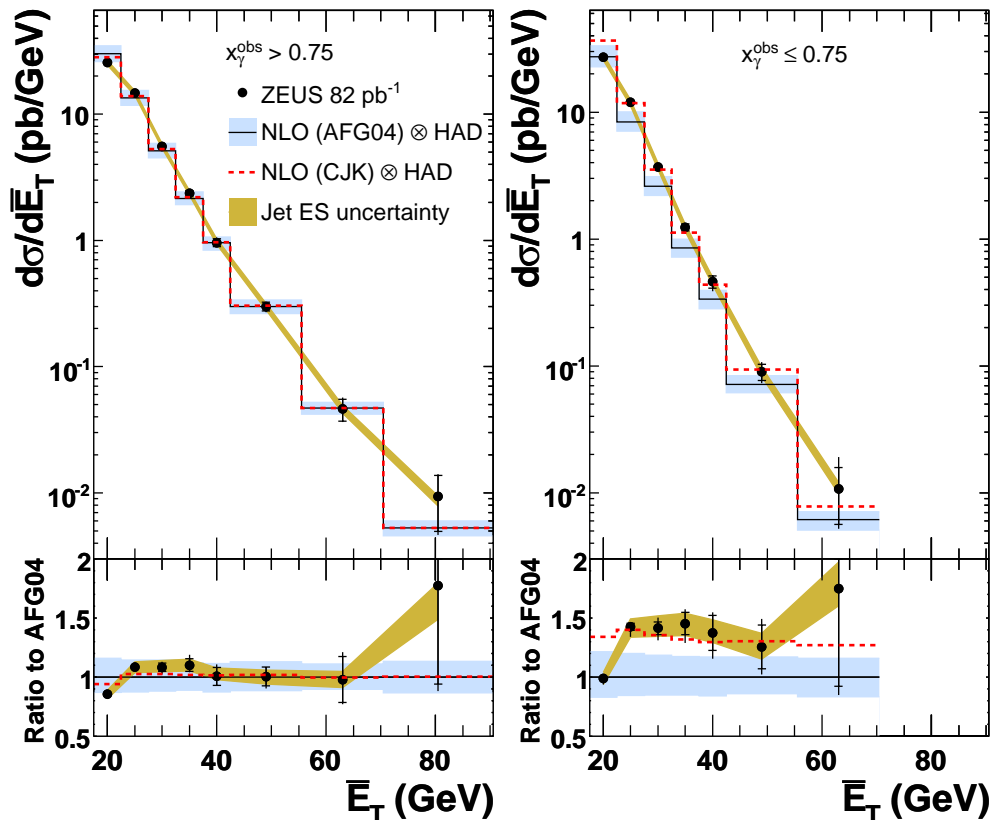
# High- $E_T$ Dijet Photoproduction

$$\int L = 81.8 \text{ pb}^{-1}, Q^2 < 1 \text{ GeV}^2, 142 < W_{\gamma p} < 293 \text{ GeV}$$

Jet parameters:  $E_T^{\text{jet}1} > 20 \text{ GeV}$ ,  $E_T^{\text{jet}2} > 15 \text{ GeV}$ ,  $-1 < \eta^{\text{jet}1,2} < 3$  (at least one  $-1 < \eta^{\text{jet}} < 2.5$ )

$$x_\gamma^{\text{obs}} = (E_T^{\text{jet}1} e^{-\eta^1} + E_T^{\text{jet}2} e^{-\eta^2}) / 2yE_e \quad \bar{E}_T = (E_T^{\text{jet}1} + E_T^{\text{jet}2}) / 2$$

## ZEUS



Good description over 4 orders of magnitude for  $x_\gamma^{\text{obs}} > 0.75$ .

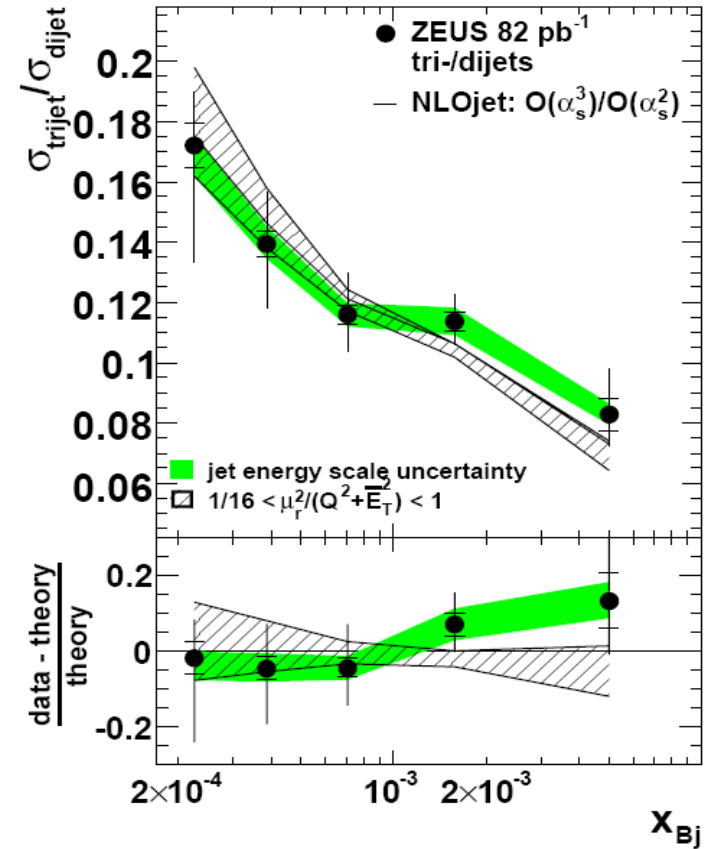
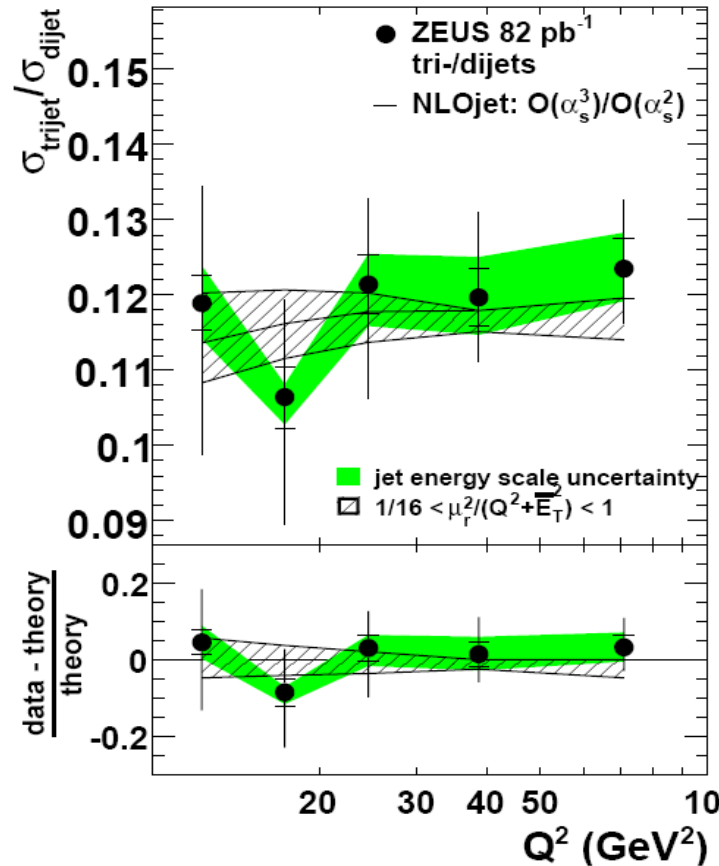
For  $x_\gamma^{\text{obs}} < 0.75$   $\gamma$  PDF differ by up to 40%  $\rightarrow$  potentially to constrain  $\gamma$  PDF.

In many cases: CJK (Cornet et al.) described data the best..

# Multijet Production at Low $x_{Bj}$

**Kinematics range:**  
 $10 < Q^2 < 100 \text{ GeV}^2$   
 $10^{-4} < x_{Bj} < 10^{-2}$   
 $0.1 < y < 0.6$

**Jet parameters:**  
 $-1.0 < \eta^{\text{jet}1,2,(3)}_{\text{Lab}} < 2.5$   
 $E_{T,\text{HCM}}^{\text{jet}1} > 7 \text{ GeV}$   
 $E_{T,\text{HCM}}^{\text{jet}2,(3)} > 5 \text{ GeV}$



- *Hatched band* - QCD renormalization scale uncertainty
- *Green band* - jet energy scale uncertainty

Relative difference between the data and theory

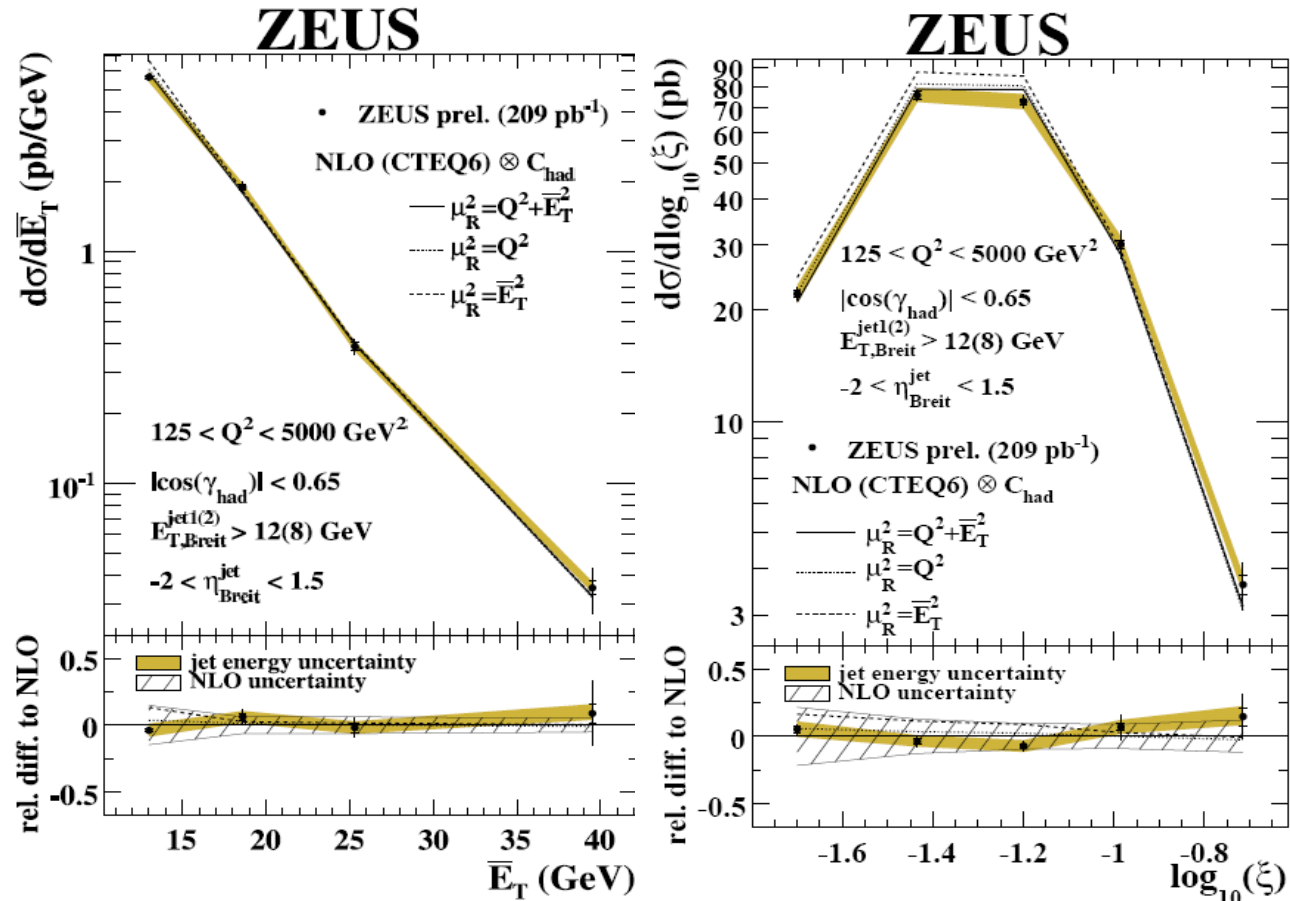
# High $E_T$ Neutral Current Dijets

HERA-II:

- $125 < Q^2 < 5000 \text{ GeV}^2$
- $E_{T}^{\text{jet1(2)}} > 12(8) \text{ GeV}$

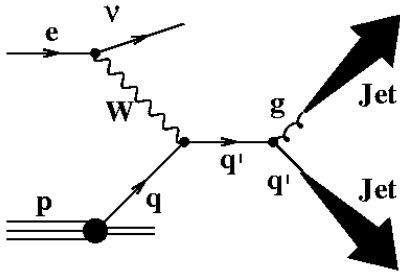
$$\xi = x (1 + M_{ij}^2/Q^2)$$

The data well described with NLO. Theoretical uncertainties dominate in many bins.



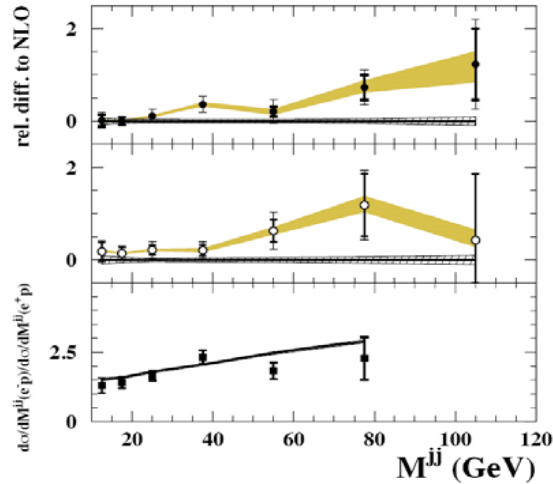
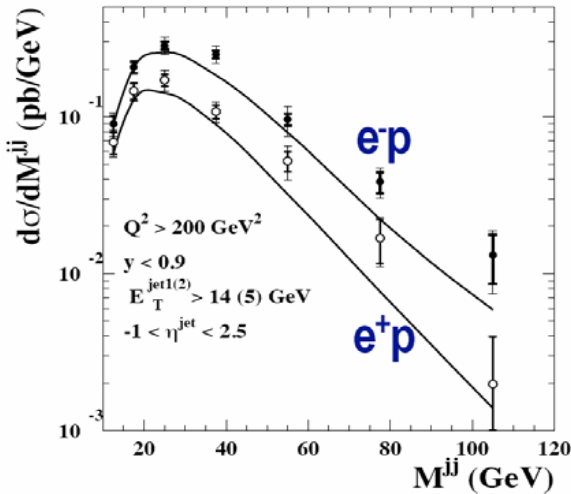
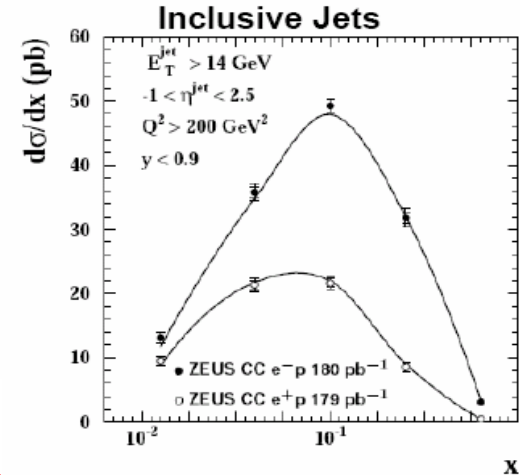


# Charged Current Multijets



HERA-II,

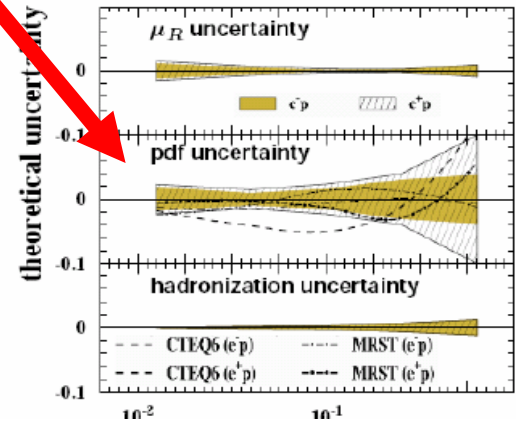
- $\int L = 359 \text{ pb}^{-1}$  polarized  $e^+p$  data.
- $Q^2 > 200 \text{ GeV}^2$ ,  $y < 0.9$
- $E_T^{\text{jet}(1,2,3)} > 14(5) \text{ GeV}$ ,  $-1 < \eta^{\text{jet}} < 2.5$
- NLO QCD based on MEPJET, with ZEUS PDF set
- $W^{(-)}$  coupled primarily to  $u(d)$
- possibly constrain d-quark PDF



$e p$

$e^+ p$

$e p / e^+ p$



- NLO fails to describe  $d\sigma/dM^{\text{jj}}$  for dijets?
- Ratio  $e-p/e^+p$  described reasonably well.

# Inclusive Jet Cross Sections at Low $Q^2$

**HERA-I: 99-00,**

$$5 < Q^2 < 100 \text{ GeV}^2$$

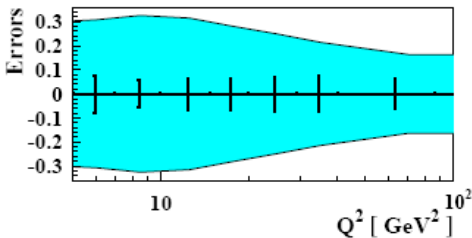
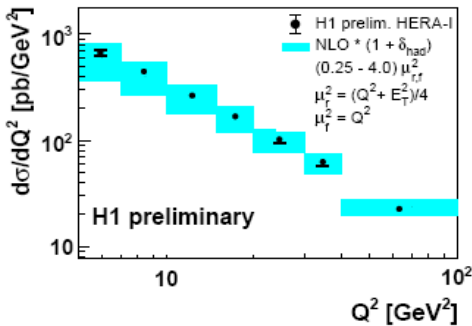
$$0.2 < y < 0.7$$

**Inclusive jets**

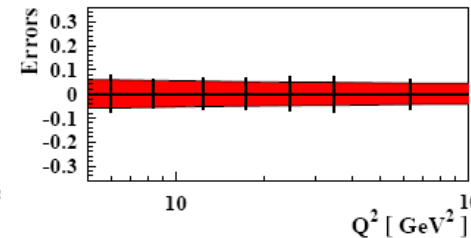
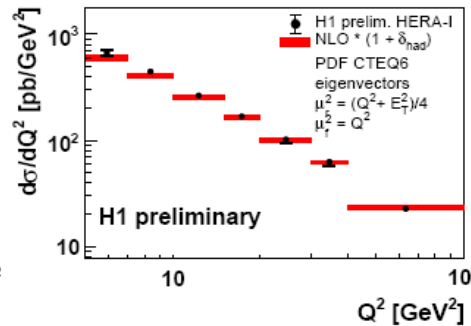
$$E_{T}^{\text{Breit}} > 5 \text{ GeV}$$

$$- 1.0 < \eta^{\text{Lab}} < 2.5$$

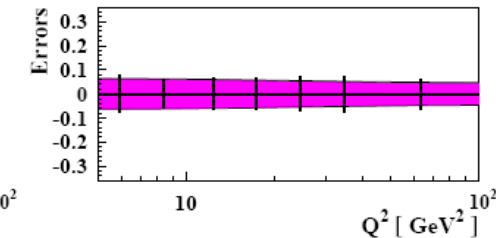
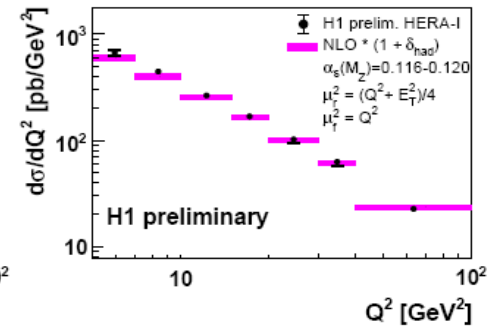
**Inclusive Jet Cross Sections  $\frac{d\sigma}{dQ^2}$**



$\mu_R$  and  $\mu_F$  uncertainties



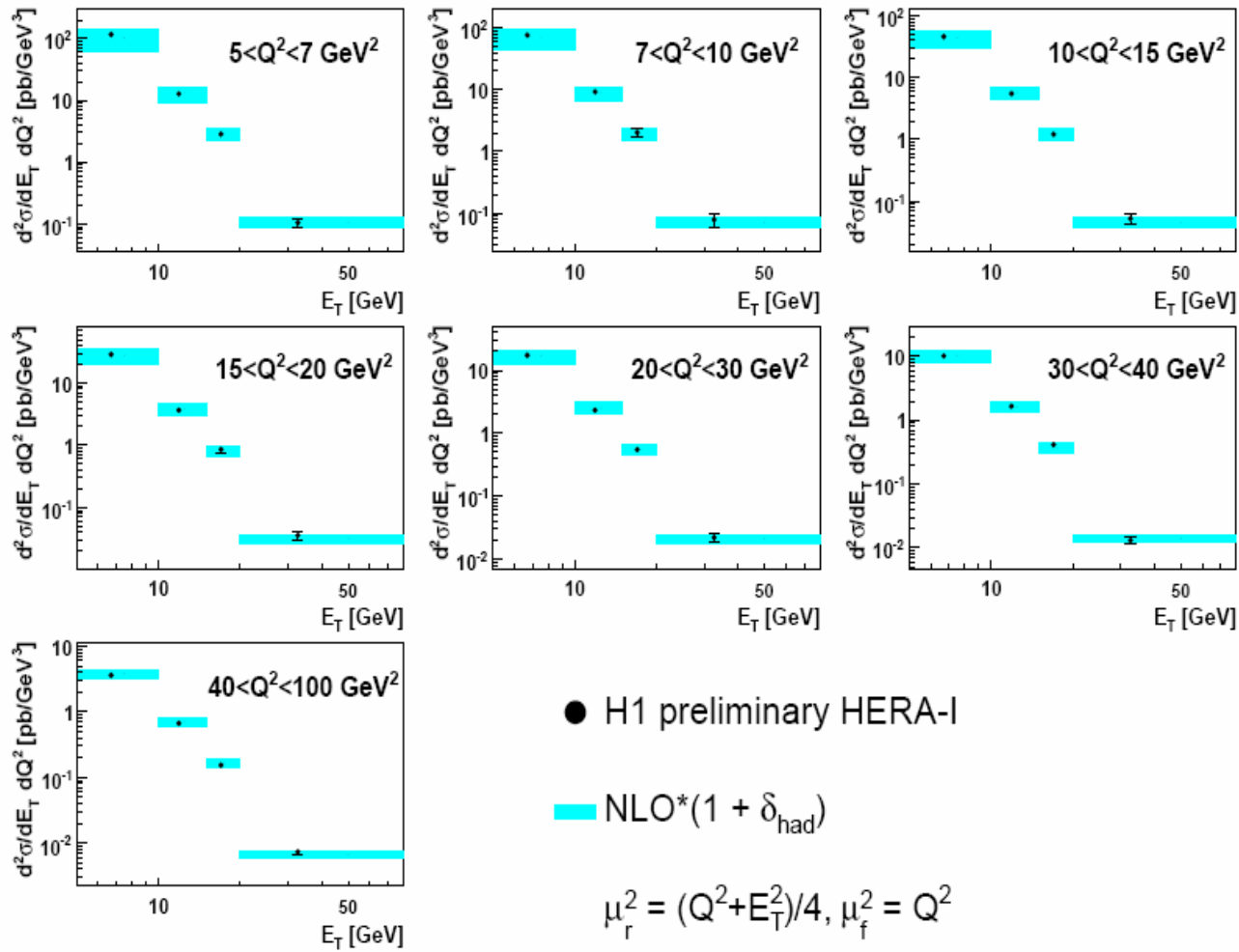
PDF uncertainties



$\alpha_S$  uncertainties

**Scale uncertainties dominated over experimental errors and other theoretical uncertainties  $\rightarrow$  theory improvement needed.**

# H1 Inclusive Jet Cross Sections $\frac{d^2\sigma}{dQ^2 dE_T}$

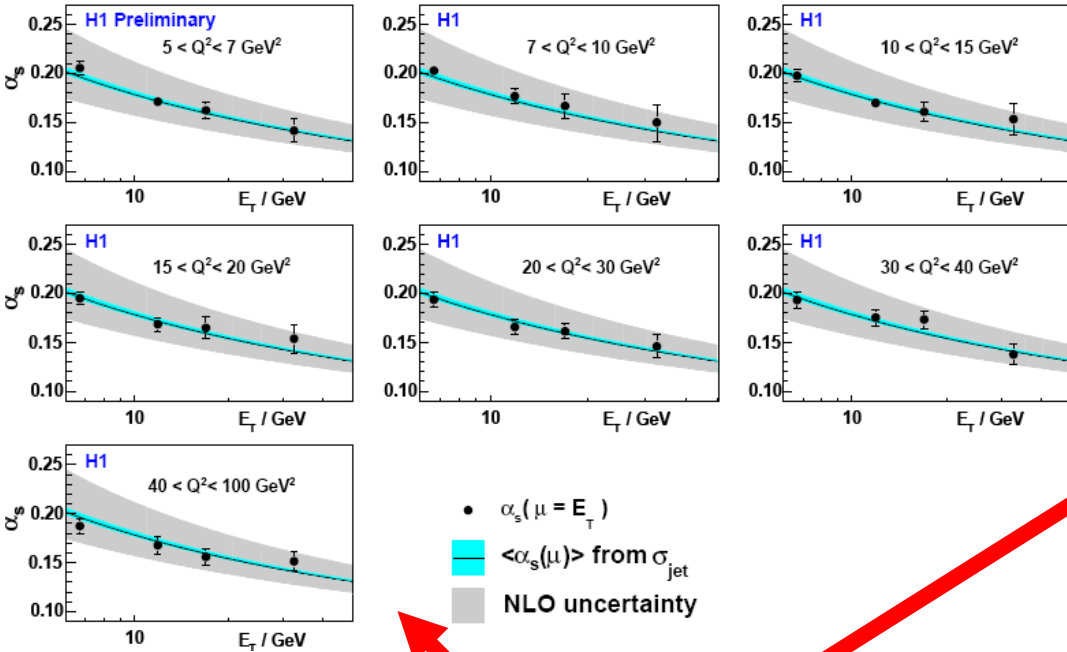


**Data well described by NLO QCD. Large scale uncertainties.**

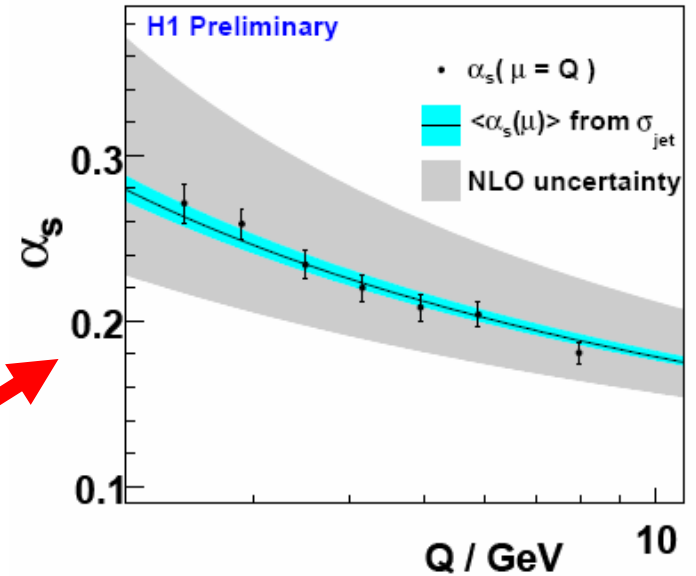
# $\alpha_s$ extraction from Low $Q^2$ DIS

Fit over 28 experimental points

$\alpha_s$  from Inclusive Jet Cross Section (HERA I)



$\alpha_s$  from Inclusive Jet Cross Section (HERA-I)



Running of  $\alpha_s$  vs.  $E_T$  and  $Q^2$

Theoretical Uncertainties are the largest

$\alpha_s$  from low  $Q^2$  data

$$0.1186 \pm 0.0014(\text{exp.})_{-0.0101}^{+0.0132}(\text{th.}) \pm 0.0021(\text{pdf})$$

$$\chi^2/\text{ndf} = 20.5/27$$

# H1-ZEUS combined QCD fit



## H1:HERA-I 99-00

$\sqrt{S} = 319 \text{ GeV}$ ,  $\int \mathcal{L} = 65 \text{ pb}^{-1}$ ,  
 $150 < Q^2 < 15000 \text{ GeV}^2$ ,  $0.2 < y < 0.7$

### Jet Selection:

$E_T^{\text{Breit}} > 7 \text{ GeV}$   
 $-1.0 < \eta^{\text{Lab}} < 2.5$

## ZEUS:HERA-I 98-00, $\int \mathcal{L} = 82 \text{ pb}^{-1}$

$Q^2 > 500 \text{ GeV}^2$  (used in fit)

### Jet Selection:

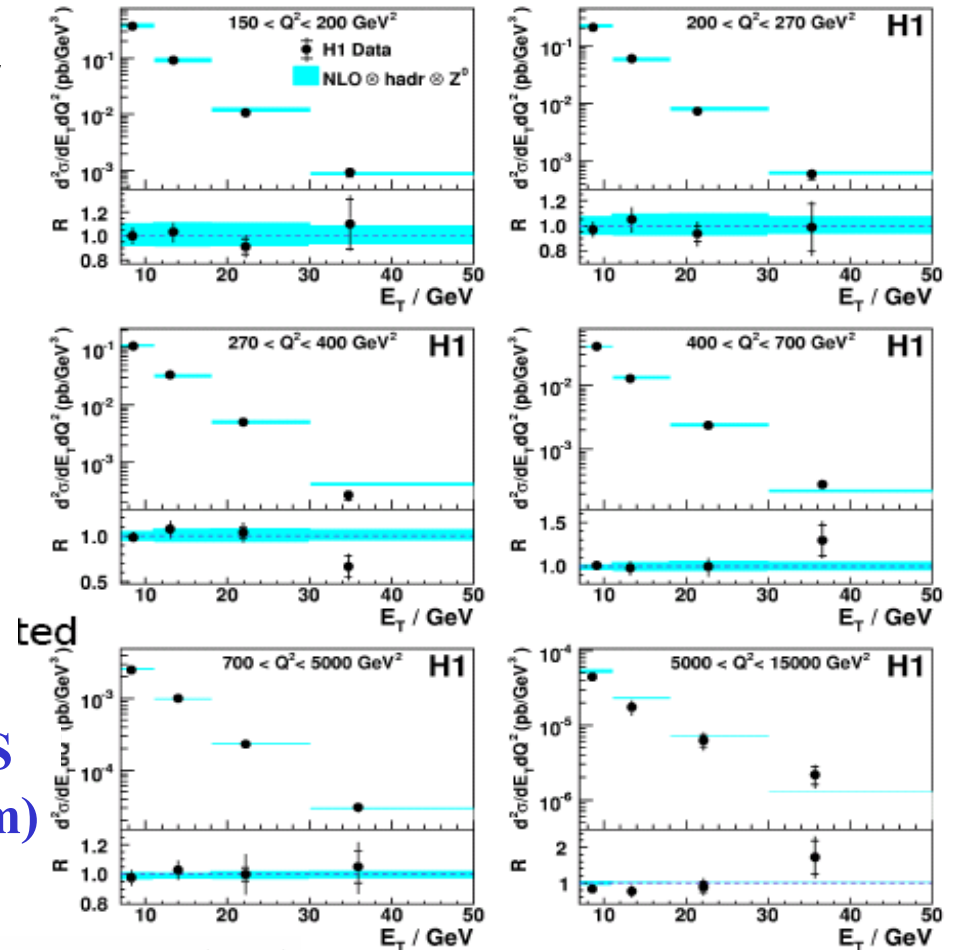
$E_T^{\text{Breit}} > 8 \text{ GeV}$   
 $|\cos \gamma_h| < 0.65$   
 $-2. < \eta^{\text{Breit}} < 1.$

NLOJet++/FastNlo & DISENT (ZEUS  
 grid program)

$\mu_R = E_T$ ,  $\mu_F = Q$ , PDF MRST2001

$\alpha_s(M_Z) = 0.1198 \pm 0.0019 \text{ (exp.)} \pm 0.0026 \text{ (th.)}$

## Inclusive Jet Cross Section



$\chi^2/\text{ndf} = 27.4/29$

# Inclusive and Multi Jet Cross Sections at High $Q^2$

**HERA-I+II:**  $\sqrt{S} = 319 \text{ GeV}$ ,  $\int L = 395.0 \text{ pb}^{-1}$

$150 < Q^2 < 15000 \text{ GeV}^2$ ,  $0.2 < y < 0.7$

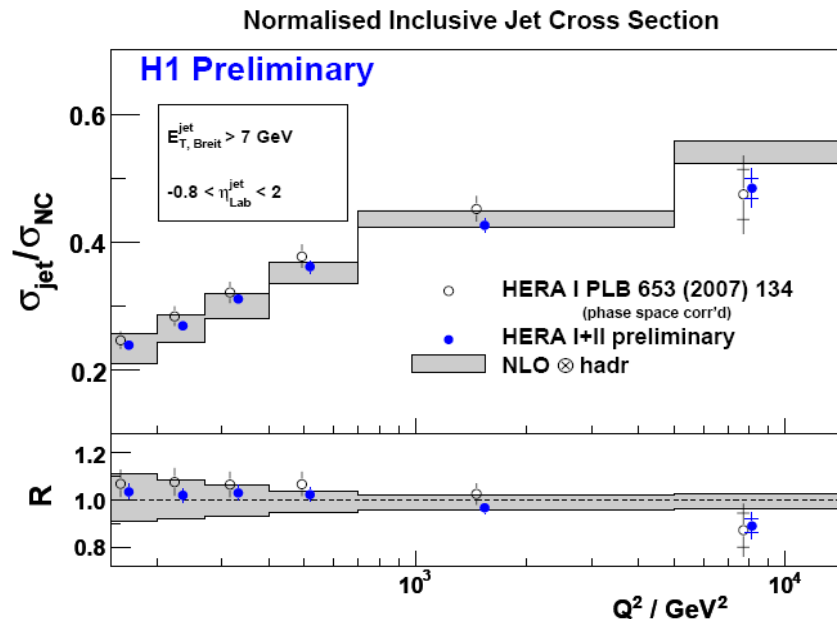
Normalization to  $\sigma_{\text{NC}}$  used for reducing errors

## Inclusive Jets:

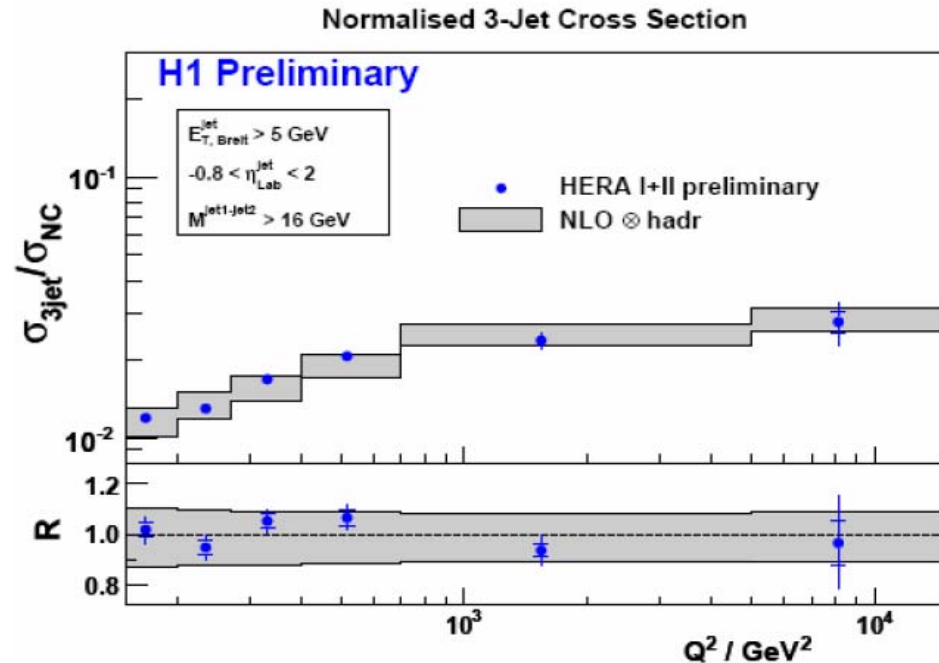
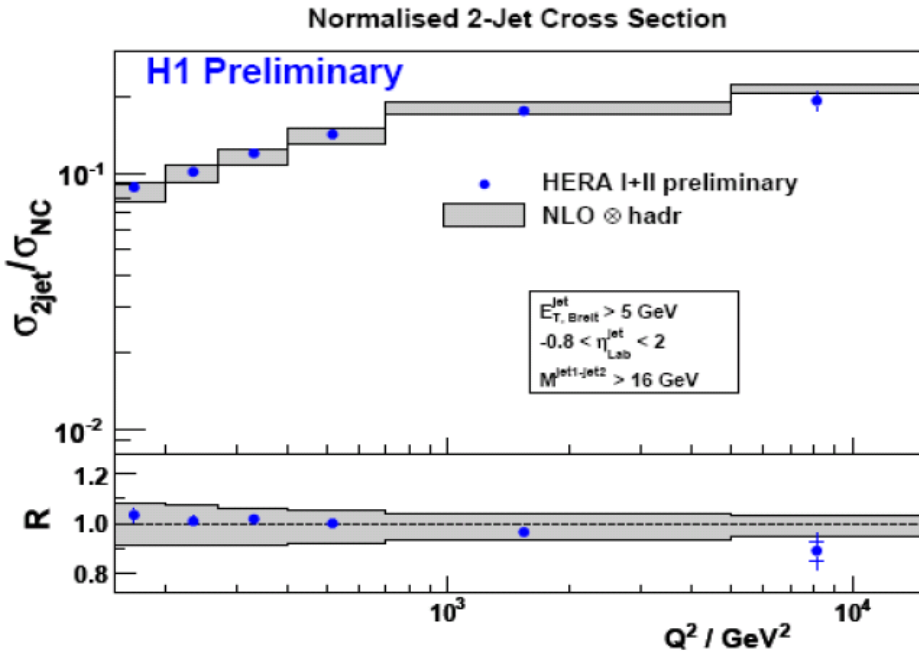
- $E_{\text{T}}^{\text{Breit}} > 7 \text{ GeV}$
- $-0.8 < \eta^{\text{Lab}} < 2.0$

## Multijets:

- $E_{\text{T}}^{\text{Breit}} > 5 \text{ GeV}$
- $-0.8 < \eta^{\text{Lab}} < 2.0$
- $M_{\text{jj}} > 16 \text{ GeV}$



# Normalized Inclusive and Multijets Jet Cross Sections at High $Q^2$



Well described by NLO QCD prediction. Experimental uncertainties (2-6%) smaller than the theoretical ones (5-10 %).

Trijets experimental uncertainties dominated by statistical errors and model dependence uncertainties. They are less than NLO QCD uncertainties.

# $\alpha_s$ extraction from High $Q^2$ DIS

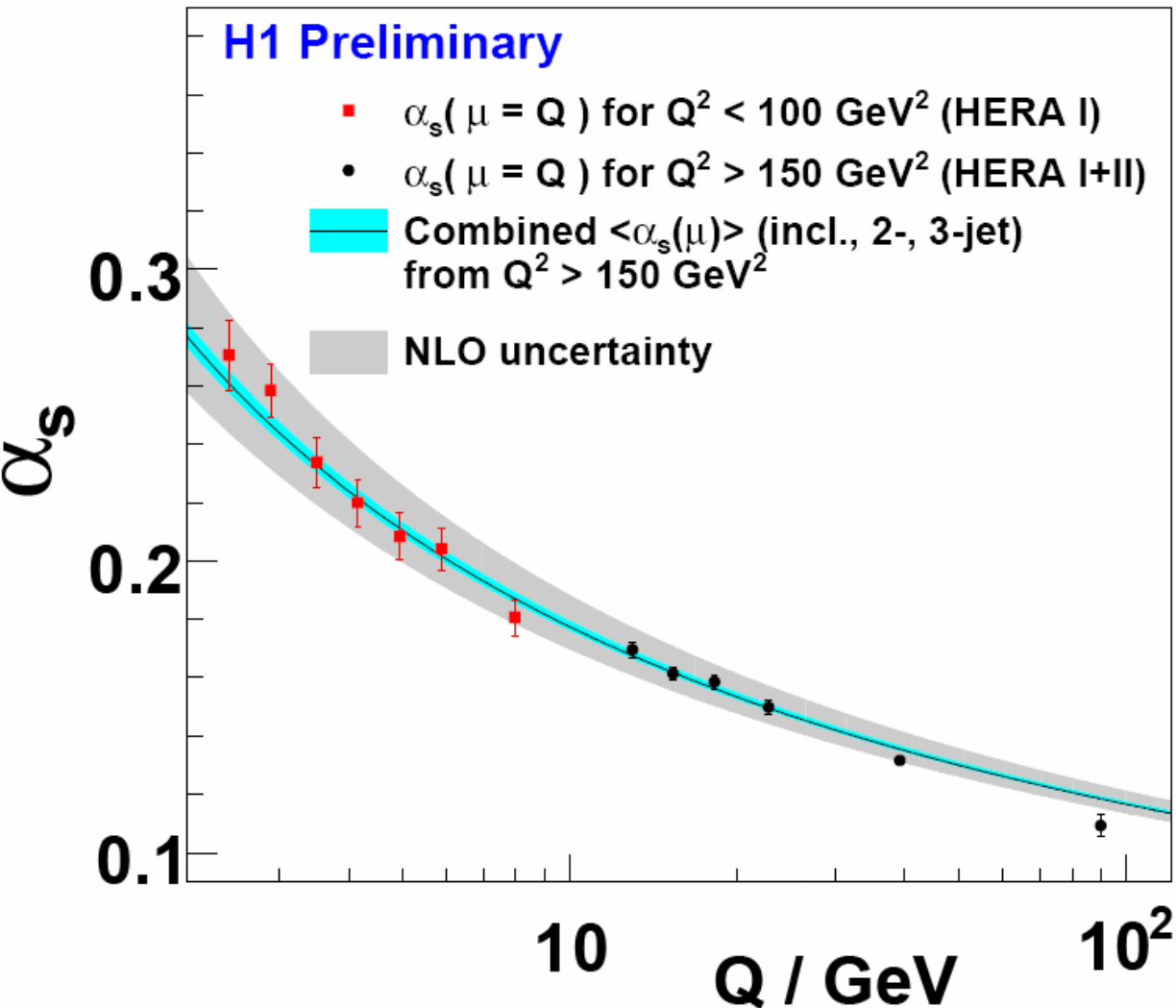
$\alpha_s$  extracted for DIS normalized inclusive jets, dijets, trijets.  
Theoretical uncertainties are larger than experimental ones.

Observable	$\alpha_s$	Exp. error	Theory err.		$\chi^2/\text{NDF}$
			Scales	PDF	
$\frac{\sigma_{3JET}}{\sigma_{NC}} = f(Q^2)$	<b>0.1179</b>	0.0014	+0.0056 - 0.0034	0.0009	4.53/5
$\frac{\sigma_{2JET}}{\sigma_{NC}} = f(Q^2, \langle E_T \rangle)$	<b>0.1171</b>	0.0010	+0.0048 - 0.0036	0.0018	28.1/23
$\frac{\sigma_{JET}}{\sigma_{NC}} = f(Q^2, E_T)$	<b>0.1196</b>	0.0010	+0.0049 - 0.0036	0.0019	26.8/23
$\frac{\sigma_{1JET}}{\sigma_{DIS}} \& \frac{\sigma_{2JET}}{\sigma_{DIS}} \& \frac{\sigma_{3JET}}{\sigma_{DIS}}$	<b>0.1182</b>	0.0008	+0.0041 - 0.0031	0.0018	54.8/53



# Running $\alpha_s$ ( $Q^2=5-15000 \text{ GeV}^2$ )

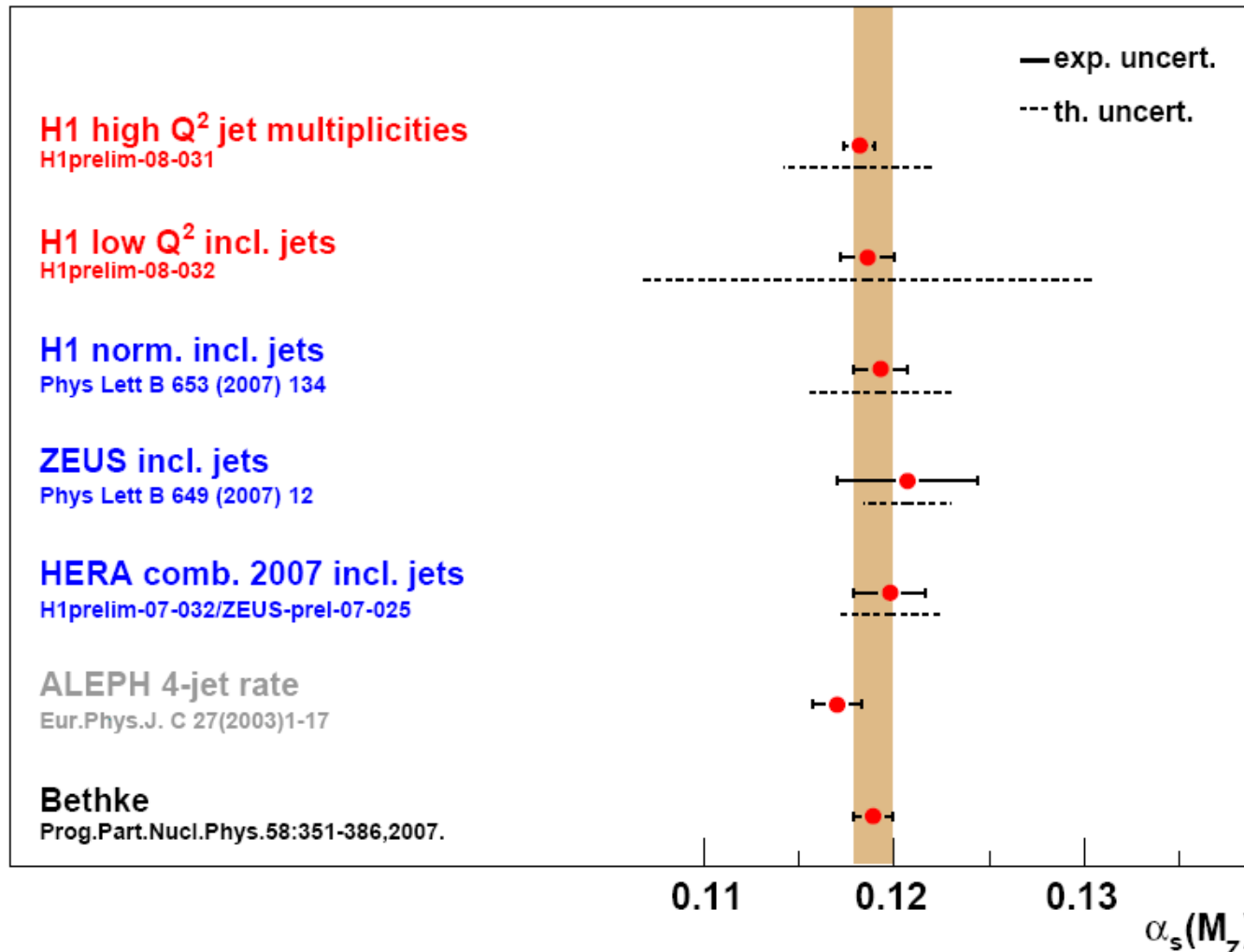
$\alpha_s$  from Jet Cross Sections



Running  $\alpha_s$  (from high  $Q^2$ ).

- NLO and  $\langle \alpha_s(\mu) \rangle$  extrapolated from high ( $>150 \text{ GeV}^2$ ) to low ( $<100 \text{ GeV}^2$ )  $Q^2$  region.
- $\alpha_s$  from Low  $Q^2$  added to high  $Q^2$  curves. A striking agreement between low and high  $Q^2$  data observed.

# Comparison of $\alpha_s(M_Z)$ values



**New  $\alpha_s$  measurements from low and high  $Q^2$  jets data compatible with the world average**

# Summary

1. Presented new measurements on jet data
  - multijet production at low  $x_{Bj}$
  - high- $E_T$  dijet photoproduction
  - multijet production in charged current
  - differential and double differential cross sections at low and high  $Q^2$
  - $\alpha_S$  extraction at low and high  $Q^2$
2. The jet data could constrain further the parton densities in proton and photon
3. Data well described with NLO.
4.  $\alpha_S$  running verified over two orders of magnitude in  $Q$  ( $5 < Q^2 < 15000 \text{ GeV}^2$ ).  
A striking agreement between the low and high  $Q^2$ .
5. Theory scale uncertainties dominated over experimental ones  $\rightarrow$  theory improvements needed
6. HERA-II new data analysis are in progress  $\rightarrow$  new high precision measurements are expected.