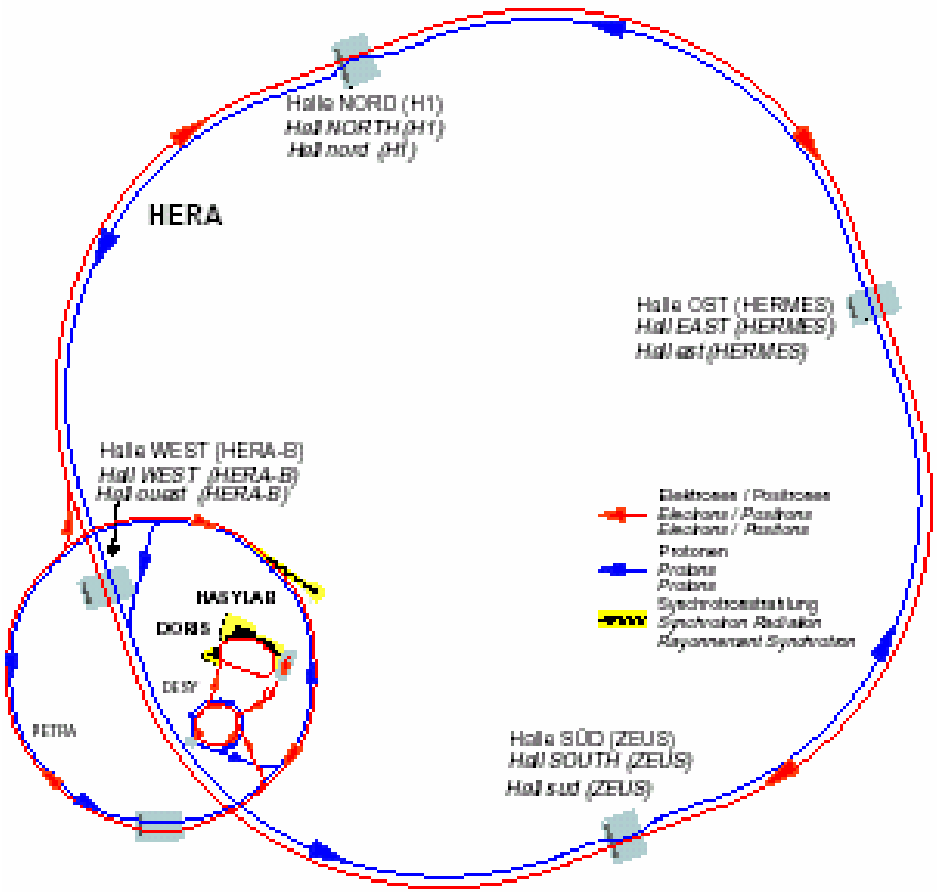
Future Physics with HERA



- Measuring hadron structure.
- Nucleon spin.
- Approaching the confinement region.
- Studying parton radiation.
- Generalised parton distributions.
- High parton densities.
- Physics beyond the standard model at HERA.
- Summary.

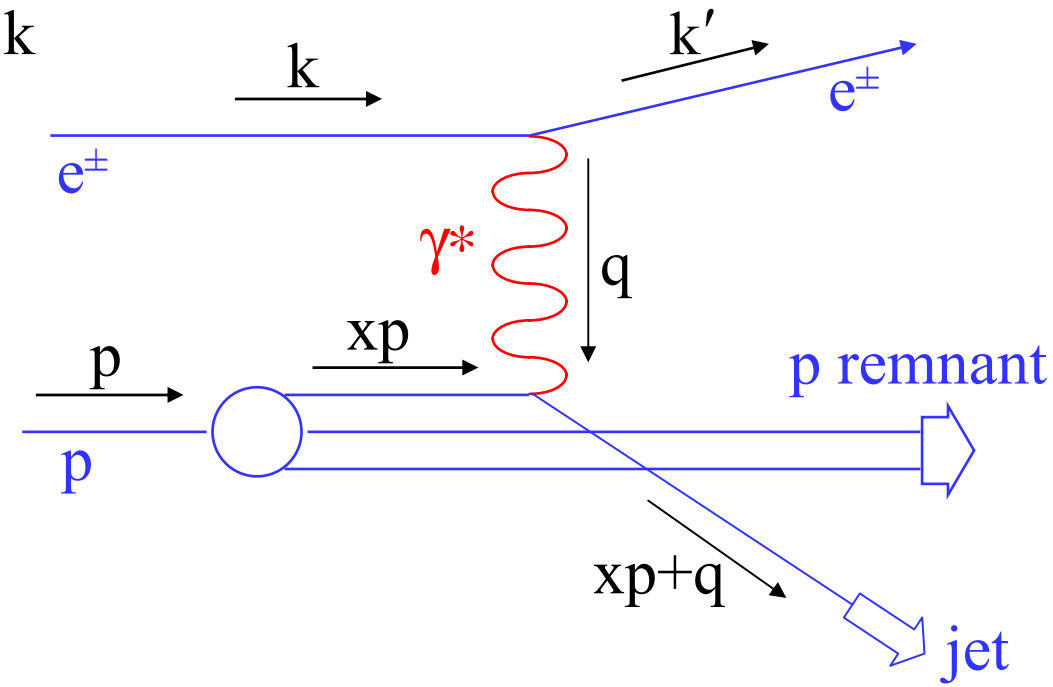
Deep Inelastic Scattering

- Describe in terms of:

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

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

$$\frac{d^2\sigma_{ep\to eX}}{dx\,dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left(y^2 xF_1(x,Q^2) + (1-y)F_2(x,Q^2)\right)$$

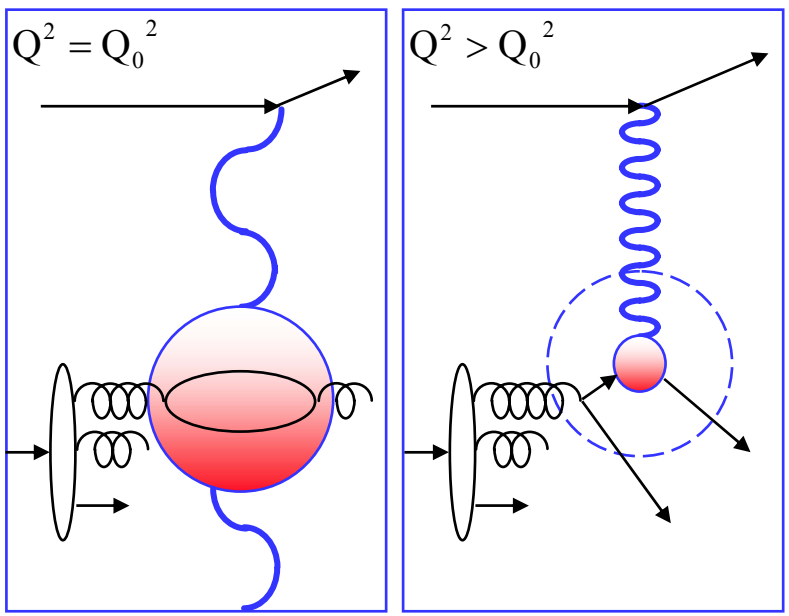


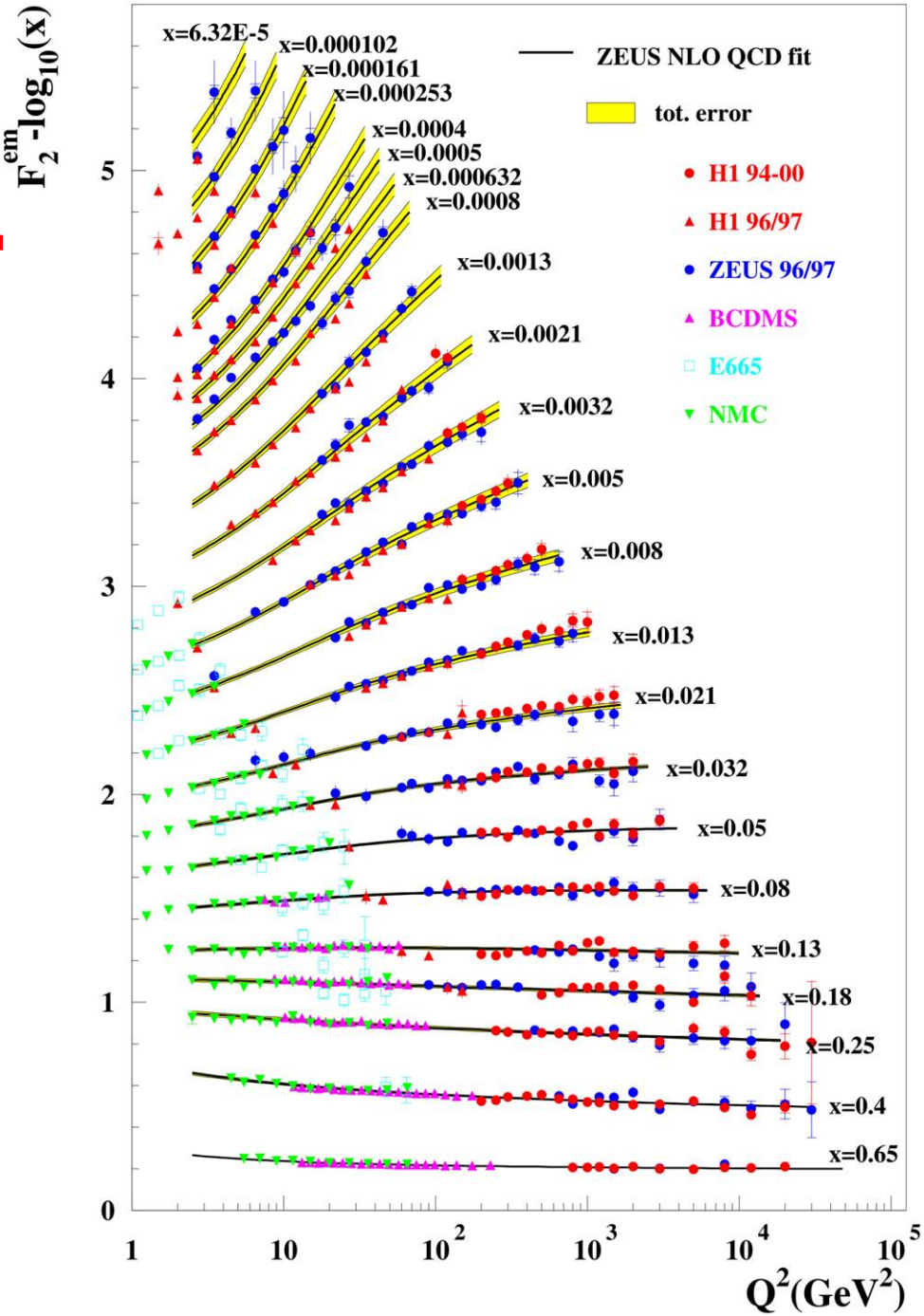
- Structure functions related to quark densities:

$$F_2(x,Q^2) = 2xF_1(x,Q^2)$$
$$= x\sum_q e_q^{\,2}\left(q(x,Q^2) + \bar{q}(x,Q^2)\right)$$

Measuring hadron structure

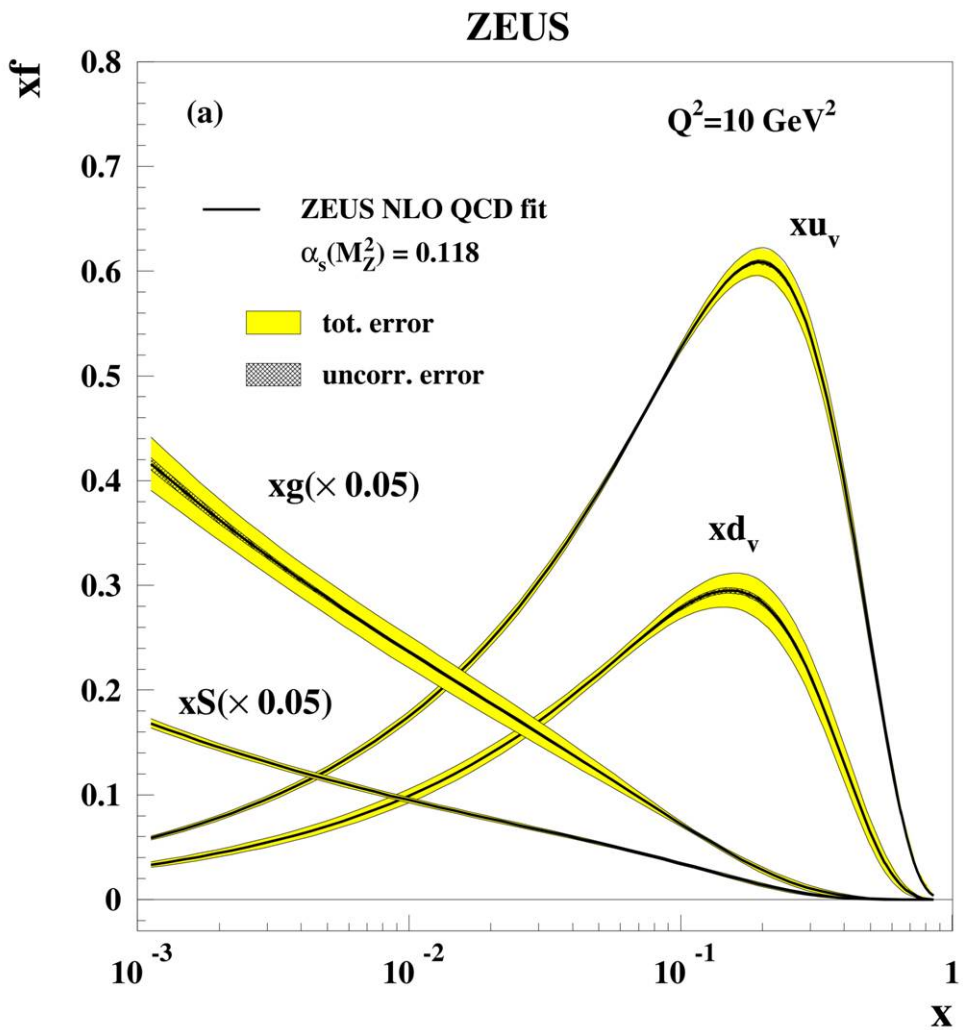
- Current HERA inclusive data beautifully described by QCD.
- Fit using NLO DGLAP formalism allows determination of parton distribution functions and α_S.





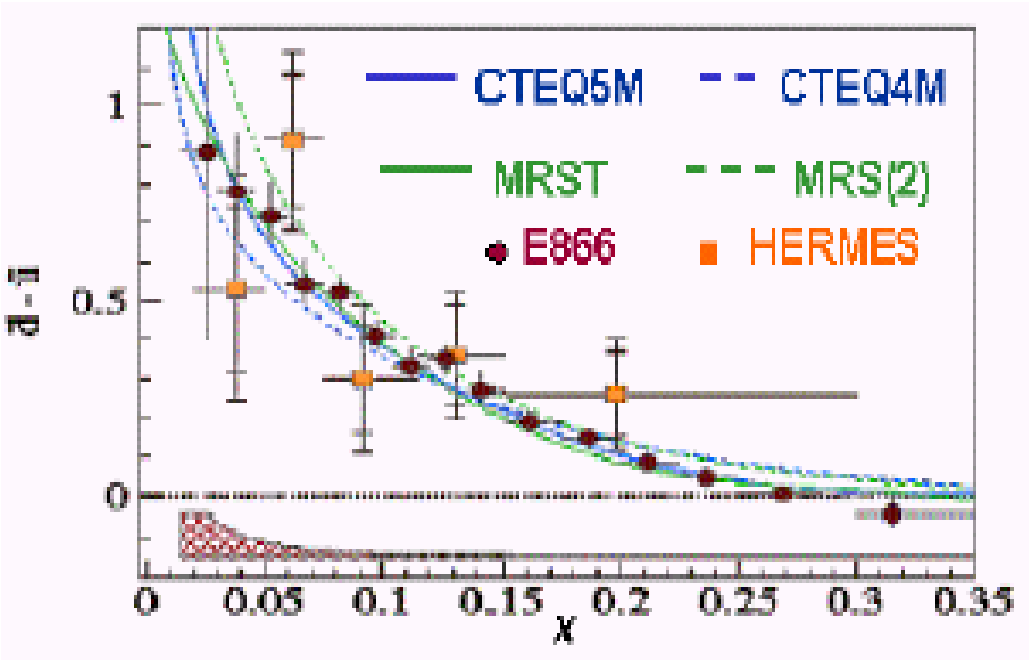
Measuring hadron structure

- E.g. from H1:
  $$\alpha_S(M_Z^2) = 0.1150 \pm 0.0017(\text{exp.}) \; {}^{+0.0009}_{-0.0005}(\text{mod.}) \pm 0.005(\text{scale})$$
- Measured PDFs not full story.
- Rise at low x must be tamed.
- How can this be measured? Return to this later!
- Assumption: sea quarks produced via $g \rightarrow q\bar{q}$.
- Plausible as both $m_u \sim 3$ MeV and $m_d \sim 6$ MeV $<< \Lambda_{QCD}$.



Measure $\bar{d} - \bar{u}$

- Surprise…

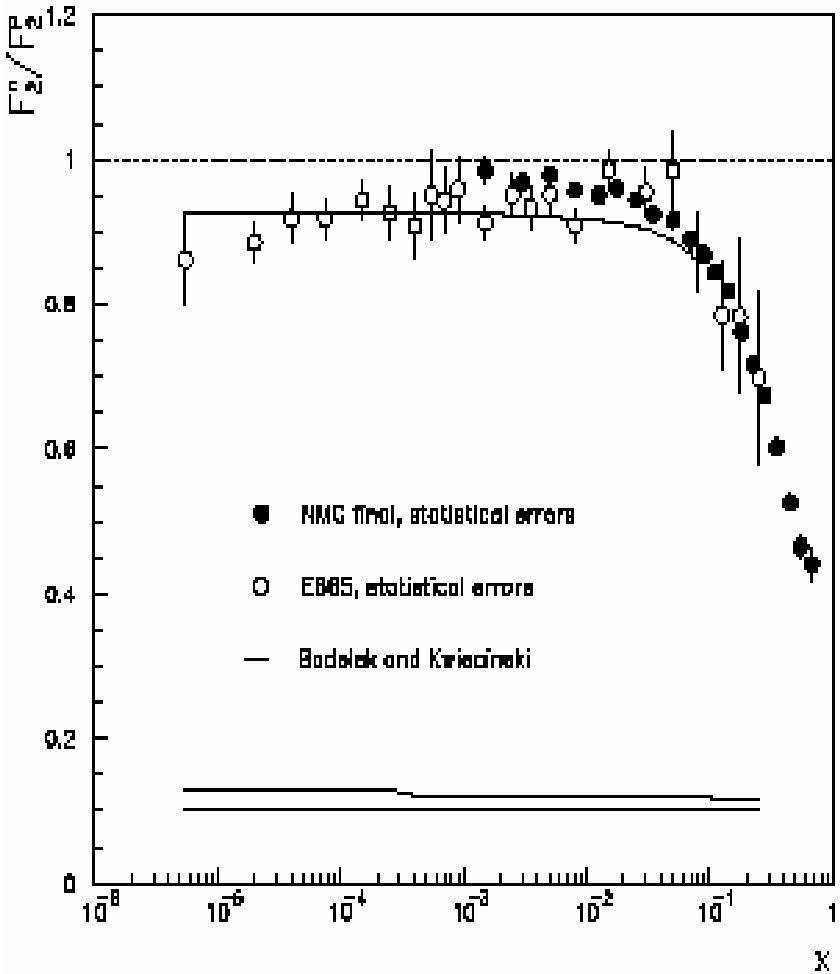


- Global fits assume $\bar{d} = \bar{u}$ at small x!
- How can this be studied?

- Recall for proton
  $F_2^p = x\left(\frac{4}{9}u_v + \frac{1}{9}d_v + \frac{8}{9}\bar{u} + \frac{2}{9}\bar{d}\right)$
- Hence neutron given by
  $F_2^p = x\left(\frac{1}{9}u_v + \frac{4}{9}d_v + \frac{2}{9}\bar{u} + \frac{8}{9}\bar{d}\right)$
- Can extract $\bar{d} - \bar{u}$ from
  $\frac{1}{2}\left(F_2^p + F_2^n\right) - F_2^p$
  $= x\left(\frac{1}{6}d_v - \frac{1}{6}u_v + \frac{1}{3}\bar{d} - \frac{1}{3}\bar{u}\right)$
  $\approx \frac{1}{3}x\left(\bar{d} - \bar{u}\right)$ at low x.
- But "nucleon structure"
  $F_2^N = \frac{1}{2}\left(F_2^p + F_2^n\right) \approx \frac{1}{2}F_2^D$
- Need high energy eD experiment!

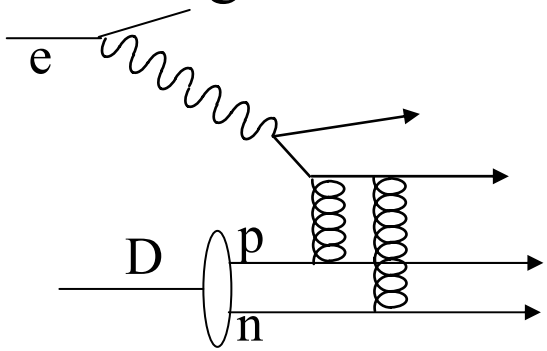
Shadowing

- Why $F_2^D \neq F_2^p + F_2^n$?
- Partons have momentum xp.
- Hence localised within 1/xp.
- At small x partons (gluons) from proton overlap with those from neutron, recombination can occur.
- Hence $F_2^D < F_2^p + F_2^n$ at low x.
- Fusion produces partons with larger x, so in high x region $F_2^D > F_2^p + F_2^n$
- Problem for $\bar{d} = \bar{u}$ measurement?

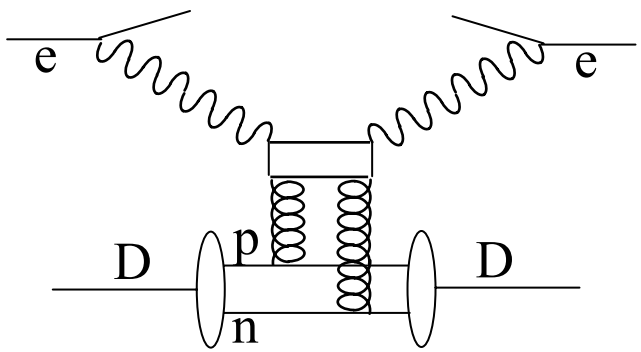


Measuring $\bar{d} - \bar{u}$

- Shadowing…

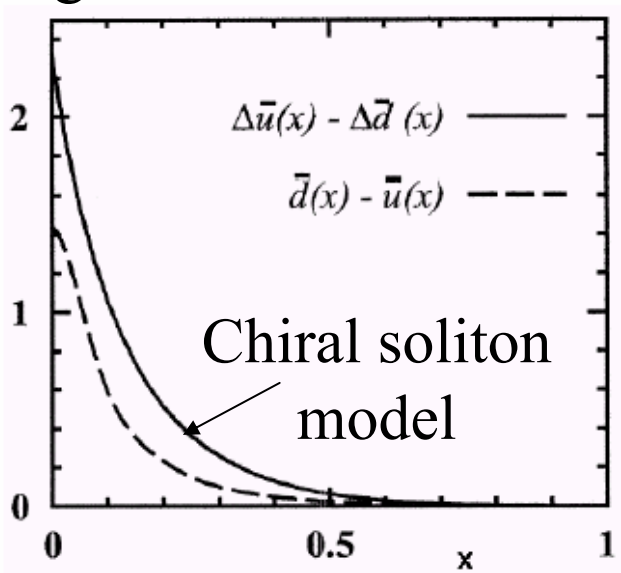


- …related to diffraction.

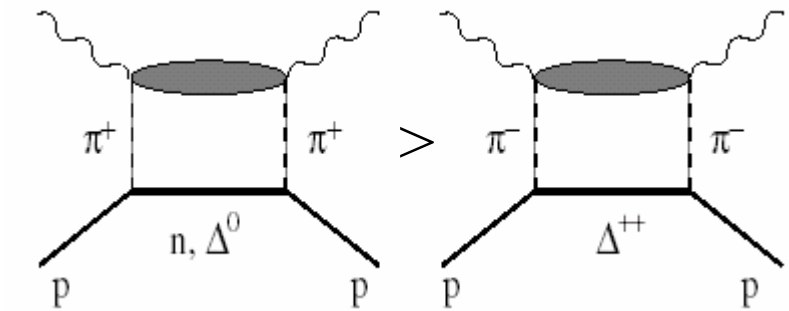


- Measure and correct in extraction of $\bar{d} - \bar{u}$.

- Distinguish models for $\bar{d} - \bar{u} > 0$?



- No spin asymmetry in Sullivan model.



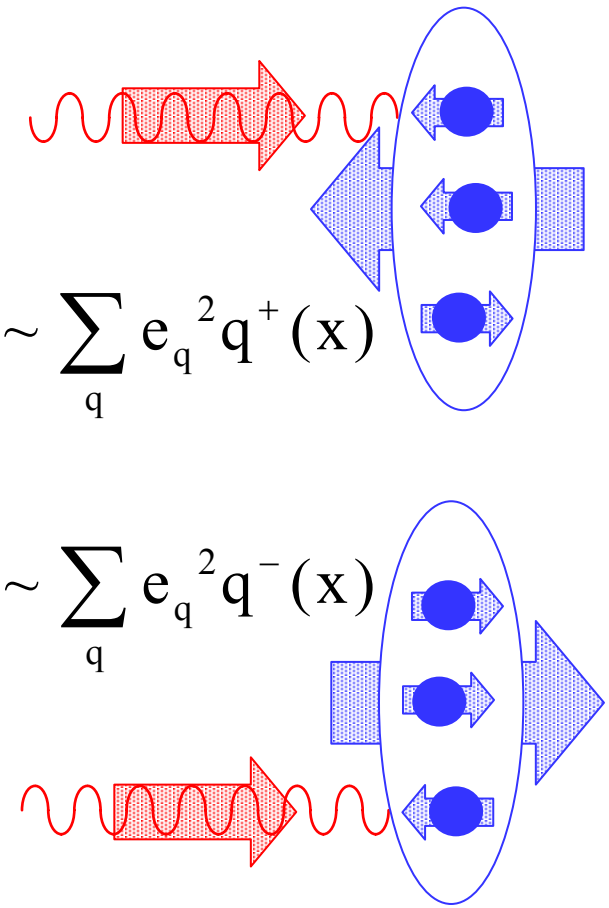
Spin structure measurements

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

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

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

$$\approx \frac{g_1(x)}{F_1(x)}$$



$$\sigma_{1/2} \sim \sum_q e_q^{\,2} q^+(x)$$

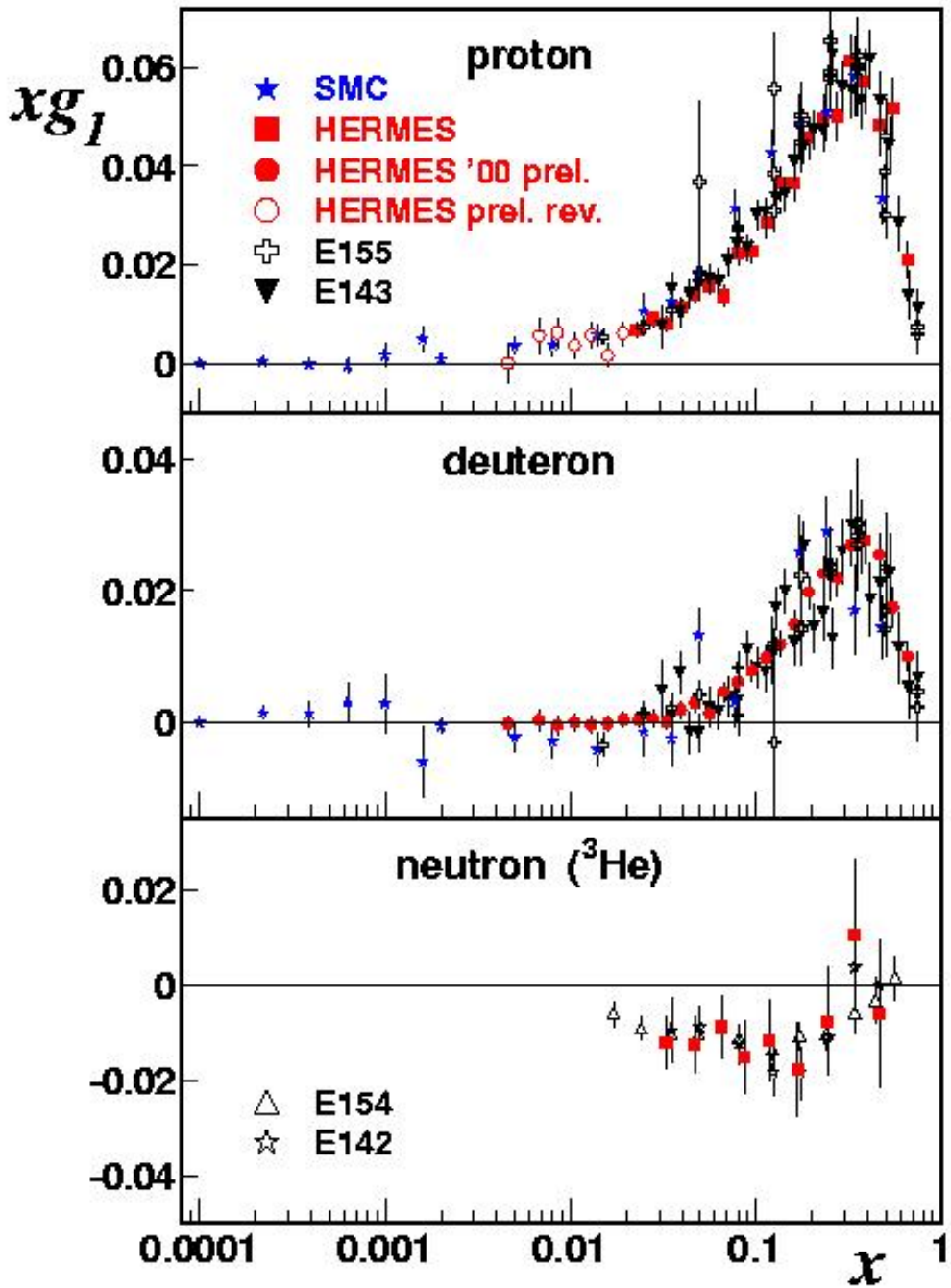
$$\sigma_{3/2} \sim \sum_q e_q^{\,2} q^-(x)$$

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

$$F_1(x) = \tfrac{1}{2}\sum e_q^{\,2}\left(q^+(x) + q^-(x)\right) = \tfrac{1}{2}\sum e_q^{\,2} q(x)$$

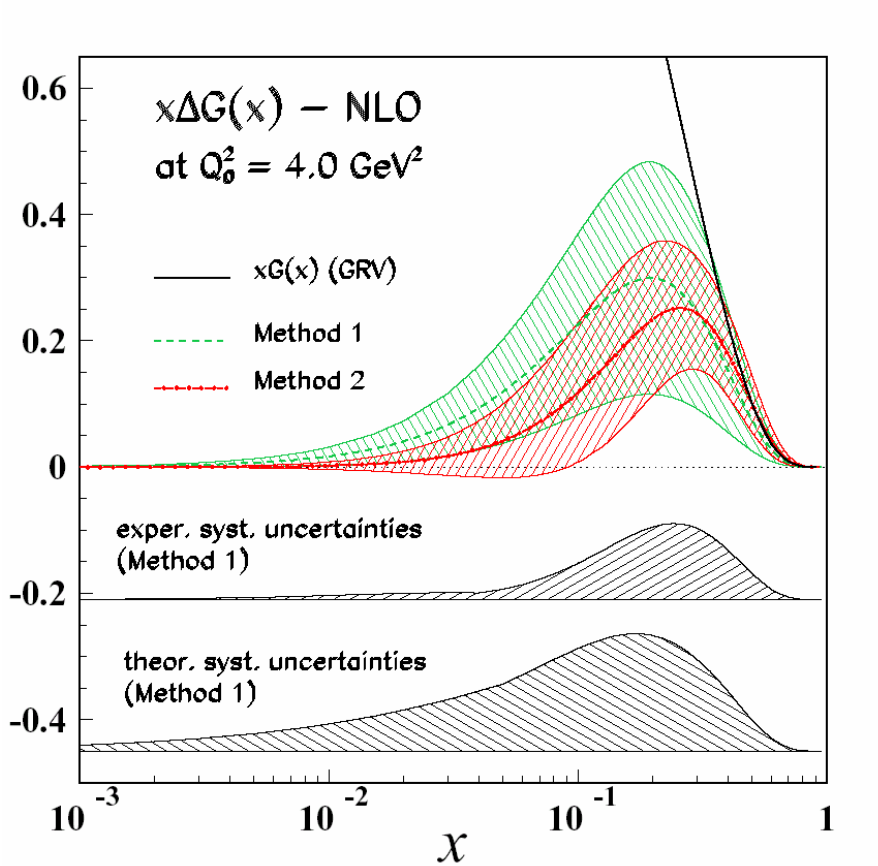
Spin structure measurements

- Proton spin given by
  $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$
- Current world data suggest spin carried by quarks
  $\Delta\Sigma \sim 0.15 \ldots 0.2$
- Remainder carried by gluons, orbital angular momentum?
- Can measure gluon contribution by studying Q^2 evolution of $g_1(x,Q^2)$.

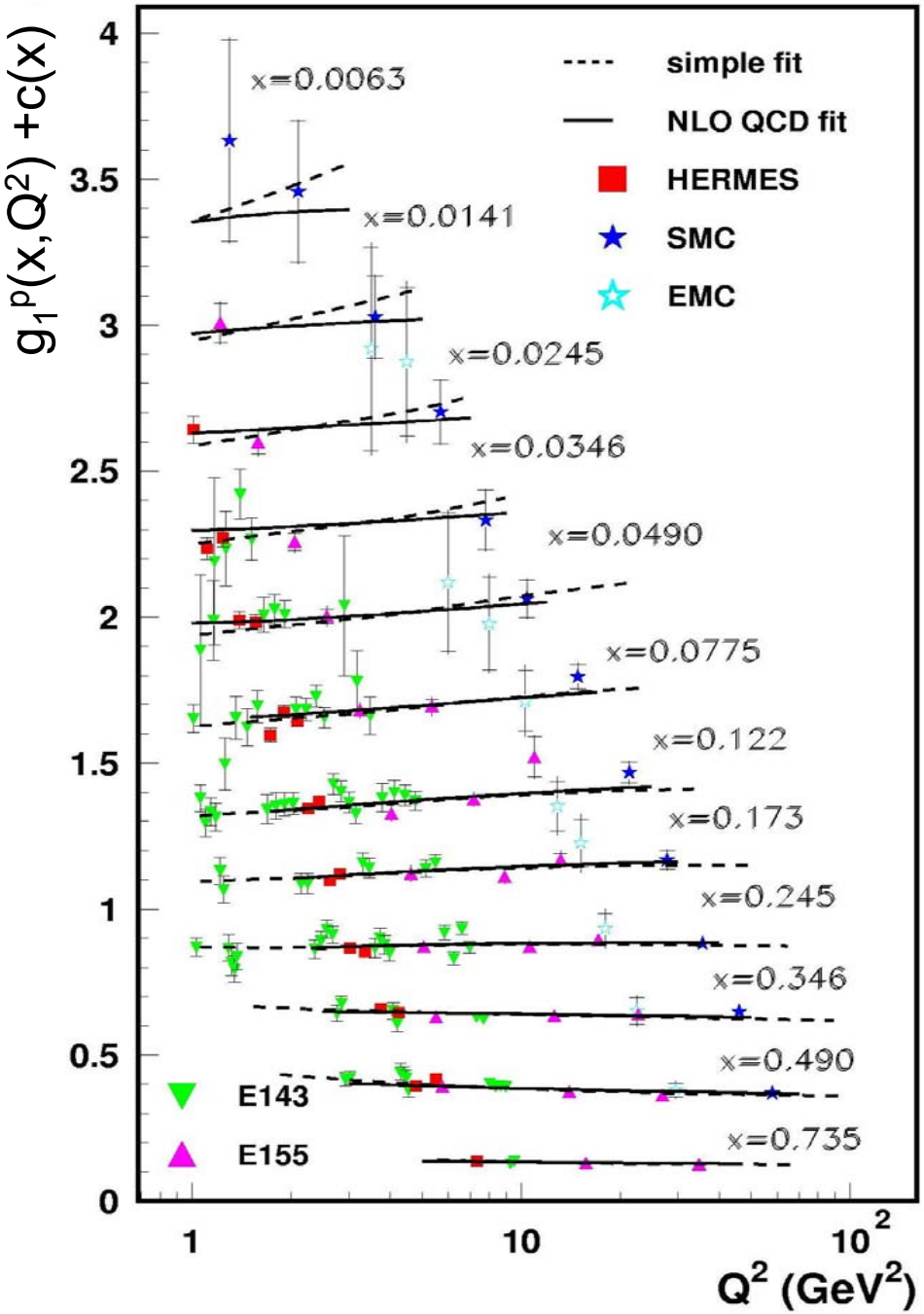


Spin structure measurements

- NLO QCD fit gives:

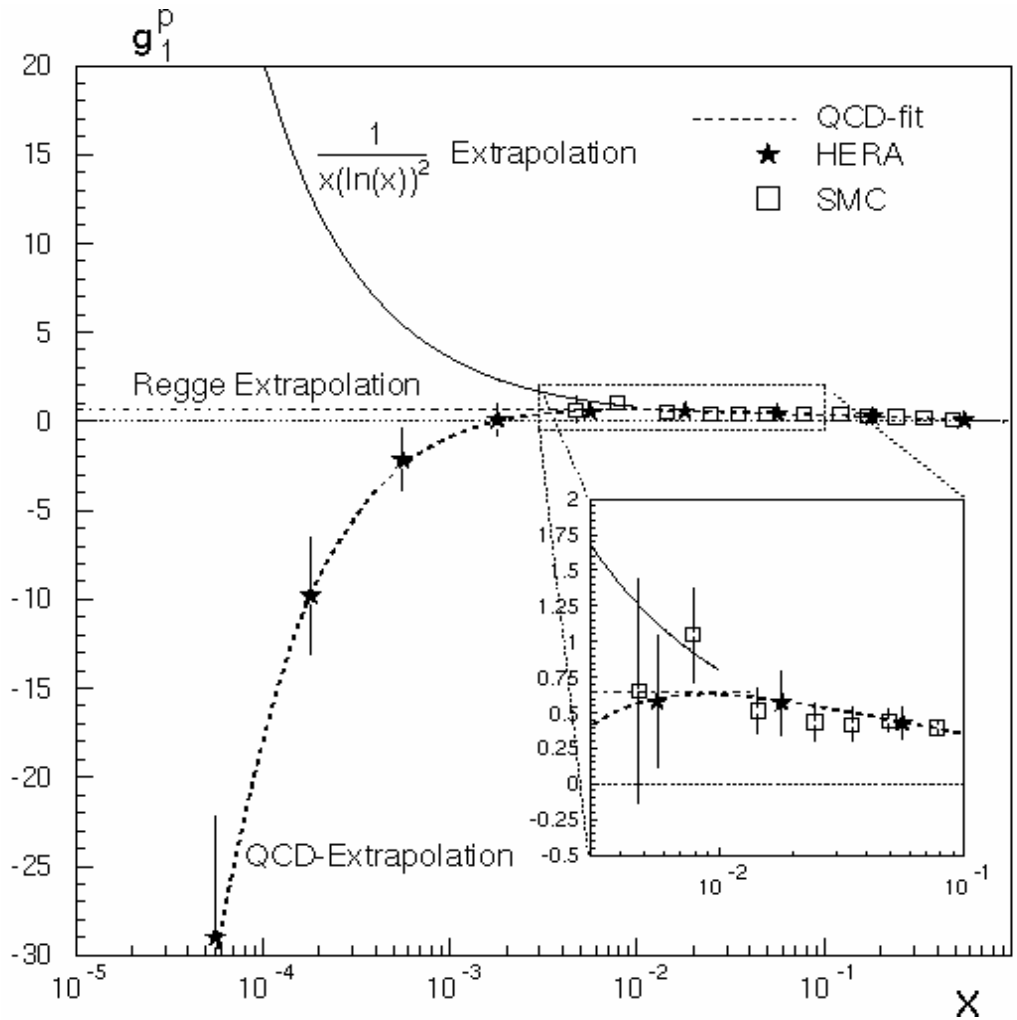


- $\Delta G = 0.616 \pm 0.318 \pm 0.400$



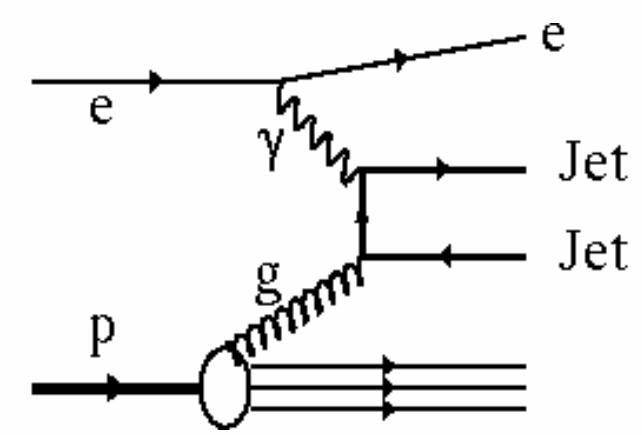
Spin at HERA

- $g_1(x,Q^2)$ can be measured down to small x.
- Q^2 range of measurements extended by orders of magnitude.
- Allows extraction of ΔG, $\Delta \Sigma$.



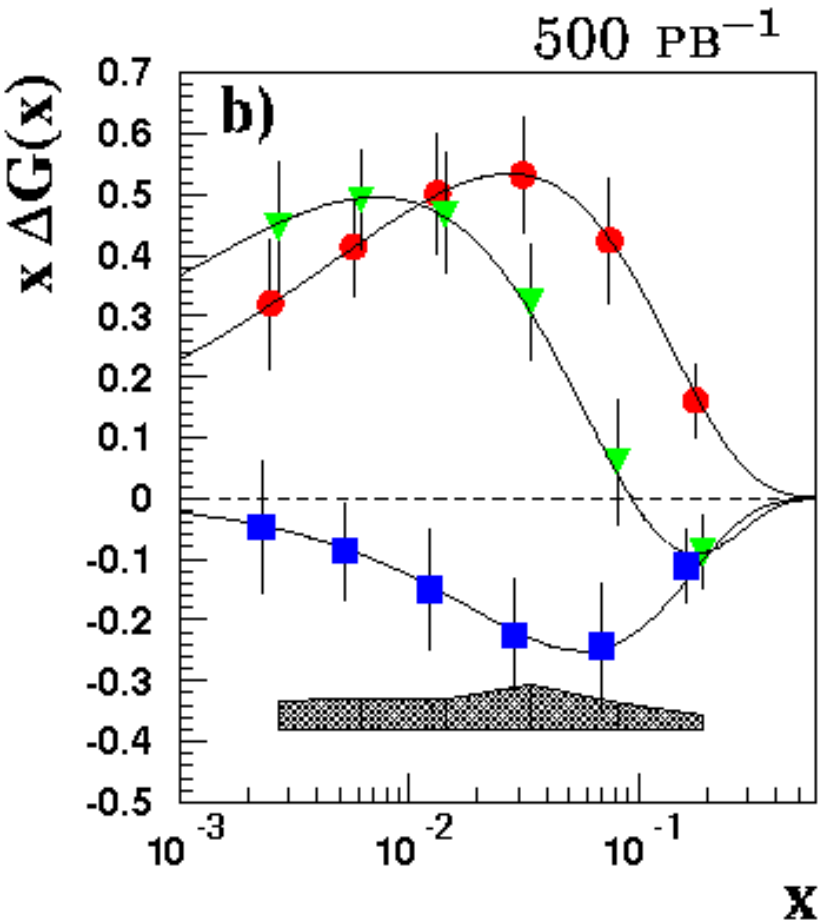
Spin at HERA

- Can also "tag" gluon events.



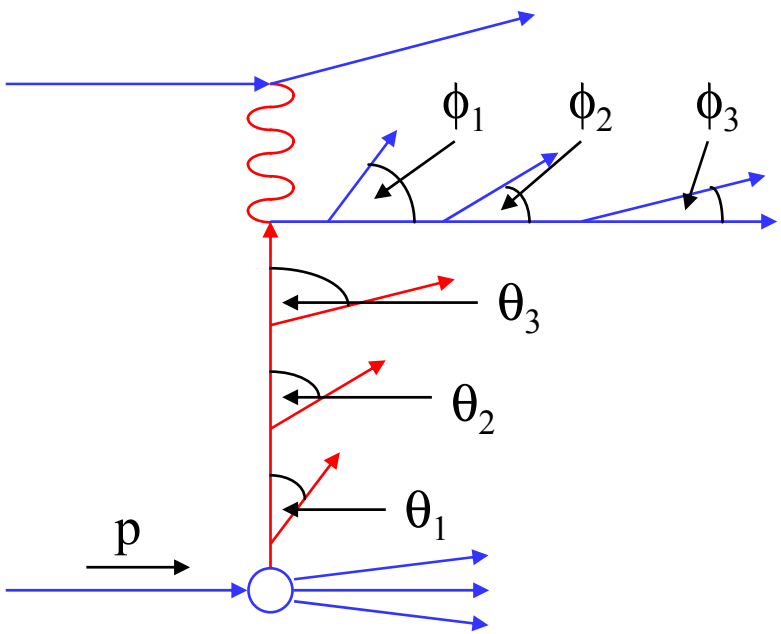
- Allows "direct" measurement of ΔG down to low x.
- Is it possible to measure contribution of L?

- Precision achievable:



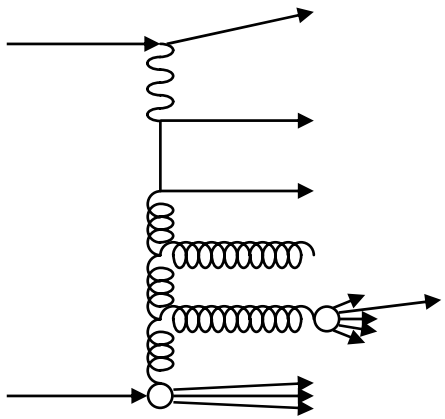
Test QCD evolution schemes

- Interference effects give rise to angular ordering of partons.

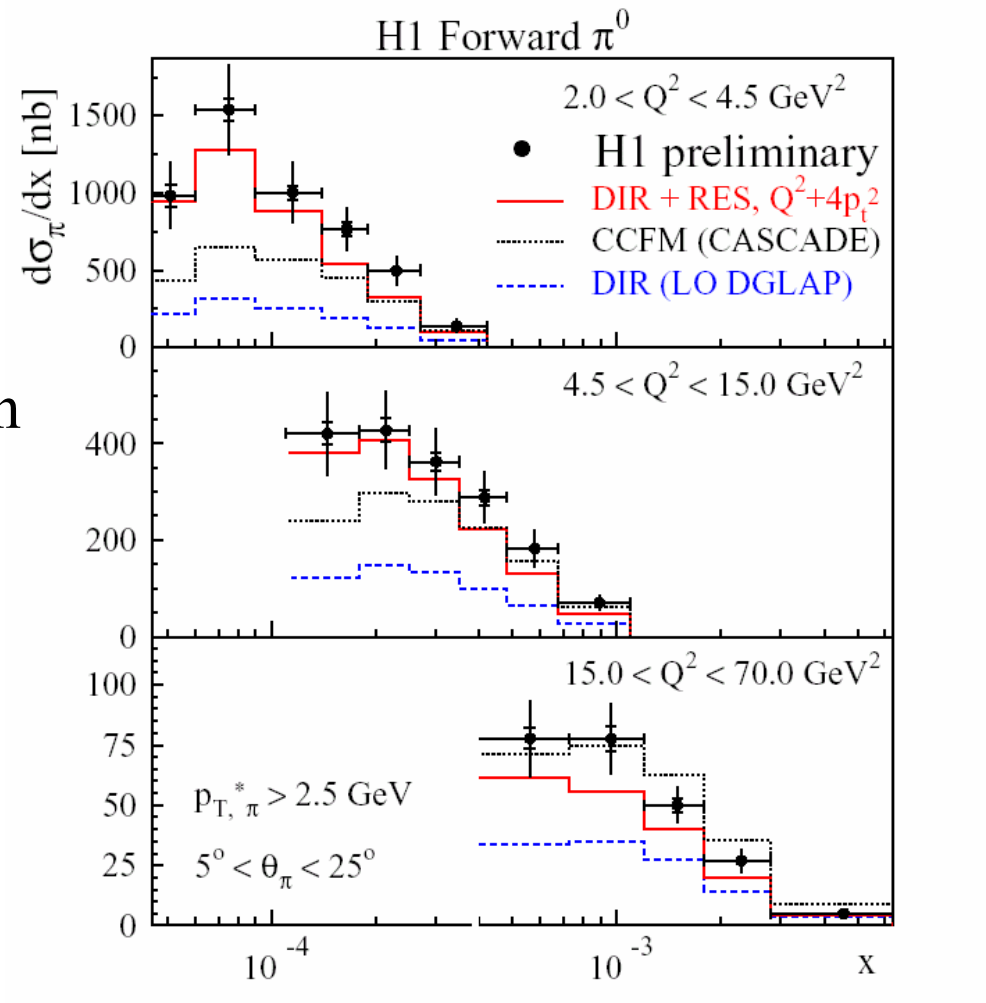


- Treated in various approximations
  - DGLAP $\theta_1 < \theta_2 < \theta_3 \cdots$
    $\rightarrow k_{T1} < k_{T2} < k_{T3} \cdots$
    valid at large Q^2.
  - BFKL $\theta_1 < \theta_2 < \theta_3 \cdots$
    $\rightarrow x_1 > x_2 > x_3 \cdots$
    valid at small x.
- CCFM equation contains angular ordering.

Forward π^0 production



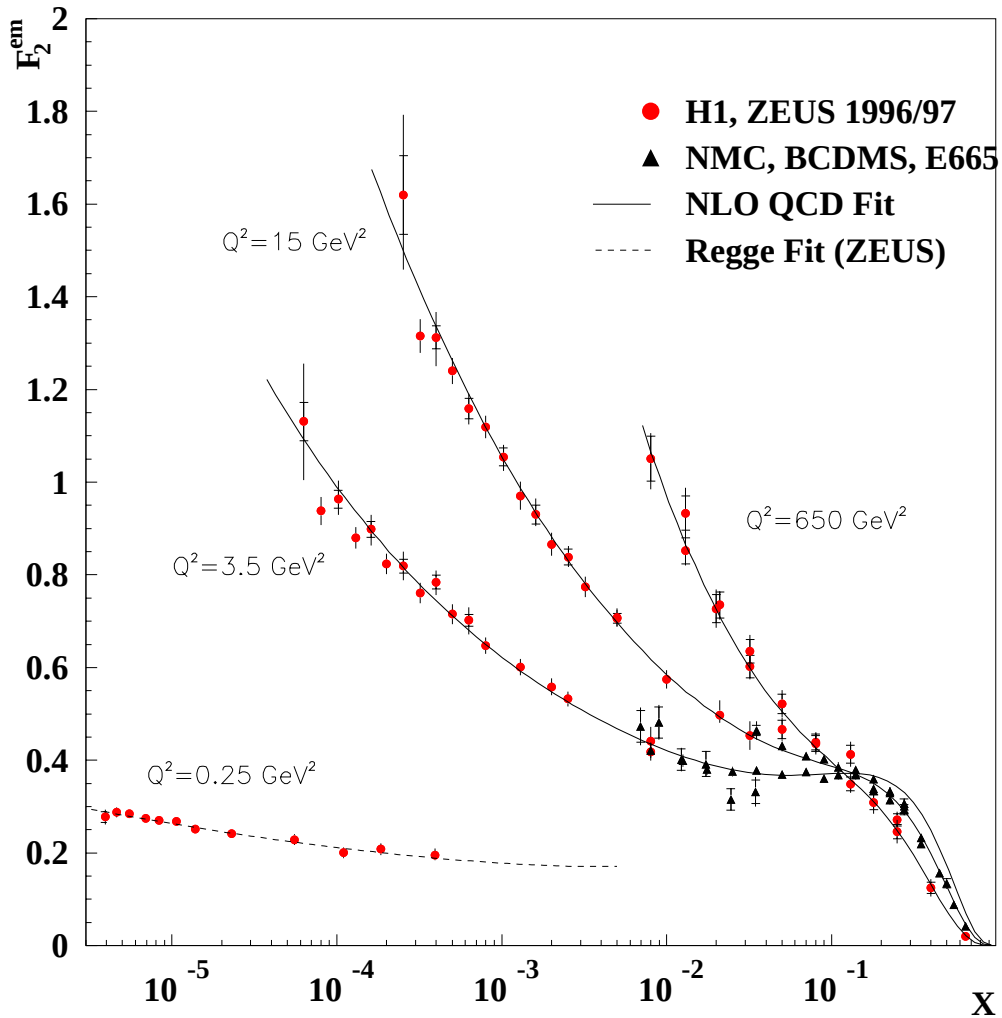
- Select energetic forward pions, with $k_{T\pi} \sim Q^2$, in low x DIS events.
- Simple DGLAP description fails.
- BFKL reasonable agreement.
- CCFM fails.
- Jet results similar.
- Parton radiation at low x not well understood!



Approaching the confinement region

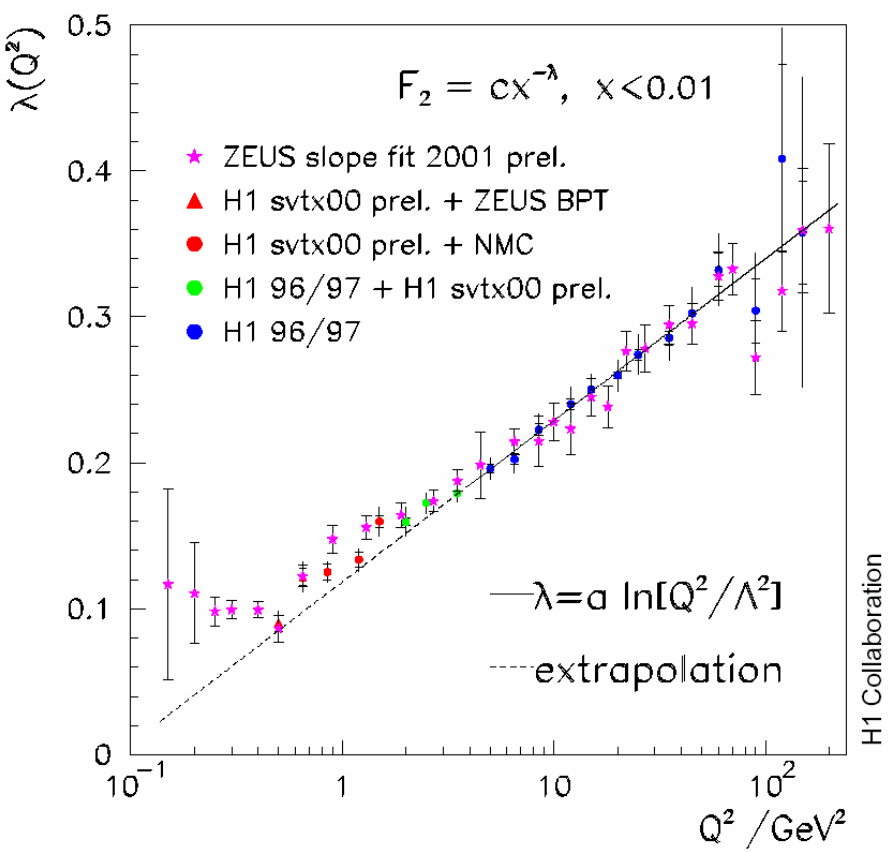
- Gluon radiation at small x gives rise to behaviour
  $x\,q(x,Q^2) \sim x^{-\delta}$

  $\delta = 0.3...0.5$
- Behaviour of $F_2(x,Q^2)$ with x at low x can be parameterised with form $F_2(x,Q^2) \sim x^{-\lambda(Q^2)}$.

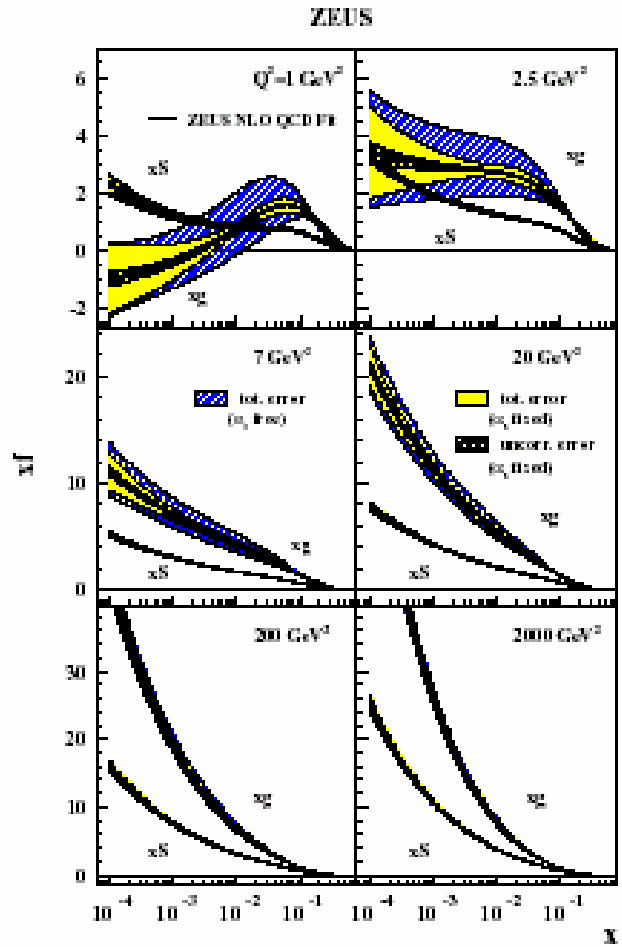


Approaching the confinement region

- Indications that nature of radiation in proton changes below scale ~ 1 GeV^2?



- Simple partonic picture of proton breaks down at same scale.



Approaching the confinement region

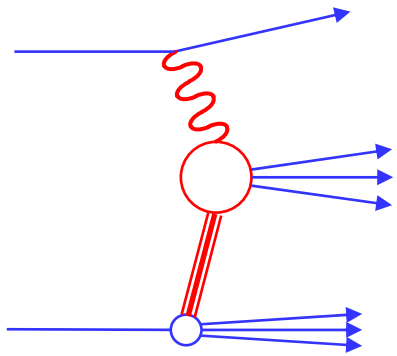
- Study gluon distribution by measuring $F_L(x,Q^2)$.
- Indication of new scale of proton structure?
- "Collective behaviour" of partons?
- Experimental hint at relationship between current and constituent quarks?

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

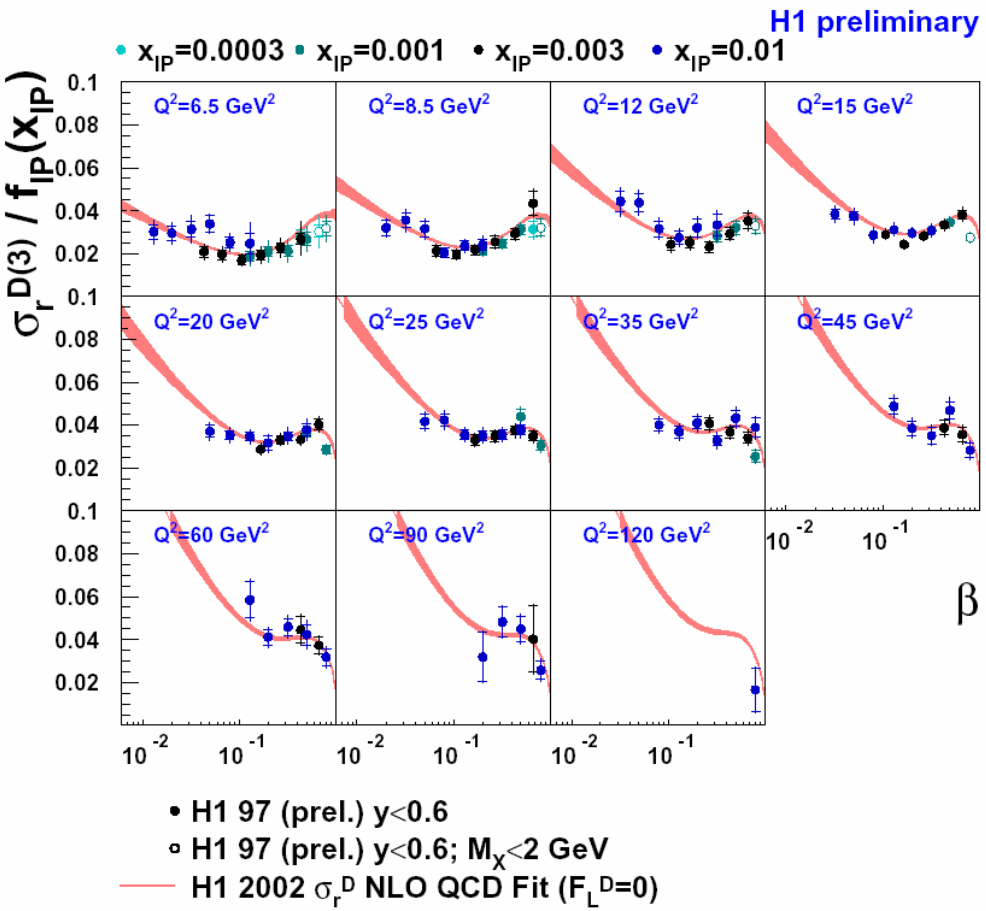
Baryon (mass in MeV)	Composition (q = u, d)	Predicted mass (MeV)
N(939)	qqq	939
Λ(1116)	qqs	1114
Σ(1193)	qqs	1179
Ξ(1318)	qss	1327
Δ(1232)	qqq	1239
Σ(1384)	qqs	1381
Ξ(1533)	qss	1529
Ω(1672)	sss	1682

Collective phenomena – diffraction

- Interaction with colourless component of the proton.

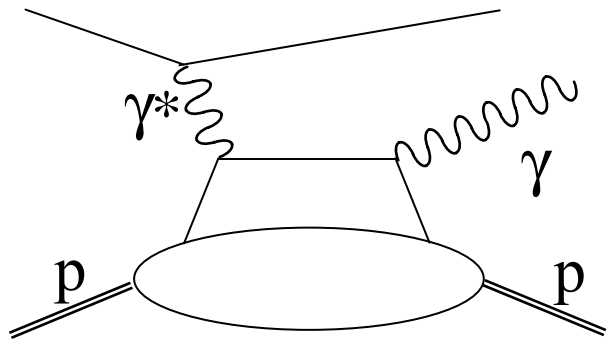


- Measurements and QCD analysis of F_2^D show "pomeron" structure is gluon dominated.
- Colourless nature implies at least two gluons involved.

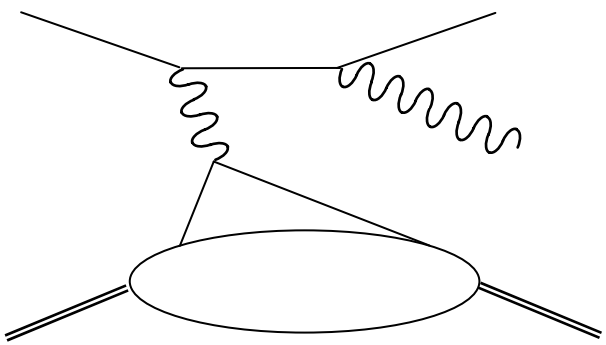


DVCS and generalised parton distributions

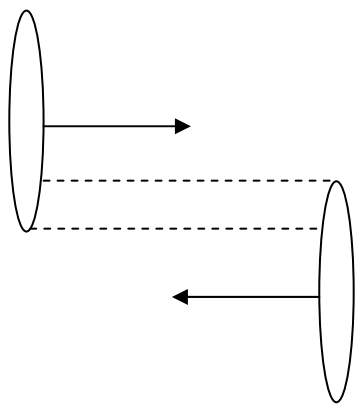
- DVCS ideal process for investigation of collective phenomena.



- Interference with:

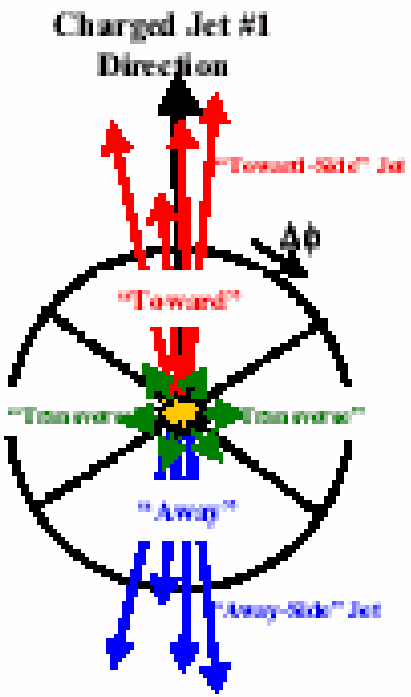


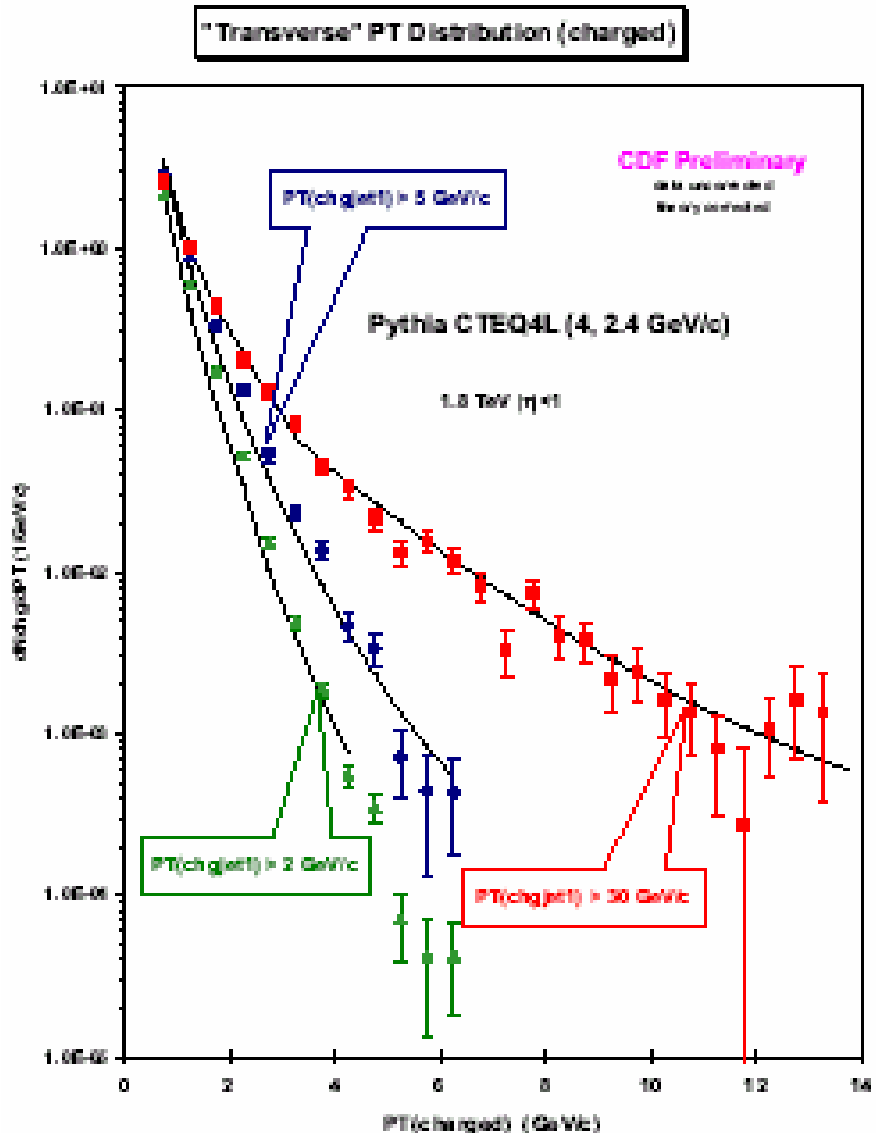
- Extract generalised parton distributions (GPDs).
- GPDs encode spatial distribution of partons in nucleon.
- "Impact parameter" dependence of parton distributions?
- Needed for description of hadron-hadron collisions at LHC energies?



Multiple interactions

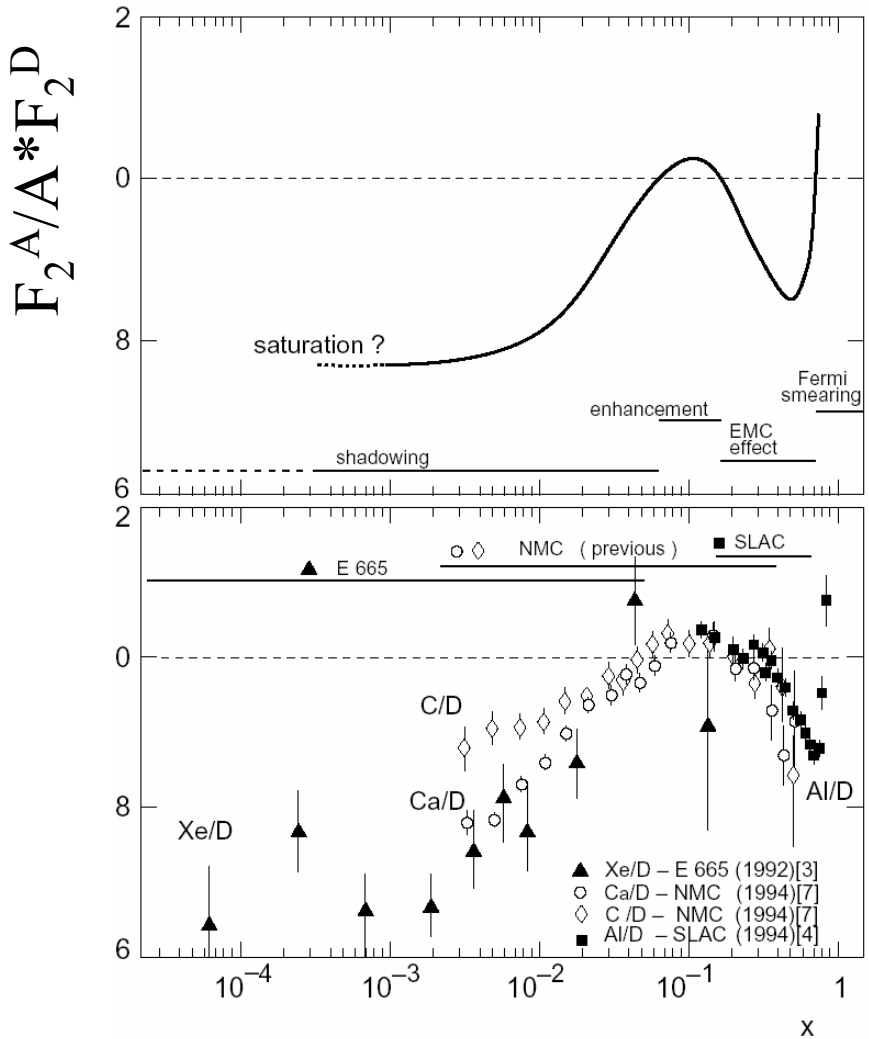
- PDF including impact parameter dependence in Pythia describes Tevatron multiple interaction data.





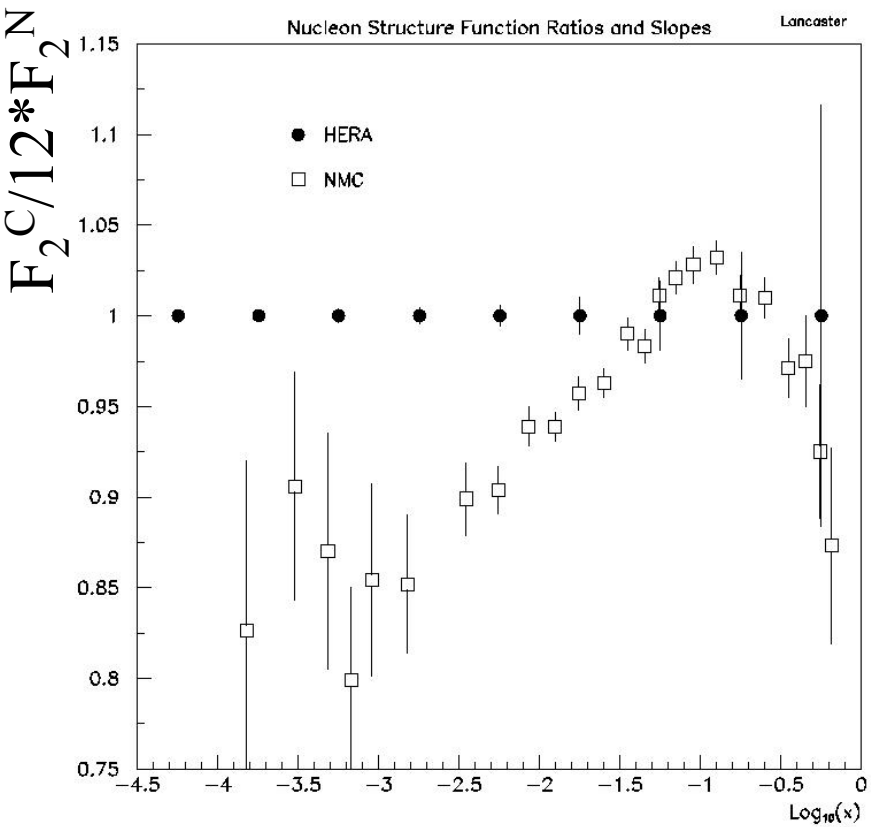
Gluons at high density

- Overlap of gluons from different nucleons in nucleus leads to high parton densities within kinematic reach of HERA.
- Study effects analogous to those that tame rise of $F_2(x,Q^2)$, shadowing.
- Note, below x = 0.01, mean Q^2 of current data < 2 GeV^2.

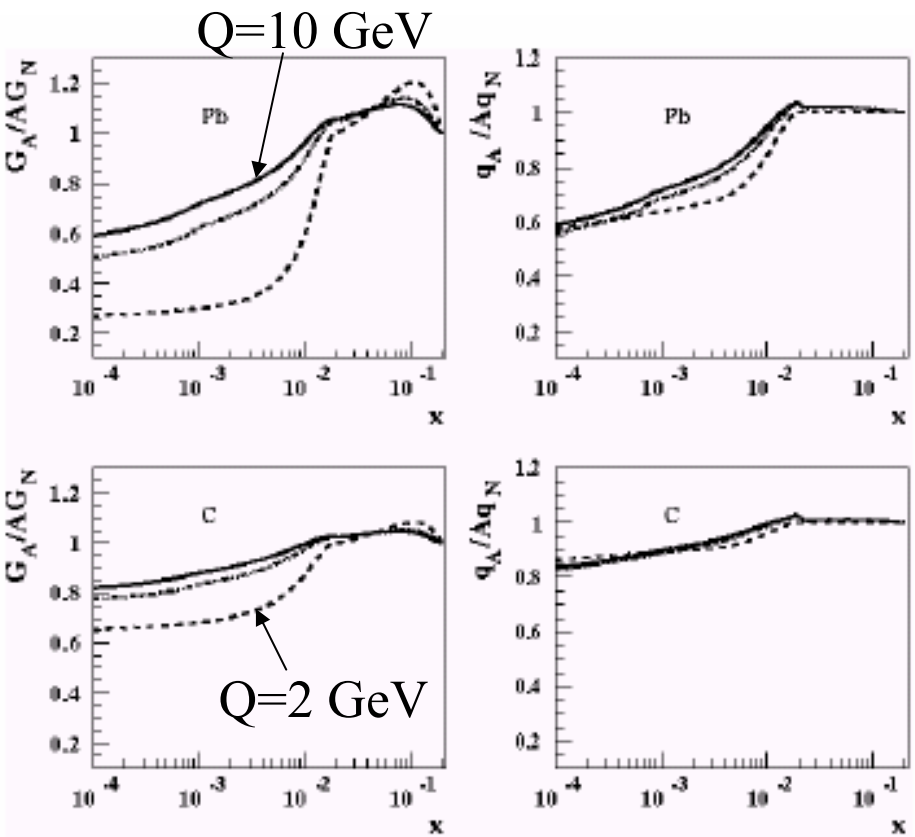


Nuclear parton distributions

- C.f. accuracy of HERA and current results:

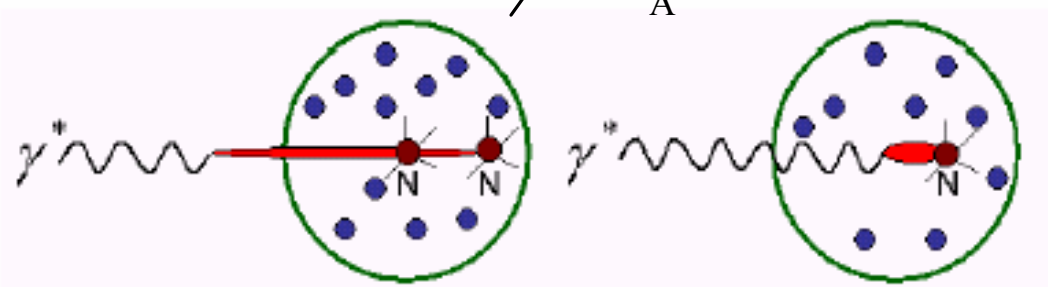


- Extend to determination of nuclear PDFs.



Space-time correlations in QCD

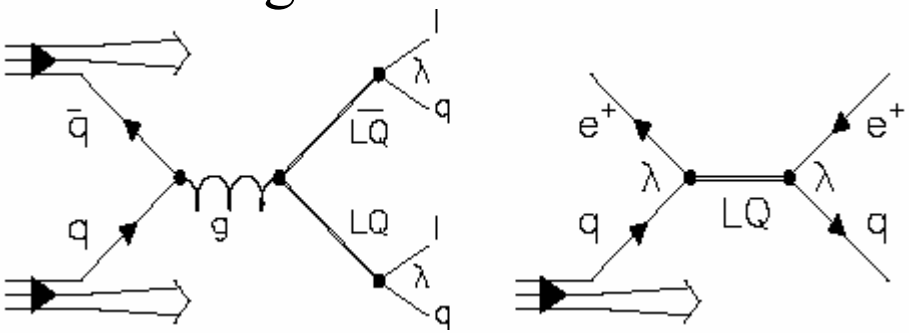
- Use nucleus as “vertex detector”.
- Virtual photon fluctuates into $q\bar{q}$ pair of size ~ 1/Q, travels distance $L = 1/2m_A x$.



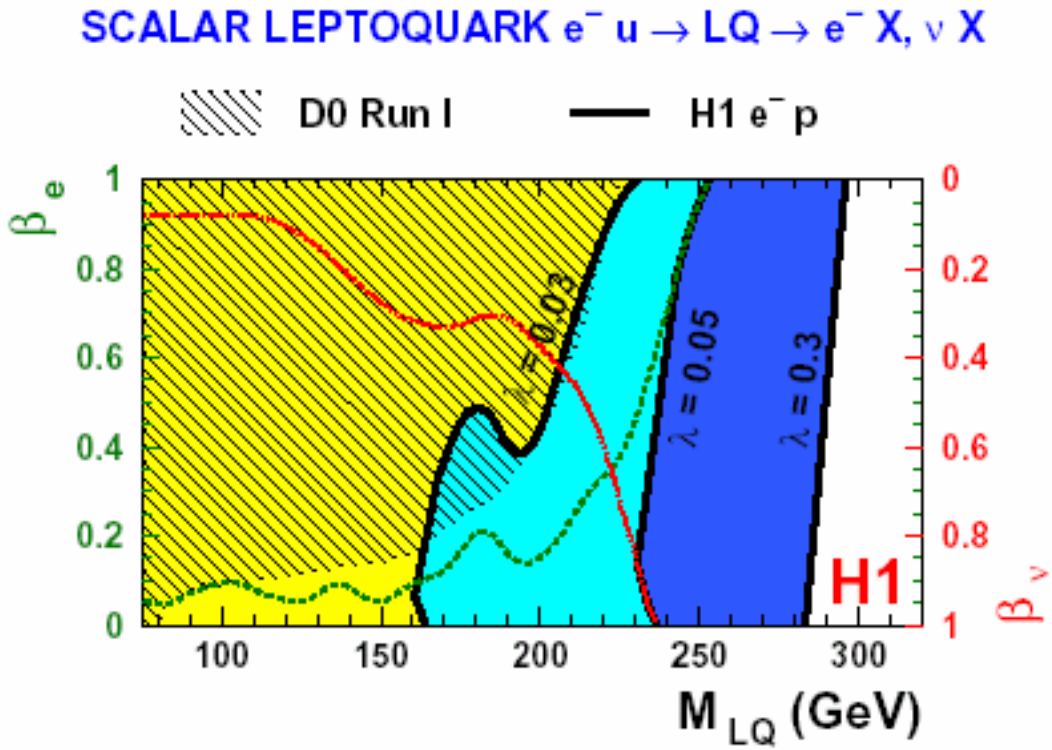
- Measure energy loss of partons, dependence on distance traversed, broadening of p_T spectra.
- Energy loss in quark gluon plasma larger than in “cold” nuclear medium.
- HERA can probe kinematics similar to heavy ion collisions at RHIC/LHC.
- Comparison of eA and heavy ion results will improve understanding of signatures for “hot” QCD matter.

Searches for new physics

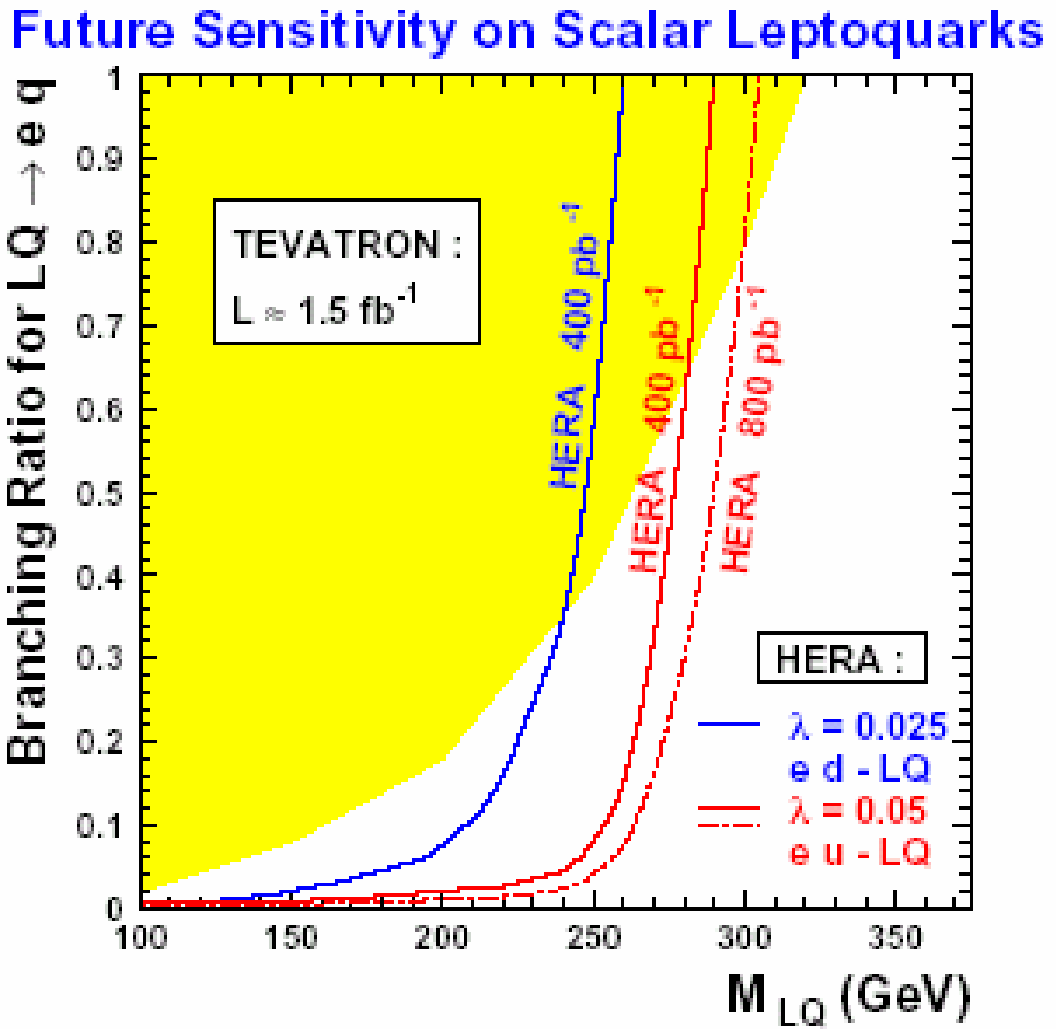
- Leptons and quarks connected through new interaction?



- Competition from Tevatron, but HERA phase space uncovered for:
  - Lepton flavour violation.
  - Excited quarks and leptons.
  - Quark substructure.
  - R-parity violating SUSY.
  - Leptoquarks.
- Current HERA results from ~ 20 pb^{-1} e^-p data:



Searches for new physics



- Can increase beam energies to further extend HERA discovery reach.
  - E_e 27.5 GeV → 30 GeV.
  - E_p 920 GeV → 1000 GeV.
  - $\sqrt{s}$ = 318 GeV → 346 GeV.

Summary

- Many aspects of QCD still incompletely understood.
  - Complete map of partonic structure of nucleons.
  - Partonic origins of nucleon spin.
  - Connection between constituent and current quarks.
  - Parton radiation patterns.
  - QCD at high density
- HERA is unique facility for study of these problems.
- Further potential for discovery of new physics still to be exploited.