New QCD Results from H1

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On behalf of the

H1 Collaboration

- Kinematics of $e\,p \to e'\,X$ scattering
- Event shape variables in DIS

  Power corrections and pQCD

  Means of event shape variables $\langle F \rangle$ vs Q

  Differential event shape distributions $\mathrm{d}n/\mathrm{d}F$
- Di-jet events in DIS

  Di-jet rates R_2 at low Q^2

  Differential 2+1 jet rate $\mathrm{d}n/\mathrm{d}y_2$
- Diffraction in DIS

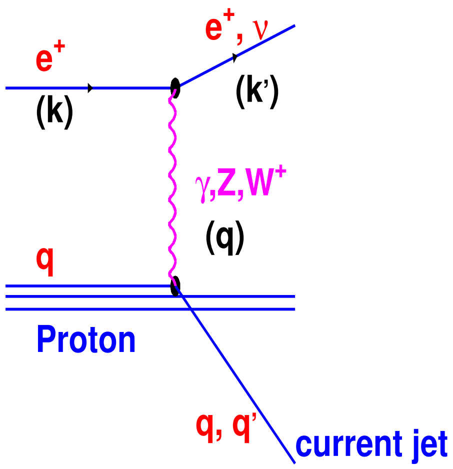
  Structure function $F_2^{D(3)}$ and QCD

  Structure function $F_2^{LP(3)}$ with leading protons
- Summary

Kinematics of deep inelastic $e\,p$ scattering

HERA: $E_e = 27.5$ GeV $\times$ $E_p = 820$ GeV $\quad \sqrt{s} = 300$ GeV

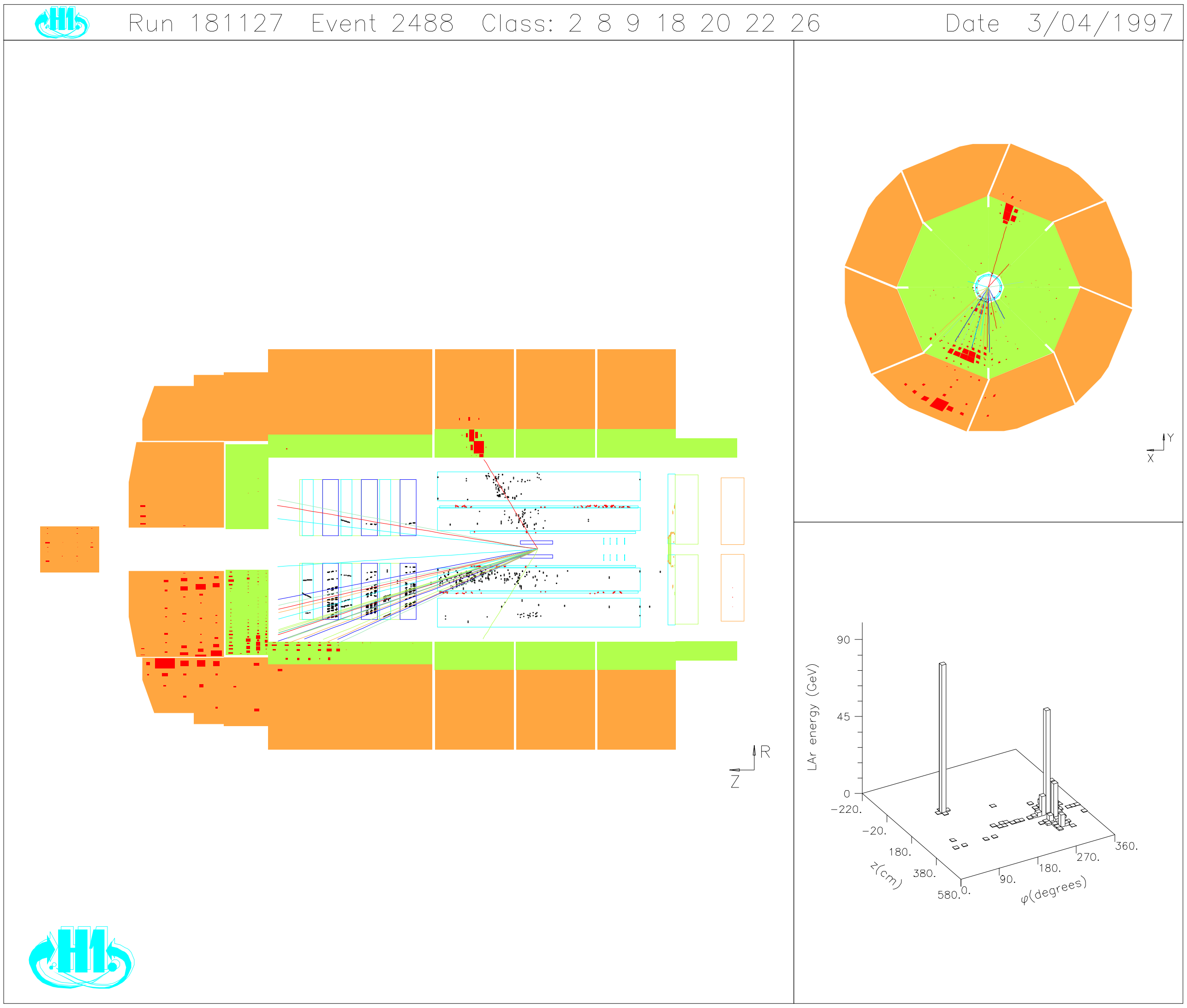
– large accessible DIS kinematic range



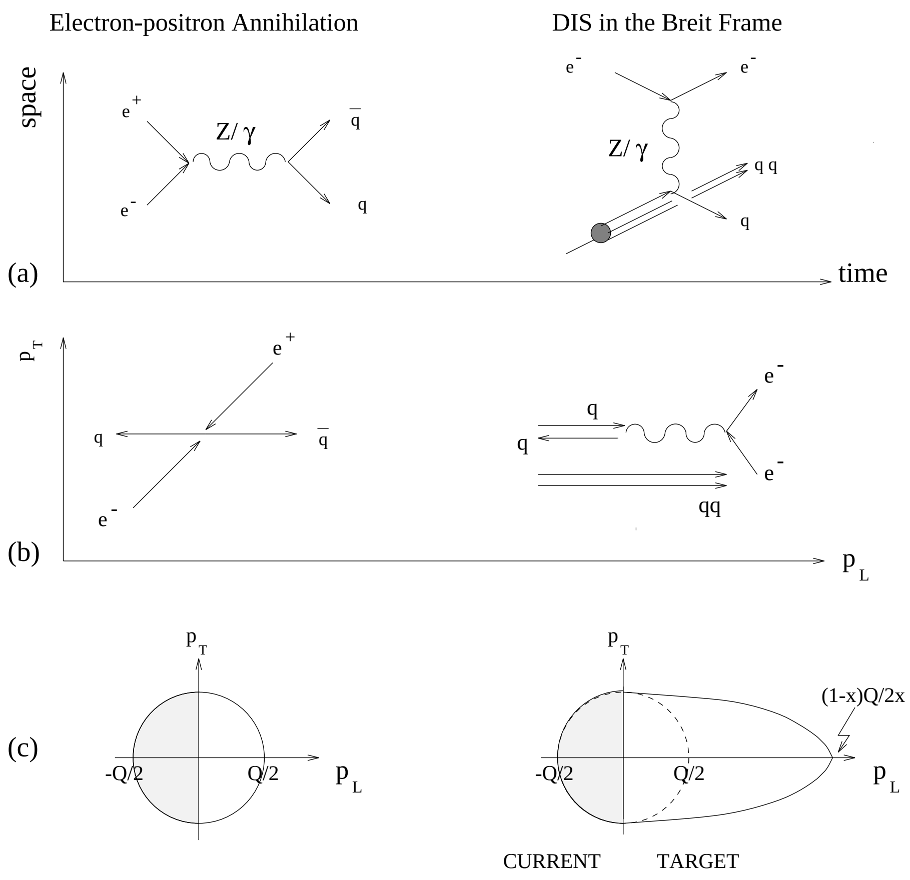
$$Q^2 = -q^2 = 4\,E_e\,E_e'\,\cos^2\frac{\theta_e}{2}$$
$$\simeq 0.3 \div 50,000\ \mathrm{GeV}^2$$

$$y = 1 - \frac{E_e'}{E_e}\,\sin^2\frac{\theta_e}{2}$$
$$\simeq 0.03 \div 0.9$$

$$x = Q^2/(y\,s)$$
$$\simeq 6\cdot 10^{-6} \div 0.7$$



DIS Event Shapes in the Breit Frame



- Clean separation between current and target fragmentation in Breit frame
- Phase space in Current Hemisphere of the Breit frame for $e\,p \to e'\,X$ events $\quad Q/2$
- No 'natural' axis in $e^+e^- \to q\,\bar{q}$ events phase space in one hemisphere $\quad \sqrt{s}/2$

$\rightarrow$ Comparison of event shapes in $e\,p$ and e^+e^- scattering at a scale $\quad Q = \sqrt{s_{ee}}$

$\Rightarrow$ DIS QCD studies over large range of $Q = 7 - 100$ GeV in a single experiment

Definition of Event Shape Variables

Define infrared safe variables, calculable in pQCD

Sum over all hadrons h in Breit current hemisphere

- **Thrust T_c** (plot always $1 - T_c$)

$$T_c = \max \frac{\sum_h |\mathbf{p}_h \cdot \mathbf{n}_T|}{\sum_h |\mathbf{p}_h|} \qquad \mathbf{n}_T \equiv \text{thrust axis}$$

- **Thrust T_z** (plot always $1 - T_z$)

$$T_z = \frac{\sum_h |\mathbf{p}_h \cdot \mathbf{n}|}{\sum_h |\mathbf{p}_h|} = \frac{\sum_h |\mathbf{p}_{z\,h}|}{\sum_h |\mathbf{p}_h|} \qquad \mathbf{n} \equiv \gamma/Z \text{ axis}$$

- **Jet Broadening B_c**

$$B_c = \frac{\sum_h |\mathbf{p}_h \times \mathbf{n}|}{2\sum_h |\mathbf{p}_h|} = \frac{\sum_h |\mathbf{p}_{\perp\,h}|}{2\sum_h |\mathbf{p}_h|} \qquad \mathbf{n} \equiv \gamma/Z \text{ axis}$$

- **Jet Mass ρ_c**

$$\rho_c = \frac{M^2}{Q^2} = \frac{(\sum_h p_h)^2}{Q^2}$$

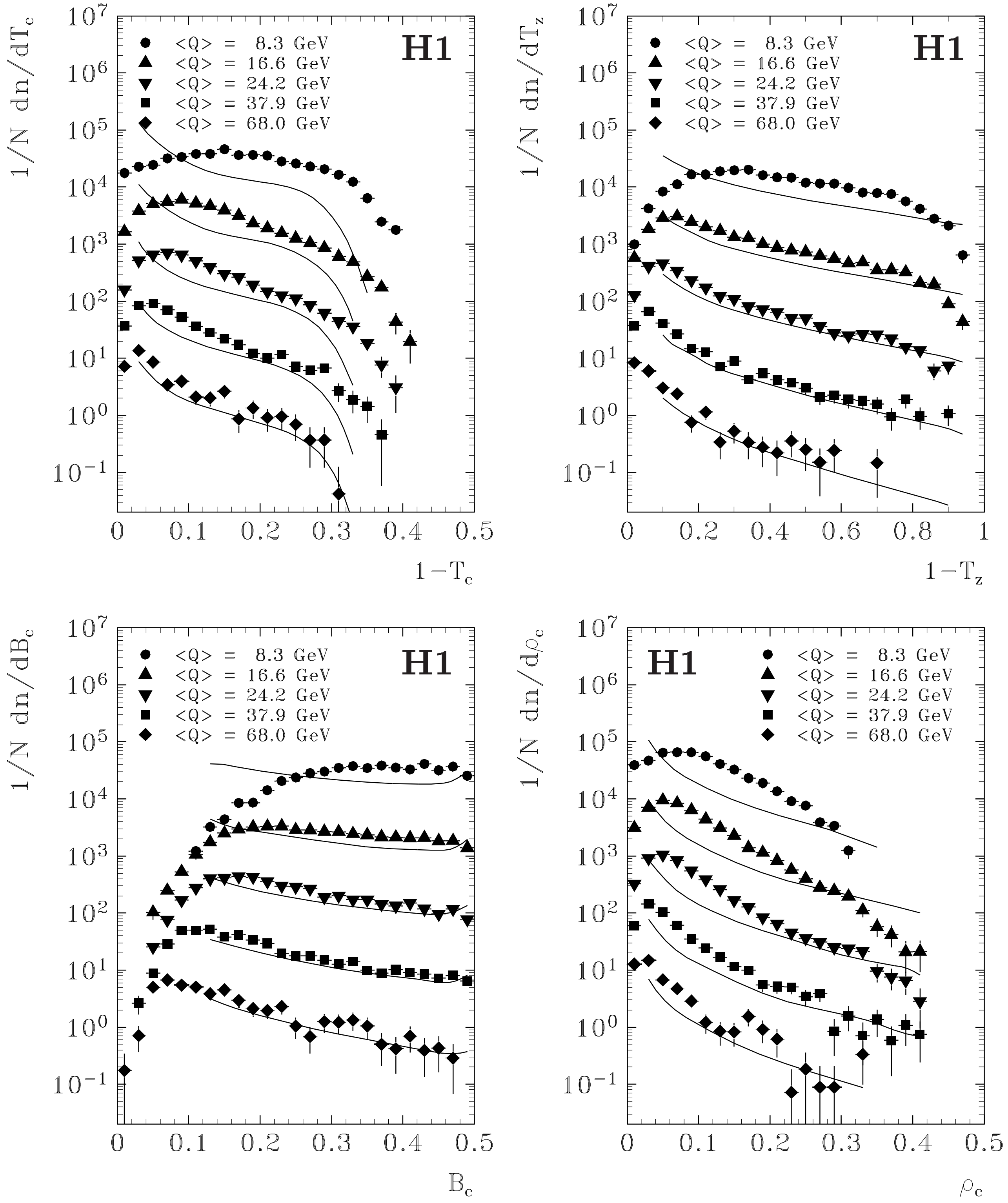
e

pQCD and Power Corrections

- **Event shapes become more collimated with rising Q**
- **Q or energy dependence of event shape variables due to**
  (i) change of strong coupling constant $\quad \alpha_s(Q) \propto 1/\ln(Q/\Lambda)$
  (ii) power or 'hadronisation' corrections $\quad \propto 1/Q$
- **Concept** Yu.L. Dokshitzer and B.R. Webber, PL B 352 (1995) 451
  $1/Q$ corrections not necessarily related to hadronisation, but may instead be a universal soft gluon phenomenon associated with the behaviour of the running coupling at small scales
  Attribute hadronisation effects on event shape variables to power corrections without any assumption on fragmentation models
- **Mean value of any infrared safe event shape variable $\langle F\rangle$**
  e.g. $F = 1 - T_c,\ 1 - T_z,\ B_c,\ \rho_c$
  $$\langle F\rangle \;=\; \langle F\rangle^{\mathrm{pert}} + \langle F\rangle^{\mathrm{pow}}$$
  – **Perturbative part**
  $$\langle F\rangle^{\mathrm{pert}} \;=\; c_1\,\alpha_s(Q) + c_2\,\alpha_s^2(Q)$$
  $\rightarrow$ **coefficients $c_1,\ c_2$ from $\mathcal{O}(\alpha_s^2)$ DISENT in $\overline{\mathrm{MS}}$**
  (S. Catani and M. Seymour, hep-ph/9602277)
  – **Power corrections**
  $$\langle F\rangle^{\mathrm{pow}} \;=\; a_F\,\frac{16}{3\,\pi}\,\frac{\mu_I}{Q}\,\ln^p\frac{Q}{\mu_I}\left[\bar{\alpha}_0(\mu_I) - \alpha_s(Q) - \frac{\beta_0}{2\,\pi}\left(\ln\frac{Q}{\mu_I} + \frac{K}{\beta_0} + 1\right)\alpha_s^2(Q)\right]$$
  $\rightarrow$ **contain a non-perturbative parameter $\quad \bar{\alpha}_0(\mu_I)$**
  $\bar{\alpha}_0(\mu_I) \equiv$ effective strong coupling below μ_I in LO
  new 'infrared matching' scale $\quad \Lambda_{QCD} \ll \mu_I \ll Q$
  $\rightarrow a_F,\ p$ predicted by theory
  (M. Dasgupta and B.R. Webber, hep-ph/9704297)

Event Shape Spectra and pQCD

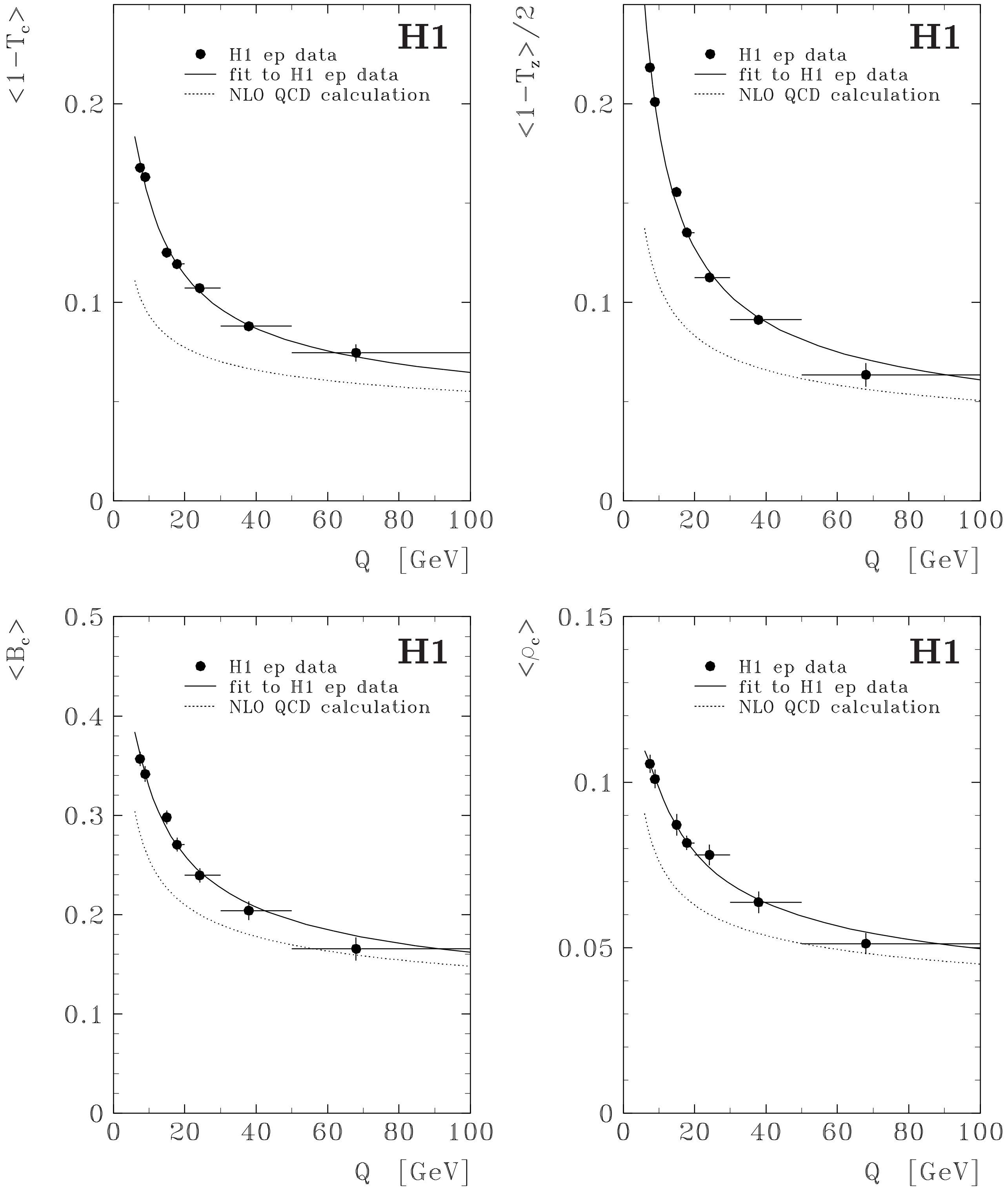
Data + pQCD using MRS H with $\alpha_s(M_Z) = 0.1115$



QCD Fits to Event Shape Means

- $\langle F \rangle^{\text{pow}} \propto 1/Q$ for all event shapes, no $1/Q^2$ terms

$\Rightarrow$ expected dependence $\langle B_c \rangle^{\text{pow}} \propto 1/Q \ln Q$
not supported by H1 $e\,p$ data



Observable	$\bar{\alpha}_0(\mu_I = 2\ \mathrm{GeV})$	$\alpha_s(M_Z)$	χ^2/ndf
H1 $e\,p$ data			
$\langle 1 - T_c \rangle$	$0.497 \pm 0.005\ ^{+0.070}_{-0.036}$	$0.123 \pm 0.002\ ^{+0.007}_{-0.005}$	5.0/5
$\langle 1 - T_z \rangle / 2$	$0.507 \pm 0.008\ ^{+0.109}_{-0.051}$	$0.115 \pm 0.002\ ^{+0.007}_{-0.005}$	8.5/5
$\langle B_c \rangle$	$0.408 \pm 0.006\ ^{+0.036}_{-0.022}$	$0.119 \pm 0.003\ ^{+0.007}_{-0.004}$	5.3/5
$\langle \rho_c \rangle$	$0.519 \pm 0.009\ ^{+0.025}_{-0.020}$	$0.130 \pm 0.003\ ^{+0.007}_{-0.005}$	3.1/5
common fit (ignoring corrrelations between event shapes)			
$T_c,\ T_z,\ \rho_c$	$0.491 \pm 0.003\ ^{+0.079}_{-0.042}$	$0.118 \pm 0.001\ ^{+0.007}_{-0.006}$	39/19
e^+e^- data			
$\langle 1 - T_{ee} \rangle$	$0.519 \pm 0.009\ ^{+0.093}_{-0.039}$	$0.123 \pm 0.001\ ^{+0.007}_{-0.004}$	10.9/14
$\langle M_H^2/s \rangle$	$0.431 \pm 0.020\ ^{+0.071}_{-0.030}$	$0.115 \pm 0.002\ ^{+0.005}_{-0.003}$	7.8/14

- **Two parameter fit to $\bar{\alpha}_0$ and $\alpha_s(M_Z)$**

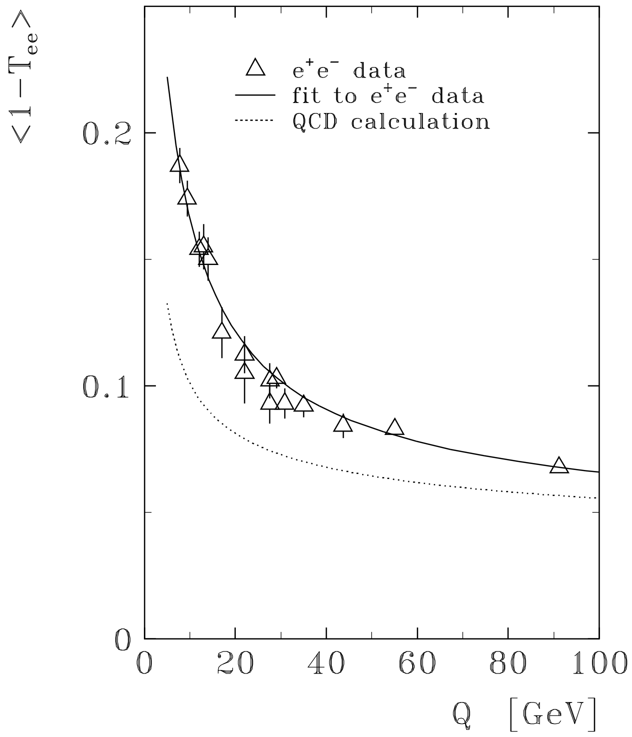
$\Rightarrow$ **Universal power correction parameters $\quad \bar{\alpha}_0 \simeq 0.5 \pm 0.1$**

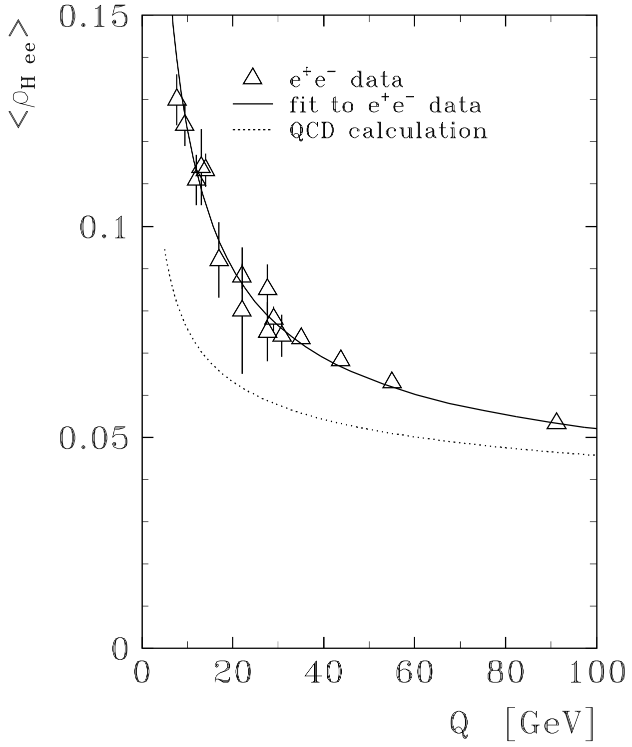
- **Precision limited by theoretical uncertainties**
  $\rightarrow$ need higher order QCD calculations!
- **Test universality concept: combined fit to $T_c,\ T_z,\ \rho_c$**
- **Results consistent with e^+e^- experiments**

$\rightarrow$ H1 Collaboration, C. Adloff et al., DESY 97-098 and hep-ex/9706002,
'Measurement of Event Shape Variables in Deep Inelastic $e\,p$ Scattering'

QCD Fits to e^+e^- Event Shape Means

- **Energy dependence of e^+e^- data, available for**
  - thrust $\langle 1 - T_{ee} \rangle$
  - heavy jet mass $\langle \rho_{H\,ee} \rangle = \langle M^2_{H\,ee}/s \rangle$





DIS Event Shape Distributions

- **Power corrections to differential thrust distribution calculated for $e^+e^- \to q\,\bar{q}$**

  (Yu.L. Dokshitzer and B.R. Webber, hep-ph/9704298)

  – excellent fit to data within $0.05 < 1 - T_{ee} < 0.35$

  – cms energy range $\sqrt{s} = 14 - 161$ GeV

$$\begin{aligned} \bar{\alpha}_0 &= 0.46 \pm 0.02 \\ \alpha_s(M_Z) &= 0.1185 \pm 0.0025 \end{aligned}$$

- **Theory expected, although not yet proven, to hold for deep inelastic $e\,p$ scattering as well**

$\Rightarrow$ **Try generalized ansatz for DIS event shape variables**

- **Event shape distribution $\Phi(F)$ in $\mathcal{O}(\alpha_s^2)$**

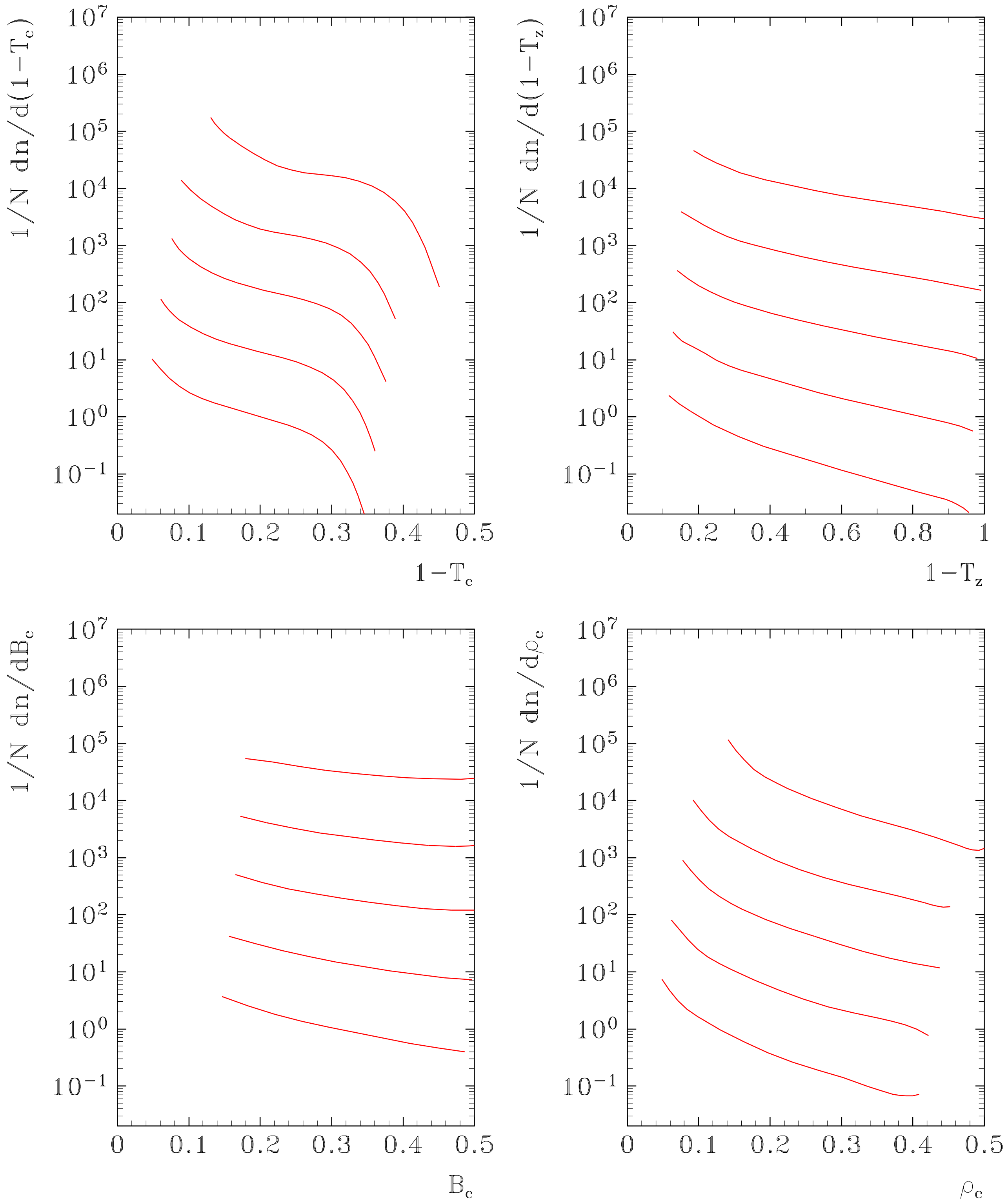
$$\Phi^{\rm pert}(F) \equiv \frac{1}{\sigma_{\rm tot}} \frac{{\rm d}\sigma}{{\rm d}F} = A(F)\,\alpha_s(Q) + B(F)\,\alpha_s^2(Q)$$

$\to$ **functions $A(F)$, $B(F)$ from DISENT**

- **Leading non-perturbative effect** $(F \gtrsim \mu_I/Q)$

$$\begin{aligned} \Phi(F) &= \Phi^{\rm pert}(F - \delta F) \\ \delta F &= a_F\,\frac{16}{3\,\pi}\,\frac{\mu_I}{Q}\left[\bar{\alpha}_0(\mu_I) \right. \\ &\qquad \left. - \alpha_s(Q) - \frac{\beta_0}{2\,\pi}\left(\ln\frac{Q}{\mu_I} + \frac{K}{\beta_0} + 1\right)\alpha_s^2(Q)\right] \\ &\equiv \langle F \rangle^{\rm pow} \end{aligned}$$

pQCD + power corrections



⇒ **Data can be described by pQCD + power corrections within certain regions of event shape spectra**

- **Power correction parameters $\bar{\alpha}_0$ are of about the same size as from Q dependence of event shape means**

Di-jet Events in DIS

- **Di-jet production in $\mathcal{O}(\alpha_s)$ QCD via**

  boson-gluon fusion $\quad \gamma + g \to q + \bar{q}$

  QCD Compton $\quad \gamma + q \to q + g$

  $\Rightarrow$ **2 + 1** (proton remnant) **jet configuration**

- **Determination of $\alpha_s(Q)$ and/or gluon density in proton**

- **Reconstruct n jets with any infrared stable jet algorithm resolution parameter y**

- **Di-jet rate**

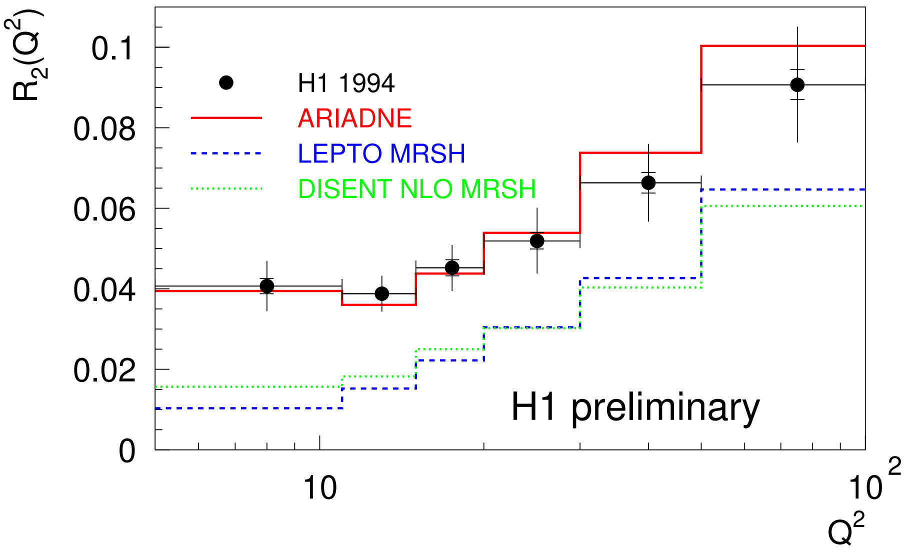
$$R_2(Q^2) \quad = \quad \frac{N_{2+1}(Q^2)}{\sum_i N_{i+1}(Q^2)} \quad = \quad \mathcal{F}(\alpha_s(Q^2))$$

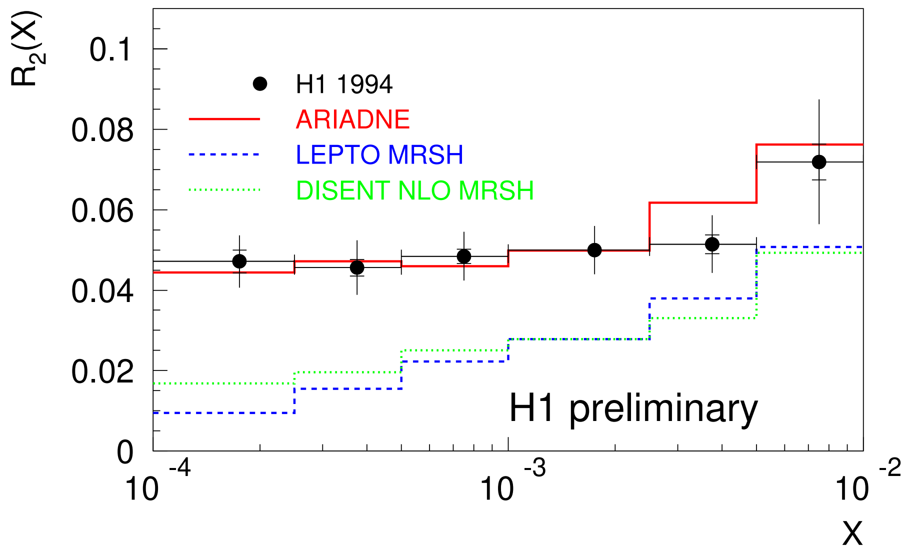
- **Differential di-jet rate**
  y_2 = resolution at which 2 + 1 jets are resolved

$$\frac{1}{N}\frac{dn}{dy_2} \quad = \quad A(y_2)\,\alpha_s(Q^2) + B(y_2)\,\alpha_s^2(Q^2)$$

Di-jet Rates at low Q^2

- Analysis in hadronic $\gamma\, p$ cms $\quad 5 < Q^2 < 100$ GeV^2
  jets defined by cone algorithm $\quad R_{cone} = 1$
  2 jets with $p_\perp^* > 5$ GeV $\quad \Delta\eta^* < 2$

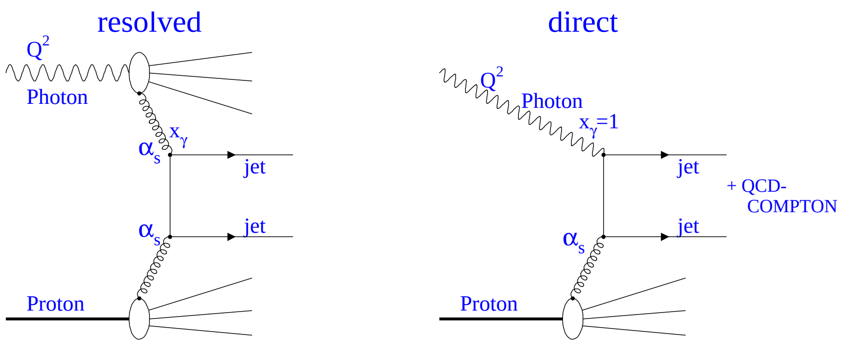




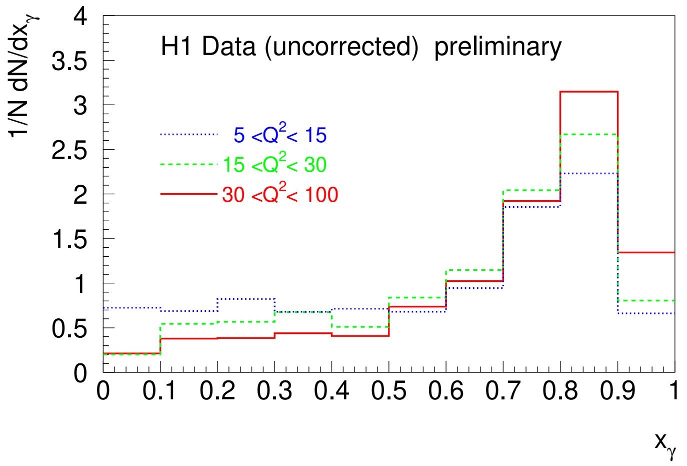
- Ariadne, colour dipole model, describes the data
- LEPTO, LO ME + PS à la DGLAP, fails
- DISENT, $\mathcal{O}(\alpha_s^2)$ calculation, fails

$\Rightarrow$ Problematic to use R_2 for α_s measurement at low Q^2
need reliable MC to unfold data to parton level

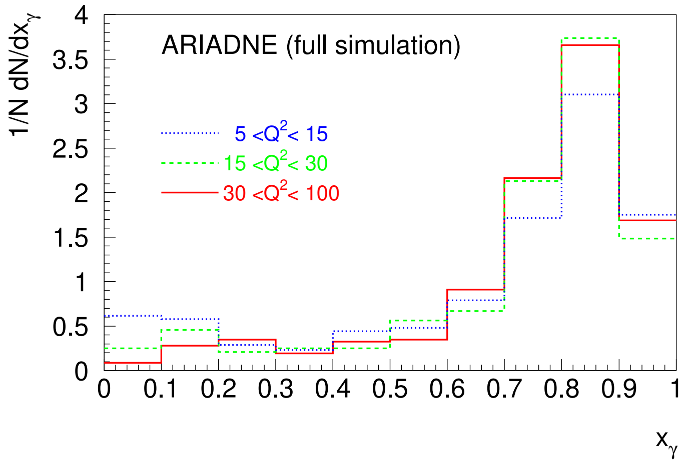
- **Contribution from resolved γ in DIS?**
  - photon no longer pointlike if $p_\perp^2 \gg Q^2$
  - may fluctuate into partons before hard interaction
    x_γ = fraction of γ momentum carried by parton

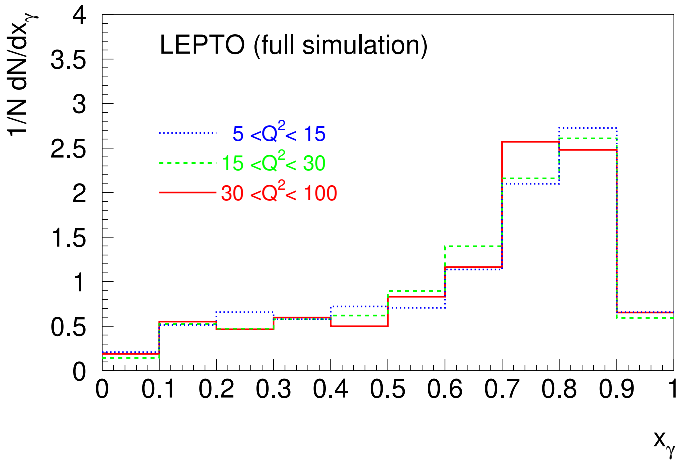


$x_\gamma < 1$ $\qquad$ $x_\gamma = 1$



$$x_\gamma = \sum_{jets} E_\perp^{jet}\, e^{-\eta^{jet}} / 2\, E_\gamma$$



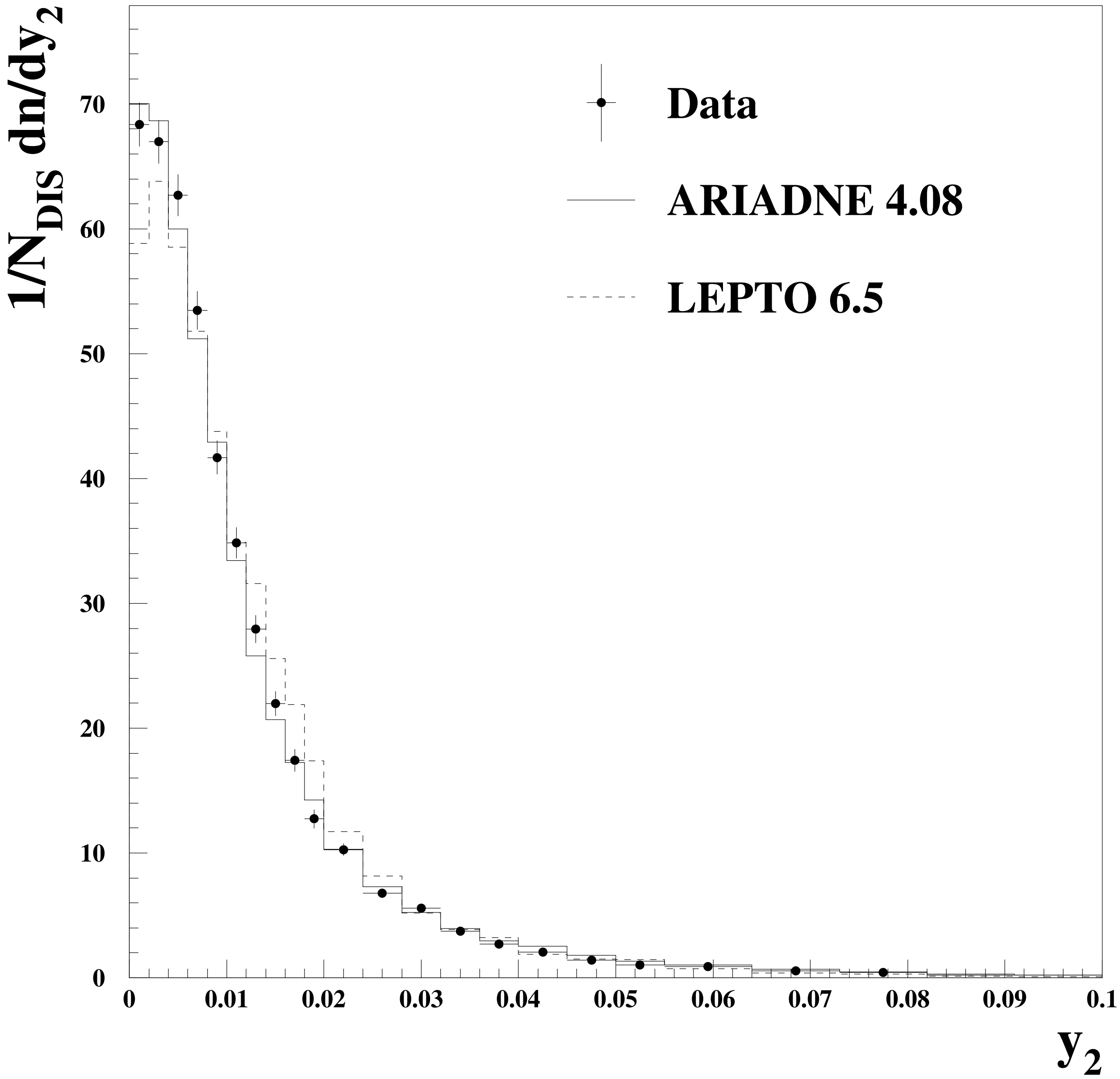


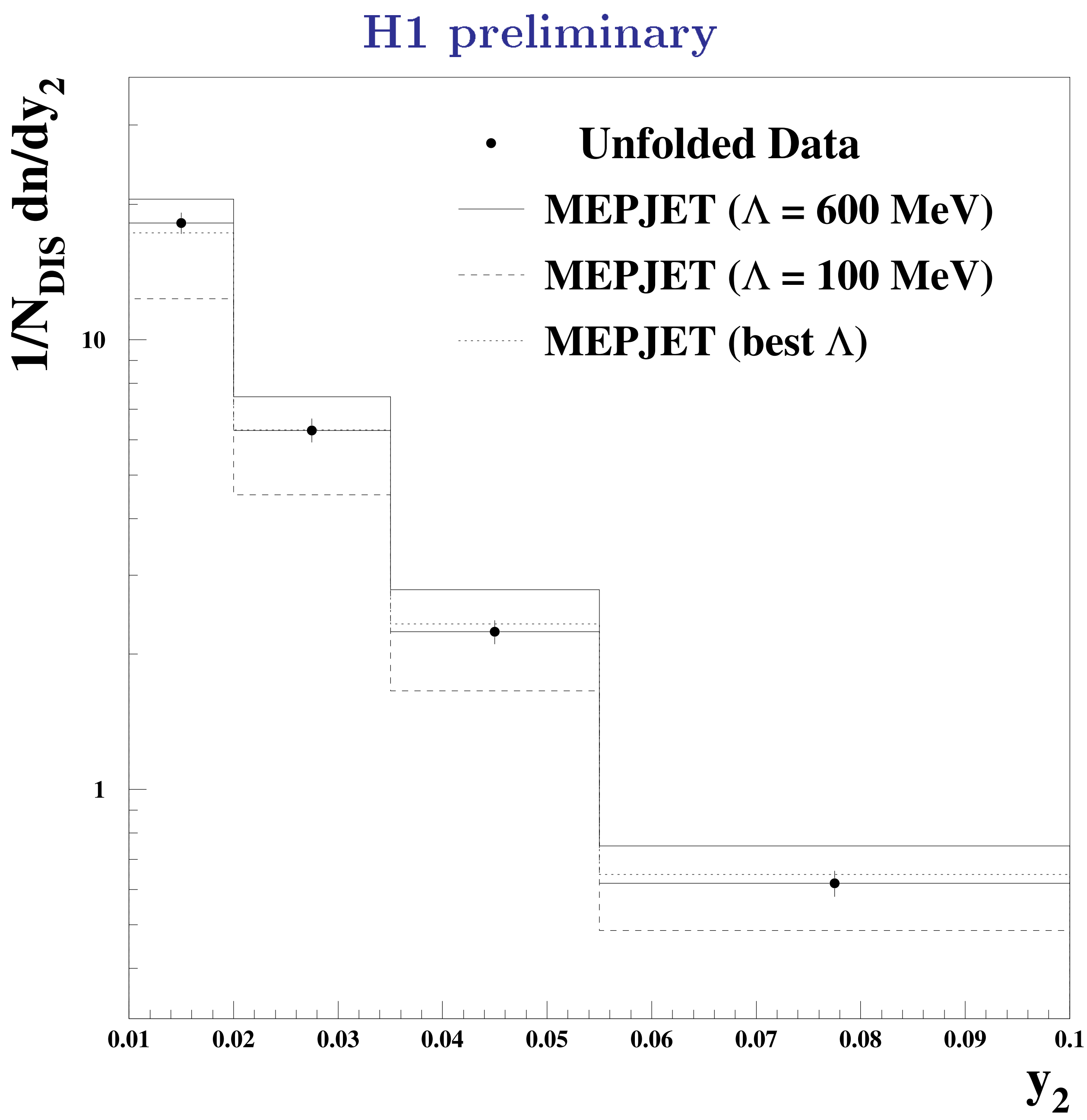
- **Data rise at low x_γ with decreasing Q^2**
  - similar trend in Ariadne
  - no Q^2 dependence in LEPTO ME + PS

Differential Di-jet Rate

- Analysis of differential di-jet rate $\rightarrow \alpha_s(M_Z)$
- JADE cluster algorithm $m_{ij}^2 = 2\, E_i\, E_j\, (1 - \cos\theta_{ij})$
  - clustering stops when exactly 2 + 1 jets are left
  - $y_2 \equiv \min m_{ij}^2 / W^2$ of all combinations in event
- Data $200 < Q^2 < 10000\ \mathrm{GeV}^2,\ W^2 > 5000\ \mathrm{GeV}^2$
  - unfolded for detector and hadronisation effects using Ariadne

H1 preliminary





- **QCD analysis using $\mathcal{O}(\alpha_s^2)$ MEPJET calculations**
  (E. Mirkes and D. Zeppenfeld, hep-ph/9511448)

- **Expected sensitivity to strong coupling constant**

$$\delta\alpha_s(M_Z) \quad = \quad \pm 0.002 \;(\mathrm{stat})\; {}^{+0.007}_{-0.009} \;(\mathrm{sys})\; {}^{+0.006}_{-0.005} \;(\mathrm{scale})$$

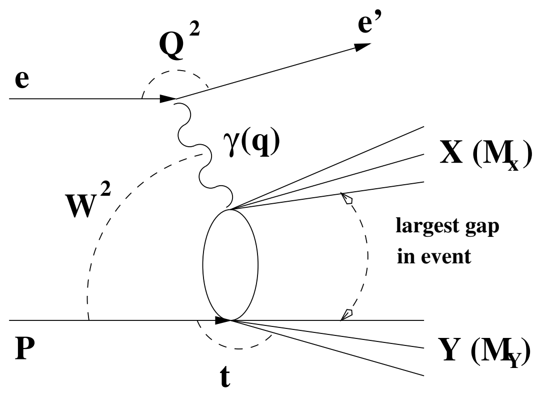
- experimental systematics dominated by
  – hadronic energy scale uncertainty
  – model depenence Ariadne/LEPTO

- large theoretical uncertainties due to renormalisation scale dependence, variation within $Q^2/4 < \mu_R^2 < 4\,Q^2$

Diffraction in DIS

- $\mathcal{O}(10\,\%)$ of DIS events have a large rapidity gap between hadronic activity and proton

$\Rightarrow$ Signature of diffractive process
– exchange of colourless particle $I\!P$



- Kinematic variables $\quad x_{I\!P},\ \beta,\ x_{Bj} = \beta\, x_{I\!P}$

$$x_{I\!P} \simeq \frac{Q^2 + M_X^2}{Q^2 + W^2} \qquad\qquad \beta \simeq \frac{Q^2}{Q^2 + M_X^2}$$

$x_{I\!P}$ = momentum fraction of exchanged particle $I\!P$ in p
β = momentum fraction of parton in $I\!P$

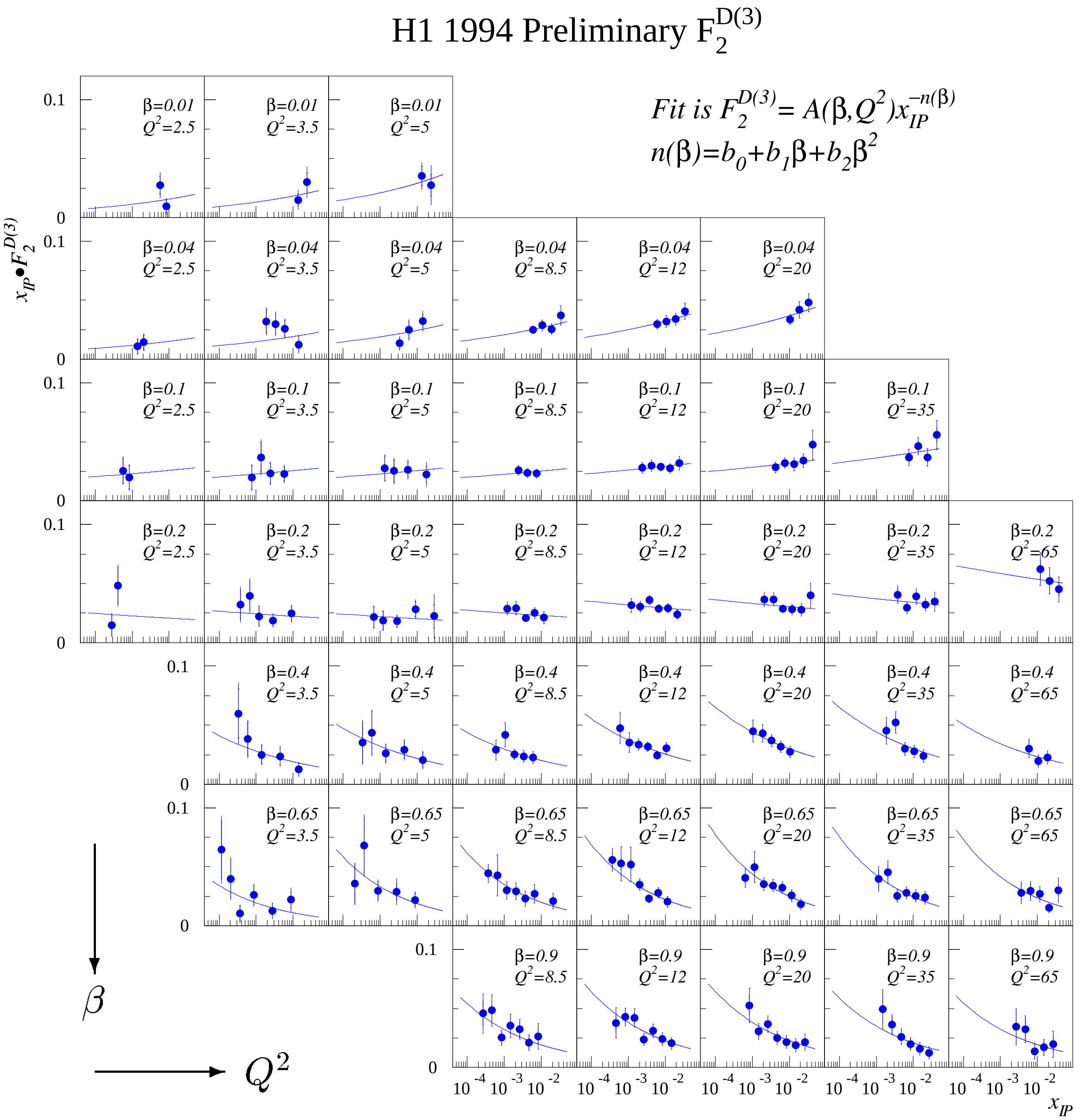
- Kinematic range

$2.5 < Q^2 < 65\ \mathrm{GeV}^2$	$\lvert\, t \,\rvert \lesssim 1\ \mathrm{GeV}^2$
$0.01 < \beta < 0.9$	$M_Y \lesssim 1.6\ \mathrm{GeV}$
$10^{-4} < x_{I\!P} < 0.05$	

- Differential cross section $\Rightarrow F_2^{D(3)}(Q^2, \beta, x_{I\!P})$

$$\frac{\mathrm{d}^3\sigma(ep \to e' X Y)}{\mathrm{d}\beta\, \mathrm{d}Q^2\, \mathrm{d}x_{I\!P}} = \frac{4\,\pi\,\alpha^2}{\beta\, Q^4} (1 - y + \frac{y^2}{2})\, F_2^{D(3)}(Q^2, \beta, x_{I\!P})$$

$F_2^{D(3)}$ – Test of Factorisation



- **Factorisation hypothesis**

$$F_2^{D(3)}(Q^2, \beta, x_{I\!P}) \quad = \quad A(Q^2, \beta) \cdot x_{I\!P}^{-n\,(Q^2,\beta)}$$

$\Rightarrow$ **Clear evidence for factorisation breaking**
$\rightarrow n(\beta) \neq$ **const,** **while** $n(Q^2) =$ **const**

$\Rightarrow$ **More than one particle exchanged?**

$I\!P$omeron + Meson Trajectories

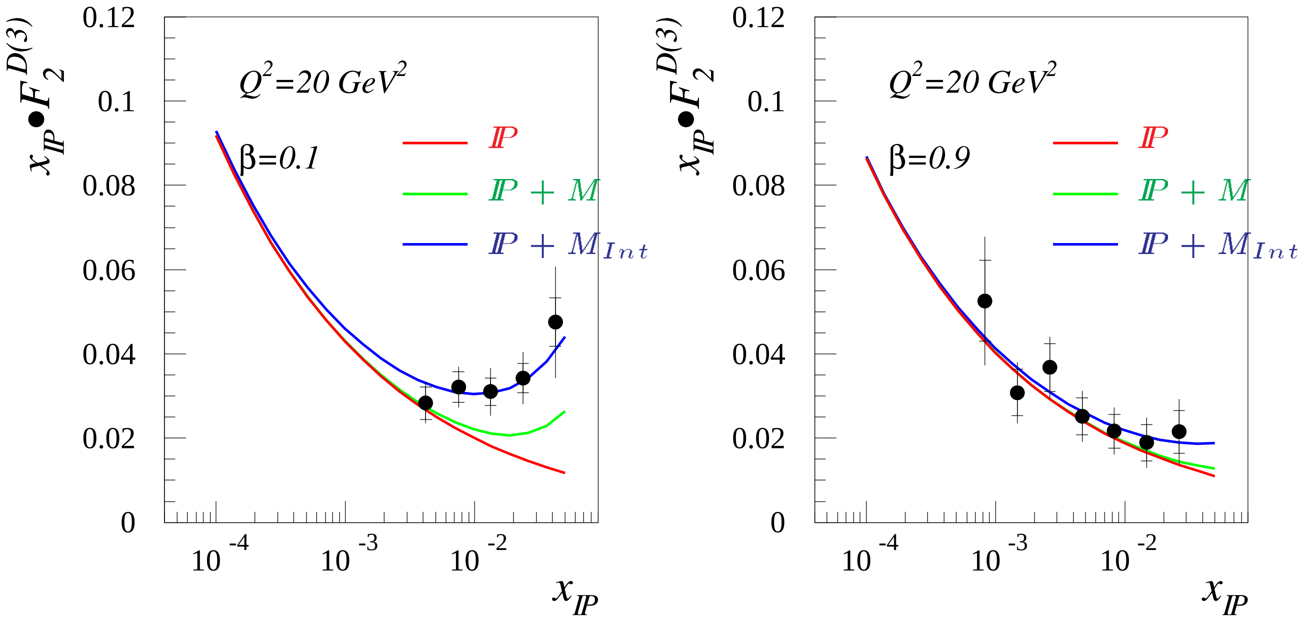
- Phenomenological ansatz $I\!P$omeron + Meson

$$F_2^{D(3)}(Q^2,\beta,x_{I\!P}) \;=\; F_2^{I\!P} x_{I\!P}^{-n_{I\!P}} + C_M\, F_2^M x_{I\!P}^{-n_M} + \mathrm{Int}_{45^\circ}$$

- Fit of $F_2^{I\!P}(Q^2,\beta)$, $n_{I\!P}$, C_M, n_M with $F_2^M = F_2^\pi$ (GRV)

$n_{I\!P} = 1.29 \pm .03$ $n_M = 0.3 \pm 0.3$ $\chi^2/\mathrm{ndf} = 170/156$

H1 Preliminary 1994



$\Rightarrow$ Large meson contribution at small β and $x_{I\!P} \gtrsim 0.01$

$\Rightarrow$ Few % meson intensity at $x_{I\!P} < 0.01$

$\Rightarrow$ Large interference contribution

- Assuming peripheral t dependence $d\sigma/dt \propto e^{b\,t}$

$n = 2\,\alpha - 1$ $\alpha = \alpha(0) + \alpha'\,t$

expect $\alpha_{I\!P}(0) \simeq 1.1$ $\alpha_{f_2}(0) \simeq 0.5$ $\alpha_\pi(0) \simeq 0$

$\alpha'_M = 1.0,\; b_M = 5$ $\alpha_M(0) = 0.6 \pm 0.1 \pm 0.3$

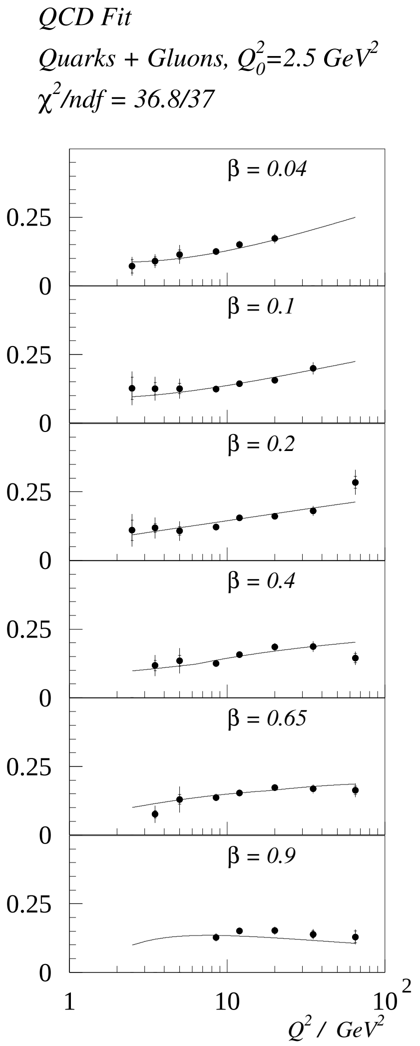
$\alpha'_{I\!P} = 0$ $\alpha_{I\!P}(0) = 1.15 \pm 0.02 \pm 0.04$

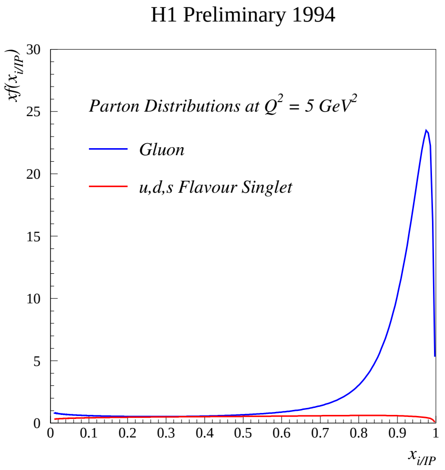
$\alpha'_{I\!P} = 0.3,\; b_{I\!P} = 6$ $\alpha_{I\!P}(0) = 1.18 \pm 0.02 \pm 0.04$

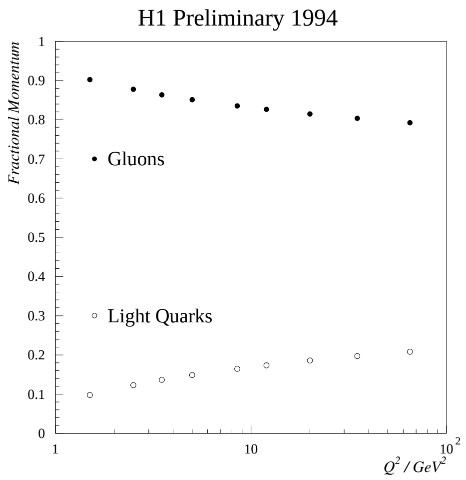
Partonic Structure of Diffractive Exchange

$$\tilde{F}_2^D(Q^2,\beta) = \int F_2^{D(3)}(Q^2,\beta,x_{I\!P})\,\mathrm{d}x_{I\!P}$$

$$\propto \quad F_2^{I\!P}(Q^2,\beta) \qquad \text{in factorisation models}$$







⇒ **Clear evidence for scaling violation in $\tilde{F}_2^D(Q^2,\beta)$**
– rise with $\log Q^2$ persists to large values of β
→ signature for gluons?

- **QCD analysis of $\tilde{F}_2^D(Q^2,\beta)$ quarks + gluons needed**

⇒ **'Leading gluon' phenomenon $x_{g/I\!P} \to 1$ at $Q^2 \sim Q_0^2$**

DIS with Leading Protons

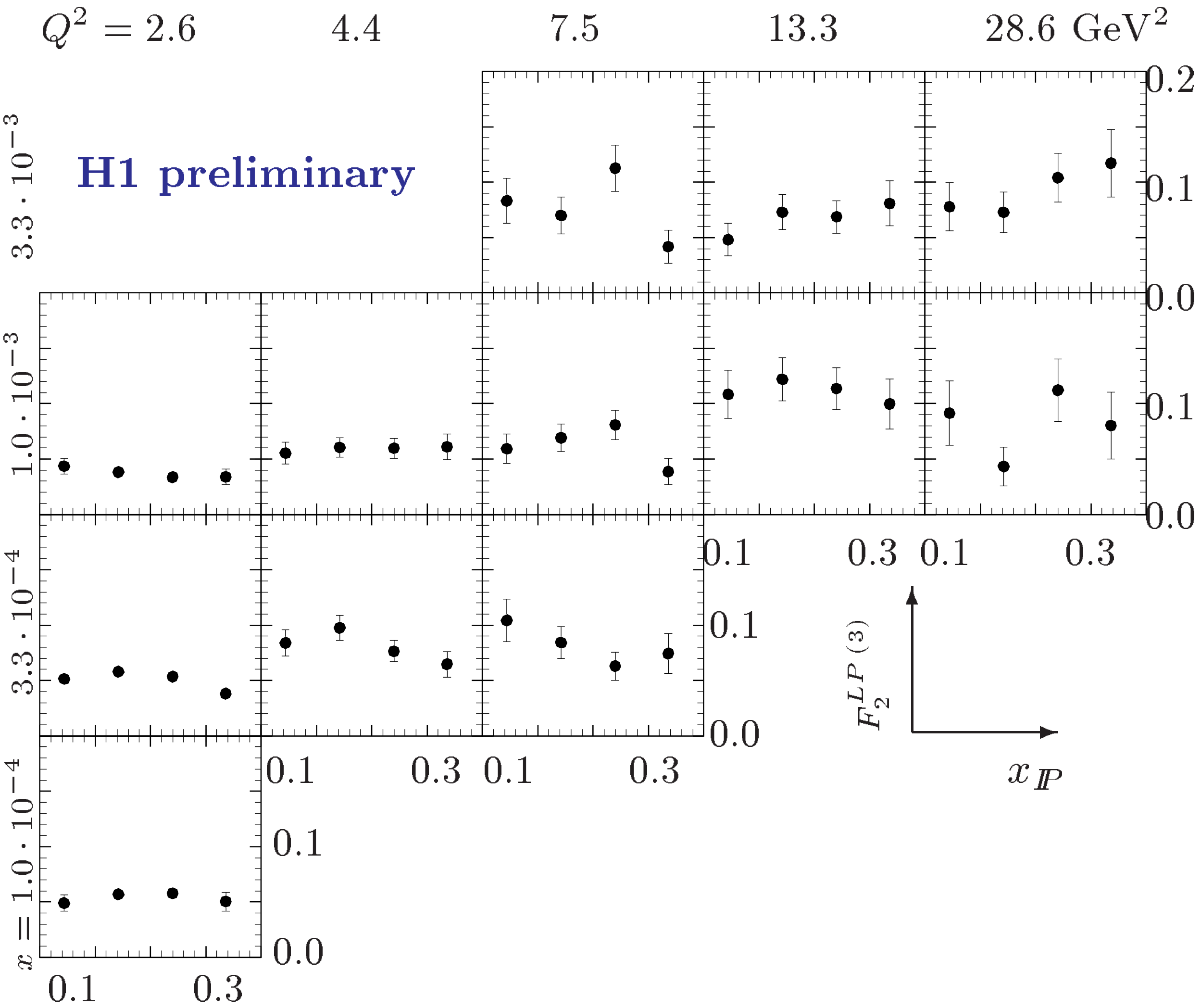
- DIS events with protons of $p_\perp < 200$ MeV measured with the Forward Proton Spectrometer

  $\rightarrow$ new kinematic domain $\quad E'_p = 580 - 740\,\mathrm{GeV}$

  $x_{I\!P} = 1 - E'_p/E_p = 0.1 - 0.3$

- Cross section $\Rightarrow$ semi-inclusive structure function $F_2^{LP\,(3)}$

$$\frac{d^3\sigma(ep \rightarrow e'p'X)}{dx\, dQ^2\, dx_{I\!P}} = \frac{4\pi\alpha^2}{x\,Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LP\,(3)}(Q^2, x, x_{I\!P})$$

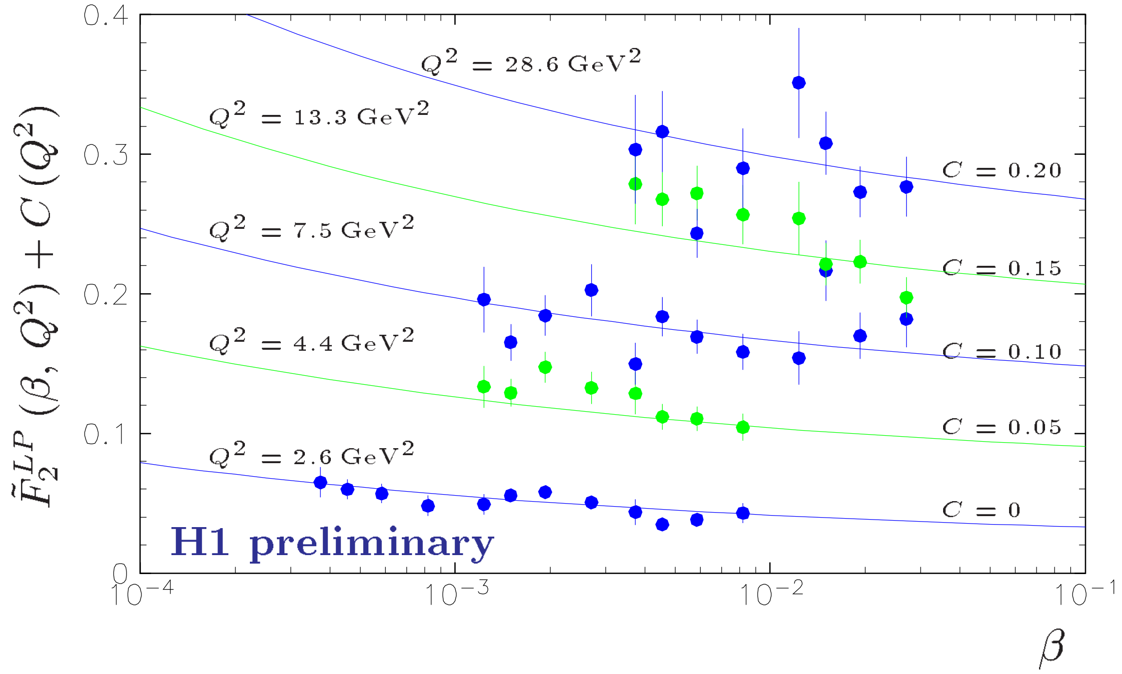


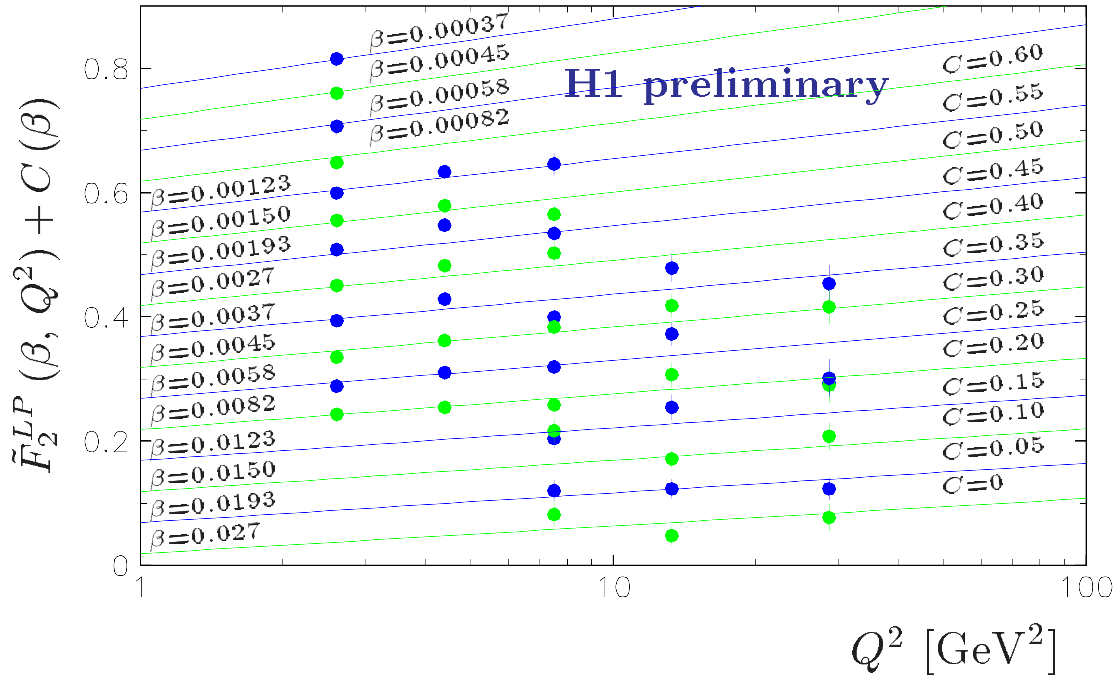
- $F_2^{LP(3)}$ weak $x_{I\!P}$, x dependence, rise with Q^2
- Exchange of meson, π, f_2, ... ?

- **Factorisation hypothesis** global fit to $F_2^{LP\,(3)}$

$$F_2^{LP\,(3)}(Q^2,\beta,x_{I\!P}) \;=\; f(x_{I\!P})\cdot \tilde{F}_2^{LP}(Q^2,\beta)$$

normalisation of $f(x_{I\!P})$ uncertain





- $\tilde{F}_2^{LP}(Q^2,\beta)$ **rises with Q^2 and decreasing β**
  $\rightarrow$ similar to hadron structure function
  note: $\beta = x/x_{I\!P}$ momentum fraction of quark in $I\!P$

Summary

- **Event shape variables in DIS**
  - ⋆ First measurement of thrust, jet broadening, jet mass over a large range of $Q = 7 - 100$ GeV
  - ⋆ New concept to determine simultaneously power corrections and the strong coupling $\alpha_s(M_Z)$ independently of fragmentation models

    → Q dependence of event shape means

    → first look at event shape spectra encouraging

    → universal power correction parameters $\bar{\alpha}_0$ consistent with e^+e^- annihilation

    Present precision limited by theoretical uncertainties

- **Di-jet events in DIS**
  - ⋆ DGLAP based MC models insufficient at low Q^2

    Observe resolved γ contribution at $Q^2 \sim 10$ GeV^2
  - ⋆ First measurement of differential 2+1 jet rate

    Good prospects to determine $\alpha_s(M_Z)$

- **Diffraction in DIS**
  - ⋆ $F_2^{D(3)}$ measured at $Q^2 < 65$ GeV^2, $x_{I\!P} = 10^{-4} - 0.05$

    Evidence for factorisation breaking interpreted as meson exchange at $x_{I\!P} \gtrsim 0.01$ and low β

    QCD analysis indicates 'leading gluon' behaviour of $I\!P$
  - ⋆ New measurement with leading protons extends kinematic region to $x_{I\!P} = 0.1 - 0.3$

    $F_2^{LP(3)}$ shows weak $x_{I\!P}$, x dependence, rise with Q^2

    → meson exchange

    Factorized $\tilde{F}_2^{LP}$ similar to hadron structure function