

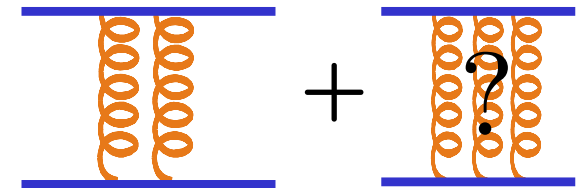
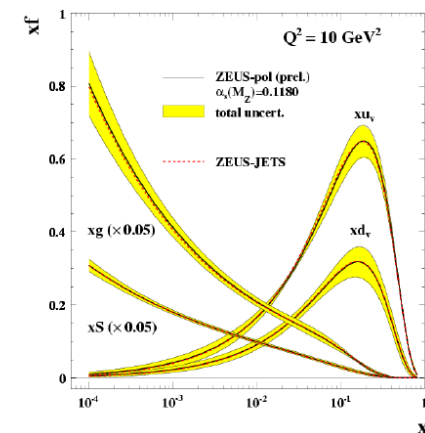
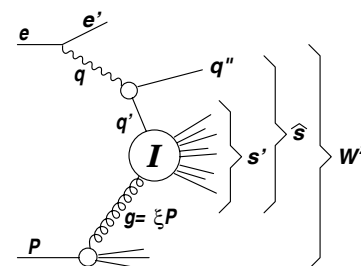
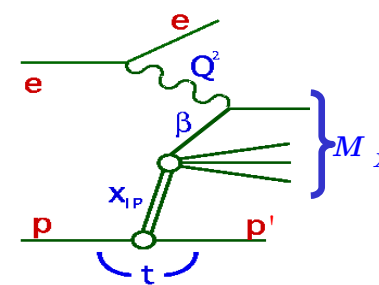
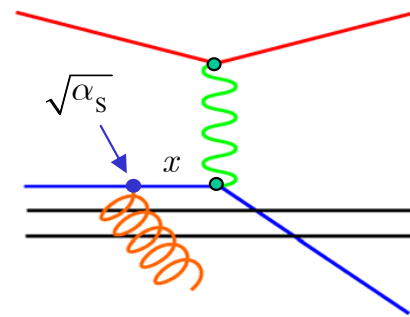
Implication of the HERA Measurements on Astroparticle Data Interpretation



Christian Kiesling
Max-Planck-Institute for Physics, München



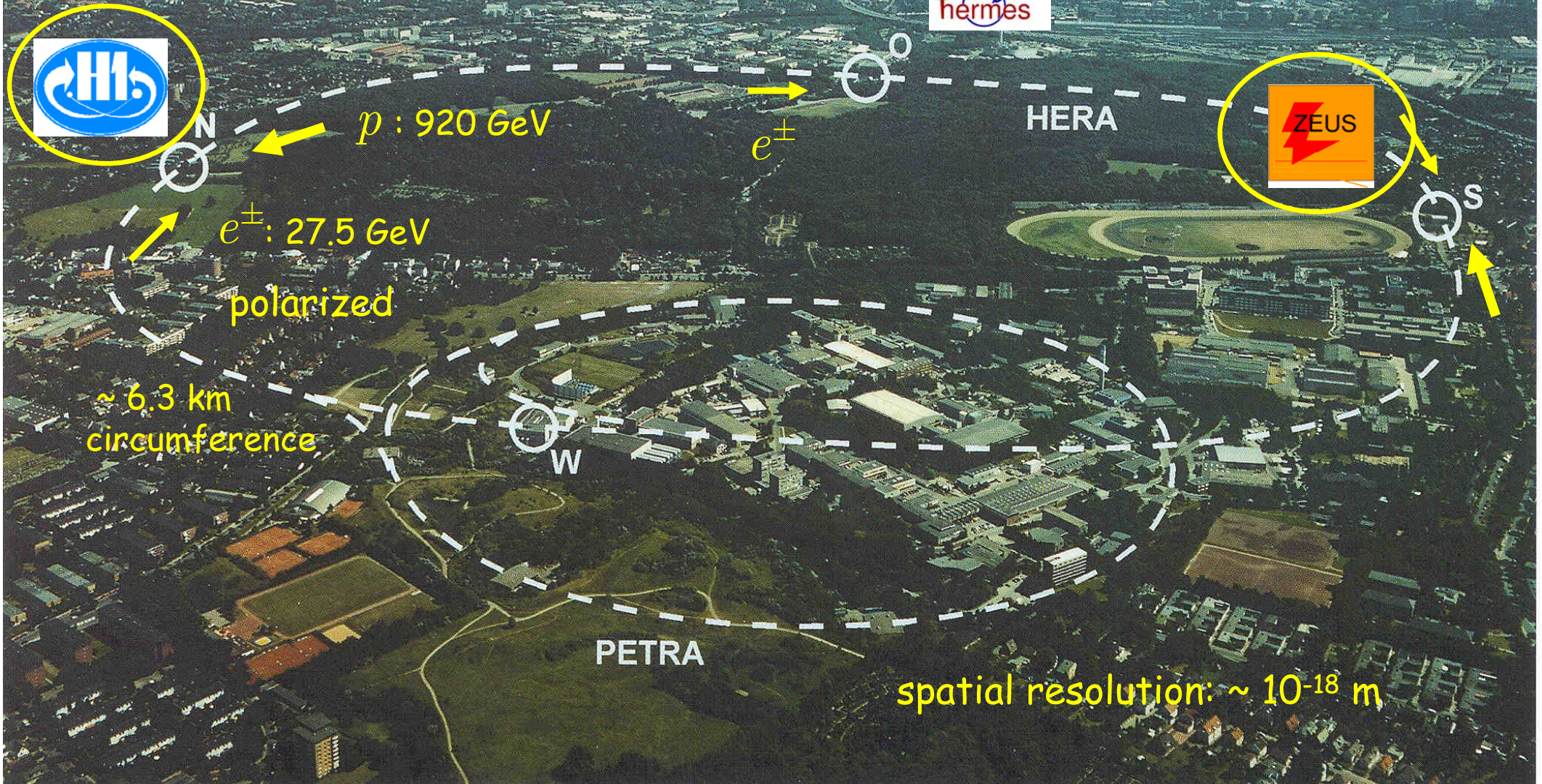
- HERA, the QCD-machine
- Inclusive Scattering
- Diffraction at HERA
- Hadronic Final States (Jets)
- Pomeron and Odderon
- Instanton Effects
- Summary and Conclusions



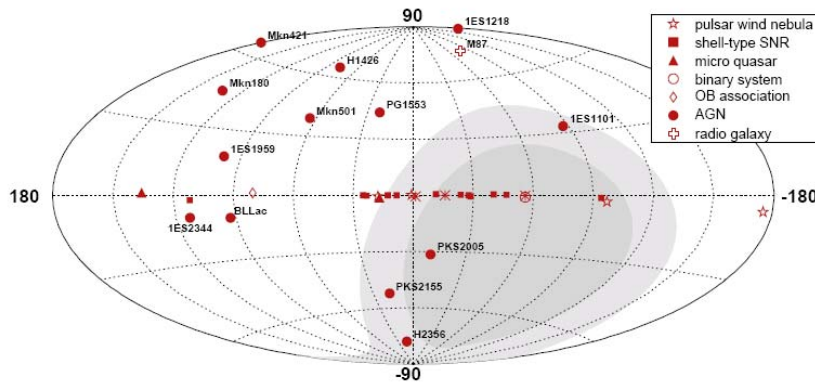
HERA - the world's largest electron microscope (Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany)

Shutdown on June 30, 2007, 23:00

HERA start: 1992
upgraded in 2001: „HERA II“



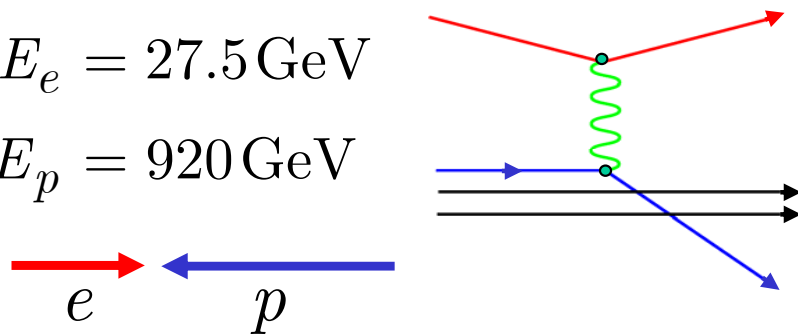
HERA and VHE γ -rays



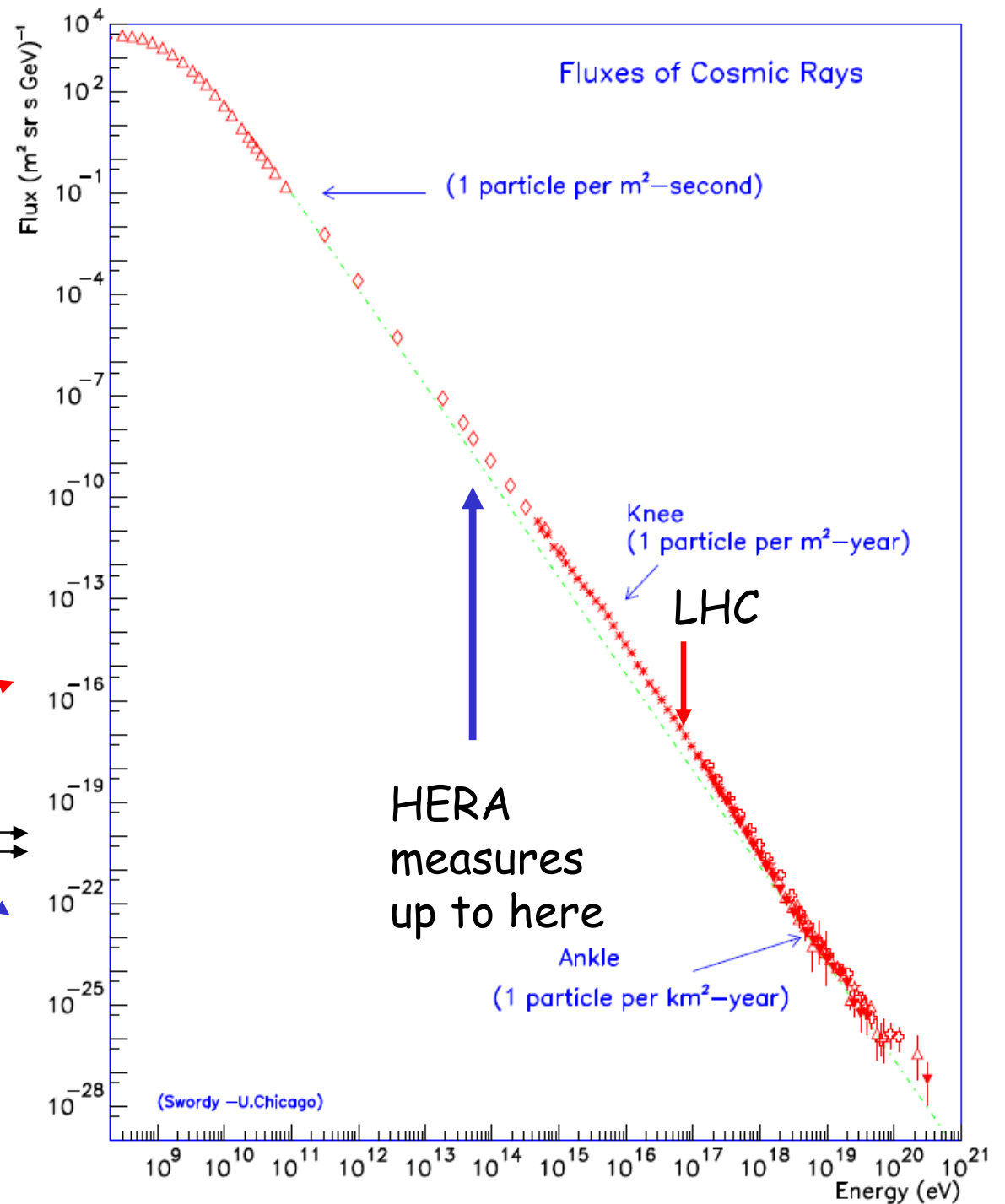
HERA is a collider:

$$E_e = 27.5 \text{ GeV}$$

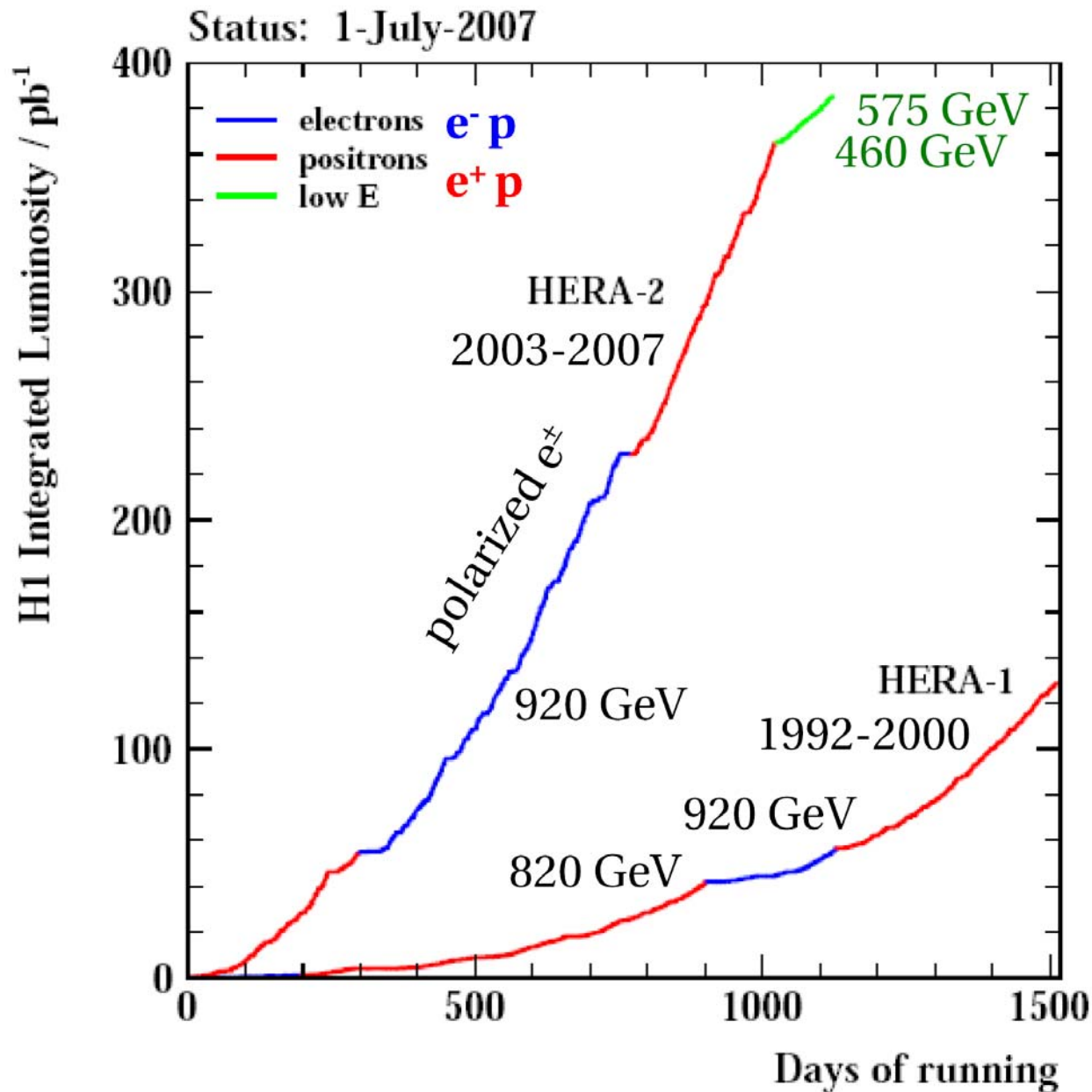
$$E_p = 920 \text{ GeV}$$



→ 50 TeV photon beam on a stationary proton target



HERA Luminosity



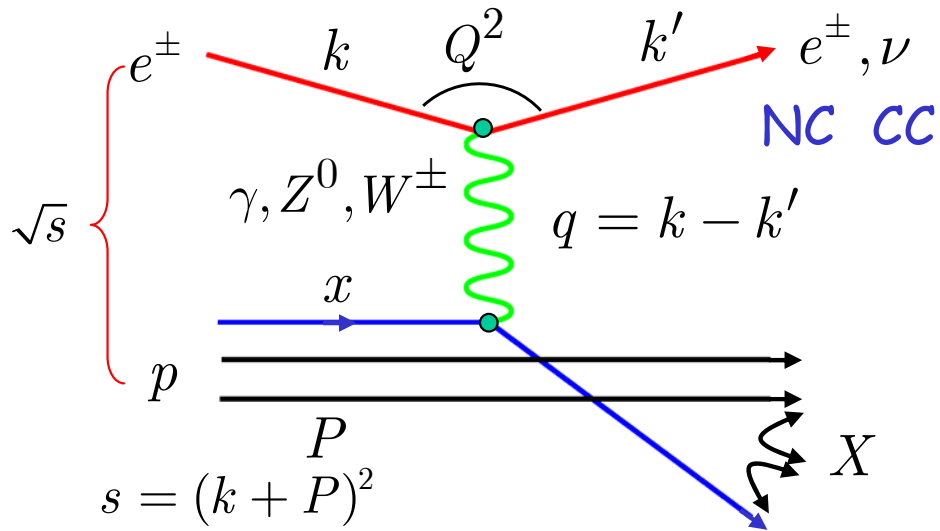
HERA I: 1992-2000

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 upgrades also for the detectors



Deep Inelastic Scattering (DIS)



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

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

$$x = \frac{Q^2}{2 P \cdot q}$$

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)

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

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

“reduced cross section” σ_r

γ exchange only:

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

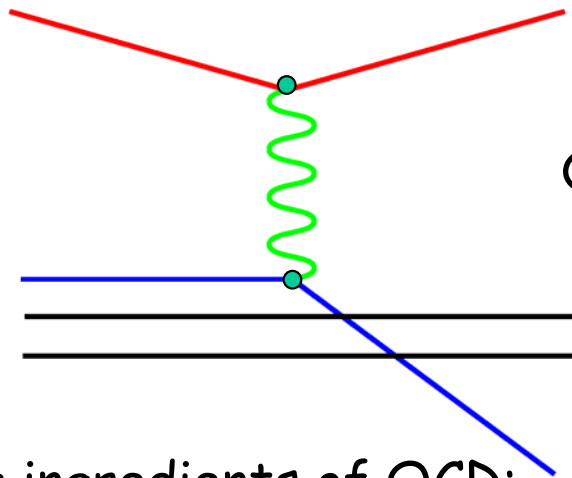
parton densities $xf_i(x)$ (pdf)

W^\pm exchange only:

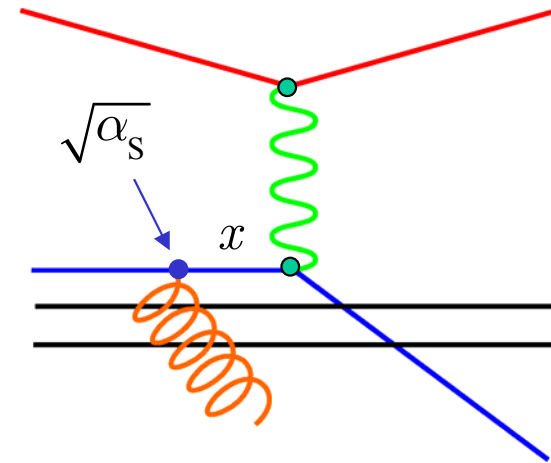
$$e^- p : F_2(x) \sim xq_u(x)$$

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

Quantum Chromodynamics (QCD)



QPM \rightarrow QCD



Basic ingredients of QCD:

1. Asymptotic freedom :

$$\alpha_s \rightarrow 0 \text{ at short distances}$$

\rightarrow perturbative QCD (pQCD)

2. Factorization :

„hard“ scale Q^2

$$\sigma = \sum_i \sigma_{\gamma_i^*}(Q^2) \otimes xf_i(x)$$

non-perturbative part

3. Evolution (calculable in pQCD) :

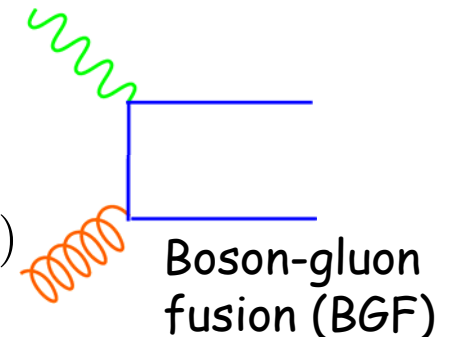
Parton densities become functions of Q^2

$$xq_i(x) \rightarrow xq_i(x, Q^2) \quad \text{quarks}$$

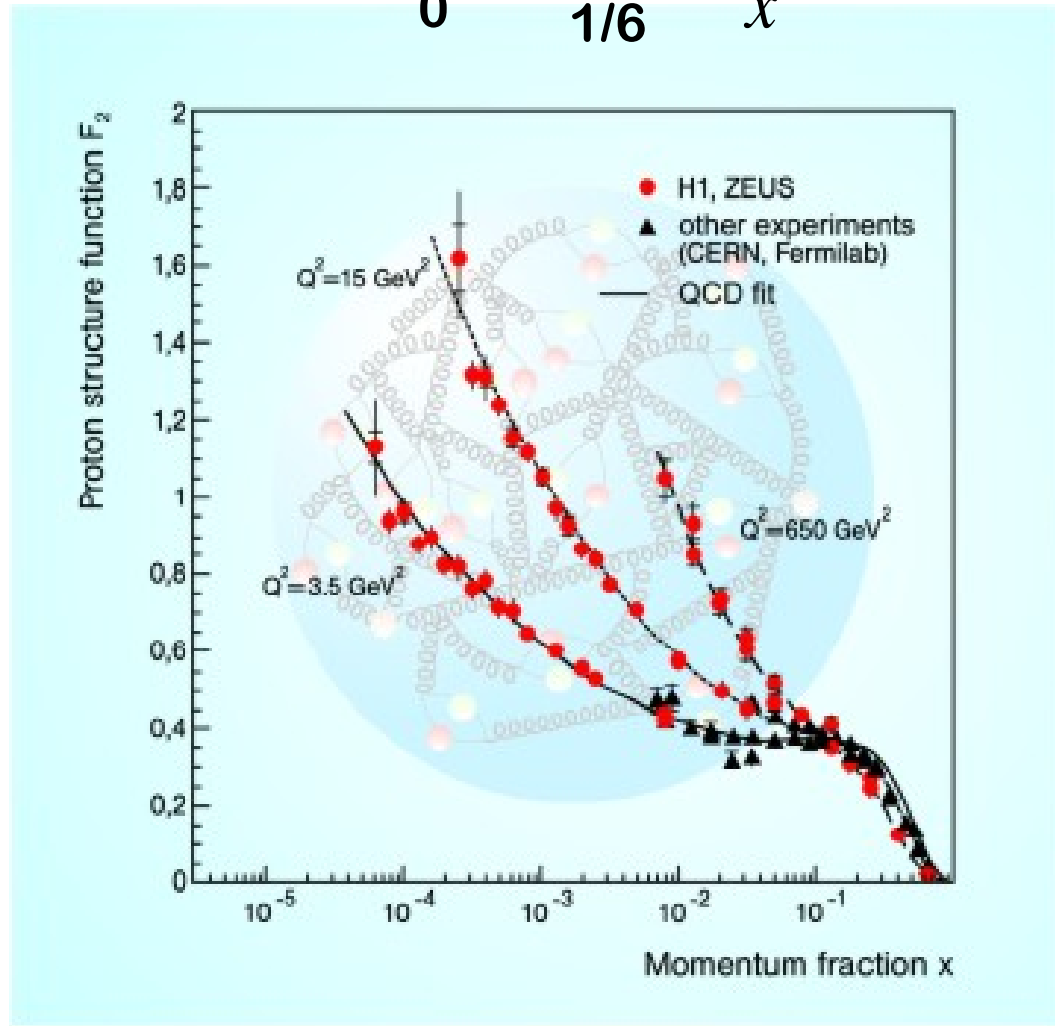
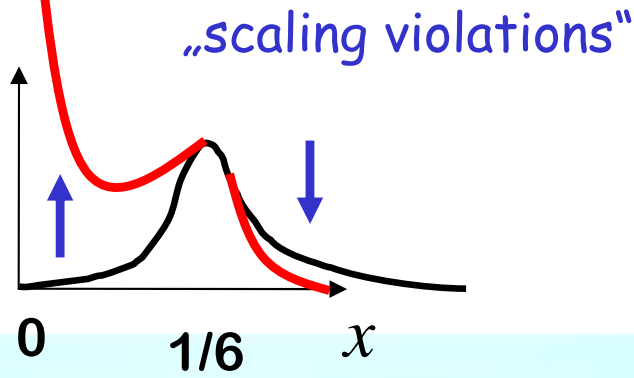
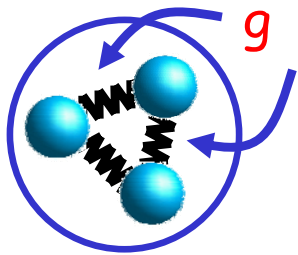
$$x\bar{q}_i(x, Q^2) \quad \text{antiquarks}$$

+ gluons

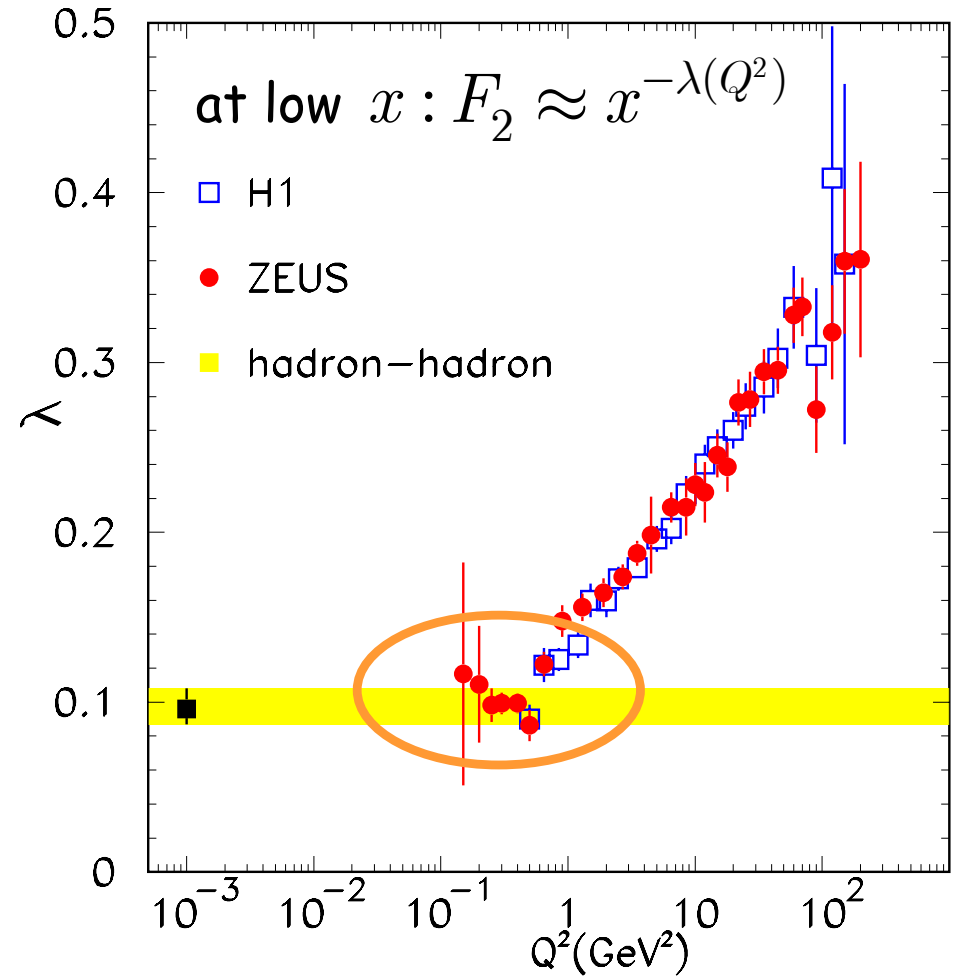
$$g(x, Q^2)$$



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



λ HERA



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

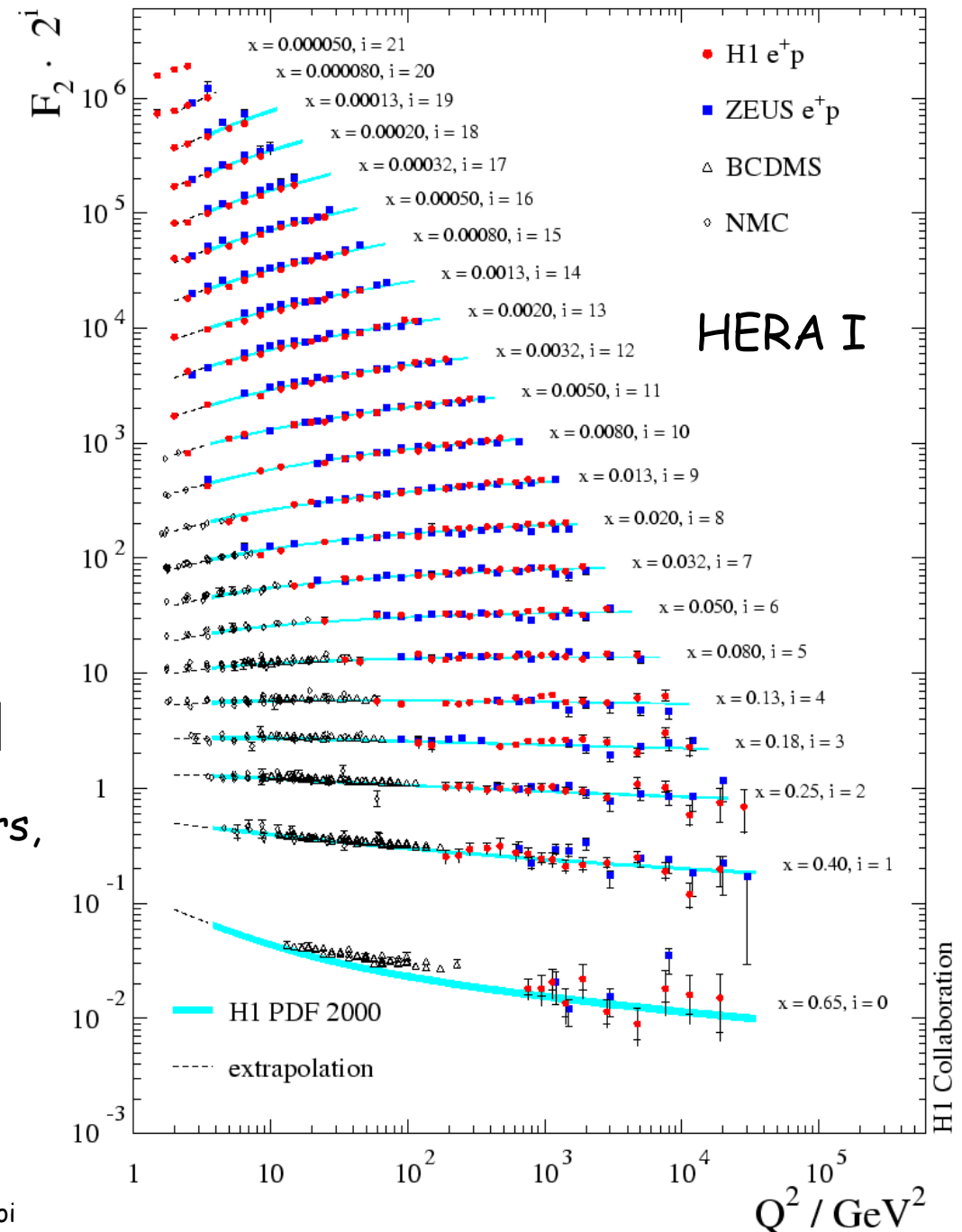
Clear scaling violation observed, violation is driven by gluon emission

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

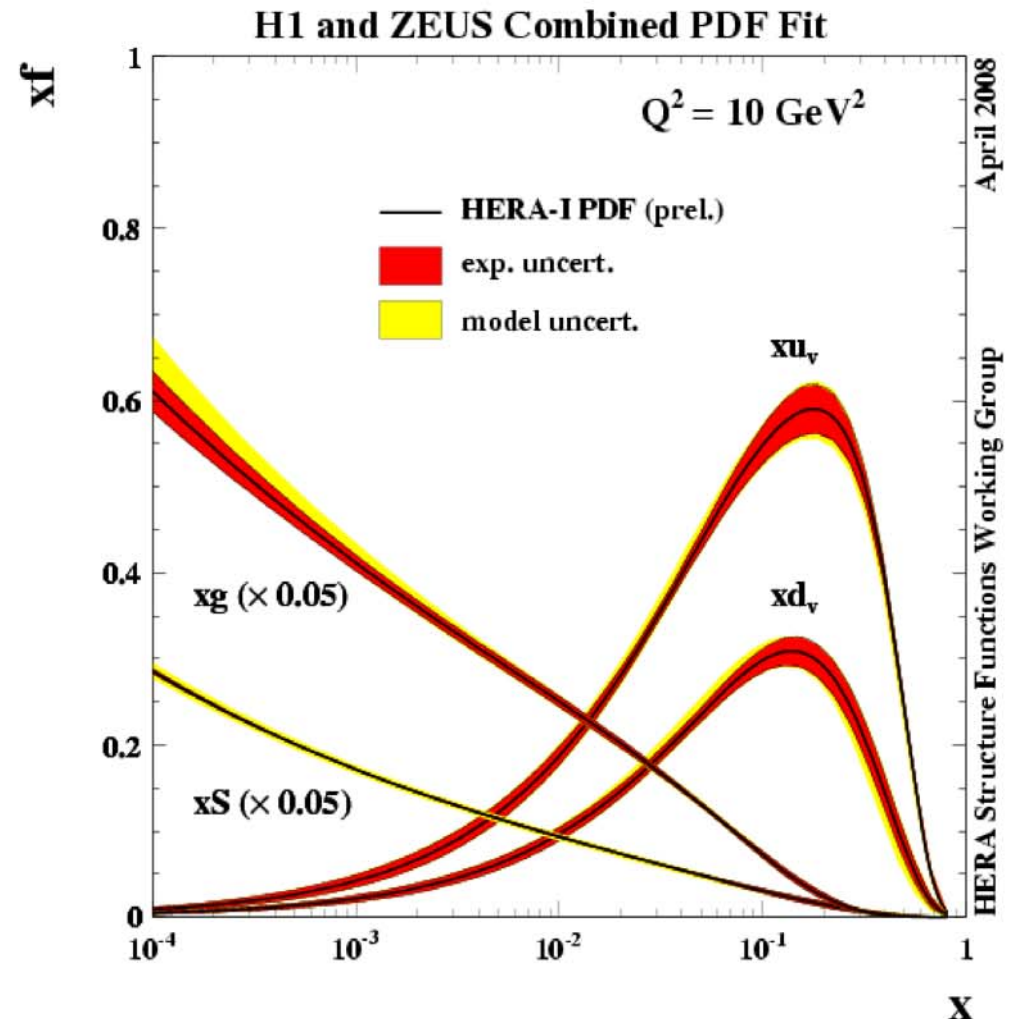
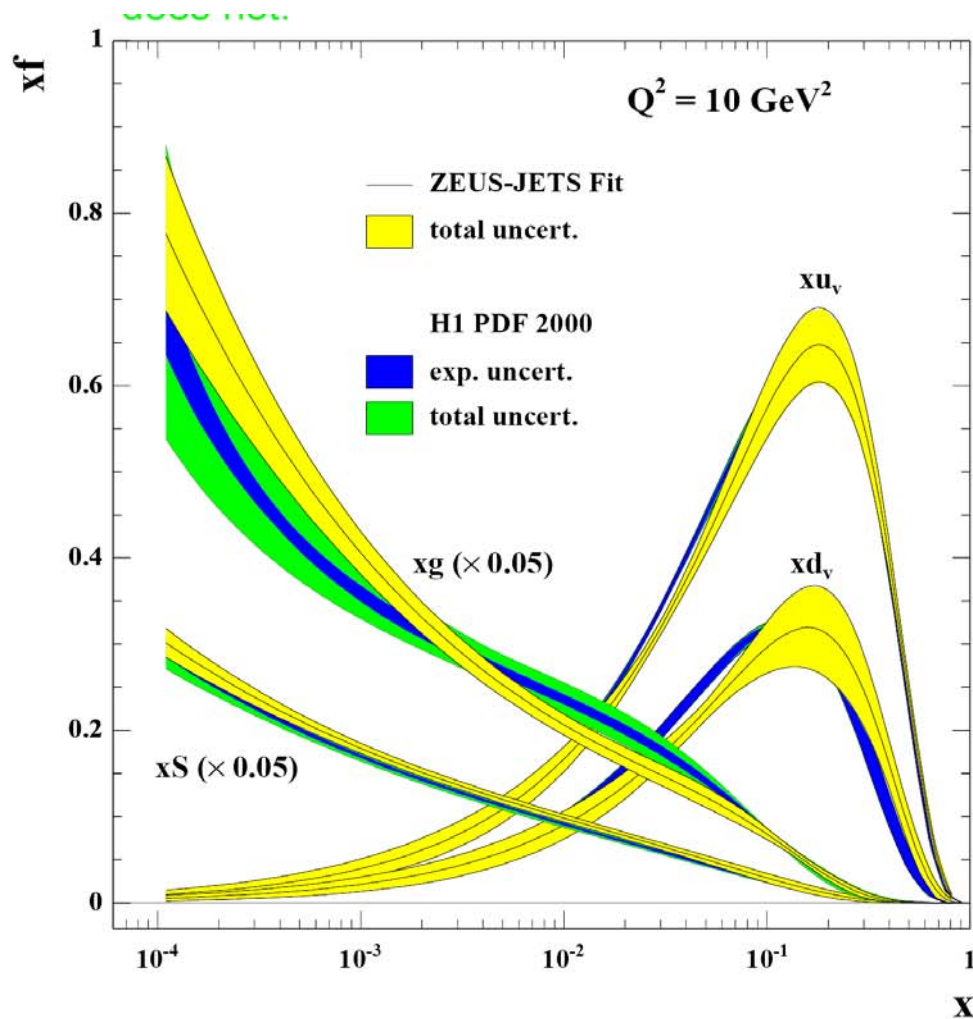
$$F_2(x) = \sum_i e_i^2 x f_i(x, Q^2)$$

- Parameterize parton densities, typically $xf(x, Q_0) = Ax^B(1-x)^C [1 + D\sqrt{x} + Ex]$
- Fit data to obtain the various parameters, evolution in Q^2 , using DGLAP equations

Data are very well described by QCD

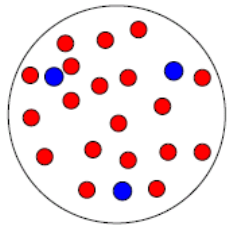
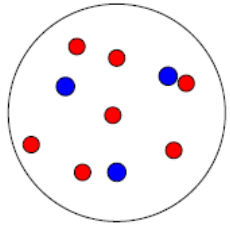
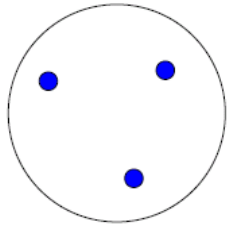


Parton densities: First Combined Fit of H1 and ZEUS data



Precise determination of pdf's down to $x \sim 10^{-4}$

Low x, Large Parton Densities and Saturation



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

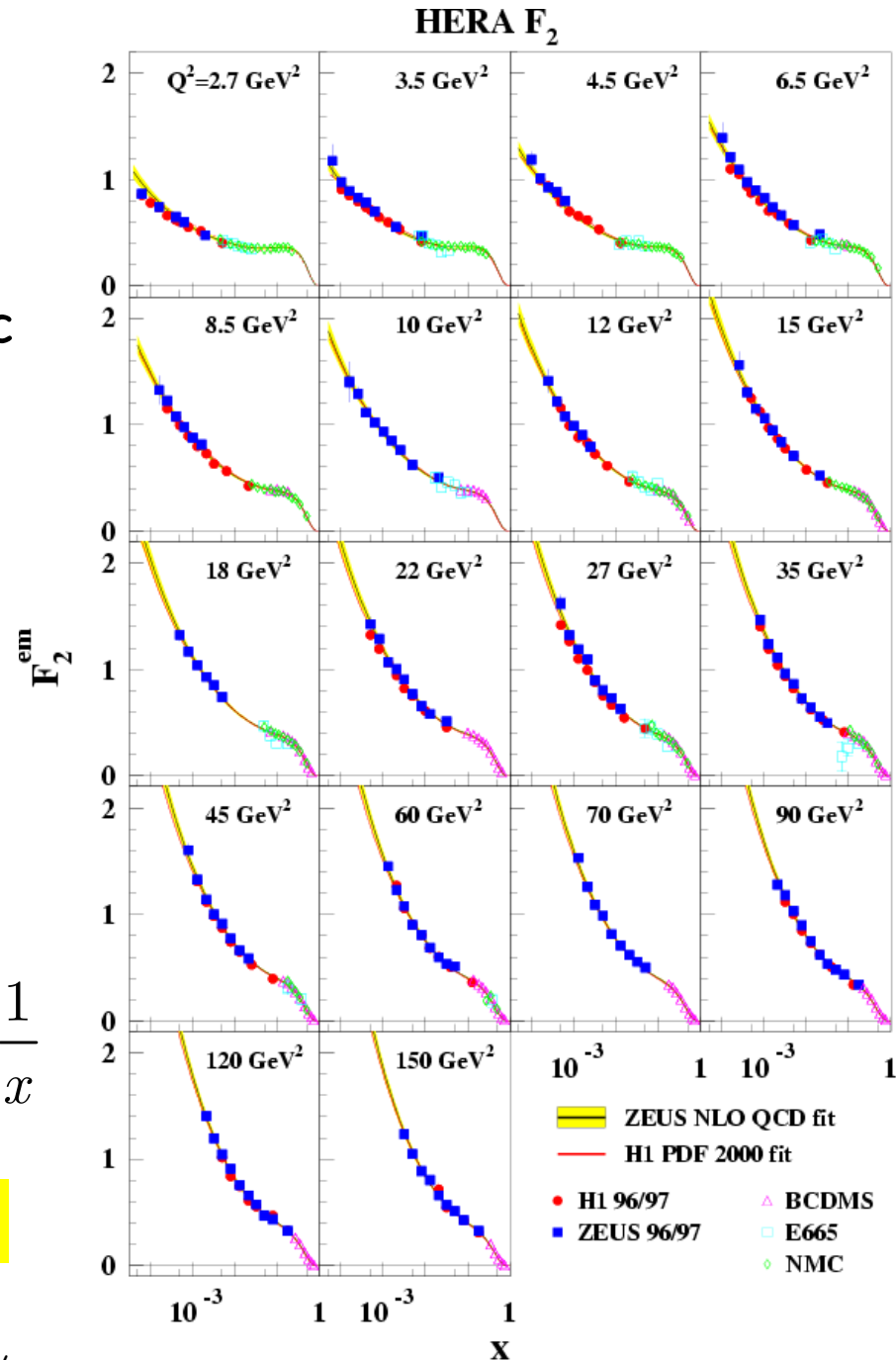
low x $x = \frac{Q^2}{Q^2 + W^2}$

ultimately expect parton overlaps („saturation“)

Rise of pdf should flatten with decreasing x

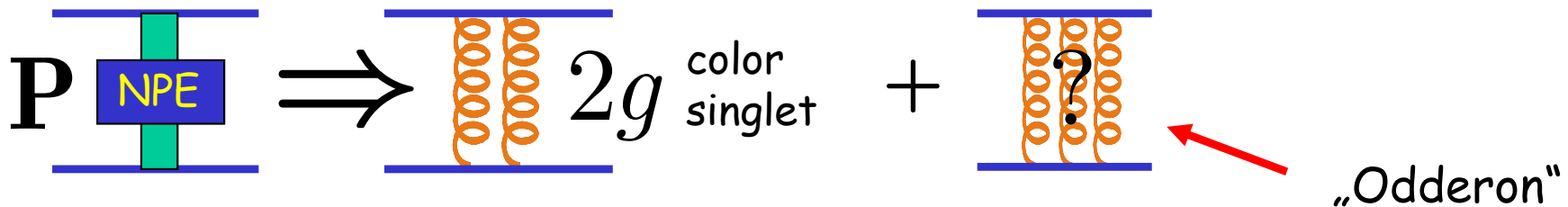
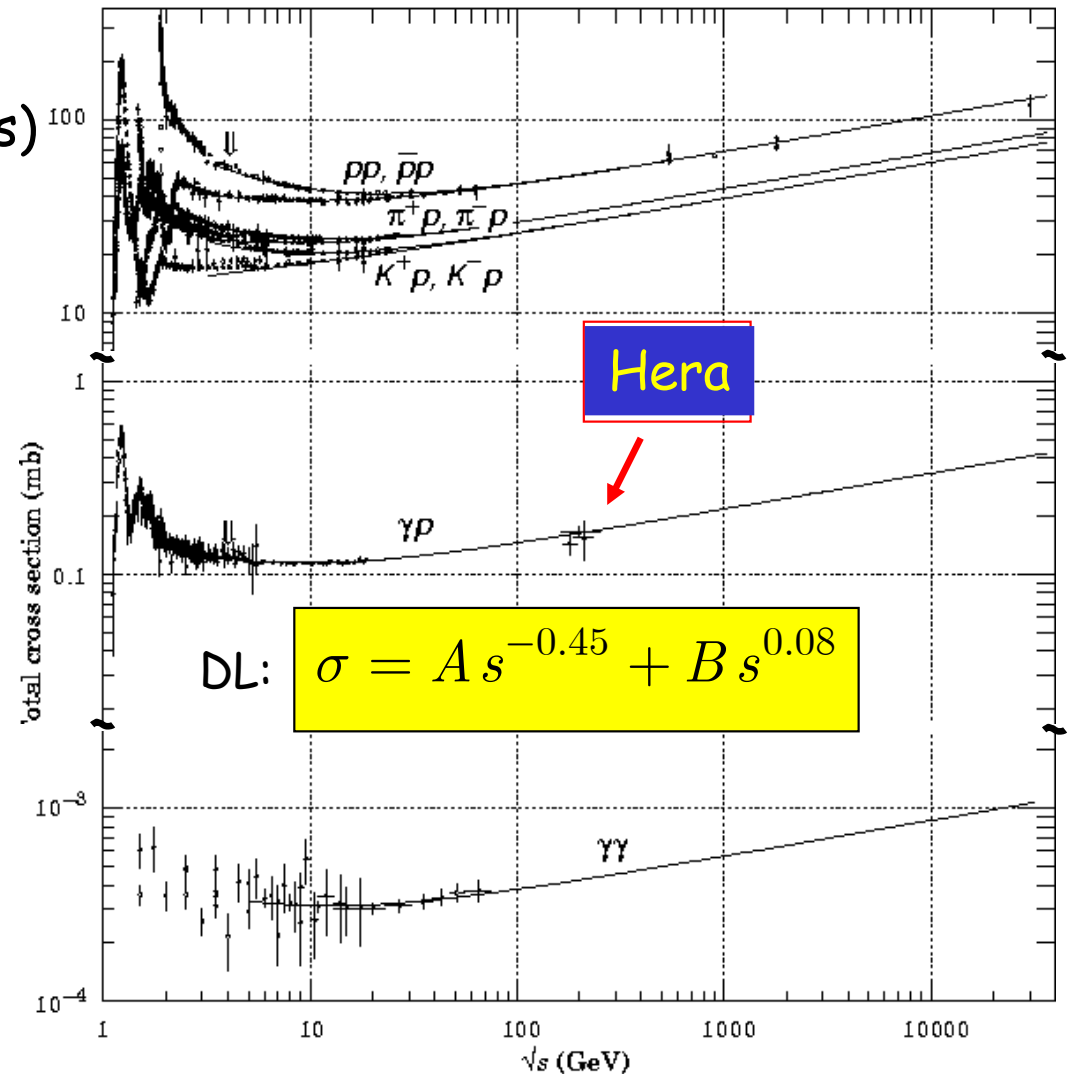
$$\left(\frac{1}{x}\right)^\lambda \rightarrow \ln \frac{1}{x}$$

No saturation observed at HERA

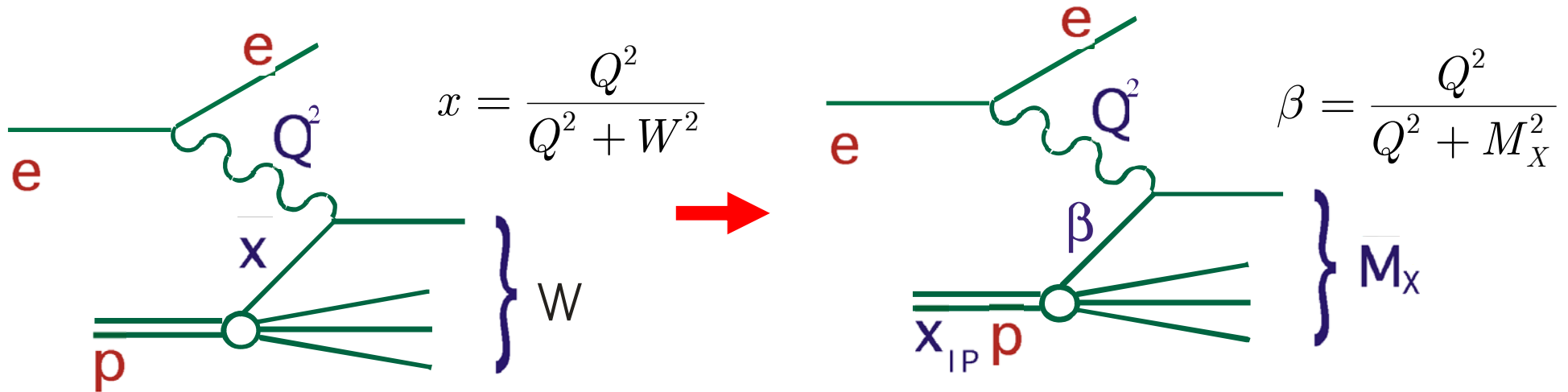


Diffraction

- 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
Glueons, quarks in a color singlet ?



From Inclusive Scattering to Diffraction: Kinematics



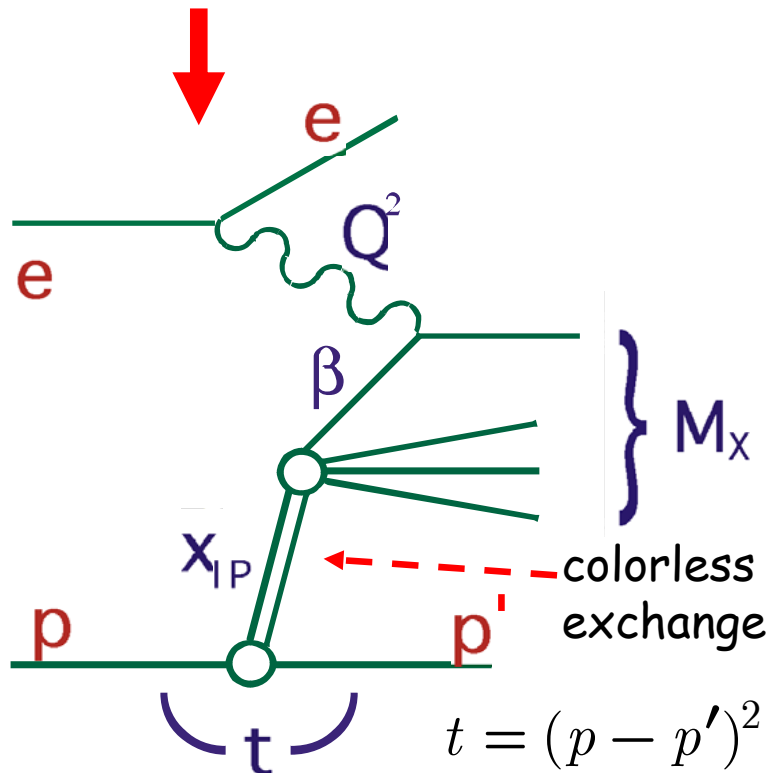
$$x_P = \frac{Q^2 + M_X^2}{Q^2 + W^2}$$

$$x \text{ (DIS)} \Leftrightarrow \beta \text{ (Diff. DIS)}$$

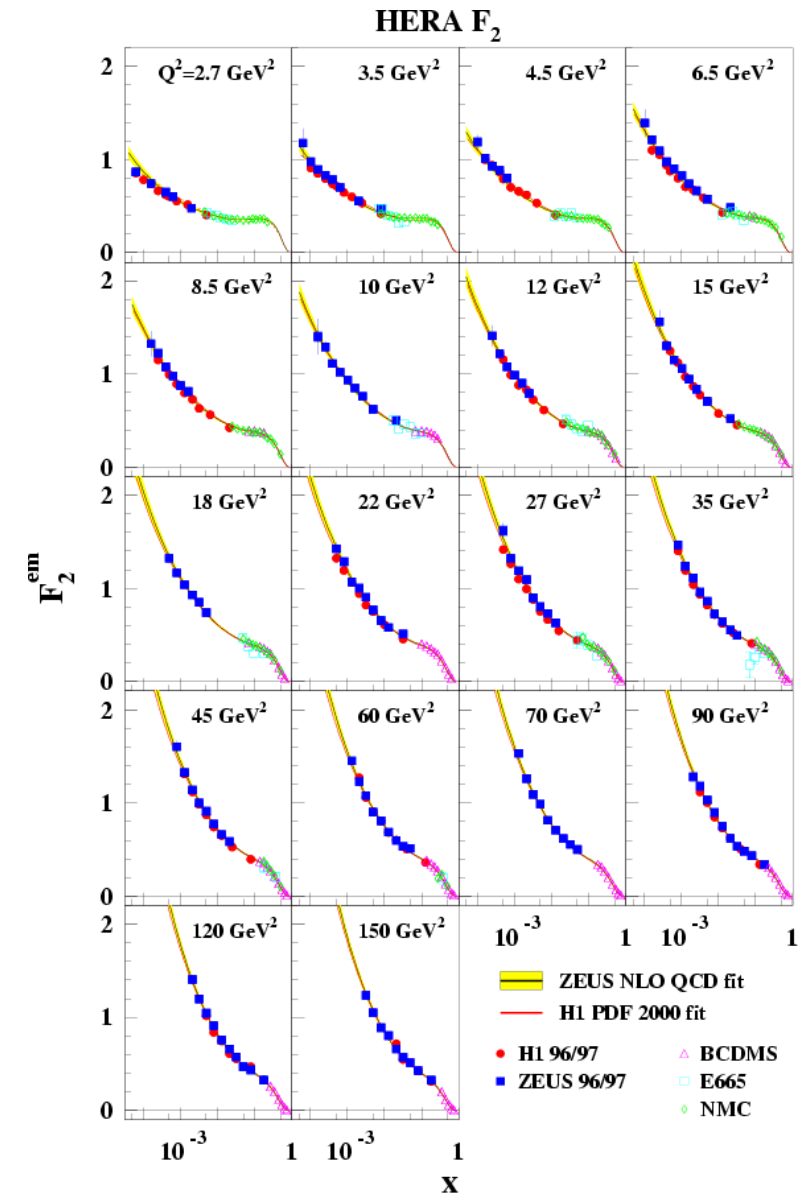
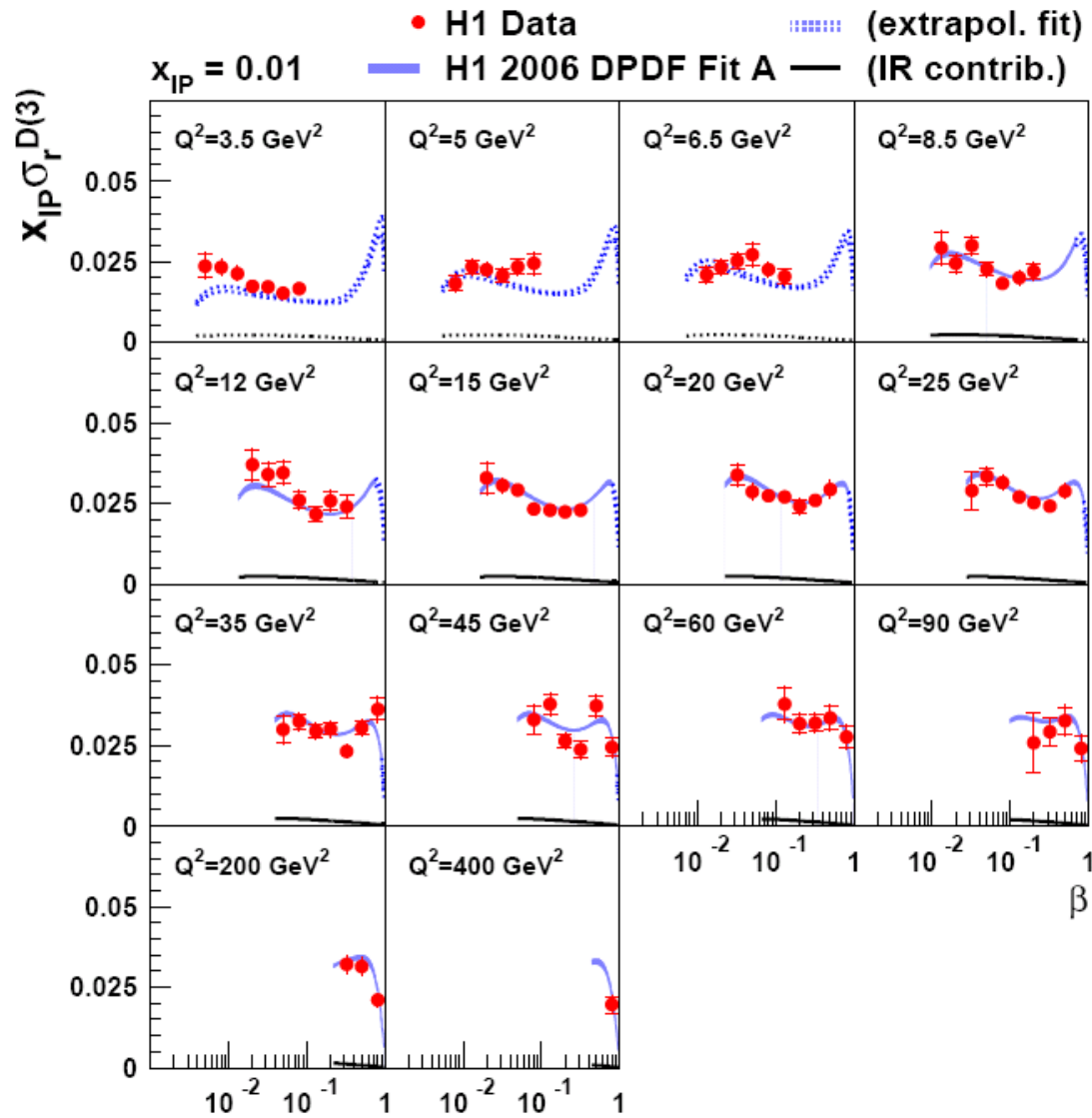
momentum fraction of color singlet exchange relative to the proton

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

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

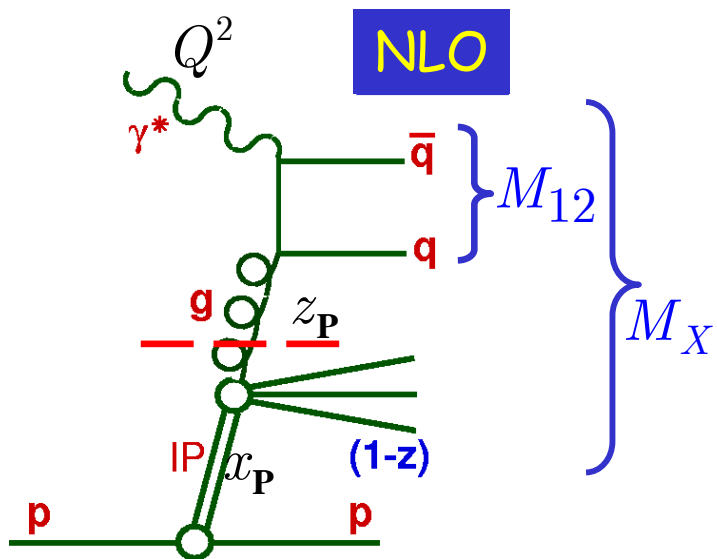


$$t = (p - p')^2 \text{ (momentum transfer)}^2 \text{ at proton vertex}$$



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

Partonic Structure of Diffraction from the Inclusive Data

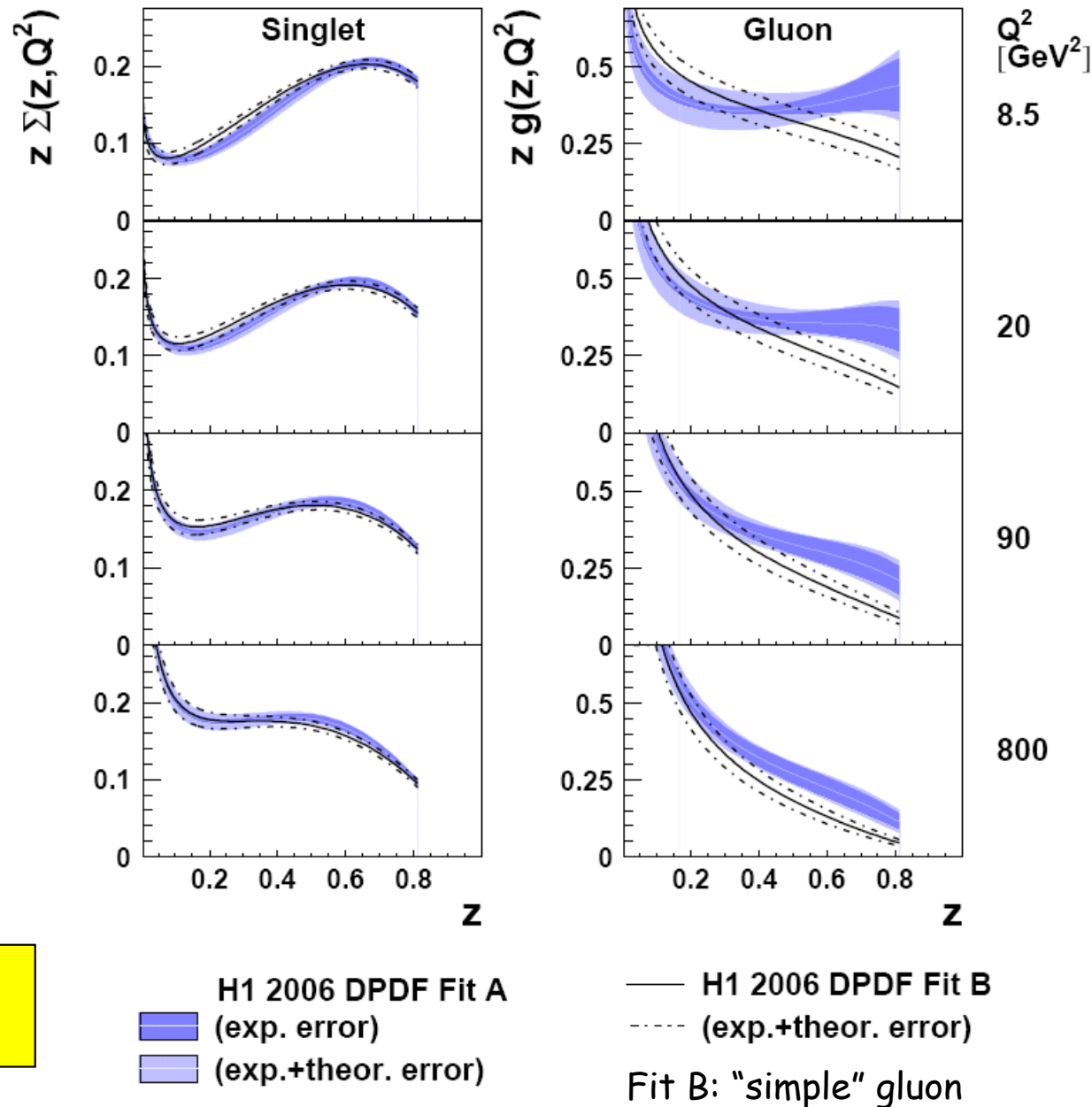


$$z_P = \frac{Q^2 + M_{12}^2}{Q^2 + M_X^2}$$

Gluon momentum fraction:

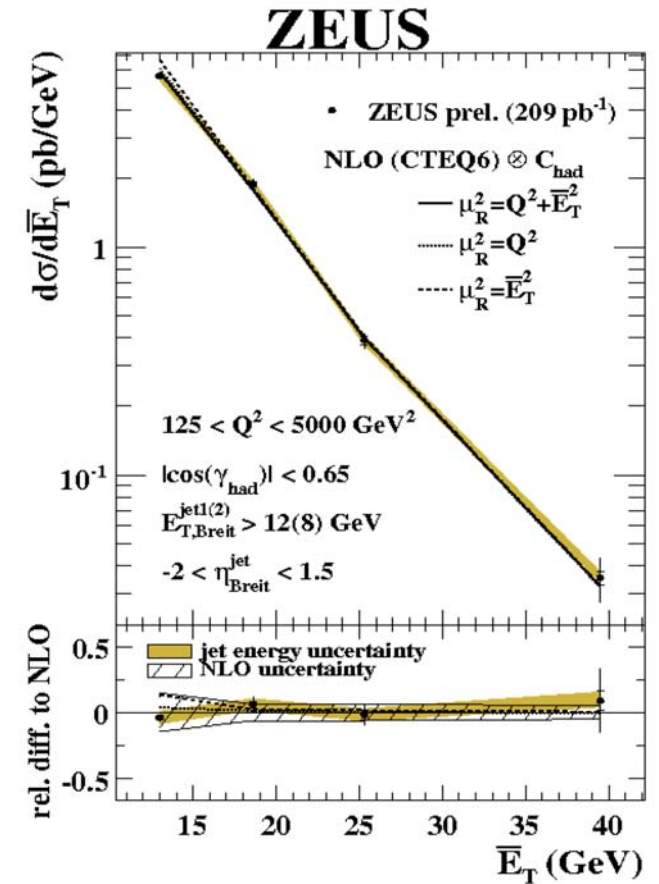
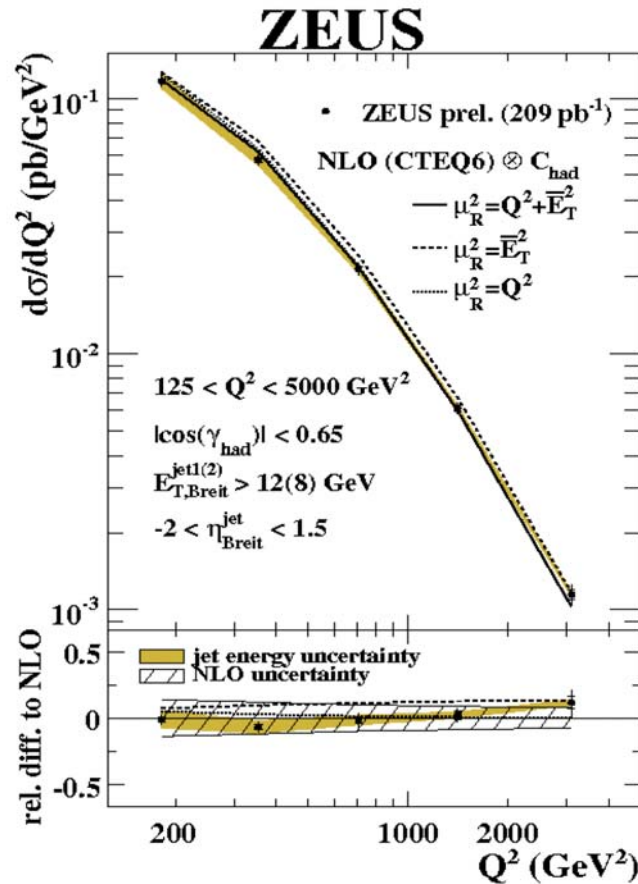
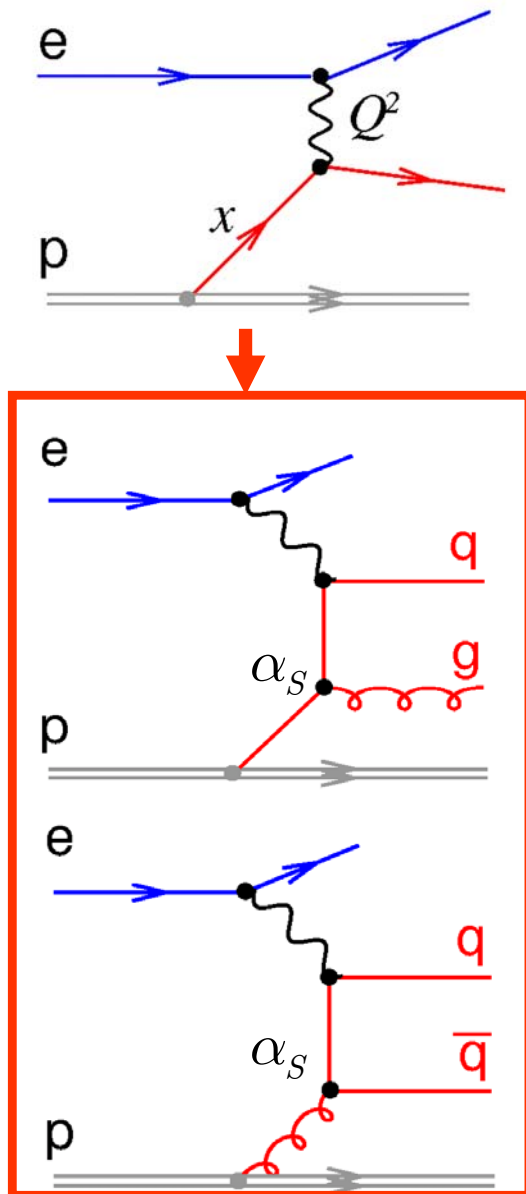
$(70 \pm 5)\%$

Diffraction is **gluon-dominated**



Jets at HERA

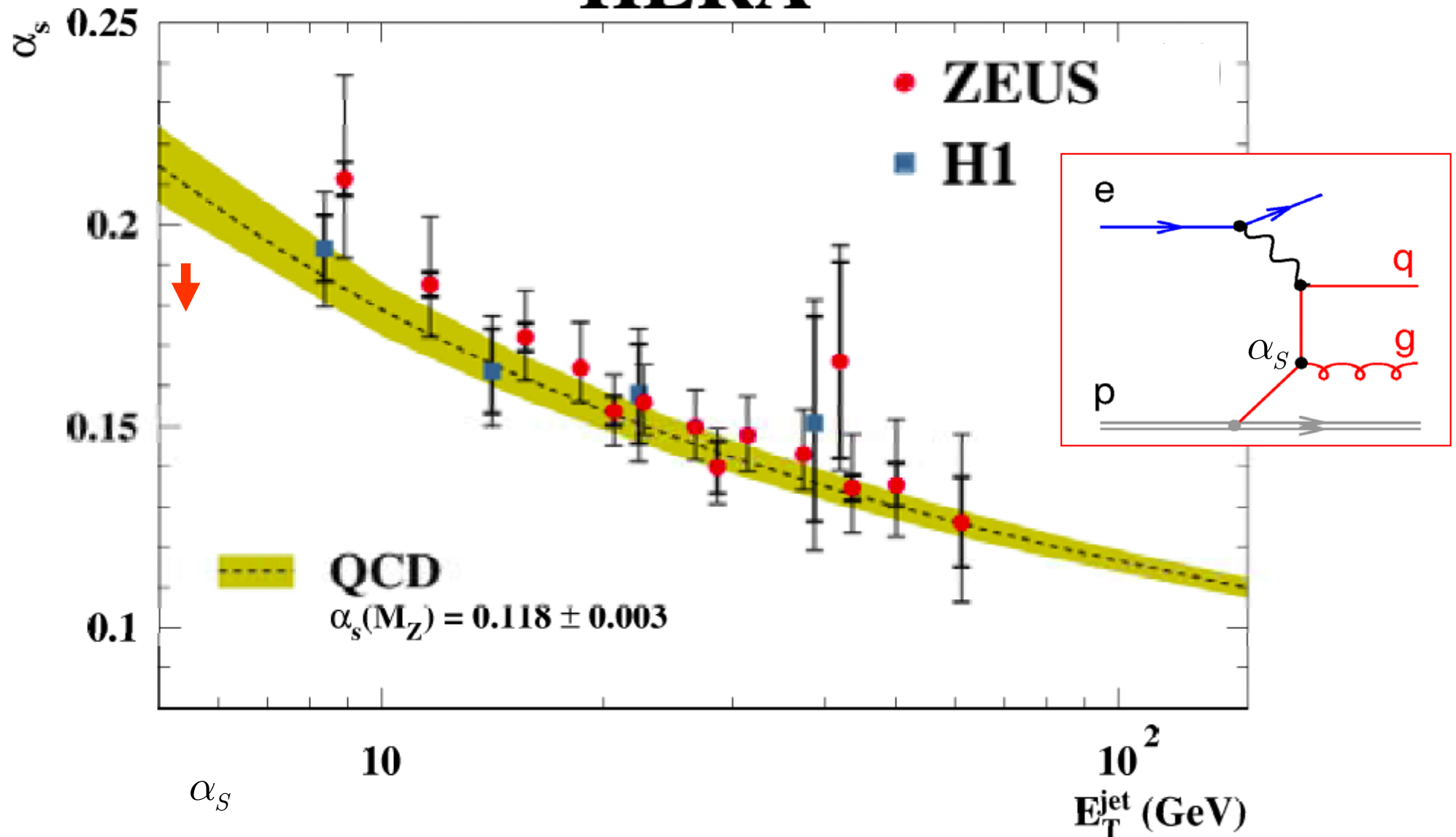
Dijets (and Multijets)



2 „hard scales“: Q^2 and $E_T(\text{jet})$

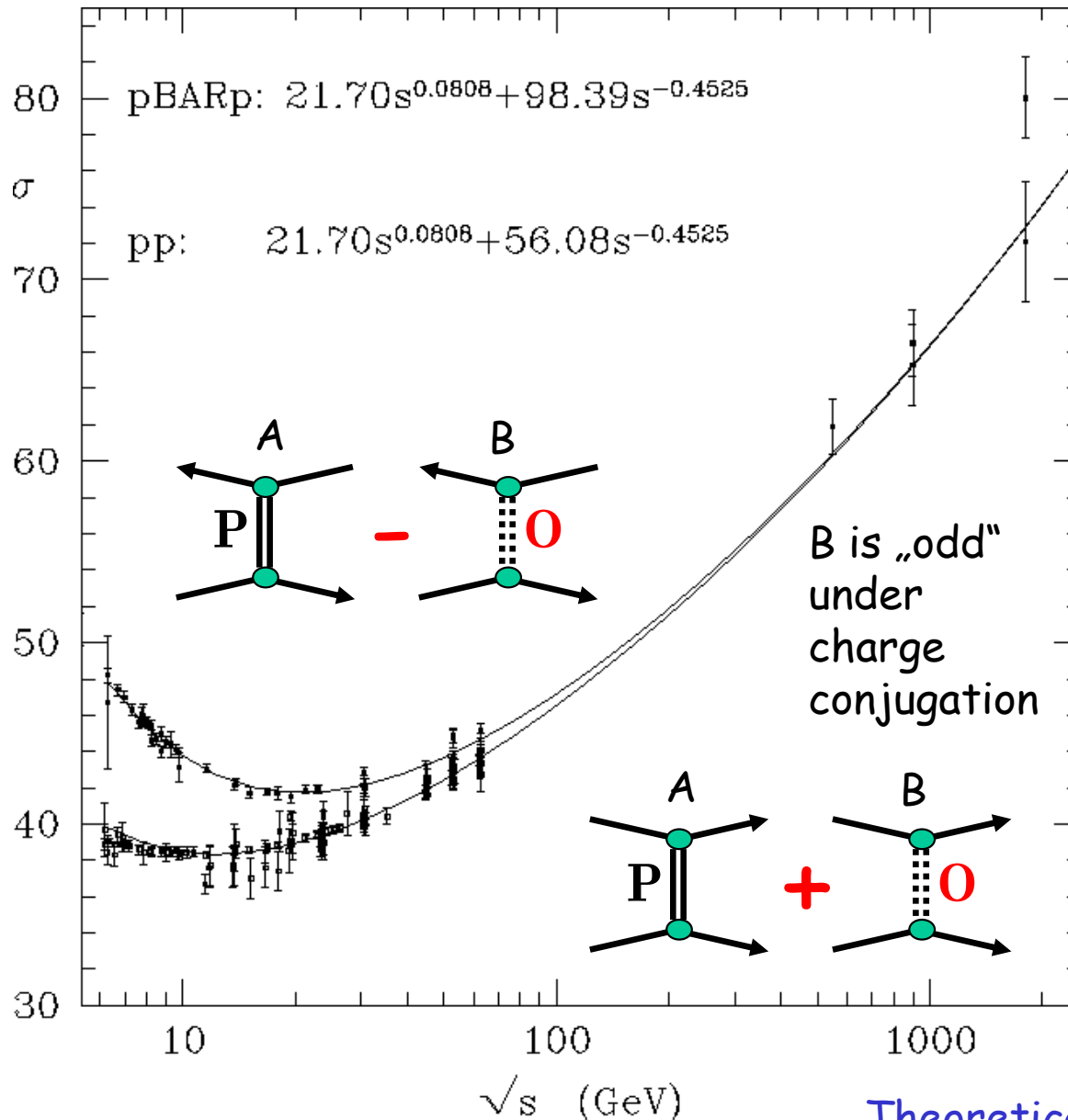
NLO prediction describes data very well !

HERA



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):

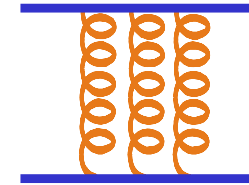
- Subtraction of 2 large numbers
- No data on pp at high energy !

Theoretical problem: Odderon possibly suppressed in pp reactions

Do we need an Odderon ?

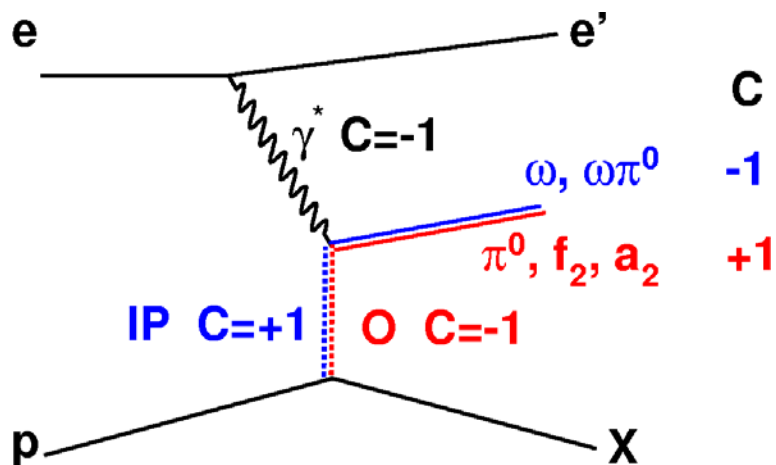
→ firm prediction from pQCD: 3-gluon state with $C = P = -1$

If so, how to find it :



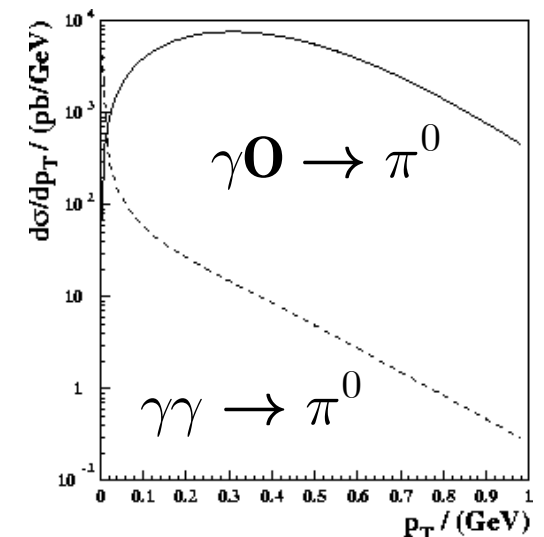
HERA is an ideal place to study the Odderon:

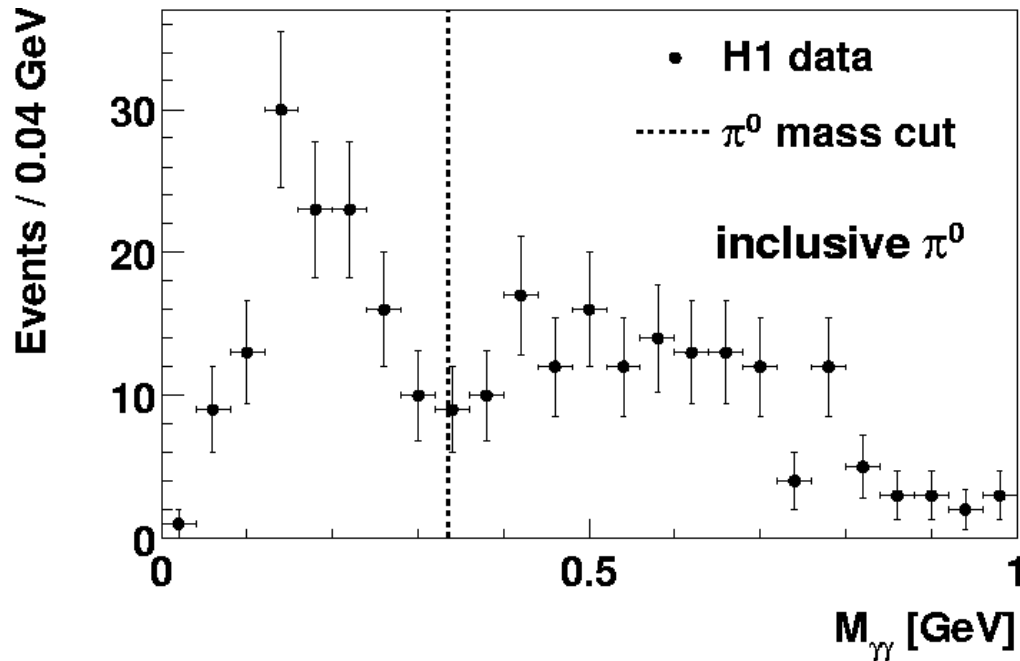
- very high photon-proton center-of-mass energies (up to 300 GeV)
- can select exclusive processes where the Pomeron cannot contribute (thus measure a potential Odderon contribution directly, no subtraction)
- theoretical (non-pQCD) model exist for exclusive processes:
E. R. Berger, A. Donnachie, H.G.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



C
-1
+1
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



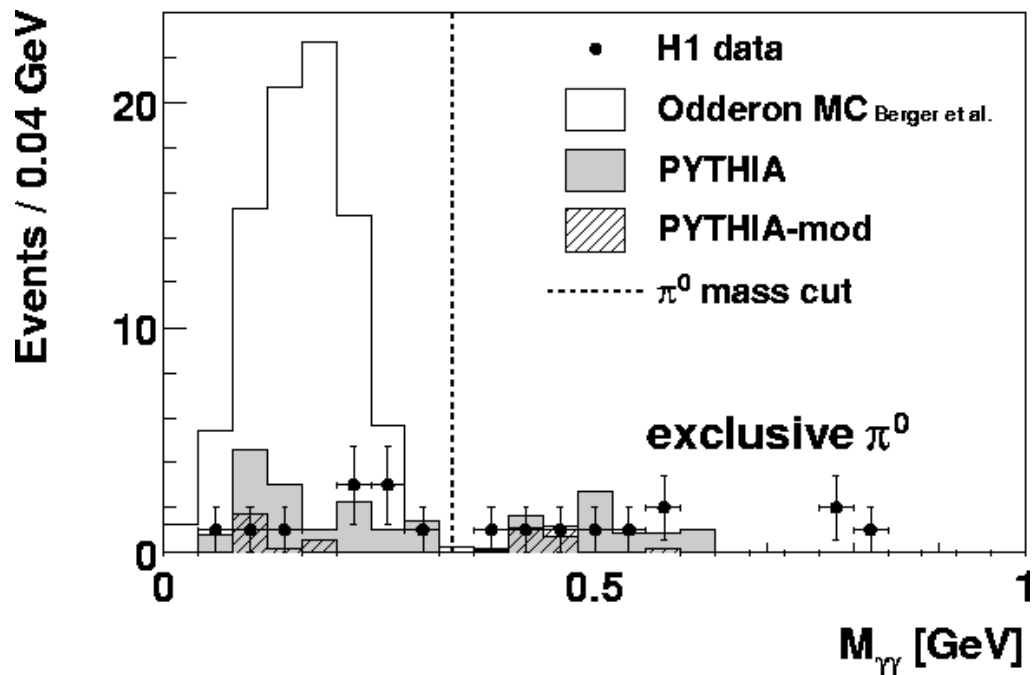
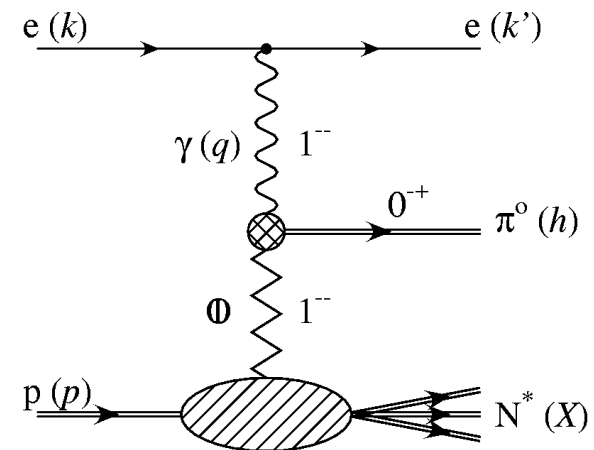


$$ep \rightarrow eX\pi^0$$

← inclusive pion signal

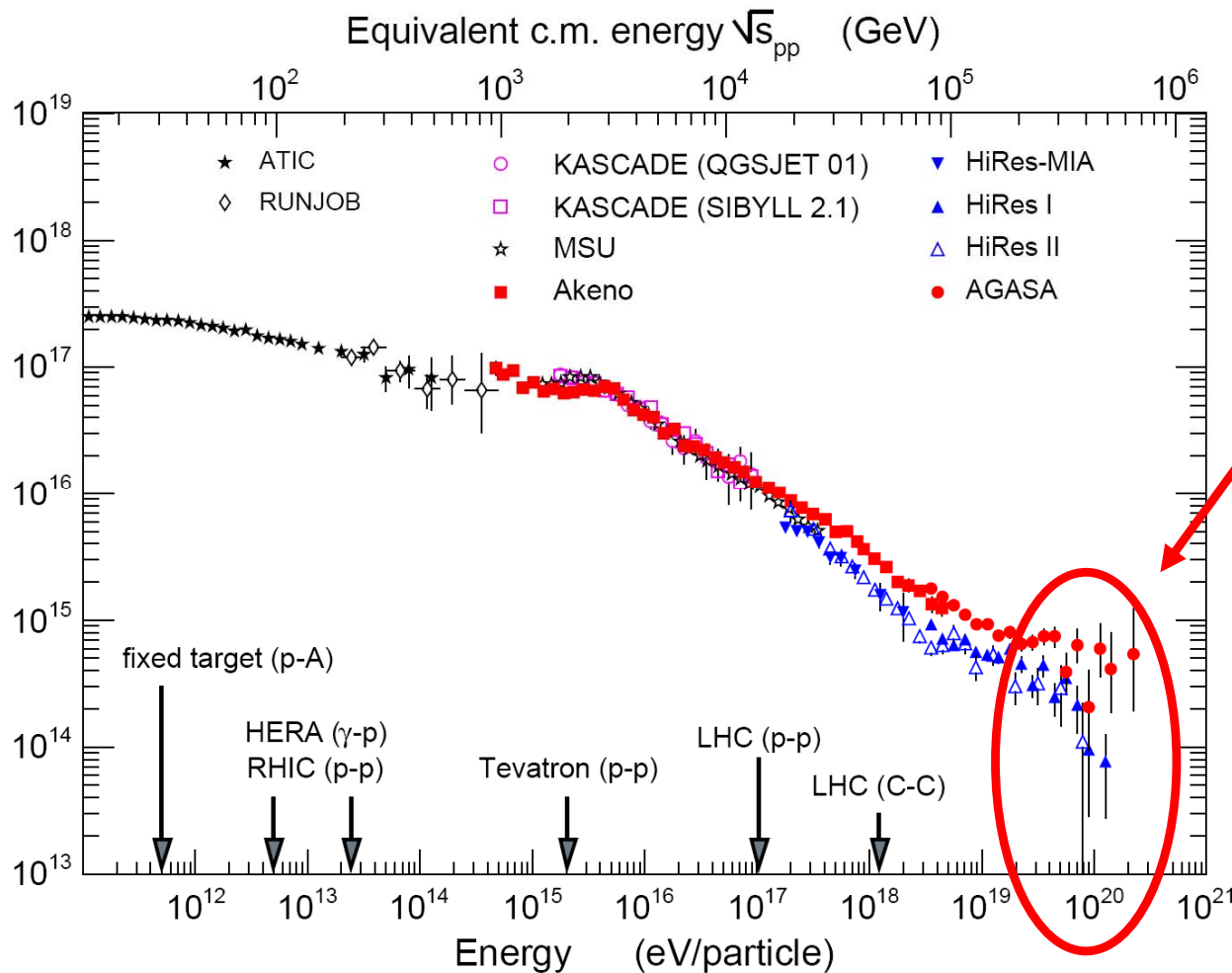
after cut for exclusive state:

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



Expected signal from Berger et al. model is not seen

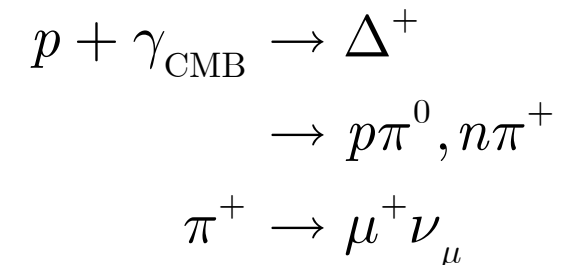
Cosmic Ray Events beyond the GZK Limit ?



Greisen Zatsepin Kuzmin:

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

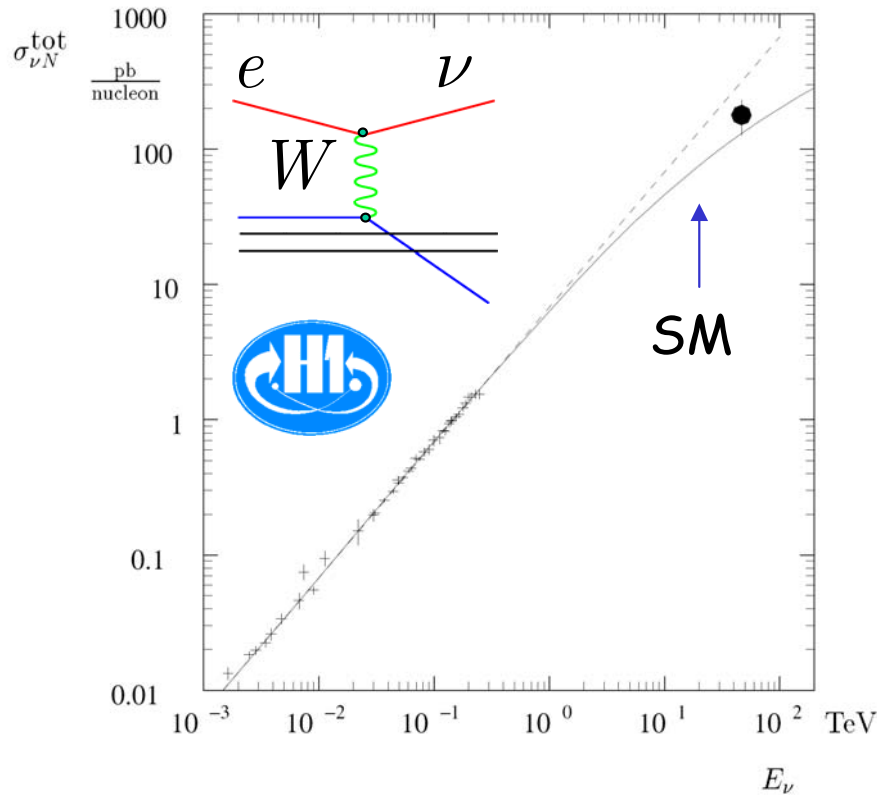
Collisions of primary protons with the photons from the microwave background:



No such limit for neutrinos!

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

Cross Sections for VHE Neutrinos

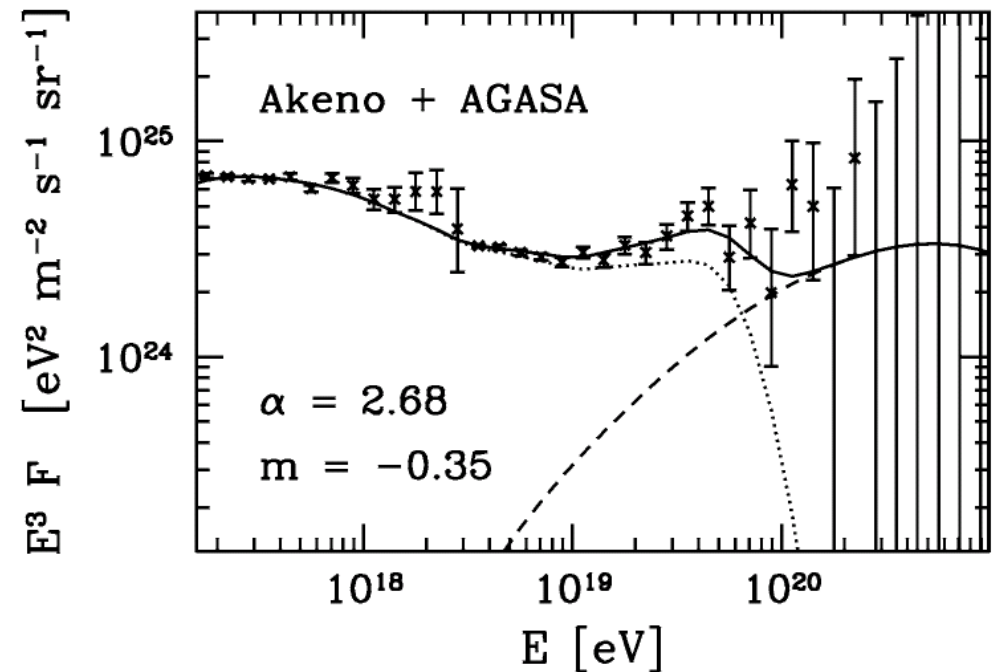


HERA data (1994 and ever since):

Neutrino cross sections are as expected up to 50 TeV ($\sim 10^{13}$ eV)

Fodor, Katz, Ringwald, Tu (2004)

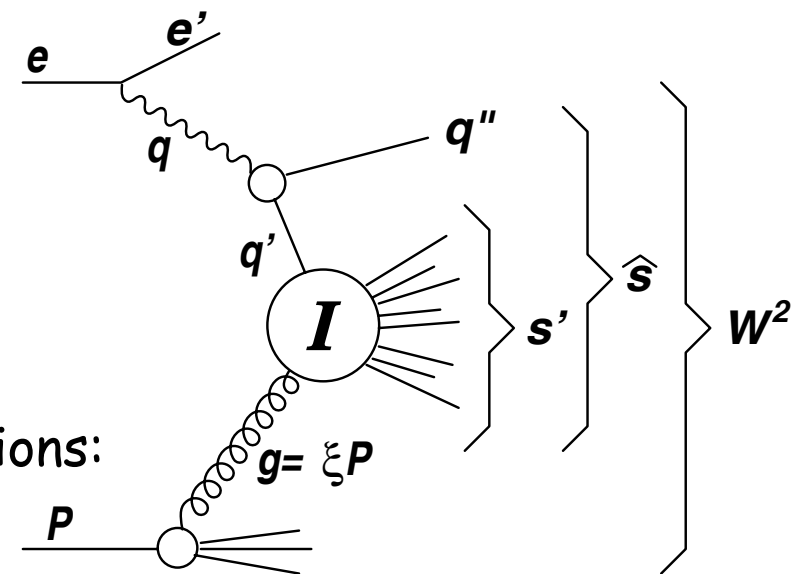
EW Instanton effects may produce $O(\text{mb})$ cross sections for neutrinos on protons:



Searches for Instanton-induced Events at HERA

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

- "Instantons"
suppressed by $\exp(-4\pi/\alpha)$:
hopeless for EW at HERA
but very interesting for strong interactions:
 $\rightarrow \alpha \rightarrow \alpha_s$



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

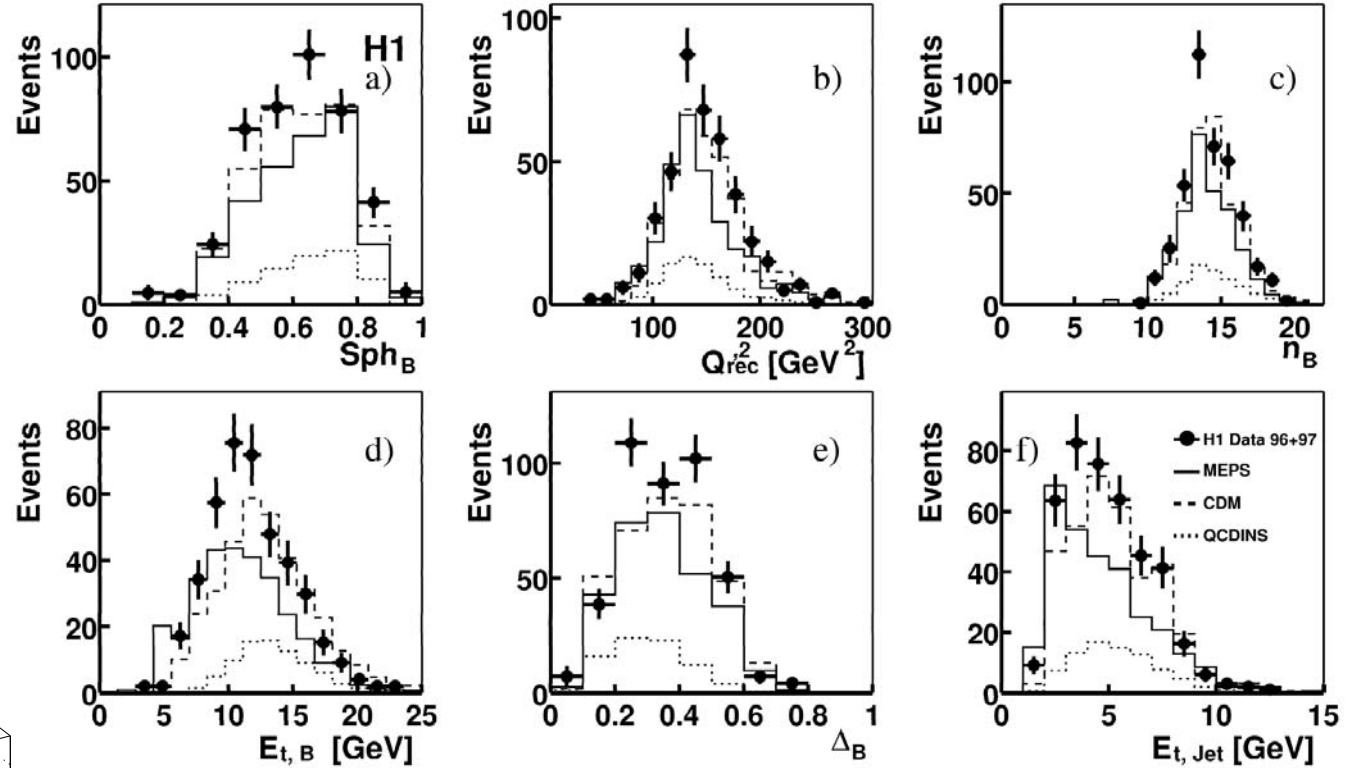
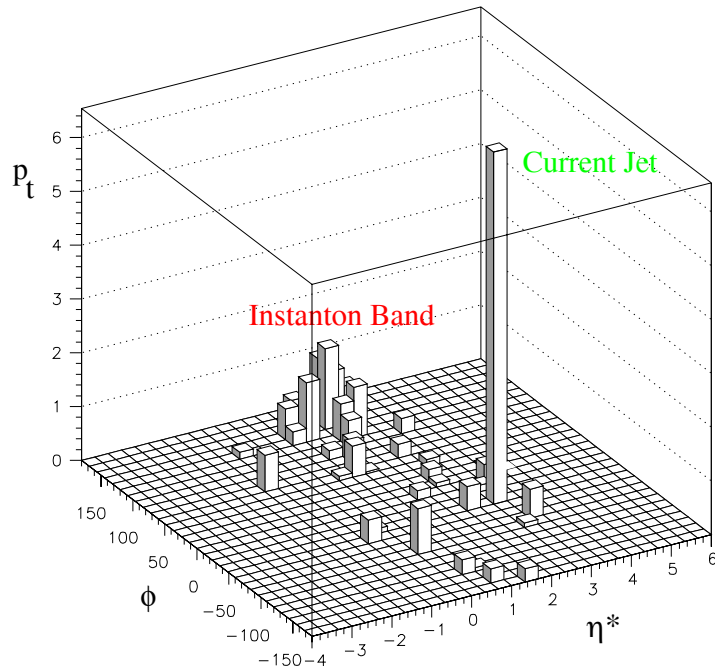
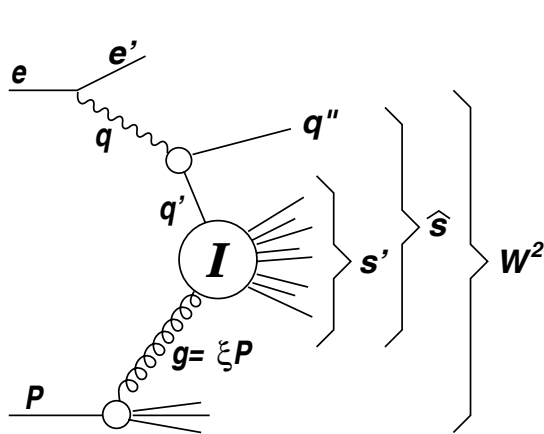
$$d\sigma_{q'g}^{(I)}(x', Q^2) \cong \frac{\Sigma(x')}{Q'^2} \left(\frac{4\pi}{\alpha_s(\mu(Q'))} \right)^{21/2} \exp \left[-\frac{4\pi}{\alpha_s(\mu(Q'))} F(x') \right]$$

- 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 $\sim 1/1000$

Event Shape Variables

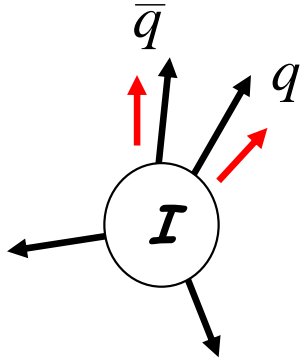


multi-variate analysis using shape variables,
(here from H1)

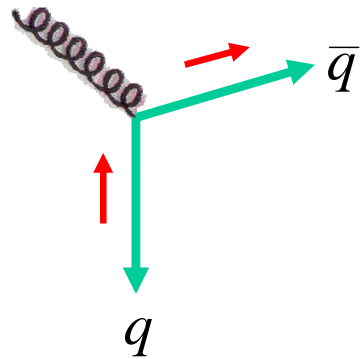
ZEUS limit: $\sigma < 29$ pb (8.9 pb predicted)

Instanton not excluded with
early ($L \sim 30$ pb⁻¹) HERA data

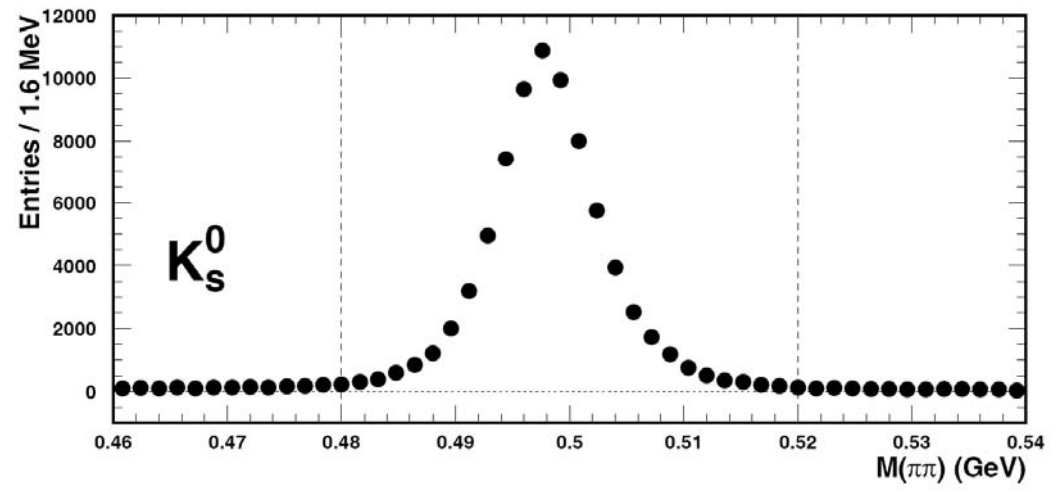
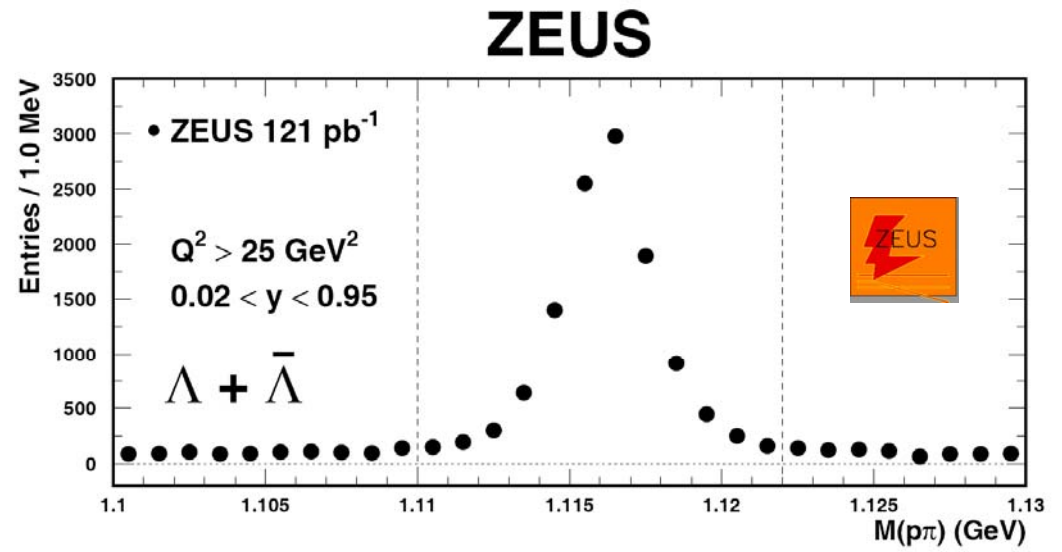
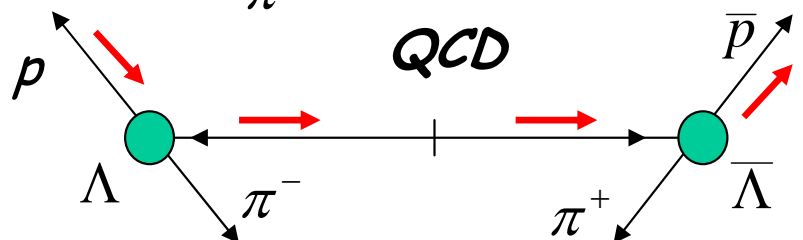
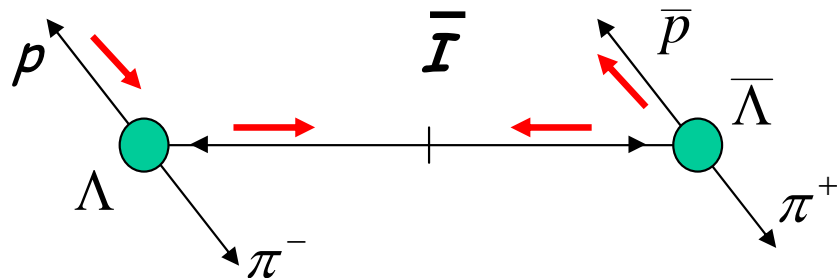
A unique signature of Instantons: Chirality Violation



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