High E_T Jet Physics at HERA

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On behalf of the H1 and ZEUS collaborations

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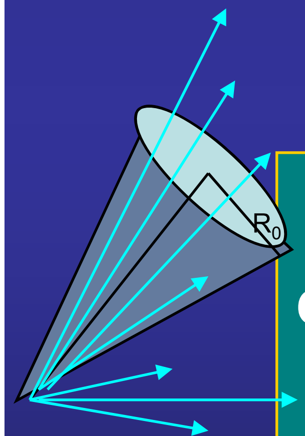
Introduction: Jets, Algorithms…

Definition of a generic hadronic jet:

Group of particles which are 'close' to each other

Partons in QCD calculations
Final state hadrons in data and MC



Many definition of 'closeness'

Cone algorithms

use geometrical information (no E)

$\Delta R = \sqrt{\Delta^2\eta+\Delta^2\varphi} < R_0$

Clustering algorithms

use geometrical information + E

e.g. $d_{ij} = \min(E_{T,i}^2, E_{T,i}^2)(\Delta^2\eta+\Delta^2\varphi)/R_0^2 >$ any $E_{T,k}^2$

Theoretical problems with
overlapping cones
→ large uncertainty
Not used at HERA since early days

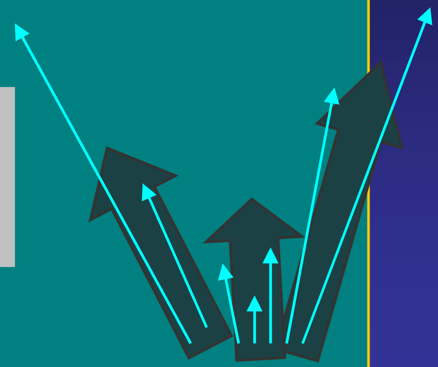
Clustering Algorithms

Group particles together if

Mass

$$d_{ij} = 2\, E_i E_j (1 - \cos\theta_{ij}) < d_{cut}$$

JADE algorithm
used extensively in e^+e^-
problems with ghost jets



k⊥

$$d_{ij} = 2 \min(E_i^2, E_j^2)(1 - \cos\theta_{ij})/E_0^2 < d_{cut}$$ E_0…hard scale

Durham algorithm
allows to vary resolution scale d_{cut}
⟶ subjets

Longitudinally invariant k⊥

$$d_{ij} = \min(E_{T,i}^2, E_{T,j}^2)(\Delta\eta^2 + \Delta\varphi^2)/R_0^2 > \text{any } E_{T,k}^2$$ R_0…radius, chosen =1

Longitudinally Invariant k⊥ algorithm
combines features of cone and durham

The remaining objects are called **Jets**

Hadronisation corrections

Needed to compare data and QCD calculations

Hadronisation corrections applied to NLO

Obtained from LO+PS Monte Carlos

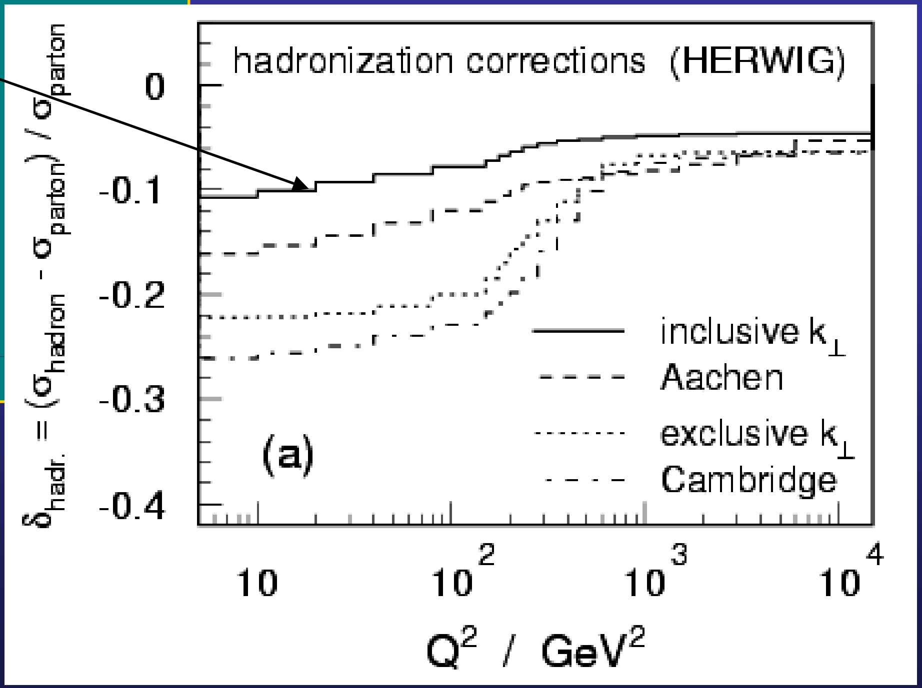
Describe jet production at HERA (apart from normalization)

Longitudinally invariant k_T algorithm

Smallest hadronisation correction
(smallest uncertainty?)
Preferred algorithm at HERA

Durham (exclusive) k_T algorithm

Allows to vary scale
Only used for subjet studies



Major experimental uncertainties

Error on Jet cross sections

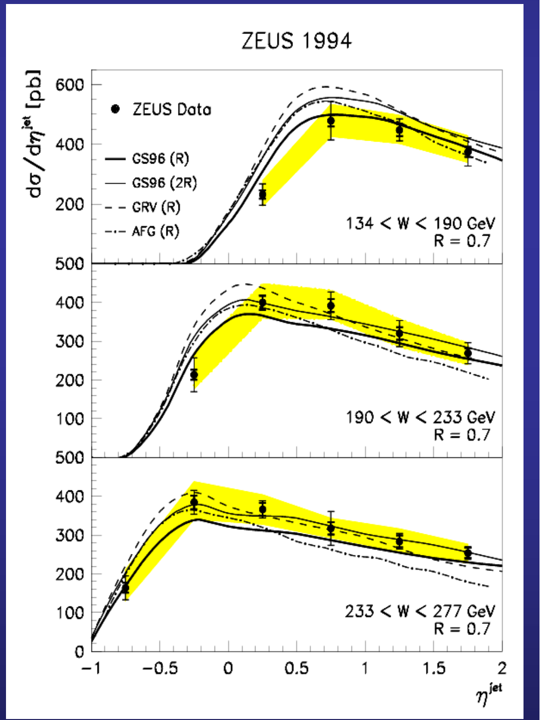
Energy scale of scattered electron (±1%)	< ± 1%
Uncertainty in detection efficiency for scattered electron (±2%)	± 2%
Uncertainties in trigger efficiencies and event selections	< ± 3%
Uncertainties in correction for detector acceptances	< ± 3%

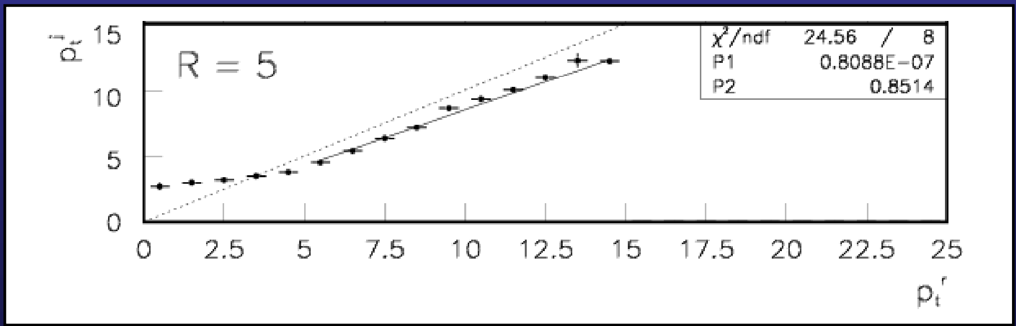
Jet Energy Scale

E_T(jet) spectrum exponentially falling → **Dominant** error
First ZEUS jet publications ±10% error in cross section

Select Jets with **high(er) E_T**
Dedicated **effort** to understand hadronic energy scale

Use of fact that **p_T** (scattered electron) = **p_T** (hadronic system)
Study events with single jets and small remaining hadronic energy





Current Jet Energy Scale Uncertainty ± 1% **(for E_T(jet) > 10 GeV)** **± 3%**

$$d\sigma_{jet} = \sum_{a=q,\bar{q},g} \int dx\ f_a(x, \alpha_S, \mu_F)\ d\hat{\sigma}_a(x, \alpha_S(\mu_R), \mu_R, \mu_F)\ D(z, \mu_{F'}, \alpha_s)$$

PDFs — **hard scattering cross section** — **Fragmentation function**

Major theoretical uncertainties

Hadronisation corrections

Typical uncertainty ± 1%

Corrections in general small <10%

Uncertainty taken as difference between estimations based on different MCs (unsatisfactory)

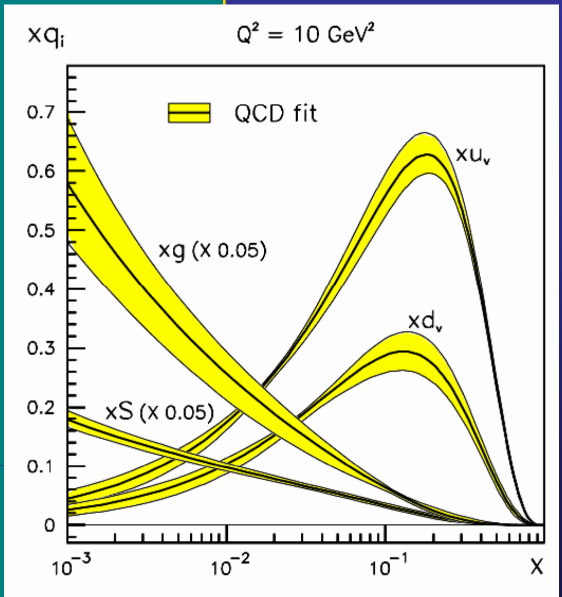
Proton PDFs

Typical uncertainty ± 1-2%

Traditionally taken from difference obtained with various sets of PDFs (unsatisfactory)

Covariance matrix $V_{p\mu,p\lambda}$ of the fitted parameters $\{p_\lambda\}$ available correct evaluation of error on cross section

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



In γP: additional uncertainty due to PDFs of photon

$$d\sigma_{jet} = \sum_{a=q,\bar{q},g} \int dx\, f_a(x, \alpha_S, \mu_F)\, d\hat{\sigma}_a(x, \alpha_S(\mu_R), \mu_R, \mu_F)\, D(z, \mu_{F'}, \alpha_s)$$

PDFs — hard scattering cross section — Fragmentation function

Strong coupling α_S

Current uncertainty ± 1.7%

Enters PDFs value assumed to evolve to different scales in fit to inclusive DIS data
Enters $d\sigma_a$ governs strength of interaction

Current world average value $\alpha_S(M_Z) = 0.1176 \pm 0.0020$

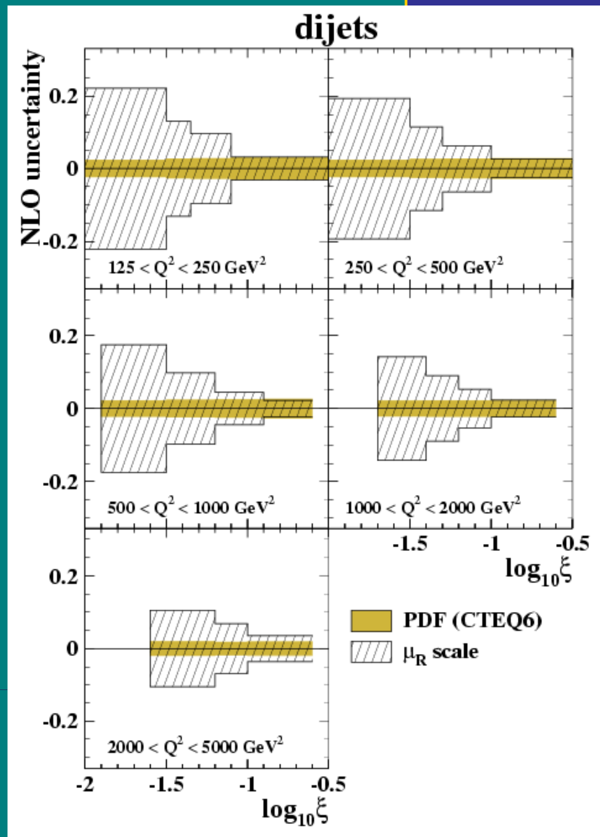
Used **consistently** in PDFs and $d\sigma_a$

Only free **parameter** of pQCD: jet cross sections sensitive to it

Terms beyond α_S^2

Uncertainty can be large
Dominating theoretical error

Corresponding uncertainty **NOT** known
Estimated through residual dependence on renormalization μ_R and factorization μ_F scales
→ **Choice** of scales: Q, $E_{T,jet}$ or linear combination
Customary, but **arbitrary** to vary scales by factor 2



Jet Production Processes at HERA

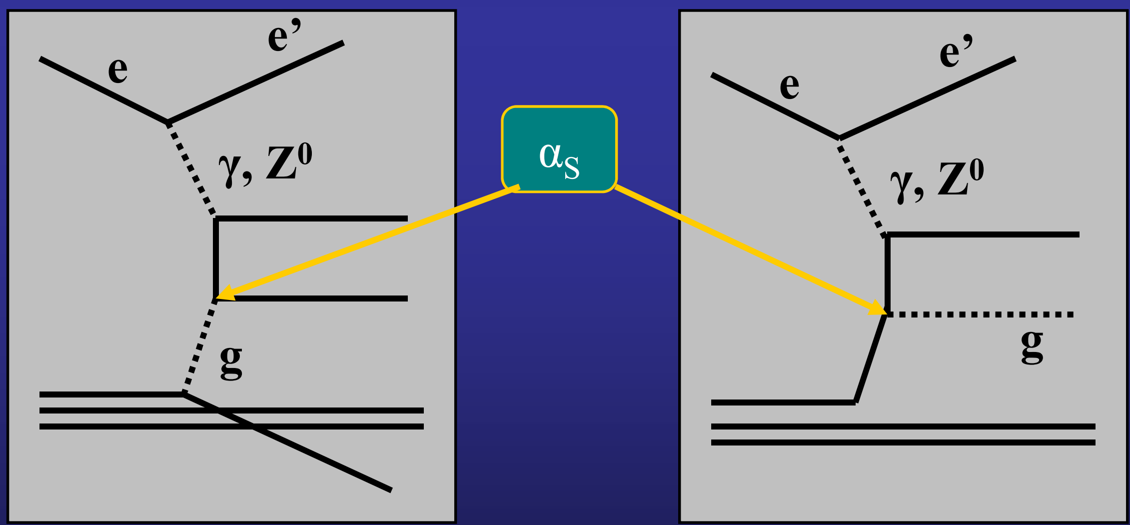
Event classes

Photoproduction: Q^2 ~0 (real photons)
Deep inelastic scattering: Q^2 > few GeV^2 (virtual photons)

Jet production mechanisms (LO in α_S)

Boson-Gluon Fusion

QCD Compton Scattering



Di-jets

Multi-jet

Higher order processes (α_S^n, n>1)
Multi-parton interactions (→ L. Stanco)

Inclusive-Jet Cross Sections in DIS

Data sample

$Q^2 > 125\ GeV^2$
$L = 82\ pb^{-1}$ of $e^{\pm}p$ collisions

Jet reconstruction

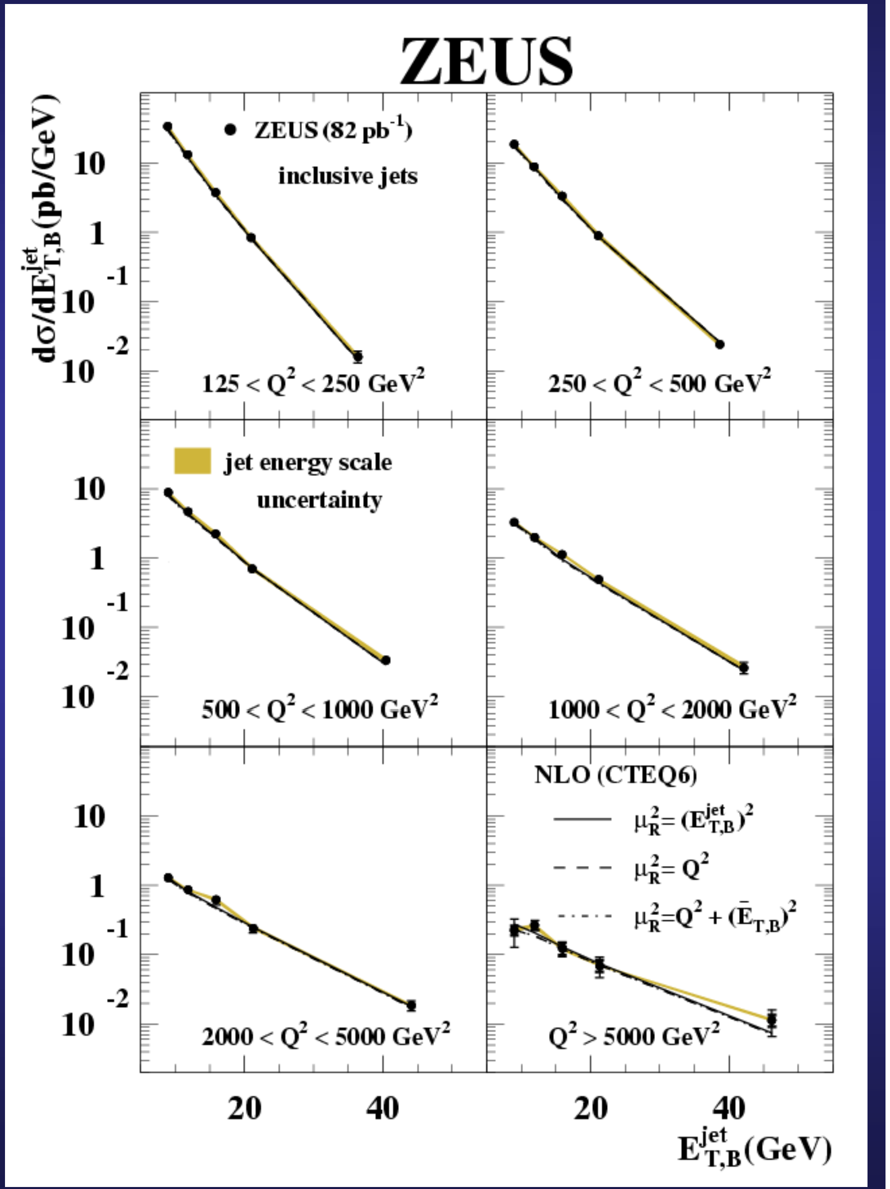
With k_T algorithm in the
longitudinally invariant inclusive mode
And in the Breit frame

Jet selection

E_T^{Jet} (Breit) > 8.0 GeV
E_T^{Jet} (lab) > 2.5 GeV
$-2 < \eta^{Jet}$ (Breit) < 1.5

Results

$d\sigma/dE_T^{jet}$(Breit) in large range of Q^2
Nice description by NLO QCD

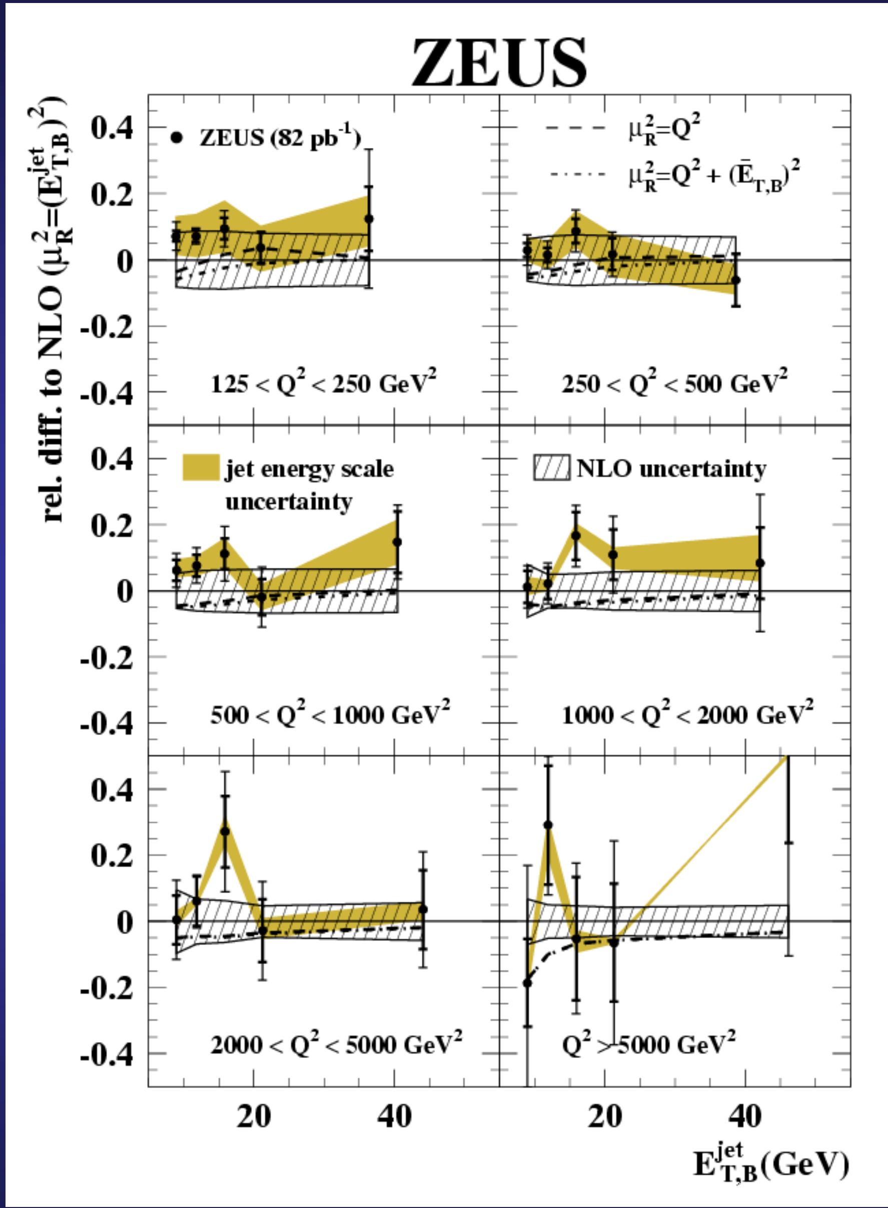


Ratio to NLO QCD

Dominant experimental uncertainty: energy scale

Theoretical uncertainty ~ experimental uncertainty

With HERA II data statistical uncertainty at high Q^2 will be significantly reduced



Determination of strong coupling constant $\alpha_S(M_Z)$

$Q^2 > 500$ GeV^2
- Smaller experimental (E scale) uncertainties
- Smaller theoretical (PDFs and scale) uncertainties

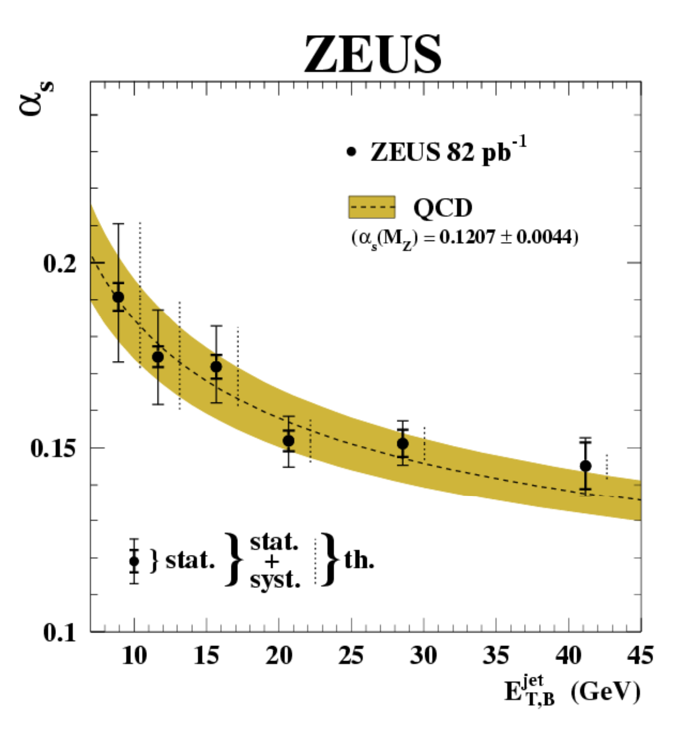
Parameterize theoretical cross section as

$$d\sigma/dQ^2(\alpha_S(M_Z)) = C_1\alpha_S(M_Z) + C_2\alpha_S^2(M_Z)$$

(same value of α_s in PDF and calculation)

Determine C_1 and C_2 from χ^2 fits

Fit parameterized theoretical cross $d\sigma/dQ^2(\alpha_S(M_Z))$ to measurement



Result

$$\alpha_S(M_Z) = 0.1207 \pm 0.0014\ (\text{stat.})\ {}^{+0.0035}_{-0.0033}\ (\text{syst.})\ {}^{+0.0022}_{-0.0023}\ (\text{theo.})$$

One of world's most precise…

PDG: $\alpha_S(M_Z) = 1.176 \pm 0.002$

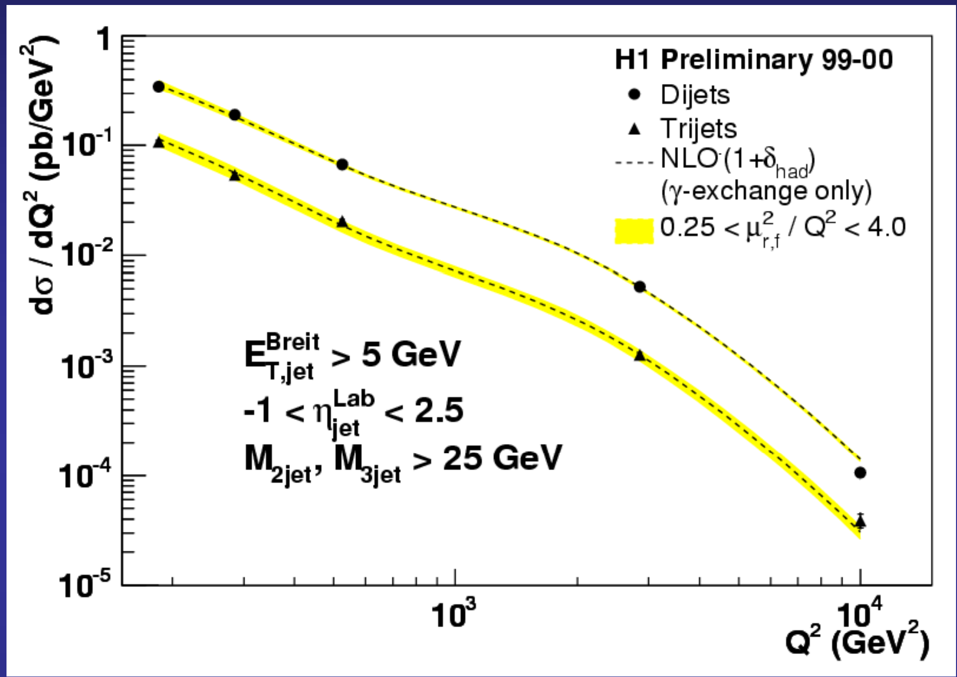
Multi-Jets in DIS

Data sample

150 GeV^2 < Q^2 < 15,000 GeV^2
L = 65 pb^{-1} of e^+p collisions

Jet reconstruction

With k_T algorithm in the longitudinally invariant inclusive mode
And in the Breit frame



Jet selection

E_T^{Jet} (Breit) > 5.0 GeV
-1 < η^{Jet} (lab) < 2.5
Dijets: m_{2jet} > 25 GeV
Trijets: m_{3jet} > 25 GeV

} To reduce infrared regions ($E_T^1 \sim E_T^2$)

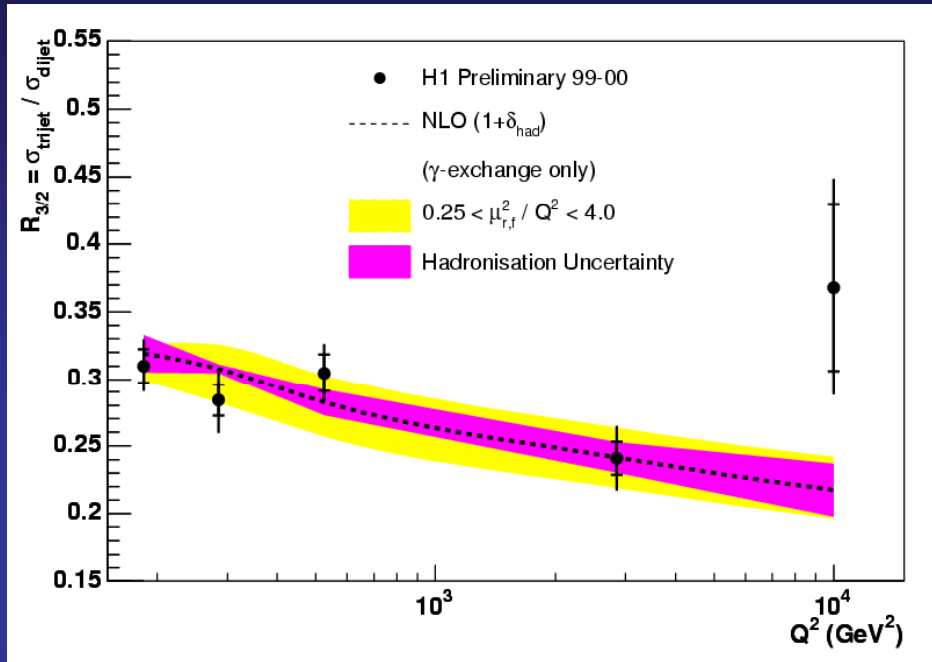
Results

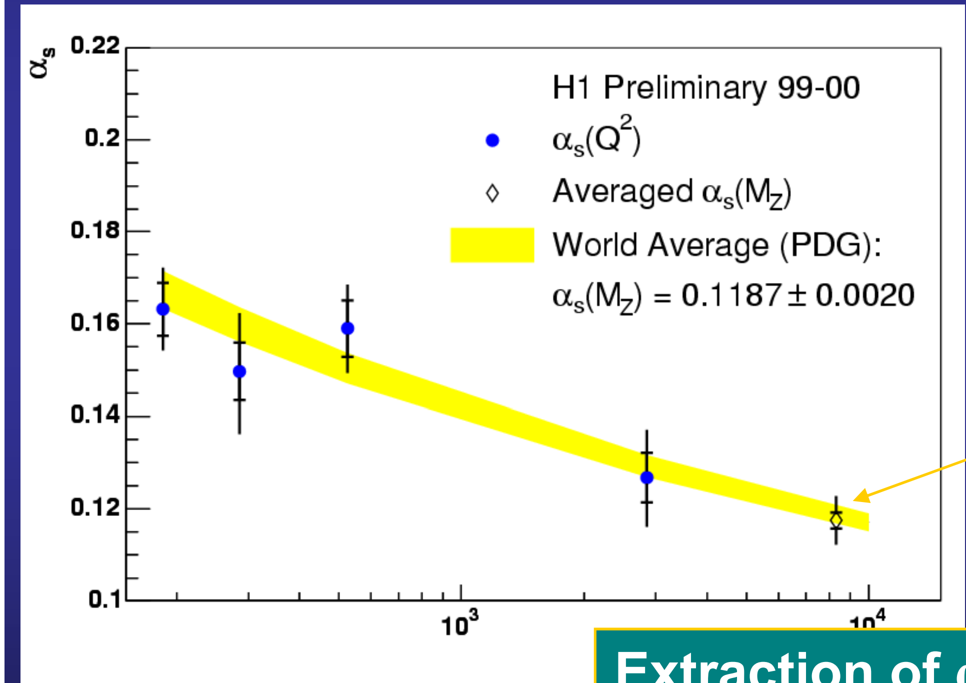
$d\sigma/dQ^2$ in large range of Q^2
Nice description by NLO QCD

Ratio of 3-jet/2-jet

Many experimental uncertainties cancel

Theoretical uncertainty ~ experimental uncertainty





Average $\alpha_S(M_Z)$

Extraction of $\alpha_S(M_z)$

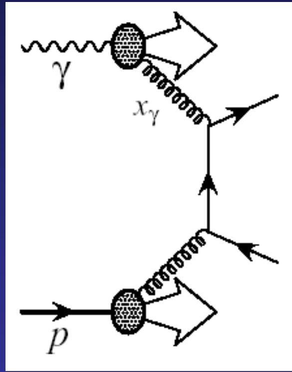
Similar procedure as with incl. jets

$$\alpha_S(M_z) = 0.1175 \pm 0.0017 \text{ (stat.)} \pm 0.005 \text{ (syst.)} {}^{+0.0054}_{-0.0068} \text{ (theo.)}$$

Di-Jets in Photoproduction

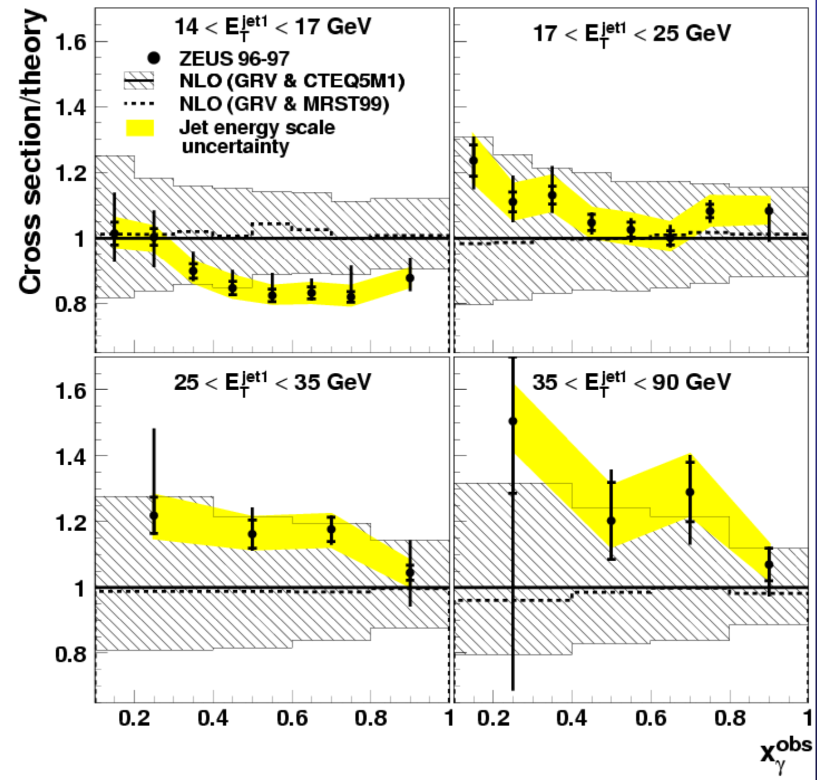
Data sample

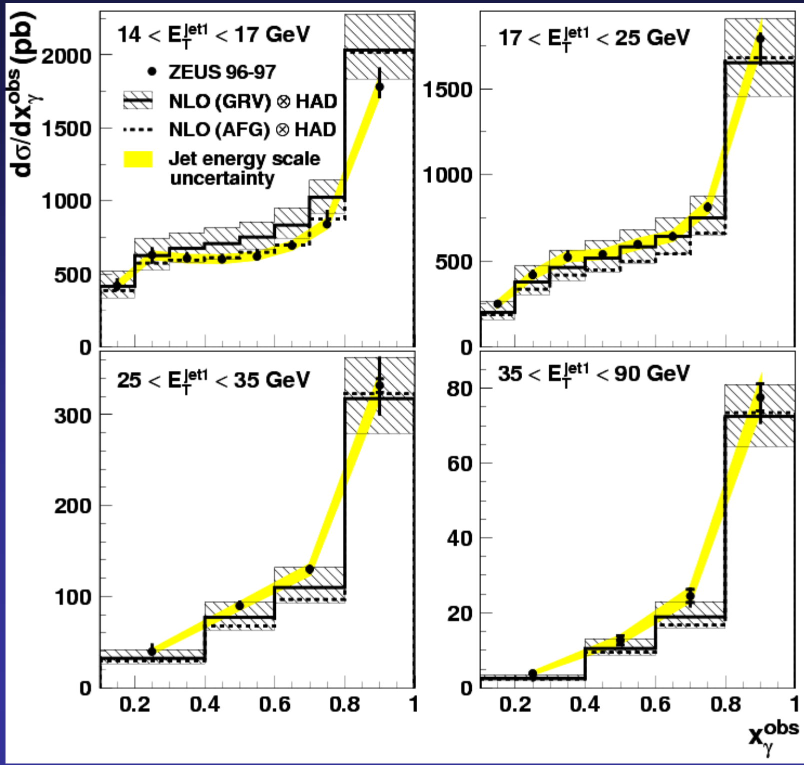
$Q^2 < 1$ GeV^2
134 < W < 277 GeV



Jet reconstruction

With k_T algorithm in the longitudinally invariant inclusive mode





Jet selection

E_T^{Jet} > 14.0 and 11.0 GeV
$-1 < \eta^{Jet}$ (lab) < 2.4

$d\sigma/dx_\gamma$ in bins of E_T^{jet}

Large discrepancy with theory

→ Photon PDF inadequate?
NLO pQCD calculation inadequate?

Photon PDFs determined from $\gamma\gamma$ **interactions** at low scales

At HERA photon PDFs being **probed at high scales** (jet E_T)

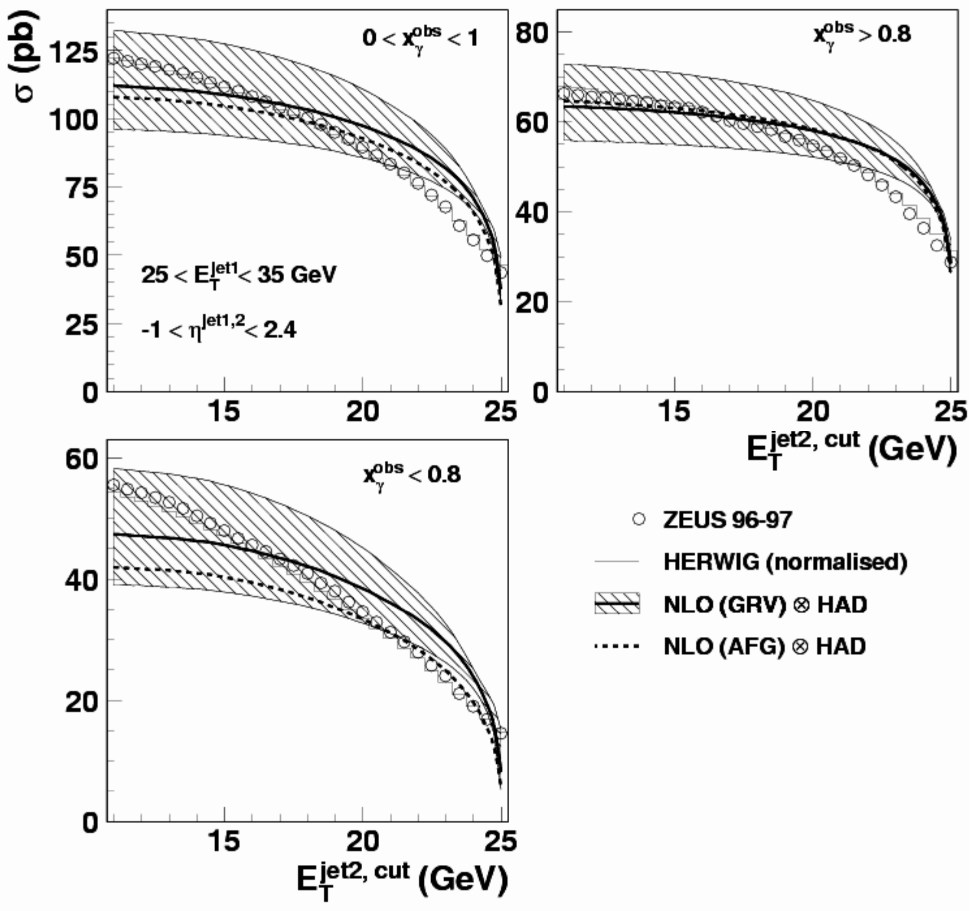
Similar study of H1 shows 'perfect' **agreement** with NLO pQCD ???

H1 uses **slightly higher $E_{T,2}$ cut** at 15 GeV

Study of **dependence** on $E_{T,2}$ cut

Dependence **NOT** reproduced by NLO

H1 cut more fortunate



NNLO calculations needed

Until then, no meaningful constraint on photon PDFs

Event Shapes

Data sample

$196 < Q^2 < 40{,}000$ GeV^2
L = 106 pb^{-1} of $e^{\pm}p$ data

Event shape of hadronic final state

Thrust wrt to boson axis

$$\tau = 1 - T \quad \text{with} \quad T = \frac{\sum_h |\vec{p}_{z,h}|}{\sum_h |\vec{p}_h|}$$

Thrust wrt to n_T^{max}

$$\tau_C = 1 - T_C \quad \text{with} \quad T = \max_{\vec{n}_T} \frac{\sum_h |\vec{p}_h \cdot \vec{n}_T|}{\sum_h |\vec{p}_h|}$$

Jet broadening

$$B = \frac{\sum_h |\vec{p}_{t,h}|}{2\sum_h |\vec{p}_h|}$$

Squared jet mass

$$\rho = \frac{(\sum_h E_h)^2 - (\sum_h \vec{p}_h)^2}{(2\sum_h |\vec{p}_h|)^2}$$

C-parameter

$$C = \frac{3}{2} \frac{\sum_{h,h'} |\vec{p}_h||\vec{p}_{h'}| \cos^2\theta_{hh'}}{(\sum_h |\vec{p}_h|)^2}$$

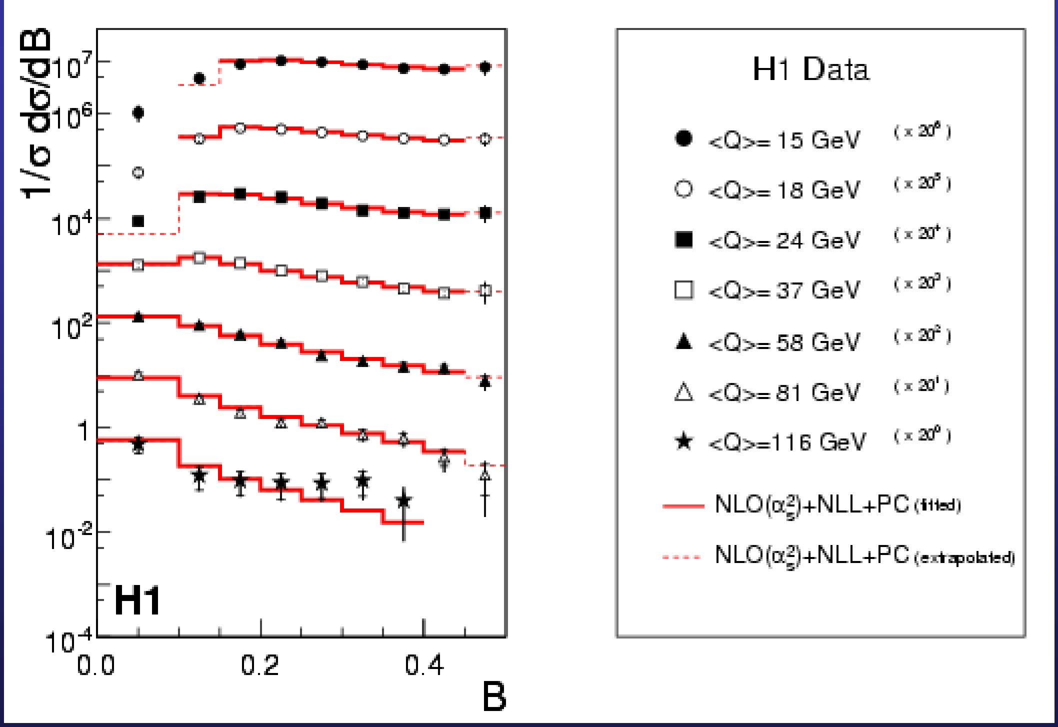
Theoretical calculations

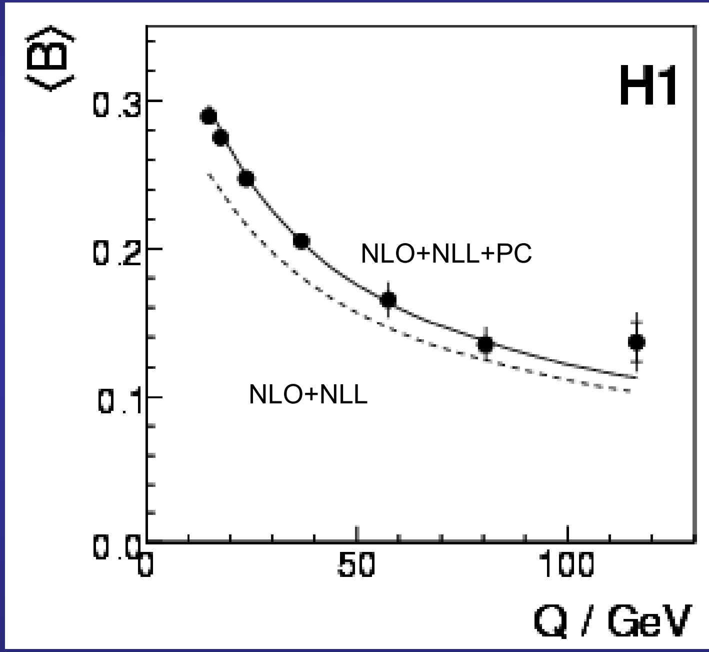
Available at NLO level including resummed next-to-leading logarithms (NLO+NLL)
Hadronisation corrections taken care of by calculable **power corrections** (~ 1/Q)

$P_v \sim \alpha_0 P_V^{calc}$ where α_0 is a universal parameter (independent of ES variable V)

Differential distribution

Nicely reproduced by NLO+NLL+PC



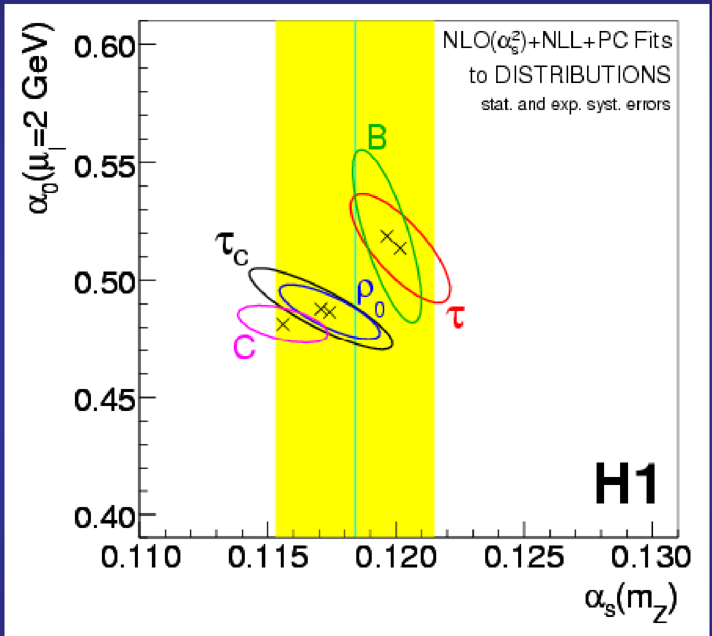


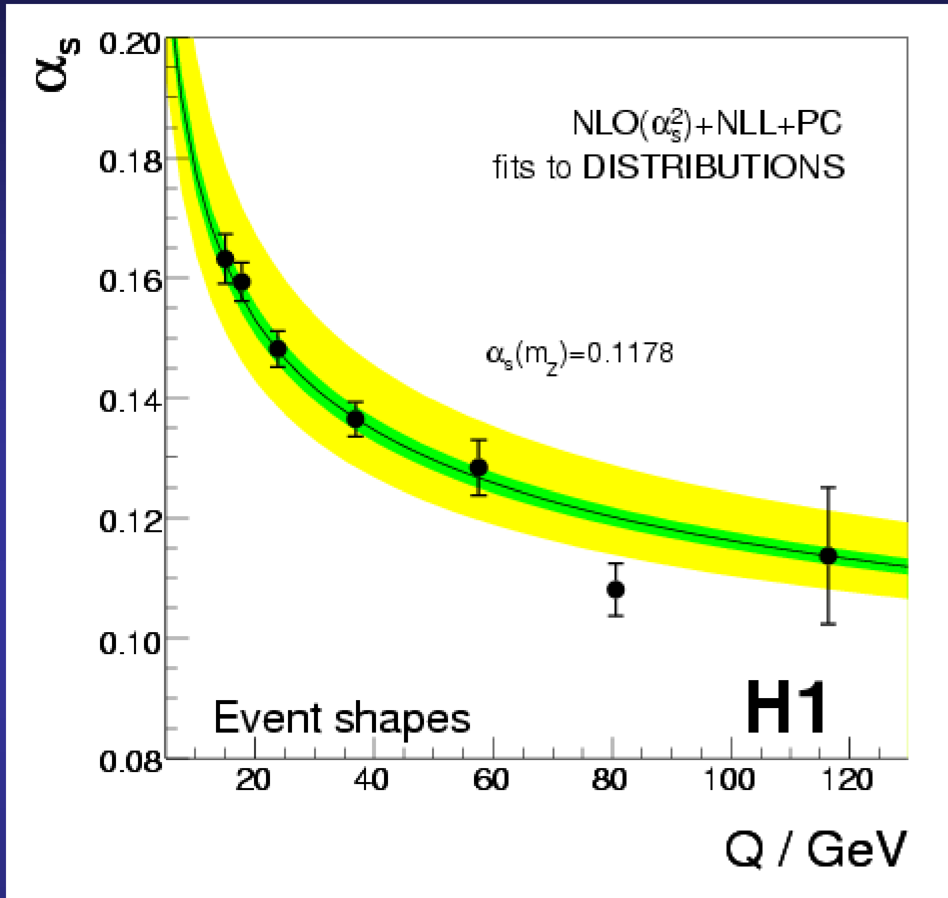
Mean of ES Variable versus Q

Nicely reproduced by NLO+NLL+PC
(2 parameter fit: α_S and α_0)

Fit to differential distributions

→ ~Consistent values of α_S and α_0
(α_0 indeed universal within 10%)



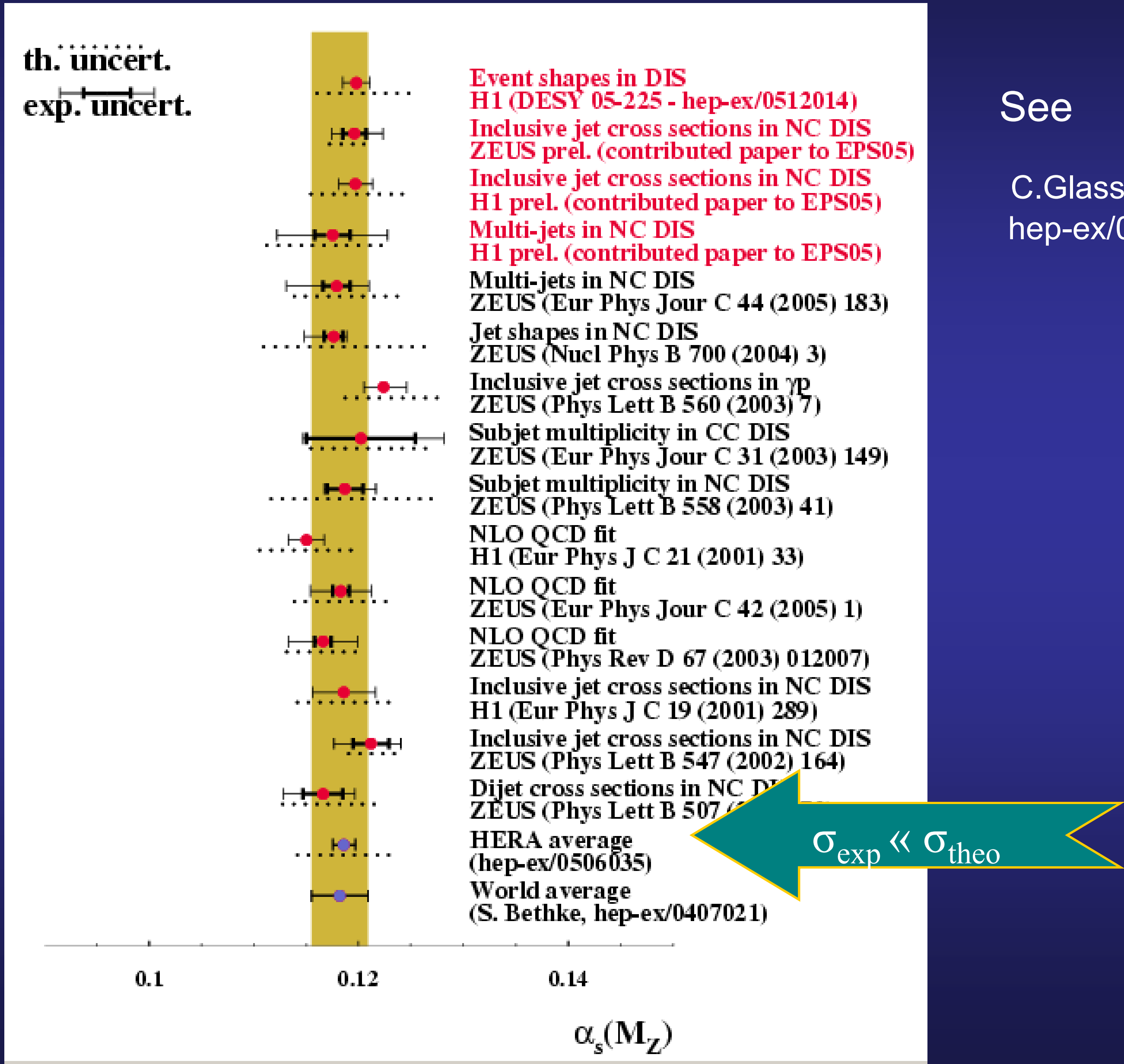


Combined fit over all ES Variables

→ $\alpha_S(M_Z) = 0.1198 \pm 0.0013$ (exp) $^{+0.0056}_{-0.0043}$ (theo)

→ $\alpha_0 = 0.476 \pm 0.008$ (exp) $^{+0.0018}_{-0.0059}$ (theo)

HERA Measurements of α_S



See

C.Glassman
hep-ex/0506035

Conclusions

Precision jet physics at HERA

Experimental uncertainties often < 3%
Uncertainties dominated by jet energy scale uncertainty

Performed large number of measurements

Photoproduction (inclusive jets, dijets, multijets…)
DIS NC (inclusive, dijets, multijets, subjets…)
DIS CC (inclusive…)

Results provide

Constraints on proton PDF (included in NLO QCD fits of F_2)
Constraints on photon PDF (needs better calculations)
High precision measurements of the strong coupling constant $\alpha_S(M_Z)$

$$\alpha_S(M_Z)_{HERA} = 0.1193 \pm 0.0005\ (exp)\ \pm 0.0025\ (theo)$$

Backup Slides

Frames for Jet Finding

e^+e^- annihilation

Laboratory frame = center-of-mass frame
(unless there is significant initial state radiation)

$p\bar{p}$ colliders

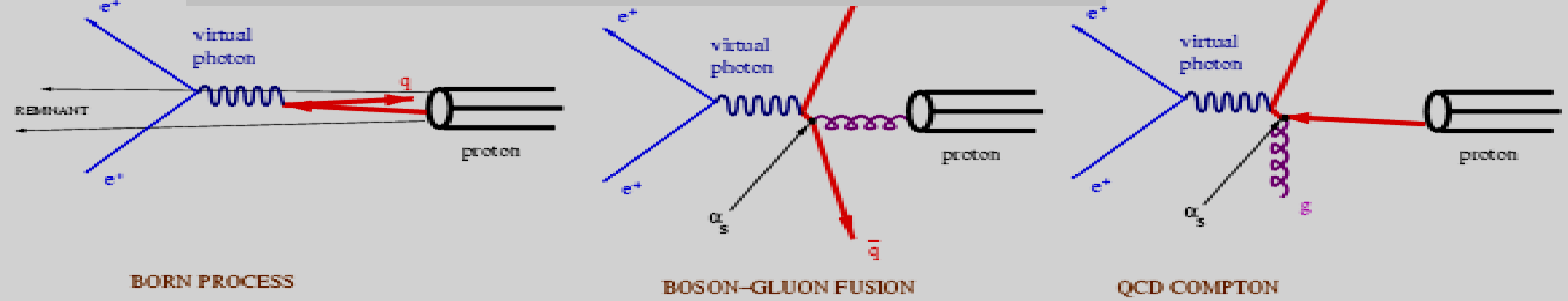
Events p_T balanced
Cone algorithm invariant to longitudinal boost
→ Analysis in **laboratory** frame

Deep Inelastic Scattering

Hadronic system recoils against scattered electron
→ jets have p_T in laboratory frame

BREIT FRAME $2x_{BJ} + \vec{p} = 0$

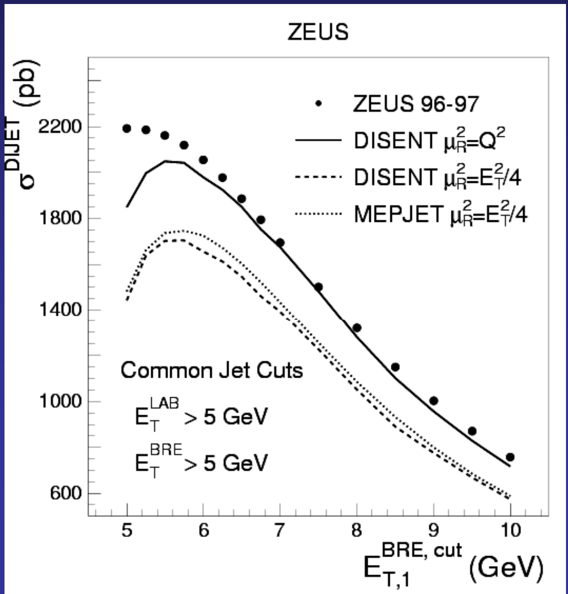
Virtual photon purely space-like $\vec{q} = (0, 0, 0, -2x_{BJ}p)$
Photon collides head-on with proton



High-E_T Jet Production in Breit Frame

→ suppression of Born contribution
suppression of Beam remnant jet(s)

E_T – Cuts for Dijet Selection



Symmetric cuts

For instance $E_{T,1}$, $E_{T,2}$ > 5 GeV

Reduced phase space for real emission of soft gluons close to cut

Complete cancellation of the soft and collinear singularities with the corresponding singularities in the virtual contributions **not possible**

Unphysical behavior of calculated cross section

Solutions

Additional cut on **Sum of E_T**

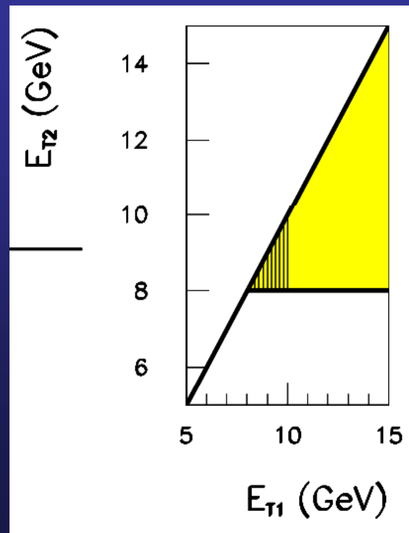
for instance $E_{T,1} + E_{T,2}$ > 13 GeV

H1

Asymmetric cuts

for instance $E_{T,1}$ > 8 GeV, $E_{T,2}$ > 5 GeV

ZEUS



Jets in Photo-production

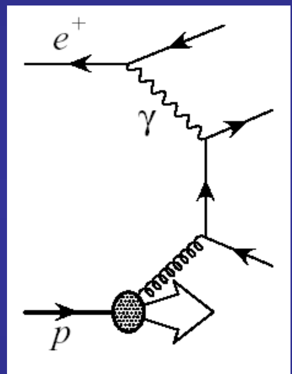
Photon has very **low virtuality** $Q^2 \sim 0$ GeV^2

Only one inclusive variable **$W_{\gamma P}$** … photon – proton center of mass

To $\mathcal{O}(\alpha\alpha_S)$ → **2 types of processes** contribute to jet production

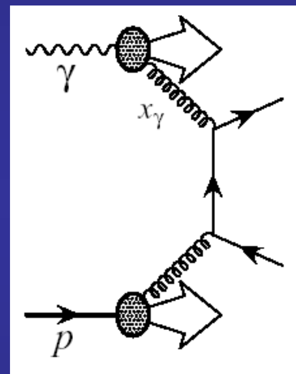
Direct photo-production

Photon interacts as an entity



Resolved photo-production

A parton with momentum fraction x_γ in the photon enters the hard scattering process



Momentum fraction x_γ

Can be reconstructed as

$$x_\gamma = \frac{\Sigma_{\mathrm{jets}}(E - p_z)}{\Sigma_{\mathrm{all\ hadrons}}(E - p_z)}$$

Direct $x_\gamma = 1$ Resolved $x_\gamma < 1$