Jets in Photoproduction & at low Q^2 at HERA

On behalf of the

H1 and **ZEUS** Collaborations

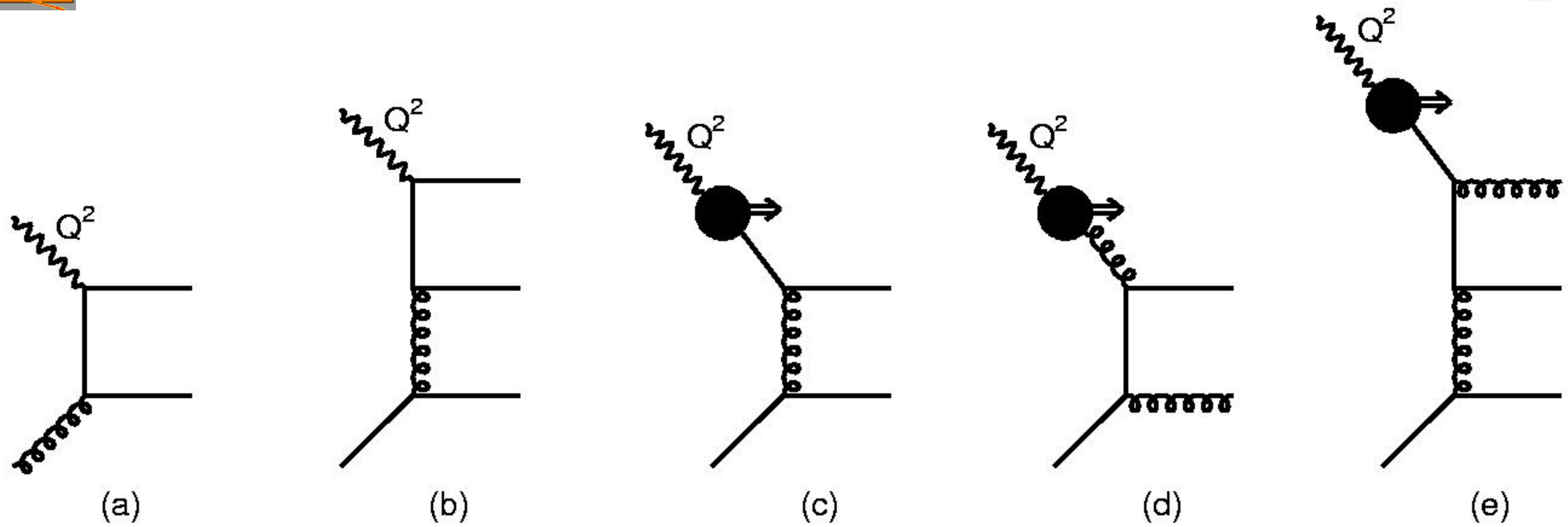
ISDM August 2005, Kromeriz

Kamil Sedlak, University of Oxford

Outline

- Photoproduction of dijets
- Transition between the photoproduction and DIS
- Tri-Jets: Color dynamics in photoproduction
- Conclusions

Dijet Photoproduction



- Direct photon interactions (a) and (b): photon acts as a point-like object. It is there for any Q^2.
- Resolved photon interactions (c), (d) and (e): photon emits quarks and gluons before the hard interaction. It is there (must be taken into account) in photoproduction ($Q^2 \sim 0$), can be included at low $Q^2 \sim 1$ GeV^2, and dies out for large Q^2. More precisely, resolved photon interactions should be taken into account for $Q^2 < (E_{T\ jets})^2$ ($E_{T\ jets}$ = hard scale).
- Experimental distinction between direct and resolved phot. interactions:
  - $x_\gamma = \Sigma_{jets1,2}(E_j^* - p_z^*) \,/\, \Sigma_{hadrons}(E^* - p_z^*)$

ZEUS:

Data 96-97, Eur.Phys.J.C23,615 (2002)

E_e = 27.5 GeV; E_p = 820 GeV

Int. lumi = 38.6 pb^{-1}

$Q^2 < 1\ GeV^2$

$E_{T,jet1} > 14$ GeV

$E_{T,jet2} > 11$ GeV

$-1 < \eta_{\ jet1,2} < 2.4$

$134 < W_{\gamma p} < 277$ GeV

Photon PDF … GRV HO

Proton PDF … CTEQ5M1

NLO QCD … Frixione et al.

H1:

Data 99-00, H1 preliminary

E_e = 27.5 GeV; E_p = 920 GeV

Int. lumi = 66.6 pb^{-1}

$Q^2 < 1\ GeV^2$

$E_{T,jet1} > 25$ GeV

$E_{T,jet2} > 15$ GeV

$-0.5 < \eta_{\ jet1,2} < 2.75$

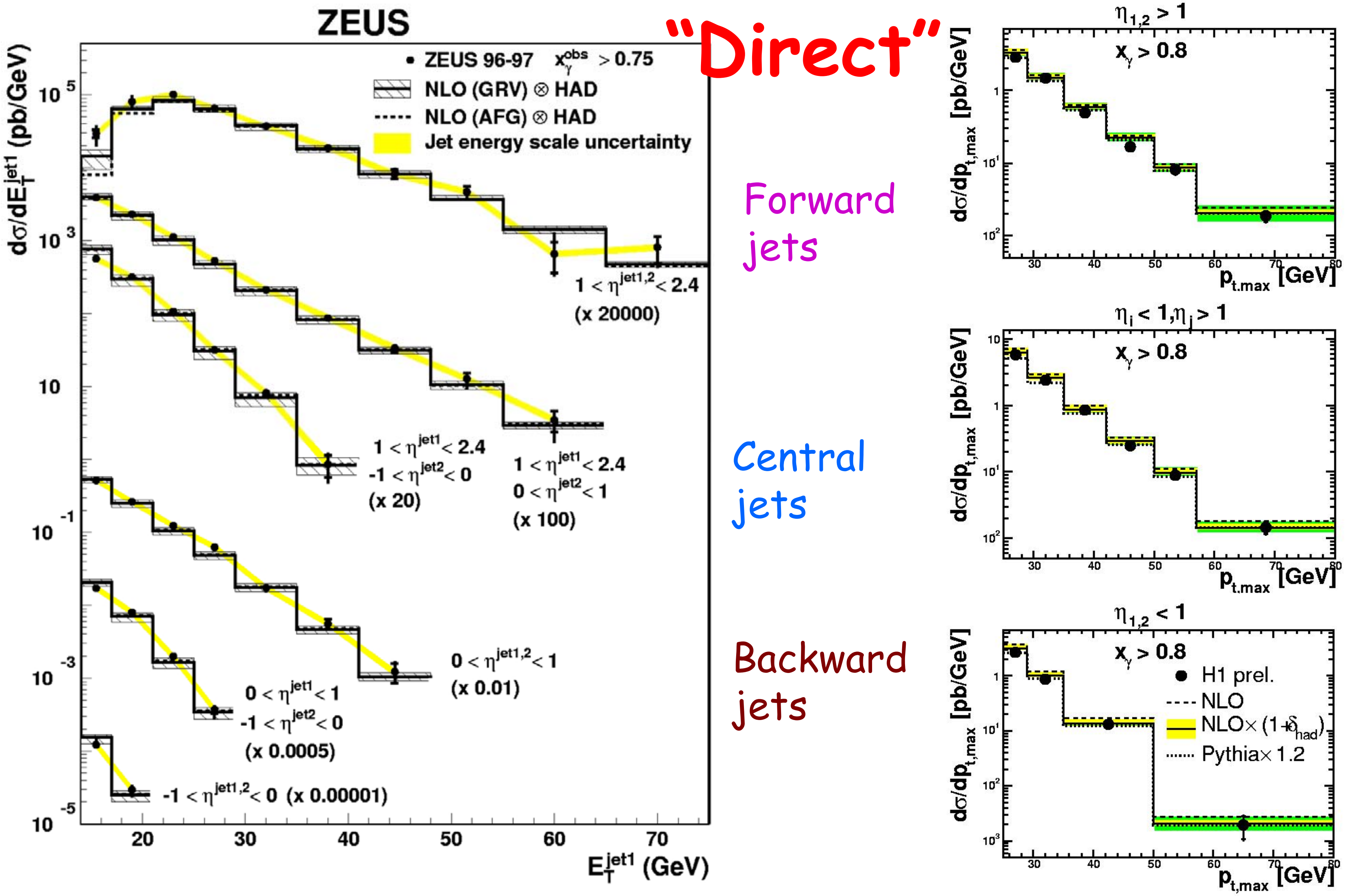
$0.1 < y < 0.9$

Photon PDF … GRV HO

Proton PDF … CTEQ6M

NLO QCD … Frixione et al.

Dijets: $E_{T\ jet1}$ Spectrum



"Direct"

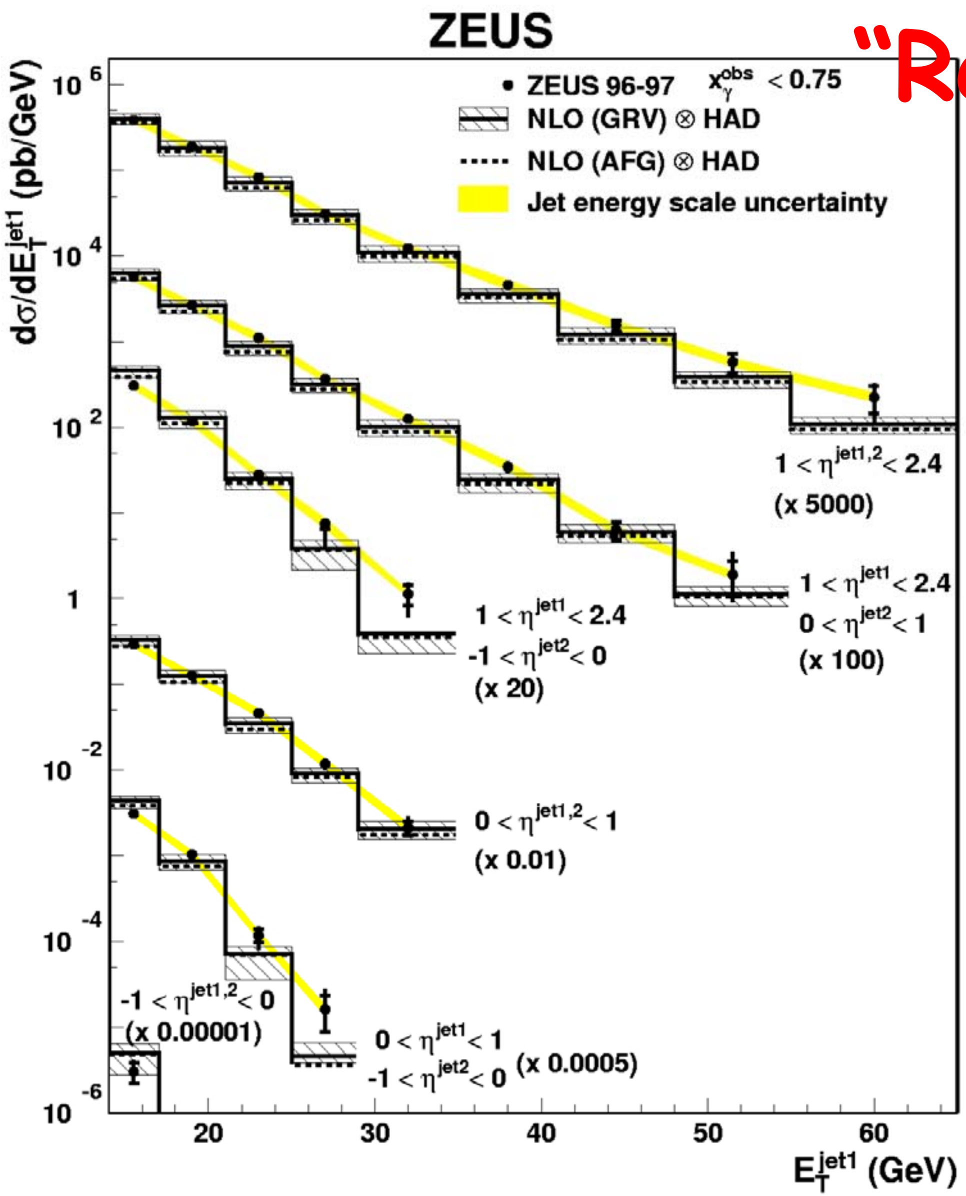
Forward jets

Central jets

Backward jets

Dijets: $E_{T\ jet1}$ Spectrum

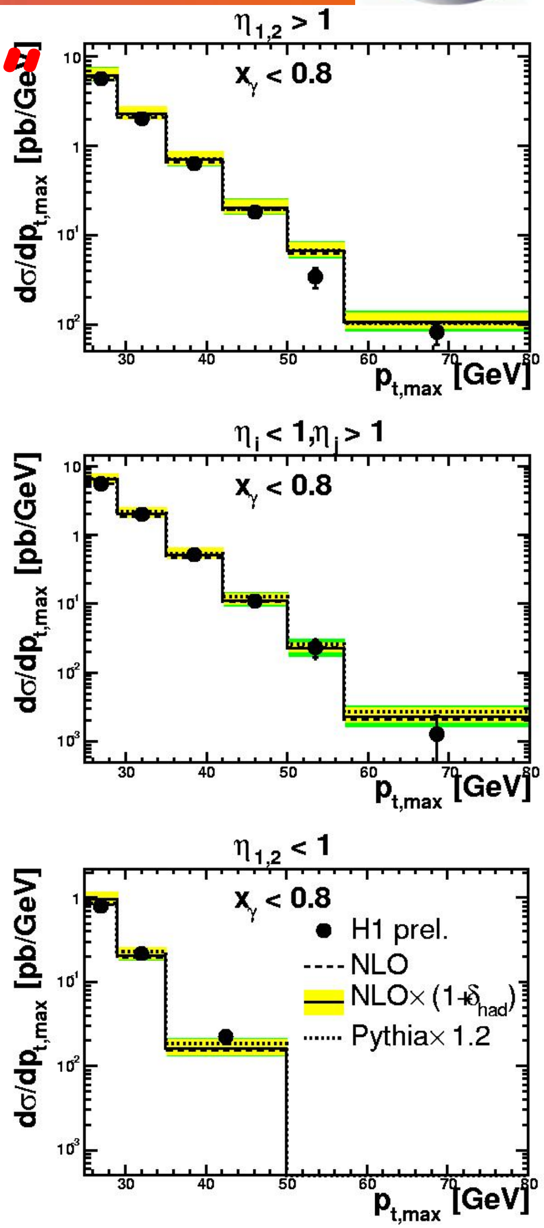
"Resolved"



Forward jets

Central jets

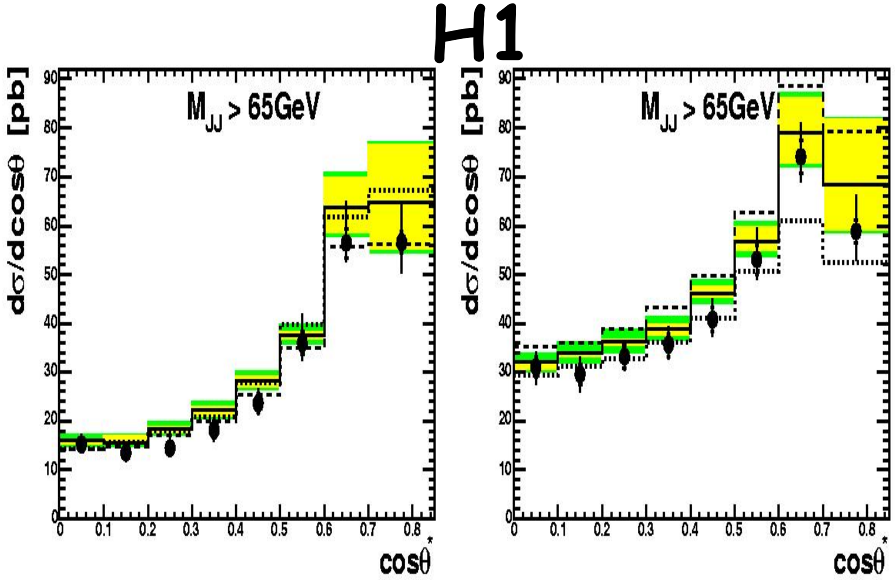
Backward jets



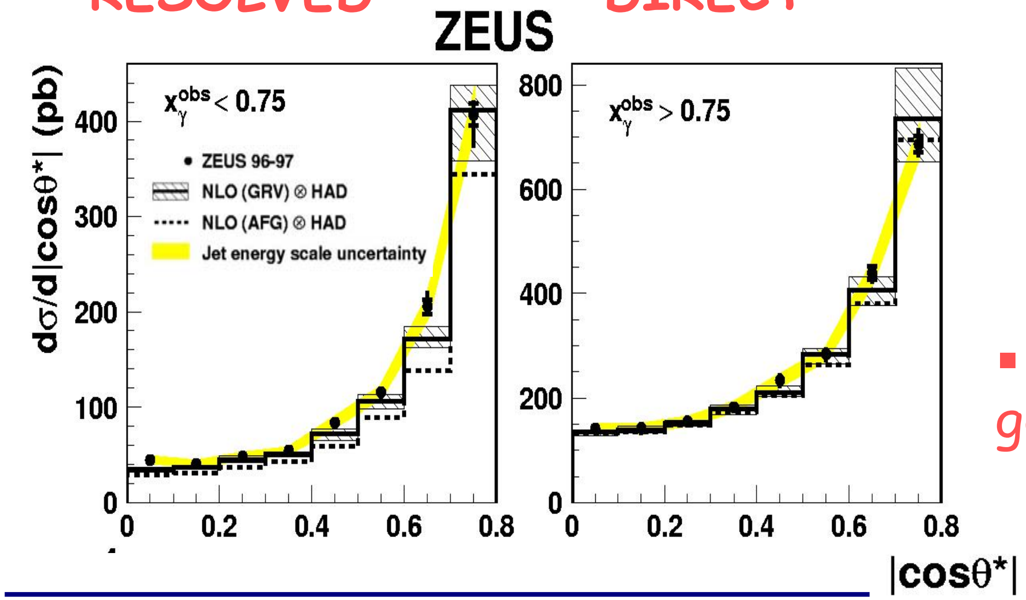
Dijets: $E_{T\ jet1}$ Spectrum

- Direct photon interactions:
  - Both H1 and ZEUS find good agreement of the NLO QCD predictions with the data.
- Resolved photon interactions:
  - Both H1 and ZEUS data well approximated by NLO at low E_T jets.
- HERA photoproduction dijet cross sections are suitable for constraining the proton and photon PDFs.

Dijet Cross Section as a Function of |cos Θ*|



RESOLVED DIRECT



- cos Θ* … | $\tanh(\eta^1 - \eta^2)/2$ |
- Shapes consistent with expectations from dominant propagators:
  - "gluon" ~ $(1-|\cos\Theta^*|)^{-2}$ (resolved phot. interactions)
  - "quark" ~ $(1-|\cos\Theta^*|)^{-1}$ (direct photon interactions)
- NLO QCD description quite good within the errors.

Transition between Photoprod. & DIS

ZEUS:

Data 96-97, Eur.Phys.J.C35,487 (2004)

E_e = 27.5 GeV; E_p = 820 GeV

Int. lumi = 38.6 pb^{-1}

$Q^2 < 2000$ GeV^2

$E_{T,jet1} > 7.5$ GeV

$E_{T,jet2} > 6.5$ GeV

$-3 < \eta^*_{jet1,2} < 0$

$0.2 < y < 0.55$

Photon PDF … GRV & AFG

Proton PDF … CTEQ5M

NLO QCD:

- Photoproduction: … Frixione et al.
  - $\mu^2 = (E_T)^2$
- DIS: … DISASTER++
  - $\mu^2 = Q^2+(E_T)^2$ or $\mu^2 = Q^2$

H1:

Data 99-00, Eur.Phys.J.C37,141 (2004)

E_e = 27.5 GeV; E_p = 920 GeV

Int. lumi = 57 pb^{-1}

$2 < Q^2 < 80$ GeV^2

$E_{T,jet1} > 7$ GeV

$E_{T,jet2} > 5$ GeV

$-2.5 < \eta^*_{jet1,2} < 0$

$0.1 < y < 0.85$

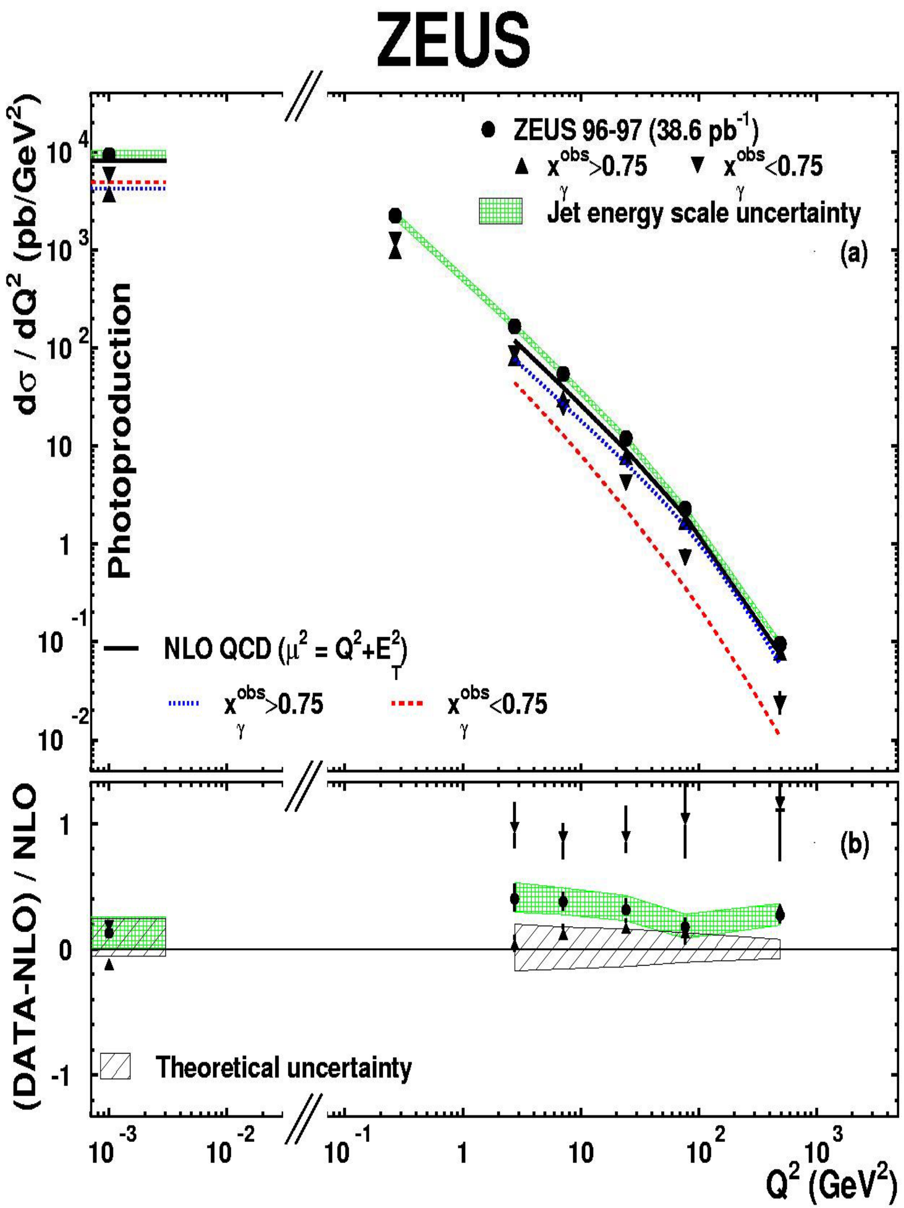
Photon PDF … SAS1D (γ_T), Chyla (γ_L)

Proton PDF … CTEQ5L / CTEQ6M

NLO QCD … DISENT, JETVIP, NLOJET++

$\mu^2=(E_T)^2$

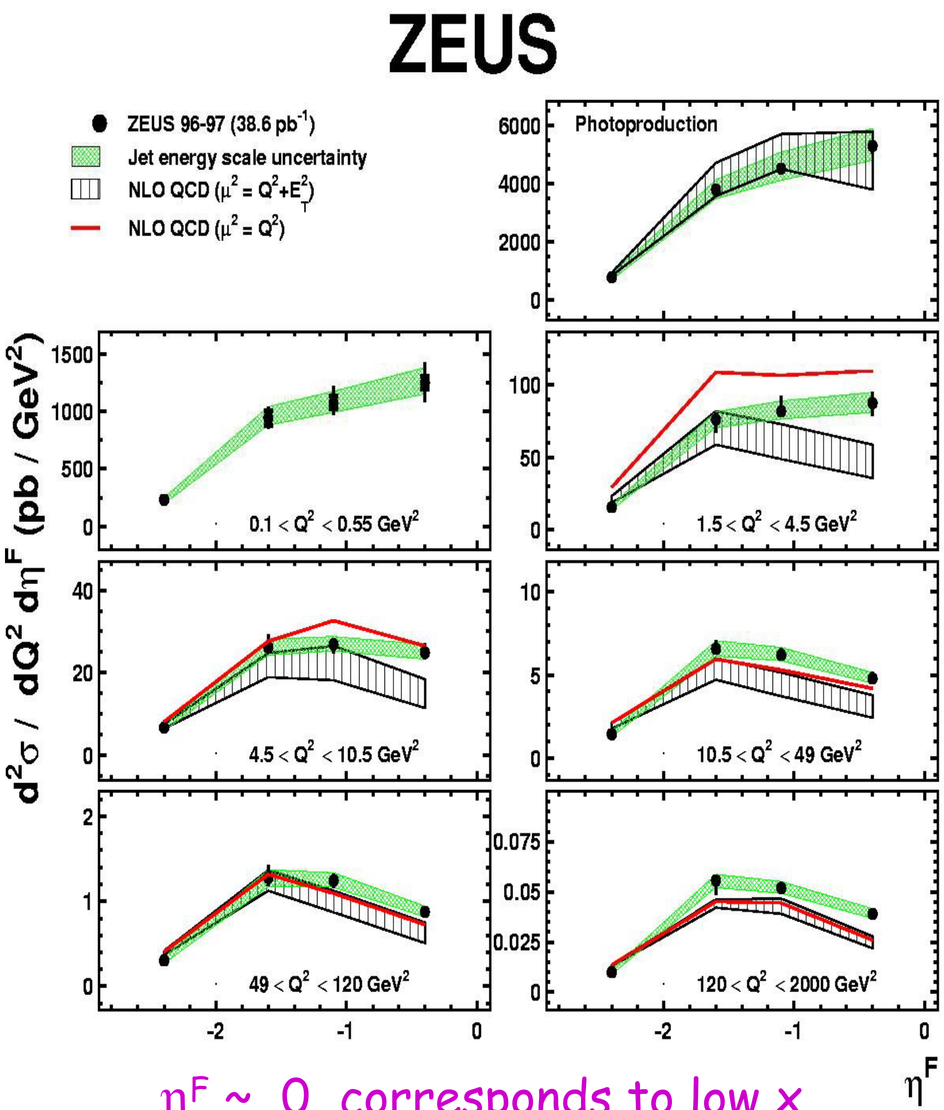
ZEUS Dijets: Q^2 dependence



- Photoproduction:
  - Data described well by NLO QCD (Frixione & Ridolfi)
- DIS:
  - NLO QCD without resolved photon interactions (DISASTER++) describes data for $x_\gamma > 0.75$ only.
  - NLO QCD is too low for $x_\gamma < 0.75$

Hard scale: $\mu^2 = Q^2 + (E_T)^2$

ZEUS Dijets: η dependence

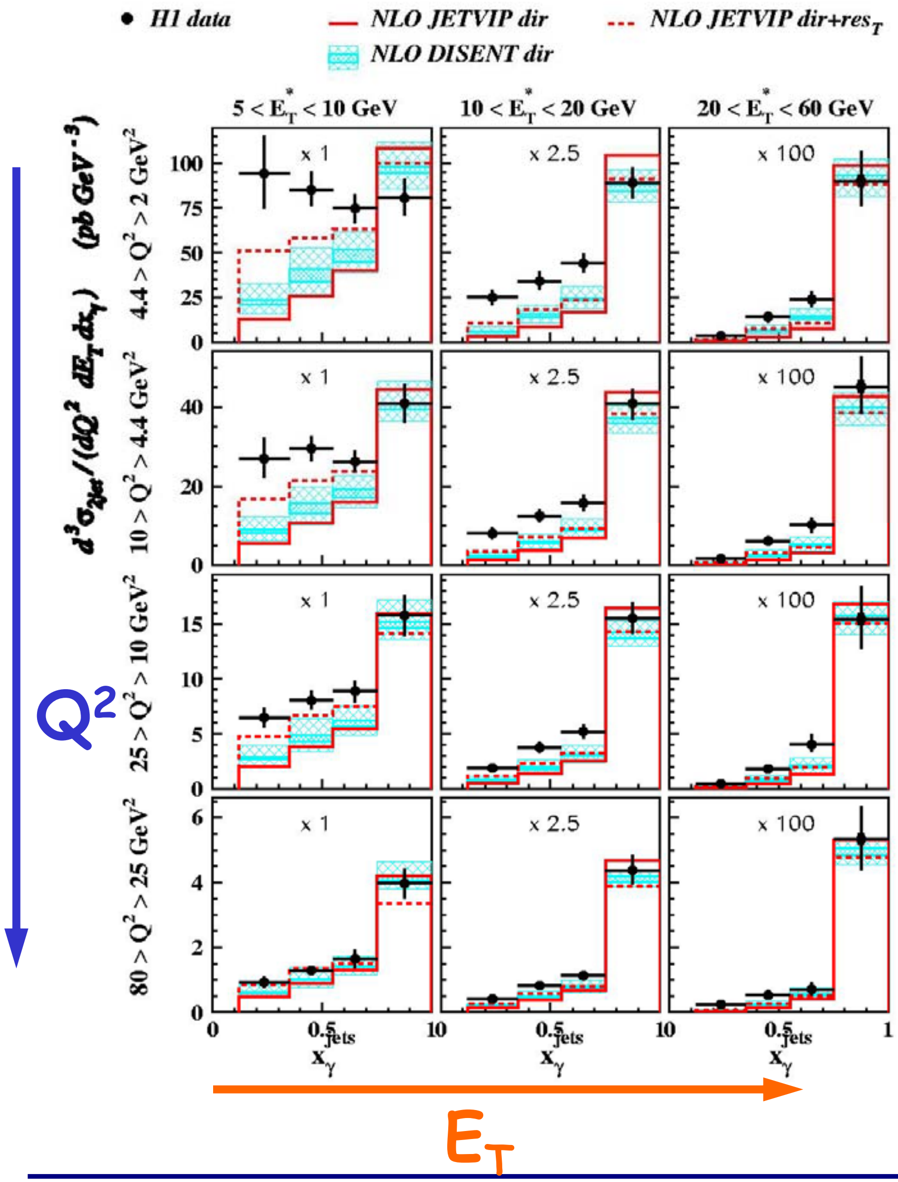


$\eta^F \sim 0$ corresponds to low x_γ

$\eta^F \sim -2$ corresponds to high x_γ

- Photoproduction:
  - Data described well by NLO QCD (Frixione & Ridolfi).
- DIS:
  - DISASTER++ describes the data in the backward jet region, but it is too low in the forward jet region when using the (reasonable) choice of the hard scale $\mu^2 = Q^2 + (E_T)^2$. The disagreement is largest at low Q^2 ➔ missing resolved photon interactions in DISASTER++ ?
  - Large theoretical uncertainty for the hard scale $\mu^2 = Q^2$ (not shown). This "hard" scale is quite soft at low Q^2.

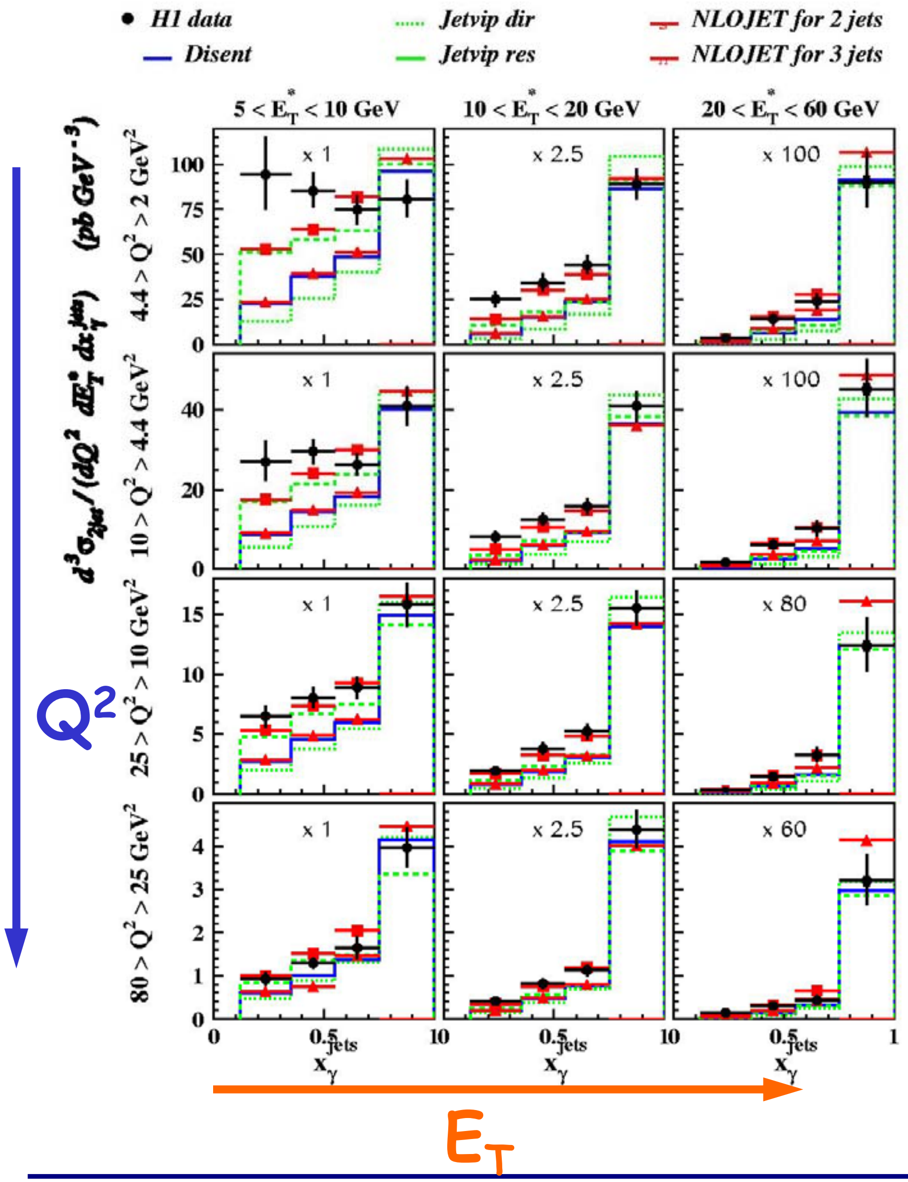
H1 dijects: NLO description



- **H1**: $2 < Q^2 < 80$ GeV^2
- Data well reproduced by the NLO QCD calculations at high x_γ or when Q^2 is large.
- NLO calculations fail at low x_γ , low Q^2 and low E_T.
- Transversally polarised resolved photon contribution in JETVIP helps to get closer to the data, but still not enough.

Limited reliability of JETVIP due to the "y_{cut}" instability

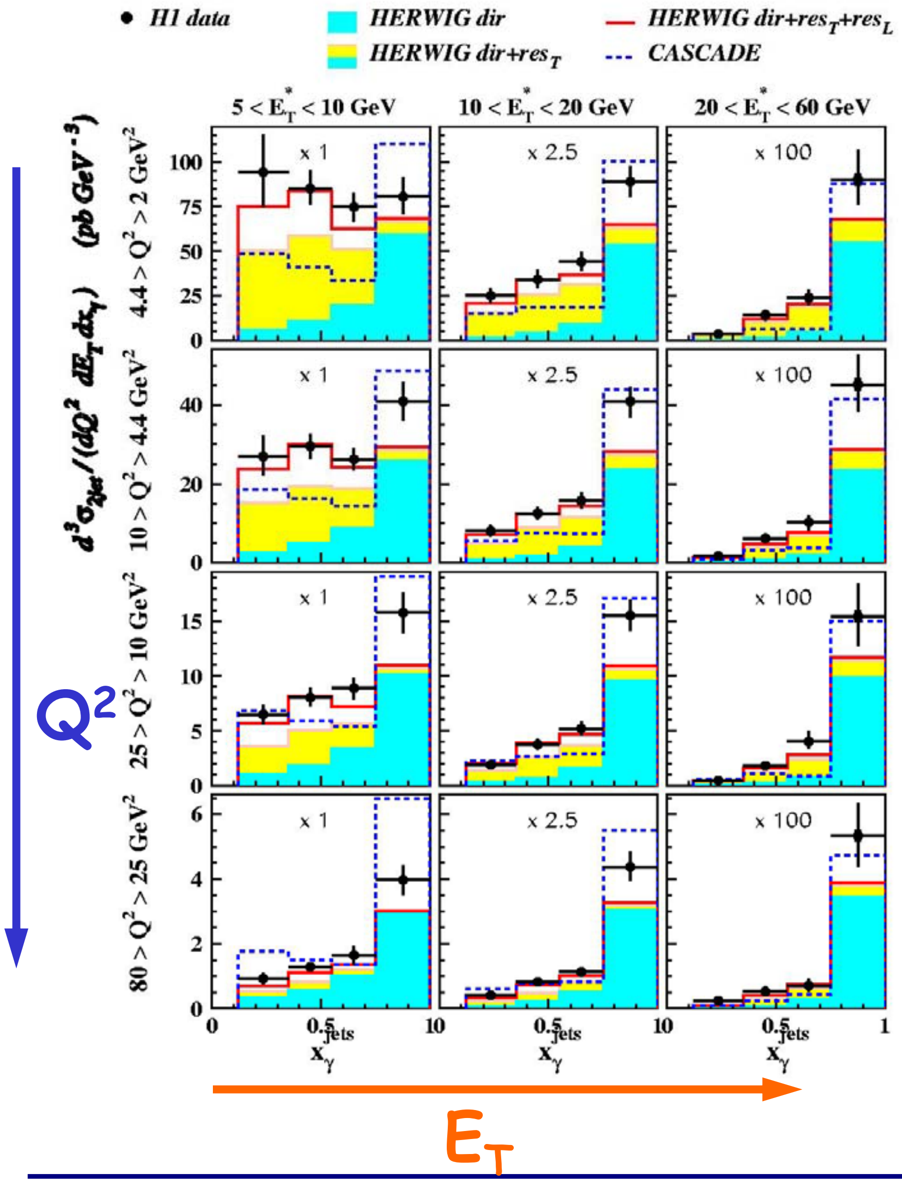
H1 dijets: NLOJET++ ("NNLO")



- NLOJET++ in 2 jet mode in a very good agreement with DISENT.
- NLOJET++ in 3 jet mode takes into account one more QCD order with respect to DISENT, but it can only be used for $x_\gamma < 1$, (since there are always at least 3 jets guaranteed for $x_\gamma < 1$).
- NLOJET++ in 3 jet mode much closer to the data than DISENT, but …
- still not enough to describe dijet cross section at low x_γ in the lowest Q^2 and E_T region.

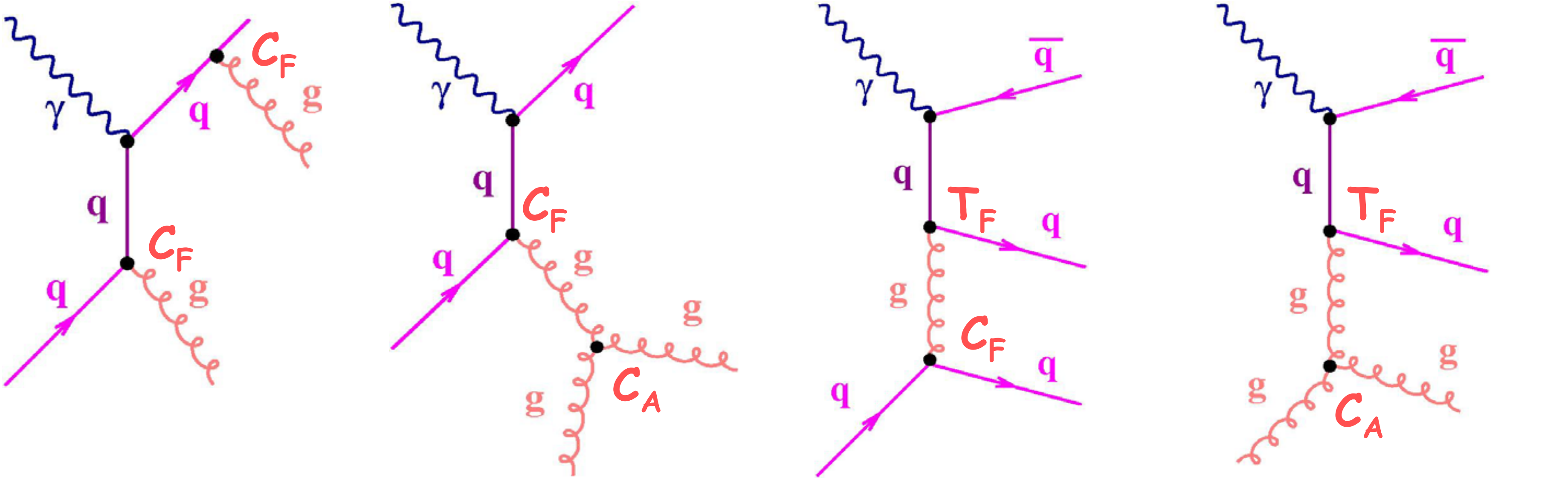
(Eur.Phys.J.C40:469-472, 2005)

H1 dijets: LO MC



- The best description at low x_γ, low Q^2 and low E_T is provided by LO MC program (HERWIG) that takes into account:
  - parton showers
  - longitudinally polarised photon in resolved interactions
- However, HERWIG fails to describe the data at $x_\gamma \sim 1$.
- CASCADE, based on CCFM evolution equations and ignoring resolved photon interactions, describes data only in part of the phase space.

3-jets at ZEUS: Color Dynamics



$(C_F)^2$ | $C_F \cdot C_A$ | $C_F \cdot T_F$ | $T_F \cdot C_A$

- The color factors C_F, C_A and T_F represent the relative strength of the $q \to qg$, $g \to gg$ and $g \to qq$ processes.
- Their values are predicted by the underlying gauge-group structure (e.g. SU(N): $C_F=(N^2-1)/2N$, $C_A=N$, $T_F=1/2$).
- Since the qqg and ggg couplings have different spin structures, the color factors give rise a specific pattern of angular correlations between the final-state jets.

$$\sigma_{eP \to 3jets} = C_F C_F \cdot \sigma_A + C_F C_A \cdot \sigma_B + C_F T_F \cdot \sigma_C + T_F C_A \cdot \sigma_D$$

Variables to highlight the contributions from the different color configurations ➔ angular correlations between the jets:

- θ_H, the angle between the highest $E_{T\,jet}$ and the beam plane and the two lowest $E_{T\,jet}$ plane.
- α_{23}, the angle between two lowest $E_{T\,jet}$ jets.
- $\cos(\beta_{KSW})$, defined as

  $$\cos\tfrac{1}{2}\{\angle[(p_1 \times p_3),(p_2 \times p_B)] + \angle[(p_1 \times p_B),(p_2 \times p_3)]\},$$

  where p_i (p_B) are the momenta of the jets (unit vector in the direction of the proton beam).

ZEUS preliminary data

3 jet events

Data 95-00

E_e = 27.5 GeV; E_p = 820/920 GeV

Int. lumi = 127 pb^{-1}

$Q^2 < 1$ GeV^2

$E_{T,jet1,2,3} > 14$ GeV

$-1 < \eta_{jet1,2,3} < 2.5$

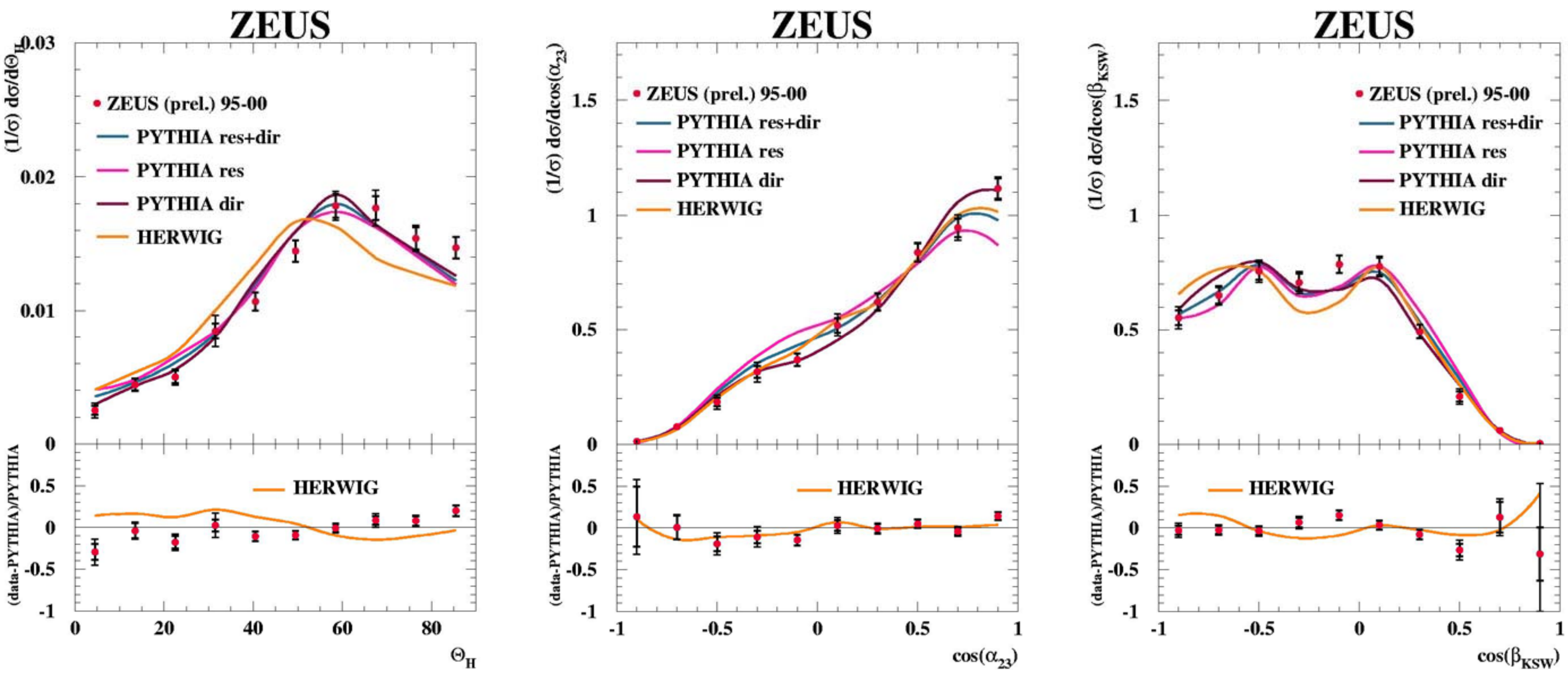
$0.2 < y < 0.85$

$X_\gamma > 0.7$ (direct enhanced sample)

PDF … MRST99

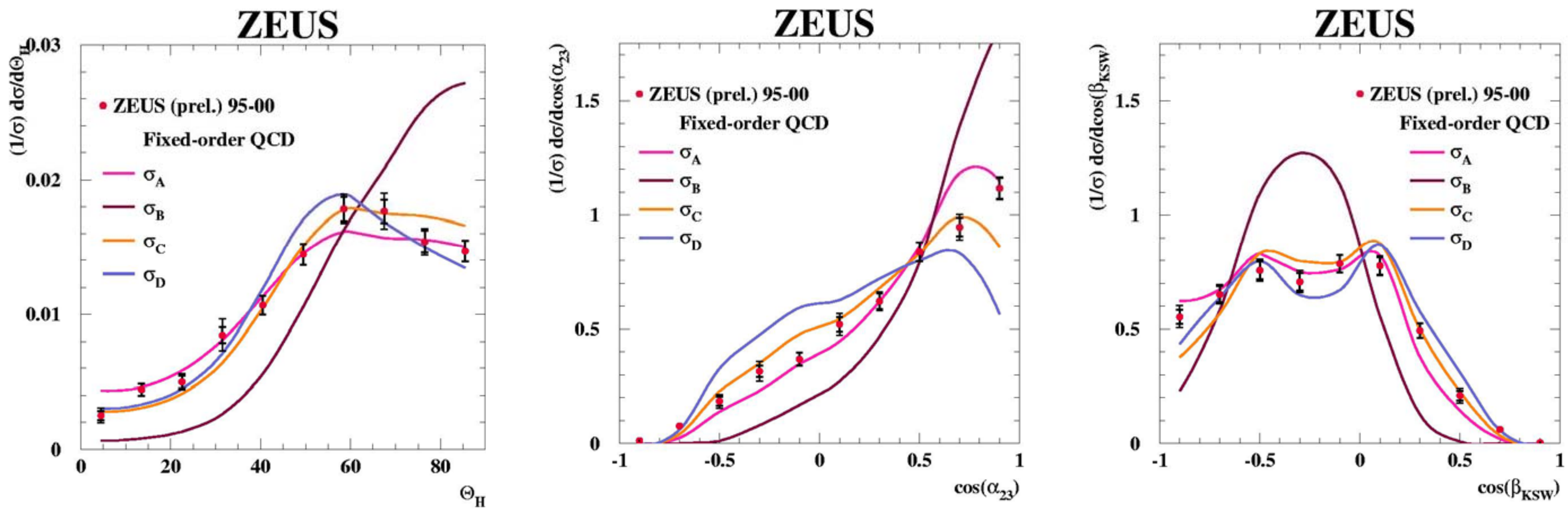
NLO QCD … Klasen, Kleinwort & Kramer

ZEUS: Color Dynamics



- PYTHIA (SU(3)) reproduces the measured distributions reasonably well.
- The distributions for direct and resolved photon (~34%) processes are very similar.
- HERWIG (SU(3)) gives a poorer description than PYTHIA.

ZEUS: Color Dynamics



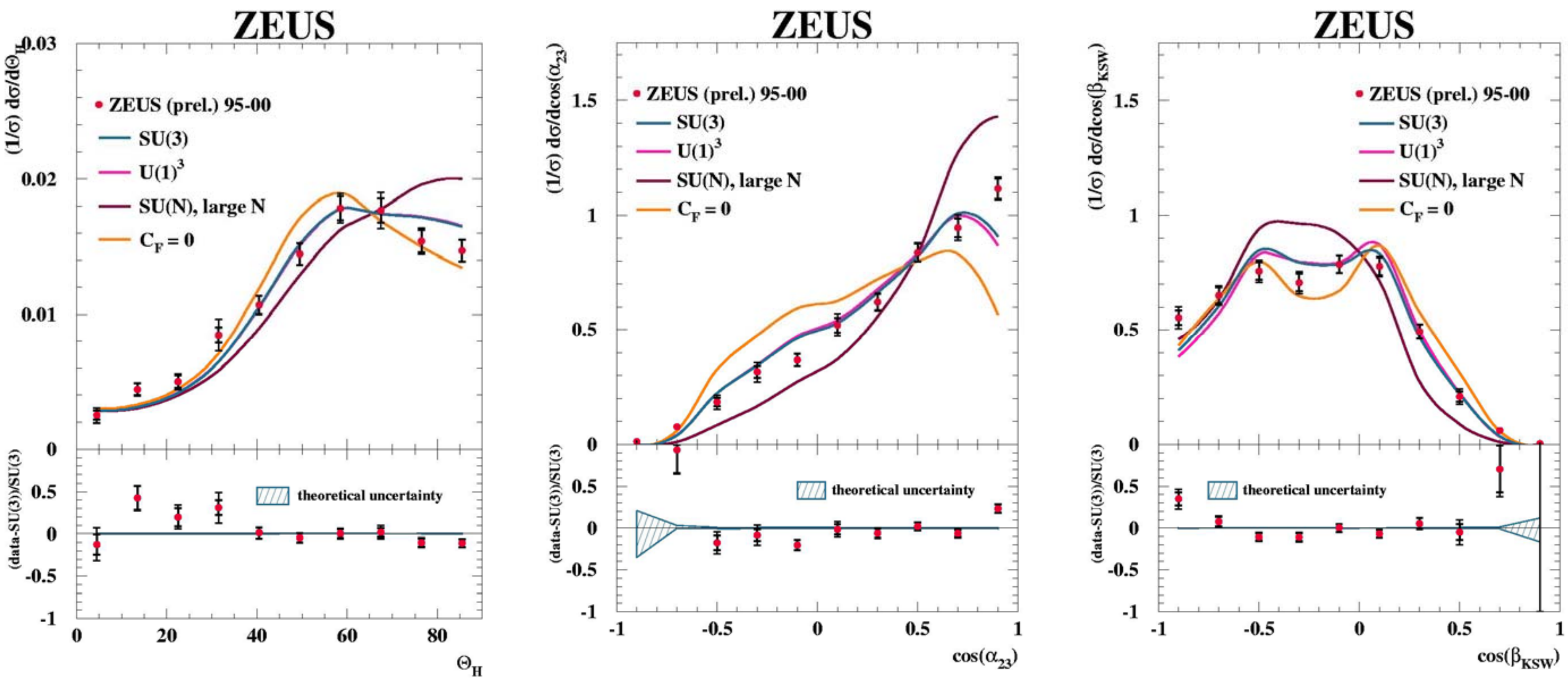
- The contribution σ_B exhibits a very different shape than the other contributions in all three distributions.
- The other contributions are best separated by α_{23}.

  ➔ These distributions are sensitive to different color configurations and show a potential to extract the color factors.

SU(3):

σ_A … 13%
σ_B … 10%
σ_C … 45%
σ_D … 32%

ZEUS: Color Dynamics



- The predictions of SU(3) describe the data reasonably well.
- $U(1)^3$ similar to SU(3) due to the smallness of σ_B.
- Data disfavour $T_F/C_F \sim 0$ (e.g. SU(N) for large N).
- Data disfavour $C_F=0$ (which would correspond to no q→qg splitting).

CONCLUSIONS

- Dijets in photoproduction are well described by the NLO QCD calculations. They are suitable for constraining both proton and photon PDFs.
- The intermediate Q^2 region between photoproduction and DIS is not described by the theory yet. Possible areas for improvements:
  - Higher order calculations (beyond NLO).
  - Parton showers at NLO (MC@NLO).
  - Resolved photon interactions at low Q^2 in NLO.
  - Longitudinally polarised resolved photon.
- Jet angular correlations are consistent with the admixture of color configurations predicted by SU(3). Other gauge groups are clearly disfavoured, however new variables are needed to enhance the resolution power.