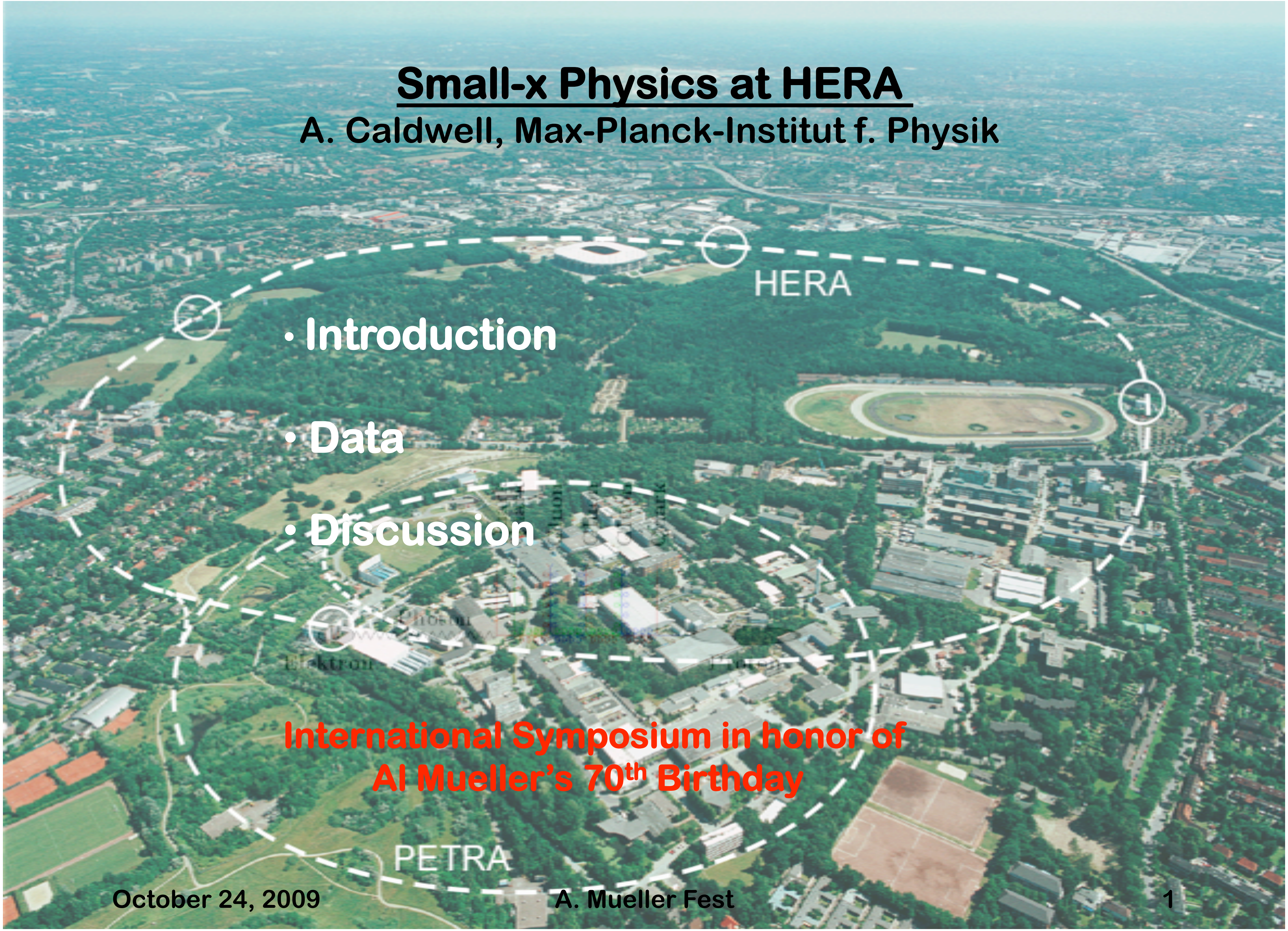
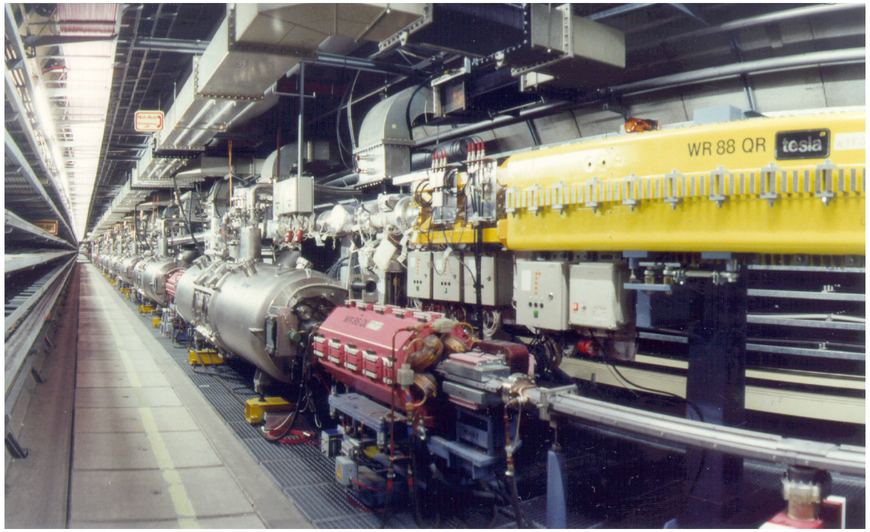
Small-x Physics at HERA

A. Caldwell, Max-Planck-Institut f. Physik



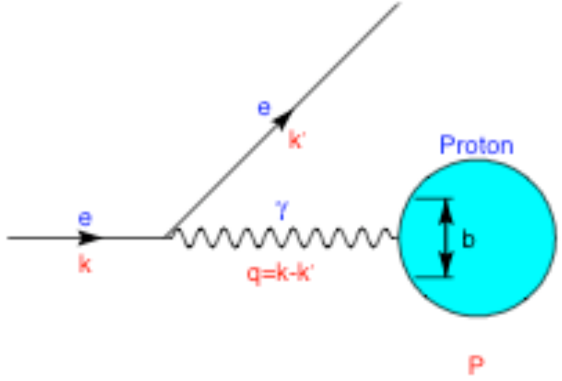
- Introduction
- Data
- Discussion

International Symposium in honor of Al Mueller's 70th Birthday



HERA: a 6.3km circumference accelerator of electrons and protons. Two experiments observed the collisions (H1, ZEUS) + two fixed target experiments (HERMES - eN, HERA-B - pN). Ended running 31/6/07.

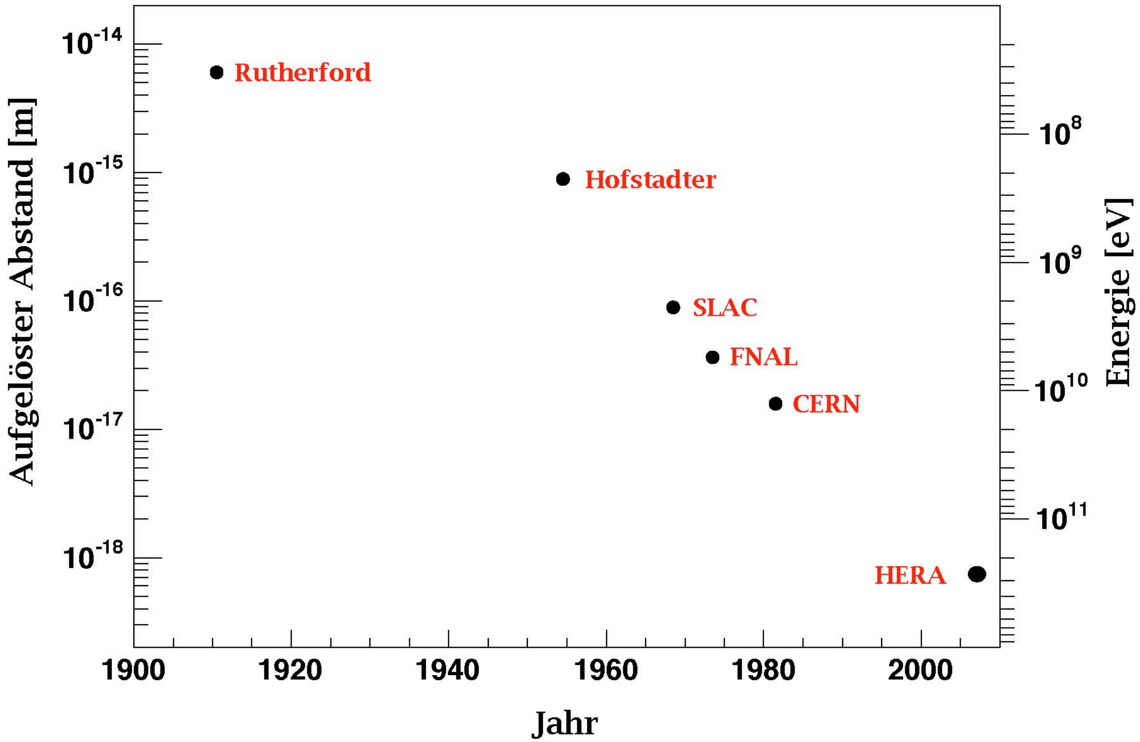
HERA Kinematics



E_e=27.5 GeV
E_P=920 GeV
s=(k+P)^2 = (320 GeV)^2

Transverse distance scale:

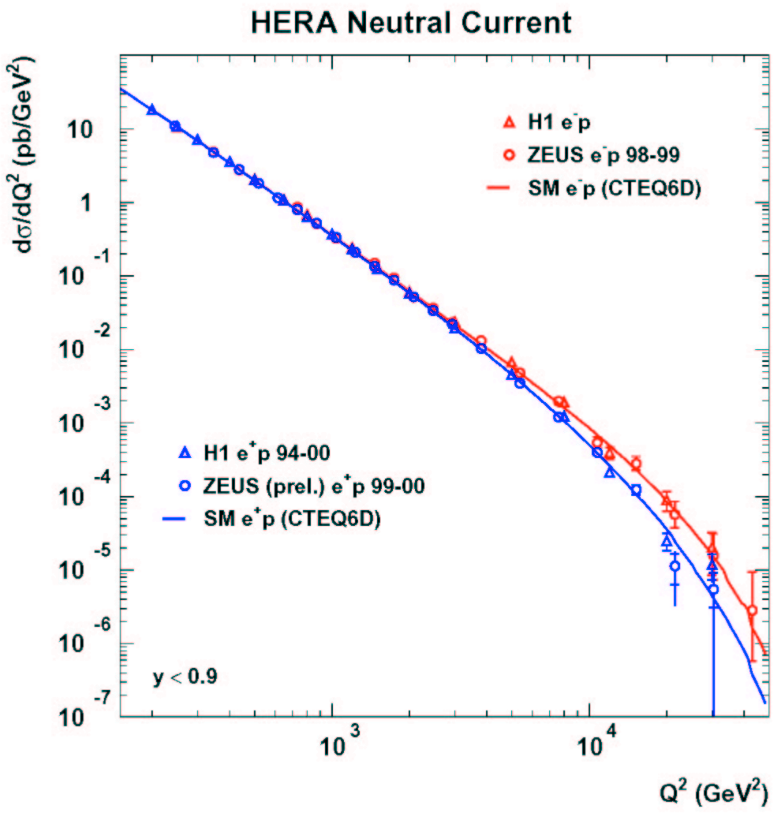
$$b \approx \frac{\hbar c}{Q} = \frac{0.2\ \text{fm}}{Q(GeV)}$$



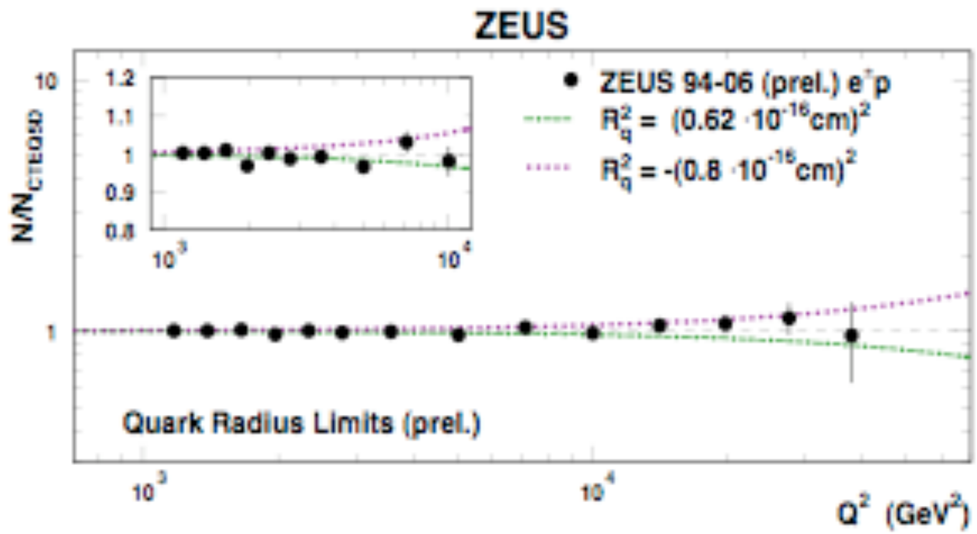
Is there substructure to quarks ?

Assuming $R^2Q^2 << 1$

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2}\left(1 - \frac{R^2{}_e}{6}Q^2\right)^2\left(1 - \frac{R^2{}_q}{6}Q^2\right)$$



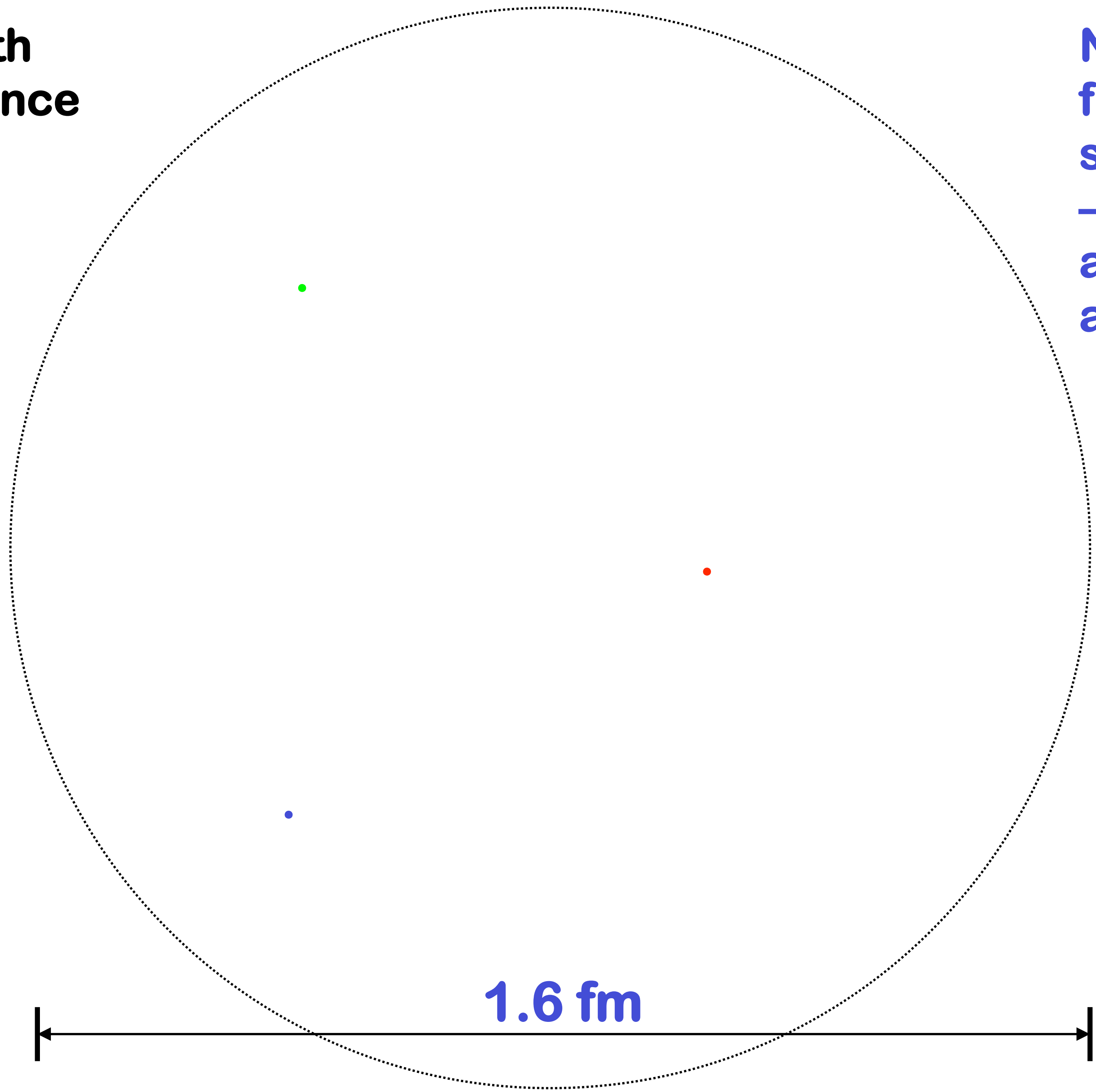
ZEUS 1994-2006:



$R_q < 0.62 \cdot 10^{-16}$ cm

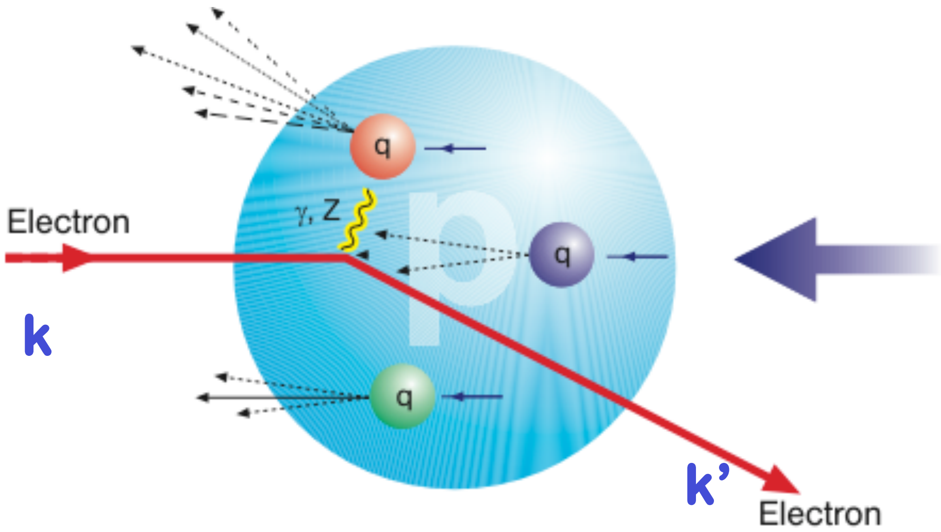
‘point-like’

Proton with three valence quarks



No sign of further substructure – quarks are as point-like as electrons

Structure Functions



$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[(1+(1-y)^2)F_2 - y^2F_L \pm xF_3\right]$$

'structure functions'

What we measure

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

$$0 \le x \le 1$$ Parton momentum

$$0 \le y \le 1$$ Inelasticity

New Results in Deep Inelastic Scattering from the ZEUS Collaboration

presented by A. Caldwell, 18/5/93

I. Introduction

II. Some experimental aspects

III. Measurement of $F_2(x, Q^2)$ ⬅

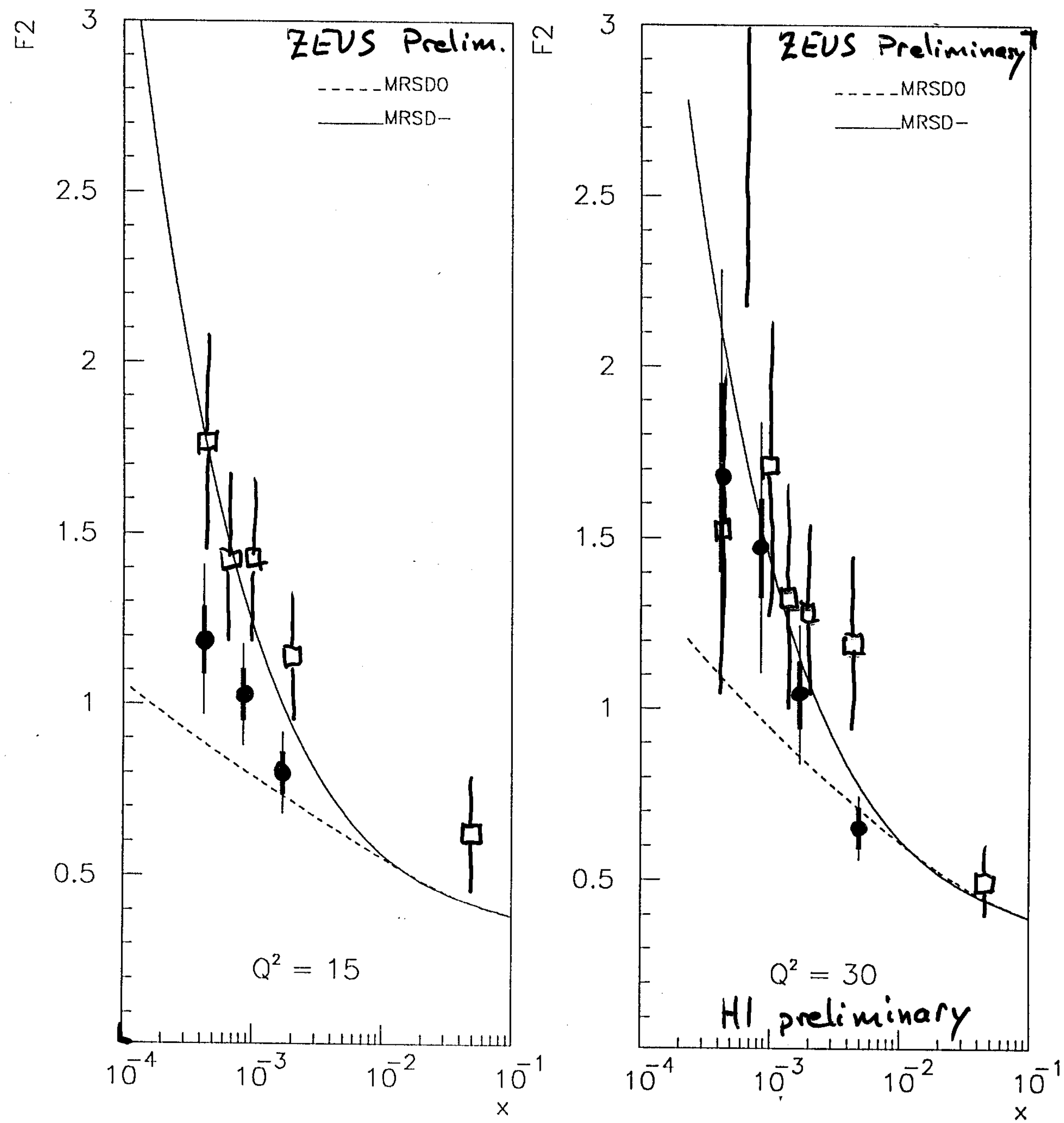
IV. Hadronic energy flow

V. A new class of events ⬅

<$30 nb^{-1}$

H1

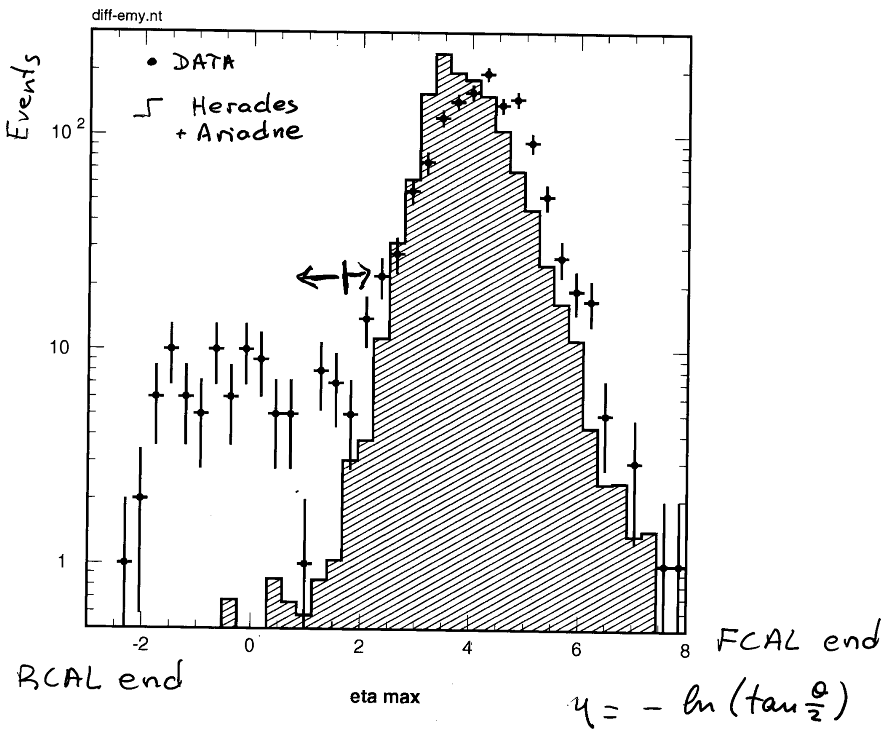
ZEUS



The search for BFKL was on !

Observation of large rapidity gap events: diffraction at large Q^2

Distribution of η for the calorimeter cluster closest to the proton direction.



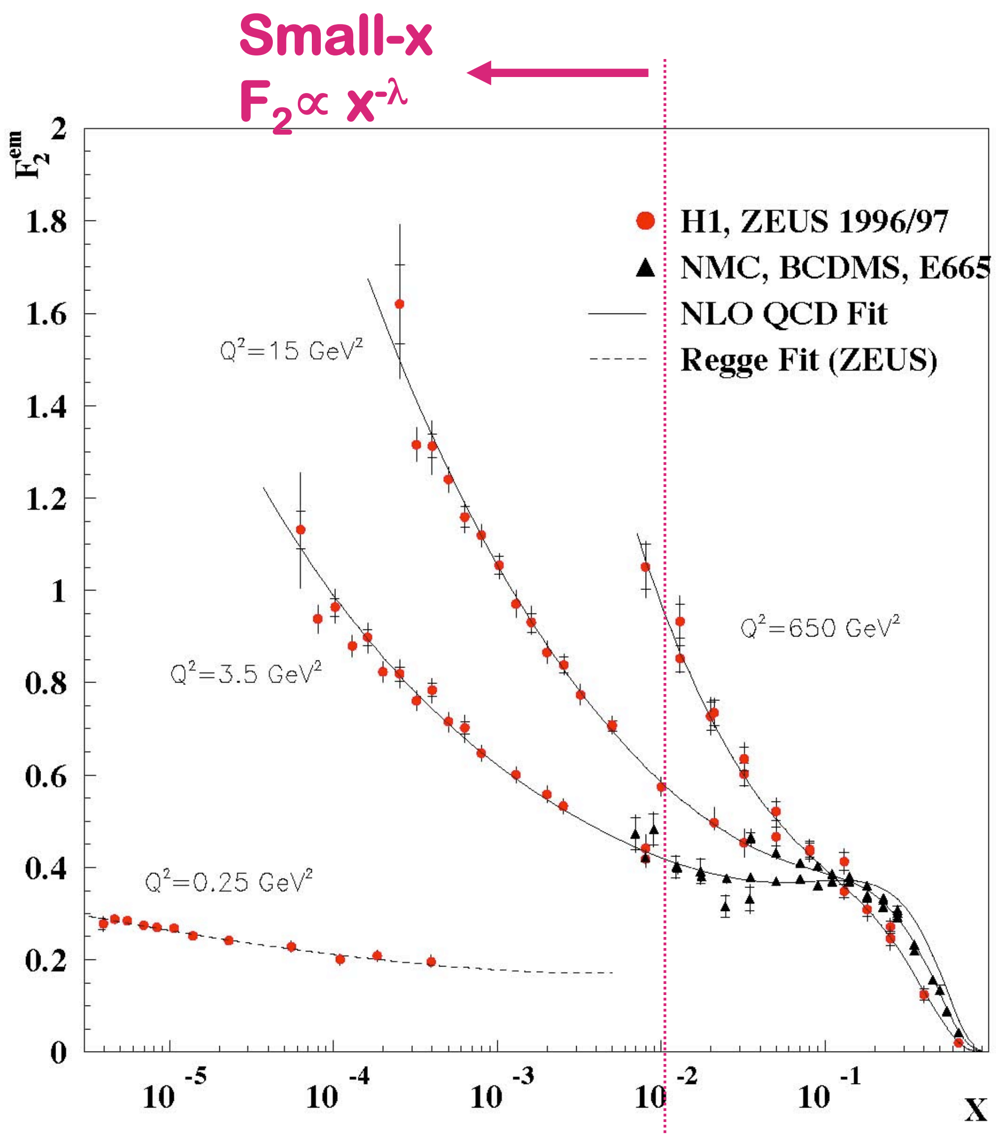
$\eta = -\ln(\tan\frac{\theta}{2})$

Separate the data into two classes

$\eta_{MAX} < 1.8$ cluster more than 18° from p direction

$\eta_{MAX} > 1.8$

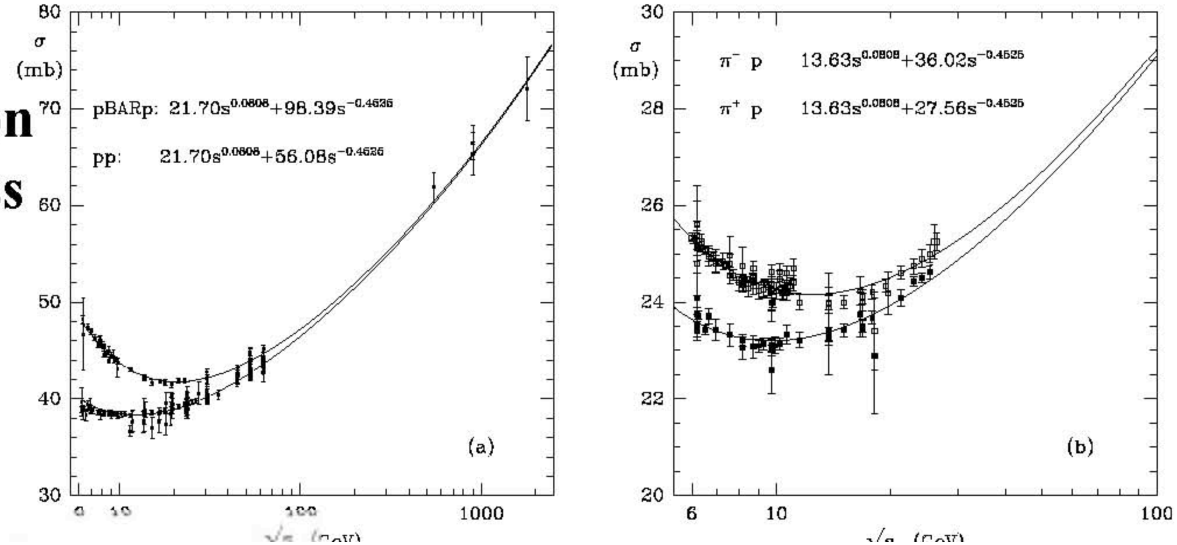
The rise of F_2 with decreasing x is strongly dependent on Q^2. Large density of quarks and antiquarks, and gluons since they are the source of the quarks and antiquarks.



Small fraction of HERA data

Hadron-Hadron Cross Section

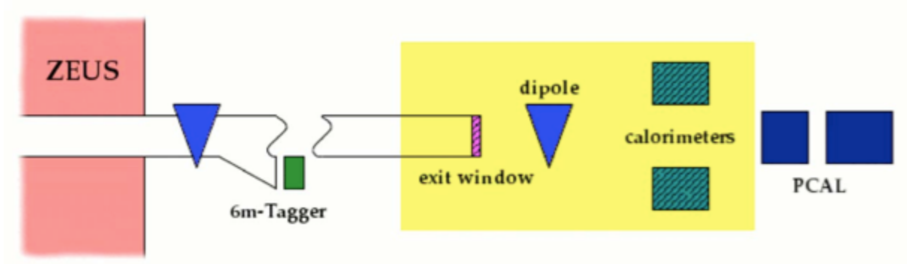
Hadron-hadron scattering cross section versus CM energy



$\sigma \propto s^{0.08}$

HERA: total photoproduction cross section

$$s_{\gamma P} = W^2 \approx \frac{Q^2}{x}$$



$\sigma \propto (W^2)^{\varepsilon}$

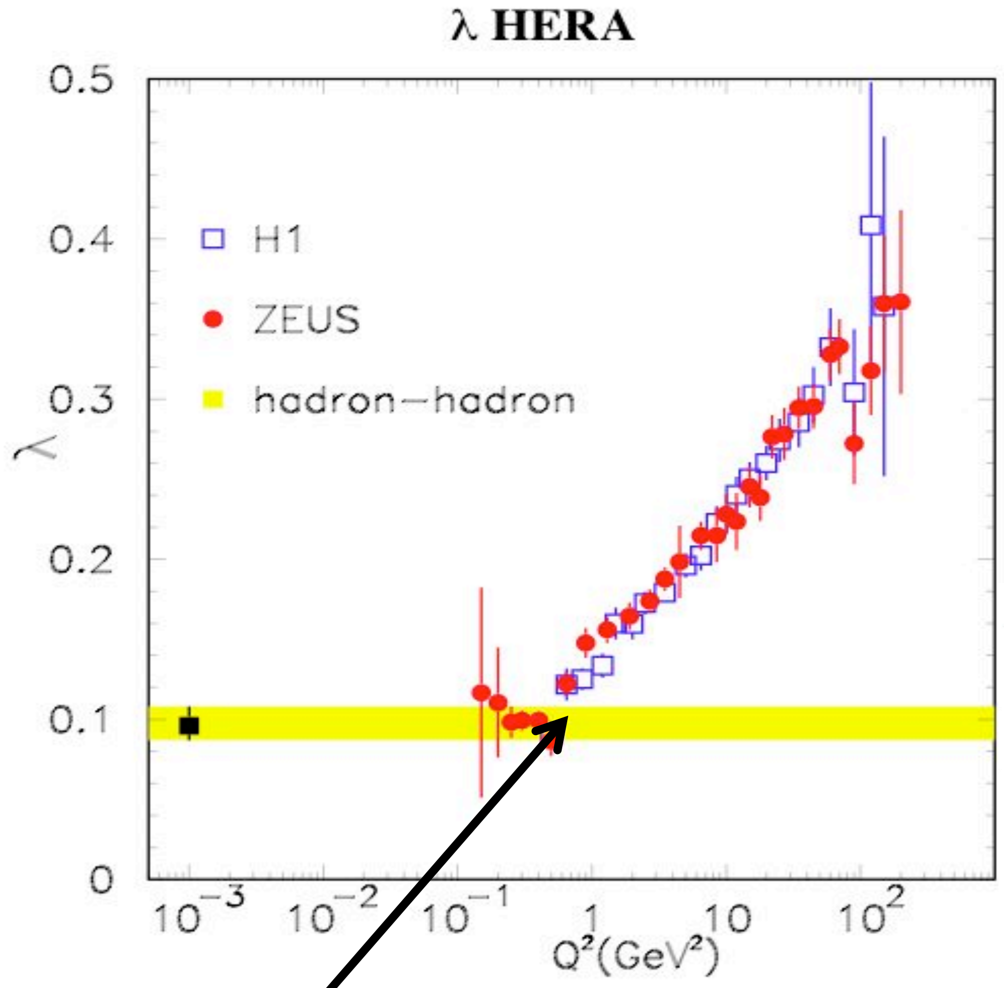
$$\varepsilon = 0.070 \pm 0.007(\text{stat.}) \pm 0.021(\text{syst.}) \pm 0.050(\text{6mT})$$

ZEUS prel.

The rise at small x

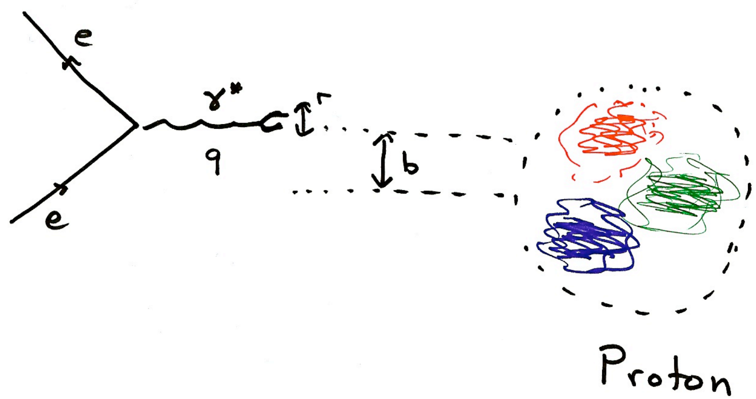
Parametrize:

$$F_2 = C(Q^2)x^{-\lambda} \qquad x < 0.01$$



Below $Q^2 \approx 0.5$ GeV^2, see same x (energy) dependence as observed in hadron-hadron scattering

$$r \sim \frac{\hbar c}{Q}$$



Transition region

Q=1 GeV corresponds to about 0.2 fm

Electron scattered at very small angle

What can we learn from the Caldwell plot? *

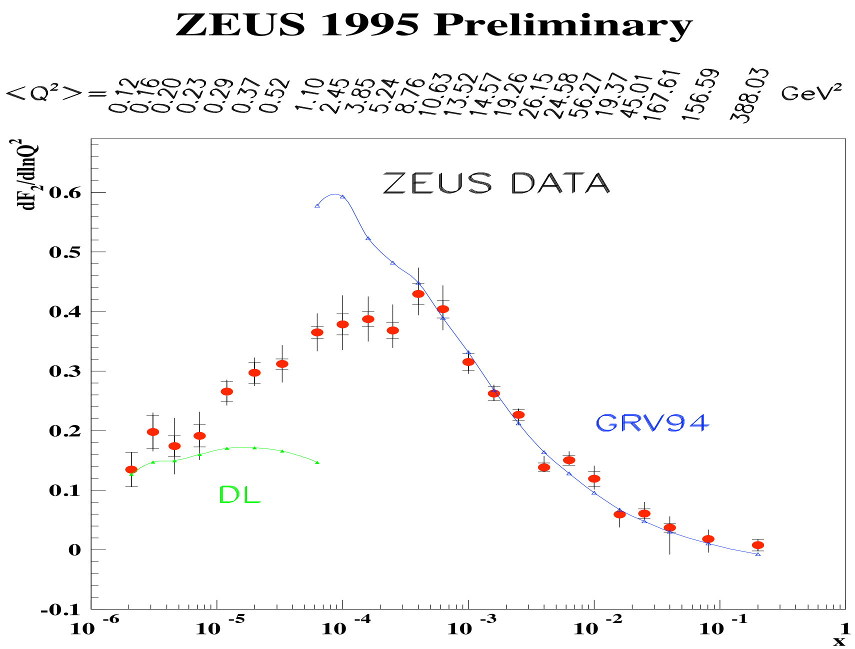
E. Gotsman [a]

[a] School of Physics and Astronomy, Tel Aviv University, Ramat Aviv, 69978, Israel

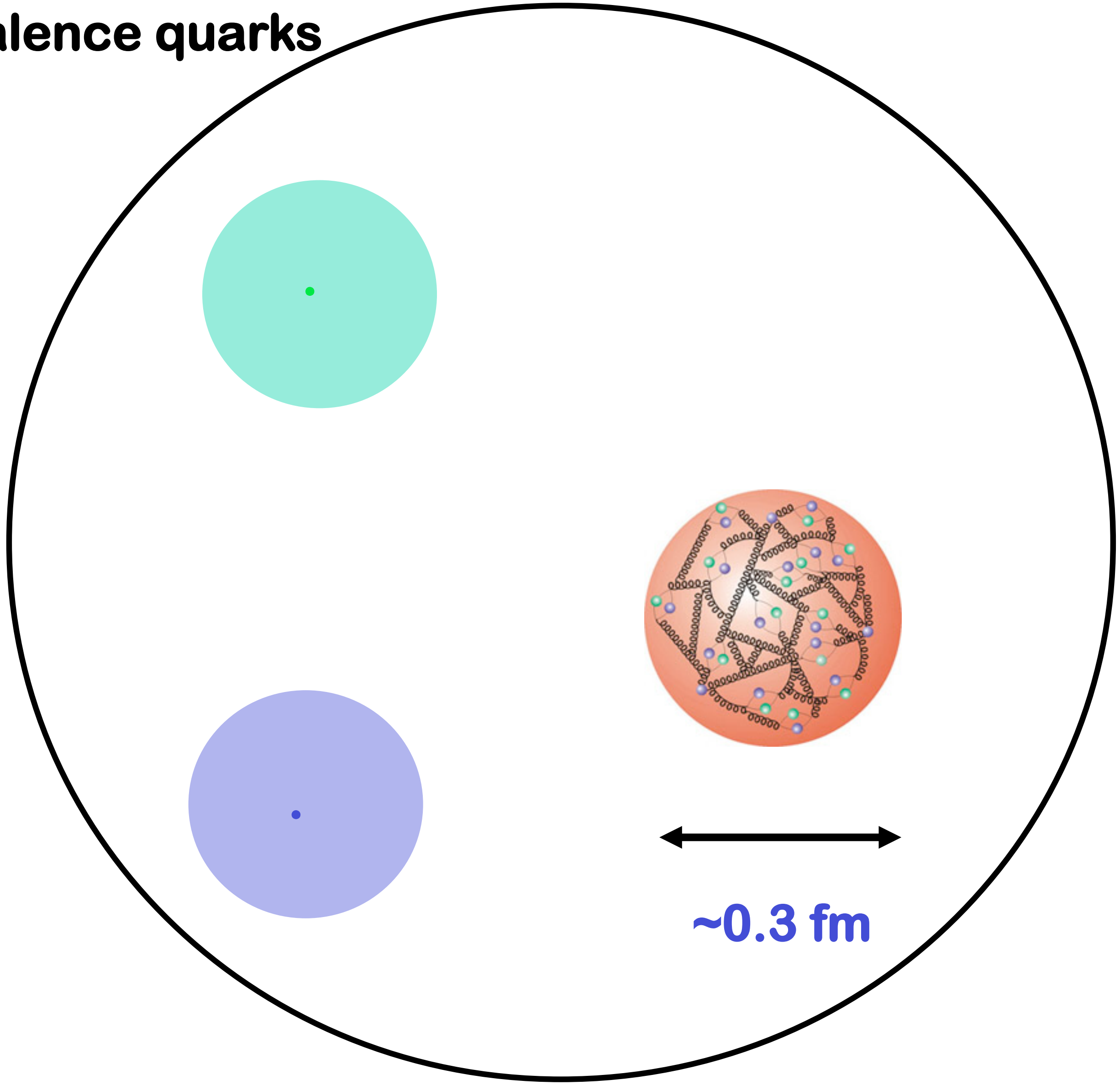
We show that when screening corrections are included $\frac{\partial F_2(x,Q^2)}{\partial ln(Q^2/Q_0^2)}$ is consistent with the behaviour that one expects in pQCD. Screening corrections explain the enigma of the Caldwell plot.

1. Introduction

The Caldwell plot [1] of $\frac{\partial F_2(x,Q^2)}{\partial ln(Q^2/Q_0^2)}$ presented at the Desy Workshop in November 1997 suprized the community. The results appeared to indicate that we have reached a region in the x and Q^2 where pQCD was no longer valid. DGLAP evolution lead us to expect that $\frac{\partial F_2(x,Q^2)}{\partial ln(Q^2/Q_0^2)}$ at fixed Q^2 would be a monotonic increasing function of $\frac{1}{x}$, whereas a superficial glance at the data suggests that the logarithmic derivative of F_2 deviates from the expected pQCD behaviour, and has a turnover in the region of $2 \leq Q^2 \leq 4$ GeV^2 (see fig.1 where the ZEUS data and the GRV'94 predictions are shown). Opinions were also voiced that the phenomena was connected with the tran-

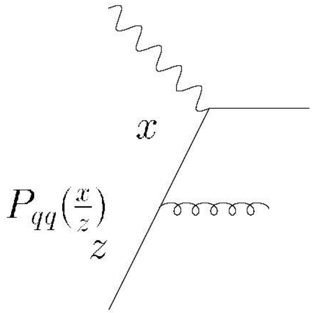


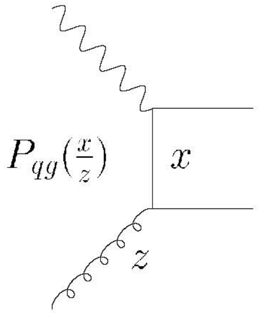
Proton with three 'dressed' valence quarks



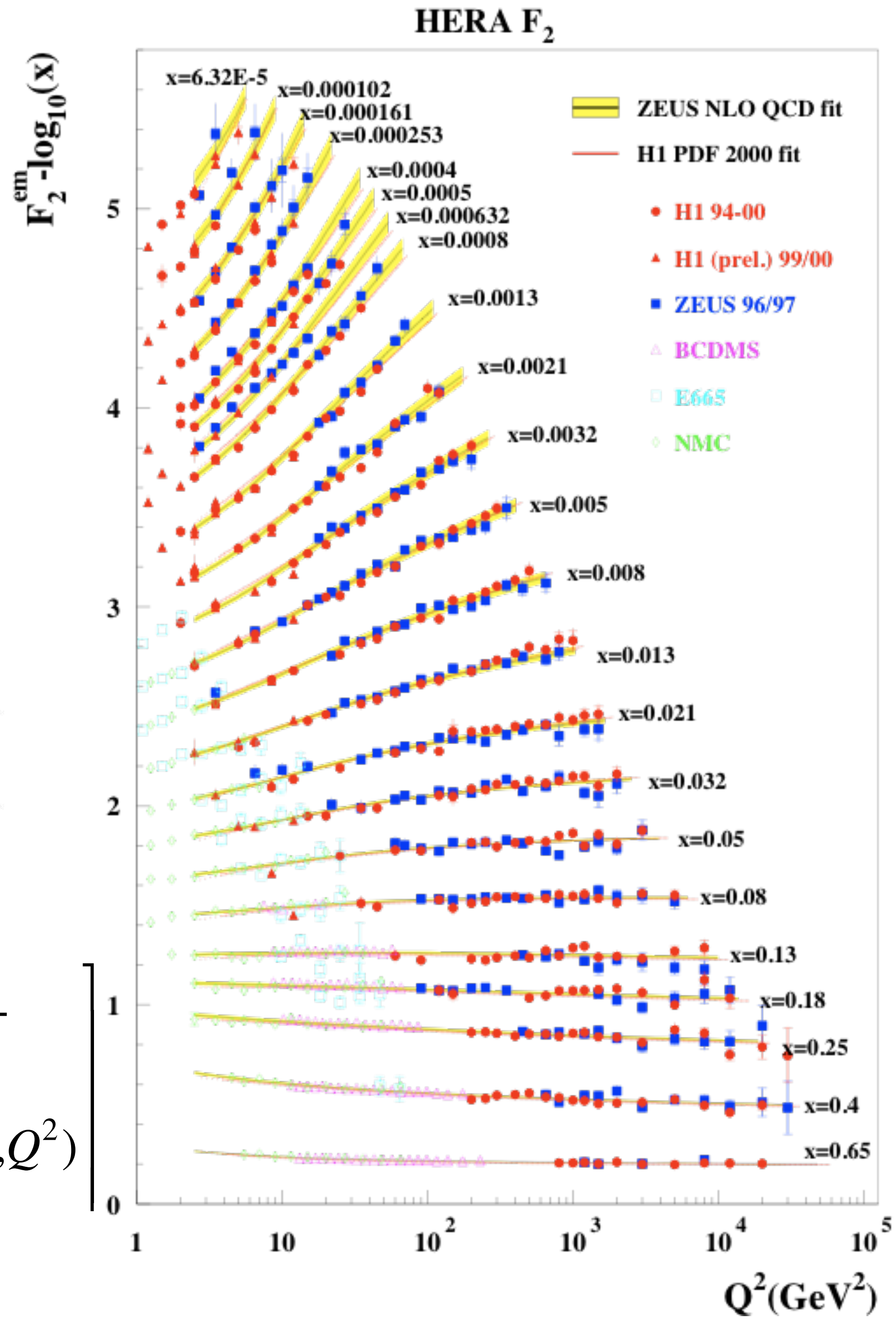
'Quark substructure' can be seen when we get resolution smaller than about 0.3 fm. With finer resolution, see that the three quarks are composed of many subconstituents.

The variation in F_2 with Q^2 (for Q^2> few GeV^2) is in excellent agreement with the expectations of standard perturbative QCD (famous Dokshitzer, Gribov, Lipatov, Altarelli, Parisi evolution equations).

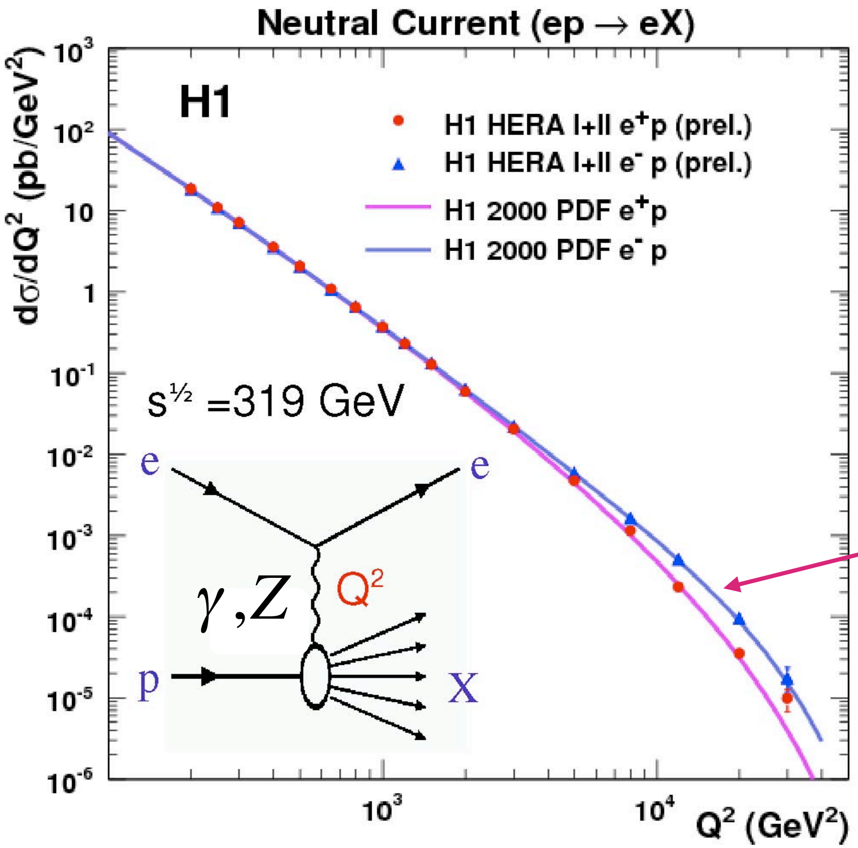




$$\frac{dF_2}{d\ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi}\left[\int_x^1 \frac{dz}{z}\left(\frac{x}{z}\right)P_{qq}\left(\frac{x}{z}\right)F_2(z,Q^2) + \int_x^1 2\sum_q e_q^2 \frac{dz}{z}\left(\frac{x}{z}\right)P_{qg}\left(\frac{x}{z}\right)zg(z,Q^2)\right]$$



Valence Quarks from xF_3

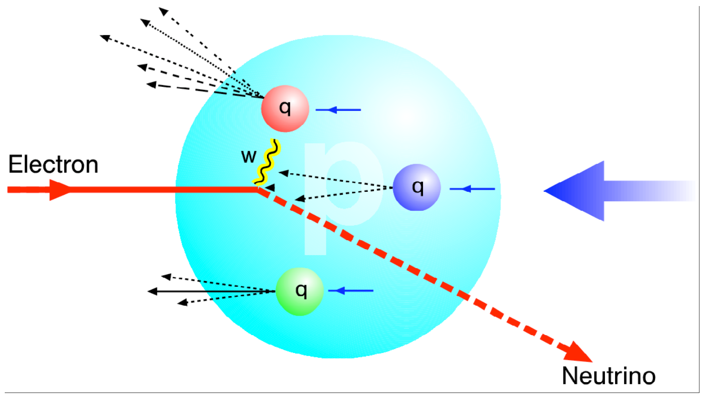


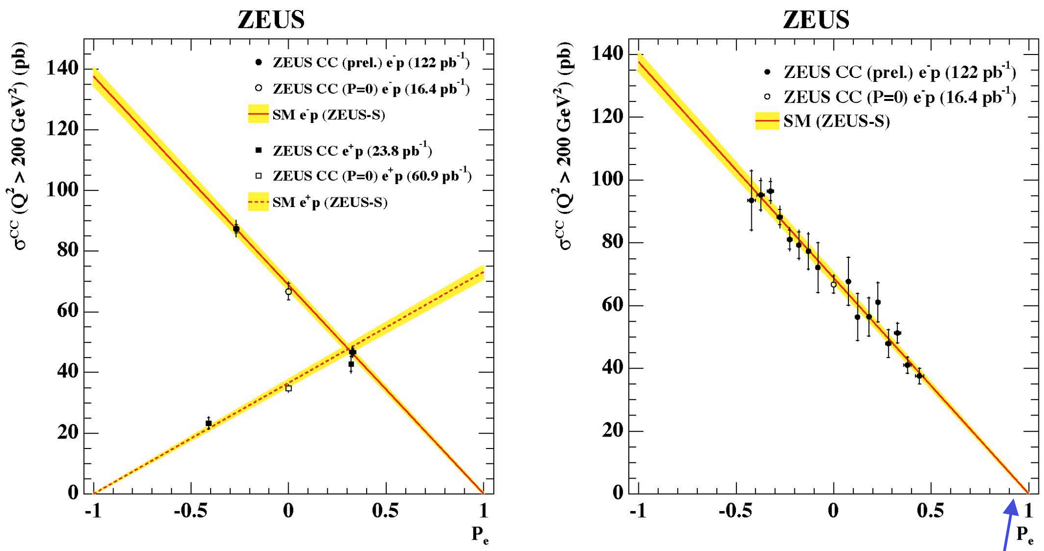
$$\frac{d^2\sigma(e^{\mp}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[(1+(1-y)^2)F_2 - y^2F_L \pm xF_3\right]$$

$$F_3 = \sum_q e_q^2 x\left\{q(x,Q^2) - \bar{q}(x,Q^2)\right\}$$

Note: information on valence quarks comes primarily from pre-HERA fixed target experiments.

Charged current cross sections





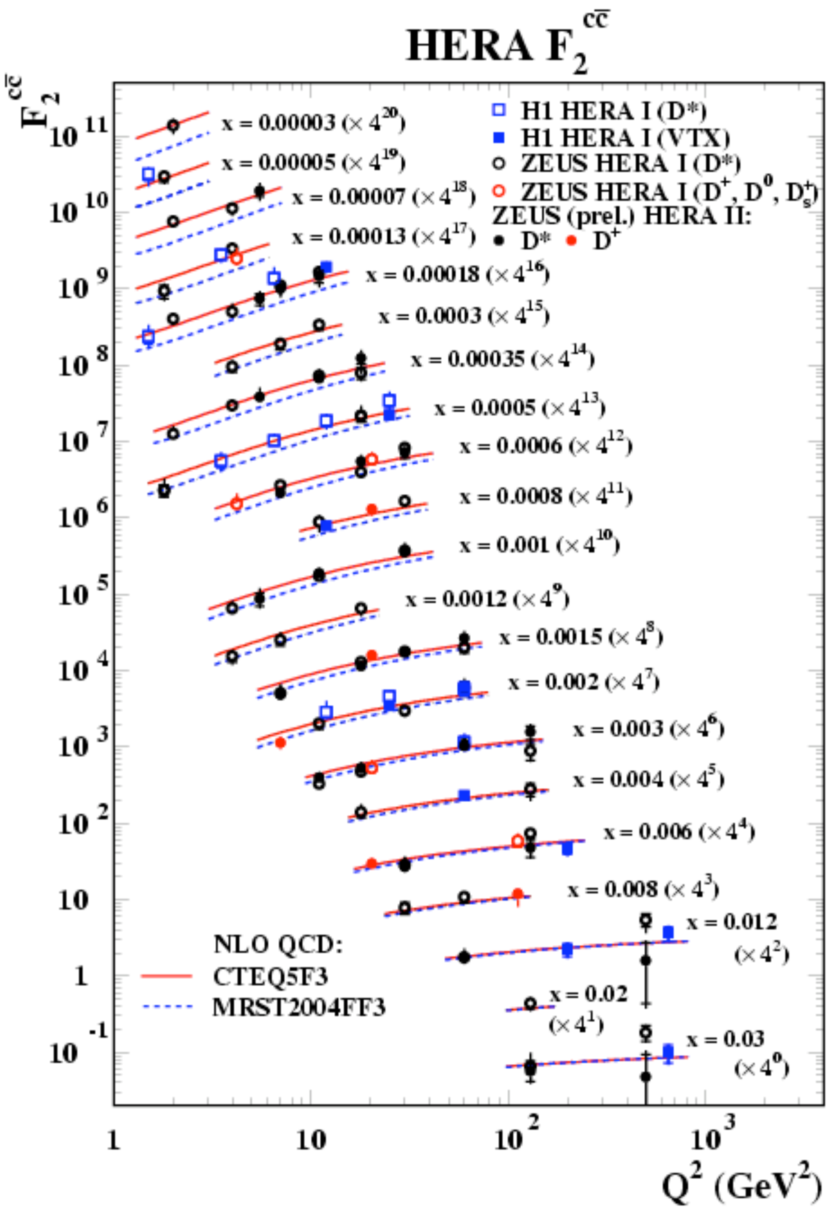
CC DIS cross section in QPM:

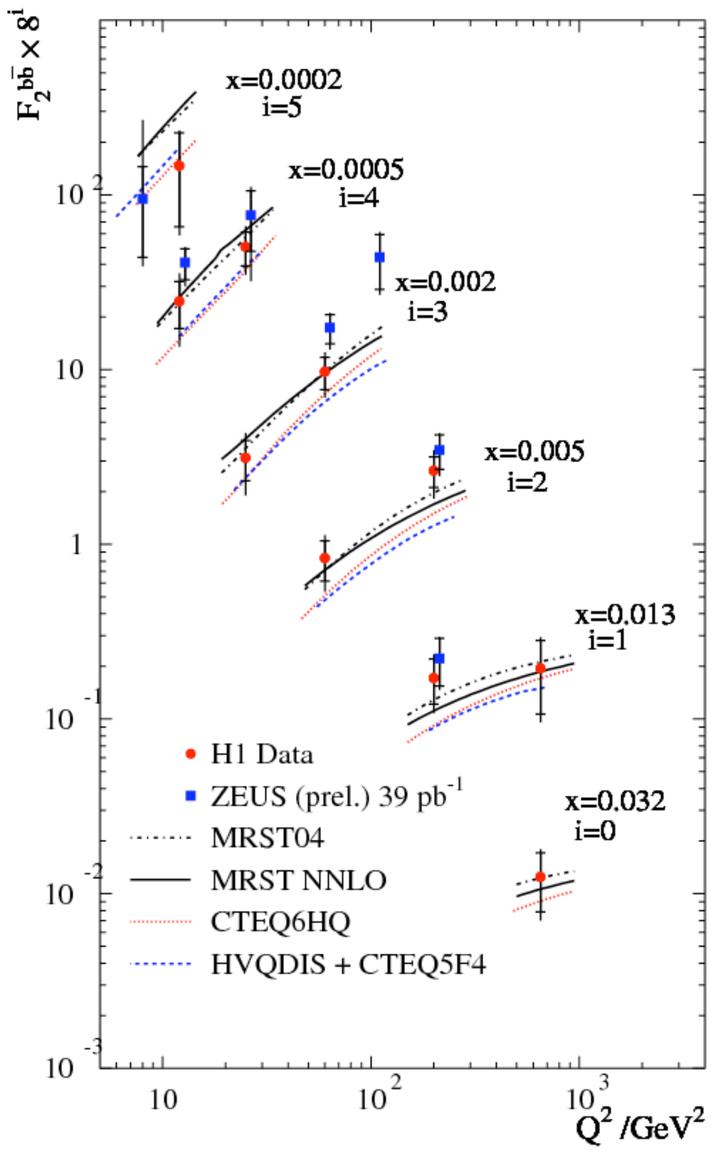
$$\frac{d^2\sigma_{CC}^{e^-p}}{dx\,dQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^4}{(M_W^2+Q^2)^2}\sum_{i=1}^{2}\left[u_i(x,Q^2)+(1-y)^2\bar{d}_i(x,Q^2)\right] \times (1-P_{e^-})$$

$$\frac{d^2\sigma_{CC}^{e^+p}}{dx\,dQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^4}{(M_W^2+Q^2)^2}\sum_{i=1}^{2}\left[\bar{u}_i(x,Q^2)+(1-y)^2 d_i(x,Q^2)\right] \times (1+P_{e^+})$$

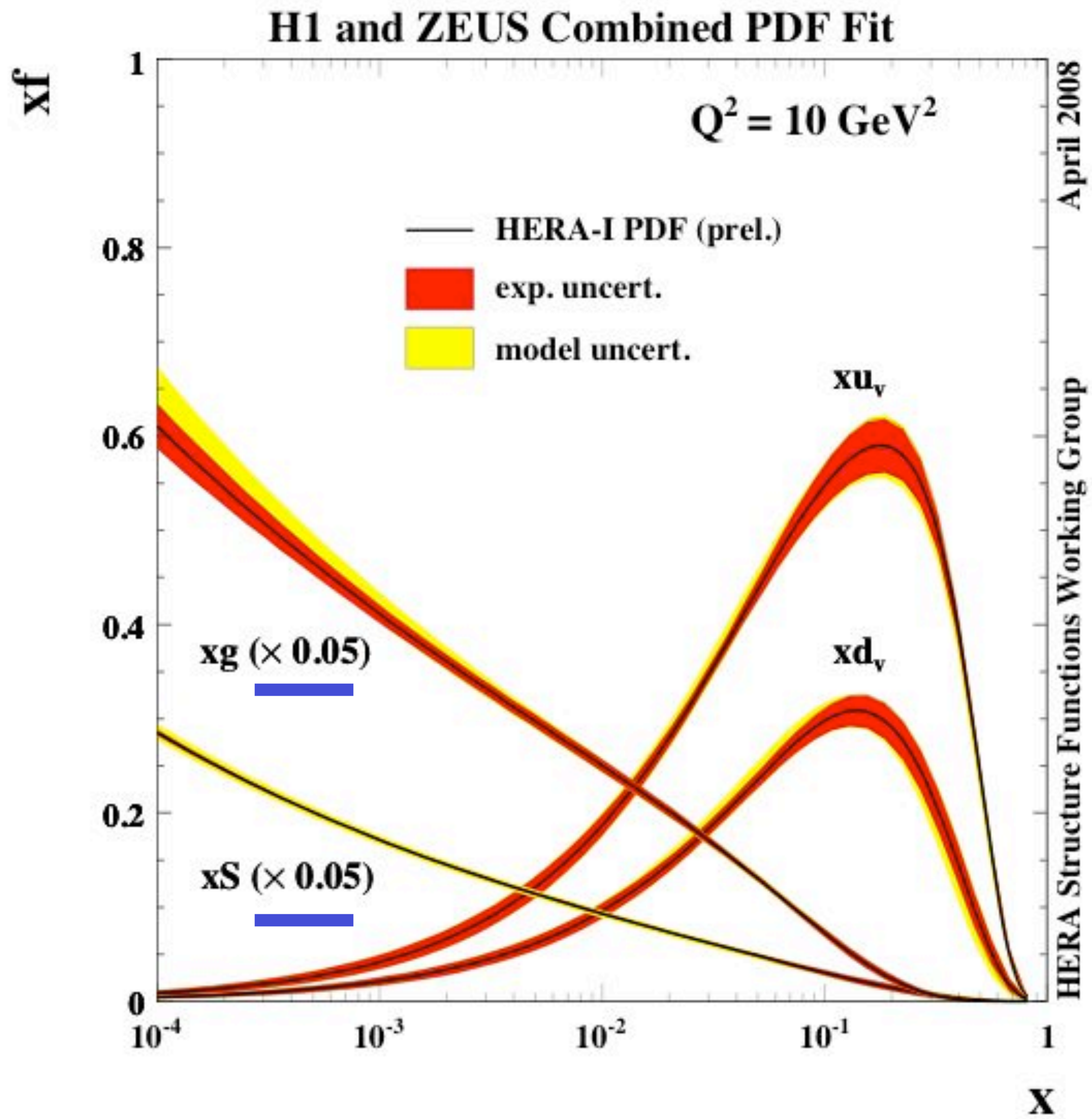
No sign of a W_R

Heavy Quarks





Analysis of cross sections in terms of parton densities (quarks and gluons)



F_L

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2(x,Q^2) - y^2F_L(x,Q^2)\right]$$

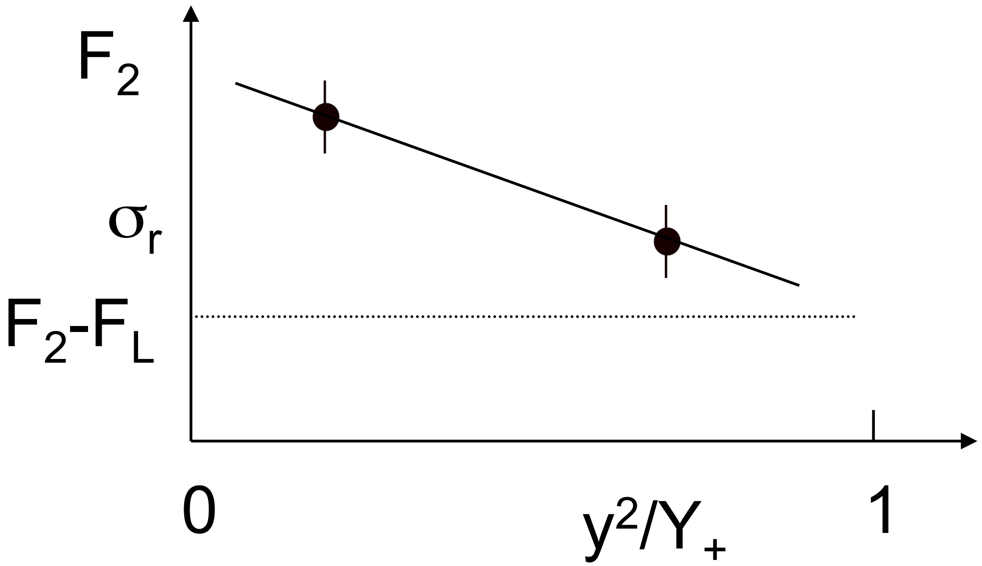
small Q^2

Need to measure differential cross section at two beam energies (at least).

$$F_L = \frac{\alpha_S}{4\pi}x^2\int_x^1\frac{dz}{z^3}\left[\frac{16}{3}F_2 + 8\sum e_q^2(1-x/z)zg\right]$$

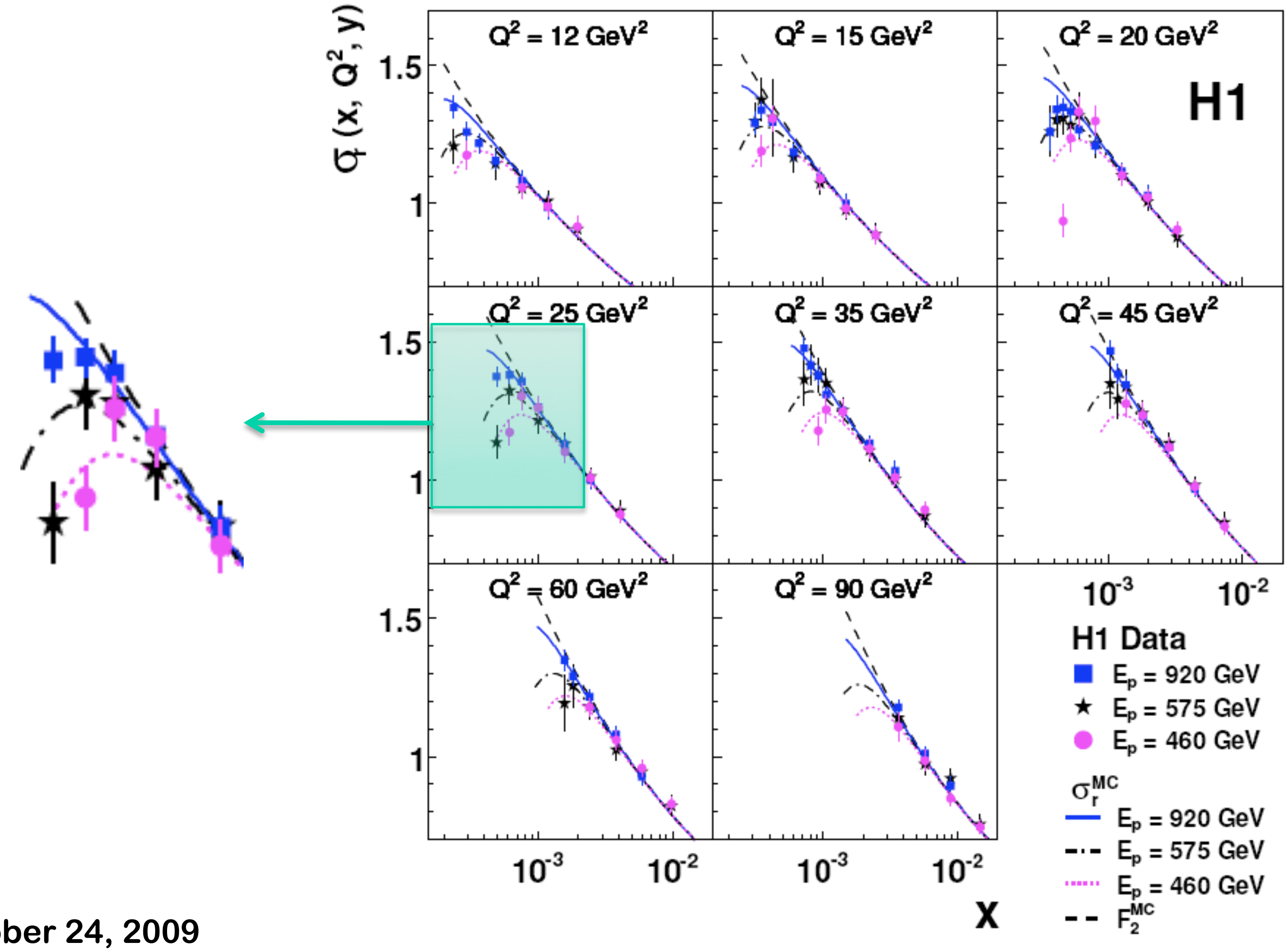
LO pQCD

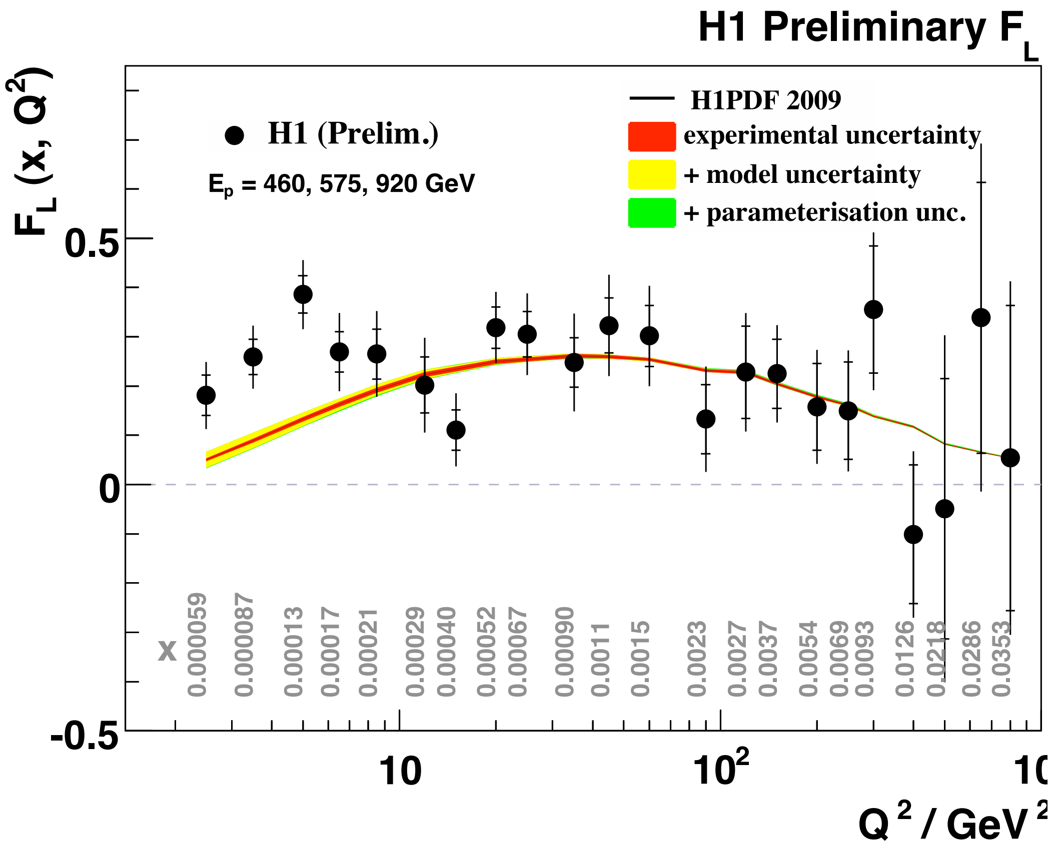
Expected to dominate at small-x

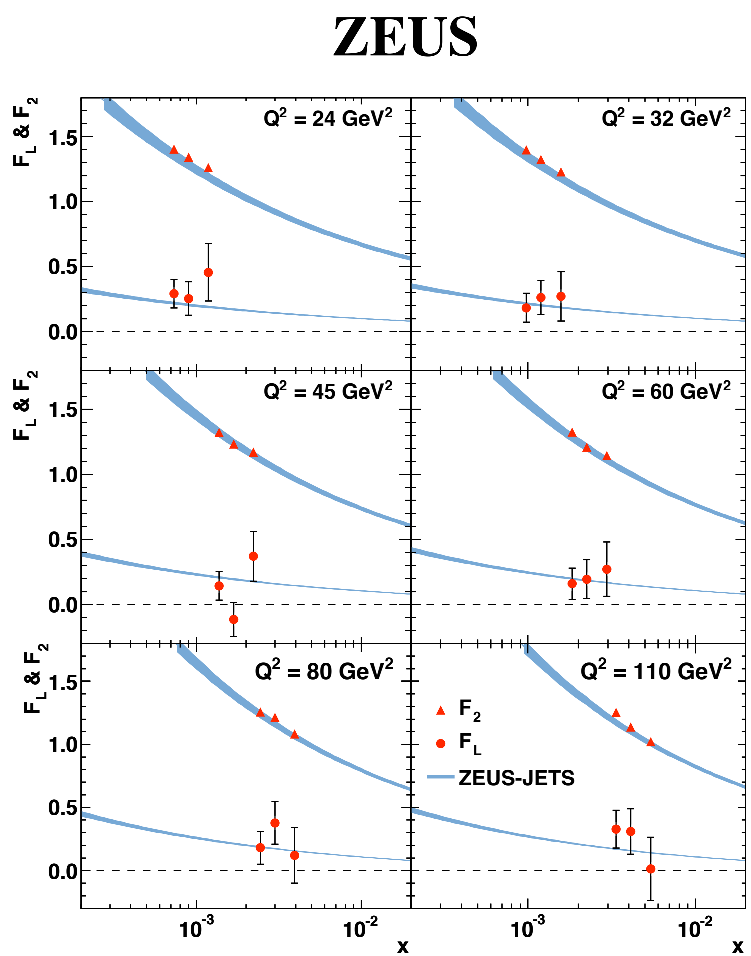


Available luminosity		(pb^{-1})
HER E_p=920 GeV	e^+p	>300
	e^-p	>200
MER E_p=575 GeV	e^+p	8
LER E_p=460 GeV	e^+p	14

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2(x,Q^2) - y^2 F_L(x,Q^2)\right]$$

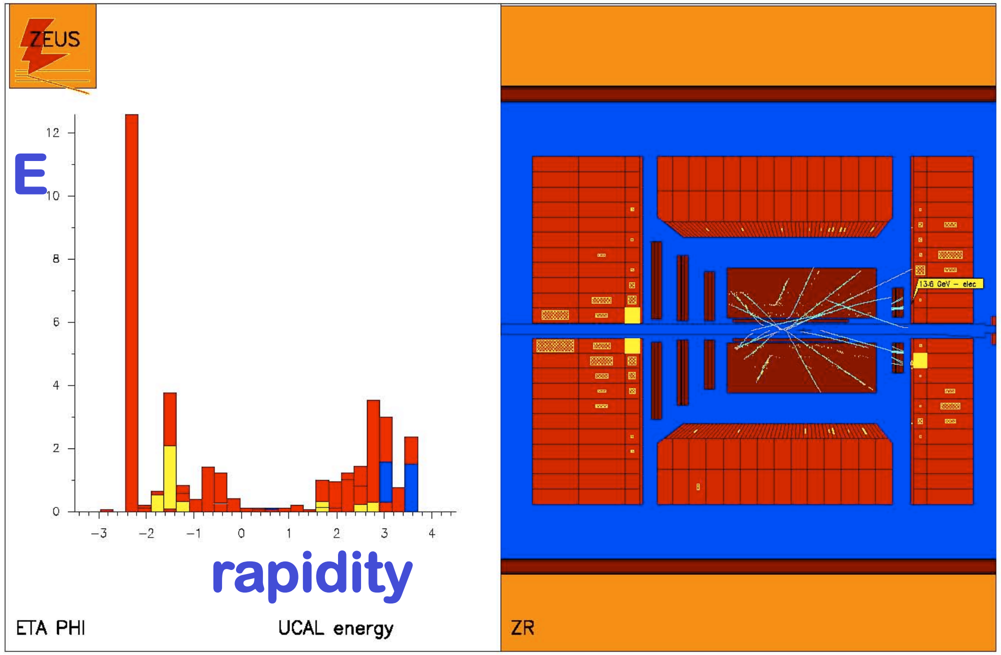


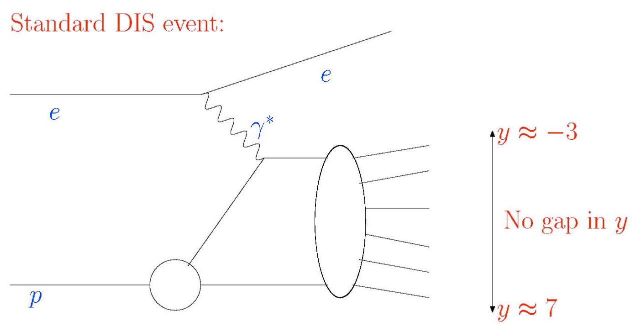


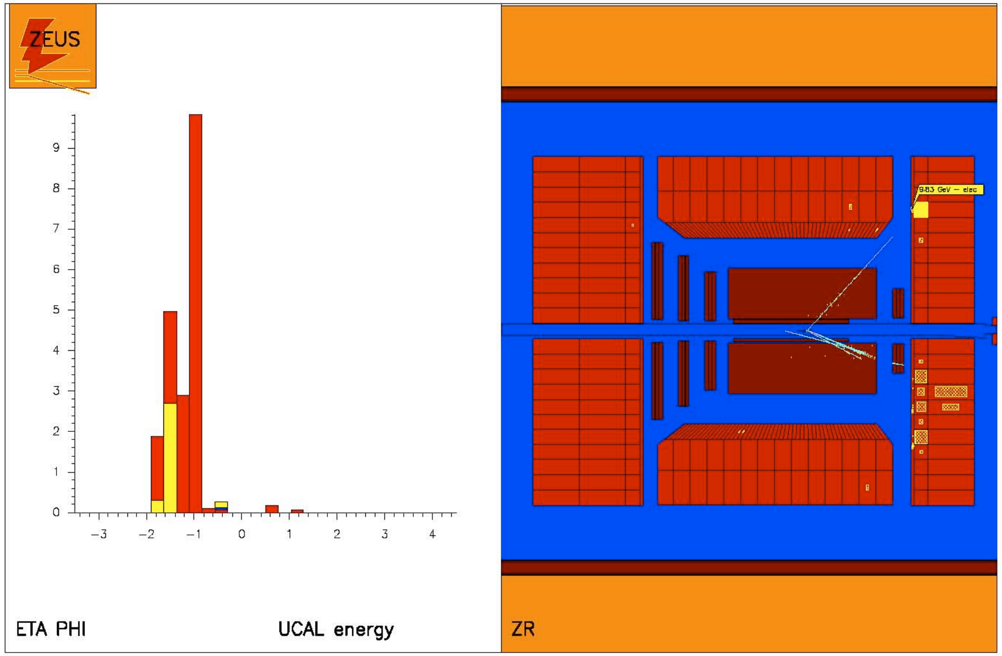


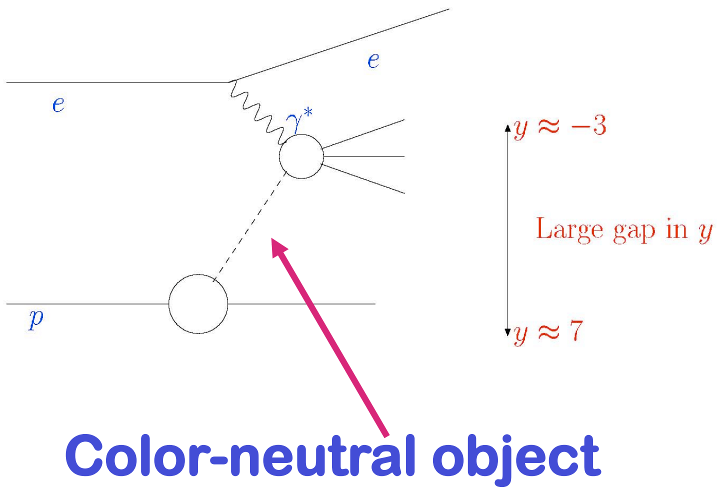
Standard parton density extraction gives predictions for F_L in good agreement with measurements, except for Q^2<10 GeV^2. Note that dipole model predictions of R≈0.2 in good agreement with all data.

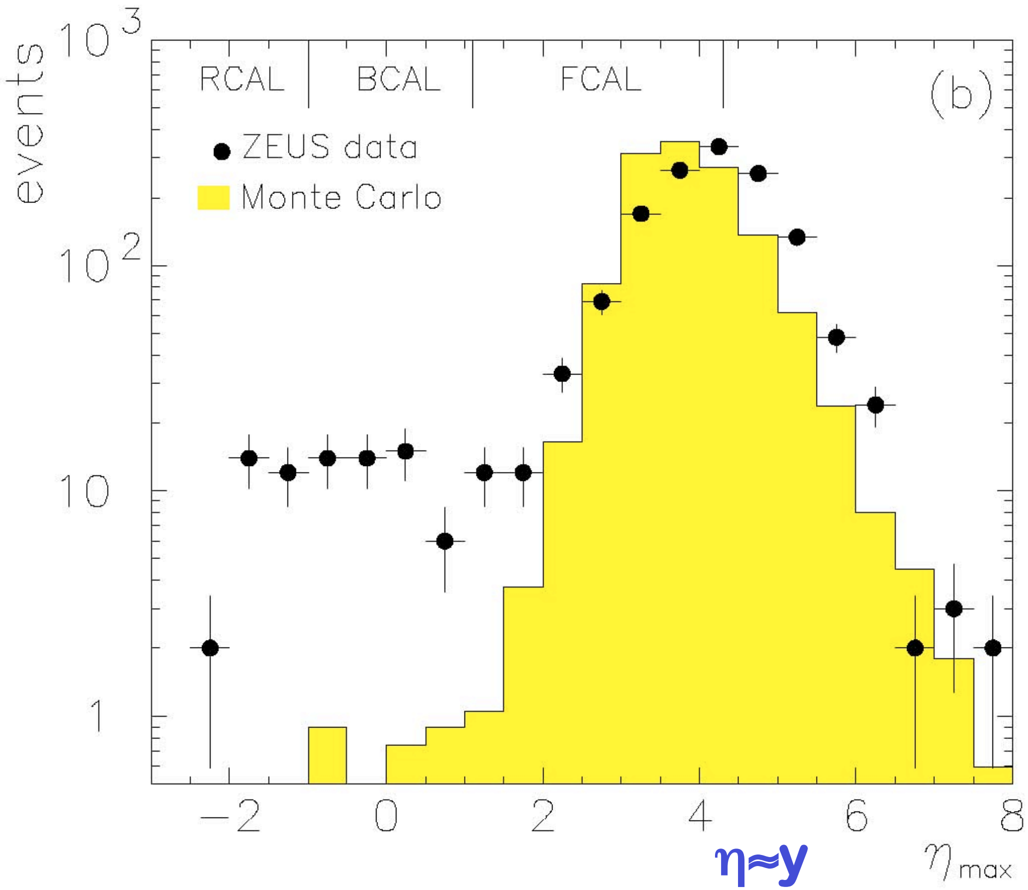
Observation of large rapidity gaps





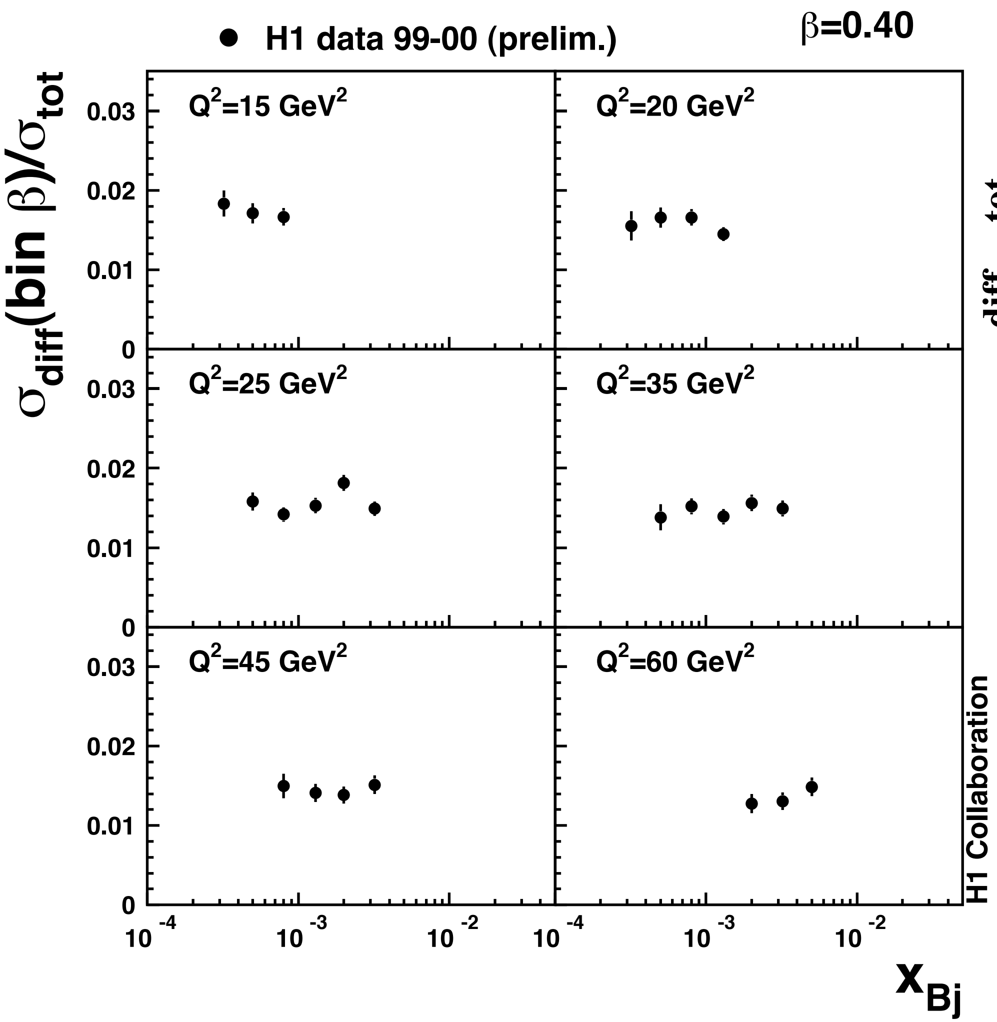


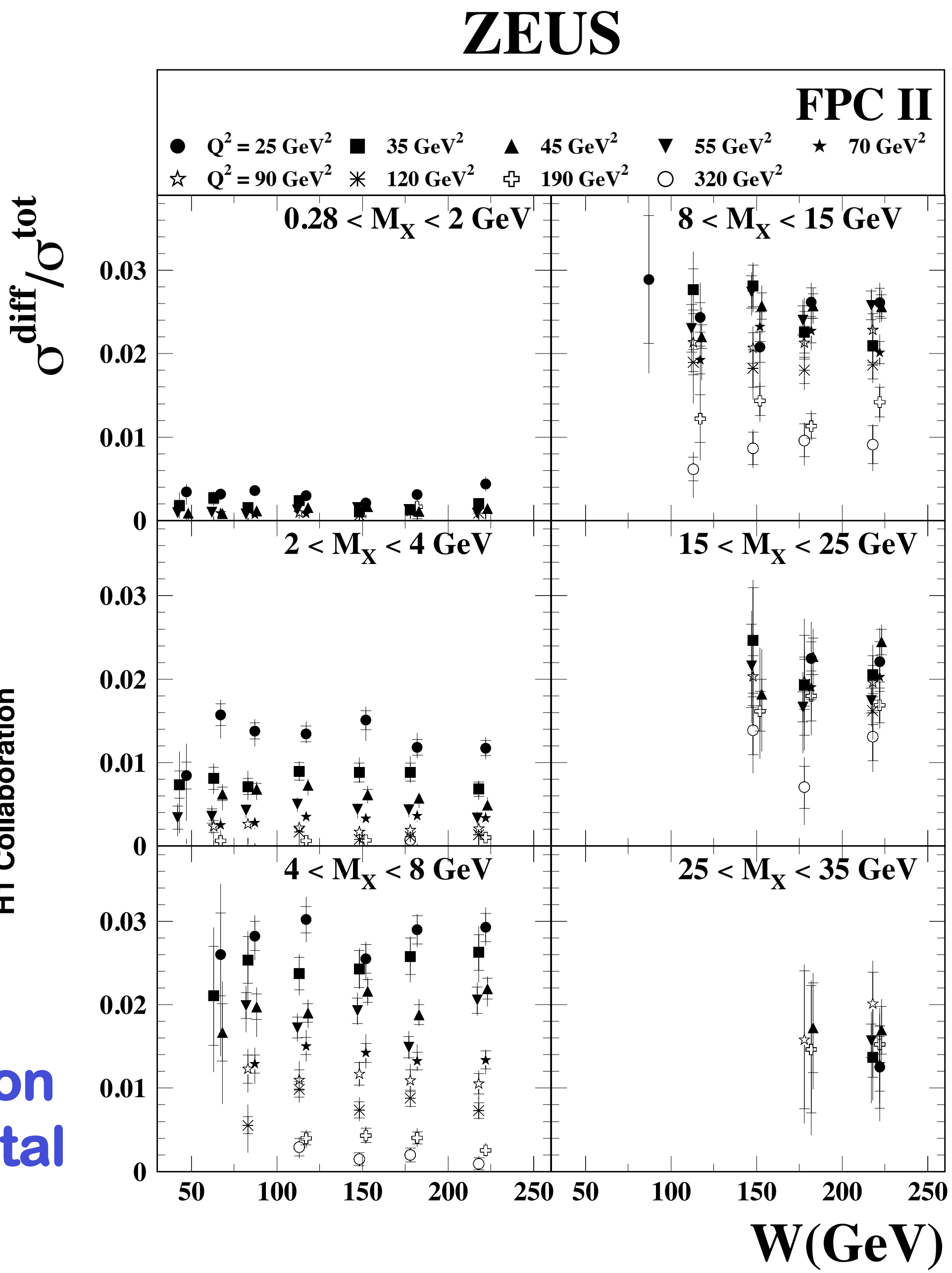




≥10% of events have large rapidity gap !
Implies scattering on color neutral cluster: at least two gluons. Sometimes called 'Pomeron'. Connection to String Theory ?

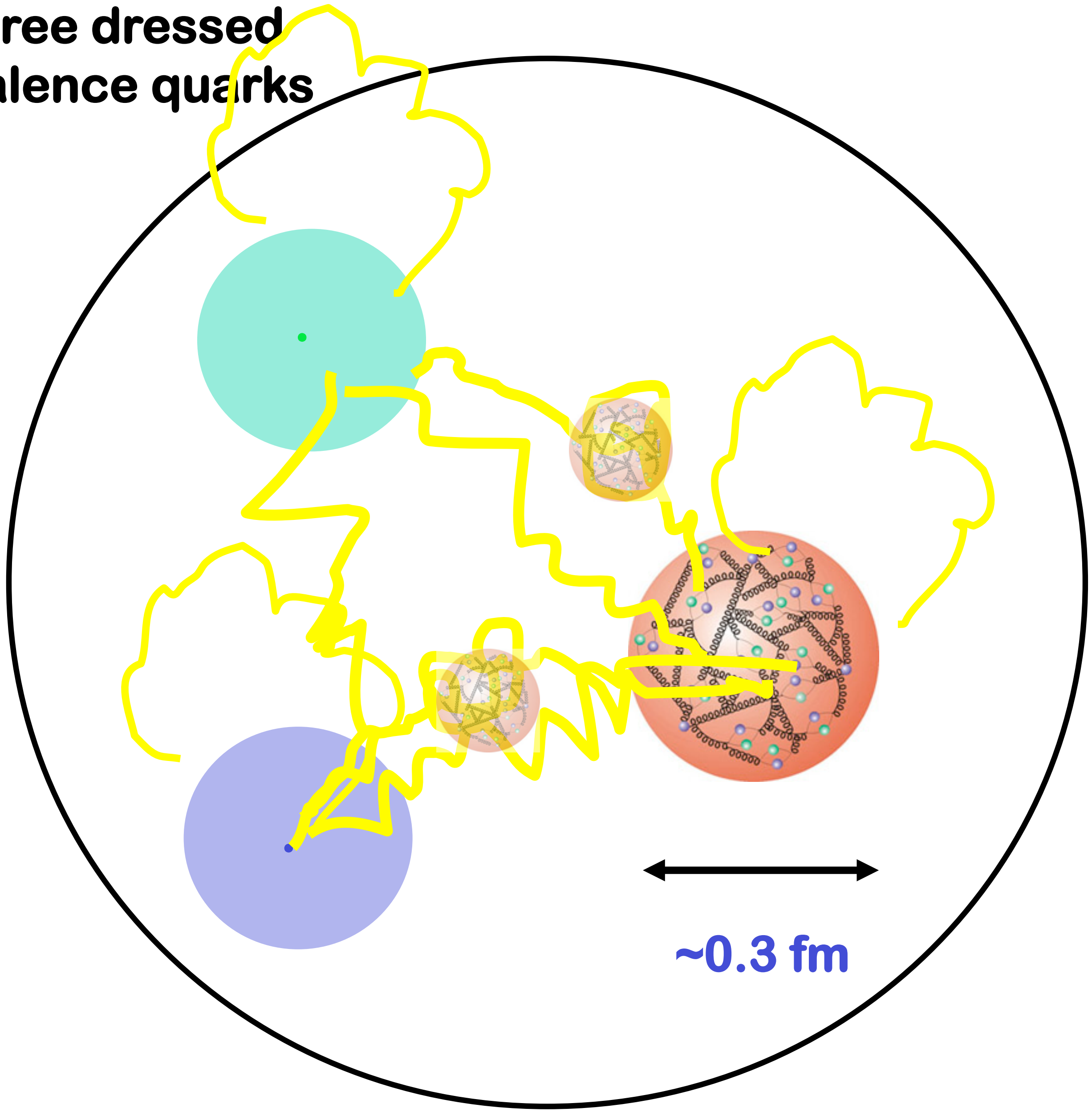
e.g.,
The Pomeron and Gauge/String Duality
Richard C. Brower, Joseph Polchinski, Matthew J. Strassler and Chung-I Tan





The 'inclusive' diffractive cross section has the same x dependence as the total cross section.

Proton with three dressed valence quarks +

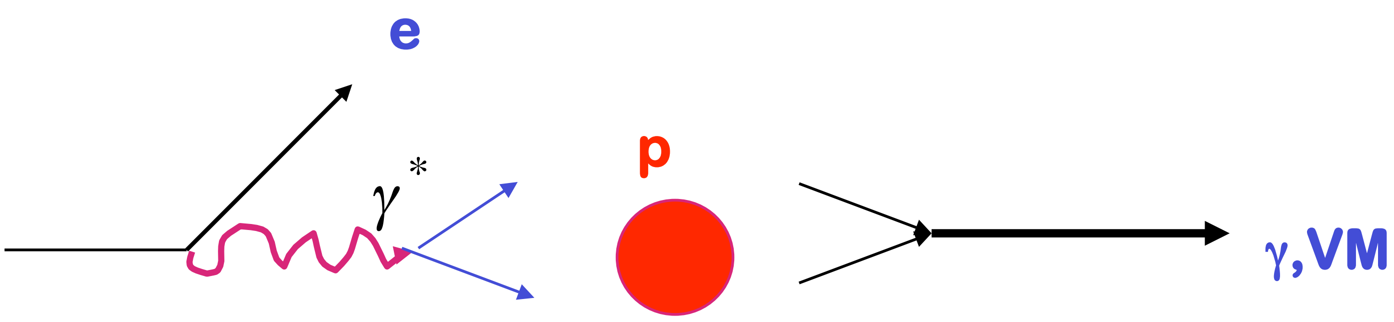


'Quark substructure' can be seen when we get resolution smaller than about 0.3 fm. With finer resolution, see that the three quarks are composed of many subconstituents.

Small colorless gluon clusters between the valence quarks. Colorless clusters have similar structure as valence quarks.

Plus short lived fuzz outside (the expanding proton).

Exclusive Processes



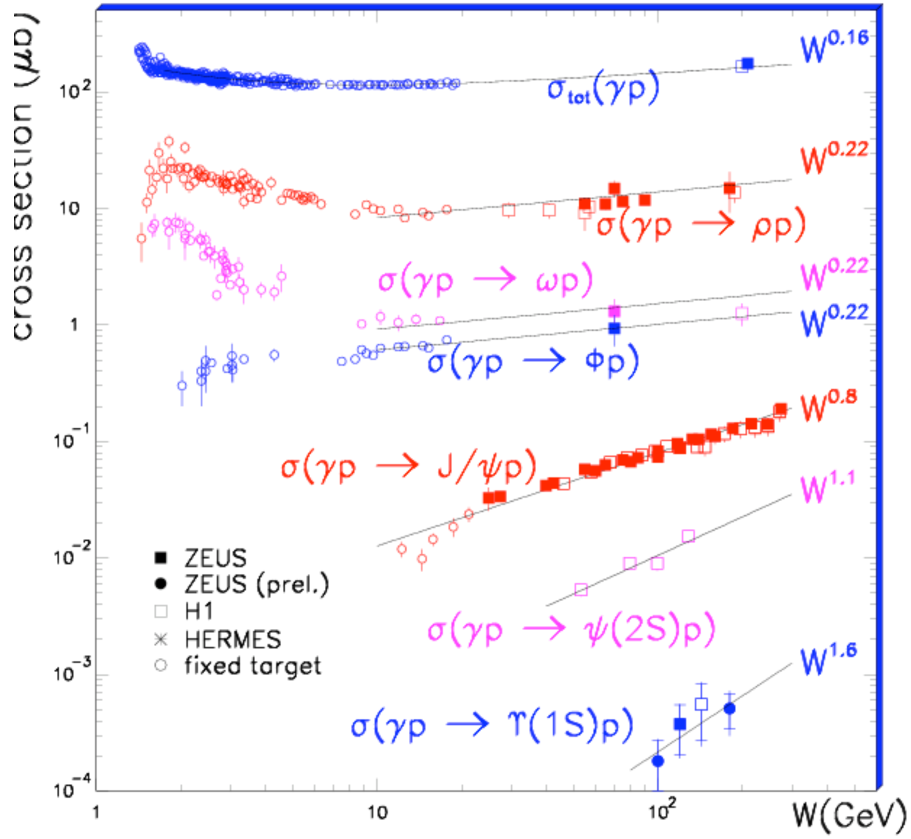
A long list of processes have been measured:

$$eP \rightarrow ePV \quad V = \rho,\omega,\varphi,J/\psi$$

$$eP \rightarrow eNV \quad V = \rho,\omega,\varphi,J/\psi$$

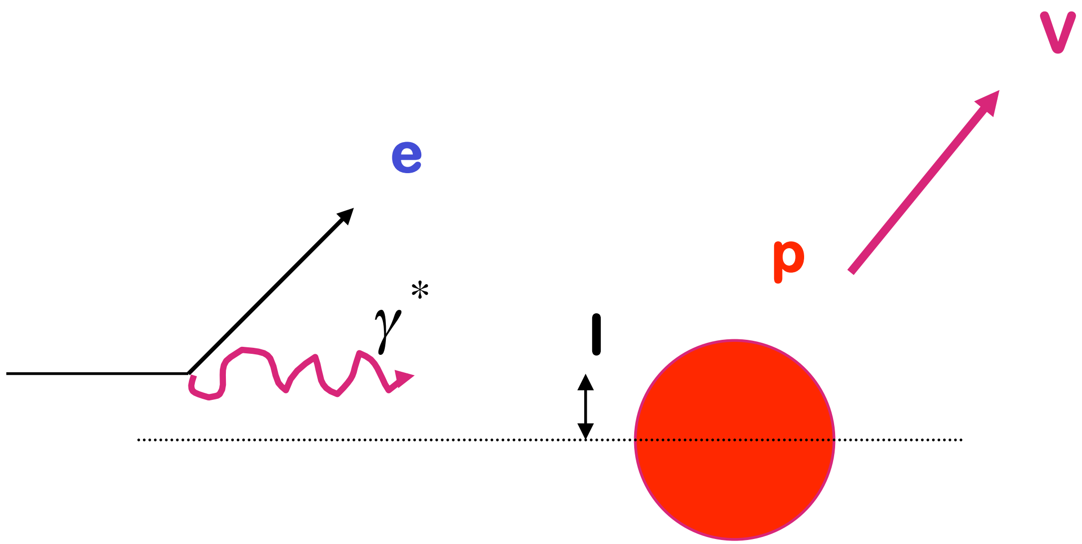
N is low mass system

and $\quad eP \rightarrow eP\gamma \quad$ QCD

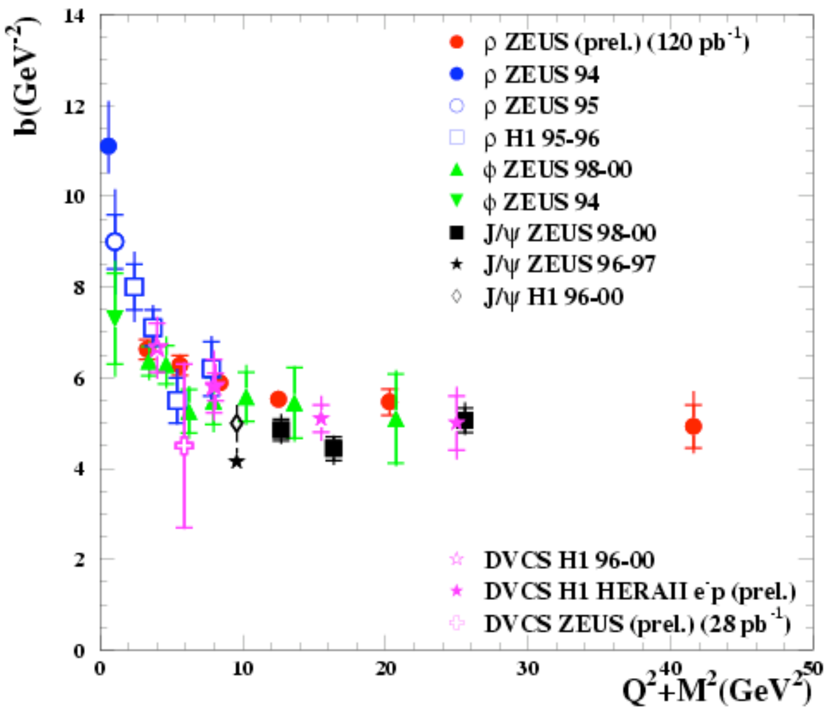


Mass set virtuality scale

Exclusive Processes



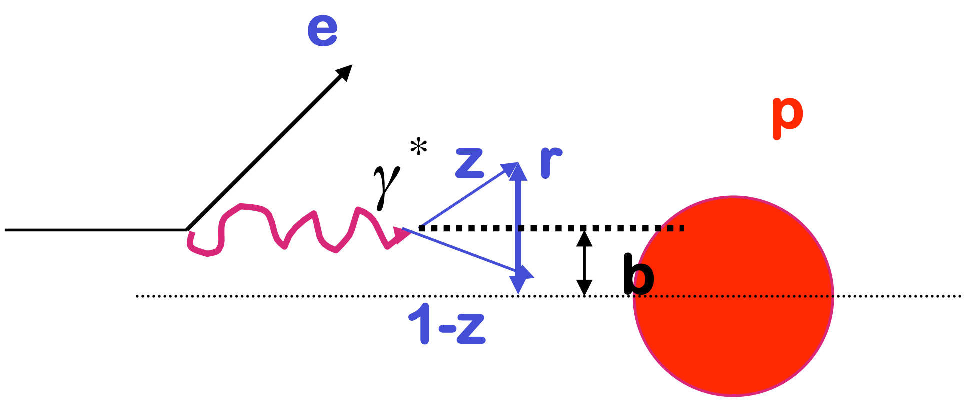
$$\frac{d\sigma}{dt} \propto e^{-bt}, \qquad b \to R_g$$



b=4 GeV^{-2} found corresponds to an rms impact parameter of 0.56 fm. smaller than the proton charge radius of 0.870 [PDG] …

Wealth of data, not clear how to incorporate diffraction in DGLAP.

Color Dipole Model



Components:

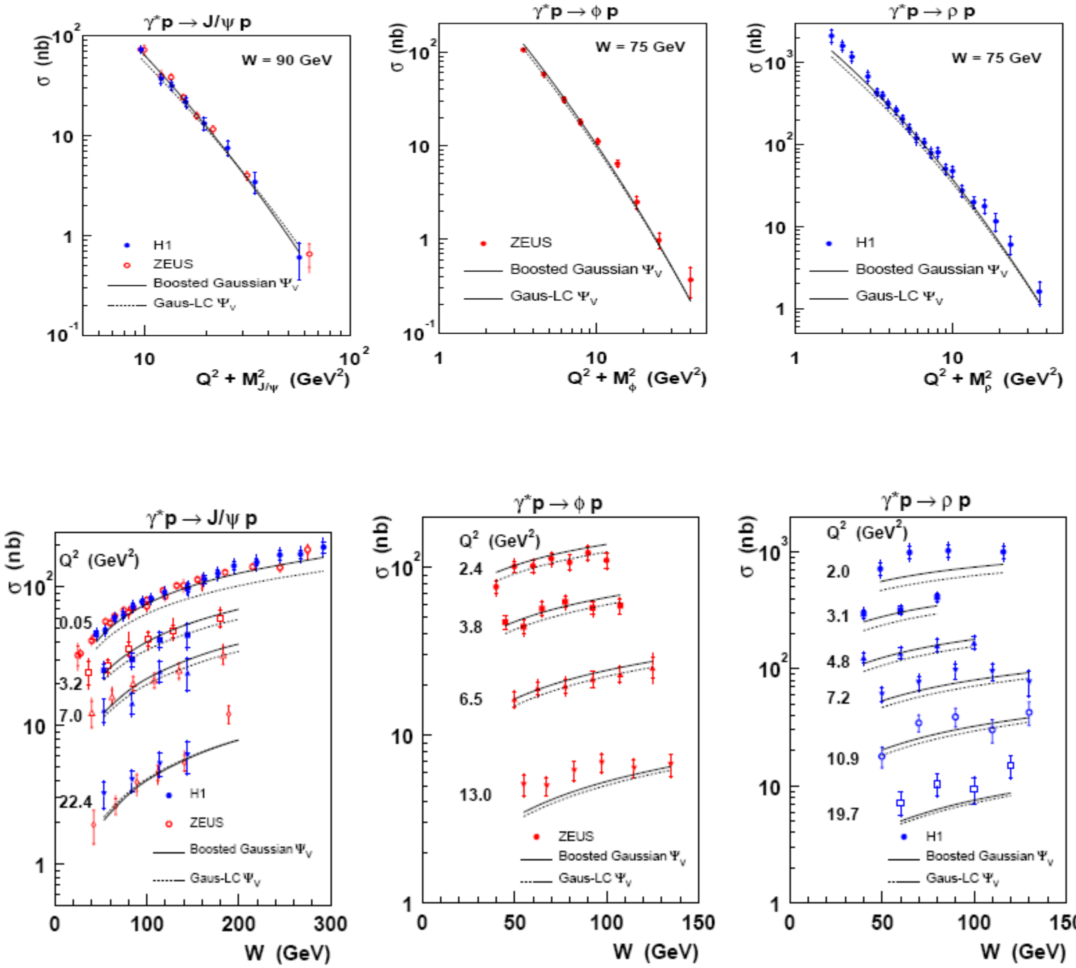
$\Psi(r,z)$ the quark-antiquark wavefunction of the photon, known from QED

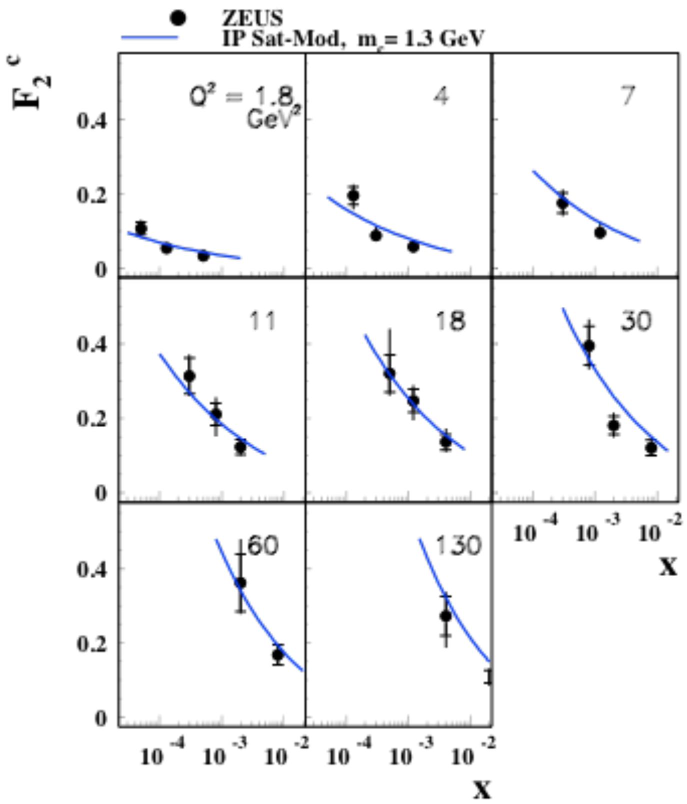
$\sigma_{q\bar{q}p}$ the dipole scattering cross section. Depends on impact parameter,b, and dipole transverse size, r

$$\sigma^{\gamma P} = \int d^2\vec{r}\int_0^1 dz \int d^2 b \Psi^* \sigma_{q\bar{q}p} \Psi$$

Dipole model vs data

Improved versions – DGLAP evolution, impact parameter dependence





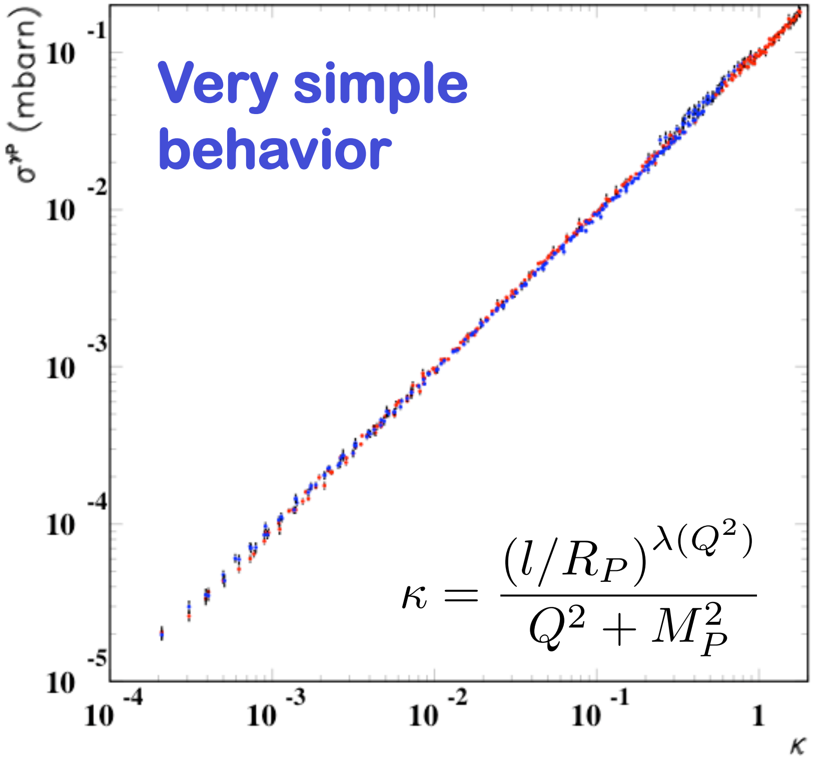
Dipole model gives unified description of inclusive, diffractive and exclusive processes

Theory of small-x

So far, the theory is very complicated. BFKL, dipole scattering, travelling waves, stochastic differential equations, chaos, biological evolution … It seems to be a wonderful theoretical playground with connections to many things.

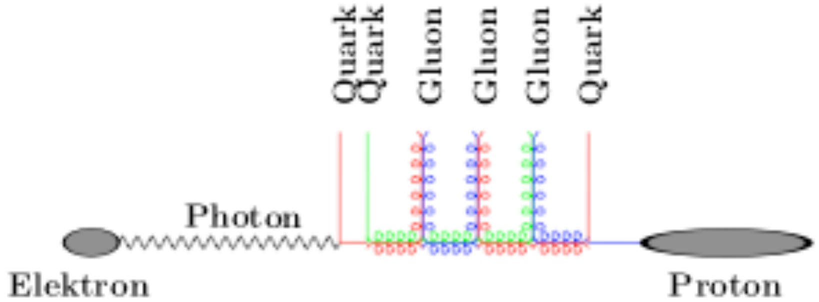
Sometimes, I feel I understand something (usually after talking with Al), but it usually doesn't last

Small-x data

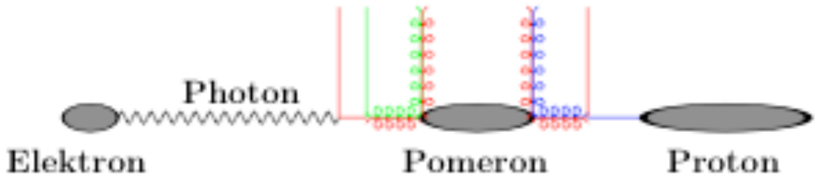


Geometric scaling (Kwiecinski, Golec-Biernat, Stasto)
Color Glass Condensate (McLerran, Venugopalan)

Small-x physics experimentally shows universal and simple behavior



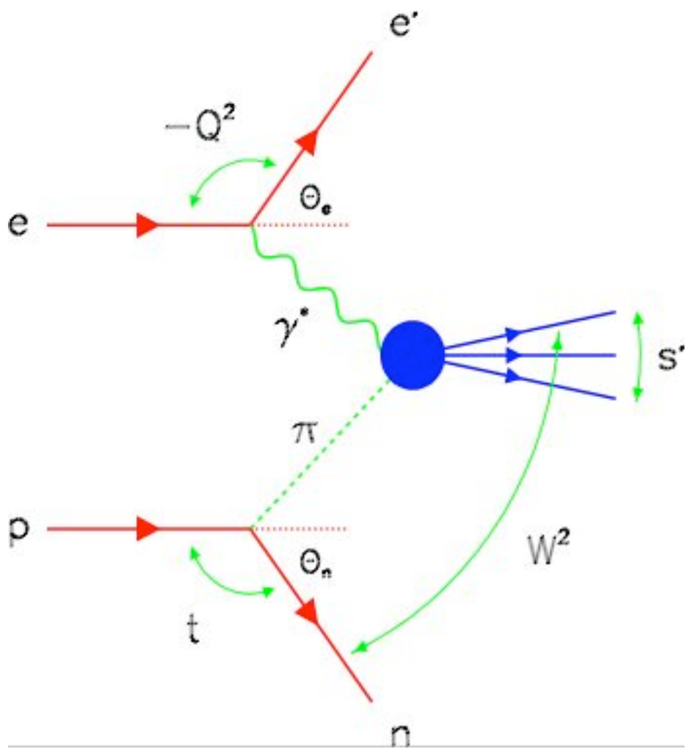
standard

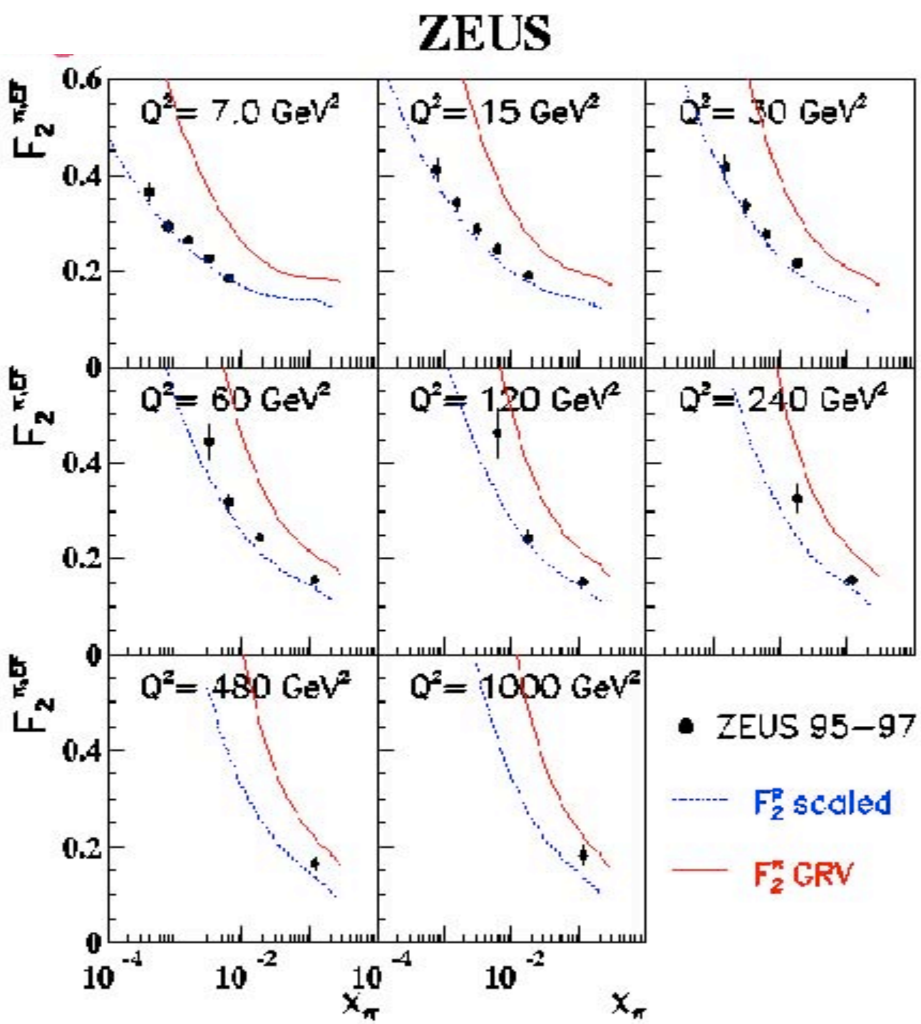


Rapidity gap

I showed the energy dependence is same

Forward neutron production electron - pion scattering





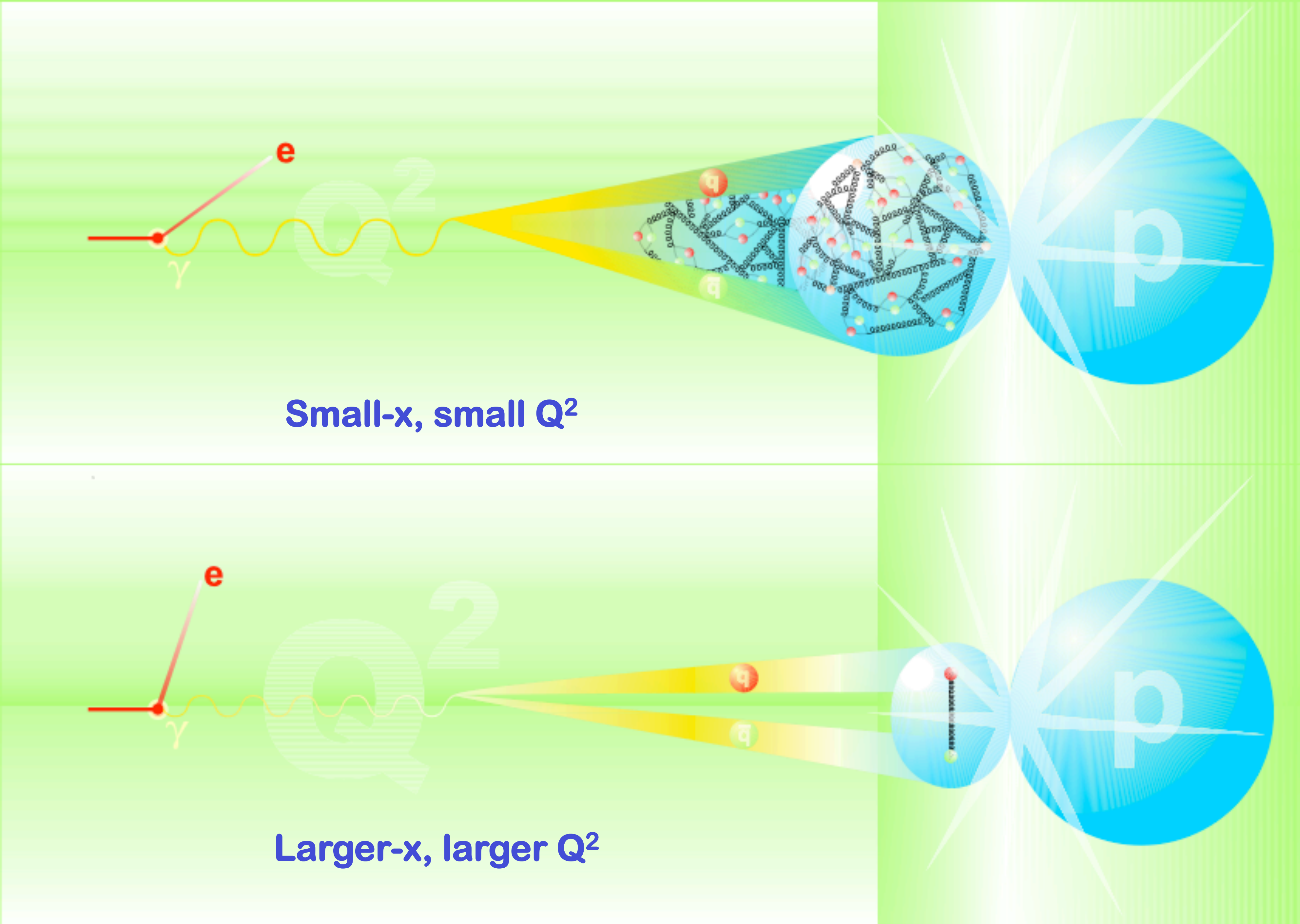
Pion scattering also shows same x dependence

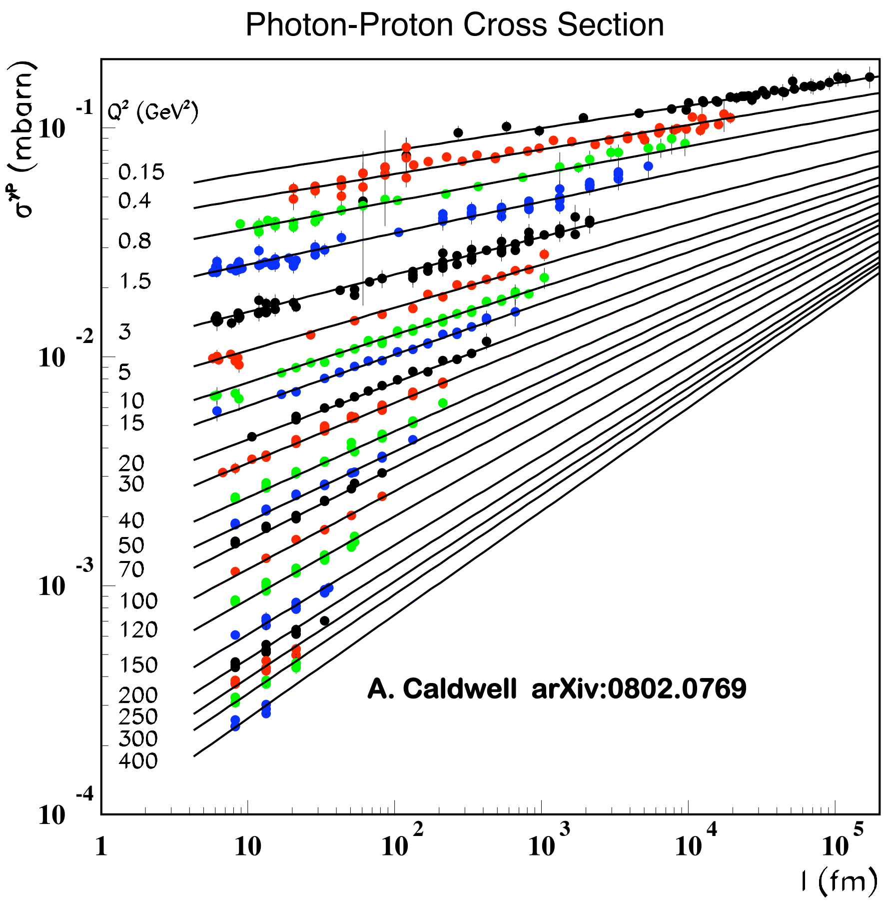
Alternative Picture - proton rest frame

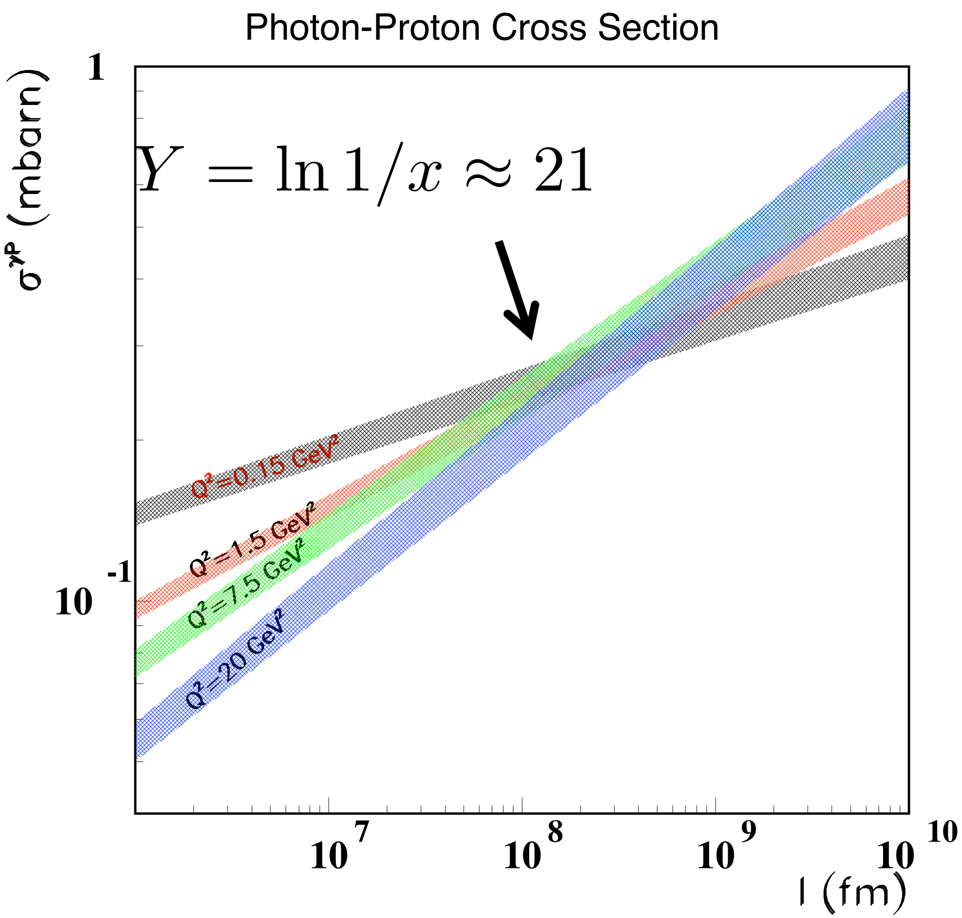
$$\Delta E_\gamma = \sqrt{P_\gamma^2 + M_X^{\ 2}} - \sqrt{P_\gamma^2 + q^2} \approx \frac{Q^2}{E_\gamma} \qquad M_X = Q$$

$$E_\gamma = W^{\ 2}/2M_P \qquad \Delta E_\gamma \approx \frac{2M_P Q^2}{W^{\ 2}} \qquad l \approx \frac{0.2\,fm}{2M_P x}$$

So, small-x means long-lived photon fluctuations (not proton structure)

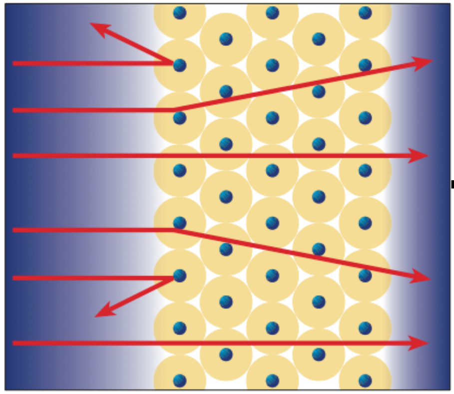

e
γ
Q^2
q
$\bar{q}$
p
Small-x, small Q^2
e
γ
Q^2
q
$\bar{q}$
p
Larger-x, larger Q^2

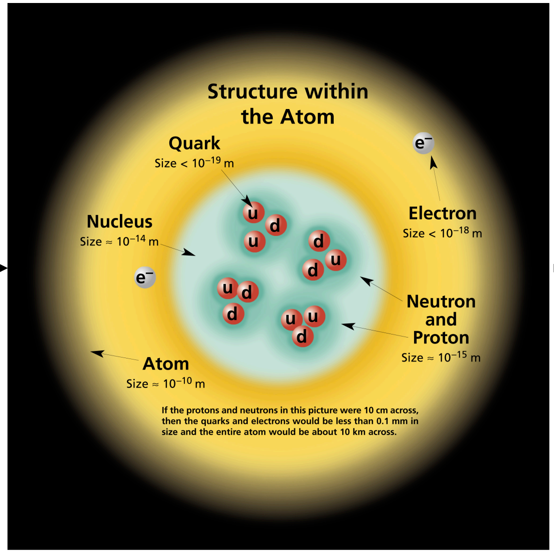


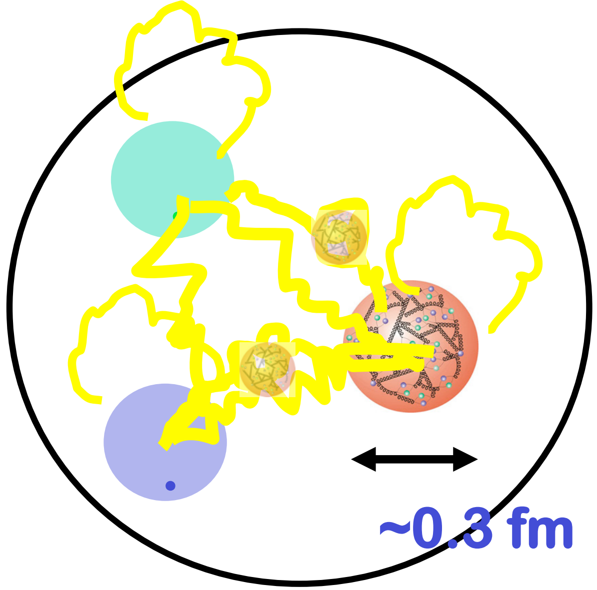


Slope of the cross section with l increases with Q^2. Extrapolation of the cross section with fixed slope.

indicates that the cross section becomes independent of Q at large enough l (small enough x).







With HERA, we see resolved constituent quarks - still missing the full evolution picture. Small-x partons are a universal property of matter → fundamental physics. Several options for new experiments are under discussion.

Al, thanks for being so patient in explaining the beauty of small-x physics to us.