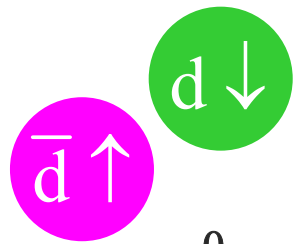
New Results from HERA on Hadron Structure

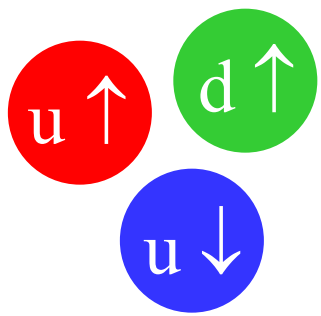
- Hadrons and quarks
- Measuring proton structure in DIS
- Proton spin
- Low Q^2 and x
- Rapidity gaps
- Summary

Hadrons and quarks

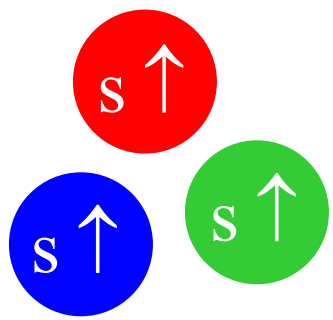
- Quarks spin ½ fundamental fermions.
- Mesons (π^0) quark and anti-quark.
- Baryons (p, Ω) three quarks.
- Held together by strong force.
- Additional quantum number necessary, “colour”.
- Strong force QCD, due to interactions between colour charges.
- QCD similar to QED at short range.
- Long range, confinement.



π^0



p



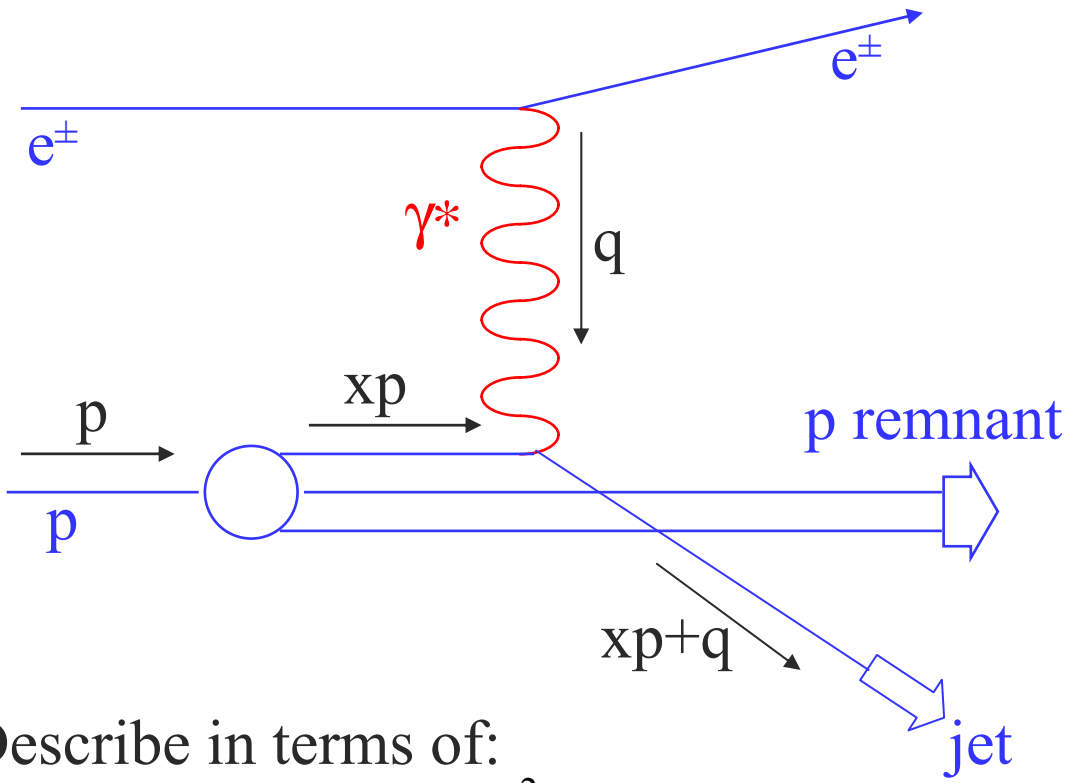
Ω

Masses of baryons from hyper-fine splitting

- Using $m_u = m_d = 363\,\text{MeV},\ m_s = 538\,\text{MeV}$:

Baryon	Composition (q = u, d)	Predicted mass (MeV)	Measured mass (MeV)
N(939)	qqq	939	939
Λ(1116)	qqs	1114	1116
Σ(1193)	qqs	1179	1193
Ξ(1318)	qss	1327	1318
Δ(1232)	qqq	1239	1232
Σ(1384)	qqs	1381	1384
Ξ(1533)	qss	1529	1533
Ω(1672)	sss	1682	1672

Measuring hadron structure – Deep Inelastic Scattering



- Describe in terms of:

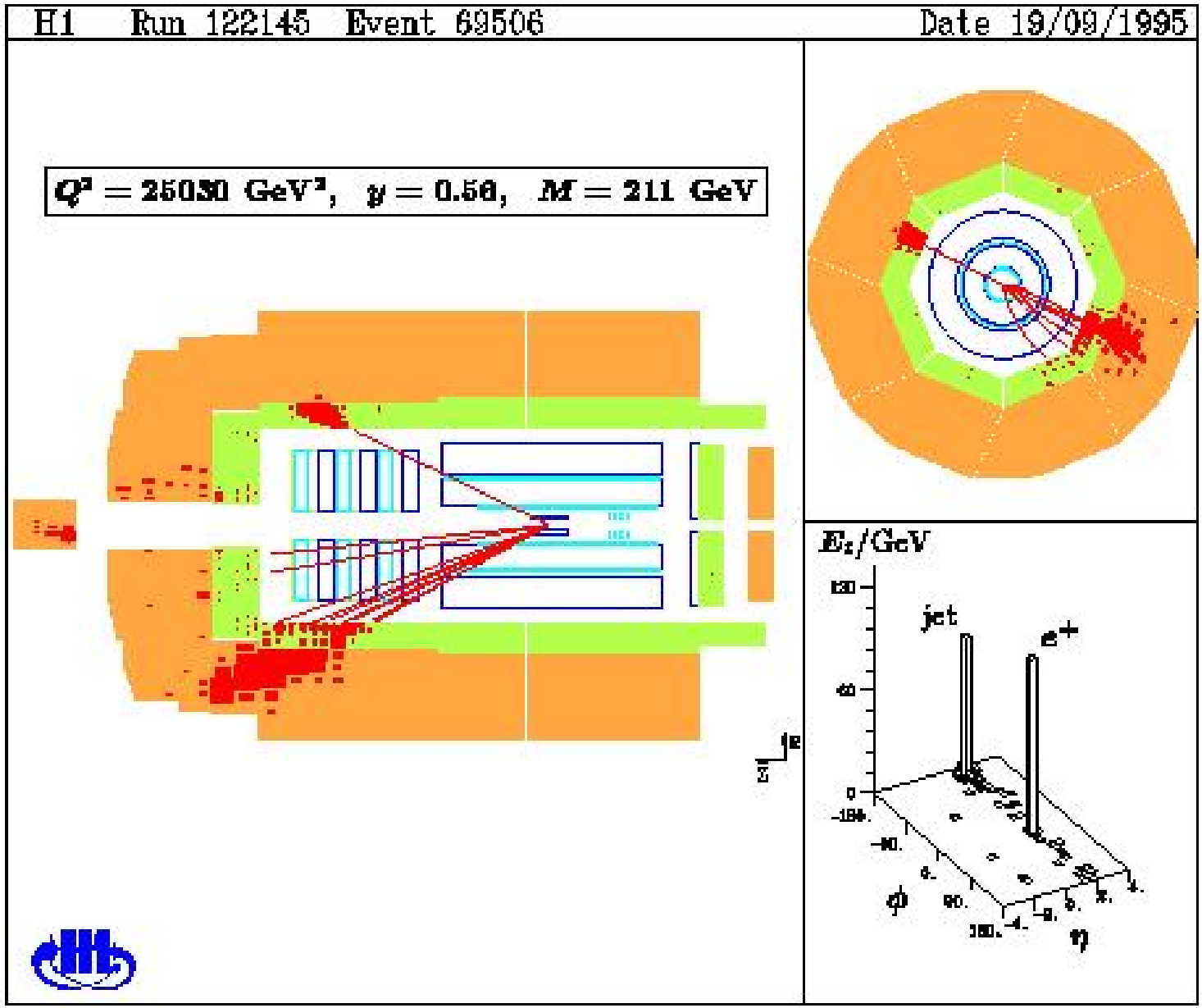
$$Q^2 = -q^2 \text{ and } x = \frac{Q^2}{2p \cdot q}$$

- Cross section for $Q^2 < M_Z^2$:

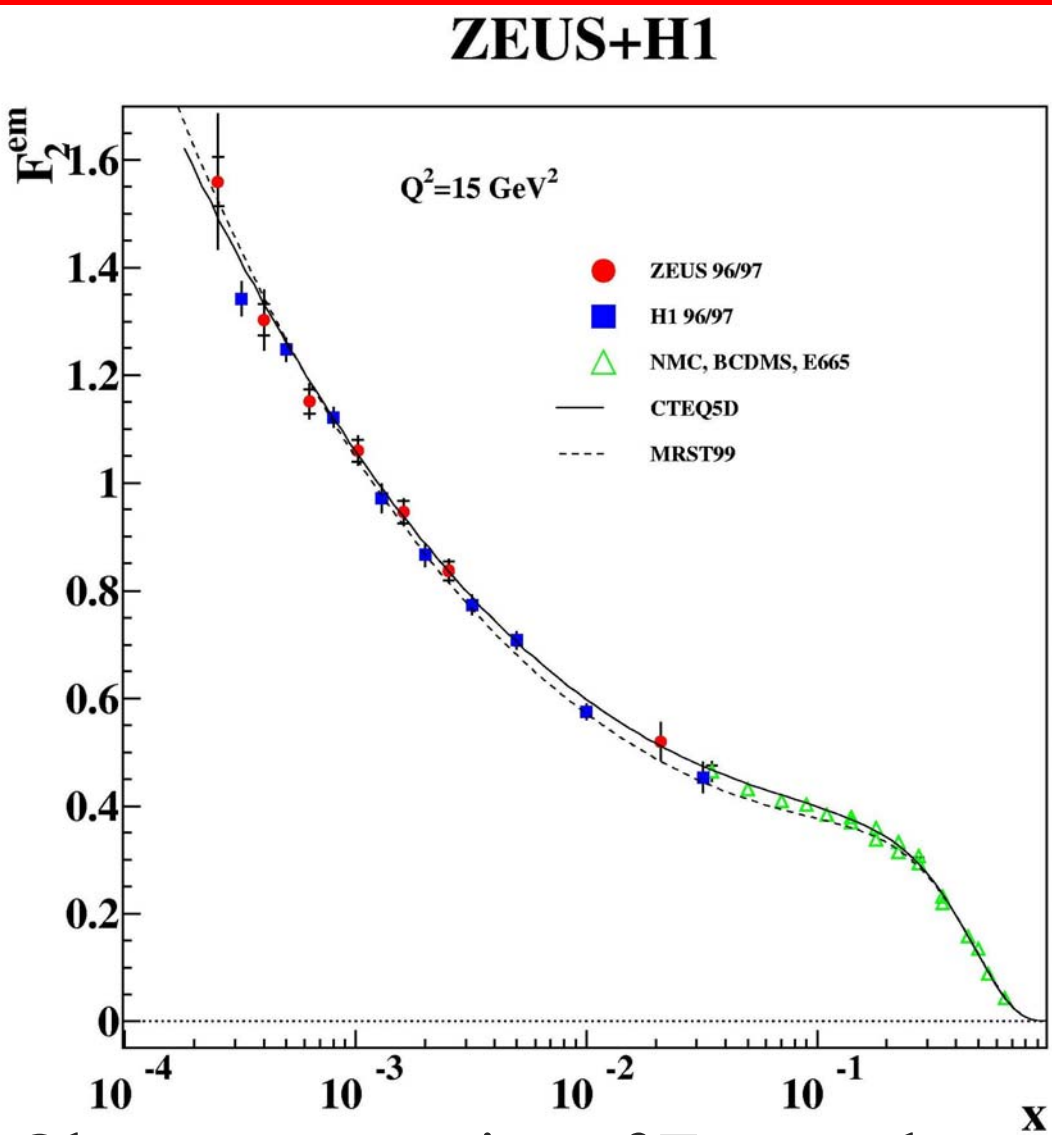
$$\frac{d^2\sigma_{ep\to eX}}{dx\,dQ^2} \approx \frac{2\pi\alpha^2}{xQ^4} F_2(x,Q^2)$$

- Structure function related to quark densities:

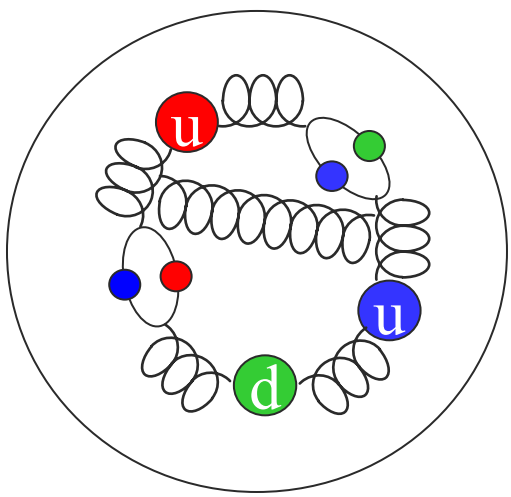
$$F_2(x,Q^2) = x\sum_q e_q^{\,2}\left(q(x,Q^2) + \bar{q}(x,Q^2)\right)$$


H1 Run 122145 Event 69506 Date 19/09/1995
$Q^2 = 25030\ \mathrm{GeV}^2$, $y = 0.56$, $M = 211\ \mathrm{GeV}$
E_t/GeV
jet
e+
60
0
-180.
-90.
0.
90.
180.
ϕ
η

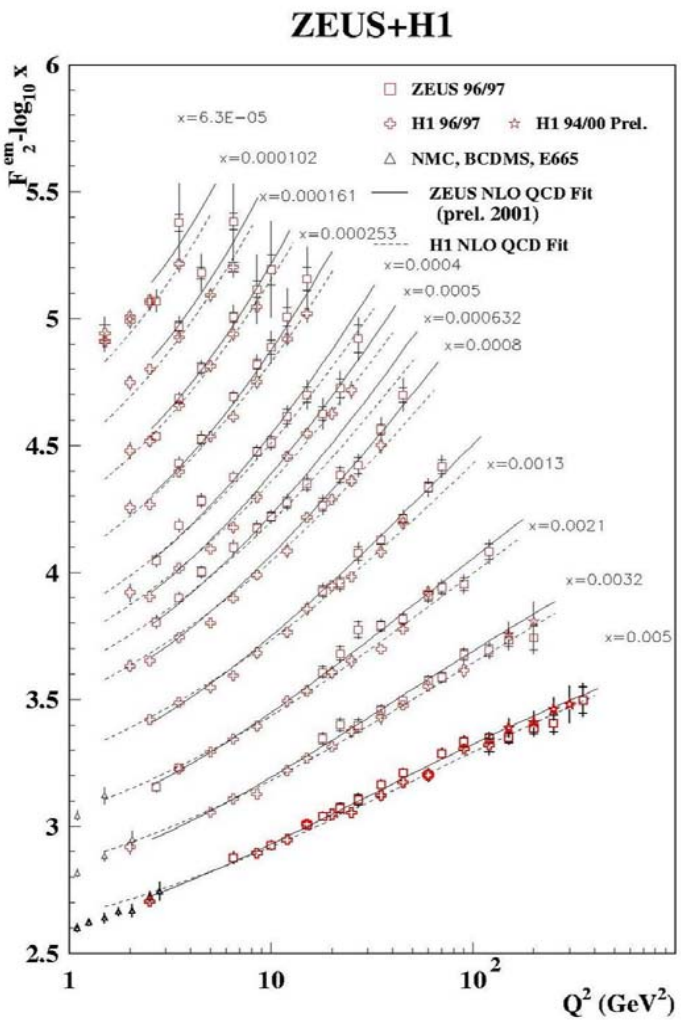
Measurements of F2(x,Q2)

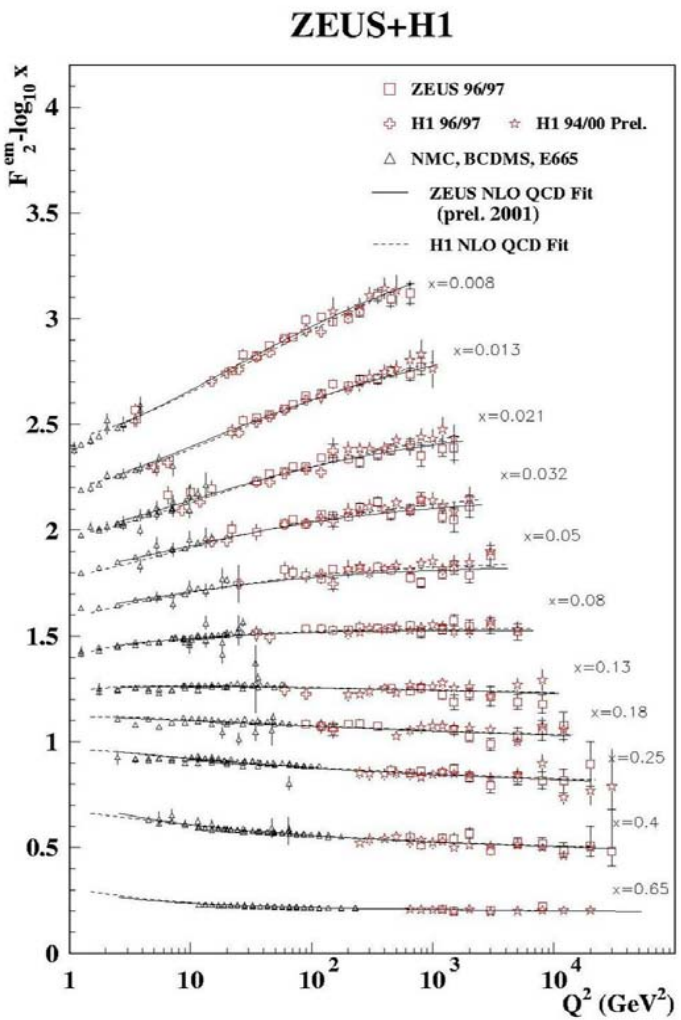


- Observe steep rise of F_2 as x decreases.



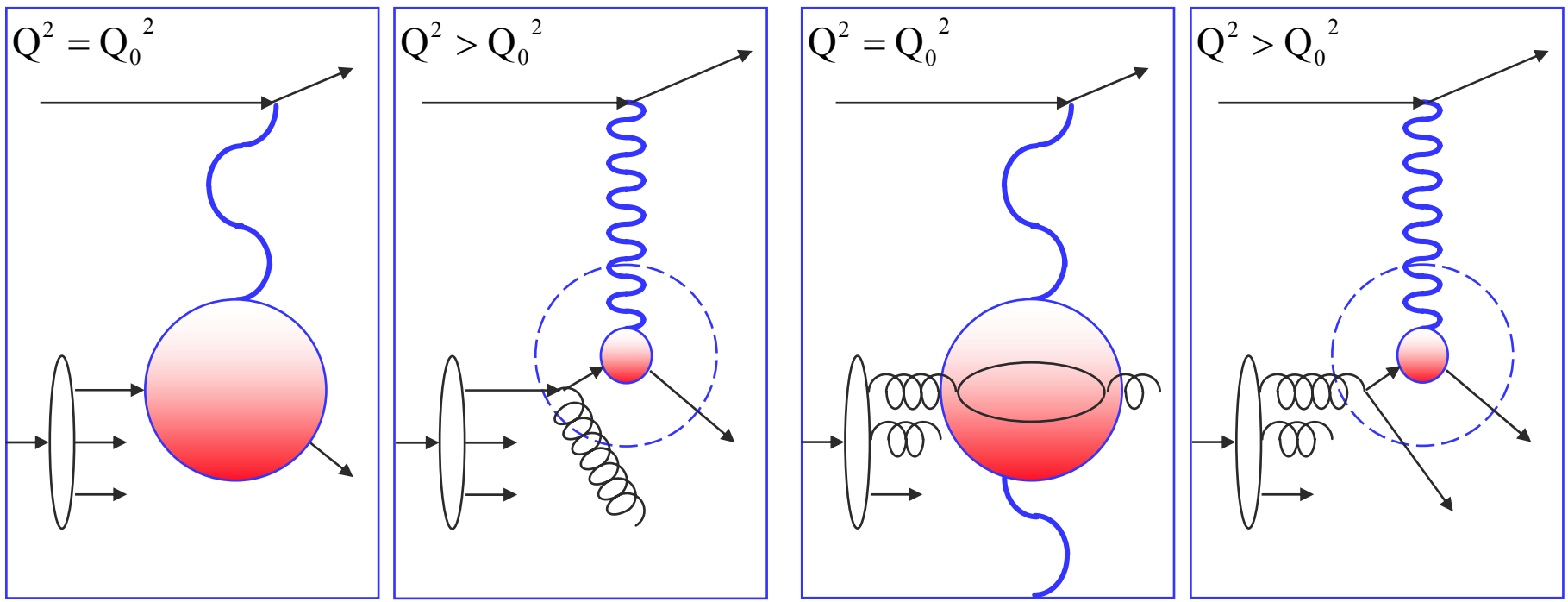
Measurements of $F_2(x,Q^2)$





QCD and scaling violations

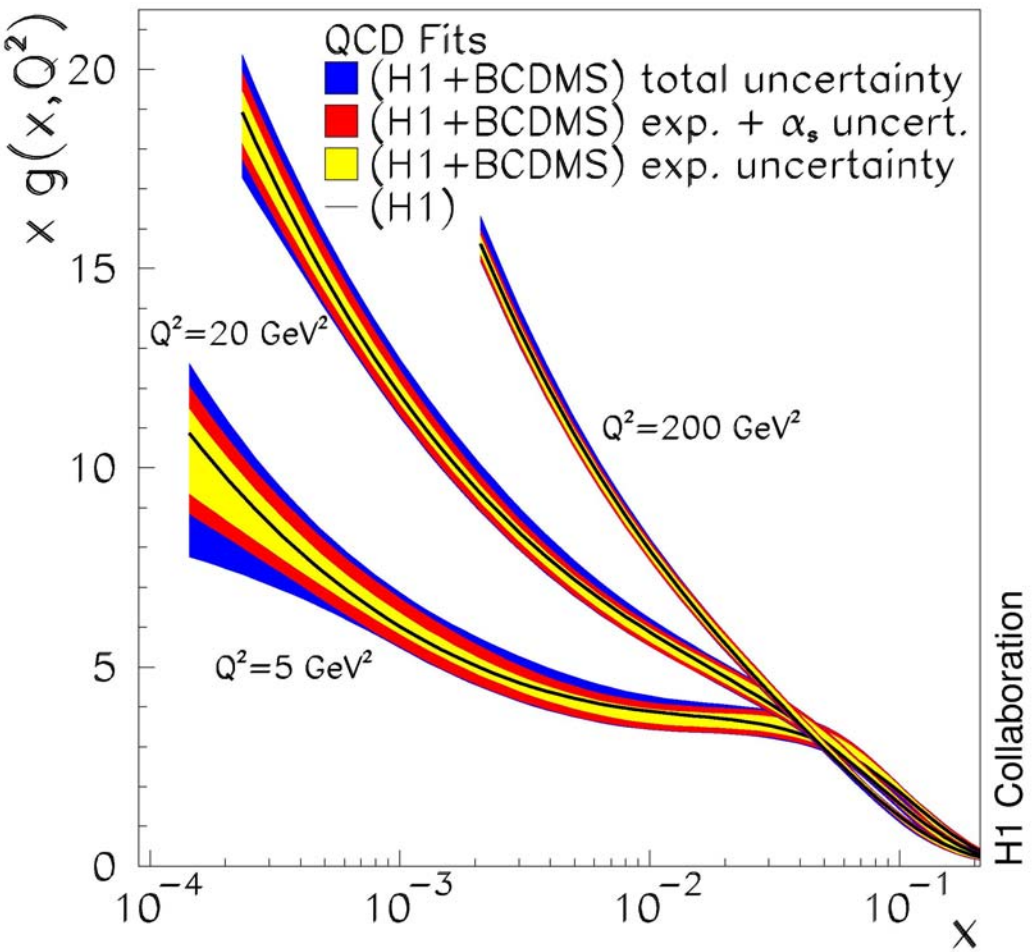
- If quarks dominate:
  $Q^2 \uparrow \Rightarrow F_2 \downarrow$ at a given x
- If gluons dominate
  $Q^2 \uparrow \Rightarrow F_2 \uparrow$ at a given x



QCD and scaling violations

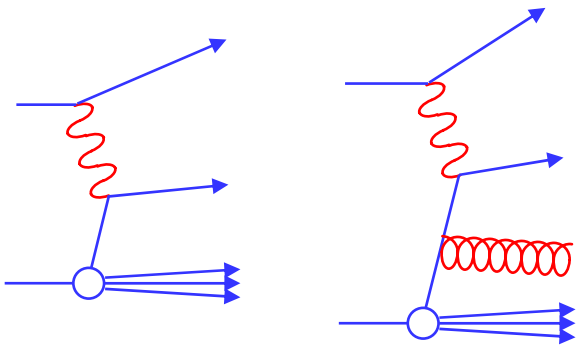
- QCD fit (NLO DGLAP) gives simultaneously:
  - $\alpha_S(M_Z^2) = 0.1150 \pm 0.0017(\text{exp.})$

    $^{+0.0009}_{-0.0005}(\text{mod.}) \pm 0.005(\text{scale}).$
  - Parton distribution functions (PDFs), e.g. gluon.



Jet production in DIS

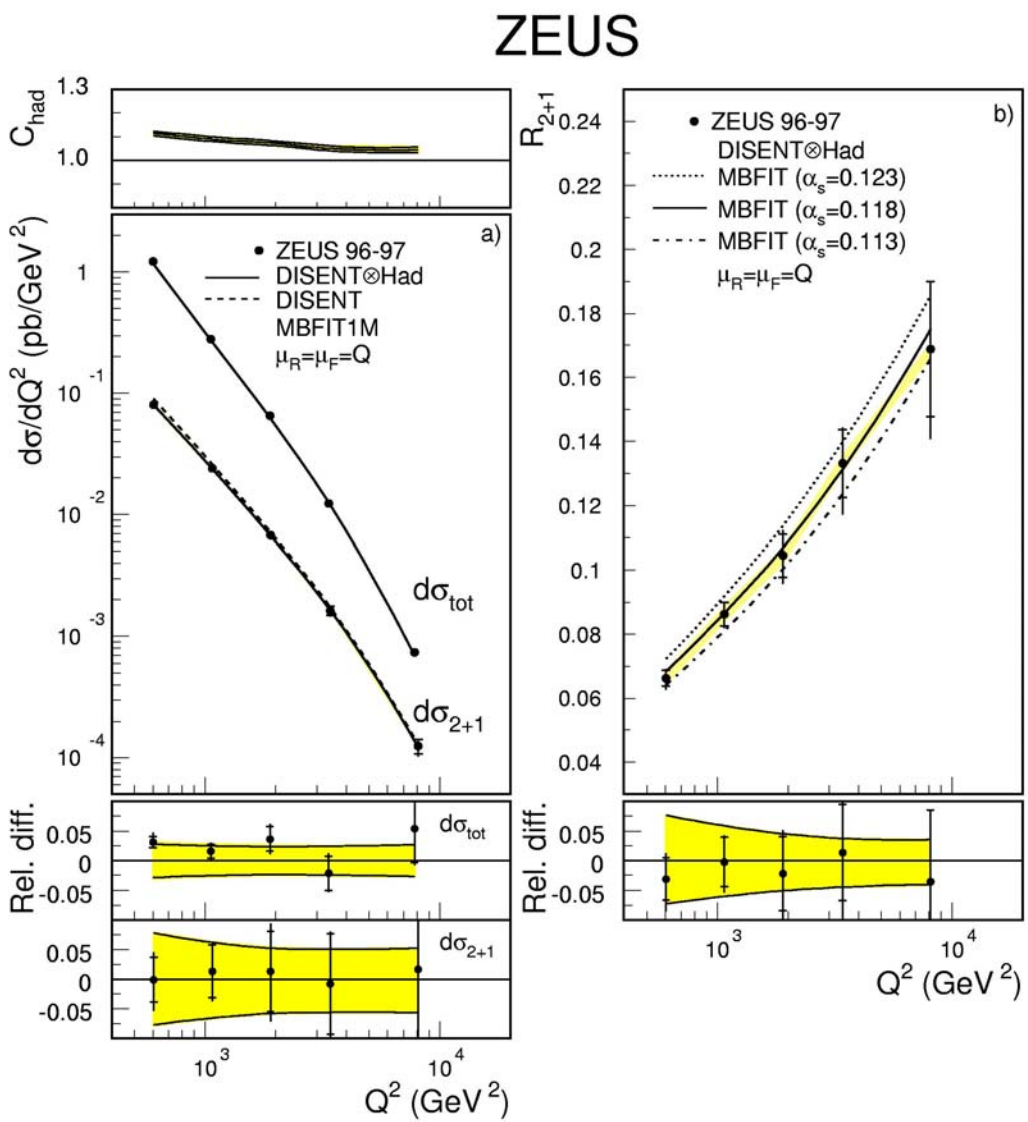
- Described by NLO QCD.



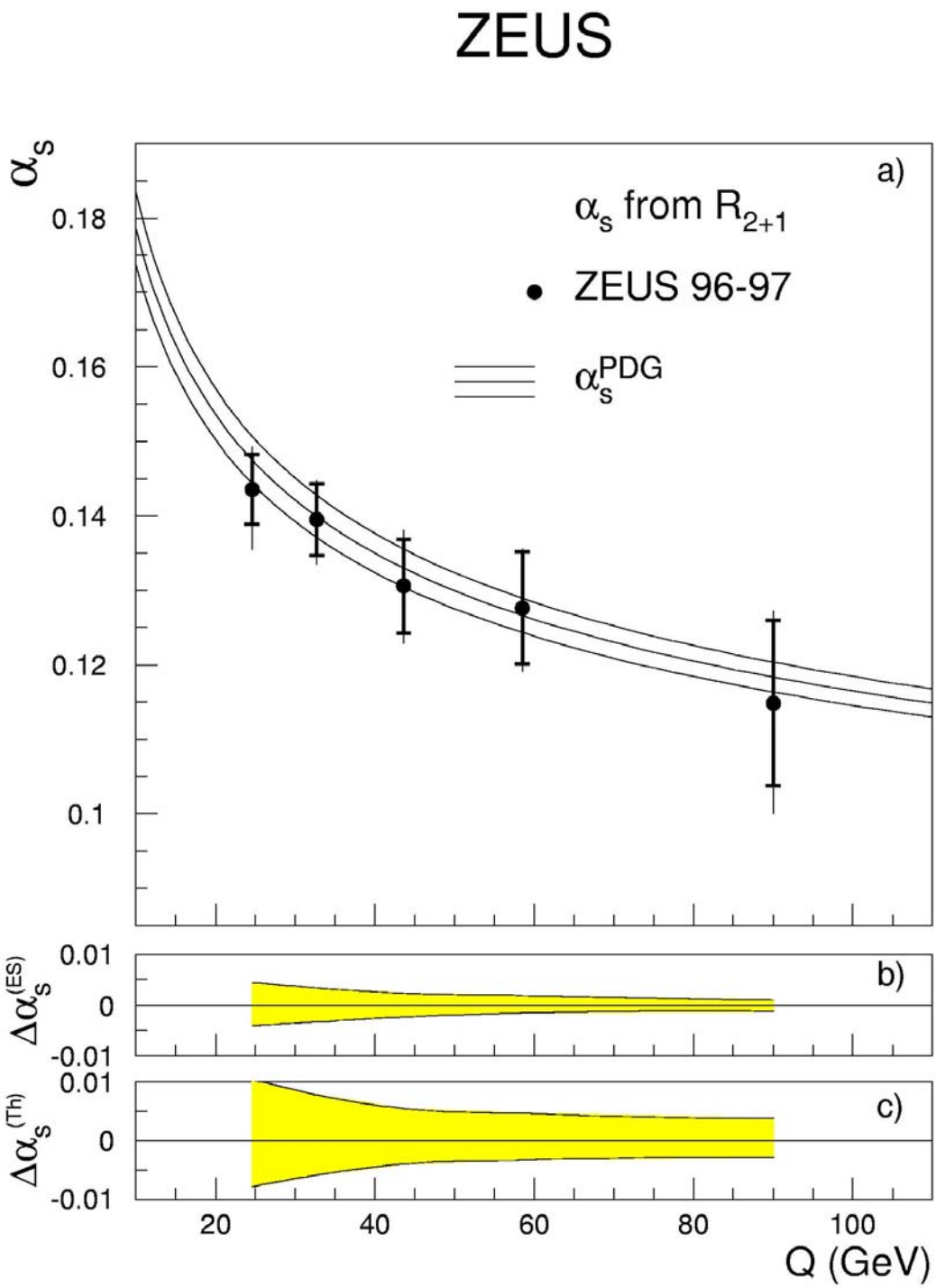
- $\alpha_S(M_Z^2) = 0.1177 \pm 0.0019(\text{stat.})$

$^{+0.0024}_{-0.0033}(\text{exp.})\,^{+0.0057}_{-0.0044}(\text{theo.})$

- Again, NNLO calculations are underway and will reduce "theoretical" errors.



Running of strong coupling



- Running of α_S observed with one experiment.

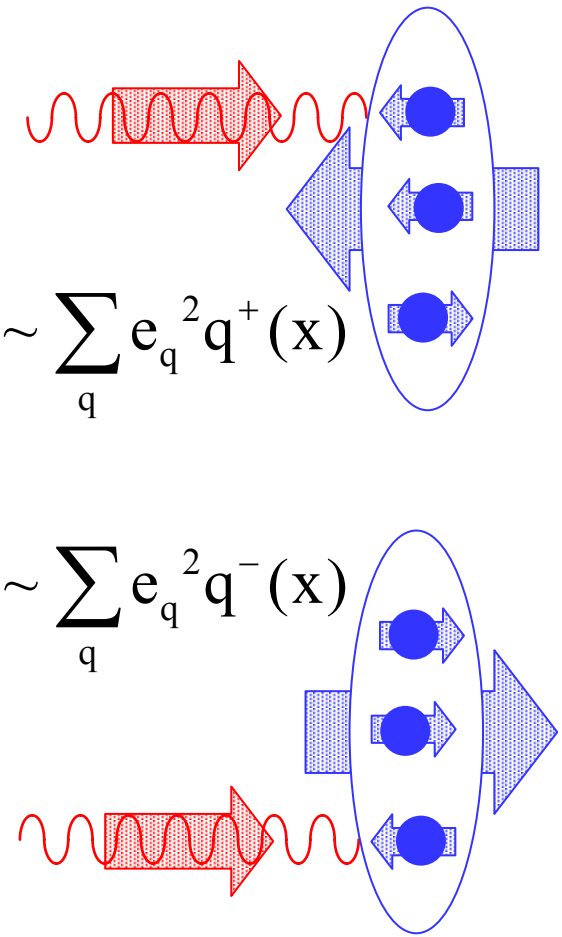
Spin structure measurements

- Use polarised target and polarised electron beam.
- Extract asymmetry

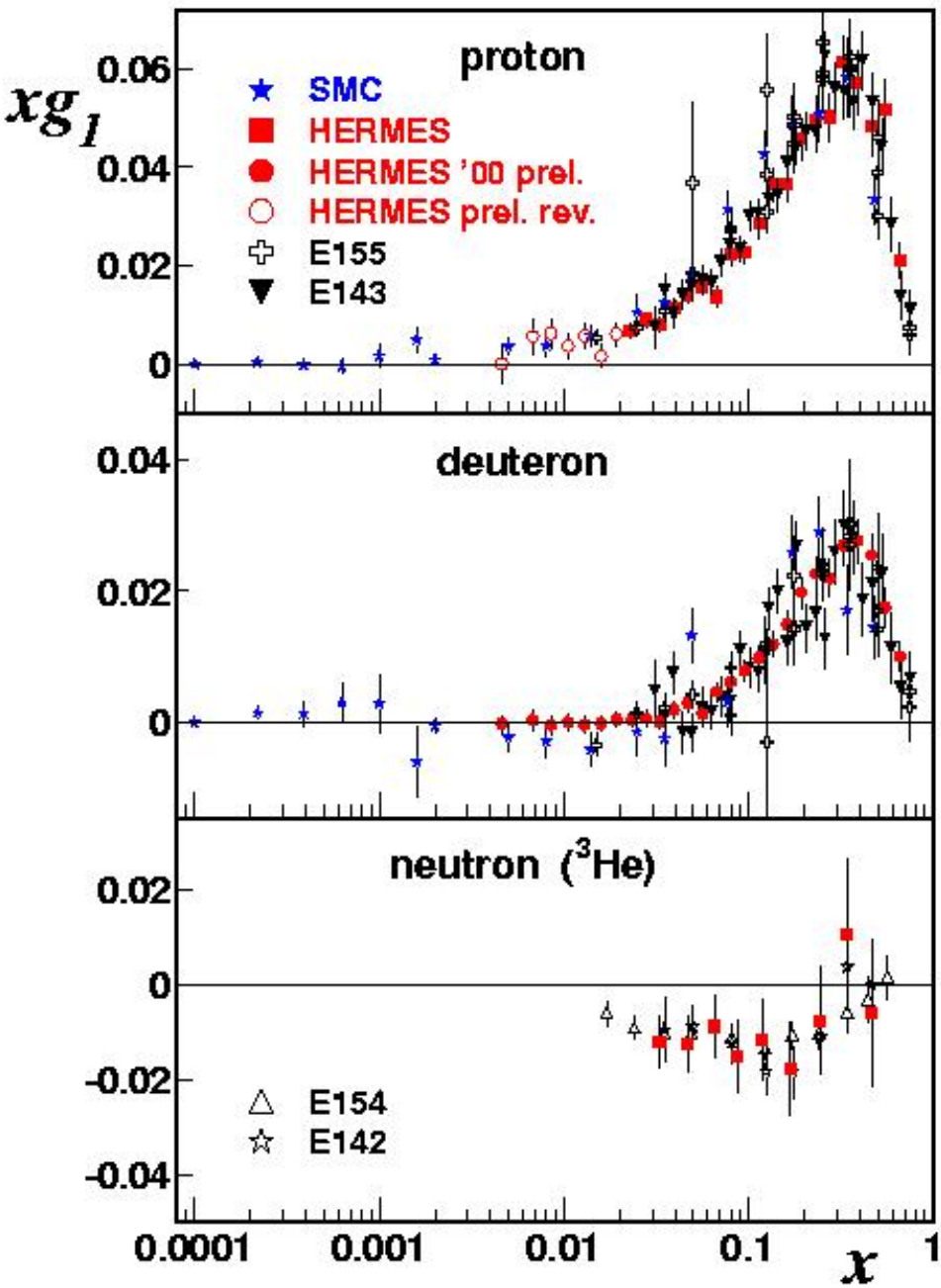
$$A = \left(\sigma_{1/2} - \sigma_{3/2}\right) / \left(\sigma_{1/2} + \sigma_{3/2}\right)$$

$$\approx \frac{\sum e_q^{\,2}\left(q_+(x) - q_-(x)\right)}{\sum e_q^{\,2}\left(q_+(x) + q_-(x)\right)}$$

- $g_1(x) = \frac{1}{2}\sum e_q^{\,2}\left(q^+(x) - q^-(x)\right)$

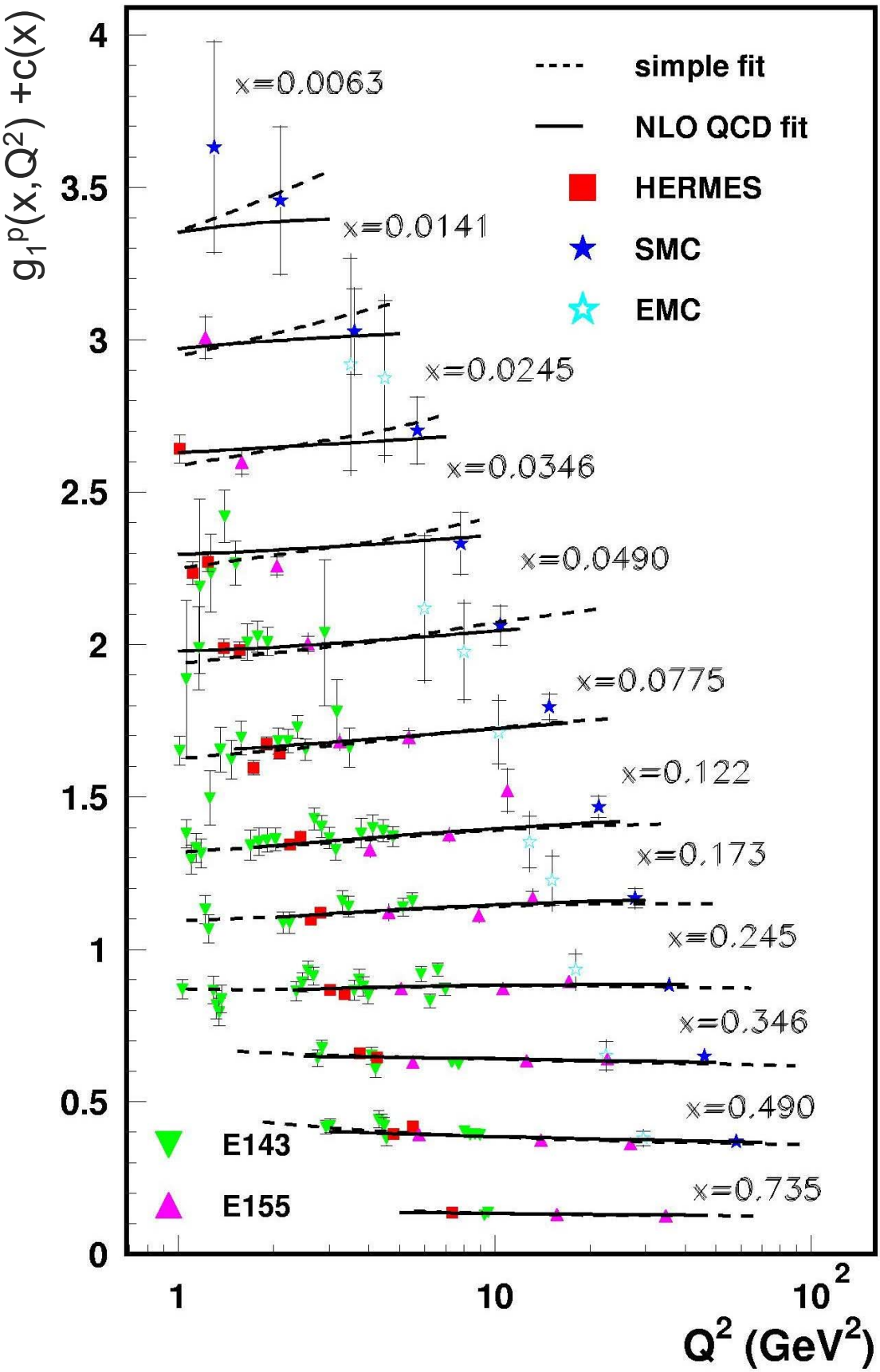


Measurements of $g_1(x,Q2)$



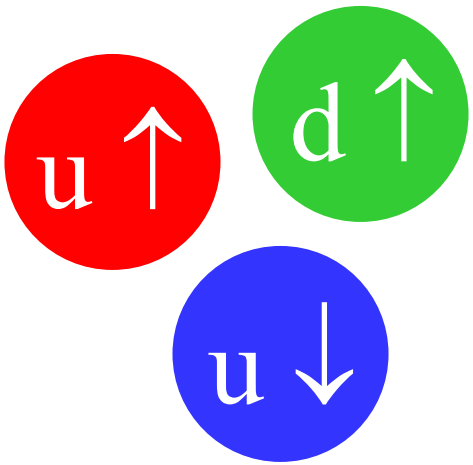
- "Take away" message, about 30% of the proton's spin is carried by quarks.

Scaling violations, $g_1(x,Q^2)$



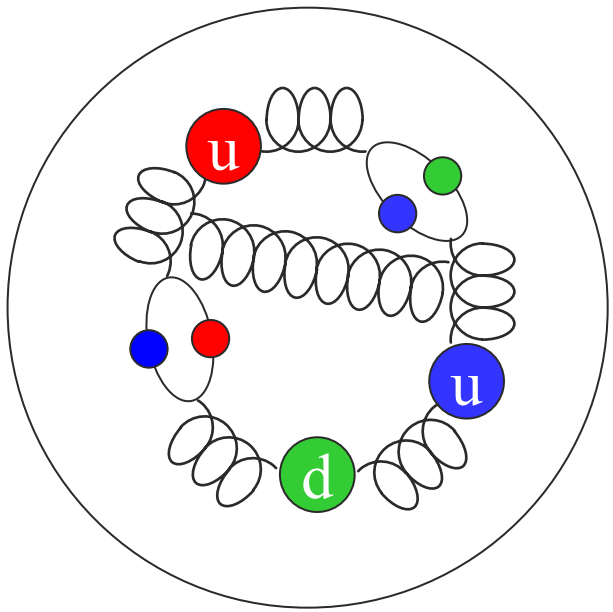
Two pictures of proton

- Constituent quark picture:



- Proton made of three quarks.
- Spin is result of adding quark spins.
- Quark masses ~ 360 MeV.

- QCD improved QPM:



- Proton many quarks and gluons.
- Spin is result of complicated conspiracy.
- Quark masses ~ 4 MeV.

Rise of parton densities at small x

- Probability of g emission:

$$dP \sim \frac{\alpha_s(k_T^2)}{\pi} C_A dy$$

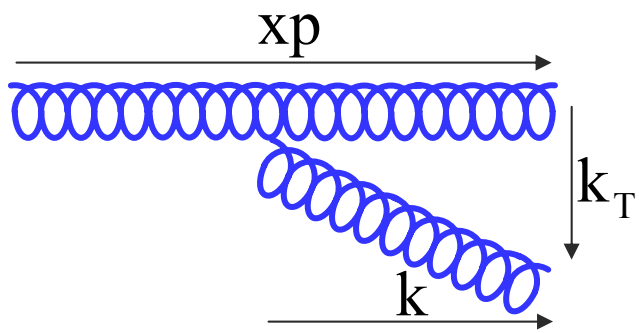
- For n^{th} gluon, if treat g charges as random:

$$dP_n \sim \frac{\alpha_S(k_T^2)}{\pi} n C_A dy$$

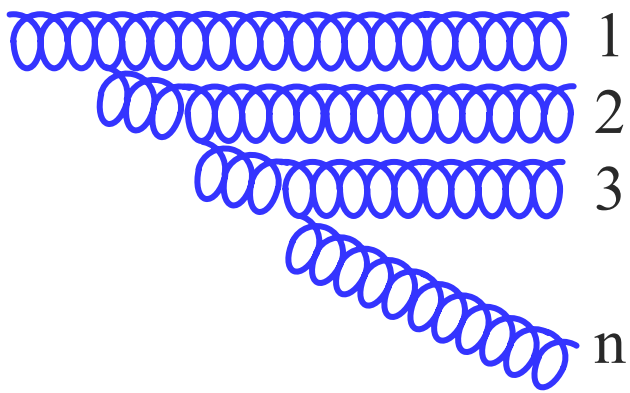
- Prob. of g emission rises with number of gluons!
- BFKL result:

$$x\,q(x,Q^2) \sim x^{-\delta}$$

$$\delta = 0.3...0.5$$

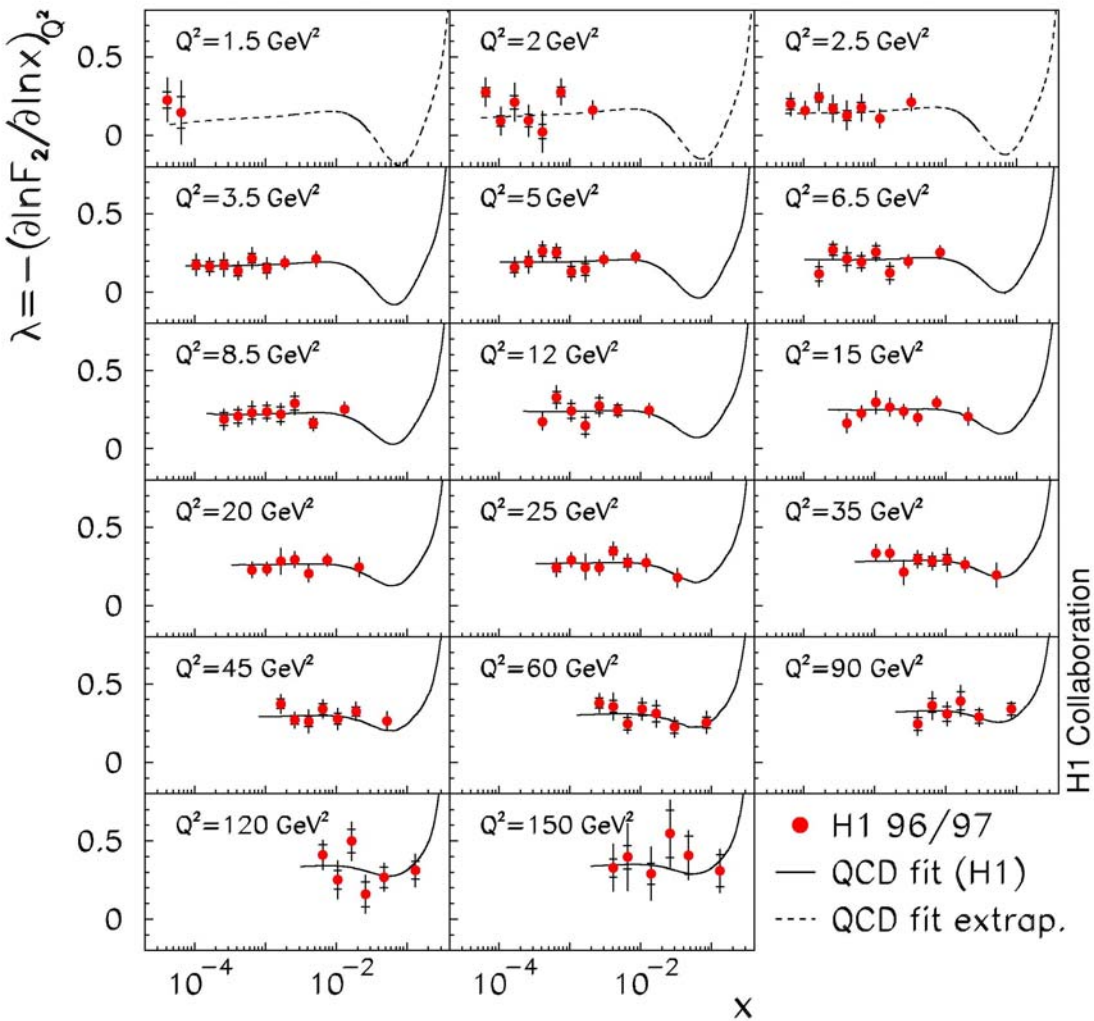


$$y \sim \ln \frac{2k}{k_T}$$

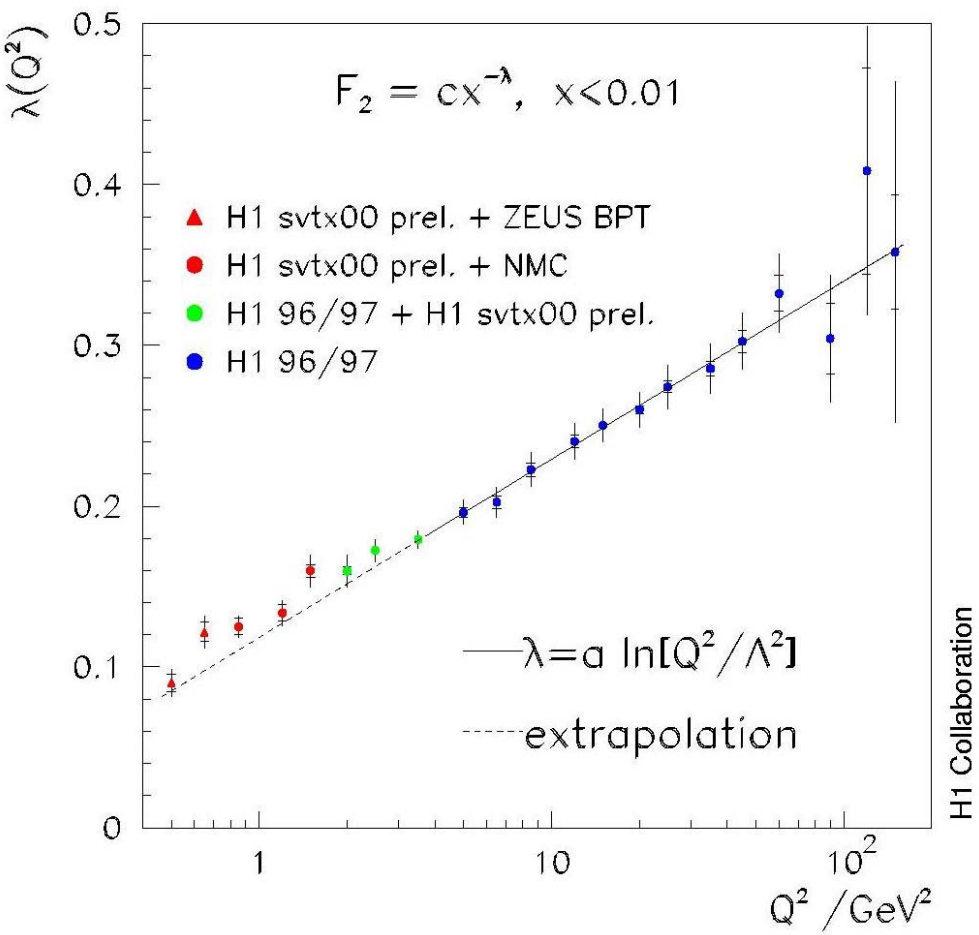


Variation of $F_2(x,Q^2)$ with x

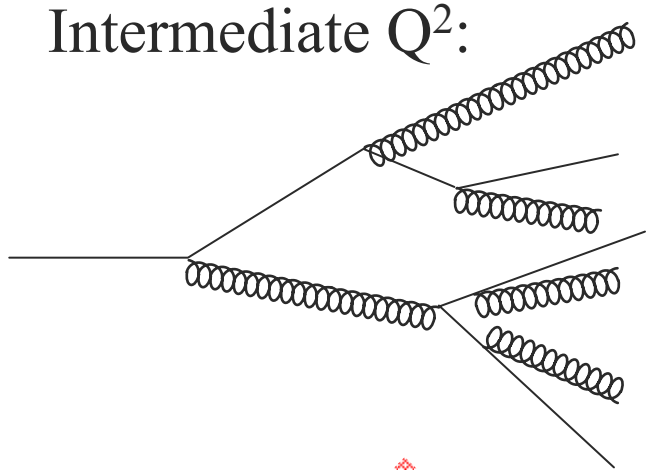
- Does data show $F_2(x,Q^2) \sim x^{-\lambda}$?
- Study derivative $\dfrac{\partial \ln F_2}{\partial \ln x} = -\lambda$
- Data consistent with $F_2 \sim x^{-\lambda}$ for $x < 0.01$



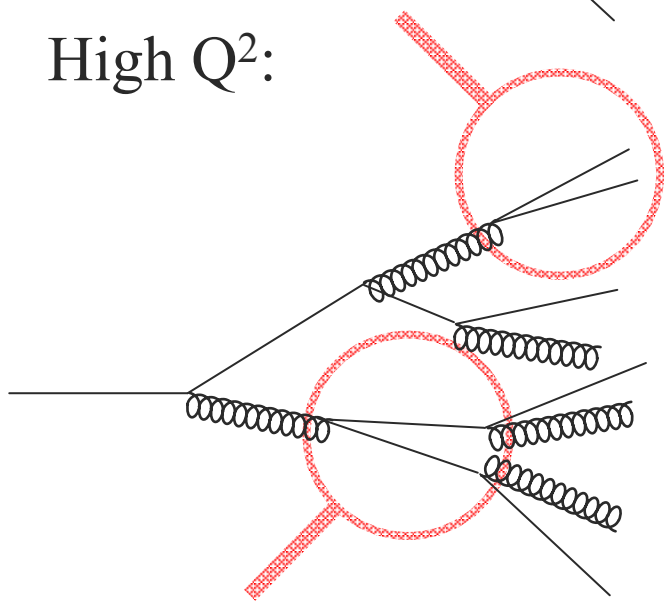
Change of F_2 with x and Q^2



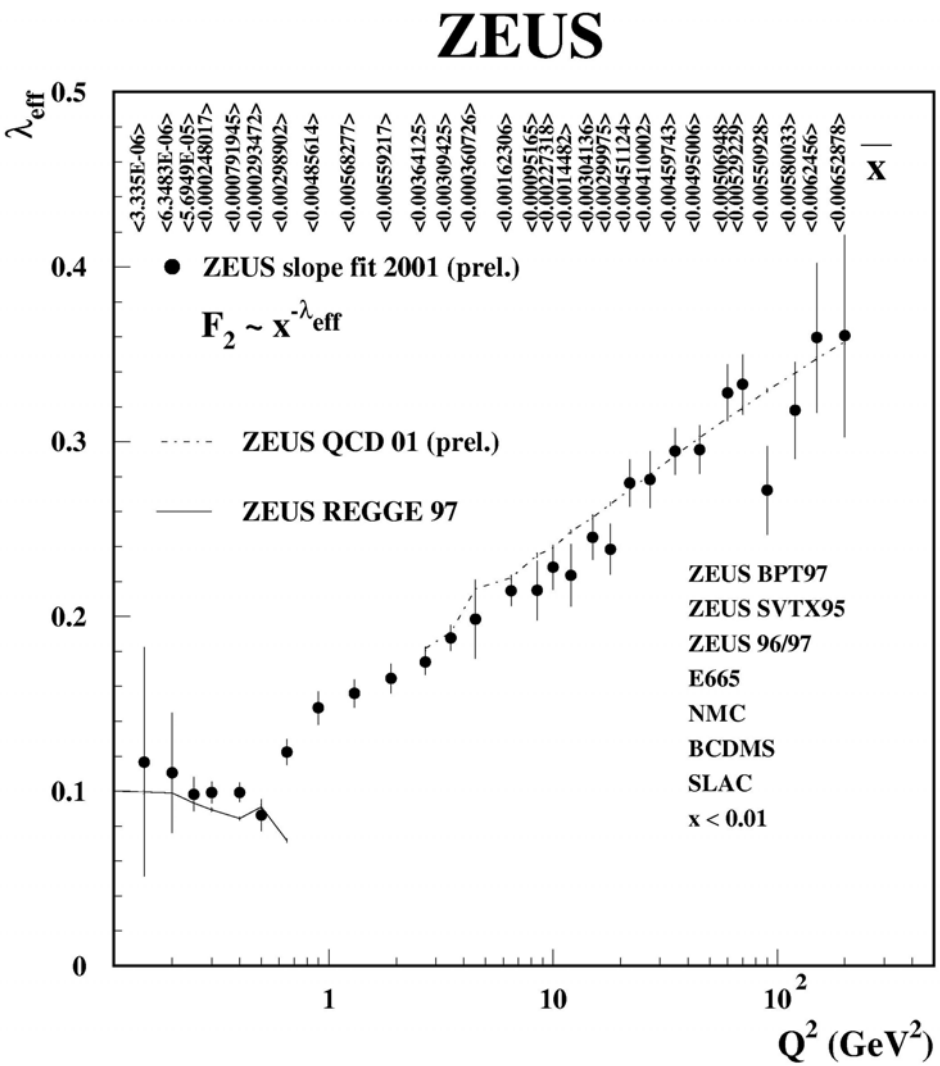
- Intermediate Q^2:



- High Q^2:

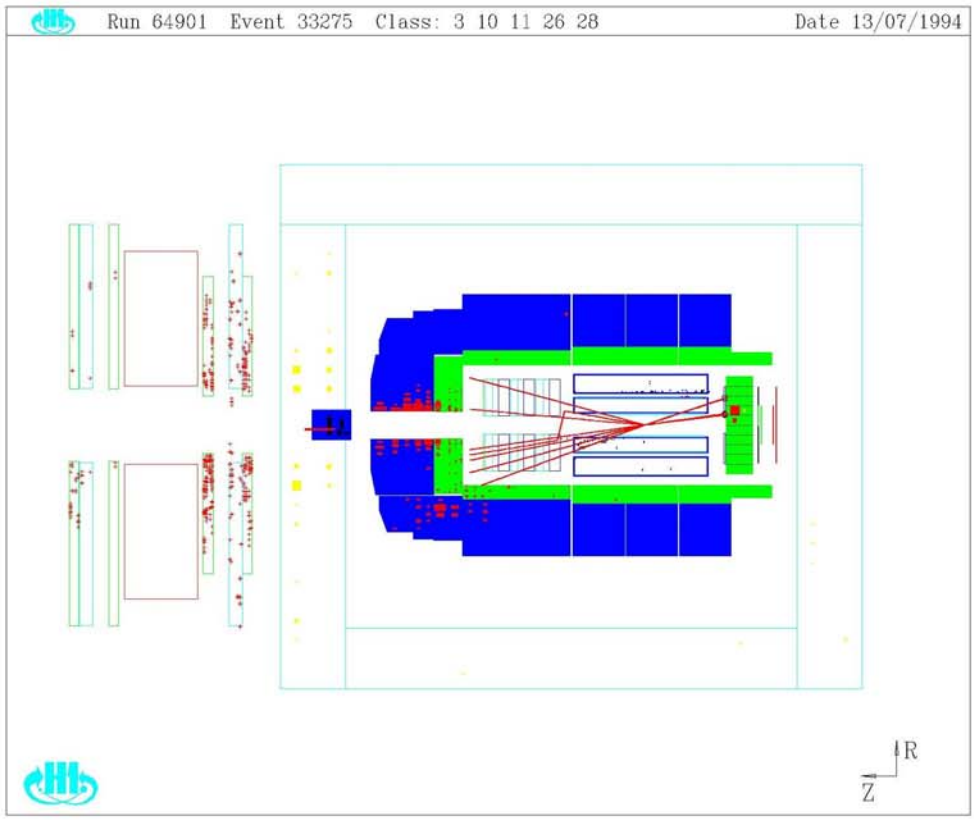


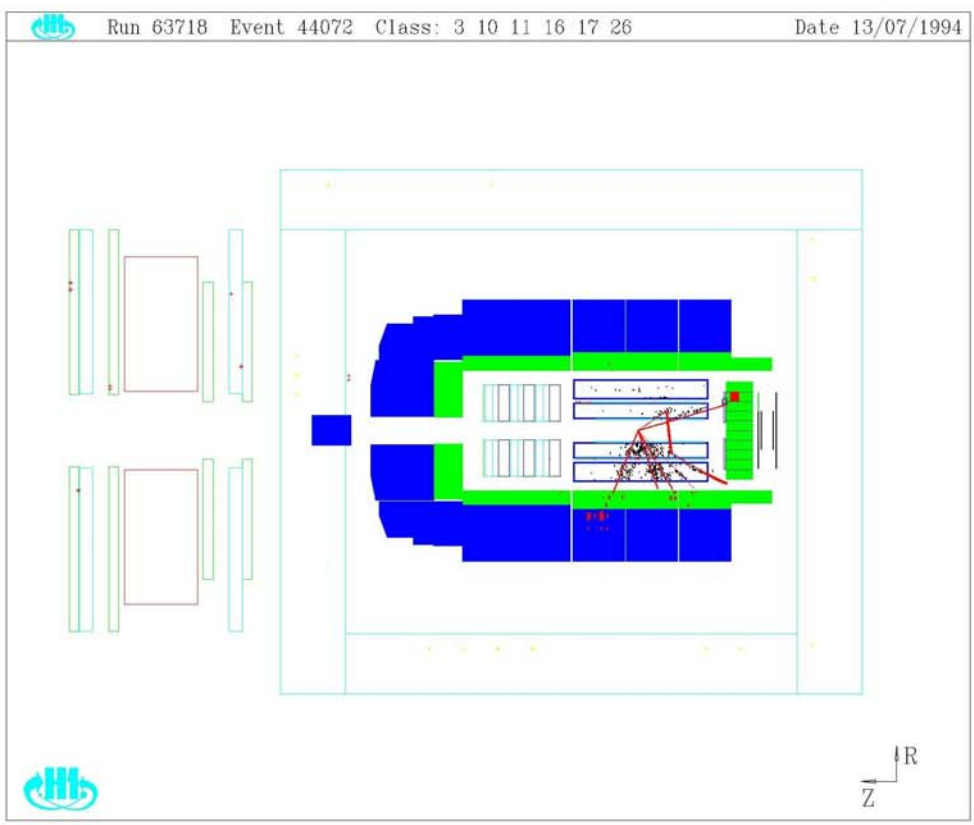
Behaviour at low Q^2



- What happens at the "ankle" at $Q^2 \sim 0.6$ GeV^2?
- Amount of radiation decreases and becomes "resolution independent".
- Corresponds to length $r \sim 0.2 \ldots 0.3$ fm.
- C.f. proton radius $r_p = 0.8$ fm.
- "Non-partonic" sub-structure within proton?

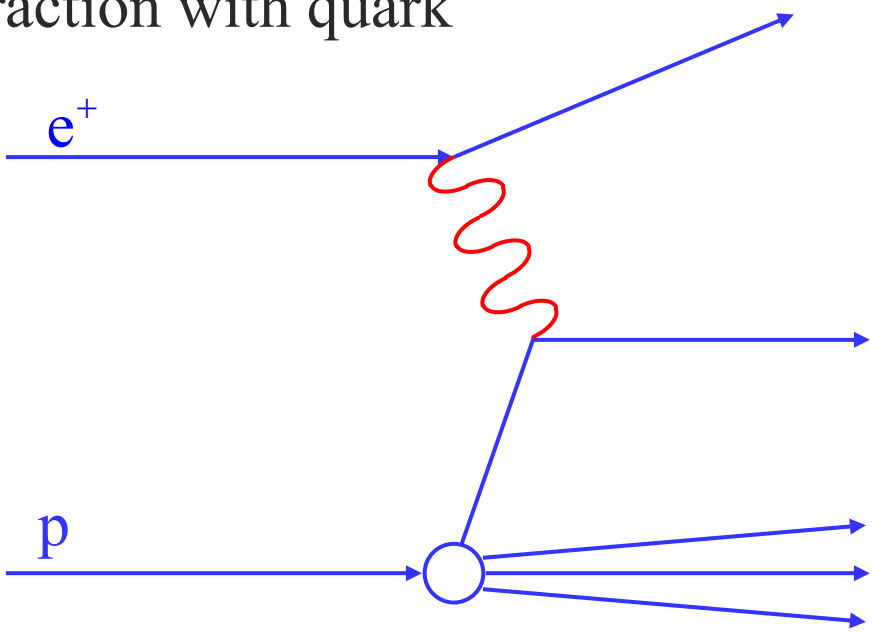
Rapidity gap events



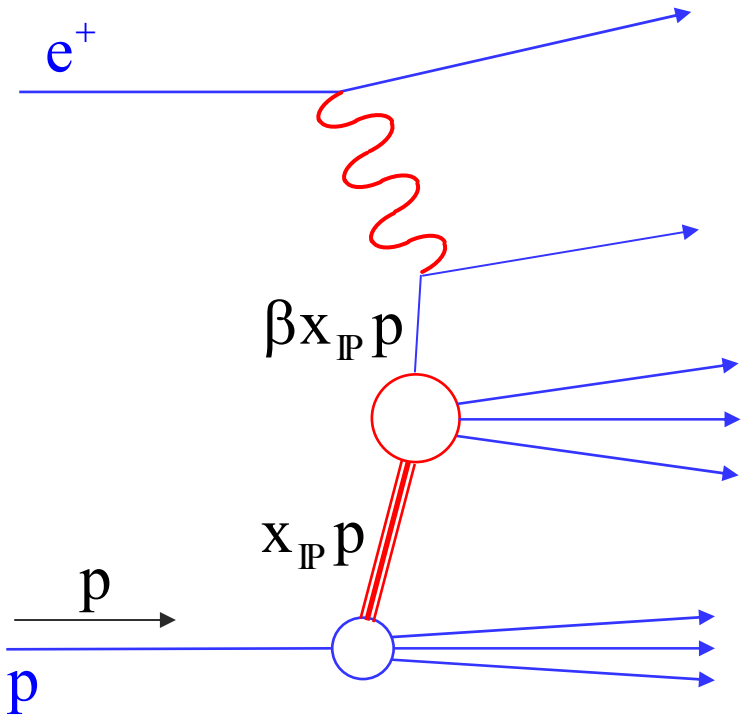


Rapidity gap events

- Interaction with quark

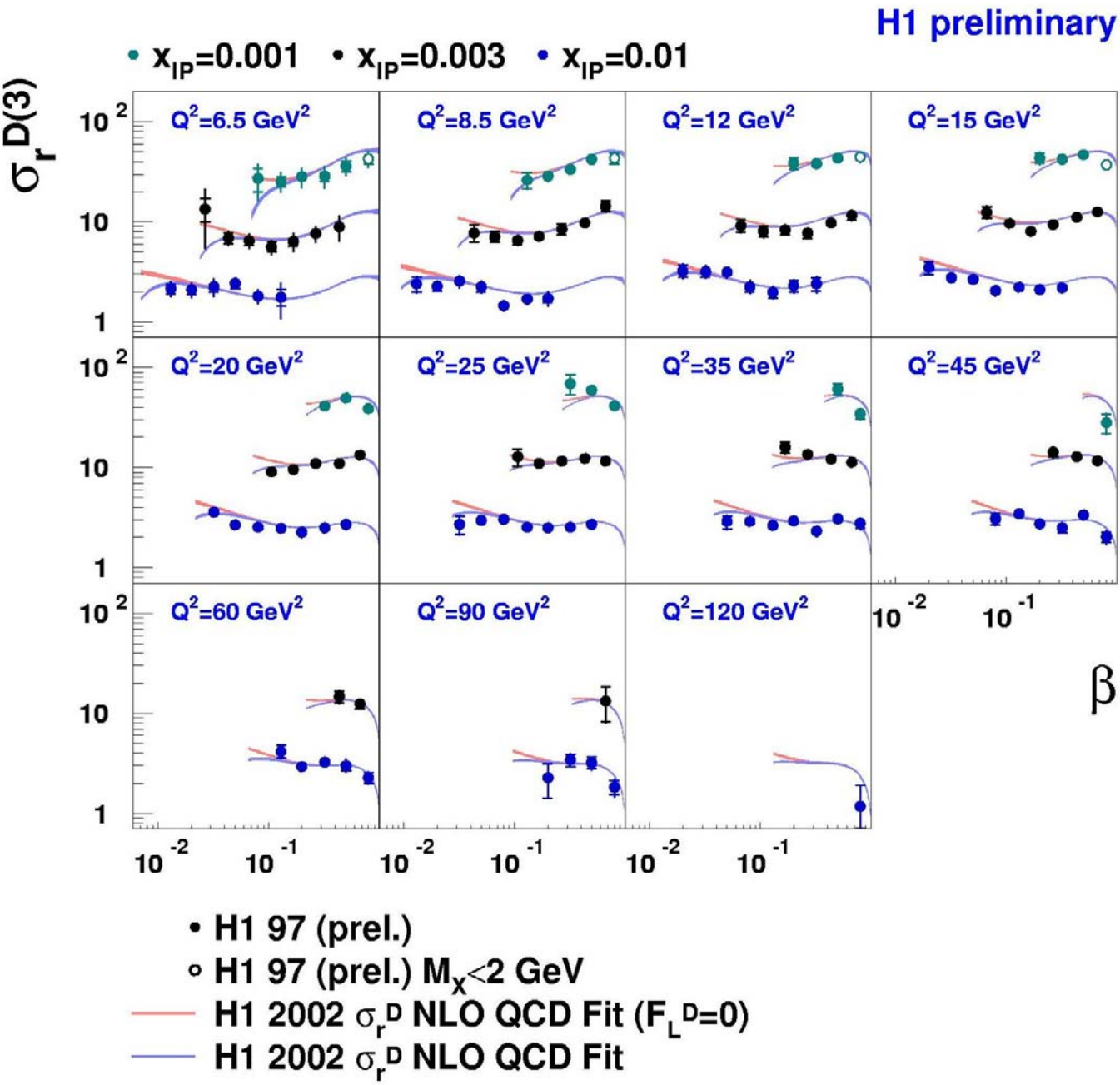


- Interaction with colourless component of proton



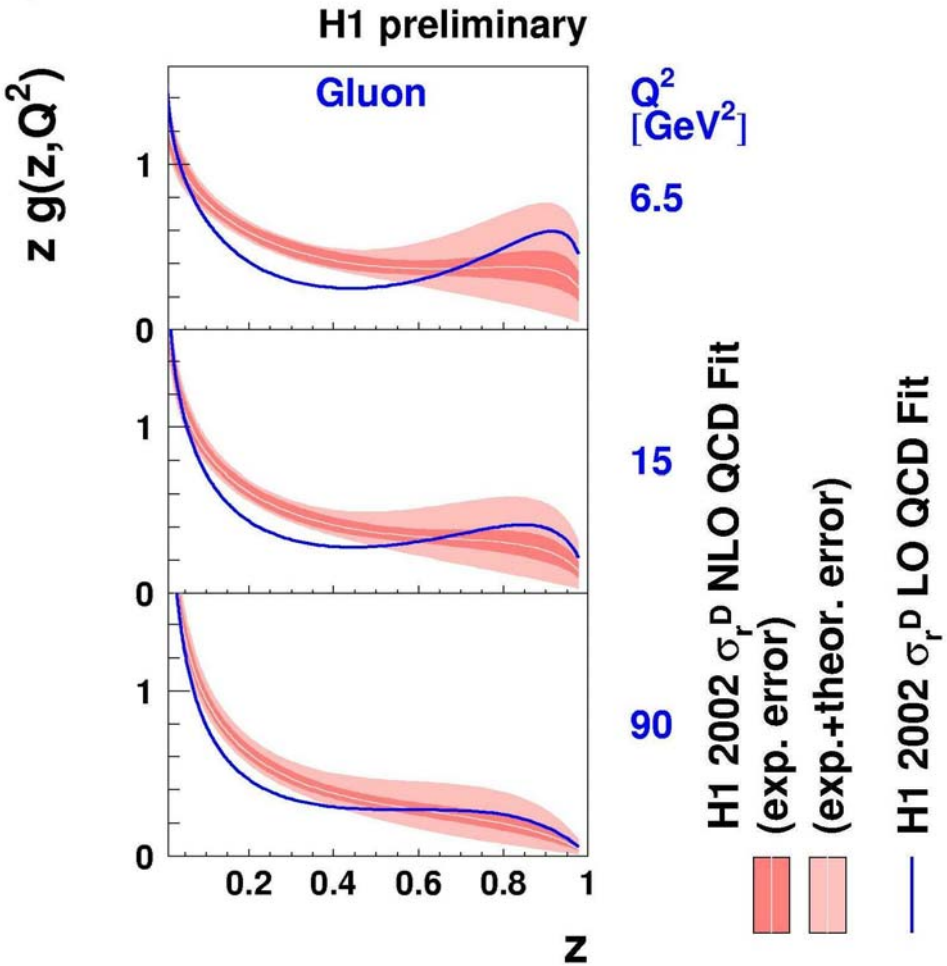
Investigate colourless component of proton

- Structure function $F_2^{D(3)} \sim \sigma_r^{D(3)}$.

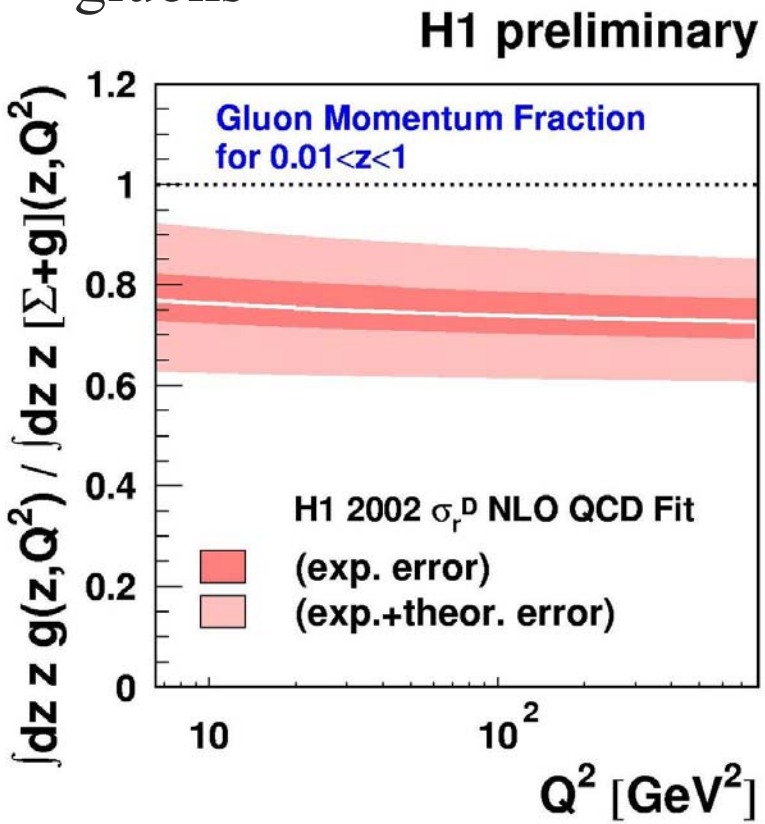


Investigate colourless component of proton

- Parton distributions

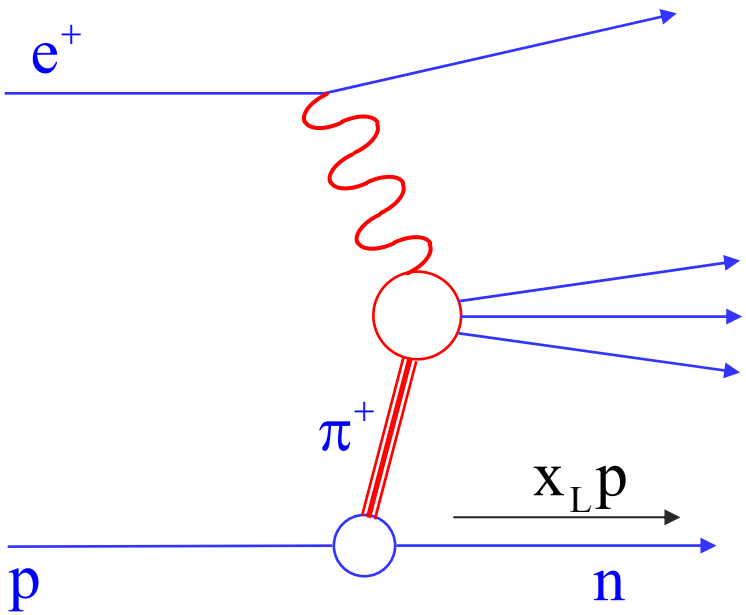


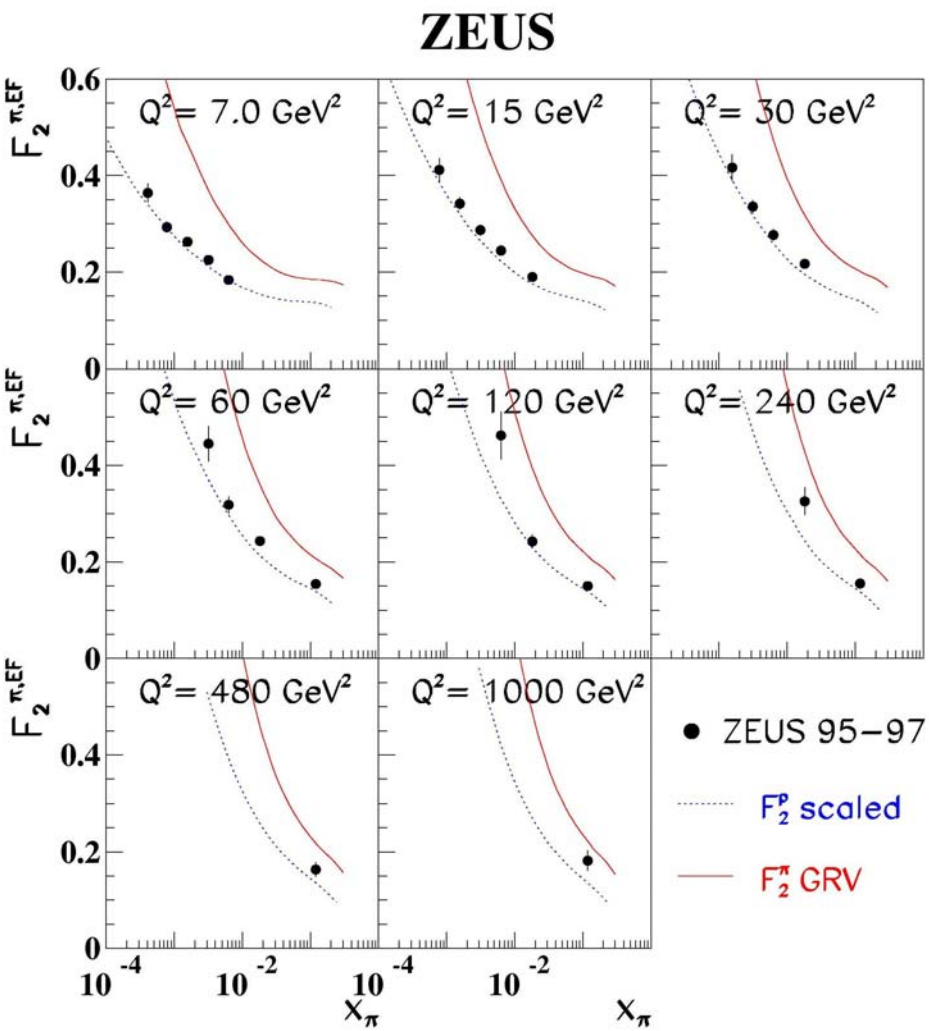
- Momentum carried by gluons



“Quark dominated” colourless component of proton

- Look for leading neutrons





Summary

- HERA has uncovered a wealth of structure at low x in the proton.
- Continuing theoretical and experimental improvements in study of perturbative QCD; in regions of applicability obtain good description of:
  - Unpolarised and polarised structure functions.
  - Hadronic final state.
- Perhaps starting to see features in data in low x and Q^2 region that will help development of understanding of links between constituent and QCD improved QPM pictures of the proton.