

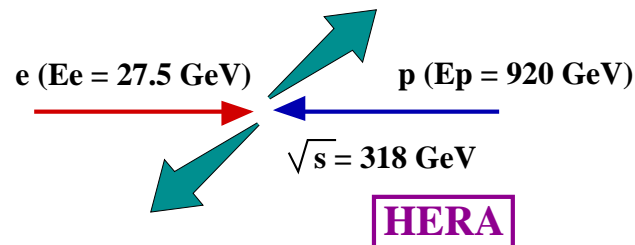
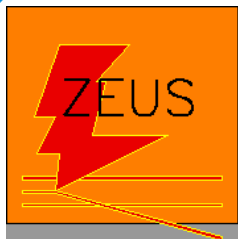
Isola d'Elba, HCP 2007

May 24th, 2007

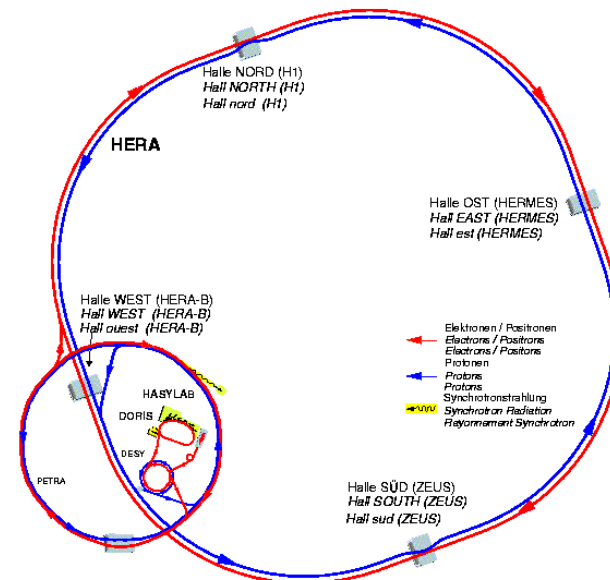


# QCD at HERA

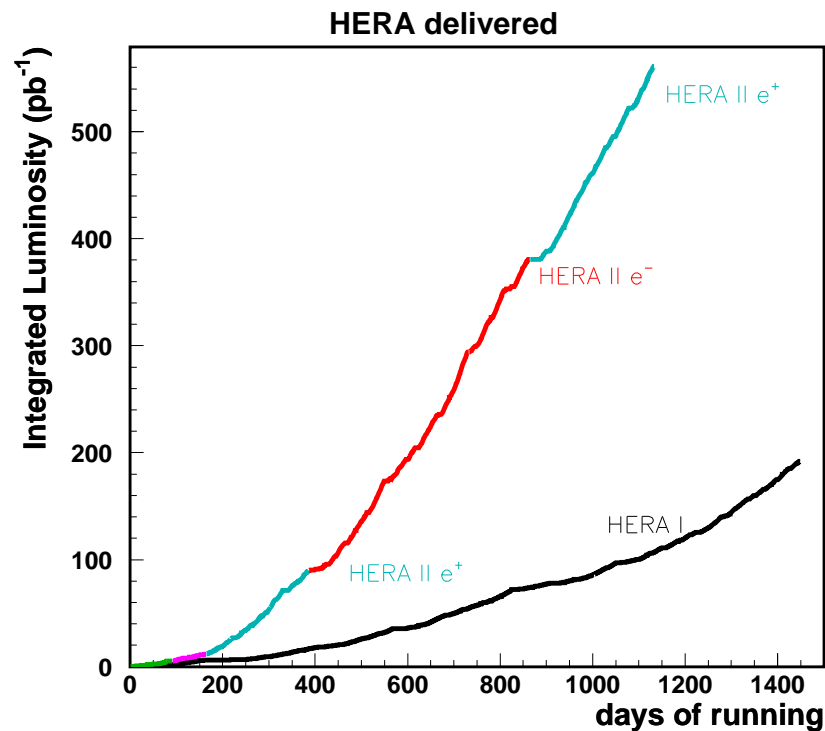
Juan Terrón (Universidad Autónoma de Madrid, Spain)



H1 and ZEUS Collaborations



## Performance of HERA collider and ZEUS and H1 experiments

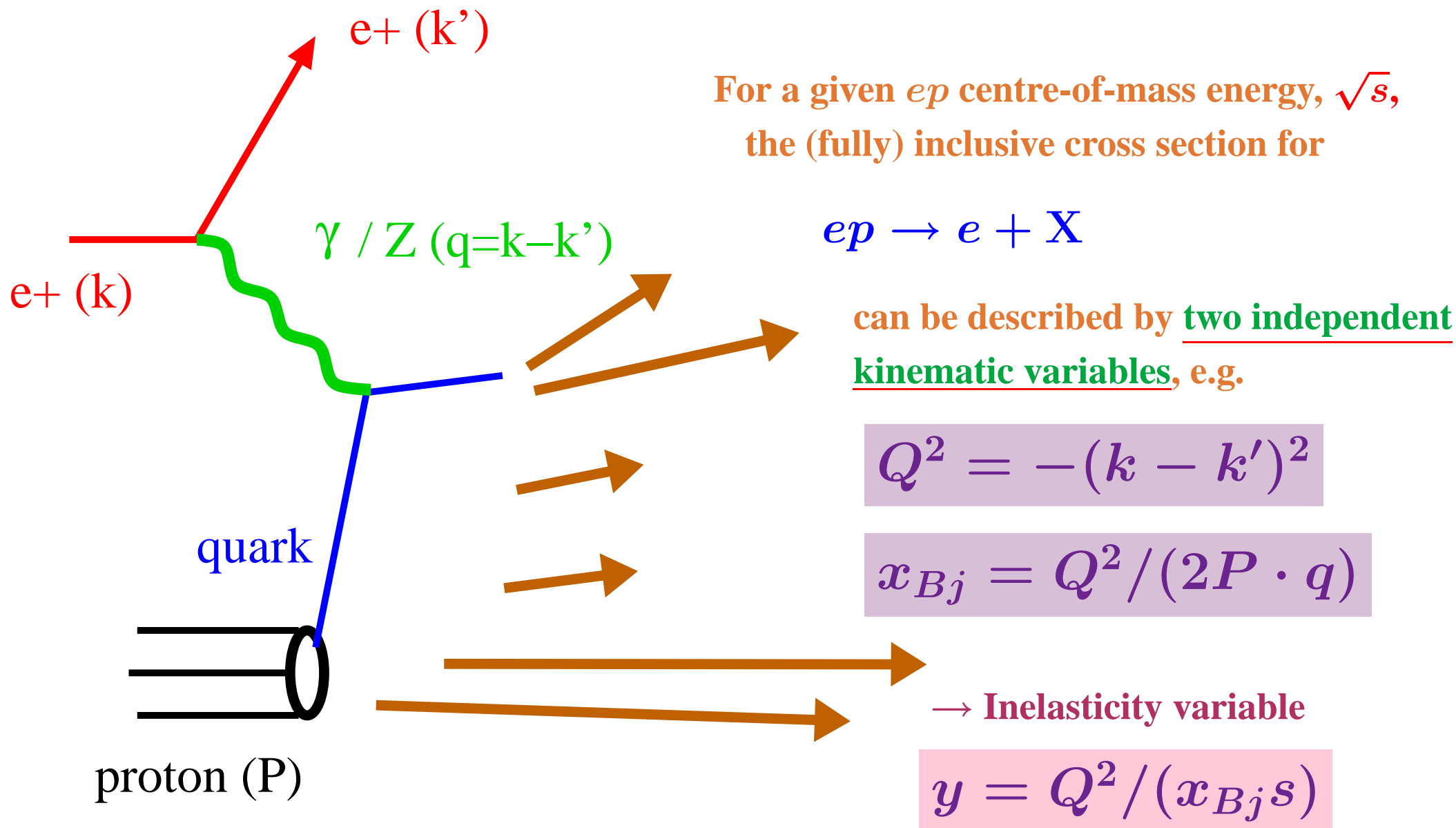


- High Energy Running ( $\sqrt{s} = 300 - 320 \text{ GeV}$ )
    - ended on March 20th, 2007
    - luminosity delivered by HERA:  $758 \text{ pb}^{-1}$
    - H1 physics luminosity :  $\sim 478 \text{ pb}^{-1}$
    - ZEUS physics luminosity :  $\sim 504 \text{ pb}^{-1}$
  - Low Energy Running ( $E_p = 460 \text{ GeV}$ ,  $\sqrt{s} = 225 \text{ GeV}$ )
    - ongoing, more than  $10 \text{ pb}^{-1}$  by now
    - measurement of  $F_L$
- ⇒ End of HERA: July 2nd, 2007

### ● Outline

- Jet production in neutral current deep inelastic scattering at high  $Q^2$
- Jet production at low  $x$
- Improving the gluon density in the proton by using jet data

# Kinematics of Neutral Current Deep Inelastic Scattering

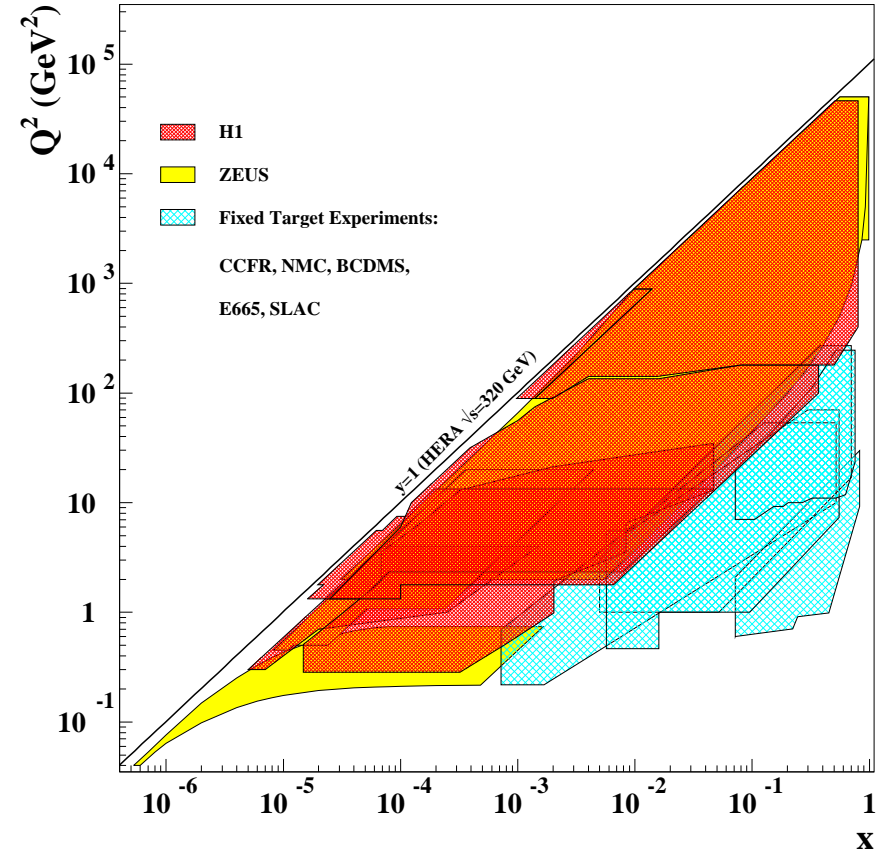
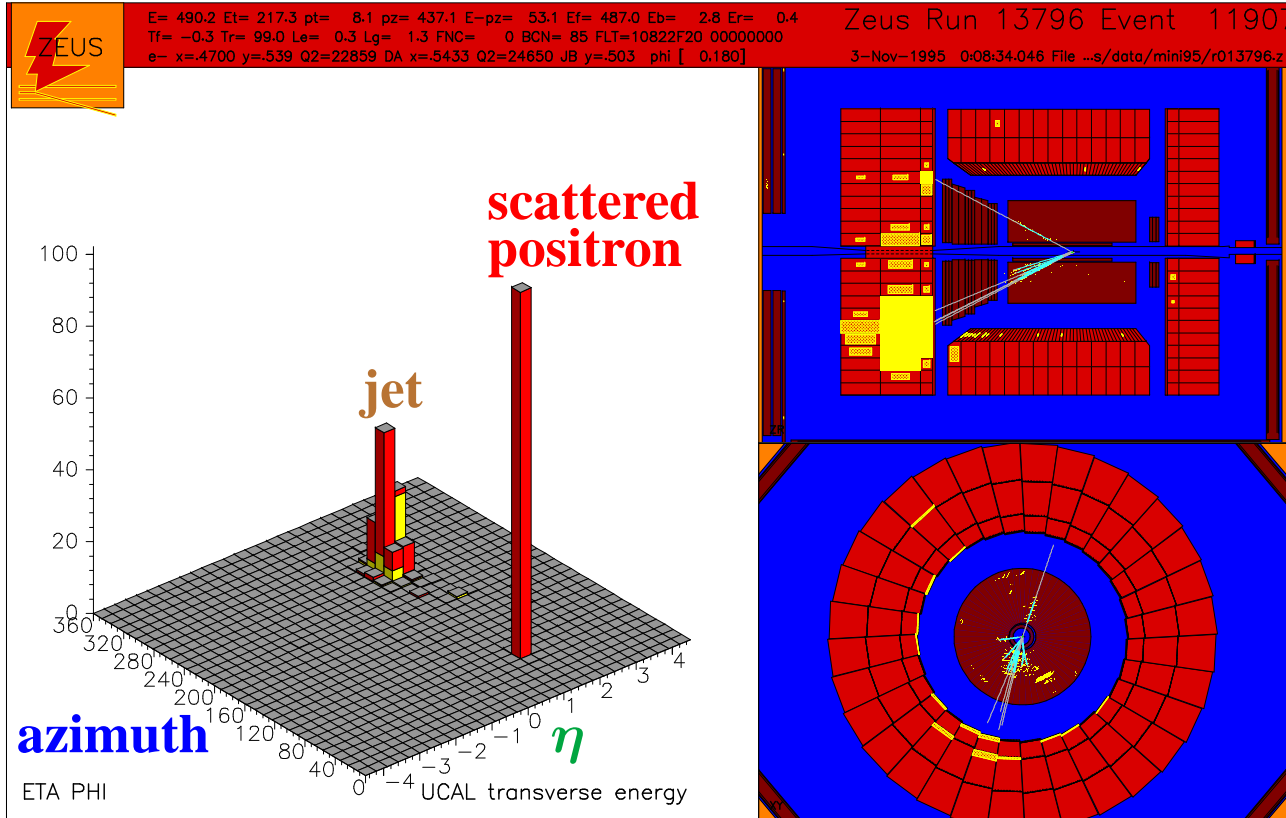


# Neutral Current Deep Inelastic Scattering

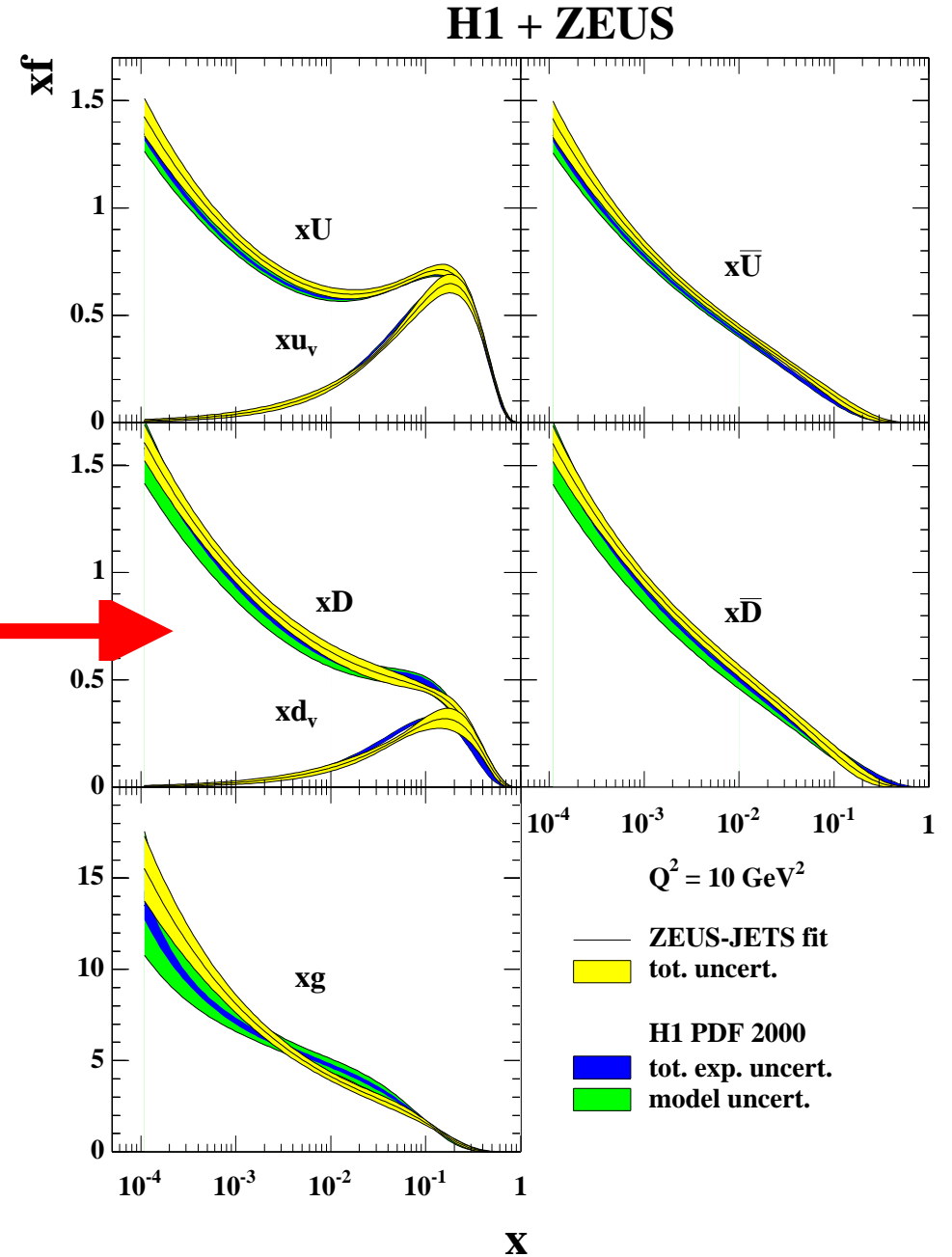
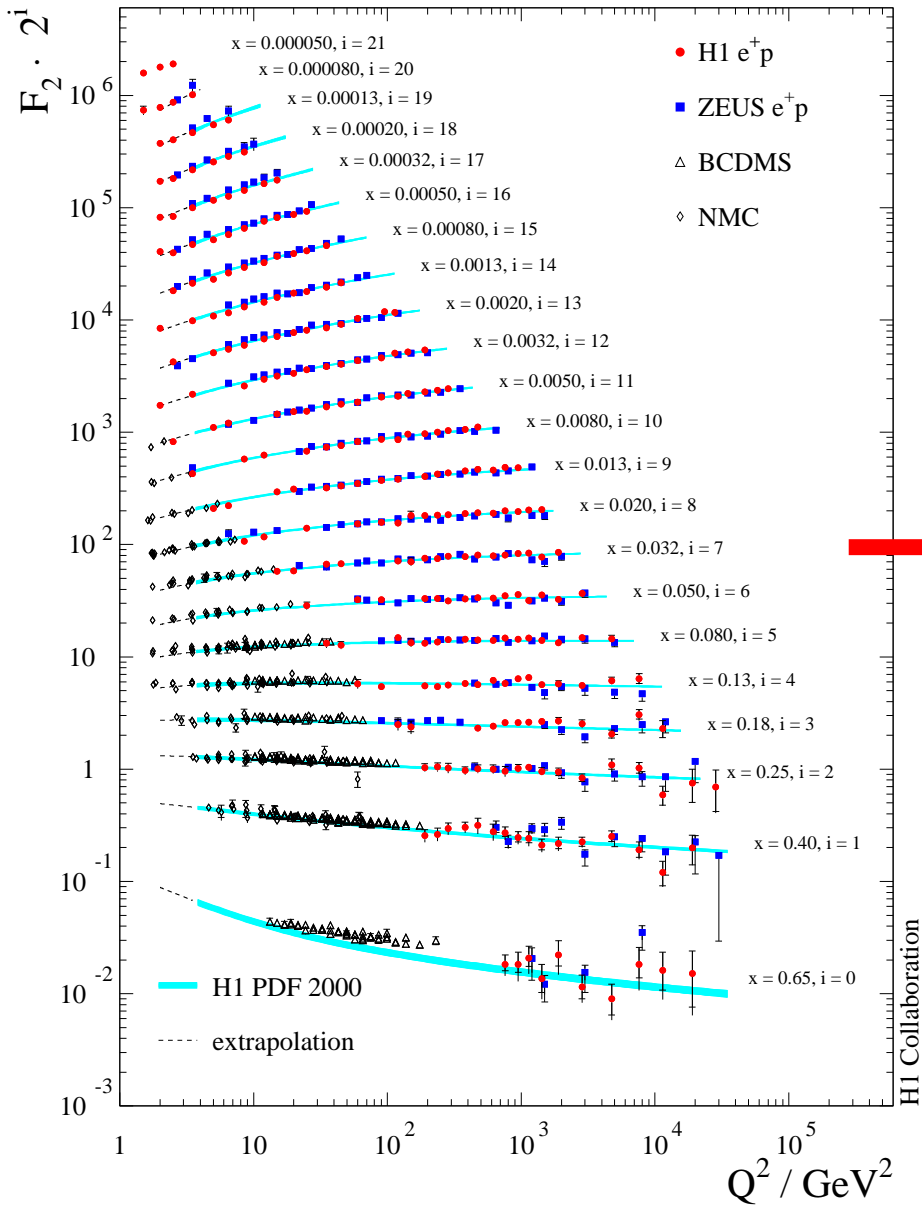
- Neutral Current DIS event candidate

$Q^2 \sim 24000 \text{ GeV}^2$  and  $x_{Bj} \sim 0.5$

- Coverage of kinematic plane ( $Q^2, x_{Bj}$ )

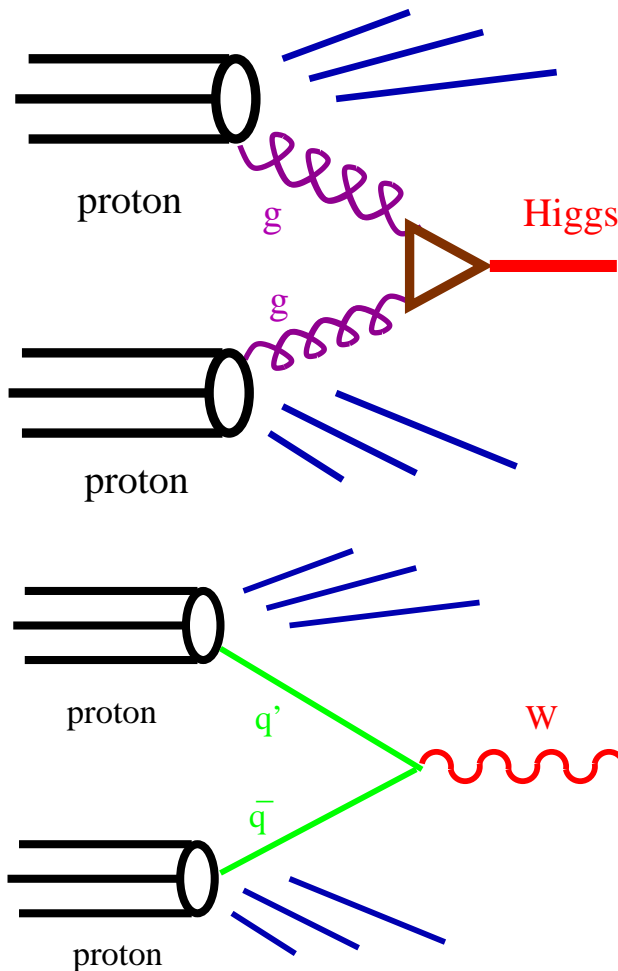


# One of the legacies of HERA



# Universality (and usefulness) of Proton PDFs

$$\sigma_{pp \rightarrow H(W,Z,\dots)+X} = \sum_{a,b} \int_0^1 dx_1 f_{a/p}(x_1, \mu_F^2) \int_0^1 dx_2 f_{b/p}(x_2, \mu_F^2) \hat{\sigma}_{ab \rightarrow H(W,Z,\dots)}$$



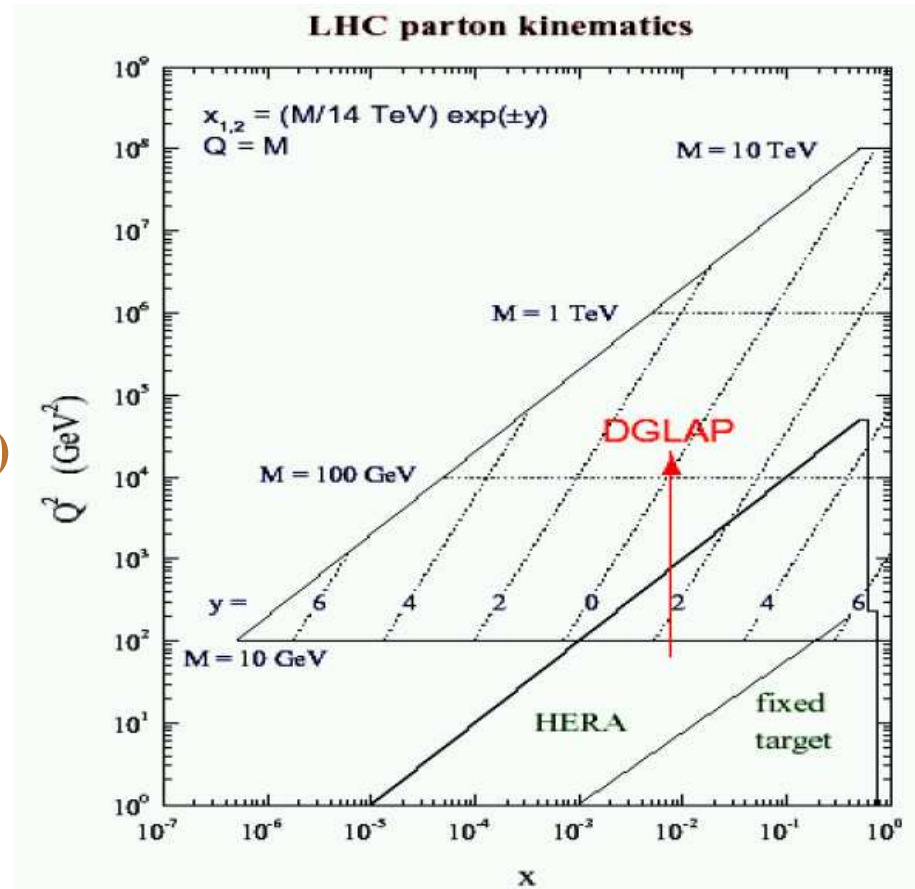
$\sigma_H$  sensitive to gluon distribution at

$x \sim \frac{M_H}{\sqrt{s}} \sim 8 \cdot 10^{-3}$   
 and  $\mu_F^2 \sim M_H^2 \sim 13000 \text{ GeV}^2$

(for  $M_H = 115 \text{ GeV}$ )

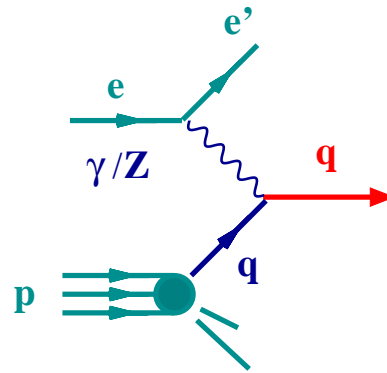
$\sigma_W$  sensitive to sea distribution at

$x \sim \frac{M_W}{\sqrt{s}} \sim 6 \cdot 10^{-3}$   
 and  $\mu_F^2 \sim M_W^2 \sim 6400 \text{ GeV}^2$

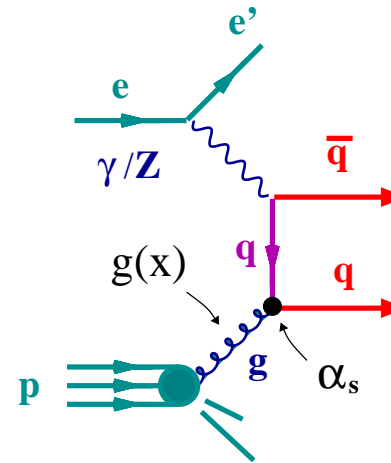


# Jet Production in Neutral Current Deep Inelastic Scattering

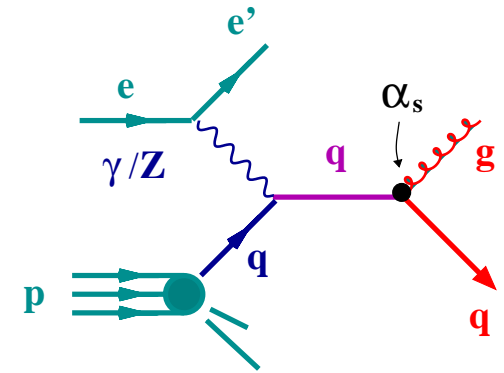
- Jet production in neutral current deep inelastic scattering up to  $\mathcal{O}(\alpha_s)$ :



Quark-Parton Model



Boson-Gluon Fusion



QCD Compton

- Perturbative QCD calculations of jet cross sections:

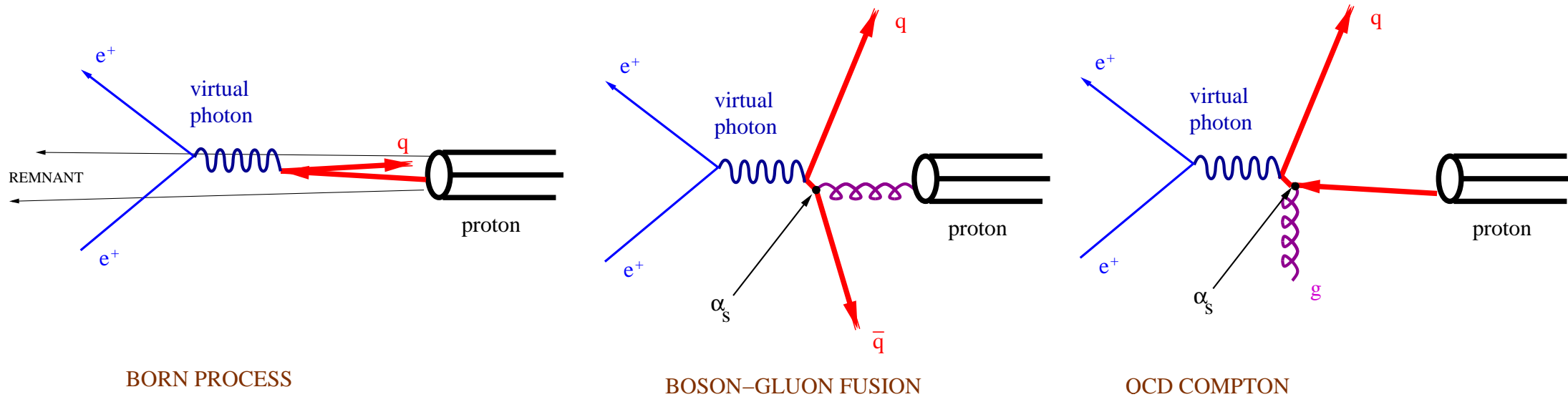
$$d\sigma_{jet} = \sum_{a=q,\bar{q},g} \int dx f_a(x, \mu_F^2) d\hat{\sigma}_a(x, \alpha_s(\mu_R), \mu_R^2, \mu_F^2)$$

- $f_a$ : parton  $a$  density in the proton, determined from experiment; **long-distance structure of the target**
- $\hat{\sigma}_a$ : subprocess cross section, calculable in pQCD; **short-distance structure of the interaction**

## Jet Production in Neutral Current Deep Inelastic Scattering

- In the region where the wealth of data from fixed-target and collider experiments has allowed an accurate determination of the proton PDFs, measurements of jet production in NC DIS provide
  - a sensitive test of the pQCD predictions of the short-distance structure
  - a determination of the strong coupling constant  $\alpha_s$
- To perform a stringent test of the pQCD predictions and a precise determination of  $\alpha_s$ :
  - \* Observables for which the predictions are directly proportional to  $\alpha_s$ 
    - Jet cross sections in the Breit frame
  - \* Small experimental uncertainties → Jets with relatively high transverse energy
  - \* Small theoretical uncertainties → NLO QCD calculations
    - Jet algorithm: longitudinally invariant  $k_T$  cluster algorithm (Catani et al)  
(small parton-to-hadron effects, infrared safe, suppression of beam-remnant jet)
    - Jet selection criteria
- Exploration of the parton evolution at low  $x$   $\Rightarrow$  footprints of BFKL effects?

# High- $E_T$ Jet Production in the Breit Frame



- In the Breit frame the virtual boson collides head-on with the proton
- High- $E_T$  jet production in the Breit frame
  - suppression of the Born contribution (struck quark has zero  $E_T$ )
  - suppression of the beam-remnant jet (zero  $E_T$ )
  - **lowest-order non-trivial contributions from  $\gamma^* g \rightarrow q\bar{q}$  and  $\gamma^* q \rightarrow qg$**
  - ⇒ **directly sensitive to hard QCD processes ( $\alpha_s$ )**

# Inclusive Jet Cross Sections in NC DIS at $Q^2 > 125 \text{ GeV}^2$

- **New measurement of inclusive jet cross sections in the kinematic region defined by  $Q^2 > 125 \text{ GeV}^2$  and  $|\cos \gamma| < 0.65$  for jets with  $E_{T,jet}^B > 8 \text{ GeV}$  and  $-2 < \eta_{jet}^B < 1.5$  using  $\mathcal{L} = 81.7 \text{ pb}^{-1}$**
- for different values of the radius-like parameter ( $R$ ) of the  $k_T$ -cluster algorithm:  $R = 0.5, 0.7, 1$

- **Advantages:**

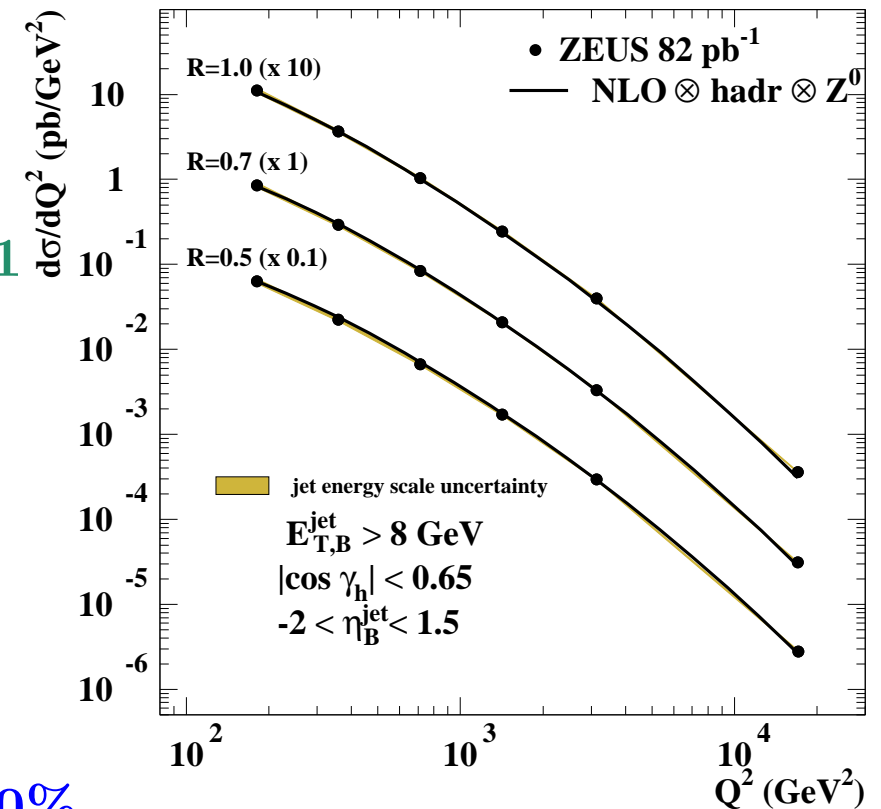
- infrared insensitivity (no dijet cuts!)
- smaller theoretical uncertainties than for dijet

- **Small experimental uncertainties:**

- jet energy scale (1% for  $E_{T,jet} > 10 \text{ GeV}$ )  
 $\Rightarrow \sim \pm 5\%$  on the cross sections

- **Small parton-to-hadron corrections ( $C_{had}$ ):  $< 10\%$**

- **NLO QCD calculations ( $\mathcal{O}(\alpha_s^2)$ ) using  $\mu_R = E_{T,jet}^B$ ,  $\mu_F = Q$  and the ZEUS-S parametrisations of the proton PDFs describe the measurements well**



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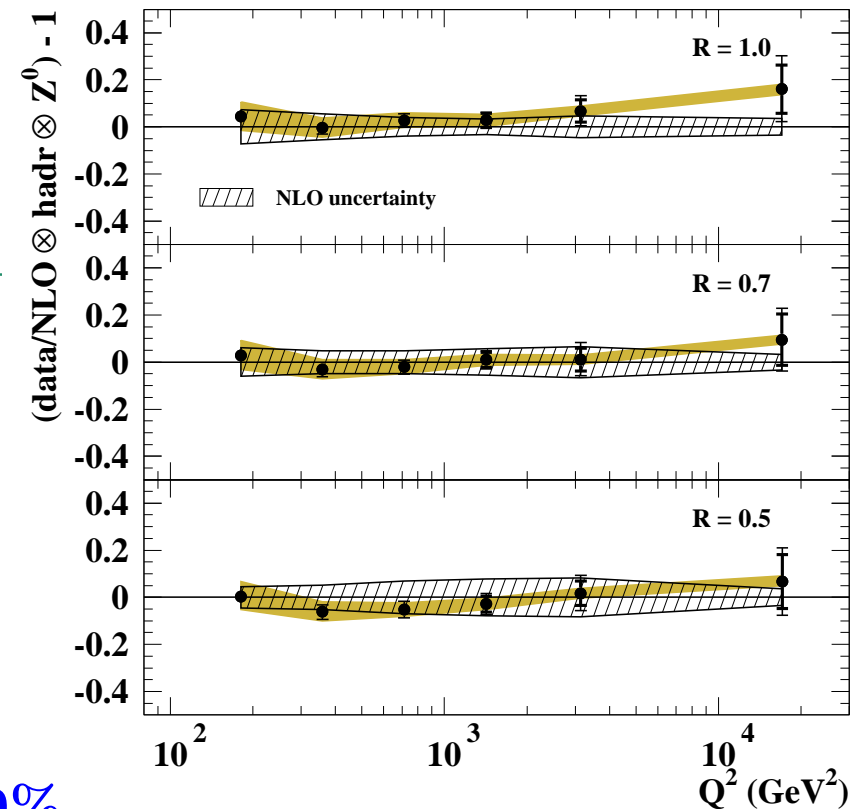
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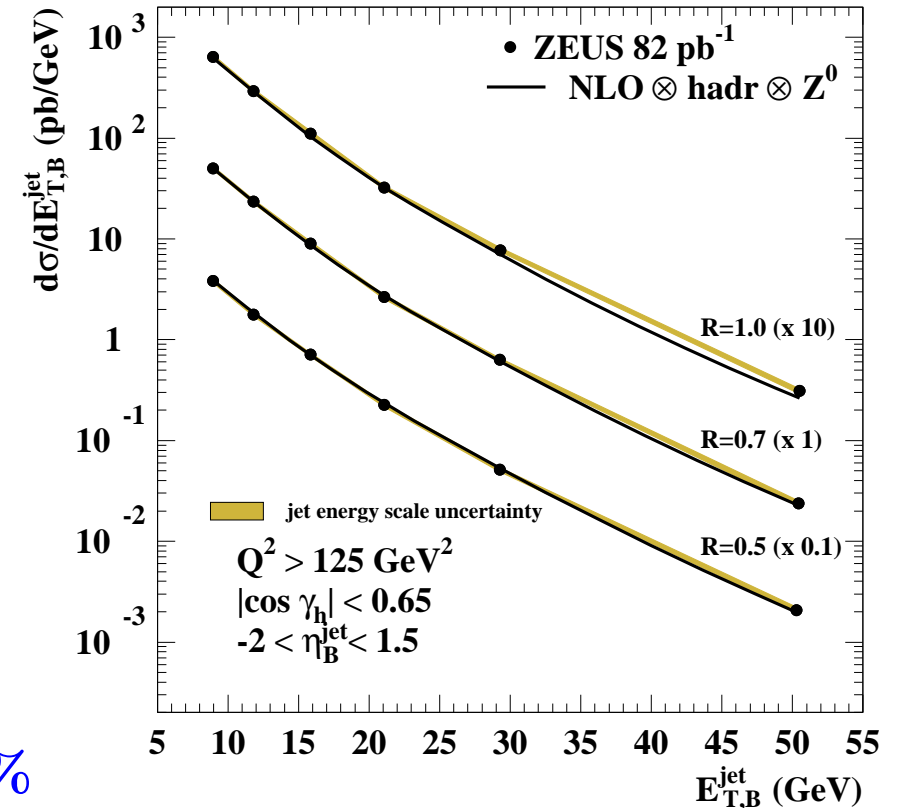
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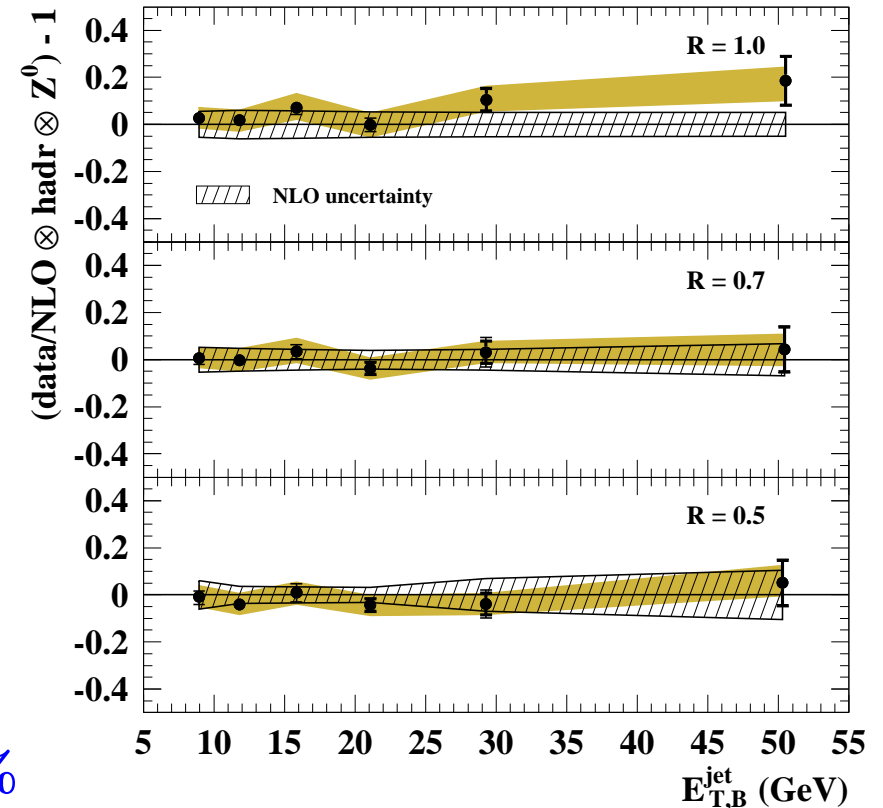
# Inclusive Jet Cross Sections in NC DIS at $Q^2 > 125 \text{ GeV}^2$

- **New measurement of the inclusive jet cross section  $d\sigma/dE_{T,jet}^B$  in the kinematic region defined by  $Q^2 > 125 \text{ GeV}^2$  and  $|\cos \gamma| < 0.65$  for jets with  $E_{T,jet}^B > 8 \text{ GeV}$  and  $-2 < \eta_{jet}^B < 1.5$**
- **Small theoretical uncertainties ( $R = 1$ ):**
  - higher-order terms ( $> \text{NLO}$ ); varying  $\mu_R$  between  $\frac{1}{2} \cdot E_{T,jet}^B$  and  $2 \cdot E_{T,jet}^B \Rightarrow \pm 5\%$
  - uncertainties on the proton PDFs;  $\Rightarrow \pm 3\%$
  - uncertainty on  $\alpha_s(M_Z)$  ( $\pm 0.0010$ );  $\Rightarrow \pm 2\%$
  - hadronisation corrections;  $\Rightarrow \pm 1.4\%$
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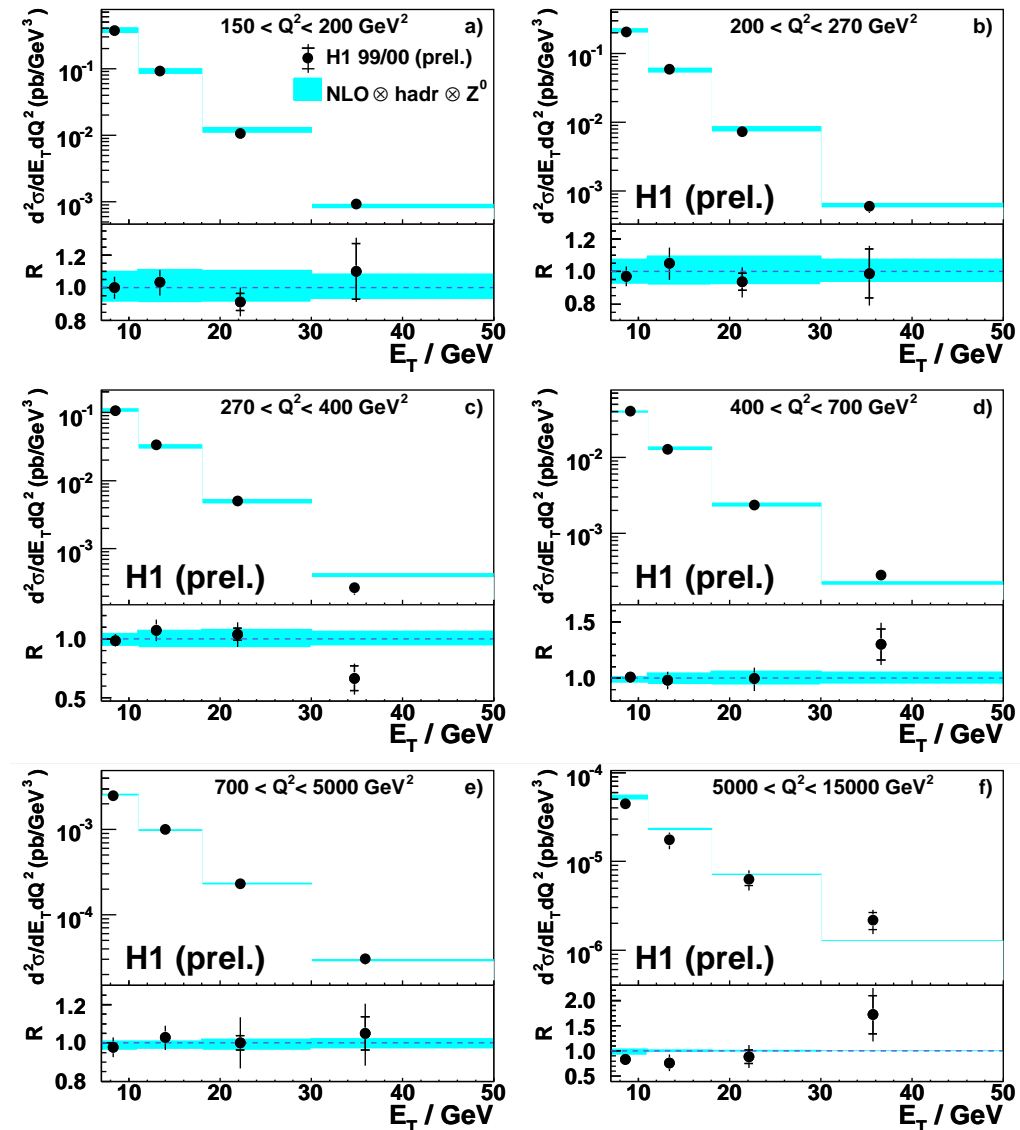
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# Inclusive Jet Cross Sections in NC DIS at $Q^2 > 150 \text{ GeV}^2$

- **New** measurement of the double differential cross-section  $d^2\sigma/dE_T dQ^2$  for jets with  $7 < E_{T,jet}^B < 50 \text{ GeV}$ ,  $-1 < \eta_{jet}^{lab} < 2.5$  in the kinematic region defined by  $150 < Q^2 < 15000 \text{ GeV}^2$ ,  $0.2 < y < 0.7$  using  $\mathcal{L} = 65 \text{ pb}^{-1}$
- Small experimental uncertainties:  $\sim 5\%$ , hadronic energy scale and model dependence
- The  $E_T$  spectrum gets harder with increasing  $Q^2$
- Good description of the data by NLO QCD (corrected for hadronisation effects,  $\mathcal{O}(10\%)$ ) using  $\mu_R = E_{T,jet}^B$ ,  $\mu_F = Q$  and the CTEQ6.5 parametrisations of the proton PDFs

## Inclusive Jet Cross Section



# Inclusive Jet Cross Sections and extraction of $\alpha_s$ (ZEUS)

- The inclusive jet cross section  $d\sigma/dQ^2$  at  $Q^2 > 500 \text{ GeV}^2$  has been used to extract  $\alpha_s(M_Z)$

$$\alpha_s(M_Z) = 0.1207 \pm 0.0014 \text{ (stat.)}$$

$$+0.0035 \text{ (exp.)} \quad +0.0022 \text{ (th.)}$$

$$-0.0033 \text{ (exp.)} \quad -0.0023 \text{ (th.)}$$

- Experimental uncertainties: 2% from jet energy scale

- Theoretical uncertainties:

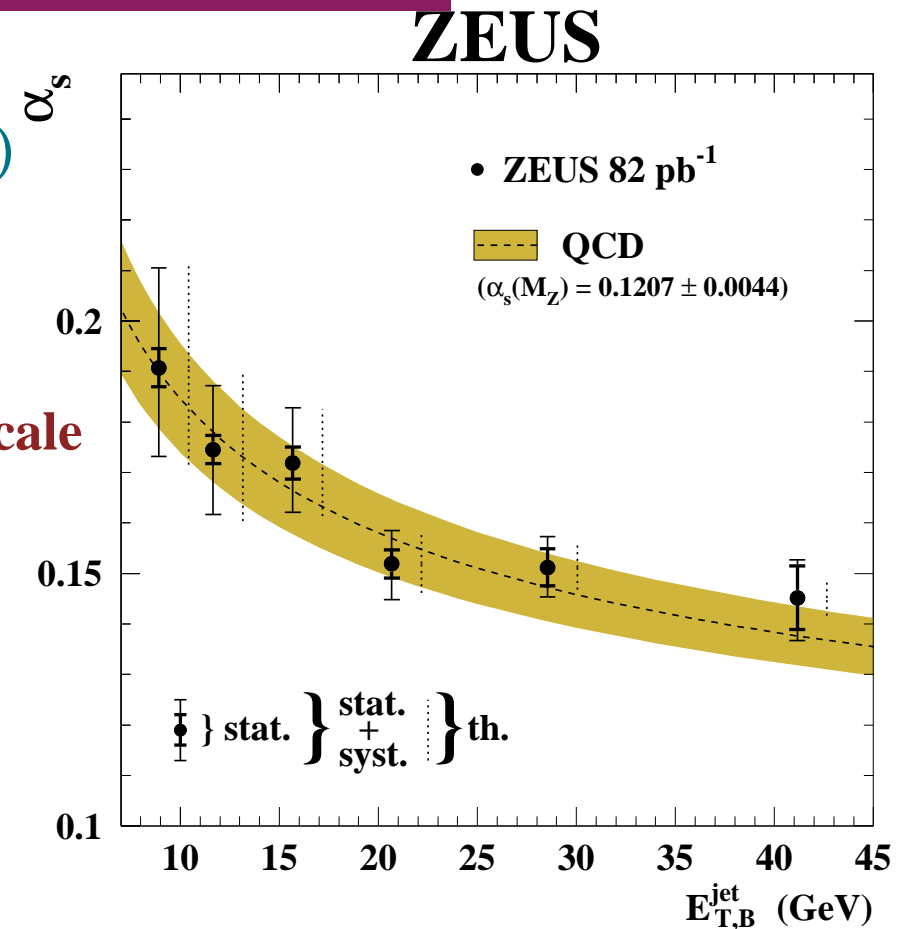
- terms beyond NLO  $\Delta\alpha_s(M_Z) = 1.5\%$
- uncertainties proton PDFs  $\Delta\alpha_s(M_Z) = 0.7\%$
- hadronisation corrections  $\Delta\alpha_s(M_Z) = 0.8\%$

- Consistent with other determinations of  $\alpha_s$

- Very precise determination of  $\alpha_s(M_Z)$ !

- Study of the scale dependence of  $\alpha_s(E_{T,jet}^B)$ : from the measured  $d\sigma/dE_{T,jet}^B$  in each  $E_{T,jet}^B$  region  $\rightarrow \alpha_s(\langle E_{T,jet}^B \rangle)$  is extracted

- The measurements are consistent with the running of  $\alpha_s$  predicted by perturbative QCD



# Inclusive Jet Cross Sections and extraction of $\alpha_s$ (H1)

- A value of  $\alpha_s(\mu_R)$  has been extracted from each data point of  $d^2\sigma/dE_t dQ^2$   
→ the results are compatible
- Averages of  $\alpha_s(\mu_R)$  determinations in  $Q^2$  or  $E_t$  intervals ⇒ demonstration of the running of  $\alpha_s$
- The results are used to extract  $\alpha_s(M_Z)$ :

$$\alpha_s(M_Z) = 0.1179 \pm 0.0024 \text{ (exp.)}$$

$$+0.0052 \text{ (th.)} \pm 0.0030 \text{ (pdf.)}$$

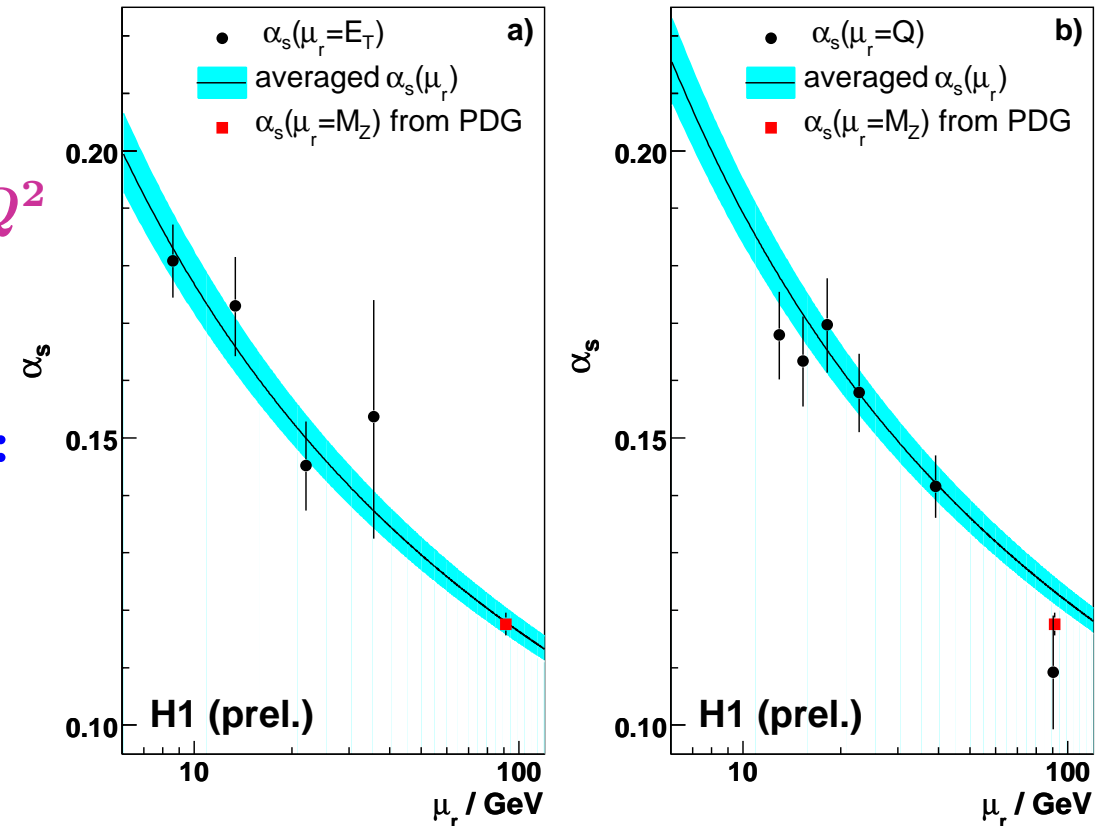
- Reduction of experimental and PDF uncertainties by using “normalised” inclusive jet cross sections ( $\sigma_{jets}/\sigma_{NCDIS}$ ):

$$\alpha_s(M_Z) = 0.1193 \pm 0.0014 \text{ (exp.)} +0.0046 \text{ (th.)} -0.0032 \text{ (pdf.)} \pm 0.0016 \text{ (pdf.)}$$

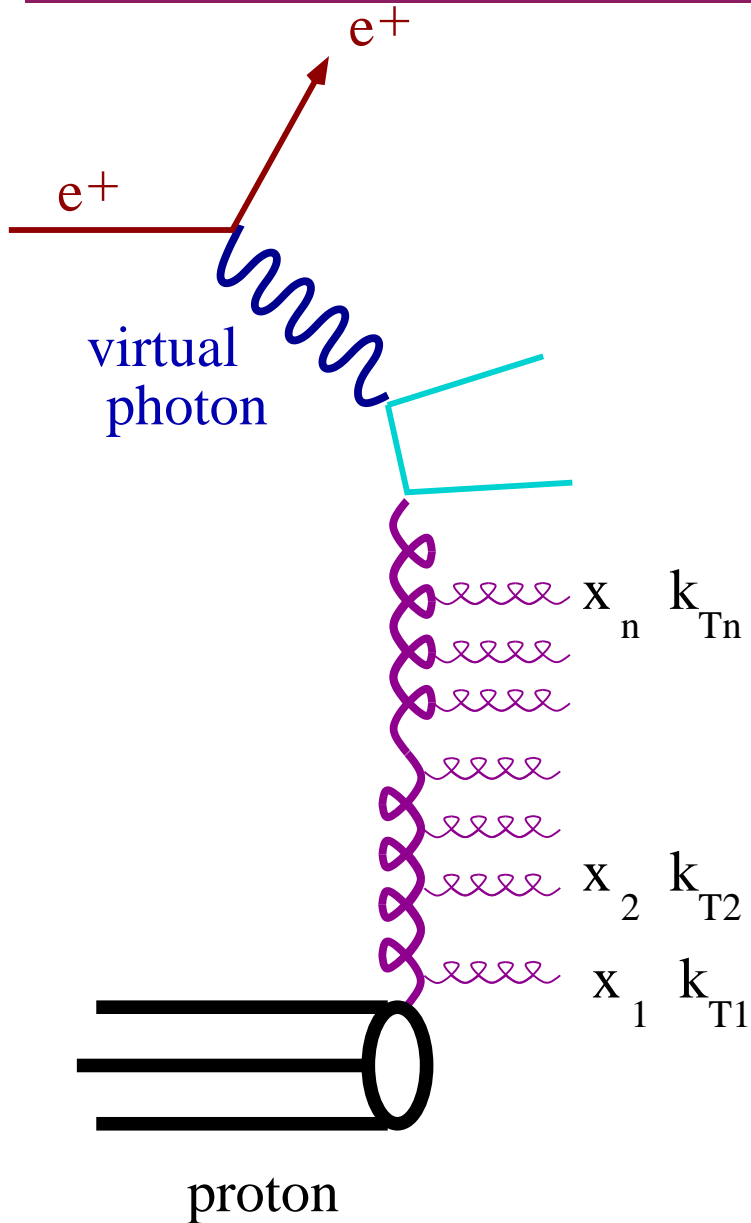
⇒ precise determination of  $\alpha_s(M_Z)$ ; consistent with the world average

→ theoretical uncertainty dominant (major contributions from  $\mu_{R,F}$  variations)

## $\alpha_s$ from Inclusive Jet Cross Section



# Parton evolution at low $x$



## Searching for BFKL-induced effects

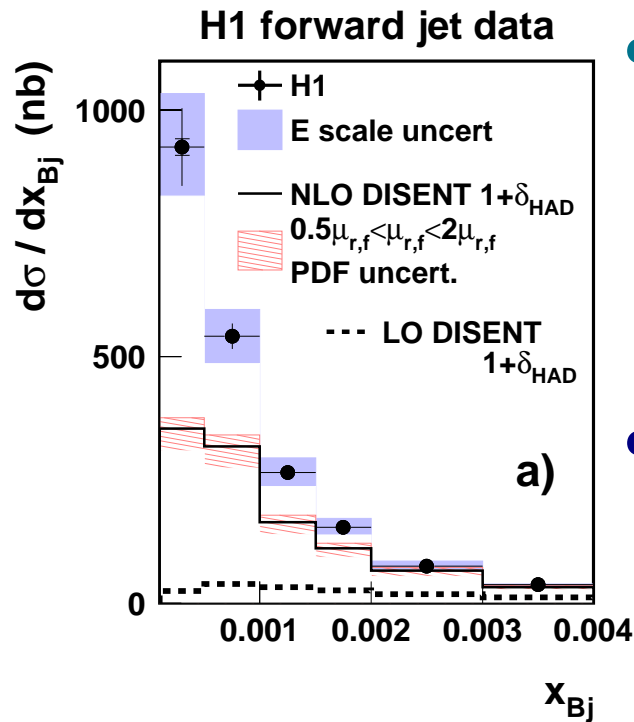
- DGLAP equations sum the leading powers of  $\alpha_s \log Q^2$  in the region of strongly-ordered transverse momenta

$$Q^2 \gg k_{Tn}^2 \gg \dots \gg k_{T2}^2 \gg k_{T1}^2$$

- When  $\log Q^2 \ll \log 1/x$  terms proportional to  $\alpha_s \log 1/x$  become important and need to be summed the BFKL equation accomplishes that; the integration is taken over the full  $k_T$  phase space of the gluons  $\Rightarrow$  no  $k_T$  ordering

- Mueller and Navelet's proposal: forward (proton's direction) jet production with  $x_1/x$  as large as possible and  $k_{T1} \sim Q$

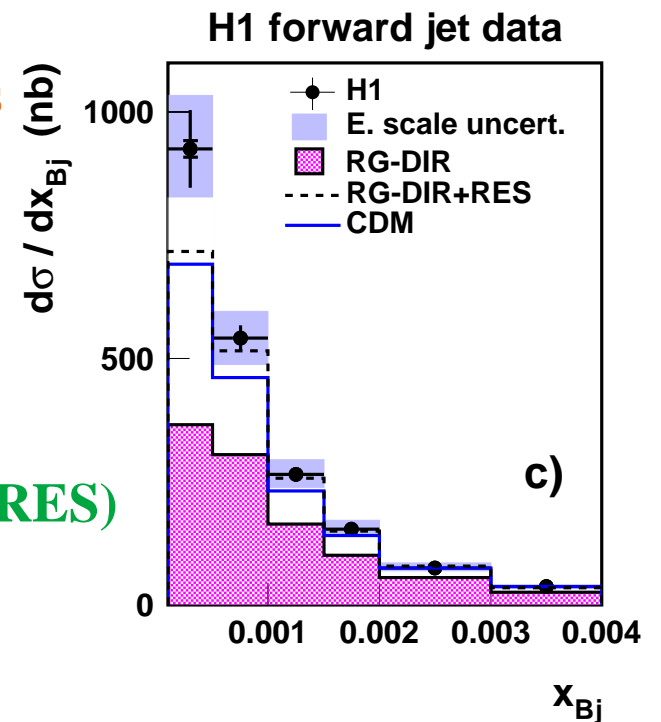
# Measurement of Forward Jet Production at low $x$



- Measurement of the differential cross section  $d\sigma/dx$  for jet production with  $p_{t,jet} > 3.5 \text{ GeV}$ ,  $7^\circ < \theta_{jet} < 20^\circ$ ,  $0.5 < p_{t,jet}^2/Q^2 < 2$  and  $x_{jet} = E_{jet}/E_p > 0.035$  in the kinematic region  $10^{-4} < x < 4 \cdot 10^{-3}$  and  $5 < Q^2 < 85 \text{ GeV}^2$
- Strong rise towards low  $x$  is observed

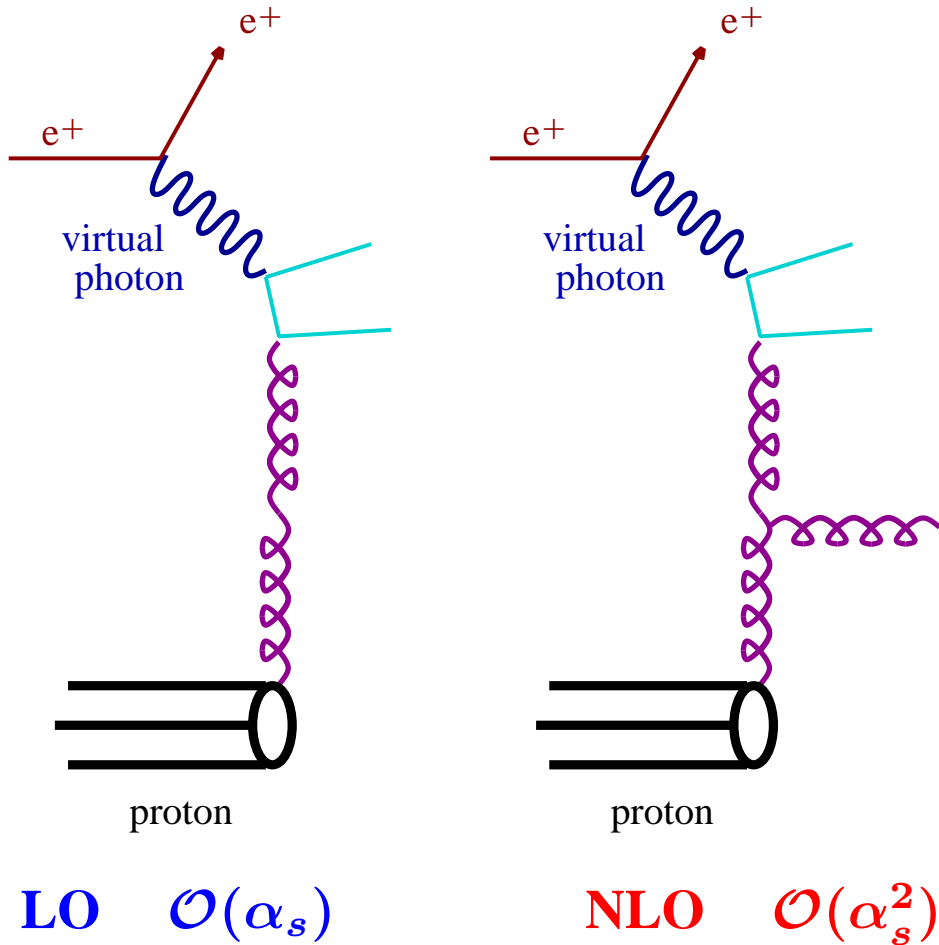
• Comparison to calculations

- NLO QCD (DGLAP) lies well below the data at low  $x$
- MC models with extra parton radiation provide an improved description of the data
- inclusion of a resolved-photon component (RG-DIR+RES)
- parton emissions not ordered in  $k_T$  (CDM)

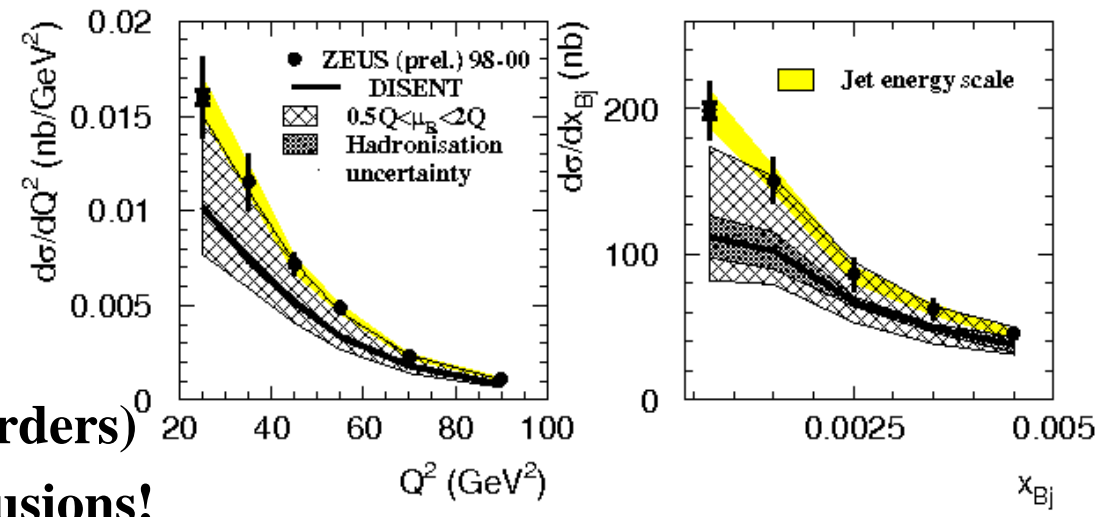


# Measurement of Forward Jet Production at low $x$

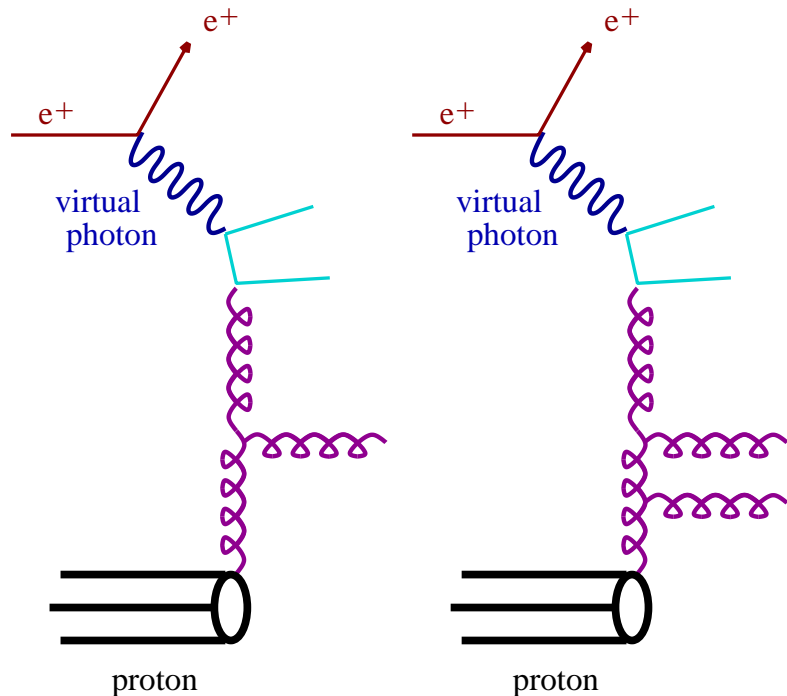
- **LO QCD ( $\mathcal{O}(\alpha_s)$ ):** hardly any phase space available for forward jet production
- **NLO QCD ( $\mathcal{O}(\alpha_s^2)$ ):** huge increase in cross section ( $\text{NLO} \gg \text{LO}$ ) due to opening of new channel (gluon exchange in t-channel)
- **NLO QCD becomes an “effective” LO,** with large theoretical uncertainties



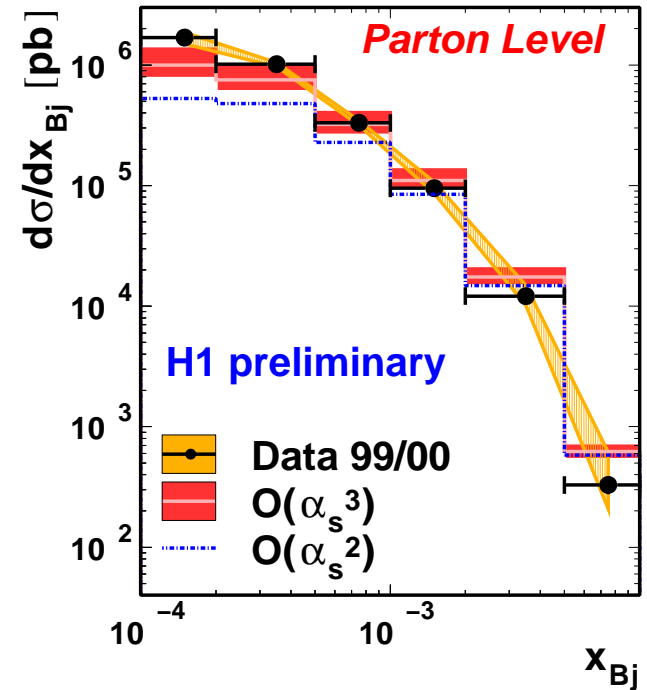
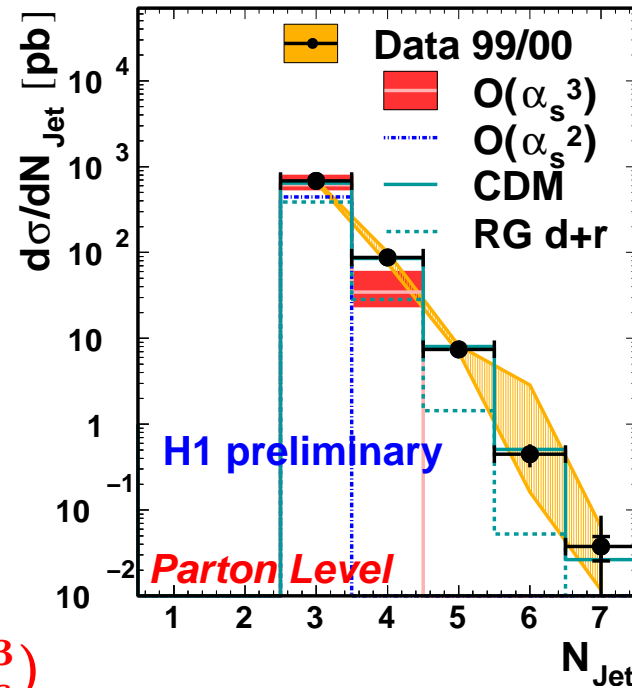
⇒ Large theoretical uncertainties (higher-orders) in pQCD calculations prevent firm conclusions!



# Measurements of Three-jet Production at low $x$

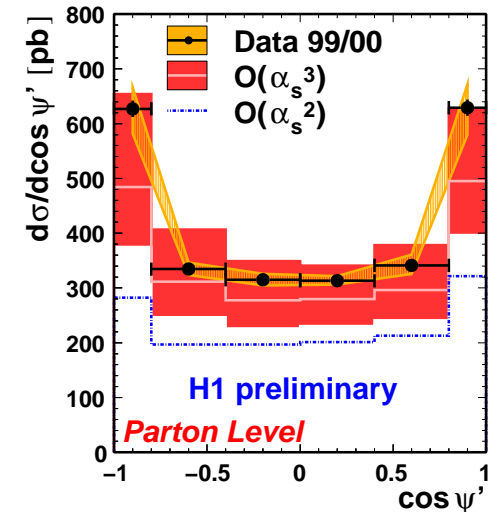
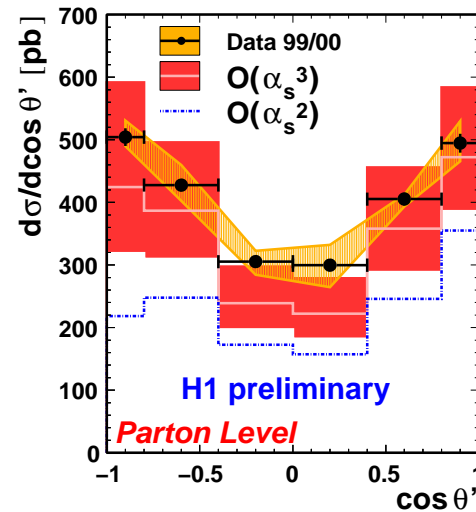
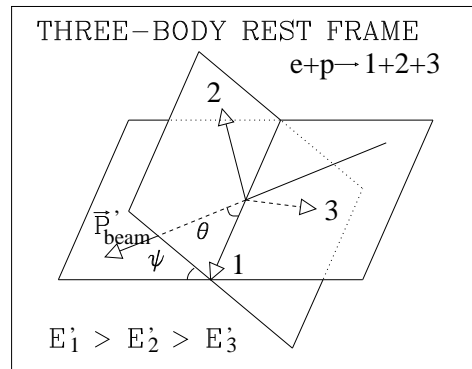
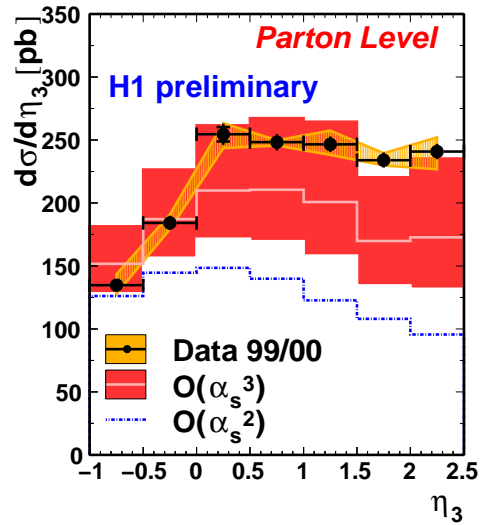
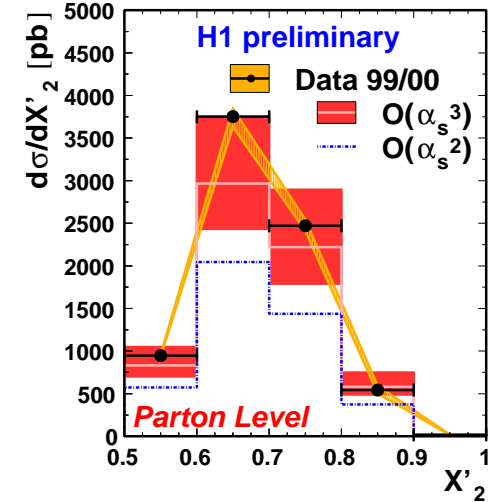
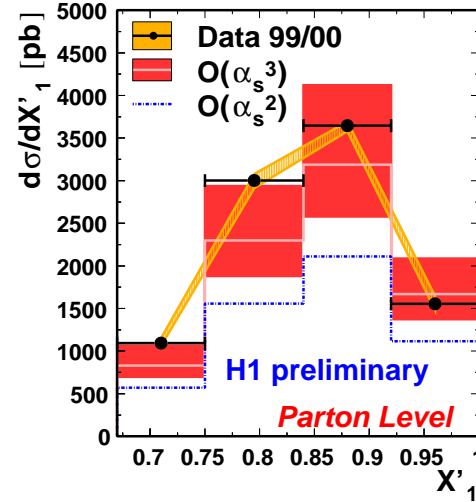
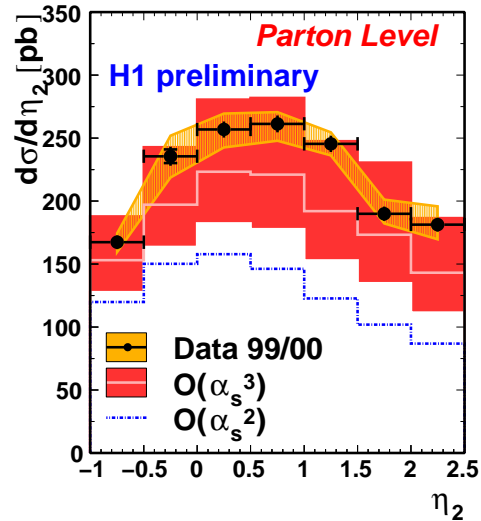
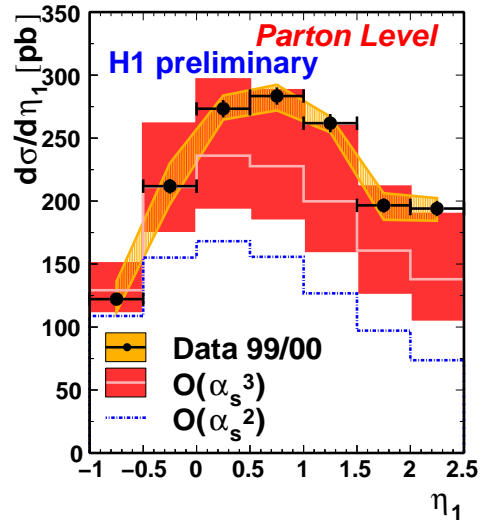


LO  $\mathcal{O}(\alpha_s^2)$       NLO  $\mathcal{O}(\alpha_s^3)$



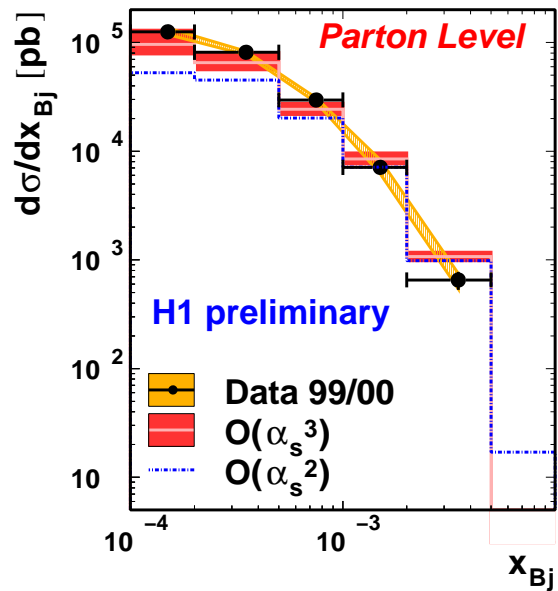
- Measurements of three-jet production using the  $k_T$  cluster algorithm in the  $\gamma^* p$  frame with  $E_{\perp, jet}^* > 4 \text{ GeV}$ ,  $E_{\perp, jet1}^* + E_{\perp, jet2}^* > 9 \text{ GeV}$ ,  $-1 < \eta_{jet}^{lab} < 2.5$  (one central jet  $-1 < \eta_{jet}^{lab} < 1.3$ ) in the kinematic region defined by  $0.1 < y < 0.7$  and  $4 < Q^2 < 80 \text{ GeV}^2 \Rightarrow$  The inclusion of yet another radiated gluon ( $\mathcal{O}(\alpha_s^3)$ ) improves dramatically the description of the data at low  $x$

# Measurements of Three-jet Production at low $x$



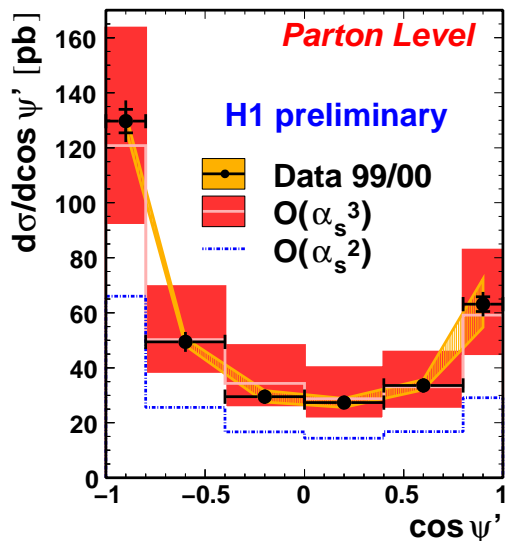
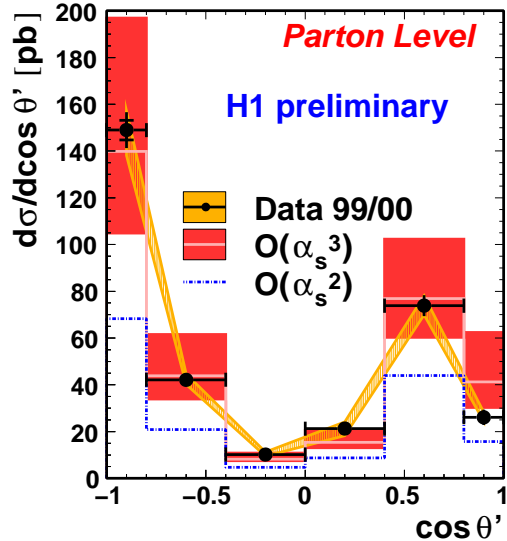
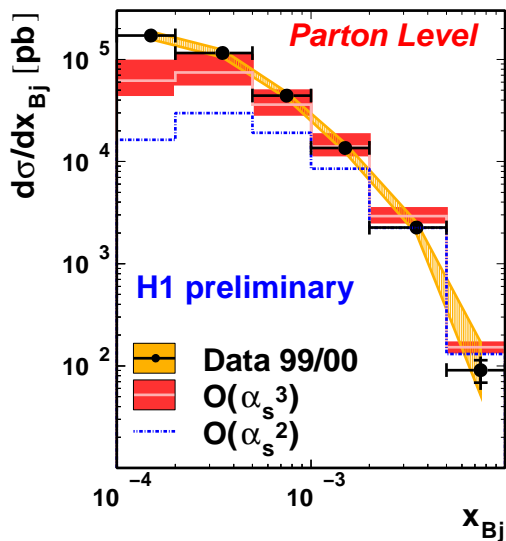
⇒ The inclusion of yet another radiated gluon ( $O(\alpha_s^3)$ ) improves dramatically the description of the data at low  $x$

# Measurements of Three-jet Production at low $x$



← Sample of events with “2 central jets + 1 forward jet”

↓ Sample of events with “1 central jet + 2 forward jets”

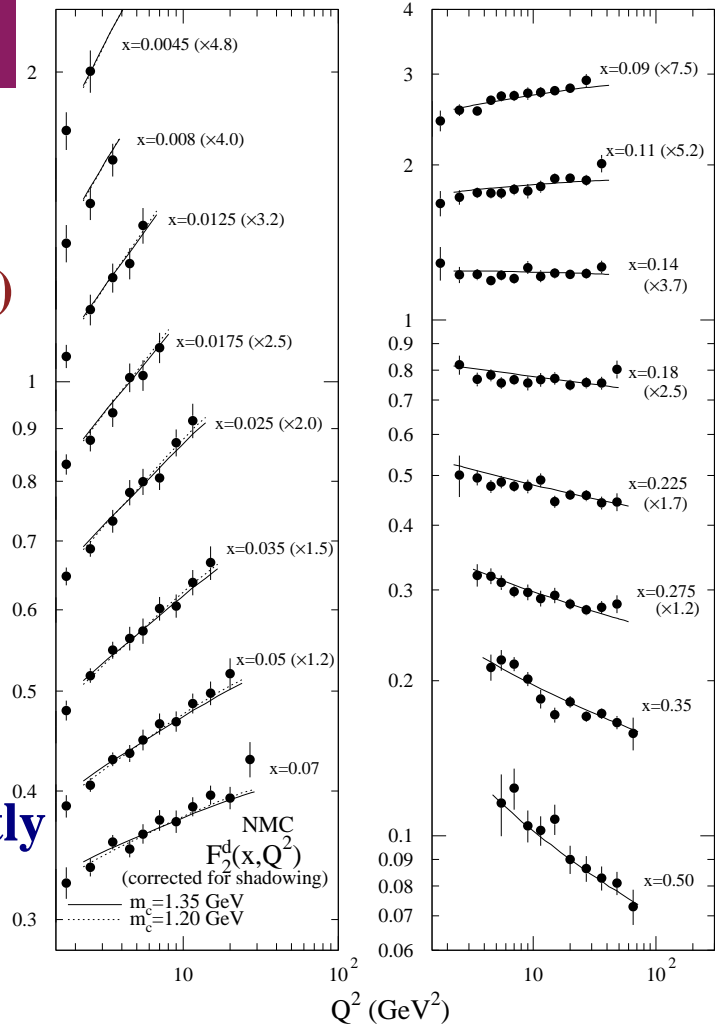
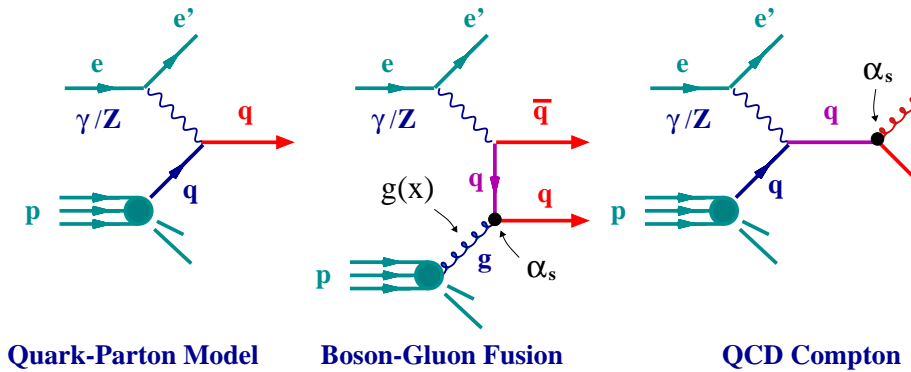


(↑ NLO scaled up for shape comparison ↑)

- The inclusion of  $\mathcal{O}(\alpha_s^3)$  corrections provides an improved description of the data
  - particularly dramatic for the sample with two forward jets (sample most sensitive to additional gluon radiation) → good description of the topology of three-jet events
- ⇒ Success of perturbative QCD  $\mathcal{O}(\alpha_s^3)$  at describing multijet production at low- $x$ 
  - almost ... still the data above NLO at  $x \sim 10^{-4}$  for “1 central +2 forward jets” sample

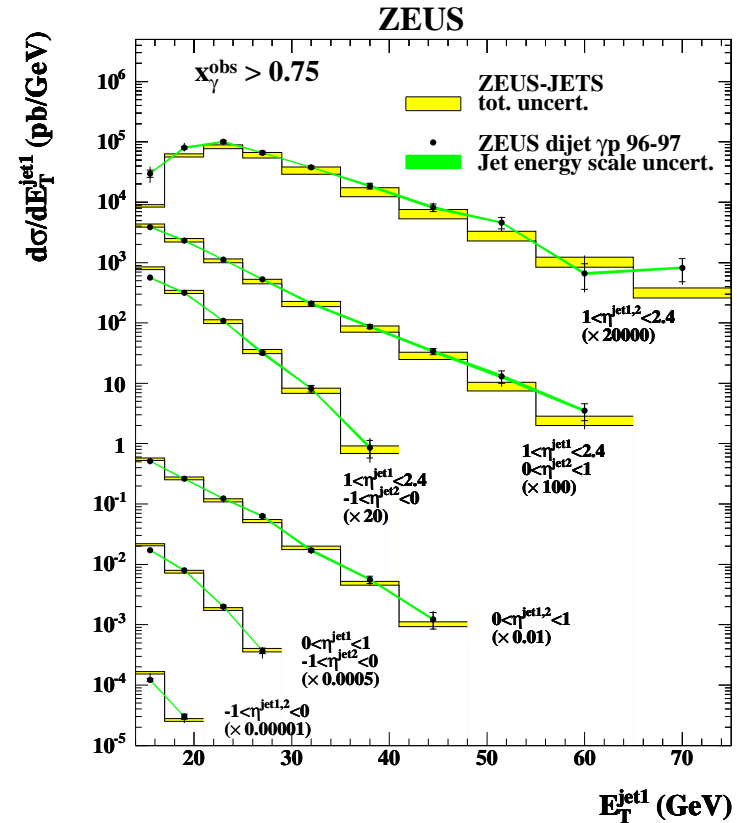
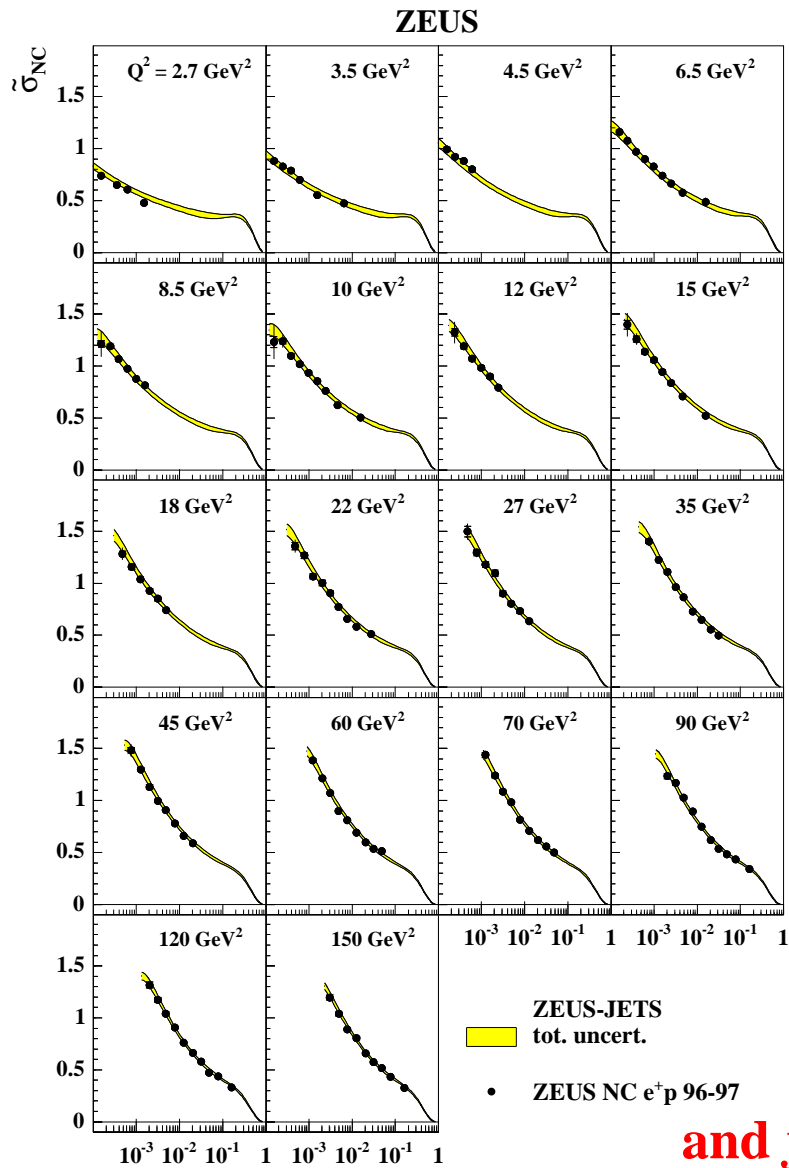
# Improving the Determination of the Proton PDFs

- **Observables used in the fits to determine the proton PDFs:**
  - **Inclusive measurements of deep inelastic  $lN$  scattering**
  - **Advantages:** → inclusive (only final-state lepton is tagged)
  - ⇒ **no QCD corrections associated to the final-state lepton**



- **Disadvantages:** the gluon distribution contributes indirectly
- **Observables based on jets have hardly been used**
  - large QCD corrections and hadronisation corrections
- **Fixed-target DIS:** higher twists, heavy-target corrections and isospin-symm. assumptions
- **That's the past! NOW there are measurements of jet cross sections at HERA**
  - ⇒ **directly sensitive to the gluon density with small experimental+theoretical uncertainties!**
- **Sufficient sensitivity to determine the proton PDFs within a single ( $ep$ ) experiment**

# Determination of PDFs using structure function and jet data from ZEUS



• Determination of the proton PDFs using SF data

$$\Rightarrow 6.3 \cdot 10^{-5} < x < 0.65, 2.7 < Q^2 < 30000 \text{ GeV}^2$$

and jet data in NC DIS and  $\gamma p$  collisions from ZEUS only (!)

• Sufficient sensitivity to determine the proton PDFs within a single experiment

# Determination of PDFs using structure function and jet data from ZEUS

- Data sets used in the fit (577 data points):

→ Structure function measurements: reduced double differential cross sections in  $x$  and  $Q^2$

- neutral current DIS  $e^+p$  and  $e^-p$
- charged current DIS  $e^+p$  and  $e^-p$

→ Jet cross section measurements:

- inclusive jet production in NC DIS
- dijet production in  $\gamma p$  collisions

- Evolution of the PDFs with the energy scale:

DGLAP equations at NLO ( $\overline{MS}$  scheme);

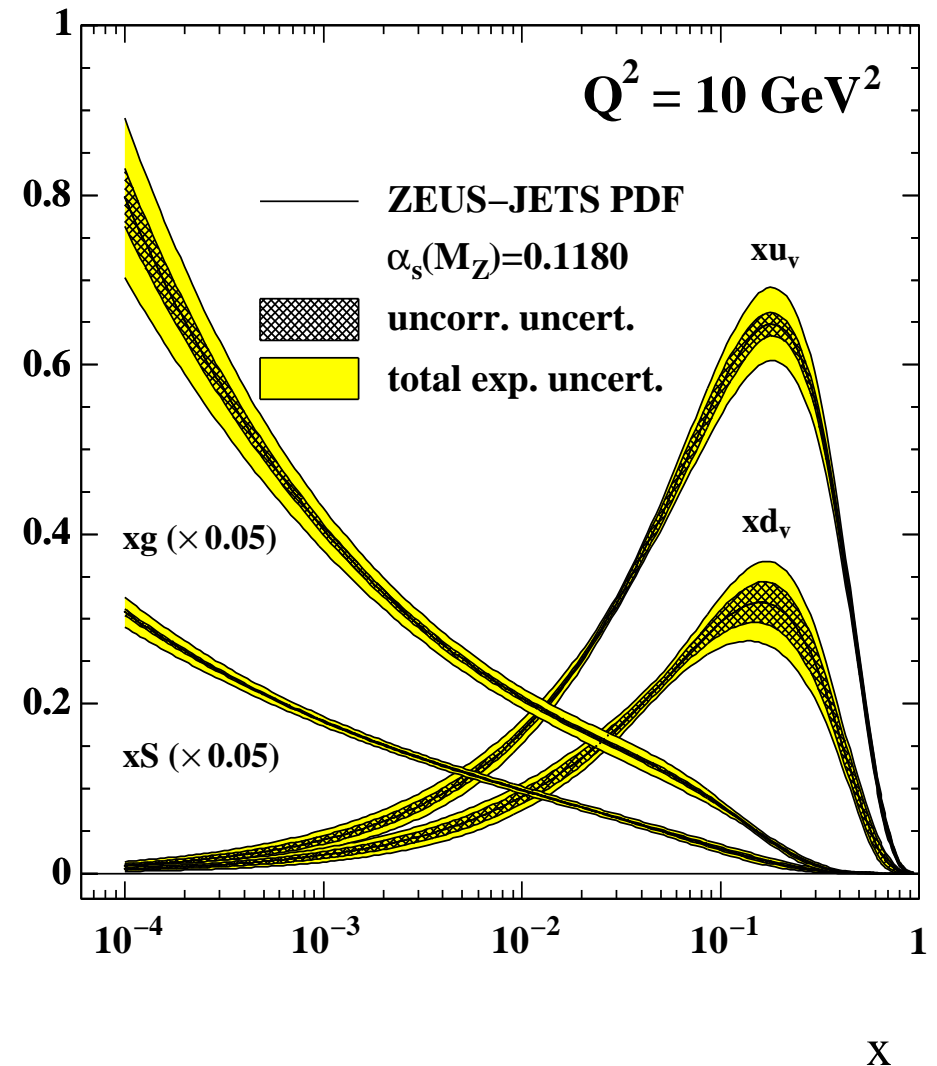
11 free parameters ( $+\alpha_s$  when free)

- Full account of correlated experimental uncertainties using the offset method

- A good description of the data is obtained:

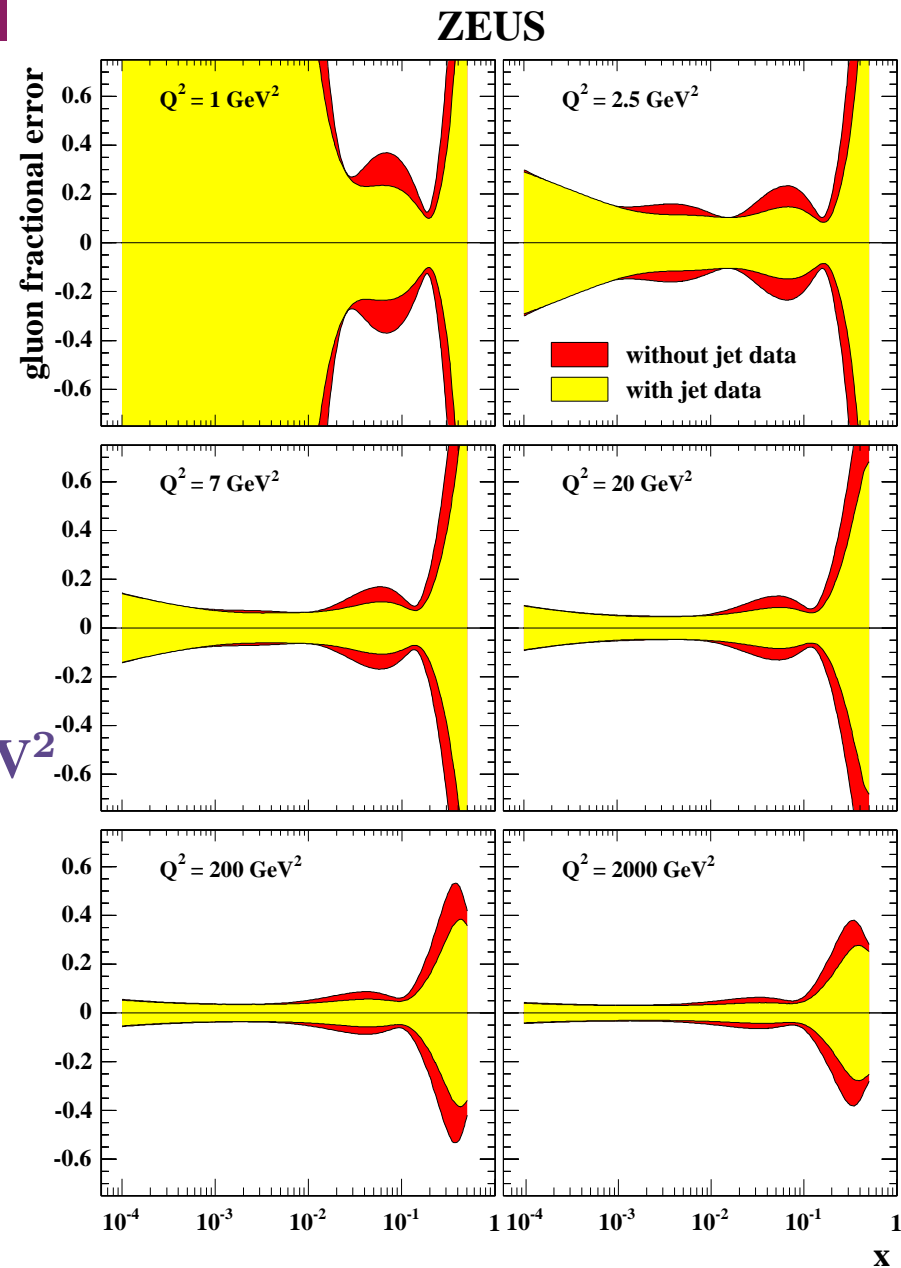
$\chi^2 = 470$  for 577 data points

## ZEUS

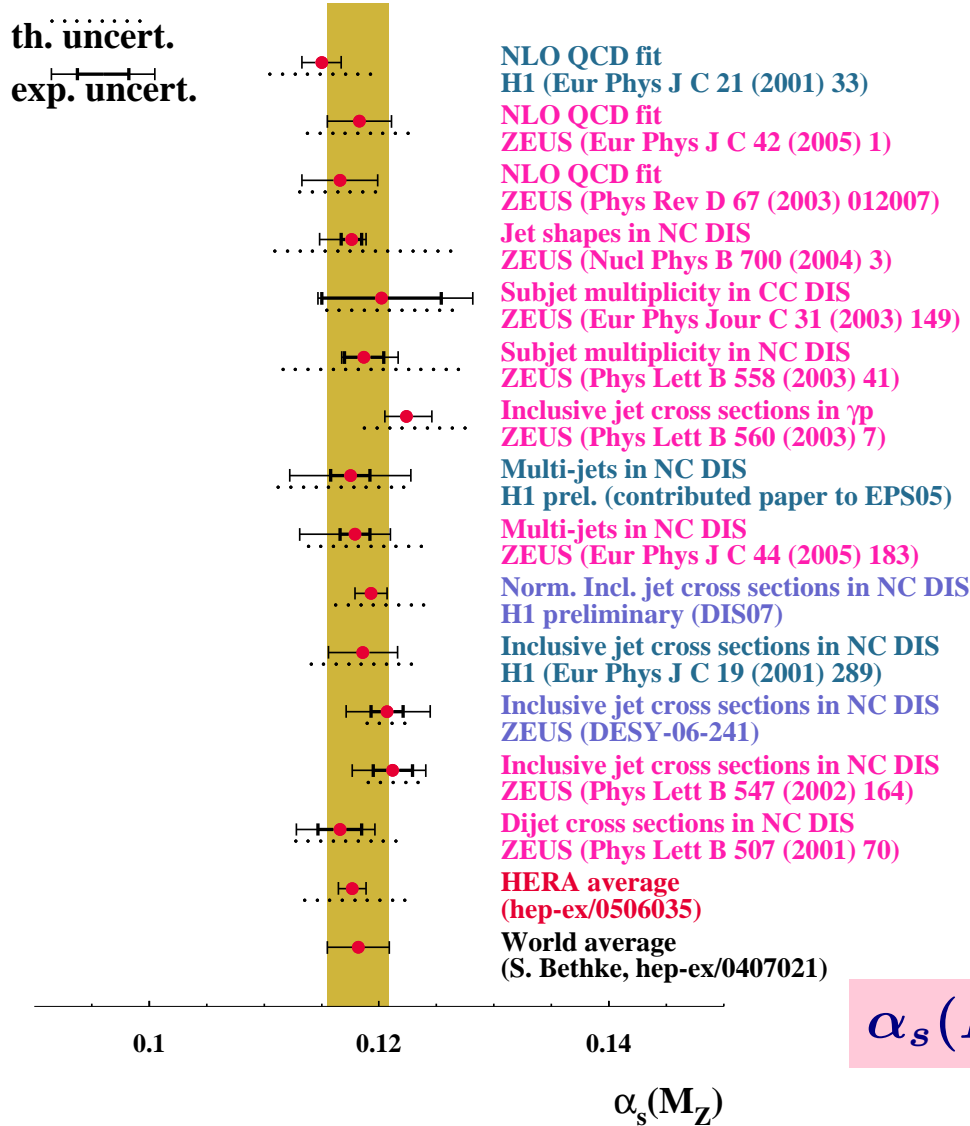


## Improving the gluon distribution: jet data

- Comparison of gluon distributions from fits with and without jet data
  - no significant change of the shape: no tension between jet and inclusive data
  - the jet cross sections constrain the gluon density in the range 0.01 – 0.4
  - **Sizeable reduction of the gluon uncertainty**
- e.g. from 17% to 10% at  $x = 0.06$  and  $Q^2 = 7 \text{ GeV}^2$
- similar reduction by a factor of two in the mid- $x$  region over the full  $Q^2$  range



# Summary of $\alpha_s$ determinations



● Wealth of determinations of  $\alpha_s$  at HERA from a variety of observables:

→ NLO QCD analyses of structure functions

→ Inclusive jet production in NC DIS

→ Dijet production in NC DIS

→ Tri-jet/Dijet rate in NC DIS

→ Jet substructure in NC DIS

→ Jet substructure in CC DIS

→ Inclusive jet photoproduction

● Theoretical uncertainties are dominant

→ Biggest contrib. from terms beyond NLO

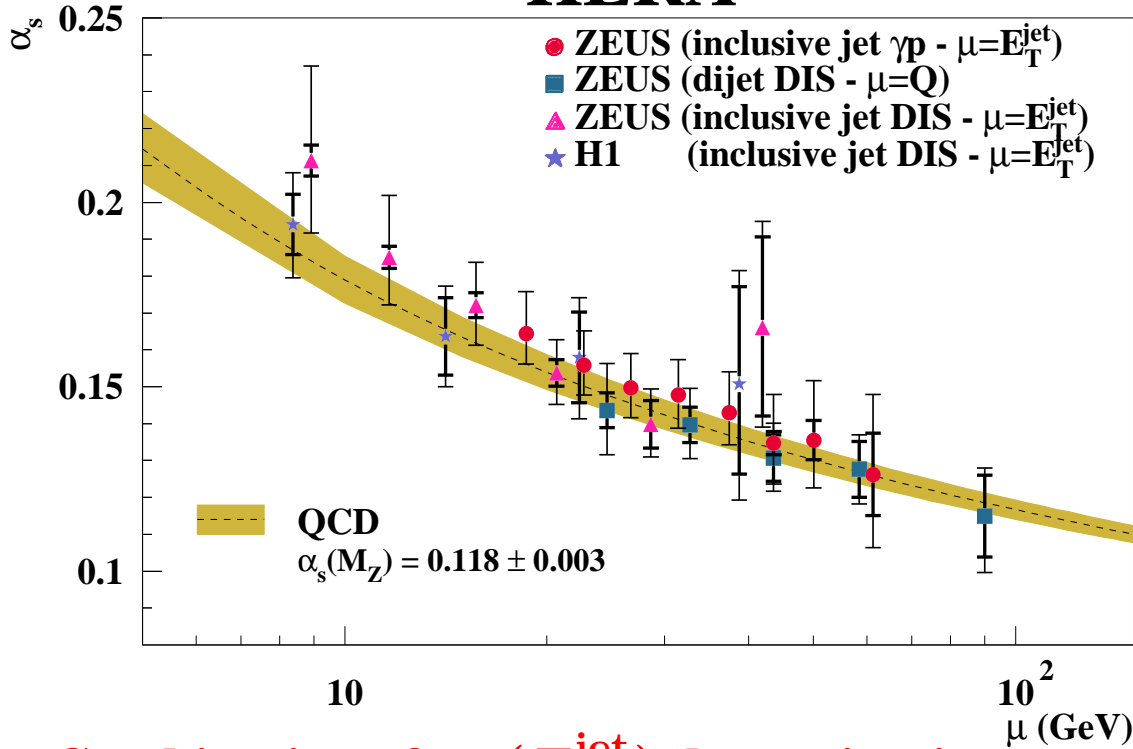
● Average of HERA determinations

$$\alpha_s(M_Z) = 0.1186 \pm 0.0011(\text{exp.}) \pm 0.0050(\text{th.})$$

(most recent ones not yet included)

# The running of $\alpha_s$ from HERA data alone

## HERA

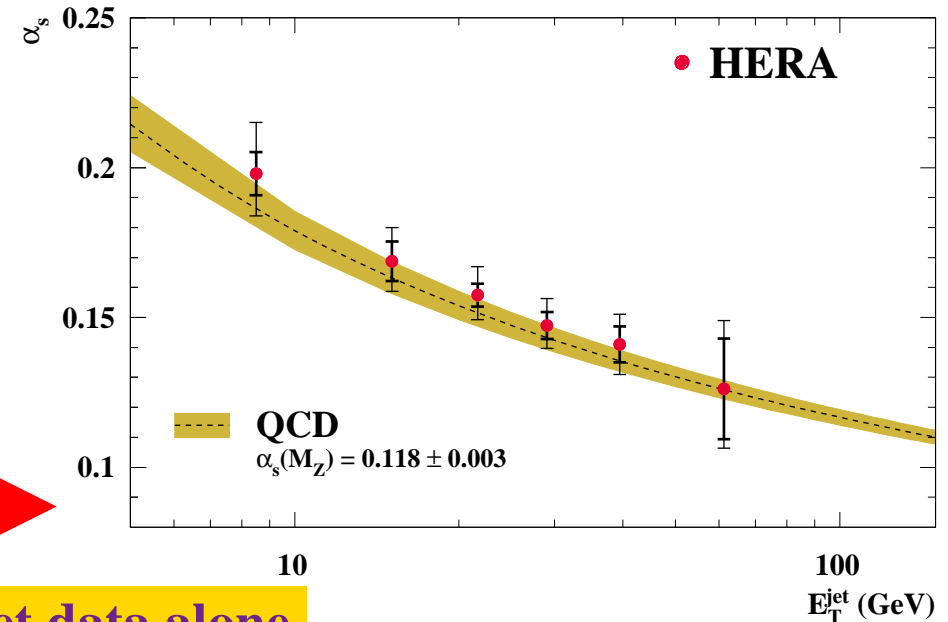


### ● Determinations of $\alpha_s(\mu)$ :

→ Dijet NC DIS ( $\mu = Q$ )

→ Inclusive jet NC DIS ( $\mu = E_T^{\text{jet}}$ )

→ Inclusive jet  $\gamma p$  ( $\mu = E_T^{\text{jet}}$ )



● Combination of  $\alpha_s(E_T^{\text{jet}})$  determinations at similar energy scales



Observation of the running of  $\alpha_s$  from HERA jet data alone

→ Consistent with the running predicted by QCD over a large range in  $E_T^{\text{jet}}$

## Summary and Outlook

- HERA I has made possible precise measurements of jet cross sections and jet substructure in neutral current deep inelastic  $ep$  scattering and photoproduction
- These measurements have provided
  - tests of perturbative QCD beyond LO
  - precise determinations of  $\alpha_s$
  - improved determination of the gluon density in  $p$
  - tests of the partonic structure of the photon
  - exploration of parton dynamics at low  $x$
- In many areas the measurements have reached a level of precision such that the theoretical uncertainties dominate in the accuracy of the final results
- HERA I + II have provided  $\sim 0.5 \text{ fb}^{-1}$  of physics luminosity per experiment
  - jet analyses with full luminosity just started
  - ⇒ improvements expected on  $\alpha_s$  and proton and photon structure

