Prague, PIC 2005

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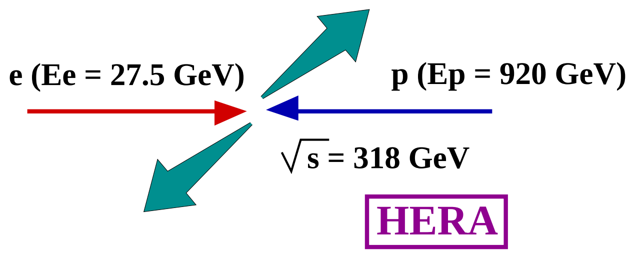
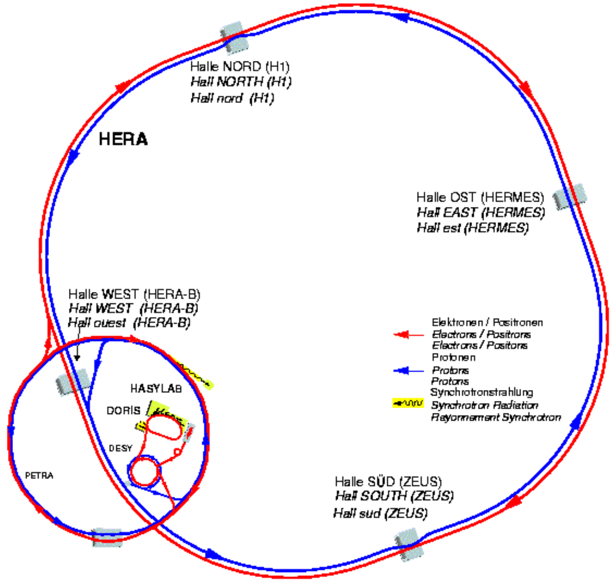
Tests of perturbative QCD with hadronic final states in *ep* collisions

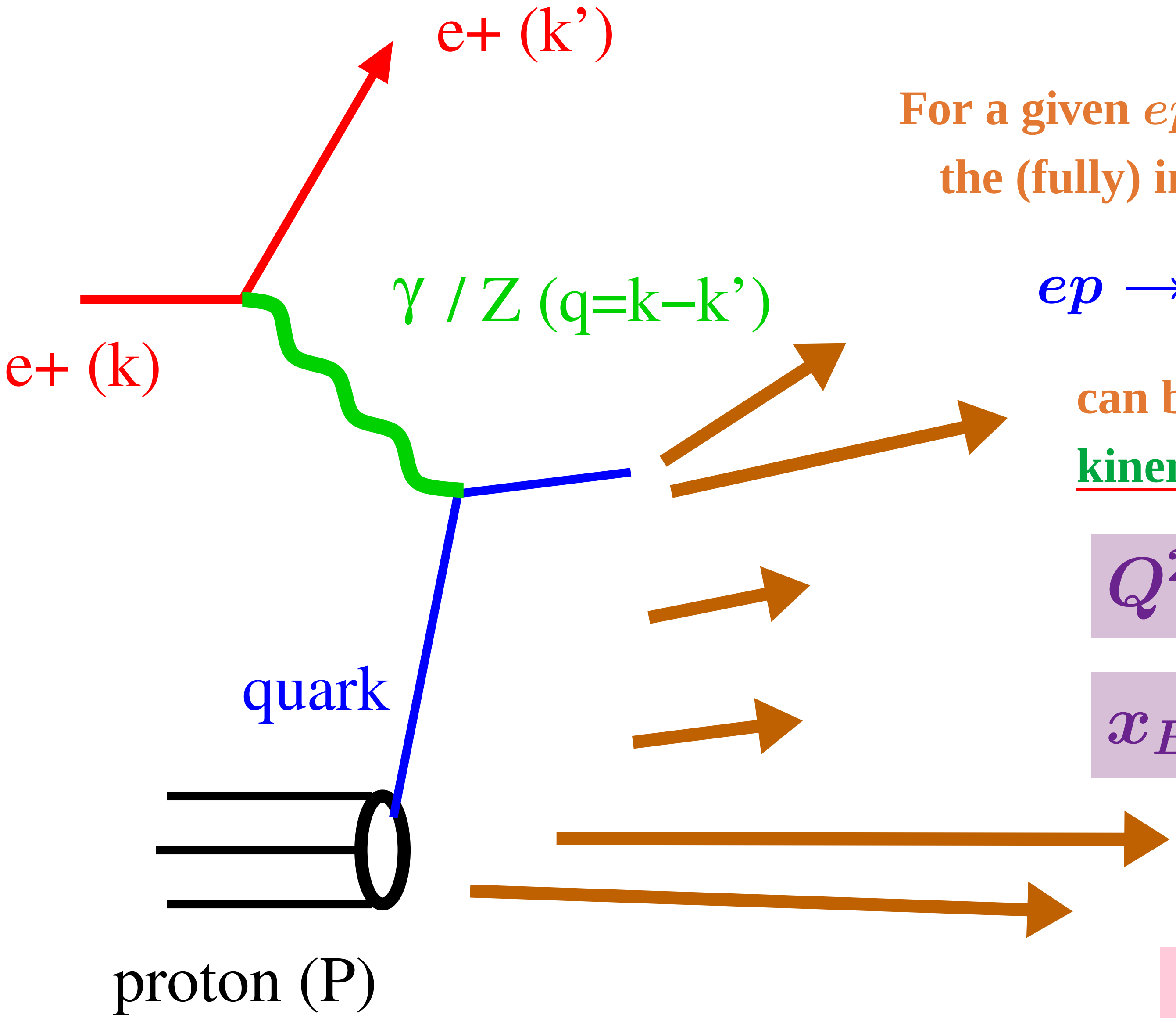
Juan Terrón (Universidad Autónoma de Madrid, Spain)





H1 and ZEUS Collaborations

Kinematics of Neutral Current Deep Inelastic Scattering



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

$$ep \rightarrow e + X$$

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

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

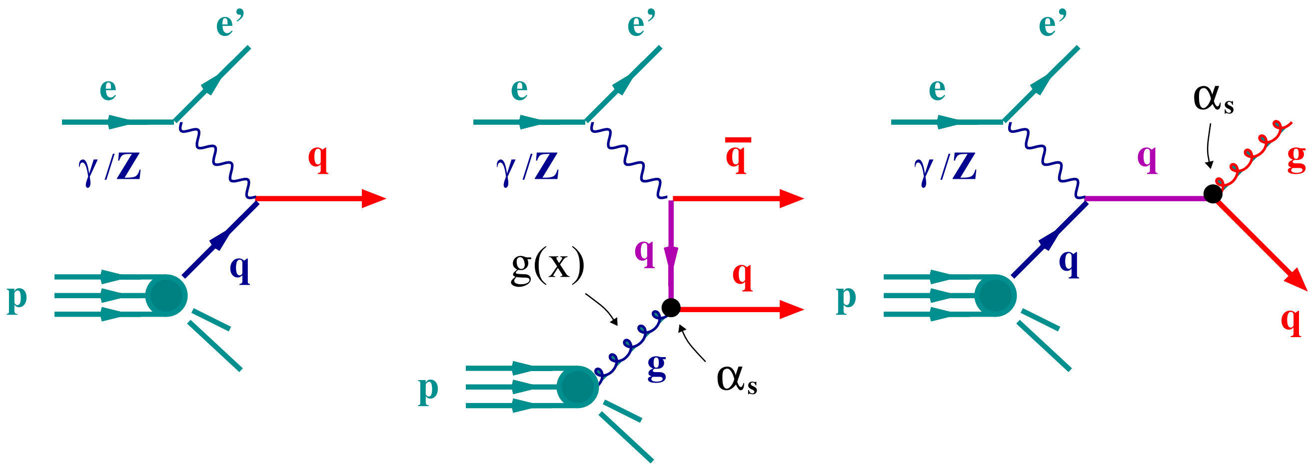
$$x_{Bj} = Q^2/(2P \cdot q)$$

→ Inelasticity variable

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

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:

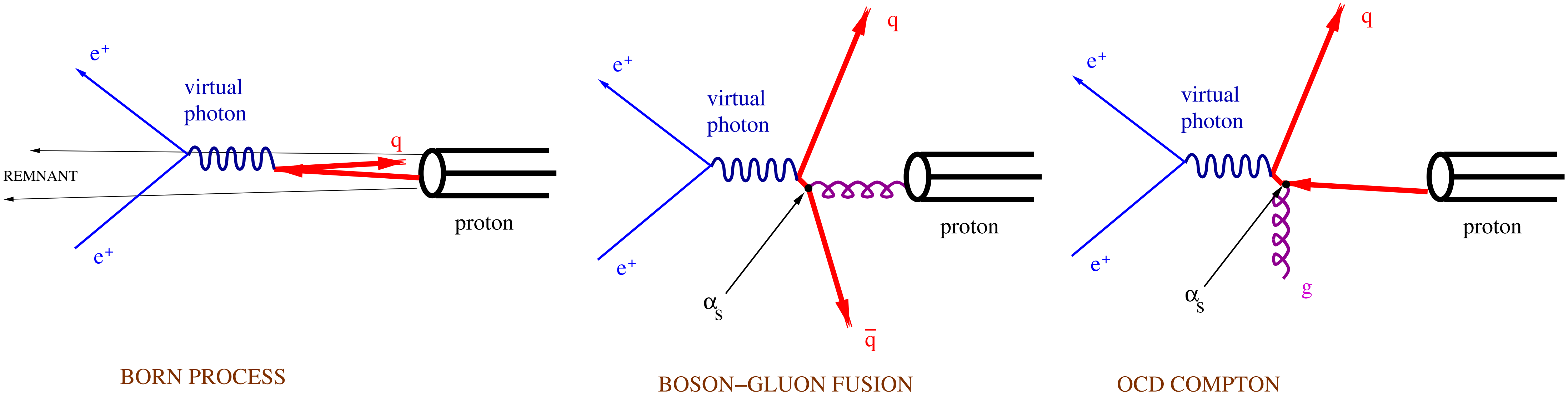
$$d\sigma_{jet} = \sum_{a=q,\bar{q},g} \int dx\, f_a(x, \mu_F^2)\, d\hat{\sigma}_a(x, \alpha_s(\mu_R), \mu_R^2, \mu_F^2)$$

  – 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
  - $\longrightarrow$ 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**

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

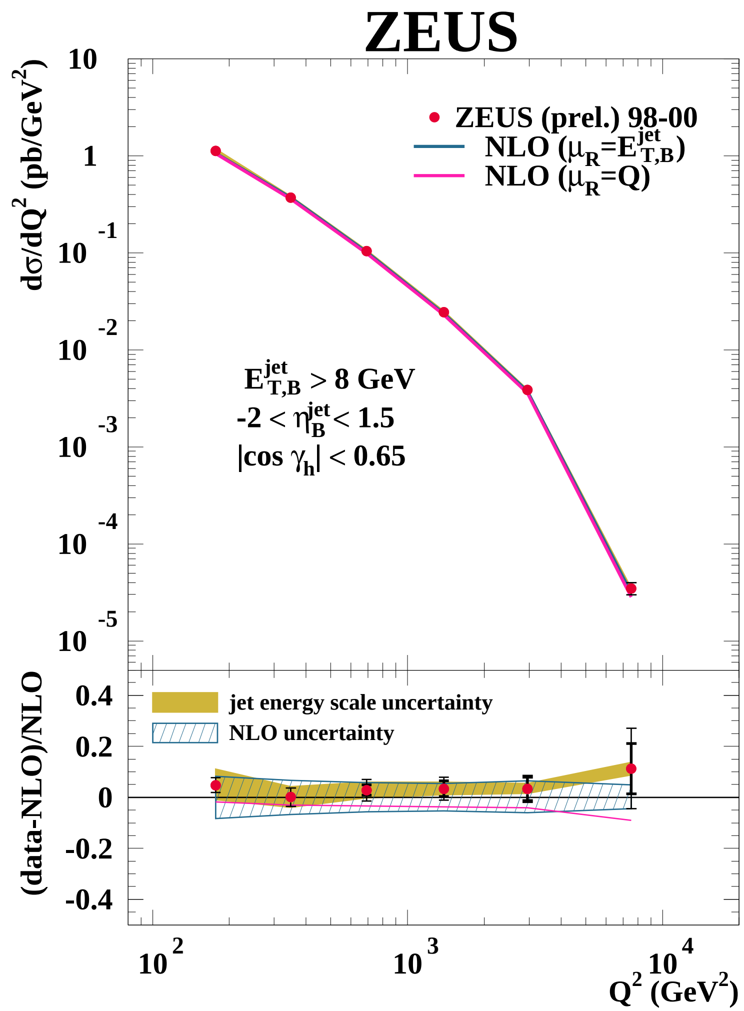
  $\rightarrow$ suppression of the beam-remnant jet (zero E_T)

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

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

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

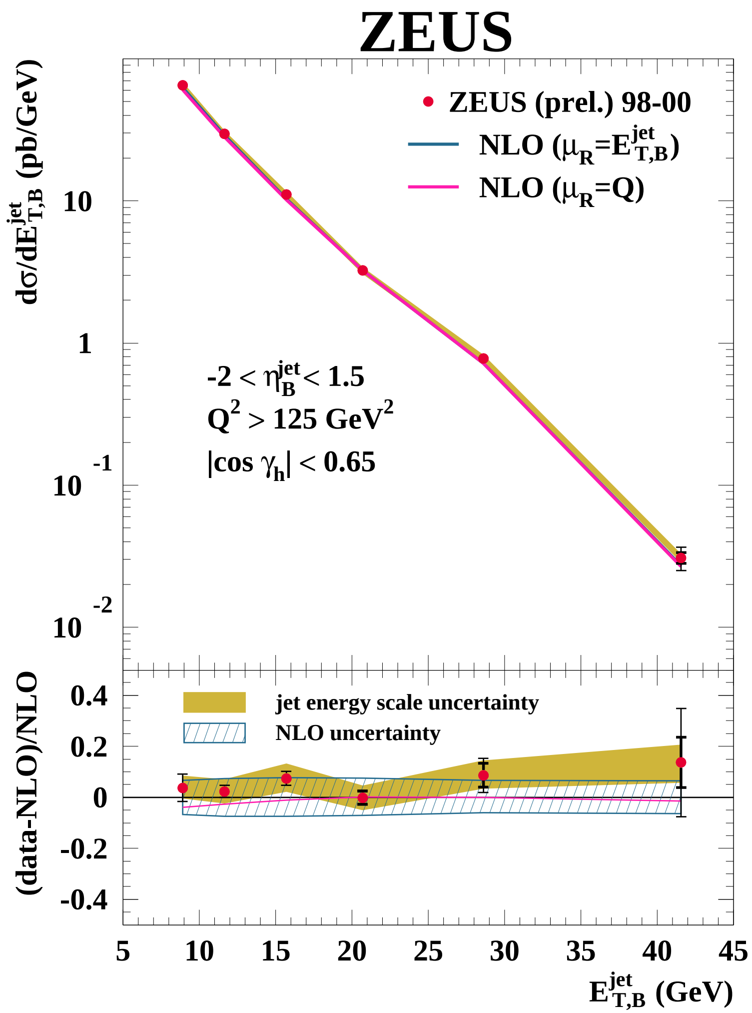
- **New measurement of inclusive jet cross sections in the kinematic region defined by $Q^2 > 125$ GeV^2 and $|\cos\gamma| < 0.65$ for jets with $E^B_{T,jet} > 8$ GeV and $-2 < \eta^B_{jet} < 1.5$ using $\mathcal{L} = 81.7$ pb^{-1}**
  - **$\longrightarrow$ no cut is applied in the laboratory frame**
- **Advantages:**
  - **$\longrightarrow$ infrared insensitivity (no dijet cuts!)**
  - **$\longrightarrow$ suited to test resummed calculations**
  - **$\longrightarrow$ smaller theoretical uncertainties than for dijet**
- **Small experimental uncertainties:**
  - **$\longrightarrow$ 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 MRST99 parametrisations of the proton PDFs describe the measurements well**

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 $-2 < \eta^B_{jet} < 1.5$

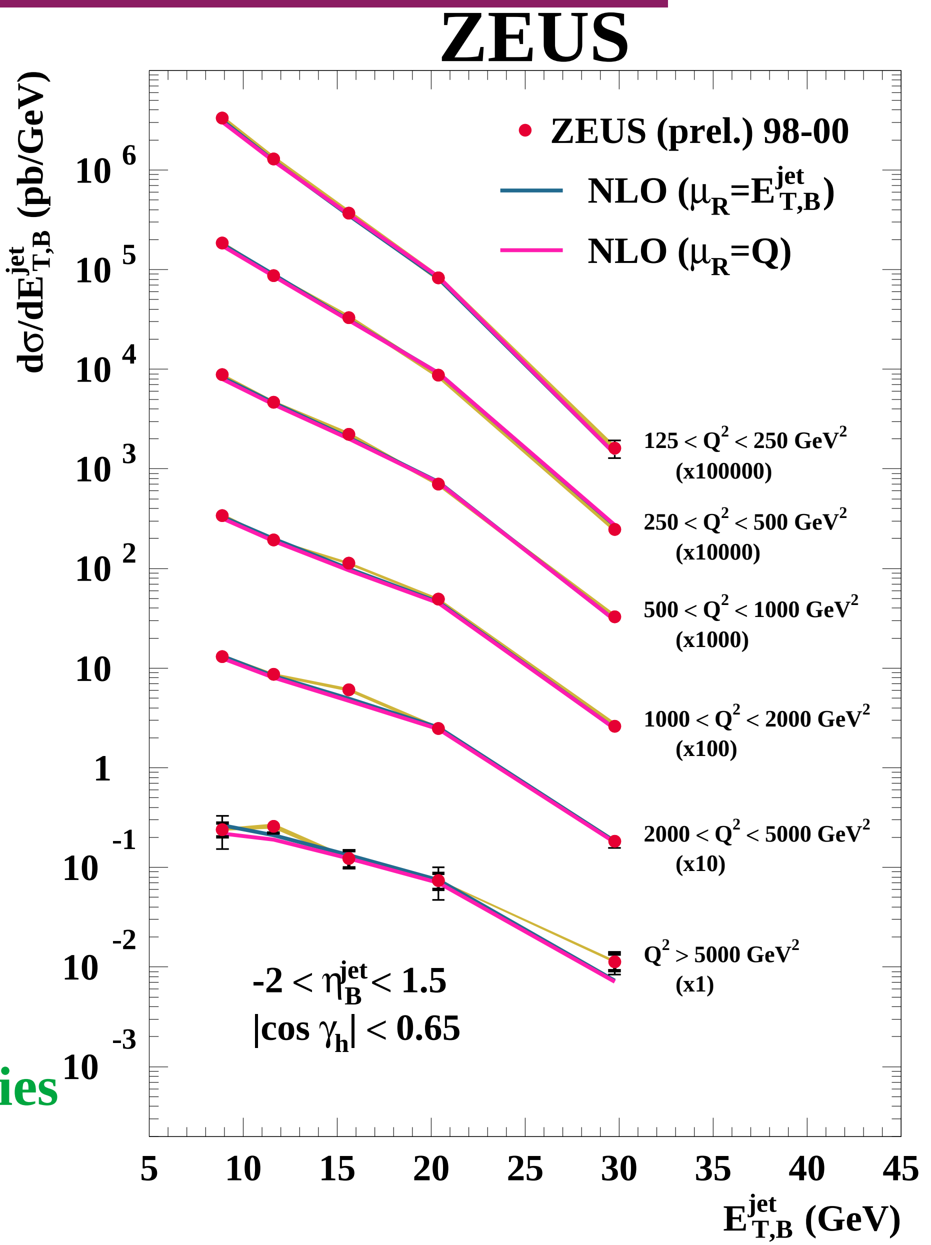


- Small theoretical uncertainties:
  - → higher-order terms (> NLO); varying μ_R between $\frac{1}{2} \cdot E^B_{T,jet}$ and $2 \cdot E^B_{T,jet} \Rightarrow \pm 5\%$
  - → uncertainty on $\alpha_s(M_Z)$ (± 0.0027); $\Rightarrow \pm 4\%$
  - → uncertainties on the proton PDFs; $\Rightarrow \pm 3\%$

- NLO QCD calculations ($\mathcal{O}(\alpha_s^2)$) using $\mu_R = E^B_{T,jet}$, $\mu_F = Q$ and the MRST99 parametrisations of the proton PDFs describe the measurements well

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 different regions of Q^2 for jets with $E^B_{T,jet} > 8$ GeV and $-2 < \eta^B_{jet} < 1.5$**
- **NLO QCD calculations provide a good description of the data $\longrightarrow$ validity of the description of the dynamics of inclusive jet production by pQCD at $\mathcal{O}(\alpha_s^2)$**
- **Inclusive jet cross sections in NC DIS in the Breit frame provide direct sensitivity to α_s and the gluon density in the proton with small experimental and theoretical uncertainties**



Inclusive Jet Cross Sections and extraction of α_s

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

$$\alpha_s(M_Z) = 0.1196 \pm 0.0011\ (\text{stat.})\ ^{+0.0025}_{-0.0019}\ (\text{exp.})\ ^{+0.0017}_{-0.0029}\ (\text{th.})$$

- Experimental uncertainties:

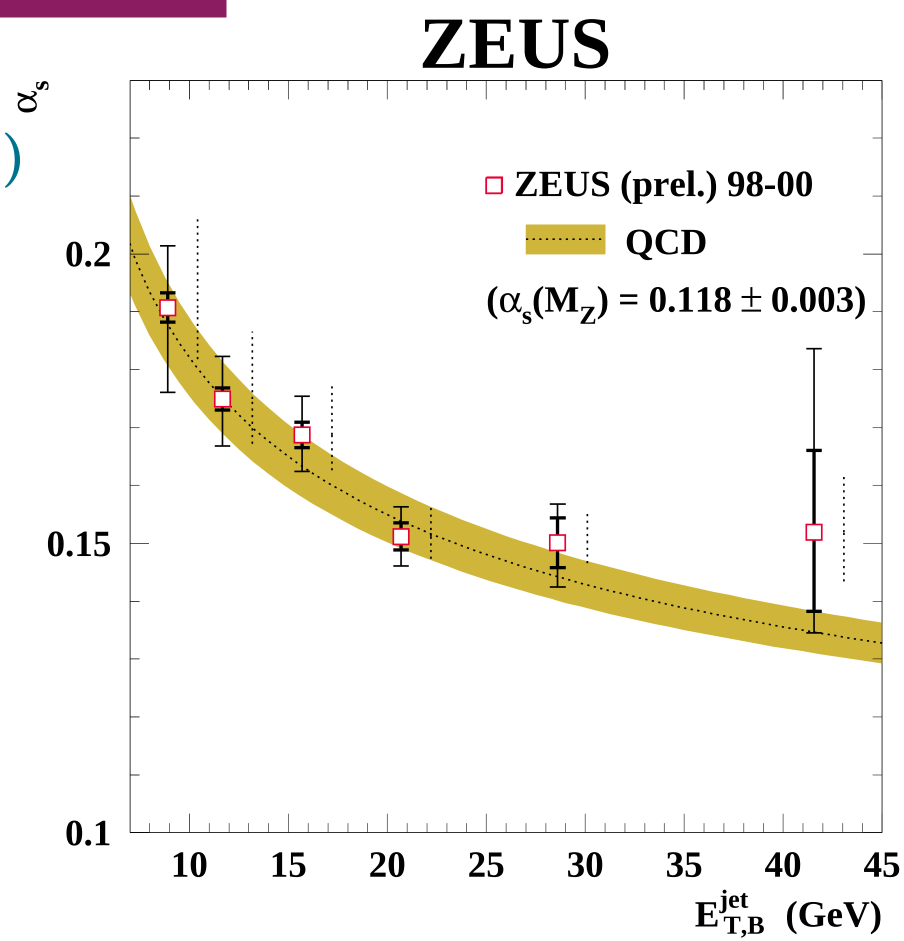
$\longrightarrow$ jet energy scale (1% for $E_{T,jet} > 10$ GeV)

- Theoretical uncertainties:

$\longrightarrow$ terms beyond NLO $\Delta\alpha_s(M_Z) = 1 - 2\%$

$\longrightarrow$ uncertainties proton PDFs $\Delta\alpha_s(M_Z) = 1\%$

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



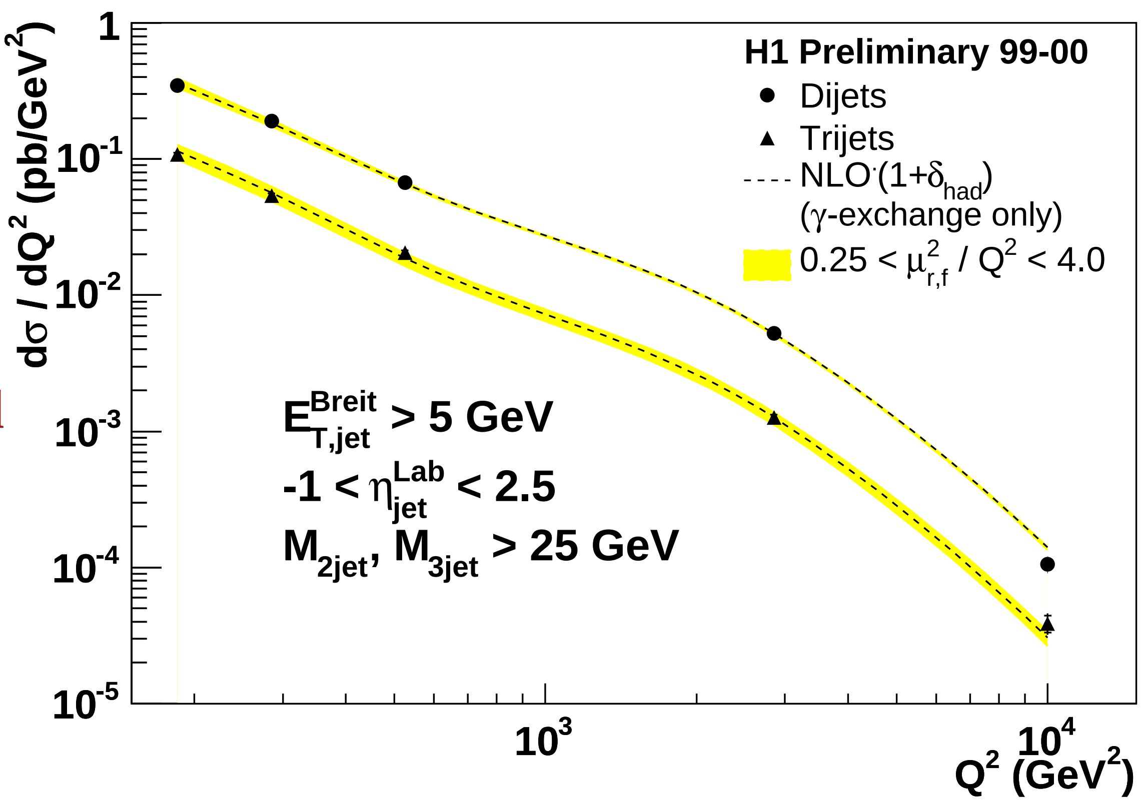
- Study of the scale dependence of $\alpha_s(E^B_{T,jet})$: from the measured $d\sigma/dE^B_{T,jet}$ in each $E^B_{T,jet}$ region $\rightarrow \alpha_s(< E^B_{T,jet} >)$ is extracted
- The measurements are consistent with the running of α_s predicted by perturbative QCD

Dijet and Trijet Cross Sections in NC DIS ($150 < Q^2 < 15000$ GeV^2)

- **New measurement of dijet and trijet cross sections over a wide range in Q^2 $\rightarrow$ $150 < Q^2 < 15000$ GeV^2 and $0.2 < y < 0.6$ for jets with**
  E_T^{jet}(Breit)> 5 GeV, $-1 < \eta^{jet}$(Lab)< 2.5, $M_{jj} > 25$ GeV ($M_{jjj} > 25$ GeV)
  using $\mathcal{L} = 65.4$ pb^{-1}
- **Trijet cross sections test QCD beyond LO directly $\rightarrow$ $\sigma_{3jet} \propto \alpha_s^2$**

- **Comparison with NLO QCD calculations:**
  $\rightarrow$ $\mu_R = \mu_F = Q$
  $\rightarrow$ CTEQ5M set of proton PDFs
  $\rightarrow$ parton-to-hadron corrections applied

- **NLO QCD gives a good description of the data over a wide range in Q^2**



Dijet and Trijet Cross Sections in NC DIS ($150 < Q^2 < 15000$ GeV^2)

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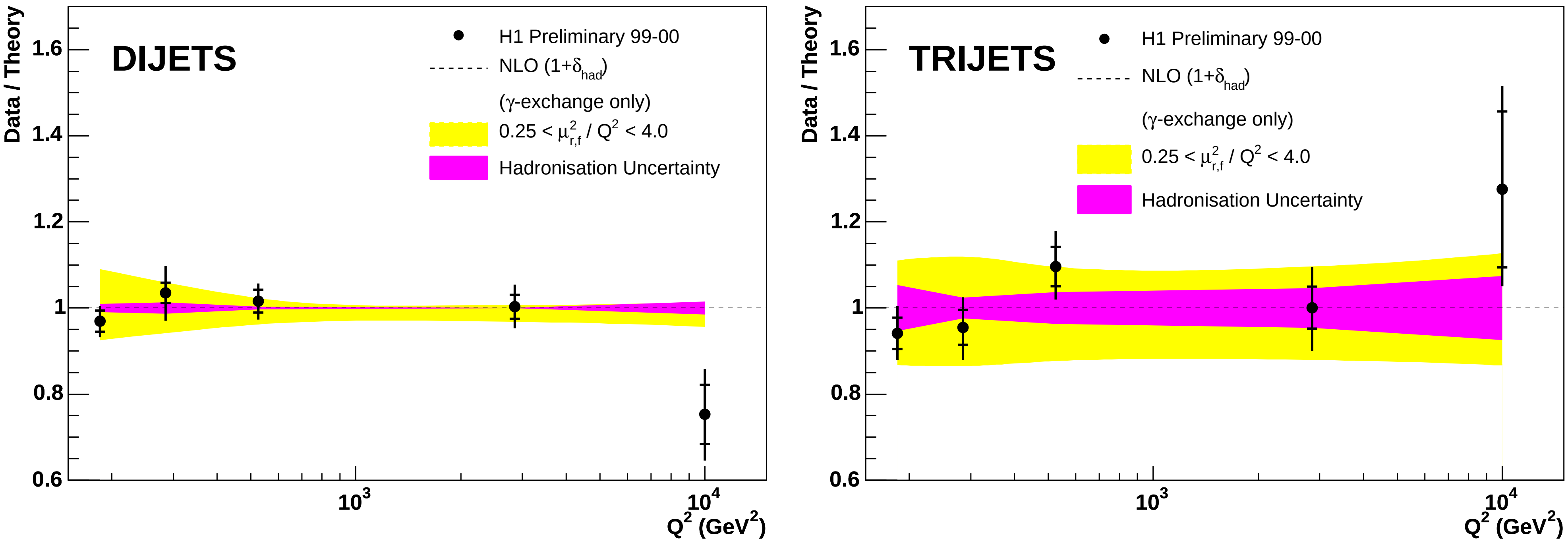
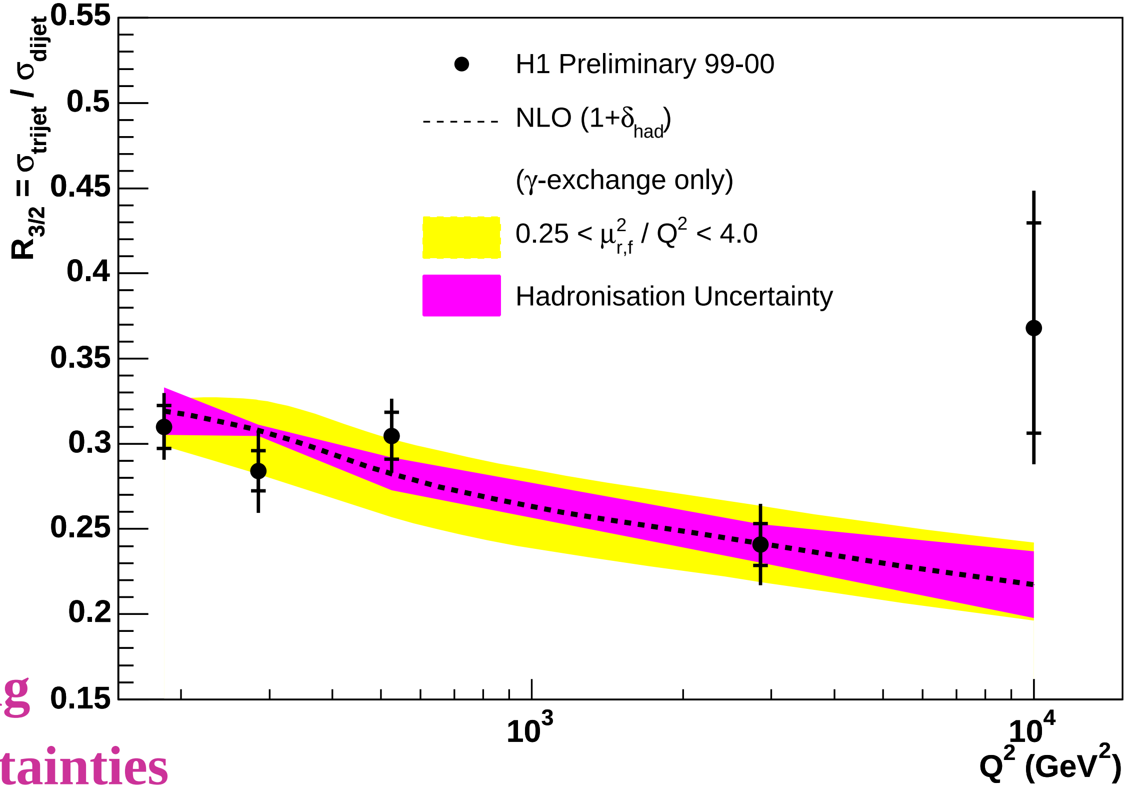


- **NLO QCD gives a good description of the data over a wide range in Q^2**
  (Z^0-exchange effects not included in NLO; significant only for the highest Q^2 point)

Dijet and Trijet Cross Sections in NC DIS ($150 < Q^2 < 15000$ GeV^2)

- **New measurement of the ratio of the trijet to dijet cross section over a wide range in Q^2**

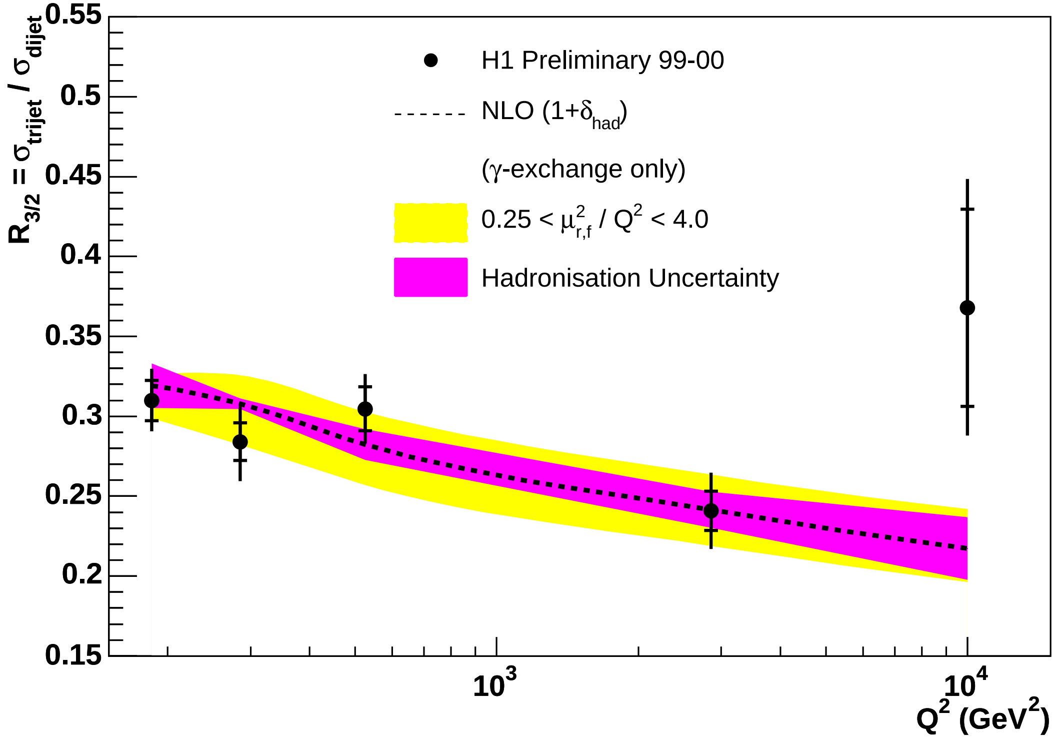
→ $R_{3/2} \equiv \frac{\sigma_{\text{trijet}}(Q^2)}{\sigma_{\text{dijet}}(Q^2)}$



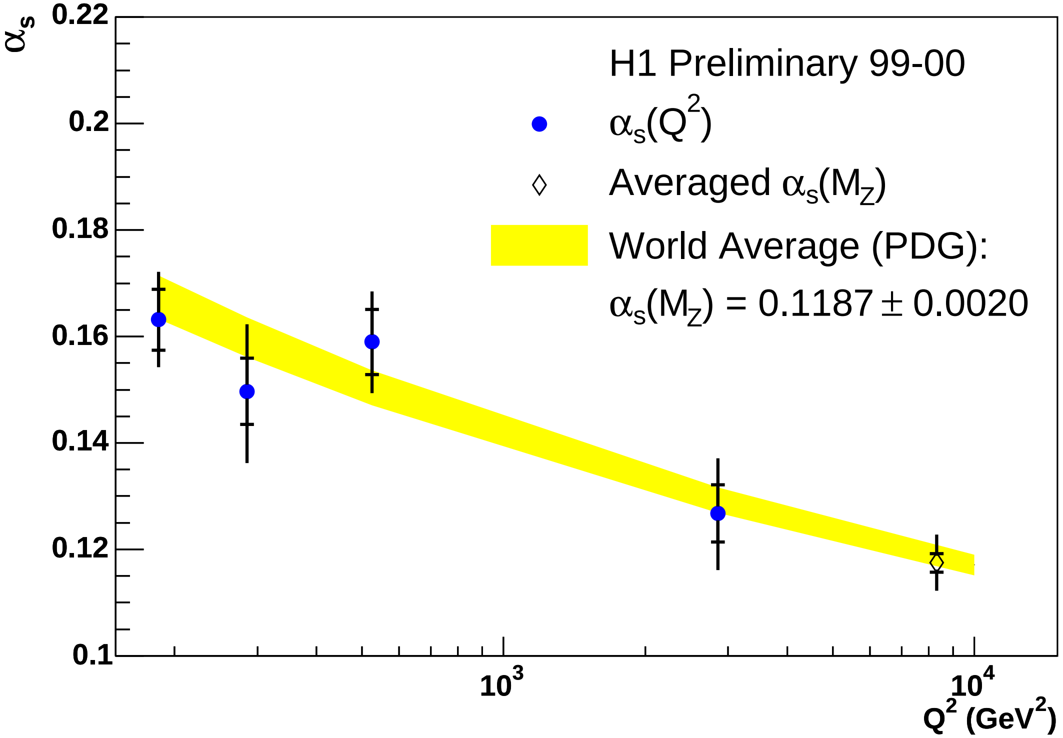
- **Small experimental uncertainties.**
- **Small theoretical uncertainties:**
  → uncertainties on the proton PDFs
  → higher-order terms (> NLO) (reduced to $\sim 5\%$)
- **Since $R_{3/2} \propto \alpha_s$ at LO it allows a determination of the strong coupling constant with small theoretical uncertainties**
- **The measured values of $R_{3/2}$ have been fitted with NLO QCD calculations to extract a combined value of $\alpha_s(M_Z)$:**

$$\alpha_s(M_Z) = 0.1175 \pm 0.0017\ (\text{stat.}) \pm 0.0050\ (\text{syst.})^{+0.0054}_{-0.0068}\ (\text{th.})$$

Dijet and Trijet Cross Sections in NC DIS ($150 < Q^2 < 15000$ GeV^2)

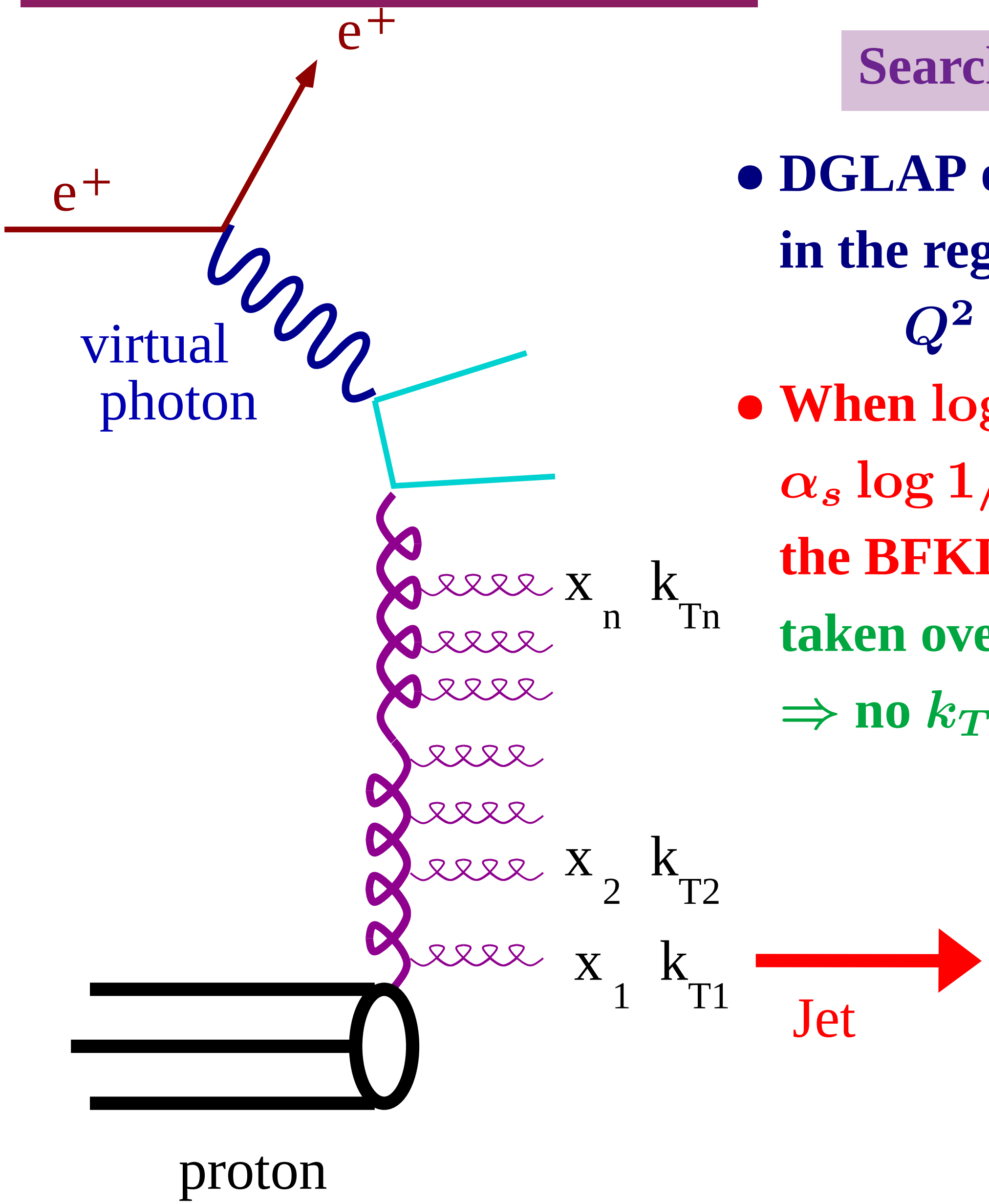


- **Determination of α_s as a function of the energy scale using the measured values of $R_{3/2}$**



- **The observed dependence of α_s with Q^2 is consistent with the prediction of QCD →**

Parton evolution at low x



Searching for BFKL-induced effects

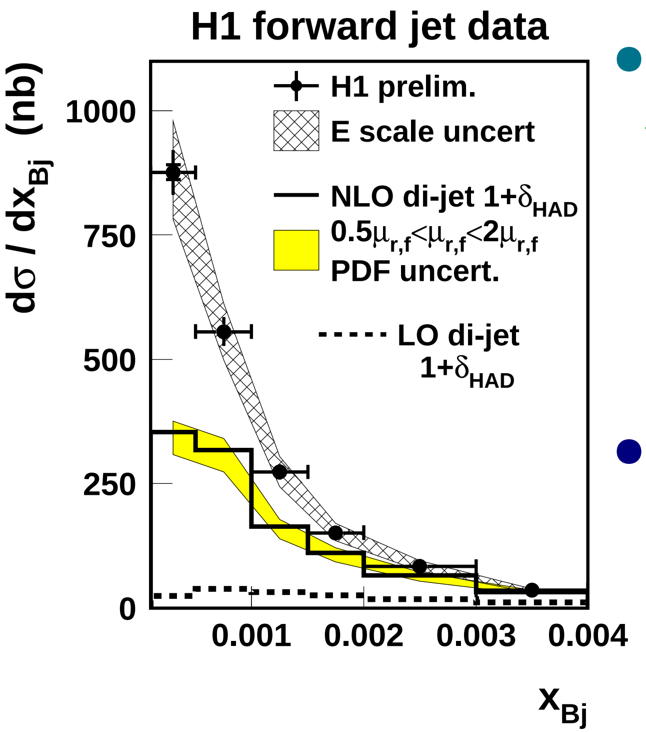
- DGLAP equations sum the leading powers of $\alpha_s \log Q^2$ in the region of strongly-ordered transverse momenta

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

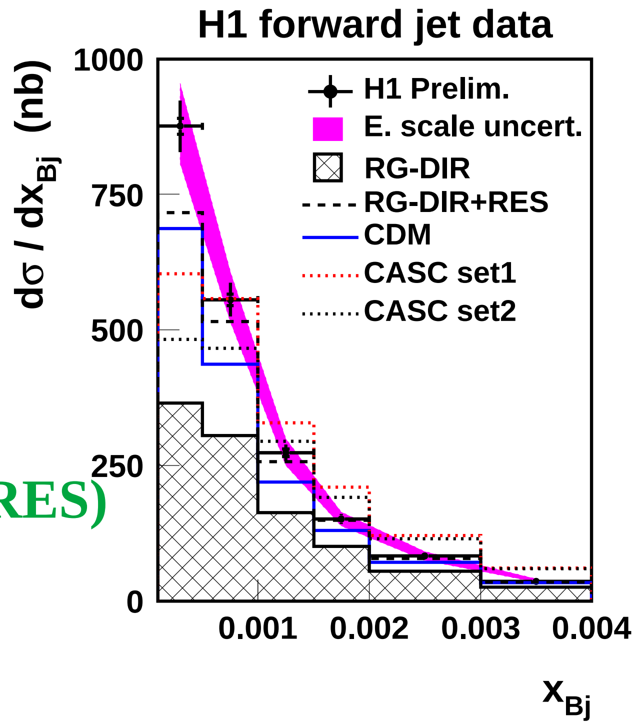
- When $\log Q^2 \ll \log 1/x$ terms proportional to $\alpha_s \log 1/x$ become important and need to be summed the BFKL equation accomplishes that; the integration is taken over the full k_T phase space of the gluons $\Rightarrow$ no k_T ordering

  - 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, $7° < \theta_{\rm jet} < 20°$, $0.5 < p^2_{t,jet}/Q^2 < 2$ 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



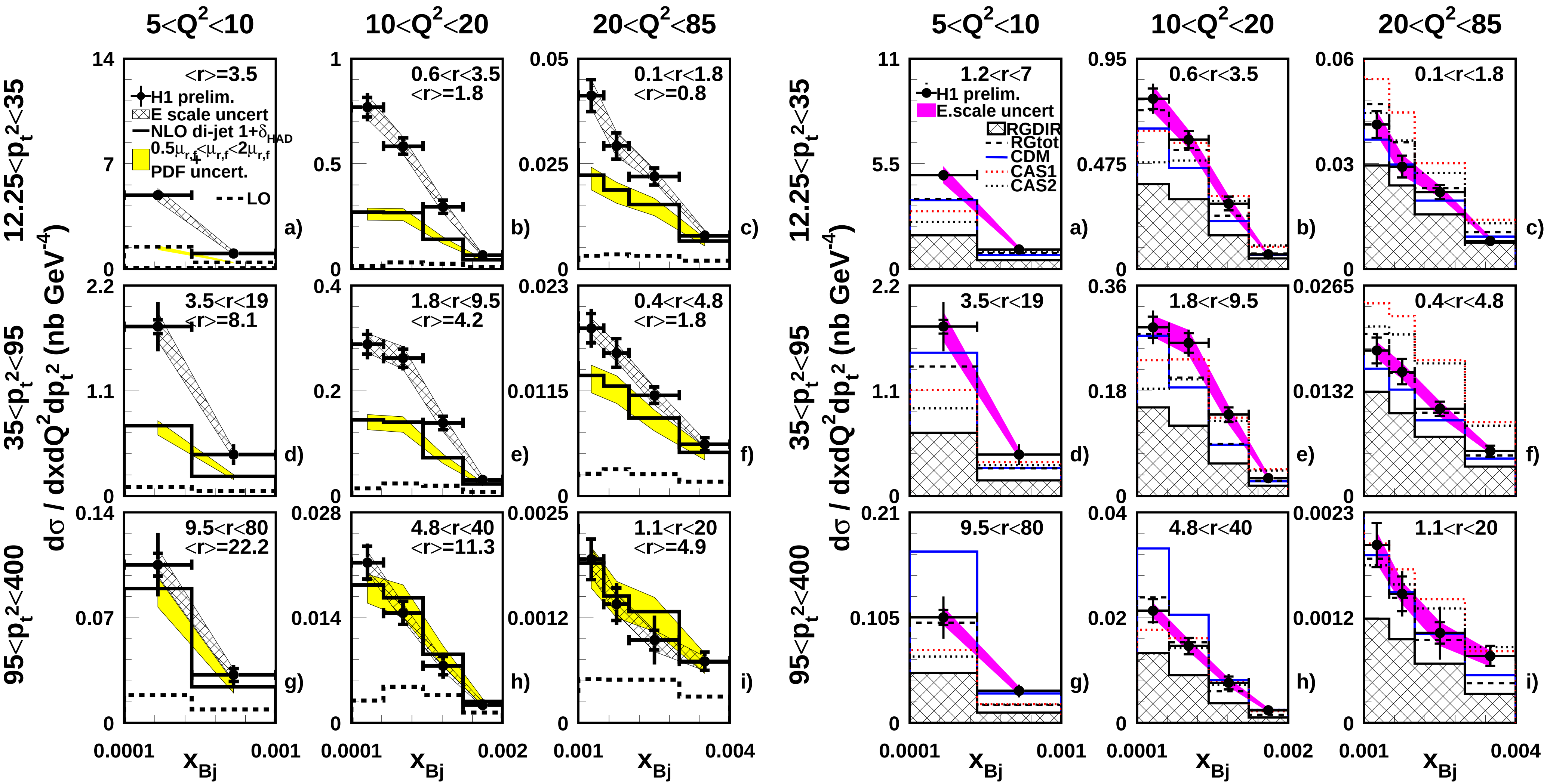
$\longrightarrow$ NLO QCD (DGLAP) lies well below the data at low x

$\longrightarrow$ MC models with extra parton radiation provide an improved description of the data

$\longrightarrow$ inclusion of a resolved-photon component (RG-DIR+RES)

$\longrightarrow$ parton emissions not ordered in k_T (CDM)

Measurement of Forward Jet Production at low x



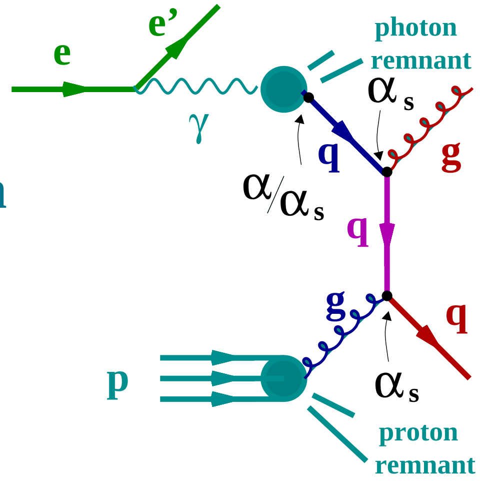
- Measurement of the triply-differential cross section $d^3\sigma/dxdQ^2dp_t^2$

$\longrightarrow$ NLO QCD fails at low Q^2, x, p_t $\longrightarrow$ RG-DIR+RES best overall

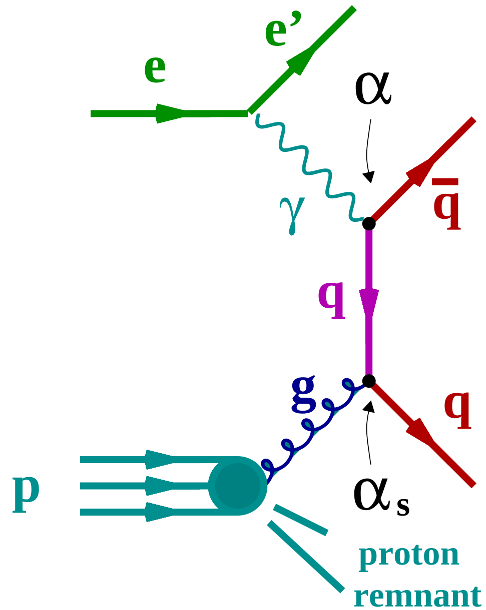
Photoproduction of Jets

- Production of jets in γp collisions has been measured via ep scattering at $Q^2 \approx 0$

- At lowest order QCD, two hard scattering processes contribute to jet production ⇒



Resolved process



Direct process

- pQCD calculations of jet cross sections

$$d\sigma_{jet} = \sum_{a,b} \int_0^1 dy\, f_{\gamma/e}(y) \int_0^1 dx_\gamma\, f_{a/\gamma}(x_\gamma, \mu^2_{F\gamma}) \int_0^1 dx_p\, f_{b/p}(x_p, \mu^2_{Fp})\ d\hat{\sigma}_{ab\to jj}$$

longitudinal momentum fraction of γ/e^+ (y), parton a/γ (x_γ), parton b/proton (x_p)

→ $f_{\gamma/e}(y)$ = flux of photons in the positron (WW approximation)

→ $f_{a/\gamma}(x_\gamma, \mu^2_{F\gamma})$ = parton densities in the photon (for direct processes $\delta(1 - x_\gamma)$)

→ $f_{b/p}(x_p, \mu^2_{Fp})$ = parton densities in the proton

→ $\sigma_{ab\to jj}$ subprocess cross section; short-distance structure of the interaction

Photoproduction of Jets

- **Measurements of jet photoproduction provide**

→ **Test of NLO QCD predictions based on current parametrisations of the proton and photon PDFs**

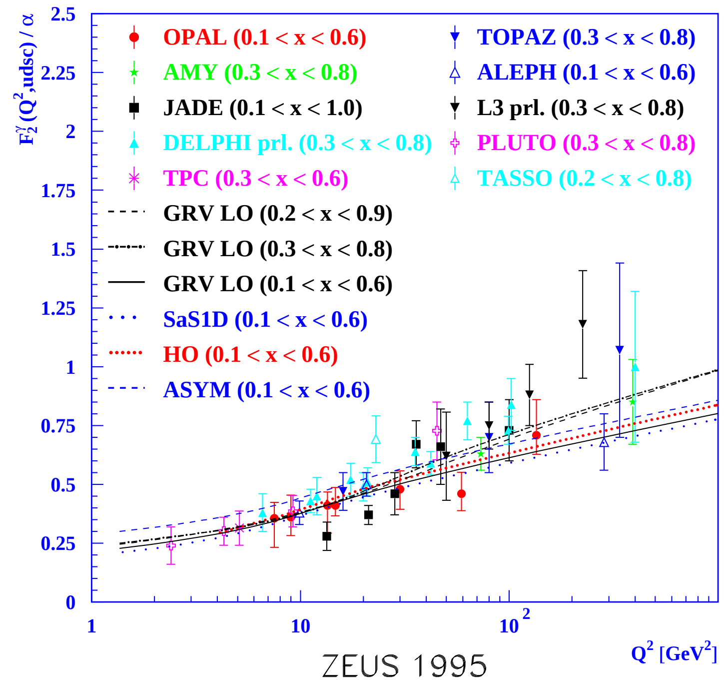
→ **Dynamics of resolved and direct processes**

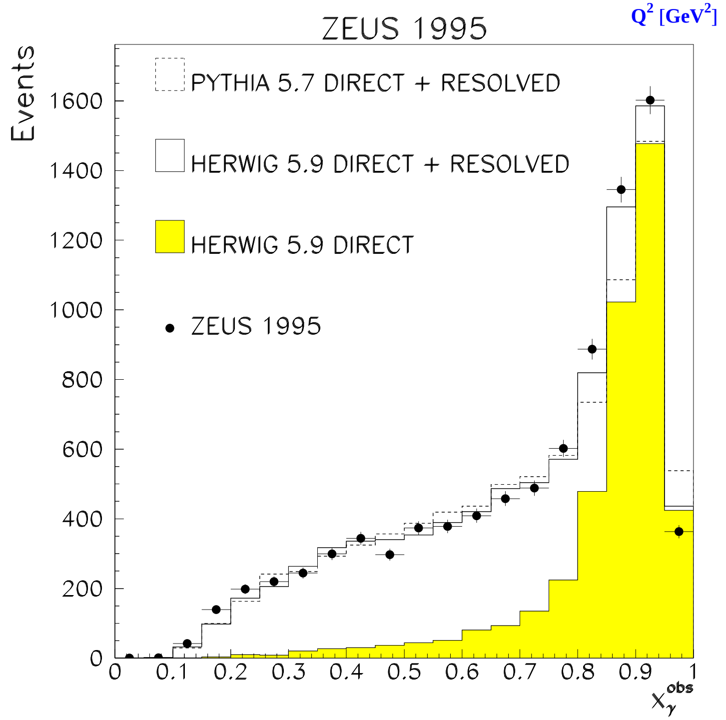
→ **Photon structure: information on quark densities from F_2^γ in e^+e^-; gluon density poorly constrained. Jet cross sections in photoproduction are sensitive to both the quark and gluon densities in the photon at larger scales $\mu^2_{F\gamma} \sim E^2_{T,jet}$ $(200 - 10^4$ GeV$^2)$**

→ **Proton structure: well constrained by DIS except for the gluon density at high x. Jet cross sections in γp are sensitive to parton densities at x_p up to ~ 0.6**

- **Observable to separate the contributions: the fraction of the photon's energy participating in the production of the dijet system**

$$x_\gamma^{OBS} = \frac{1}{2E_\gamma} \sum_{i=1}^{2} E_T^{jet_i} e^{-\eta^{jet_i}}$$





Dijet Photoproduction: photon structure

- **New measurement of the dijet cross sections $d\sigma/dx_\gamma$ and $d\sigma/dx_p$ for dijet events with**

  $E_{T,max} > 25$ **GeV,** $E_{T,second} > 15$ **GeV and** $-0.5 < \eta^{jet} < 2.75$ **(both jets)**

  in the kinematic region $Q^2 < 1$ **GeV**^{2} **and** $0.1 < y < 0.9$

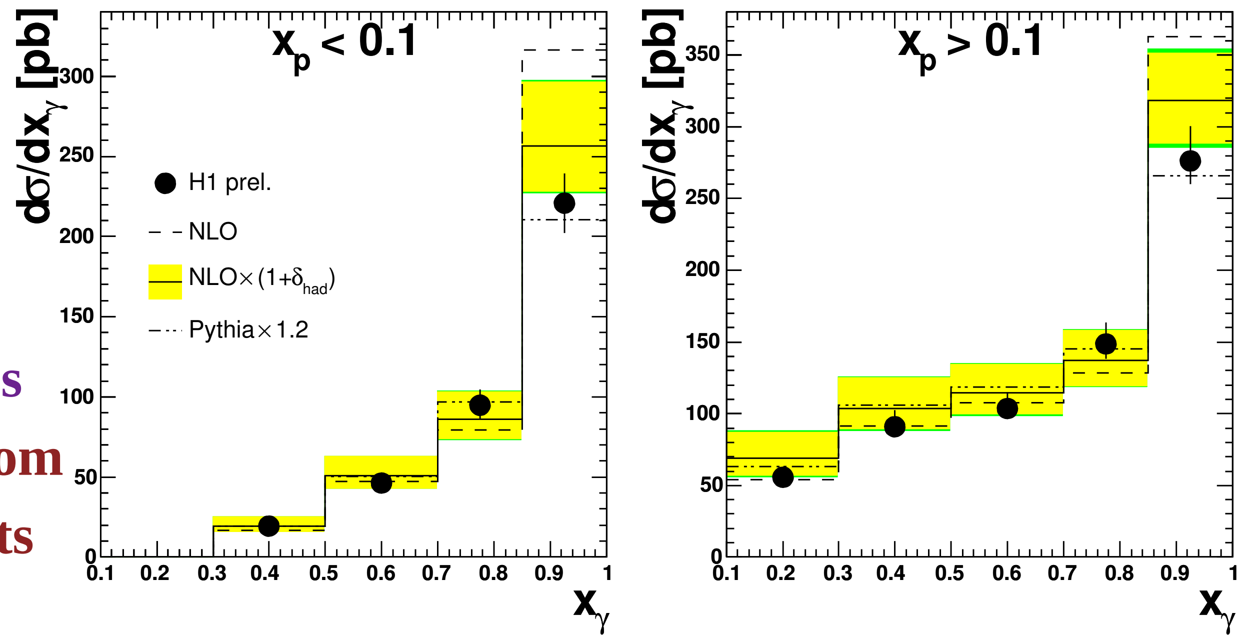
- x_p **variable:** $x_p = \frac{1}{2E_p} \sum_{i=1}^{2} E_T^{jet_i} e^{\eta^{jet_i}}$

- **Measurements of** $d\sigma/dx_\gamma$ **for** $x_p < 0.1$ **(**g_p **processes) and** $x_p > 0.1$ **(**q_p **processes)**

- **Comparison to NLO calculations using CTEQ6M (proton) and GRV-HO (photon) PDFs**

$\longrightarrow$ **Good description of the data along the entire range of** x_γ **for both ranges in** x_p

- **Consistent with QCD-evolved photon PDFs determined from measurements in** $\gamma\gamma$ **at lower scales and proton PDFs as determined from HERA and fixed-target experiments**



Dijet Photoproduction: proton structure

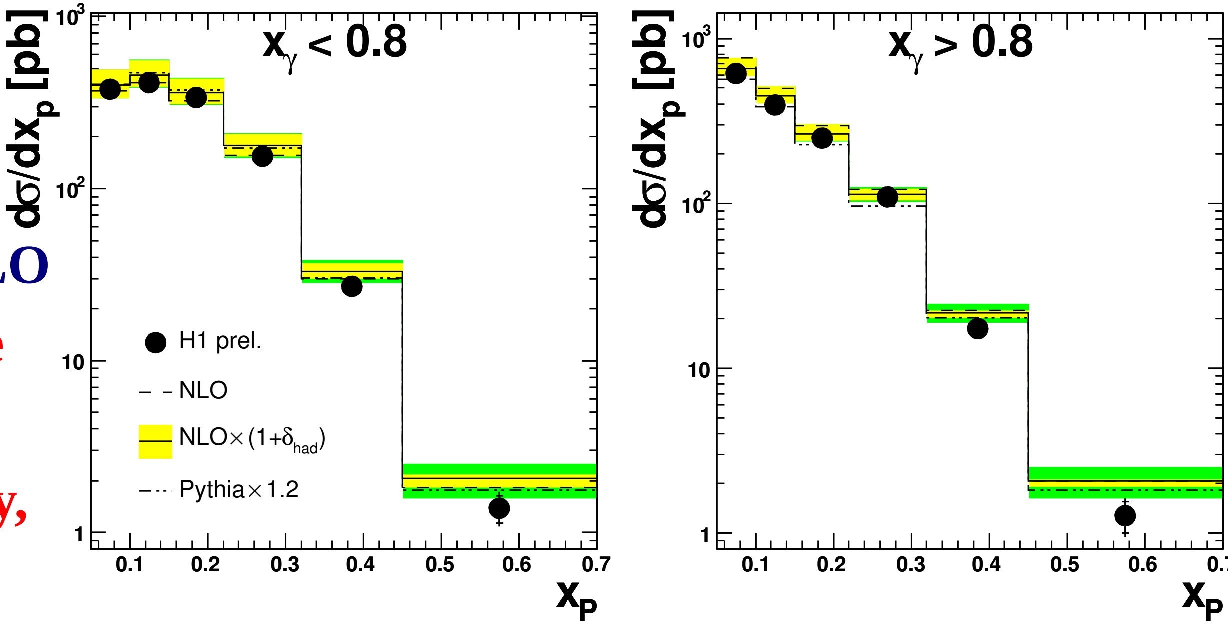
- New measurements of $d\sigma/dx_p$ for $x_\gamma < 0.8$ (resolved processes) and $x_\gamma > 0.8$ (direct processes)
- Comparison to NLO calculations using CTEQ6M (proton) and GRV-HO (photon) PDFs
- Theoretical uncertainties:

→ terms beyond NLO; estimated by varying μ_R up and down by a factor of 2
 ⇒ dominant at low x_p

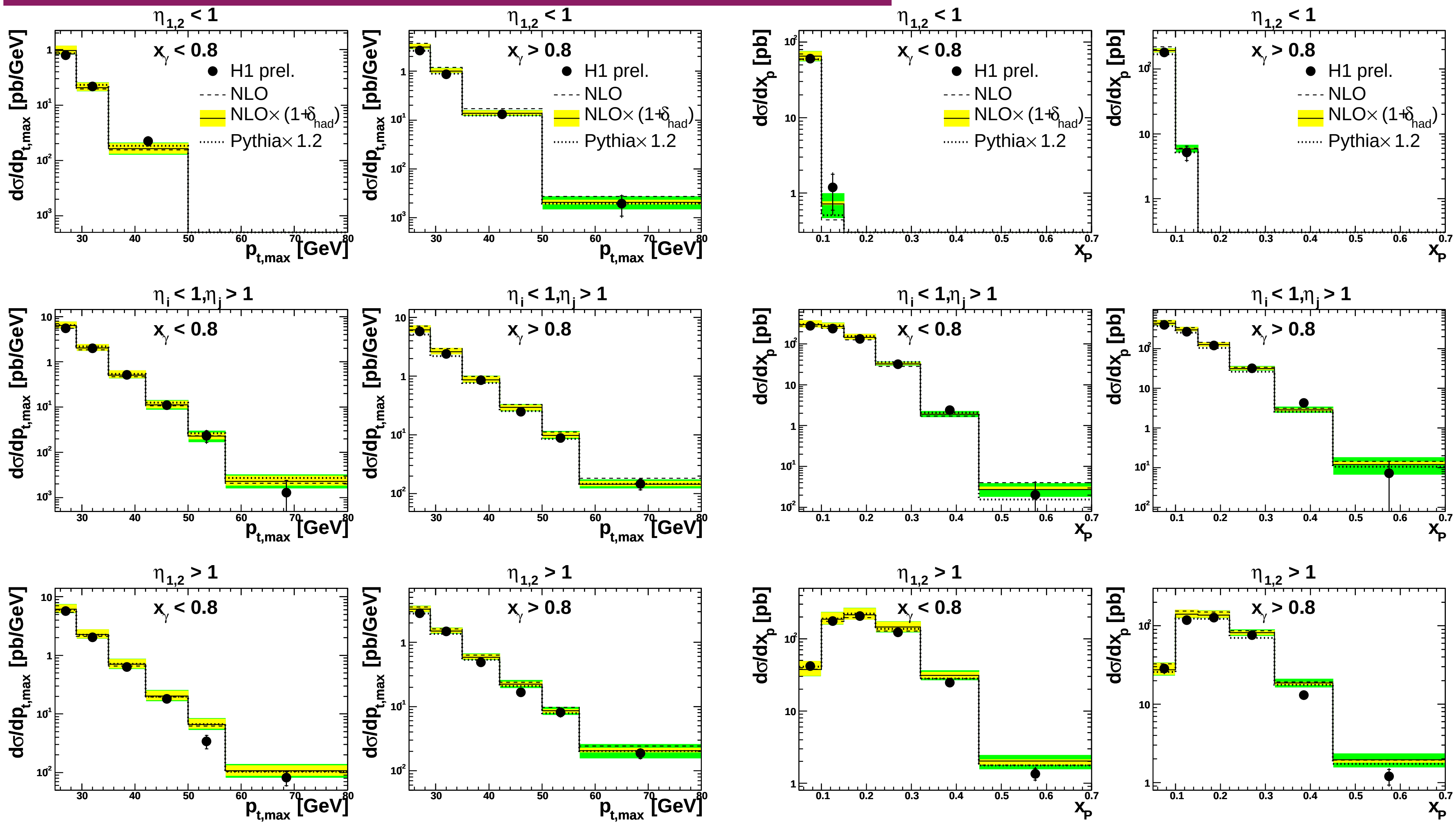
→ uncertaintites of the proton PDFs; ⇒ increasingly important as x_p increases

- The NLO QCD calculations agree with the data in the low x_p range
- At high x_p ($x_p > 0.32$) there are discrepancies between data and NLO

→ Measurements at high x_γ provide further constraints on the proton PDFs, particular the gluon density, free from the photon PDFs



Dijet Photoproduction: proton structure



Measurements at $x_\gamma > 0.8 \Rightarrow$ useful constrain in a global determination of proton PDFs

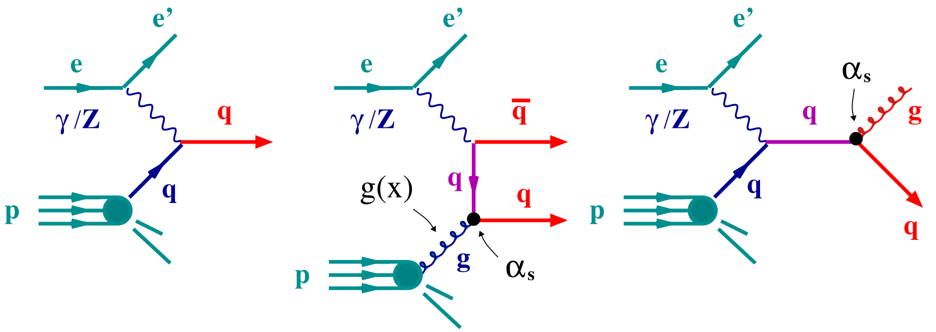
Improving the Determination of the Proton PDFs

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

→ **Inclusive measurements of deep inelastic lN scattering**

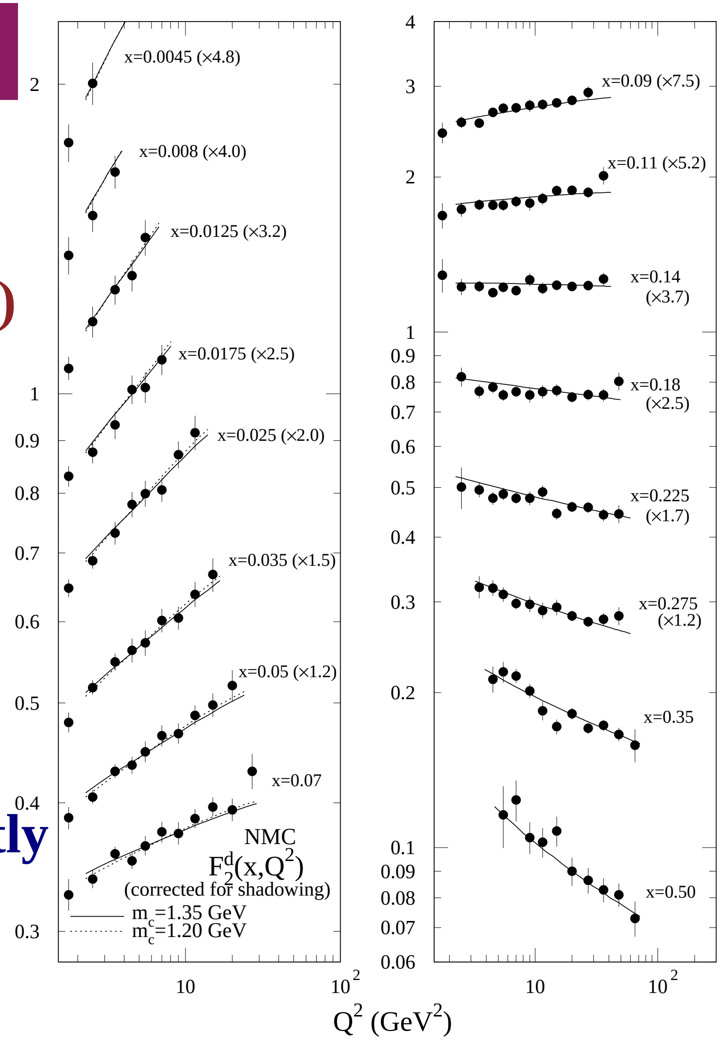
- **Advantages:** → **inclusive (only final-state lepton is tagged)**

⇒ **no QCD corrections associated to the final-state lepton**



Quark-Parton Model **Boson-Gluon Fusion** **QCD Compton**

- **Disadvantages:** **the gluon distribution contributes indirectly**



- **Observables based on jets have hardly been used**

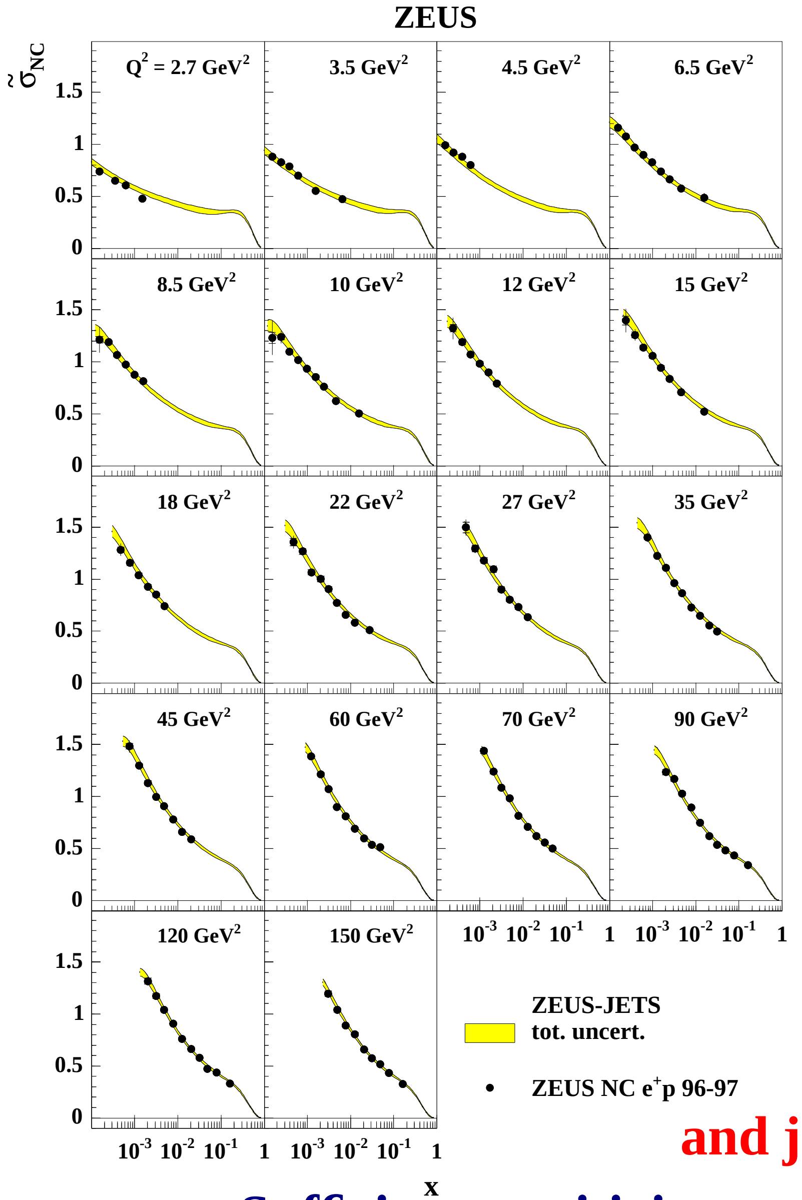
→ **large QCD corrections and hadronisation corrections**

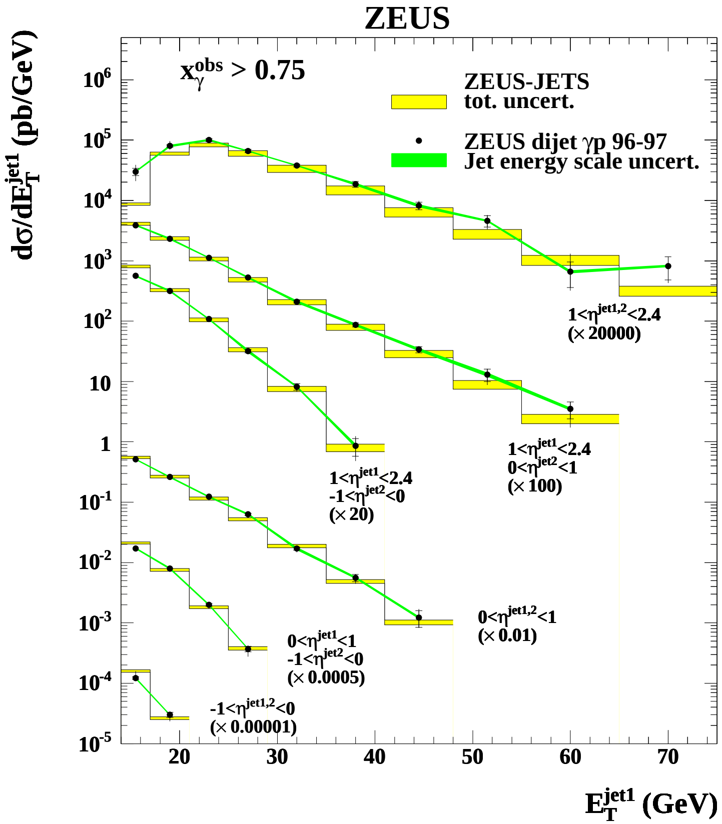
- **Fixed-target DIS: higher twists, heavy-target corrections and isospin-symm. assumptions**
- **That's the past! NOW there are measurements of jet cross sections at HERA**

⇒ **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 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):

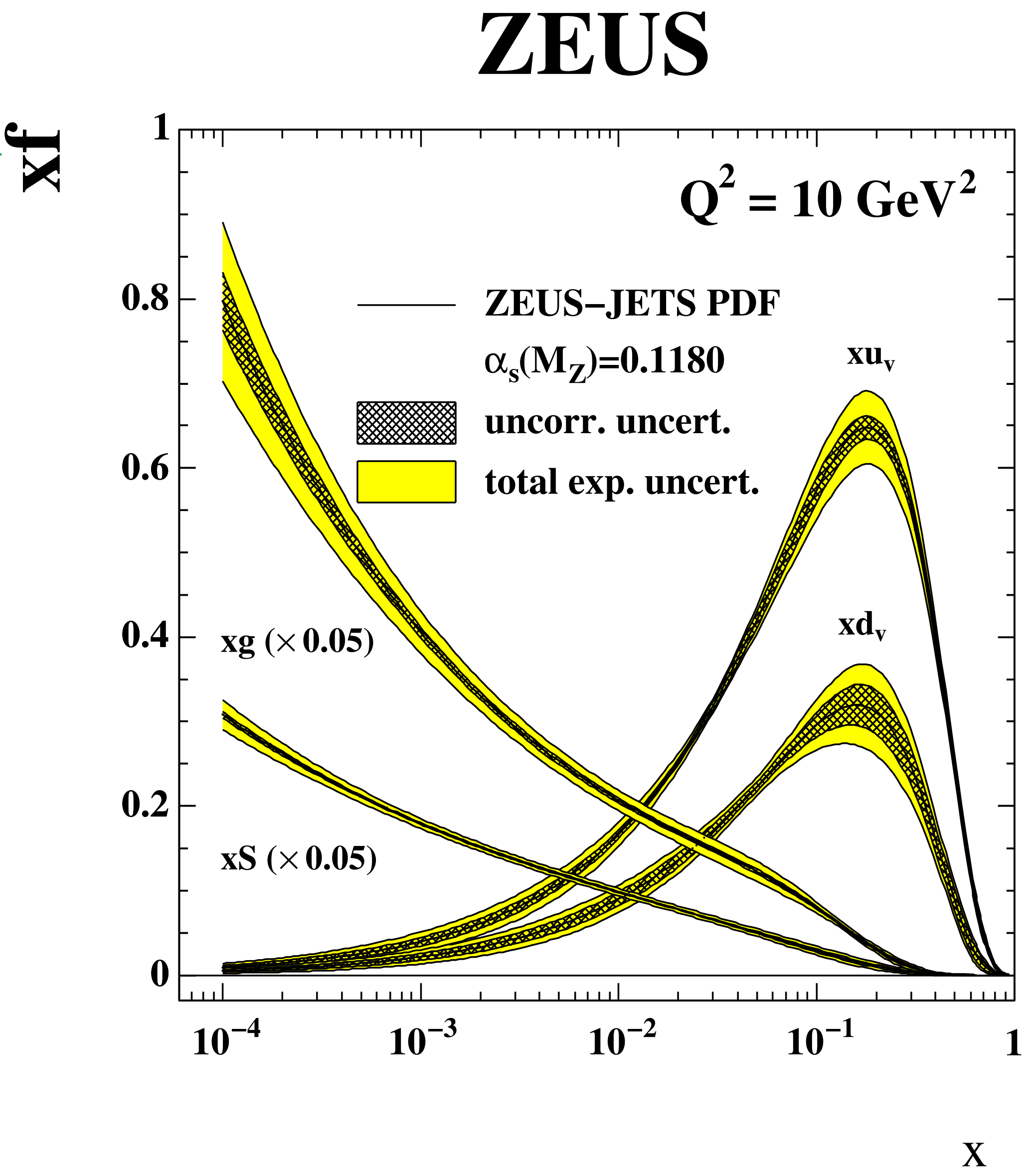
$\longrightarrow$ Structure function measurements: reduced double differential cross sections in x and Q^2

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

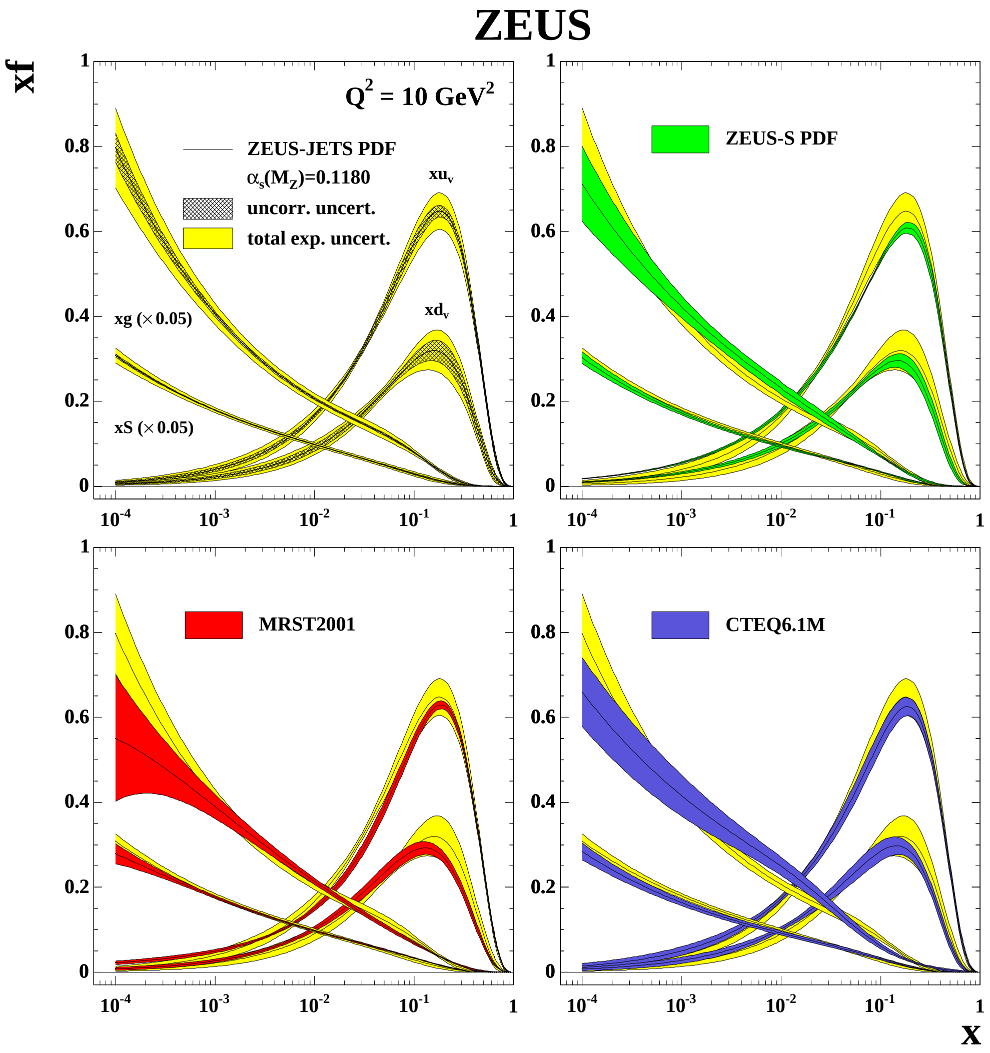
$\longrightarrow$ Jet cross section measurements:

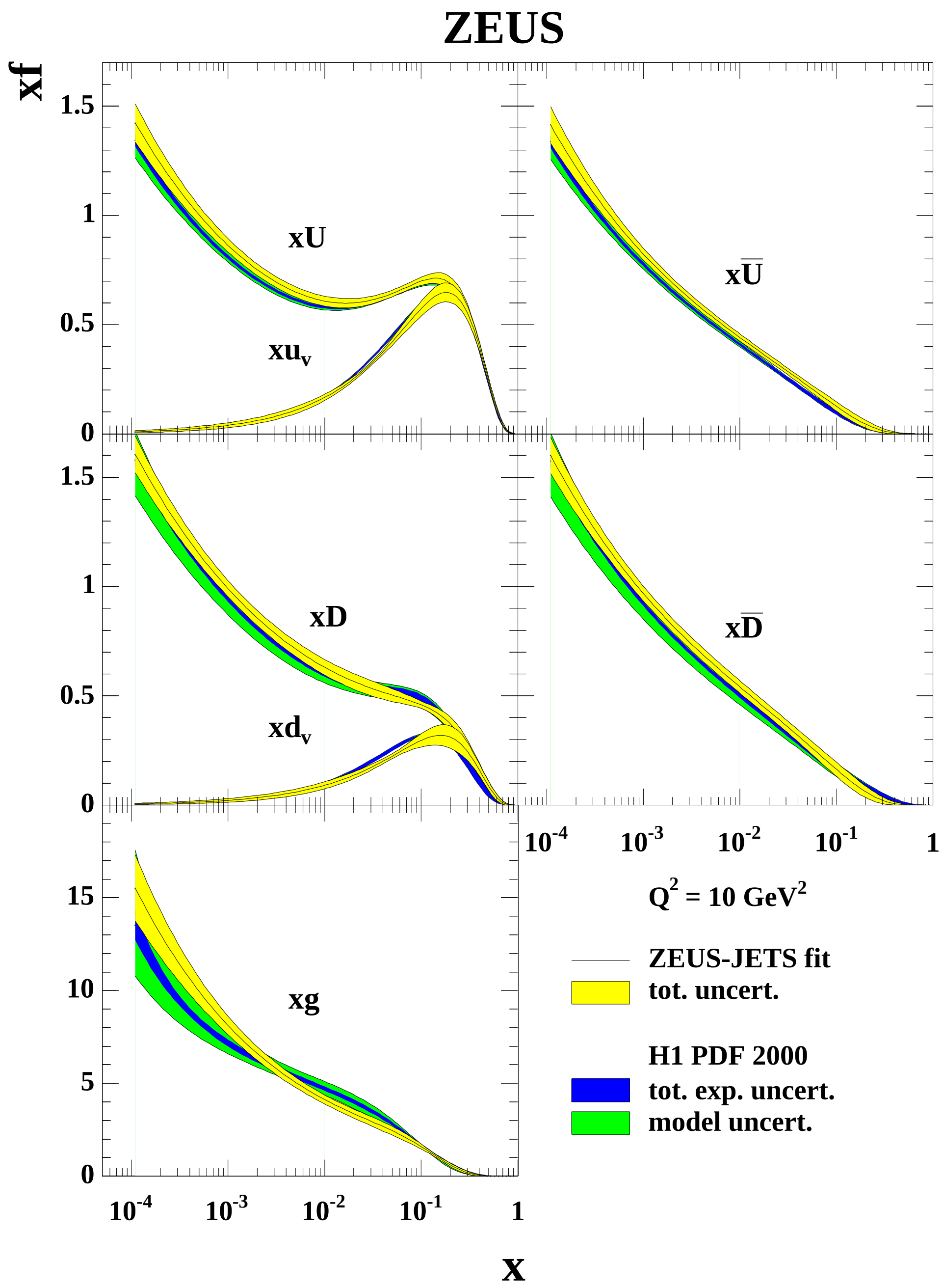
  - inclusive jet production in NC DIS
  - dijet production in γp collisions

- 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



Comparison of proton PDFs





- Compatible with MRST2001 and CTEQ6.1M
- Compatible with H1 analysis

Improving the gluon distribution: jet data

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

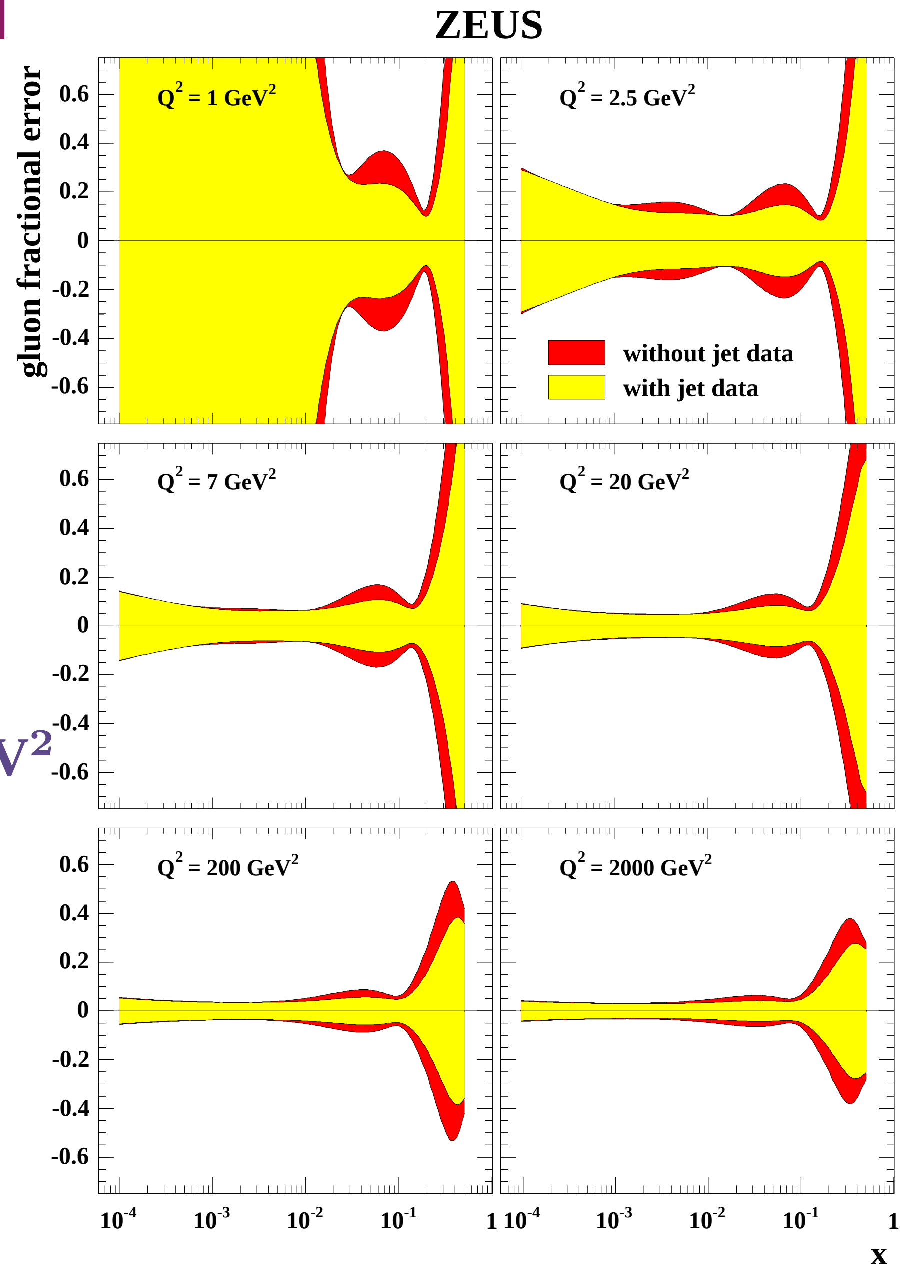
→ no significant change of the shape: no tension between jet and inclusive data

→ 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

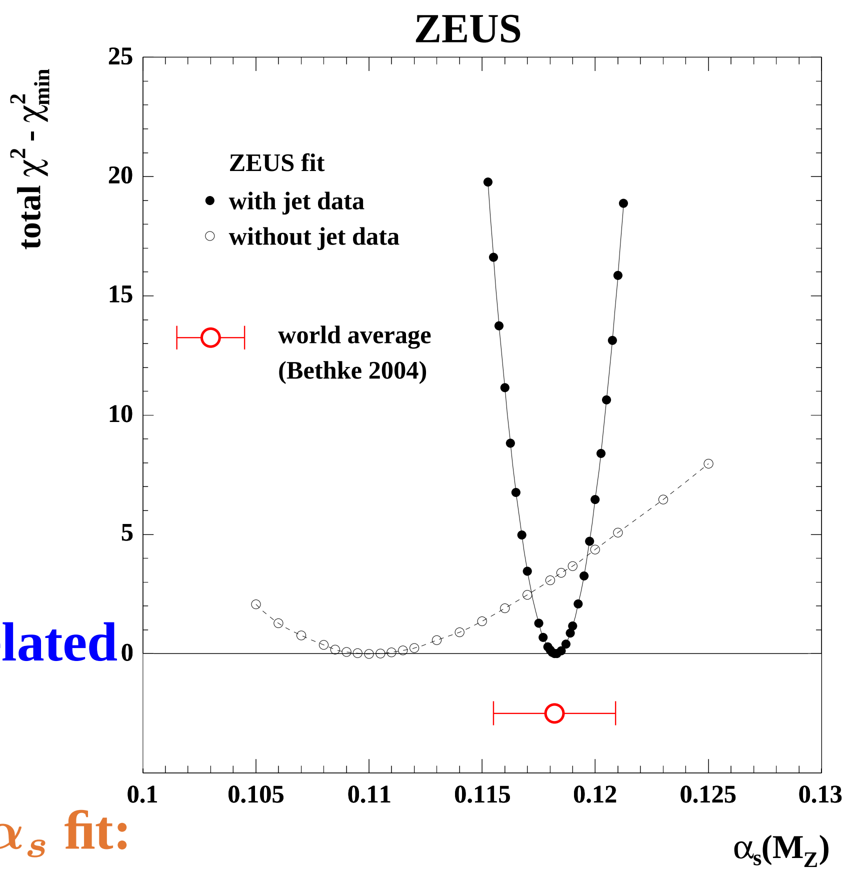
→ similar reduction by a factor of two in the mid-x region over the full Q^2 range



Determination of $\alpha_s(M_Z)$

- Simultaneous determination of the proton PDFs and $\alpha_s(M_Z)$
- Jet cross sections are directly sensitive to $\alpha_s(M_Z)$
  via $\gamma^{(*)}g \to q\bar{q}$ (coupled to gluon density) and
  via $\gamma^{(*)}q \to qg$ (NOT coupled to gluon density)

$\Rightarrow$ The inclusion of the jet cross sections allows an extraction of $\alpha_s(M_Z)$ that is NOT strongly correlated to the gluon density



- Determination of $\alpha_s(M_Z)$ from the ZEUS-JETS-α_s fit:

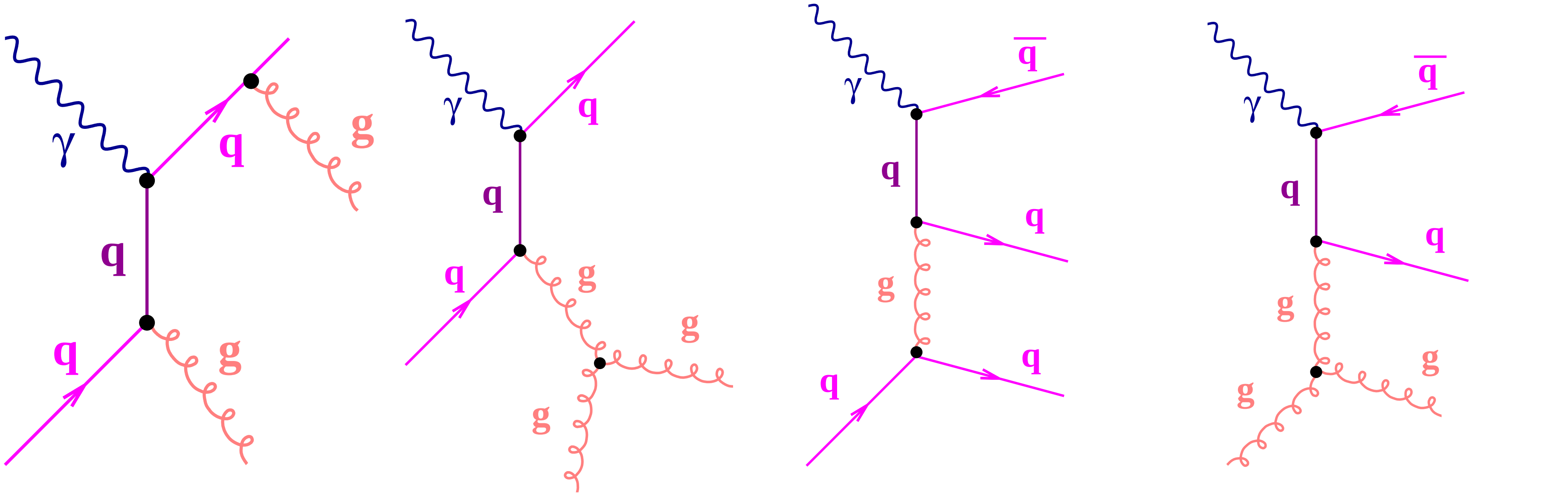
$$\alpha_s(M_Z) = 0.1183 \pm 0.0007\ (\text{uncorr.}) \pm 0.0022\ (\text{corr.}) \pm 0.0016\ (\text{norm.}) \pm 0.0008\ (\text{model})$$

$+$ estimation of the uncertainty due to terms beyond NLO $\rightarrow \Delta\alpha_s(M_Z) = \pm 0.0050$

$\Rightarrow$ Precise determination $\boxed{\alpha_s(M_Z) = 0.1183 \pm 0.0058}$ from ZEUS data alone

Photoproduction of Three-Jet Events: Colour Factors

- **Direct processes** provide a clean way to study the effects of the different color configurations

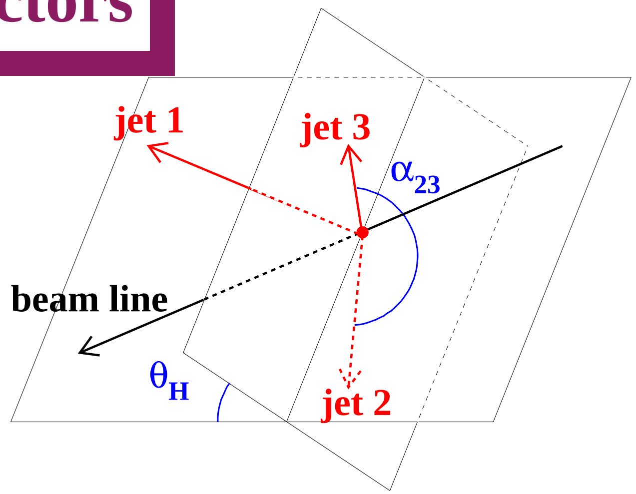


C_F^2 $\quad$ $C_F \cdot C_A$ $\quad$ $C_F \cdot T_F$ $\quad$ $T_F \cdot C_A$

- The predicted cross section at $\mathcal{O}(\alpha\alpha_s^2)$ can be written as

$$\sigma_{ep\to 3\mathrm{jets}} = C_F^2 \cdot \sigma_A + C_F C_A \cdot \sigma_B + C_F T_F \cdot \sigma_C + T_F C_A \cdot \sigma_D$$

Photoproduction of Three-Jet Events: Colour Factors



- **Variables** to highlight the contributions from the different color configurations
  $\Rightarrow$ **angular correlations between the jets**

$\longrightarrow$ θ_H (Muñoz-Tapia, Stirling);

$\longrightarrow$ α_{23}

$\longrightarrow$ $\cos\beta_{KSW} = \cos\frac{1}{2}[\angle[(\vec{p}_1 \times \vec{p}_3),(\vec{p}_2 \times \vec{p}_B)] + \angle[(\vec{p}_1 \times \vec{p}_B),(\vec{p}_2 \times \vec{p}_3)]]$,
where $\vec{p}_i$ is the momentum of jet i (ordered according to decreasing $E_T^{\rm jet}$) and $\vec{p}_B$ is a unit vector in the direction of the proton beam;

- Fixed-order ($\mathcal{O}(\alpha\alpha_s^2)$) calculations using direct processes

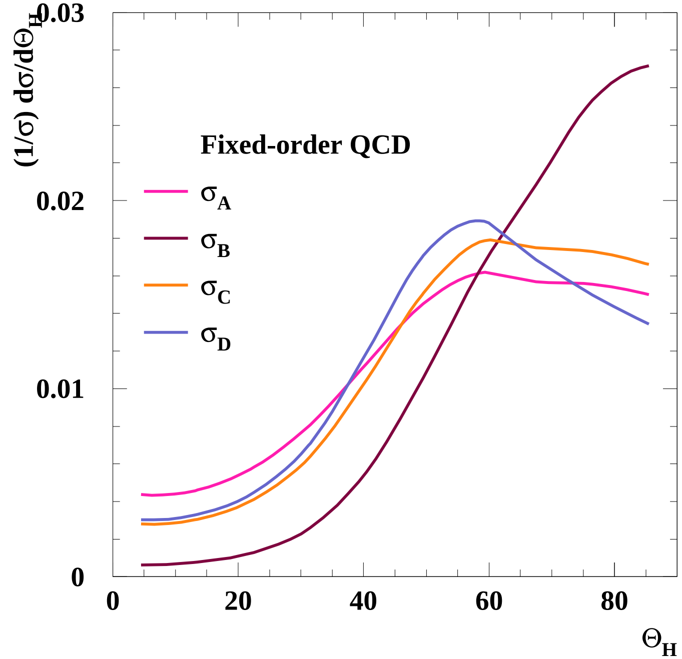
$\longrightarrow$ separation of the different colour components

$$\sigma_{ep\to 3\rm jets} = C_F^2\cdot\sigma_A + C_F C_A\cdot\sigma_B + C_F T_F\cdot\sigma_C + T_F C_A\cdot\sigma_D$$

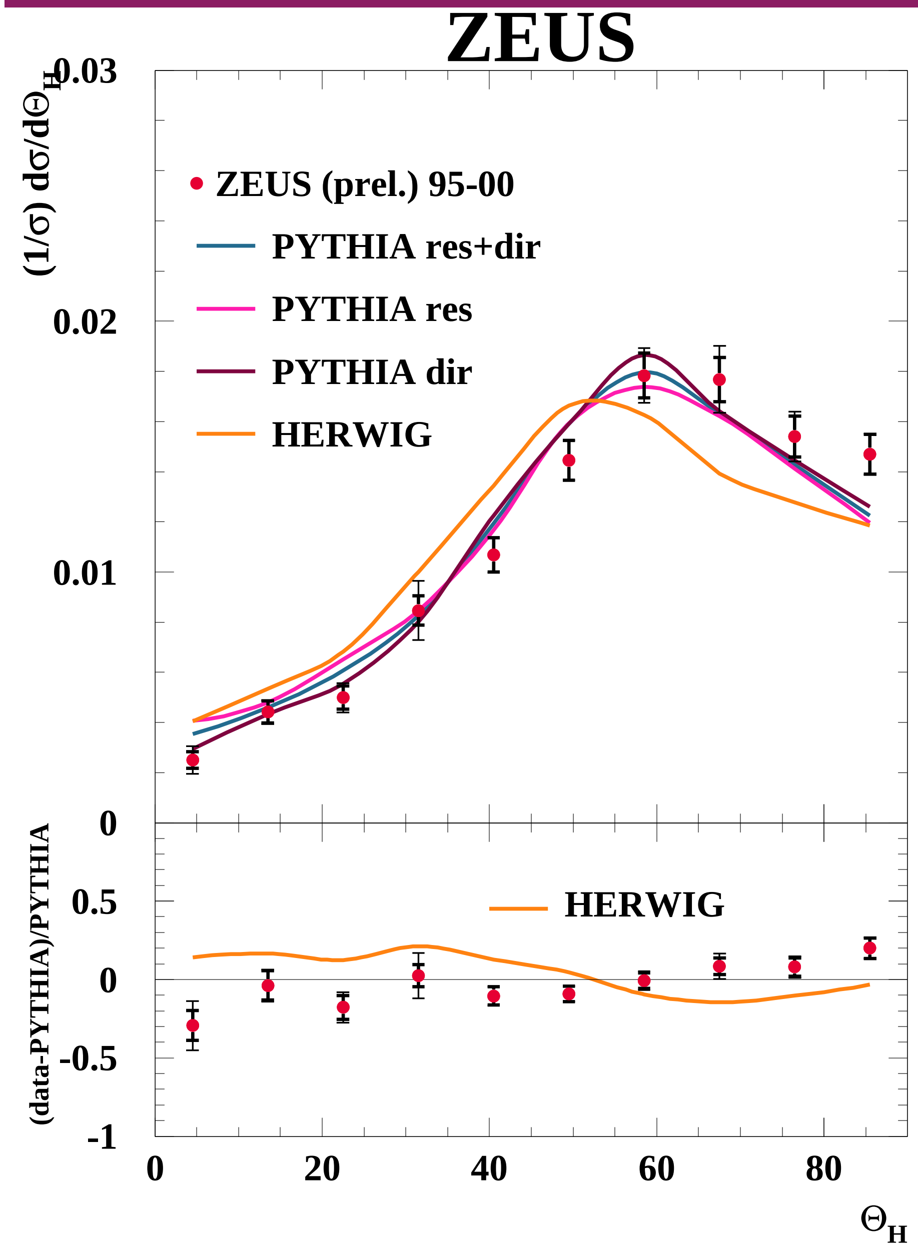
$\longrightarrow$ The predicted relative contributions for $SU(3)$:

A $\rightarrow$ 13%, B $\rightarrow$ 10%, C $\rightarrow$ 45%, D $\rightarrow$ 32%

- Example: the distribution in θ_H for the contribution σ_B is particularly distinct from the other color configurations



Photoproduction of Three-Jet Events: Colour Factors



- Measurement of the normalised cross section $1/\sigma \; d\sigma/d\theta_H$ for the production of events with three jets satisfying

  $E_T^{\rm jet} > 14$ GeV, $-1 < \eta^{\rm jet} < 2.5$

  and $x_\gamma^{\rm obs}(3{\rm jets}) > 0.7$

  in the kinematic region

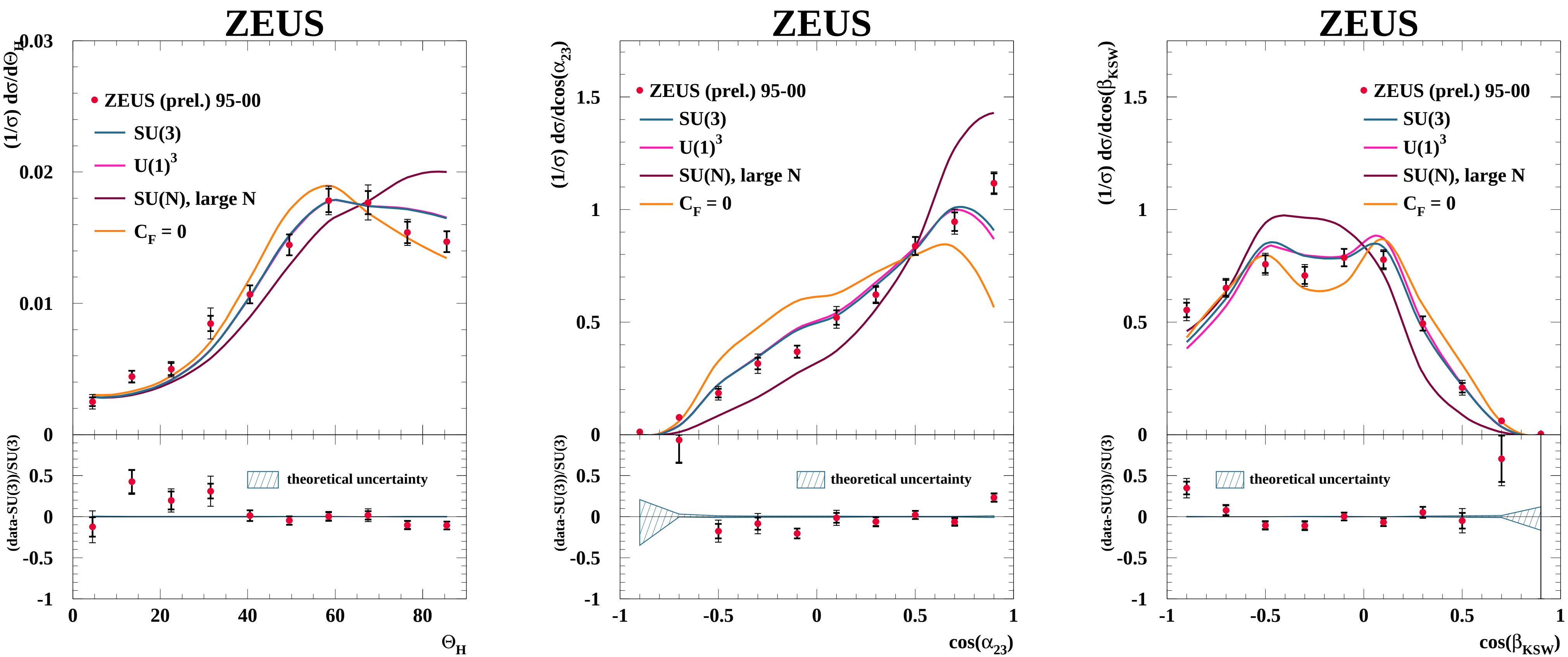
  $Q^2 < 1$ GeV^2 and $0.2 < y < 0.85$

- Comparison to the predictions of PYTHIA and HERWIG (leading-logarithm parton-shower calculations based on SU(3))

  → PYTHIA reproduces reasonably well the measured distribution

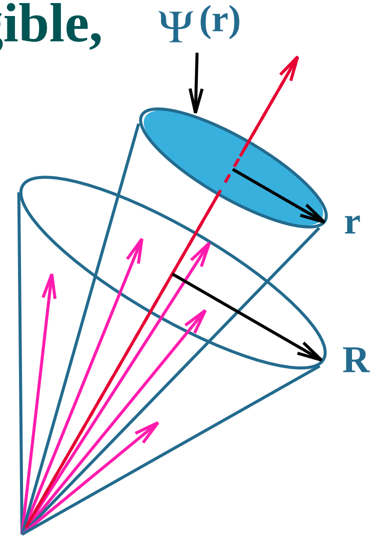
  → The distributions for direct and resolved processes ($\sim 34\%$) are very similar

Photoproduction of Three-Jet Events: Colour Factors



- Comparison to fixed-order calculations based on differente symmetry groups $SU(3)$, $SU(N)$ with $N \gg 1$, $U(1)^3$ and the extreme choice $C_F = 0$
- $U(1)^3$ vs $SU(3)$: similar shapes due to the smallness of σ_B
- The data disfavour $T_F/C_F \approx 0$ ($SU(N \gg 1)$) or $C_F = 0$
- The predictions of $SU(3)$ describe reasonably well the data

Jet Substructure



- At sufficiently high E_T^{jet}, where fragmentation effects become negligible, the jet substructure is expected to be calculable by pQCD
- Measurement of jet substructure allows investigations on

$\longrightarrow$ the differences between quark- and gluon-originated jets and

$\longrightarrow$ the dynamics of the different partonic final states,

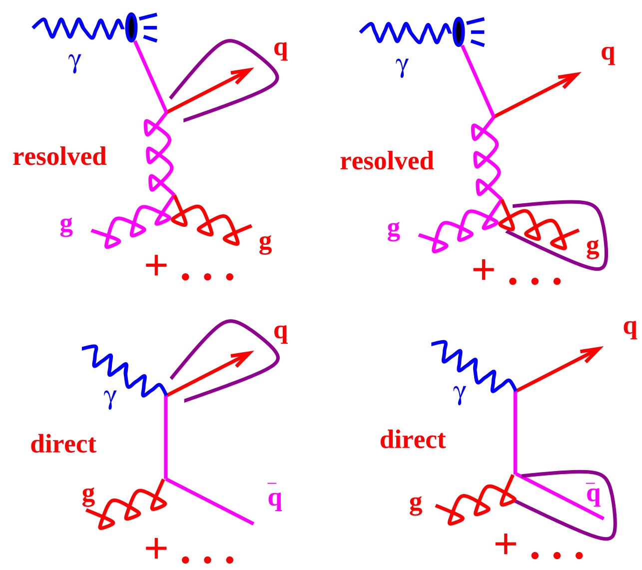
$\longrightarrow$ as well as determinations of α_s

- **Integrated jet shape:** $\langle\Psi(r)\rangle = \dfrac{1}{N_{jets}} \sum_{jets} \dfrac{E_T(r)}{E_T(r=1)}$

- Jet substructure in photoproduction:

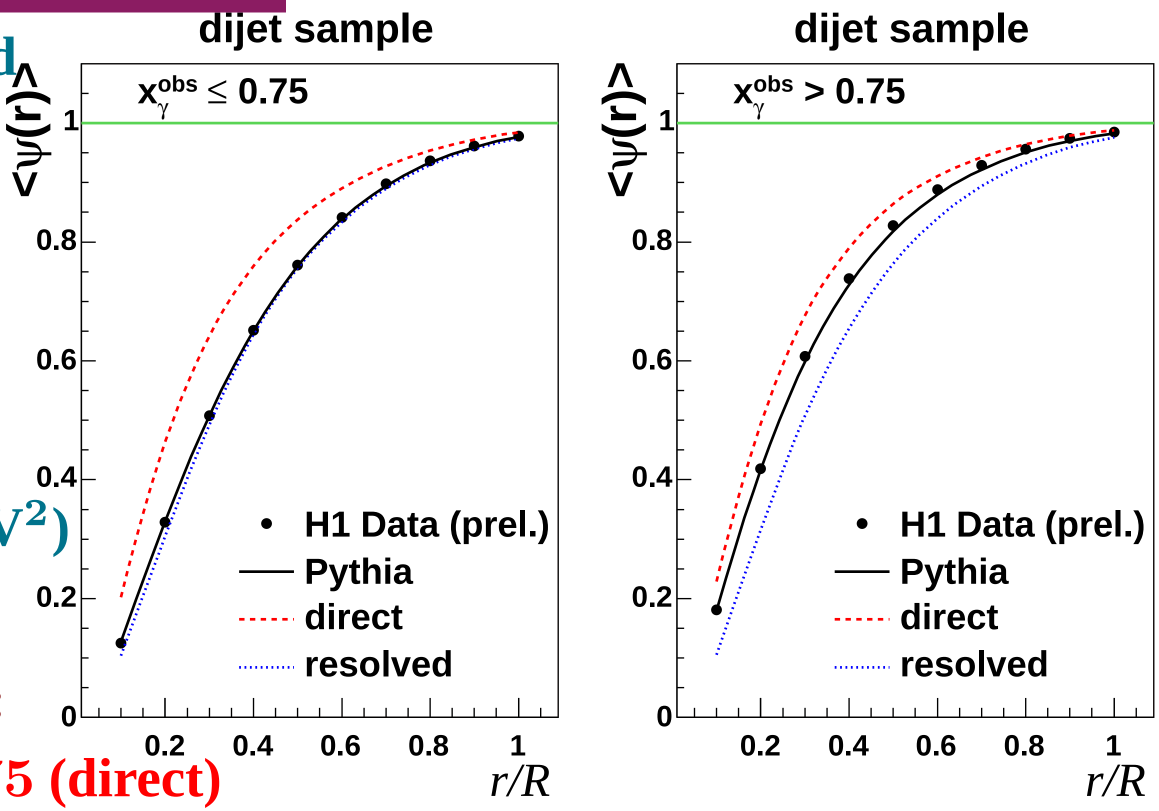
$\longrightarrow$ Resolved processes give rise to quark and gluon jets through $q_\gamma g_p \longrightarrow qg$, $g_\gamma g_p \longrightarrow gg$, ...

$\longrightarrow$ Direct processes give rise mostly to quark jets through $\gamma g \longrightarrow q\bar{q}$



$\Rightarrow$ The η^{jet} dependence of the jet substructure should show: quark-like jets for $\eta^{jet} < 0$ and gluon-like jets in the forward direction

Jet Substructure in Photoproduction



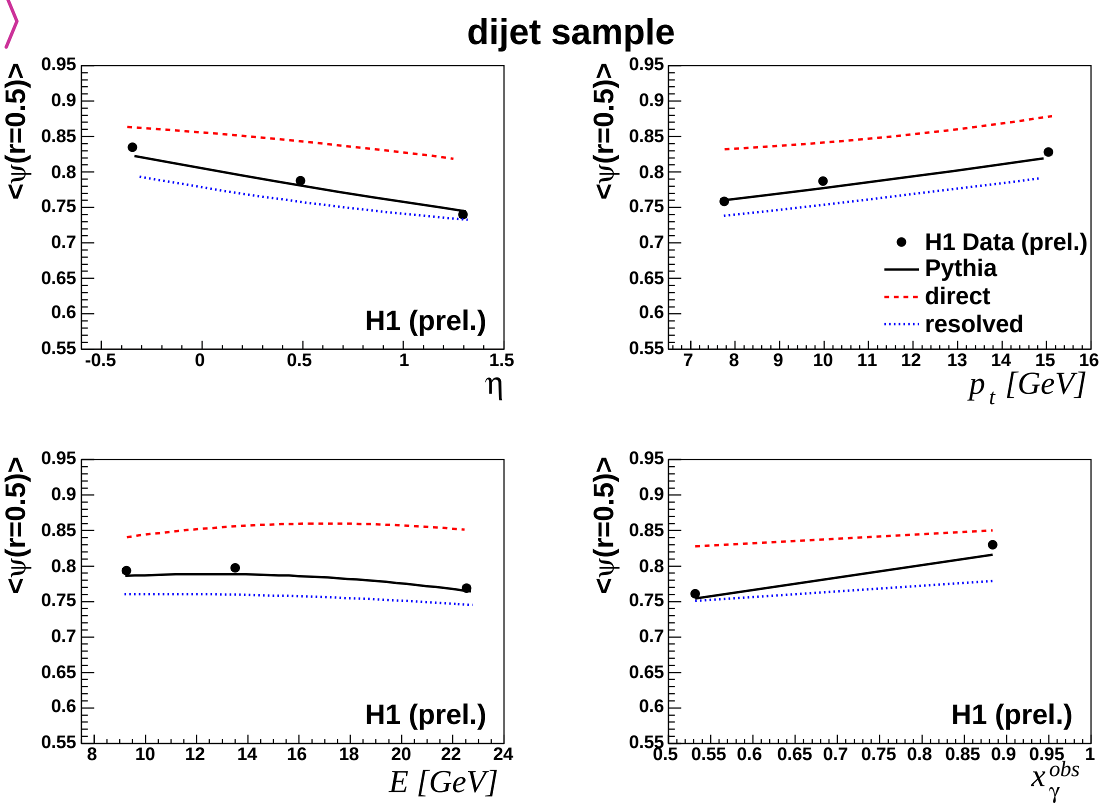
- **New measurements of the integrated jet shape $\langle\Psi(r)\rangle$ for a sample of dijet events**
  $E_T^{jet,1}$(Lab)> 7 GeV
  $E_T^{jet,2}$(Lab)> 6 GeV
  $20^\circ < \theta^{jet}$(Lab)$< 160^\circ$
  in photoproduction ($Q^2 < 0.01$ GeV^2) with $0.3 < y < 0.65$
- **Measurements in two regions of x_γ: $x_\gamma < 0.75$ (resolved) and $x_\gamma > 0.75$ (direct)**
- **Comparison with model predictions for resolved and direct processes including initial- and final-state QCD radiation (PYTHIA): good description of the data**
- **The jets in the region $x_\gamma < 0.75$ are broader than in the region $x_\gamma > 0.75$, consistent with a larger fraction of gluon (broad) jets in resolved-photon events than in direct-photon events**

Jet Substructure in Photoproduction

- **The dependence of $\langle\Psi(r=0.5)\rangle$ on η^{jet}, E_T^{jet}, E^{jet} and x_γ:**

  $\longrightarrow$ the jet becomes broader as η^{jet} increases (proton direction)

  $\longrightarrow$ the jet becomes narrower as E_T^{jet} or x_γ increases (direct processes)
- **The measured dependencies of $\langle\Psi(r=0.5)\rangle$ on the different variables are well described by the predictions of PYTHIA**
- **The observed decrease in $\langle\Psi(r=0.5)\rangle$ as η^{jet} increases is consistent with the increase in the fraction of gluon jets as predicted by PYTHIA**



- **Dominant hard subprocesses:**

  $\gamma g \longrightarrow q\bar{q}$ in direct processes

  $q_\gamma g_p \longrightarrow qg$ in resolved processes

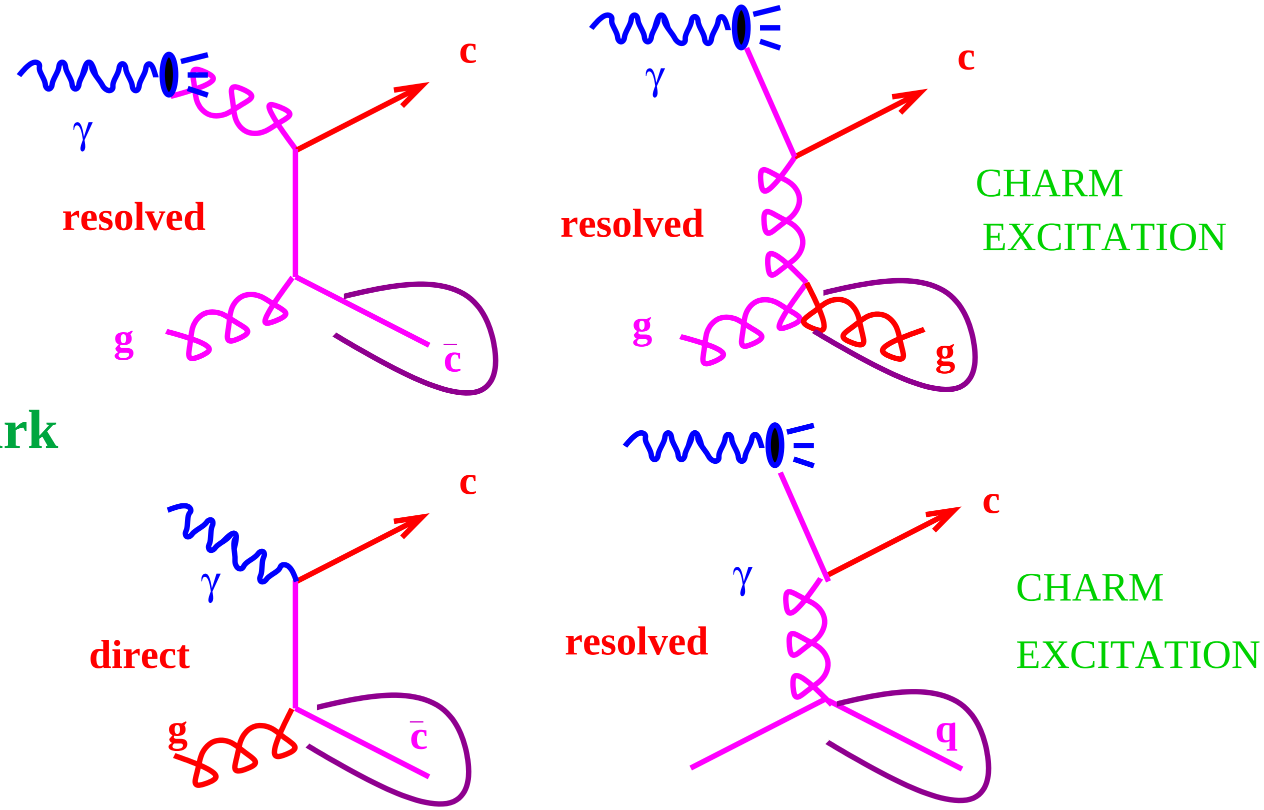
  with a large and increasing fraction of gluon jets as η^{jet} increases ($\hat{t}$-pole)

Jet Substructure in Photoproduction: Charm jets

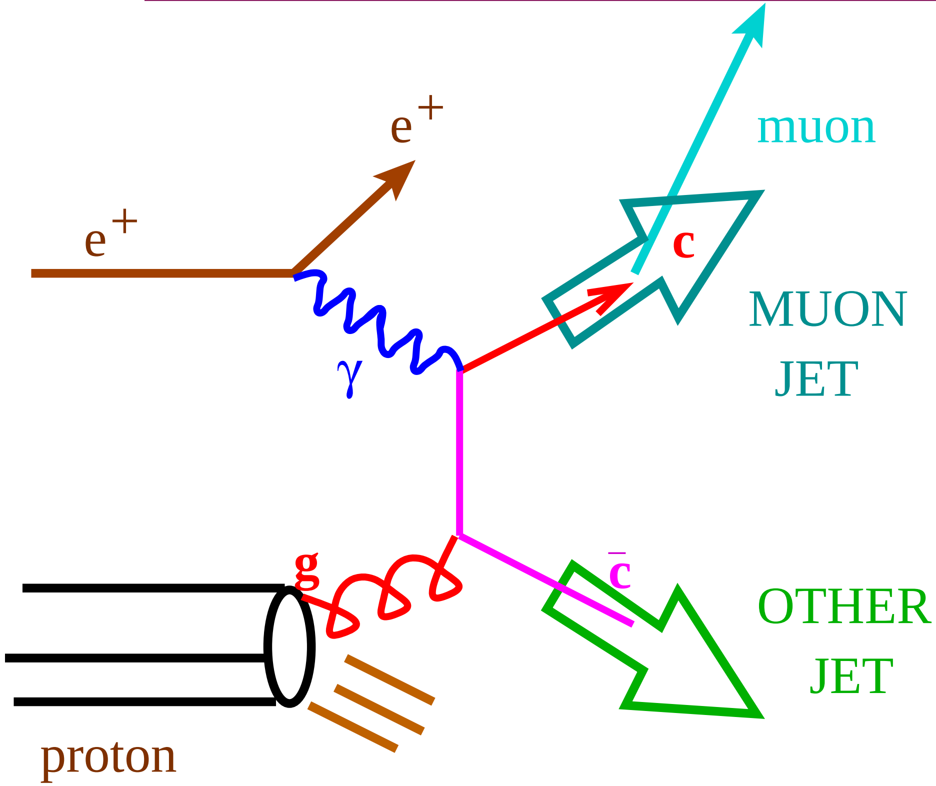
- Investigation of the different processes contributing to charm photoproduction by selecting dijet events with one jet tagged as the charmed jet and measuring the jet shape of the "other jet" in the event
- At high x_γ the major process contributing to the sample is boson-gluon fusion $\Rightarrow$ the "other jet" in an event is also a charm quark
- At low x_γ there are several contributing processes:

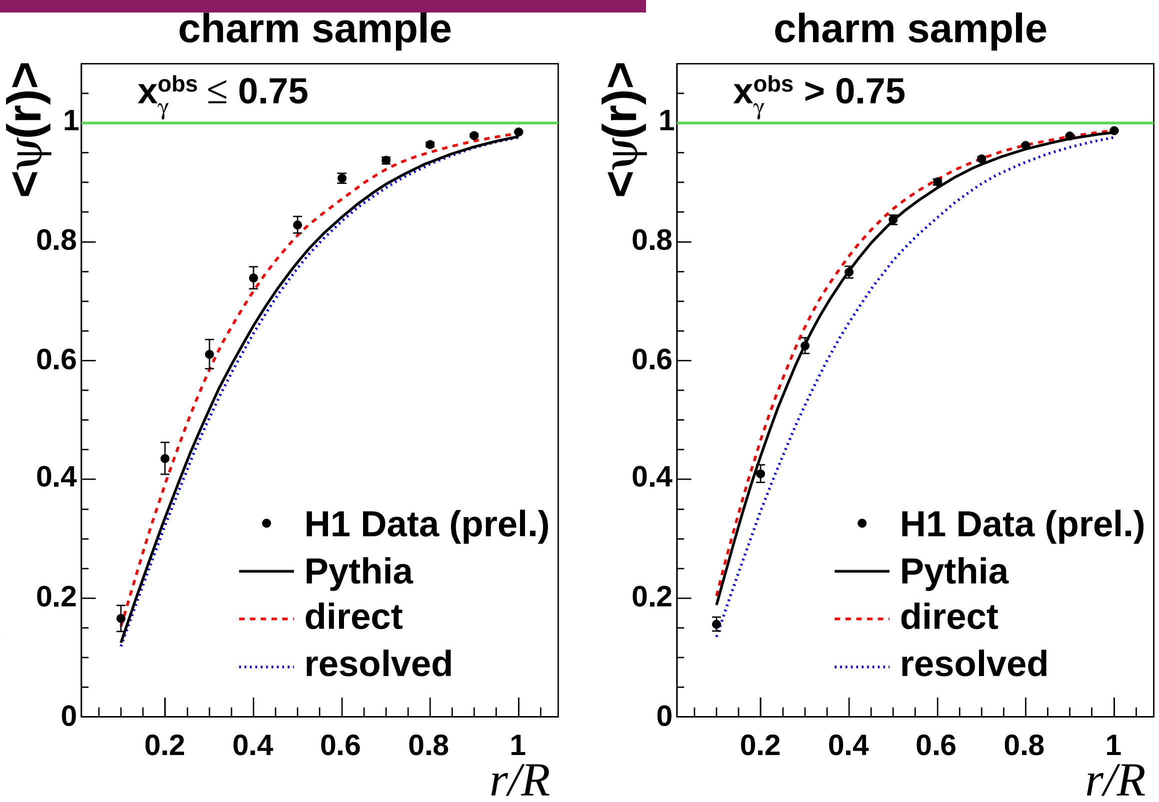
$\longrightarrow$ gluon-gluon fusion; the "other jet" is a charm quark

$\longrightarrow$ charm-excitation processes; the "other jet" is a gluon or a quark



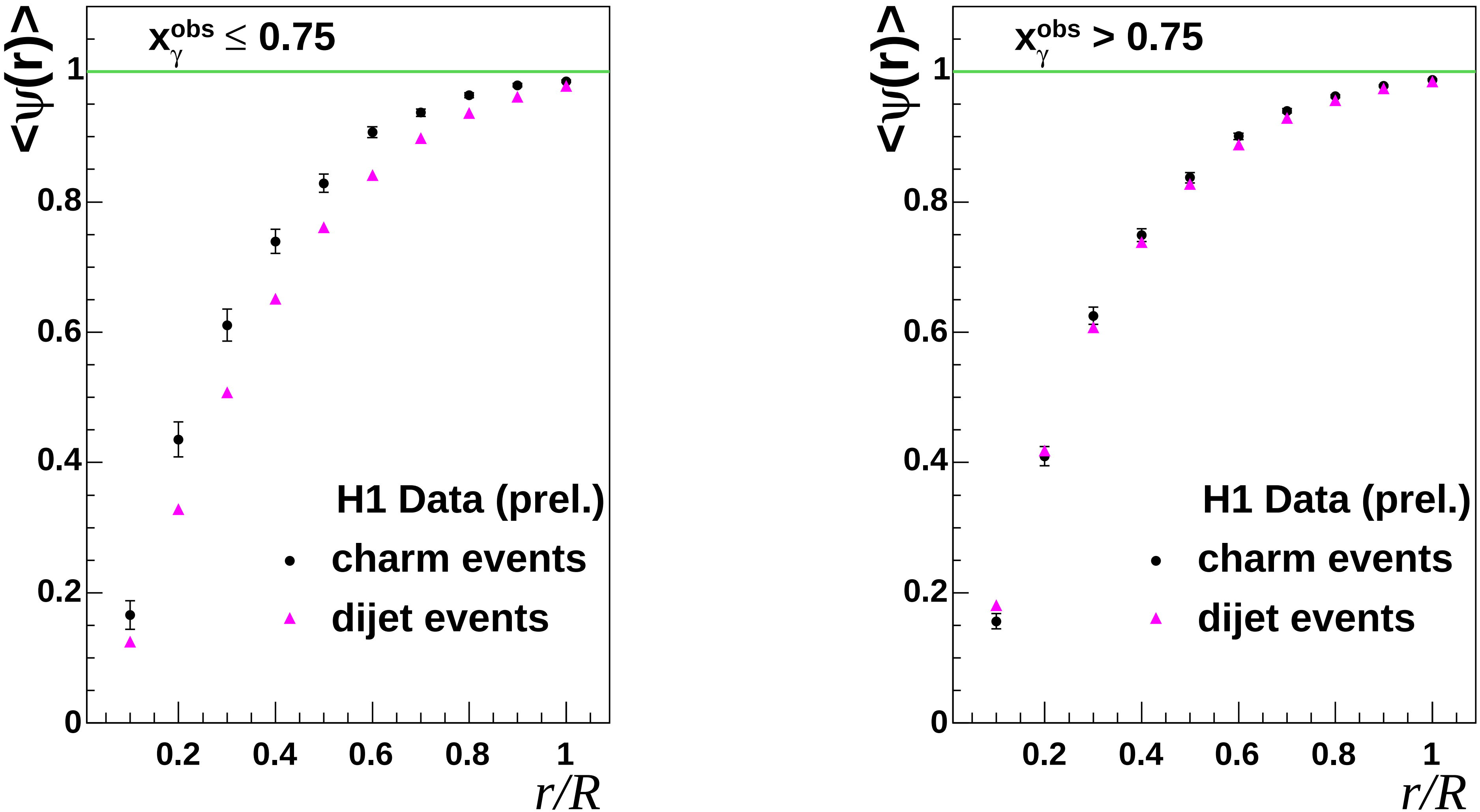
Jet Substructure in Photoproduction: Charm jets





- Sample of dijet events with a μ-tagged jet: measurement of $\langle\Psi(r)\rangle$ for the "other" jet (purity of the tagged jet: $71-73\%$; the background is statistically subtracted)
- The predictions of PYTHIA (including charm-excitation) describes well the data in the region $x_\gamma > 0.75$; differences are observed in the region $x_\gamma < 0.75$
  $\Rightarrow$ the data suggest a smaller fraction of gluon jets at low x_γ than predicted by PYTHIA

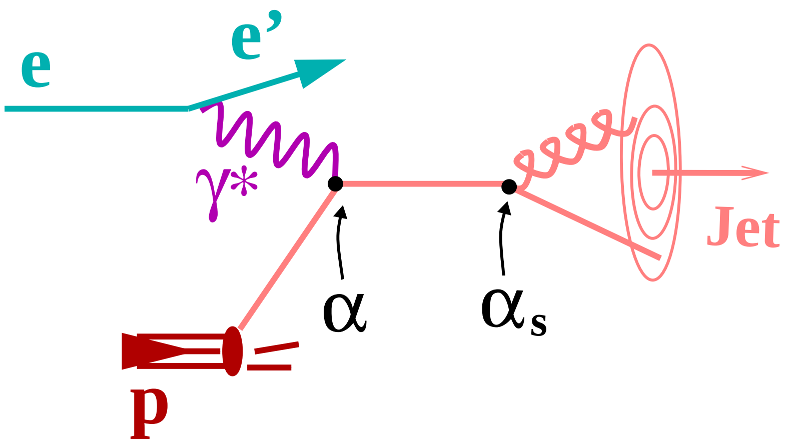
Jet Substructure in Photoproduction: Charm jets



- **Comparison of the measurements of $\langle\Psi(r)\rangle$ between inclusive dijet events and the "other jet" in μ-tagged dijet events ("charm events")**

Jet Substructure in Neutral Current Deep Inelastic Scattering

- The lowest non-trivial-order contribution to the measurements is given by $\mathcal{O}(\alpha\alpha_s)$ pQCD calculations

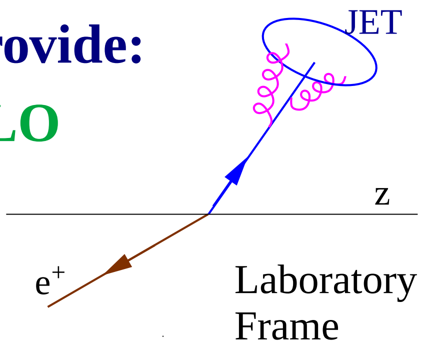


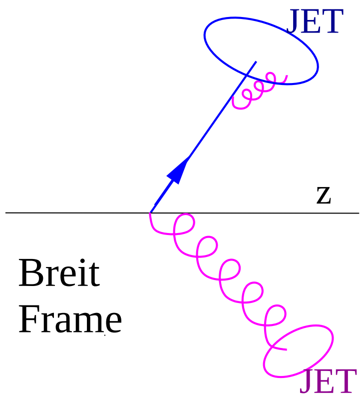
$$\langle 1 - \Psi(r) \rangle = \frac{\int dE_T \; E_T [d\sigma(ep \to 2\text{partons})/dE_T]}{E_T^{jet} \; \sigma_{\text{jet}}(E_T^{jet})}$$

- NLO QCD calculations of jet substructure can be made in the laboratory frame since it is possible to have 3 partons in the same jet (not possible in the Breit frame)
- The dependence of the pQCD calculations on the knowledge of the proton PDFs is reduced
- Measurements of jet substructure in NC DIS provide:

→ a stringent test of pQCD calculations beyond LO

→ a determination of α_s



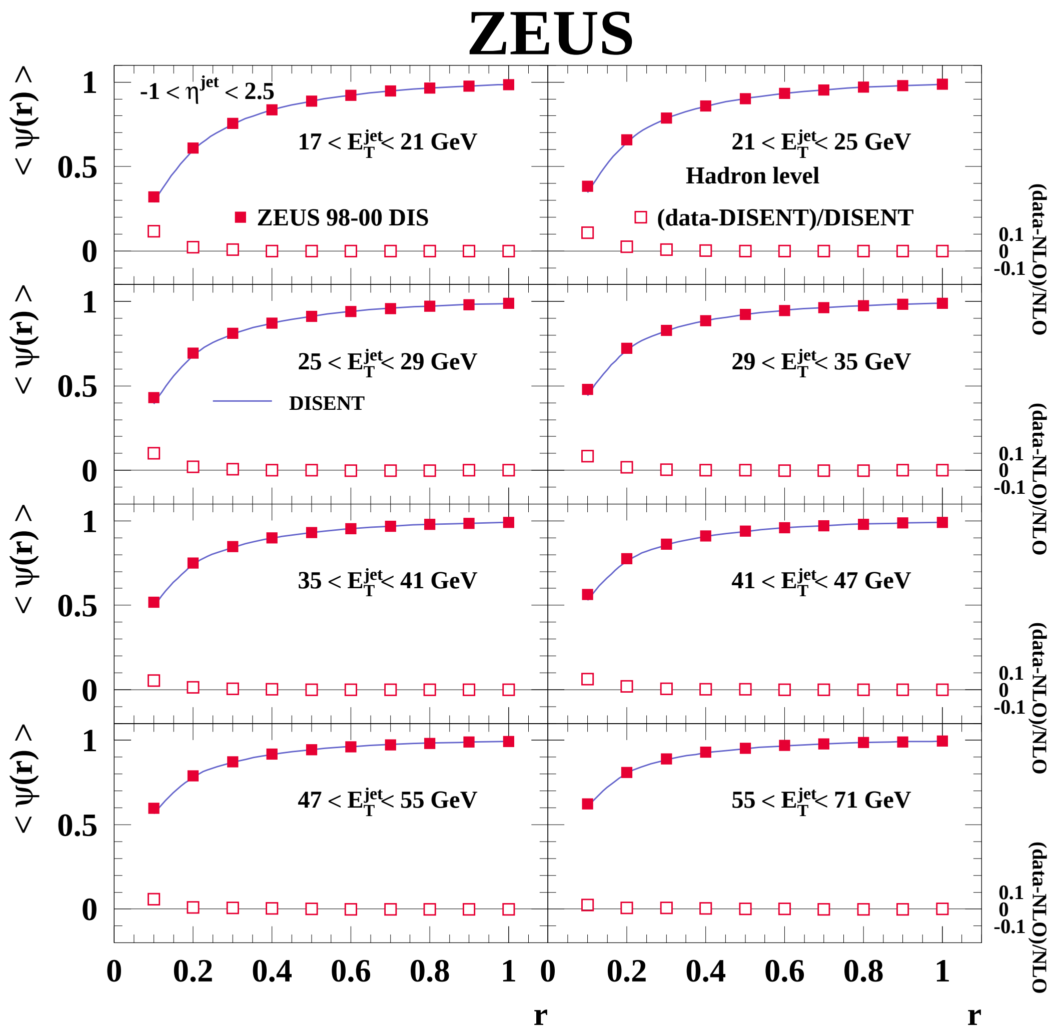


Jet Substructure in Neutral Current Deep Inelastic Scattering

- Measurement of $\langle\Psi(r)\rangle$ for an inclusive sample of jets with E_T^{jet}(Lab)> 17 GeV and $-1 < \eta^{jet}$(Lab)< 2.5 in NC DIS at $Q^2 > 125$ GeV^2

- Study of the $E_T^{\rm jet}$-dependence of $\langle\Psi(r)\rangle$: the jets become narrower as $E_T^{\rm jet}$ increases

- Comparison to NLO QCD calculations corrected for hadronisation effects ($< 5\%$ for $E_T^{\rm jet} > 21$ GeV at $r = 0.5$)



- NLO QCD calculations provide a good description of the data: $\longrightarrow$ (DATA-NLO)/NLO smaller than 0.2% for $r = 0.5$

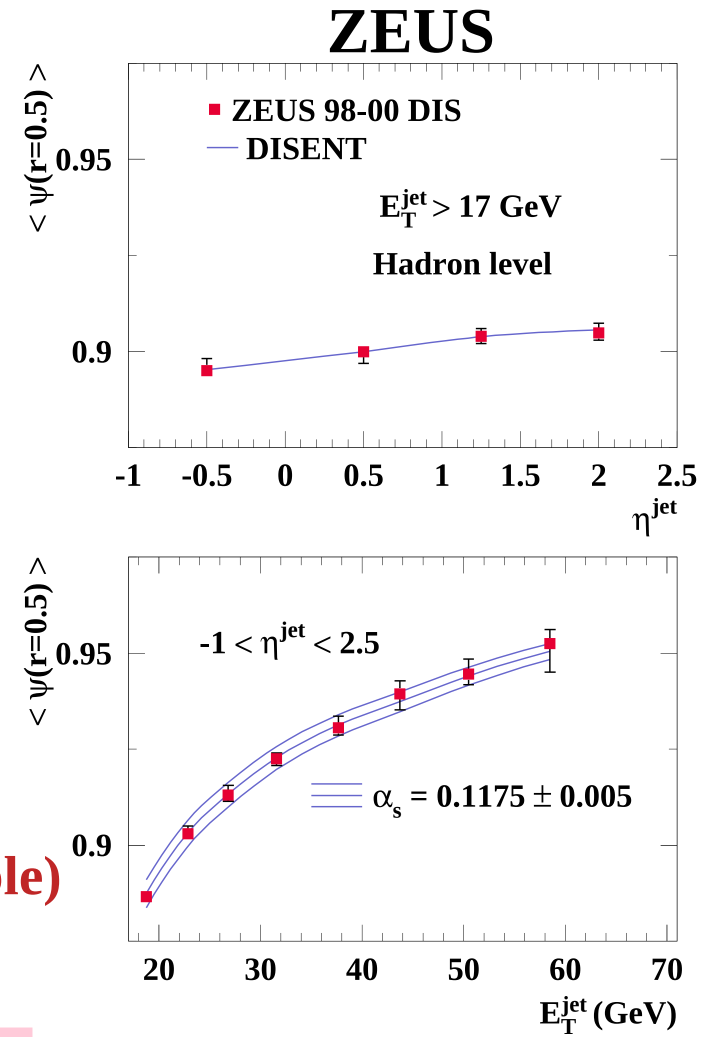
Jet Substructure in Neutral Current DIS and extraction of $\alpha_s(M_Z)$

- The measurements of $\langle\Psi(r=0.5)\rangle$ for E_T^{jet}(Lab)$>$ 21 GeV have been used to extract the value of $\alpha_s(M_Z)$:

$$\alpha_s(M_Z) = 0.1176 \pm 0.0009\ (\text{stat.})\ ^{+0.0009}_{-0.0026}\ (\text{exp.})\ ^{+0.0091}_{-0.0072}\ (\text{th.})$$

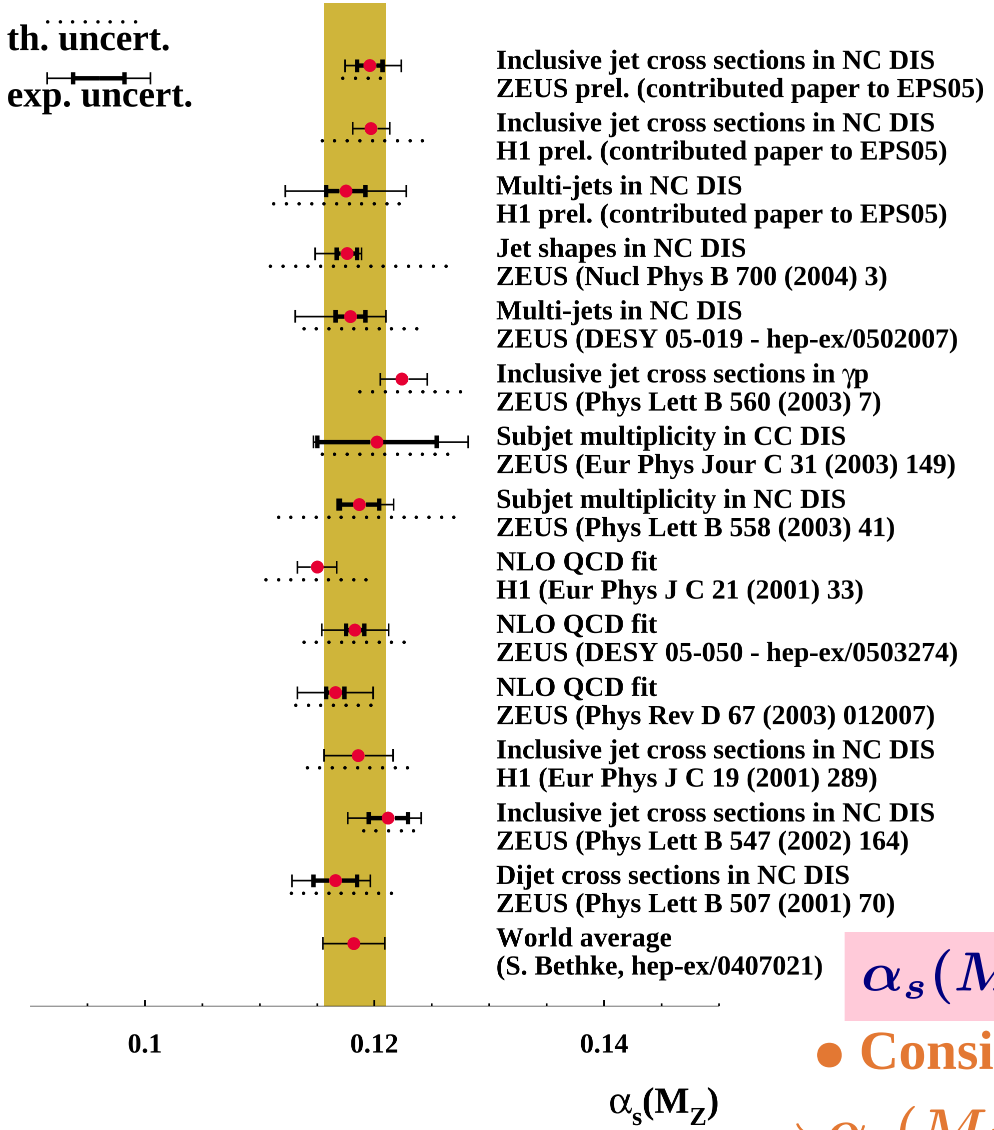
- Small experimental uncertainties: $\Delta\alpha_s/\alpha_s = ^{+0.8}_{-2.2}$ %

- The theoretical uncertainties dominate:
  - $\longrightarrow$ terms beyond NLO $\Delta\alpha_s(M_Z) = ^{+0.0089}_{-0.0070}$
  - $\longrightarrow$ parton-to-hadron effects $\Delta\alpha_s(M_Z) = \pm 0.0018$
  - $\longrightarrow$ uncertainty due to those of the proton PDFs (negligible)



Improvements depend upon further Theoretical Work

Summary of α_s determinations



- Wealth of determinations of α_s at HERA from a variety of observables:

$\rightarrow$ NLO QCD analyses of structure functions

$\rightarrow$ Inclusive jet production in NC DIS

$\rightarrow$ Dijet production in NC DIS

$\rightarrow$ Tri-jet/Dijet rate in NC DIS

$\rightarrow$ Jet substructure in NC DIS

$\rightarrow$ Jet substructure in CC DIS

$\rightarrow$ Inclusive jet photoproduction

- Theoretical uncertainties are dominant

$\rightarrow$ Biggest contrib. from terms beyond NLO

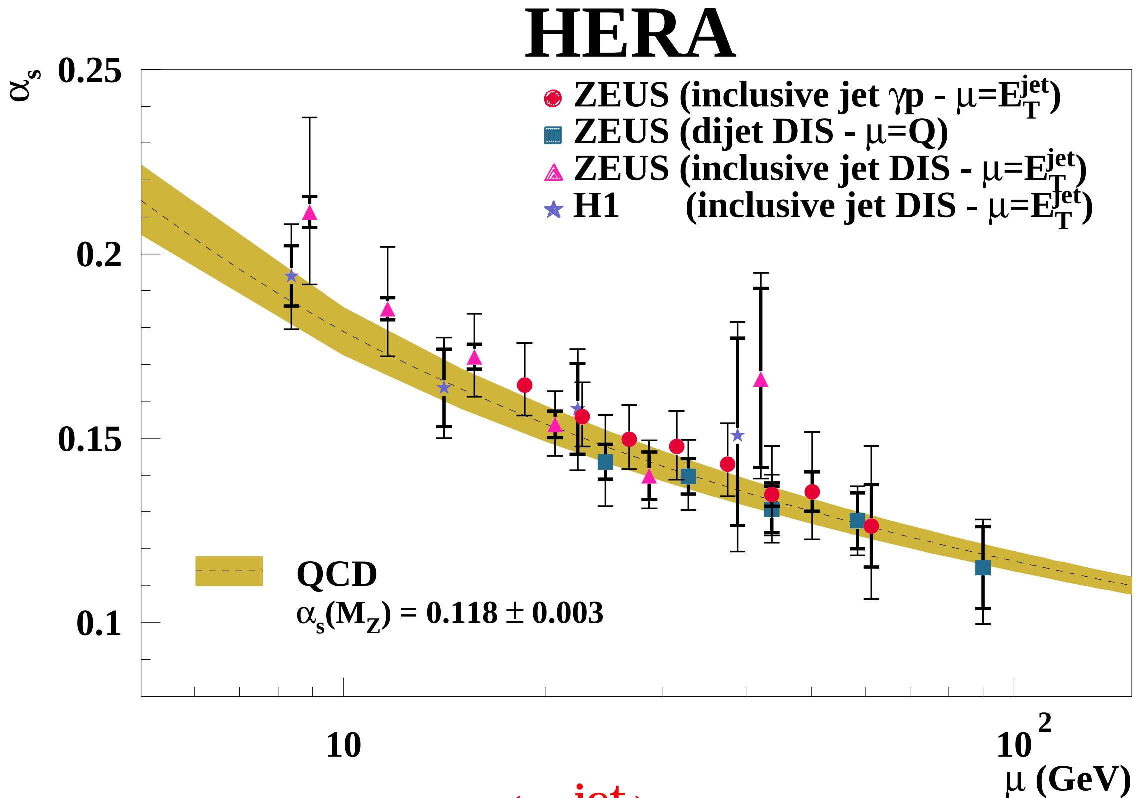
- Average of HERA determinations

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

- Consistent with world average (Bethke, 2004):

$\rightarrow \alpha_s(M_Z) = 0.1182 \pm 0.0027$ (only NNLO results)

The running of α_s from HERA data alone



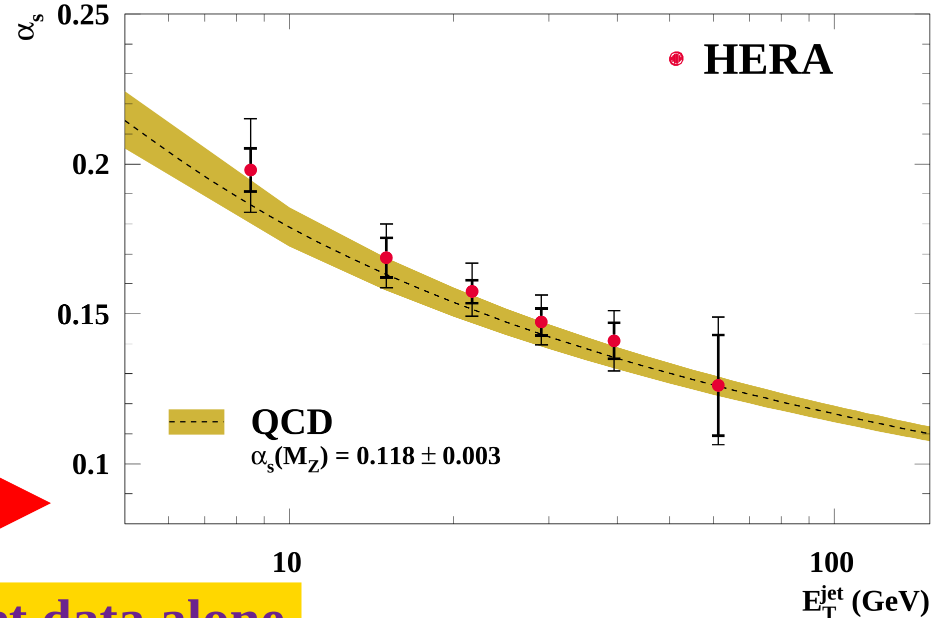
- **Determinations of $\alpha_s(\mu)$:**

$\rightarrow$ **Dijet NC DIS ($\mu = Q$)**

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

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

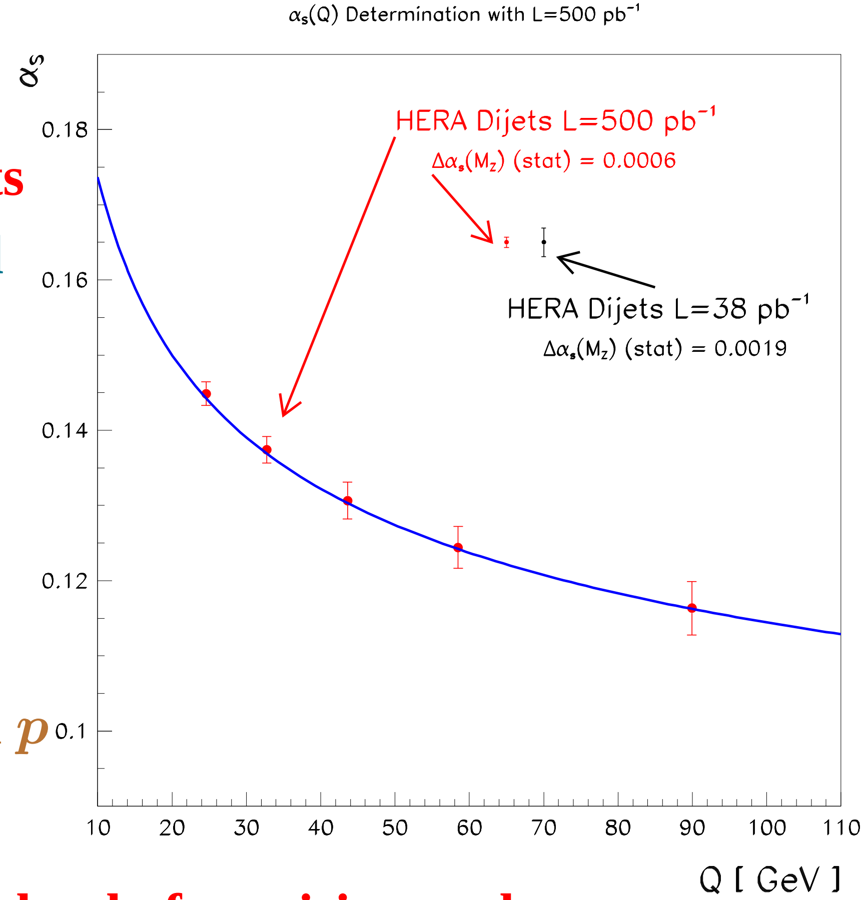
- **Combination of $\alpha_s(E_T^{\rm jet})$ determinations at similar energy scales**



Observation of the running of α_s from HERA jet data alone

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

Summary and Outlook (HERA II)



- **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 α_s

⟶ improved determination of the gluon density in p

⟶ tests of the partonic structure of the photon

- **In many areas the measurements have reached a level of precision such that the theoretical uncertainties dominate in the accuracy of the final results**

- **To further improve the accuracy of the determination of the fundamental parameters of QCD and of the tests at higher orders, and to fully exploit the HERA II programme,**

⇒ further theoretical work will be useful