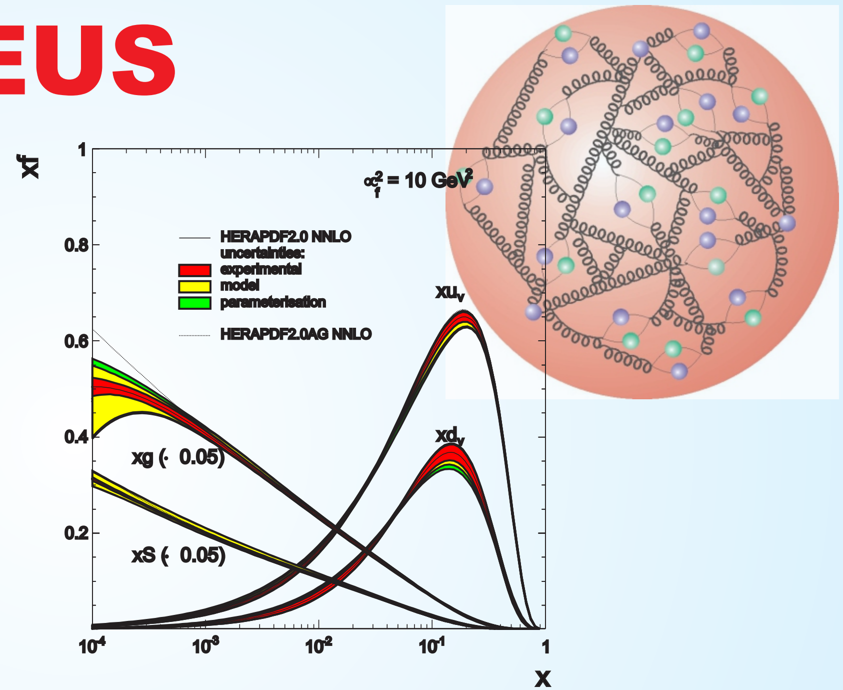
Final ep DIS cross sections from H1 and ZEUS

HERAPDF2.0

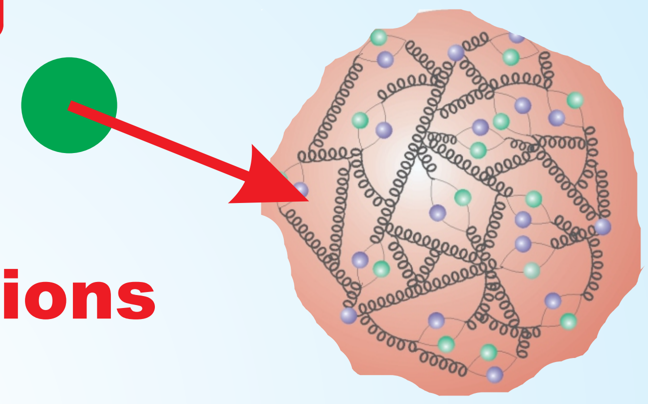


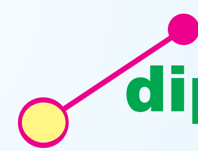
Kreuth, 8.10.2015

I.Abt, MPI München

Content

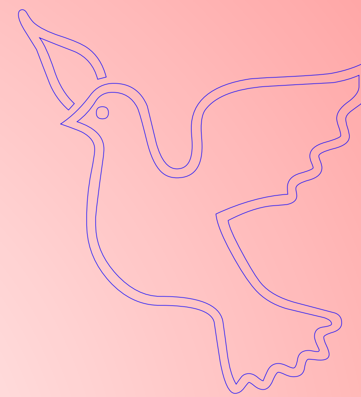
- **Deep Inelastic Scattering**
- **Cross Sections**
- **Parton Distribution Functions**
  - **HERAPDF2.0**
- **Proton Structure ?**
  - **Photon Structure ?**
- **Fruits of Precision**
- **Summary & Outlook**





dipoles ?

DISCLAIMER

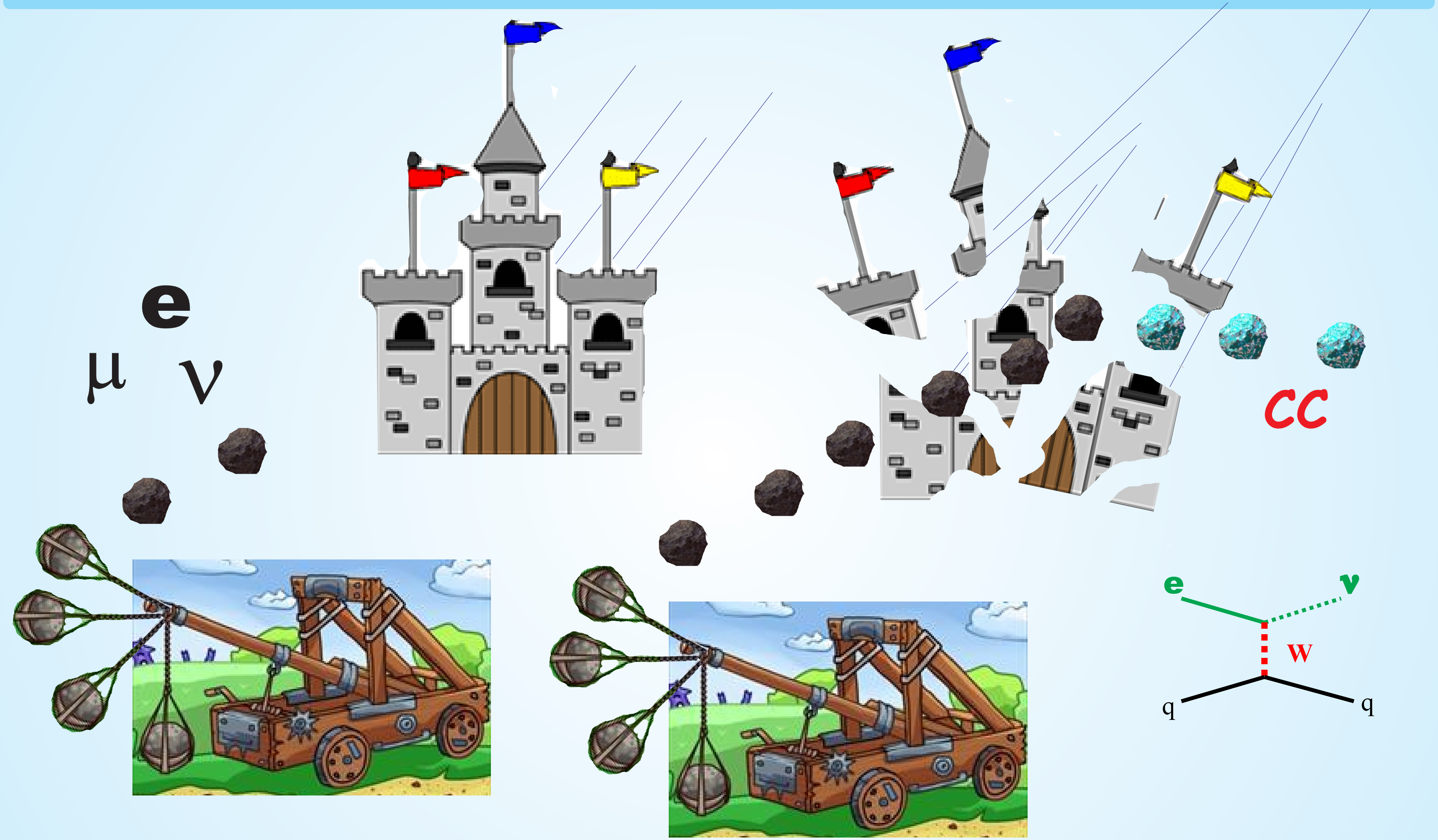


I will not try to be complete on any subject.
I have selected what I saw fit to make my point.
Any opinion is only mine and is in no way supported by either ZEUS or H1 or probably anybody else.

Nevertheless I am proud to represent H1 and ZEUS.

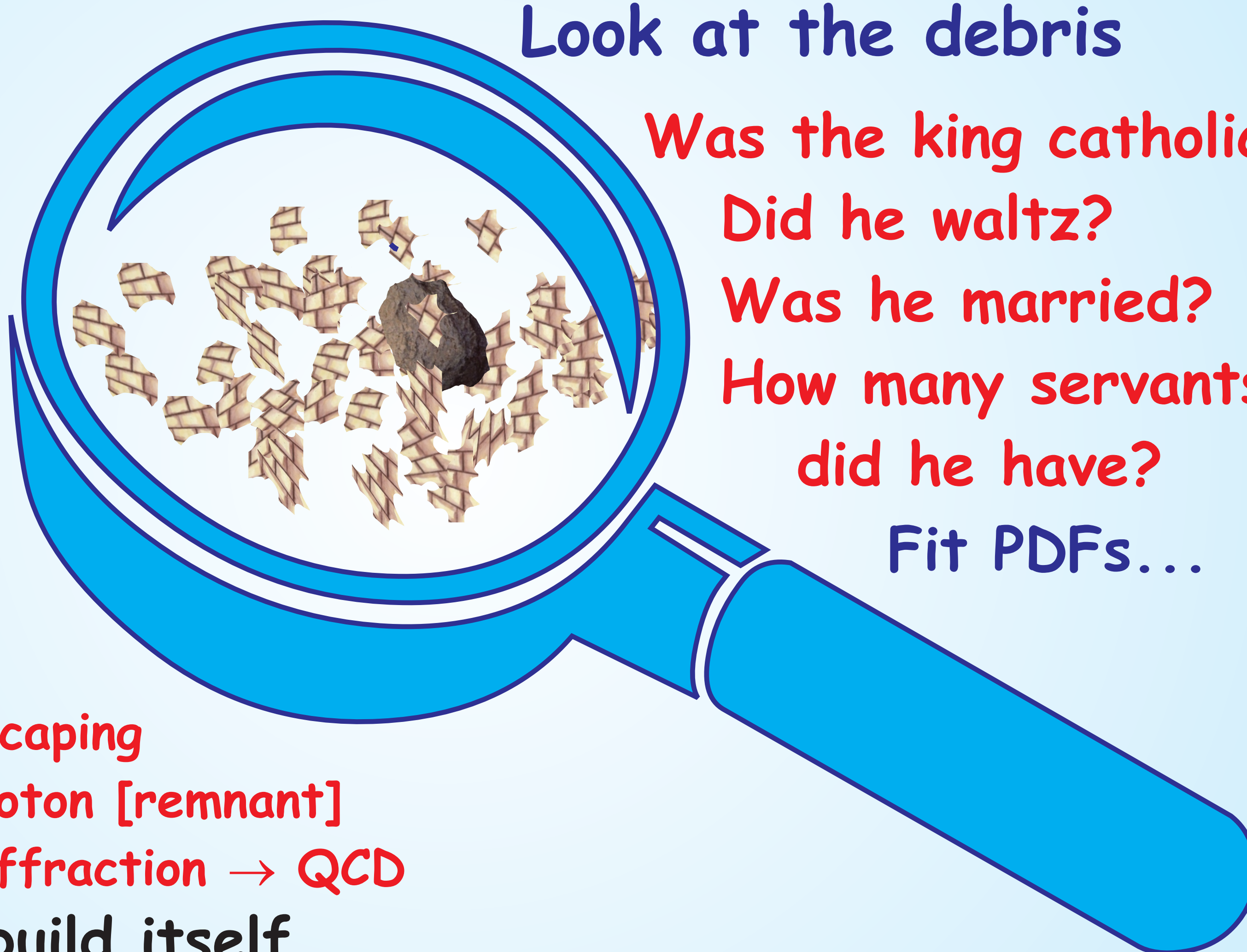
And I am sorry, if I should disturb you doing your Email or reading your favorite newspaper.

Deep Inelastic Scattering



Sorry, I do not have time for formulas.....

Deep Inelastic Scattering



Look at the debris

Was the king catholic?

Did he waltz?

Was he married?

How many servants did he have?

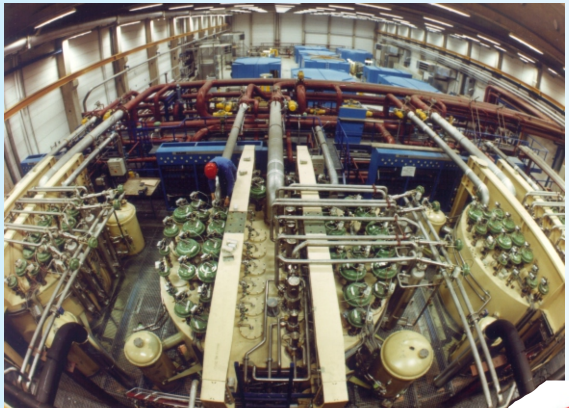
Fit PDFs...

Escaping proton [remnant]

Diffraction → QCD

This can rebuild itself

The Microscope



24.5.1993

Zeus DIS Lumi

HERA I

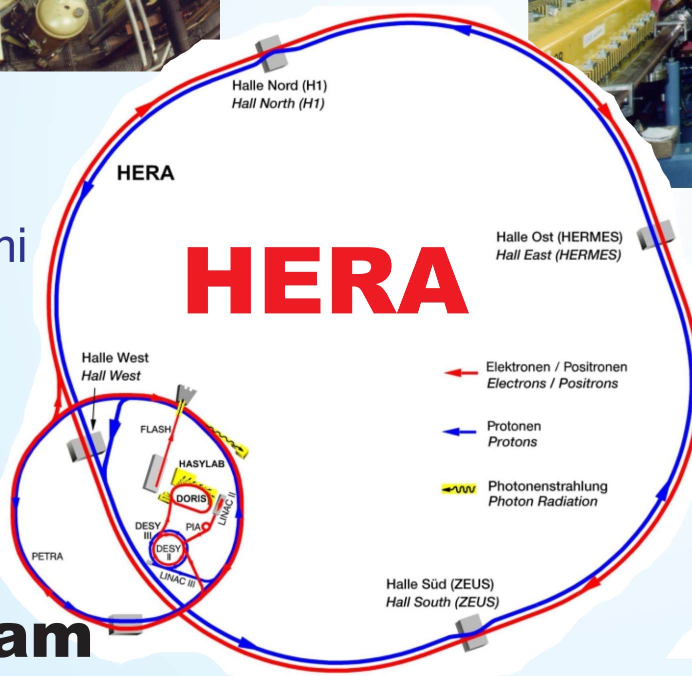
– 2000

2003 –

HERA II

last beam

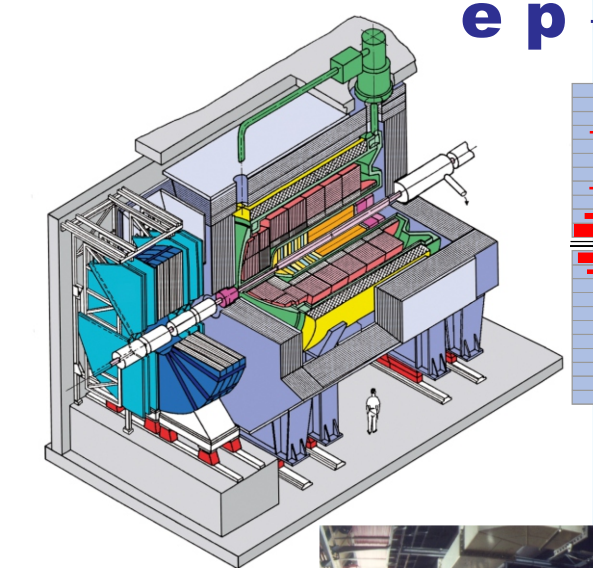
30.6.2007

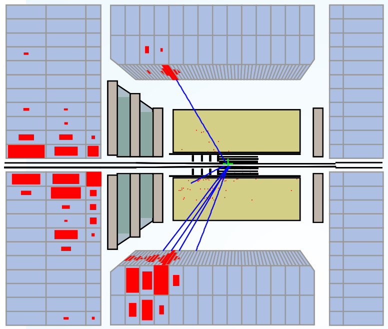


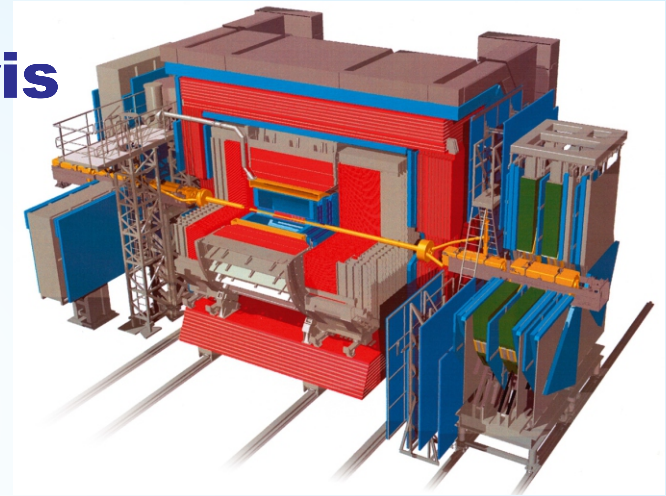
The Microscope

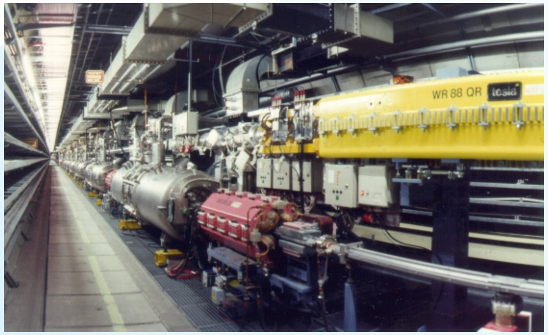
That is what we measure!

e p $\rightarrow$ e (ν) debris









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

→ **kinematic variables**

Kinematics

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

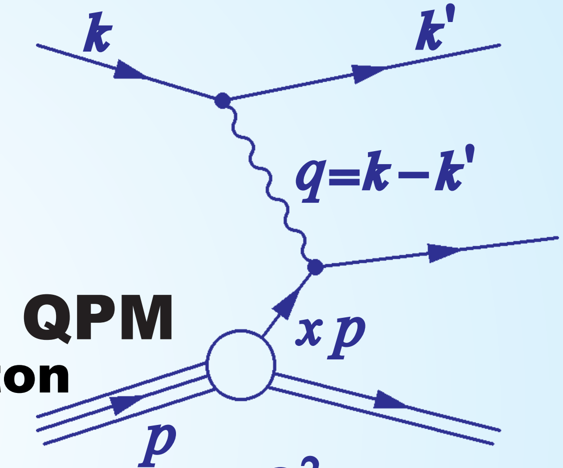
Spatial resolution of probe

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

Bjorken scaling variable:

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

Momentum fraction of struck parton



$$Q^2 = xys$$

Inelasticity: $y = pk / pq$

Energy transfer to proton (in p rest frame)

Reconstruction

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

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^*

$V^*q \to q'$

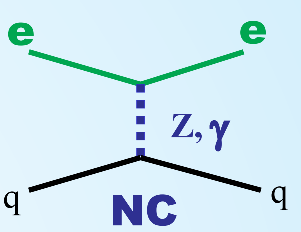
lowest-order QCD

Structure Functions

$e^{\pm}p$

tree level

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



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

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

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

$$x\tilde{F}_3 = \kappa_Z a_e \cdot xF_3^{\gamma Z} - \kappa_Z^2 \cdot 2 v_e a_e \cdot xF_3^Z$$

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 $\tilde{F}_L = 0$

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

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

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

sea quarks = anti-quarks

valence quark distributions

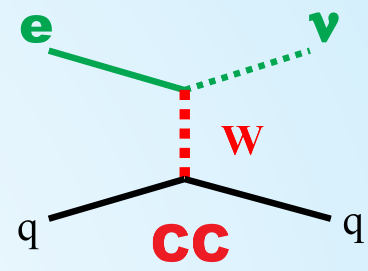
$$xu_v = xU - x\bar{U} \qquad xd_v = xD - x\bar{D}$$

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 $W_L^{\pm} = 0$

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

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

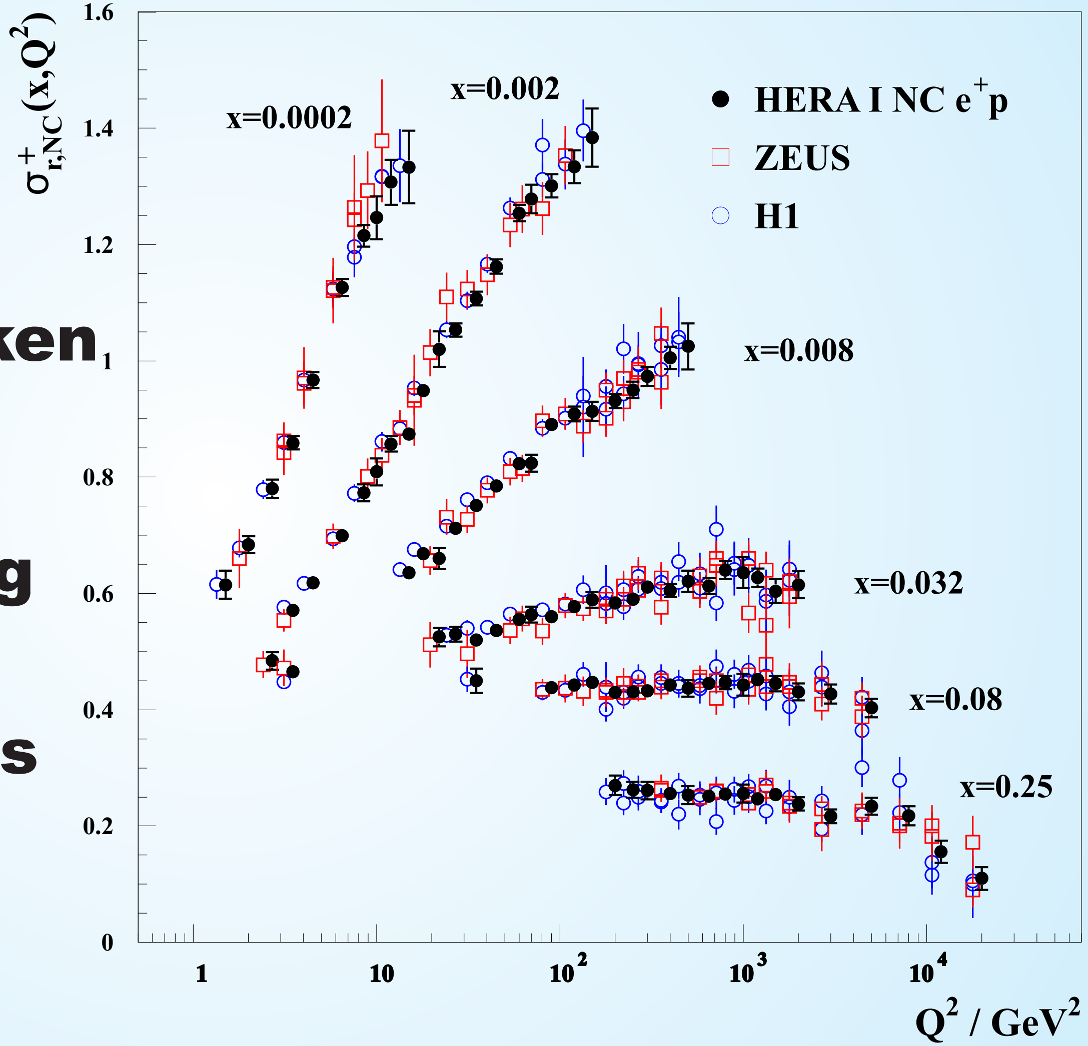
NC and CC yield valence and sea quark distribution.

QCD analysis [DGLAP] yields gluon distribution.

HERA I cross sections

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

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

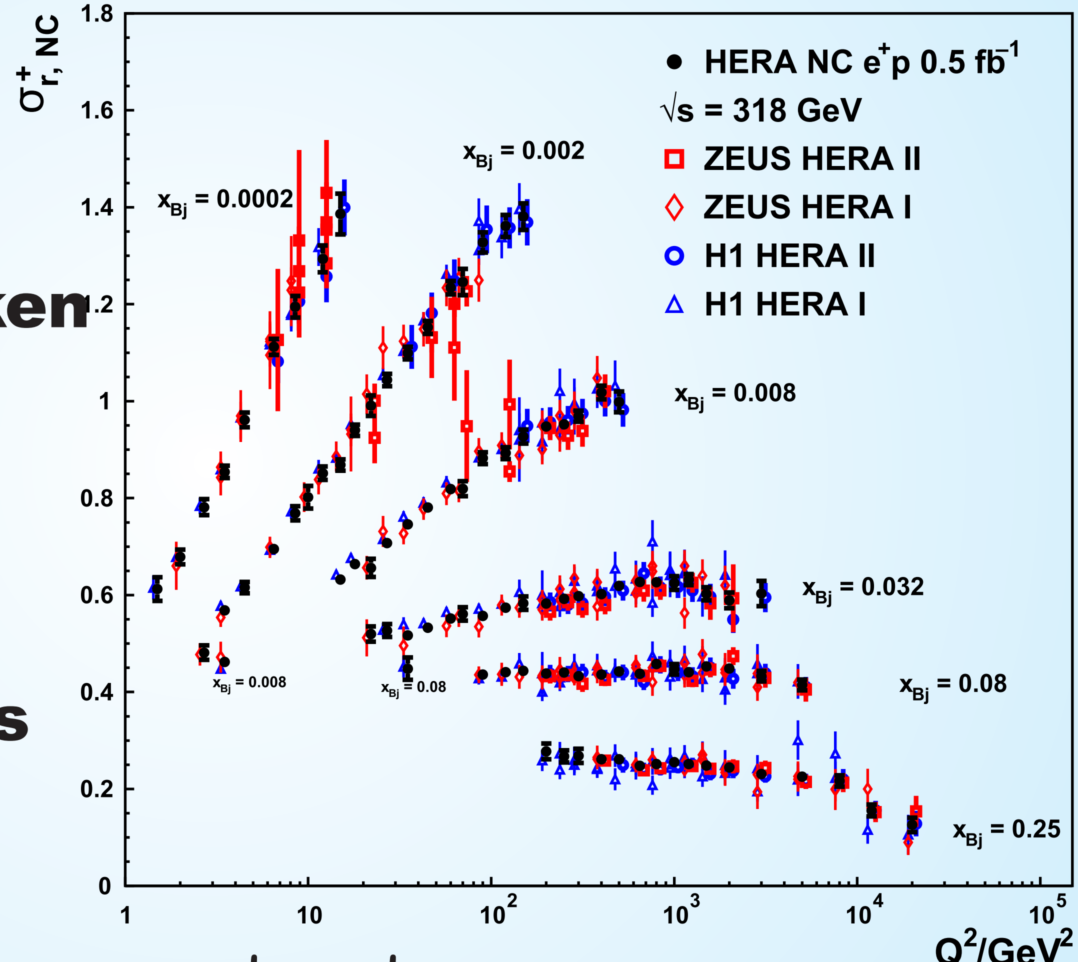


HERA cross sections

2015:

H1 and ZEUS publish combined results on data taken 1993 to 2007.

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



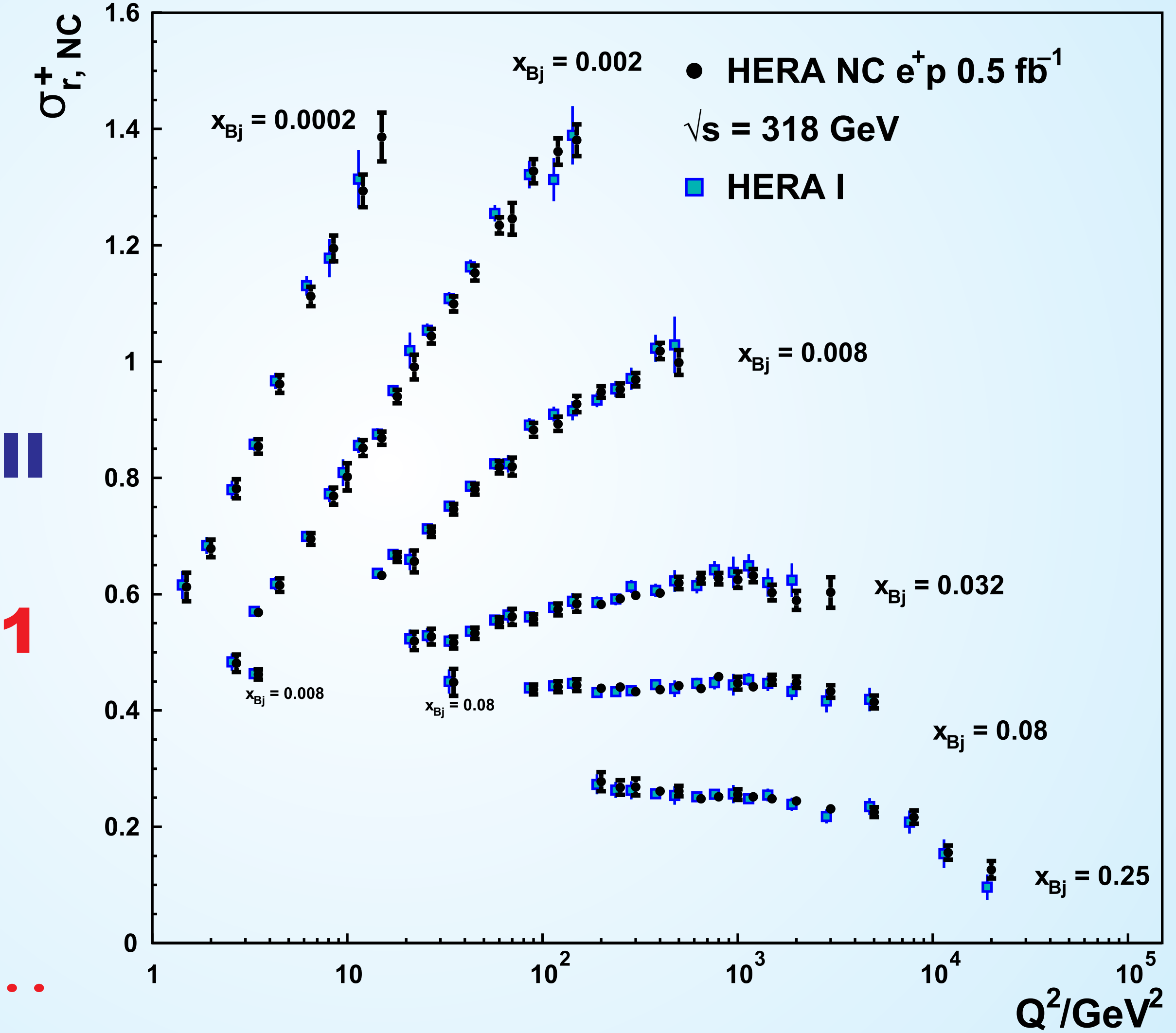
We got faster and $\sigma \rightarrow$ reduced σ

HERA cross sections

faster
and better

and we
even agree:
HERA I and II
and
ZEUS and H1

The latter
is a bit of
a miracle....

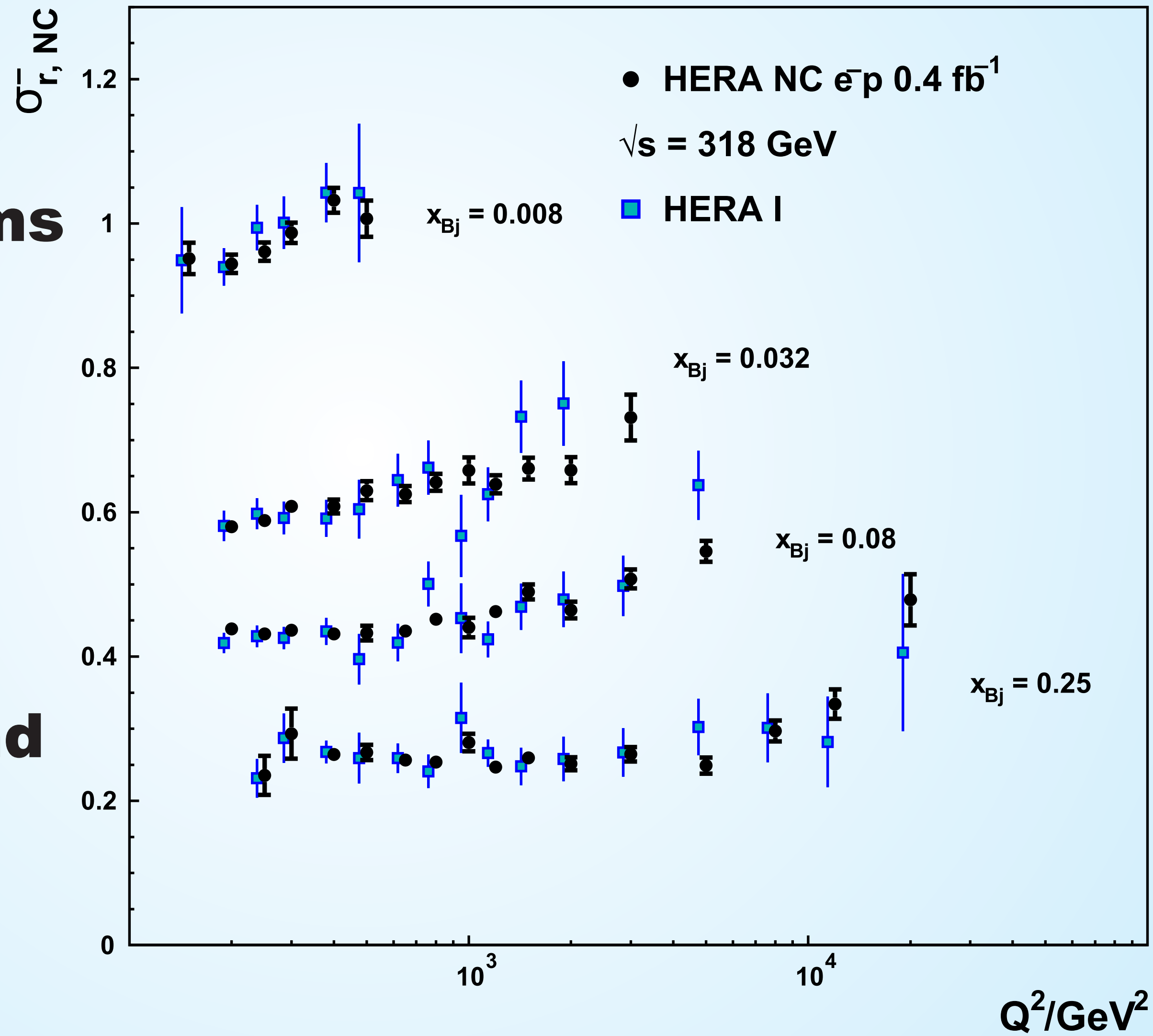


HERA cross sections

Improvement is larger for electron beams

a total of 41 data sets spanning 14 year

more plots and tables DESY 15-039



HERA cross sections

41 data sets taken over 14 years

162 correlated systematic uncertainties

correlations between correlated uncertainties

different collaborations

different x, Q^2 grids

2927 $\rightarrow$ 1307 points

χ^2/dof = 1.04

DESY 15-039

HERAPDF 2.0

All 1145 cross sections with $Q^2 \geq 3.5$ GeV^2 are input to a QCD analysis within the frame-work of DGLAP perturbative QCD.

HERAPDF2.0 NNLO NLO LO

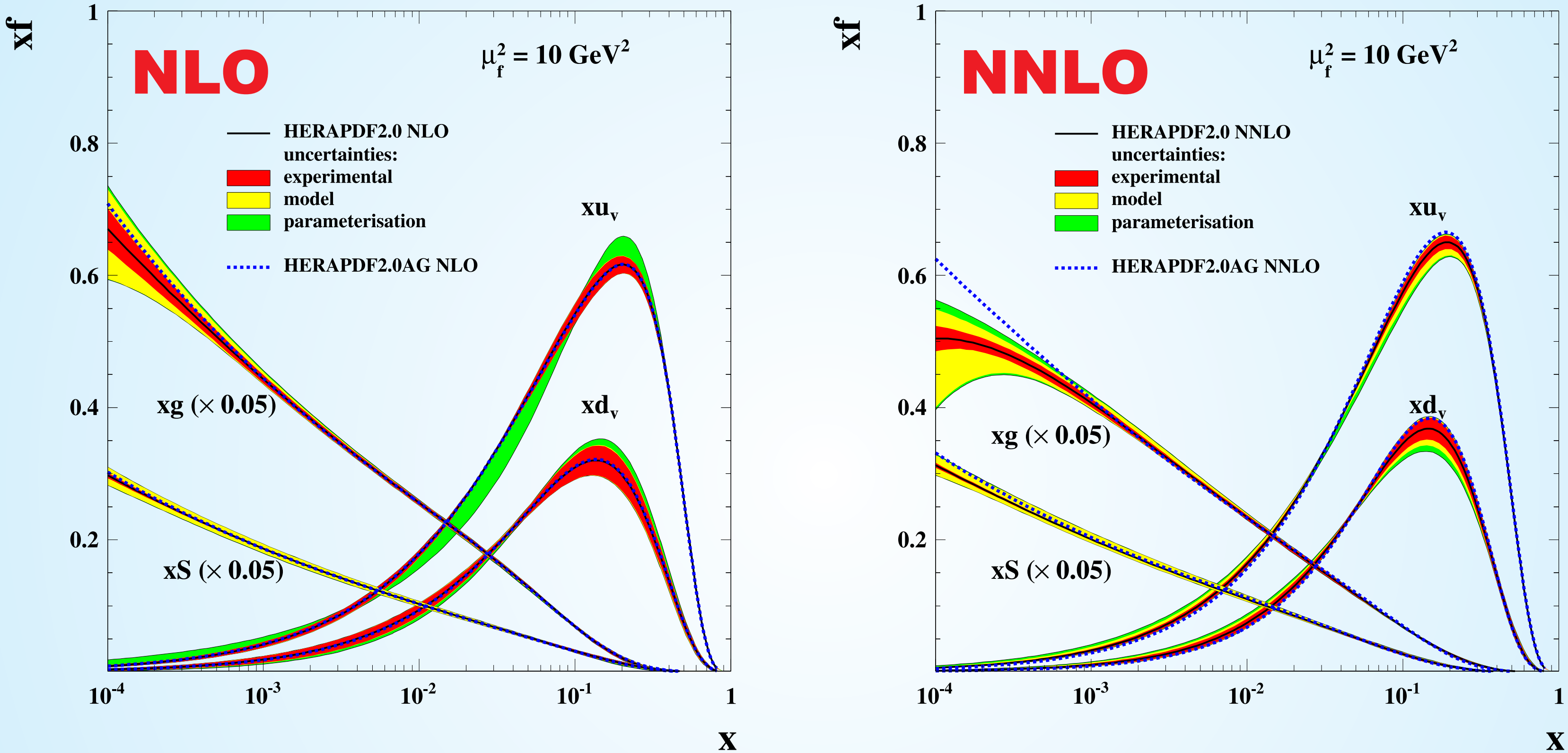
Hera likes a good fit!

high Q^2	$Q^2 > 10$ GeV^2
AG	alternative gluon
FF 3A/B	fixed flavour
Jets	includes charm and jet data $\rightarrow \alpha_s$

HERAFitter
independent code

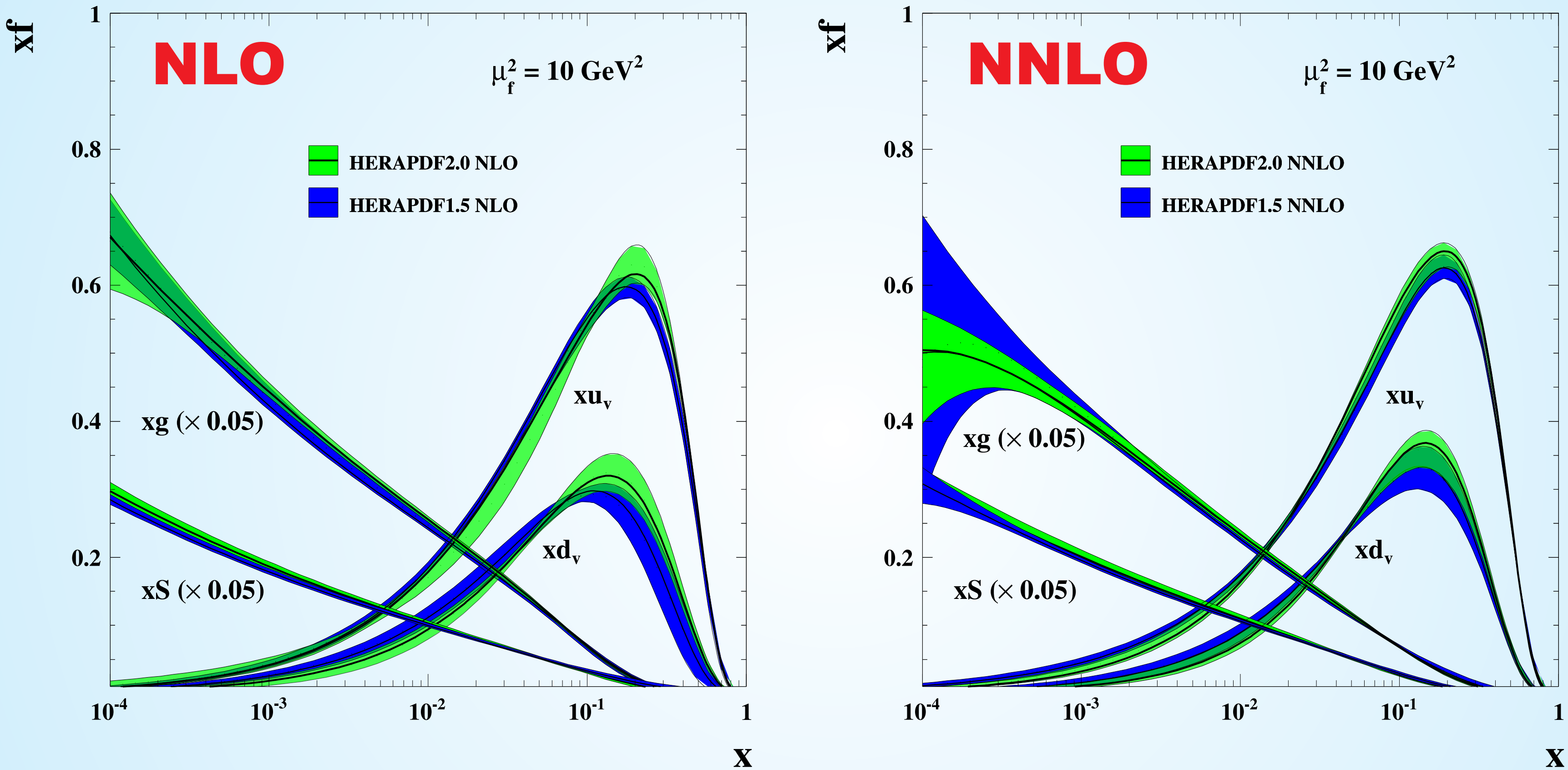
For overview, see desy 15-039 App. 1 and 2.

HERAPDF 2.0



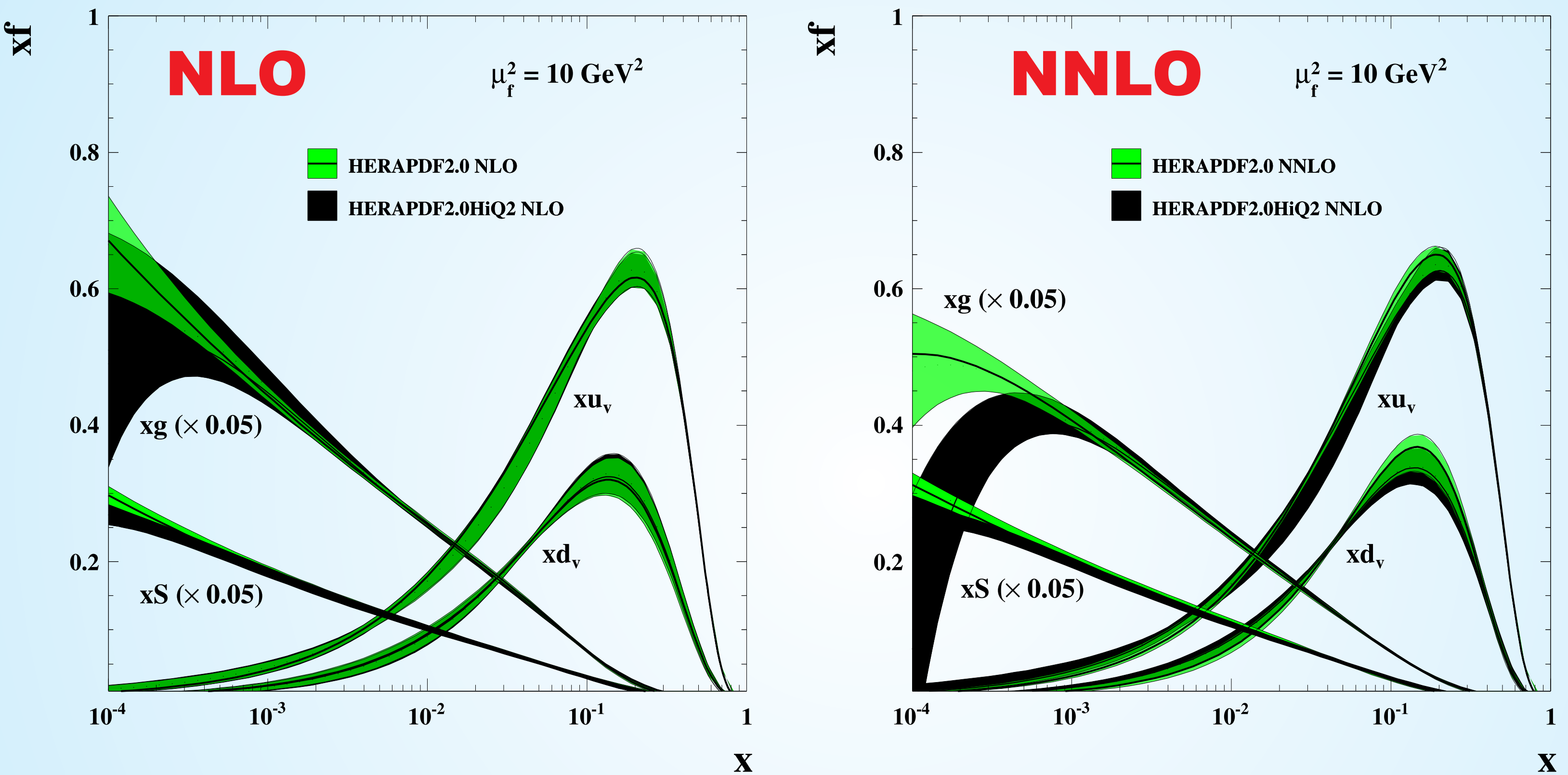
HERAPDF 2.0 NLO and 2.0 NNLO are the recommended PDFs for general useage.

HERAPDF 2.0 and 1.5



2.0 has a bit harder valence, especially at NLO and reduced gluon uncertainties at NNLO.

HERAPDF 2.0 HiQ2

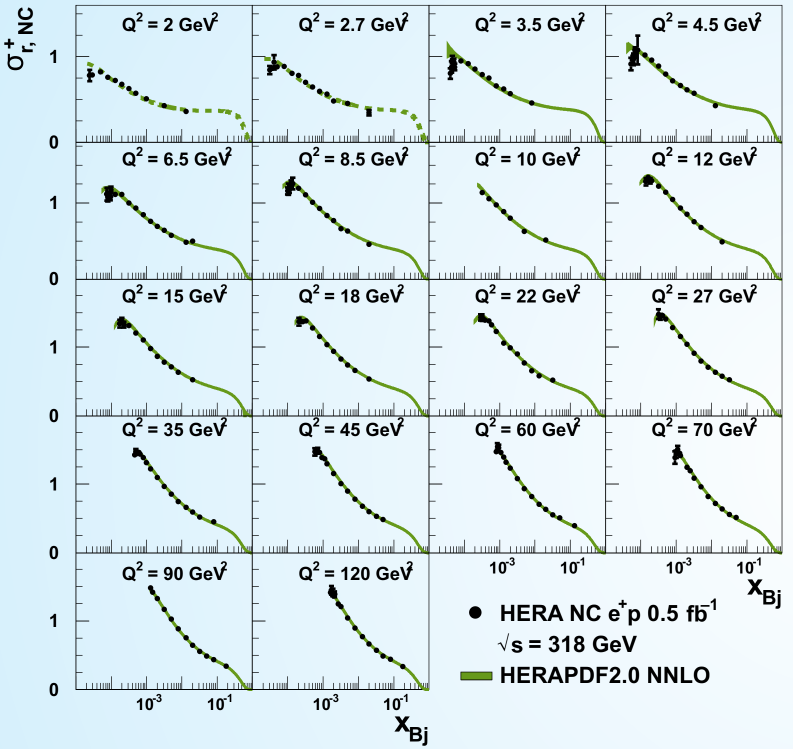


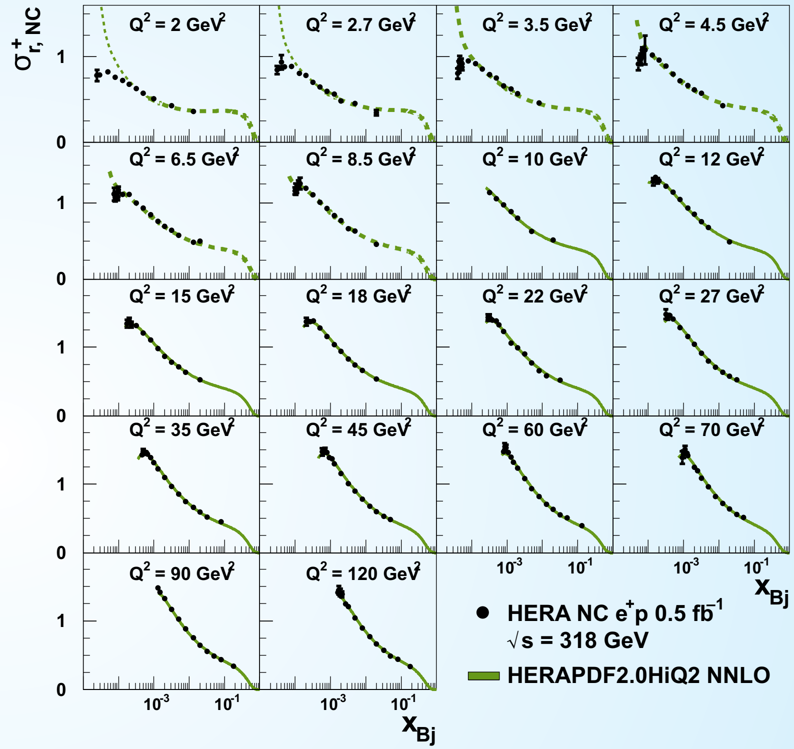
HERAPDF2.0 has a χ^2/dof of about 1.2.

Using only data with $Q^2 \geq 10 GeV^2$ reduces it to 1.15.

Heavy flavour schemes and FL make a difference, but ..

Comparison with data

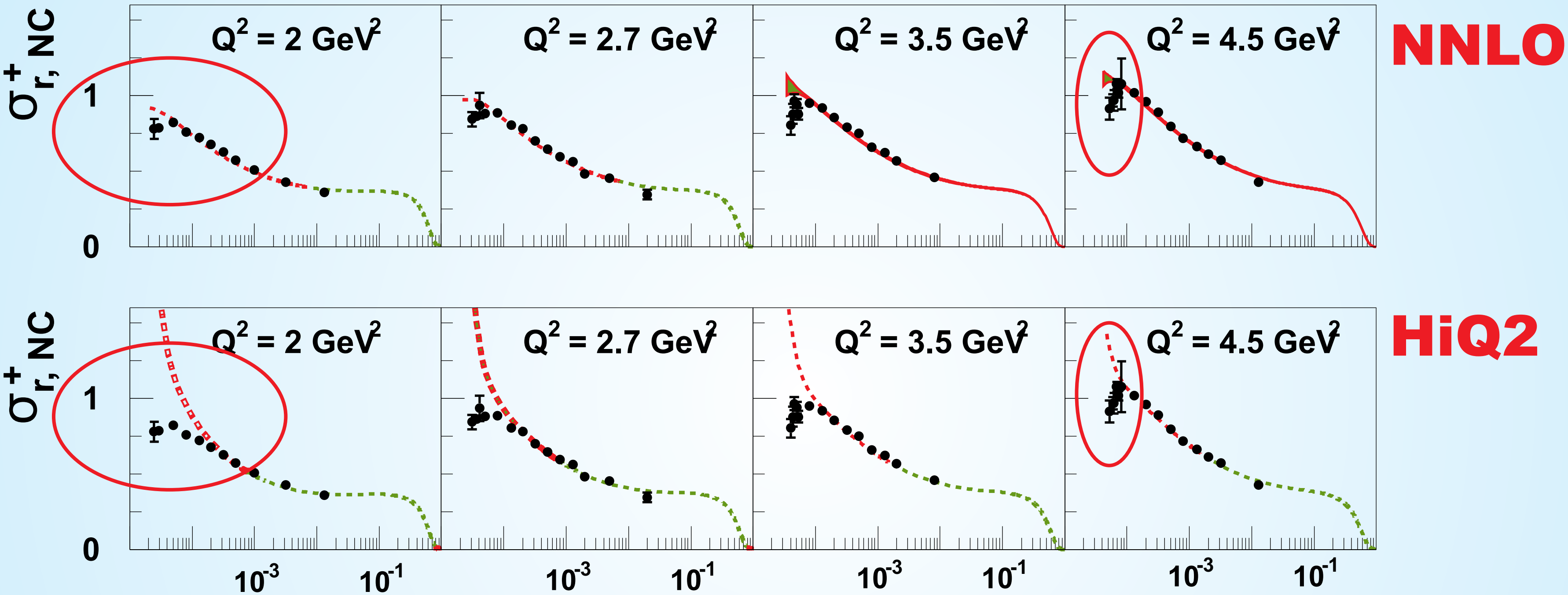




HERAPDF 2.0 NNLO **HERAPDF 2.0 HiQ2**

For all these plots where everything fits, please see desy 15-039

Comparison with data



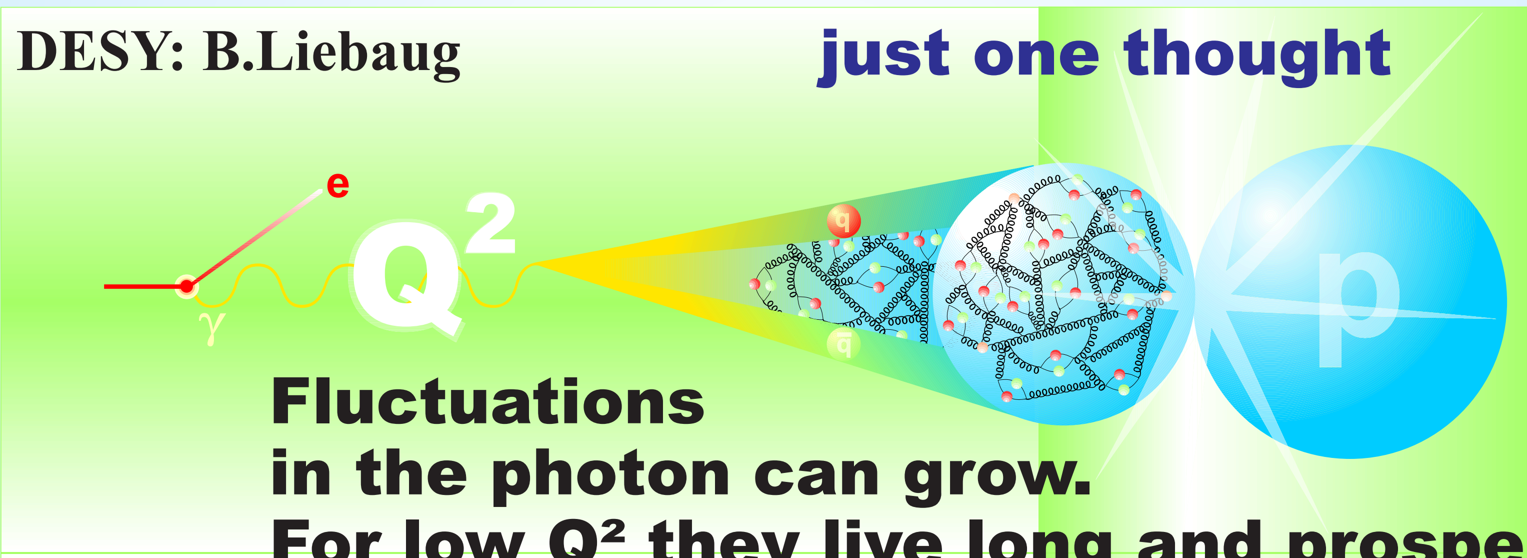
The data show a turn-over, which NNLO does not really get. And HiQ2 evolves much too fast.

Low Q2 is also low x.

Low x Partons in the Proton ?

Heisenberg is strictly against it !

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

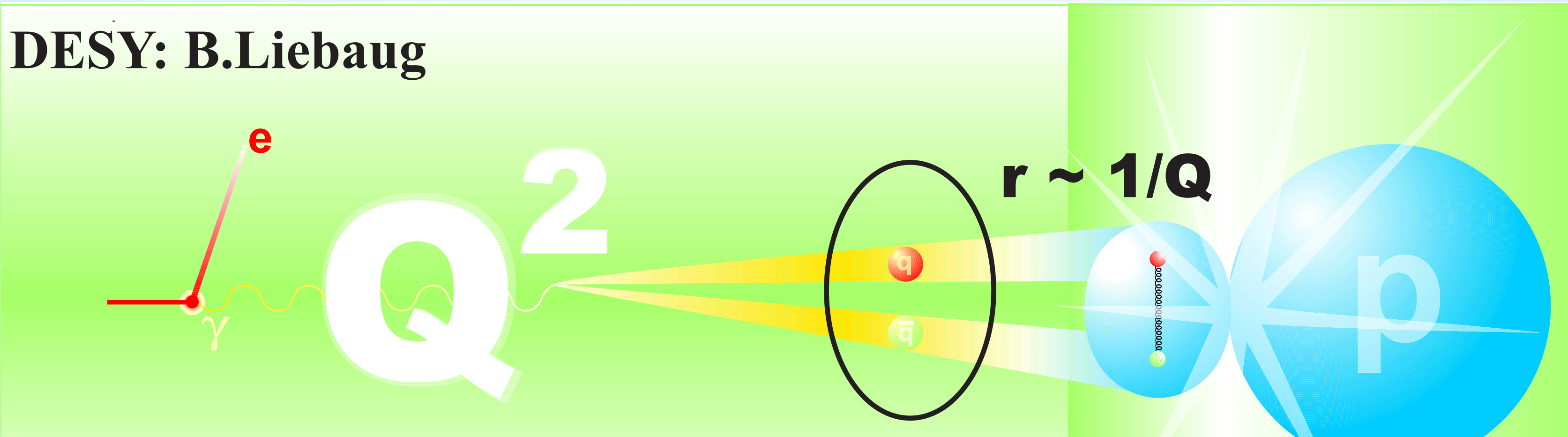


Fluctuations
in the photon can grow.
For low Q^2 they live long and prosper.

There might be more than DGLAP and pQCD.

Color Dipole Model

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

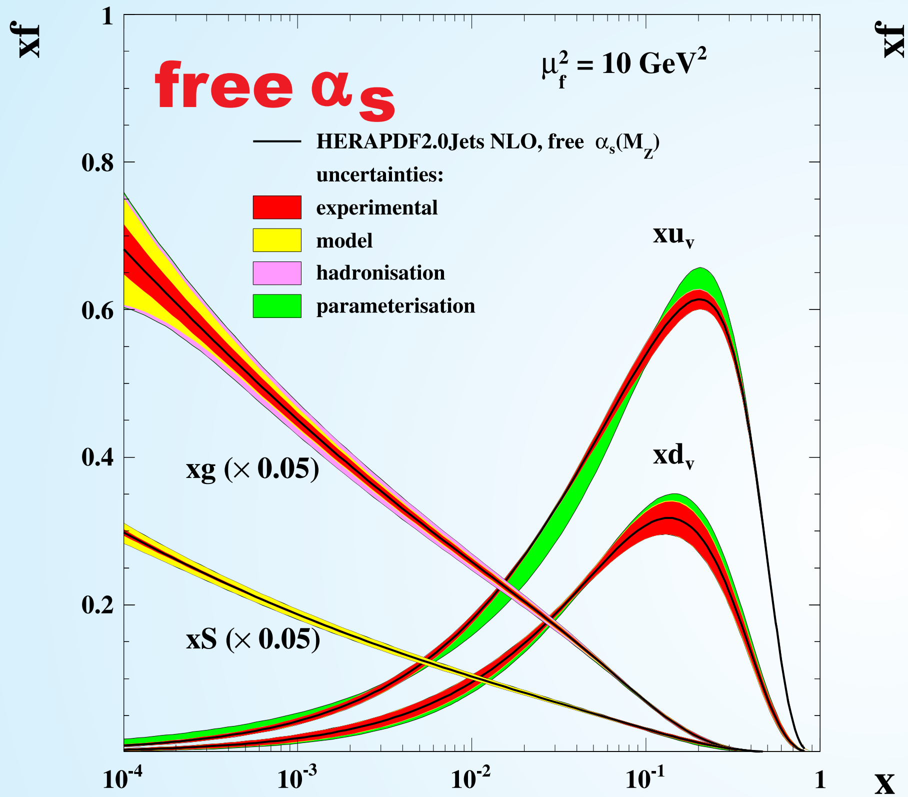


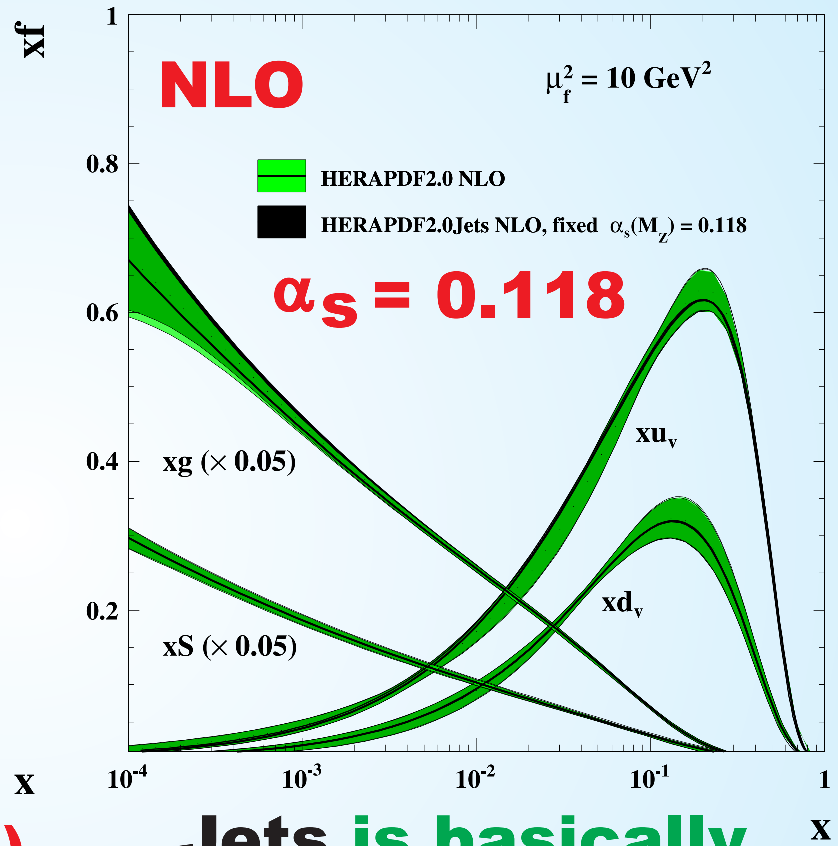
For high Q^2 only a color dipole forms.
No time for more.

About two thirds of the excess in χ^2 come from high Q^2.

Let's see what theoreticians come up with.

HERAPDF 2.0 Jets

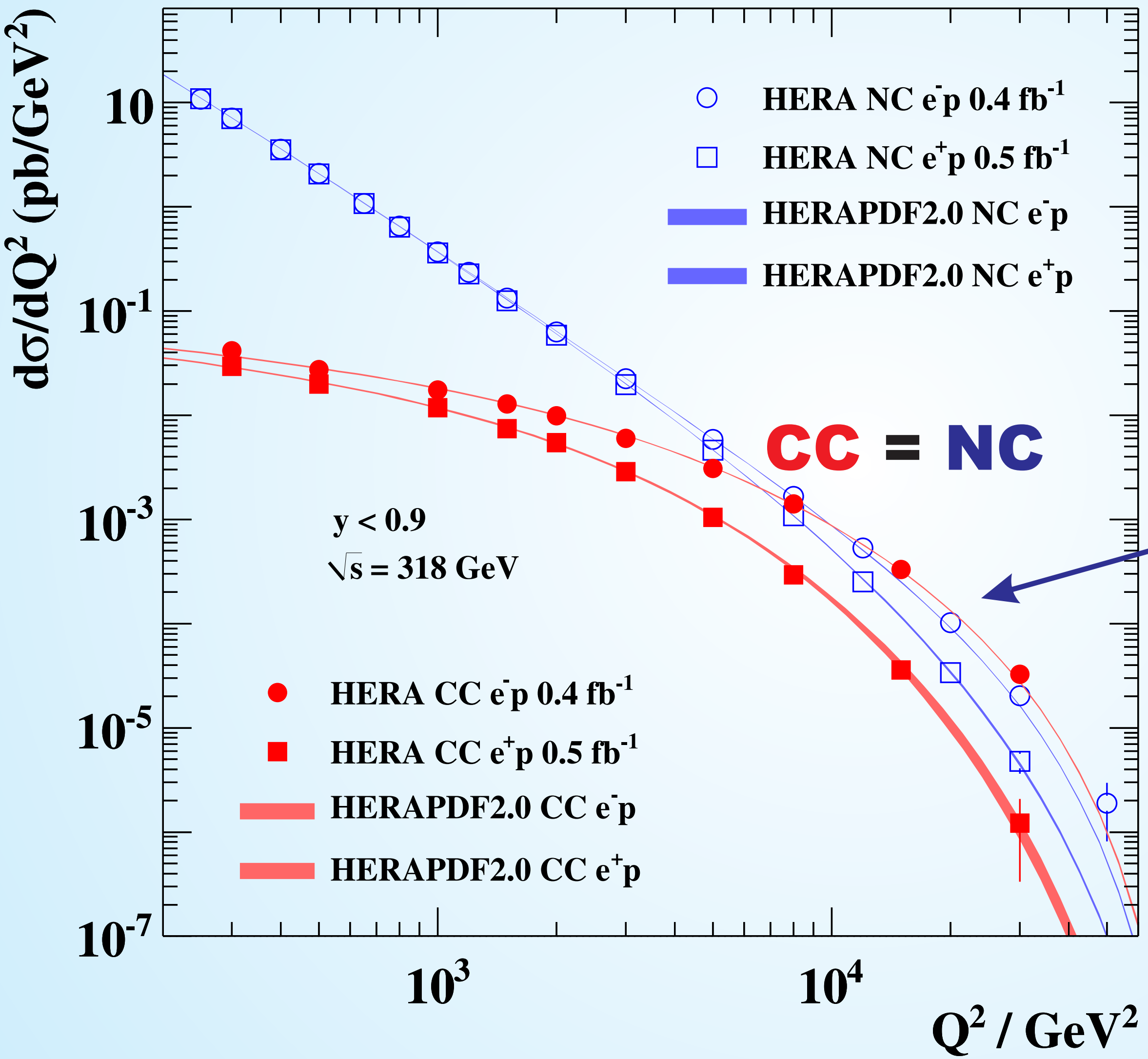




$\alpha_s = 0.1183 \pm 0.0009(\text{exp})$
$\pm\, 0.0005(\text{model/param})$
$\pm\, 0.0012(\text{hadronisation})$
$+\, 0.0037 - 0.0031\ (\text{scale})$

Jets is basically identical to NLO

Precision Cross Sections



high Q^2

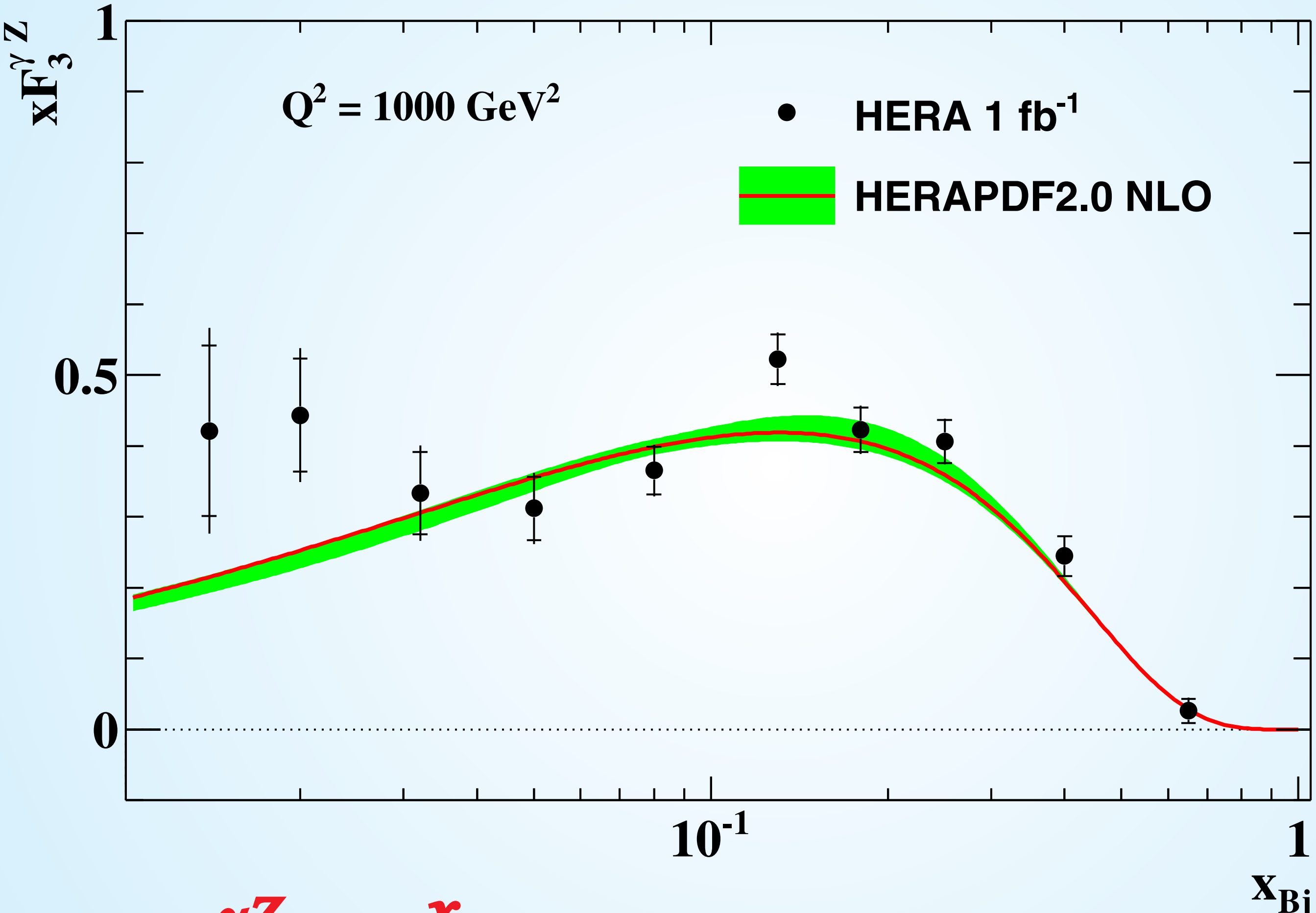
NC

CC

xF_3

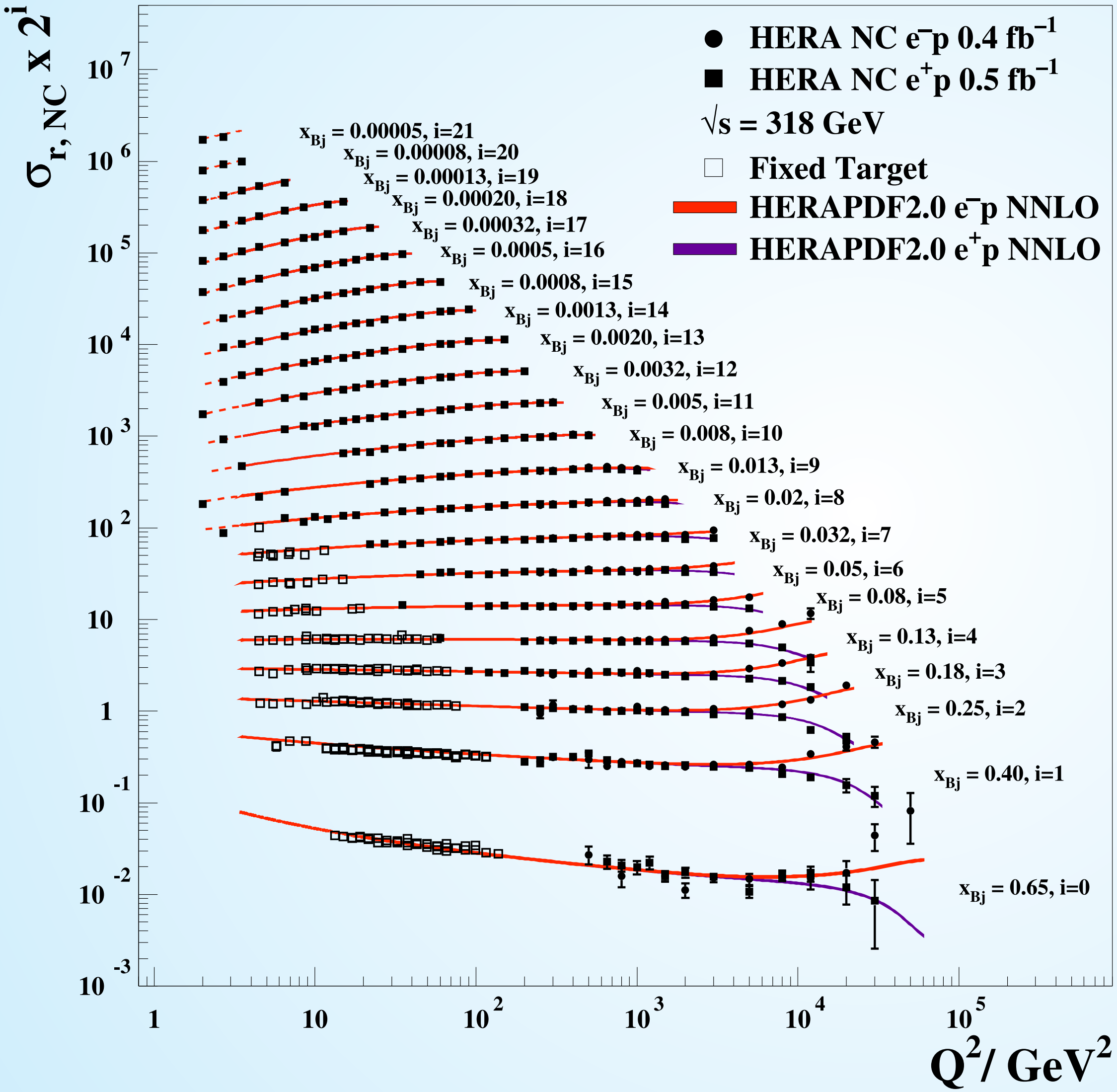
difference between positron and electron data

Valence Quarks



$$xF_3^{\gamma Z} \approx \frac{x}{3}\,[\,2u_V + d_V\,]$$

Precision Cross Sections



HERA electron and positron data and fixed target

Q^2: 2 – 50000 GeV²

x: 0.00005 – 0.65

Outlook

HERA cross sections will hopefully be used by many/all PDF groups.

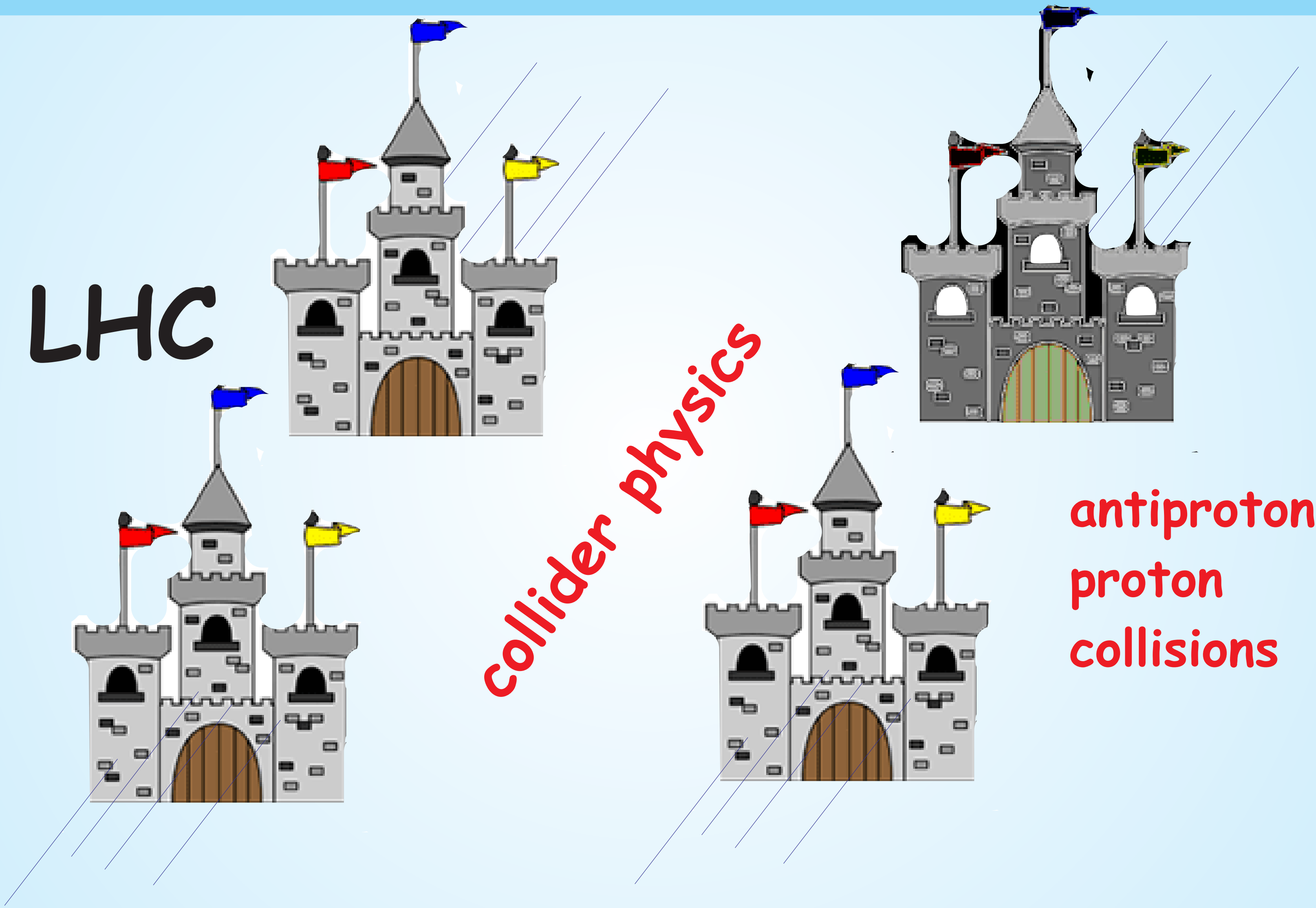
They are probably the legacy of HERA.

HERAPDF2.0 should be useful to compute LHC predictions.

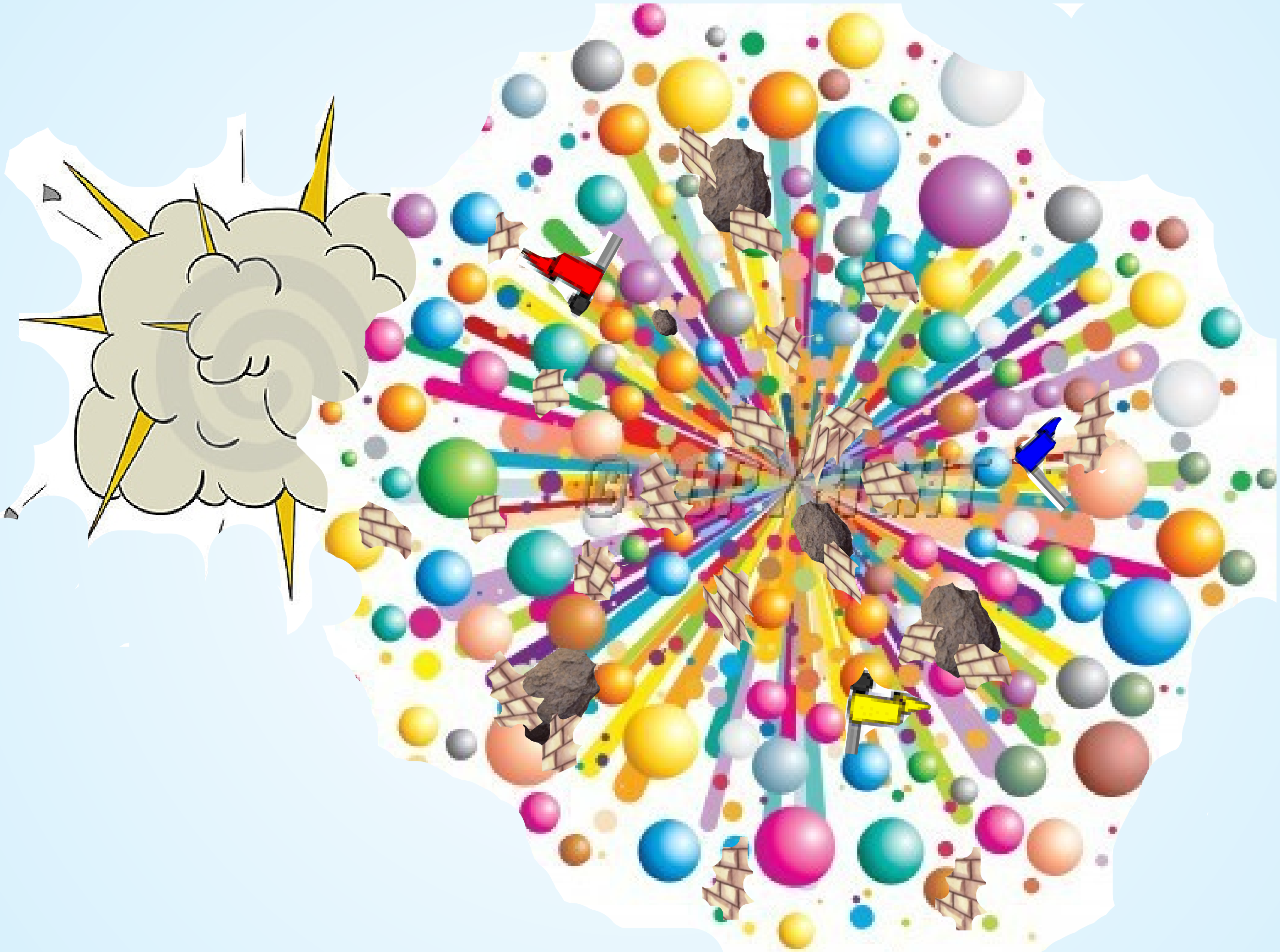
The many variants of HERAPDF2.0 seem to indicate that something is going on beyond DGLAP.

PROSA was founded to find out what.

Castle Castle Interactions



Beautiful Destruction



Outlook

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They are probably the legacy of HERA.

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The future (PROSA, more data) will reveal what.