S. Petersburg, DIS 2003
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Tests of perturbative QCD with hadronic final states in hadron-induced reactions

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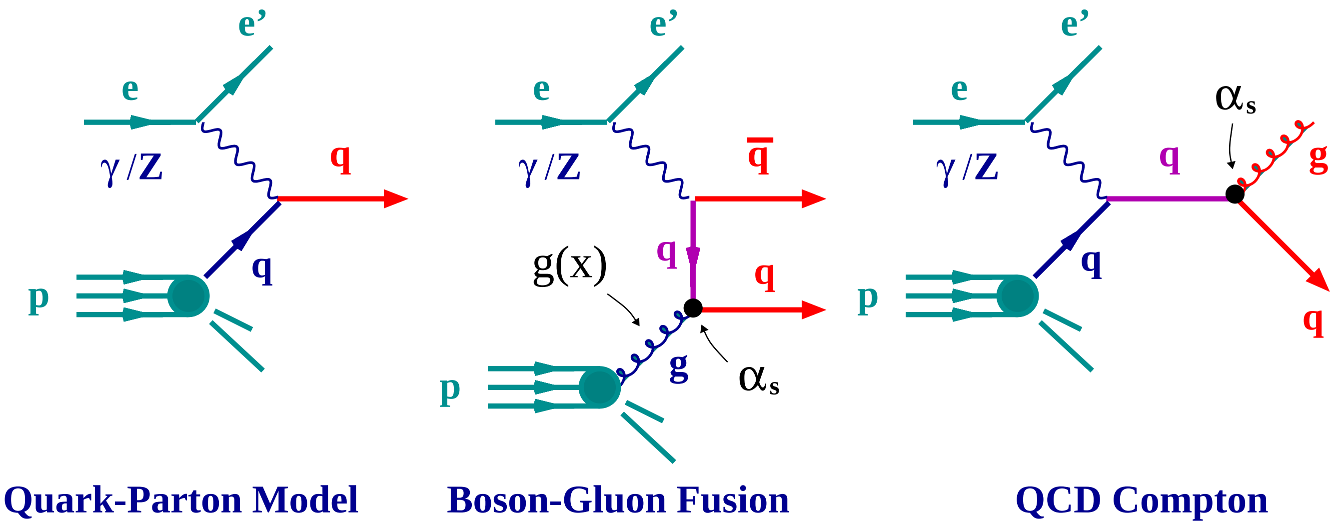
- **Outline**
  - $\rightarrow$ Deep inelastic scattering (HERA)
  - $\rightarrow$ γp collisions (HERA)
  - $\rightarrow$ $\gamma\gamma$ collisions (LEP)
  - $\rightarrow$ $p\bar{p}$ collisions (TEVATRON)

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:

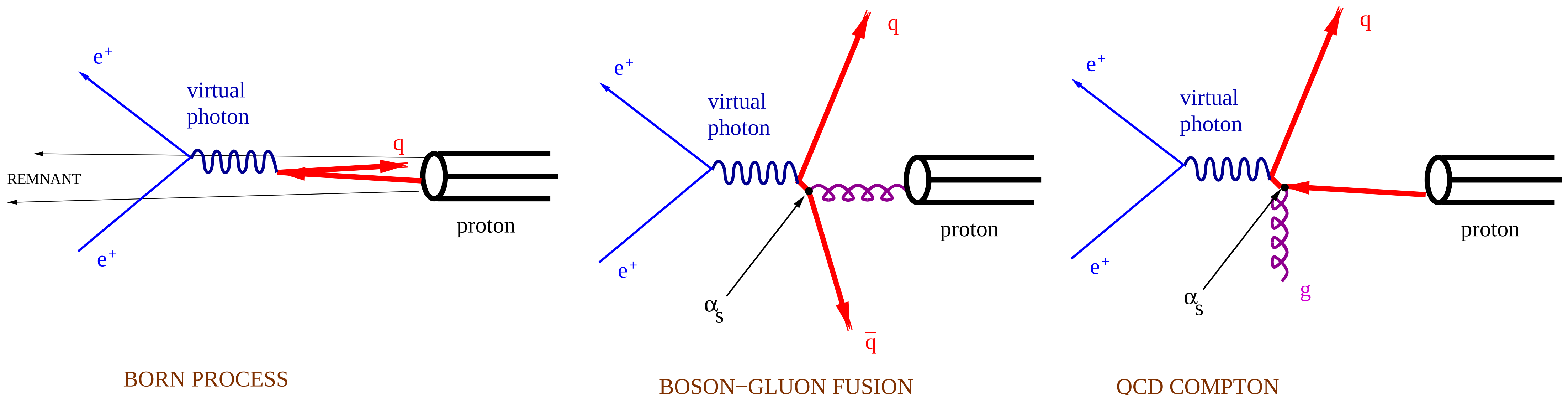
$$d\sigma_{jet} = \sum_{a=q,\bar{q},g} \int dx\ f_a(x,\mu_F^2)\ d\hat{\sigma}_a(x,\alpha_s(\mu_R),\mu_R^2,\mu_F^2)$$

  - 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?
- Exploration of the low Q^2 (transition) region $\Rightarrow$ resolved virtual photons?

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)

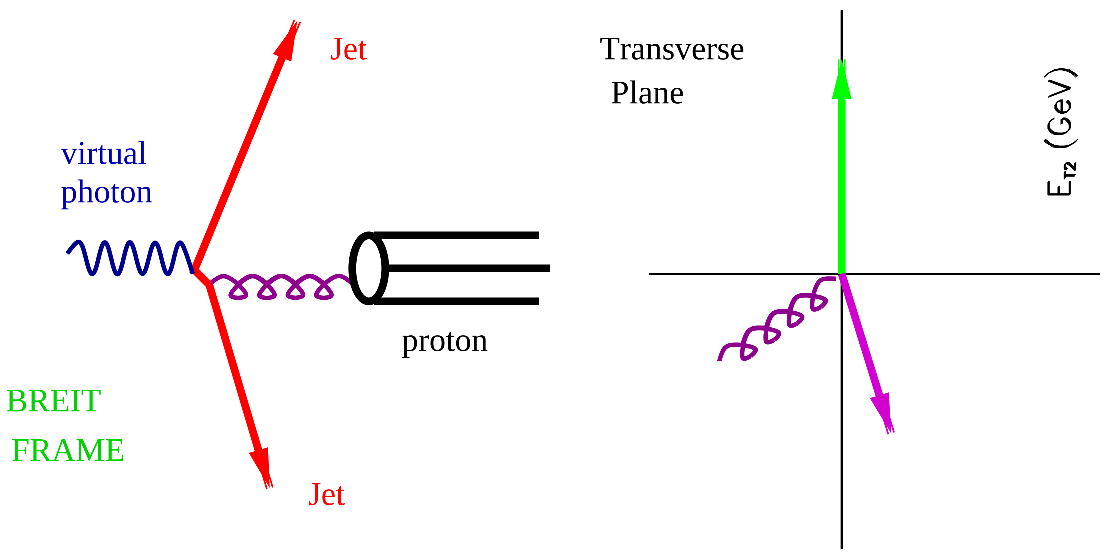
NLO QCD Calculations of Jet Cross Sections in DIS

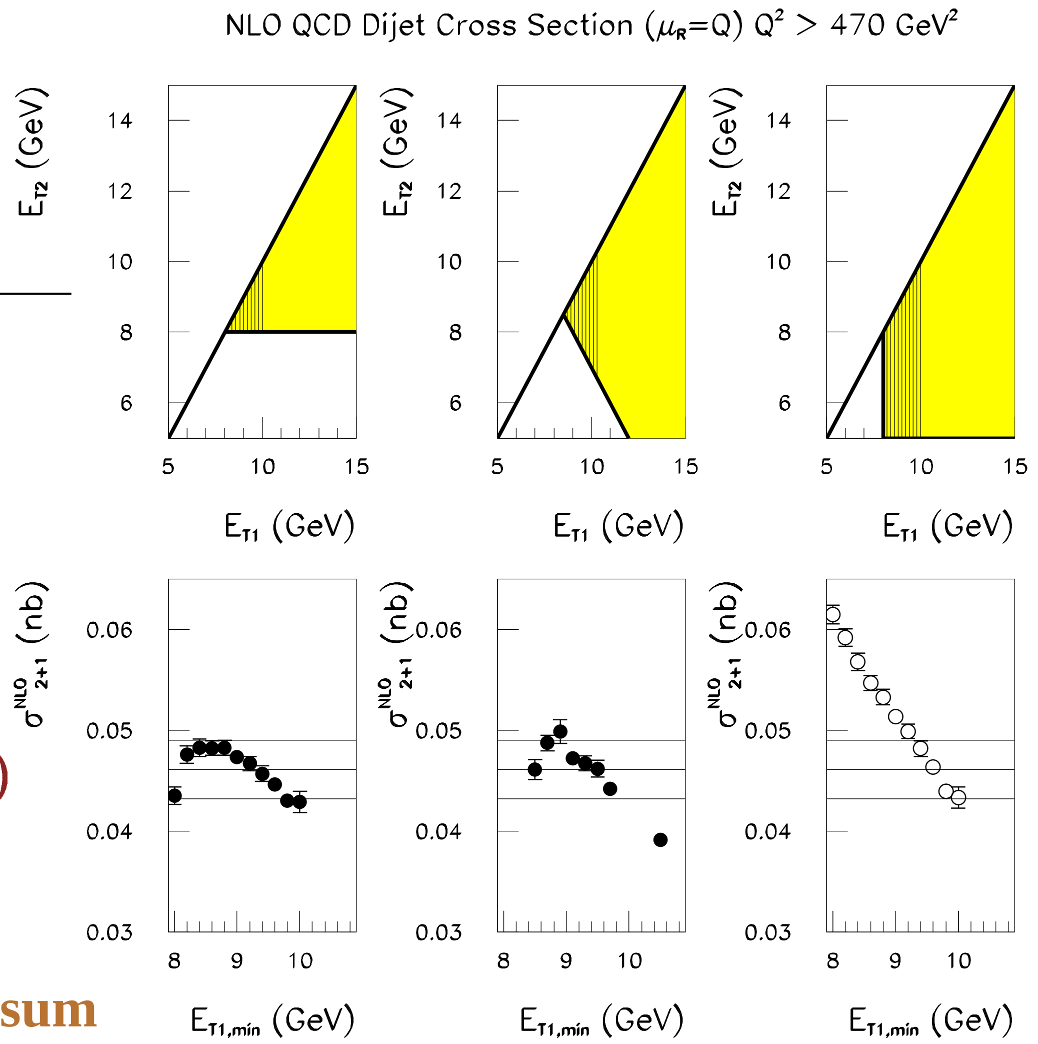
- Several NLO QCD programs are available for performing jet cross section calculations $\rightarrow$ DISENT (Catani and Seymour), MEPJET (Mirkes and Zeppenfeld), DISASTER++ (Graudenz), NLOJET (Nagy and Trocsanyi)
- NLO corrections $\rightarrow$ virtual corrections with internal particle loops
  $\rightarrow$ real corrections with a third parton in the final state
- Different methods to calculate real corrections:

$\rightarrow$ phase space slicing method (M), subtraction method (D, D++, NJ)

- Since there are two hard scales in jet production, the renormalisation and factorisation scales can be chosen as one of the two, $\mu_R,\ \mu_F = Q$ or E_T^{jet}
- The calculations are for jets of partons and the measurements are done at the hadron level $\rightarrow$ need to correct the calculations for hadronisation effects
- Theoretical uncertainties:
  $\rightarrow$ terms beyond NLO, which are usually estimated by varying μ_R by factor 2
  $\rightarrow$ uncertainties on $\alpha_s(M_Z)$ and the proton PDFs
  $\rightarrow$ uncertainty coming from the hadronisation corrections

Jet Finding and Selection Criteria for Dijet Events





- Longitudinally invariant k_T-cluster algorithm in the η-ϕ plane of Breit frame

$$d_{ij} = min(E^2_{T,i}, E^2_{T,j}) \cdot (\Delta\eta^2_{ij} + \Delta\phi^2_{ij})$$

- Dijet selection criteria:

$\rightarrow$ Symmetric cuts on $E_T^{jet,1(2)}$ $\Rightarrow$ danger

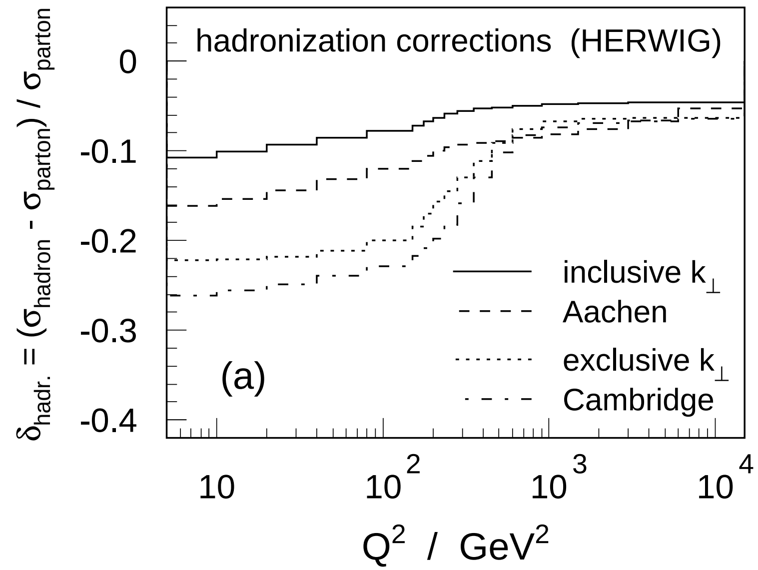
$\rightarrow$ Symmetric cuts on $E_T^{jet,1(2)}$ and cut on sum

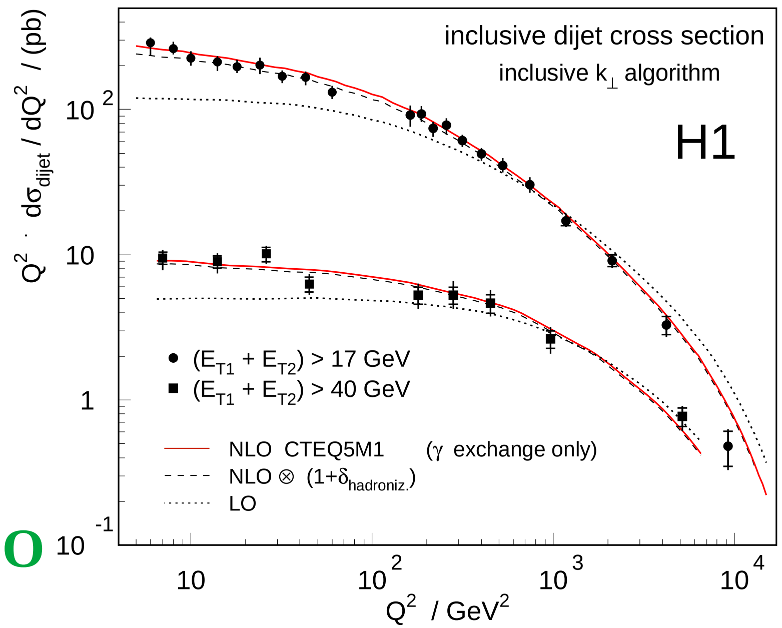
$\rightarrow$ Asymmetric cuts on $E_T^{jet,1(2)}$

$\Rightarrow$ NLO calculations for dijet cross sections can be (infrared) sensitive to the selection criteria

Dijet Cross Sections in NC DIS ($5 < Q^2 < 15000$ GeV^2)

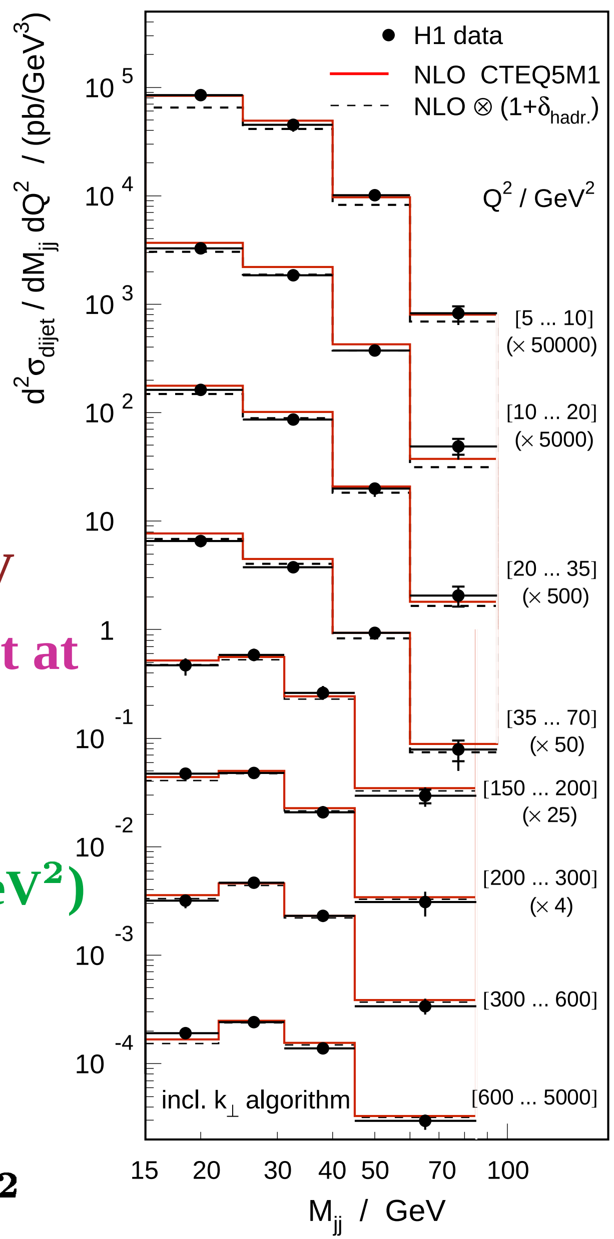
- Measurement of differential dijet cross sections over a wide range in $Q^2 \to 5 < Q^2 < 15000$ GeV^2 and $0.2 < y < 0.6$ for dijet production with
  - $E_T^{jet,1(2)}$(Breit)> 5 GeV
  - $E_T^{jet,1}$(Breit)$+E_T^{jet,2}$(Breit)> 17 GeV
  - $-1 < \eta^{jet,1(2)}$(Lab)< 2.5
- Detailed investigation of the jet algorithms:
  - $\to$ Smallest parton-to-hadron effects: inclusive k_T
- Comparison with NLO QCD calculations:
  - $\to \mu_R = \bar{E}_T, \mu_F = \sqrt{200}$ GeV
  - $\to$ CTEQ5M1 parametrisations of proton PDFs
  - $\to$ parton-to-hadron corrections applied
- NLO QCD gives a good description of the data over a wide range in Q^2 and E_T; the Q^2 dependence is observed to be reduced at high-E_T and described by NLO

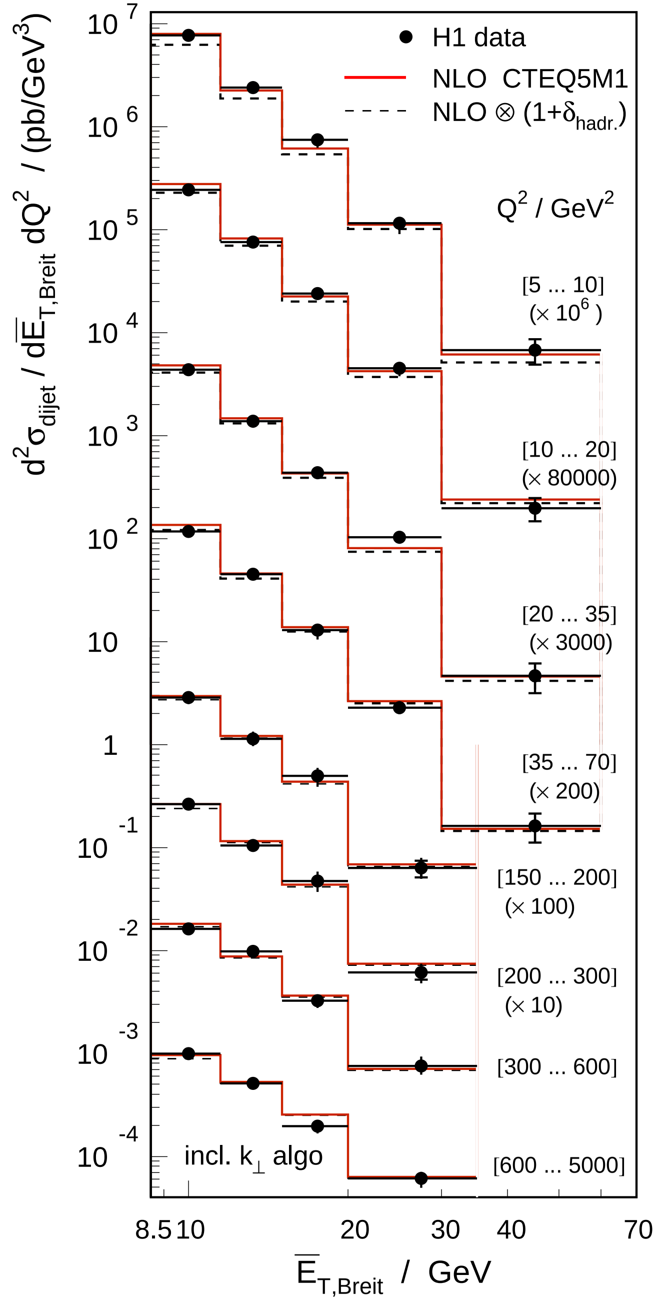




Dijet Cross Sections in NC DIS

- **Measurement of double differential cross sections $d\sigma/dM_{JJ}dQ^2$, $d\sigma/d\bar{E}_T dQ^2$ over $5 < Q^2 < 5000$ GeV^2**
- **It is observed that the spectra get harder as Q^2 increases**
- **NLO QCD describes well the data over $15 < M_{JJ} < 95$ GeV and $8.5 < \bar{E}_T < 60$ GeV except at low Q^2, where the shape is ok but not the normalisation**
- **Overview: at high Q^2 (> 70 GeV^2) NLO describes the data well; as Q^2 decreases the theoretical uncertainties become large and NLO fails for $Q^2 < 10$ GeV^2**



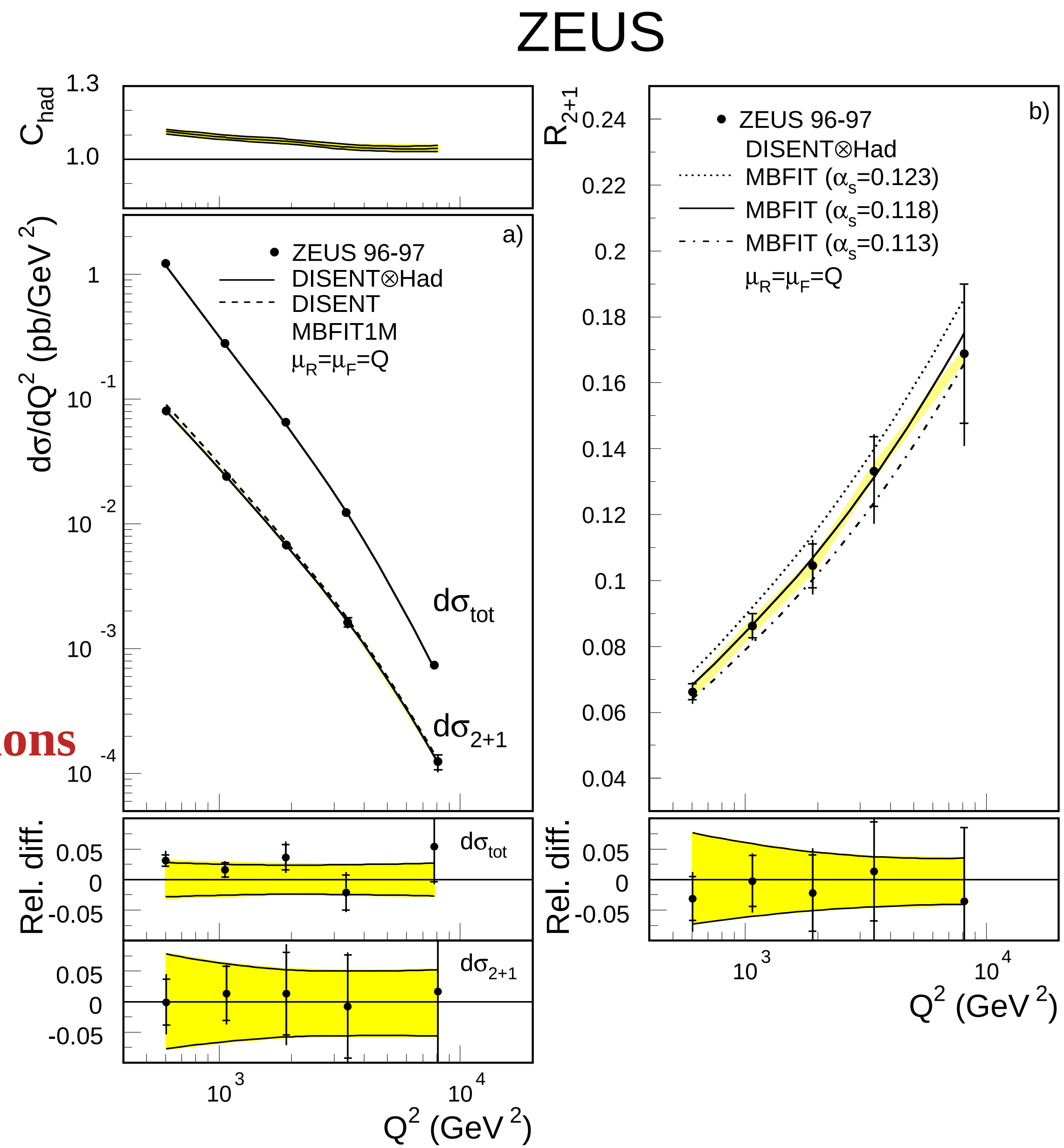


Dijet Cross Sections at $Q^2 > 470$ GeV^2 and extraction of α_s

- Dijet cross section $d\sigma_{2+1}/dQ^2$ for
  $470 < Q^2 < 20000$ GeV^2
  $E_T^{jet,1}$(Breit)> 8 GeV
  $E_T^{jet,2}$(Breit)> 5 GeV
  $-1 < \eta^{jet,1(2)}$(Lab)< 2

→ **Ratio** $R_{2+1} \equiv \frac{d\sigma_{2+1}/dQ^2}{d\sigma_{tot}/dQ^2}$

- Small experimental uncertainties.
- Comparison with NLO QCD calculations
- Small theoretical uncertainties:
  → uncertainties on the proton PDFs
  → hadronisation corrections
  → higher-order terms (> NLO)

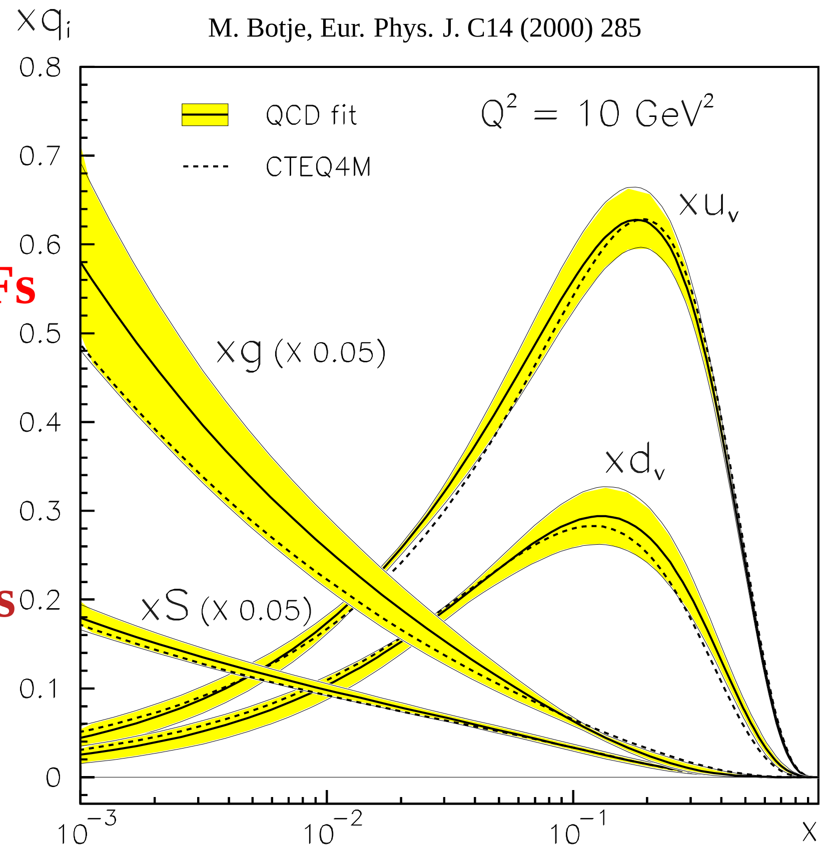


Uncertainties of the Proton PDFs: effects on jet cross sections

- Comparison of jet cross-section calculations using different parametrisations of the proton PDFs (e.g. MRST vs CTEQ) DOES NOT give a reliable estimation of the uncertainties due to the proton PDFs
- Several groups have developed methods to quantify these uncertainties by accounting (properly) for

→ the statistical and correlated systematic uncertainties of each data set used in the determination of the PDFs

→ the theoretical uncertainties affecting the extraction of the PDFs in the DGLAP fits



- Botje's analysis provides the covariance matrix (V_{p_μ,p_λ}) of the fitted PDF parameters ($\{p_\lambda\}$), the derivatives as functions of Q^2 and x (e.g. $\partial g(x,Q^2)/\partial p_\lambda$) and several sets obtained under different theoretical assumptions

$\Rightarrow$ evaluation of the uncertainty on any function of the proton PDFs (e.g. σ_{jet})

$$(\Delta\sigma_{jet})^2 = \sum_{\lambda,\mu} \frac{\partial\sigma_{jet}}{\partial p_\mu} V_{p_\mu,p_\lambda} \frac{\partial\sigma_{jet}}{\partial p_\lambda}$$

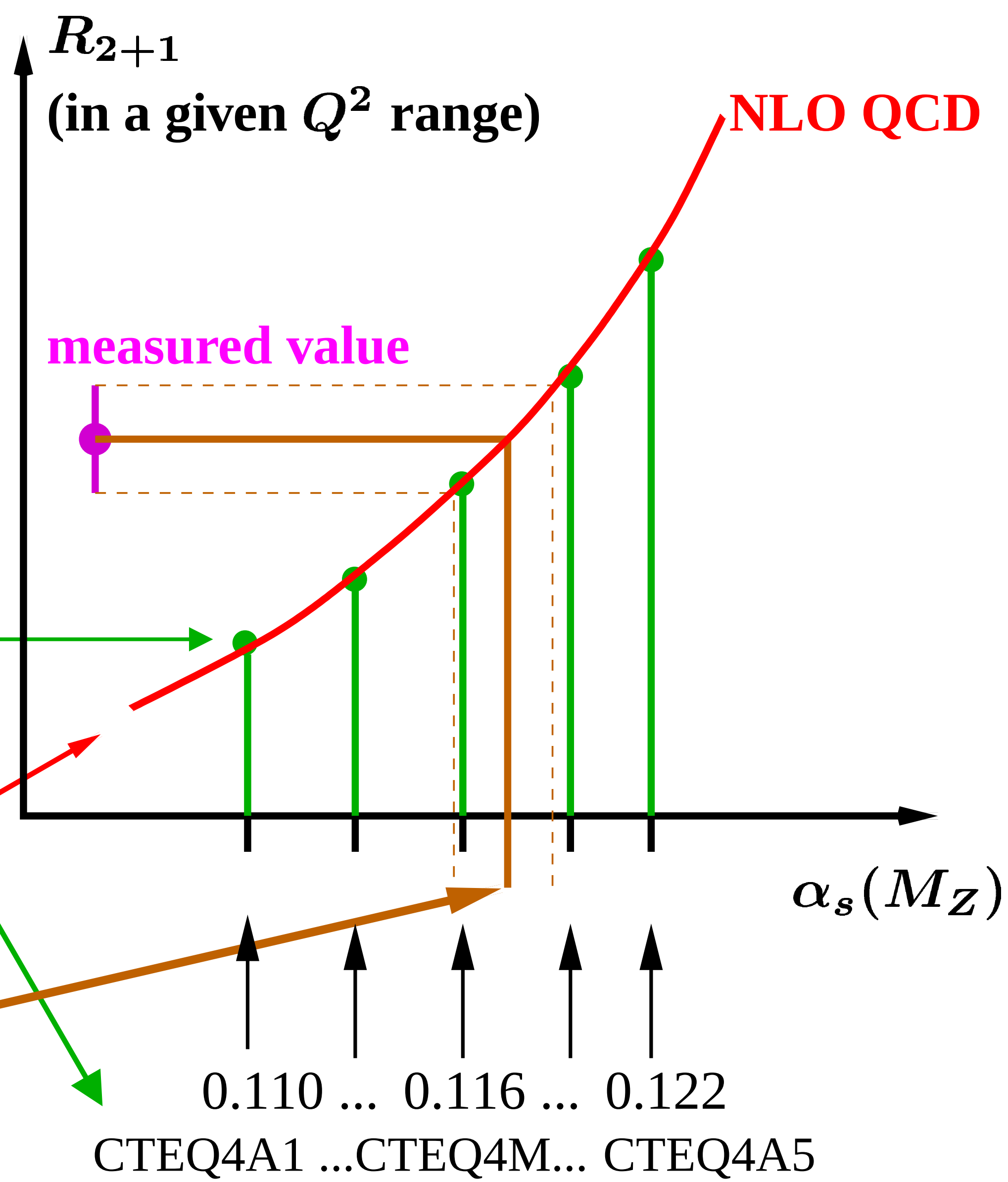
Dijet Cross Sections at $Q^2 > 470$ GeV^2 and extraction of $\alpha_s(M_Z)$

- NLO QCD calculations of $d\sigma_{2+1}/dQ^2$ depend on $\alpha_s(M_Z)$ through

→ Matrix Elements: $\hat{\sigma} \sim A \cdot \alpha_s + B \cdot \alpha_s^2$

→ proton PDFs: α_s assumed in evolution

- To take into account the correlation the NLO QCD calculations are performed using various sets of proton PDFs which assume different values of α_s
- The resulting NLO QCD calculations are parametrised as a function of $\alpha_s(M_Z)$ in each region of Q^2 of the measurements
- From the measured value of R_{2+1} in each region of Q^2 the value of $\alpha_s(M_Z)$ and its uncertainty are extracted



Dijet Cross Sections at $Q^2 > 470$ GeV^2 and extraction of α_s

- Study of the scale dependence of $\alpha_s(Q)$:
  from the measured $R_{2+1}(Q^2)$ in each Q^2 region
  $\to \alpha_s(<Q>)$ is extracted
  The measurements are consistent with
  the running of α_s predicted by perturbative QCD
- A combined value of $\alpha_s(M_Z)$ has been extracted:

$$\alpha_s(M_Z) = 0.1166 \pm 0.0019\ (\text{stat.})\ ^{+0.0024}_{-0.0033}\ (\text{exp.})\ ^{+0.0057}_{-0.0044}\ (\text{th.})$$

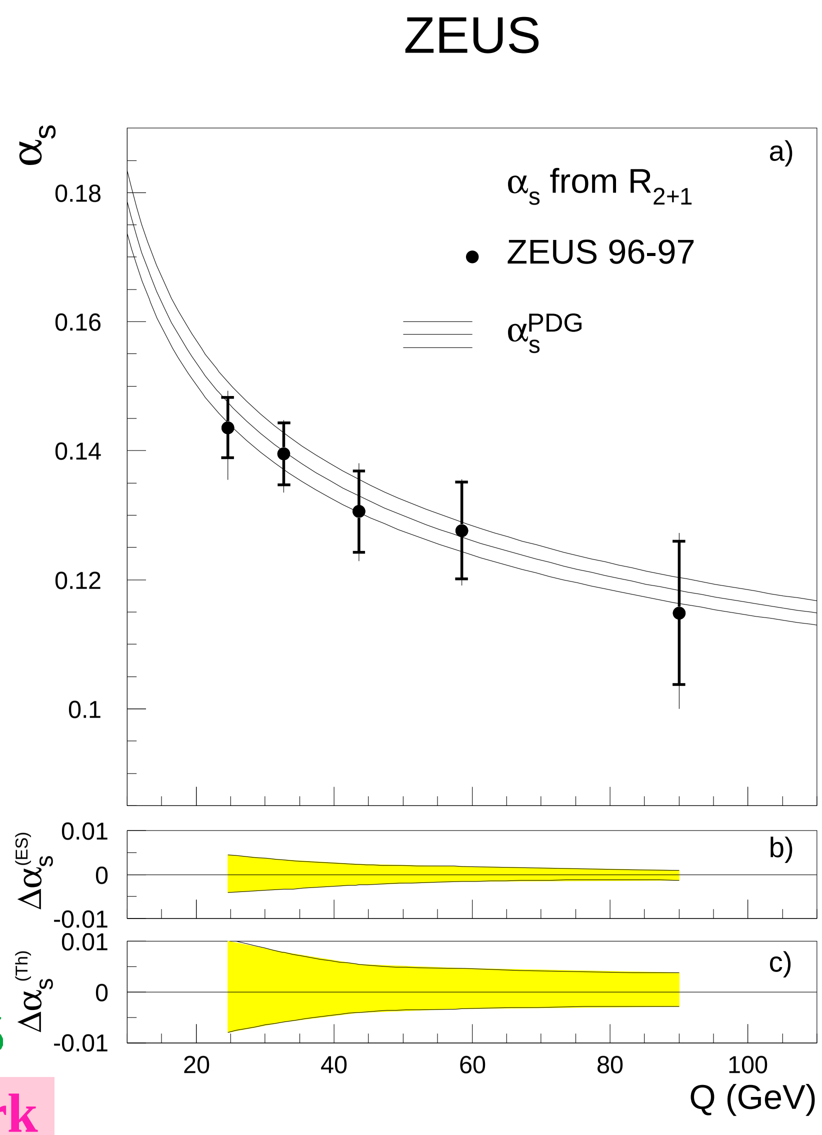
- The theoretical uncertainty dominates:

$\to$ terms beyond NLO $\Delta\alpha_s(M_Z) = ^{+0.0055}_{-0.0042}$

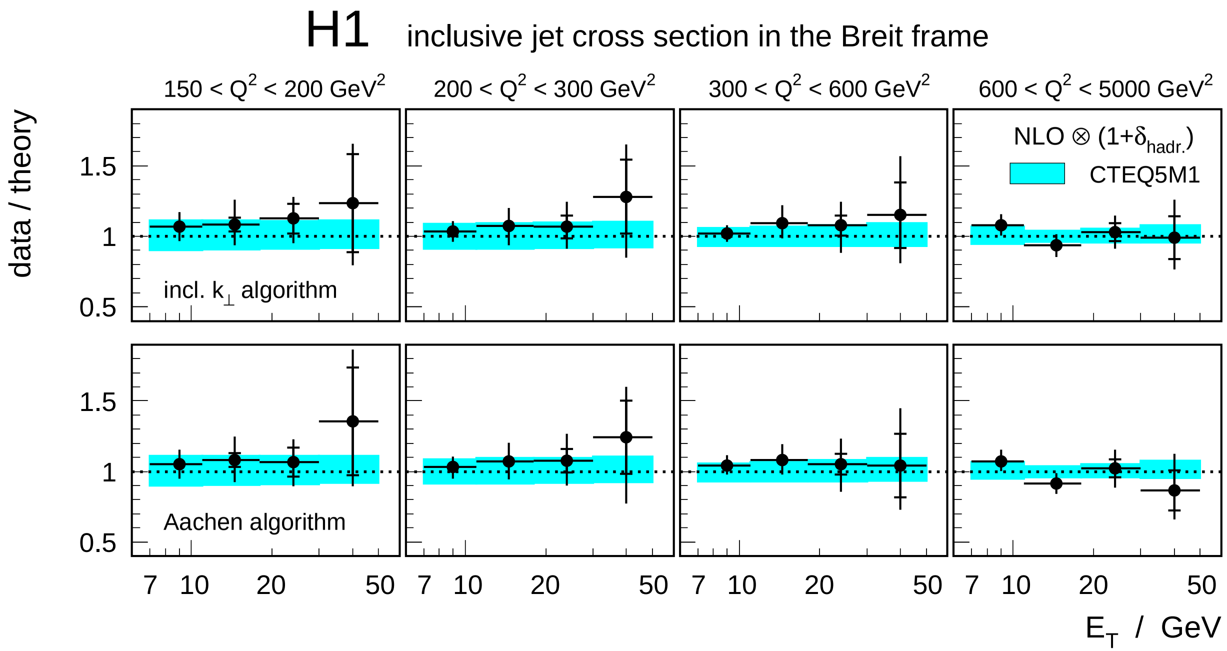
$\to$ uncertainties proton PDFs $\Delta\alpha_s(M_Z) = ^{+0.0012}_{-0.0011}$

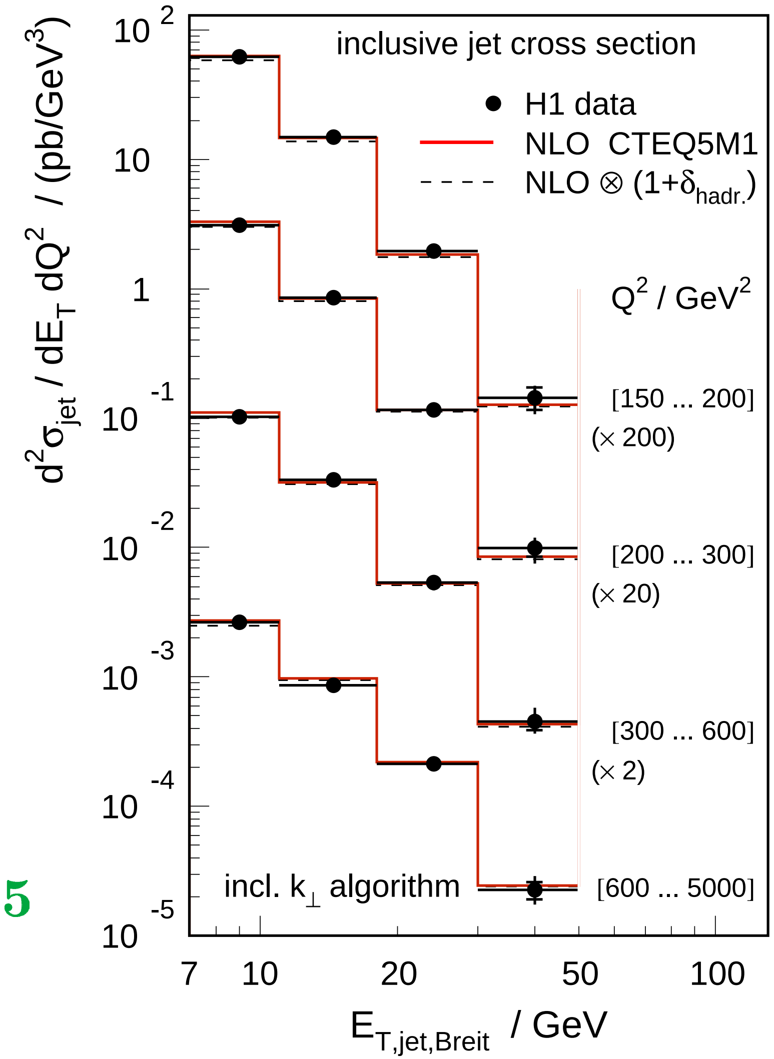
$\to$ hadronisation corrections $\Delta\alpha_s(M_Z) = \pm 0.0005$

Improvements depend upon further Theoretical Work



Inclusive jet Cross Sections in NC DIS and extraction of α_s



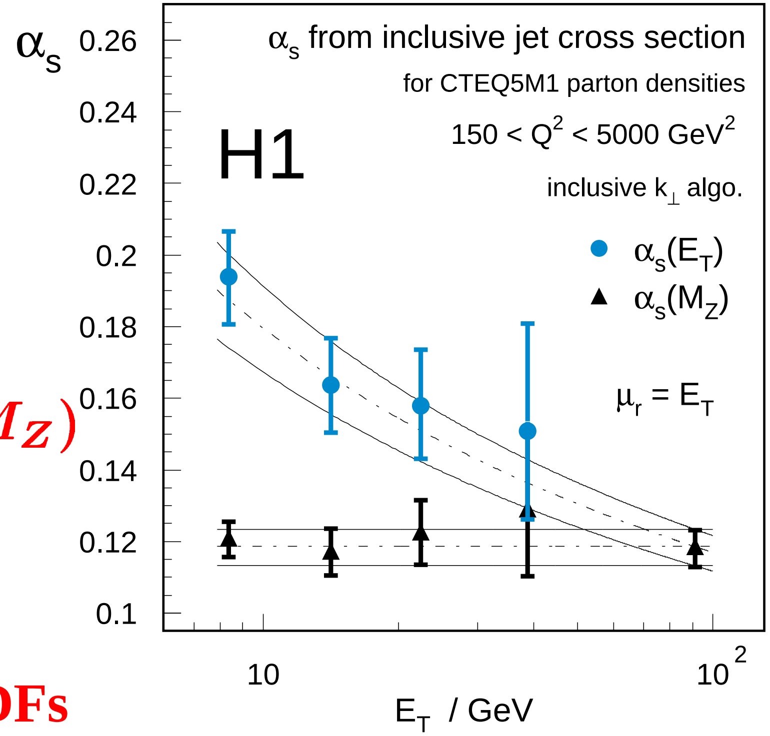


- **Measurement of the differential cross section $d\sigma/dE_T dQ^2$ for inclusive jet production with E_T^{jet}(Breit)> 7 GeV and $-1 < \eta^{jet,1(2)}$(Lab)< 2.5 over $150 < Q^2 < 5000$ GeV^2**
- **The complication of selecting dijet events is absent!**
- **NLO QCD gives a good description of the data over the whole range in E_T and Q^2**

Determination of α_s

- The inclusive jet cross section $d\sigma/dE_T dQ^2$ over $150 < Q^2 < 5000$ GeV^2 has been fitted using NLO QCD calculations and the CTEQ5M1 proton PDFs to determine $\alpha_s(E_T)$ and a combined value of $\alpha_s(M_Z)$

$$\alpha_s(M_Z) = 0.1186 \pm 0.0030\ (\text{exp.})\ ^{+0.0039}_{-0.0045}\ (\text{th.})\ ^{+0.0033}_{-0.0023}\ (\text{pdf.})$$

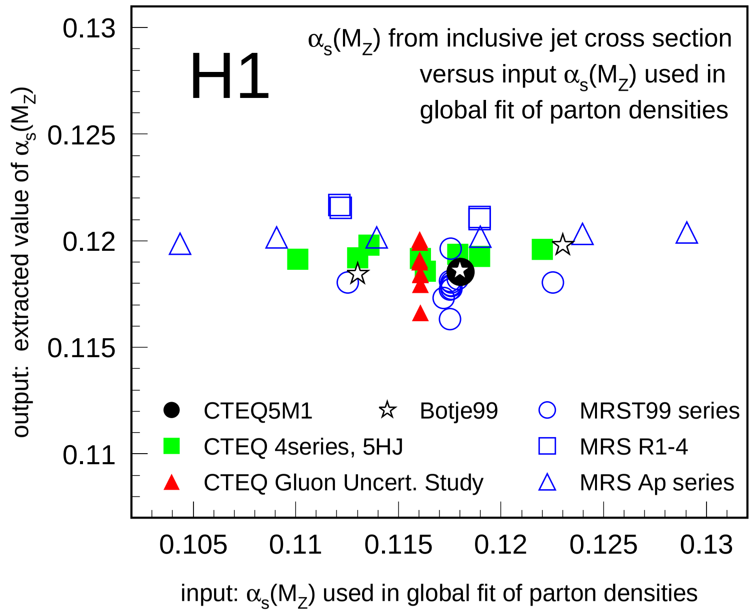


- No significant dependence on the α_s assumed in PDFs
- The theoretical uncertainty dominates:

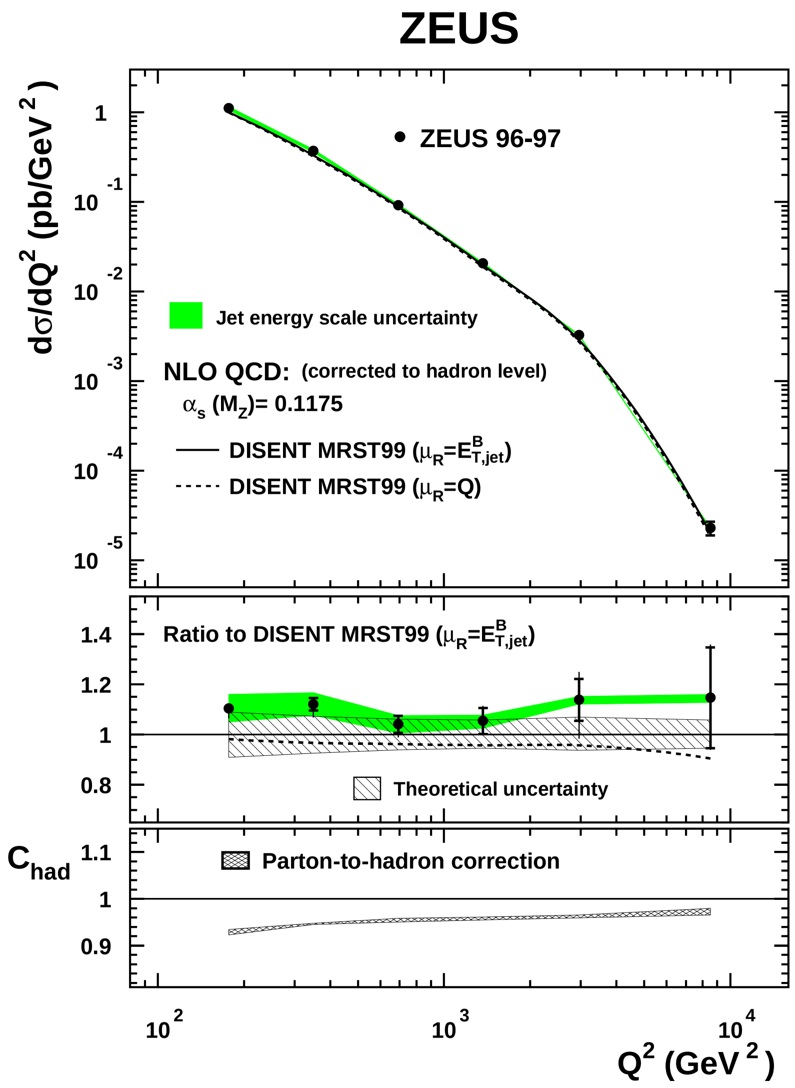
$\rightarrow$ higher orders and hadronisation $\Delta\alpha_s = ^{+0.0039}_{-0.0045}$

$\rightarrow$ uncertainties on the proton PDFs $\Delta\alpha_s = ^{+0.0033}_{-0.0023}$

- The observed E_T dependence of α_s is consistent with the running predicted by QCD
- Consistent with determination of α_s in e^+e^-
- Competitive accuracy in determination of α_s



Inclusive Jet Production in NC DIS ($Q^2 > 125$ GeV^2) and extraction of α_s



- Measurement (NEW) of inclusive jet cross sections in the Breit frame at $Q^2 > 125$ GeV^2 for jets with $E^B_{T,jet} > 8$ GeV and $-2 < \eta^B_{jet} < 1.8$

$\rightarrow$ no cut is applied in the laboratory frame

- Extraction of α_s from $d\sigma/dQ^2$ at $Q^2 > 500$ GeV^2

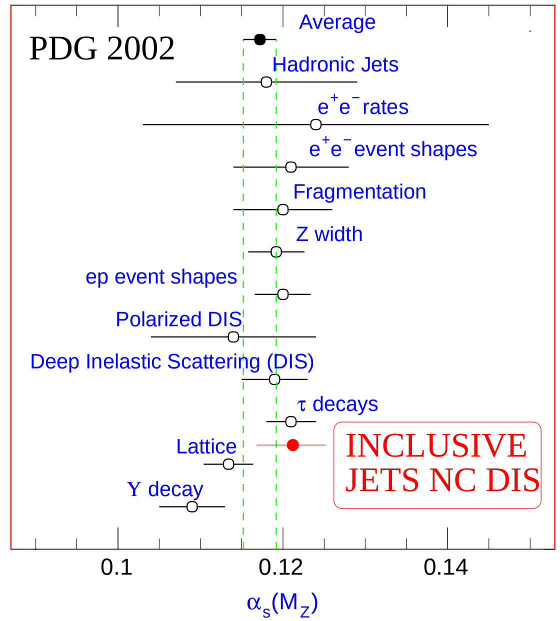
$$\alpha_s(M_Z) = 0.1212 \pm 0.0017\ (\text{stat.})^{+0.0023}_{-0.0031}\ (\text{exp.})^{+0.0028}_{-0.0027}\ (\text{th.})$$

- Theoretical uncertainties:

$\rightarrow$ terms beyond NLO (3%)

$\rightarrow$ unc. proton PDFs (1%)

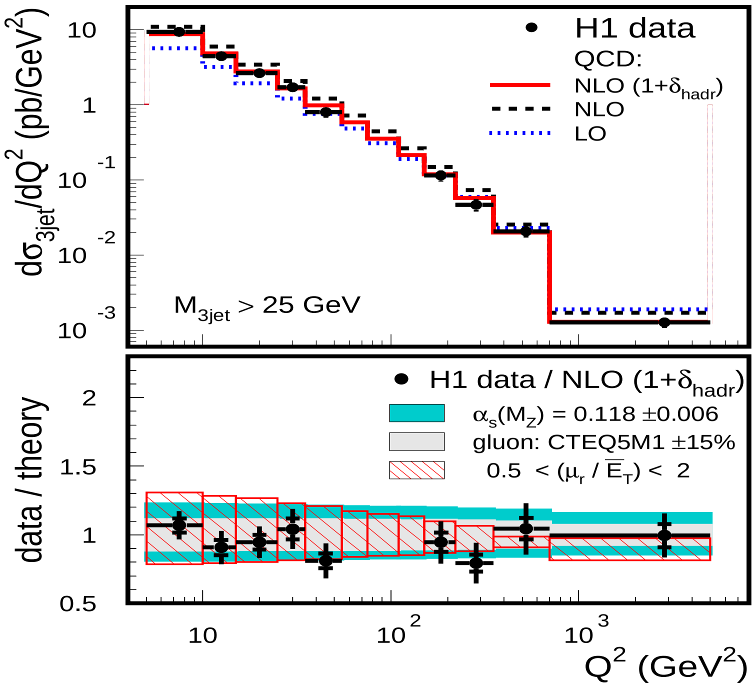
- Very precise determination of $\alpha_s(M_Z)$!
- Talk in WG-C by ZEUS speaker

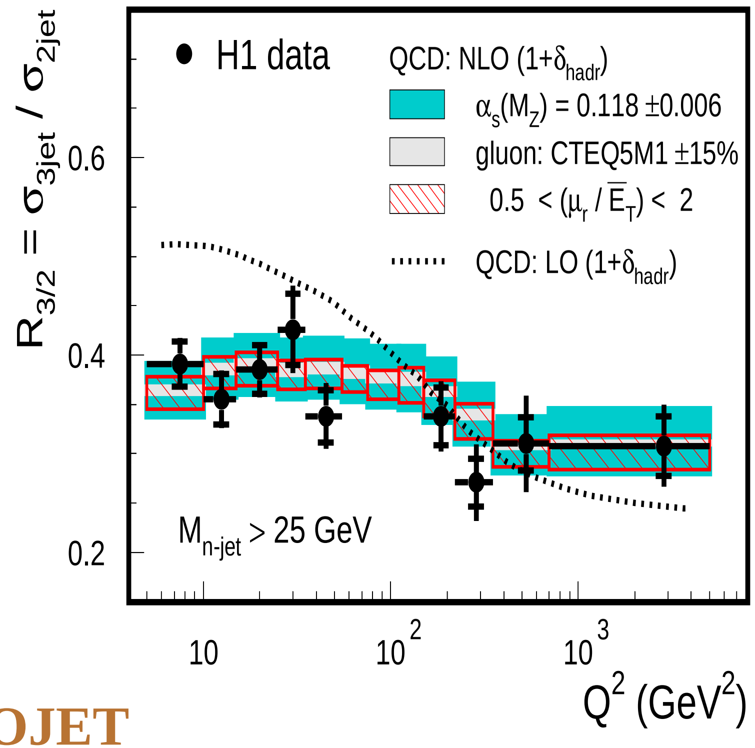


Three-jet cross sections in NC DIS

- Three-jet cross sections test QCD beyond LO directly $\rightarrow \sigma_{3jet} \propto \alpha_s^2$

- At least three jets with E_T^{jet}(Breit)> 5 GeV and $-1 < \eta^{jet}$(Lab)< 2.5
- Kinematic region: $M^{3j} > 25$ GeV, $X_3 < 0.95$ and $|\cos\theta_3| < 0.8$





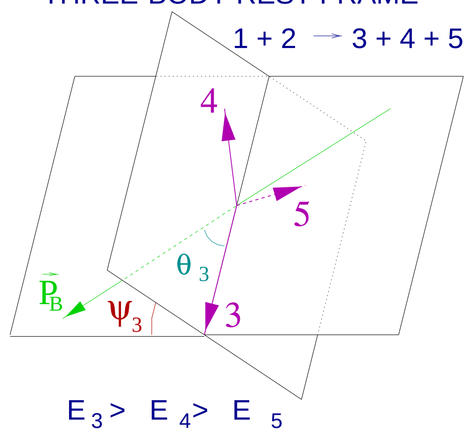
- Comparison with NLO ($\mathcal{O}(\alpha_s^3)$) calculations using NLOJET

  $\rightarrow$ The NLO calculations give a good description of the data over the whole Q^2 range

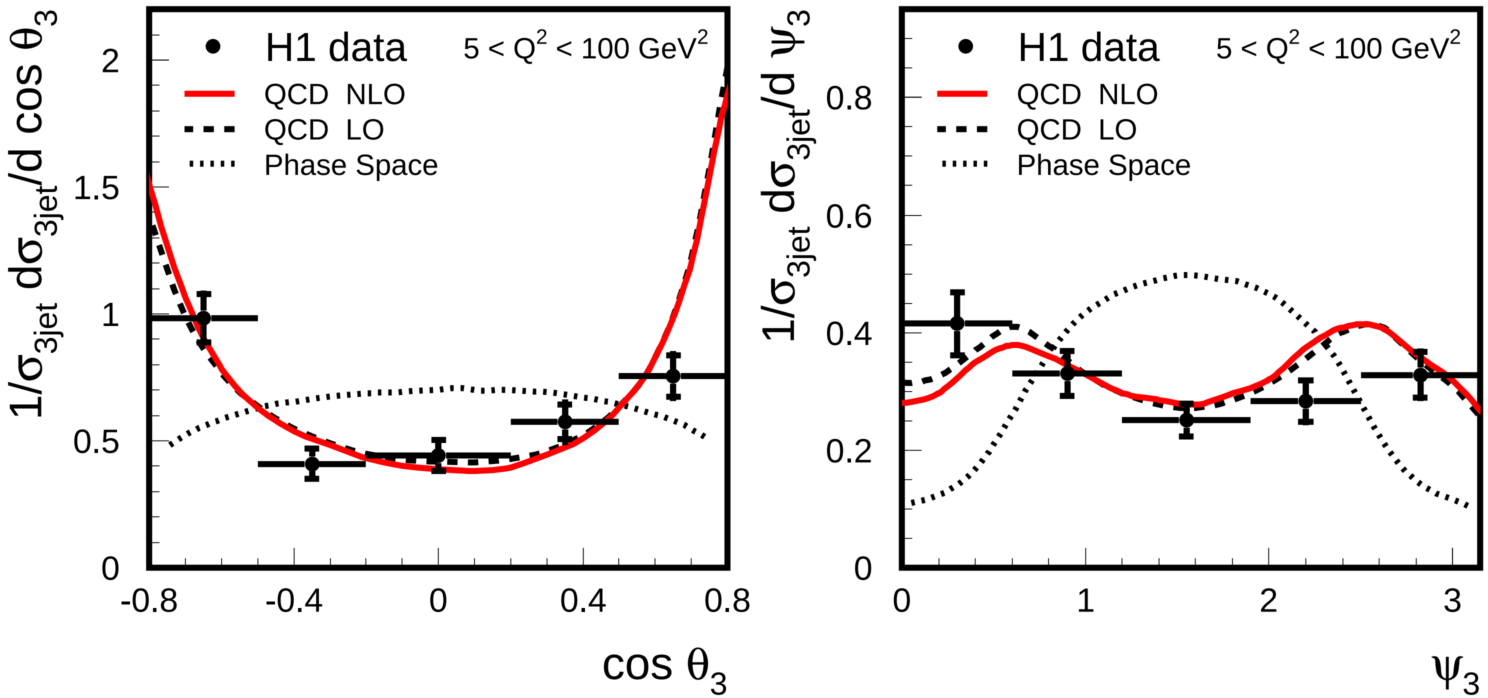
- Theoretical uncertainties from PDFs and higher order terms reduced in the three-jet to dijet ratio but relatively large hadronisation corrections ($10\% - 18\%$)

$\rightarrow$ Potentially useful observable to make an accurate determination of α_s

Three-jet cross sections in NC DIS

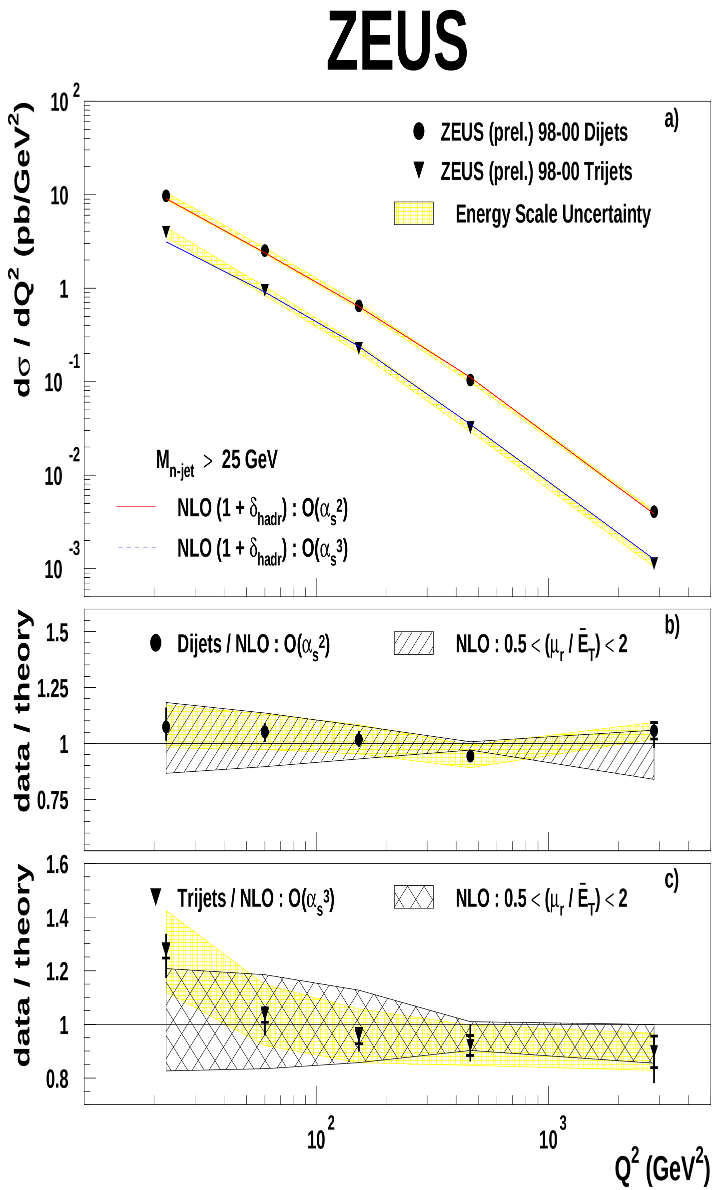


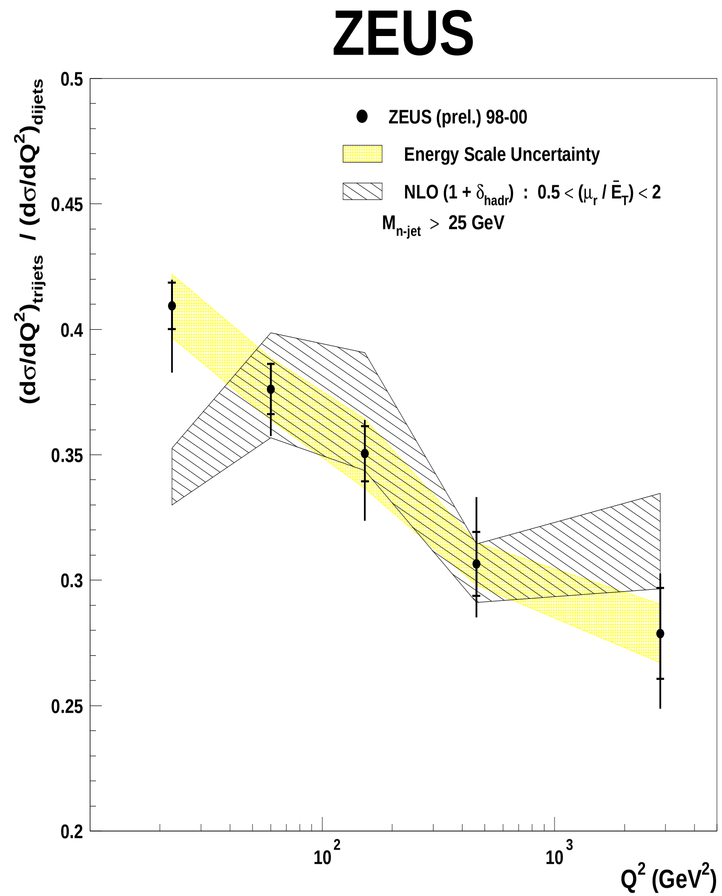
— θ_3 is sensitive to the spin of the exchanged particle
— ψ_3 reflects the orientation of the lowest energy jet



- The cos θ_3 distribution indicates that the highest energy jet tends to go either towards the proton or towards the photon directions
- The ψ_3 distribution probes the dynamics beyond LO directly
- The measured angular distributions are drastically different from phase space and in good agreement with QCD

Three-jet cross sections in NC DIS





- **Measurements (NEW) of cross sections for three jet production in the Breit frame with $\mathcal{L} = 82\ \mathrm{pb}^{-1}$**
- **Kinematic region: $10 < Q^2 < 5000$ GeV^2**

$E_{T,jet}$(Breit)> 5 GeV, $-1 < \eta_{jet}$(Lab)< 2.5

$M^{\mathrm{jets}} > 25$ GeV

- Talk in WG-C by N. Krumnack

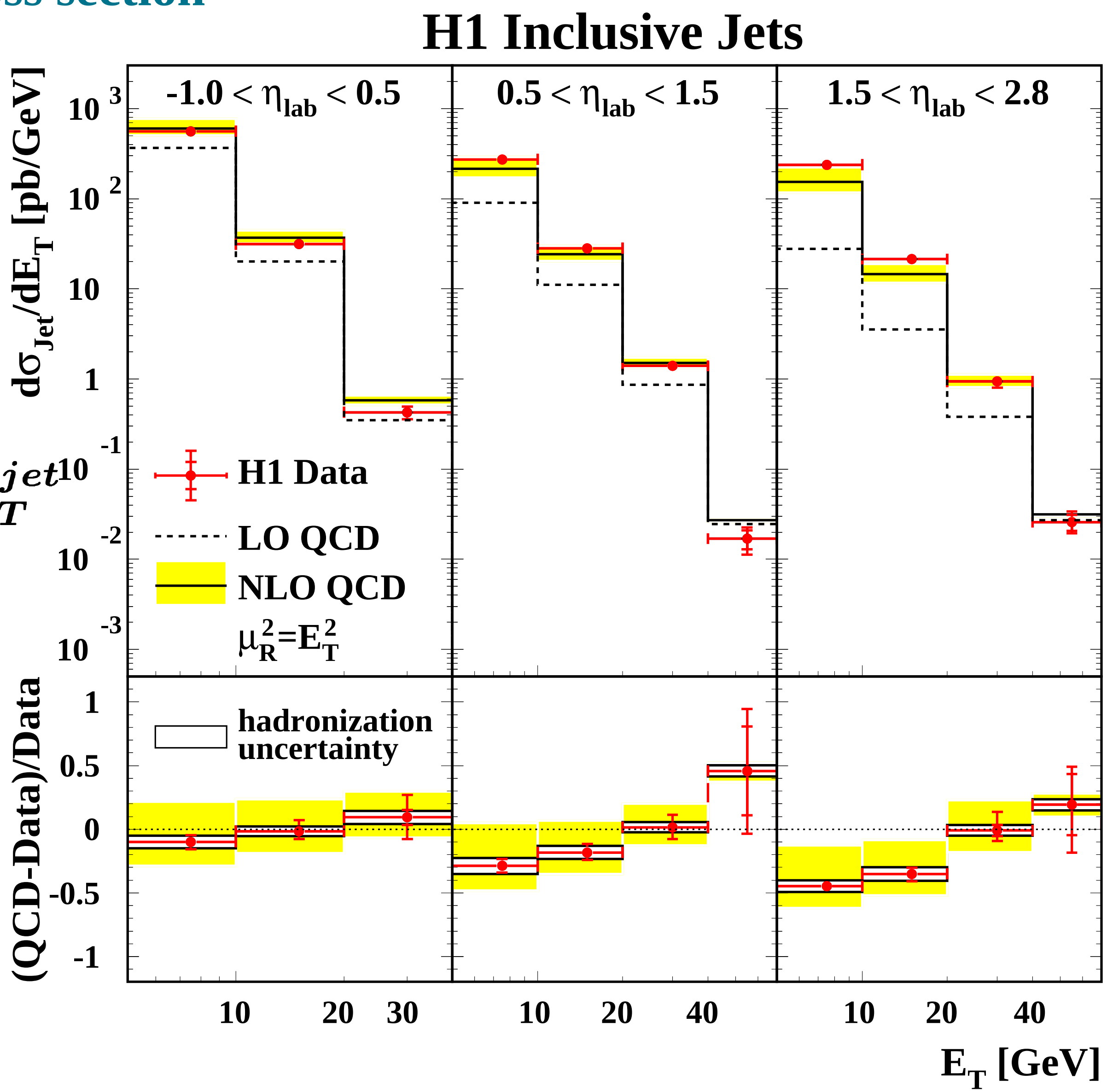
Inclusive Jet Cross Sections in NC DIS at low Q^2 ($5 < Q^2 < 100$ GeV^2)

- Measurement of the differential cross section $d\sigma/dE_T^{jet}$(Breit) for inclusive jet production with $E_T^{jet} > 5$ GeV
- Comparison to NLO calculations with $\mu_R = E_T^{jet}$ and $\mu_R = Q$

→ good description of the data in the region $-1 < \eta_{jet} < 0.5$

→ failure to describe the data at low E_T^{jet} in the region $1.5 < \eta_{jet} < 2.8$, where the NLO corrections and uncertainties (terms beyond NLO) are largest, and largest differences for $5 < Q^2 < 10$ GeV^2

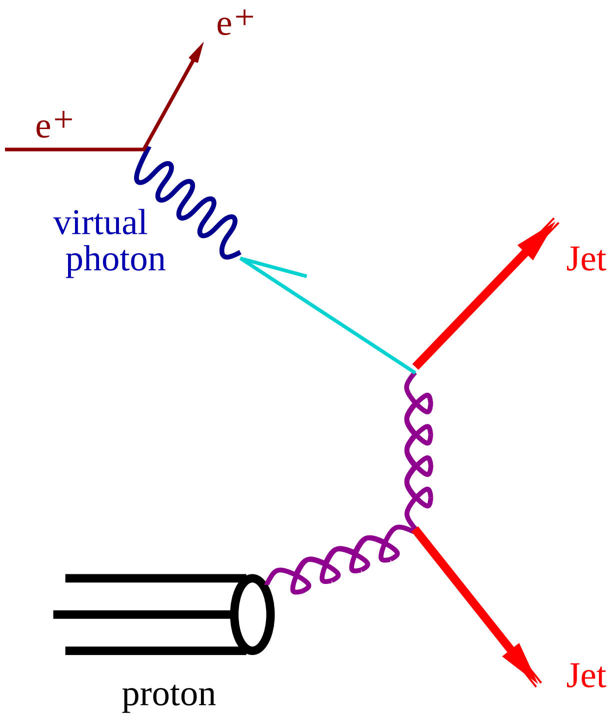
⇒ Improved calculations needed to understand jet production at low Q^2

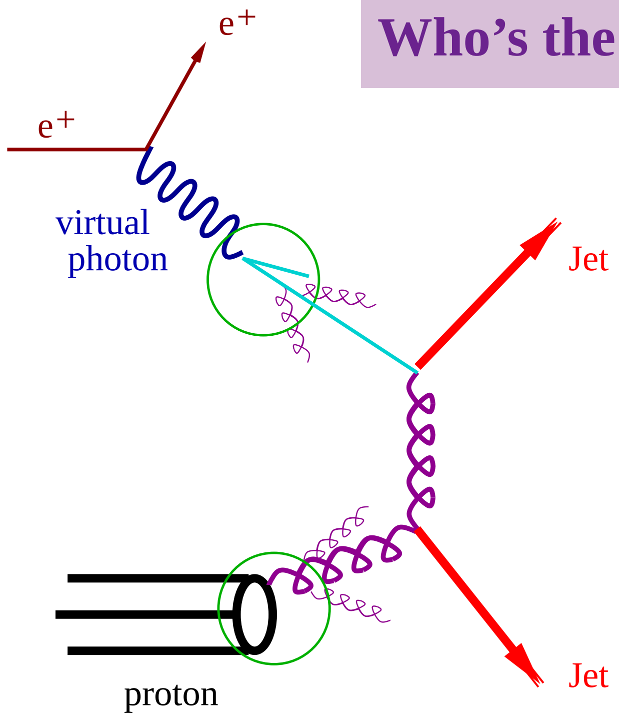


- Talk in WG-C by A. Specka

Jet Production in NC DIS at low Q^2

Who's the probe/target when $E_T^{jet} \gg Q$?

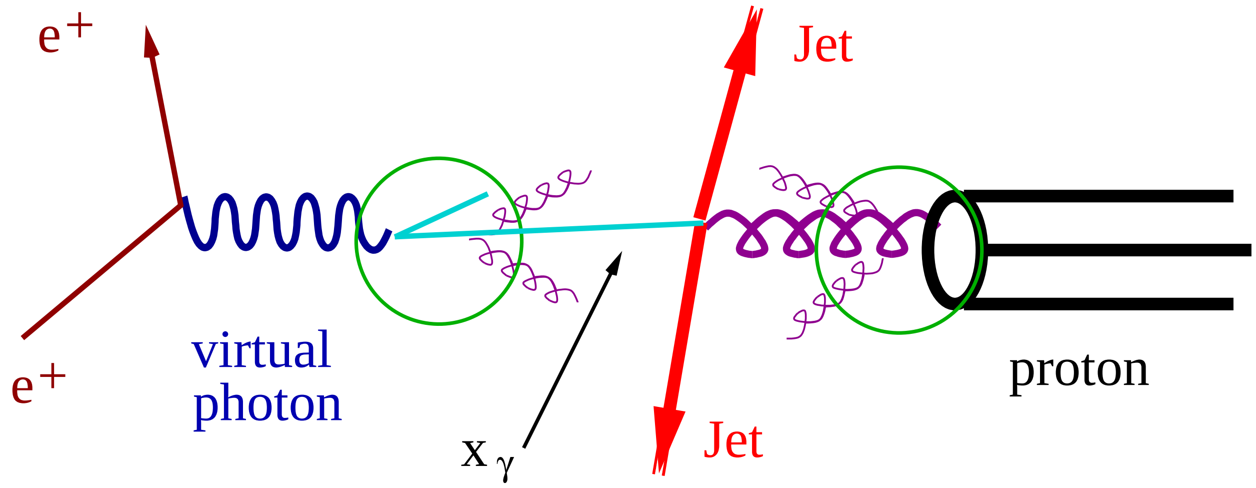




- **Large logarithms log E_T/Q can be resummed by defining PDFs for a virtual photon in a similar fashion as for the proton**
  → Improving the calculations by including higher-order terms

- **Several models for the virtual photon PDFs exist, which interpolate between the**
  → leading-log part of the real photon PDFs ⇒ log E_T/Λ_{QCD}
  → and the asymptotic behaviour predicted by pQCD ⇒ log E_T/Q
- **Parametrisations of the virtual photon PDFs:**
  Drees and Godbole, Schuler and Sjöstrand, Glück et al

Dijet Production in NC DIS at low Q^2 ($1.6 < Q^2 < 80$ GeV^2)



- **Measurement of dijet cross sections for jets defined in the $\gamma^* p$ centre-of-mass system using the inclusive k_T algorithm**
- **Phase-space region:**

  $|\eta^{jet,1} - \eta^{jet,2}| < 1$

  $-3 < \bar{\eta} < -0.5$

  $\bar{E}_T^2 > 30$ GeV^2 and $|E_T^{jet,1} - E_T^{jet,2}|/(E_T^{jet,1} + E_T^{jet,2}) < 0.25$

  $1.6 < Q^2 < 80$ GeV^2 and $0.1 < y < 0.7$
- **Useful variable: the longitudinal momentum fraction of the photon's momentum carried by the interacting parton**

$$x_\gamma^{jets} = \frac{\sum_{\text{jets } 1,2}(E^{jet} - p_z^{jet})}{\sum_{\text{all hadrons}}(E^h - p_z^h)}$$ (sum over the two highest-E_T^{jet} jets)

→ **to separate "resolved" photons ($x_\gamma^{jets} < 1$) from "direct" photons ($x_\gamma^{jets} \approx 1$)**

⇒ **Measurement of the triple-differential cross section $d^3\sigma/dQ^2 d\bar{E}_T^2 dx_\gamma^{jets}$**

Dijet Production in NC DIS at low Q^2 $(1.6 < Q^2 < 80\ \text{GeV}^2)$

- The distributions peak towards $x_\gamma^{jets} = 1$

$\rightarrow$ "direct" photon contribution

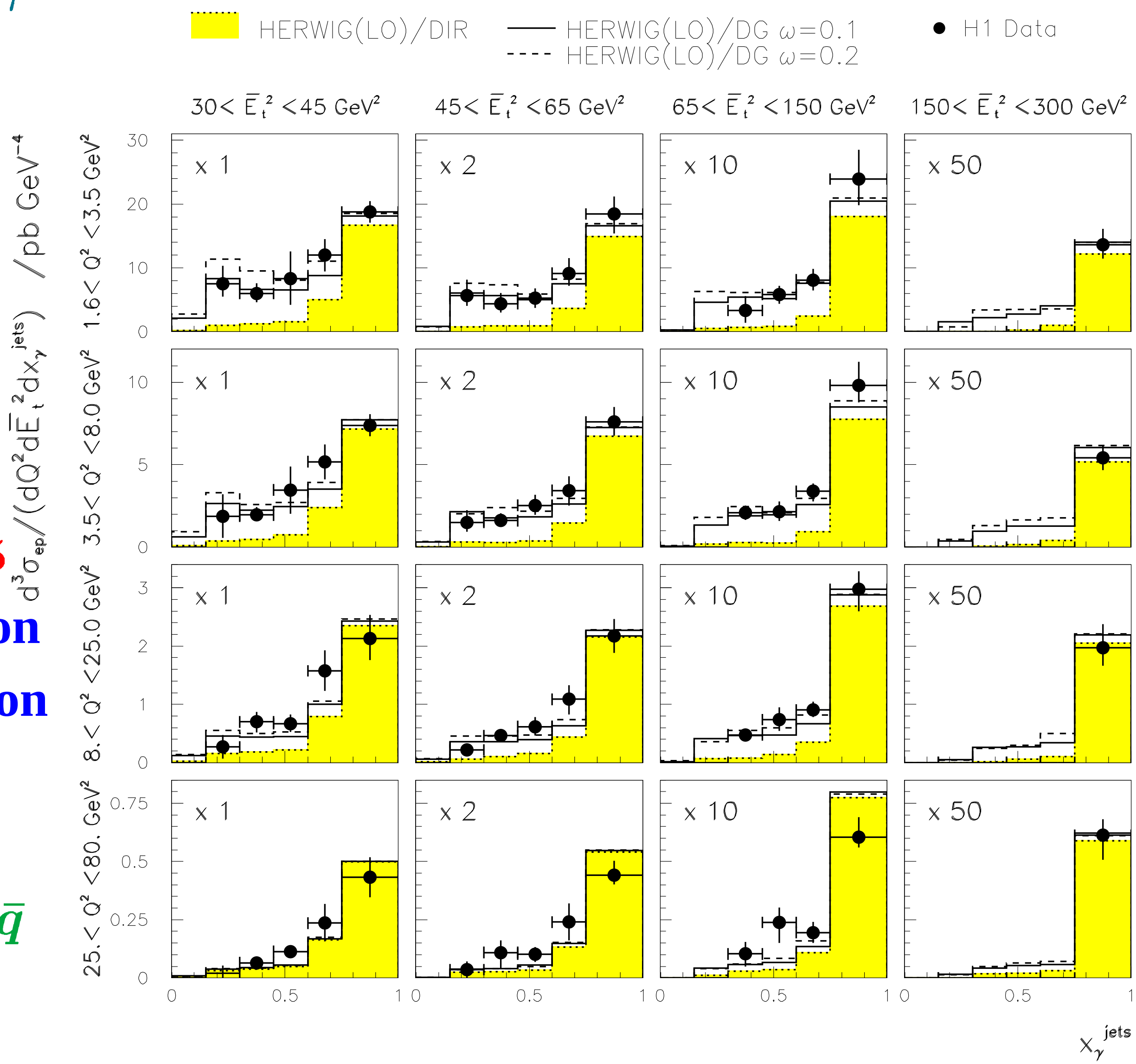
- As Q^2 increases at fixed $\bar{E}_T$ the cross section in the region $x_\gamma^{jets} < 0.75$ ("resolved" photon) decreases

- Comparison with models:

$\rightarrow$ "direct" photon only does not reproduce the data for $x_\gamma^{jets} < 0.75$

$\rightarrow$ inclusion of the "resolved" photon contribution improves the description

$\Rightarrow$ Consistent with the pQCD expectation that as $Q^2 \rightarrow \bar{E}_T^2$ the photon structure reduces to $\gamma \rightarrow q\bar{q}$



Dijet Production in NC DIS at low Q^2 ($2 < Q^2 < 80$ GeV^2)

- Measurements (NEW) of dijet cross sections in the kinematic region $2 < Q^2 < 80$ GeV^2 and $0.1 < y < 0.85$ for jets with $E_T^{jet} > 5$ GeV, $\bar{E}_T > 6$ GeV and $-2.5 < \eta_{jet}(\gamma^* p$ CMS$) < 0$
- Comparison with models which incorporate

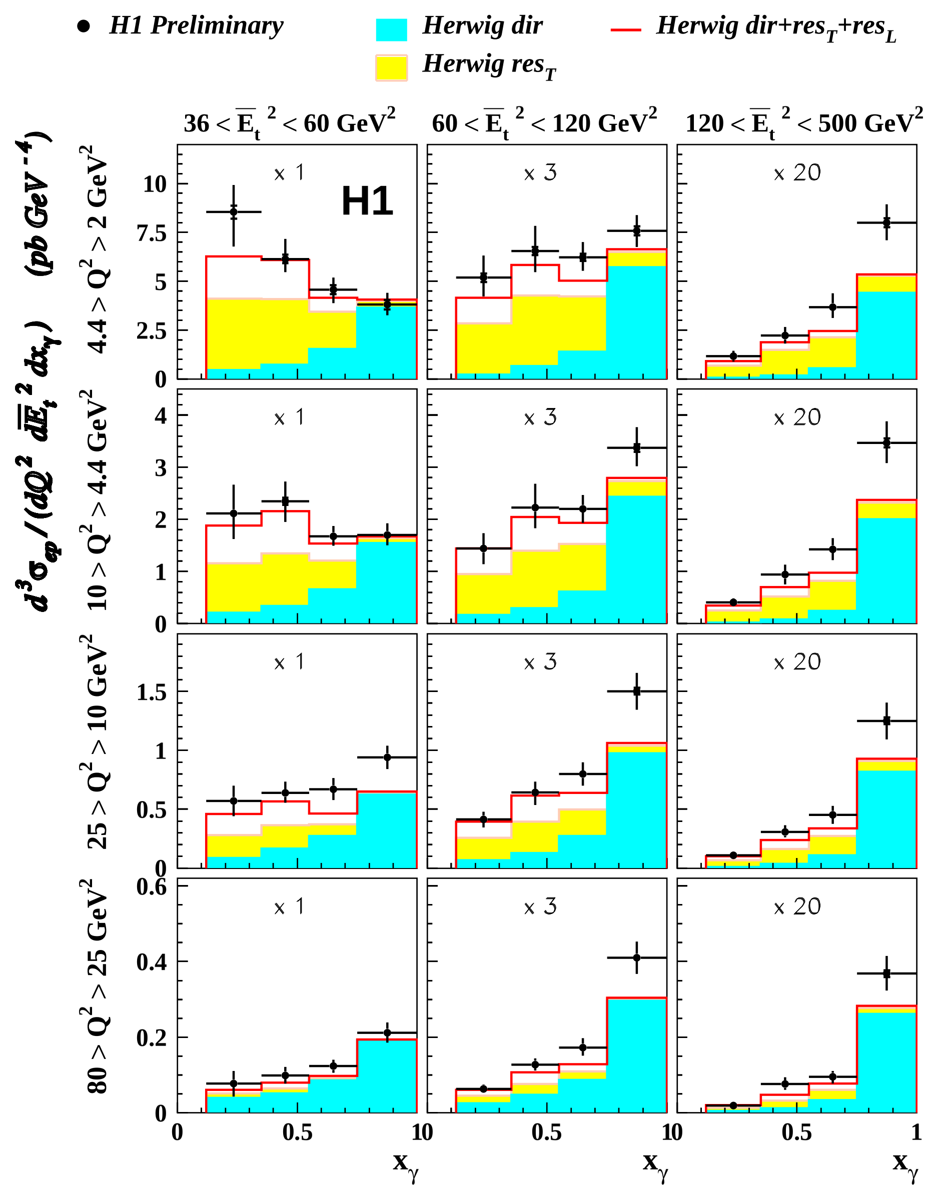
→ only "direct" photon contribution

→ transversally-polarised "resolved" photons

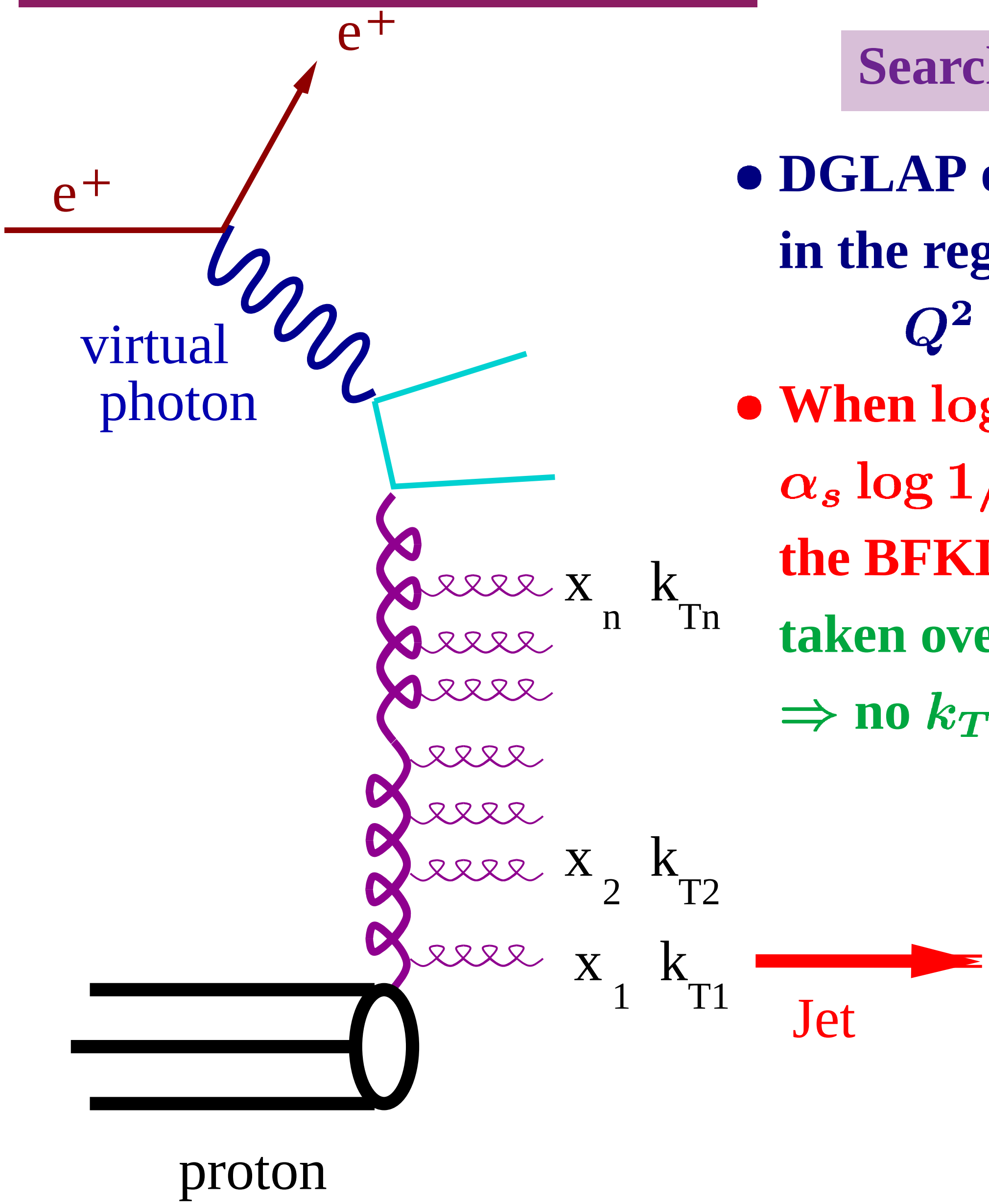
→ longitudinally-polarised "resolved" photons

→ k_T-unordered initial-state parton cascades based on CCFM evolution equations and an unintegrated gluon density function

- Improved description of the data
- Talk in WG-C by H. Jung



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 $k_{T1} \sim Q$

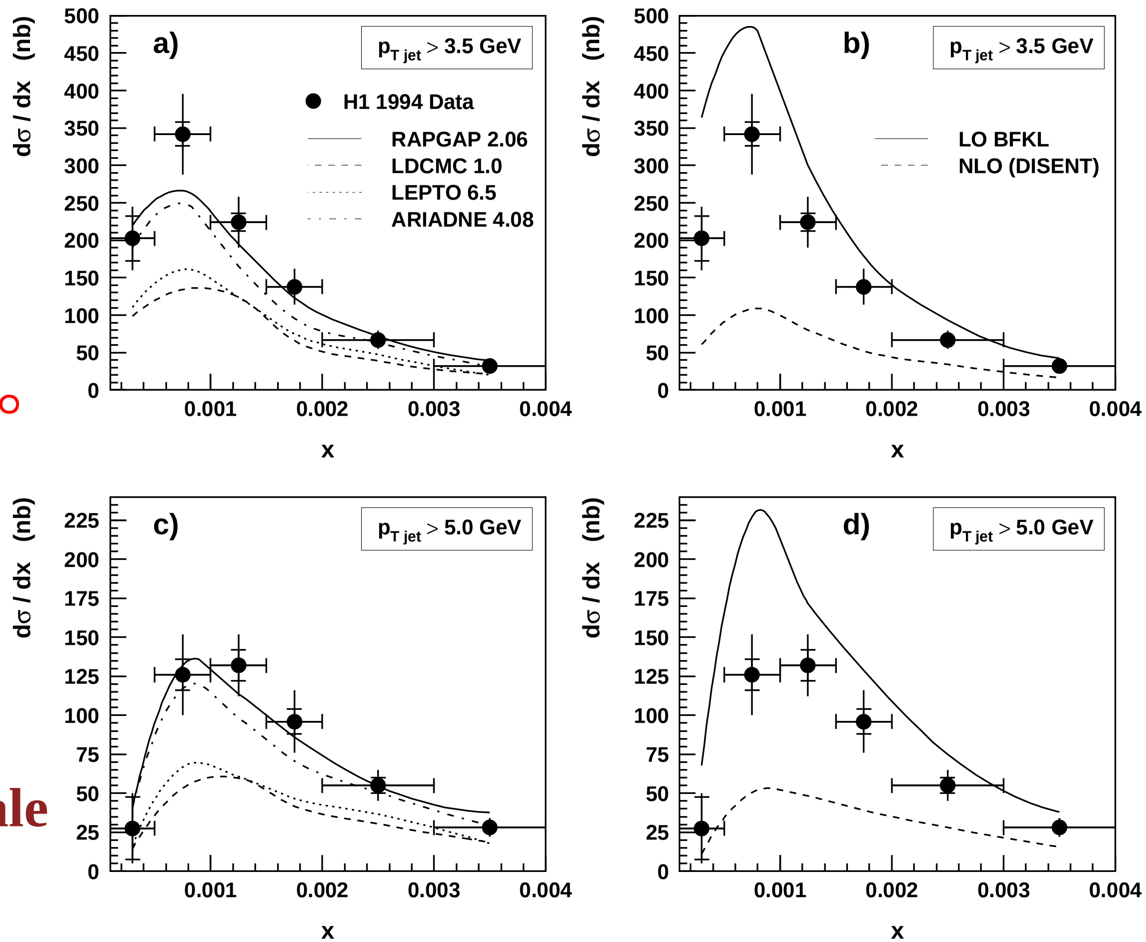
Measurement of Forward Jet Production at low x

- Measurement of the differential cross section $d\sigma/dx$ for jet production (cone algor.) in the kinematic region

$$10^{-4} < x < 4 \cdot 10^{-3}$$
$$x_{jet} = E_{jet}/E_p > 0.035$$
$$0.5 < p^2_{Tjet}/Q^2 < 2,\ 7^\circ < \theta_{jet} < 20^\circ$$
$$p_{Tjet} > 3.5 \text{ GeV } (5 \text{ GeV})$$

- Strong rise towards low x is observed
- Comparison to calculations

→ fixed-order ($\mathcal{O}(\alpha_s^2)$) lie well below the data at low x; variation of the scale (Q^2) leads to 40% uncertainty



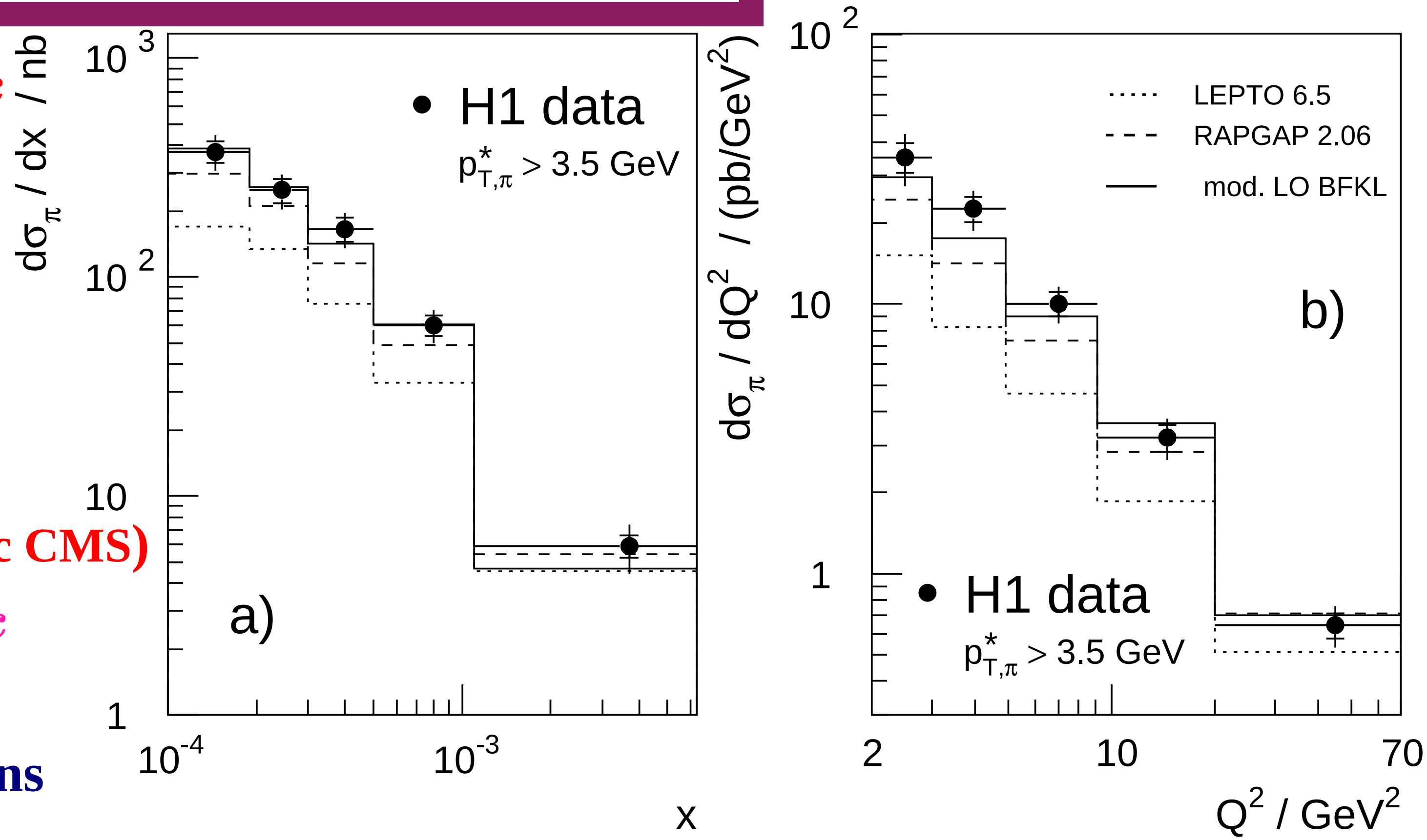
→ comparison to BFKL calculation hampered by lack of higher-order and hadronisation corrections, and implementation of jet algorithm

→ models with extra parton radiation reproduce the data **(interpretation?)**

- Talks in WG-C by L. Goerlich, S. Lammers and R. Poeschl

Measurement of Forward π^0 Production at low x

- **Measurement of $d\sigma_\pi/dx$ for π^0 production in the kinematic region**
  $2 < Q^2 < 70$ GeV^2
  $x_\pi = E_\pi/E_p > 0.01$
  $5° < \theta_\pi < 25°$
  $p^*_{T\pi} > 3.5$ GeV (hadronic CMS)
- **Strong rise towards low x is observed**
- **Comparison to calculations**



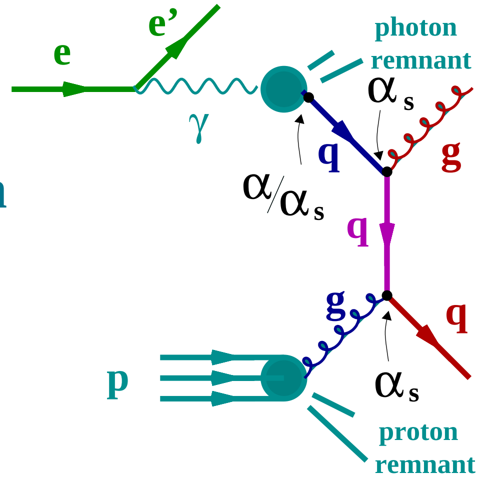
→ **a model (LEPTO) based on parton emission according to the DGLAP splitting functions agrees with the data at high x, but falls below the data at low x**

→ **a modified LO BFKL evolution equation (Kwiecinski et al) convoluted with a π^0 fragmentation function gives a good description; 60% scale uncertainty on normalisation**

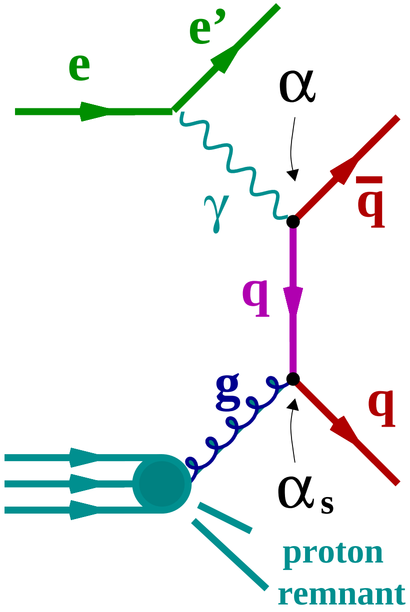
- Talk in WG-C by L. Goerlich

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 $\Rightarrow$



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)

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

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

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

$\rightarrow \sigma_{ab\to jj}$ 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**

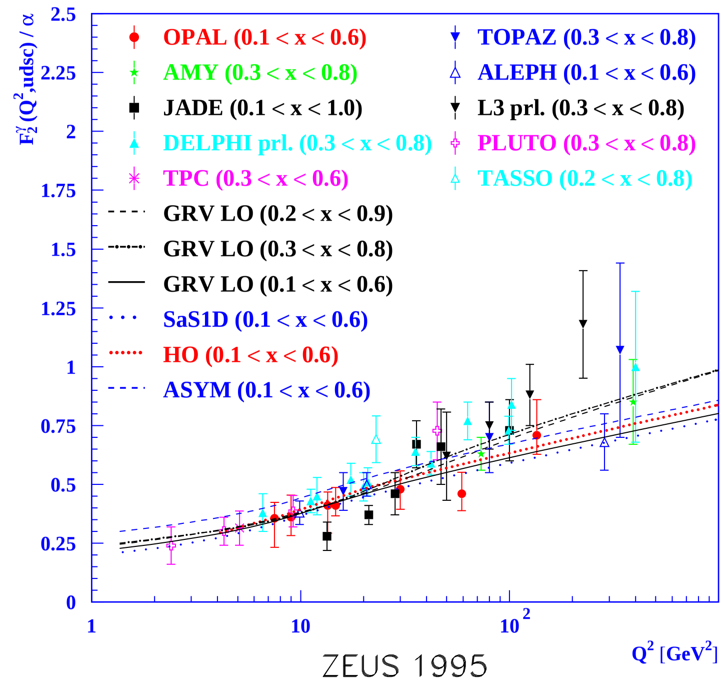
→ **Dynamics of resolved and direct processes**

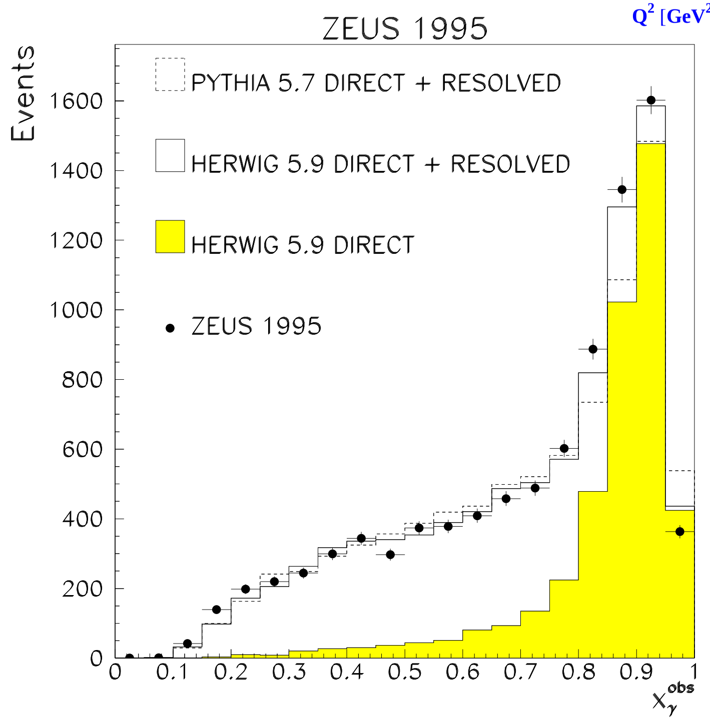
→ **Photon structure: information on quark densities from F_2^γ in e^+e^-; gluon density poorly constrained. Jet cross sections in photoproduction are sensitive to both the quark and gluon densities in the photon at larger scales $\mu_{F\gamma}^2 \sim E_{T,jet}^2$ $(200 - 10^4\ \text{GeV}^2)$**

→ **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**

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





NLO QCD Calculations of Jet Cross Sections in Photoproduction

- **Longitudinally invariant k_T-cluster algorithm in the η-ϕ plane of the laboratory frame**
- **Several NLO QCD calculations are available (phase-space slicing, subtraction method)**

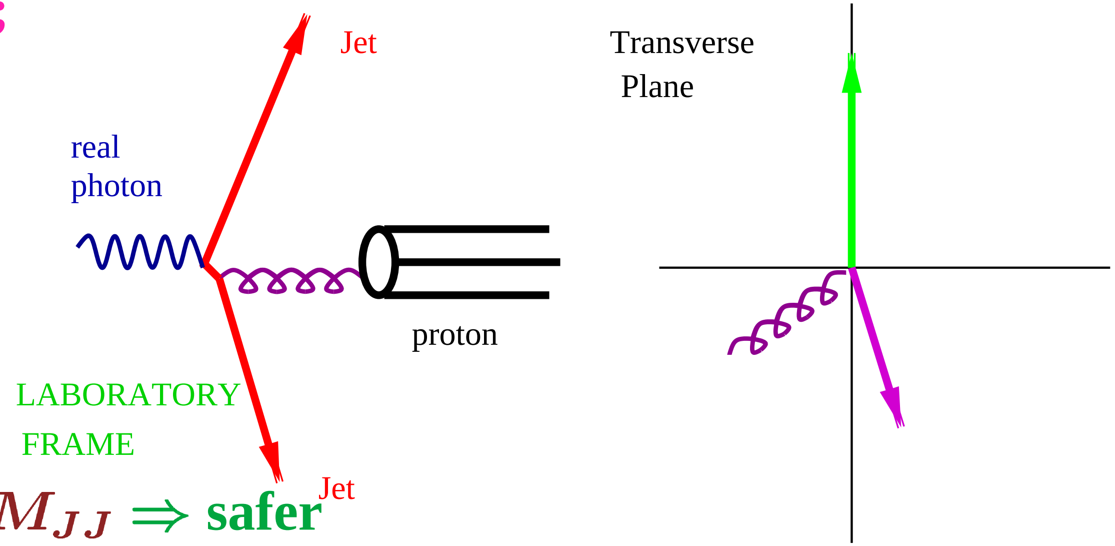
→ Klasen and Kramer, Harris and Owens, Aurenche et al, Frixione and Ridolfi

→ choice of scales: $\mu_R = \mu_F \sim E_T^{jet}$ (Reminder: $Q^2 \approx 0$!)

→ photon PDFs: NLO QCD parametrisations GRV-HO, AFG-HO

→ proton PDFs: NLO QCD parametrisations CTEQ5M, CTEQ5HJ, MRST99

- **Parton-to-hadron corrections estimated with HERWIG, PYTHIA, PHOJET**
- **Effects from the underlying event estimated with: multiparton interactions in PYTHIA, SUE model of HERWIG, PHOJET model; parameters tuned to reproduce the energy flow outside of jets.**



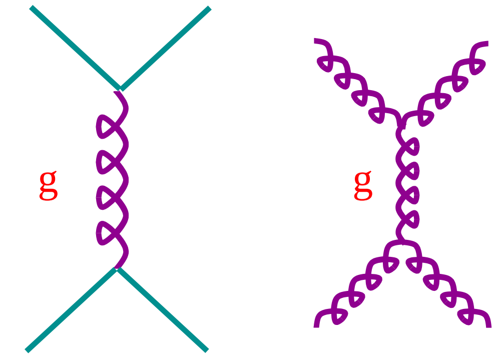
- **Dijet selection criteria:**

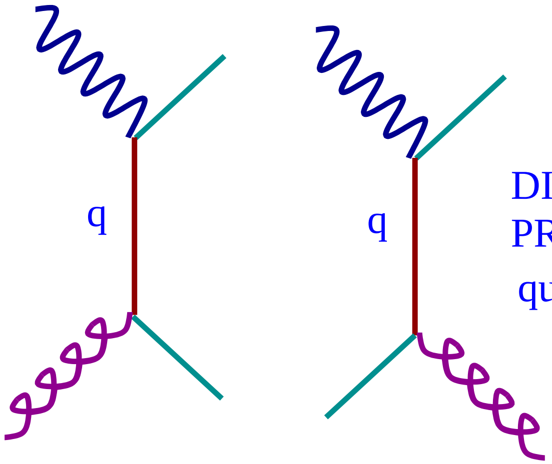
→ Symmetric cuts on $E_T^{jet,1(2)}$ ⇒ danger

→ Asymmetric cuts on $E_T^{jet,1(2)}$ ⇒ safer

→ Symmetric cuts on $E_T^{jet,1(2)}$ and cut on M_{JJ} ⇒ safer

Dijet Photoproduction: the dynamics of resolved and direct processes





- **The dynamics of dijet production has been investigated by studying the variable:**

$$\cos\theta^* \equiv tanh(\tfrac{1}{2}(\eta^{jet,1} - \eta^{jet,2}))$$

$\rightarrow$ for two-to-two parton scattering θ^* coincides with the scattering angle in the dijet CMS

- **QCD predicts different dijet angular distributions for resolved and direct:**

$\rightarrow$ **Resolved (gluon-exchange dominated)**

$$d\sigma/d|\cos\theta^*| \sim \frac{1}{(1-|\cos\theta^*|)^2}$$

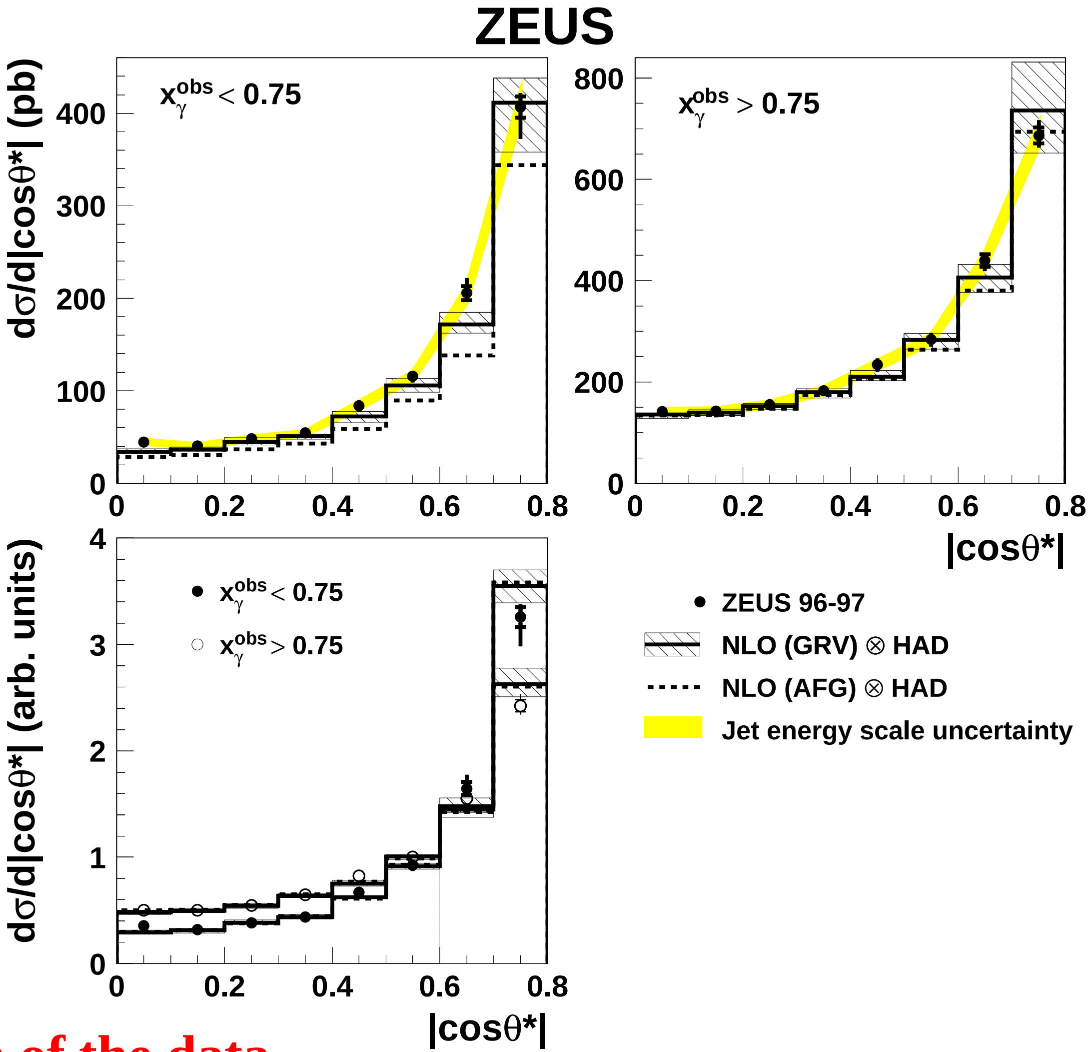
$\rightarrow$ **Direct (quark-exchange only)**

$$d\sigma/d|\cos\theta^*| \sim \frac{1}{(1-|\cos\theta^*|)^1}$$

- **The dijet angular distribution $d\sigma/d|\cos\theta^*|$ for $x_\gamma^{OBS} < 0.75$ ("resolved") should be steeper than that of $x_\gamma^{OBS} > 0.75$ ("direct") as $|\cos\theta^*| \rightarrow 1$**

Dijet Photoproduction: the dynamics of resolved and direct processes

- Measurement of the dijet differential cross section $d\sigma/d|\cos\theta^*|$ for dijet events with
  $E_T^{jet,1} > 14$ GeV, $E_T^{jet,2} > 11$ GeV
  $-1 < \eta^{jet} < 2.4$ (both jets)
  in the kinematic region
  $Q^2 < 1$ GeV^2 and $134 < W_{\gamma p} < 277$ GeV
- Phase-space region:
  $|\cos\theta^*| < 0.8$, $M_{JJ} > 42$ GeV
  $0.1 < \frac{1}{2}(\eta^{jet,1} + \eta^{jet,2}) < 1.3$
- Comparison with NLO QCD calculations:
  → High-x_γ^{OBS} ("direct"): NLO describes the shape and normalisation of the data
  → Low-x_γ^{OBS} ("resolved"): NLO describes the shape and (reasonably) the normalisation of the data
- The dijet angular distribution of the "resolved" sample is steeper than that of "direct"



High-M_{JJ} Dijet Photoproduction

- Measurement of the dijet differential cross section $d\sigma/dM_{JJ}$ in the range $47 < M_{JJ} < 160$ GeV for dijet events with $E_T^{jet} > 14$ GeV, $-1 < \eta^{jet} < 2.5$ and $|\cos\theta^*| < 0.8$
- Small experimental uncertainties:

→ jet energy scale known to 1% ⇒ 5% on $d\sigma/dM_{JJ}$

- Small theoretical uncertainties:

→ higher-order terms (varying μ_R) below 15%

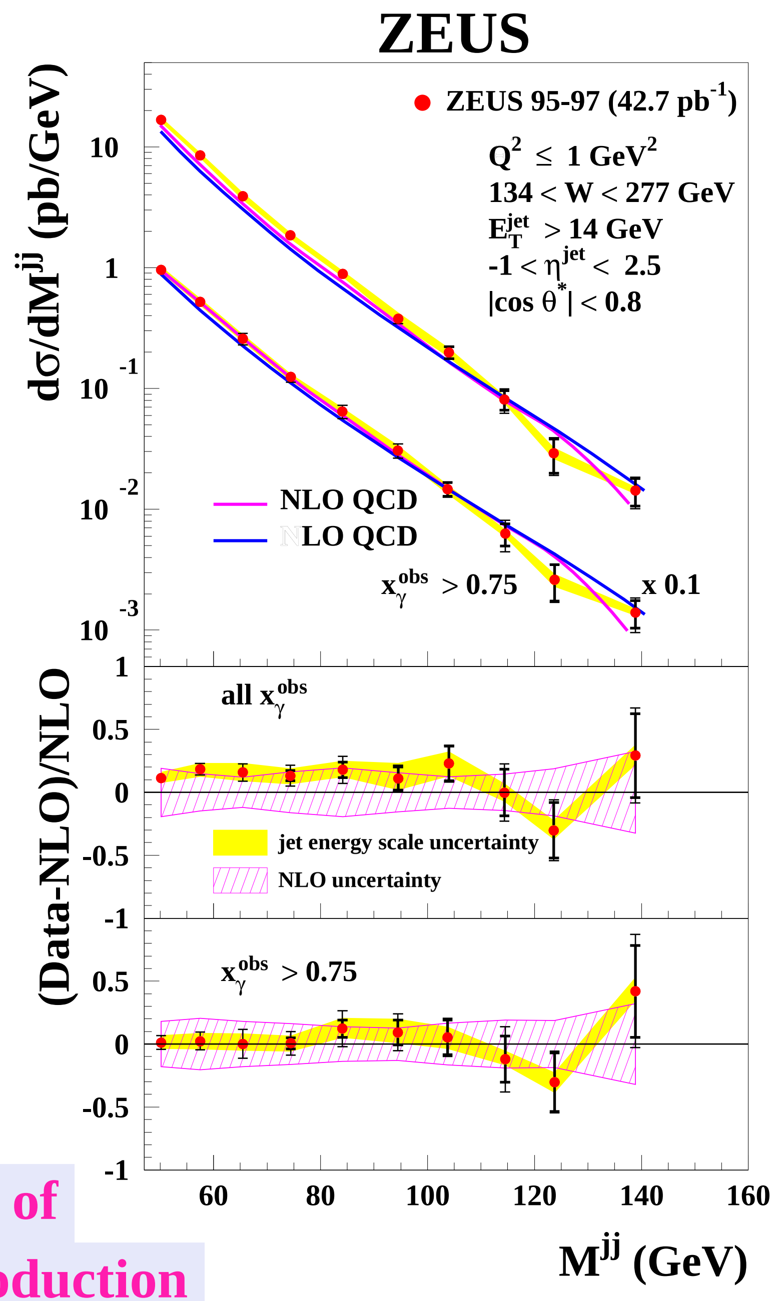
→ γ PDFs (GRV-HO,AFG-HO) below 10%

→ resolved processes suppressed at high M_{JJ}

→ small hadronisation corrections, below 5%

- NLO QCD calculations describe the shape and normalisation of the measurements well

→ Validity of the pQCD description of the dynamics of parton-parton and γ-parton interactions in photoproduction



Dijet Photoproduction: photon and proton structure

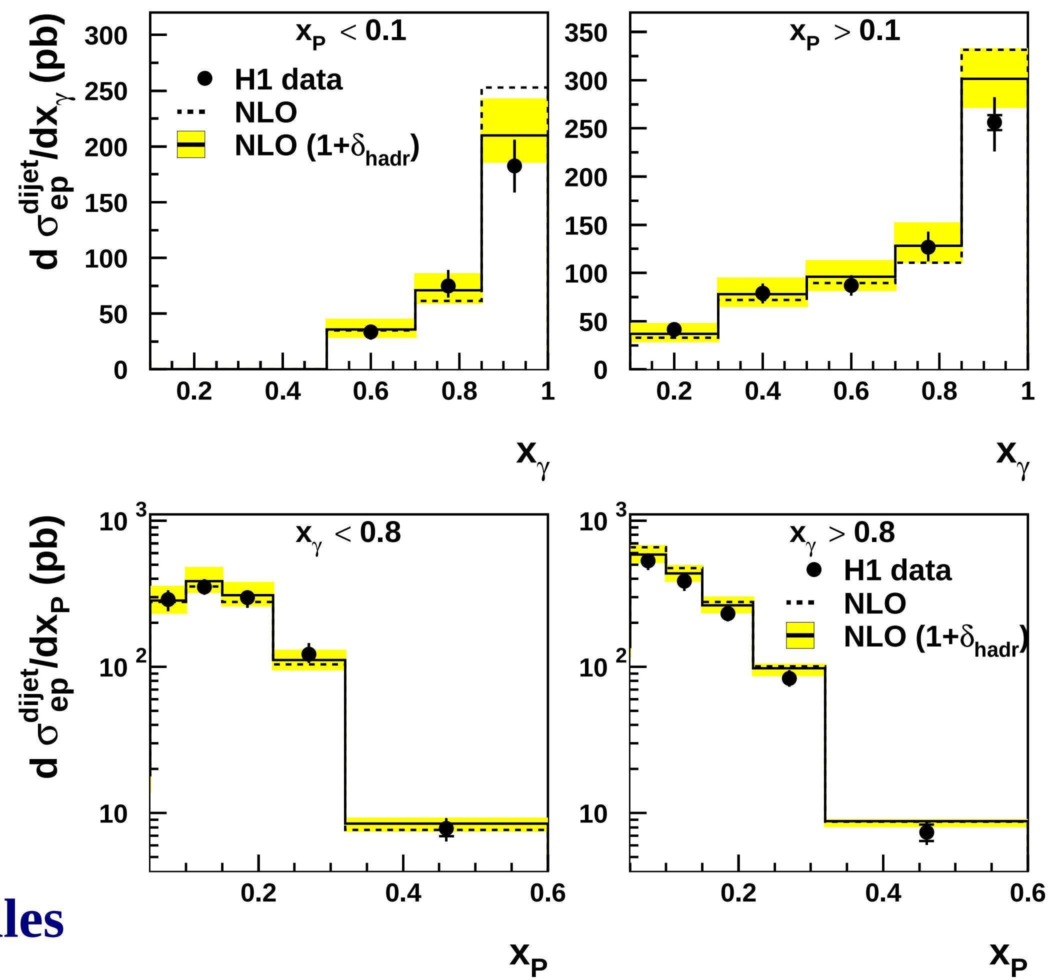
- Measurement of the dijet cross sections $d\sigma/dx_\gamma$ and $d\sigma/dx_p$ for dijet events with
  $E_{T,max} > 25$ GeV, $E_{T,second} > 15$ GeV and $-0.5 < \eta^{jet} < 2.5$ (both jets)
  in the kinematic region $Q^2 < 1$ GeV^2 and $95 < W_{\gamma p} < 285$ GeV
- x_p variable: $x_p = \frac{1}{2E_p} \sum_{i=1}^{2} E_T^{jet_i} e^{\eta^{jet_i}}$
- NLO calculations using CTEQ5M (proton) and GRV-HO (photon) describe the data
- Theoretical uncertainties:

→ terms beyond NLO ⇒ 10-20%

→ uncertainties of proton PDFs

$< 5\%$ (up to 15%) for $x_p < 0.1$ (> 0.1)

- Even up to the highest x_p, where 40% of $d\sigma/dx_p$ arises from gluon$_p$-induced processes, the data is described by NLO
- Consistent with QCD-evolved photon PDFs determined from measurements at lower scales



Dijet Photoproduction: photon structure

- Measurement of the dijet cross section $d\sigma/dx_\gamma$ for two $E_{T,max}$ regions ($\mu_{F\gamma}$ where γ is probed)

- Comparison with NLO QCD using various sets of photon PDFs (GRV-HO, AFG-HO):

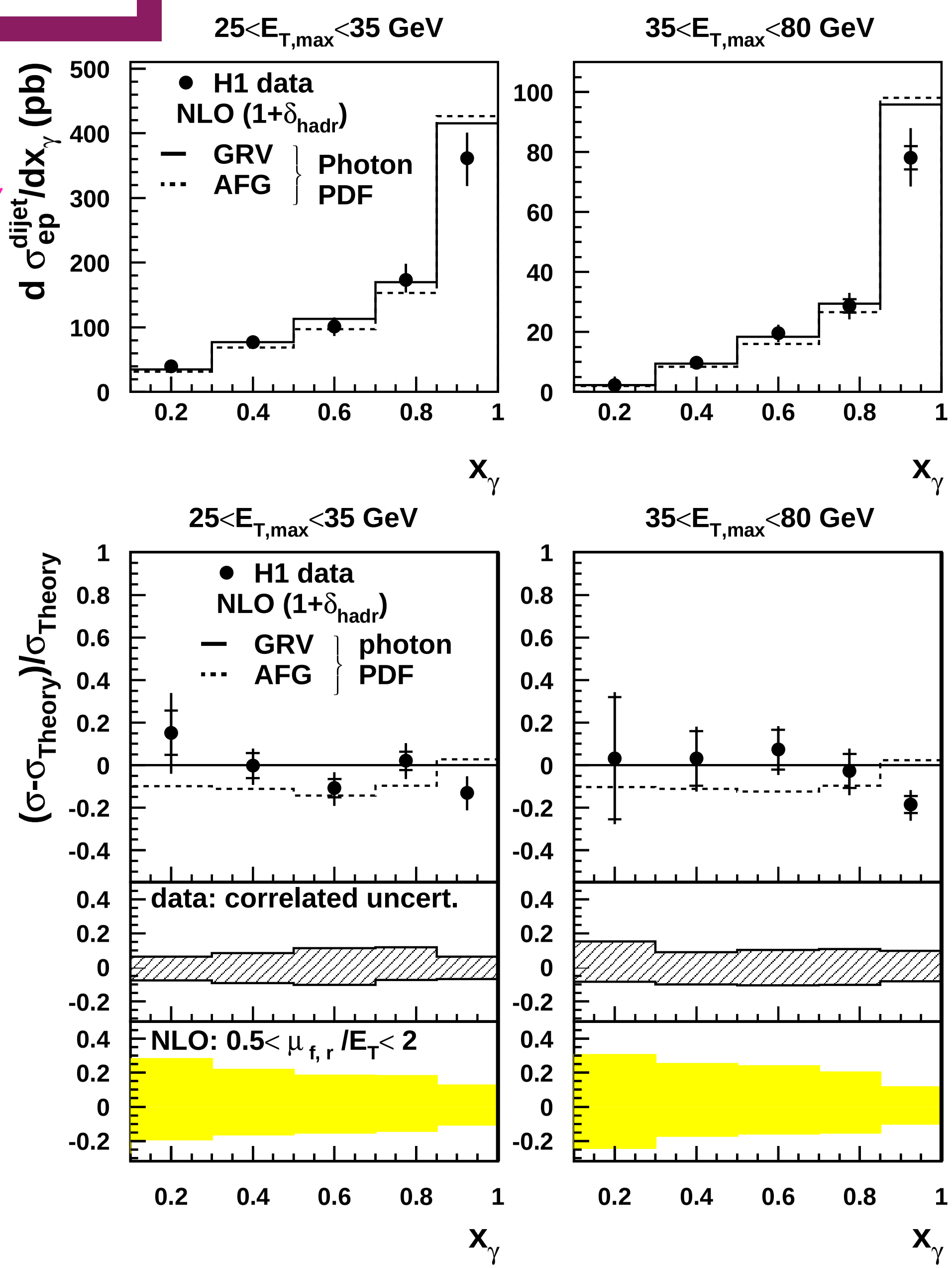
$\rightarrow$ NLO calculations describe the data well

$\rightarrow$ the variation due to the choice of γ PDFs is smaller than the NLO uncertainty due to higher orders and the correlated experimental uncertainties (jet energy scale)

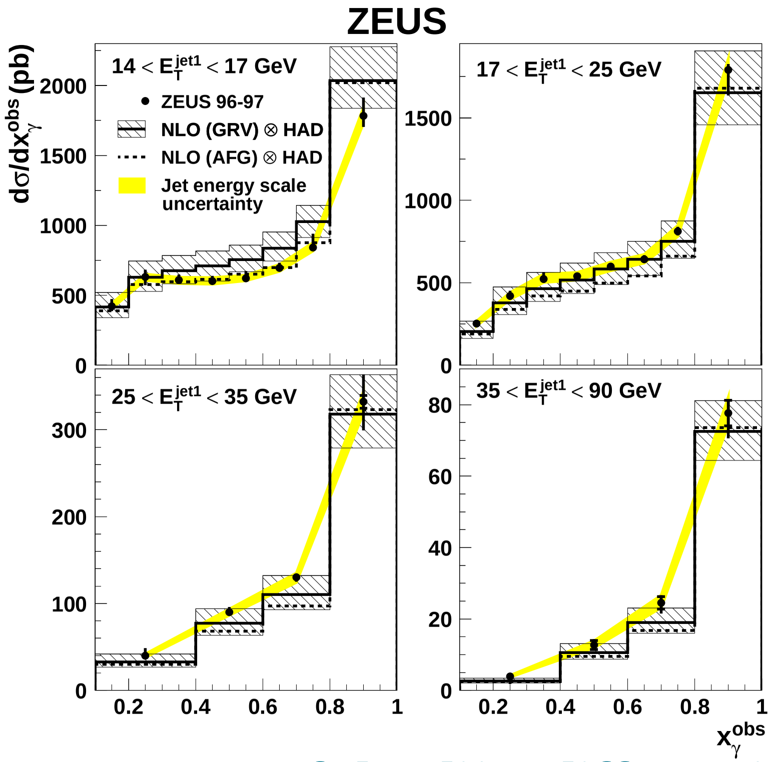
- To constrain the photon PDFs further (rather than testing existing sets)

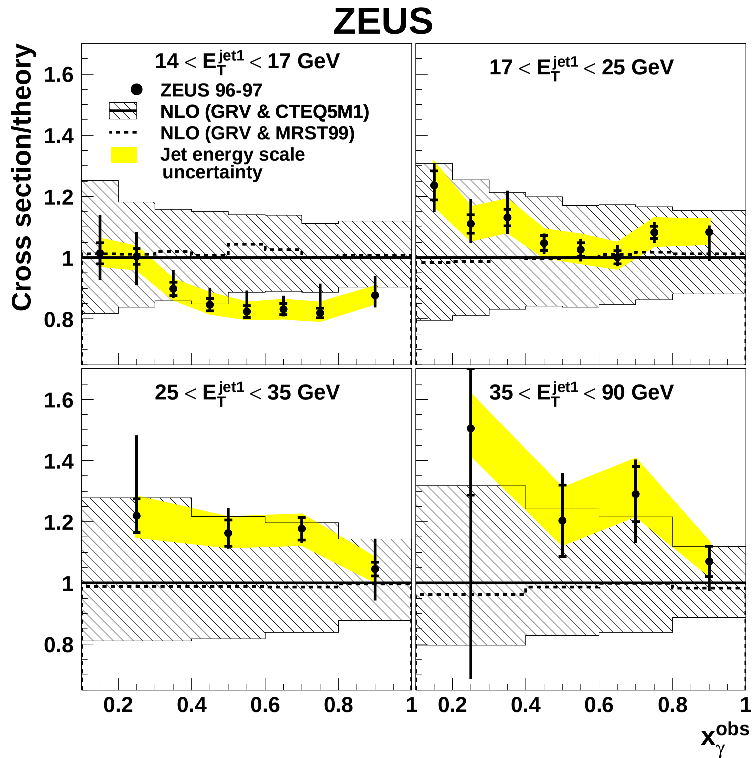
$\rightarrow$ reduction of experimental uncertainties and

$\rightarrow$ improved calculations are needed



Dijet Photoproduction: photon structure

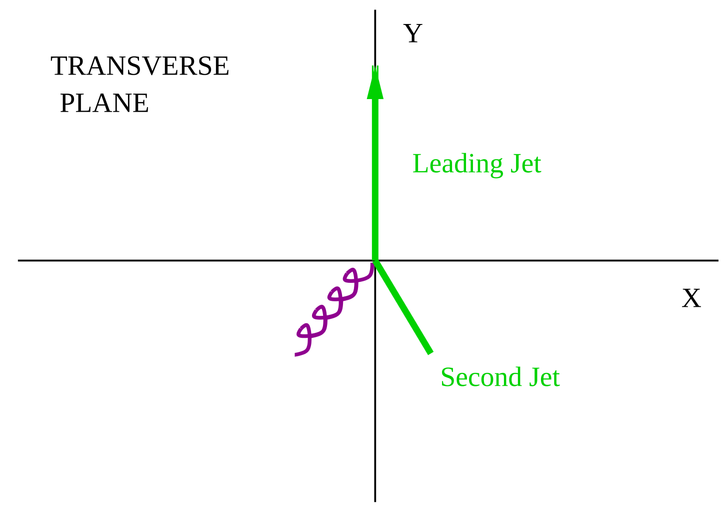




- **Measurement of the dijet differential cross section $d\sigma/dx_\gamma$ for dijet events with $E_T^{jet,1} > 14$ GeV, $E_T^{jet,2} > 11$ GeV, $-1 < \eta^{jet} < 2.4$ (both jets)**
- **Small experimental uncertainties: jet energy scale known to 1%**
- **Comparison with NLO QCD calculations (CTEQ5M1 proton, GRV/AFG-HO photon): the data at low x_γ^{OBS} fall less steeply with E_T^{jet} than NLO; sensitivity to γ-PDFs**

⇒ Useful constrain in a global determination of γ-PDFs; improved calculations would help

Dijet Photoproduction: H1 vs ZEUS



- Differences between (ZEUS vs NLO) and (H1 vs NLO)

→ The differences appear to be due to the different cuts on the second jet's E_T^{jet} ($E_{T,2}^{jetcut}$)!

→ 11 GeV in ZEUS; 15 GeV in H1

- $E_{T,2}^{jetcut}$ dependence of the NLO QCD calculations:

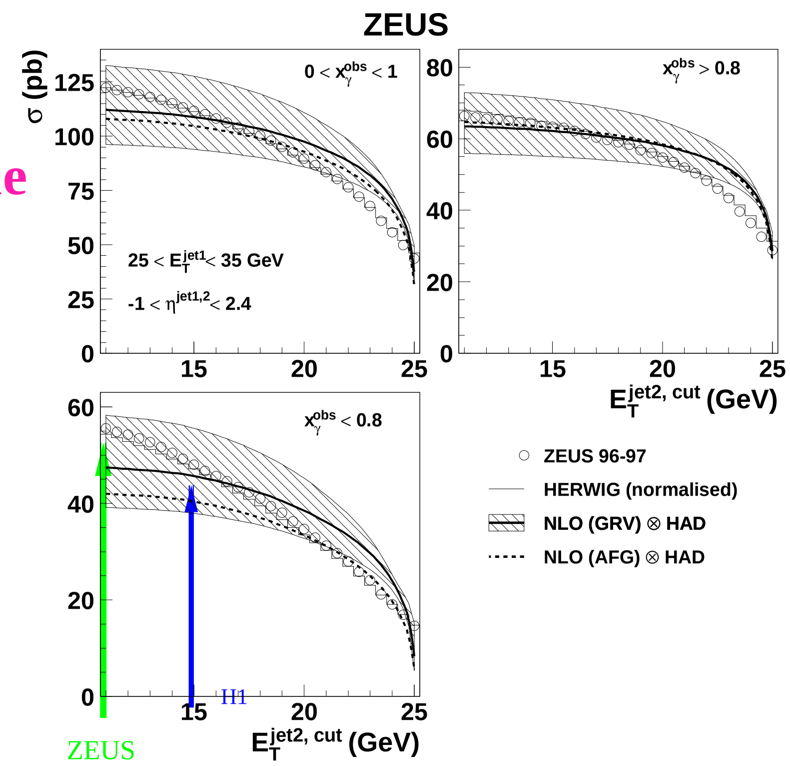
→ the measured dependence not reproduced by NLO (HERWIG reproduces the measured dependence)

→ the comparison data vs NLO depends on the cut value

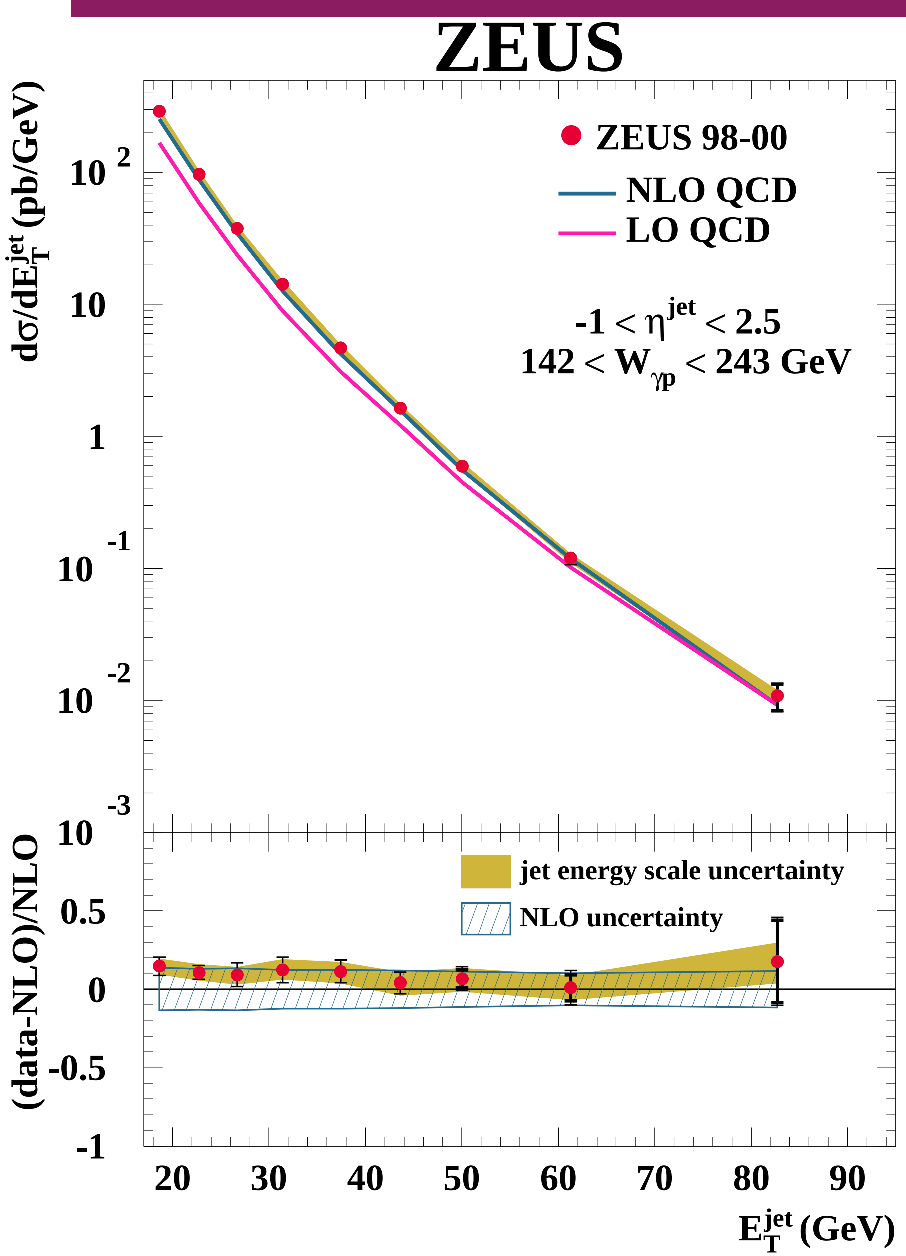
→ for $x_\gamma^{OBS} > 0.8$ the NLO converges to the data as the cut on $E_{T,2}^{jetcut}$ is decreased; there the cross is relatively insensitive to the cut value

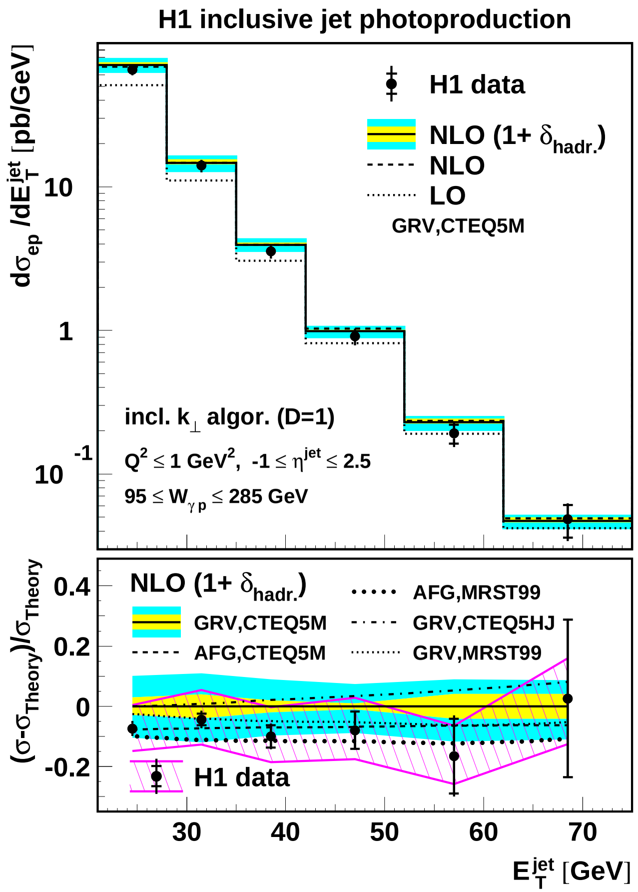
→ accounted for by the large μ_R uncertainty which is comparable to the differences between various γ PDFs

- Theoretical work on improving the dijet calculations (NNLO? selection criteria?) is needed!



Inclusive Jet Photoproduction





- Measurements (NEW) of differential cross sections for inclusive jet photoproduction

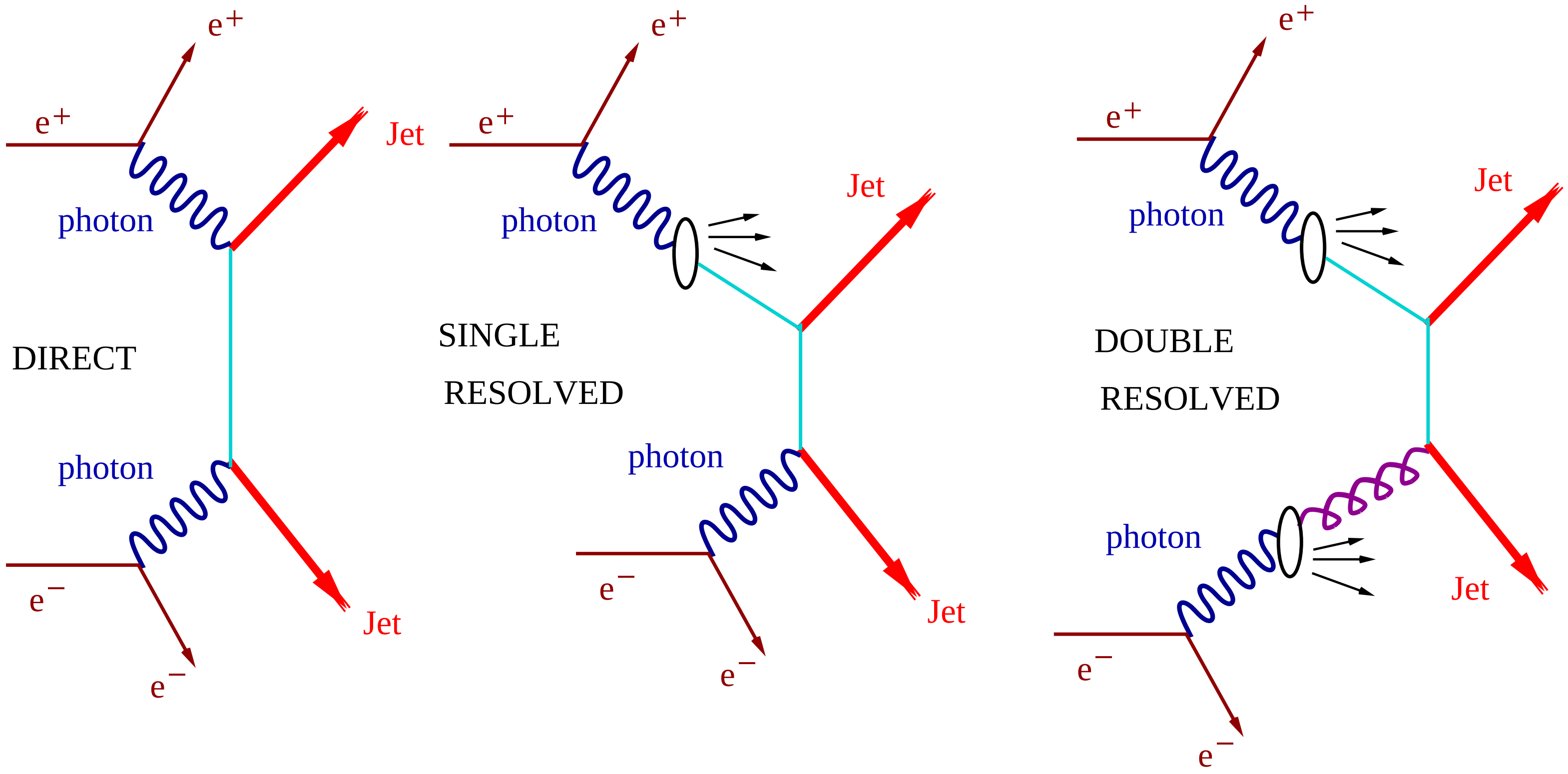
→ Smaller theoretical uncertainties

⇒ Precise test of NLO QCD calculations

⇒ Determination of α_s and its scale dependence!

- Talks in WG-C by B. Andrieu and M. Sutton

Jet Production in $\gamma\gamma$ collisions



- **Jet production in $\gamma\gamma$ collisions has been studied in e^+e^- interactions**
- **Three contributing processes: direct, single-resolved and double-resolved**
- **Measurements of jet production allow the study of**

→ dynamics of $\gamma\gamma$, γ-parton and parton-parton interactions

→ photon structure: sensitivity to quark and gluon densities in the photon

Dijet Production in $\gamma\gamma$ collisions

OPAL

- Measurement of dijet production in $\gamma\gamma$ collisions from e^+e^- data at $\sqrt{s} = 161$ and 172 GeV; jets defined using cone algorithm ($R = 1$) with $E_T^{jet} > 3$ GeV and $|\eta^{jet}| < 2$
- Observables to separate the contributions:

$$x_\gamma^\pm = \frac{\sum_{\text{jets 1,2}}(E^{jet} \pm p_z^{jet})}{\sum_{\text{all hadrons}}(E^h \pm p_z^h)}$$

→ "direct-enhanced": $x_\gamma^\pm > 0.8$

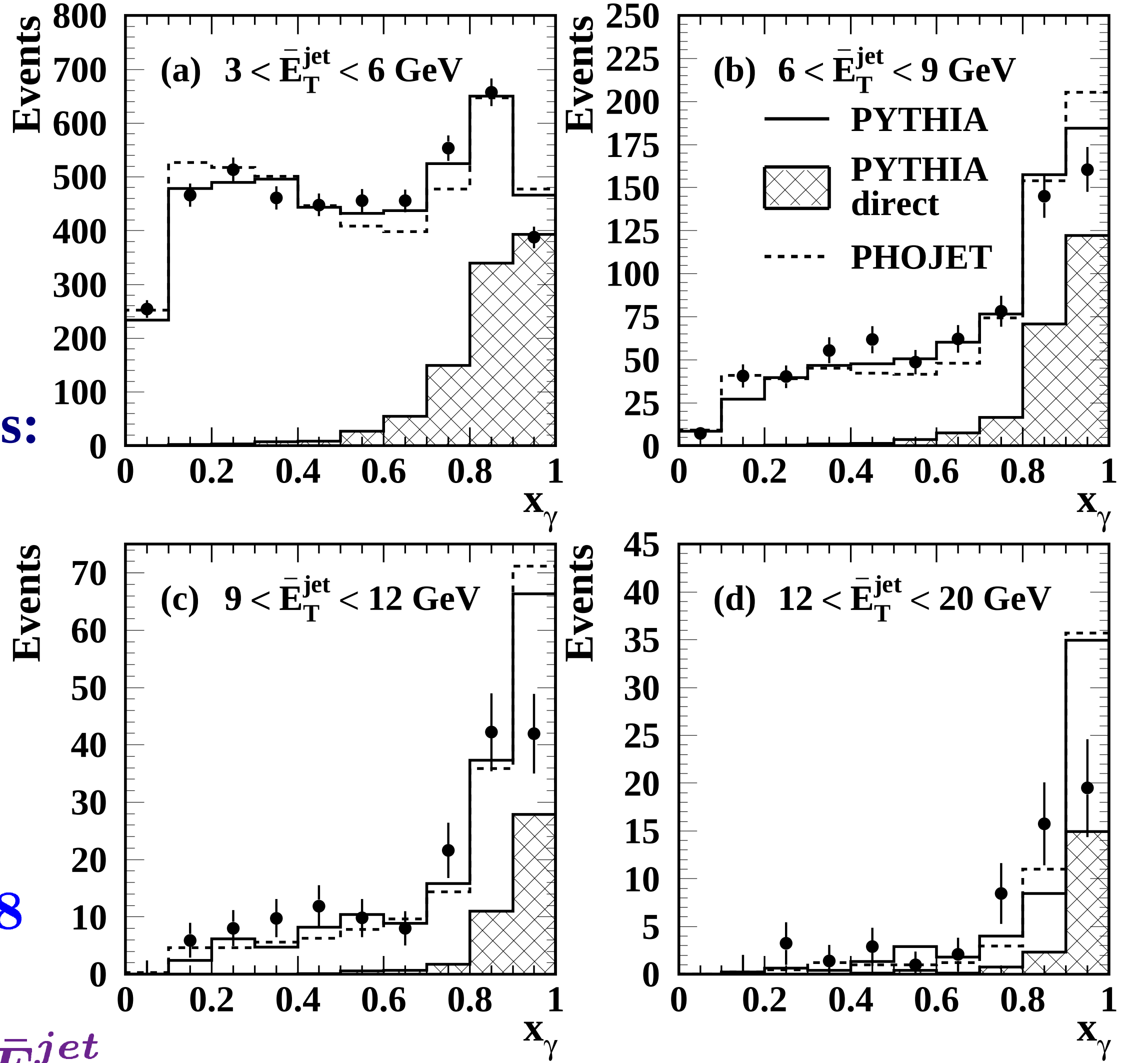
→ "single-resolved-enhanced": $x_\gamma^+ > 0.8$ and $x_\gamma^- < 0.8$ (or viceversa)

→ "double-resolved-enhanced": $x_\gamma^\pm < 0.8$

- Dependence of x_γ distribution on $\bar{E}_T^{jet}$

→ resolved contribution dominant at low $\bar{E}_T^{jet}$

→ increasing direct contribution as $\bar{E}_T^{jet}$ increases



Dijet Production in $\gamma\gamma$ collisions: the dynamics

- Measurement of $d\sigma/d|\cos\theta^*|$ in the phase-space region defined by $M_{jj} > 12$ GeV, $|\bar{\eta}^{jet}| < 1$
- "Direct-enhanced sample":

$\rightarrow$ dominated by $\gamma\gamma \rightarrow q\bar{q}$ (q-exchange)

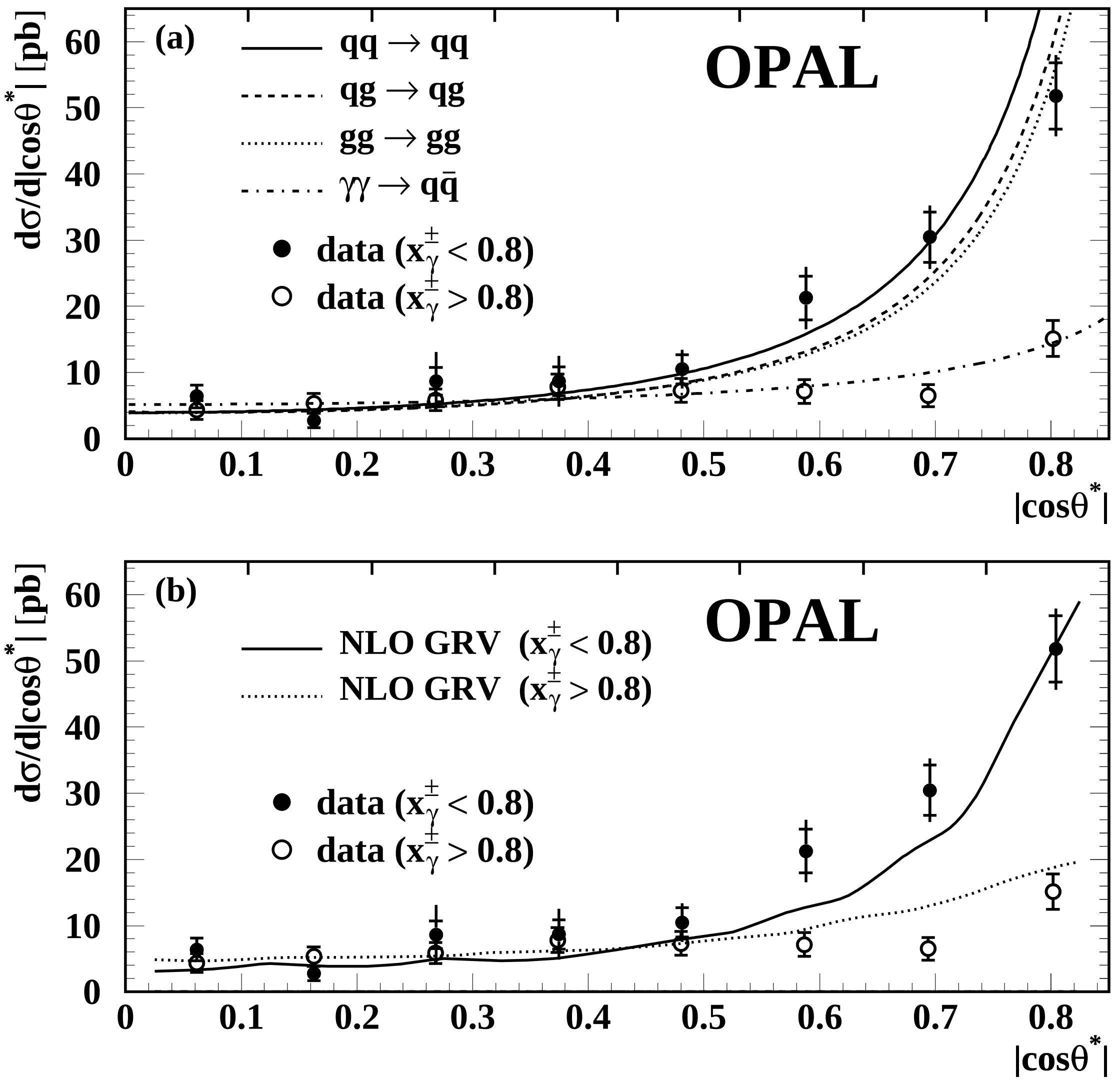
$$d\sigma/d|\cos\theta^*| \sim \frac{1}{(1-|\cos\theta^*|)^1}$$

- "Double-resolved-enhanced sample":

$\rightarrow$ dominated by parton-parton processes (g-exchange)

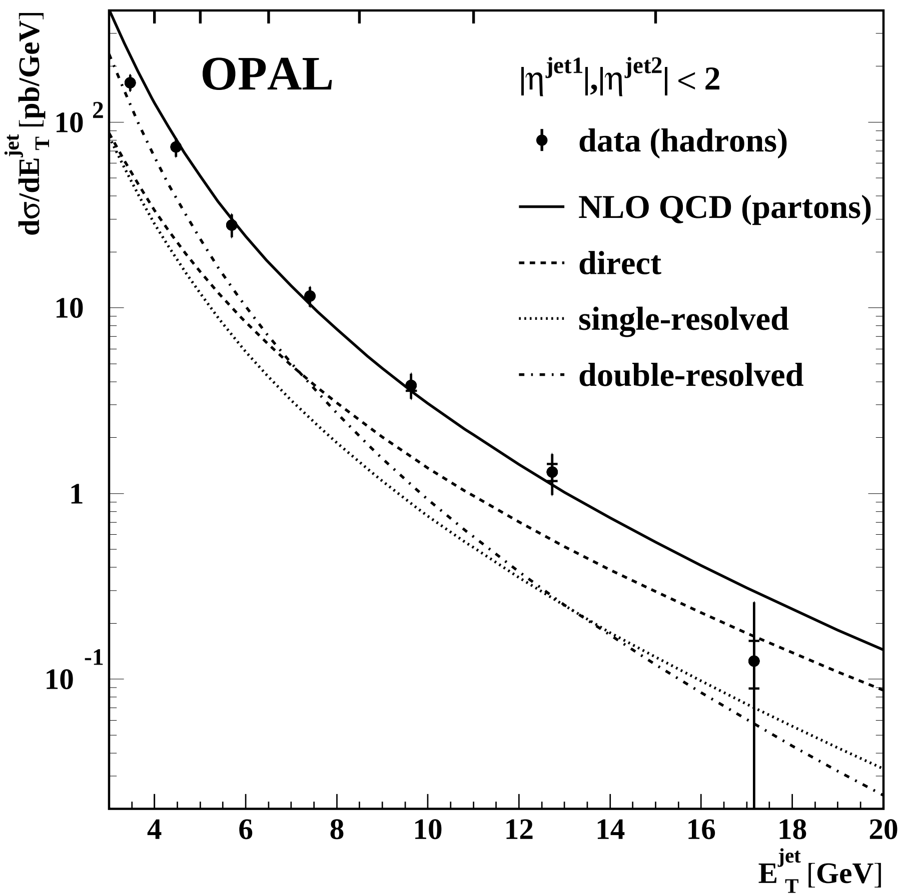
$$d\sigma/d|\cos\theta^*| \sim \frac{1}{(1-|\cos\theta^*|)^2}$$

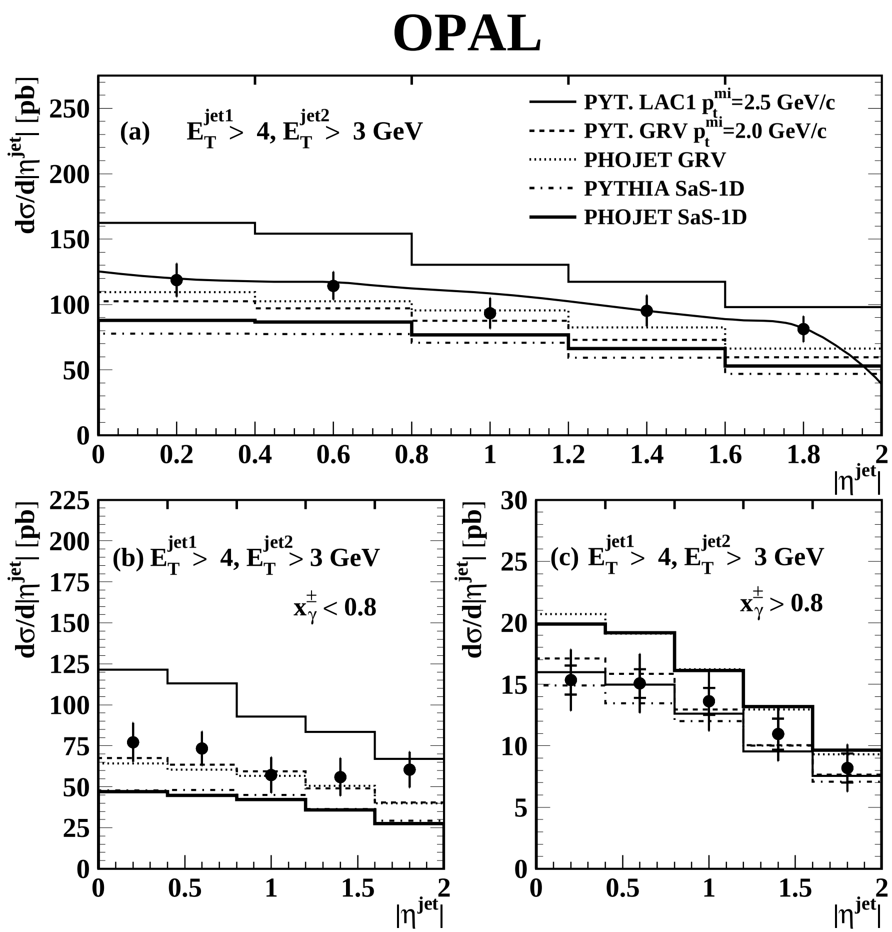
- Stronger rise as $|\cos\theta^*| \rightarrow 1$ in the "double-resolved-enhanced sample" than in the "direct-enhanced sample"



$\Rightarrow$ Shapes reproduced by LO-QCD models (PYTHIA, PHOJET) and NLO QCD

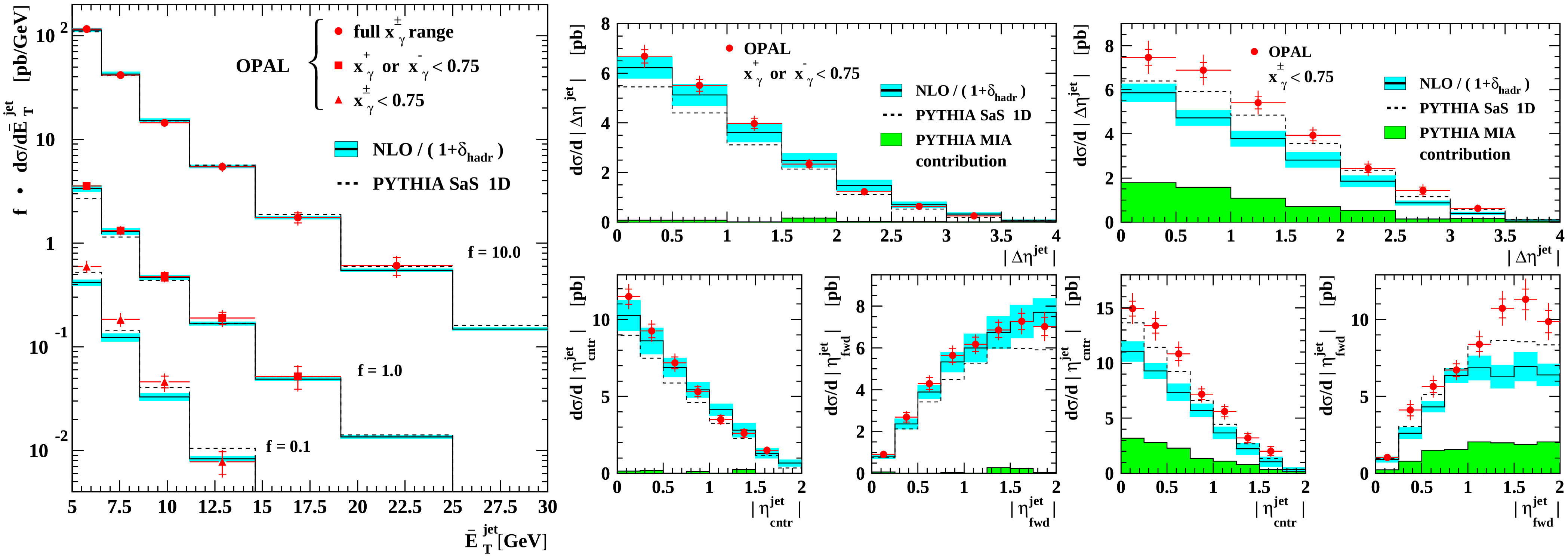
Dijet Production in $\gamma\gamma$ collisions: photon structure





- NLO QCD (without corr. for hadronis. or "underlying event") using GRV γ-PDFs reproduces the shape and normalisation of the data; NLO by Klasen et al
- Comparison to LO-QCD models (including hadronis. and "underlying event" effects) $\rightarrow$ sensitivity to γ-PDFs

Dijet Production in $\gamma\gamma$ collisions

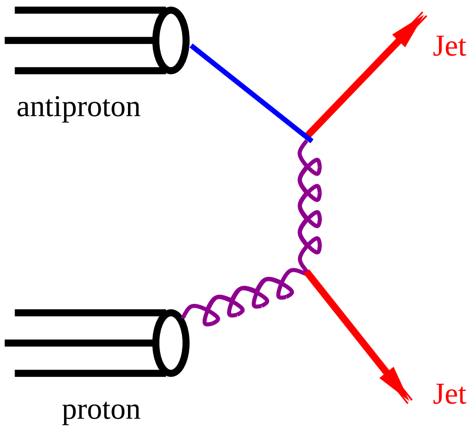


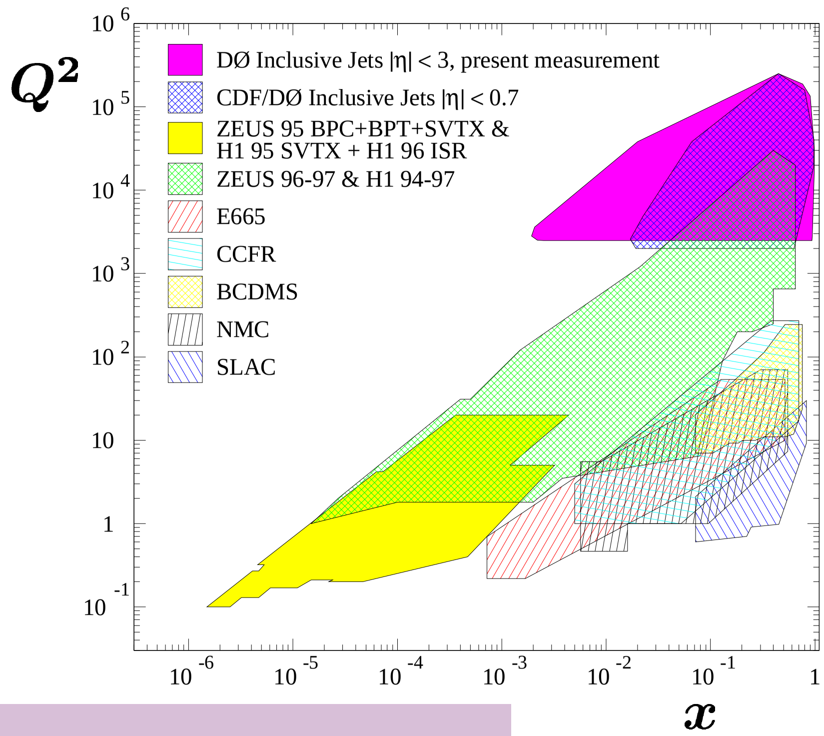
- **Measurements (NEW) of dijet production in $\gamma\gamma$ from e^+e^- at $\sqrt{s}$ = 189-209 GeV with larger luminosity and using the inclusive k_T jet algorithm**
- **Measurements of differential cross sections in different regions of the x_γ^+-x_γ^- plane:**

→ either x_γ^+ or $x_\gamma^- < 0.75$: resolved-photon processes dominate; less sensitive to "underlying event" effects; NLO QCD (GRV-HO γ-PDFs) agree well with the data

- Talks in WG-C by K. Krueger and P. Achard

Jet Production in $p\bar{p}$ collisions





- pQCD calculations of jet cross sections

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

longitudinal momentum fraction of parton a/antiproton ($x_{\bar{p}}$), parton b/proton (x_p)

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

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

- Dynamics of parton-parton interactions at the smallest distances!
- Proton structure: sensitivity to quark and gluon densities at large x and large Q^2

NLO QCD Calculations of Jet Cross Sections

- Iterative cone algorithm in the η-ϕ plane (laboratory)

$\longrightarrow$ new measurements using inclusive k_T jet algorithm

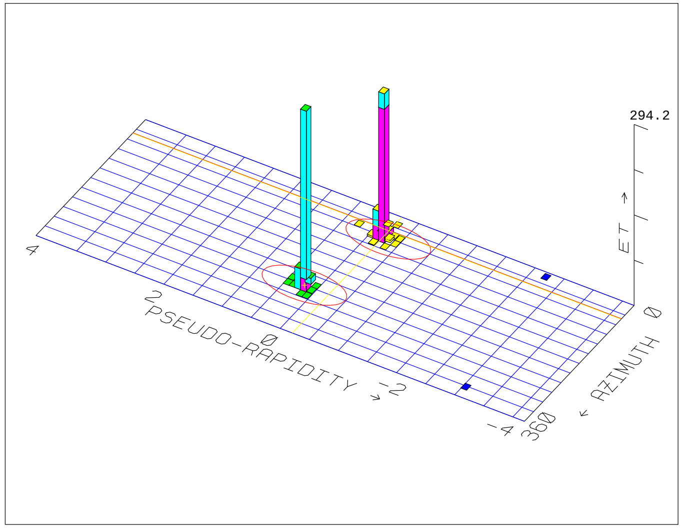
- Several NLO QCD calculations ($\mathcal{O}(\alpha_s^3)$) available

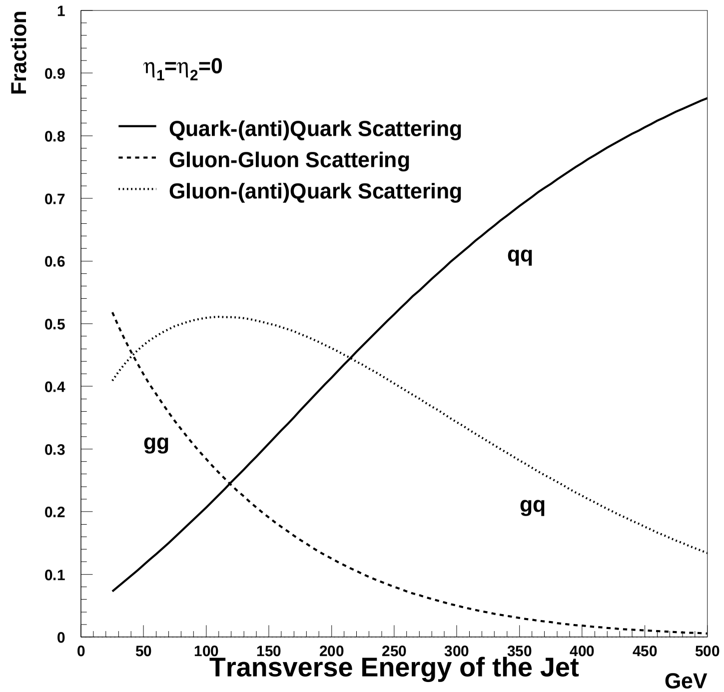
$\longrightarrow$ Ellis et al, Aversa et al, Giele et al

$\longrightarrow$ choice of scales: $\mu_R = \mu_F \sim E_T^{jet}$

$\longrightarrow$ proton PDFs: current NLO QCD parametrisations

- Cone algorithm: introduction of R_{sep} parameter to approximate experimental effects on clustering
- Effects from the underlying event estimated from minimum bias data $\longrightarrow$ Talk in WG-C by S. Lami
- At low E_T^{jet} jet production is dominated by (incoming) gg and gq scattering
- At high E_T^{jet} jet production is dominated by (incoming) qq scattering; gq about 30% at $E_T^{jet} = 350$ GeV





Measurement of Inclusive Jet Production in $p\bar{p}$ collisions

- Measurement of the differential cross section $d\sigma/dE_T^{jet}$ for inclusive jet production using the cone algorithm ($R = 0.7$) in the region $0.1 < |\eta^{jet}| < 0.7$
- Comparison to NLO QCD calculations:

$\rightarrow$ $\mu_R = \mu_F = E_T^{jet}/2$, $R_{sep} = 1.3$

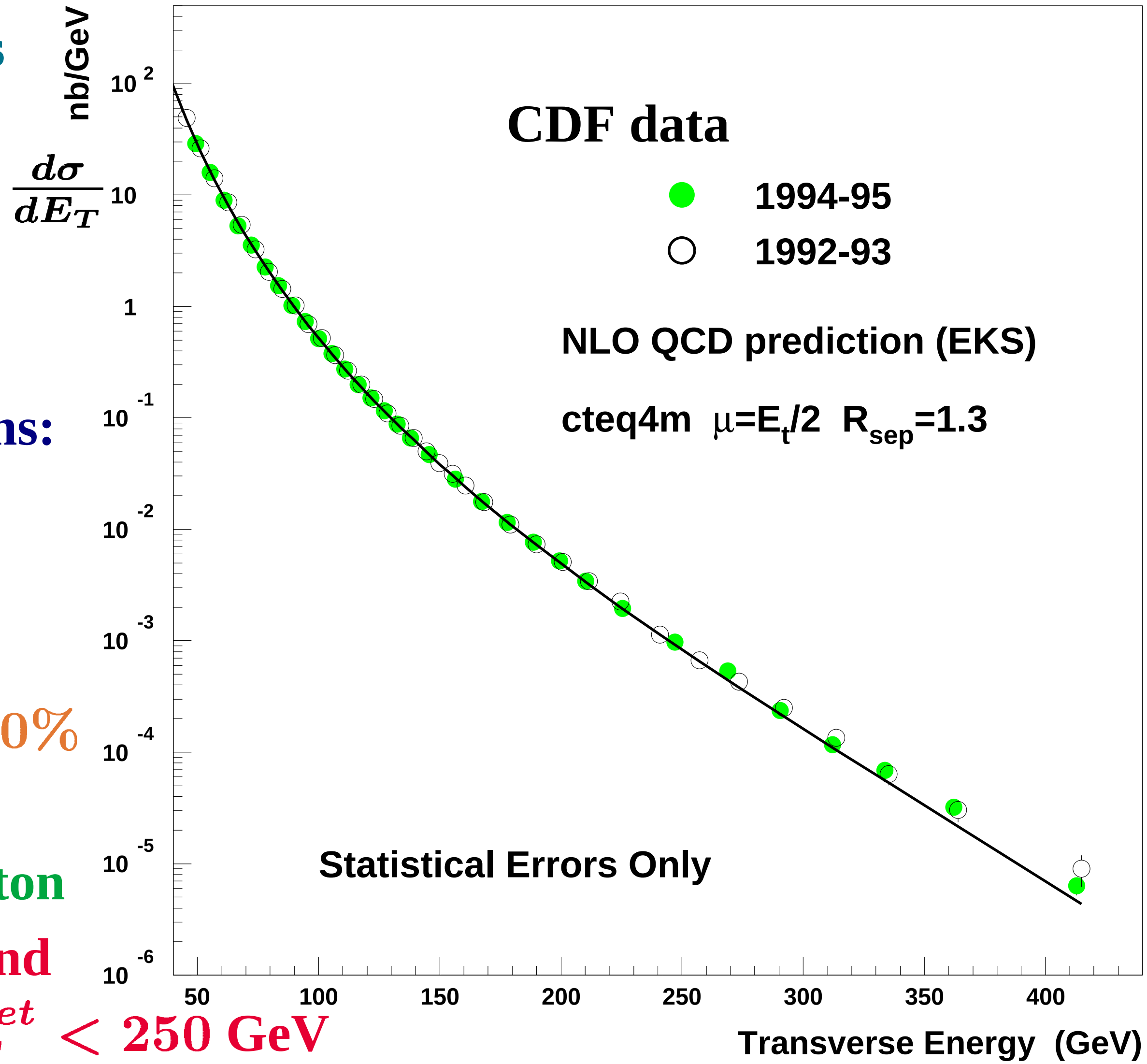
$\rightarrow$ proton PDFs CTEQ4M

- Theoretical uncertainties:

$\rightarrow$ higher-order terms (varying μ_R): 20%

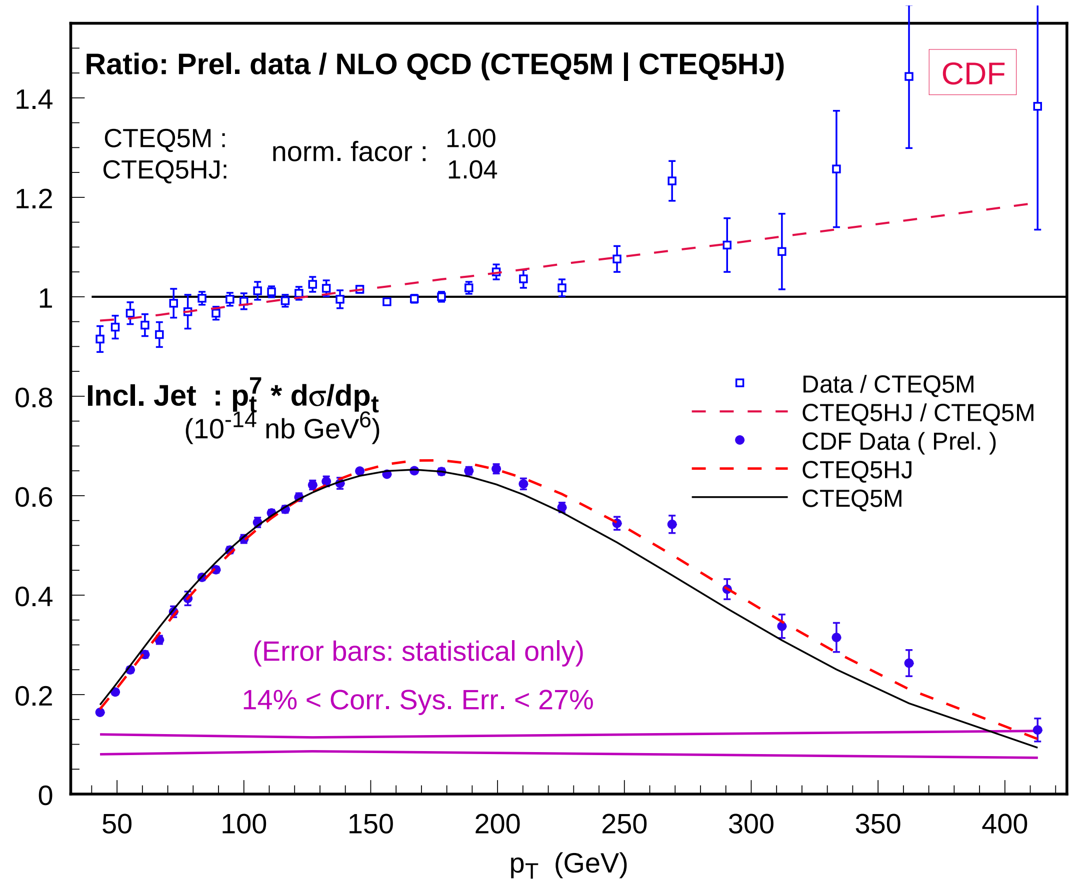
$\rightarrow$ variation of R_{sep}: 5%

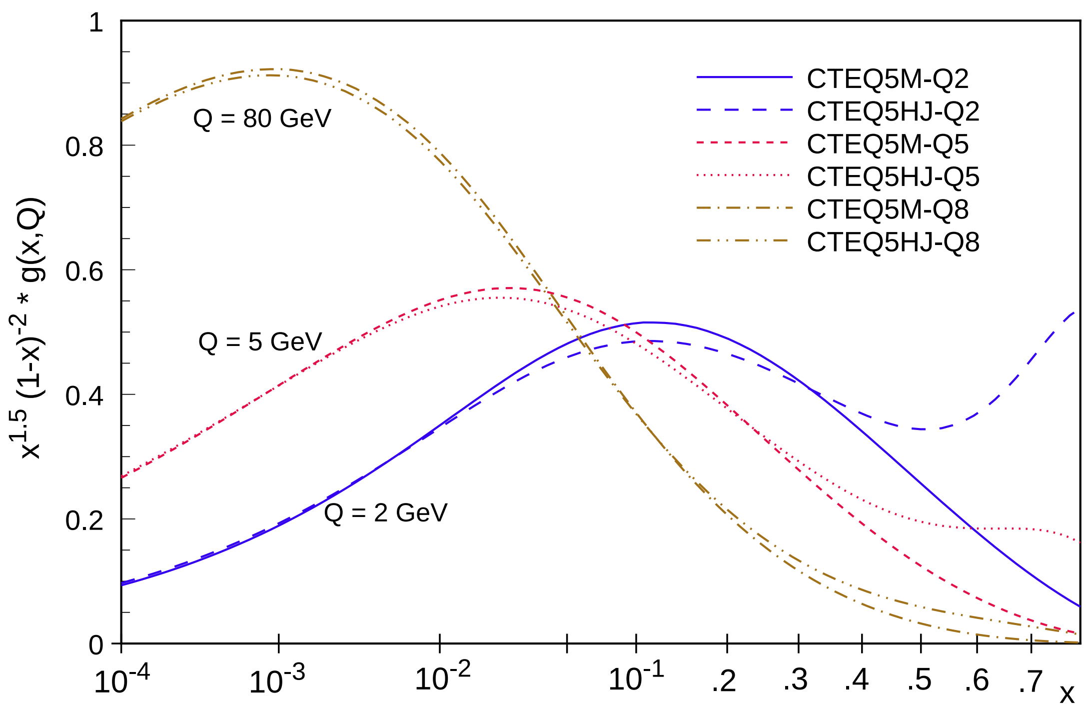
- NLO QCD calculations based on proton PDFs CTEQ4M describe the shape and normalisation of the data well for $E_T^{jet} < 250$ GeV



$\Rightarrow$ Excess at high E_T^{jet}! New physics? Parametrisations of the proton PDFs?

Revisiting the gluon density at high x





- It is possible to describe the data by increasing the gluon density at high x while maintaining a good description of other data sets used in global analyses of proton PDFs
- The CTEQ5HJ parametrisations were obtained putting extra weight to the CDF data; calculations based on the central fit, CTEQ5M, lie below the data at high E_T^{jet}

Measurement of Inclusive Jet Production in $p\bar{p}$ collisions

- Measurement of the differential cross section $d^2\sigma/dE_T^{jet}d\eta^{jet}$ for inclusive jet production using the cone algorithm ($R = 0.7$) in the region $|\eta^{jet}| < 3$
- Extended range in the (x, Q^2) plane!
- Experimental uncertainties:

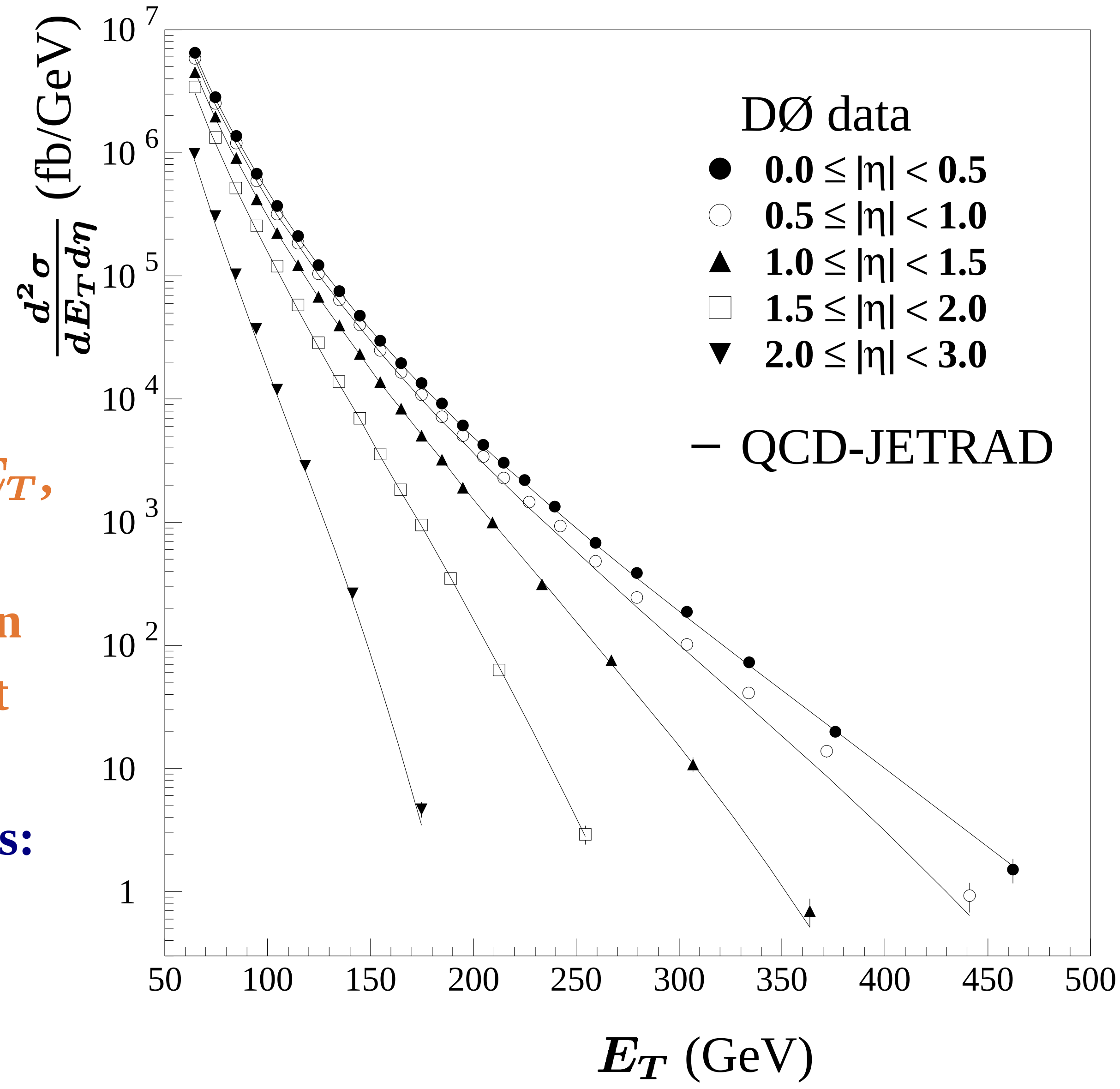
→ jet energy scale: $12 - 20\%$ at low E_T, $35 - 80\%$ at high E_T

→ jet-energy-resolution parametrisation and unfolding procedure: $3 - 5\%$ at low E_T, $10 - 20\%$ at high E_T

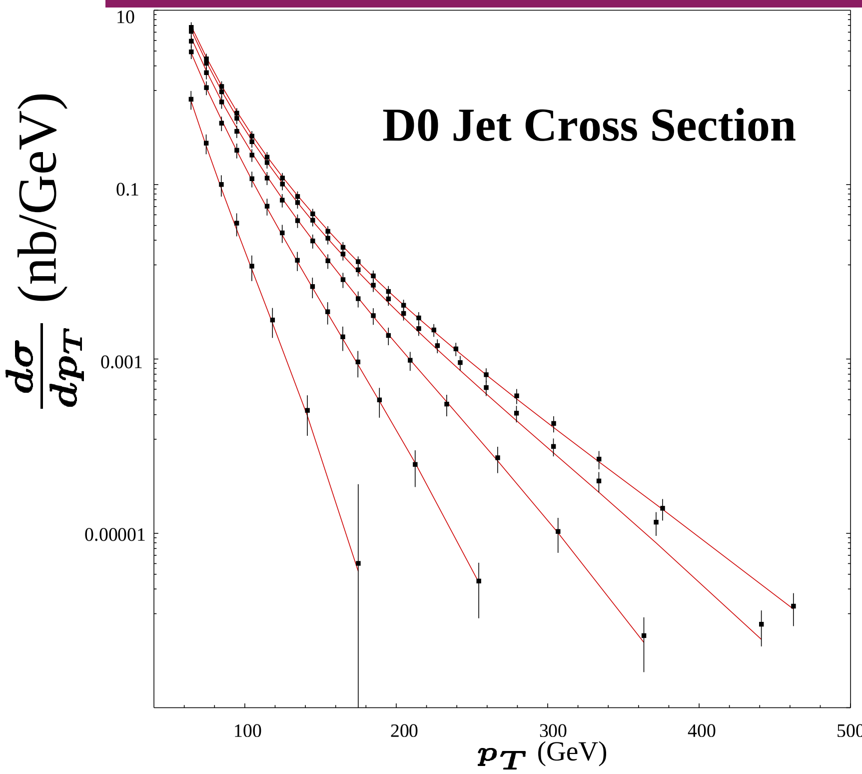
- Comparison to NLO QCD calculations:

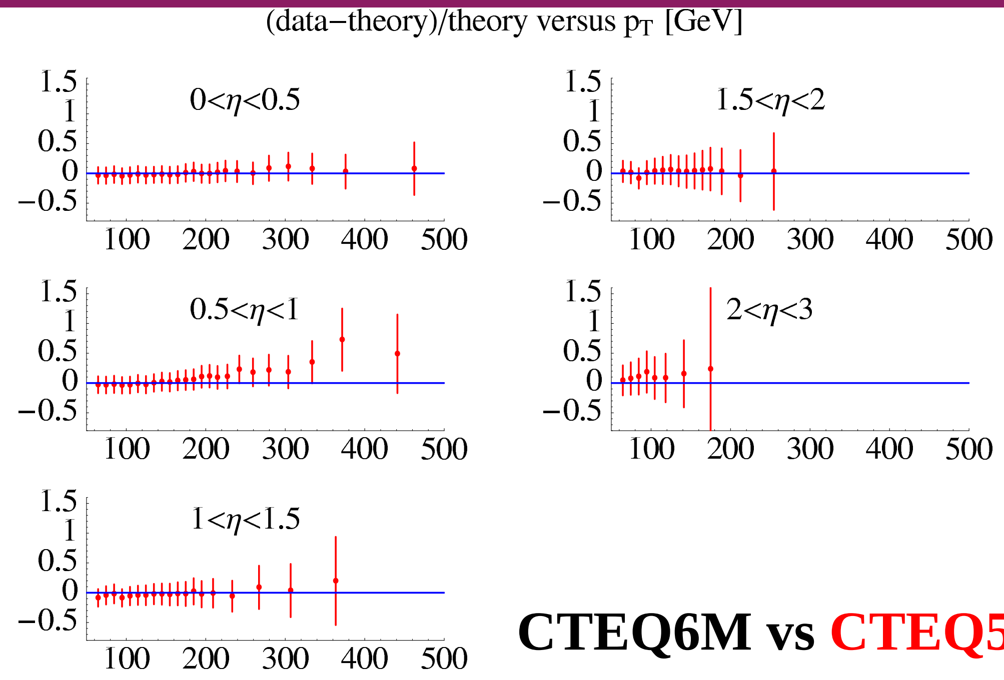
⇒ preference for proton PDFs with larger gluon content at high x

- Talk in WG-C by N. Skatchkov

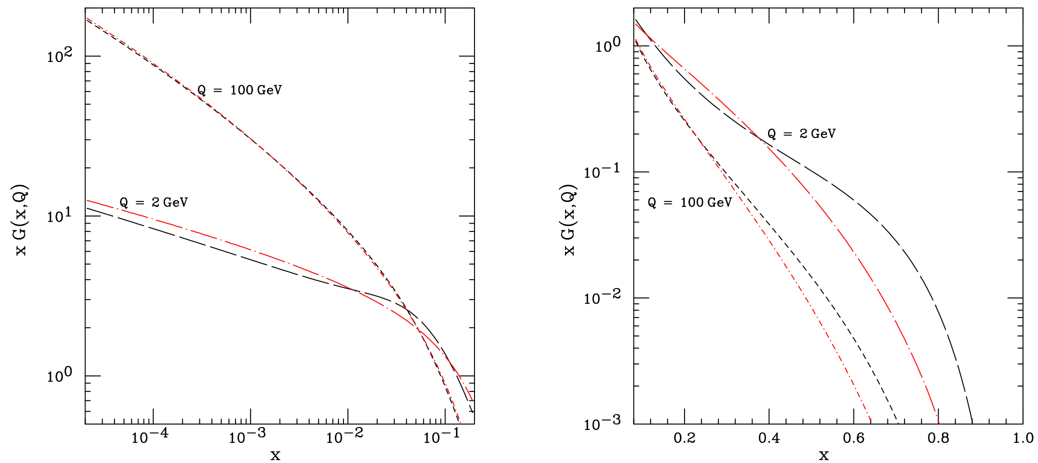


Inclusive Jet Production in $p\bar{p}$ collisions: the gluon density at high x





CTEQ6M vs CTEQ5M1



- **DØ and CDF data used in the global determination of proton PDFs (CTEQ6M) without "extra" weight ⇒ constraining the gluon density at high x**
- **⇒ good description of the data**
- **Run II measurements will help to confirm or rule out the "high-x gluon solution"** → Talk in WG-C by V. O'Dell

Last Remarks

- **In many areas further progress is limited by theoretical uncertainties!**

- **Measurements of jet production in $p\bar{p}$ included in global determination of the proton PDFs**

→ **Precise measurements of jet production in ep, γp and $\gamma\gamma$ demand a similar effort!**

- **Apologies for many omissions due to lack of time (and expertise!)**