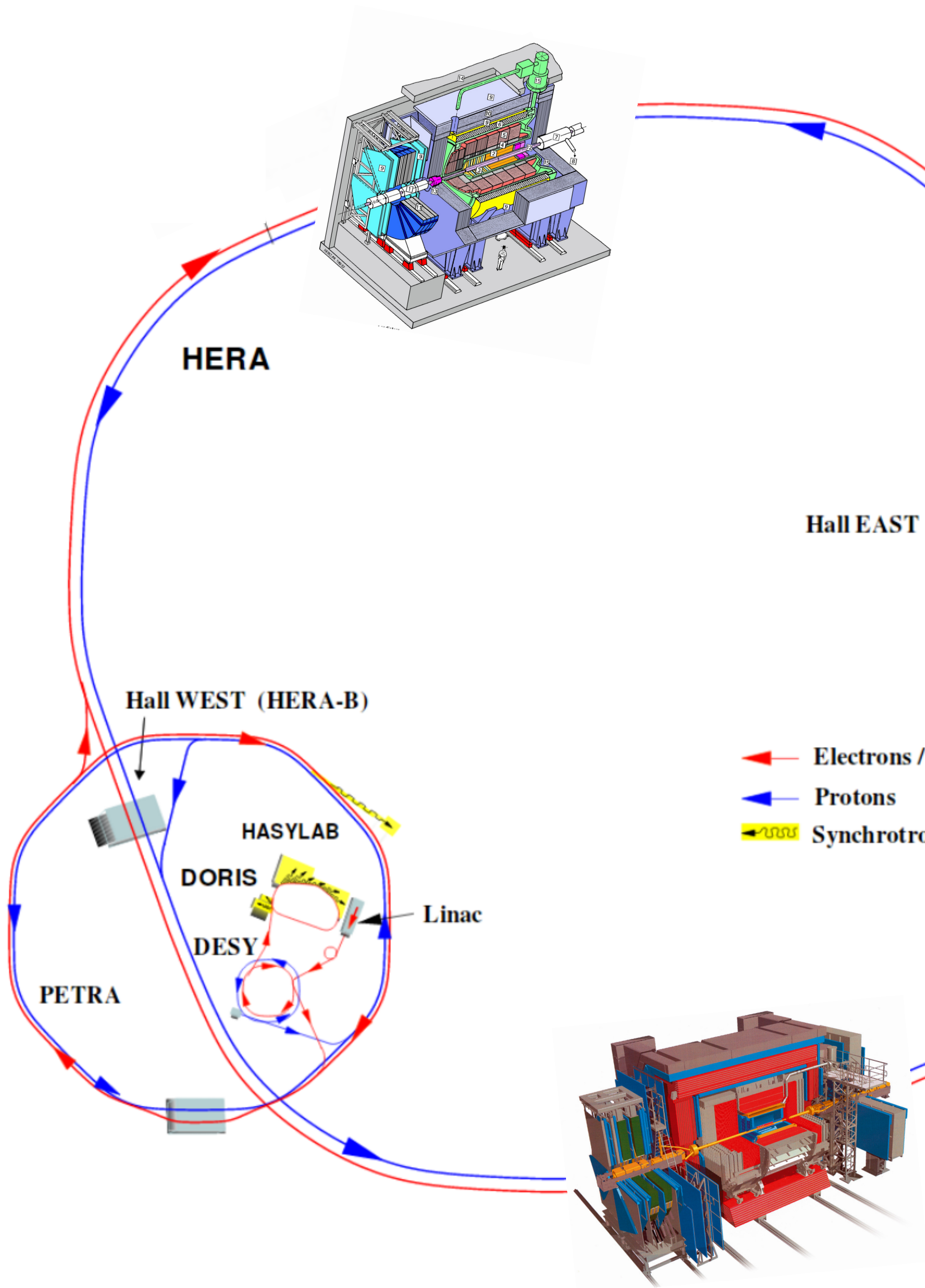
What the HERA data tell us about low-x physics

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

Prospects for a VHE eP and eA collider
Max-Plank-Institut für Physik
Munich, Germany 2017

The HERA collider and the experiments



Location: Hamburg, Germany

Research operation: 1992 - 2007

Length: 6336 m

Proton and electron (positron) beams

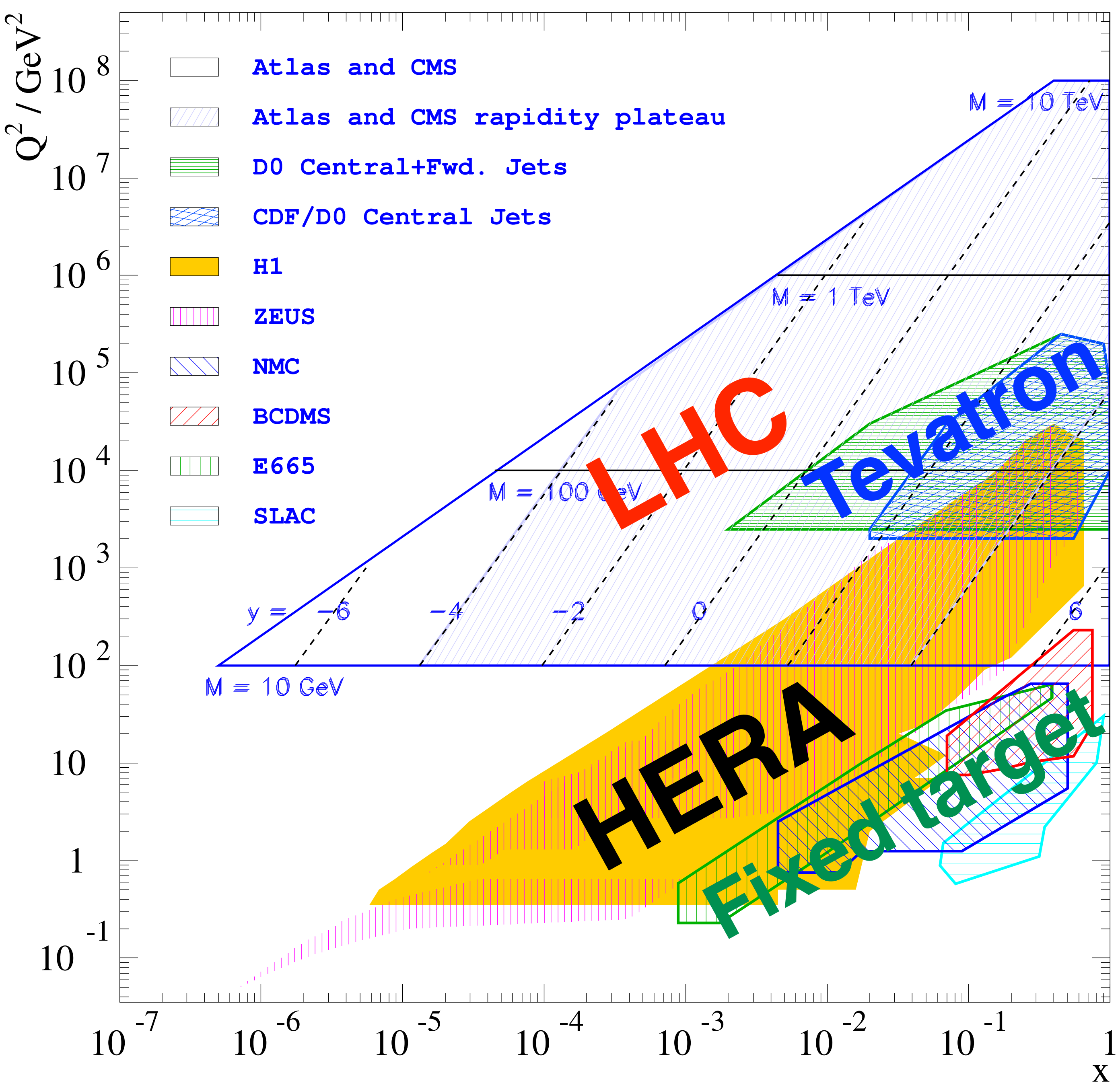
4 experimental halls

2 experiments on colliding beams

$$E_P = 920(820, 575, 460) GeV$$
$$E_e = 27.5 GeV$$
$$\sqrt{s} = 318(300, 252, 225) GeV$$

~0.5 fb^{-1} of DIS data collected by each experiment

HERA data



Collected data spans:

6 orders of magnitude in x_{Bj}

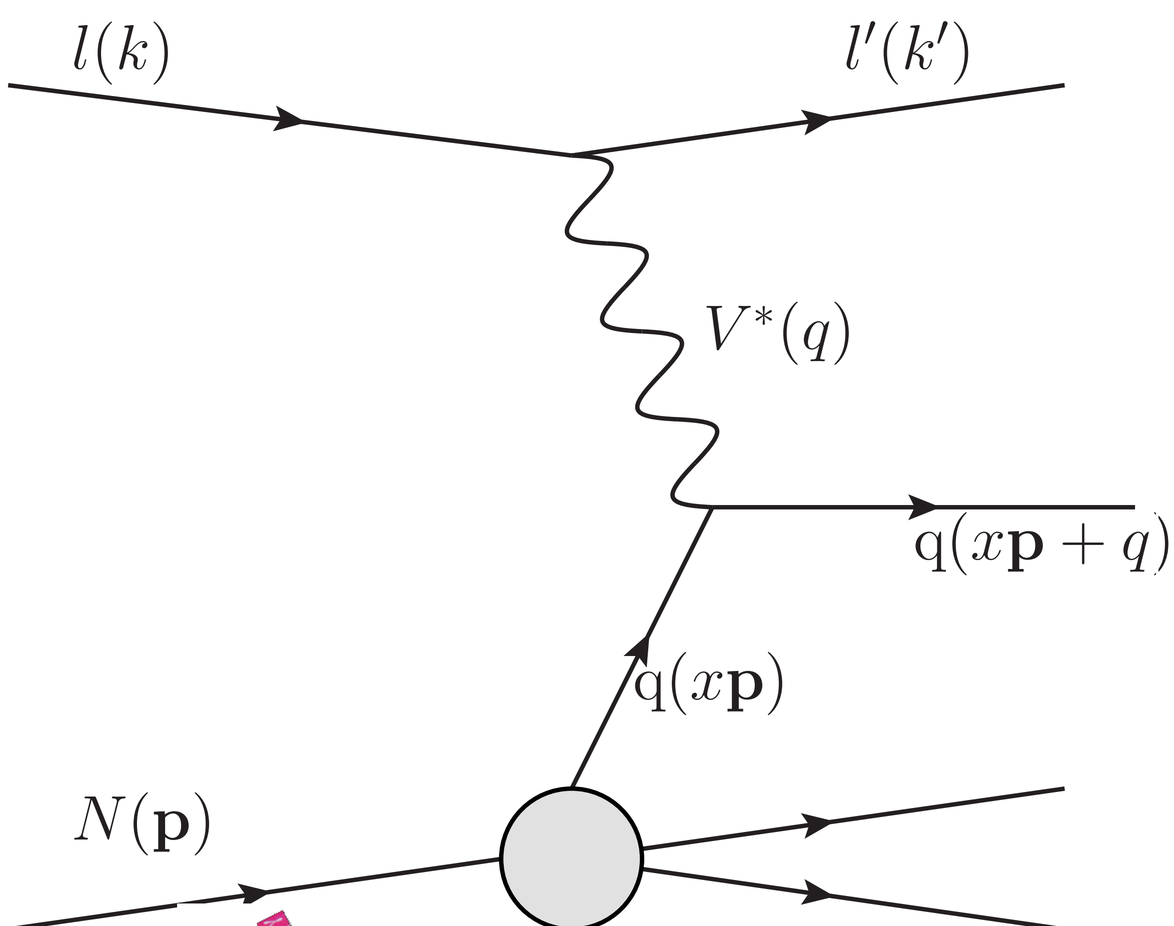
6 orders of magnitude in Q^2

Core of any PDF extraction

Basis for probing
QCD and EW physics

Unique data for testing low-x
phenomenological models

Deep-Inelastic scattering at HERA

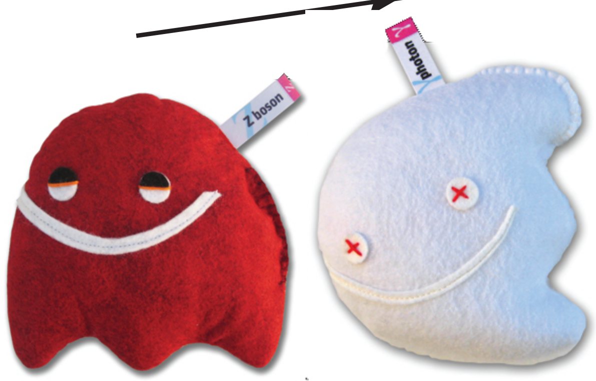


$$Q^2 = -q^2 = -(k-k')^2$$

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

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

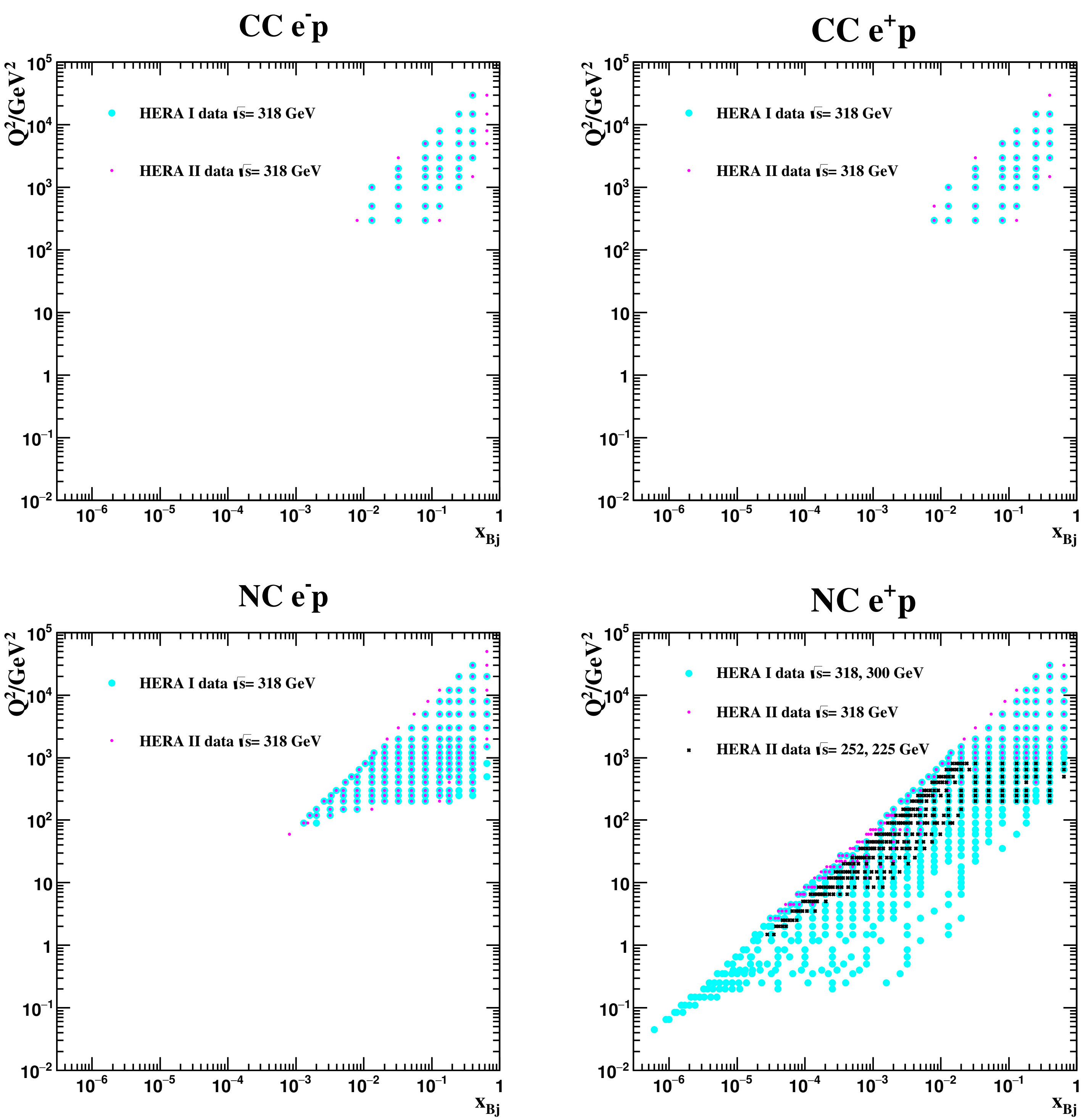
Neutral Current (**NC**) and Charged current (**CC**) reactions are possible



$$\sigma_r^{NC}(e^{\pm}p) = \frac{d^2\sigma^{NC}(e^{\pm}p)}{dxdQ^2} \cdot \frac{xQ^4}{2\pi\alpha^2 Y_+} = \widetilde{F_2^{NC}} \mp \frac{Y_-}{Y_+} x\widetilde{F_3^{NC}} - \frac{y^2}{Y_+}\widetilde{F_L^{NC}}$$

$$\sigma_r^{CC}(e^{\pm}p) = \frac{d^2\sigma^{CC}(e^{\pm}p)}{dxdQ^2} \cdot \frac{2\pi x}{G_F^2}\frac{(Q^2+M_W^2)^2}{M_W^4} = \frac{Y_+}{2}\widetilde{F_2^{CC}} \mp \frac{Y_-}{2} x\widetilde{F_3^{CC}} - \frac{y^2}{2}\widetilde{F_L^{CC}}$$

DIS in various reactions

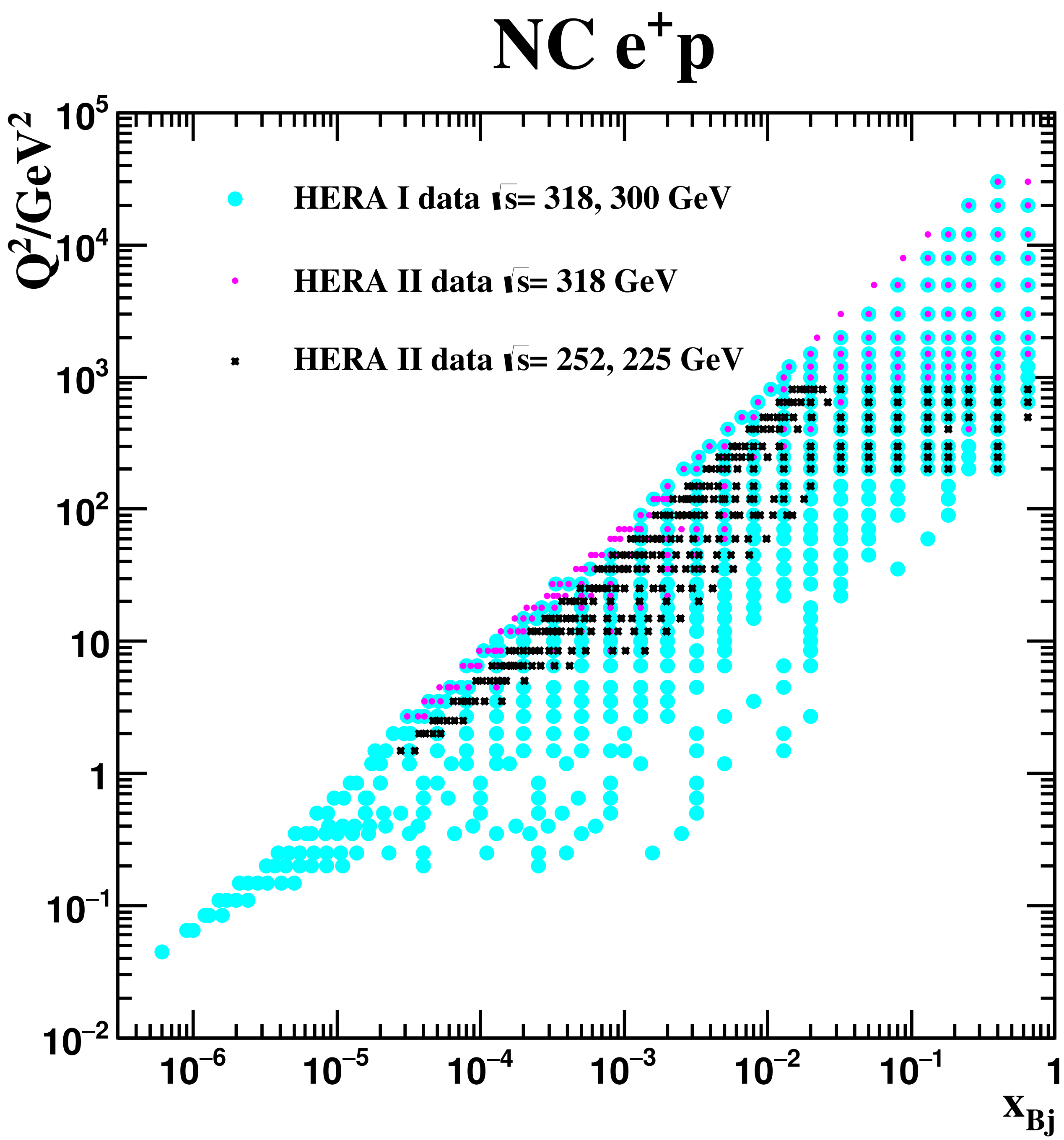


CC e±p:
Sensitive to quark-flavour decomposition.

NC e±p:
Probe valence-quark distribution (F_2, xF_3)

Gluon content of the proton (scaling violation)

NC e^+p DIS data



Covers widest cinematic range

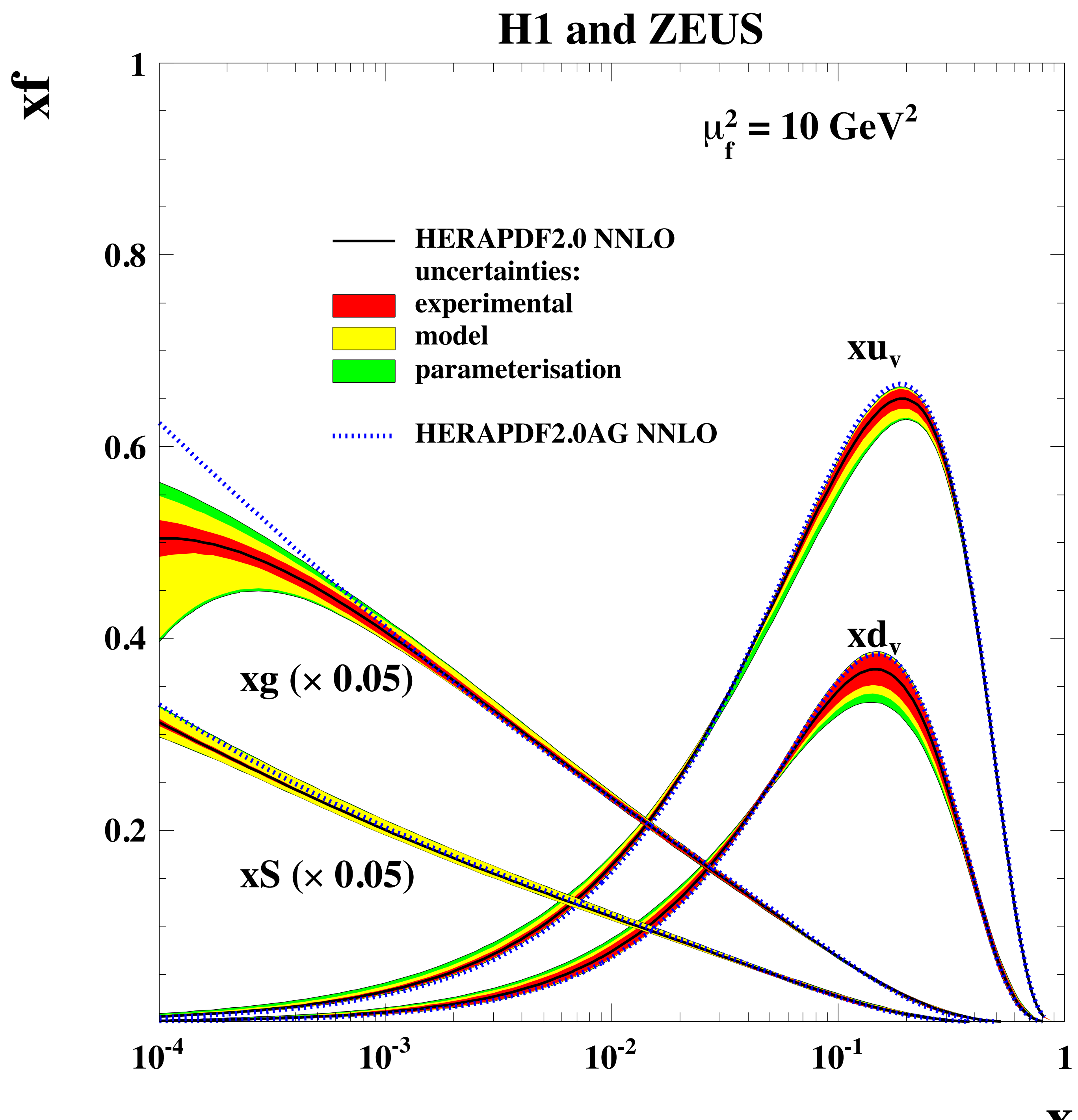
Available in several √s

NCe⁺p@(√s = 318 GeV):

Probes the lowest x_{Bj} and Q^2

Lowest-x_{Bj} data is ~16 years old!

DIS data for PDF extraction



Eur.Phys.J. C75 (2015) no.12, 580, [arXiv:1506.06042]

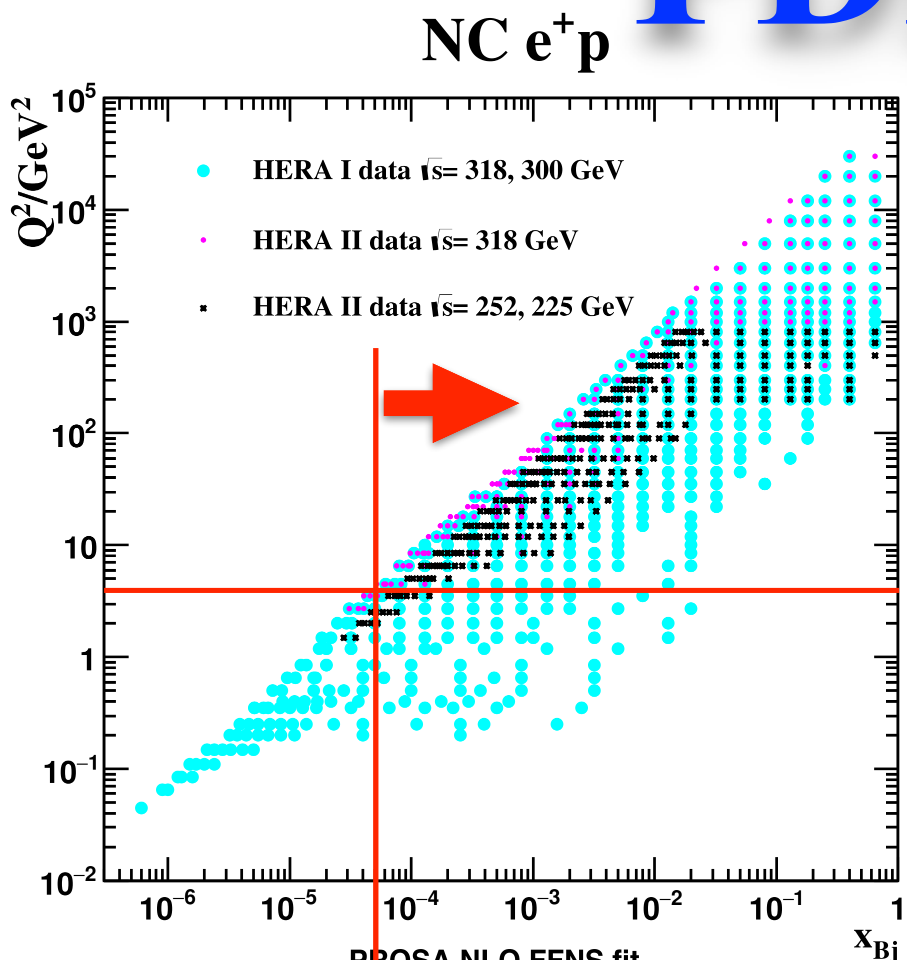
Basic idea:
fit QCD predictions to exp. data

$$\sigma_{A\to C}(q,p) = \Sigma_a \int_x^1 d\xi f^a(\xi,\mu)\sigma_{a\to C}(q,\xi,p,\mu,\alpha_s)$$

DIS data constrains the PDFs:

HERAPDF - based on HERA only
Other PDFs - use HERA as a basis

PDFs at low x

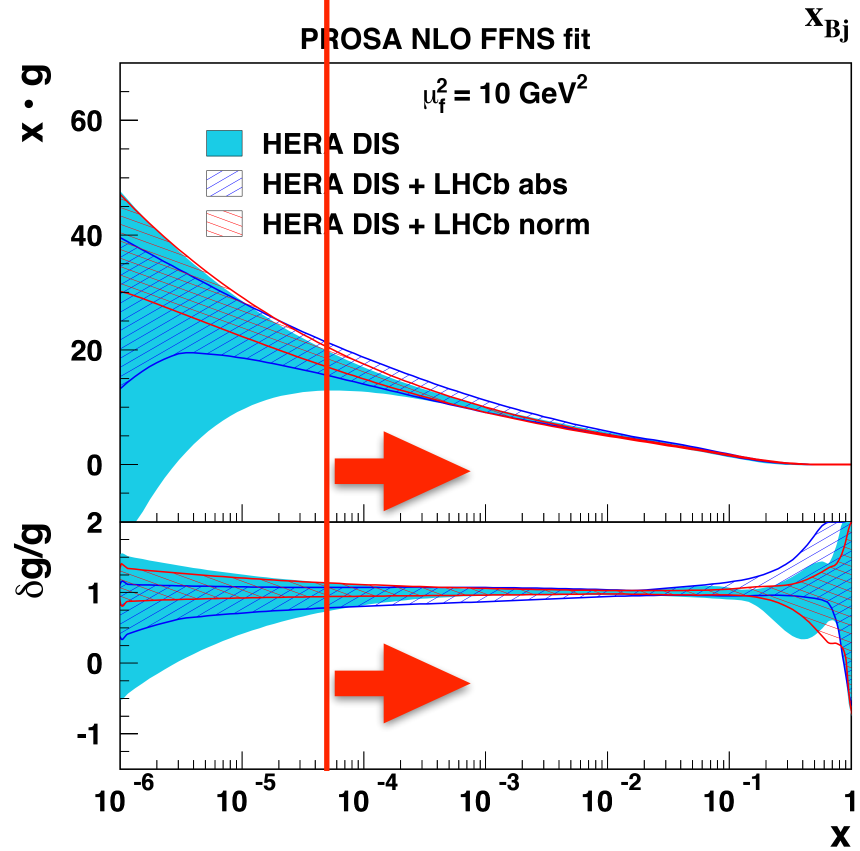


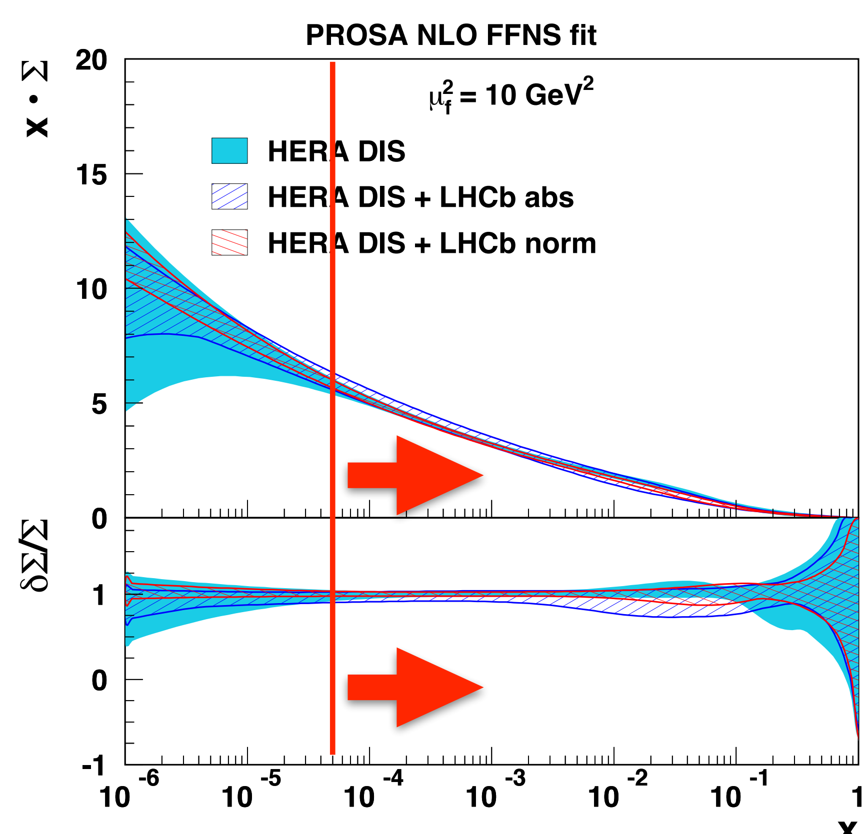
Perturbative region can <u>not</u> be extended to very low Q^2

Low $Q^2 \leftrightarrow$ low x_{Bj}

HERA data provides PDF info only down to $x_{Bj} \simeq 10^{-5}$

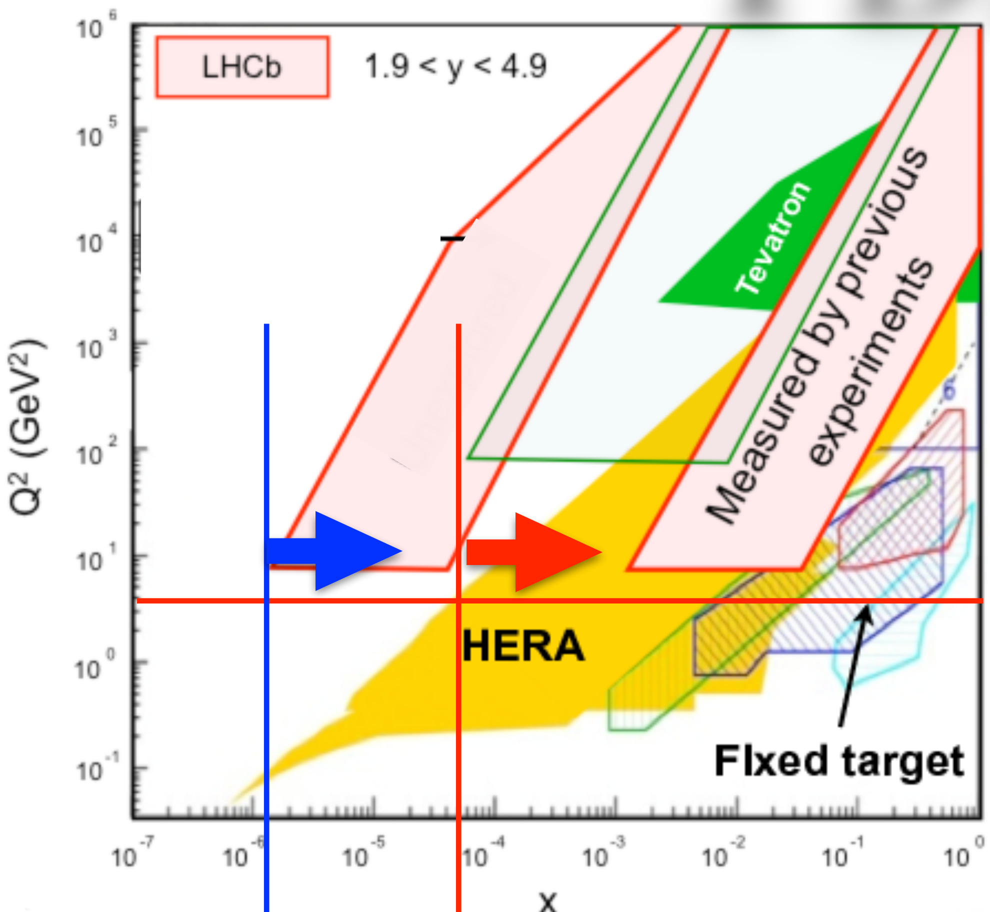
Everything below - pure extrapolation





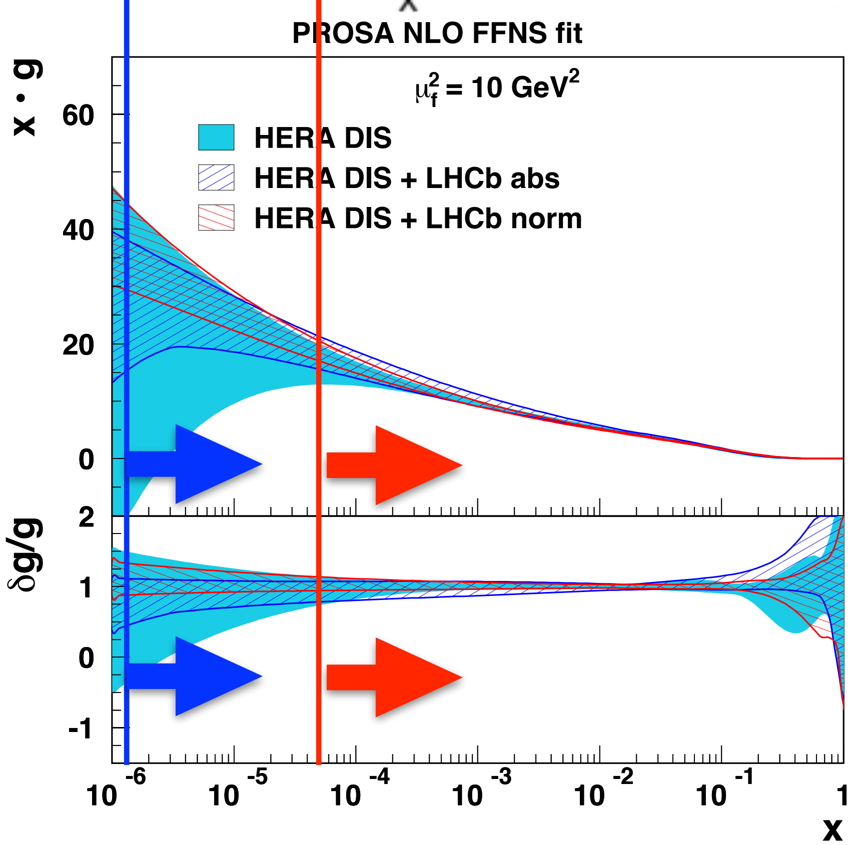
Eur.Phys.J. C75 (2015) no.8, 396, [arXiv:1503.04581]

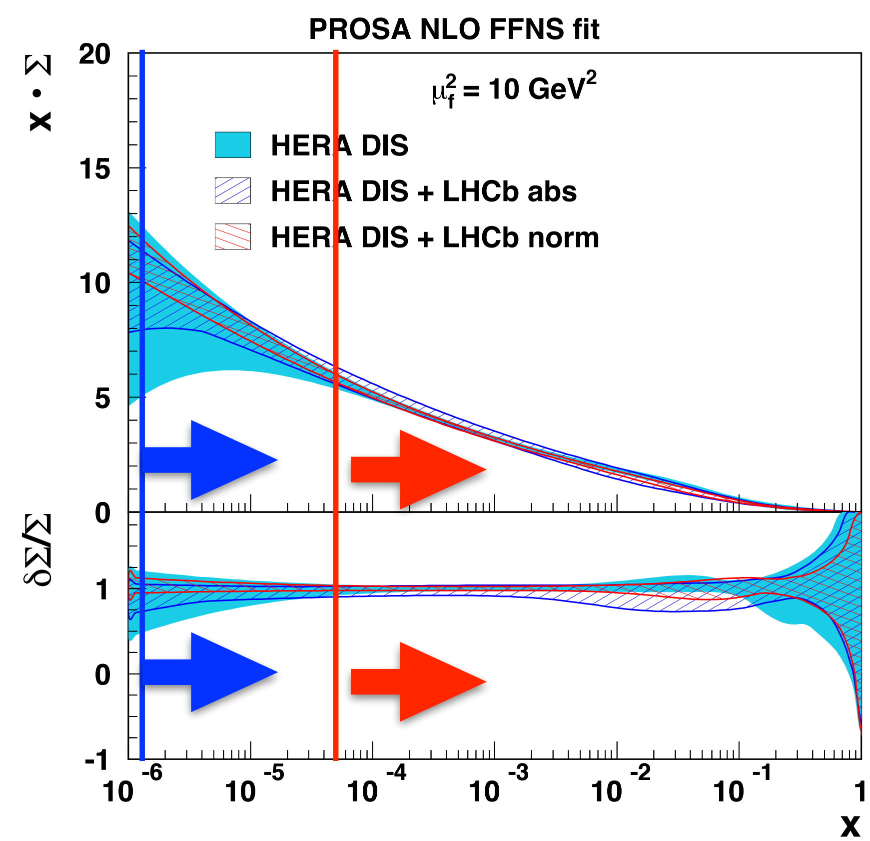
PDFs at low x



Additional low-x data helps understanding proton structure!

Any potential input from VHEeP?



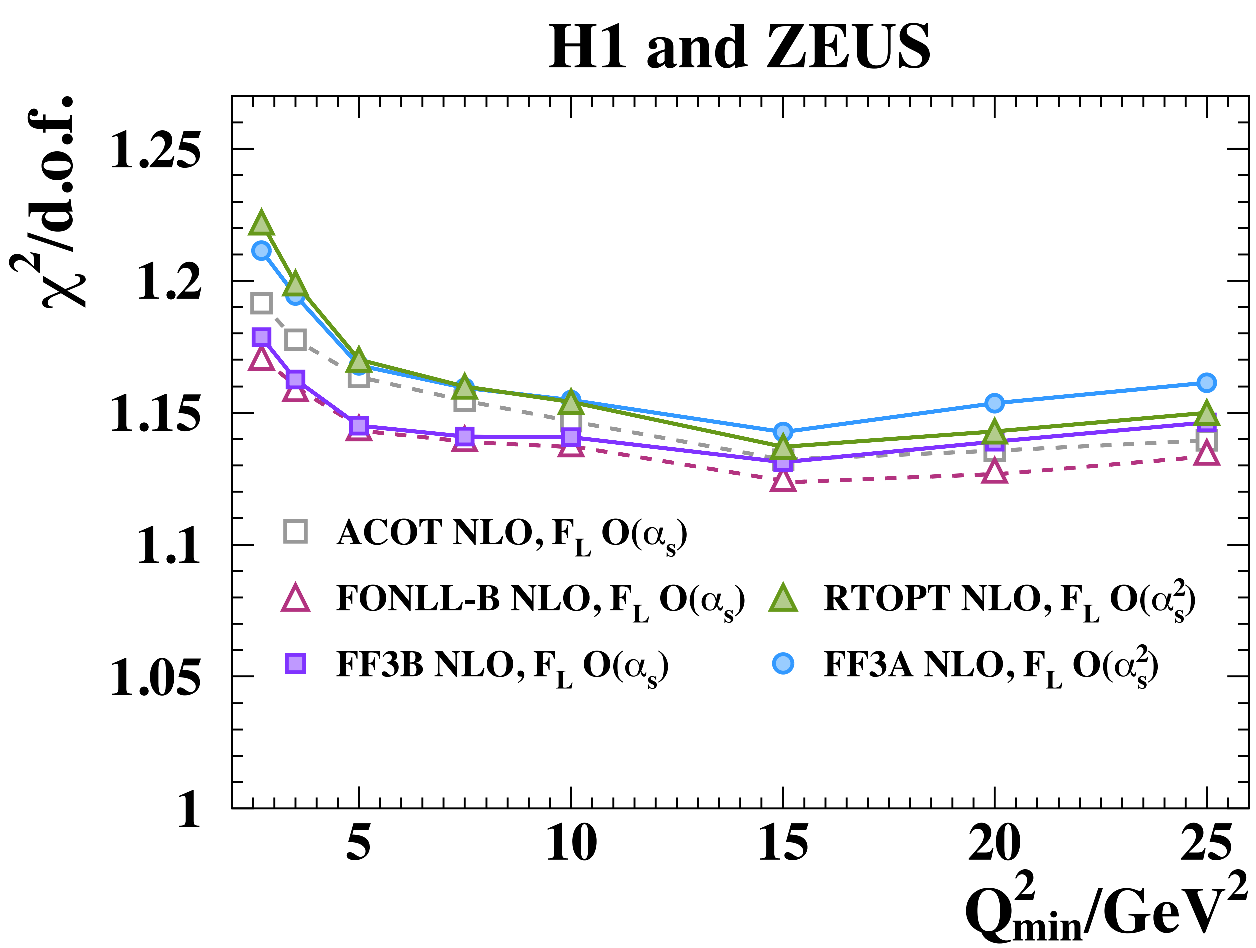


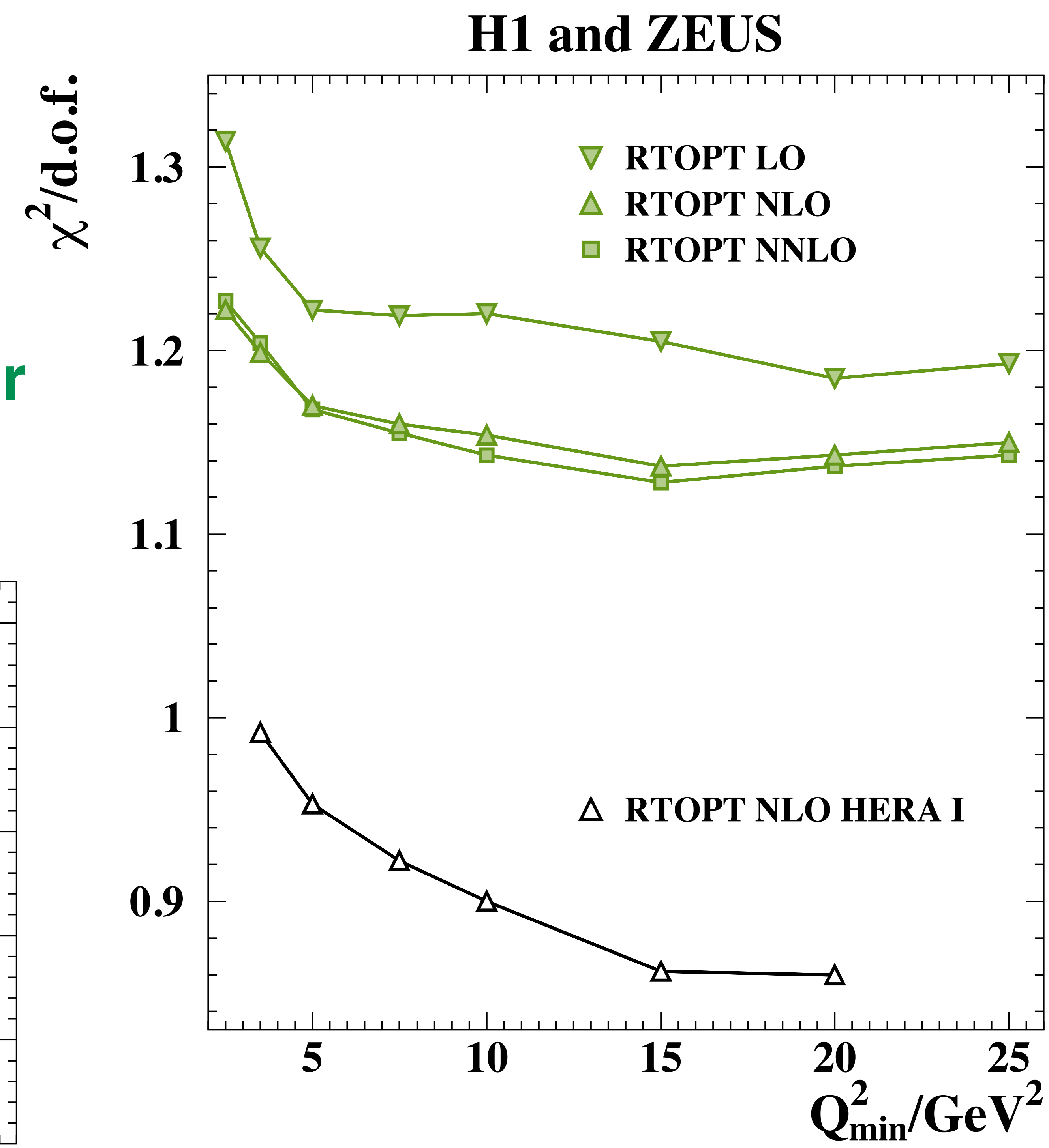
Eur.Phys.J. C75 (2015) no.8, 396, [arXiv:1503.04581]

Low-Q^2 data and pQCD

DGLAP data description
<u>worsens at low Q^2</u>

Effect independent of
HF scheme or **calculation order**



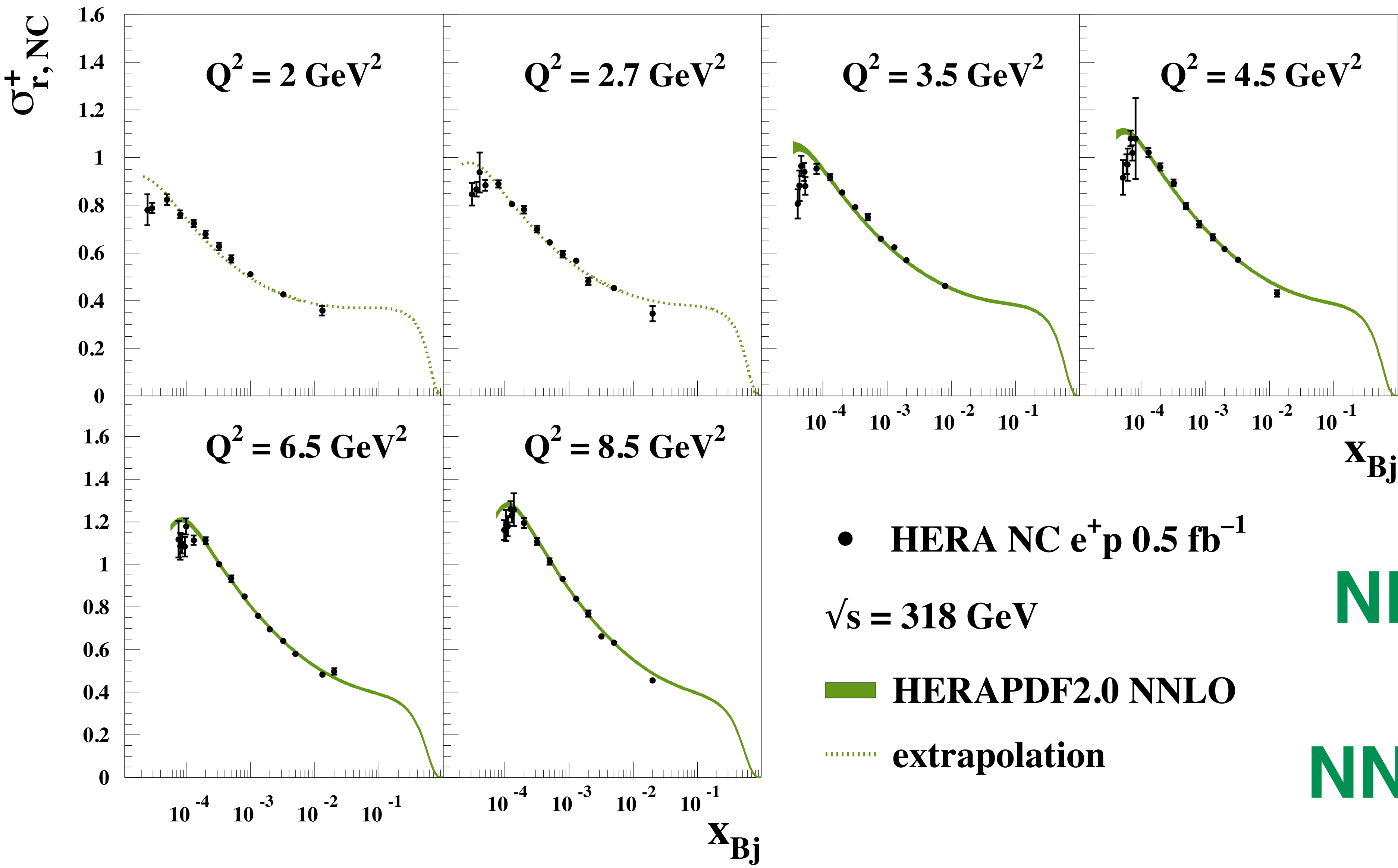


Eur.Phys.J. C75 (2015) no.12, 580, [arXiv:1506.06042]

Low x_{Bj} data and pQCD

Data at **Q^2 = [3.5, 15] GeV^2 cause ~1/3** of the excess in χ^2 / n.d.f

Rest - fluctuations overall full HERA kinematic region



NLO $\frac{\chi^2}{n.d.f} = \frac{1356}{1131} \approx 1.20$

NNLO $\frac{\chi^2}{n.d.f} = \frac{1363}{1131} \approx 1.21$

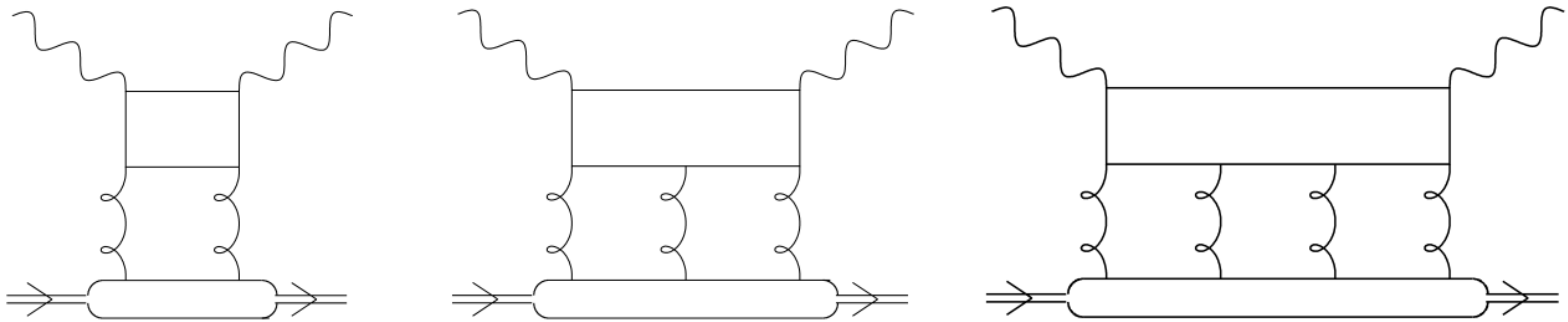
A possible solution, **a higher-twist correction**, was studied…

Higher-twist correction

The problem might be in absence of **higher-twist corrections** in the evolution equations

May be visualised as gluon leaders with recombining gluons

Eur.Phys.J. C17 (2000) 121-128, [hep-ph/0003042]



$$\sigma^{\pm}_{r,NC} = F_2 - \frac{y^2}{Y_+} F_L$$ Cross section - a linear combination of structure functions

Introduce simple twist-4 correction factor to each of st. functions

$$F_2^{HT} = F_2^{DGLAP}(1 + \frac{A_2^{HT}}{Q^2})$$
$$F_L^{HT} = F_L^{DGLAP}(1 + \frac{A_L^{HT}}{Q^2})$$

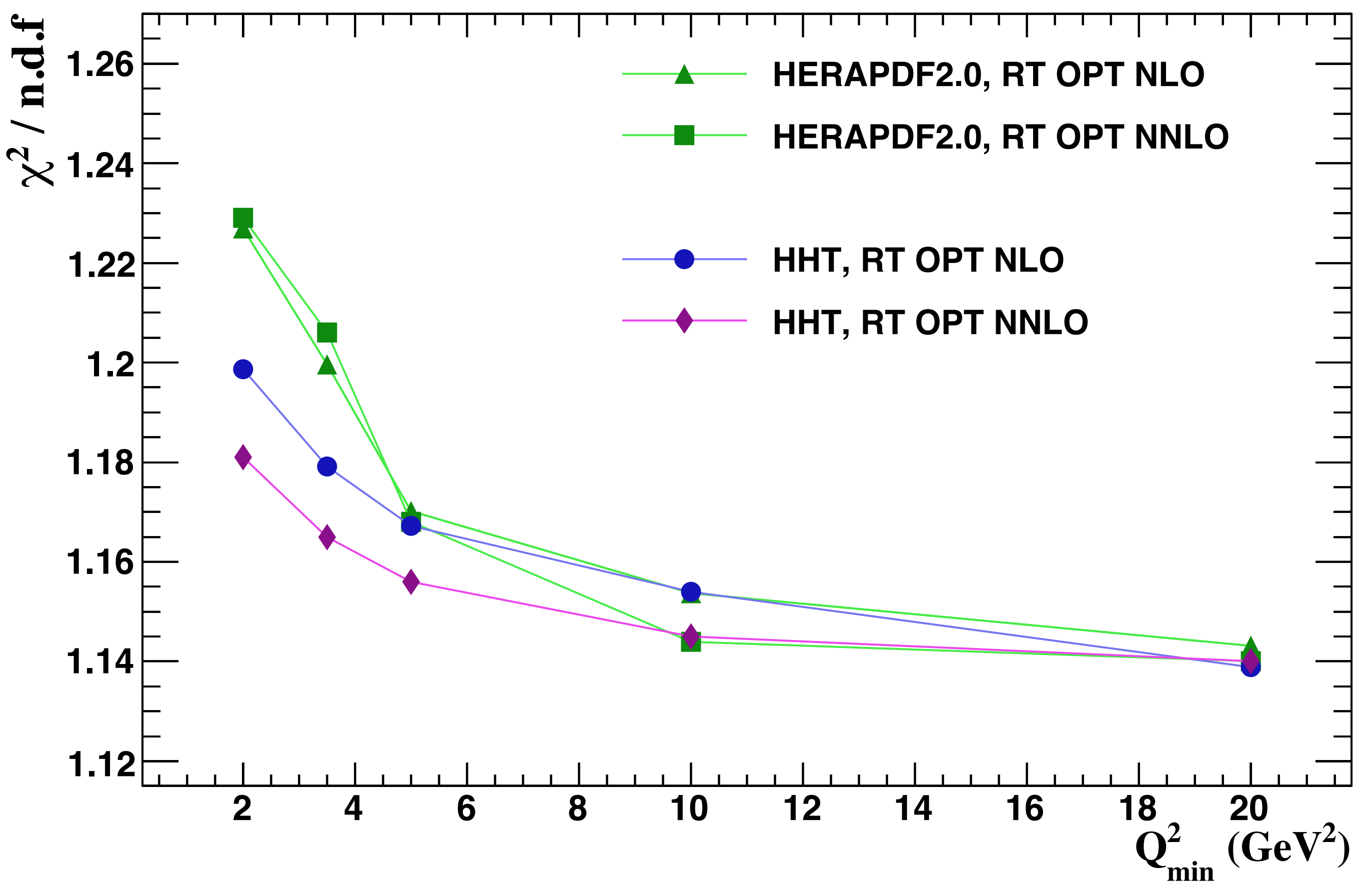
Higher-twist terms are expected to contribute to F_L...

$$F_L \frac{4\pi^2\alpha}{Q^2(1-x)} = \sigma_L$$

...and cancel for F_2

$$F_2 \frac{4\pi^2\alpha}{Q^2(1-x)} = \sigma_T + \sigma_L$$

Higher-twist-correction effect



Phys.Rev. D94 (2016) no.3, 034032, [arXiv:1604.02299]

Q^2_{min}-dependence curve flattens substantially

HHT@F_L:

NLO $\frac{\chi^2}{n.d.f.} \approx 1.18$ $\quad \Delta\chi^2 = 27$ $\quad A_L^{HT} = 4.2 \pm 0.7 GeV^2$

NNLO $\frac{\chi^2}{n.d.f.} \approx 1.16$ $\quad \Delta\chi^2 = 47$ $\quad A_L^{HT} = 5.5 \pm 0.6 GeV^2$

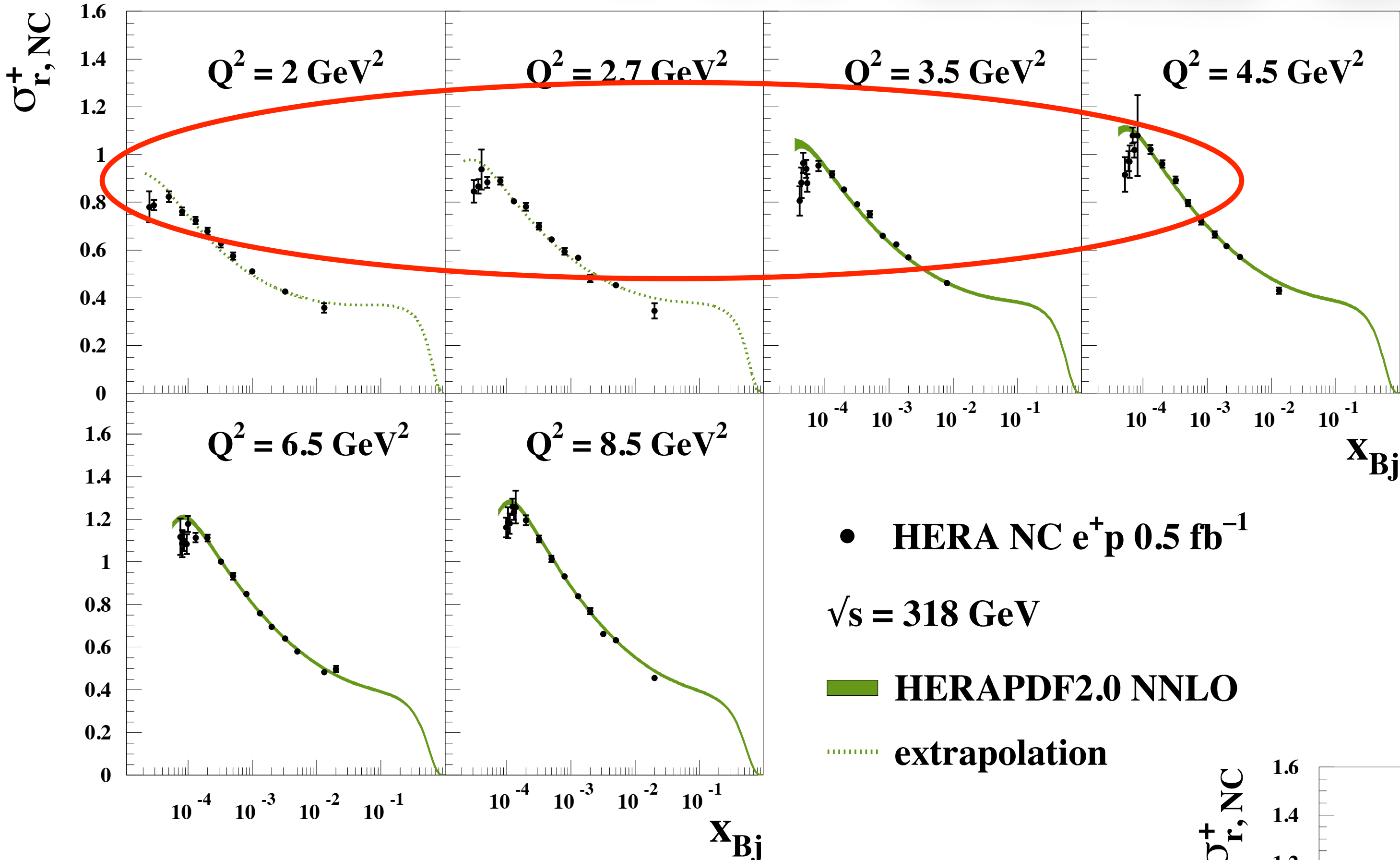
HHT@F_2:
no significant improvement

NLO $\frac{\chi^2}{n.d.f.} \approx 1.20$

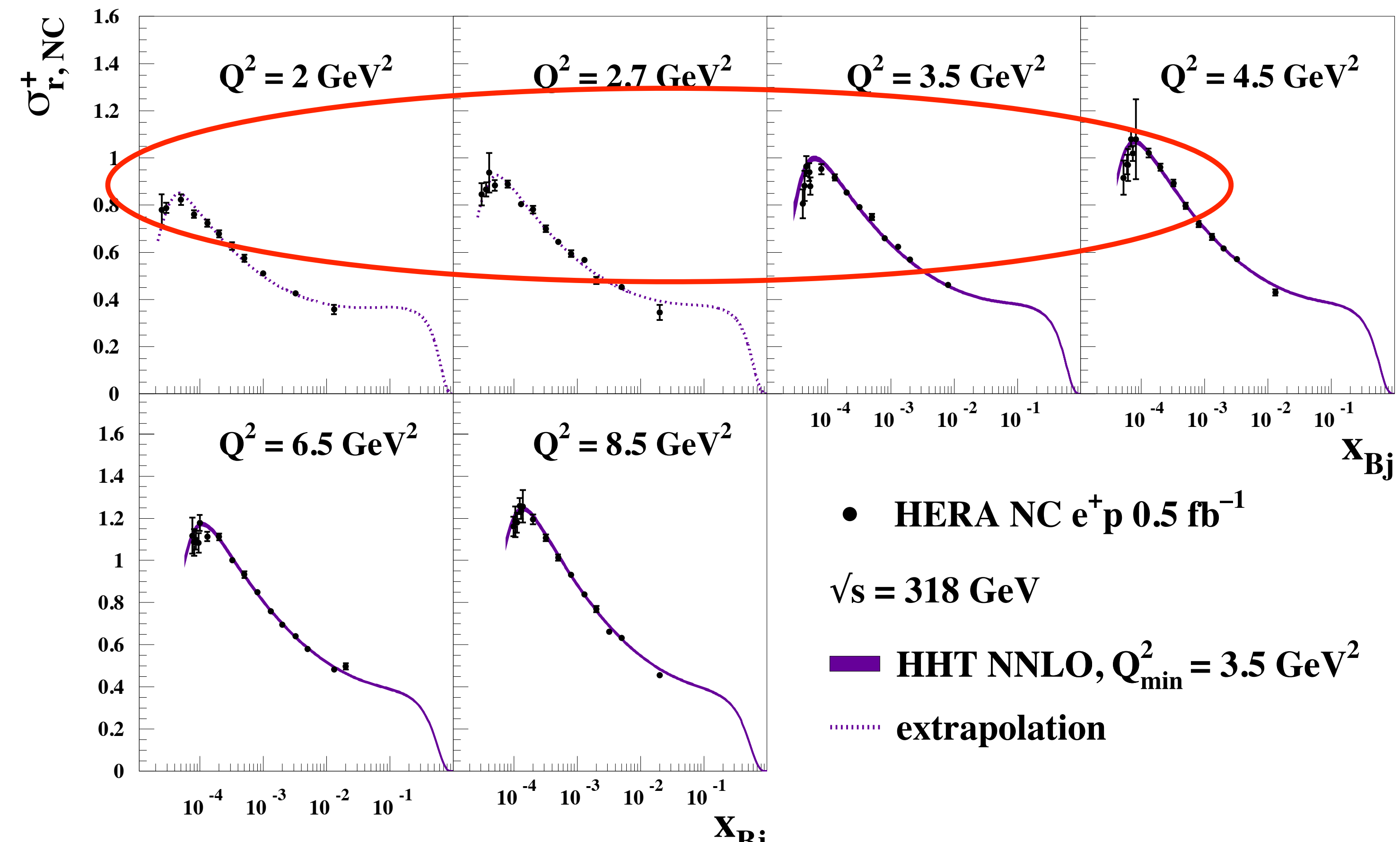
NNLO $\frac{\chi^2}{n.d.f.} \approx 1.20$

corr. factors consistent with 0

HHT: data description



HERAPDF systematically undershoots low-x data



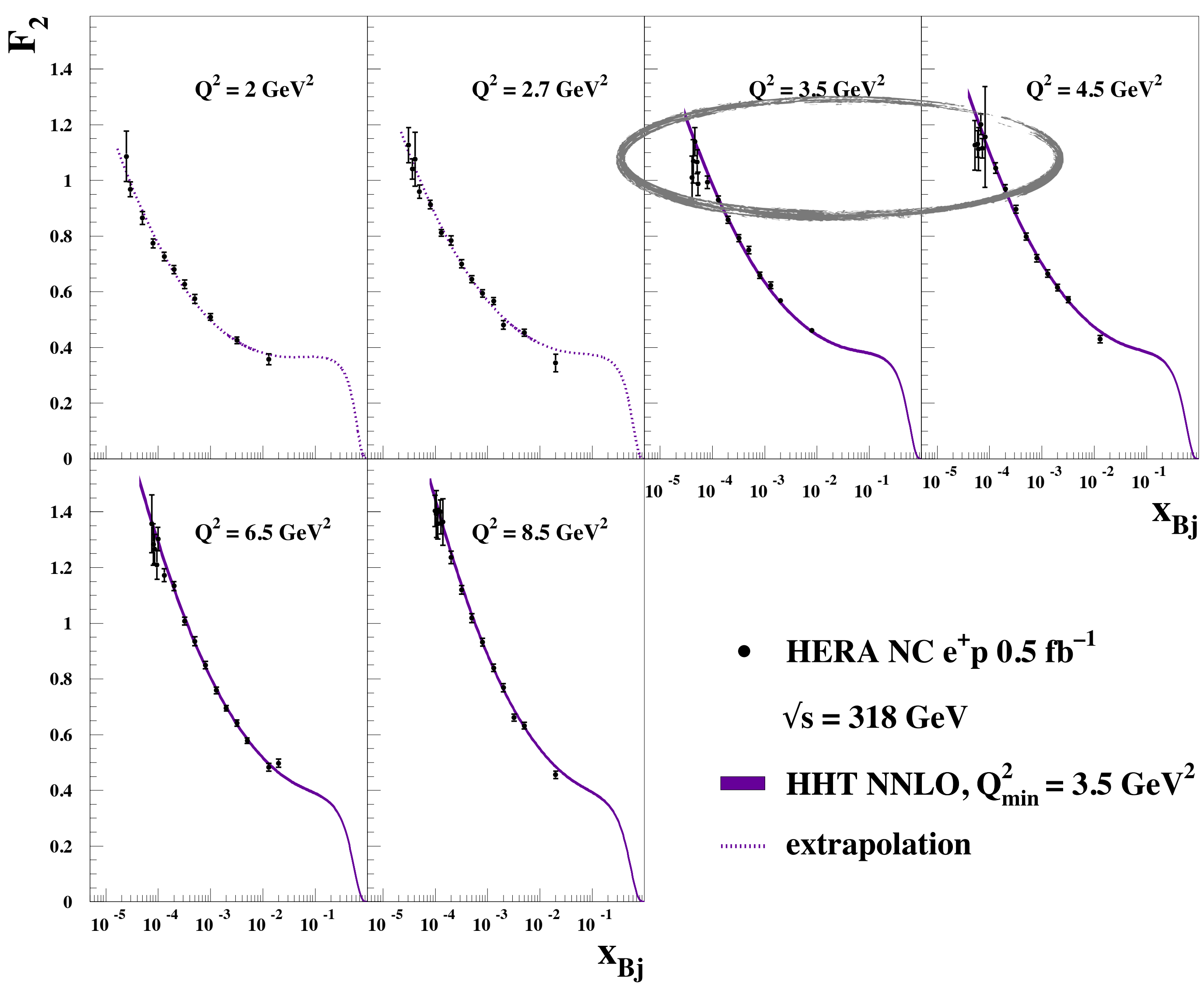
HHT improves low-x-data description significantly!

Predictions describe data even <u>below 3.5 GeV²!</u>

HHT-prediction components

HHT predictions seem to be doing a very good job! some details?

$$\sigma^{\pm}_{r,NC} = F_2 - \frac{y^2}{Y_+} F_L \quad \Rightarrow \quad \sigma^{\pm}_{r,NC} = F_2 - \frac{y^2}{Y_+} F_L \left(1 + \frac{A_L^{HT}}{Q^2}\right)$$



F_2 is extracted from σ_r:

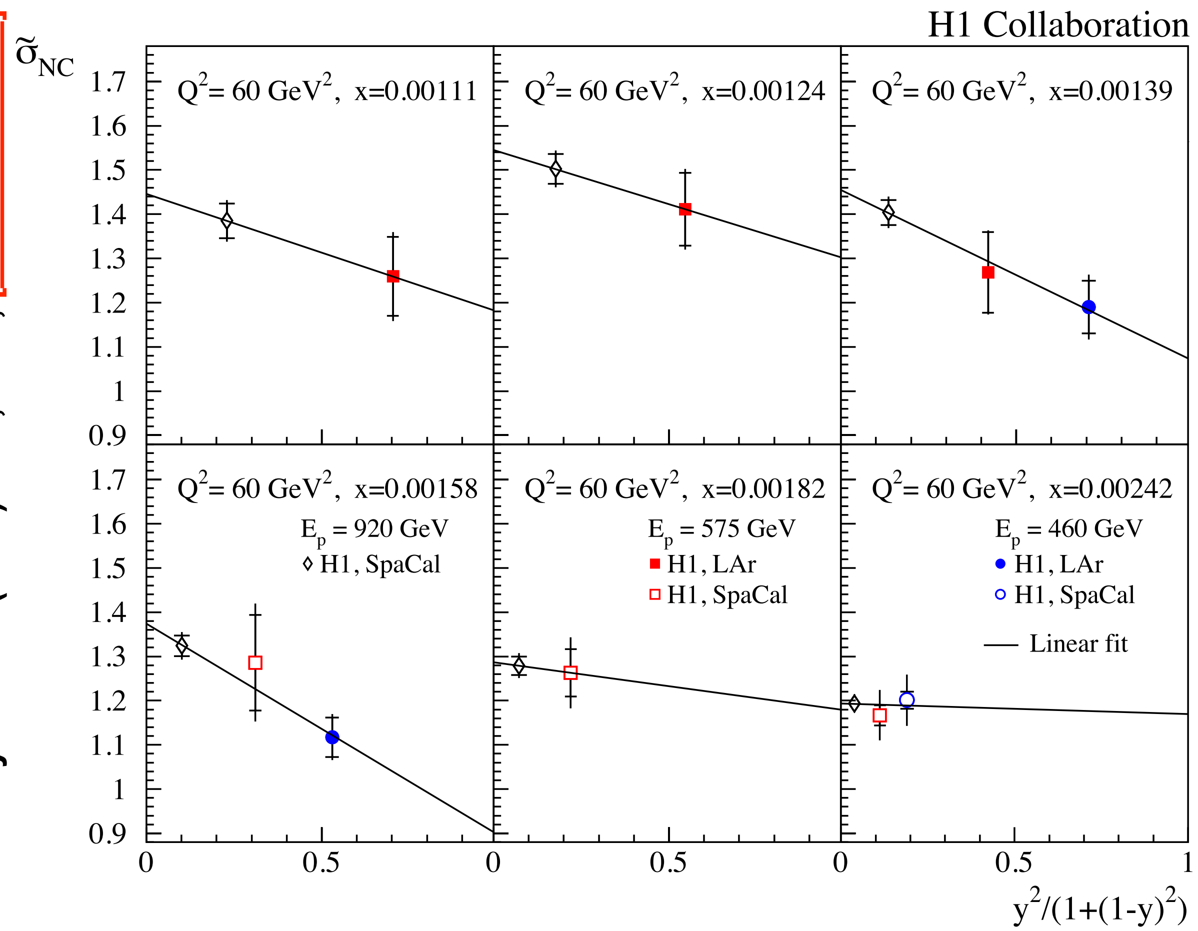
$$F_2^{extr} = F_2^{pred} \frac{\sigma_r^{meas}}{\sigma_r^{pred}}$$

The description is reasonably good…

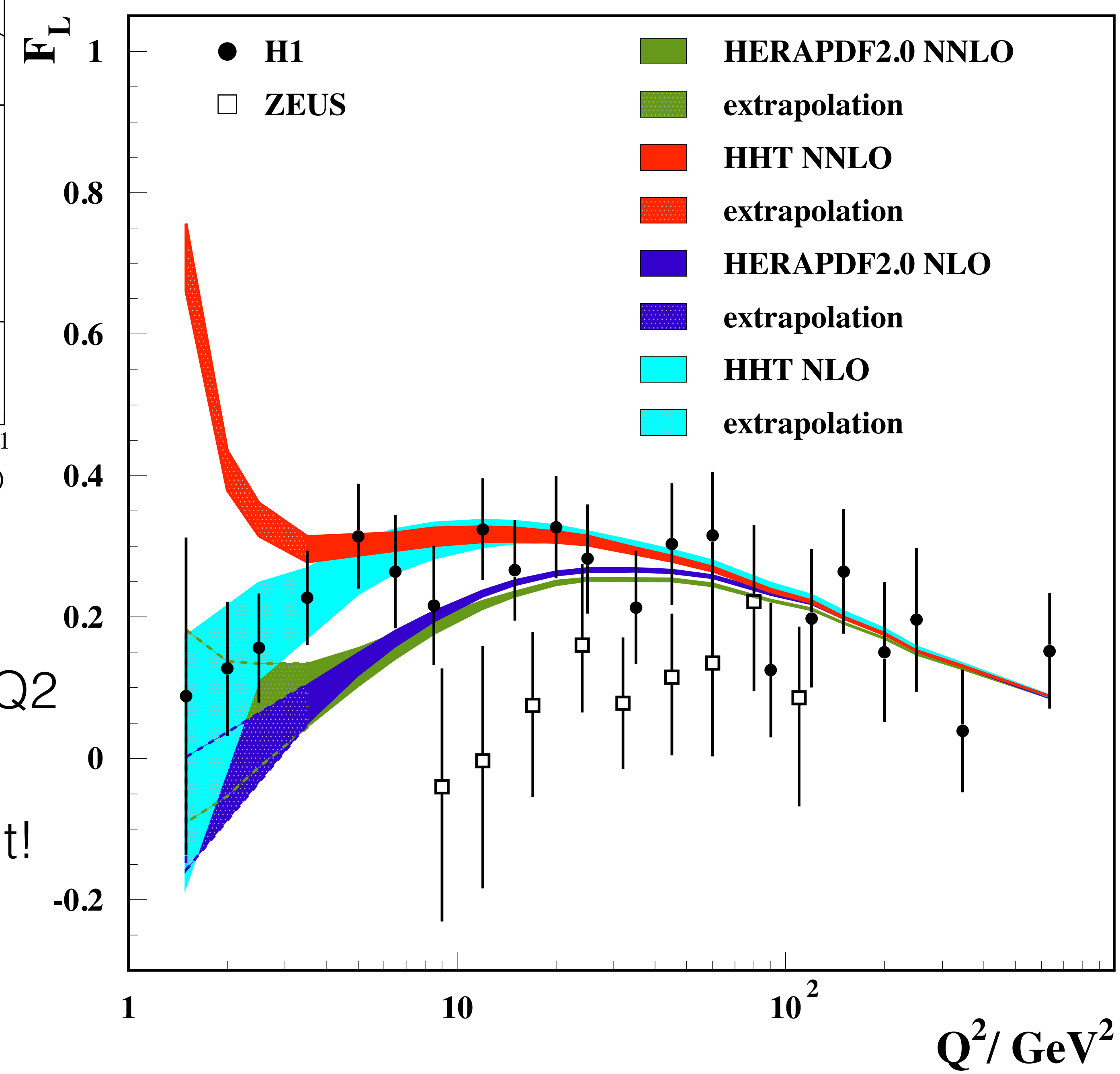
Warning:
a model-dependent extraction!

HHT-prediction components

Eur.Phys.J. C74 (2014) no.4, 2814, [arXiv:1312.4821]



Model-independent F_L measurements exists:
reduced E_P runs!

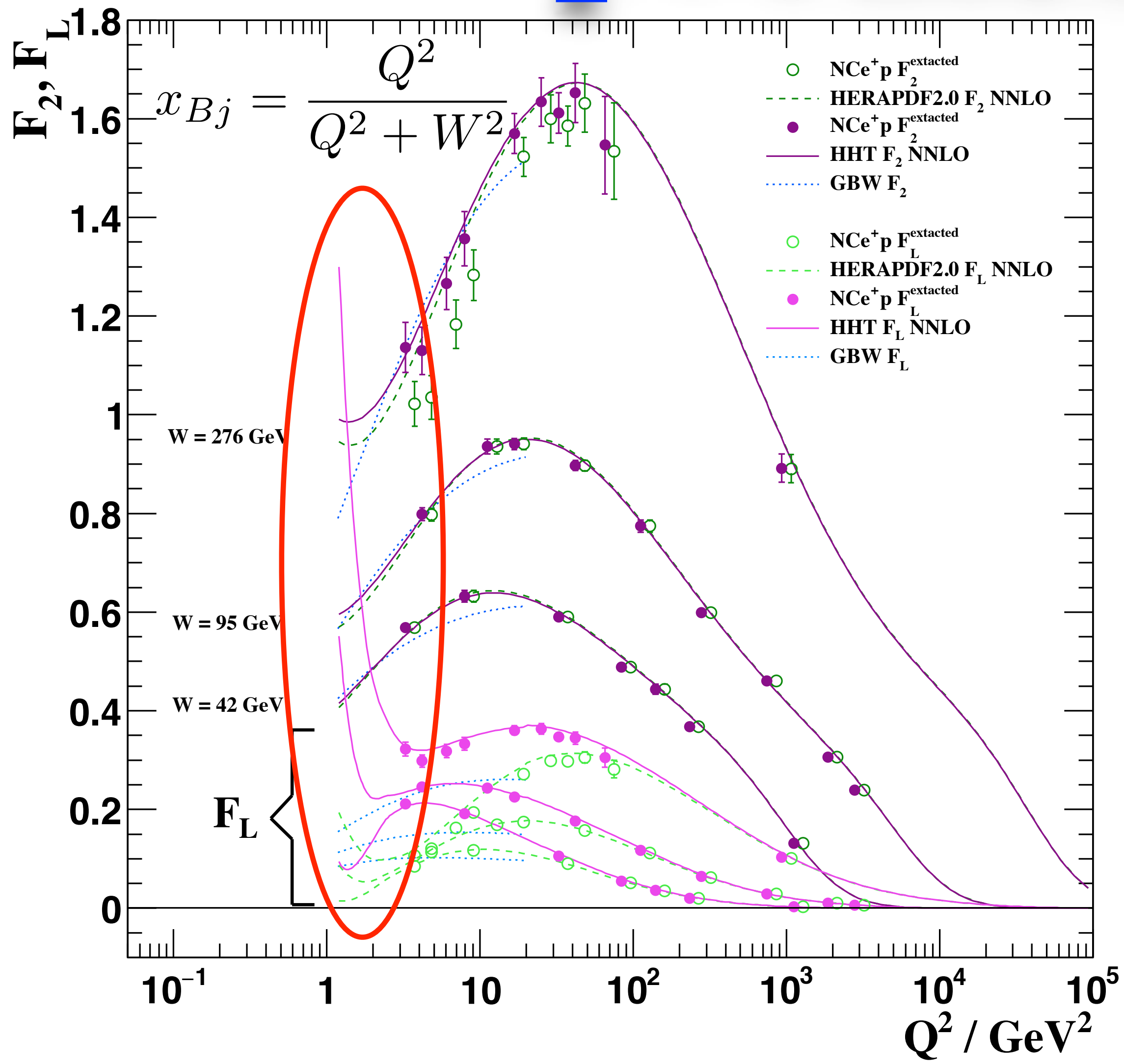


Phys.Rev. D94 (2016) no.3, 034032, [arXiv:1604.02299]

F_L@NNLO shows a huge upturn at small Q2

Direct F_L measurements do not confirm it!

HHT-prediction components



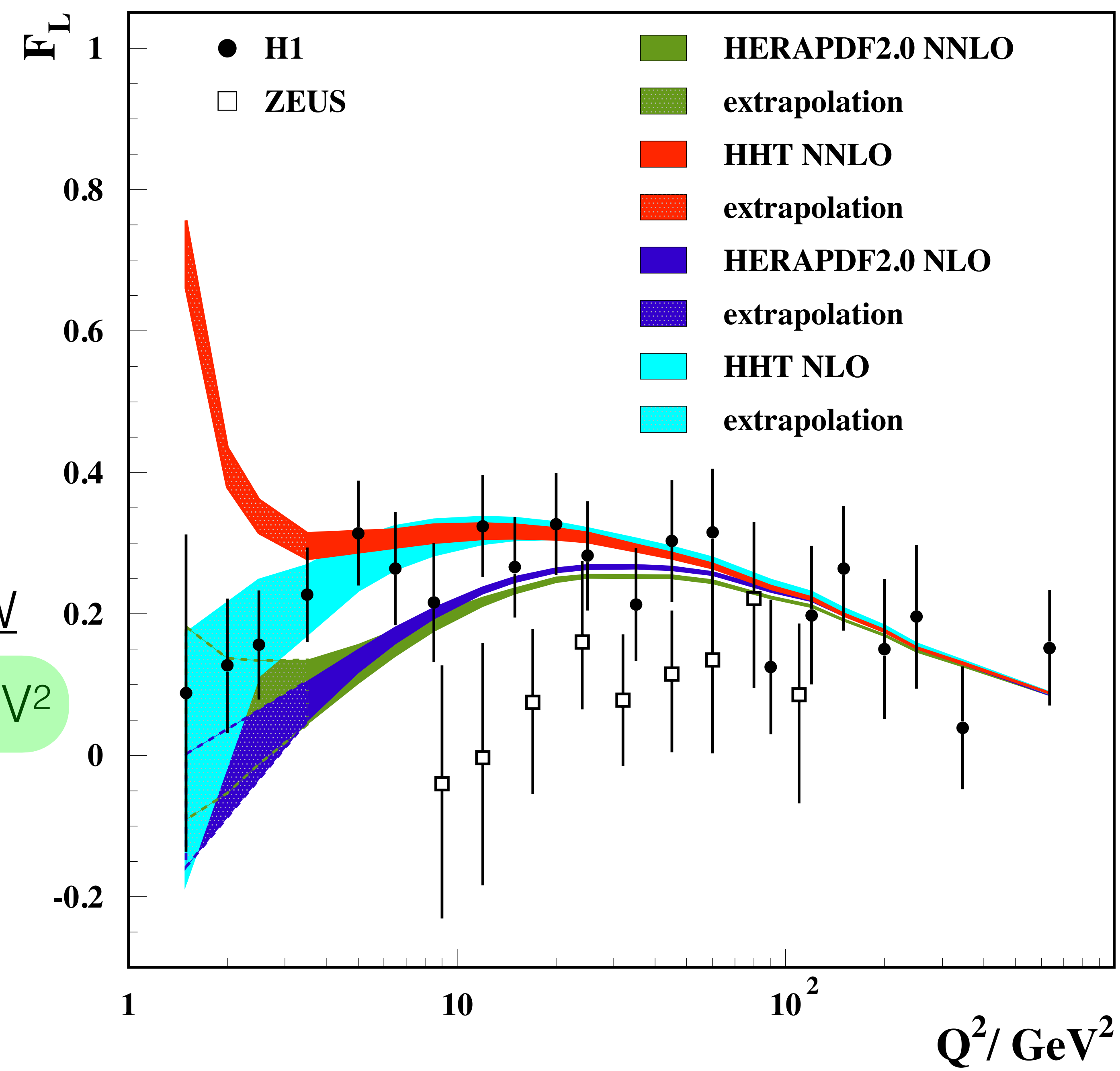
The upturn is more pronouncing at high W

Still reasonable predictions for $Q^2 > 3.5\ GeV^2$

More investigations required for

reasonable F_L predictions!

Model-independent F_L measurements exists:
reduced E_P runs!



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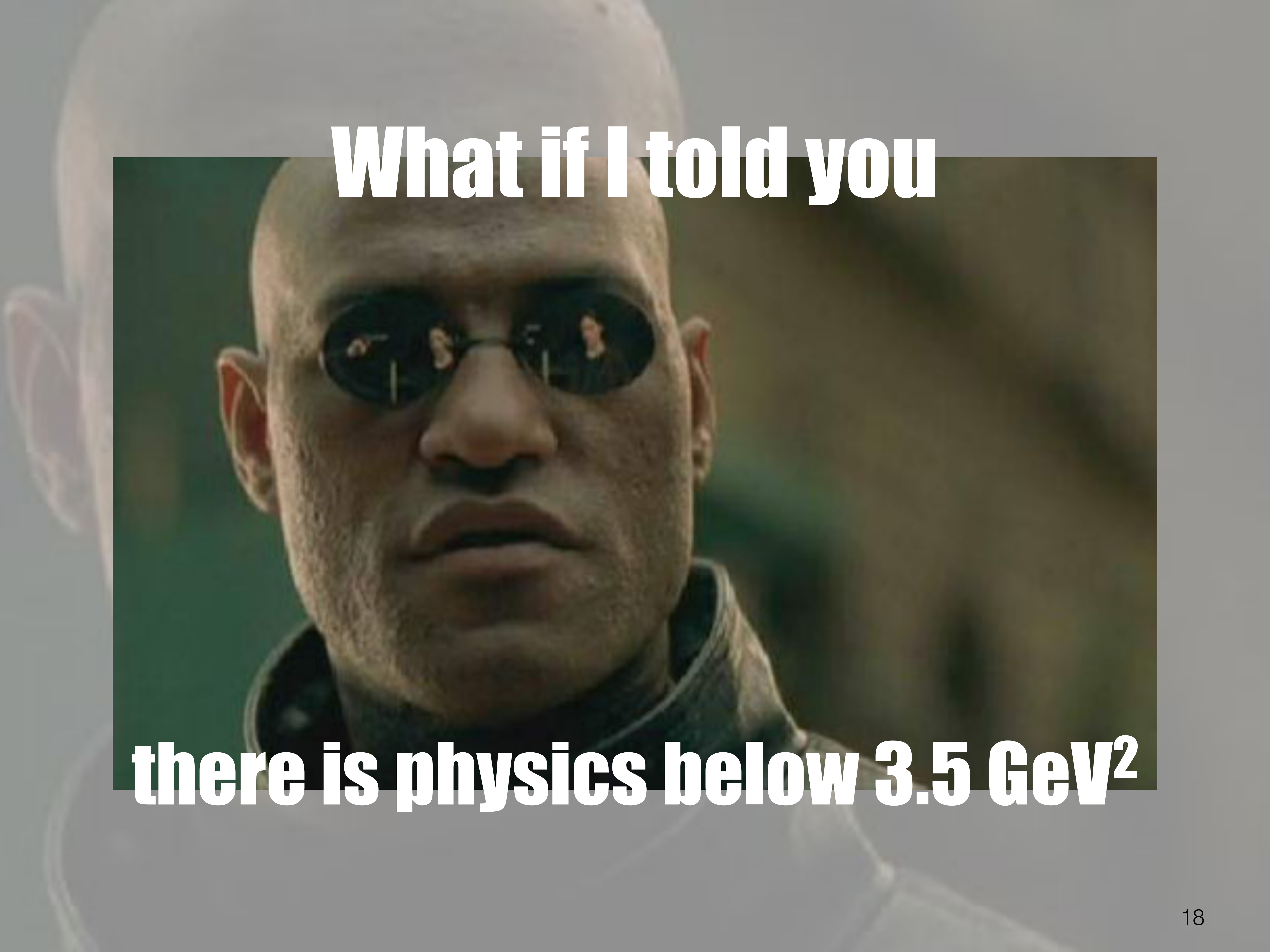
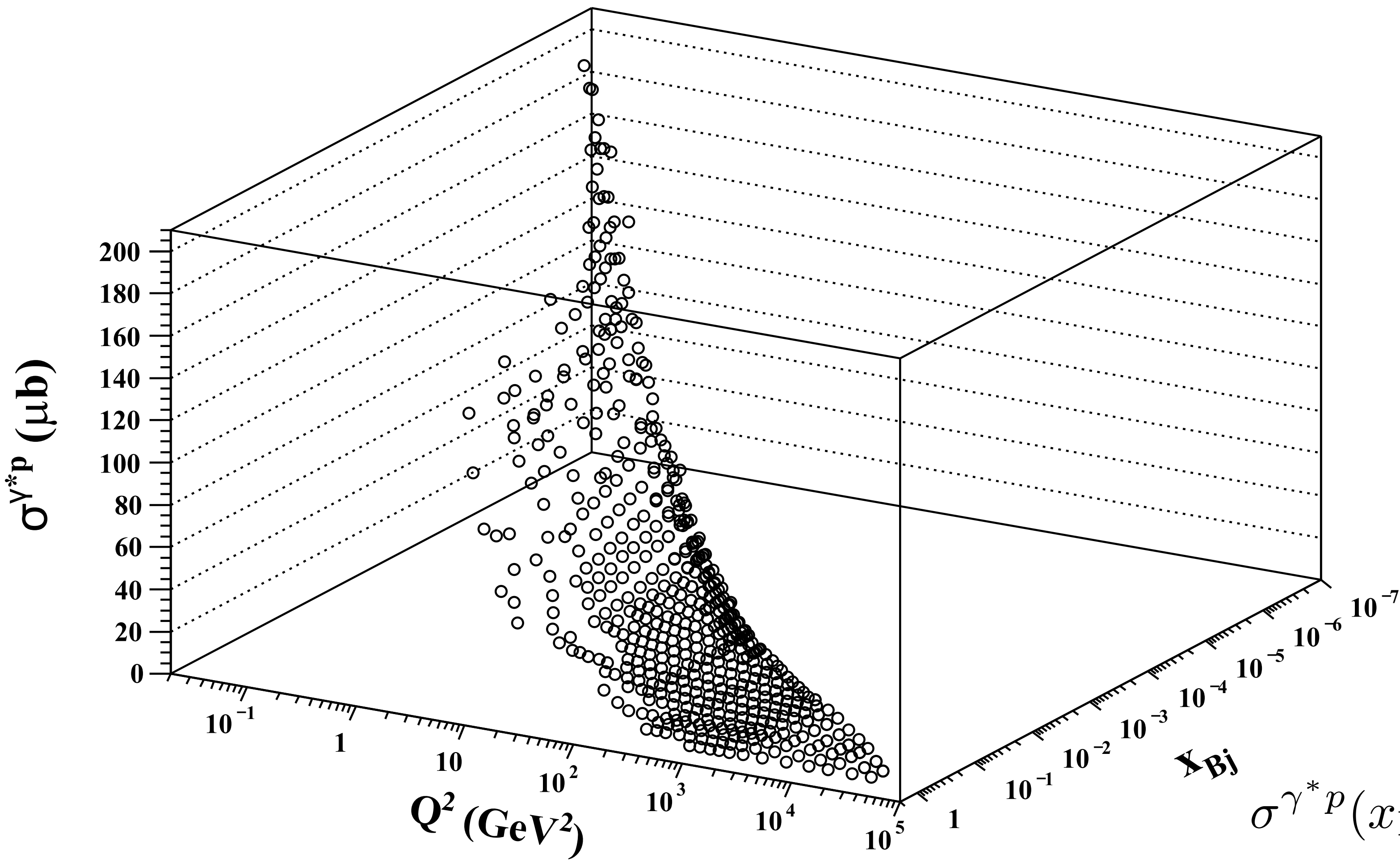

What if I told you
there is physics below 3.5 GeV^2

NC e+p from different angles

$$F_2^{extr} = F_2^{pred} \frac{\sigma_r^{meas}}{\sigma_r^{pred}}$$ will be used further

Predictions for extraction: **Q ≥ 3.5 GeV2 → HHT**; **Q2 < 3.5 GeV2→ BKS**



BKS pheno. model:
$F_L \propto Q^4$ as $Q^4 \to 0$,
Photon-gluon fusion mechanism,
Soft Pomeron exchange assumed

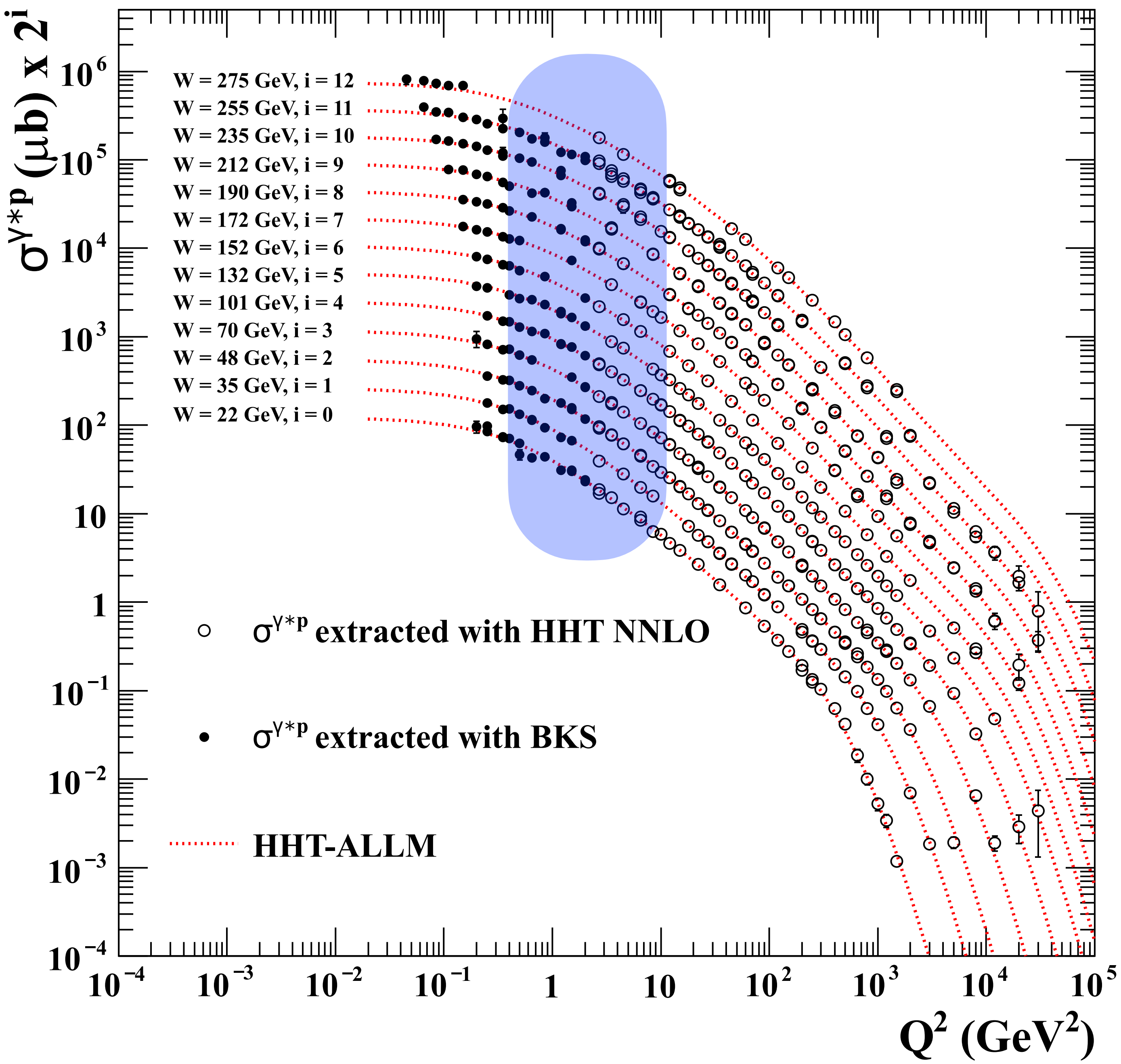
Z.Phys. C74 (1997) 297-306, [hep-ph/9603230]

$\sigma^{\gamma^* p}$ - a useful way of F2 representation

$$\sigma^{\gamma^* p}(x_{\rm Bj}, Q^2) = \frac{4\pi^2\alpha(Q^2 + (2x_{\rm Bj}m_p)^2)}{Q^4(1 - x_{\rm Bj})}\; F_2(x_{\rm Bj}, Q^2)$$

pQCD breaks at low Q2 but nature does not!

ALLM: full data description



Accepted to PRD, [arXiv:1704.03187]

ALLM model:

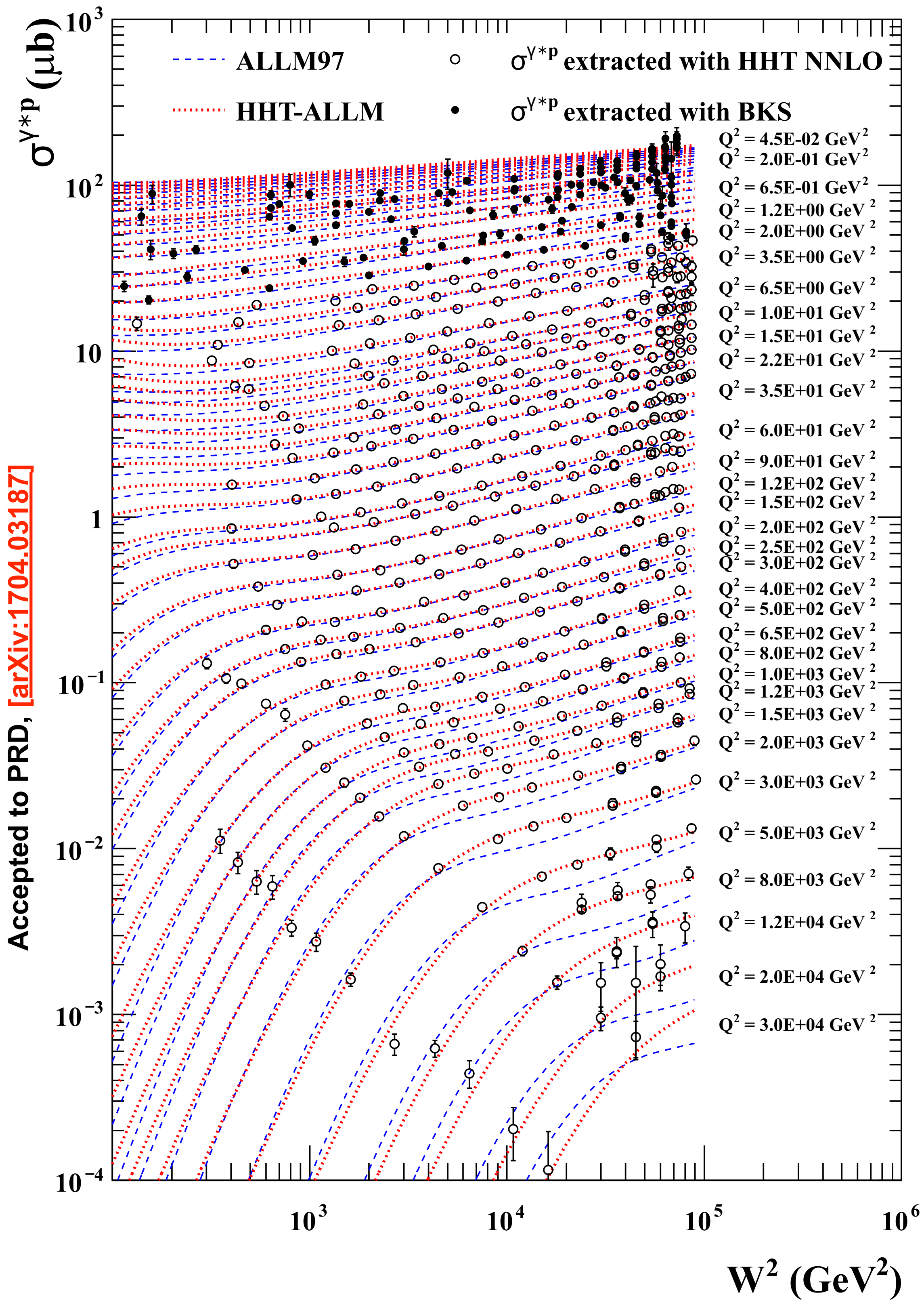
23-parameter *ansatz*

contains Pomeron and Reggeon exchange contributions

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

$$\frac{\chi^2}{n.d.f} \approx 1.06$$

ALLM: full data description



ALLM97 used only early HERA data

HHT-ALLM recent update with full HERA data

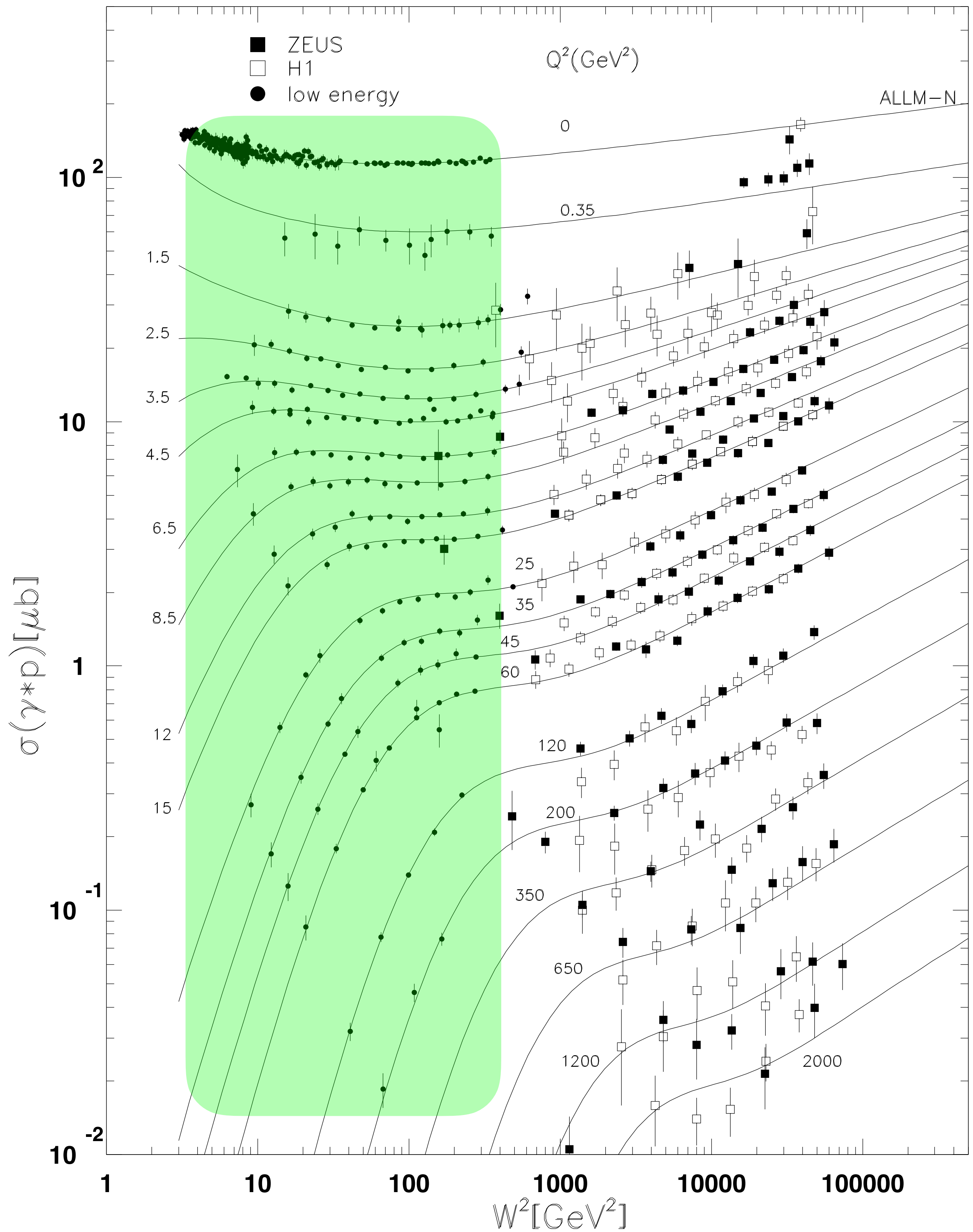
HHT-ALLM describes data remarkably well!

$$\frac{\chi^2}{n.d.f} \approx 1.06$$

Note the **smooth trend** established by the data!

ALLM: full data description

DESY-97-251, [hep-ph/9712415]

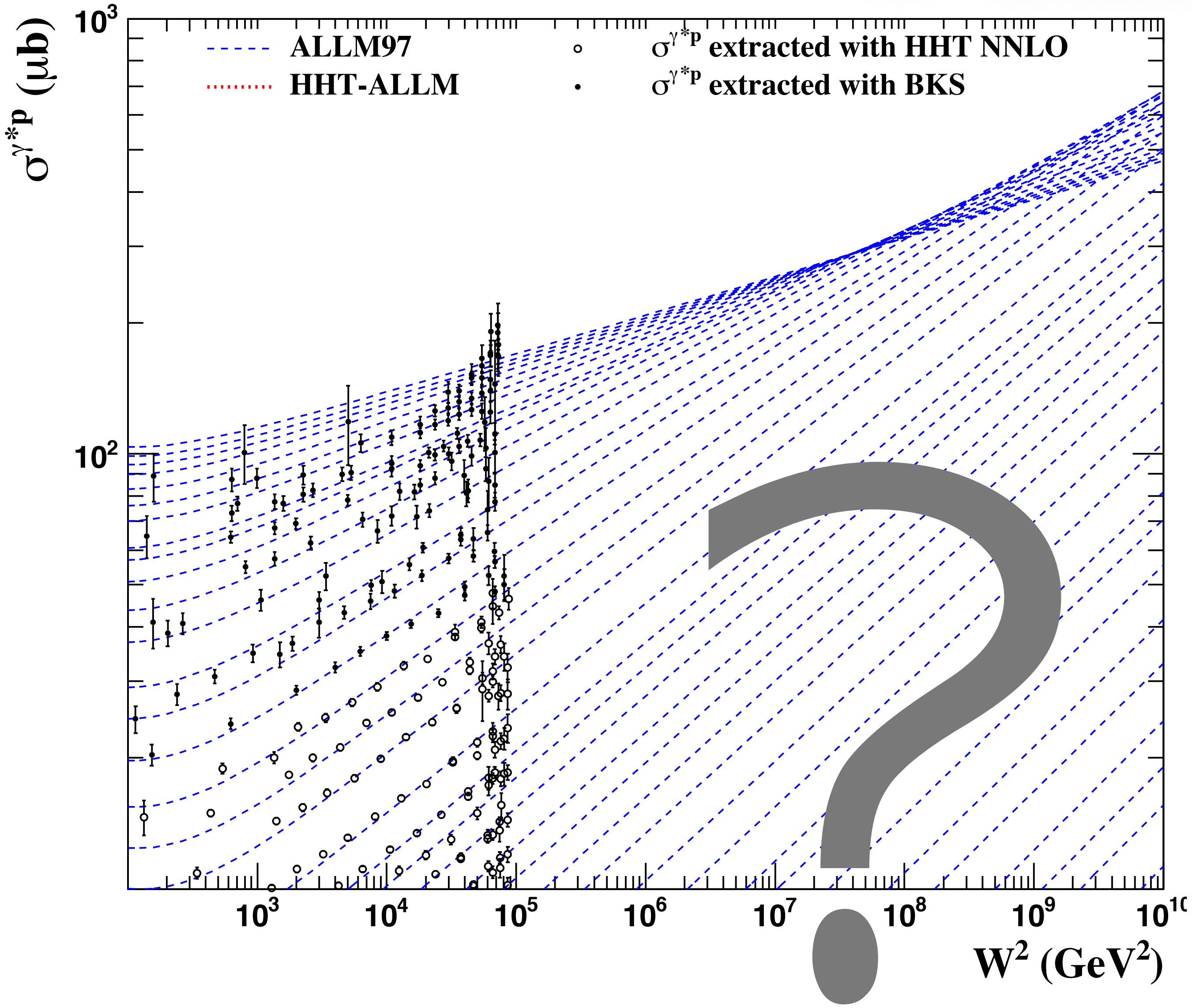


Non-trivial structures observed at **Fixed Target** at high x

Successfully described by **ALLM97**

$$W^2 = Q^2(\frac{1}{x_{Bj}} - 1) + m_P$$

ALLM extrapolation



Terra incognita at low x

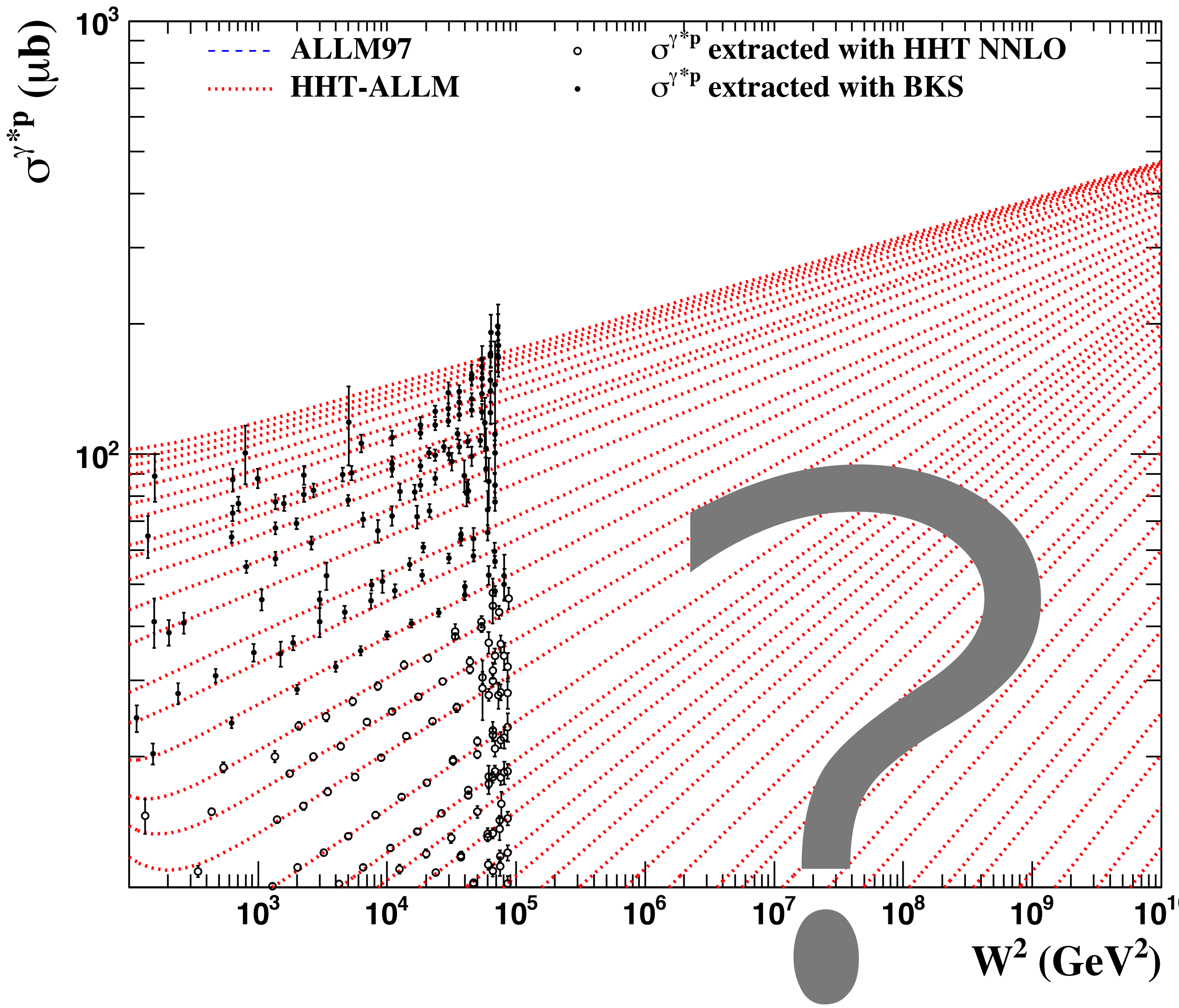
to be revealed

by future experiments

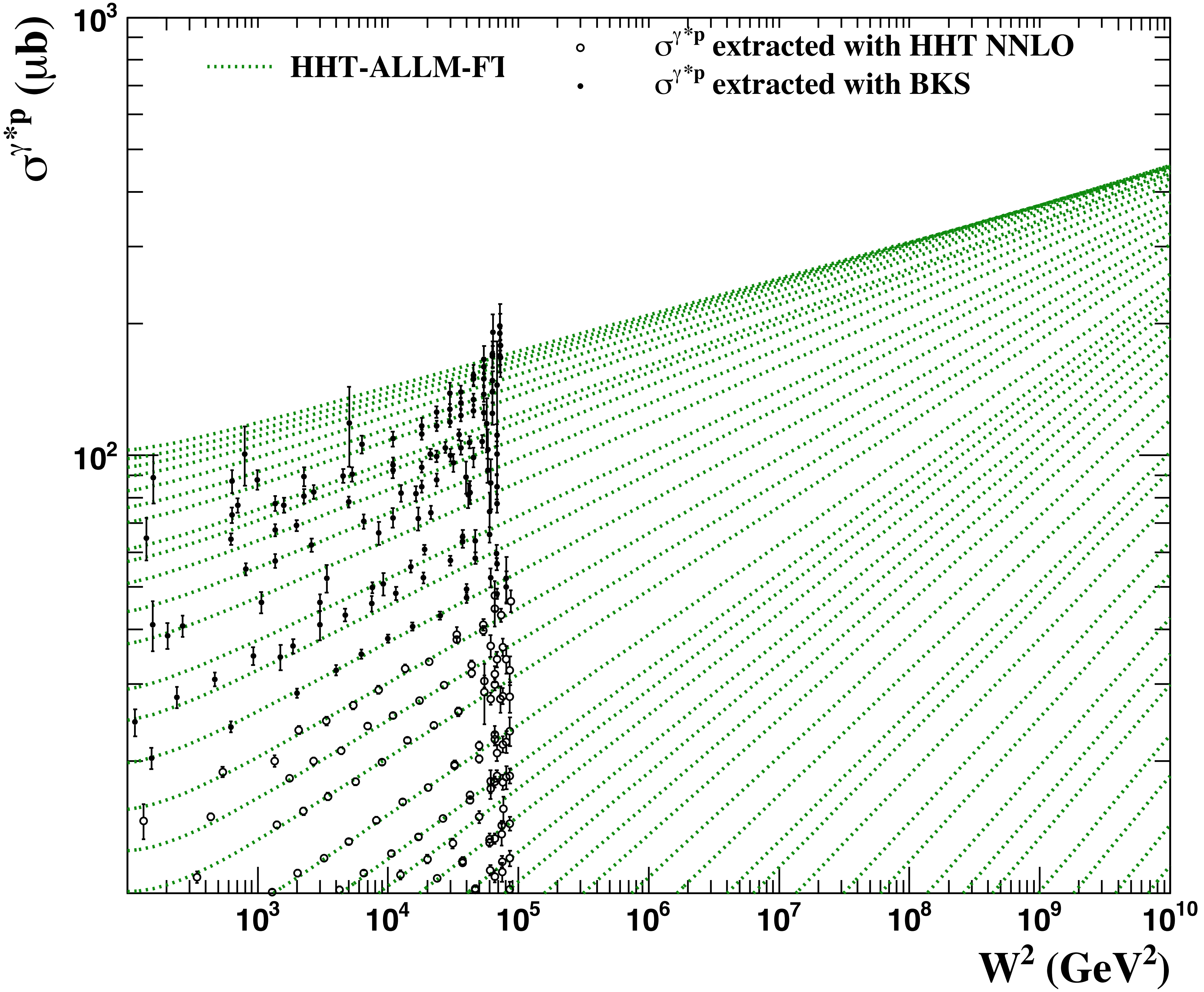
Any new

particular structures?

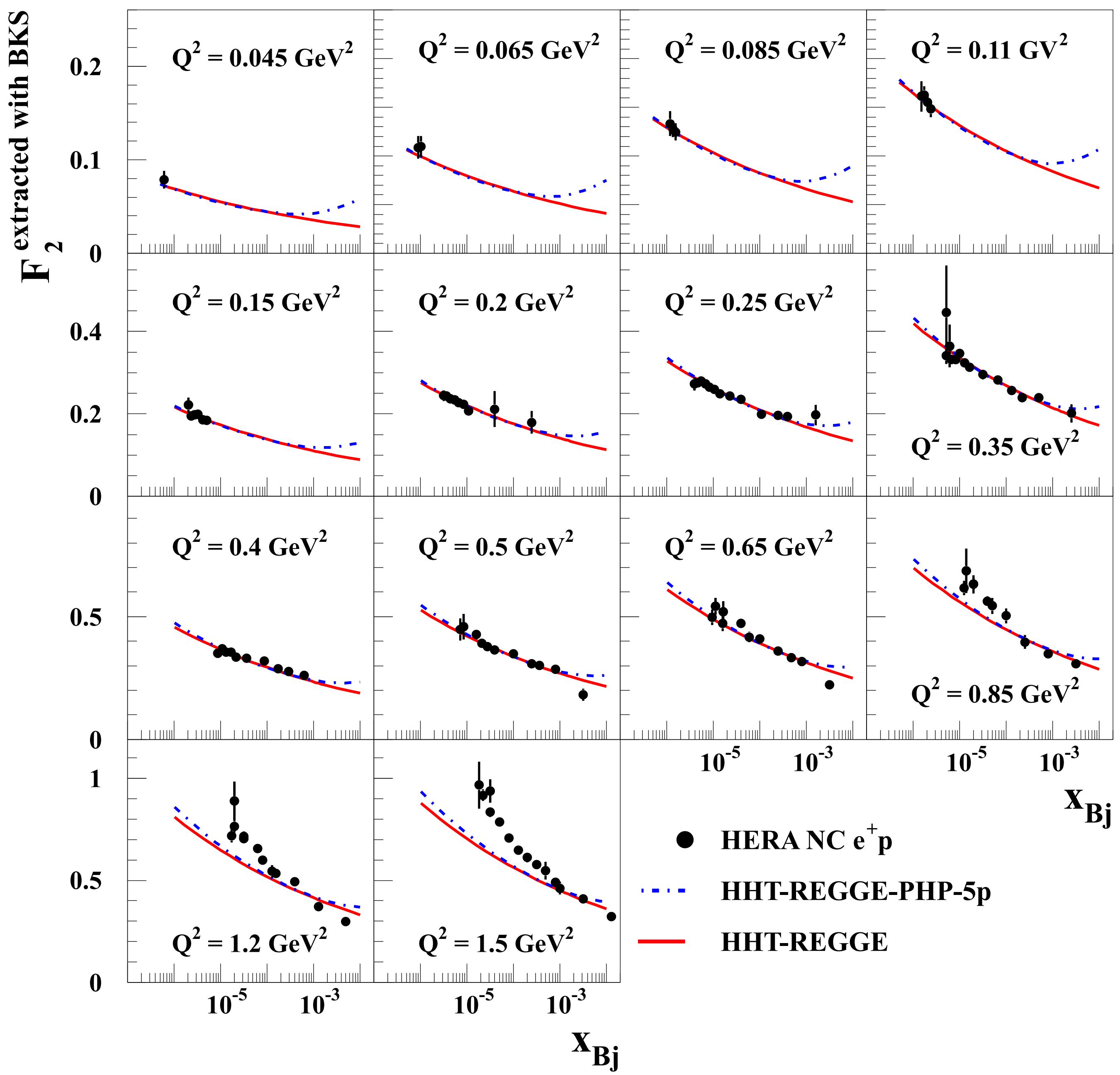
$$W^2 = Q^2(\frac{1}{x_{Bj}} - 1) + m_P$$



ALLM extrapolation



REGGE fit



Low-x data was cross-calibrated in the latest combination

HHT-REGGE - new Regge fit was performed (only *IP*)!

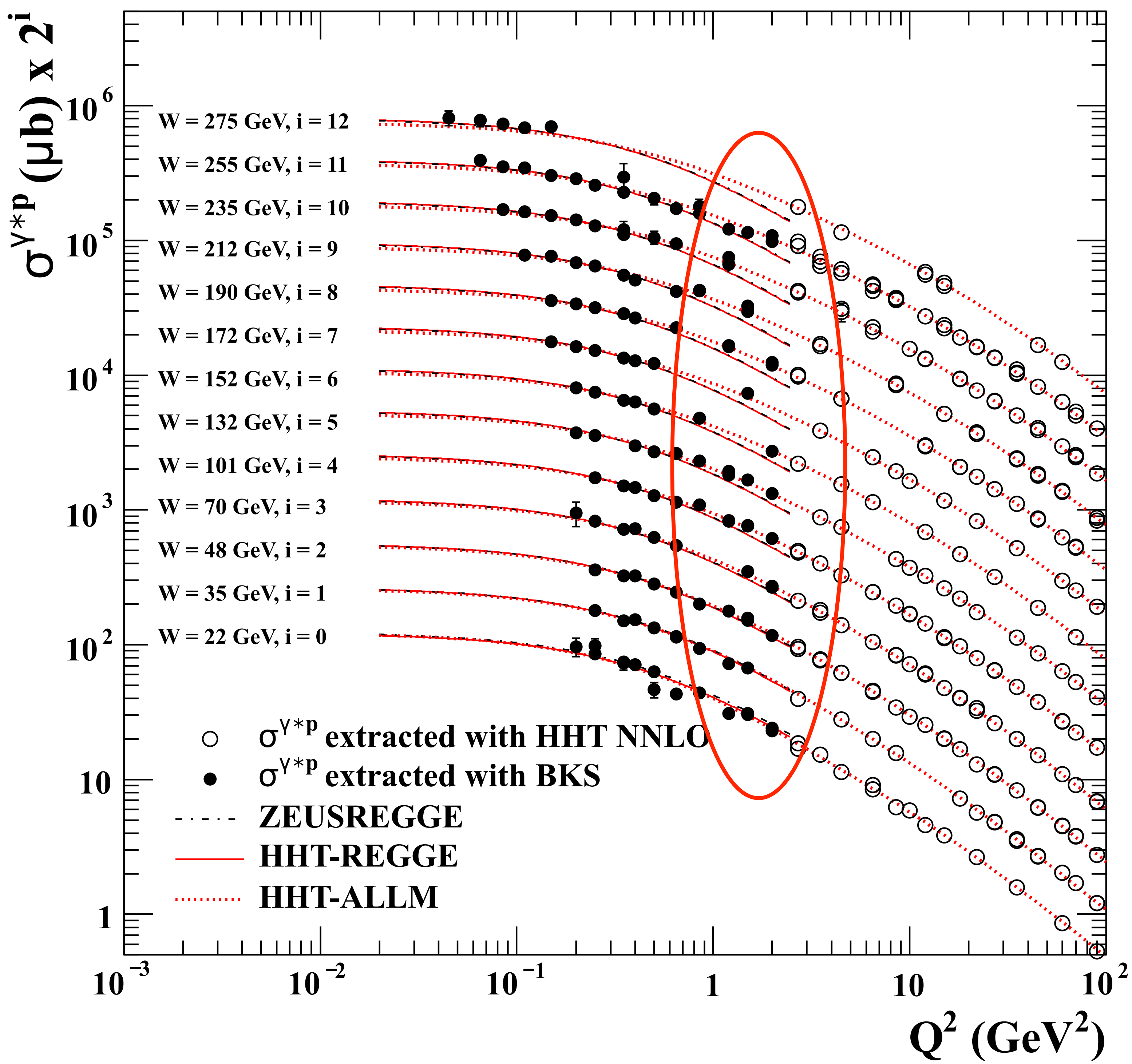
$$Q^2 \leq 0.65 GeV^2$$

HHT-REGGE-PHP-5 - done adding PhP data (+IR term)!

FT doesn't seem to help…

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

REGGE fit

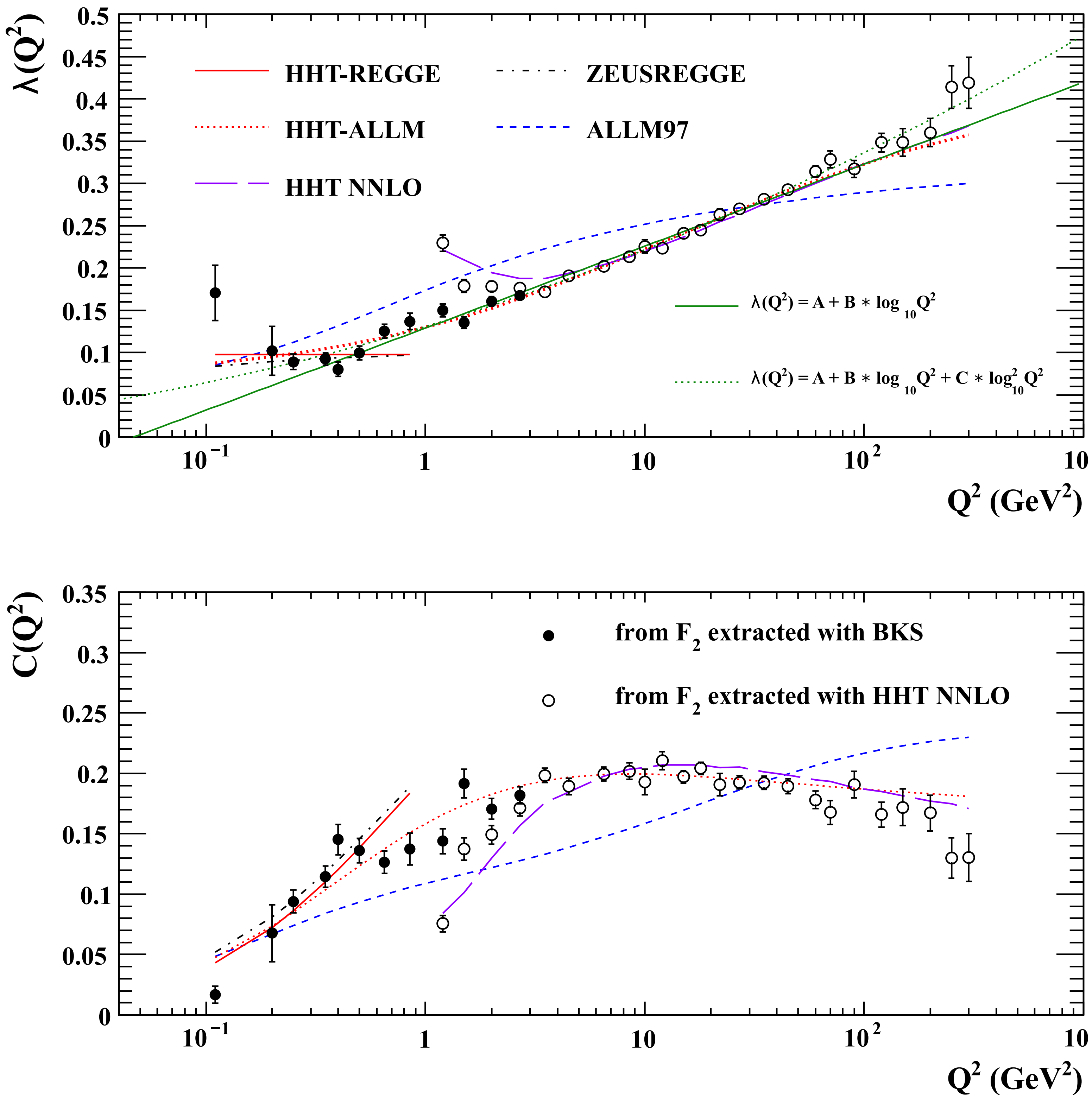


Regge diverges from data as $x_{Bj} \rightarrow 0$

Lacking data at high W (low x_{Bj})!

$$W^2 = Q^2(\frac{1}{x_{Bj}} - 1) + m_P$$

Characteristics of F_2



At fixed Q² the F_2 can be described by LO pQCD approx.: $F_2 = C(Q^2) x_{\mathrm{Bj}}^{-\lambda(Q^2)}$

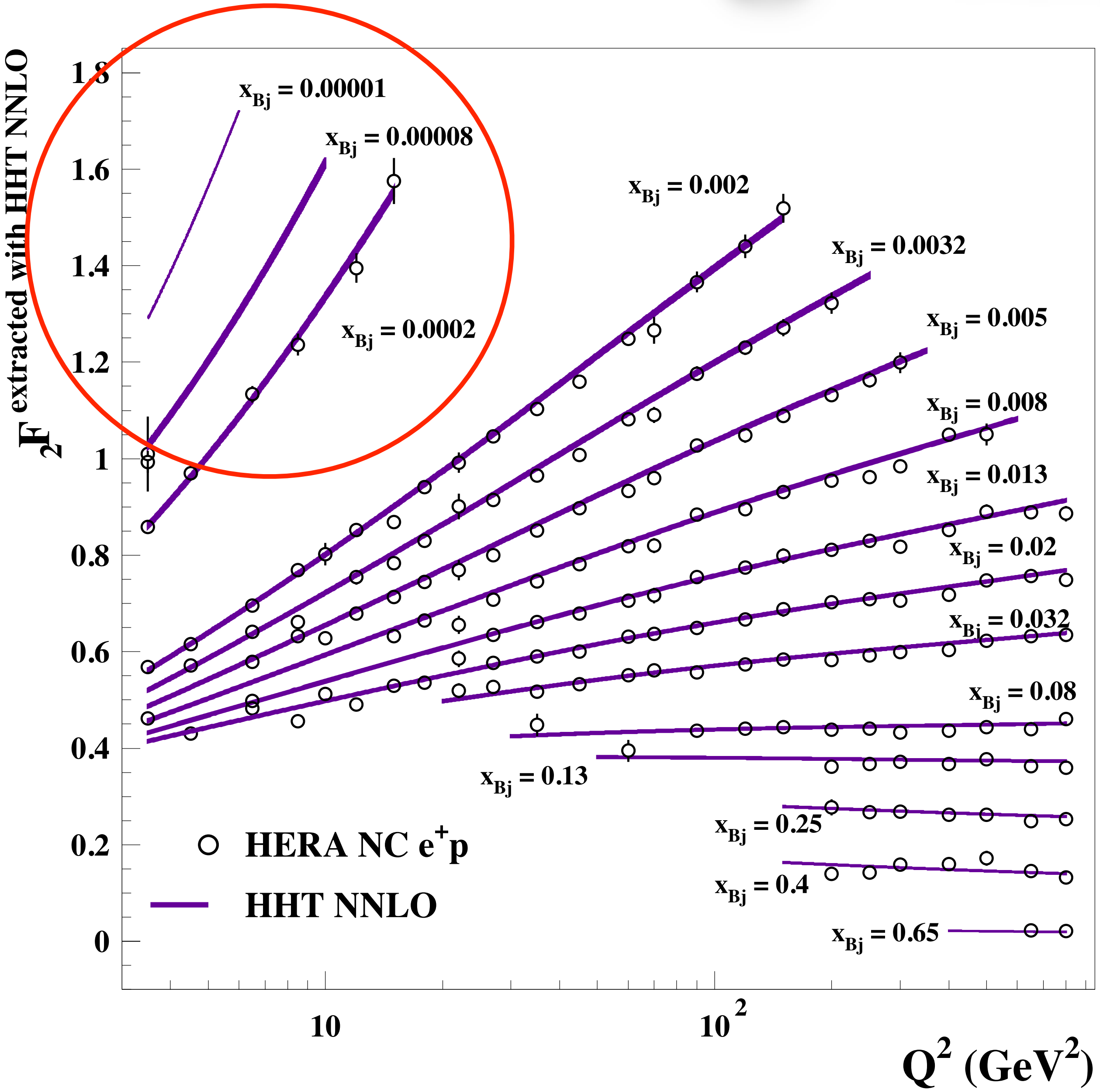
Low Q²: soft Pomeron

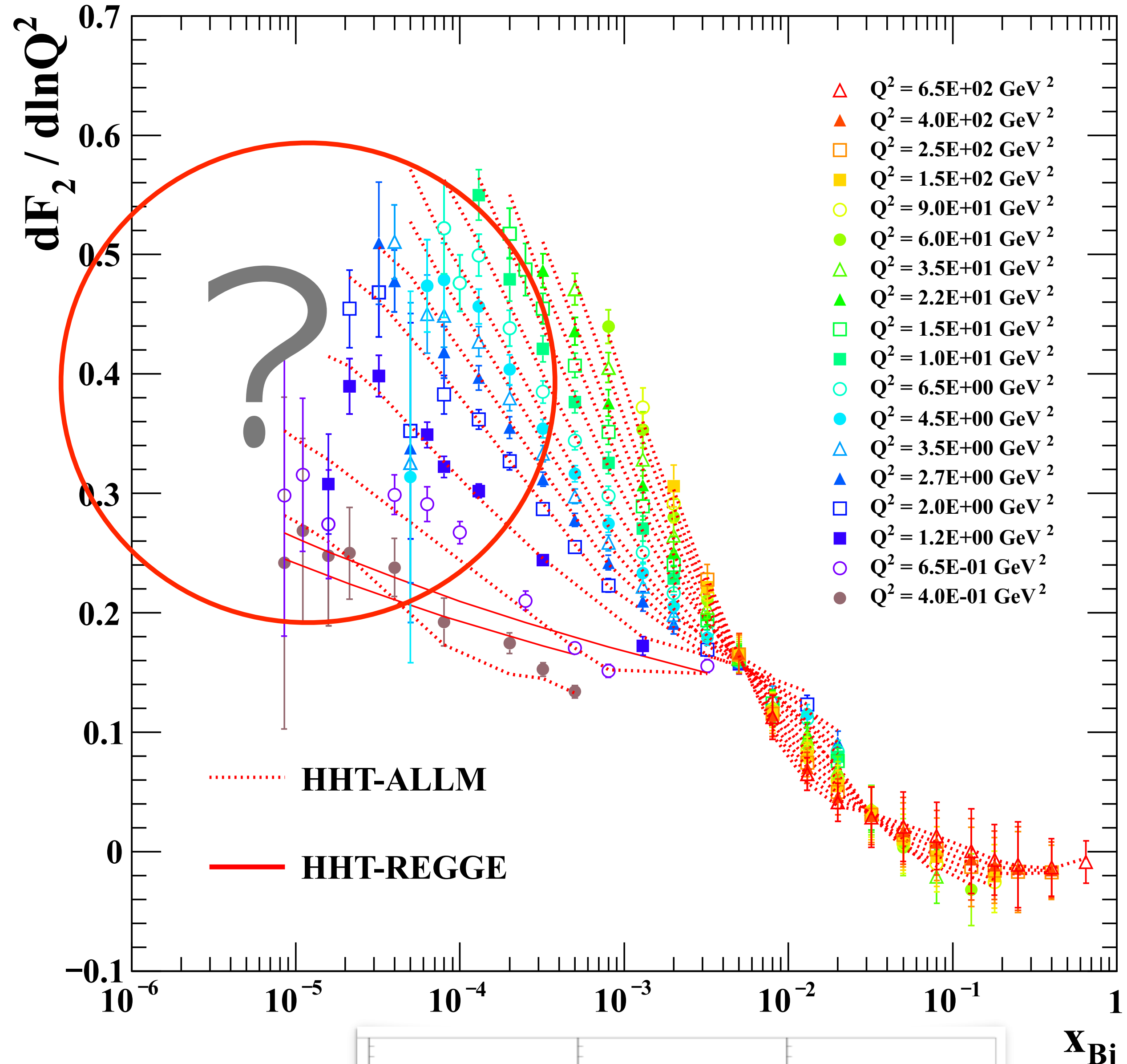
$\lambda \simeq$ *const*

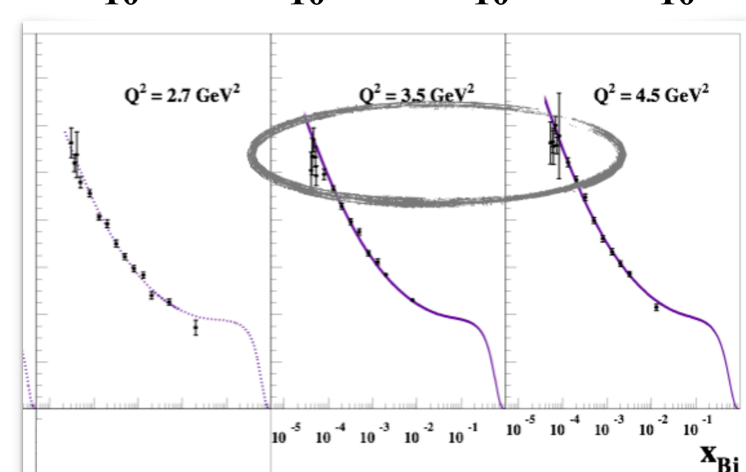
High Q²: "effective" Pomeron

Note: description by simple polynomials!

Scaling violation in DIS



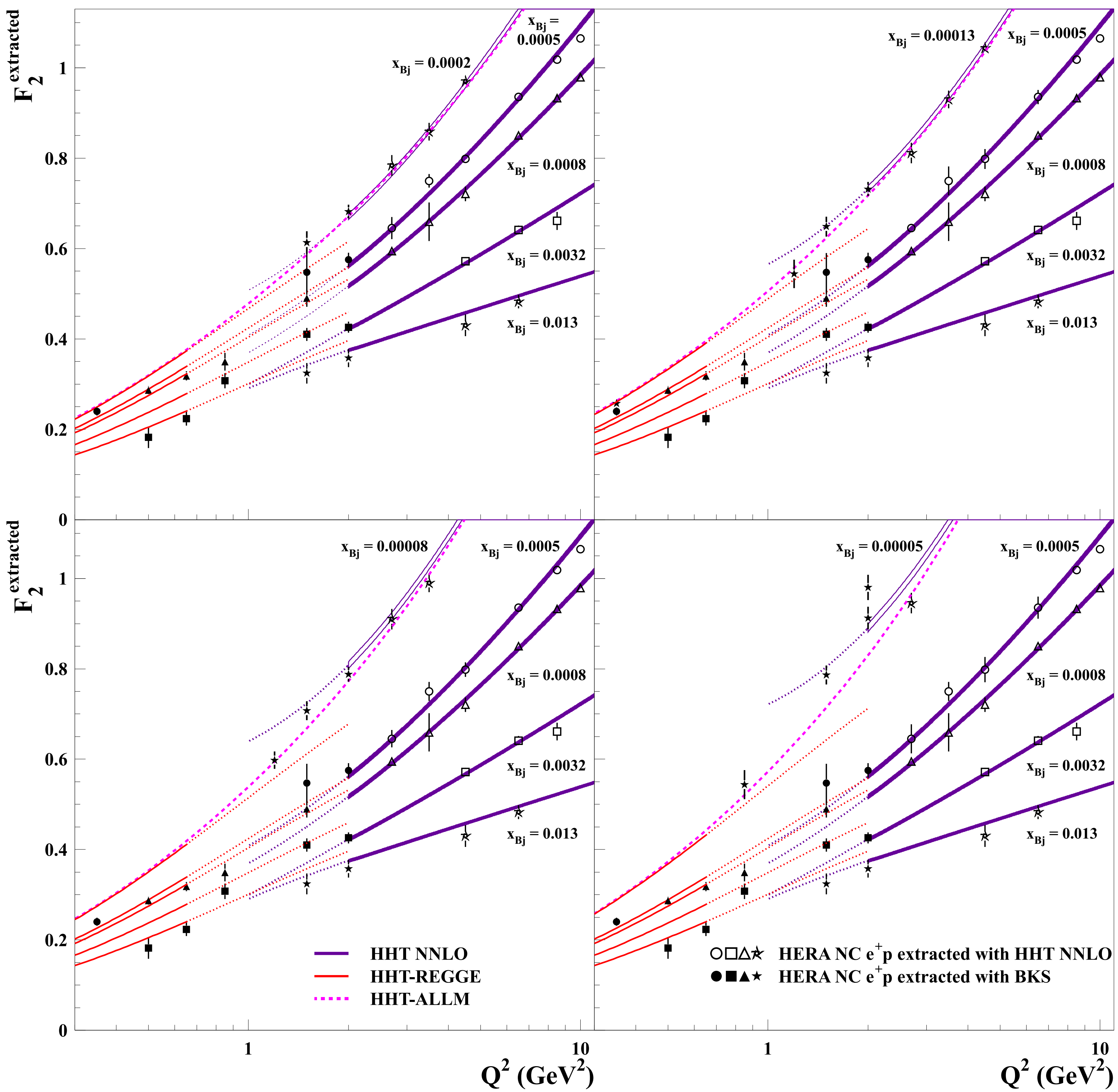




Statistical limitations at low x_{Bj}

Fluctuations? Something more significant?..

When pQCD meets Regge



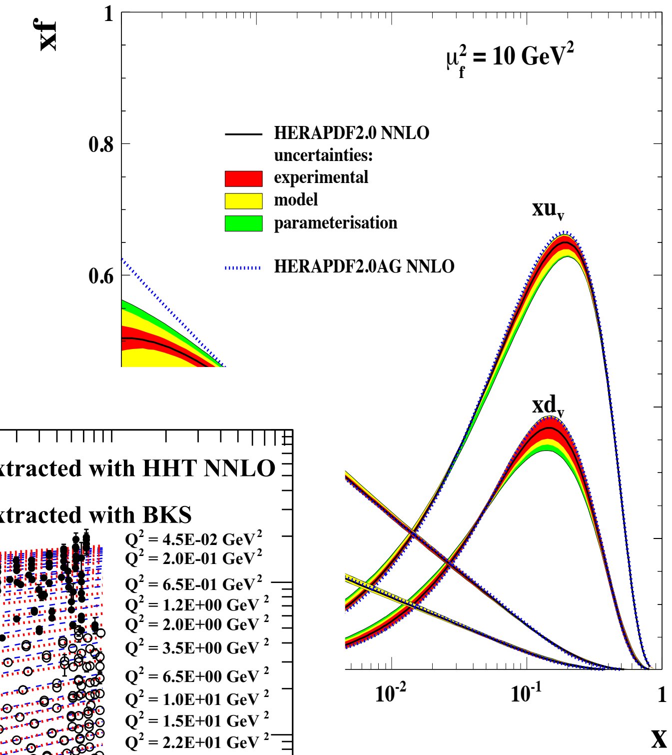
Gap between pQCD and Regge grows as $x_{Bj} \to 0$

Does nature have any preferences?..

...and, whose side are you on?

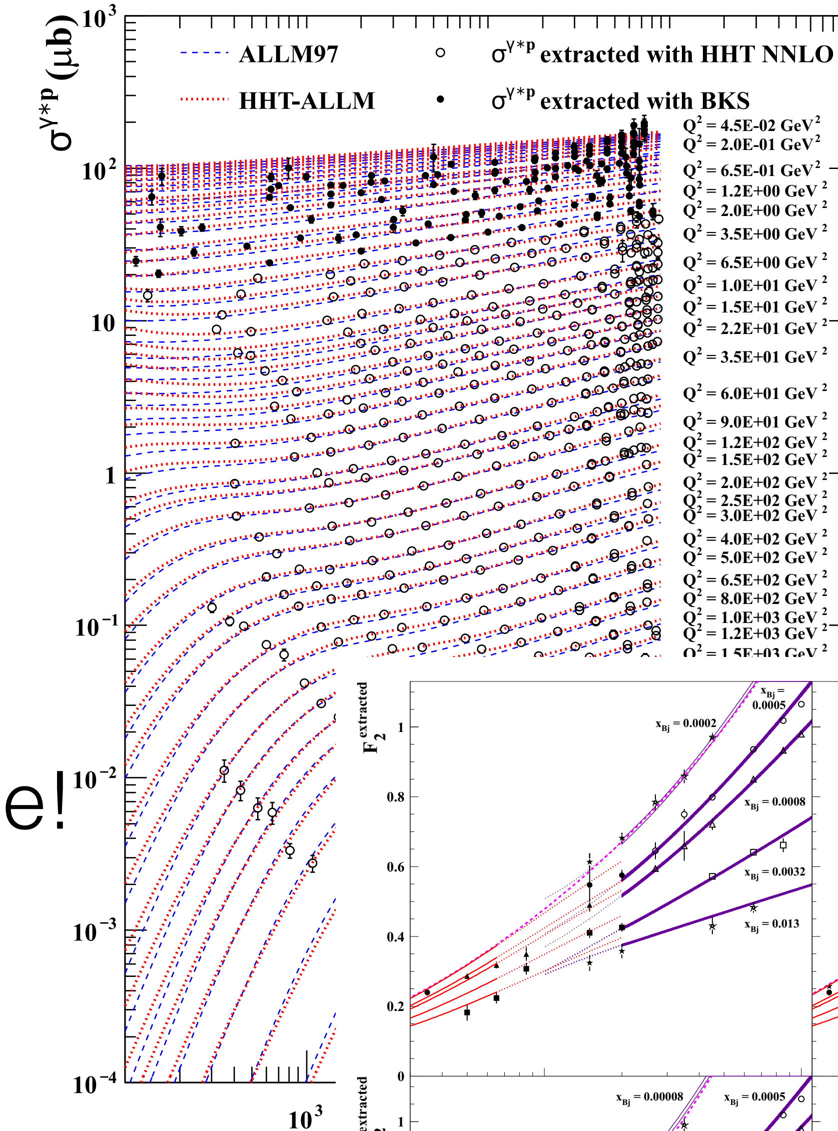
Side?! I am on nobody's side, because nobody is on my side!

Summary

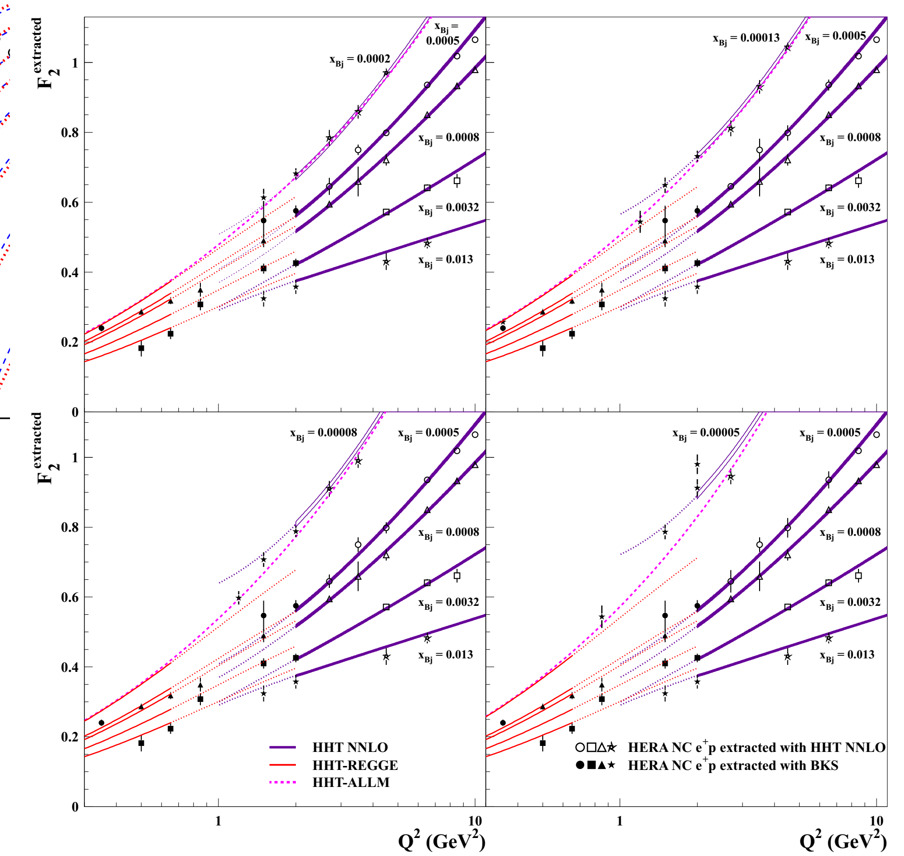


HERA provided reach possibilities of studying nature

- Proton structure
- pQCD tests
- Phenomenological models,
- Gluon saturation..?



Studies trigger more questions each time!



Time to improve our knowledge!

Time to ask more questions!

Backup
…not necessarily useful