LNS Journal Club

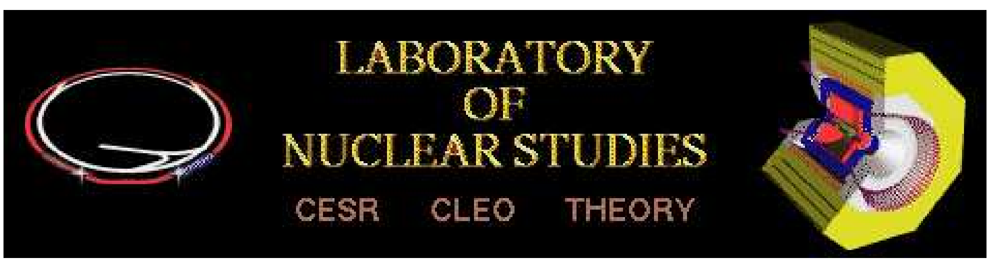
1 June 2001

High-Energy Physics Seminar

Cornell University

Nine Years of Physics at HERA

– Assessment and Perspectives –



J. A. Crittenden

Deutsches Elektronen-Synchrotron

DESY

The Hadron-Electron Ring Accelerator

The first electron-proton collider

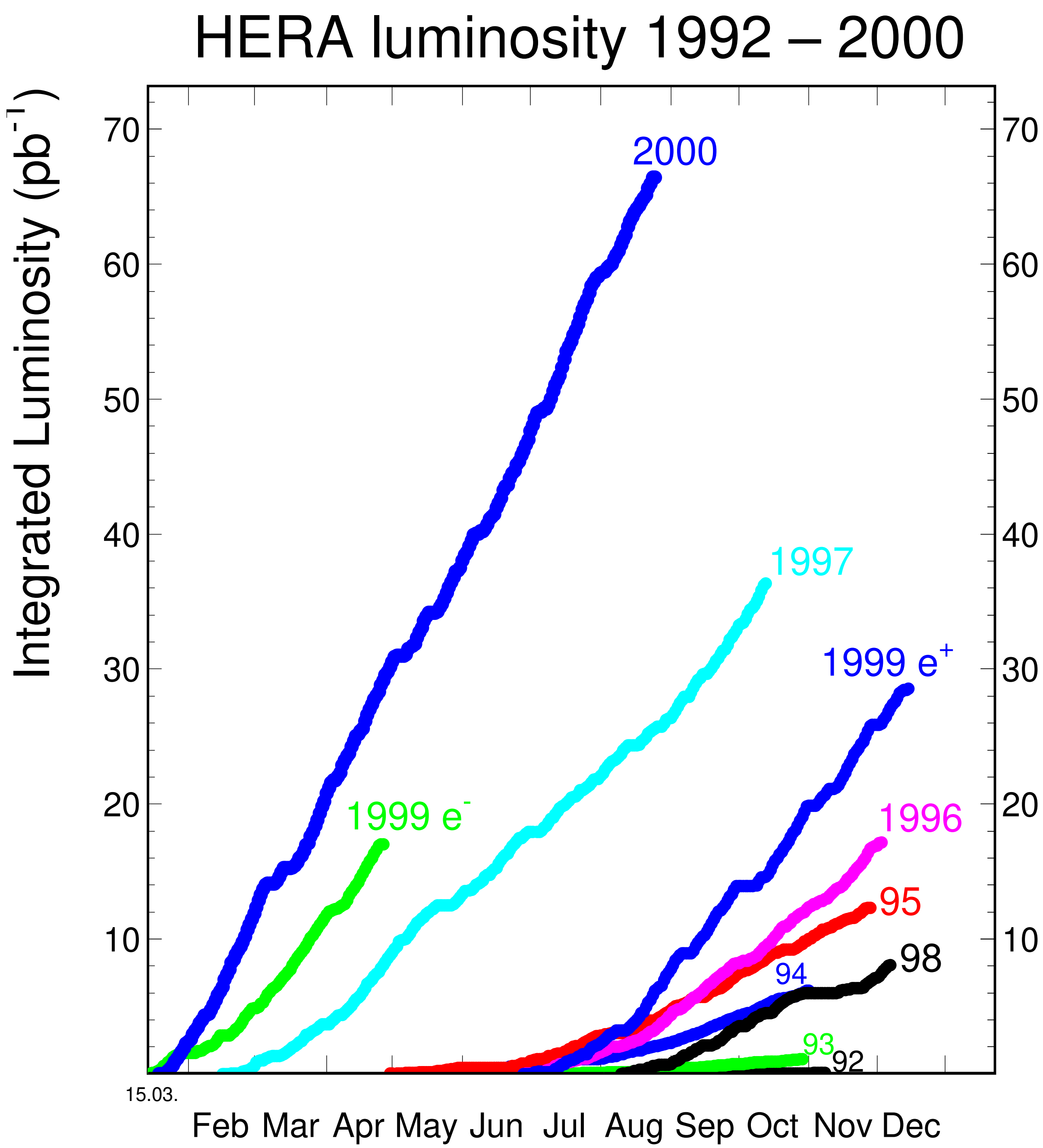
Proton energy: 920 GeV   Electron energy: 27.5 GeV

Center-of-mass energy: 318 GeV

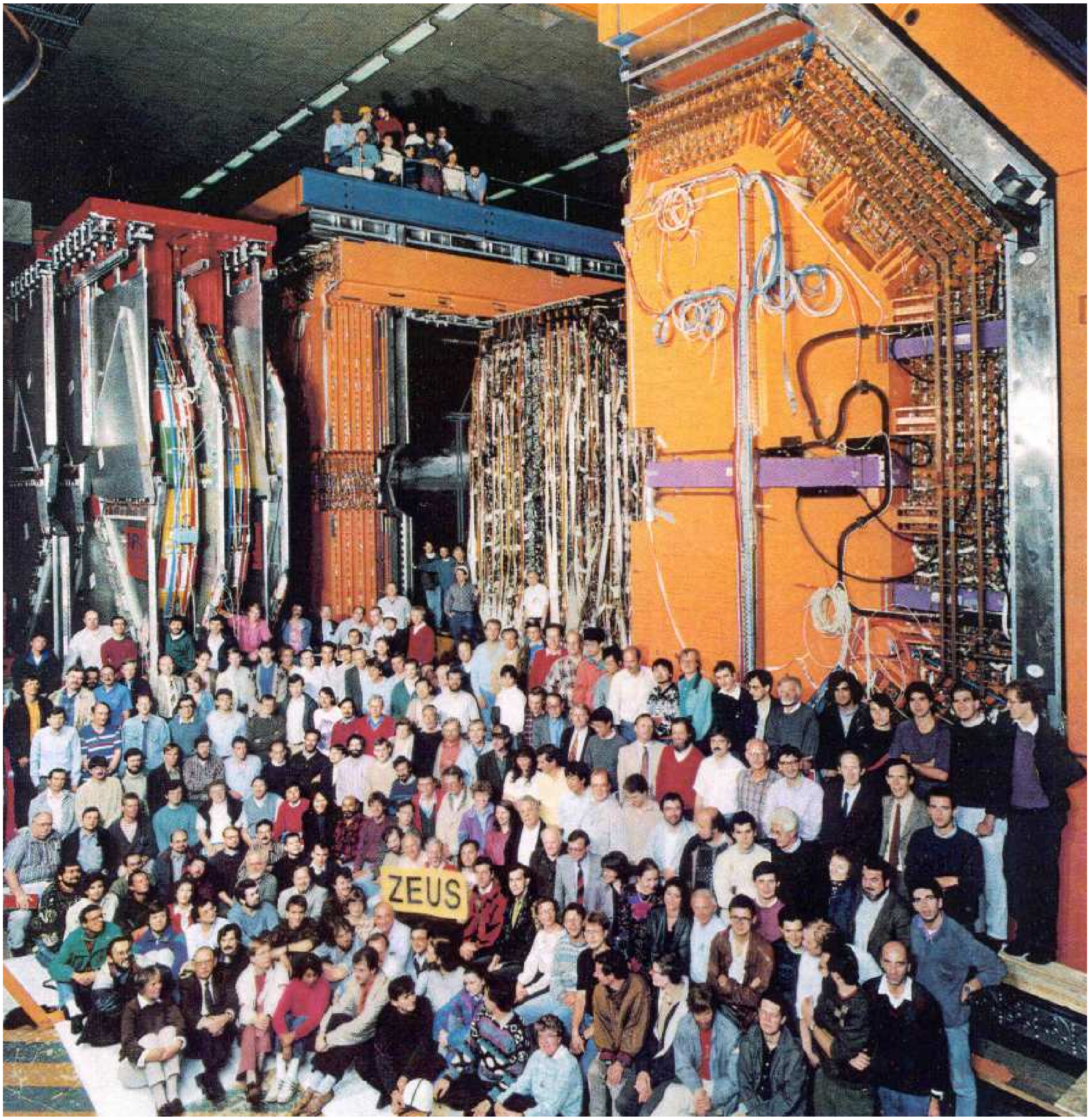
Electron energy in proton rest frame: 54.000 GeV

In operation since 1992

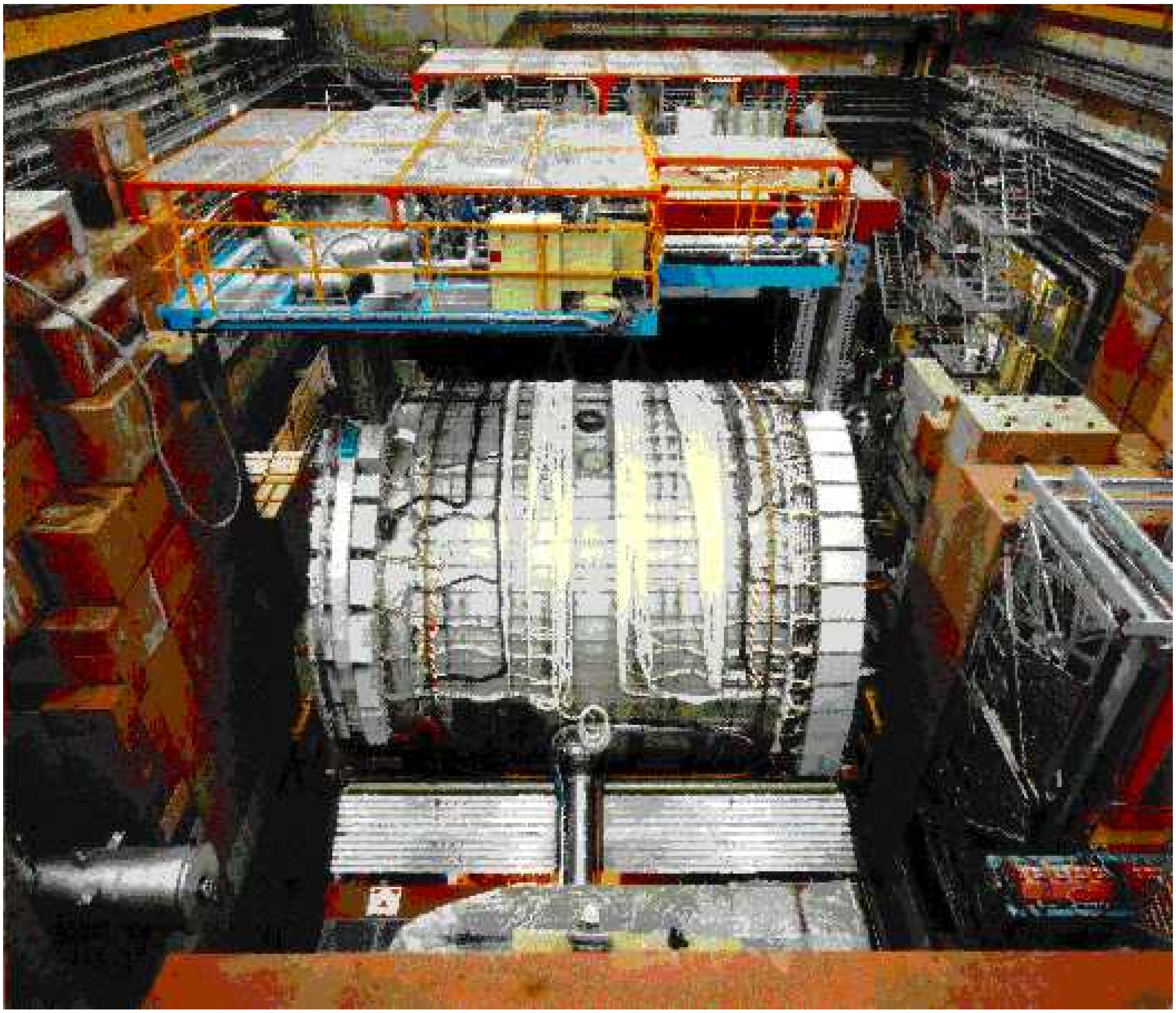
Luminosity History



The ZEUS Experiment



The H1 Detector



Variable Definitions

A. López-Durán Viani/ZEUS talk at DIS2001

Deep inelastic scattering

Kinematic variables

Virtuality of the process.

$$Q^2 = -q^2 = -(k - k')^2$$

Four momentum transfer between lepton and proton.

-0-

Momentum transfer between lepton and proton.

$$y = (p \cdot q)/(p \cdot k)$$

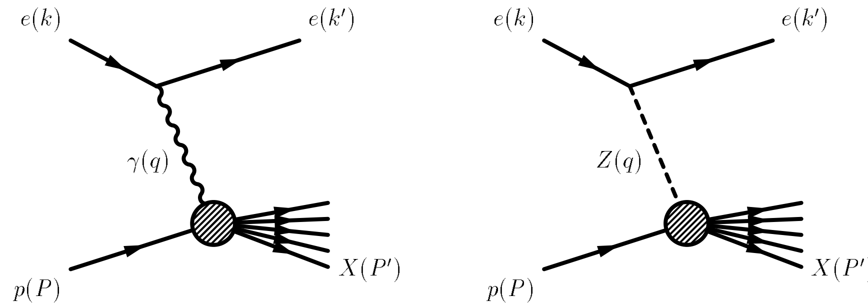
Gives the inelasticity of the process.

-0-

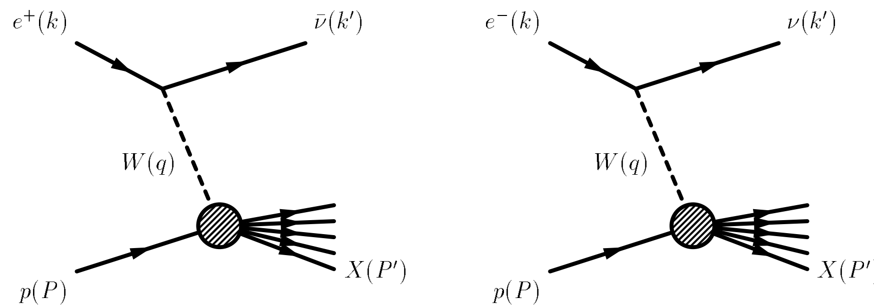
Bjorken x.

$$x = Q^2/2p \cdot q$$

Momentum fraction of the proton carried by the quark.



NC DIS processes



CC DIS processes

The Polarized $e^{\pm}p$ Neutral-Current Cross Section

[following M. Klein and T. Riemann, Z.Phys. C24 (1984) 151]

The double differential cross section for the scattering of $e^{\pm}$ (helicity λ) on unpolarized protons may be written (assuming the Callan-Gross relation and neglecting radiative corrections)

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}Q^2\,\mathrm{d}x}(e^{\pm}p \to e^{\pm}X) = \frac{2\pi\alpha^2}{xQ^4}\sigma^{\pm}(\lambda) = \frac{2\pi\alpha^2}{xQ^4}\left[\sigma_0 + \sigma_i^{\pm}(\lambda) + \sigma_Z^{\pm}(\lambda)\right]$$

$$\gamma: \quad \sigma_0 = \left[Y_+ \cdot \hat{F}_2(x,Q^2)\right]$$

$$\gamma/\mathrm{Z}: \sigma_i^{\pm}(\lambda) = \kappa(Q^2)\left[Y_+(-v \mp \lambda a)\,\hat{G}_2(x,Q^2) + Y_-(\pm a + \lambda v)\; x\hat{G}_3(x,Q^2)\right]$$

$$Z: \sigma_Z^{\pm}(\lambda) = \kappa^2(Q^2)\left[Y_+(v^2 + a^2 \pm 2\lambda va)\;\hat{H}_2(x,Q^2) + Y_-(\mp 2va - (v^2+a^2)\lambda)\; x\hat{H}_3(x,Q^2)\right]$$

$$\boxed{Y_{\pm} = 1 \pm (1-y)^2}$$

Propagator

$$\kappa(Q^2) = \kappa(\infty)\, Q^2/(Q^2 + M_Z^2)$$

$$\kappa(\infty) = \left[4\sin^2\theta_W \cos^2\theta_W\right]^{-1} \simeq 1.5$$

Weak neutral current couplings of $e^{\pm}$

$$a = I_3^L = -\tfrac{1}{2}$$

$$v = I_3^L \mp 2\sin^2\theta_W$$

Structure Functions

$$\hat{F}_2(x,Q^2) = x\,\Sigma_q(q+\bar{q})\cdot Q_q^2$$

$$\hat{G}_2(x,Q^2) = x\,\Sigma_q(q+\bar{q})\cdot 2v_qQ_q$$

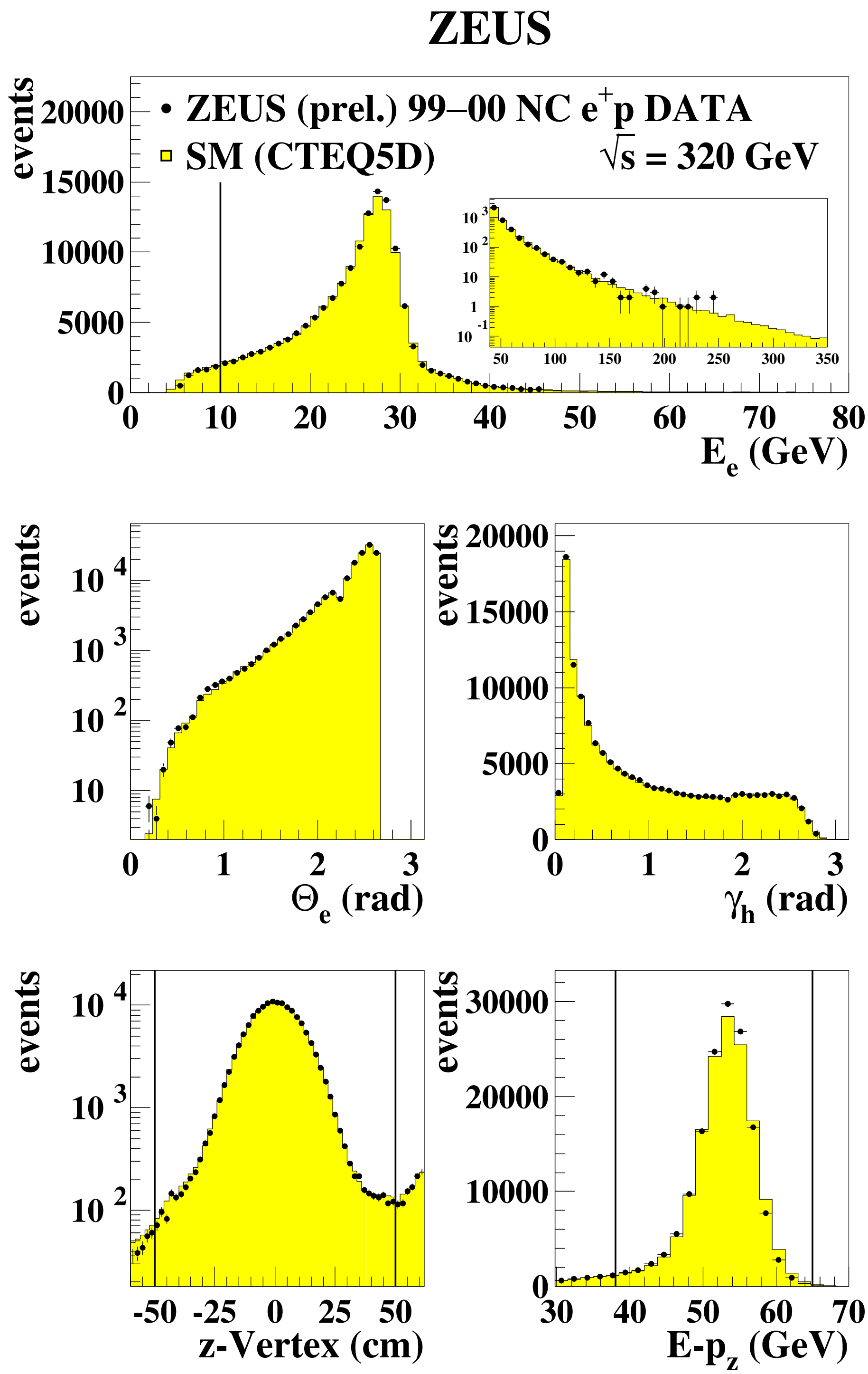
$$\hat{H}_2(x,Q^2) = x\,\Sigma_q(q+\bar{q})\cdot (v_q^2 + a_q^2)$$

$$\hat{G}_3(x,Q^2) = x\,\Sigma_q(q-\bar{q})\cdot a_qQ_q$$

$$\hat{H}_3(x,Q^2) = x\,\Sigma_q(q-\bar{q})\cdot a_qv_q$$

Control Plots

Data sample $(e^+p)^{920}$

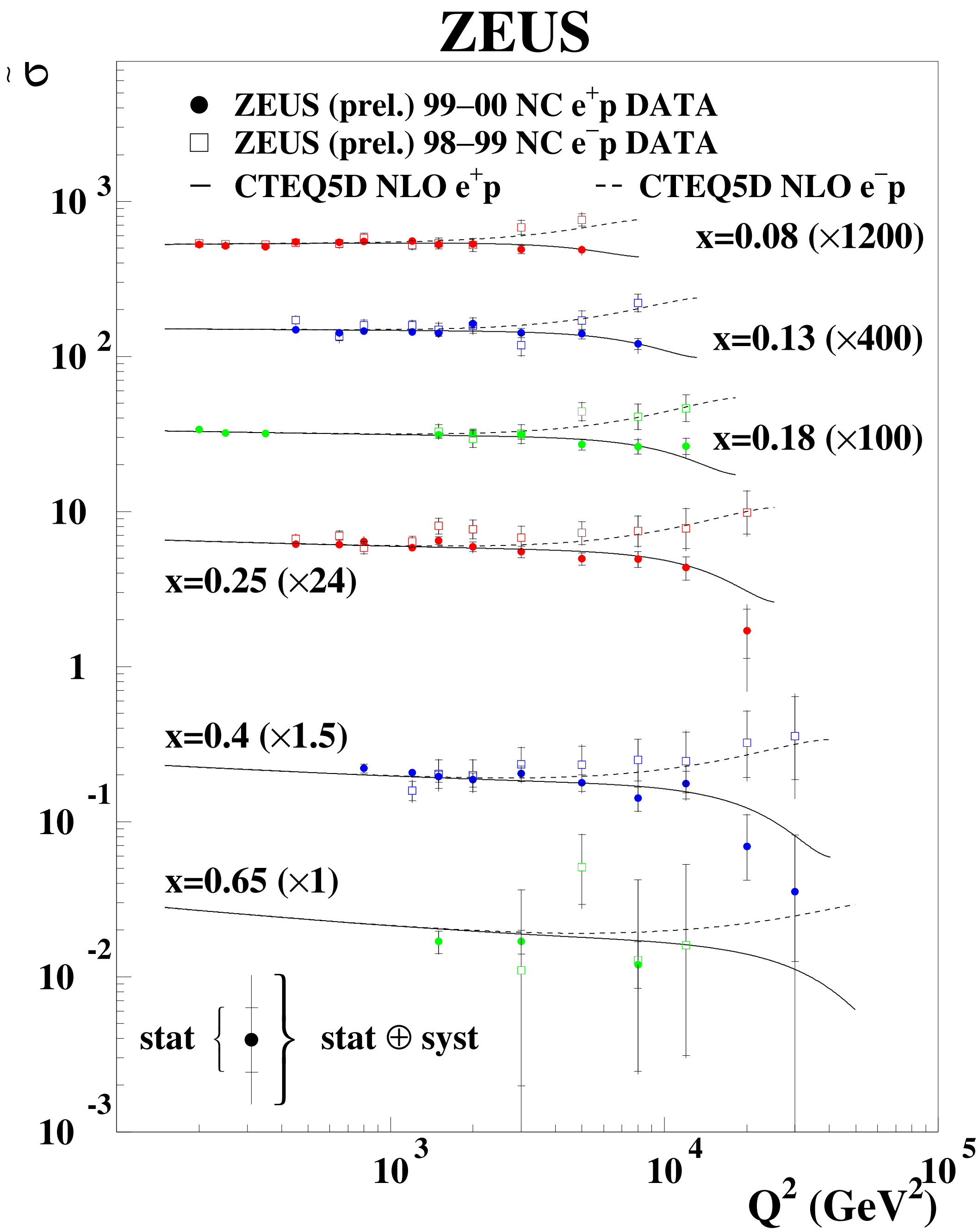


Impressive statistical precision

Neutral-Current Cross Sections

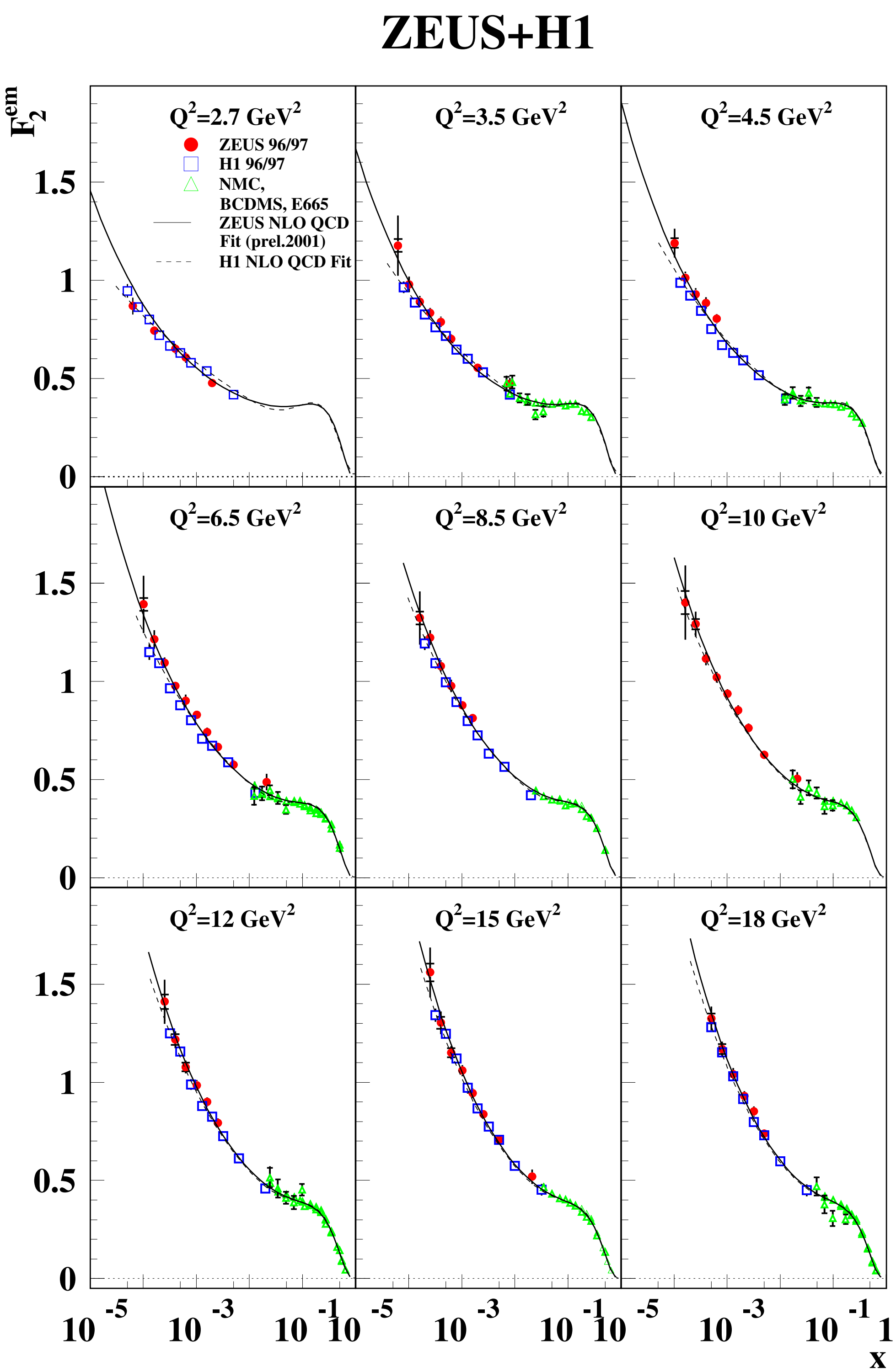
$\frac{d^2\sigma}{dx\,dQ^2}$ **in x bins for NC events**

Data sample $(e^+p)^{920}$ and $(e^-p)^{920}$



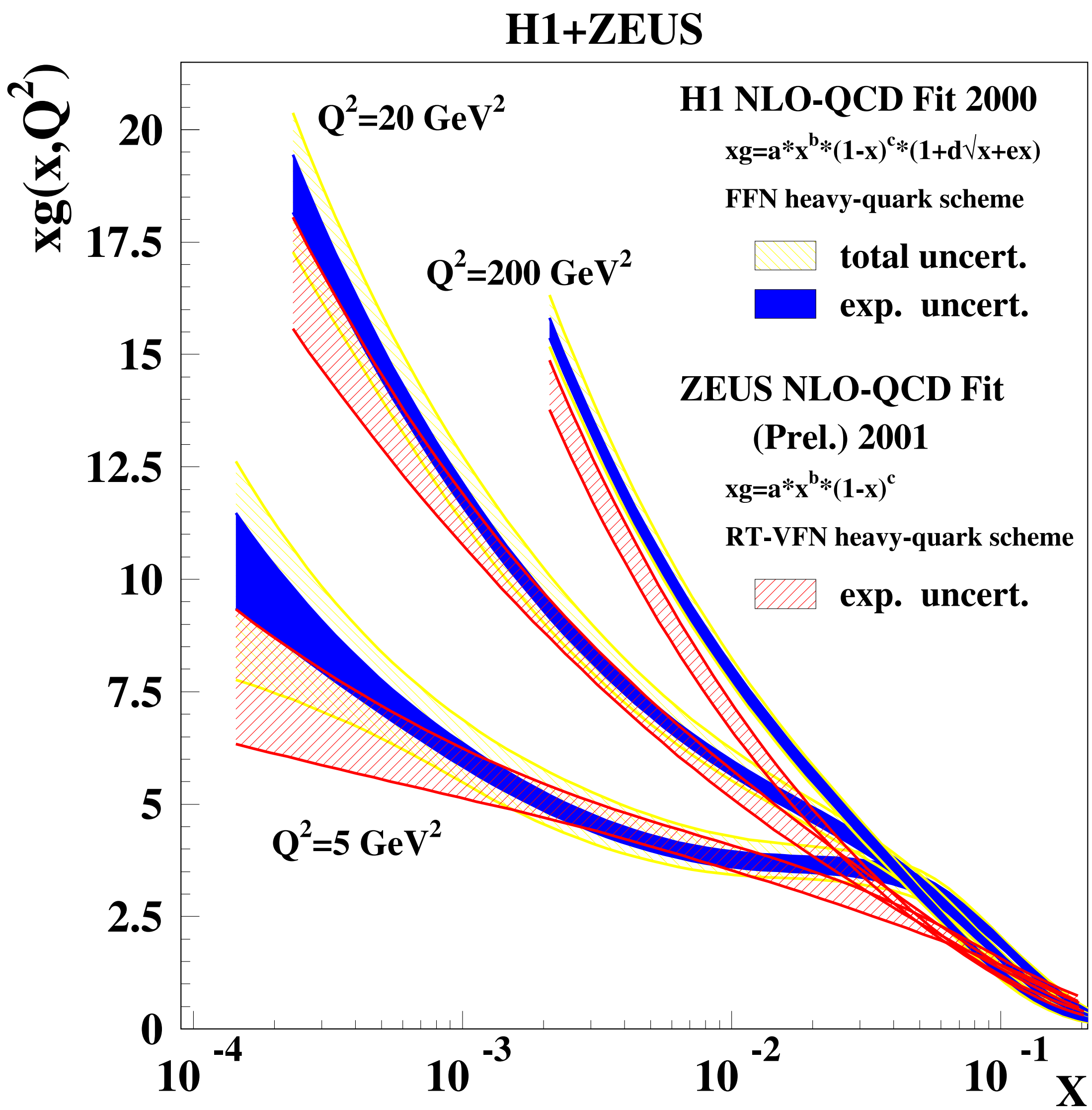
Electroweak effects clearly seen

Structure Function $F_2(x,Q^2)$ (I)



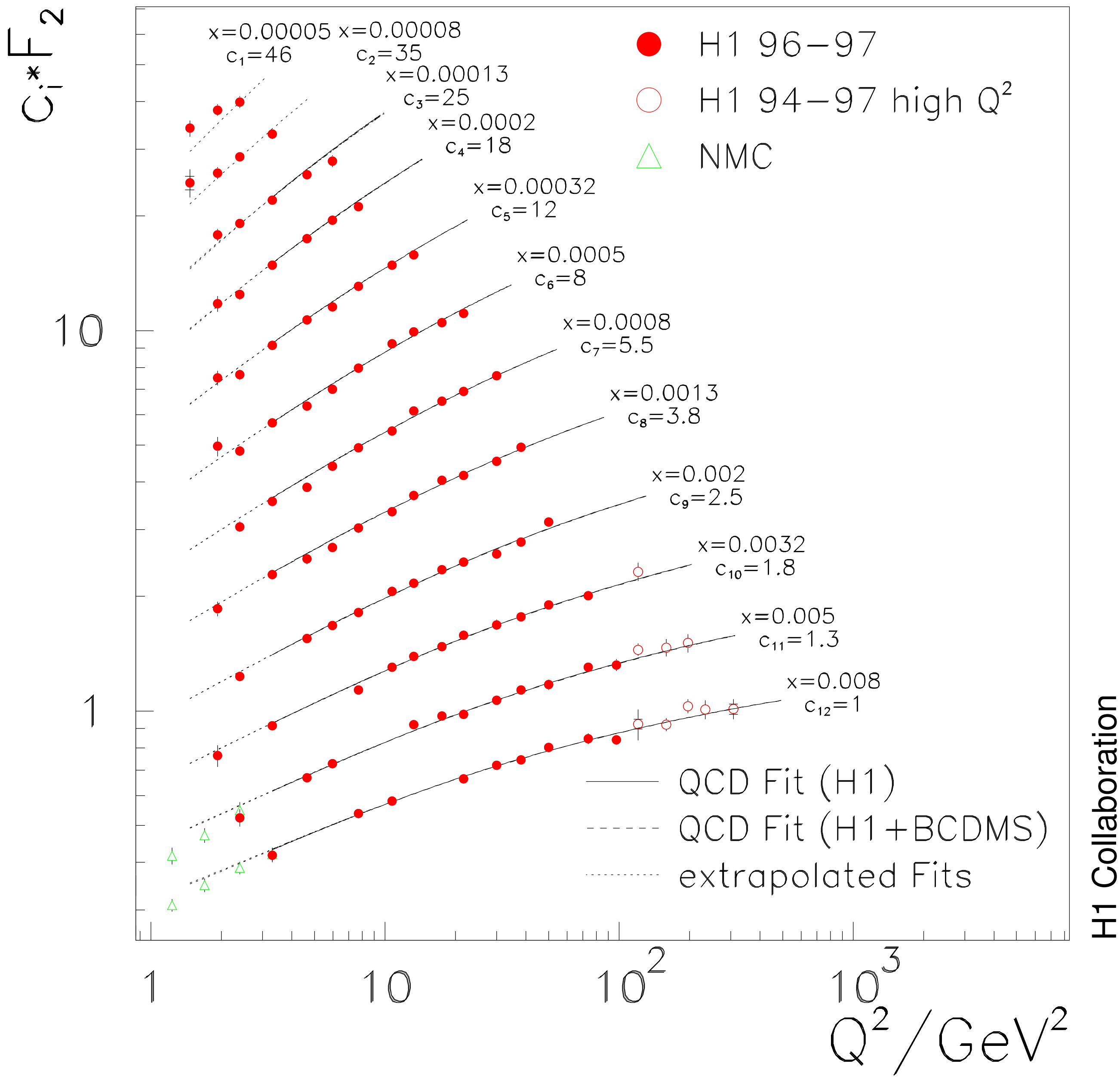
NLO DGLAP works well for $Q^2 \gtrsim 2$ GeV^2

Structure Function $F_2(x,Q^2)$ (II)



QCD fits yield an accurate determination of the gluon density

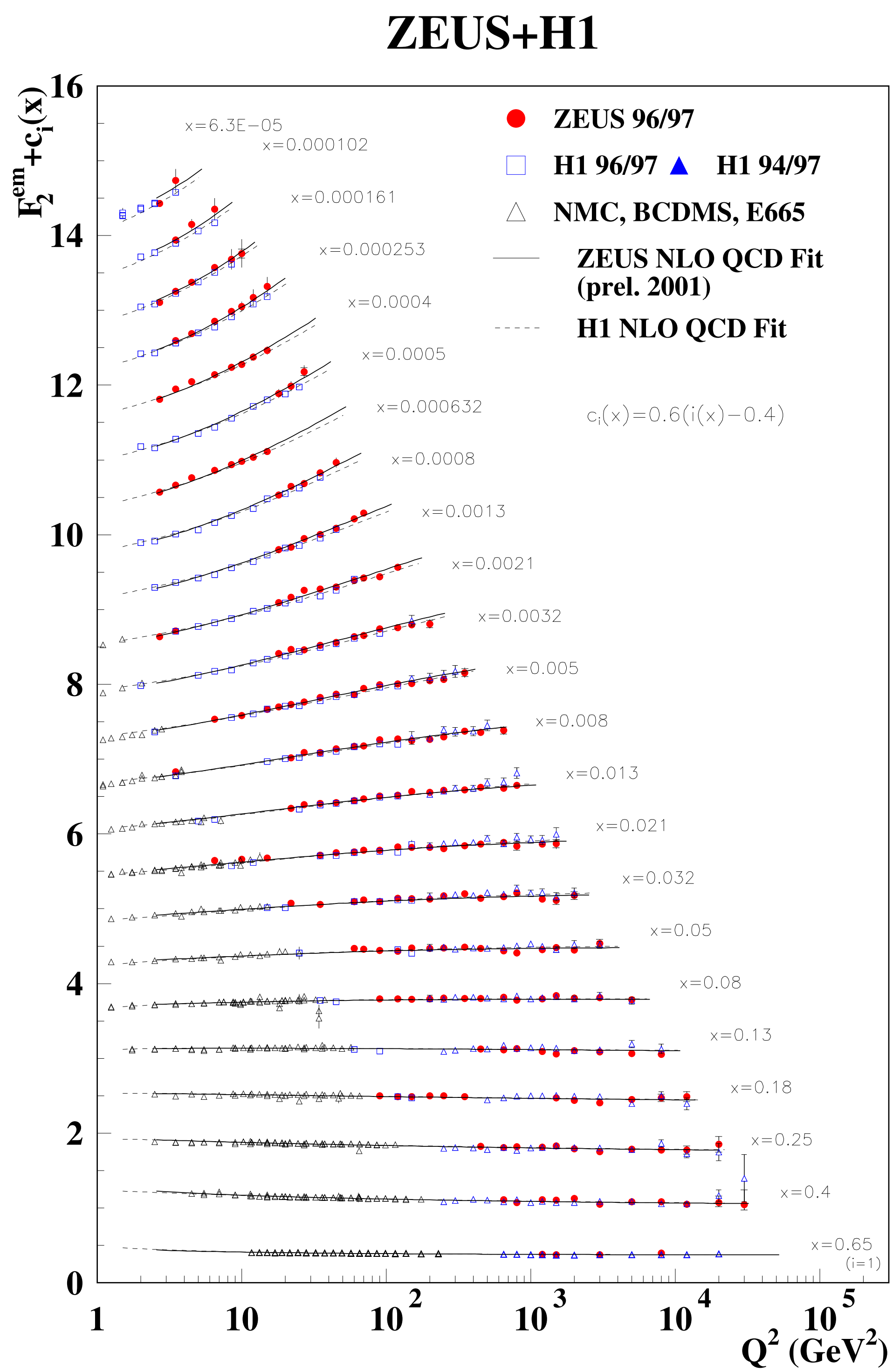
Structure Function $F_2(x, Q^2)$ (III)



$$\alpha_s(M_Z^2) = 0.1150 \pm 0.0017(\mathrm{stat})^{+0.0009}_{-0.0005}(\mathrm{model}) \pm 0.005(\mathrm{theory})$$

NNLO calculation expected later this year

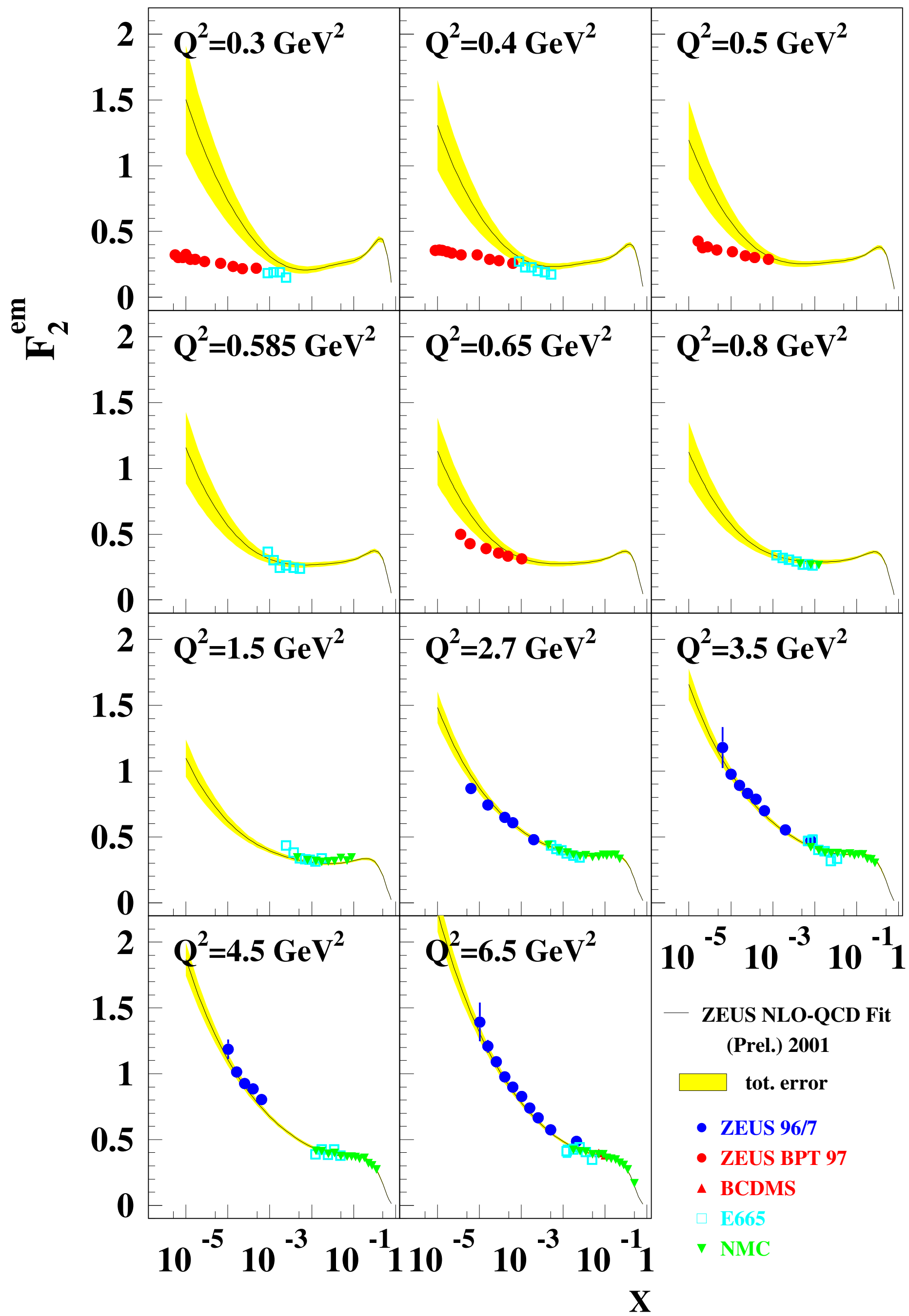
Structure Function $F_2(x, Q^2)$ (IV)



Confirmation of DGLAP expectation of strong Q^2 dependence at low x_{bj}

Structure Function $F_2(x,Q^2)$ (V)

K. Nagano/ZEUS talk at DIS2001



DGLAP breakdown at low Q^2
"Saturation"??

Charged-Current Cross Sections (I)

LO cross-sections

Propagator term

$$P(M_W^2) = \frac{G_F^2}{2x\pi}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2$$

$e^+p \to \bar{\nu}X \longrightarrow$ Probe d valence

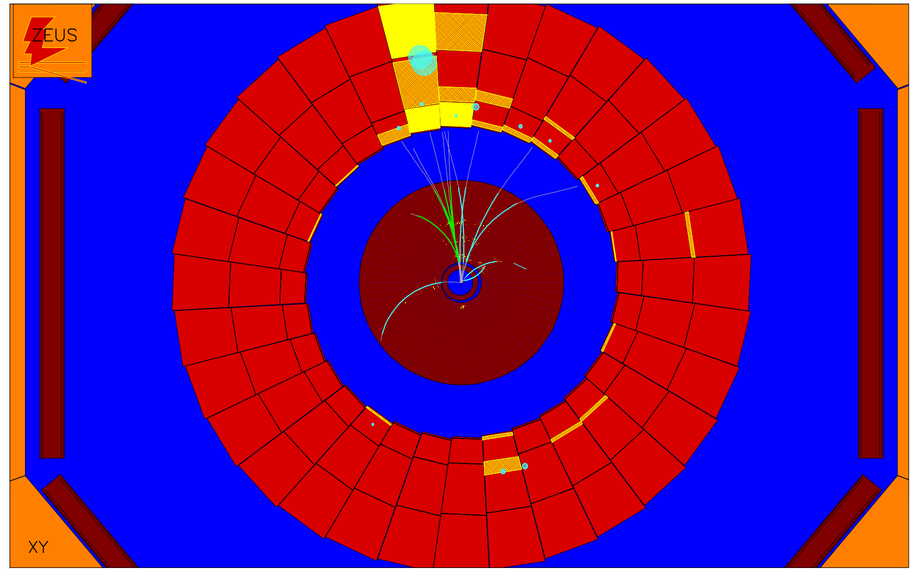
$$\frac{d^2\sigma}{dx\,dQ^2} = P(M_W^2)\left[\bar{u}+\bar{c}+(1-y)^2(d+s)\right]$$

$e^-p \to \nu X \longrightarrow$ Probe u valence

$$\frac{d^2\sigma}{dx\,dQ^2} = P(M_W^2)\left[u+c+(1-y)^2(\bar{d}+\bar{s})\right]$$

Reduced cross-section

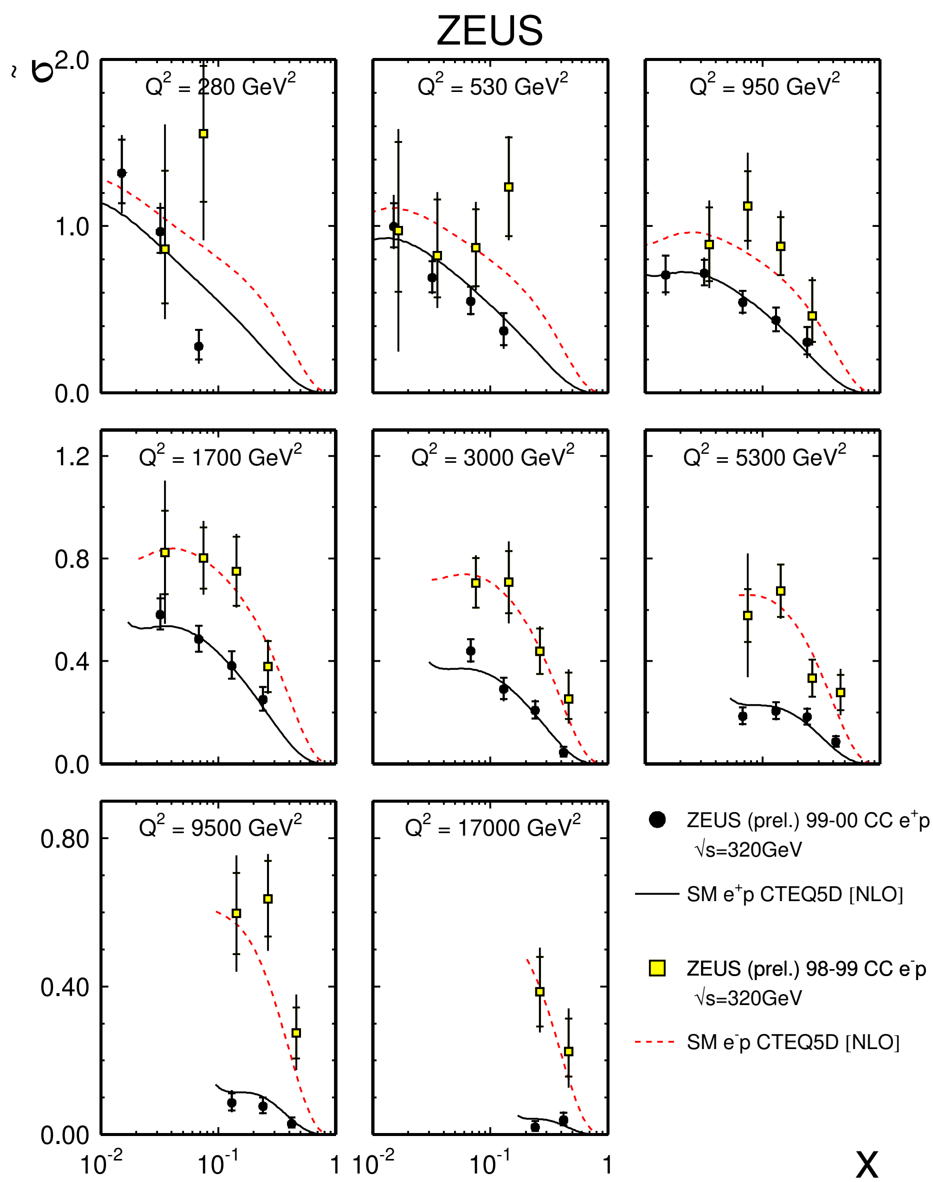
$$\tilde{\sigma} = \frac{1}{P(M_W^2)}\frac{d^2\sigma}{dx\,dQ^2}$$



Charged-Current Cross Sections (II)

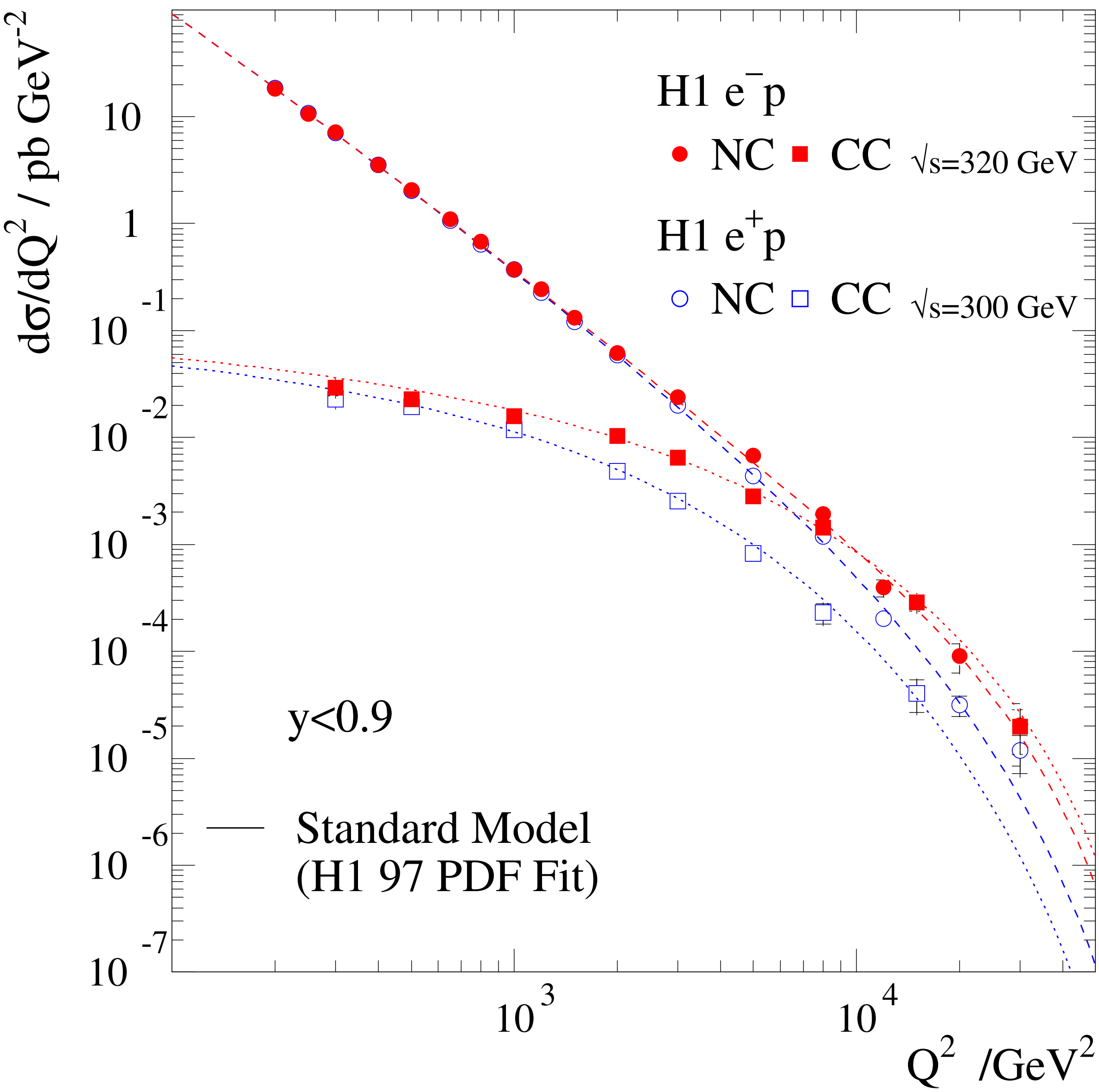
$\frac{d^2\sigma}{dx\,dQ^2}$ in Q^2 bins for CC events.

Data sample $(e^+p)^{920}$ and $(e^-p)^{920}$



Clear distinction of u_V from d_V

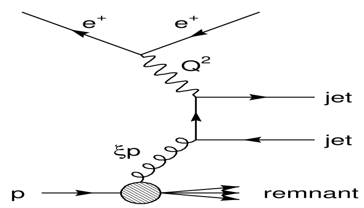
NC/CC Cross Sections

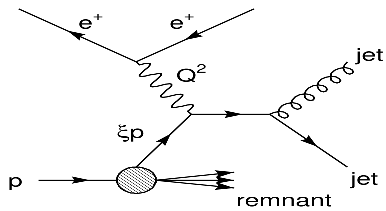


Electroweak Unification

Jets in DIS (I)

Talk by E.Tassi/ZEUS at DIS2001





(Multi)-jet cross sections in DIS at HERA:

⇒ Testing ground of pQCD, direct sensitivity to α_s and $g(x)$

Cross section:

$$d\sigma_{\rm jet} = \sum_{a=q,\overline{q},g} \int dx\, f_a(x, \mu_{\rm f}^2; \alpha_s)\, d\hat{\sigma}_a(x, \alpha_s) \cdot (1+\delta_{hadr})$$

Partonic cross section:

$$d\hat{\sigma}_a = \sum_n {\alpha_s}^n c_{a,n}$$

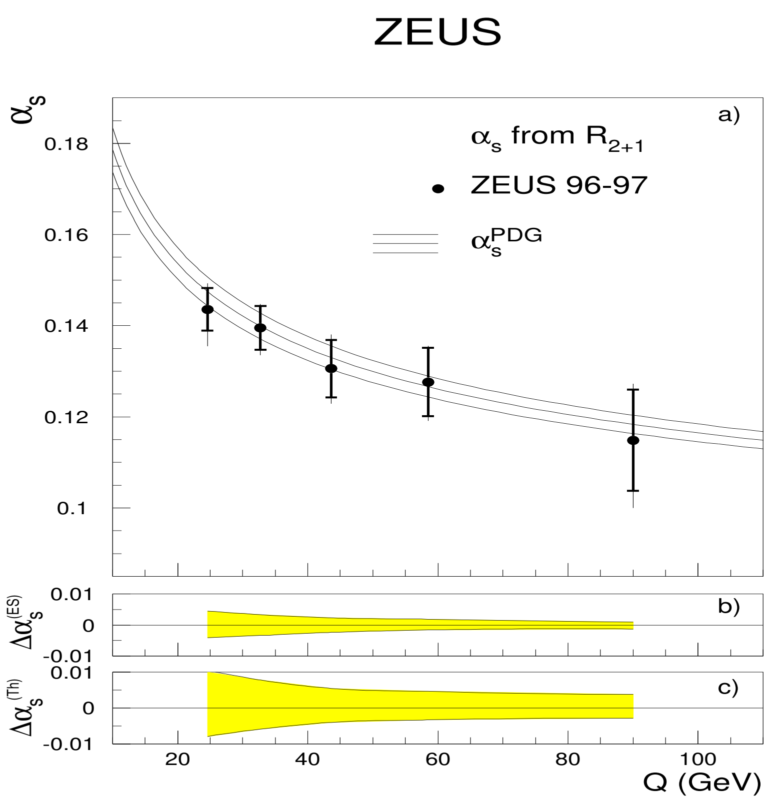
DGLAP equations:

$$\frac{d\, f_a(x, \mu_{\rm f}^2)}{d \ln \mu_{\rm f}^2} = \frac{\alpha_s}{2\pi} \sum_{b=q,\overline{q},g} \int_x^1 \frac{dz}{z}\, f_b(x/z, \mu_{\rm f}^2) P_{ab}(z, \alpha_s)$$

- predicted by QCD - process specific
  - $c_{g,n}$ and $c_{q,n}$: calculable in pQCD (NLO)
  - δ_{hadr} : MonteCarlo hadronization models
- free parameters - process independent (universal)
  - strong coupling constant: $\alpha_s(M_Z)$
  - parton densities: $f_g = g$ and $f_q = q$

Jets in DIS (II)

α_s from dijet production



$$\alpha_s(M_Z) = 0.1166 \ \pm 0.0019(\mathrm{stat.}) \ {}^{+0.0024}_{-0.0033} \ (\mathrm{exp.}) \ {}^{+0.0057}_{-0.0044} \ (\mathrm{th.})$$

- Value in excellent agreement with the world average
- Competitive uncertainty (5-6%)
- Running checked over a large range in Q
- Limited by theory ($\Rightarrow$ NNLO)

Jets in DIS (III)

α_s from inclusive jet production

Various QCD fits of $d\sigma_{\rm jet}/dQ^2$ and $d\sigma_{\rm jet}/dE_T$ have been performed:

- $\mu_r = E_T^{\rm jet}$ (default) $\mu_r = Q$ (check)
- MRST99 α_s-series (default) CTEQ4 α_s-series (check)

Results:

Full phase-space region: $d\sigma/dQ^2$

$$\alpha_s(M_Z) = 0.1241 \pm 0.0009(\mathrm{stat.})\,^{+0.0043}_{-0.0038}\,(\mathrm{exp.})\,^{+0.0052}_{-0.0036}\,(\mathrm{th.})$$

High-Q^2 region, [$Q^2 > 500$ GeV^2]: $d\sigma/dQ^2$

$$\alpha_s(M_Z) = 0.1190 \pm 0.0017(\mathrm{stat.})\,^{+0.0049}_{-0.0023}\,(\mathrm{exp.})\,^{+0.0026}_{-0.0026}\,(\mathrm{th.})$$

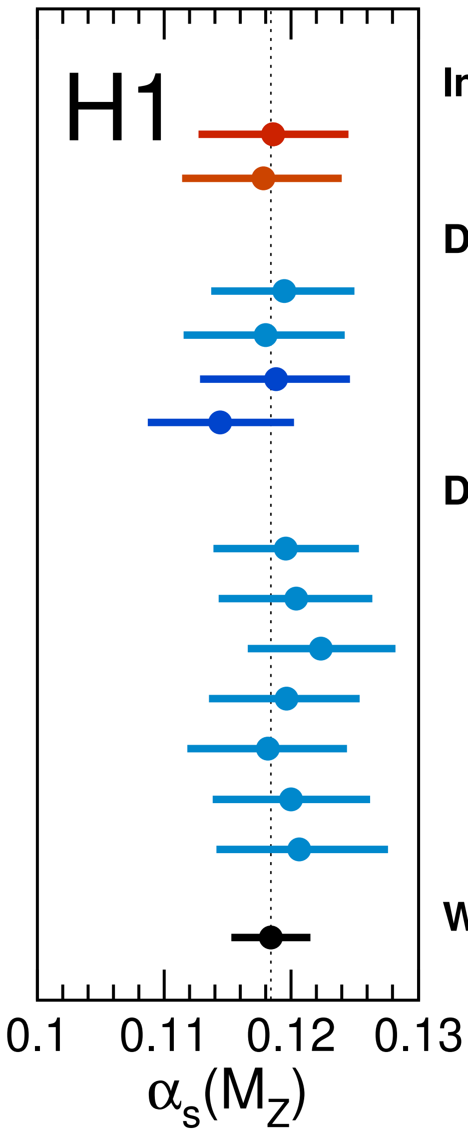
High-E_T region, [$E_T^{\rm jet} > 14$ GeV]: $d\sigma/dE_T^{\rm jet}$

$$\alpha_s(M_Z) = 0.1206 \pm 0.0015(\mathrm{stat.})\,^{+0.0058}_{-0.0045}\,(\mathrm{exp.})\,^{+0.0041}_{-0.0030}\,(\mathrm{th.})$$

- Smaller Theoretical uncertainty w.r.t dijet cross sections
- Very precise determination of α_s at high-Q^2 or high-$E_T^{\rm jet}$

Jets in DIS (IV)

α_s from jet production in DIS



$\mu_r = E_{T,\text{jet,Breit}}$

Inclusive Jet Cross Section $\frac{d^2\sigma_{\text{incl.jet}}}{dE_{T,\text{Breit}}\, dQ^2}$

inclusive $k_\perp$ algorithm
inclusive, angular algorithm (Aachen)

Dijet Cross Section $\frac{d^2\sigma_{\text{dijet}}}{d\bar{E}_{T,\text{Breit}}\, dQ^2}$

inclusive $k_\perp$ algorithm
inclusive angular algorithm (Aachen)
exclusive $k_\perp$ algorithm
exclusive angular algorithm (Cambridge)

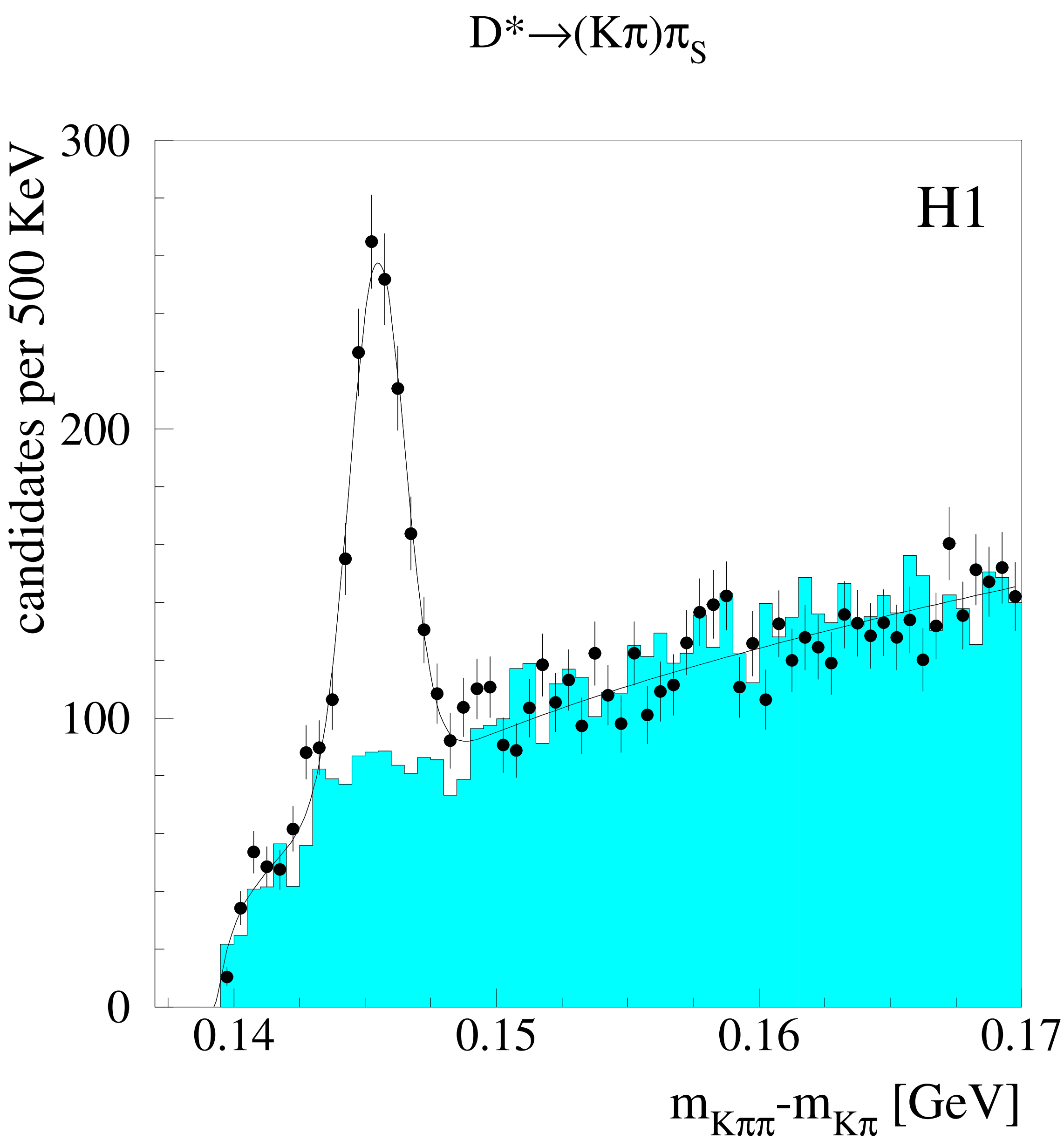
Dijet Cross Section inclusive $k_\perp$ algo.

$d^2\sigma_{\text{dijet}}$ / $dM_{jj}\, dQ^2$
$d^2\sigma_{\text{dijet}}$ / $d\xi\, dQ^2$
$d^2\sigma_{\text{dijet}}$ / $dx_p\, dQ^2$
$d^2\sigma_{\text{dijet}}$ / $dx_{Bj}\, dQ^2$
$d^2\sigma_{\text{dijet}}$ / $dy\, dQ^2$
$d^2\sigma_{\text{dijet}}$ / $d\eta'\, dQ^2$
$d^2\sigma_{\text{dijet}}$ / $d\eta'\, d\bar{E}_T$

World Average
(S. Bethke, J. Phys. G26 (2000) R27)

Heavy Quarks (I)

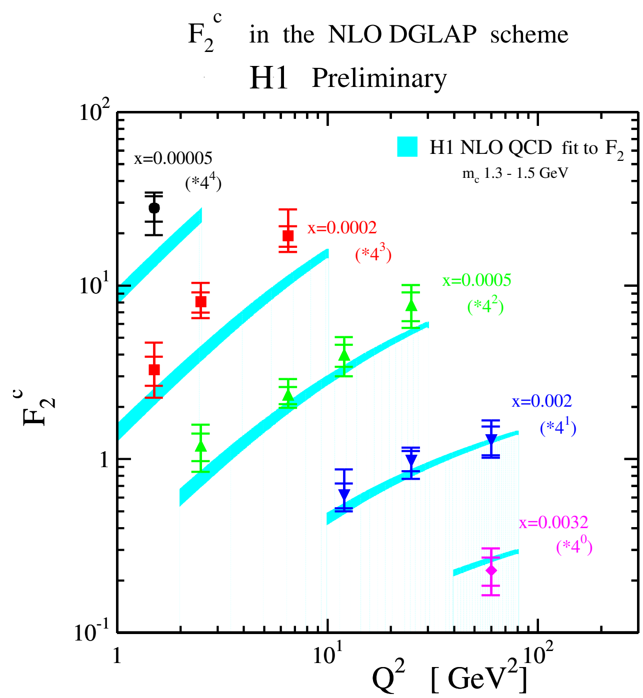
H1 D* Signal in DIS

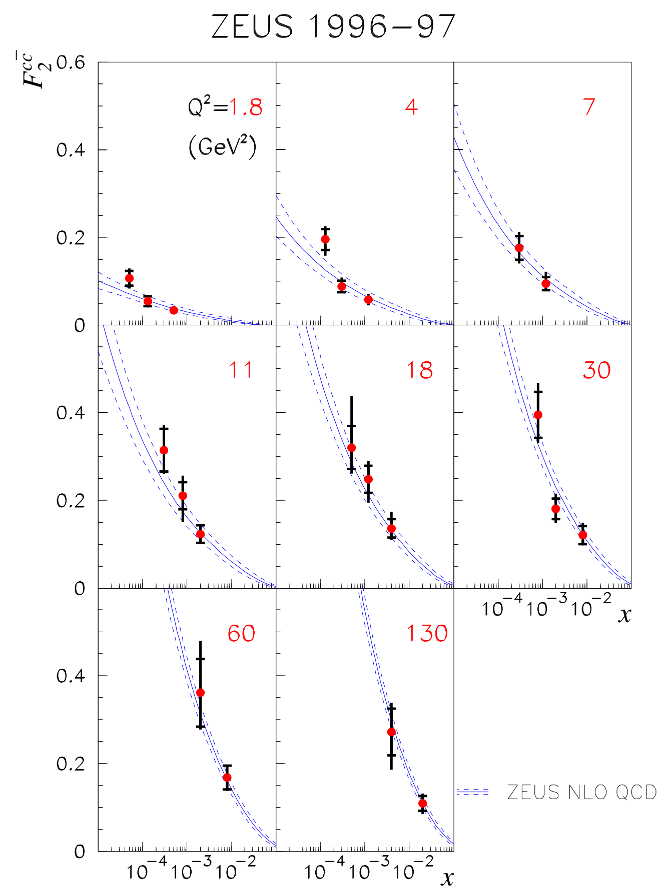


Clean check of pQCD
photon-gluon fusion mechanism

Heavy Quarks (II)

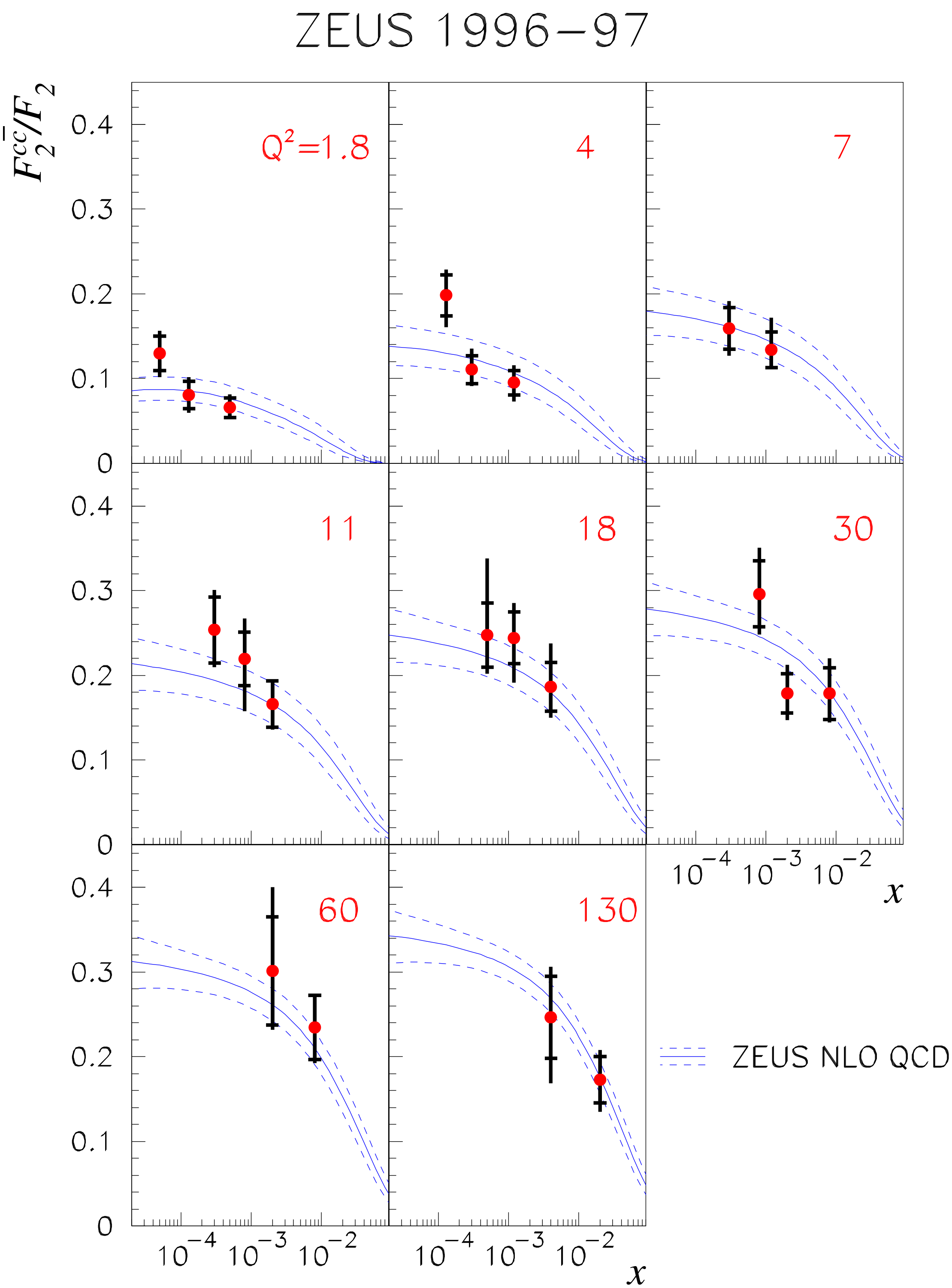
$F_2^{c\bar{c}}$





Consistent with $xG(x, Q^2)$ from F_2

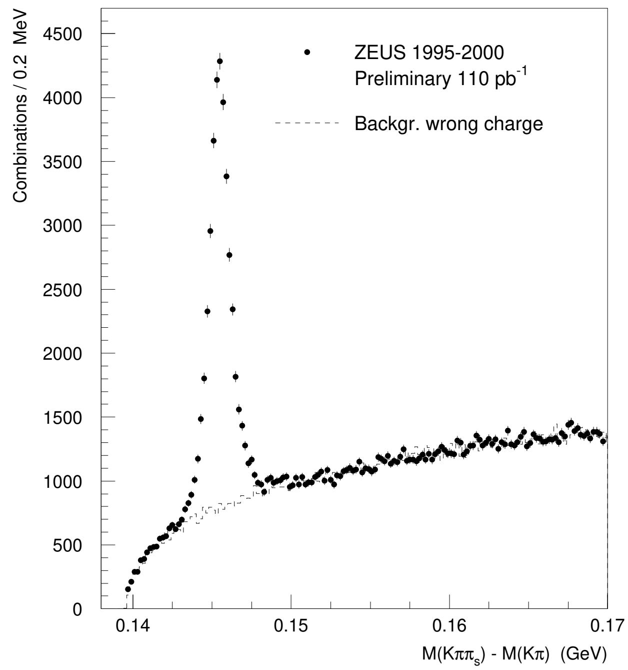
Heavy Quarks (III)



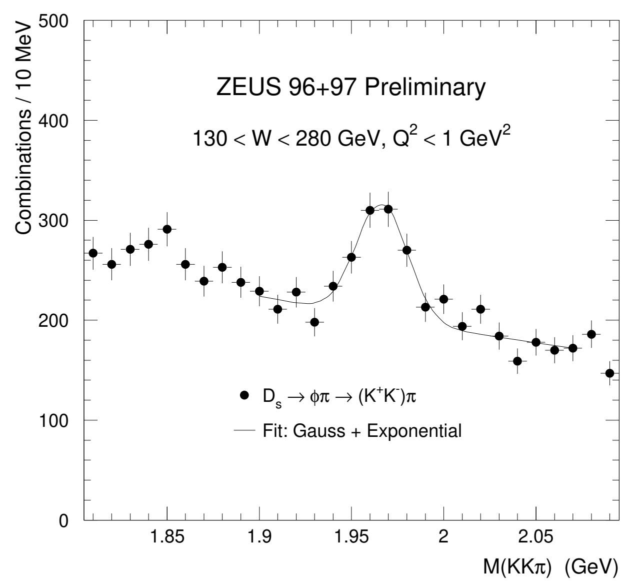
Charm makes a big contribution to F_2

Heavy Quarks (IV)

Photoproduced D*



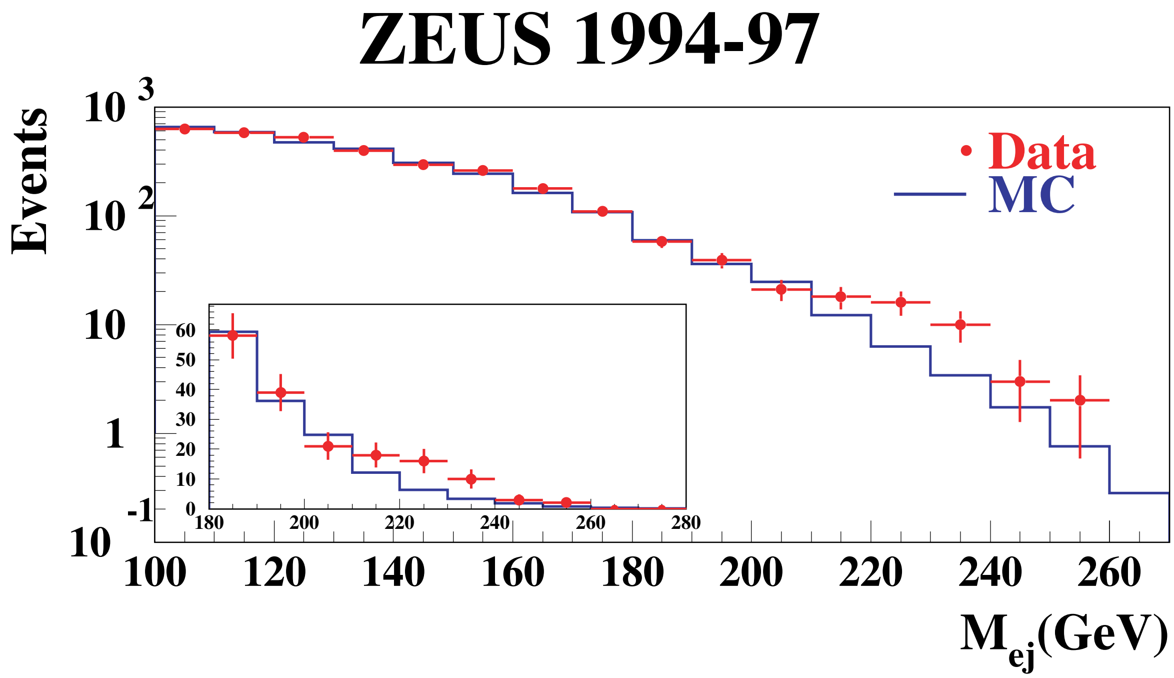
Photoproduced D_s

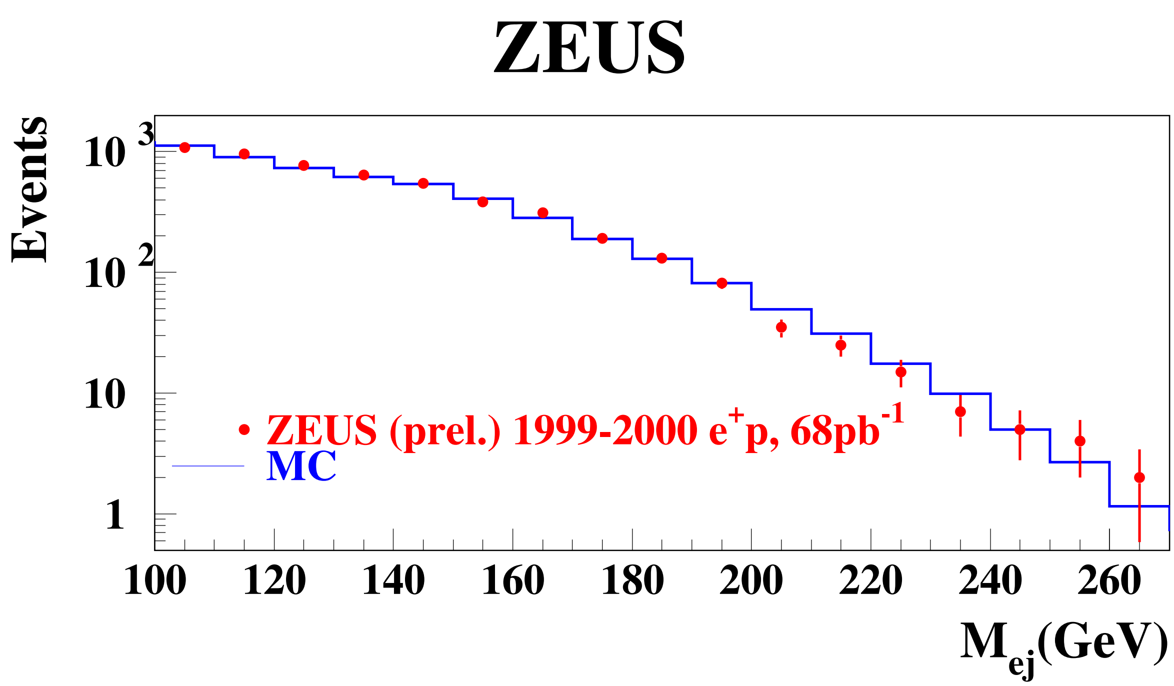


Precision spectroscopy

Searches (I)

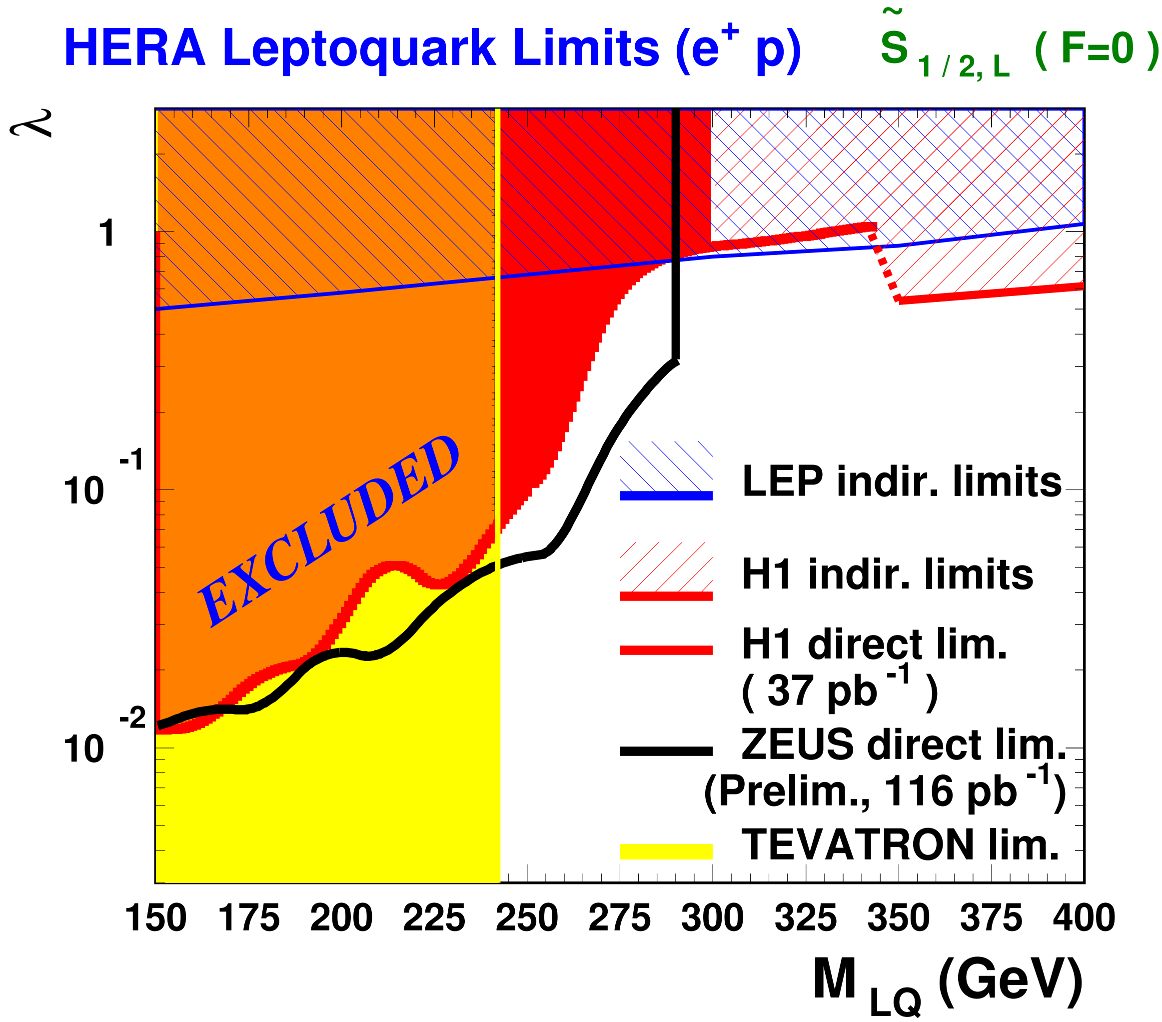
Excess at high Q^2 ??





The HERA upgrade will finally resolve this issue

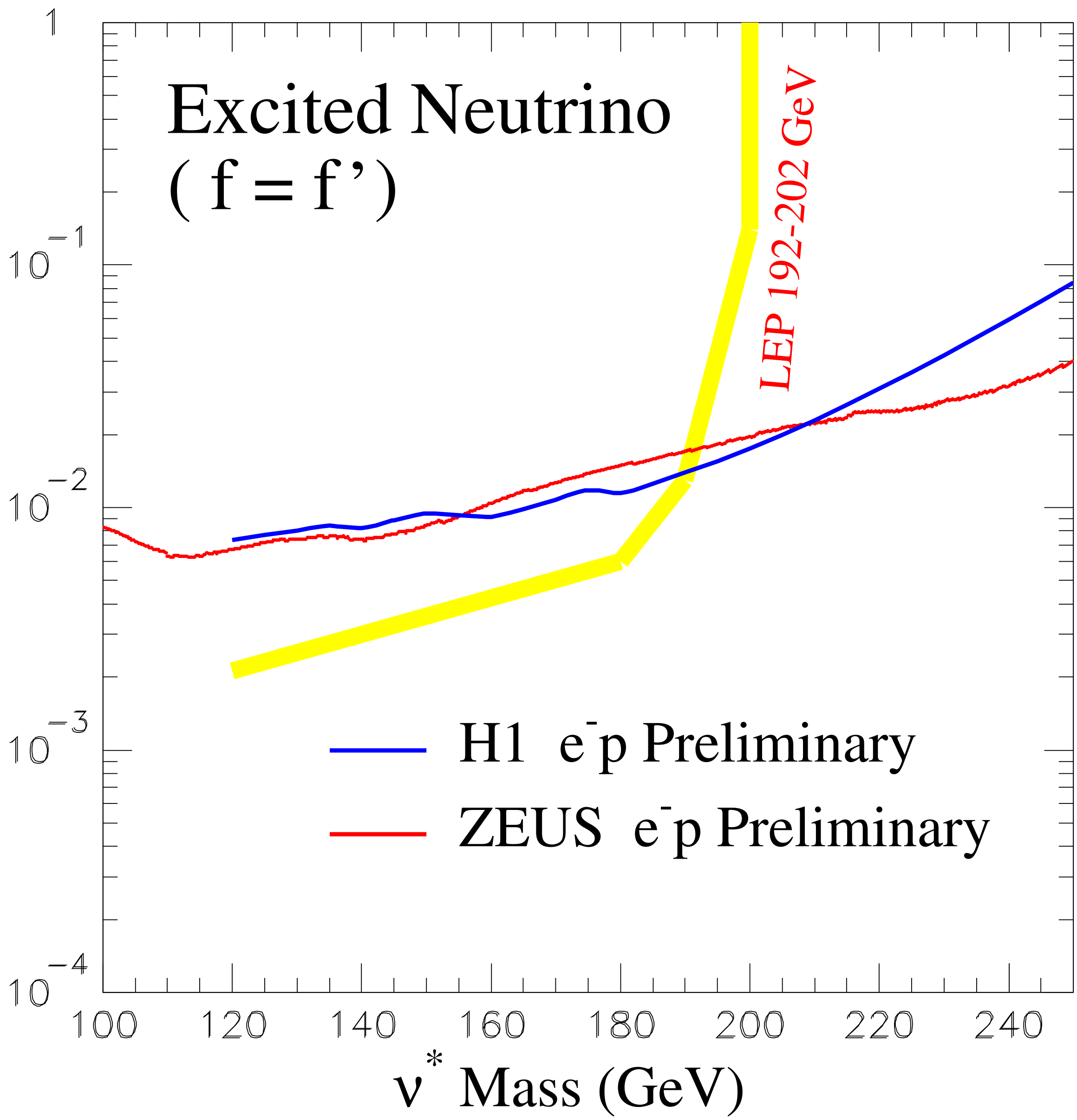
Searches (II)



Strong competition from Tevatron and LEP

HERA limits best for $M_{LQ} > 240$ GeV

Searches (III)

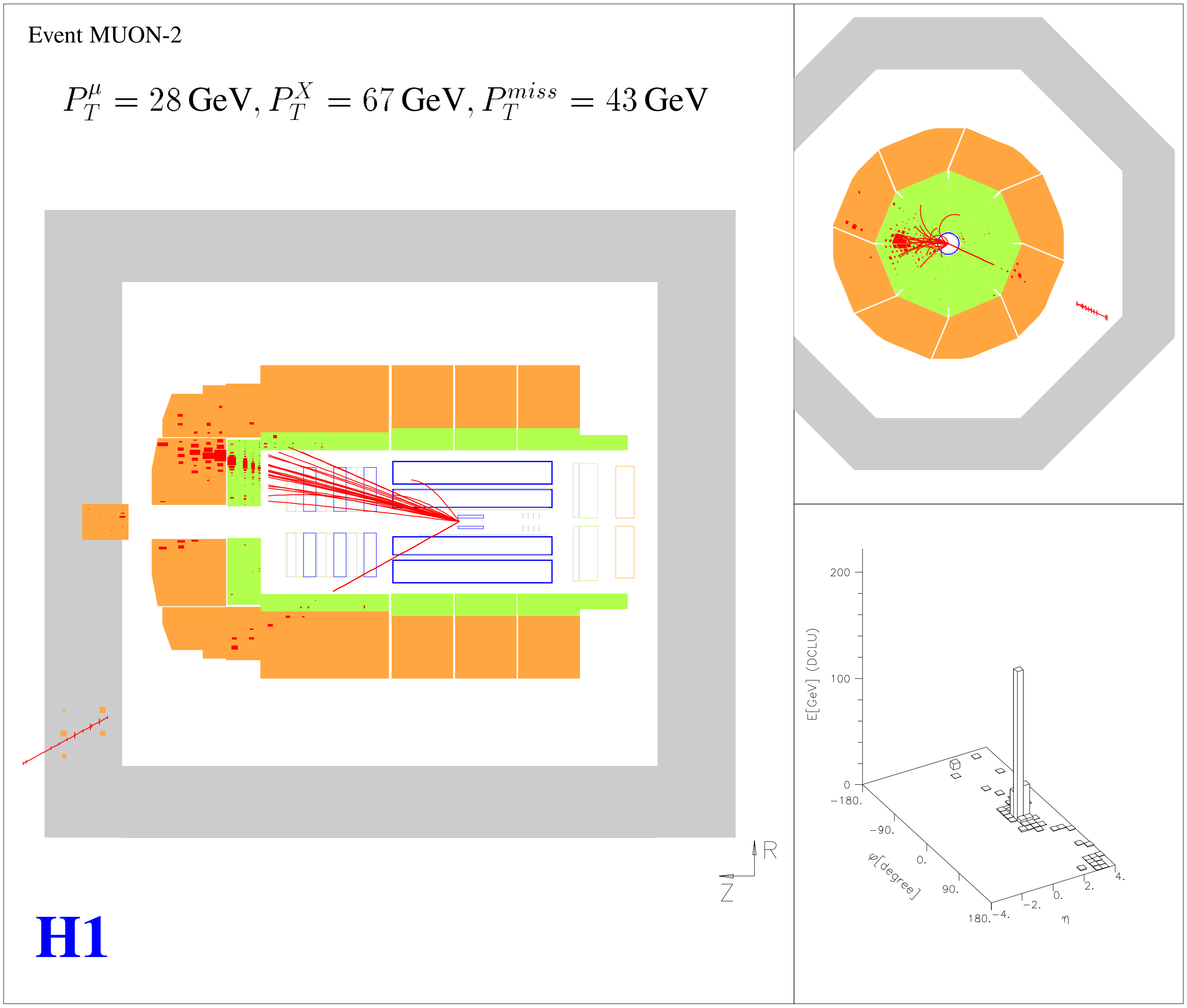


HERA most sensitive to excited neutrino's (Hagiwara model)

Searches (IV)

H1 events with high-p$_T$ lepton and missing energy

$$e^+p \to \mu^+X$$



ZEUS sees no excess above W background

Analysis repeated with H1 cuts

High Energy QCD

Virtual-Photon Lifetime

Heisenberg uncertainy relation: $\Delta t \geq \frac{1}{2\Delta E}$

Photon virtuality: $\Delta E = k_{\gamma^*} - \sqrt{k_{\gamma^*}^2 - Q^2}$

HERA energies: $200 < k_{\gamma^*} < 32\,000$ GeV

$$\Rightarrow \Delta E \approx \frac{1}{2}\frac{Q^2}{k_{\gamma^*}} = m_{\mathrm{p}}\, x$$

Condition to define γ^*p cross section: $\frac{1}{2m_{\mathrm{p}}x} > 2R_{\mathrm{p}}$

For $R_{\mathrm{p}} = 0.8$ fm,

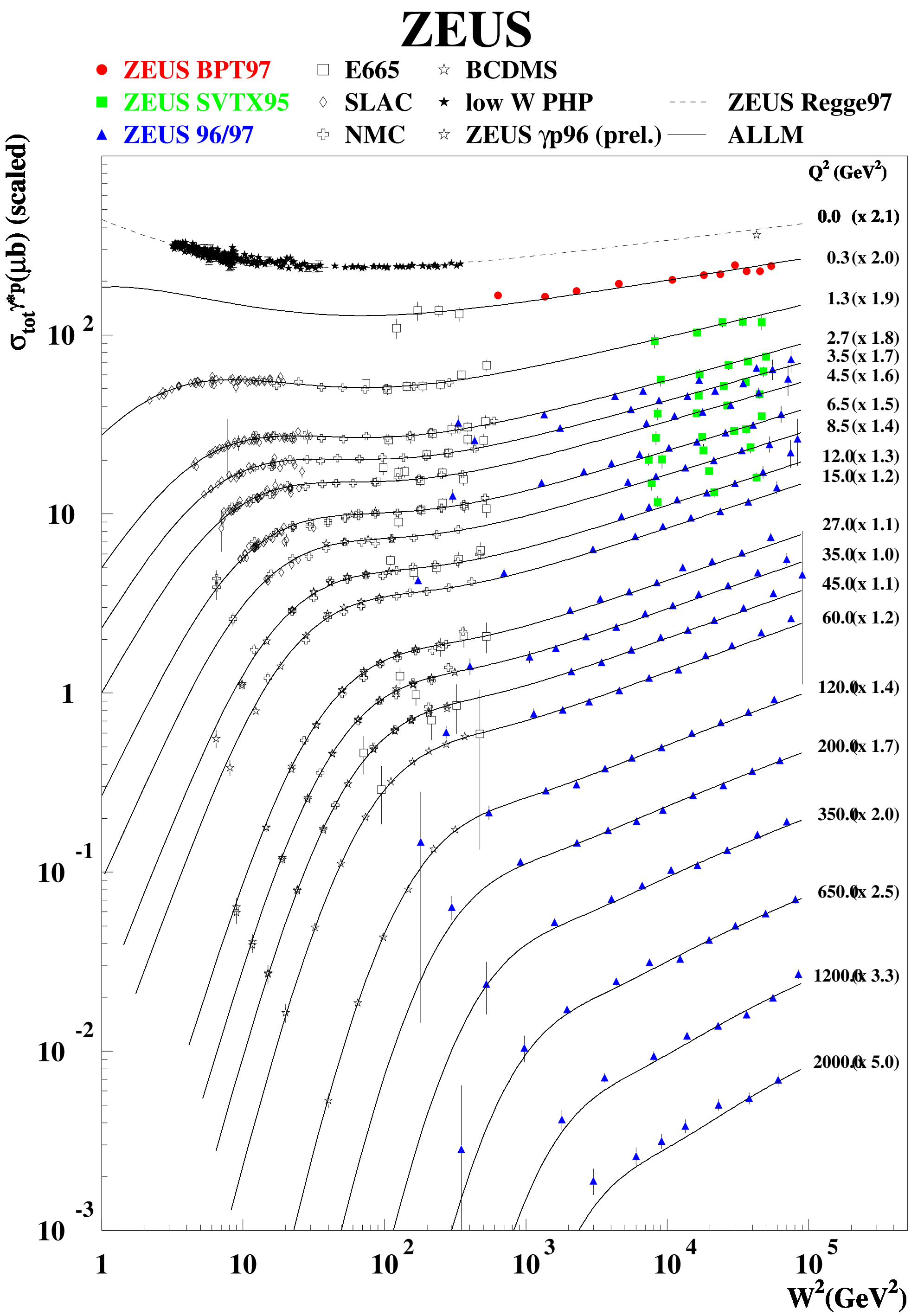
$$\boxed{x < 0.06}$$

$$W^2 = Q^2\left[\frac{1}{x} - 1\right] + m_{\mathrm{p}}^2 \approx \frac{Q^2}{x}$$

Low-x physics
is
high-energy physics
with
virtual-photon beams

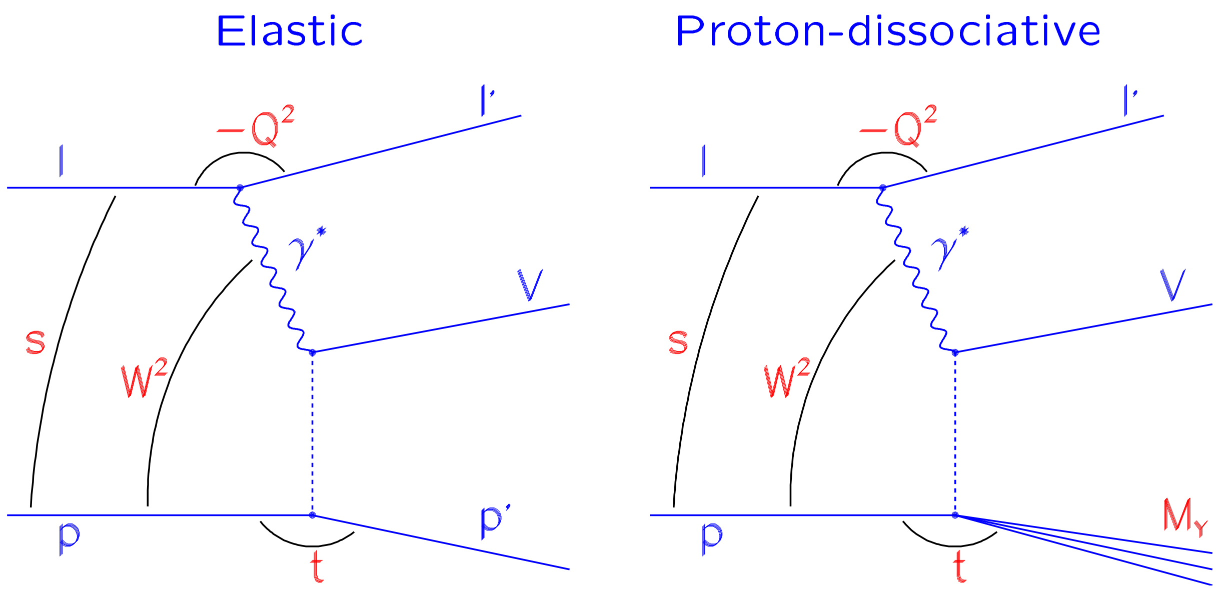
Total Photon-Proton Cross Sections

$$\sigma^{tot}_{\gamma^* p} \approx \frac{4\pi^2\alpha}{Q^2(1-x)} F_2(x, Q^2)$$



⇒ Steeply rising cross sections at high energy!

Production of Vector Mesons at HERA



$\sqrt{s}$: Center–of–mass energy of e–p system
1992-97: 300 GeV 1998-2000: 318 GeV

W: Center–of–mass energy of γ^*–p system
$20 < W < 240$ GeV

Q^2: Photon Virtuality
$10^{-10} < Q^2 < 60$ GeV^2 ($Q^2 \ll |t| \Rightarrow t \simeq -P_T^2$(V))

t: Square of Momentum Transfer at the Proton Vertex
$|t| < 13$ GeV^2
Proton-dissociative process dominates at high $|t|$

General Remarks on Exclusive VM Production at HERA

- **Investigation of vacuum-exchange processes**

  Vacuum exchange has a
  complicated, poorly understood structure

- **Study properties of strong interaction**
  - Soft interactions
    - Forward, total cross sections
    - Exponential t-slopes, shrinkage
    - Helicity rules
  - Hard interactions
    - Short-distance vacuum exchange
    - Scale definition
    - Sensitive to $|xG(\mu, x)|^2$
    - Helicity rules

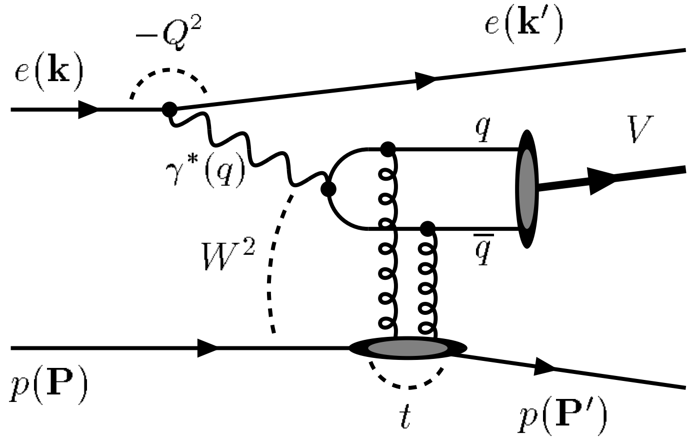
  The hard/soft transition can be studied in

  $$Q^2 \qquad M_V^2 \qquad |t|$$

- **Exclusivity allows study of helicity structure**
  - The VM helicity state is directly related to the expected scaling behavior
  - The spin-density matrix elements are directly related to meson structure

Perturbative QCD for Diffraction (?!)

☞ Exchange of a color-neutral pair of gluons



Brodsky, Frankfurt, Gunion, Mueller, Strikman
PRD50 (1994) 3134

Only longitudinal photons have point-like interactions !

$$\left.\frac{\mathrm{d}\sigma^L_{\gamma^* \mathrm{p} \to \mathrm{Vp}}}{\mathrm{d}|t|}\right|_{t=0} = A_\mathrm{V} \frac{\alpha_s^2(\bar{Q}^2)}{\alpha \bar{Q}^6} \left| \left[1 + \frac{\mathrm{i}\pi}{2} \frac{\mathrm{d}}{\mathrm{d}(\ln x)} \right] x G(x, \bar{Q}^2) \right|^2$$

Energy dependence determined by $G(x, \bar{Q}^2)$, $\quad x \approx Q^2/W^2$

Ryskin, Z.Phys. C57 (1993) 89 (J/ψ photoproduction)

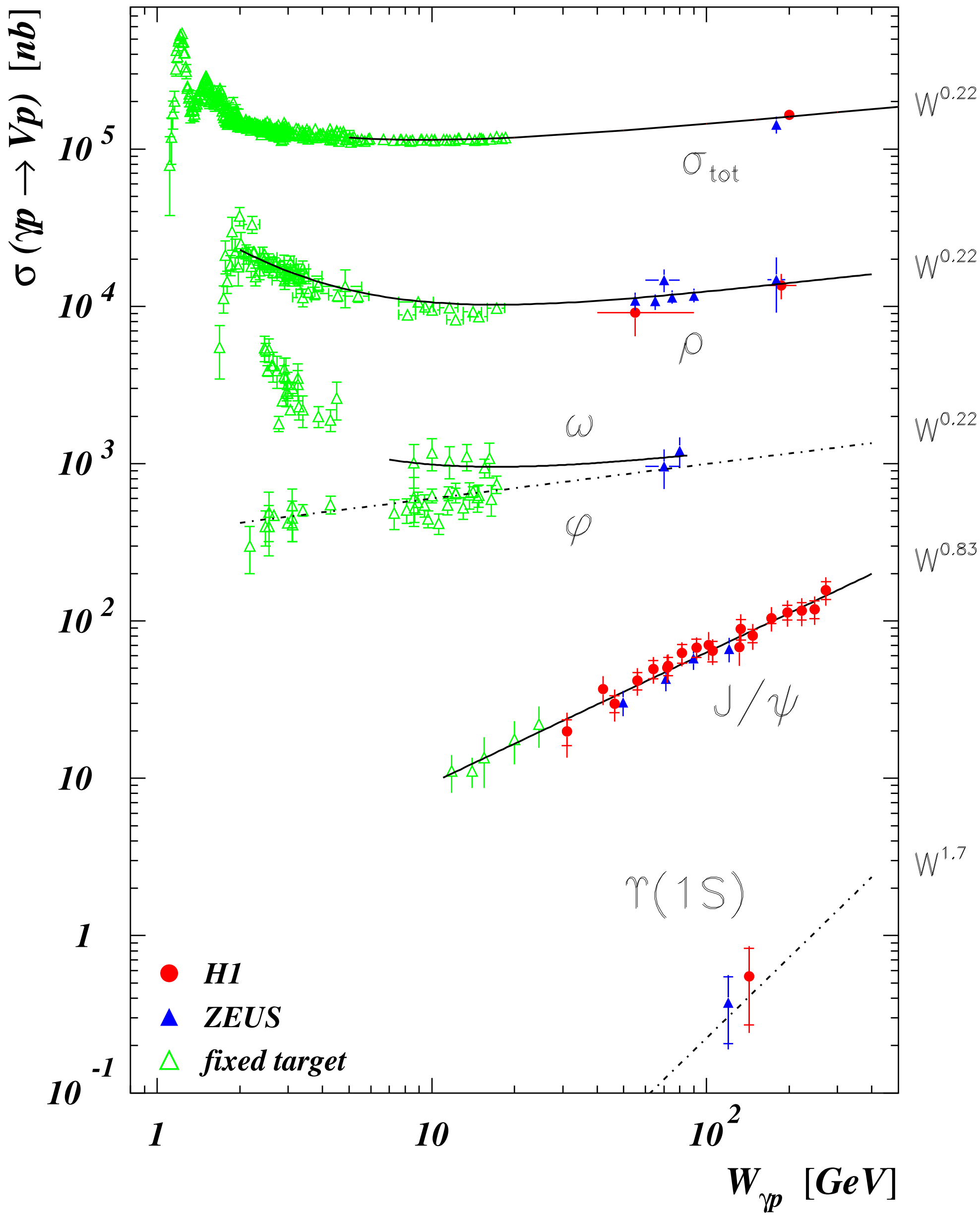
$$\bar{Q}^2 = \frac{Q^2 + M_V^2 - t}{4} \ (?)$$

Can the hard scale necessary for
perturbative QCD calculations be set by
either Q^2, M_V^2, or $|t|$??

What experimental signatures for the region of pQCD validity ?

Elastic J/ψ Photoproduction

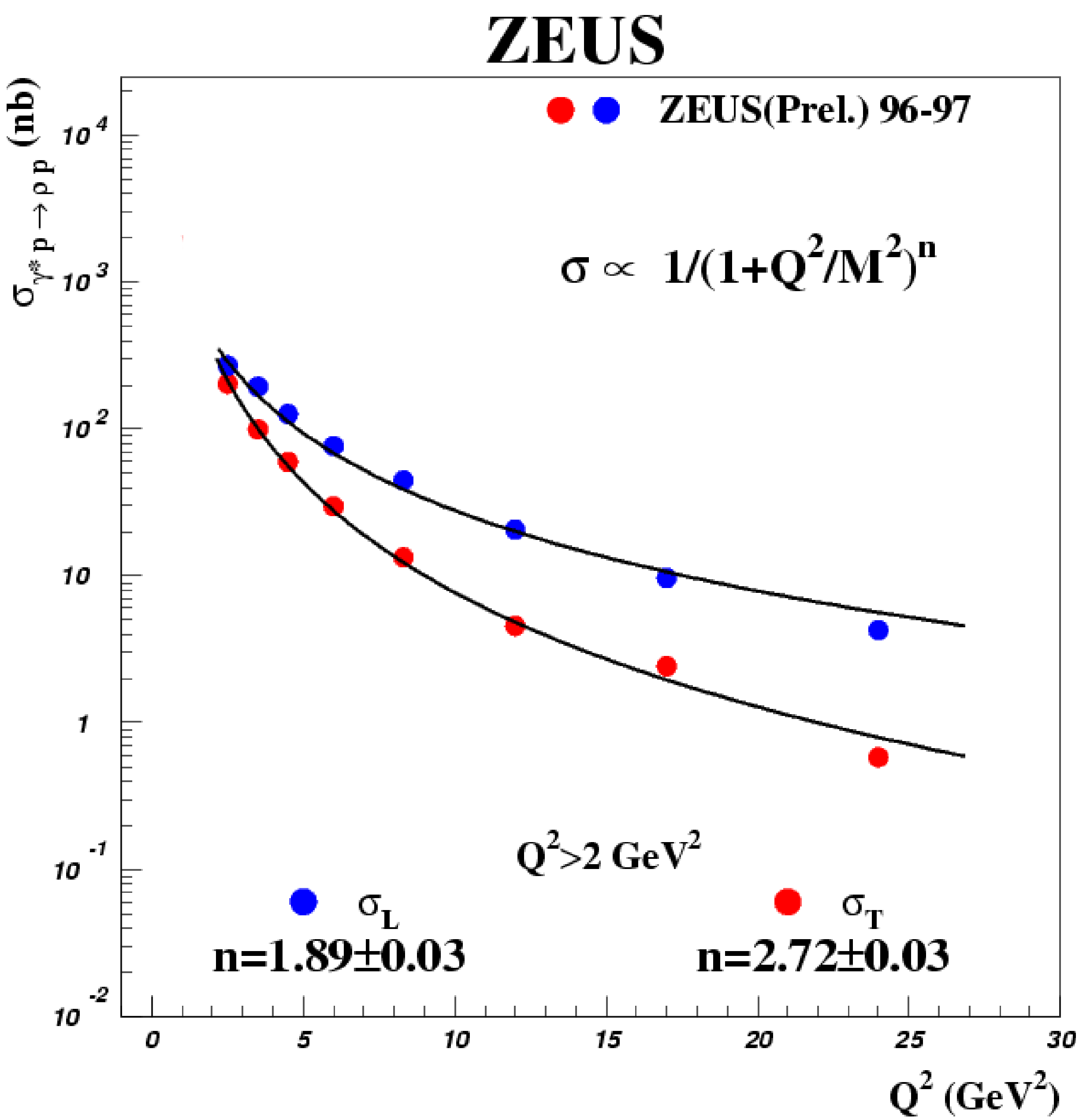
$$\gamma + p \to J/\psi + p$$



J/ψ energy dependence
consistent with steep gluon density

σ_L/σ_T in Elastic ρ^0 Electroproduction

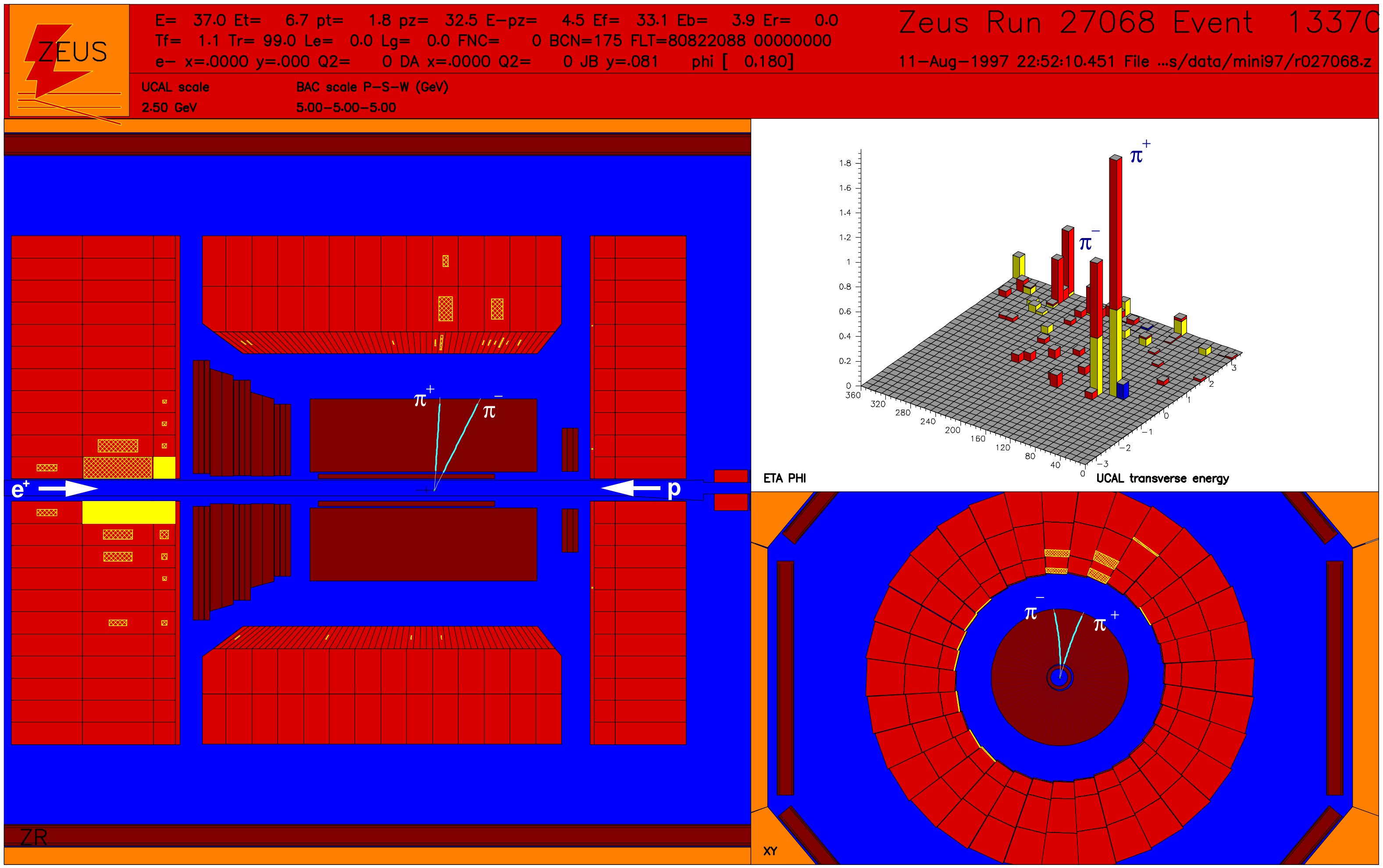
A. Kreisel at DIS2001



Remarkably hard scaling behavior for σ_T

(The Q^2 dependence is even weaker than Q^{-6})

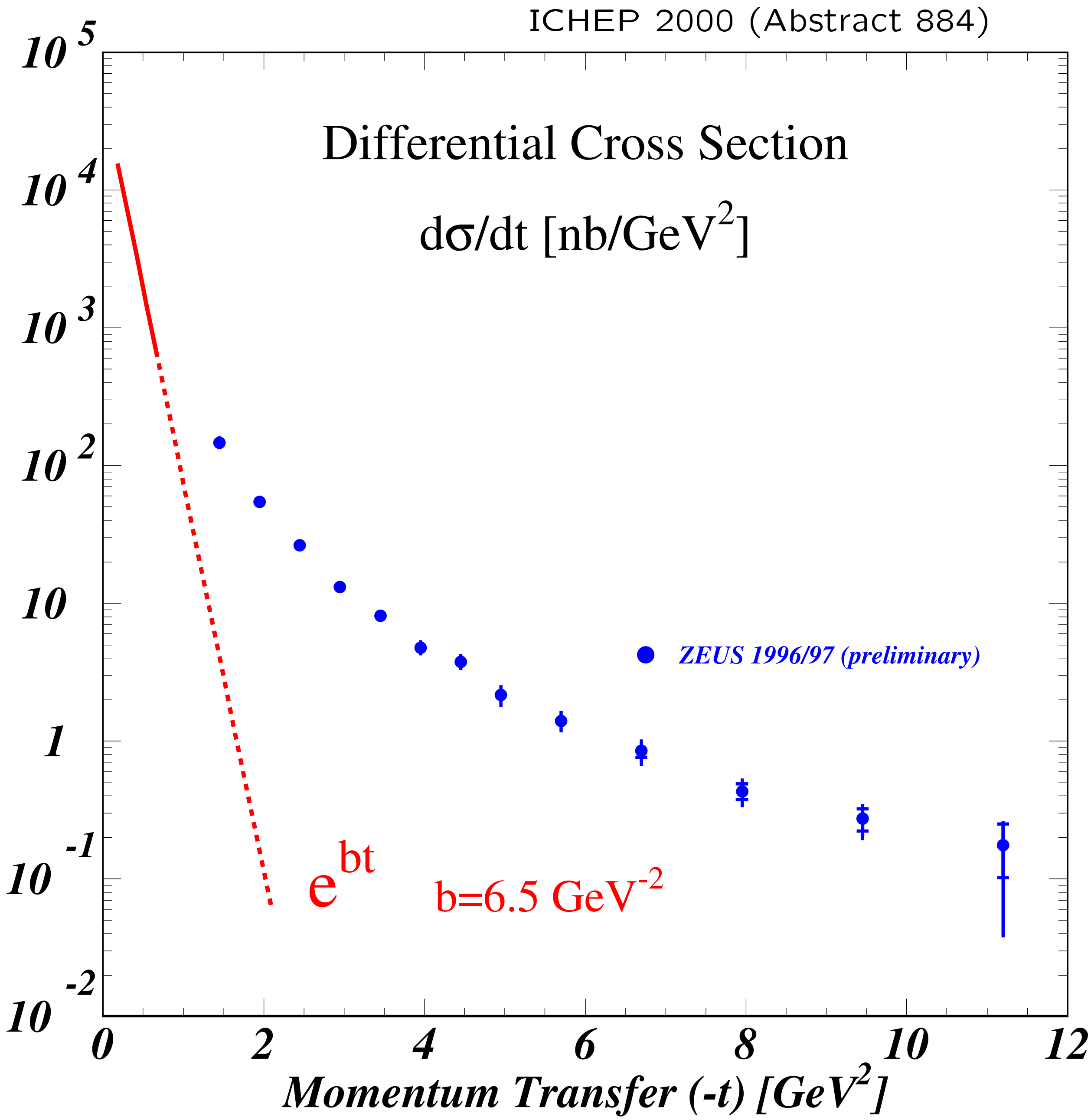
Candidate for ρ^0 Photoproduction at High $|t|$



$e^+p \to e^+N\,\rho^0 \to e^+N\,\pi^+\pi^-$ $\qquad M_{\pi^+\pi^-} = 0.78$ GeV, $t = -10.0$ GeV^2, $W = 81$ GeV

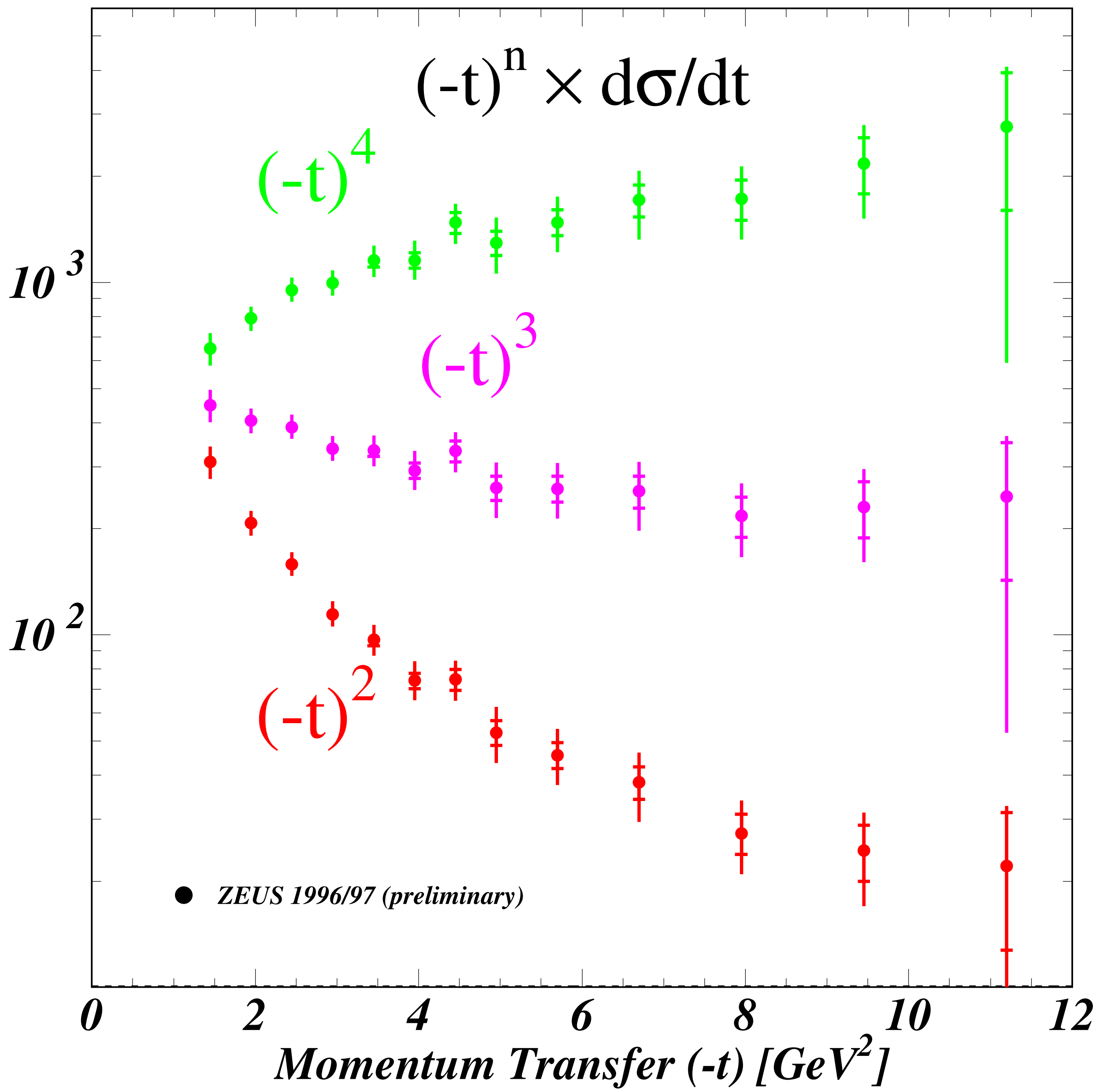
Diffractive ρ^0 Photoproduction (I)

$$\gamma + p \to \rho^0 + N$$



Asymptotic region

Diffractive ρ^0 Photoproduction (II)



Multiplying with $(-t)^n$

Some general remarks
(and some questions)

- These are the first measurements of light-vector-meson photoproduction at values of t comparable to the Q^2 values in DIS which led to the discovery of charged proton constituents in 1967.

- *BUT* this is presumably a strong interaction, rather than electromagnetic.

- We observe an extremely hard t dependence
  $\Rightarrow$ low-order process (*first* order ?)
  $\Rightarrow$ What about the meson form factor ?

- These values for t exceed the mass scales for ρ^0 and ϕ and exceed Λ^2_{QCD}
  $\Rightarrow$ Asymptotic region

  The t dependence characterizes the interaction.

Perturbative field theory

for vacuum exchange in the strong interaction (?)

What is the exchanged field?

What is the "charge"?
(Strength about 1/100 of confinement)

What is the reacting proton constituent?

Are there point-like interactions of hadronic bound states?

The HERA Luminosity Upgrade (2001-2006)

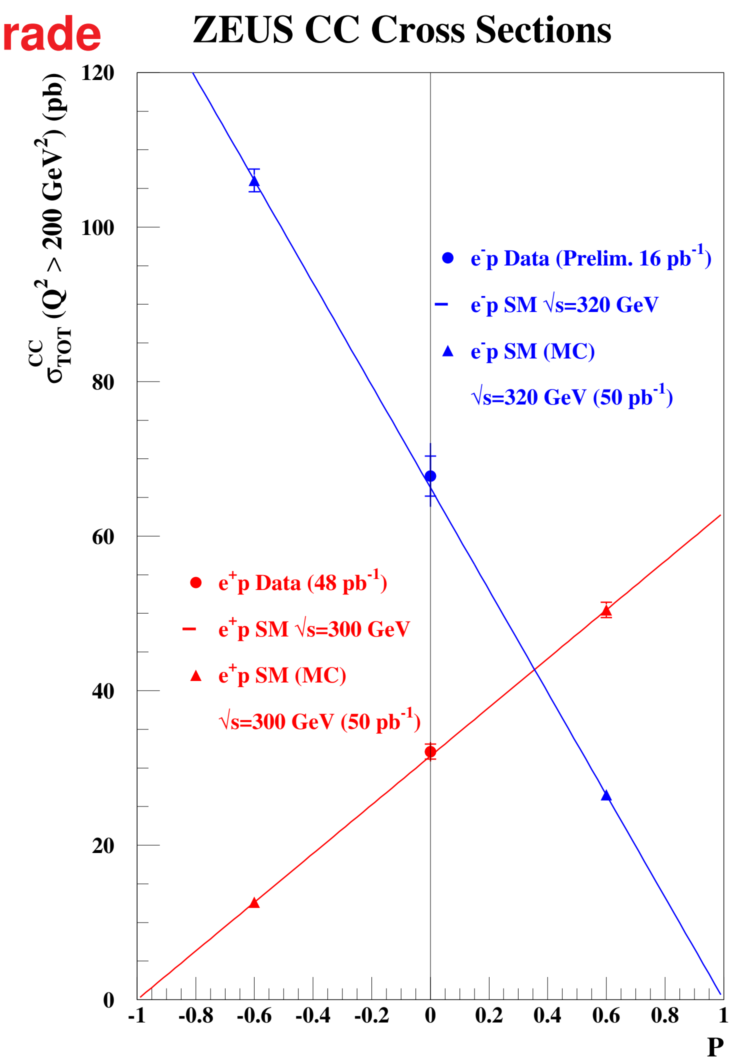
Lumi upgrade

Lumi Upgrade

- Lumi upgrade $\rightarrow$ 150 pb^{-1} per year
- After six years of running accumulated $\mathcal{L} \approx 1$ fb^{-1} of e^+p and e^-p data
- Polarized beams (designed goal 70%)

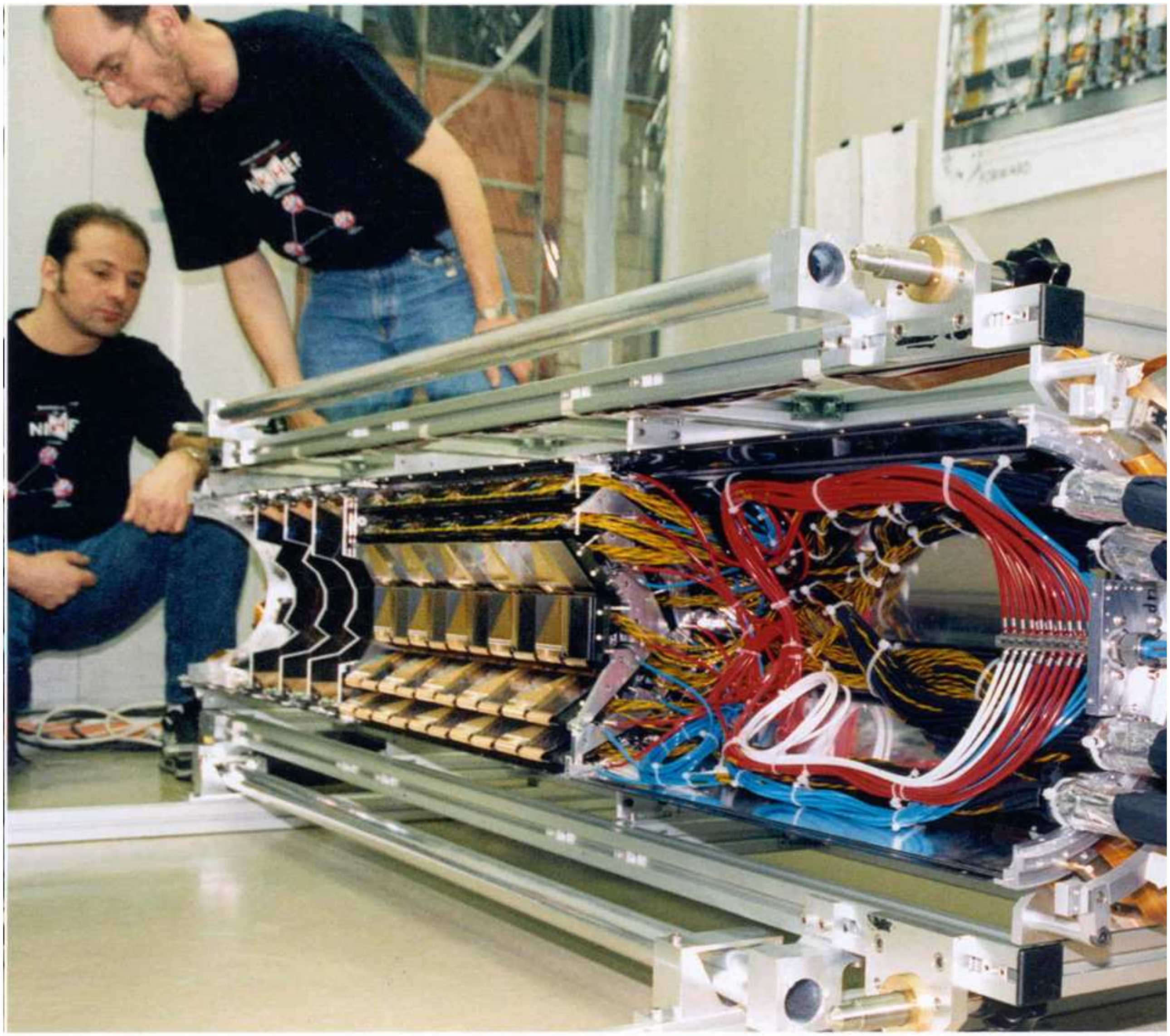
New Physic results

- Dependence of the total CC cross-section with the polarization
- Smaller errors for xF_3 $\rightarrow$ better understanding of the valence quark distributions for high x.
- Measurement of structure functions with high statistic

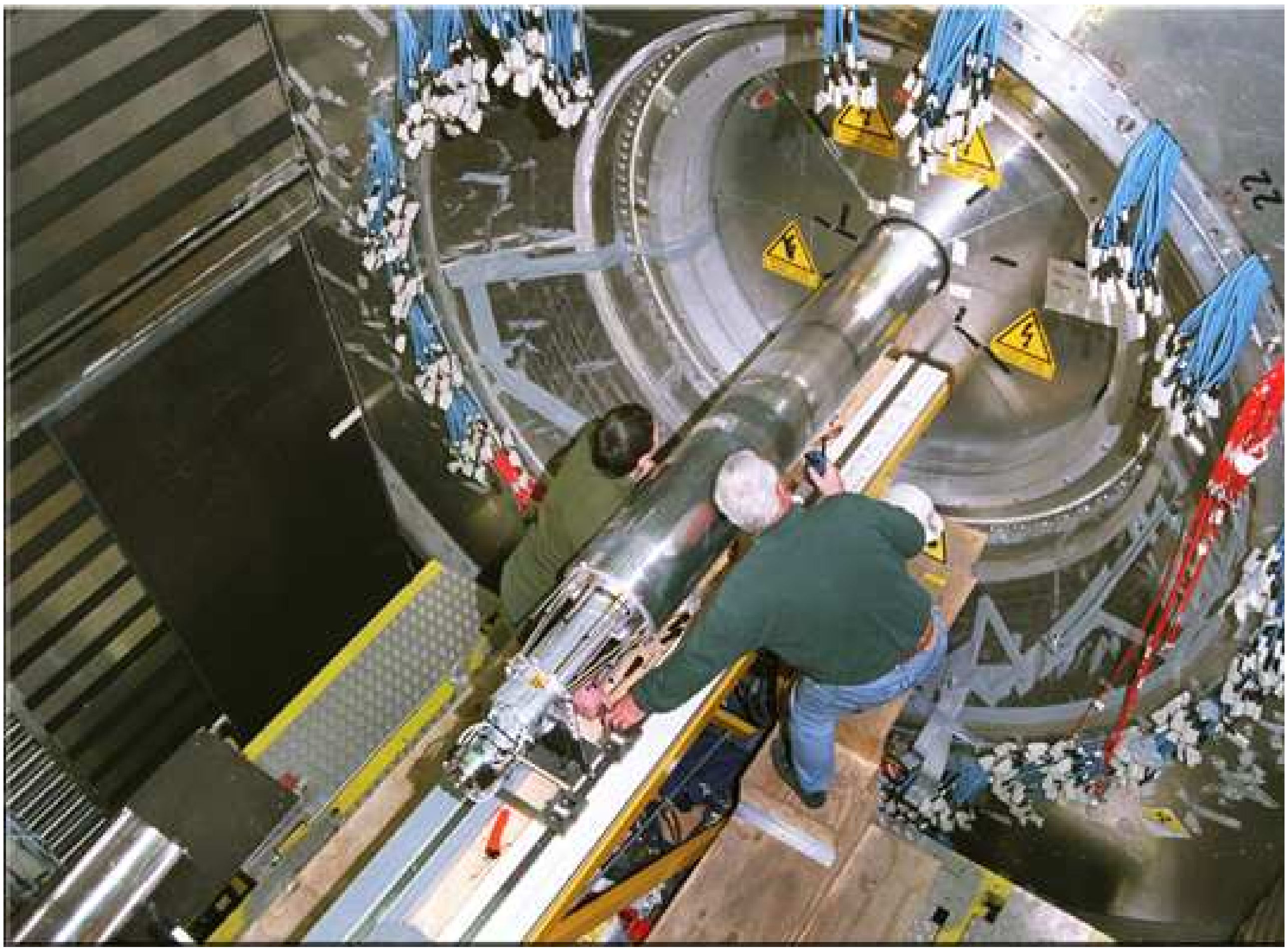


The HERA Upgrade (II)

The ZEUS Microvertex Detector



The HERA Upgrade (III)



The HERA Upgrade (IV)

D. Pitzl/H:1 DESY PRC status report, 17 May 2001

H1 for HERA II

- The goal:
  - Improve the detector to fully utilize $\int \mathcal{L}\, dt \approx 1\,\mathrm{fb}^{-1}$
- The projects:
  - 2 superconducting HERA magnets inside H1
  - 9 PRC proposals for new components, emphasis on tracking and triggering
  - 15 modifications of existing components
- The schedule:
  - The original 9 month shutdown schedule had to be extended by 5 weeks
  - Caused by production delays in the CIP front end electronics
  - H1 will be closed for beams on 6.7.2001

Assessment of HERA Results (I)

What have we learned?

- $F_2(x, Q^2)$: Steep dependence on x in DIS region
  - ✔ High density of sea quarks
  - ✔ Raging controversy over saturation
- $F_2(x, Q^2)$: Steep dependence on Q^2 at low x
  - ✔ High density of gluons
  - ✔ Precision measurement of α_s made possible
  - ✔ Reached theoretical level of precision
- Gold mine of strong interaction dynamics
  - ✔ Soft diffraction

    Pomeron intercept depends on energy, process, Δp

    Physics of $\alpha'_{\mathbb{P}}$

    Unitarity
  - ✔ Hard diffraction

    Factorization theorem, diffractive PDF's

    New scaling laws

    Discovery potential high
  - ✔ Transition regions in Q^2, W, t, M

    Best hope for unified understanding of old problems
  - ✔ Exclusive processes in QCD

    Scaling, energy dependence, helicity selection rules

Assessment of HERA Results (II)

- Heavy flavor $\rightarrow$ test of QCD at NLO
  - ✔ Precision charm
  - ✔ Treacherous beauty
- No structure to partons down to scale of 10^{-18} m
  - ✔ No leptoquarks, no contact interactions, no nuthin'
- No deviation from SM in spacelike region
  - ✔ Mechanism of electroweak unification verified to HERA accuracy

THERA makes sense

THERA Chronology

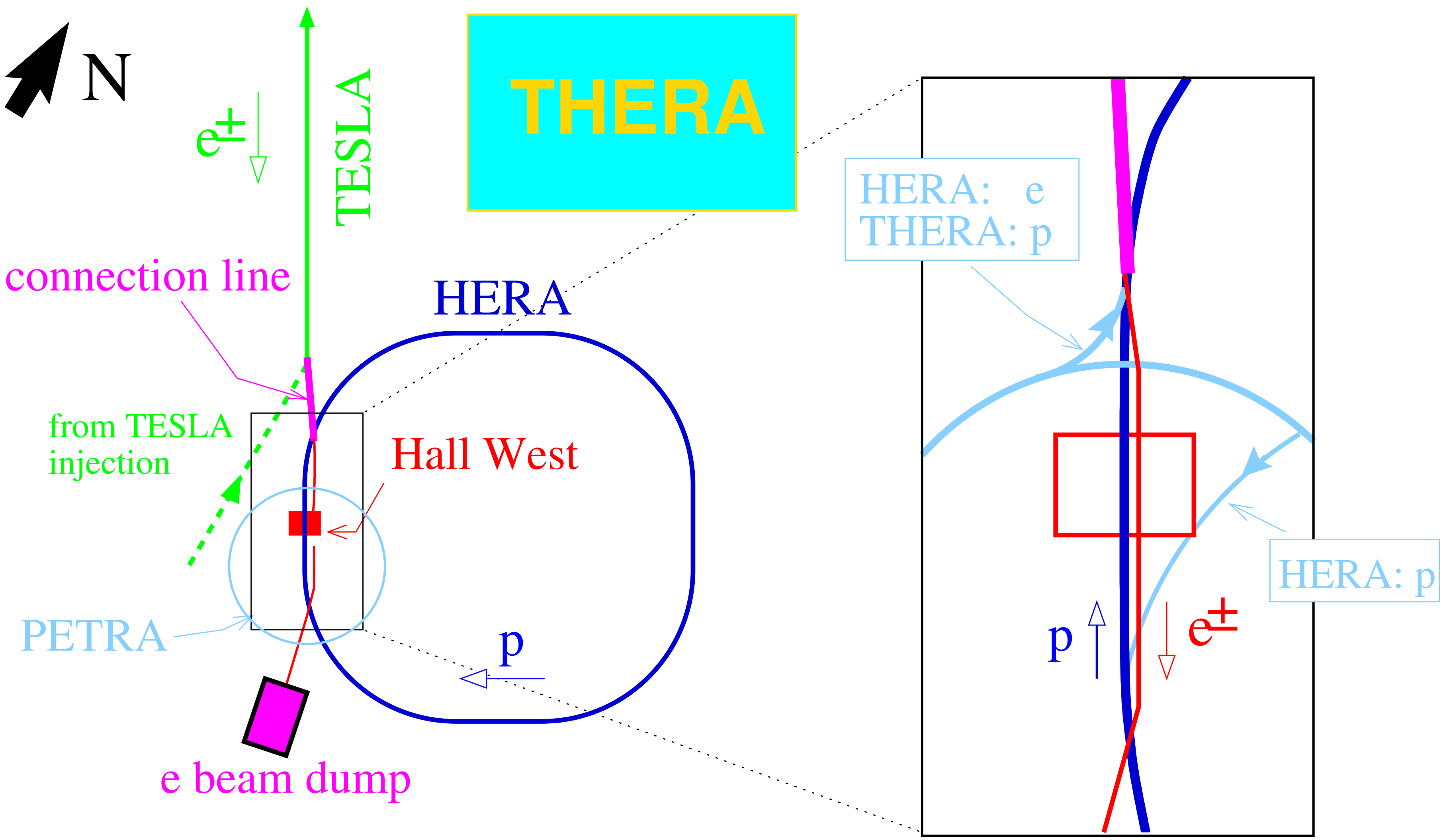
- M. Tigner, B. Wiik and F. Willeke
  IEEE Proceedings 1990
- R. Brinkmann, Tr. J. of Phys. 22 (1998) 661
  (Ankara workshop)
- A. Wagner, *Future of HERA and TESLA*
  (DIS'99, Zeuthen)

  TESLA tunnel tangential to HERA "... with the clear intention to have the future option to collide electron beams from TESLA with proton beams in HERA."

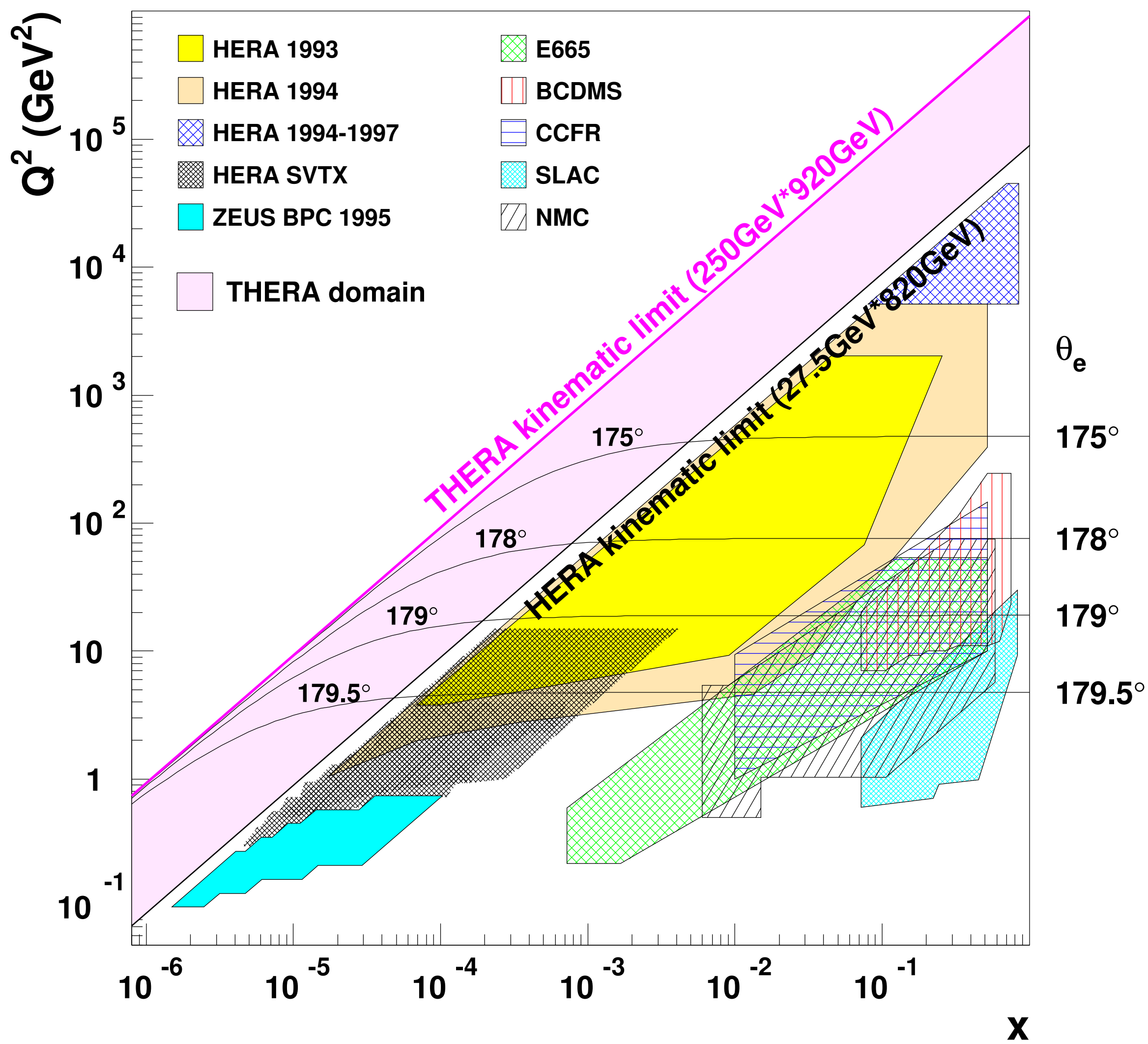
  "It would be good to include in the TDR a chapter on the physics potential of electron-proton collisions with TESLA on HERA."

- DIS Workshops
  - ✔ 1998: A. De Roeck
  - ✔ 1999: Y. Sirois
  - ✔ 2000: M. Klein
- U. Katz, *Physics with THERA*
  ECFA/DESY Linear Collider Workshop, May/2000
- The THERA Study Group
  - ✔ Convenors established in late 1999
  - ✔ Meetings/Workshops:
    February, April, October, December
  - ✔ Contribution to TDR now being edited

THERA Beam Lines



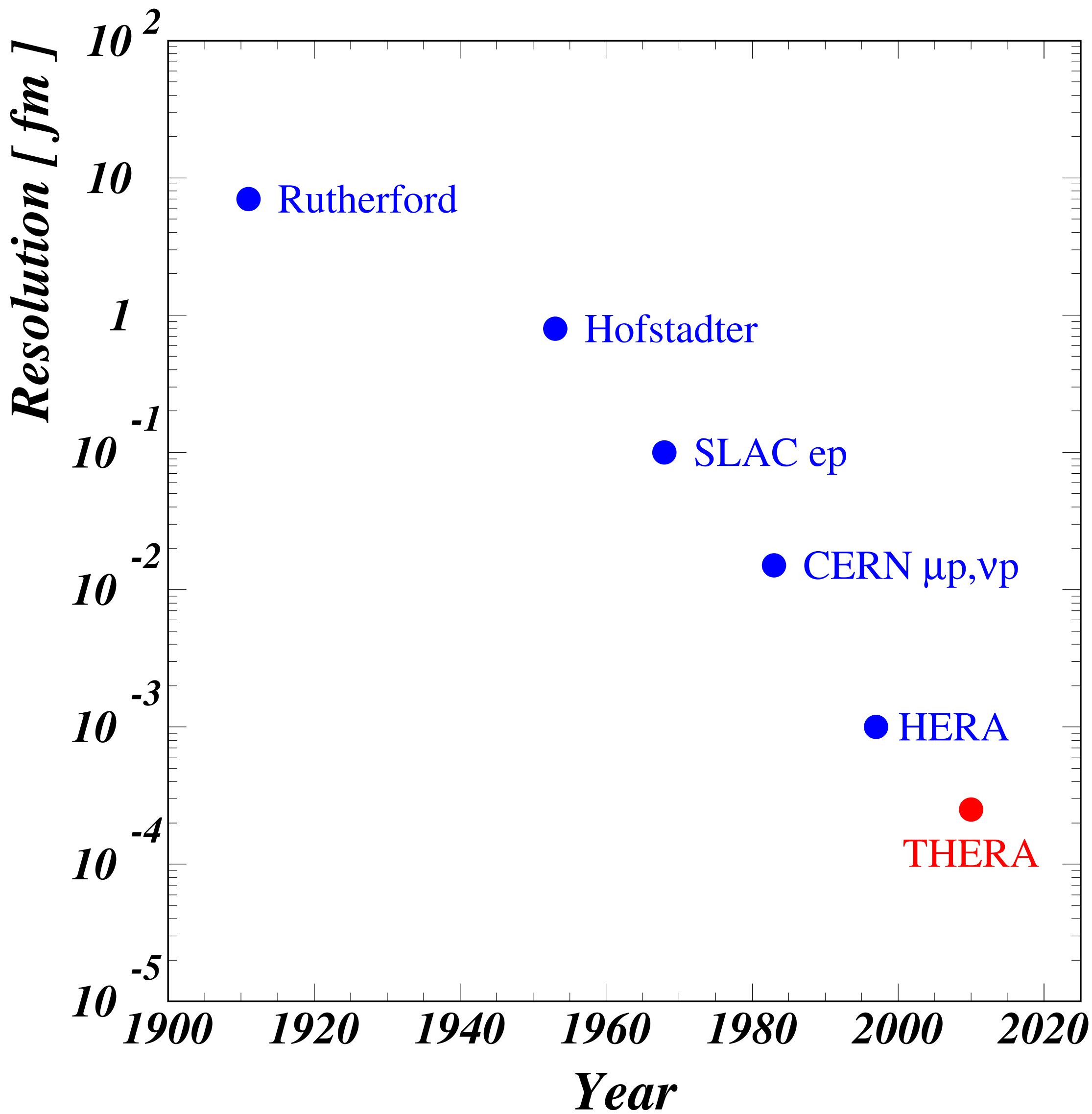
The THERA Kinematic Plane



- Extend x range down to 5×10^{-6} for $Q^2 \simeq 1$ GeV^2
- Cover factor 10 in pQCD regime at $x \simeq 10^{-4}$
- Extend one order of magnitude in Q^2 into region of electroweak unification

100 Years of Scattering Experiments

	HERA	THERA
E_e	27.5 GeV	250 GeV
E_p	920 GeV	920 GeV
E_{cm}	318 GeV	960 GeV



The next redefinition of “elementary”