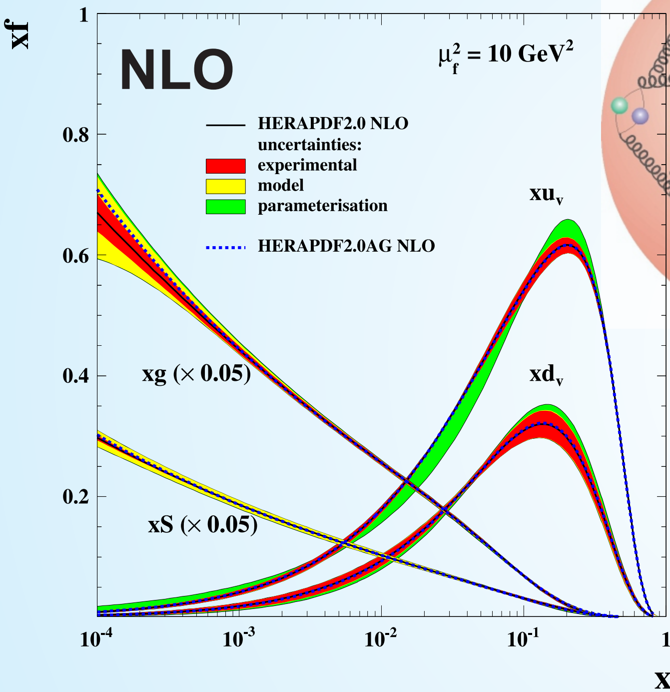
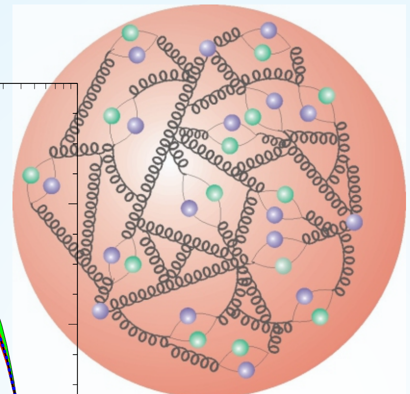
What do we really know about the proton?





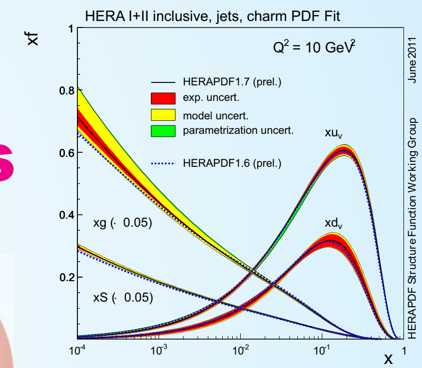
& what HERA told us x

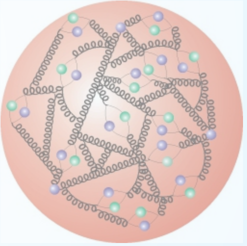
I.Abt, MPI München

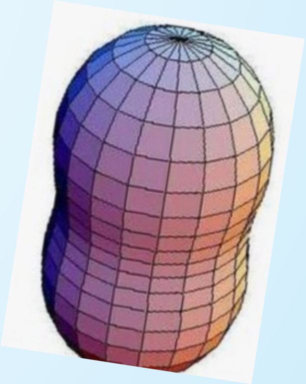
Taipeh, May 2023

Content

- Protonic Facts
- Structure and Structure Functions
  - Deep Inelastic Scattering
  - Parton Distribution Functions
  - Valence Quarks
  - Glue
- Non-perturbative regime
  - photons and color dipoles
- Proton Size and Shape
- Summary & Outlook







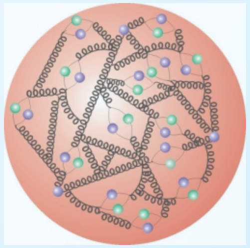
Protonic Facts

My Apologies

I really know very little about the proton:

- **mass = 1GeV = 1.67 $\cdot$ 10^{-27} kg**
- **has substructure**
- **3 valence quarks**
- **charge = +1**
- **spin = 1/2**
- **radius ≈ 1 fm; shape?**
- **lifetime » age of the universe**
- **confines it partons**

I have no real explanation for any of this!

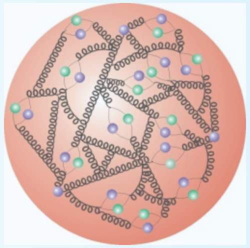


Learning about the Proton

How did we learn that the proton has substructure?

We shot electrons at the proton and measured the cross sections

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



Factorisation

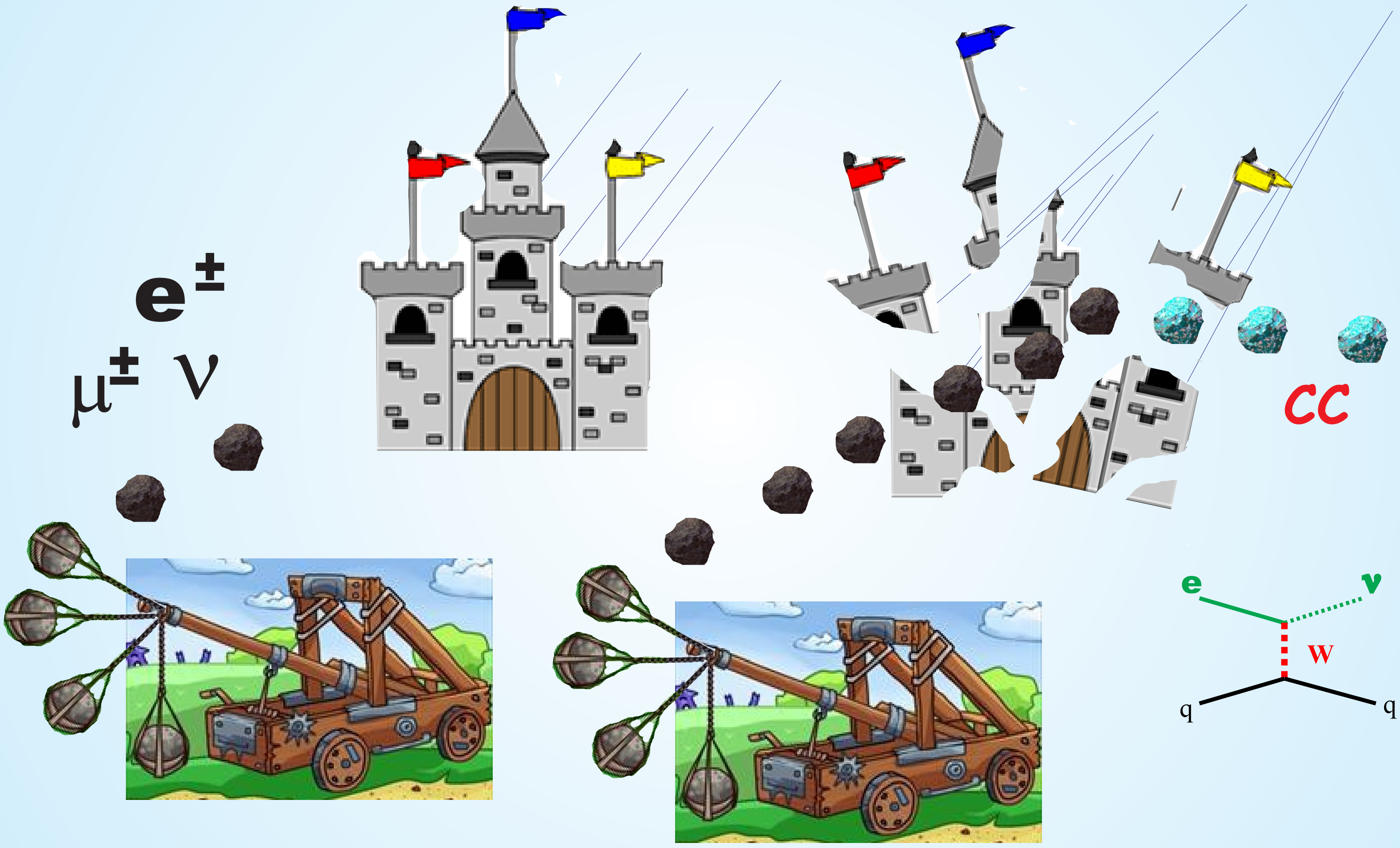
$$\sigma(ep \rightarrow e + X) = \sum_{j,j'=q,\bar{q},g} f_{j/p}(x,Q) \otimes \hat{\sigma}_{jj'}(x,Q,z) \otimes F_{H/j'}(z,Q)$$

parton distribution functions — **PDFs**

partonic cross sections

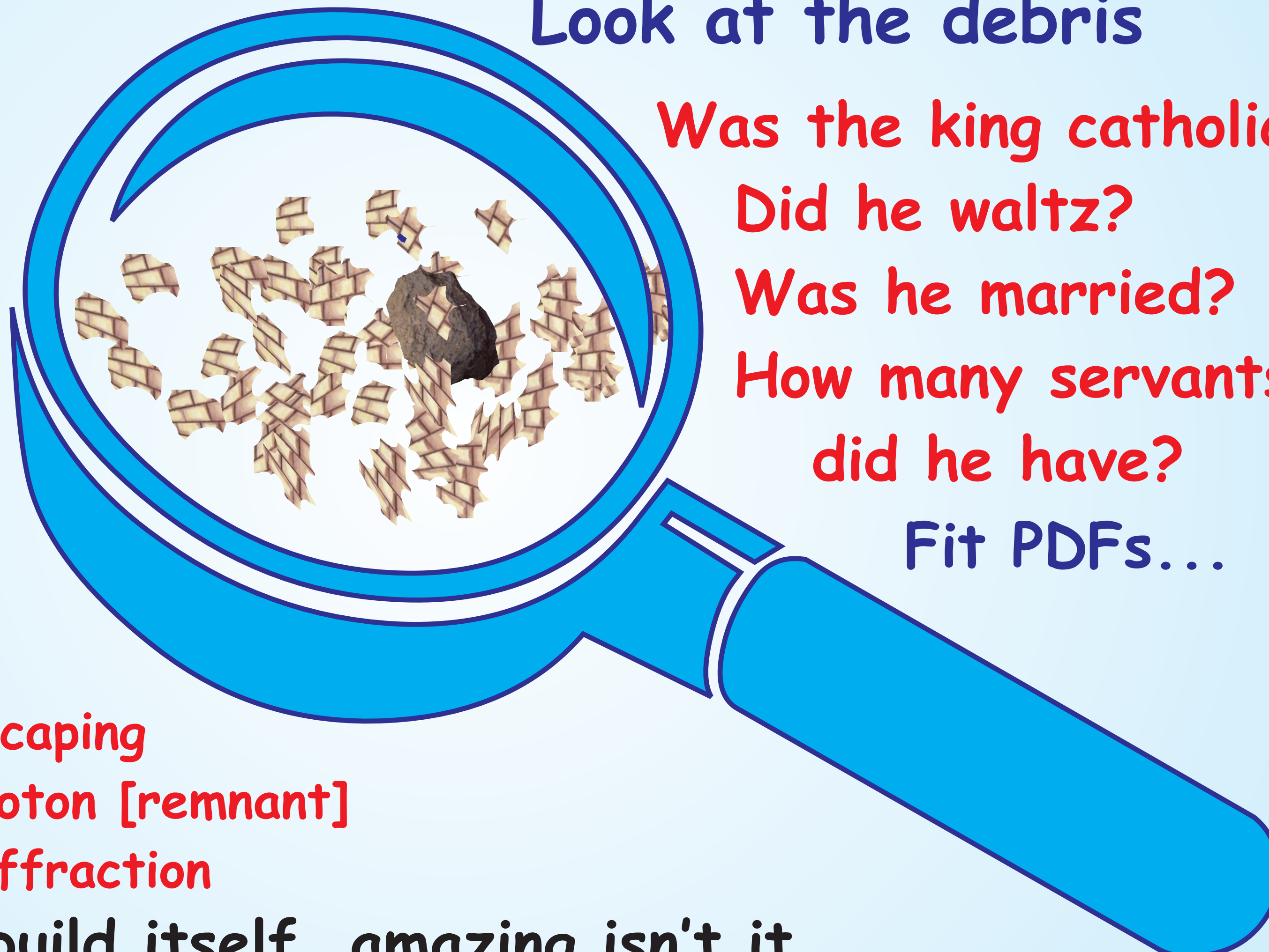
hadronisation

Deep Inelastic Scattering



Deep Inelastic Scattering

Look at the debris



Was the king catholic?

Did he waltz?

Was he married?

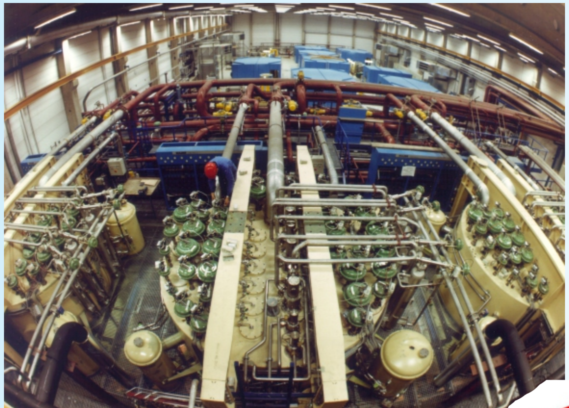
How many servants did he have?

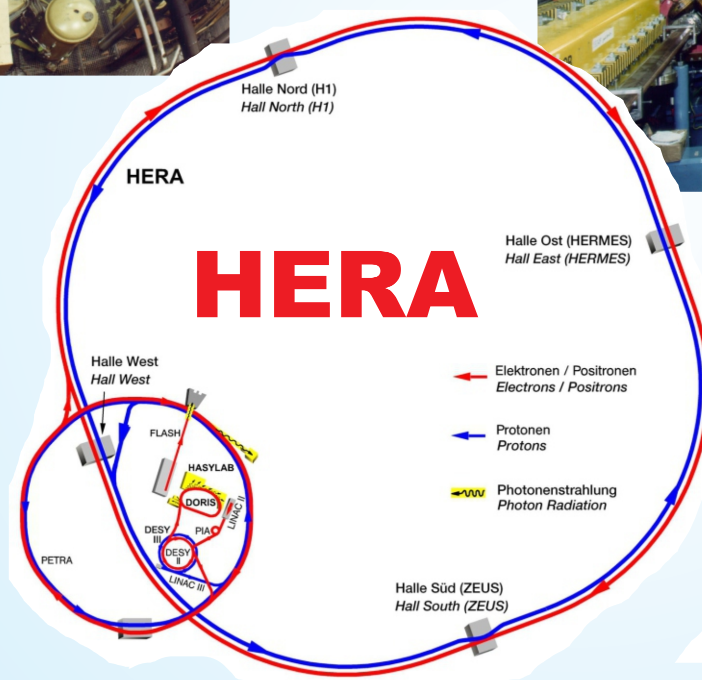
Fit PDFs...

Escaping proton [remnant] Diffraction

This can rebuild itself, amazing isn't it.

HERA, the only ep collider





24.5.1993

until

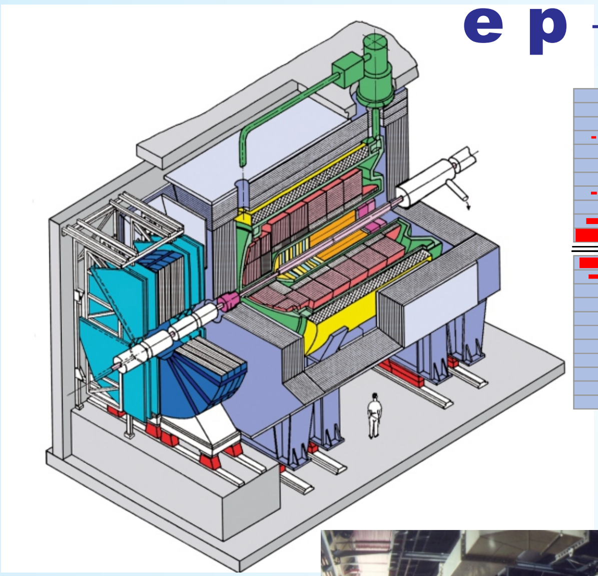
30.6.2007

legacy

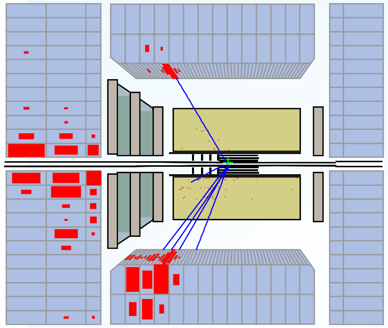
data ==> analysis ongoing

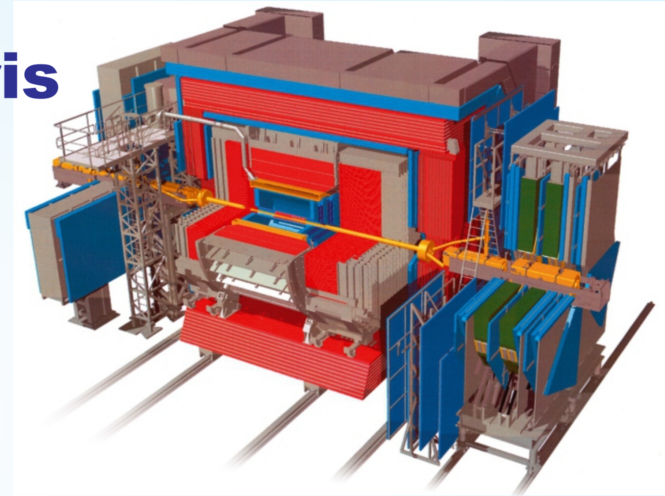
The Microscope

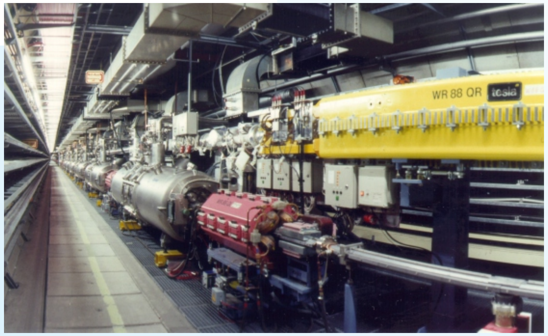
That is what we measure!



e p → e (ν) debris







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

→ **kinematic variables**

Kinematics

Momentum Transfer $Q^2 = -(k - k')^2$ **(Virtuality)**

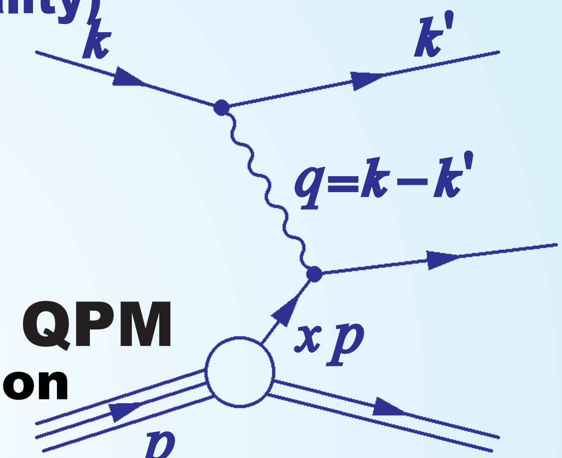
Spatial resolution of probe

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

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

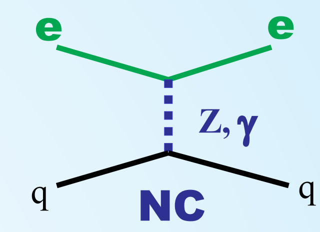
$$y_e = 1 - \frac{E'_e(1 - \cos\theta_e)}{2E_e} \qquad Q^2_e = \frac{{E'_e}^2 \sin^2\theta_e}{1 - y_e} \qquad x_e = \frac{Q^2_e}{4E_pE_ey_e}$$

Measure energies and angles

Structure Functions

$e^{\pm}p$

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



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

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

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 $\tilde{F}_L = 0$

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

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

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

sea: quark=antiquark

$xu_v = xU - x\overline{U}$ $\quad$ $xd_v = xD - x\overline{D}$

valence quarks

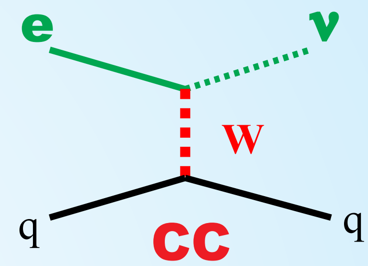
quantum numbers

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 to measure.

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

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

NC plus CC yield valence and sea quark distribution.

QCD analysis [DGLAP] yields gluon distribution.

F_L [gluons] was also measured.

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

$0.045 < Q^2 < 50000$ GeV^2

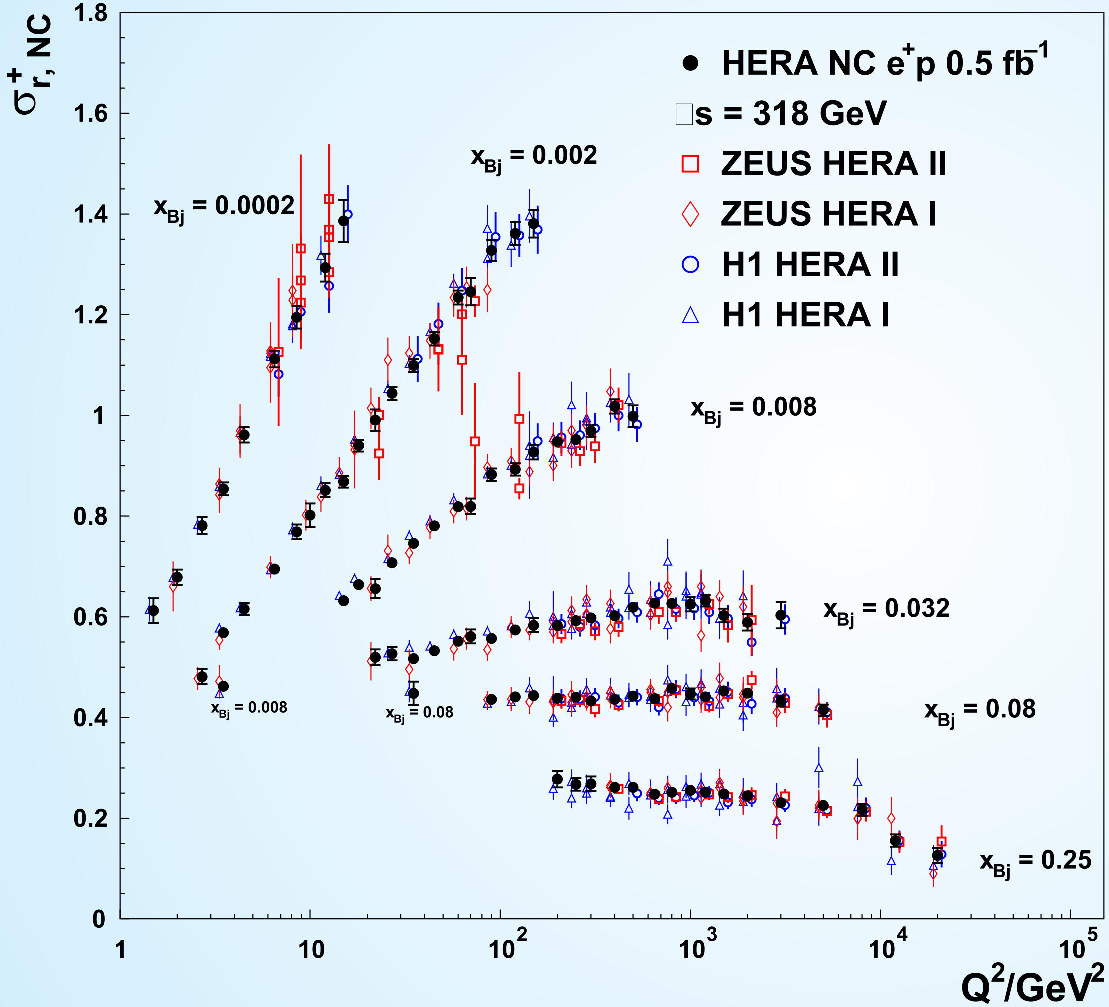
$6\ 10^{-7} < x < 0.65$

2927 $\rightarrow$ 1307 points

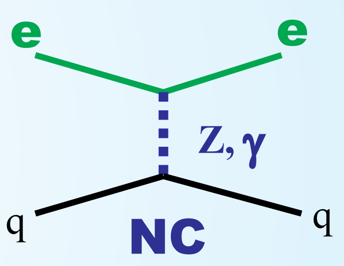
DESY 15-039

EPJ C 75(12) 1-98

HERA cross sections



Example:
NC
cross sections



Legacy
Data
even after EIC

HERAPDF 2.0

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

HERAPDF2.0 NNLO NLO LO*

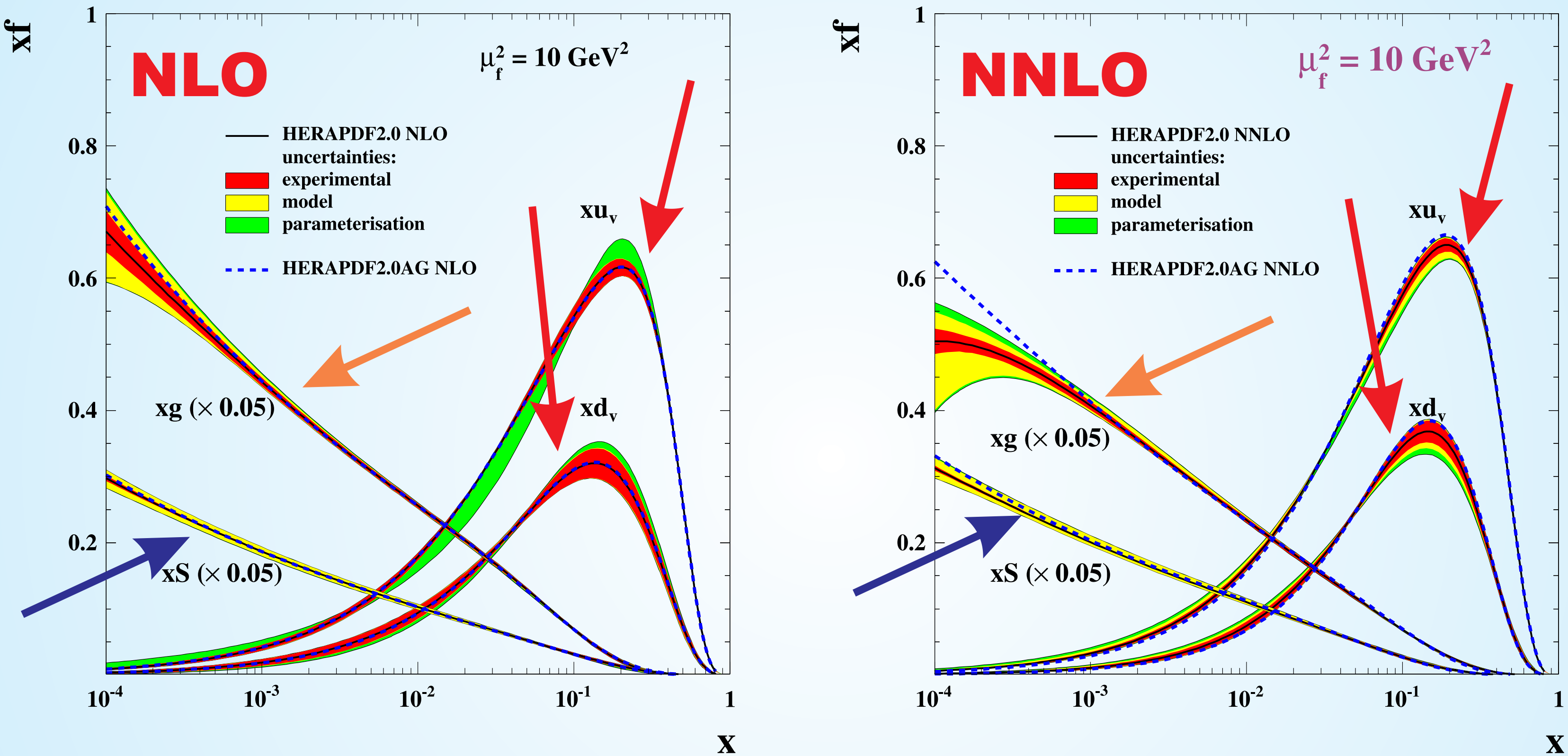
Hera likes a good fit!

The resulting PDFs depend on the order of the QCD calculation.

But the proton does not know about our calculations.

***For details, see EPJ C 75(12) 1-98 App. 1&2.**

HERAPDF 2.0

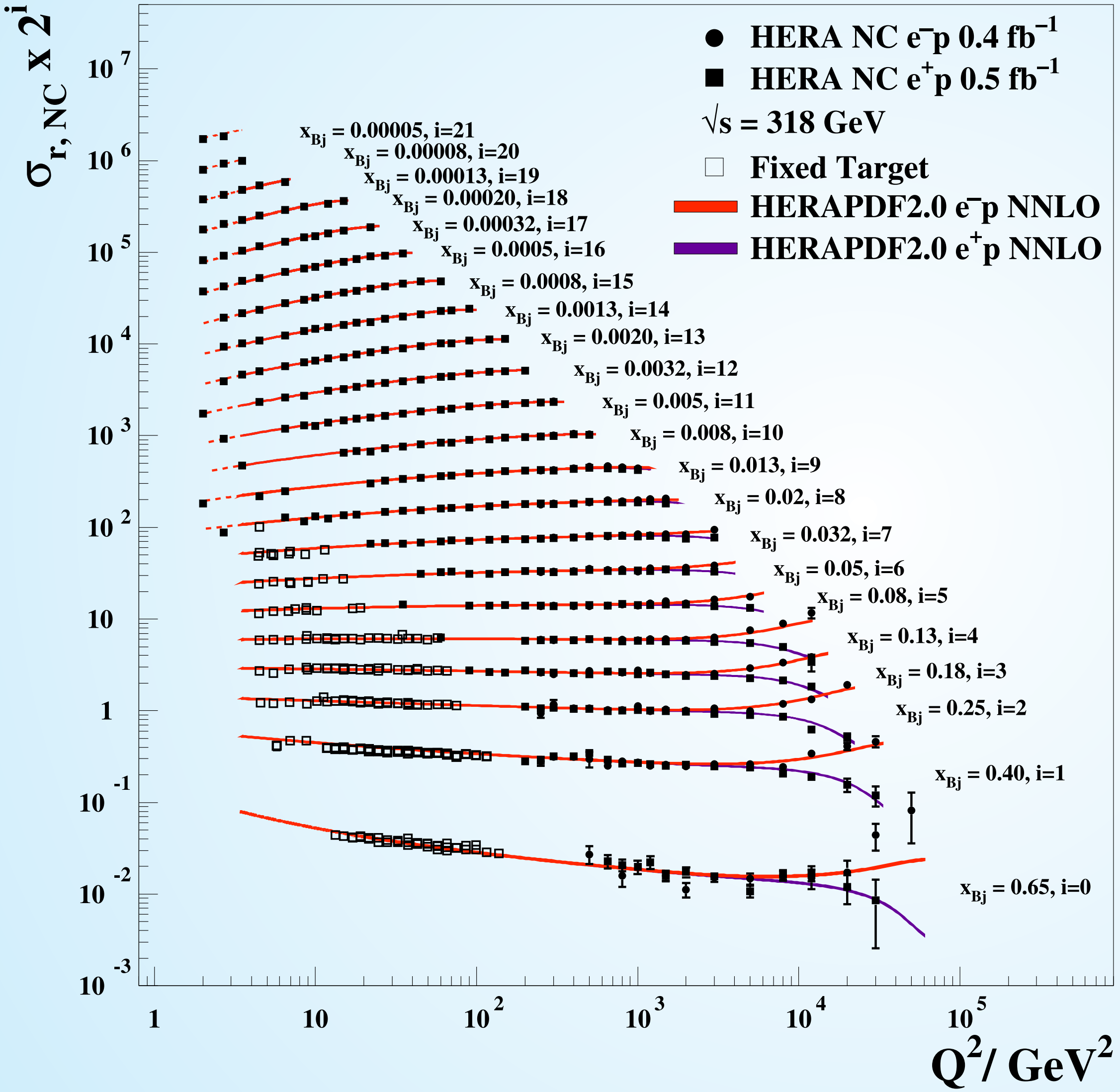


The valence and sea quarks are fitted.

The glue is what pQCD puts in – order dependent,

scale dependent ($\mu_f^2 = 10$ GeV^2).

Precision Cross Sections



HERA electron and positron data

HERAPDF2.0 NNLO

good predictions for fixed target data

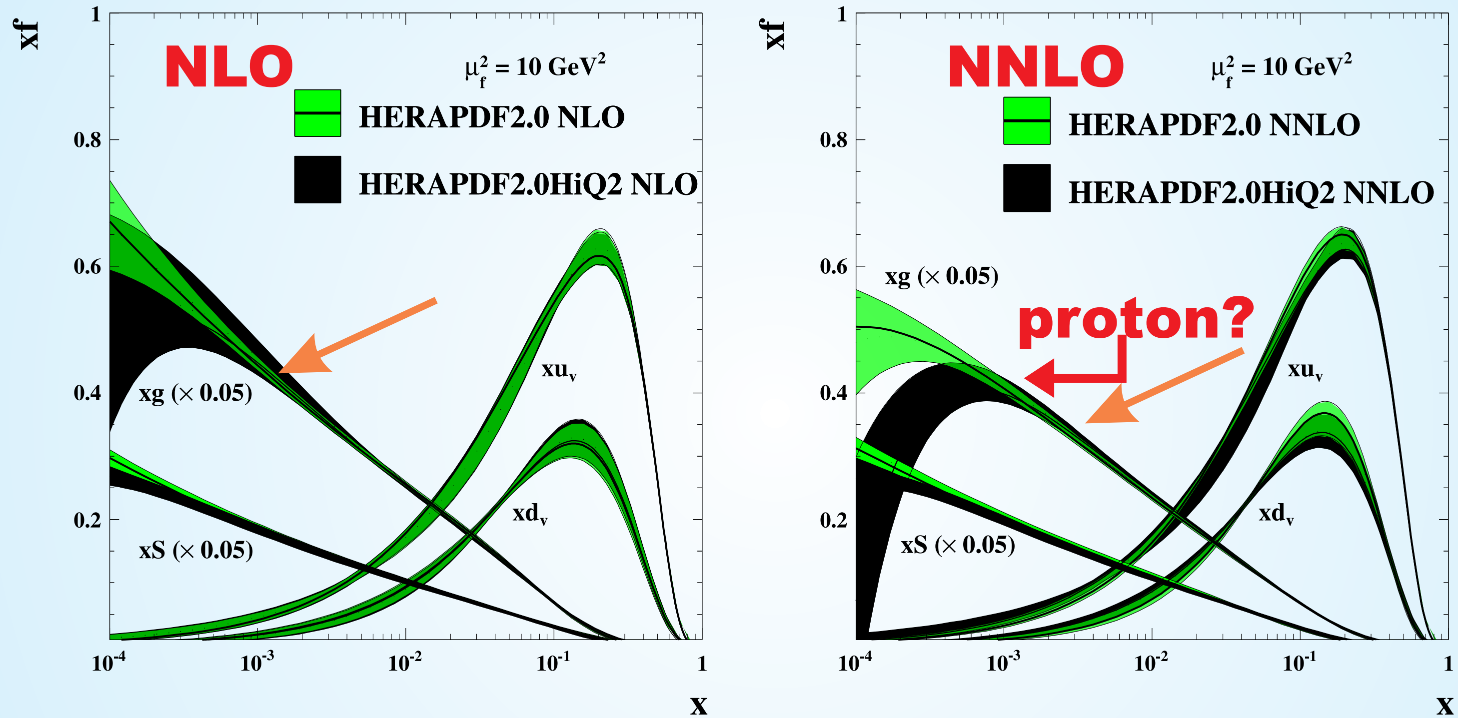
Q^2: 2 – 50000 GeV²

x: 0.00005 – 0.65

all done ?

HERAPDF 2.0 HiQ2

The $Q^2 > 10^2$ GeV² **HERAPDF2.0** at a scale of $\mu_f^2 = 10$ GeV²



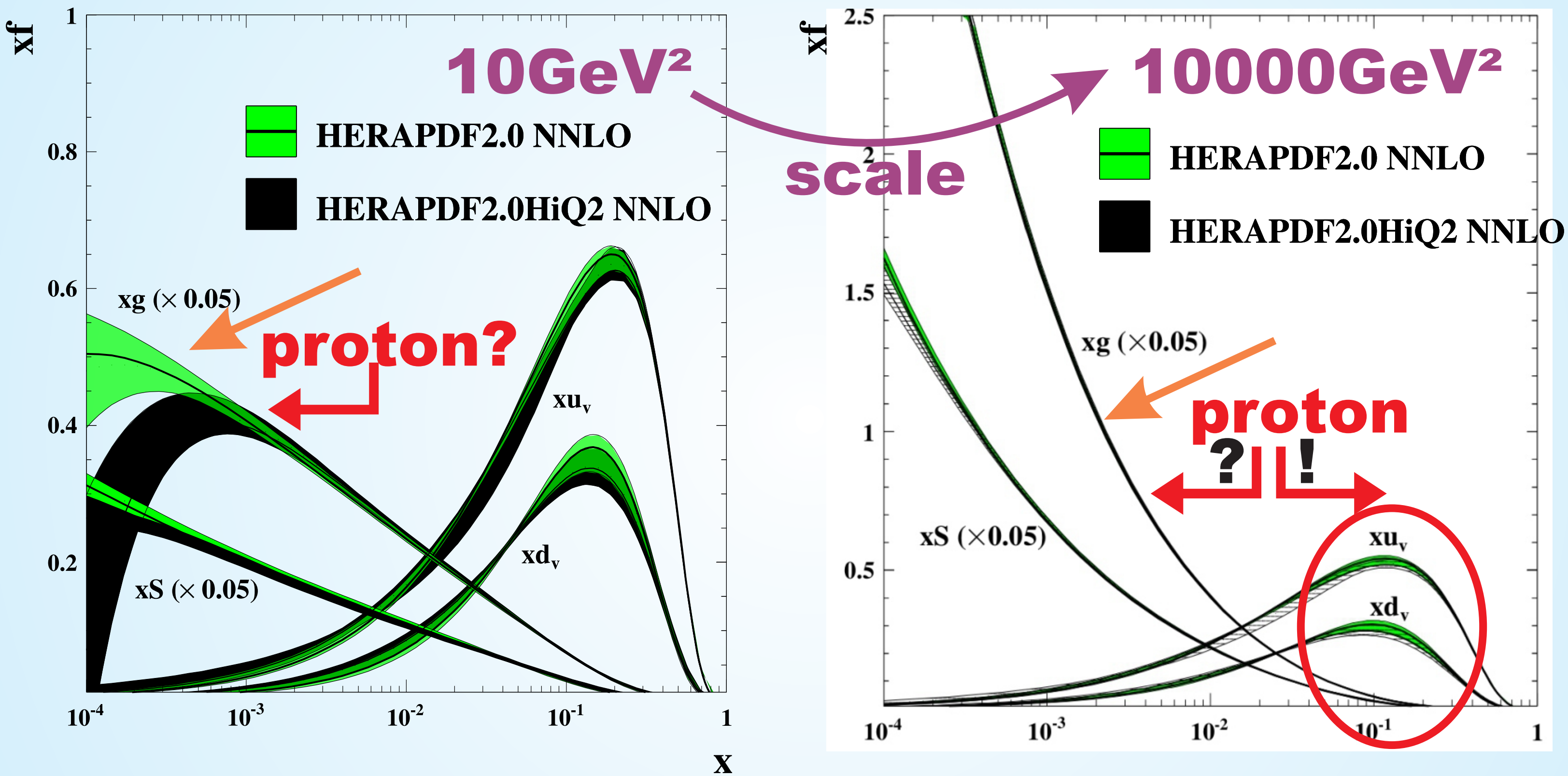
Restrict data to more perturbative region

The valence and sea quarks stay about the same.

The glue changes dramatically – negative glue ?

HERAPDF 2.0 HiQ2

The $Q^2 > 10^2$ GeV² HERAPDF2.0 at a scale of $Q^2 = \mu_f^2 =$

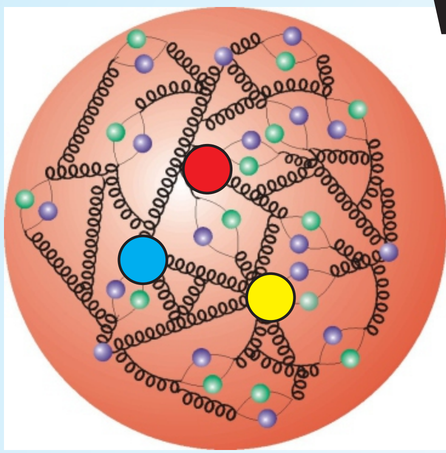


The **valence** quarks **stay about the same.**

The **glue changes dramatically** – exploding glue ?

→ **sea**

PDFs and the Proton



What have all these structure functions and PDFs to do with the proton?

PDFs do not describe the proton beyond perhaps the valence quarks, not even in momentum space.

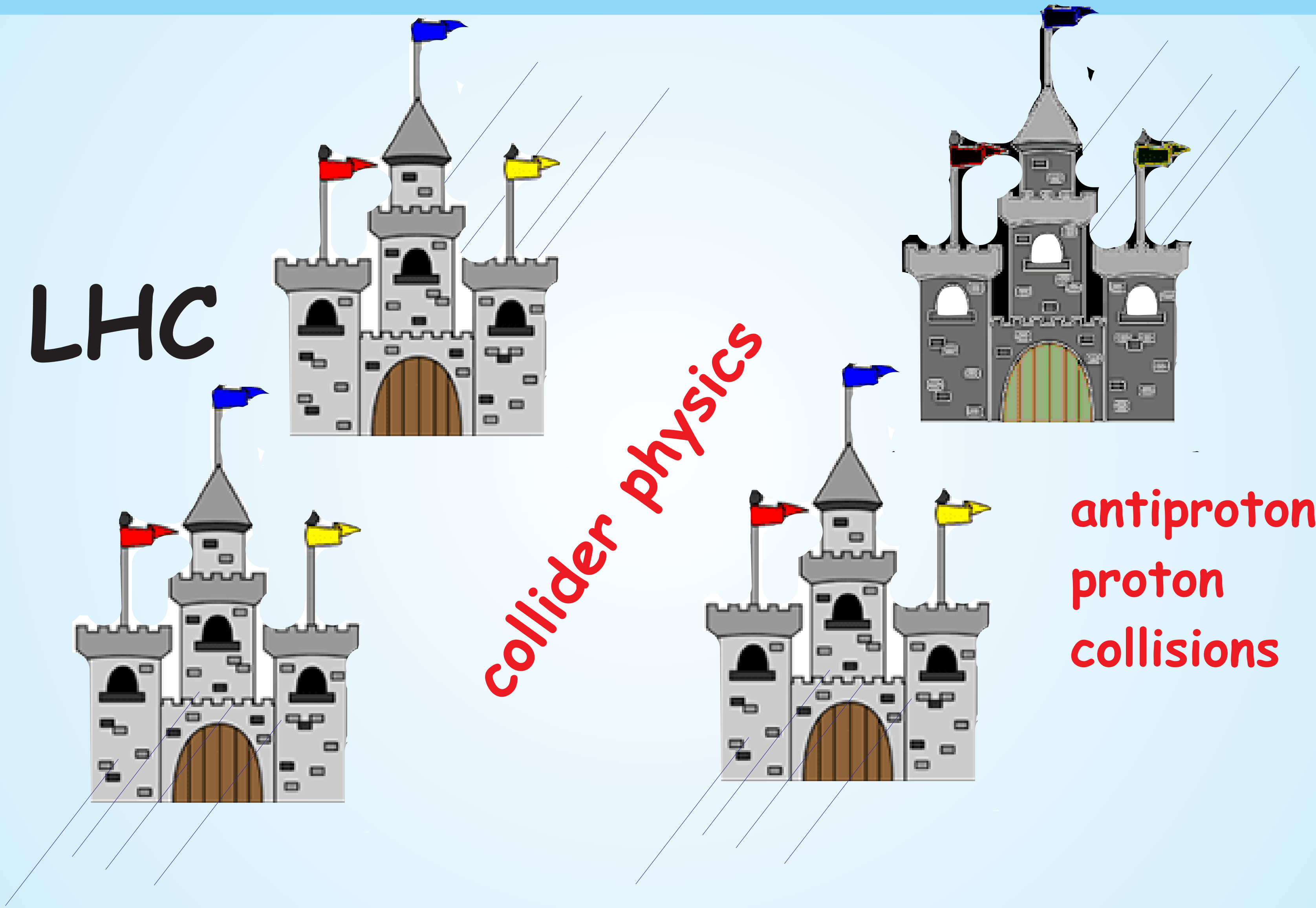
PDFs are a way to store cross sections and make it possible to make predictions for other processes.

Using PDF needs care!

There are many other PDF sets: NNPDF, MMHT, CTEQ...

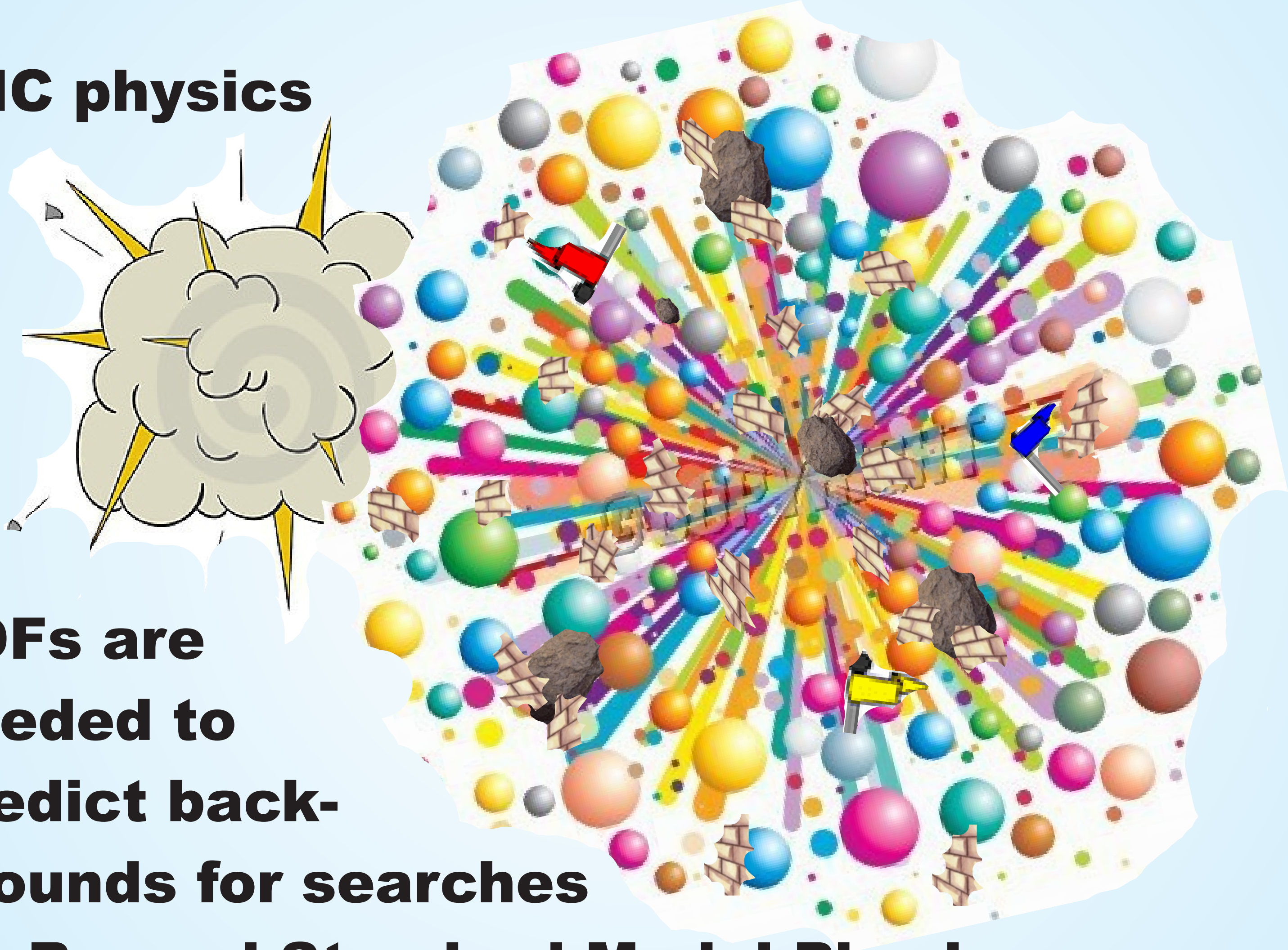
→ have a look at pp

Castle Castle Interactions



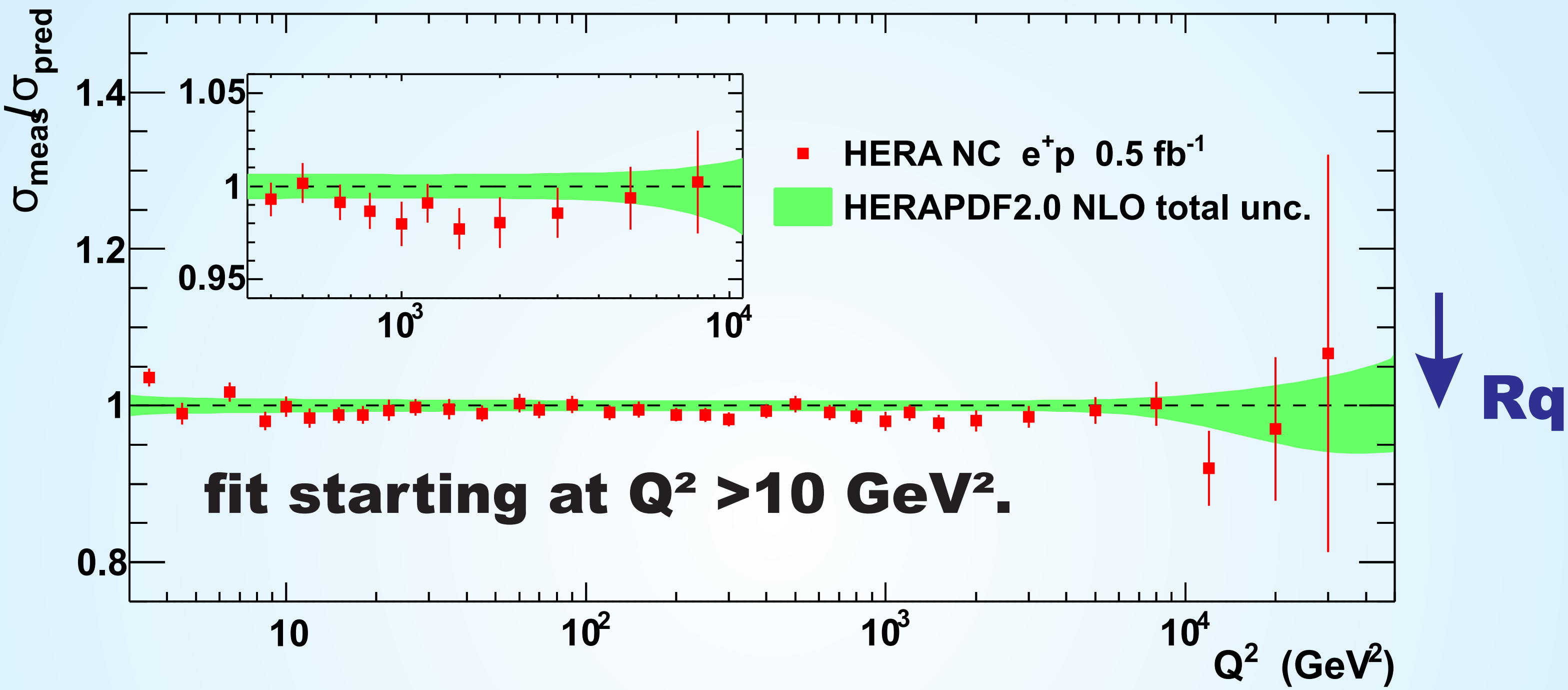
Beautiful Destruction

LHC physics



PDFs are needed to predict back-grounds for searches for Beyond Standard Model Physics

HERA also has BSM potential



e^+ plus e^- Quark Radius < 0.43 10^{-16} cm

Phys. Lett. B 757 (2016) 448

Leptoquarks & Contact Intractions

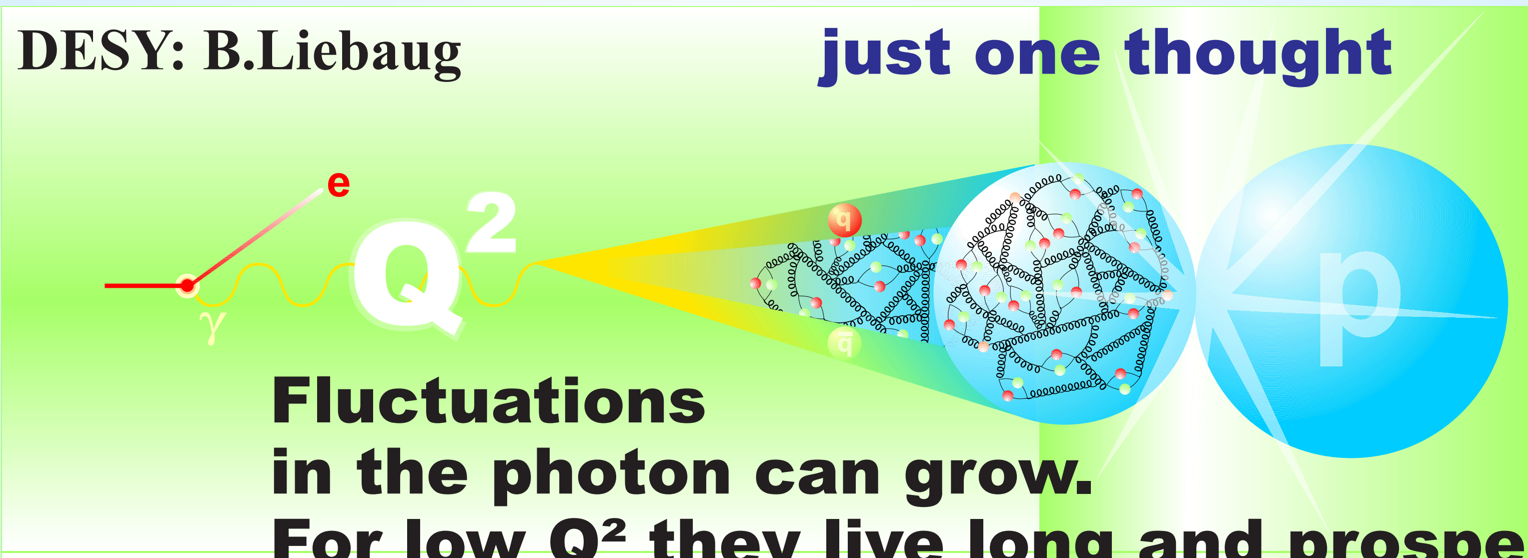
Phys. Rev. D 99 (2019) 092006

No BSM without knowledge about Proton & QCD

Low x Partons in the Proton ?

Heisenberg is strictly against it !

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



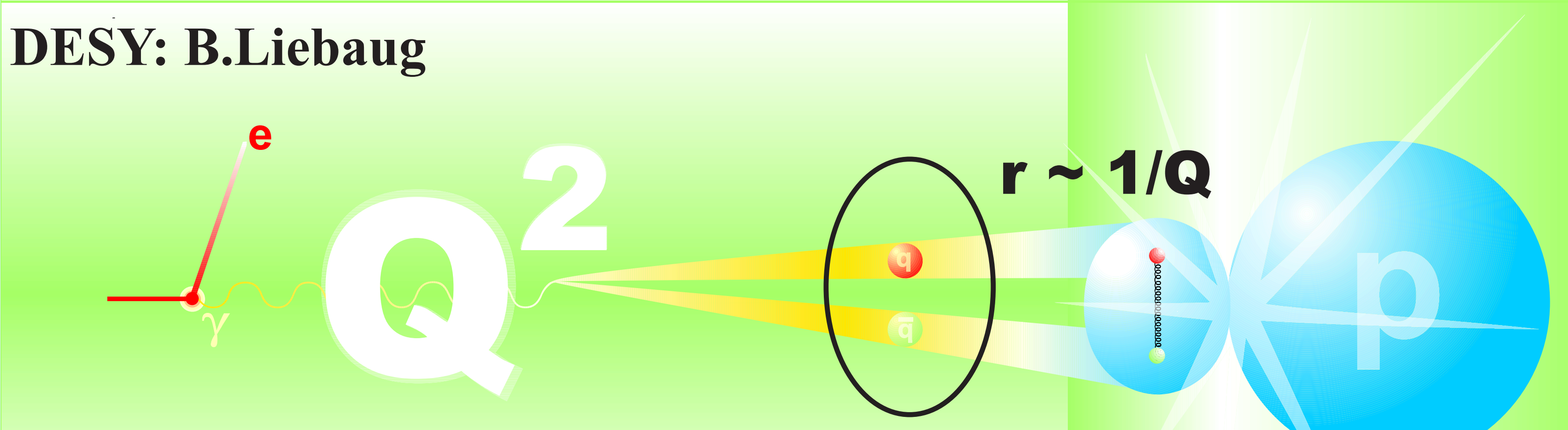
Fluctuations in the photon can grow.
For low Q^2 they live long and prosper.

The structure can also be in the photon.

There has to be more than DGLAP and pQCD.

Color Dipole Model

Coherence length: l [fm] ≈ 0.1/x

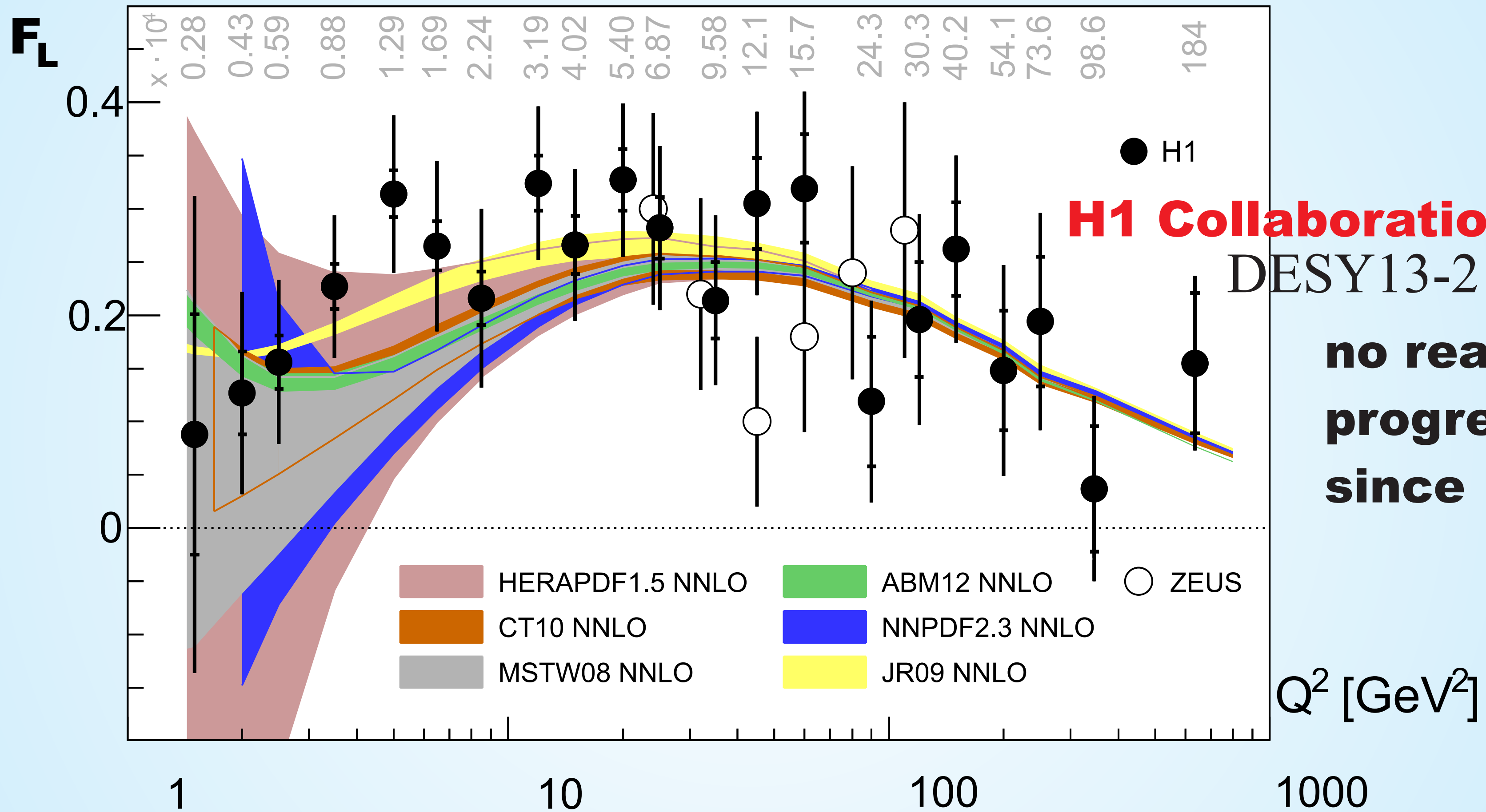


For high Q^2 only a color dipole forms.
No time for more.

Can this be tested ?

In principle, yes ! **Look at the gluons, F_L.**

Longitudinal Structure Function



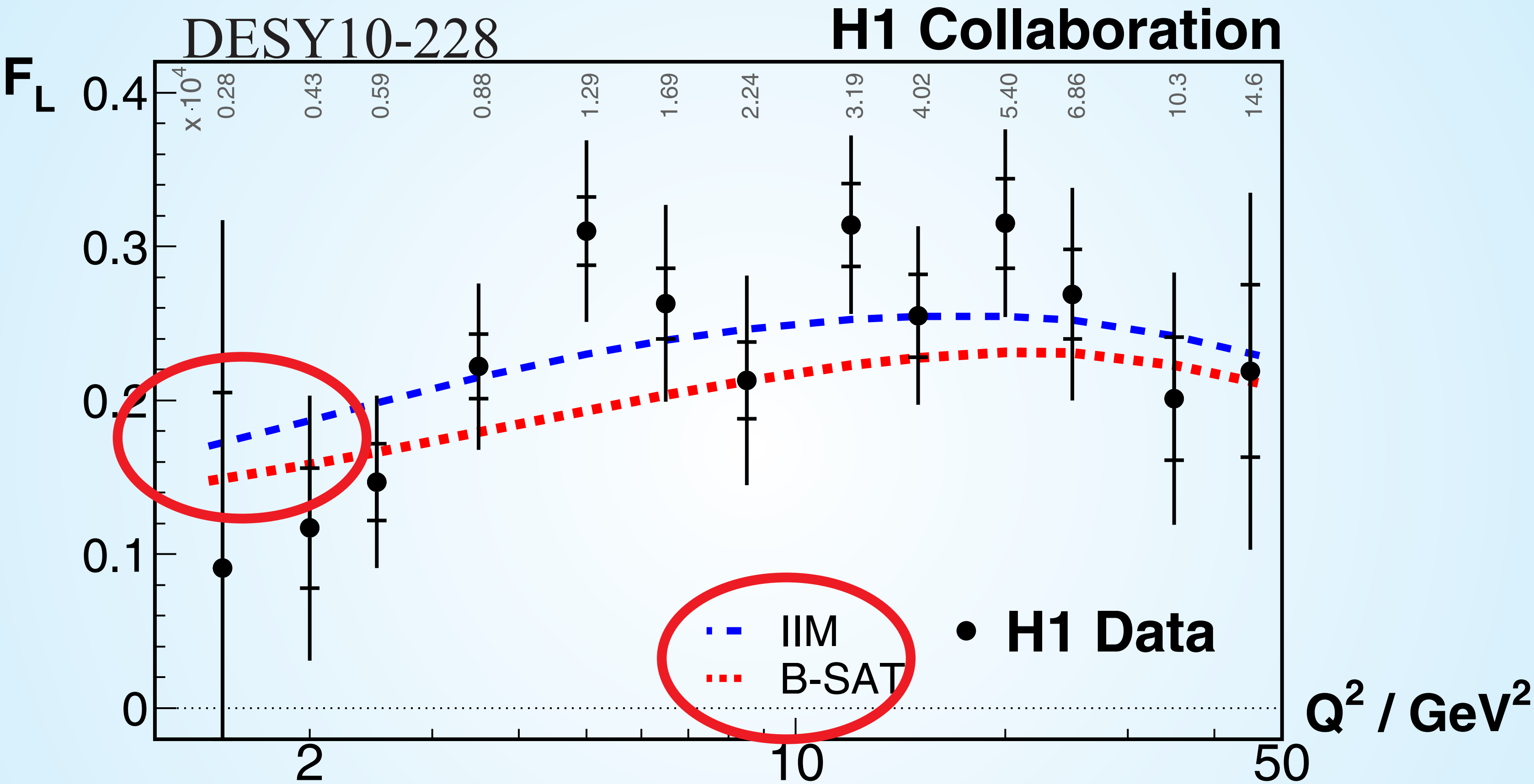
H1 Collaboration

DESY13-211

no real progress since

In practice, it is difficult to measure at low Q^2, and pQCD cannot predict precisely.

Longitudinal Structure Function



However:

Color dipole models also describe the data.

Data are simple

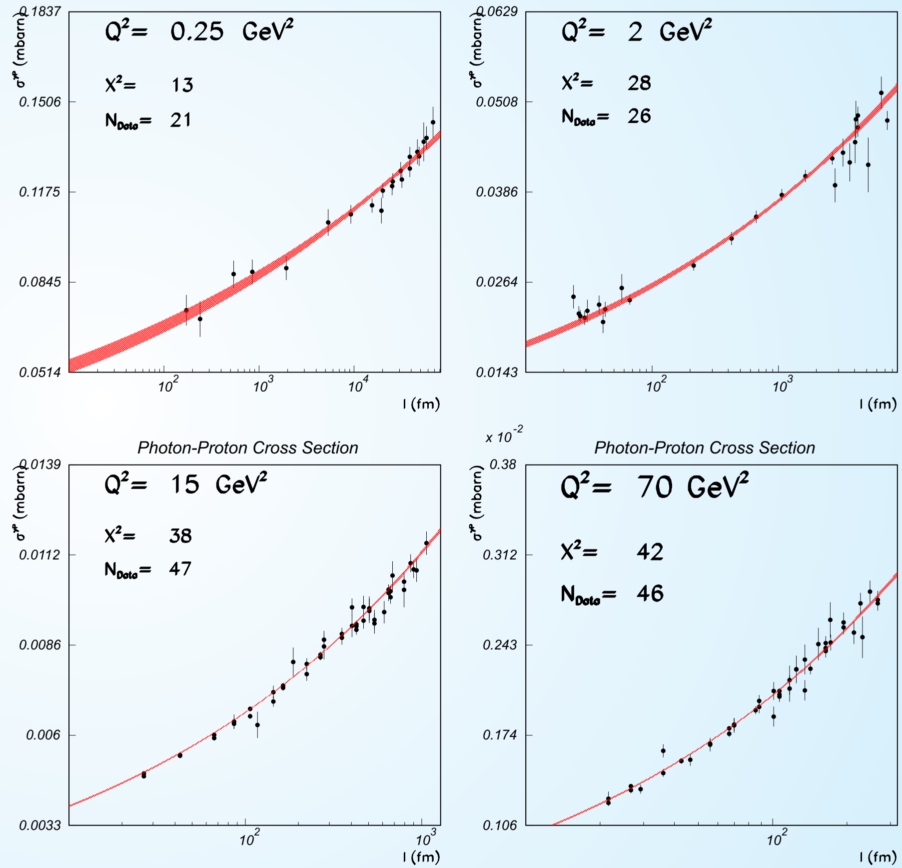
The dipole models is reasonably simple.

$$\sigma(l,Q^2) = \sigma_1(Q^2)\left(\frac{l}{1\text{fm}}\right)^{\lambda_{eff}(Q^2)}$$

It works with a coherence length and does quite well.

Works below the perturbative regime!

photon proton cross secton



New Journal of physics, Vol 18, July 2016

The proton and the perturbation regime

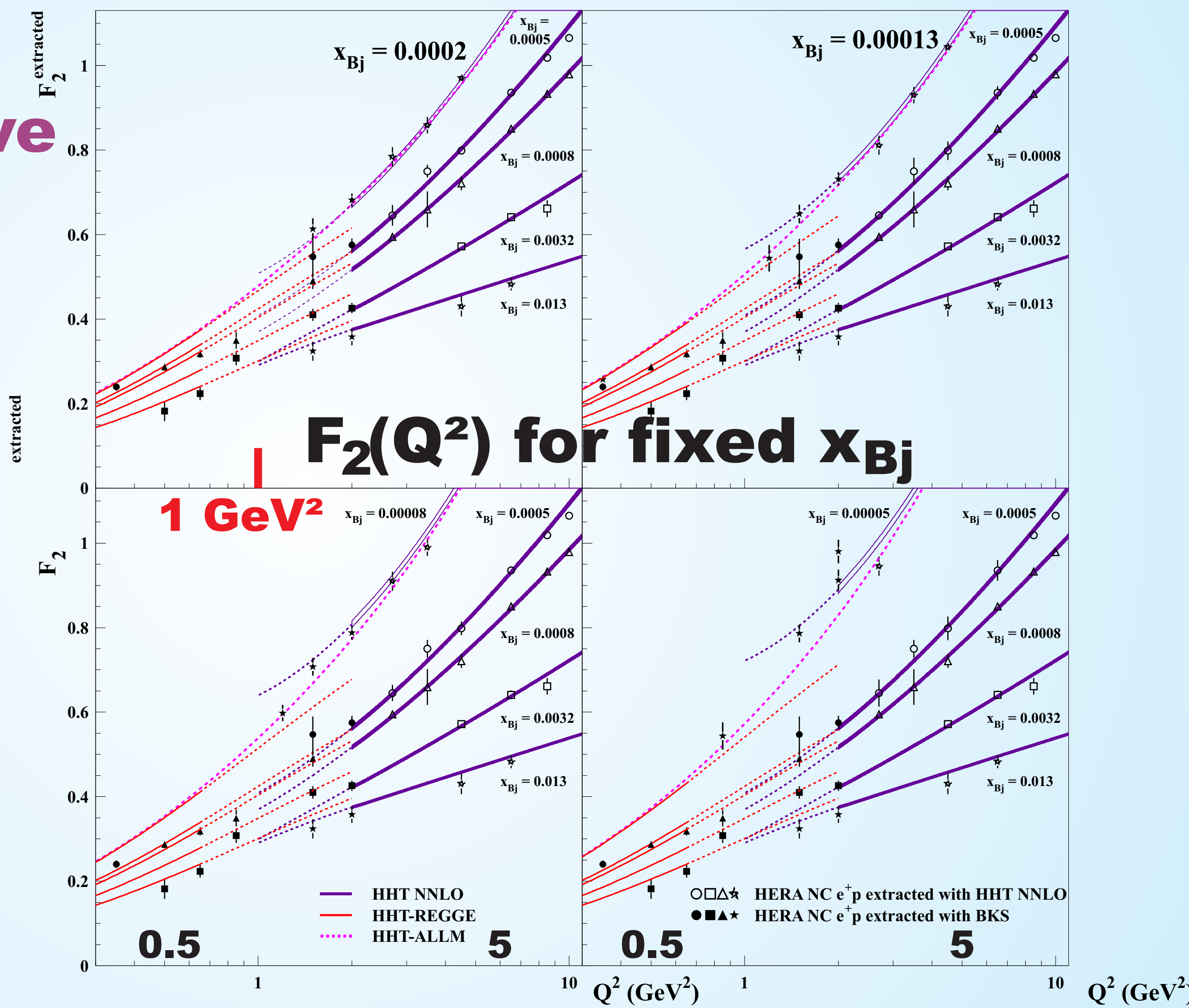
Look at the non-perturbative regime.

DGLAP

+ REGGE

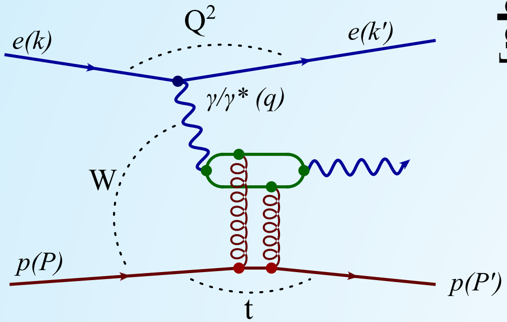
ALLM

The data show no break, only the theories change.

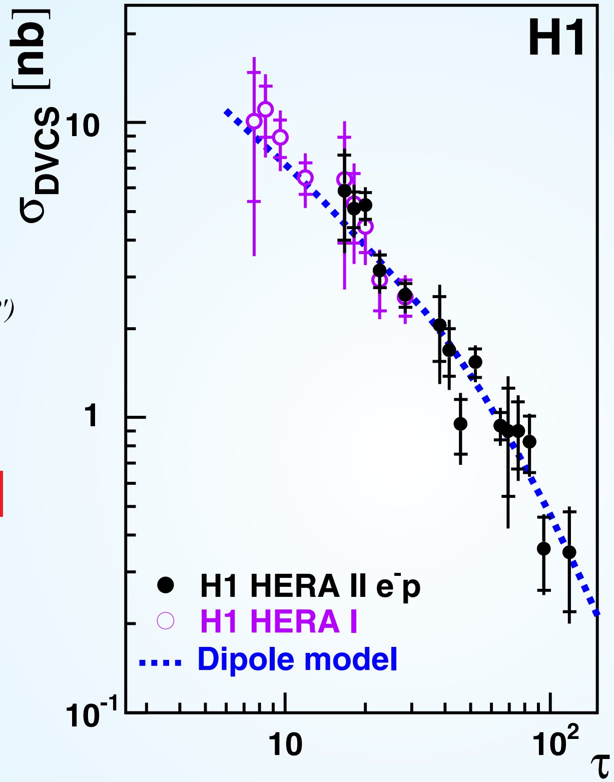


Phys. Rev. D 96 (2017) 014001

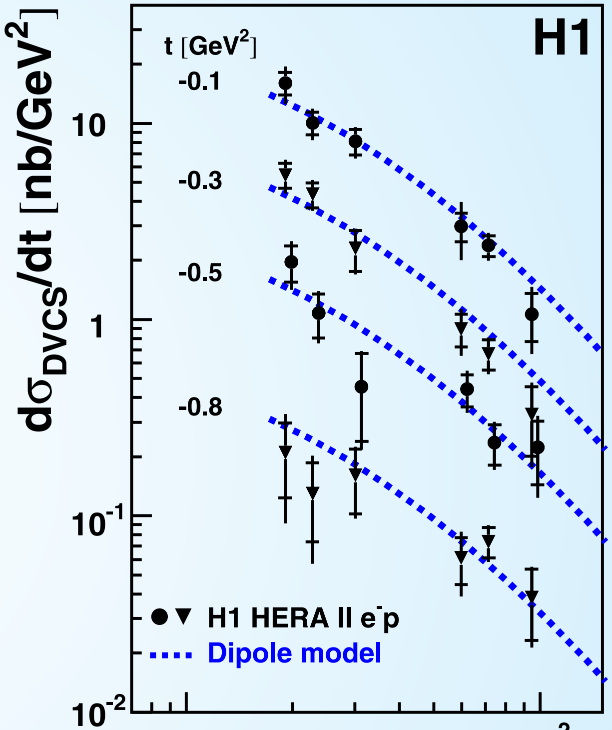
Deeply Virtual Compton Scattering



Dipole model introduces a saturation scale Qs.



DESY07-142



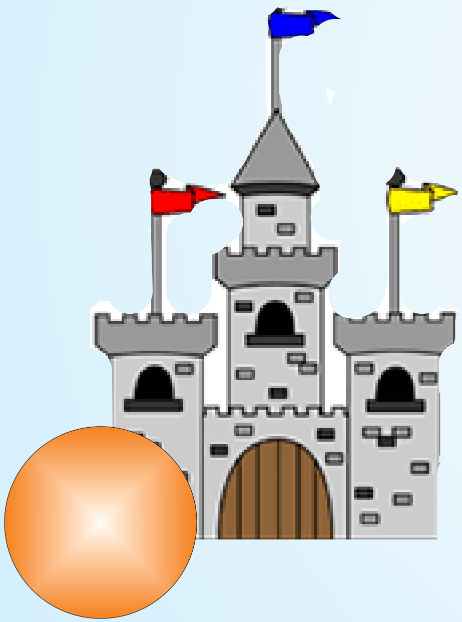
$\tau = Q^2/Q_S^2$

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

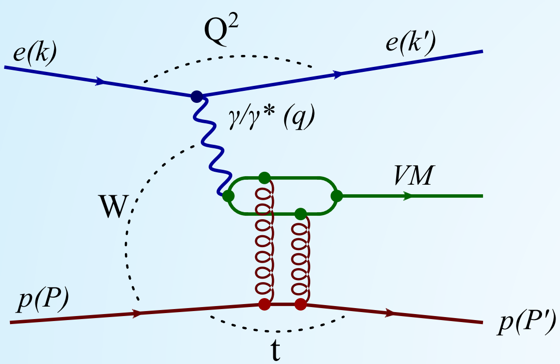
average impact parameter

0.65 ± 0.02 fm $x=0.0012$

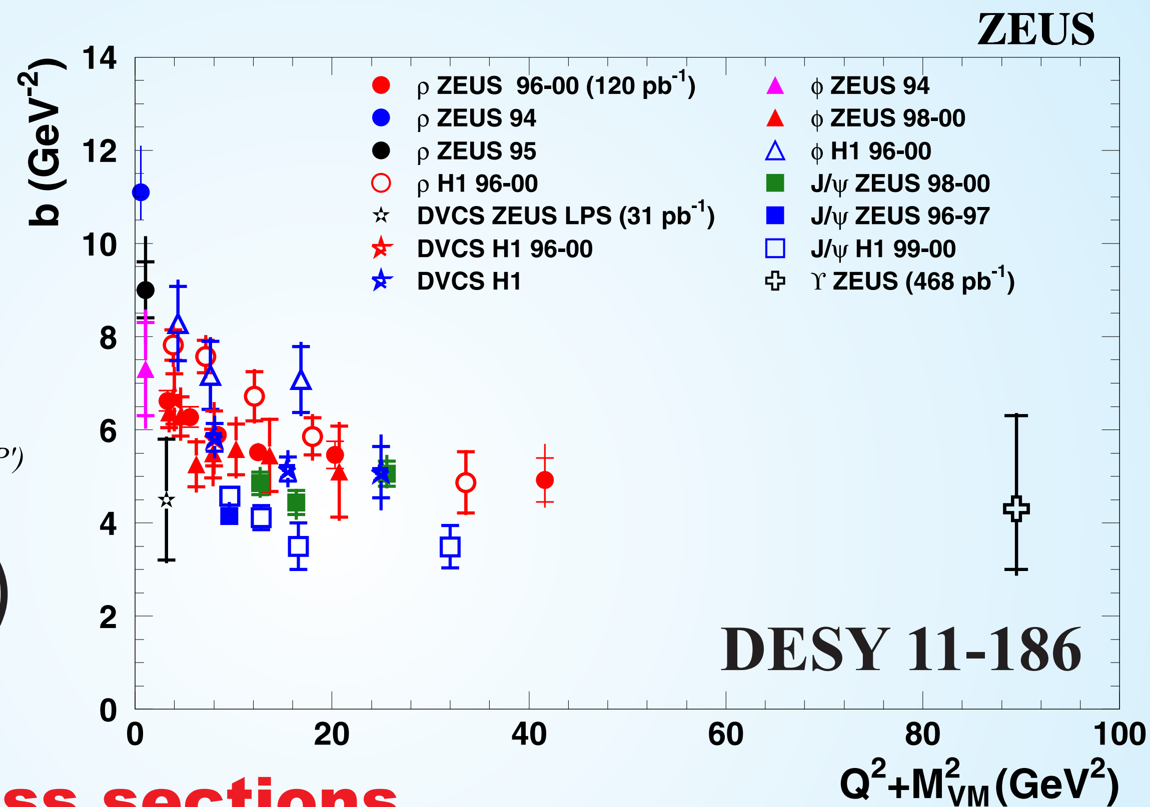
transverse expansion of partons

-- in the proton?

t-Slopes for Vector Meson Production



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



and other cross sections

and LHC ultraperipherical ion collisions

Phys. Lett. B 803 (2020)13577 and references therein

Color dipole model works!

So, how does the proton look?

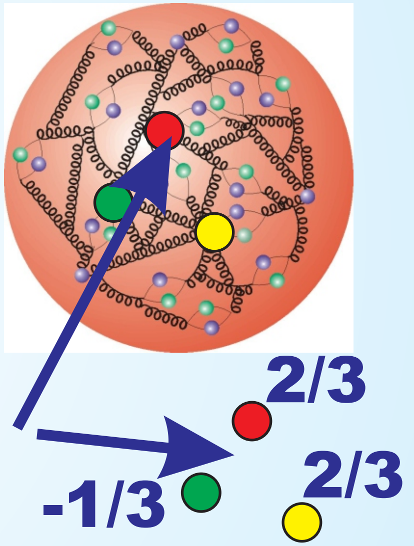
rms charge radius

electron: 0.88 fm ⟶ 0.84, 0.86 fm

muon: 0.84 fm exp. or BSM arXiv: 2304.06126

rms glue/sea radius ?

DVCS : 0.65 ± 0.02 fm



What a misleading picture....

dipole moment: < 10^{-25} ecm
arXiv: 2205.00830

Can we measure a dynamic system [spin] while averaging over time?

Heisenberg again....

EIC needs a lot of data

So, how does the proton look?

rms charge radius

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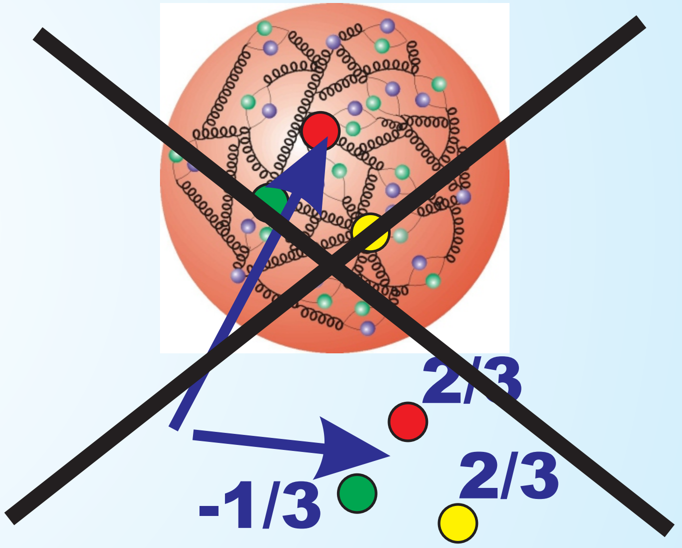


What a misleading picture....

dipole moment: < 10^{-25} ecm
arXiv: 2205.00830

Can we measure a dynamic system [spin] while averaging over time?

Heisenberg again....

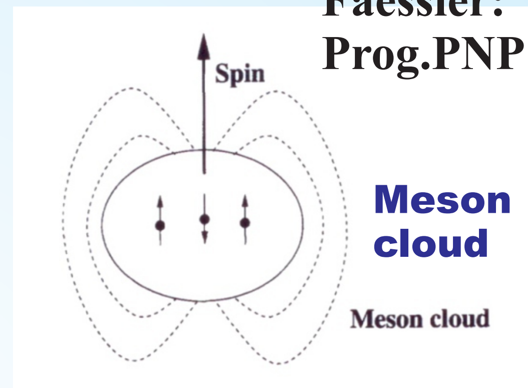
EIC needs a lot of data

Proton Shape

magnetic moment

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

→ **cannot be a sphere**



Faessler: Prog.PNP 44(2000)

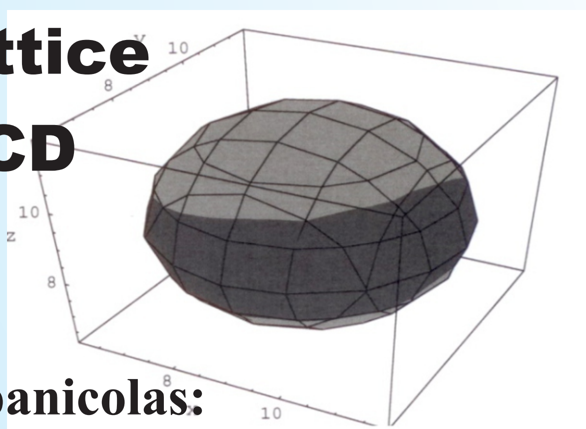
Meson cloud

EMC effect

$p \rightarrow \Delta$ excitations

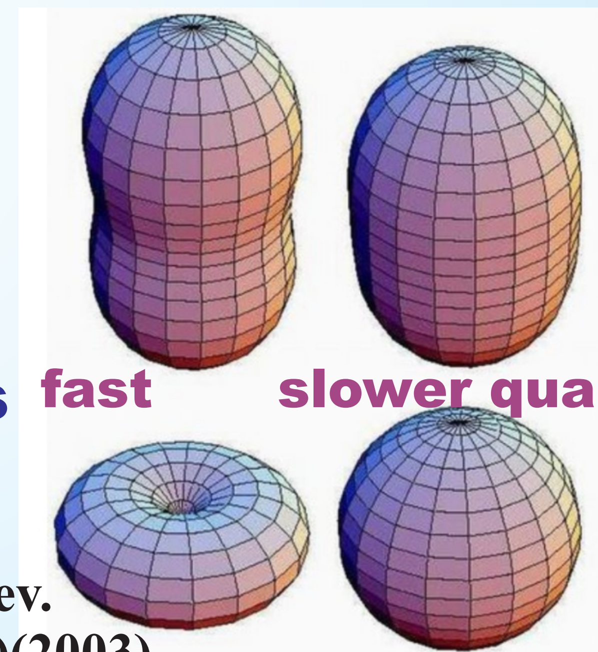
[also used for GZK cutoff]

Δ in lattice QCD



Papanicolas: EPJ A 18(2003)

Shapes depend on quark dynamics

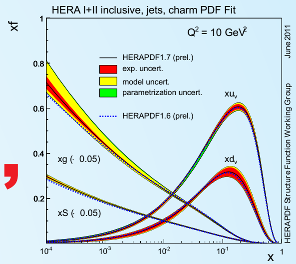


fast **slower quarks**

Miller: Phys.Rev. C 68 022201(R)(2003)

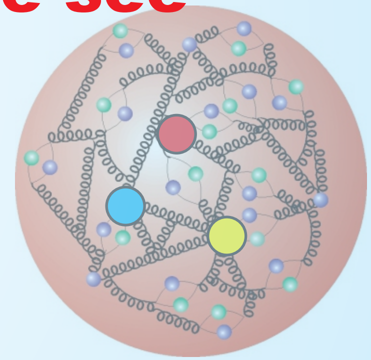
Summary

The proton is a fascinating particle.



- **It has a dynamic substructure**

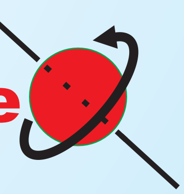
  To see it, we need to probe it. But then, the probe and the proton form a QCD quantum mechanical system. What we see is not always the proton.



- **3 valence quarks make a charge of +1**

  QM → no lasting identity – still seen

- **spin = 1/2 (½ + ½ - ½ = ½)**



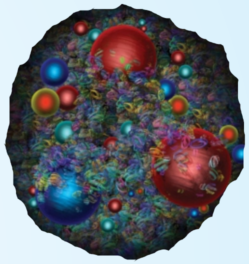
  uncertainty principle → average over time hard to find when probed

Summary

The proton is a fascinating particle.

- **mass = 1GeV = $1.67\ 10^{-27}$ kg**

  The visible mass in the universe is QCD binding energy.

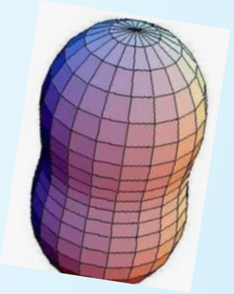


- **lifetime » age of the universe**

  Superkamiokande $1.6\ 10^{-34}$ years $\pi^{\circ}e^{+}$

  In a nucleus, it can decay..

  Otherwise, confinement is amazing.



- **radius ≈ 1 fm;**

  It is not a sphere, has no sharp boundary, and can take various shapes.

Outlook

HERA data are being used to the last bite. LHC and new fixed target experiments have joined in and PDFs will get better and better.

The proton would have to be studied with neutrinos to "separate out" the proton.

EIC is planned in the US, at BNL, not at Jefferson Lab [high-x]. Huge luminosities are planned to unfold the time integration to look for spin and to do proton tomography.