Highlights from HERA

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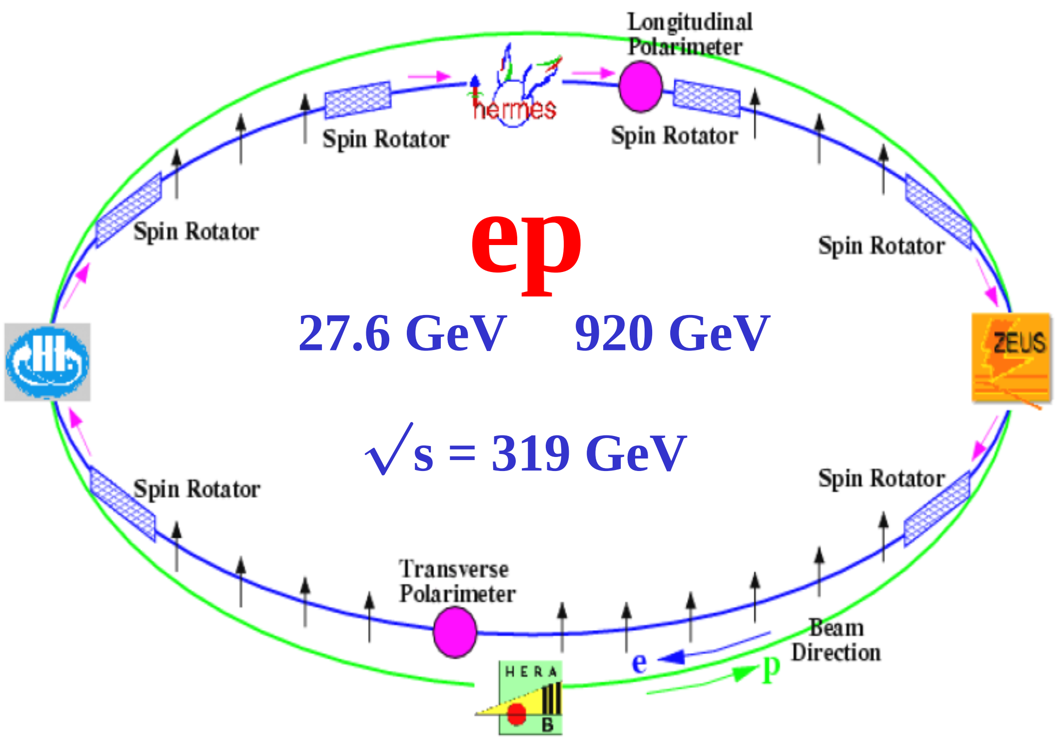
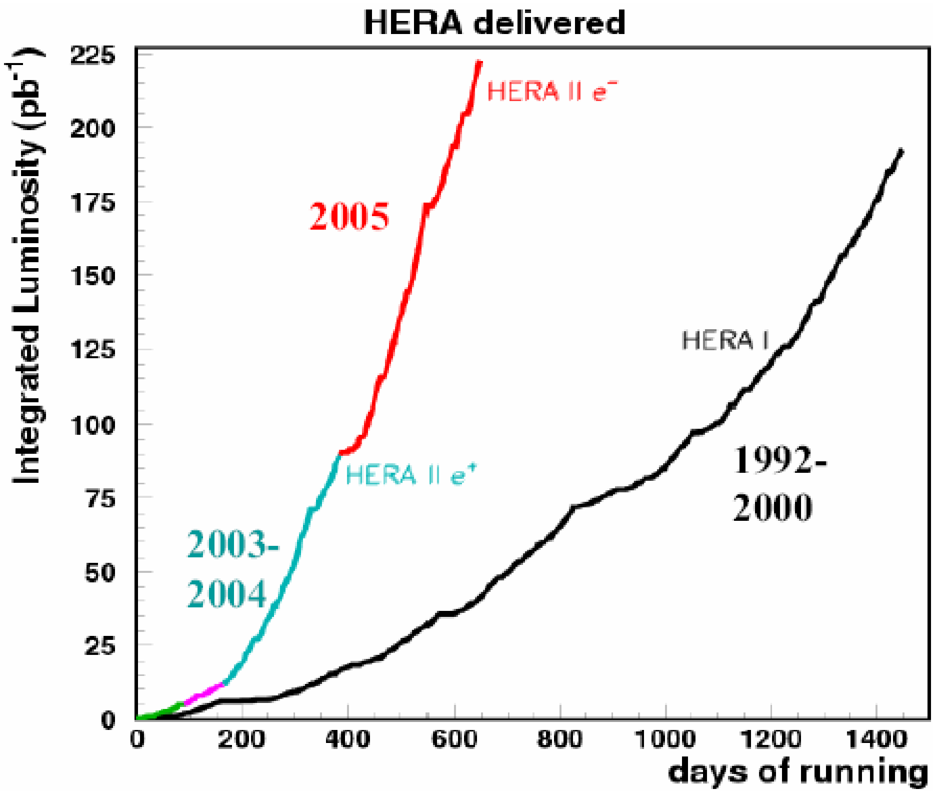


- HERA performance
- Structure functions/PDFs
- Strong coupling α_s , jets
- Heavy flavour production
- Diffr. & QCD factorisation
- J/Ψ / DVCS / GPDs
- Searches for new physics
- Summary & Outlook

HERA II performance



HERA II:

- detectors and luminosity upgrade

	e^+p	e^-p
HERA I:	100 pb^{-1}	20 pb^{-1}
HERA II:	50 pb^{-1}	100 pb^{-1}

- longitudinally polarised e beam in the colliding experiments

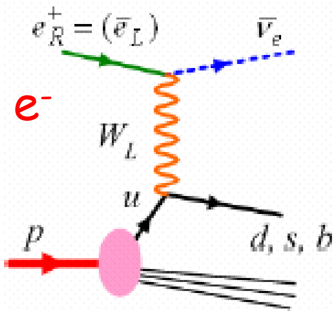
natural transverse polarisation
(Sokolov-Ternov effect)
+ spin rotators

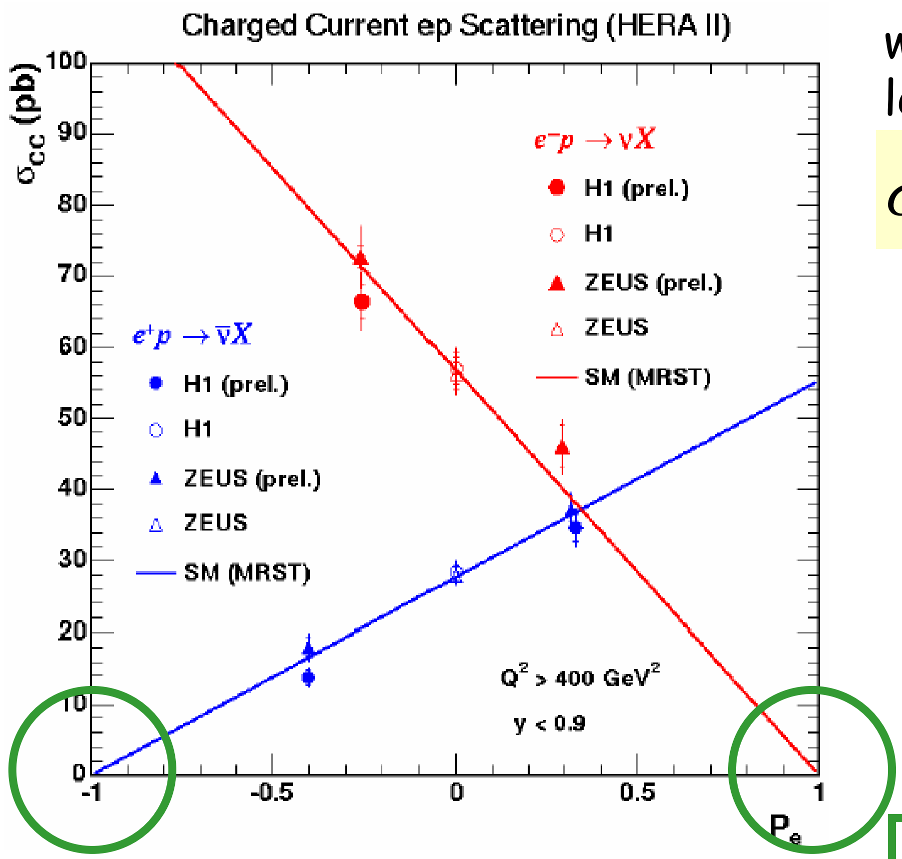
typically P_e~40%
build-up time ~30min

data taking till mid 2007:
~O(0.7) fb^{-1} per experiment in total

The first results from HERA II

σ_{CC} total cross section using longitudinally polarised e^+ and e^-





weak CC is pure left-handed (V-A):

$$\sigma_{CC}^{e^\pm p}(P_e) = (1 \pm P_e)\sigma_{CC}^{e^\pm p}(P_e = 0)$$

$P_e = (N_R - N_L)/(N_R + N_L)$

- linear dependence is firmly established both for e^+ and e^-
- in agreement with SM
- extrapolation to P_e=-1 (e^+p):

$$\sigma_{CC}^{e^+p}(P_e = -1) = -0.2 \pm 1.8(\mathrm{sta}) \pm 1.6(\mathrm{sys})\,\mathrm{pb}$$

-> consistent with zero

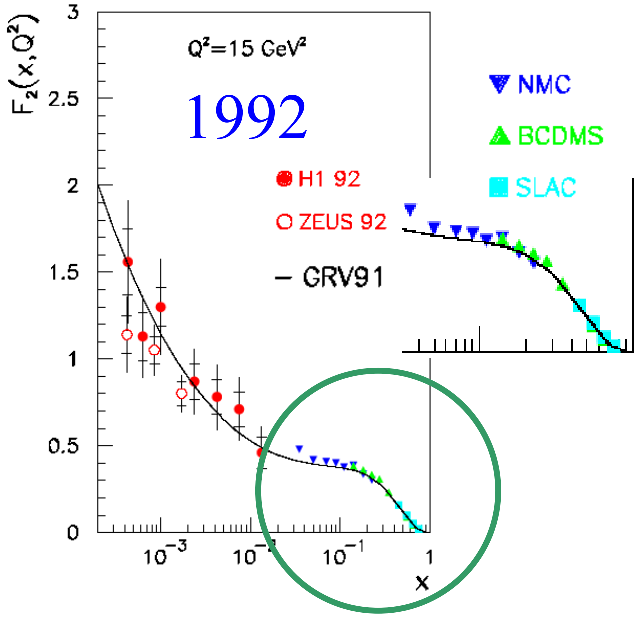
extrapolations to P_e=-1,+1 test the absence of right-handed weak current

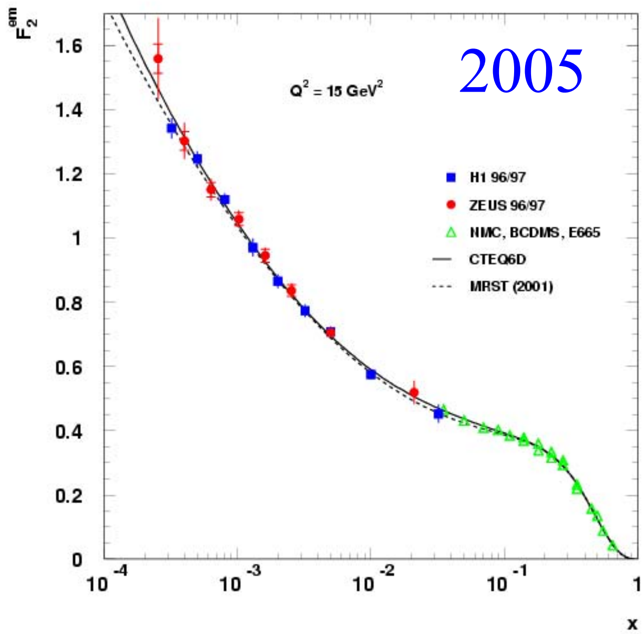
HERA: the QCD machine

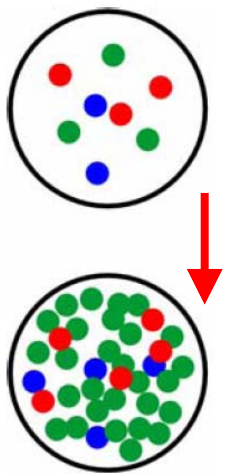
2004 Nobel Prize in Physics for the Discovery of Asymptotic Freedom

David Gross, David Politzer, Frank Wilczek

Frank Wilczek: **… The most dramatic of these (experimental consequences), that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA twenty years later**. …

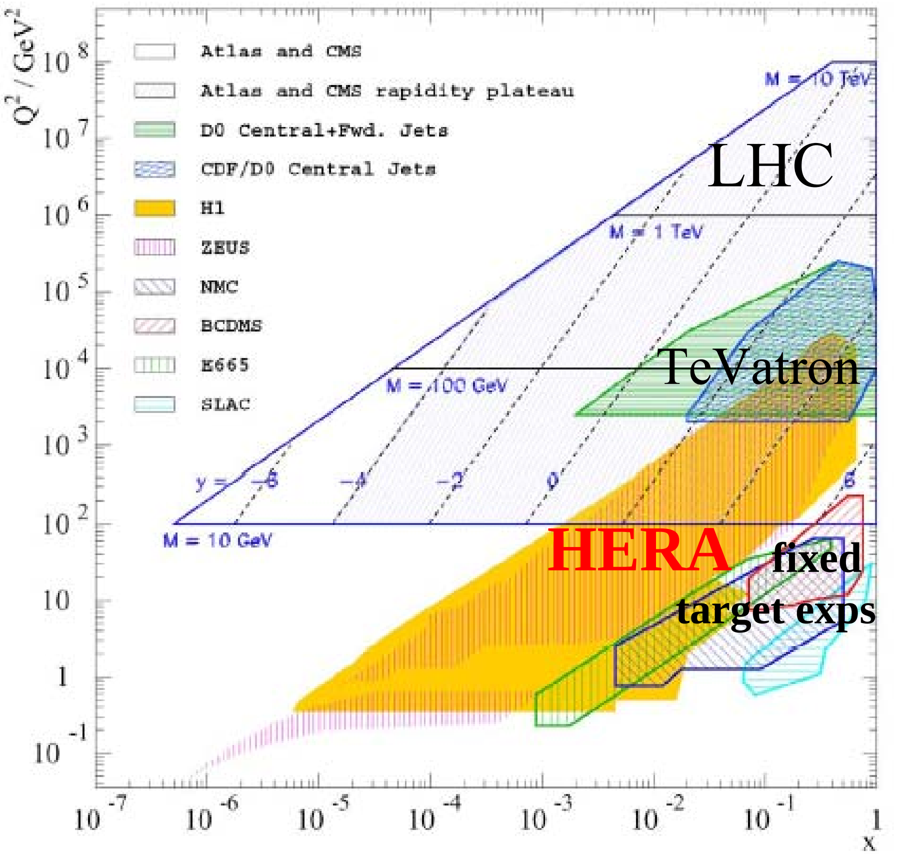






Study of the Nucleon Structure at HERA

Partonic structure

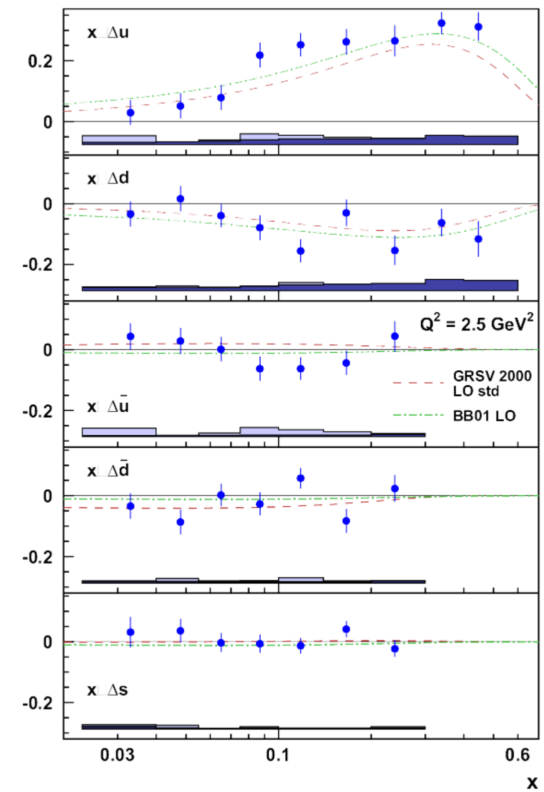


-> full HERA x range is needed for LHC

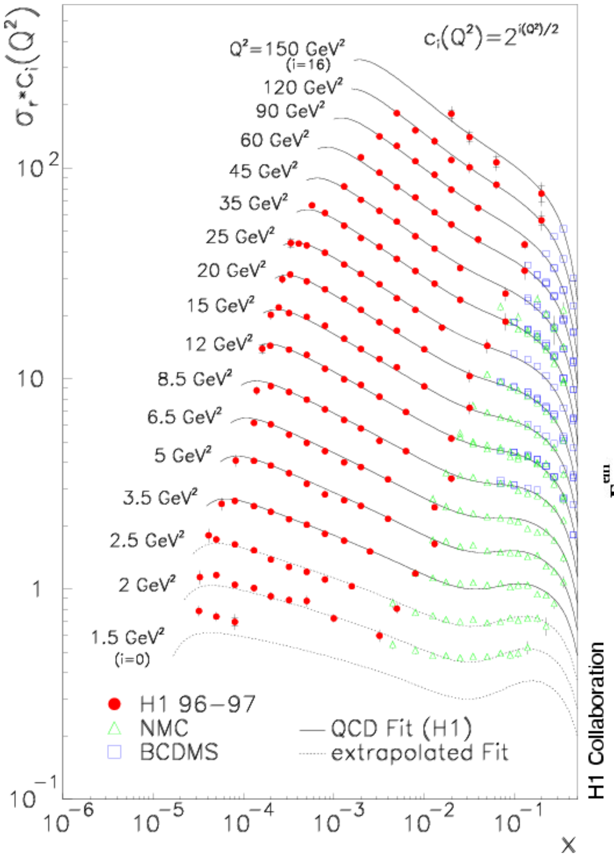
Spin structure

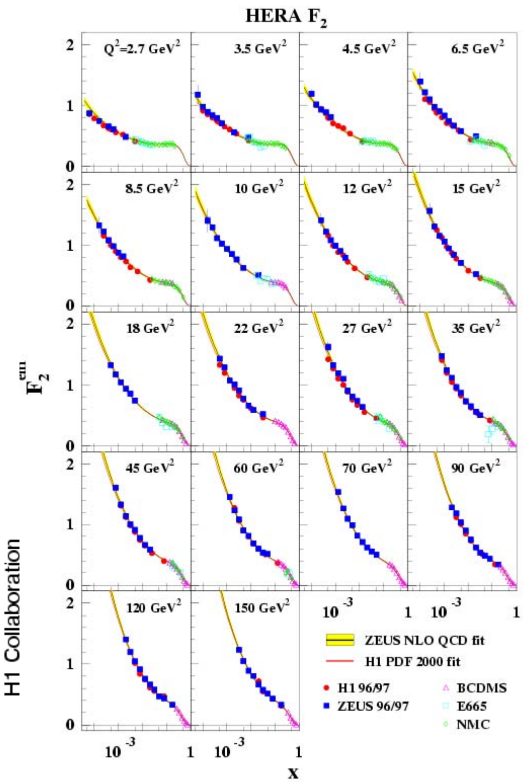
polarised target and beam (HERMES)

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + L_z$$

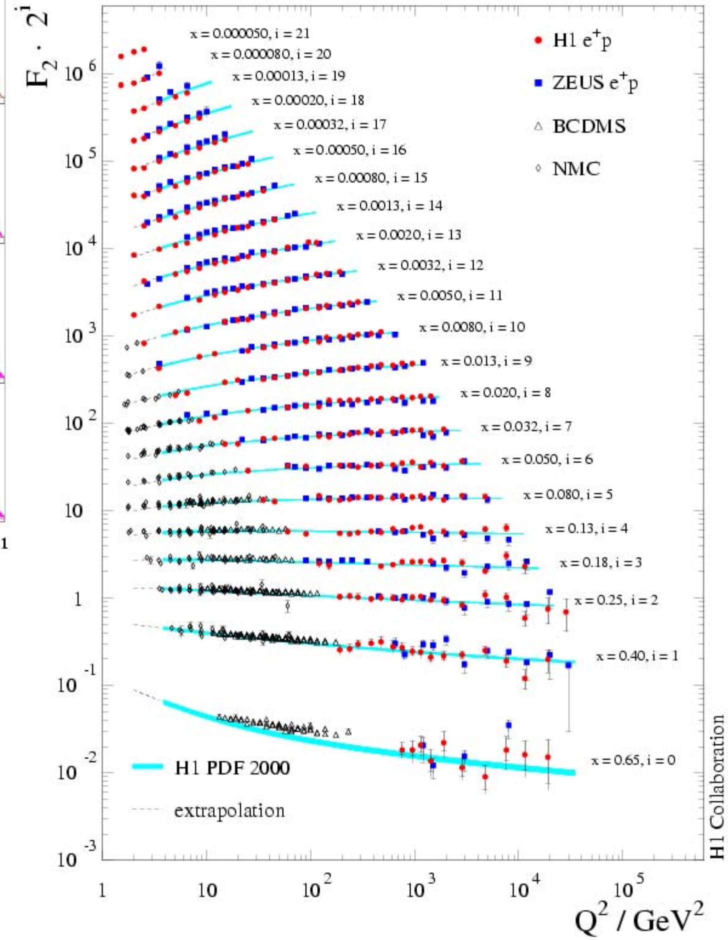


Precise SF data from HERA





precision data ±2-3%
5 decades in x
5 decades in Q^2

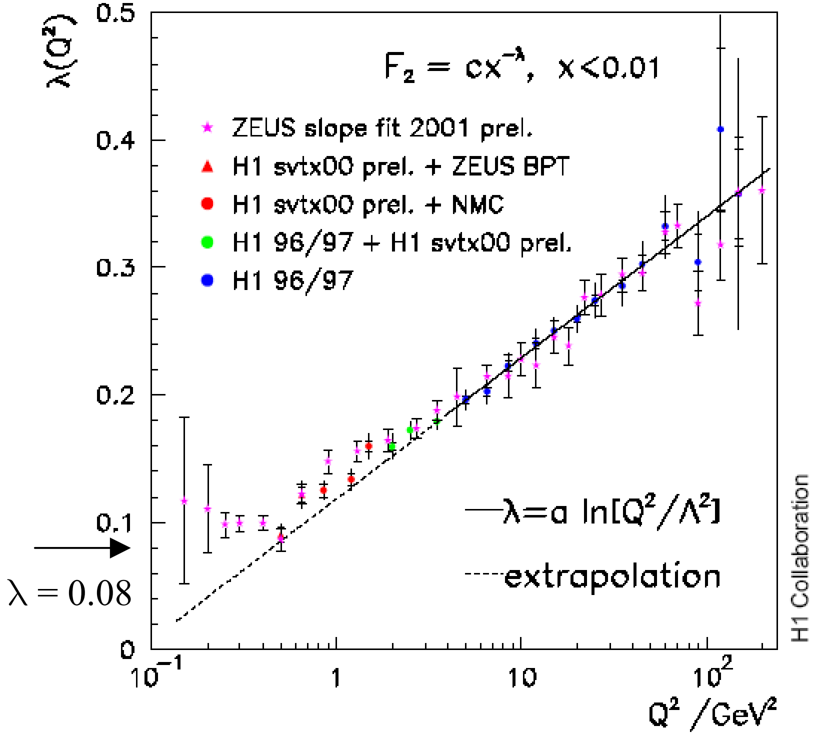


rich possibilities to determine pdfs,
test QCD (DGLAP, BFKL, …),
transition from DIS to γp, …

Low x at HERA

Rise of F_2 towards low x

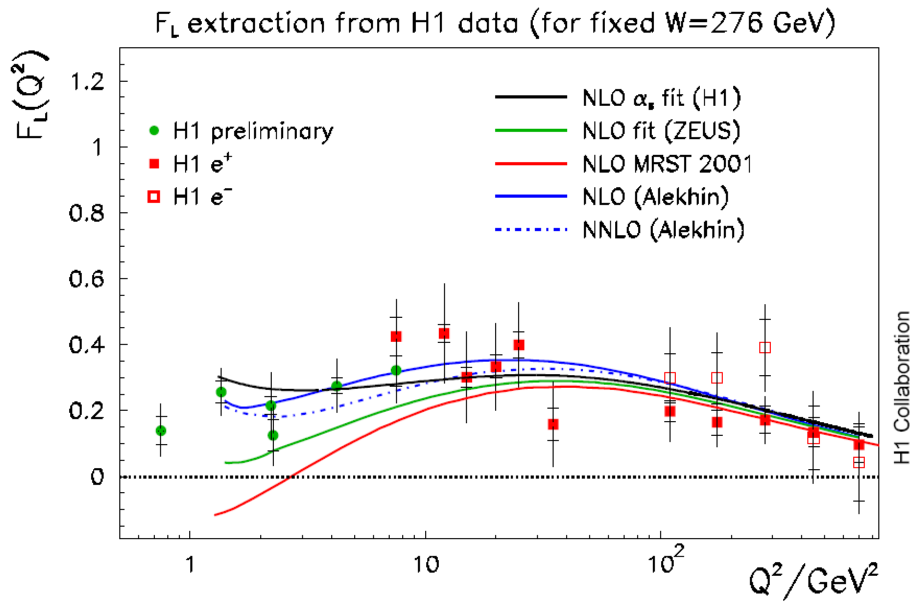
$$F_2(x,Q^2) = c(Q^2)x^{-\lambda(Q^2)}$$



- change of behavior at $Q^2 \approx 1$ GeV^2

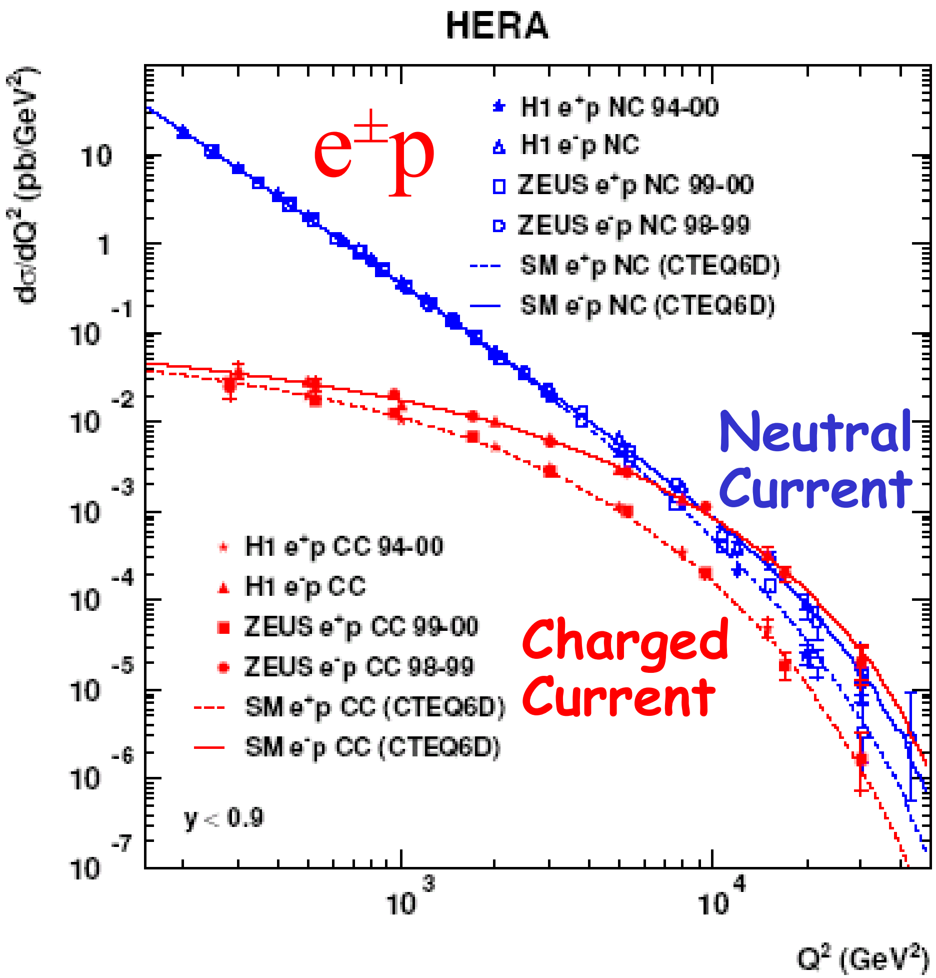
Longitudinal SF $F_L(x,Q^2)$

$$F_L = \frac{Y_+}{y^2}\left(F_2^{QCDfit} - \tilde{\sigma}_{NC}\right)$$



- direct F_L measurements not done at HERA (yet)
  → low proton beam energy running

NC and CC at High Q^2



Probe proton:

quarks are pointlike down to 1/1000 of the proton radius $r < 10^{-18}$ m

EW component of SM:

$\sigma_{NC} \approx \sigma_{CC}$ at $Q^2 \approx M_Z^2, M_W^2$

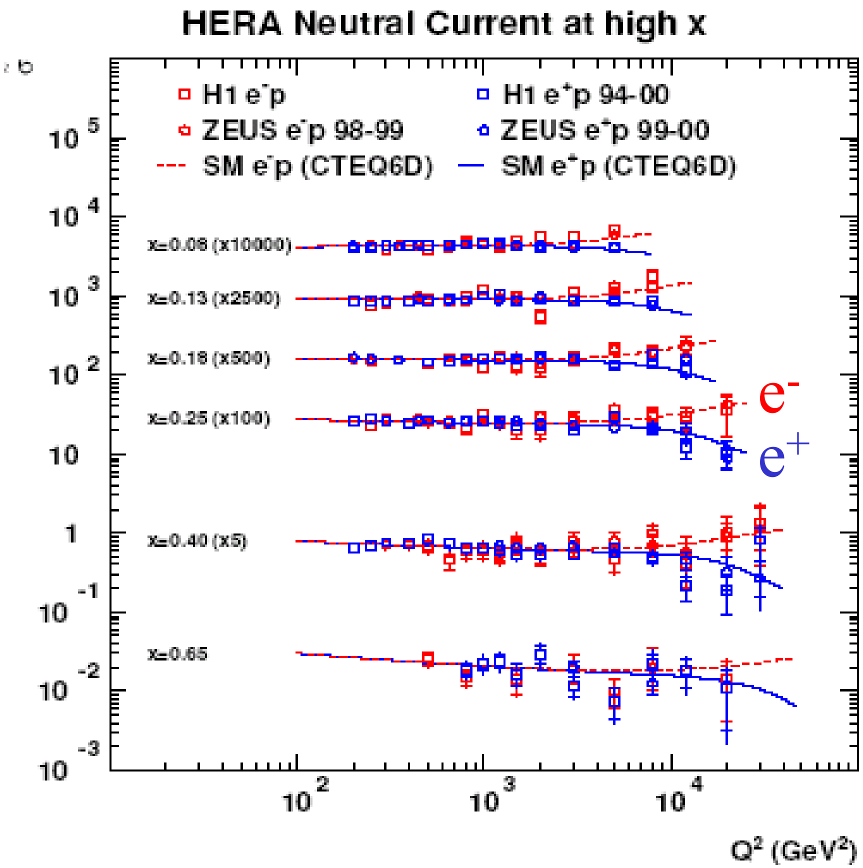
-> electro-weak unification

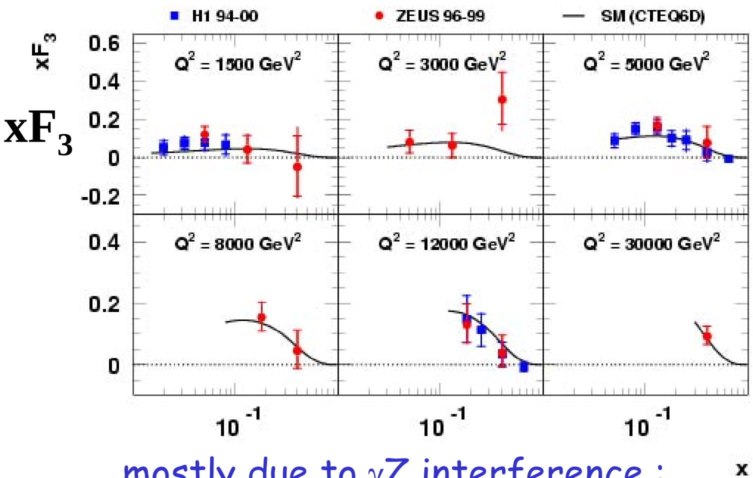
high x & high Q^2 :

-> unfold different quark flavours

NC at high x & xF_3

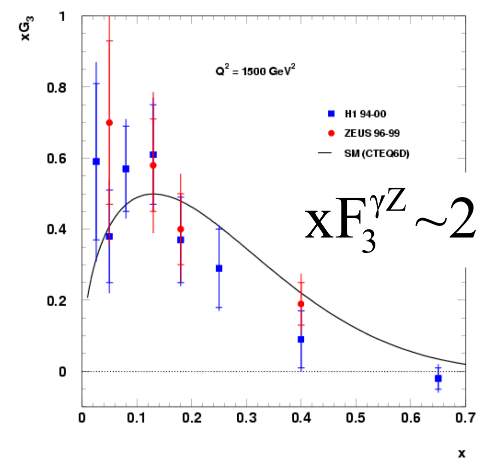
$$\tilde{\sigma}^{\pm}_{NC} = F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} xF_3$$





mostly due to γZ interference :

$$xF_3^{\gamma Z} = xF_3 / [-a_e k_w / (Q^2 + M_Z^2)]$$



$$xF_3^{\gamma Z} \sim 2u_v + d_v$$

sensitive to EW param. & polarisation

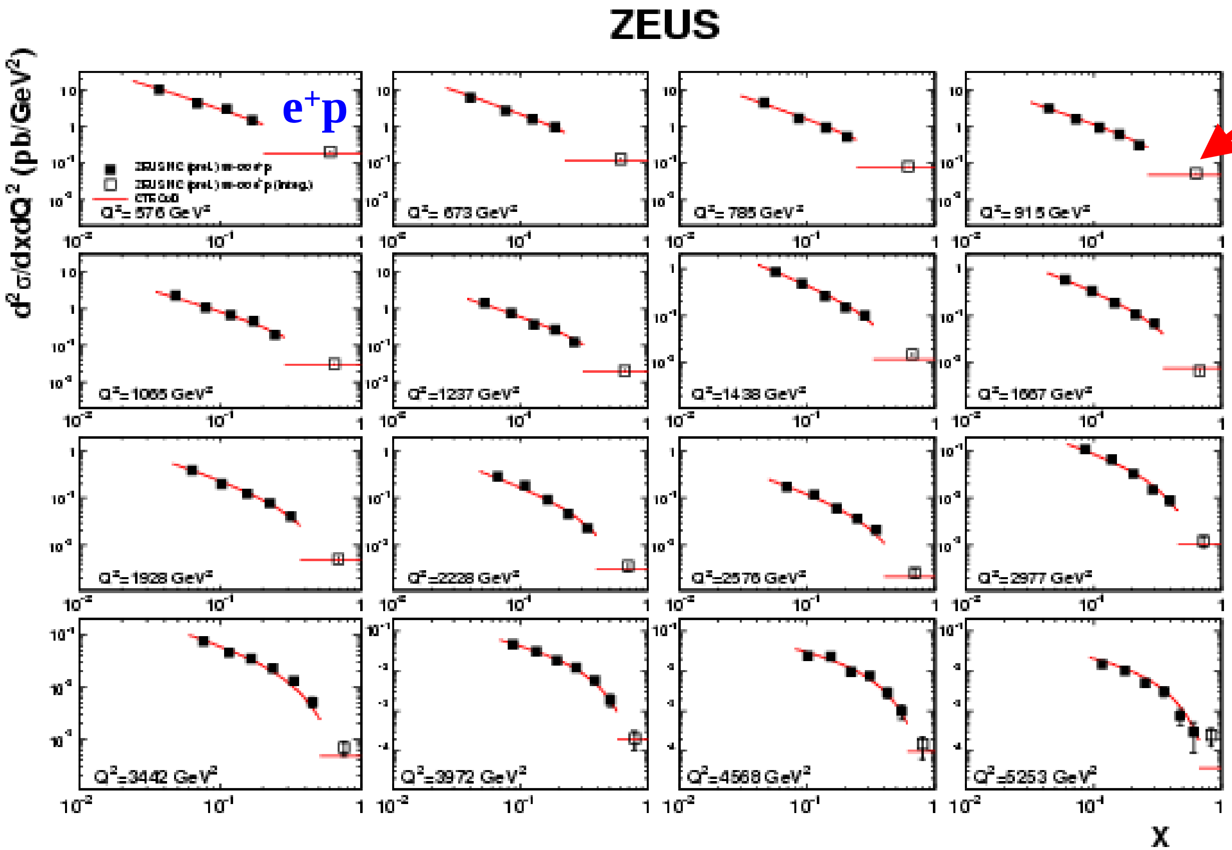
xF_3 constrains u_v, d_v at high x

NC at highest x

- **make use of E_{jet}, ϑ_{jet} and events without jets (lost in the beam pipe) to access high x**
- both for e^+p and e^-p

-> highest x point is an integrated cross section up to x=1

$$\frac{\int_{x_{max}}^{1} dx \frac{d^2\sigma}{dxdQ^2}}{1 - x_{max}}$$

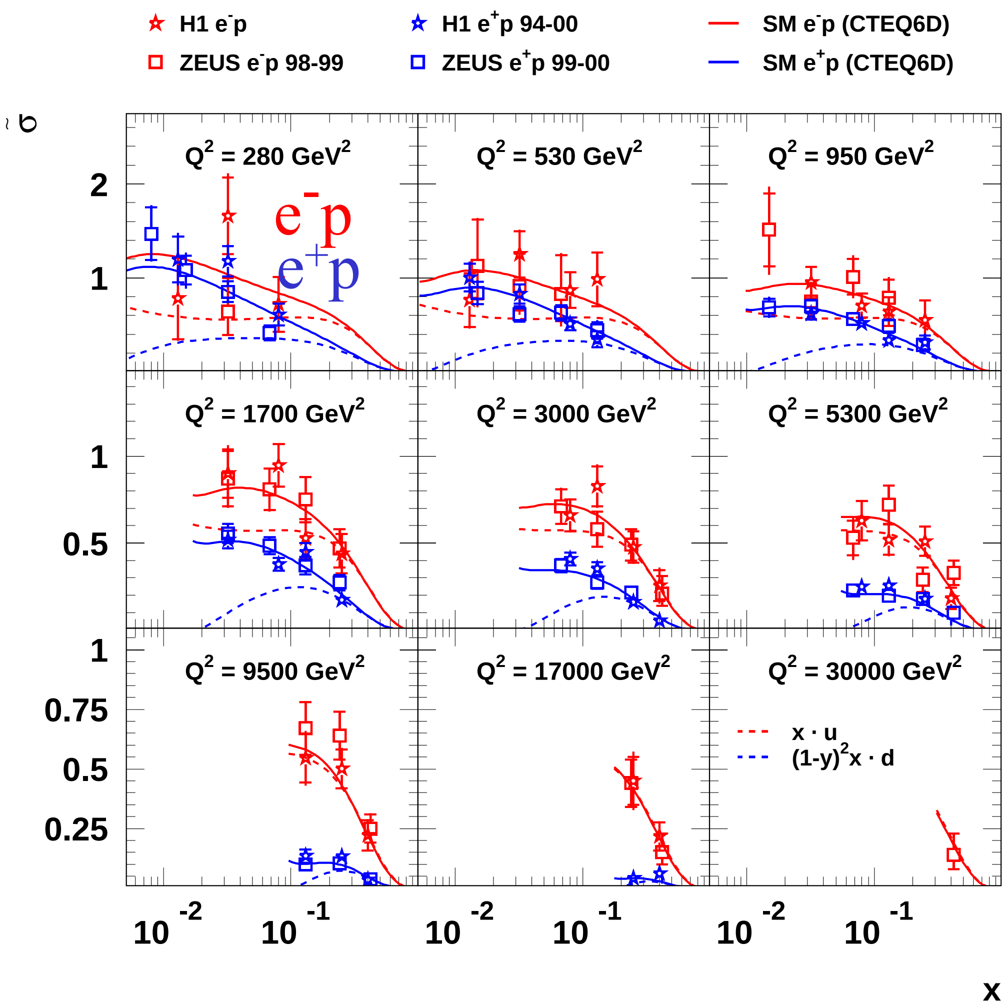


- good agreement with CTEQ6D
- input to PDF fits at high x

Charged Currents & flavour separation

$$\frac{d^2\sigma_{CC}(e^\pm p)}{dxdQ^2} = \frac{G_F^2 M_W^4}{2\pi x}\frac{1}{(Q^2+M_W^2)^2}\underbrace{\frac{1}{2}\left[Y_+W_2 - y^2 W_L \mp Y_- xW_3\right]}_{\tilde{\sigma}_{CC}(x,Q^2)}$$

$\tilde{\sigma}_{CC}(x,Q^2)$ - reduced CC cross section



The CC e^+p cross section
- dominated by d quark

$$\tilde{\sigma}_{CC}^{e^+p}(x,Q^2) \sim (\bar{u}+\bar{c}) + (1-y)^2(d+s)$$

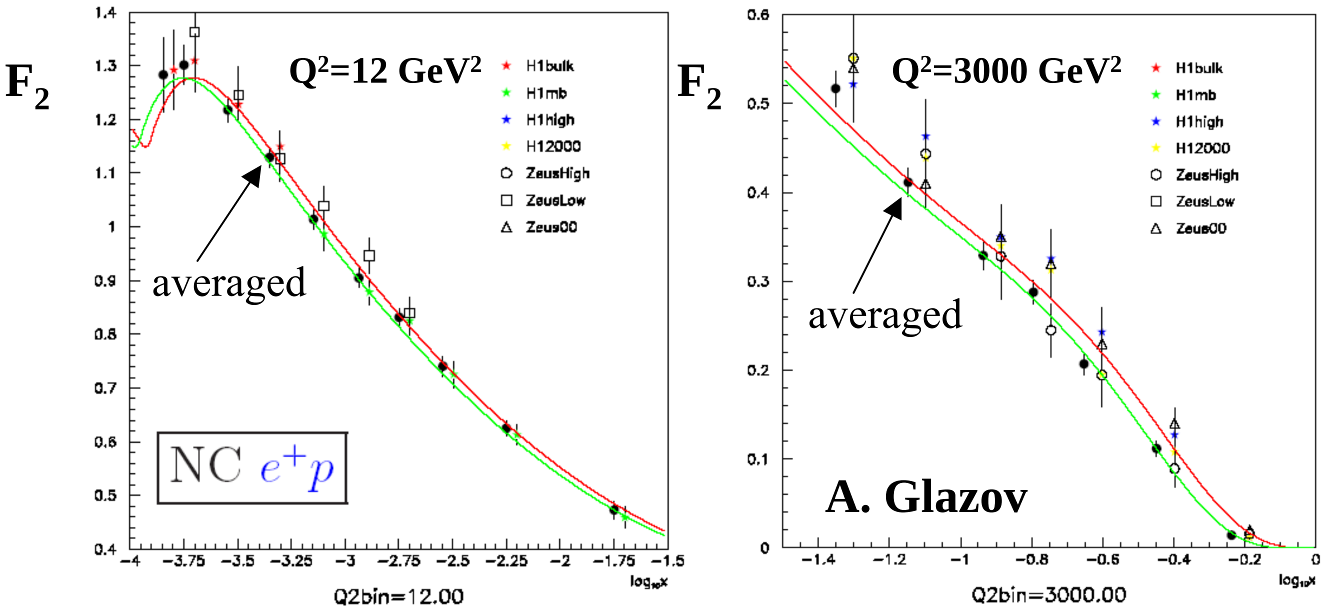
The CC e^-p cross section
- dominated by u quark

$$\tilde{\sigma}_{CC}^{e^-p}(x,Q^2) \sim (u+c) + (1-y)^2(\bar{d}+\bar{s})$$

- ***constrain d (u) quark density***
- ***free of nuclear corrections and isospin assumptions***

Towards the combined HERA SF data

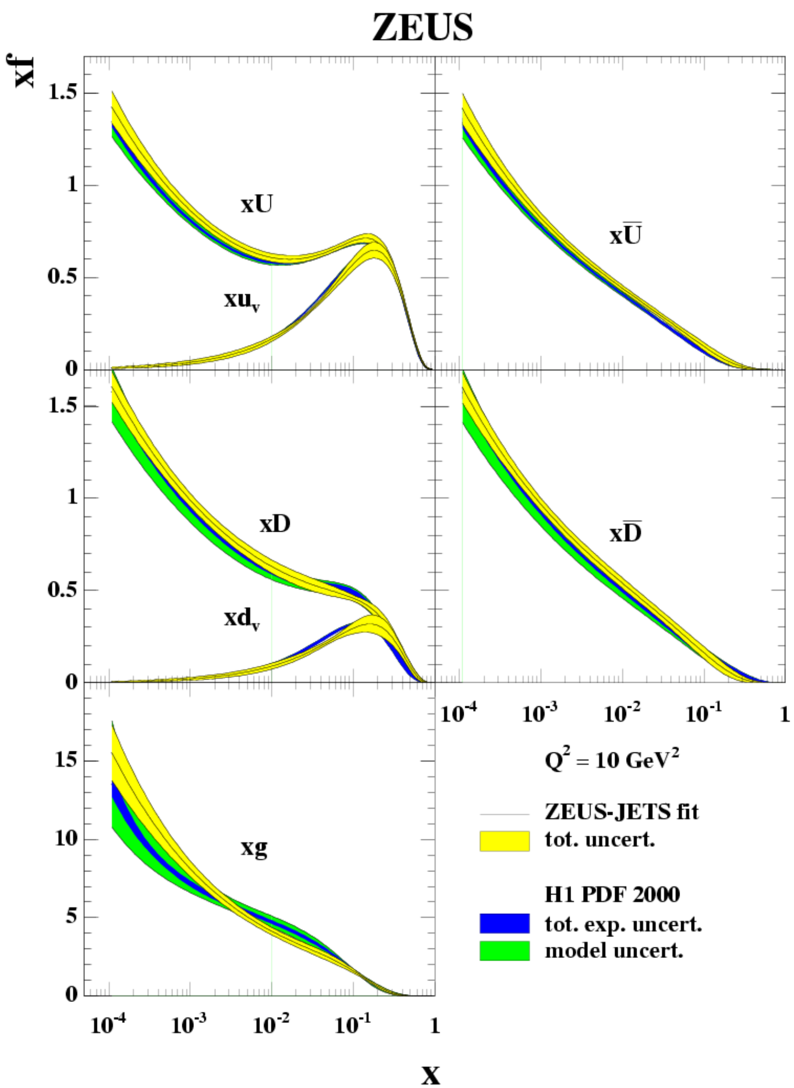
Aim: average the H1 and ZEUS published SF data in the theory free manner



- **service to HEP community**
  - **unique HERA data set**
  - **proper treatment of correlations between different data sets**
- **cross checks of systematics: H1 vs. ZEUS**

PDFs from HERA

Parton distributions (NLO): unfolded using the HERA $e^{\pm}$ p data only



H1: NC+CC $U, \bar{U}, D, \bar{D}, xg \leftrightarrow V, A, xg - \alpha_s$

ZEUS: NC+CC & jets $u_v, d_v, \bar{u} \pm \bar{d}, xg - \alpha_s$

treatment of systematics, parameterisations forms and other details are subject to conventions

→ PDFs from the H1, ZEUS and global fits are in agreement

Gluon:

- dominant at low x
- Note: the scale for xg distr. is 10 times larger

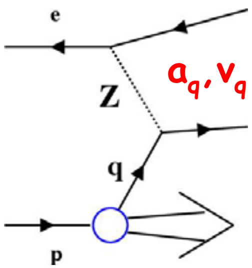
→ scaling violations

- xg is not an observable
- at Q^2 of few GeV^2 gluon becomes valence-like

→ jets, heavy flavours, $F_L(x,Q^2)$

- directly sensitive to xg
- jets constrain xg at x ~ 0.1
- F_L can pin down xg at low x

Light Quark Couplings to Z

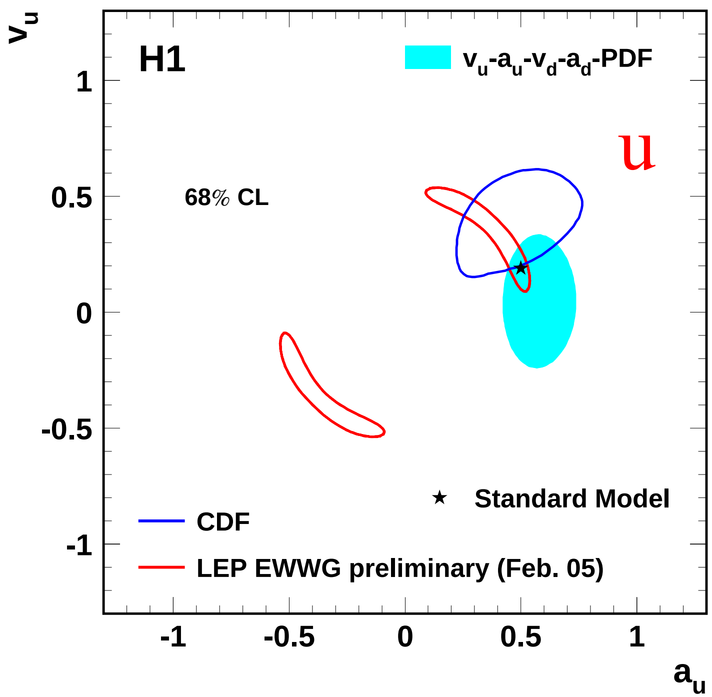


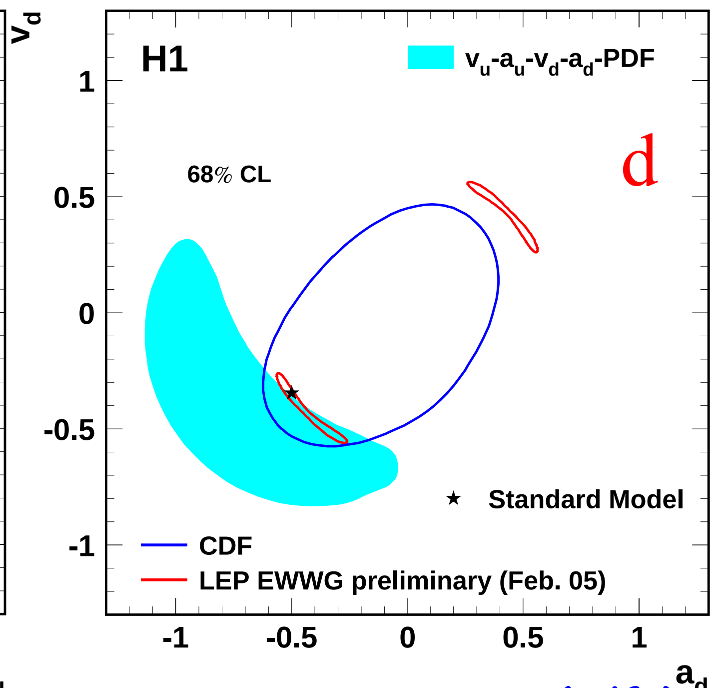
first coherent EW+PDF analysis at HERA (NC+CC data)

$$a_q = I_q^3 \rightarrow (a_u = +1/2; a_d = -1/2)$$
$$v_q = I_q^3 - 2e_q \sin^2\theta_W$$

$$F_2 \approx F_2^{em} + (v_e^2 + a_e^2) K_Z^2 \bullet x \sum (v_q^2 + a_q^2)(q + \bar{q})$$
$$xF_3^{NC} \approx -a_e K_Z \bullet 2x \sum e_q a_q (q - \bar{q})$$

$$K_Z = \frac{Q^2}{(Q^2 + M_Z^2)^2} \frac{1}{4\sin^2\theta_W \cos^2\theta_W}$$





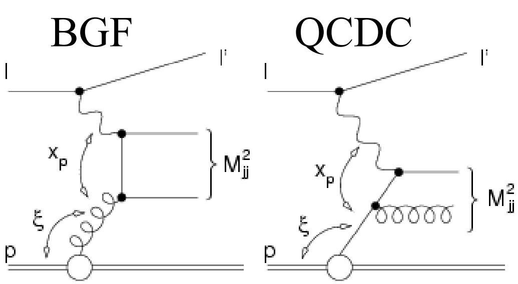
TeVatron: qq→ee Drell-Yan, A_{FB}

LEP: ee→qq(γ) $(a_q^2 + v_q^2)$

- more sensitive to u (pdfs)
- compatible precision with the TeVatron
- helps to resolve LEP ambiguities

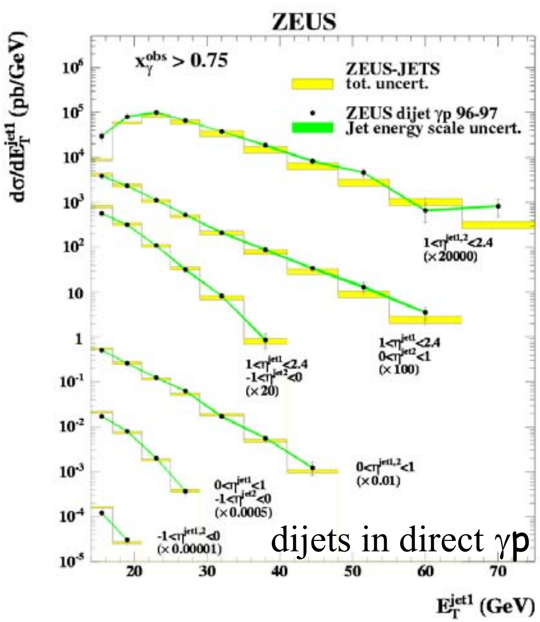
ZEUS NLO QCD fit (inclusive & jets)

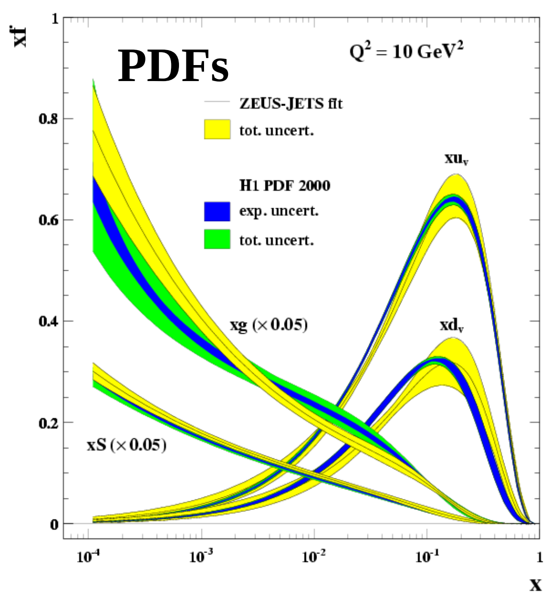
Include jets in direct γp and DIS into QCD fit



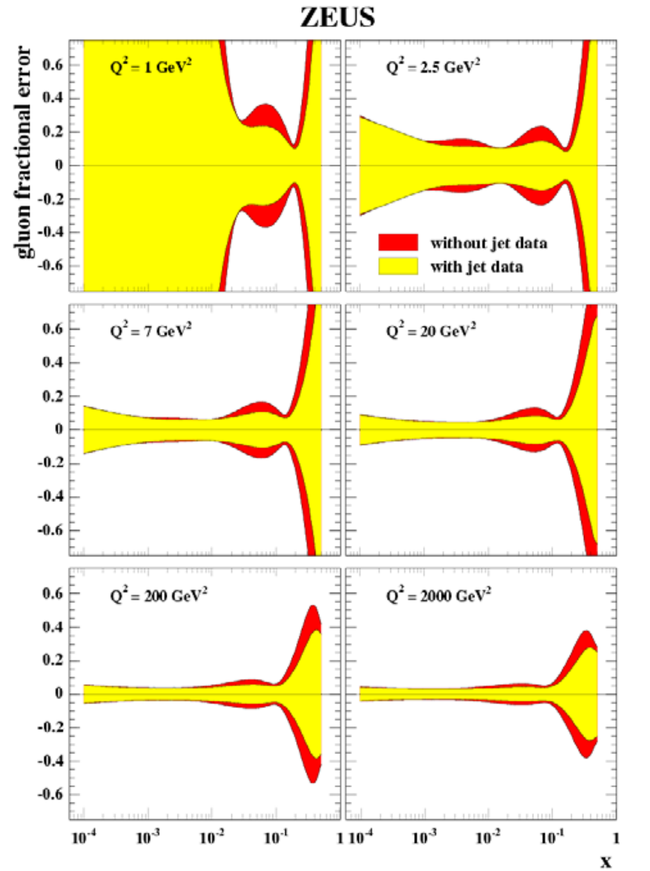
Boson Gluon Fusion :
depends on xg(x)
→ constrain gluon at medium & high x (0.01-0.4)

QCD-Compton :
depends on q(x) and α_s





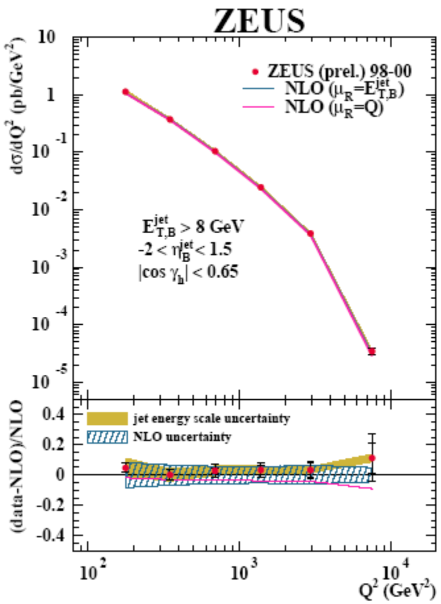
Gluon uncertainty (with/wo jets)



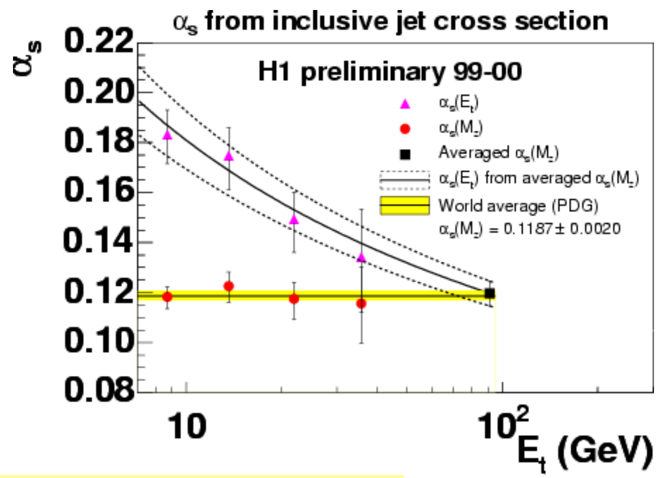
Strong coupling:

$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0028(\text{exp}) \pm 0.0008(\text{model}) \pm 0.0050(\text{scales})$$

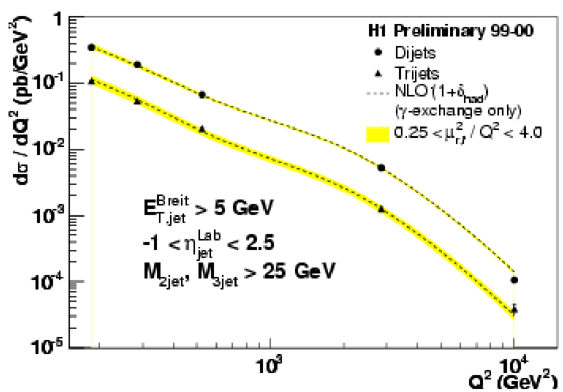
α_s from jets in DIS

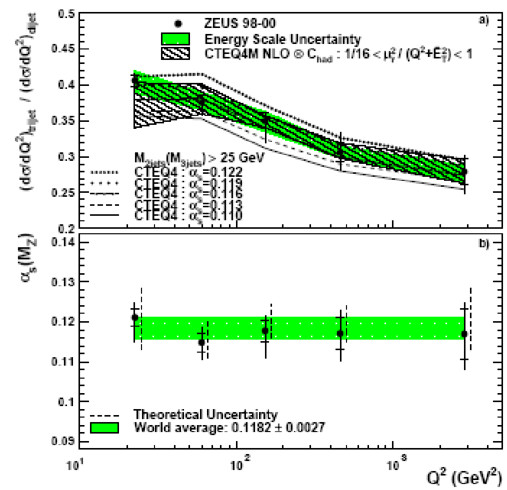


Inclusive jets in the Breit frame

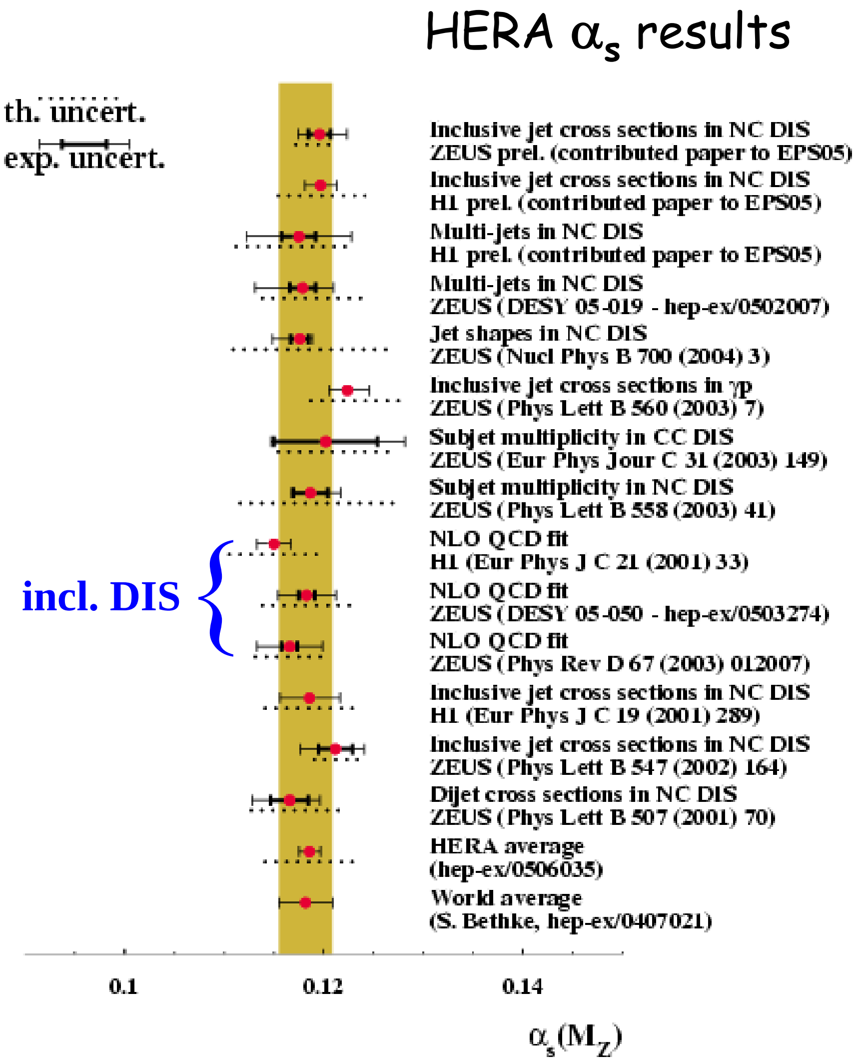


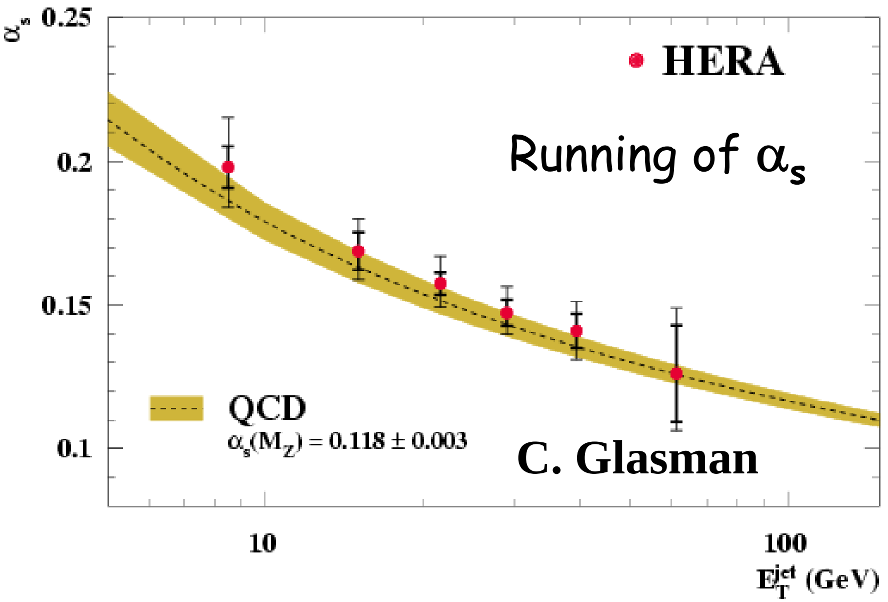
Multi jets in the Breit frame ($R_{3/2}$)





Summary for Strong Coupling at HERA





HERA-average:

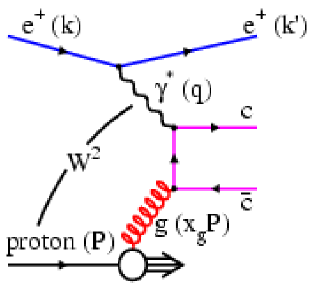
$$\alpha_s(M_Z^2) = 0.1186 \pm 0.0011(\text{exp.}) \pm 0.0050(\text{th.})$$

- small experimental error ~1%
- theory error dominates (NLO)
- call for NNLO

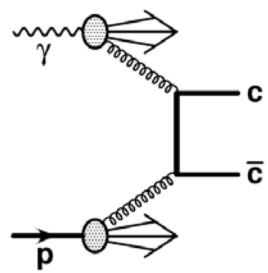
Charm Production

-> dominated by Boson Gluon Fusion (BGF)
-> resolved photon play important role in γp

p/γ PDFs ⊗ pQCD ⊗ Fragmentation



direct

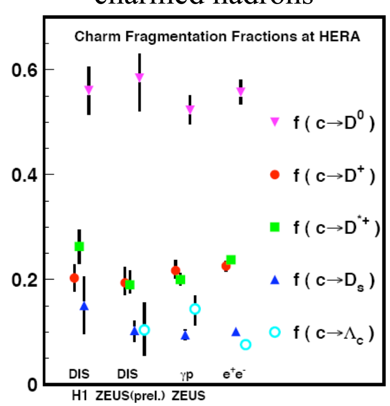


resolved

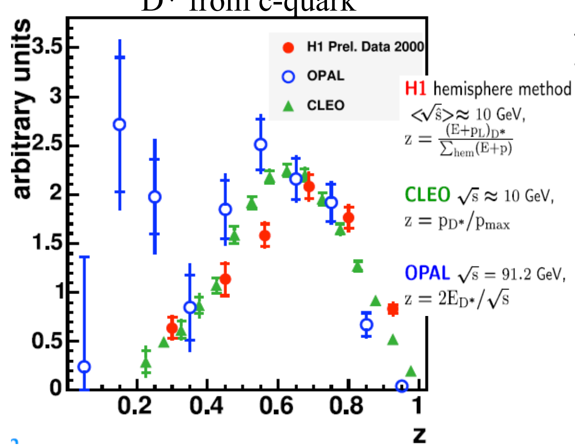
Perturbative QCD:
- hard scale m_c^2.
- multi-scale problem
  m_c^2, Q^2, p_t^2

PDFs:
- directly sensitive to xg
- photon structure

Fractional rates of charmed hadrons



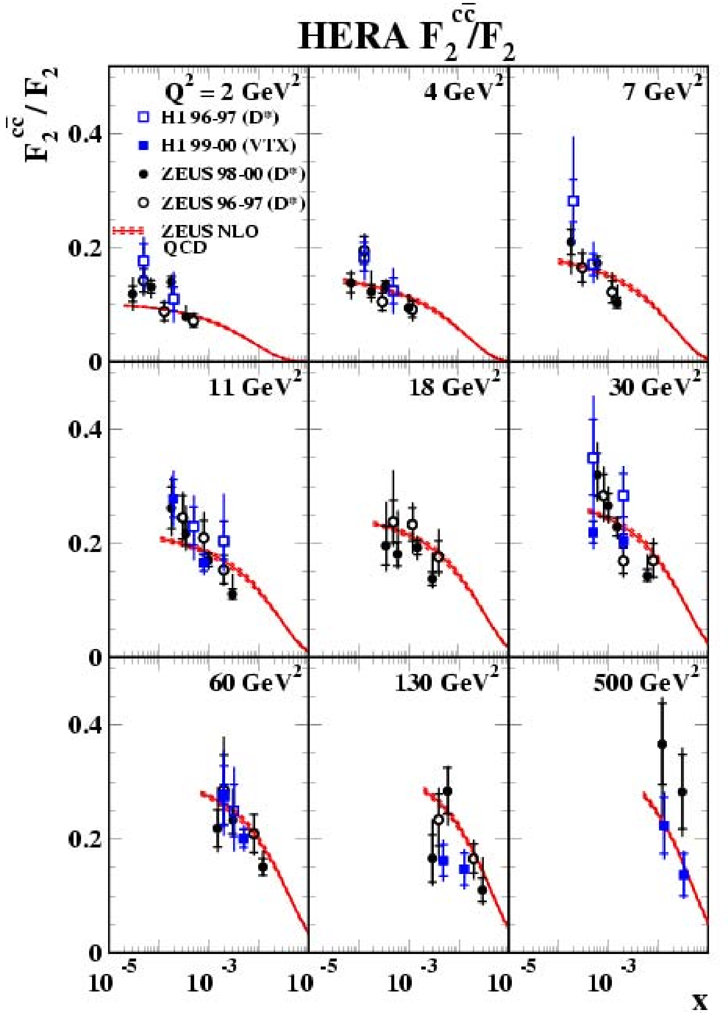
Fractional momentum of D* from c-quark

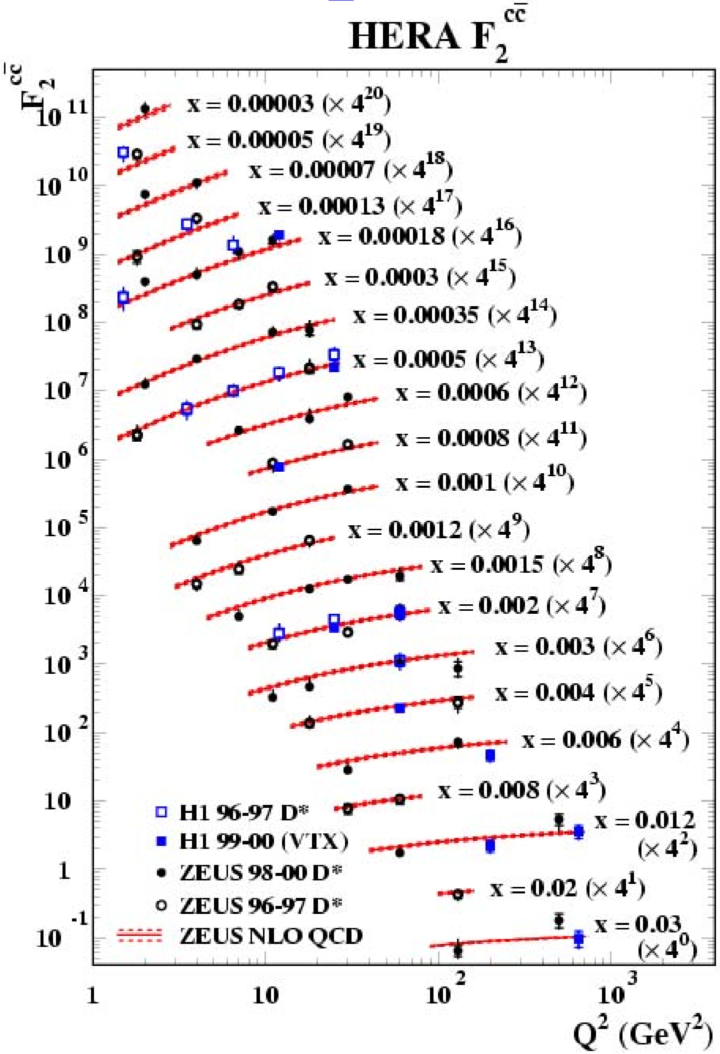


Fragmentation:

HERA ep results are consistent with e⁺e⁻ measurements supporting universality of fragmentation

Charm Structure Function $F_2^{cc}(x,Q^2)$

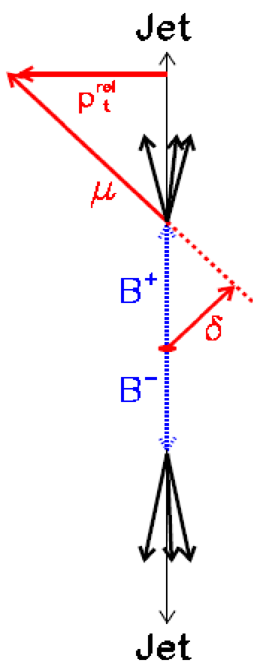




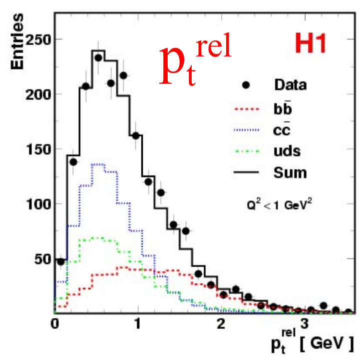
- charm contribution up to 25-30%
- consistent with gluon from scaling violations

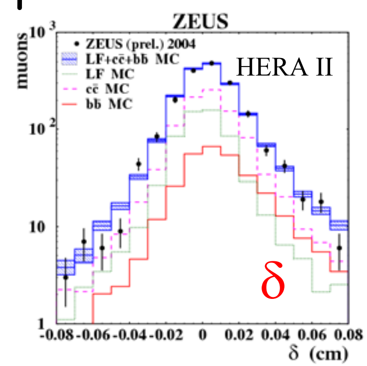
- scaling violations of F_2^{cc} are increasing with decreasing of x (similarly to F_2)

Beauty identification techniques



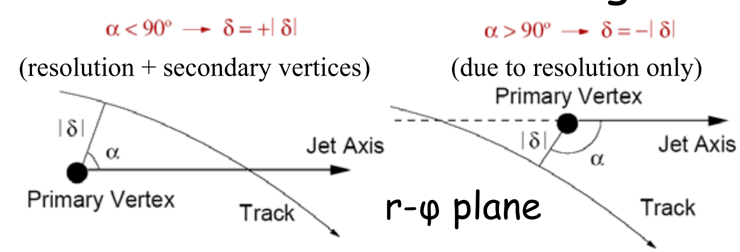
μ - transverse momentum and impact parameter



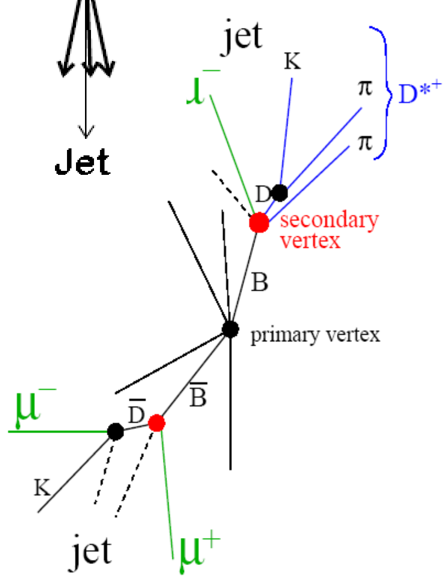


- **heavy mass**
- **long lifetime**
- **decay channels (μ,D)**
- **production (correlations)**

Inclusive lifetime tag

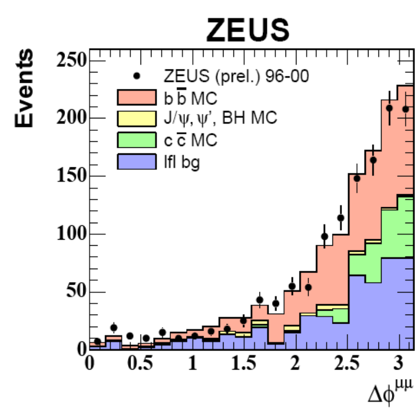


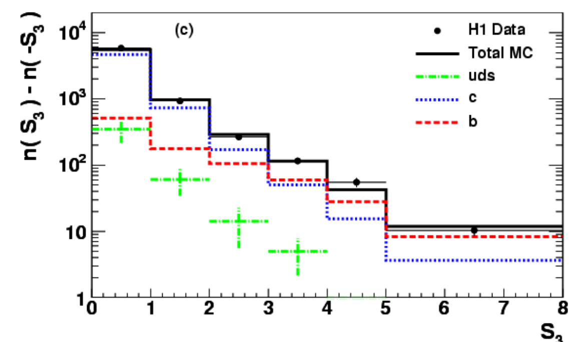
r-φ plane



Two-quark correlations

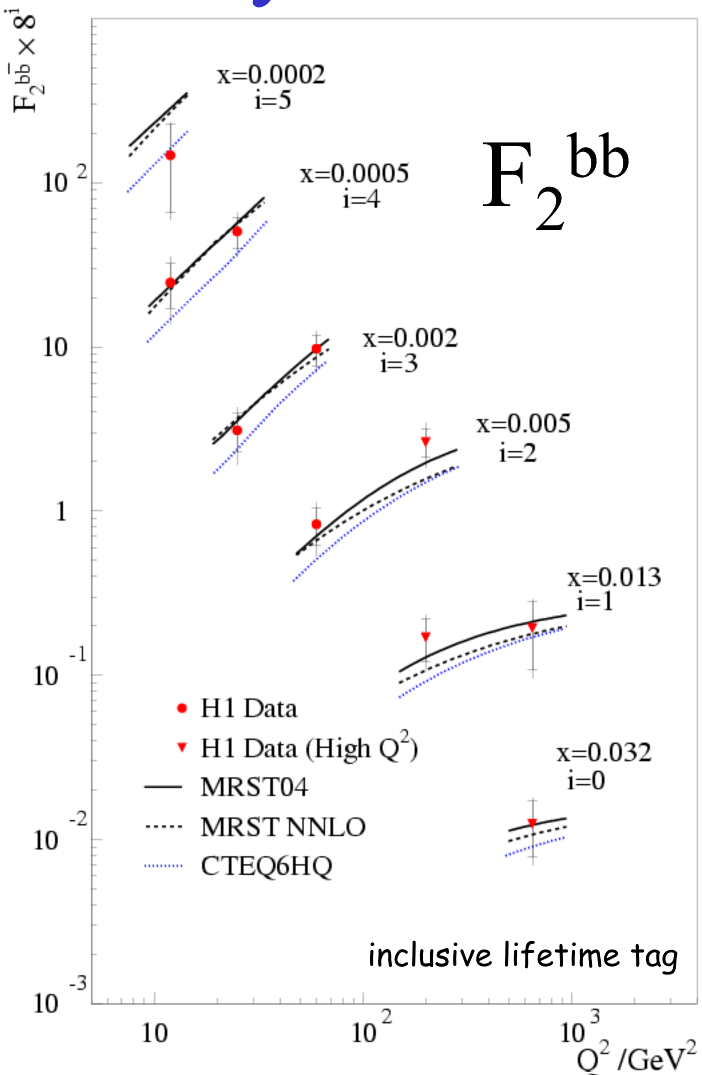
D*μ, μμ (Q, m, φ)



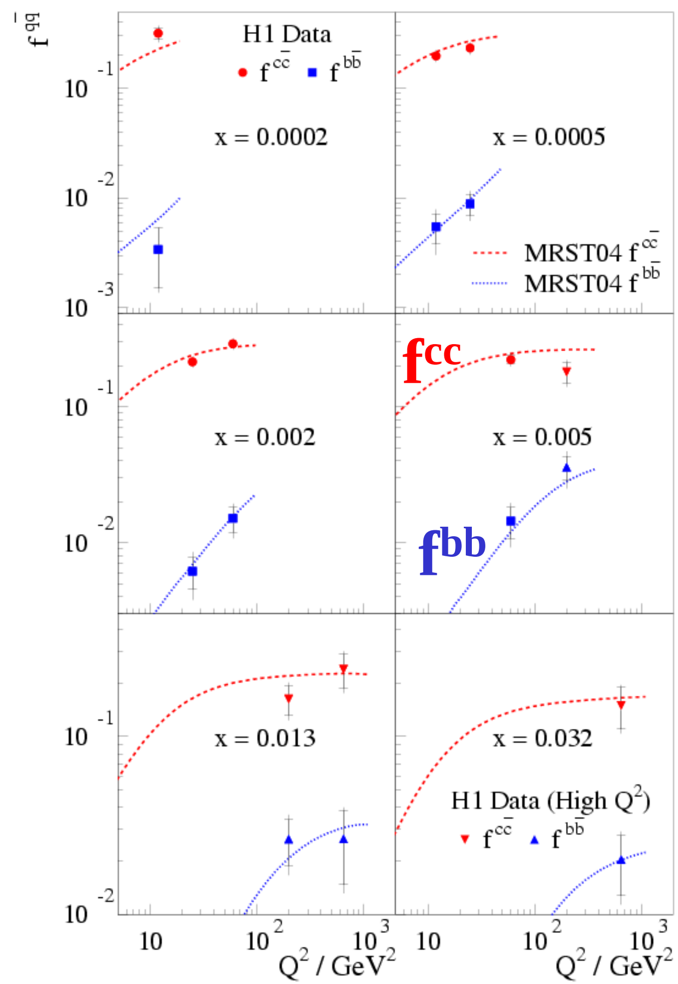


- all tracks with p_t> 500 MeV
- subtract the contents of negative bins
- both c and b are defined from the fit
- small extrapolation to the full phase space

Beauty Structure Function $F_2^{bb}(x,Q^2)$



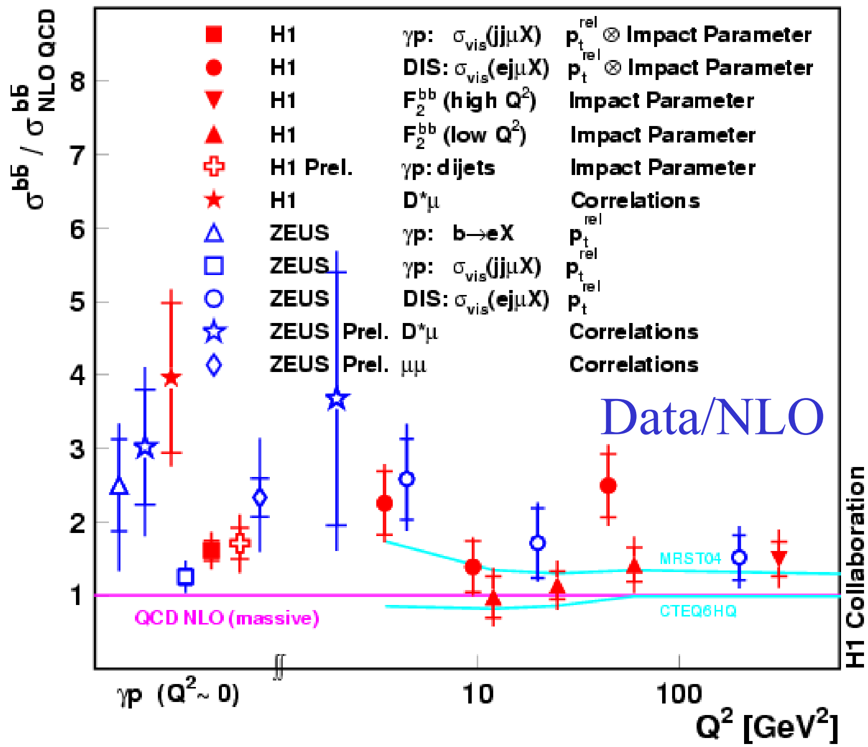
Cross section fractions

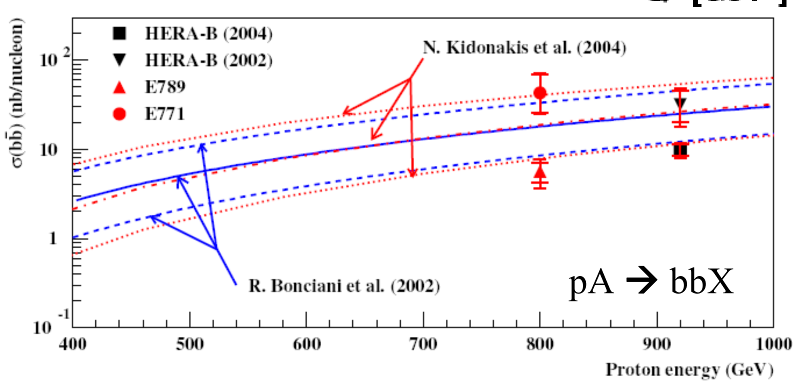


- **measured for the first time**
- **compared with NLO and NNLO**

- **charm roughly constant ~ 24%**
- **beauty changes from ~ 0.3% to ~ 3%**

Summary for beauty at HERA





HERA colliding experiments

- NLO is consistent both with DIS and γp data

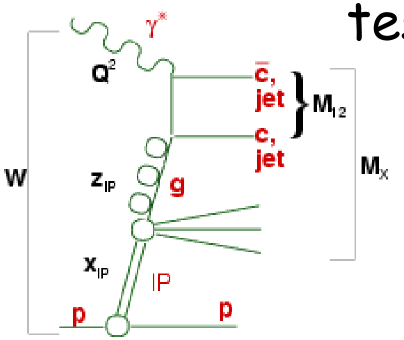
(although systematically higher)

HERA-B

- close to kinematic threshould
- old and new results are compatible within 1.5 σ

Inclusive Diffraction & DPDFs

tests of QCD factorisation in diffraction



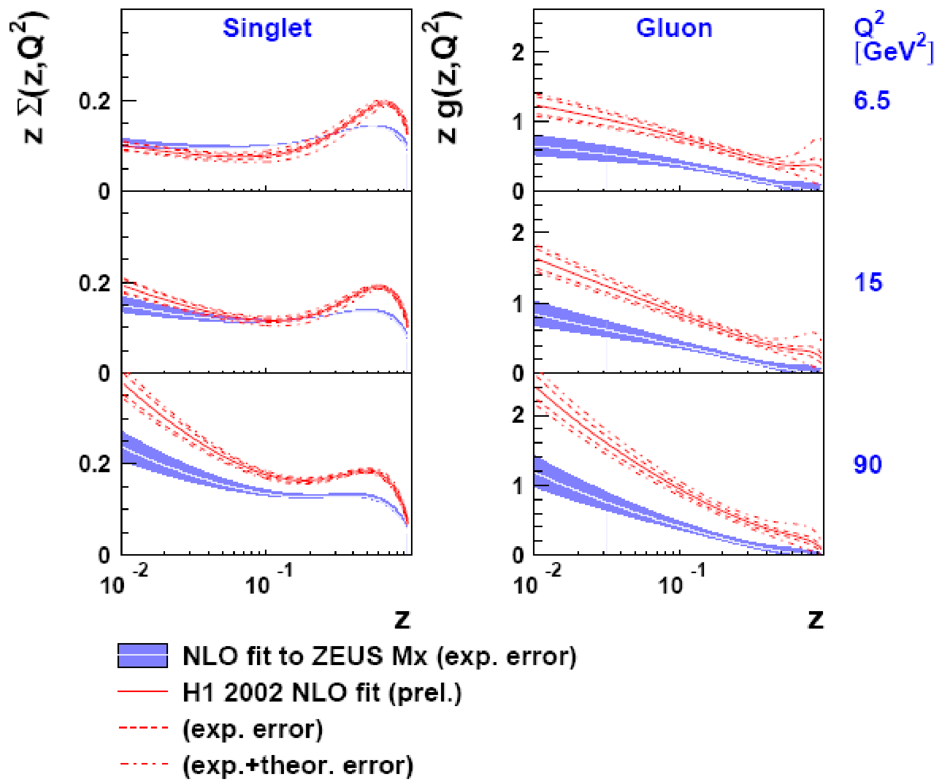
$$\sigma(\gamma^* p \to Xp) \approx p_{q/p}(x_{IP}, t; x, Q^2) \otimes \hat{\sigma}_{\gamma^* p}(x, Q^2)$$ - **QCD factorisation**

$$f_{IP/p}(x_{IP}, t) \otimes p_{q/p}(\beta, Q^2)$$ - Regge factorisation

DPDFs from F_2^D :

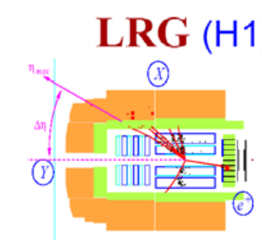
-> predictions for diffr. final states (D*, jets)

NLO QCD fits to H1 and ZEUS data

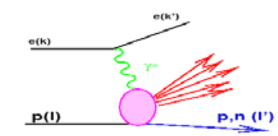


(from HERA-LHC workshop)

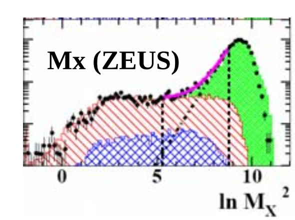
H1 2002 fit (prel.)



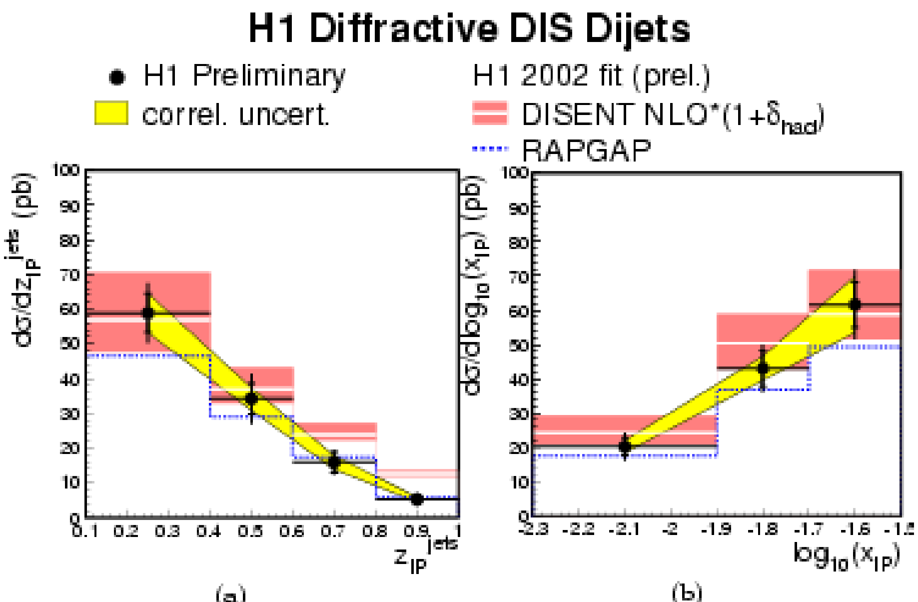
ZEUS-LPS fit



GLP fit

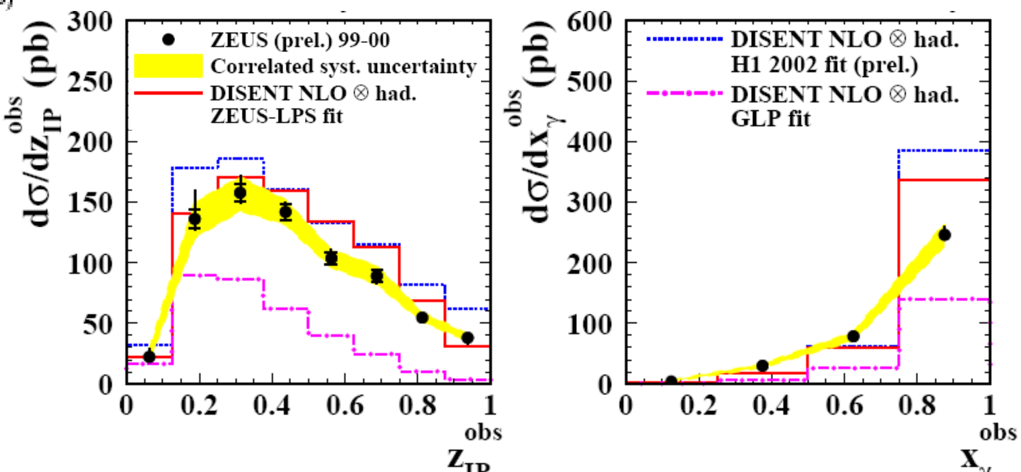


Diffractive dijets in DIS



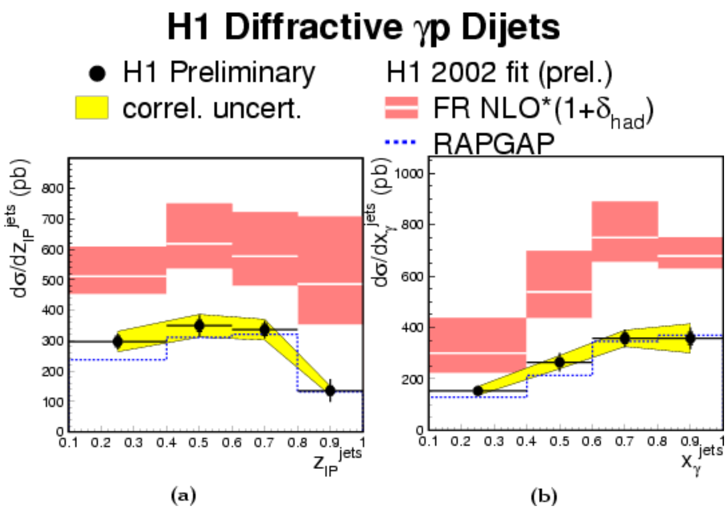
- NLO using H1 2002 fit agrees with data indicating validity of QCD factorisation

- sensitivity to the choice of DPDFs
- better understanding of DPDFs is needed

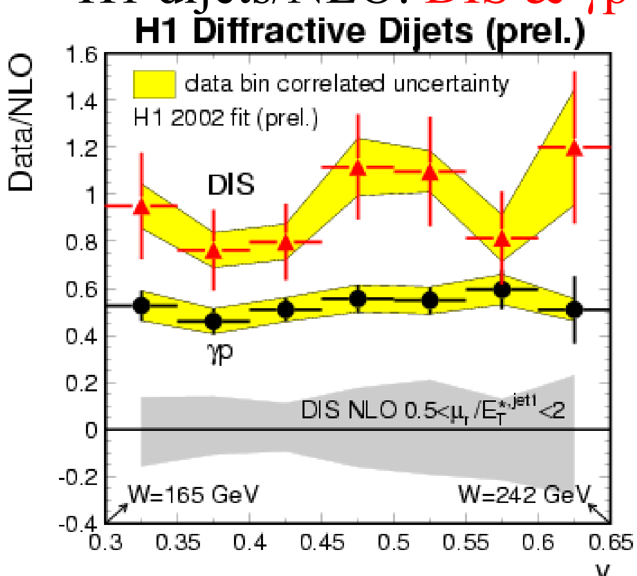


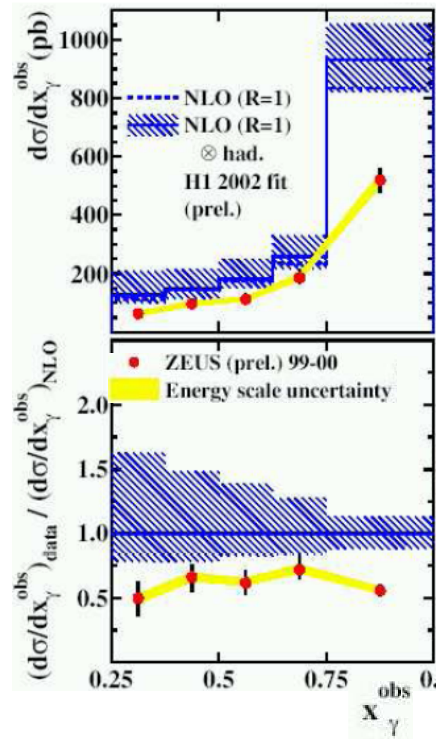
-> low GLP predictions due to small gluon at large z

Diffr. dijets in photoproduction



H1 dijets/NLO: DIS & γp





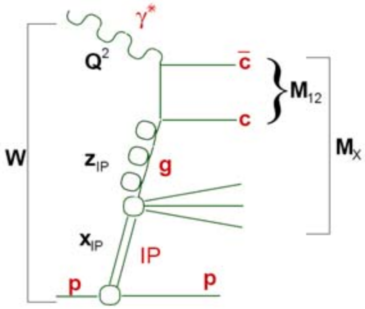
ZEUS dijets in γp

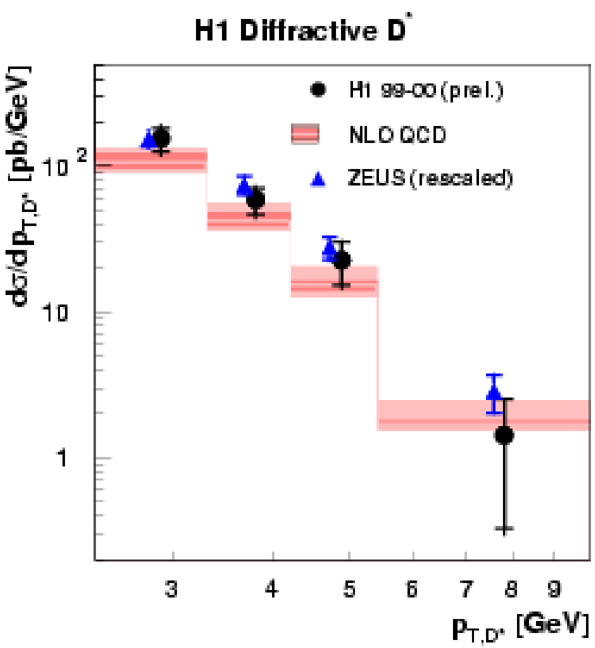
NLO from Klasen, Kramer

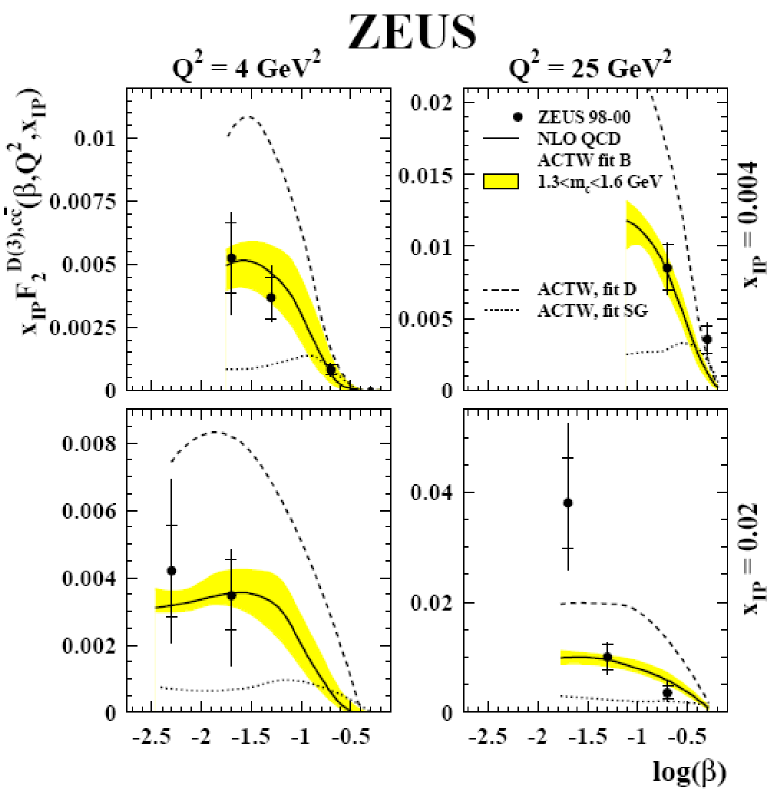
- data/NLO flat in x_γ
- global suppression by ~0.6

- NLO strongly depends on choice of DPDFs
- using H1 2002 DPDFs
  - dijets in DIS support QCD factorisation
  - in γp QCD factorisation is broken by factor of 2 independent of x_γ

Diffractive D* in DIS





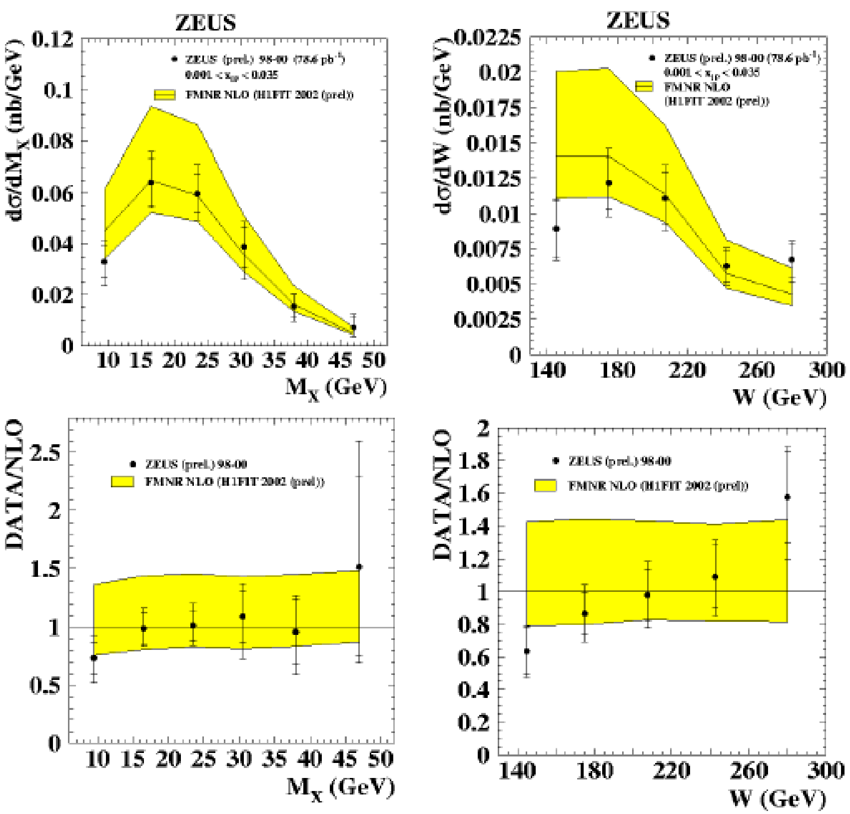


agreement of H1 and ZEUS data
(corrected for difference in phase space)

- NLO using H1 2002 fit agrees with data indicating validity of QCD factorisation
- sensitivity to the choice of DPDFs

Tests of QCD factorisation in diffr. - Summary

diffr. D* in γp



using DPDFs from H1 2002 fit

Summary for DIS :

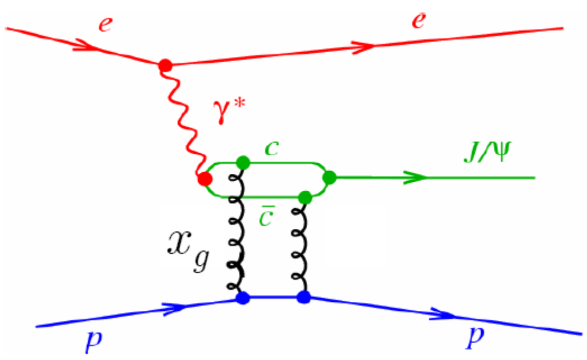
- **diff. dijets data/NLO ~ 1**
- **diff. D* data/NLO ~ 1**

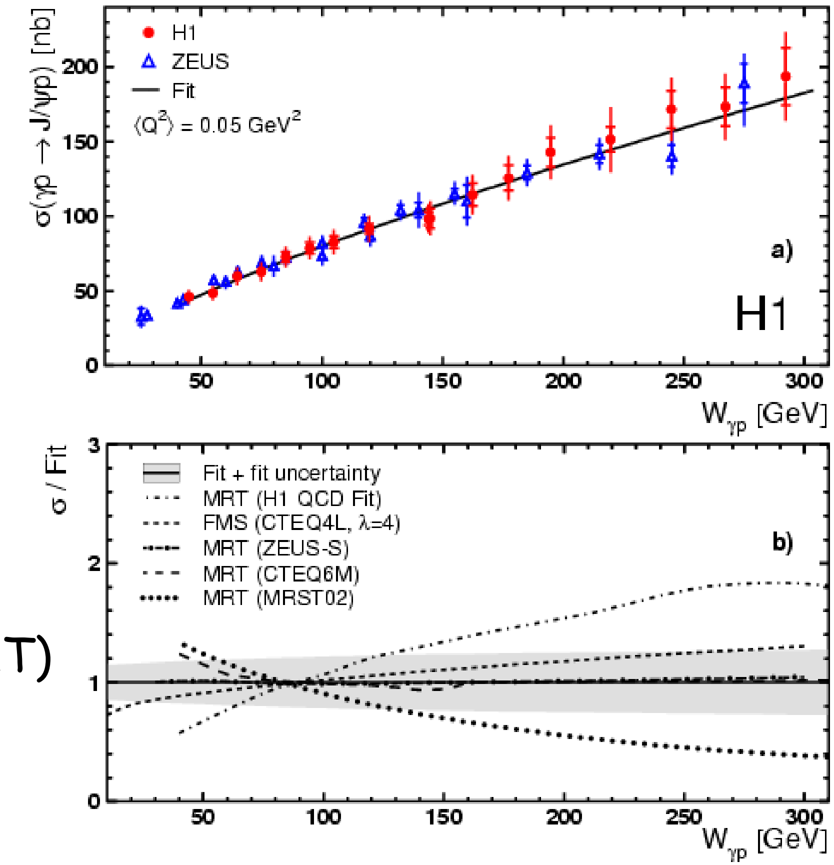
Summary for γp :

- **diffr. dijets data/NLO ~ 0.6**
  (independent of x_γ)
- **diffr. D* data/NLO ~ 1**

- direct γp contr. ~80%
- NLO agrees with diffr. D* in γp

Elastic J/Ψ production and gluon density



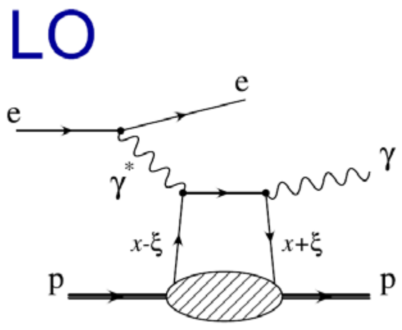


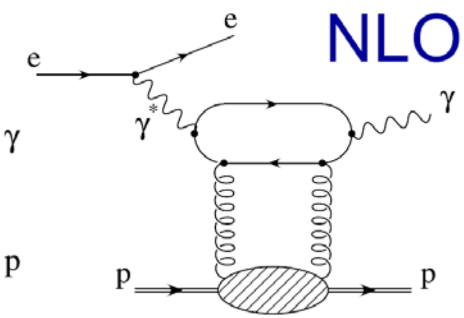
- two gluons are involved : ~ $g(x)^2$
- gluon at low x and low Q^2
- progress on the theory side (e.g. MRT)

-> high sensitivity in input gluon

Deep Virtual Compton Scattering (DVCS)

DVCS - fully calculable in pQCD





NLO Freund & Mc-Dermott :

DGLAP region: $|x| > \xi$

$\mathcal{H}^q(x,\xi,t;\mu^2) = q(x;\mu^2)\, e^{-b|t|}$ q singlet

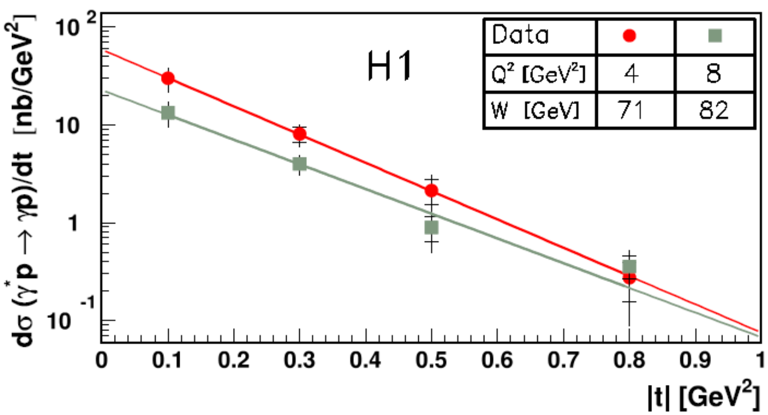
$\mathcal{H}^g(x,\xi,t;\mu^2) = x\ g(x;\mu^2)\, e^{-b|t|}$ gluons

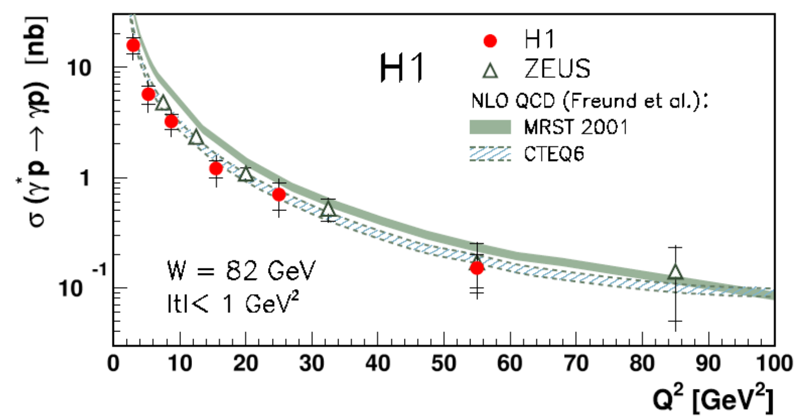
MRST2001 and CTEQ6

$\rightarrow Q^2$ and ξ generated dynamically

ERBL region: $|x| < \xi$

simple analytic function



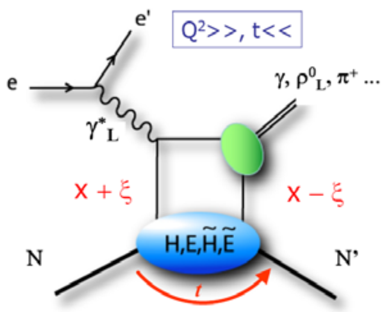


- **first t slope measurements allow absolute theoretical predictions**

- **in agreement with NLO QCD prediction, based on GPD model without intrinsic skewing**
- **constraints on gluon and sea GPDs**

DVCS in HERMES & GPDs

Generalised Parton Distributions (GPDs)



GPDs @twist-2:

H, E H̃, Ẽ

quantum number of final state selects different GPDs:

→ DVCS ←

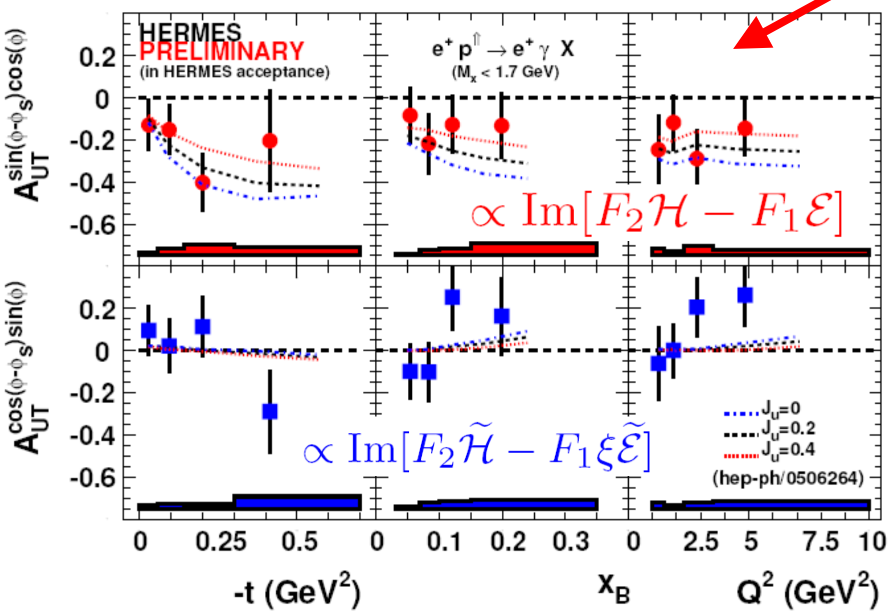
HERMES: interference between DVCS and Bethe-Heitler

DVCS asymmetries:

BCA (e^+,e^-) ~ $\mathrm{Re}\,\mathbf{H}\cdot\cos\phi$

BSA (P_{beam}^+, P_{beam}^-) ~ $\mathrm{Im}\,\mathbf{H}\cdot\sin\phi$

LTSA ($P_{targ.}^+, P_{targ.}^-$) ~ $\mathrm{Im}\,\widetilde{\mathbf{H}}\cdot\sin\phi$



Transverse Target-Spin Asymmetry

will allow the first determination of J_u through certain GPD models

$$\frac{1}{2} = \underbrace{\frac{1}{2}\overbrace{(\Delta u + \Delta d + \Delta s)}^{\sim 30\%} + L_q}_{J_q} + \underbrace{\Delta G + L_g}_{J_g}$$

Ji's Sum Rule:

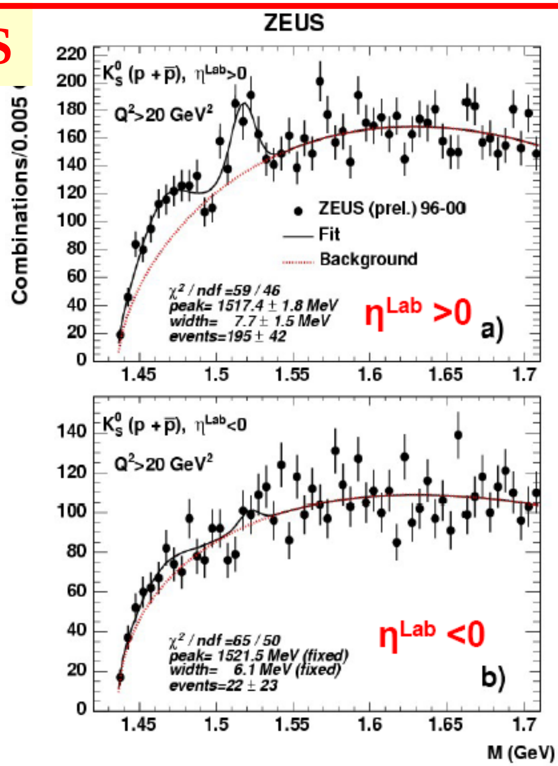
$$J_{q,g} = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} dx \cdot x \cdot [H_{q,g}(x,\xi,t) + E_{q,g}(x,\xi,t)]$$

Recoil detector (2006/2007)

- detection of recoil proton
- background free DVCS (bkg ~5% -> < 1%)

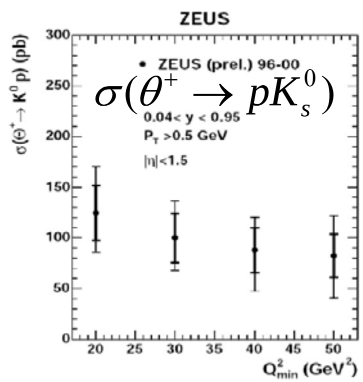
Θ^+ search at HERA

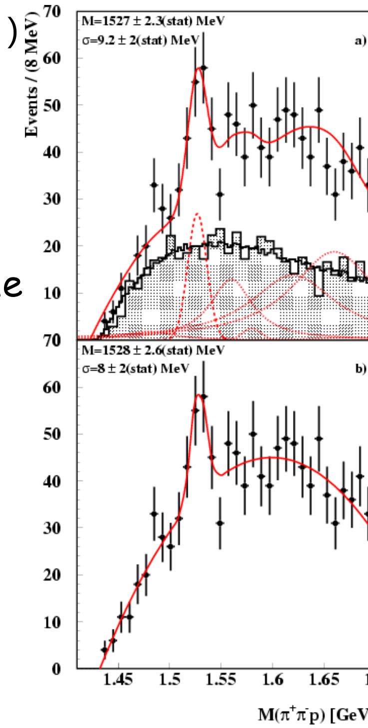
YES



ZEUS $(pK^0_s, \bar{p}K^0_s)$

M=1521±1.5±3 MeV
4.6 σ effect
- Q^2 > 20 GeV²
- both in pK_s^0, $\bar{p}K_s^0$
- predominantly in the forward direction

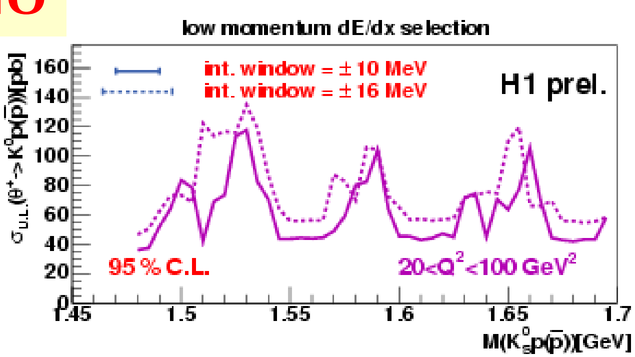




HERMES (pK_s^0)

M=1527 ± 2.3(sta) MeV
~4σ effect
no signal in $\bar{p}K_s^0$

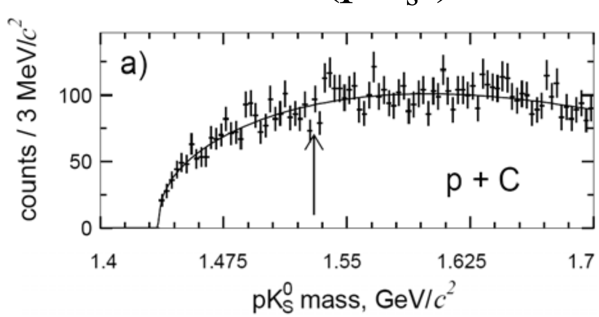
NO



H1 $(pK^0_s, \bar{p}K^0_s)$

- limits at 95% CL
- for Q²>20 GeV²:
  σ < 100-120 pb
  (ZEUS σ~120 pb)

HERA-B (pK_s^0)



limits at 95% CL:

Br×dσ/dy <3.7μb/N

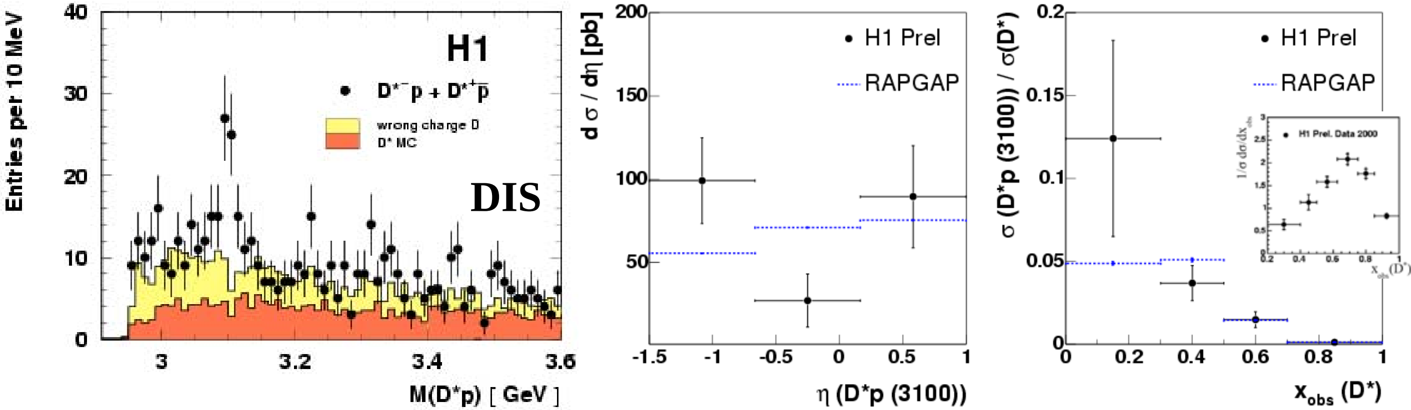
$\frac{\theta^+}{\Lambda(1520)}$<2.7%

Charmed pentaquark

YES

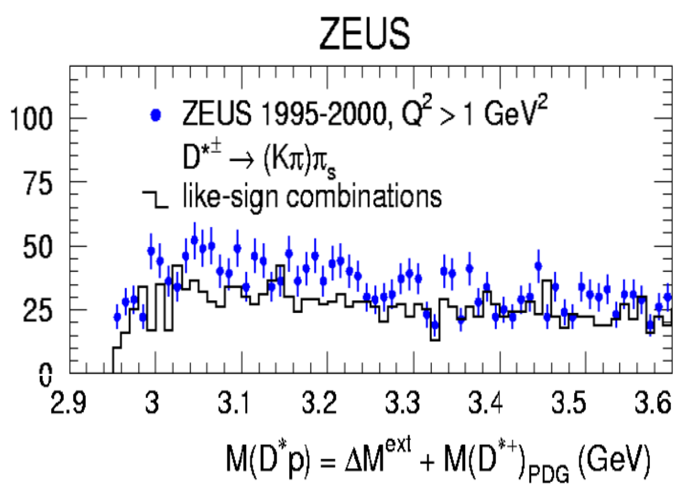
H1 observed D*p(3100) M=3099±3±5 MeV 5.4σ

not confirmed (so far) by other experiments



- suppression at central rapidity
- D*p fragm. is hard (similar to incl. D*)
- D* from D*p softer than incl. D*

NO



ZEUS

- no evidence for a signal at 3100 MeV
- in the phase space similar to H1:

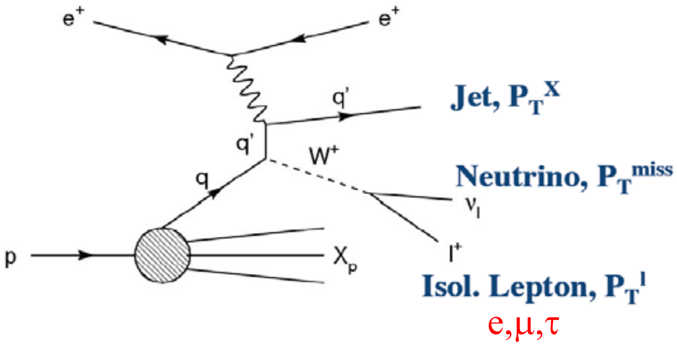
R_{corr}(D*p/D*) < 0.59% at 95% CL
< 0.51% when including D*->($K\pi\pi\pi)\pi_s$

compared to H1:

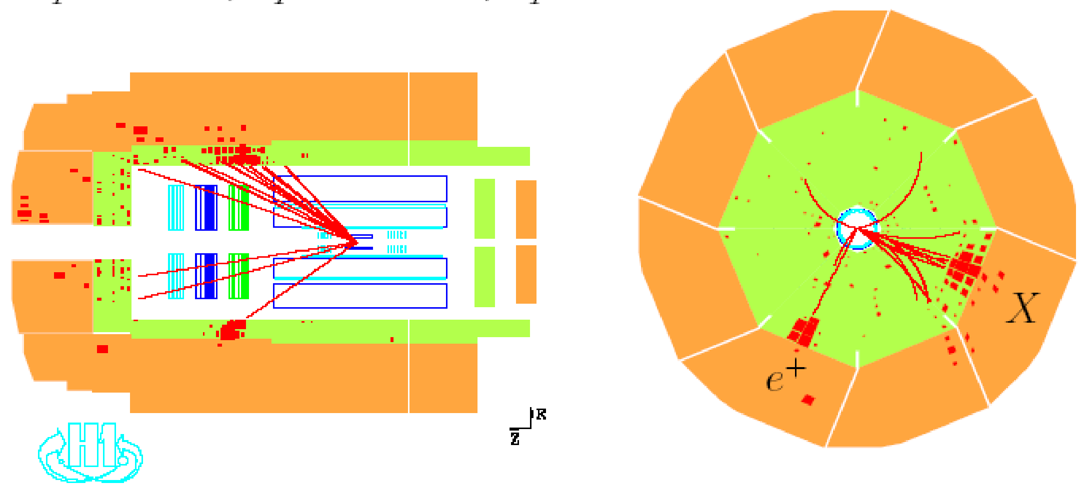
R_{corr}(D*p/D*) = (1.59±0.33+0.33-0.45)%

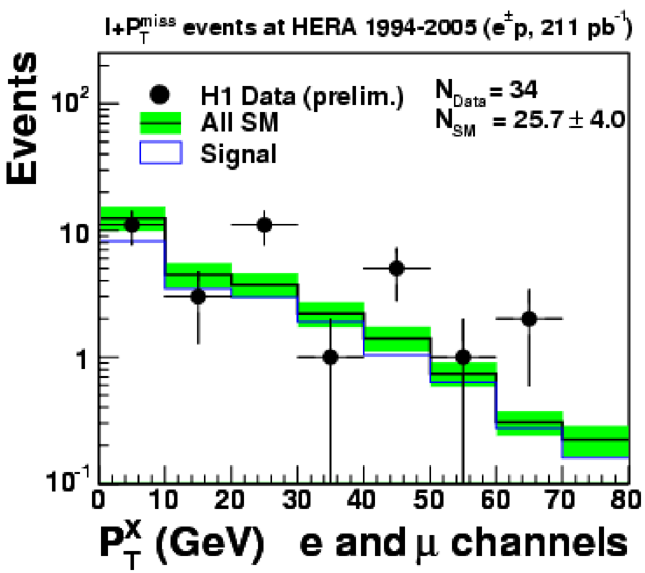
-> still incompatible

Isolated leptons with P_T^{miss} at HERA



$P_T^e = 37$ **GeV**, $P_T^{miss} = 44$ **GeV**, $P_T^X = 29$ **GeV**





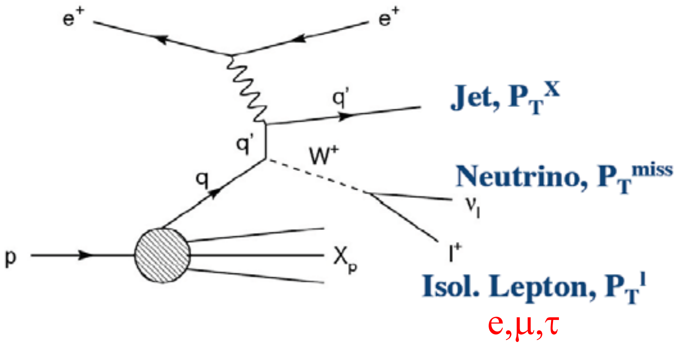
H1 e^+p, e^-p	HERA I (118 pb^{-1})		HERA I+II (211 pb^{-1})	
	e	μ	e (prel)	μ (prel)
All P_T^X	11/11.54	8/2.94	25/20.4	9/5.4
$P_T^X > 25$ GeV	**5**/1.76	**6**/1.68	**11**/3.2	**6**/3.2

Double lumi:

e - excess persists at HERA II

μ - excess comes only from HERA I

Isolated leptons with P_T^{miss} at HERA



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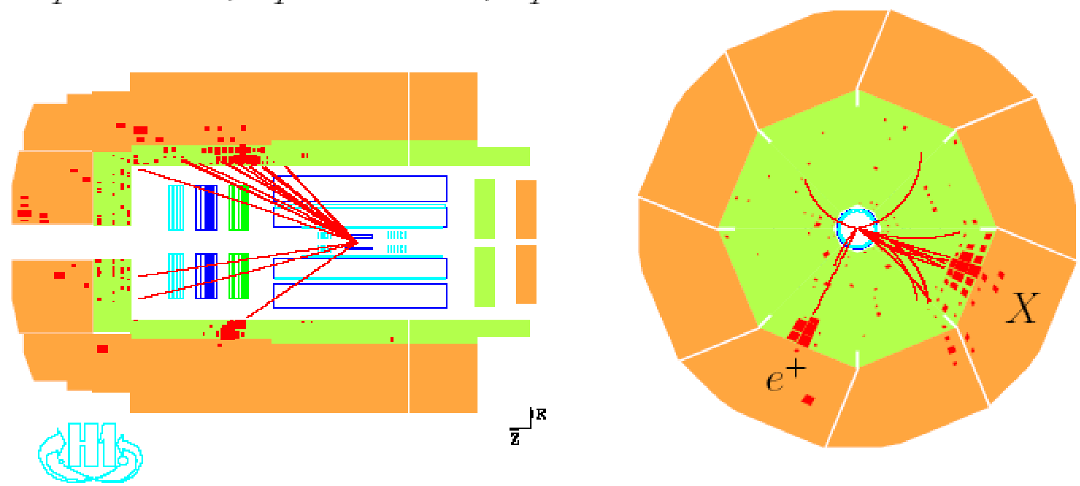

H1 e⁺p: excess over SM both in e and μ channels
no excess in e⁻p data

ZEUS in agreement with SM

H1 1994-2005	e^+p (158 pb^{-1})		e^-p (53 pb^{-1})	
	e (prel)	μ (prel)	e (prel)	μ (prel)
All P_T^X	19/14.6	9/3.9	6/5.8	0/1.5
$P_T^X > 25$ GeV	9/2.3	6/2.3	2/0.9	0/0.9

ZEUS 99-2004	e^+p (106 pb^{-1})	
$P_T^X > 25$ GeV	1/1.50	

τ channel ($P_T^X > 25$ GeV)
ZEUS (130 pb^{-1}) 2 / 0.20
H1 (108 pb^{-1}) 0 / 0.53

Summary & Outlook

Rich physics output from HERA:

- centered around QCD, but also EW, searches, …
- key word - precision

- investigate implications of QCD (evolution, scales, …)
- provide information essential for future LHC collider,
  see HERA-LHC workshop: http://www.desy.de/~heralhc/

- very often data are more precise than theory
- theory should catch up (and it happens, e.g. NNLO in DIS)

HERA II :

- **lumi** is a main issue !!! ~ $O(0.7 fb^{-1})$ per experiment in total:
  explore new detectors, clarify isolated leptons, pdfs, HF, F_L, …
- less than 2 years of running time left (till mid of 2007)