Measurement of Event Shape Variables in Deep Inelastic Scattering at HERA

- General idea of the event shape measurement
- Event shapes in Breit frame
- Power Corrections
- QCD theory of the event shapes in DIS
- Data selection
- Results and QCD fit
- Summary and conclusions

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General idea of the event shape measurement

$F_2(x,Q^2)$

$\frac{d\sigma}{dF}$

$\frac{d\sigma_j}{dE_t}$

$\sum_n PhS_n$

$\sum_n \int \mathrm{F}(PhS)_n$

$\sum_{E_t > E_{\min}} \sigma_{jet} PhS_{jet}$

Integrate over all hadronic final states

Average observable F over all hadronic final states, no min. E_t. Event shapes probe deep into nonperturbative region : test of Power Correction technique

Pick up particular jet state, perturbative

(min. E_t > e.g. 2 GeV)

F:

- Characterize event topology (different values for one- two- and multi-jet configurations)
- Are collinear and infrared safe (CIS)

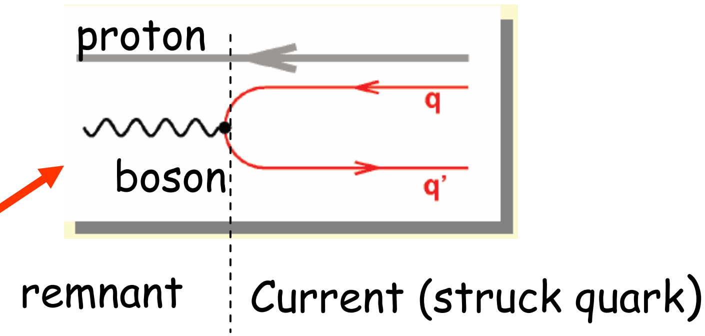
Events shapes in Breit Frame

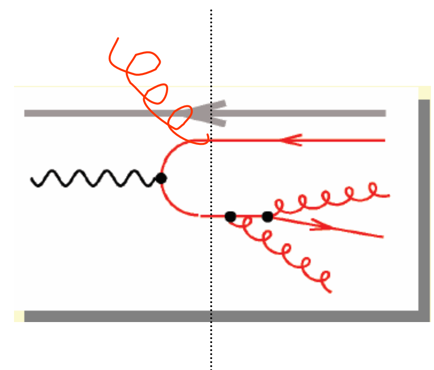
- In parton model picture (Born level) transformation to Breit Frame (BF) alignes proton, exchanged boson and struck quark

- Particles building proton remnant follow in proton direction (remnant hemisphere - RH) while struck quark fragments go into opposite, current hemisphere (CH) . BF provides best separation from proton remnant particles for which QCD calculations do not account

- Event shapes F are calculated by summing over all hadronic final state objects in current hemisphere

- In presence of QCD radiation picture is more complex : parton fragments can leak into RH, CH can be even empty so the definition of event shape contains condition of minimal energy in CH





$$\sum_h E_h > \epsilon_{\text{lim}} = Q/10$$

Event shapes in Breit Frame

- Event shapes F are defined such that F→0 for pencil-like hadron configurations aligned with z-axis.
- Born level quark in Breit Frame has $p_T=0$ so its fragments produce $F \approx 0$
- Multijet configurations produce F > 0 in extreme $F \approx 1$

$$\tau = 1 - \frac{\sum_h |\vec{p}_{z,h}|}{\sum_h |\vec{p}_h|}$$

thrust

$$B = \frac{\sum_h |\vec{p}_{t,h}|}{2\sum_h |\vec{p}_h|}$$

Jet broadning

Z-axis parallel to exchanged boson

Reference to axis external to HFS – sensitive to quark recoil effect due to QCD radiation

τ_C : thrust a la e^+e^- ; z || axis maximizing thrust

ρ: Jet invariant mass

C-parameter, hadron-hadron correlation

$$C = \frac{3}{2} \frac{\sum_{h,h'} |\vec{p}_h| |\vec{p}_{h'}| \sin^2 \theta_{h,h'}}{(\sum_h |\vec{p}_h|)^2}$$

No reference to external axis

All event shapes are normalized to total momentum – less sensitive to uncertainty of hadronic calorimeter scale !

Power correction: analytical description of hadronisation

Standard way (applied in most QCD studies) uses for hadronisation Monte Carlo programs : JETSET, PYTHIA, HERWIG, PHOJET etc.

Power corrections: part of ambitious program to describe hadronic final states in terms of Feynmann diagrams parametrizing confinement with one universal constant

Power corrections provide much cleaner connection between parton and hadron levels

$$\alpha_0 = \frac{1}{\mu_I} \int_0^{\mu_I} dk \alpha_s(k^2) \quad \mu_I = 2\,\mathrm{GeV}$$

„average infrared coupling"

„effective nonperturbative coupling"

- Choose C&IS observable, get NLO+NLL pQCD prediction
- For scales below μ_I apply α_0
- do it again for other observables
- Check that α_0 is universal, i.e. the same for different observables, processes (e^+e^-, DIS, hadron-hadron), perturbative scale Q, DIS kinematics …

QCD Theory used to fit the event shape distributions

Theory element	Package	Authors
pQCD prediction in NLO $\frac{1}{\sigma}\frac{d\sigma^{NLO}}{dF} = c_1(F,Q)\alpha_s(\mu) + c_2(F,Q)\alpha_s^2(\mu)$	DISENT DISPATCH	Graudentz, Dasgupta, Salam
Resummation of terms $L=\alpha_s \log2(1/F)$ + matching to NLO Valid for not too small F→ available only for distributions (not for means)	DISRESUM	Dasgupta, Salam (2002)
Power correction for hadronisation $\frac{1}{\sigma_{tot}}\frac{d\sigma(F)}{dF} = \frac{1}{\sigma_{tot}}\frac{d\sigma^{pQCD}(F - a_F P)}{dF}$ Factor a_F calculated from Feynman diagrams for each observable $P=P(\alpha_0,\alpha_s)$ is a universal function	Analytic form	Dokshitzer, Webber, Dasgupta, Salam

$$\mathcal{P} = \frac{16}{3\pi}\mathcal{M}\frac{\mu_I}{Q}\left[\alpha_0(\mu_I) - \alpha_s(Q) - \frac{\beta_0}{2\pi}\left(\ln\frac{Q}{\mu_I} + \frac{K}{\beta_0} + 1\right)\alpha_s^2(Q)\right]$$

The Data

- Inclusive high Q^2 NC DIS selection 1995-2000 (HERA 1): 106 pb^{-1}
- Phase space : $196 < Q^2 < 40{,}000$ GeV^2 $0.1 < y < 0.8$
  - Selected Events: 107,693 ← Large !
  - Binning in Q

# of Q bin	1	2	3	4	5	6	7
Interval/GeV	14-16	16-20	20-30	30-50	50-70	70-100	100-200
Events	26614	35324	30536	12015	2102	867	235

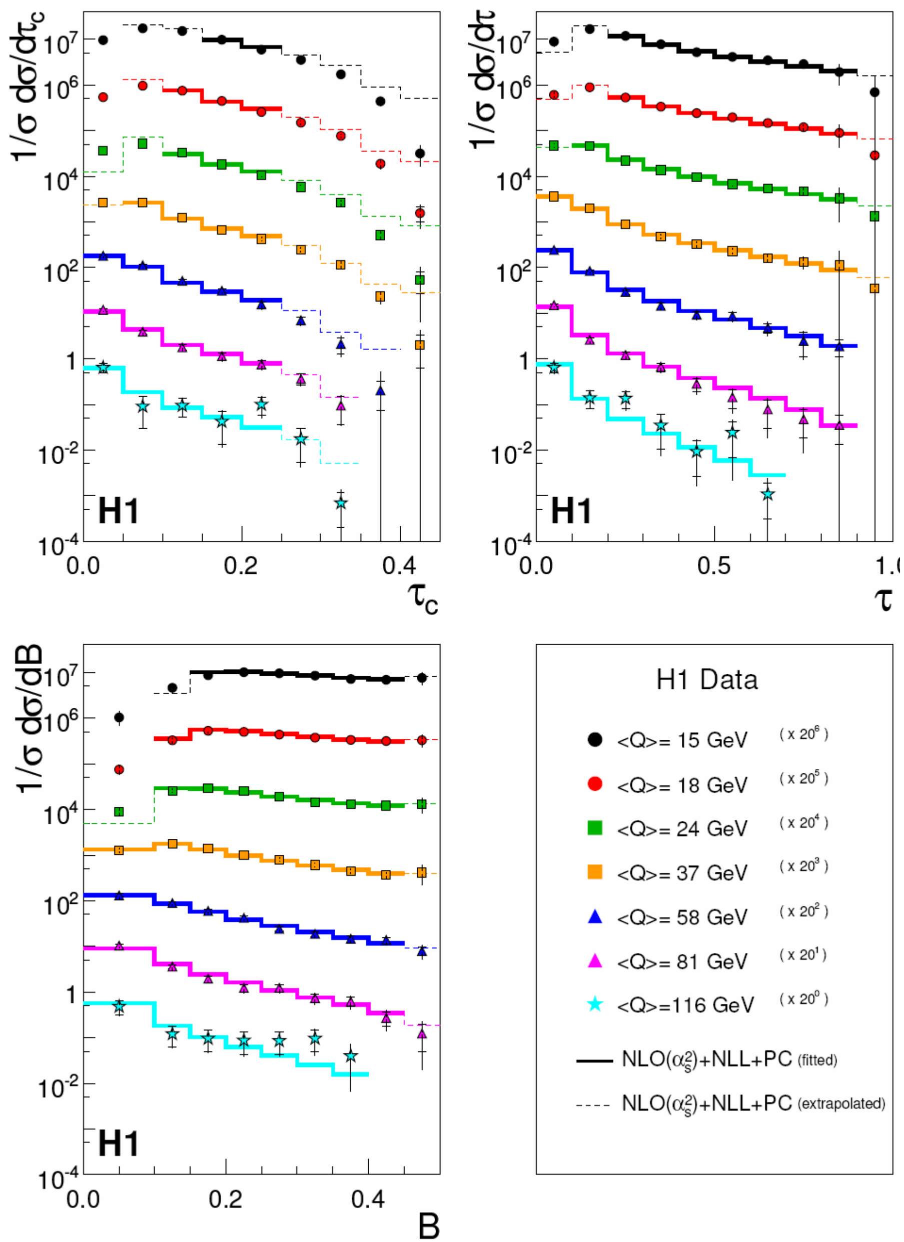
  - Binning in event shape variables, 8-10 bins

- Background (mainly from γp) negligible in all 322 bins

Corrections using RAPGAP 2.8 in two steps:

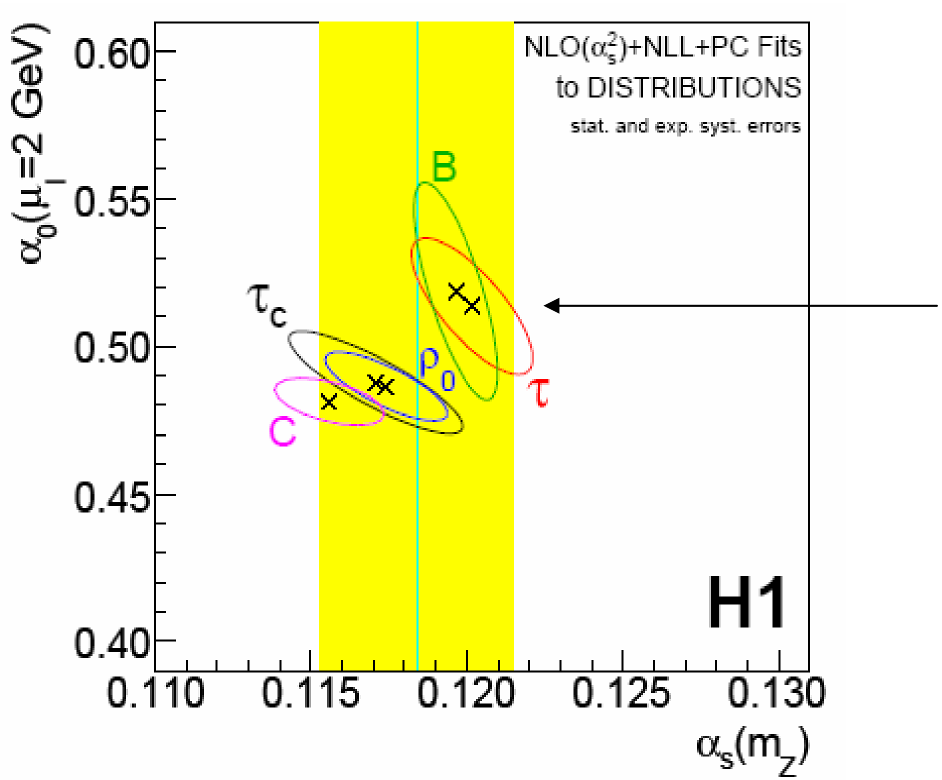
- For limited detector resolution: Bayes unfolding (d'Agostini)
- For limited acceptance & QED : bin-to-bin

H1 data for thrust, jet mass, C-parameter and jet broadning (,τ, τ_C, ρ, C, B)



- Not all data points are used in NLO+NLL+PC fit ▬ : theory has limited range of applicability
- Fit extrapolation ······ to „forbidden" data points seems to work in many cases
- Except for highest Q^2 bins errors are really small !

Fitted values of α_0 and α_s



Fitted α_s consistent with world average

- Results of NLO+NLL+PC fit to events shapes in (α_s α_0) plane
- Two groups of points correspond to event shapes with and without reference to exchanged boson axis
- Consistency within each group excellent (few %)
- Overall consistency also good α_0 = ~0.5, consistent within ~10%
- consistent with e+e- event shapes~15%
- strong support for α_0 universality !

$$\alpha_s(m_Z) = 0.1198 \pm 0.0013\ (\text{exp})\ {}^{+0.0056}_{-0.0043}\ (\text{theo})\ ,$$

$$\alpha_0 = 0.476 \pm 0.008\ (\text{exp})\ {}^{+0.018}_{-0.059}\ (\text{theo})\ ,$$

Note large theory uncertainty

Results of event shape NLO+NLL+PC fits

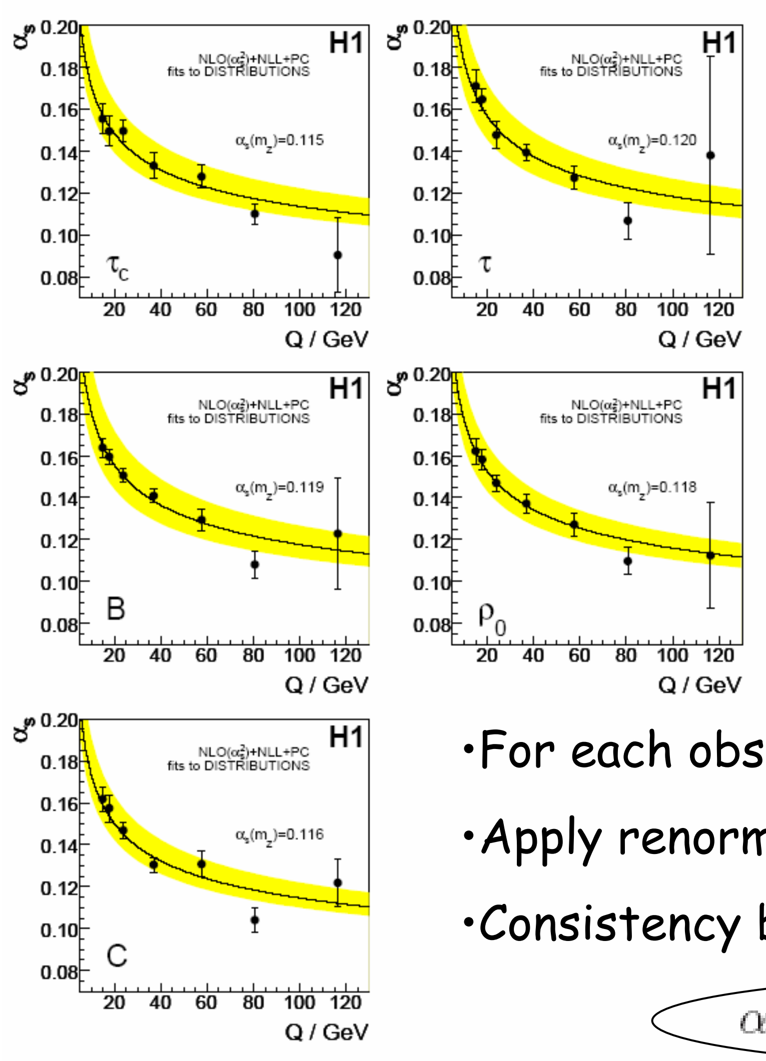
hep-ex/0512014, accepted by Eur. Phys. J.

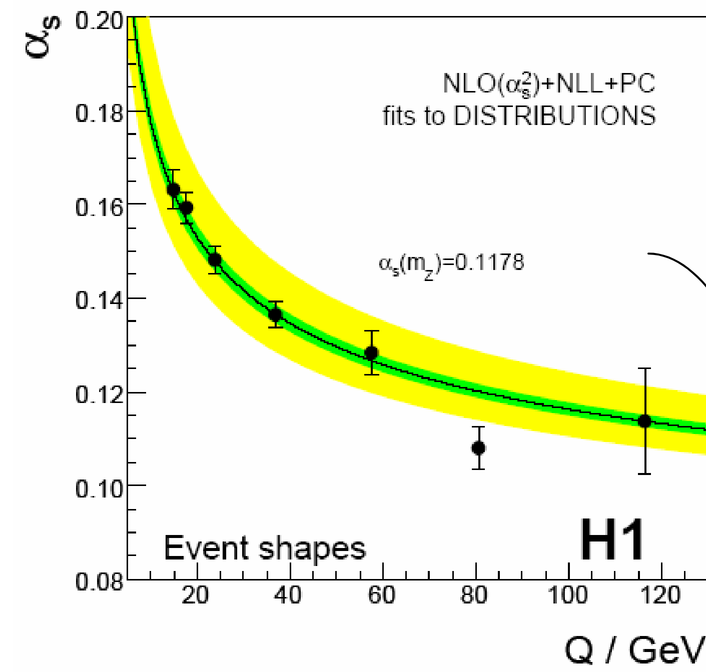
strong coupling constant $\alpha_s(m_Z)$					
event shape variable	τ_c	τ	B	ρ_0	C
central value	0.1171	0.1202	0.1196	0.1174	0.1156
uncertainties:					
total	$^{+0.0068}_{-0.0062}$	$^{+0.0072}_{-0.0058}$	$^{+0.0072}_{-0.0064}$	$^{+0.0070}_{-0.0056}$	$^{+0.0073}_{-0.0054}$
total experimental	± 0.0035	± 0.0021	± 0.0014	± 0.0021	± 0.0021
statistical experimental	± 0.0014	± 0.0006	± 0.0004	± 0.0010	± 0.0009
systematic experimental	± 0.0033	± 0.0020	± 0.0013	± 0.0019	± 0.0019
total theoretical	$^{+0.0058}_{-0.0051}$	$^{+0.0068}_{-0.0054}$	$^{+0.0071}_{-0.0063}$	$^{+0.0067}_{-0.0052}$	$^{+0.0069}_{-0.0049}$
μ_r dependence	$^{+0.0054}_{-0.0048}$	$^{+0.0058}_{-0.0043}$	$^{+0.0056}_{-0.0044}$	$^{+0.0064}_{-0.0050}$	$^{+0.0069}_{-0.0048}$
μ_I dependence	$^{+0.0002}_{-0.0002}$	$<10^{-4}$	$<10^{-4}$	$^{+0.0002}_{-0.0002}$	$<10^{-4}$
fit interval	$^{+0.0015}_{-0.0018}$	$^{+0.0007}_{-0.0022}$	$^{+0.0001}_{-0.0009}$	$^{+0.0010}_{+0.0007}$	$^{+0.0003}_{-0.0004}$
parton density functions	$^{+0.0002}_{-0.0001}$	$^{+0.0003}_{-0.0010}$	$^{+0.0006}_{-0.0007}$	$^{+0.0001}_{-0.0002}$	$^{+0.0002}_{-0.0001}$
matching scheme	$^{+0.0015}_{+0.0005}$	$^{+0.0036}_{+0.0022}$	$^{+0.0043}_{+0.0043}$	$^{+0.0018}_{+0.0009}$	$^{-0.0005}_{-0.0009}$

Results of event shape NLO+NLL+PC fits

hep-ex/0512014, accepted by Eur. Phys. J.

non perturbative coupling $\alpha_0(\mu_I = 2\,\mathrm{GeV})$					
event shape variable	τ_c	τ	B	ρ_0	C
central value	0.488	0.513	0.519	0.486	0.481
uncertainties:					
total	$^{+0.037}_{-0.035}$	$^{+0.034}_{-0.039}$	$^{+0.059}_{-0.049}$	$^{+0.023}_{-0.035}$	$^{+0.028}_{-0.042}$
total experimental	±0.021	±0.025	±0.039	±0.014	±0.008
statistical experimental	±0.009	±0.009	±0.006	±0.006	±0.005
systematic experimental	±0.019	±0.023	±0.038	±0.013	±0.007
total theoretical	$^{+0.030}_{-0.027}$	$^{+0.022}_{-0.029}$	$^{+0.044}_{-0.029}$	$^{+0.019}_{-0.032}$	$^{+0.026}_{-0.041}$
μ_r dependence	$^{+0.020}_{-0.026}$	$^{+0.018}_{-0.027}$	$^{+0.030}_{-0.028}$	$^{+0.017}_{-0.027}$	$^{+0.022}_{-0.038}$
fit interval	$^{+0.022}_{-0.007}$	$^{+0.008}_{-0.005}$	$^{+0.030}_{+0.006}$	$^{-0.003}_{-0.016}$	$^{+0.006}_{-0.003}$
parton density functions	$^{+0.001}_{-0.001}$	$^{+0.006}_{+0.004}$	$^{+0.011}_{+0.003}$	$^{+0.001}_{-0.001}$	$^{+0.001}_{-0.002}$
matching scheme	$^{-0.005}_{-0.012}$	$^{-0.009}_{-0.023}$	$^{+0.006}_{-0.010}$	$^{-0.006}_{-0.009}$	$^{-0.014}_{-0.014}$
correlation coefficient α_s,α_0	-0.85	-0.76	-0.75	-0.78	-0.51
χ^2 / d.o.f. (experimental errors)	1.13	0.51	0.81	1.40	1.20



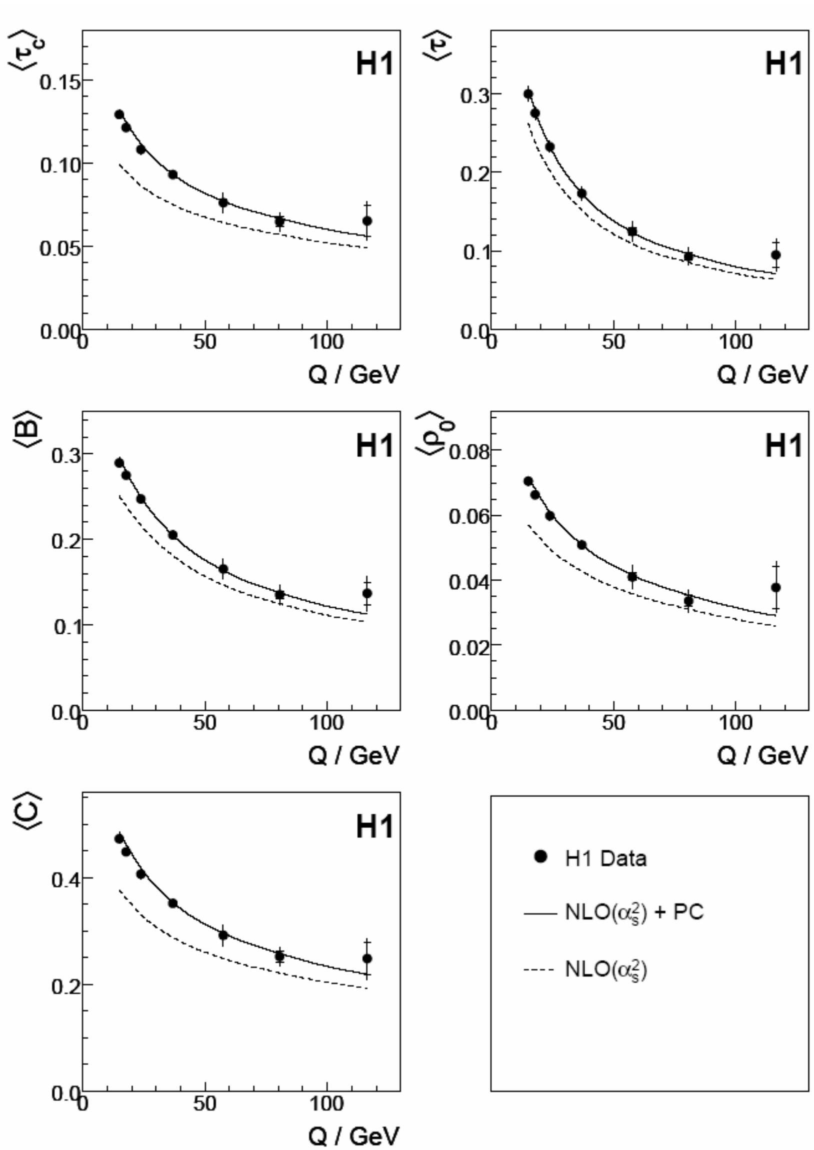


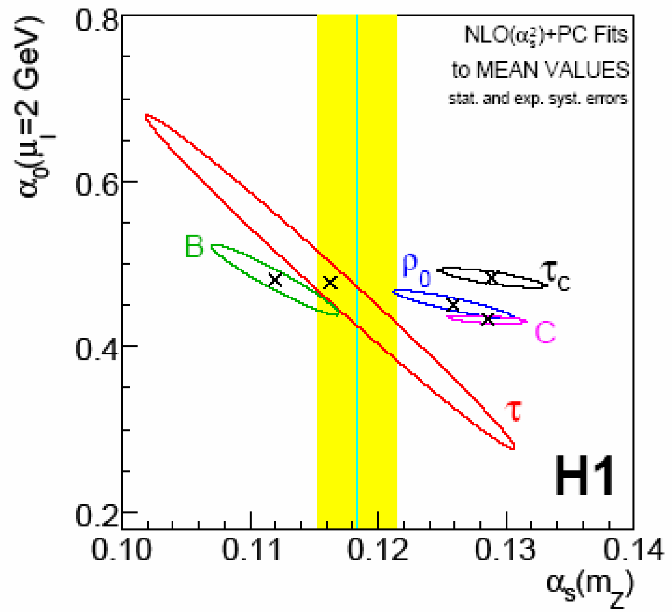
- For each observable fit α_s in Q bins and universal α_0
- Apply renormalization group eq. → $\alpha_s(M_Z^2)$
- Consistency between observables good → take average

$$\alpha_s(m_Z) \;=\; 0.1178 \pm 0.0015\,(\mathrm{exp})\,{}^{+0.0081}_{-0.0061}\,(\mathrm{theo})$$

Δ Theory >> Δ exp.!

Fits to mean values of event shapes





- Fits to mean values of event shapes do not include resummation (resummation valid only for distributions)
- consitency between event shapes much worse
- consistency with α_s world average much worse than for fits to spectra

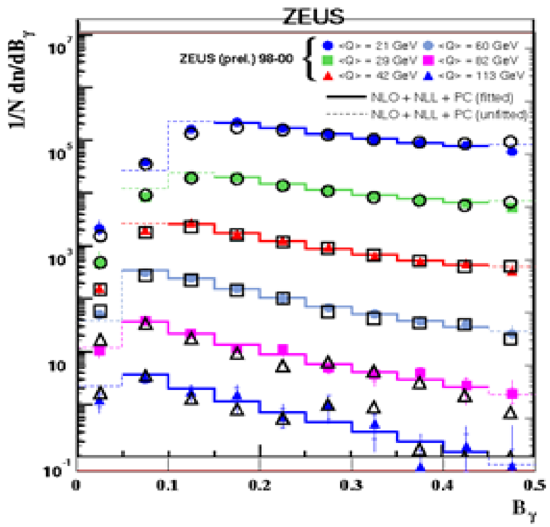
We guess: triumph of resummed theory

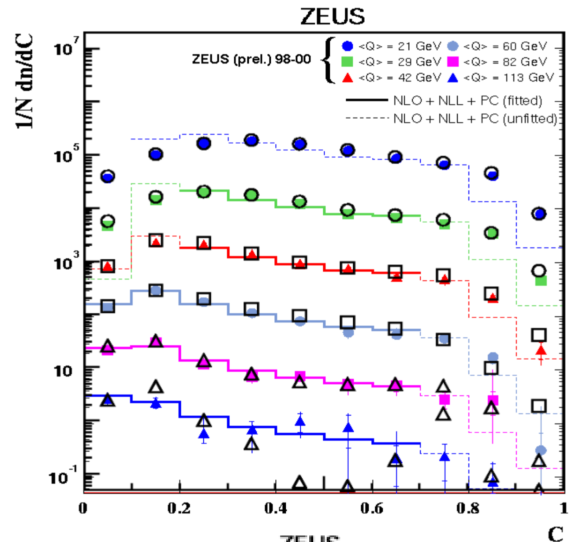
Summary and Conclusions

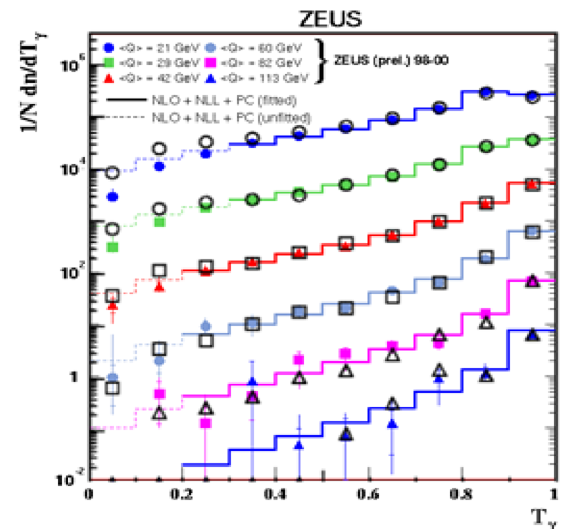
- Accurate measurements of event shape variables in deep-inelastic *ep* scattering based on 106 pb^{-1} in the kinematic region $14 < Q < 200$ GeV $0.1 < y < 0.8$ were presented
- Resummed perturbative QCD predictions together with power corrections give good description of spectra of thrust, jet broadning, jet mass and *C*-parameter
- The results of a two-parameter fit of the strong coupling constant α_s and the effective nonperturbative coupling α_0 are consistent with each other. The values of α_s agree with world average.
- The parameter α_0 which accounts for hadronisation is consistently within 10% around theoretically expected value 0.5. Similar results are obtained in e^+e^- event shape analyses. Universality of effective nonperturbative coupling finds strong support from event shapes measurements
- Caveat: theoretical uncertainty is much larger then experimental

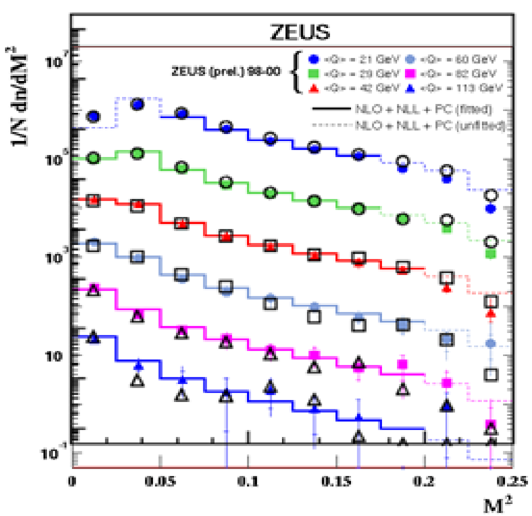
Backup slides

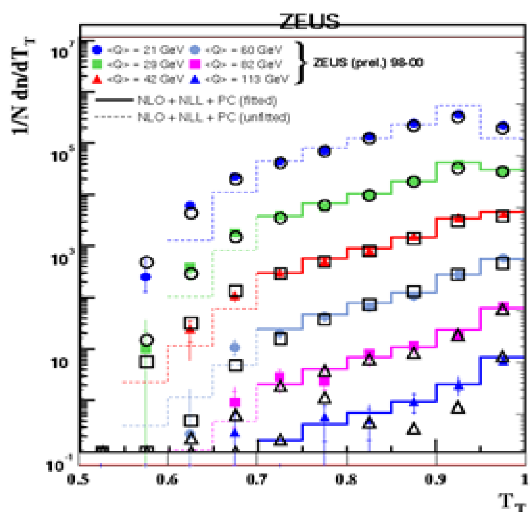
Comparison of ZEUS and H1 event shapes (unofficial)





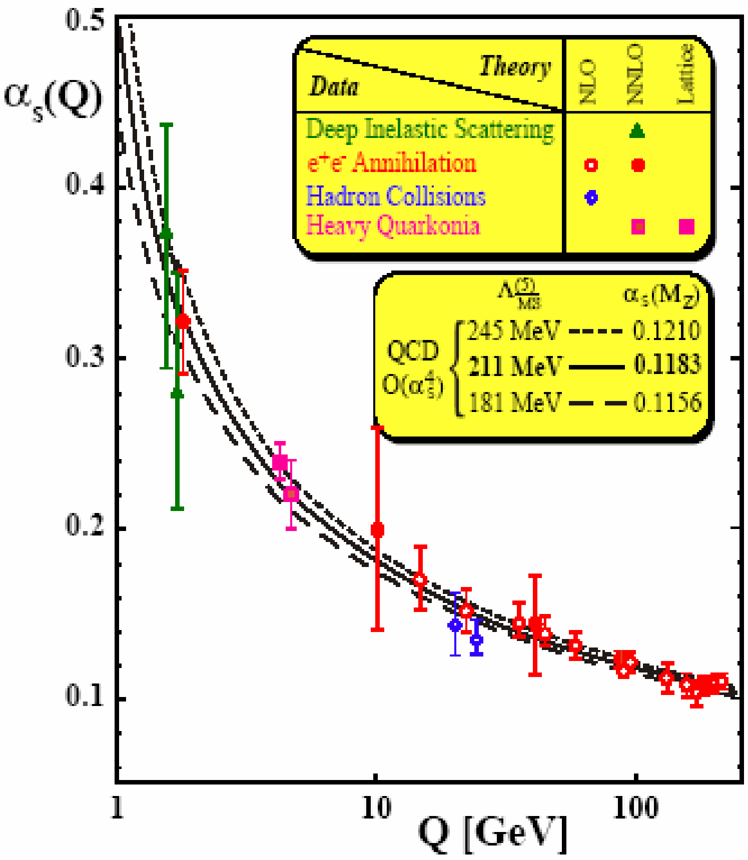


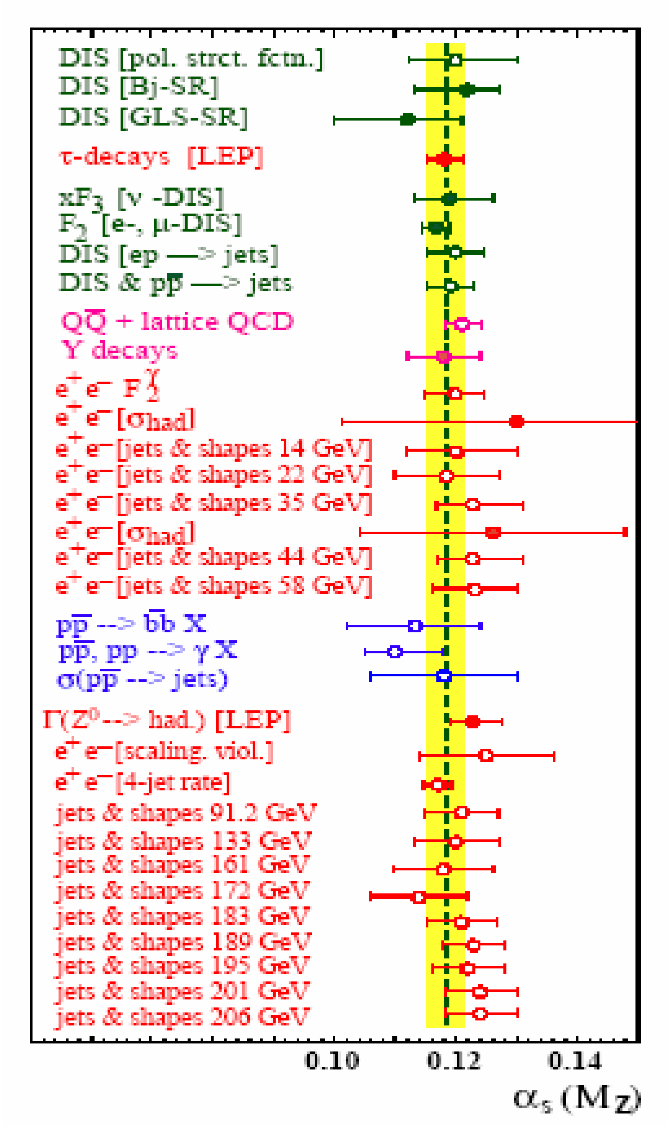




Open black circles are H1 data recalculated in ZEUS Q and F bins

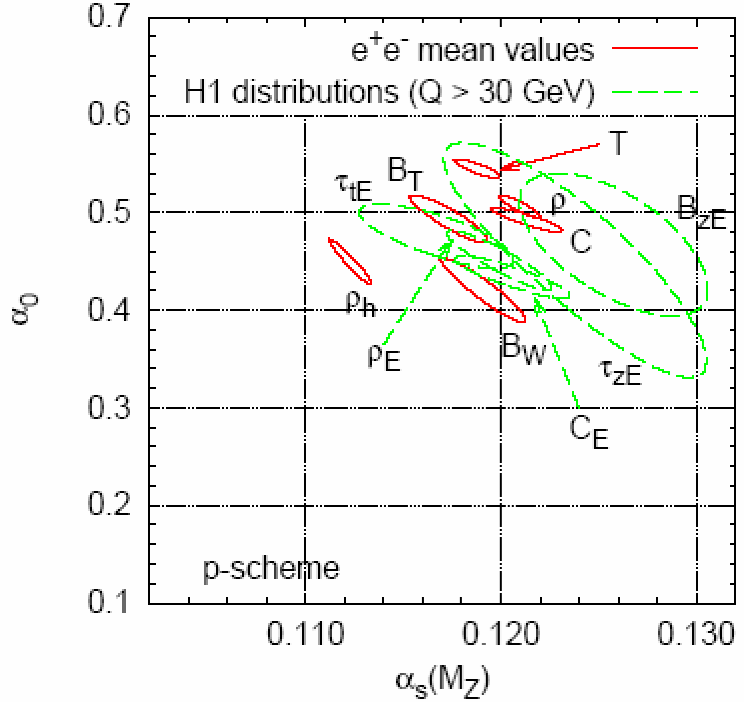
World measurements of α_s





Universality of the infrared coupling

5.3 On the universality of the infrared coupling – 2003



One standard deviation ellipses in the $\alpha_s(M_Z) - \alpha_0$ plane [57].

Results of event shape NLO+NLL+PC fits

$$\alpha_s(m_Z) = 0.1198 \pm 0.0013\,(\mathrm{exp})\,{}^{+0.0056}_{-0.0043}\,(\mathrm{theo})\,,$$

$$\alpha_0 = 0.476 \pm 0.008\,(\mathrm{exp})\,{}^{+0.018}_{-0.059}\,(\mathrm{theo})\,,$$

$$\chi^2/\mathrm{d.o.f.} = 4.9/2.$$

All event shapes combined

The theoretical uncertainties on the fitted values of α_0 and $\alpha_s(m_Z)$ are determined from the changes to the results under variation in the procedure as follows:

- bins with lower boundaries at $F = 0$ are omitted;
- the renormalisation scale μ_r is varied from $Q/2$ to $2Q$;
- the infrared matching scale μ_I is varied from $1.5\,\mathrm{GeV}$ to $2.5\,\mathrm{GeV}$;
- the CTEQ proton pdfs are replaced by three versions of the MRST2001 set [36], which differ in $\alpha_s(m_Z)$ from 0.117 to 0.121;
- instead of $\log R$ the modified M and modified M^2 matching schemes [10] are used.

Event shapes:

With reference to boson axis:

$$\tau = 1 - T \quad \text{with} \quad T = \frac{\sum_h |\vec{p}_{z,h}|}{\sum_h |\vec{p}_h|}$$

$$B = \frac{\sum_h |\vec{p}_{t,h}|}{2\sum_h |\vec{p}_h|}$$

- Thrust = $\parallel$ momentum component
- Jet Broadening = $\perp$ momentum component

Sensitive to radiation (quark recoil effect)

Without reference to boson axis (like in e^+e^-)

$$\tau_C = 1 - T_C \quad \text{with} \quad T_C = \max_{\vec{n}_T} \frac{\sum_h |\vec{p}_h \cdot \vec{n}_T|}{\sum_h |\vec{p}_h|}$$

$$\rho = \frac{(\sum_h E_h)^2 - (\sum_h \vec{p}_h)^2}{(2\sum_h |\vec{p}_h|)^2}$$

$$C = \frac{3}{2} \frac{\sum_{h,h'} |\vec{p}_h||\vec{p}_{h'}| \sin^2 \theta_{hh'}}{(\sum_h |\vec{p}_h|)^2}$$

- Thrust (maximizing $\parallel$ component)
- Jet mass
- Hadron-hadron correlation