Results from Deep Inelastic ep Scattering at HERA

Richard Nisius (CERN) PPE Seminar, 04.12.95

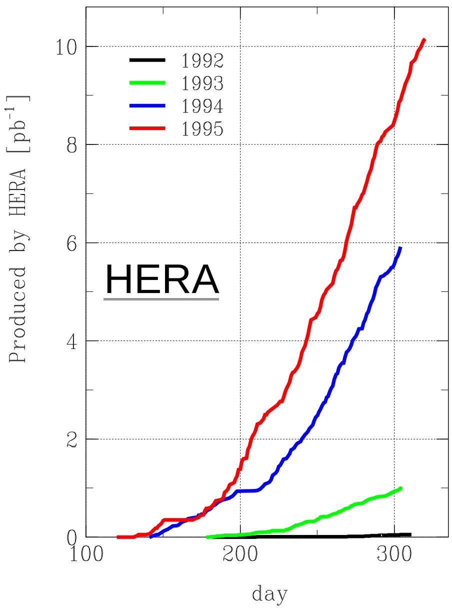
- Introduction

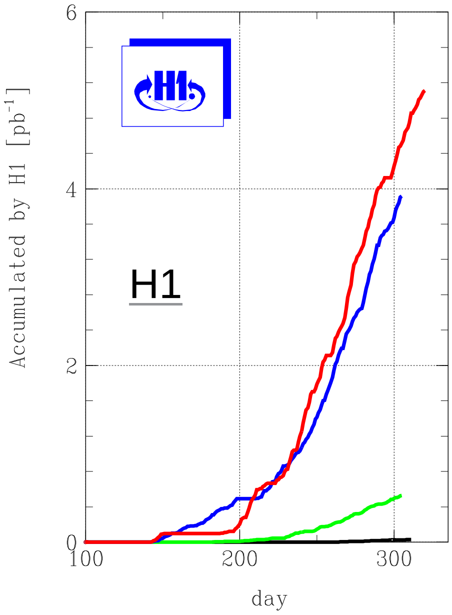
1. The Structure Function $F_2(x, Q^2)$
2. Diffractive Scattering
3. The Gluon Density of the Proton
4. The α_s Measurement

- Conclusions

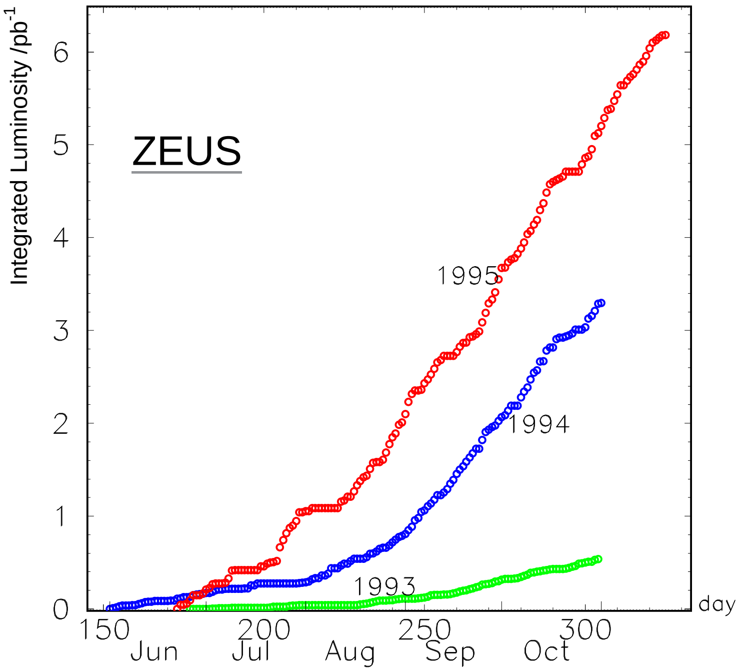
Accumulated Luminosities

INTEGRATED LUMINOSITY



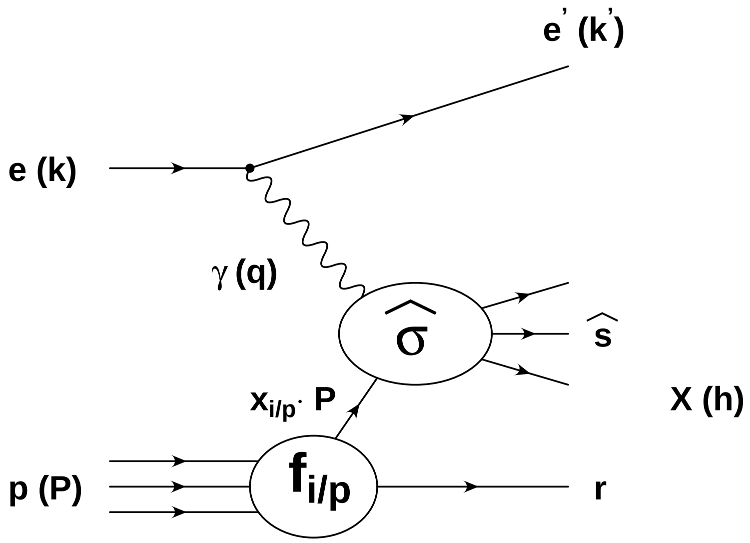


Evtake Luminosity 1993-1995



Deep Inelastic ep Scattering

$$e(k)\,p(P) \rightarrow e^{'}(k^{'})X(h)$$



$$Q^2 \equiv -q^2 = -(k-k^{'})^2$$

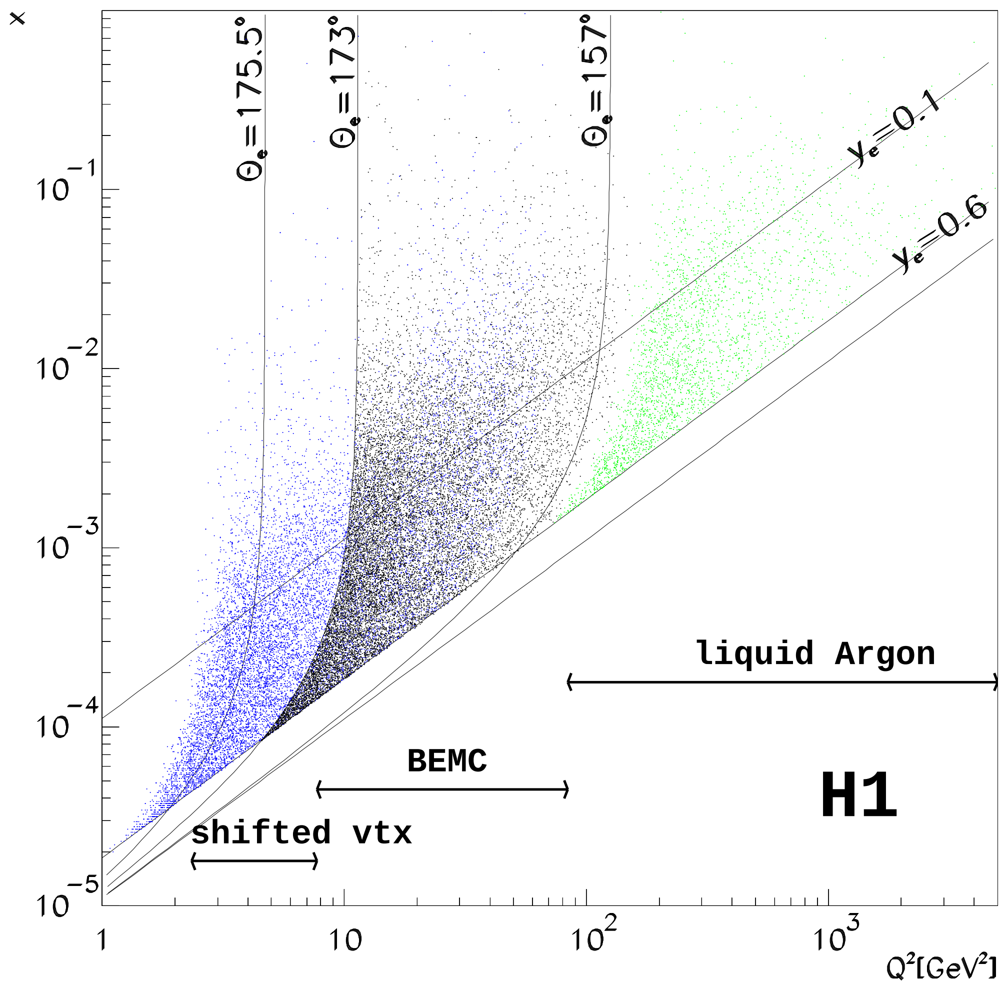
$$x \equiv \frac{Q^2}{2Pq}, \quad y \equiv \frac{Pq}{Pk}, \quad W^2 = Q^2 \cdot \frac{1-x}{x}$$

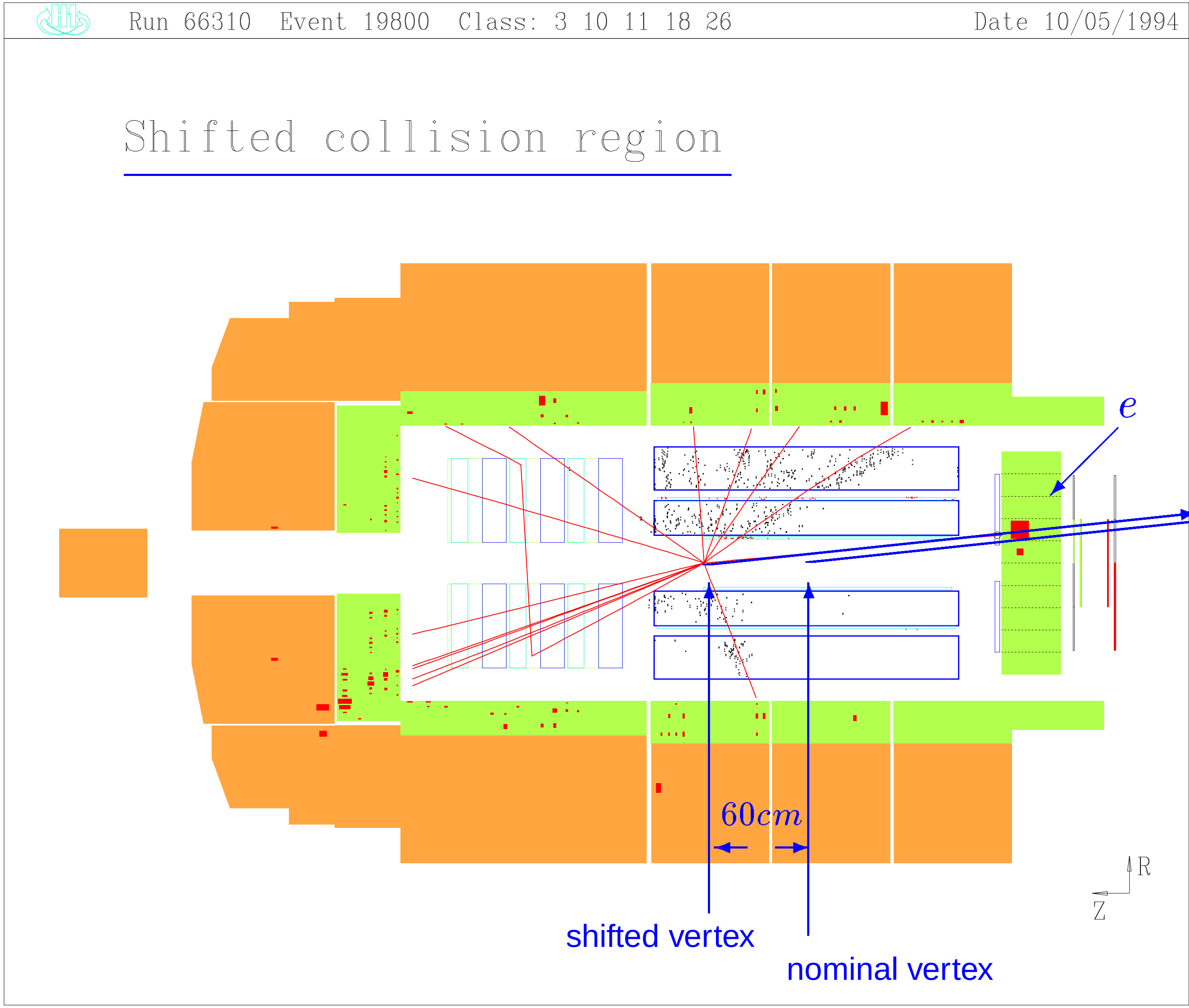
$$s_{ep} = (P+k)^2 = 2Pk$$

$$\frac{d^2\sigma_{ep\rightarrow e'X}}{dx\,dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left(1-y+\frac{y^2}{2[1+R]}\right)F_2\left(x,Q^2\right)$$

$$R\left(x,Q^2\right) = \frac{F_2\left(x,Q^2\right)}{2xF_1\left(x,Q^2\right)} - 1$$

$x,\ Q^2$ Range accessible at HERA




Run 66310 Event 19800 Class: 3 10 11 18 26
Date 10/05/1994
Shifted collision region
e
60cm
shifted vertex
nominal vertex
R
Z

Details on $F_2(x, Q^2)$ from H1

- Three data sets:

$2.2\,pb^{-1}\ \pm 1.5\%$	nominal vertex data
$68\,nb^{-1}\ \pm 5.0\%$	early ($\approx 2ns$) proton satellite bunch
$58\,nb^{-1}\ \pm 4.5\%$	vertex shifted by $62\,cm$

- R is taken as an input, calculated using the GRV PDF's.
- All efficiencies are taken from the data and verified via Monte Carlo studies.
- Redundant measurements of x, Q^2:

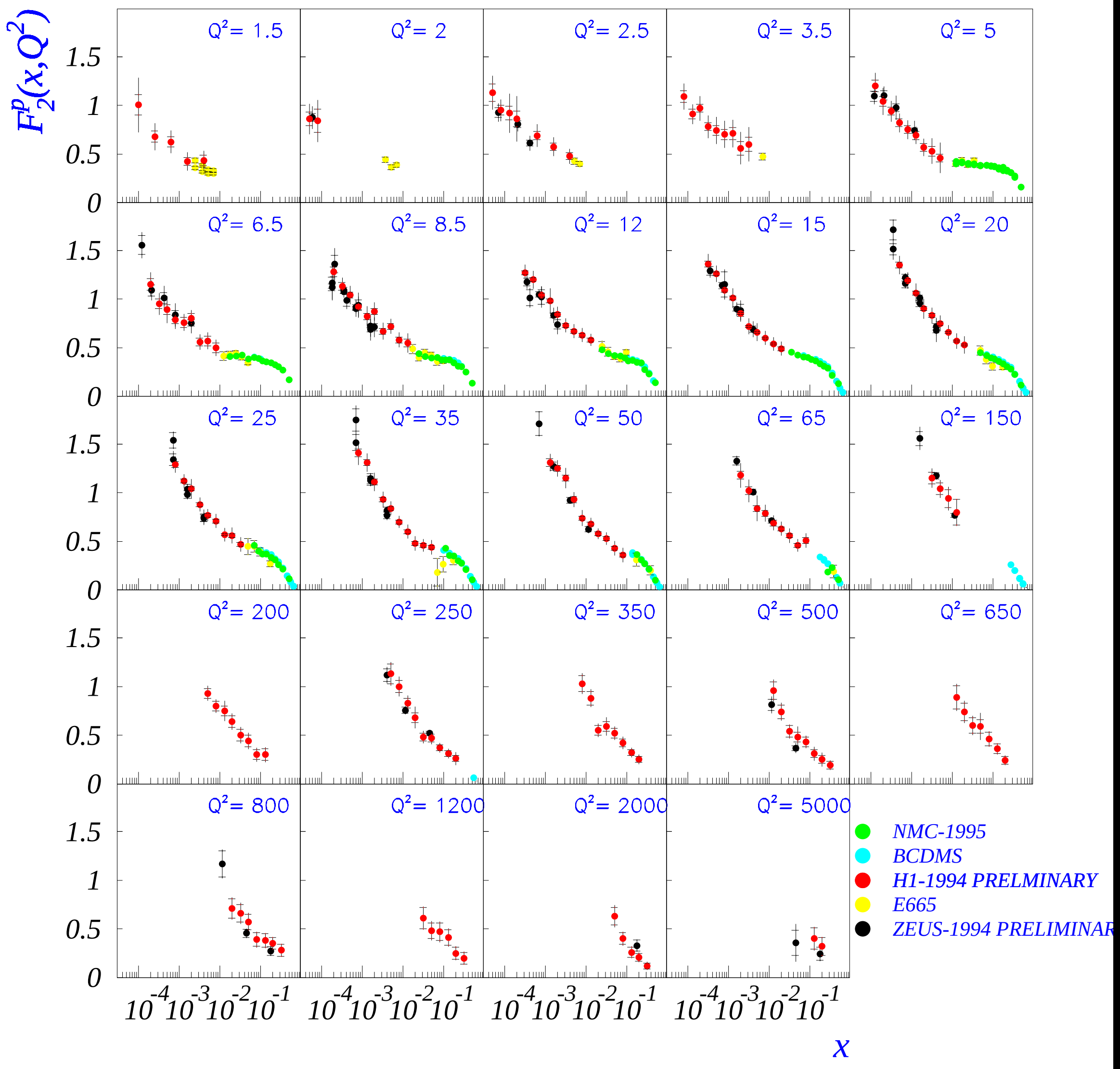
$y > 0.15$	Electron alone, which gives the best resolution at large y.
$y < 0.15$	Σ method, uses hadronic and electronic variables, has low radiative corrections.

- Background:

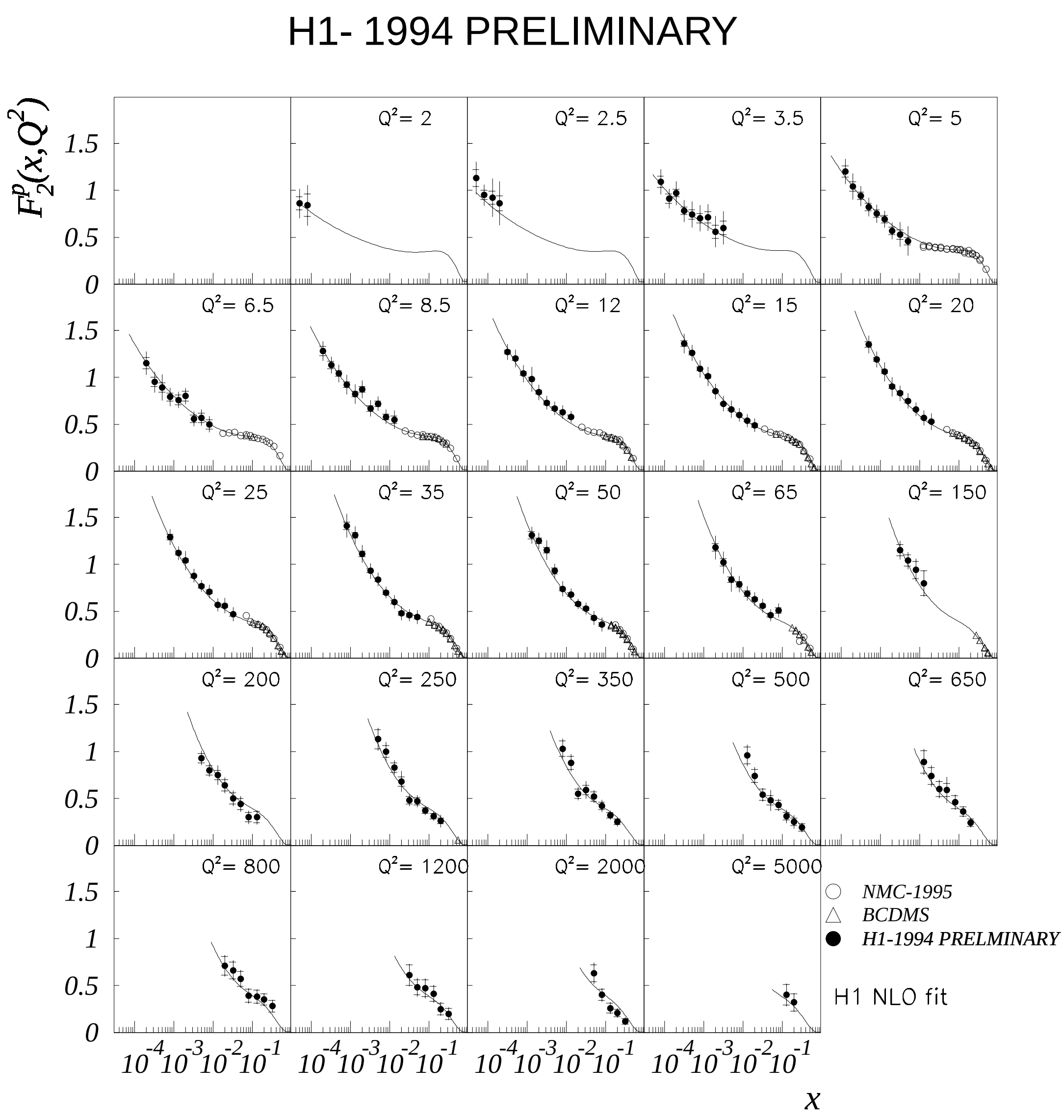
  (Beam-wall, beam-gas, halo μ, cosmics) < 1%,

  γp below 15% everywhere, 12/172 bins have bgd > 3%.
- Systematic error in total $\approx 10\%$.

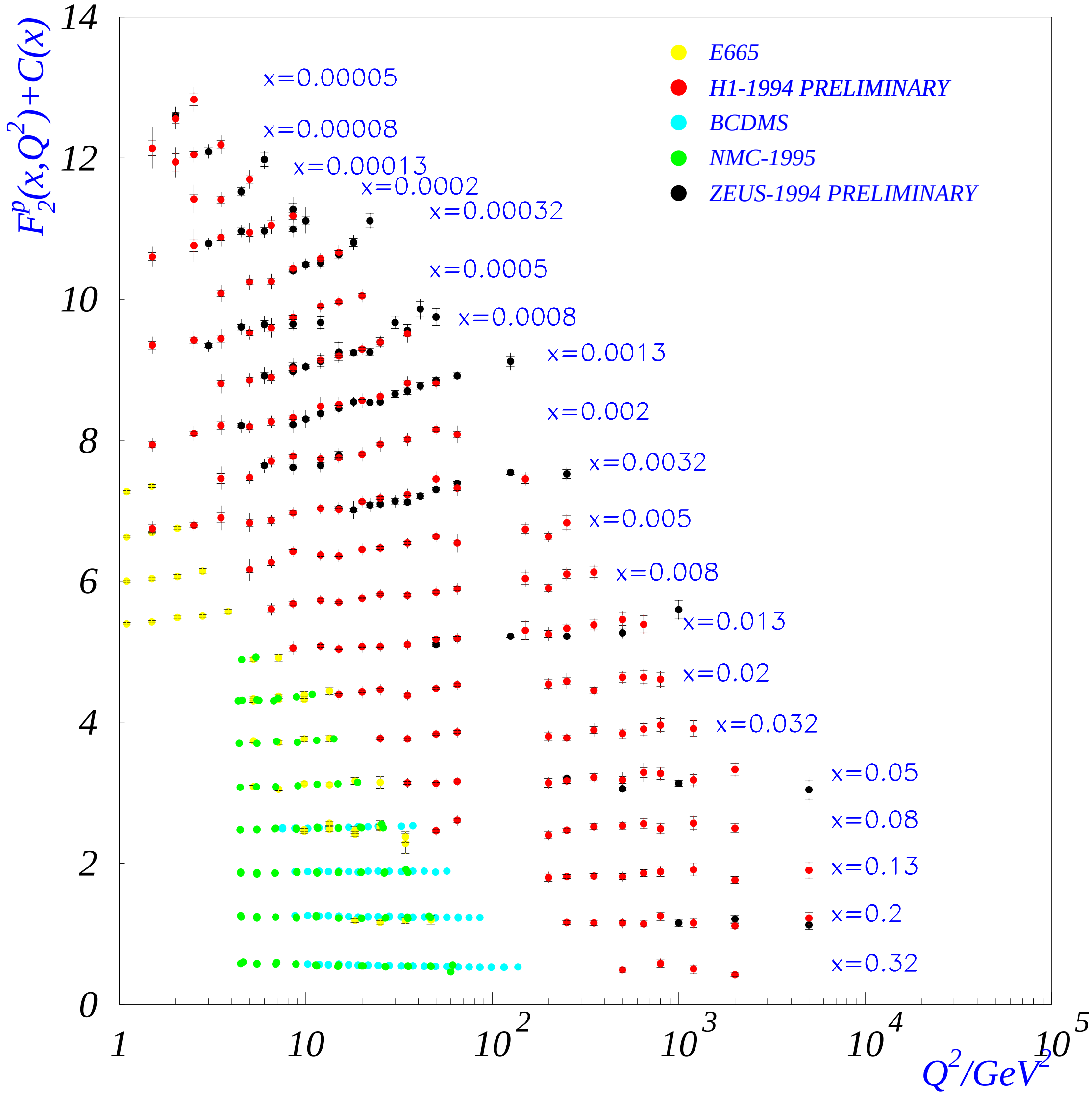
$F_2\,(x, Q^2)$ in Bins of Q^2



NLO Fit to $F_2(x, Q^2)$



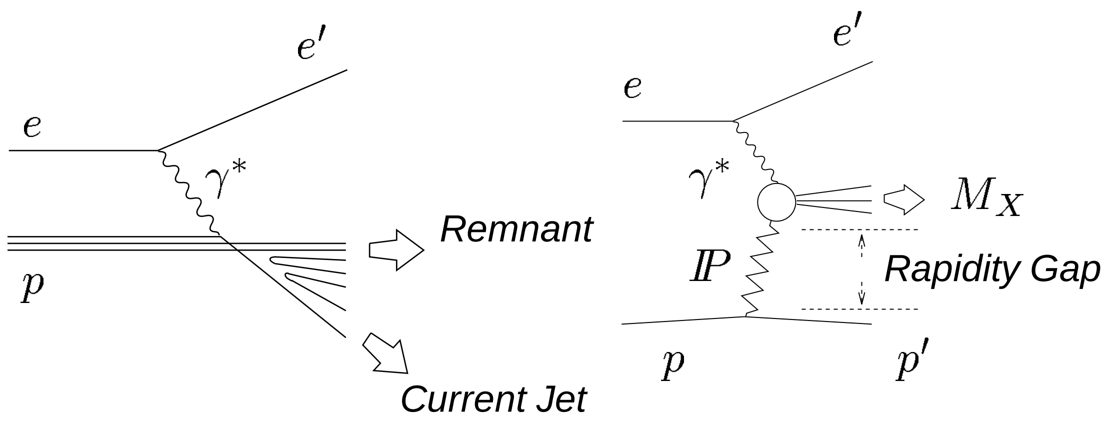
Scaling Violations of $F_2(x, Q^2)$



Results derived from $F_2\,(x, Q^2)$

- At HERA $F_2\,(x, Q^2)$ is measured in the range $5 \cdot 10^{-5} < x < 0.32$ and $(2 < Q^2 < 5000)\ GeV^2$.
- The results of the two experiments H1 and ZEUS are in very good agreement.
- A smooth transition from the fixed target regime into the HERA regime is visible.
- A distinct rise of $F_2\,(x, Q^2)$ with decreasing x at fixed Q^2 down to $Q^2 = 2\ GeV^2$ and $x = 5 \cdot 10^{-5}$ is observed.
- The violation of scaling gets stronger for low x values.

Diffractive Scattering



a) standard DIS

b) diffractive DIS

$I\!P = x_{I\!P}\ p, \quad t = (p - p')^2$

Variables:

$$x_{I\!P} = \frac{q \cdot (P - P')}{q \cdot P} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2 - M_p^2} \approx \frac{Q^2 + M_X^2}{Q^2 + W^2}$$

$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t} \approx \frac{Q^2}{Q^2 + M_X^2}, \qquad x = \beta x_{I\!P}$$

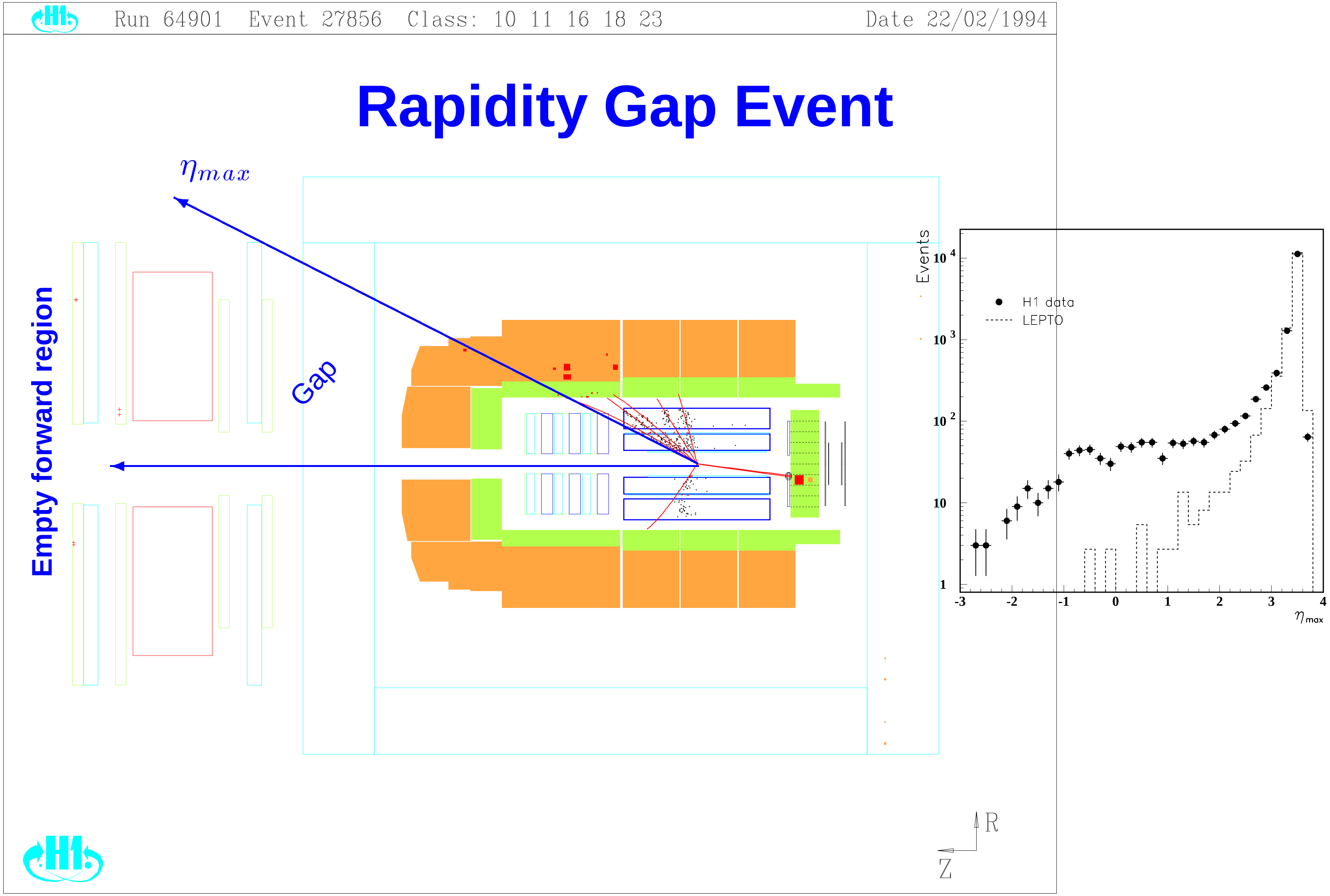
Cross Sections:

$$\frac{d^4\sigma_{ep \to e'p'X}}{dx\, dQ^2\, dx_{I\!P}\, dt} = \frac{4\pi\alpha^2}{xQ^4} \left\{ 1 - y + \frac{y^2}{2[1 + R^{D(4)}]} \right\} F_2^{D(4)}$$

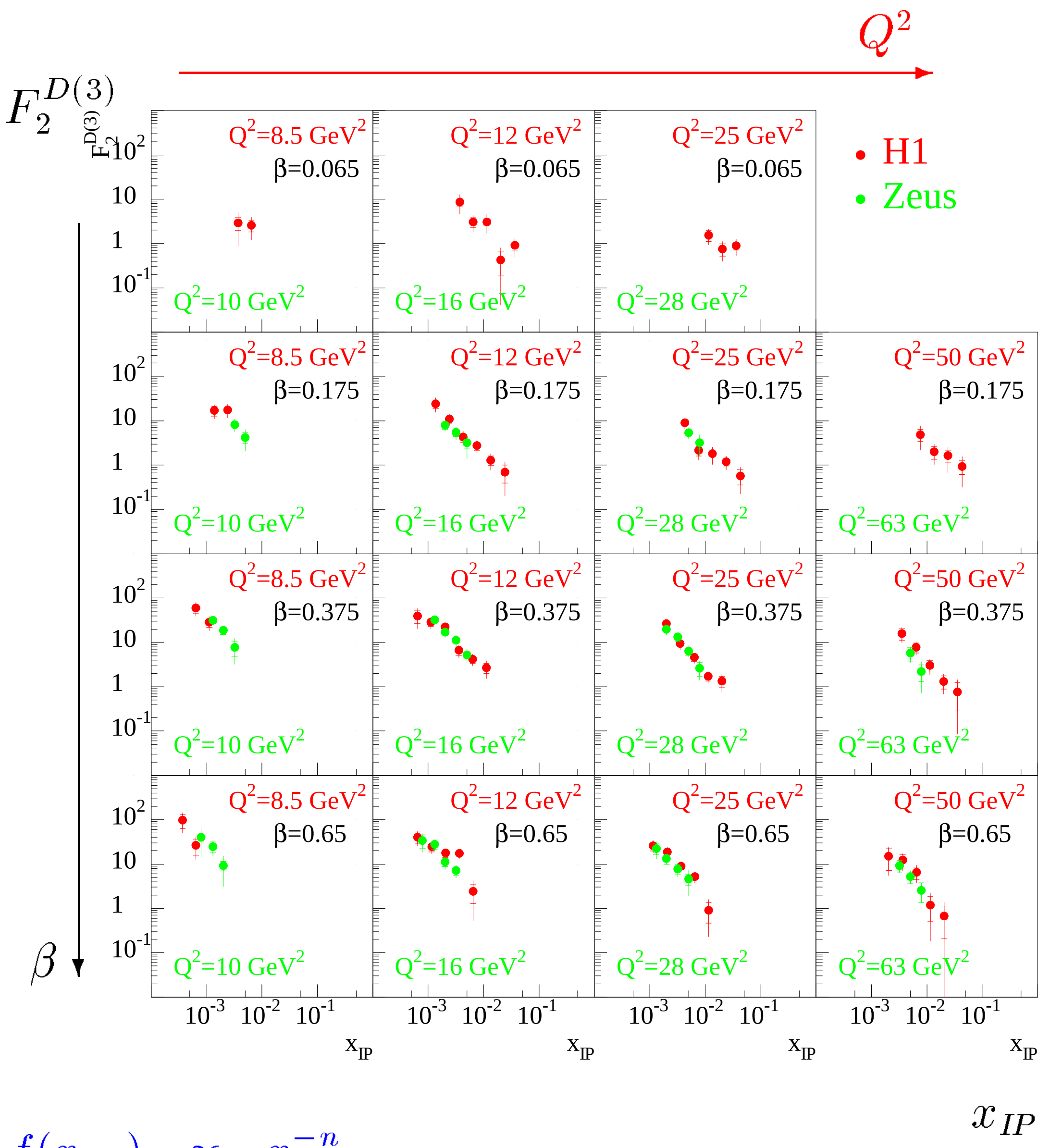
with $R^{D(4)}(x, Q^2, x_{I\!P}, t) = 0$ and t Integration:

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

Rapidity Gap Event



Diffractive Contribution to $F_2(x, Q^2)$

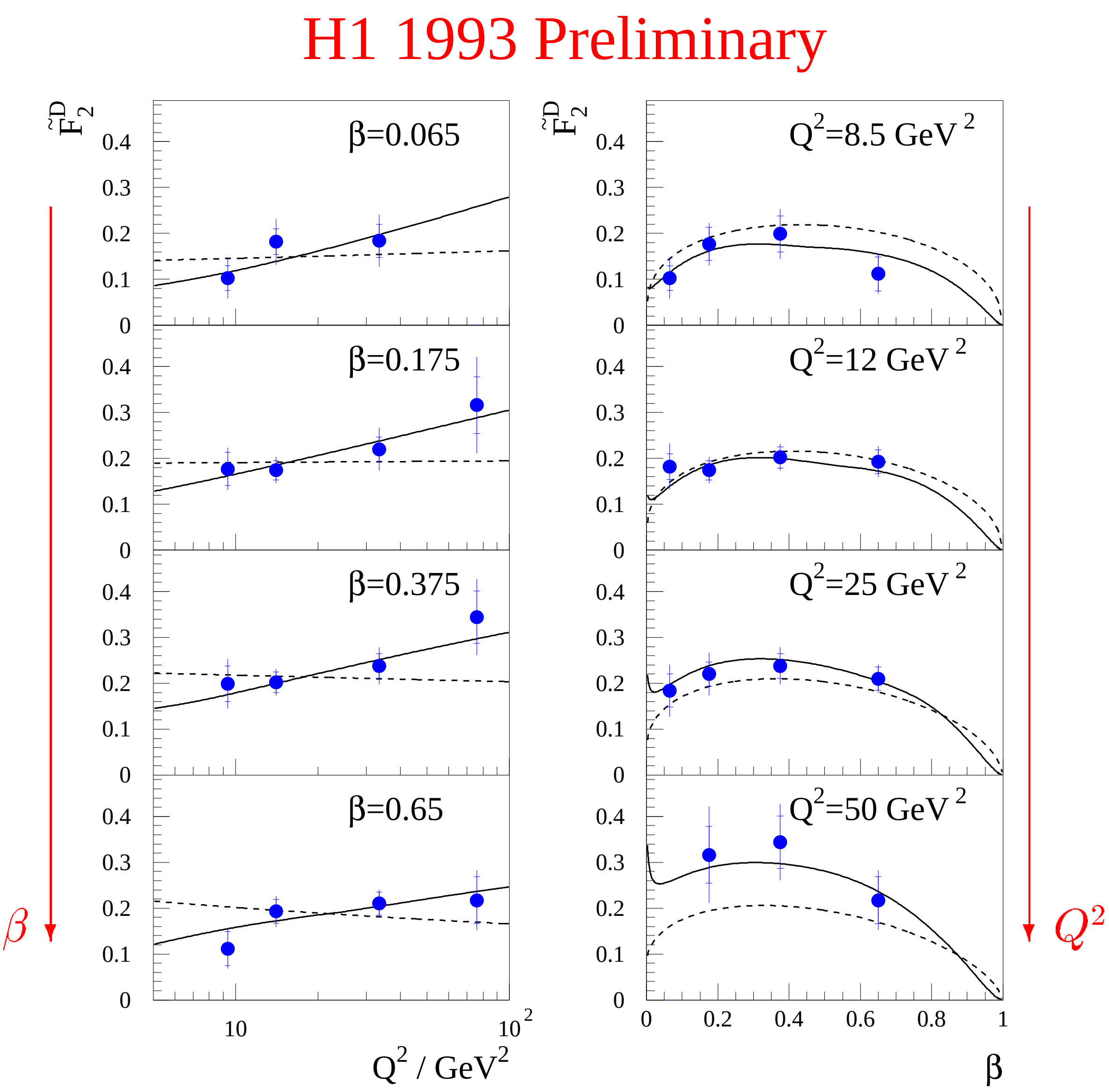


$$f(x_{IP}) \propto x_{IP}^{-n}$$

$$n = 1.19 \pm 0.06\,(stat.) \pm 0.07\,(sys.) \quad H1(93)$$

$$n = 1.30 \pm 0.08\,(stat.)\,{}^{+0.08}_{-0.14}\,(sys.) \quad ZEUS(93)$$

Dependence on Q^2 and β



A Partonic Model of Diffraction

- Assume DIS is mainly electron gluon scattering and neglect contributions from q and $\bar{q}$ to F_2 at small $x_{i/p}$.
- Work in massive gluon scheme and use $g(x_{g/p}) = A_g \cdot x_{g/p}^{-1-\lambda}$.

$$\Rightarrow \quad F_2(x,Q^2) \simeq \frac{\alpha_S}{3\pi} \sum_q e_q^2 x g(x) \left(\frac{2}{3} + \ln \frac{Q^2}{m_g^2} \right)$$

- Fit to data $\Rightarrow$ $\lambda = 0.23$, $m_g = 1.0\, GeV$, $A_g \alpha_S \sum_q e_q^2 = 0.61$.
- Assume that the colour rotation due to soft interactions is rapid so that 1/9 of the $q\bar{q}$ states leave the proton as colour singlets.

$$\begin{aligned} F_2^{D(3)}(\beta, Q^2, x_{g/p}) &\simeq \frac{1}{9} \frac{\alpha_S}{2\pi} \sum_q e_q^2 g(x_{g/p}) F_2^g(\beta, Q^2) \\ F_2^g(\beta, Q^2) &= \beta \left[(\beta^2 + (1-\beta)^2) \right. \\ &\quad \left. \ln \frac{Q^2}{m_g^2 \beta^2} - 2 + 6\beta(1-\beta) \right] \end{aligned}$$

$\Rightarrow$ Parameter free prediction:

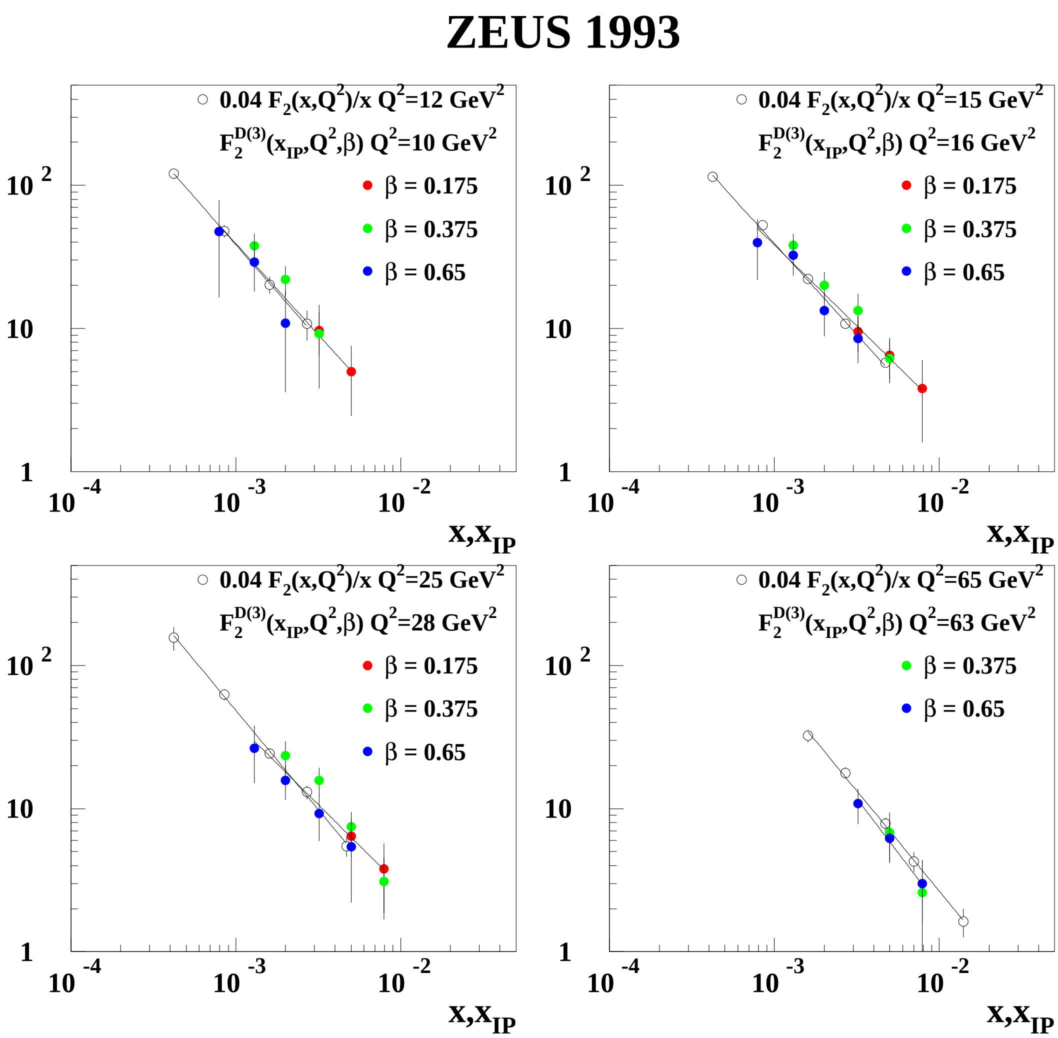
$$r_D = \frac{\int_x^{0.05} F_2^{D(3)}(x,Q^2,x_{g/p})\,dx_{g/p}}{F_2(x,Q^2)} \simeq \frac{1}{9}$$

- $F_2^g(\beta, Q^2) \approx F_2^g(\beta = 0.4, Q^2)$ flat in $0.2 < \beta < 0.6$.

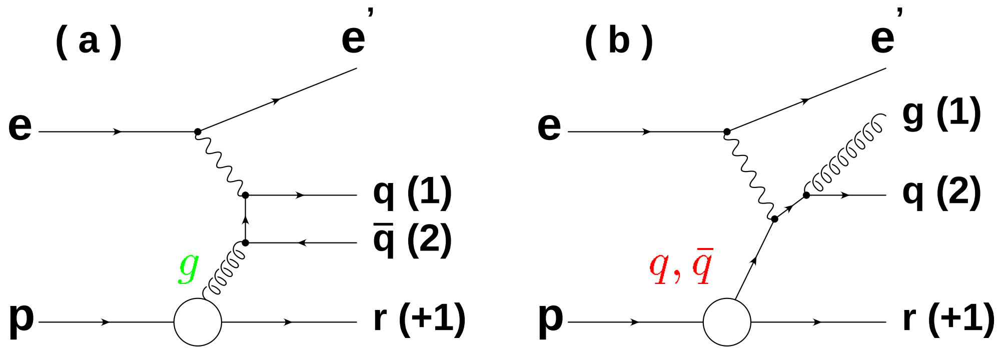
$\Rightarrow$ Scaling prediction:

$$F_2^{D(3)}(\beta, Q^2, x_{g/p}) \simeq \frac{0.04}{x_{g/p}} F_2(x_{g/p}, Q^2)$$

The Buchmüller Scaling Law



LO (2+1)-jet Diagrams



gluon initiated: $i = g$ quark initiated: $i = q, \bar{q}$

sensitive to $\alpha_s(\mu^2)$, choose $\mu_f^2 = \mu^2 = Q^2 = -q^2$

$$x_{i/p} = x(1 + \frac{\hat{s}}{Q^2}) \quad y_c = \frac{m_{ij}^2}{W^2} \quad W^2 = Q^2 \cdot \frac{1-x}{x}$$

$$\Rightarrow \quad (2+1) - jets: \quad x_{i/p} = y_c + x(1 - y_c) > y_c$$

$$(1+1) - jets: \quad x_{i/p} = x$$

Hard Jets for $(2+1) - jet$ events via :

$$y_c > 0.02\,, \quad W^2 > 5000\, GeV^2 \quad \Rightarrow \hat{s} > 100\, GeV^2$$

Gluon Density Determinations

Direct method:

1. Measure jet production in $g \longrightarrow q\bar{q}$ as a function of $x_{g/p} = x(1 + \frac{\hat{s}}{Q^2})$.

Indirect methods:

1. NLO fit to $\frac{\partial F_2(x,Q^2)}{\partial \log(Q^2)}$.
2. Approximations
   - Prytz method:
     Scaling violations proceeds mainly via $g \longrightarrow q\bar{q}$.
     $xg(x)$ related to $\frac{\partial F_2(x/2,Q^2)}{\partial \log(Q^2)}$
   - EKL method:
     F_2 and the gluon density behave as $x^{-\omega_0}$.
     $xg(x)$ related to $F_2(x, Q^2)$ and $\frac{\partial F_2(x,Q^2)}{\partial \log(Q^2)}$

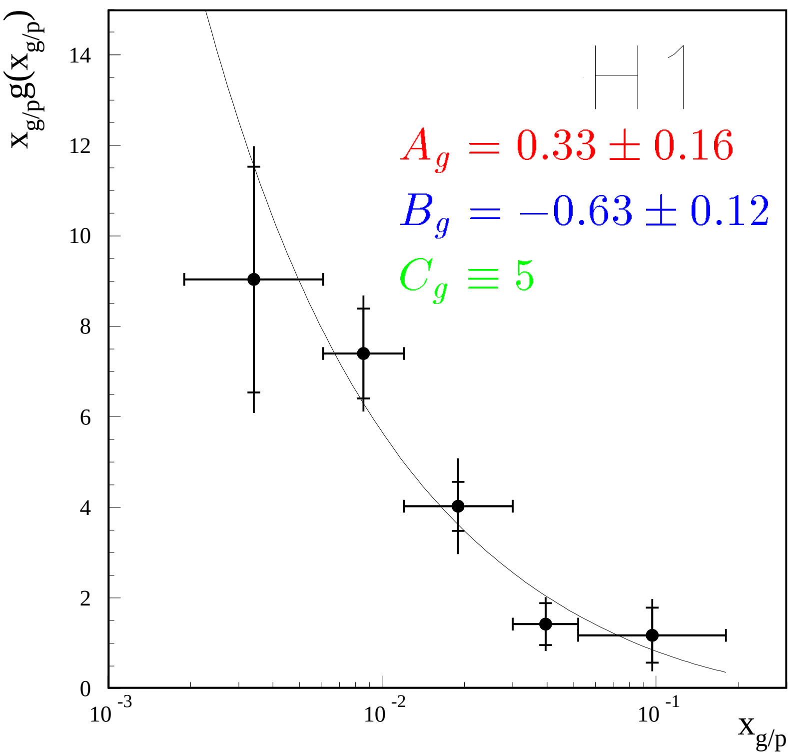
$x_{g/p} \cdot g(x_{g/p}, Q^2)$ from Jets

Event requirements:

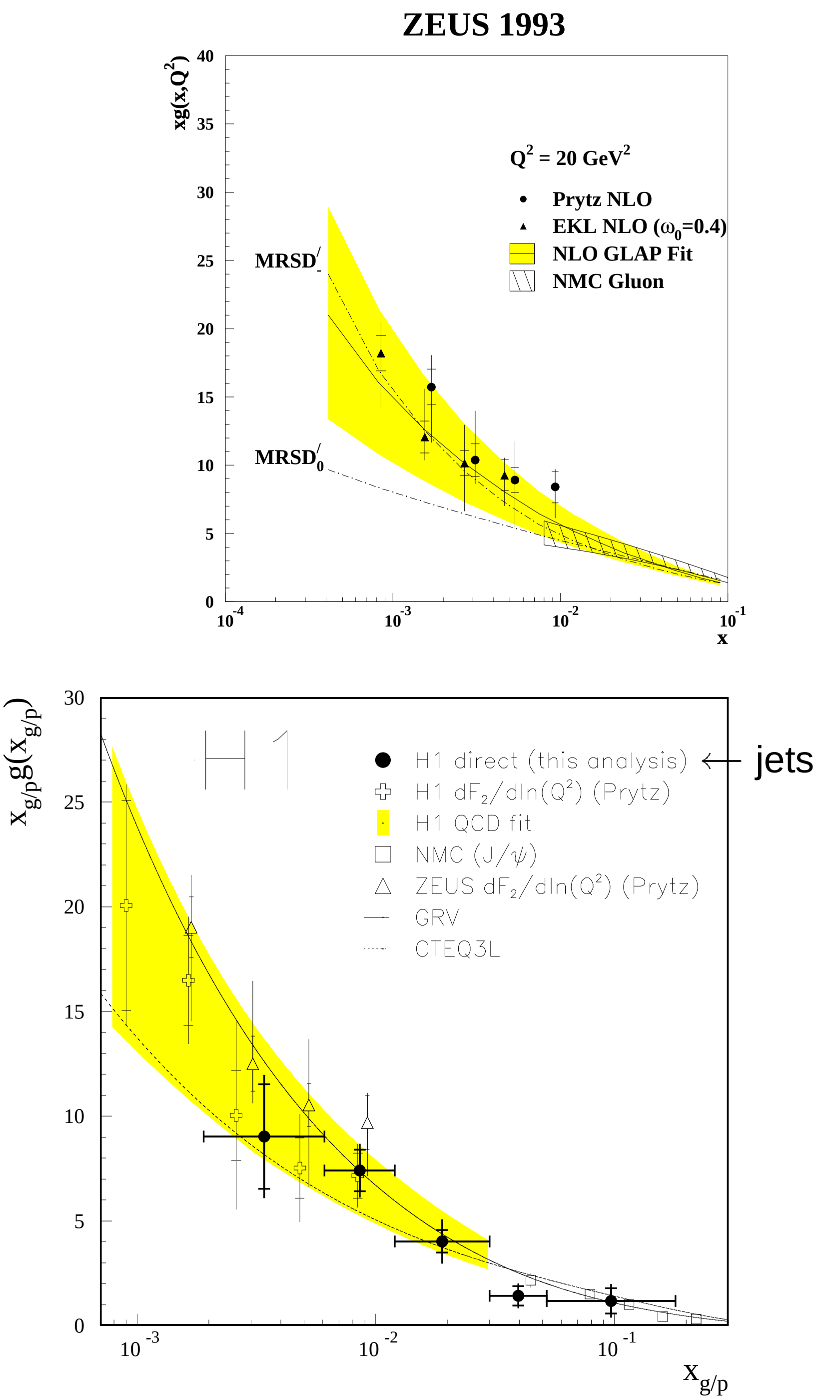
- $(12.5 < Q^2 < 80)\ GeV^2$, $0.05 < y_e < 0.625$.
- 2 (+1) cone jets in $\gamma^\star p$ - CMS system.
- $\Delta R = 1.0$, $p_T^\star > 3.5\ GeV$, $\hat{s} > 100\ GeV^2$.
- $(10^\circ < \vartheta_{jet} < 150^\circ$ and $\Delta\eta_{jj} < 2.0)$ in LAB system.

$\Rightarrow$ 328 Events for $\mathcal{L}_{int} = 242\ nb^{-1}$

Fit: $x_{g/p} \cdot g(x_{g/p}, Q^2) \quad = \quad A_g \cdot x_{g/p}^{B_g} \cdot (1 - x_{g/p})^{C_g}$



Experimental Results on $xg(x)$



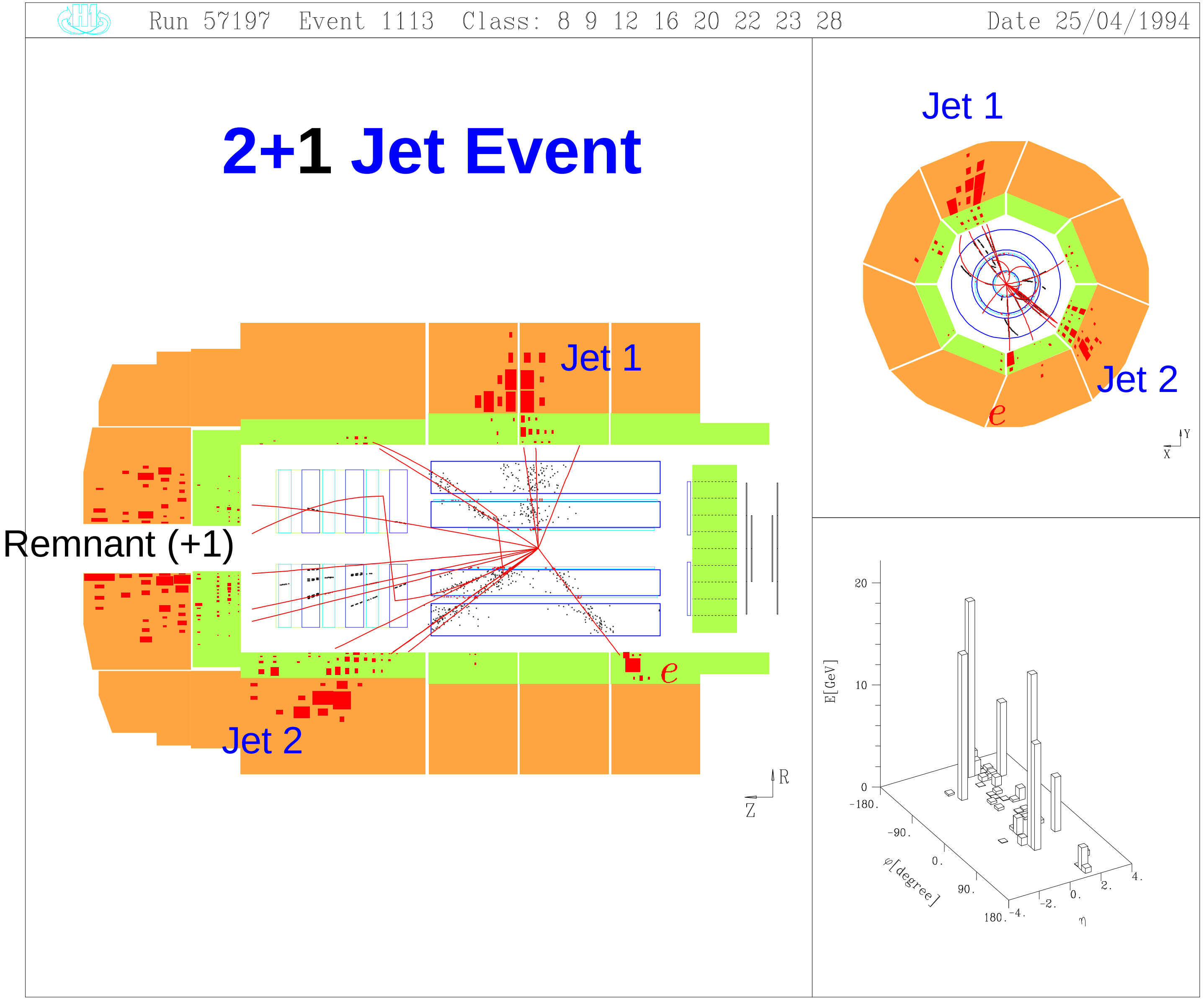
The modified Jade Jet Algorithm

- Use calorimetric energy deposits.
- Include a pseudo particle with four momentum $(P_z^{miss}, 0, 0, P_z^{miss})$ as best estimate of the unseen remnant. $P_z^{miss} = P_z^e + P_z^p - P_z^{vis}$.
- Calculate W^2 as invariant mass of all objects including the pseudo particle .
- Take the Jade recombination scheme.

$$y_c = \frac{m_{ij}^2}{W^2}$$

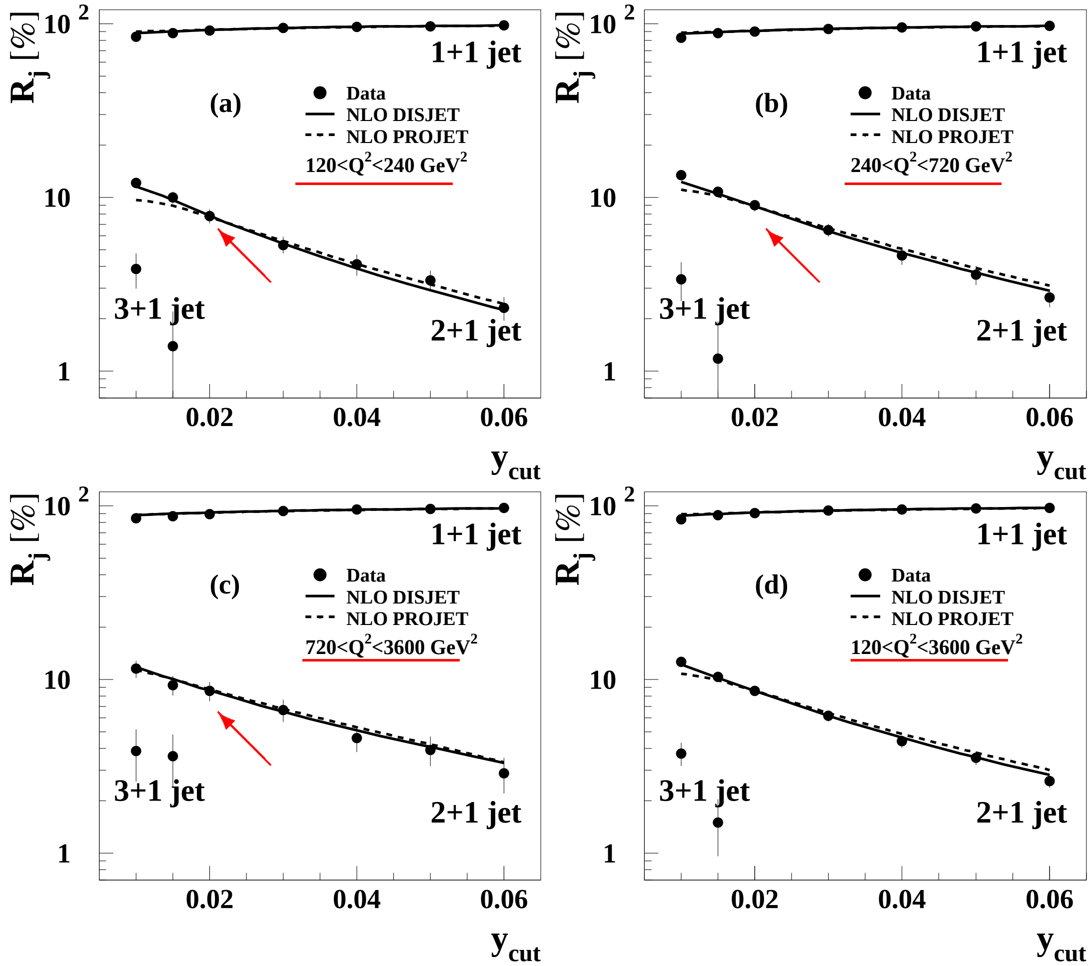
$$m_{ij}^2 = 2E_iE_j(1 - \cos\theta_{ij})$$

$$p_k = p_i + p_j$$


Run 57197 Event 1113 Class: 8 9 12 16 20 22 23 28 Date 25/04/1994
2+1 Jet Event
Jet 1
Jet 2
Remnant (+1)
e
R
Z
Jet 1
Jet 2
e
Y
X
E[GeV]
20
10
0
-180.
-90.
0.
90.
180.
φ[degree]
-4.
-2.
0.
2.
4.
η

Jet Rates as a Function of y_c

ZEUS 1994



⇒ Good description by NLO Monte Carlos

PROJET by D. Graudenz and DISJET by E. Mirkes et al

α_s Measurement in NLO at HERA

$$R_{2+1}(Q^2, y_c) = \frac{d\sigma_{2+1}(Q^2, \alpha_s, y_c)}{d\sigma_{tot}(Q^2, \alpha_s)}$$

$$R_{2+1} = \alpha_s \frac{A_{31}}{A_{20}} \left[1 + \left(\frac{A_{32}}{A_{31}} - \frac{A_{21} + A_{31}}{A_{20}} \right) \alpha_s + \mathcal{O}(\alpha_s^2) \right]$$

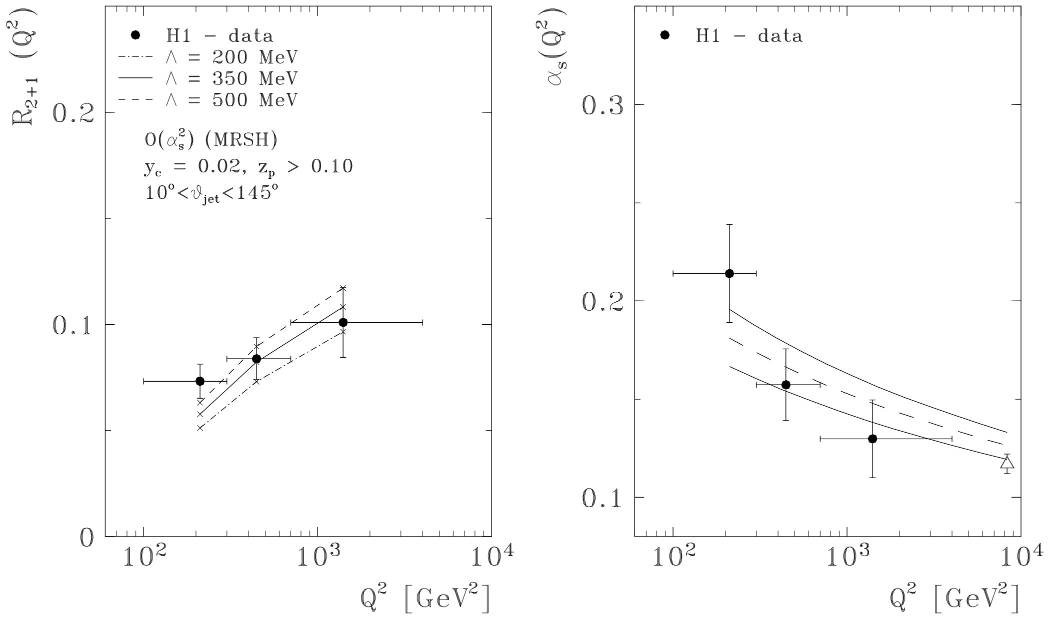
$$\alpha_s(Q^2) = \mathcal{F} \left[\underbrace{A_{ij}(Q^2, y_c)}_{Theory}, \underbrace{R_{2+1}(Q^2, y_c)}_{Data} \right]$$

$$\chi^2(\Lambda^2_{n_f, \overline{MS}}) = min \sum_{k=1}^{N} \frac{\left[\alpha_s(Q_k^2) - \alpha_s(Q_k^2, \Lambda^2_{n_f, \overline{MS}}) \right]^2}{\left[\sigma \left[\alpha_s(Q_k^2) \right] \right]^2}$$

where $A_{ij} \equiv$ i=N+1 Jets to $\mathcal{O}(\alpha_s^j)$

$R_{2+1}(Q^2) \Rightarrow \alpha_s(Q^2)$

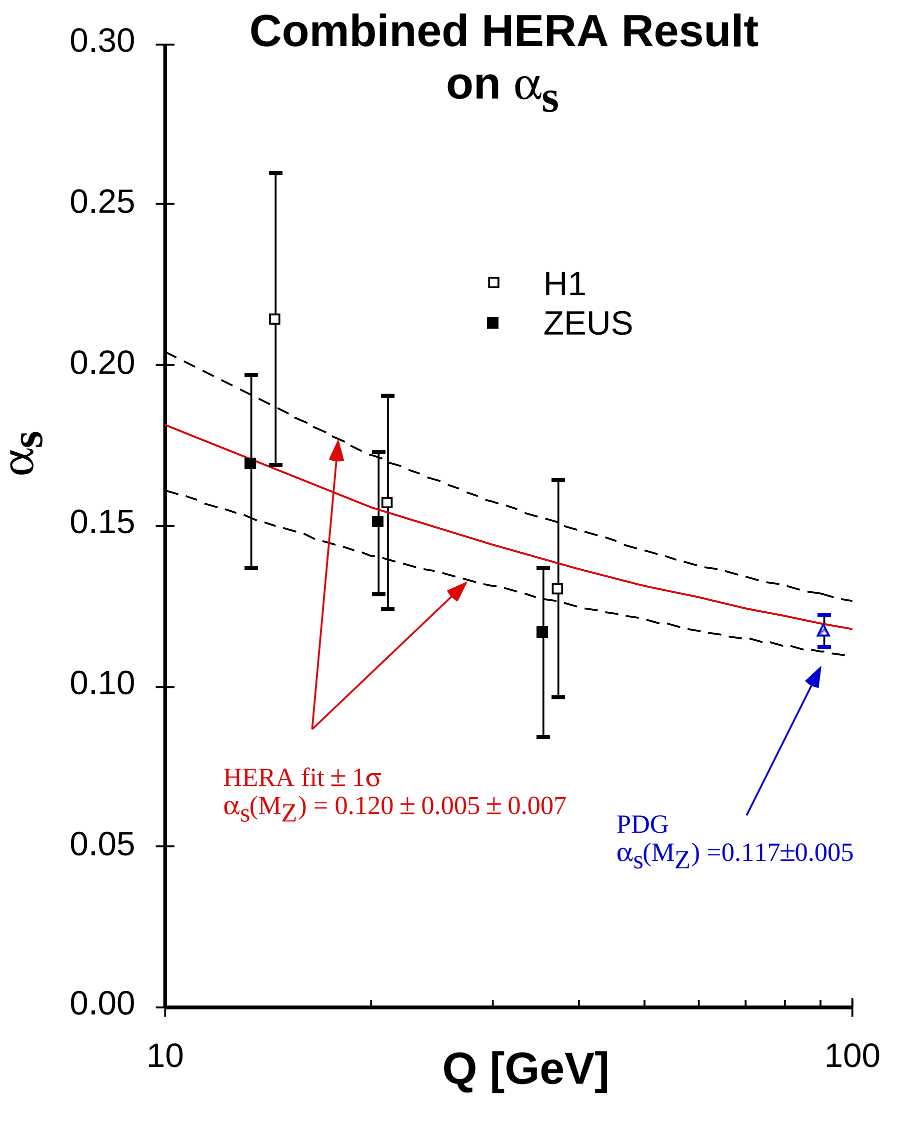
H1-1994 PRELIMINARY



$$\alpha_s(M_z^2) = 0.126 \pm 0.007\,(stat.) \pm 0.008\,(sys.)$$

Statistics	$\pm\, 0.007$
ϑ_{jet} and z_p Cut	$\pm\, 0.004$
y_c Dependence	$\pm\, 0.002$
Hadronic Energy Scale	$\pm\, 0.007$
Parton Density Functions	$\pm\, 0.002$
$\Lambda_{4,\overline{MS}}$ used in the PDF's	$\pm\, 0.002$
Renormalization and Factorization Scale	$\pm\, 0.003$

$\alpha_s(Q^2)$ from (2+1) Jet Events



Conclusions

1. The structure function $F_2\,(x, Q^2)$ has been measured at HERA in a new kinematic regime $5 \cdot 10^{-5} < x < 0.32$ and $(2 < Q^2 < 5000)\; GeV^2$.
2. $F_2\,(x, Q^2)$ is found to rise with decreasing x at fixed Q^2.
3. Diffractive deep inelastic scattering has been observed at HERA. It can be explained by a partonic model relying on electron gluon scattering and fast colour rotation.
4. The gluon density of the proton has been measured using several methods. The measured range in x has been extended down to $x = 2 \cdot 10^{-4}$.
5. The α_s measurement in NLO from Jets at HERA leads to
   $\alpha_s(M_z^2) = 0.120 \pm 0.005\,(stat.) \pm 0.007\,(sys.)$

Slides: http://wwwcn1.cern.ch/˜nisius/talks/CERN041295.html