QCD at High Energies at HERA

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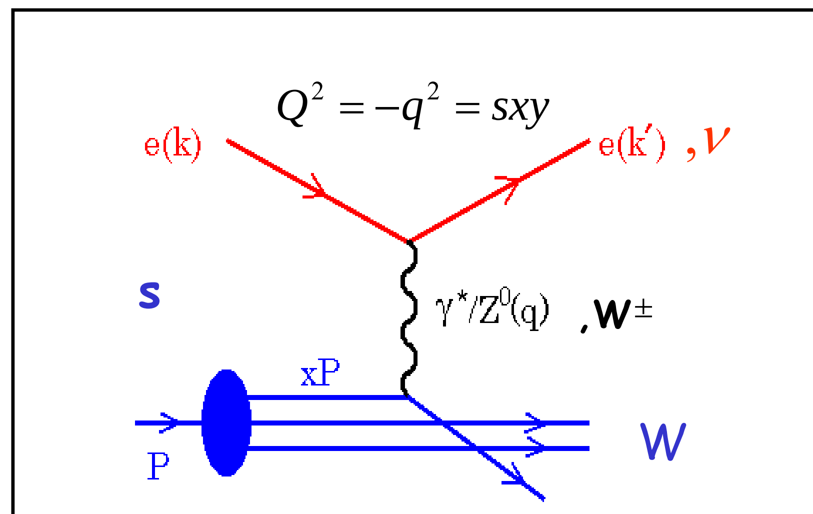
- The Quark Structure of the Proton
- The Strong Coupling Constant and xg
- Heavy Flavour Production
- Diffractive ep Scattering
- New Ideas and Developments
- First Results at HERA II and Outlook



Deep Inelastic Scattering and Photoproduction (Q^2~0)

A summary of recent QCD results obtained by H1, ZEUS and HERMES

$$E_e = 27.6 GeV, E_p = 920 GeV$$

$$\sqrt{s} = 2\sqrt{E_e E_p} = 319 GeV \Leftrightarrow E_e^{ft} = 54.1 TeV$$

$$polarisation: P(e) = -0.5 \ldots 0 \ldots +0.5$$

$$L_{spec} \approx 4 \ldots 16 \cdot 10^{29} cm^{-2} s^{-1} mA^{-2}$$

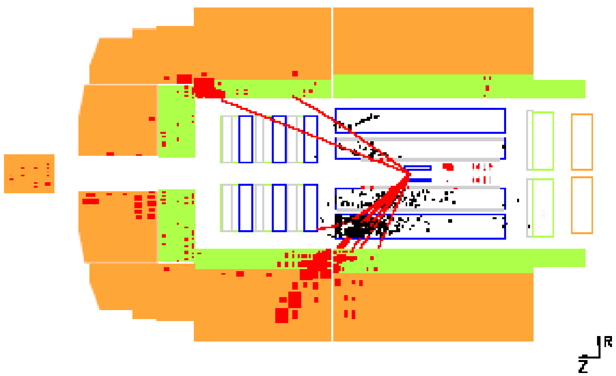
$$I_e = 20 \ldots 50 mA, I_p = 60 \ldots 100 mA$$

ep-collider expts H1, ZEUS @319GeV and polarised target expt HERMES @7GeV

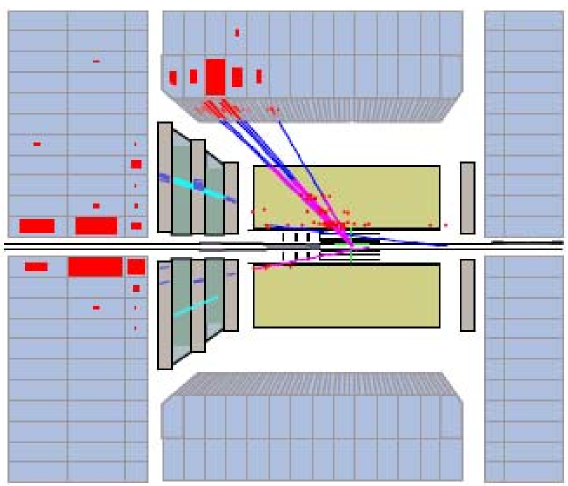
Volker Soergel and the Minister of Science of Germany, Heinz Riesenhuber, at DESY (Hamburg) announcing on 6th of April 1984 that HERA will be built.

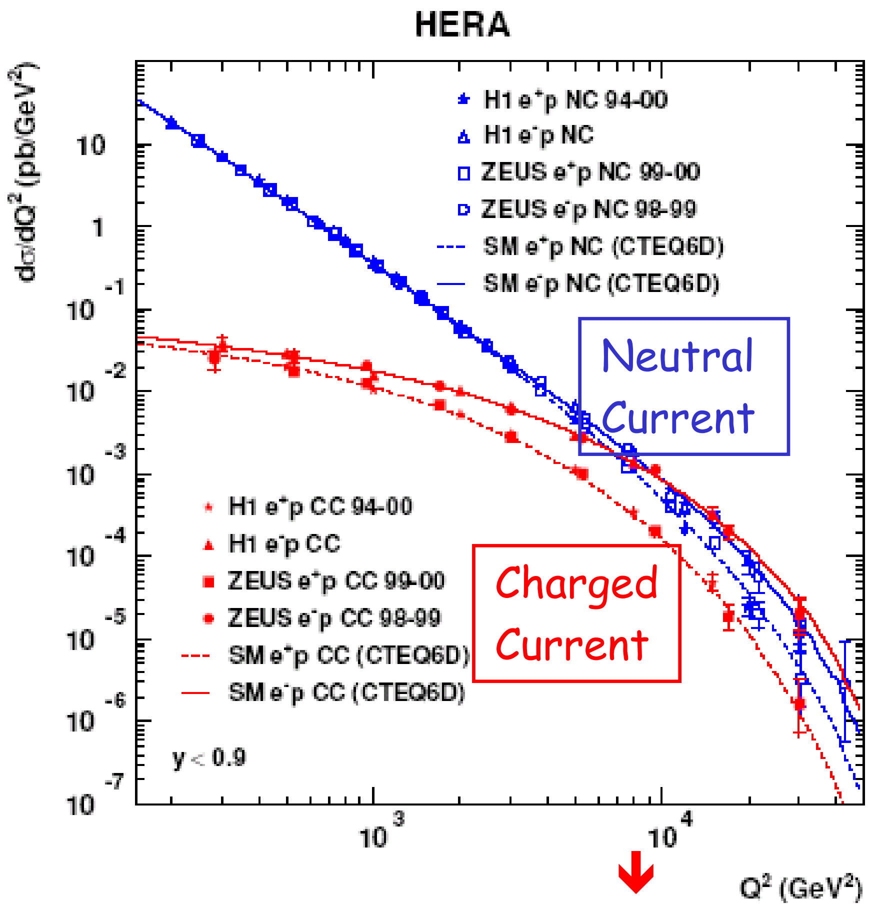
1. The Quark Structure of the Proton

Neutral current $e^+ p \to e^+ X$



Charged current $e^+ p \to \bar{\nu} X$



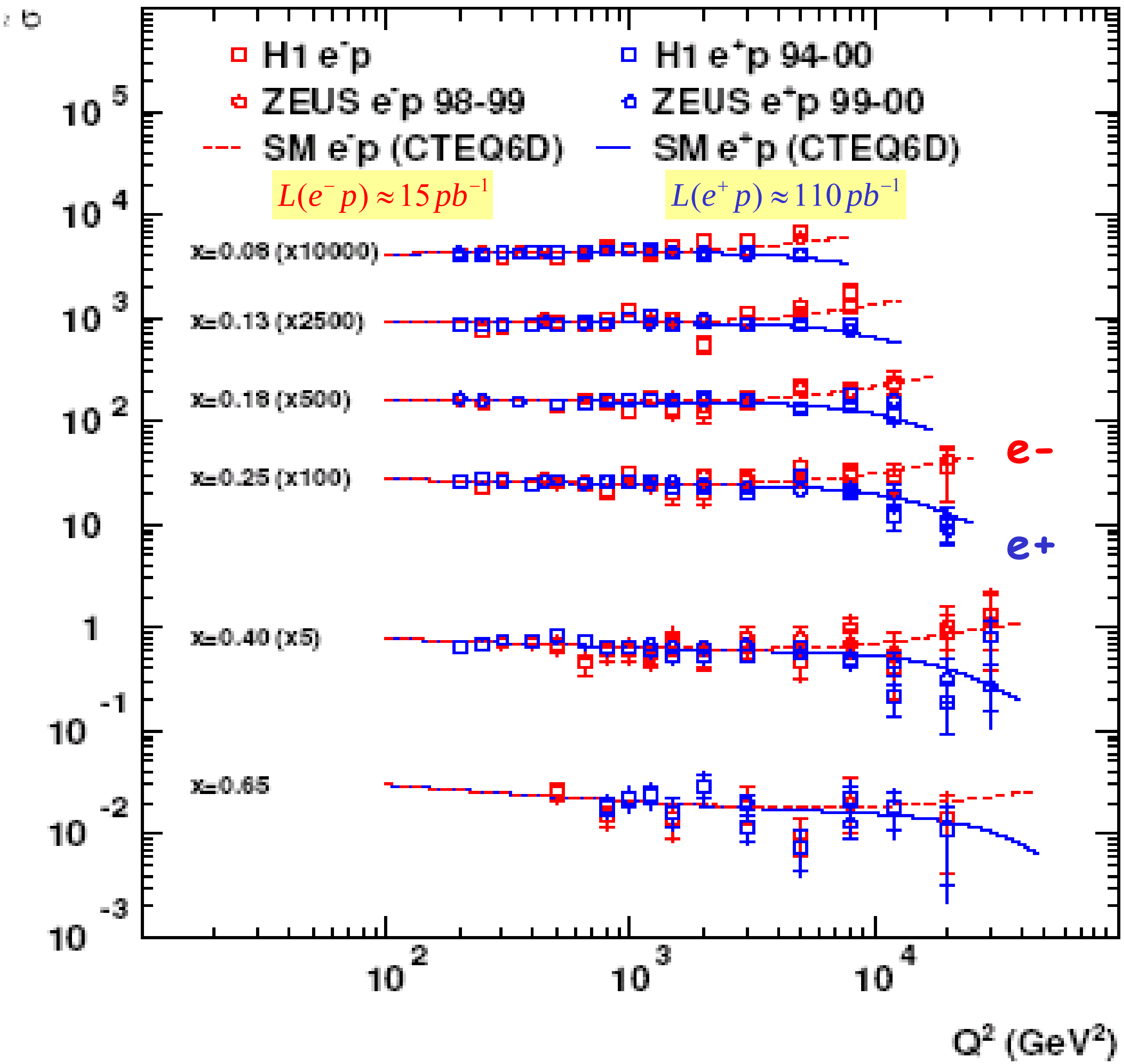


$$\sigma^{\pm}_{NC} \approx \sigma^{\pm}_{CC} \leftrightarrow Q^2 \approx M_Z^2 \approx 10^4 GeV^2$$

quarks are pointlike down to proton radius/1000

ZEUS r < 0.85 H1 r < 1.0 10^{-18}m

Reduced neutral current scattering cross section at large x

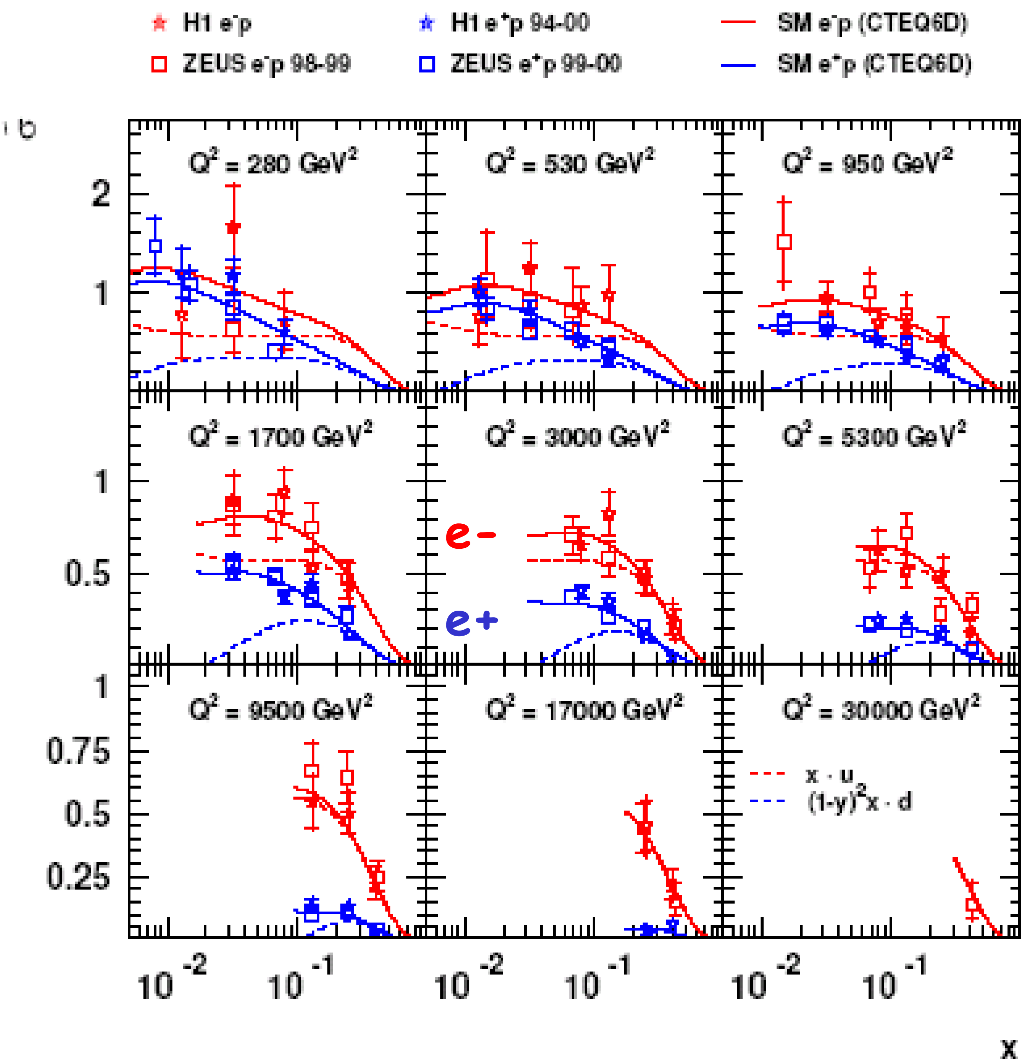


$$\sigma_{NC}^{\pm}(x,Q^2) \sim F_2 \mp f(y) xF_3$$
$$F_2 = e_u^2 x(U+\overline{U}) + e_d^2 x(D+\overline{D})$$
$$xF_3^{\gamma Z} = x(2u_v + d_v)/3$$

$$U = u + c + b$$
$$D = d + s$$

Z exchange enhances electron proton cross section and reduces positron proton cross section at large Q2

Reduced charged current scattering cross section

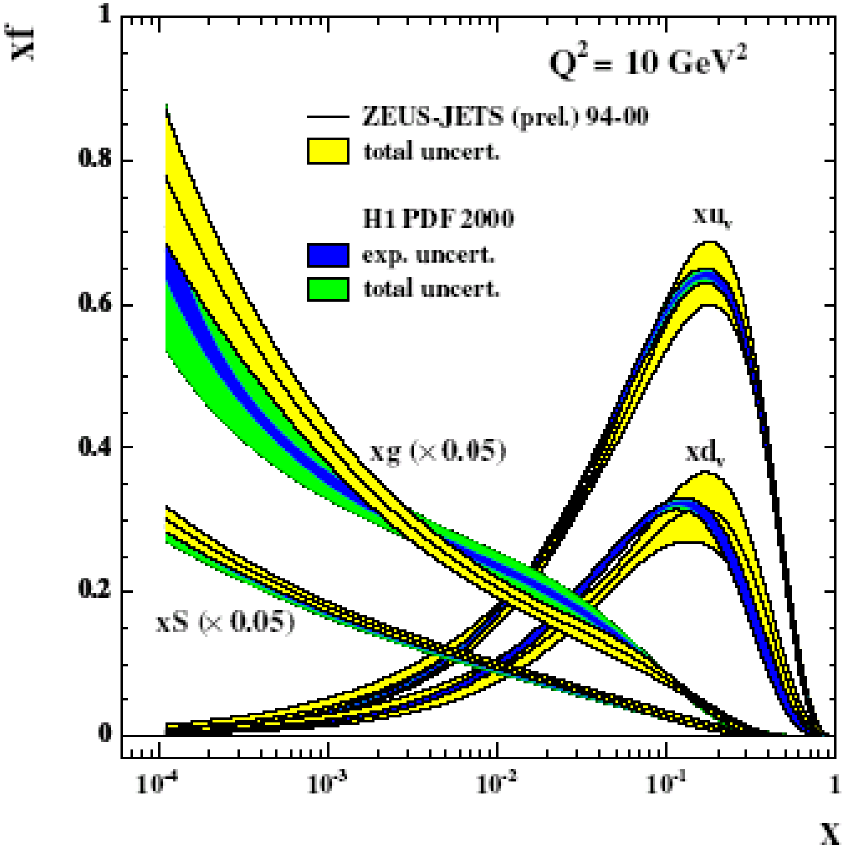


$$\sigma_{CC}^{-} \sim xU + (1-y)^2 x\overline{D} \rightarrow xu_v$$

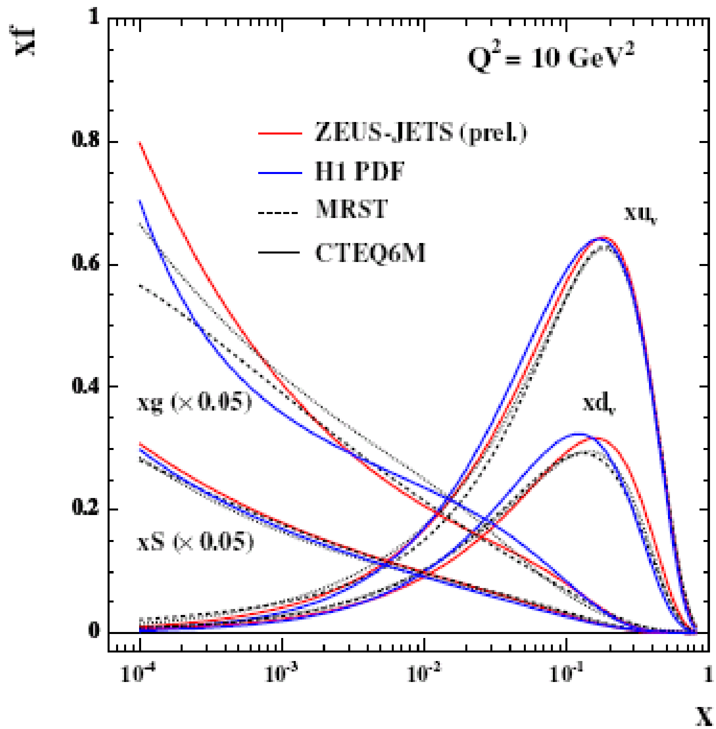
$$\sigma_{CC}^{+} \sim x\overline{U} + (1-y)^2 xD \rightarrow (1-y)^2 xd_v$$

HERA can disentangle parton distributions at large Q^2 and large x > 0.01 within single experiments, independently of nuclear corrections and free of higher twists

Parton distributions unfolded with H1 data and with ZEUS data only



comparison to global fits



- H1 and ZEUS parton distributions are in agreement
- HERA experiment's fits agree with global fits
- Gluon at low x and Q^2 not well constrained
- Treatment of systematic, model and theoretical errors subject to conventions

QCD fits parameterise initial PDFs

H1 $U, \overline{U}, D, \overline{D}, xg \leftrightarrow V, A, xg - \alpha_s$

ZEUS $u_v, d_v, \overline{u} \pm \overline{d}, xg - \alpha_s$

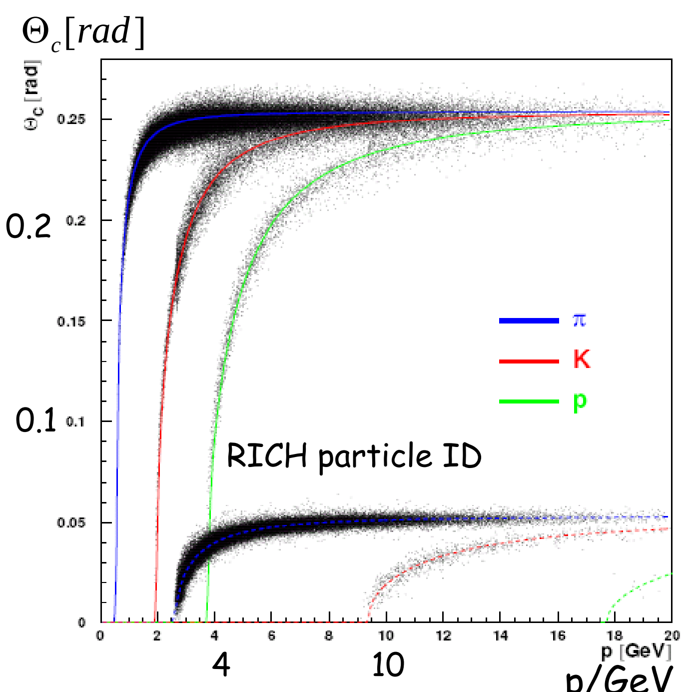
Polarized quark distributions

$$A_1^h \approx \frac{\int dz \sum e_q^2 \Delta q(x,Q^2) D_q^h(z,Q^2)}{\int dz \sum e_q^2 q(x,Q^2) D_q^h(z,Q^2)}, z = E_h / \nu$$

HERMES: (semi-) inclusive polarised eN
using polarised gas target internal to HERA-e

$$q = q^+ + q^-$$
$$F_1 = \frac{1}{2} \sum e_q^2 q$$
$$\Delta q = q^+ - q^-$$
$$g_1 = \frac{1}{2} \sum e_q^2 \Delta q$$

Measure double spin asymmetries
to resolve valence and,
for the first time,
sea spin composition



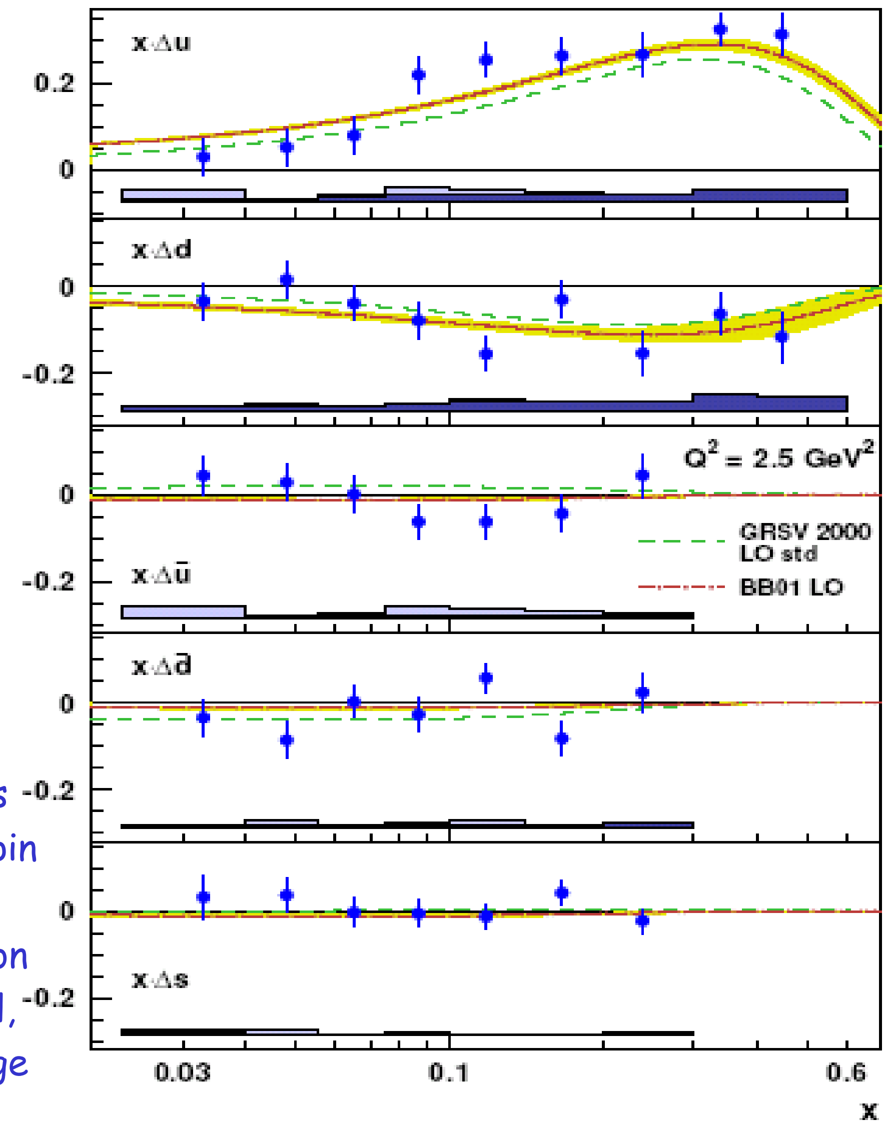
$ep, D \rightarrow ehX$

$h = p, K^{\pm}, \pi^{\pm}$

$ep, D \rightarrow eX$

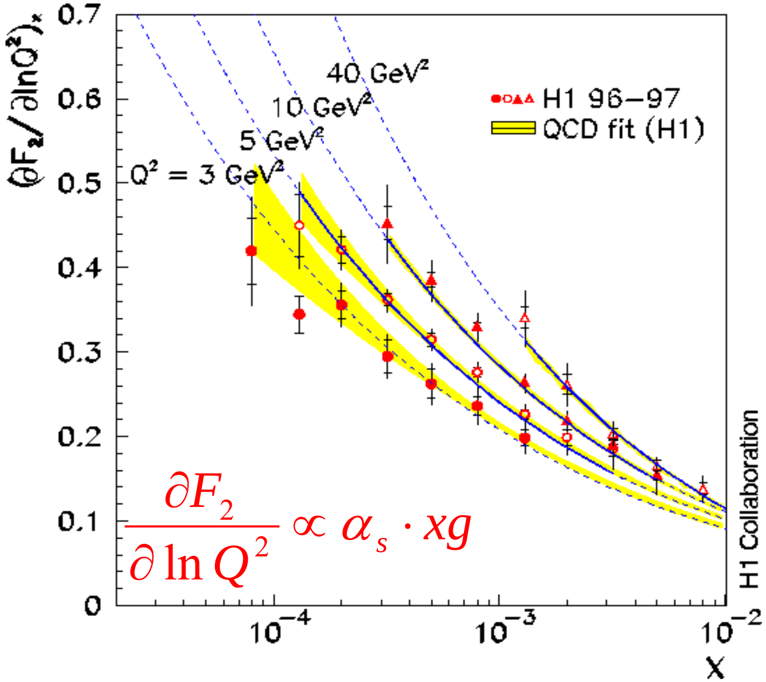
Valence quarks
determine p spin

Sea polarisation
resolved: small,
also for strange

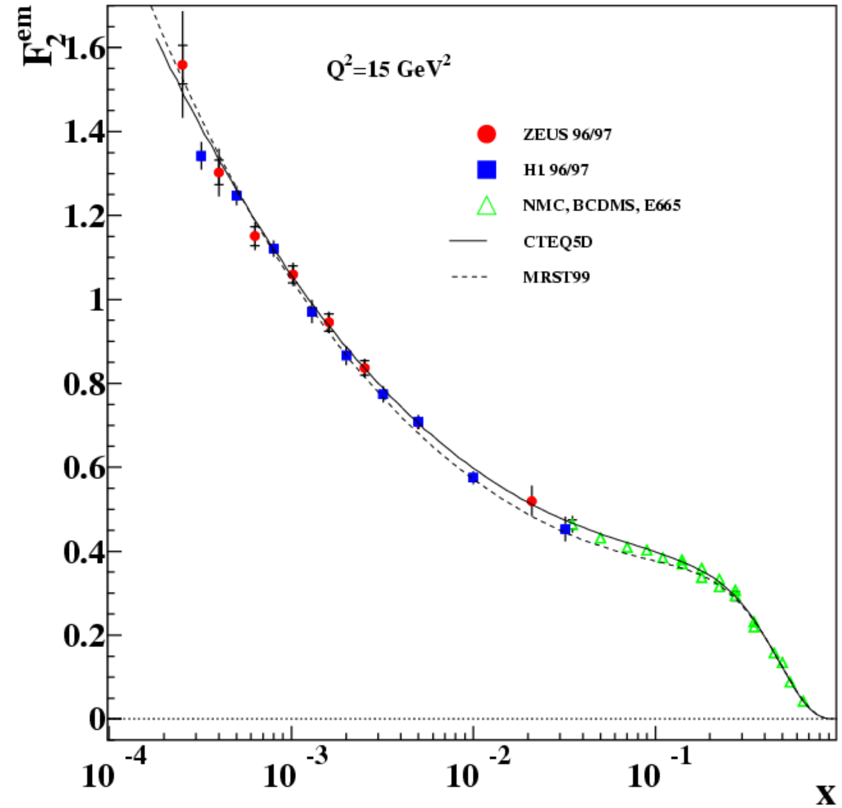


2. The Strong Coupling Constant and the Gluon Distribution

$$\frac{\partial F_2}{\partial \ln Q^2} \propto \alpha_s[\underbrace{P\otimes g}_{\text{low } x} + \underbrace{P\otimes F_2}_{\text{high } x}]$$



Derivative constrains gluon to ~20% at low x



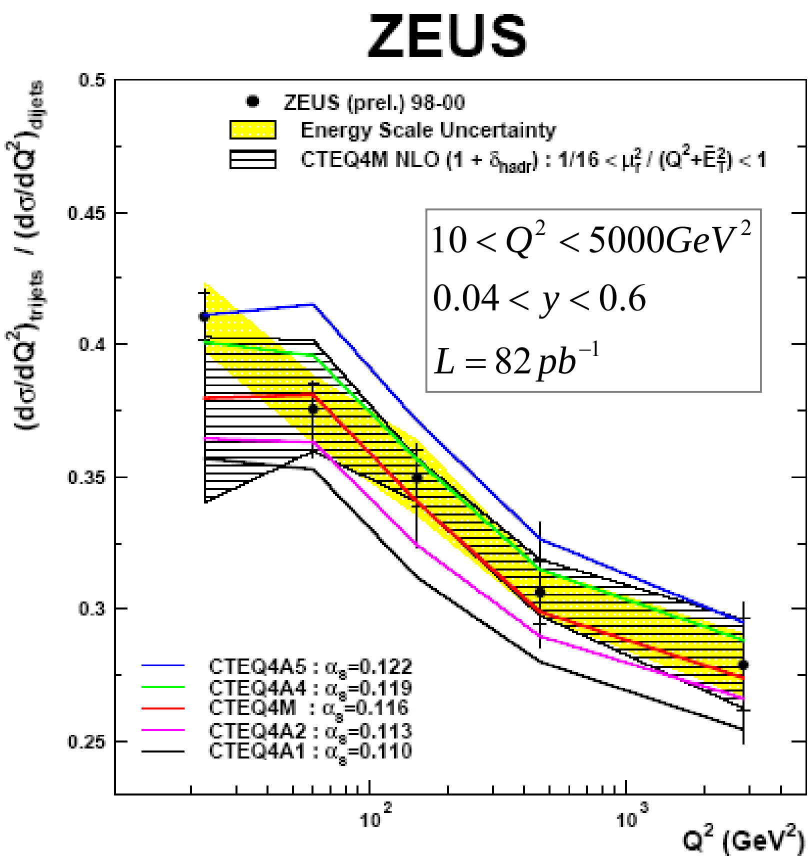
Precision on F_2 in bulk region 2-3%

ep → eX: measure scattered e and X

control systematics ($E_{e,h}$ scales to 0.3-2%)

still potential for increased accuracy

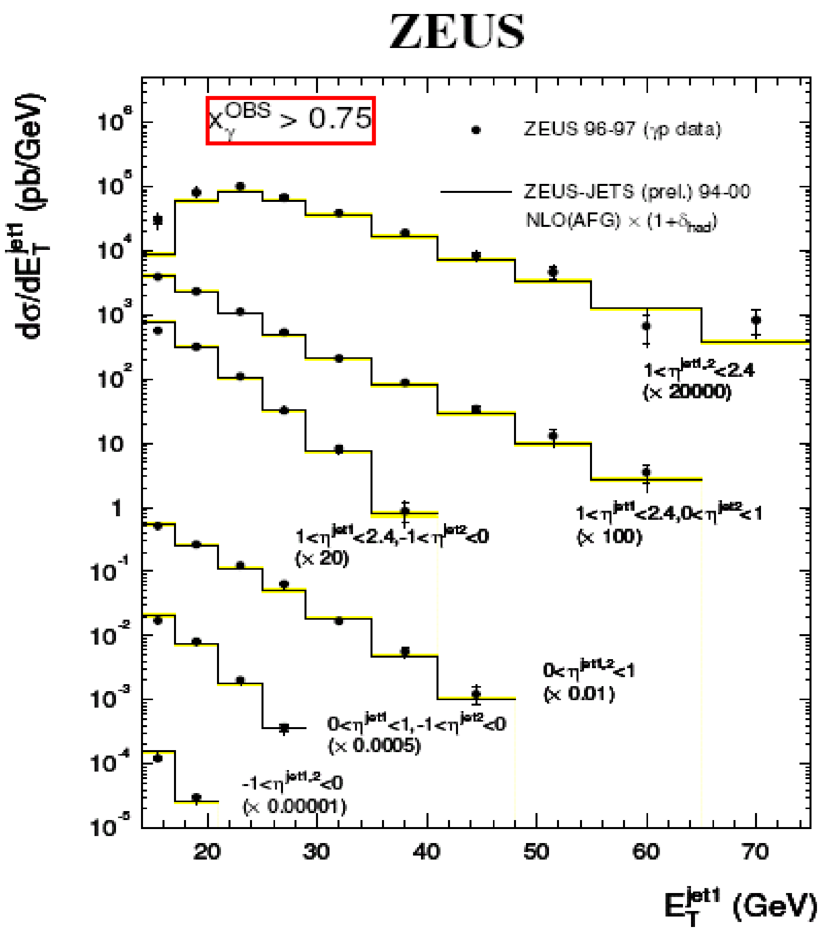
Trijets in deep inelastic scattering
new results



$$\alpha_s(M_z) = 0.1179 \pm 0.0013(stat.)^{+0.0028}_{-0.0046}(syst.)^{+0.0061}_{-0.0047}(th.)$$

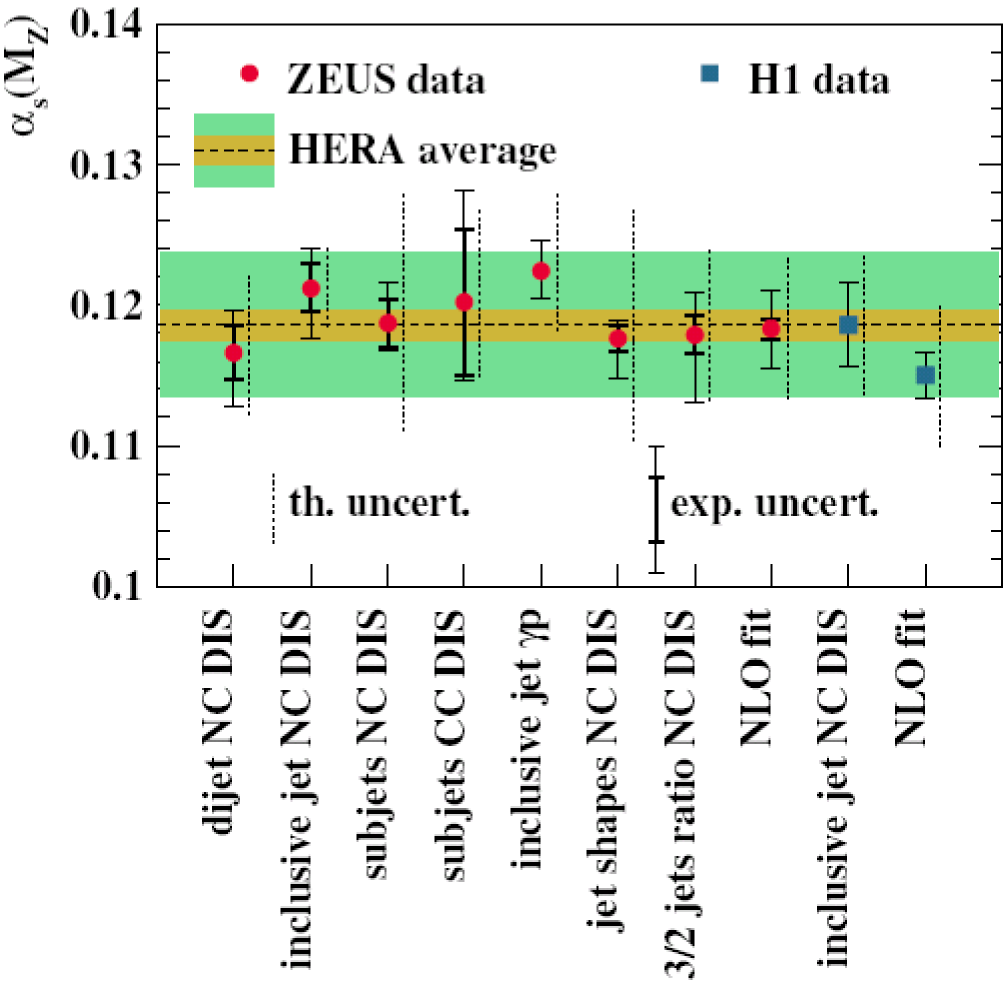
Interesting results also on subjets [ZEUS] and on event shapes [ZEUS+H1]

Dijets in direct photoproduction
novel NLO fit



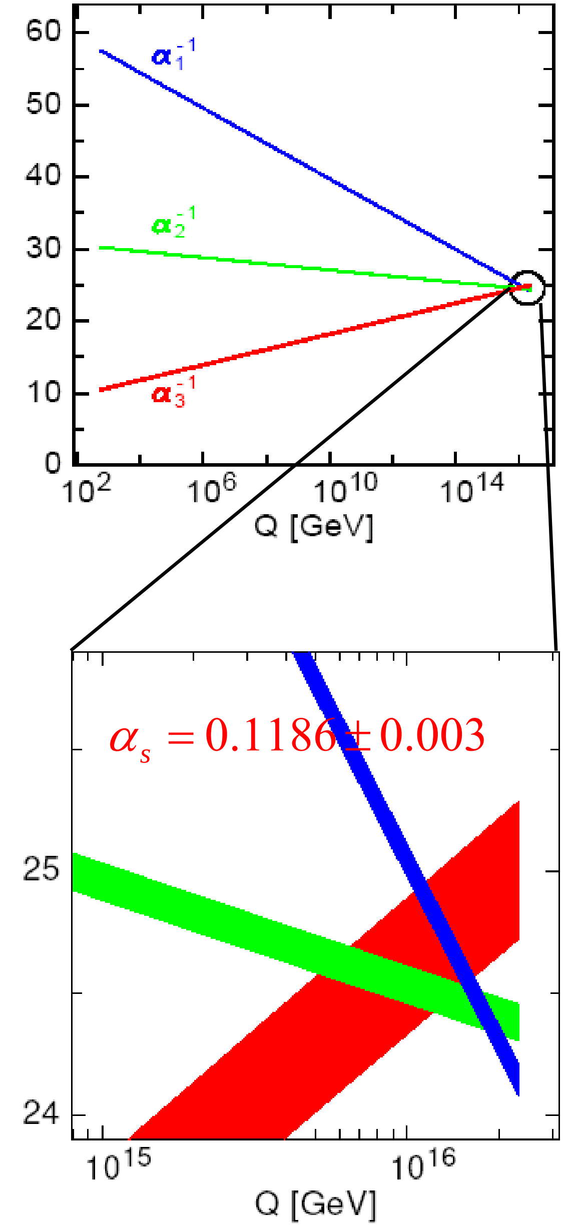
Data were essential to improve determination of strong coupling constant in "ZEUS+jets" fit using NLO calculation (Frixione, Ridolfi). QCD fit includes also DIS jet data using DISENT (Frixione, Seymour)

$$HERA(prel.) - \alpha_s(M_Z^2) = 0.1186 \pm 0.0011(\exp) \pm 0.005(thy)$$



$$\alpha_s(M_Z^2) = 0.1209 \pm 0.0015(\exp) \pm^{0.0048}_{0.0049} (thy) - ZEUS$$

$$\alpha_s(M_Z^2) = 0.1160 \pm 0.0016(\exp) \pm^{0.0058}_{0.0046} (thy) - H1$$



hep-ph/0407067 B.Allanach … P.Zerwas

NNLO singlet splitting functions

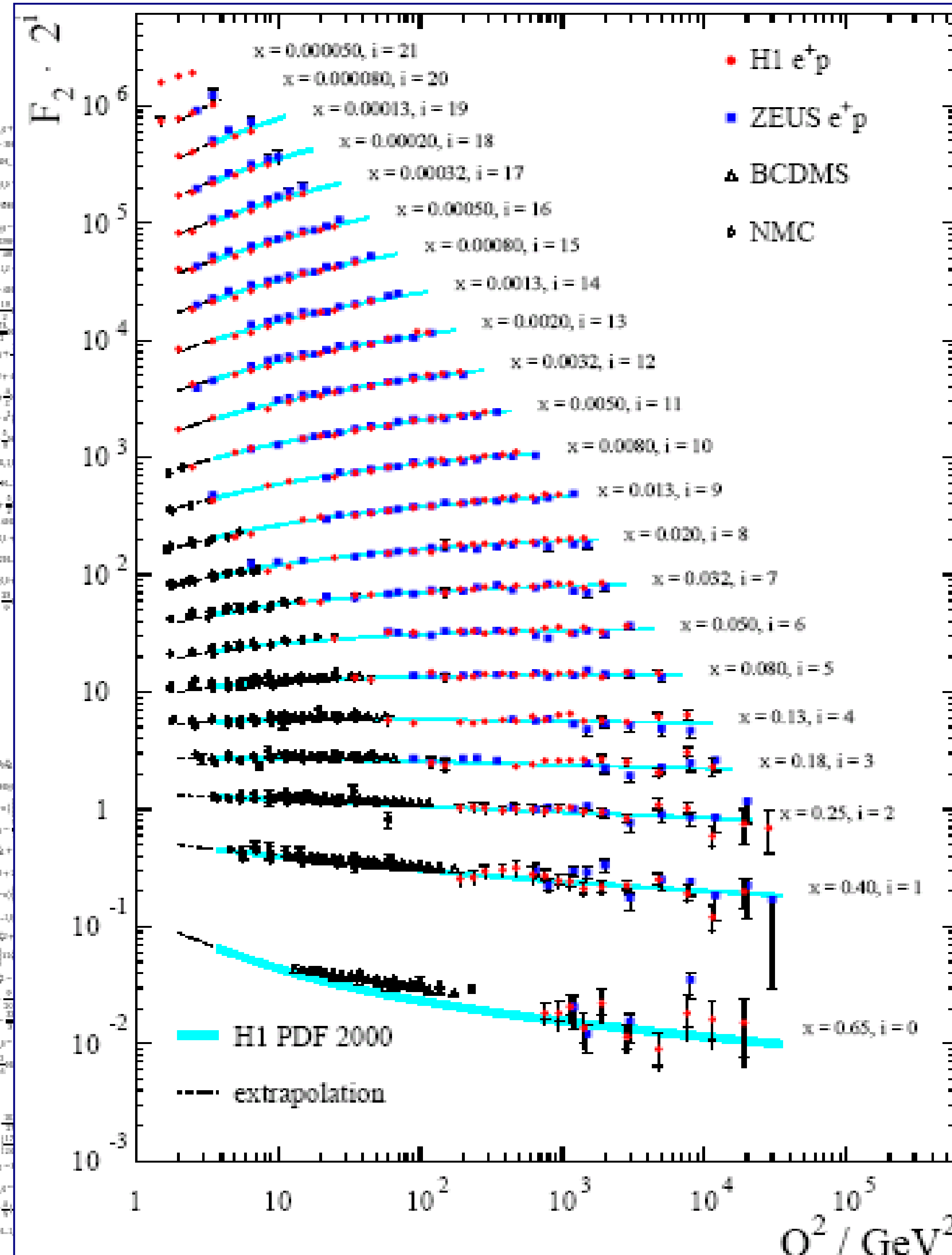
S.Moch, J.Vermaseren, A.Vogt

hep-ph/0403192 & 0404111

Towards highest precision
NNLO calculation
challenges experiment

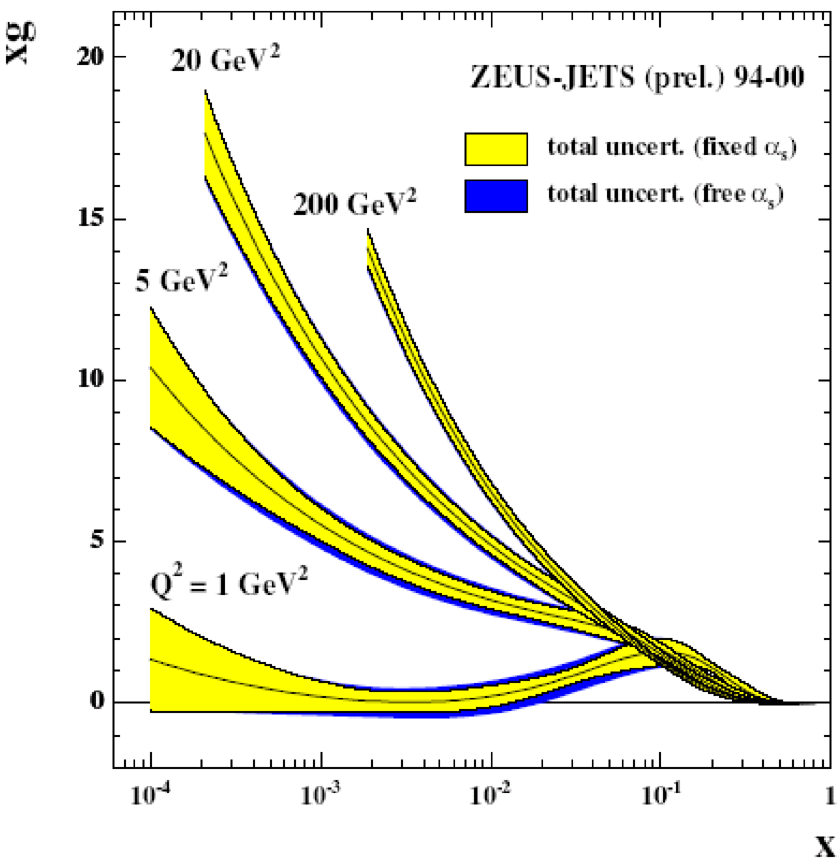
- Largest possible coverage of x, Q^2 plane
- Improved precision
- Higher statistics at high x
- Fully exploit data: jets, charm
- measure F_L

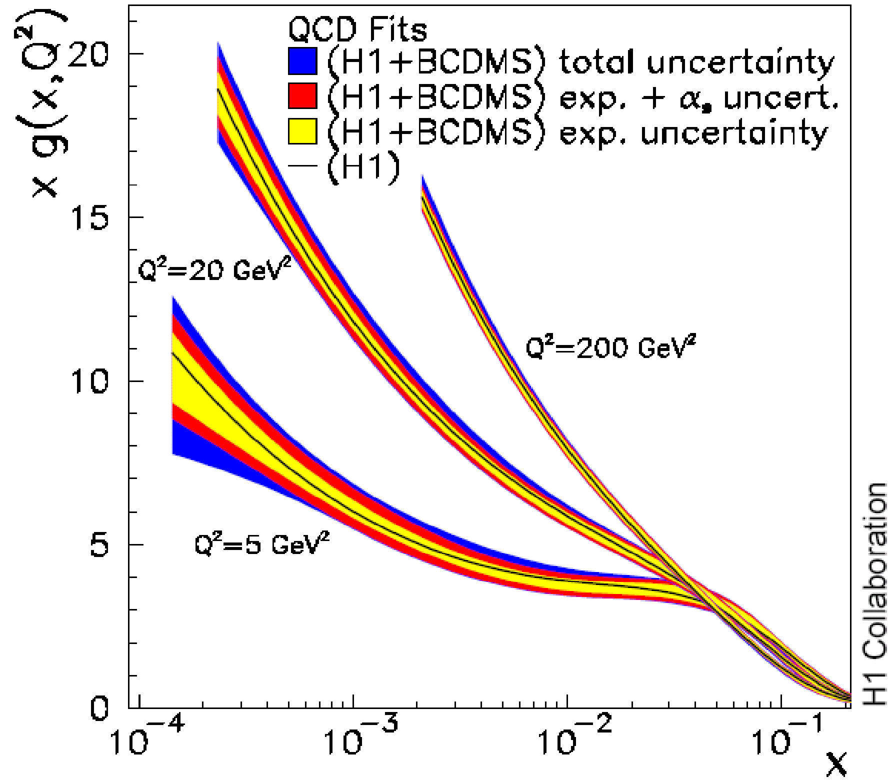
Current HERA + FT DIS data on F_2



ZEUS inclusive NC+CC & jets

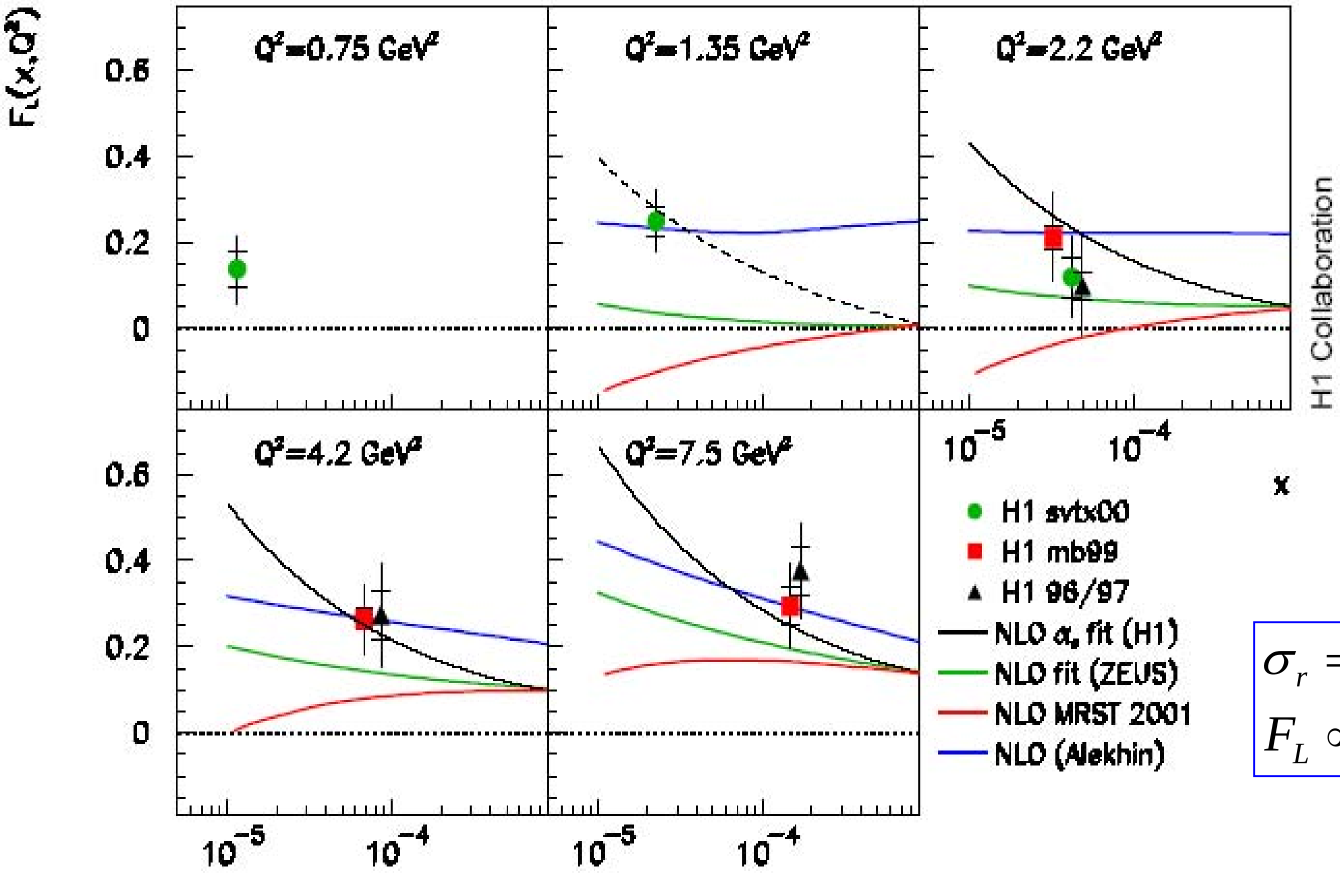
H1 inclusive NC+CC





- Gluon distribution in the proton being pinned down: scaling violations, charm, jets, FL
- HERA QCD fits, due to the wide range and accuracy, resolve correlation of $xg \leftrightarrow \alpha_s$
- xg is NOT an observable. Charm treatment important (ZEUS: VFNS RT, H1: FFNS)
- In the region of low x and Q^2 ~ 1 GeV^2 the gluon distribution becomes very small

→ transition from hadronic to partonic behaviour at about 0.3 fm

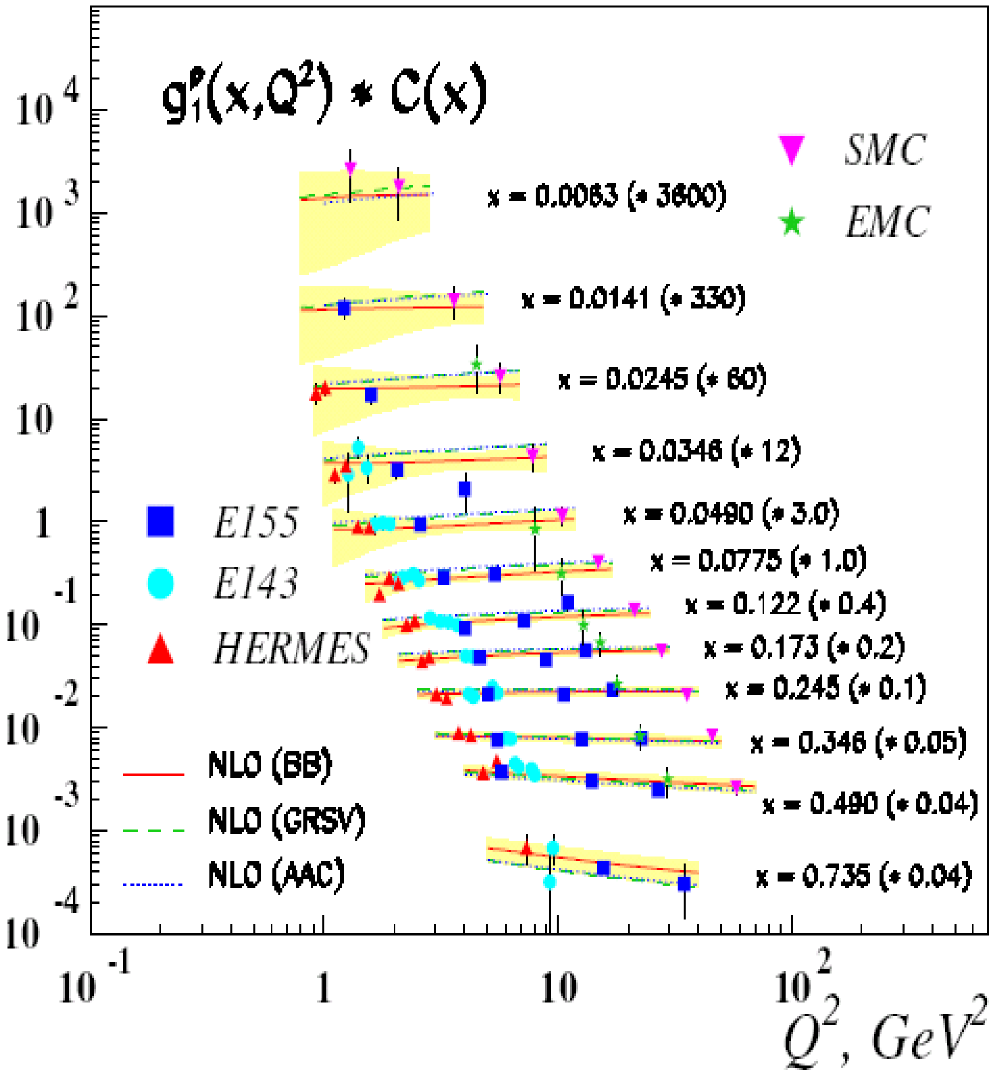


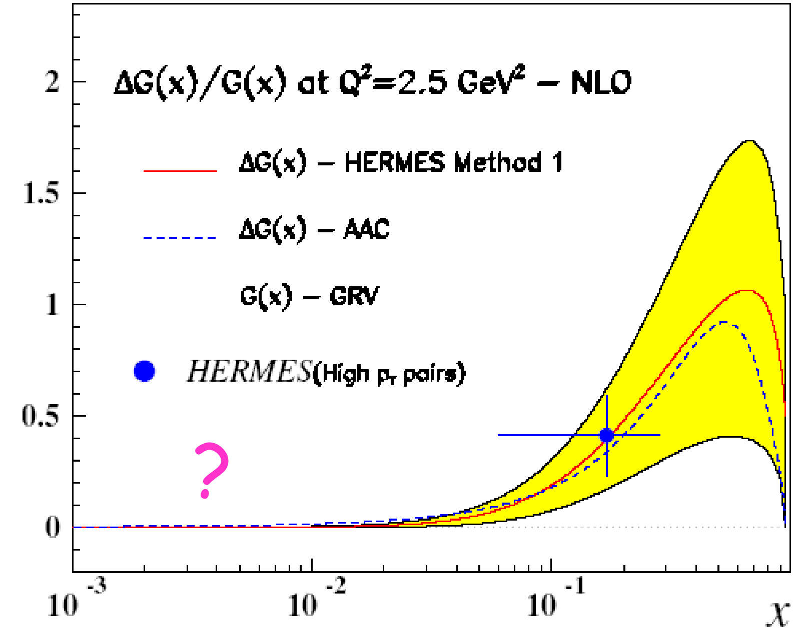
$$\sigma_r = F_2 - f(y)F_L$$

$$F_L \propto \alpha_s xg$$

F_L data point to positive gluon distribution in the transition region

Polarised gluon distribution ΔG





Some sign that ΔG > 0
→ more data needed …COMPASS, RHIC…
Future requires luminous collider

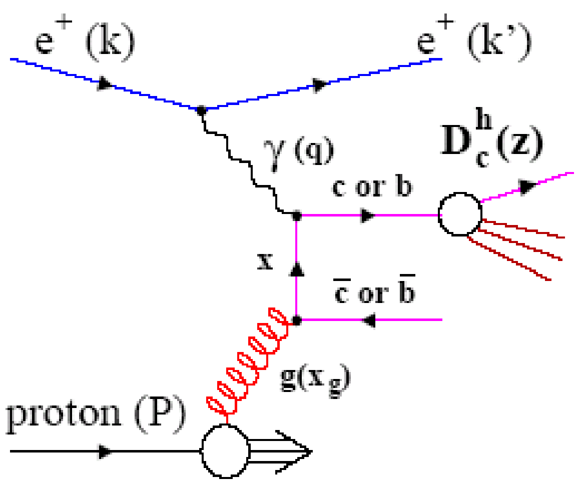
polarised data also sensitive to α_S

BB : Blümlein, Böttcher,
GRSV: Glück, Reya, Stratman, Vogelsang
AAC : Asymmetry Analysis Collaboration
GRV : Glück, Reya, Vogt

3. Heavy flavour physics at HERA

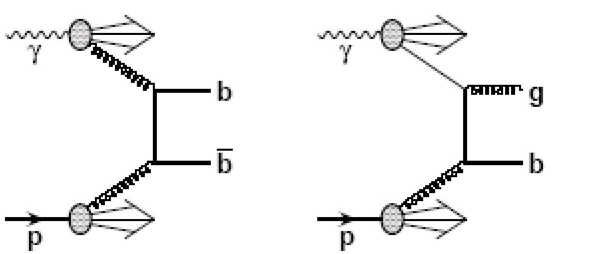
$$q(p) \otimes \sigma(\gamma g \to b\bar{b}) \otimes q(\gamma) \otimes D_c^h$$

Boson-Gluon fusion



- evolved test of QCD at NLO [+jets, diffraction]
  γp: FMNR (Frixione, Mangano, Nason, Ridolfi)
  DIS: HVQDIS (Harris, Smith)

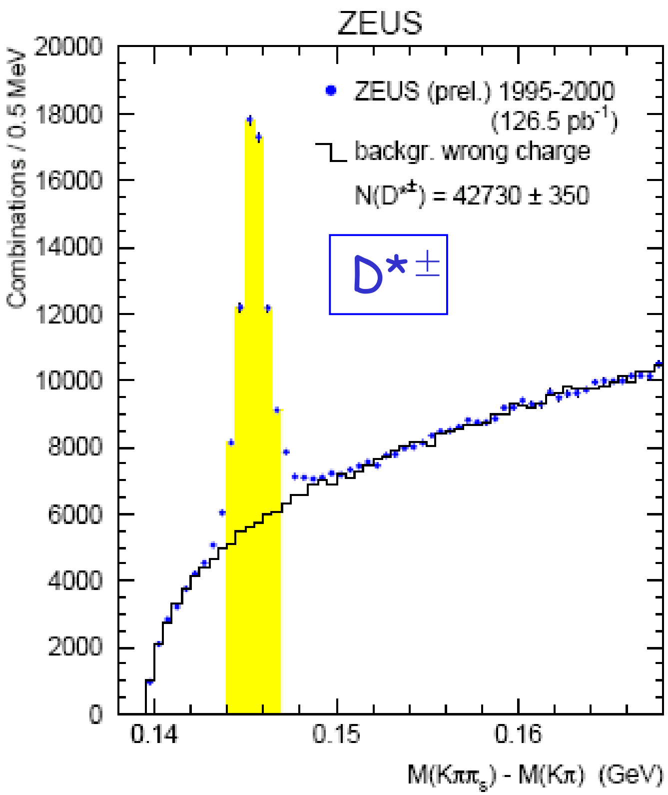
Heavy flavours in photoproduction



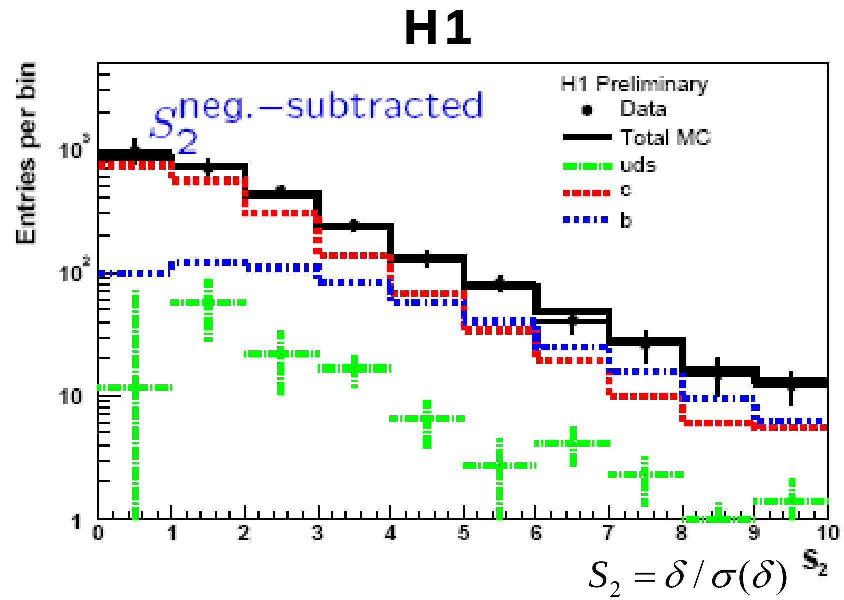
hadron-like: $gg \to b\bar{b}$ b-excitation: $bg \to gb$

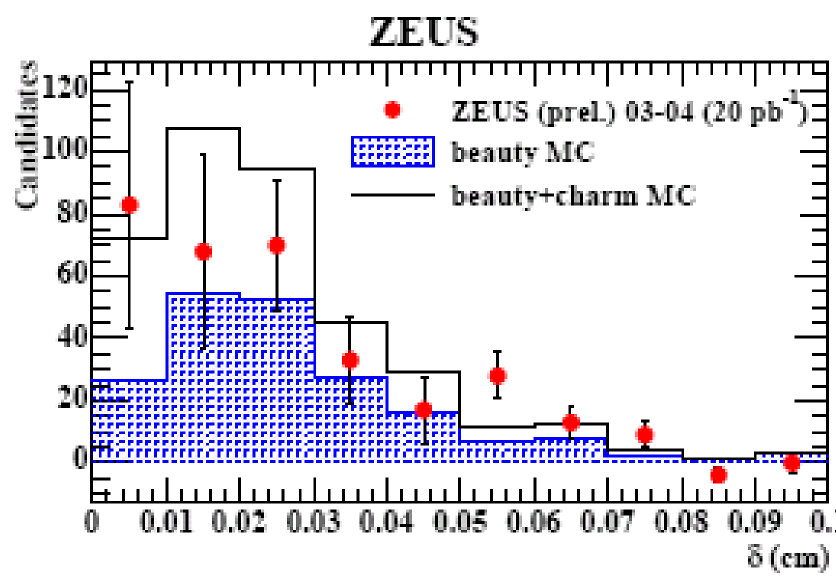
- Fraction of c,b to inclusive F_2 → F_2^c, F_2^b
- Treatment of c,b in QCD evolution : extrinsic or intrinsic, heavy or light?
- Parton radiation (DGLAP vs CCFM)
- Fragmentation functions – universal?
- Gluon in the proton
- Heavy quark and gluon content of the photon

Heavy flavour identification at HERA



Impact parameter tagging of beauty





Classic techniques: D* and $p_t^{rel}(\mu)$

Si-vertex detectors :

H1: CST: charm and beauty → ICHEP

ZEUS: new MVD sees b's at HERA II

Charm fragmentation in ep scattering

$$D^+, D^0, D_s^+, D^{*+}, \Lambda_c$$

$$R_{u/d} = \frac{c\bar{u}}{c\bar{d}} = \frac{\sigma(D^{0,*0})}{\sigma(D^{\pm,*\pm})} = \frac{\sigma^{untag}(D^0)}{\sigma(D^\pm) + \sigma^{tag}(D^0)}$$

The vacuum as seen by the charm quark contains an equal number of u and d quarks

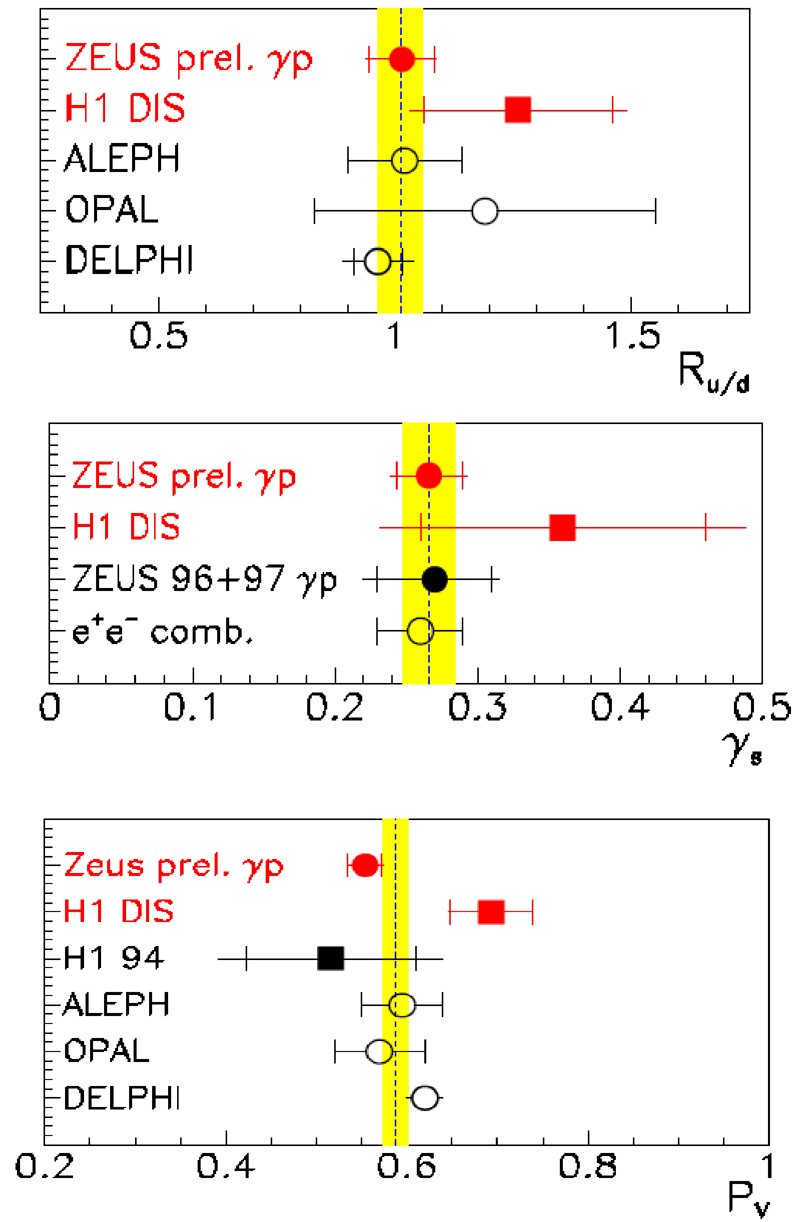
$$\gamma_s = \frac{2c\bar{s}}{c\bar{d} + c\bar{u}} = \frac{2\sigma(D_s^\pm)}{\sigma^{dir}(D^\pm) + \sigma^{dir}(D^0) + 2\sigma(D^{*\pm})}$$

s quarks are suppressed by a factor of 4

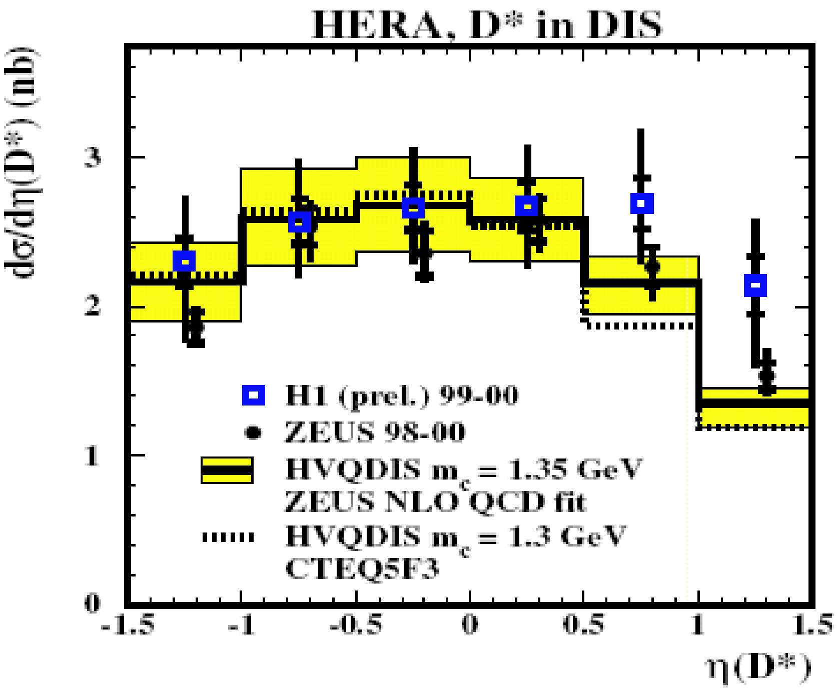
$$P_V = \frac{V}{V+P} = \frac{\sigma(D^*)}{\sigma(D^*) + \sigma^{dir}(D)} \neq 3/4$$

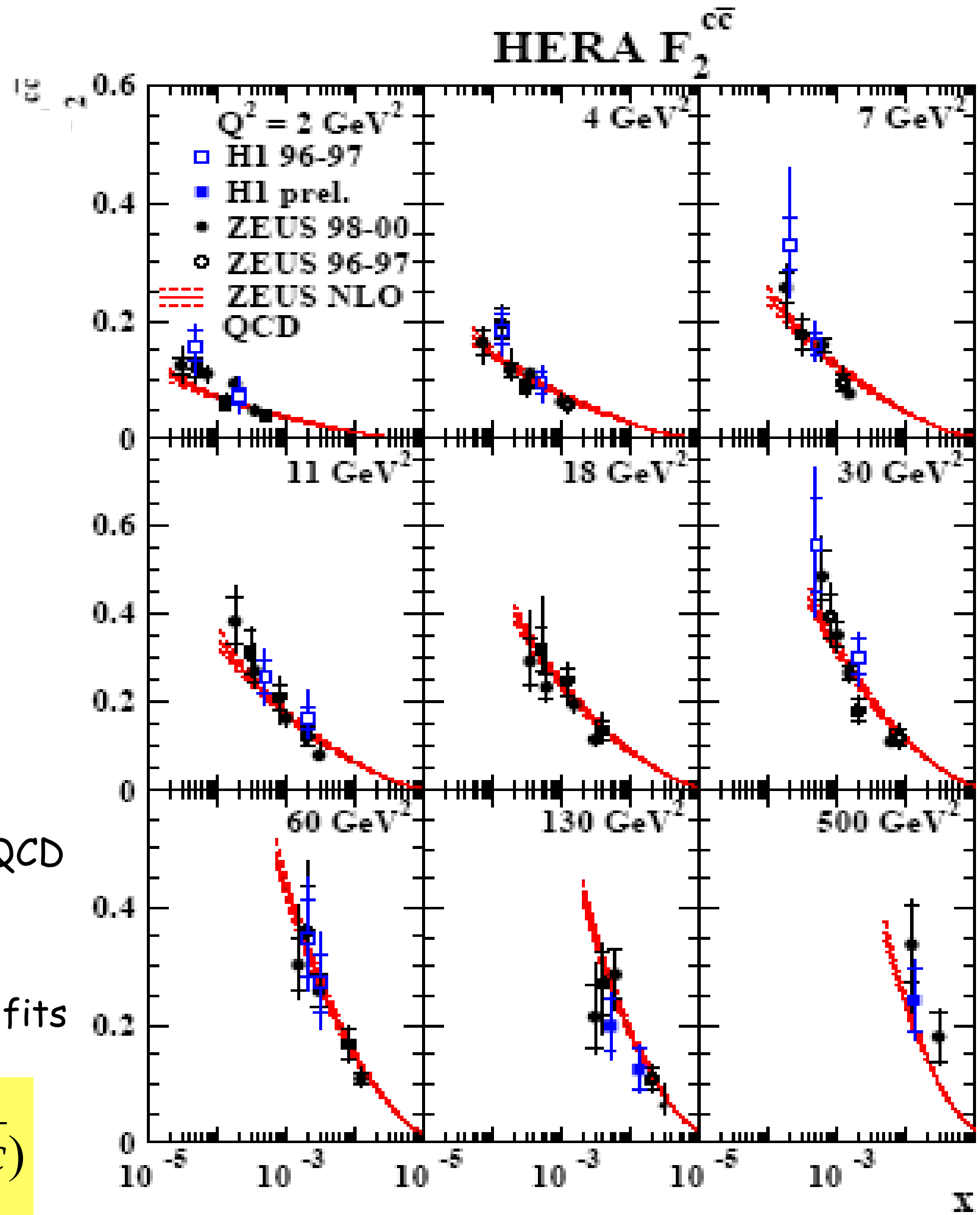
Naïve spin counting does not work for charm

Fragmentation fractions f(c→D), f(c→Λ_c) also determined. Agree/compete with e+e- → universal behaviour of charm fragmentation



Inclusive charm production in deep inelastic scattering

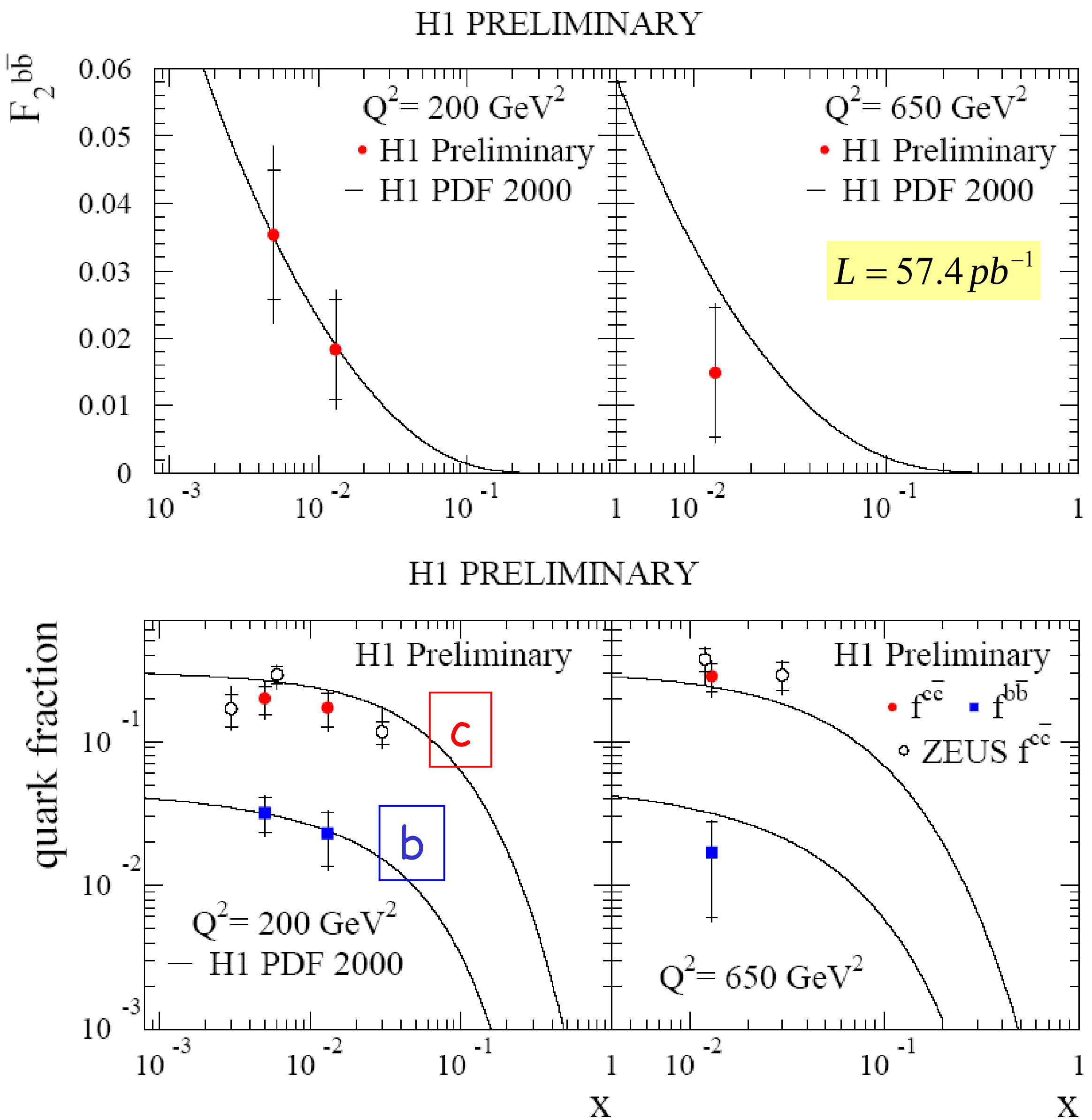




- Inclusive measurements consistent with NLO QCD
- Discrepancies when associated with jets.
- Large theoretical uncertainties (scale)
- Data accurate to 10-30% → can constrain PDF fits

$$\frac{d\sigma^{ep\to ec\bar{c}X}}{dx\,dQ^2} \propto \frac{F_2^{c\bar{c}}(x,Q^2)}{Q^4}, F_2^{c\bar{c}} = \frac{4}{9}x(c+\bar{c})$$

Inclusive beauty production in deep inelastic scattering



First measurement of bottom structure function, uses b lifetime tagging.

Charm F_2 data with D* (ZEUS) and tagging (H1) agree. Reach now high Q2

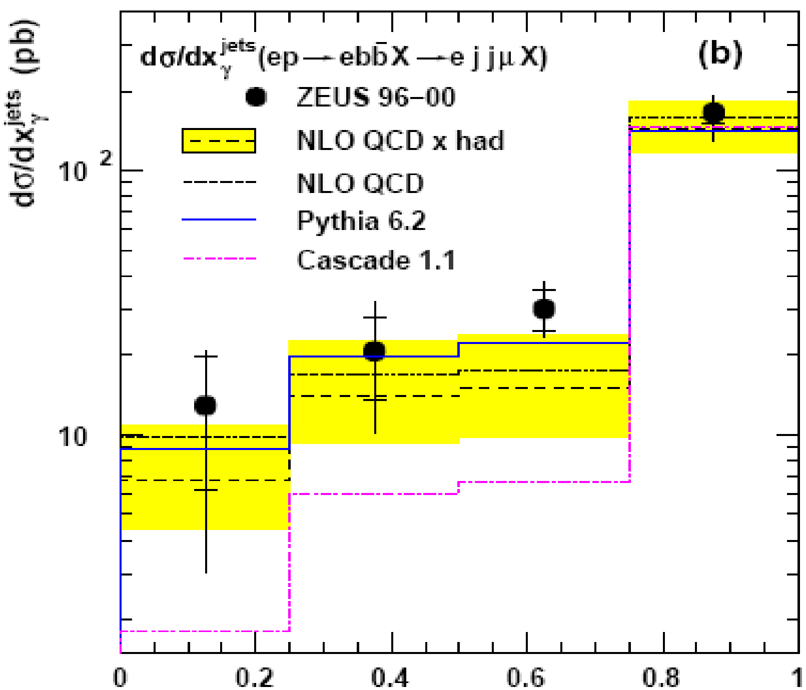
Charm is 20% of F_2. Beauty only 2% below valence quark region

Beauty dijets in photoproduction

$ep \to eb\bar{b}X \to ejj\mu X'$

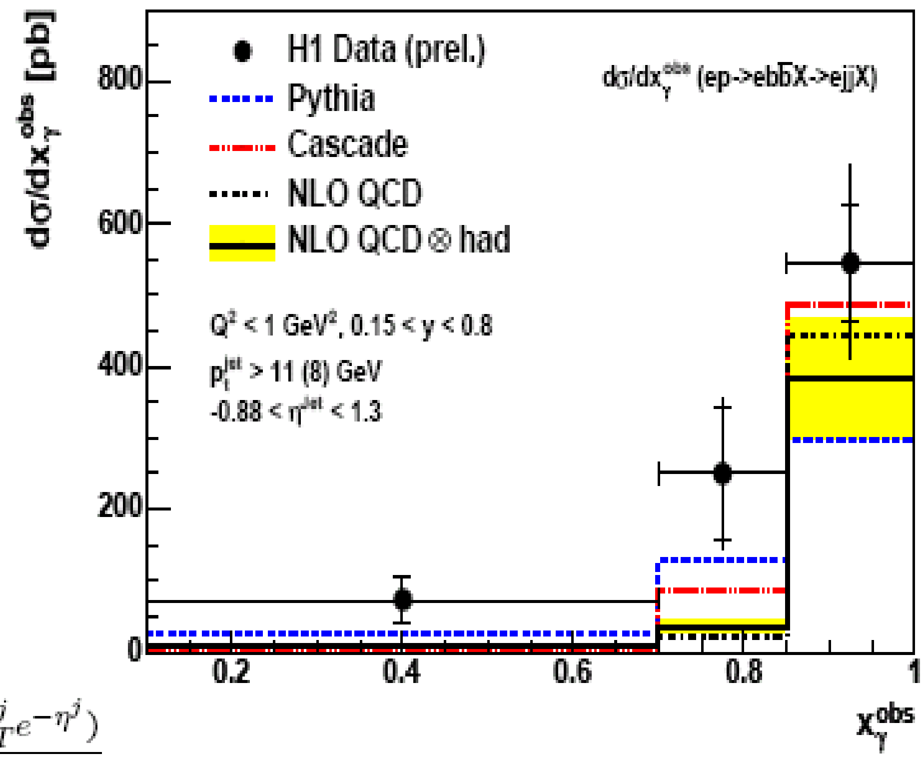
$ep \to eb\bar{b}X \to ejjX'$

ZEUS



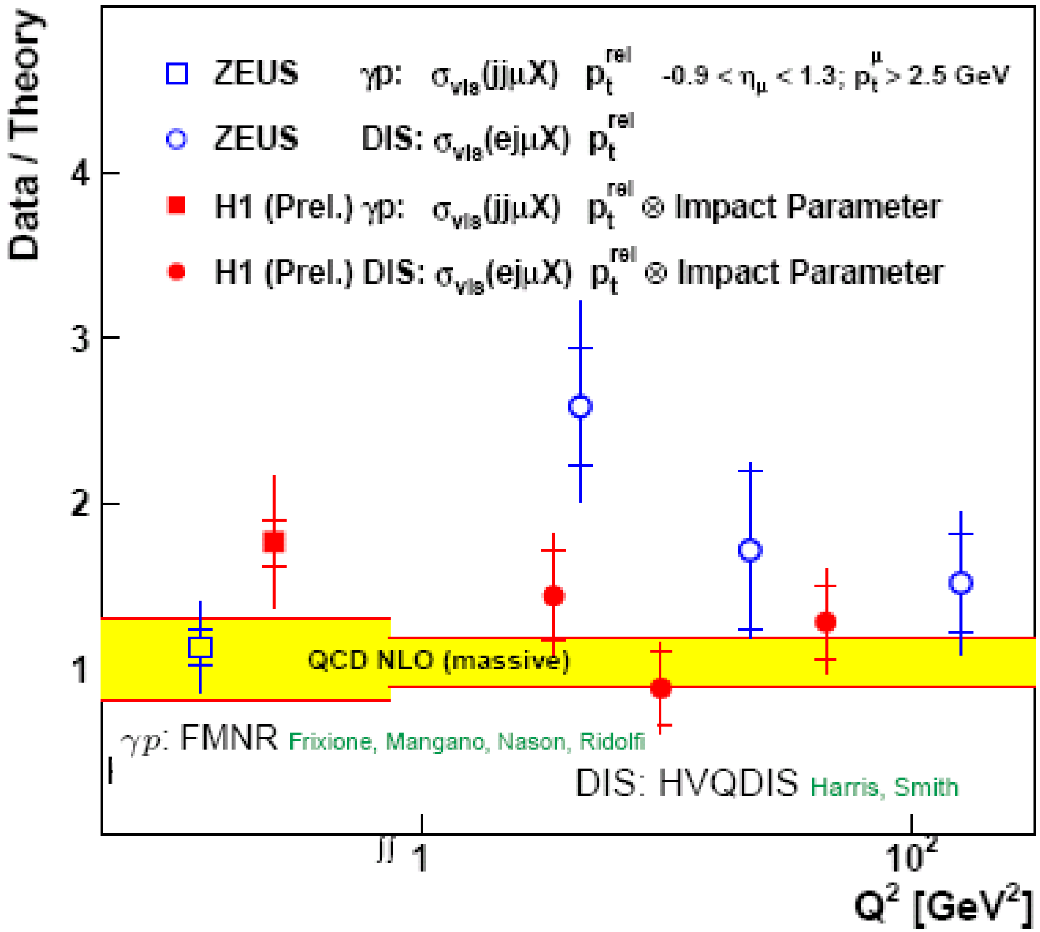
$$x_\gamma^{\text{jets}} = \frac{\sum_{j1,j2}(E_T^j e^{-\eta^j})}{2yE_e}$$

H1



- Direct production dominant, similar to behaviour of charm
- Resolved component measured, perhaps larger than NLO QCD
- Can lead to determination of the beauty content of the photon (c.f. charm)

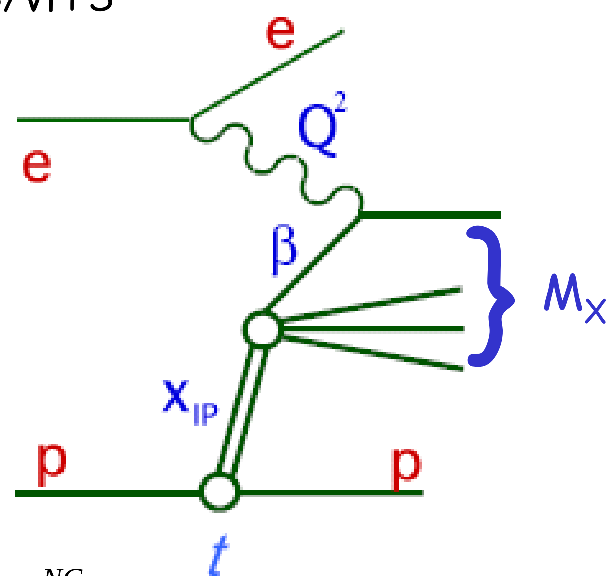
Summary of beauty data from HERA vs NLO QCD



Data of increased accuracy are above but not inconsistent with QCD

4. Hard Diffractive ep Scattering

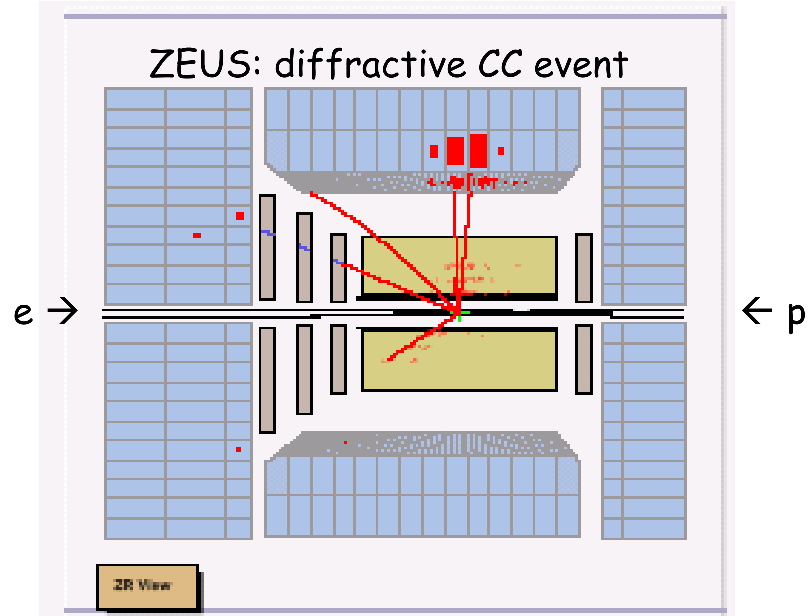
~10% of NC DIS events have gap between p and central tracks. Measure gap or detect p with LPS/VFPS



$$\frac{d\sigma_{diff}^{NC}}{dx_{IP}\,dt\,d\beta\,dQ^2} \propto \frac{1}{Q^4} F_2^{D(4)}(x_{IP}, t, \beta, Q^2)$$

Cross section factorises into coefficient functions and diffractive parton distributions

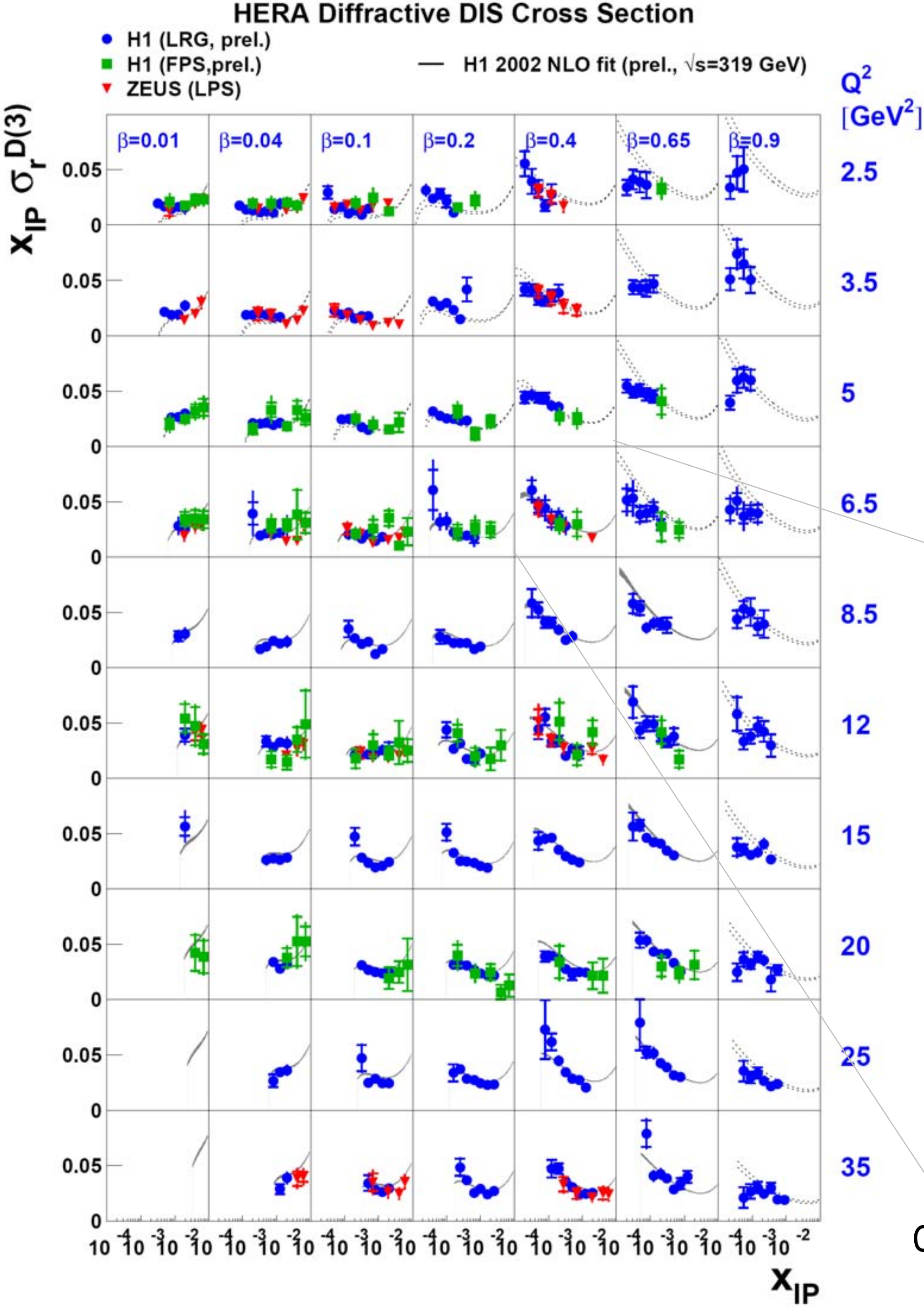
(Trentadue, Veneziano, Berera, Soper, Collins, ...)



First observation by ZEUS and H1 of diffraction in charged current scattering at high Q^2: 2-3%

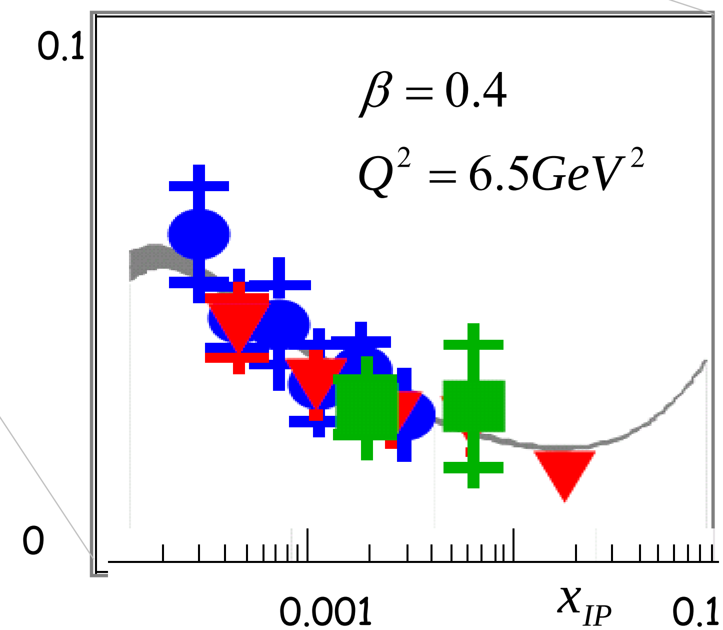
- Why does the p sometimes remain intact?
- Understand nature of diffractive exchange
- Does diffraction affect p PDF's [Martin et al]
- Is diffractive exchange universal, ep – pp?
- 2 g exchange → high gluon density – unitarity?
- Study an old phenomenon at hard scales!

HERA allows detailed, quantitative studies. Many new results presented to ICHEP04 (inclusive, resolved y, CC, charm, jets..)

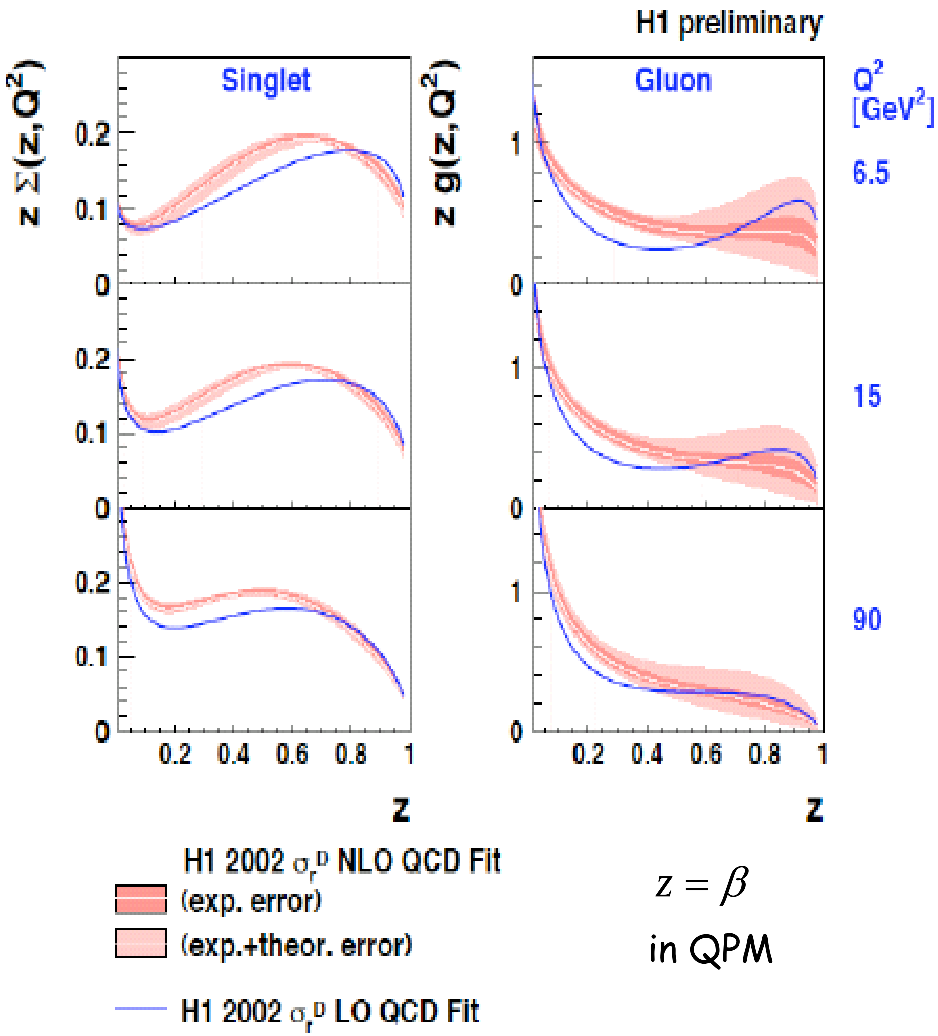


- New diffractive DIS data tagged with:
  - Large rapidity gap i.e. forward detector veto.
  - Tagged proton using Forward p Spectrometer FPS (H1) Leading p Spectrometer LPS (ZEUS)
- Good agreement between all data

$$x_{IP}\sigma_r^{D(3)} = x_{IP}[F_2^{D(3)} - f(y)F_L^{D(3)}]$$



Diffractive parton distributions

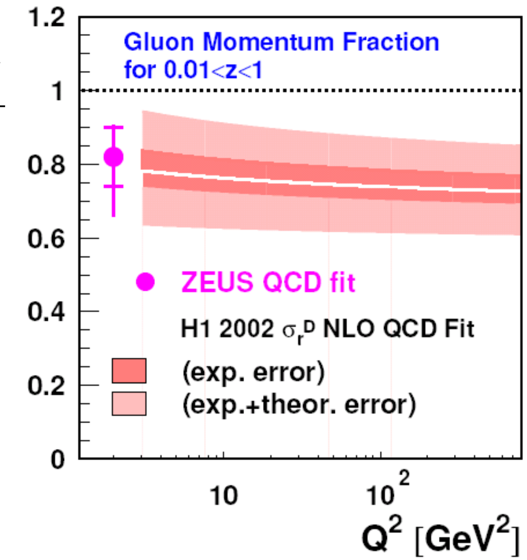


$z = \beta$

in QPM

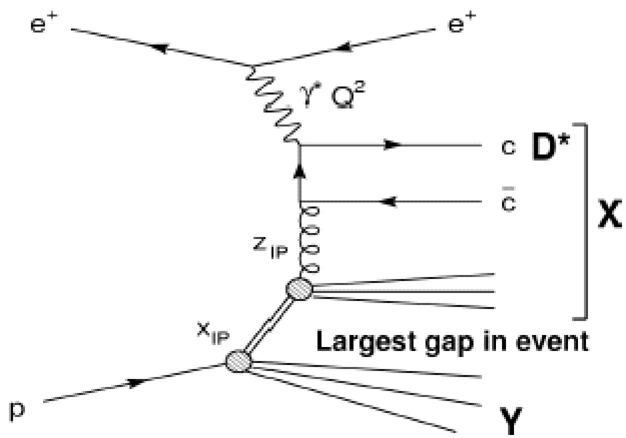
uses Regge flux ('resolved Pomeron model')

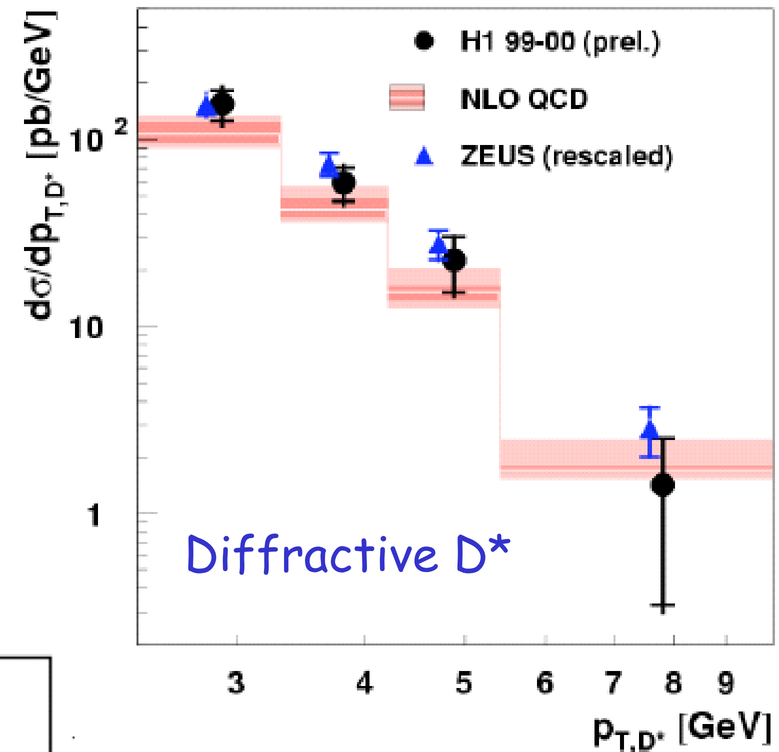
$$\frac{\int zg(z,Q^2)dz}{\int z[g+\Sigma]dz}$$

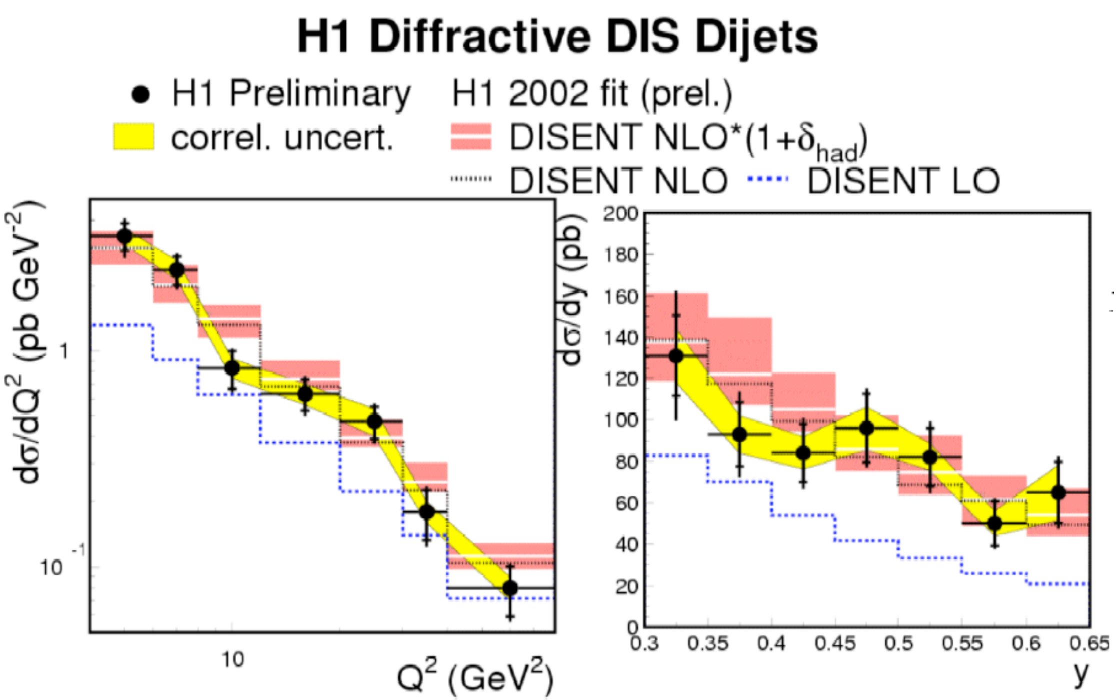


- Extract diffractive PDFs from NLO fit to inclusive diffractive structure functions
- Momentum distribution of quarks and gluons in the 'Pomeron': gluons dominate at large z > 0.01 unlike the non diffractive xg.
- QCD evolution (DGLAP) fits recent F_2^D data up to Q^2=2000 GeV^2.
- If factorisation holds, these PDFs are universal and NLO QCD should describe diffractive final states and Tevatron data

Final states in diffractive deep inelastic scattering

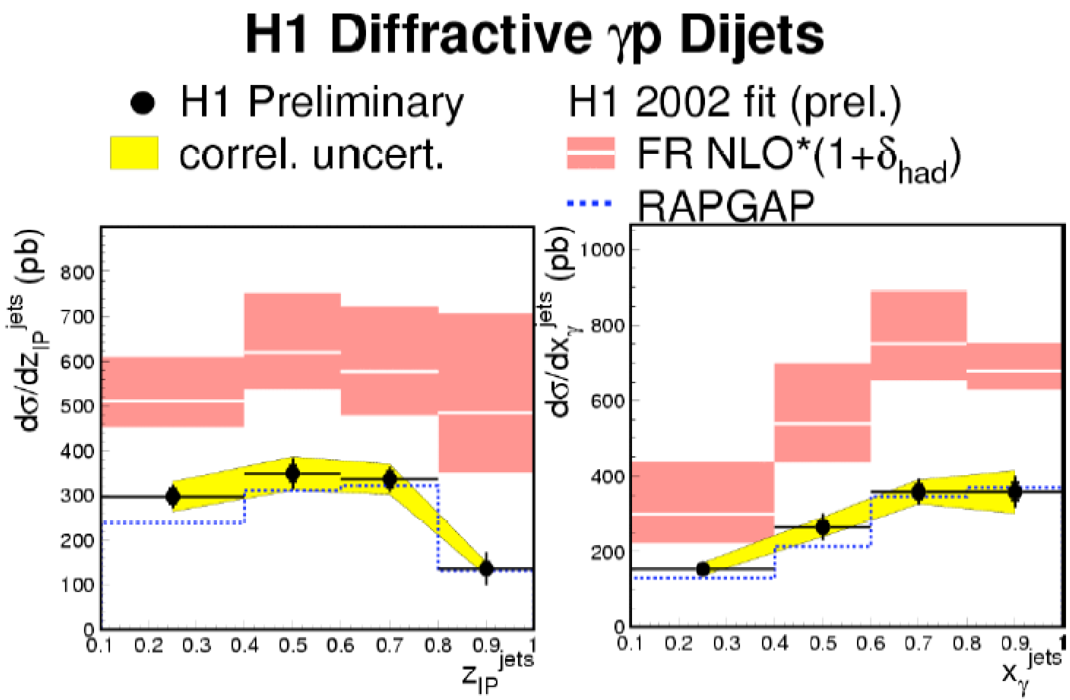


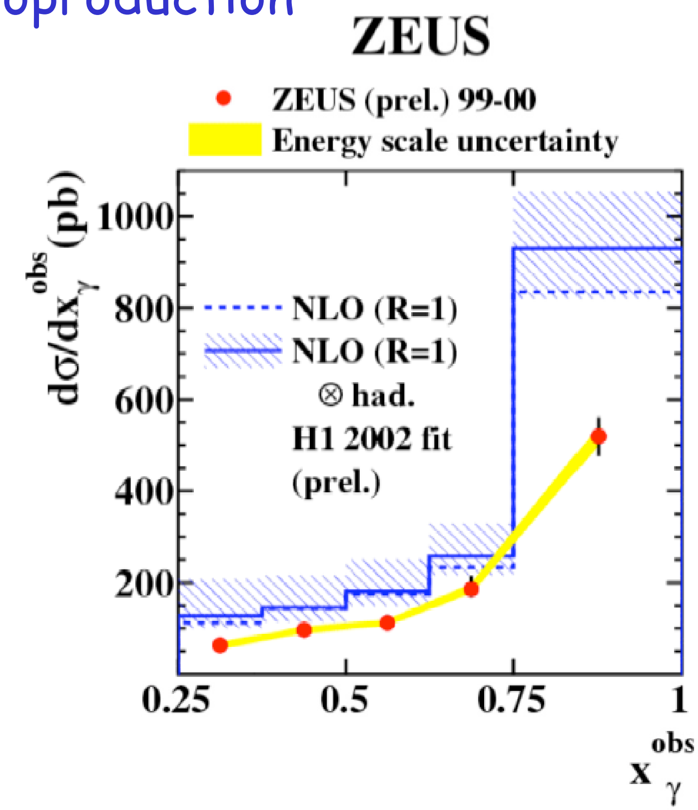


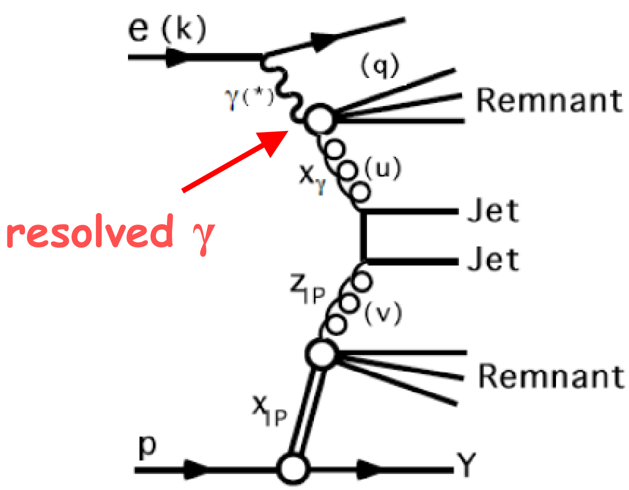


➔ factorisation holds in DIS – jets, D*

Final states in diffractive photoproduction





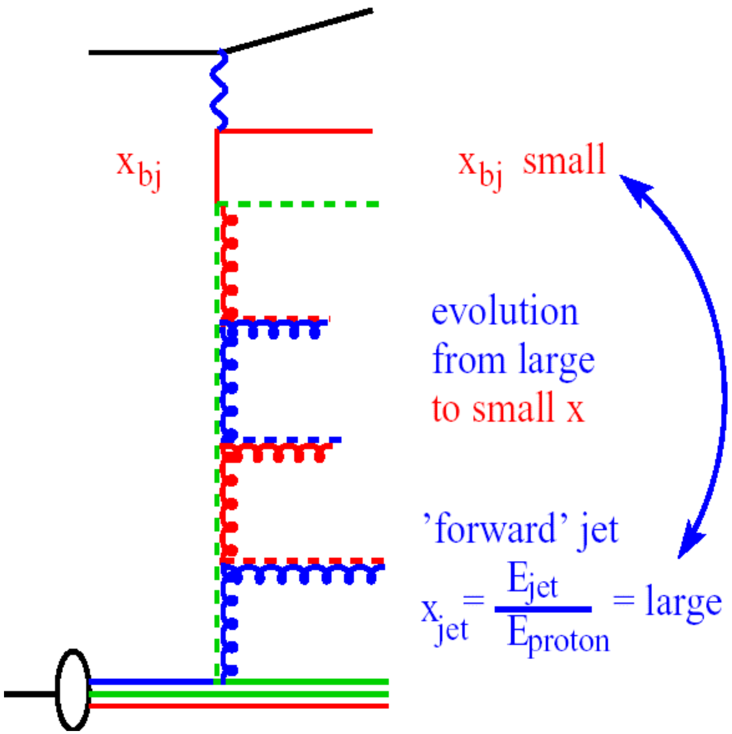


In photoproduction need factor of ~2 suppression of NLO theory to describe the data, both in the resolved region, which is similar to pp where a factor of ~10 is needed, and in the direct region which resembles DIS

Kaidalov et al.: predicted suppression of only the resolved part

5. New Ideas and Developments

Low x parton radiation: forward particle production (in p direction).



How are partons (gluons) emitted?

kt ordered

- DGLAP(Dokshitzer-Gribov-Lipatov-Altarelli-Parisi)
  DISENT/NLOJET

angular ordered

- CCFM(Ciafaloni-Catani-Fiorani-Marchesini)
  CASCADE

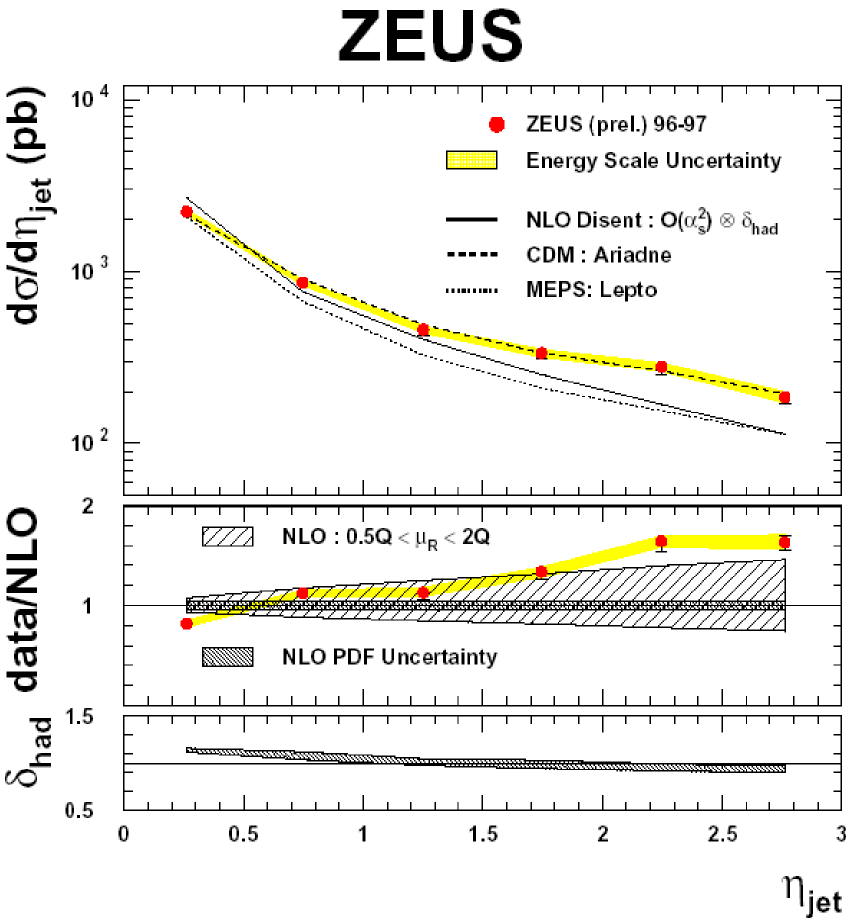
x ordered

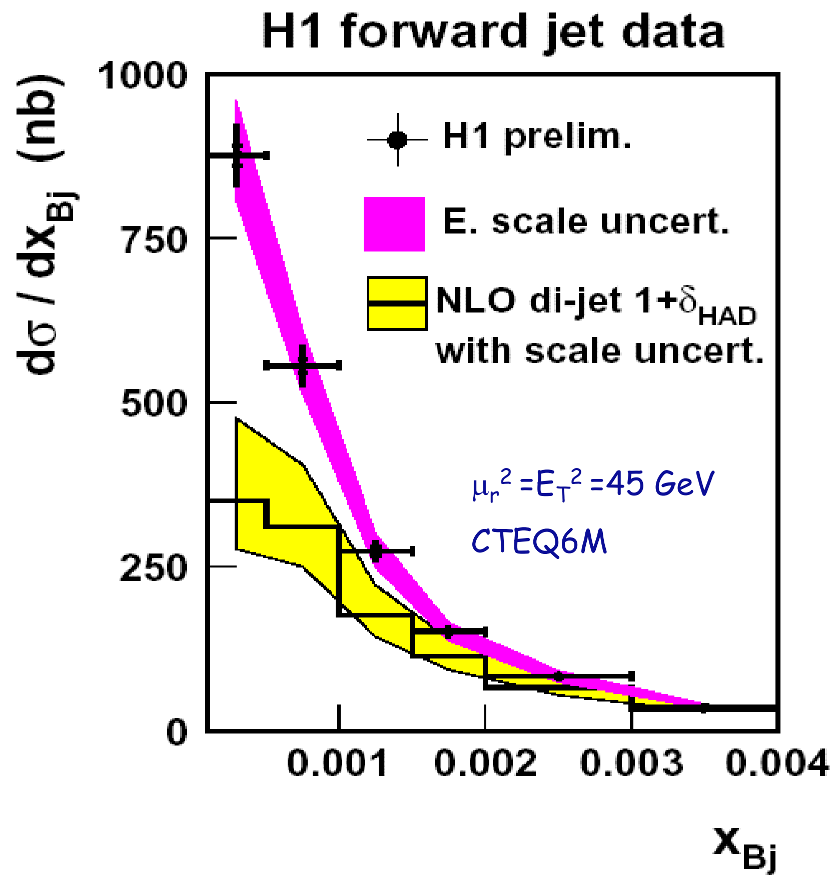
- BFKL(Balitsky-Fadin-Kuraev-Lipatov)
  ARIADNE (colour dipole. random in kt)

$x_{jet} = E_{jet}/E_{proton} \gg x_{Bj}$ enhances BFKL effect

$E^2_{T,jet} \sim Q^2$ suppress DGLAP evolution

Forward jet production in deep inelastic scattering

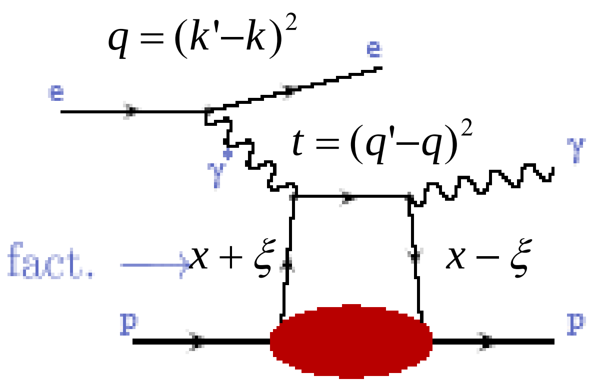


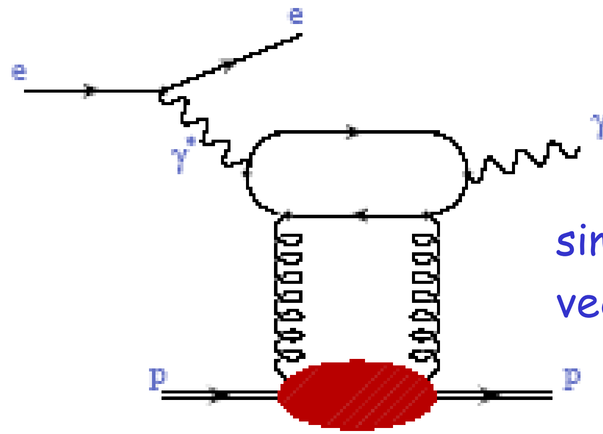


- Standard NLO pQCD prescription poor at lowest x for jets in forward direction where scale uncertainty is largest (higher orders? different radiation mechanism? best described by Ariadne – CDM – "BFKL like")

[interesting azimuthal (de)correlations. Also: kt dependent ("unintegrated") pdf's] ← no time

Deeply Virtual Compton Scattering – Generalised Parton Distributions





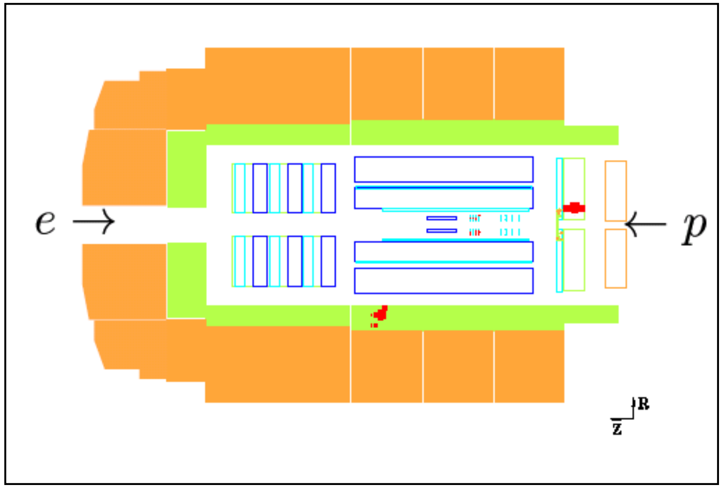
similar to diffractive vector meson production

$$H(x,\xi,t,Q^2), E, \tilde{H}, \tilde{E}$$

$$H^q(x,0,0) = q(x)$$

$$\tilde{H}^q(x,0,0) = \Delta q$$

$$J_q = \frac{1}{2}\Delta\Sigma + L_q = \frac{1}{2}\sum_q \int_{-1}^{1} x\,dx\,(H^q + E^q), t = 0$$

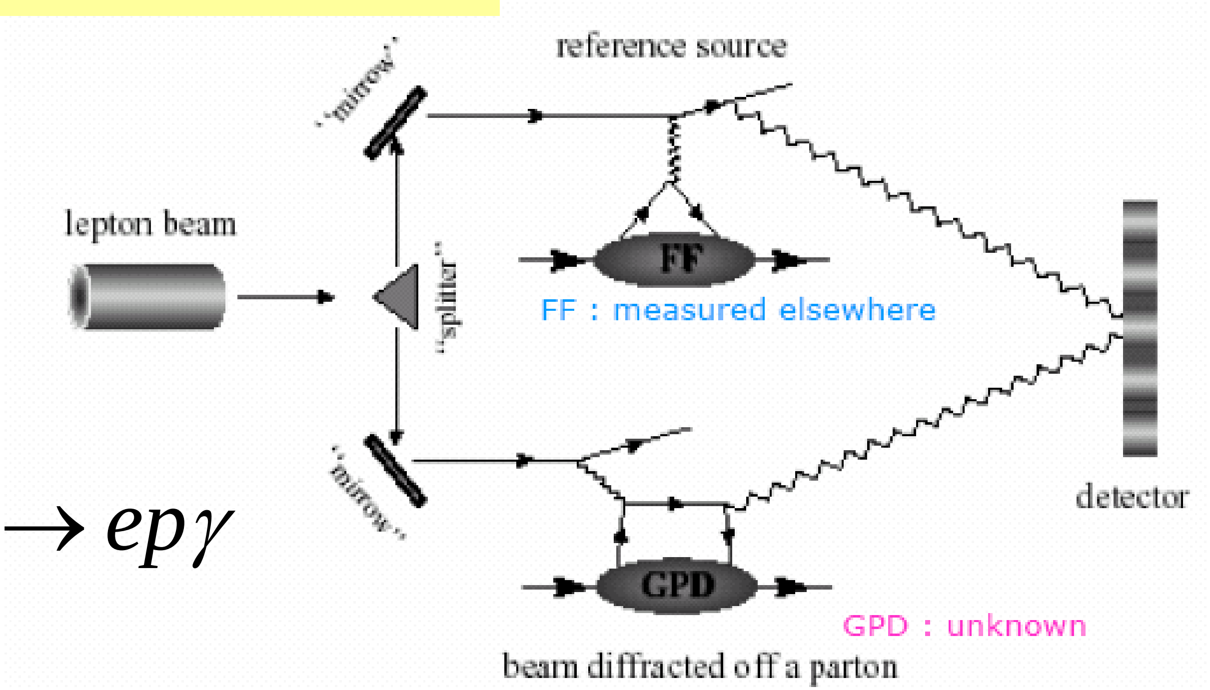


access to parton correlation functions and to angular momentum of partons

[V.Belitsky, D.Müller,hep-ph/0206306]

nucleon hologram with leptoproduction: interference of Bethe-Heitler (reference) and DVCS (sample) amplitudes

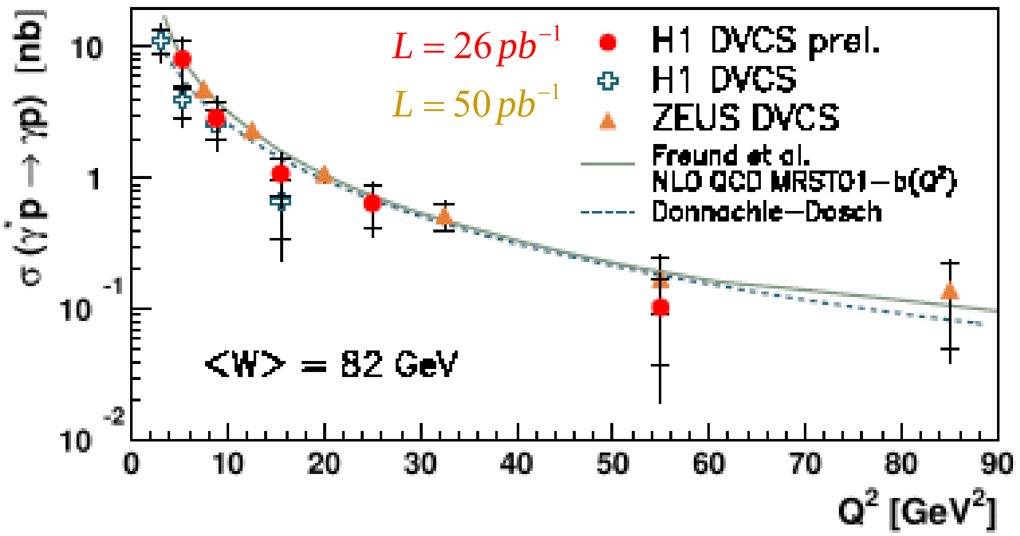
map transverse proton size by measuring t

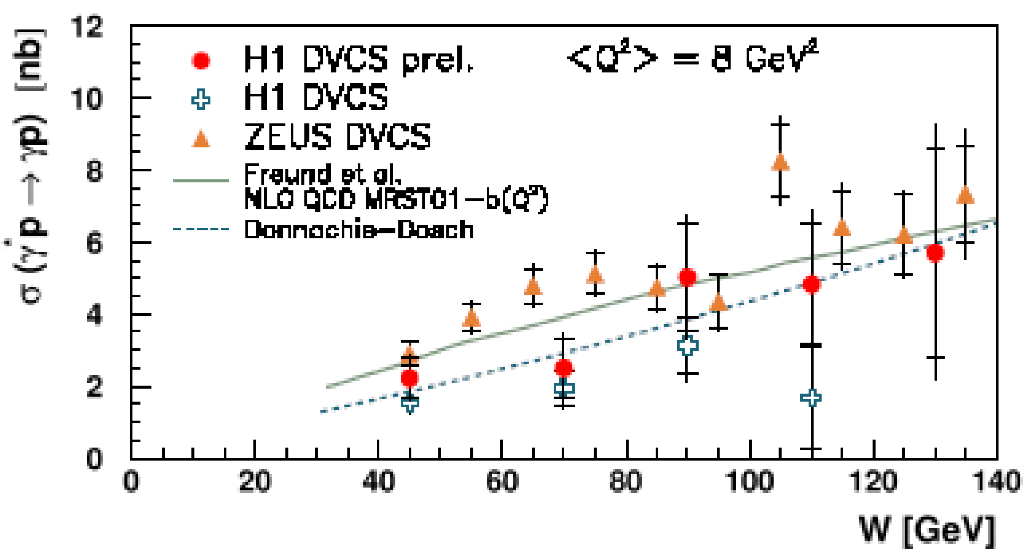


$$ep \to ep\gamma$$

$$\sigma \propto \left|A_{DVCS}\right|^2 + \left|A_{BH}\right|^2 + (A^*_{DVCS} A_{BH} + A_{DVCS} A^*_{BH})$$

DVCS cross section measurements





Assume :

$$GPD \propto PDF \cdot e^{-b|t|}$$

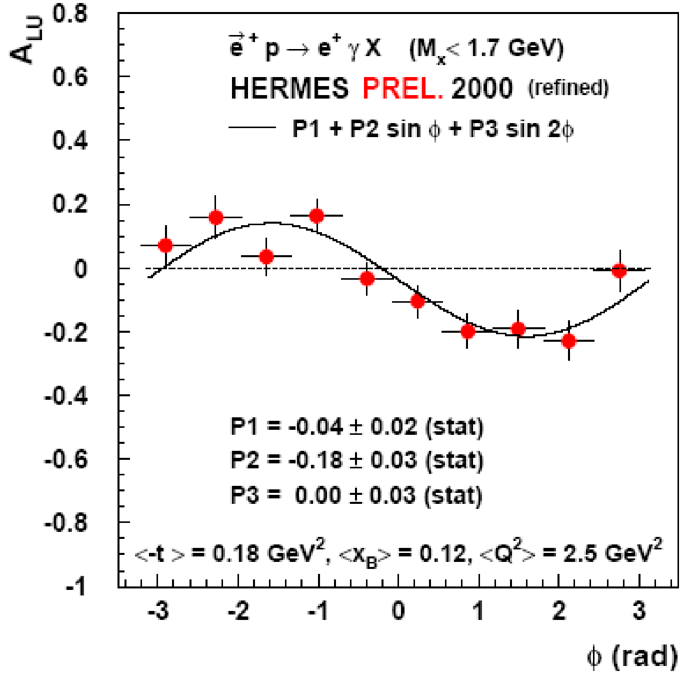
Beginning of GPD phenomenology.
Low x description also with colour dipole models.
Need to measure t dependence: more data needed:

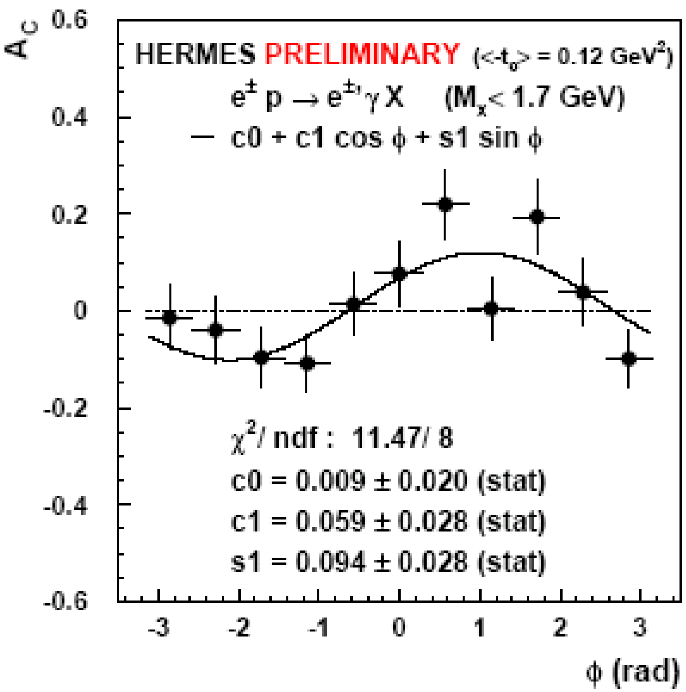
Prospects for collider experiments
H1 + ZEUS
- Beam charge and spin asymmetries
- Tag forward protons (H1 VFPS,FPS)
- Higher statistics at HERA II

W^{δ} FIT:
H1 PREL: 0.98 ± 0.44
ZEUS e^{+}: $0.75 \pm 0.15^{+0.08}_{-0.06}$

Hard QCD process as δ large c.f.
$\sigma(J/\Psi) \propto W^{\delta}$

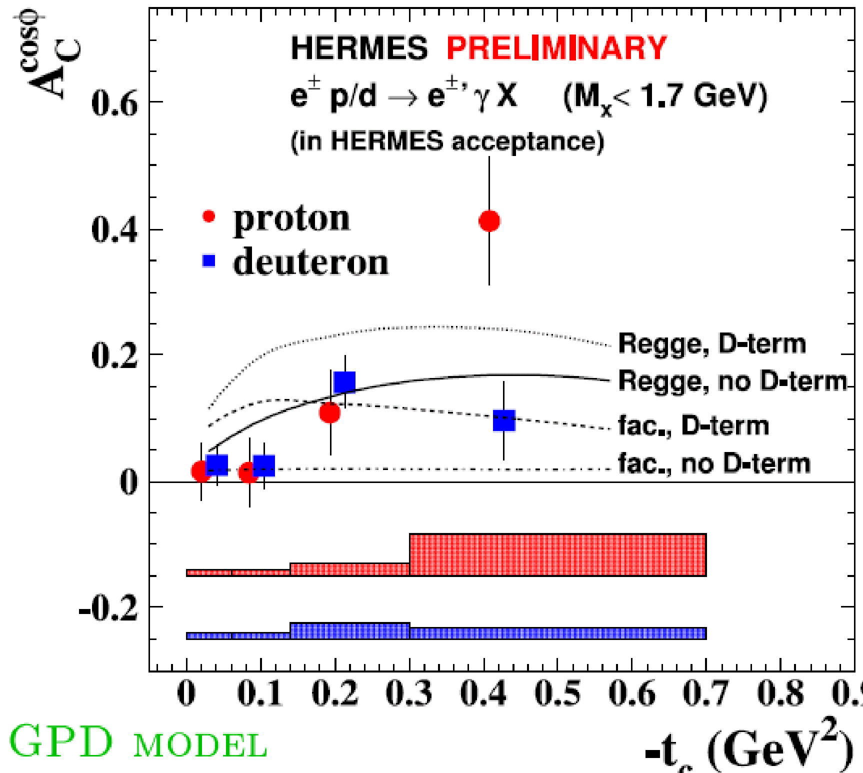
DVCS asymmetry measurements





Beam spin asymmetry $\propto \sin(\Phi)\,\mathrm{Im}(A_{DVCS})$

Beam charge asymmetry $\propto \cos(\Phi)\,\mathrm{Re}(A_{DVCS})$



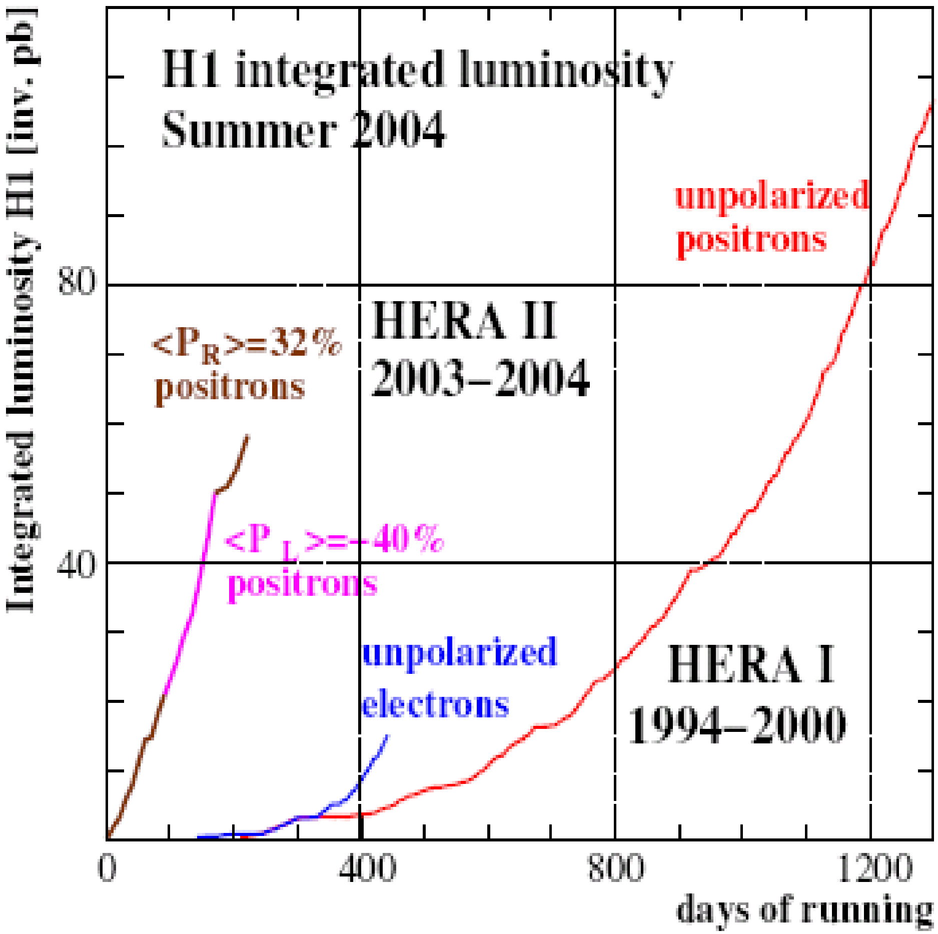
GPD MODEL

(VANDERHAEGHEN ET AL.)

Prospects for fixed target experiment HERMES

- Beam charge and spin asymmetries
- Tag recoiling proton
- Higher statistics at HERA II

6. First Results from HERA II



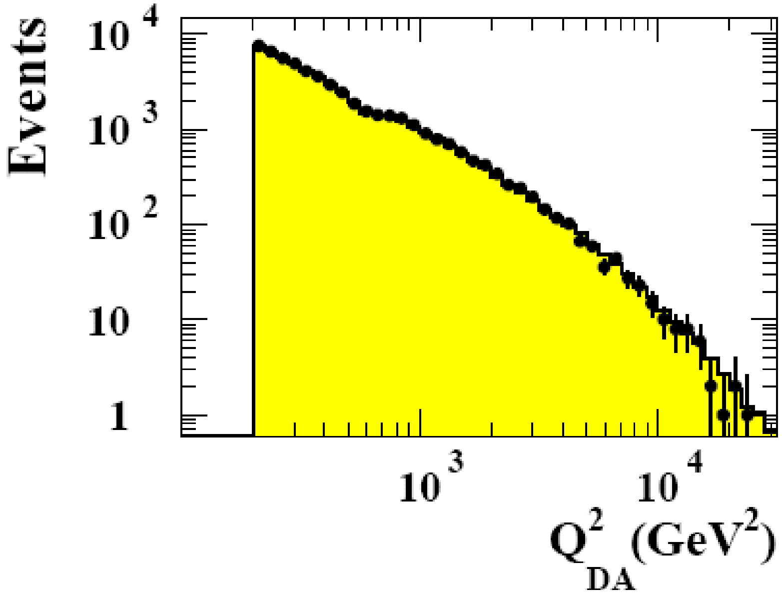
HERA II:

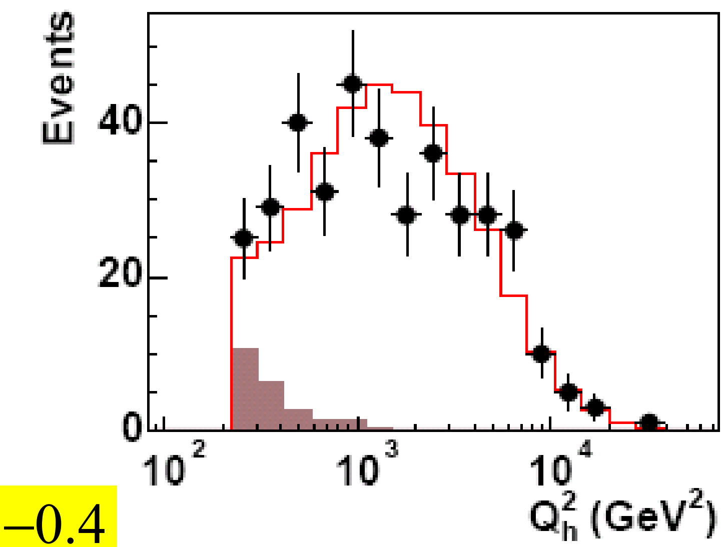
- detector and luminosity upgrade
- large, unexpected backgrounds
- identified and overcome in 2002/03
- efficient data taking since 10/03
- long run period scheduled till 2007
- polarised electron/positron p data with spin rotators at the 3 IR's
- first data presented to ICHEP04 [HERMES: first measurement of the transverse spin structure of p hep-ex/0408013 PRL submitted]

cross section measurements with HERA II data from 2004

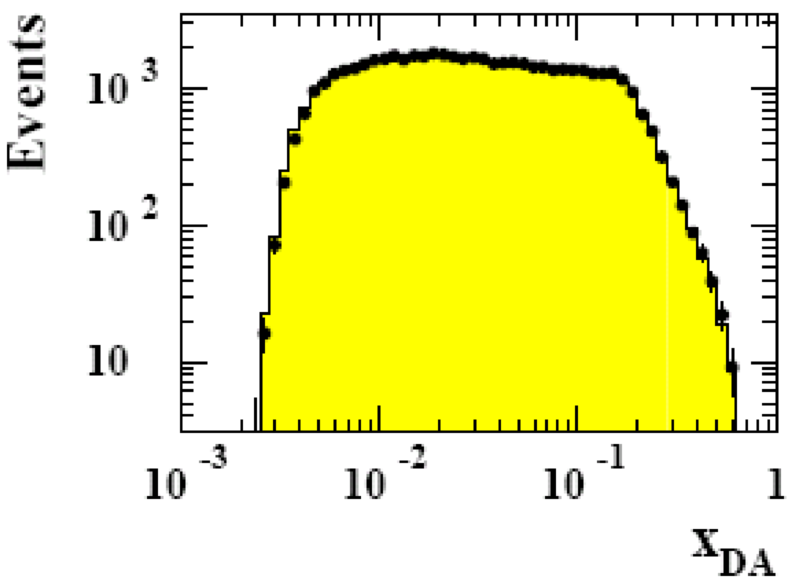
$e^+ p \rightarrow e^+ X$ ZEUS

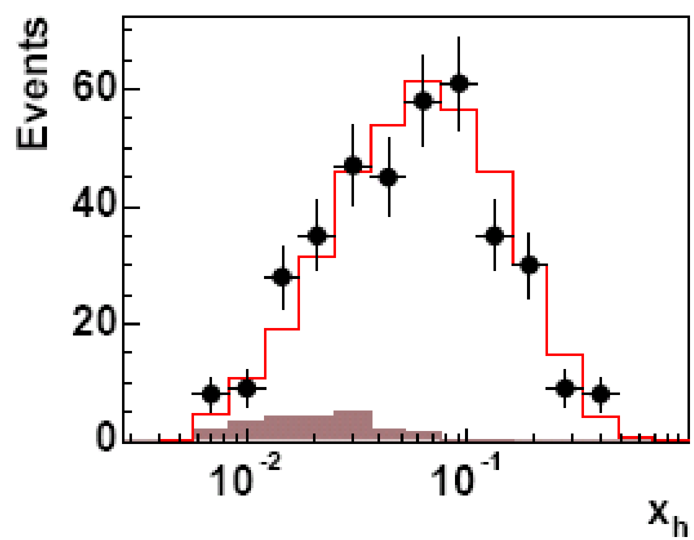
$e^+ p \rightarrow \bar{\nu} X$ H1



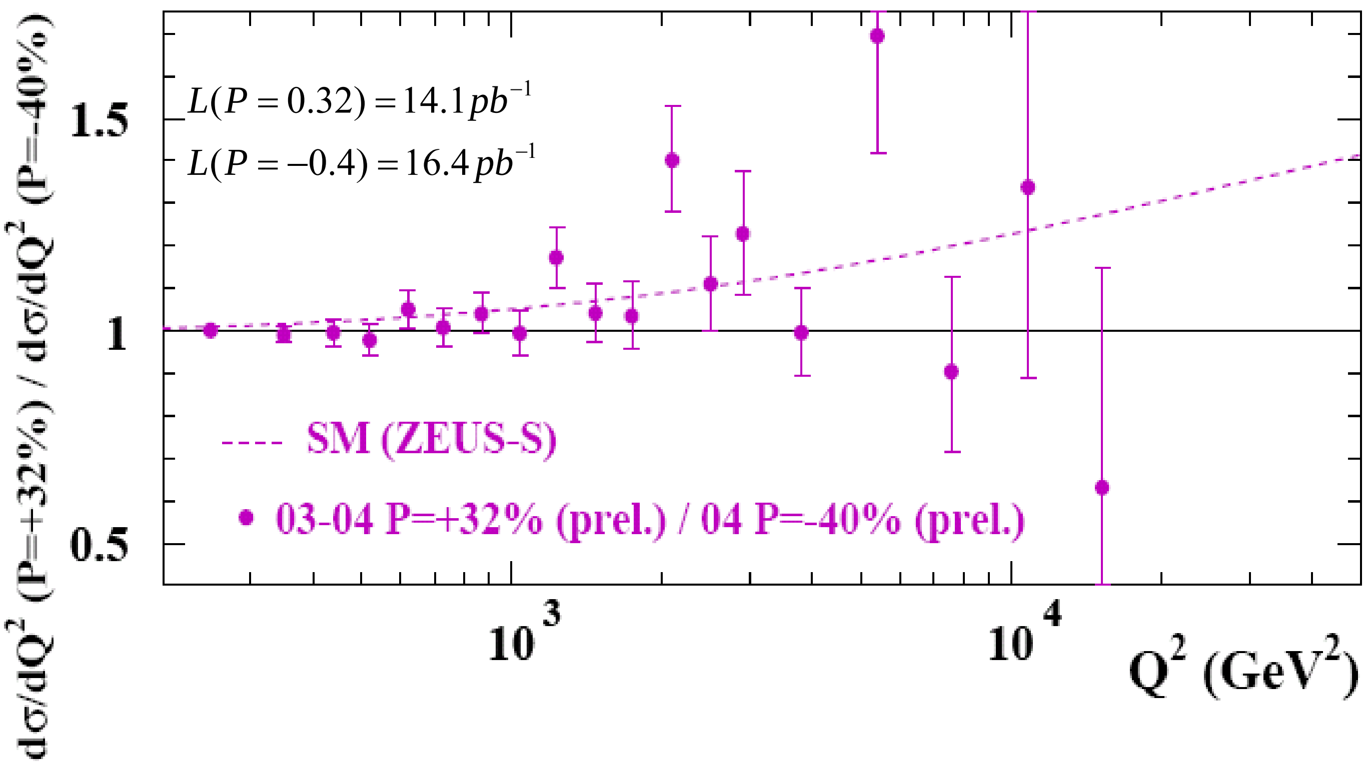


$P_e = -0.4$





ZEUS



$$\sigma_r^{NC,e^+}(P) \cong F_2 - P a_e \kappa F_2^{\gamma Z}$$

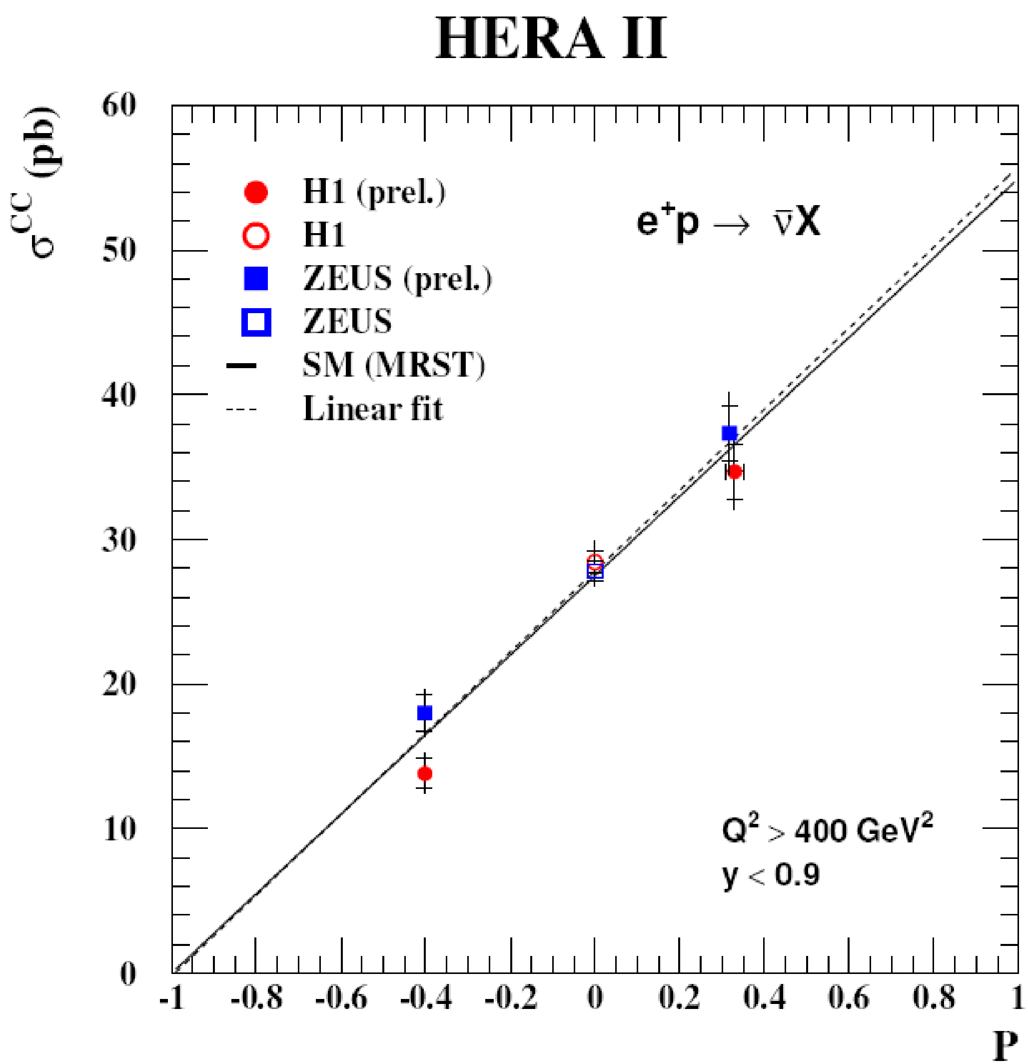
$$F_2 = x\sum e_q^2(q+\bar{q}) \leftrightarrow F_2^{\gamma Z} = x\sum e_q v_q (q+\bar{q})$$

$$\frac{\sigma_r(P_1)}{\sigma_r(P_2)} \cong 1-[P_1-P_2]\cdot \kappa a_e \frac{F_2^{\gamma Z}}{F_2} \sim 1+0.3\cdot 10^{-4} Q^2/GeV^2$$

parity violation ~$a_e v_q$

at very high Q^2

needs still larger lumi.



In the SM LH coupling $\bar{\nu}$ is excluded unless RH currents exist

Expect zero cross section at P=-1 and linear dependence on P

HERA II: can now prescribe positron beam helicity also in ep collider mode

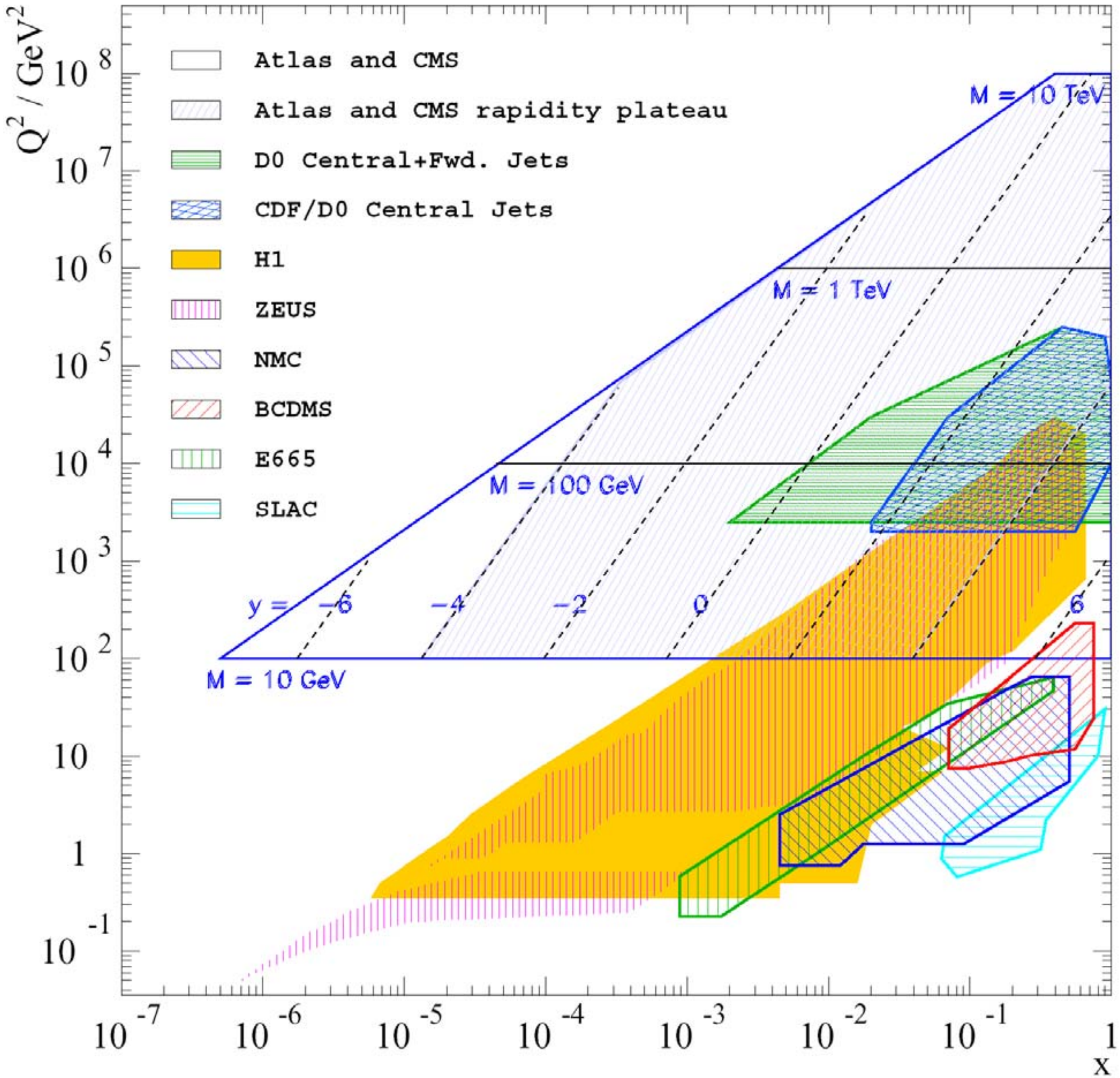
Polarisation dependence firmly established for the first time.

(remember CHARM $\bar{\nu}Fe \to \mu^+(P)X$ M.Jonker et al, PL 86(1979)229)

$$\sigma_{e^+p\to\bar{\nu}X}(P_{e^+} = -1) = 0.2 \pm 1.8(sta) \pm 1.6(sys)\, pb$$

$$\chi^2_{dof} = 5.4/4$$

- combined H1 and ZEUS
- result consistent with 0



Outlook

HERA & LHC

$u_v, d_v, \bar{u}, \bar{d}, c, b$

parton luminosities
→ highest precision

α_s
unification

gluon
Higgs and any QCD

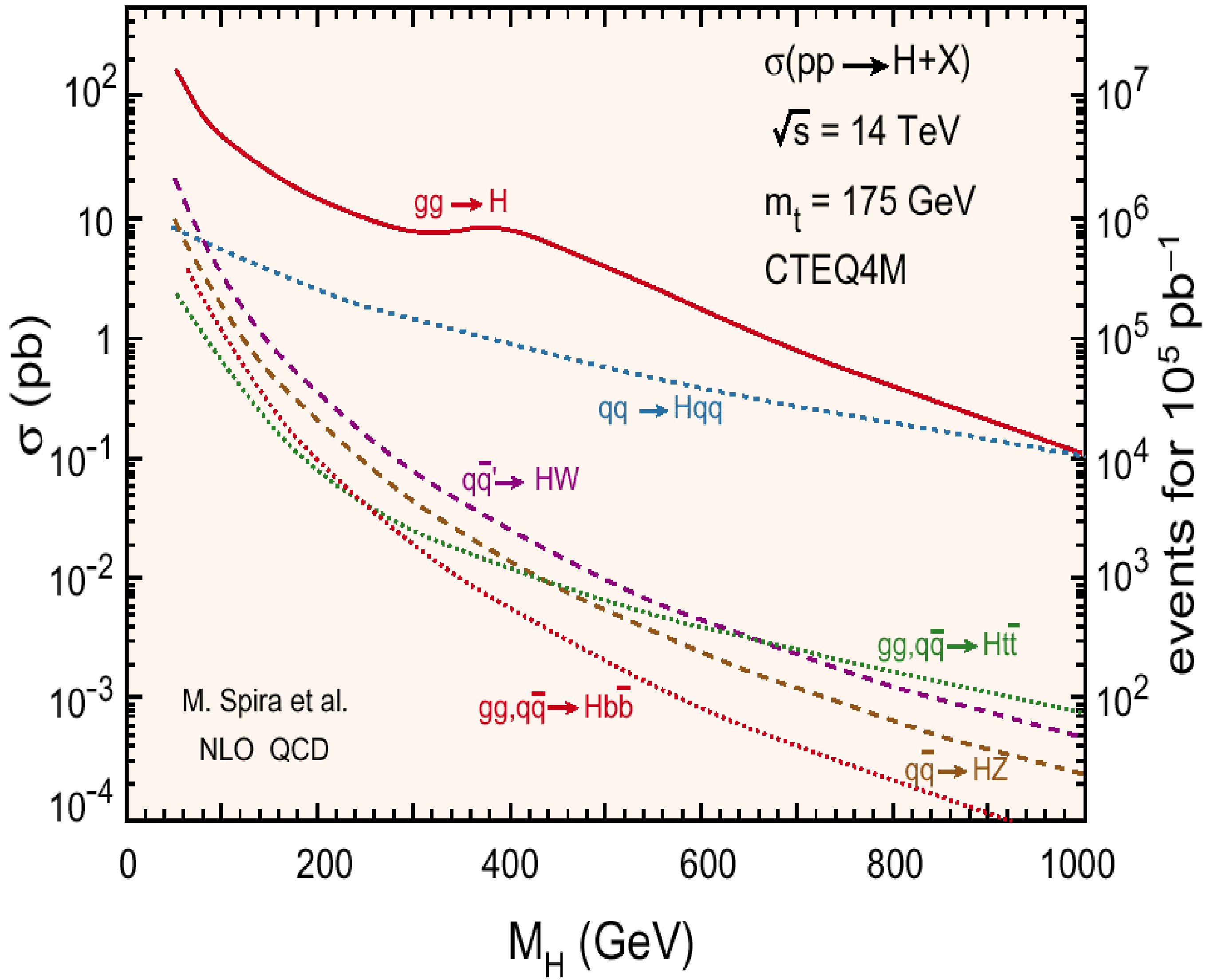
Low x parton radiation

DGLAP – CCFM - BFKL?
QGP, astrophysics

diffraction

saturation of xg
Higgs

HERA is an important part of HEP and is doing well again



Gluon and quark distributions essential to measure the Higgs cross section

- HERA experiments submitted ~100 papers to Beijing.

- With thanks to all the HERA activists.

- Thanks to the organisers and speakers.

- Special thanks to

Elke-Caroline Aschenauer,
Mandy Cooper-Sarkar,
Karin Daum,
Didar Dobur,
Claudia Glasman,
Claire Gwenlin,
Delia Hasch,
Ewelina Lobodzinska,
Uta Stößlein

and to a few more men for help with this presentation.