PARTICLE PHYSICS 2000

QCD at HERA

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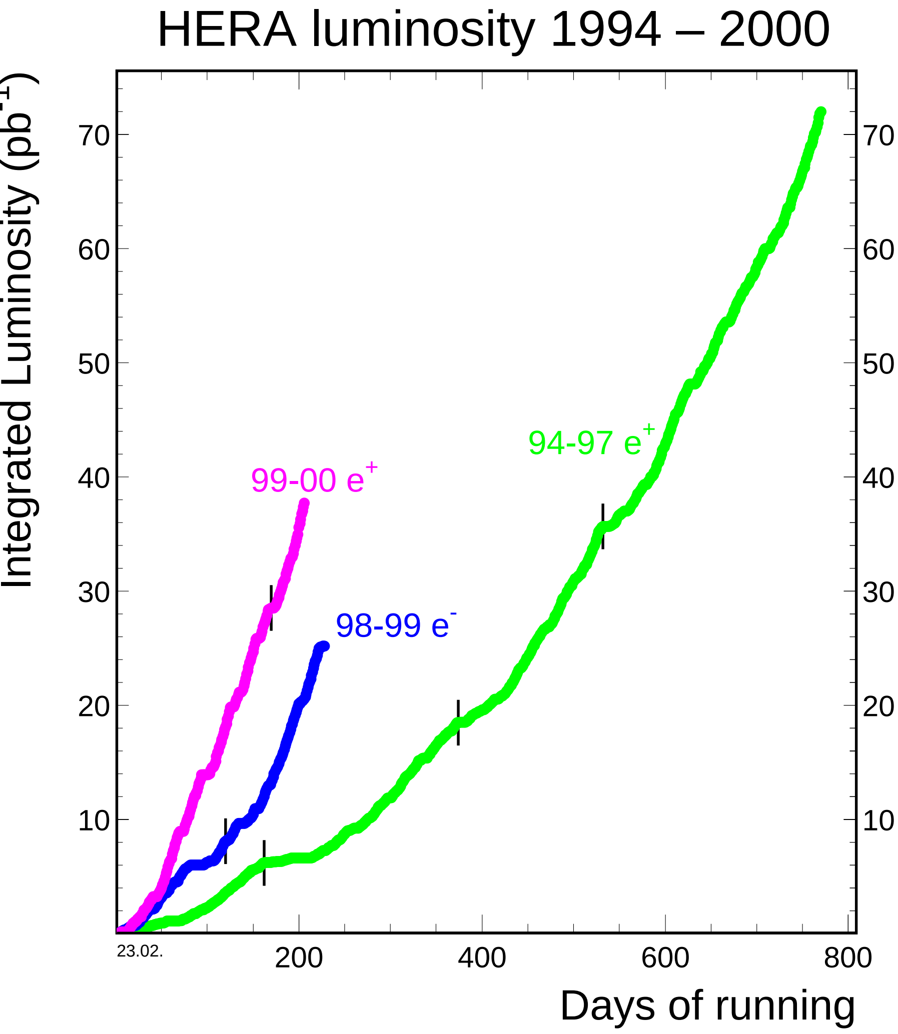
- Measurement of F_2
- BFKL dynamics
- Event Shapes

HERA Accelerator

e^+/e^- beam - 27.5 GeV

Proton beam - 820/920 GeV

Luminosity available for physics (ZEUS):



1994-97 ~ 48 pb^{-1} e^+p

$\sqrt{s}$ = 300 GeV

1998-99 ~ 17 pb^{-1} e^-p

$\sqrt{s}$ = 320 GeV

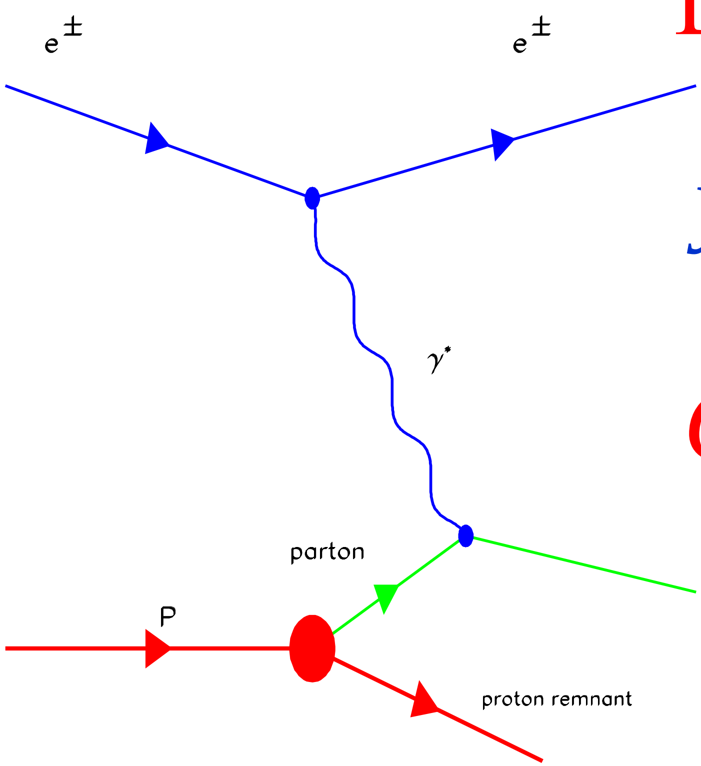
1999-2000 ~ 25 pb^{-1} e^+p

$\sqrt{s}$ = 320 GeV

Total ~ 90 pb^{-1}

+ running until September 2000

Naïve Quark Parton Model (QPM)



Lorentz scalars: y, Q^2,x

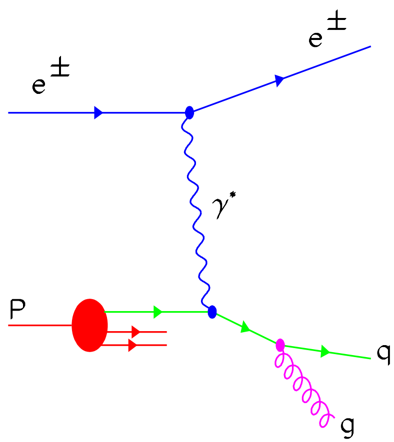
$$y = 1 - \frac{E_e^{'}}{2E_e}(1 - \cos\vartheta)$$

$$Q^2 = 2E_e^{'}E_e(1 + \cos\vartheta)$$

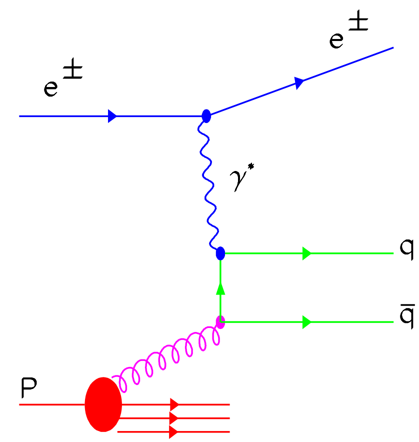
$$x = \frac{Q^2}{ys}$$

where $\sqrt{s}$ is the eP centre of mass energy

QCD Improved QPM



(a)



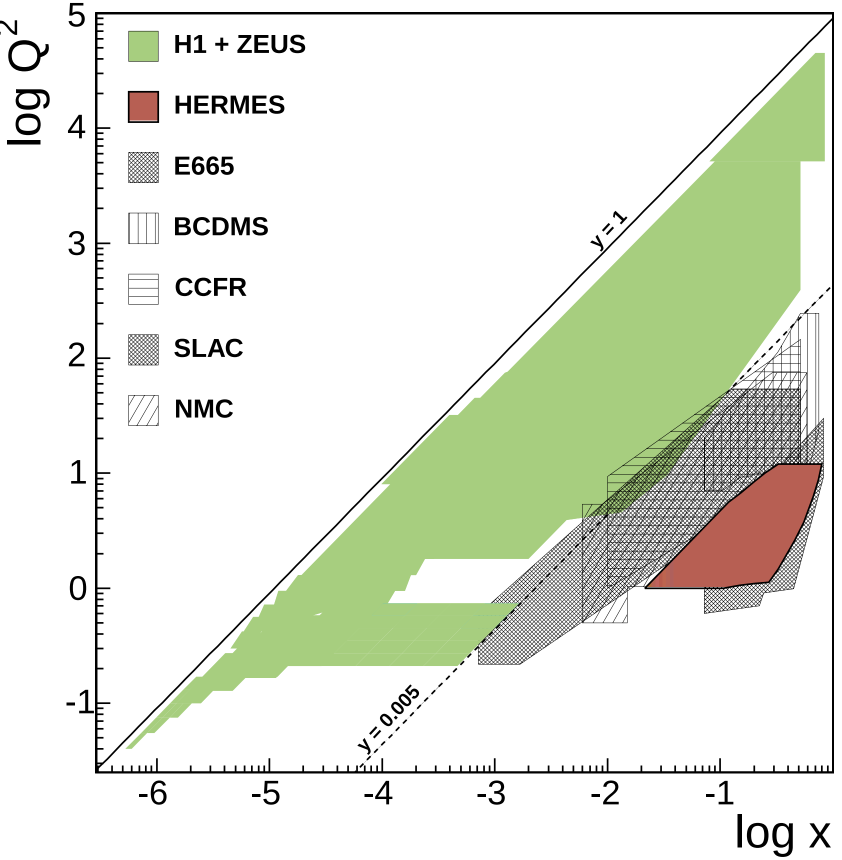
(b)

Leading order $O(\alpha_s)$ modifies QPM picture:

There are 2 contributions:

- QCD Compton - the quark radiates a gluon before or after being stuck by the virtual photon
- Boson Gluon Fusion - the virtual photon & a gluon inside the proton produce a quark-antiquark pair

HERA kinematic range



HERA extends the kinematic reach of previous DIS expt:

- Q^2 in range 10^{-1} to 10^5 GeV^2
- x down to 10^{-6}

extension by two orders of magnitude in both x and Q^2

DIS NC X-section

$$\frac{d^2\sigma^{e^\pm p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left(Y_+ F_2(x,Q^2) - y^2 F_L(x,Q^2) \quad Y_- x F_3(x,Q^2)\right)$$

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

$$F_2 = \quad e_i^2\left(q(x) + \bar{q}(x)\right) \quad \text{(in QPM)}$$

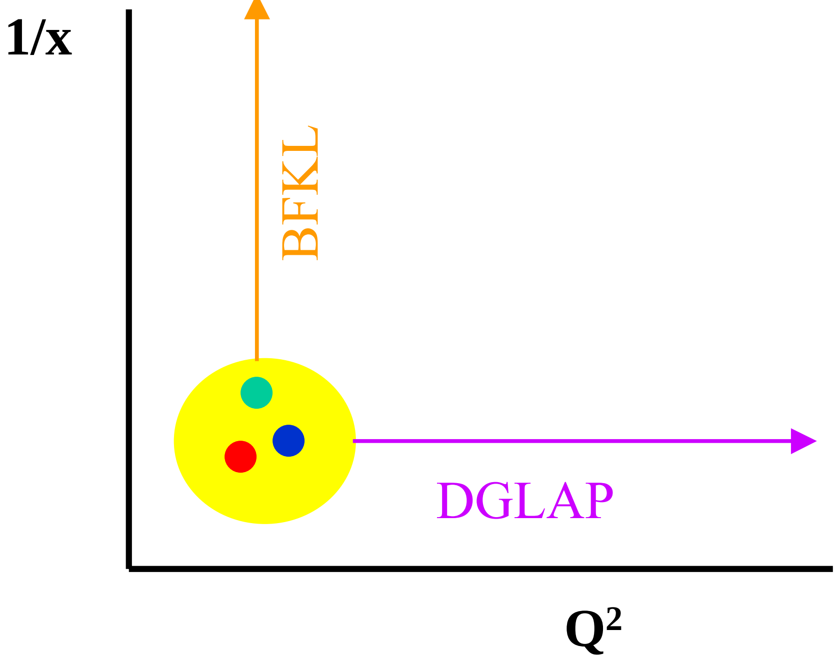
F_L – long. str. fnc; important only for $y > 0.6$

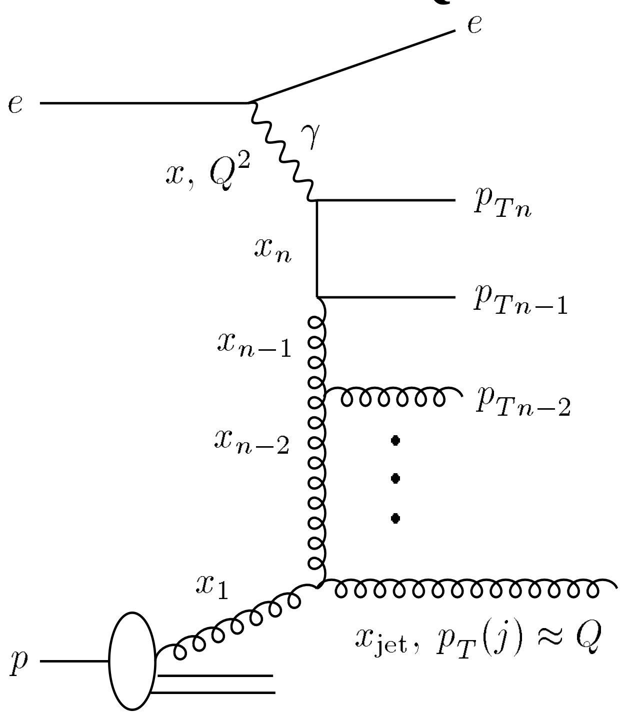
F_3 – arises from Z-exchange;

negligible for $Q^2 < 5000\ \text{GeV}^2$

DGLAP vs BFKL

Parton Evolution in DIS





DGLAP	BFKL
Strong p_T ordering	No p_T ordering
Soft frac. mom. ordering	Strong frac. mom. ordering

NLO QCD Fits

DGLAP predicts Q^2 evolution of $F_2(x,Q^2)$ for given parton densities at $Q^2 = Q^2_0$

H1 fit

$Q^2_0 = 1$ GeV^2

$$\text{gluon}: xg(x,Q_0^2) = A_g x^{B_g}(1-x)^{C_g}$$

$$\text{valence } u_v : xu_v(x,Q_0^2) = A_u x^{B_u}(1-x)^{C_u}(1+D_u x^{E_u})$$

$$\text{valence } d_v : xd_v(x,Q_0^2) = A_d x^{B_d}(1-x)^{C_d}(1+D_d x^{E_d})$$

$$\text{sea}: xS(x,Q_0^2) = A_S x^{B_S}(1-x)^{C_S}$$

strange quarks: $\bar{s} = \bar{u}/2$

assume $\bar{u}-\bar{d}$ param. from MRS

$\alpha_s(M_Z)=0.118$

ZEUS fit

$Q^2_0 = 7$ GeV^2

$$\text{gluon}: xg(x,Q_0^2) = A_g x^{\delta_g}(1-x)^{\eta_g}(1+\gamma_g x)$$

$$\text{sea}: xS(x,Q_0^2) = A_S x^{\delta_S}(1-x)^{\eta_S}(1+\gamma_S x+\varepsilon_S\sqrt{x})$$

$$u-d \text{ difference}: x\Delta_{ud}(x,Q_0^2) = A_\Delta x^{\delta_\Delta}(1-x)^{\eta_\Delta}$$

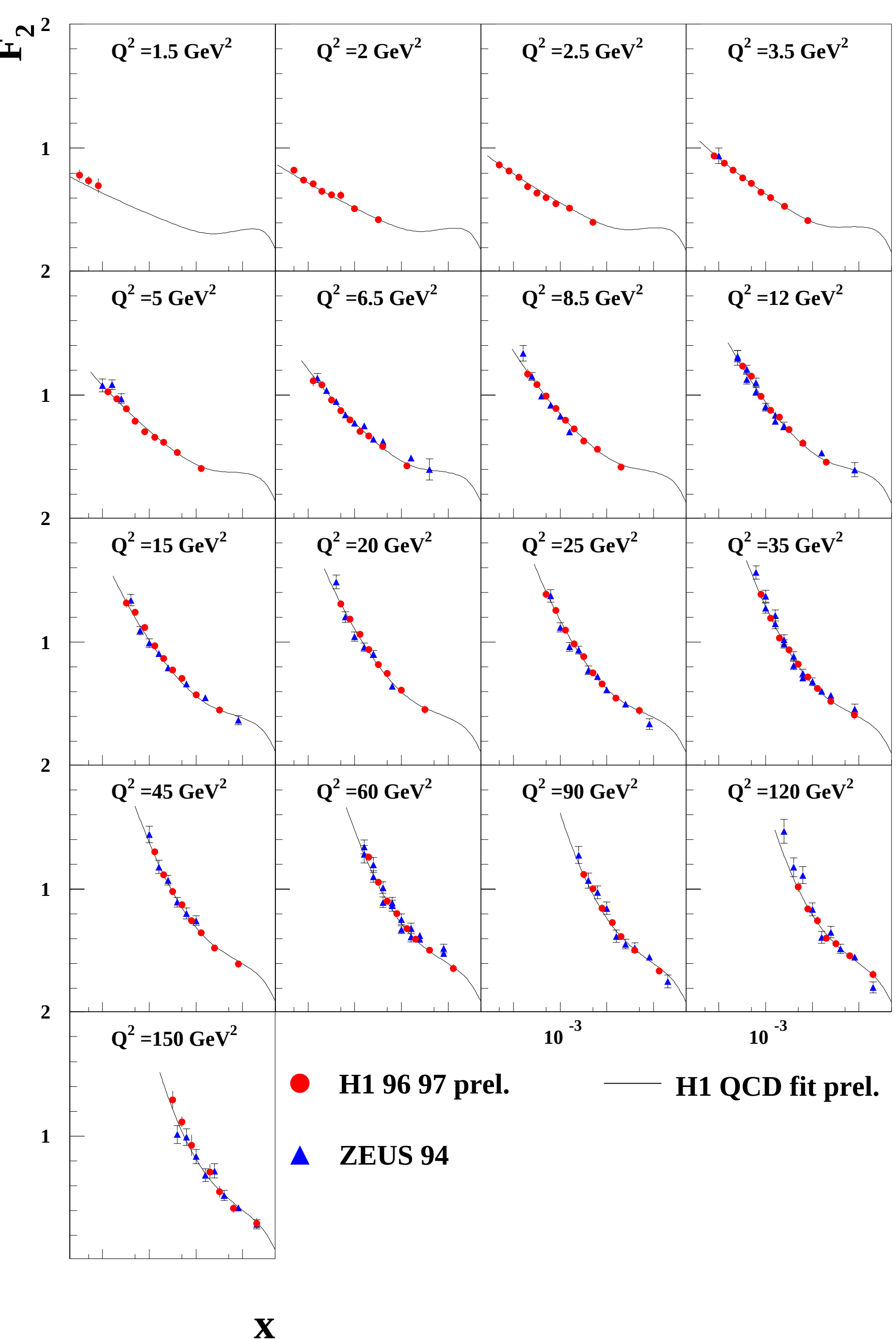
strange quark assumed 20% of sea

valence quarks from MRS(R2)

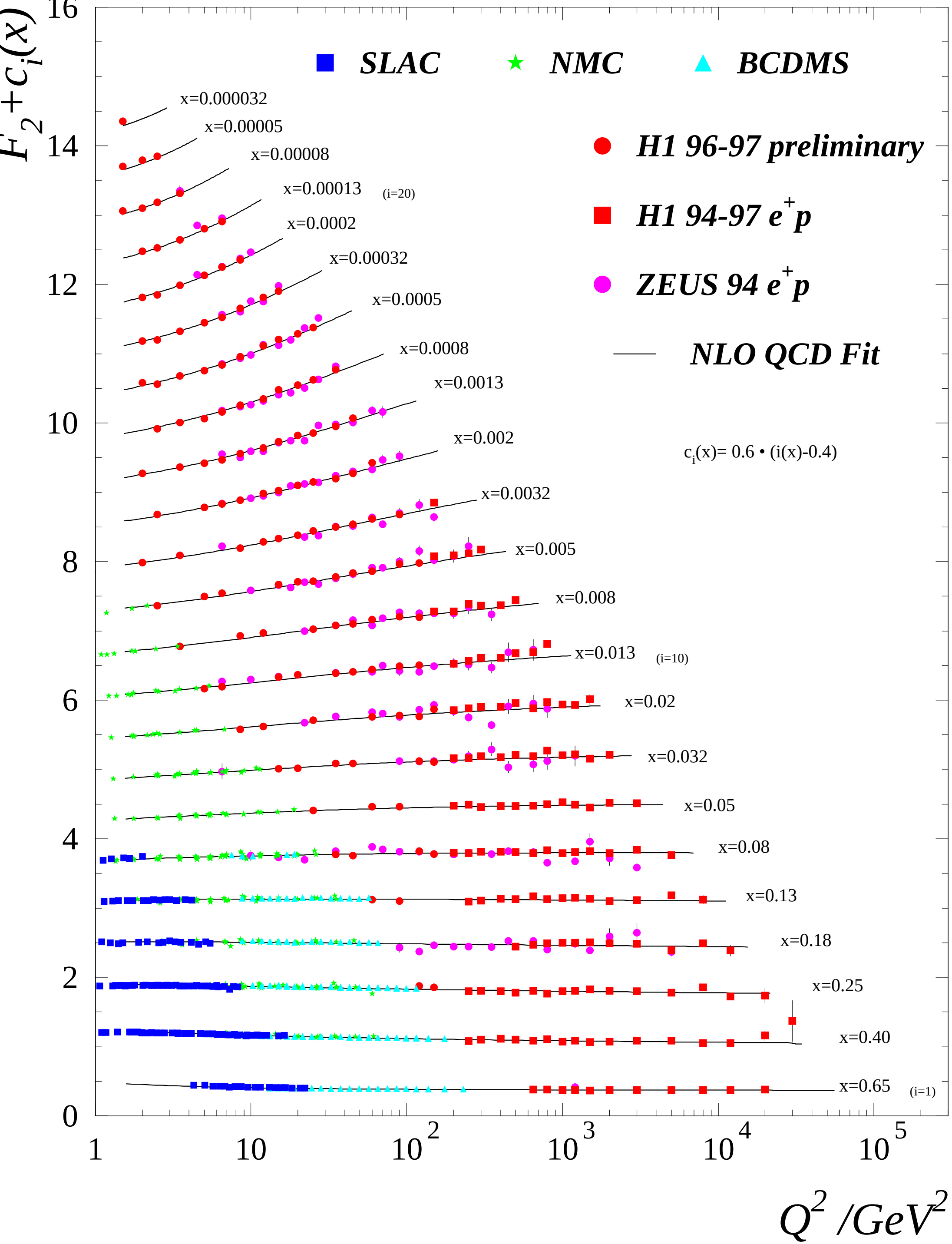
$\alpha_s(M_Z)=0.118$

- fixed flavour scheme - 3 light flavours, heavy flavours in NLO via BGF
- momentum sum rule
- quark counting rules

HERA



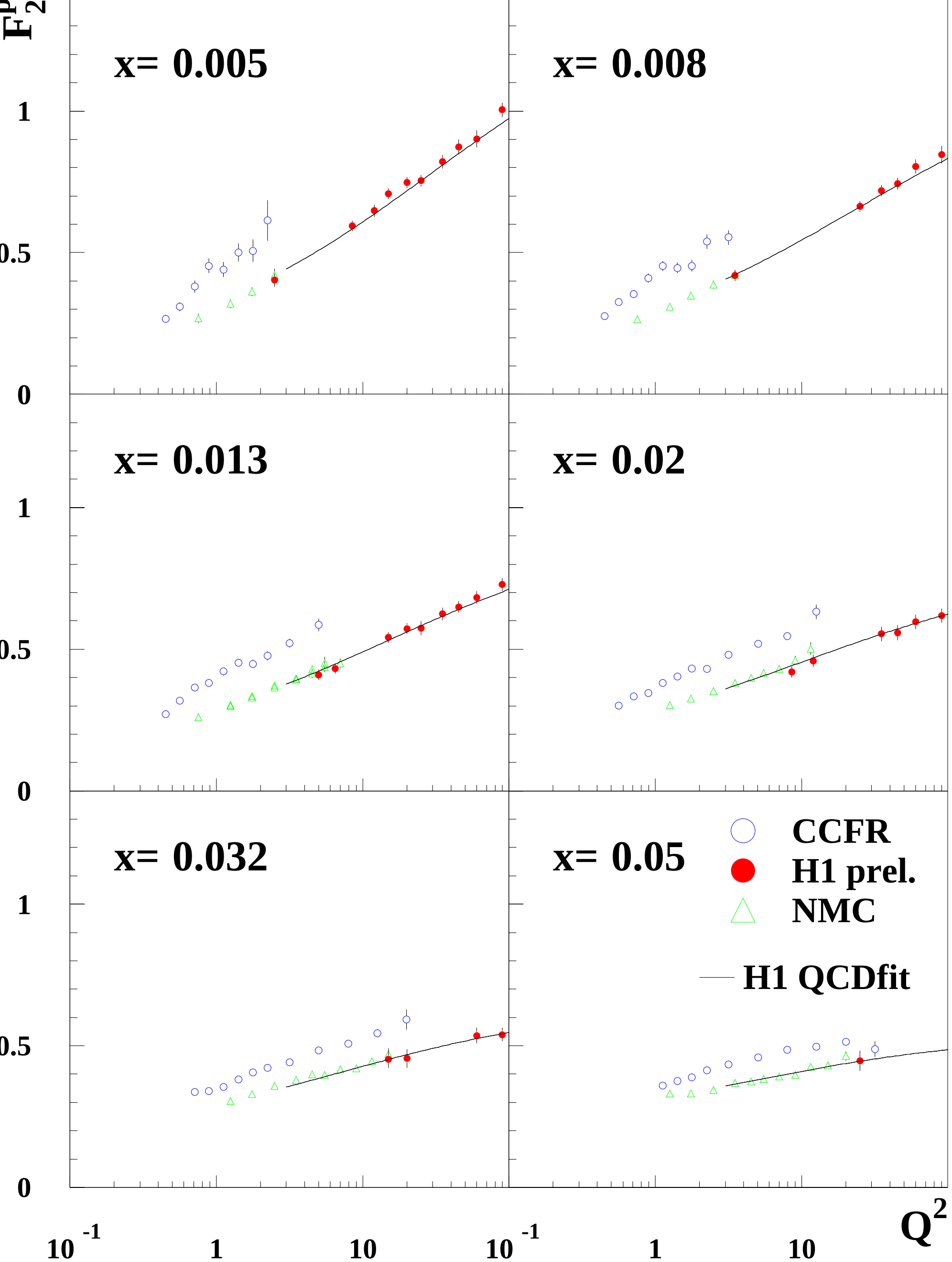
- strong rise of F_2 at low x
- good agreement between expts
- systematically dominated (2-3%) up to $Q^2 \approx 1000$ GeV^2



NLO DGLAP fit gives good description of the HERA & fixed target data

Scaling violation well interpreted by QCD

No indication of $(\log 1/x)^n$ corrections in HERA regime

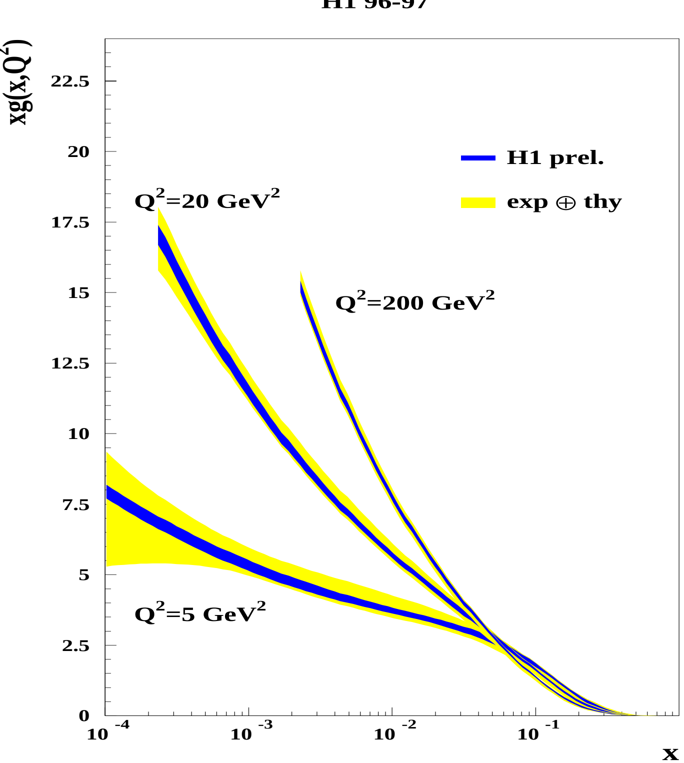


Long standing controversy between μp (NMC, E665) and νN (CCFR) data

H1 data overlap and extrapolate well to μp data

CCFR data being re-analysed, with new treatment of charm and shadowing

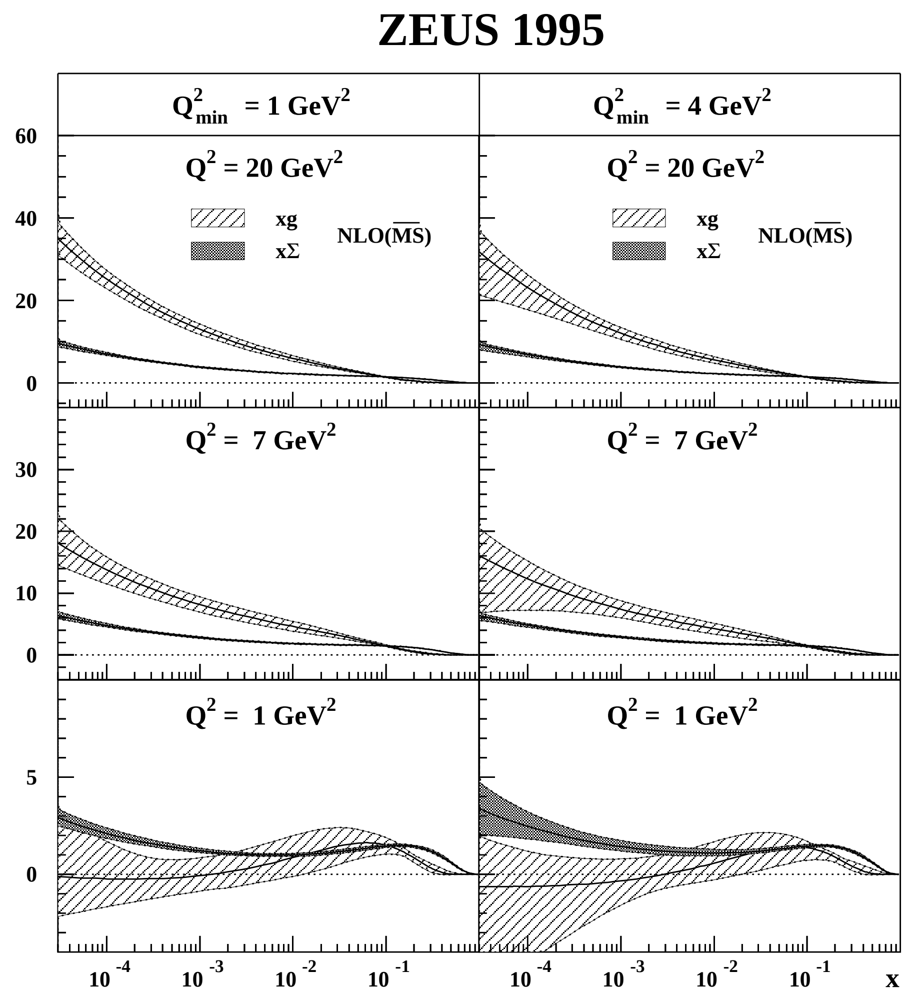
Gluon Determination



Strong rise in xg as x↓

10% uncertainty at Q^2=20 GeV^2 & x=5×10^{-5}

F_2 rise at low x not completely driven by the increase of gluon density from parton splitting



Extraction of F_L

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

- subtraction method

$$\sigma_r = \left(\frac{xQ^4}{2\pi\alpha^2 Y_+} \right) \frac{d^2\sigma}{dx\,dQ^2} = F_2 - \frac{y^2}{Y_+} F_L$$

measure σ_r at high y - for $Q^2 << M_Z^2$

fitted F_2 at low y extrapolated to high y & subtract out F_L

★ derivative method

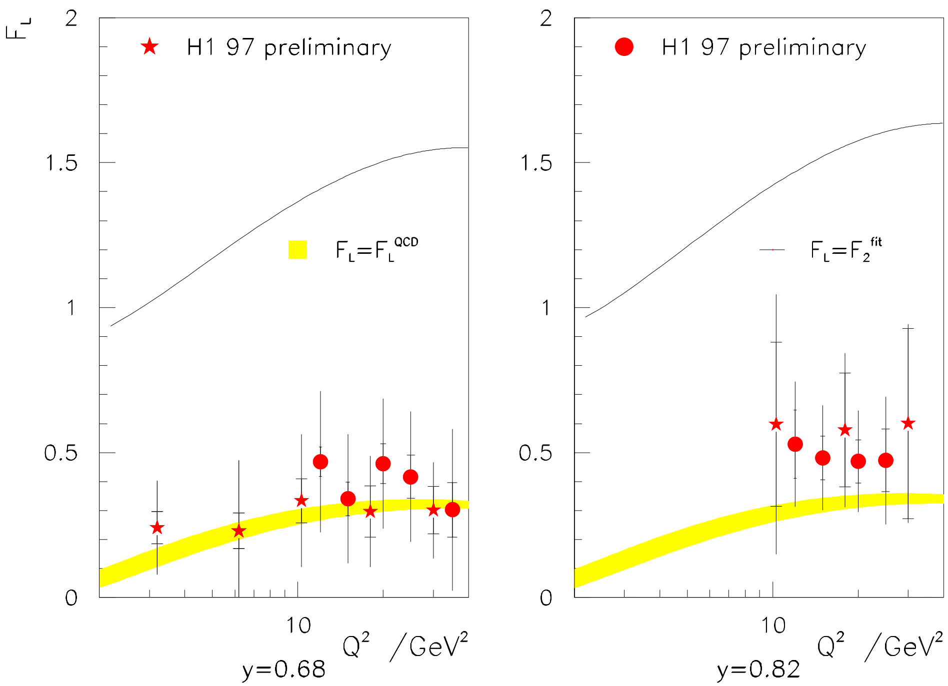
$$\frac{d\sigma_r}{d\log y} = -\frac{dF_2}{d\log y} - 2y^2 \frac{2-y}{Y_+^2} F_L + \frac{y^2}{Y_+} \frac{dF_L}{d\log y}$$

assume $\frac{dF_2}{d\log y} = A\log y + B$

straight line fit to $d\sigma_r / d\log y$ Q^2 bins at $y < 0.2$

Extraction of F_L

★ derivative ● subtraction

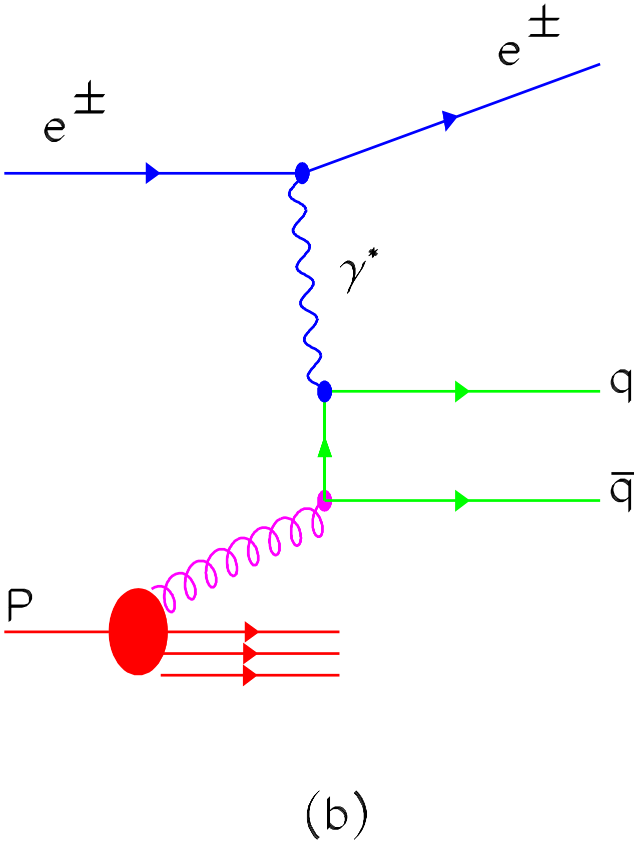


F_L compatible with QCD predictions

Both methods in agreement

Direct measurement needs different beam energies or ISR events

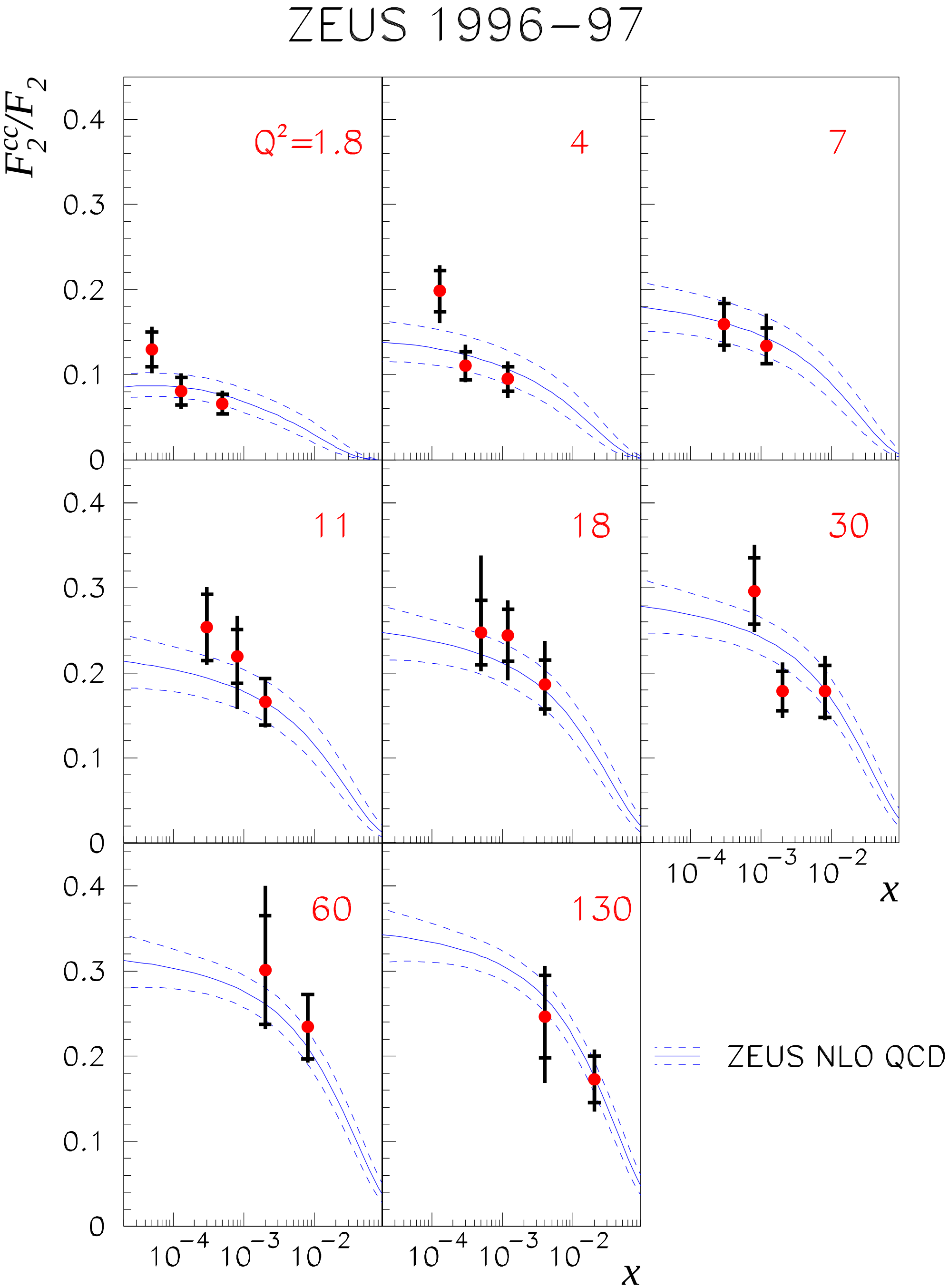
Investigation of gluon via charm production



- Charm production dominated by BGF diagram

probe of the gluon density

- investigate via D^* production



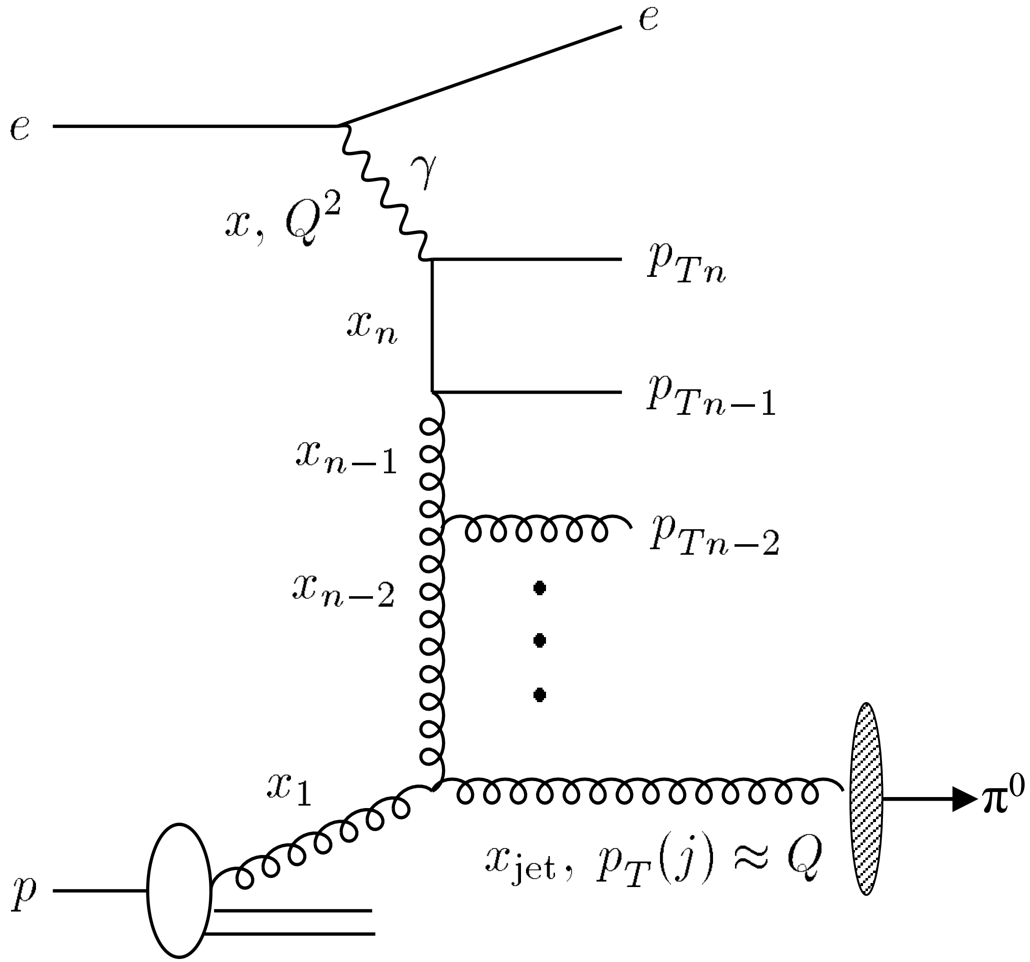
$F_c \approx 25\%$ at low x & high Q^2

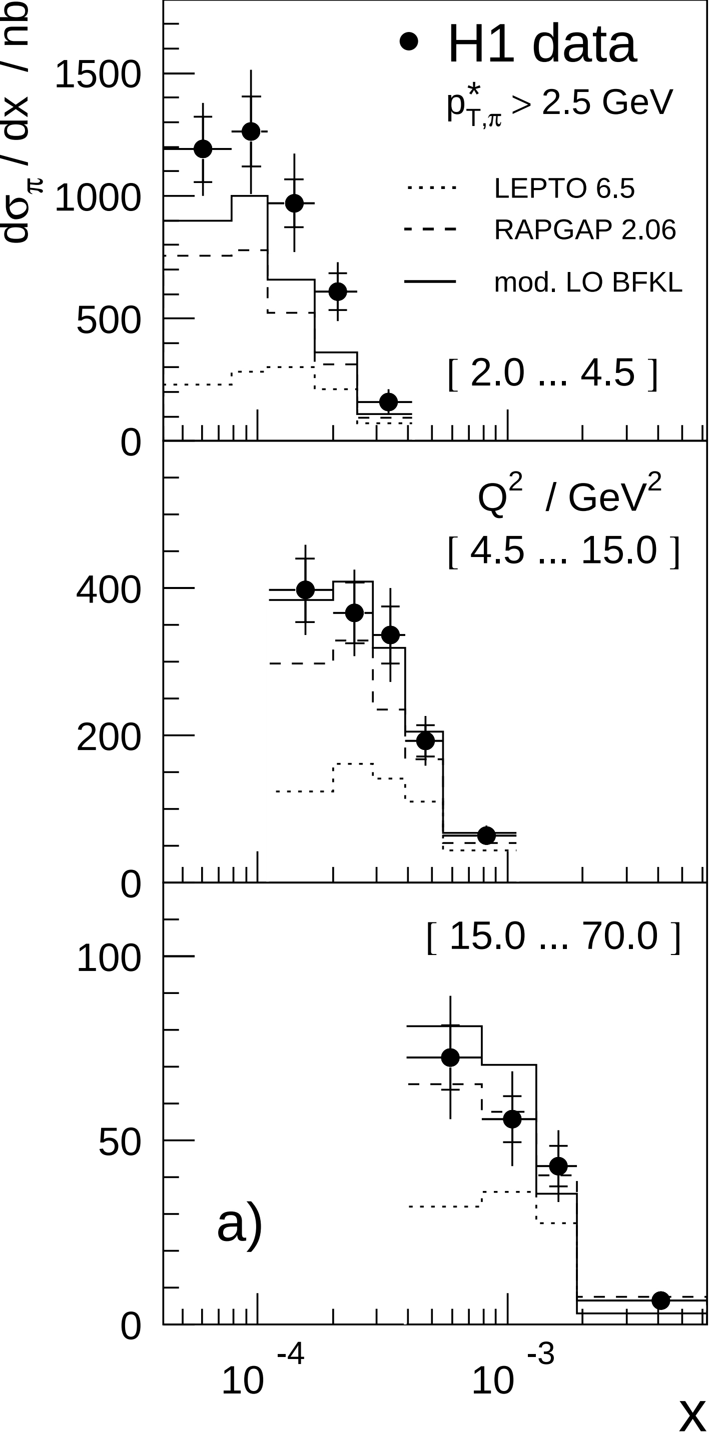
F_c at Q^2=1.8 GeV^2 is $\approx 10\%$

F_c rising quicker than F_2

DGLAP vs BFKL –forward π^0 production

BFKL predicts greater forward π^0 production than DGLAP expectation





MC models implementing DGLAP evolution fail to describe π^0 data

adding resolved component to incoming virtual photon improves description of data

BFKL formalism gives good description of data. Still question marks over absolute normalisation

Event Shape Variables

Any 'infra-red' safe event variable <F> can be written as

$$\langle F \rangle = \langle F \rangle^{\text{pert}} + \langle F \rangle^{\text{pow}}$$

Log change of the strong coupling const ∝ 1/log(Q)

Power corrections or hadronisation effects ∝ 1/Q

1/Q corrections not necessarily related to hadronisation

BUT

soft gluon phenomenon at small momentum scales

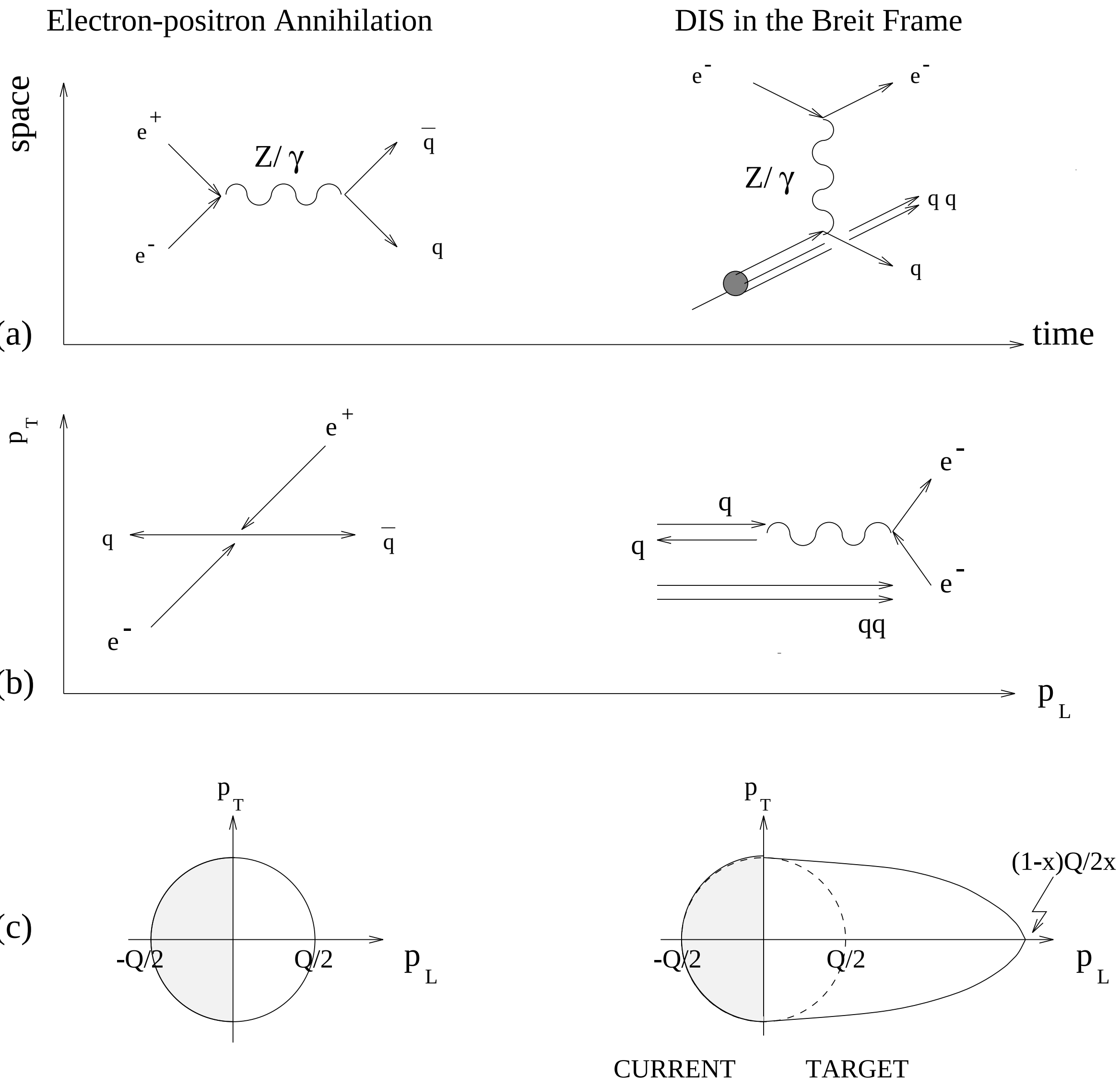
$$\langle F \rangle^{\text{pert}} = c_1(x,Q)\alpha_s(\mu_R) + \left[c_2(x,Q) + \frac{\beta_0}{2\pi}\log\left(\frac{\mu_R}{Q}\right)c_1(x,Q) \right]\alpha_s^2(\mu_R)$$

c_1 & c_2 are coefficients in the $\overline{\text{MS}}$ scheme

μ_R is the renormalisation scale taken to be Q

The Breit Frame

`Brickwall' frame



Phase space for e^+e^- annihilation evolves with $Q/2 = \sqrt{s}/2$

Current hemisphere of Breit frame evolves as Q/2

Current region ≡ e^+e^- annihilation

Thrust T_C or T_m

$$\tau_C = 1 - T_C = 1 - \max \frac{{}_h\left|p_h . n_T\right|}{{}_h\left|p_h\right|} ; n_T \equiv \text{thrust axis}$$

C parameter

$$C = 3\left(\lambda_1\lambda_2 + \lambda_2\lambda_3 + \lambda_3\lambda_1\right)$$

where λ_i are the eigenvalues of the momentum tensor

$$\Theta_{jk} = \frac{{}_h p_{j_h} p_{k_h} \big/ \left|p_h\right|}{{}_h\left|p_h\right|}$$

Thrust T or T_Z

$$\tau = 1 - T = 1 - \frac{{}_h\left|p_h . n\right|}{{}_h\left|p_h\right|} ; n \equiv \text{hemisphere axis}$$

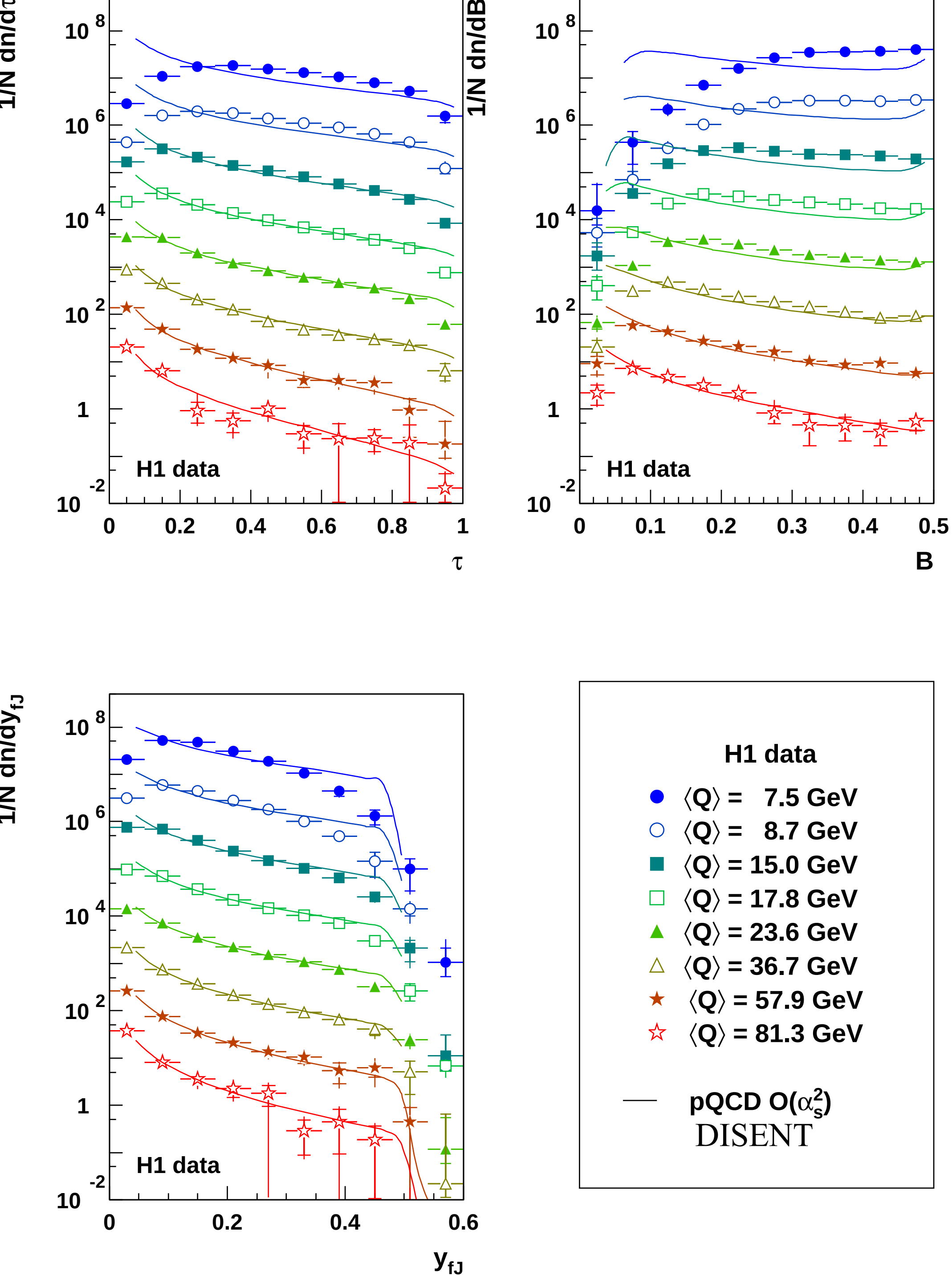
y_{fJ} & y_{k_t} are transition values for (2+1) →(1+1) jets for the factorisable JADE algo. & the k_t algo. respectively

Jet mass ρ

$$\rho = \frac{M^2}{\left(2E_{\text{tot}}\right)^2} = \frac{\left({}_h p_h\right)^2}{4\left({}_h E_h\right)^2}$$

Jet Broadening B

$$B = \frac{{}_h\left|p_h \times n\right|}{2\ {}_h\left|p_h\right|} = \frac{{}_h\left|p_{\perp h}\right|}{2\ {}_h\left|p_h\right|}$$



Data vs NLO

Events more pencil like as $Q^2 \uparrow$

Non-pert corrections decrease as $Q^2 \uparrow$

Non-pert correction for jet variables smaller over all Q^2

$$\langle F \rangle^{\text{pow}} = a_F \frac{32}{3\pi^2} \frac{M}{p} \left(\frac{\mu_I}{Q} \right)^p \left[\overline{\alpha}_{p-1}(\mu_I) - \alpha_s(Q) - \frac{\beta_0}{2\pi} \left(\ln\frac{Q}{\mu_I} + \frac{K}{\beta_0} + \frac{1}{p} \right) \alpha_s^2(Q) \right]$$

β_0, K are constant dependent on number of flavours

μ_I - \`infra-red' matching scale, $\mu_I = 2$ GeV

Power correction fit

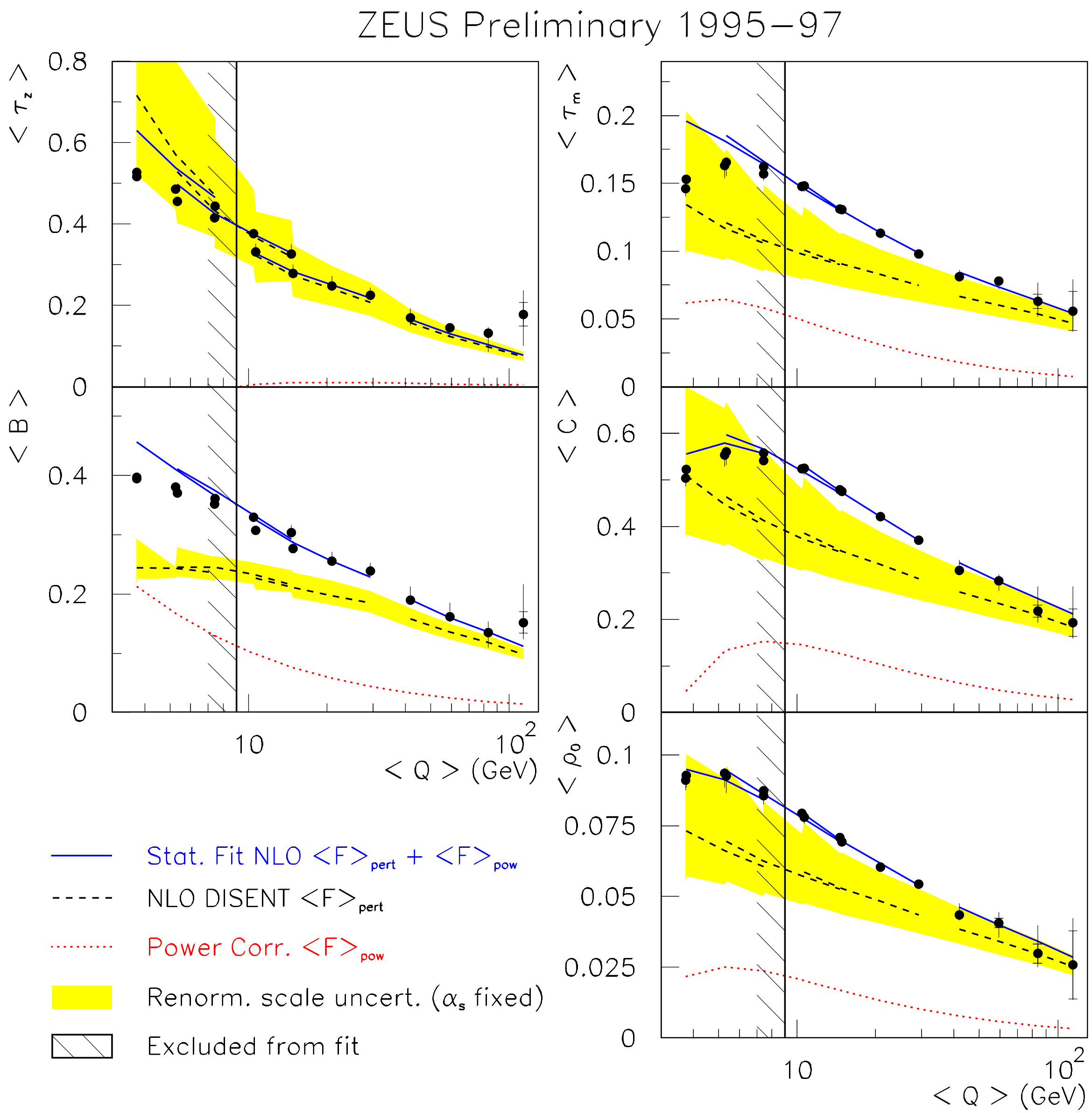
a_F, p - calculable coeff dependent on observable F

$p = 1$ except for y_{k_t} where $p = 2$

For $B, a_F = \mathrm{F}(\alpha_{s-CMW}(Qe^{-3/4}), N_f)$

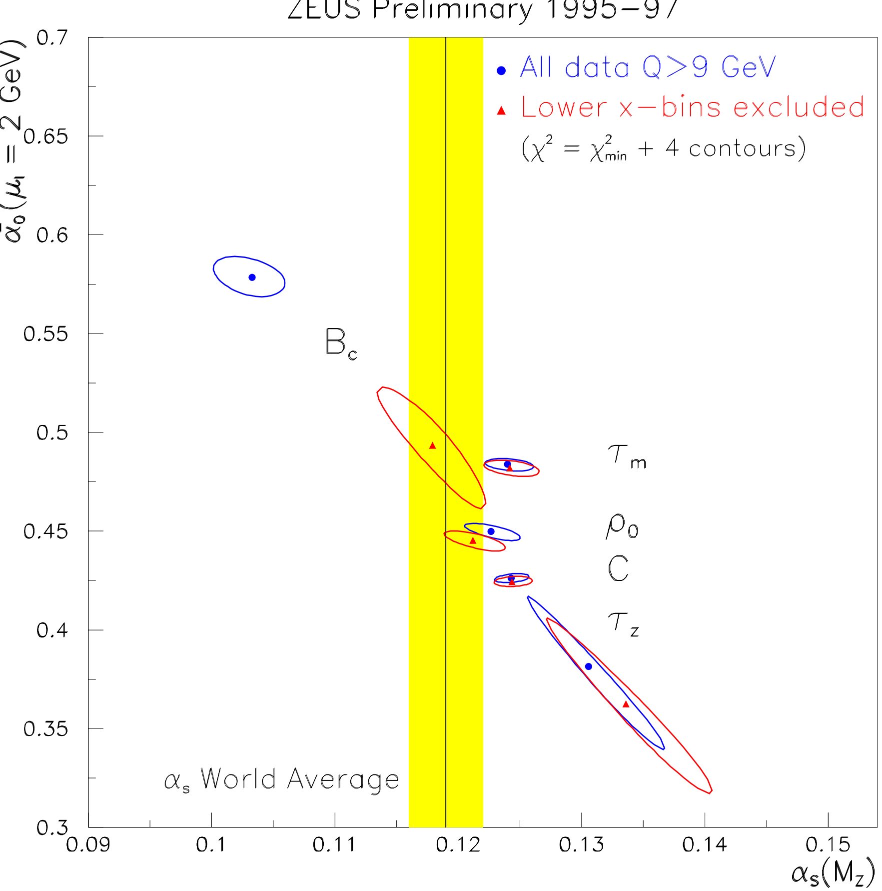
$M \approx 1.43$ - 2-loop correction (Milan factor)

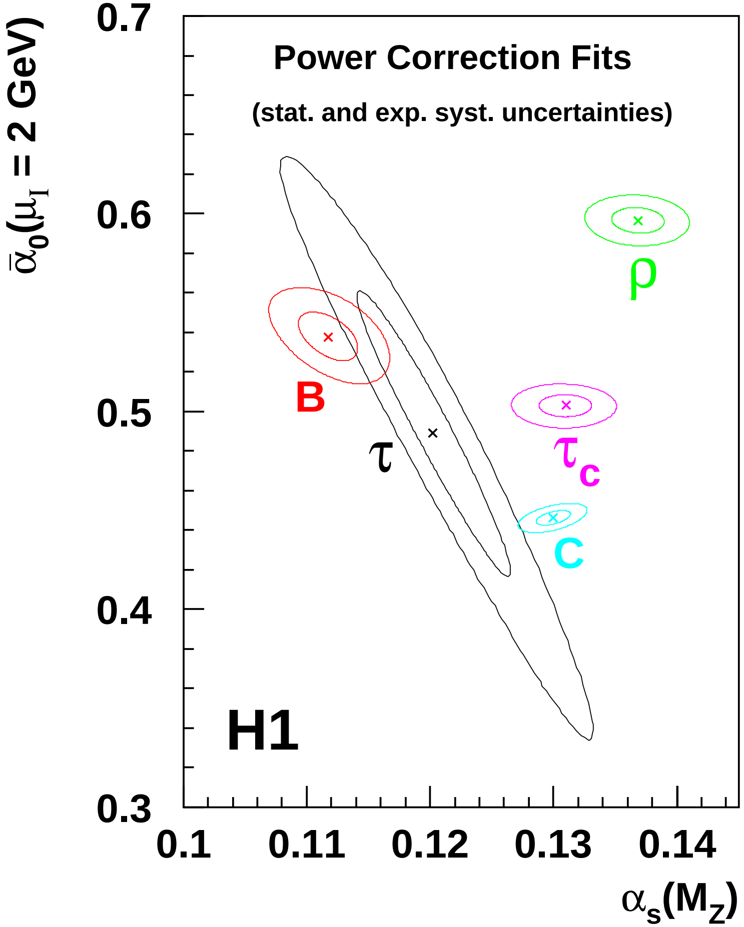
$\overline{\alpha}_{p-1}$ - an universal, non-pert. effective strong coupling below μ_I



Reasonable fit to data

Closer examination shows NLO calculation (for B in particular) has wrong x dependence



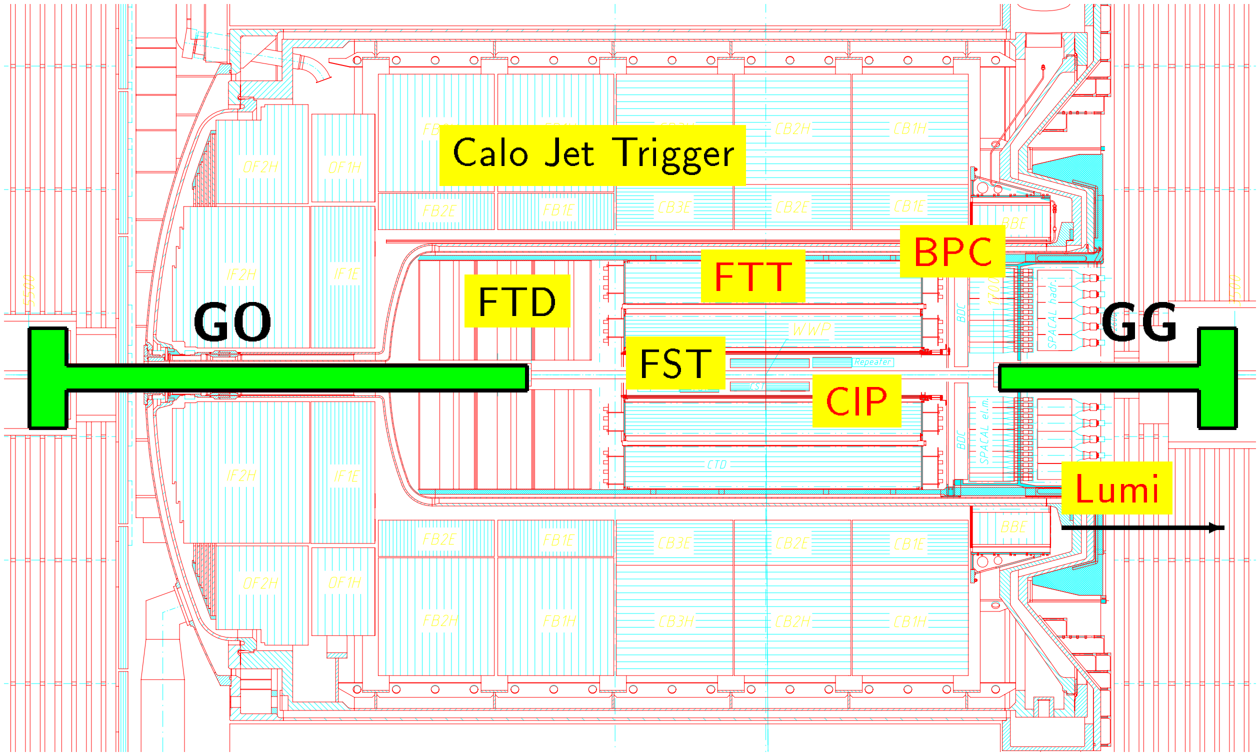


x-dependence on result, particular for *B* and *T*

H1 & ZEUS consistent (exception ρ, where different def^n used)

y_{fJ} power correction coeff a_F not compatible with data

Upgrade of HERA & Detectors



- Magnets around beamline (including inside detector vol)
- β functions reduced by factors of 4-5
- increased currents

  factor of 5 increase in luminosity

e-polarisation

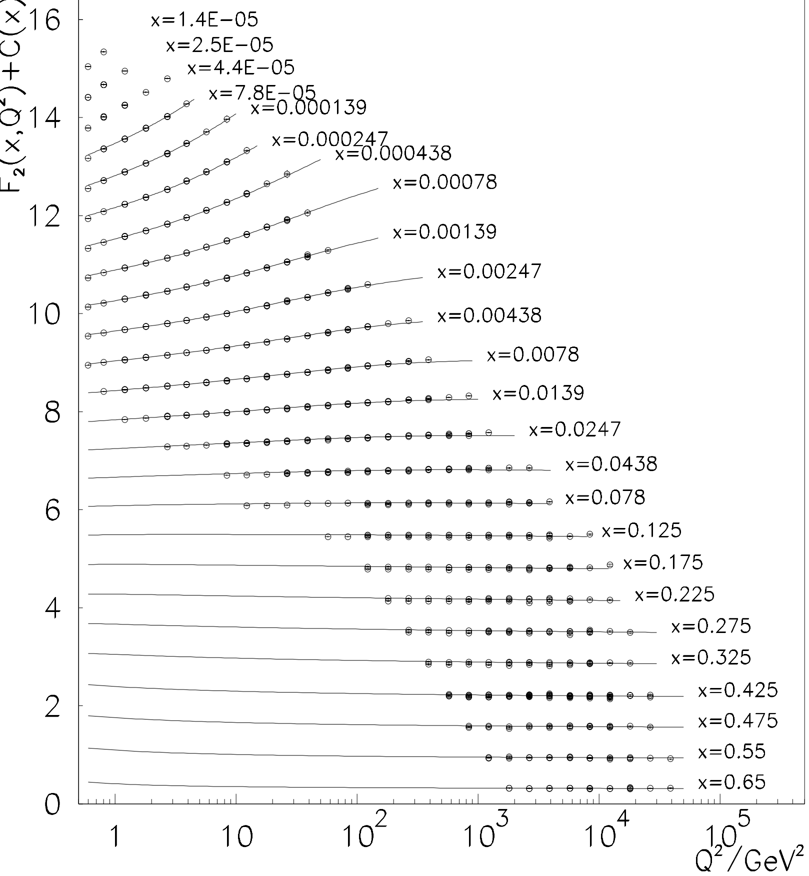
forward tracking upgrade

new lumi detectors

microvertex detector(ZEUS)

improved tracking trigger (H1)

⋮



simulation of F_2 with 1 fb^{-1} at HERA

measurements of F_c and F_b to 5% & 10% respectively

stringent tests of QCD evolution

important expt. input to future hadron colliders !

precision on $\alpha_s(M_Z)$ 0.001

gluon density extraction to 1%

Summary

- structure func precision a few %

- DGLAP evolution OK down to $Q^2 \approx 1$ GeV^2

- F_c up to 25% of F_2

- an indirect measurement of F_L

- event shapes in reasonable agreement with NLO & power corrections. Still outstanding questions

- HERA high luminosity running deliver 1 fb^{-1} per expt. during 2001 $\rightarrow$ 2006