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

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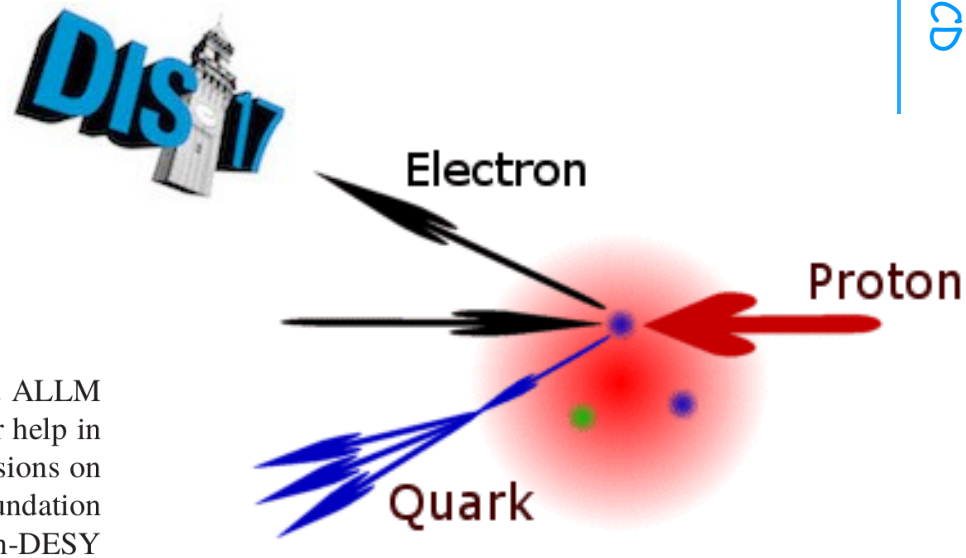
DESY-17-051



Acknowledgements

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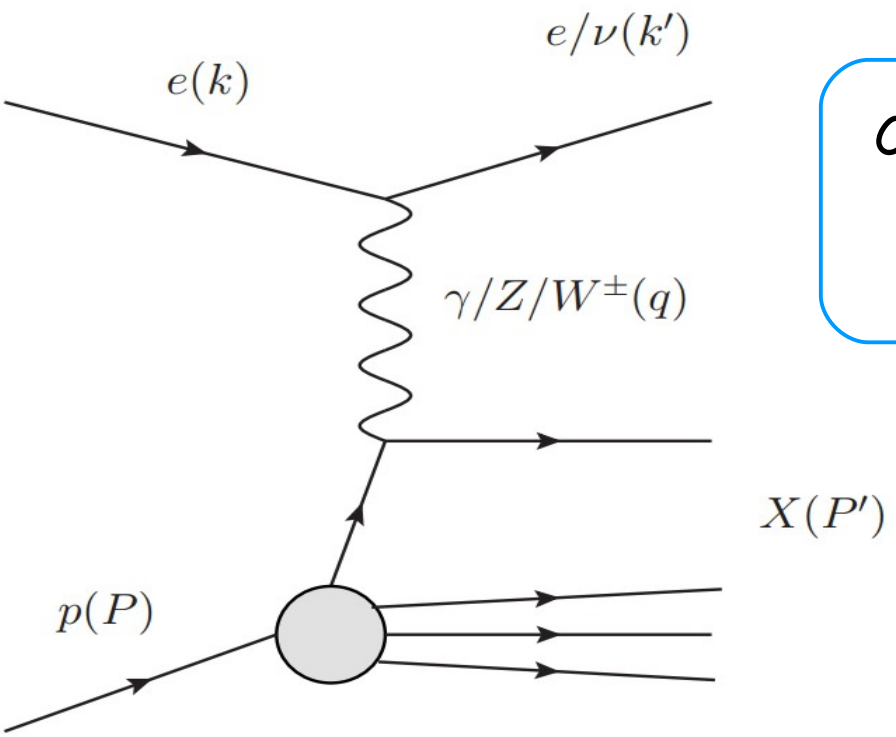
Deep Inelastic Scattering at HERA



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

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

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

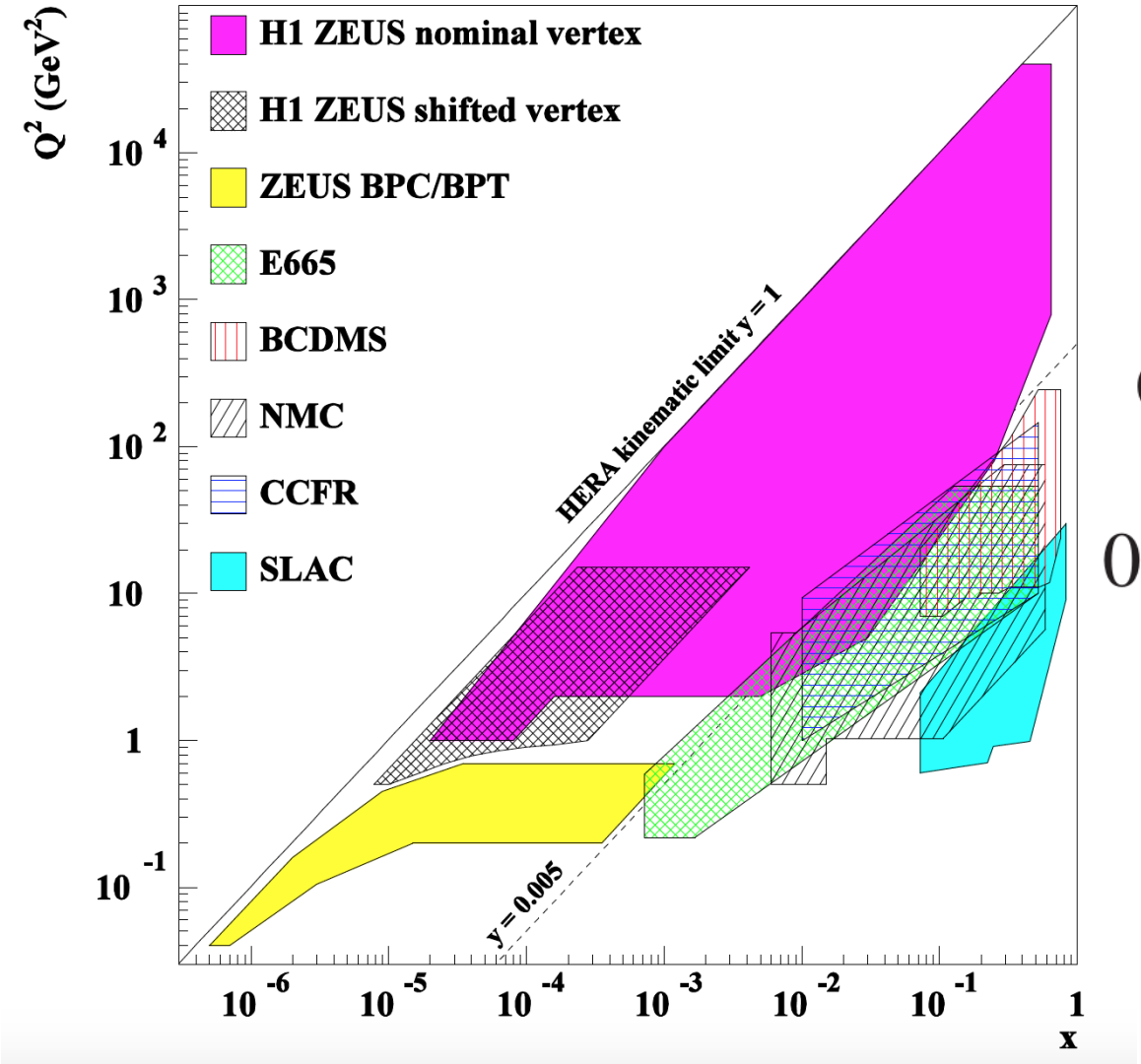
$$x_{Bj} = \frac{Q^2}{2\,pq} \qquad y = \frac{pq}{pk}$$

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

Experimental luminosity (H1 & ZEUS):

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

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



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

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

Low-x twist-4 terms in HHT (HERA data only)

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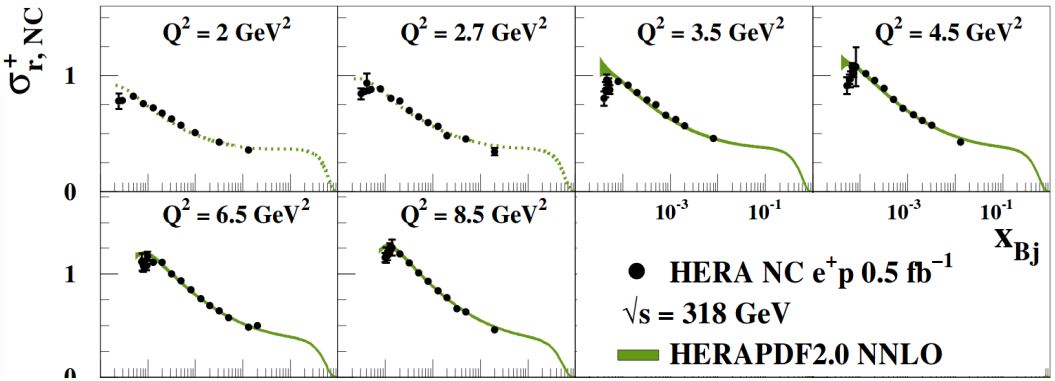
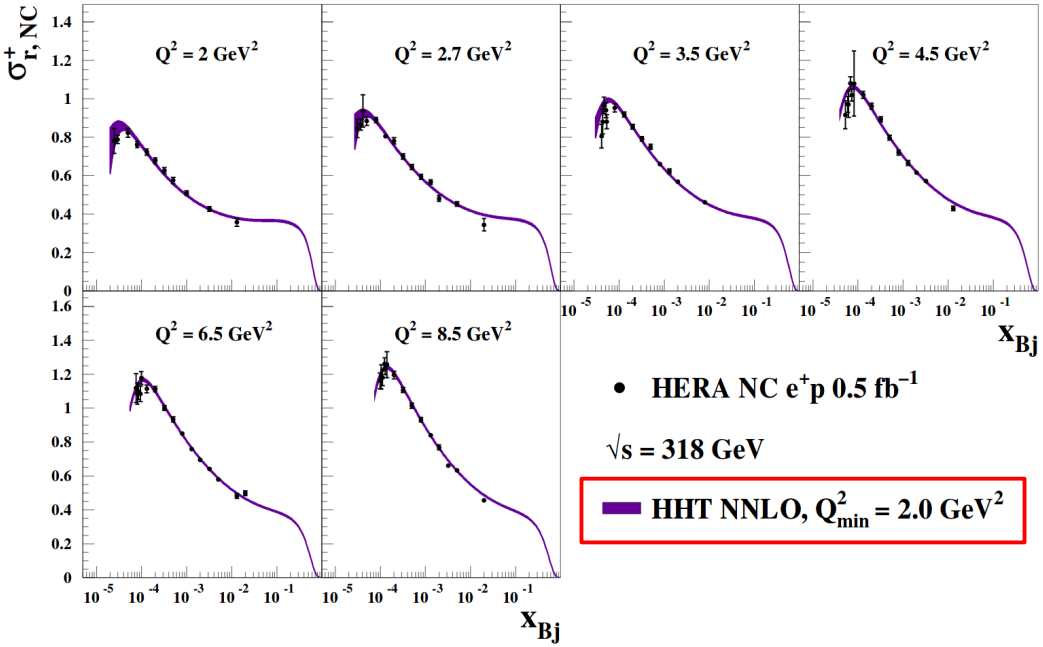
- Description of low-Q^2 low-x region improved by adding twist-4 terms

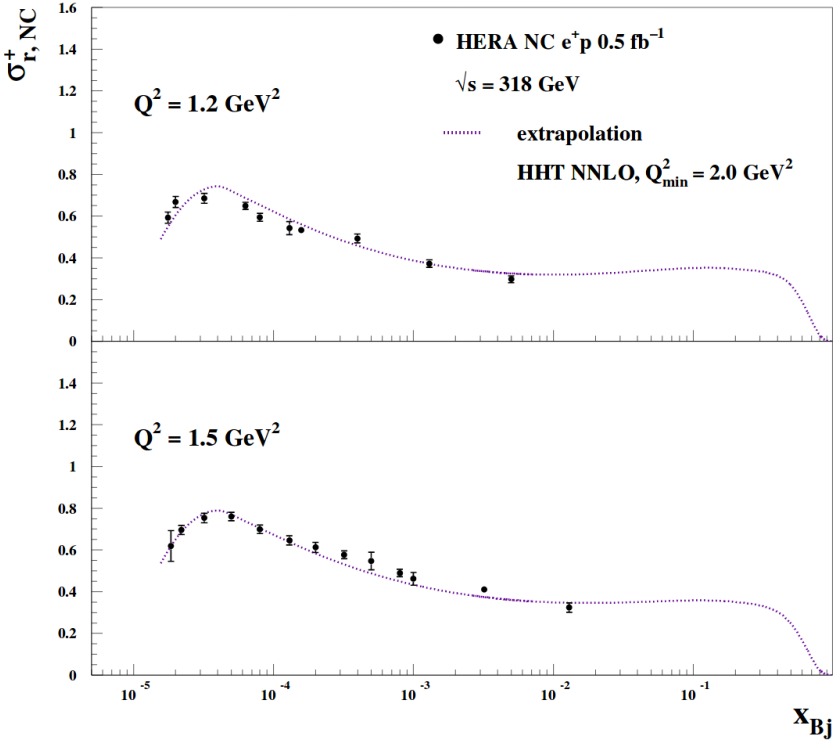
$$F_L^{HT} = F_L^{DGLAP} (1 + A_L^{HT}/Q^2)$$

H1 and ZEUS





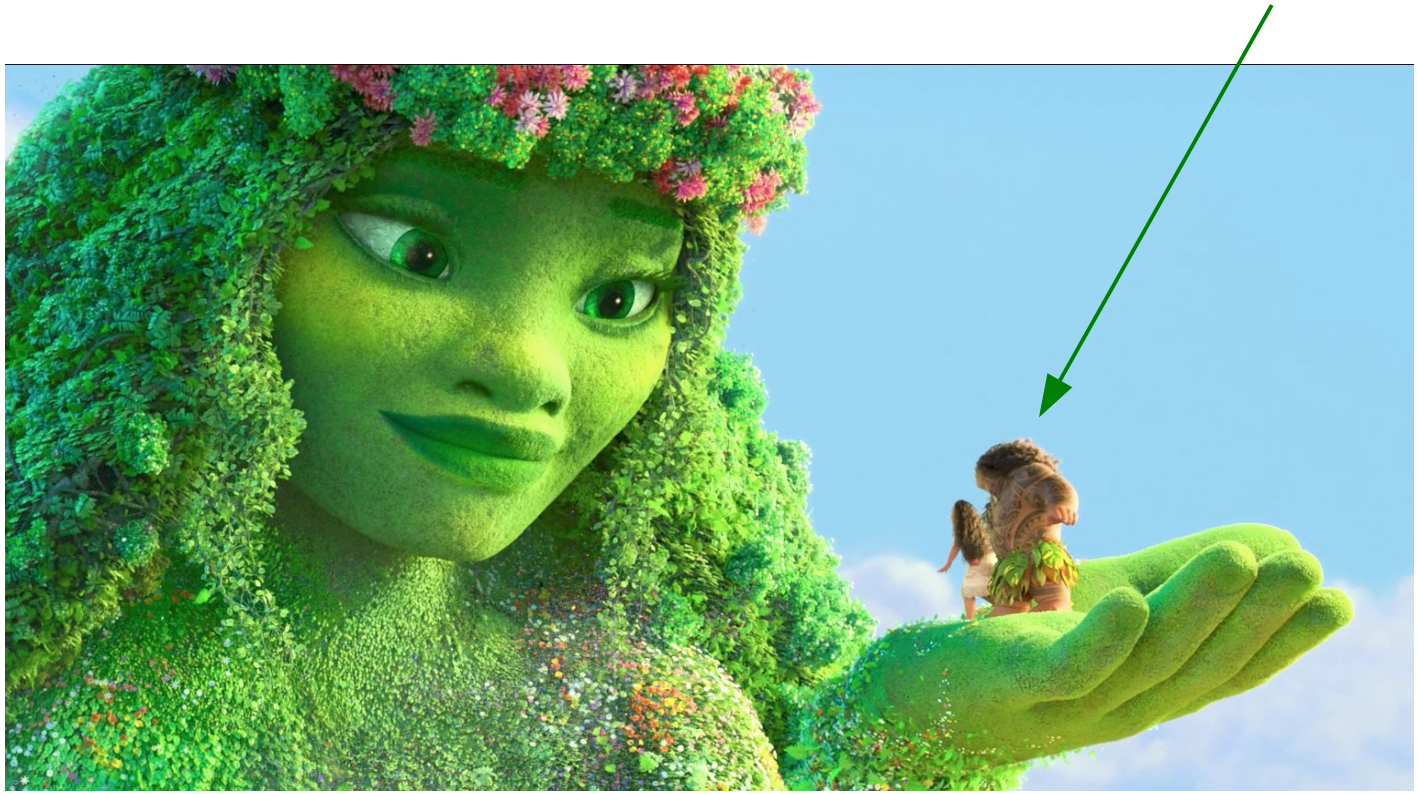
extrapolation works down to 1 GeV^2 but F_L becomes unphysical in this



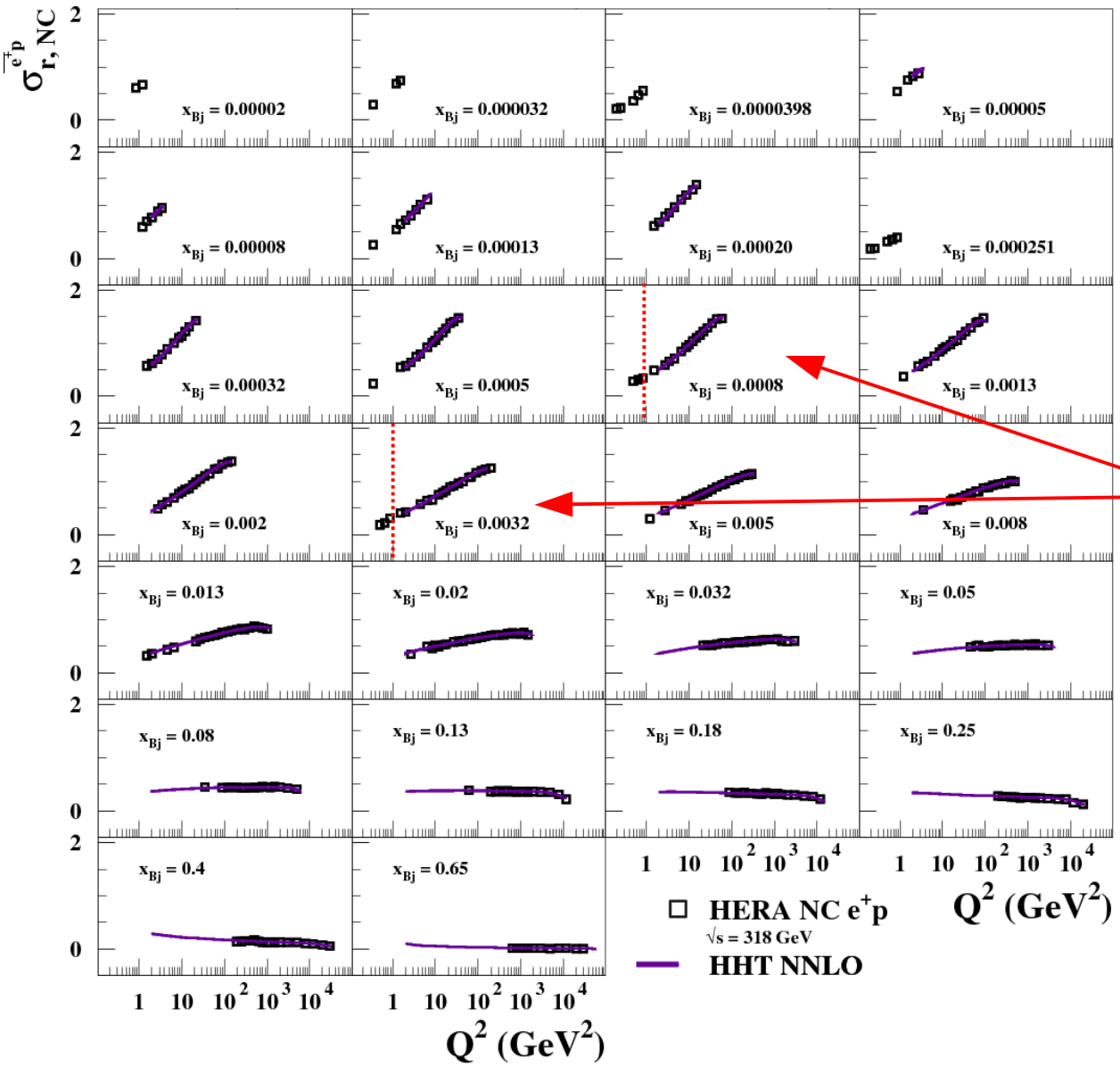
good description of data down to ~1 GeV^2

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

$$\sigma^{e^+p}_{r,\mathrm{NC}} = \tilde{F}_2(x_{\mathrm{Bj}}, Q^2) - \frac{Y_-}{Y_+} x\tilde{F}_3(x_{\mathrm{Bj}}, Q^2) - \frac{y^2}{Y_+} F_{\mathrm{L}}(x_{\mathrm{Bj}}, Q^2)$$

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

$$\sigma^{e^+p}_{r,\mathrm{NC}} = F_2 - \frac{y^2}{Y_+} F_\mathrm{L}$$

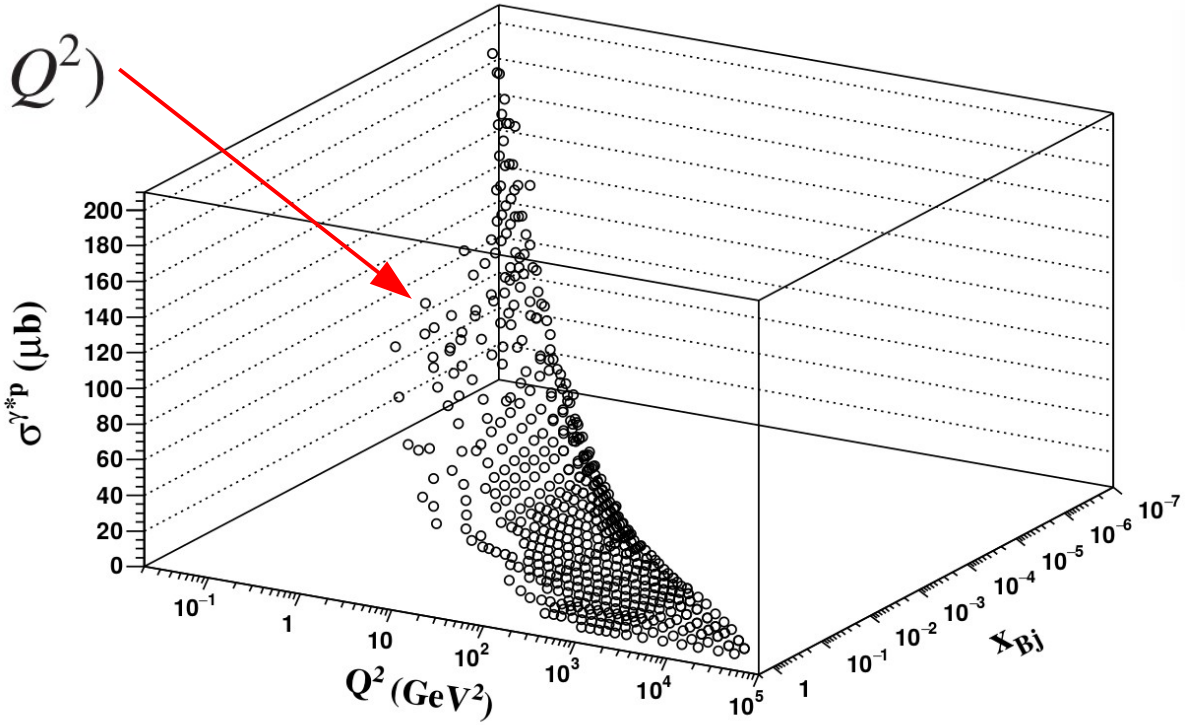
- Extracting F_2 tricky – no unbiased way exists

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

- 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

ALLM parameterisation

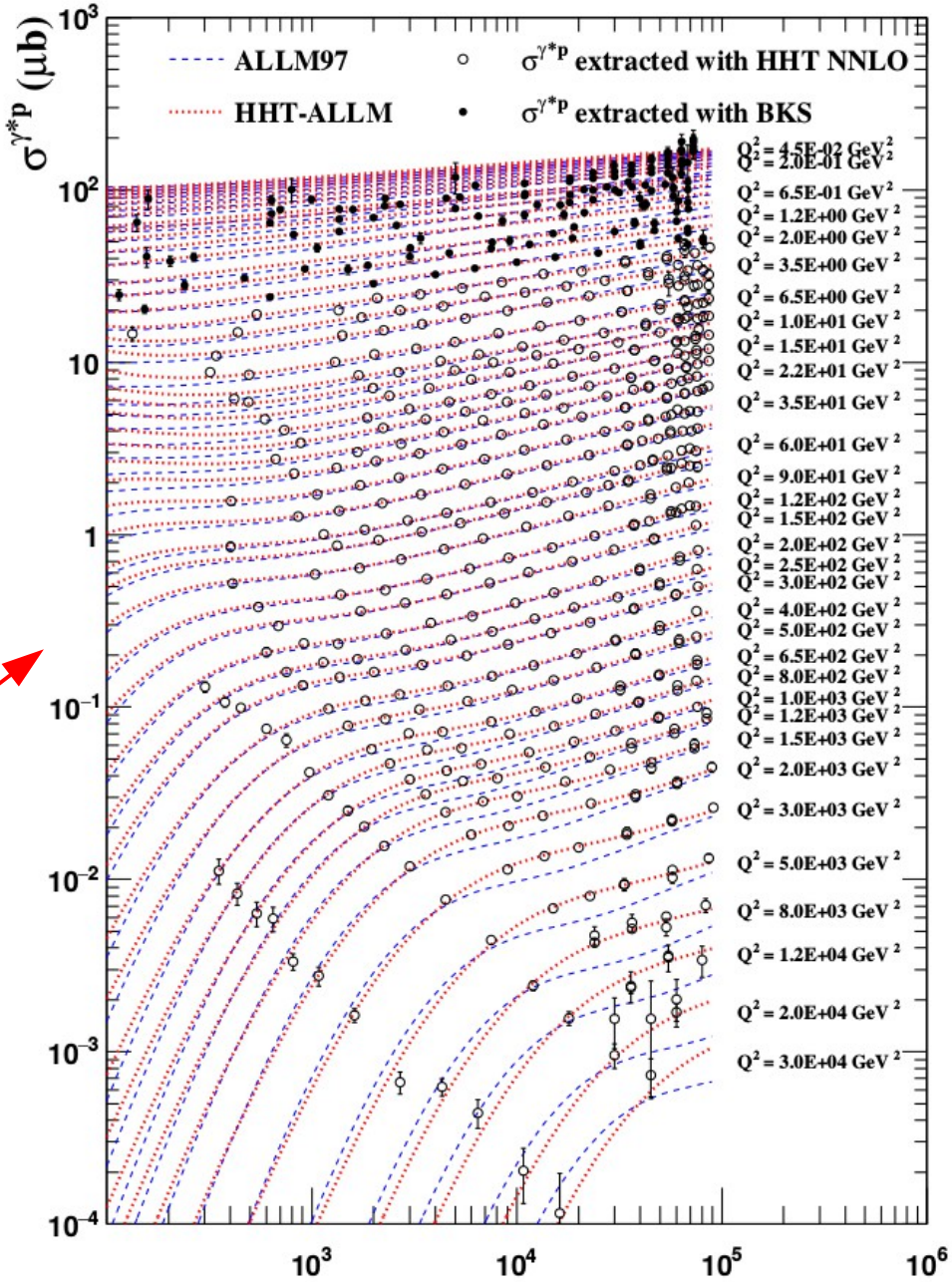
- Inspired by Regge theory
- Incorporates ideas of pQCD

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

proton mass

- Overall 23 free parameters

Describes data well across the whole kinematic range

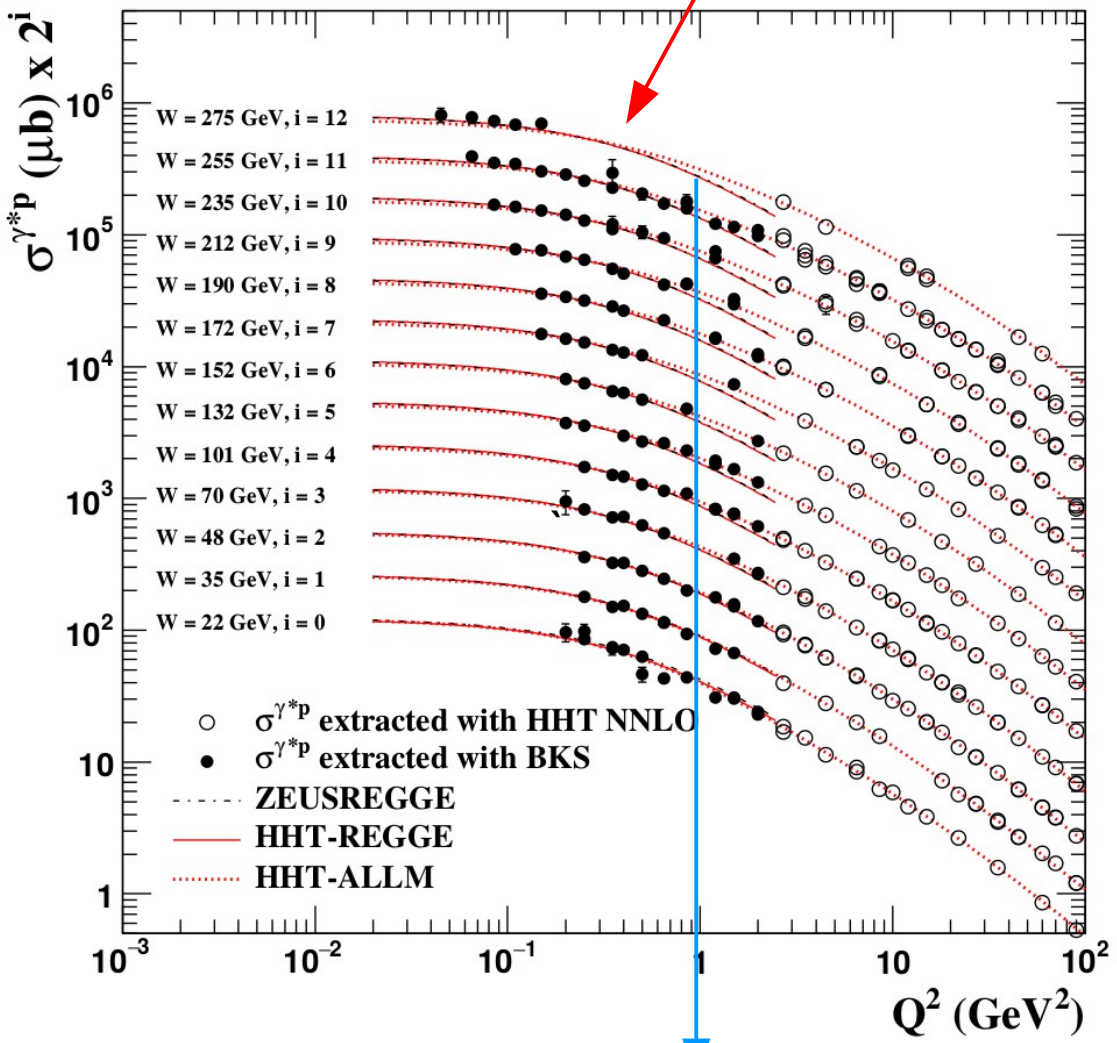


$$W^2 = Q^2(1/x_{\mathrm{Bj}} - 1) + m_p^2$$

$\sigma^{\gamma^* p}$ for selected W values

$$\sigma^{\gamma^* p} \propto W^{2(\alpha_{IP}(0)-1)}$$

- $\sigma^{\gamma^* p}$ 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 $\sigma^{\gamma^* p}$ drops as $1/Q^2$
  → at low Q^2 $\sigma^{\gamma^* p}$ 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

How about Regge phenomenology?

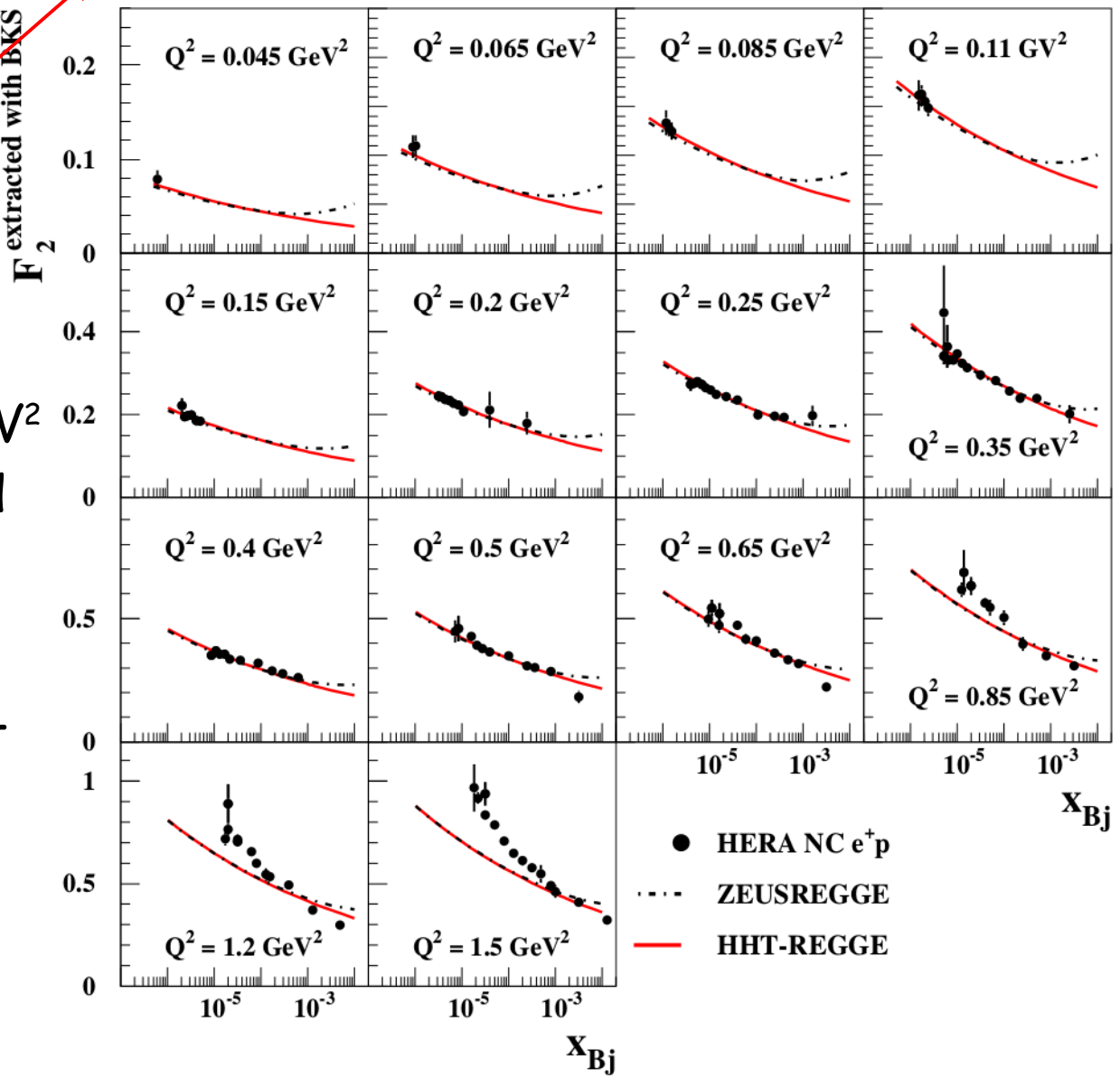
$$F_2(x_{\mathrm{Bj}}, Q^2) = \frac{Q^2}{4\pi^2\alpha} \cdot \frac{M_0^2}{M_0^2 + Q^2} \cdot \left(A_{I\!P} \left(\frac{Q^2}{x_{\mathrm{Bj}}} \right)^{\alpha_{I\!P}(0)-1} + A_{I\!R} \left(\frac{Q^2}{x_{\mathrm{Bj}}} \right)^{\alpha_{I\!R}(0)-1} \right)$$

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

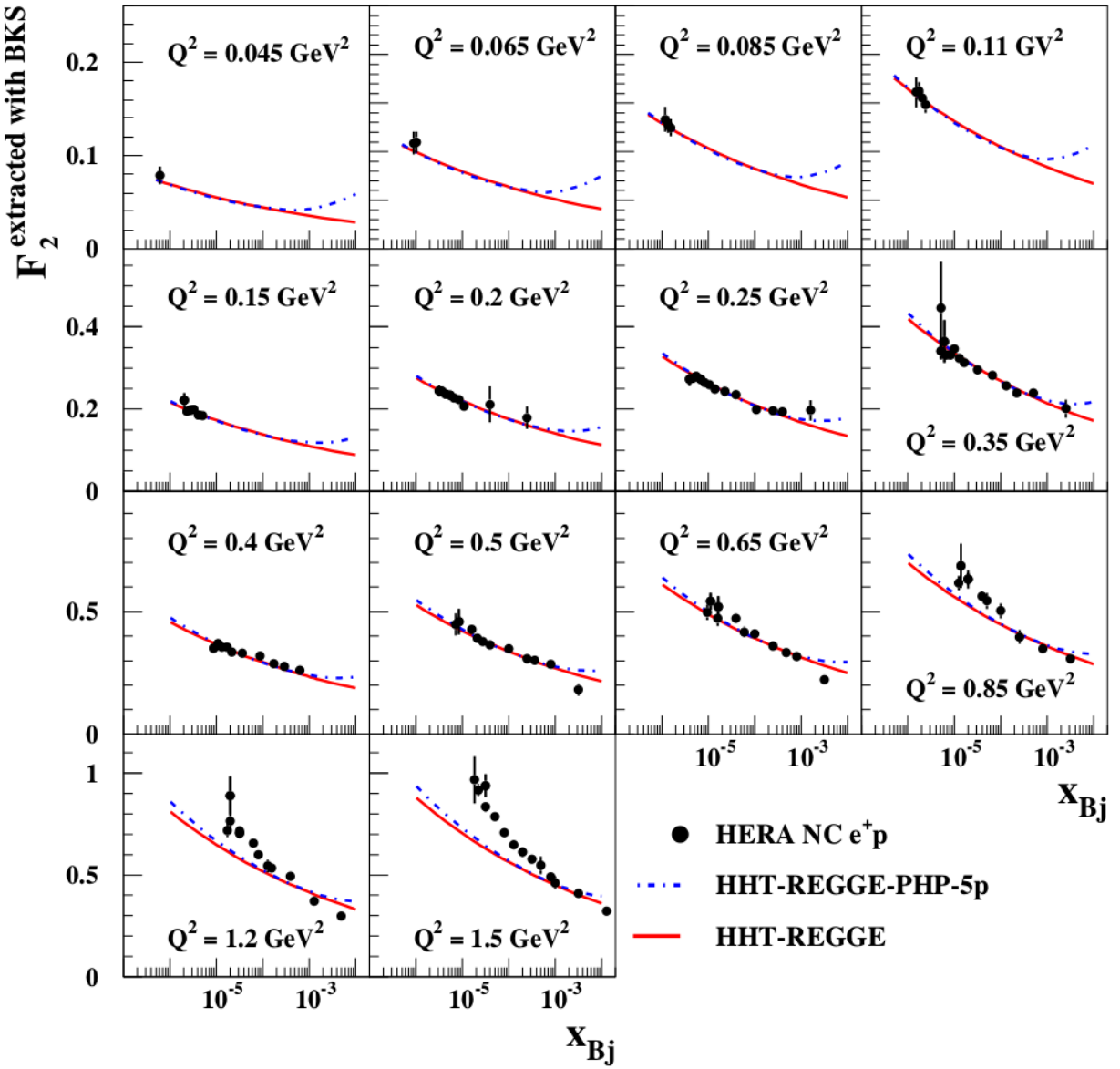
→ All fits compatible with soft Pomeron expectations

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



HHT-REGGE fits

- 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



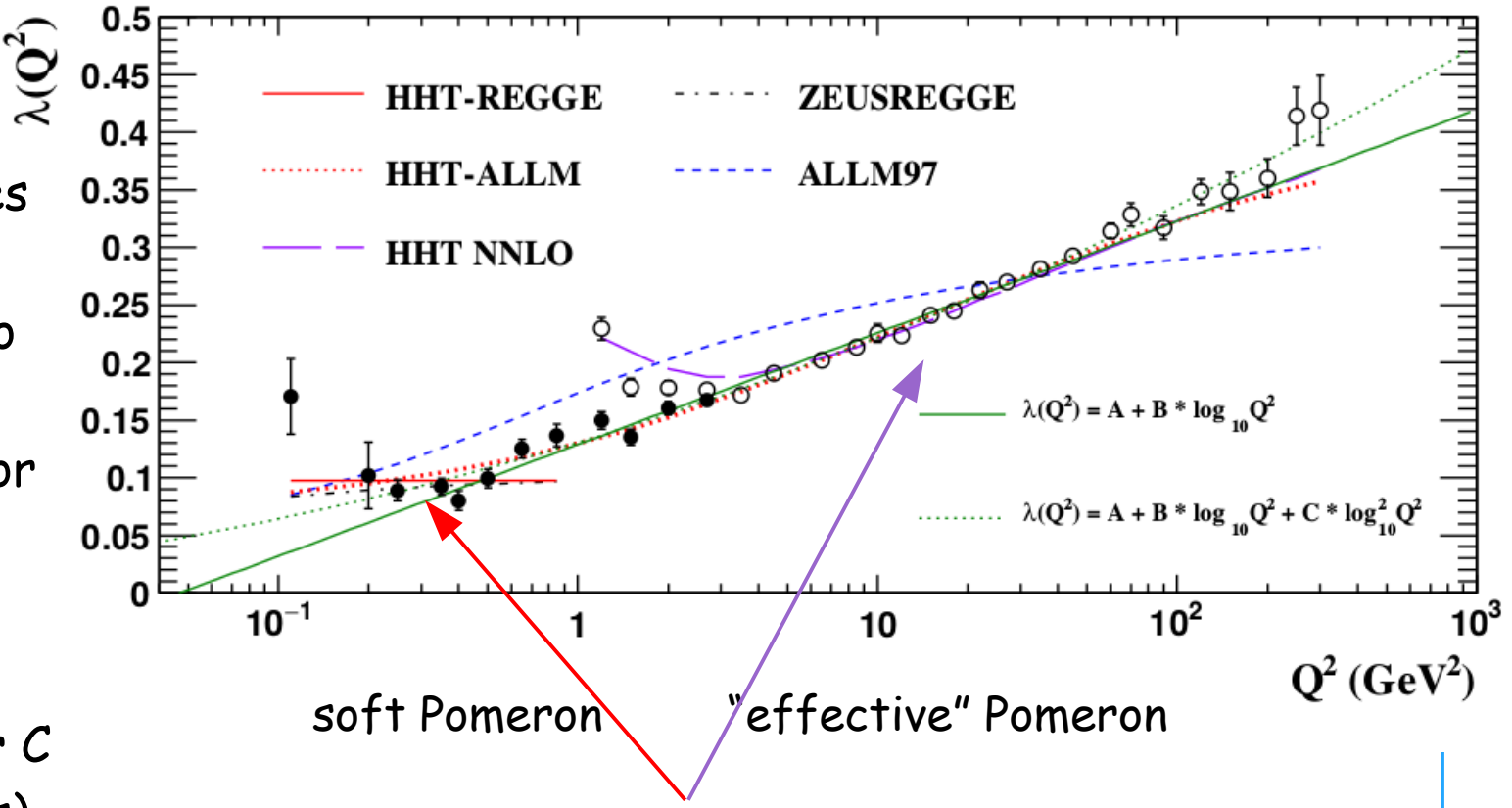
Extracting λ and C parameters

- 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

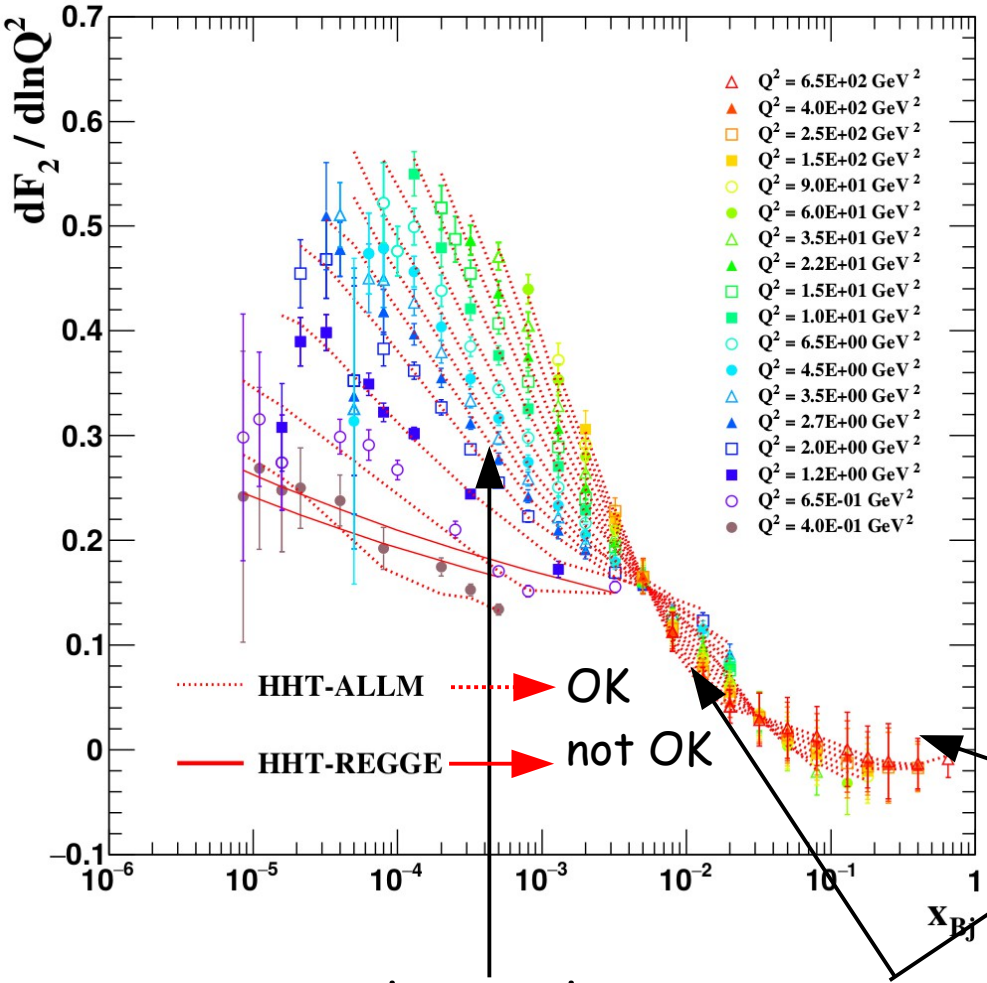


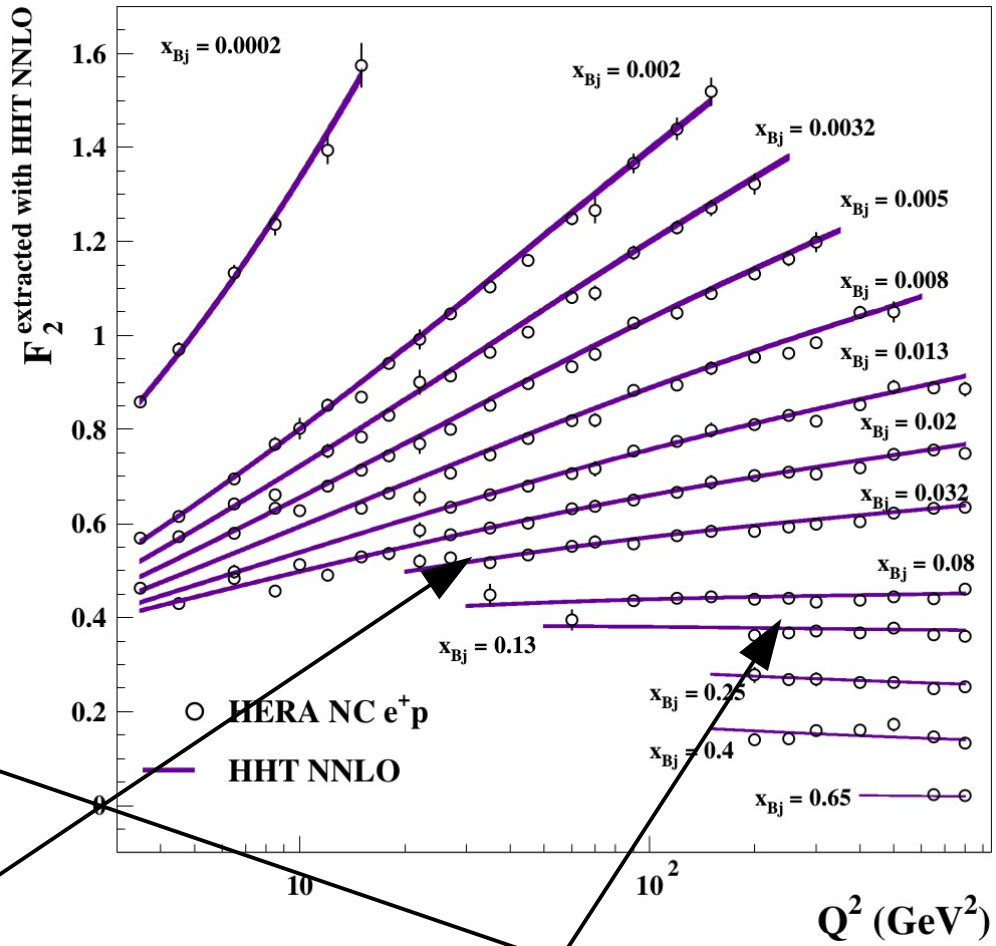
$$\lambda = \alpha_{I\!P}(0) - 1$$

→ Same conclusions for C (figure in backup slides)

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

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





strong scaling violation
depends on Q^2

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

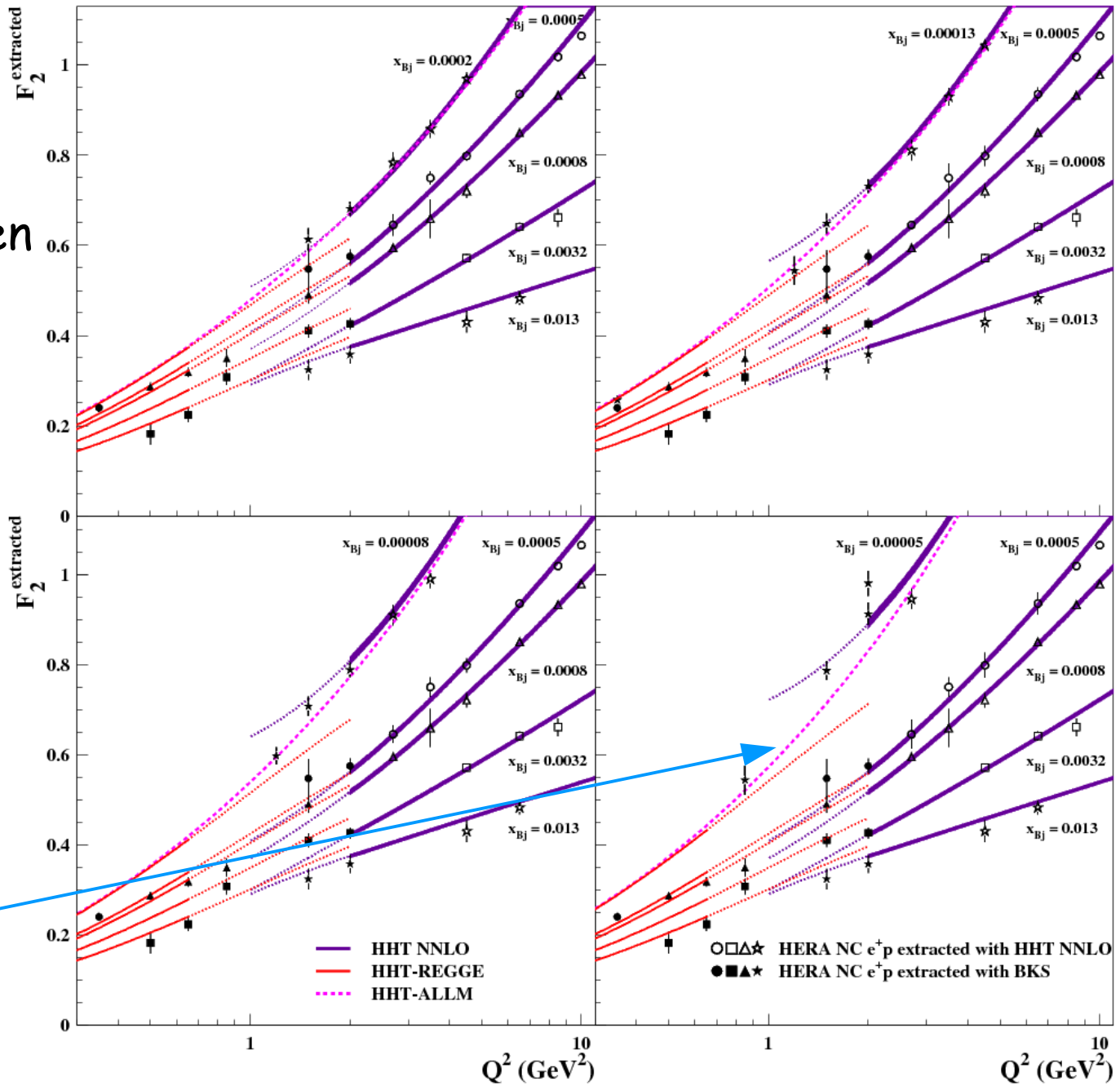
scaling

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

- Structure-function F_2 and photon-proton cross section $\sigma^{\gamma^* p}$ extracted from HERA combined data
  - 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 in their regions of applicability

→ No abrupt transition between soft and hard regions observed

→ **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

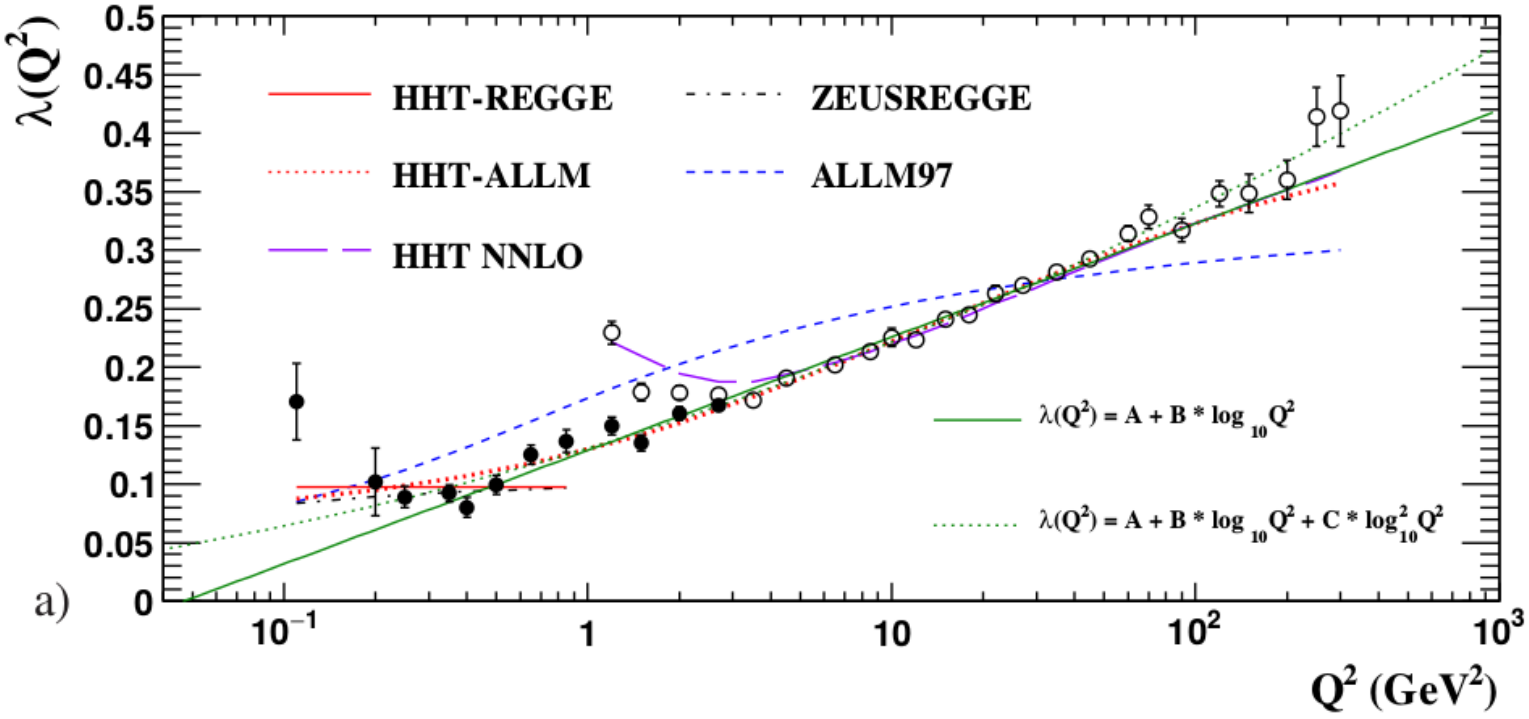
Additional slides

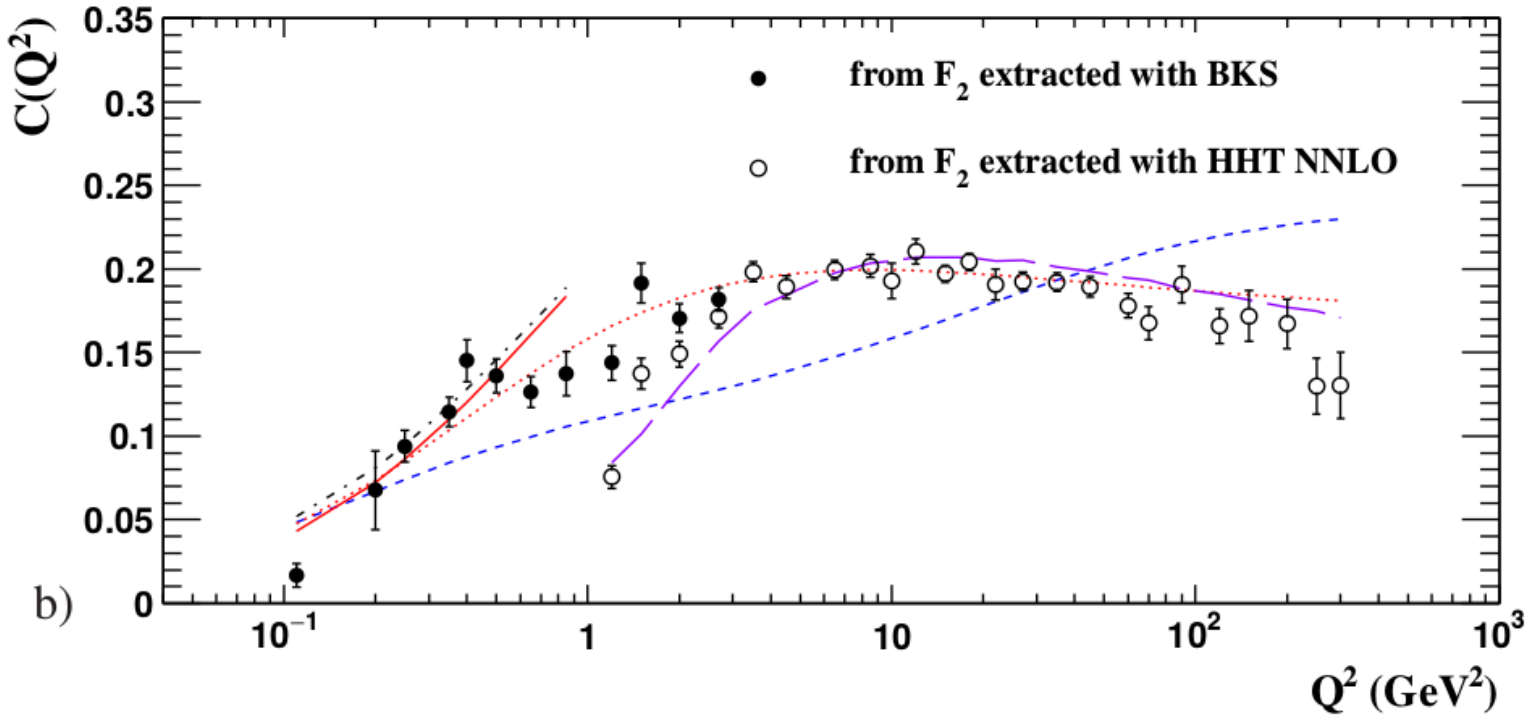
Regge fits

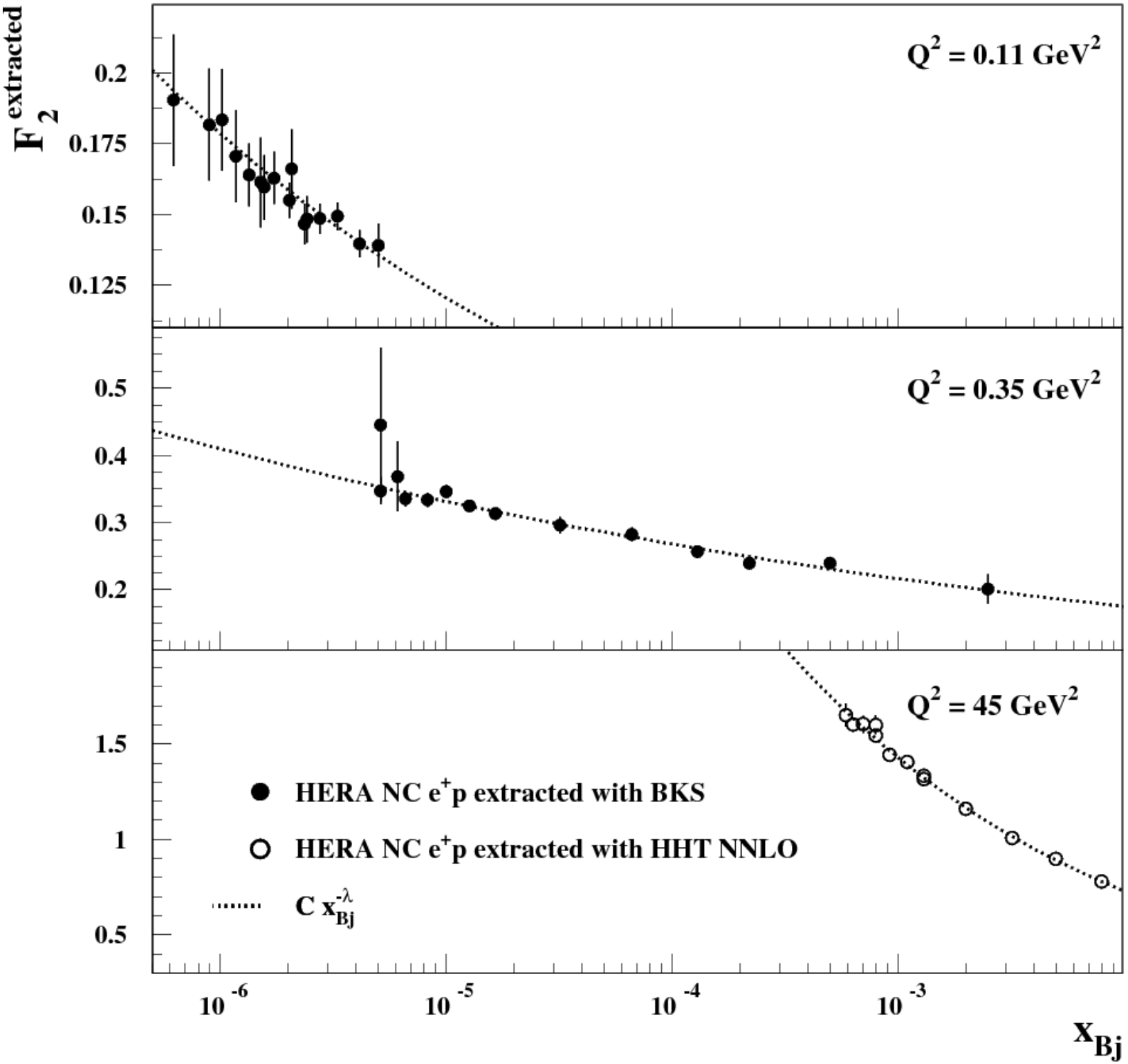
Name of Fit	Fit Parameters					χ^2/ ndf
	M_0^2 (GeV^2)	$A_{I\!P}$ (μb)	$\alpha_{I\!P}(0)$	$A_{I\!R}$ (μb)	$\alpha_{I\!R}(0)$	
HHT-REGGE	0.50 ±0.03	66.3 ± 3.2	1.097 ± 0.004	fixed to 0	–	0.83
3p-.85	0.58 ±0.03	58.5 ± 2.5	1.105 ± 0.003	fixed to 0	–	1.13
4p	0.49 ±0.03	78.5 ± 7.1	1.082 ± 0.008	−230 ±105	fixed 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	–

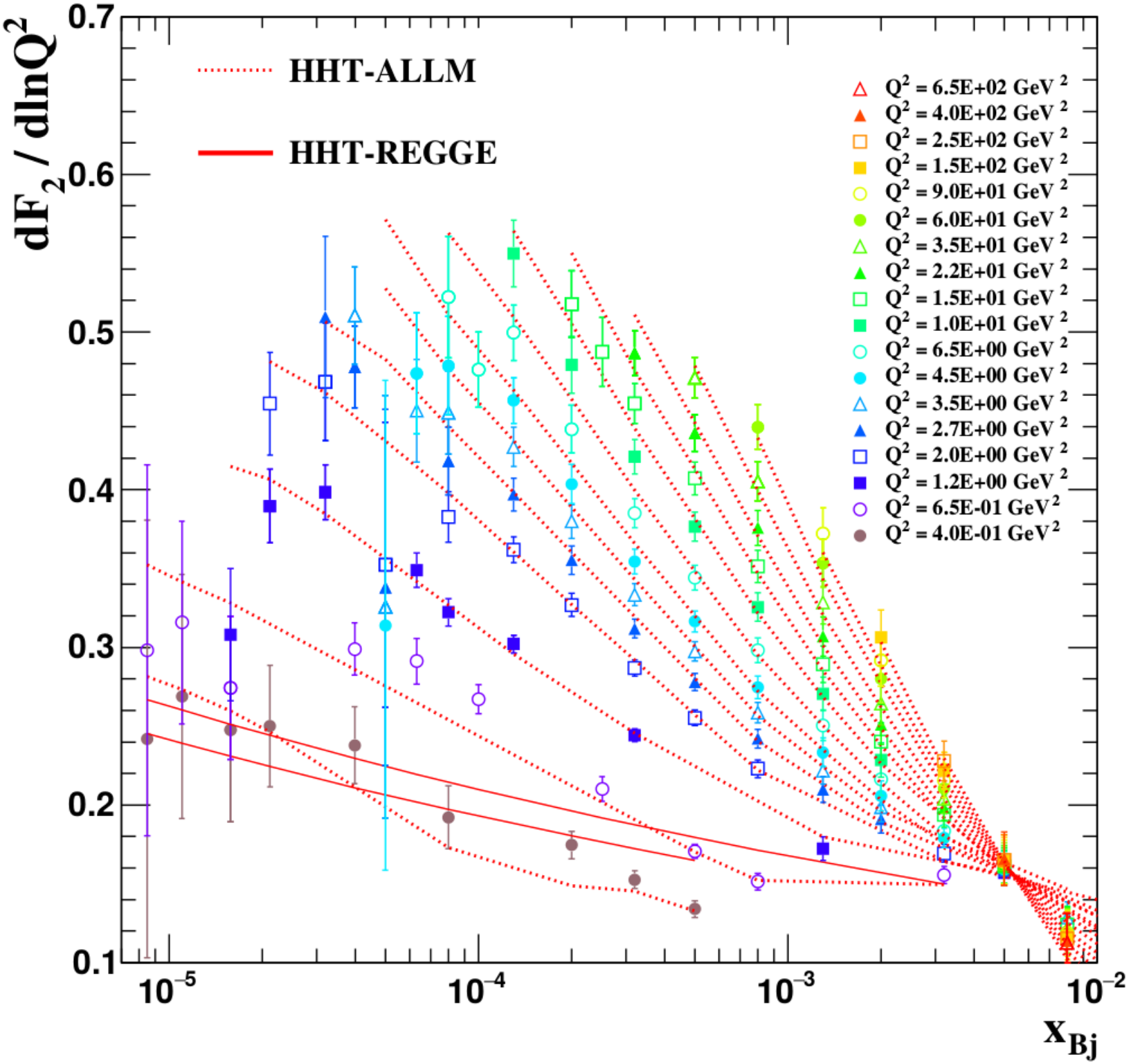
Pomeron trajectory $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} \cdot t$

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

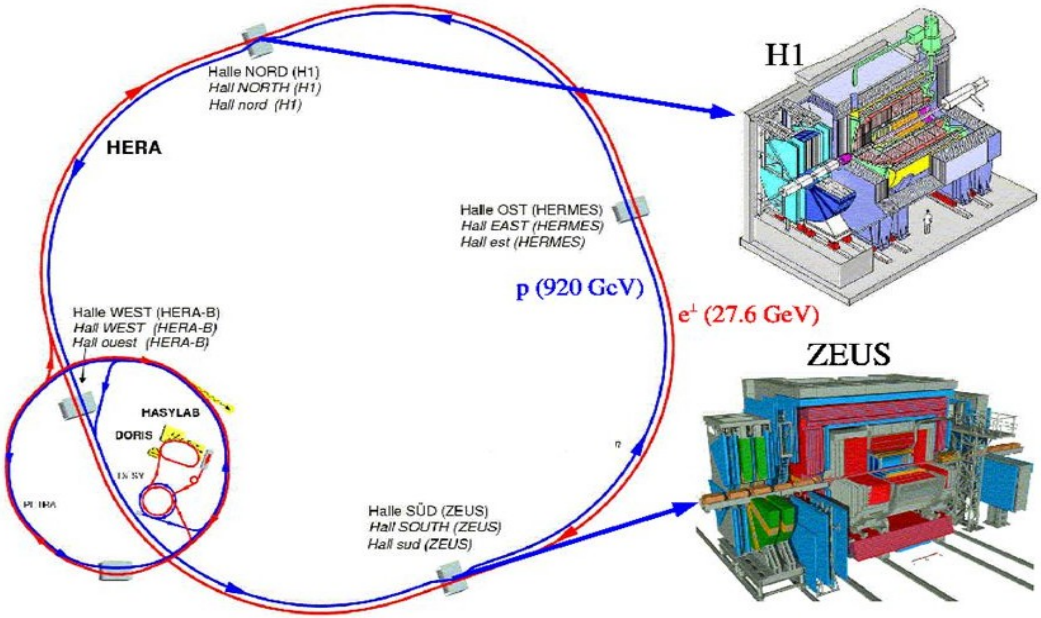

λ(Q²)
HHT-REGGE
ZEUSREGGE
HHT-ALLM
ALLM97
HHT NNLO
λ(Q²) = A + B * log 10 Q²
λ(Q²) = A + B * log 10 Q² + C * log²10 Q²
a)
Q² (GeV²)


C(Q²)
from F2 extracted with BKS
from F2 extracted with HHT NNLO
b)
Q² (GeV²)

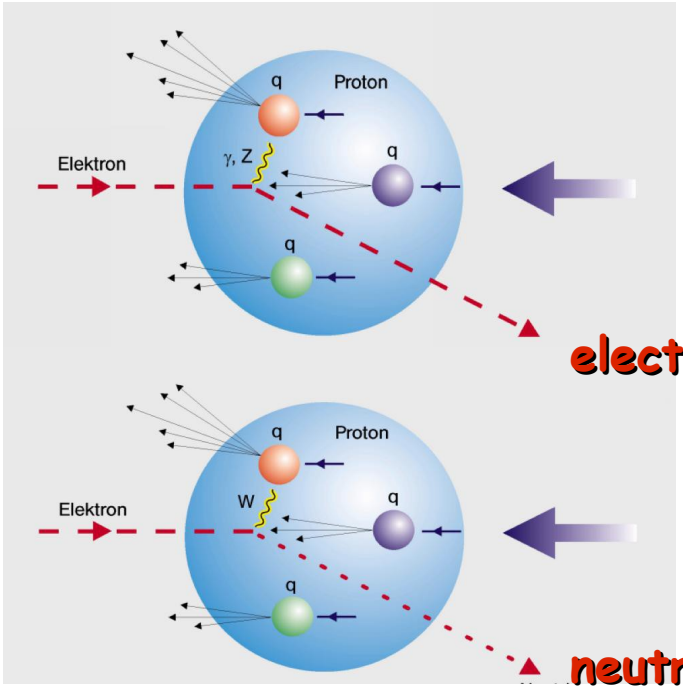

$F_2^{extracted}$
Q^2 = 0.11 GeV^2
Q^2 = 0.35 GeV^2
Q^2 = 45 GeV^2
HERA NC e$^+$p extracted with BKS
HERA NC e$^+$p extracted with HHT NNLO
C $x_{Bj}^{-\lambda}$
x_{Bj}


HHT-ALLM
HHT-REGGE
Q^2 = 6.5E+02 GeV^2
Q^2 = 4.0E+02 GeV^2
Q^2 = 2.5E+02 GeV^2
Q^2 = 1.5E+02 GeV^2
Q^2 = 9.0E+01 GeV^2
Q^2 = 6.0E+01 GeV^2
Q^2 = 3.5E+01 GeV^2
Q^2 = 2.2E+01 GeV^2
Q^2 = 1.5E+01 GeV^2
Q^2 = 1.0E+01 GeV^2
Q^2 = 6.5E+00 GeV^2
Q^2 = 4.5E+00 GeV^2
Q^2 = 3.5E+00 GeV^2
Q^2 = 2.7E+00 GeV^2
Q^2 = 2.0E+00 GeV^2
Q^2 = 1.2E+00 GeV^2
Q^2 = 6.5E-01 GeV^2
Q^2 = 4.0E-01 GeV^2
$dF_2 / d\ln Q^2$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
10^{-5}
10^{-4}
10^{-3}
10^{-2}
x_{Bj}

HERA and DIS



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



Deep Inelastic Scattering

Neutral Current (NC)

γ, Z^0 exchange

Charged Current (CC)

$W^{\pm}$ exchange

HERAPDF2.0 @ low Q^2 and low x

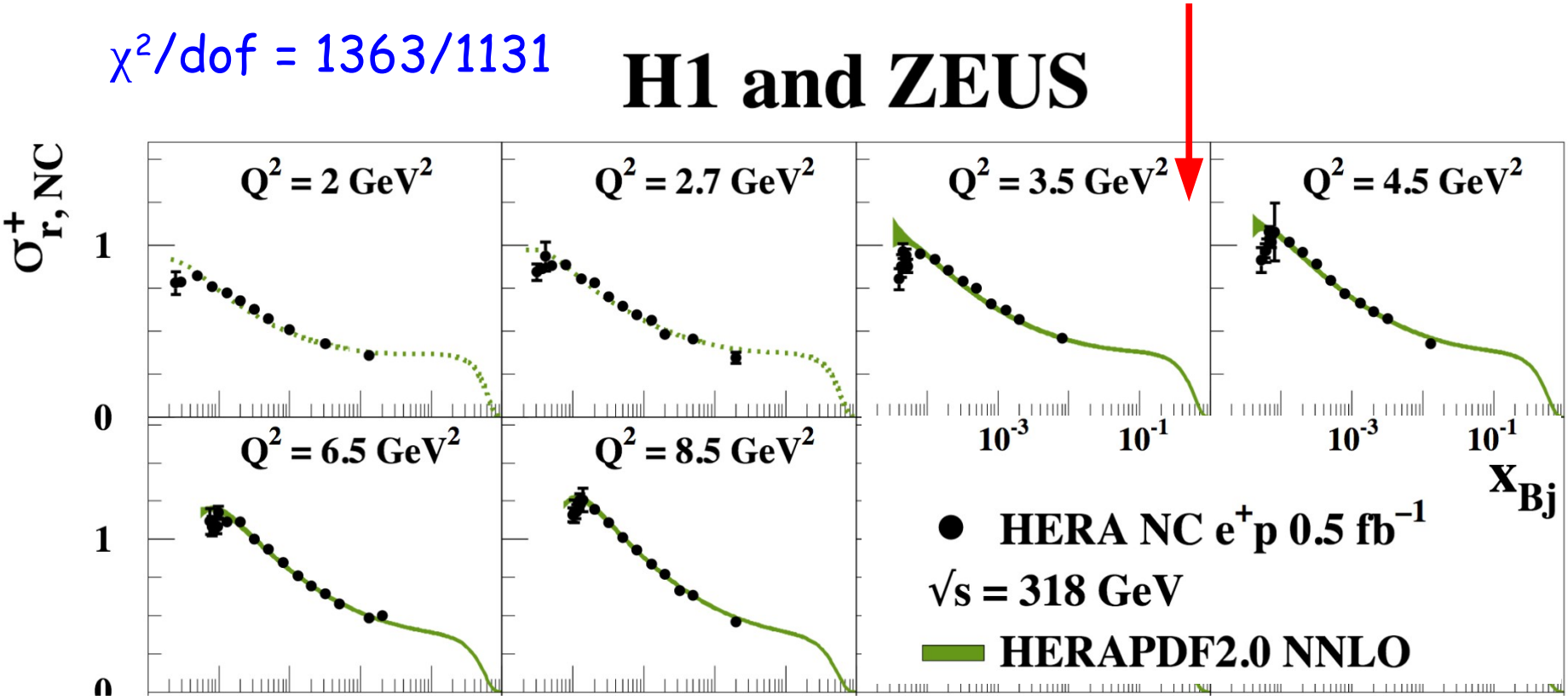
- NLO fit for Q^2_{min} = 3.5 GeV^2

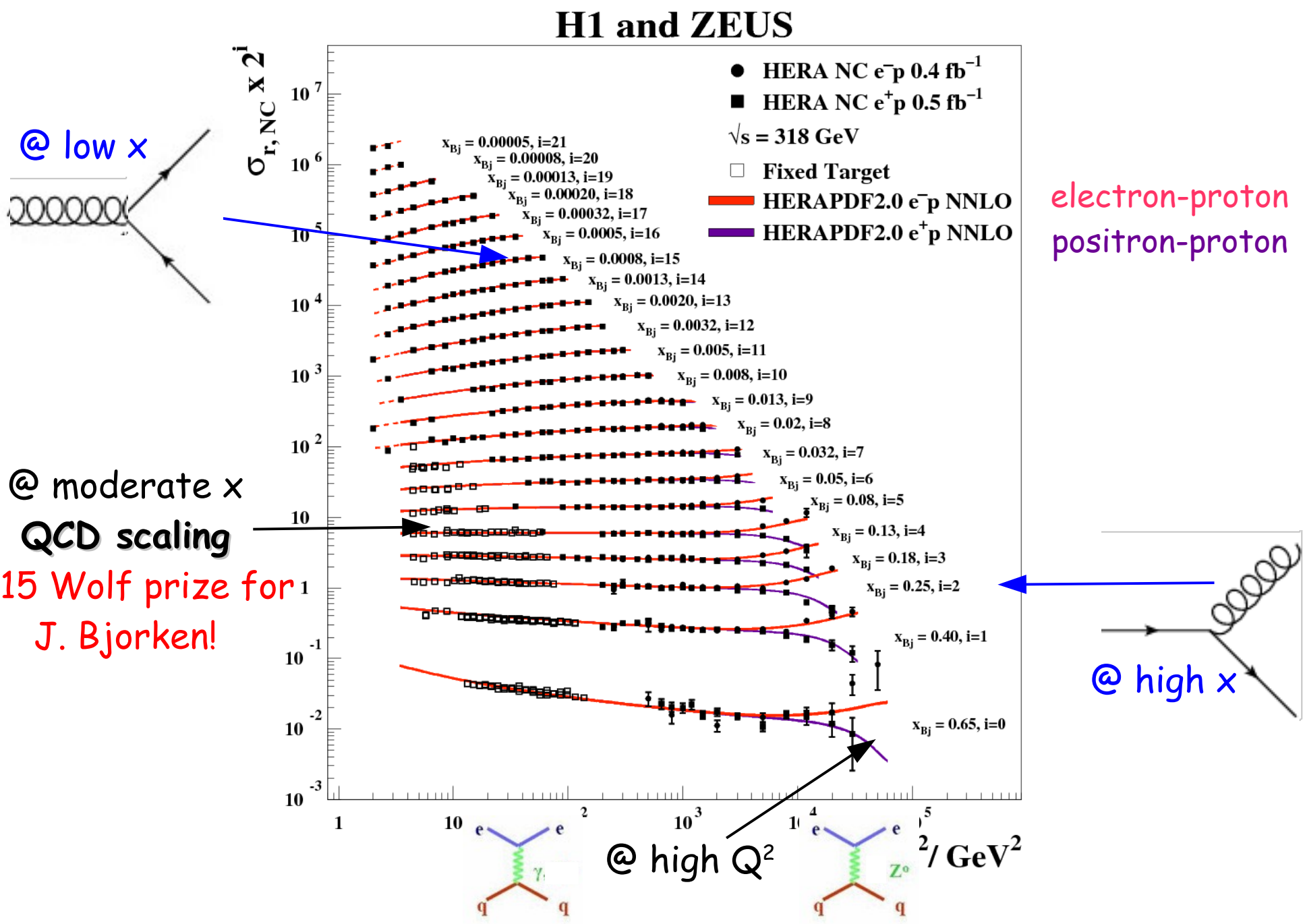
  χ^2/dof = 1357/1131

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

  χ^2/dof = 1363/1131

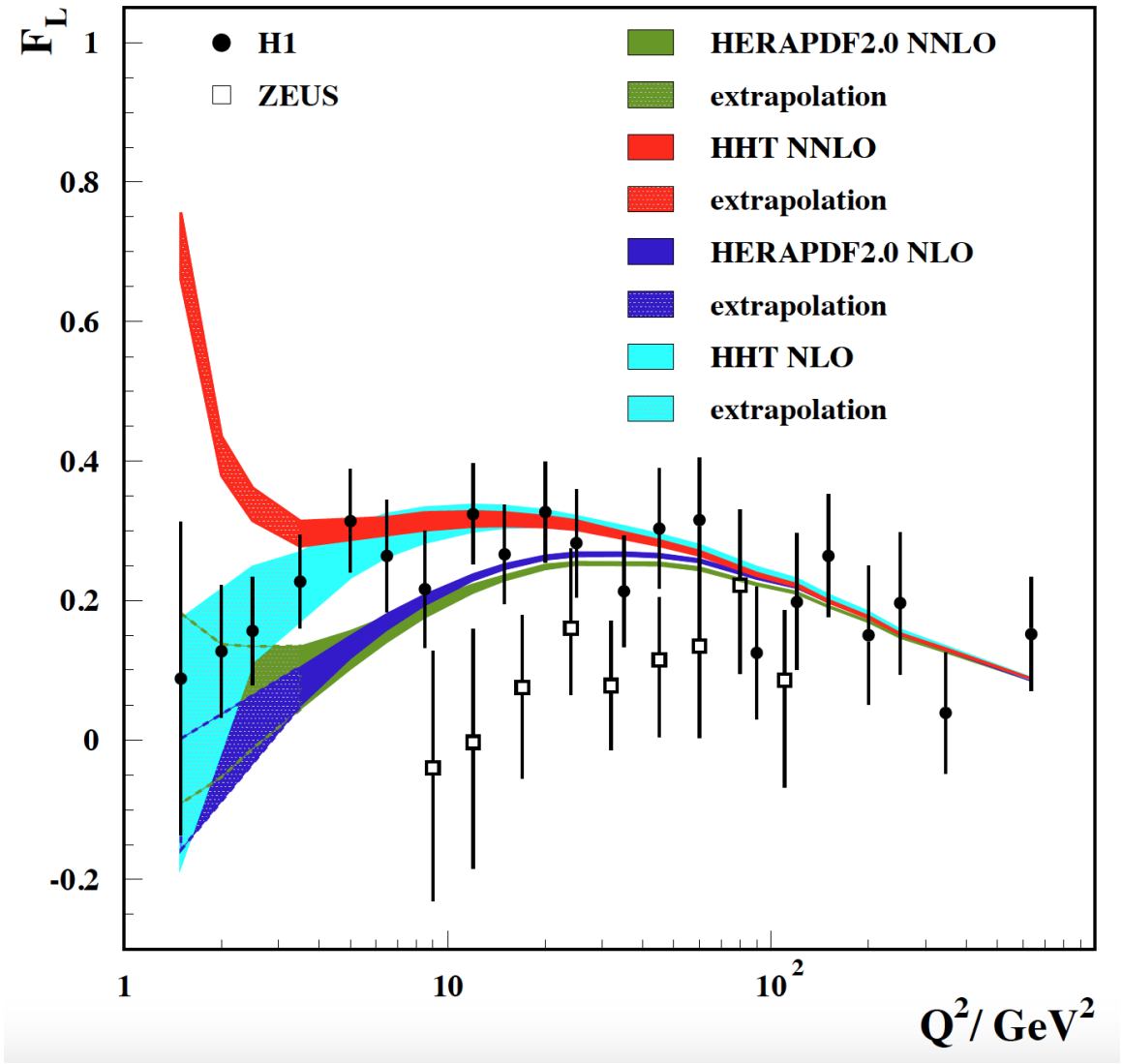
- Let's see how HERA low Q^2, low x data are described by predictions
  - Not that great...





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

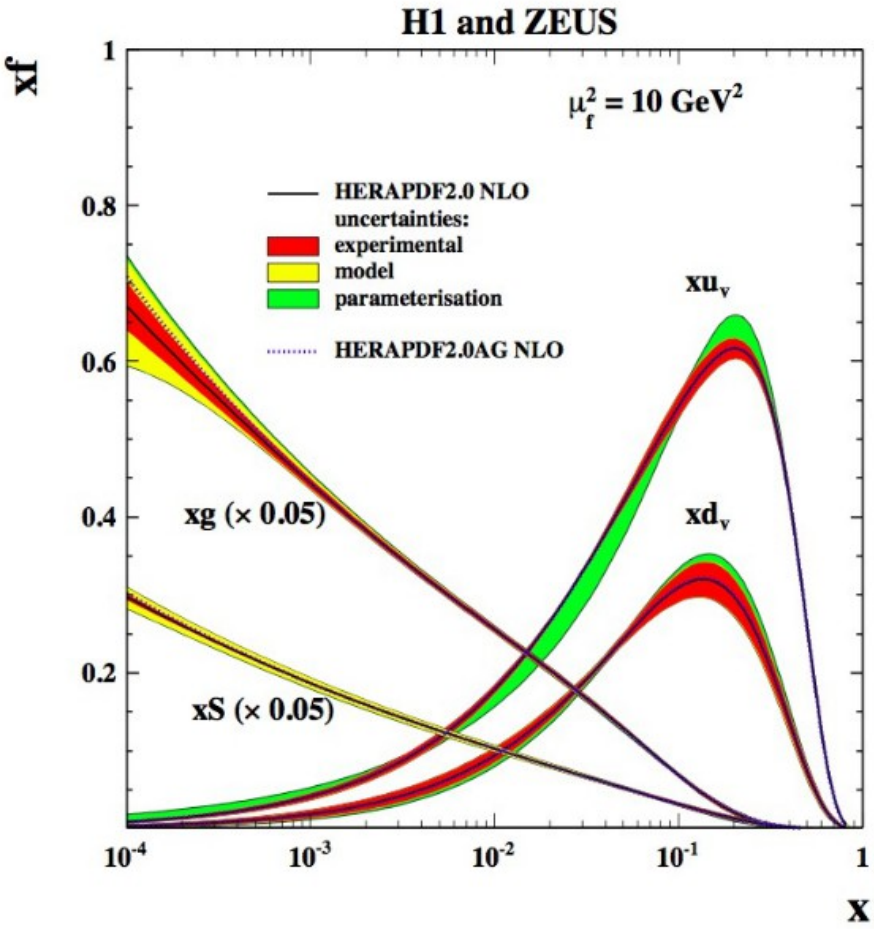
- QCD fits are performed using HERAFitter package
- PDFs (14p) are parametrised at $Q_0^2 = 1.9$ GeV^2

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

- A_{u_v}, A_{d_v}, A_g are constrained by QCD sum rules
- $x\bar{u} \overset{x\to 0}{\to} x\bar{d}$
- $A_{\bar{U}}, A_{\bar{D}}$ 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



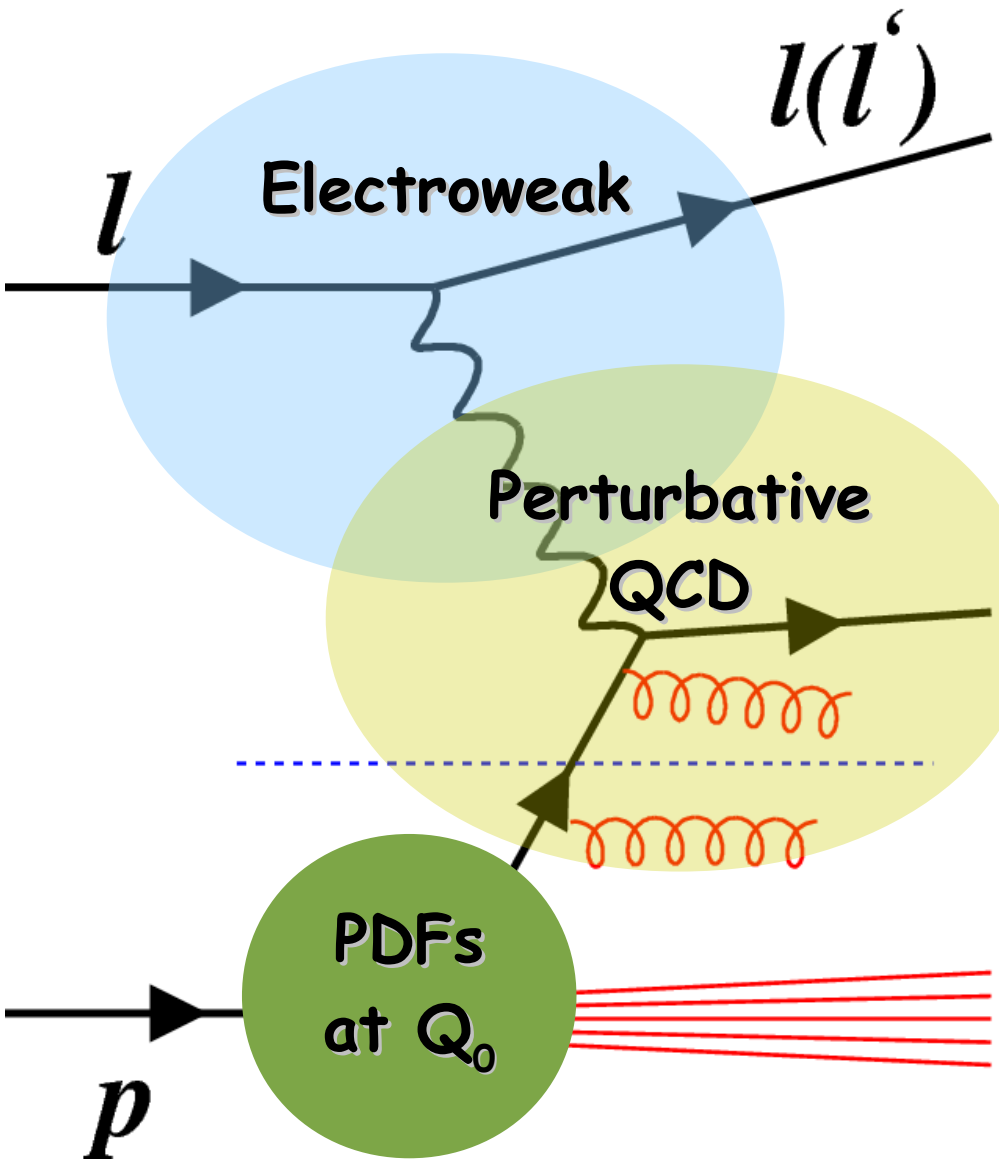
- Experimental uncertainties:
  - Hessian method
  - Conventional $\Delta\chi^2 = 1$ => 68% CL

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