Recent Results from HERA

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on behalf of the

H1, ZEUS and Hermes Collaborations

WHEPP-6, Chennai (India) , 3.1.2000

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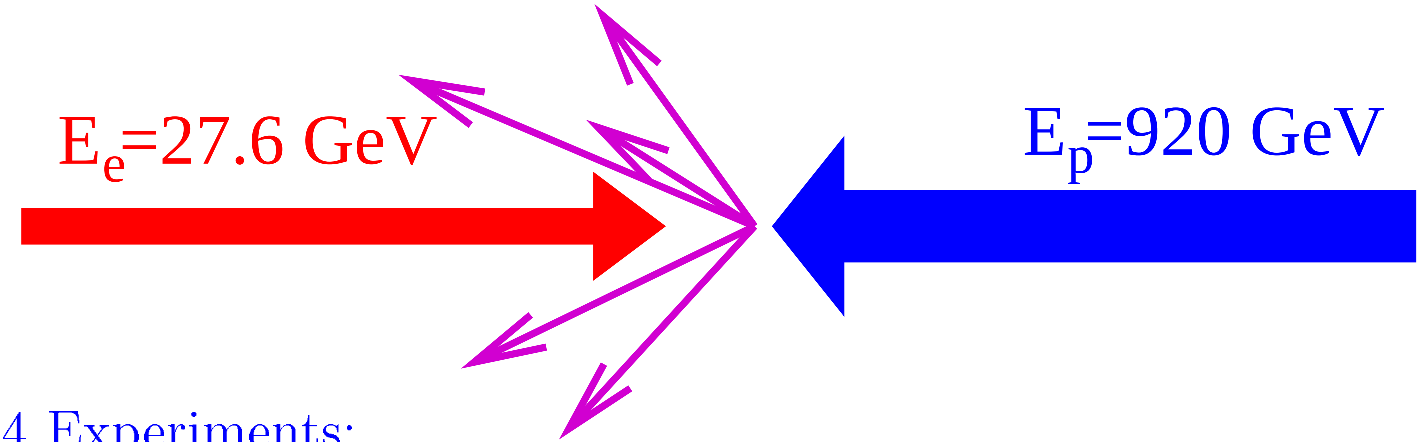
HERA



4 Experiments:

– H1 and ZEUS: e and p beam: CMS-energy $\sqrt{s} \approx 320$ GeV

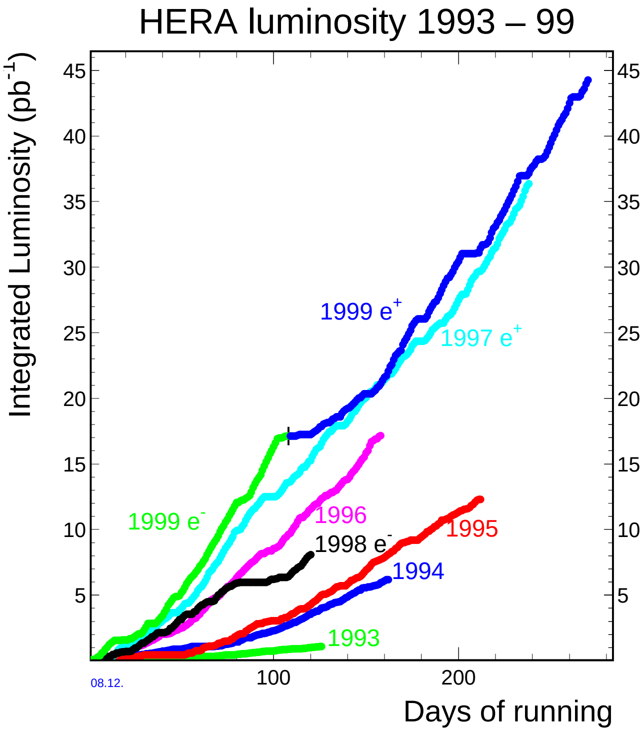
$\Rightarrow$ probe proton structure ($\lambda \approx 10^{-18}$ m)

– HERMES: polarised e beam on polarised and heavy nuclear targets

$\Rightarrow$ measure spin structure of the nucleon

– HERA-B: p beam (starts operation this year)

$\Rightarrow$ measure CP violation in $B_0\bar{B}_0$ system



1994-97: e^+p

– $E_p = 820$ GeV

$\Rightarrow \sqrt{s} = 300$ GeV

– $\mathcal{L} \approx 40$ pb^{-1} per Exp.

1998-99: e^-p

– $E_p = 920$ GeV

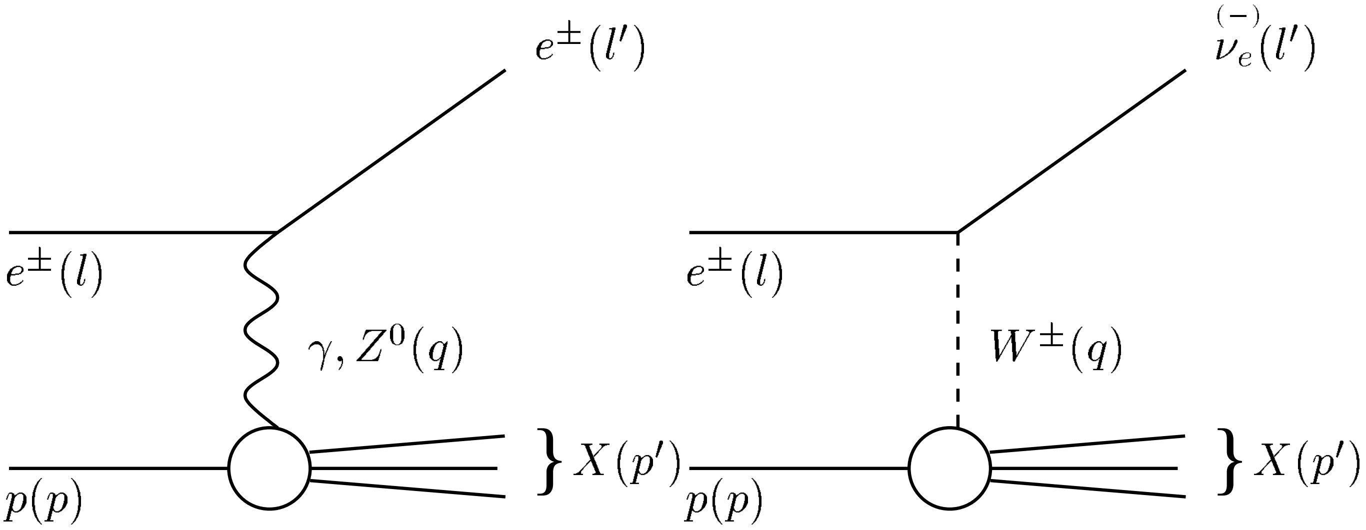
$\Rightarrow \sqrt{s} = 320$ GeV

– $\mathcal{L} \approx 15$ pb^{-1} per Exp.

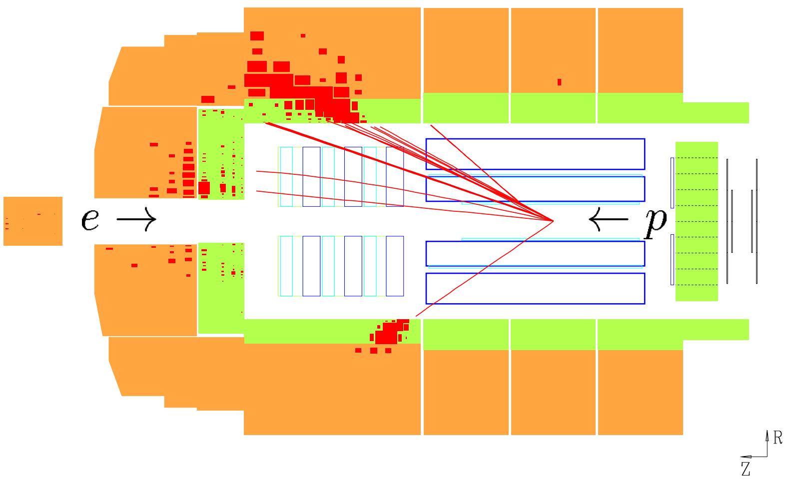
HERA performance improving every year

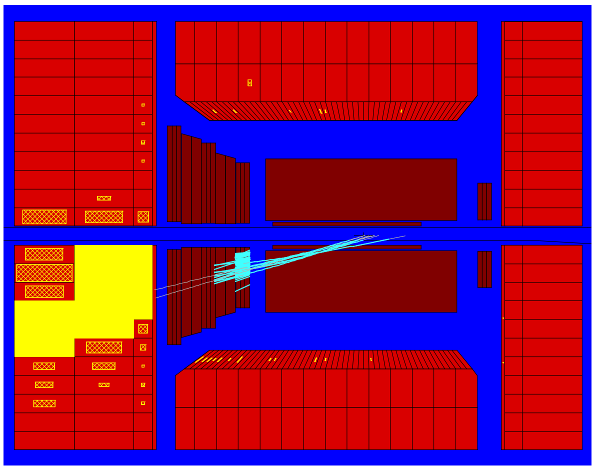
Deep Inelastic Scattering

NC: $e^{\pm}p \rightarrow e^{\pm}X$ CC: $e^{\pm}p \rightarrow \nu X$



H1 **ZEUS**

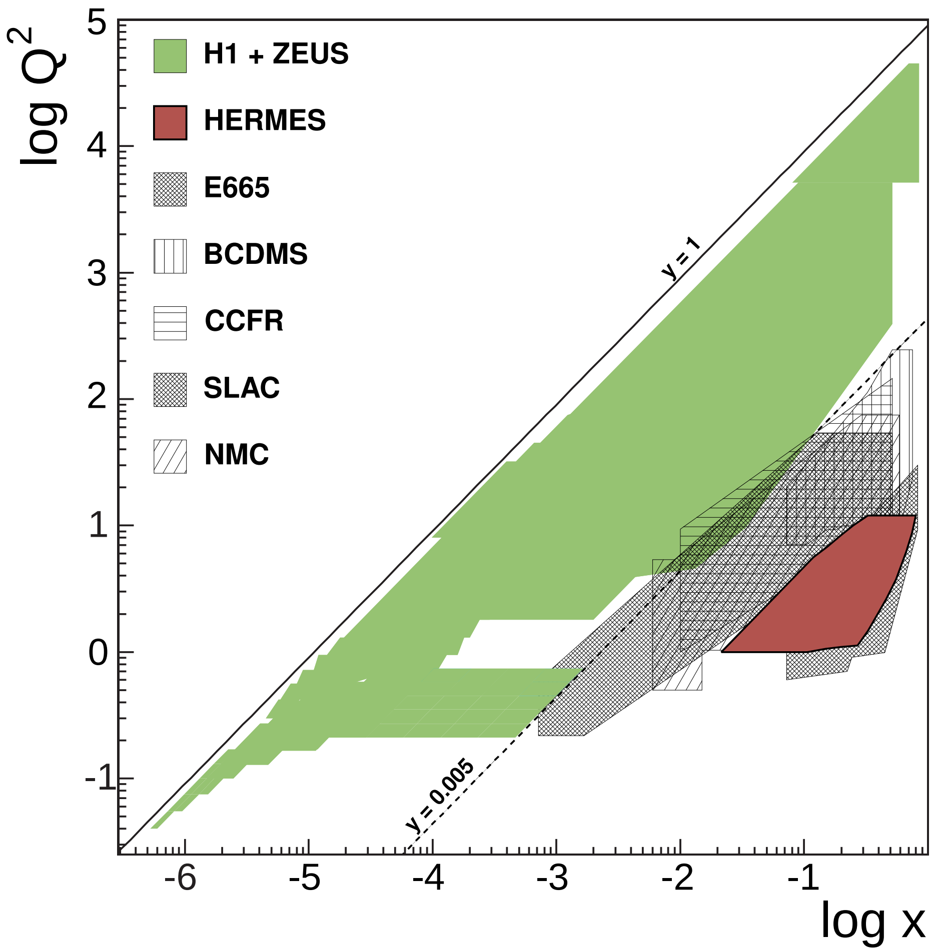




Kinematic Variables

$Q^2 = -q^2 = -(l-l')^2$	squared 4-momentum transfer
$x = Q^2/(2p \cdot q)$	Bjorken-x
$y = p \cdot q/(p \cdot l)$	Inelasticity
$s = (p+l)^2 = Q^2/xy$	Squared CMS energy
$W^2 = (p+q)^2 \approx ys$	Squared CMS energy of p and γ

Kinematic Range



$x \rightarrow 10^{-6}$ $\Rightarrow$ low x limit of pQCD

$y_{\mathrm{HERA}} \rightarrow 0.005$ $\Rightarrow$ overlap with fixed target experiments

$Q^2 \rightarrow 0.045\ \mathrm{GeV}^2$ $\Rightarrow$ transition from $\gamma^* p$ to γp $(Q^2 \approx 0)$

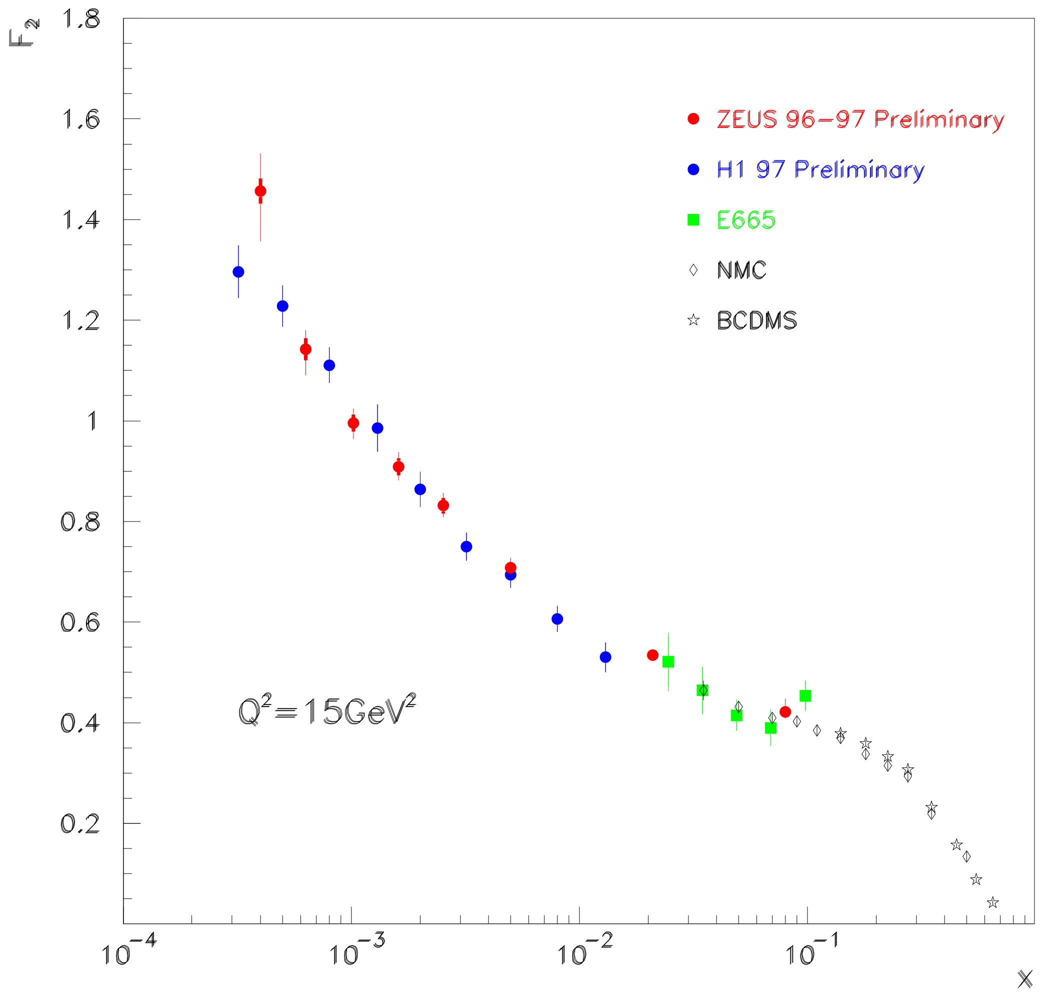
$Q^2 \rightarrow 50000\ \mathrm{GeV}^2$ $\Rightarrow$ EW sector, (new physics?)

Structure of the Proton

For $Q^2 \ll M_Z^2$:

$$\frac{d\sigma^{NC}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+ F_2 - y^2 F_L) \qquad Y_\pm = 1 \pm (1-y)^2$$

F_2 dominant at HERA for $y \lesssim 0.7$

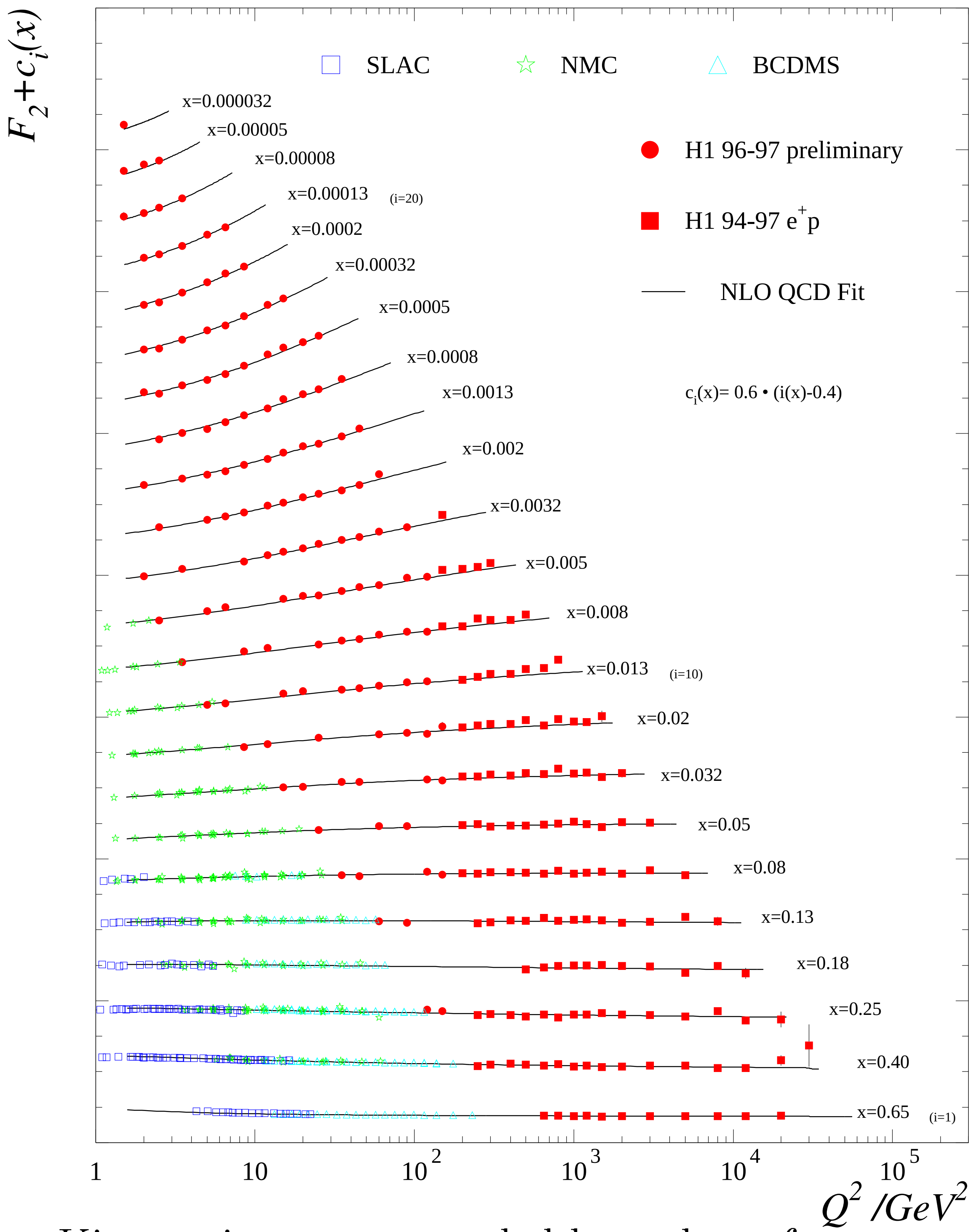


- Strong rise of F_2 towards low x

$\Rightarrow$ increasing parton density at low x

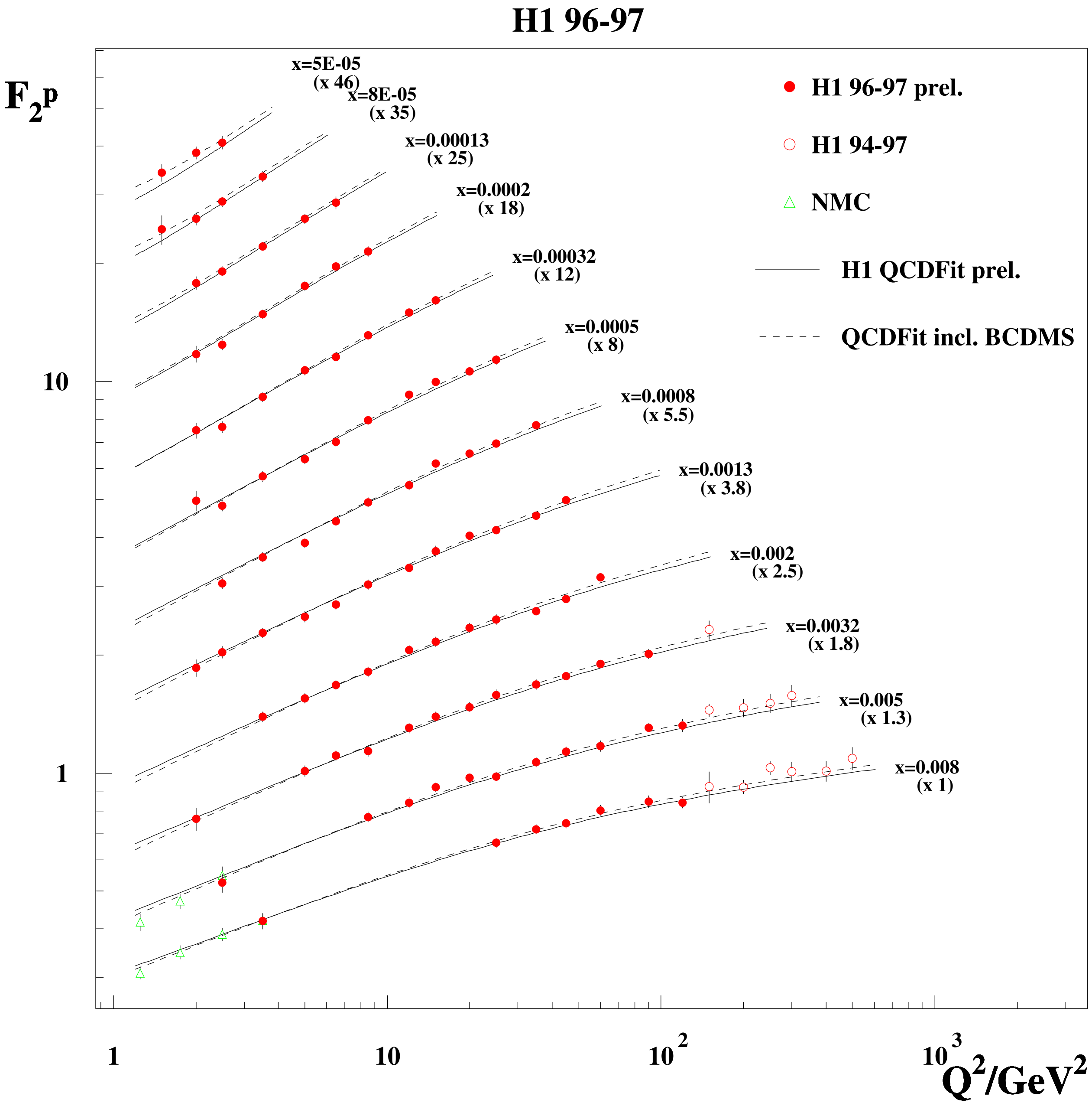
- High Precision: 1% (stat) $\oplus$ 3 – 4% (syst)
- Good Agreement between H1 and Zeus
- Overlap with Fixed-Target Experiments

Overview of F_2 Measurements



- Kinematic range extended by orders of magnitude in Q^2 and x
- Scaling violations: positive at low x, negative at high x
- Data described by QCD down to $Q^2 \approx 1$ GeV^2

F_2 at low x



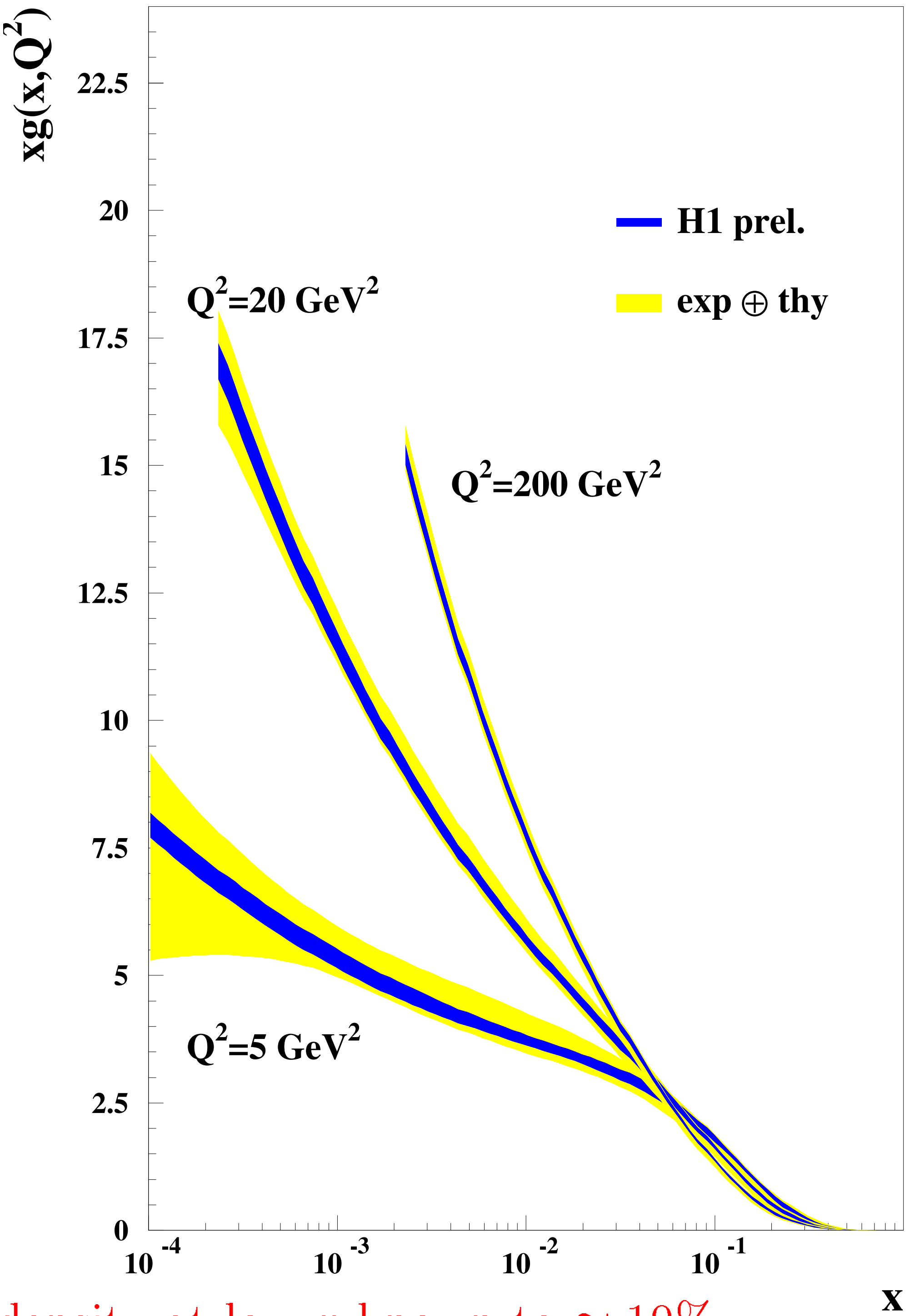
- Strong scaling volations observed $\Rightarrow$ gluon density
- QCD fit based on DGLAP evolution

  describes data

Gluon Density

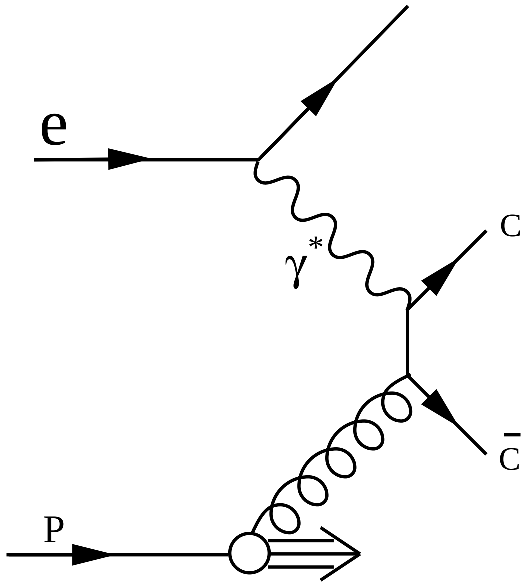
NLO QCD Analysis

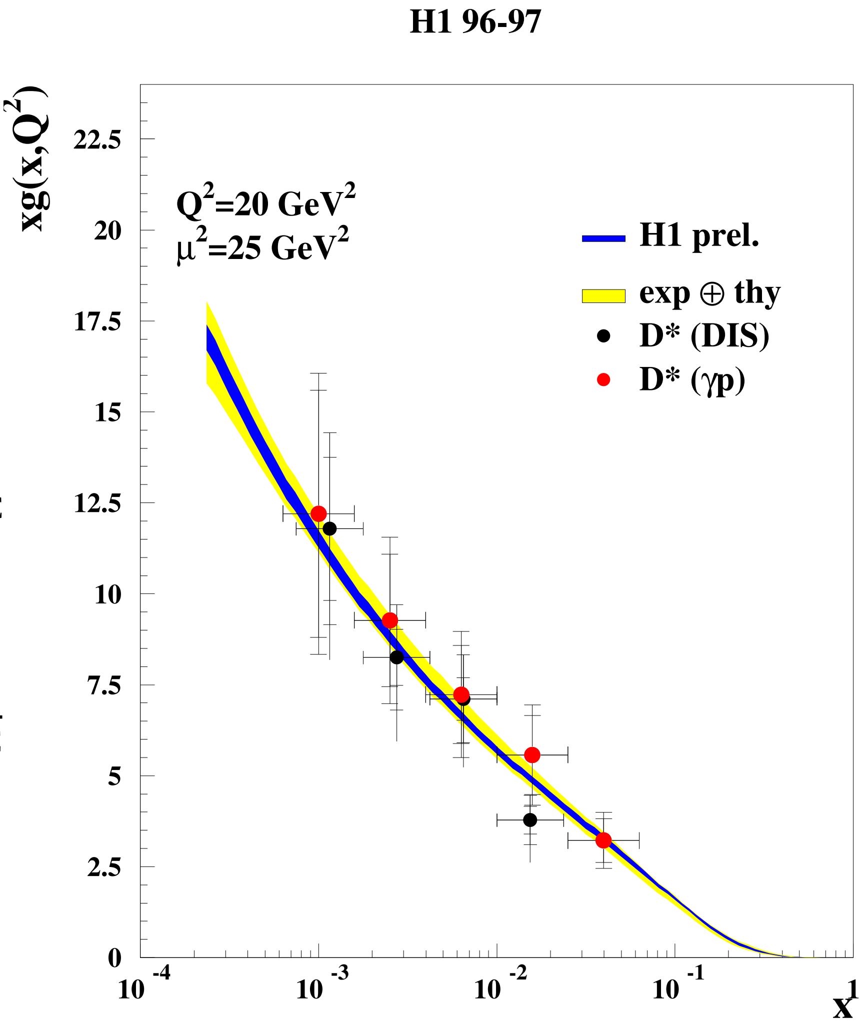
- NMC and H1 data: $Q^2 > 4$ GeV^2
- include experimental systematic errors
- theoretical unc. $\Rightarrow$ vary assumptions of fit (α_s, m_c, etc.)



Gluon density at low x known to $\approx 10\%$

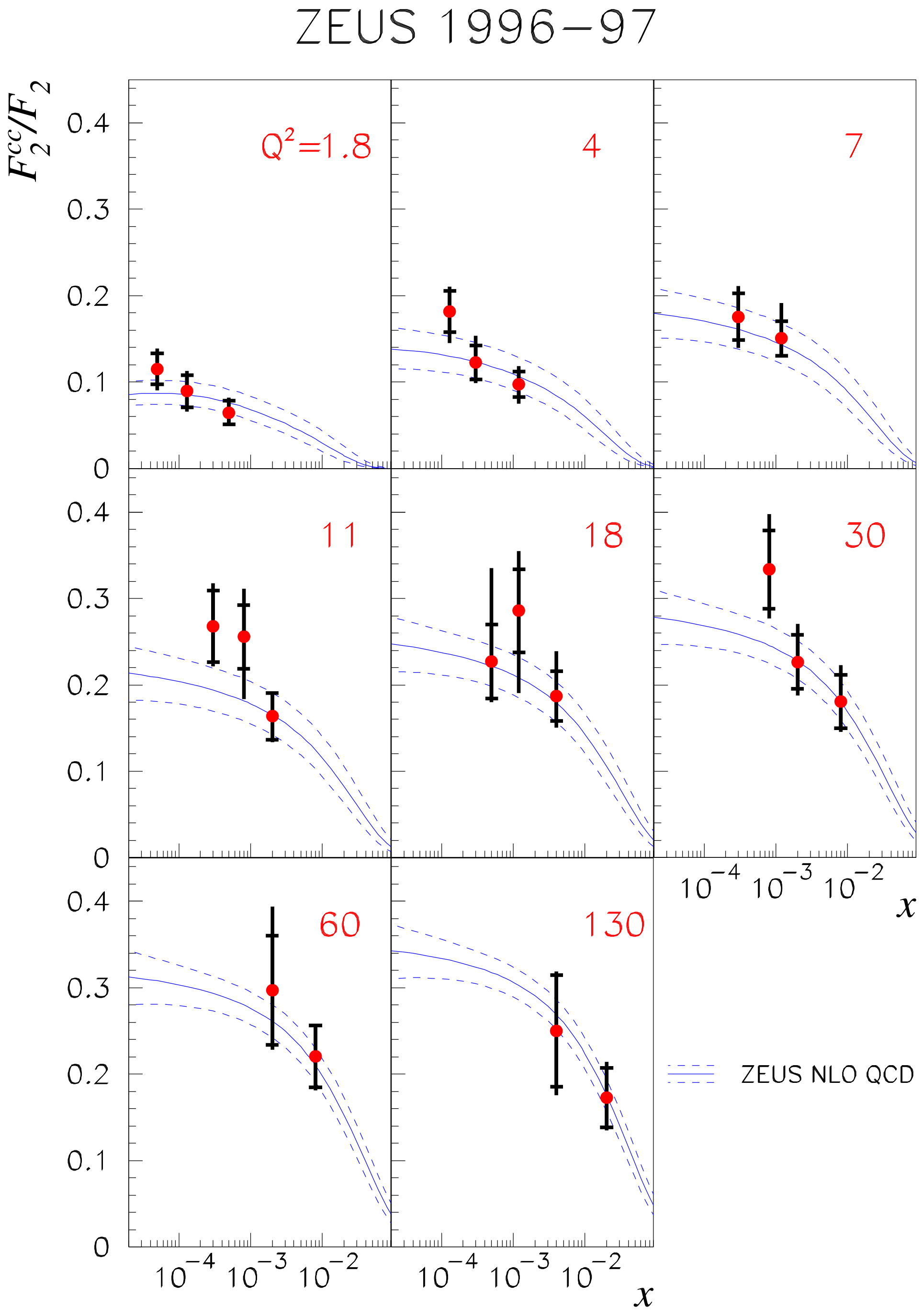
Gluon from Charm





- Gluon extracted from D^* measurements
- Measurement in DIS and γp
- Good agreement with QCD fit to F_2
- Impressive test of the universality of PDFs

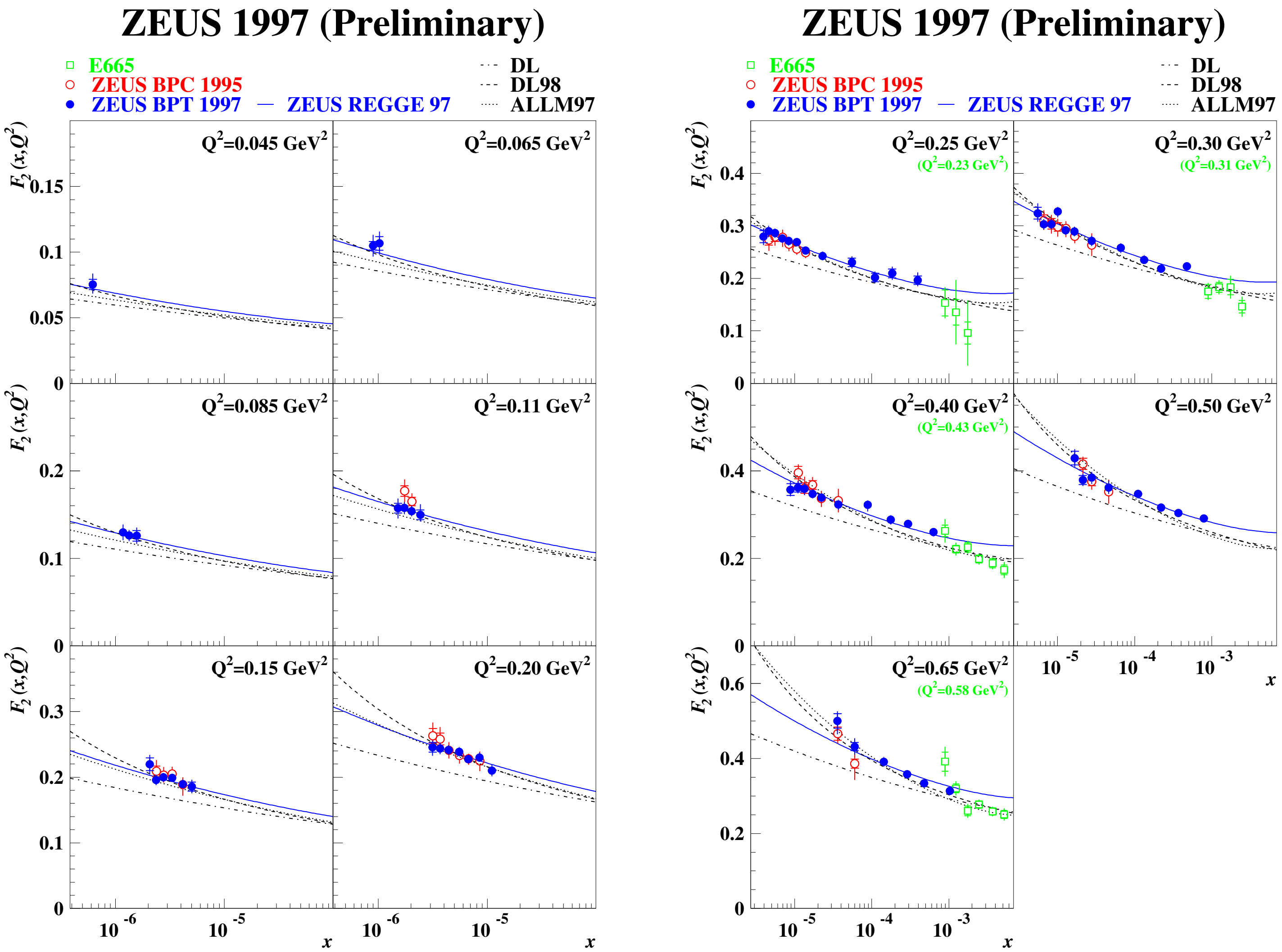
Charm contribution to F_2



- $F_2^{c\bar{c}}$ extrapolated from D^* cross section
- Charm makes up 10-30% of DIS cross section at low x
- Contribution increases with Q^2
- Excellent description by NLO QCD

F_2 at very low Q^2

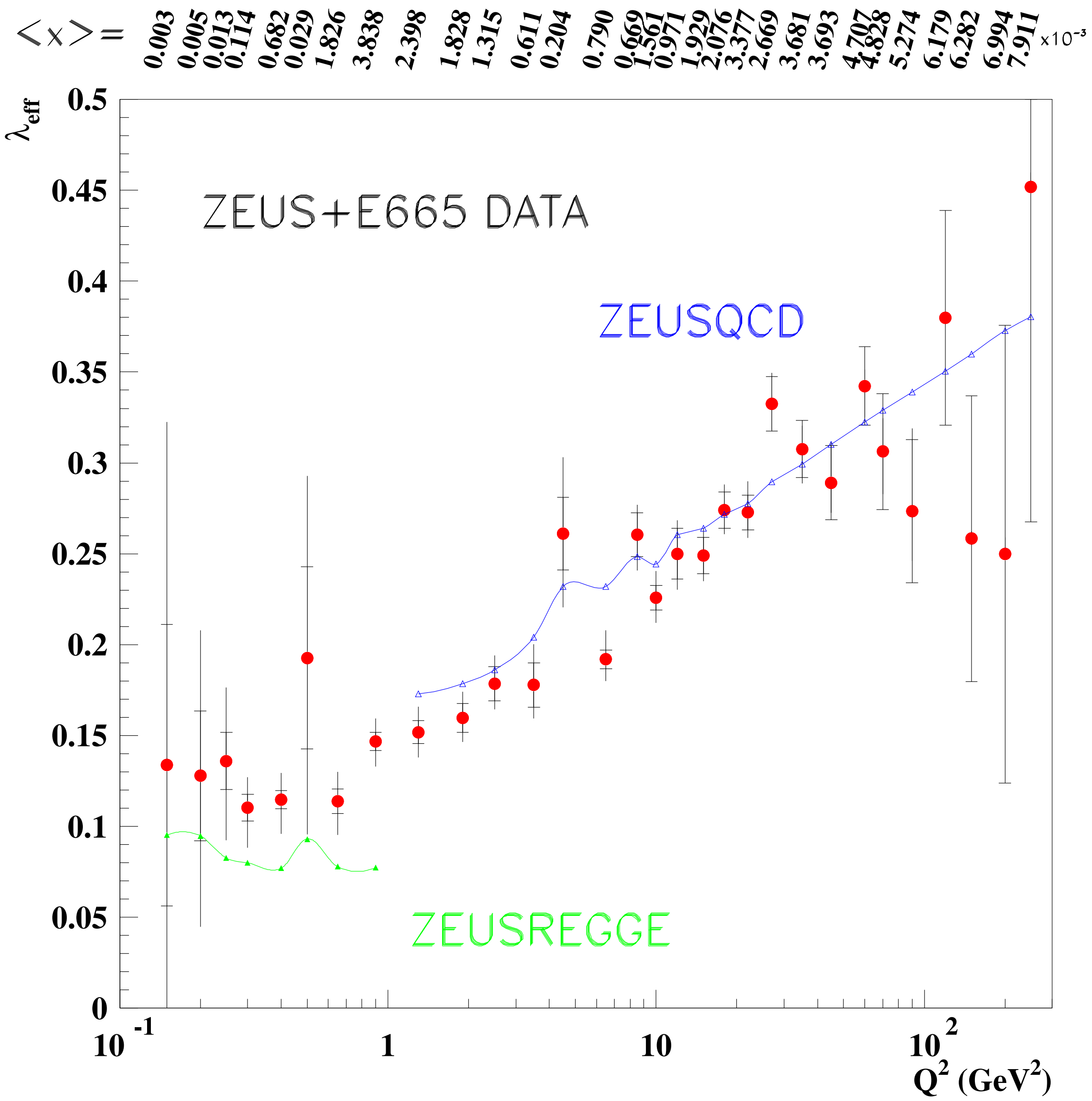
Transition between perturbative and non-perturbative QCD



- F_2 rises even at lowest Q^2
- F_2 is small ($F_2 \propto Q^2$ for $Q^2 \to 0$)
- Comparisons with Regge inspired models

Very Low Q^2

Fit the form $F_2 \propto x^{-\lambda_{eff}}$



- F_2 rises more steeply towards low x as Q^2 increases
- QCD describes behaviour for $Q^2 > 1$ GeV^2
- At low Q^2 the data approach the soft pomeron limit ($\lambda_{eff} \approx 0.085$)

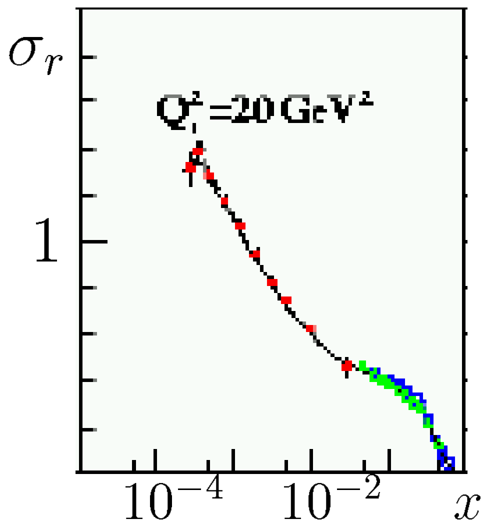
Longitudinal Structure Function

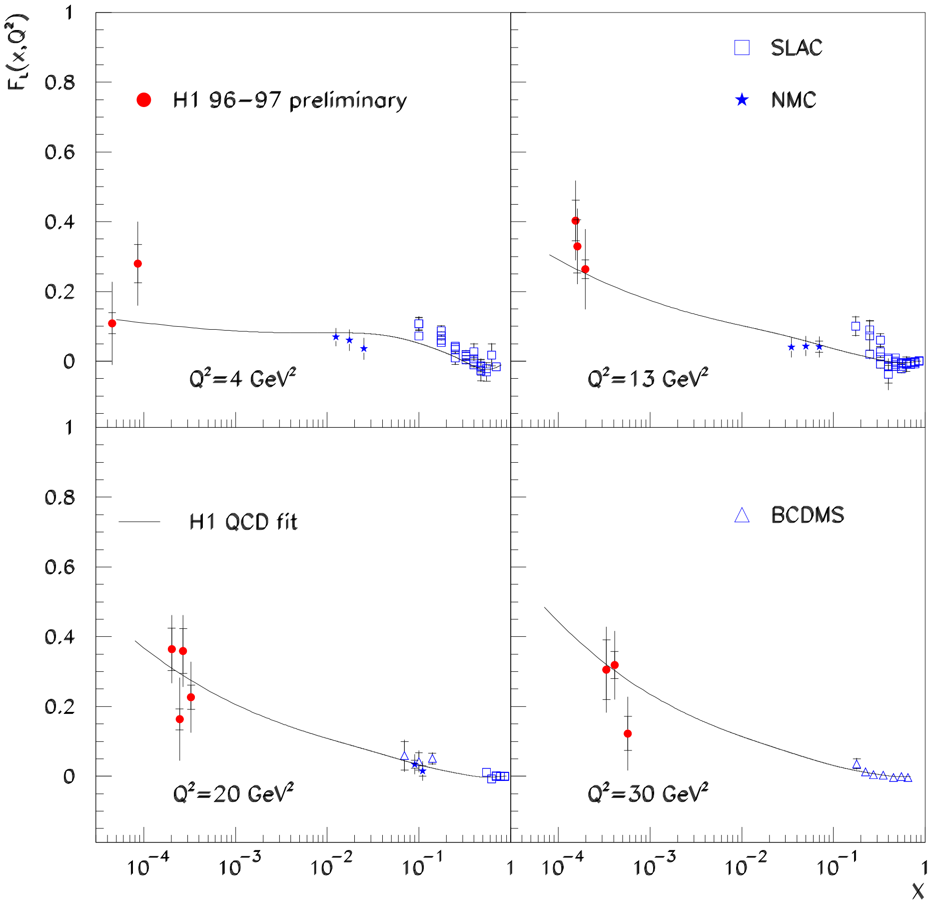
$$\sigma_r = F_2 - \frac{y^2}{Y_+} F_L$$

Assume Q^2 evolution of F_2

(QCD Fit to data with $y < 0.4$)

$\Rightarrow$ Indirect measurement of F_L





- F_L in agreement with NLO QCD fit
- x values 1000 times smaller than previous measurements
- Direct measurement at HERA in future by varying the beam energies

A-dependent R at low Q^2?

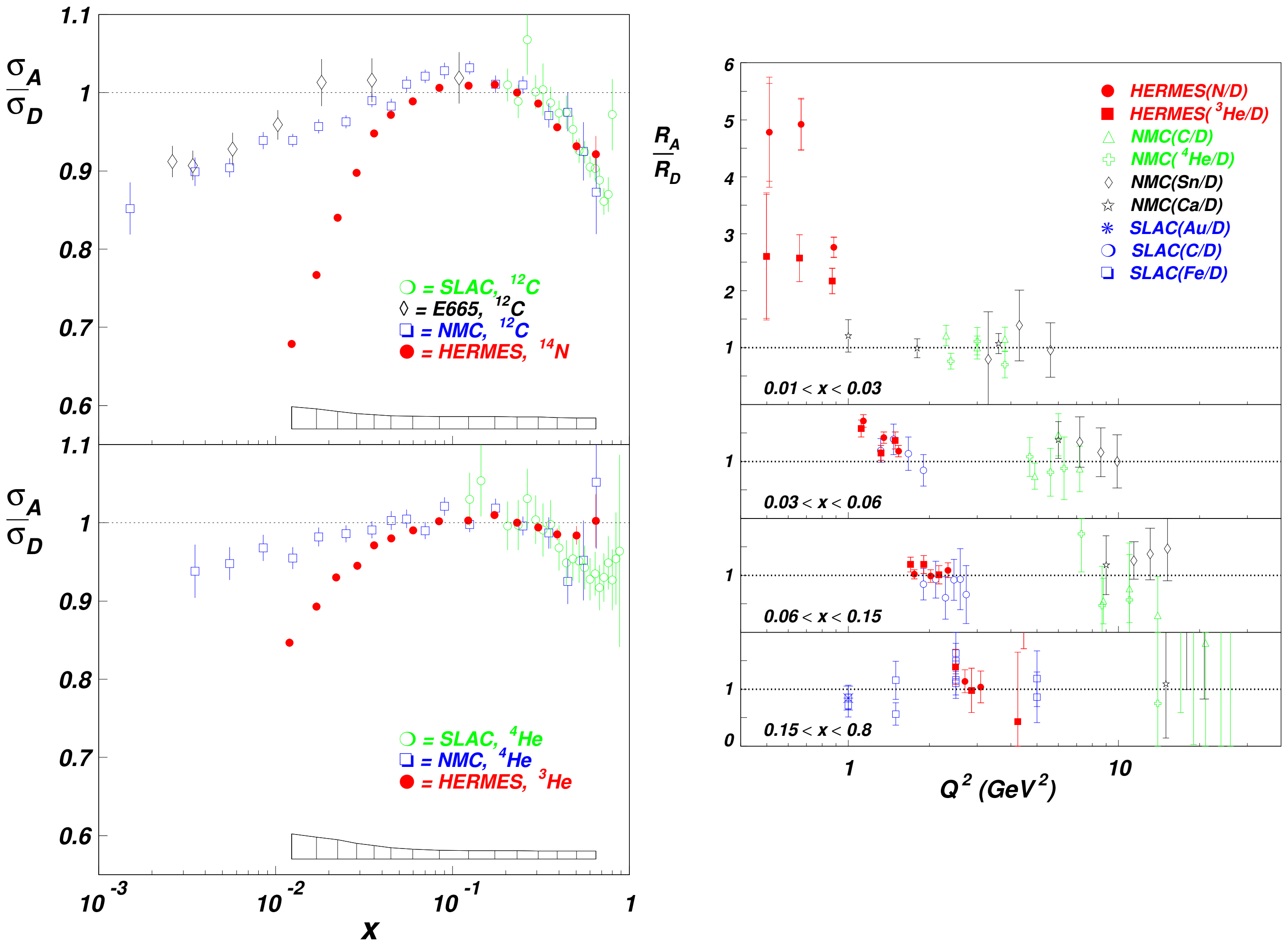
- Ratio of DIS cross sections for ^3He and ^{14}N to ^2D

$\Rightarrow$ HERMES inconsistent with NMC and SLAC results

BUT related to $R = \sigma_L/\sigma_T = F_L/(F_2 - F_L)$

- relation to F_2 and R: $\frac{\sigma_A}{\sigma_D} = \frac{F_2^A}{F_2^D} \frac{(1+\epsilon R_A)(1+R_D)}{(1+R_A)(1+\epsilon R_D)}$

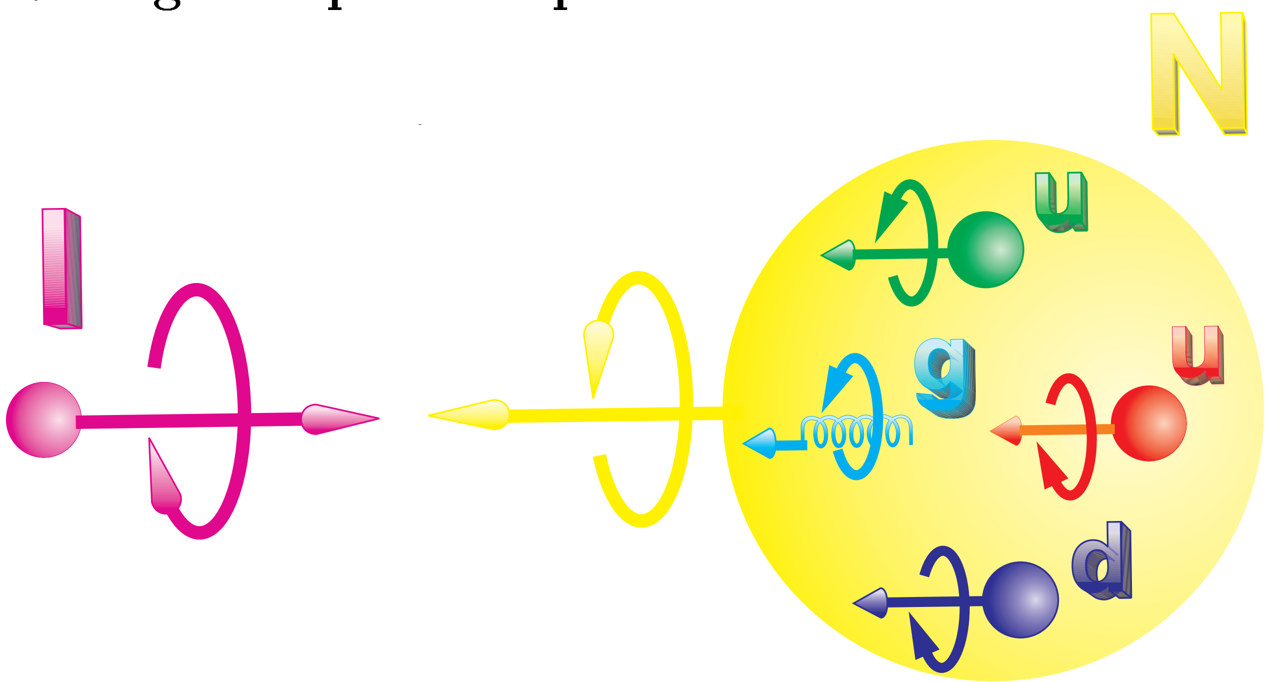
$\Rightarrow$ fit data with F_2^A/F_2^D and R_A/R_D free: $\epsilon = \epsilon(y, Q^2, E)$



- R_A/R_D **consistent with 1 for** $Q^2 \gtrsim 3$ **GeV**^{2}
- R_A/R_D **increases towards low** Q^2
- **effect increasing with A?** $\Rightarrow$ **recent data with** ^{84}Kr

Spin Structure of the Nucleon

Scatter polarised e off polarised nucleon
$\Rightarrow$ origin of proton spin ?



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G$$

From Deep Inelasitc Scattering:

– **quark spins** $\Delta\Sigma = \Delta u + \Delta d + \Delta s \approx 0.3$
– **gluon spins** $\Delta G = ?$
– **orbital angular momenta** $L_q, L_G = ?$

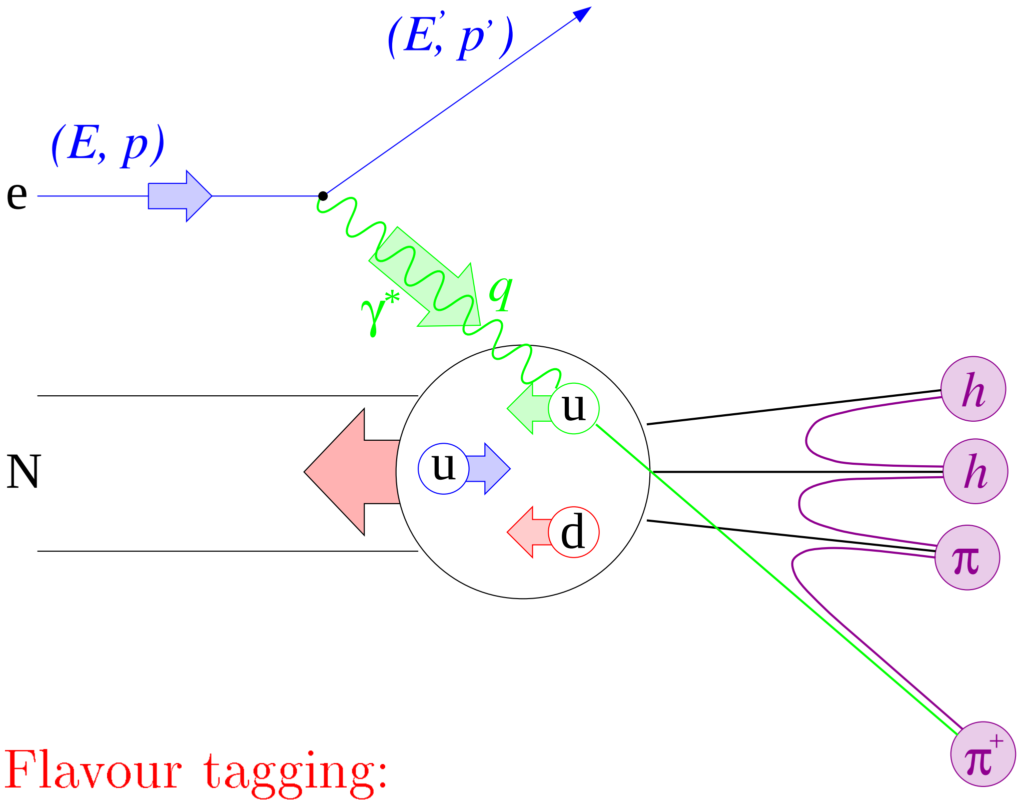
with $\Delta q(x) = q^{+}(x) - q^{-}(x)$

HERMES: measure Δu, Δd, Δq_s and ΔG

Targets: ^{3}He and H until 1997, D since 1998

Semi-Inclusive Measurements

In semi-inclusive DIS a hadron is detected in coincidence with the scattered lepton



Flavour tagging:

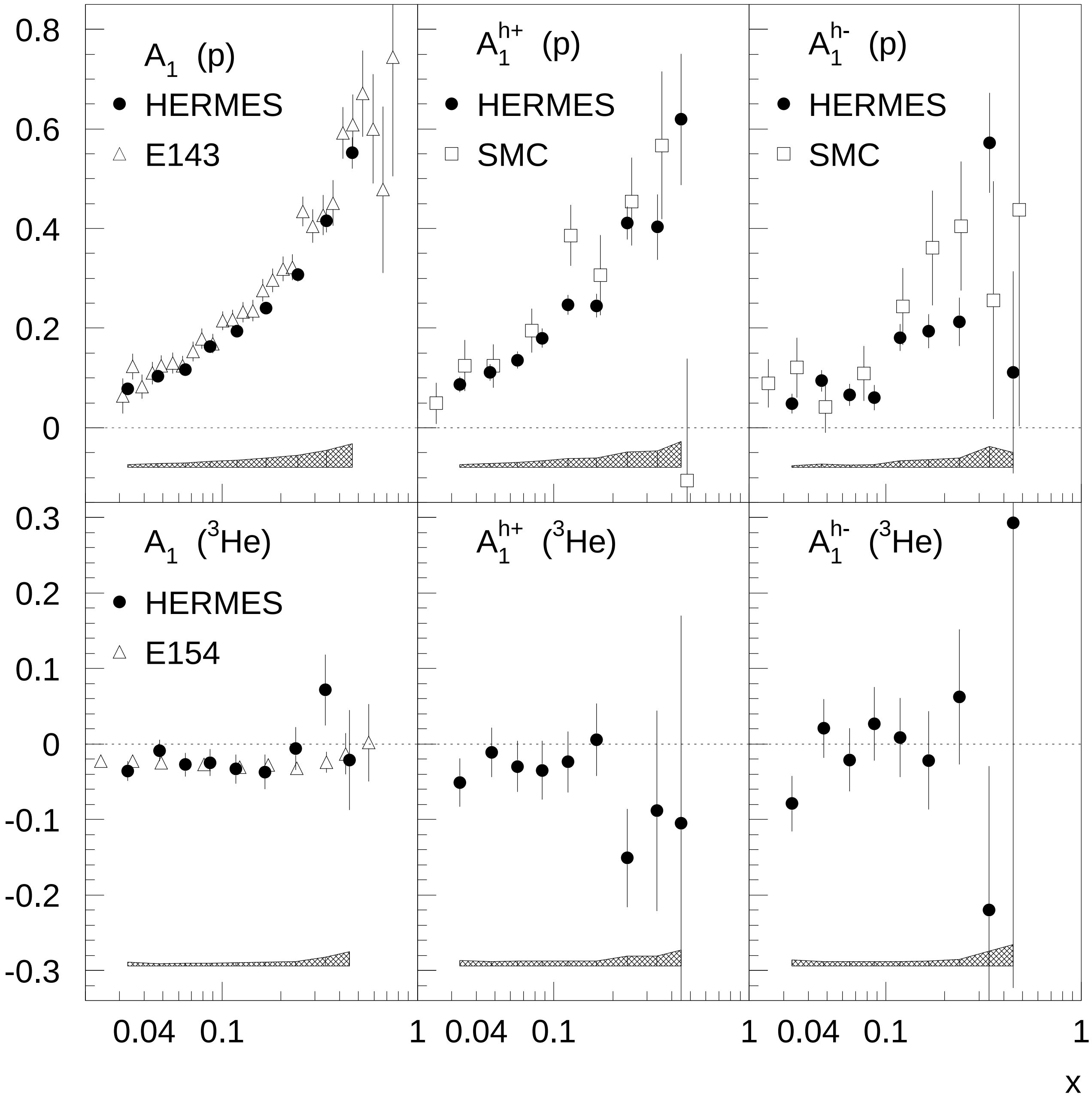
- Select hadrons from current hemisphere by cuts on $z = E_h/\nu$ and $x_F = 2p_{||}/W$
- Measure spin asymmetries for production of h^+ and h^-

$$A_{||}^h = \frac{1}{\langle P_T P_B \rangle} = \frac{(N_h/\mathcal{L})^{\uparrow\Uparrow} - (N_h/\mathcal{L})^{\downarrow\Uparrow}}{(N_h/\mathcal{L})^{\uparrow\Uparrow} + (N_h/\mathcal{L})^{\downarrow\Uparrow}}$$

- Inclusive Asymmetry: $A_1^h = \left(\frac{g_1}{F_1}\right)^h = \frac{A_{||}^h}{D(1+\gamma\eta)}$

γ, η kinematic factors, D depolarization

Semi-Inclusive Asymmetries



- Related to Δq:

$$A_1^h(x) \simeq \sum_q P_q^h(x) \cdot \frac{\Delta q(x)}{q(x)}$$

with purity $P_q^h(x)$ being probability that a quark $q(x)$ was struck when a hadron h is detected

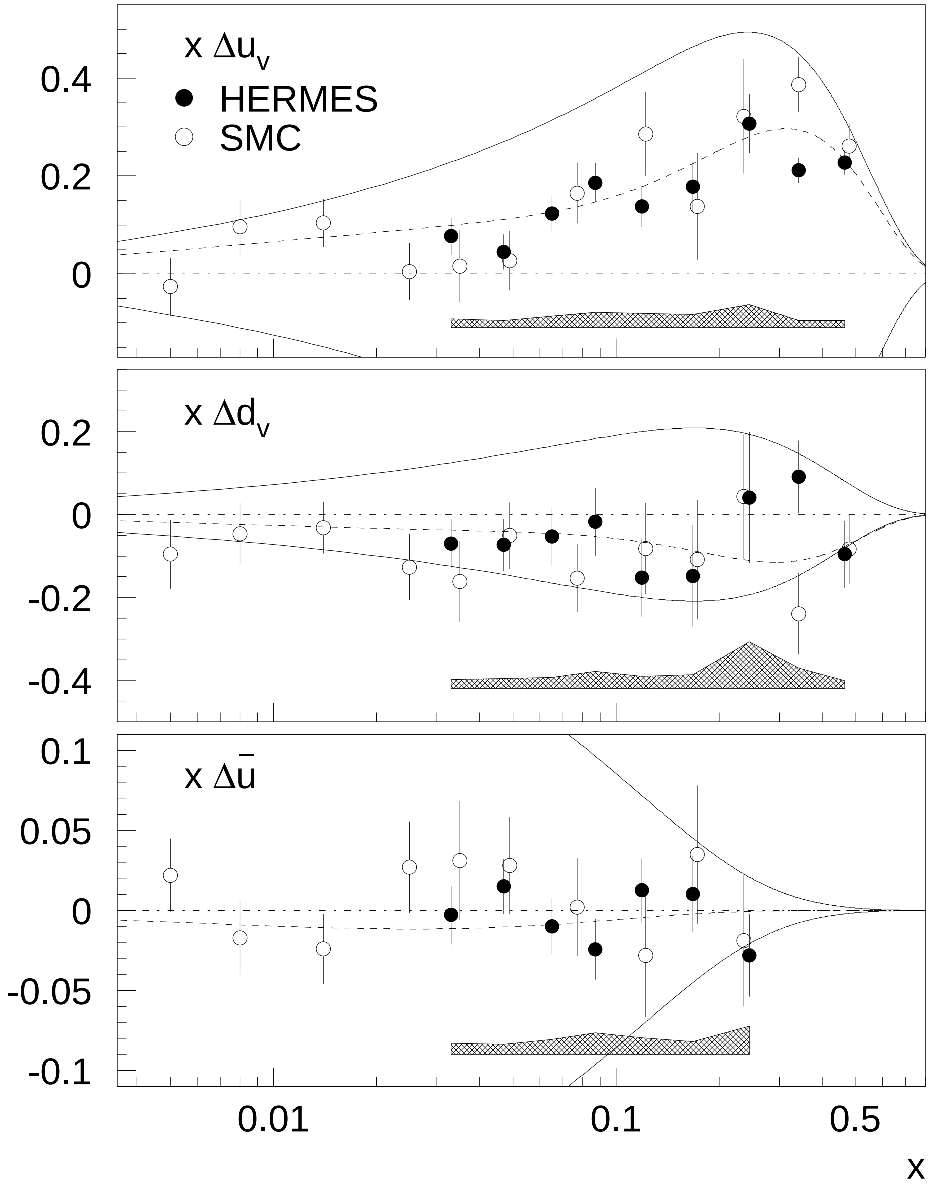
Spin Contribution of the Quarks

Assume symmetric behaviour of sea quarks

HERMES: $\Delta u_s/u_s = \Delta d_s/d_s = \Delta s/s$

SMC: $\Delta u_s = \Delta d_s = \Delta s$

(not sensitive to those assumptions)



- Good agreement between SMC and HERMES results
- Good agreement with QCD: T. Gehrmann et al. (1996)
- $\boldsymbol{\Delta u_v > 0,\ \Delta d_v < 0,\ \Delta q_s \approx 0}$

Spin Contribution and $SU(3)_f$

Spin of quarks: HERMES and SMC

	HERMES	SMC
Δu_v	$0.52 \pm 0.05 \pm 0.08$	$0.59 \pm 0.08 \pm 0.07$
Δd_v	$-0.19 \pm 0.11 \pm 0.13$	$-0.33 \pm 0.11 \pm 0.09$
$\Delta \bar{u}$	$-0.01 \pm 0.02 \pm 0.03$	$0.02 \pm 0.03 \pm 0.02$
$\Delta \bar{d}$	$-0.02 \pm 0.03 \pm 0.04$	$0.02 \pm 0.03 \pm 0.02$

Good agreement between HERMES and SMC

Comparison of integrals with predictions of $SU(3)_f$

	total integral	prediction	Q^2 (GeV^2)
$\Delta u + \Delta \bar{u}$	0.56 ± 0.04	0.66 ± 0.03	2.5
$\Delta d + \Delta \bar{d}$	-0.25 ± 0.08	-0.35 ± 0.03	2.5
$\Delta s + \Delta \bar{s}$	-0.02 ± 0.05	-0.08 ± 0.02	2.5

$SU(3)_f$ violated? $\Delta s = 0$ or negative?

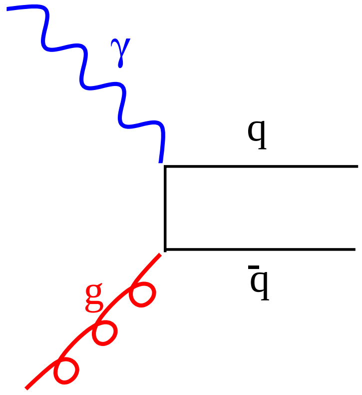
Direct measurement of Δs required

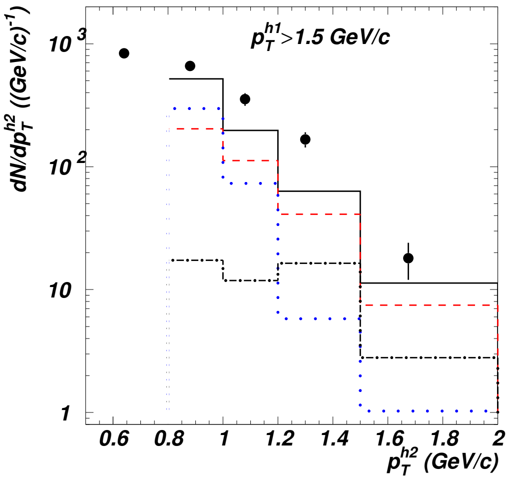
$\Rightarrow$ upgrade of HERMES (RICH)

How to measure $\Delta G/G$?

Possibilities

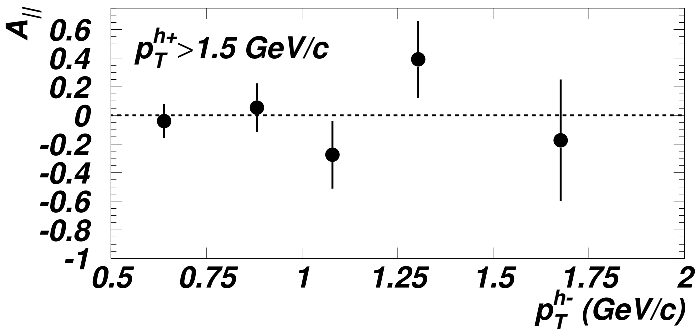
- Scaling violations of $g_1 \Rightarrow Q^2$ range too small
- Tagging of charm events $\Rightarrow$ low statistics
- Tagging of photon-gluon-fusion (PGF) events ($\gamma g \rightarrow q\bar{q}$)





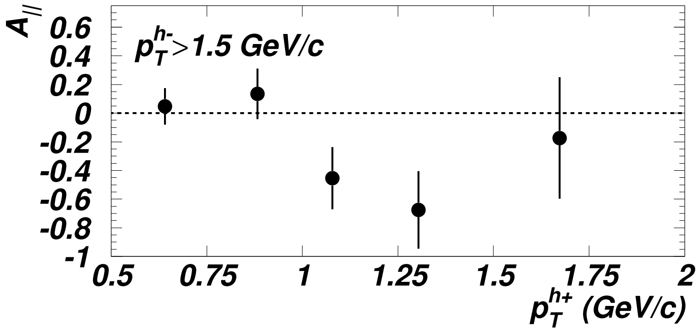
Experimental Procedure:

- two hadrons with opposite charge in spectrometer
- $p_t^{1(2)} > 1.5(0.5)$ GeV and $M(2\pi) > 1$ GeV
- NO requirement of scattered positron (photoproduction)



– at high p_T BGF dominant

– $\langle A_{||} \rangle = 0.28 \pm 0.12 \pm 0.02$

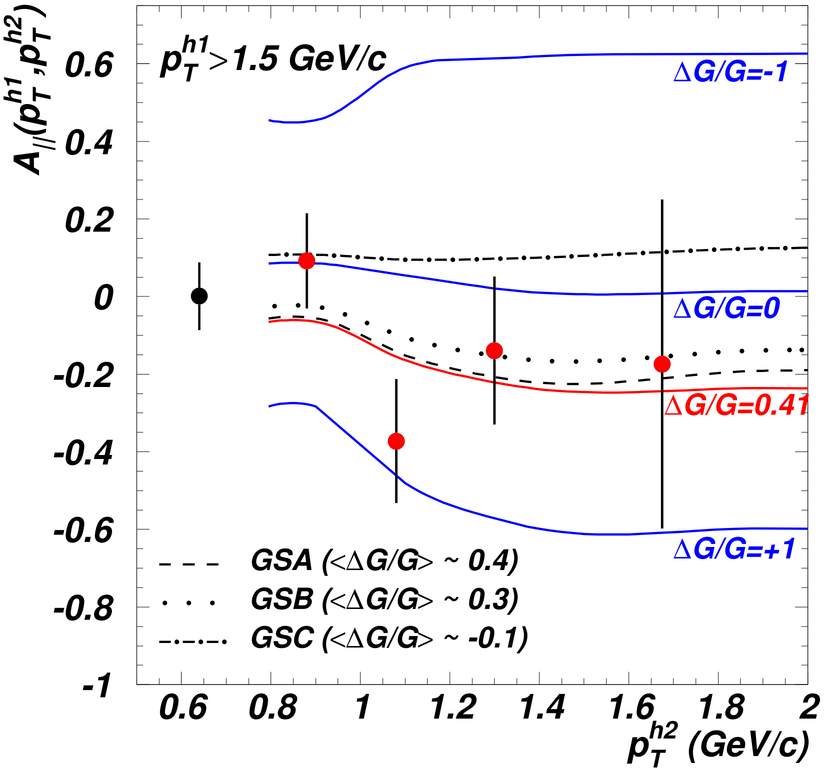


– $\langle A_{||} \rangle \approx 0$ at lower p_T

Asymmetry caused by $\Delta G/G \neq 0$?

Determination of $\Delta G/G$

- Assume PYTHIA model for contributions of individual diagrams (PGF,VMD,QCDC,QPM)
- Neglect resolved component of photon (expected to be small for HERMES energies)



$$\langle \Delta G/G \rangle = 0.41 \pm 0.18(\text{stat.}) \pm 0.03(\text{exp. syst.})$$

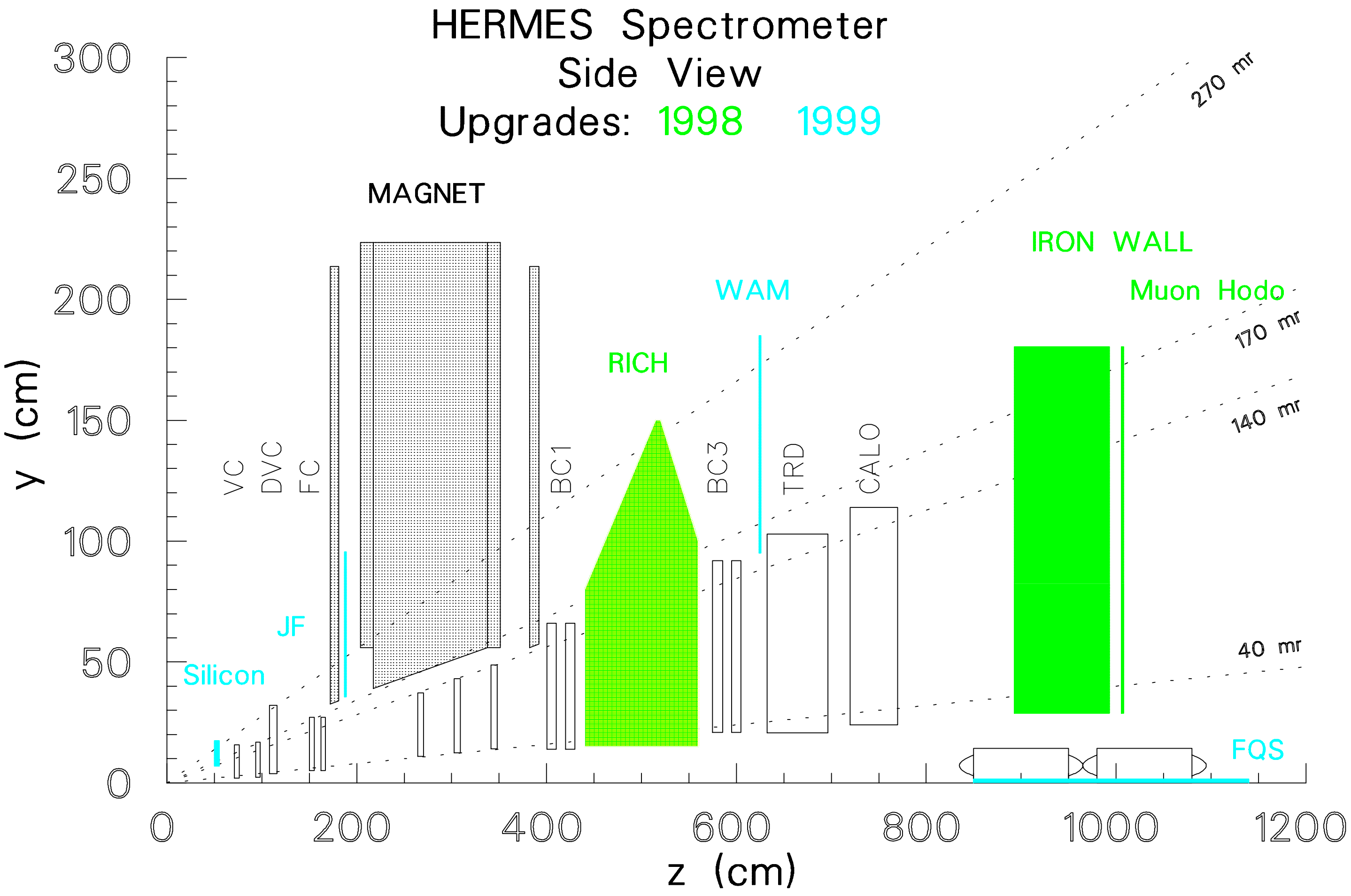
$$\text{at } \langle x_G \rangle = 0.17 \text{ and } \langle \hat{P}_T^2 \rangle = 2.1 \text{ GeV}^2$$

Upgrade of Hermes 1998

$\Rightarrow$ better acceptance and efficiency for charm tagging

$\Rightarrow$ Less model dependent extractions of $\Delta G/G$ soon using charm tagging

1998/99 Upgrade of HERMES



- RICH: better π, K, p separation

  $\Rightarrow$ open charm and strange

- FQS: $e^{\pm}$ at very small angles

  $\Rightarrow$ low Q^2 (R,high p_T hadrons,...)

- Iron Wall: μ-ID improved

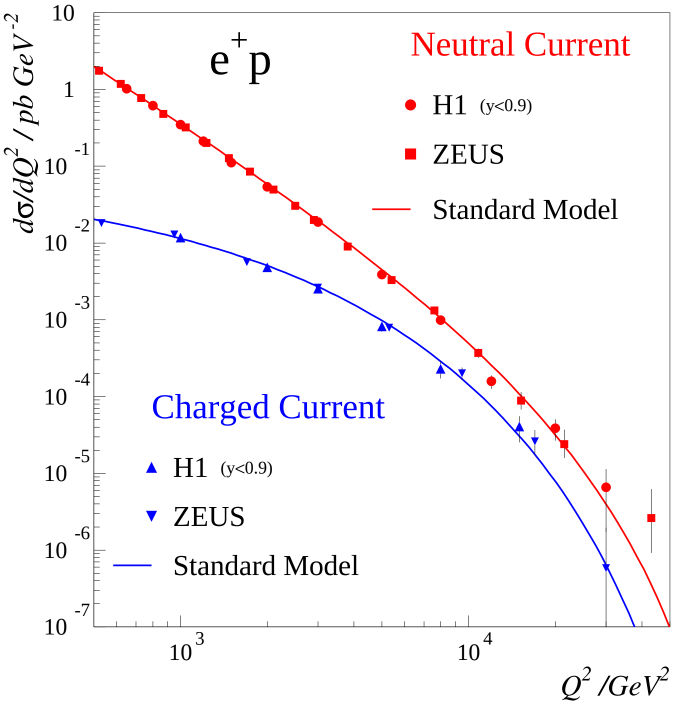
  $\Rightarrow$ 4 times more J/ψ

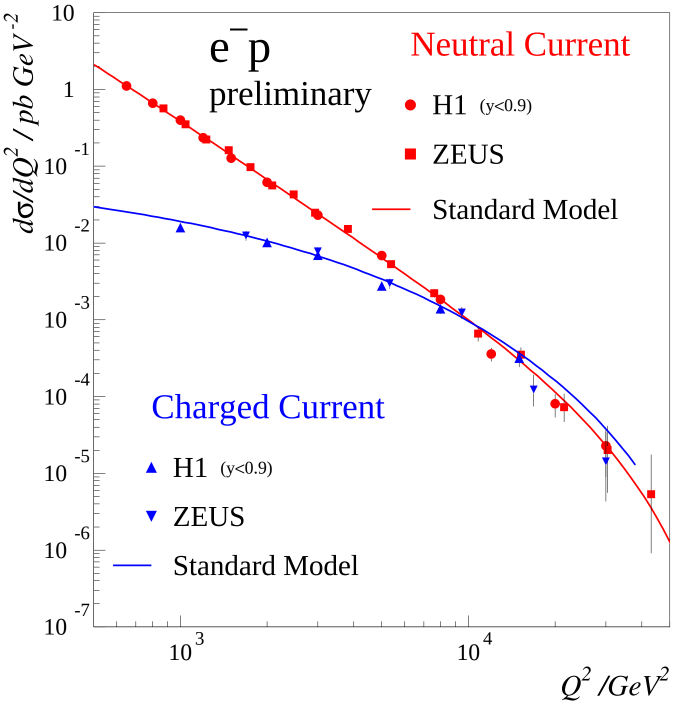
...and more improvements...

Testing the Electroweak Sector

$$\frac{\mathrm{d}^2\sigma^{\pm}_{NC}}{\mathrm{d}x\mathrm{d}Q^2} \simeq \frac{e^4}{8\pi x}\left(\left[\frac{1}{Q^2}\right]^2 Y_+ F_2 + a_e^2\kappa_w^2\left[\frac{1}{Q^2+M_Z^2}\right]^2 Y_+ F_2^Z \mp 2a_e\kappa_w\left[\frac{1}{Q^2(Q^2+M_Z^2)}\right] Y_- x F_3^{\gamma Z}\right)$$

$$\frac{\mathrm{d}^2\sigma^{\pm}_{CC}}{\mathrm{d}x\mathrm{d}Q^2} \simeq \frac{g^4}{64\pi x}\left[\frac{1}{Q^2+M_W^2}\right]^2 (Y_+ W_2^{\pm} \mp Y_- x W_3^{\pm})$$





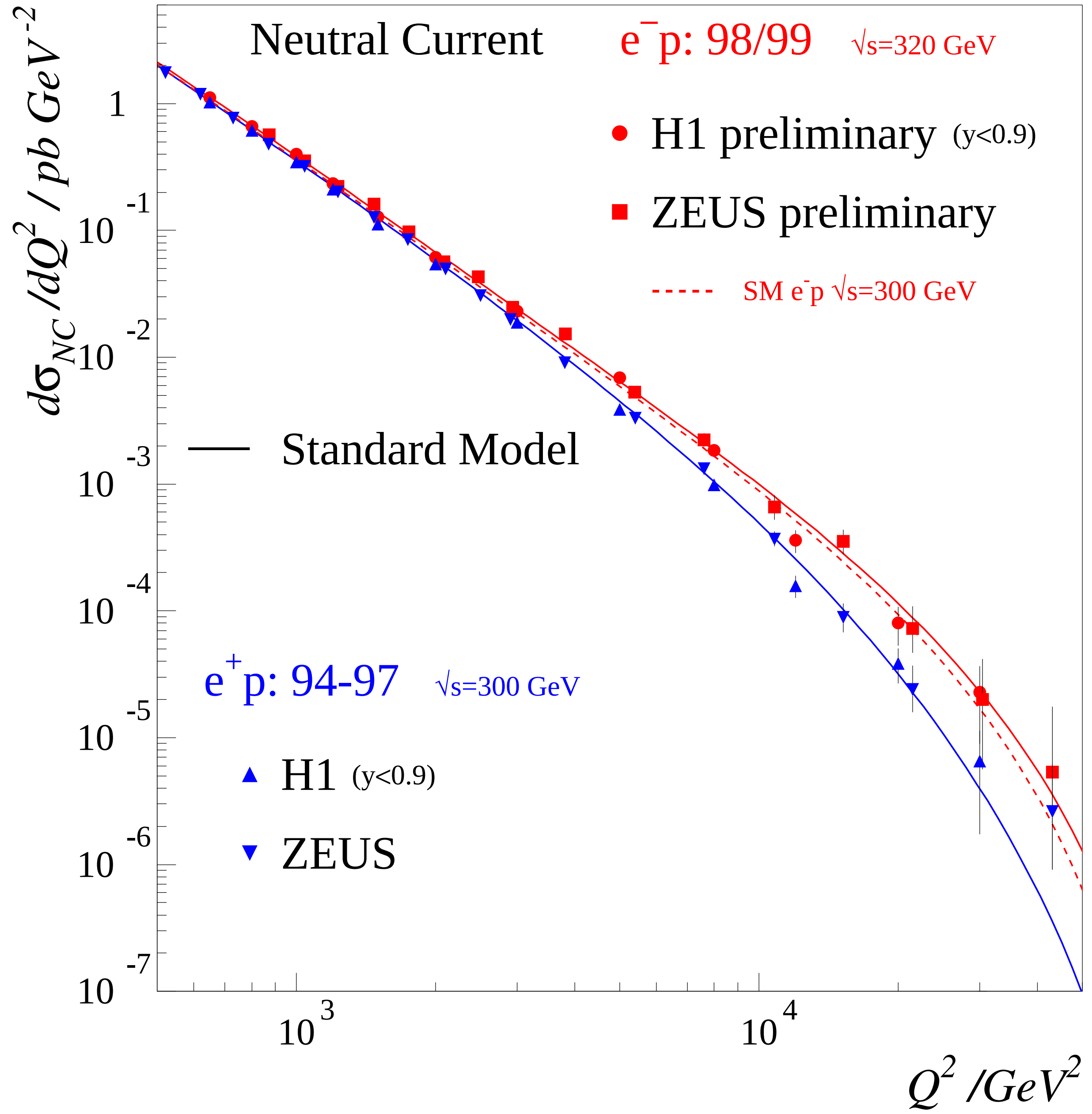
- NC cross section falls as $1/Q^4$
- W propagator suppresses CC cross section at low Q^2

Electroweak unification at $Q^2 \approx M_W^2 \approx M_Z^2$

γZ - Interference

$$\frac{d\sigma^{e^{\pm}p}}{dx dQ^2} \simeq \frac{2\pi\alpha^2}{xQ^4}[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3]$$

$\Rightarrow$ difference between $e^{\pm}$ due to γZ interference term



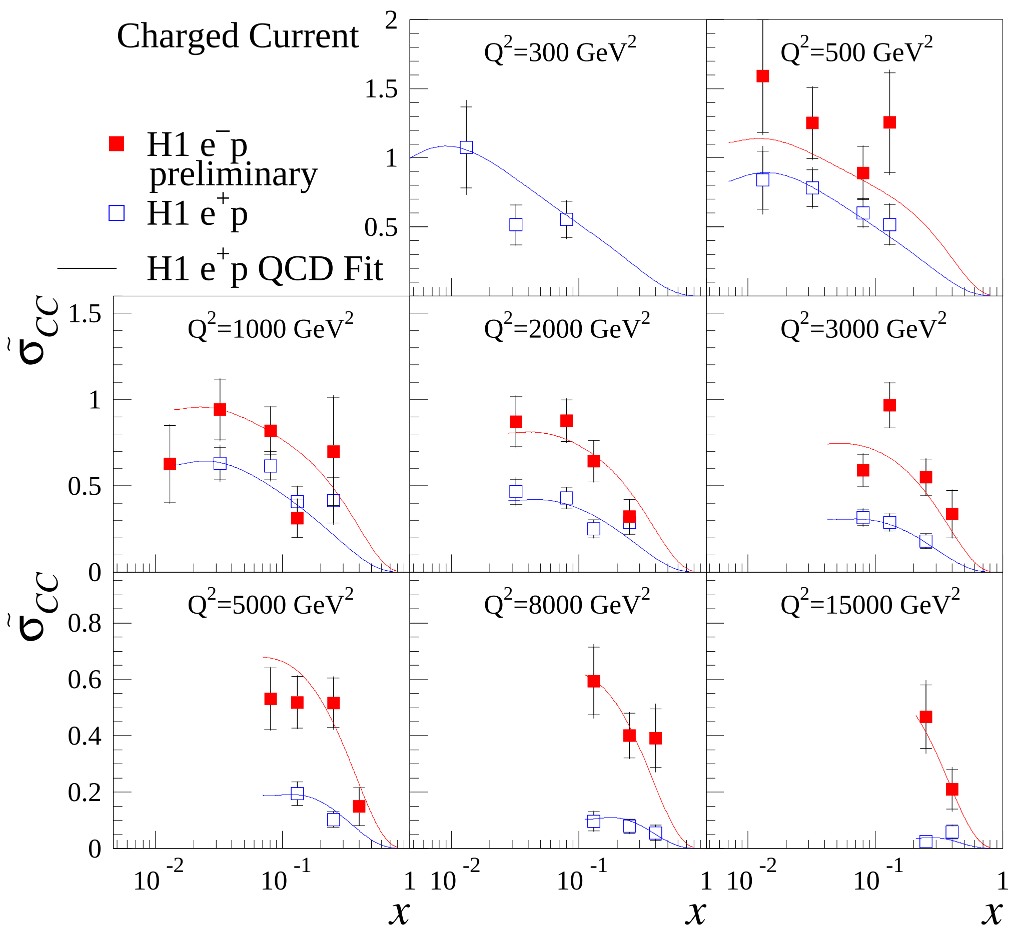
- Difference between e^- and e^+ clearly observed
- Cross sections in agreement with Standard Model

CC Cross Section

At leading order:

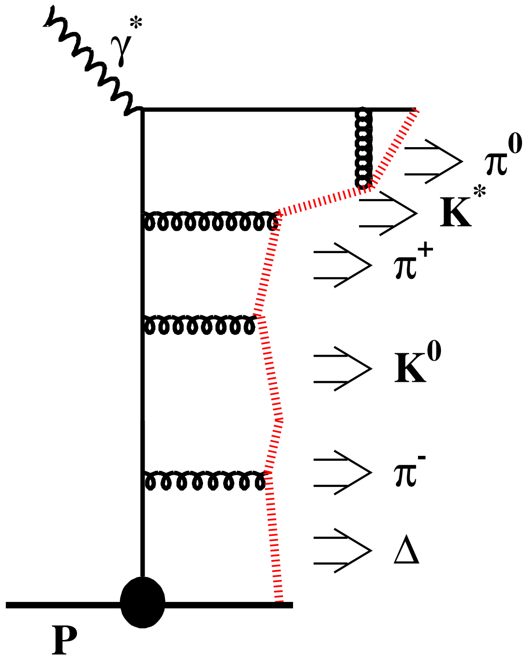
$$\tilde{\sigma}^{+}_{CC} = x[\bar{u} + \bar{c} + (1 - y^2)(d + s)]$$

$$\tilde{\sigma}^{-}_{CC} = x[u + c + (1 - y^2)(\bar{d} + \bar{s})]$$



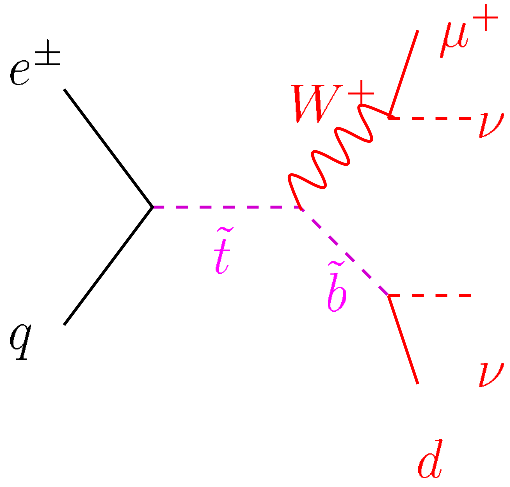
- Low Q^2: sea quarks dominate $\Rightarrow e^-p \approx e^+p$
- High Q^2: valence quarks dominate $\Rightarrow e^-p \gg e^+p$
- e^+p: test d-density at high x / $\bar{u}$-density at low x
- e^-p: test u-density
- Data well described by QCD fit

Final States and Searches



- **Final State Measurements**
  - α_s from Jets at high Q^2
  - Event shapes
  - Photon structure
  - Heavy flavour production
  - Pion structure
  - Forward particle production
  - Diffraction
  - Vector meson production
  - W and Z production
  - Fragmentation functions

- **Searches for New Physics**
  - Contact interactions
  - 1st generation leptoquarks
  - Flavour-changing NC: $eq \to \mu q$, $eq \to \tau q$
  - R_p-violating supersymmetry
  - MSSM: $\tilde{e}$ and $\tilde{q}$
  - Excited fermions
  - Quark substructure
  - Instantons



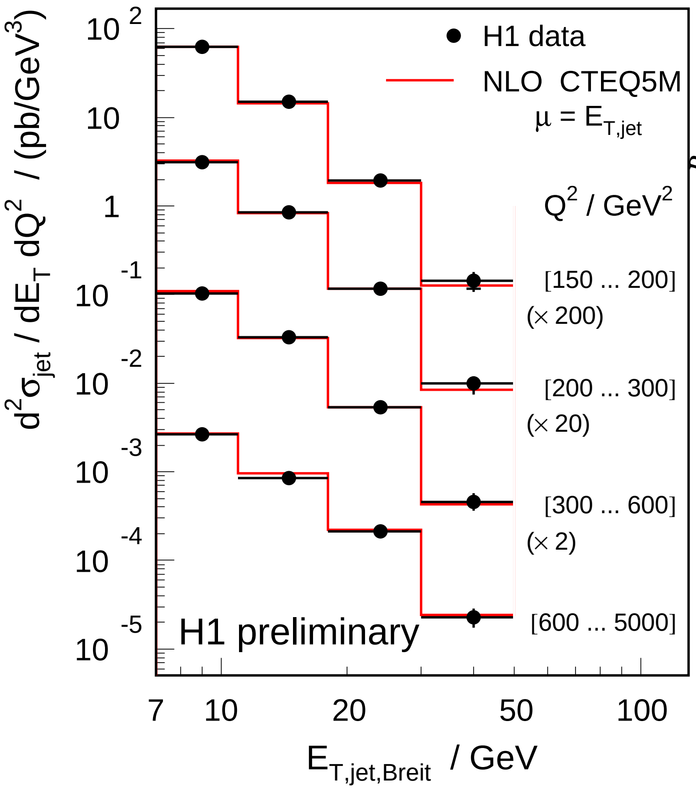
Jet Cross Sections at High Q^2

- Jet cross sections sensitive to higher order processes
- Jets provide additional hard scale

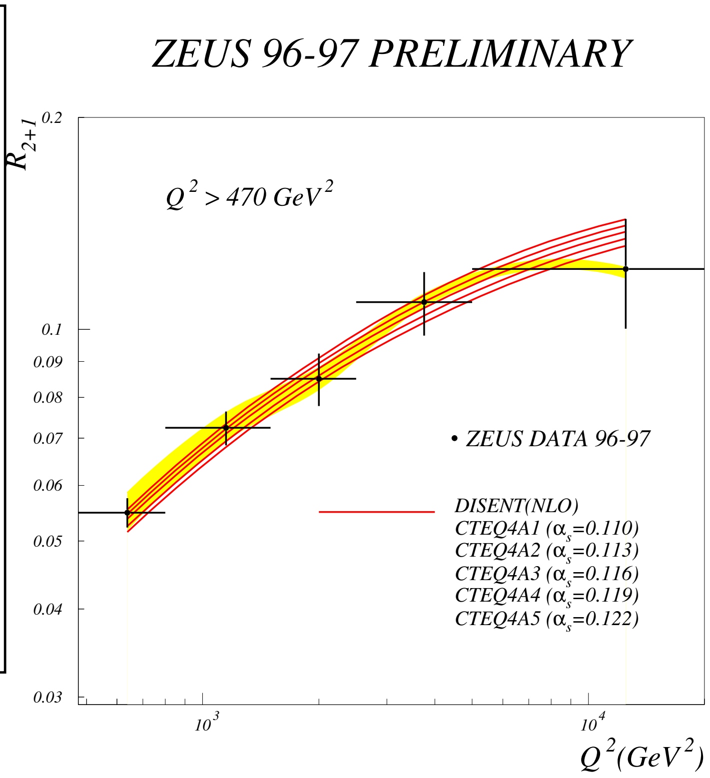
$\Rightarrow$ Important test of perturbative QCD

Example jet cross sections at high Q^2

Jet Cross Section In Breit Frame

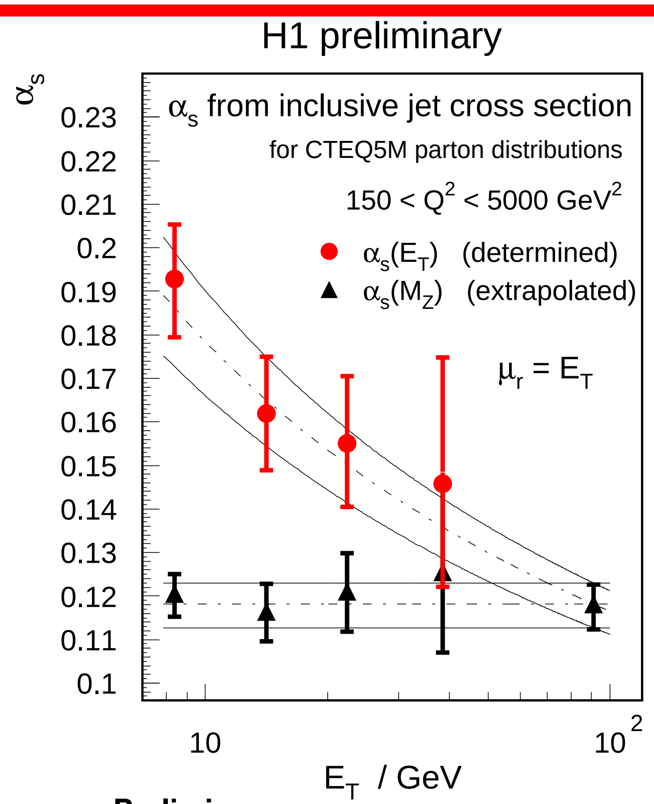


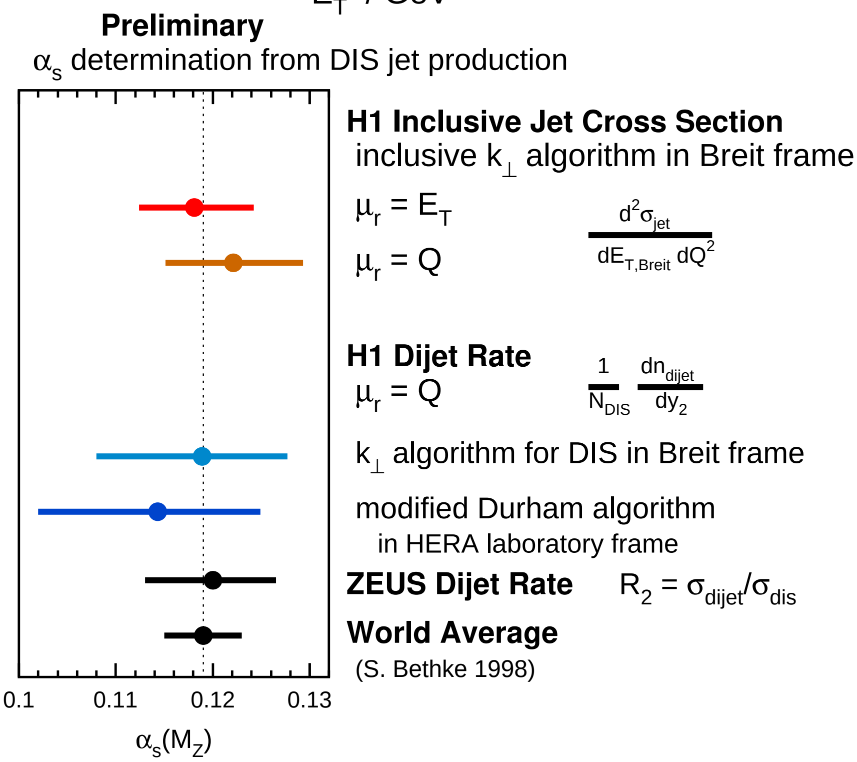
Ratio 2 Jet to all Events



- Cross sections described by NLO QCD
- Use to measure gluon in the proton and α_s $\Rightarrow$

Determination of α_s





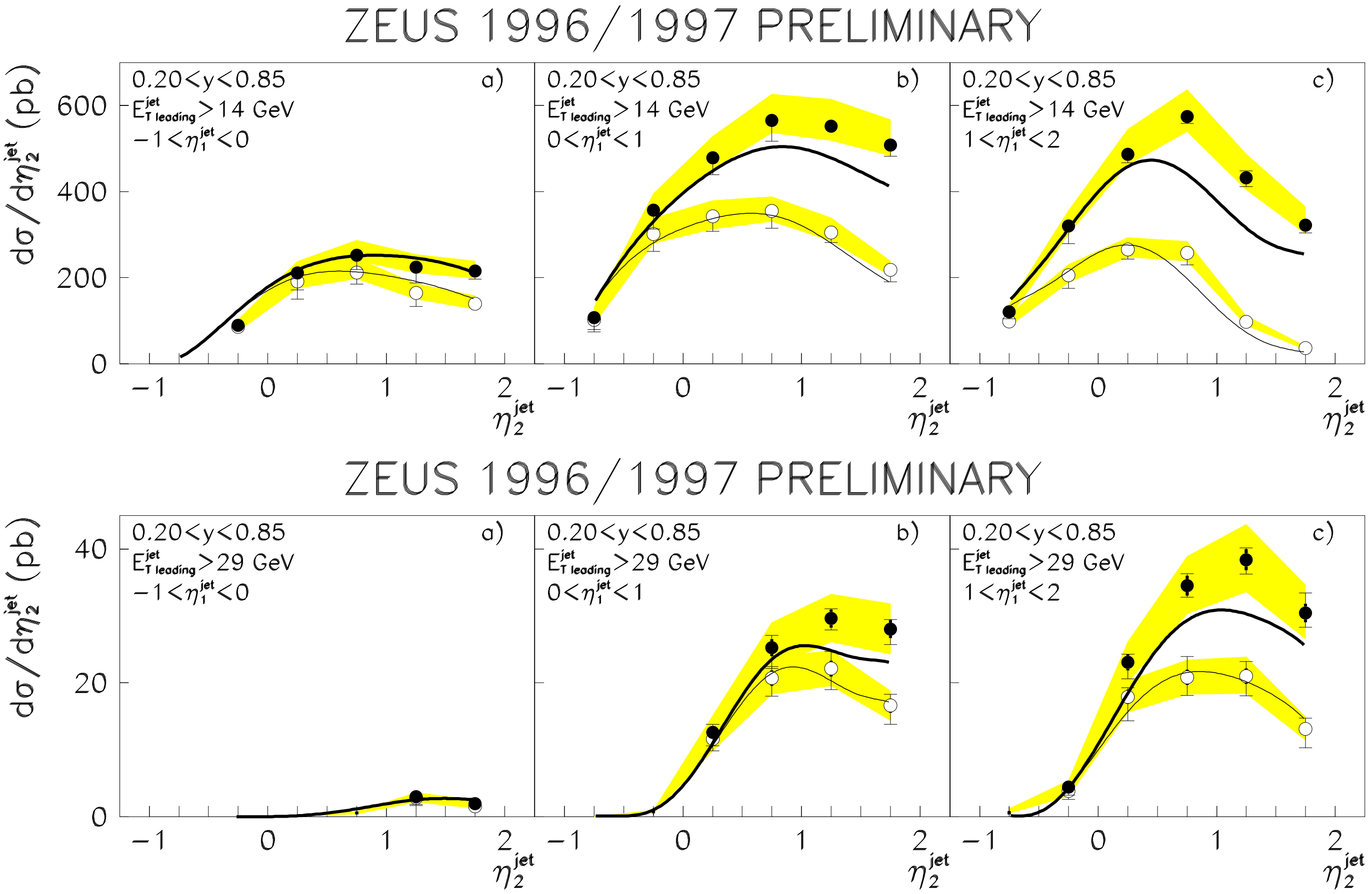
- Running of α_s tested in a single experiment
- α_s measurements from DIS jets in good agreement with world average

Successful test of QCD!

Photon Structure

- probe photon structure with jets: $E^2_{t,jet} \gg Q^2$
- $E_{t,jet1} > 14$ GeV $\Rightarrow$ hard scale for pQCD
- Define $x_\gamma^{obs} = \frac{E^{jet}_{T,1} e^{\eta_1^{jet}} + E^{jet}_{T,2} e^{\eta_2^{jet}}}{2yE_e}$
  - "direct": photon pointlike, $x_\gamma^{obs} \gtrsim 0.75$
  - "resolved": photon has partonic structure: $x_\gamma^{obs} \lesssim 0.75$
- Leading Order QCD:

x_γ^{obs} = fractional momentum carried by parton in photon



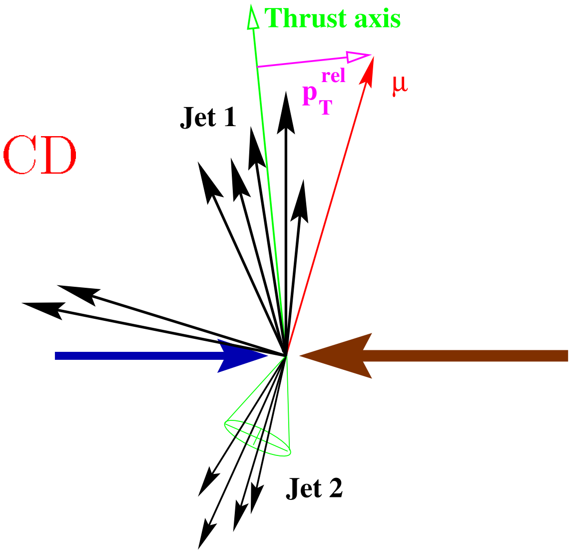
$\longrightarrow x_\gamma$ decreasing $\longrightarrow$

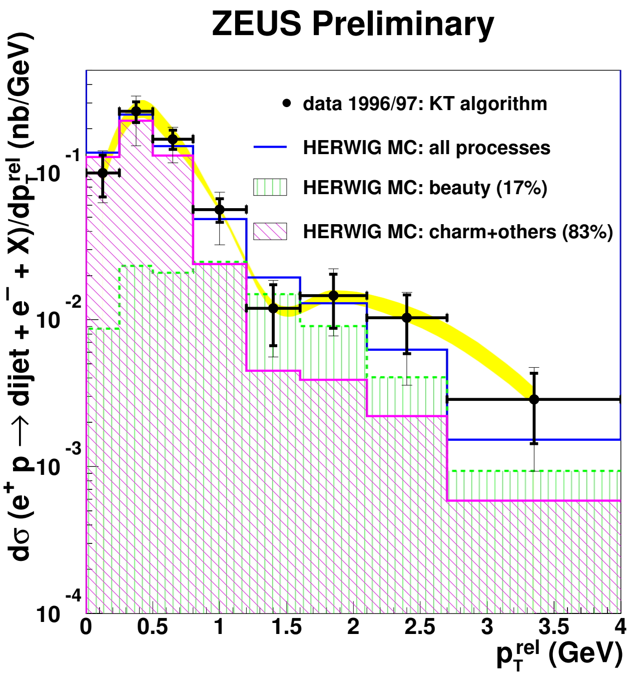
- NLO QCD prediction describes "direct" region
- Low x_γ region needs better understanding

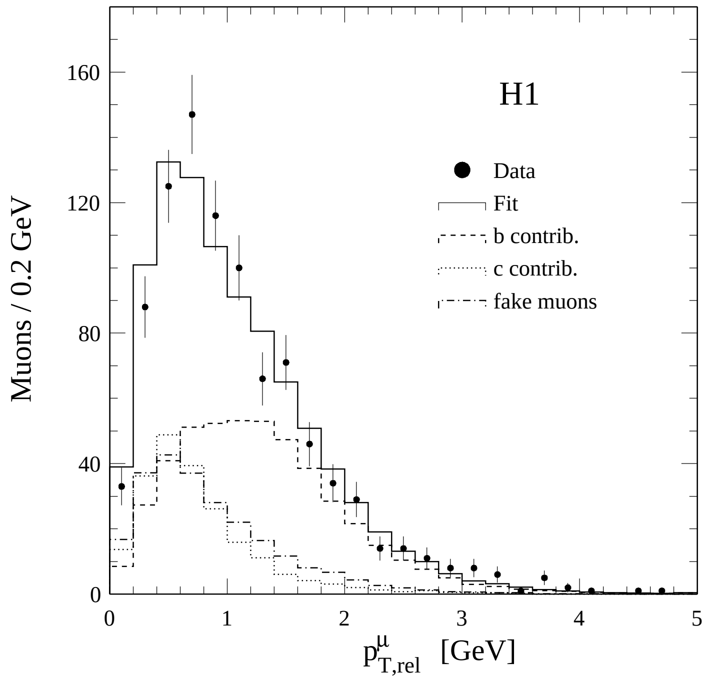
Improving understanding of $\boldsymbol{\gamma}$ structure

Open Beauty Production

- Tag lepton (e or μ) from semi-leptonic b-decay: $b \rightarrow c l \nu_l$
- require high $p^l_{T,rel}$
- $m_b \approx 5$ GeV $\Rightarrow$ hard scale for pQCD
- Photoproduction: $Q^2 < 1$ GeV^2
- e- and μ-channel





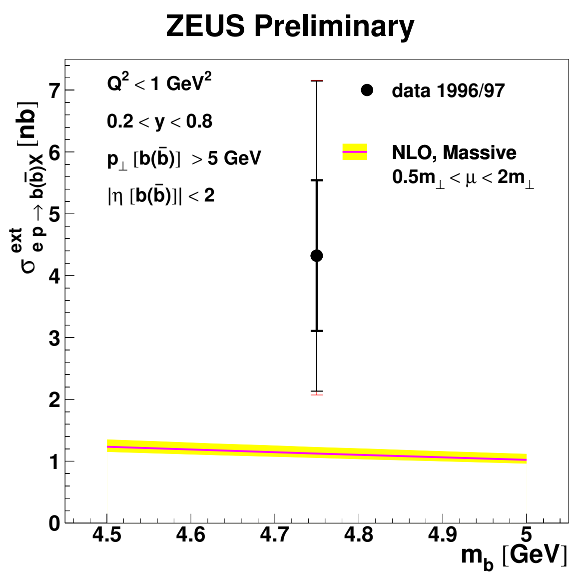


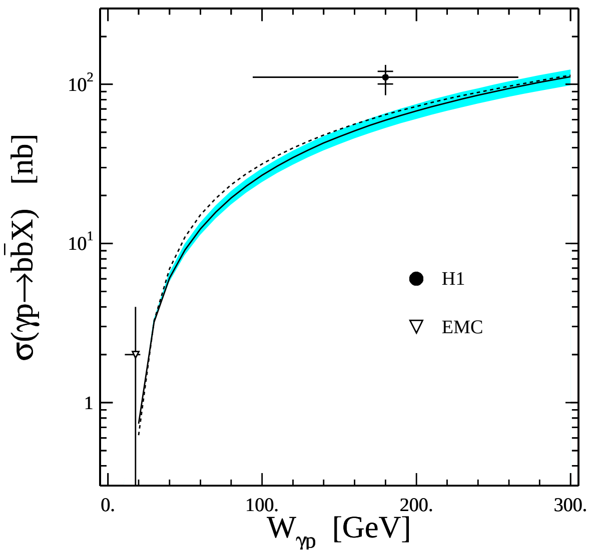
- relative contribution of c and b determined by fit
  - shape taken from MC simulation
  - two normalisation parameters free

$\Rightarrow$ Extract cross sections

Beauty Cross Section

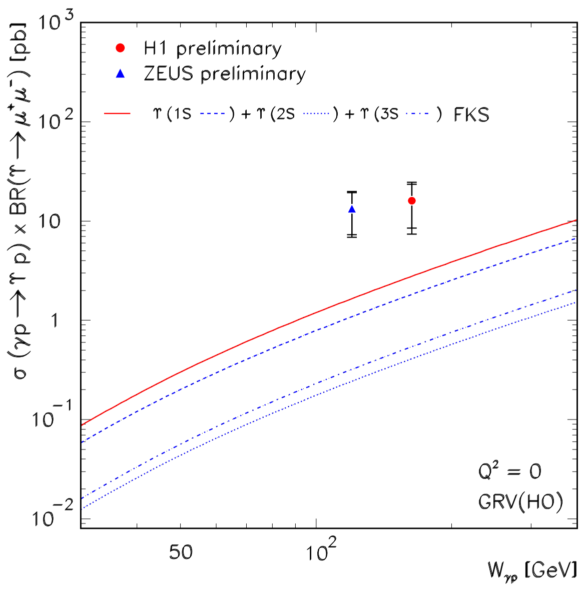
- Visible Cross section larger than NLO QCD in both e and μ channels for H1 and ZEUS





Hard scale! ⇒ Why does NLO QCD not work?

- missing higher orders?
- theo. uncertainty underestimated?
- resolved component of photon?



Similar disagreement observed for Υ (closed b) production

Forward πs – Testing QCD Evolution

DGLAP evolution explains inclusive measurements

Can DGLAP explain exclusive final states?

DGLAP resums $\log(\frac{Q^2}{Q_0^2})$ terms

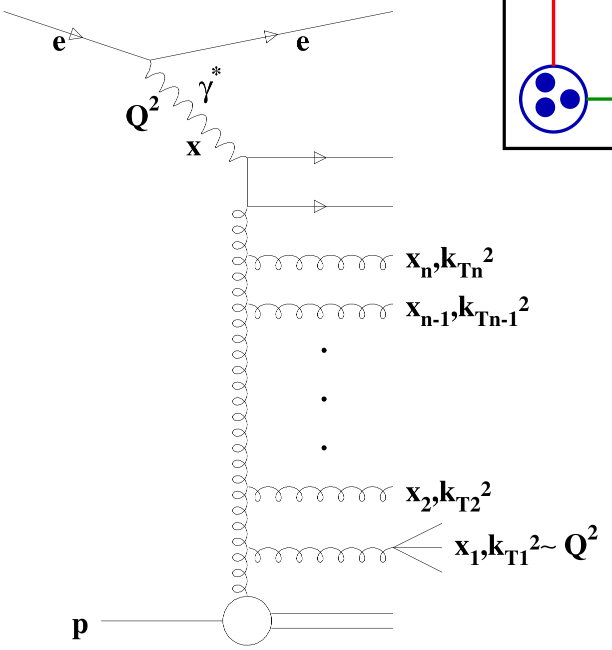
with $k_{Tk}^2 \gg k_{Tk-1}^2 \gg \ldots,$

and $x_1 > x_2 > \ldots$

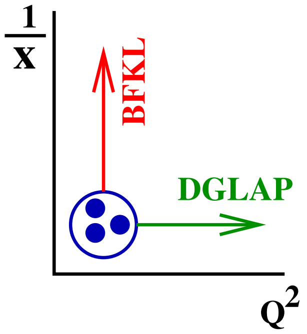
BFKL resums $\log(\frac{1}{x})$ terms

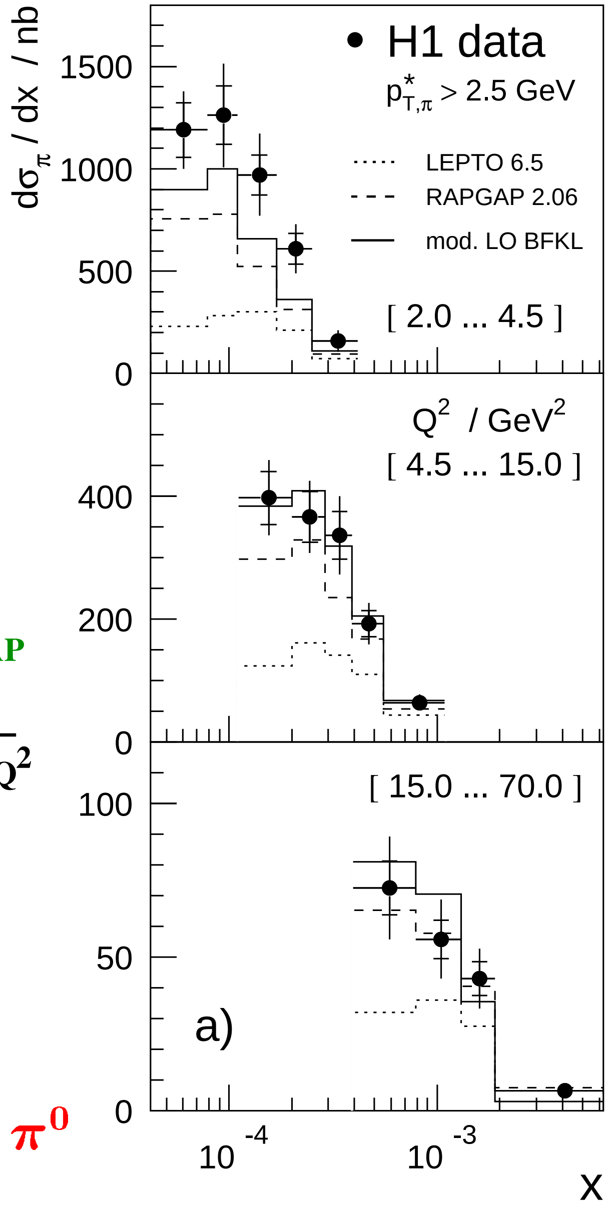
with $k_{Tk}^2 \sim k_{Tk-1}^2$

and $x_1 \gg x_2 \gg \ldots$



$\rightarrow \pi^0$



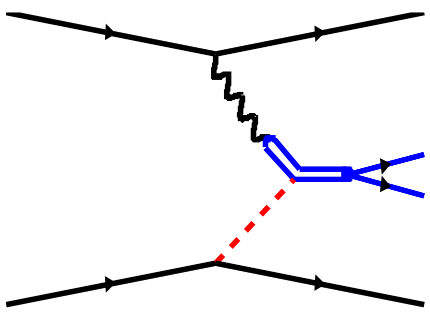


- DGLAP evolution can't describe π^0 production
- BFKL calculation comes closest to data points

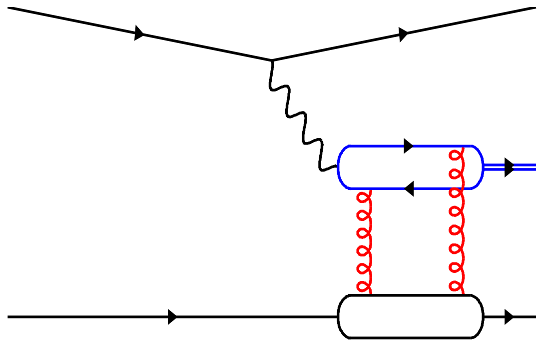
Sensitivity to $\log(1/x)$ terms?

Structure of the Pomeron

Pomeron: colourless object with quantum numbers of vacuum



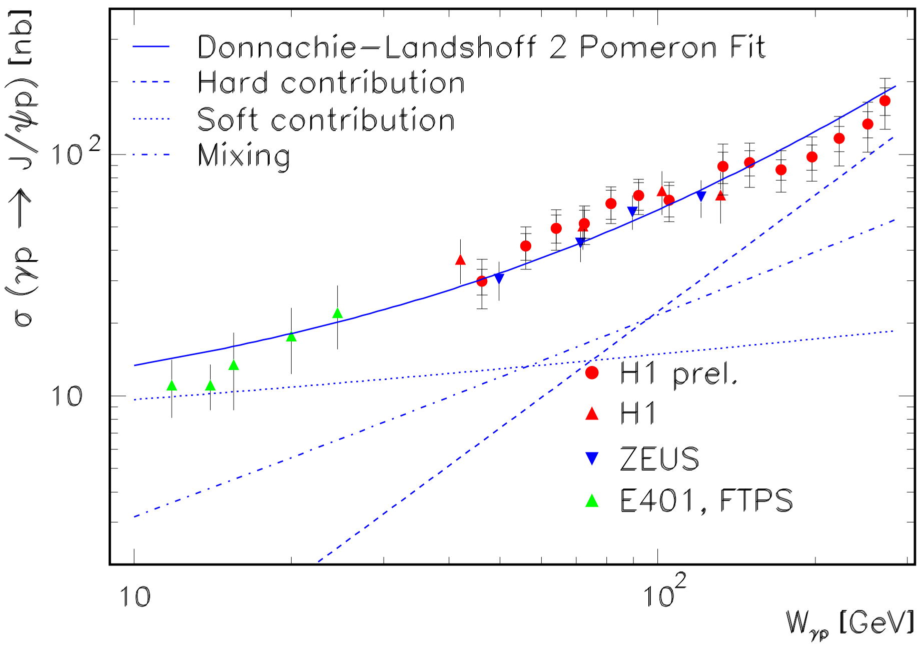
Regge-Ansatz



QCD-Ansatz

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

- Require a hard scale: e.g. Q^2, M_{VM}, t,...



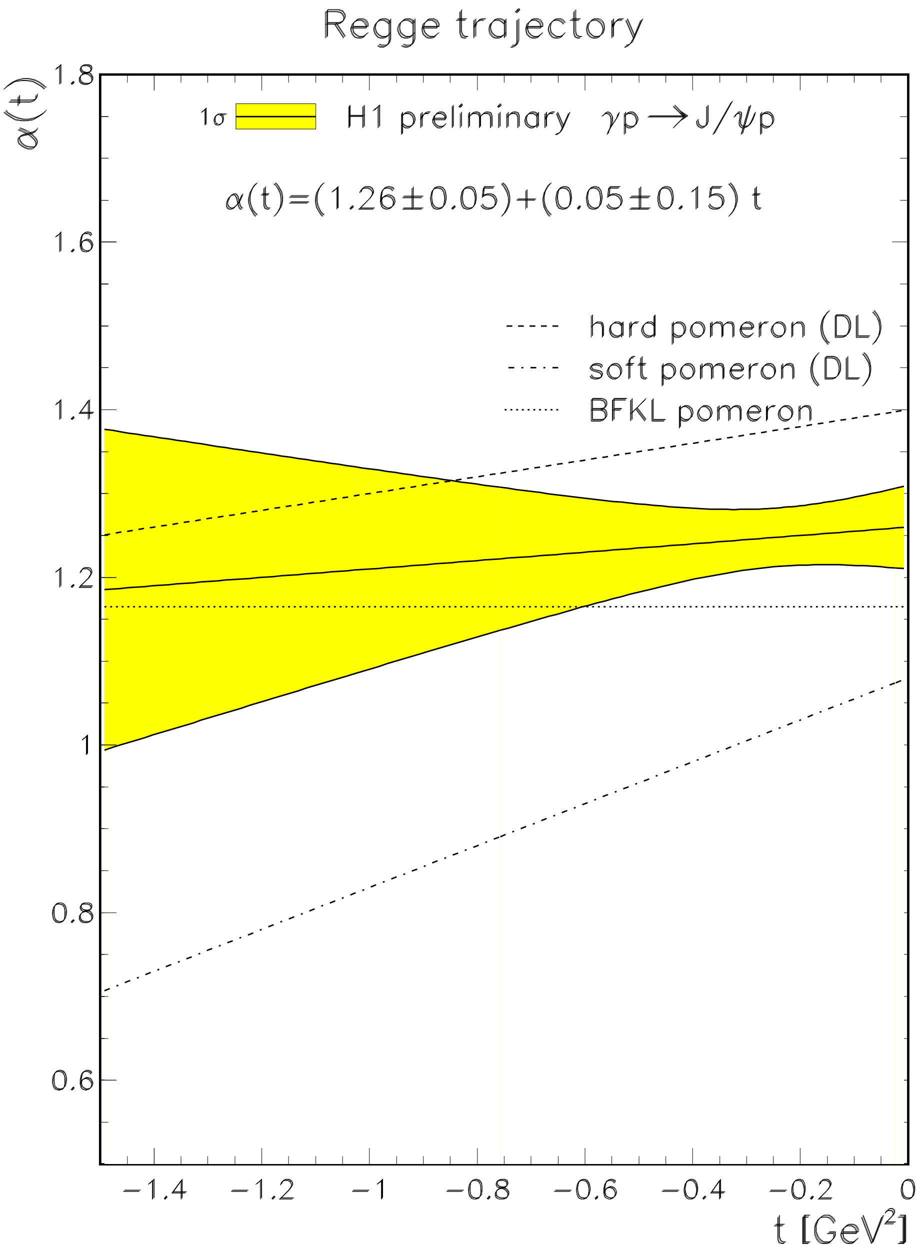
- strong rise with increasing W
- "hard" pomeron needed to describe data

Diffractive J/ψ Production

Regge-Trajectorie: $\alpha(t) = \alpha_0 + \alpha' \cdot t$

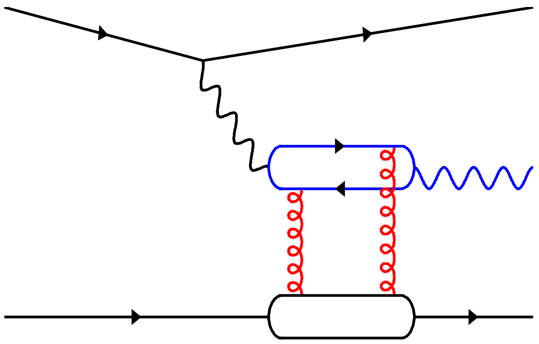
$\Rightarrow$ Fit W-dependence for different values of t

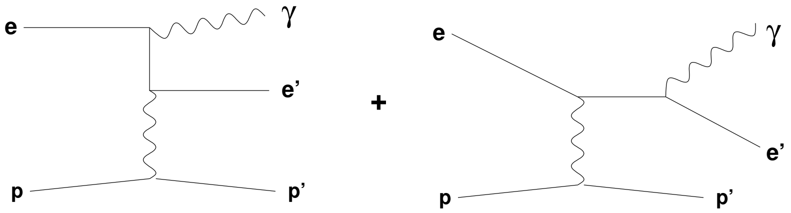
QCD: $\alpha' = 0 \Rightarrow$ No t-dependence
Regge-Model: $\alpha' > 0 \Rightarrow t$-dependent



- Data in agreement with QCD prediction

Deeply Virtual Compton Scattering (DVCS)



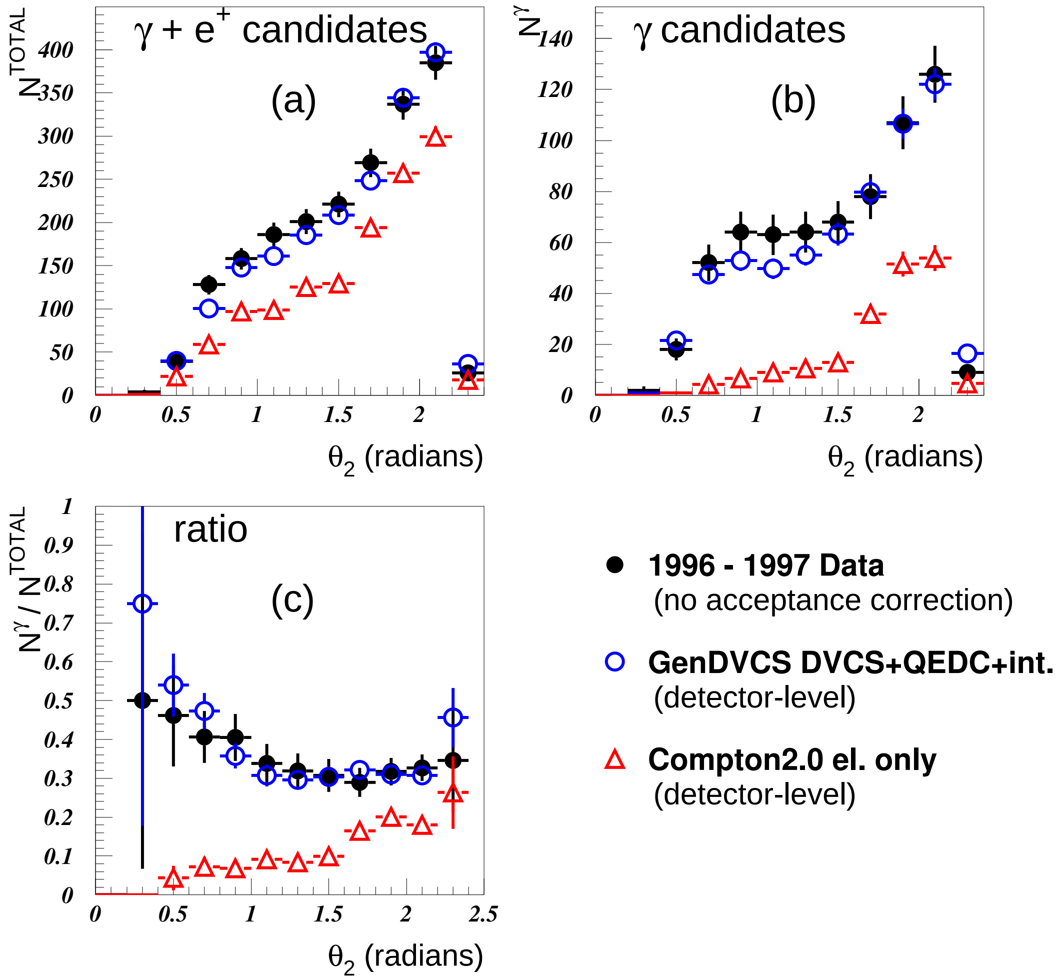


DVCS   QED Compton

Advantage over VM's: "easy" to calculate

(only QED / no hadronization)

ZEUS 1996/97 Preliminary

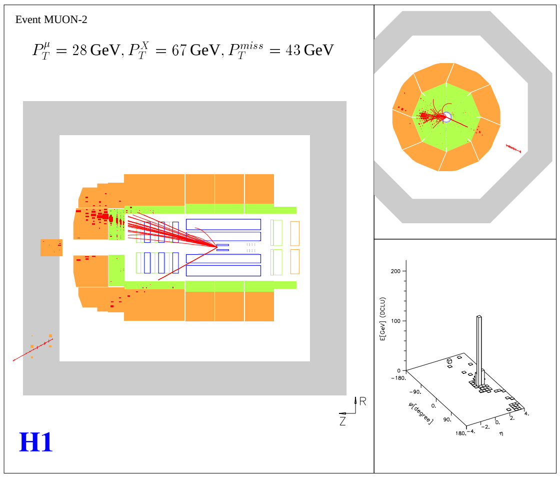


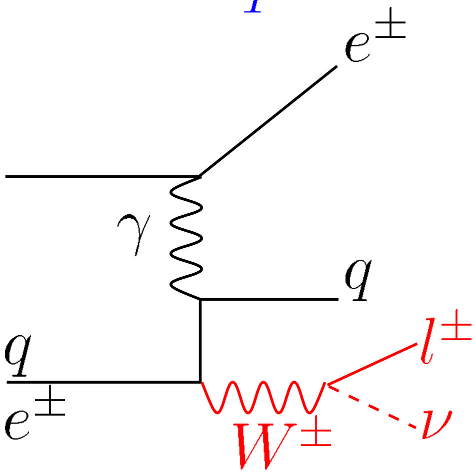
1st observation of such events at HERA

High p_t Lepton Results

Look for high P_T lepton + P_T^{miss}

$e^+p \to \mu^+X$





H1 e^+p data (1994-7)

Electron	Data	SM expectation	W
$P_T^X > 0$ GeV	3	3.12 ±0.70	2.24 ±0.67
$P_T^X > 12$ GeV	1	1.15 ±0.25	0.78 ±0.23
$P_T^X > 40$ GeV	0	0.16 ±0.04	0.14 ±0.04

Muon	Data	SM expectation	W
$P_T^X > 12$ GeV	5	1.01 ± 0.28	0.87 ± 0.26
$P_T^X > 40$ GeV	3	0.21 ± 0.06	0.19 ± 0.06

Zeus e^+p data (1994-7)

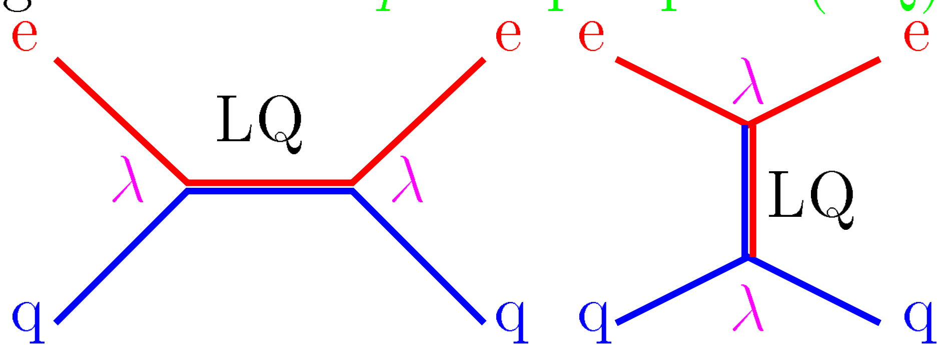
Lepton	Data	SM expectation	W
Electron	3	3.2	2.1
Muon	0	1.4	0.8

- ZEUS results in agreement with SM expectation
- H1 observes 3 outstanding μ events
- No outstanding events in e^-p scattering

$\Longrightarrow$ taking more e^+p data NOW

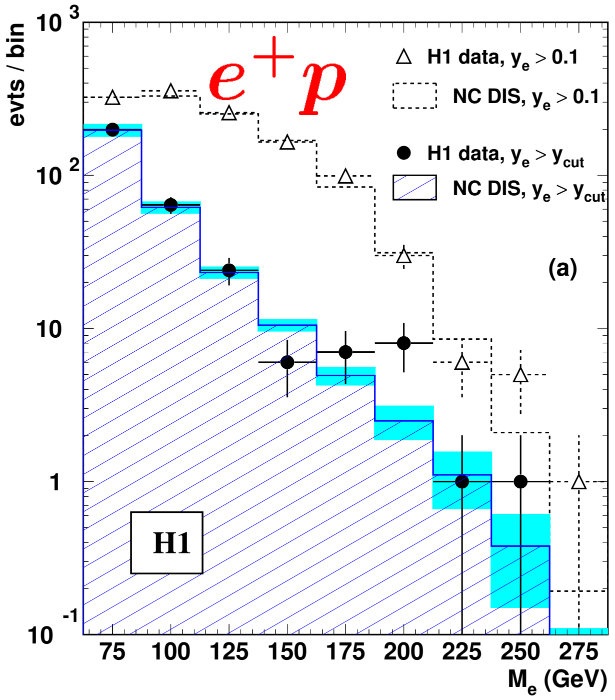
Search for Leptoquarks

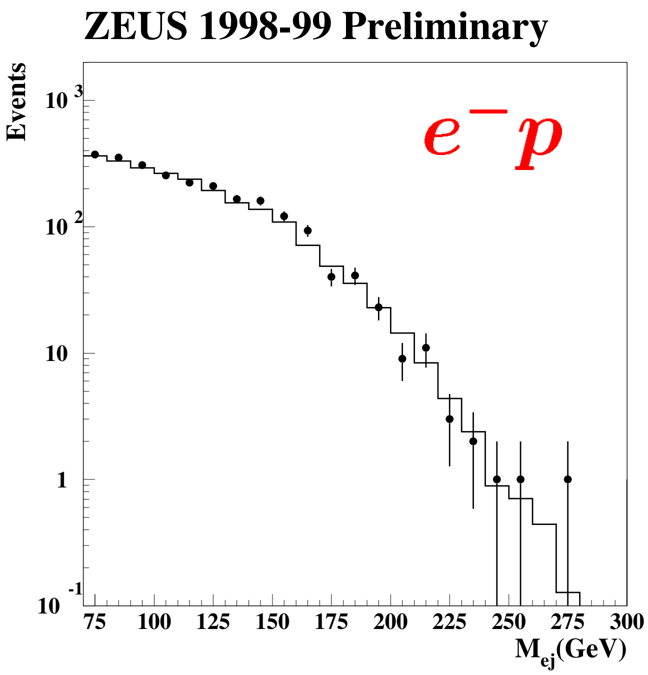
1st generation: $eq \rightarrow$ leptoquark(LQ) $\rightarrow eq$



separate from DIS background:

- mass distribution: $M_{\mathrm{LQ}} = \sqrt{xs} = M_{e+jet}$
- y-dependence:– DIS NC: $\mathrm{d}\sigma/\mathrm{dy} \propto 1/y^2$
  – scalar LQ: $\mathrm{d}\sigma/\mathrm{dy}$ independent of y
  – vector LQ: $\mathrm{d}\sigma/\mathrm{dy} \propto (1-y)^2$





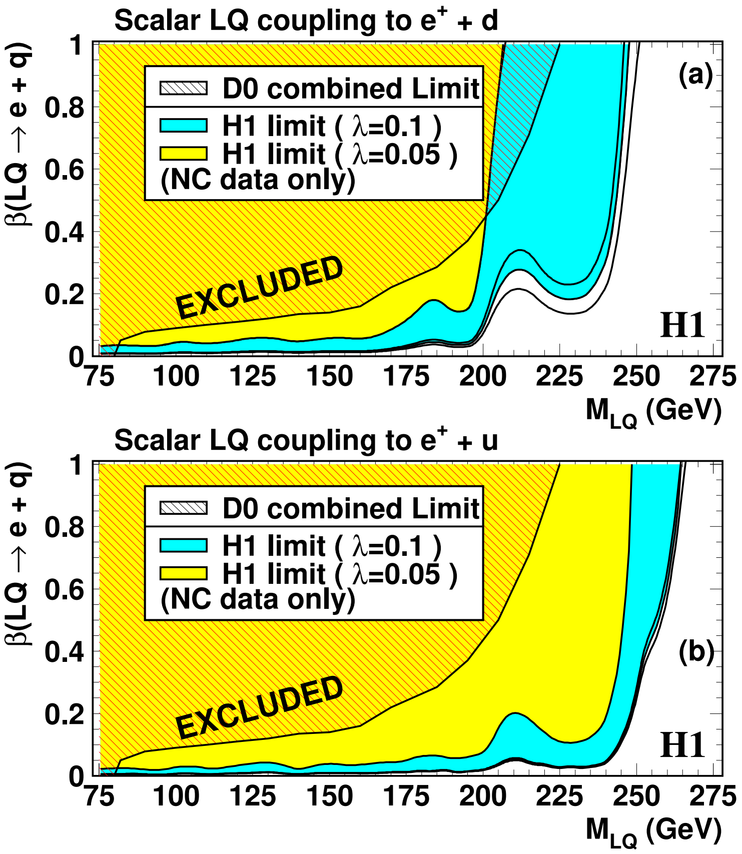
- No significant deviation from SM expectation

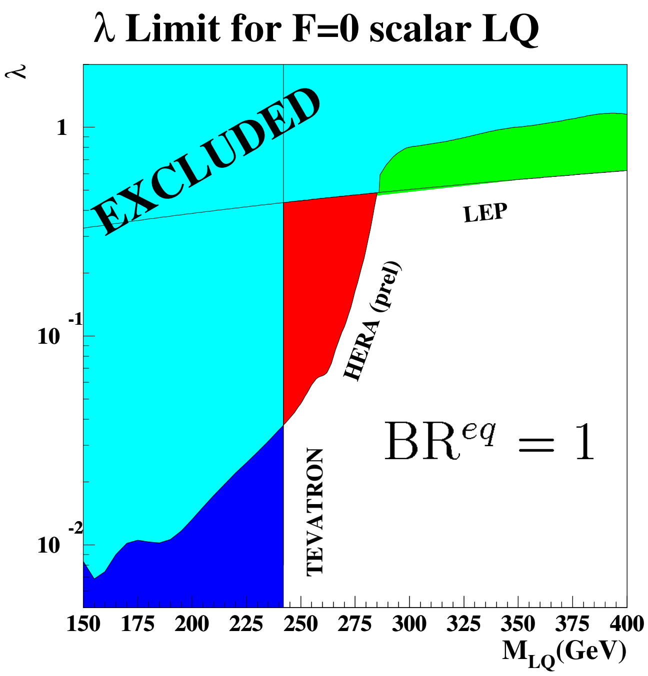
$\Rightarrow$ **derive limits!**

Limits for Leptoquarks

derive limits as function of λ, M_{LQ} and β

e^+p e^-p

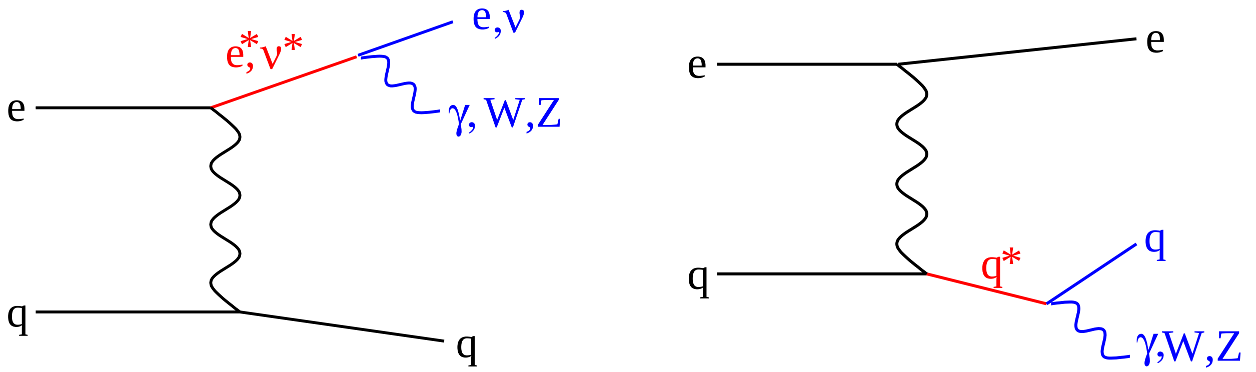




- "Bump" in e^+p related to excess of events in 1994-96 data
- For small branching ratios HERA limits best by far
- Also stringent limits for 2nd and 3rd generation LQs

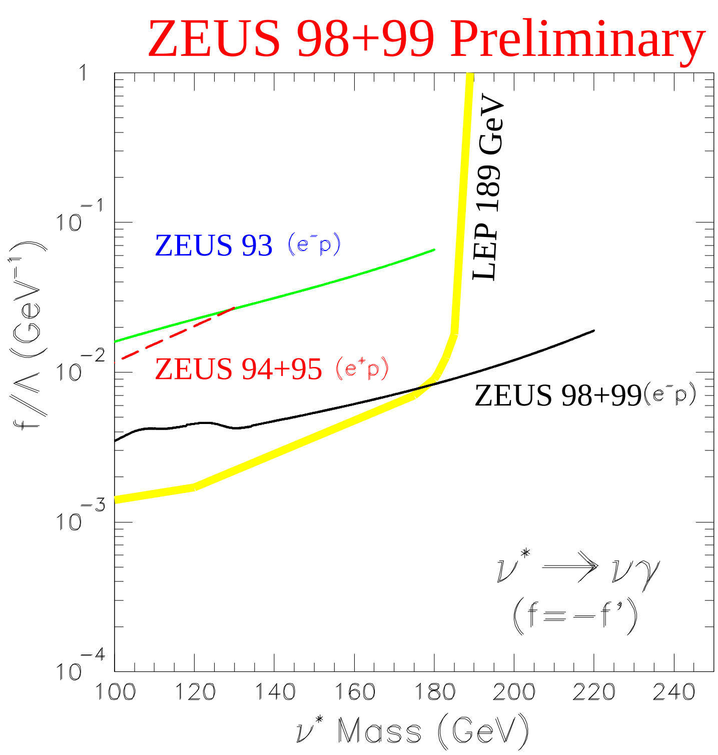
Large discovery potential!

Search for Excited Fermions



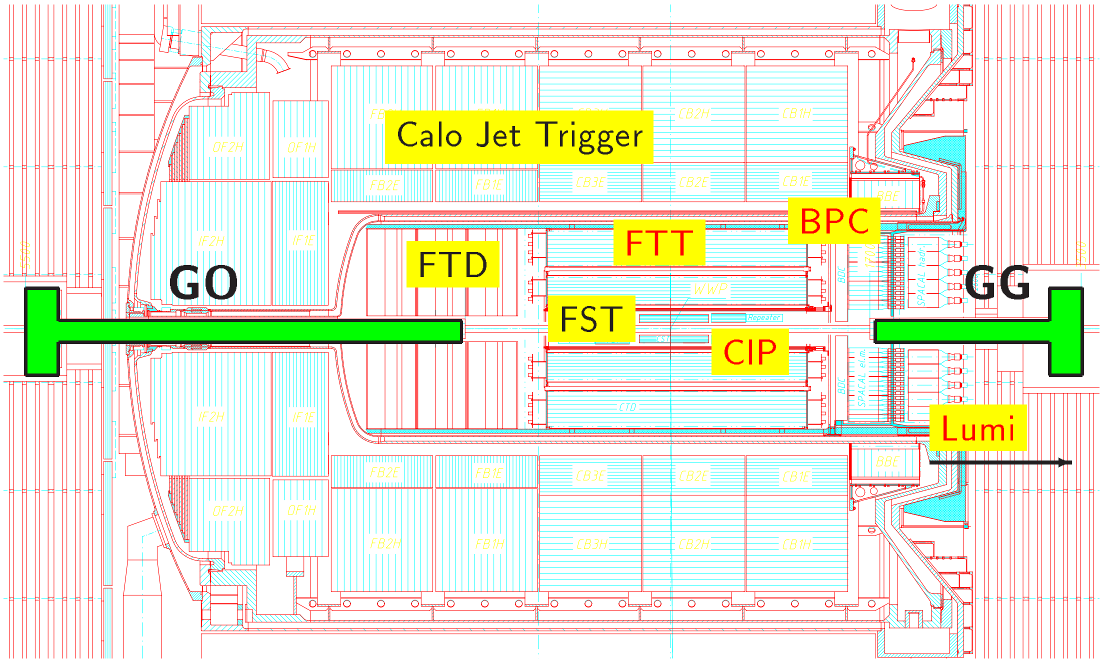
- high mass excited fermion states f^*
- couple to ground-state fermions and gauge bosons
- Model: $\mathcal{L}_{ff^*} = \frac{1}{\Lambda} f_R^* [f(gV)_{SU(2)} + f'(gV)_{U(1)} + f_s(gV)_{SU(3)}]$

  by Hagiwara, Komamiya, Zeppenfeld



HERA discovery potential at high masses

Upgrade of HERA and Detectors



- Magnets placed around beam line including inside detector volume
- β functions reduced by factor of 4-5
- Increased electron and proton Currents

$\Rightarrow$ Factor of 5 increase in luminosity

- Longitudinal polarisation of lepton beam
- Major upgrades of detectors:
  - Microvertexdetector (ZEUS)
  - Forward Tracking (H1+ZEUS)
  - Improved Track Triggering (H1)

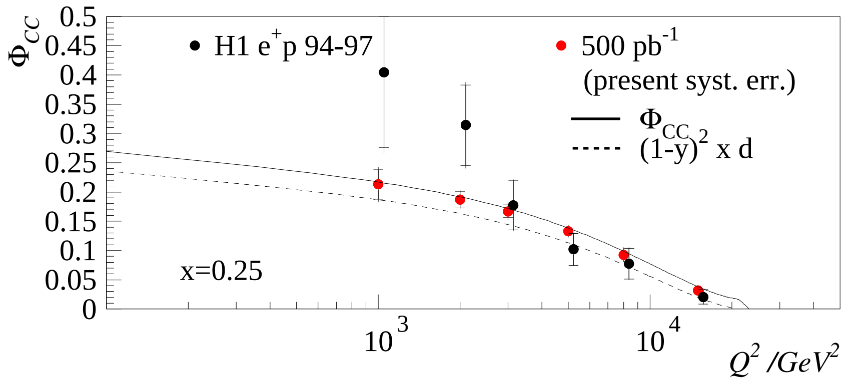
  ...and more...

HERA Upgrade

2000 $\rightarrow$ HERA runs with $L = 300\ \mathrm{pb}^{-1}$ per year (luminosities for H1+ZEUS together)

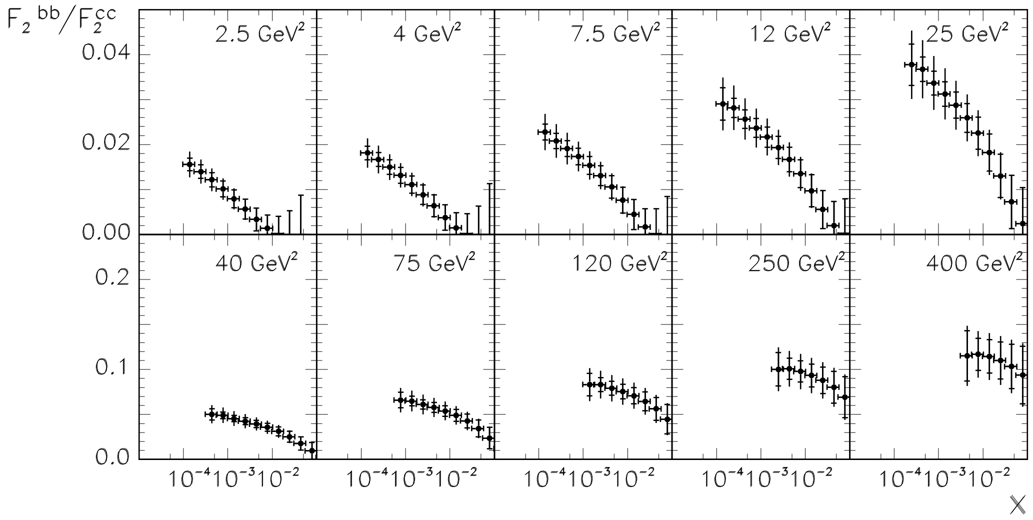
$\Rightarrow$ estimated total integrated luminosity of 2 fb^{-1}

- eg. 5% Error on CC cross section



- eg. NC cross section measured better than 10% up to $Q^2 = 20000\ \mathrm{GeV}^2$ (verifying or refuting excess seen in 94-97 data).

- eg. Measurement of F_2 charm to 5% and F_2 bottom to 10% utilising new detectors and increased statistics



- eg. 40 to 100 W events.

HERA Has a Bright Future!

Summary

- ★ **HERA is a leading facility for studies of the QCD sector**

- ★ **Important input from HERMES for understanding the origin of nucleon spin**

- ★ **Precision permanently increased**
  $\Rightarrow$ higher sensitivity to new physics and better accuracy for QCD tests

- ★ **The upgrade of HERA and the experiments will allow us to optimally exploit the discovery potential at HERA**