Jet Physics and Event Shape Studies at HERA

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On behalf of ZEUS and H1

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- Deep Inelastic Scattering at HERA and Jet Production
- Inclusive Cross Sections in DIS and Photoproduction
- α_s from Inclusive and Dijet Production
- Studies of Dijet Production
- 3-jet Production in DIS
- α_s from Jet Substructure: Subjet Multiplicities and Jet Shapes in DIS
- Event Shapes: Power Corrections and Resummations
- Conclusions and Summary

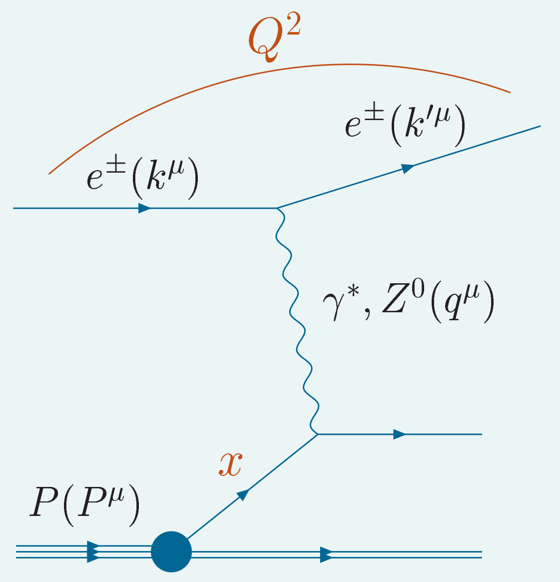
DEEP INELASTIC SCATTERING AT HERA

Kinematics:

$$\sqrt{s} \approx 300 \text{ GeV } (\text{-}1997), 320 \text{ GeV } (1998\text{-})$$

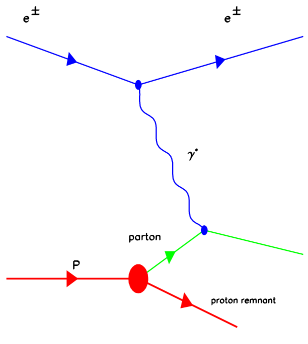
$$Q^2 = -q^2 = (k - k')^2$$

$$x = \frac{Q^2}{2P.q}$$



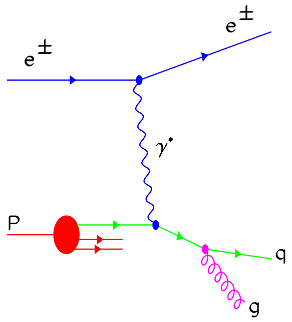
Up to $\mathcal{O}(\alpha_s)$ jet production occurs via:

Quark Parton Model ($\mathcal{O}(\alpha_s^0)$)



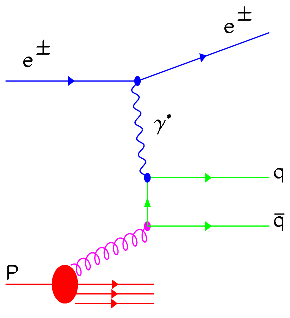
(c)

QCD-Compton



(a)

Boson-Gluon Fusion



(b)

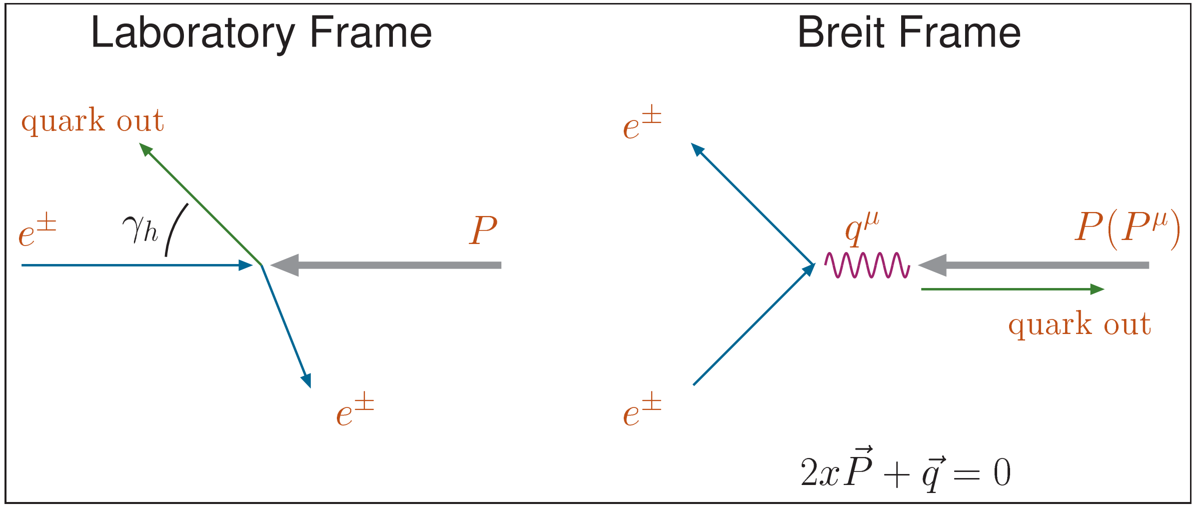
JET PRODUCTION IN DIS

- Inclusive Jet / Dijet Cross Sections
  ⇒ test of pQCD calculations
  ⇒ sensitivity to parton densities (PDFs)
  ⇒ extraction of α_s

Jet studies in the Breit frame:

▷ high-E_T jets in the Breit frame $\Longleftrightarrow$ hard pQCD processes

▷ 2 possible hard energy scales: Q and E_T $\Leftrightarrow$ choice of renormalisation scale



INCLUSIVE CROSS SECTIONS IN DIS IN THE BREIT FRAME

Advantages of inclusive measurements:

- ▷ no infrared sensitivity problems related to the jet selection cuts as in dijet analyses
- ▷ smaller theoretical uncertainties compared to dijet calculations

- 1996-97 Data, Kinematic range

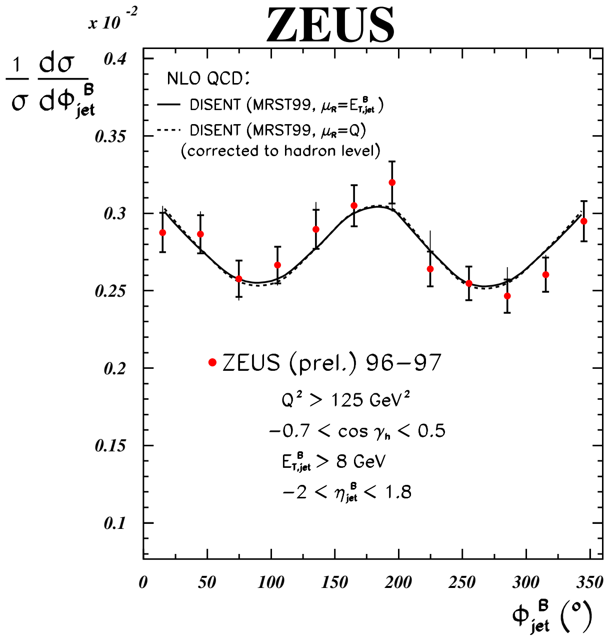
$$Q^2 > 125 \text{ GeV}^2$$
$$-0.7 < \cos\gamma_h < 0.5$$

(assure good reconstruction)

- k_T-cluster algorithm used

Jet cuts ONLY in Breit frame:

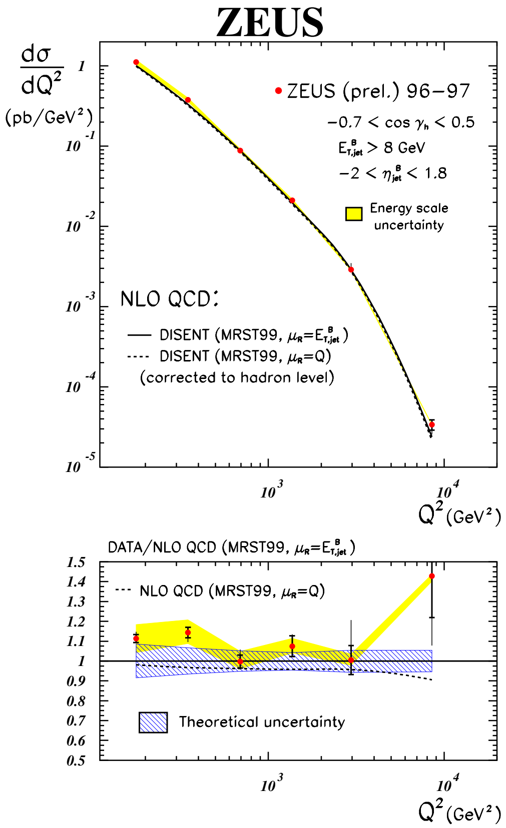
$$E^{\rm B}_{\rm T,jet} > 8 \text{ GeV}$$
$$-2 < \eta^{\rm B}_{\rm jet} < 1.8$$



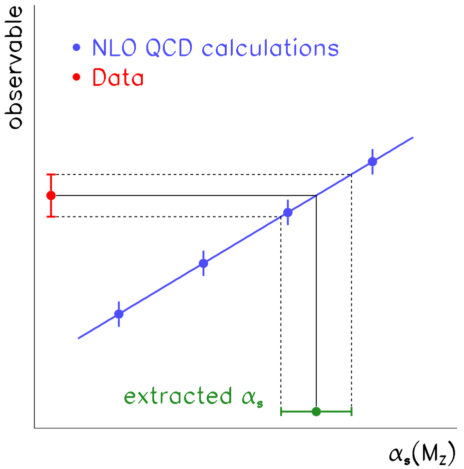
1st observation in jets of $\frac{d\sigma}{d\phi^B_{jet}} \propto A + C\cos 2\phi^B_{jet}$

(ϕ^B_{jet} = jet azimuthal angle wrt lepton scattering plane)

α_s FROM INCLUSIVE CROSS SECTIONS



α_s extraction method:



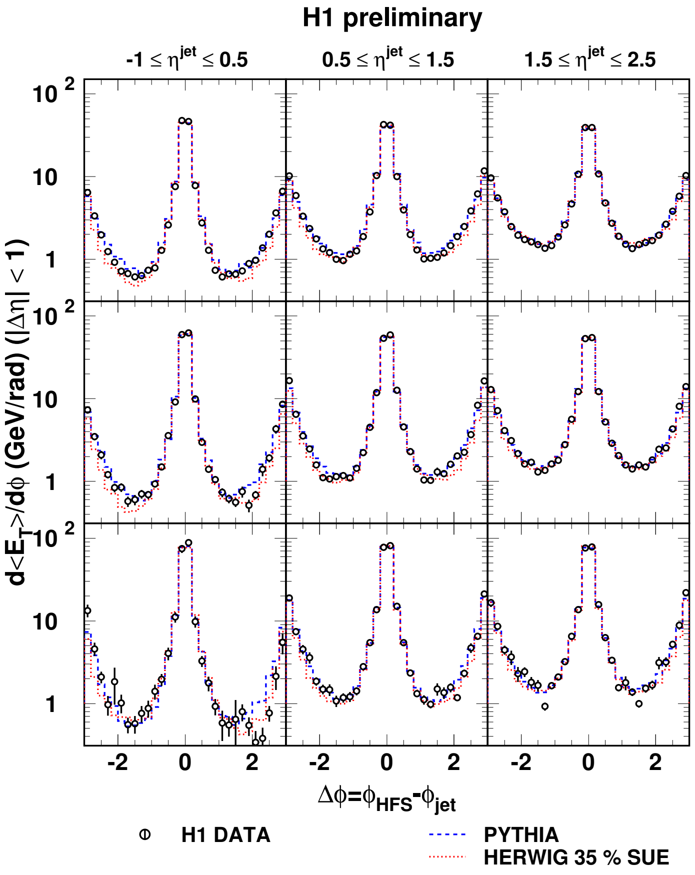
- reasonable NLO description of the data over all Q^2 range (within $10-15\%$)
- $d\sigma/dQ^2$ falls over 5 orders of magnitude

σ^{incl} very sensitive to value of $\alpha_s \Rightarrow$ powerful method of extraction of α_s

$$\alpha_s(M_Z)^{1} = 0.1190 \pm 0.0017(\mathrm{stat})\,^{+0.0049}_{-0.0023}(\mathrm{syst})\,^{+0.0026}_{-0.0026}(\mathrm{th})\ (Q^2 > 500\ \mathrm{GeV}^2)$$

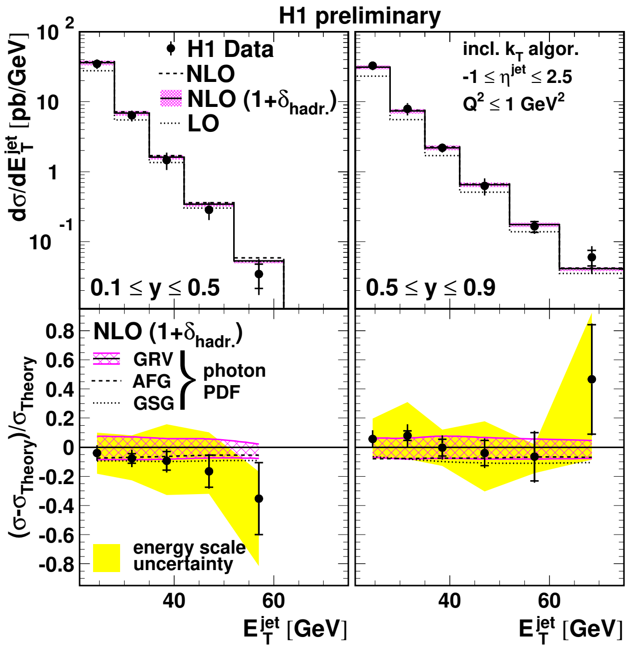
$$\alpha_s(M_Z) = 0.1186 \pm 0.0030(\mathrm{exp})\,^{+0.0039}_{-0.0045}(\mathrm{th})\,^{+0.0033}_{-0.0023}(\mathrm{pdf})\ (\text{incl. jets - }\mathbf{H1})$$

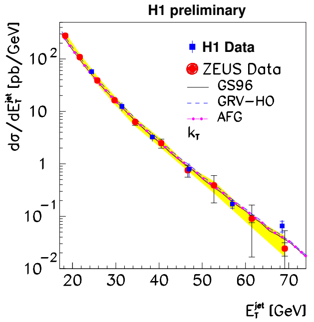
INCLUSIVE HIGH-E_T JET CROSS SECTIONS IN PHOTOPRODUCTION



$E_{\rm T}^{\rm jet} > 21$ GeV

$-1 < \eta^{\rm jet} < 2.5$



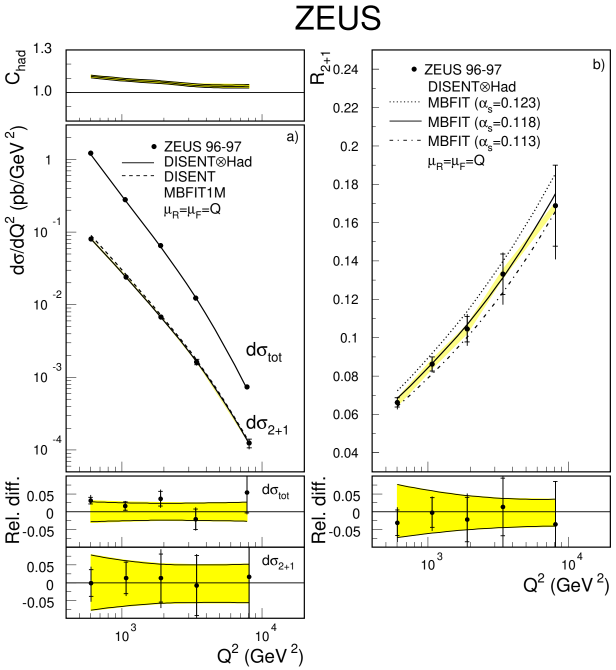


- good description of the jet azimuthal energy flow
- NLO describes data reasonably well

α_s FROM DIJET RATES AT HIGH Q^2

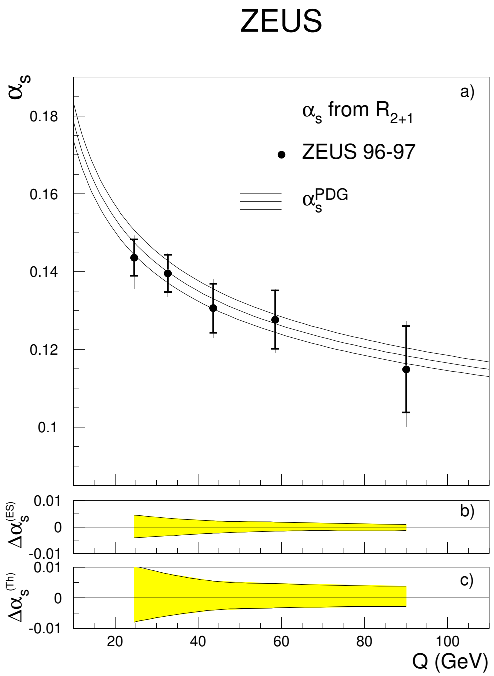
- $470 < Q^2 < 20000$ GeV^2
- $E_{T,Breit}^{jet,1} > 8$ GeV , $E_{T,Breit}^{jet,2} > 5$ GeV^2
- $-1 < \eta_{lab}^{jet} < 2$

- $\boxed{R_{2+1}(Q^2) = d\sigma_{2+1}/d\sigma_{tot}}$ not very sensitive to PDFs & exp. uncertainties largely cancel in the ratio $\Rightarrow$ suited for α_s extraction
- α_s extraction from QCD fit up to $\mathcal{O}(\alpha_s^2)$



▷ $R_{2+1} \nearrow$ with Q^2

▷ Good description from NLO



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

DIJET RATES AT MEDIUM Q^2

Motivations:

- ▷ test NLO pQCD in dijet production at medium Q^2
- ▷ what is the effect of the choice of μ_R ?

■ 1996-97 Data, Kinematic range

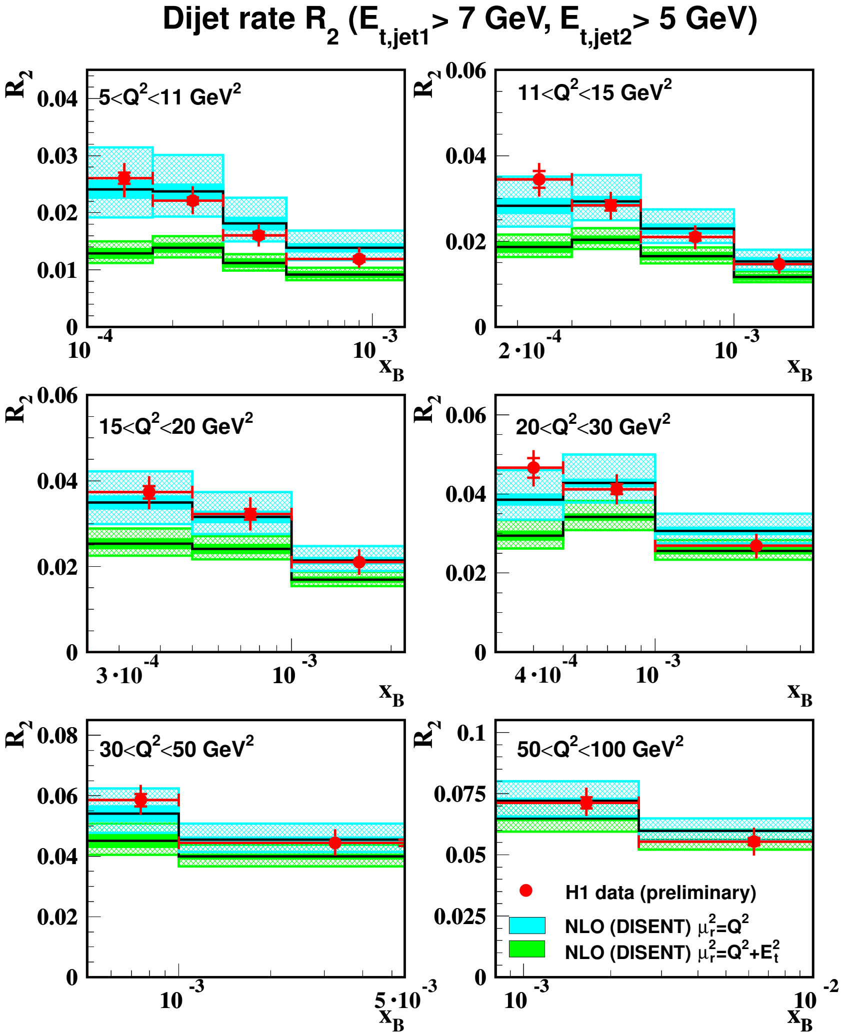
$$10^{-4} < x < 10^{-2}$$
$$5 < Q^2 < 100 \text{ GeV}^2$$

■ k_T-cluster algorithm applied in HCM frame

$$E_{T,HCM}^{jet,1} > 7 \text{ GeV} \quad , \quad E_{T,HCM}^{jet,2} > 5 \text{ GeV}^2$$

$$-1 < \eta_{lab}^{jet} < 2$$

- $\mu_R = Q^2 \Rightarrow$ large scale unc.
  but NLO describes data
- $\mu_R = Q^2 + \overline{E}_T^{jet} \Rightarrow$ smaller scale unc.
  but NLO unable to describe data



DIJET PRODUCTION IN DIS AT SMALL JET SEPARATION

Motivations:

- ▷ investigate minimum inter-jet separation necessary to allow accurate description of the dijet rate using NLO pQCD

- ■ 1995-97 Data, Kinematic range

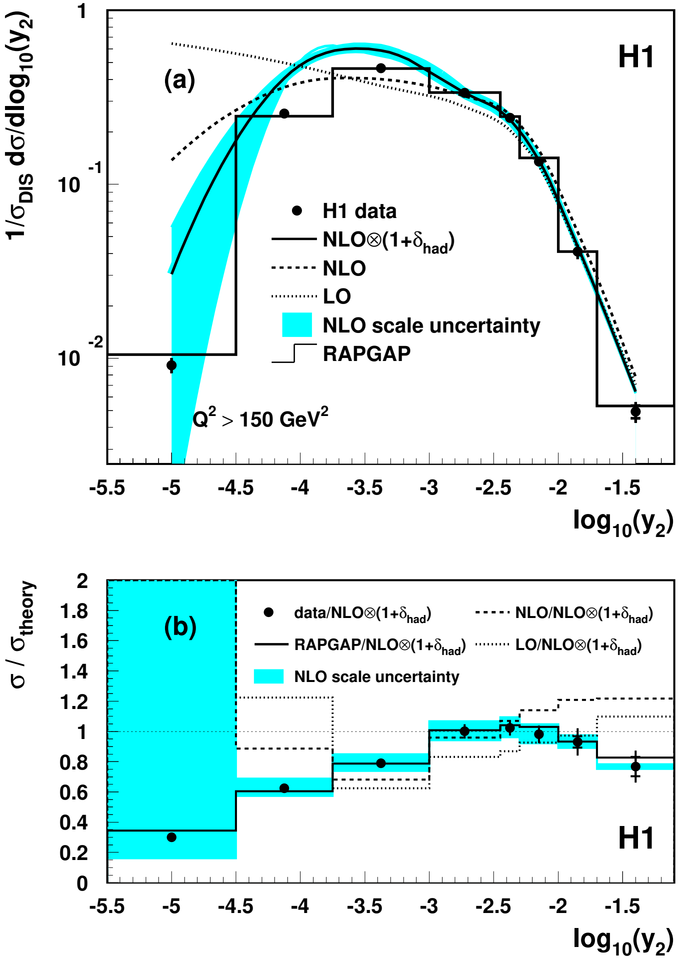
$$150 < Q^2 < 35000\ \text{GeV}^2$$
$$0.1 < y < 0.7$$

- ■ modified Durham algorithm applied in lab. frame

$$y_2 = \frac{\min k_{Ti,j}^2}{W^2}\ ,\ \left(\begin{smallmatrix}W^2 = \text{ inv. mass}\\ \text{of had. system}\end{smallmatrix}\right)$$

$$k_{Ti,j}^2 = 2\min[E_i^2, E_j^2](1-\cos\theta_{ij})$$

- for $y_2 > 0.001$, NLO describes data well: y_2, $\overline{E}_T^{jet}$ and η^{jet} distributions
- RAPGAP performs very well over all y_2 range
- $1/3$ events classified as dijets for $y_2 > 0.001$ (compared to $\approx 1/10$ in standard analyses)

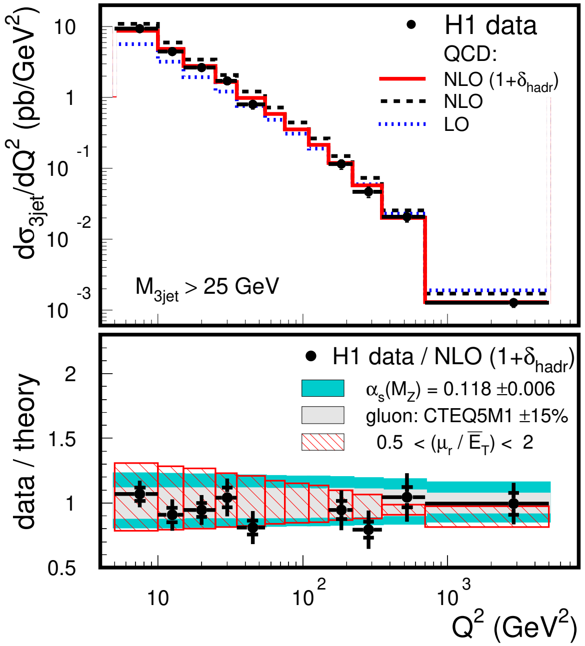


← smaller jet separation

Three-Jet Production in DIS

Motivations:

- ▷ LO contribution is $\mathcal{O}(\alpha_s^2) \rightarrow$ high sensitivity
- ▷ detailed test of pQCD



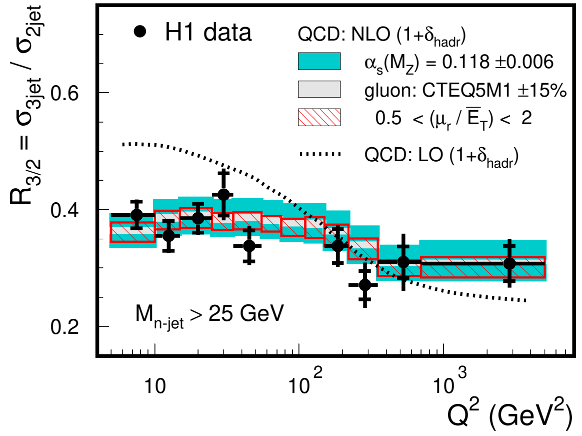
- ■ 1995-97 Data, Kinematic range

$$5 < Q^2 < 5000 \text{ GeV}^2$$

- ■ k_T-cluster algorithm applied in Breit frame

$$E_{T,Breit}^{jet} > 5 \text{ GeV}$$

$$-1 < \eta_{lab}^{jet} < 2.5$$



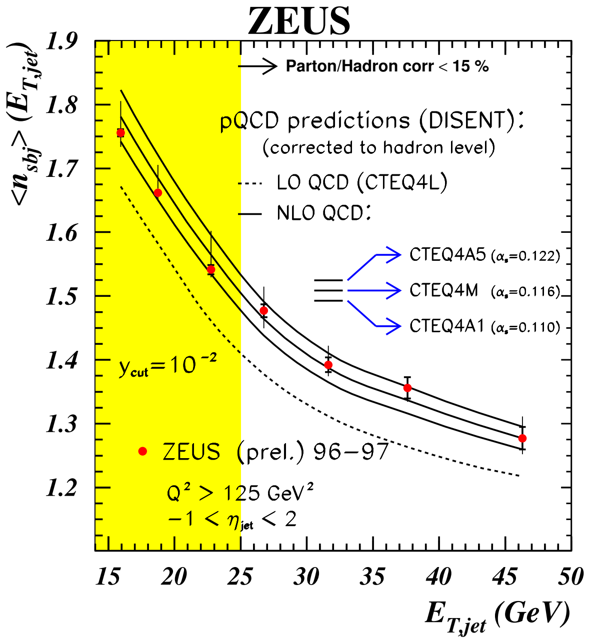
- NLO describes the data reasonably well over all Q^2 range, and the μ_R and gluon PDF dependences largely cancel in the ratio
  $\Rightarrow$ potential extraction of α_s
  BUT need for more stats ...

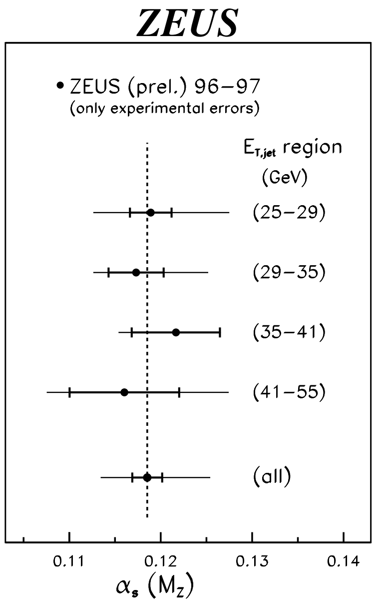
α_s FROM SUBJET MULTIPLICITIES

jet substructure with subjets infrared-safe to all orders ⟺ theoretically interesting

- k_T-cluster algorithm in the Lab. frame
  - $Q^2 > 125$ GeV^2
  - $E_{T,jet} > 15$ GeV , $-1 < \eta_{jet} < 2$

- NLO QCD describes well the data
- the measurement is rather sensitive to α_s ⇒ suited for α_s extraction



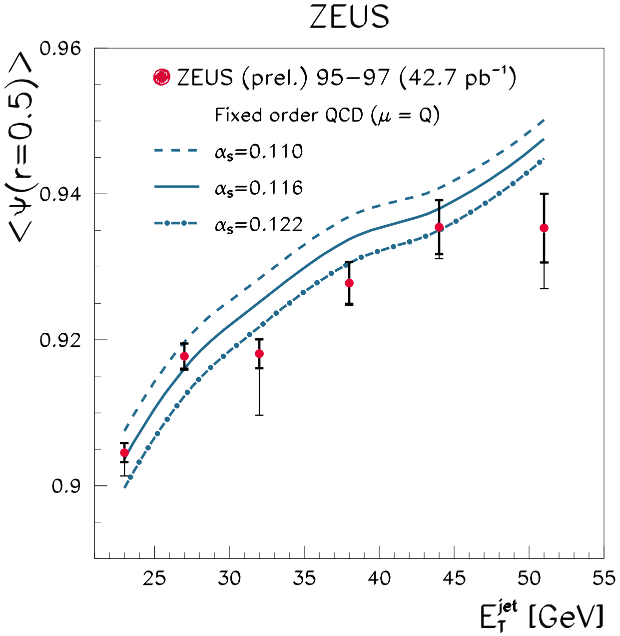


$$\alpha_s(M_Z) = 0.1185 \pm 0.0016(stat)^{+0.0067}_{-0.0048}(syst)^{+0.0089}_{-0.0071}(th) \; (E_{T,jet} > 25 \text{ GeV})$$

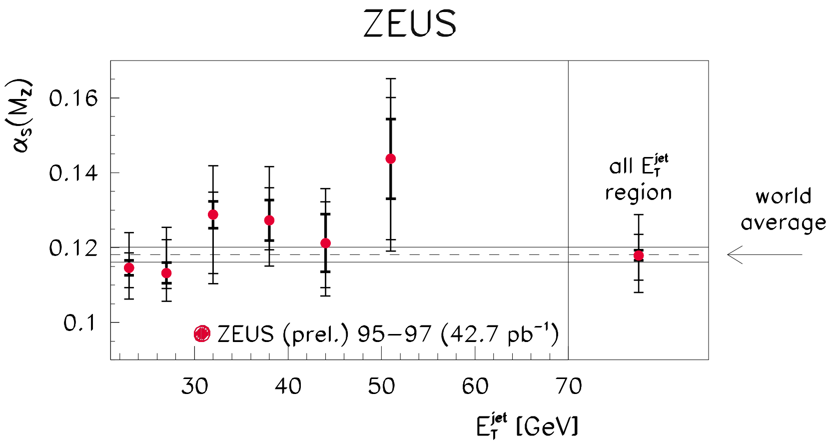
α_s FROM THE INTEGRATED JET SHAPE

jet substructure at high $E_T^{\rm jet}$ (frag. effects are less important) $\Longleftrightarrow$ detailed test of pQCD

- k_T-cluster algorithm in the Lab. frame
  - $Q^2 > 125$ GeV^2
  - $E_T^{\rm jet} > 21$ GeV , $-1 < \eta_{jet} < 2$



- $\Psi(r)$ = integrated jet shape:
  average fraction of the $E_T^{\rm jet}$ that lies inside a cone of radius
  $r = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ concentric with the jet's axis
  (in the $\eta - \phi$ plane)
- NLO describes the distributions $\Psi(r)$ very well (not shown)
- the measurement is rather sensitive to α_s
  $\Rightarrow$ suited for α_s extraction



$$\alpha_s(M_Z) = 0.1179 \pm 0.0014(stat)^{+0.0054}_{-0.0065}(exp.)^{+0.0094}_{-0.0073}(th)$$

Event Shapes: Power Corrections and Resummations

Event shape variables:

thrust $\tau_\gamma = 1 - T_\gamma = 1 - \frac{\sum_i |\vec{p}_i.\vec{n}|}{\sum_i |\vec{p}_i|} = 1 - \frac{\sum_i p_{i,z}}{\sum_i |\vec{p}_i|}$

jet broadening $B_\gamma = \frac{\sum_i |\vec{p}_i \times \vec{n}|}{2\sum_i |\vec{p}_i|} = \frac{\sum_i p_{i,\perp}}{2\sum_i |\vec{p}_i|}$

normalised invariant jet mass $\rho = \frac{\left(\sum_i p^\mu\right)^2}{\left(2\sum_i E\right)^2}$

C-parameter $C = \frac{3\sum_{ij} |\vec{p}_i|\,|\vec{p}_j| \sin^2\theta_{ij}}{2\sum_{ij} |\vec{p}_i|\,|\vec{p}_j|}.$

- H1 uses massive hadrons
- ZEUS assumes massless hadrons (P-scheme: $|\vec{p}_h|$ preserved, E_h rescaled)

Theory:

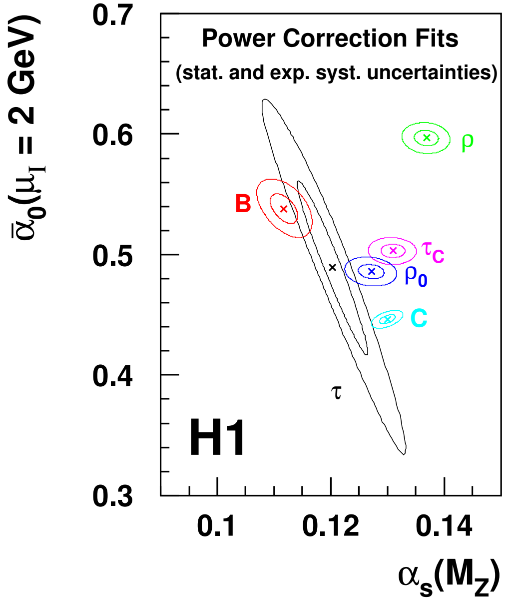
- Event shapes F computed with

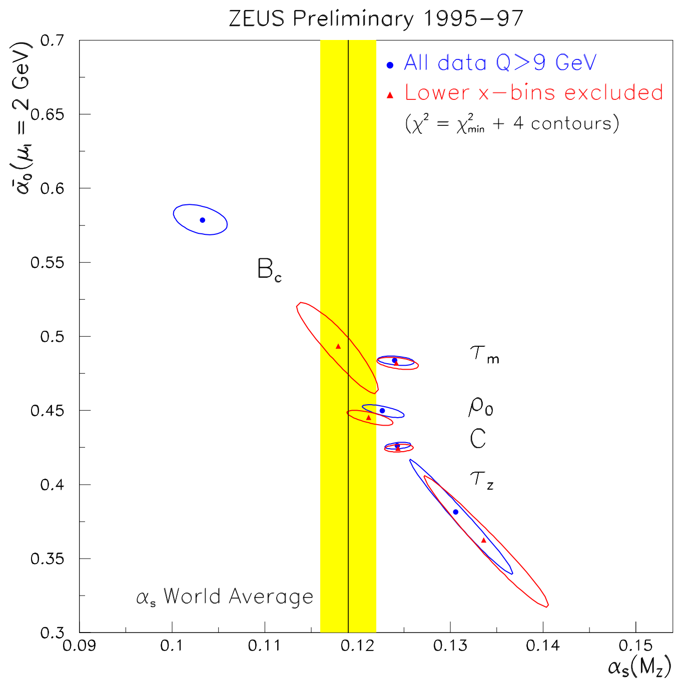
  $$< F > (Q) = \underbrace{< F >^{pQCD}}_{\mathcal{O}(\alpha_s^2)} + \underbrace{< F >^{Pow.Corr.}}_{f(\alpha_s, \overline{\alpha}_0)}$$

  ↗ NLO program ↗ non-perturbative effects

- Power corrections depend on α_s and non-pert. parameter $\overline{\alpha}_0$
  $\Rightarrow$ 2-dim. fits to data
- H1 also fitted the event shape distributions

EVENT SHAPES:
POWER CORRECTIONS AND RESUMMATIONS (II)





- $\rho \Leftrightarrow m_h \neq 0 \quad , \quad \rho_0 \Leftrightarrow m_h = 0$
  → mass effects important for jet mass ($f(p_h^\mu)$)

- ZEUS fits show a strong x-dependence for B

▷ fits suggest $\overline{\alpha}_0 \approx 0.5 \pm 20\%$

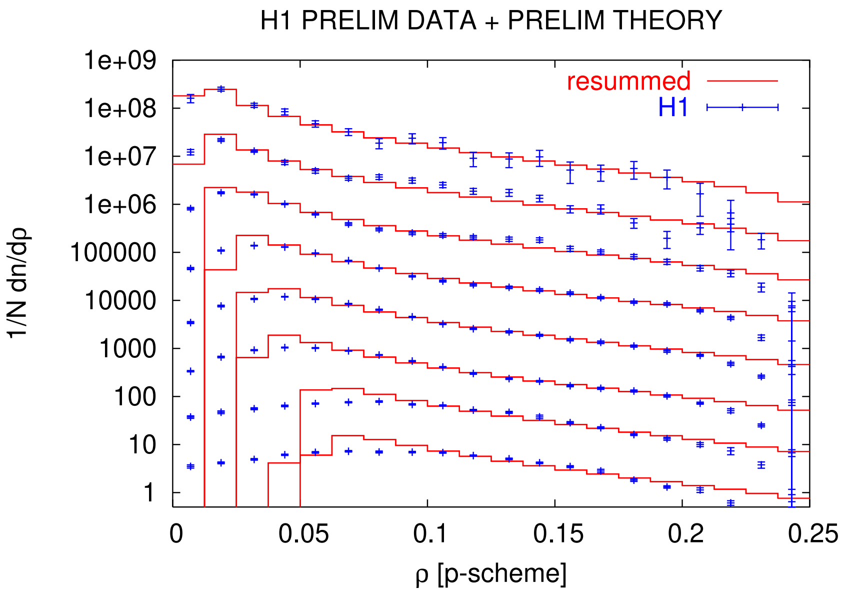
▷ spread in $\alpha_S(M_Z)$ suggests need for higher order corrections

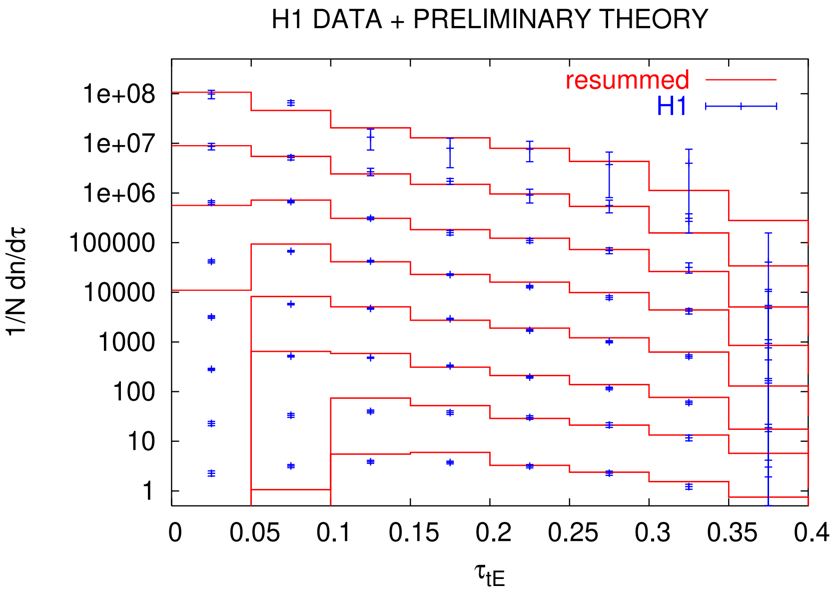
▷ general reasonable and consistent description:
ZEUS and H1 fits agree in general within errors, but some discrepancies still remain (τ_C)

EVENT SHAPES: POWER CORRECTIONS AND RESUMMATIONS (III)

- H1 has performed fits also to event shapes spectra:
  - $\alpha_s - \overline{\alpha}_0$ simultaneous fit → fit yields values inconsistent with those from event shapes means
    $\Rightarrow$ can resummed QCD calculations help?

H1 data on jet mass ρ and thrust τ (wrt thust axis) spectra and QCD resummed results
($\alpha_s = 0.118$ and $\overline{\alpha}_0 \approx 0.5$ were used)


H1 PRELIM DATA + PRELIM THEORY


H1 DATA + PRELIMINARY THEORY

$\Rightarrow$ preliminary studies of event shape distributions are encouraging …

CONCLUSIONS

- NLO pQCD in general describes well jet data over large Q^2 and E_T^{jet} ranges
  BUT the theoretical uncertainties are among the largest, and limit high precision QCD tests

  ⇒ future jet studies at HERA will strongly benefit from higher order theoretical calculations

- α_s is extracted in DIS from a variety of jet observables
- the various α_s extracted values are consistent with each other and the world average