Jets and QCD at HERA

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DESY

On behalf of H1 and ZEUS Collaborations

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Jet Physics at HERA

HERA ep collider: $E_e = 27.5\ GeV$ and $E_p = 820\ GeV/920\ GeV$

- **Jet data are precise at high transverse energy where experimental and non-perturbative effects are small.**
  - **Test our understanding of QCD**
  - **Constrain proton and photon PDFs**

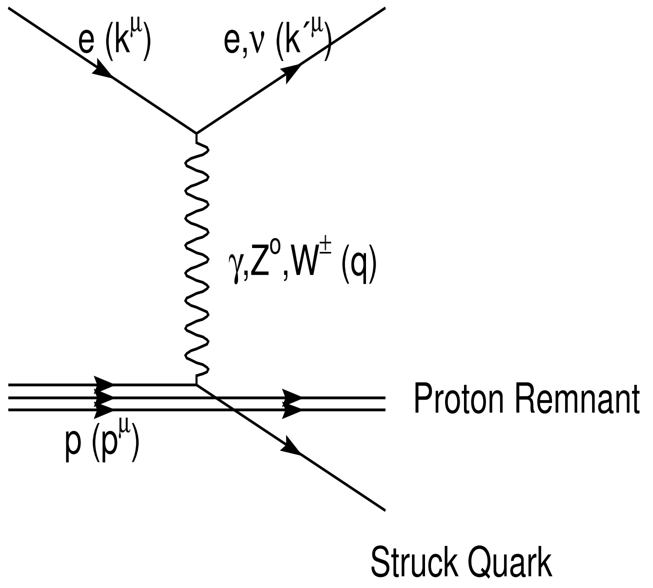
- **Study of process proportional to α_s and high orders**

- **Extraction of QCD parameter if experimental and theory uncertainties are small**
  - **Fit data using NLO QCD calculations $\Rightarrow$ extract α_s**

- **Explore parton evolution at low x region $\longrightarrow$ BFKL effects ?**

- **Explore the low Q^2 region $\longrightarrow$ resolved photon ?**

HERA kinematics



- **Momentum transfer**
  $Q^2 = -q^2 = -(k - k')^2$

- **Bjorken scaling variable**
  $x = Q^2/(2pq)$

- **Inelasticity** $y = pq/pk$

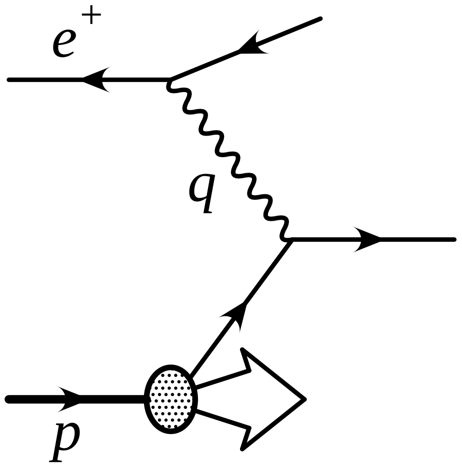
- **Hadronic invariant mass**
  $W^2 = (p + q)^2 = 2pq - Q^2$

- **Deep Inelastic Scattering:** $Q^2 \gg 1\ GeV^2$

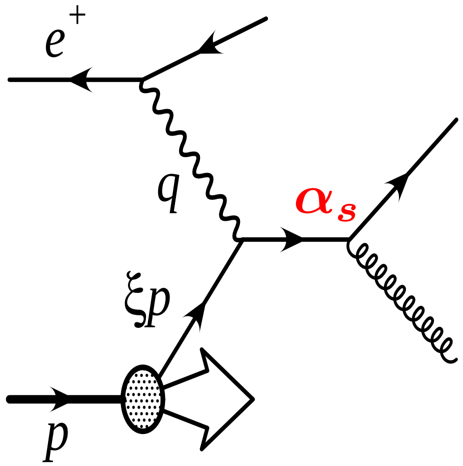
- **Photoproduction:** $Q^2 \sim 0\ GeV^2$

Jet production in Deep Inelastic Scattering

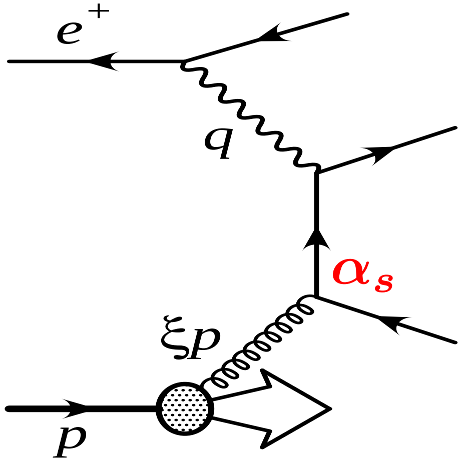
- **Jet production up to $\mathcal{O}(\alpha_s)$**



Born level process



QCD compton



Boson gluon fusion

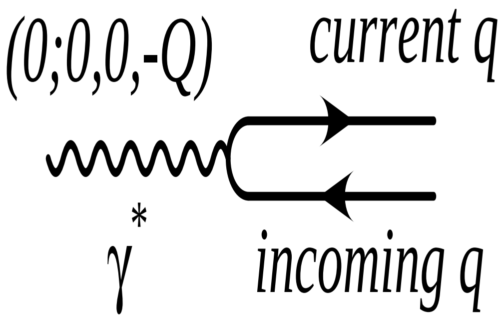
- **Jet production cross section**

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

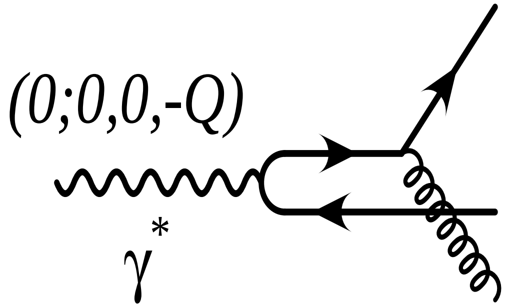
  – f_a: parton a density in the proton
  – $\hat{\sigma}_a$: subprocess cross section, calculable in pQCD

Jet finder and reference frame

- **Jet finder: Longitudinally invariant k_T algorithm**
- **Reference frame:**
  - **Lab frame**
  - **$\gamma^{\star}p$ center of mass system defined by $p + q = 0$**
  - **Breit frame defined by $2xp + q = 0$**



Born level



QCD Compton

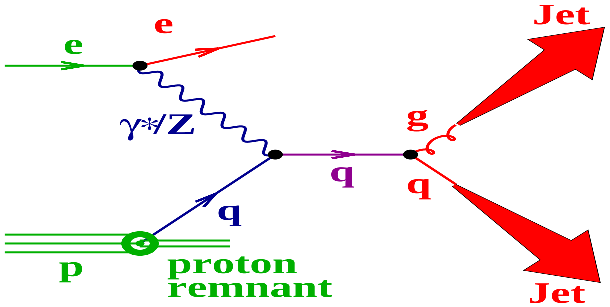
- **High E_t jet production in Breit and $\gamma^{\star}p$ cms frame**
  - **suppresses Born contribution (struck quark has zero E_t)**
  - **suppresses beam-remnant jet contribution (zero E_t)**
  - **lowest order contribution from QCDC and BGF process**
  - **directly sensitive to QCD at $\mathcal{O}(\alpha\alpha_s)$.**

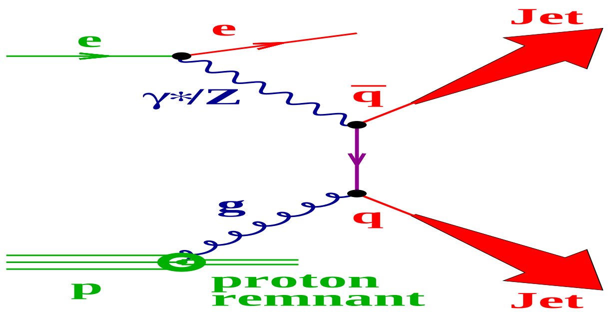
NLO QCD calculation for jets in DIS

- Several NLO ($\mathcal{O}(\alpha\alpha_s)$) programs are available
  - Dijet production: DISENT, DISASTER, MEPJET
  - Two and three jet production: NLOJET
- Jet production has two hard scales Q and E_T
- Calculation at parton level $\longrightarrow$ correction for hadronization effects
- Theoretical uncertainty
  - Terms beyond NLO: vary scale μ_R by factor 2
  - Hadronisation corrections
  - Uncertainties in α_s and proton PDFs

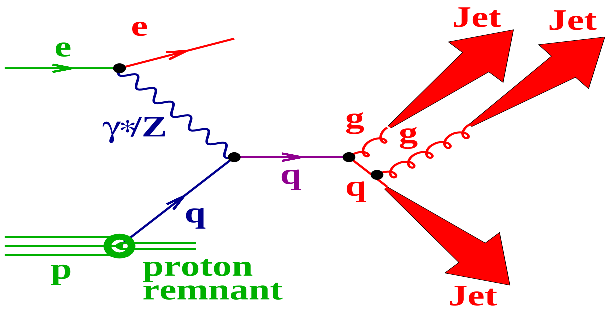
Dijet and trijet production in DIS

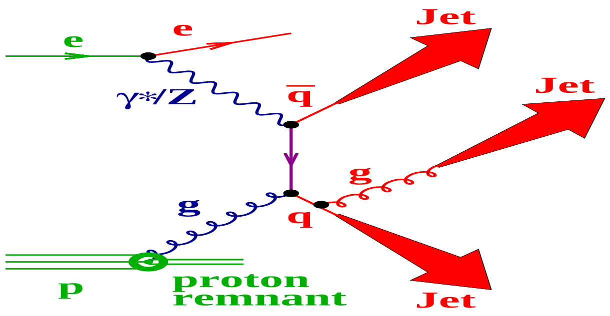
- 2-Jet production at $\mathcal{O}(\alpha_s)$: $\gamma^\star g \longrightarrow q\bar{q}$ and $\gamma^\star q \longrightarrow qg$





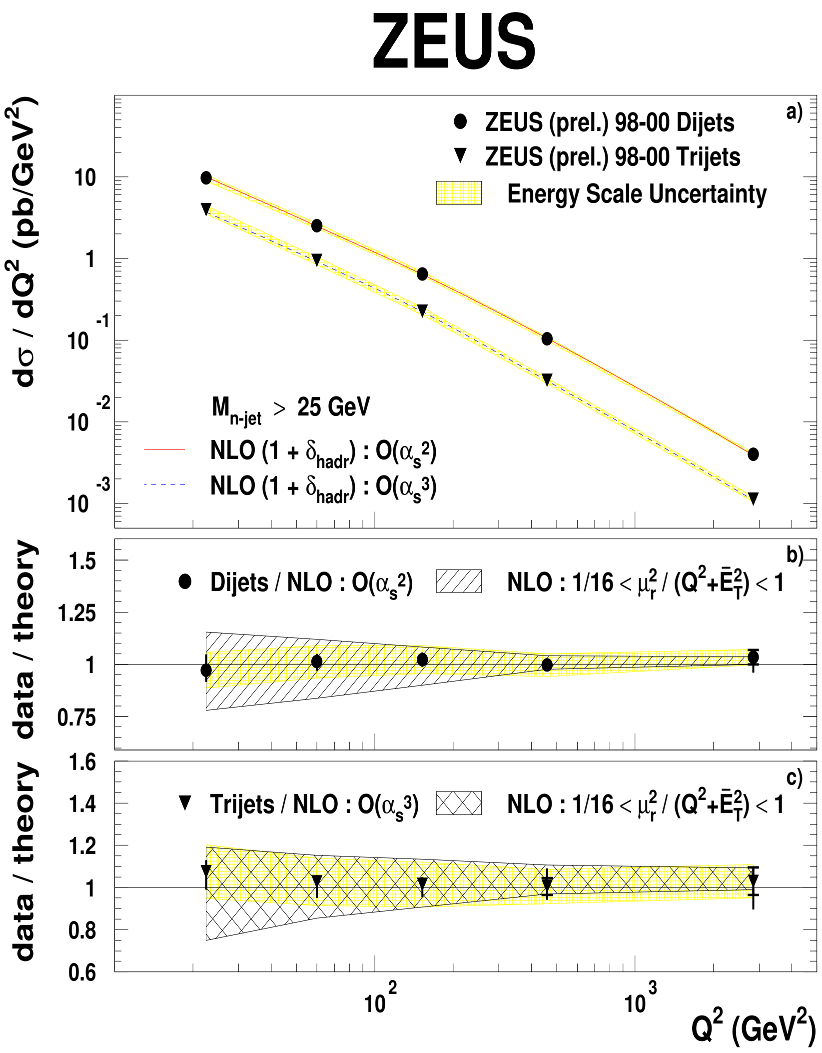
- 3-Jet production at $\mathcal{O}(\alpha_s^2)$: $\gamma^\star g \longrightarrow gq\bar{q}$ and $\gamma^\star q \longrightarrow qgg$





Dijet and trijet in DIS

- **Selection information**
  - k_T algorithm in the Breit frame
  - $10 < Q^2 < 5000$ GeV^2
  - $0.04 < y < 0.6$
  - $E_{T,B}^{jet} > 5GeV$
  - $-1 < \eta_{T,Lab}^{jet} < 2.5$
  - Selected jet number $\geq 2(3)$
  - $M_{3j}/M_{2j} > 25$ GeV



- **NLO QCD calculation (NLOJET)**
  - $\mu_R = \mu_F = \bar{E}_T$
  - Parton PDFs: CTEQ6

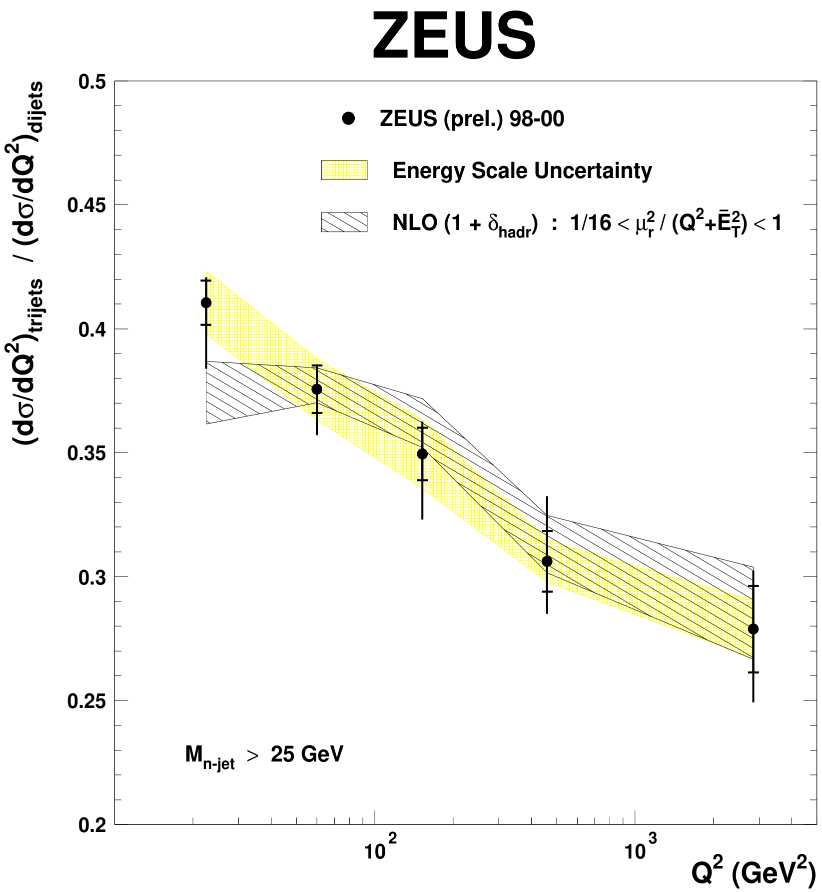
- **The dijet and trijet cross sections are well described by the predictions.**

$R_{3/2} = \sigma_3/\sigma_2$ in DIS

- The cross section ratio $R_{3/2}$ reduces the experimental and theoretical uncertainties.
  $\Longrightarrow$ precise test of pQCD

- The ratio is well described by the NLO calculations.

- Extract α_s from the ratio $R_{3/2}$
  - For each bin i in Q^2, fit of $[R_{3/2}]^i = C_1^i \cdot \alpha_s + C_2^i \cdot \alpha_s^2$ with C_1^i and C_2^i obtained from NLO QCD calculations



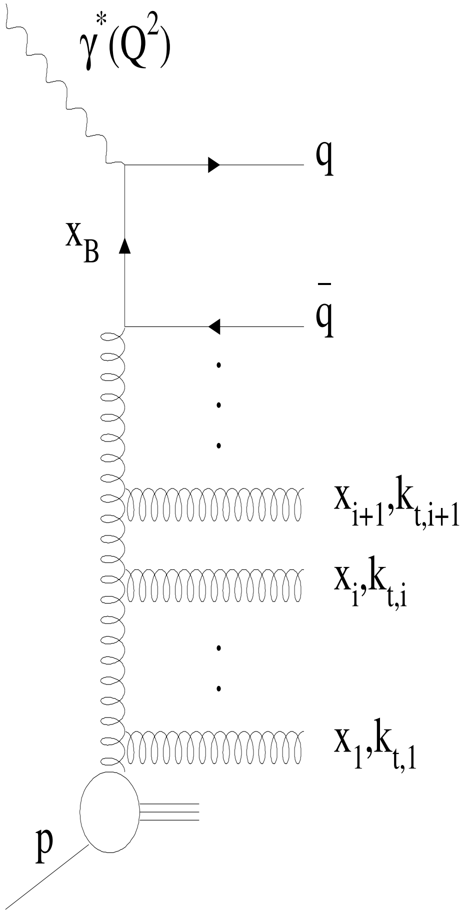
$$\alpha_s(M_z) = 0.1170 \pm 0.0013(stat.)^{+0.0028}_{-0.0046}(exp.)^{+0.0061}_{-0.0047}(th.)$$

$\Longrightarrow$ consistent with current world average of $\alpha_s(M_z) = 0.1182 \pm 0.0027$

Parton evolution schemes

Parton evolution equations: $\sim A_{mn}(\log(Q^2))^m(\log(1/x))^n$

- **DGLAP evolution**
  - Resum terms $\sim \alpha_s \log(Q^2)$
  - Strong ordering of parton k_T
- **BFKL evolution**
  - Resum terms $\sim \alpha_s \log(1/x)$
  - No k_T ordering
  - k_T depended gluon distribution
- **CCFM evolution**
  - Angular ordering
  - Equivalent to BFKL for $x \to 0$ and to DGLAP at large x



Forward jet selection at H1

Large x_{jet}/x_{bj} enhance phase space for BFKL evolution

$\Downarrow$

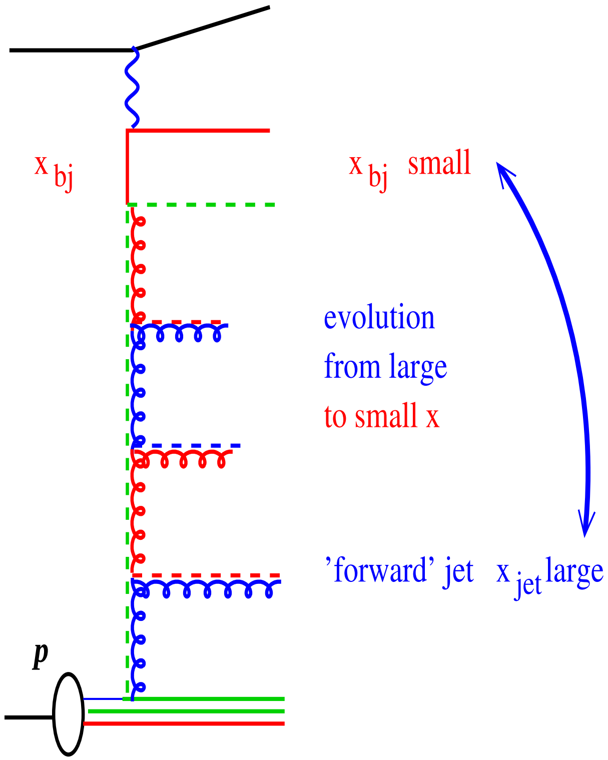
$x_{jet} = E_{jet}/E_p > 0.035$

(selecte event in $0.0001 < x < 0.004$)

$E^2_{t,jet} \sim Q^2$ to suppress DGLAP evolution

$\Downarrow$

$0.5 < E_T^2/Q^2 < 5$



Suppress jets from Proton remnant

$\Downarrow$

$E_T > 3.5GeV$

forward jet

$\Downarrow$

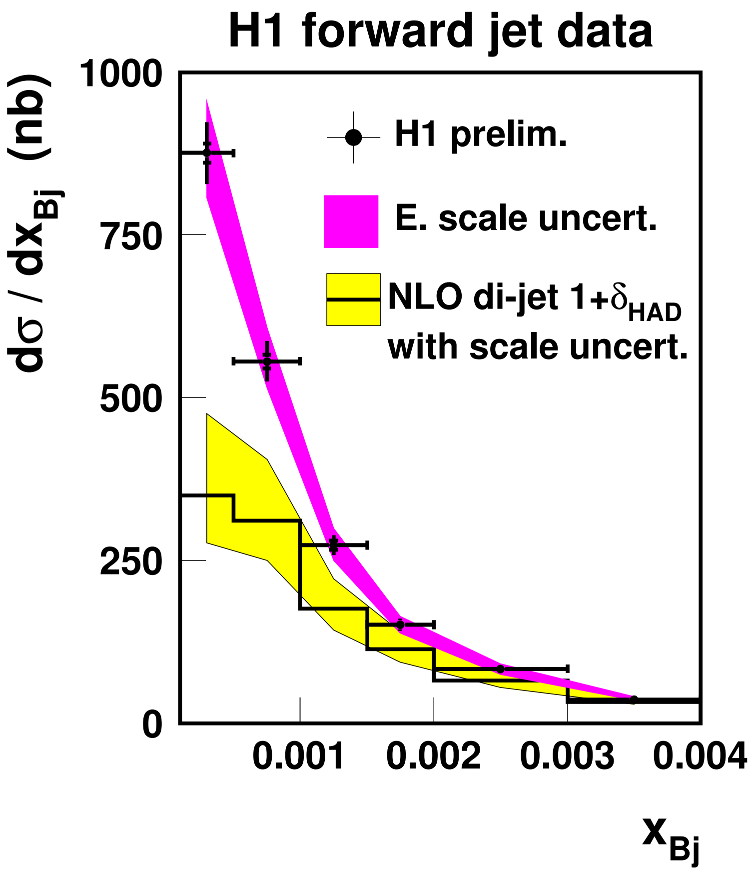
$1.74 < \eta_{jet} < 2.79$

$\Uparrow$

$\eta = -\ln(\tan\frac{\theta}{2})$

Forward jet cross section at low x

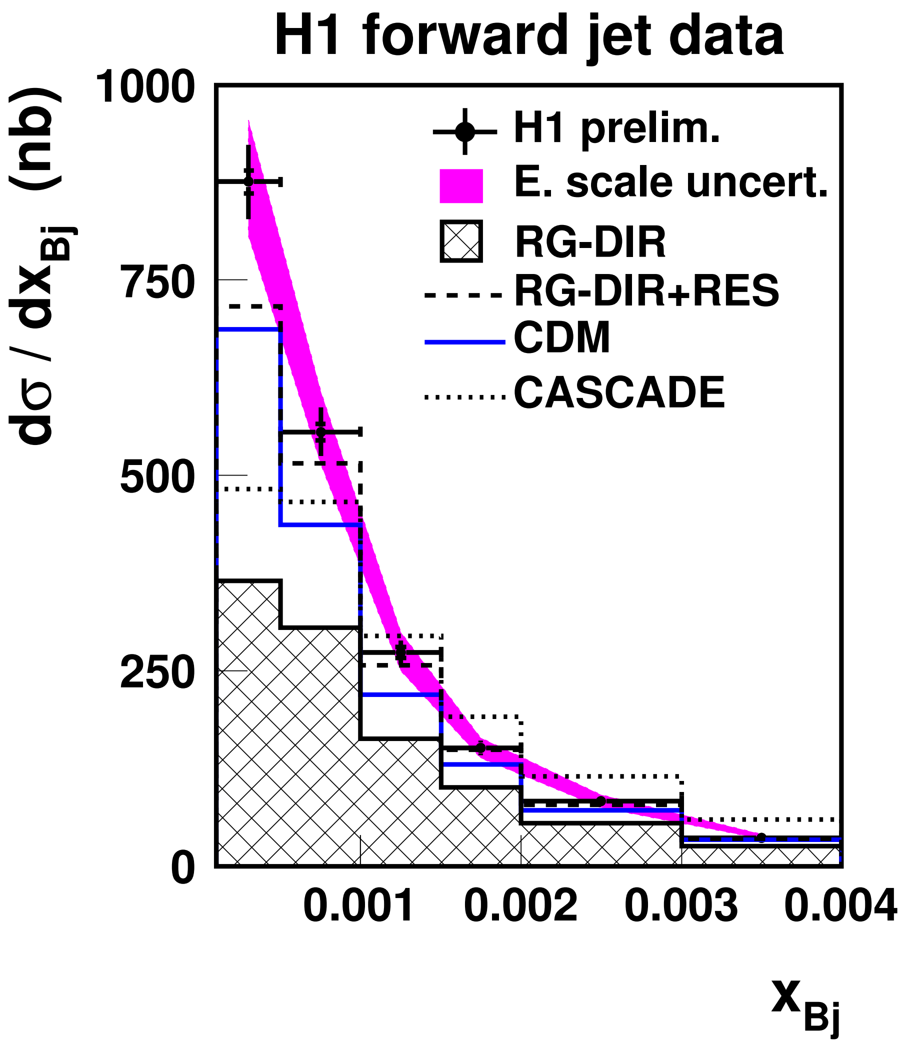
- **Selection information**
  - k_T algorithm in the Lab frame
  - $5 < Q^2 < 85 GeV^2$
  - $0.0001 < x < 0.004$
- **NLO theory prediction (DISENT)**
  - $\mu_R^2 = < E_T^2 > = 45 GeV^2$
  - PDF of the proton: CTEQ6M



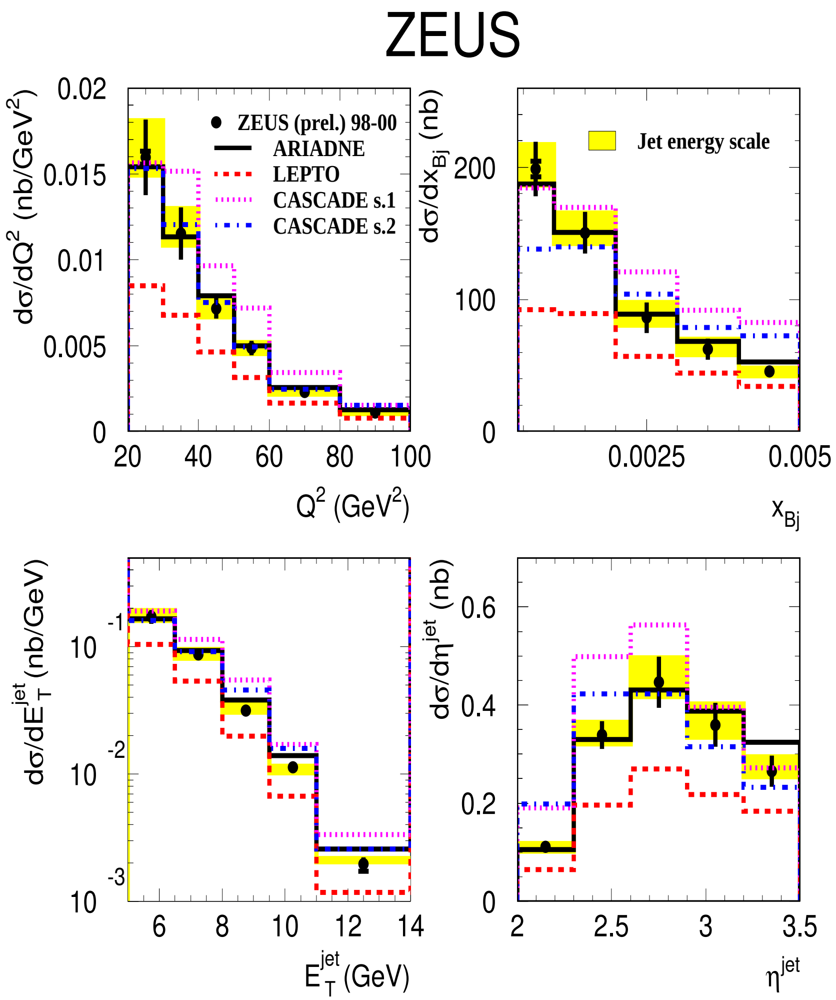
For large x values, the NLO (DGLAP) calculation is OK. At low x values, the calculation undershoots the data.

Foward jet cross section at low x

- Forward jet cross section rises with decreasing x
- Comparison with Monte Carlo
  - RAPGAP DIR (DGLAP): similar to NLO prediction
  - RAPGAP RES+DIR (DGLAP): good description of data for $x > 0.001$
  - CDM: describes the data well for $x > 0.001$
  - CASCADE (CCFM): lower (higher) than data at low (high) x
- No model can describe the sharp rise of the data at very low x.

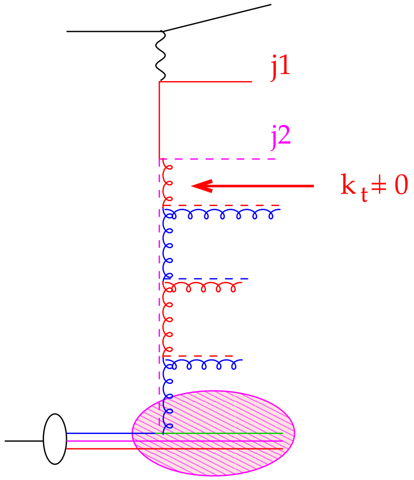


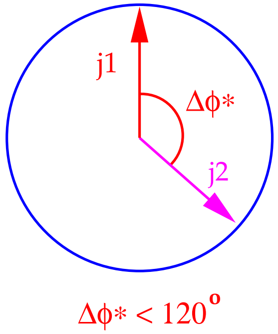
Foward jet cross section at low x



- **LEPTO (DGLAP): lower than the data by a factor of two**
- **ARIADE (CDM): reproduces the data**
- **CASCADE (CCFM): close to the data and sensitive to the unintegrated gluon distribution.**

Azimuthal jet separation in DIS





- **Azimuthal jet separation $\Delta\phi^\star$ of the two hardest jets**

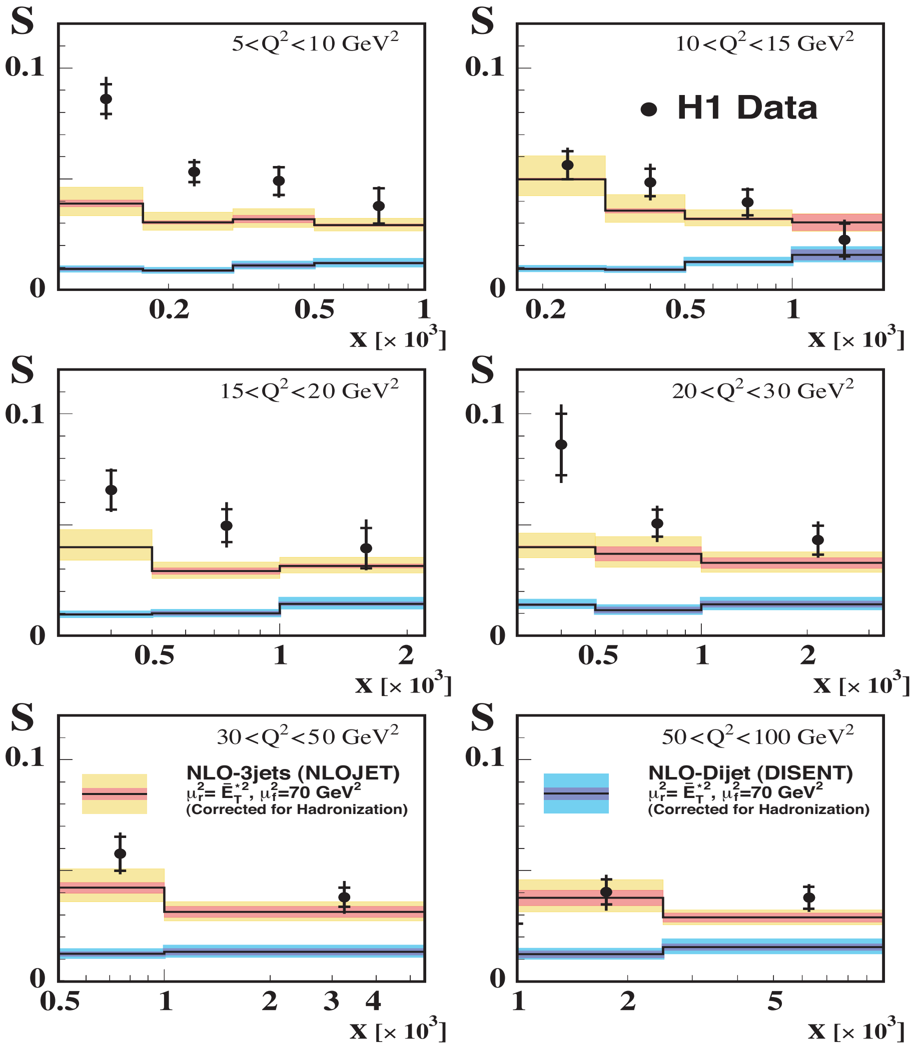
- **The ratio**
$$S = \frac{\int_0^{2\pi/3} N_{2jet}(\Delta\phi^\star, x, Q^2) d\Delta\phi^\star}{\int_0^{\pi} N_{2jet}(\Delta\phi^\star, x, Q^2) d\Delta\phi^\star}$$

- **DGLAP: $\Delta\phi^\star = \pi$ at LO**

- **BFKL and CCFM: Partons enter the hard process with large k_T, the two partons produced in the hard process are no longer balanced in transverse momentum. The number of events with $\Delta\phi^\star < \pi$ is increased.**

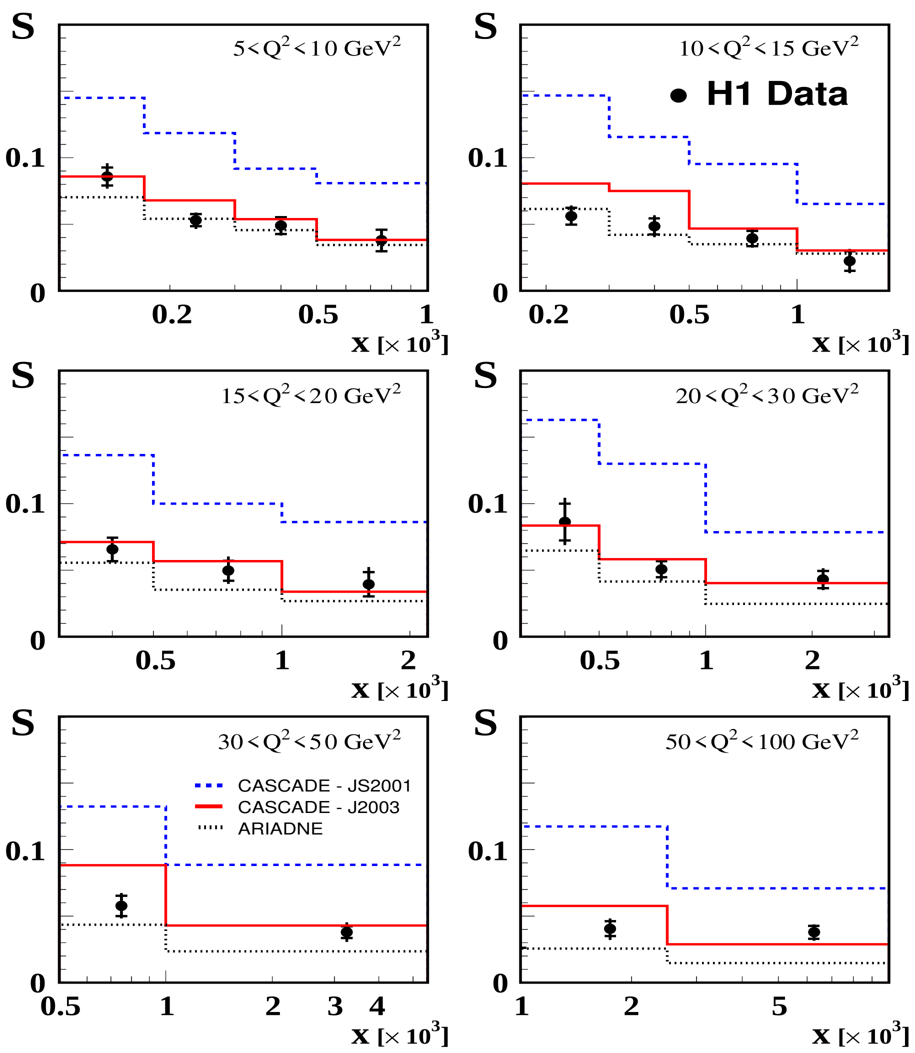
$\Longrightarrow$ **S is sensitive variable for testing small x effects.**

x and Q^2 dependence of S



- The data rise towards low x, particularly in lowest Q^2 range
- NLO 2-jet predictions (DISENT)
  - Significantly below the data
  - No rise towards low x
- NLO 3-jet predictions (NLOJET)
  - Describe the data at high Q^2 and large x
  - Fail to describe the increase towards low x, especially at Q^2

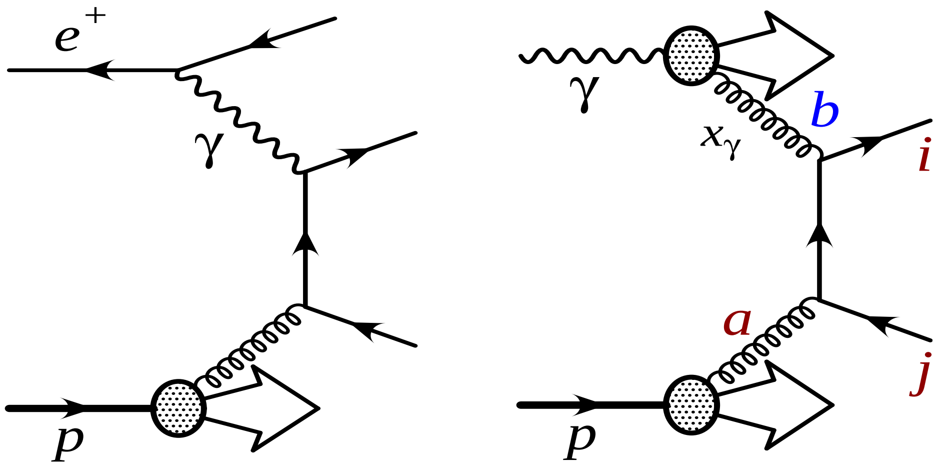
x and Q^2 dependence of S



- **Comparison to CDM predictions (ARIADNE)**
  - **Good description of data at low x and Q^2**
  - **Fail to describe the data at high Q^2**
- **Comparison to CCFM predictions (CASCADE)**
  - **Predictions based on JS2003 describe the data, those based on JS2001 do not.**
  - **S is sensitive to the details of the unintegrated gluon distribution**

Jets in photoproduction

- E_T of jet as hard scale
- At $\mathcal{O}(\alpha_s)$ two processes
  - direct (photon interacts directly)
  - resolved (parton from photon interacts)



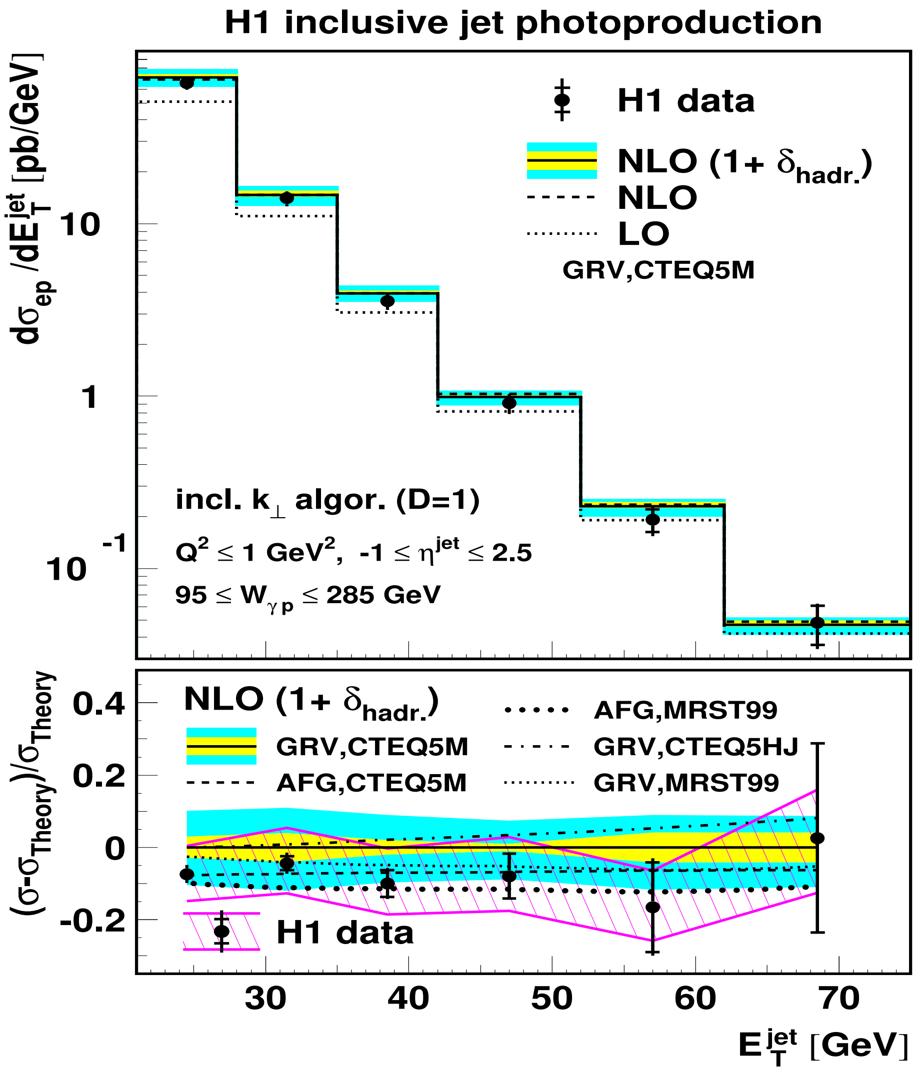
Direct process　　Resolved process

- Jet cross section for resolved process

$$d\sigma = \sum_{a,b} \int_y dy f_{e\to\gamma}(y) \int_{x_p} dx_p f_{p\to a}(x_p, \mu^2_{F_P}) \int_{x_\gamma} dx_\gamma f_{\gamma\to b}(x_\gamma, \mu^2_{F_\gamma}) d\sigma(ab \to ij)$$

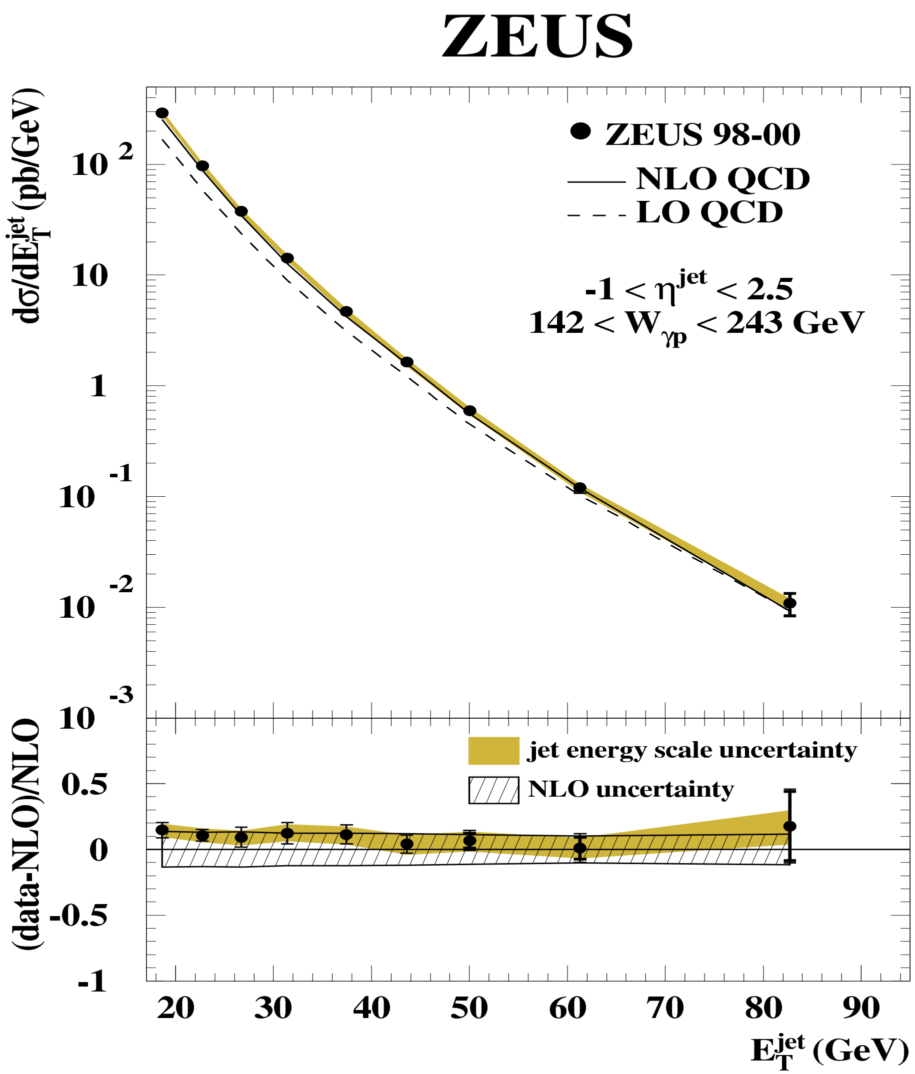
photon flux $f_{e\to\gamma}(y)$, PDF's in the proton $f_{p\to a}(x_p, \mu^2_{F_P})$ and photon $f_{\gamma\to b}(x_\gamma, \mu^2_{F_\gamma})$

Inclusive jets in Photoproduction



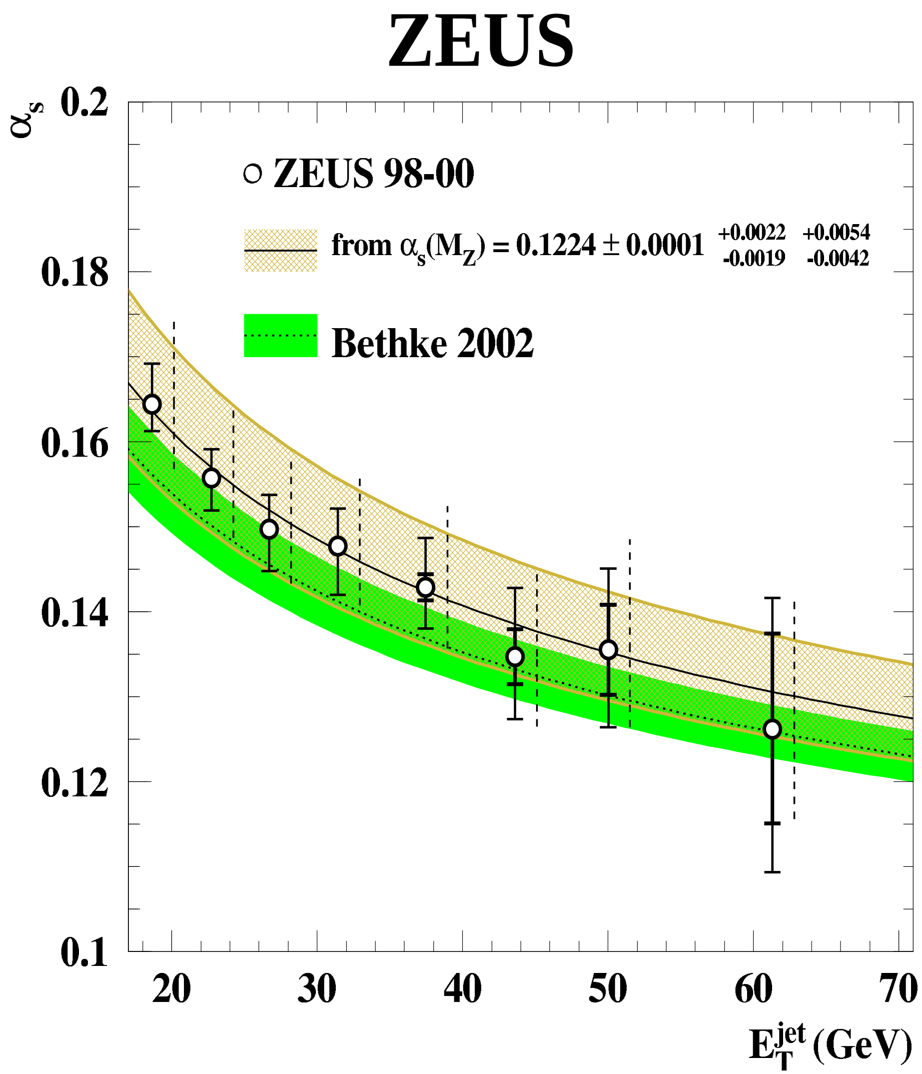
- **Selection information**
  - k_t algorithm in $\gamma^\star p$ cms
  - $E_T > 21 GeV$
- **NLO calculation reproduces the data well, LO QCD calculation underestimates the cross section**
- **Different choices of photon and proton PDFs describe the data within errors (at level 5-10%)**

Inclusive jet in Photoproduction



- Selection information
  - k_t algorithm in Lab frame
  - $17 < E_T < 95\ GeV$
- Small theory uncertainties
- Good agreement of NLO with the data over many orders of magnitude, $\rightarrow \alpha_s$ measurement
- For bin i of E_T, fit of $[d\sigma/dE_T^{jet}(\alpha_s)]^i = C_1^i \cdot \alpha_s + C_2^i \cdot \alpha_s^2$ with C_1^i and C_2^i obtained from NLO QCD calculations

Inclusive jets in Photoproduction



- **Clear running of α_s in a signal experiment.**
- $\boldsymbol{\alpha_s(M_Z) = 0.1224 \pm 0.0001(stat.)^{+0.0022}_{-0.0019}(exp.)^{+0.0054}_{-0.0042}(the.)}$
- **Competitive value is consistent with the current world average of 0.1182 ± 0.0027**

Internal structure of jets

- The study of internal structure of jets looks into the transition between a parton and experimentally observable hadrons.

- The internal structure of jets is expected to depend on the type of primary parton.

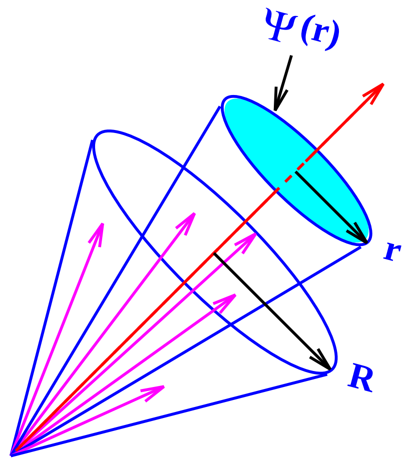
- QCD predictions:
  - At high E_T, the fragmentation effects are negligible, the jet structure is decided by gluon emission off the primary parton, calculable in pQCD.
  - Gluon jets are broader than quark jets due to the larger colour charge of the gluon.

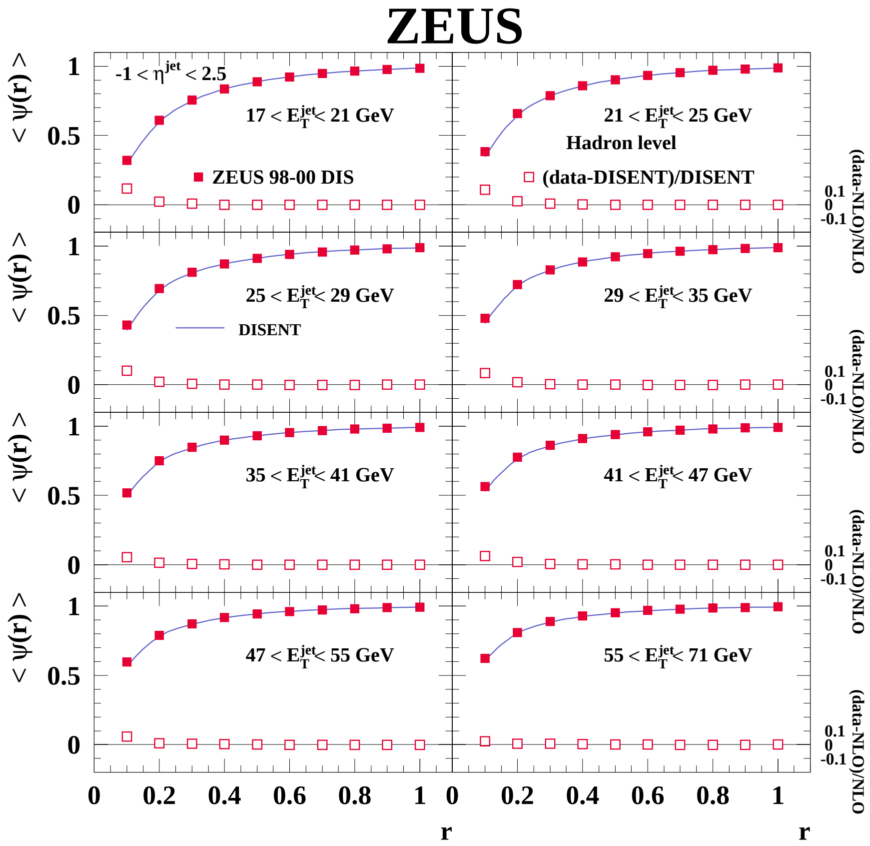
$\Longrightarrow$ Measurements of jet structure provide a test of pQCD calculation.

Jet shape in NC DIS

Jet shape $\phi(r)$: fraction of the jet E_T inside a cone in the $\eta-\phi$ plane of radius r

$$<\phi(r)>=\frac{1}{N_{jets}}\sum_{jets}\frac{E_T(r)}{E_T(r=1)}$$

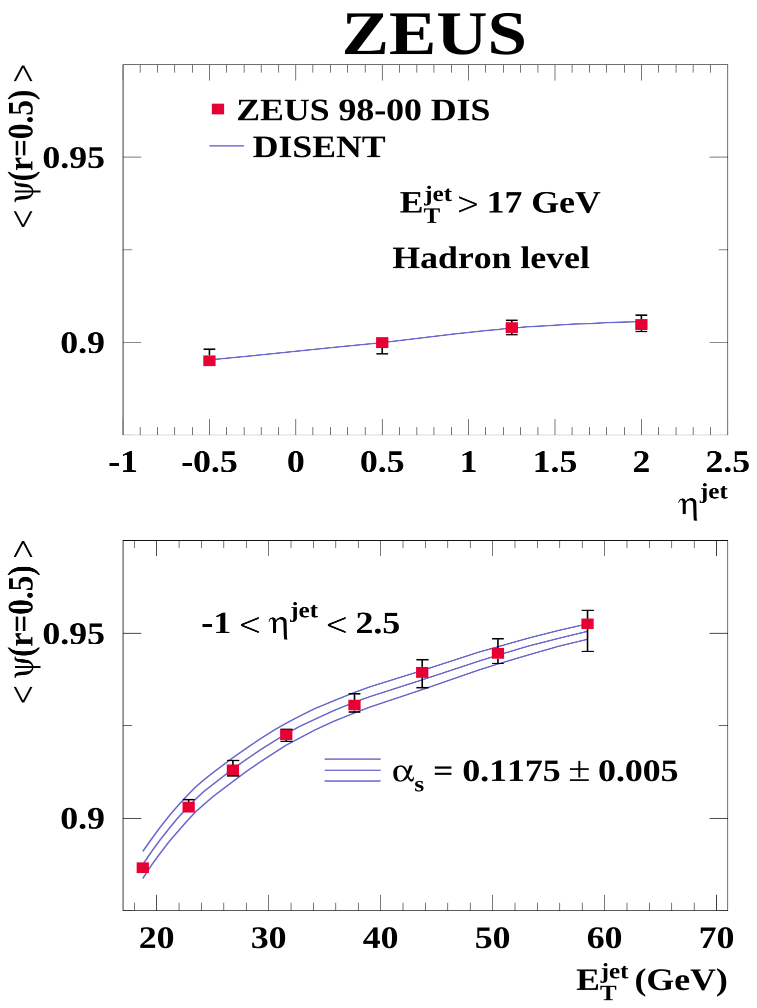




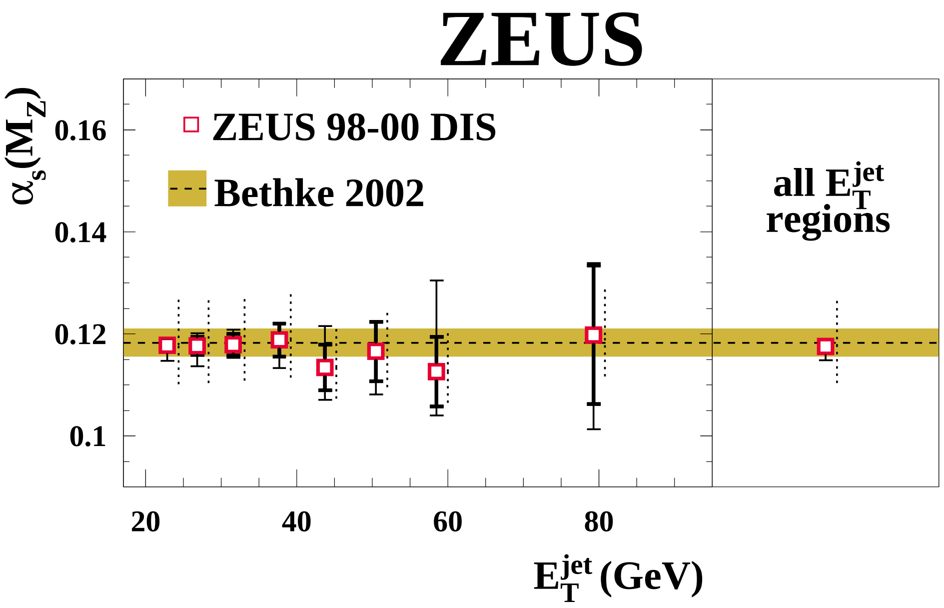
- NLO QCD calculation reproduce the jet shape well.

Jet shape in NC DIS

- **The jet shape is sensitive to α_s**
- **For each bin i in E_T, fit of $[<\phi(r=0.5)>(\alpha_s)]^i = C_1^i \cdot \alpha_s + C_2^i \cdot \alpha_s^2$ with C_1^i and C_2^i obtained from NLO QCD calculations**



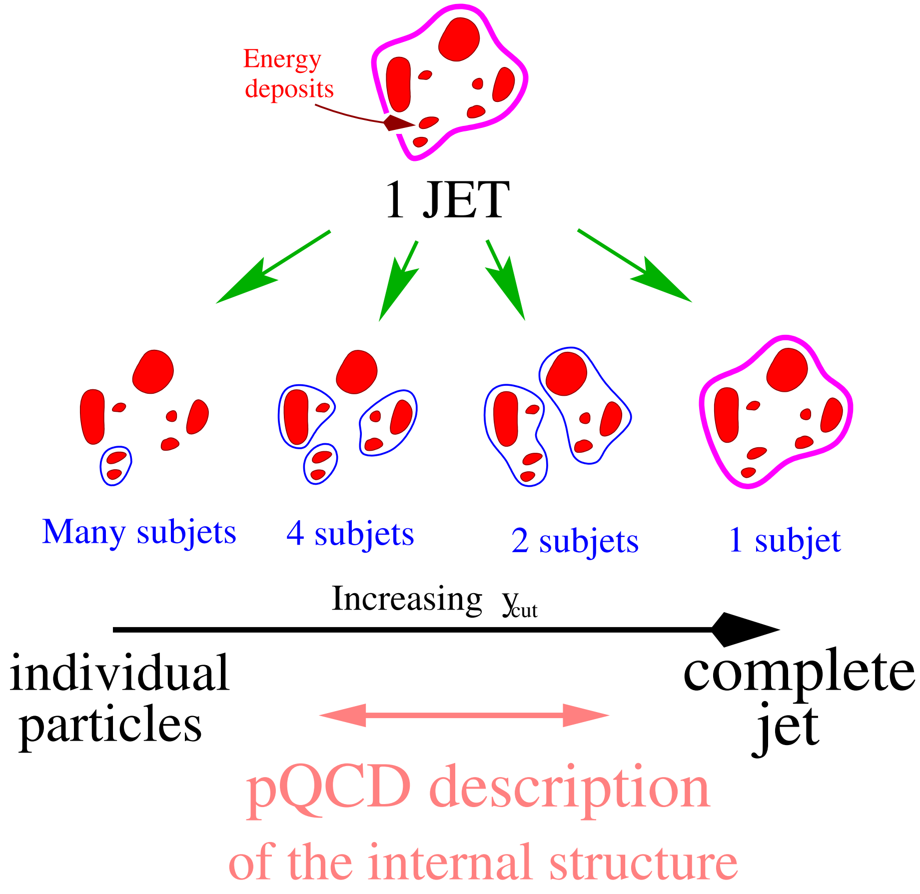
Jet shape: α_s



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

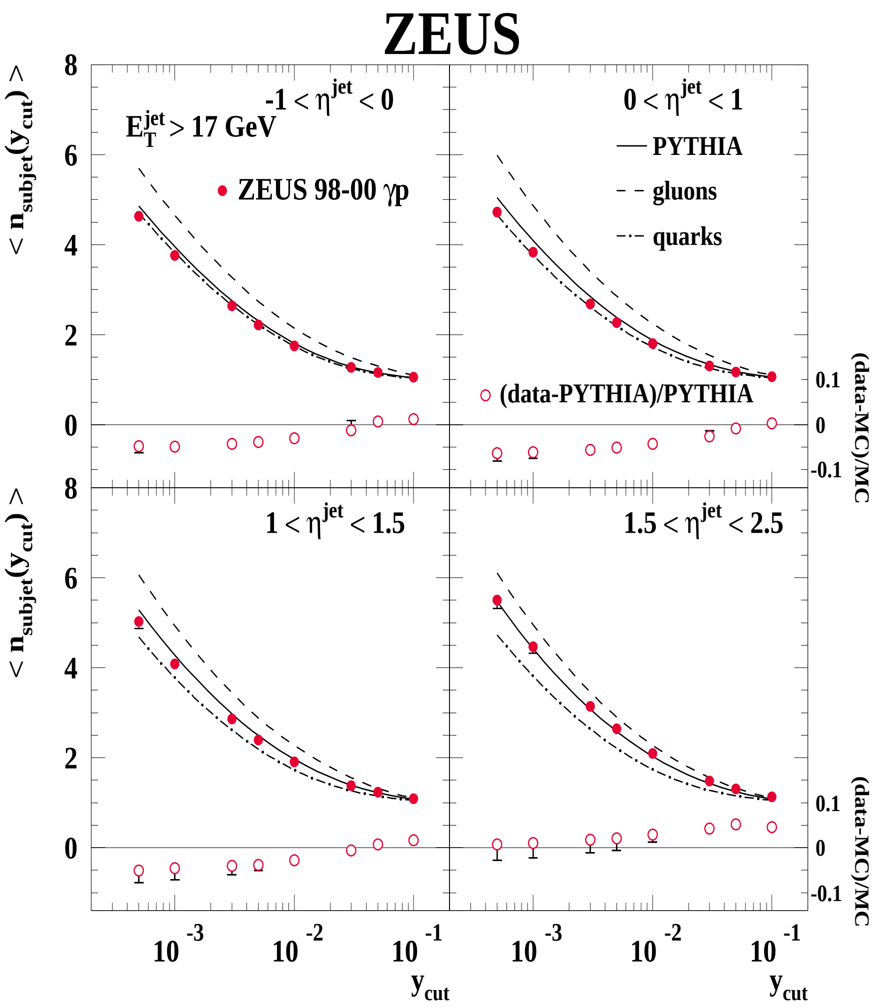
Subjet multiplicity

- Subjet are resolved within a jet by applying the k_T algorithm to the particles belonging to a jet and changing the resolution parameter y_{cut}
- Clusters found within a jet are called subjets.
- The subjet structure depends on the value chosen for the resolution parameter y_{cut}

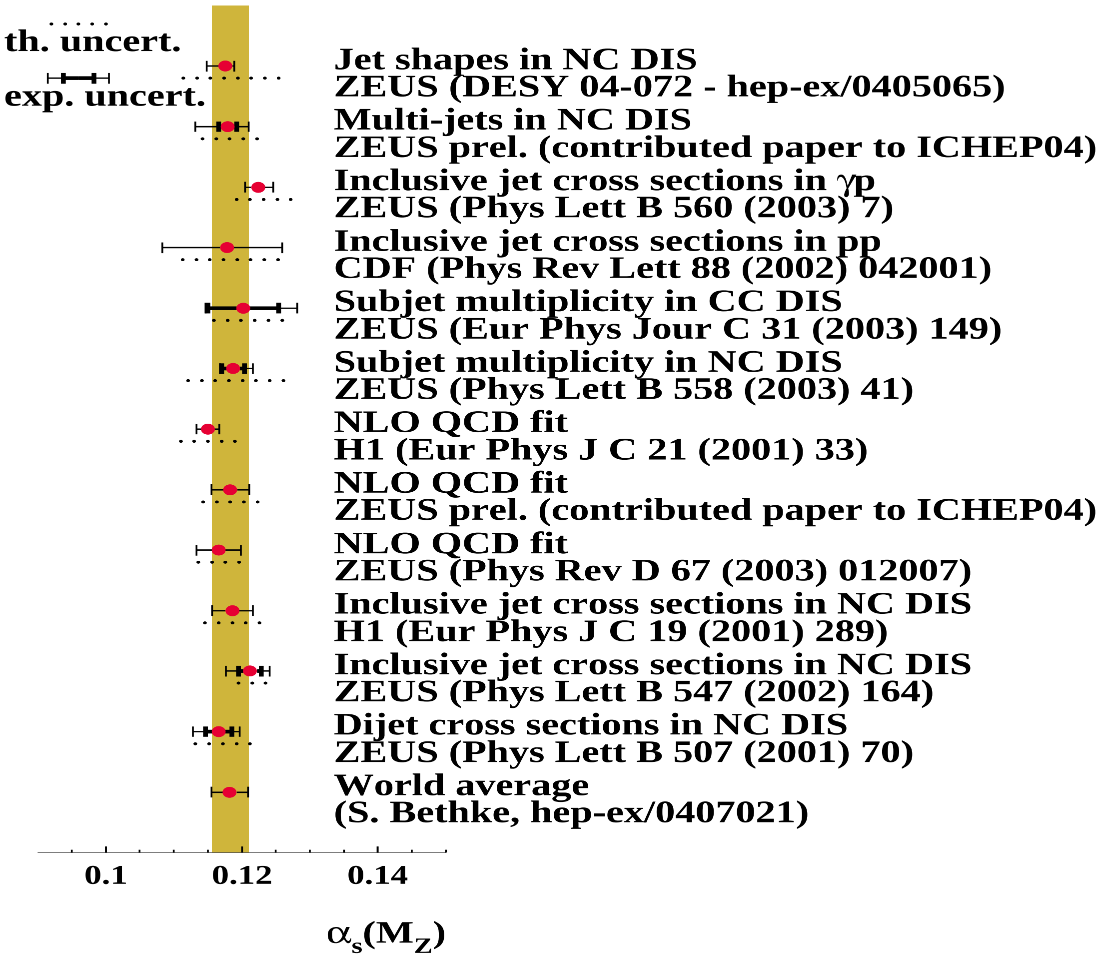


Subjet multiplicity in NC

- Selection information
  - k_T algorithm in the Lab frame
  - $Q^2 > 125GeV^2$
  - At least one jet with $E_T > 17GeV$ and $-1.0 < \eta < 2.5$
- The predicted $< n_{subjet} >$ is larger for gluon-initiated jets than for quark-initiated jets in each region of η
- The measured jets are quark-like for $-1 < \eta < 0$, and are gluon-like for $\eta > 1.5$



Measurement of α_s at HERA



- Considerable progress has led to precise measurements of α_s
- Jet observables give α_s consistent with world average
- Improved calculations are needed for better accuracy

Summary

- **H1 and ZEUS have measured jet data in DIS, photoproduction.**
- **The α_s value is competitive with world average.**
- **NLO QCD calculations based on DGLAP evolution describe the data at high Q^2 and E_T.**
- **At low x and low Q^2, further studies are required to understand parton evolution $DGLAP \Longleftrightarrow BFKL \Longleftrightarrow CCFM$.**
- **The NLO QCD calculations describe the jet shape and subjet multiplicity in NC DIS.**