Final State Studies at HERA

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on behalf of H1 and ZEUS collaborations

- Search for instanton-induced events
- Event shapes & power corrections
- Baryon-antibaryon asymmetry
- Azimuthal asymmetries
- Multiplicity study

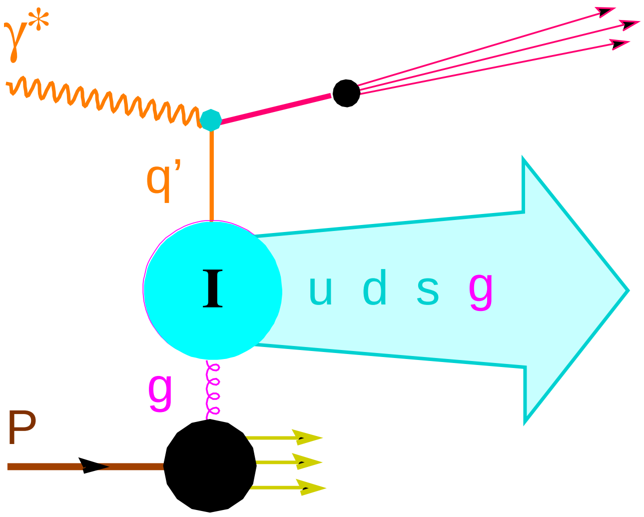
Instantons at HERA

H1 Collaboration

- Non-perturbative fluctuations of non-abelian gauge fields
- Represent topology changing tunneling transitions
- Induce hard processes forbidden in conventional pert. theory
- Violate: Chirality in QCD (B+L conservation in QFD)

[Ringwald & Schrempp, '94 - '00, papers 250, 251, 252, 254, 255]:

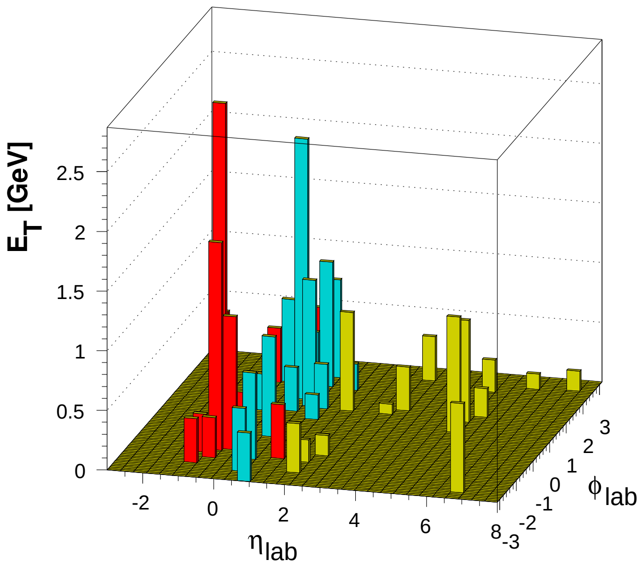
- At HERA, unique opportunity to discover QCD instantons
- **DIS**: Calculable rate, $\mathcal{O}(100)$ pb, **and** characteristic signature



- Current Jet
- "Band"-Region: ⇔

"fireball" decays **isotropically** in I-restsystem: $\mathcal{O}(10)$ partons

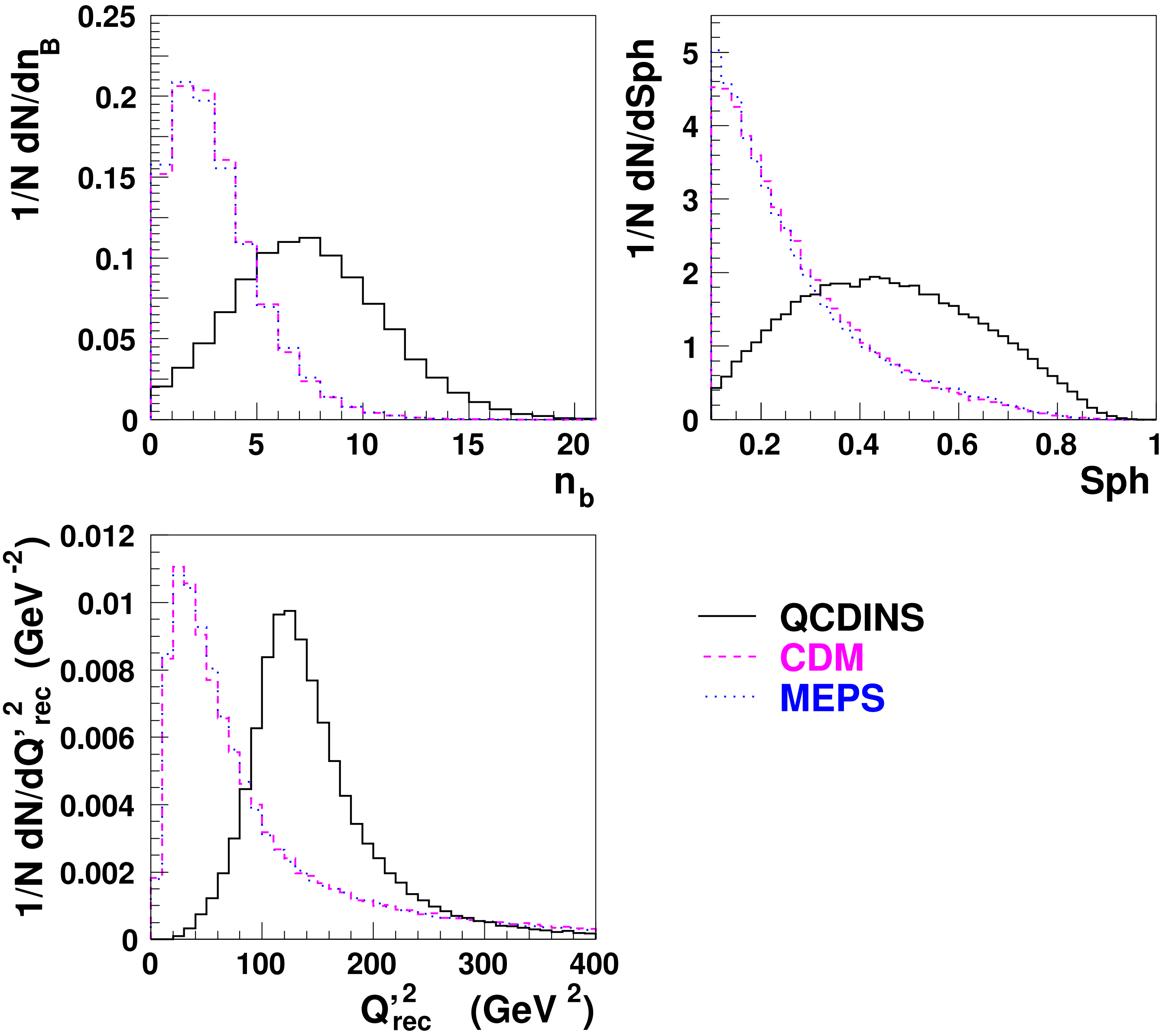
$$W_I^2 = (q' + g)^2 = Q'^2(\frac{1}{x'} - 1)$$



Experimental Signature [#251]:

◇ Large total E_t
◇ Large multiplicity
◇ "u, d, s flavour-democracy":
Strangeness ⇒ K's, Λ's
◇ no further jet

Search Strategy



Cut values:

$n_{\mathrm{b}} \geq 5, 6, 7, 8, 9$

$\mathrm{Sph} \geq 0.4, 0.5, 0.55, 0.6, 0.65$

$95, 100, 105, 110, 115 < Q'^2 < 200\,\mathrm{GeV}^2$

in total 125 combinations!

DIS Event Selection

Data 1997: $\int \mathcal{L} = 15.78\,\mathrm{pb}^{-1}$

Observables

Find highest E_{T} jet ("current jet"): cone algorithm, $R = 0.5$

1) Transverse energy of jet: E_{Tjet} in hCMS

2) Virtuality of quark entering I-subprocess: Q'^2

Remove particles of jet to define band:
With $\bar{\eta} = \sum_h E_{\mathrm{T}h}\,\eta_h / \sum_h E_{\mathrm{T}h}$, define band as $\bar{\eta} \pm 1.1$

3) Count number of charged particles: n_{b}

4) Sphericity in the rest system of particles not in jet: Sph

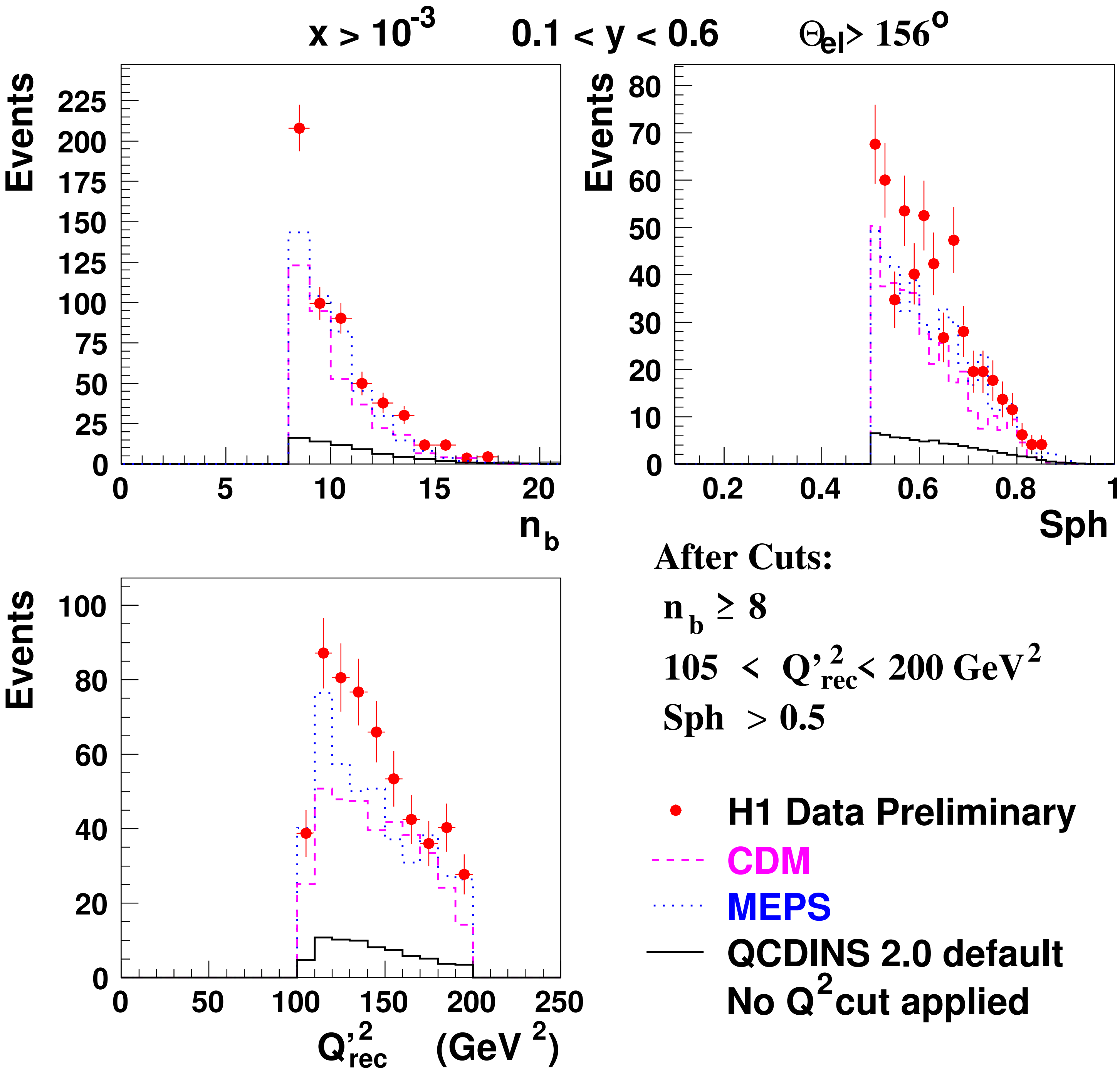
Selection of Cuts Scenario

Scenario	Cuts			ϵ_{ins}	$\frac{\epsilon_{\mathrm{ins}}}{\epsilon_{\mathrm{DIS}}}$	
	$Q'^2\,\mathrm{GeV}^2$	Sph	n_{b}		CDM	MEPS
A	95.0-200.0	0.40	5	32 %	35	34
B	105.0-200.0	0.40	7	21 %	56	52
C	105.0-200.0	0.50	8	11 %	86	71

A) Highest instanton efficiency (ϵ_{ins})
B) High ϵ_{ins} at reasonable separation power ($\frac{\epsilon_{\mathrm{ins}}}{\epsilon_{\mathrm{DIS}}}$)
C) Highest separation power at $\epsilon_{\mathrm{ins}} > 10\%$

Observable Distributions after Cuts C

Observables used to cut:



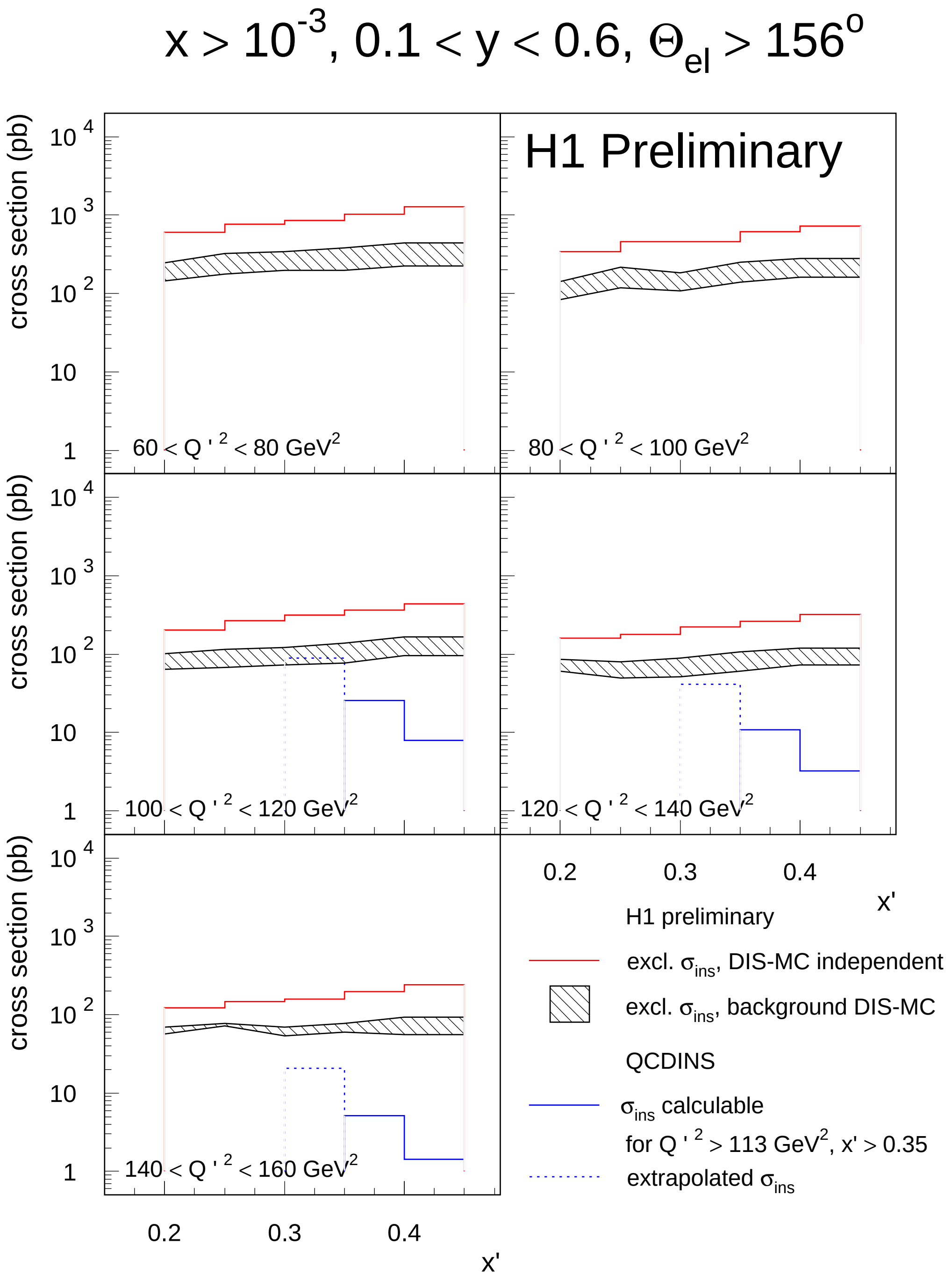
Background reduction by factor $\sim 600 - 800$.

549 events measured

363^{+22}_{-26} (CDM) and 435^{+36}_{-22} (MEPS) expected

Expected instanton signal at the level of discrepancy of QCD Models

Cross Section Upper Limits



- Red Lines: Upper limit assuming standard-DIS $\sigma = 0$
- Bands: Upper limit from difference data and CDM/MEPS
- Exclude $\sigma^{(\mathrm{I})} \sim 100 - 1000\,\mathrm{pb}$

Conclusions

- H1 searched for Instanton-induced DIS events predicted to be measurable at HERA by A. Ringwald and F. Schrempp

- 549 events have been measured in the data,
  363^{+22}_{-26} (CDM) and 435^{+36}_{-22} (MEPS) are expected
  Qualitative similarity between observed excess and shape predicted by QCDINS for 3 observables used in cuts

- Predicted Instanton cross section is at the level of the difference between the pQCD models (CDM/MEPS)

- Need more understanding of pQCD in this region

- Experimental upper limits $(100 - 1000\,\mathrm{pb})$ exclude rapid rise of $\sigma^{(\mathrm{I})}$ with ρ as would follow from naive extrapolation of Instanton perturbation theory

Event Shape Studies at HERA

ZEUS & H1 results

Data & Analysis Method

- DIS analysis in Breit frame
  - clean separation between current and target fragmentation
  - permits event shapes in current hemisphere to be compared directly to those in e^+e^-

- QCD studies over large Q range in single experiment

ZEUS	H1
$\mathcal{L} \simeq 45\,\text{pb}^{-1}$	$\mathcal{L} \simeq 38\,\text{pb}^{-1}$
$Q = 9 - 140$ GeV	$Q = 7 - 100$ GeV
tracks & clusters	calorimeter clusters
$E_{\text{CH}} > 0.03\,Q$	$E_{\text{CH}} > 0.10\,Q$

to be insensitive to soft particle migration from target region

(results are not sensitive to exact value of the cut)

spectra $1/N\,dn/dF$ unfolded to hadron level

bin-by-bin corrections	Bayes matrix unfolding

- QCD analysis
  - pQCD calculations to $\mathcal{O}(\alpha_s^2)$ DISENT
  - hadronisation treated by analytical power corrections à la Dokshitzer & Webber

Event Shapes in Current Hemisphere

- Infrared & collinear safe observables, calculable in QCD

- Thrust

$$\tau_z = 1 - \frac{\sum_h |p_{h\,z}|}{\sum_h |\mathbf{p}_h|} \qquad p_{||} \text{ wrt } \gamma/Z \text{ axis}$$

$$\tau_m = 1 - \max_{\mathbf{n}_T} \frac{\sum_h |\mathbf{p}_h \cdot \mathbf{n}_T|}{\sum_h |\mathbf{p}_h|} \qquad p_{||} \text{ wrt thrust axis}$$

- Jet Broadening

$$B = \frac{\sum_h |\mathbf{p}_{h\,\perp}|}{2\sum_h |\mathbf{p}_h|} \qquad p_{\perp} \text{ wrt } \gamma/Z \text{ axis}$$

- C Parameter

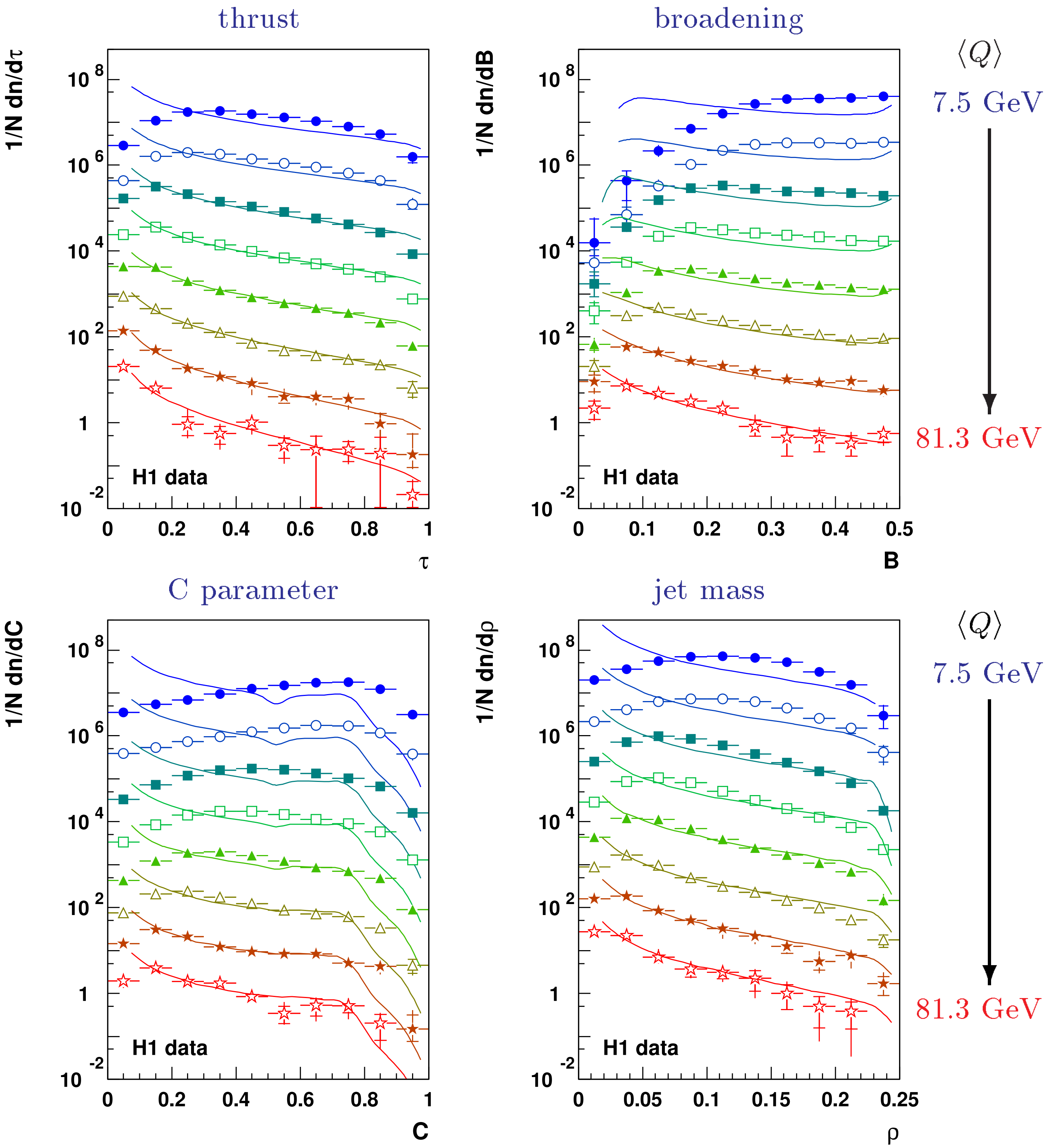
$$C = \frac{3\sum_{i,j} |\mathbf{p}_i||\mathbf{p}_j| \sin^2\theta_{ij}}{(2\sum_i |\mathbf{p}_i|)^2}$$

- Jet Mass

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

variant ρ_0 with $E_h = |\mathbf{p}_h|$, i.e. assume $m_h = 0$ motivated by massles QCD calculations

H1 Measurements: Spectra



▷ Event shape spectra compared to $\mathcal{O}(\alpha_s^2)$ pQCD

- Hadronisation corrections important, becoming smaller with increasing Q

pQCD & Power Corrections

- Mean value $\langle F\rangle$ of event shape variable
  $\langle F\rangle = \langle F\rangle^{\rm pert} + a_F \mathcal{P}$

  ▷ Perturbative part $\mathcal{O}(\alpha_s^2)$ DISENT in $\overline{\rm MS}$
  $\langle F\rangle^{\rm pert} = c_1(x,Q)\,\alpha_s(Q) + c_2(x,Q)\,\alpha_s^2(Q)$

  ▷ Simplistic forms of hadronisation

  $$a_F\mathcal{P} = \lambda_1/Q \quad \text{or} \quad a_F\mathcal{P} = \lambda_2/Q^2$$

  are unsatisfactory to describe the data

  ▷ Power corrections Dokshitzer & Webber

$$\mathcal{P} = \frac{16}{3\,\pi}\mathcal{M}'\left(\frac{\mu_I}{Q}\right)^p\left[\bar{\alpha}_{p-1}(\mu_I) - \alpha_s(Q) - \frac{\beta_0}{2\,\pi}\left(\ln\frac{Q}{\mu_I} + \frac{K}{\beta_0} + \frac{1}{p}\right)\alpha_s^2(Q)\right]$$

* a_F calculable coefficients dependent on F
* p predictable power $p = 1$ (except y_{k_t})
* $\bar{\alpha}_0$, $\bar{\alpha}_1$ non-perturbative universal parameters

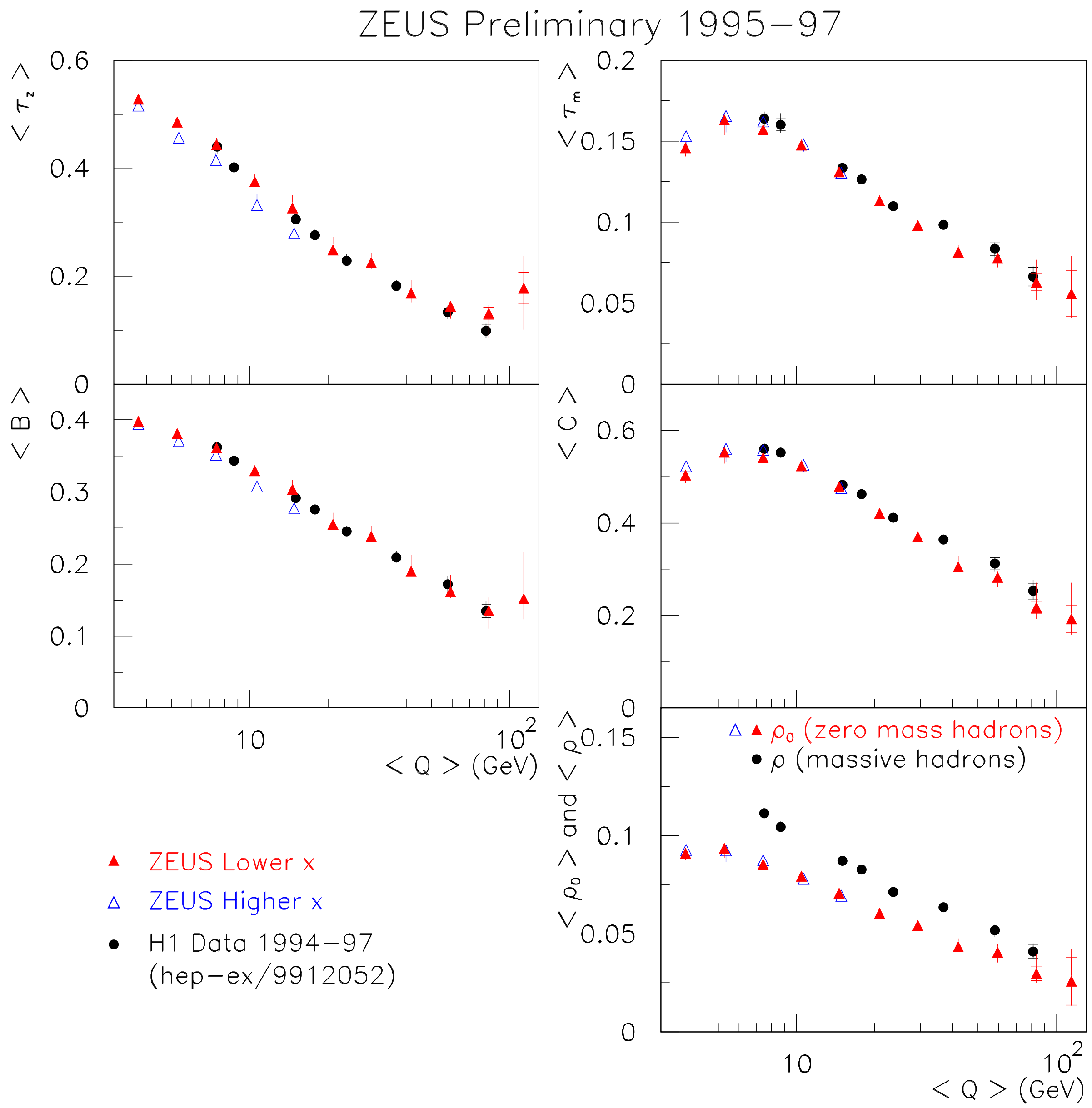
$$\bar{\alpha}_{p-1}(\mu_I) = p\,\mu_I^{-p}\int_0^{\mu_I}\mathrm{d}k_\perp\,k_\perp^{p-1}\,\alpha_s(k_\perp)$$

infrared matching scale $\mu_I = 2\,\mathrm{GeV}$

* $\mathcal{M}'$ two-loop corrections ($\simeq 0.95$)

⇒ 2 free parameters: $\bar{\alpha}_{p-1}$ & $\bar{\alpha}_s$

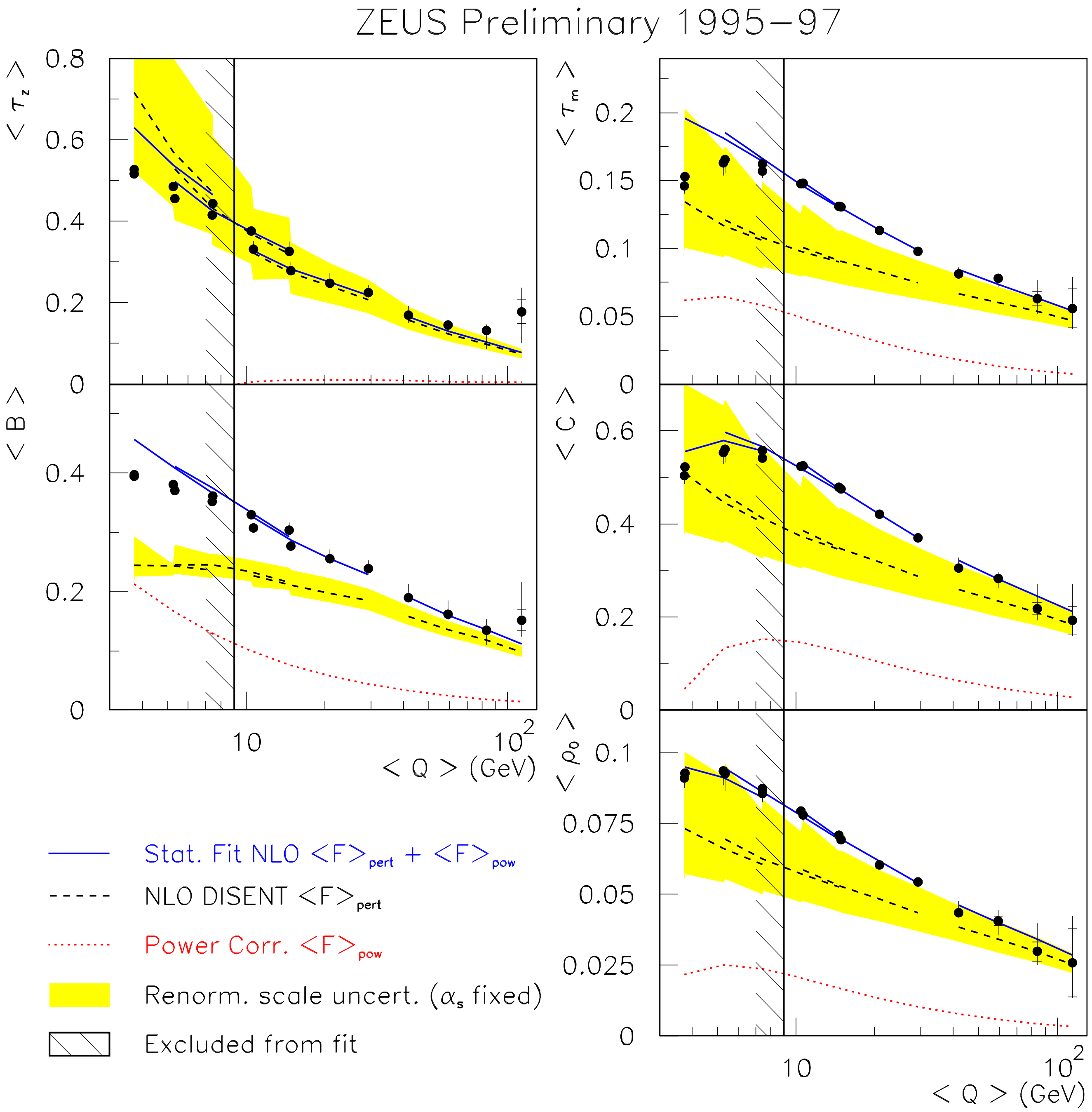
ZEUS & H1 Measurements: Mean Values



Event shape mean values $\langle F \rangle$ vs. Q

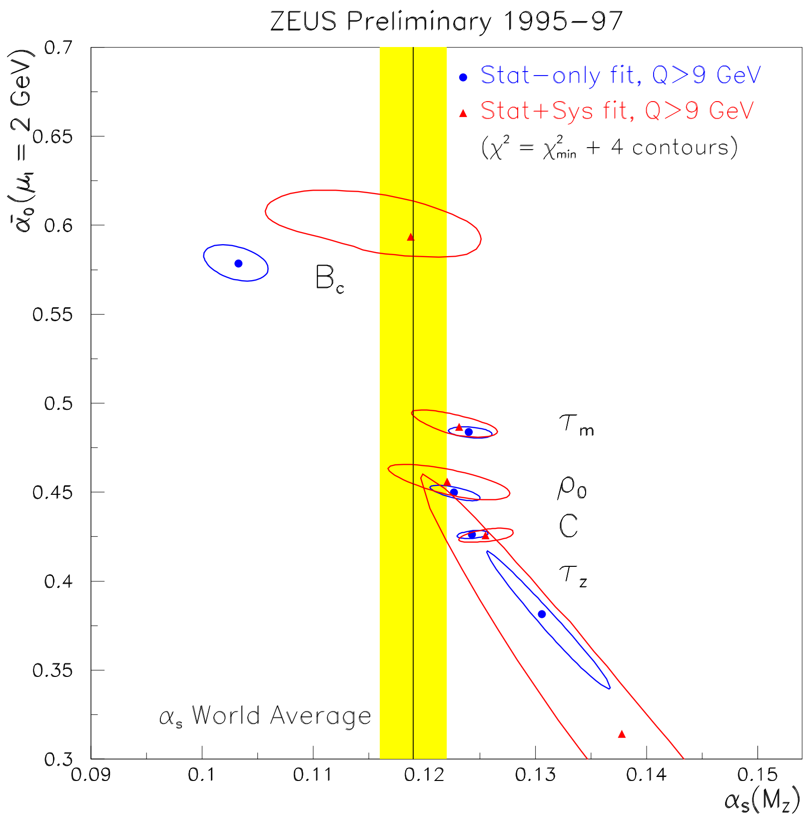
- Event topology gets more collimated with rising Q
- Reasonable agreement between ZEUS and H1 data
- ZEUS: x-dependent measurements, most apparent in τ_z, B

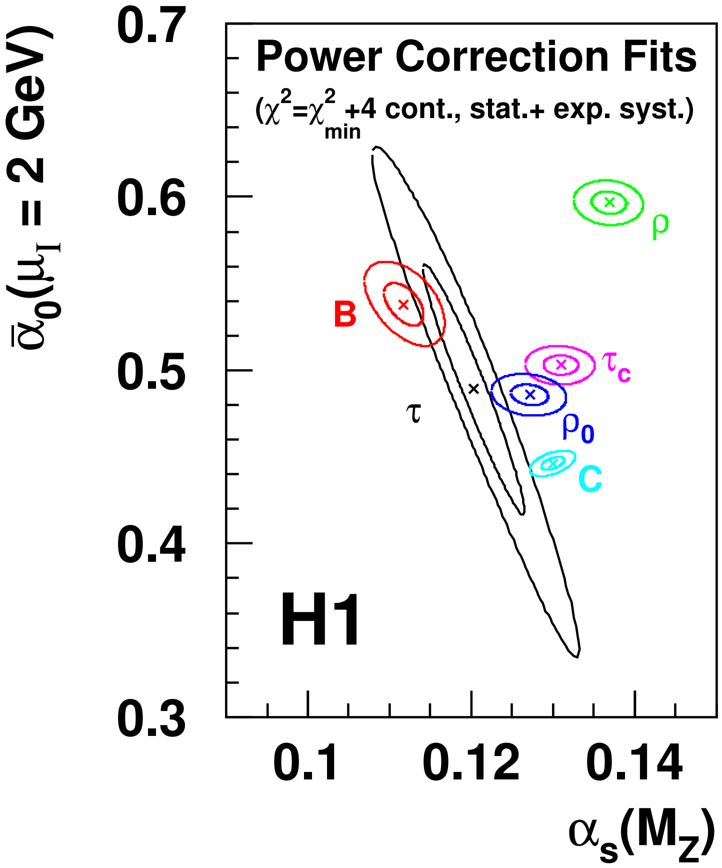
Fits à la Dokshitzer, Webber et al.



- e^+e^- type variables (C, τ_m, ρ_0) fit well
- ZEUS data highlight problems with the x-dependence in DIS specific variables $(B$ and $\tau_z)$
- Large scale uncertainties

Correlations $\bar{\alpha}_0$ vs. $\alpha_s(M_Z)$





- approximate universal power corrections $\bar{\alpha}_0 \simeq 0.5 \pm 0.1$
- spread in α_s: higher order QCD, x dependence?

See details in H.-U. Martyn ICHEP 2000, Osaka, EPJC 14, 225, July 2000

Conclusions

- ZEUS and H1 provide consistent data on event shape variables in DIS over a large range of $Q = (7 - 140)\,\mathrm{GeV}$

- Sizeable hadronisation for τ, τ_c, B, C, ρ, Q dependence of mean values well described by

  1. pQCD & power corrections
  2. universal parameter $\bar{\alpha}_0 \simeq 0.5 \pm 20\%$
  3. spread in $\alpha_s(M_Z)$: missing higher orders?

- Support the basic concept of approximate universal power corrections

Baryon-Antibaryon Asymmetry at HERA

H1 Collaboration

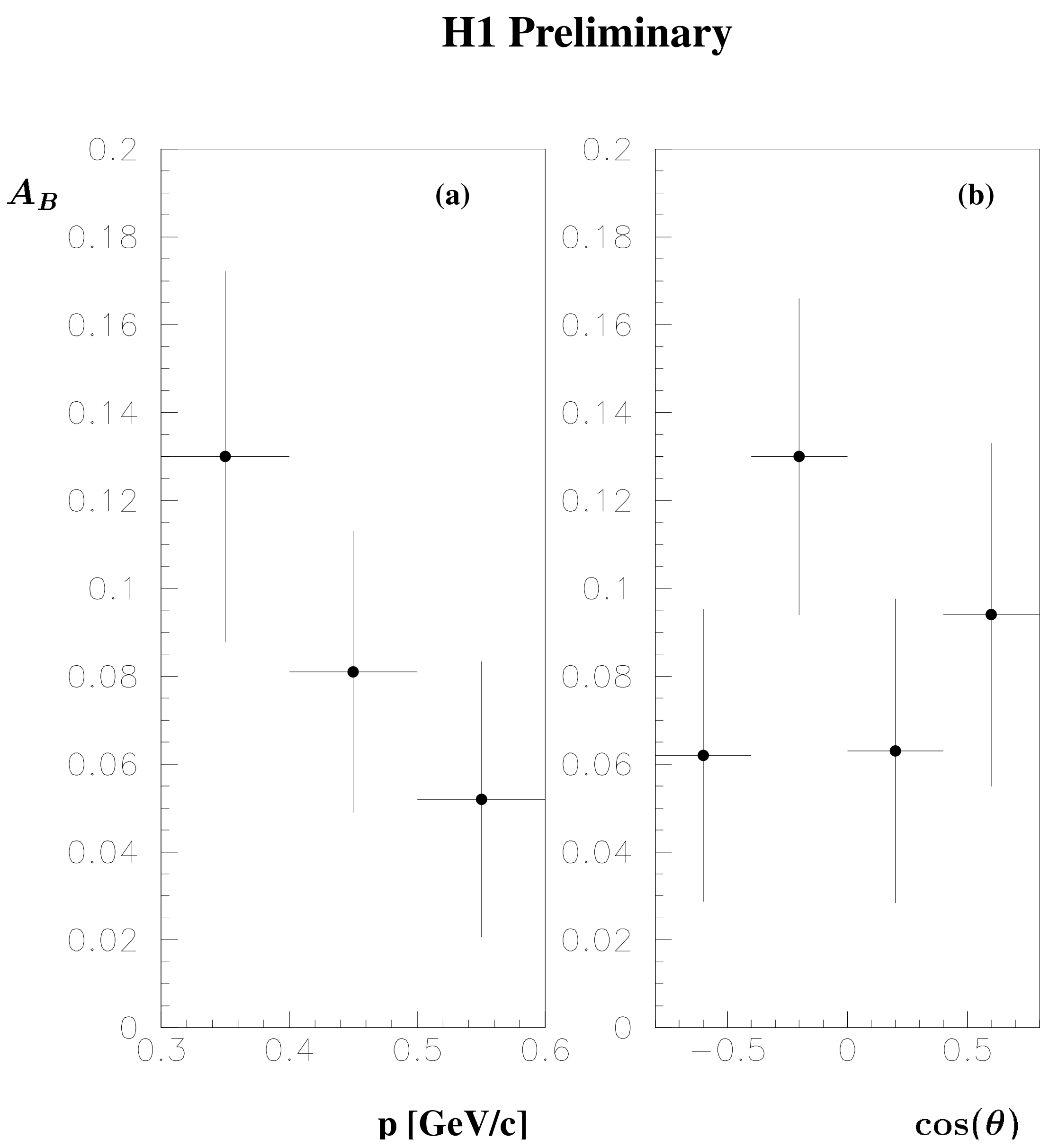
HERA provides a unique opportunity to study the baryon number transfer mechanism.

- One incident particle (photon) does not carry Baryon Number
- Large rapidity interval (about 7 units) between the initial baryon and the photon hemisphere
- At such large rapidity intervals the gluonic mechanism gives a dominant contribution to baryon number transfer. B. Kopeliovich, B. Povh: Phys. Lett. B446, 321, 1999.. F. Bopp: talk at this session

H1 measured the baryon asymmetry in photoproduction of protons and antiprotons:

- $0.3 < p < 0.6\,\mathrm{GeV}/c$ and $|\cos(\theta)| < 0.8$ in LAB system
- use dE/dx for identification

$$A_{\mathrm{B}} = 2\frac{(N_{\mathrm{p}} - N_{\bar{\mathrm{p}}})}{(N_{\mathrm{p}} + N_{\bar{\mathrm{p}}})} = (8.0 \pm 1.0 \pm 2.5)\%$$



Conclusions

- A non-vanishing baryon asymmetry in the photon hemisphere
- No significant dependence of the baryon asymmetry on the proton polar angle and momentum

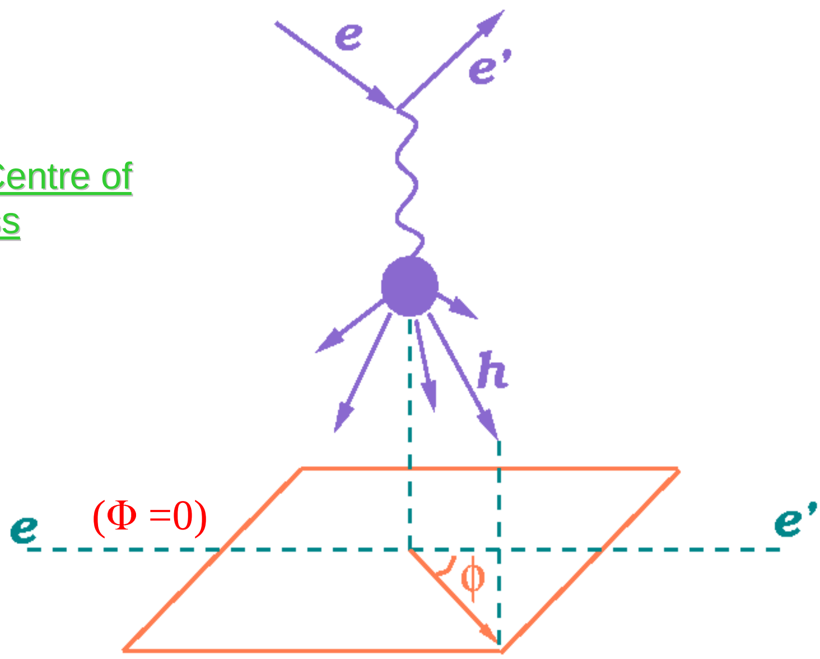
Azimuthal Asymmetries in DIS

ZEUS Collaboration

Azimuthal Distribution

Which angle

Hadronic Centre of mass



Clean test of pQCD (Georgi & Politzer, Phys Rev Lett 40 (1978) 3)

However

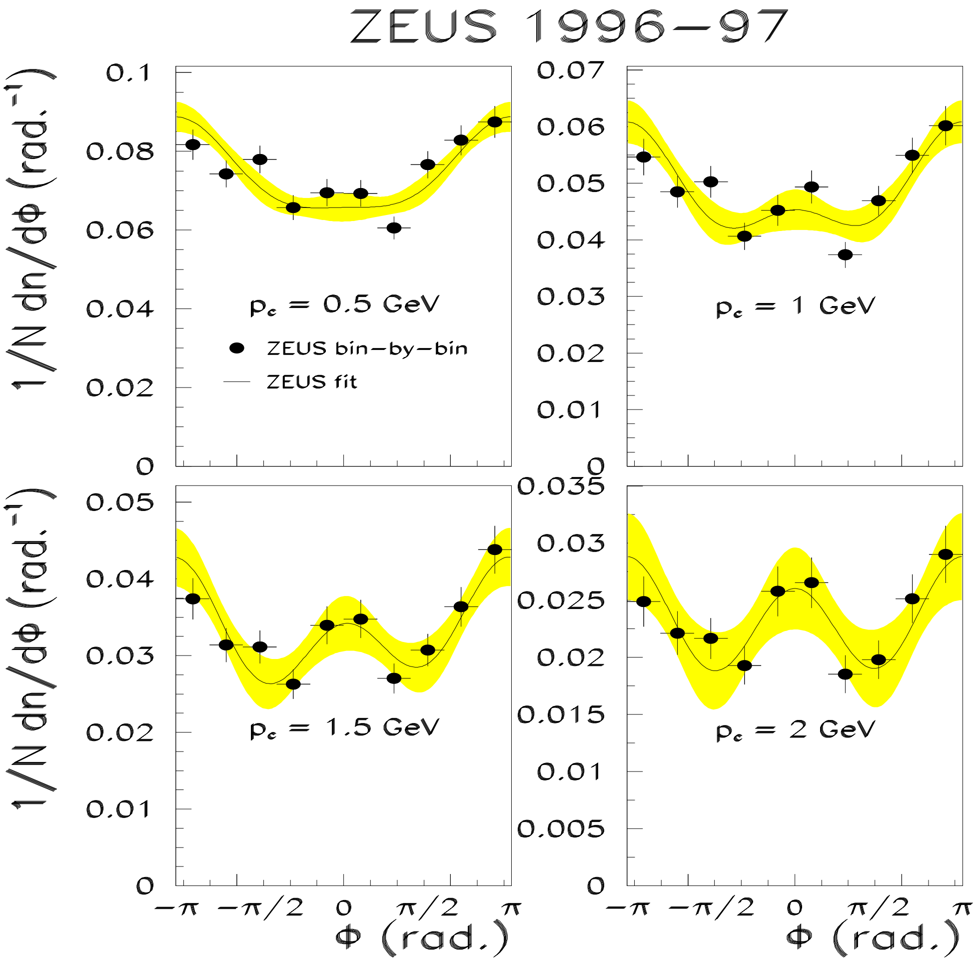
may be affected by non-pert. effects (intrinsic kt), Cahn Phys Lett B78 (1978) 269

But

pQCD effect can dominate at HERA energy (Chay, Ellis & Stirling, Phys Lett B269 (1991) 175)

Origin: polarization of the photon and spin of the quarks & gluons (& also coherence effects)

Azimuthal Distributions



Data: 38pb^{-1}; $180 < Q^2 < 7220$ GeV^2

'track' cut on z_h variable to select 'leading' particle:

$$z_h = \frac{P.p_h}{P.q}$$

where P is proton 4-vec; q exch boson 4-vec; p_h hadron 4-vec

$$0.2 < z_h < 1.0$$

boosted to hadronic centre of mass ($\gamma^* P$ frame)

at low p_c a clear cosΦ term

as $p_c \uparrow$ cos2Φ term becomes prominent

Theoretical Form

$$\frac{1}{N}\frac{dn}{d\Phi} = A + B\cos\Phi + C\cos 2\Phi + D\sin\Phi$$

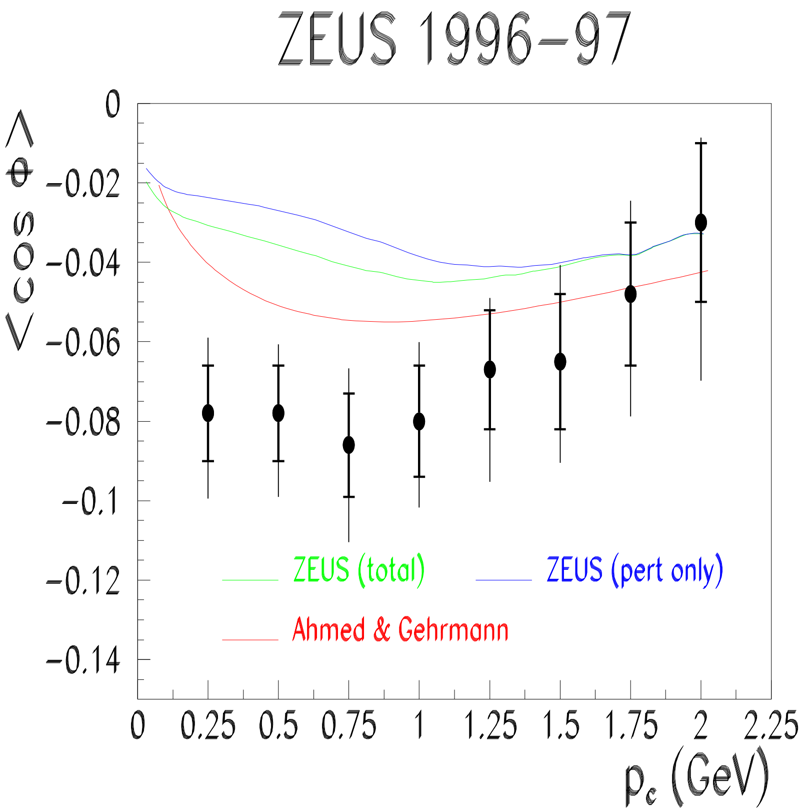
Moments: $\langle \cos \Phi \rangle = B/2A$

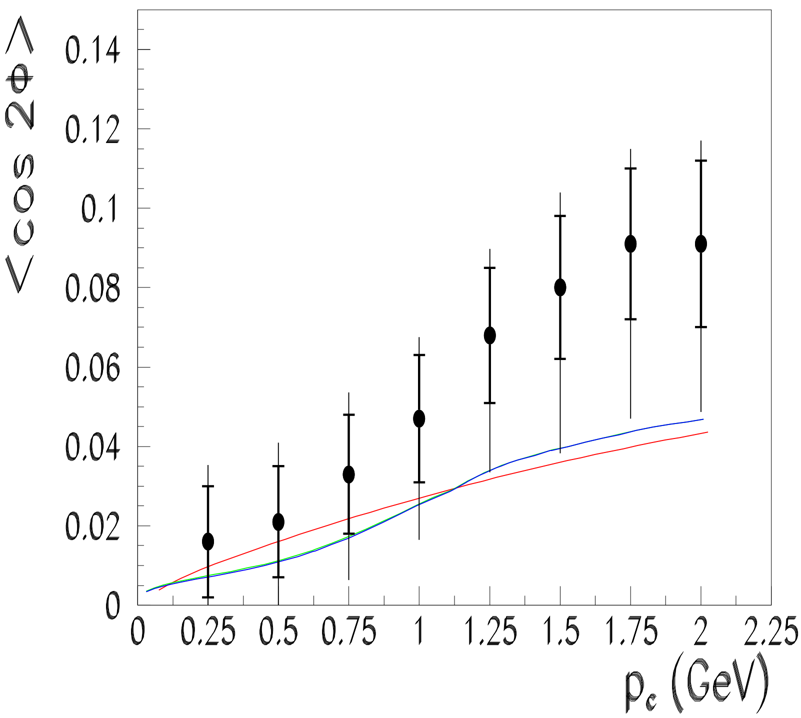
$\langle \cos 2\Phi \rangle = C/2A$ $\langle \sin \Phi \rangle = D/2A$

Theoretical code gives predictions for moments:

- ZEUS - based on work of Chay et al
- Ahmed/Gehrmann (Phys Lett B465 (1999) 297) - based on work of Hagiwara et al Phys Rev D27 (1983) 84

Comparison to LO theory





LO curves qualitatively reproduce the trends observed in the data - though they underestimate the magnitude

Possible reasons:

- BGF contribution ?

- non-perturbative effects ?

Non-pert effects (for mean intrinsic kt & frag p_T both set to 0.5 GeV) is at most 20% for cosΦ and negligible for cos2Φ

Summary

- cosΦ term is –ve
- first measurement of a cos2Φ term
- cos2Φ insensitive to non-pert effects
- first measurement of azimuthal asymmetry due to pert QCD
- LO predictions qualitatively describe the data

Multiplicity Moments in DIS at HERA

ZEUS Collaboration

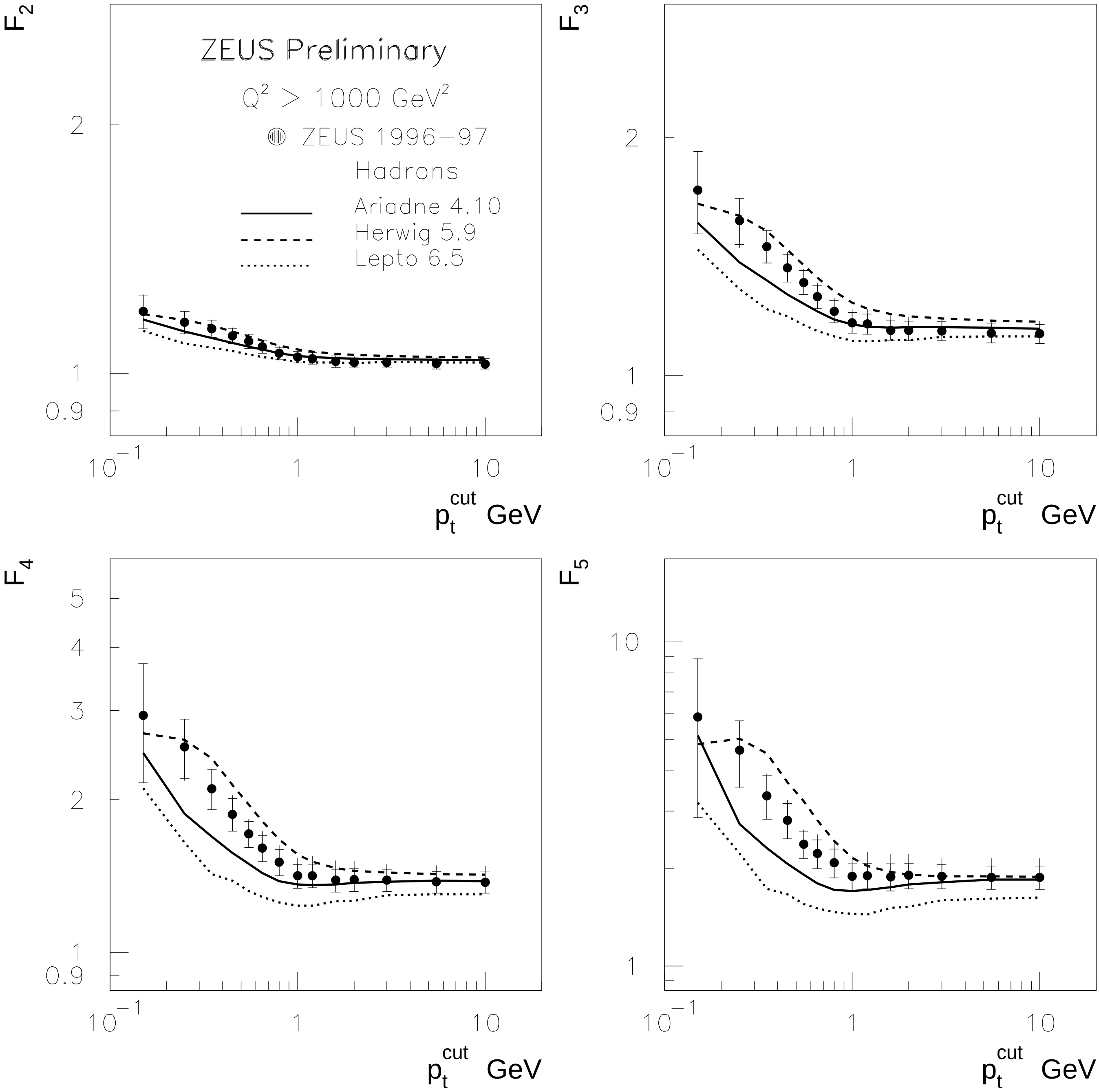
QCD calculations give for the normalized factorial moments of the multiplicity distributions:

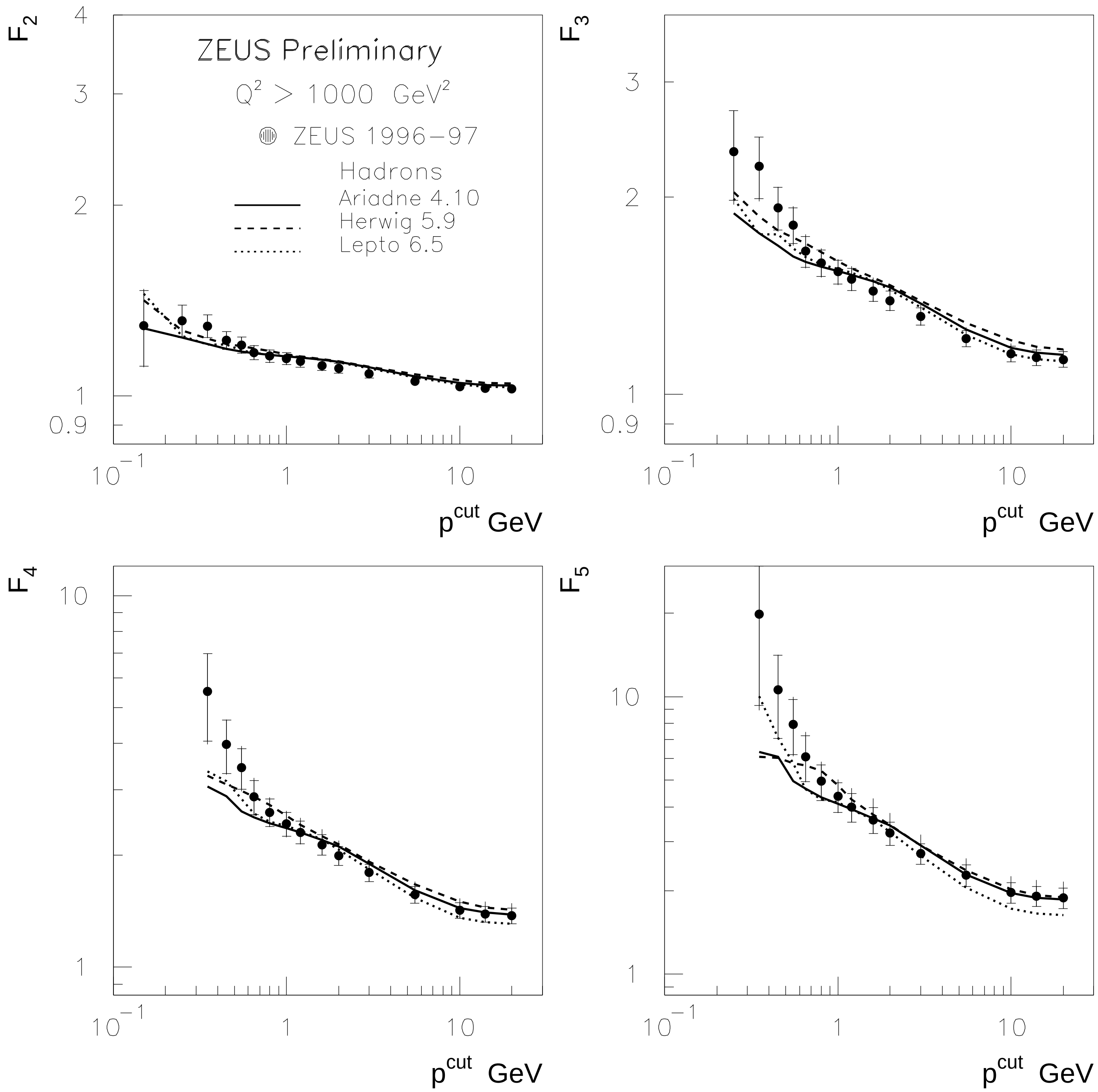
$F_q(p_t^{cut} \to 0) \simeq 1$

$F_q(p^{cut} \to 0) \simeq \mathrm{const} > 1$ (S. Lupia, W. Ochs and J. Wosiek)

Data: $Q^2 > 1000\,\mathrm{GeV}^2$

- Moments in current region of Breit frame show rise for $p_t/p \to 0$
- Suggest large non-perturbative effects





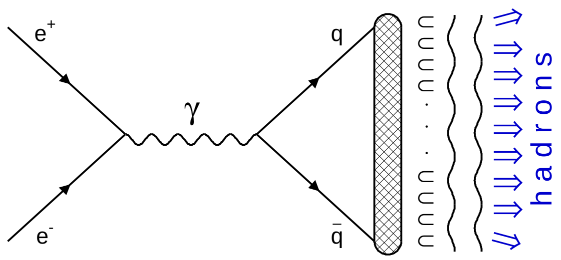
Conclusions

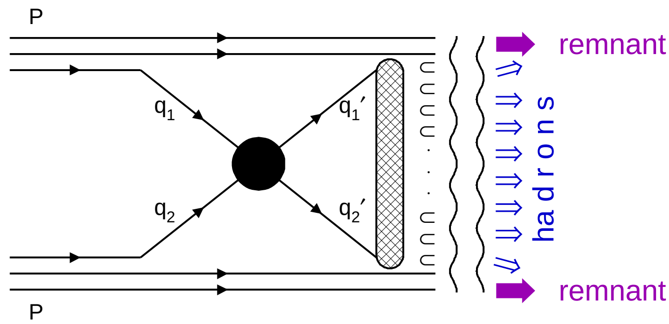
- The multiplicity moments measured in the current region of the Breit frame show a strong rise as the size of the restricted interval in p_t/p decreases
- Analytic calculations for partons do not show the same increase and thus cannot reproduce the correlation pattern of the hadronic final state
- Important to include hadronisation dynamics

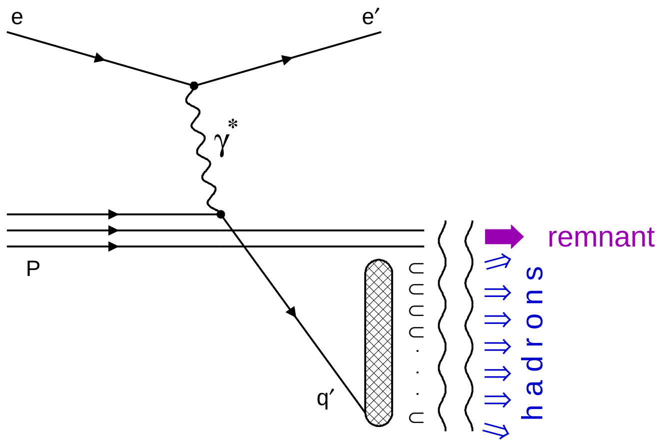
Multiplicity Distributions in DIS
ZEUS Collaboration

- study of colour dynamic at the pre-hadronisation stage

- check whether the universality of the multiplicity behaviour observed in lower energy experiments holds



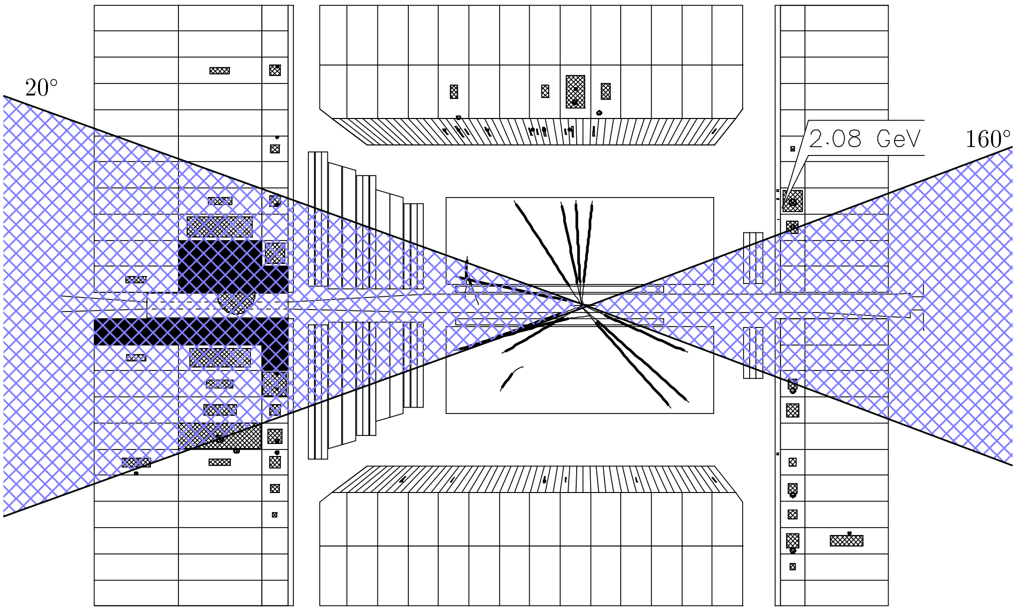




study: $\langle n_{\mathrm{ch}} \rangle$ vs. M_{eff}

$\Uparrow$ CTD $\quad$ $\Uparrow$ CAL within the CTD acceptance

$$M_{\mathrm{eff}}^2 = (\sum_{i \neq \mathrm{e}'} E^i)^2 - (\sum_{i \neq \mathrm{e}'} p_x^i)^2 - (\sum_{i \neq \mathrm{e}'} p_y^i)^2 - (\sum_{i \neq \mathrm{e}'} p_z^i)^2$$

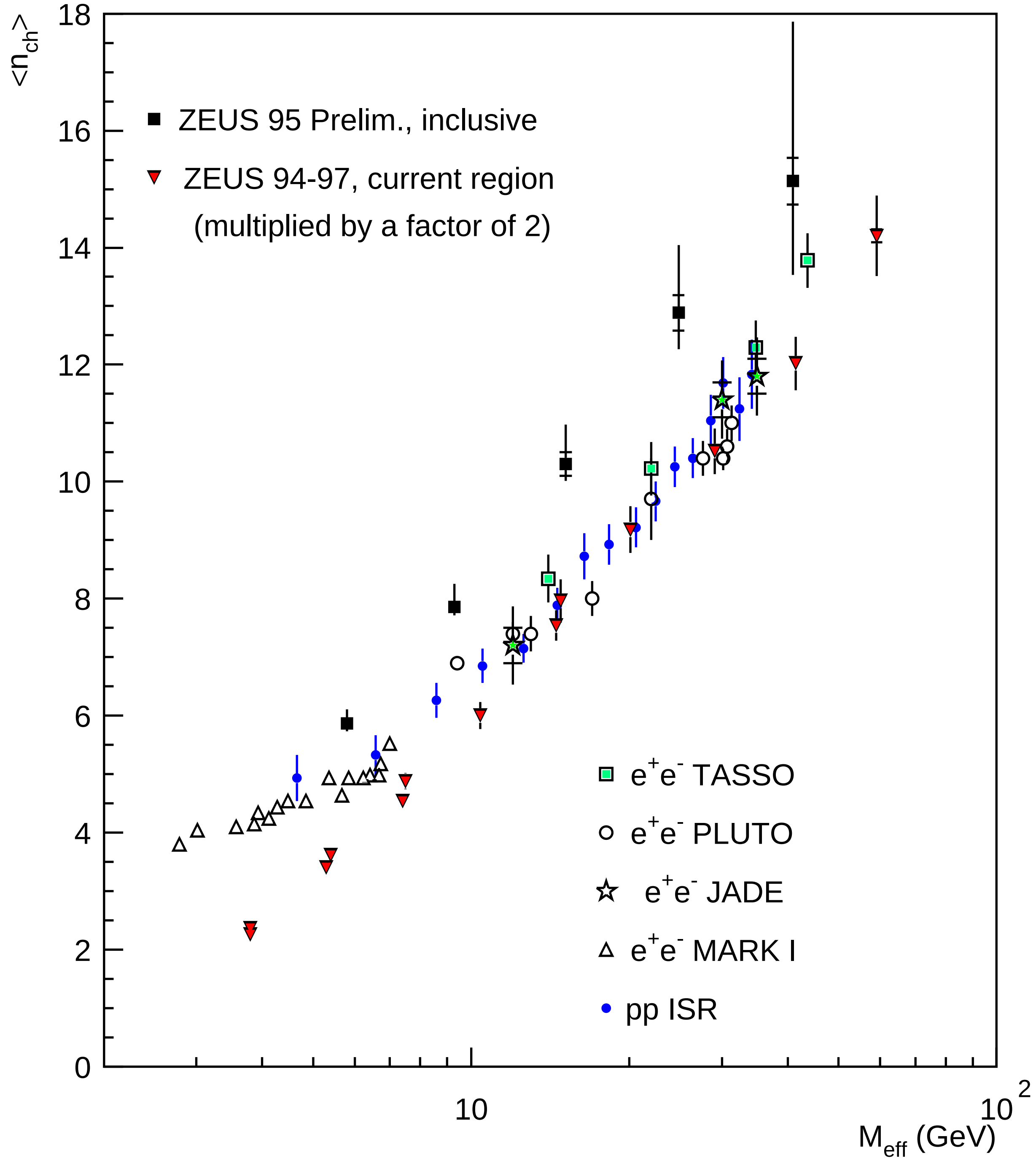


Kinematic Selections

1995 data $(5.5\,\mathrm{pb}^{-1})$

$8 < Q^2_{\mathrm{DA}} < 1200\,\mathrm{GeV}^2$

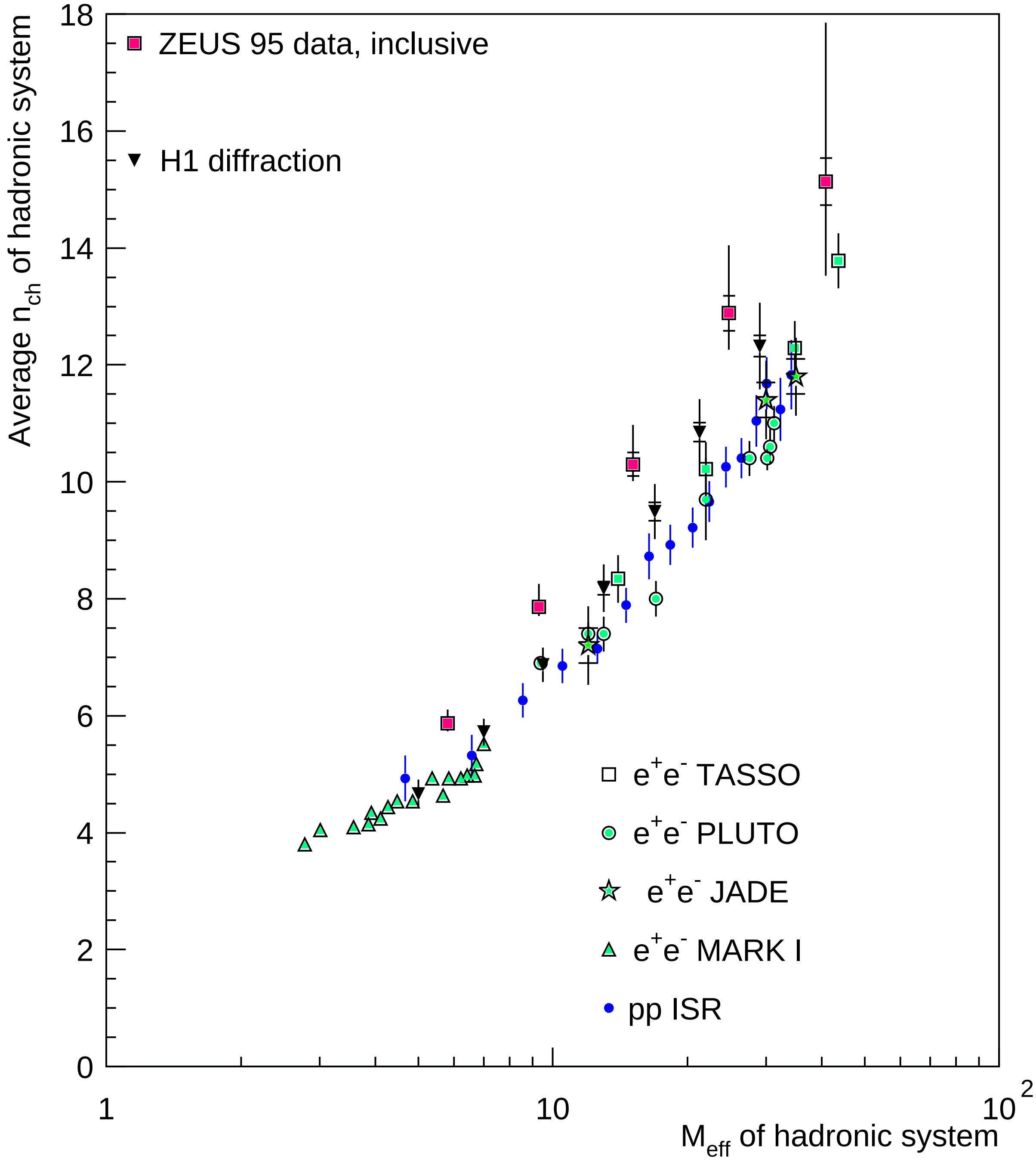
Particles with the angular acceptance $|\eta_{\mathrm{lab}}| < 1.75$



Comparison of the ZEUS data with the data from reactions with different initial particles.

For e^+e^- data $\rightarrow M_{\rm eff} = \sqrt{s_{e^+e^-}}$

For the ZEUS points in the current region $\rightarrow M_{\rm eff} = \sqrt{Q}$.



Comparison of the ZEUS inclusive data with the H1 diffractive data and with the data from other experiments

Conclusions:

- discrepancy with earlier data
- $\Rightarrow$ suggest non-negligible contribution from additional pQCD mechanism (due to colour octet charge radiation)

Summary

Hadronic final states proved to be a powerful tool for study of various aspects of the multiparticle dynamics:

- DIS instantons (H1)
- event shapes & power corrections (H1, ZEUS)
- baryon-antibaryon asymmetry (H1)
- azimuthal asymmetry (ZEUS)
- multiplicity studies (ZEUS)

A good laboratory to study the hadronisation physics - one of the least understood areas of non-perturbative QCD

Rich program of studies at HERA: many results not shown; many studies in progress . . .