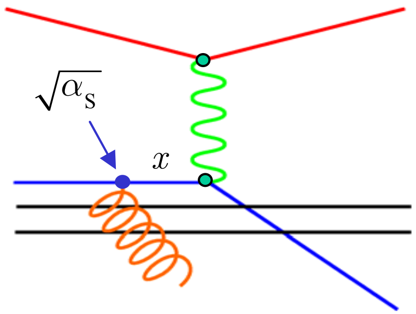
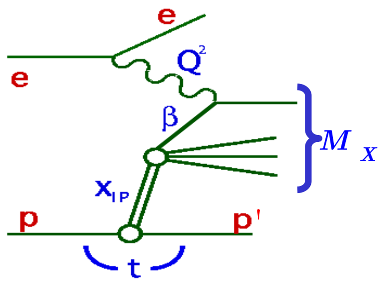
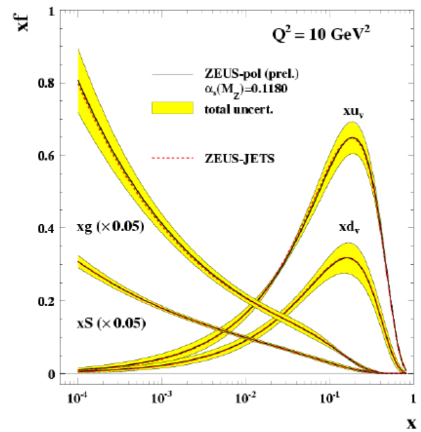
Implication of the HERA Measurements on Astroparticle Data Interpretation

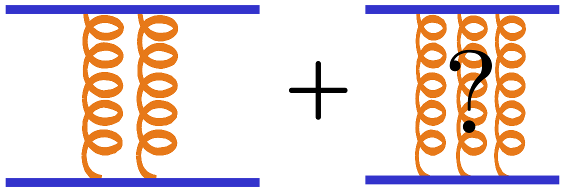
Christian Kiesling
Max-Planck-Institute for Physics, München

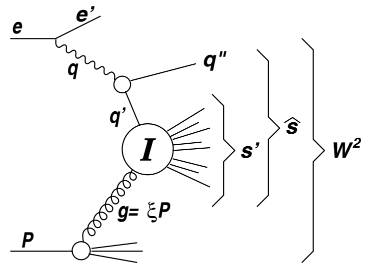
- HERA, the QCD-machine
- Inclusive Scattering
- Diffraction at HERA
- Hadronic Final States (Jets)
- Pomeron and Odderon
- Instanton Effects
- Summary and Conclusions



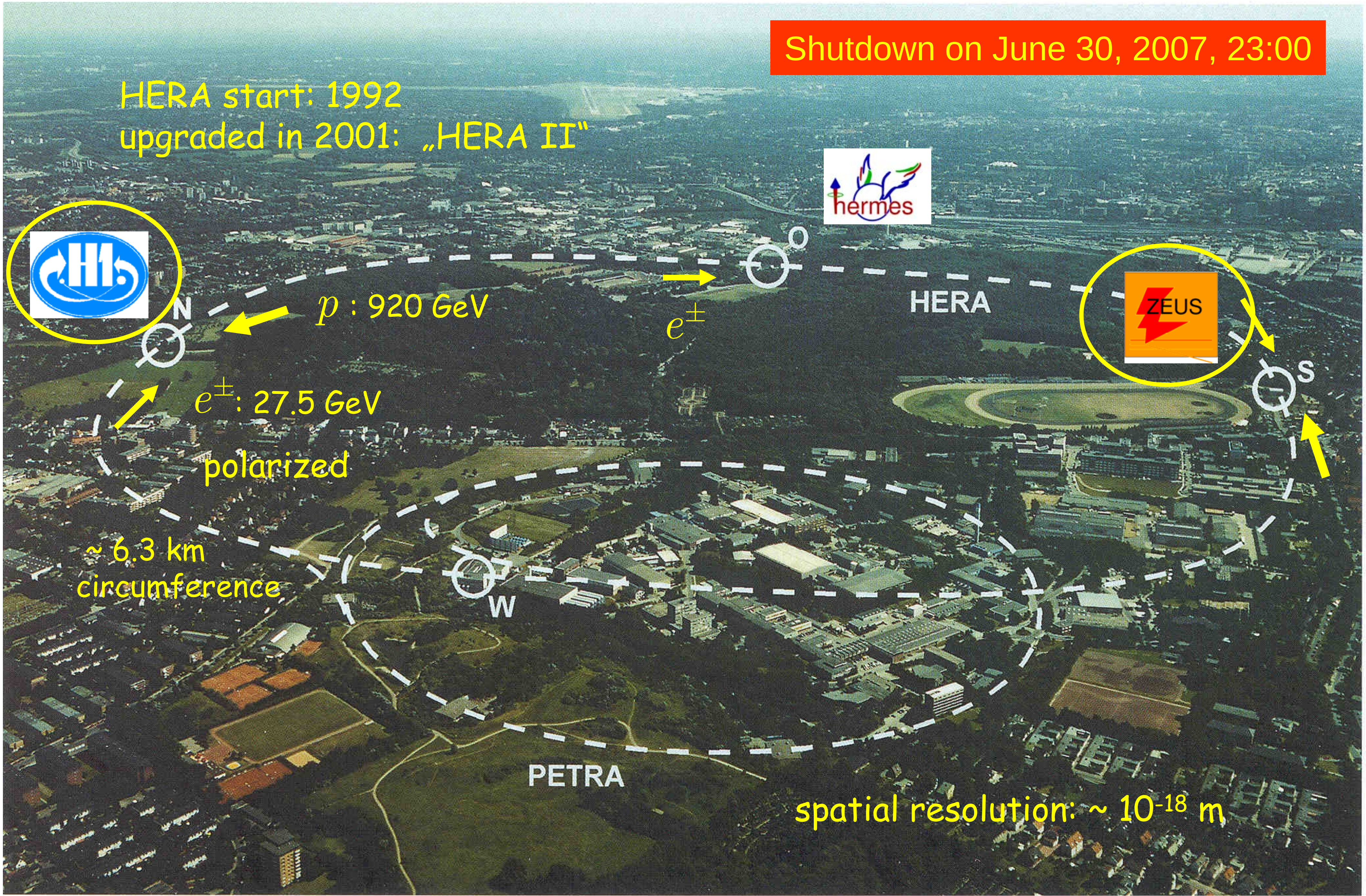




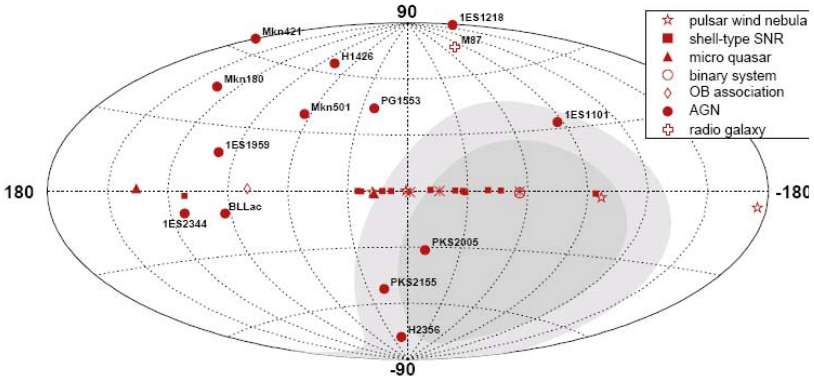




HERA – the world's largest electron microscope
(Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany)



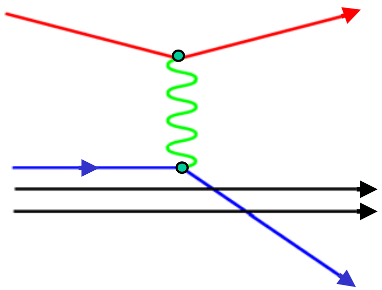
HERA and VHE γ-rays

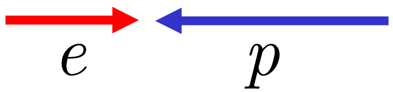


HERA is a collider:

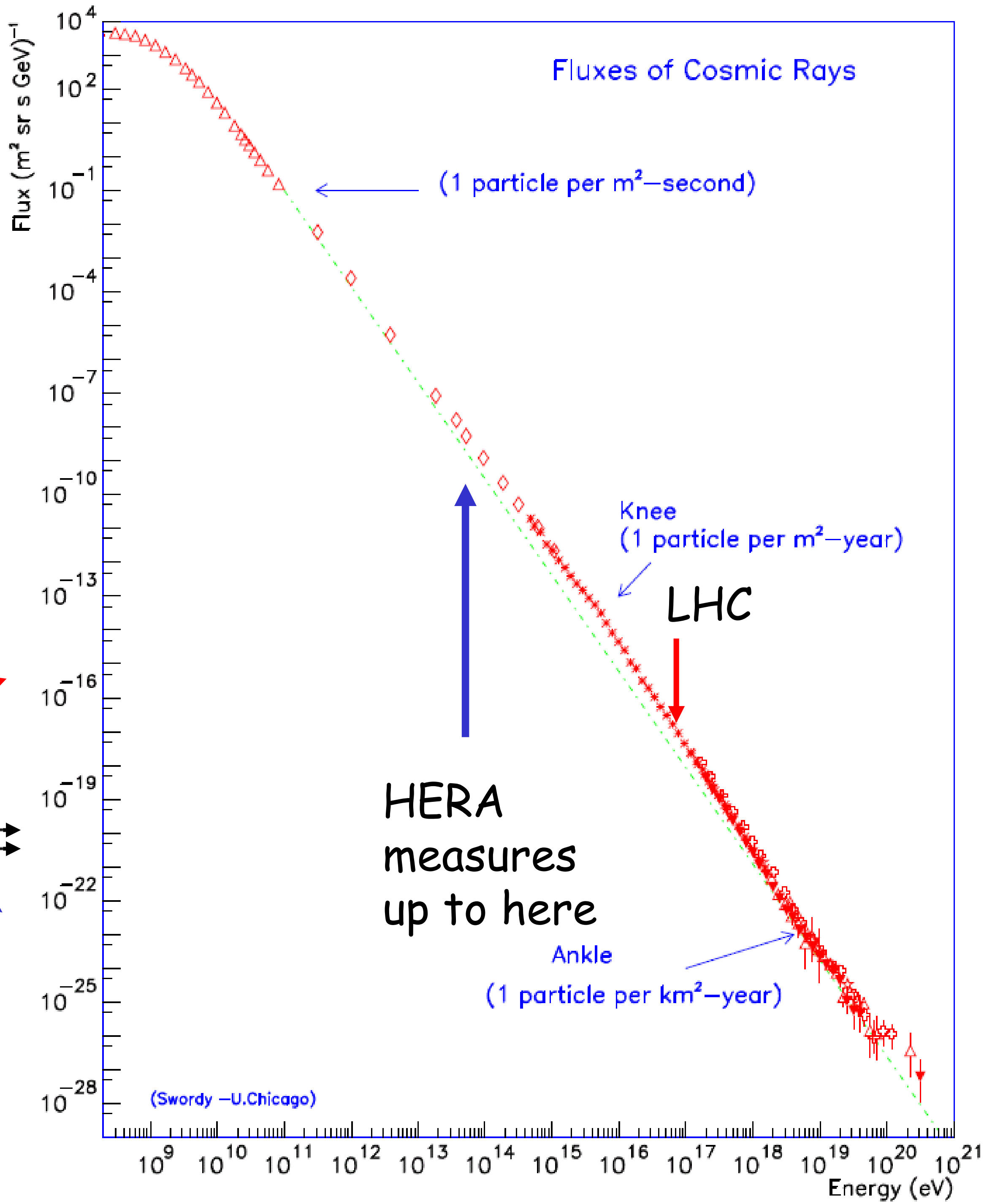
$$E_e = 27.5\,\mathrm{GeV}$$

$$E_p = 920\,\mathrm{GeV}$$

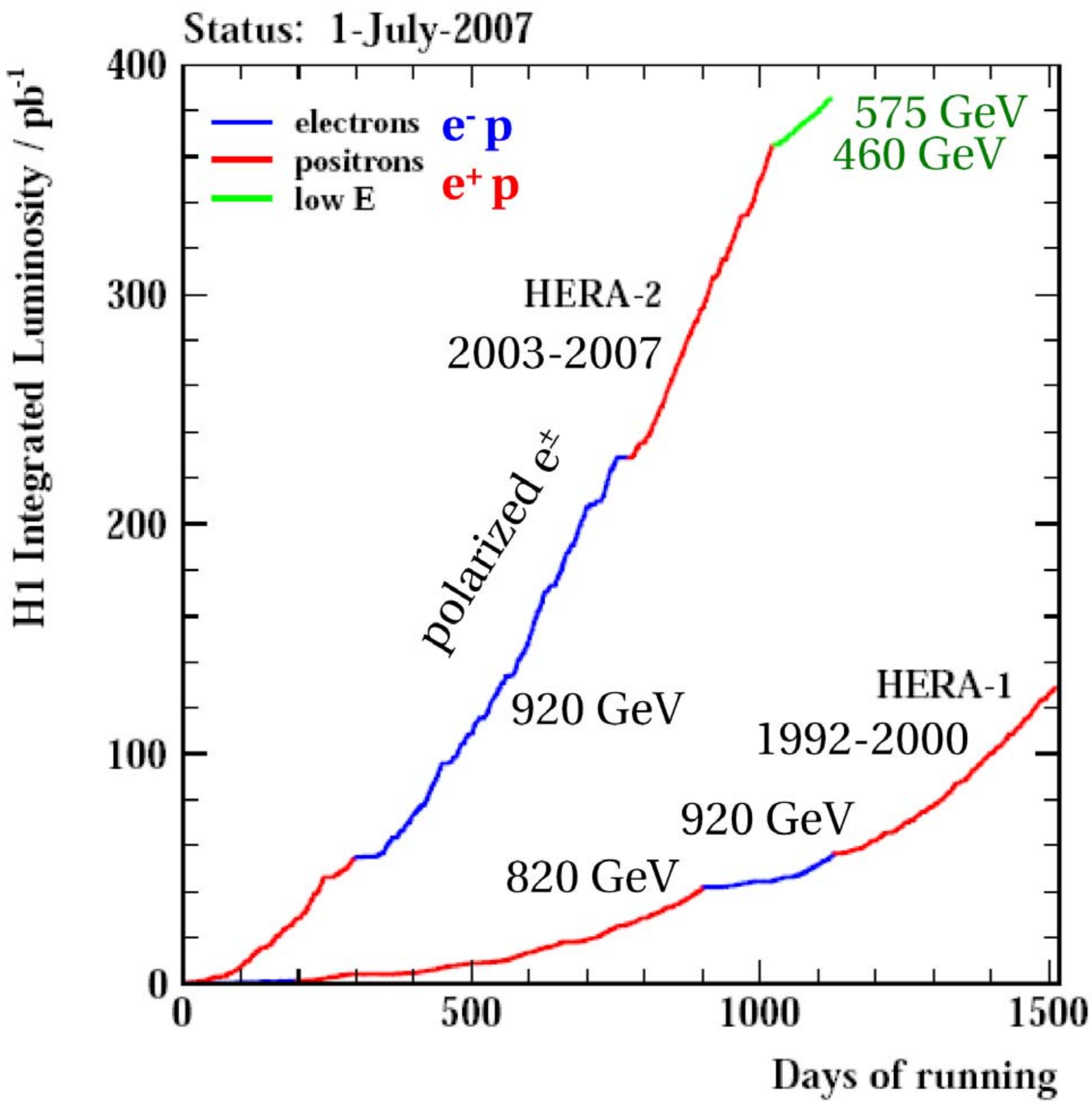




→ 50 TeV photon beam on a stationary proton target



HERA Luminosity



HERA I: 1992-2000

HERA II upgrade:

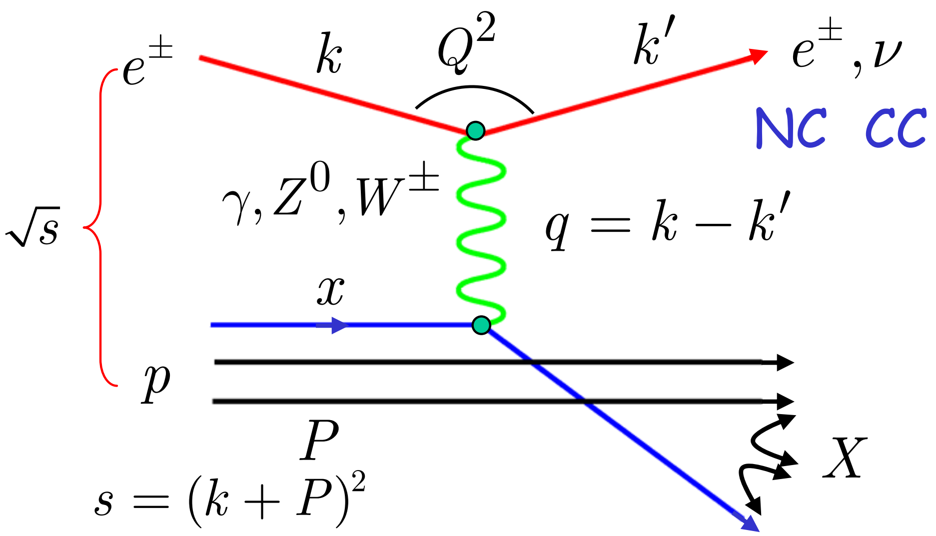
- luminosity
- longitudinal polarization of the lepton beams (spin rotator pairs around the interaction regions)

$$\langle P_e \rangle \sim 30 - 40\%$$

- massive upgardes also for the detectors

- running efficiently from 2003 onwards

Deep Inelastic Scattering (DIS)



$$s = (k+P)^2$$

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

$$W^2 = M_X^2 = (q+P)^2$$

$$x = \frac{Q^2}{2\,P\cdot q}$$ fraction of the proton momentum carried by the charged parton

$$y = \frac{P\cdot q}{P\cdot k}$$ fraction of the electron energy carried by the virtual photon („inelasticity")

$$Q^2 = sxy$$ fixed s: 2 indep. variables

DIS :

electron scatters off a charged constituent (parton) of the proton (= elastic scattering)

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

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

"reduced cross section" σ_r

γ exchange only:

$$F_2(x) = \sum_{i=u,d} e_i^2 x q_i(x)$$

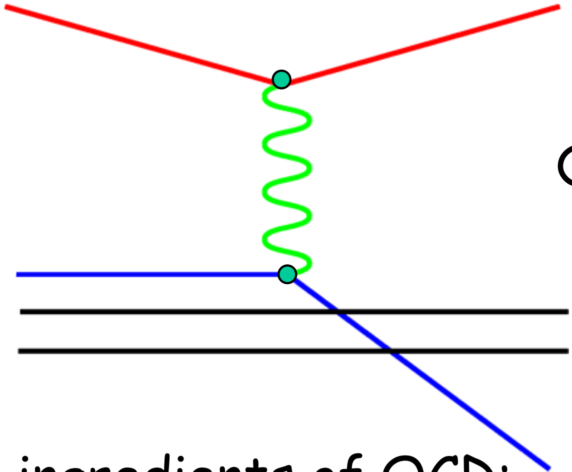
parton densities $xf_i(x)$ (pdf)

$W^\pm$ exchange only:

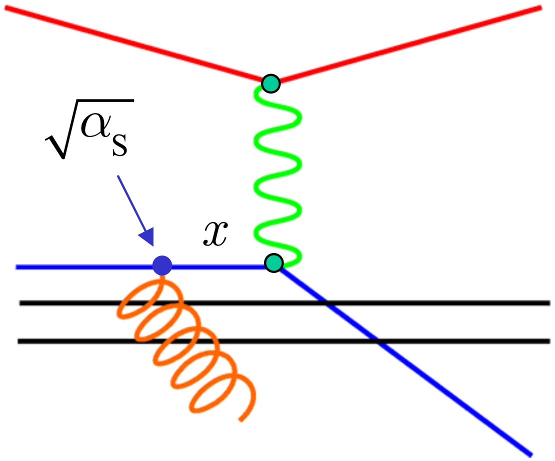
$$e^- p: \quad F_2(x) \sim xq_u(x)$$

$$e^+ p: \quad F_2(x) \sim (1-y)^2 xq_d(x)$$

Quantum Chromodynamics (QCD)



QPM → QCD



Basic ingredients of QCD:

1. Asymptotic freedom :

$\alpha_s \to 0$ at short distances

→ perturbative QCD (pQCD)

2. Factorization :

„hard" scale Q^2

$$\sigma = \sum_i \sigma_{\gamma^* i}(Q^2) \otimes x f_i(x)$$

non-perturbative part

3. Evolution (calculable in pQCD) :

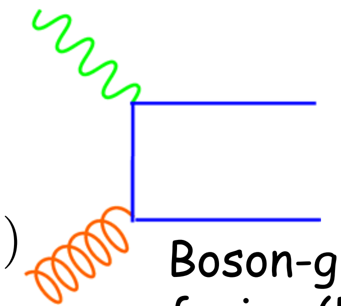
Parton densities become functions of Q^2

$xq_i(x) \to xq_i(x, Q^2)$ quarks

$x\bar{q}_i(x, Q^2)$ antiquarks

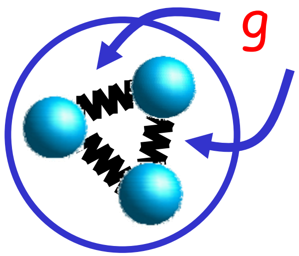
+ gluons

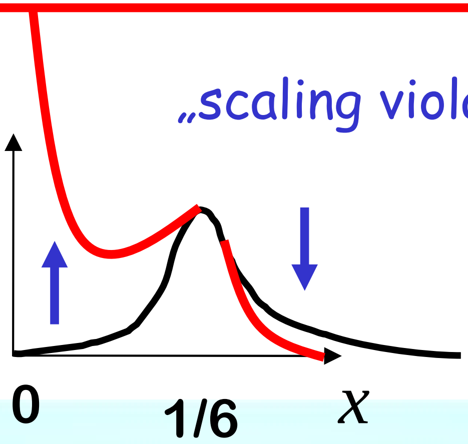
$g(x, Q^2)$

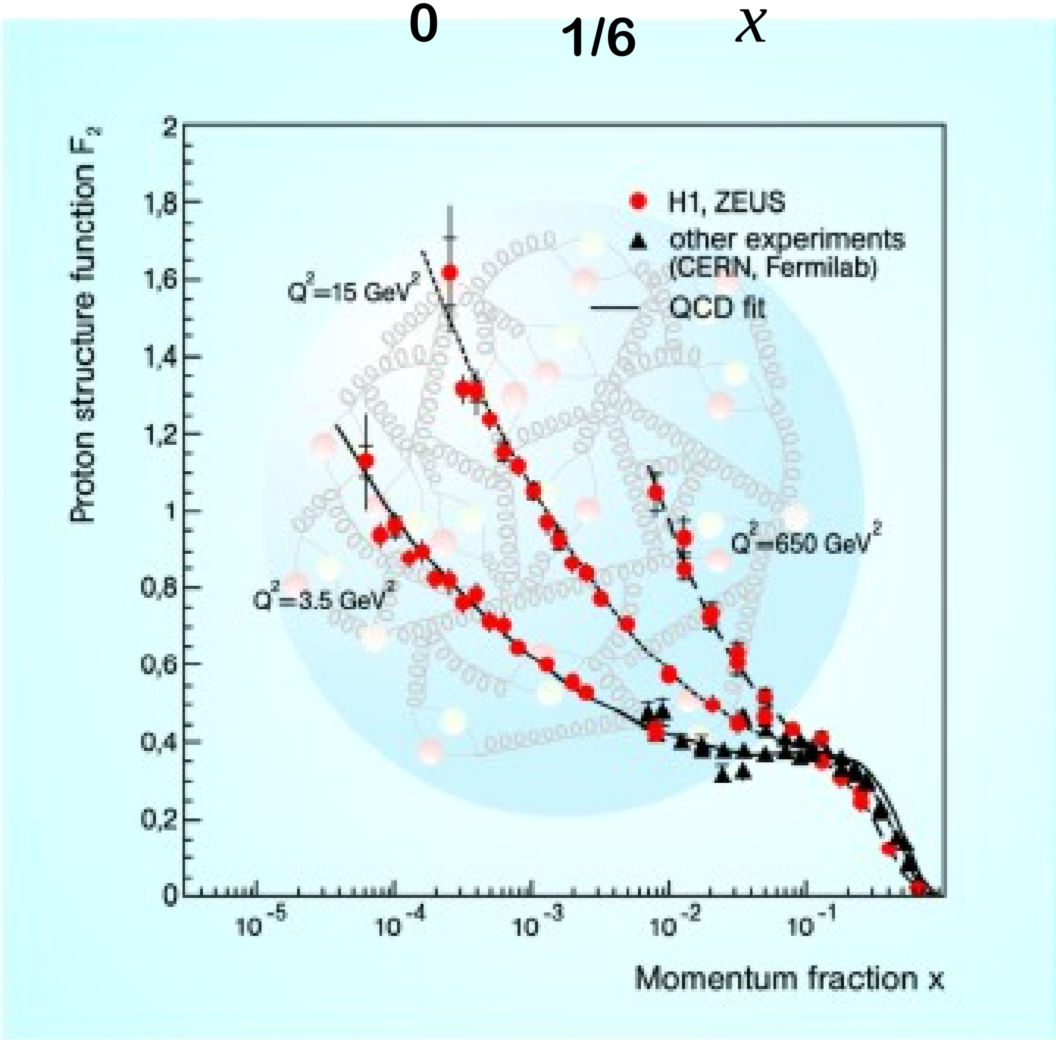


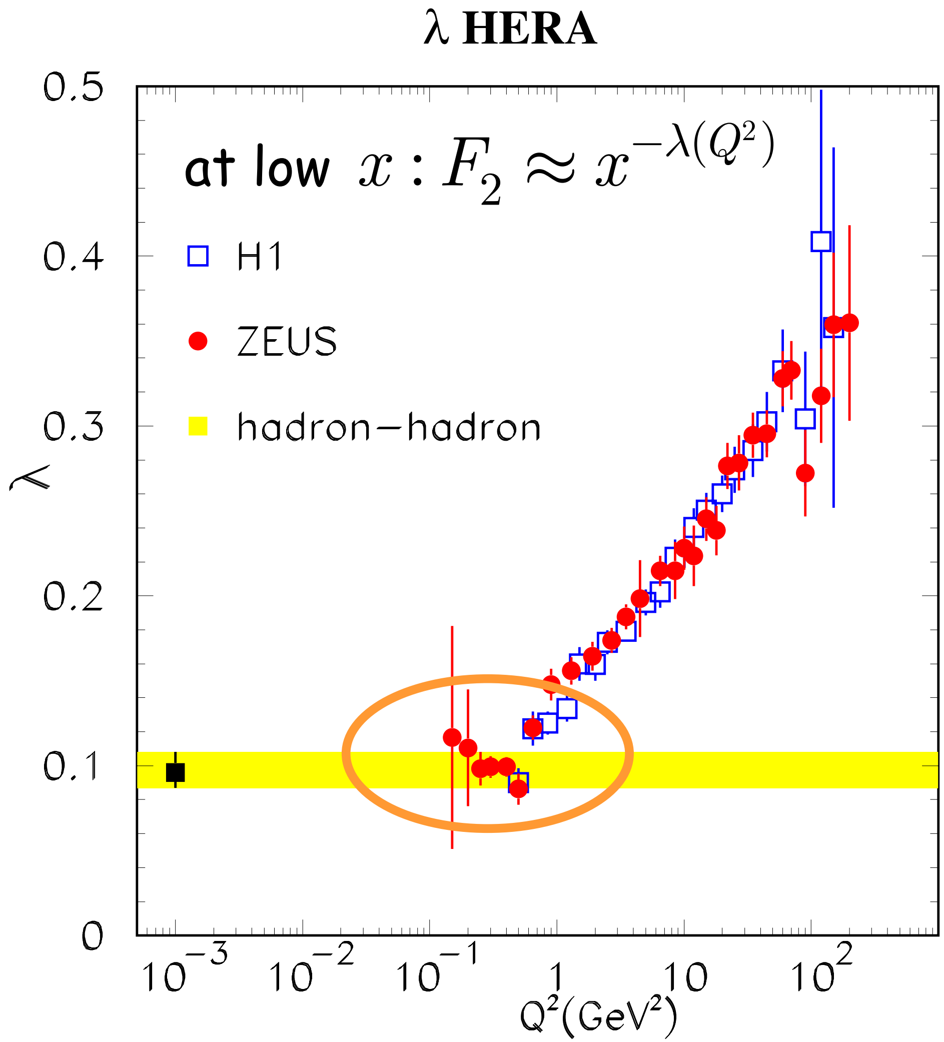
Boson-gluon fusion (BGF)

HERA's discovery: The Strong Rise of F_2 towards low x









Transition from the perturbative to the non-perturbative regime

QCD Analysis of F_2 data (low and high Q^2)

Very precise measurements of F_2 provided by ZEUS and H1

Clear scaling violation observed, violation is driven by gluon emission

Describing this data in a QCD fit gives access to the parton densities within the proton

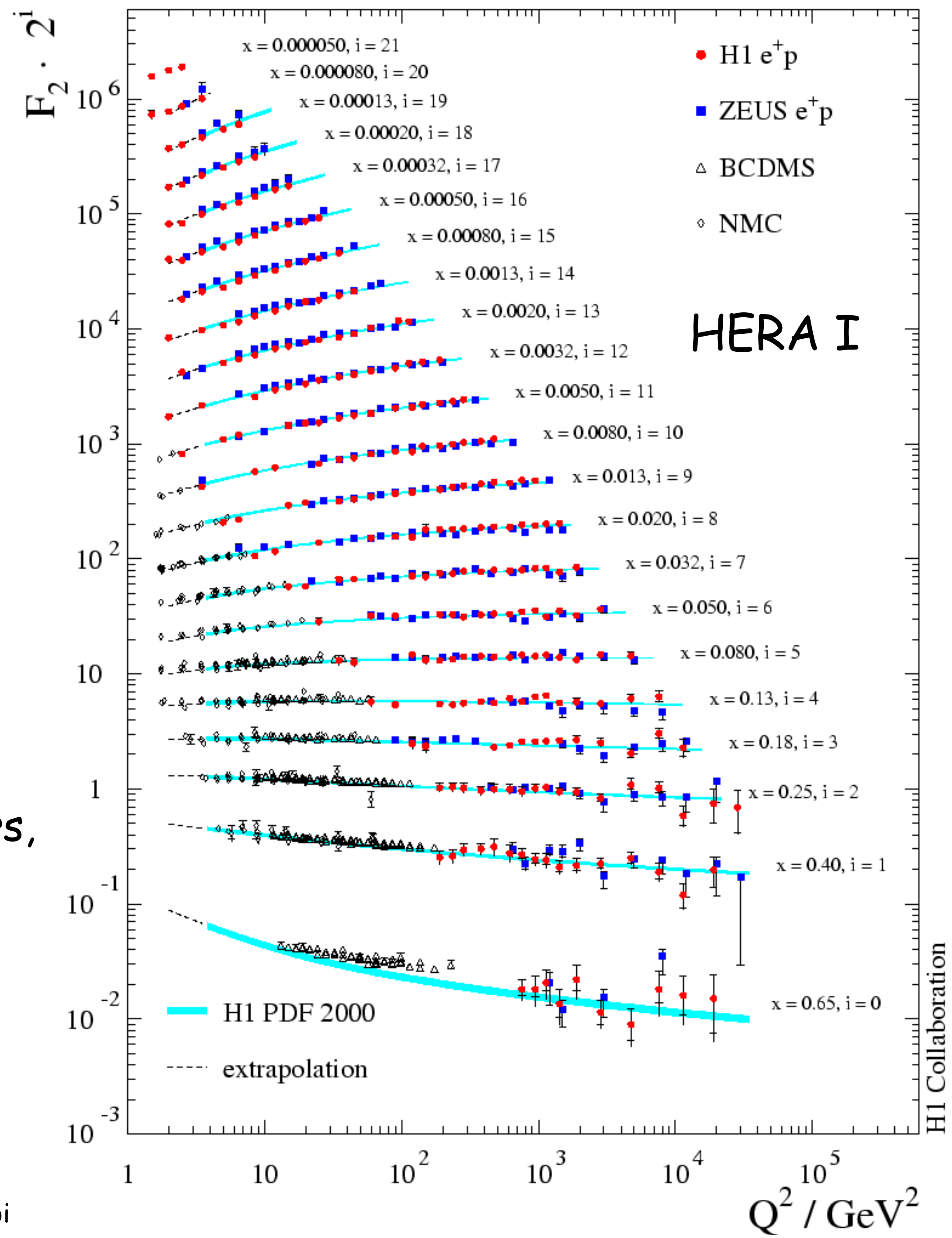
$$F_2(x) = \sum_i e_i^2 x f_i(x, Q^2)$$

- Parameterize parton densities, typically

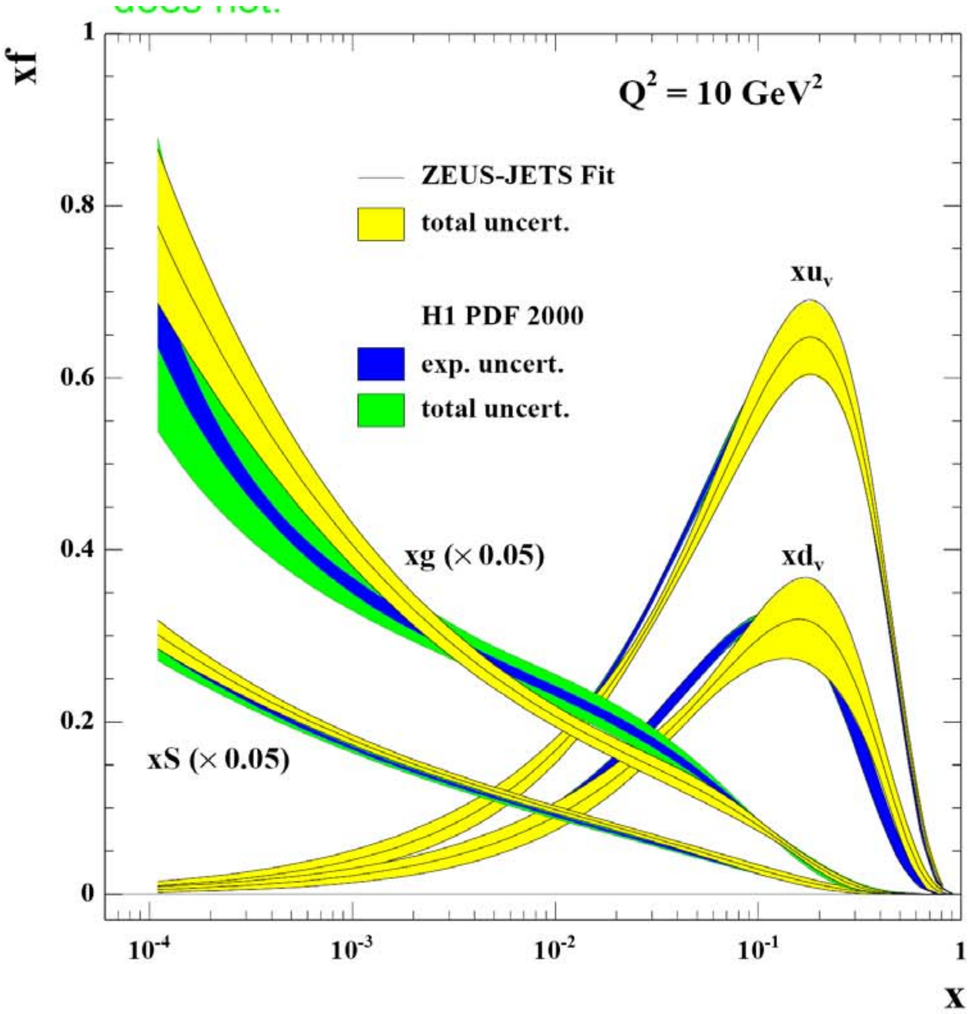
$$xf(x, Q_0) = Ax^B (1-x)^C \left[1 + D\sqrt{x} + Ex\right]$$

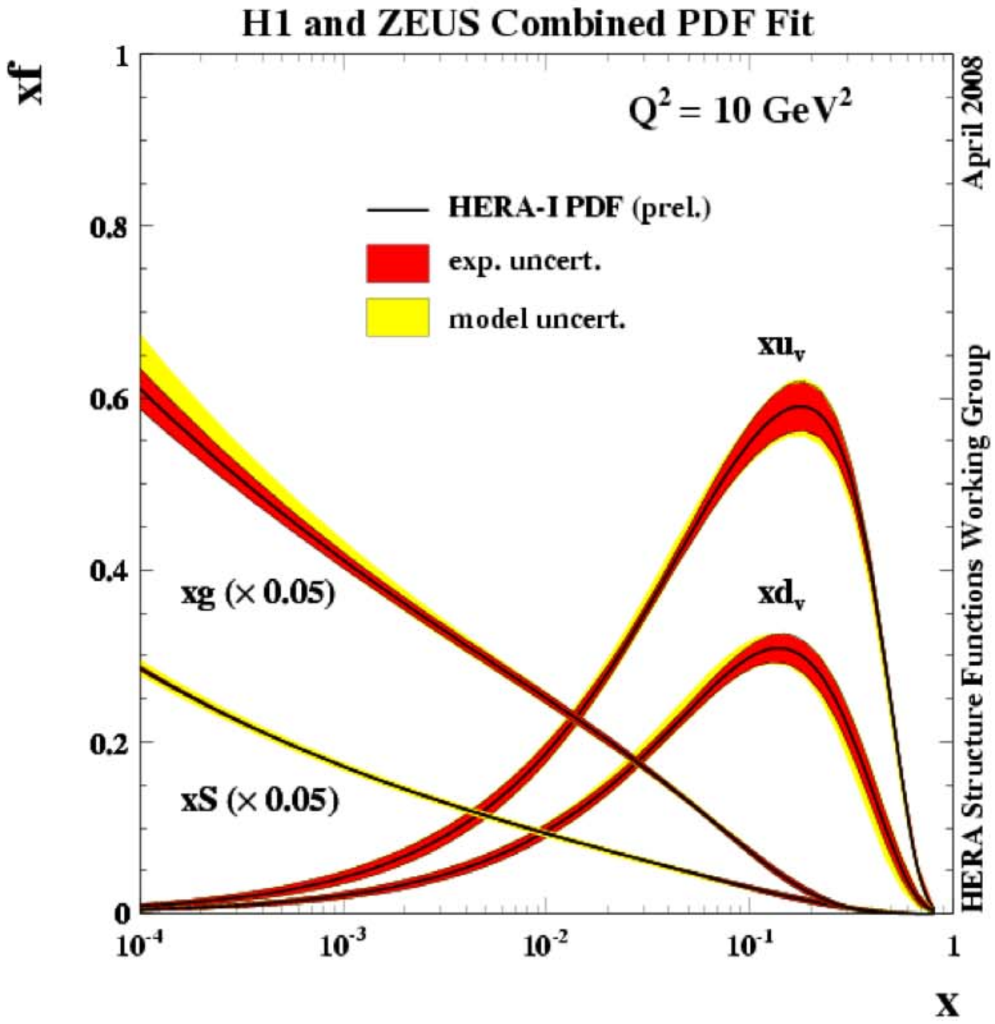
- Fit data to obtain the various parameters, evolution in Q^2, using DGLAP equations

Data are very well described by QCD



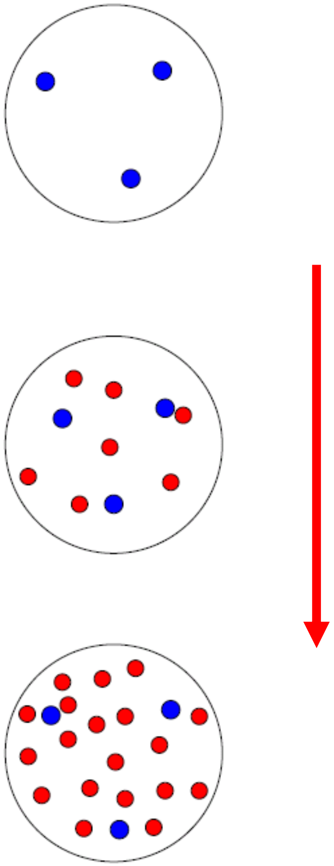
Parton densities: First Combined Fit of H1 and ZEUS data





Precise determination of pdf's down to x ~ 10^{-4}

Low x, Large Parton Densities and Saturation



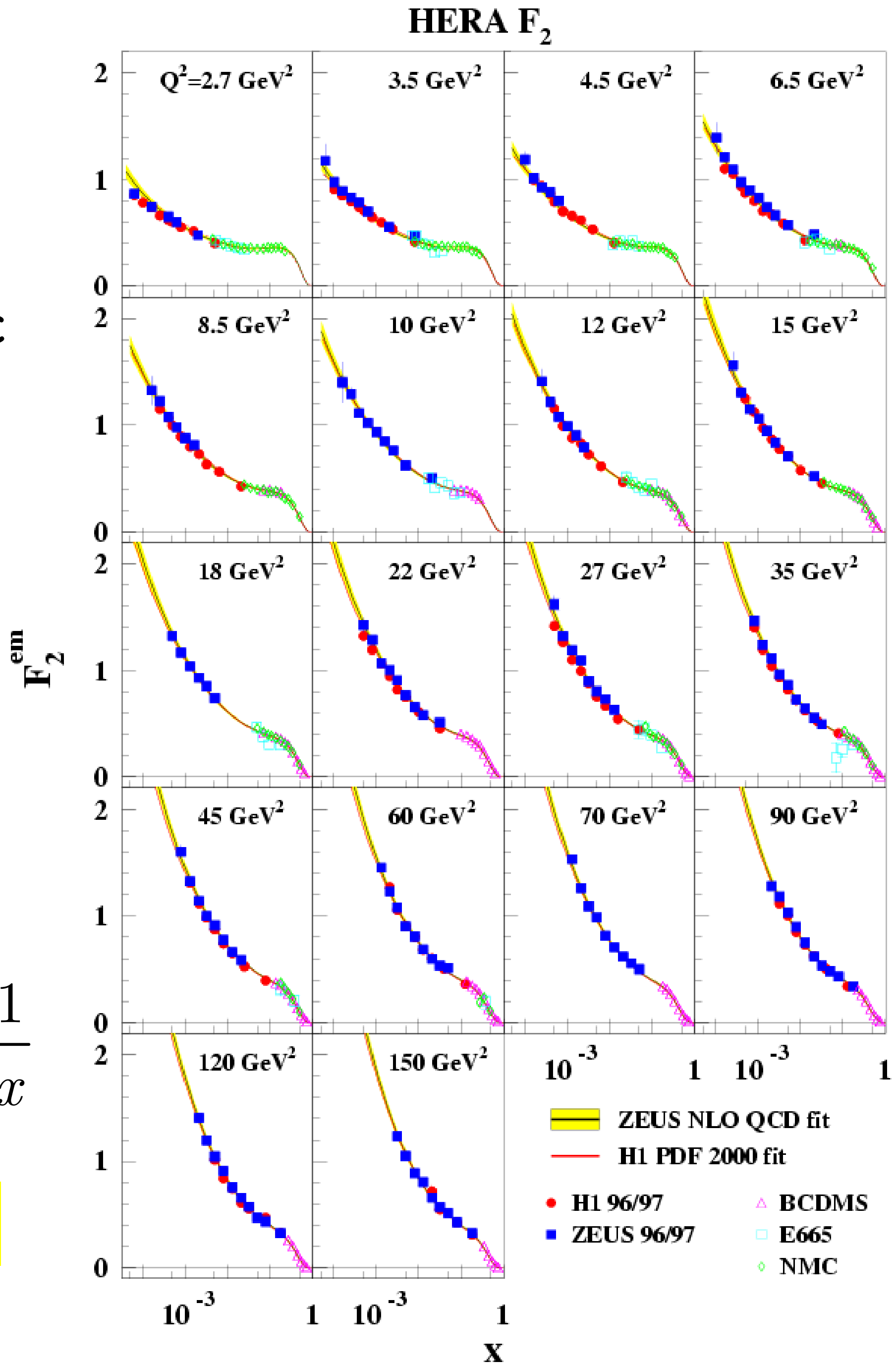
at fixed resolution scale (Q^2) go to very large hadronic center of mass energy

low x $$x = \frac{Q^2}{Q^2 + W^2}$$

ultimately expect parton overlaps („saturation")

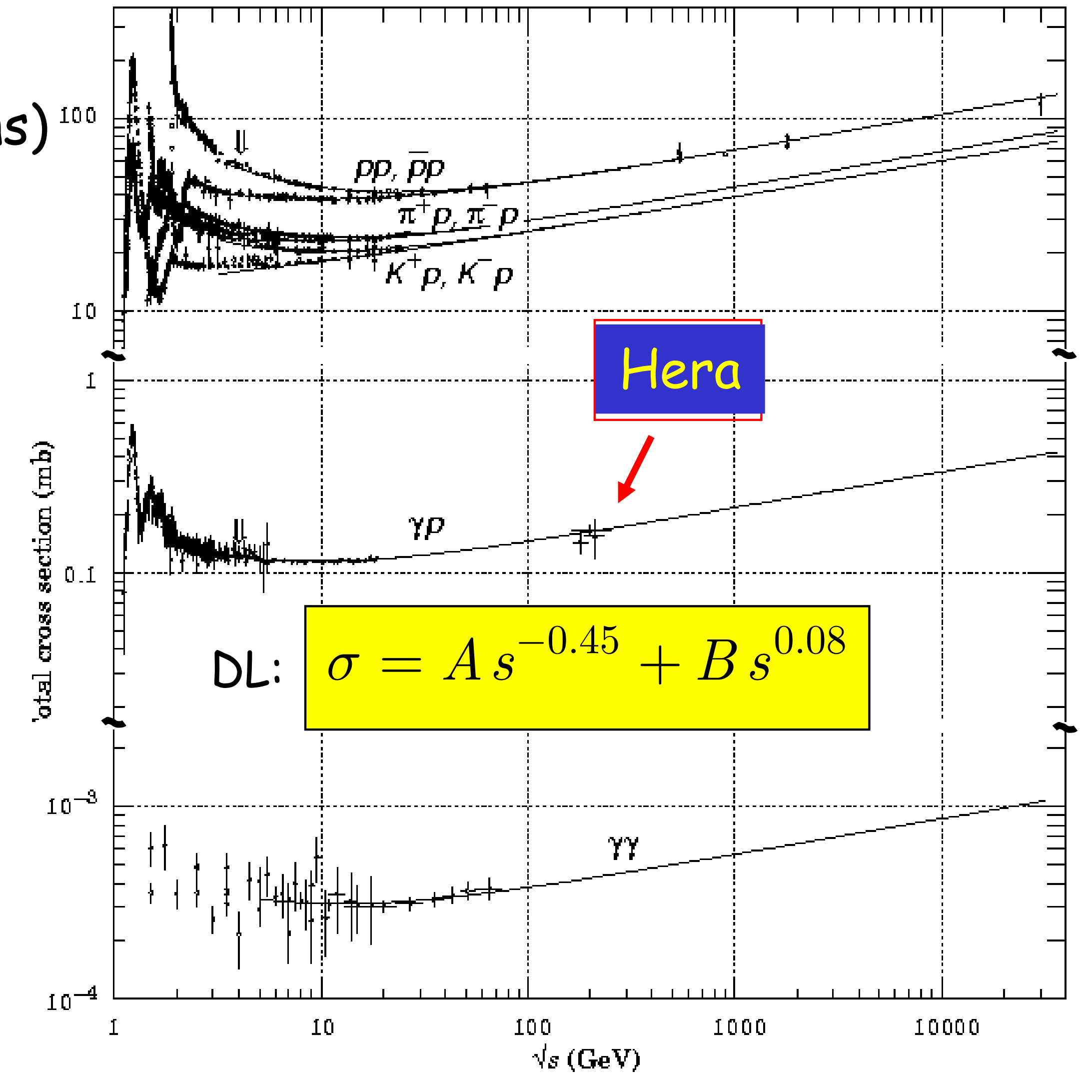
Rise of pdf should flatten with decreasing x $$\left(\frac{1}{x}\right)^{\lambda} \rightarrow \ln\frac{1}{x}$$

No saturation oberserved at HERA

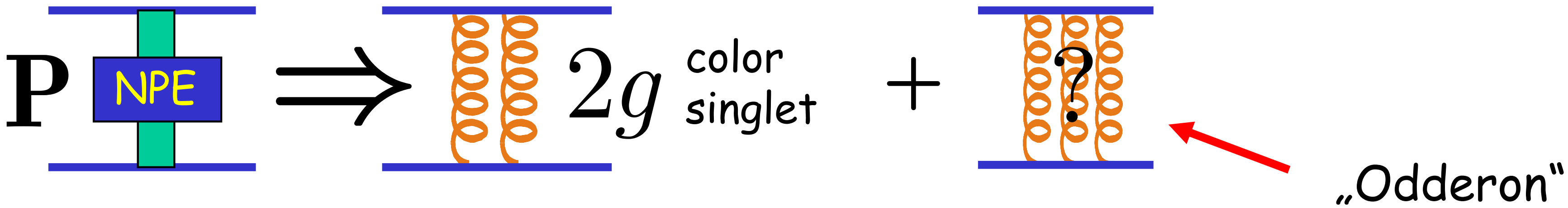


Diffraction

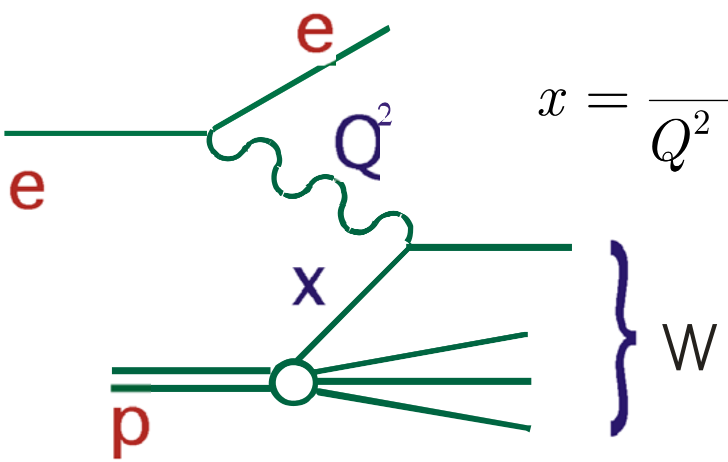
- All total cross sections involving strongly interacting particles (hadrons) show approximate constancy, more precisely: a universal slow rise towards high energy
- „constant" cross sections arise from Diffractive Phenomena
- (non-perturbative) Regge theory: trajectory in the t-channel
  vacuum QNE = „Pomeron"
- pert. QCD: colorless exchange
  Gluons, quarks in a color singlet ?



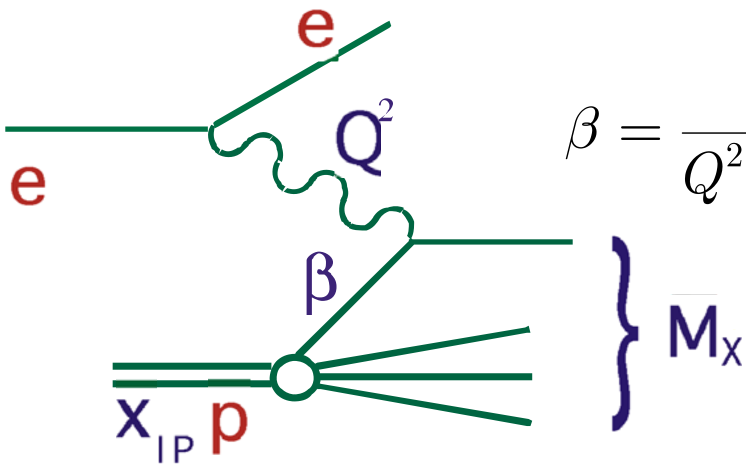
DL: $\sigma = A\, s^{-0.45} + B\, s^{0.08}$



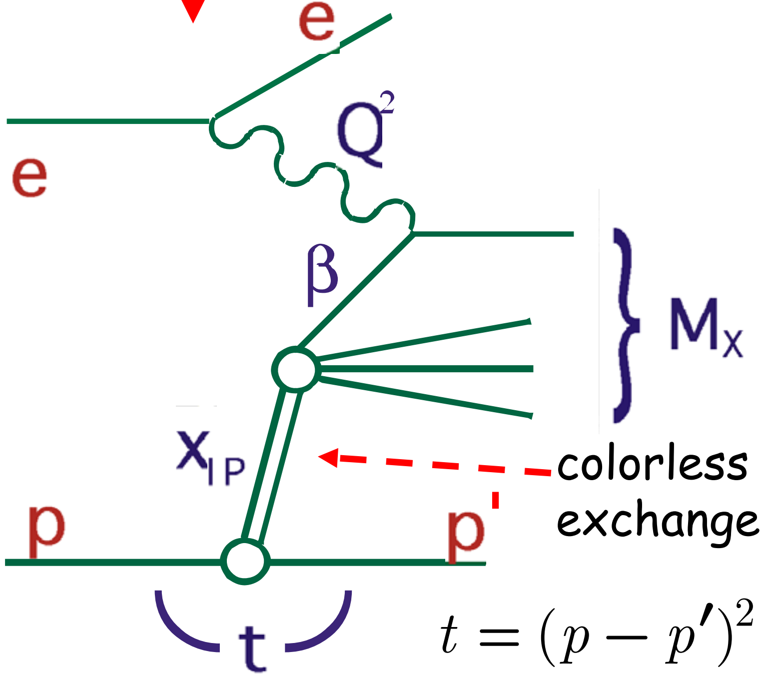
From Inclusive Scattering to Diffraction: Kinematics



$$x = \frac{Q^2}{Q^2 + W^2}$$



$$\beta = \frac{Q^2}{Q^2 + M_X^2}$$



$$x_{\mathbf{P}} = \frac{Q^2 + M_X^2}{Q^2 + W^2}$$

x (DIS) $\Leftrightarrow$ β (Diff. DIS)

momentum fraction of color singlet exchange relative to the proton

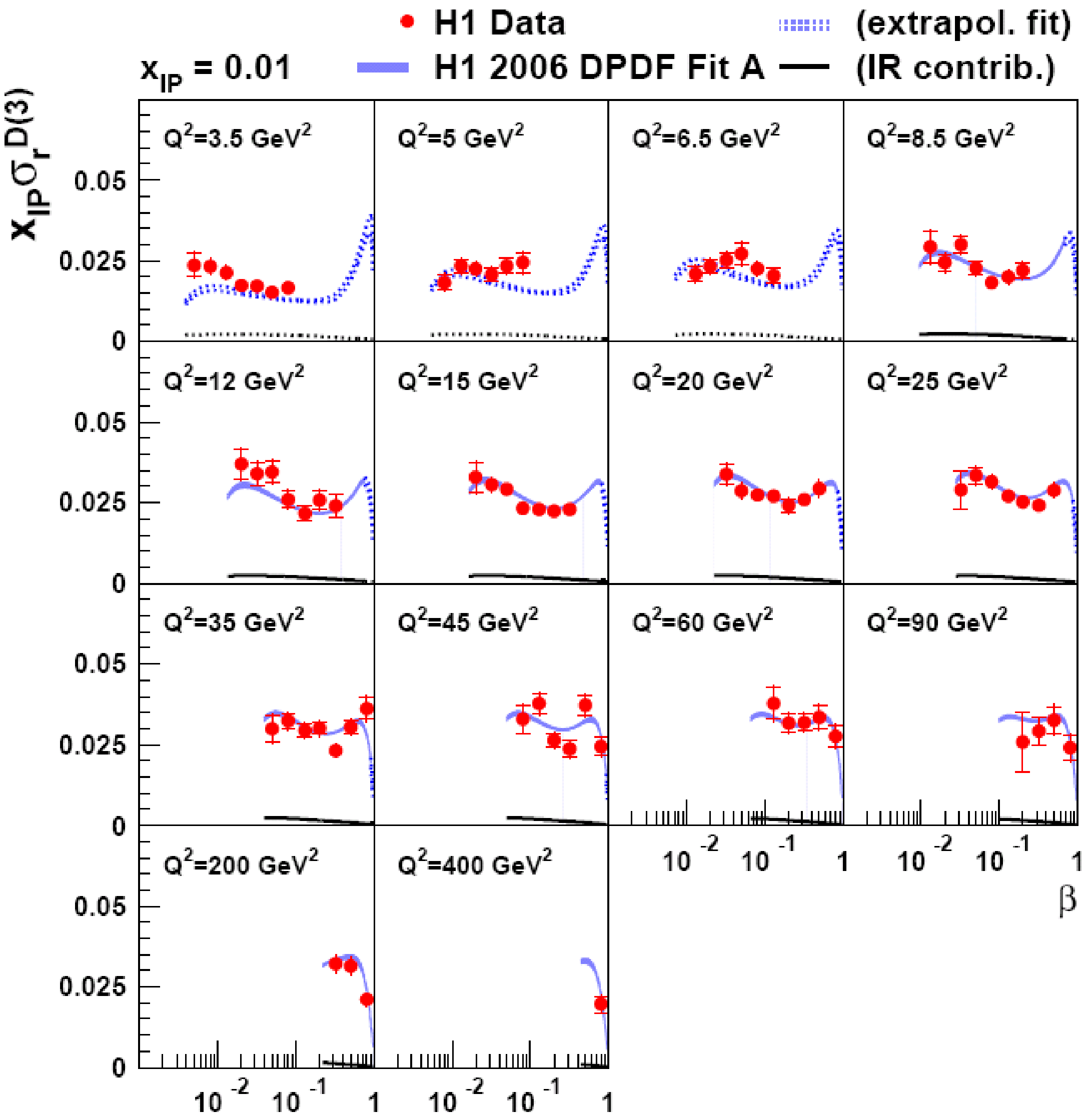
$$\beta = \frac{Q^2}{Q^2 + M_X^2} = x \,/\, x_{\mathbf{P}}$$

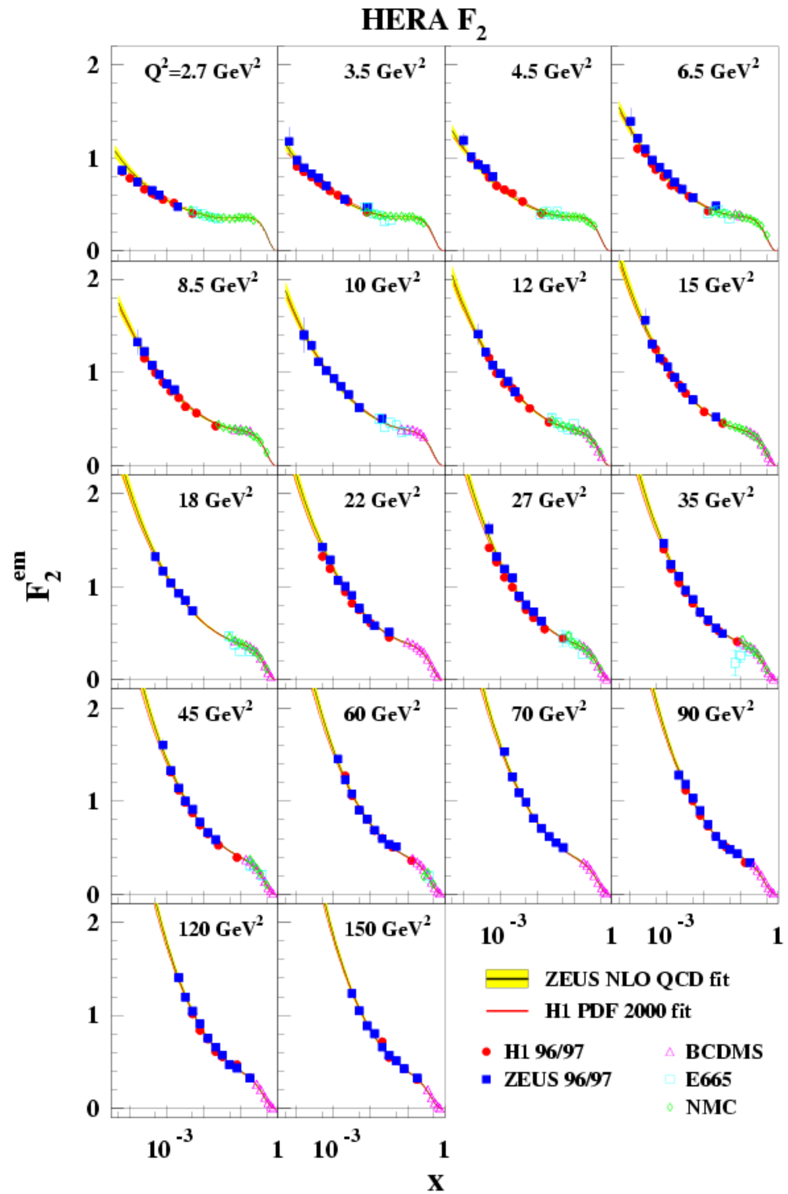
momentum fraction of charged constituent of the diffractive exch., participating in the hard scattering

$t = (p - p')^2$ (momentum transfer)^2 at proton vertex

Diffractive vs Inclusive DIS: x-dependence

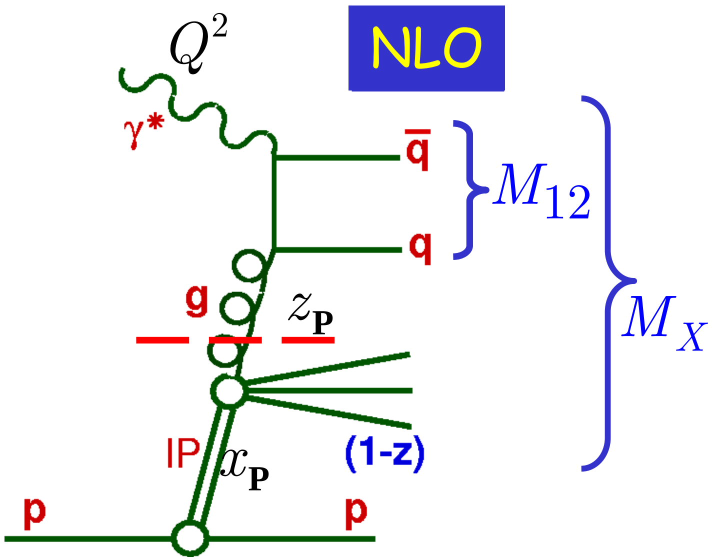
β (Diff. DIS) $\Leftrightarrow$ x (DIS)





weak dependence on β , similar to the photon (few partons ?)

Partonic Structure of Diffraction from the Inclusive Data

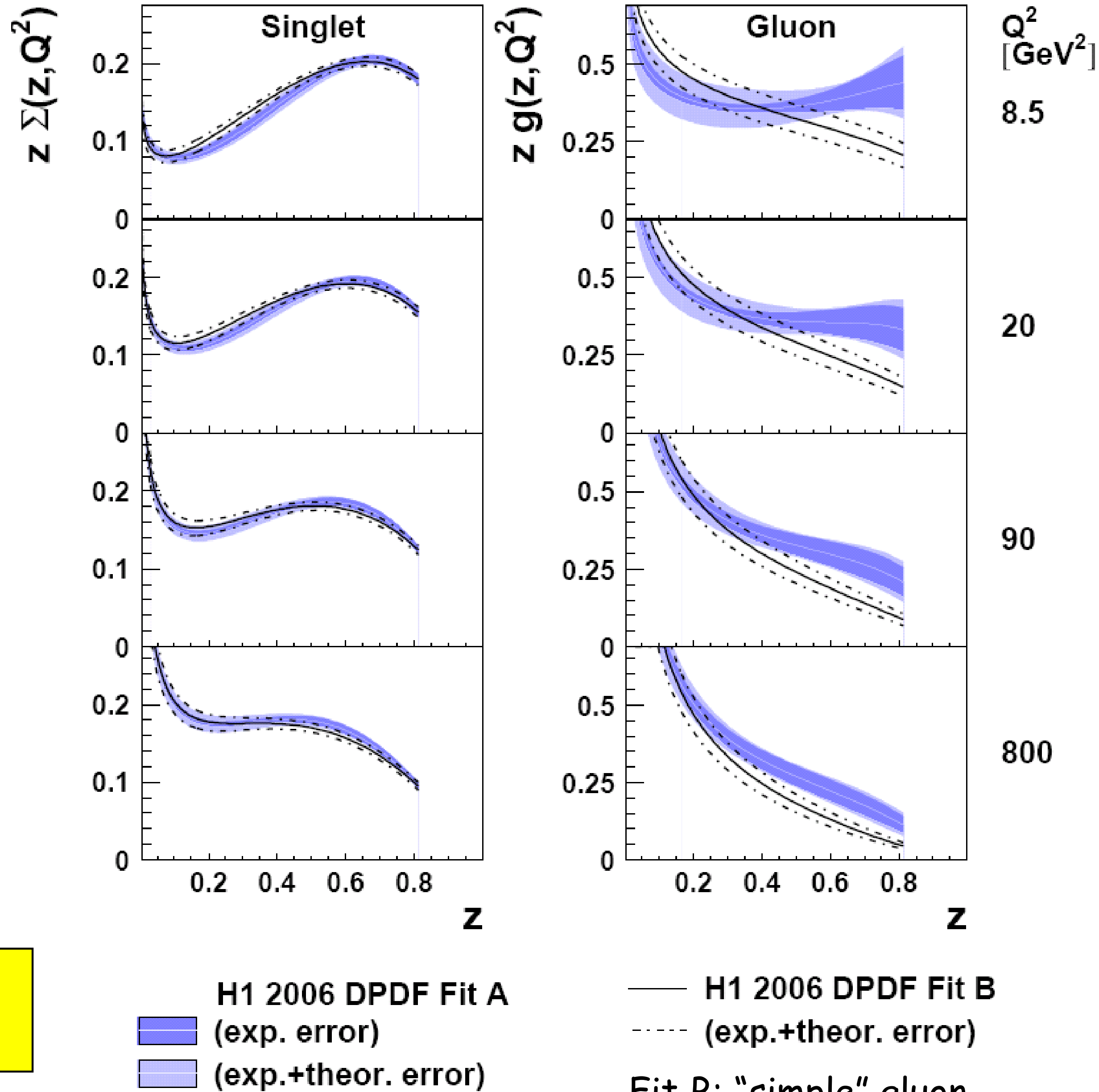


$$z_{\mathbf{P}} = \frac{Q^2 + M_{12}^2}{Q^2 + M_X^2}$$

Gluon momentum fraction:

$$(\mathbf{70} \pm \mathbf{5})\,\%$$

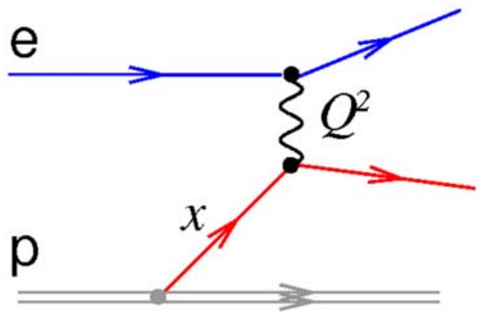
Diffraction is gluon-dominated

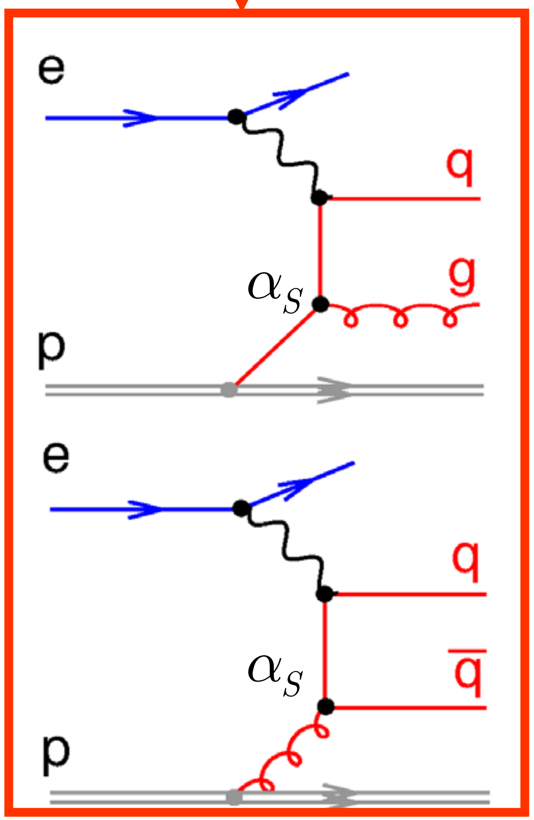


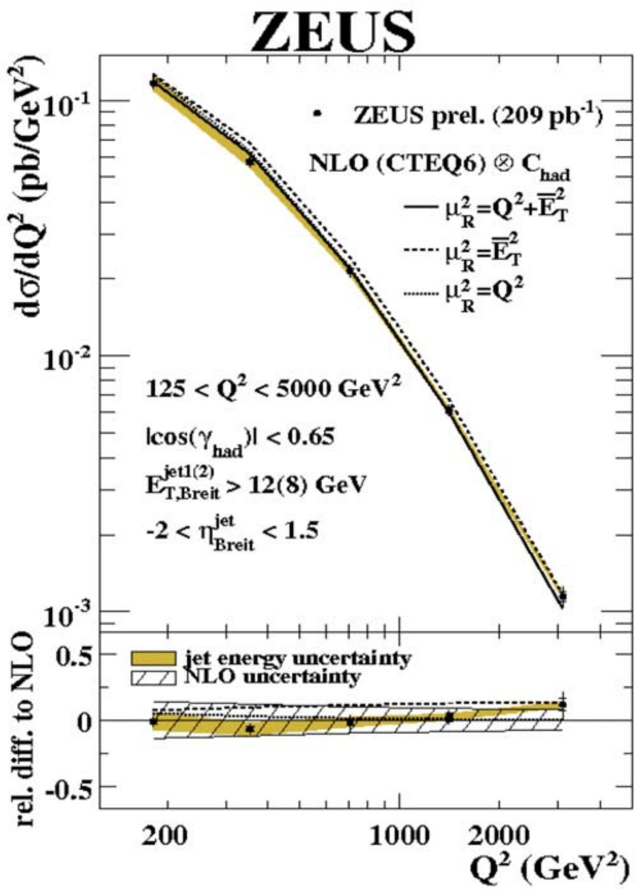
Fit B: "simple" gluon

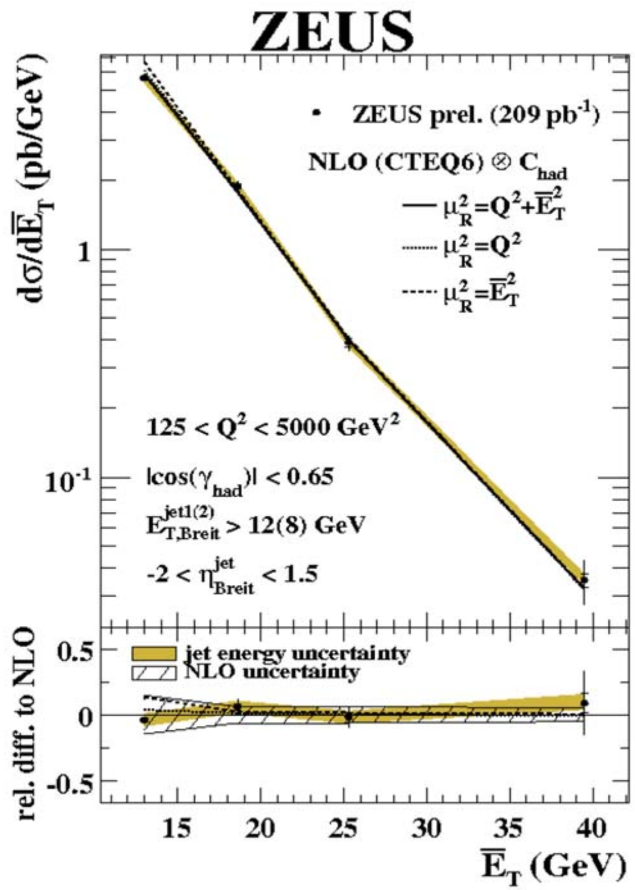
Jets at HERA

Dijets (and Multijets)





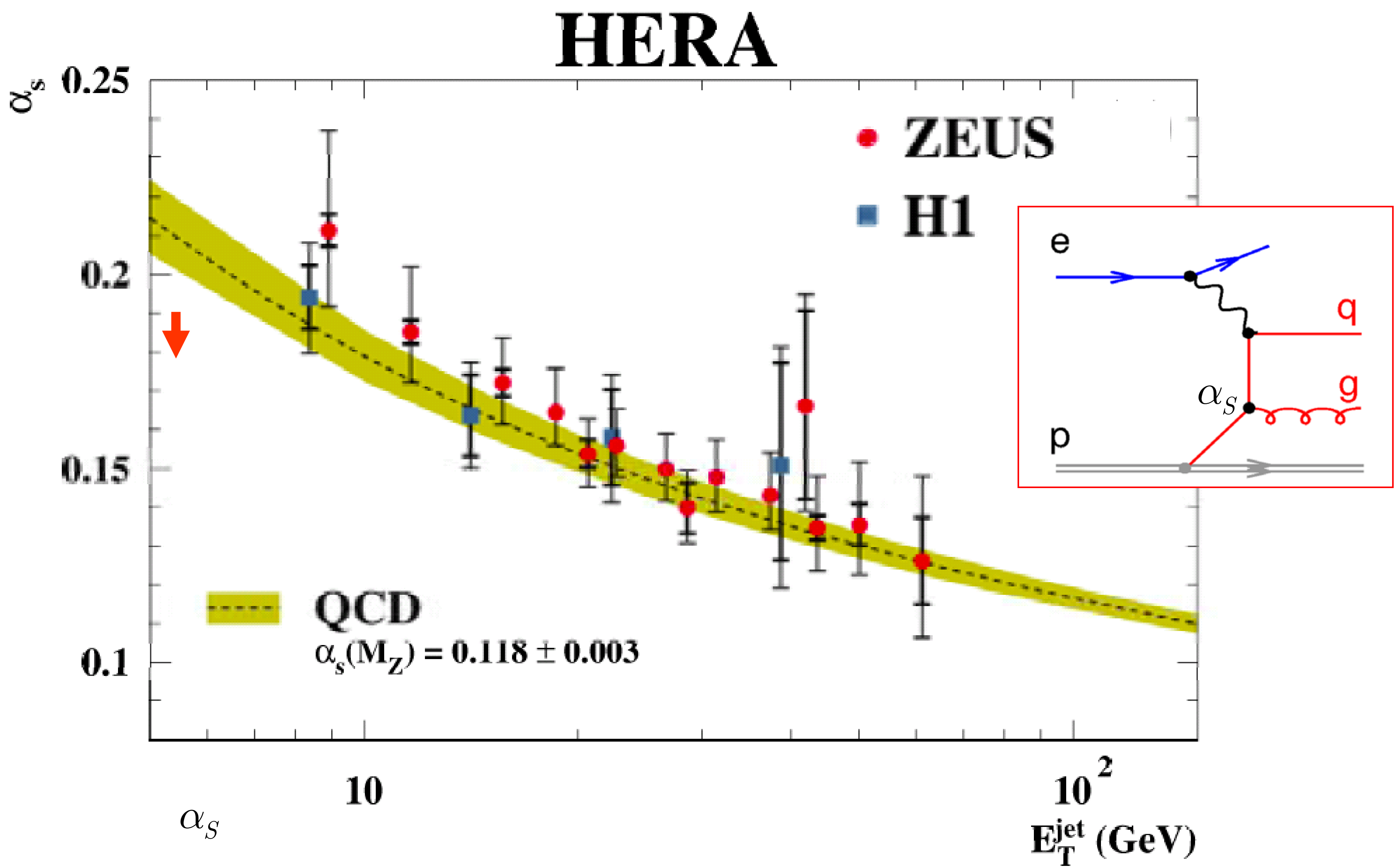




2 „hard scales“: Q^2 and E_T(jet)

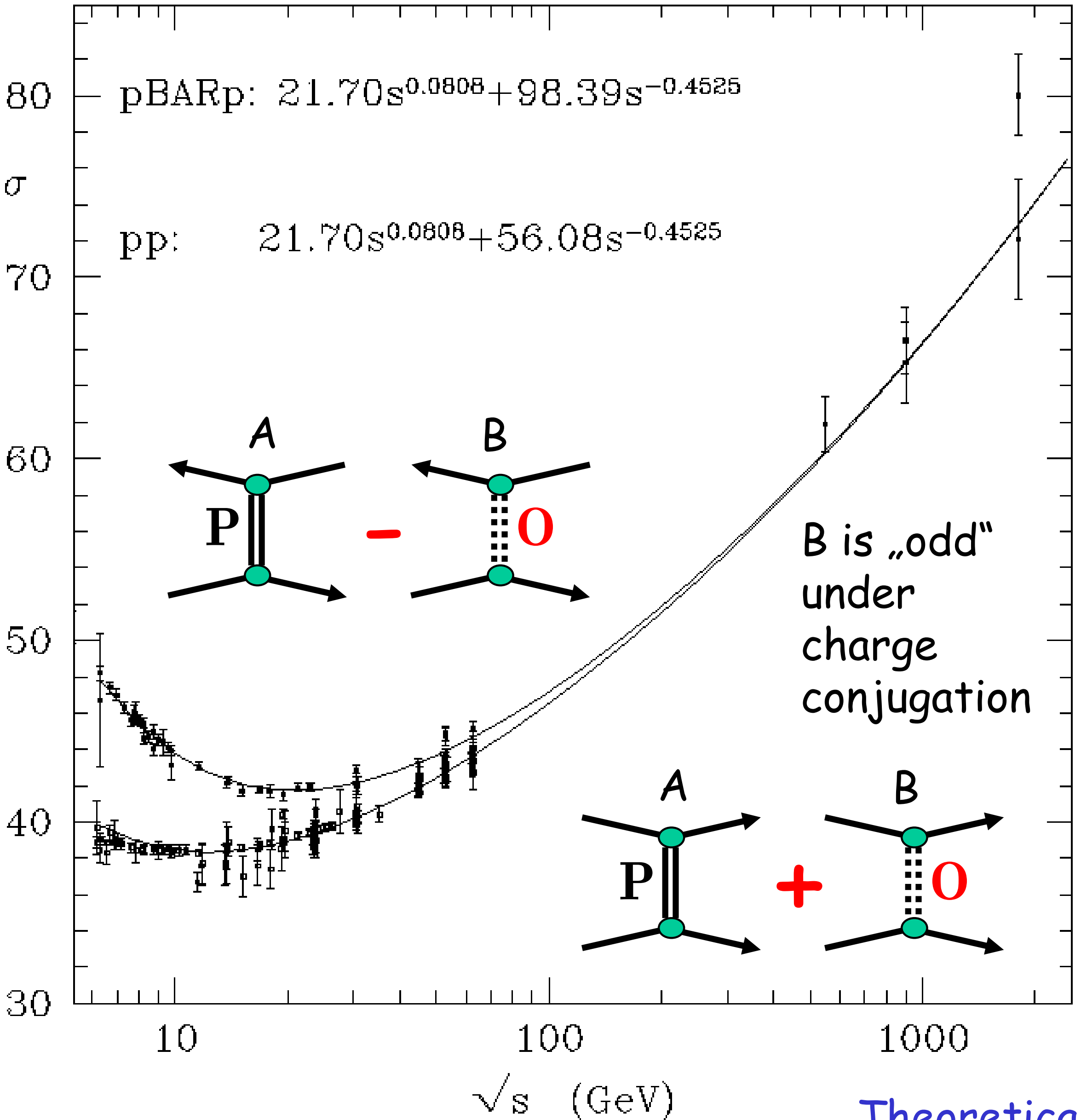
NLO prediction describes data very well !

Strong Coupling, from Jet Variables



Running of α_S observed in a single experiment!

The Odderon



invented by Lukaszuk and Nicolescu (1973) to account for possible differences in hadron-hadron and antihadron-hadron scattering at High En.

If B non-zero at high energies, i.e. a diffractive amplitude:

$$\Delta\sigma = \sigma(pp) - \sigma(\bar{p}p) \neq 0$$

for $s \rightarrow \infty$

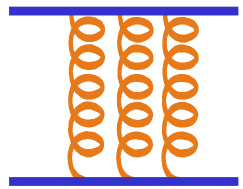
Experimental difficulties (due to presence of the Pomeron):

- Subtraction of 2 large numbers
- No data on pp at high energy !

Theoretical problem: Odderon possibly suppressed in pp reactions

Do we need an Odderon ?

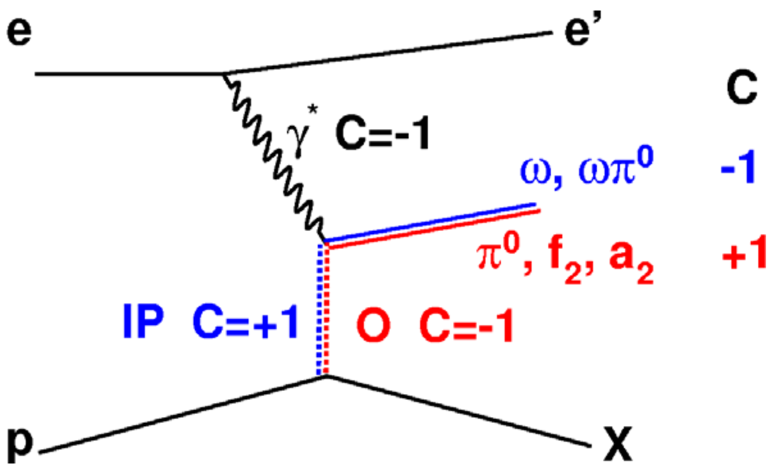
→ firm prediction from pQCD: 3-gluon state with $C = P = -1$



If so, how to find it :

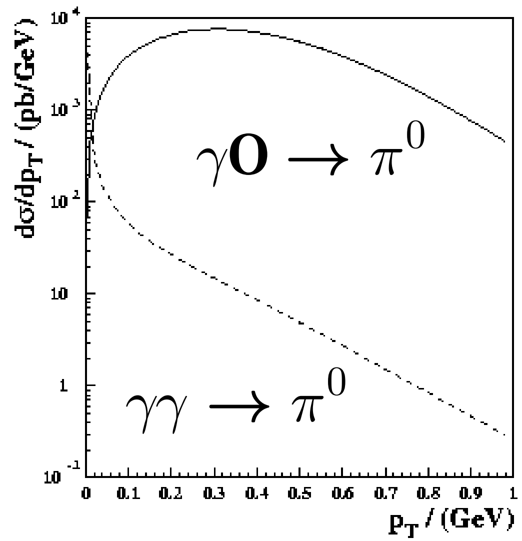
HERA is an ideal place to study the Odderon:

- very high photon-proton center-of-mass energies (up to 300 GeV)
- can select exculsive processes where the Pomeron cannot contribute (thus measure a potential Odderon contribution directly, no subtraction)
- theoretical (non-pQCD) model exist for exclusive processes: E. R. Berger, A. Donnachie, H.G. Dosch, W. Kilian, O. Nachtmann, M. Rueter

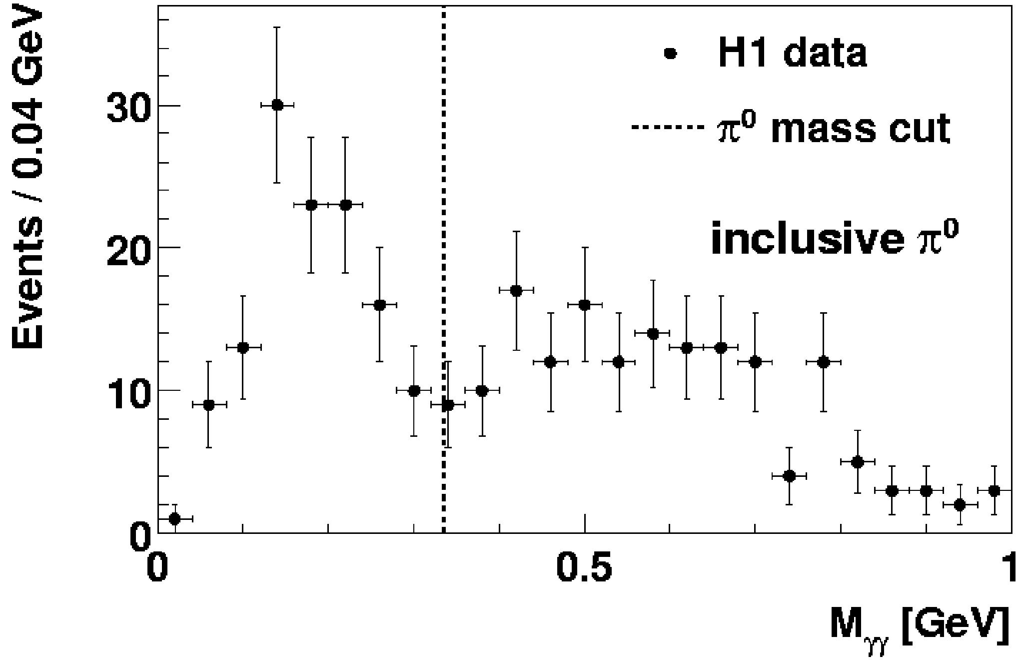


Cross section NOT suppressed if state X is a negative-parity baryon (e.g. N^*)

Cross sections for f_2, a_2 an order of magnitude smaller



Exclusive π^0 Photoproduction

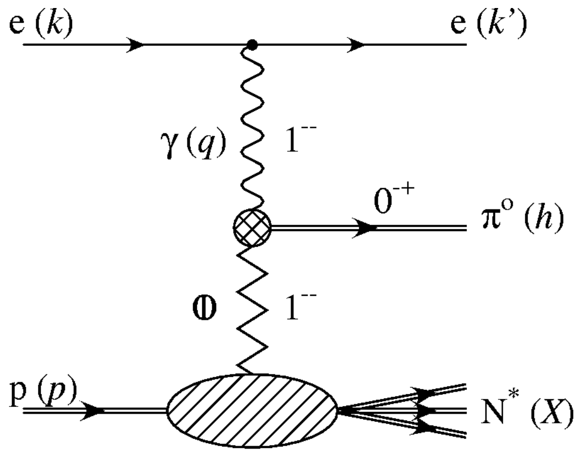


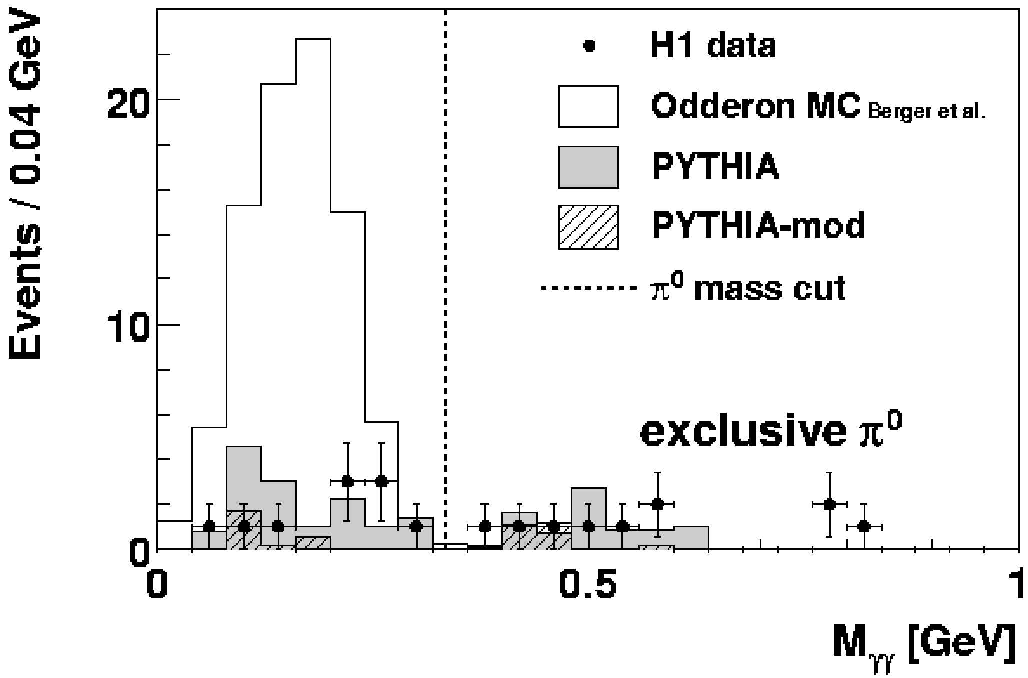
$$ep \to eX\pi^0$$

inclusive pion signal

after cut for exclusive state:

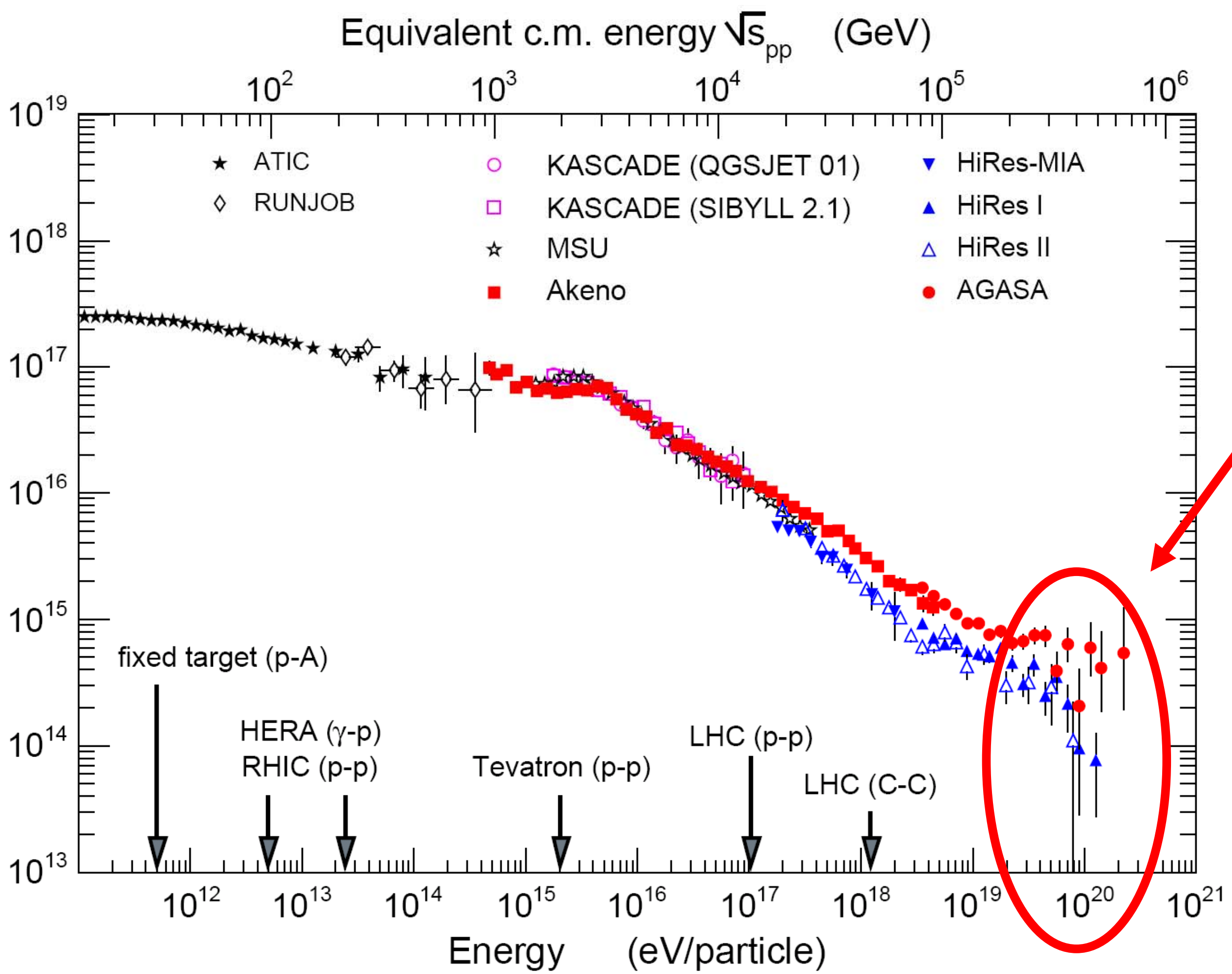
$$ep \to e'N^*\pi^0$$





Expected signal from Berger et al. model is not seen

Cosmic Ray Events beyond the GZK Limit ?



Greisen Zatsepin Kuzmin:

CR have natural limit of energy, when source is far away (> 50 Mpc)

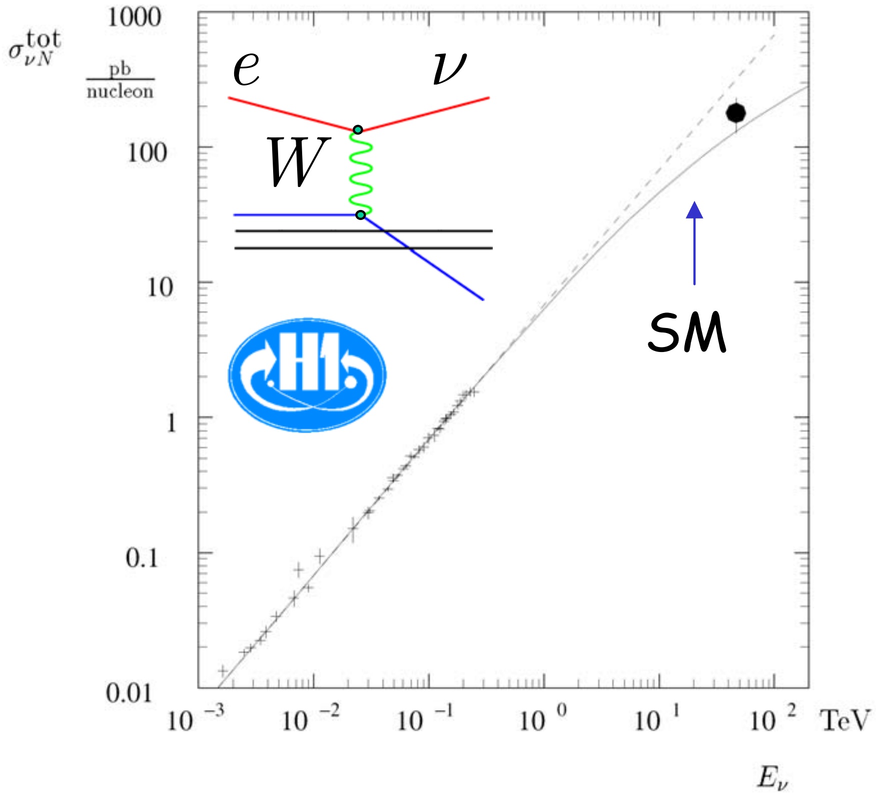
Collisions of primary protons with the photons from the microwave background:

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+$$
$$\rightarrow p\pi^0, n\pi^+$$
$$\pi^+ \rightarrow \mu^+\nu_\mu$$

No such limit for neutrinos!

If neutrinos generate the spectrum, they must have a large (strong!) cross section

Cross Sections for VHE Neutrinos

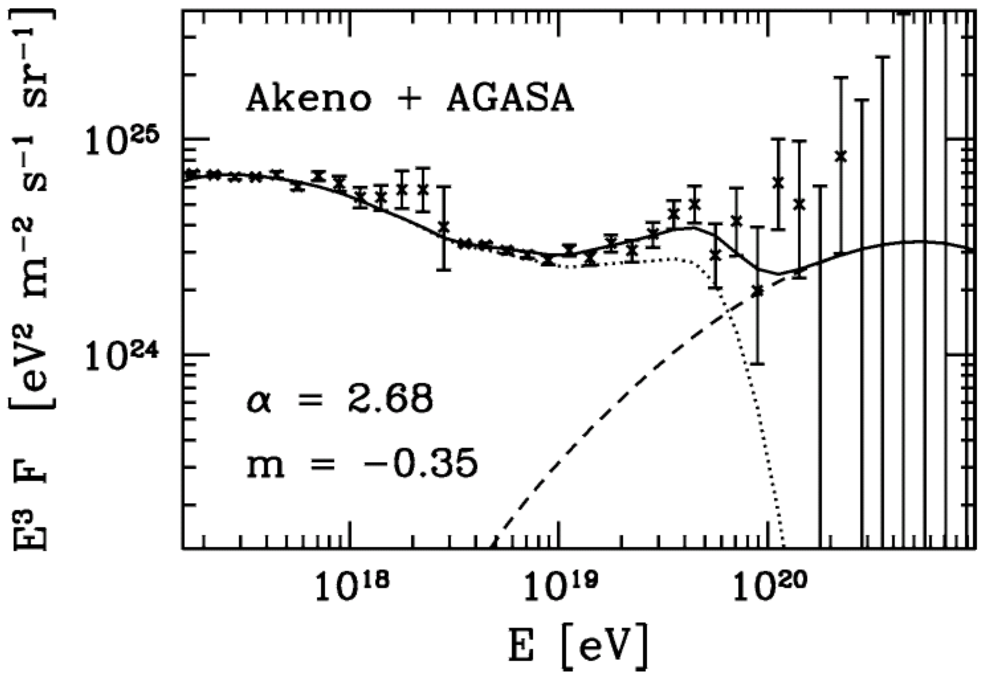


HERA data (1994 and ever since):

Neutrino cross sections are as expected up to 50 TeV (~ 1013 eV)

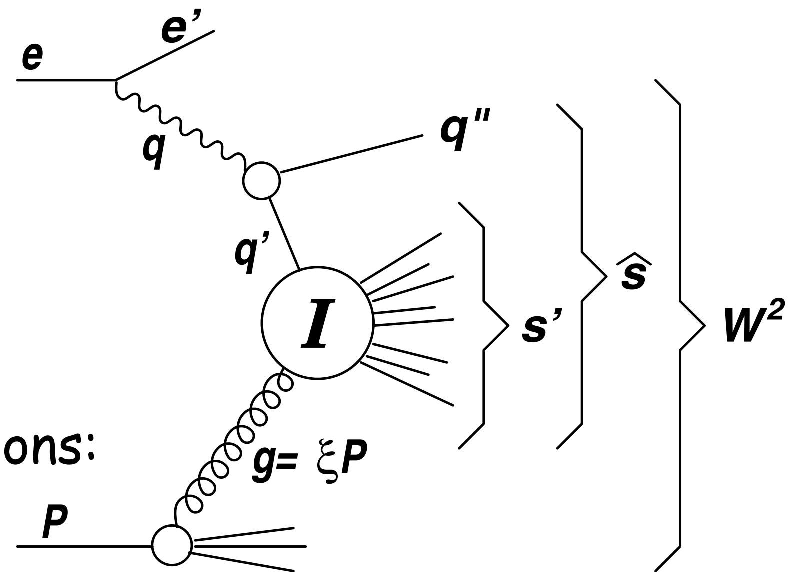
Fodor, Katz, Ringwald, Tu (2004)

EW Instanton effects may produce O(mb) cross sections for neutrinos on protons:



Searches for Instanton-induced Events at HERA

Non-Abelian Gauge Theories:
degenerate vacua of different topology
allow for non-perturbative transitions



- "Instantons"
  suppressed by exp(-4π/α):
  hopeless for EW at HERA
  but very interesting for strong interactions:

  ⇒ $\alpha \longrightarrow \alpha_S$

QCD instantons (Ringwald & Schrempp): $Q'^2 = -q'^2, \quad x' = Q'^2 / (2g \cdot q')$

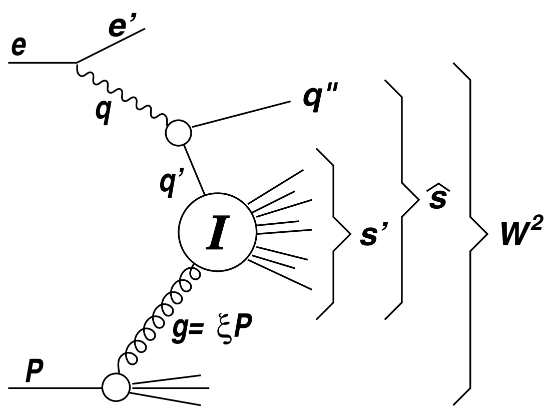
$$d\sigma_{q'g}^{(I)}(x', Q^2) \cong \frac{\Sigma(x')}{Q'^2} \left(\frac{4\pi}{\alpha_S(\mu(Q'))} \right)^{21/2} \exp\left[-\frac{4\pi}{\alpha_S(\mu(Q'))} F(x') \right]$$

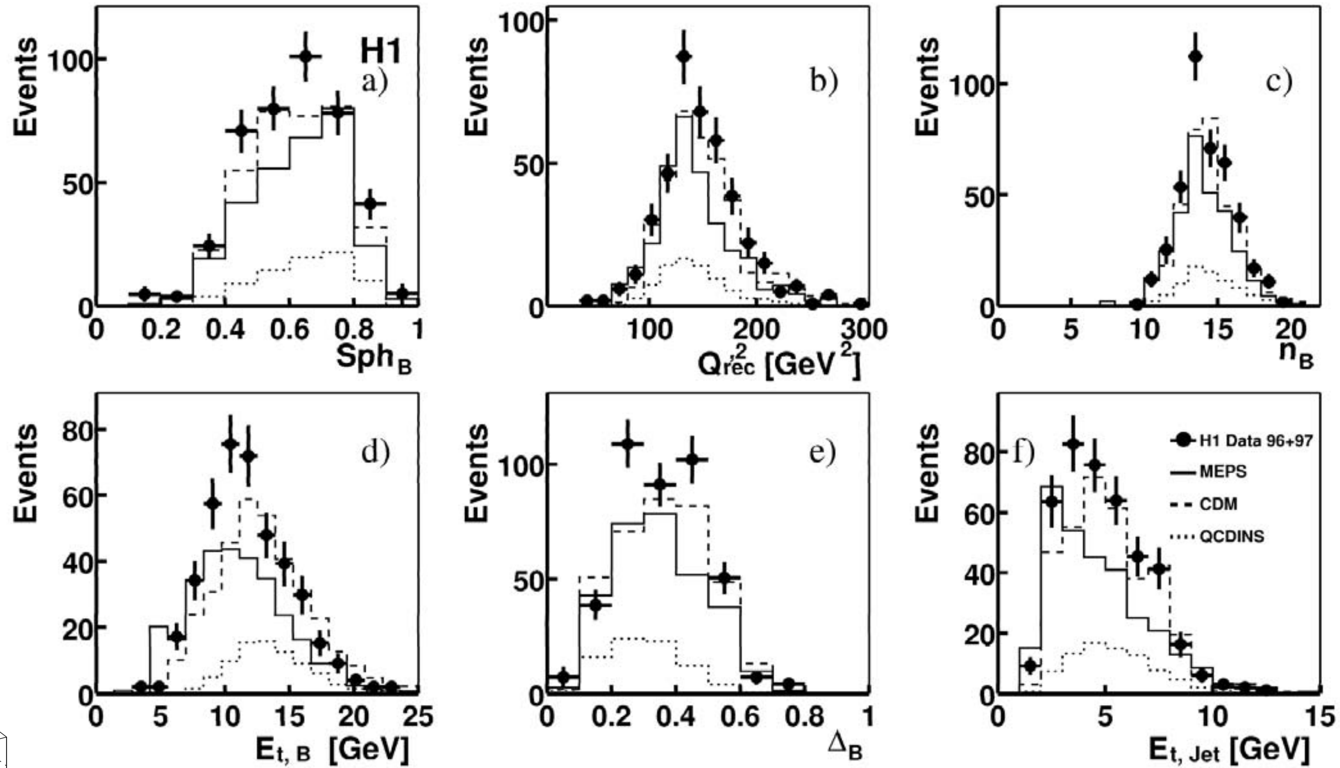
- Instanton cross section enhanced by gauge boson emission ("fireball events")
- "Holy Gral" function $F(x')$ decreases with x'

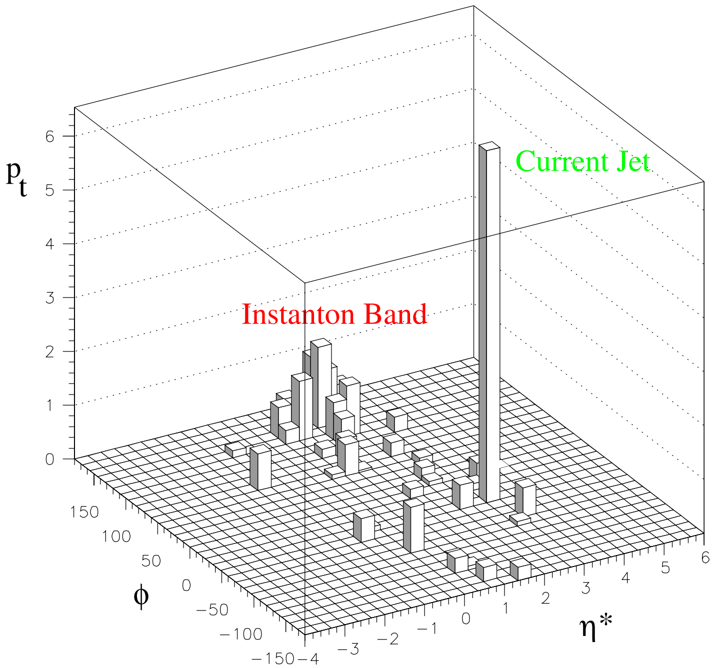
BUT: calculations for $F(x')$ very uncertain for $x' < 0.2$

Expected
rate ~ 1/1000

Event Shape Variables





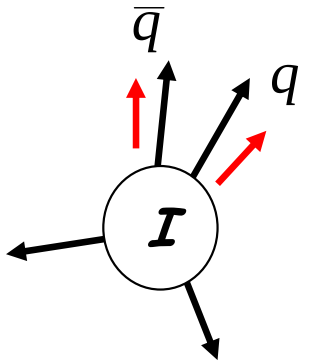


multi-variate analysis using shape variables, (here from H1)

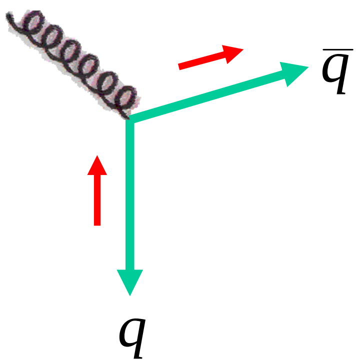
ZEUS limit: $\sigma < 29$ pb (8.9 pb predicted)

Instanton not excluded with early (L ~30 pb^{-1}) HERA data

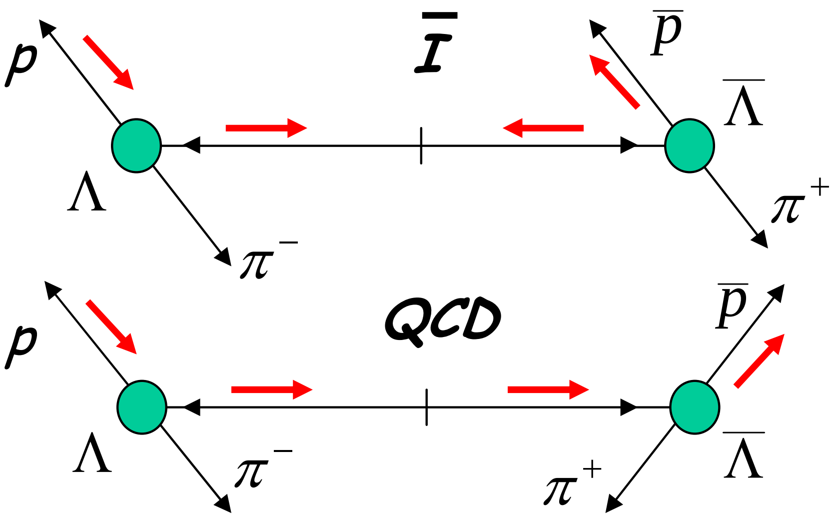
A unique signature of Instantons: Chirality Violation

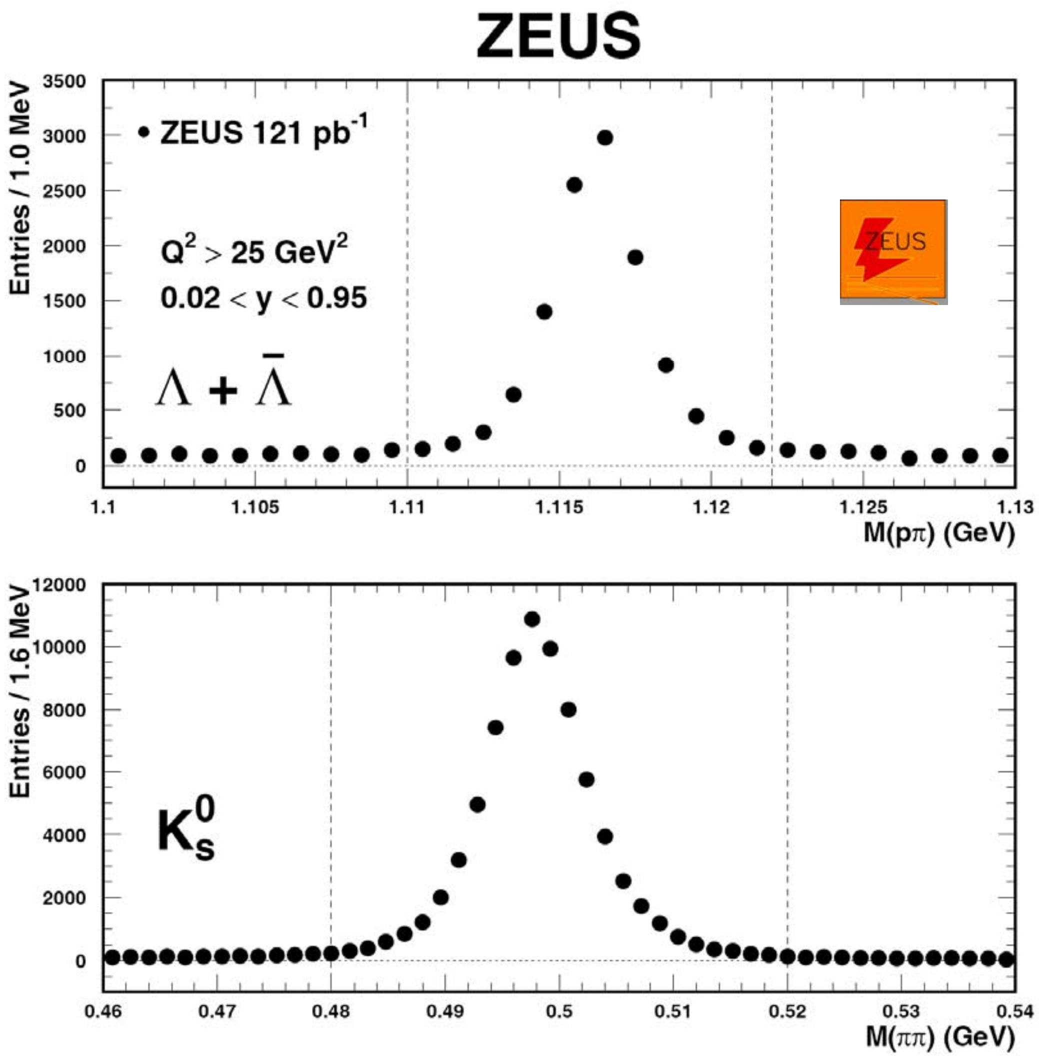


Instantons:
all fermions and antifermions have the same helicity



QCD:
fermions and antifermions have opposite helicity





Look for $\Lambda, \bar{\Lambda}$ events with full HERA stat.
(15 times more data now)

No limit in Q^2 needed: use photoproduction!!

Summary and Conclusions

HERA provides an equivalent of a 50 TeV photon beam.
-> beautiful test laboratory for UHE γ-rays
-> very useful input for models of CR interactions with matter

- Precise set of proton pdfs exist (for $x > 10^{-4}$), the gluon dominates the low x regime. no sign of parton saturation.
- Diffraction, contributing a large part of the cross section in soft hadronic interactions, is also a substantial part of hard scattering at HERA. QCD models based on colorless gluon exchange work nicely.
- DGLAP evolution verified to NLO, exception possibly in forward jets
- Odderon responsible for possible differences of particle and antiparticle cross sections on matter: no sign of the Odderon
- CRs beyond the GZK limit (if they exist) could be from neutrinos with „strong interaction" cross section, caused by Instantons: not yet excluded