HERA Collider Physics

Durham, 6.12.2001

Peter Schleper

DESY

HERA results in 2006

a personal selection

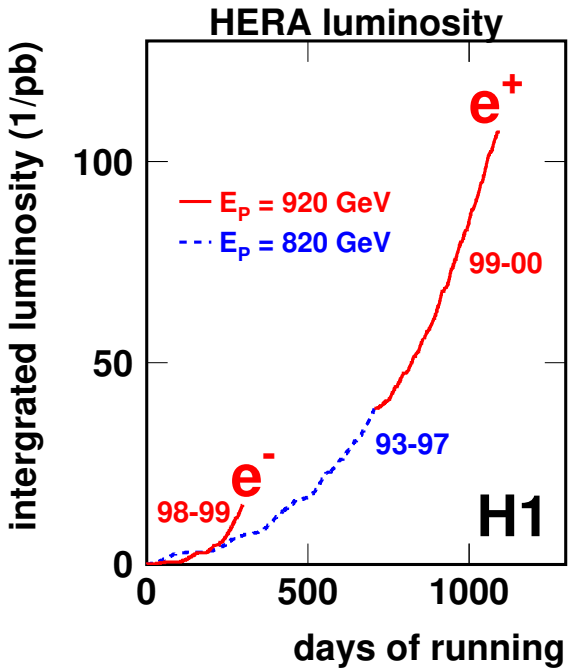
incomplete

speculative

$e^{\pm}p$ collisions at HERA I and II

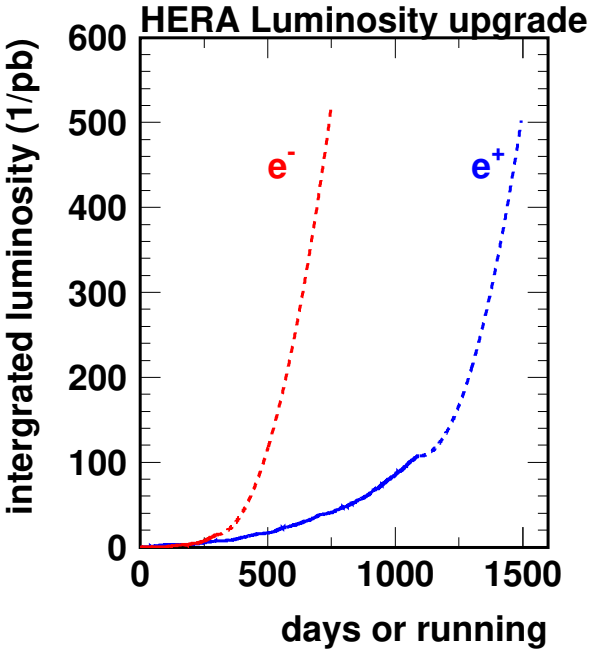
HERA I: 1993-2000

- E_{p_0} =820...920 GeV
  E_{e_0} =27.5 GeV
- $\sqrt{s}$=320 GeV
- $L \gtrsim 100\ \mathrm{pb}^{-1}$

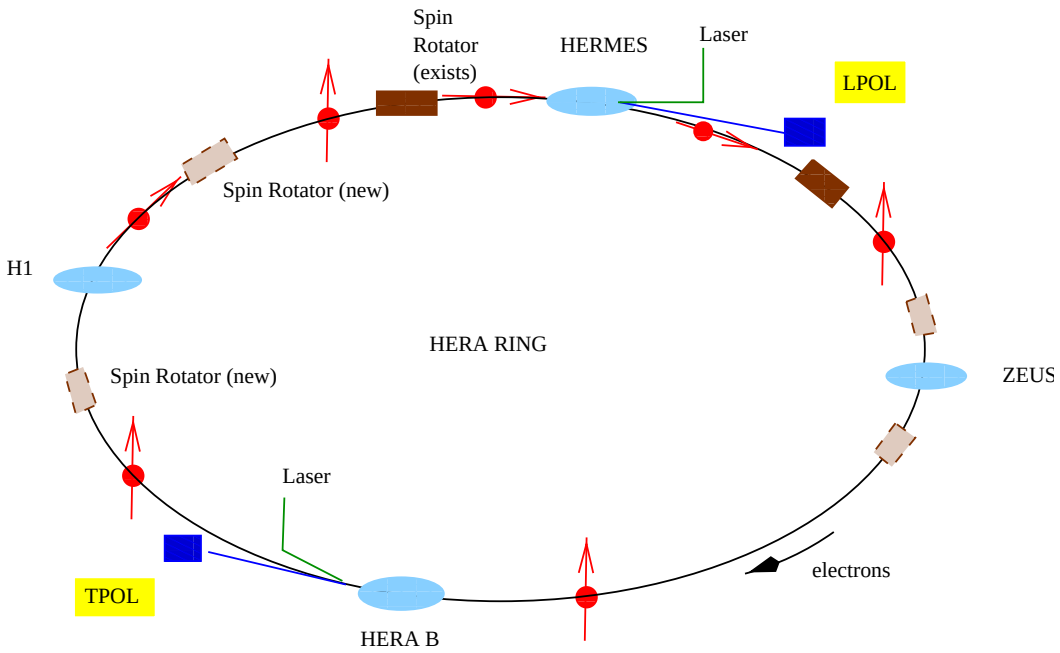


HERA II: 2001-2006 (?)

- Increase to L=1000 pb^{-1}
- e^+ and e^- equally shared
- $e^{\pm}$ polarisation $\approx 55\%$
- Runs with lower/higher E_{p_0}



HERA II



Collider experiments: H1, ZEUS

- Stronger focussing close to experiments
- Spin rotators
- New beam lines

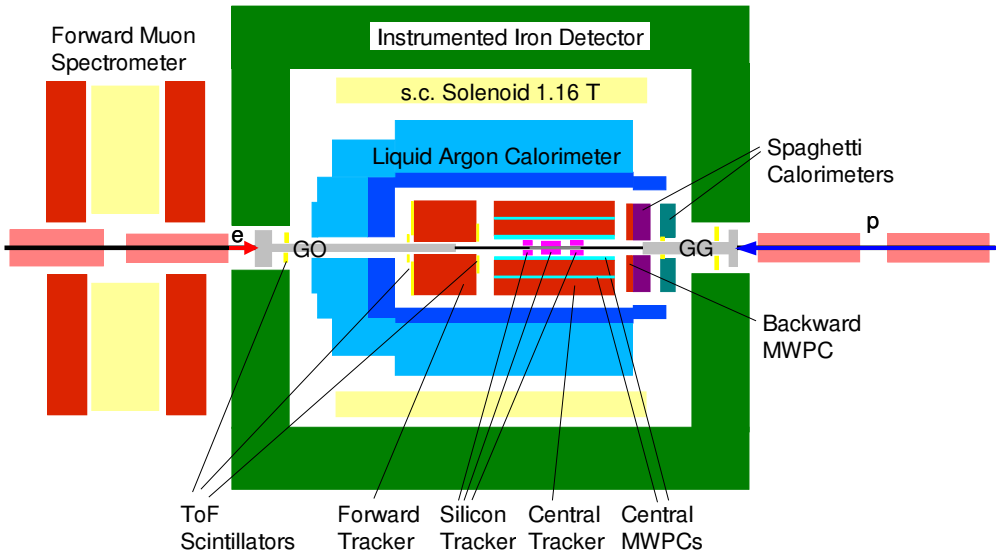
HERMES, HERA-B

- not affected

HERA II

The HERA upgrade

- Strong focussing at interaction point
- Magnets inside main detector



The Challenges

- Synchrotron radiation
- Back scattering from magnets

The Detector upgrades

- Trigger !
- New forward tracking
- Extended silicon tracking
- New Forward proton spectrometer
- Smaller acceptance at low angles: $Q^2 > 8$ GeV^2

Virtues of ep scattering at HERA

large Q^2 lever arm: precision QCD

- α_s, quark and gluon densities

small - x: high parton densities

- novel quantum system

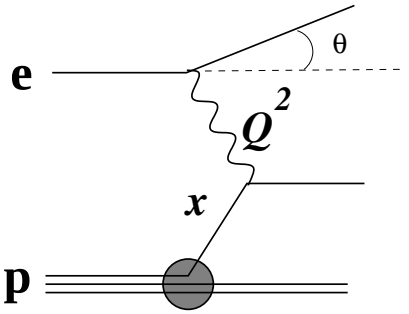
small Q^2: large distance QCD

- non-perturbative, confinement

large CMS energy:

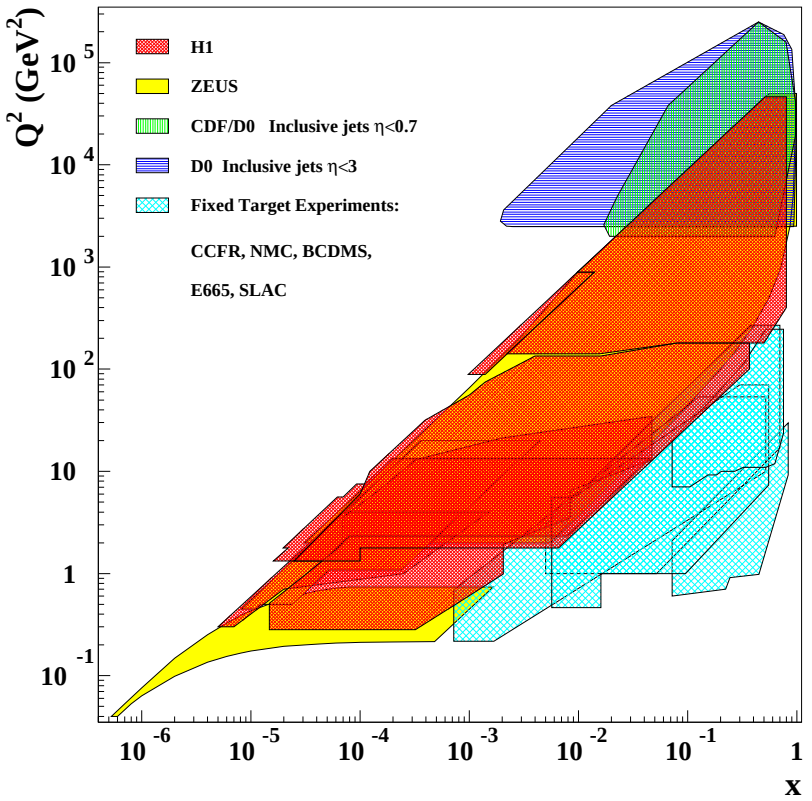
- (beyond) the EW standard model (largest E_{CMS} with lepton in initial state)

$\rightarrow$ reason why H1 / ZEUS are leading QCD experiments



$Q^2 = \gamma$ -virtuality

$x = E_{\text{parton}} \,/\, E_p$



Partons in the Proton

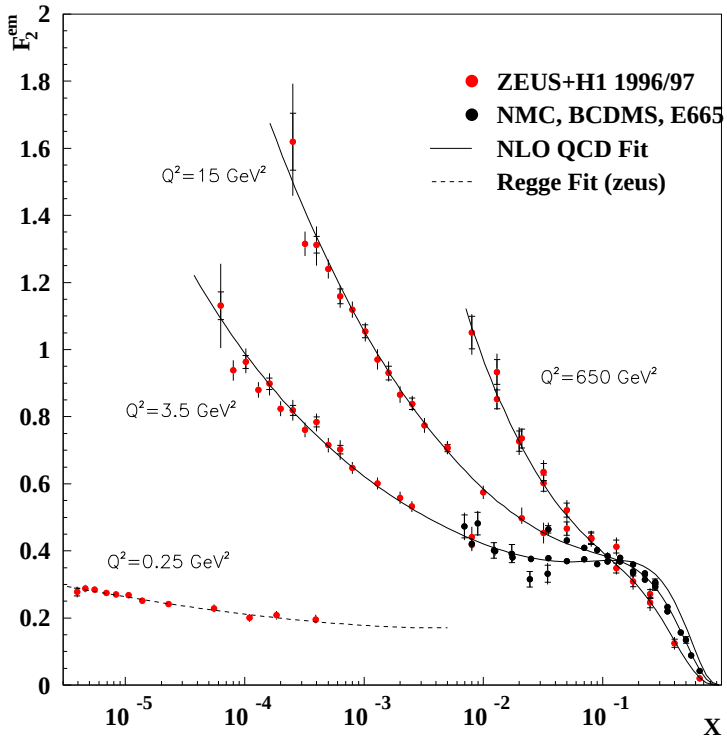
$ep \to eX$ at small Q^2:

$$\frac{d^2\sigma}{dx\,dQ^2} \approx \frac{2\pi\alpha^2}{xQ^4} F_2$$

momentum distribution of quarks:

$$F_2\left(x,Q^2\right) \approx \sum e_q^2 q\left(x,Q^2\right)$$

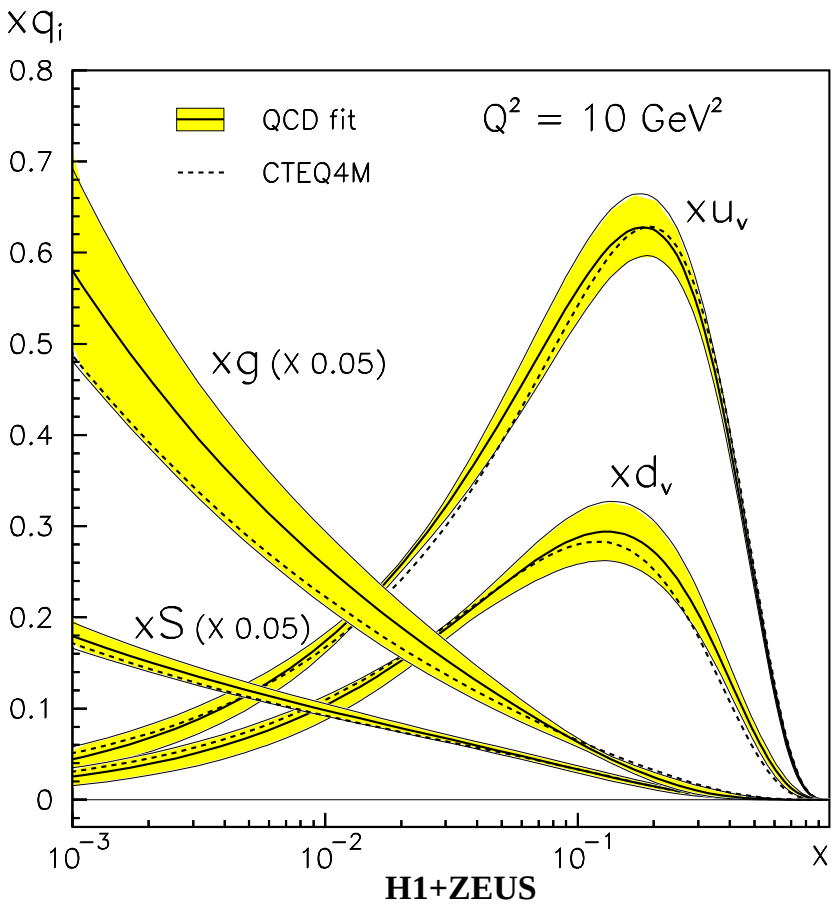
$$dF_2/d\ln Q^2|_x \approx \alpha_s \times g\left(x,Q^2\right)$$

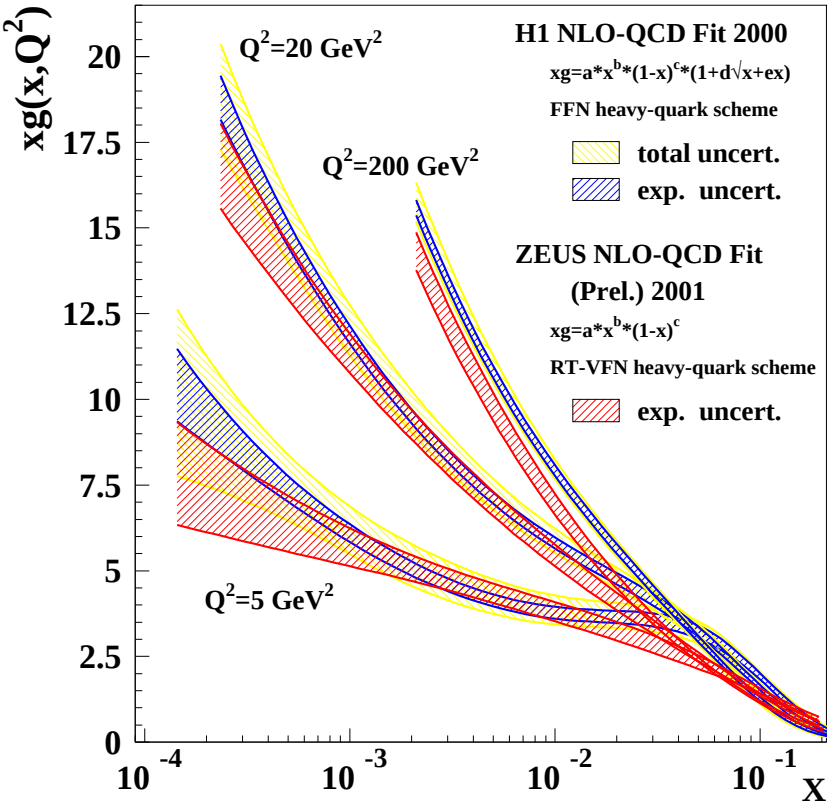


small $x \to$ high quark density

$\to$ strong rise of quark density $\to$ high gluon density

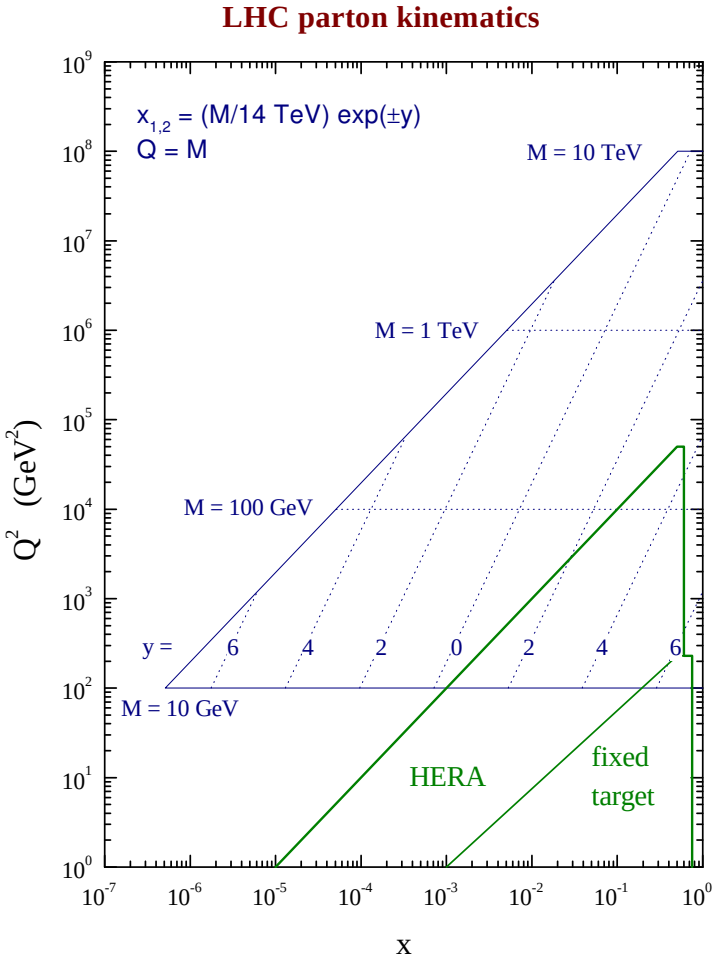
Quark/Gluon Distribution in the Proton





Higgs Produktion at LHC

$M_{\mathrm{H}} > 108$ GeV



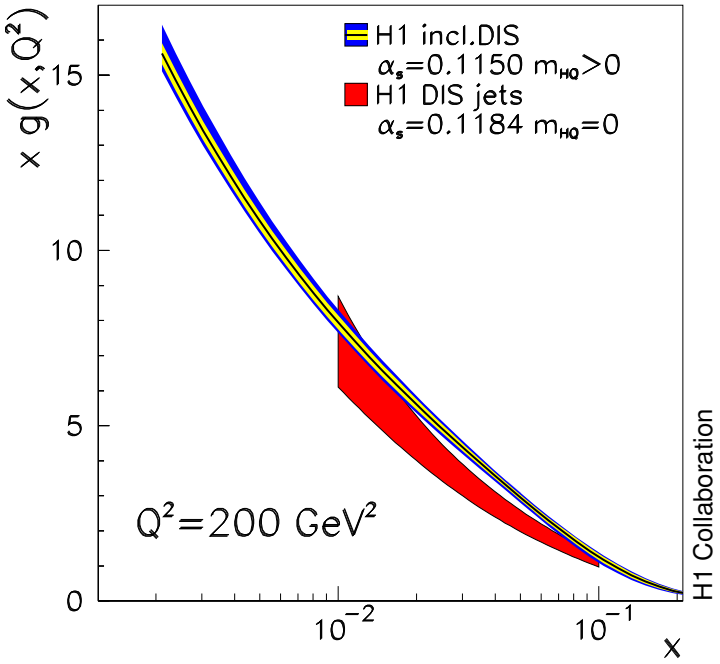
depends on gluon density at $x \lesssim 10^{-3}$

only process: DIS at HERA

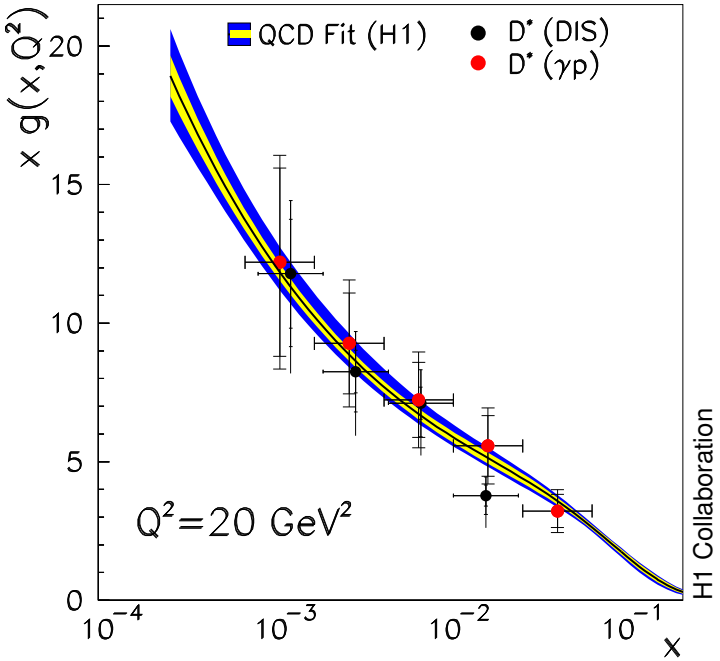
but: $x \lesssim 10^{-4} \rightarrow Q^2 \lesssim 1$ GeV

Gluon induced processes

Verification of gluon density: intermediate x



jet production



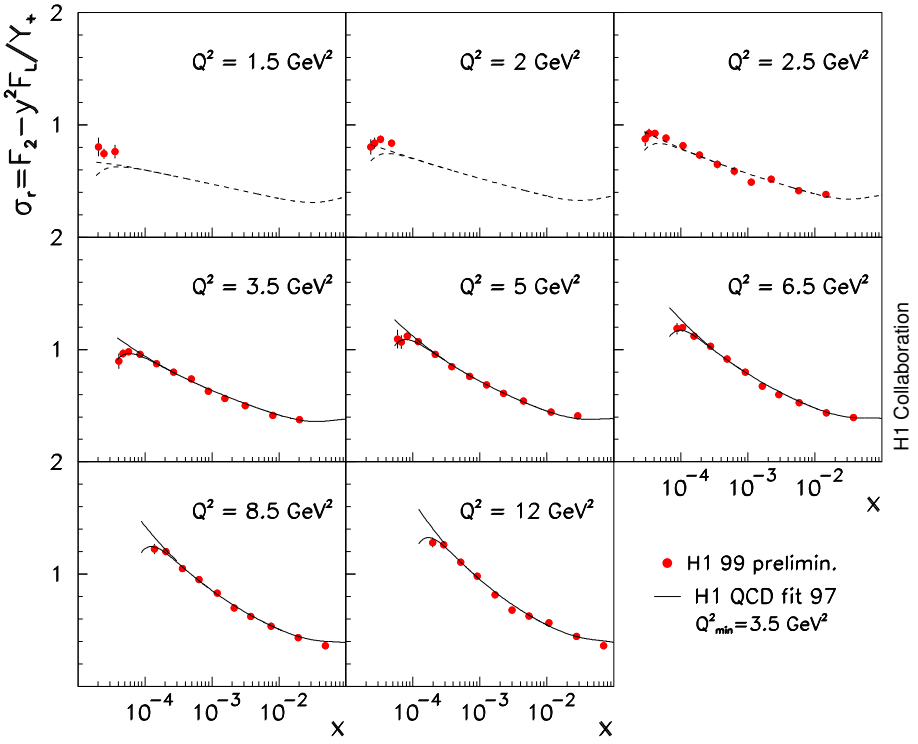
charm production

Longitudinal Structure Function F_L

Verification of gluon density: small x

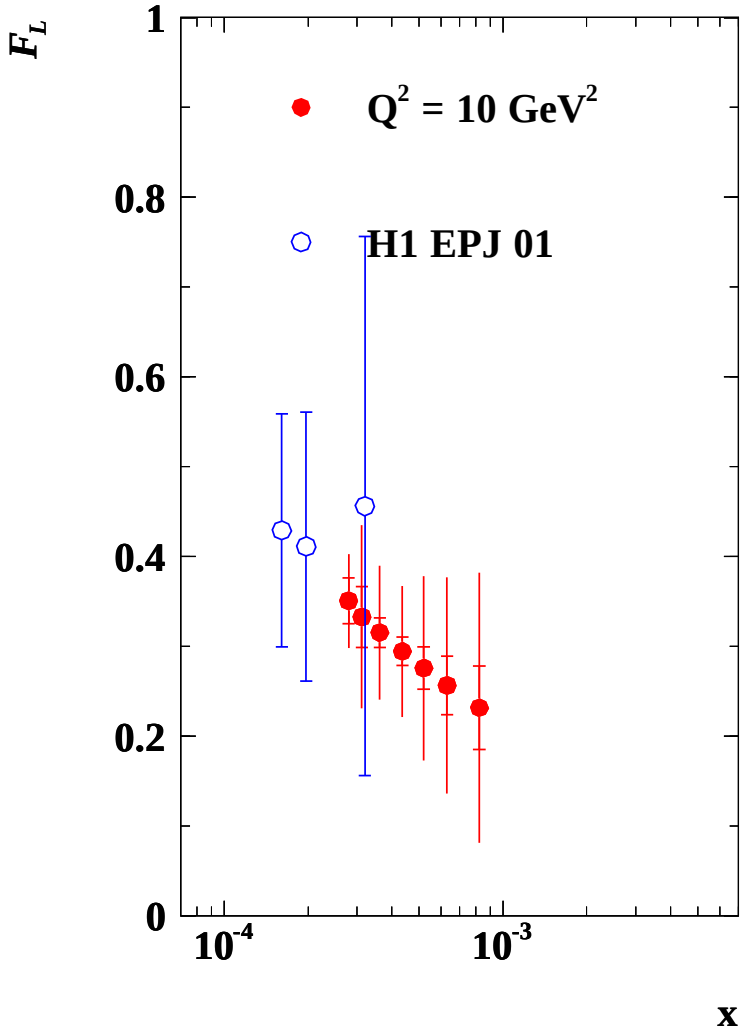
$F_L \sim \sigma_r - F_{2,\mathrm{extrapol.}}$

- depends on assumption for extrapolation towards high y
- limited in precision
- includes small x



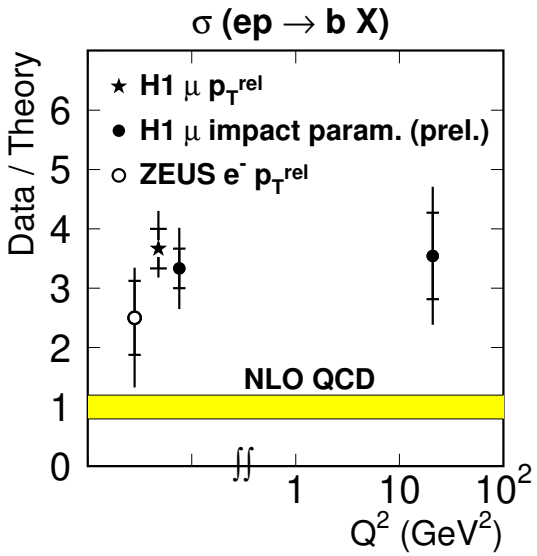
F_L from reduced beam energy

- e.g. E_P=300,350,465 GeV

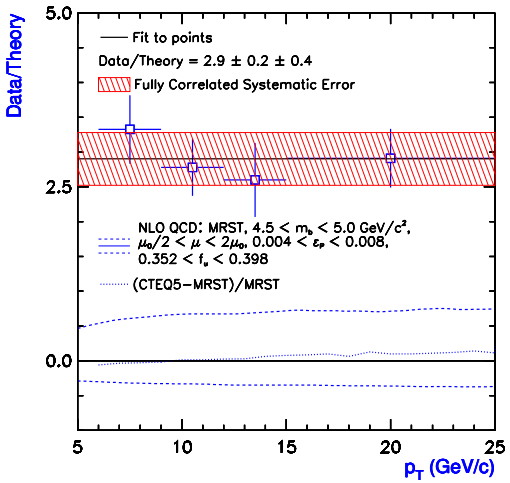


Bottom production: Unexplained

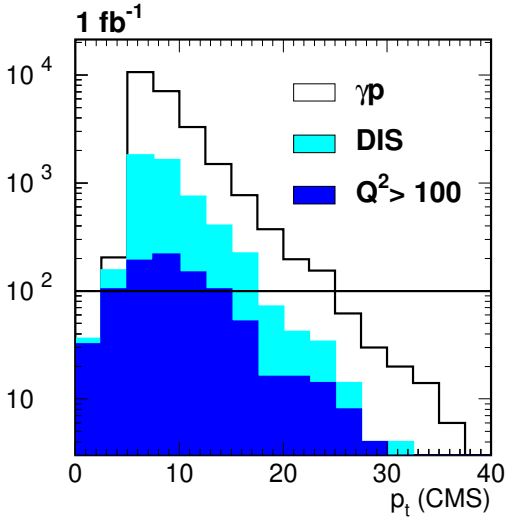
HERA now



CDF



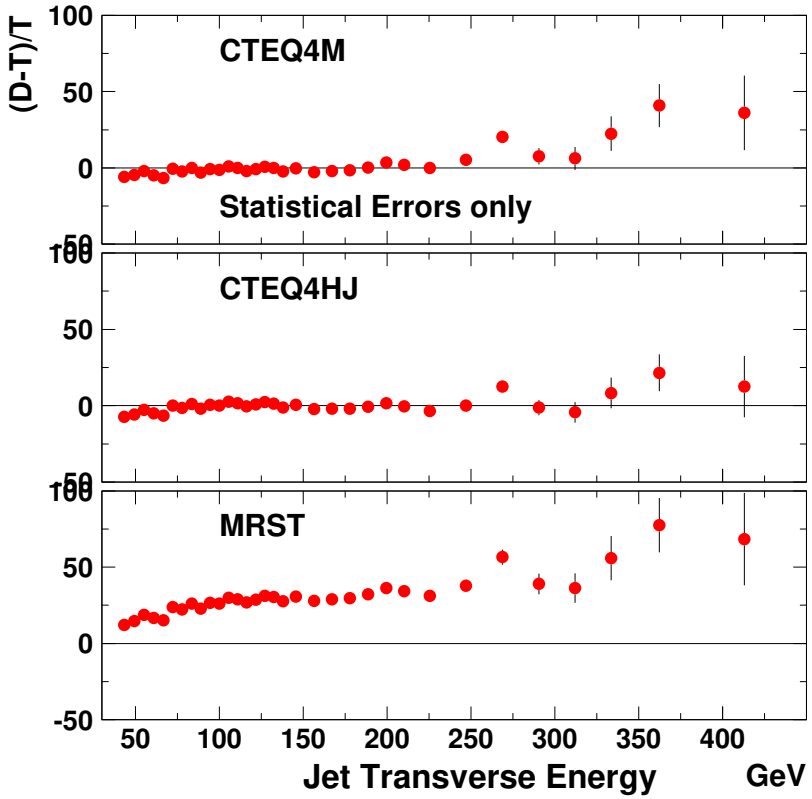
HERA II



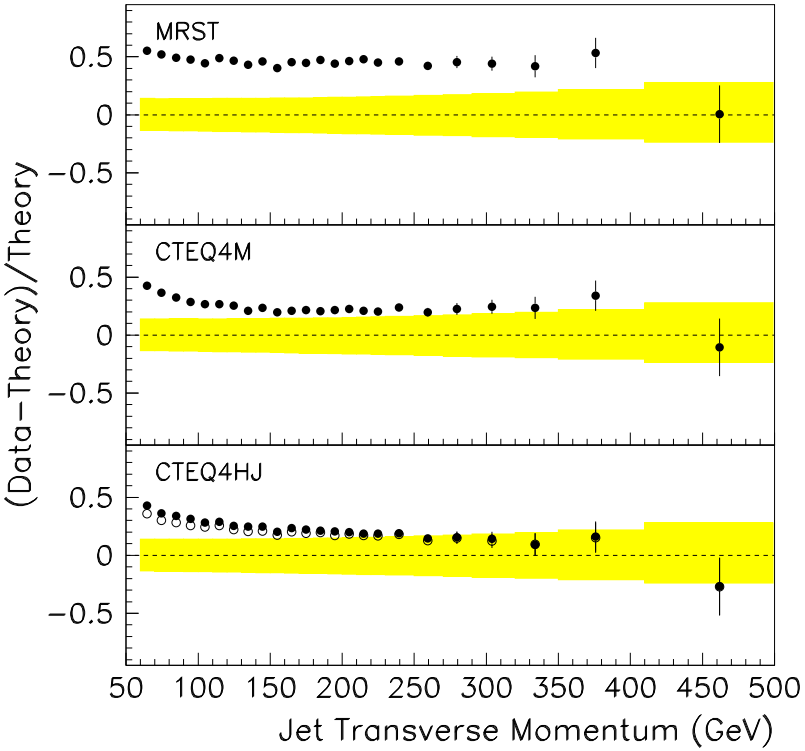
much enhanced B-tagging

Tevatron jets at high P_T: gluons at high x

CDF: cone algorithm



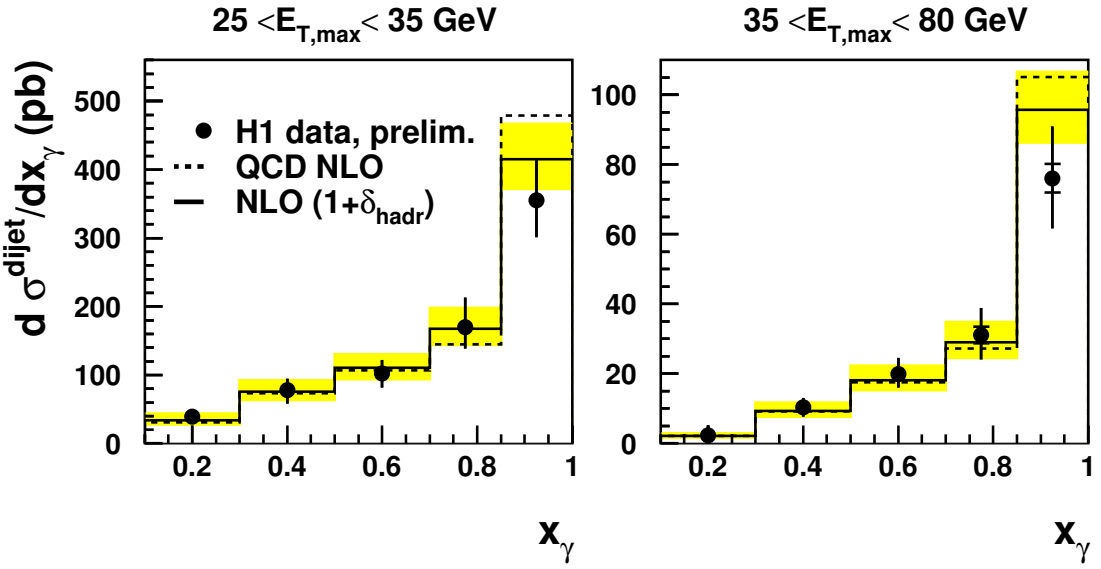
D0: K_T algorithm



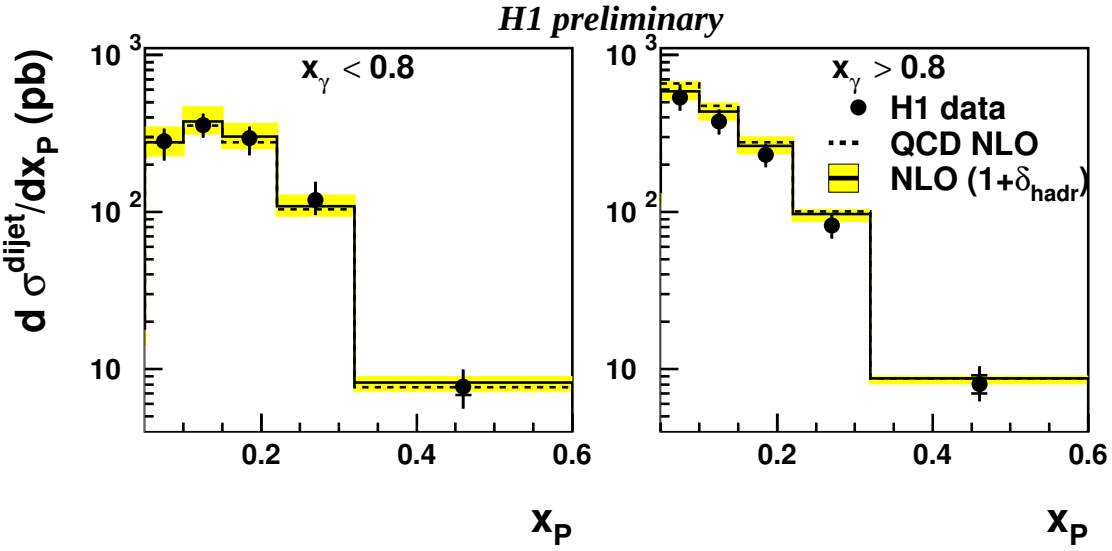
open questions...

Photon and Proton at High x

jets in γp at high E_T

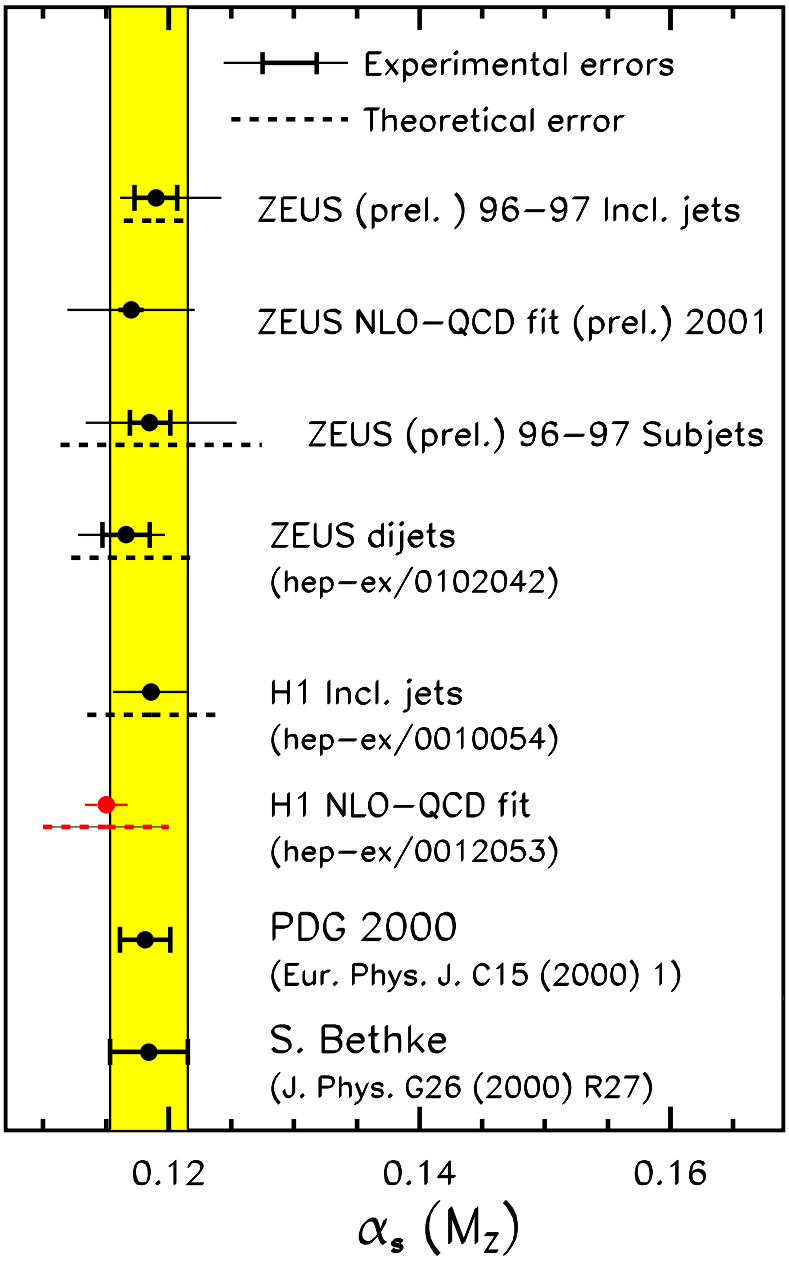


access to proton at high x !



- dominated by direct + pointlike part of γ
- significant contribution from gluon in proton
  $\rightarrow$ Tevatron high E_T jets

HERA summary on α_s



- NNLO calculations for F2 (and 2-jet production ?)

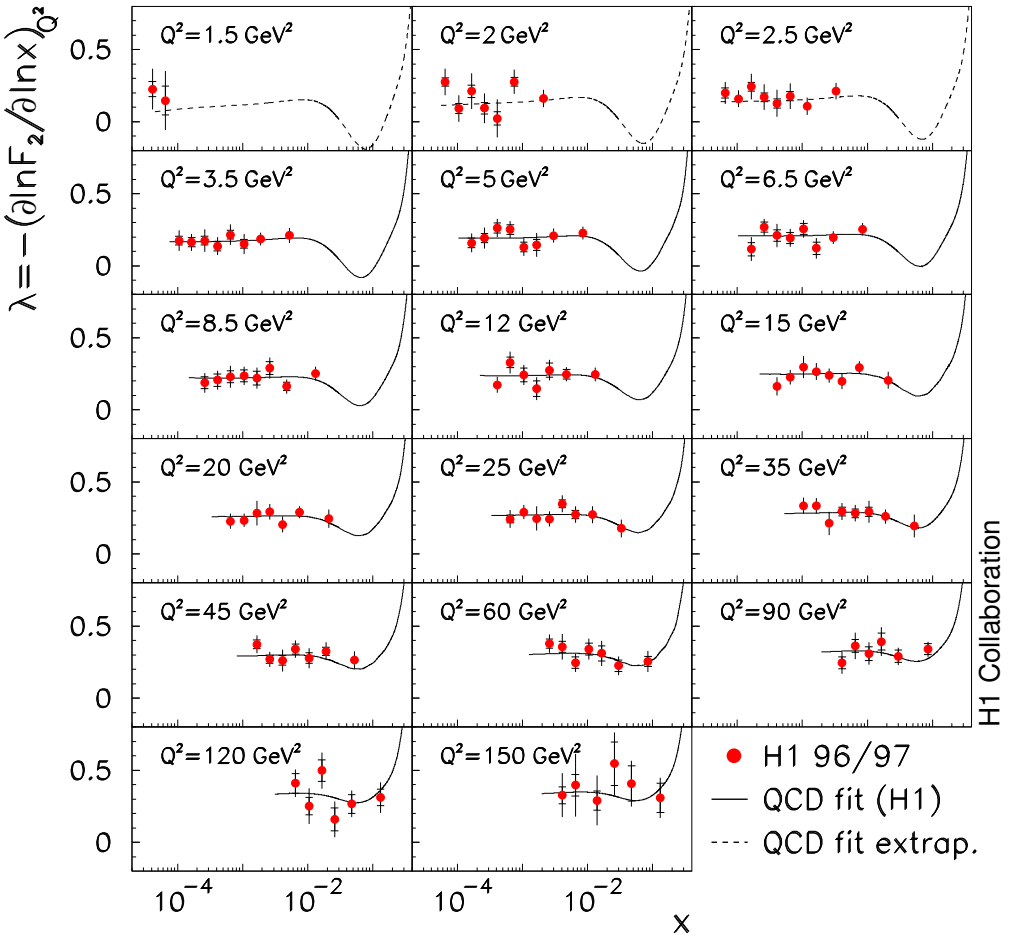
$\rightarrow$ reduction of scale errors by factor 2-3 !!

the CHALLENGE: get best α_s ($\pm$ 1%)

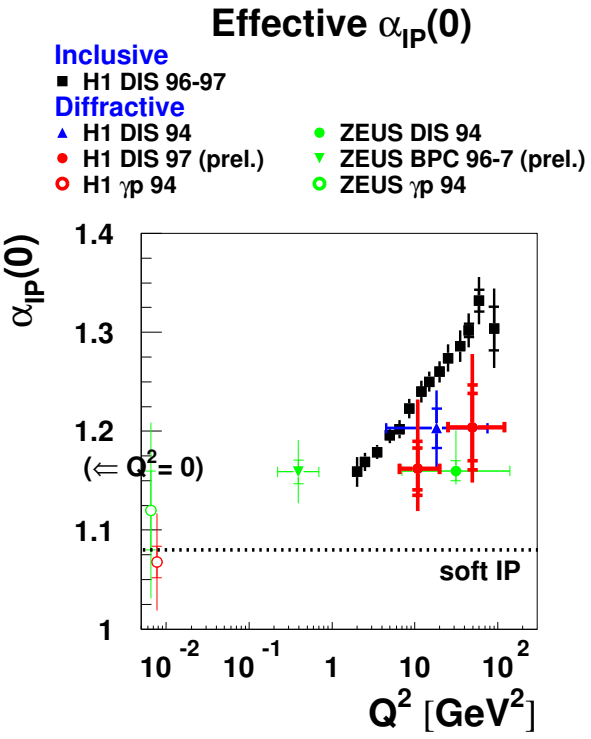
needs reduction also of experimental errors !!

Low-x behaviour of $\mathrm{F_2}$

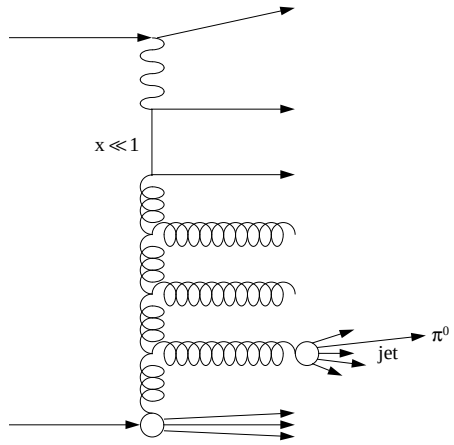
$$\lambda =: -\left(\frac{\mathrm{d}\ln F_2}{\mathrm{d}\ln x}\right)_{Q^2}$$



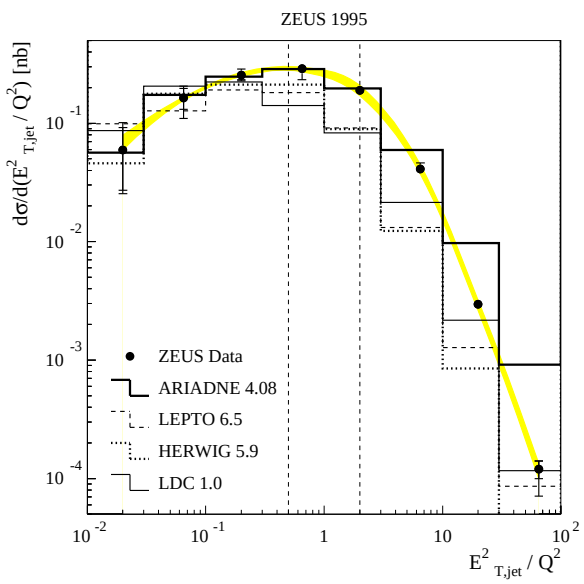
- no sign of deviation from $\mathbf{x^{-\lambda(Q^2)}}$ at small x
- no saturation visible in F_2

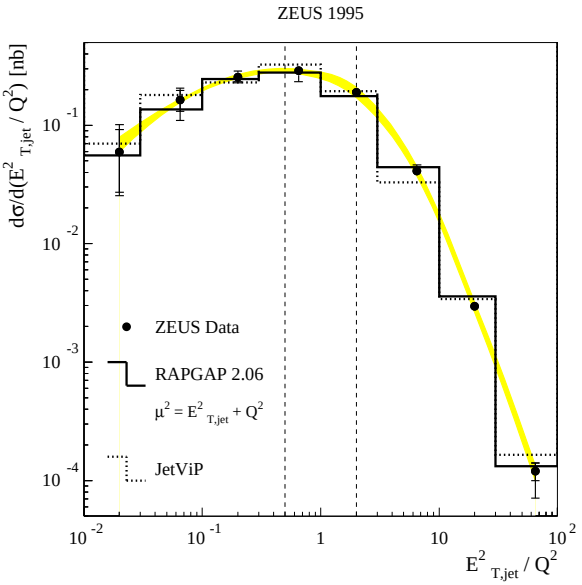


Low-x Parton Dynamics



- small-x, forward jet (π^0), $Q^2 \approx E^2_{T,jet}$
- no k_T order, test case for DGLAP–BFKL-CCFM-$\gamma^*_{\rm resolved}$
- unintegrated parton distributions

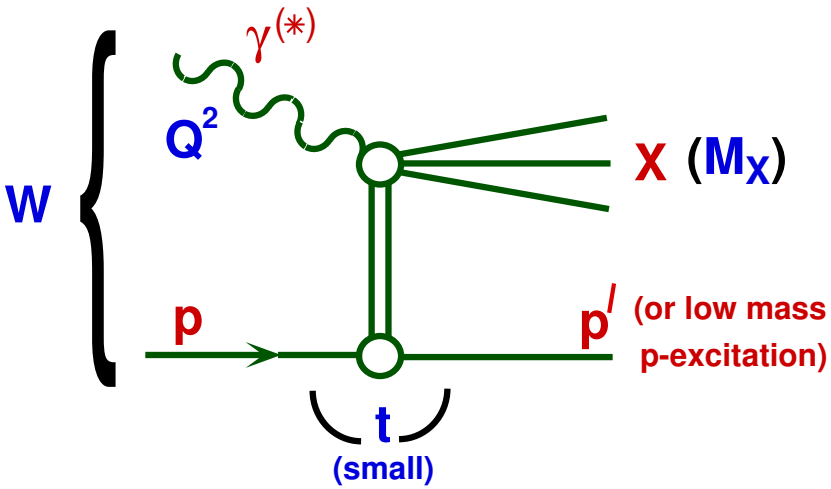




No direct dynamical evidence up to now

- CCFM (CASCADE): some success for F_2^{charm}
- NNLO for jet production needed

Hard Diffraction



colour singlet exchange of more than one parton (2 gluons or more)

$\rightarrow$ Correlations

Hard scattering factorization

$$\sigma \sim \sum_i f_{i/p}(x_{I\!P}, t, x, Q^2) \times \hat{\sigma}_i(x, Q^2)$$

with DGLAP evol. $f_{i/p}(x_{I\!P}, t, x, Q^2)$ at fixed $x_{I\!P}, t$.

- Proof for diffractive DIS
- Experimental test ?
- Partonic picture of diffraction

Colour Dipol Picture of DIS

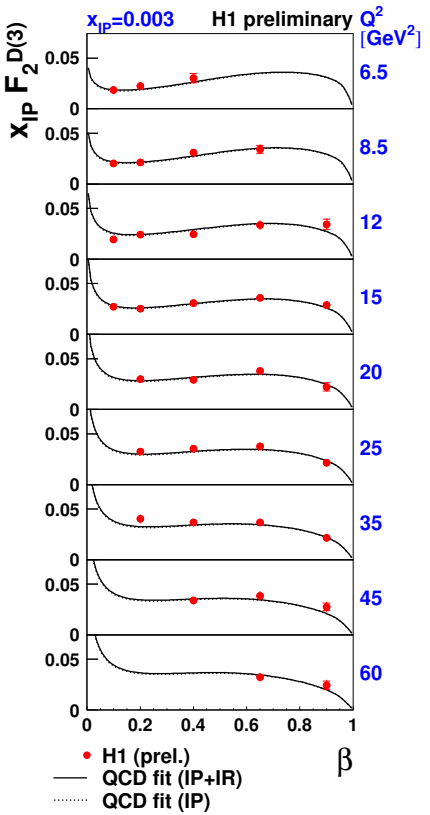
- hope to unify description of DIS and Diffraction

GPD's: Generalized Parton Distributions

- $f_{i/p}(x_1, x_2, Q^2)$

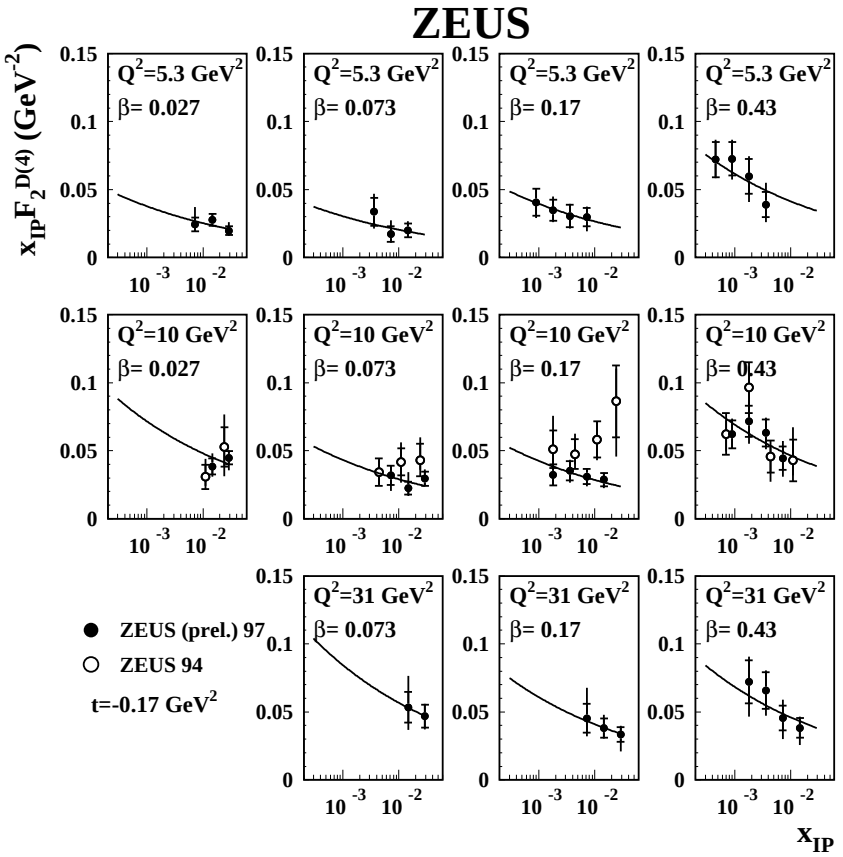
Diffractive Structure Functions

$F_2^{D(3)}$



limited by systematics

$F_2^{D(4)}$



limited by statistics

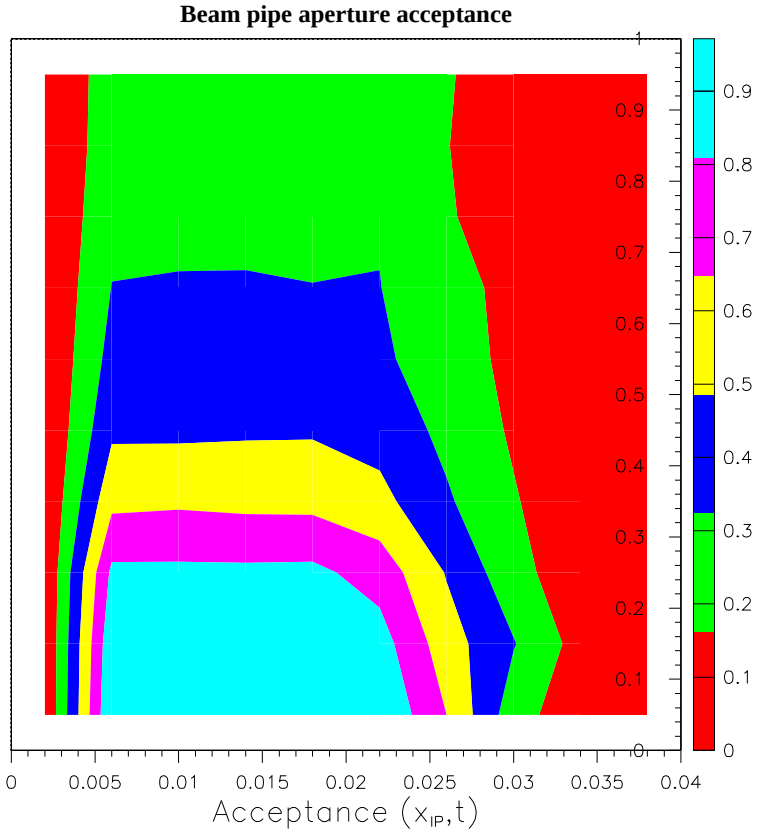
Very Forward Proton Spectrometer (VFPS)

New detector at $z = 200m$

- full acceptance at
  $0.005 < x_{I\!P} < 0.02$,
  $|t| < 0.25$ GeV^2
- trigger for all diffractive processes
- $|t|$, ϕ measurement
- no contribution from p-dissociation

$\rightarrow$ High statistics test of QCD interpretation of diffraction: $F_2^{D(4)}$, jets, charm, DVCS

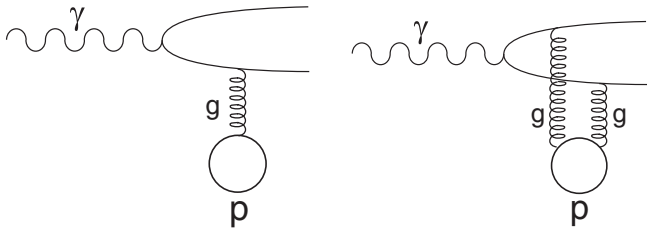
H1 VFPS acceptance



Colour Dipol Picture of DIS

Assume factorisation:

$$\sigma \;=\; \Psi(\gamma^* \;\rightarrow\; qq(g)) \;\times\; \sigma_{\mathrm{dipol}}$$



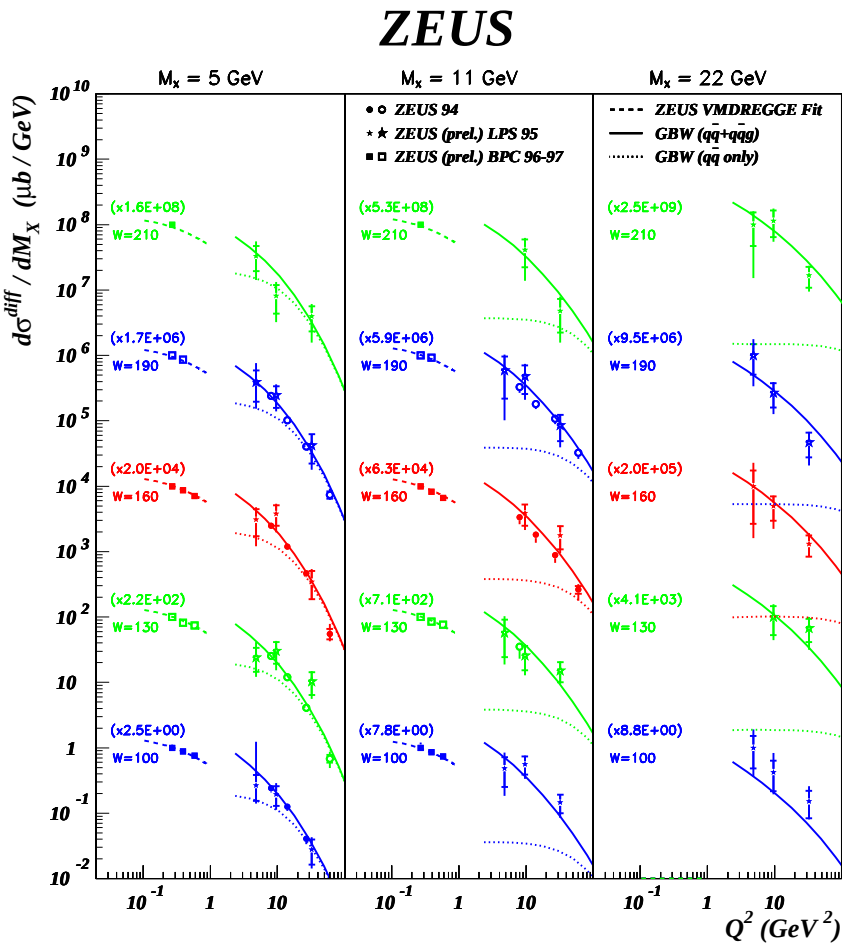
Success of Colour Dipol Models

- fit σ_{dipol} to F_2
- predict F_2^D, diffractive $J\Psi$, jets
- Connection to BFKL

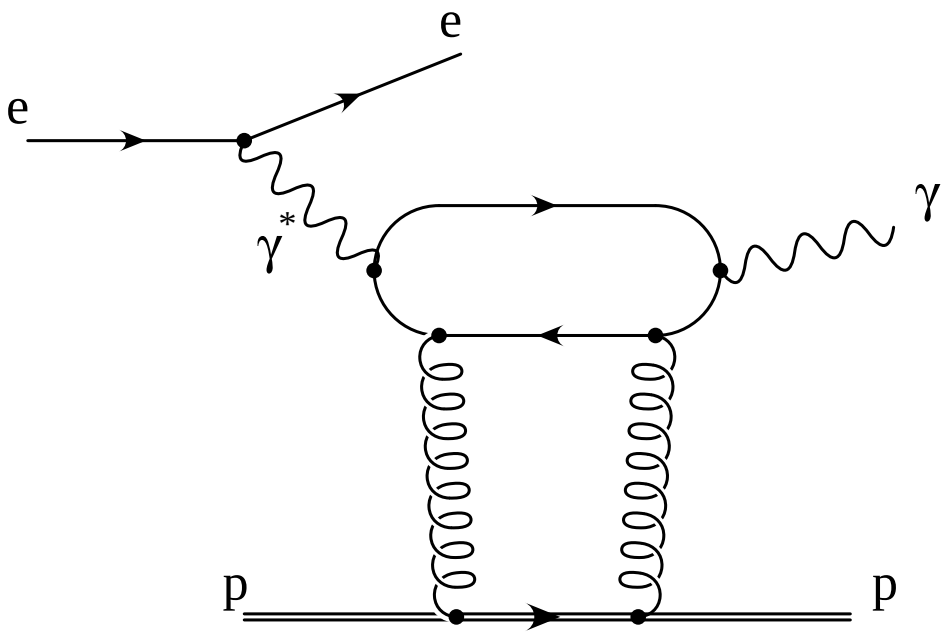
$Q^2 \rightarrow 0$: saturation of σ_{dipol}

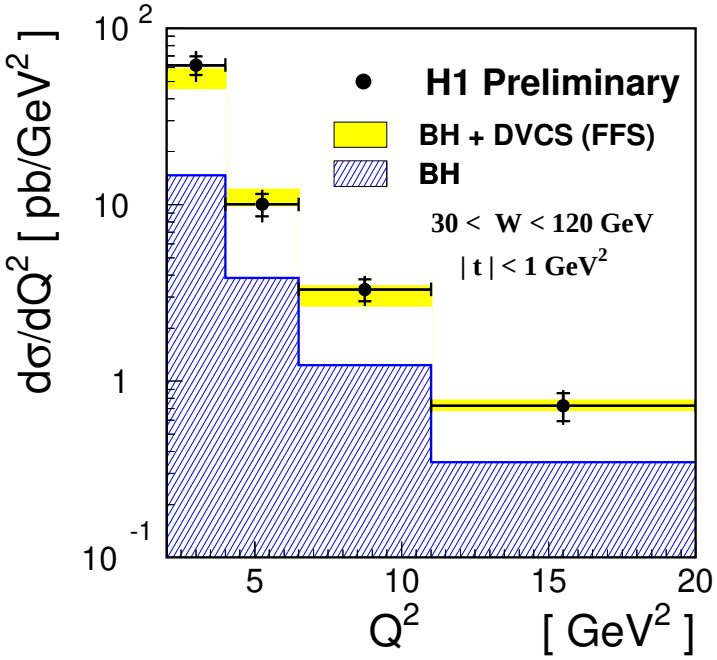
(Golec-Biernat, Wüsthoff)

- not yet successful at $Q^2 < 1$ GeV^2



Deeply Virtual Compton Scattering





γ- $\times$ gluon-pair $\rightarrow$ QCD describes data !

access to parton correlations: “skewed pdf’s”

$\rightarrow$ new forward proton tagger, $e^{\pm}_{L,R}$

DIS cross section

Neutral Current

$$\frac{\mathrm{d}^2\sigma^{e^{\pm}p}_{NC}}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2(x,Q^2) \mp Y_- x\tilde{F}_3(x,Q^2) - y^2\tilde{F}_L(x,Q^2)\right]$$

$$Y_\pm \equiv 1 \pm (1-y)^2$$

$$\tilde{F}_2 \equiv F_2 - v_e\,\frac{\kappa_w Q^2}{(Q^2+M_Z^2)}\,F_2^{\gamma Z} + (v_e^2+a_e^2)\left(\frac{\kappa_w Q^2}{Q^2+M_Z^2}\right)^2 F_2^Z = x\sum A_i(q_i+\bar{q}_i)$$

$$x\tilde{F}_3 \equiv -a_e\,\frac{\kappa_w Q^2}{(Q^2+M_Z^2)}\,xF_3^{\gamma Z} + (2v_e a_e)\left(\frac{\kappa_w Q^2}{Q^2+M_Z^2}\right)^2 xF_3^Z = x\sum B_i(q_i-\bar{q}_i)$$

v_e, a_e - *vector and axial couplings,* $\quad \kappa_w^{-1} = 4\frac{M_W^2}{M_Z^2}(1-\frac{M_W^2}{M_Z^2})$

Charged Current

$$\frac{\mathrm{d}^2\sigma^{\pm}_{\mathrm{CC}}}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{G_F^2 M_W^4}{2\pi x}\frac{1}{(Q^2+M_W^2)^2}\,\phi^{\pm}_{\mathrm{CC}}(x,Q^2)$$

$$\phi^{+}_{\mathrm{CC}} = x\left[(\bar{u}+\bar{c}) + (1-y)^2(d+s)\right] \qquad (in\ \mathrm{LO})$$

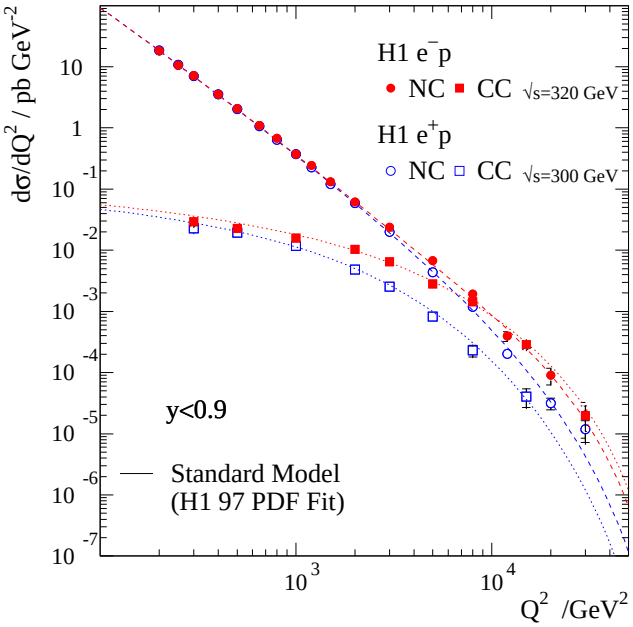
$$\phi^{-}_{\mathrm{CC}} = x\left[(u+c) + (1-y)^2(\bar{d}+\bar{s})\right]$$

Reduced NC and CC cross sections

$$\tilde{\sigma}_{NC}(x,Q^2) \equiv \frac{1}{Y_+}\,\frac{Q^4\,x}{2\pi\alpha^2}\,\frac{\mathrm{d}^2\sigma_{NC}}{\mathrm{d}x\mathrm{d}Q^2} = F_2(1+\Delta_{F_2}+\Delta_{F_3}+\Delta_{F_L})$$

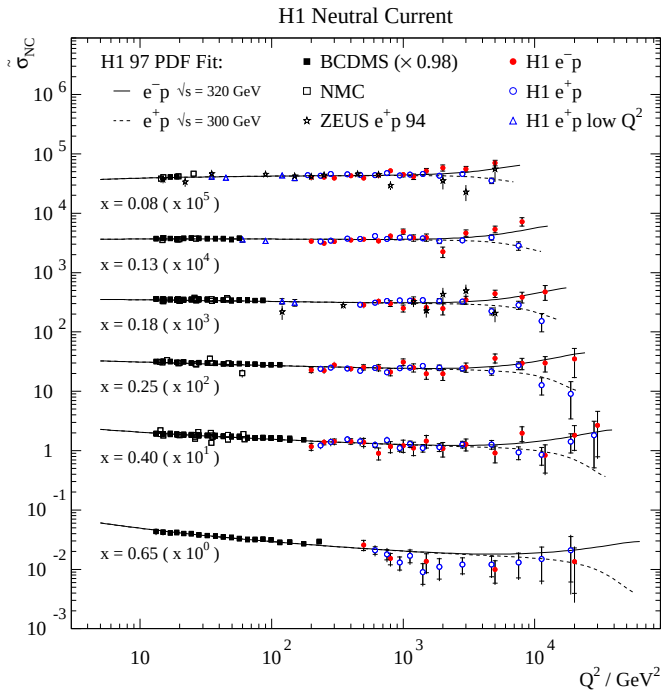
$$\tilde{\sigma}_{CC}(x,Q^2) \equiv \frac{2\pi x}{G_F^2}\left(\frac{M_W^2+Q^2}{M_W^2}\right)^2\frac{\mathrm{d}^2\sigma_{CC}}{\mathrm{d}x\mathrm{d}Q^2}$$

High Q^2 and Weak Interaction



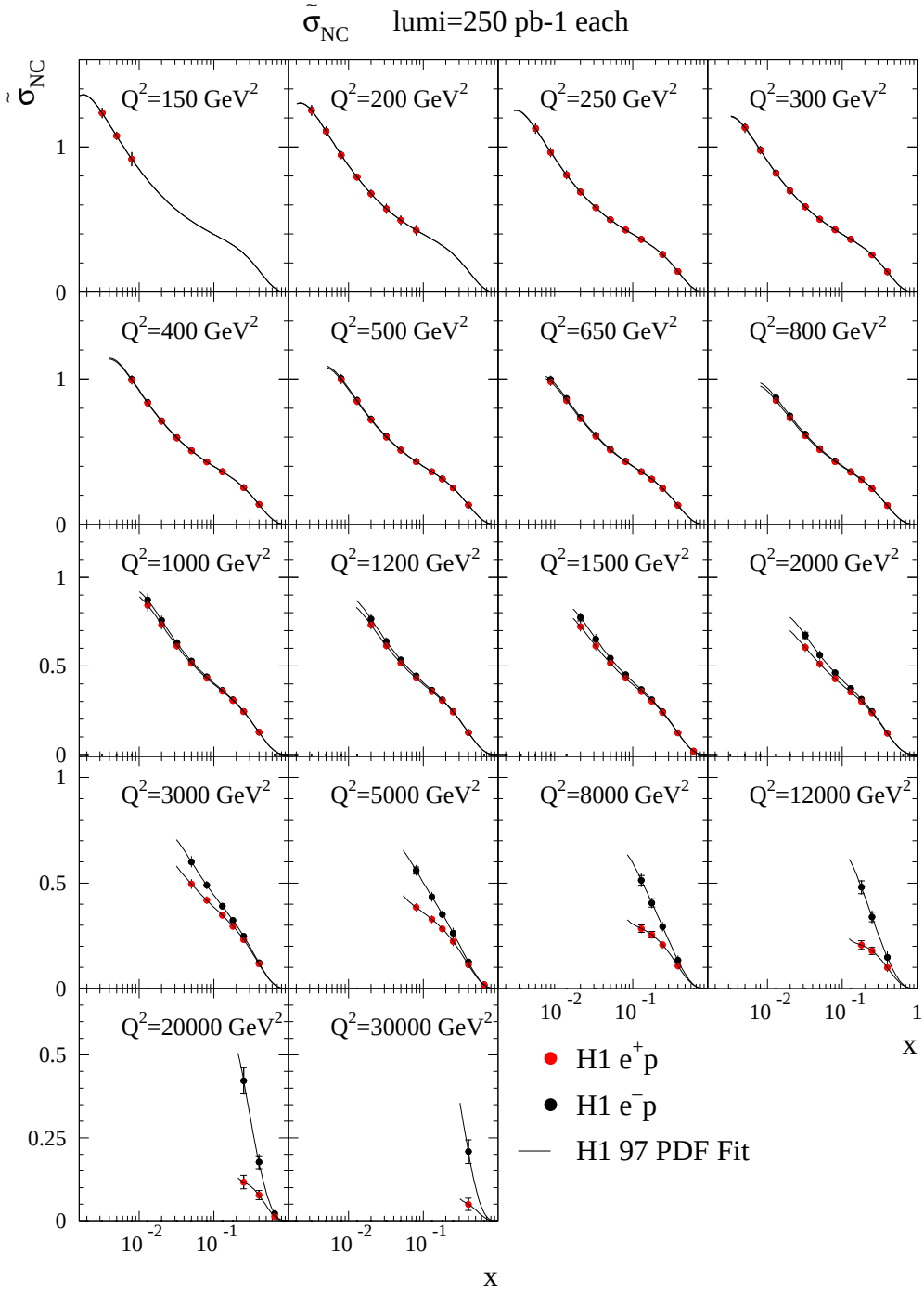
$\gamma/Z \approx W$

Unification



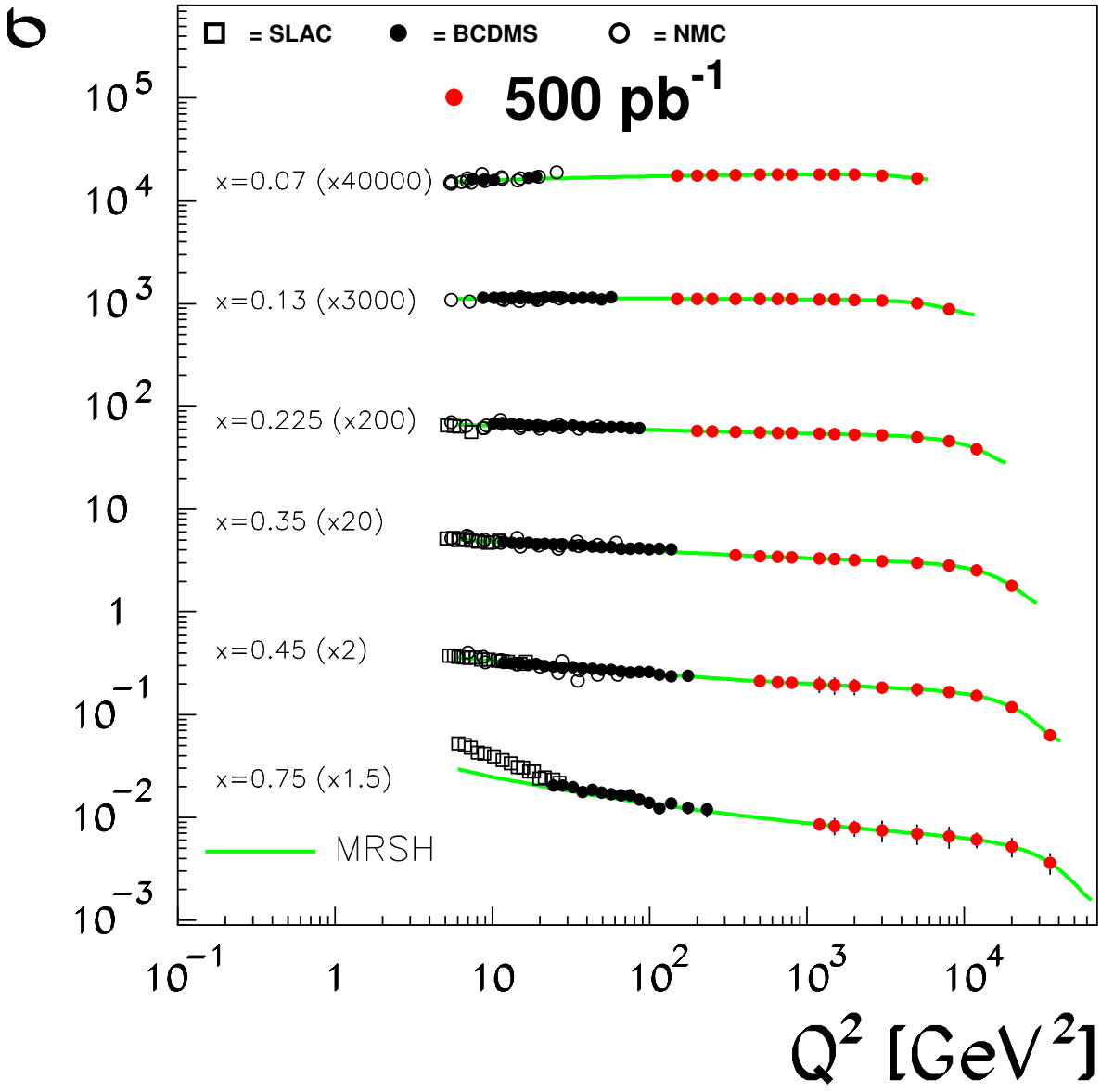
needs more data at large x, Q^2 !

Cross sections at high Q^2



γ/Z: mainly u- quarks

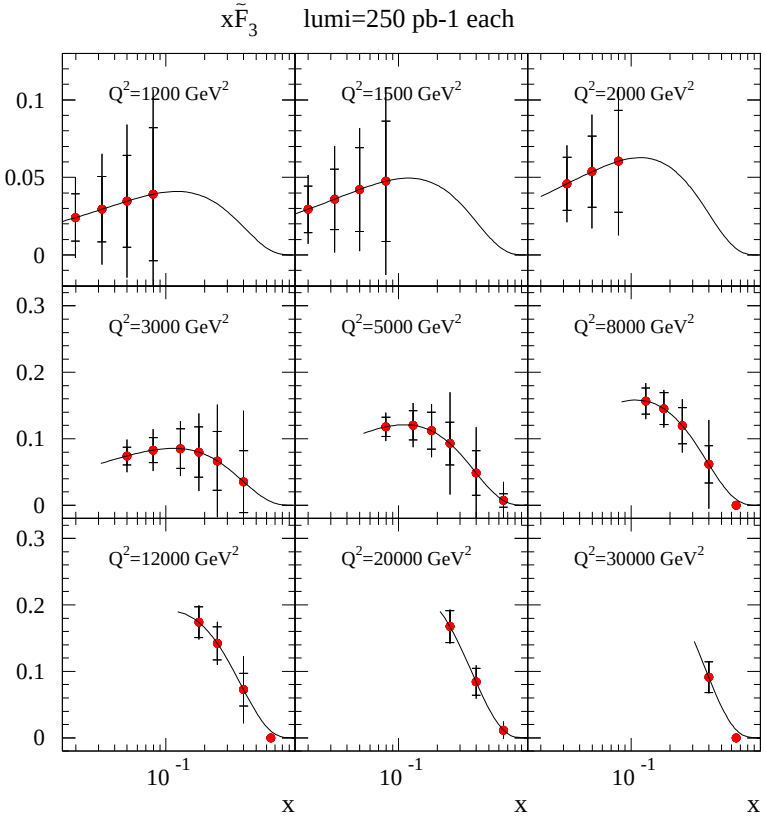
Cross sections at high Q^2



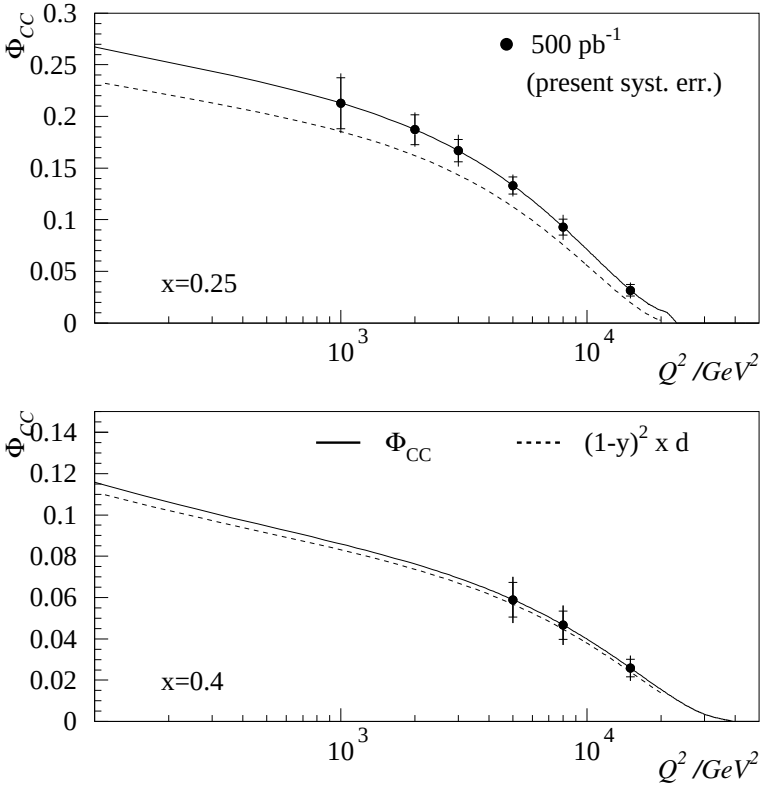
γ/Z: mainly u- quarks

Cross sections at high Q^2

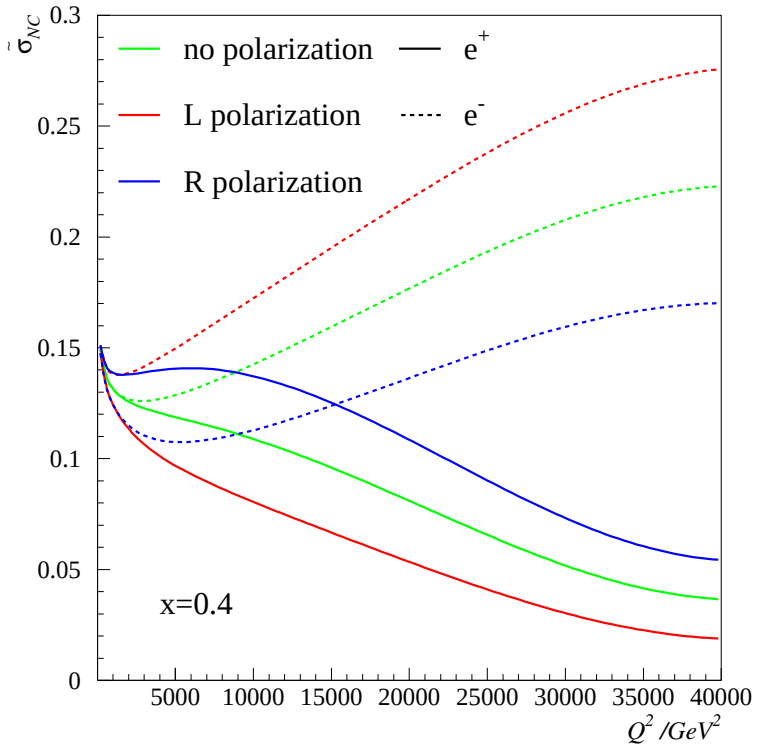
xF_3: Valence quarks



W-exchange: mainly d- quarks: $\pm$ 10%



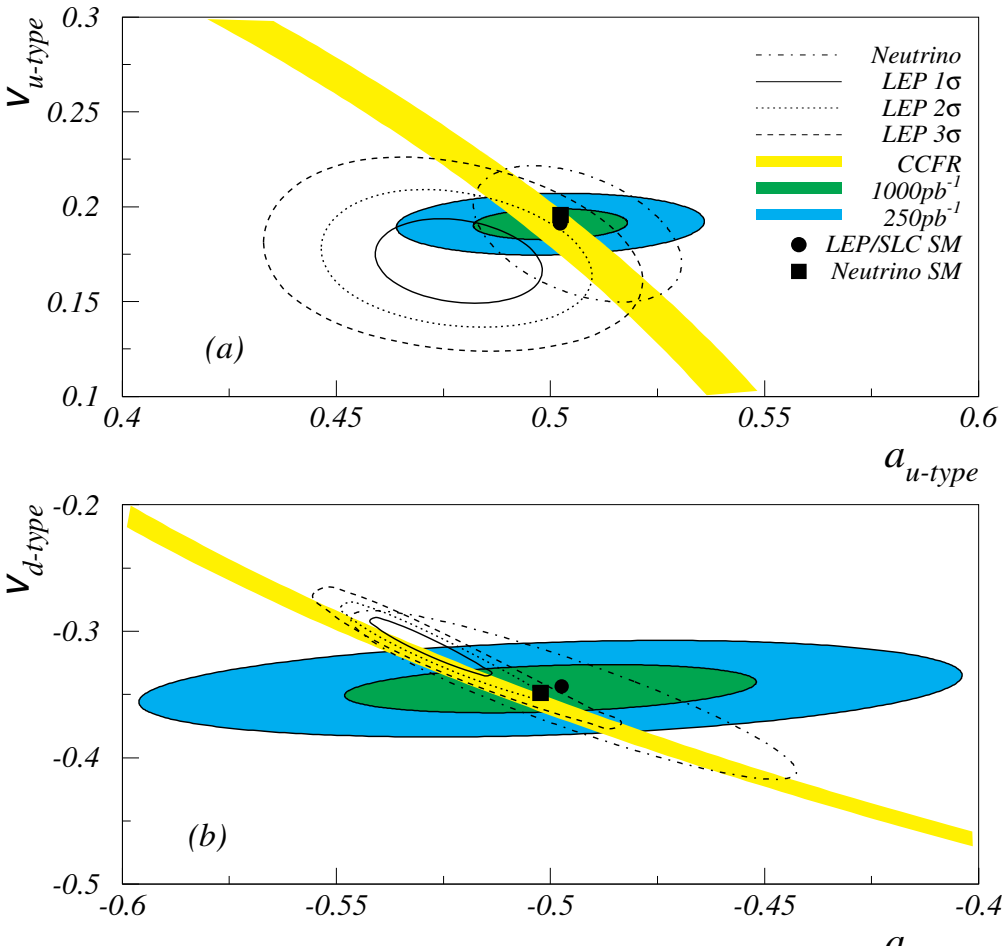
Polarized NC Cross Sections



γZ interference

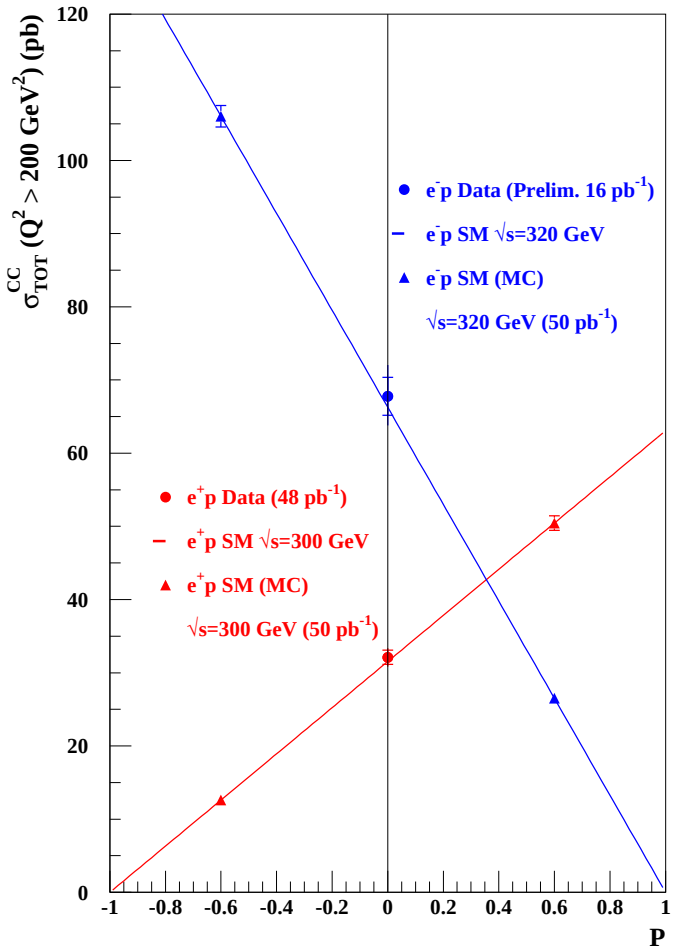
- $\gamma^2 \approx \gamma Z \approx Z^2$ for
  $\frac{\kappa Q^2}{Q^2+M_Z^2} = 1$
  $\rightarrow Q^2 \approx 2M_Z^2 \approx 16000$ GeV^2
- positive / negative interference for
  e^-p/ e^+p
- 10% effect at high Q^2

Weak couplings of light quarks



- needs measurement of $e_L^+, e_L^-, e_R^+, e_R^-$
- only light quarks from proton
- similar precision as from LEP

Right handed weak currents: W_R

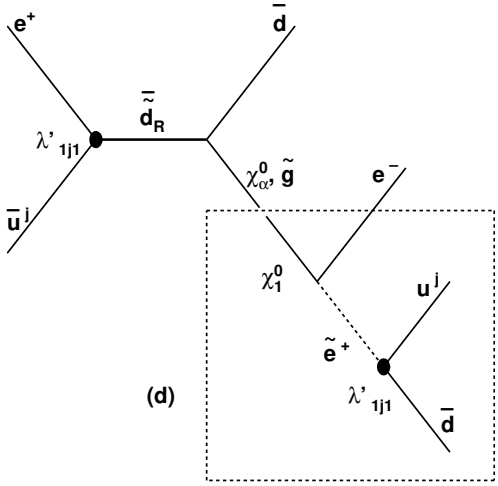


Polarized charged currents

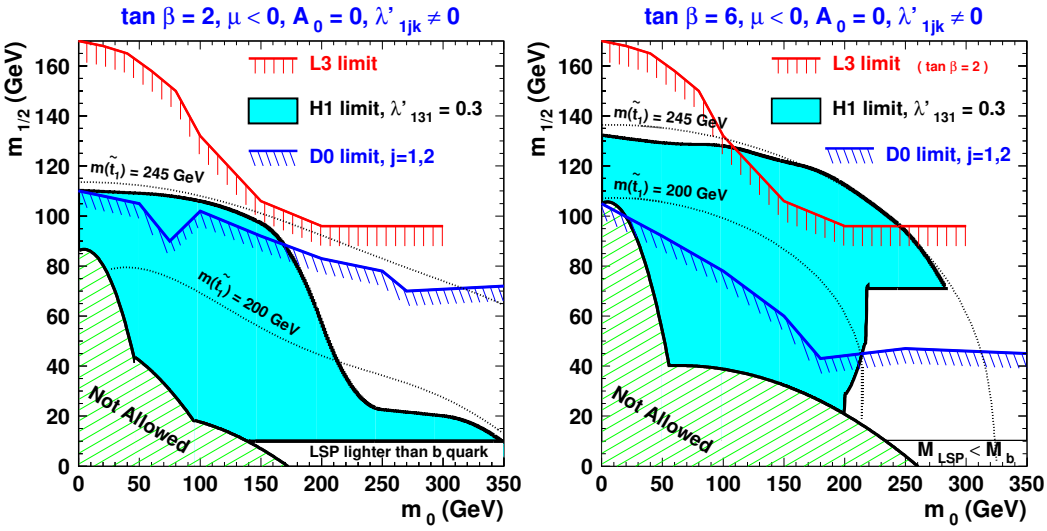
- $\sigma_{CC}(e^{\pm}_P) = (1 \pm P)\, \sigma_{CC}(e^{\pm}_{P=0})$
- needs high polarisation
- needs high precision of polarisation
- $M_{W_R} \lesssim 600$ GeV
- similar to direct search at Tevatron

Beyond the Standard Model: Supersymmetrie

single production of squarks in R-parity violating models



Minimal Supergravity + R_p Violation



- nothing found yet up to $M_{\tilde{q}}$ =245 GeV
- will reach sensitivity of $M_{\tilde{q}} \approx$ 300 GeV

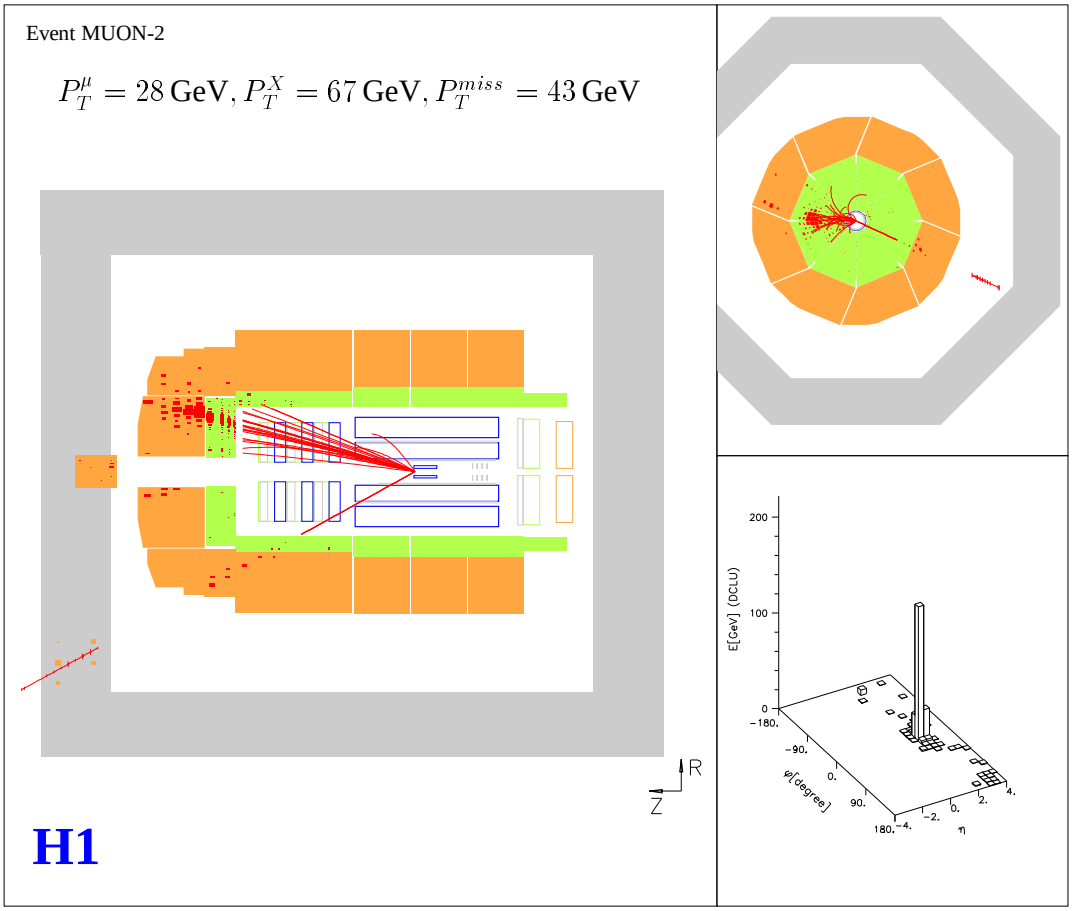
Summary

What did / will we learn from HERA ?

- low-x: new regime of QCD
  the main theoretical activity so far
  QCD picture of Diffraction
  colour dipole $-$ BFKL ??
- precision QCD:
  world best value of α_s
  Final (?) word on proton structure at HIGH and LOW x
- high Q^2: only just started
  luminosity upgrade
  precision test of SM at 10^{-18} m
- searches:
  high P_T lepton events ?
  Supersymmetry with R_P violation
  contact interactions
  + ??

The unexpected

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



No explanation up to now !

Anomalous W production, $e \to \mu$, supersymmetry ?

To be verified at HERA II