Event Shape Studies at HERA

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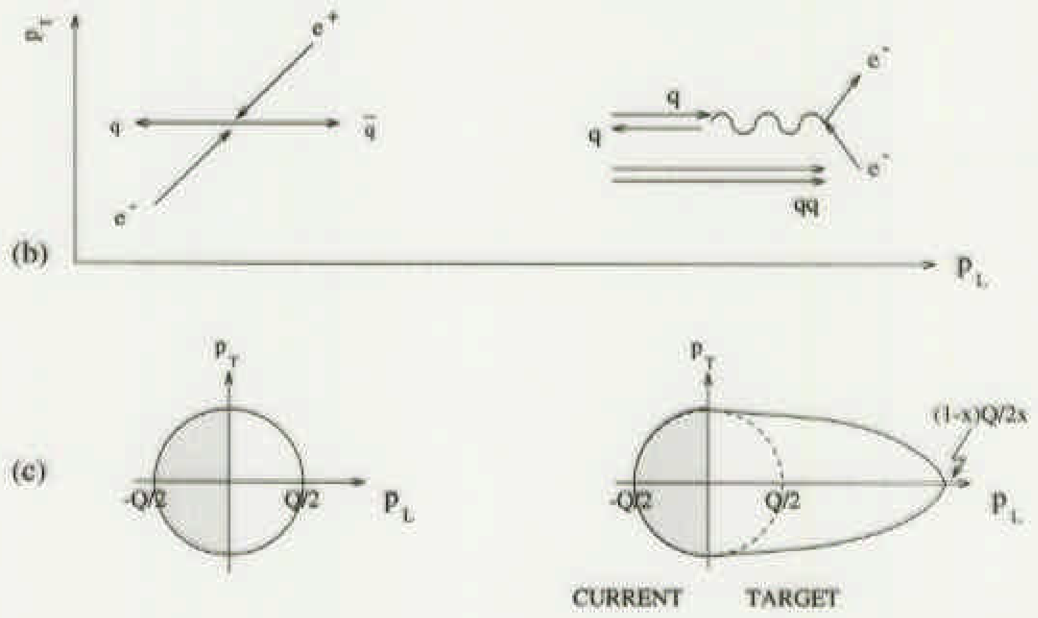
on behalf of ZEUS & H1

- ▷ **Data & Analysis Method**
- ▷ **Event Shapes in Current Hemisphere**
- ▷ **Power Corrections to Mean Values**
- ▷ **Jet Rates**
- ▷ **Event Shape Spectra**
- ▷ **Conclusions**

Data & Analysis Method

- **DIS analysis in Breit frame**

e^+e^- annihilation — ep DIS



- clean separation between current and target fragmentation
- particles in current hemisphere ⇔ e^+e^- hemisphere

▷ **QCD studies over large Q range in single experiment**

ZEUS #909, preliminary	**H1** #1006, EPJC 14, 255
$\mathcal{L} \simeq 45\ \mathrm{pb}^{-1}$	$\mathcal{L} \simeq 38\ \mathrm{pb}^{-1}$
$Q = 9 - 140$ GeV	$Q = 7 - 100$ GeV
tracks & clusters	calorimeter clusters
$E_{CH} > 0.03\,Q$	$E_{CH} > 0.10\,Q$
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**

▷ **Event shapes defined in Breit current hemisphere**

sum over all $p_h = \{E_h, \mathbf{p}_h\} \epsilon \, \mathrm{CH}$

- **Thrust**

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

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

- **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**

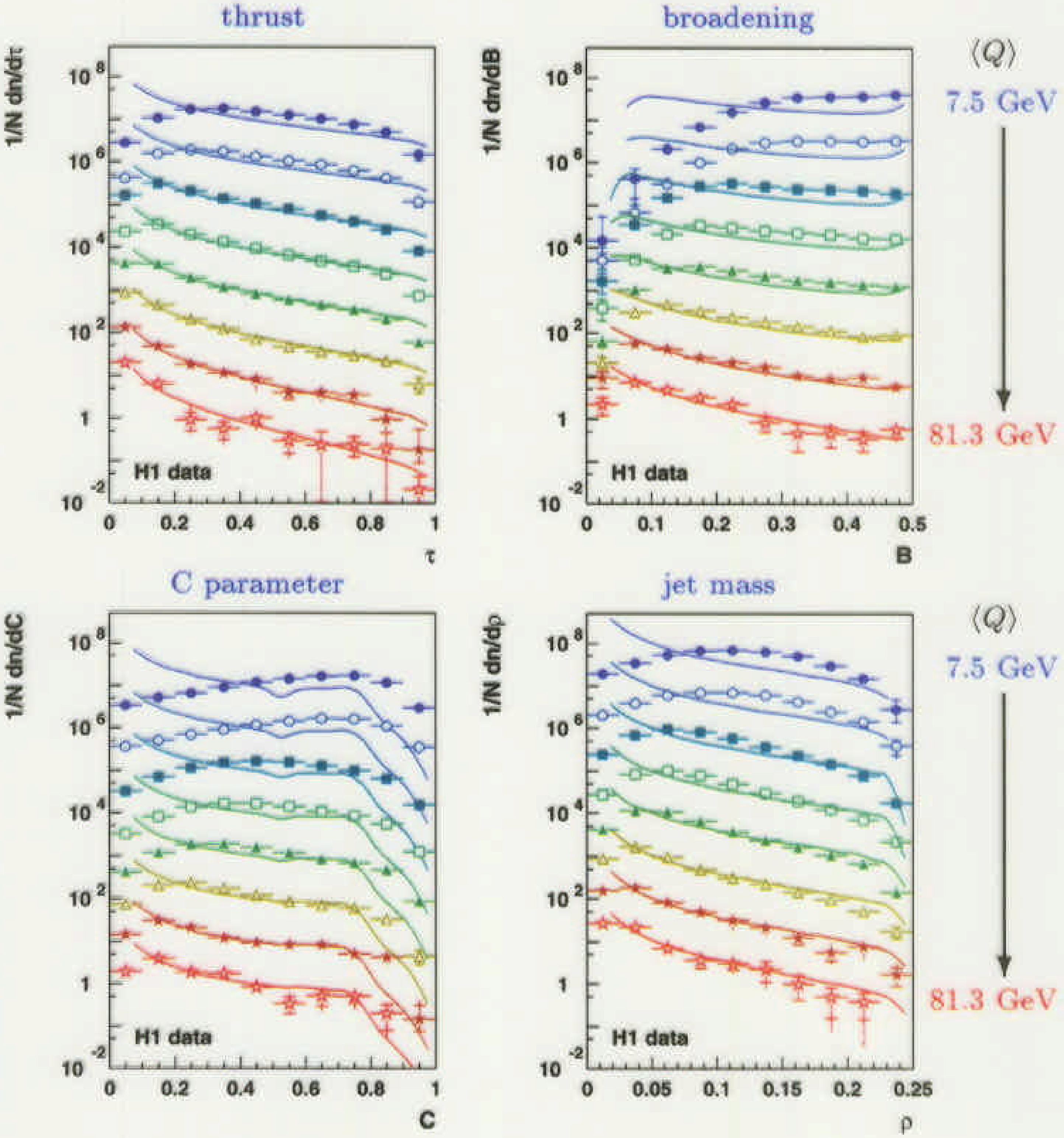
$$C = \frac{3\sum_{i,j} |\mathbf{p}_i||\mathbf{p}_j| \sin^2\theta_{ij}}{(2\sum_i |\mathbf{p}_i|)^2}$$

- **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

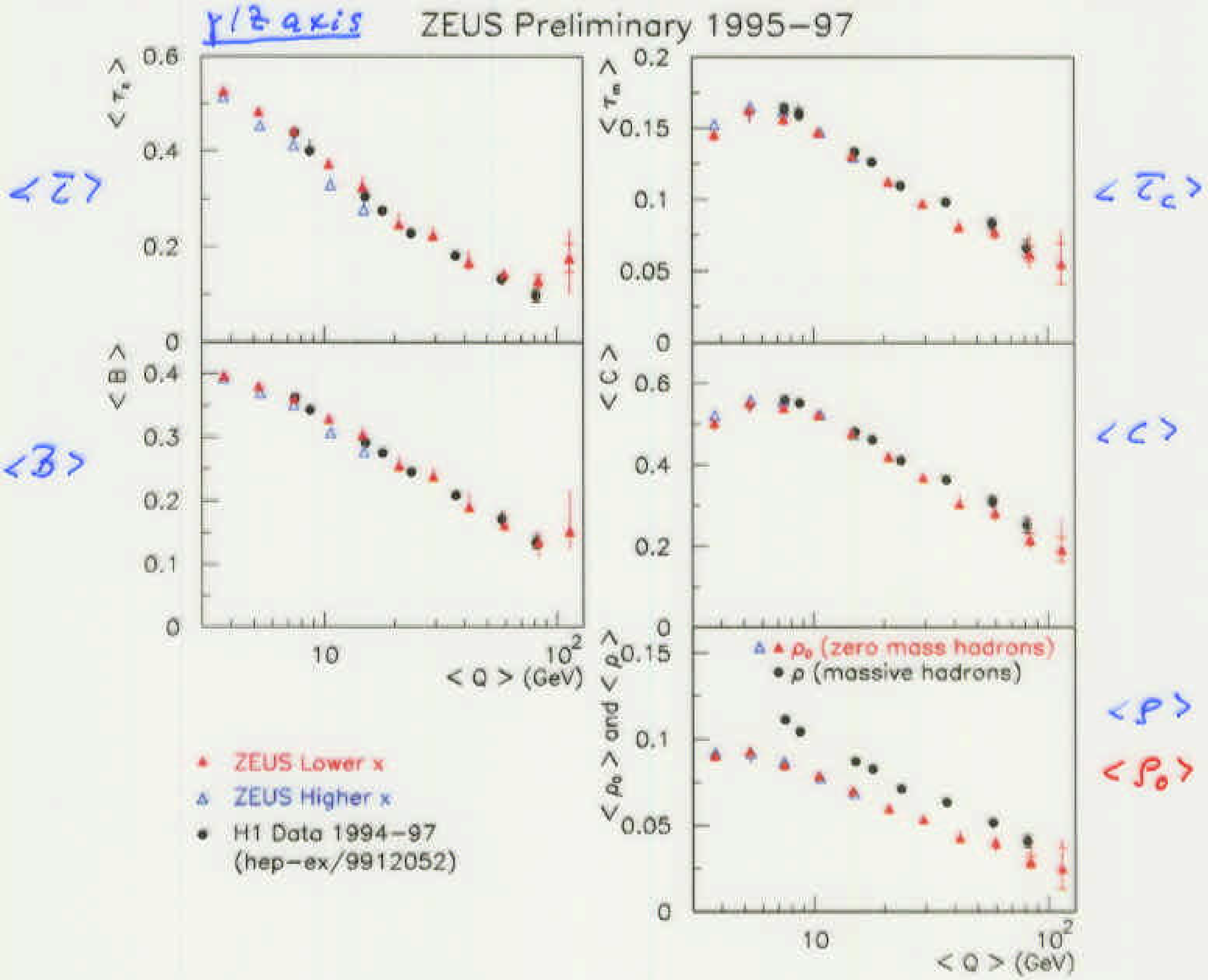
H1 Measurements Spectra



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

- Hadronisation corrections important, becoming smaller with increasing Q

ZEUS & H1 Measurements Mean Values



▷ **Event shape means $\langle F \rangle$ vs Q**
event topology gets more collimated with rising Q

- **Reasonable agreement between ZEUS and H1 data**
- **Jet mass different treatment of hadrons**

  ZEUS ρ_0 massless hadrons
  H1 ρ massive hadrons

- **ZEUS x dependent measurements**
  most apparent in τ_z, B

pQCD & Power Corrections

- **Mean value $\langle F \rangle$ of event shape variable**

$$\langle F \rangle = \langle F \rangle^{\text{pert}} + a_F \mathcal{P}$$

▷ **Perturbative part** $\mathcal{O}(\alpha_s^2)$ DISENT in $\overline{\text{MS}}$

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

▷ **Power corrections** Dokshitzer & Webber

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

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

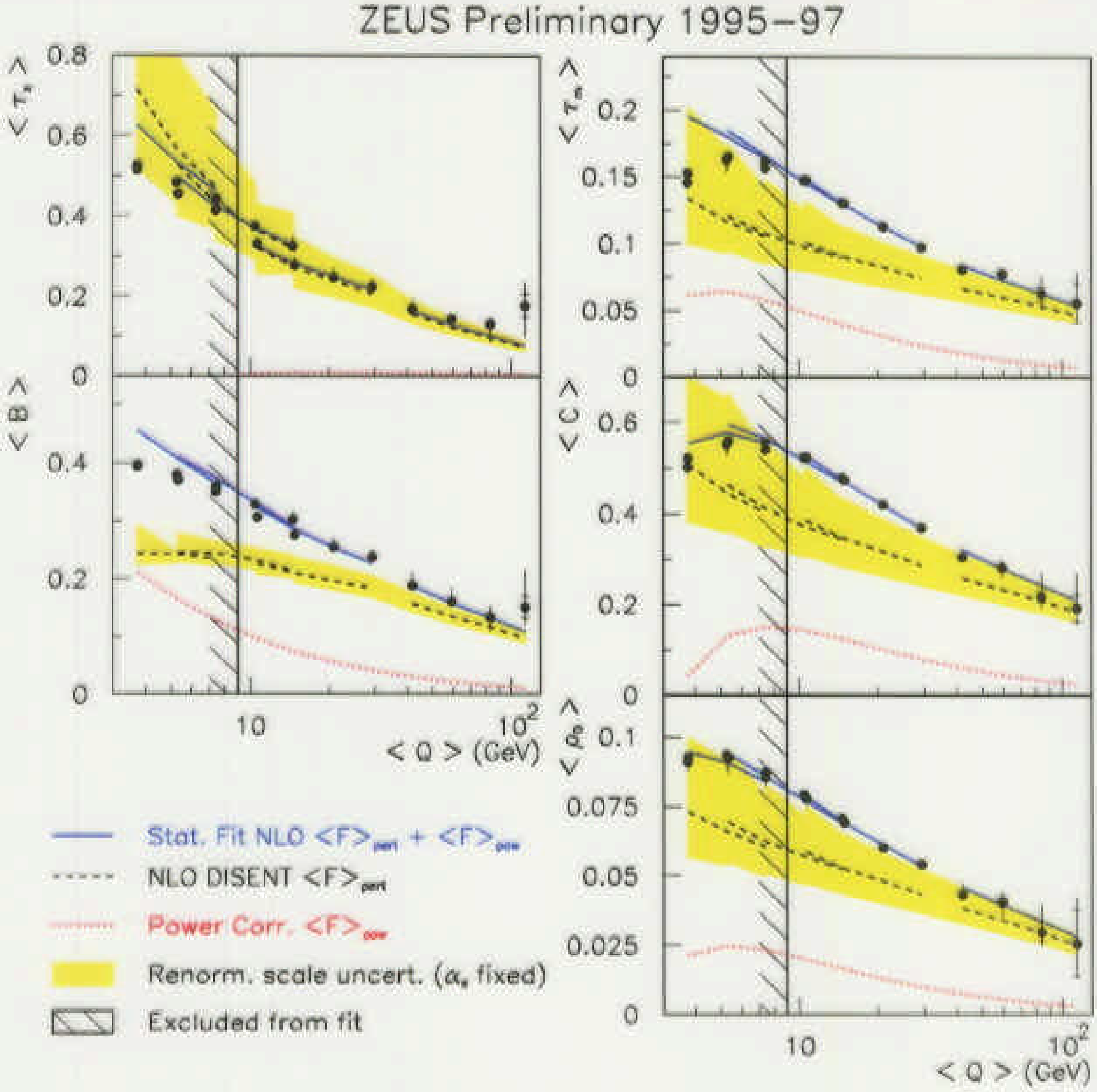
$$\bar{\alpha}_{p-1}(\mu_I) = p\,\mu_I^{-p}\int_0^{\mu_I} \mathrm{d}k_\perp\, k_\perp^{p-1}\,\alpha_s(k_\perp)$$

infrared matching scale $\mu_I = 2$ GeV

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

⇒ **2 free parameters** $\overline{\alpha}_{p-1}$ & α_s

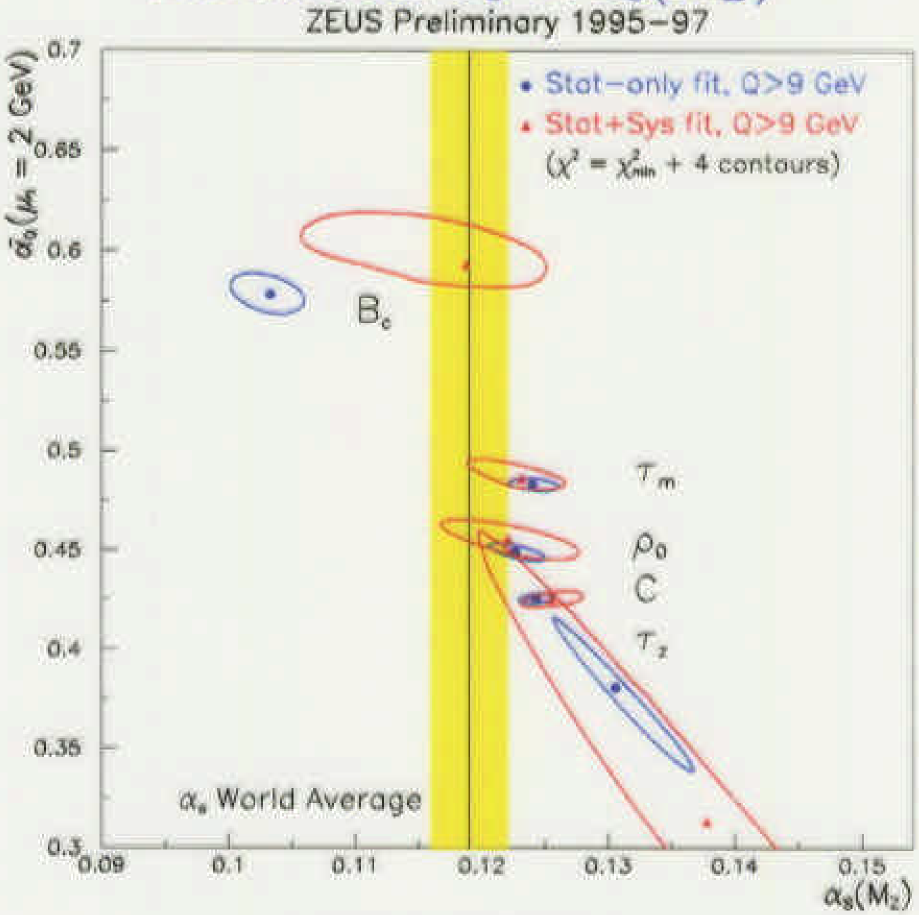
ZEUS QCD Fits $\overline{\alpha}_0$ & α_s



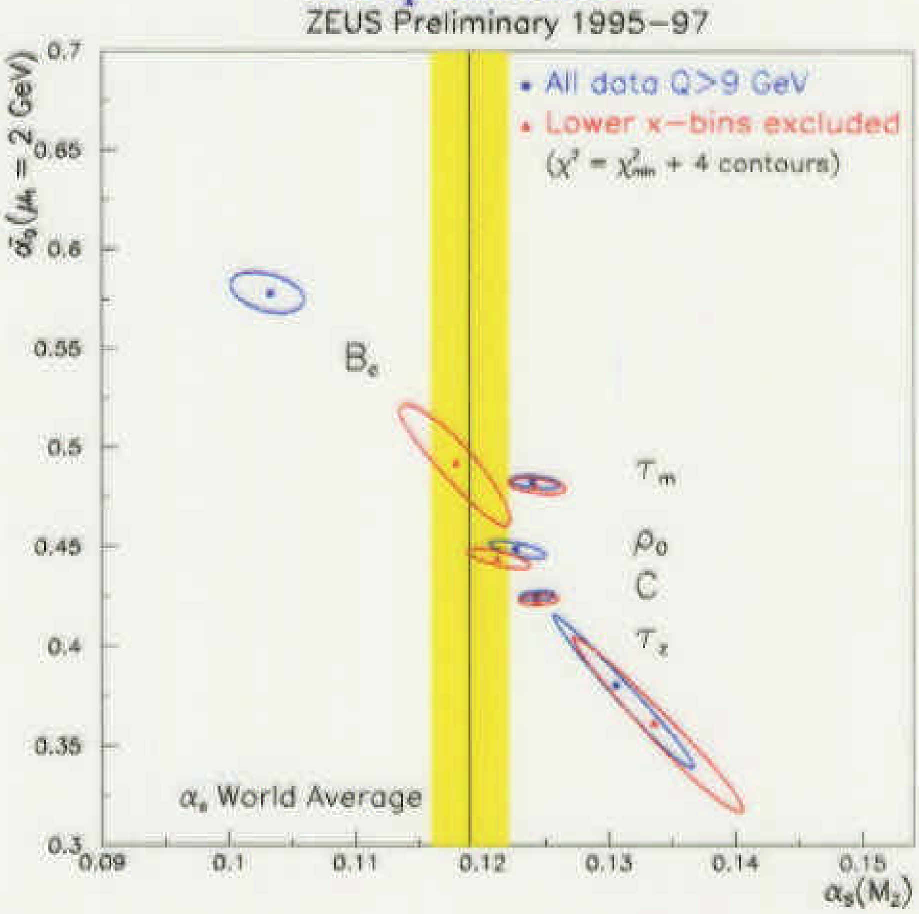
▷ **QCD analysis $Q > 9$ GeV, fit 2 parameters $\overline{\alpha}_0$ and α_s**

- **event shape variables τ_C, C, ρ_0 fit well common $\overline{\alpha}_0 \sim 0.5$ and α_s**
- **problems with event shapes B, τ_z** (def. wrt γ/Z axis) **apparent x dependence not well reproduced**
- **τ_z fit requires very small power corrections but strong correlations between $\overline{\alpha}_0$ and α_s**
- **large renormalisation scale uncertainties** (exceeding experimental errors by far!)

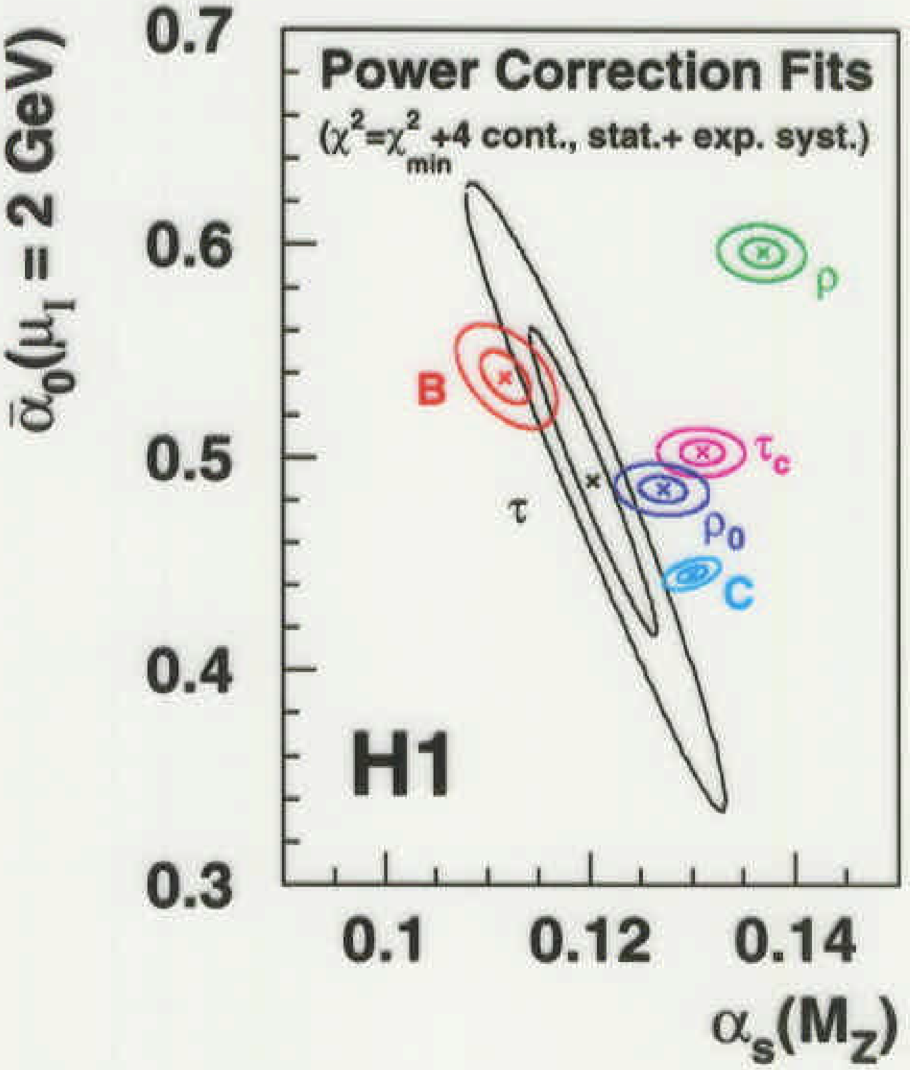
Correlations $\overline{\alpha}_0$ vs $\alpha_s(M_Z)$



x dependence



H1 Fits $\overline{\alpha}_0$ & α_s



- $\rho \to \rho_0$ large effect on massive/massless hadrons
- approximate universal power corrections $\overline{\alpha}_0 \simeq 0.5 \pm 0.1$
- spread in α_s higher order QCD, x dependence?

$\langle F \rangle$	$\overline{\alpha}_0(\mu_I = 2\text{GeV})$	$\alpha_s(M_Z)$
$\langle \tau \rangle$	$0.503\ ^{+0.043}_{-0.053}\ ^{+0.053}_{-0.068}$	$0.1190\ ^{+0.0075}_{-0.0054}\ ^{+0.0073}_{-0.0069}$
$\langle B \rangle$	$0.537\ ^{+0.017}_{-0.012}\ ^{+0.028}_{-0.039}$	$0.1113\ ^{+0.0036}_{-0.0028}\ ^{+0.0049}_{-0.0051}$
$\langle \tau_C \rangle$	$0.503\ ^{+0.008}_{-0.010}\ ^{+0.043}_{-0.047}$	$0.1310\ ^{+0.0023}_{-0.0028}\ ^{+0.0098}_{-0.0089}$
$\langle C \rangle$	$0.447\ ^{+0.005}_{-0.007}\ ^{+0.032}_{-0.038}$	$0.1301\ ^{+0.0016}_{-0.0020}\ ^{+0.0103}_{-0.0091}$
$\langle \rho \rangle$	$0.597\ ^{+0.009}_{-0.010}\ ^{+0.050}_{-0.057}$	$0.1374\ ^{+0.0024}_{-0.0032}\ ^{+0.0110}_{-0.0096}$
$\langle \rho_0 \rangle$	$0.486\ ^{+0.008}_{-0.010}\ ^{+0.043}_{-0.047}$	$0.1271\ ^{+0.0023}_{-0.0030}\ ^{+0.0102}_{-0.0089}$

Differential Jet Rates

▷ **Jet rates defined in whole Breit system of current *and* target region**

- **Event shapes employing jet algorithms**
- **Distance measures to combine particles into n jets and with the proton remnant $(+1)$**
  - **factorisable JADE algorithm**

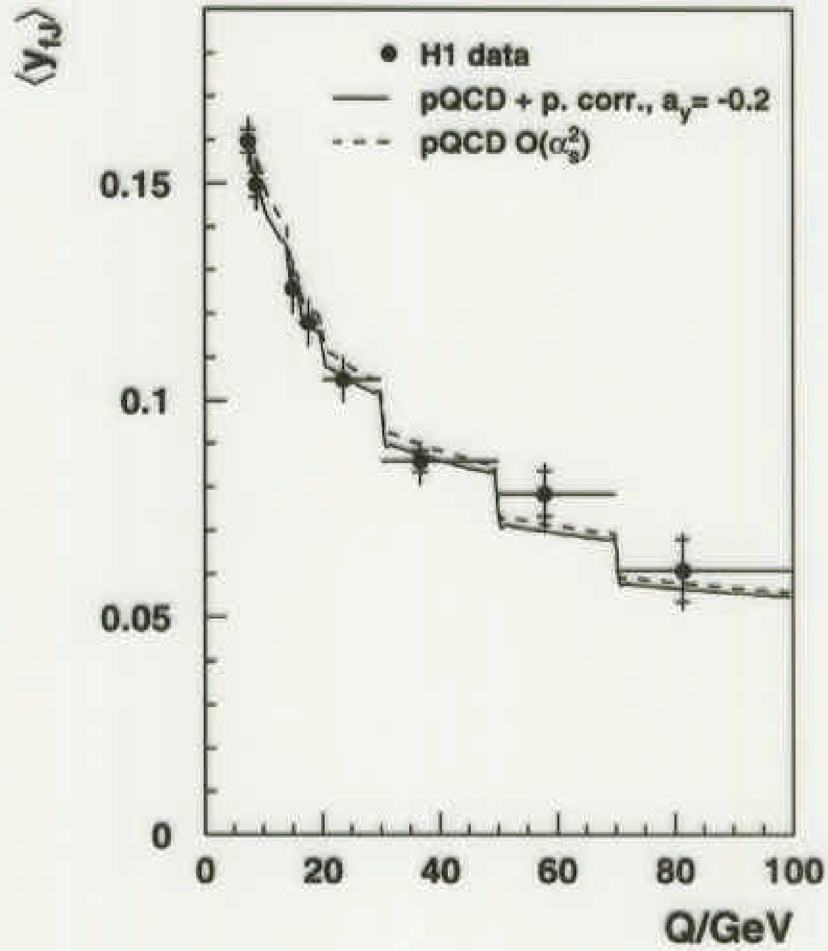
$$
\begin{aligned}
y_{ij} &= \frac{2\,E_i\,E_j(1-\cos\theta_{ij})}{Q^2} \\
y_{ir} &= \frac{2\,E_i\,x\,E_p(1-\cos\theta_i)}{Q^2}
\end{aligned}
$$

  - **Durham or k_T algorithm**

$$
\begin{aligned}
y_{ij} &= \frac{2\min(E_i^2,E_j^2)(1-\cos\theta_{ij})}{Q^2} \\
y_{ir} &= \frac{2\,E_i^2(1-\cos\theta_i)}{Q^2}
\end{aligned}
$$

▷ **Event shape variables y_{fJ} and y_{k_t} defined as the y_{ij} values at the transition $(2+1)\to(1+1)$ jets**

Factorisable JADE Algorithm $\langle y_{fJ} \rangle$



▷ **Observation of small hadronisation effects**

- **Predicted power corrections**

$$a_{y_{fJ}} = 1 \quad \text{and} \quad \mathcal{P} \propto 1/Q$$

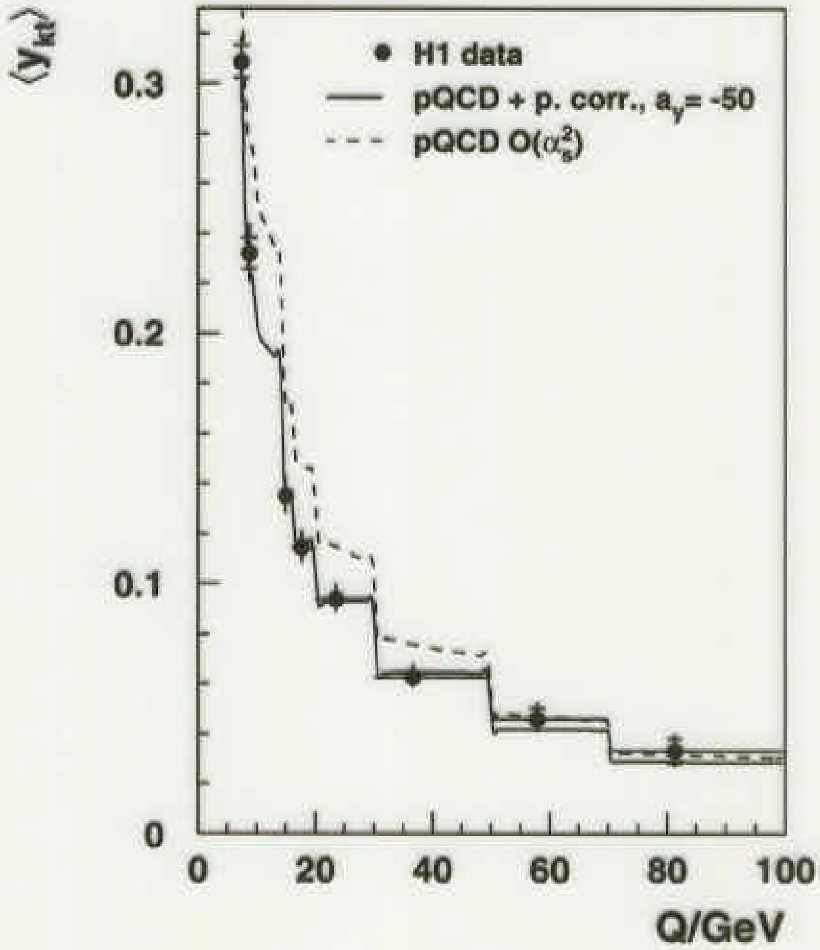
⇒ **Conjectured coefficient $a_{y_{fJ}}$ not supported by H1 data unreasonably low $\overline{\alpha}_0$**

- **Consistent fit obtainable with small negative coefficient**

$\langle F \rangle$	$a_{y_{fJ}}$	$\overline{\alpha}_0$	α_s	χ^2/df
$\langle y_{fJ} \rangle$	1	$0.28 ^{+0.02}_{-0.02}$	$0.105 ^{+0.005}_{-0.006}$	0.8
	-0.2	$0.37 ^{+0.20}_{-0.21}$	$0.116 ^{+0.008}_{-0.009}$	0.6

▷ **Need reevaluation of power correction calculations**

Durham or k_t Algorithm $\langle y_{k_t} \rangle$



▷ **Observation of small hadronisation effects**

- **Power corrections $\mathcal{P} \propto 1/Q^2$ expected**
  no calculations for $a_{y_{kt}}$ no estimate for $\overline{\alpha}_1$

⇒ **Behaviour $1/Q$ disfavoured by H1 data**

- **Consistent fit with power $1/Q^2$ and negative coefficient**

$\langle F \rangle$	$a_{y_{kt}}$	p	$\overline{\alpha}_{p-1}$	α_s	χ^2/df
$\langle y_{kt} \rangle$	1	1	$0.65\,^{+0.03}_{-0.04}$	$0.001\,^{+0.022}_{-0.012}$	7.2
	-50	2	$0.34\,^{+0.12}_{-0.11}$	$0.124\,^{+0.015}_{-0.014}$	0.6

▷ **Need calculation of $a_{y_{kt}}$**

Event Shape Spectra

▷ **Power corrections to event shape distribution**

$$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma(F)}{dF} = \frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{\rm pert}(F - a_F\mathcal{P})}{dF}$$

→ **shift identical to contribution to event shape mean**

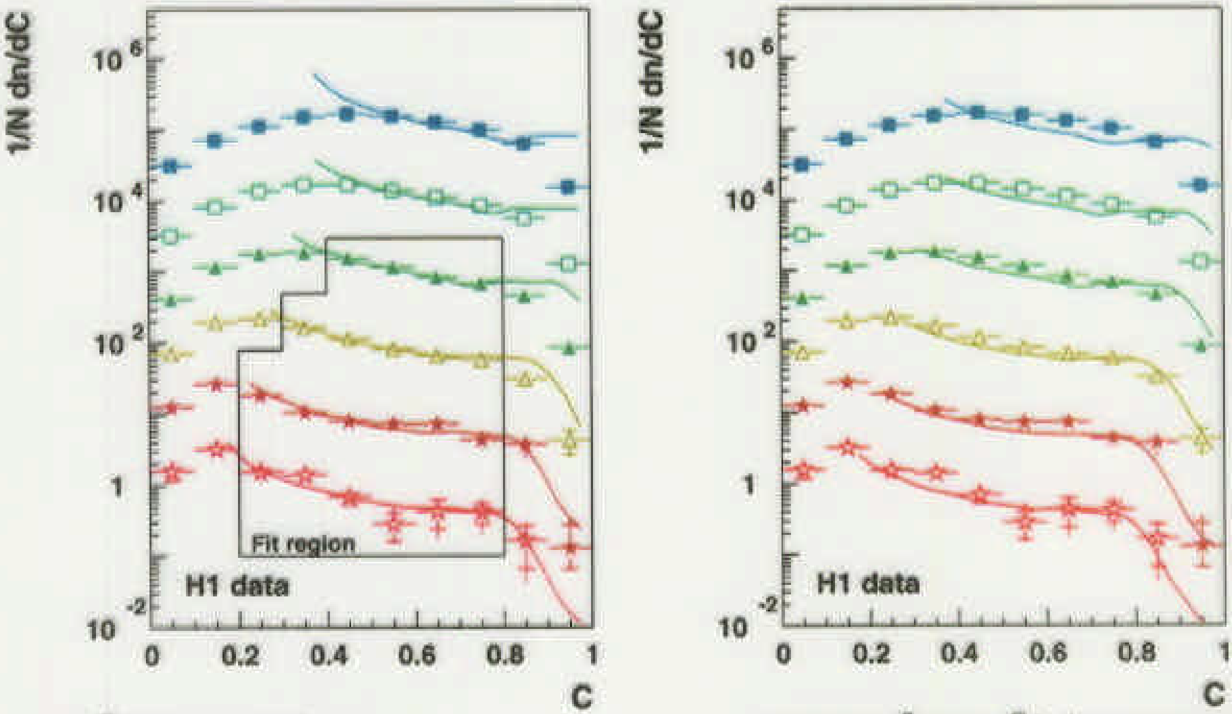
→ **applicable in central region** $\mu_I/Q \ll F \ll F_{max}$

- **Use data $Q > 14$ GeV to avoid huge hadronisation**

▷ **Event shapes in current hemisphere**

- **$\bar{\alpha}_0$ and $\alpha_s(M_Z)$ from fits to spectra in general inconsistent with those from fits to means**
  (larger values $\overline{\alpha}_0$, α_s preferred)

C parameter



fit to spectra $\bar{\alpha}_0 = 0.62,\ \alpha_s = 0.131$

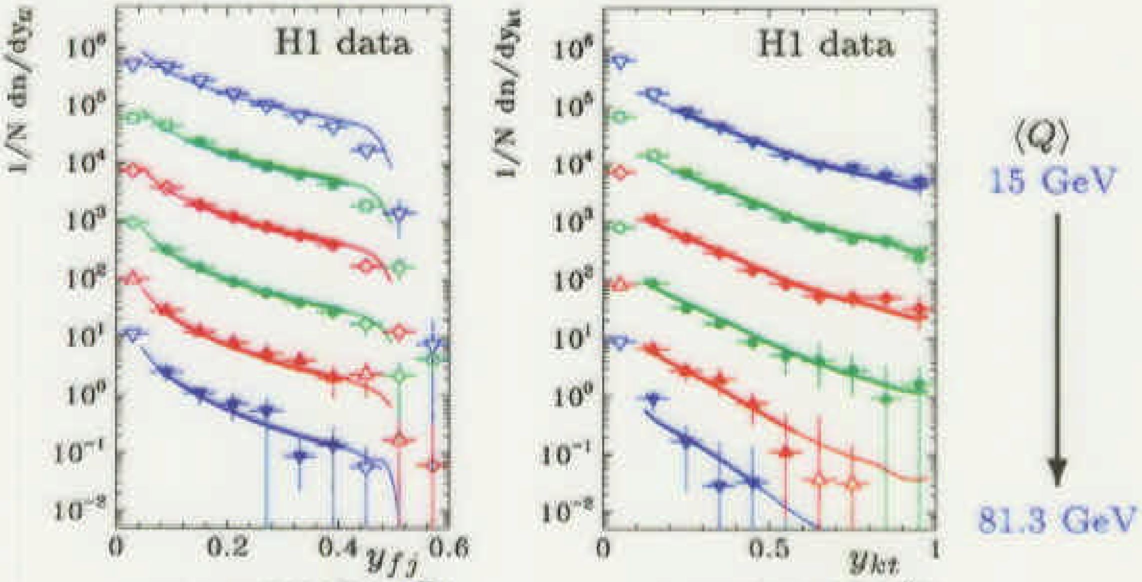
curves from fit to means $\bar{\alpha}_0 = 0.45,\ \alpha_s = 0.130$

⇒ **Hope: better understanding with resummed calculations**

work in progress   theory & experiment

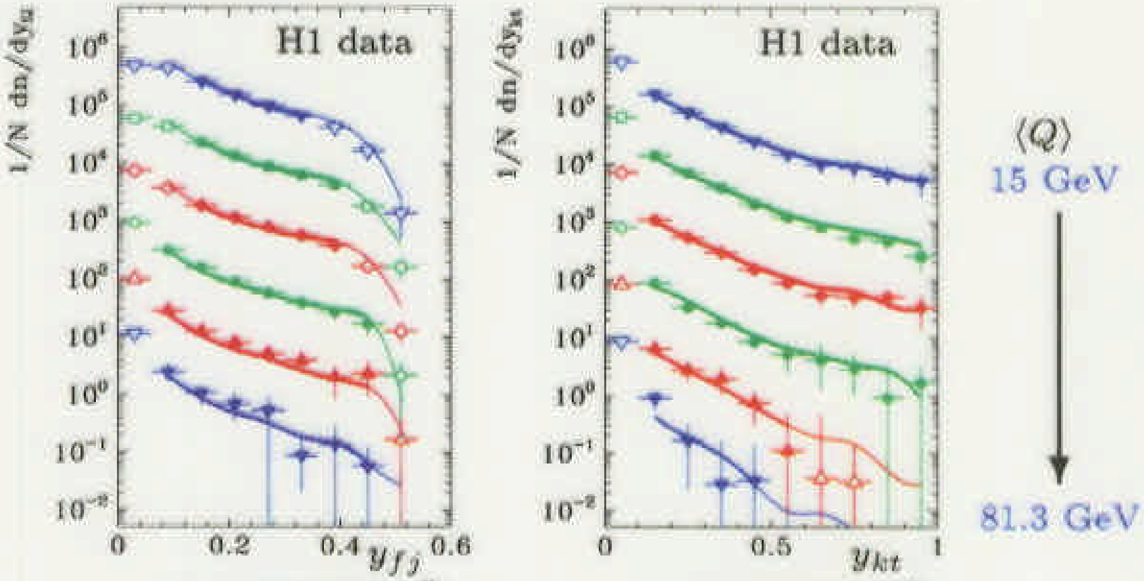
▷ **Jet rates y_{fJ} & y_{kt} small hadronisation contributions**

a) discard power corrections $a_y \mathcal{P} = 0$



$\alpha_s = 0.116(3)^{y_{fj}}$ $\alpha_s = 0.118(3)^{y_{kt}}$

b) apply MC hadronisation corrections (< 20%) to pQCD



$\alpha_s = 0.119(3)^{y_{fj}}$ $\alpha_s = 0.116(3)^{y_{kt}}$

▷ **Spectra in central part well described by pQCD without and with hadronisation corrections**

▷ **Encouraging prospects to determine $\alpha_s(M_Z)$**

Conclusions

- ▷ Zeus and H1 provide precise and consistent data on event shape variables in DIS over a large range of momentum transfer $Q = 7 - 140$ GeV
- ▷ Sizeable hadronisation for τ, τ_c, B, C, ρ, ρ_0

  Q dependence of mean values well described by
  - pQCD & power corrections
  - universal parameter $\overline{\alpha}_0 \simeq 0.5 \pm 20\%$

  Data require refinement of theory
  - spread in $\alpha_s(M_Z)$ missing higher orders?
  - x dependence of B, τ reliability of coeff. a_F?
- ▷ Small, negative hadronisation for jetrates y_{fJ}, y_{kt}
  - Jade y_{fJ} conjectured coeff. $a_{y_{fJ}} = 1$ excluded
  - Durham y_{kt} support $1/Q^2$ power, $a_{y_{kt}}$ unknown

  ⇒ more work to be done for y_2 variables
- ▷ Event shape spectra – a rich potential
  - fits to spectra (without resummation) inconsisitent with results from means
  - spectra of jet rates reasonably well described even without power corrections

  ⇒ improvements with resummed calculations?
- ▷ Event shape studies at HERA support the basic concept of approximate universal power corrections