Hadronic final states at HERA

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On behalf of the

H1 and ZEUS collaborations

- Physics motivations
- Azimuthal asymmetries
- Inclusive and forward jets at low Q^2
- Event shapes and power corrections
- Summary

H1

Physics motivations

Hadronic final states measurements in ep collisions allow to test QCD predictions :

- Azimuthal asymmetries

⇒ Test of QCD spin structure

⇒ Estimation of non-perturbative effects

- Inclusive and forward jets at low Q^2

⇒ Test of NLO predictions

⇒ New QCD dynamics (BFKL instead of DGLAP)?

⇒ Resolved photon ?

- Event shape variables

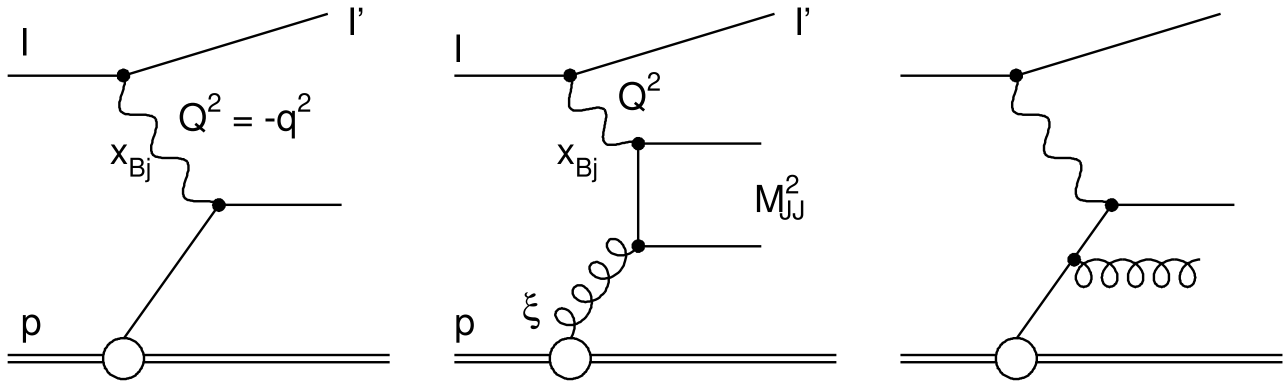
⇒ Interplay between non-perturbative and perturbative QCD

⇒ Test of power-law corrections

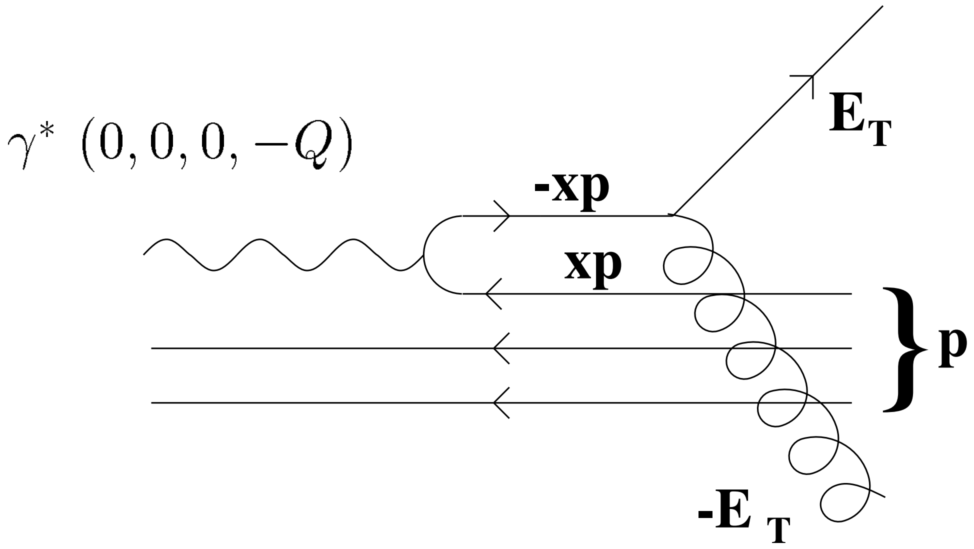
Breit frame

Deep-inelastic scattering :

$O(\alpha_S^0)$: Born process $O(\alpha_S)$: Boson-gluon fusion - QCD Compton



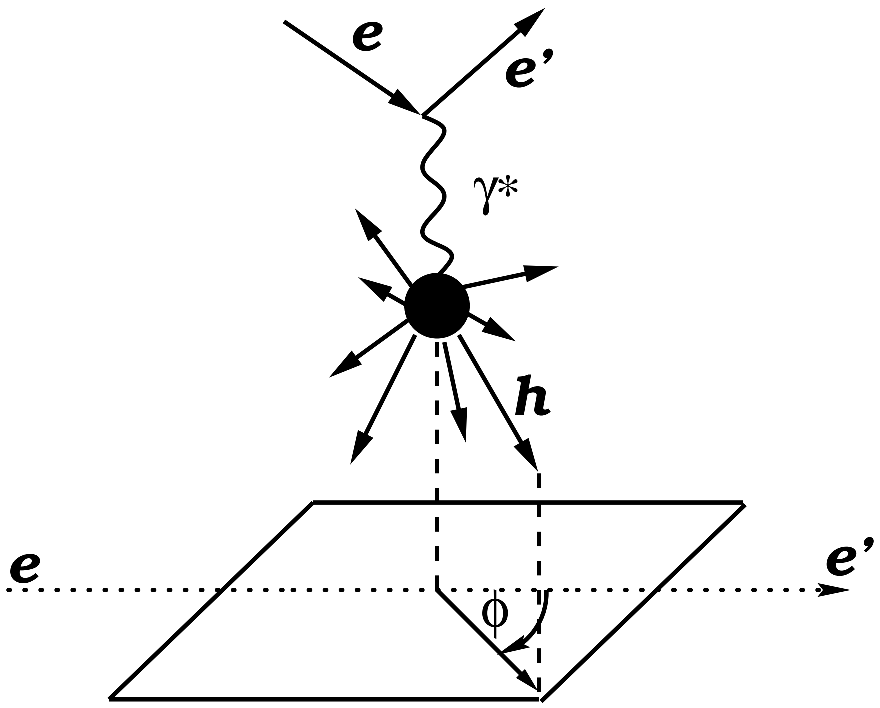
Breit frame : head on collision of γ and p



- Born process $\Rightarrow$ $E_T = 0$
- $E_T > 0$ selects predominantly $O(\alpha_S)$ subprocesses

Azimuthal asymmetries

Measurement of $d\sigma/d\phi$



ϕ of leading particle reflects angular distribution of outgoing parton

Non-zero p_T in hadronic cms (i.e. $O(\alpha_S)$ processes, or intrinsic k_T)

$\Rightarrow$ asymmetries in ϕ

$$d\sigma/d\phi = A + B\cos\phi + C\cos 2\phi$$

- Functional form reflects polarisation of exchanged boson
- B and C depend on parton helicities, parton k_T and colour coherence
- Non-perturbative part (i.e. from k_T) decreases with increasing Q^2
- Perturbative part weakly dependent on Q^2
- At LO in α_S, B comes from QCDC, C from BGF

Azimuthal asymmetries

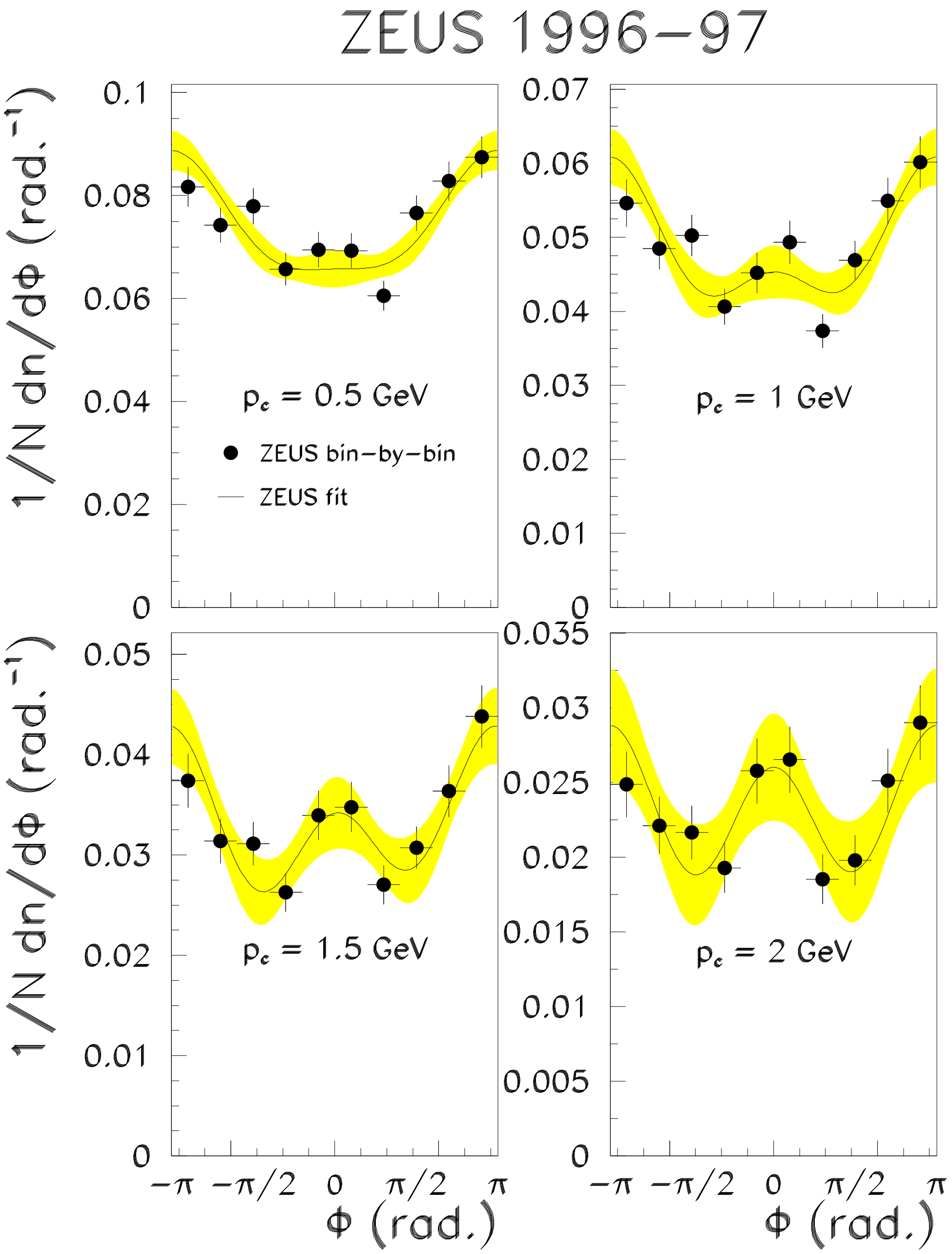
Data selection

Data 1996 to 1997, L=38 pb^{-1}, $0.01 < x < 0.1$, $0.2 < y < 0.8$

Tracks : $|\eta| < 1.75$ (lab), $p_T > p_C$, $0.2 < z_h = P \cdot p_h / P \cdot q < 1.0$

Main analysis method : fit theoretical distribution (smeared for detector effects) to the data

Check with traditional bin-by-bin corrected experimental distribution



← $\cos\phi$ dominant

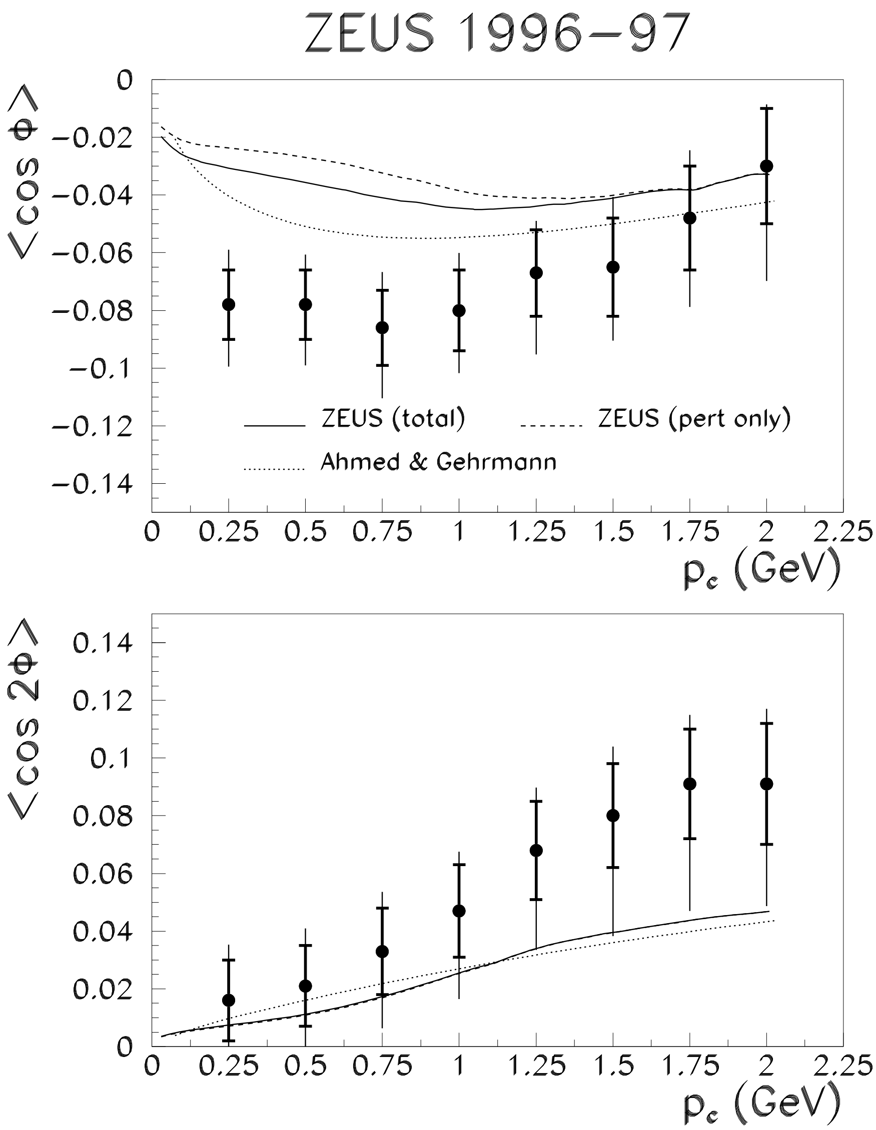
← $\cos 2\phi$ dominant

Azimuthal asymmetries

Comparison to LO calculations

Evolution of the moments $\langle \cos\phi \rangle$ and $\langle \cos 2\phi \rangle$ with p_C

From the fit : $\langle \cos\phi \rangle = B/2A$ and $\langle \cos 2\phi \rangle = C/2A$



- Ahmed & Gehrmann calculation at fixed $\langle x \rangle = 0.022$ and $\langle Q^2 \rangle = 750$ GeV^2

- ZEUS calculation :
  - non-perturbative effects
  - integration over x, Q^2

- Non-pert. effects :
  - at most 20 % for $\langle \cos\phi \rangle$
  - negligible for $\langle \cos 2\phi \rangle$

Remark : sensitivity to HO corrections examined with DISENT

$\Rightarrow$ HO corrections large at low p_C for $\langle \cos\phi \rangle$ and small for $\langle \cos 2\phi \rangle$

Inclusive jets at low Q^2

Measurements

- $d\sigma/dE_T$ in bins of η_{lab} (Q^2)
- $d\sigma/d(E_T^2/Q^2)$ in bins of η_{lab} (Q^2)
- $d\sigma/dx_{Bj}$ in bins of η_{lab}

Motivations

$\Rightarrow$ check NLO calculation

$\Rightarrow$ study interplay of DIS scales E_T^2 vs Q^2

$\Rightarrow$ study resolved photon at $Q^2 > 0$

$\Rightarrow$ new QCD regime : BKFL vs DGLAP?

H1 Data selection

Data 1996 to 1997, L=30 pb^{-1}, $5 < Q^2 < 100$ GeV^2, $0.2 < y < 0.6$

Jets : inclusive k_T, $E_T > 5$ GeV (Breit), $-0.5 < \eta < 2.8$ (lab)

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

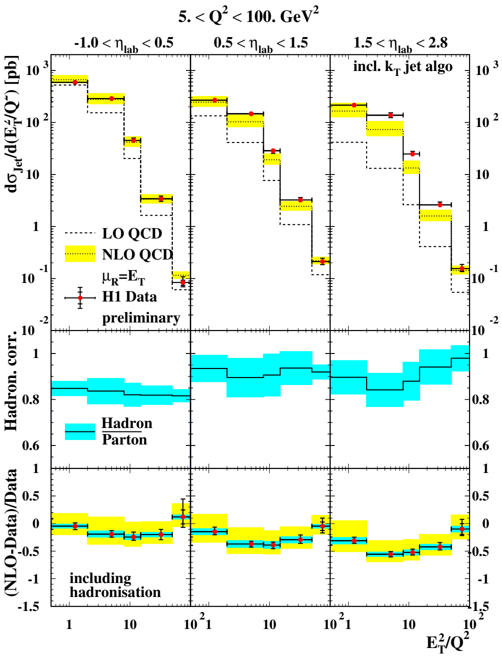
$\Rightarrow$ high statistics for differential analysis : 140000 jets

Data corrected for detector effects and QED radiation

Comparison with NLO calculation

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

Inclusive jets at low Q^2 : $d\sigma/d(E_T^2/Q^2)$



$$\mu_R^2 = E_T^2$$

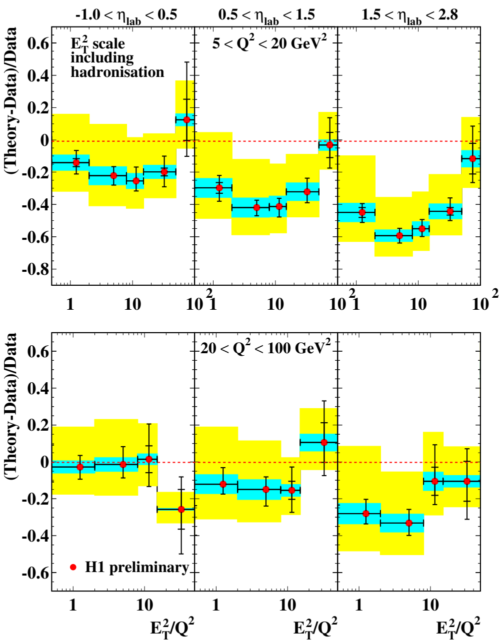
$\leftarrow$ cross-section

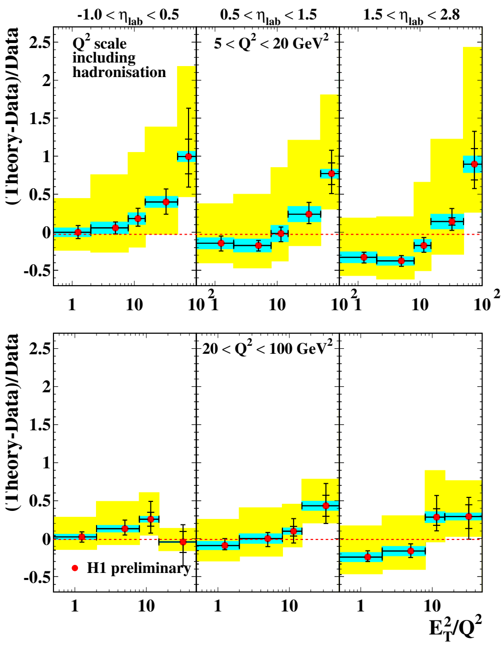
$\leftarrow$ hadronisation correction

$\leftarrow$ (NLO-Data)/Data

Now separate in two Q^2 domains, for the two scales :

$\mu_R^2 = E_T^2$ $\qquad\qquad$ $\mu_R^2 = Q^2$





- $\mu_R^2 = E_T^2 \Rightarrow$ Problem for low Q^2, medium E_T^2/Q^2 forward
- $\mu_R^2 = Q^2 \Rightarrow$ Problem for low Q^2, high E_T

Forward jets : $d\sigma/d(E_T^2/Q^2)$

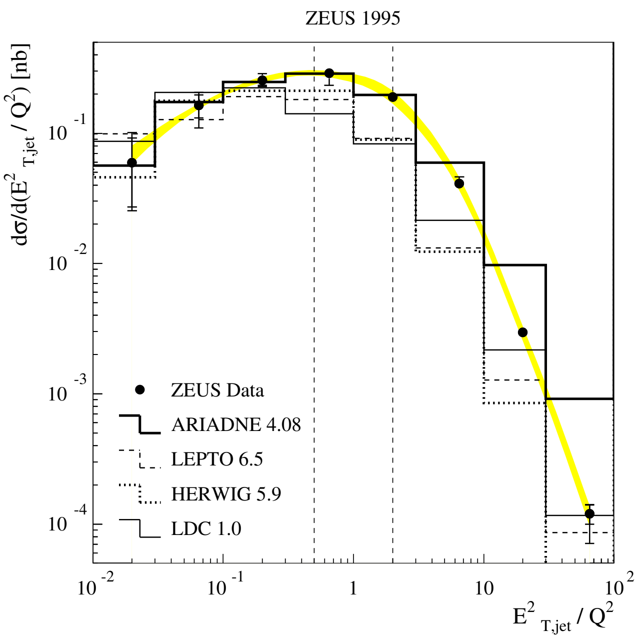
ZEUS data selection

Data 1995, L=6.4 pb^{-1}, $10 < Q^2$ GeV^2, $2.5\ 10^{-4} < x < 8\ 10^{-2}$, $0.1 < y$

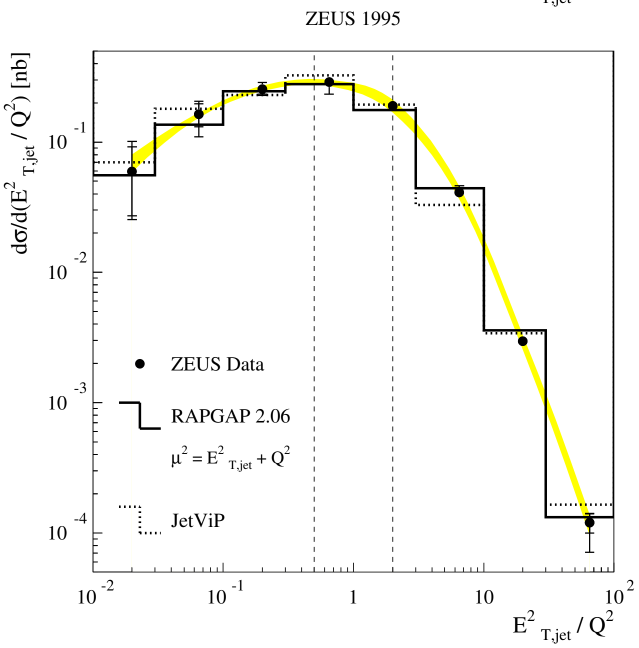
Jets : cone $R = 1$, $E_T > 5$ GeV, $\eta < 2.6$, $x_{jet} = \frac{p^Z_{jet}}{P} > 0.036$ (lab),

$p^Z_{jet} > 0.$ (Breit)

Data corrected for detector effects



$\Leftarrow$ LO MCs using only direct γ processes fail to describe data for medium values of E_T^2/Q^2 (2-50)



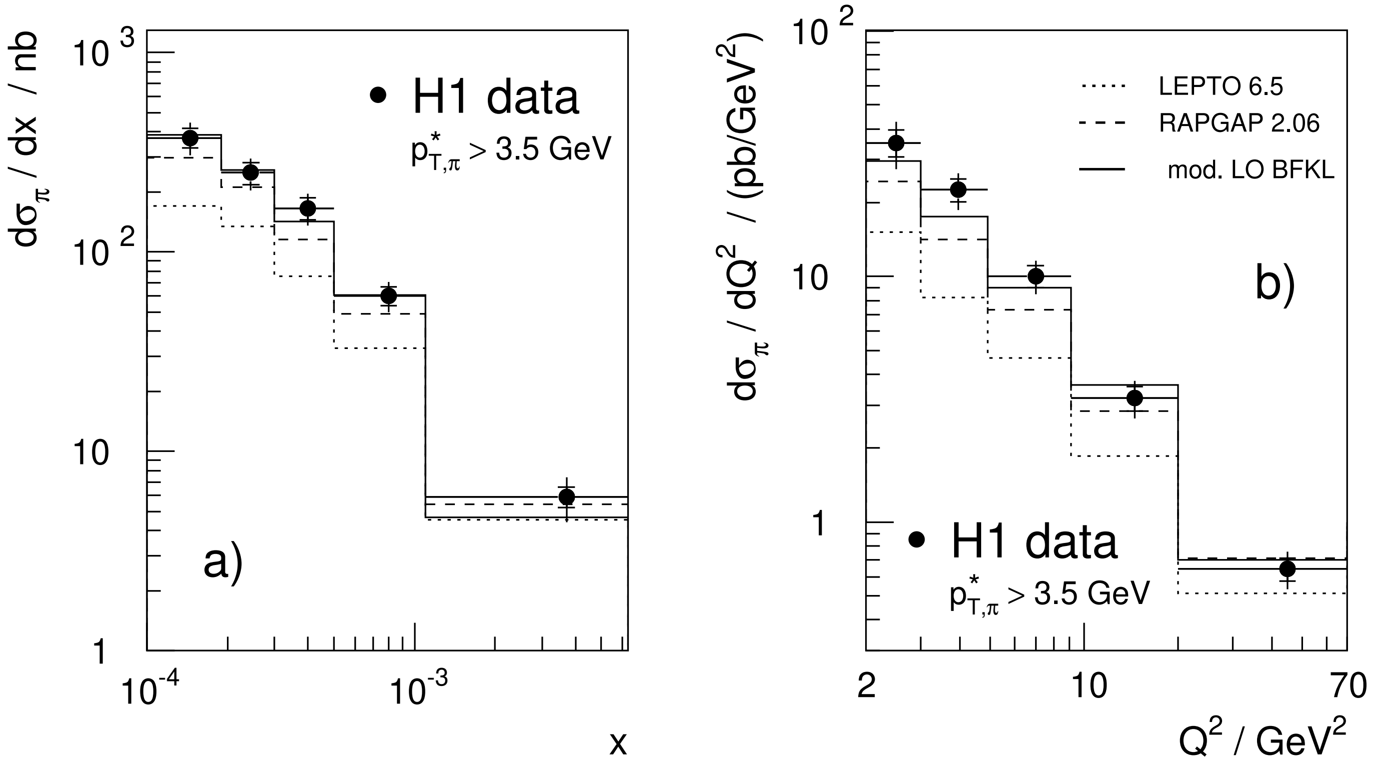
$\Leftarrow$ Calculations including resolved photons seem to work everywhere

Forward π_0 : $d\sigma/dx$

H1 Data selection

Data 1996, L=5.8 pb^{-1}, $2 < Q^2 < 70$ GeV^2, $0.1 < y < 0.6$

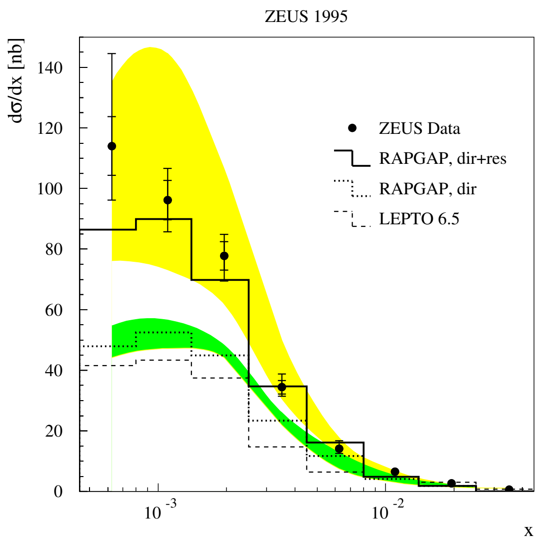
π_0 : $x_\pi = \frac{p_\pi^Z}{P} > 0.01$, $5^o < \theta_\pi < 25^o$, $p_\pi^T > 3.5$ GeV (in hadronic cms)



- LO MCs (direct and direct+resolved) too low
- BFKL calculation OK

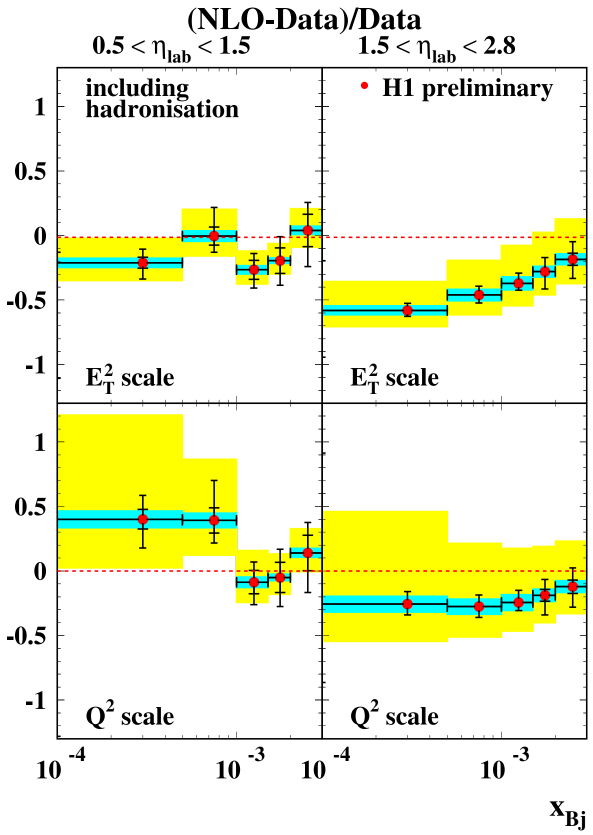
Forward jets : $d\sigma/dx$

Forward jets in ZEUS : $x_{jet} > 0.036$, $0.5 < E_T^2/Q^2 < 2$.



Data well reproduced by RAPGAP, but large scale uncertainties

Forward jets in H1 : $x_{jet} > 0.035$



- E_T^2 scale too low, especially forward and at low x_Bj
- Q^2 scale OK except for central low x_Bj, but large uncertainties

Event shapes and power corrections

Measurements

- Event shapes relative to the boson axis :

- 1-thrust : $\tau = 1 - \frac{\sum_{i(CH)} |p_z^i|}{\sum_{i(CH)} |p^i|}$

- jet broadening : $B = 1 - \frac{\sum_{i(CH)} |p_T^i|}{2\sum_{i(CH)} |p^i|}$

- Event shapes without reference to the boson axis :

- 1-thrust$_C$: $\tau_C = 1 - max_{n,n^2=1} \frac{\sum_{i(CH)} |p^i.n|}{\sum_{i(CH)} |p^i|}$

- jet mass : $\rho = \frac{(\sum_{i(CH)} p^i)^2}{4(\sum_{i(CH)} E^i)^2}$

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

(λ_i eigenvalues of the momentum tensor)

Can mean values of these variables be described by power law $O(1/Q^p)$ corrections with perturbatively calculable coefficients?

Power correction formalism

$< F >=< F >_{pert.} + < F >_{power}$

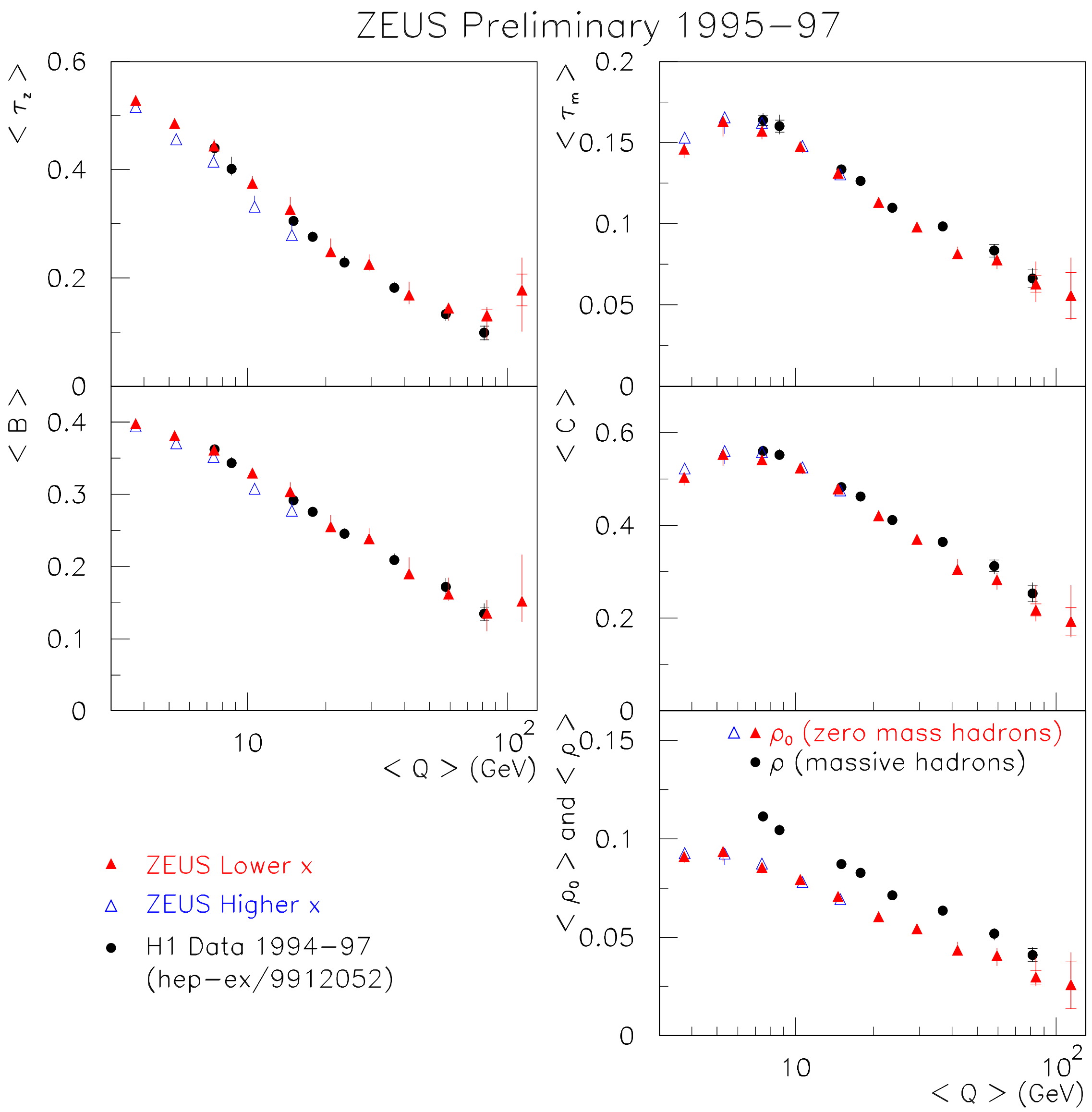
- $< F >_{pert.}$ calculated with DISENT

- $< F >_{power} = a_F \frac{4C_F}{\pi p} M (\frac{\mu_I}{Q})^p$

$$\left[\overline{\alpha}_{p-1}(\mu_I) - \alpha_S(Q) - \frac{\beta_0}{2\pi}\left(ln\frac{Q}{\mu_I} + \frac{K}{\beta_0} + \frac{1}{p}\right)\alpha_S^2(Q)\right]$$

with $\alpha_{p-1}(\mu_I)$: universal non-perturbative parameter

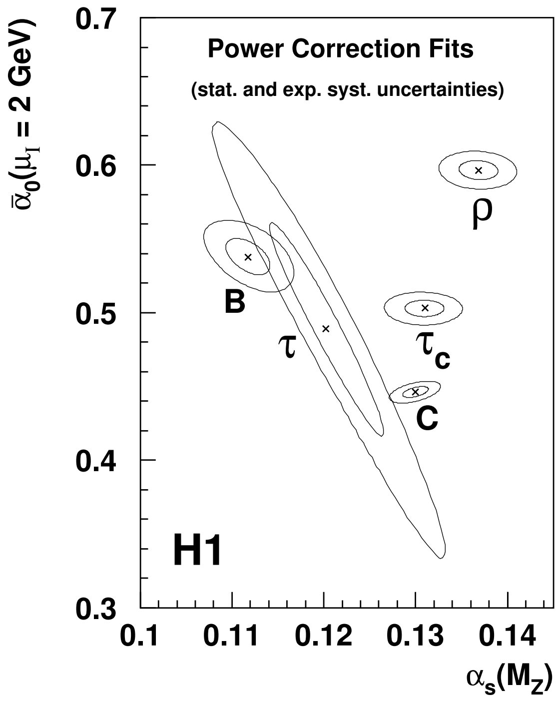
Mean event shapes



- Events become more collimated with increasing Q
- Good agreement between experiments
- Jet mass definition different between H1 and ZEUS
- x-dependence apparent in ZEUS data

$\Rightarrow$ explicit binning in x

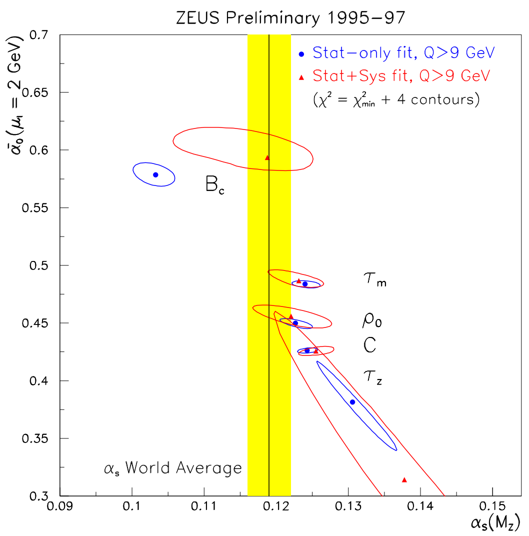
Event shapes : fit results



H1

Fit results reasonable :

- $\overline{\alpha}_0 = 0.5 \pm 20\%$
- large spread in $\alpha_S(M_Z)$



ZEUS

e^+e^- type variables :

- small spread in $\overline{\alpha}_0$, $\alpha_S(M_Z)$ compatible with world average

DIS specific variables :

- large spread in $\alpha_S(M_Z)$
- Fit results for B and τ_Z depend on error taken in the fit

H1 and ZEUS data consistent :

- universal $\overline{\alpha}_0 = 0.5 \pm 20\%$
- for e^+e^- type variables (C, ρ, τ_C) common value of $\alpha_S(M_Z)$
- for DIS specific variables (B, τ) large spread of $\alpha_S(M_Z)$

Summary

Azimuthal asymmetries :

- General agreement with QCD predictions
- First measurement of $< \cos 2\phi >$

  $\Rightarrow$ clear evidence for perturbative QCD effect
- LO predictions qualitatively describe data, but NLO probably needed for quantitative agreement

Inclusive and forward jets :

- Many measurements, no single model describes all data
- Choice of scale : E_T^2, Q^2?
- BFKL? NNLO? Resolved photon?

Event shapes :

- General agreement with power corrections scheme
- Universal $\overline{\alpha}_0 = 0.5 \pm 20\%$
- Problem with DIS specific variables B and τ

HADRONIC FINAL STATES

improve our understanding of

QCD IN DIFFERENT REGIMES

BUT WORK STILL NEEDED BOTH FROM THEORETICAL AND EXPERIMENTAL SIDES