Low x Workshop, Cracow,
26/6/01-30/6/01

Jets and Energy Flow at HERA Status and Outlook.

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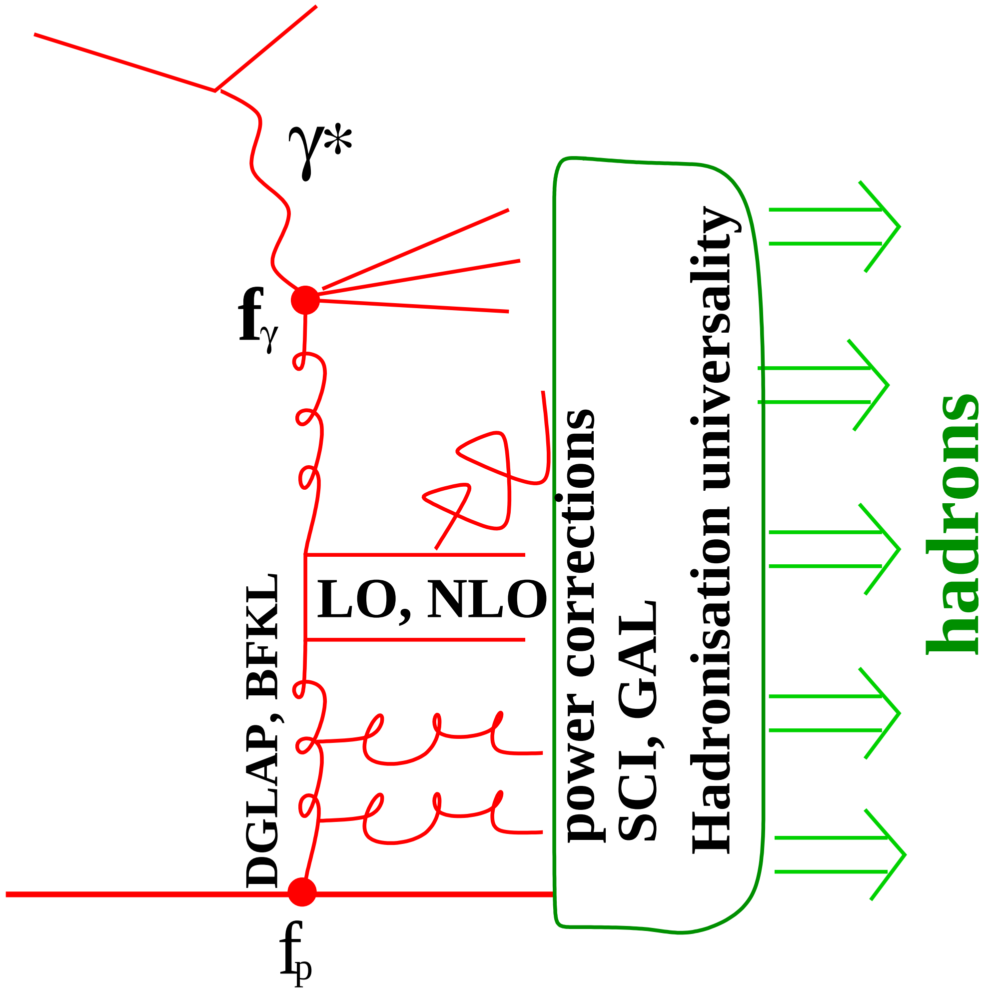
The University of Liverpool

The Hadronic Final State at HERA

What do we measure ?

What does that reveal about QCD and γ,p structure ?

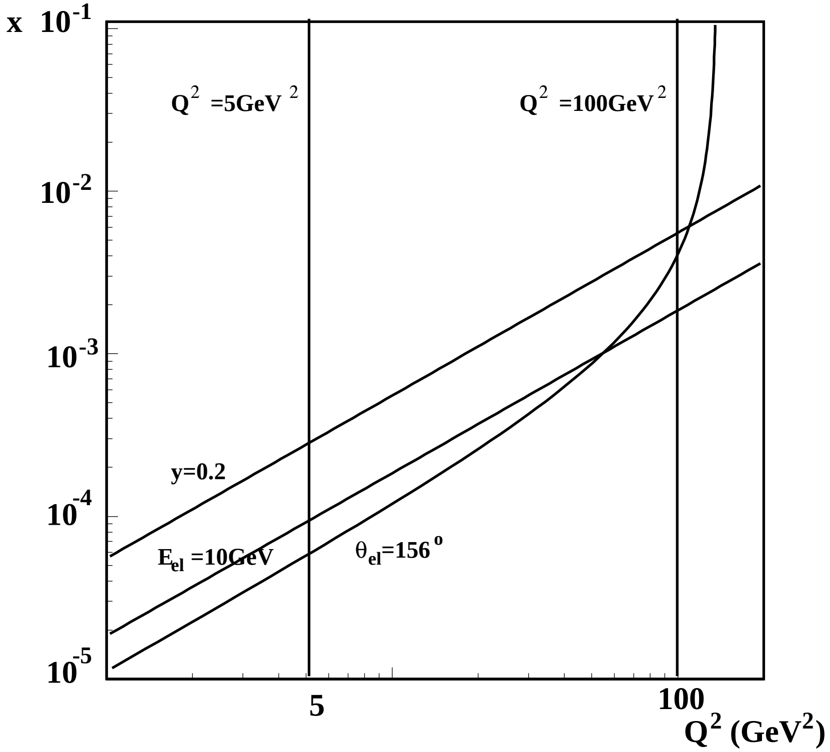


- **Inclusive jet production in DIS and γp.**
  - f_p, f_γ, NLO, QCD evolution, α_s ...
- **Energy flow and Event Shapes**
  - LO programs + fragmentation models
  - power corrections, NLO

How can we improve on this for HERA II ?
... and where are the bottlenecks ?

Single Inclusive DIS Jet Cross-sections

Test pQCD with the highest statistical precision.



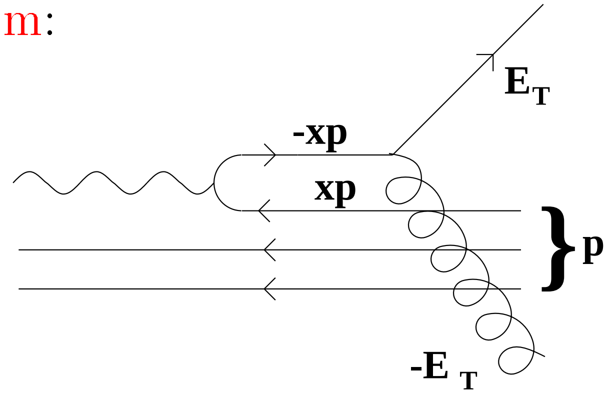
$5 < Q^2 < 100$ GeV^2

$E_T < 70$ GeV, $0.25 < E_T^2/Q^2 < 100$

140000 jets from 1996/97 data

=> high statistics for differential analysis

Jet finding with the inclusive k_T cluster algo in the Breit reference system:



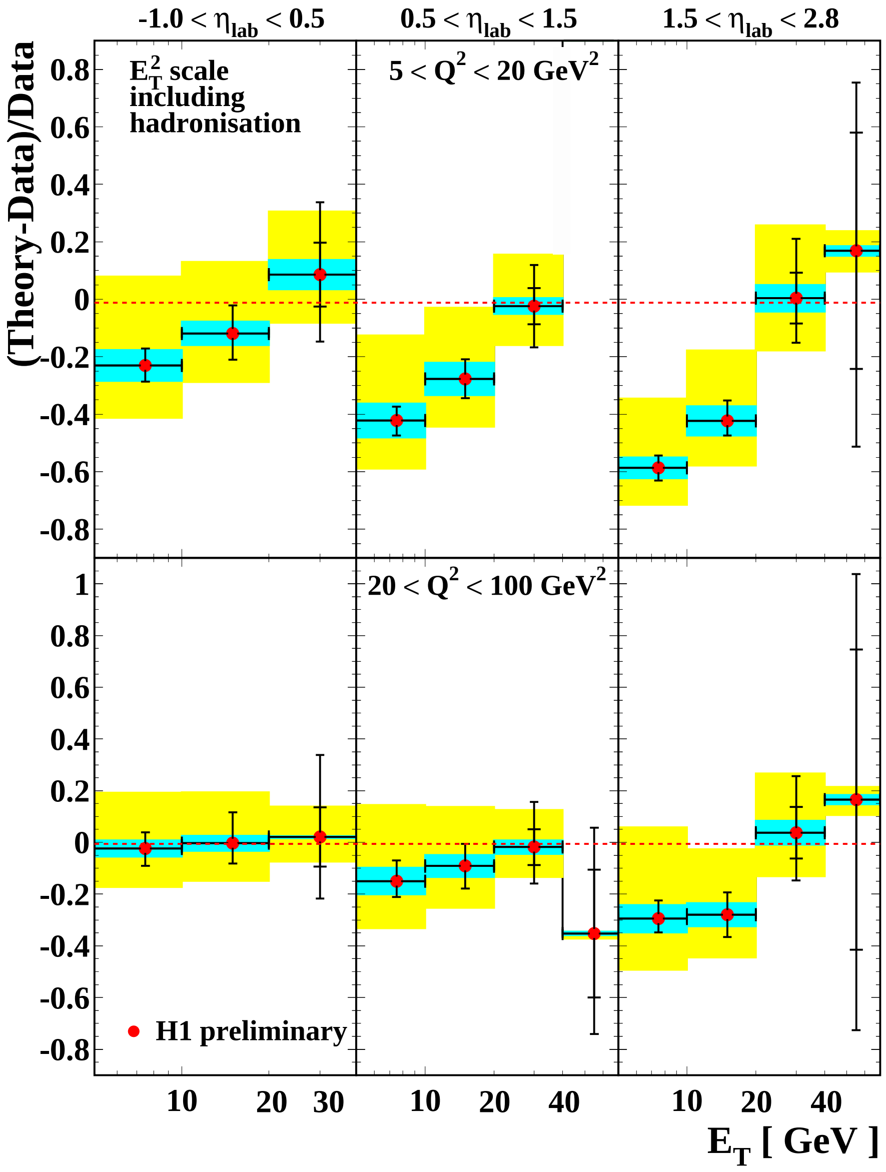
Cuts on jets:

$E_T > 5$ GeV, -0.5 $< \eta_{lab} <$ 2.8

NLO calculations:

- DISENT: direct processes,
  $\mu_F^2 = Q^2$, $\mu_R^2 = E_T^2$ or Q^2
- JetViP: resolved processes,
  $\mu_F^2 = \mu_R^2 = Q^2 + E_T^2$

$\mathrm{d}\sigma/\mathrm{d}E_T$ Measurements: Description by NLO



- (NLO-Data)/Data including hadronisation
- $\mu_r^2 = E_T^2$
- top: $5 < Q^2 < 20$ GeV^2
- bottom: $20 < Q^2 < 100$ GeV^2

Description fails for low $E_T < 20$ GeV at low Q^2 in the forward direction, also k factors large

=> Scales? NNLO?

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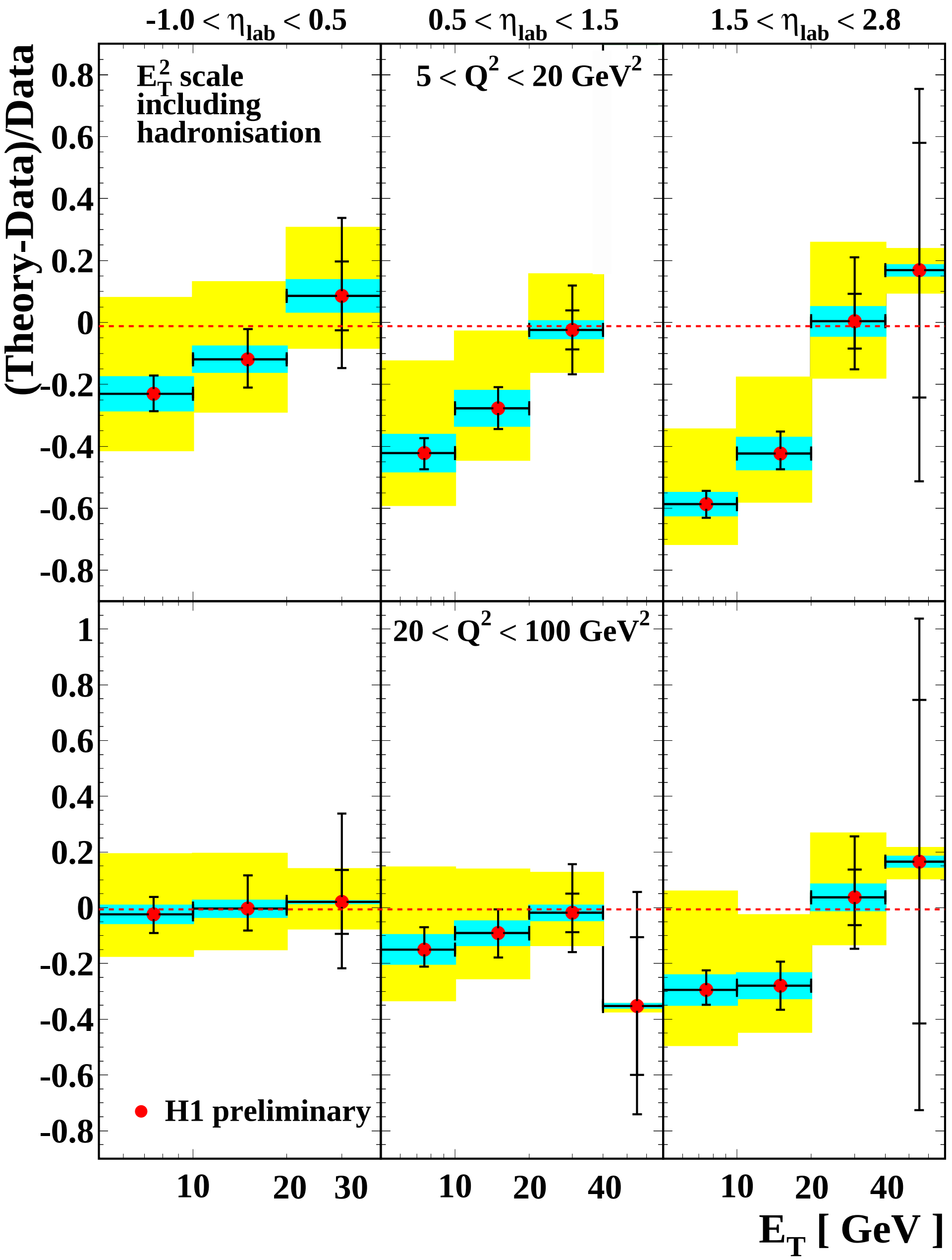

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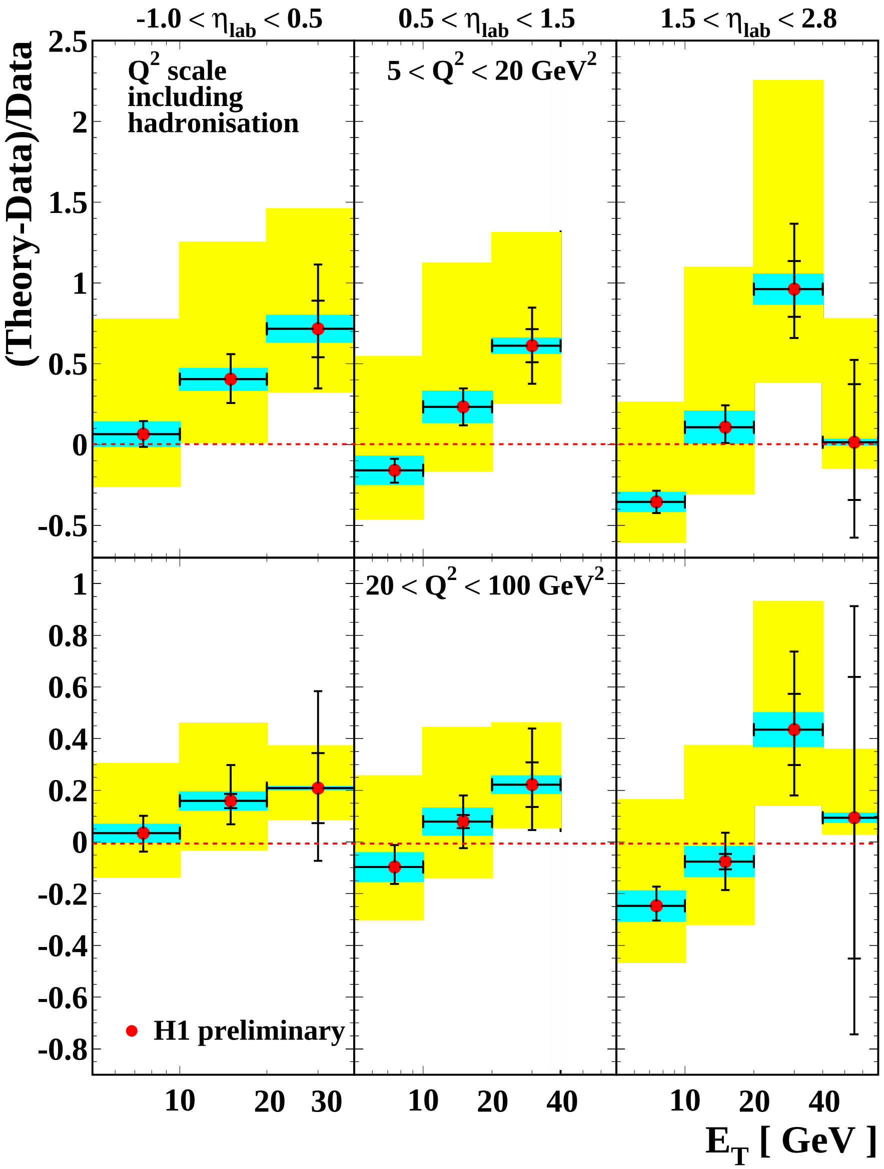
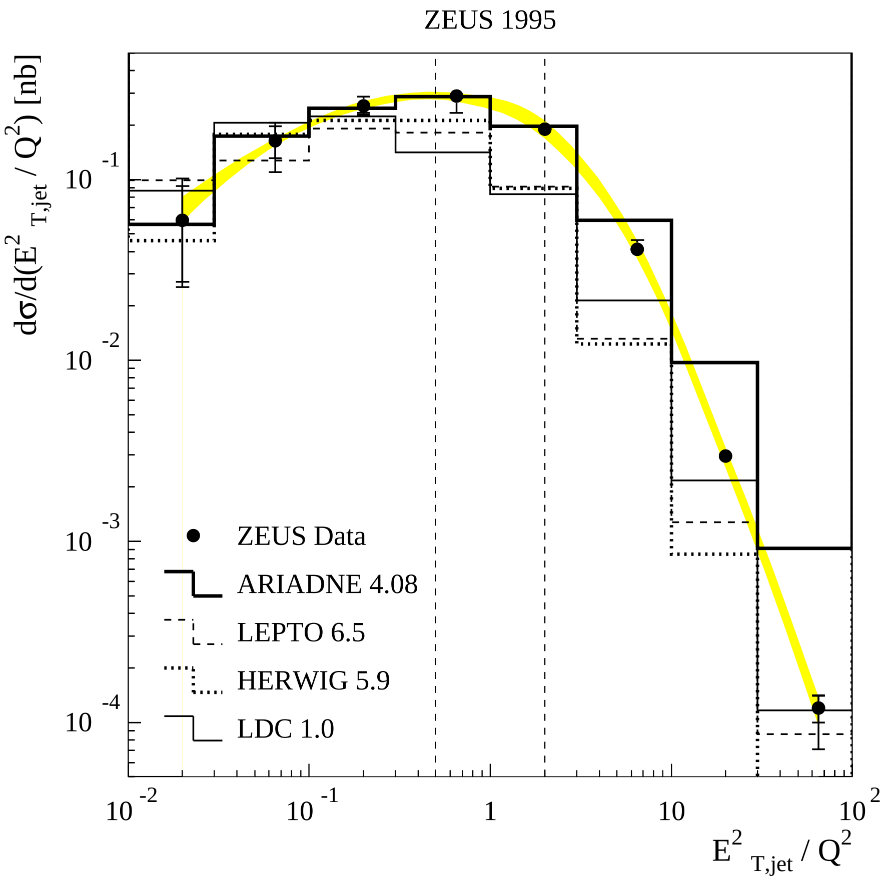
$\mathrm{d}\sigma/\mathrm{d}E_T$ Measurements: Description by NLO



- (NLO-Data)/Data including hadronisation
- $\mu_r^2 = Q^2$
- top: $5 < Q^2 < 20$ GeV^2
- bottom: $20 < Q^2 < 100$ GeV^2
- Scale uncertainties larger than for $\mu_R^2 = E_T^2$

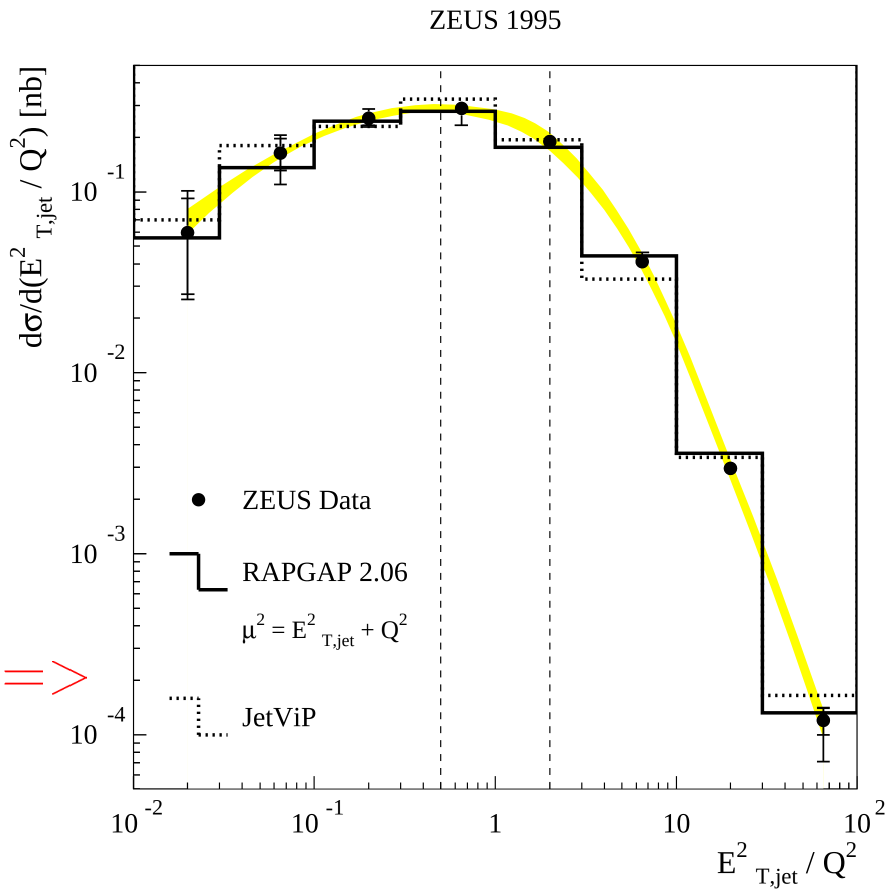
Description fails for high E_T
=> Q^2 bad scale if $E_T^2 \geq Q^2$?

Interplay of DIS Scales: $d\sigma/d(E_T^2/Q^2)$ at ZEUS



$(10 < Q^2 < 10000\ \mathrm{GeV}^2,\ x_{jet} > 0.036)$

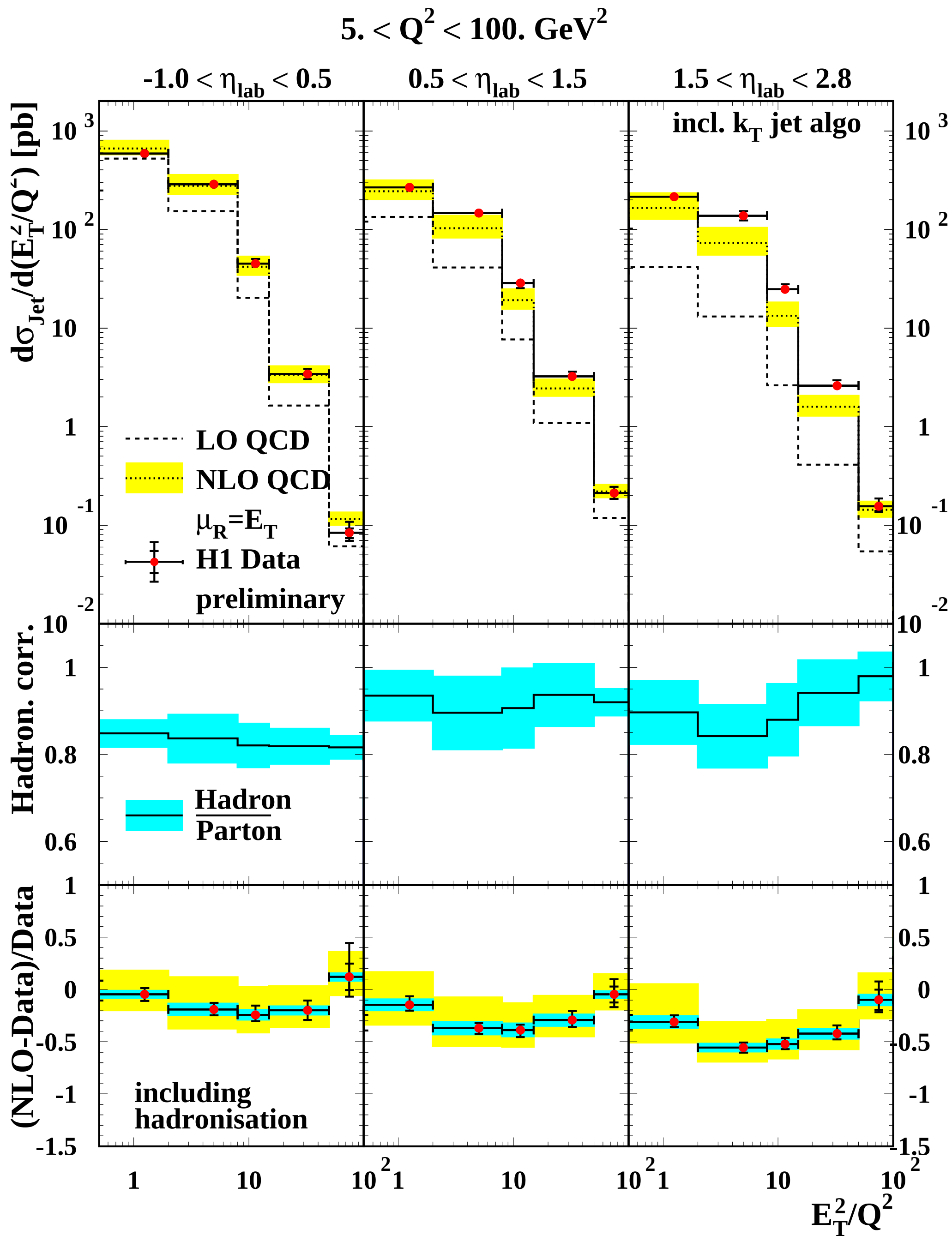
$<=$ **LO Monte Carlos for direct γ processes fail to describe data for medium values of E_T^2/Q^2 (2-50).**



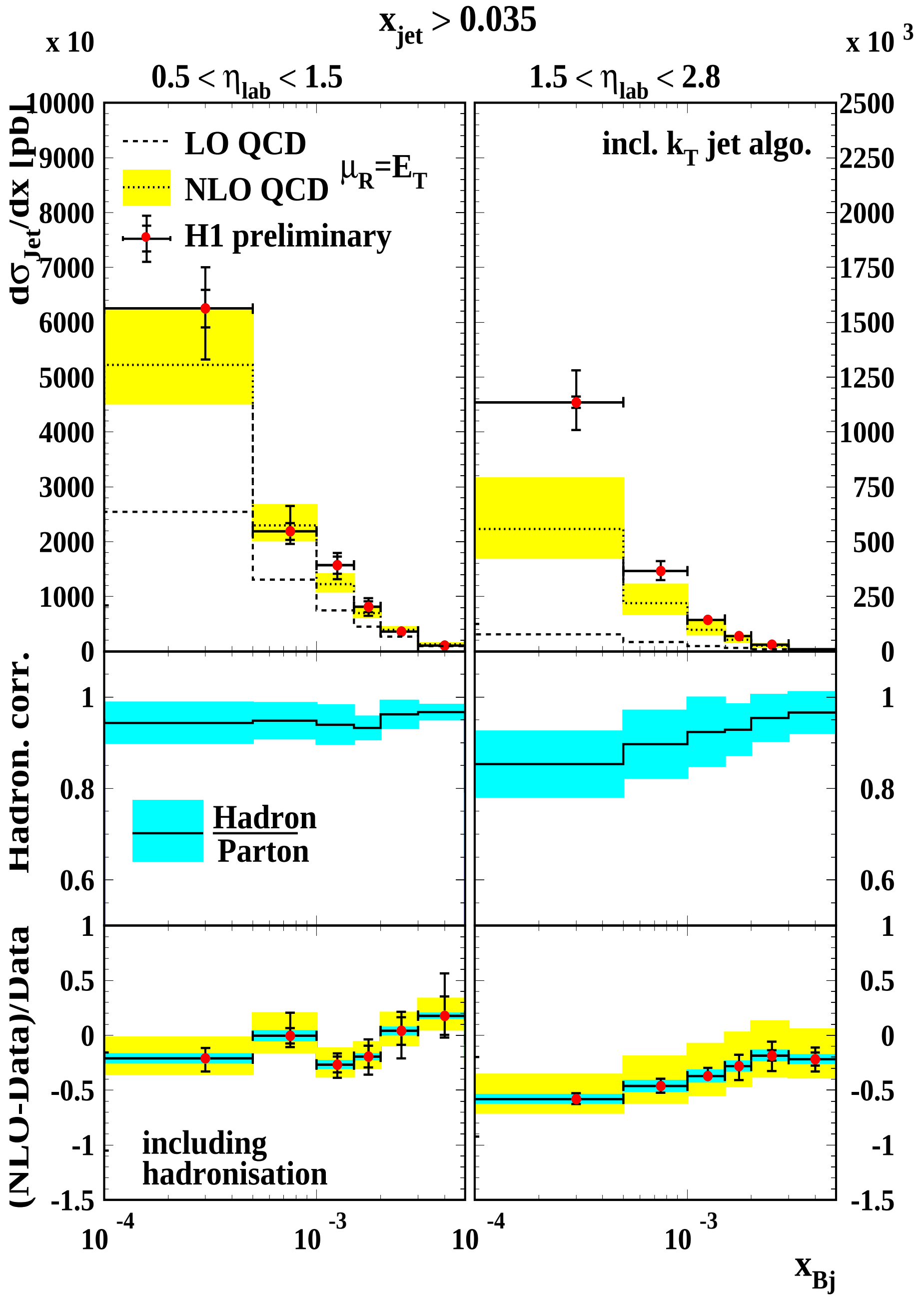
Calculations including resolved photons seem to work also for $2 < E_T^2/Q^2 < 50$. $=>$

$d\sigma/d(E_T^2/Q^2)$ in η_{lab} bins

- $\mu_R^2 = E_T^2$
- cross section $d\sigma/d(E_T^2/Q^2)$
  - yellow band: direct NLO
  - statistical error: 5 %
  - systematic errors: 5-15 %
- hadronisation
  - correction $\sim$ 15 %$\pm$ 10 %
- (NLO-Data)/Data
  - theoretical error larger than exp. uncertainty
- LO/NLO calculations below data for $2 < E_T^2/Q^2 < 50$.

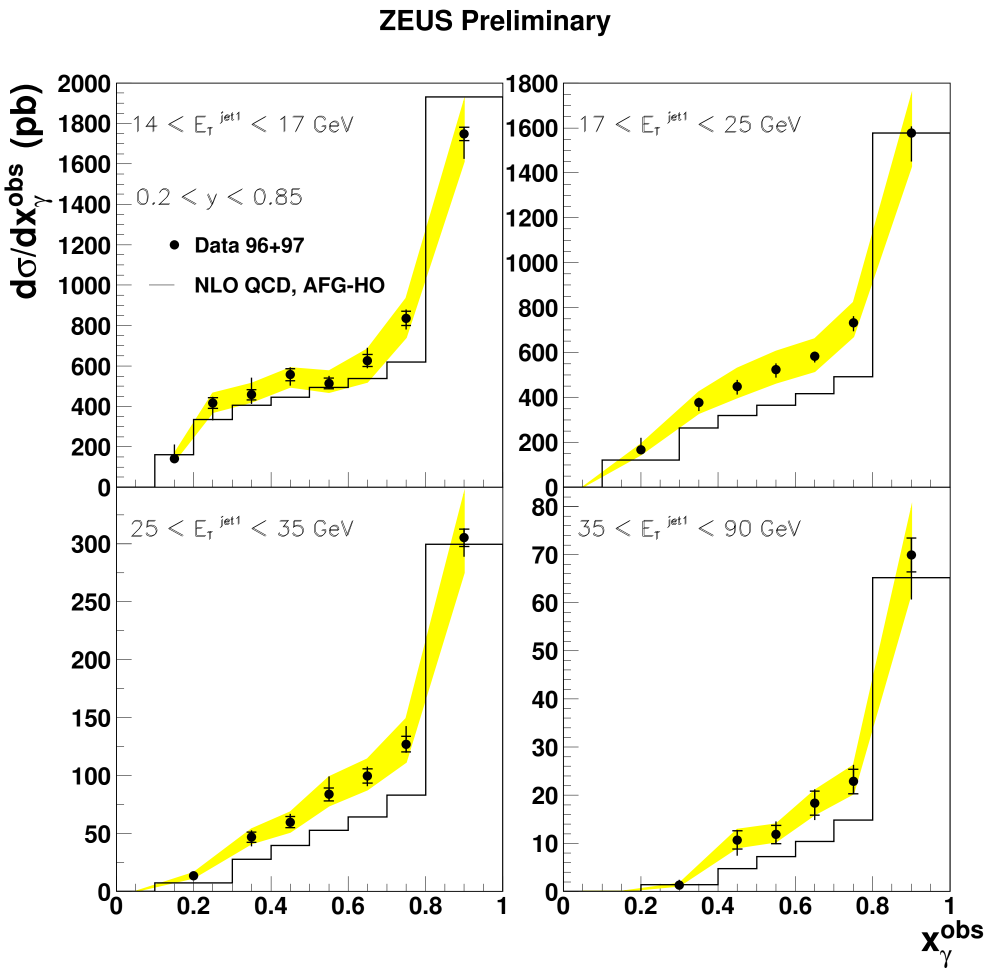


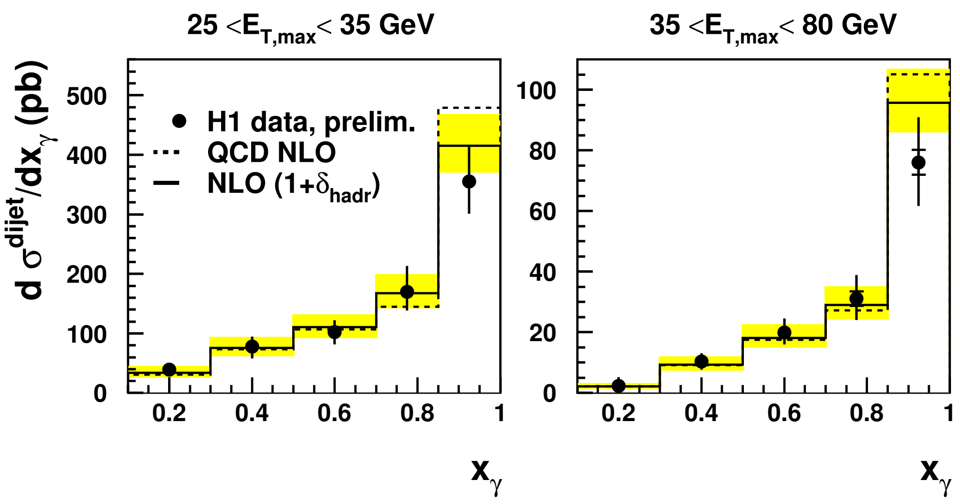
Forward Jets: $d\sigma/dx_{Bj}$



Dijet Rates in Photoproduction

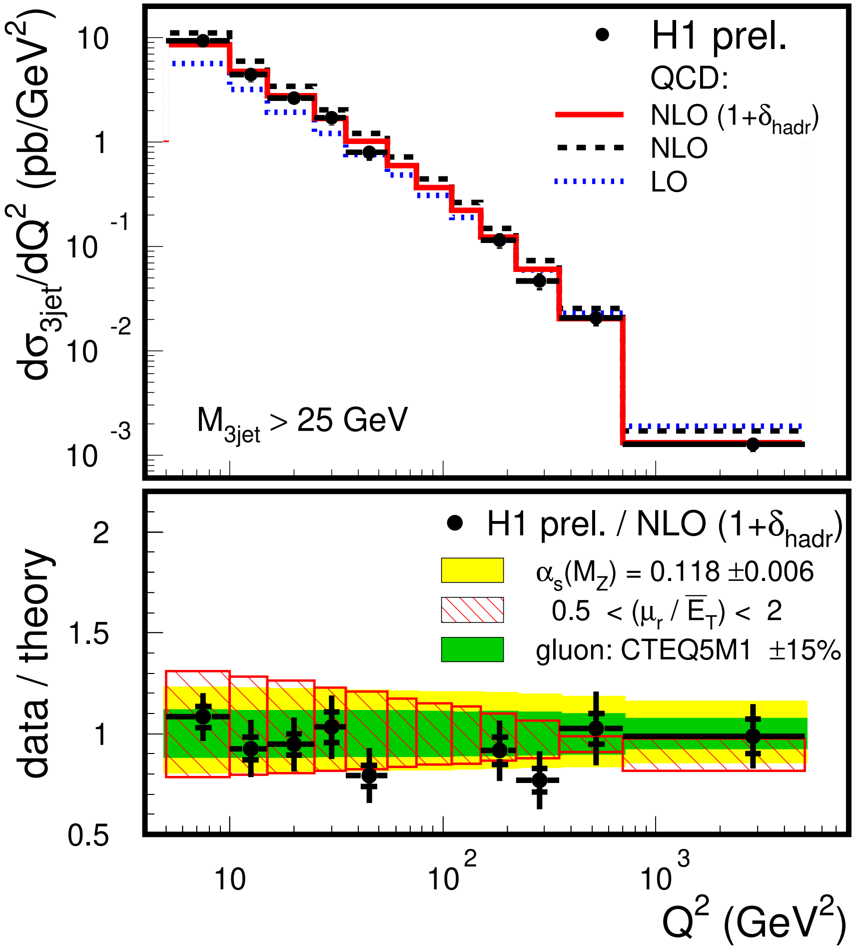
Sensitivity to photon structure.





Differences in conclusions between H1 and ZEUS (interpretation of theory).

3-Jet Cross-Section in DIS



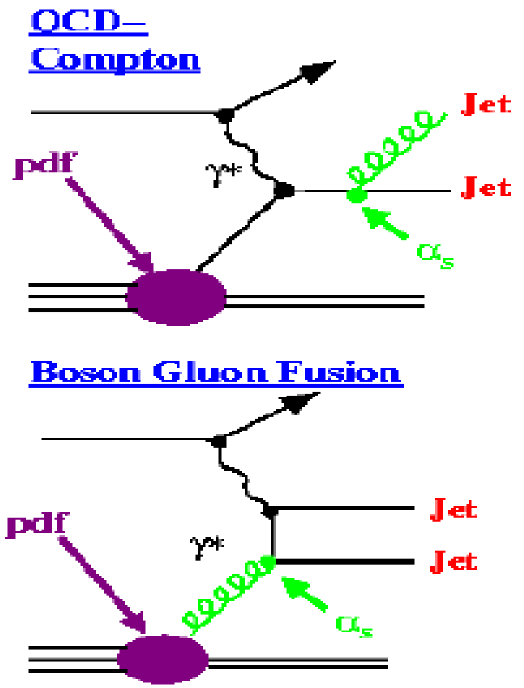
recent theoretical progress:
brandnew NLO calculation (Z. Nagy)

good agreement theory / data

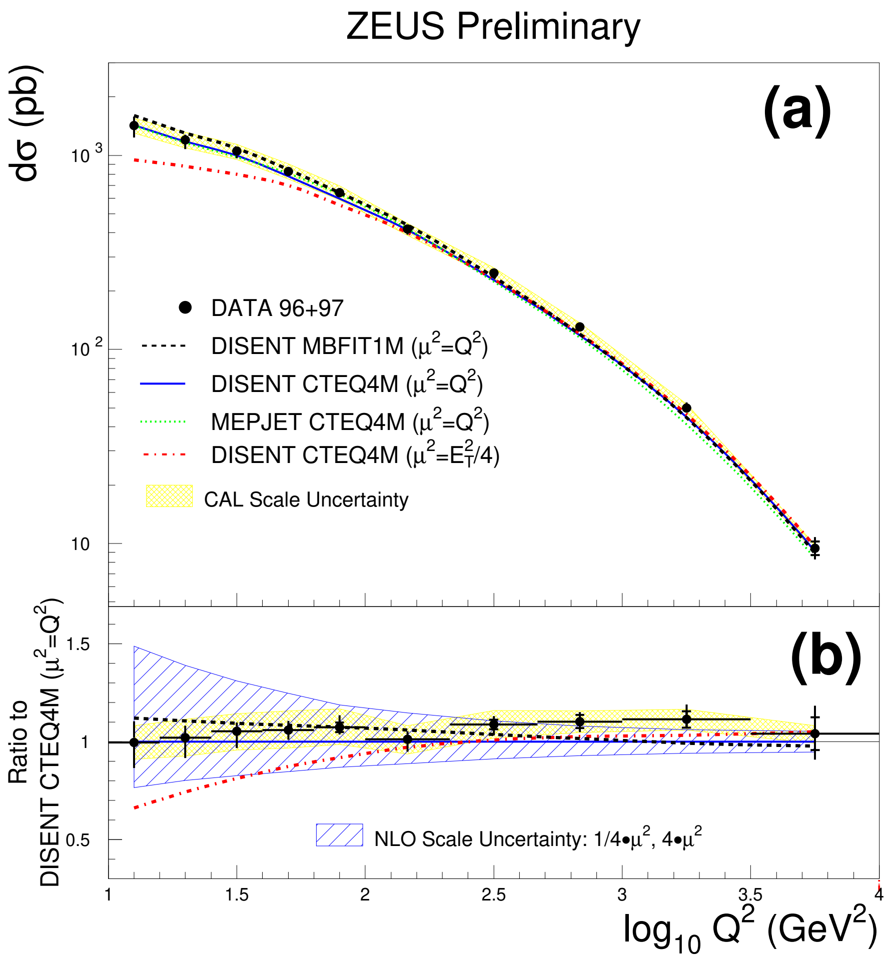
σ_{3jet}: high sensitivity to $\alpha_s(M_Z)$

currently limited by statistics
($\rightarrow$ go to higher E_T, M_{3jet})
($\rightarrow$ double differential distributions)

Dijet Cross-Sections in DIS

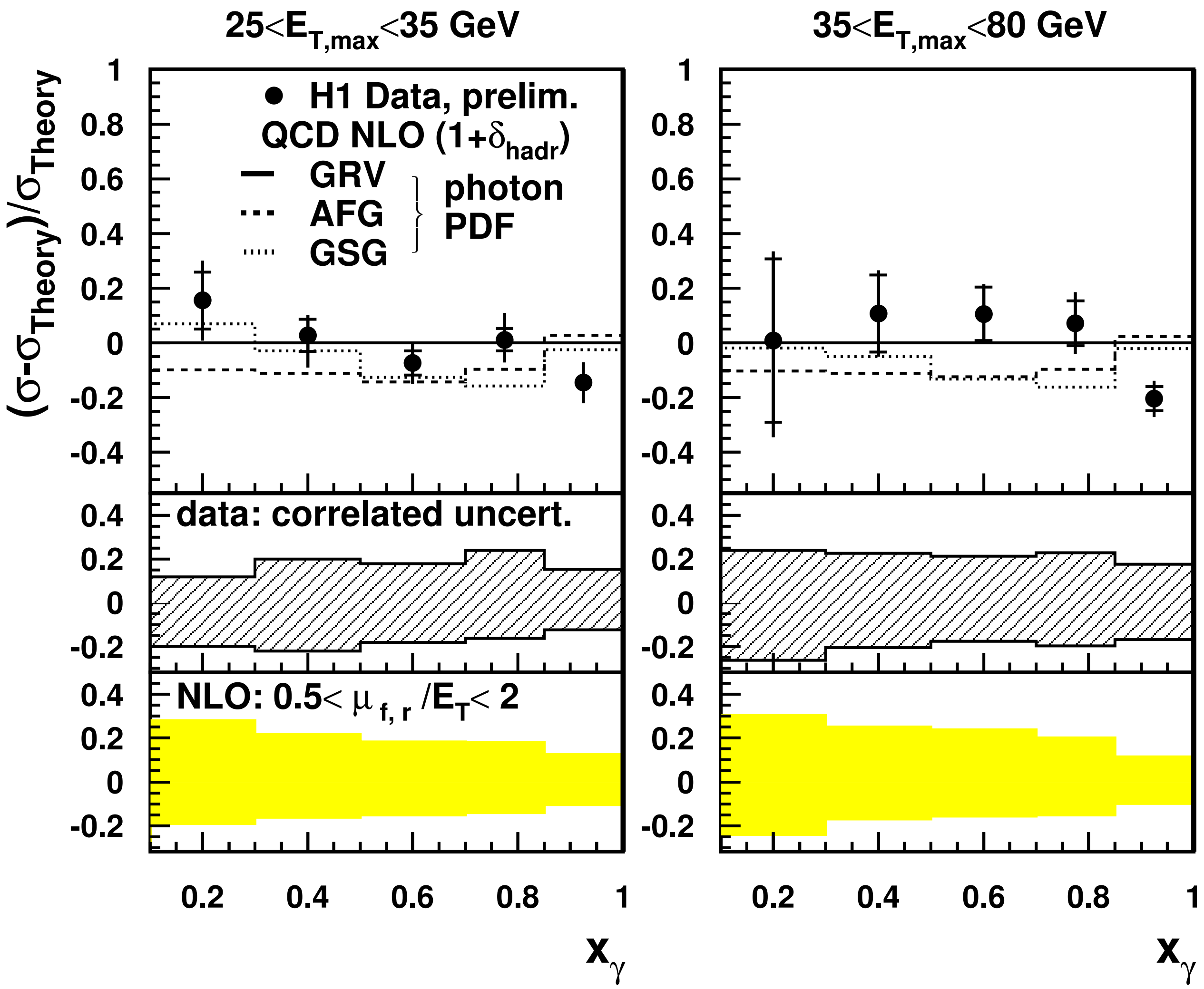


$$\boxed{\sigma_{jet} = \sum_n \alpha_s^n \sum_{i=G,q} C_{i,n} \otimes \mathrm{pdf}_i}$$



Description of data by NLO for $Q^2 > 150\ \mathrm{GeV}^2$ with small scale uncertainties.

Detailed Comparison of γp Dijets with Theory



NLO describes well data and measurements offer sensitivity to γ pdf's but..

we need to work on our scale errors and theorists need to work on theirs.

Strategy for QCD Analysis

Studies of high E_T jet production show

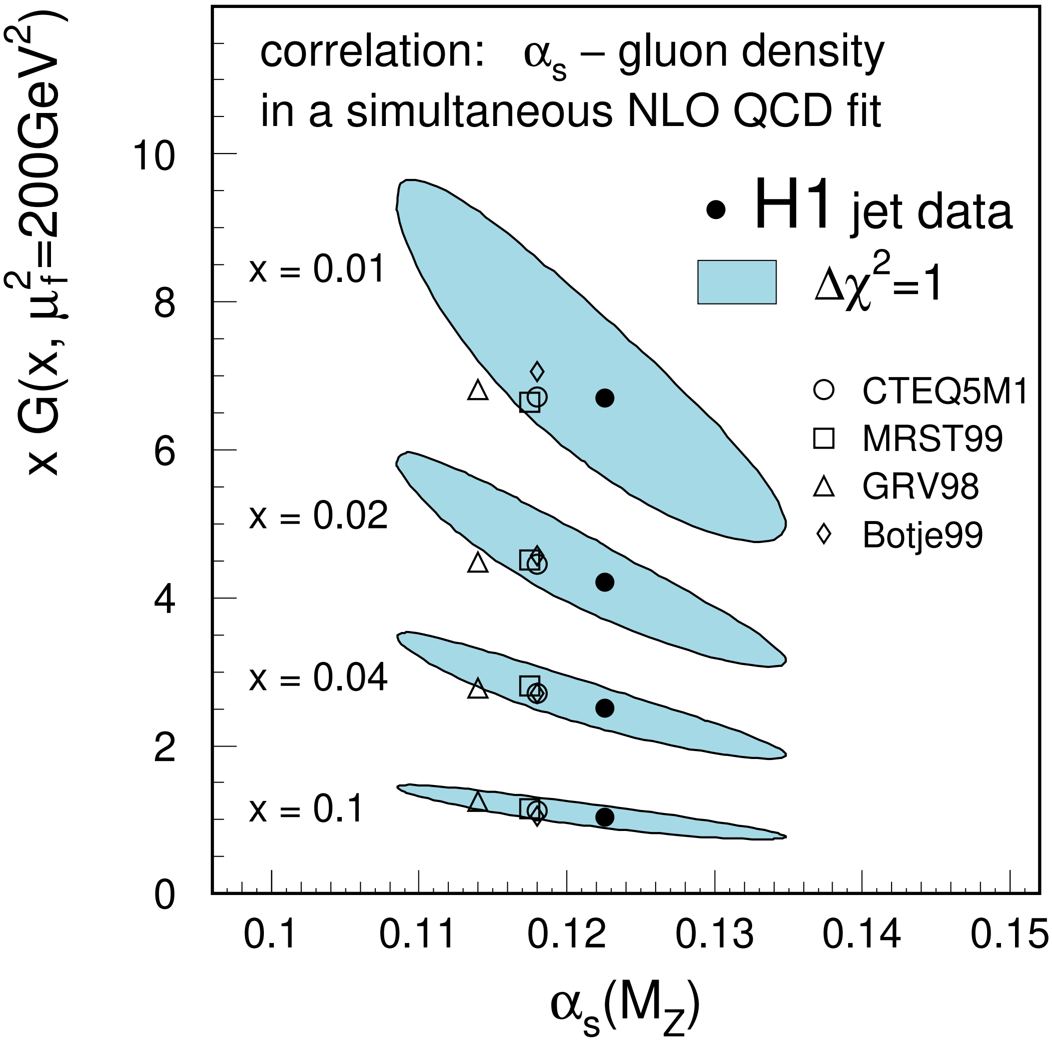
- NLO pQCD calculations not predictive for $Q^2 < 100$ GeV^2
- For $Q^2 > 200$ GeV^2
  - small NLO corrections
  - small renormalisation scale dependence
  - small non-perturbative corrections

$\Rightarrow$ Perform quantitative studies at high Q^2

- Fit simulataneously $\alpha_s(M_z)$, the gluon and quark densities.
- Take external knowledge of proton pdf's and fit α_s
- Take world average $\alpha_s(M_z)$ and extract the gluon and quark densities in the proton.

Simultaneous fits: $\alpha_s(M_z)$ and $xg(x)$

inclusive DIS cross section	$d^2\sigma_{\mathrm{DIS}}/dQ^2\,dx_{\mathrm{Bj}}$
dijet cross section	$d^2\sigma_{\mathrm{dijet}}/d\xi\,dQ^2$
inclusive jet cross section	$d^2\sigma_{\mathrm{jet}}/dE_T\,dQ^2$

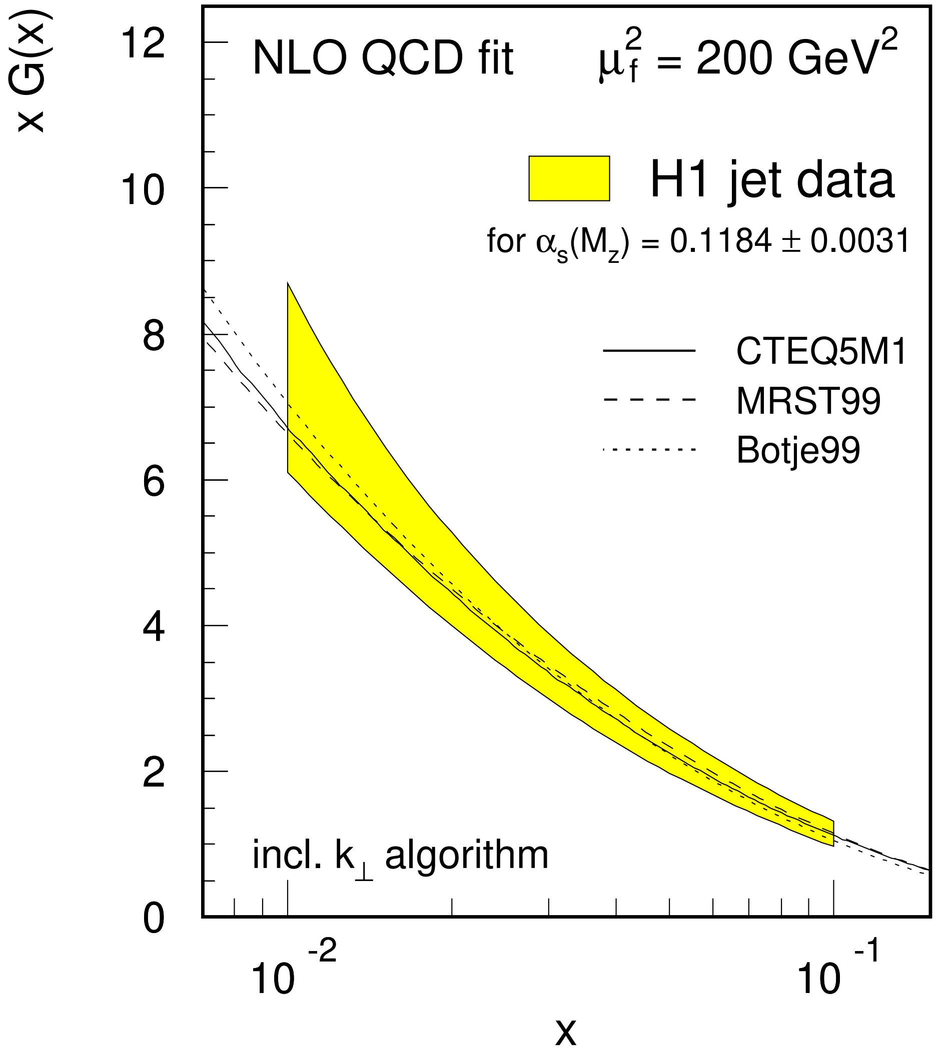


Large anticorrelation between α_s and gluon visible.

Currently small sensitivity to both single parameters but reasonably sensitive to the product.

Derivation of the Gluon Density in the Proton

inclusive DIS cross section	$d^2\sigma_{\mathsf{DIS}}/dQ^2\,dx_{\mathsf{Bj}}$
dijet cross section	$d^2\sigma_{\mathsf{dijet}}/d\xi\,dQ^2$
inclusive jet cross section	$d^2\sigma_{\mathsf{jet}}/dE_T\,dQ^2$

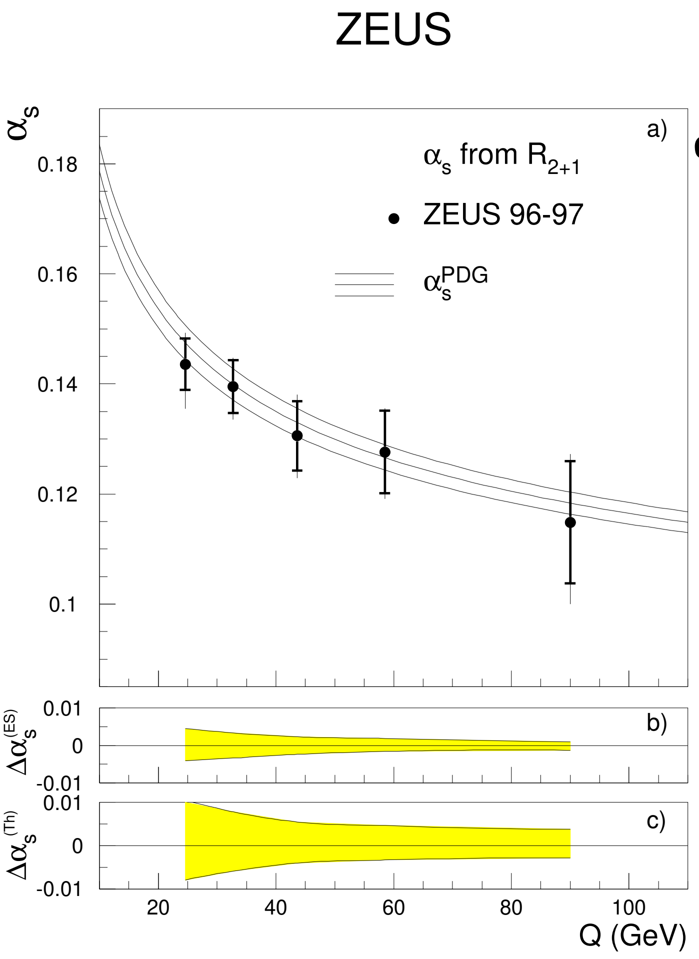


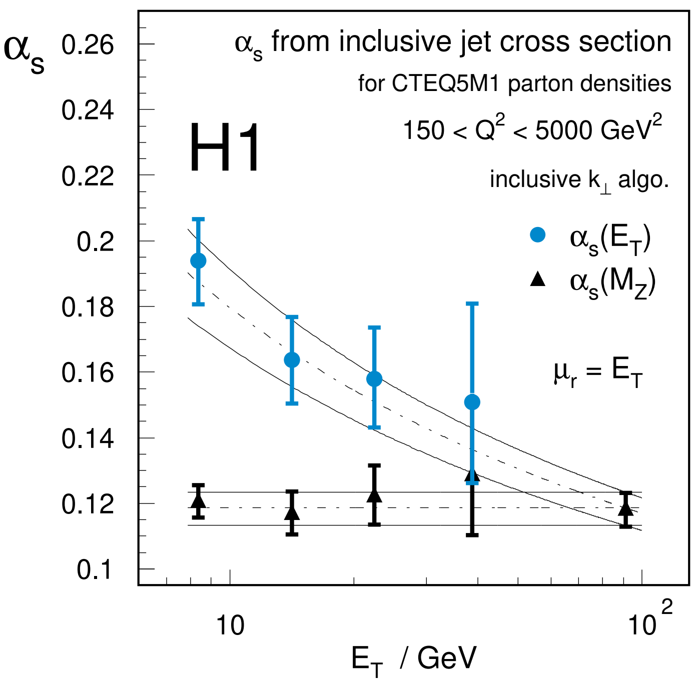
Direct determination from jets at $0.01 < x < 0.1$ consistent with results from global fits.

$\Rightarrow$ Universality of gluon density.

Determination of α_s

US: $\mu_r = Q$ – use Q^2 dependence of dijet rate
: $\mu_r = E_T$
se E_T dependence of inclusive jet cross section

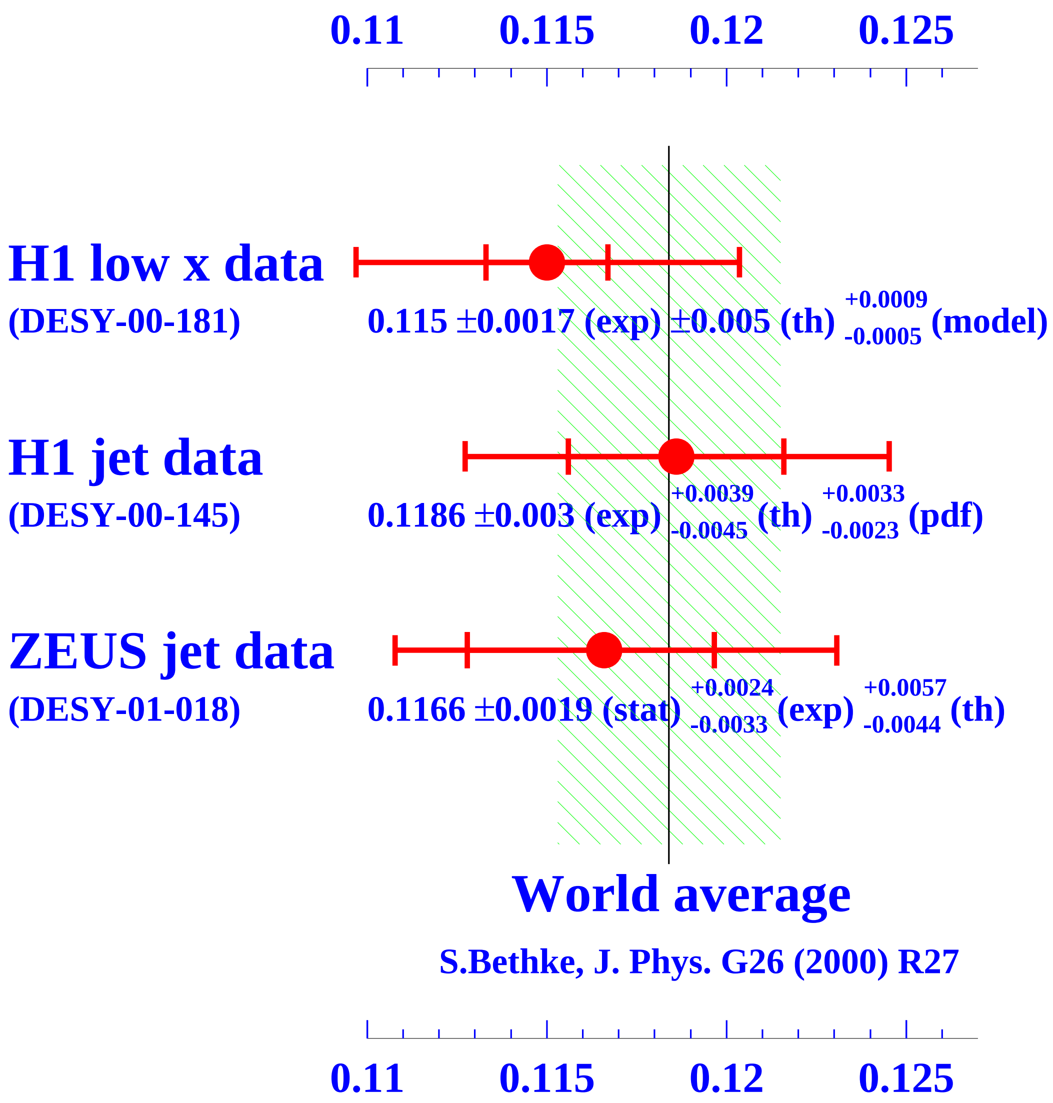




Energy dependence of $\alpha_s(M_z)$ consistent with prediction of renormalisation group equation.

α_s from Jet and Inclusive Measurements

Recent α_s measurements at HERA

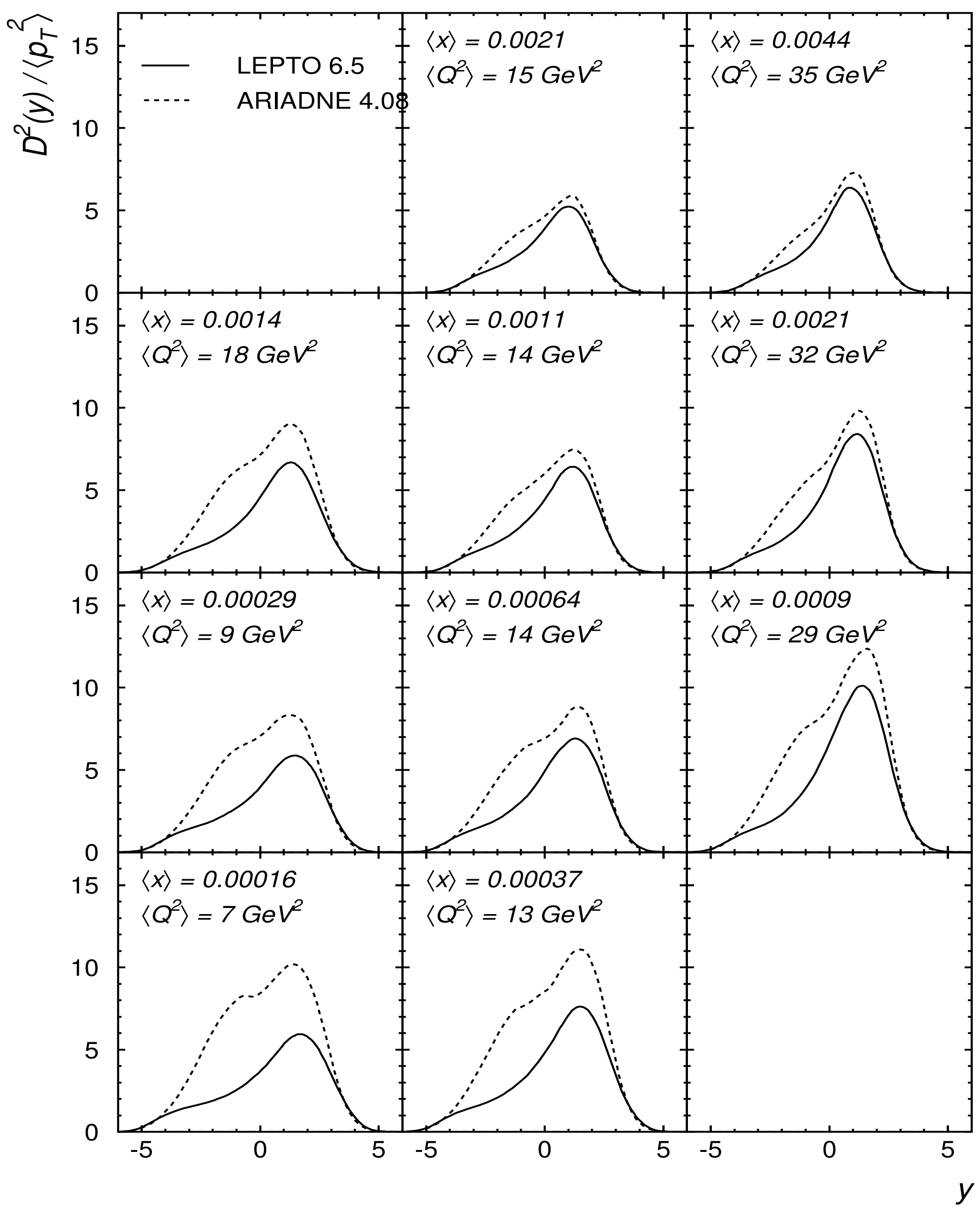


→ Consistent picture of α_s measurements from HERA.

Momentum dispersion in bins of x and Q^2

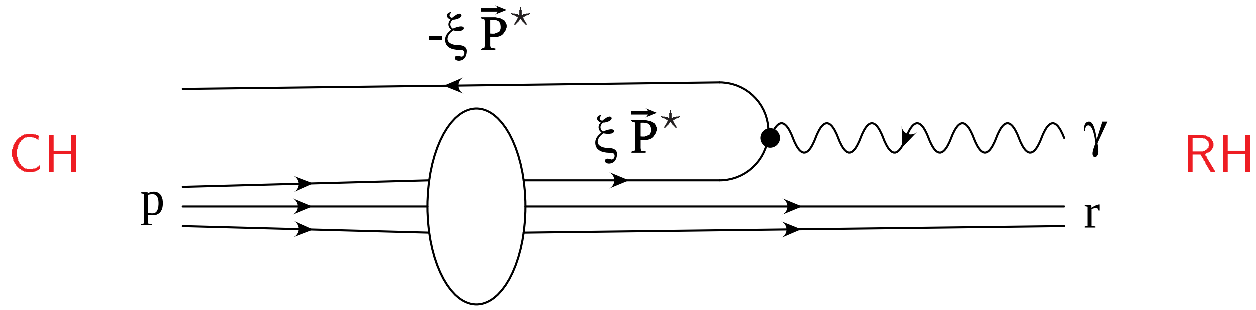
Next step after forward jets and π's; use the full event information.

Non-ordered k_T emissions produce larger momentum dispersions.



Low x sensitivity to parton ordering.

From Hard to Soft, Measurements of Event Shapes



QPM-type ep collision in the Breit frame.*

- Event shapes employing the boson axis $\vec{q}^{\,\star}$ as event axis $\vec{n}$:

1−thrust:

$$\tau := 1 - \frac{\sum\limits_{i\in\mathrm{CH}} |\vec{p_i}^\star \cdot \vec{n}|}{\sum\limits_{i\in\mathrm{CH}} |\vec{p_i}^\star|} = 1 - \frac{\sum\limits_{i\in\mathrm{CH}} |p^\star_{li}|}{P^\star}$$

jet broadening:

$$B := \frac{\sum\limits_{i\in\mathrm{CH}} |\vec{p_i}^\star \times \vec{n}|}{2\sum\limits_{i\in\mathrm{CH}} |\vec{p_i}^\star|} = \frac{\sum\limits_{i\in\mathrm{CH}} |p^\star_{ti}|}{2P^\star}$$

Event Shape Definitions Continued

- Event shapes without reference to the boson axis as event axis:

1−thrust_C:

$$\tau_C := 1 - \max_{\vec{n}, \vec{n}^2=1} \frac{\sum\limits_{i \in \mathrm{CH}} |\vec{p}_i^{\,\star} \cdot \vec{n}|}{\sum\limits_{i \in \mathrm{CH}} |\vec{p}_i^{\,\star}|} = 1 - \frac{\sum\limits_{i \in \mathrm{CH}} |\vec{p}_i^{\,\star} \cdot \vec{n}_T|}{P^\star}$$

jet mass:

$$\rho := \frac{\left(\sum\limits_{i \in \mathrm{CH}} p_i^\star\right)^2}{4\left(\sum\limits_{i \in \mathrm{CH}} E_i^\star\right)^2} = \frac{M^2}{4E^{\star 2}}$$

C parameter:

$$C := 3(\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1)$$

with $\lambda_i\,, i = 1, 2, 3$ being the eigen values of the momentum tensor

$$\Theta_{jk}^\star := \frac{\sum\limits_{i \in \mathrm{CH}} \frac{p_{j_i}^\star p_{k_i}^\star}{|\vec{p}_i^{\,\star}|}}{\sum\limits_{i \in \mathrm{CH}} |\vec{p}_i^{\,\star}|}$$

Event Shape Studies

- Motivation:

  Insight of the interplay between Perturbative and non-perturbative QCD effects

- Definition: sums extend over all hadrons in the current hemisphere for each observable.

  Thrust - $\mathrm{n_T}$ is a unit vector parallel to the thrust axis

  $T_c = 1 - \max\frac{\Sigma_h |p_h.\mathrm{n}_T|}{\Sigma_h |p_h|}$ $(\tau_c = 1 - T_c)$

  Thrust - n is a unit vector parallel photon axis

  $T = 1 - \frac{\Sigma_h |p_h.\mathrm{n}|}{\Sigma_h |p_h|}$ $(\tau = 1 - T)$

  Jet broadening $B = \frac{\Sigma_h |p_h \times \mathrm{n}|}{2\Sigma_h |p_h|}$

  Jet Mass - normalised to total energy in current region

  $\rho = \frac{(\Sigma_h p_h)^2}{(2\Sigma_h E_h)^2}$

  C Parameter - Eigenvalues λ_i of $\theta_{jk} = \frac{\Sigma_h p_{jh} p_{kh} / |\bar{p_h}|}{\Sigma_h |\bar{p_h}|}$

  C=$3(\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1)$

  y_{fj} and y_{kt} - transition values for (2+1) $\rightarrow$ (1+1) jets for JADE and k_T algorithms.

Theoretical Framework - PQCD and Power Corrections

- Mean value of an infrared safe event shape variable $\langle F \rangle$
  e.g. $F = 1 - T_c,\ 1 - T_z,\ B_c,\ \rho_c$

$$\langle F \rangle \quad = \quad \langle F \rangle^{\text{pert}} + \langle F \rangle^{\text{pow}}$$

(Yu.L. Dokshitzer and B.R. Webber, PL 352 (1995) 451)

- Perturbative part

$$\langle F \rangle^{\text{pert}} \quad = \quad c_1\, \alpha_s(Q) + c_2\, \alpha_s^2(Q)$$

$\rightarrow$ coefficients $c_1,\ c_2$ from $\mathcal{O}(\alpha_s^2)$ DISENT in $\overline{\text{MS}}$
(S. Catani and M. Seymour, hep-ph/9602277)

- Power correction Ansatz

$$\langle F \rangle^{\text{pow}} \quad = \quad a_F\, \frac{16}{3\,\pi}\, \frac{\mu_I}{Q} \left[\, \bar{\alpha}_0(\mu_I) - \alpha_s(Q) - b_0 \alpha_s^2(Q) \,\right]$$

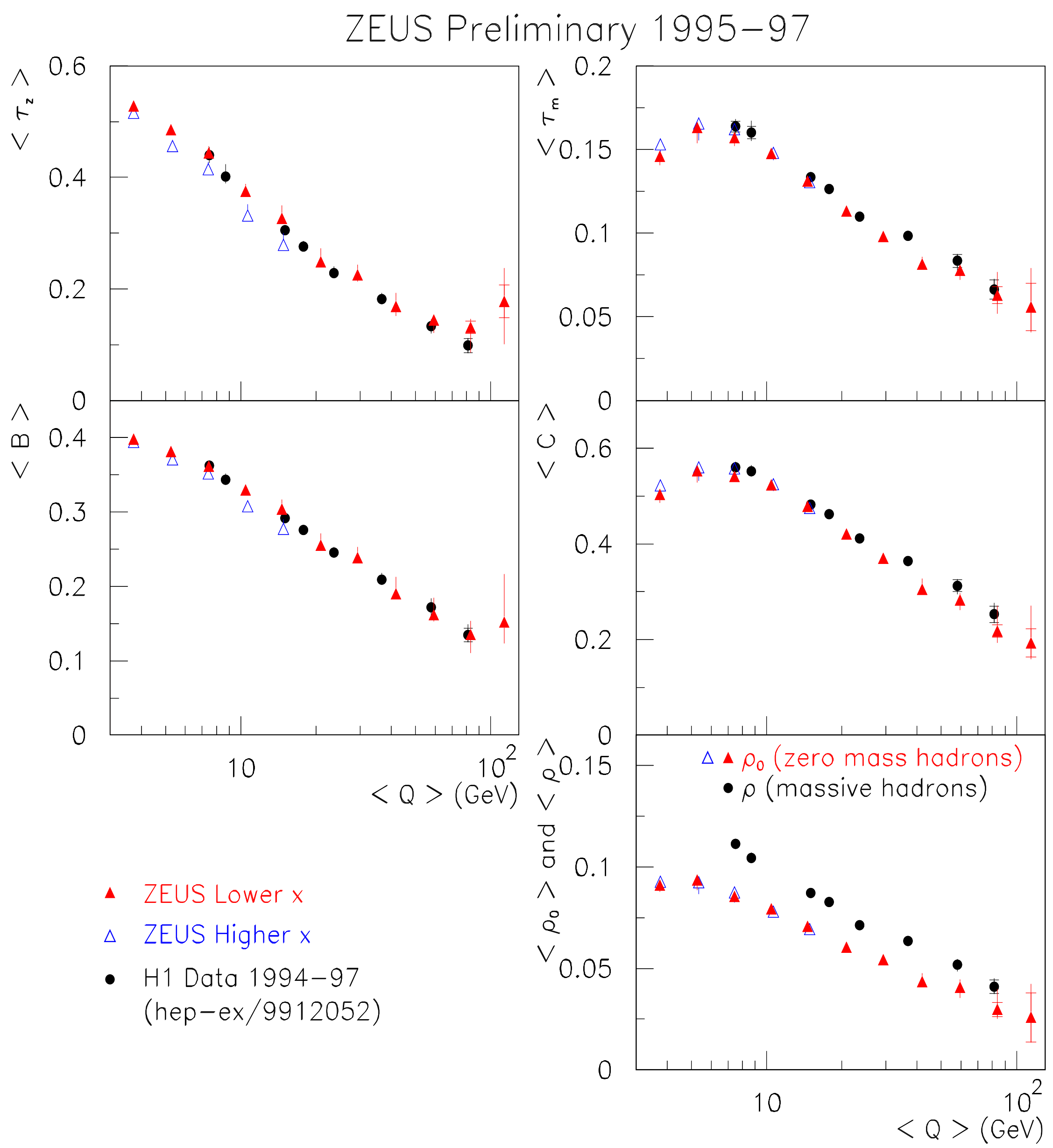
μ_I is an infrared matching scale to mark the boundary between the perturbative and nonperturbative pieces
$\Rightarrow \Lambda_{\text{QCD}} < \mu_I < Q$

$\overline{\alpha}_o(\mu_I)$ is a nonperturbative parameter
$\equiv$ effective strong coupling for energy scales below μ_I in LO

$a_F,\ p$ are coefficients that depend on the choice of F

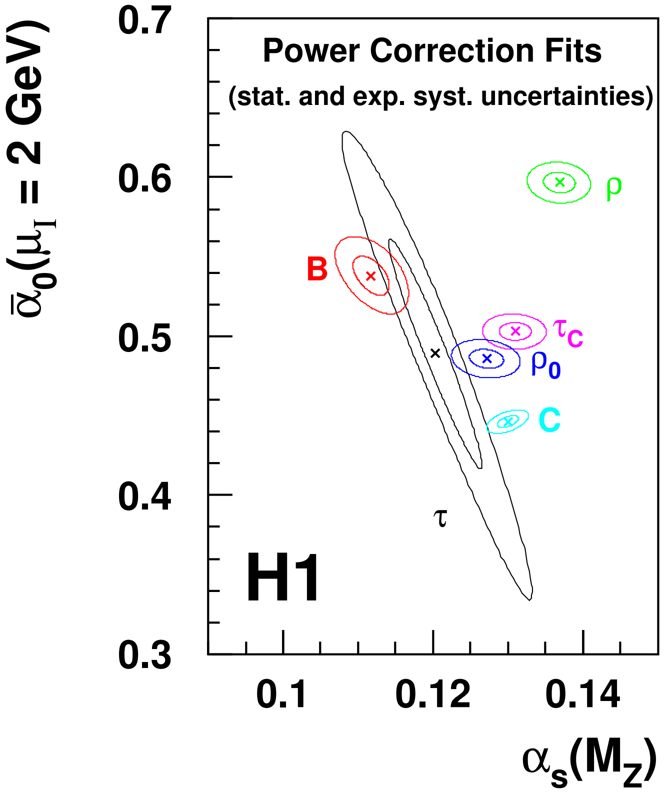
(M. Dasgupta and B.R. Webber, hep-ph/9704297)

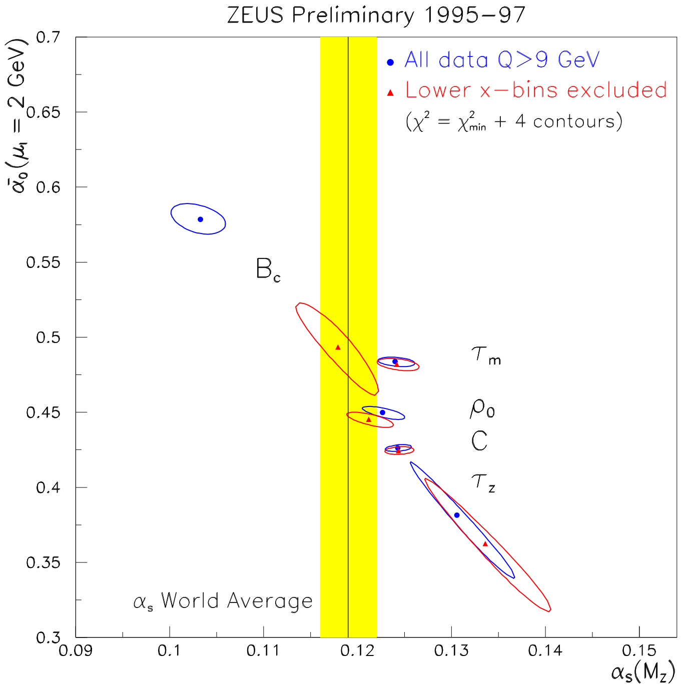
Measurements of Mean Event Shapes



Events are increasingly more collimated with Q
H1 and ZEUS consistent (different definition of ρ)
No large x dependence observed.

Comparison of NLO+Power Correction Fits





Strong x-dependence on B-parameter
Fit results reveal some H1 and ZEUS discrepancies
- Sensitivity of fits to slopes of measured distributions ?
α_s broadly consistent among H1 and ZEUS
α_s spread in shape variables may be due to higher order corrections ?
Fit results broadly suggest universal α_0.

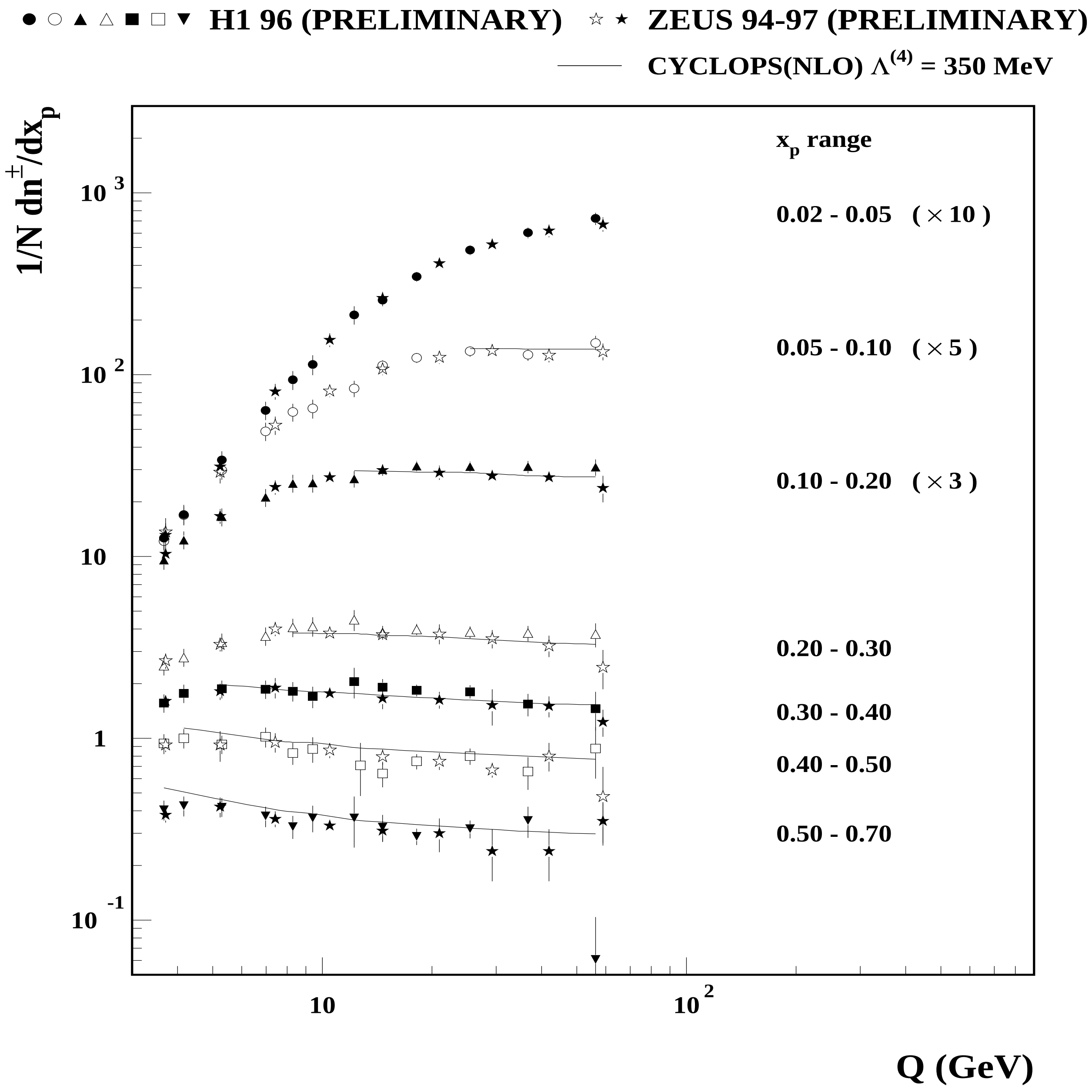
Summary and Outlook

Results from the ep hadronic final state shown.

- **HERA measurements now approaching LEP precision.**
  - **Limiting systematic errors are energy scale and MC dependence.**
- ***NLO* QCD performs well at high Q^2, x.**
  - **Jet rates offer competitive and universal $\alpha_s(M_z)$ and $xg(x)$.**
  - **Theoretical errors dominated by renormalisation scale dependence.**
  - **9 years after turn-on, the forward problem still remains!**
- **Event shape studies suggest universal fragmentation power correction.**

Scaling Violations in Charged Particle Fragmentation Functions

Measure variation of x_p with Q in current region of Breit Frame



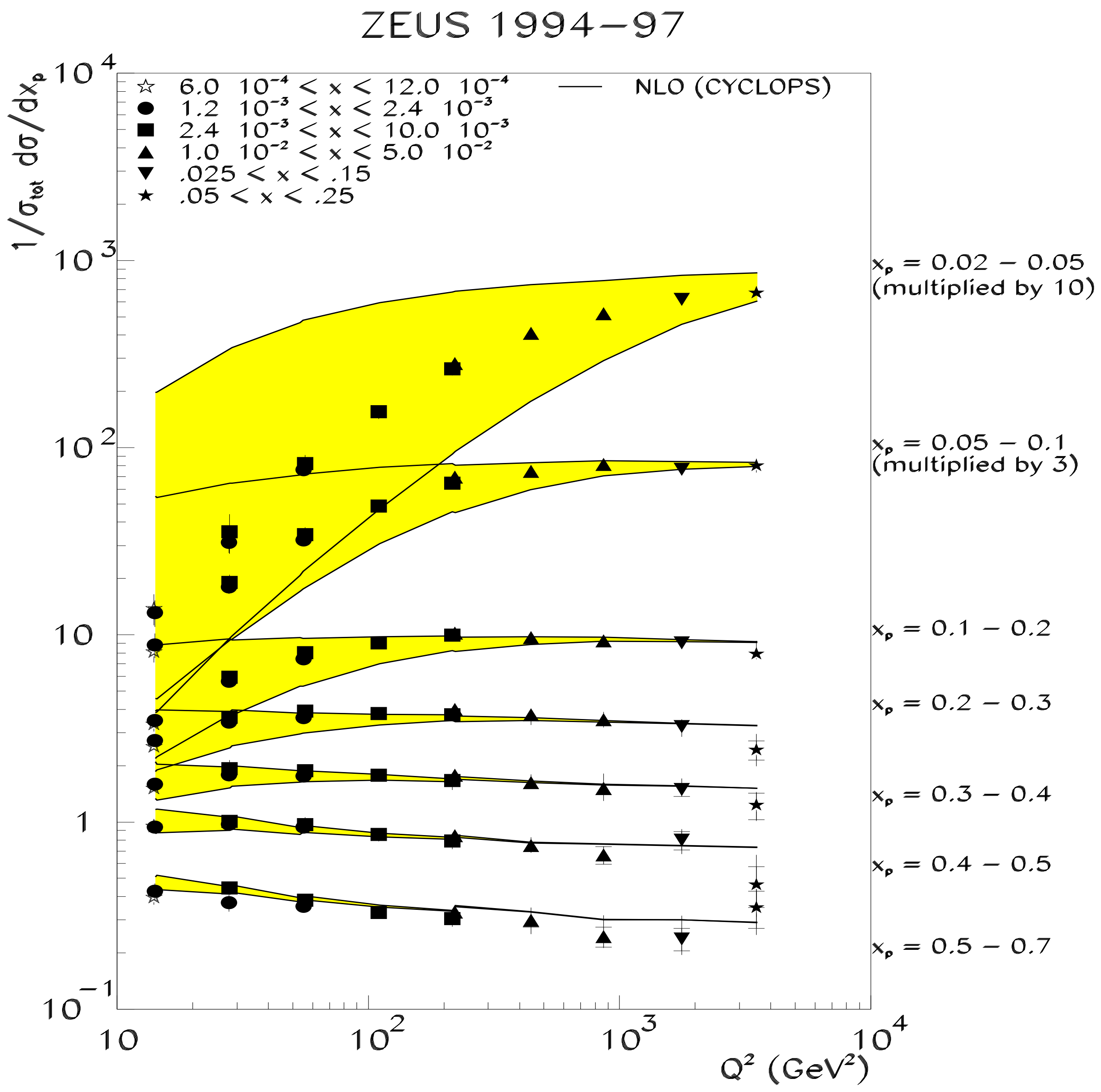
Measurements span orders of magnitude in Q and x_p

More phase space for QCD emissions with higher Q

NLO calculations provide excellent description of the data

Using Power Corrections to Describe Scaling Violations

Can a power corrections ansatz perform hadronisation step ?

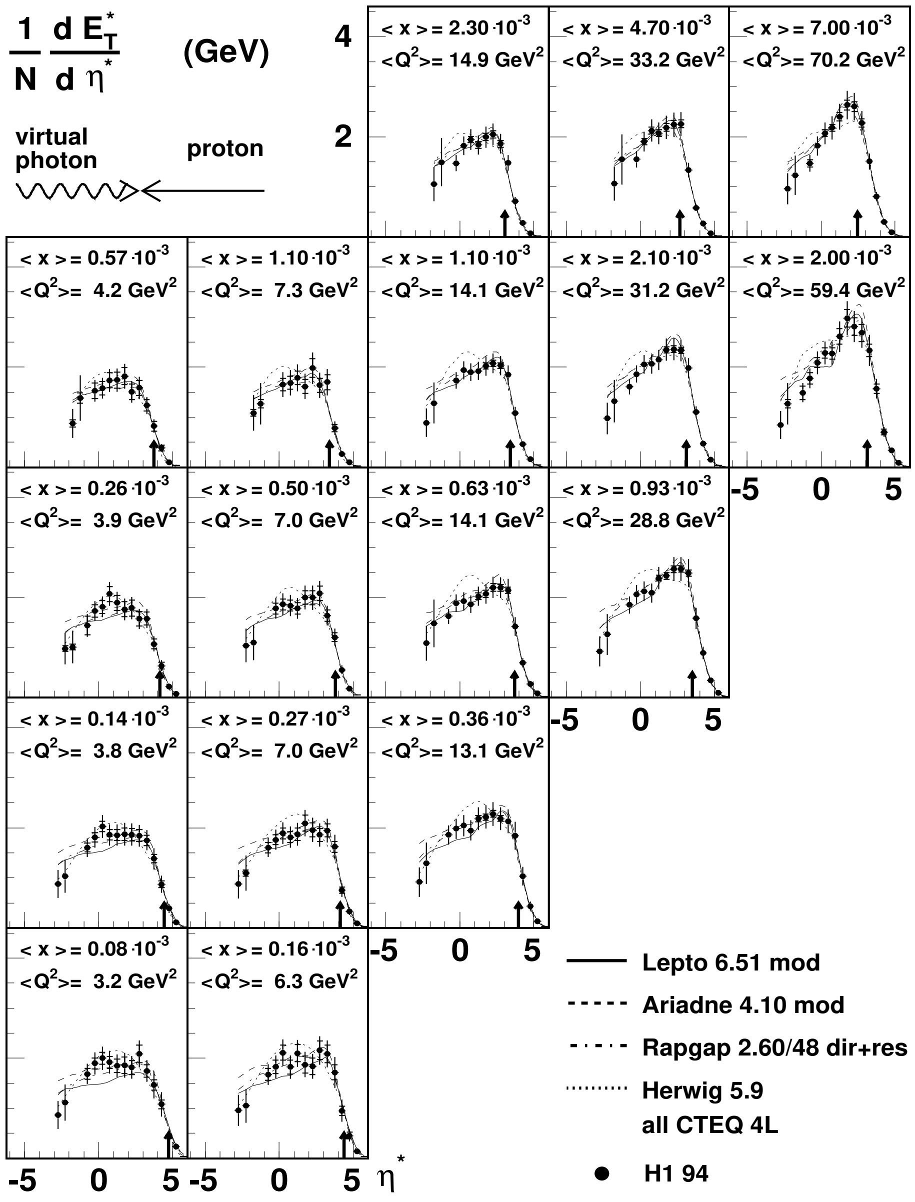


Excellent description from such a simple approach.
Can it be used to derive $\alpha_s(M_z)$?

Transverse Energy Flow

Coverage of > 8 rapidity units.

GAL produces insufficient E_T flow away from the current region.



Energy flow far more collimated at higher Q^2 and x.

Failure of DGLAP calculations at low x and Q^2.

No QCD-based model gives perfect description $\Rightarrow$ larger systematic errors.