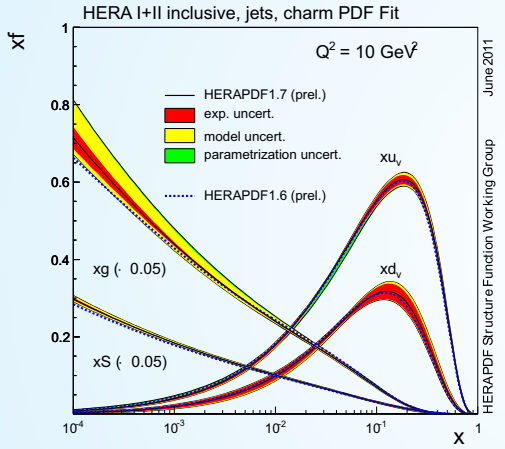
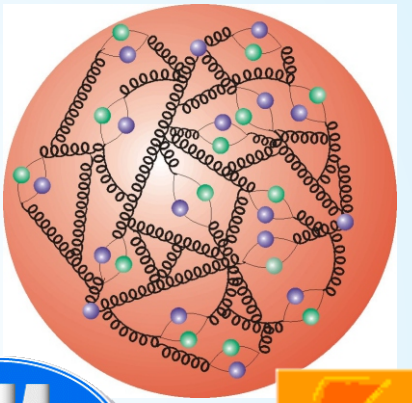
Precision Measurements of the Proton Structure

Functions at HERA



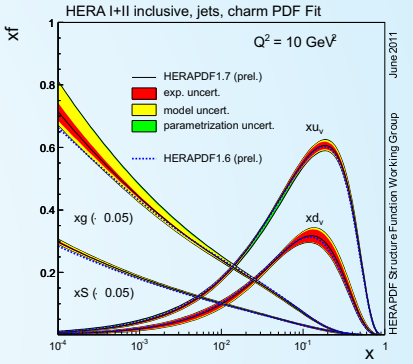


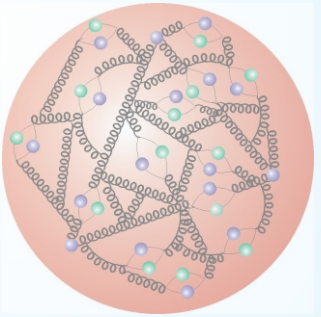
Bonn 26.3.2012

I.Abt, MPI München

Content

- Protonic Facts
- Cross Sections and Structure Functions
  - Measurements
  - Parton Distribution Functions
- Predictions
  - charm and glue
- Proton Structure ?
  - Photon Structure ?
- Proton Size and Shape
- Summary & Outlook





Before I start

Multiple Apologies

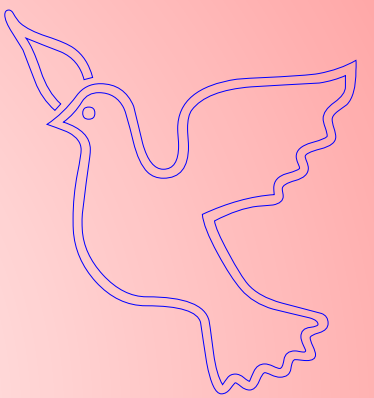
I really know very little about the proton:

- **mass = 1GeV = 1.67 10 $^{-27}$ kg**
- **3 valence quarks**
- **charge = +1**
- **spin = 1/2 $\rightarrow$ Spin**
- **radius $\approx$ 1 fm; shape?**
- **lifetime » age of the universe**
- **afflicted by QCD**

I have no real explanation for any of this!

And I am sorry, if I should disturb you doing your Email or reading your favorite newspaper.

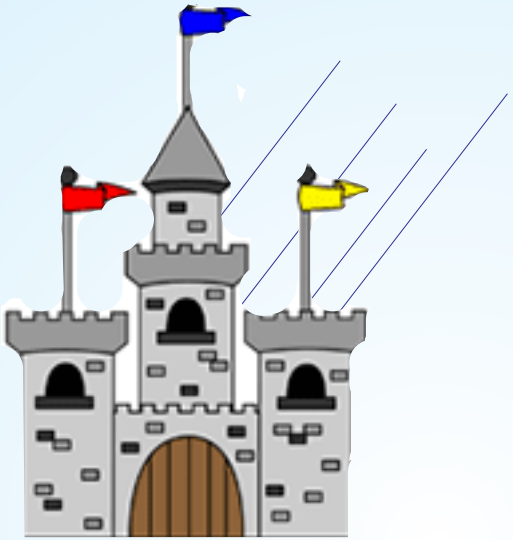
DISCLAIMER



I will not try to be complete
on any subject.
I have selected what I saw fit
to make my point.
Any opinion is only mine and is
in no way supported by either
ZEUS or H1 or probably anybody else.

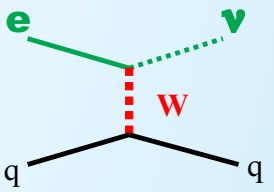
Nevertheless I am proud to represent
H1 and ZEUS.

Deep Inelastic Scattering



e

μ ν



Deep Inelastic Scattering

Look at the debris

Was the king catholic?

Did he waltz?

Was he married?

How many servants did he have?

Escaping proton [remnant]

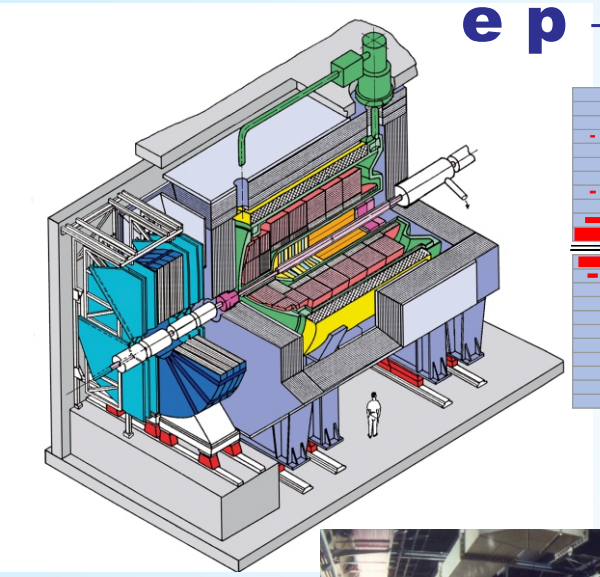
Diffraction → QCD

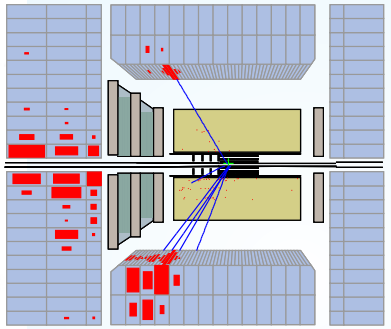
This can rebuild itself

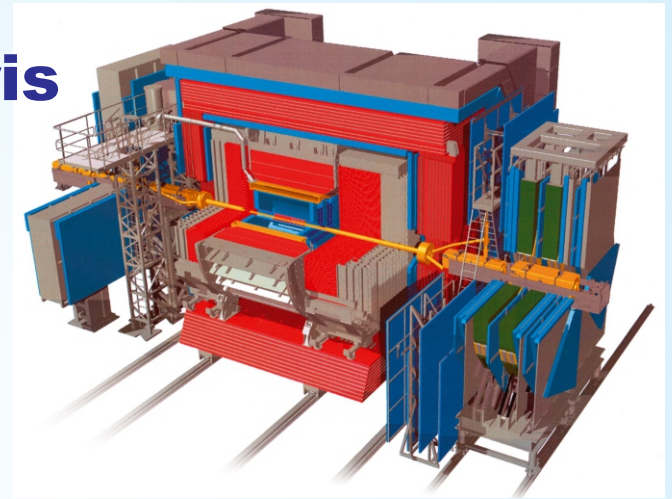
The Microscope

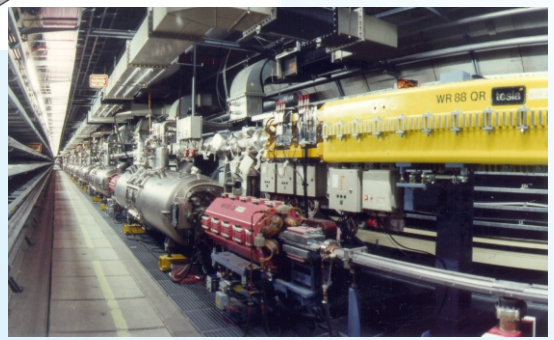
That is what we measure!

$e\ p \rightarrow e\ (\nu)$ debris









We sort events,
classify, count,
plot and interpret.

→ kinematic variables

Kinematics

Virtuality $Q^2 = -(k-k')^2$

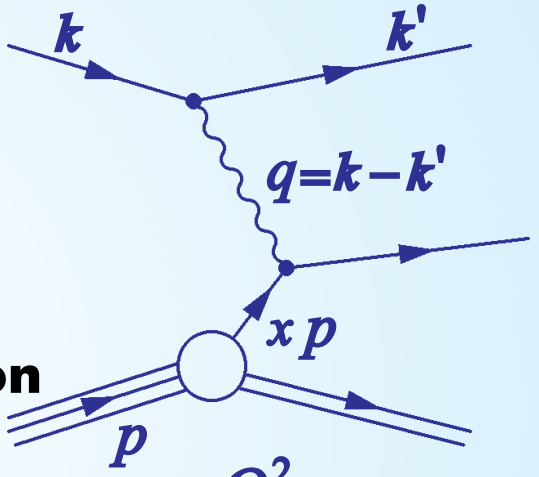
Spatial resolution of probe

$$\lambda \sim 1/\sqrt{Q^2}$$

Bjorken scaling variable:

$$x = Q^2/2pq$$

Momentum fraction of struck parton



Inelasticity: $y = pk/pq$

$Q^2 = xys$

Energy transfer to proton (in p rest frame)

Reconstruction

$$y_e = 1 - \frac{E'_e(1-\cos\theta_e)}{2E_e} \qquad Q^2_e = \frac{E'^2_e \sin^2\theta_e}{1-y_e} \qquad x_e = \frac{Q^2_e}{4E_pE_ey_e}$$

Factorisation

Decompose cross section:

$$\sigma(ep \to e + H + X) = \sum_{j,j'=q,\bar{q},g} f_{j/p}(x,Q) \otimes \hat{\sigma}_{jj'}(x,Q,z) \otimes F_{H/j'}(z,Q)$$

parton distribution functions

PDF

partonic cross section

hadronisation

NC $V^* = \gamma^*, Z^*$

Born $V^*q \to q$

boson-gluon-fusion $V^*g \to q\bar{q}$

QCD-Compton-scattering $V^*q \to qg$

CC W^*

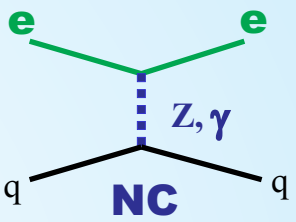
$V^*q \to q'$

lowest-order QCD

Structure Functions

$e^{\pm}p$

tree level $\quad \sigma^{\pm}_{r,NC} = \frac{d^2\sigma^{e^{\pm}p}_{NC}}{dxdQ^2} \cdot \frac{Q^4 x}{2\pi\alpha^2 Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$



$$\tilde{F}_2 = F_2 - \kappa_Z v_e \cdot F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2) \cdot F_2^Z$$
$$\tilde{F}_L = F_L - \kappa_Z v_e \cdot F_L^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2) \cdot F_L^Z$$
$$x\tilde{F}_3 = \kappa_Z a_e \cdot xF_3^{\gamma Z} - \kappa_Z^2 \cdot 2v_e a_e \cdot xF_3^Z$$

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

v_e vector
a_e axial-vector
eZ weak couplings

$$\kappa_Z(Q^2) = Q^2/[(Q^2 + M_Z^2)(4\sin^2\theta_W \cos^2\theta_W)] \quad (2)$$

QPM $\quad \tilde{F}_L = 0$

$$(F_2, F_2^{\gamma Z}, F_2^Z) = [(e_u^2, 2e_u v_u, v_u^2 + a_u^2)(xU + x\bar{U}) + (e_d^2, 2e_d v_d, v_d^2 + a_d^2)(xD + x\bar{D})]$$

$$(xF_3^{\gamma Z}, xF_3^Z) = 2[(e_u a_u, v_u a_u)(xU - x\bar{U}) + (e_d a_d, v_d a_d)(xD - x\bar{D})]$$

$xU = xu + xc \qquad x\bar{U} = x\bar{u} + x\bar{c} \qquad xD = xd + xs \qquad x\bar{D} = x\bar{d} + x\bar{s}$

sea quarks = anti-quarks
valence quark distributions

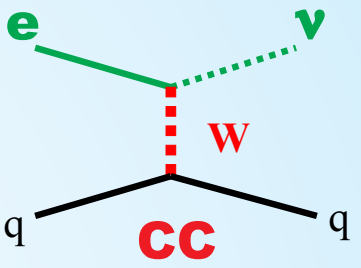
$xu_v = xU - x\bar{U} \qquad xd_v = xD - x\bar{D}$

Structure Functions

$e^{\pm}p$

tree level

$$\sigma^{\pm}_{r,CC} = \frac{Y_+}{2} W_2^{\pm} \mp \frac{Y_-}{2} x W_3^{\pm} - \frac{y^2}{2} W_L^{\pm}$$



CC is unfortunately a bit more difficult.

QPM $W_L^{\pm} = 0$

$$W_2^+ = x\bar{U} + xD \qquad xW_3^+ = xD - x\bar{U} \qquad W_2^- = xU + x\bar{D} \qquad xW_3^- = xU - x$$

$$\sigma^+_{r,CC} = x\bar{U} + (1-y)^2 xD \qquad \sigma^-_{r,CC} = xU + (1-y)^2 x\bar{D}$$

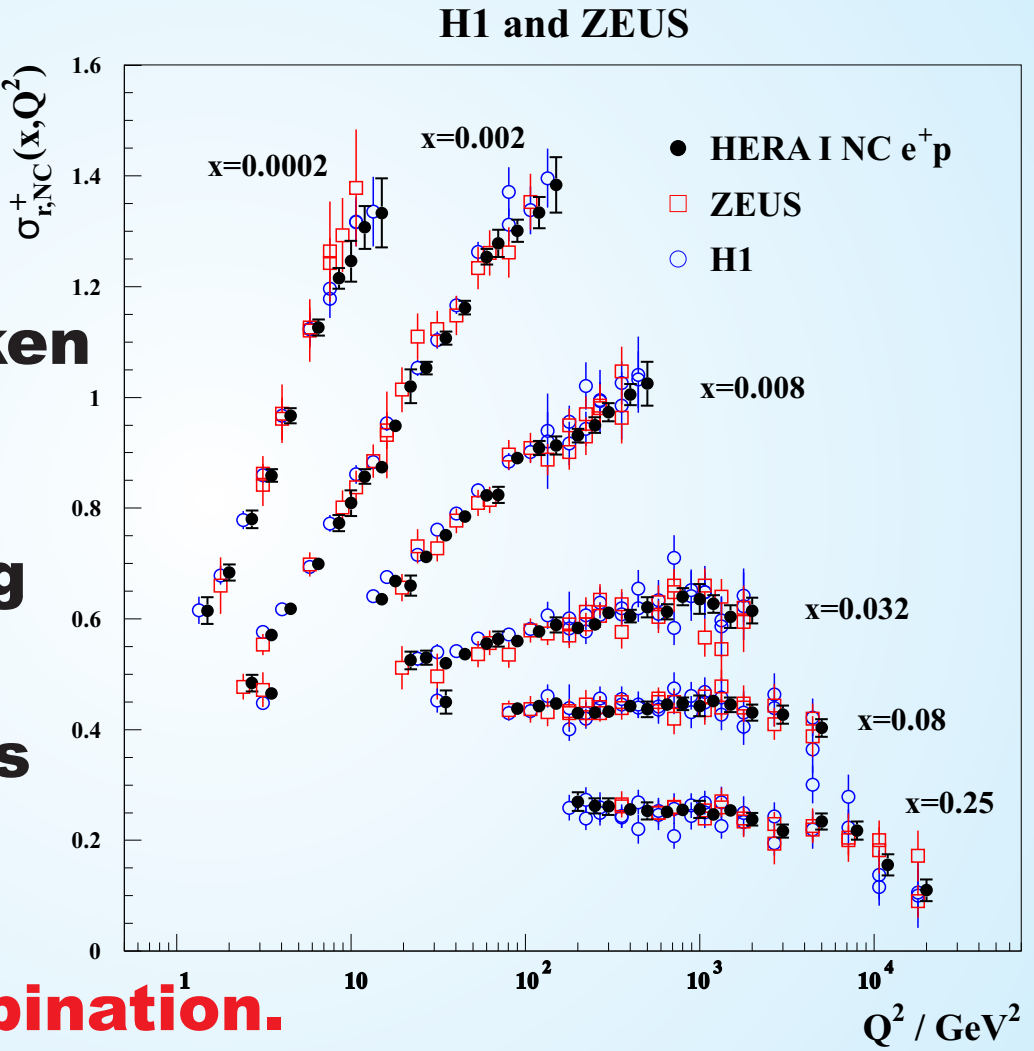
NC and CC yield valence and sea quark distribution.

QCD analysis [DGLAP] yields gluon distribution.

Advent of Precision

2010:
H1 and ZEUS publish combined results on data taken 1993 to 2000.

10 years of fighting to understand detectors, methods and systematics.

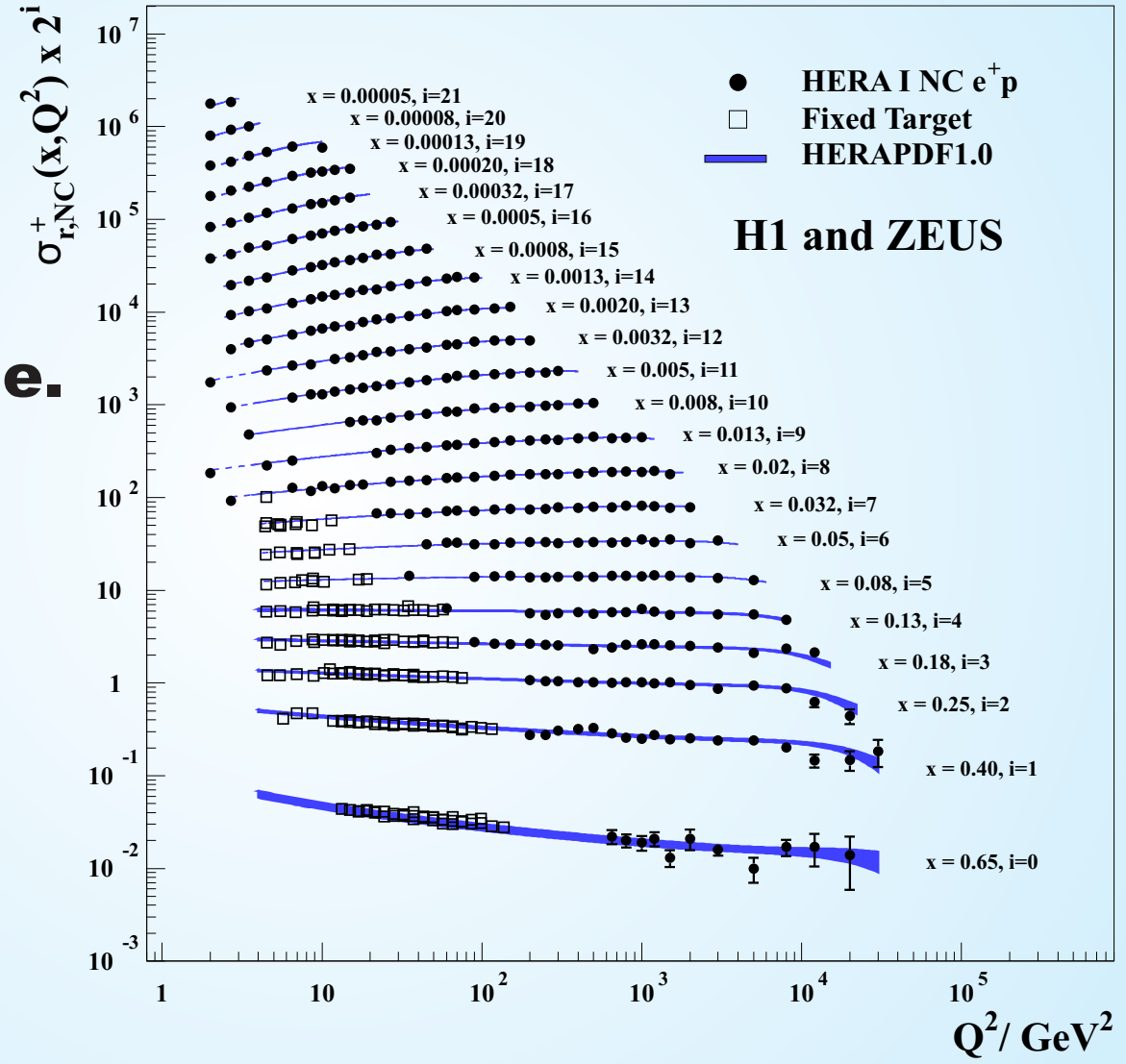


The power of combination.

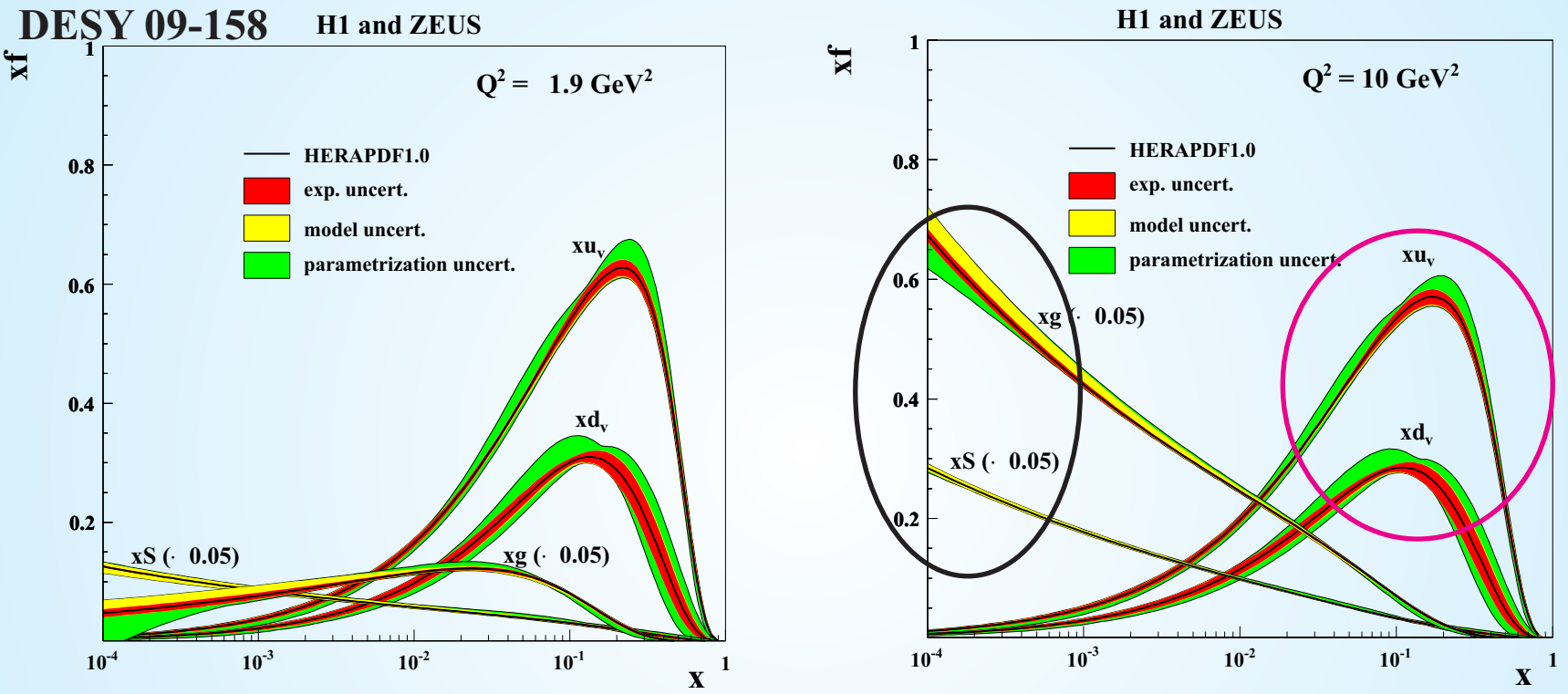
Reduced Cross Section

Cross section data over a very large kinematic range.

HERA data were used as only input to fit HERAPDF 1.0



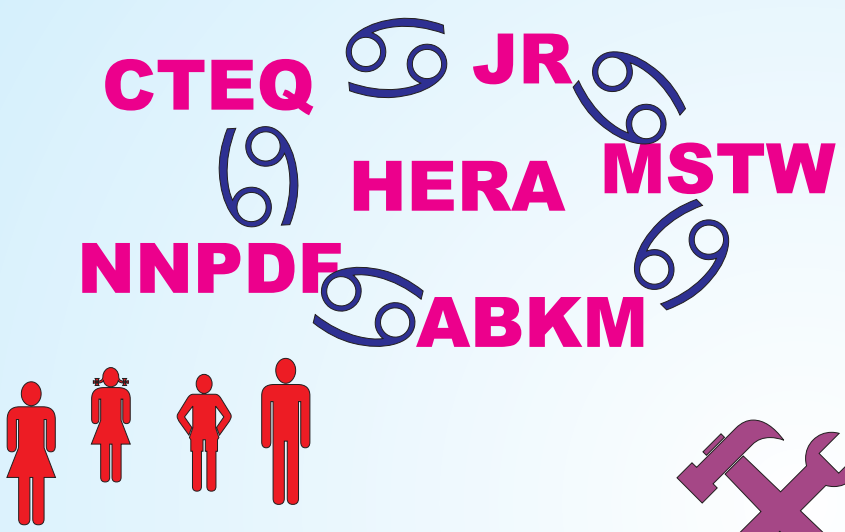
HERAPDF1.0

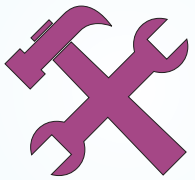


The proton pdfs reveal the valence quarks plus glue and sea evolving with Q^2.

Inclusive DIS data alone can do this.

The PDF Community





SF:We 12.00

[HERA]fitter

Schemes

Parametrisations

systematic uncertainties

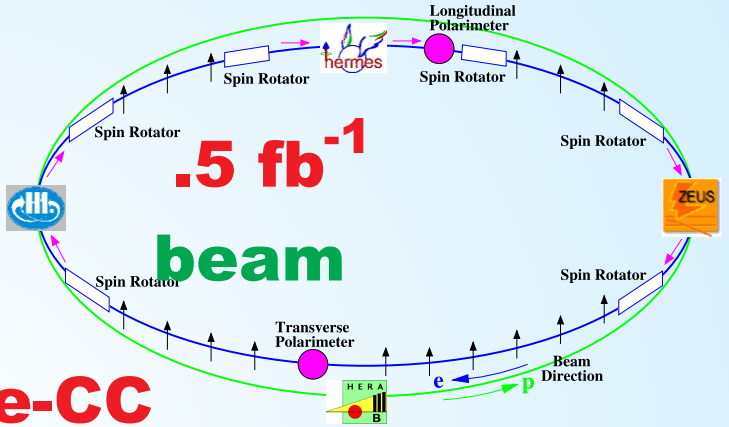
DATA → PDF → Prediction

Consistency between fit and "→" for prediction is essential.

High Statistics Data

HERA II 2003-2007

ZEUS and H1 both got to ≈ .5 fb^{-1} polarised electron/positron beam



	e+ NC	e-NC	e+CC	e-CC
ZEUS	prel.	published		
H1	preliminary			

Everything high Q^2 to be published soon.

In addition:

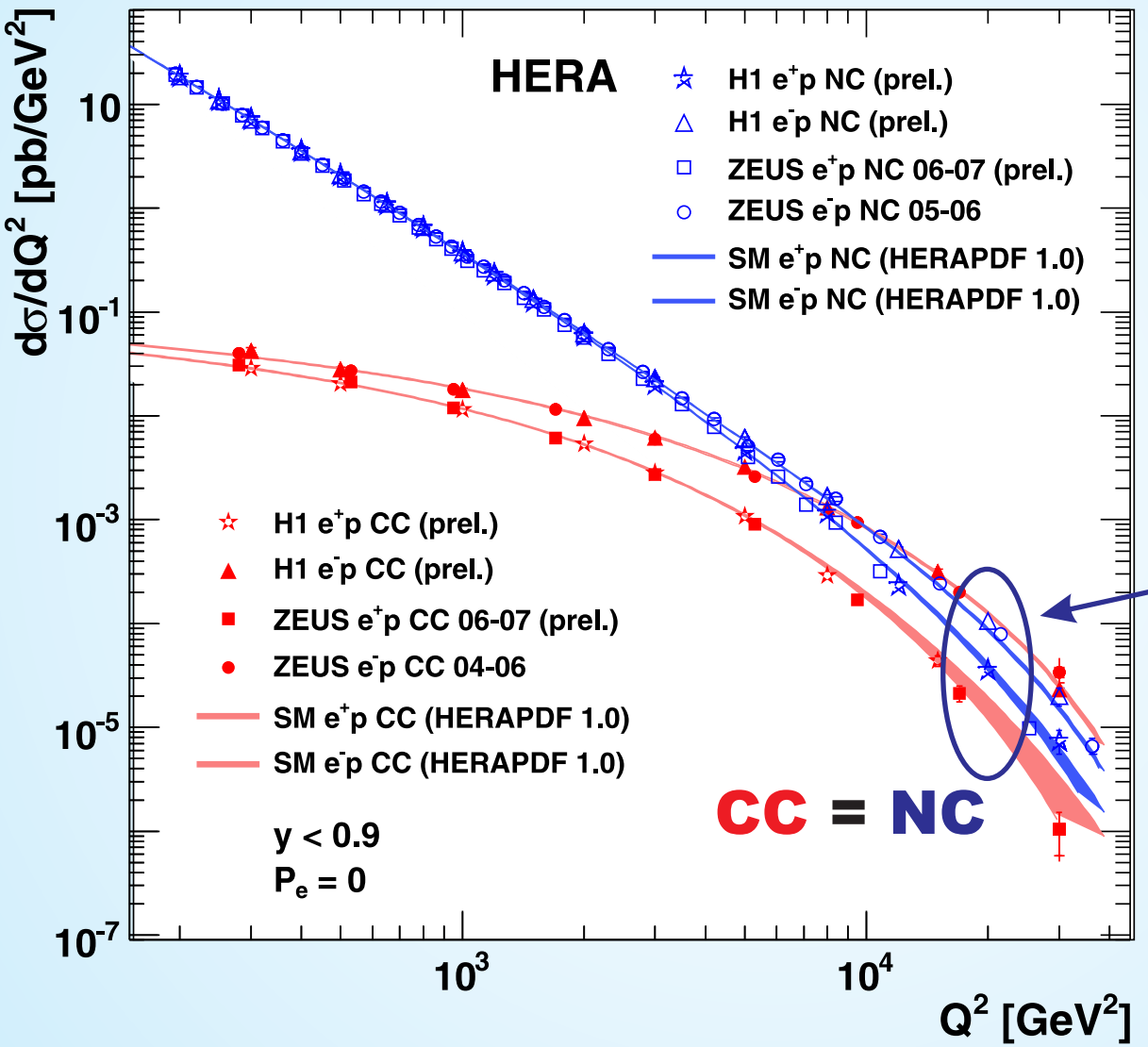
F_{2c} F_{2b} F_L

F2diff Diffraction

jets HFS

QCD P:K. Daum Mo 14.55

A Taste of Precision



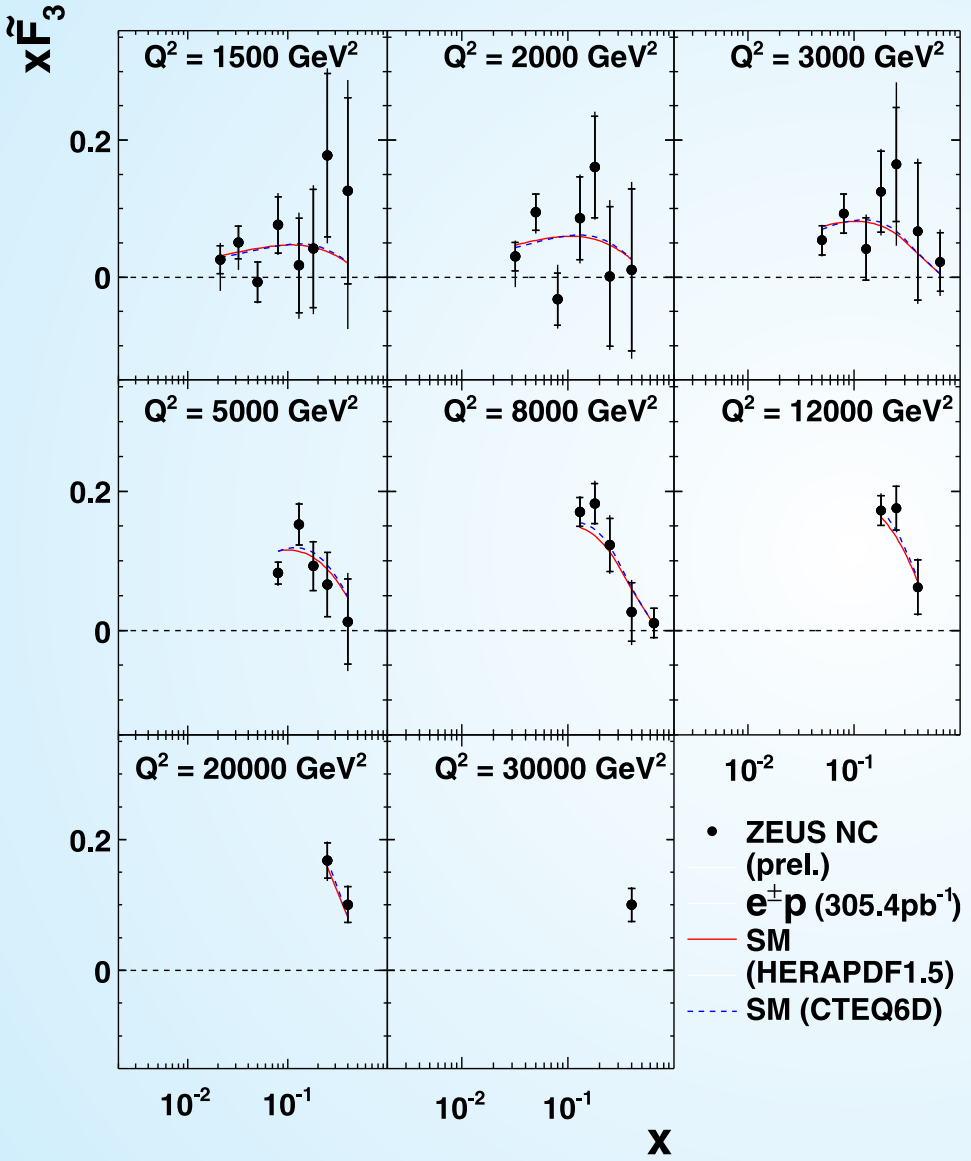
high Q^2

NC

CC

xF_3 **difference between positron and electron data**

A Taste of Precision



ZEUS

NC

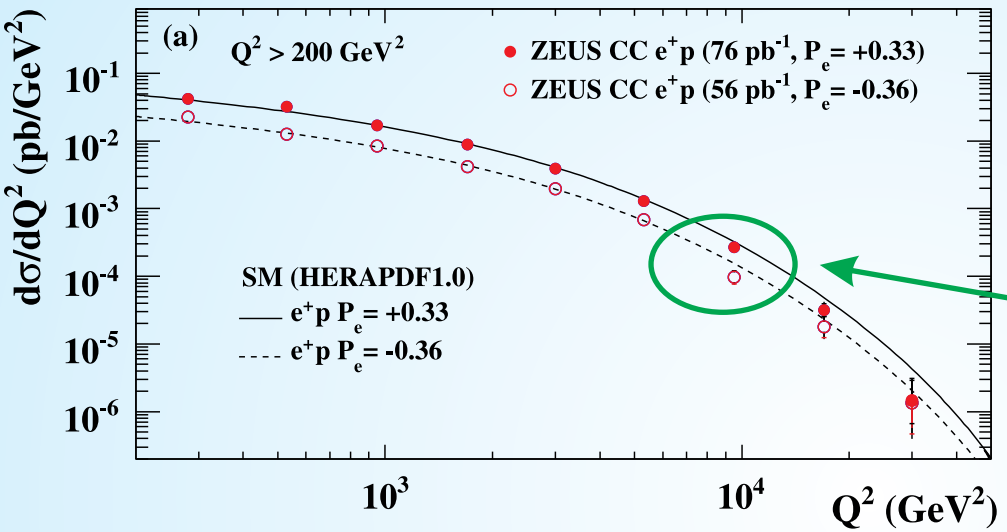
positron and electron data

SF: We 9.00

ZEUS-prel-11-003

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}\left(\sigma^-_{r,NC} - \sigma^+_{r,NC}\right)$$

A Taste of Precision



DESY 10-129

ZEUS

CC

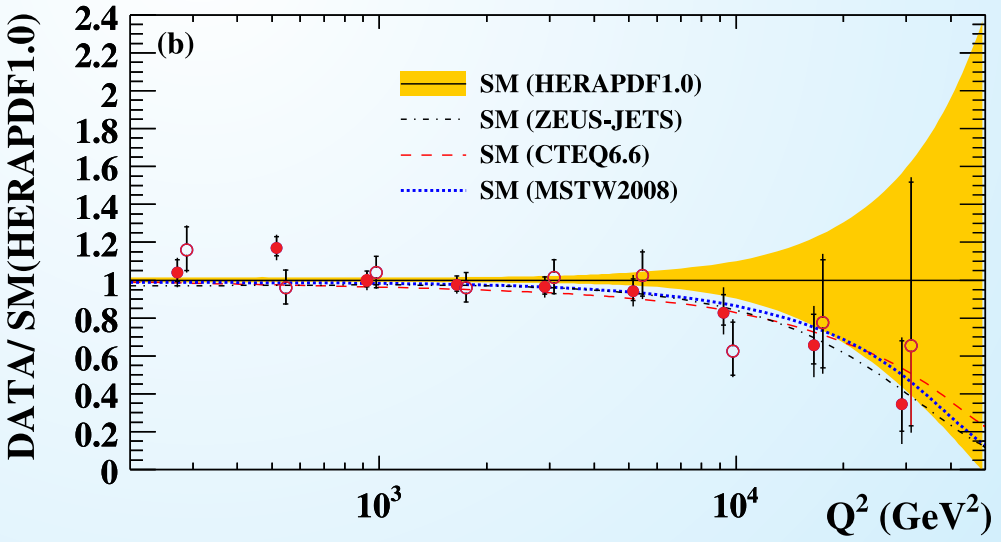
polarised

positron data

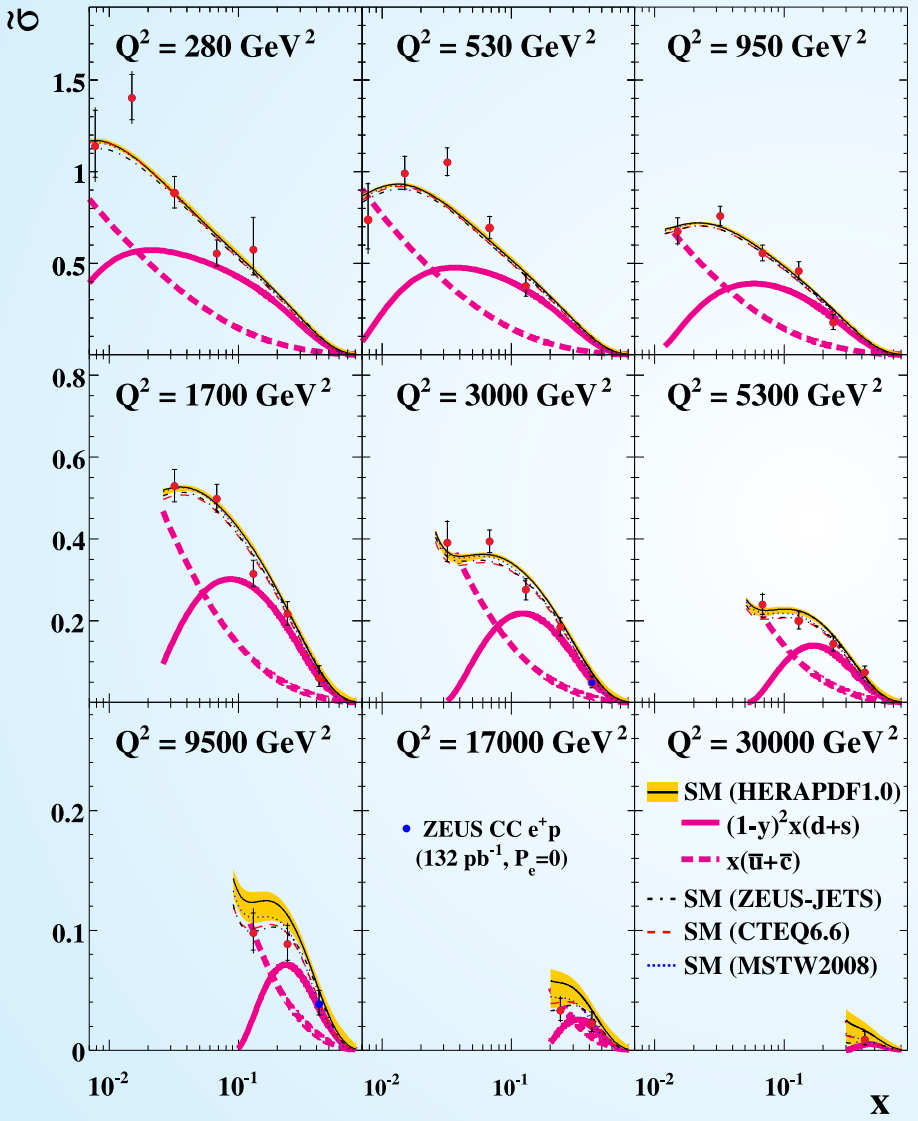
Beautiful

input

for fits



A Taste of Precision



ZEUS

DESY-10-129

cc

positron data

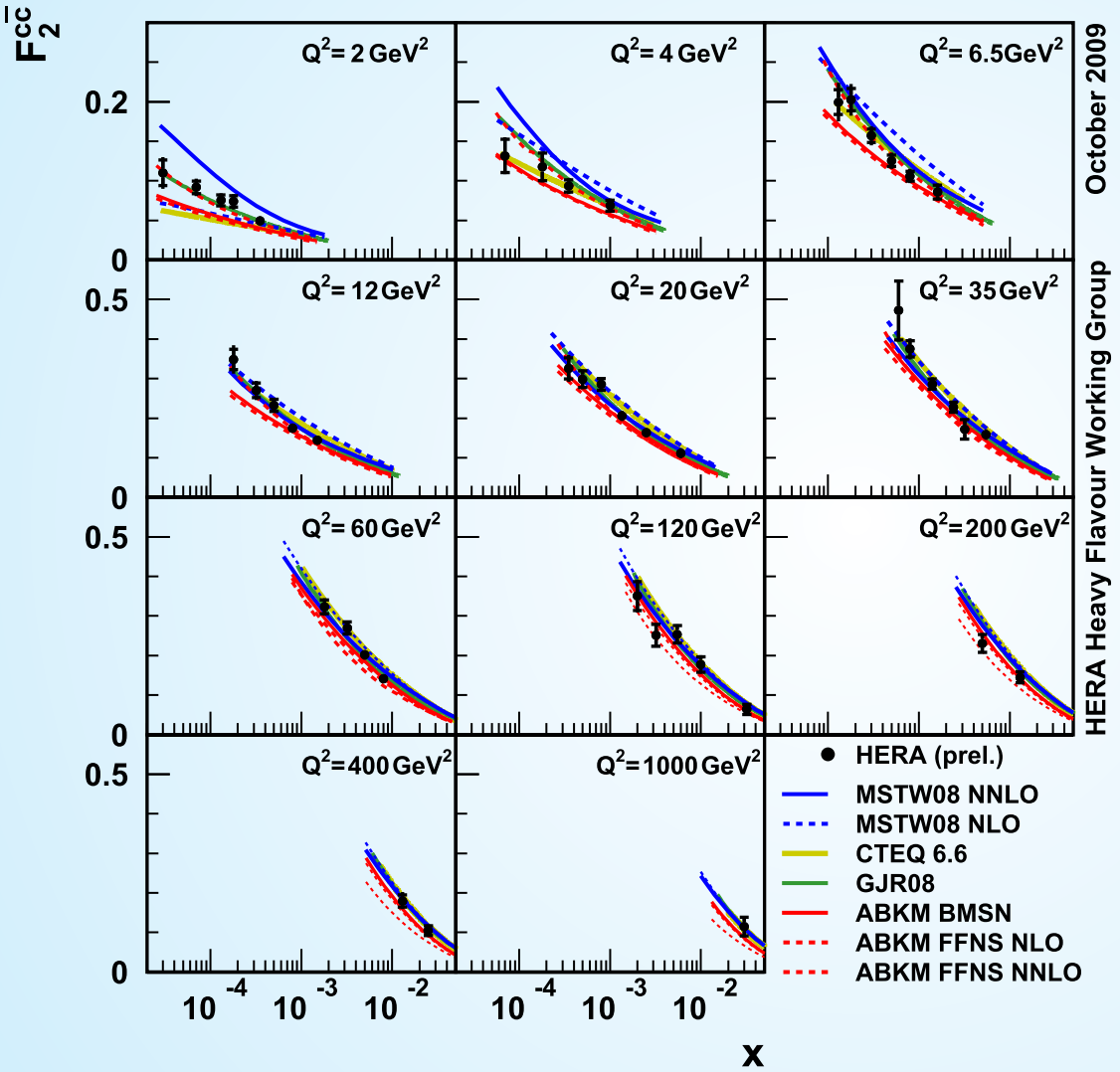
$$\sigma^{+}_{r,c\bar{c}} = x\bar{U} + (1-y)^2 xD$$

$$xD = xd + xs$$

$$x\bar{U} = x\bar{u} + x\bar{c}$$

a hint of charm

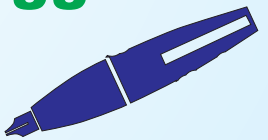
Charm Structure Function



$xU = xu + xc$

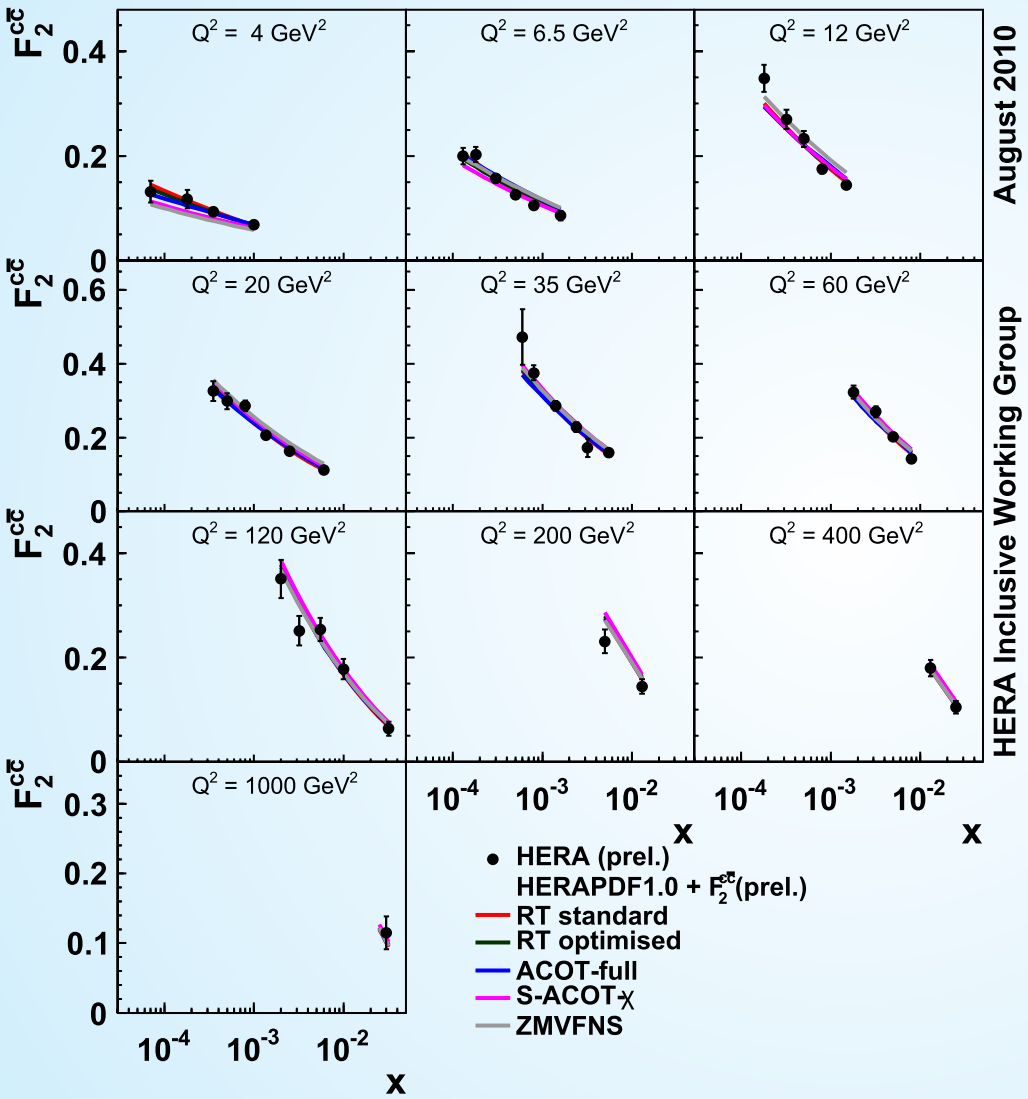
a handle on charm

NC : produce all kinds of D mesons [tagged somehow]



H1prel-09-0171
ZEUS-prel-09-015

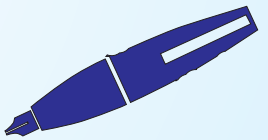
Charm Structure Function



$$xU = xu + xc$$

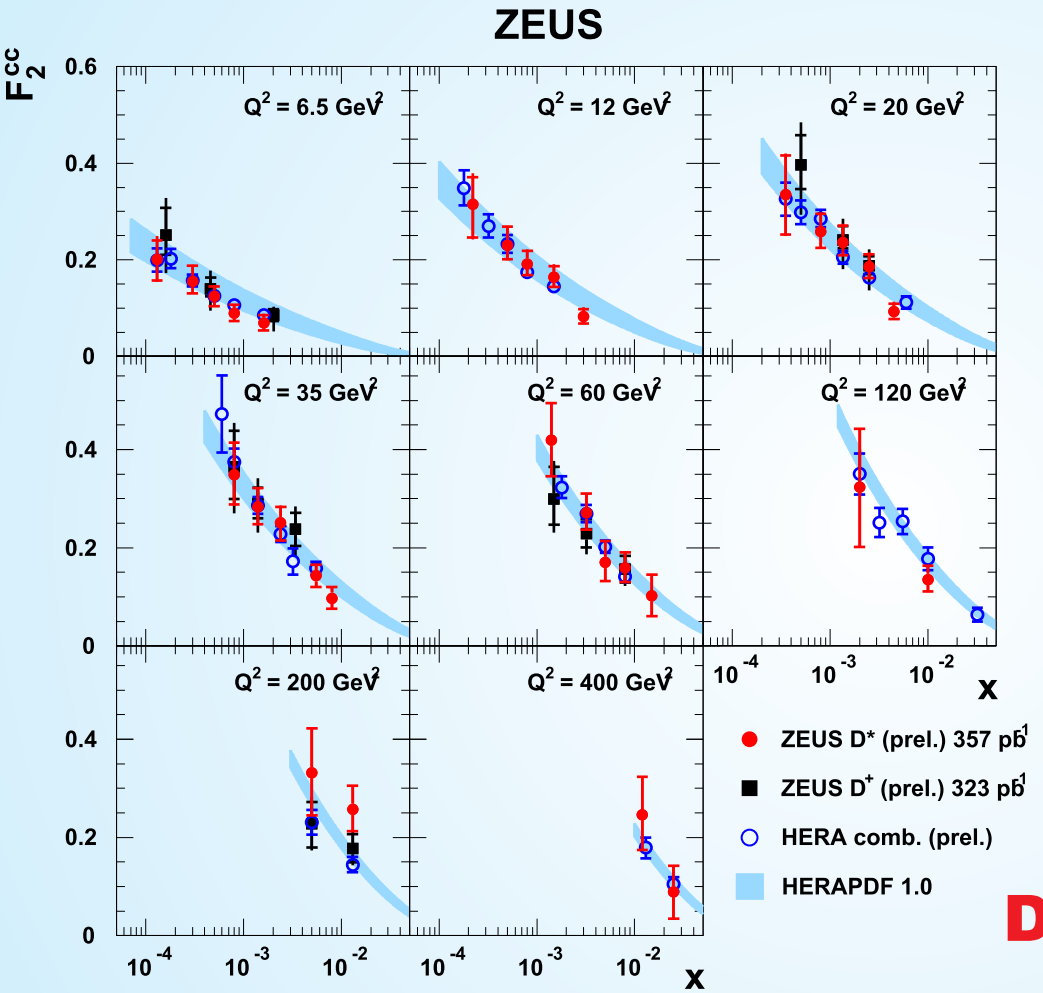
HERAPDF1.0 plus preliminary charm data

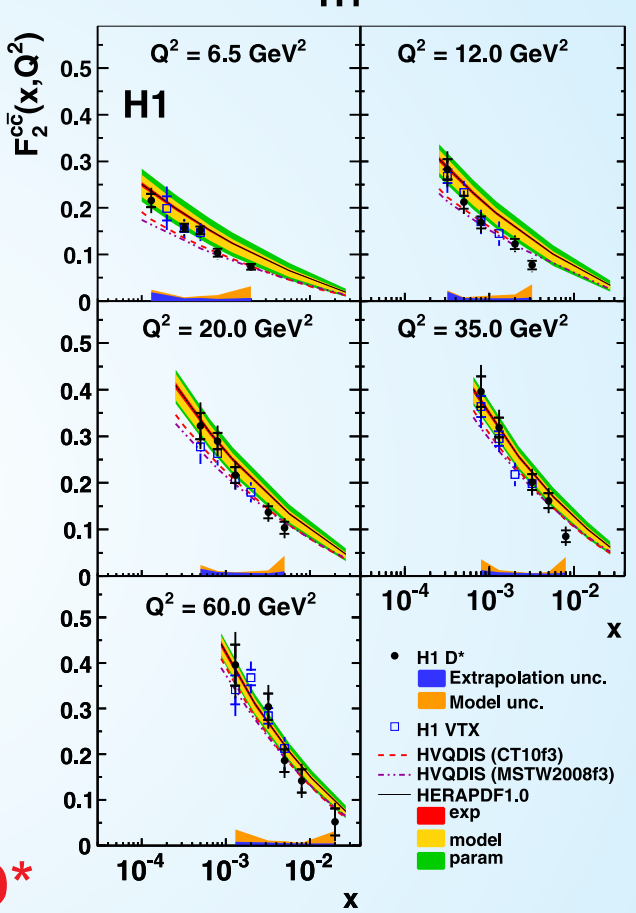
charm mass scan



H1prel-10-143
ZEUS-prel-10-019

Charm Structure Function





D*

ZEUS-prel-11-012
HFL: Thursday 11.00 + 11.18 Z-prel-12-002

H1 DESY 11-066
HFL: Thursday 11.36

HERAPDF Family

recommended version

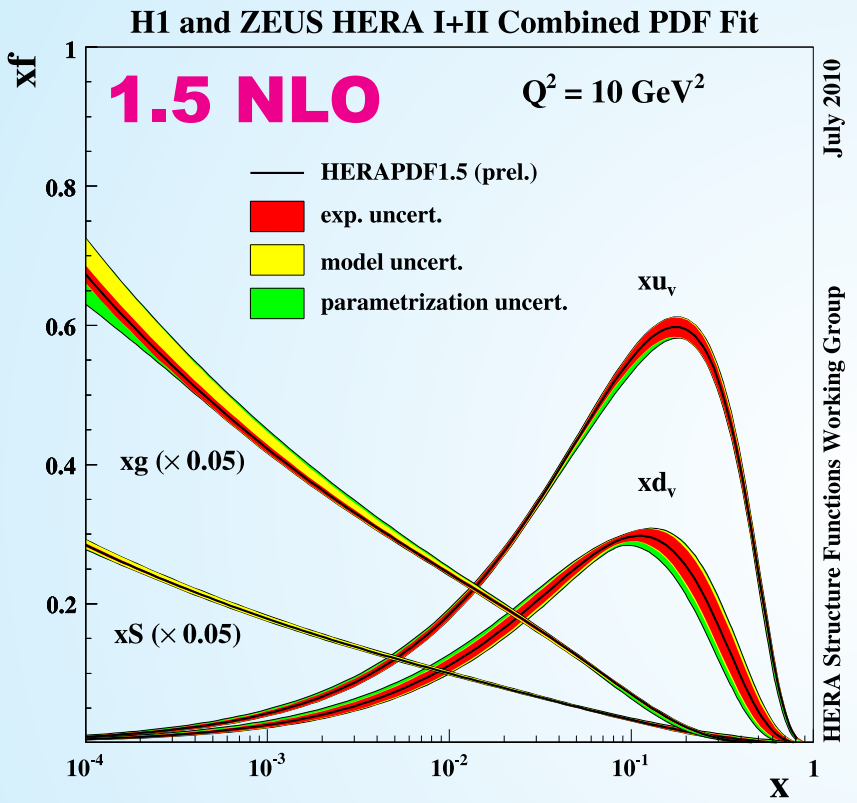
NAME	NC and CC DIS	NC, lower E(p_beam)	Jets	Charm	Docu	Grids	Data comparison	Date
HERAPDF1.7 NLO	HERAI + partial HERAII	H1+ZEUS	H1 and ZEUS(1)	H1+ZEUS	Figures	N.A.		June 2011
HERAPDF1.6 NLO	HERAI + partial HERAII	---	H1 and ZEUS(1)	---	Writeup and figures	N.A.		March 2011
HERAPDF 1.5 NNLO	HERAI + partial HERAII	---	---	---	Figures	LHAPDF beta 5.8.6		March 2011
HERAPDF 1.5 NLO	HERAI + partial HERAII	---	---	---	Figures	LHAPDF beta 5.8.6		July 2010
Charm mass scan	HERAI	---	---	H1+ZEUS	Writeup and figures	---		August 2010
HERAPDF1.0 NNLO	HERAI	---	---	---	ICHEP2010 writeup and figures	Docu for LHAPDF		April 2010
	HERAI	H1+ZEUS	---	---	Writeup and figures	N.A.		April 2010
	HERAI	---	---	H1+ZEUS	DIS2010 writeup and figures	N.A.		April 2010
HERAPDF1.0 NLO PUBLISHED	HERAI	---	---	---	Paper HERAPDF1.0 page	LHAPDF	Benchmarking HERAPDF1.0	Nov. 2009

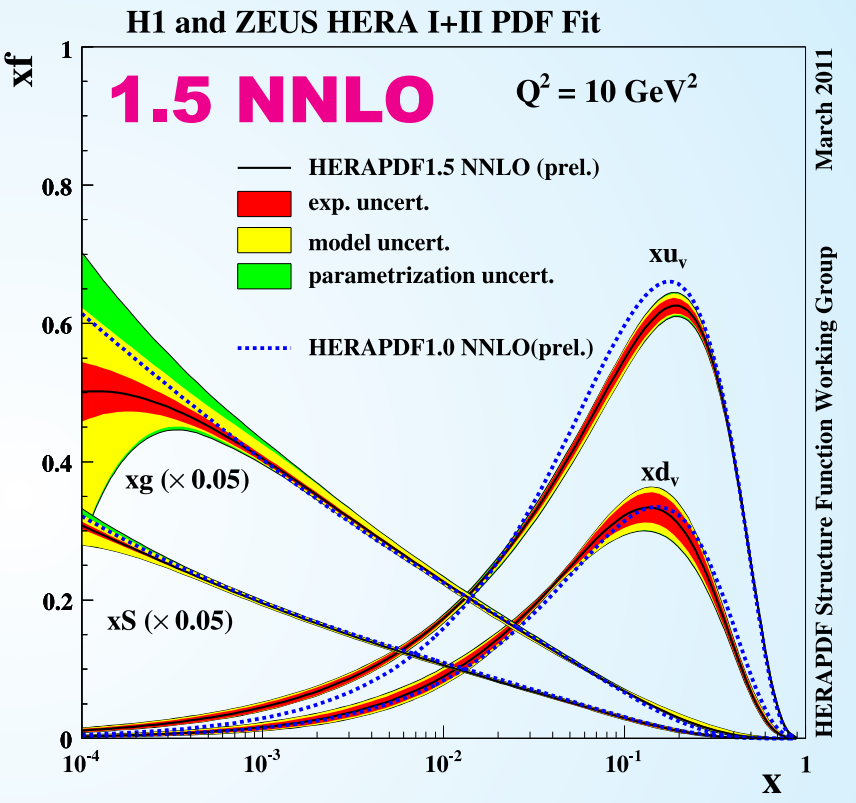
More and more data are being added.

A major release will come as soon as all inclusive data published.

SF: Tu 10.05
H1prel-11-143
ZEUS-prel-11-010

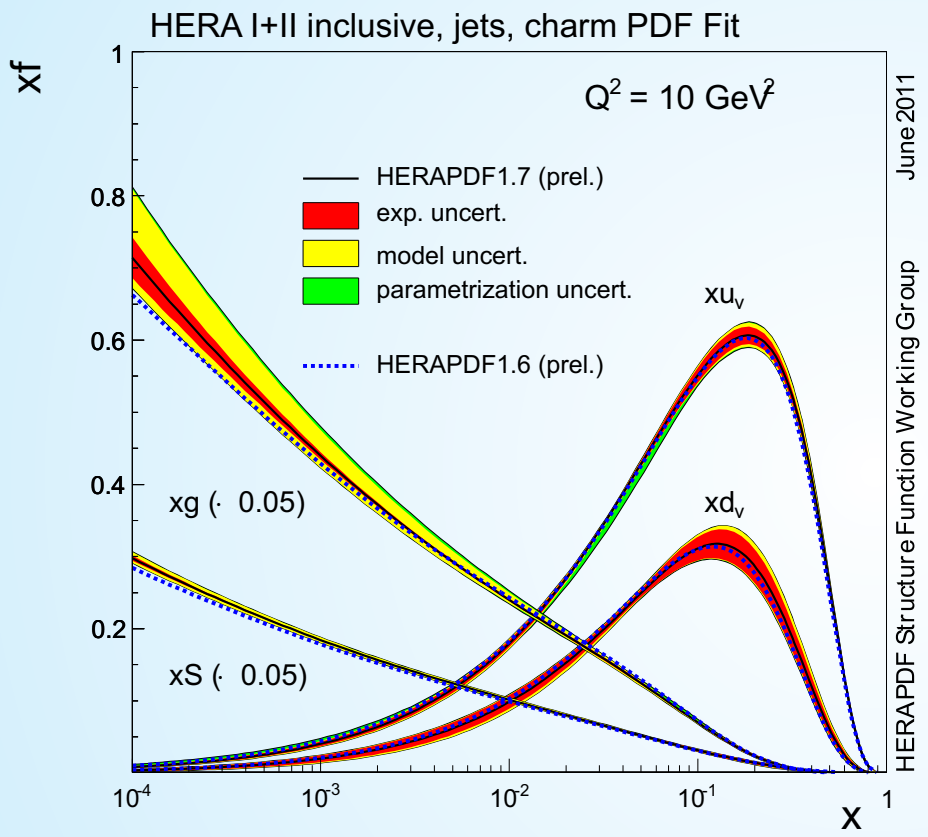
HERAPDF Family





HERAPDF 1.5 NLO and 1.5 NNLO are the family members recommended for general use.

HERAPDF Family



H1prel-11-143
ZEUS-prel-11-010

SF: Tu 10.05

HERAPDF 1.7 is the newest member based on inclusive, low Ep, jets and charm data.

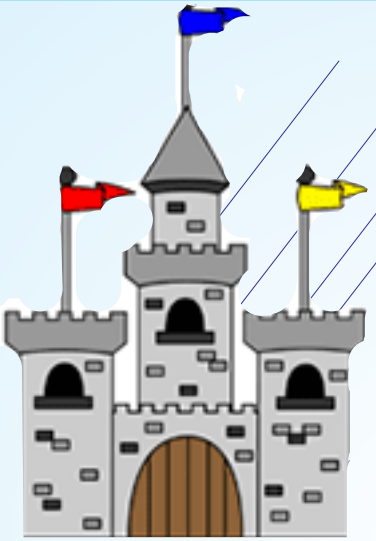
steeper low-x gluon than ever before:

low Ep data

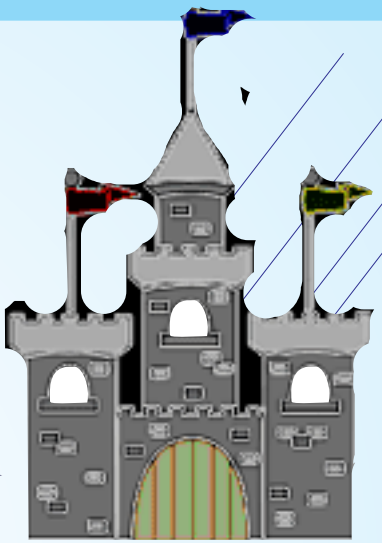
m_c: 1.4 → 1.5 GeV
RT optimal scheme

Castle Castle Interactions

proton
proton
collisions

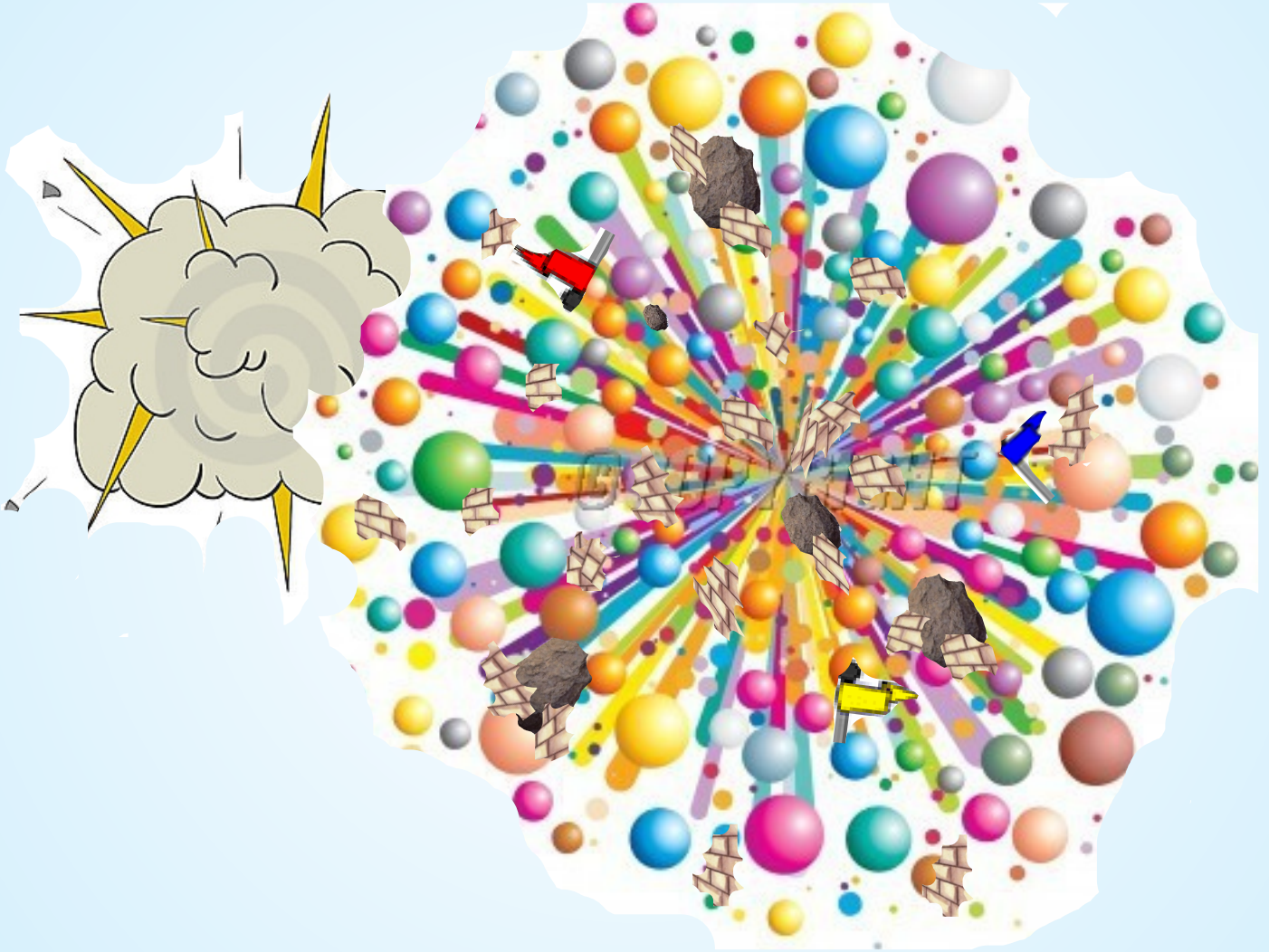


collider physics



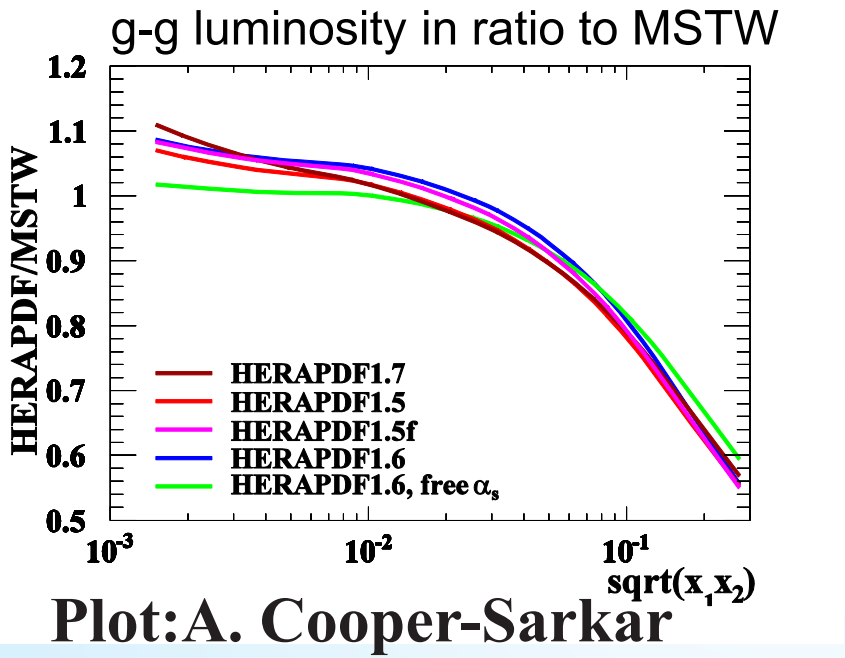
antiproton
proton
collisions

Beautiful Destruction

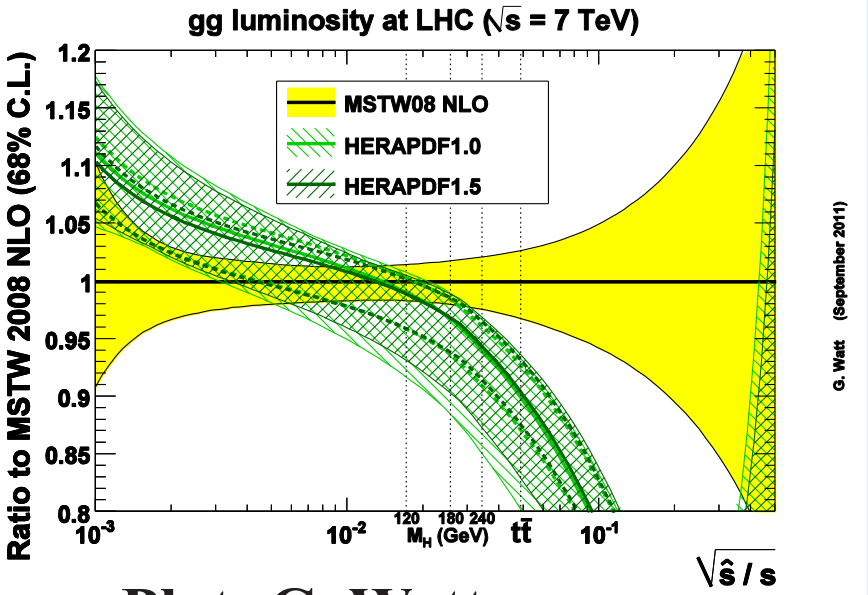


HERAPDF Predictions

LHC needs PDFs to predict SM distributions



Plot:A. Cooper-Sarkar



Plot: G. Watt

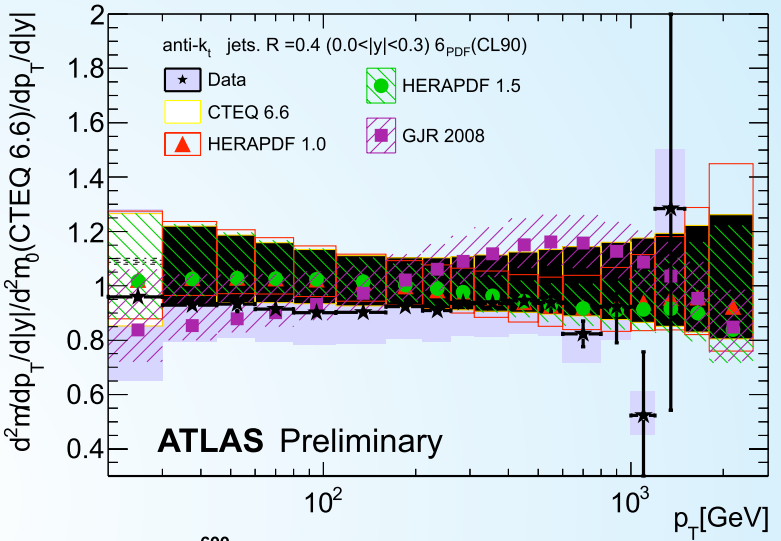
No reliable PDFs

$\Rightarrow$ no reliable searches

HERAPDF used by ATLAS and CMS

Jet production measurement:

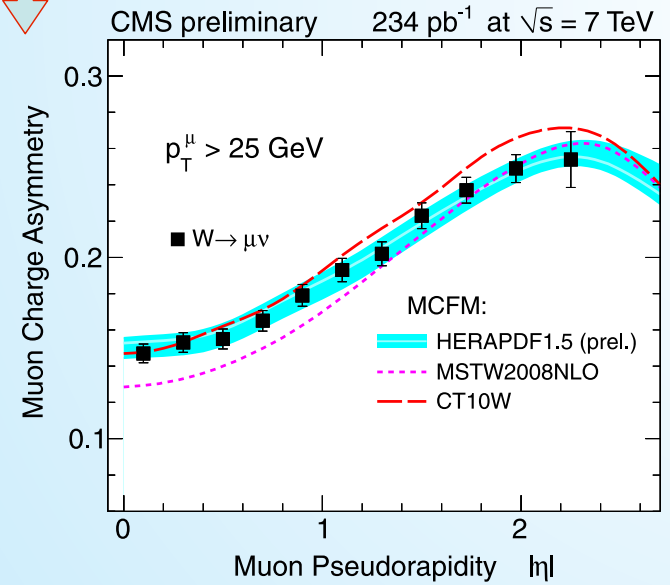
sensitive to gluon distribution, $\alpha_S(M_Z)$



W muon charge asymmetry:

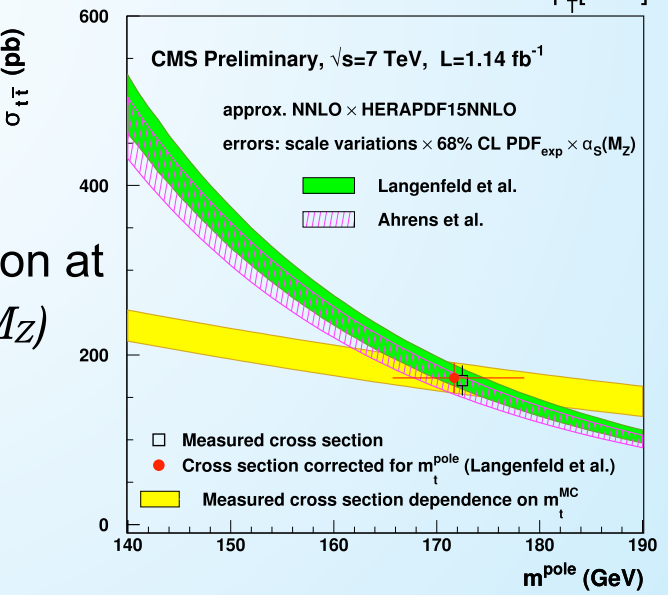
sensitive to difference between u and d

$$A_W = \frac{W^+ - W^-}{W^+ + W^-} \approx \frac{u_v - d_v}{u_v + d_v + 2u_{sea}}$$



Top pair production:

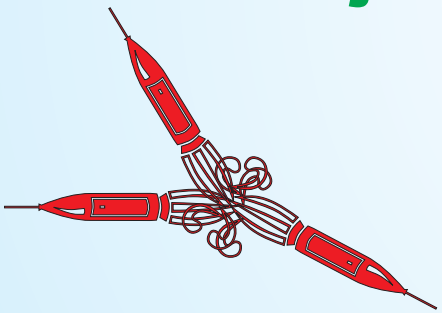
sensitive to gluon at high x, $\alpha_S(M_Z)$

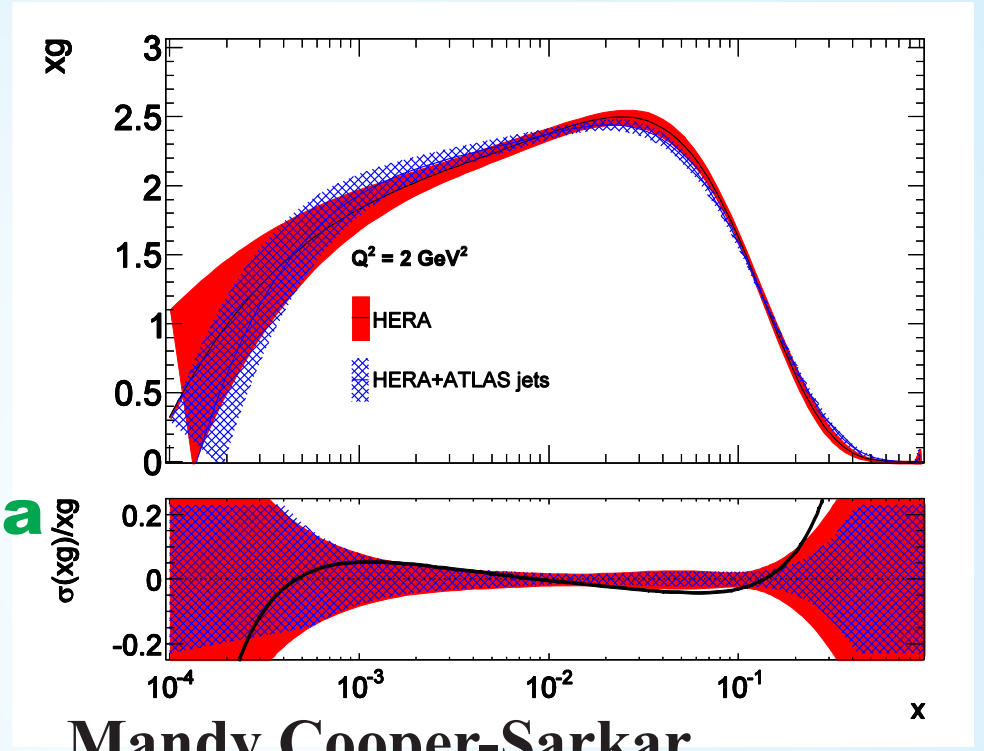


LHC can contribute

HERAPDF 1.5f

plus ATLAS jet data





Mandy Cooper-Sarkar

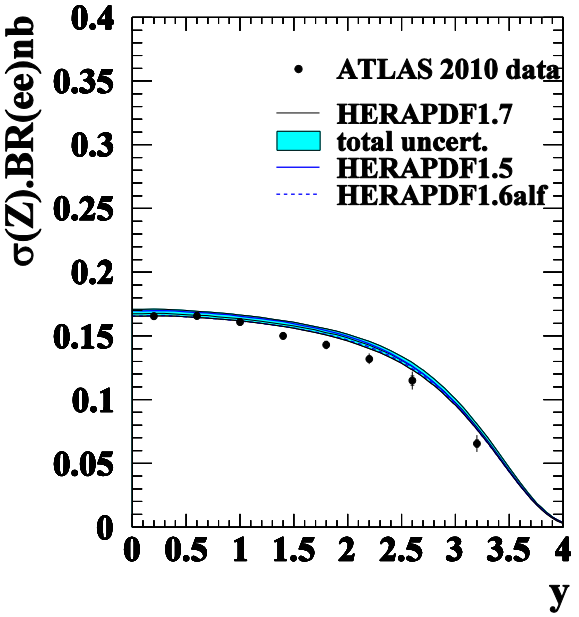
Work done on published ATLAS data

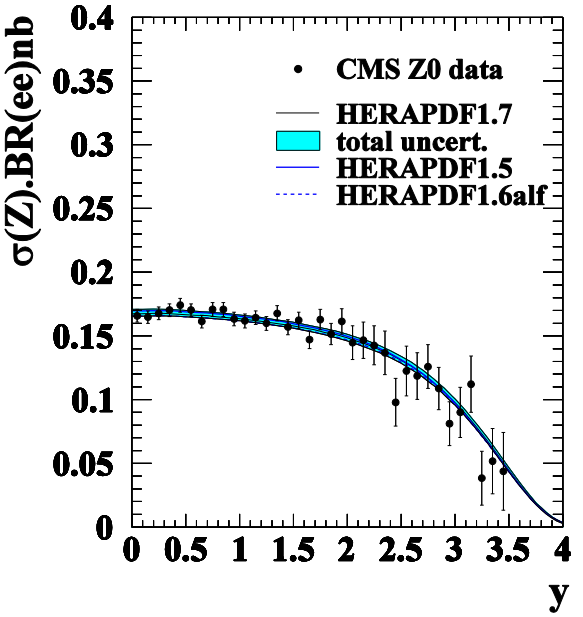
ATLAS jets would like high-x gluon to be harder.

HERA also still has jet data. DESY 12-045 HFS: Tu 17.50

HERAPDF Predictions

Z° production at the LHC





Private communication from Mandy Cooper-Sarkar

HERAPDF 1.7 is doing quite well.

The differences to HERAPDF1.5/1.6 are small.

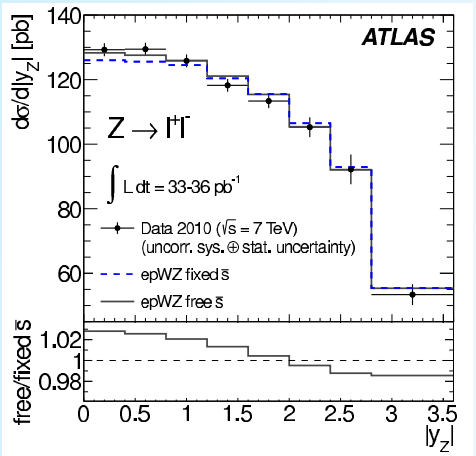
The strange sea is so far restricted in HERAPDF.

LHC can contribute

Strangeness

3

strange quark would need **CC** analysis of Ds at HERA .... mission impossible



ATLAS measures rapidity distribution of Z° production

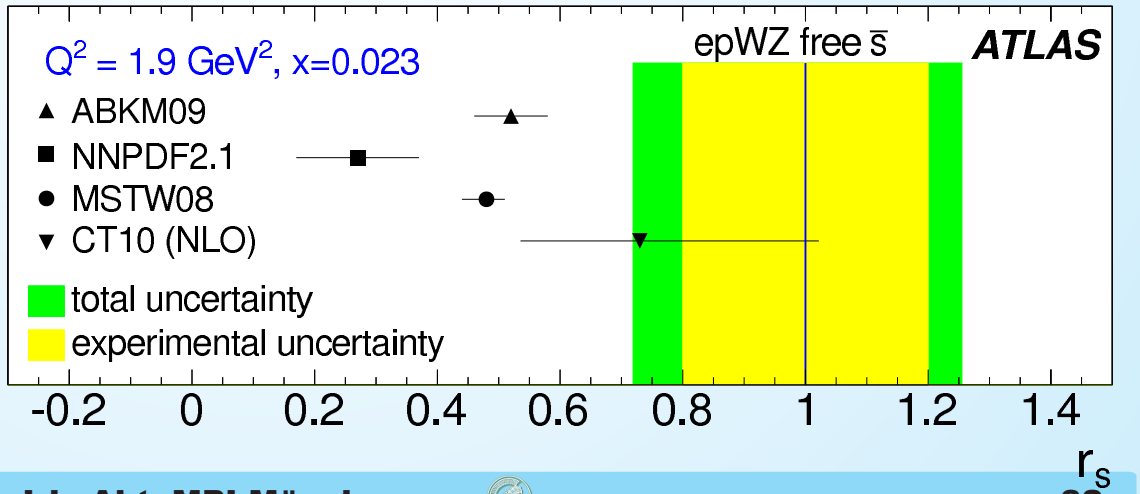
Fit $r_s = 0.5(s+\bar{s})/\bar{d}$ $\quad x\bar{s}(x) = A_s x^{B_{\bar{d}}}(1-x)^{C_s}$

HERAfitter

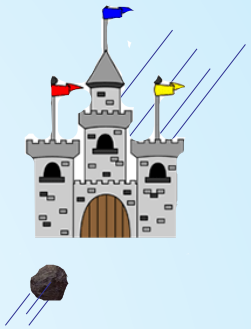
arxiv:1203.4051

$$r_s = 1.00 \pm 0.20_{\text{exp}} \pm 0.07_{\text{mod}}{}^{+0.10}_{-0.15}{}_{\text{par}}{}^{+0.06}_{-0.07}\alpha_S \pm 0.08_{\text{th.}}$$

SF: Tu 9.40



Longitudinal Structure Function



F_L is a high y phenomenon:

$$\sigma_r(x,Q^2) = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$$

Need cross section for varying y at fixed x and Q^2

$Q^2 = xys$ $\Rightarrow$ **need to change** s

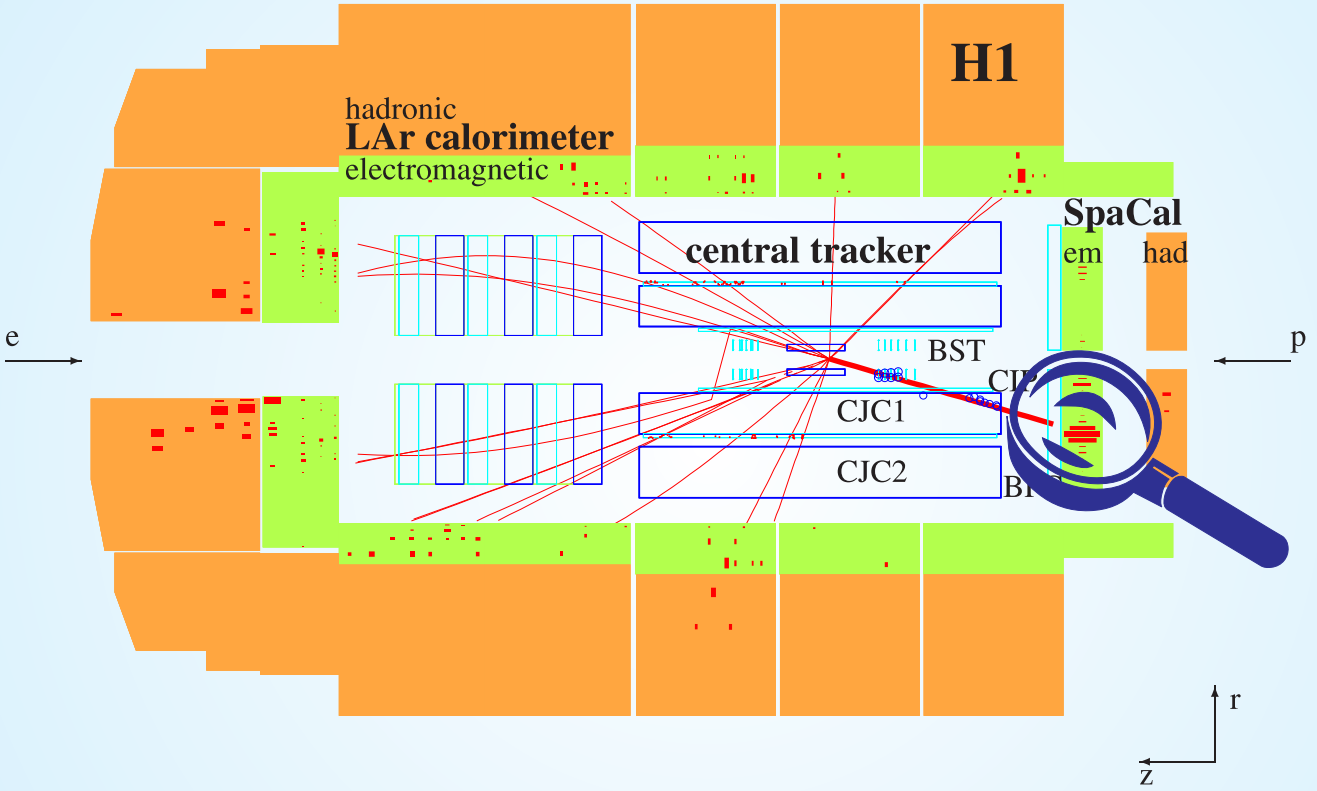
$E_p = 920\,\text{GeV}$ $E_p = 575\,\text{GeV}$ $E_p = 460\,\text{GeV}$

Low Q^2 and high y $\Rightarrow$ low energy of scattered electron

This is a challenge!

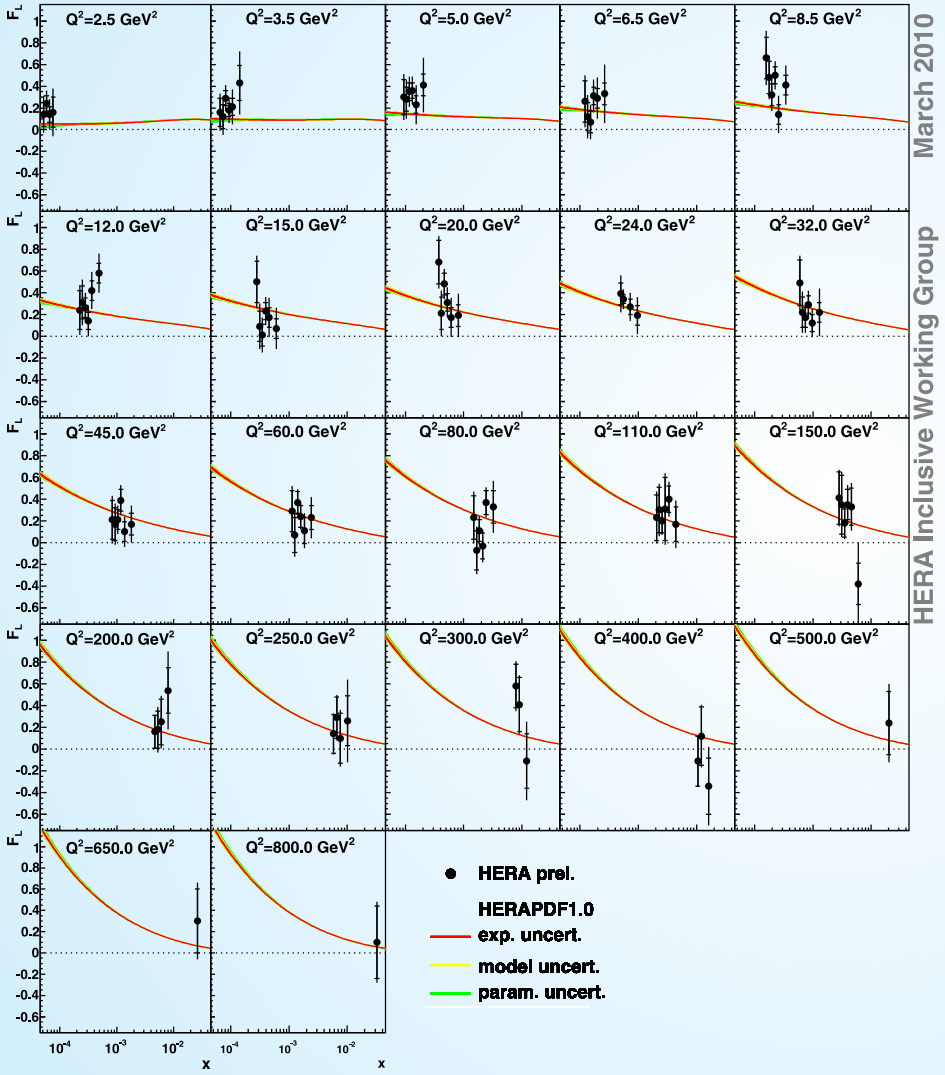
Direct access to glue!

Longitudinal Structure Function



Events down to electron energies of 3.4 GeV
for ZEUS 6.0 GeV

Longitudinal Structure Function

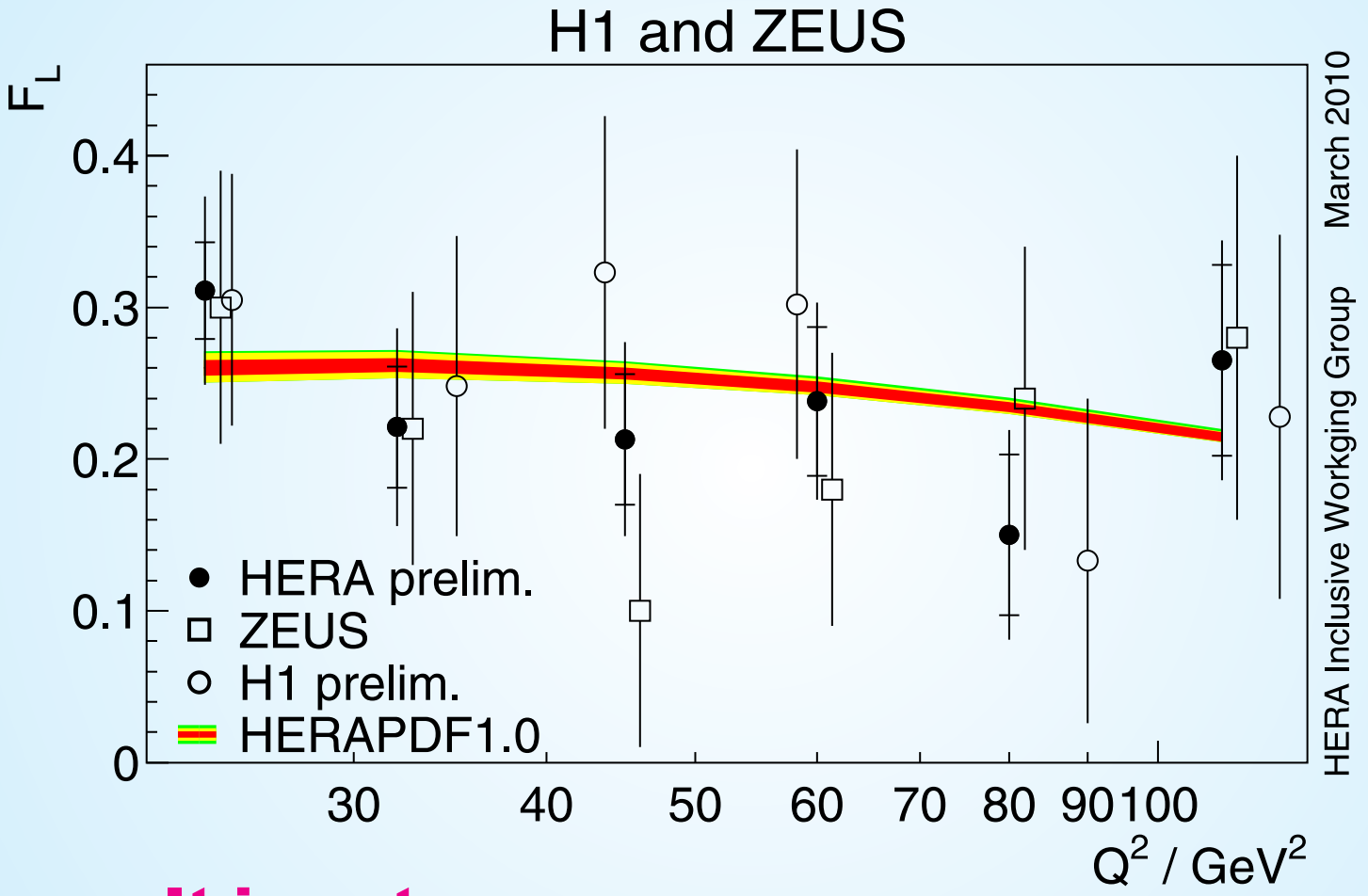


H1 and ZEUS combined

wide range of Q^2 and down to $x \approx 0.00003$

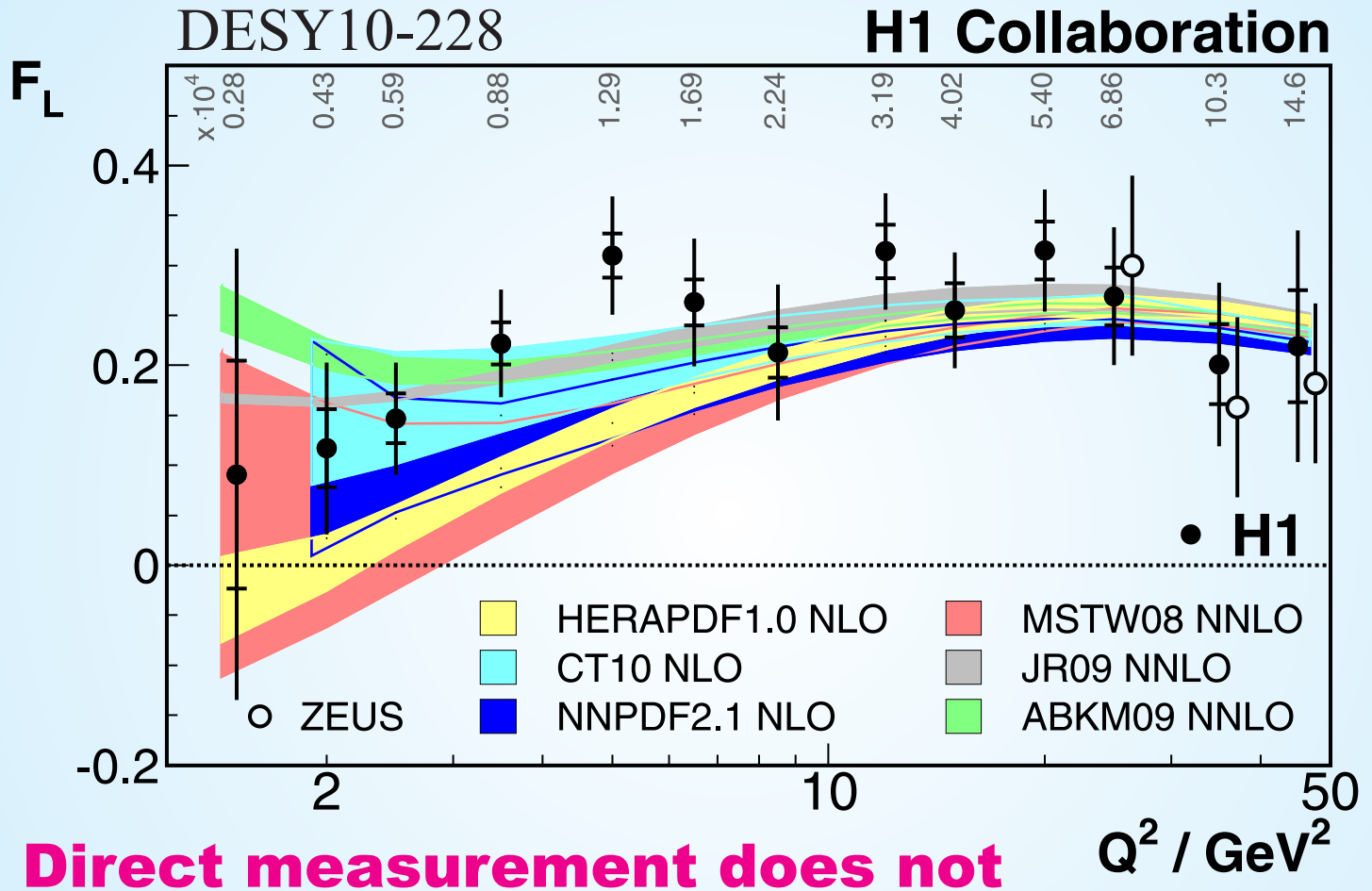
Fixed Target could only access high x region, where F_L is small.

Longitudinal Structure Function



It is not zero.

Longitudinal Structure Function



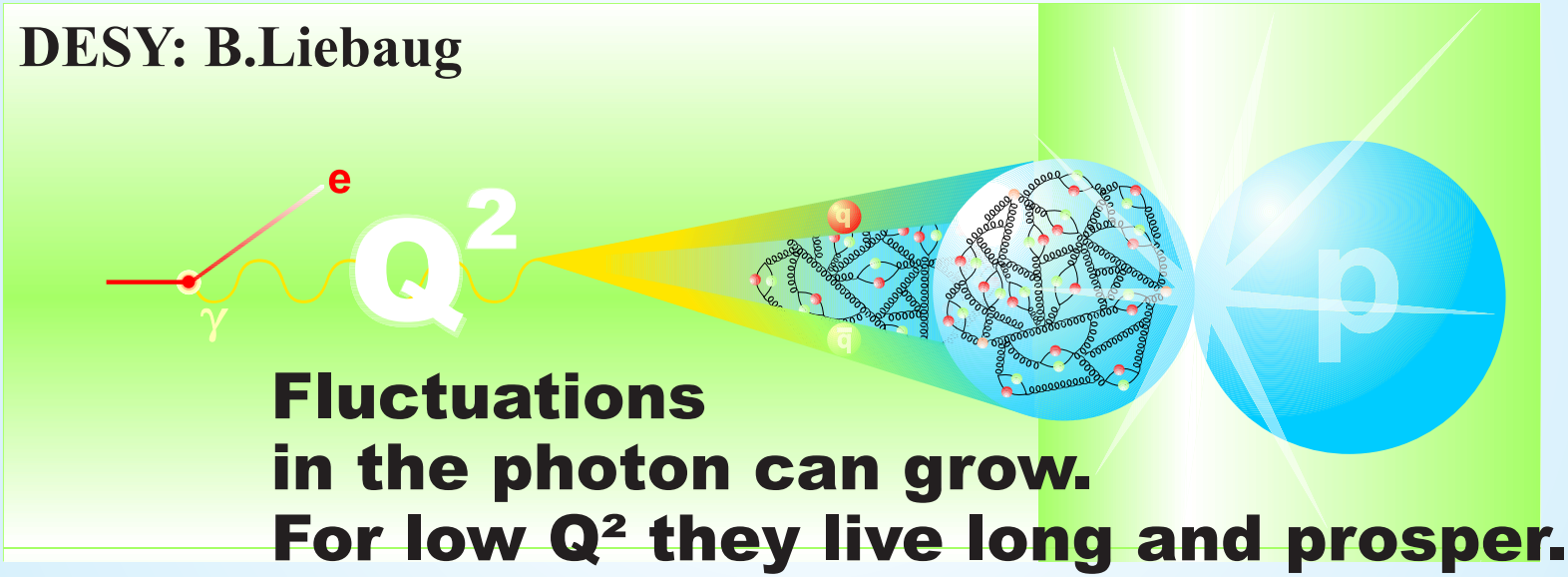
Direct measurement does not contradict PDF predictions.

But there is something else.

Low x Partons in the Proton ?

Heisenberg is strictly against it !

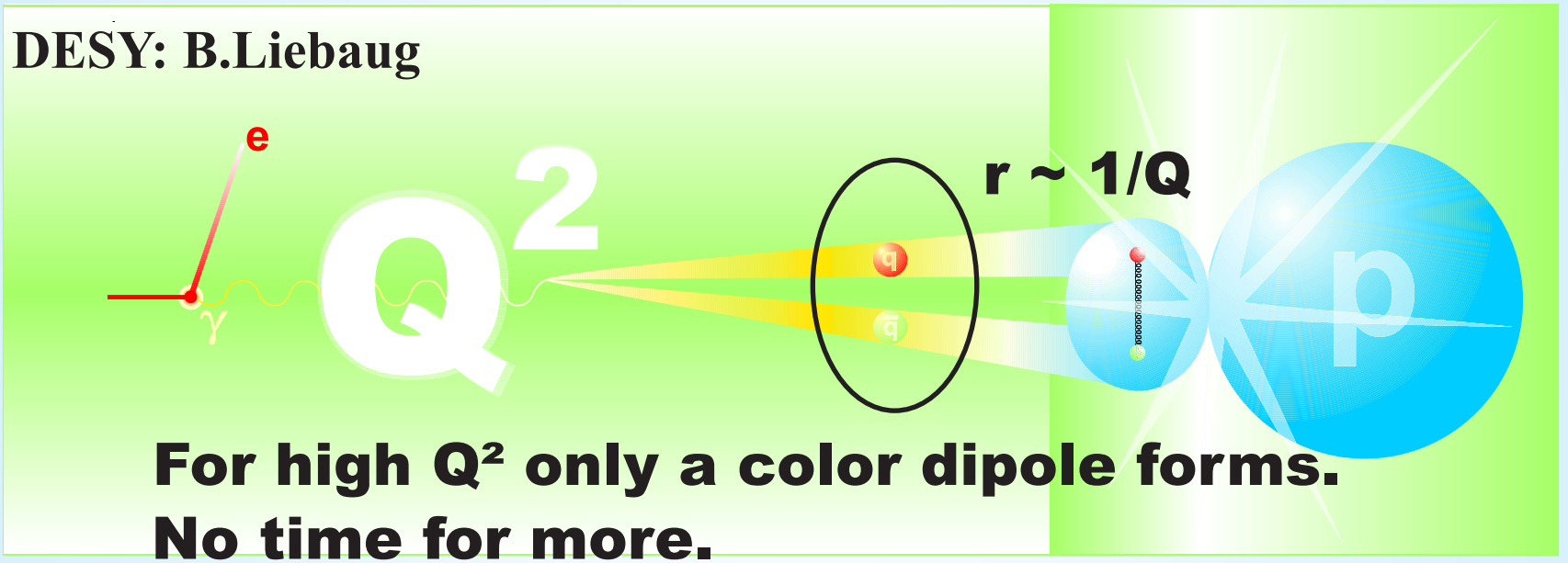
That x is a fraction of the proton momentum is only an interpretation.



Its a parton distribution, but not necessarily in the proton. Has the parametrisation a meaning?

Color Dipole Model

Coherence length: l [fm] ≈ 0.1/x



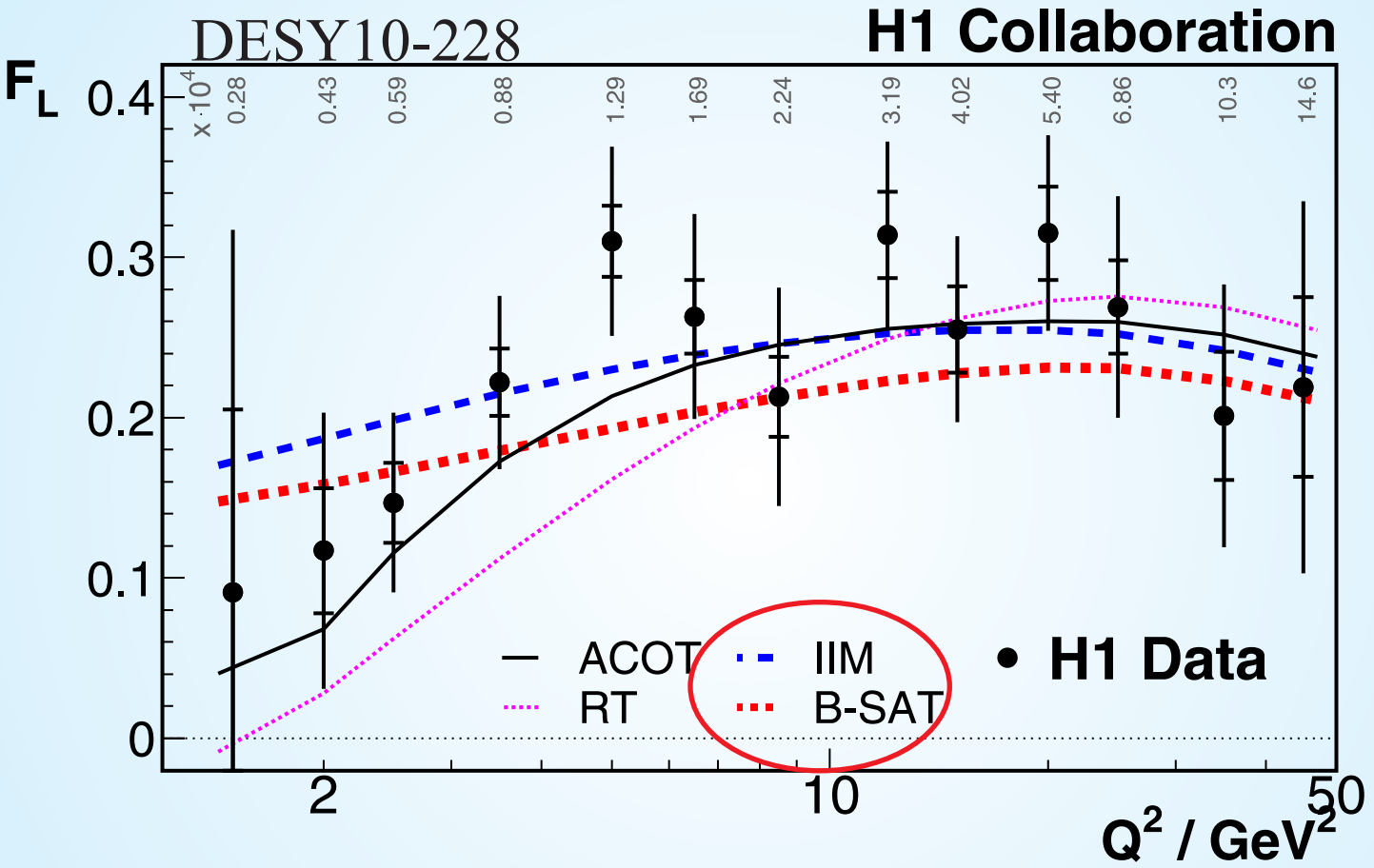
For high Q² only a color dipole forms.
No time for more.

The fluctuation might forget where it came from.

Do I get the same PDFs for neutrino - nucleon or nucleon nucleon scattering? Is factorisation holding?

SF: Tu 16.30

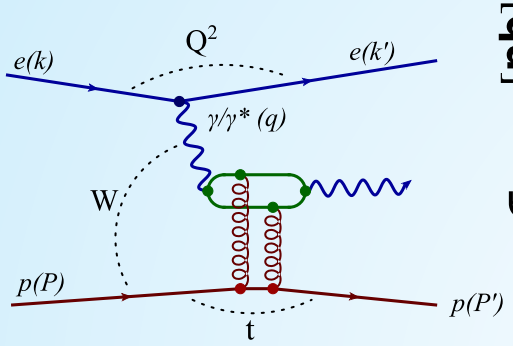
Longitudinal Structure Function



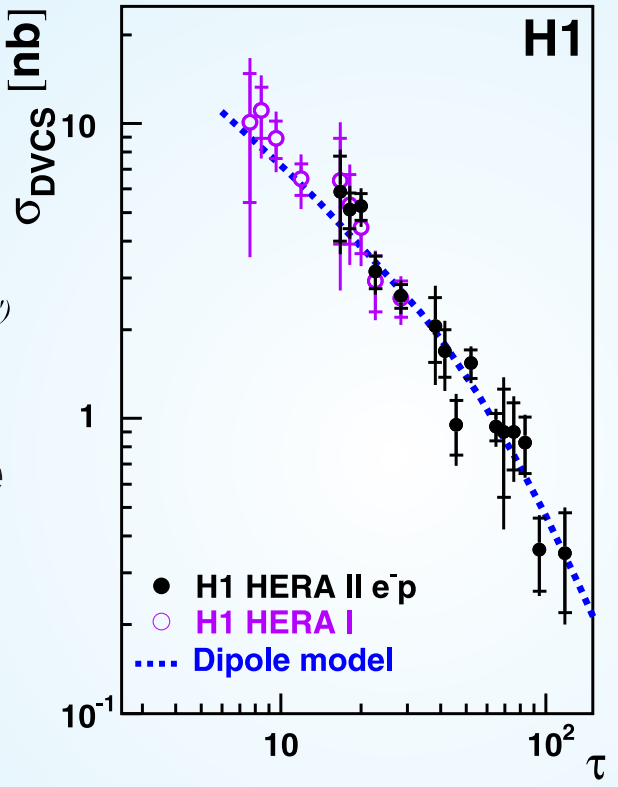
Color dipole models also describe the data.

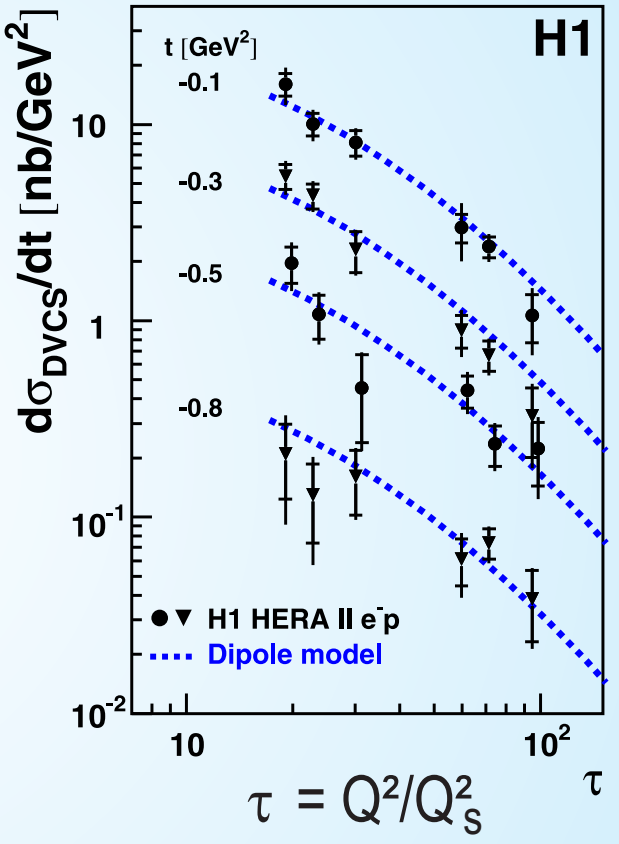
SF: Tu 16.45

Deeply Virtual Compton Scattering



t-dependence of the cross section is also of interest.





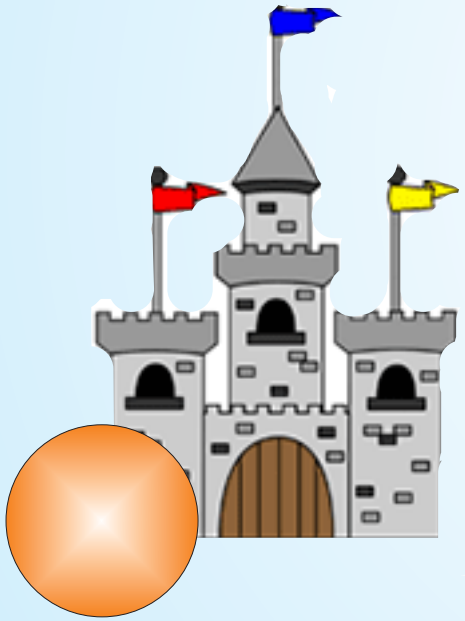
DESY07-142

The dipole model does well.

Deeply Virtual Compton Scattering

Generalised parton distribution functions are used for two gluons.

Interpretation in longitudinal momentum space and transverse position space



$$d\sigma/dt \sim \exp(-b|t|)$$

$$b = 5.45 \pm 0.19 \pm 0.34\ /\mathrm{GeV}^2$$

DESY07-142

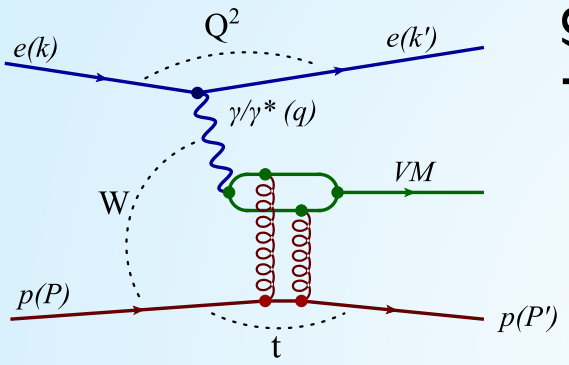
average impact parameter

0.65 ± 0.02 fm x=0.0012

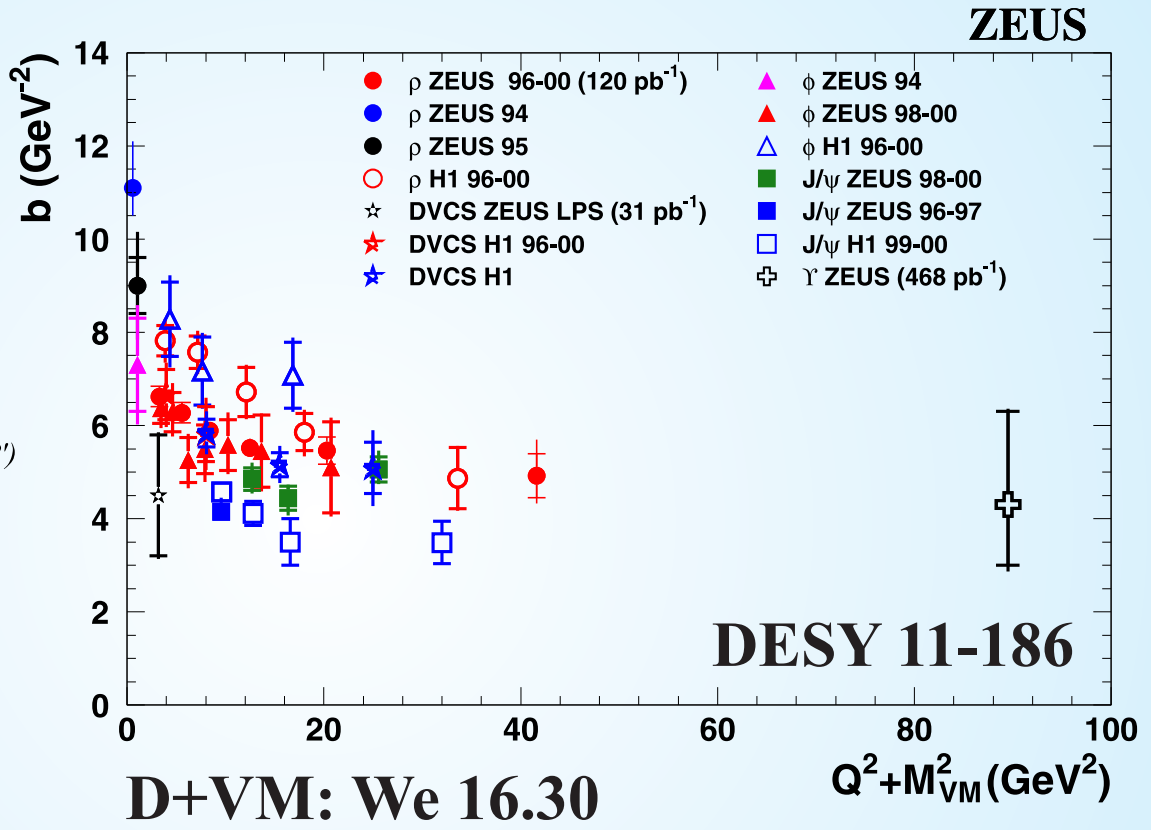
transverse expansion of partons -- in the proton?

D+VM: We 14.00

t-Slopes for Vector Meson Production



$d\sigma/dt \sim \exp(-b|t|)$



D+VM: We 16.30

Should be analysed with respect to proton size.

More data: D+VM We 15.05, 15.25, 15.45

Proton Size and Dynamics

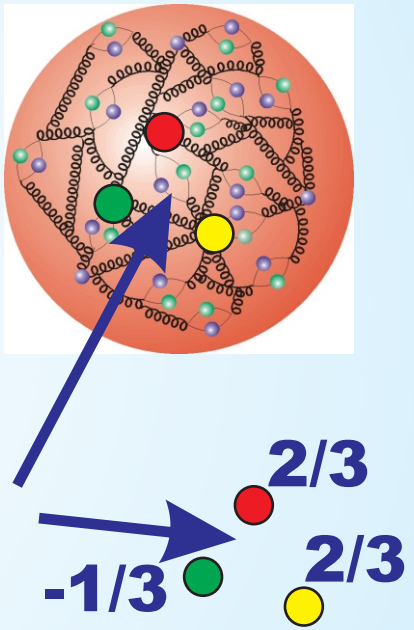
rms charge radius

electron: 0.8786 ± 0.0069 fm

muon: 0.84184 ± 0.00067 fm

rms glue/sea radius

DVCS : 0.65 ± 0.02 fm



What a misleading picture....

dipole moment: < 0.54 10^{-23} ecm

Can we measure a dynamic system while averaging over time. Heisenberg again....

Proton Shape

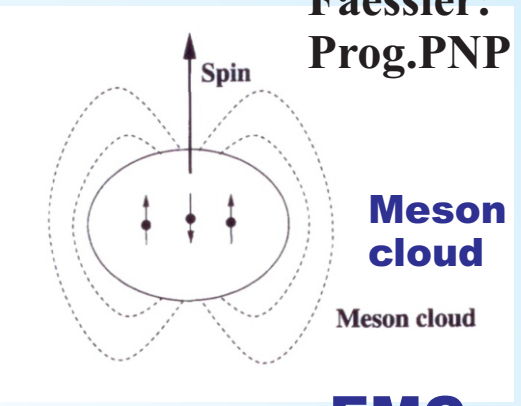
magnetic moment

$\mu_p/\mu_N = 2.792847356 \pm 0.000000023$

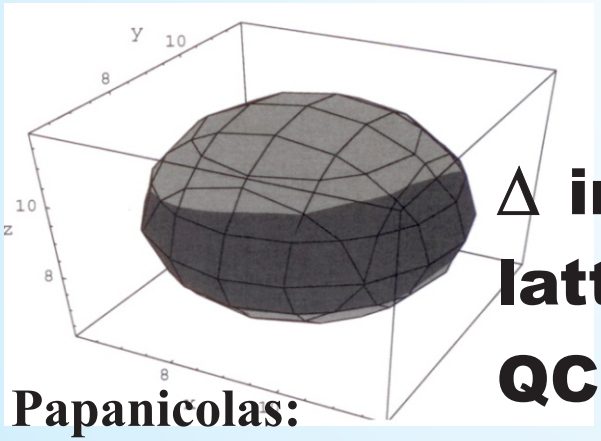
$p \rightarrow \Delta$ excitations

[also used for GZK cutoff]

Faessler:
Prog.PNP 44(2000)



EMC effect



Papanicolas:
EPJ A 18(2003)

Δ in lattice QCD

There has to be some cloud, otherwise they cannot interact.

Can we see the proton behind the strong field?

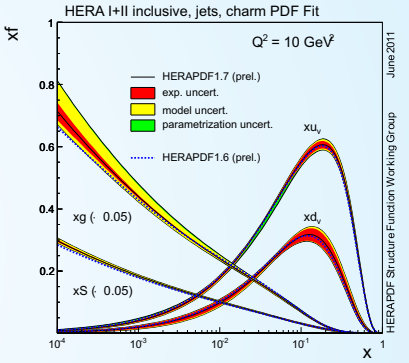
Summary

The proton still holds a lot of secrets.

Proton PDFs are getting measured with high precision, HERA was a success.

This allows for effective predictions and thus searches.

The interpretation of proton PDFs is not trivial.



There is more to the proton than PDFs.

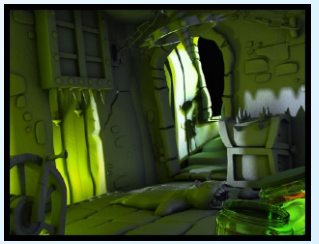
There are many questions about size, shape and the spatial distribution of quarks and glue.

It might take more than pQCD to understand the proton.

Outlook

HERA data will be used to the last bite.
LHC and new fixed target experiment will join in and we will have perfect PDFs.

Different communities will join and we will have a 3d picture of the valence, sea and glue structure of the proton.

We open the door and look inside.

That is my vision.