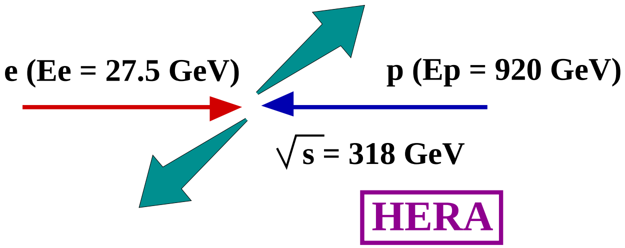
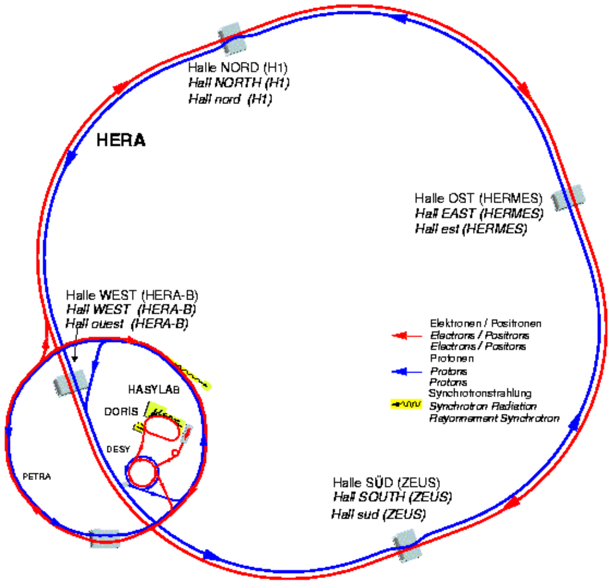
Isola d'Elba, HCP 2007

May 24th, 2007

QCD at HERA

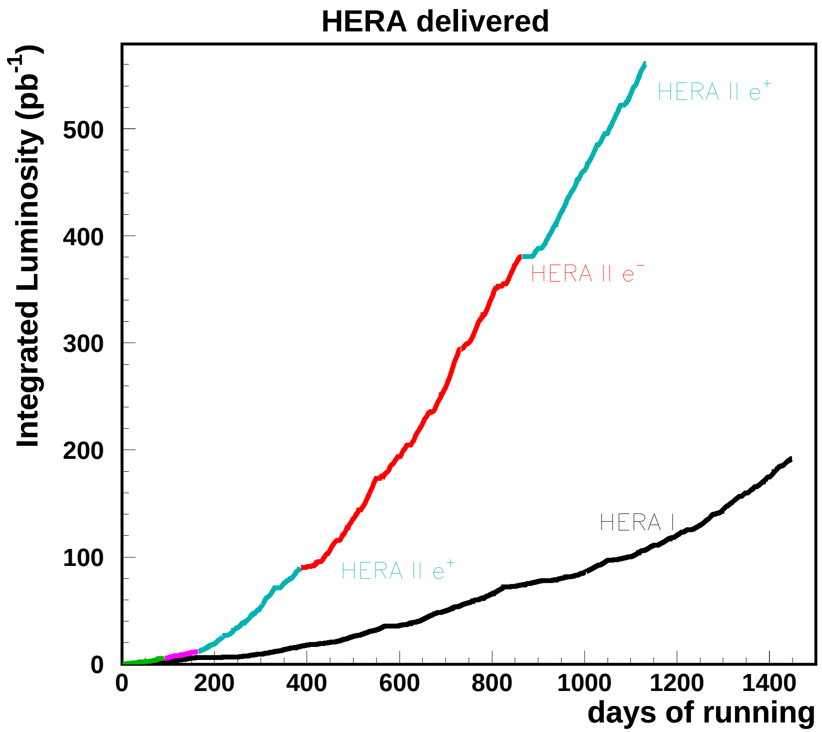
Juan Terrón (Universidad Autónoma de Madrid, Spain)





H1 and ZEUS Collaborations

Performance of HERA collider and ZEUS and H1 experiments



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

⇒ **End of HERA: July 2nd, 2007**

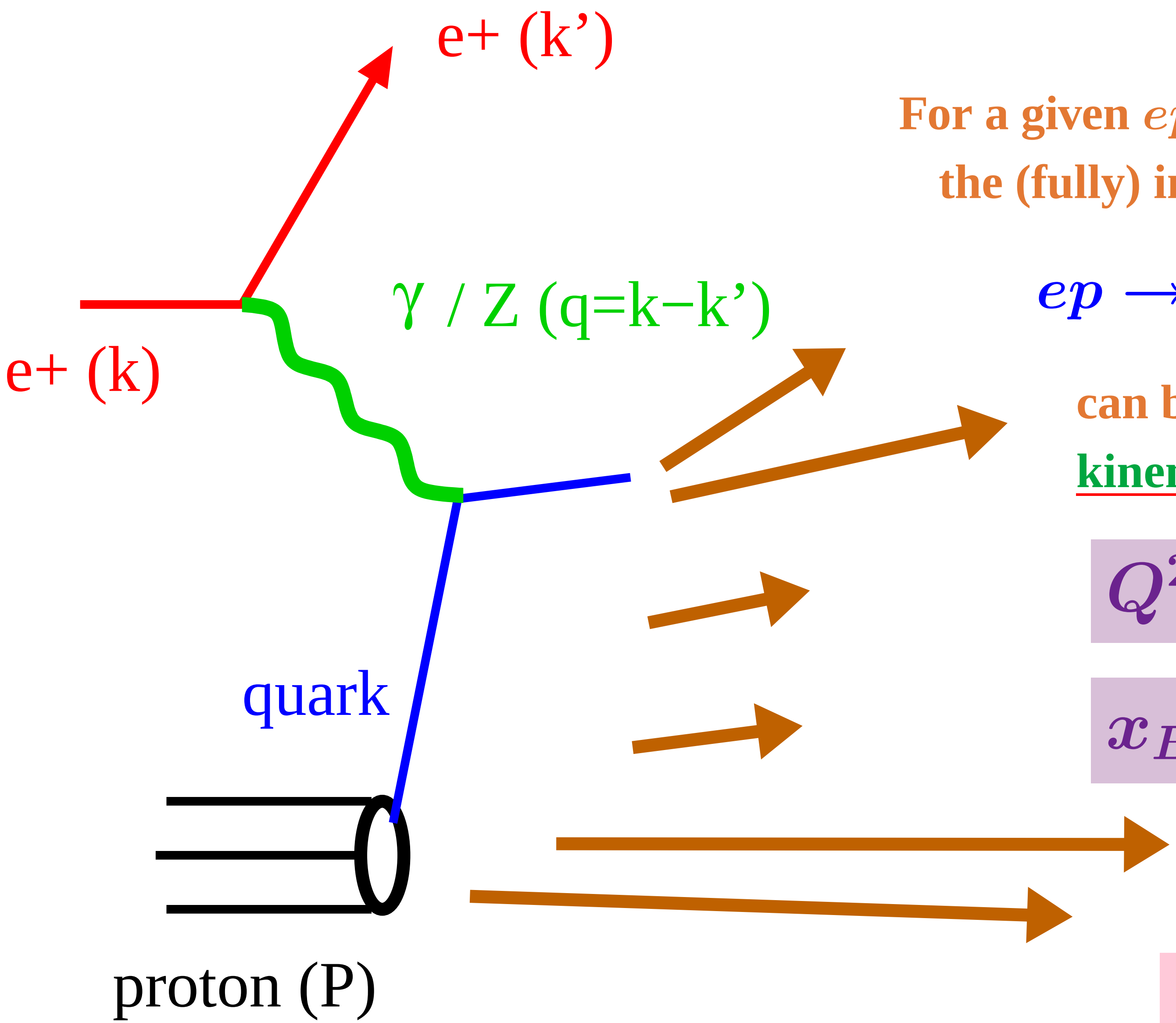
- **Outline**

→ **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



For a given ep centre-of-mass energy, $\sqrt{s}$, the (fully) inclusive cross section for

$$ep \rightarrow e + \mathrm{X}$$

can be described by two independent kinematic variables, e.g.

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

$$x_{Bj} = Q^2/(2P \cdot q)$$

$\rightarrow$ Inelasticity variable

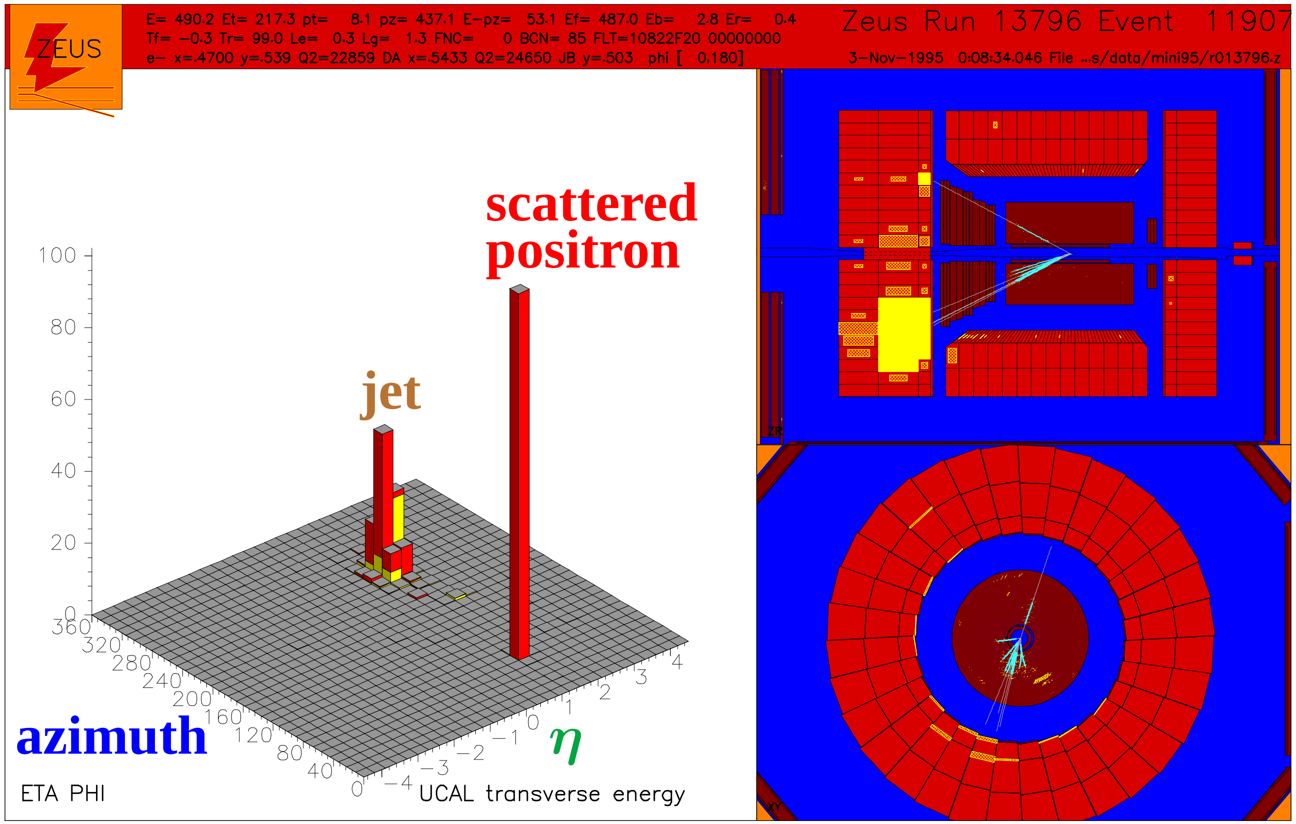
$$y = Q^2/(x_{Bj}s)$$

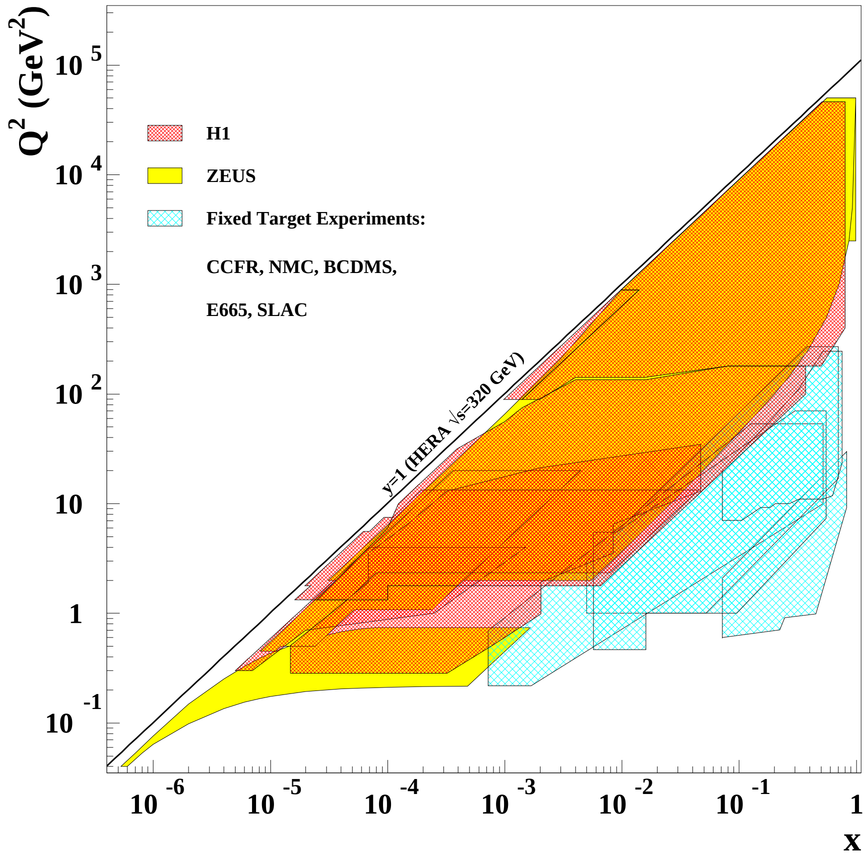
Neutral Current Deep Inelastic Scattering

- **Neutral Current DIS event candidate**

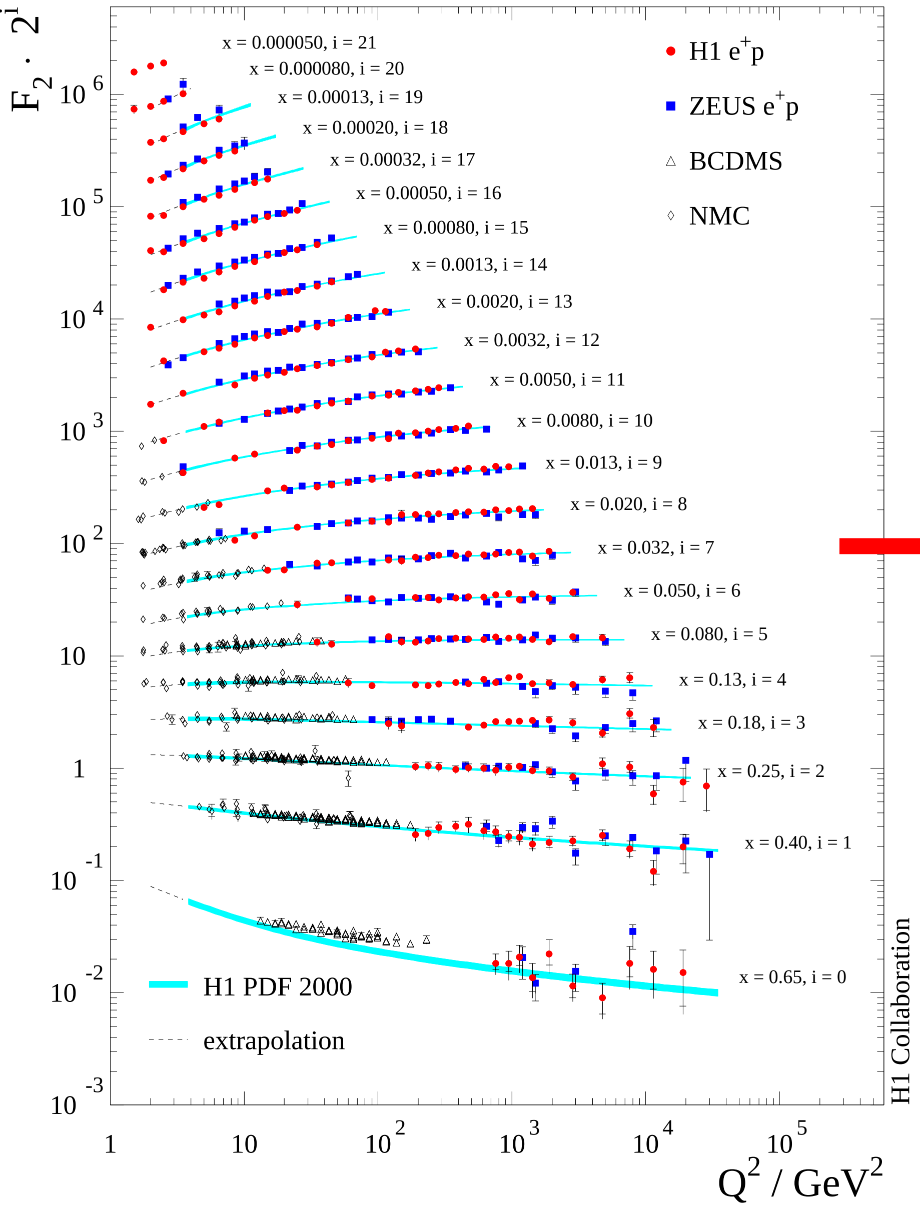
  $Q^2 \sim 24000$ GeV^2 and $x_{Bj} \sim 0.5$

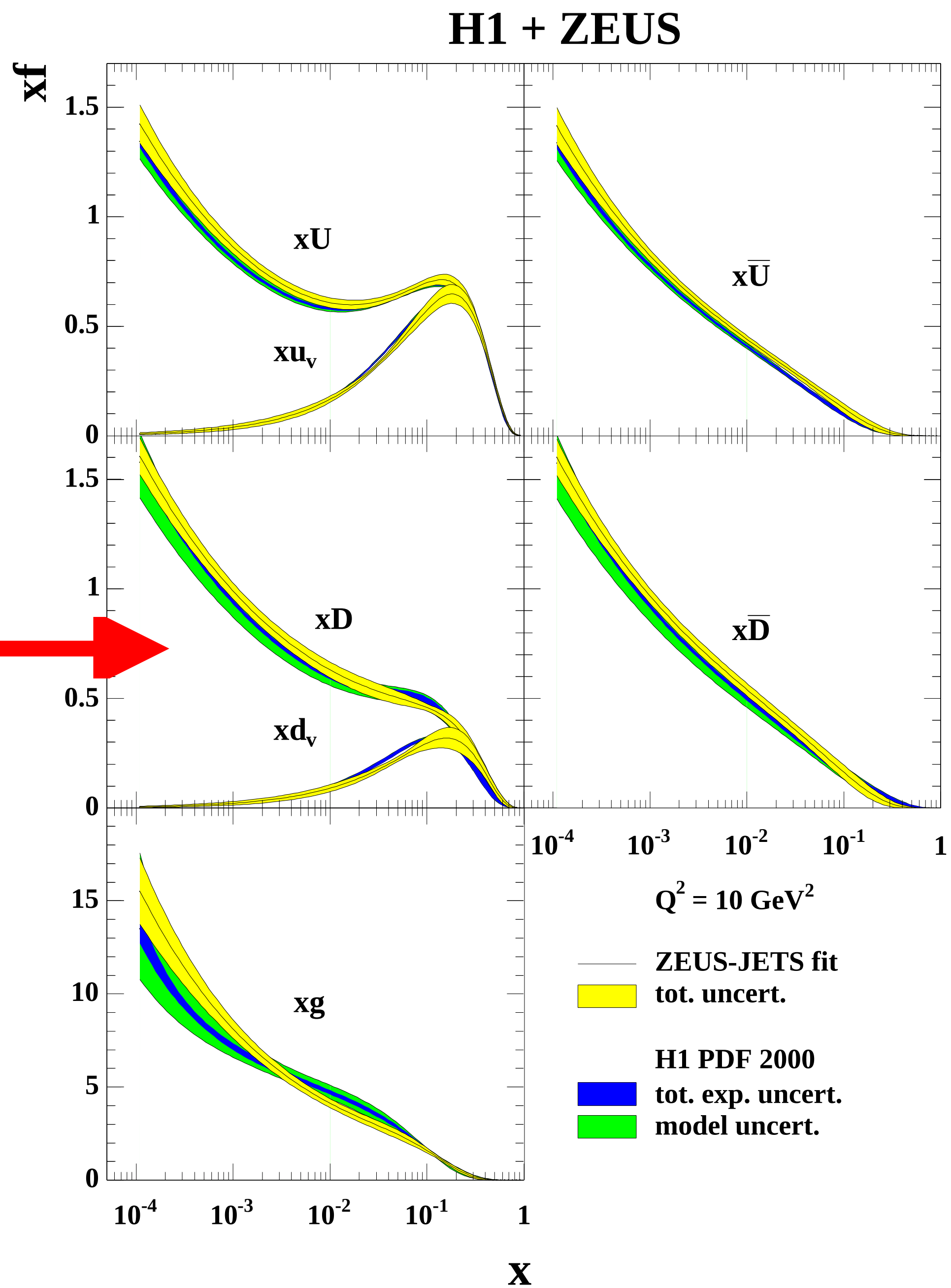
- **Coverage of kinematic plane (Q^2,x_{Bj})**





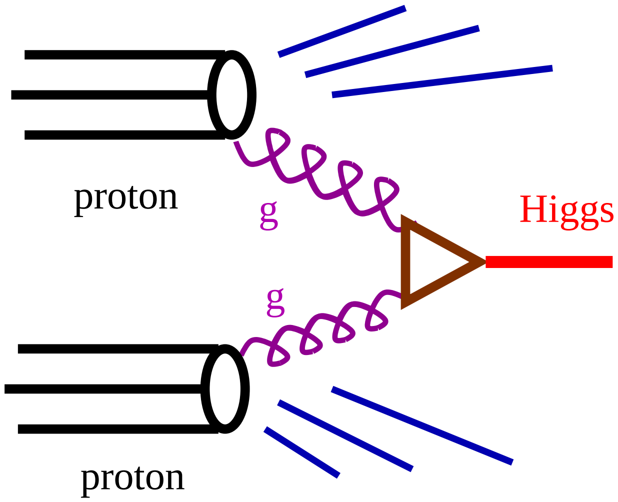
One of the legacies of HERA





Universality (and usefulness) of Proton PDFs

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



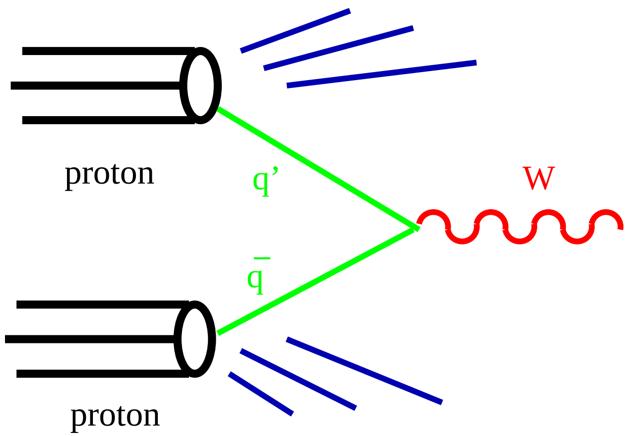
σ_H sensitive to gluon distribution at

$x \sim \frac{M_H}{\sqrt{s}} \sim 8\cdot 10^{-3}$

and $\mu_F^2 \sim M_H^2 \sim$

~ 13000 GeV^2

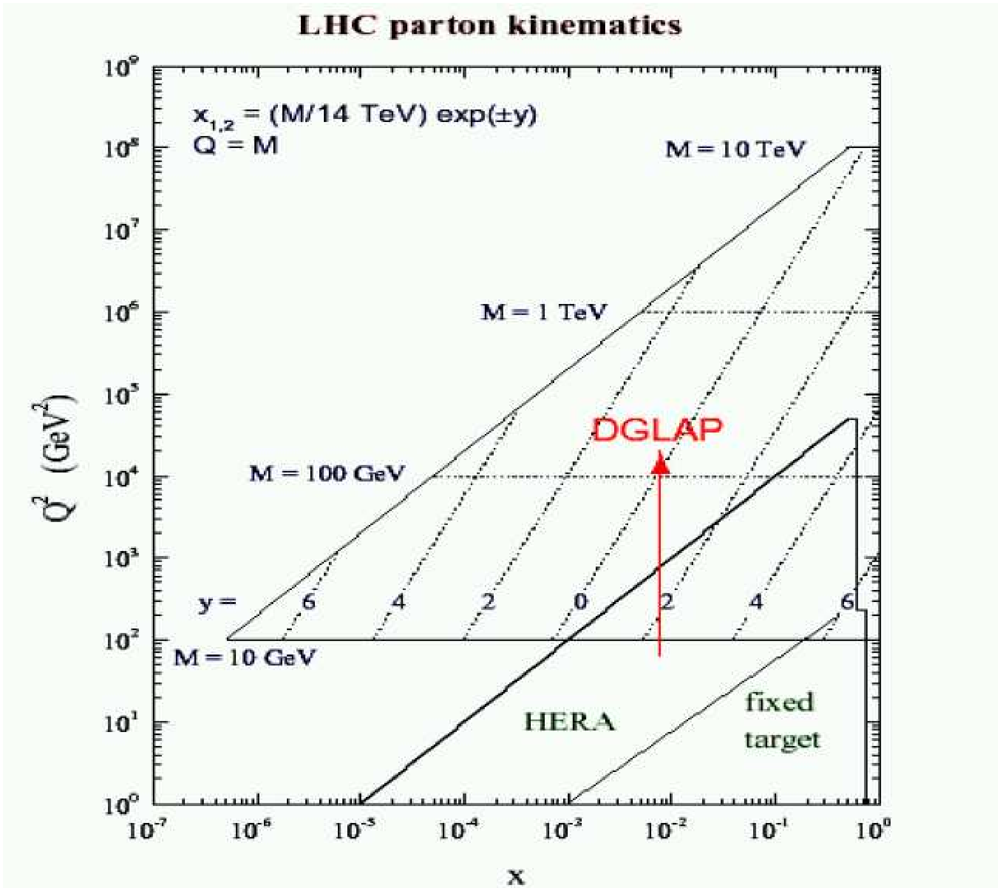
(for $M_H = 115$ GeV)



σ_W sensitive to sea distribution at

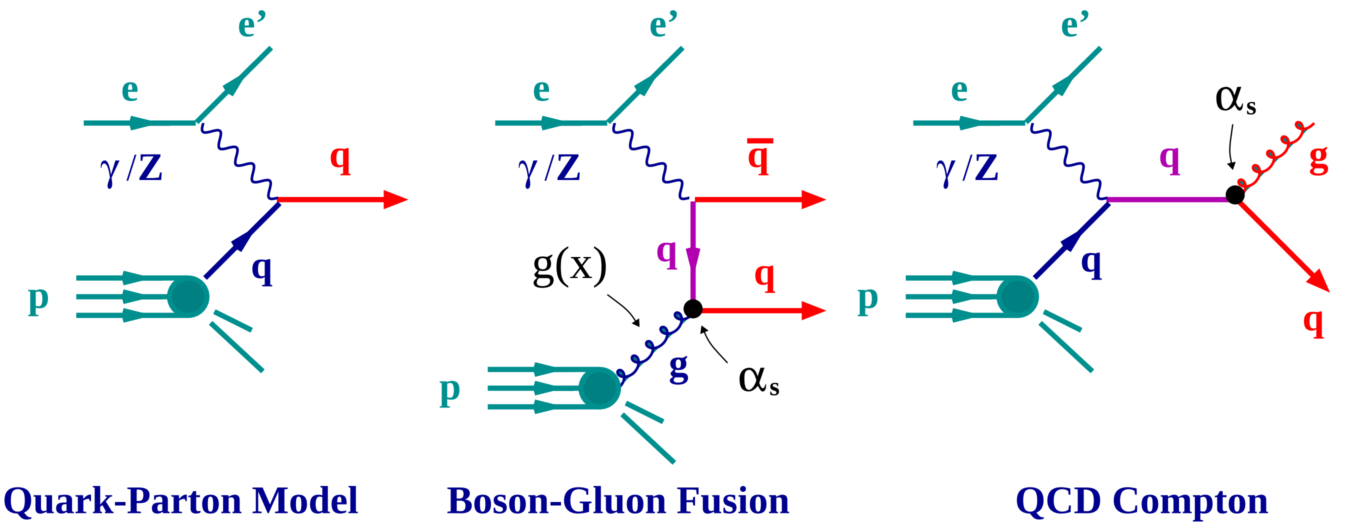
$x \sim \frac{M_W}{\sqrt{s}} \sim 6\cdot 10^{-3}$

and $\mu_F^2 \sim M_W^2 \sim 6400$ GeV^2



Jet Production in Neutral Current Deep Inelastic Scattering

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



- **Perturbative QCD calculations of jet cross sections:**

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

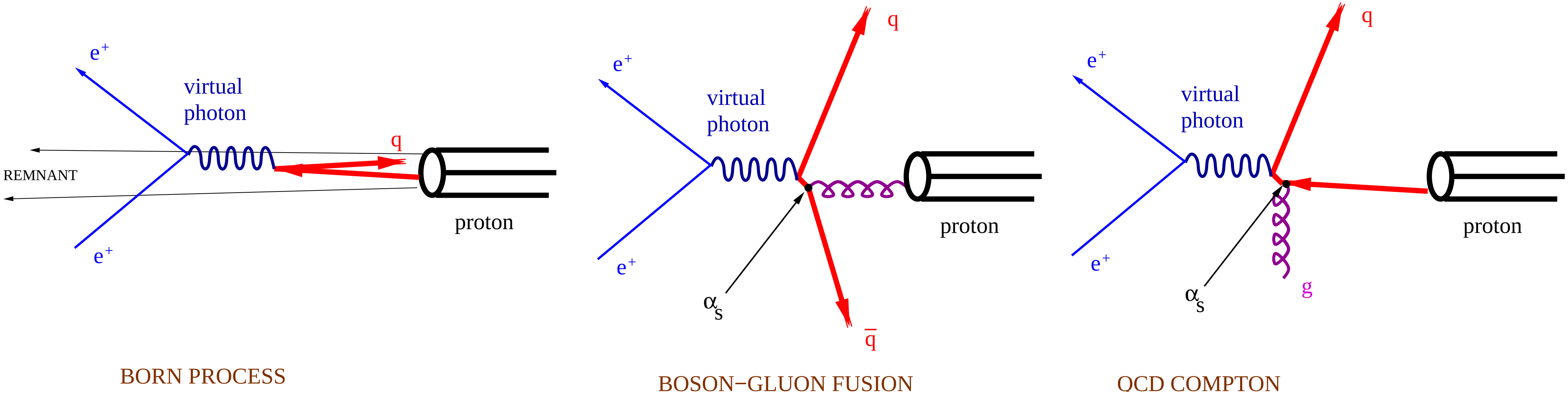
  - f_a: parton a density in the proton, determined from experiment; long-distance structure of the target
  - $\hat{\sigma}_a$: subprocess cross section, calculable in pQCD; short-distance structure of the interaction

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
  - $\longrightarrow$ a sensitive test of the pQCD predictions of the short-distance structure
  - $\longrightarrow$ a determination of the strong coupling constant α_s
- To perform a stringent test of the pQCD predictions and a precise determination of α_s:
  - $*$ Observables for which the predictions are directly proportional to α_s
    - $\longrightarrow$ Jet cross sections in the Breit frame
  - $*$ Small experimental uncertainties $\longrightarrow$ Jets with relatively high transverse energy
  - $*$ Small theoretical uncertainties $\longrightarrow$ NLO QCD calculations
  - $\longrightarrow$ Jet algorithm: longitudinally invariant k_T cluster algorithm (Catani et al) (small parton-to-hadron effects, infrared safe, suppression of beam-remnant jet)
  - $\longrightarrow$ 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**

$\longrightarrow$ suppression of the Born contribution (struck quark has zero E_T)

$\longrightarrow$ suppression of the beam-remnant jet (zero E_T)

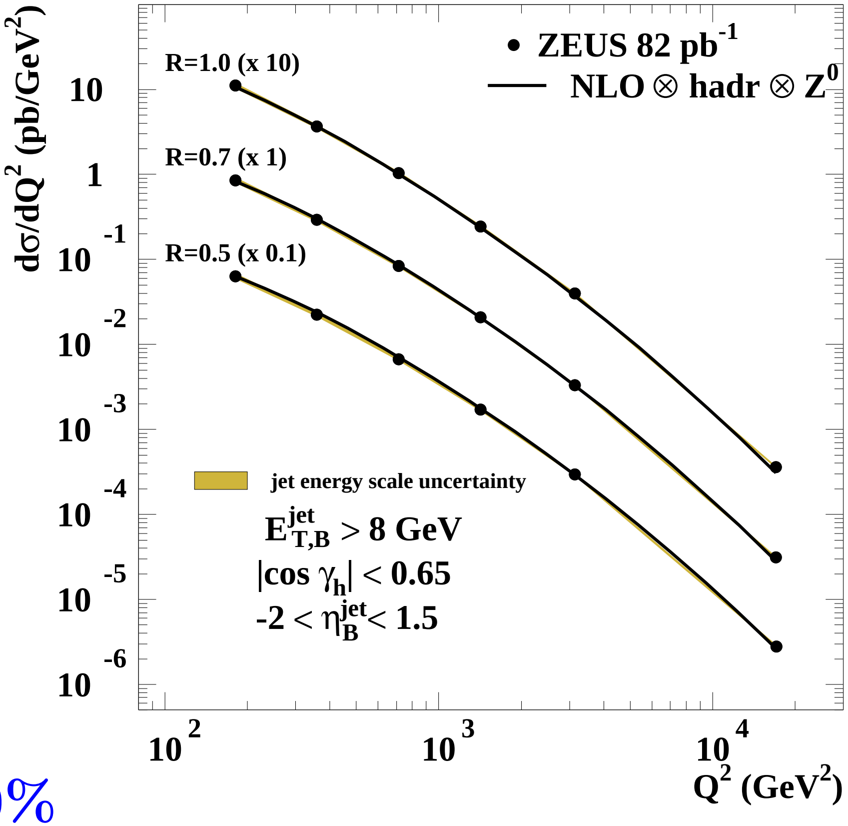
$\longrightarrow$ lowest-order non-trivial contributions from $\gamma^* g \to q\bar{q}$ and $\gamma^* q \to qg$

$\Rightarrow$ directly sensitive to hard QCD processes (α_s)

Inclusive Jet Cross Sections in NC DIS at $Q^2 > 125$ GeV^2

- New measurement of inclusive jet cross sections in the kinematic region defined by $Q^2 > 125$ GeV^2 and $|\cos\gamma| < 0.65$ for jets with $E^B_{T,jet} > 8$ GeV and $-2 < \eta^B_{jet} < 1.5$ using $\mathcal{L} = 81.7$ 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 $E_{T,jet} > 10$ 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 $\mu_R = E^B_{T,jet}$, $\mu_F = Q$ and the ZEUS-S parametrisations of the proton PDFs describe the measurements well

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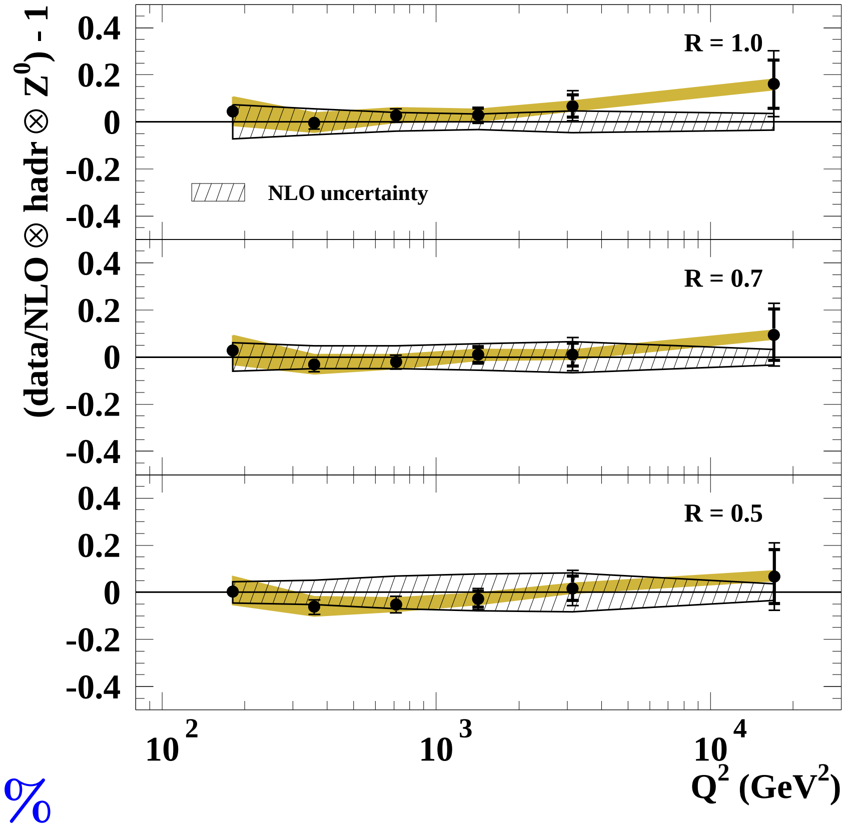

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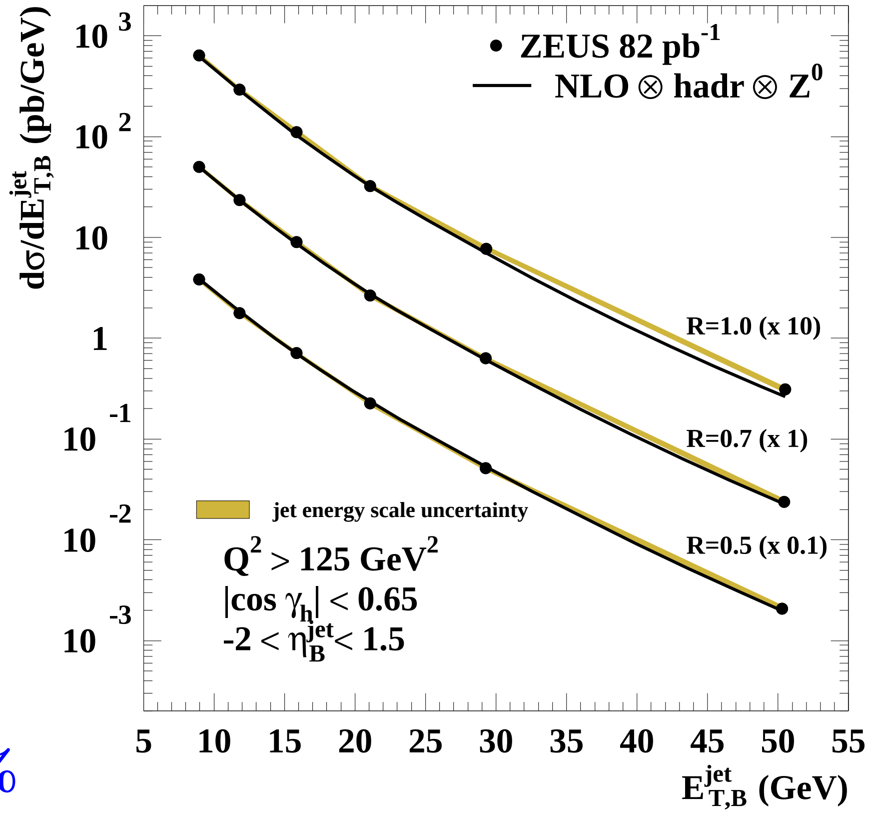
Inclusive Jet Cross Sections in NC DIS at $Q^2 > 125$ GeV^2

- New measurement of the inclusive jet cross section $d\sigma/dE^B_{T,jet}$ in the kinematic region defined by $Q^2 > 125$ GeV^2 and $|\cos\gamma| < 0.65$ for jets with $E^B_{T,jet} > 8$ GeV and $-2 < \eta^B_{jet} < 1.5$



- Small theoretical uncertainties ($R = 1$):
  - → higher-order terms (> NLO); varying μ_R between $\frac{1}{2} \cdot E^B_{T,jet}$ and $2 \cdot E^B_{T,jet}$ ⇒ ±5%
  - → uncertainties on the proton PDFs; ⇒ ±3%
  - → uncertainty on $\alpha_s(M_Z)$ (±0.0010); ⇒ ±2%
  - → hadronisation corrections; ⇒ ±1.4%

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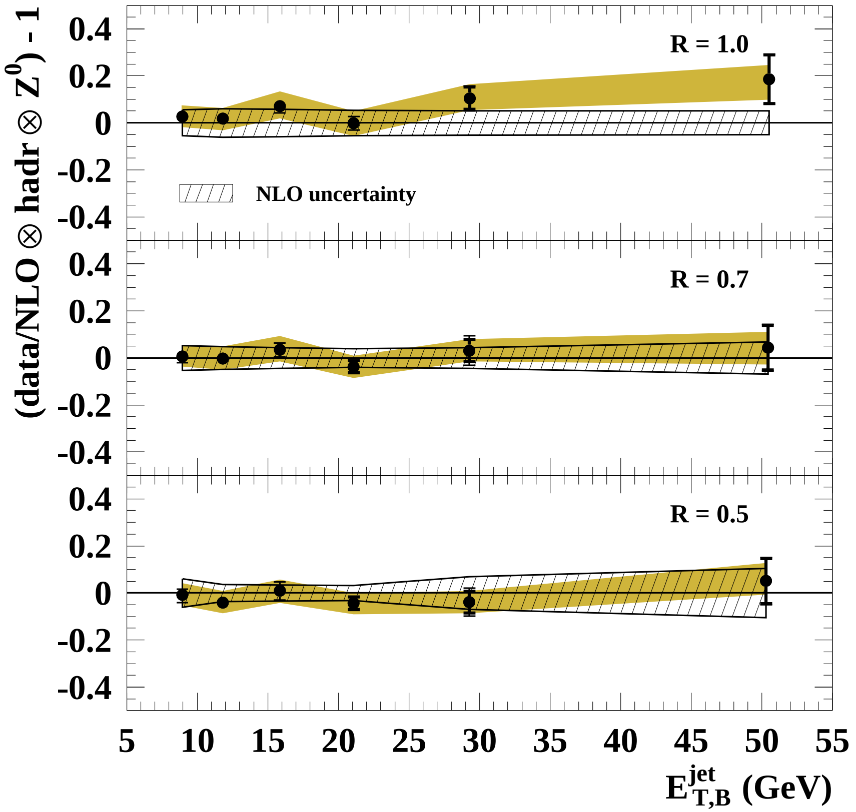
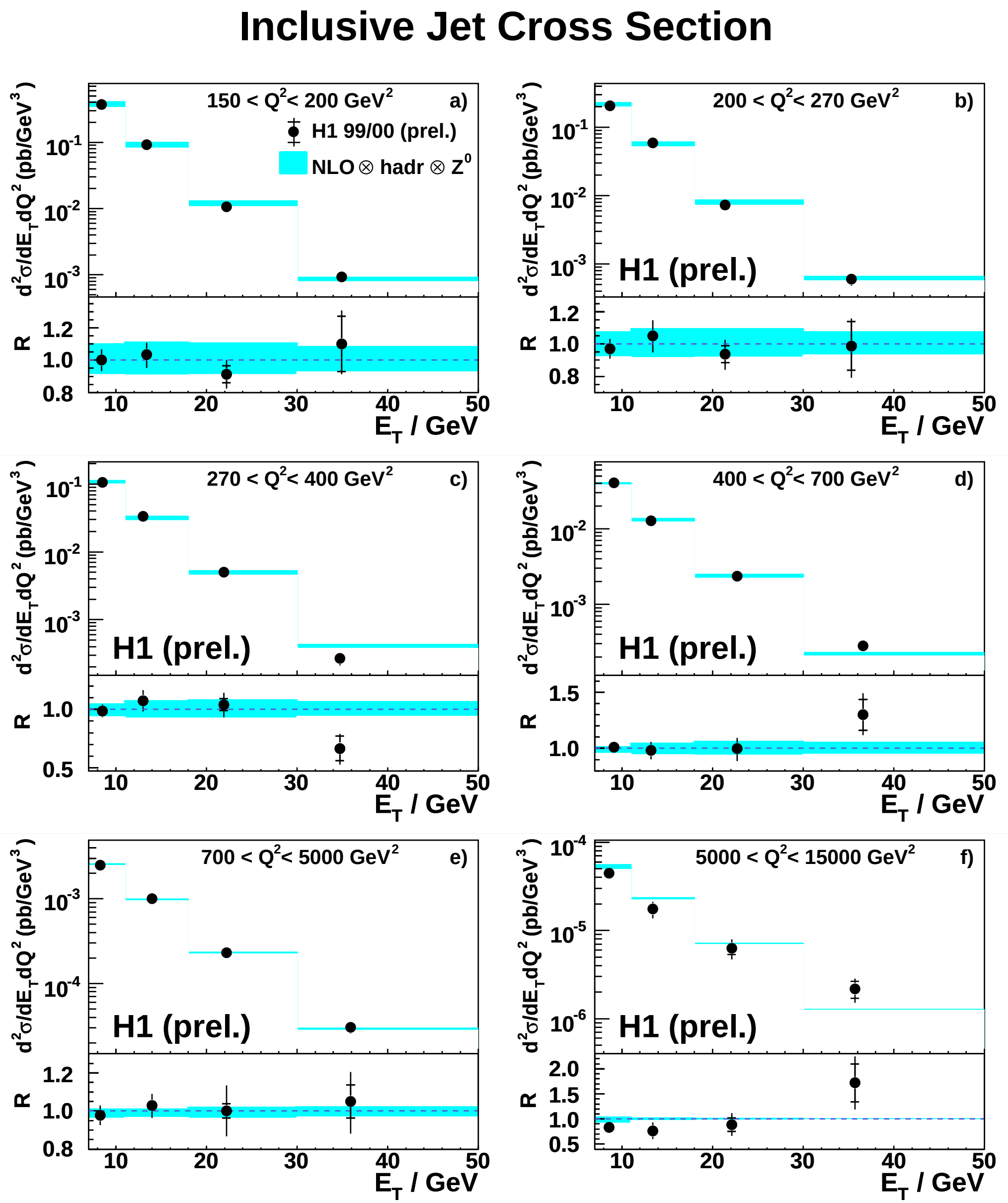


- Small theoretical uncertainties ($R = 1$):
  - → higher-order terms ($>$ NLO); varying μ_R between $\frac{1}{2} \cdot E^B_{T,jet}$ and $2 \cdot E^B_{T,jet} \Rightarrow \pm 5\%$
  - → uncertainties on the proton PDFs; $\Rightarrow \pm 3\%$
  - → uncertainty on $\alpha_s(M_Z)$ (± 0.0010); $\Rightarrow \pm 2\%$
  - → hadronisation corrections; $\Rightarrow \pm 1.4\%$

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

Inclusive Jet Cross Sections in NC DIS at $Q^2 > 150$ GeV^2

- New measurement of the double differential cross-section $d^2\sigma/dE_T dQ^2$ for jets with $7 < E^B_{T,jet} < 50$ GeV, $-1 < \eta^{lab}_{jet} < 2.5$ in the kinematic region defined by $150 < Q^2 < 15000$ GeV^2, $0.2 < y < 0.7$ using $\mathcal{L} = 65$ 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 $\mu_R = E^B_{T,jet}$, $\mu_F = Q$ and the CTEQ6.5 parametrisations of the proton PDFs



Inclusive Jet Cross Sections and extraction of α_s (ZEUS)

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

$$\alpha_s(M_Z) = 0.1207 \pm 0.0014\ \text{(stat.)}\ ^{+0.0035}_{-0.0033}\ \text{(exp.)}\ ^{+0.0022}_{-0.0023}\ \text{(th.)}$$

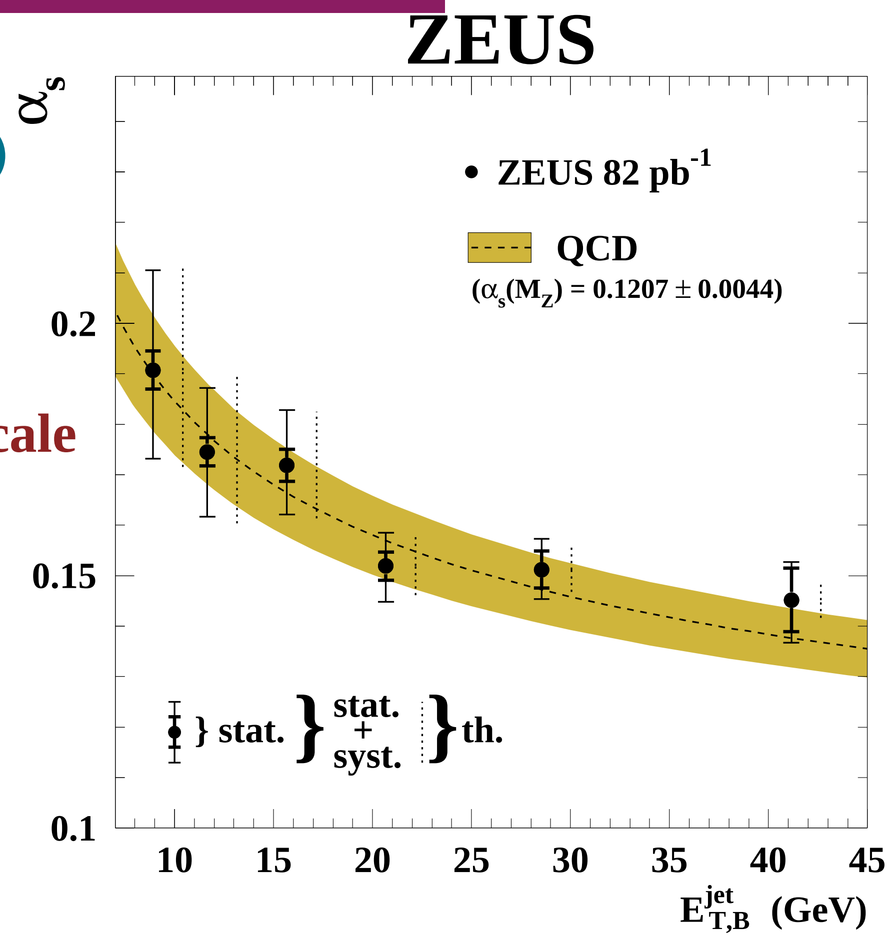
- Experimental uncertainties: 2% from jet energy scale
- Theoretical uncertainties:

$\longrightarrow$ terms beyond NLO $\Delta\alpha_s(M_Z) = 1.5\%$

$\longrightarrow$ uncertainties proton PDFs $\Delta\alpha_s(M_Z) = 0.7\%$

$\longrightarrow$ hadronisation corrections $\Delta\alpha_s(M_Z) = 0.8\%$

- Consistent with other determinations of α_s
- Very precise determination of $\alpha_s(M_Z)$!

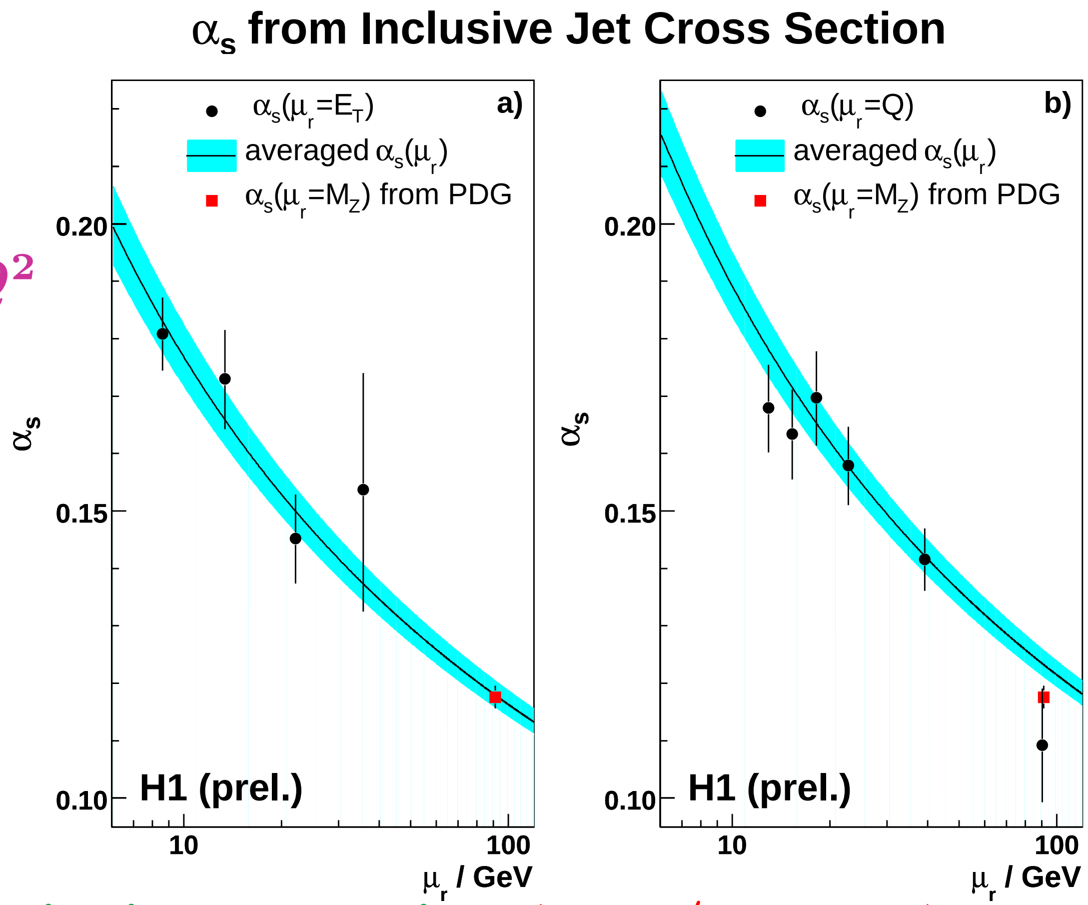


- Study of the scale dependence of $\alpha_s(E^B_{T,jet})$: from the measured $d\sigma/dE^B_{T,jet}$ in each $E^B_{T,jet}$ region $\rightarrow \alpha_s(< E^B_{T,jet} >)$ is extracted
- The measurements are consistent with the running of α_s predicted by perturbative QCD

Inclusive Jet Cross Sections and extraction of α_s (H1)

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

$$\alpha_s(M_Z) = 0.1179 \pm 0.0024\ (\text{exp.})\ {}^{+0.0052}_{-0.0032}\ (\text{th.}) \pm 0.0030\ (\text{pdf.})$$



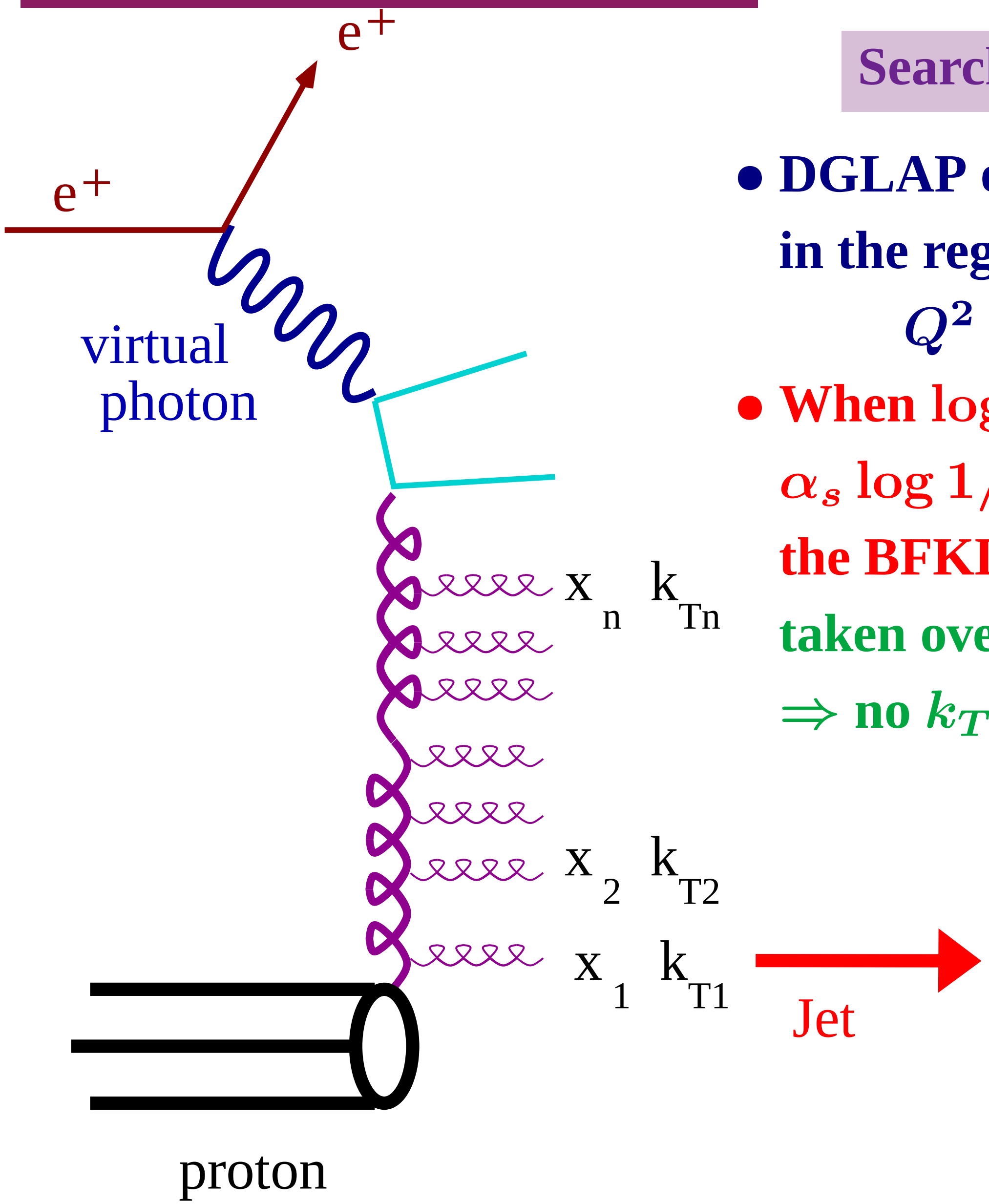
- Reduction of experimental and PDF uncertainties by using "normalised" inclusive jet cross sections ($\sigma_{jets}/\sigma_{NCDIS}$):

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

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

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

Parton evolution at low x



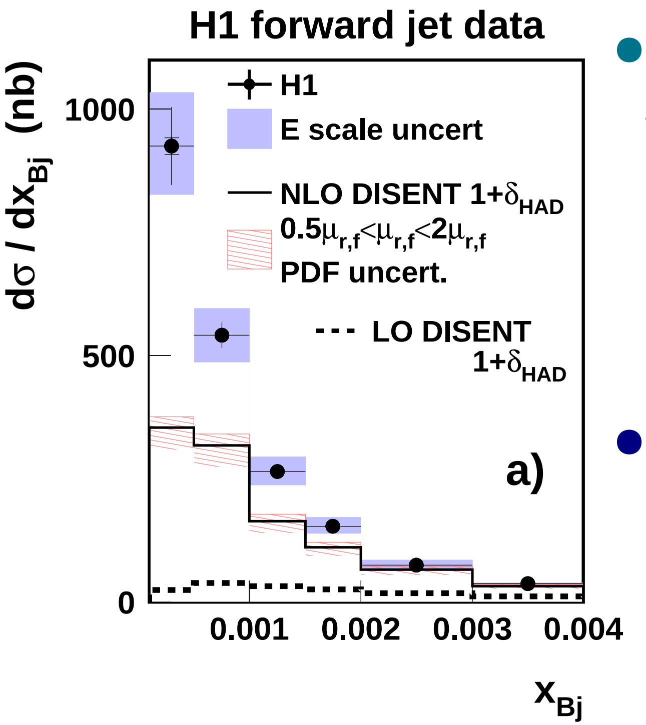
Searching for BFKL-induced effects

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

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

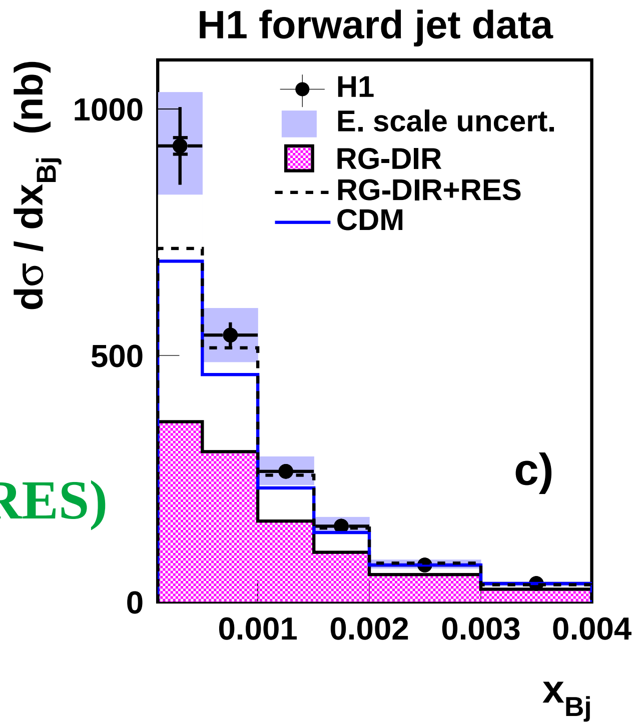
- When $\log Q^2 \ll \log 1/x$ terms proportional to $\alpha_s \log 1/x$ become important and need to be summed the BFKL equation accomplishes that; the integration is taken over the full k_T phase space of the gluons $\Rightarrow$ no k_T ordering
  - Mueller and Navelet's proposal: forward (proton's 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 $p_{t,jet} > 3.5$ GeV, $7° < \theta_{\text{jet}} < 20°$, $0.5 < p^2_{t,jet}/Q^2 < 2$ and $x_{jet} = E_{jet}/E_p > 0.035$ in the kinematic region $10^{-4} < x < 4 \cdot 10^{-3}$ and $5 < Q^2 < 85$ GeV^2
- Strong rise towards low x is observed

- Comparison to calculations



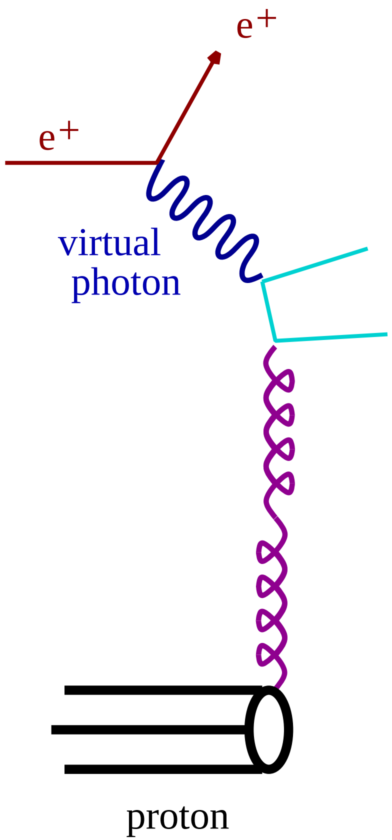
→ NLO QCD (DGLAP) lies well below the data at low x

→ MC models with extra parton radiation provide an improved description of the data

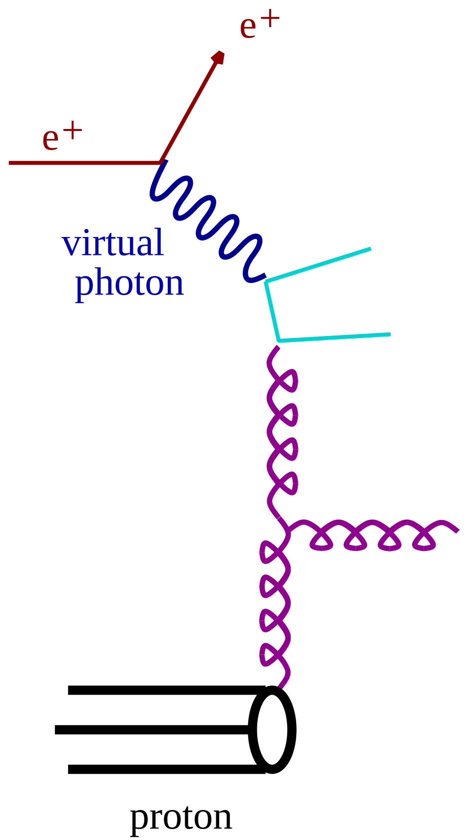
→ inclusion of a resolved-photon component (RG-DIR+RES)

→ parton emissions not ordered in k_T (CDM)

Measurement of Forward Jet Production at low x



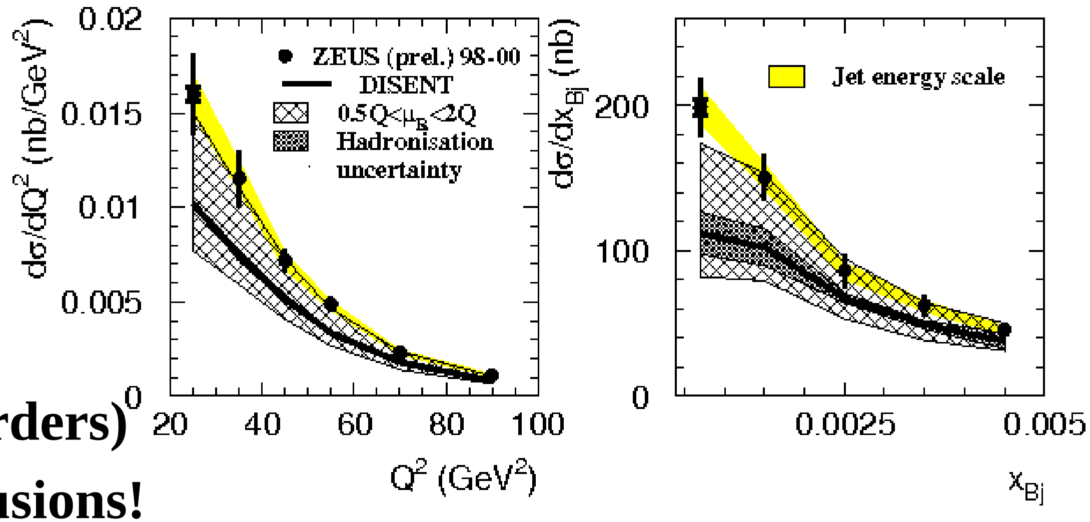
LO $\mathcal{O}(\alpha_s)$



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

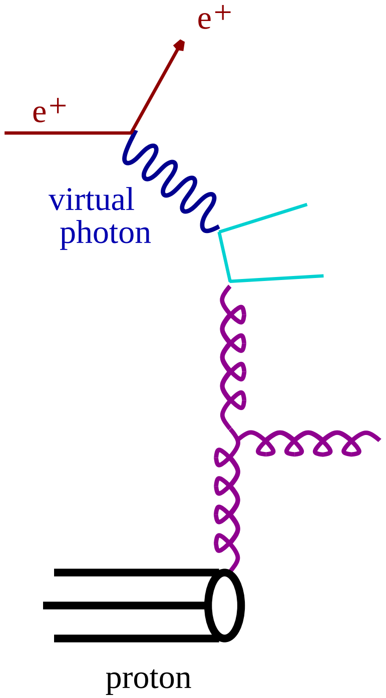
- **LO QCD ($\mathcal{O}(\alpha_s)$): hardly any phase space available for forward jet production**
- **NLO QCD ($\mathcal{O}(\alpha_s^2)$): huge increase in cross section (NLO $\gg$ LO) due to opening of new channel (gluon exchange in t-channel)**

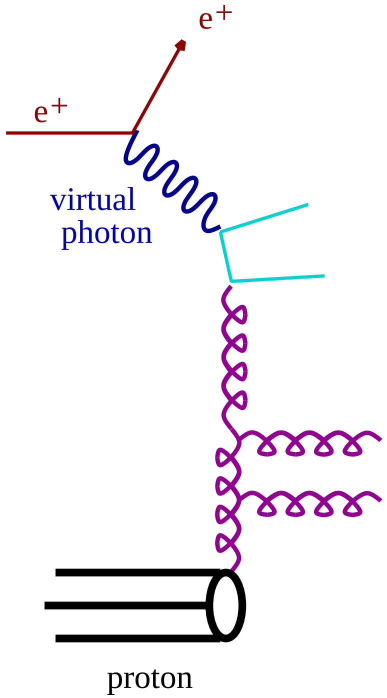
  $\longrightarrow$ NLO QCD becomes an "effective" LO, with large theoretical uncertainties



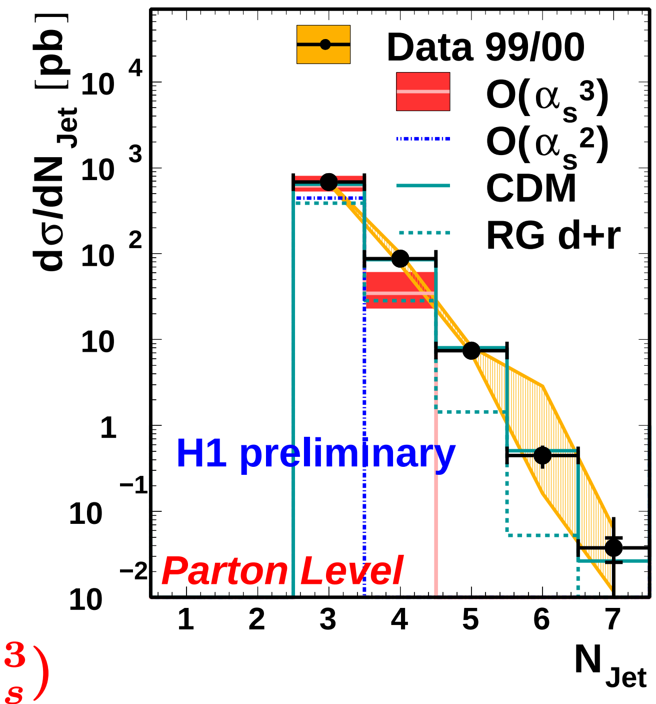
$\Rightarrow$ **Large theoretical uncertainties (higher-orders) in pQCD calculations prevent firm conclusions!**

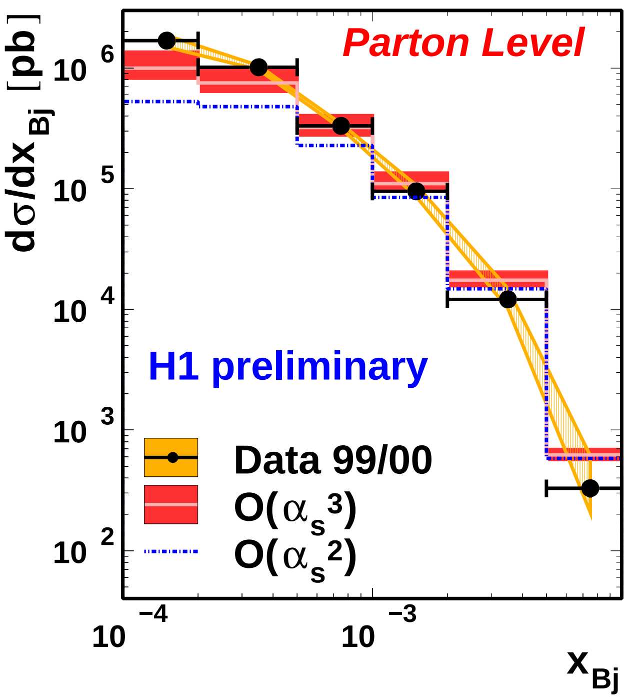
Measurements of Three-jet Production at low x





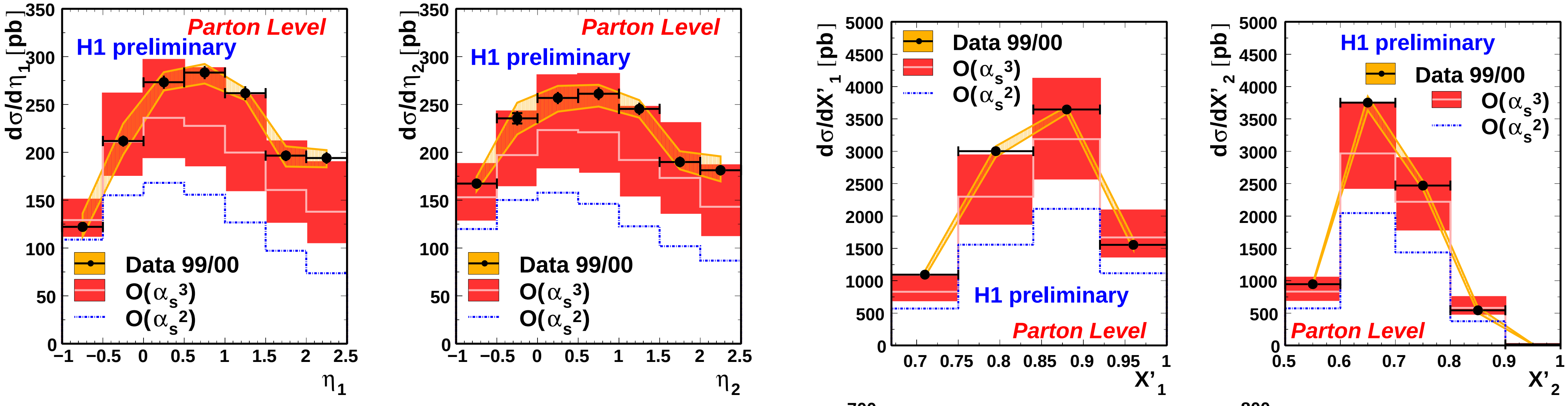
LO $\mathcal{O}(\alpha_s^2)$ **NLO** $\mathcal{O}(\alpha_s^3)$

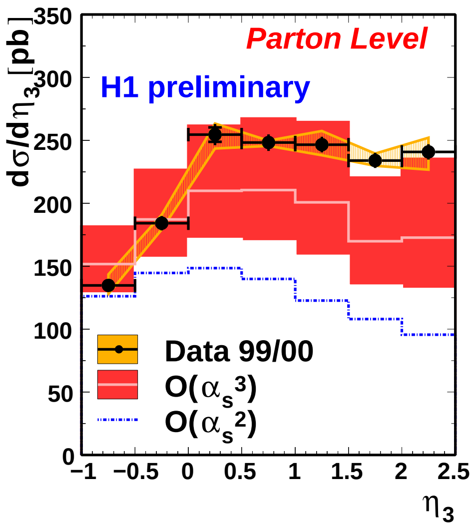


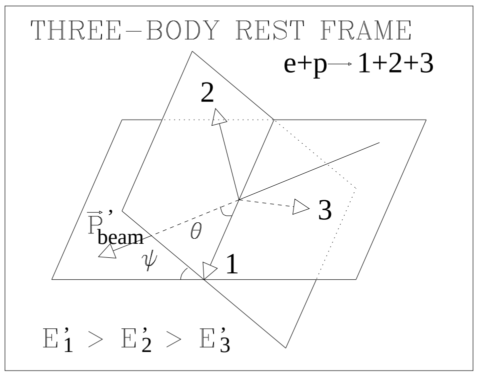


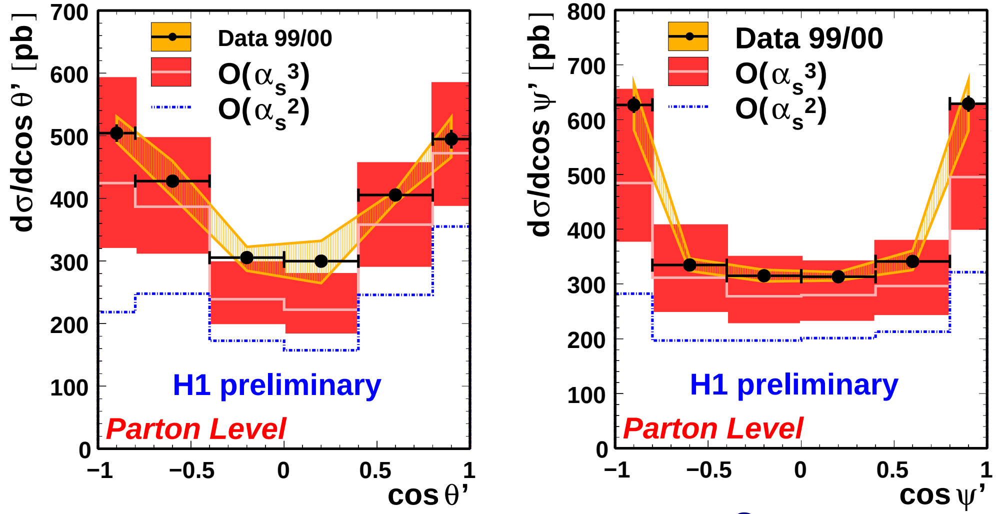
- **Measurements of three-jet production using the k_T cluster algorithm in the $\gamma^* p$ frame with $E^*_{\perp,jet} > 4$ GeV, $E^*_{\perp,jet1} + E^*_{\perp,jet2} > 9$ GeV, $-1 < \eta^{lab}_{jet} < 2.5$ (one central jet $-1 < \eta^{lab}_{jet} < 1.3$) in the kinematic region defined by $0.1 < y < 0.7$ and $4 < Q^2 < 80$ 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









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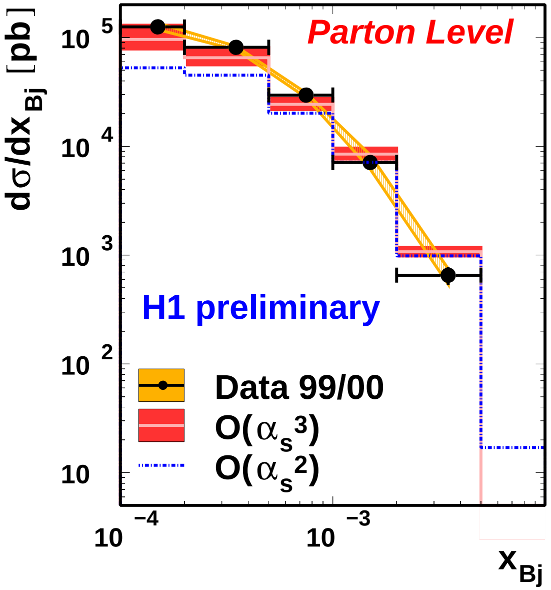
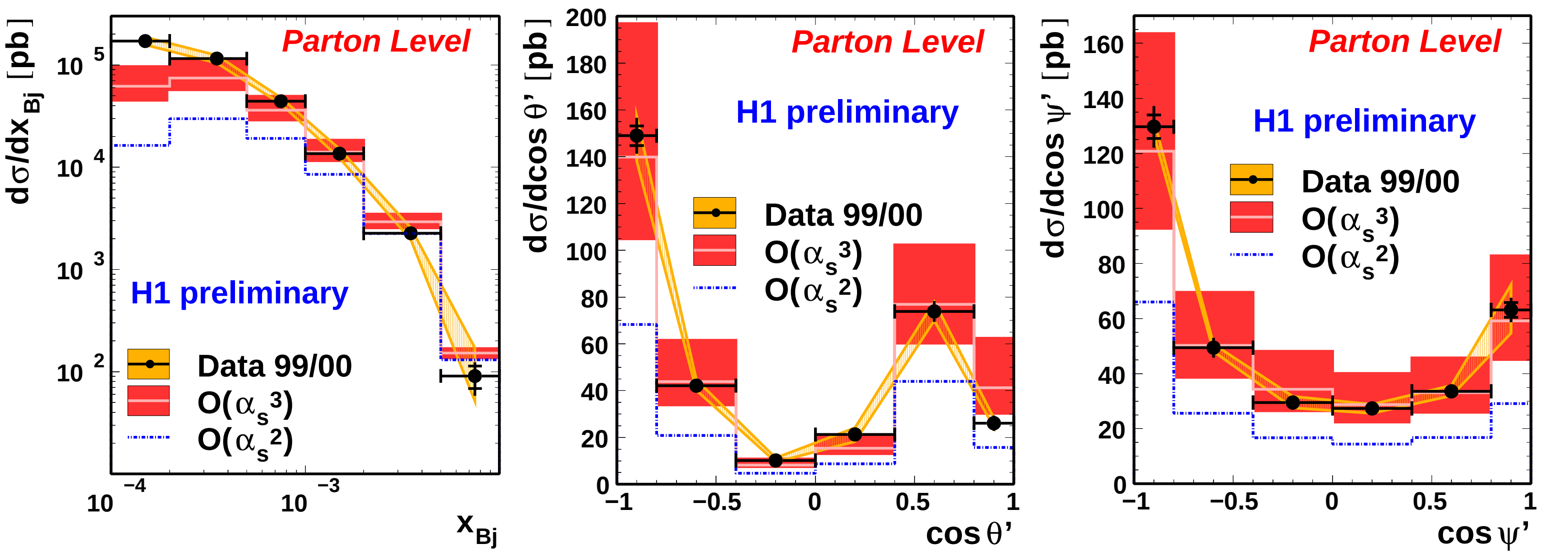
Measurements of Three-jet Production at low x



⇐ 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

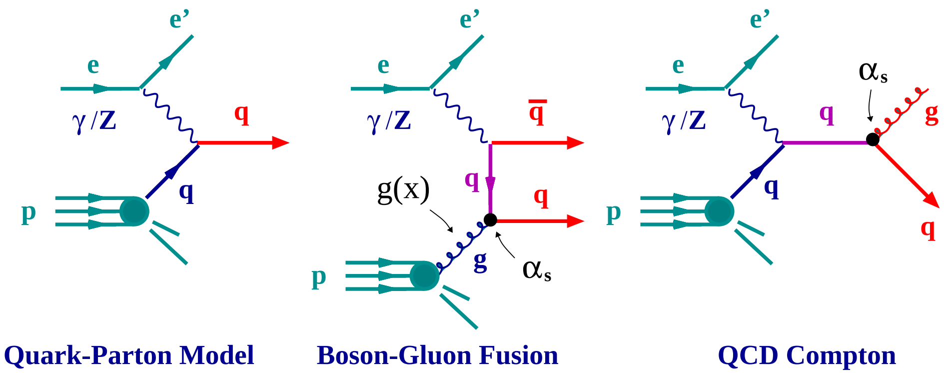
Improving the Determination of the Proton PDFs

- Observables used in the fits to determine the proton PDFs:

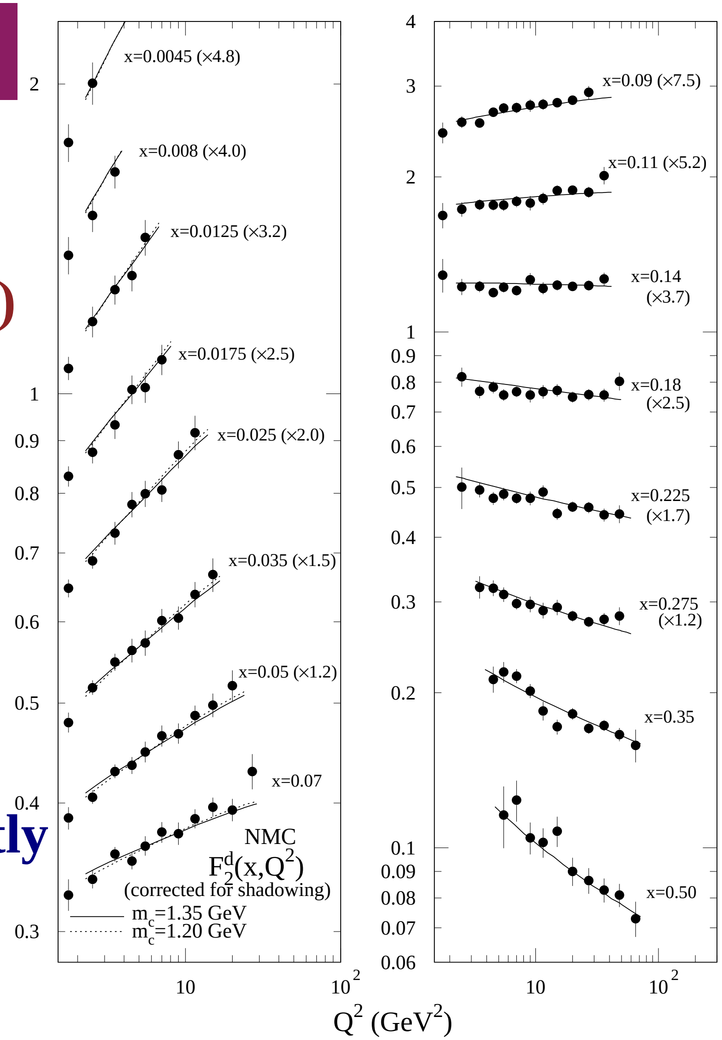
→ Inclusive measurements of deep inelastic lN scattering

- 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

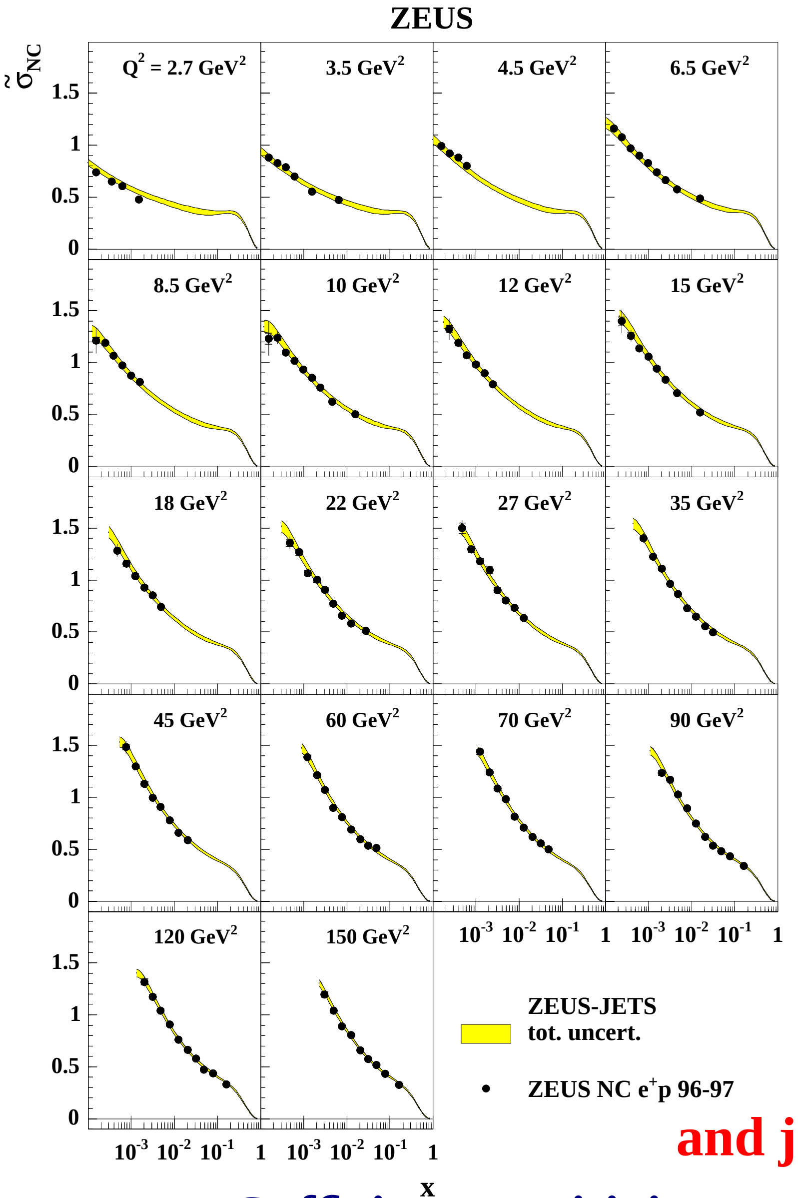
  → large QCD corrections and hadronisation corrections

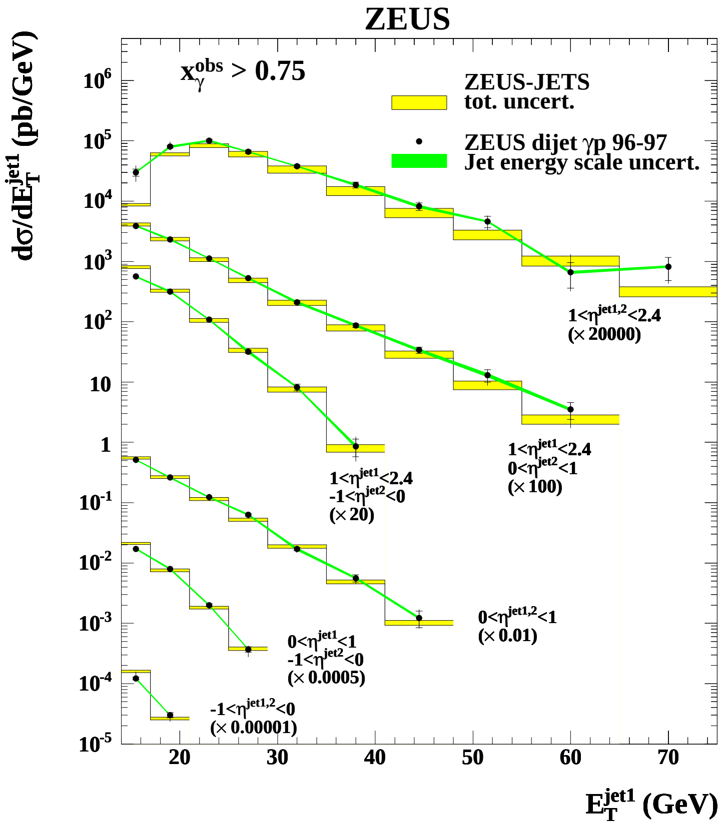
- Fixed-target DIS: higher twists, heavy-target corrections and isospin-symm. assumptions
- That's the past! NOW there are measurements of jet cross sections at HERA

⇒ 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**

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

and jet data in NC DIS and γp 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):

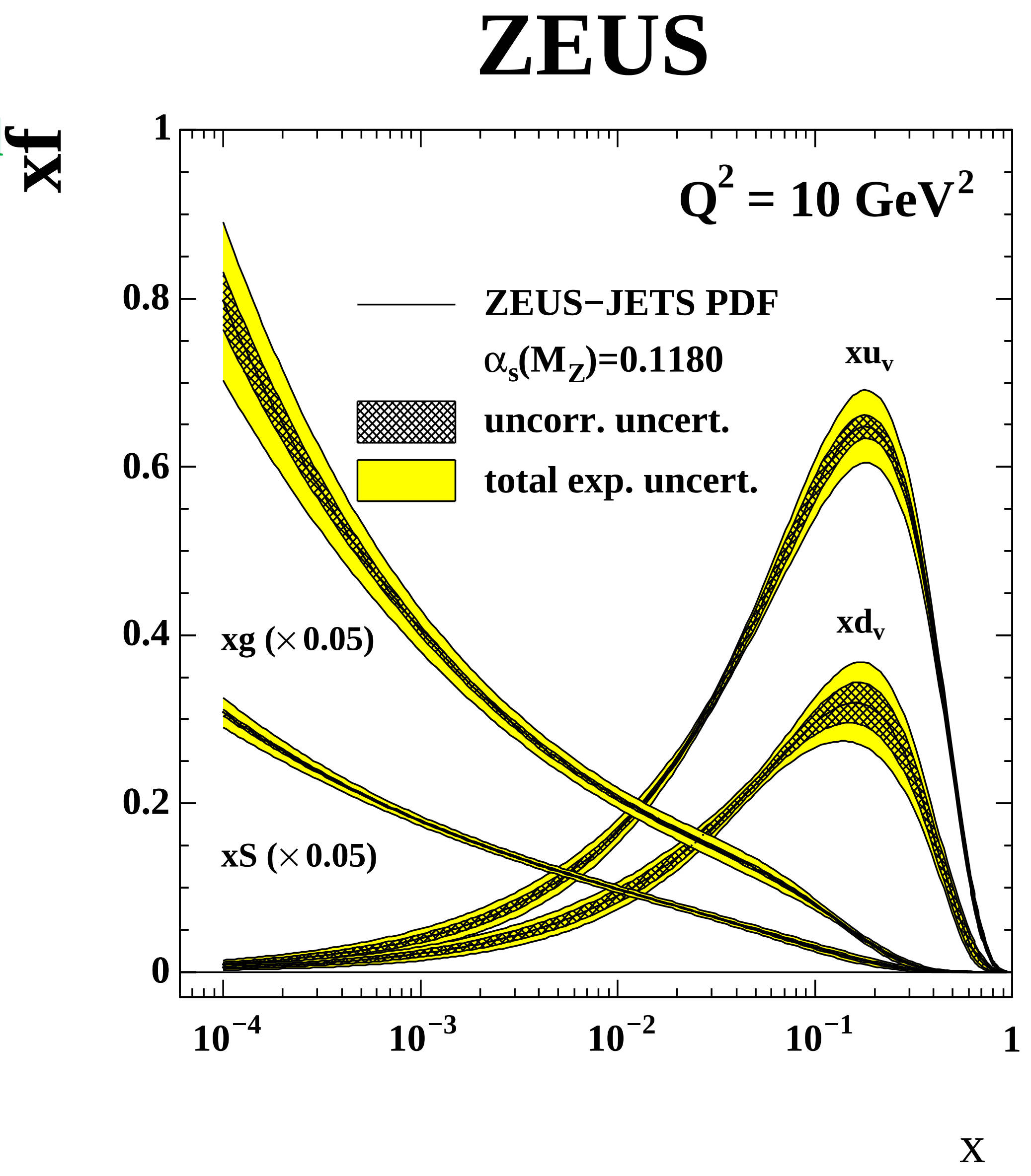
→ Structure function measurements: reduced double differential cross sections in x and Q^2

  - 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 γp 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



Improving the gluon distribution: jet data

- Comparison of gluon distributions from fits with and without jet data

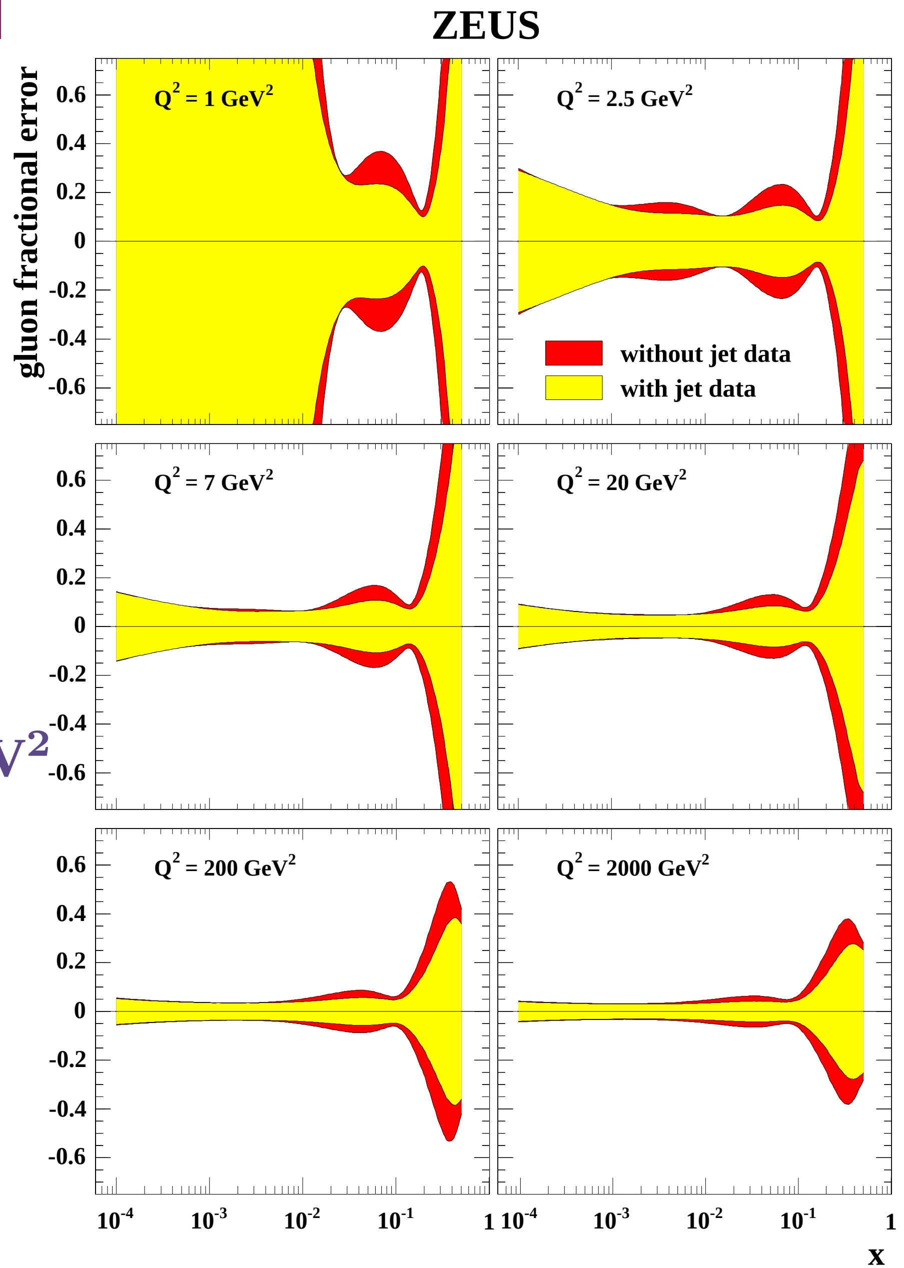
→ no significant change of the shape: no tension between jet and inclusive data

→ the jet cross sections constrain the gluon density in the range $0.01 - 0.4$

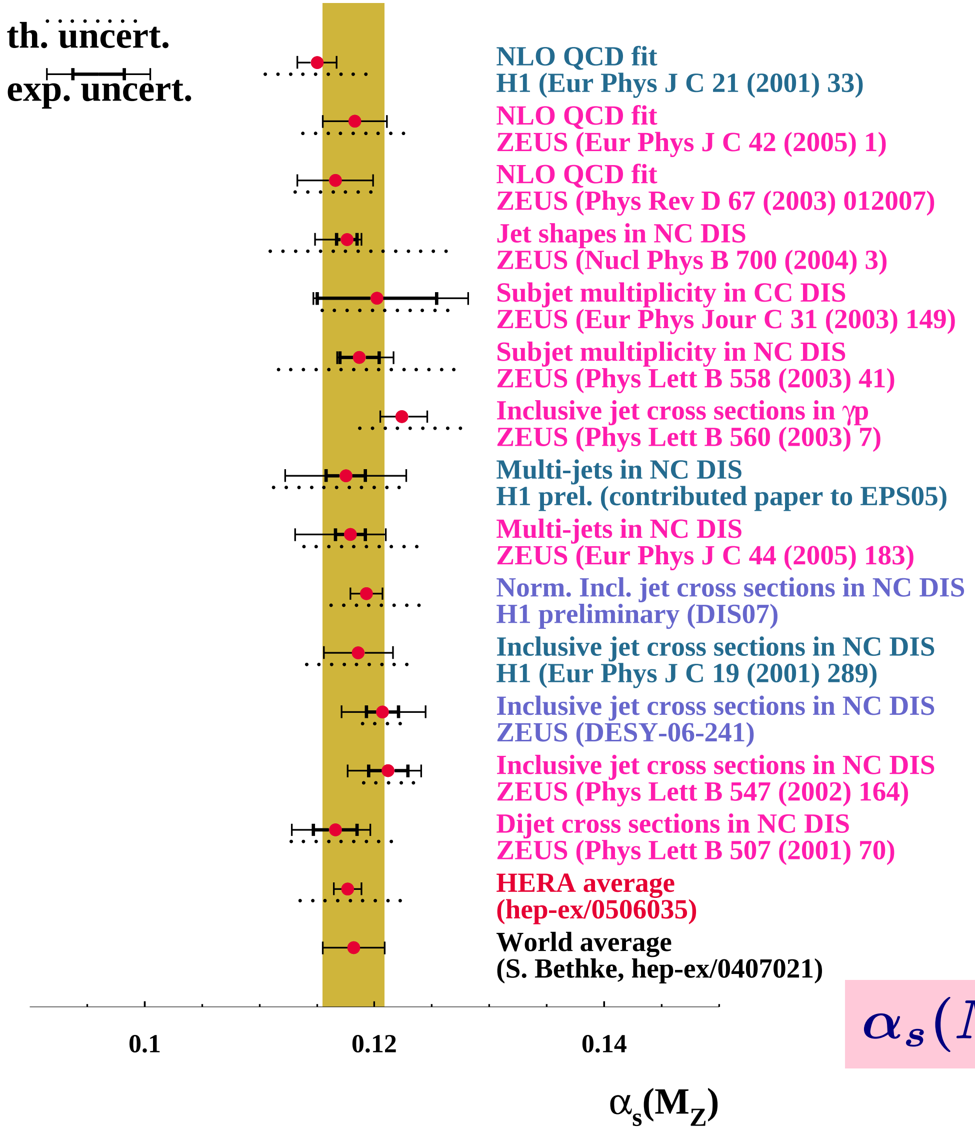
→ **Sizeable reduction of the gluon uncertainty**

e.g. from 17% to 10% at $x = 0.06$ and $Q^2 = 7$ GeV^2

→ similar reduction by a factor of two in the mid-x region over the full Q^2 range



Summary of α_s determinations



- Wealth of determinations of α_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

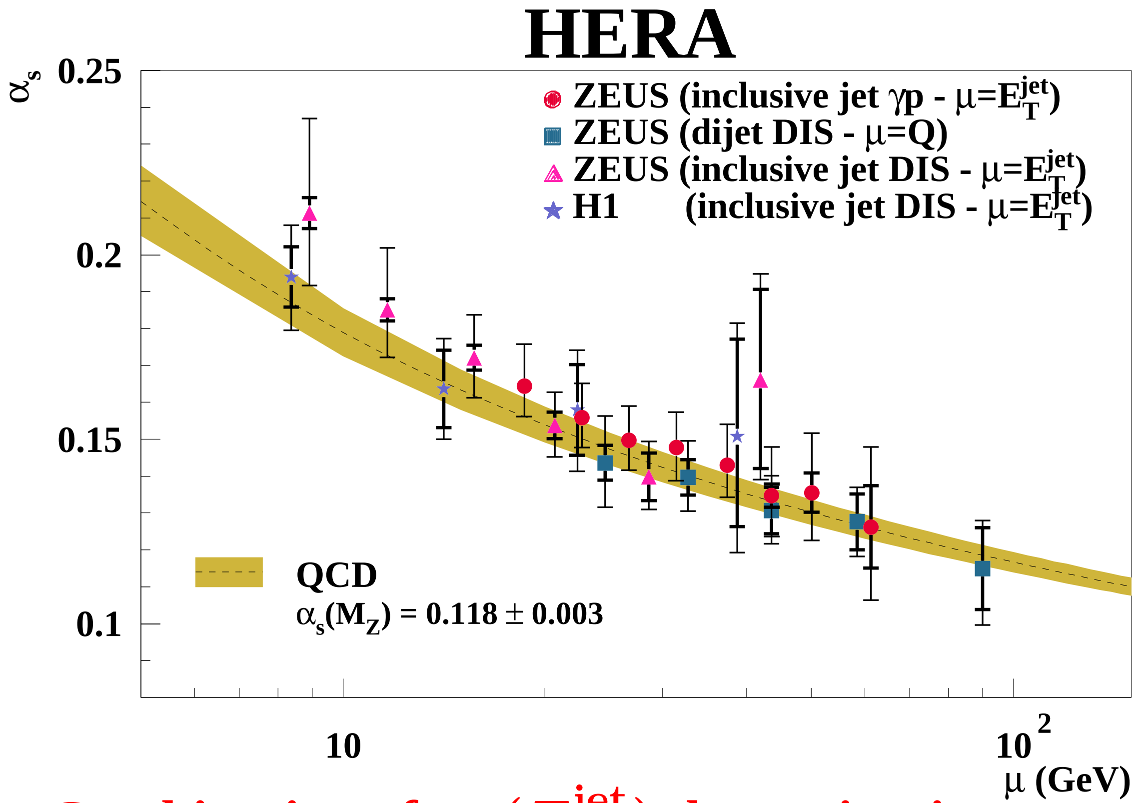
→ Biggest contrib. from terms beyond NLO

- 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 α_s from HERA data alone



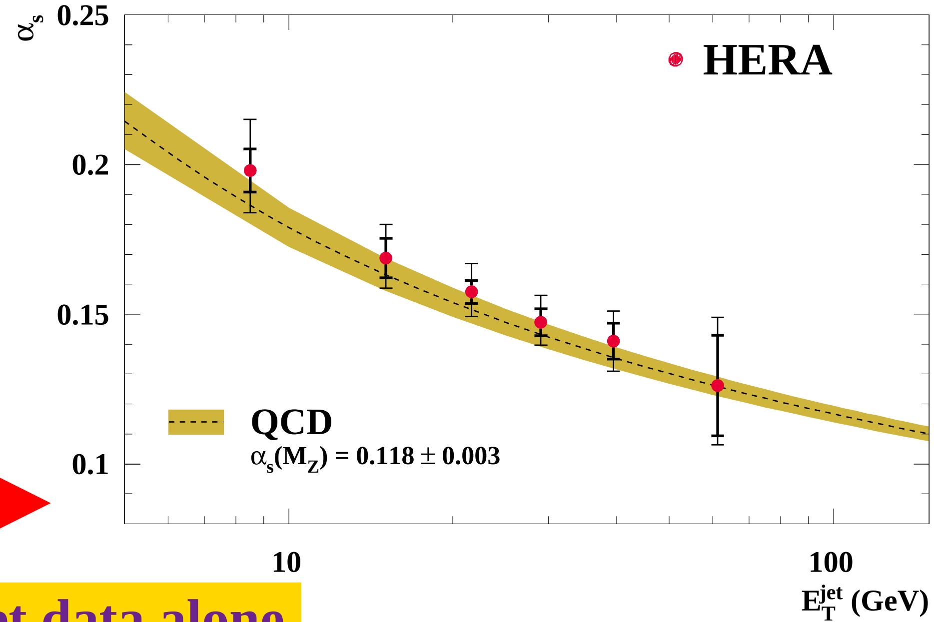
- **Determinations of $\alpha_s(\mu)$:**

$\longrightarrow$ Dijet NC DIS ($\mu = Q$)

$\longrightarrow$ Inclusive jet NC DIS ($\mu = E_T^{\rm jet}$)

$\longrightarrow$ Inclusive jet γp ($\mu = E_T^{\rm jet}$)

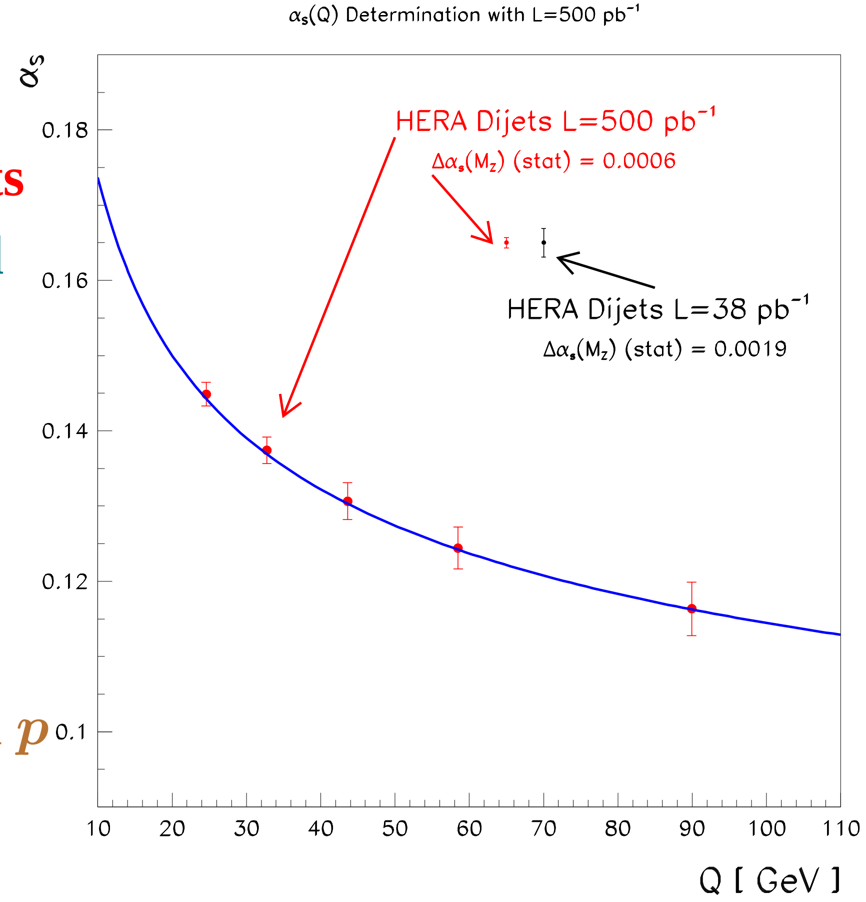
- **Combination of $\alpha_s(E_T^{\rm jet})$ determinations at similar energy scales**



Observation of the running of α_s from HERA jet data alone

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

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

$\longrightarrow$ tests of perturbative QCD beyond LO

$\longrightarrow$ precise determinations of α_s

$\longrightarrow$ improved determination of the gluon density in p

$\longrightarrow$ tests of the partonic structure of the photon

$\longrightarrow$ 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 ~ 0.5 fb^{-1} of physics luminosity per experiment

  $\longrightarrow$ jet analyses with full luminosity just started

  $\Rightarrow$ improvements expected on α_s and proton and photon structure