Brian, the ZEUS years

A M Cooper-Sarkar
FosterFest, Sep 11th 2024

ZEUS ran from 1992 to 2007
Preparation started a lot earlier in the mid eighties

But I met Brian a lot earlier than that in 1975, when he was just arriving in Oxford as a graduate student and I was just leaving for my first post-doc
I think I passed some code to him for amplitude analysis of $K^- p \rightarrow Y^* \pi$
A Y* is a spin 3/2 baryon that we now call the Σ(1385), but you don't need to know that, or what an amplitude analysis was.

Particle Physics has changed.
In 1975 we didn't have the Standard Model.
We didn't have EW unification
We didn't have QCD
OK some theoreticians had thought of the right ideas, but we didn't have experimental evidence.

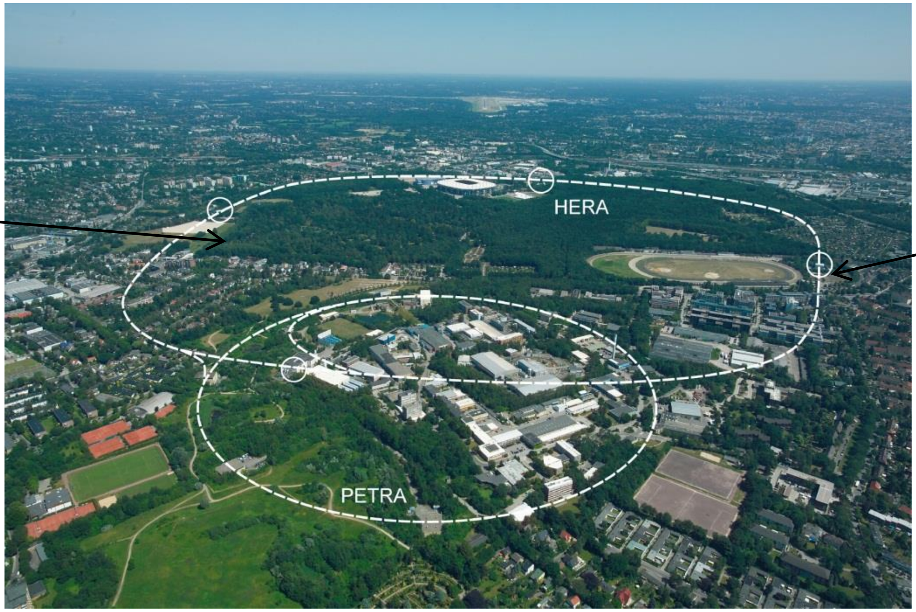
We had JUST observed weak neutral currents,
and the J/ψ,
And there were suggestions from SLAC of partons—not necessarily that they were quarks.
There was no coherent understanding.

This came through the later 70's and 80's as

- EW unification a la Weinberg Salam was established by observation of parity violation in polarised electron-nucleon scattering, 1979
- QCD scaling violations were observed in neutrino-nucleon scattering (1978-80's) and then in muon-nucleon scattering, partons are (anti-)quarks and ..
- The gluon was observed in 3-jet events at DESY~1980
- The W and Z bosons were actually observed proton-antiproton scattering, 1983.

This led to the ideas that EW could be better explored in e^+e^- scattering ---LEP
And QCD could be better explored in e p scattering----HERA
(To take a somewhat Eurocentric view)
(And not to imply that this is all that either of these facilities achieved)

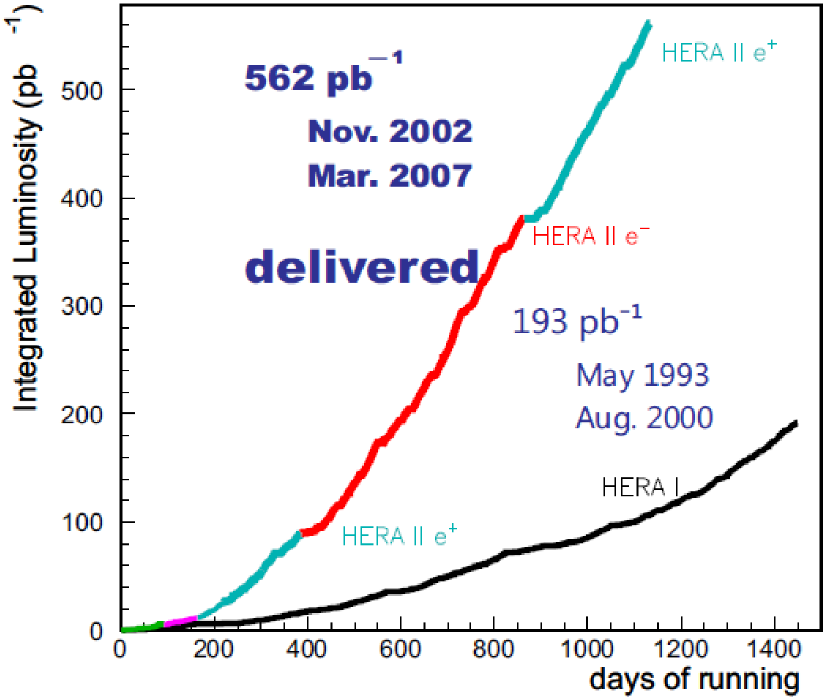
So what was ZEUS?
A electron(positron) – proton deep inelastic scattering machine at HERA, Hamburg



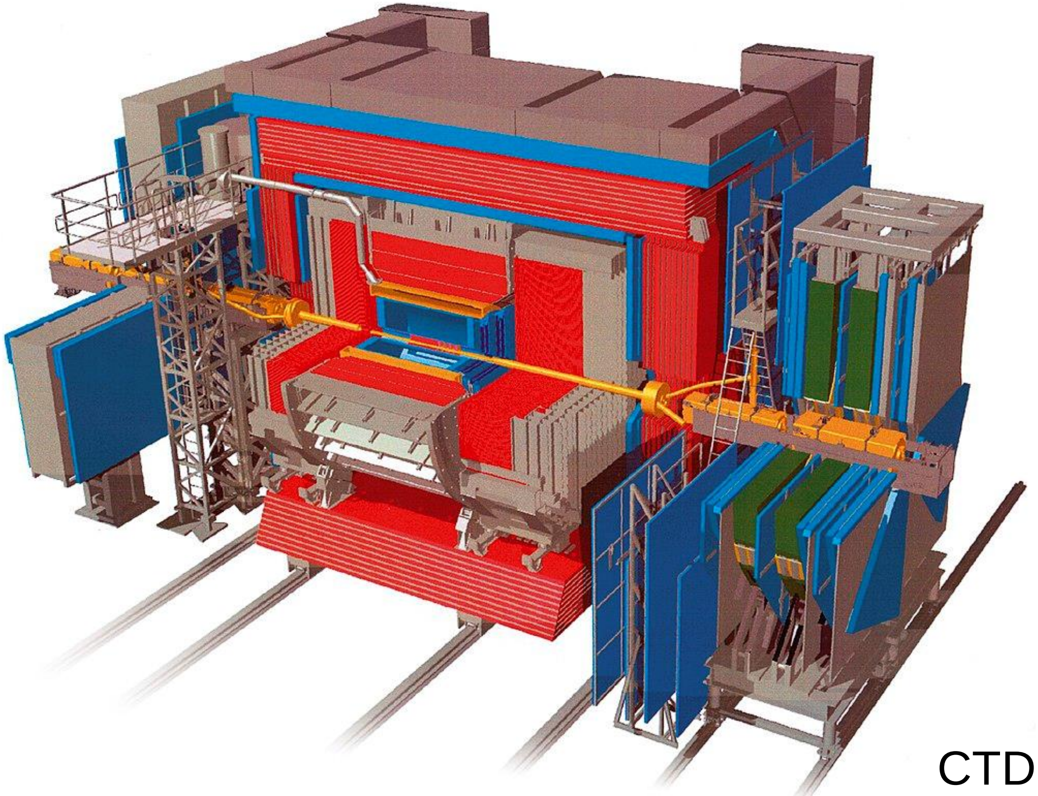
HERA running periods 1992-2000, upgrade, 2002-2007 with 5X luminosity (Brian heavily involved as ZEUS spokesman)

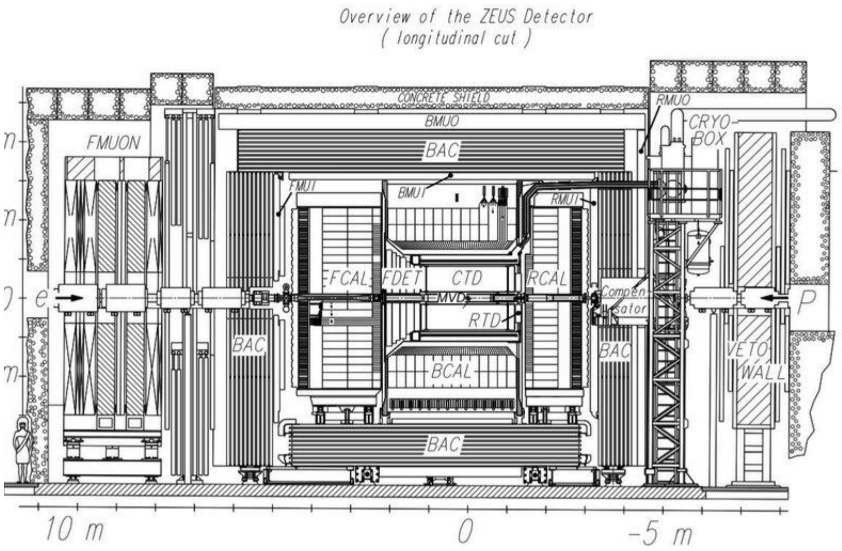
Final inclusive data combination from all HERA running
~500pb^{-1} per experiment split ~equally between e^{+} and e^{-} beams

Running at Ep = 920, 820, 575, 460 GeV, Ee = 27 GeV
$\sqrt{s}$ = 318, 300, 251, 225 GeV
Most luminosity at the highest energy



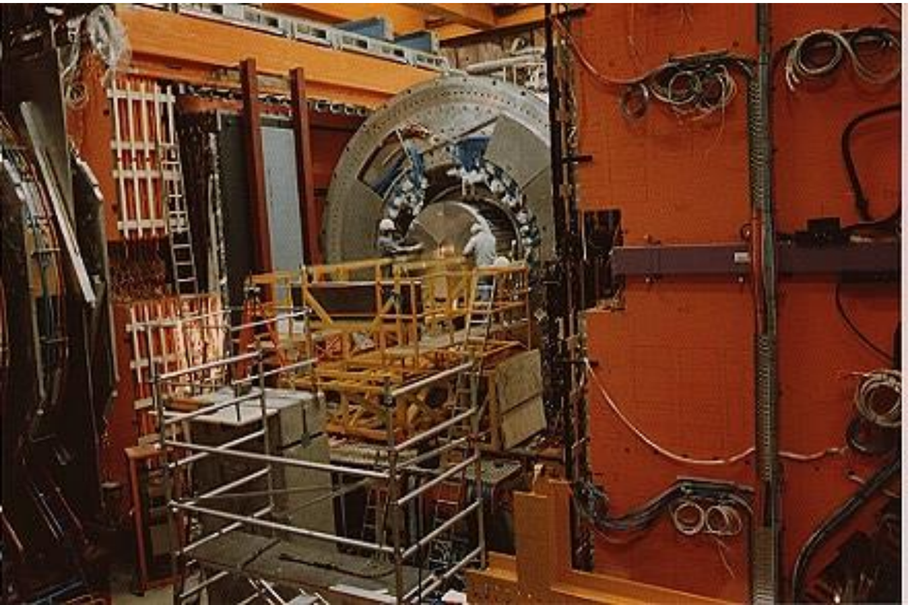
ZEUS and its

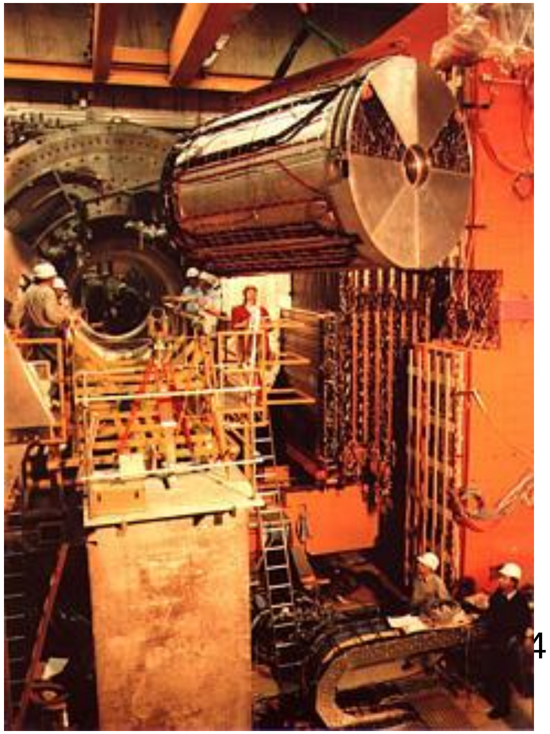


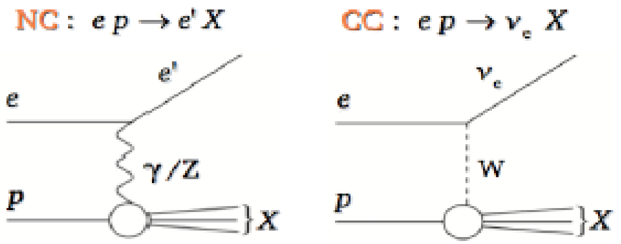


CTD
Central
Tracking
Detector

A large part
of Brian's
involvement
in ZEUS







- Kinematic variables:

$Q^2 = -q^2 = -(k-k')^2$ Virtuality of the exchanged boson

$x = \frac{Q^2}{2p \cdot q}$ Bjorken scaling parameter

$y = \frac{p \cdot q}{p \cdot k}$ Inelasticity parameter

$s = (k+p)^2 = \frac{Q^2}{xy}$ Invariant c.o.m.

We had never before run at energies at which the exchange of W and Z were on a par with γ for ep scattering

Neutral current:

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\alpha\pi^2}{xQ^4}\left(Y_+ F_2 \mp Y_- xF_3 - y^2 F_L\right)$$

$F_2 \propto \sum_i e_i^2 (xq_i + x\bar{q}_i)$ quark distributions

$xF_3 \propto \sum_i (xq_i - x\bar{q}_i)$ valence quarks

$F_L \propto \alpha_s \times g$ gluon at NLO

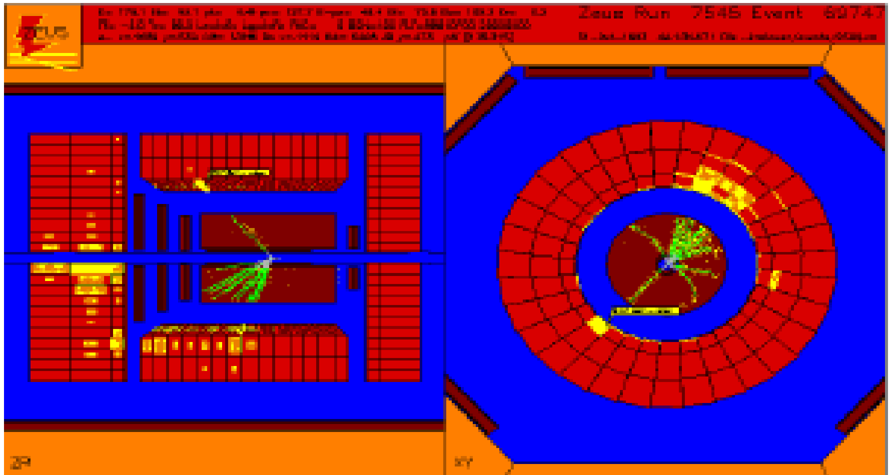
Charged current:

$$\frac{d^2\sigma^{-}_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^2}{M_W^2+Q^2}\left(u+c+(1-y^2)(\bar{d}+\bar{s})\right)$$

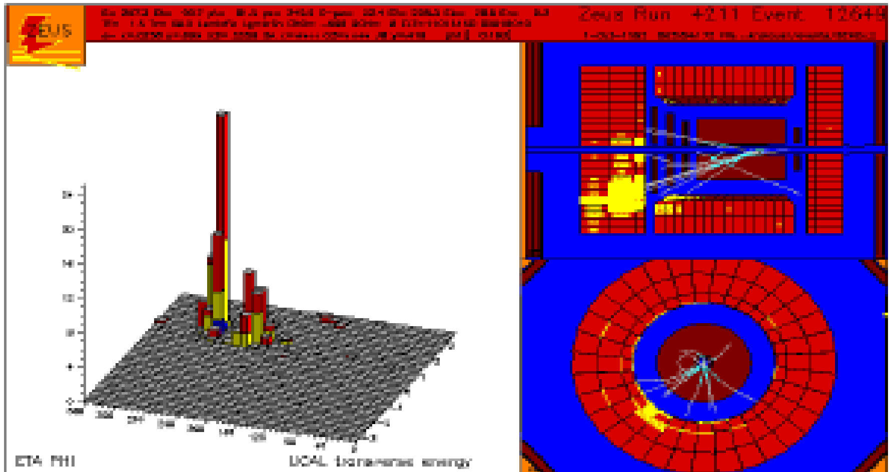
$$\frac{d^2\sigma^{+}_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^2}{M_W^2+Q^2}\left(\bar{u}+\bar{c}+(1-y^2)(d+s)\right)$$

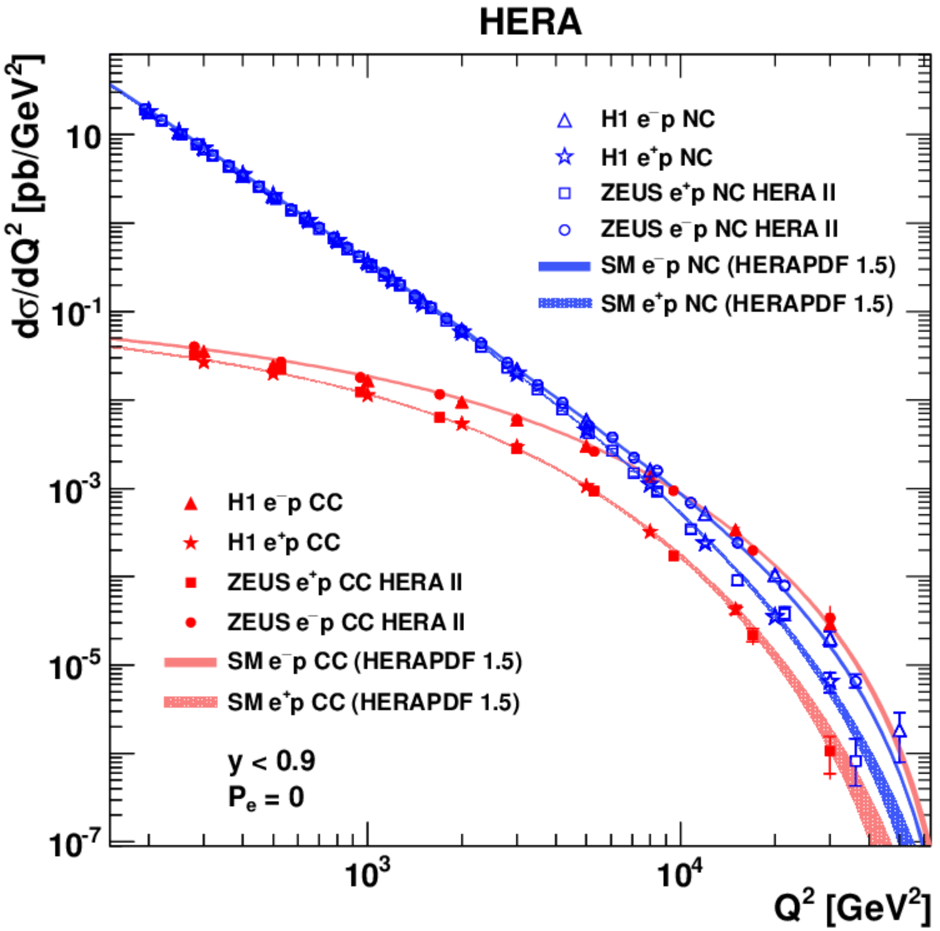
flavour decomposition

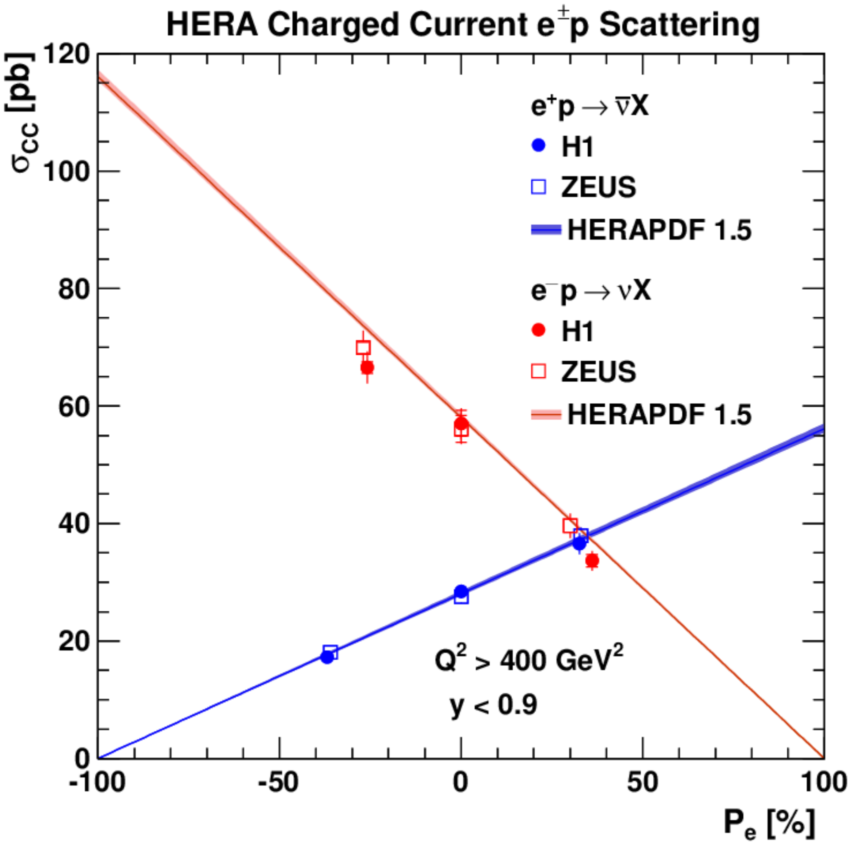
NC



CC







So here are the plots of the e^+ and e^- NC and CC cross sections as a function of the scale of the probe Q^2

The weak interaction is not weak, provided the scale of the probe is above M_W^2

The electron/positron beams could be polarised

e^+p scattering with fully left hand polarisation =0, no left handed antineutrinos

e^-p scattering with fully right hand polarisation =0, no right handed neutrinos

And while we are looking at EW aspects….

Quark couplings to Z

Decompose the NC cross sections into polarised and unpolarised pieces. Cross sections are related to parton distribution functions PDFs and electroweak parameters

The total cross-section : $\sigma = \sigma^0 + P\,\sigma^P$

The unpolarised cross-section is given by $\sigma^0 = Y_+ F_2^0 + Y_- xF_3^0$

LO expressions for illustration

$$F_2^0 = \Sigma_i\, A_i^0(Q^2)\,[xq_i(x,Q^2) + x\bar{q}_i(x,Q^2)]$$

$$xF_3^0 = \Sigma_i\, B_i^0(Q^2)\,[xq_i(x,Q^2) - x\bar{q}_i(x,Q^2)]$$

$$A_i^0(Q^2) = e_i^2 - 2\,e_i\,\mathbf{v_i}\,\mathbf{v_e}\,\chi_Z + (v_e^2+a_e^2)(\mathbf{v_i}^2+\mathbf{a_i}^2)\,\chi_Z^2$$

$$B_i^0(Q^2) = \quad - 2\,e_i\,\mathbf{a_i}\,a_e\,\chi_Z + \quad 4\mathbf{a_i}\,a_e\,\mathbf{v_i}\,v_e\,\chi_Z^2$$

SM values

$$v_u = 1/2 - 4/3\sin^2\theta_W,\ a_u = 1/2$$

$$v_d = -1/2 + 2/3\sin^2\theta_W,\ a_d = -1/2.$$

The polarised cross-section is given by $\sigma^P = Y_+ F_2^P + Y_- xF_3^P$

$$F_2^P = \Sigma_i\, A_i^P(Q^2)\,[xq_i(x,Q^2) + x\bar{q}_i(x,Q^2)]$$

$$xF_3^P = \Sigma_i\, B_i^P(Q^2)\,[xq_i(x,Q^2) - x\bar{q}_i(x,Q^2)]$$

$$\chi_Z = \frac{1}{\sin^2 2\theta_W}\,\frac{Q^2}{M_Z^2+Q^2}\,\frac{1}{1-\Delta R}$$

$$A_i^P(Q2) = \quad 2\,e_i\,\mathbf{v_i}\,a_e\,\chi_Z - \quad 2\,v_e\,a_e\,(\mathbf{v_i}^2+\mathbf{a_i}^2)\,\chi_Z^2$$

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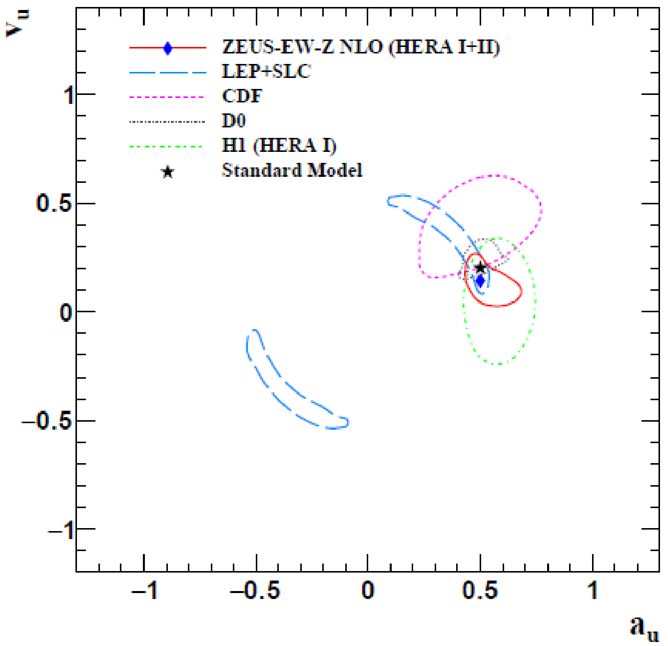
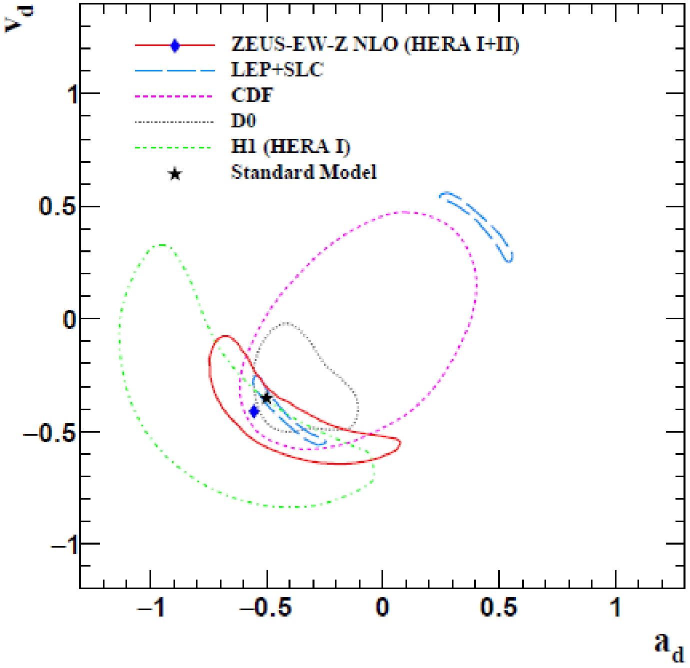
$\chi_Z \gg \chi_Z^2$ (γZ interference is dominant)

$\mathbf{v_e}$ is very small (~0.04).

→

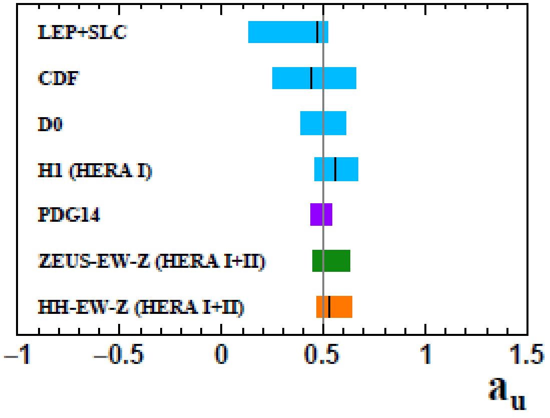
unpolarized $xF_3 \rightarrow a_i$,
polarized $F_2 \rightarrow v_i$



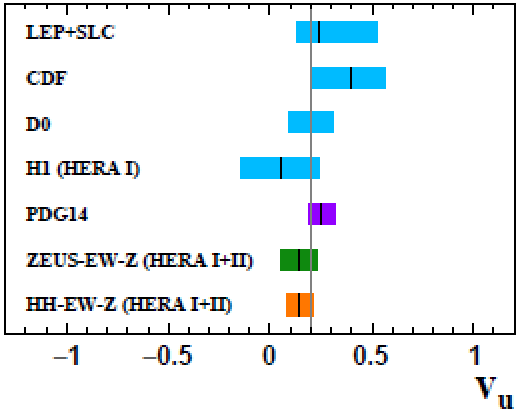


Brian and I were heavily involved with a ZEUS paper presenting a simultaneous fit to PDF parameters and Z couplings using ZEUS data.

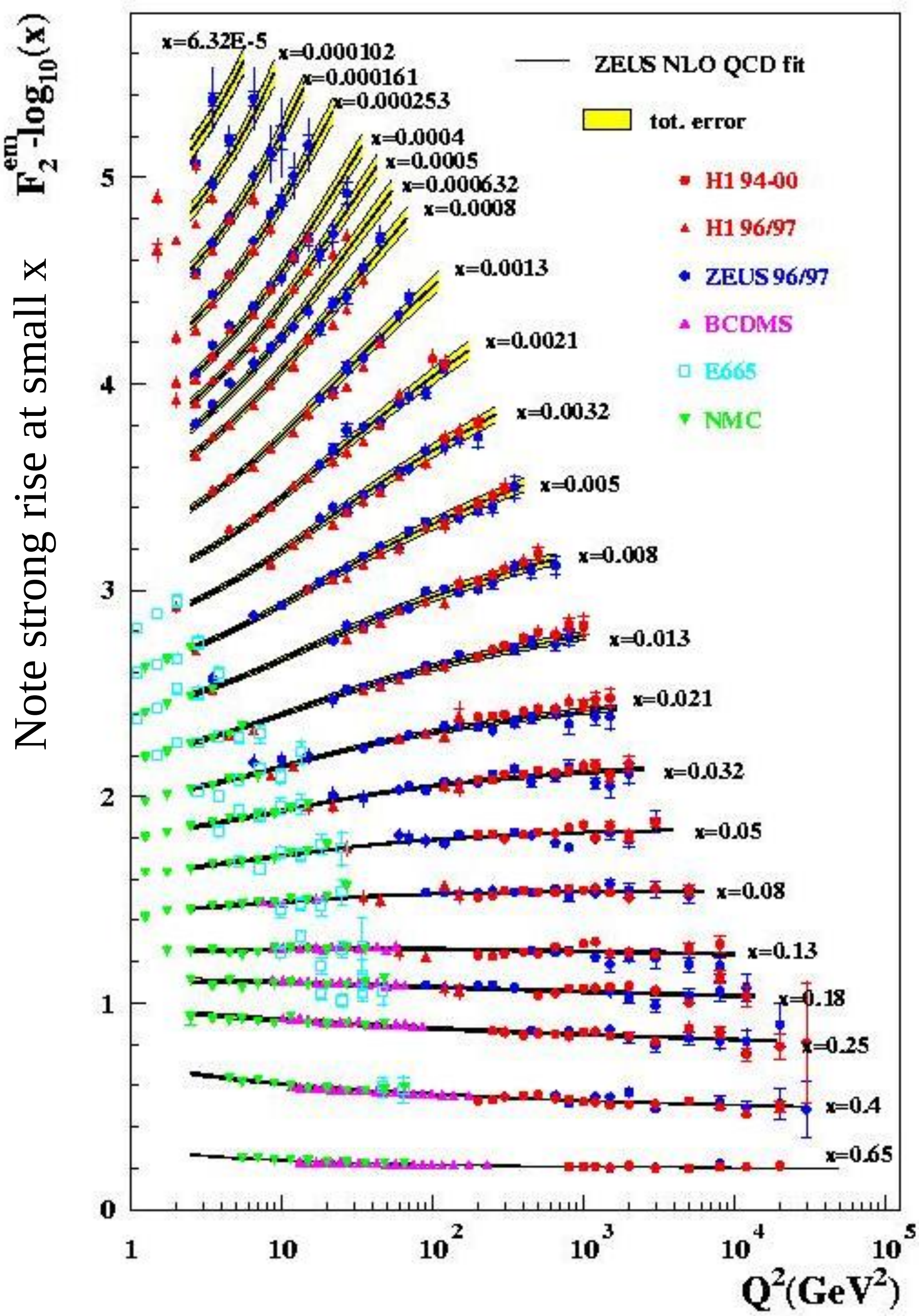
The ZEUS result is the best for a single measurement for a_u, v_u **Arxiv: 1603.09628**



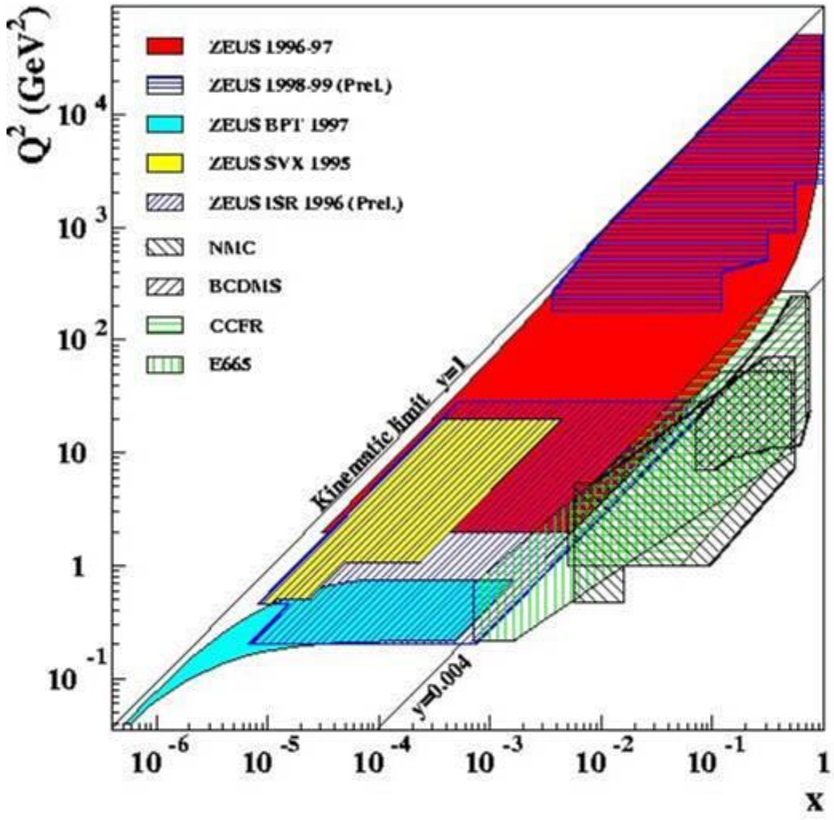
We (Brian, myself and a few others) even improved on it in a small number of authors paper **Arxiv:1604.05083** using both H1 and ZEUS public data—but this was never an official combination



Now to QCD –we started doing our own QCD fits to extract parton distributions within ZEUS in ~2001



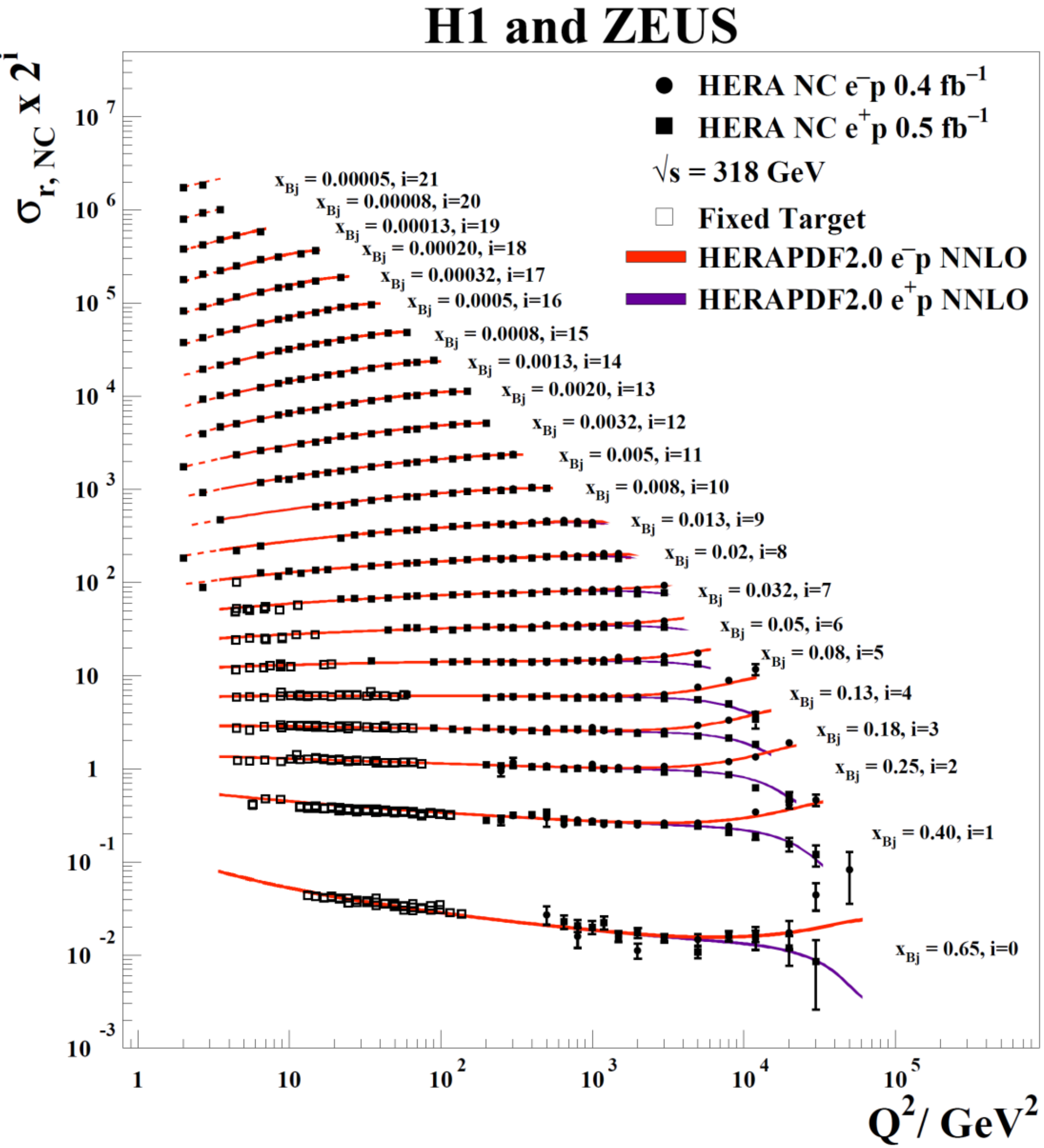
Note strong rise at small x



Terrific expansion in measured range across the x, Q^2 plane due to HERA data

Brian, as spokesman, was very supportive of my efforts. In particular of an honest and rigorous evaluation of the role of systematic uncertainties, which was in its infancy at the time

Now to the HERA combination, first combination 2008/9, second with post upgrade data in 2015



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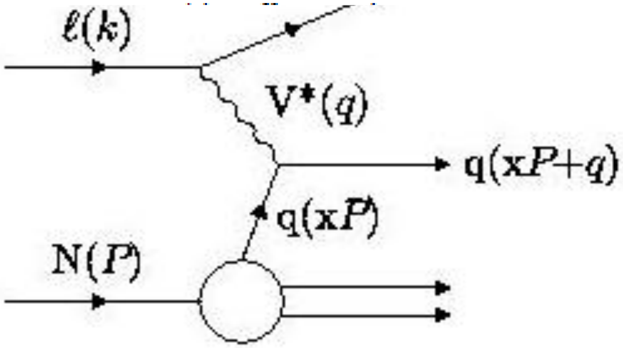
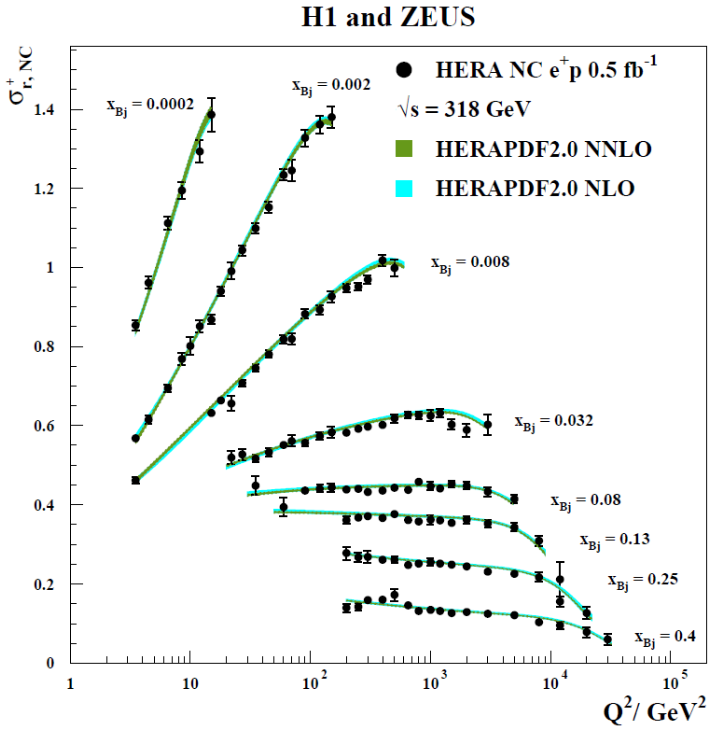


The fractional momentum of a struck quark is the measurable kinematic variable x

Arxiv:1506.06042

NOTE: low x happens at low Q^2

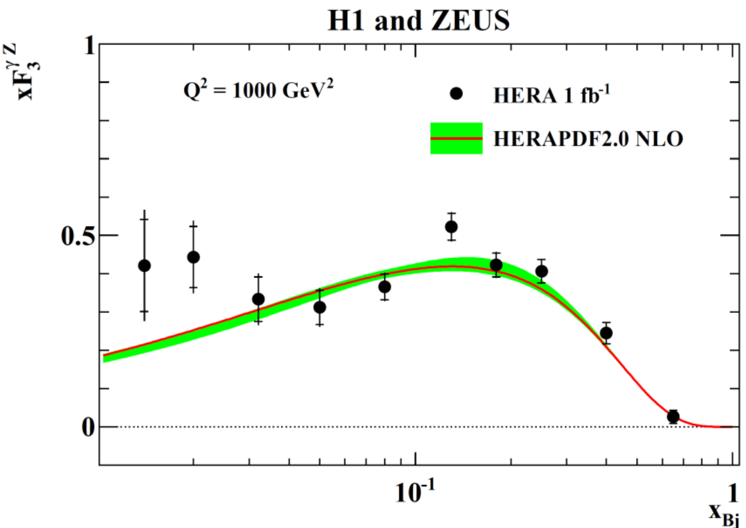


Notable features:

Strong rise of reduced cross section with Q^2 at low-x and decrease at high-x as predicted by QCD. HERAPDF QCD fit at NNLO is superimposed.

Strong rise of structure function F2 as x decreases, getting steeper as Q^2 increases

Difference in e^+ and e^- NC cross sections at high Q2 due to the Z exchange gives us a new structure function xF3



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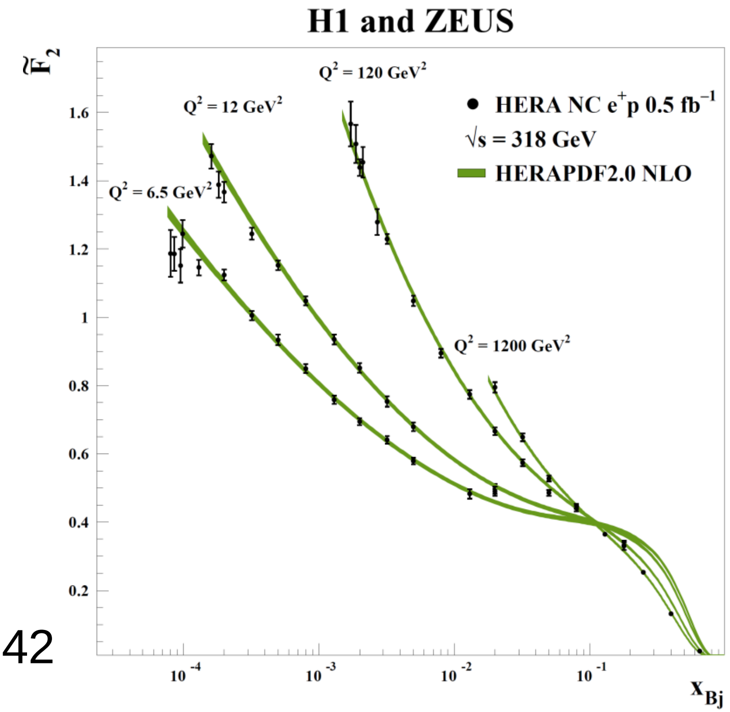


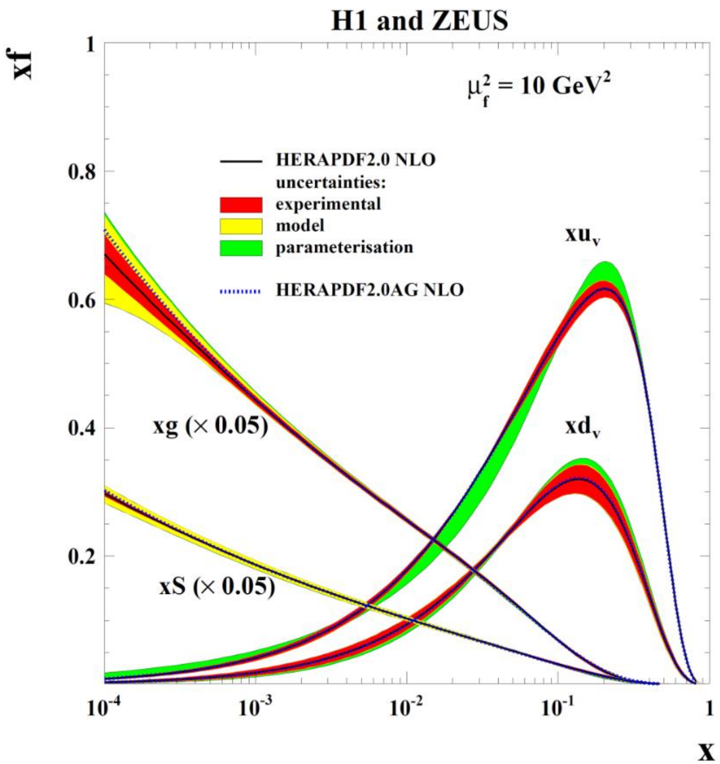
We used all the cross sections to produce the HERAPDF using only HERA (H1 and ZEUS combined) data.

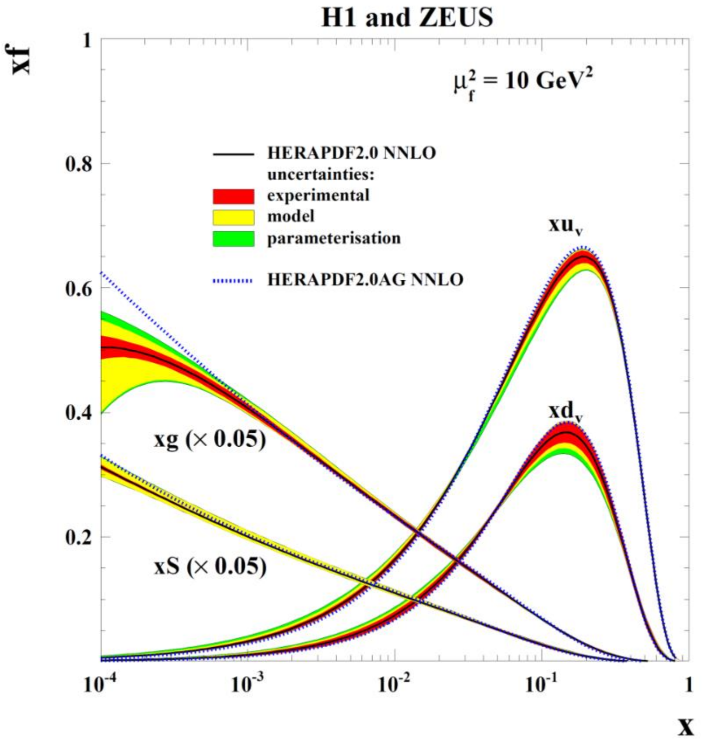
The combination of the HERA data yields a **very accurate and consistent data set for 4 different processes**: e^+p and e^-p Neutral and Charged Current reactions and for e^+p Neutral Current at 4 different beam energies. It has the best understood correlated systematic uncertainties of any input to PDF fits to date

F_2 (NC) gave us quarks and antiquarks, xF_3 (NC) gave us valence quarks

CC cross sections gave us flavour separation

And the rate of scaling violations plus the F_L structure function (measured using different c. of m. energies) gave us the gluon



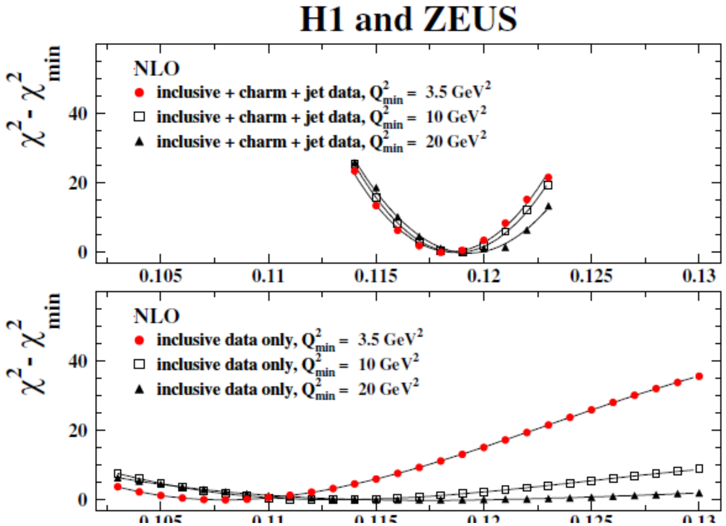


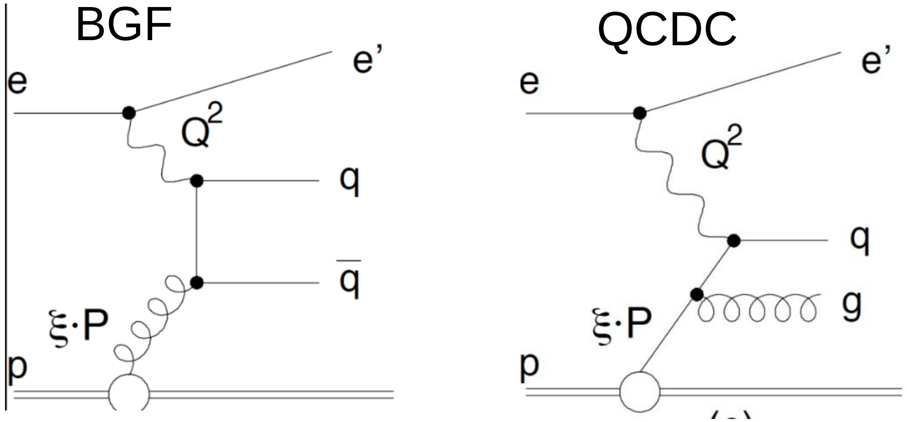
Arxiv:1506.06042

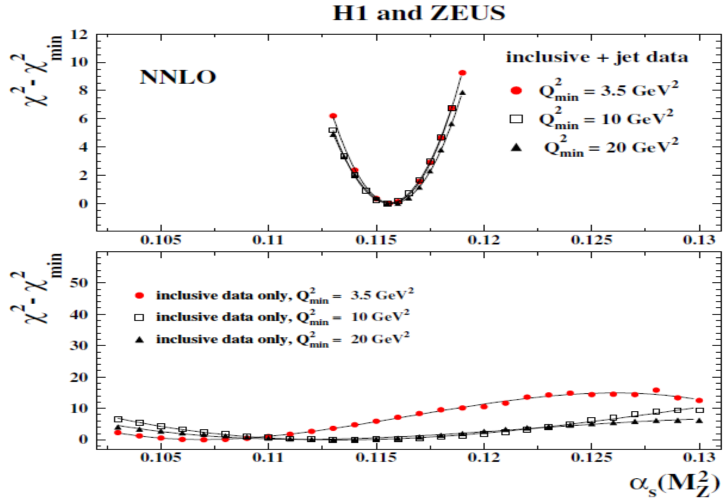
Of course the rate of scaling violations is not only determined by the gluon but also by the strong coupling non-constant $\alpha_S(Q^2)$, we can thus extract $\alpha_S(M_Z^2)$ simultaneously with the parton distributions BUT it is strongly coupled to the gluon if we use only inclusive scattering data

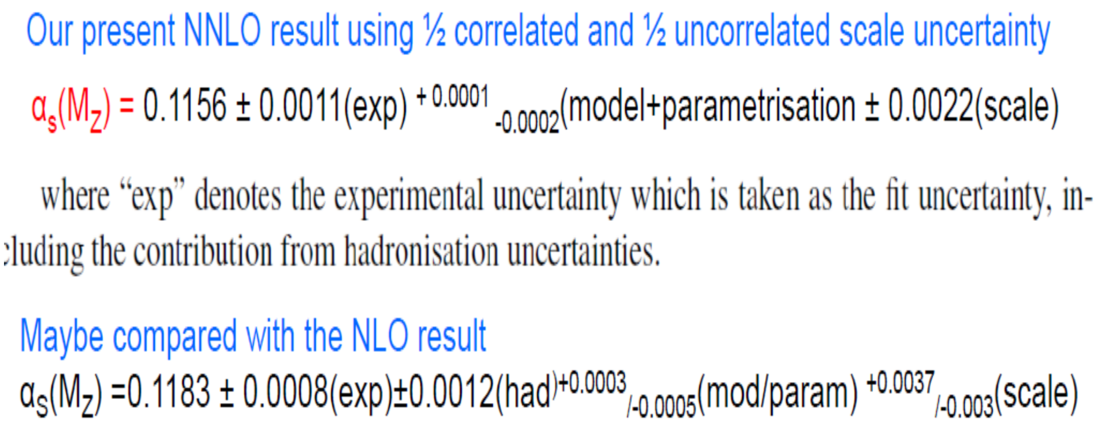
$$\frac{\partial F}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qg}\left(\frac{x}{y}\right) 2\sum_i e_i^2\, x\, g(y, Q^2)\right]$$

It makes sense to use jet production data for additional information









Our present NNLO result using ½ correlated and ½ uncorrelated scale uncertainty

$\alpha_s(M_Z) = 0.1156 \pm 0.0011(\text{exp})\ ^{+0.0001}_{-0.0002}(\text{model+parametrisation}) \pm 0.0022(\text{scale})$

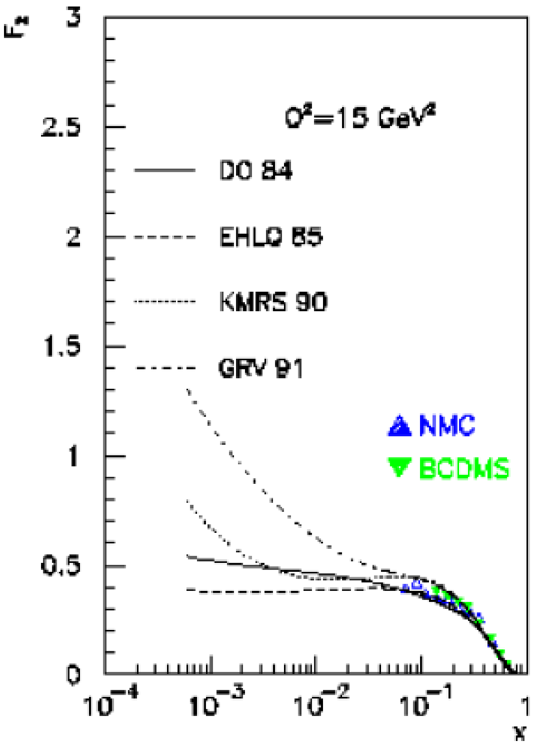
where "exp" denotes the experimental uncertainty which is taken as the fit uncertainty, including the contribution from hadronisation uncertainties.

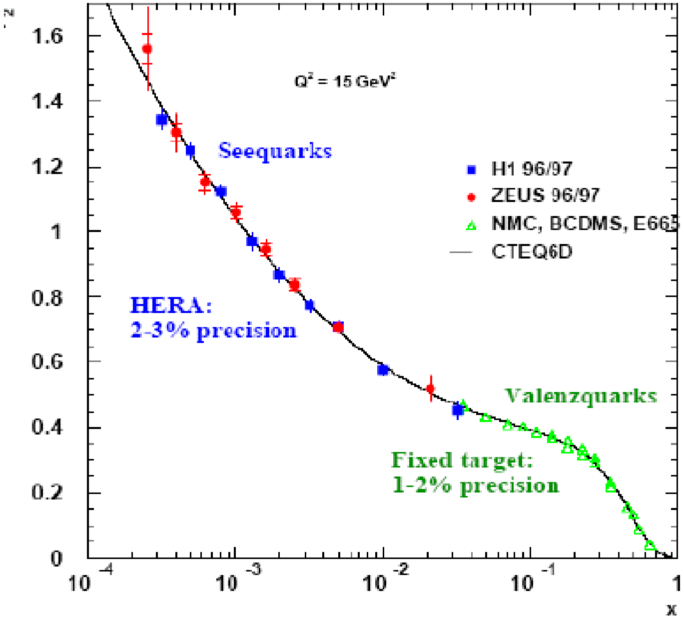
Maybe compared with the NLO result

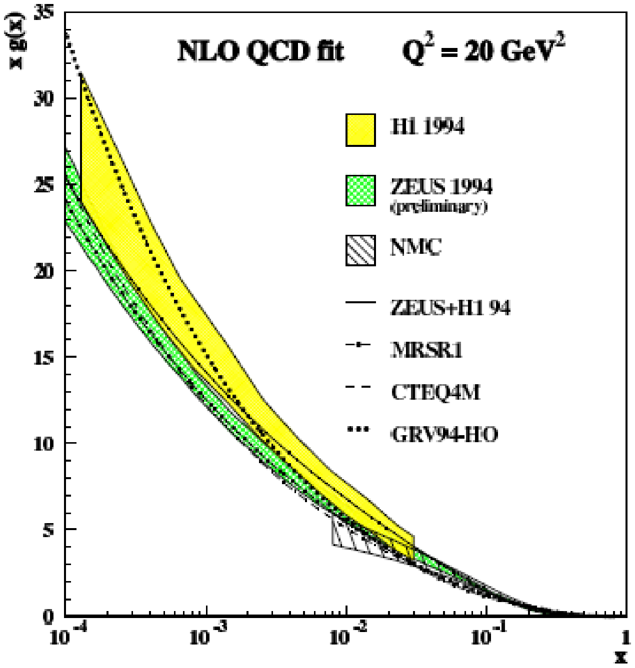
$\alpha_s(M_Z) = 0.1183 \pm 0.0008(\text{exp}) \pm 0.0012(\text{had})\ ^{+0.0003}_{-0.0005}(\text{mod/param})\ ^{+0.0037}_{-0.003}(\text{scale})$

Arxiv:1506.06042 and **ArXiv:2112.01120 at NNLO**

Let us look at low-x physics at HERA





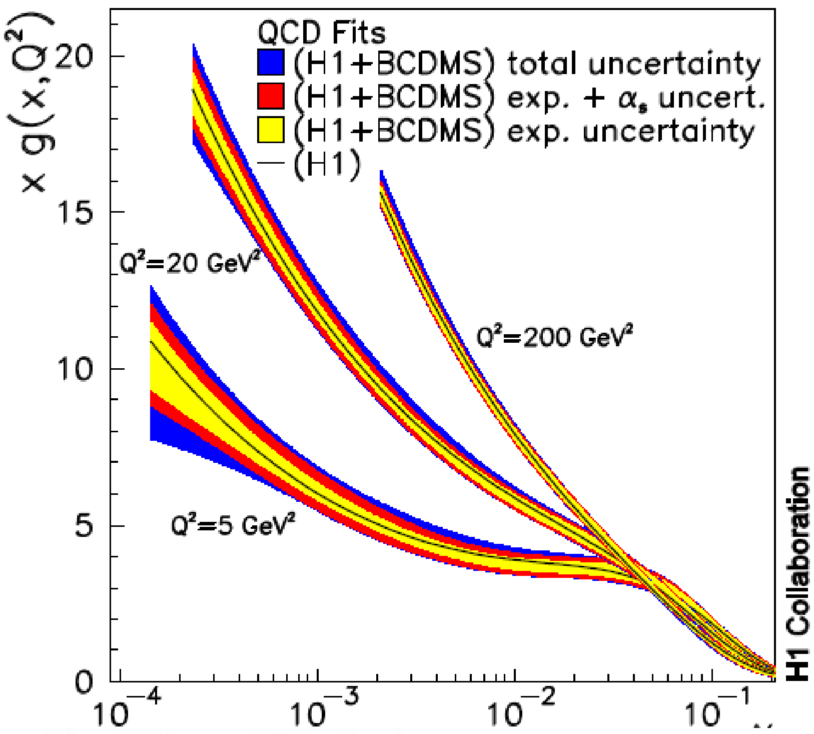


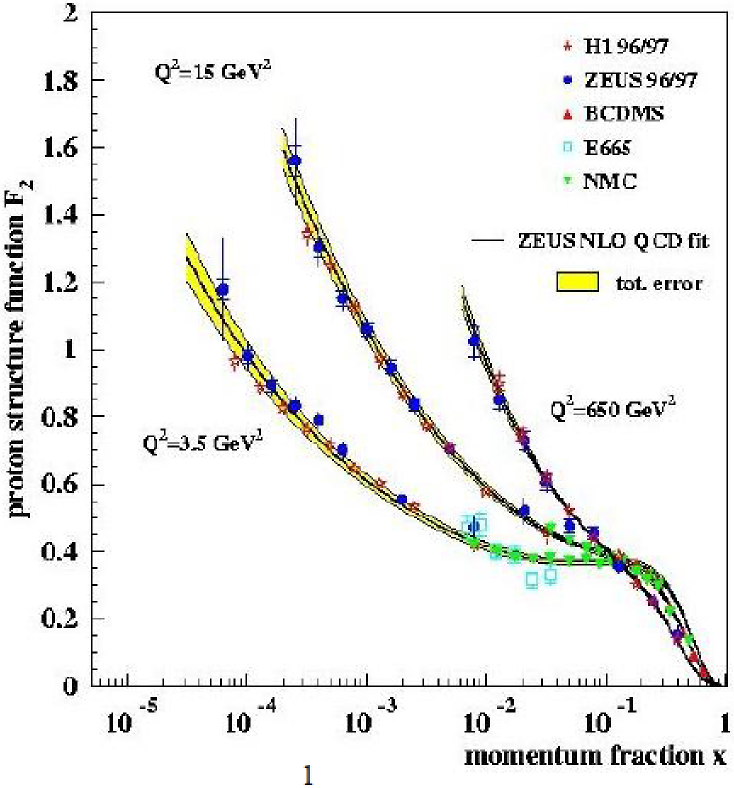
Before the HERA measurements many of the predictions for low-x behaviour of the structure functions and the gluon PDF were wrong – most theoreticians expected it to flatten out. It actually rises steeply

AND YET—DGLAP does predict the rise that we saw!

Now we see this as conventional DGLAP working TOO WELL
at low Q^2/low-x

Low-x





$$\frac{dg(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_0^1 \frac{dy}{y}\left[\Sigma_q P_{gq}(z)q(y,Q^2) + P_{gg}(z)g(y,Q^2)\right]$$

At small x,

small z=x/y

$$P_{gq} \to \frac{C_F}{z}, \quad P_{gg} \to \frac{2C_A}{z}$$

Gluon splitting functions become singular

$$\frac{dg(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_0^1 \frac{dy}{y}\frac{6}{z}g(y,Q^2)$$

$xg(x,Q^2) \sim x^{-\lambda g}$

$$\lambda_g = \left(\frac{12\ln(t/t_0)}{\beta_0 \ln(1/x)}\right)^{\frac{1}{2}}, \quad t = \ln Q^2/\Lambda^2$$

$\alpha_s \sim 1/\ln Q^2/\Lambda^2$

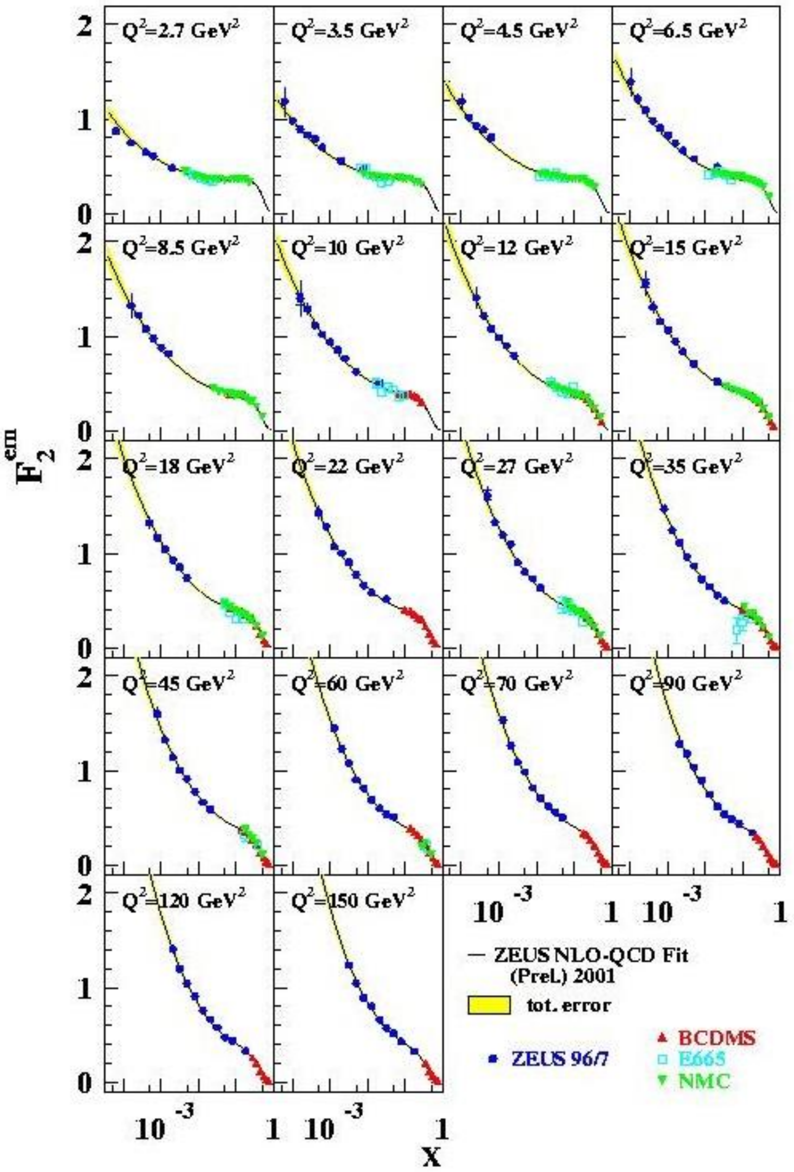
A flat gluon at low Q^2 becomes very steep **AFTER Q^2 evolution** AND F_2 becomes gluon dominated

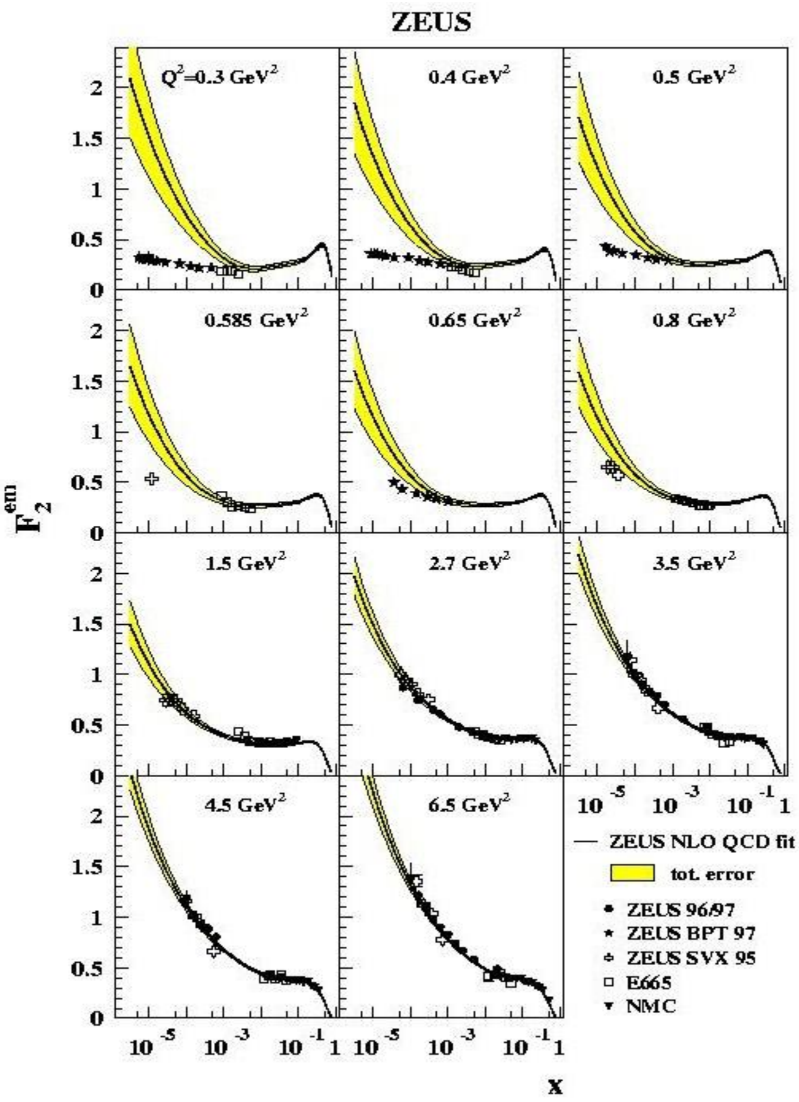
$F_2(x,Q^2) \sim x^{-\lambda s}$, $\lambda s = \lambda g - \varepsilon$

The point is that steepness should set in AFTER evolution, so at higher Q^2

So what's the problem?– this expected steepness of F_2 is happening TOO EARLY

ie too low in Q^2 with no lever arm for Q^2 evolution





So it was a surprise to see F_2 steep at small x - for low Q^2, Q^2 ~ 1 GeV^2

1 Should perturbative QCD work? α_s is becoming large - α_s at $Q^2 \sim 1$ GeV^2 is ~ 0.4

2 At HERA low Q2 is also low-x so ln(1/x) is becoming large

Should we resum logs of 1/x as well as logs of Q^2 ?

BFKL formalism (at leading order)

$$\rightarrow \quad x\,g(x, Q^2) \sim x^{-\lambda}$$

$$\lambda = \frac{\alpha_s}{\pi} C_A \ln 2 \simeq 0.5$$ for $\alpha_s \sim 0.25$ (low Q^2)

→ A singular gluon behaviour even at low-ish Q^2

→ Is this the reason for the steep behaviour of F_2 at low-x ?

3 Furthermore if the **gluon density becomes large** there maybe **non-linear effects**

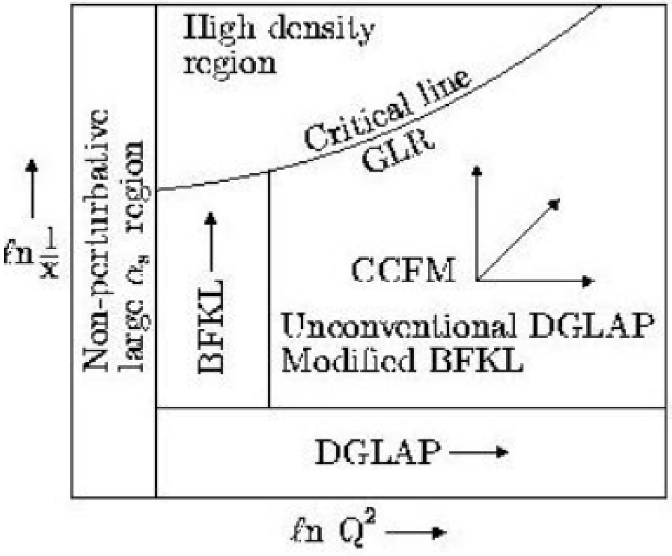
Gluon recombination g g → g

$\sigma \sim \alpha_s^2 \rho^2 / Q^2$

may compete with gluon evolution g → g g

$\sigma \sim \alpha_s \rho$

where ρ is the gluon density



5

Does the data *need* unconventional explanations?

Afficionados claim χ^2 improvements over conventional NLLA DGLAP..

But, one seems to be able to use DGLAP by absorbing unconventional behaviour in the boundary conditions i.e. the unknown shapes of the non-perturbative parton distributions at Q_0^2

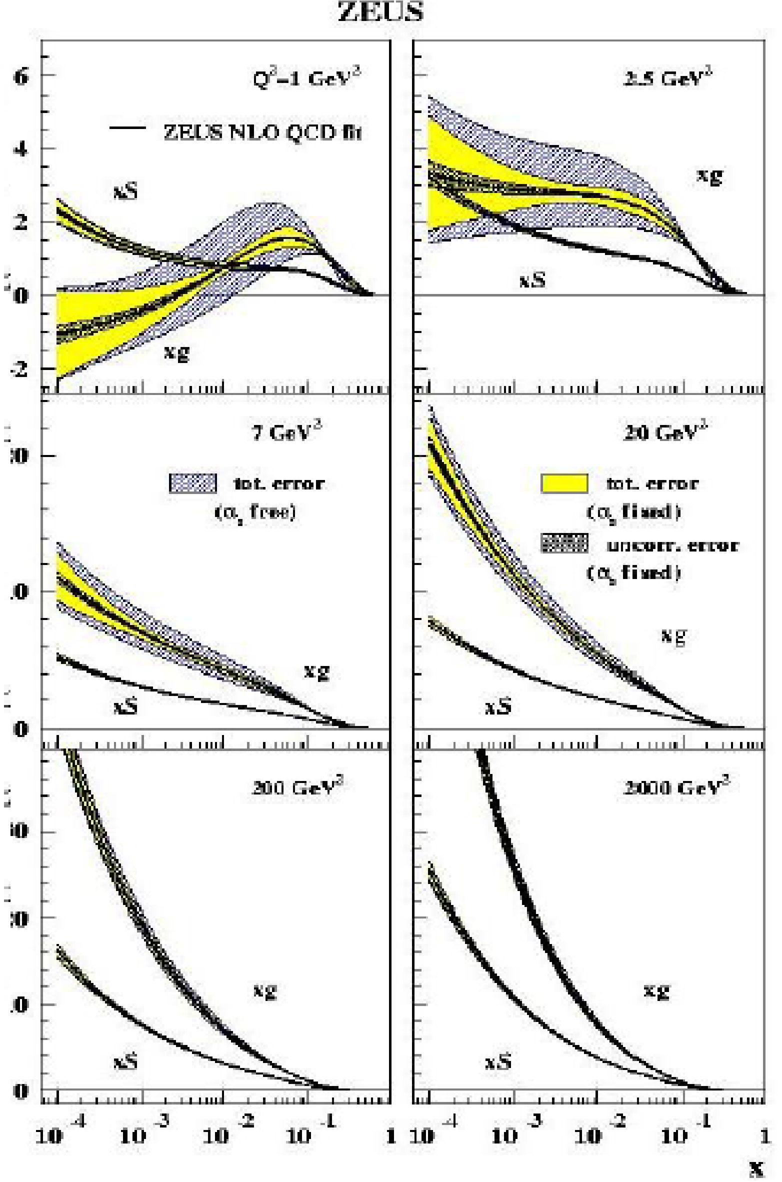
We measure, $F_2 \sim x\,q$

$$\frac{d F_2}{d \ln Q^2} \sim P_{qg} \cdot x\,g$$

we can explain unusually steep $\frac{d F_2}{d \ln Q^2}$ by:

unusual P_{qg} → eg $\ln(^1/_x)$, BFKL
OR unusual $x\,g(x,Q_0^2)$ → “valence-like” gluon etc.

→ measure other gluon sensitive quantities at low x: F_L , $F^2_{c\bar{c}}$

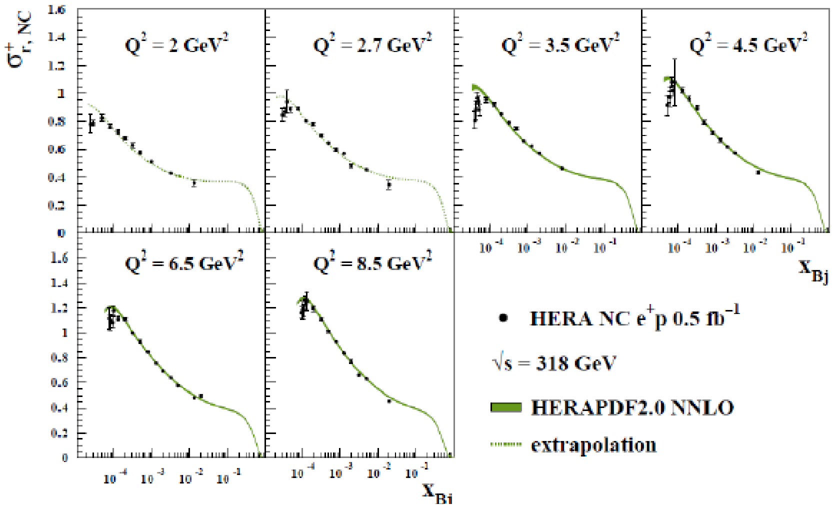


Conventional DGLAP needs a valence-like gluon but a singular sea

But F^2_c gave us more information on the heavy quark scheme than on the gluon….

And F_L? Well we can see that it is not so well described in the conventional DGLAP QCD fits by looking at the turn over of the reduced cross section at low x, Q^2

Just DGLAP



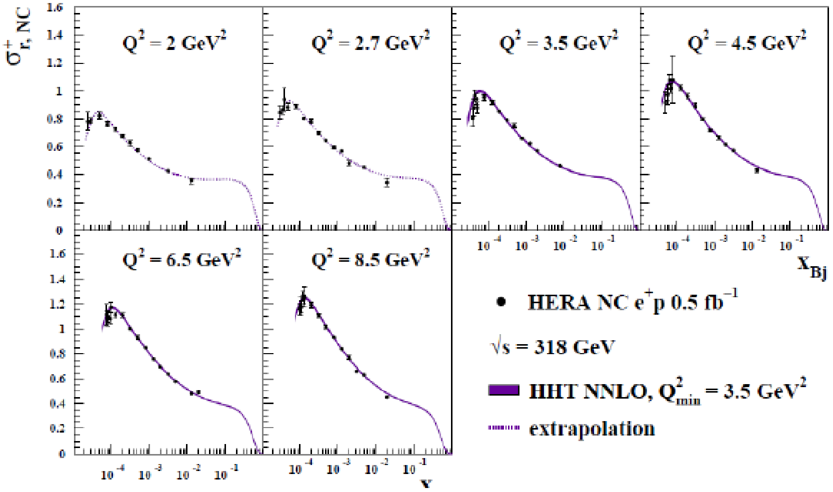
$$\sigma_{red} = F_2 - y^2/Y_+ F_L$$

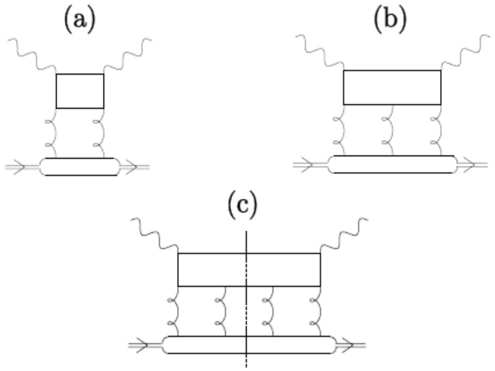
The data clearly wants a larger F_L

Brian, myself and a few others tried adding higher twist in the HHT fit **Arxiv:1604.02299**

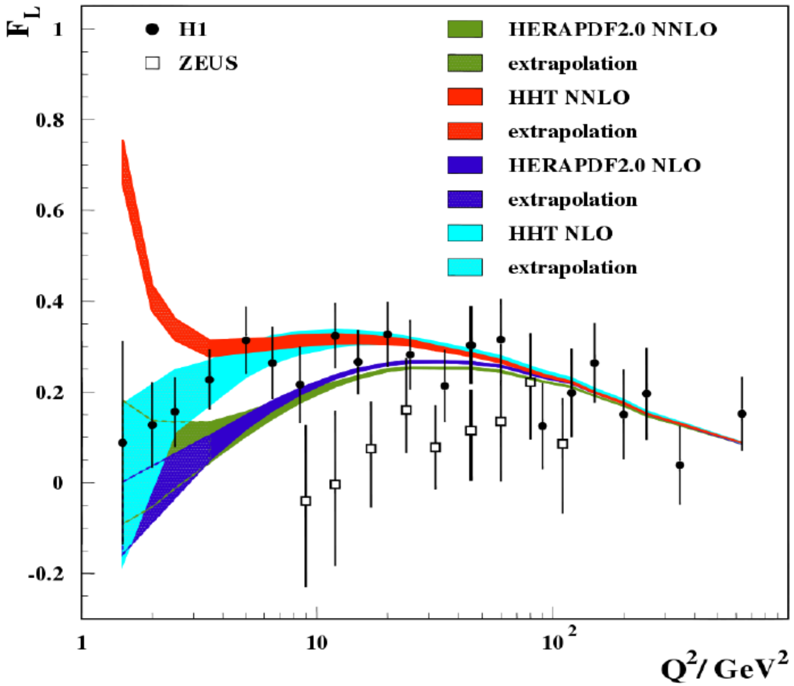
What is higher twist? It is $1/Q^2$ terms generated by diagrams you don't usually account for

DGLAP + higher twist





And F_L itself ?



Regular DGLAP, shown in dark colours (both NLO and NNLO), does not describe it too well (unfortunately for ZEUS people, H1 smaller uncertainties dominate in the combined data)

DGLAP +higher twist is shown in pale blue (NLO) and red (NNLO)

Try the simplest of possible modification to the structure functions F_2 and F_L as calculated from HERAPDF2.0 formalism

$$F_{2,L} = F_{2,L}\,(1 + A_{2,L}^{HT}/Q^2)$$

We find that such a modification of F_L is favoured, whereas for F_2 it is not.

At NNLO the $\chi 2$/ndof = 1363/1131 for HERAPDF2.0

If A_2^{HT} is added this becomes 1357/1130 and $A_2^{HT} = 0.12 \pm 0.07$ GeV^2

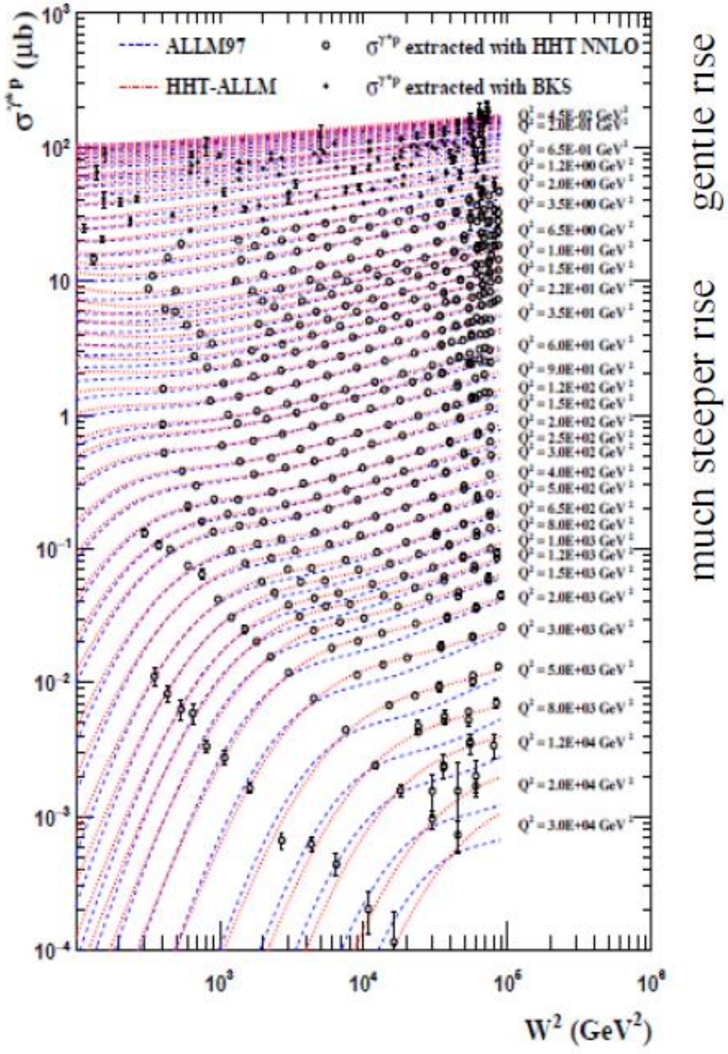
If A_L^{HT} is added this becomes 1316/1130 and $A_L^{HT} = 5.5 \pm 0.6$ GeV^2

If both A_L^{HT} and A_2^{HT} are added the result is consistent with just adding A_L^{HT}

BUT you can't push it too far!! Too far down in Q^2 that is

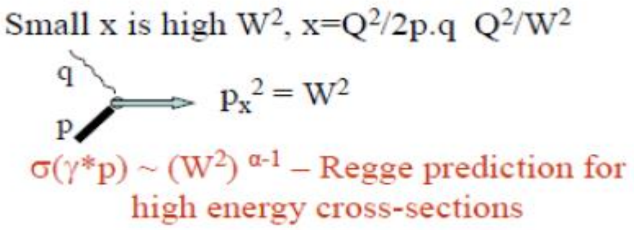
ZEUS also made measurements at very low Q^2, below the perturbative regime

Brian, myself and a few others **(arxiv:1704.03187)** made many plots of the transition to the non-perturbative regime, which are still providing theorists with much to think about and providing a guide to possibilities at the EIC



For example, here is the plot of the HERA data in terms of the virtual-photon proton cross section as a function of centre of mass energy $W^{2,}$ for increasing virtuality of the photon.

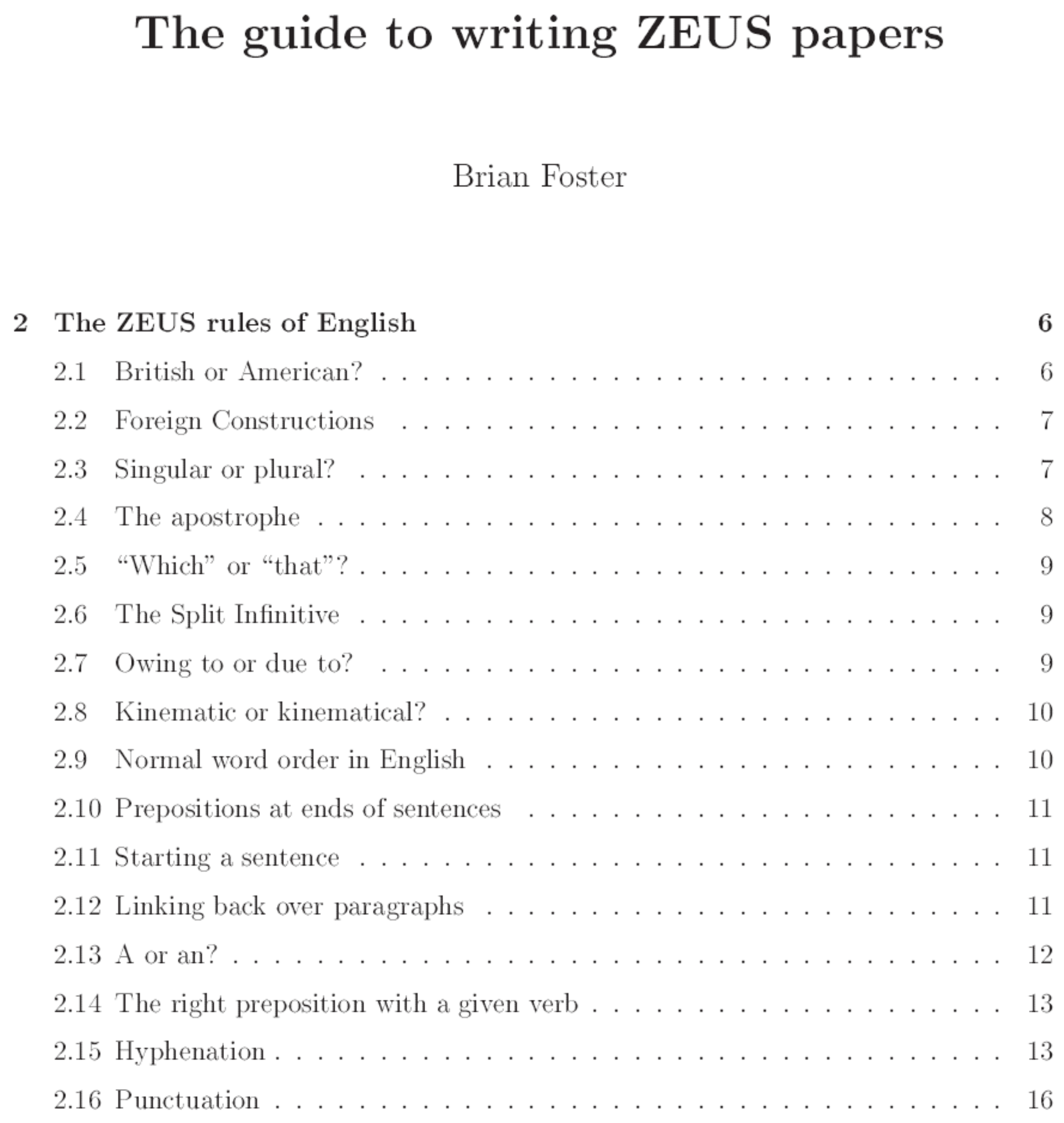
We can see the rise of the cross section changing from the gentle rise of the soft-Pomeron when the photon is almost real, to the steep rise of the hard-pomeron when it is highly virtual



Small x is high W^2, $x=Q^2/2p.q$ Q^2/W^2

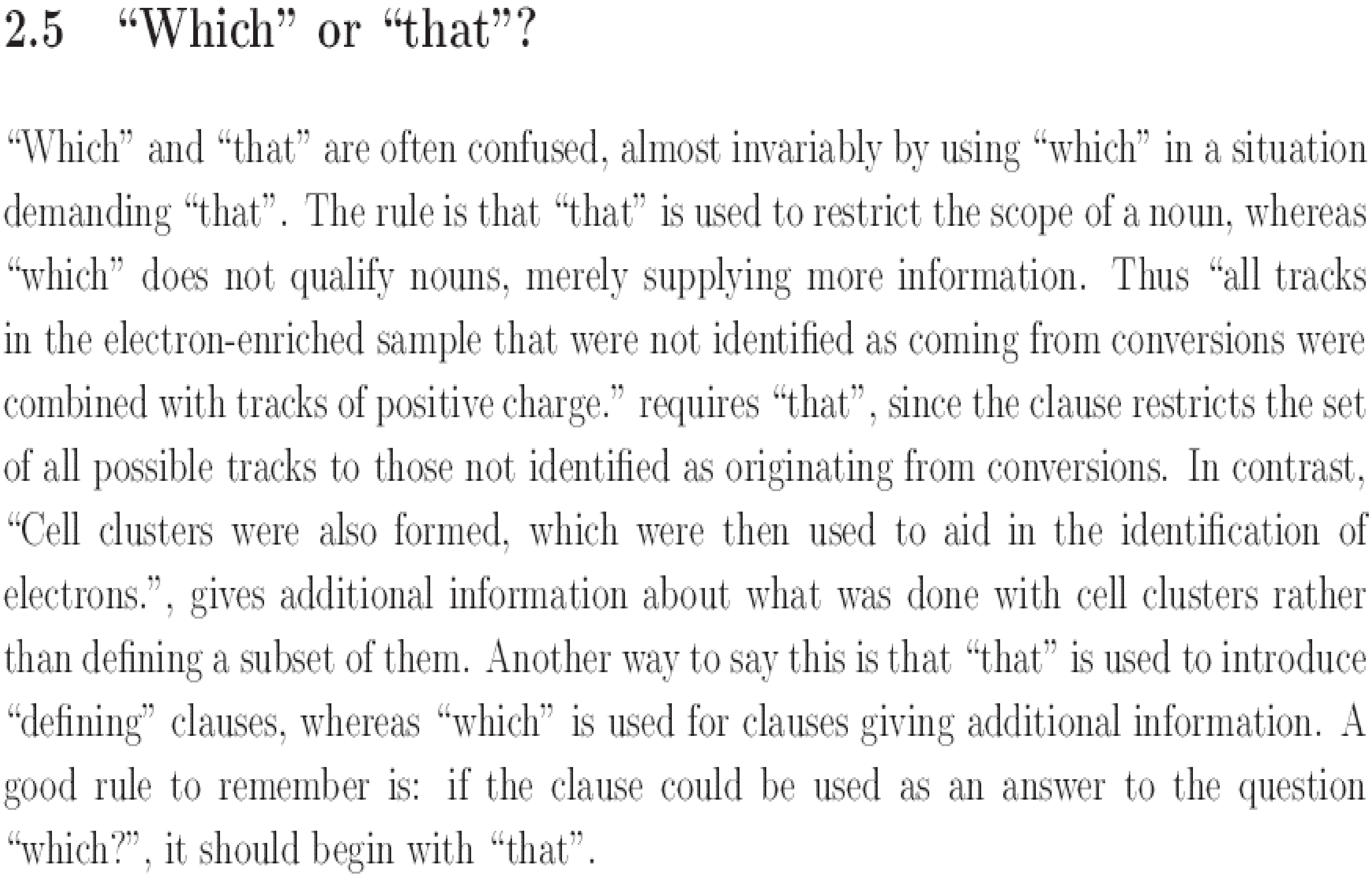
$\sigma(\gamma^* p) \sim (W^2)^{\alpha-1}$ – Regge prediction for high energy cross-sections

And finally Brian’s greatest contribution?



The guide to writing ZEUS papers

Brian Foster



2.5 “Which” or “that”?

“Which” and “that” are often confused, almost invariably by using “which” in a situation demanding “that”. The rule is that “that” is used to restrict the scope of a noun, whereas “which” does not qualify nouns, merely supplying more information. Thus “all tracks in the electron-enriched sample that were not identified as coming from conversions were combined with tracks of positive charge.” requires “that”, since the clause restricts the set of all possible tracks to those not identified as originating from conversions. In contrast, “Cell clusters were also formed, which were then used to aid in the identification of electrons.”, gives additional information about what was done with cell clusters rather than defining a subset of them. Another way to say this is that “that” is used to introduce “defining” clauses, whereas “which” is used for clauses giving additional information. A good rule to remember is: if the clause could be used as an answer to the question “which?”, it should begin with “that”.

Thanks Brian, for all those years

Back-up