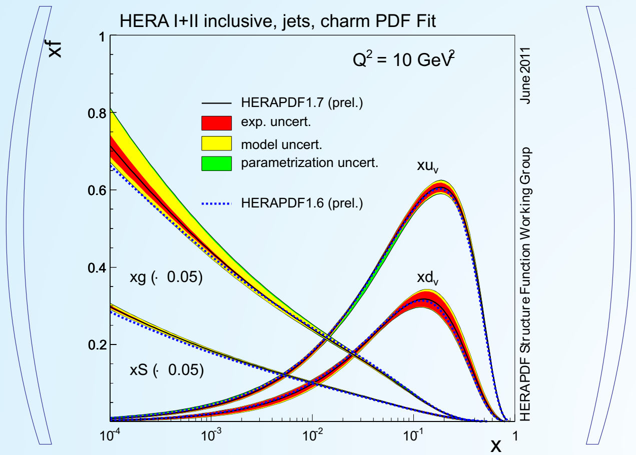
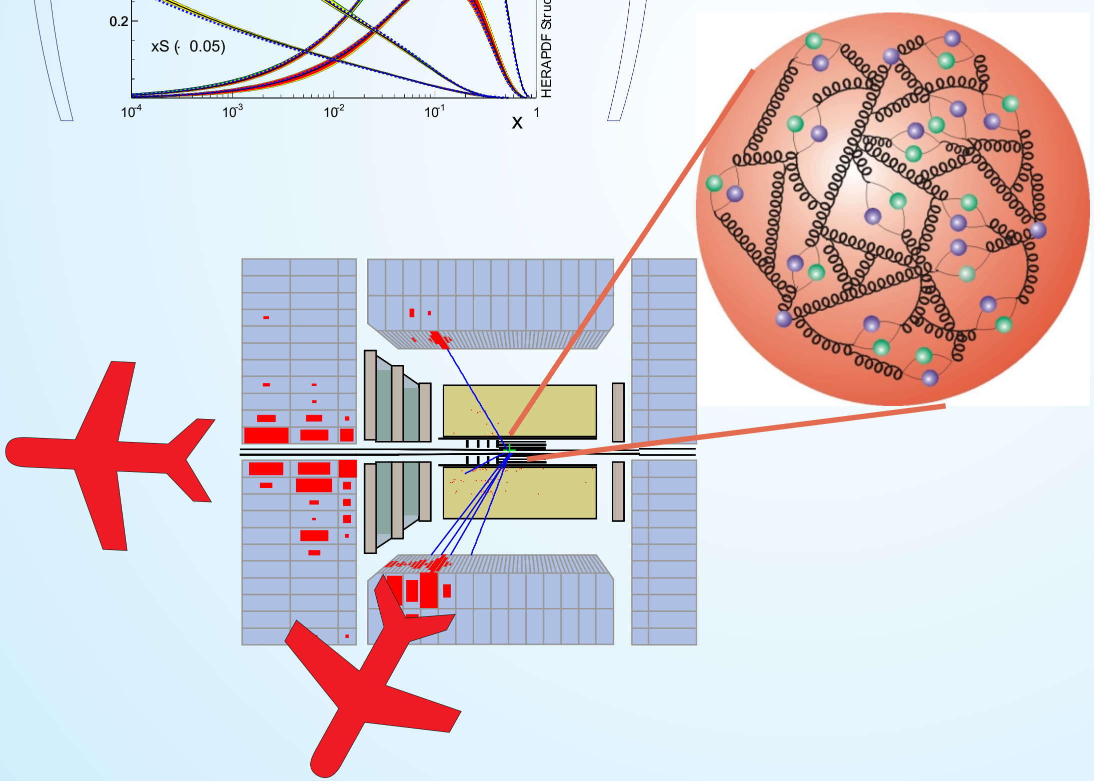
Proton Structure Functions and Tests of QCD at HERA



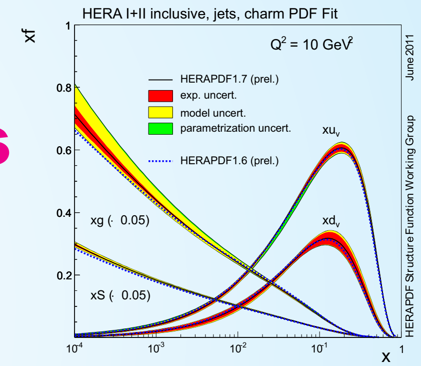


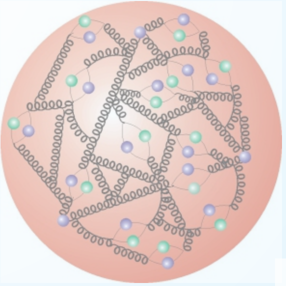
Beijing, 4.9.2013

I.Abt, MPI München

Content

- Protonic Facts and Elastic Scattering
- Cross Sections and Structure Functions
  - Measurements
  - Parton Distribution Functions
- QCD
  - Jets and alpha_s
- Proton Structure ?
  - Photon Structure ?
- Proton Size and Shape
- Summary & Outlook





Before I start

Multiple Apologies

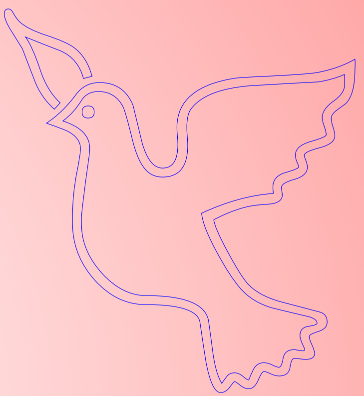
I really know very little about the proton:

- mass = 1GeV = 1.67 10^{-27} kg
- 3 valence quarks
- charge = +1
- spin = 1/2
- radius ≈ 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.

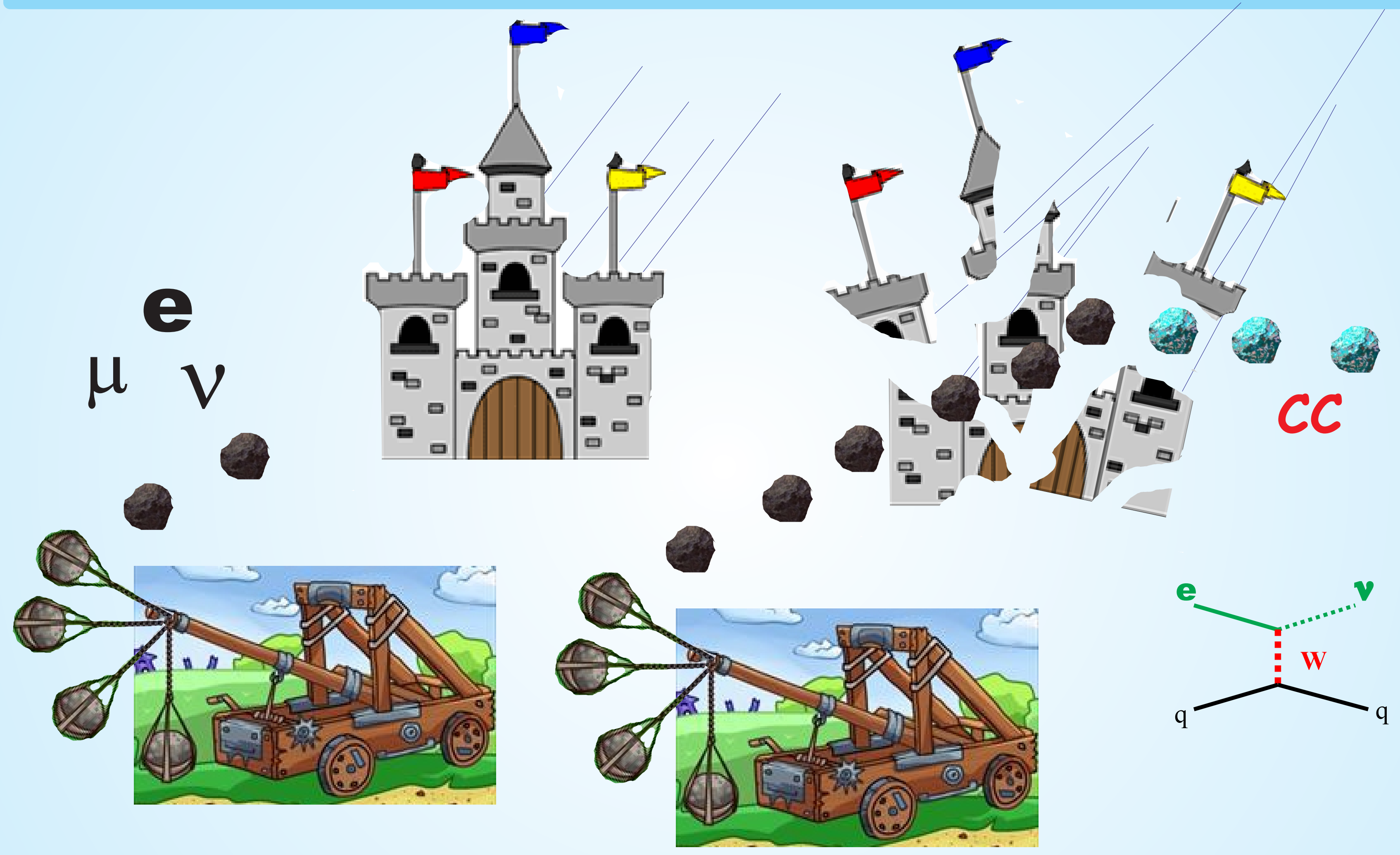
DISCLAIMER



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

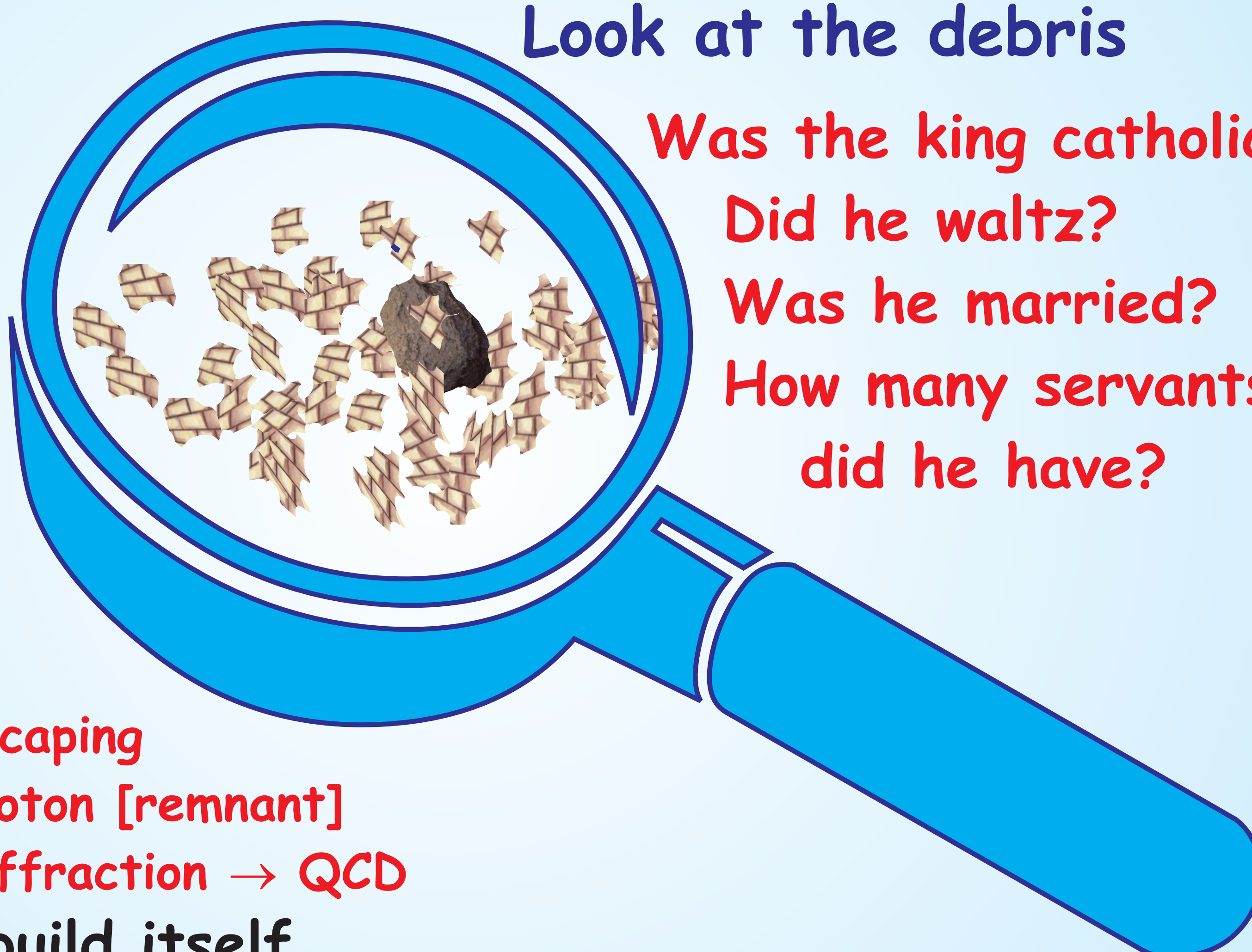
Nevertheless I am proud to represent H1 and ZEUS.

Deep Inelastic Scattering



Deep Inelastic Scattering

Look at the debris



Was the king catholic?

Did he waltz?

Was he married?

How many servants did he have?

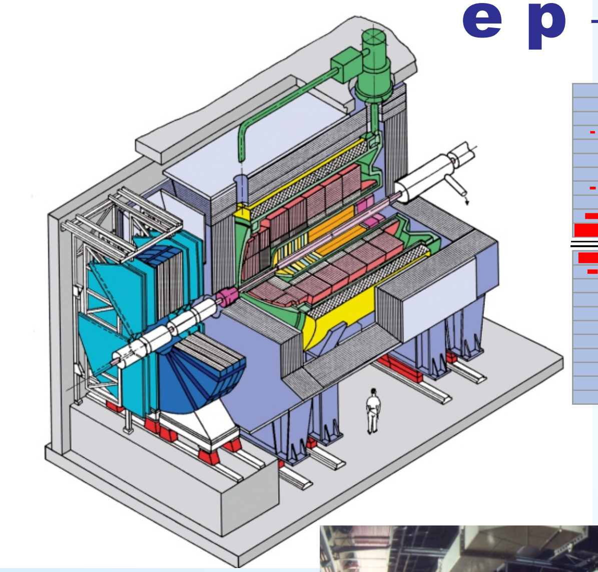
Escaping proton [remnant]

Diffraction → QCD

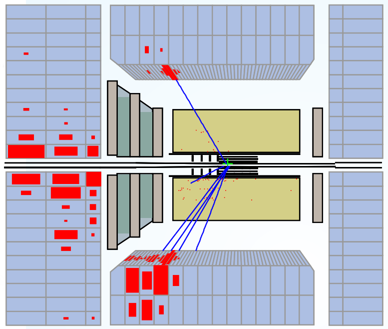
This can rebuild itself

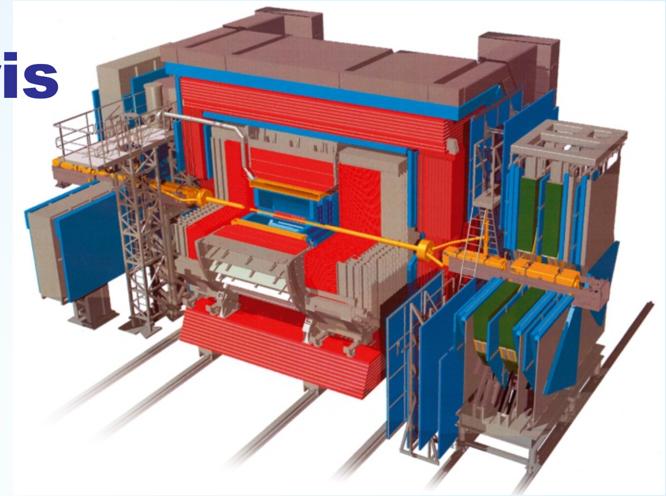
The Microscope

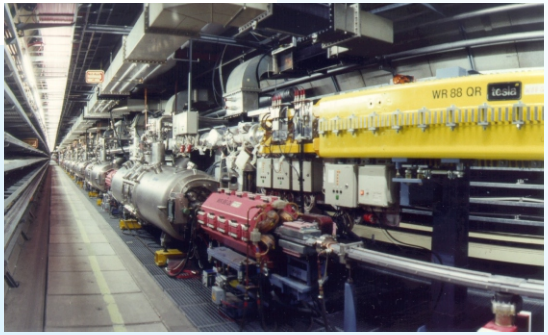
That is what we measure!



e p $\rightarrow$ e (ν) debris







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

$\rightarrow$ **kinematic variables**

Kinematics

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

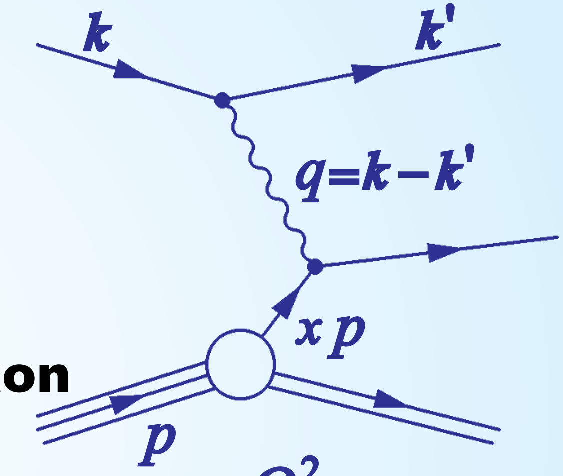
Spatial resolution of probe

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

Bjorken scaling variable:

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

Momentum fraction of struck parton



$$Q^2 = xys$$

Inelasticity: $y = pk / pq$

Energy transfer to proton (in p rest frame)

Reconstruction

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

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** ($f_{j/p}$)

partonic cross section ($\hat{\sigma}_{jj'}$)

hadronisation ($F_{H/j'}$)

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^*

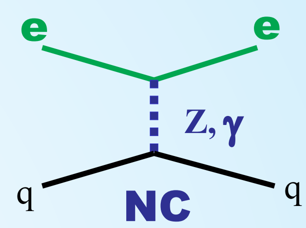
$V^* q \to q'$

lowest-order QCD

Structure Functions

$e^{\pm}p$

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



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

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

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 $\tilde{F}_L = 0$

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

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

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

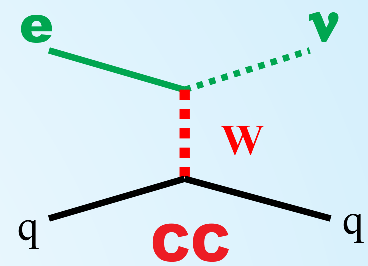
sea quarks = anti-quarks
valence quark distributions $\quad$ $xu_v = xU - x\bar{U}$ $\quad$ $xd_v = xD - x\bar{D}$

Structure Functions

$e^{\pm}p$

tree level

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



QPM $W_L^{\pm} = 0$

CC is unfortunately a bit more difficult.

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

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

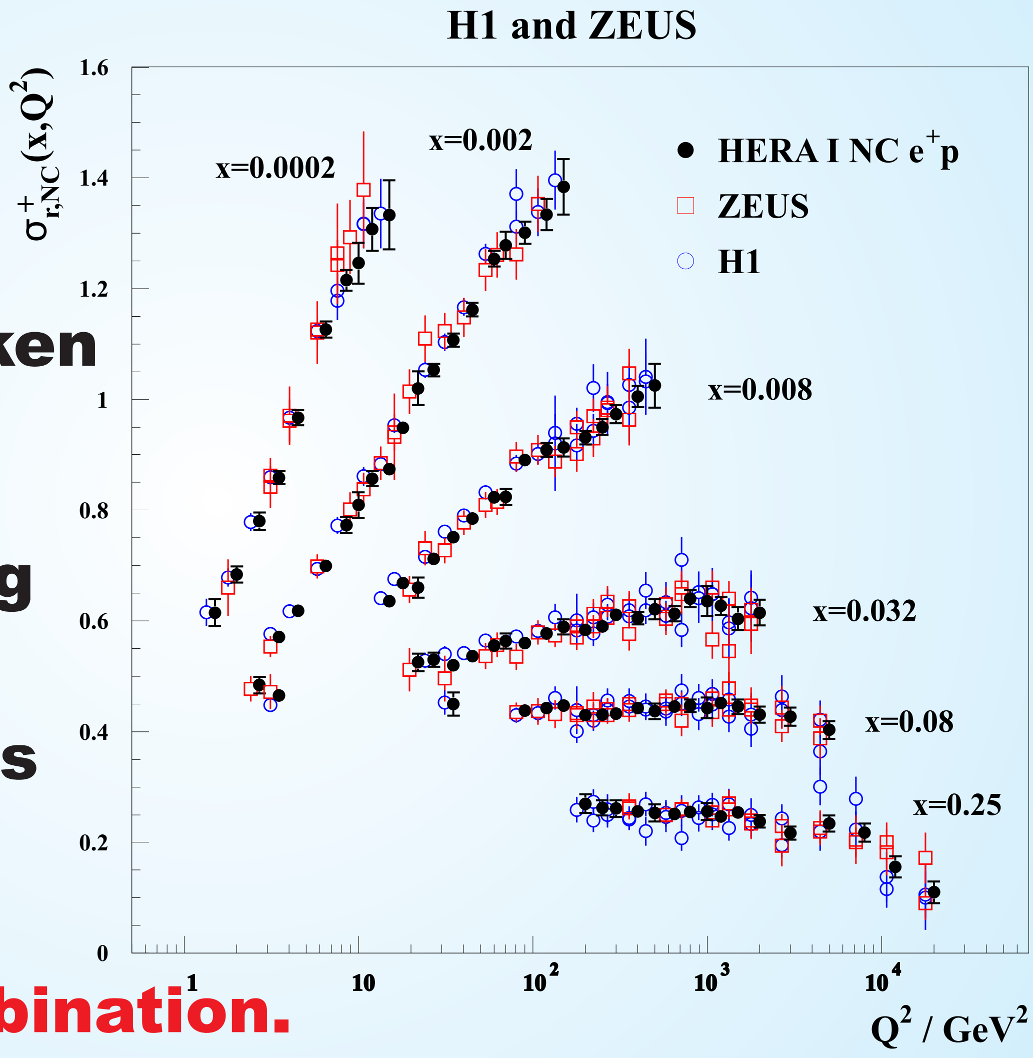
NC and CC yield valence and sea quark distribution.

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.

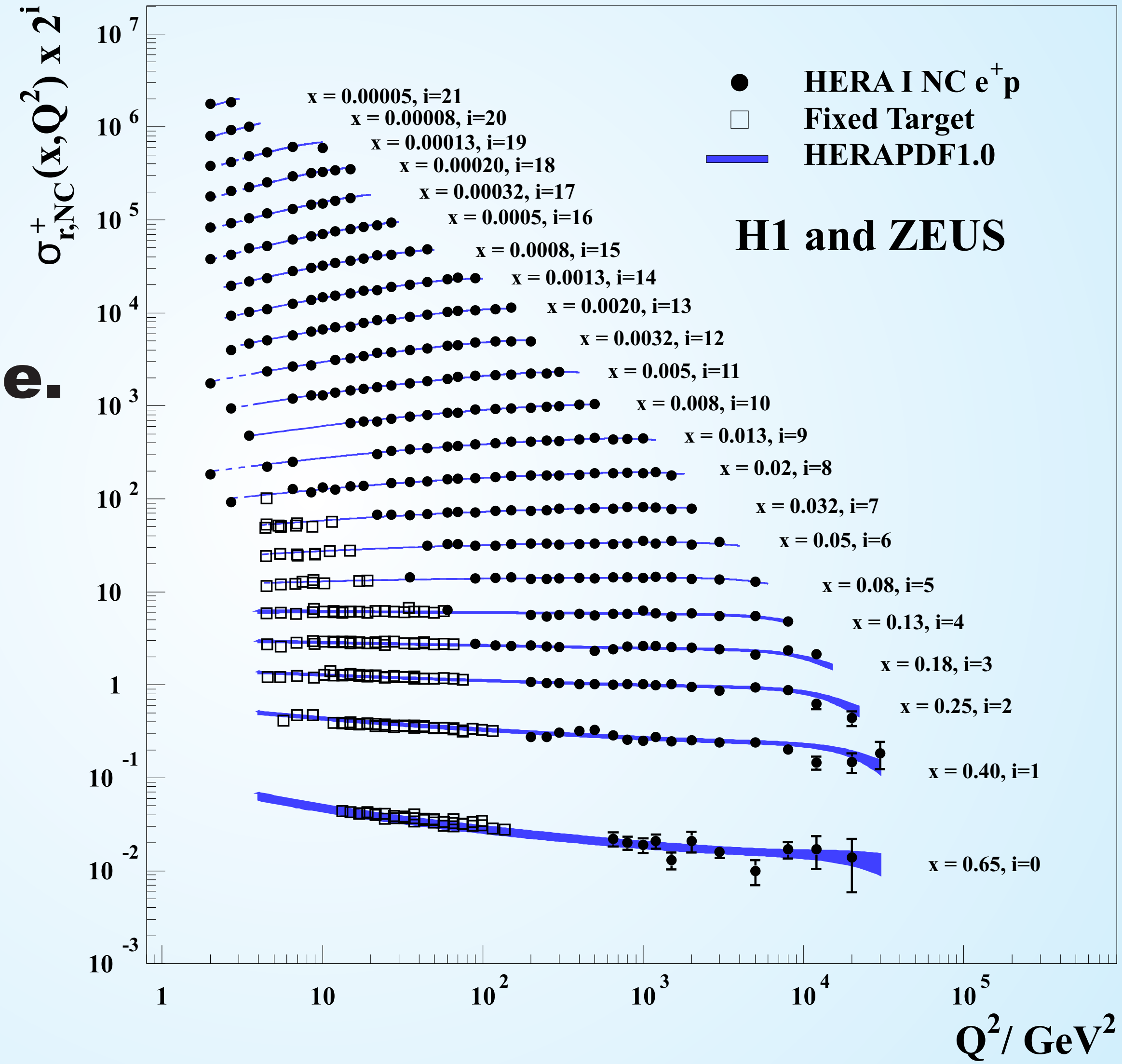


The power of combination.

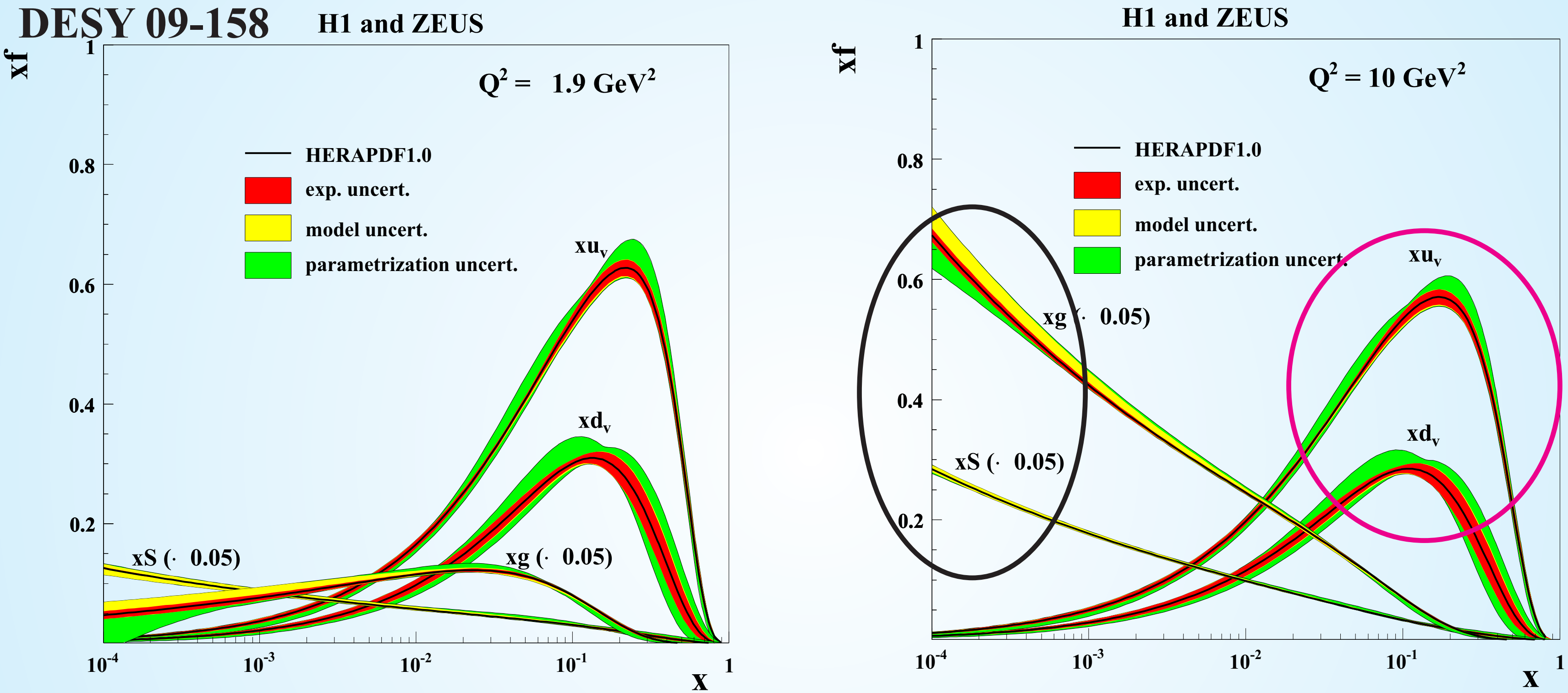
Reduced Cross Section

Cross section data over a very large kinematic range.

HERA data were used as only input to fit HERAPDF 1.0



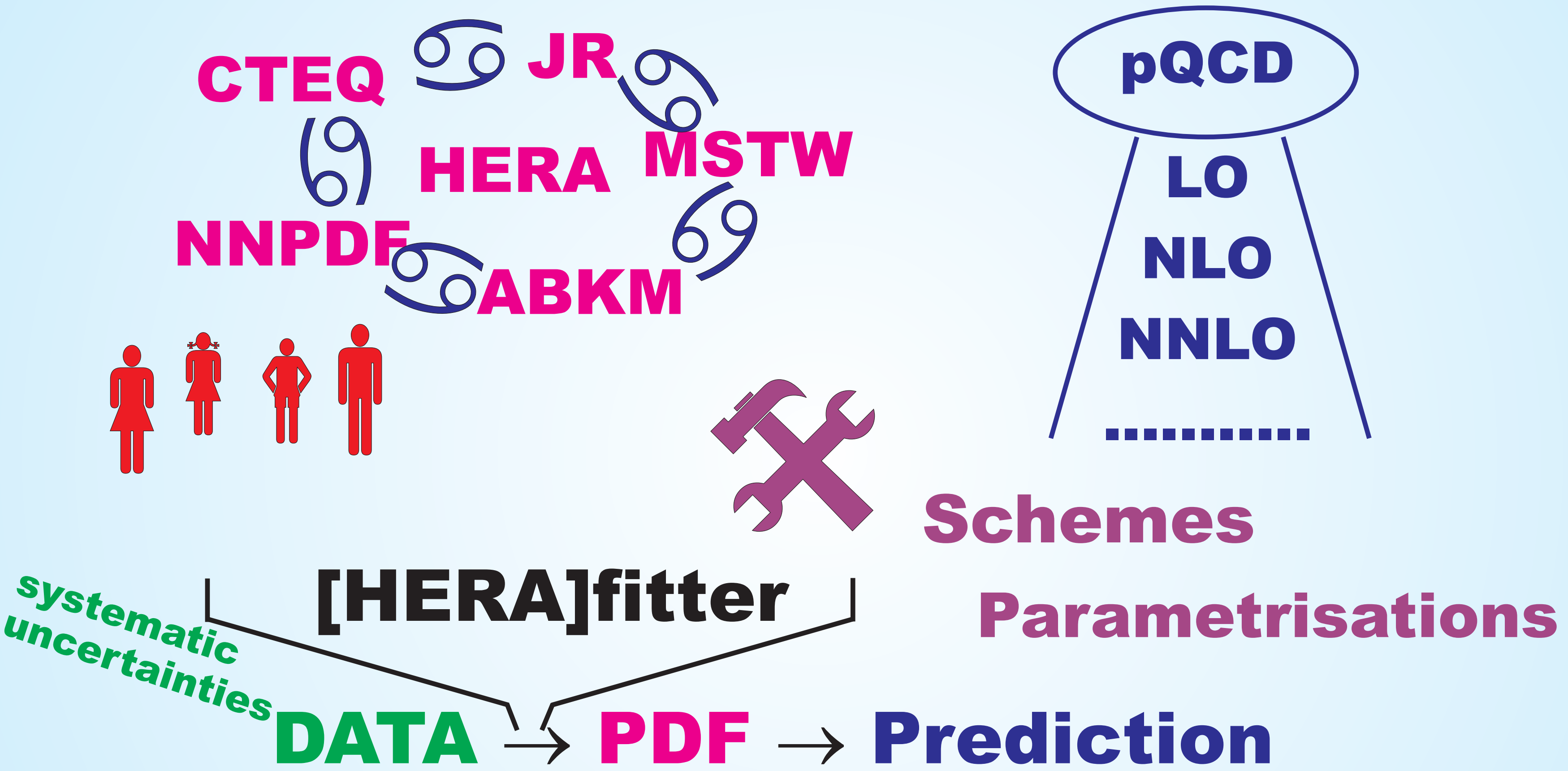
HERAPDF1.0



The proton pdfs reveal the valence quarks plus glue and sea evolving with Q².

Inclusive DIS data alone can do this.

The PDF Community



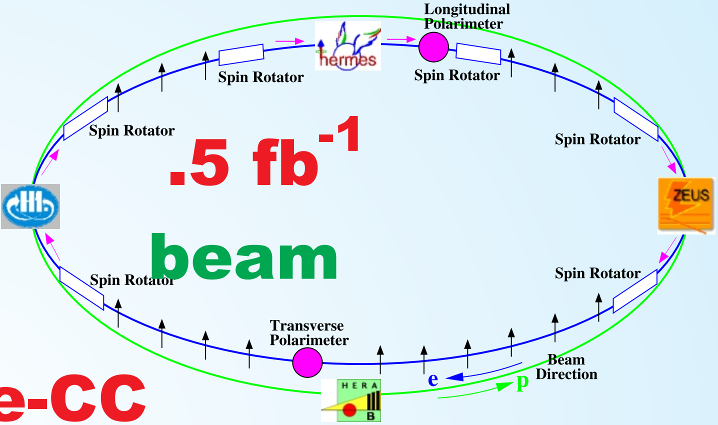
Consistency between fit and "→" for prediction is essential.

High Statistics Data

HERA II 2003-2007

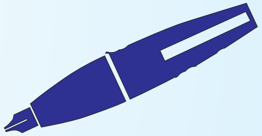
ZEUS and H1 both got to ≈ .5 fb^{-1}

polarised electron/positron beam



e+ NC e-NC e+CC e-CC

Everything high Q^2 is published !

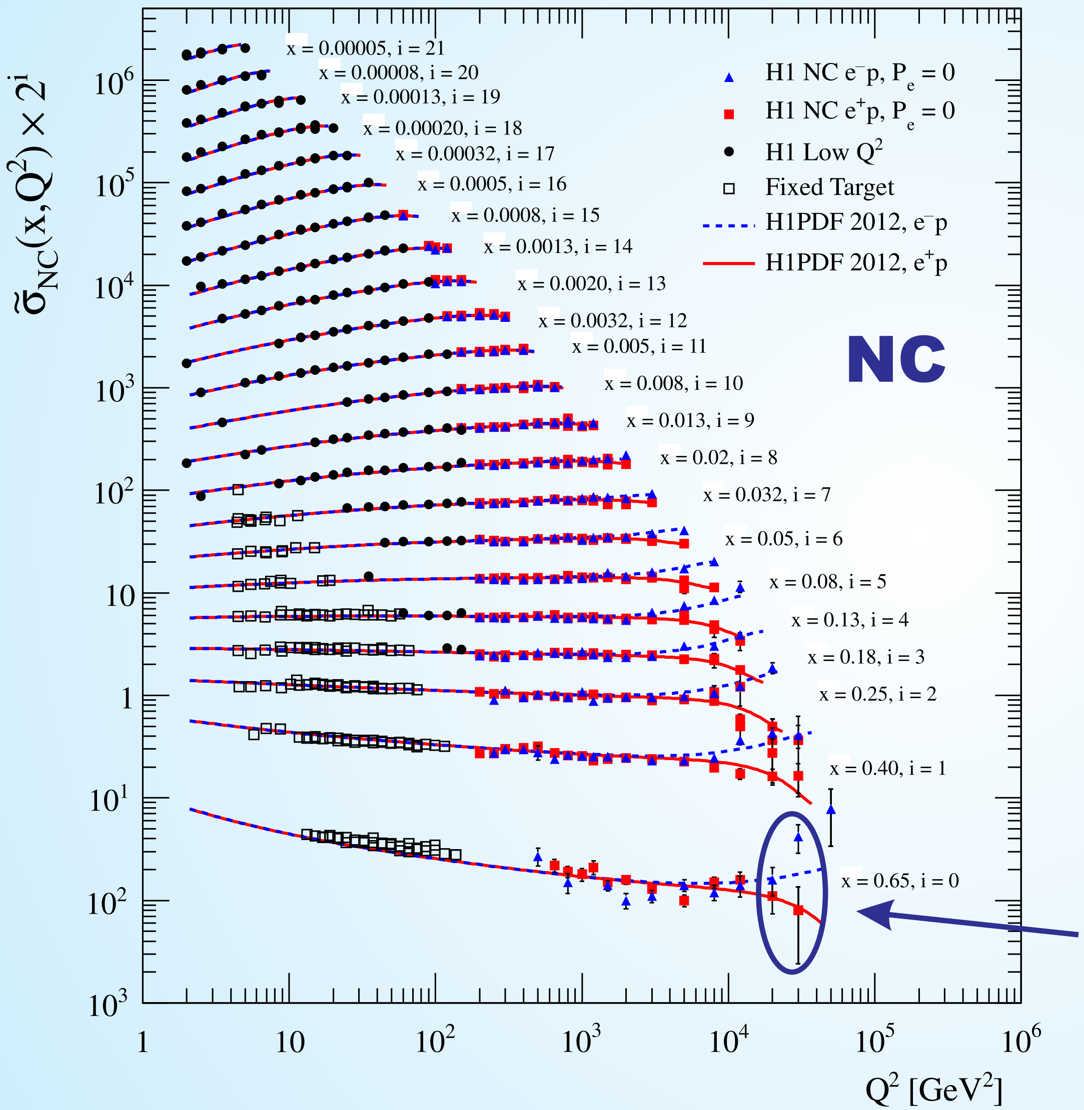


In addition:

F_{2c} F_{2b} F_L

F2diff jets — **QCD**

High Statistics Data



H1 Collaboration

HERA I + II

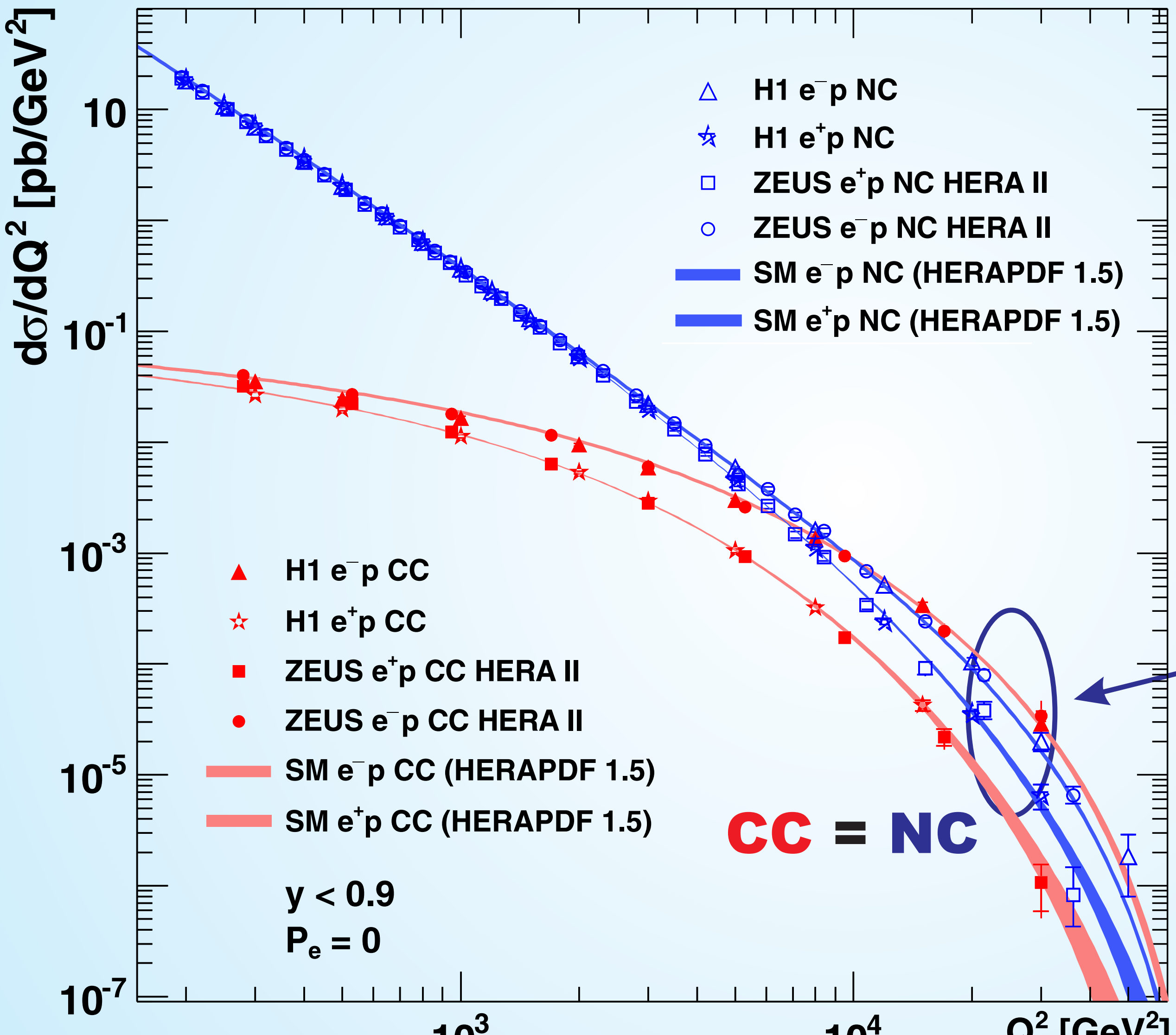
Each experiment now has the precision of the HERA I combination.

Combining them is exciting!

difference between positron and electron data

DESY 12-107

High Statistics Data



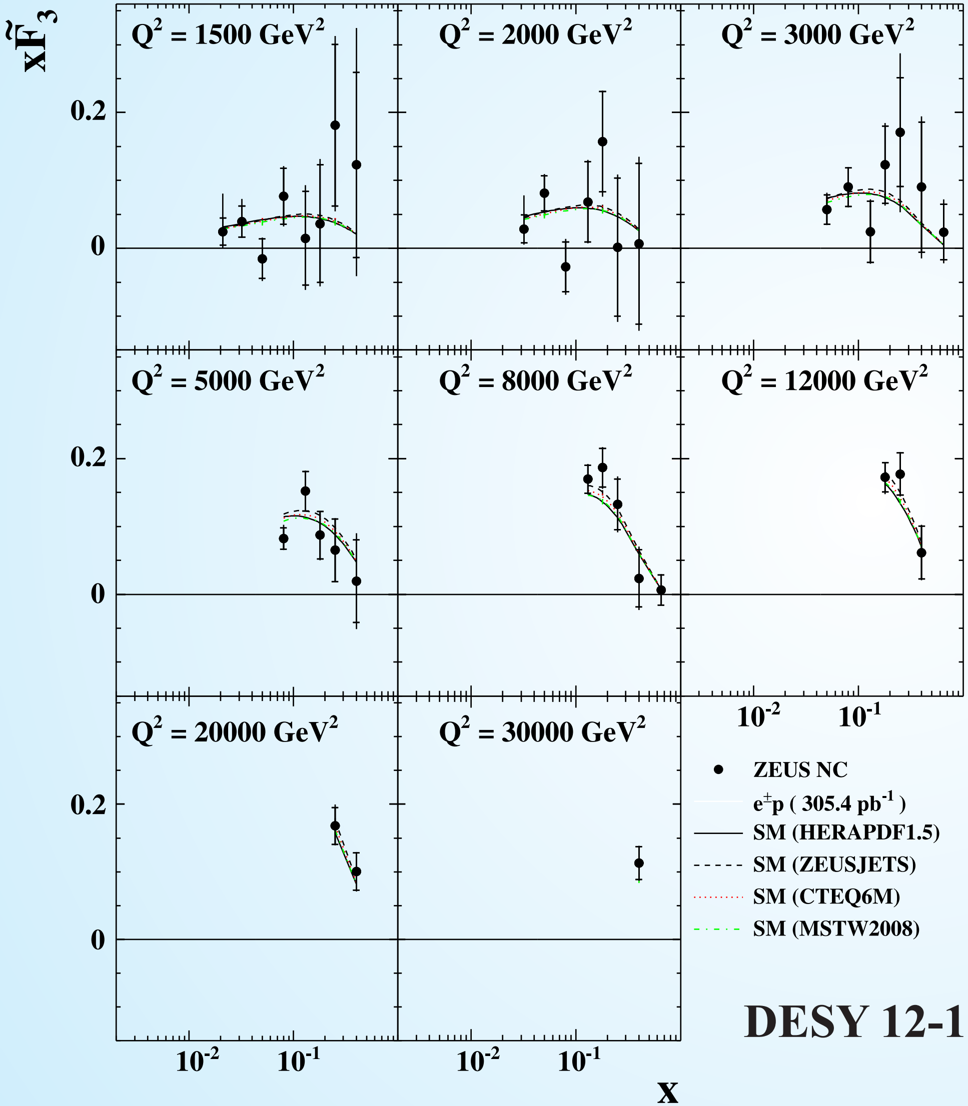
high Q^2

NC CC

all published, combination ongoing !

xF_3 difference between positron and electron data

Valence Revealed



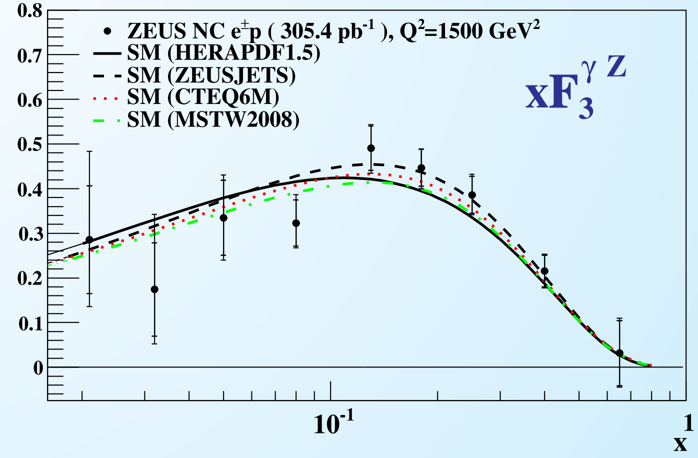
DESY 12-145

ZEUS

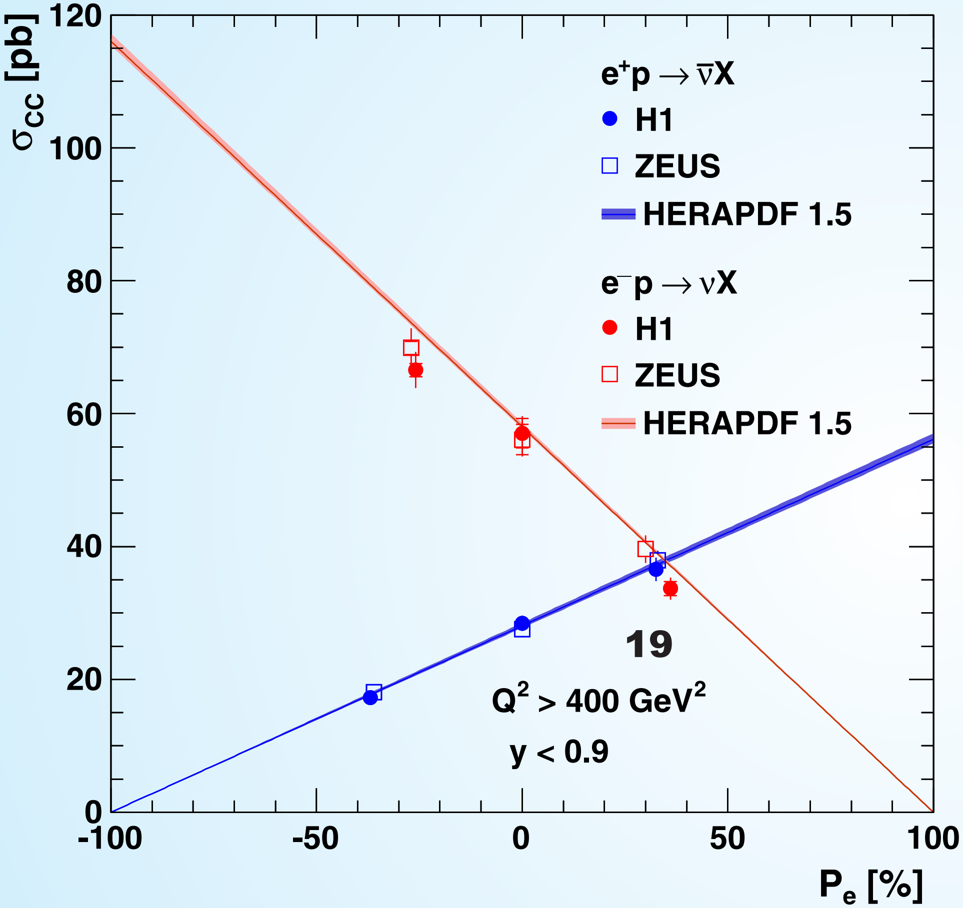
NC

positron and electron data

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



Electroweak Effects

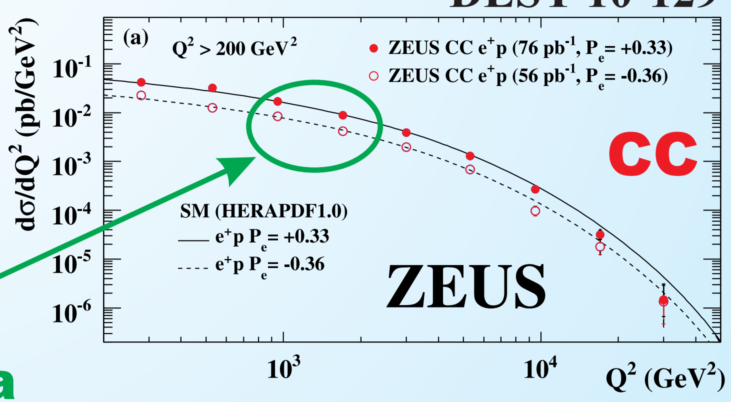


H1 and ZEUS

HERA Charged Current $e^{\pm}p$ Scattering

Electroweak analysis is ongoing

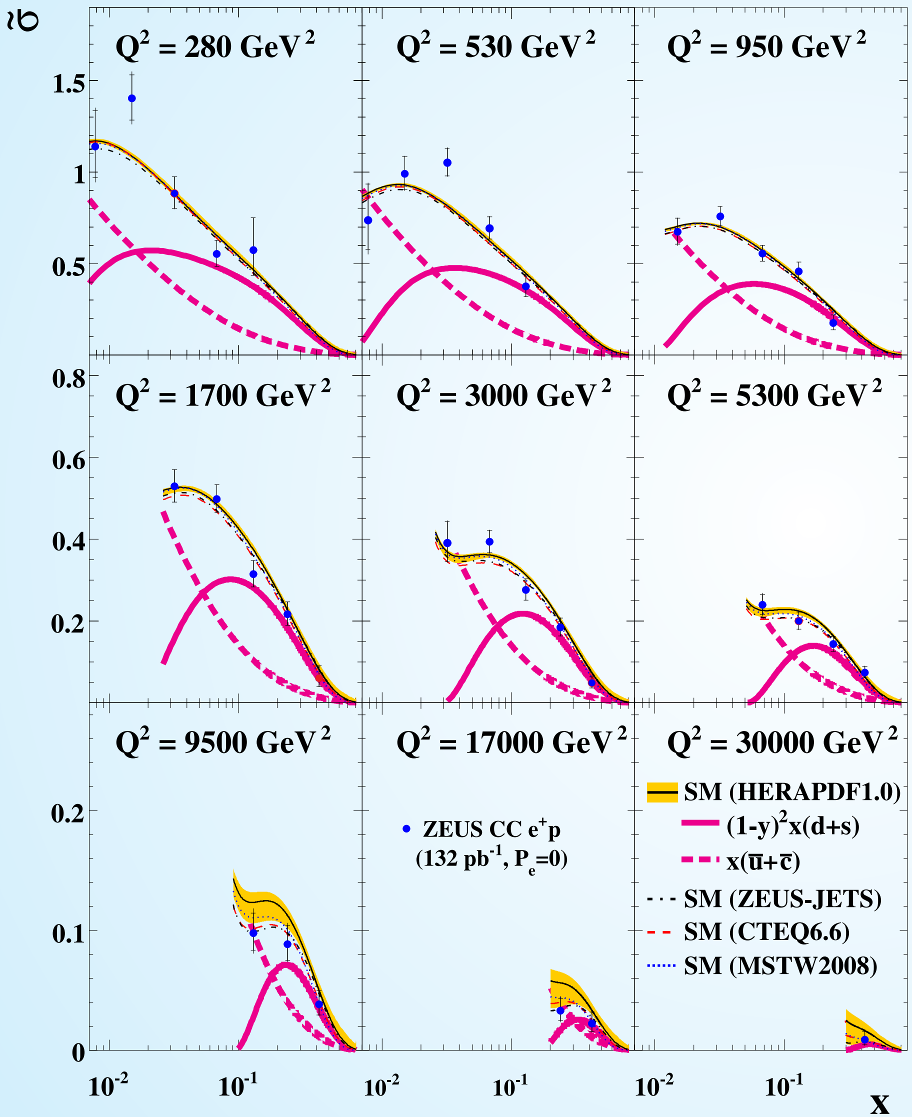
DESY 10-129



CC

polarised positron data

The Charmed Sea



ZEUS

DESY-10-129

CC

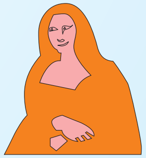
positron data

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

$$xD = xd + xs$$

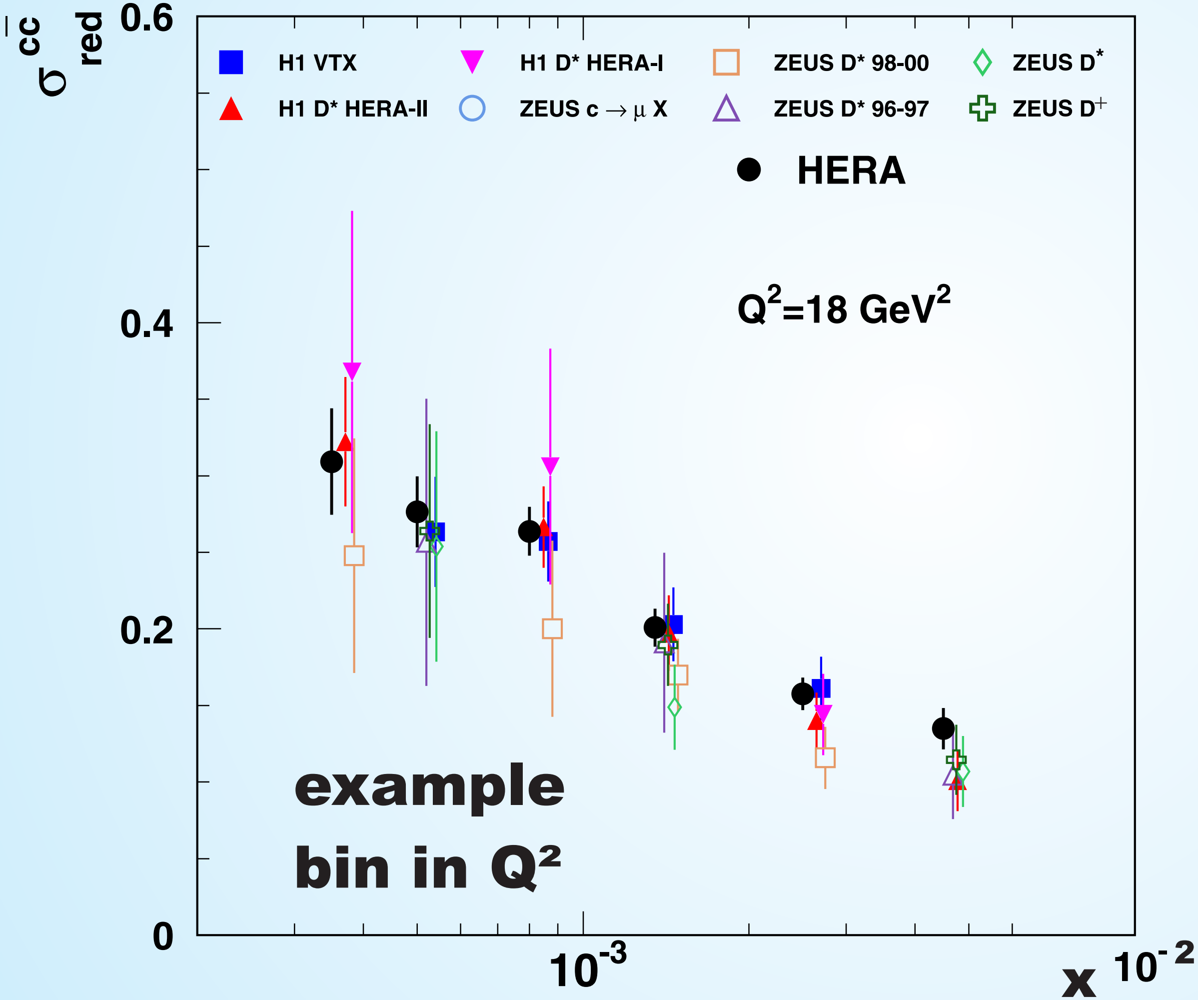
$$x\overline{U} = x\bar{u} + x\bar{c}$$

a hint of charm



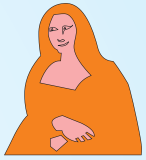
Charm Structure Function

H1 and ZEUS



$xU = xu + xc$

a handle on charm



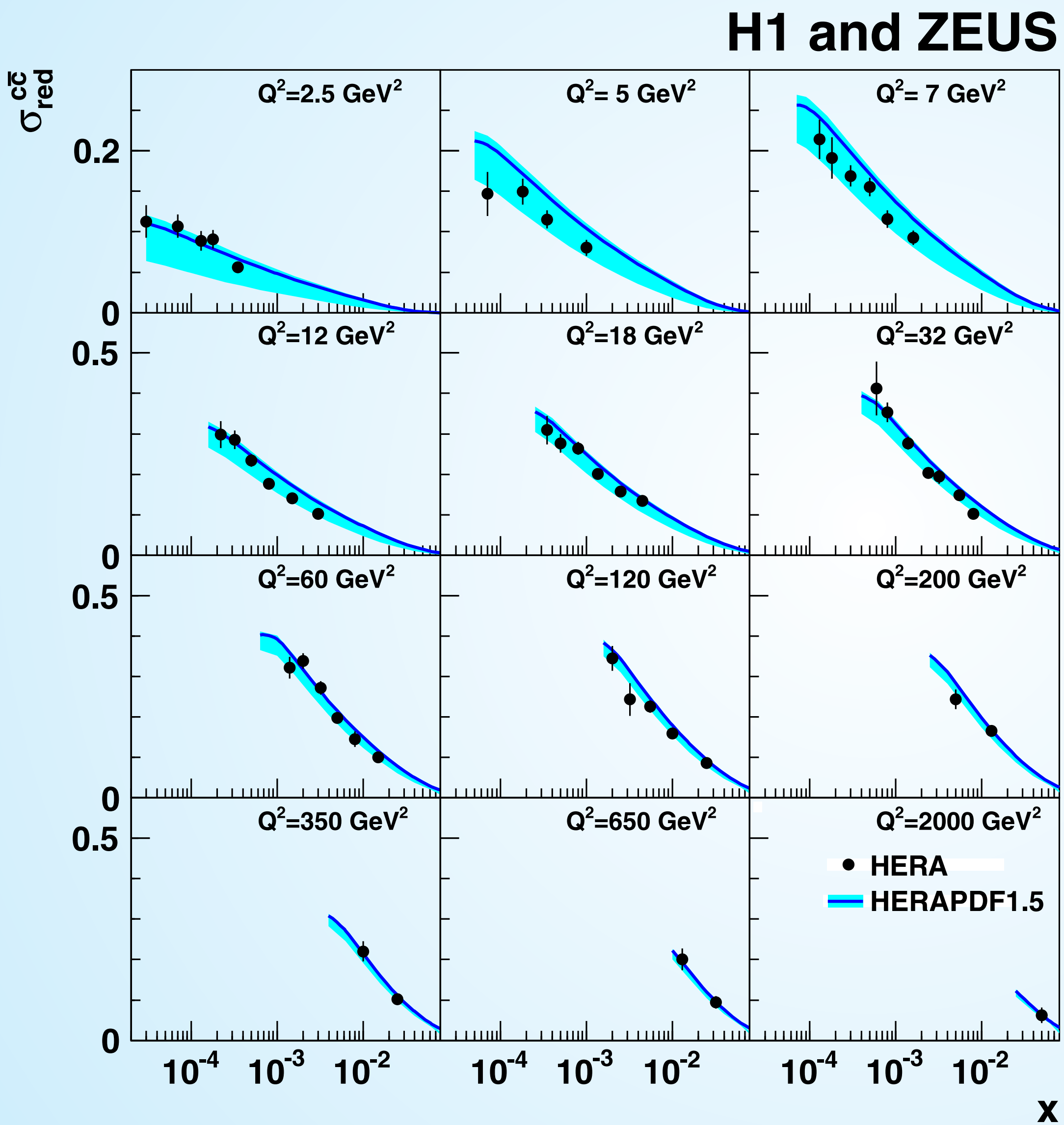
NC :

produce all kinds of D mesons [tagged somehow]

DESY 12-172

Some more data have been published for future combination.

Charm Structure Function

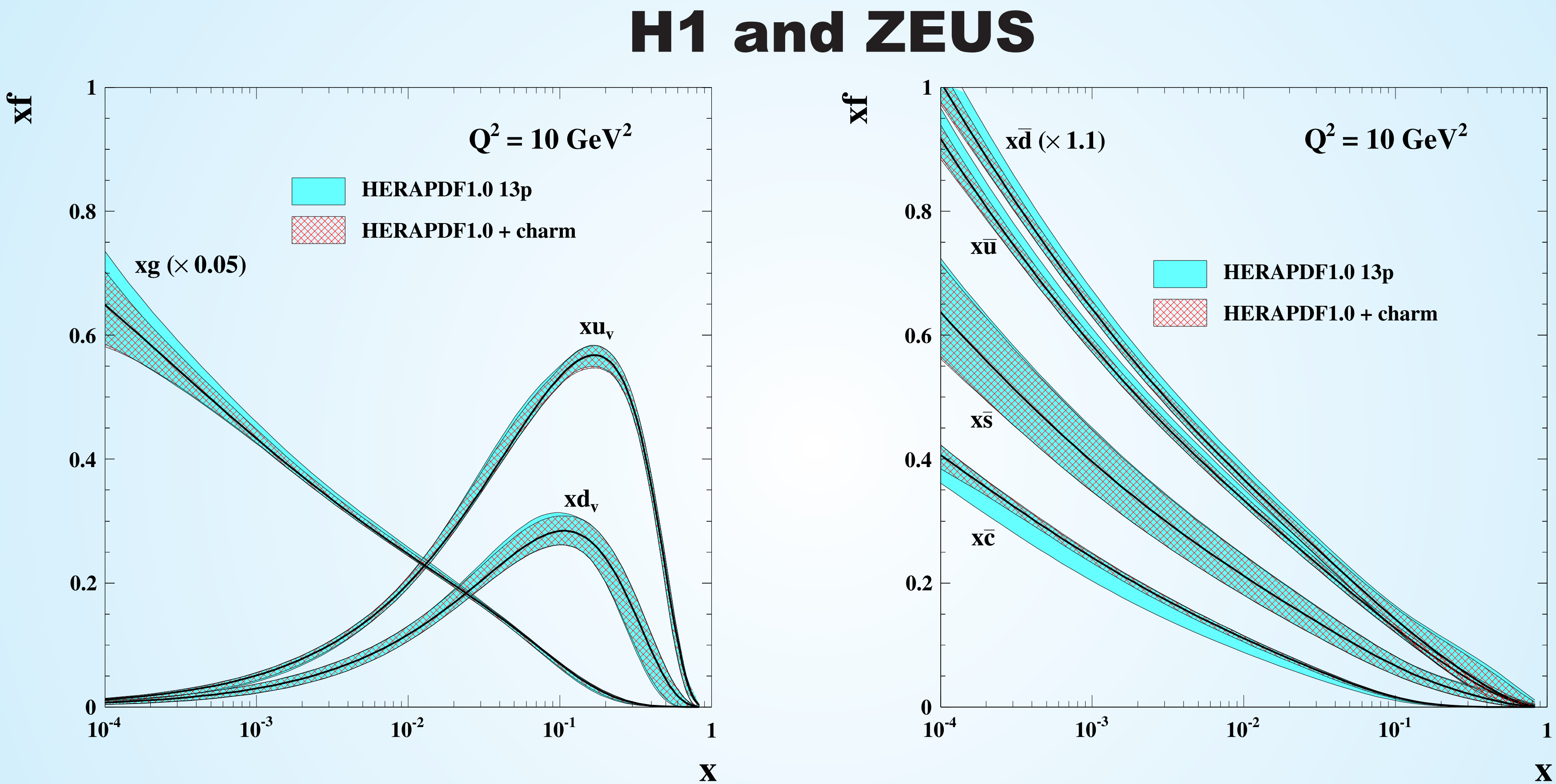


HERAPDF1.5

NLO prediction
RT standard
Mc =1.4 GeV

Uncertainty dominated by uncertainty on Mc.

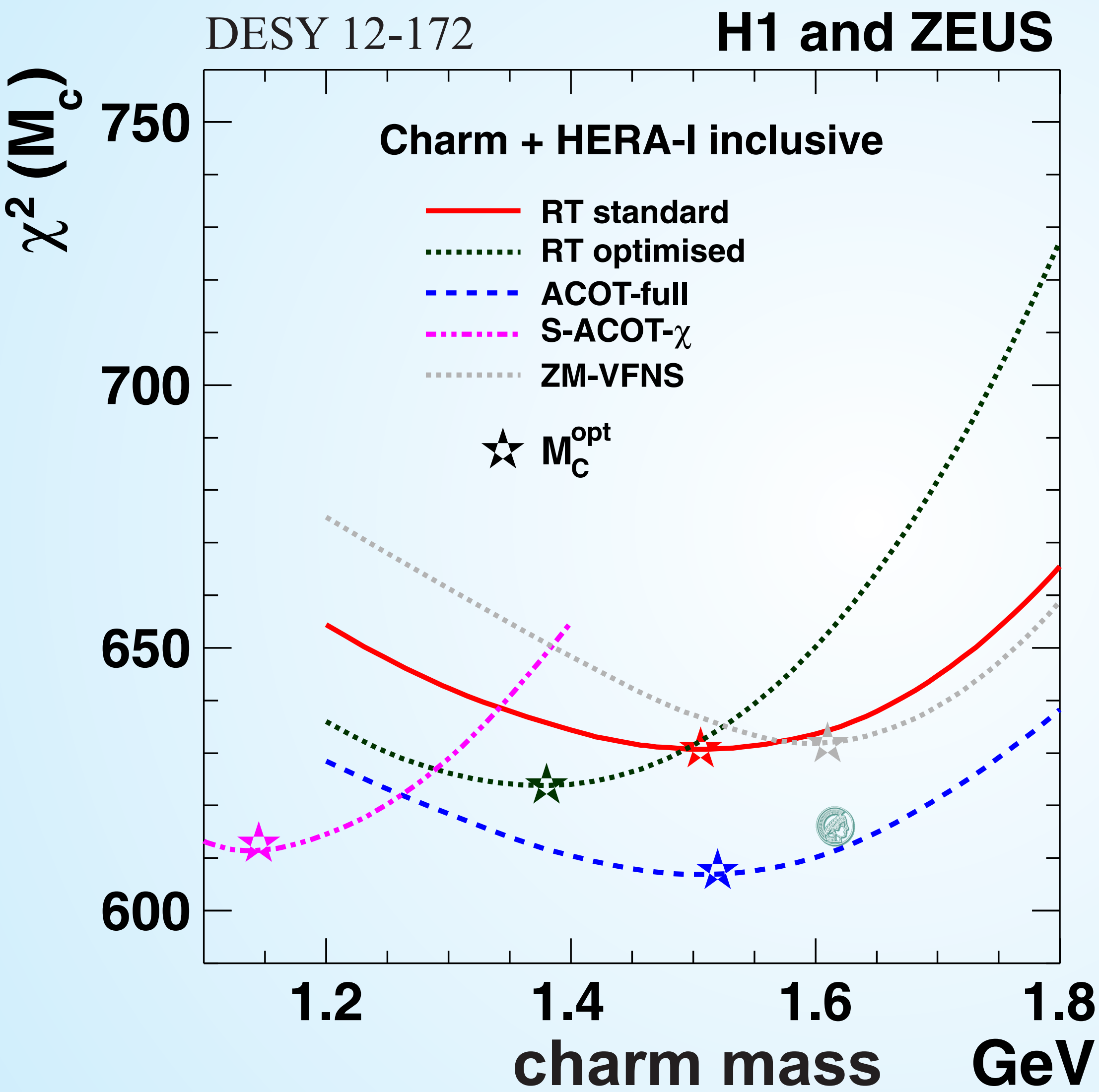
HERAPDF with CHARM



The charm data are sensitive to glue and sea

and to the charm mass....

Charm Mass



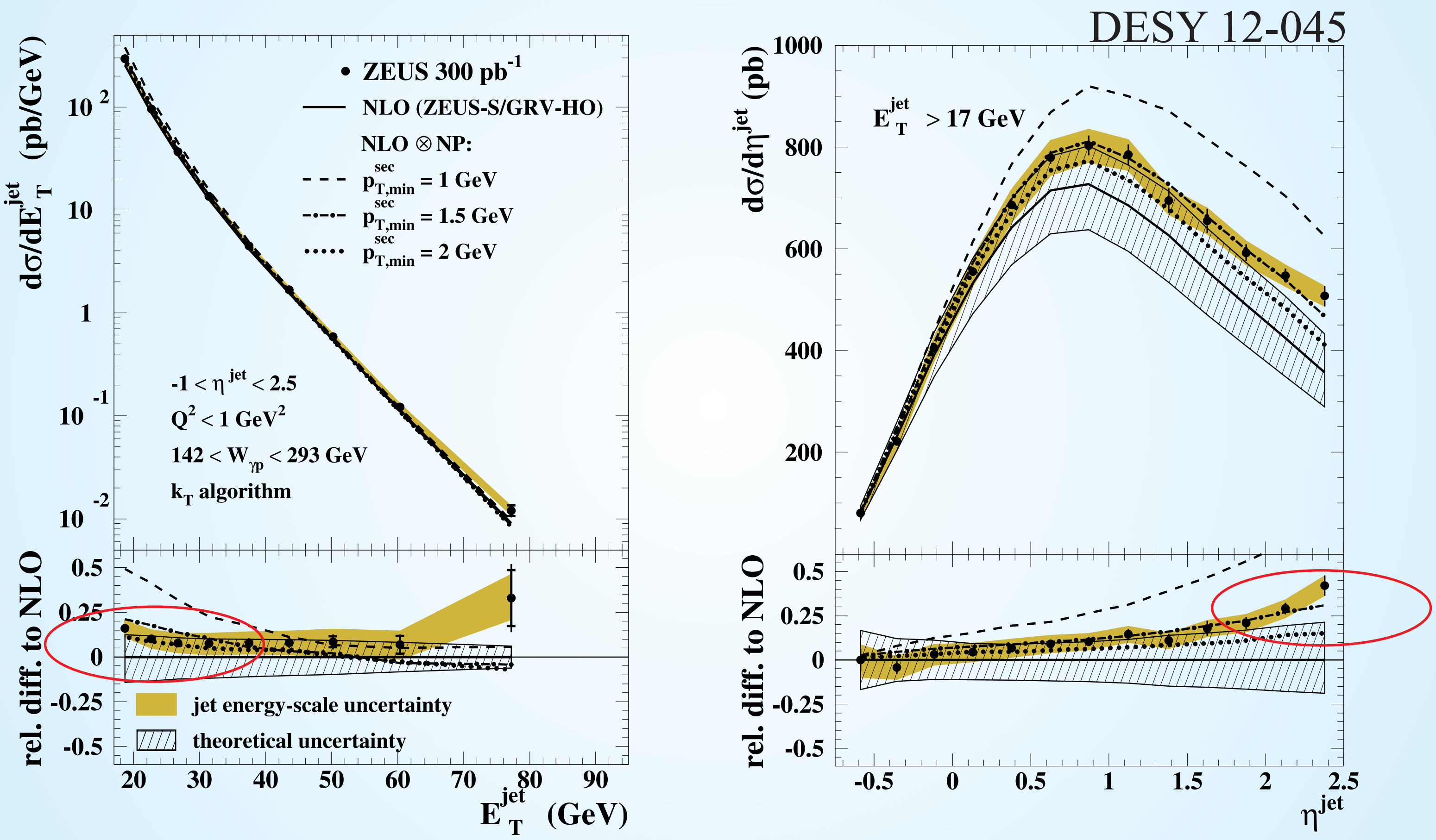
Scan for the charm mass

The charm mass is a very splendid thing, it is a parameter that depends on the framework you are working in.

All part of the QCD fit.

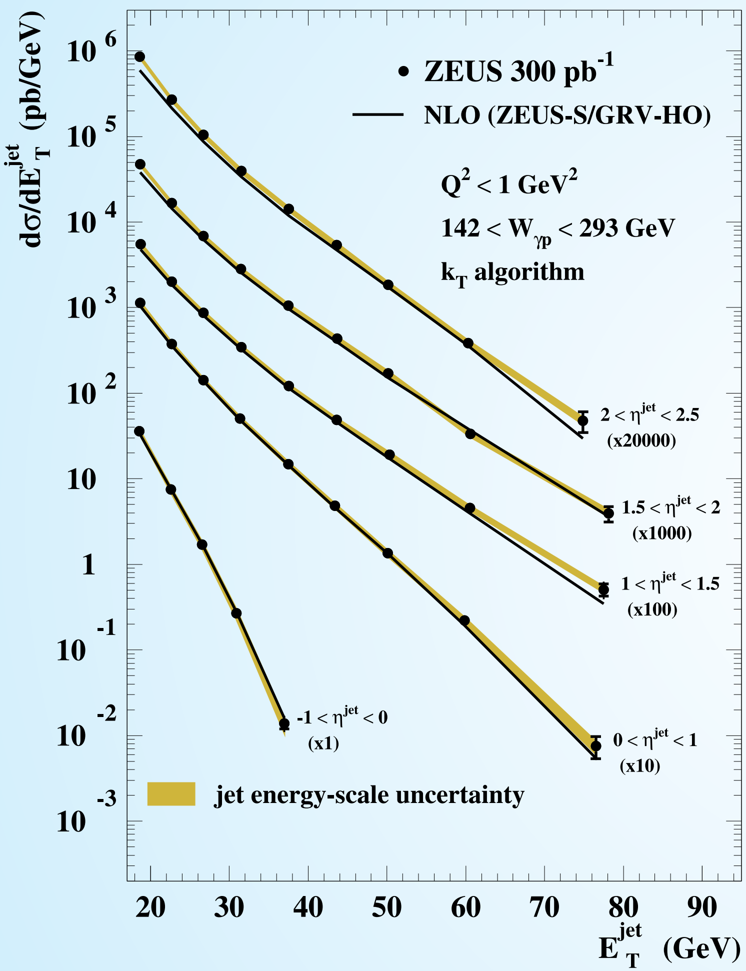
Jets are also QCD objects

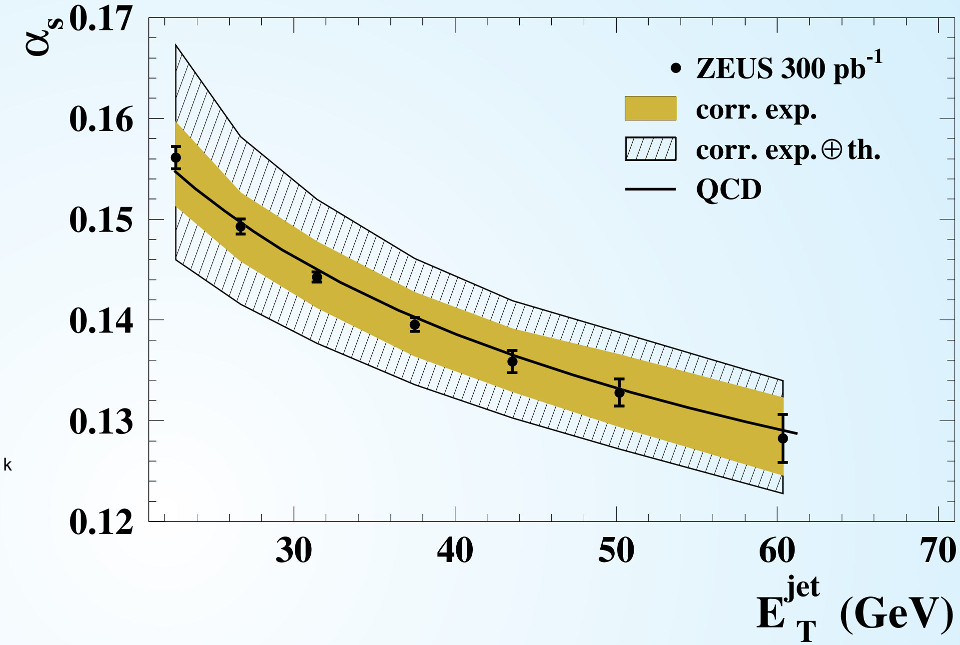
ZEUS: inclusive in photoproduction



a hint of non perturbativeness

Jets and α_s



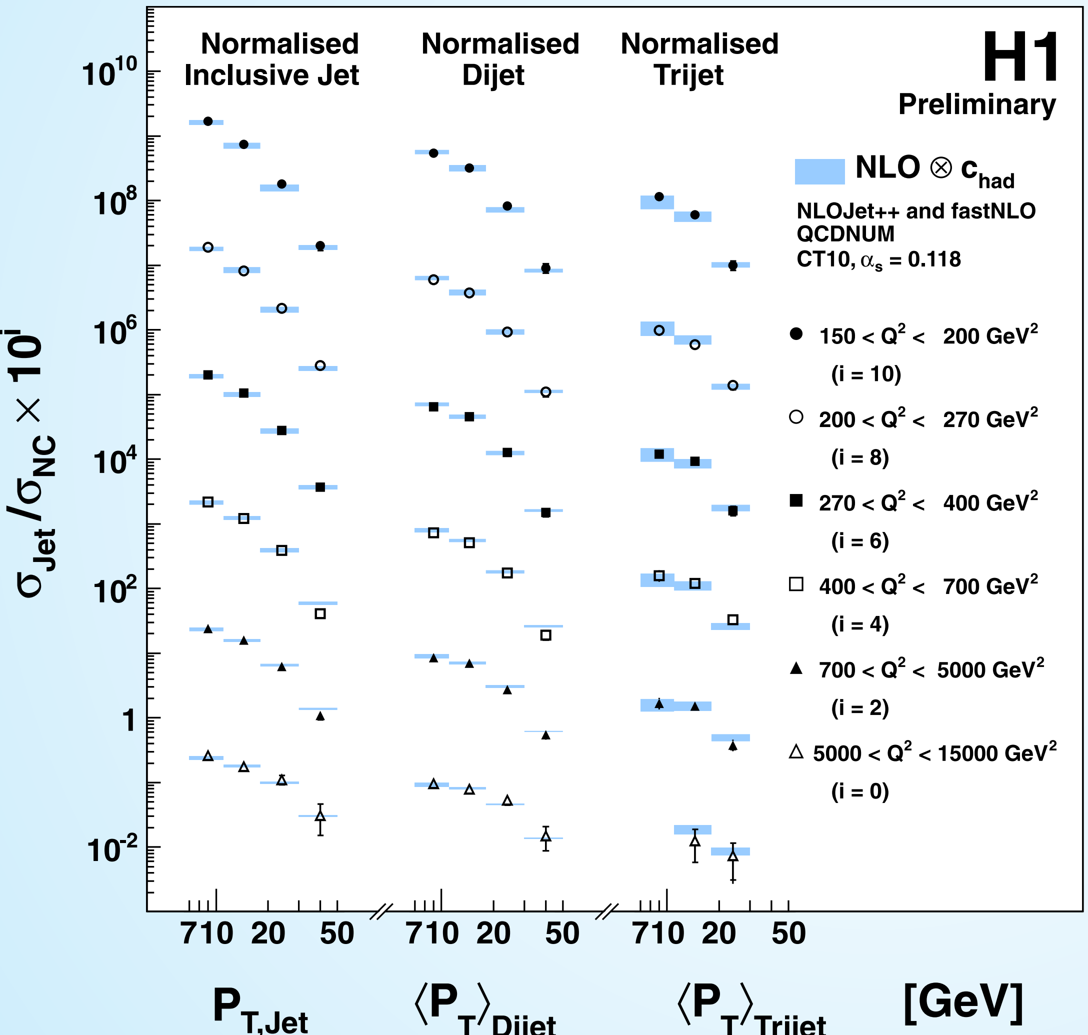


$$\alpha_s(M_Z)|_{k_T} = 0.1206 \; ^{+0.0023}_{-0.0022} \,(\text{exp.}) \; ^{+0.0042}_{-0.0035} \,(\text{th.})$$

The determination of α_s is limited by theory.

Jets and α_s

H1: inclusive, dijet and trijet in DIS



Simultanious fit to all normalised cross sections.

$\alpha_s(M_Z)$ =

0.1163 ± 0:0011 (exp.)

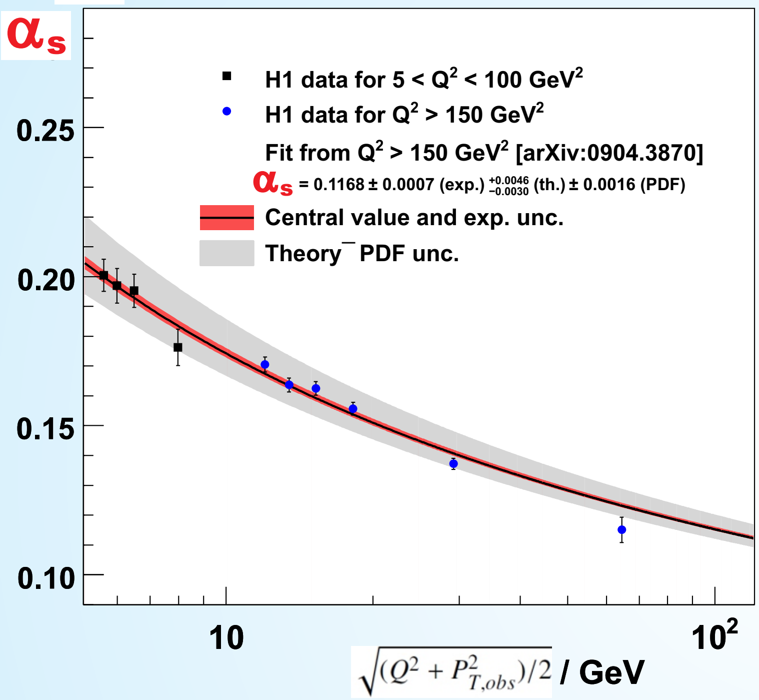
± 0.0008 (had)

$^{+0.0044}_{-0.0035}$ (th.) ± 0.0014 (PDF)

H1-prel-12-031

Jets and α_s

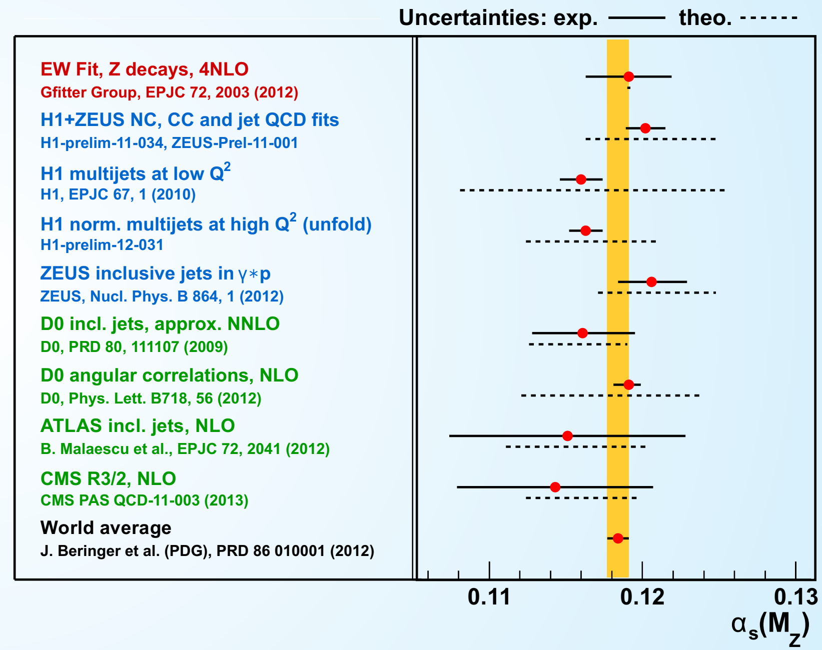
α_s from Jet Cross Sections in DIS



Fit from Q^2 > 150 GeV^2 [arXiv:0904.3870]

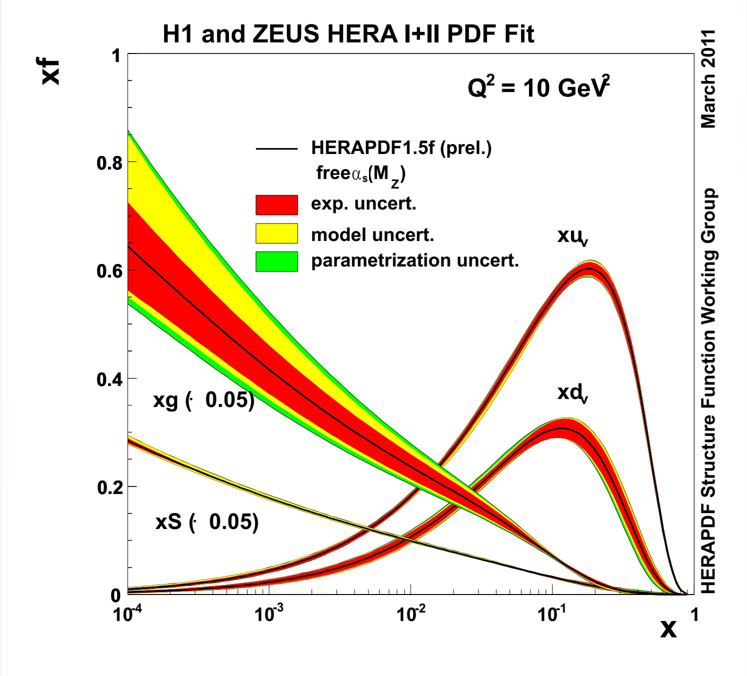
α_s = 0.1168 ± 0.0007 (exp.) $^{+0.0046}_{-0.0030}$ (th.) ± 0.0016 (PDF)

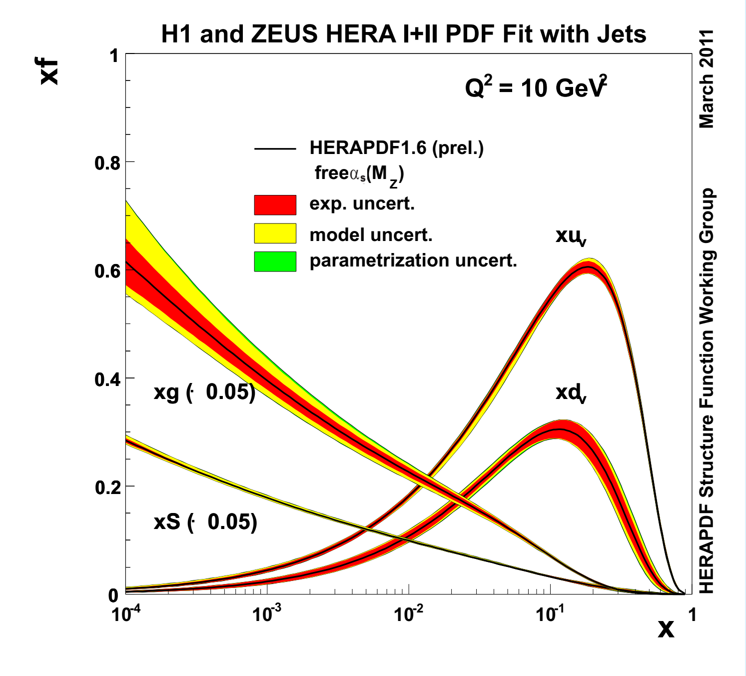
α_s is measured at HERA and elsewhere



Everybody agrees within uncertainties.

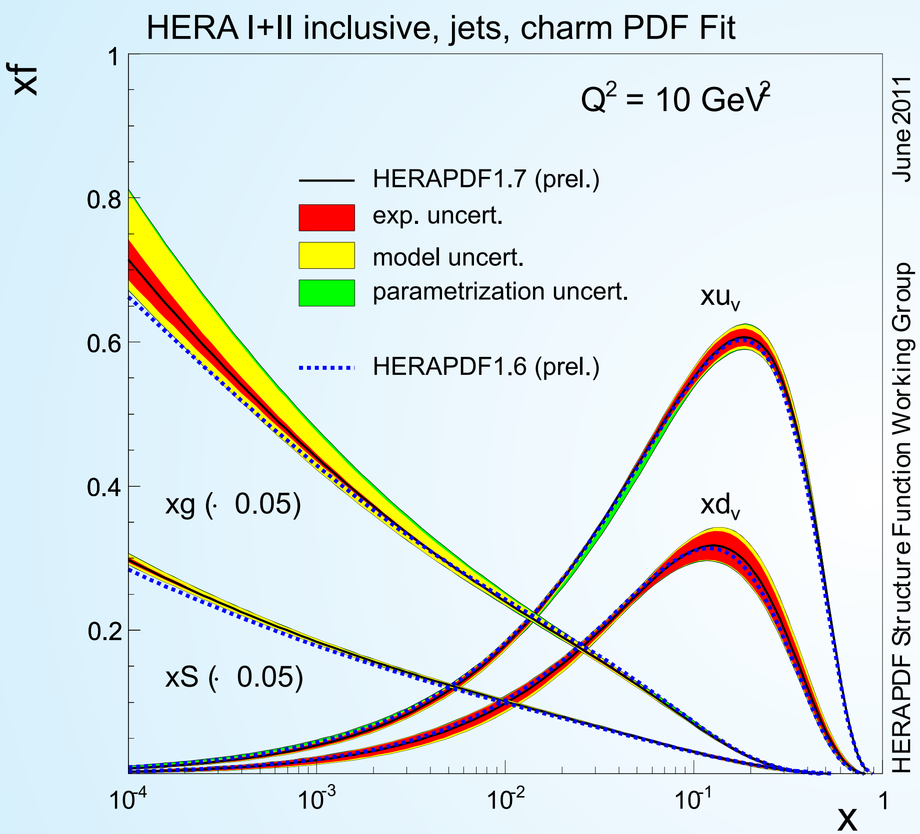
HERAPDFs with JETS





Jets reduce the uncertainty on the glue.

HERAPDFs with JETS and CHARM



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

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

steeper low-x gluon than ever before:

HERAPDF is a large family!

HERAPDF Family

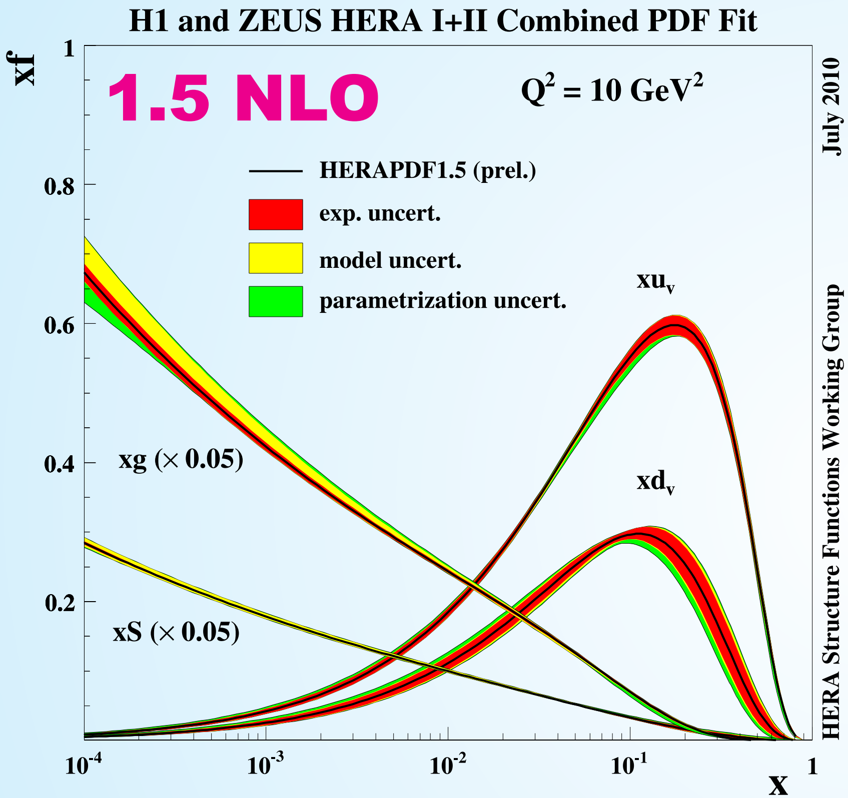
recommended version →

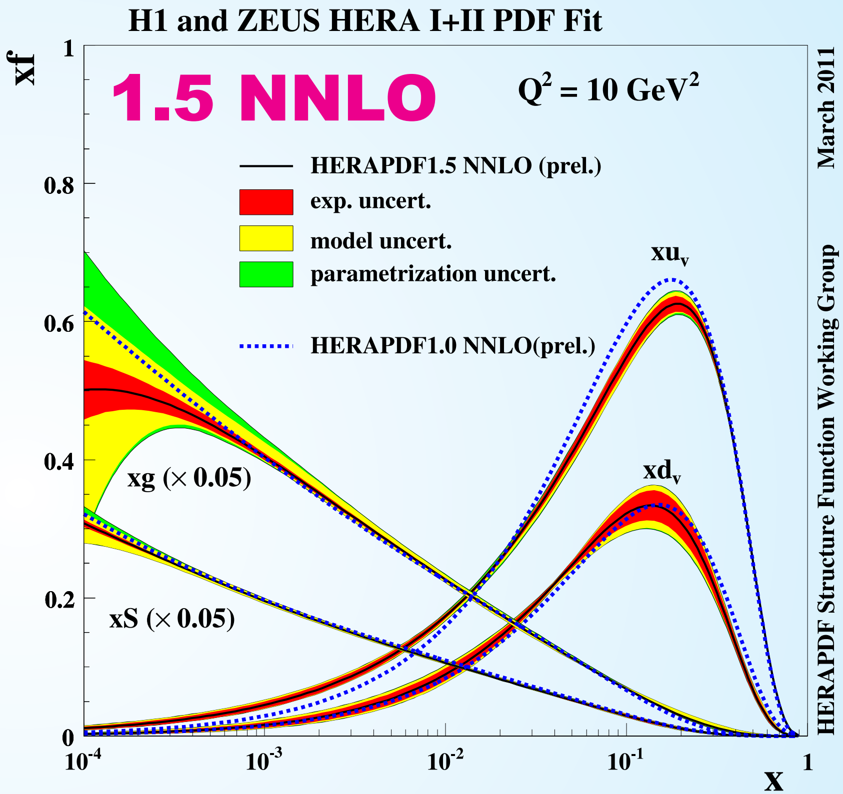
NAME	NC and CC DIS	NC, lower E(p_beam)	Jets	Charm	Docu	Grids	Data comparison	Date
HERAPDF1.7 NLO	HERAI + partial HERAII	H1+ZEUS	H1 and ZEUS(1)	H1+ZEUS	Figures	N.A.		June 2011
HERAPDF1.6 NLO	HERAI + partial HERAII	---	H1 and ZEUS(1)	---	Writeup and figures	N.A.		March 2011
HERAPDF 1.5 NNLO	HERAI + partial 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

https://www.desy.de/h1zeus/combined_results/herapdftable/

HERAPDF 2.0 is being worked on, stay tuned.

HERAPDF Family



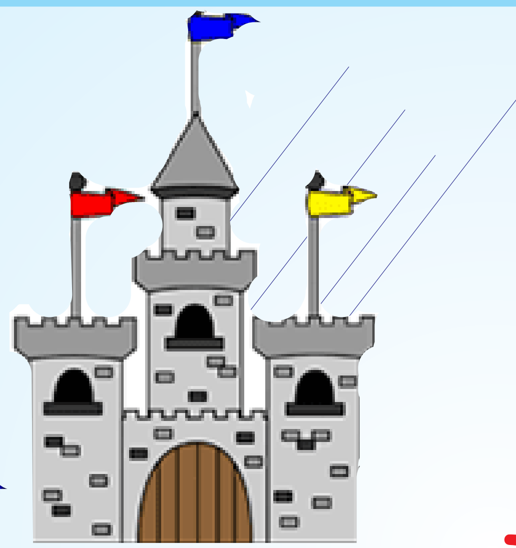


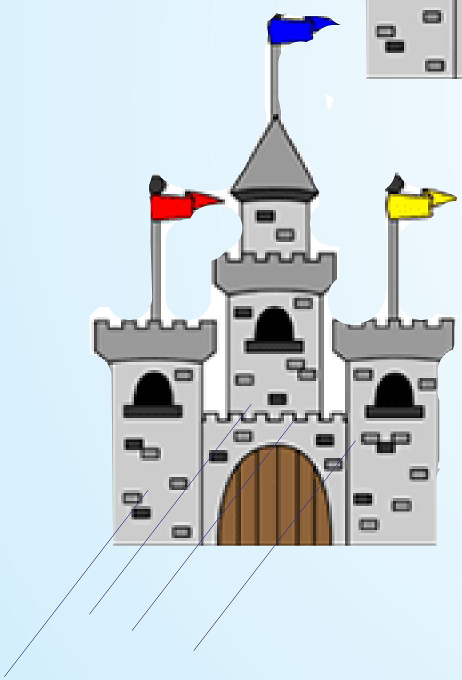
HERAPDF 1.5 NLO and 1.5 NNLO are the family members recommended for general use.

Who needs PDFs anyhow?

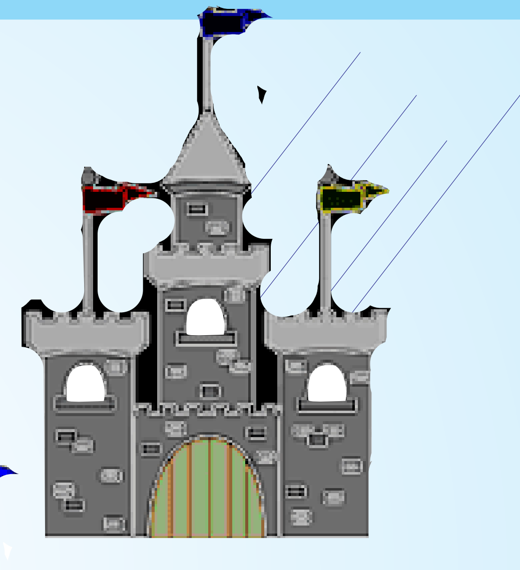
Castle Castle Interactions

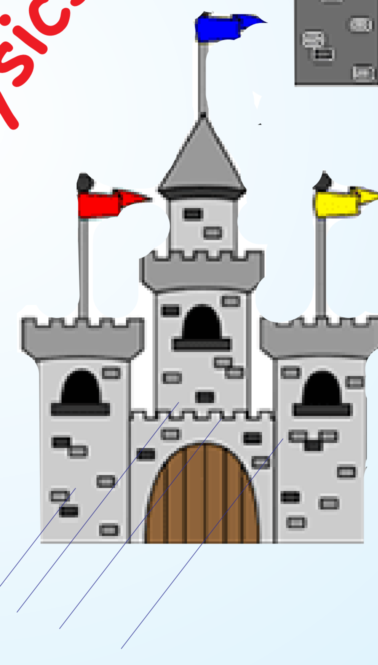
proton
proton
collisions





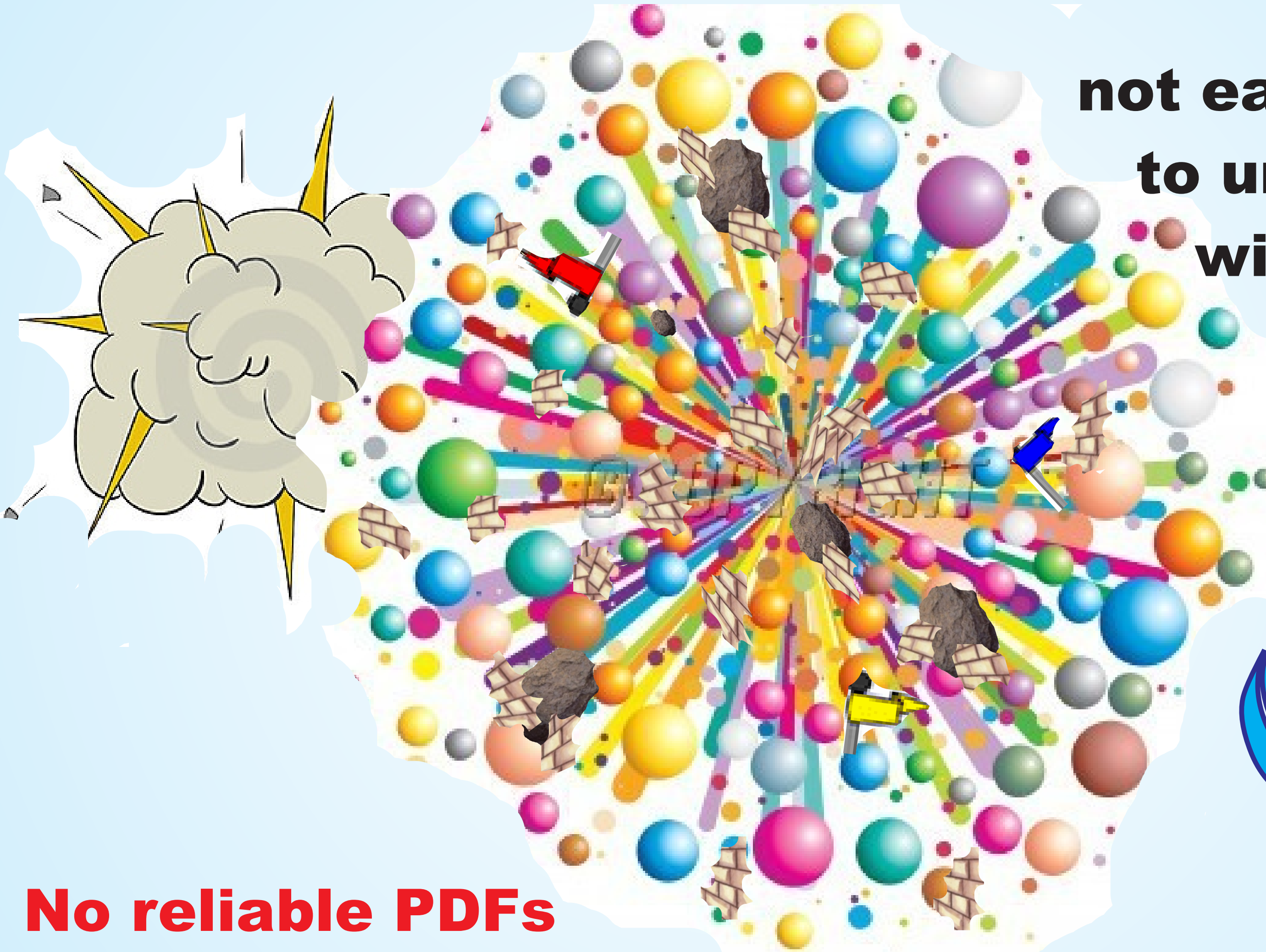
collider physics





antiproton
proton
collisions

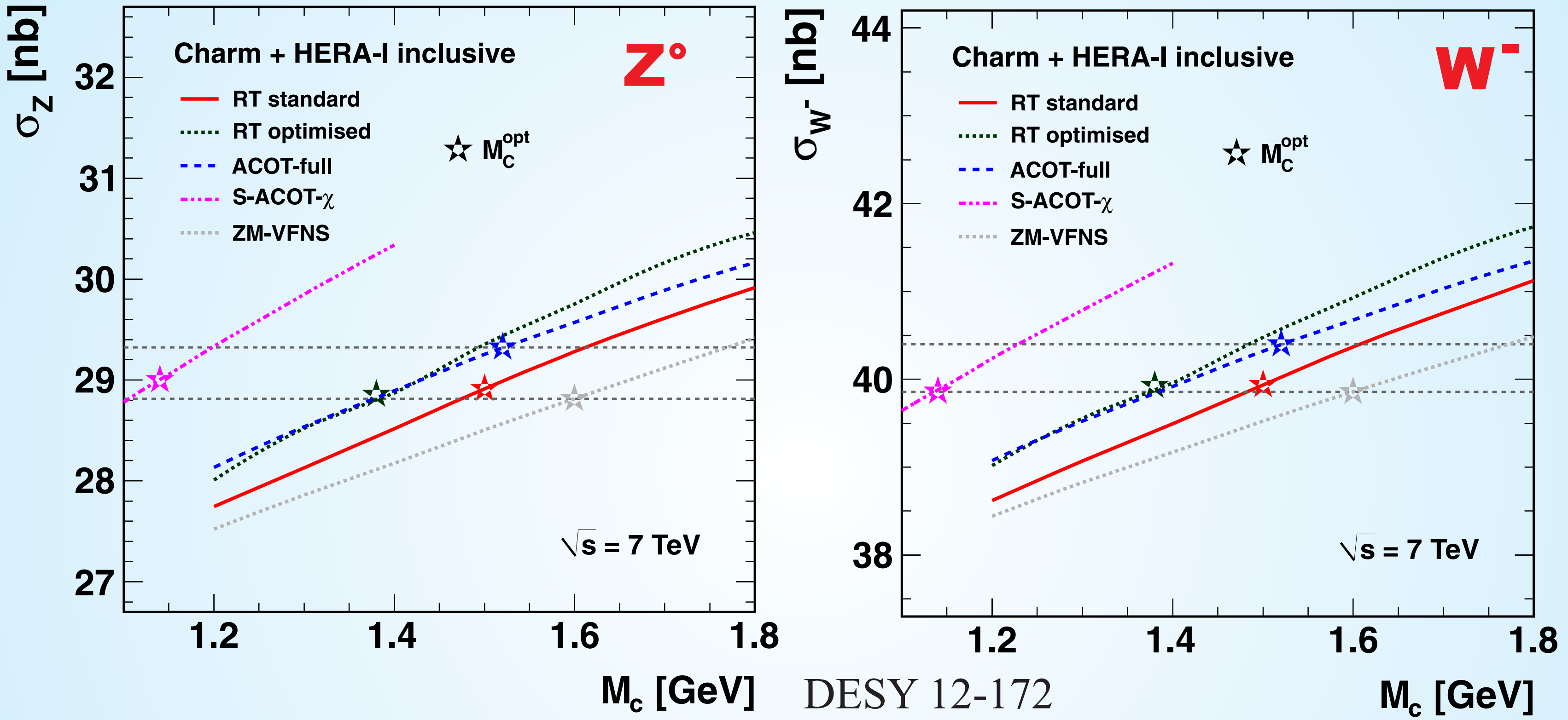
Beautiful Destruction



not easy
to understand
without input

No reliable PDFs
$\Rightarrow$ no reliable searches

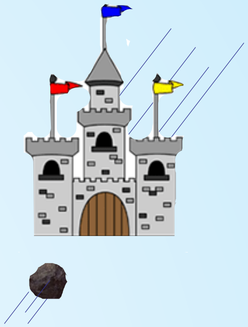
Cross-Section Predictions



DESY 12-172

With the proper treatment of the parameter charm mass, different schemes give the same predictions for the cross sections, even if different charm masses are used.

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

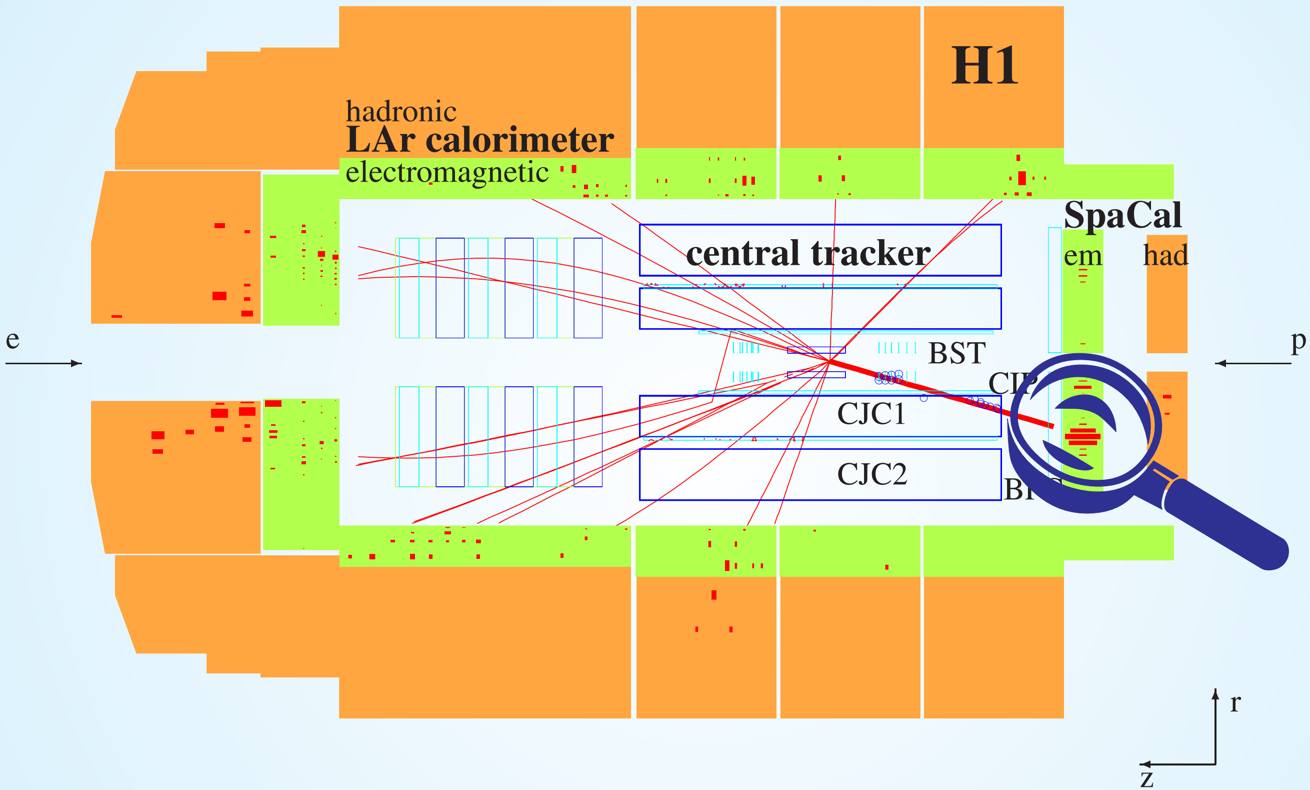
$E_p = 920\ \mathrm{GeV}$ $E_p = 575\ \mathrm{GeV}$ $E_p = 460\ \mathrm{GeV}$

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

This is a challenge!

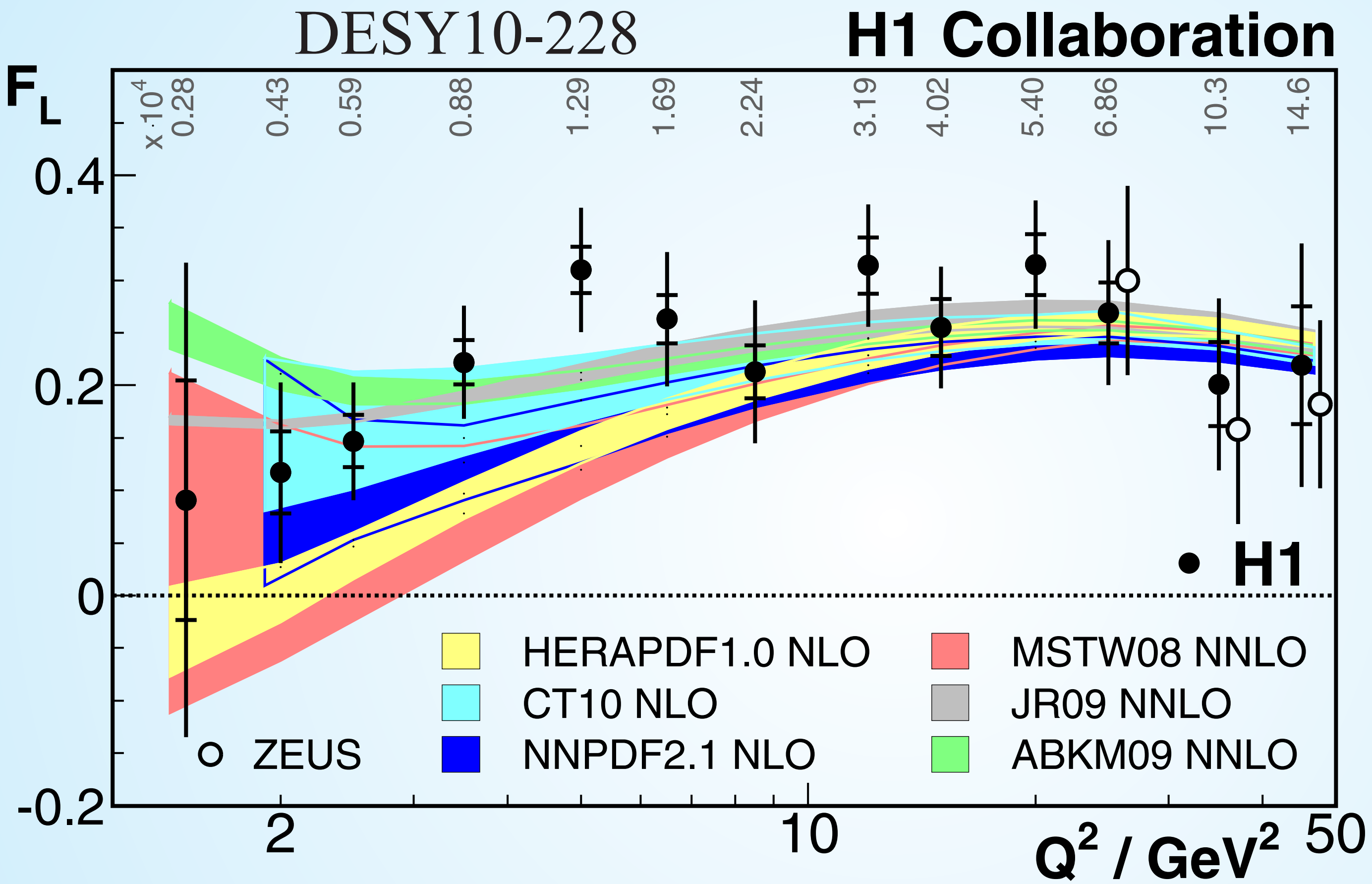
Direct access to glue!

Longitudinal Structure Function



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

Longitudinal Structure Function



down to x ≈ 0.00003

and wide range of Q²

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

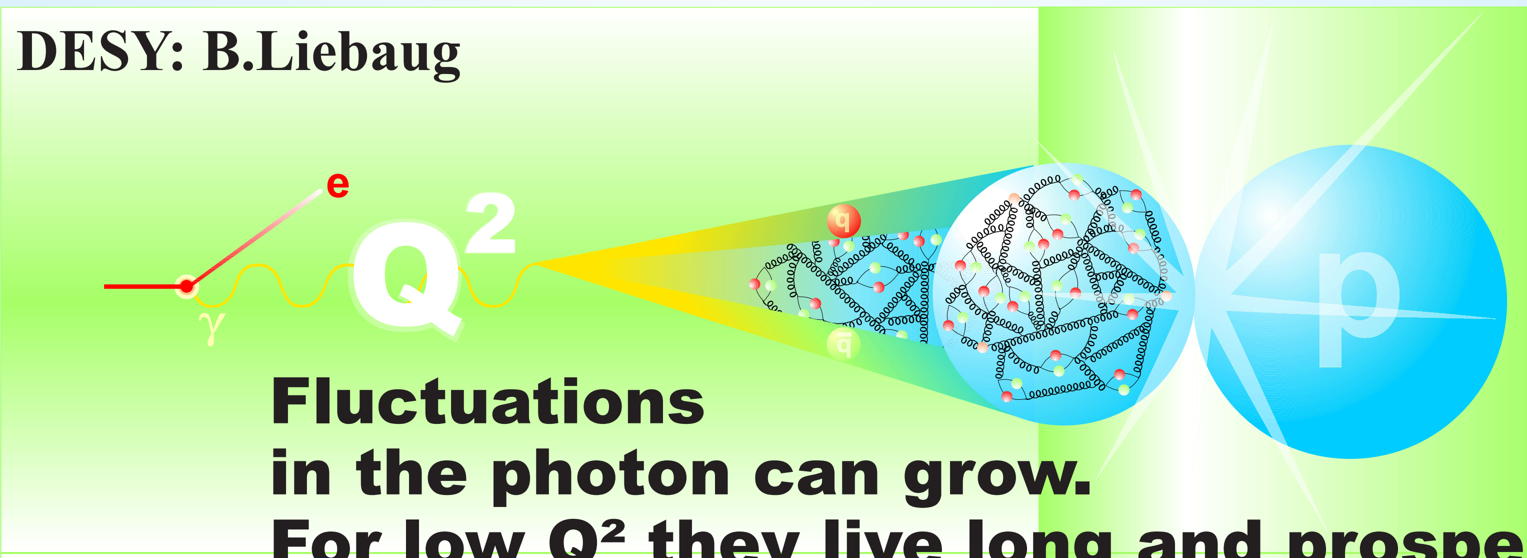
Direct measurement does not contradict PDF predictions.

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.

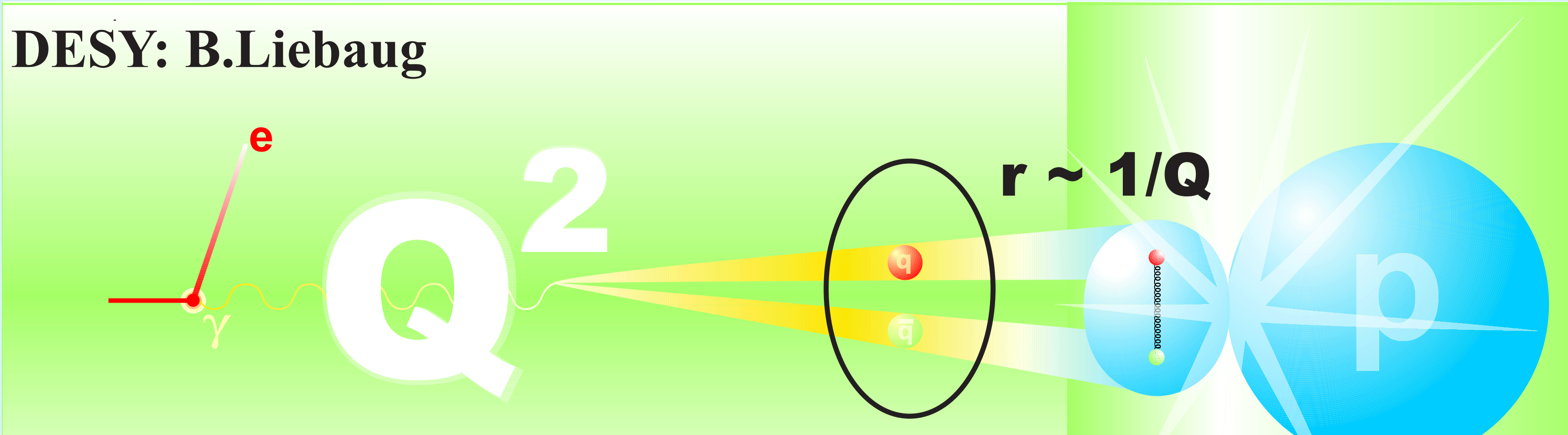


Fluctuations in the photon can grow.
For low Q^2 they live long and prosper.

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

Color Dipole Model

Coherence length: l [fm] $\approx$ 0.1/x

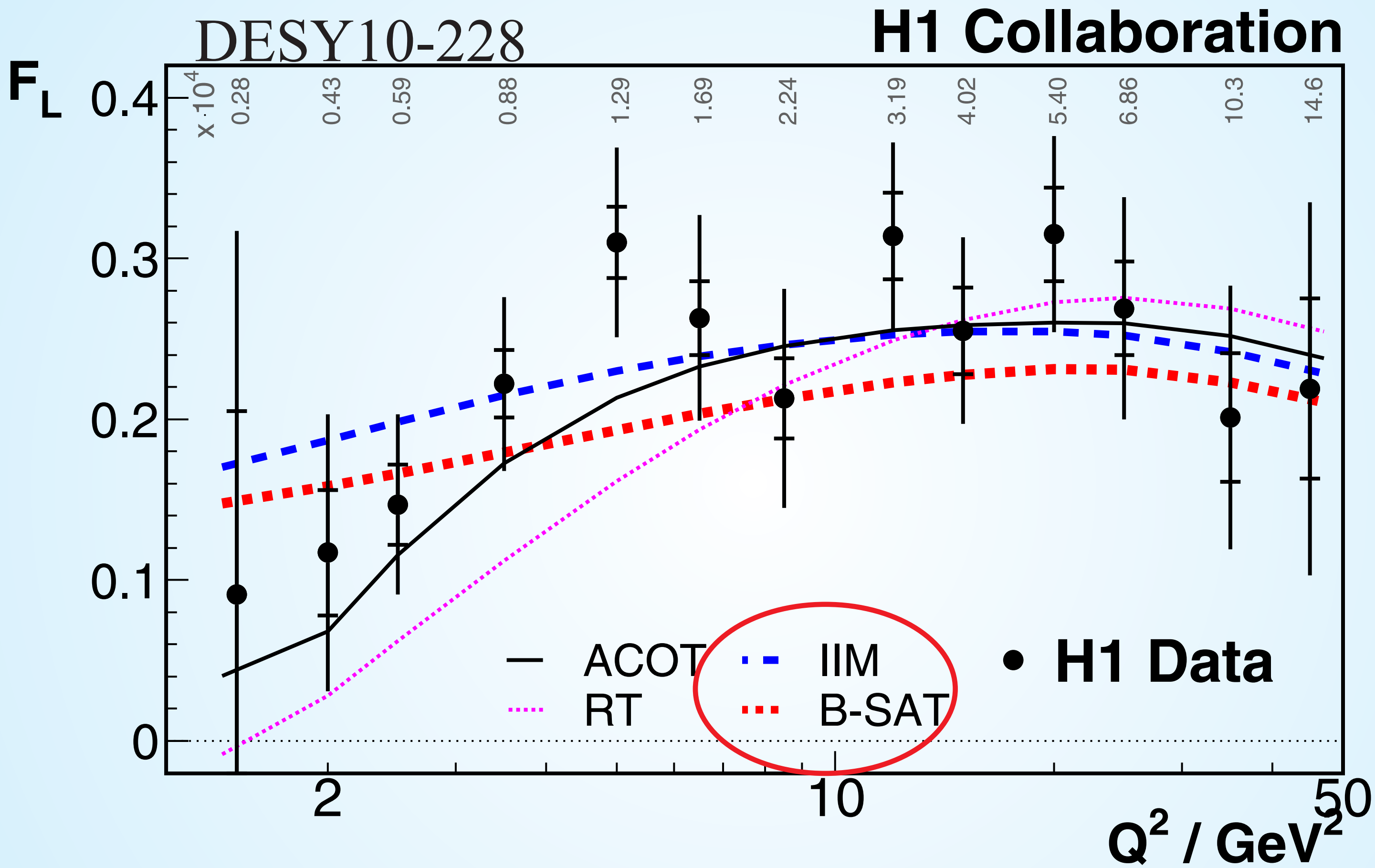


For high Q^2 only a color dipole forms.
No time for more.

The fluctuation might forget where it came from.

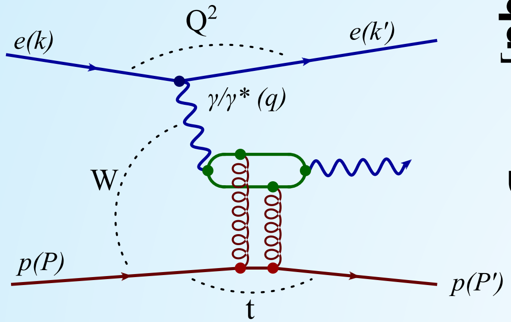
Do I get the same PDFs for neutrino - nucleon or nucleon nucleon scattering? Is factorisation holding?

Longitudinal Structure Function



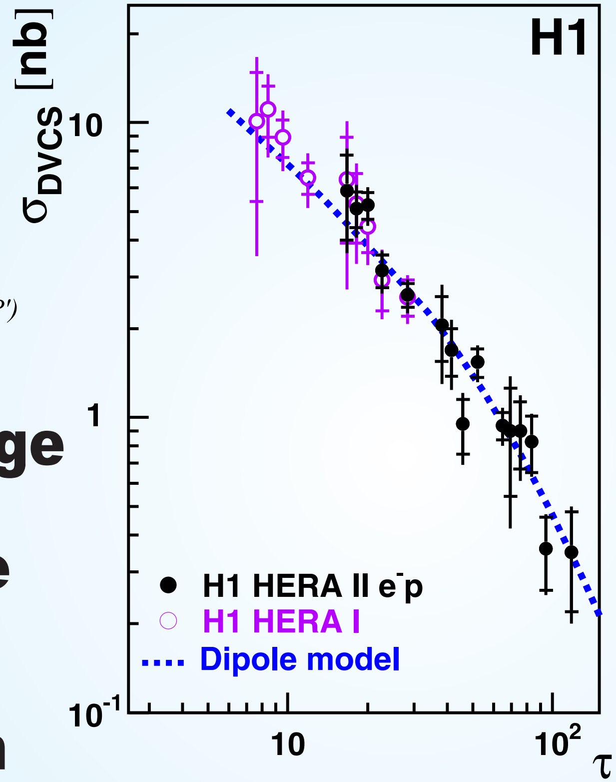
Color dipole models also describe the data.

Deeply Virtual Compton Scattering

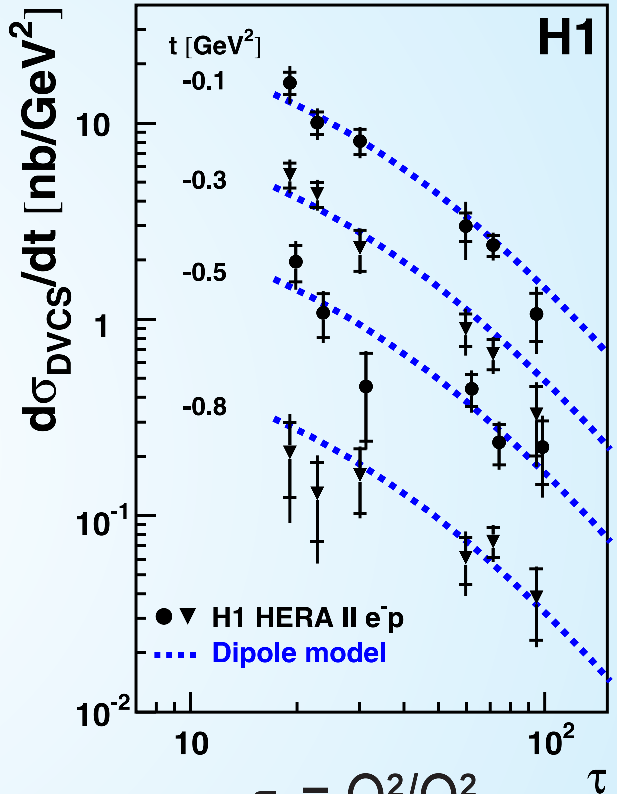


2 gluon exchange

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



DESY07-142



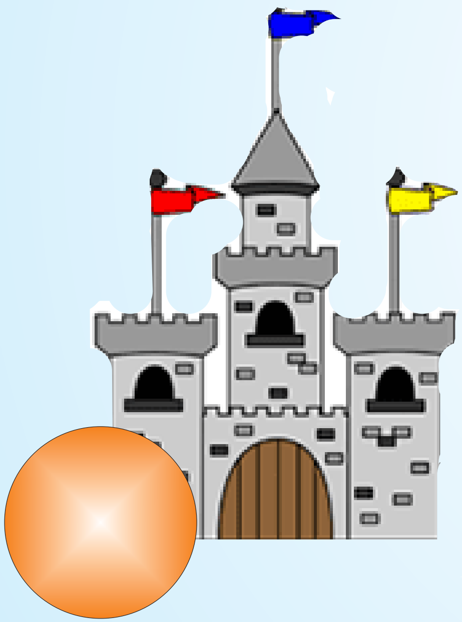
$\tau = Q^2/Q^2_S$

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

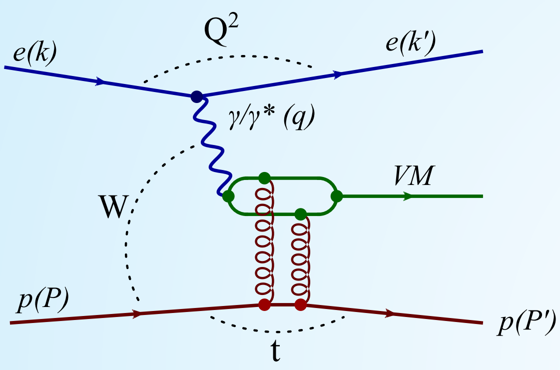
average impact parameter

0.65 ± 0.02 fm $x=0.0012$

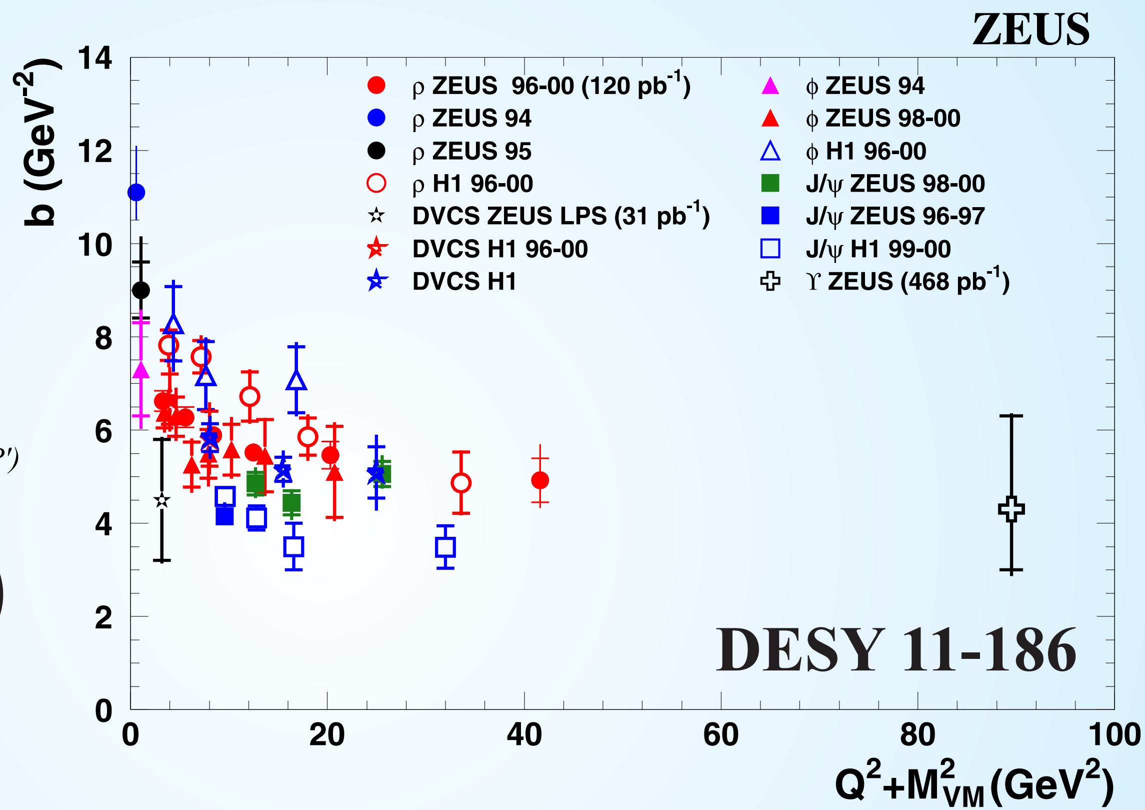
transverse expansion of partons

-- in the proton?

t-Slopes for Vector Meson Production



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



Should be analysed with respect to proton size.

Proton Size and Dynamics

rms charge radius

electron: 0.8786 ± 0.0069 fm

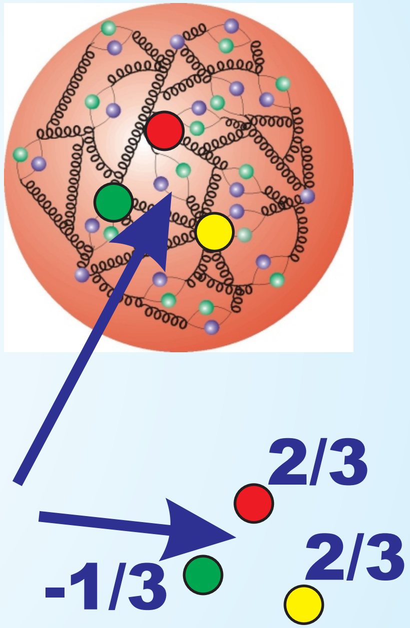
muon: 0.84184 ± 0.00067 fm

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

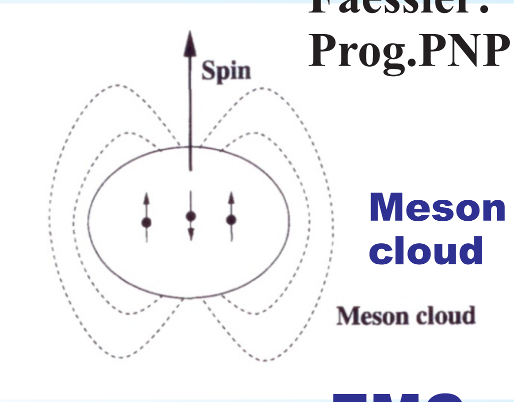
magnetic moment

μ_{p}/μ_{N} = 2.792847356 ± 0.000000023

$p \rightarrow \Delta$ excitations

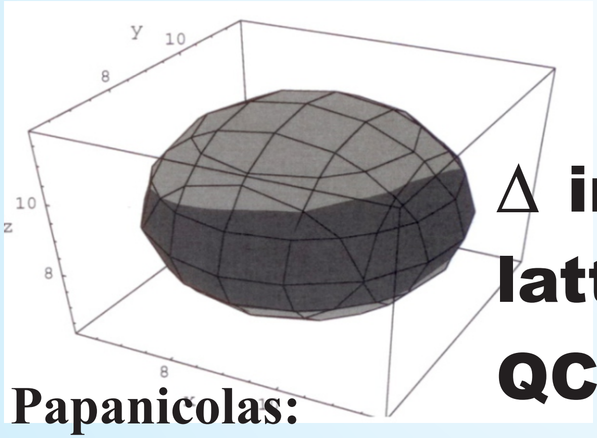
[also used for GZK cutoff]

Faessler:
Prog.PNP 44(2000)



Meson cloud

EMC effect



Δ in lattice QCD

Papanicolas:
EPJ A 18(2003)

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

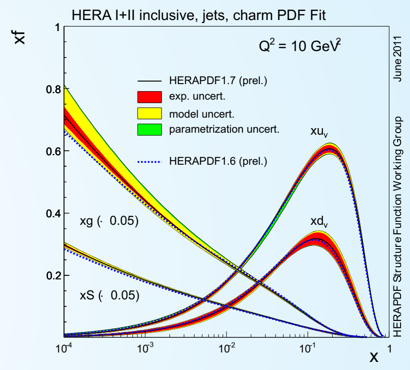
Can we see the proton behind the strong field?

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.

There is more than pertubative QCD, even in the proton.

Outlook

The combination of H1 and ZEUS data is ongoing.

HERAPDF 2.0 is the next step.

The high precision data also test pQCD.

Eventually theory will improve and we will better understand non perturbative QCD.

We open the door and look inside.