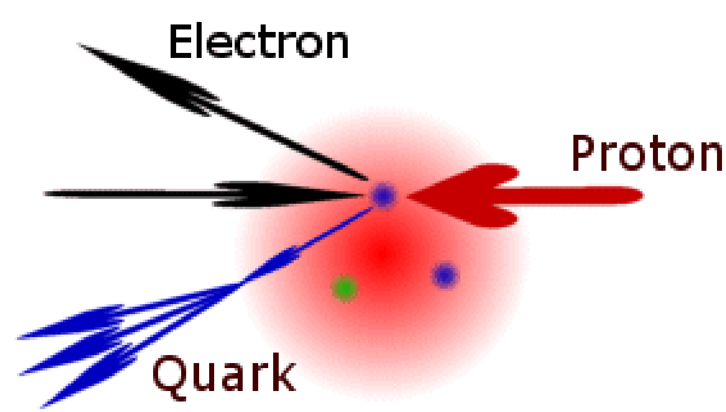
Does Nature know about perturbation theory? A study of HERA data at low Q^2

Hansestadt Hamburg Team:

I. Abt, A. Cooper-Sarkar, B. Foster, V. Myronenko, K. Wichmann, M. Wing

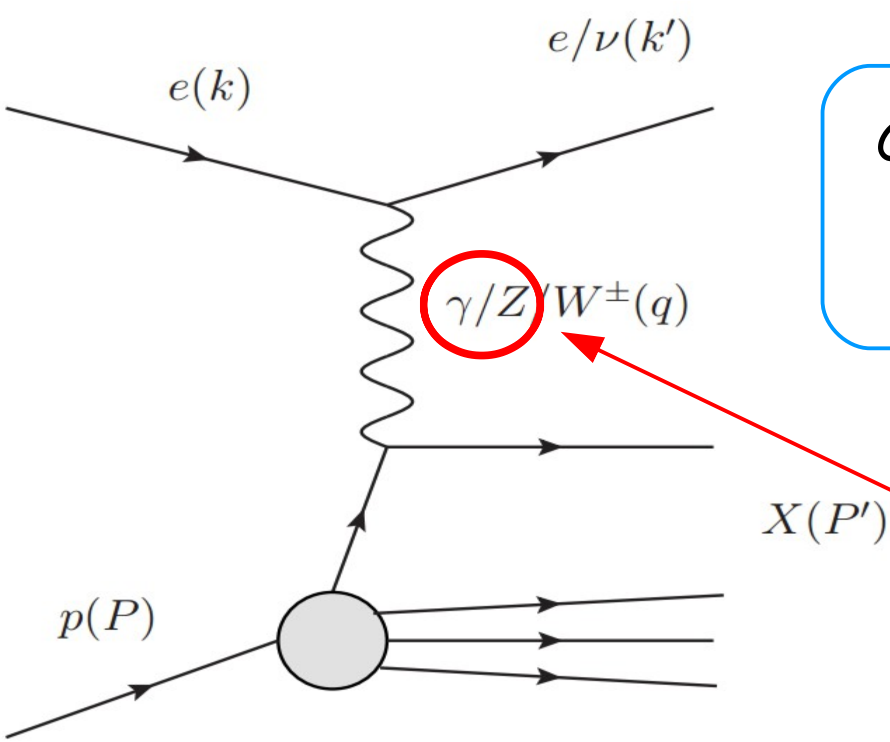
Phys. Rev. D 94, 034032 (2016), DESY-17-051 (accepted by PRD)



Acknowledgements

We would like to thank Halina Abramowicz and Aharon Levy for discussions about ALLM and Barbara Badełek and Anna Stasto for the discussions on the BKS model and their help in providing their results numerically. We would like to thank Paul Newman for discussions on Regge phenomenology. We thank our funding agencies, especially the Humboldt foundation and the MPG, for financial support and DESY for the hospitality extended to the non-DESY authors.

Deep Inelastic Scattering at HERA



Combined H1/ZEUS inclusive DIS cross sections → final word from HERA → HERA legacy

Neutral Current (NC)

$$\sqrt{s} = 318\,(300,\,225,\,252)\,GeV$$

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

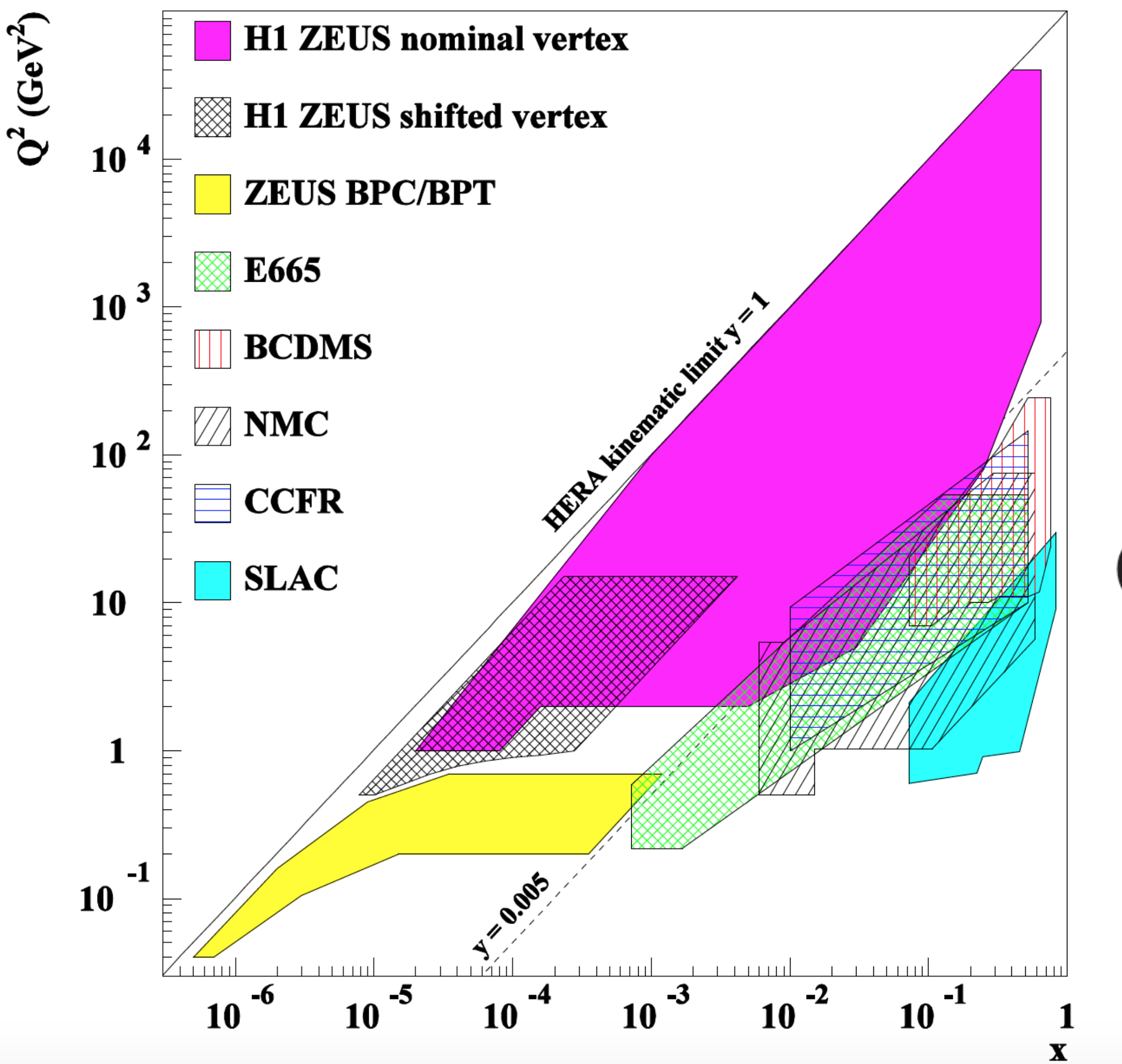
$$x_{Bj} = \frac{Q^2}{2\,pq} \qquad y = \frac{pq}{pk}$$

$$s = (p+k)^2 \qquad Q^2 = xys$$

Experimental luminosity (H1 & ZEUS):

~ 0.5fb^{-1} data from each experiment

@ HERA low $Q^2 \rightarrow$ low x



$$6.21 \cdot 10^{-7} \leq x_{\mathrm{Bj}} \leq 0.65$$

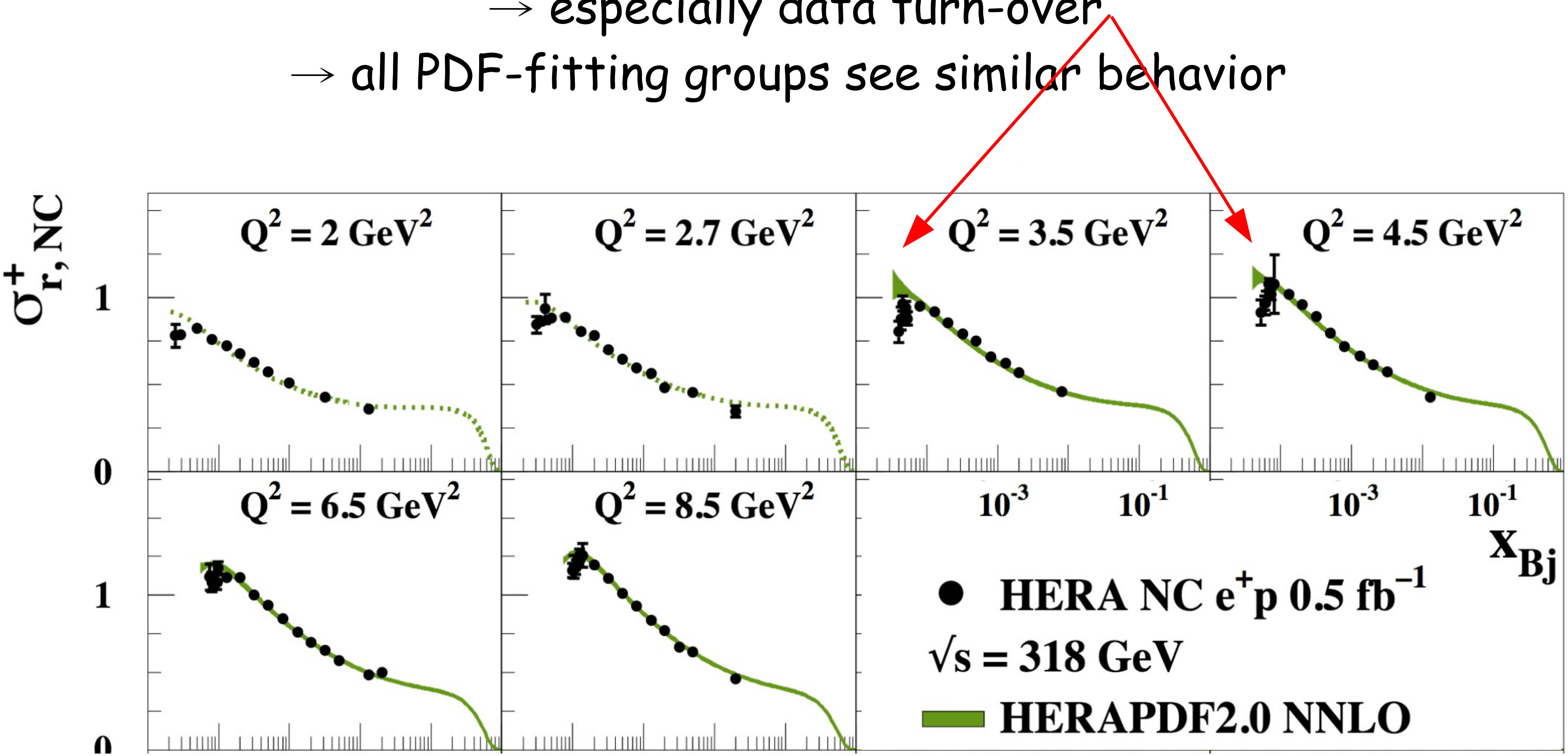
$$0.045 \leq Q^2 \leq 30000\,\mathrm{GeV}^2$$

HERAPDF2.0 @ low Q^2 and low x

- HERA low Q^2, low x data are not described very well by predictions @ NLO and NNLO

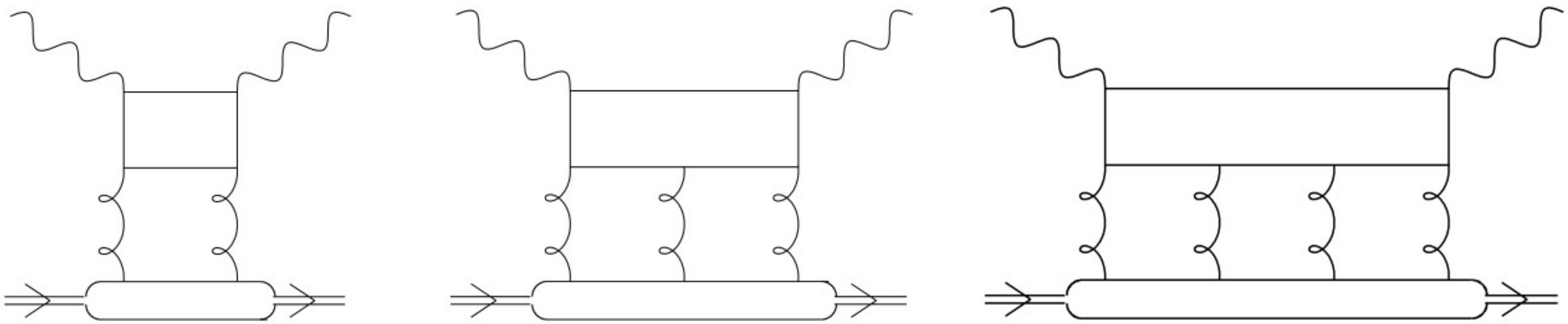
→ especially data turn-over

→ all PDF-fitting groups see similar behavior



Higher-twist corrections

Phys. Rev. D 94, 034032 (2016)

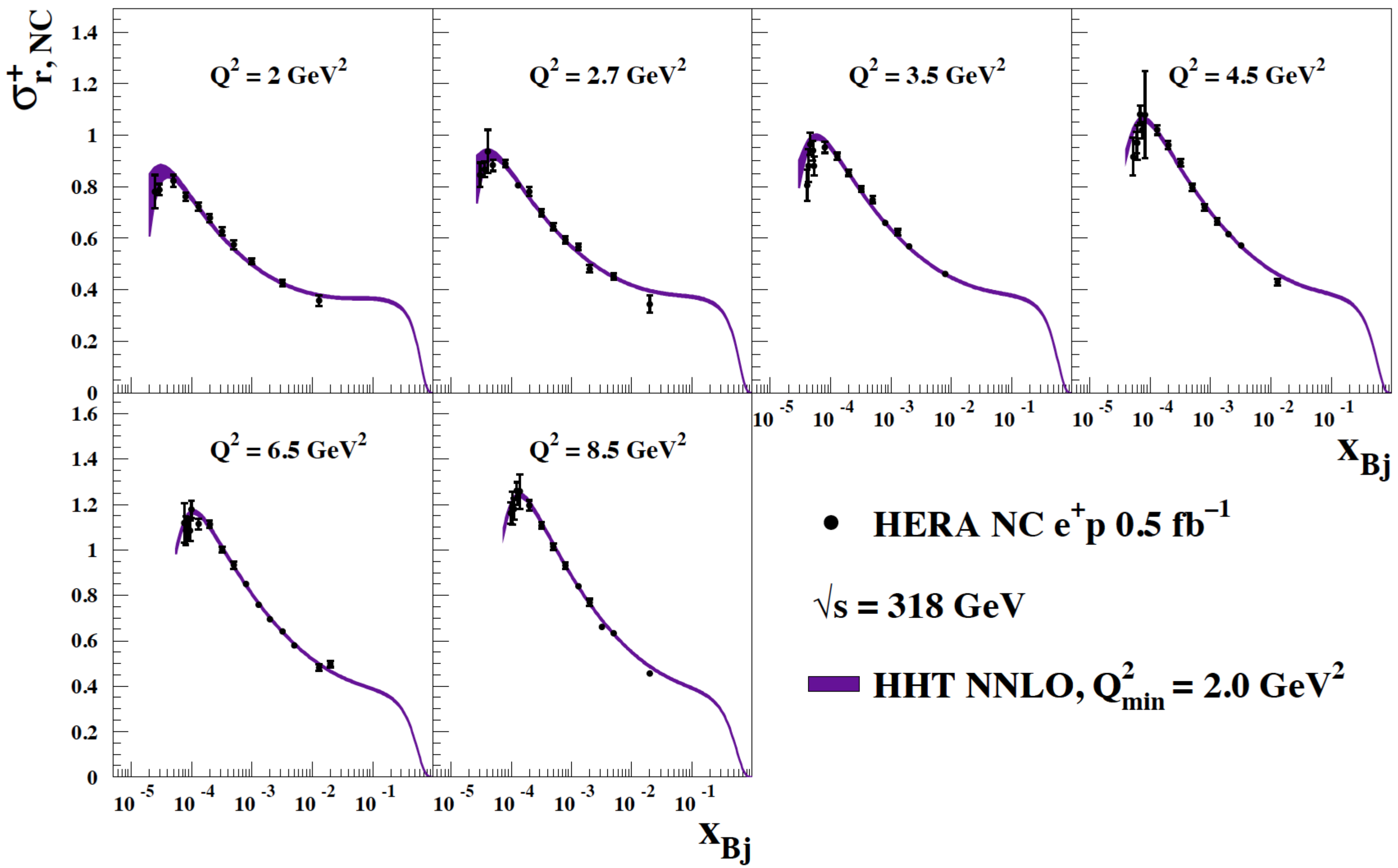


- higher twist terms acting at low-x considered
- their origin COULD be connected with the recombination of gluon ladders
- Bartels, Golec-Biernat, Peters suggested that such higher twist terms would cancel between σ_L and σ_T in F_2, but remain strong in F_L
- simplest possible modification to structure functions F_2 and F_L as calculated from HERAPDF2.0 formalism tried

$$F_2^{\mathrm{HT}} = F_2^{\mathrm{DGLAP}} (1 + A_2^{\mathrm{HT}}/Q^2)$$ → has almost no effect, A consistent with 0

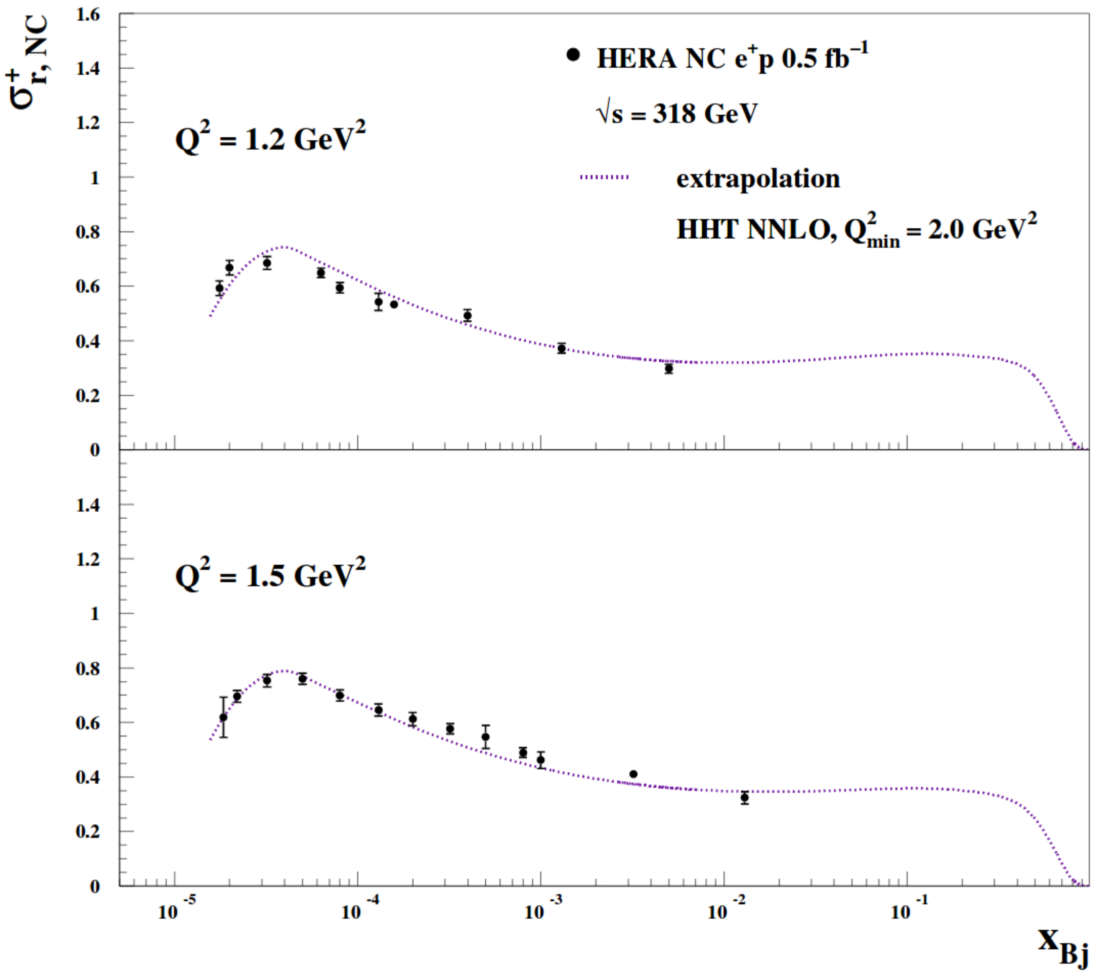
$$F_L^{\mathrm{HT}} = F_L^{\mathrm{DGLAP}} (1 + A_L^{\mathrm{HT}}/Q^2)$$ → **helps a lot, A ~ 4-5**

Let's be bold and fit from $Q^2 = 2$ GeV^2



Look at the excellent description at low Q^2

Being even bolder - extrapolation down to $Q^2 \sim 1$ GeV^2



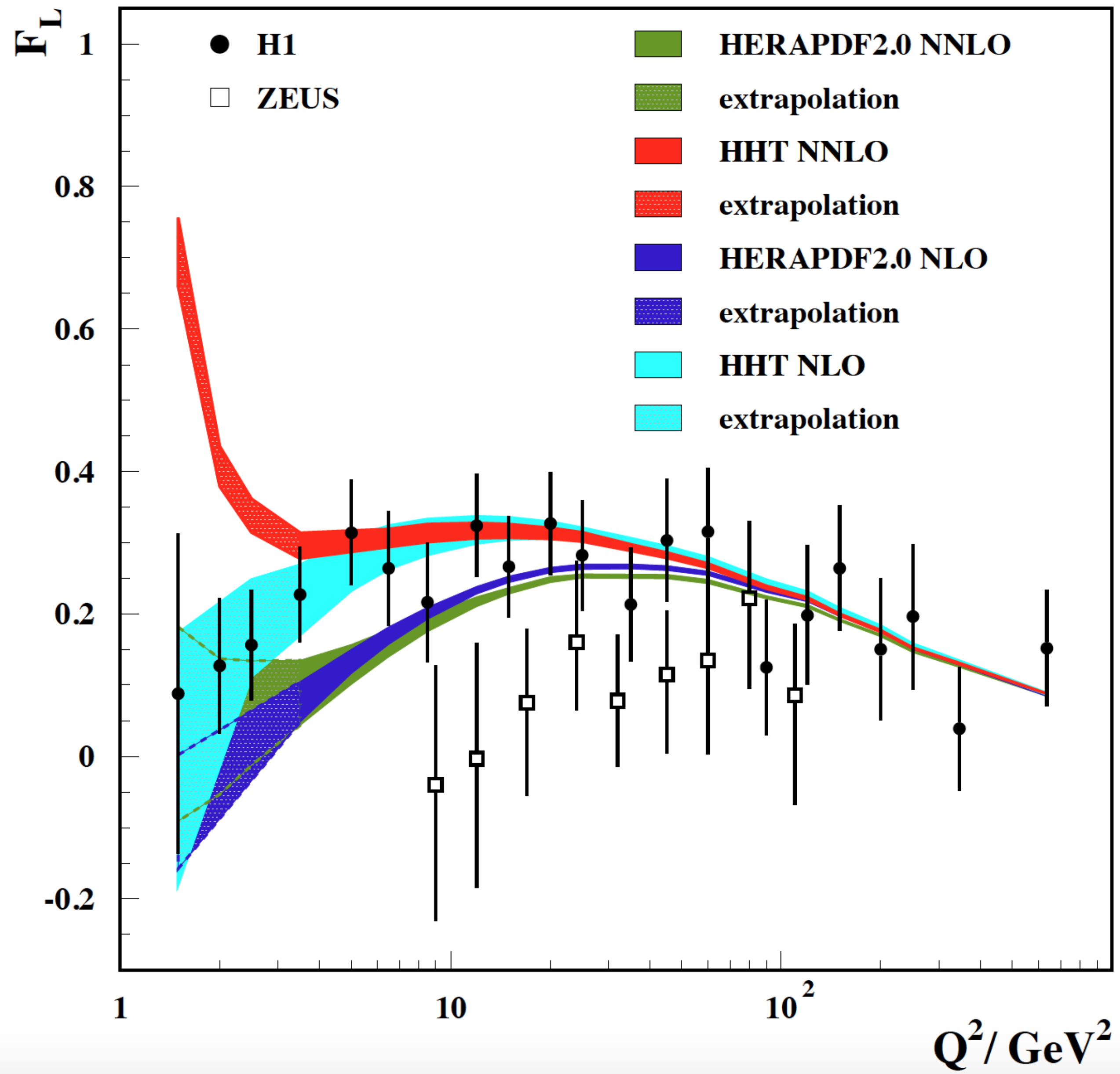
good description of data down to ~1 GeV^2

But beware… is this actually reasonable?

What does F_L itself look like?

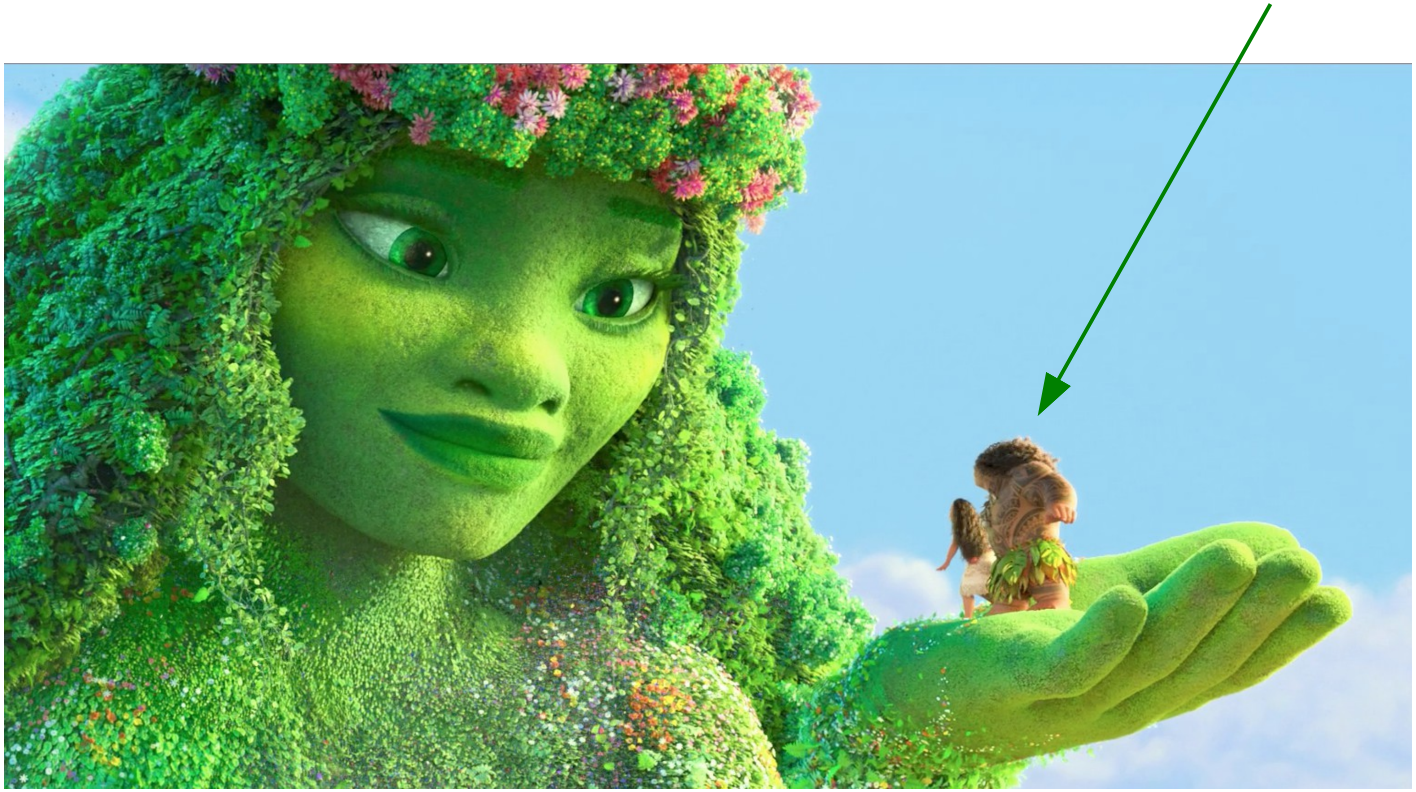
F_L measurements & predictions

- Various predictions compared to unbiased extraction of F_L
- NNLO HHT FL prediction untamed at low Q^2
- this approach cannot be pushed too far
- this comes from NNLO coeff. functions and $1/Q^2$ term makes it worse

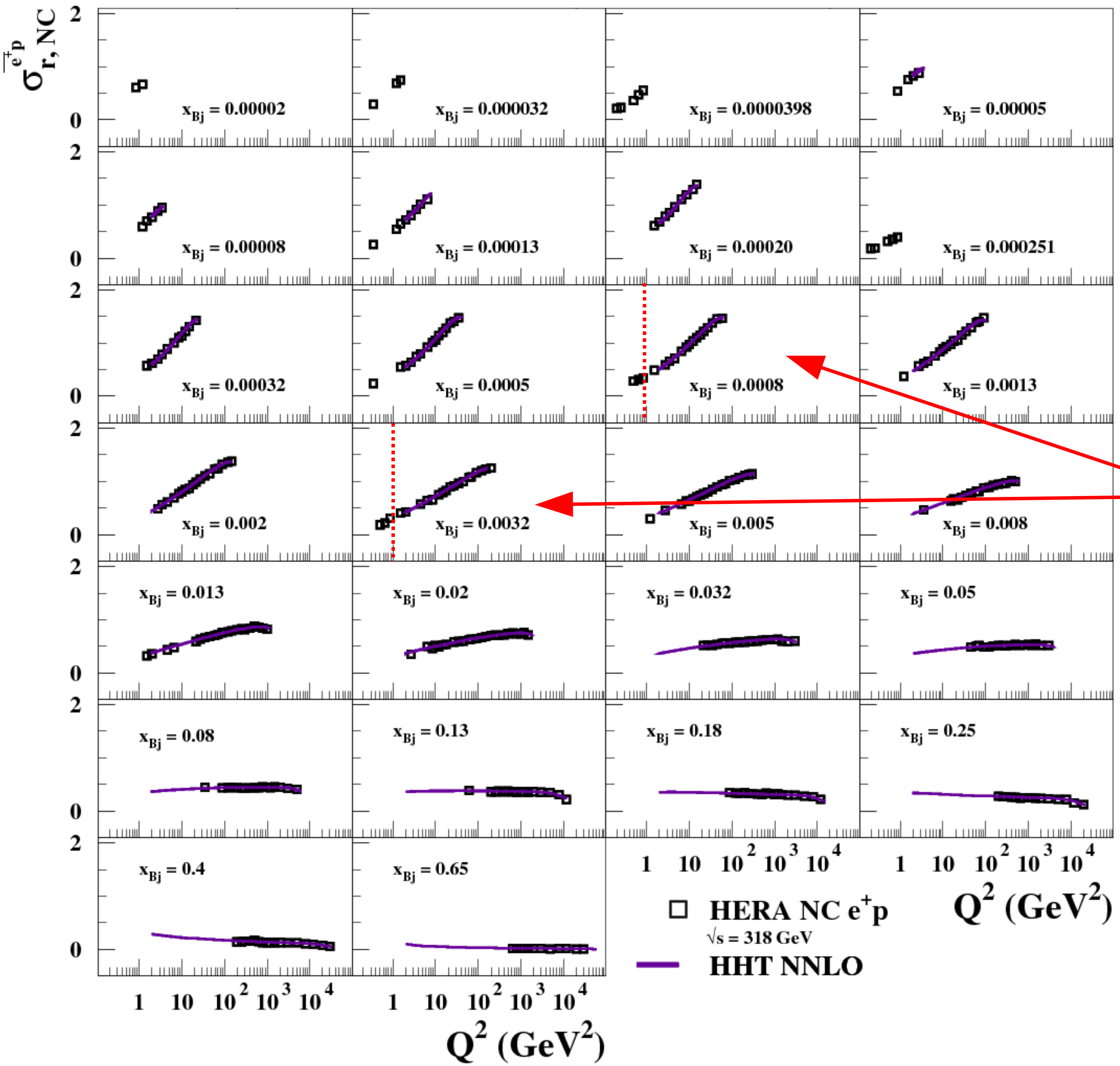


The overlap region between soft and hard physics is of particular interest

Does Nature know about pQCD?



Reduced cross sections



- Scaling violations well established

→ good description by pQCD

- No dramatic change observed around transition point ~ 1 GeV^2

Nature seems not to know about perturbation theory

$$\sigma_{r,NC}^{e^+p} = \tilde{F}_2(x_{Bj}, Q^2) - \frac{Y_-}{Y_+} x\tilde{F}_3(x_{Bj}, Q^2) - \frac{y^2}{Y_+} F_L(x_{Bj}, Q^2)$$

F_2 and $\sigma^{\gamma^* p}$

$$\sigma_{r,\mathrm{NC}}^{e^+p} = F_2 - \frac{y^2}{Y_+} F_L$$

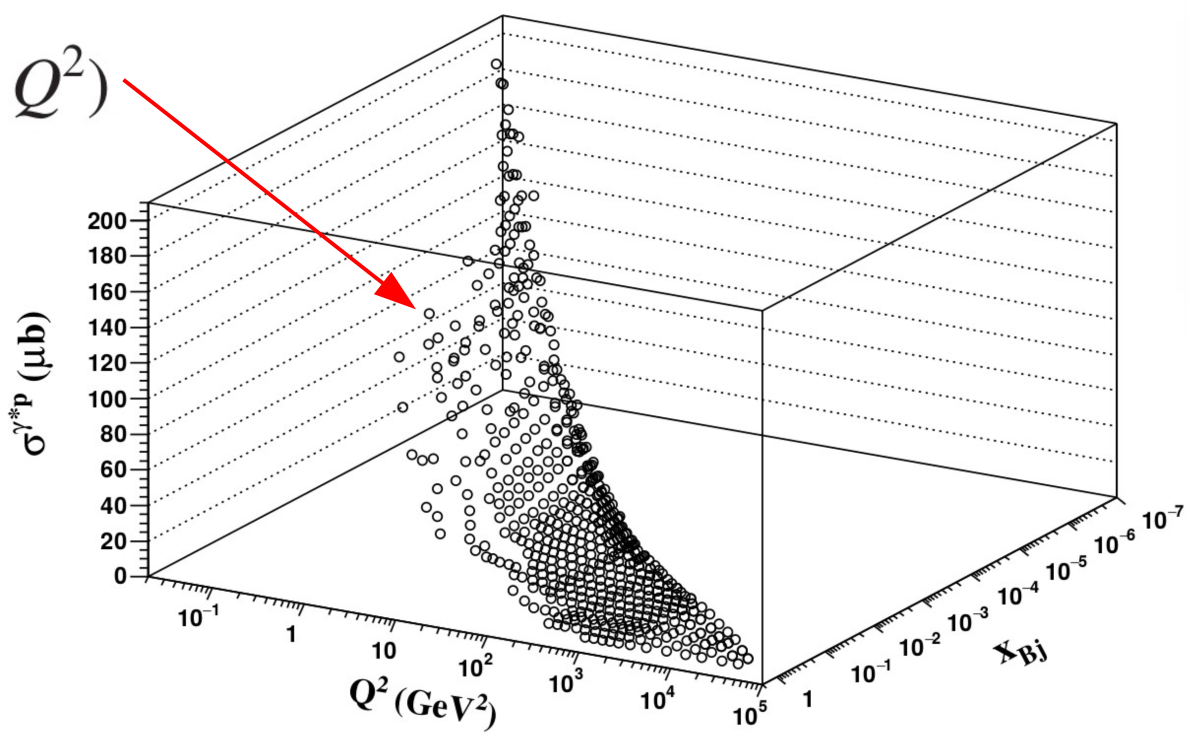
- Extracting F_2 tricky – no unbiased way exists

$$F_2^{\mathrm{extracted}} = F_2^{\mathrm{predicted}} \frac{\sigma_r^{\mathrm{measured}}}{\sigma_r^{\mathrm{predicted}}}$$

  - Low Q^2: Regge inspired BKS
  - **High Q^2: pQCD HHT NNLO**

- Extracting cross section for virtual photon exchange, $\sigma^{\gamma^* p}$, tricky

$$\sigma^{\gamma^* p}(x_{\mathrm{Bj}}, Q^2) = \frac{4\pi^2\alpha}{Q^2} F_2(x_{\mathrm{Bj}}, Q^2)$$



$\sigma^{\gamma^* p}$ forms smooth plane
→ no abrupt features around
transition point ~ 1 GeV^2

Possible parameterisations

Regge phenomenology

$Q^2 \lesssim 0.65\,\mathrm{GeV}^2$

$$F_2(x_{\mathrm{Bj}}, Q^2) = \frac{Q^2}{4\pi^2\alpha} \cdot \frac{M_0^2}{M_0^2 + Q^2} \cdot \left(A_{I\!P} \left(\frac{Q^2}{x_{\mathrm{Bj}}} \right)^{\alpha_{I\!P}(0)-1} + A_{I\!R} \left(\frac{Q^2}{x_{\mathrm{Bj}}} \right)^{\alpha_{I\!R}(0)-1} \right)$$

Describes data well up to < 1 GeV²
IP intercept consistent with $\alpha_{I\!P}(0) \approx 1.08$

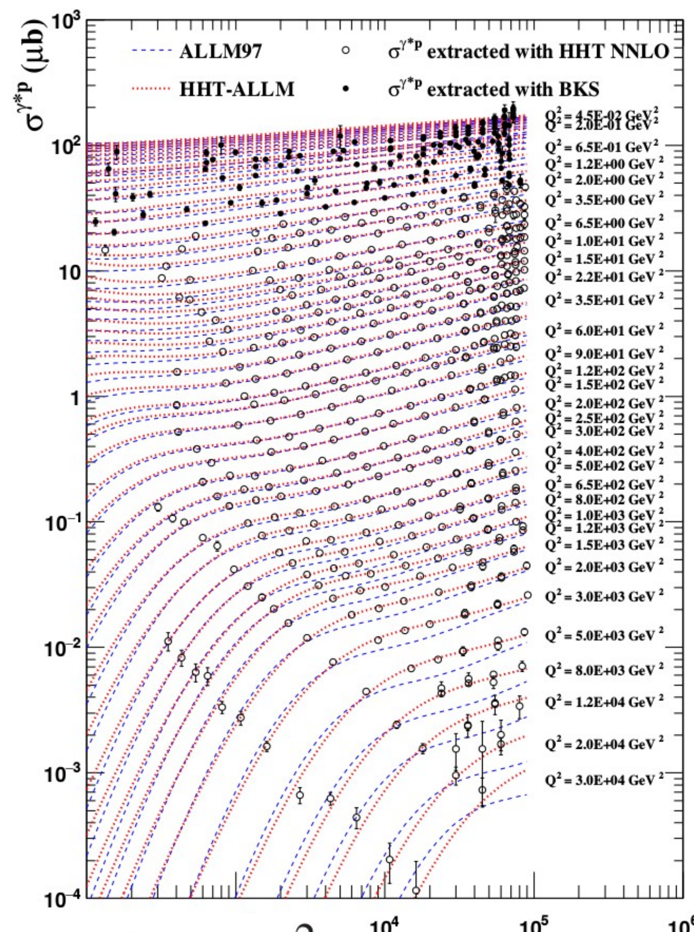
ALLM parameterisation

- Inspired by Regge theory
- Incorporates ideas of pQCD

$$F_2 = \frac{Q^2}{Q^2 + m_0^2} \cdot (F_2^{I\!P} + F_2^{I\!R})$$

- Overall 23 free parameters

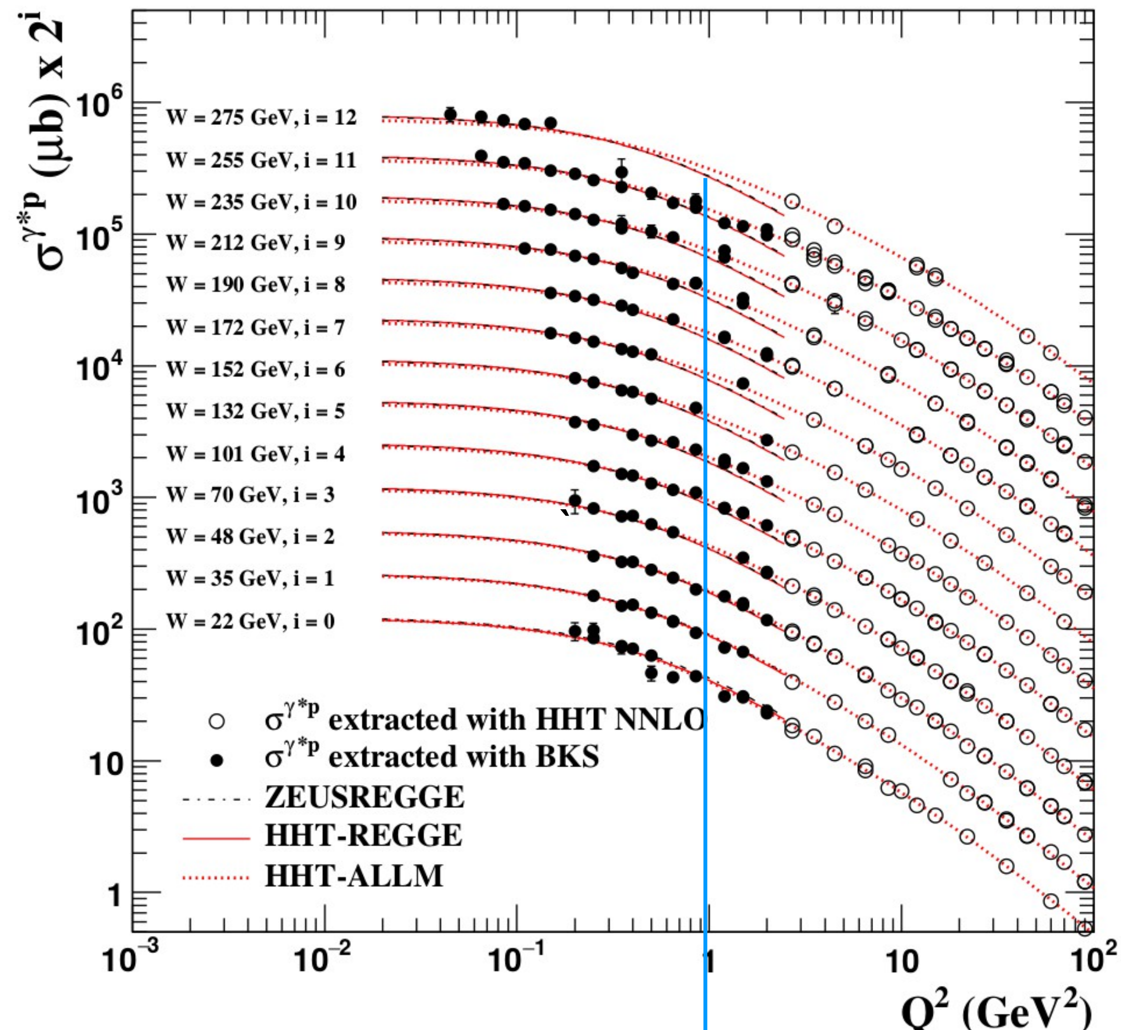
Describes data well across the whole kinematic range



$$W^2 = Q^2(1/x_{\mathrm{Bj}} - 1) + m_p^2$$

σ^{γ^*p} for selected W values

- σ^{γ^*p} extracted with HHT NNLO and BKS depending on Q^2
- Points connect smoothly at change-over value of 2 GeV^2
- Low & high Q^2 behavior differs
  → at high Q^2 σ^{γ^*p} drops as $1/Q^2$
  → at low Q^2 σ^{γ^*p} flattens out
- Good description by HHT-ALLM and Regge fits (fits very similar)



Lack of a break in transition region ~1 GeV^2 is striking

Extracting λ and C parameters

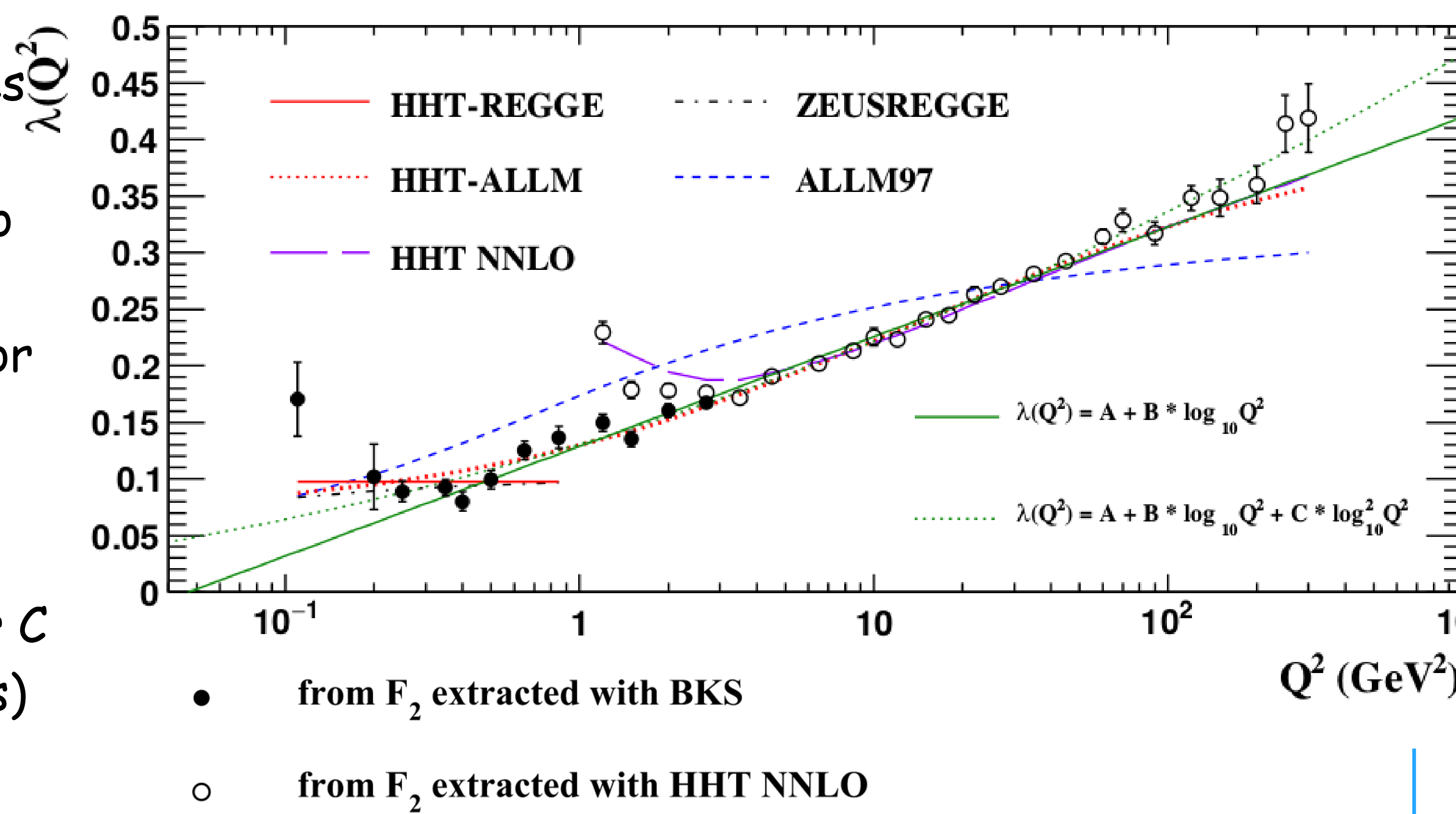
- HHT NNLO: $Q^2 > 1.2$ GeV^2 → good down to ~2 GeV^2
- BKS: $Q^2 < 2.7$ GeV^2 → connects smoothly to HHT NNLO ~2 GeV^2

→ Different in overlap region

$$F_2 = C(Q^2)x_{\mathrm{Bj}}^{-\lambda(Q^2)} \qquad x_{\mathrm{Bj}} < 0.01$$

- HHT-ALLM describes data well
- REGGE fit good up to ~0.5 GeV^2
- λ can be fit with 1st or 2nd order polynomial

→ Same conclusions for C (figure in backup slides)

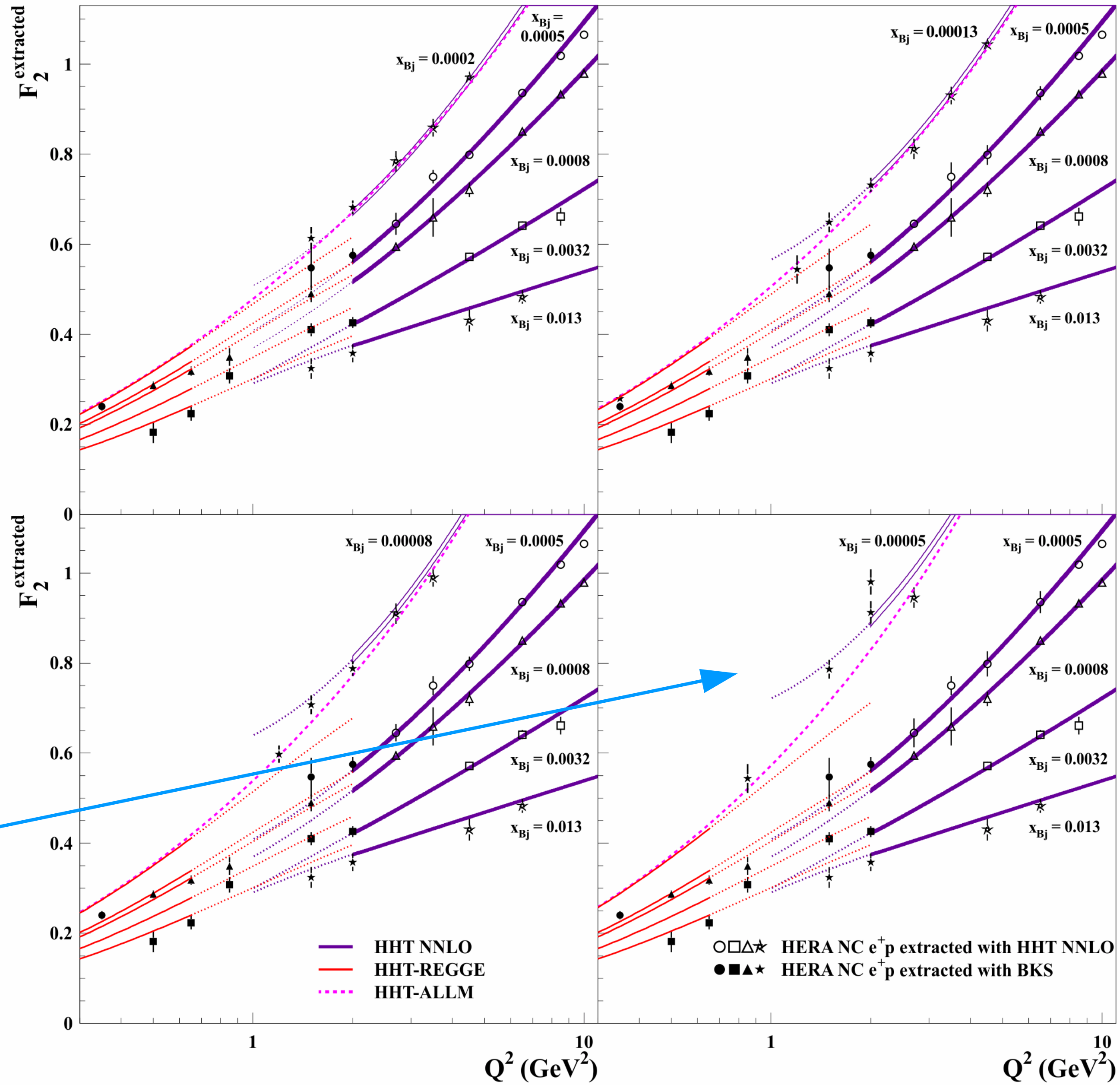


F_2 at lowest x_{Bj}

- As x_{Bj} falls, growing gap opens up between pQCD and Regge extrapolations in transition region

This gap is smoothly bridged by data!

- Region of very low x_{Bj} pinpointed



Summary & Outlook

- HERA low-Q^2 low-x data well described by simple twist 4 term at F_L
  → however for lowest Q^2 F_L gets unphysical
- Structure-function F_2 and photon-proton cross section $\sigma^{\gamma^* p}$ extracted
  - Using HHT NNLO in pQCD region $Q^2 > 2$ GeV^2
  - Using Regge-inspired BKS for $Q^2 < 2$ GeV^2

  → data agree well around this transition point
- Characteristics of F_2, $\sigma^{\gamma^* p}$ and $dF_2/d\ln Q^2$ studied in detail
- Data well described by HHT NNLO, HHT-ALLM and HHT-REGGE fits

→ No abrupt transition between soft and hard regions observed in the data
→ Nature seems not to know about perturbation theory

- Future electron-proton/electron-ion collider needed
- Presented data important for model building @ low x and low Q^2

Additional slides

Data in fits from $Q^2 > 3.5$ GeV^2

HERAPDF2.0

NLO $\frac{\chi^2}{ndf} = \frac{1356}{1131} \approx 1.20$

NNLO $\frac{\chi^2}{ndf} = \frac{1363}{1131} \approx 1.21$

- Introducing $F_2^{HT} = F_2^{DGLAP}(1 + \frac{A_2^{HT}}{Q^2})$ **has almost no effect,** *A consistent with 0*

HHT@F_2

NLO $\frac{\chi^2}{ndf} = \frac{1354}{1130} \approx 1.20$

NNLO $\frac{\chi^2}{ndf} = \frac{1357}{1130} \approx 1.20$

- Introducing $F_L^{HT} = F_L^{DGLAP}(1 + \frac{A_L^{HT}}{Q^2})$ **helps a lot**

HHT@F_L

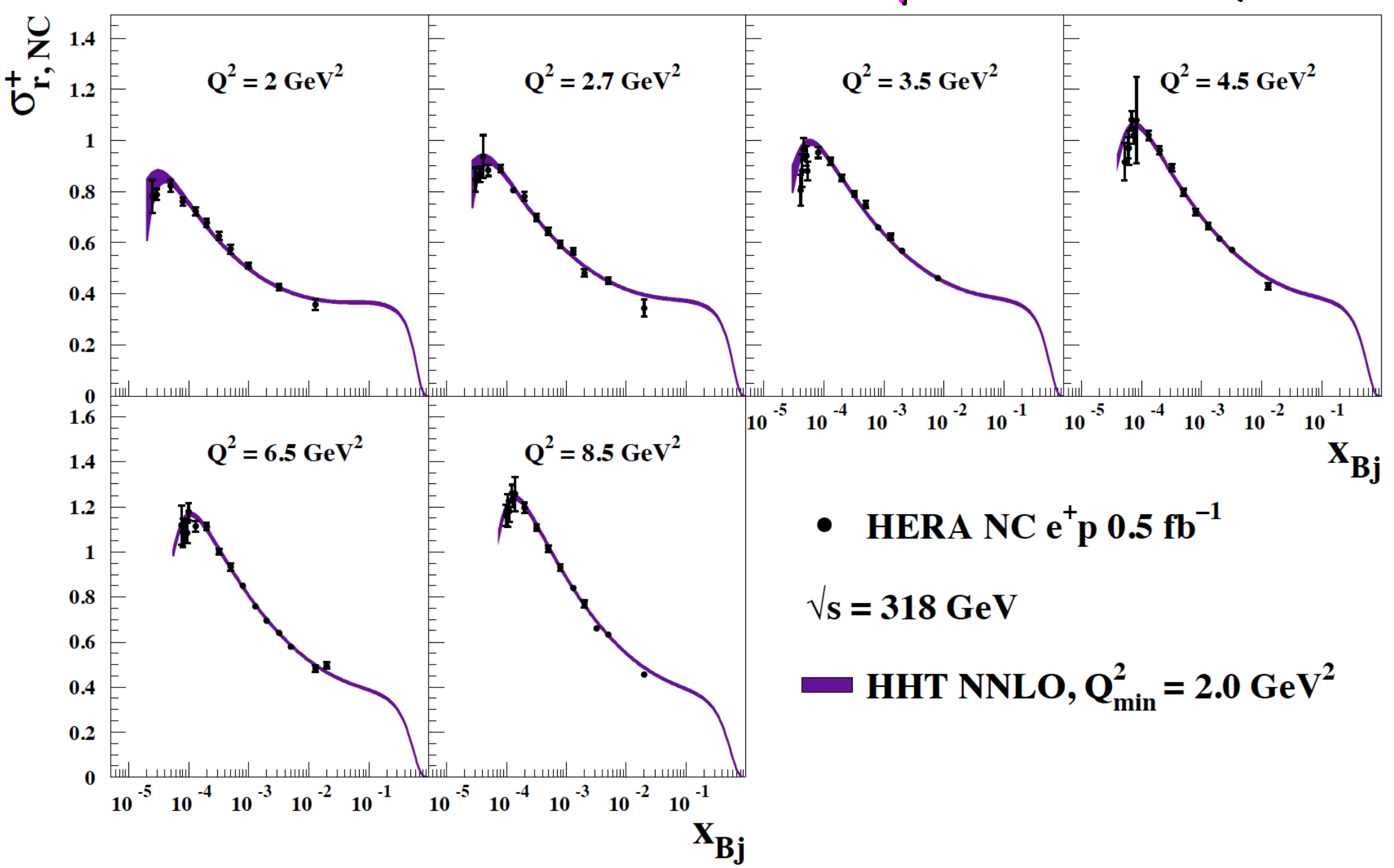
NLO $\frac{\chi^2}{ndf} = \frac{1329}{1130} \approx 1.18$ $\Delta\chi^2 = 27$ $A_L^{HT} = 4.2 \pm 0.7$ GeV^2

NNLO $\frac{\chi^2}{ndf} = \frac{1316}{1130} \approx 1.16$ $\Delta\chi^2 = 47$ $A_L^{HT} = 5.5 \pm 0.6$ GeV^2

Let's be bold and fit from $Q^2 = 2$ GeV^2

	Q^2_{min} = 3.5 GeV^2		Q^2_{min} = 2 GeV^2
NLO	A_L^{HT} = 4.2 ± 0.7 GeV^2	→	A_L^{HT} = 4.0 ± 0.6 GeV^2
NNLO	A_L^{HT} = 5.5 ± 0.6 GeV^2	→	A_L^{HT} = 5.2 ± 0.7 GeV^2

Look at the excellent description at low Q^2



ALLM parameterisation

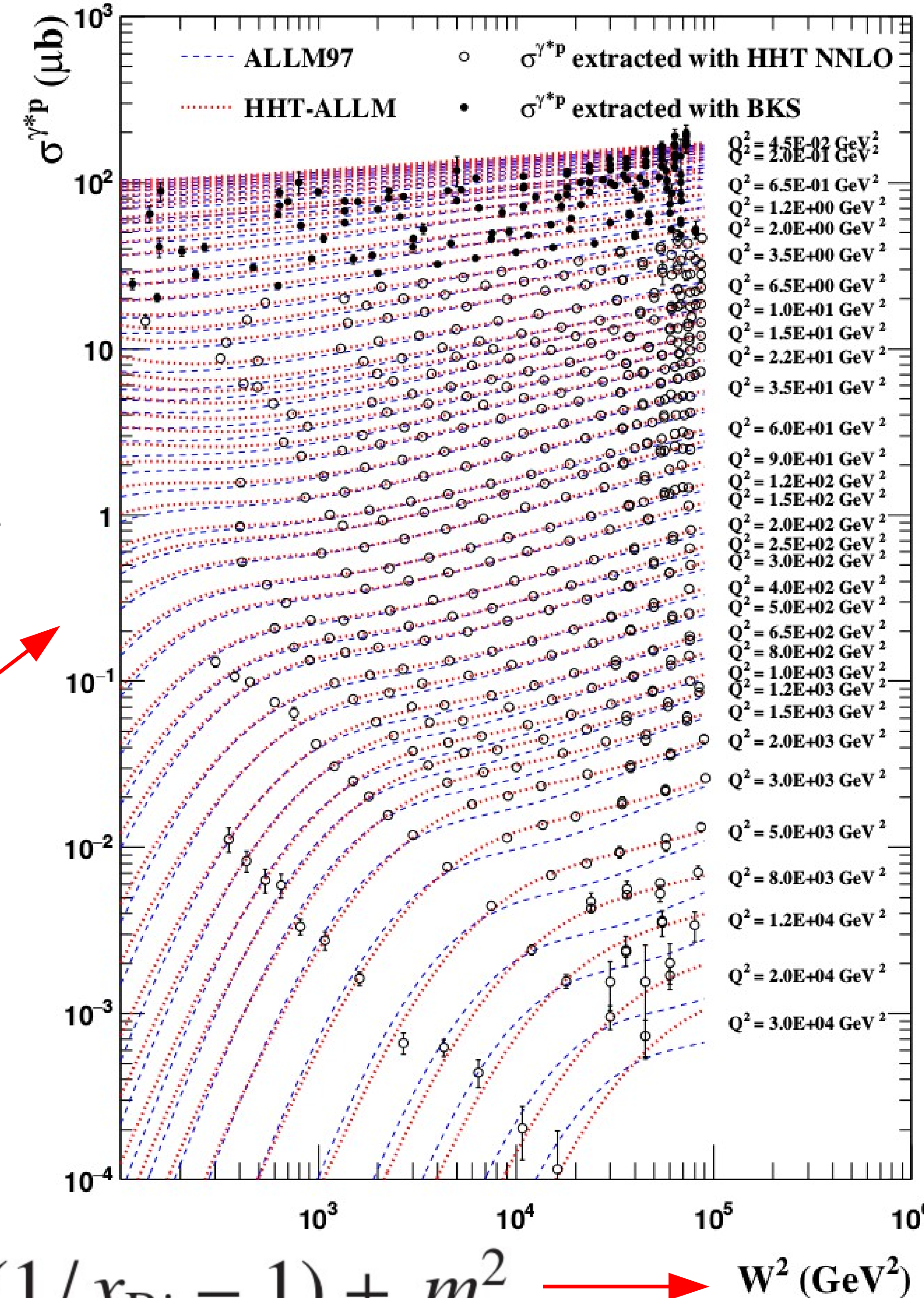
- Inspired by Regge theory
- Incorporates ideas of pQCD

$$F_2 = \frac{Q^2}{Q^2 + m_0^2} \cdot (F_2^{IP} + F_2^{IR})$$

proton mass

- Overall 23 free parameters

Describes data well across the whole kinematic range



$$W^2 = Q^2(1/x_{Bj} - 1) + m_p^2$$

How about Regge phenomenology?

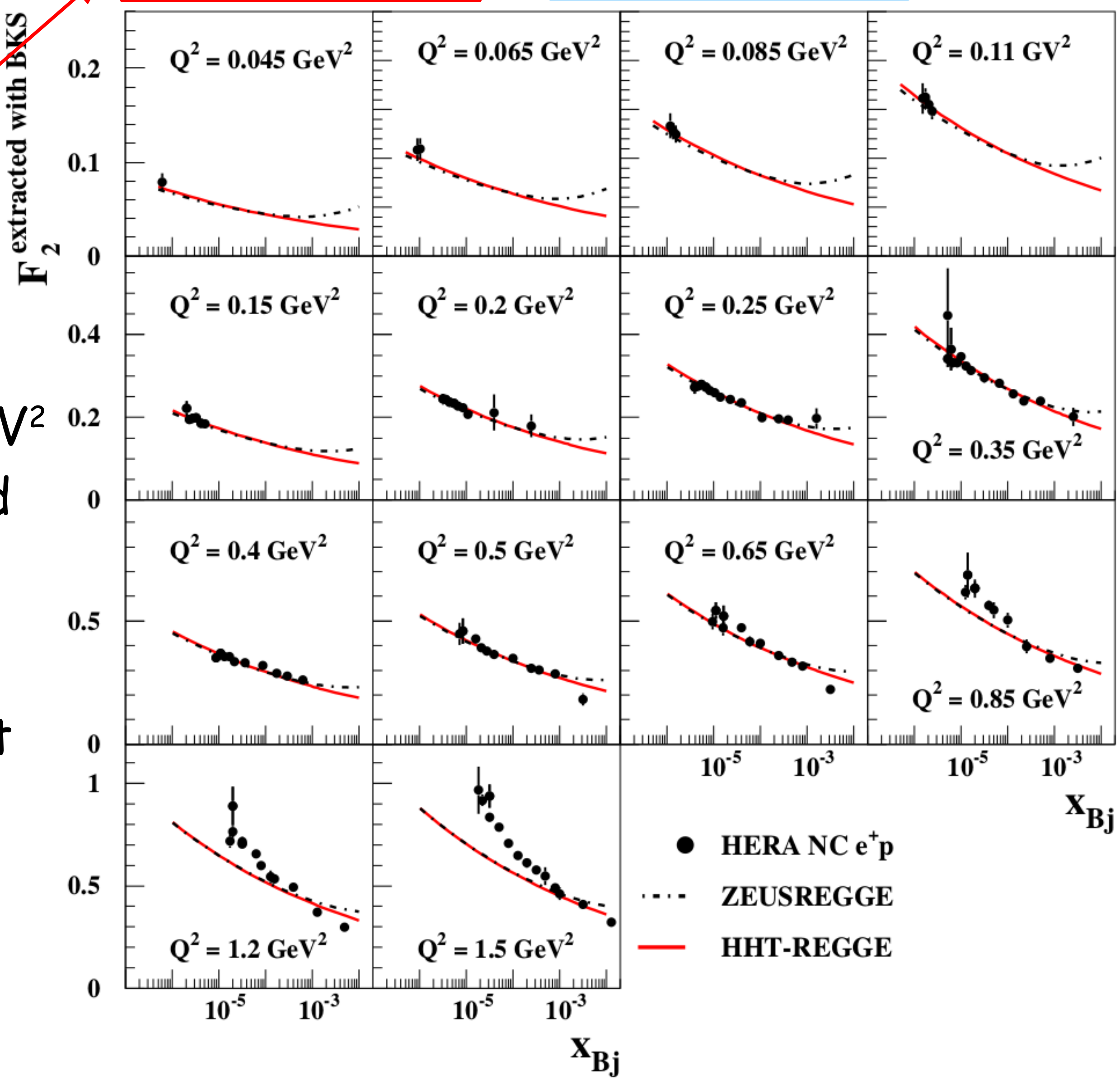
$$F_2(x_{Bj}, Q^2) = \frac{Q^2}{4\pi^2\alpha} \cdot \frac{M_0^2}{M_0^2 + Q^2} \cdot \left(A_{I\!P} \left(\frac{Q^2}{x_{Bj}} \right)^{\alpha_{I\!P}(0)-1} + A_{I\!R} \left(\frac{Q^2}{x_{Bj}} \right)^{\alpha_{I\!R}(0)-1} \right)$$

GVMD

- HHT-REGGE
  - 3 parameters fitted to P
  - $Q^2 \lesssim 0.65\,\mathrm{GeV}^2$
- Good description to ~0.65 GeV²
  - Regge formalism expected to break around that Q²
- Various fits tested

→ All fits compatible with soft Pomeron expectations

$$\alpha_{I\!P}(0) \approx 1.08$$

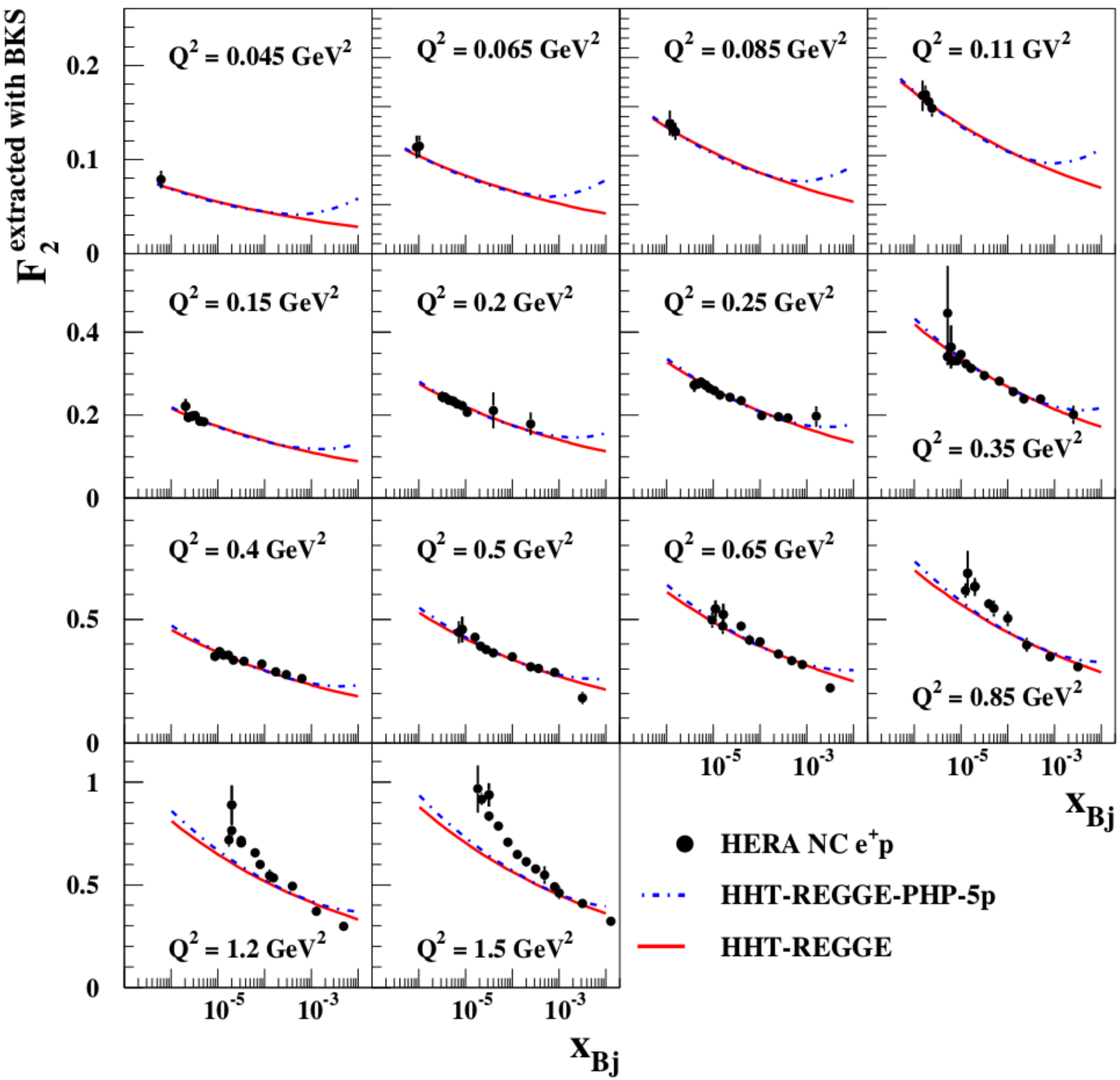


K. Wichmann

HHT-REGGE fits

K. W

- With addition of low-W PhP data Reggeon parameters can be constrained
- Within kinematic range of HERA data description the same
- Adding fixed target data does not improve fits

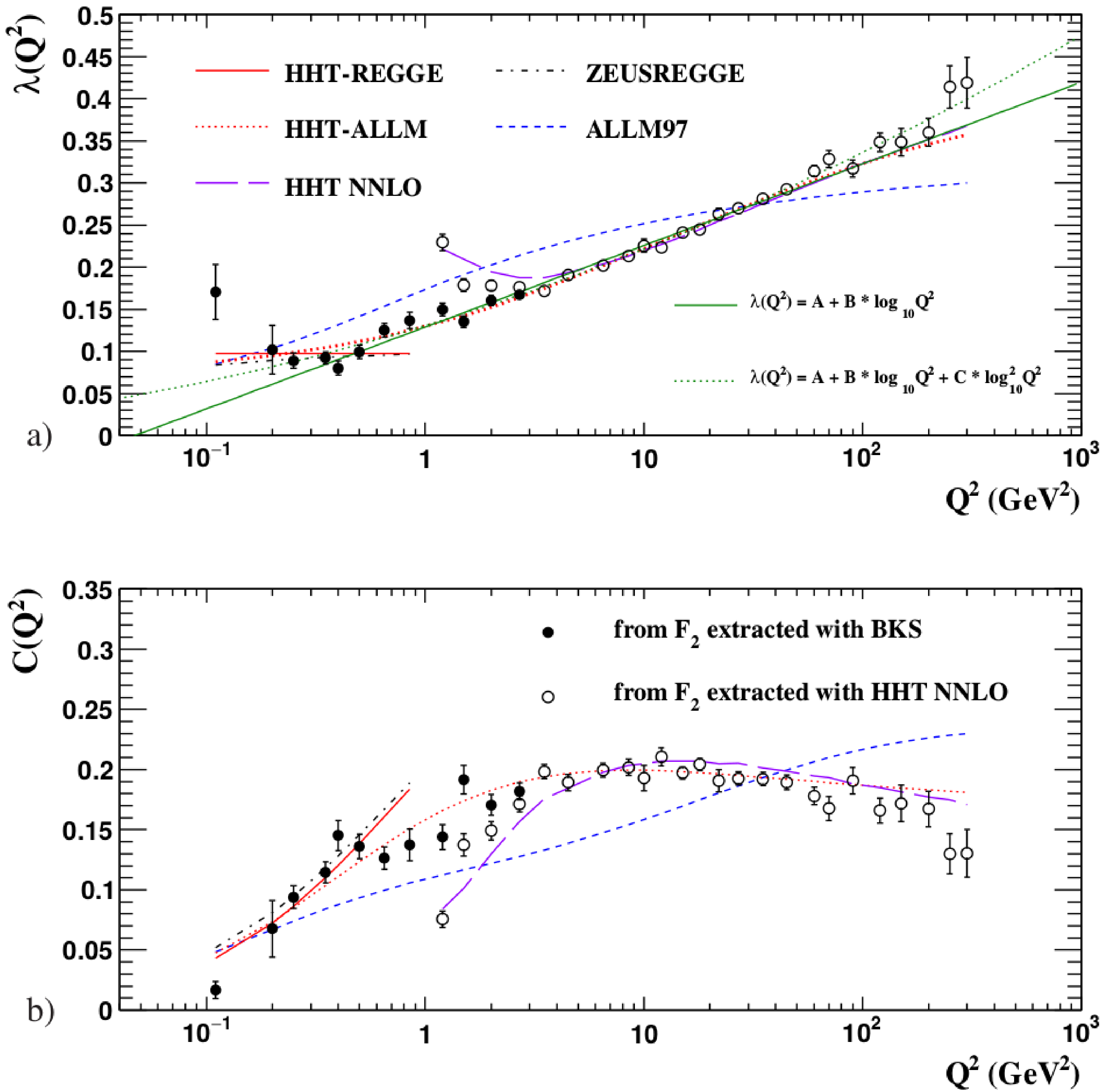


Regge fits

Name of Fit	Fit Parameters					χ^2/ ndf
	M_0^2 (GeV^2)	$A_{I\!P}$ (μb)	$\alpha_{I\!P}(0)$	$A_{I\!R}$ (μb)	$\alpha_{I\!R}(0)$	
HHT-REGGE	0.50 ±0.03	66.3 ± 3.2	1.097 ± 0.004	fixed to 0	–	0.83
3p-.85	0.58 ±0.03	58.5 ± 2.5	1.105 ± 0.003	fixed to 0	–	1.13
4p	0.49 ±0.03	78.5 ± 7.1	1.082 ± 0.008	−230 ±105	fixed to 0.5	0.78
FT-4p	0.50 ±0.02	77.4 ± 5.6	1.083 ± 0.006	−217 ± 60	fixed to 0.5	0.75
PHP-5p	0.52 ±0.01	57.0 ± 4.7	1.110 ± 0.007	193 ± 51	0.50 ±0.11	1.16
PHP-FT-5p	0.48 ±0.01	58.9 ± 3.0	1.110 ± 0.005	263 ± 69	0.39 ±0.09	1.35
ZEUSREGGE	fixed to 0.53	63.5 ± 0.9	1.097 ± 0.002	145 ± 2	fixed to 0.5	1.12
update	0.52 ± 0.04	62.0 ± 2.3	1.102 ± 0.007	148 ± 5	fixed to 0.5	–

Pomeron trajectory $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} \cdot t$

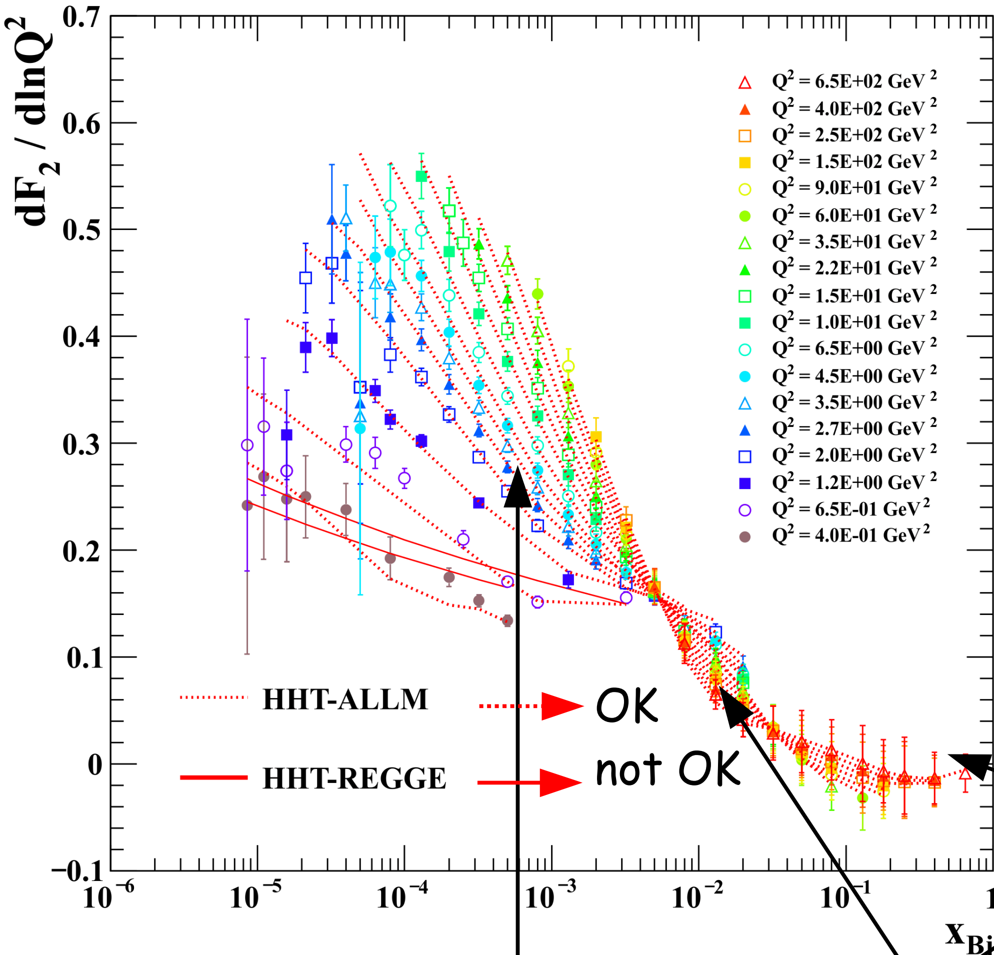
soft Pomeron: $\alpha_{I\!P}(0) \approx 1.08$


λ(Q²)
HHT-REGGE
ZEUSREGGE
HHT-ALLM
ALLM97
HHT NNLO
λ(Q²) = A + B * log₁₀Q²
λ(Q²) = A + B * log₁₀Q² + C * log²₁₀Q²
a)
Q² (GeV²)
C(Q²)
from F₂ extracted with BKS
from F₂ extracted with HHT NNLO
b)
Q² (GeV²)

F_2 derivatives $dF_2/d\ln Q^2 \rightarrow$ info on gluon

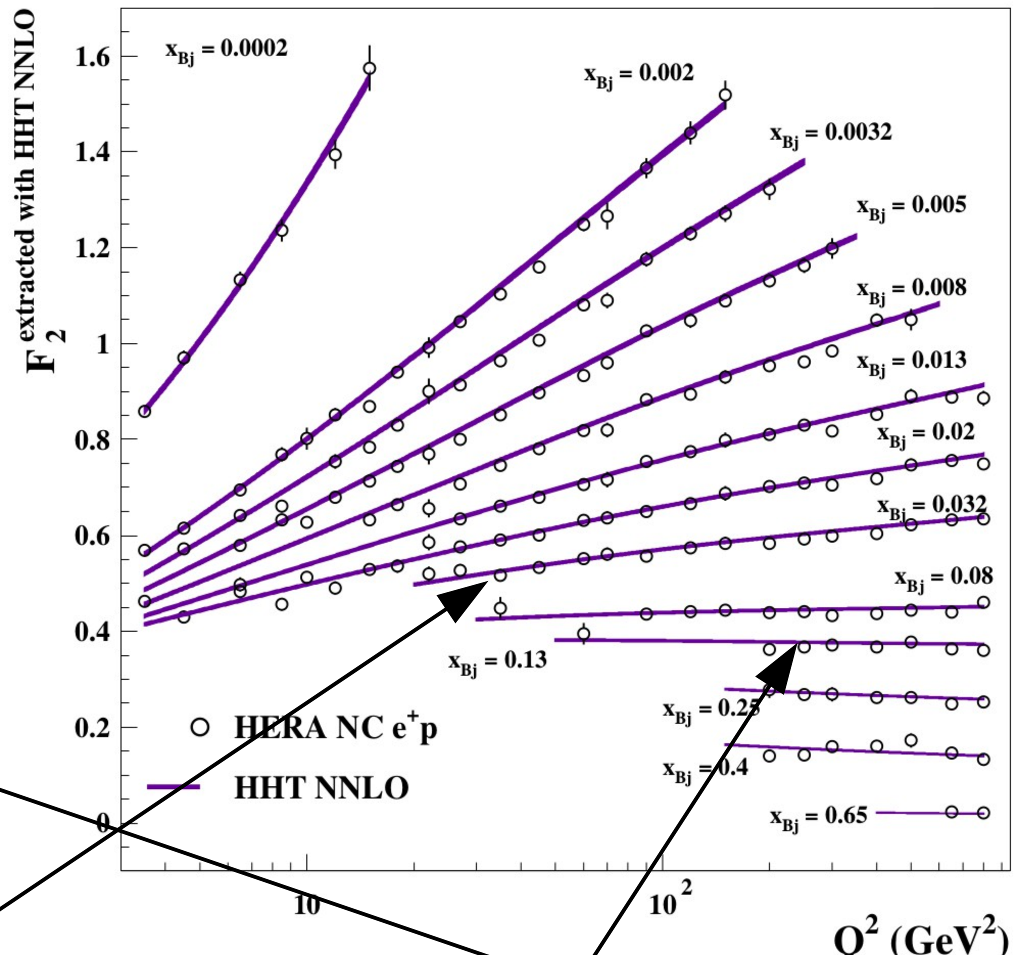
K. Wichman

- Fits to extracted F_2 $\quad F_2 = A(x_{Bj}) + B(x_{Bj}) \ln Q^2 + C(x_{Bj}) \ln^2 Q^2$



OK

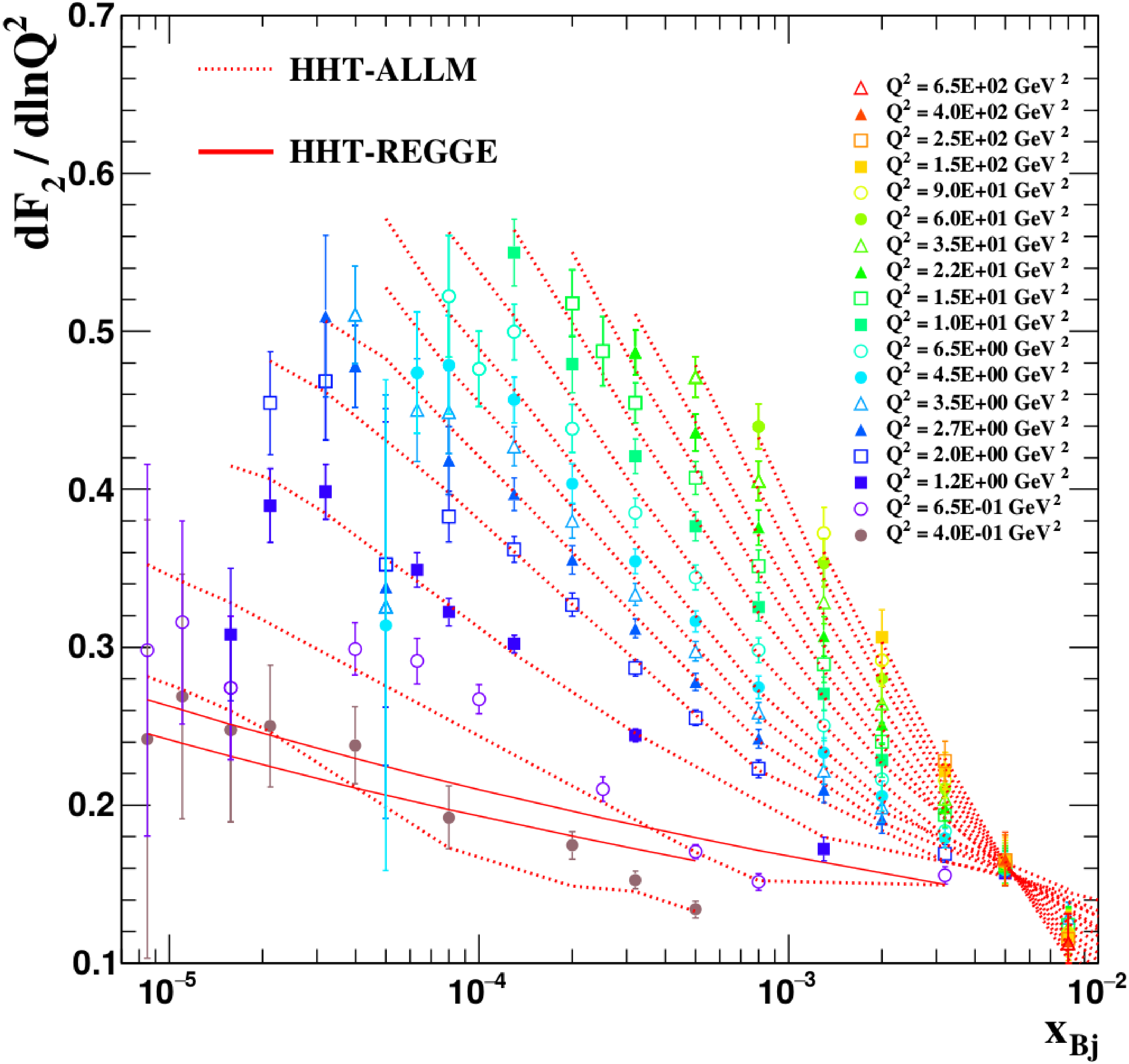
not OK



strong scaling violation
depends on Q^2

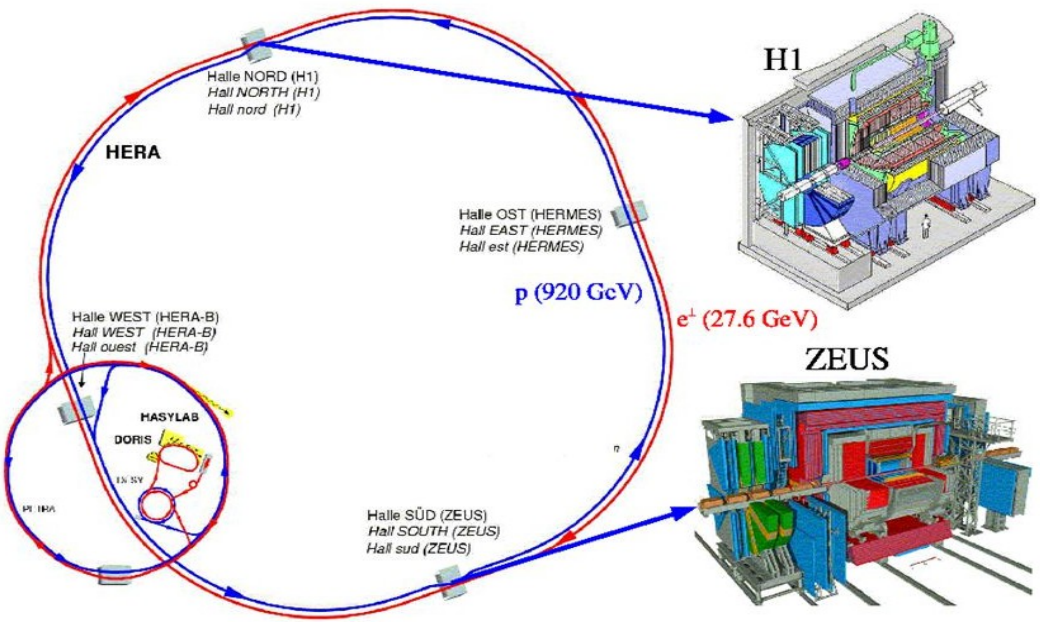
scaling violation
depends on $\alpha_s\,(Q^2)$

scaling



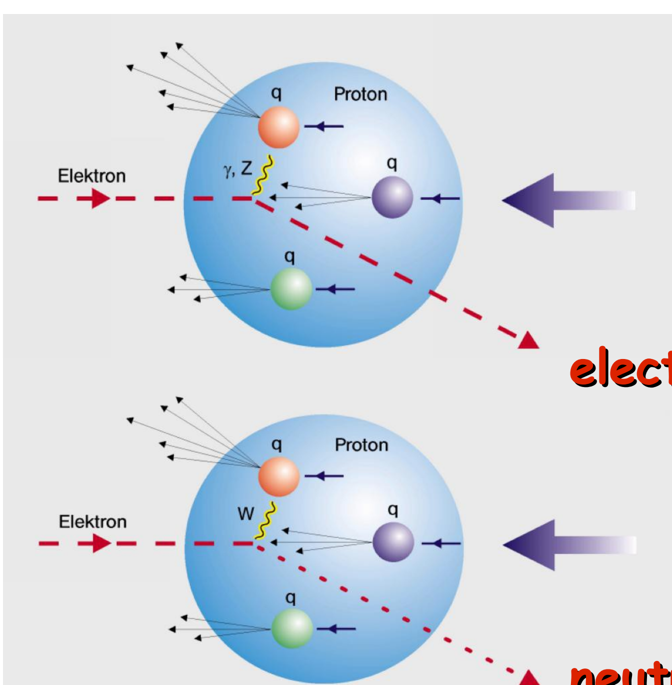
HHT-ALLM
HHT-REGGE
Q² = 6.5E+02 GeV²
Q² = 4.0E+02 GeV²
Q² = 2.5E+02 GeV²
Q² = 1.5E+02 GeV²
Q² = 9.0E+01 GeV²
Q² = 6.0E+01 GeV²
Q² = 3.5E+01 GeV²
Q² = 2.2E+01 GeV²
Q² = 1.5E+01 GeV²
Q² = 1.0E+01 GeV²
Q² = 6.5E+00 GeV²
Q² = 4.5E+00 GeV²
Q² = 3.5E+00 GeV²
Q² = 2.7E+00 GeV²
Q² = 2.0E+00 GeV²
Q² = 1.2E+00 GeV²
Q² = 6.5E-01 GeV²
Q² = 4.0E-01 GeV²
dF₂ / dlnQ²
x_Bj
0.1
0.2
0.3
0.4
0.5
0.6
0.7
10⁻⁵
10⁻⁴
10⁻³
10⁻²

HERA and DIS



- HERA: ep collider in Hamburg
- Operation: 1992-2007
- Colliding experiments: H1 and ZEUS

Deep Inelastic Scattering



electron

neutrino

Neutral Current (NC)

γ, Z^0 exchange

Charged Current (CC)

$W^\pm$ exchange

HERAPDF2.0 @ low Q^2 and low x

- NLO fit for Q^2_{min} = 3.5 GeV^2

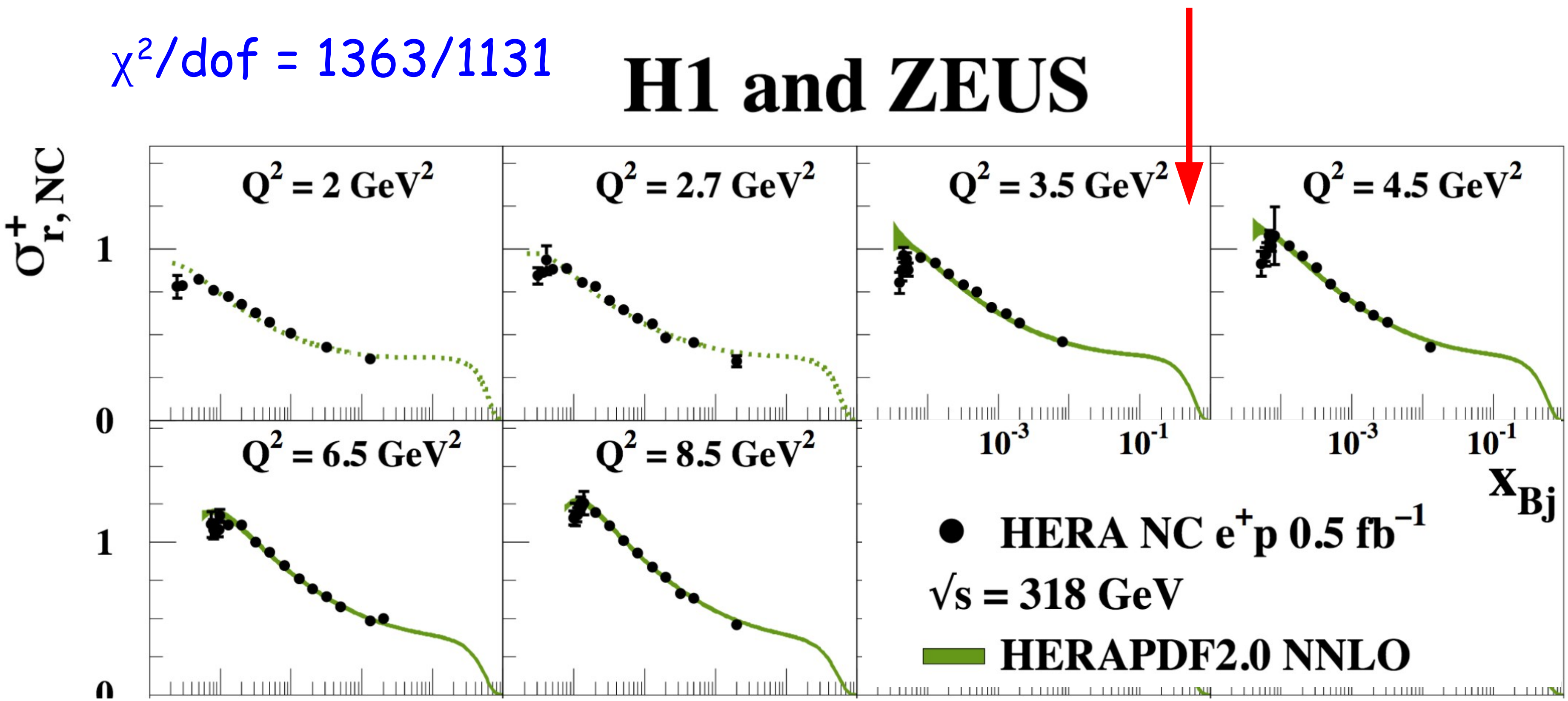
  χ^2/dof = 1357/1131

- NNLO fit for Q^2_{min} = 3.5 GeV^2

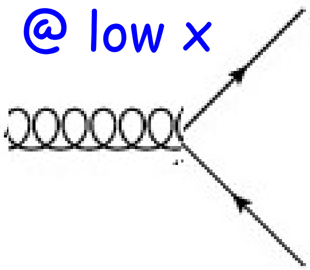
  χ^2/dof = 1363/1131

- Let's see how HERA low Q^2, low x data are described by predictions
  - Not that great...

-



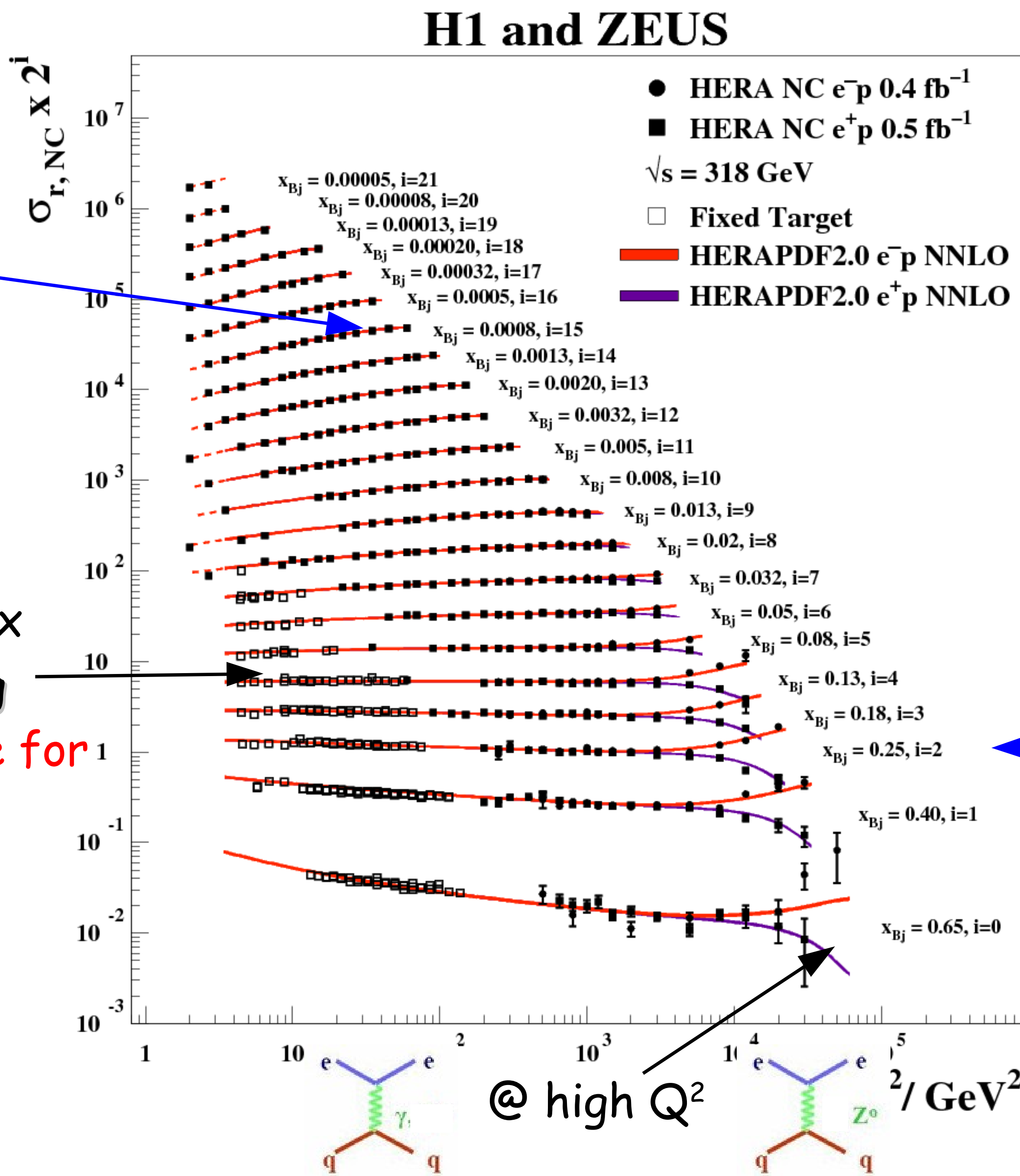
@ low x



@ moderate x

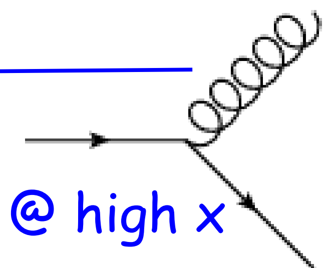
QCD scaling

2015 Wolf prize for J. Bjorken!



electron-proton

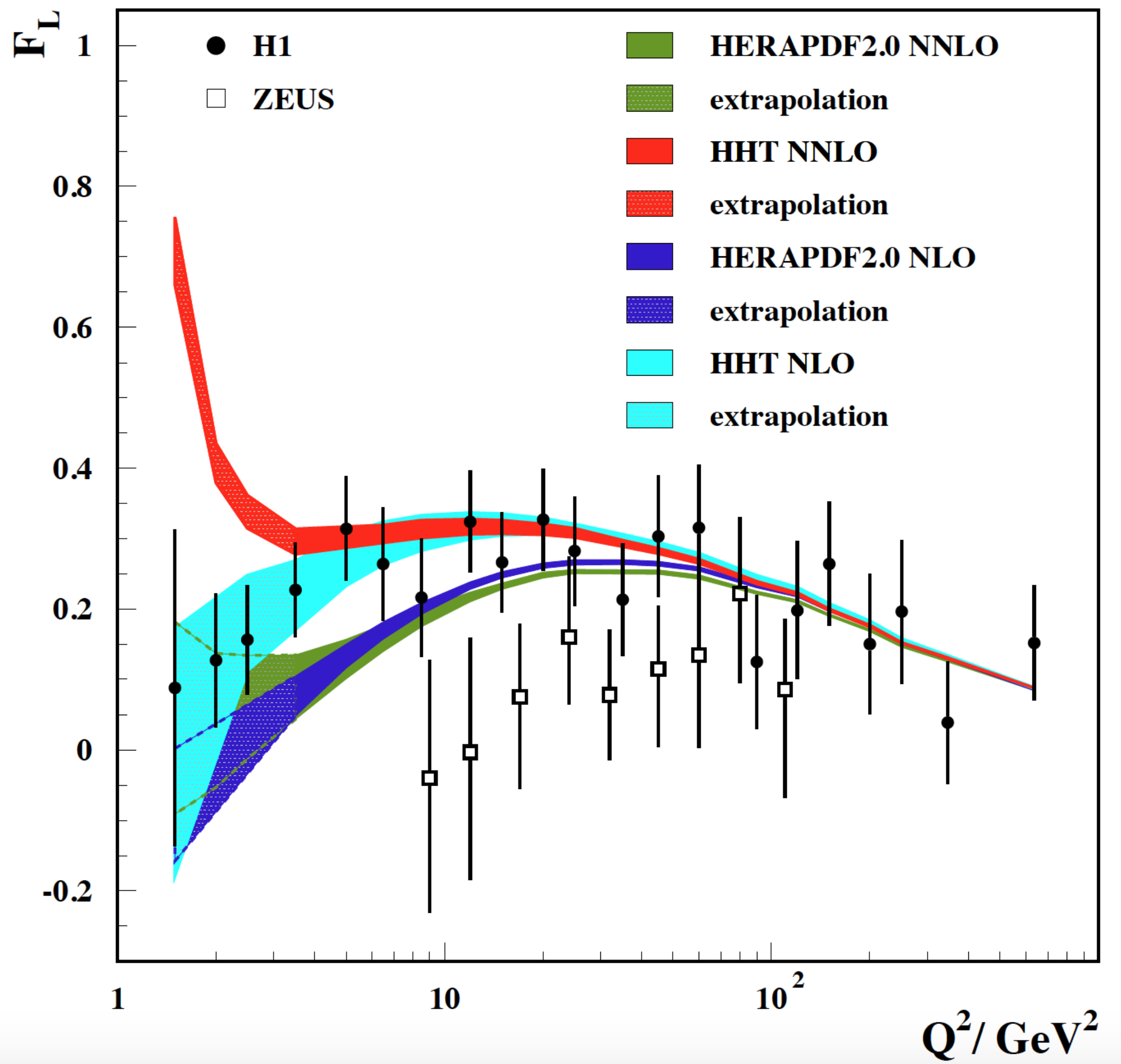
positron-proton



@ high x

Text book plots of fundamental properties of particle interactions

F_L measurements & predictions



- NNLO HHT FL prediction untamed at low Q^2
- this approach cannot be pushed too far
- this comes from NNLO coeff. functions and the $1/Q^2$ term makes it worse

HERAPDF2.0: settings for QCD fit

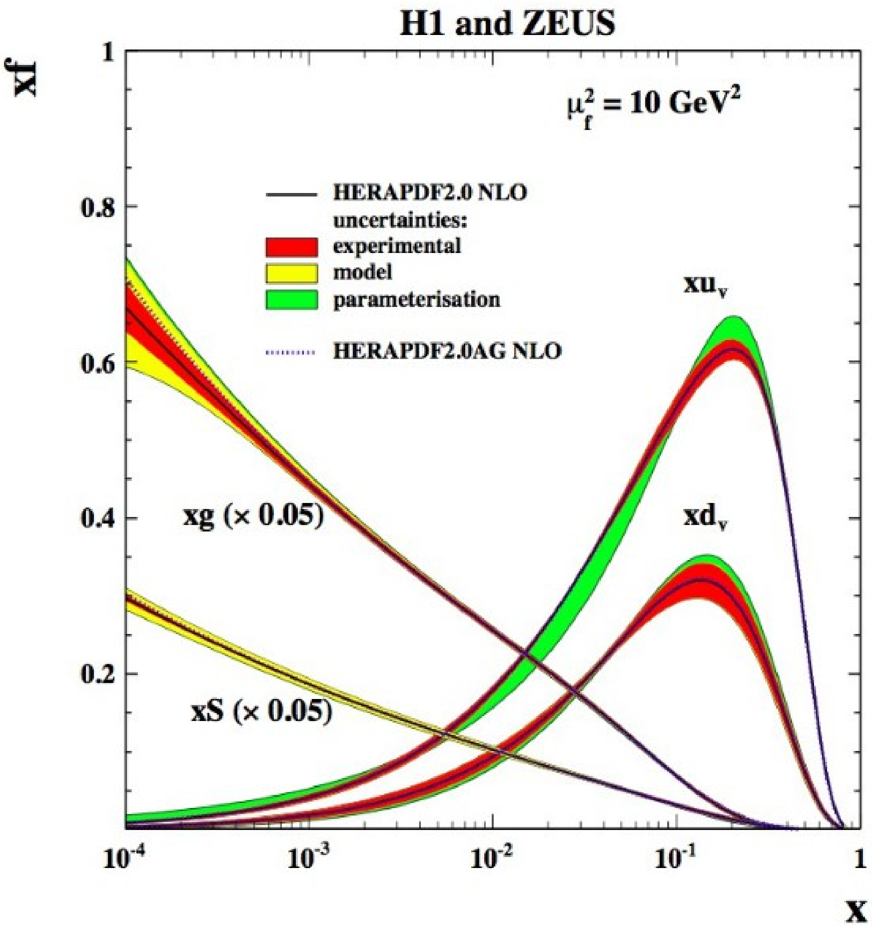
- QCD fits are performed using HERAFitter package
- PDFs (14p) are parametrised at $Q_0^2 = 1.9$ GeV^2

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x), \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

- A_{u_v}, A_{d_v}, A_g are constrained by QCD sum rules
- $x\bar{u} \xrightarrow{x\to 0} x\bar{d}$
- $A_{\bar{U}}, A_{\bar{D}}$ are constrained via $x\bar{s} = f_s x\bar{D}$
- PDF evolution is performed using DGLAP equations
- Heavy flavour coeffitients are obtained within GM VFNS (RT OPT)

$$
\chi^2 = \sum_i \frac{\left[\mu_i - m_i\left(1-\sum_j \gamma^i_j b_j\right)\right]^2}{\delta^2_{i,uncor} m_i^2 + \delta^2_{i,stat}\mu_i m_i\left(1-\sum_j \gamma^i_j b_j\right)} + \sum_j b_j^2 + \sum_i \ln \frac{\delta^2_{i,uncor} m_i^2 + \delta^2_{i,stat}\mu_i m_i}{\delta^2_{i,uncor}\mu_i^2 + \delta^2_{i,stat}\mu_i^2}
$$

Color decomposition of uncertainties



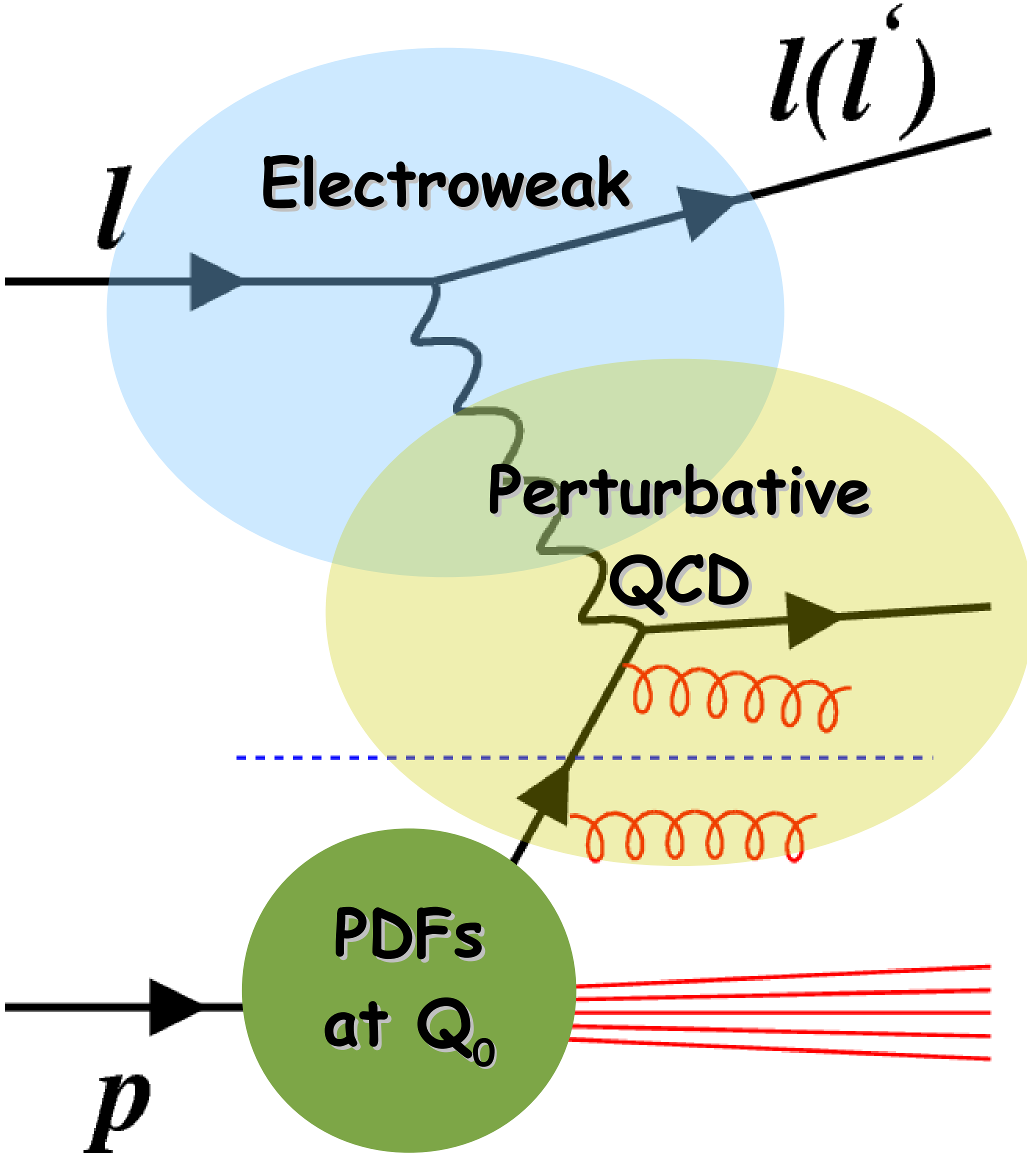
- **Experimental uncertainties:**
  - Hessian method
  - Conventional $\Delta\chi^2 = 1$ => 68% CL

Variation	Standard Value	Lower Limit	Upper Limit
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_{min} [GeV^2] HiQ2	10.0	7.5	12.5
M_c(NLO) [GeV]	1.47	1.41	1.53
M_c (NNLO) [GeV]	1.43	1.37	1.49
M_b [GeV]	4.5	4.25	4.75
f_s	0.4	0.3	0.5
μ_{f_0} [GeV]	1.9	1.6	2.2

Adding D and E parameters to each PDF

- **Parametrisation uncertainties**
  - largest deviation
- **Model uncertainties**
  - all variations added in quadrature

Deep Inelastic Scattering @ HERA



- Fix pQCD & PDFs
  ! Test Electroweak
- Fix Electroweak
  ! Test pQCD & PDFs

- Fix Electroweak & pQCD
  ! Determine PDFs