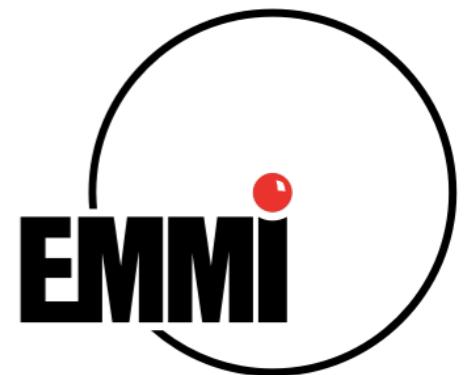


The Tensor Pomeron and Low-x Deep Inelastic Scattering



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References

- Daniel Britzger, CE, Sasha Glazov, Otto Nachtmann, Stefan Schmitt
The Tensor Pomeron and Low-x Deep Inelastic Scattering
arXiv:1901.08524
- CE, Markos Maniatis, Otto Nachtmann
A Model for Soft High-Energy Scattering: Tensor Pomeron and Vector Odderon
Annals Phys. 342 (2014) 31; arXiv:1309.3478
- CE, Piotr Lebiedowicz, Otto Nachtmann, Antoni Szczurek
Helicity in elastic proton-proton scattering and the spin structure of the pomeron
Phys. Lett. B763 (2016) 382; arXiv: 1606.08067
- many applications to exclusive processes: see talk by A. Szczurek
Lebiedowicz, Nachtmann, Szczurek;
Bolz, CE, Maniatis, Nachtmann, Sauter, Schöning

The pomeron in high energy scattering

- High-energy reactions are dominated by pomeron exchange.
- For soft reactions, first-principle calculations are not possible. We use Regge models to describe soft high-energy scattering.
- Here, we want to discuss DIS in the framework of Regge models.
- Spin structure of the pomeron has not been considered in much detail until recently.

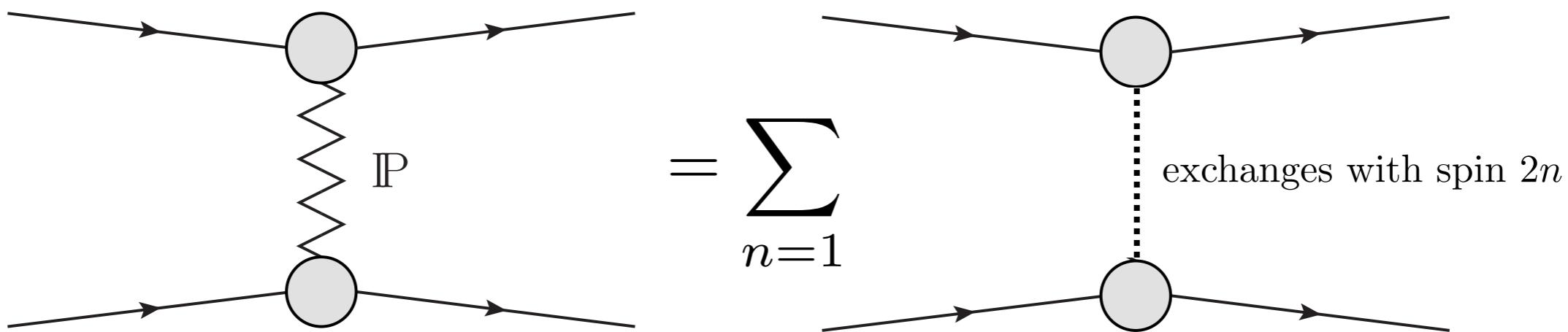
Spin structure of the pomeron

- Pomeron has vacuum quantum numbers:
charge, color, isospin, charge conjugation

But what about spin?

Pomeron is superposition of spins 2, 4, 6, ...

Nachtmann

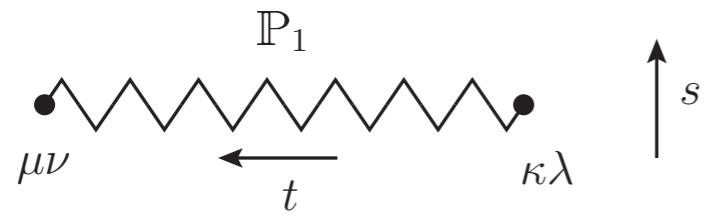


Tensor couplings: the tensor pomeron

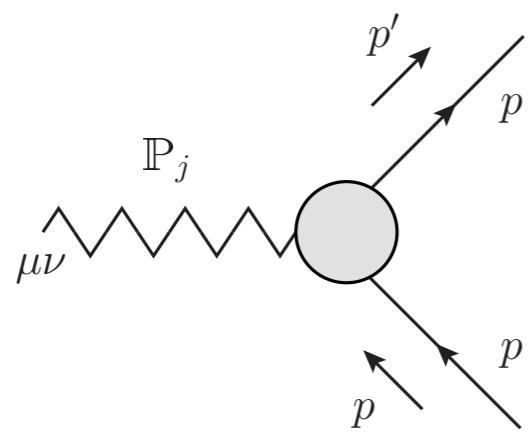
- Donnachie-Landshoff pomeron uses vector-type coupling to external particles.
- Coupling of pomeron to external particles should in our opinion be described by **tensor couplings**.
- An effective theory with such a tensor pomeron and reggeons (and a vector odderon) has been constructed, with propagators and vertices derived from Lagrangians for the couplings.

Pomeron: tensor vs vector

- tensor pomeron (eff. symmetric tensor exchange)



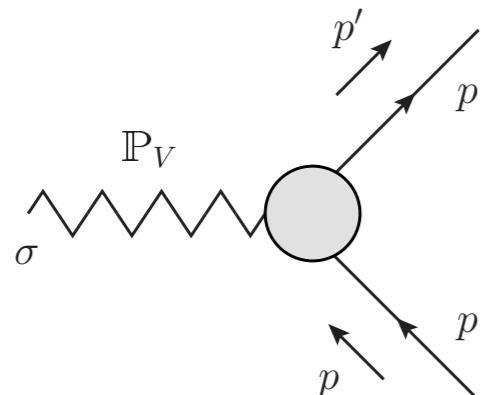
$$i\Delta_{\mu\nu,\kappa\lambda}^{(\mathbb{P}_1)}(s,t) = \frac{1}{4s} \left(g_{\mu\kappa}g_{\nu\lambda} + g_{\mu\lambda}g_{\nu\kappa} - \frac{1}{2}g_{\mu\nu}g_{\kappa\lambda} \right) (-is\tilde{\alpha}'_1)^{\alpha_1(t)-1}$$



$$\begin{aligned} i\Gamma_{\mu\nu}^{(\mathbb{P}_j pp)}(p',p) = & -i 3\beta_{jpp} F_1^{(j)} [(p' - p)^2] \\ & \times \left\{ \frac{1}{2} [\gamma_\mu (p' + p)_\nu + \gamma_\nu (p' + p)_\mu] - \frac{1}{4} g_{\mu\nu} (\not{p}' + \not{p}) \right\} \end{aligned}$$

- vector pomeron

$F_1(t)$: Dirac e.m. form factor



$$i\Gamma_\sigma^{(\mathbb{P}_V pp)}(p',p) = -i 3\beta_{\mathbb{P}_V pp} F_1 [(p - p')^2] M_0 \gamma_\sigma$$

Vector pomeron does not work

- Vector pomeron gives opposite signs for proton-proton and proton-antiproton total cross sections (!)

$$\sigma_{\text{tot}}(\bar{p}p) = -\sigma_{\text{tot}}(pp)$$

CE, Lebiedowicz, Nachtmann, Szczurek

- Vector pomeron decouples in photoproduction: its contribution to real Compton scattering and hence to photoproduction cross section $\sigma_{\gamma p}$ vanishes exactly.
(in analogy to Landau-Yang theorem)

Britzger, CE, Glazov, Nachtmann, Schmitt

Pomeron spin and elastic pp scattering

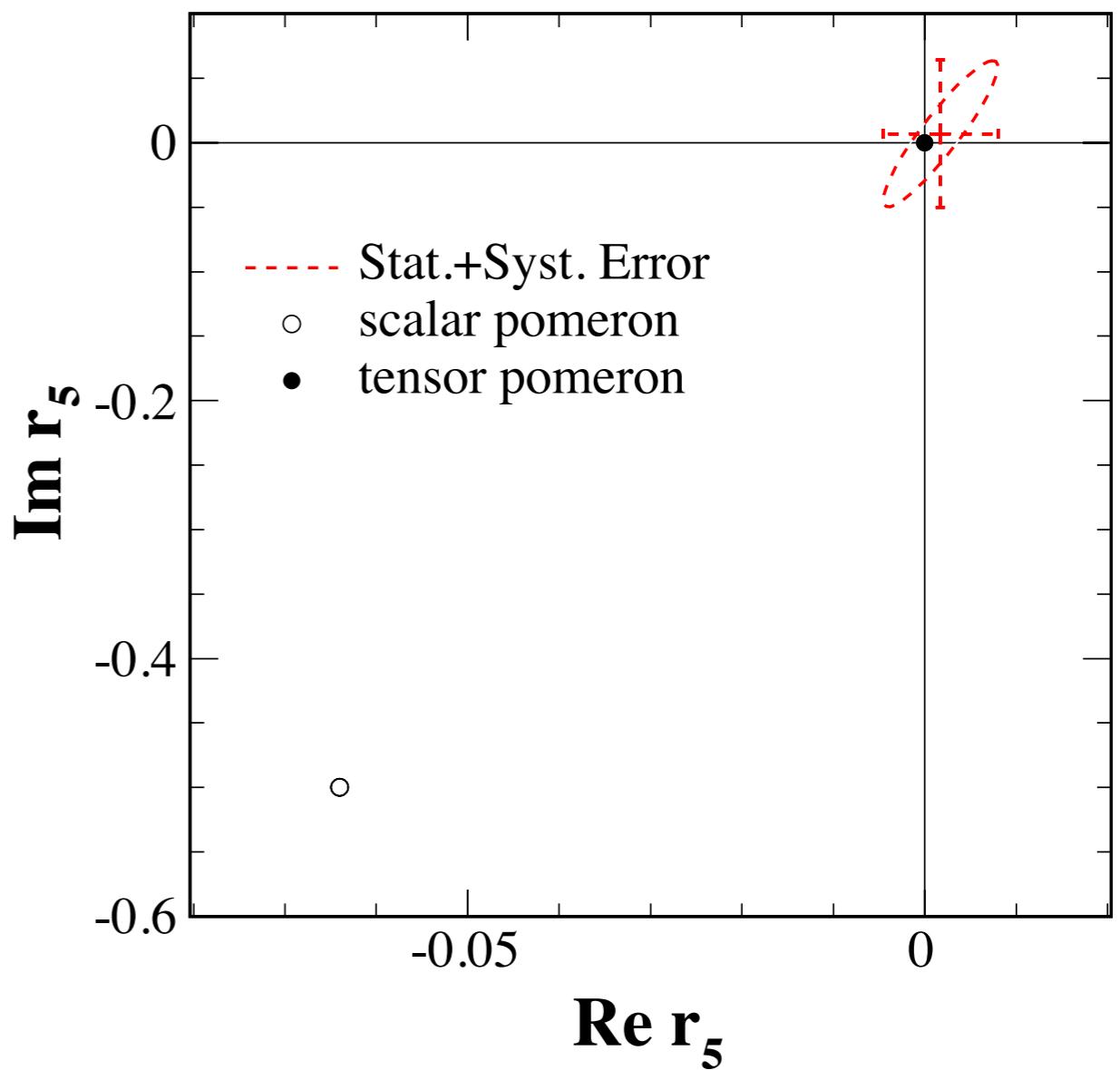
- Could the pomeron have scalar couplings?

Polarized pp elastic scattering (STAR)
clearly favors tensor:

helicity amplitudes:

ratio of single-flip to
non-flip amplitudes

$$r_5(s, t) = \frac{2m_p \phi_5(s, t)}{\sqrt{-t} \operatorname{Im} [\phi_1(s, t) + \phi_3(s, t)]}$$



DIS

- **variables:**

$$s = (p + k)^2 ,$$

$$q = k - k' ,$$

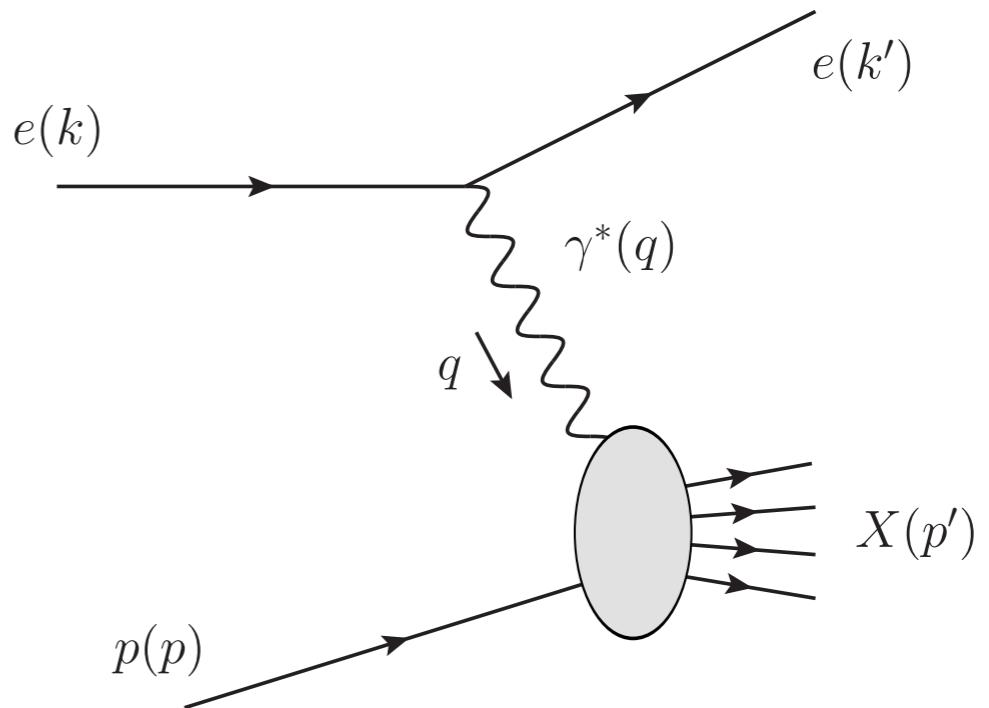
$$Q^2 = -q^2 ,$$

$$W^2 = p'^2 = (p + q)^2 ,$$

$$\nu = \frac{p \cdot q}{m_p} = \frac{W^2 + Q^2 - m_p^2}{2m_p} ,$$

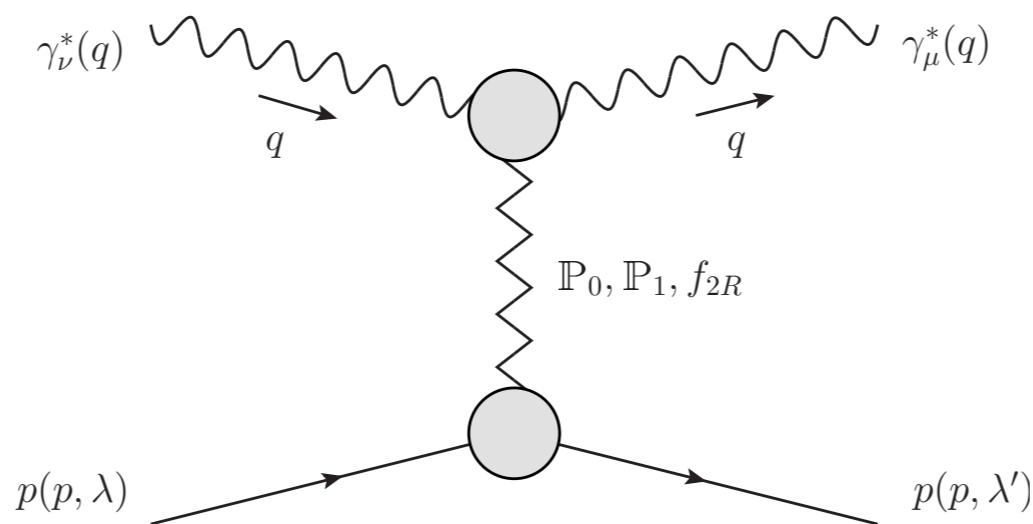
$$x = \frac{Q^2}{2m_p \nu} = \frac{Q^2}{W^2 + Q^2 - m_p^2} ,$$

$$y = \frac{p \cdot q}{p \cdot k} = \frac{W^2 + Q^2 - m_p^2}{s - m_p^2} .$$



DIS in 2-pomeron model

- DIS data successfully described using 2-pomeron model by Donnachie & Landshoff ... but with vector pomeron
- Can we describe DIS (and photoproduction) in a 2-tensor-pomeron model?
→ extend soft tensor pomeron model by adding hard tensor pomeron



Cross sections

- cross sections for transverse and longitudinal photons in 2-tensor pomeron model:

$$\begin{aligned}\sigma_T(W^2, Q^2) &= 4\pi\alpha_{\text{em}} \frac{W^2 - m_p^2}{W^2} \sum_{j=0,1,2} 3\beta_{jpp} (W^2 \tilde{\alpha}'_j)^{\epsilon_j} \cos\left(\frac{\pi}{2} \epsilon_j\right) \\ &\quad \times \left\{ \hat{b}_j(Q^2) \left[1 + \frac{2Q^2}{W^2 - m_p^2} + \frac{Q^2(Q^2 + 2m_p^2)}{(W^2 - m_p^2)^2} \right] \right. \\ &\quad \left. - 2Q^2 \hat{a}_j(Q^2) \left[1 + \frac{2Q^2}{W^2 - m_p^2} + \frac{Q^2(Q^2 + m_p^2)}{(W^2 - m_p^2)^2} \right] \right\} \\ \sigma_L(W^2, Q^2) &= 4\pi\alpha_{\text{em}} \frac{W^2 - m_p^2}{W^2} Q^2 \sum_{j=0,1,2} 3\beta_{jpp} (W^2 \tilde{\alpha}'_j)^{\epsilon_j} \cos\left(\frac{\pi}{2} \epsilon_j\right) \\ &\quad \times \left\{ 2\hat{a}_j(Q^2) \left[1 + \frac{2Q^2}{W^2 - m_p^2} + \frac{Q^2(Q^2 + m_p^2)}{(W^2 - m_p^2)^2} \right] + \hat{b}_j(Q^2) \frac{2m_p^2}{(W^2 - m_p^2)^2} \right\}\end{aligned}$$

Cross sections

- Actually, we use reduced cross section:

$$\begin{aligned}\sigma_{\text{red}}(W^2, Q^2, y) = & \frac{1 + (1 - y)^2 + y^2 \delta(W^2, Q^2)}{1 + (1 - y)^2} [1 + 2\delta(W^2, Q^2)]^{-1} \frac{Q^2}{4\pi^2 \alpha_{\text{em}}} (1 - x) \\ & \times \left[\sigma_T(W^2, Q^2) + \sigma_L(W^2, Q^2) - \tilde{f}(W^2, Q^2, y) \sigma_L(W^2, Q^2) \right],\end{aligned}$$

where

$$\tilde{f}(W^2, Q^2, y) = 1 - \epsilon = \frac{y^2 [1 + 2\delta(W^2, Q^2)]}{1 + (1 - y)^2 + y^2 \delta(W^2, Q^2)}$$

and

$$\delta(W^2, Q^2) = \frac{2m_p^2 Q^2}{(W^2 + Q^2 - m_p^2)^2}$$

Fit to DIS and photoproduction

- We perform a fit to the available DIS and photoproduction data with

$$6 \text{ GeV} \leq \sqrt{s} \leq 318 \text{ GeV}$$

$$0 < Q^2 < 50 \text{ GeV}^2 \quad \text{and} \quad x < 0.01$$

- fit to σ_{red} , containing full exp. information
- fit with 25 parameters
- comparison to HERA data;
also shown: extrapolation to $Q^2 > 50 \text{ GeV}^2$

Fit parameters

	hard pomeron \mathbb{P}_0	soft pomeron \mathbb{P}_1	reggeon f_{2R}
intercept	$\alpha_0(0) = 1 + \epsilon_0$	$\alpha_1(0) = 1 + \epsilon_1$	$\alpha_2(0) = 1 + \epsilon_2$
slope parameter	α'_0	α'_1	α'_2
W^2 parameter	$\tilde{\alpha}'_0$	$\tilde{\alpha}'_1$	$\tilde{\alpha}'_2$
pp coupling parameter	β_{0pp}	β_{1pp}	β_{2pp}
$\gamma^*\gamma^*$ coupling functions	$\hat{a}_0(Q^2), \hat{b}_0(Q^2)$	$\hat{a}_1(Q^2), \hat{b}_1(Q^2)$	$\hat{a}_2(Q^2), \hat{b}_2(Q^2)$

Fit quality

- Very good fit obtained.

Partial χ^2 and goodness of fit:

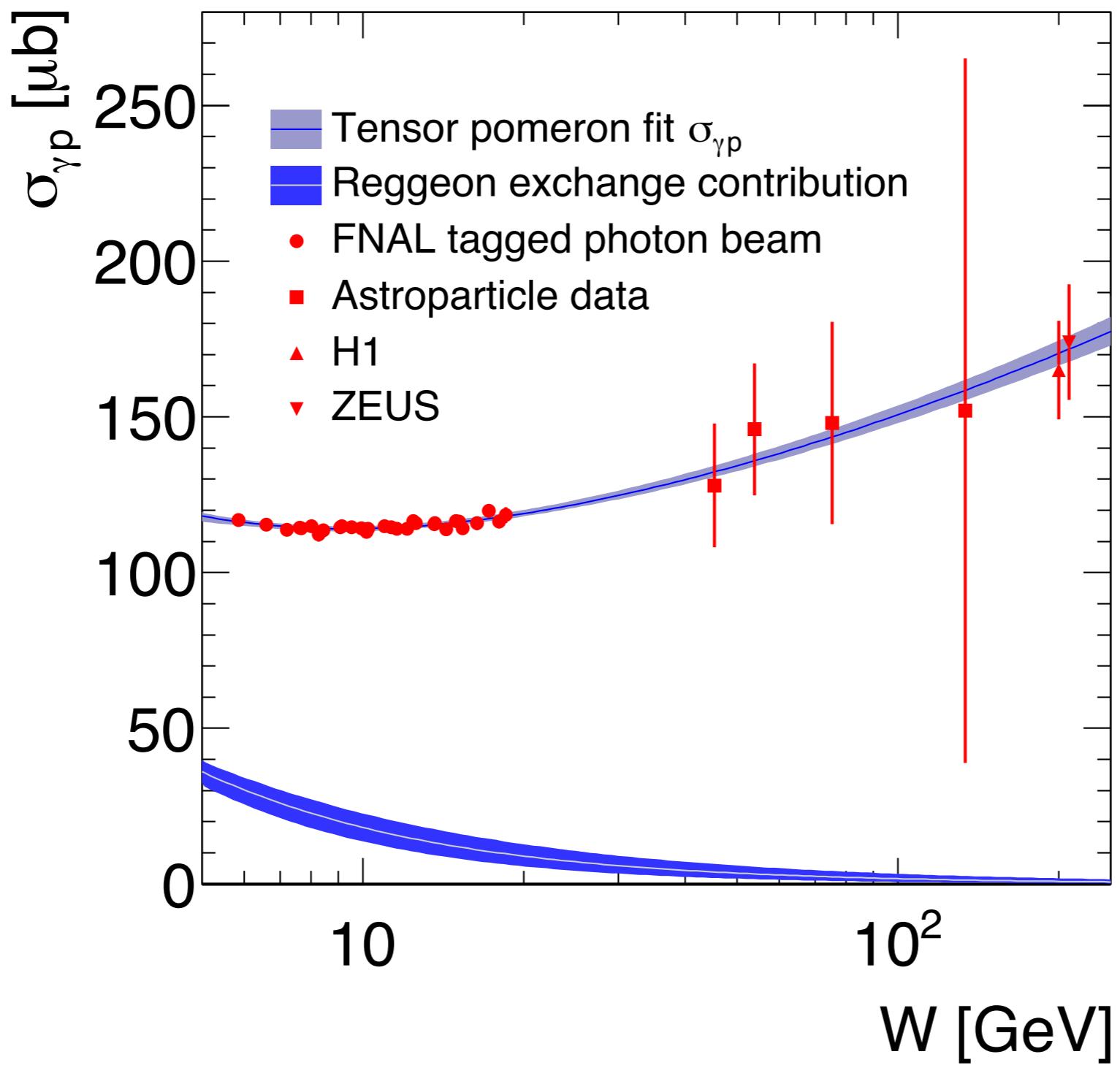
dataset	χ^2	number of points
DIS $\sqrt{s} = 225$ GeV	104.98	91
DIS $\sqrt{s} = 251$ GeV	113.12	118
DIS $\sqrt{s} = 300$ GeV	60.38	71
DIS $\sqrt{s} = 318$ GeV	271.82	245
HERA DIS data, all \sqrt{s}	553.77	525
H1 photoproduction	0.23	1
ZEUS photoproduction	0.03	1
cosmic ray data	0.62	4
tagged photon beam	33.29	30
all datasets	587.94	$N_{DF} = (561 - 25)$, probability 6.0%

Fit results: parameter values

- parameters for hard pomeron (P_0), soft pomeron (P_1), f_2 reggeon

	parameter	default value used	fit result
P_0	intercept		$\alpha_0(0) = 1 + \epsilon_0$ $\epsilon_0 = 0.3008 (+^{73}_{-84})$
	slope parameter	$\alpha'_0 = 0.25 \text{ GeV}^{-2}$	
	W^2 parameter	$\tilde{\alpha}'_0 = 0.25 \text{ GeV}^{-2}$	
	pp coupling parameter	$\beta_{0pp} = 1.87 \text{ GeV}^{-1}$	
P_1	intercept		$\alpha_1(0) = 1 + \epsilon_1$ $\epsilon_1 = 0.0935 (+^{76}_{-64})$
	slope parameter	$\alpha'_1 = 0.25 \text{ GeV}^{-2}$	
	W^2 parameter	$\tilde{\alpha}'_1 = 0.25 \text{ GeV}^{-2}$	
	pp coupling parameter	$\beta_{1pp} = 1.87 \text{ GeV}^{-1}$	
f_{2R}	intercept		$\alpha_2(0) = 0.485 (+^{88}_{-90})$
	slope parameter	$\alpha'_2 = 0.9 \text{ GeV}^{-2}$	
	W^2 parameter	$\tilde{\alpha}'_2 = 0.9 \text{ GeV}^{-2}$	
	pp coupling parameter	$\beta_{2pp} = 3.68 \text{ GeV}^{-1}$	

Fit results: photoproduction



Observations: photoproduction

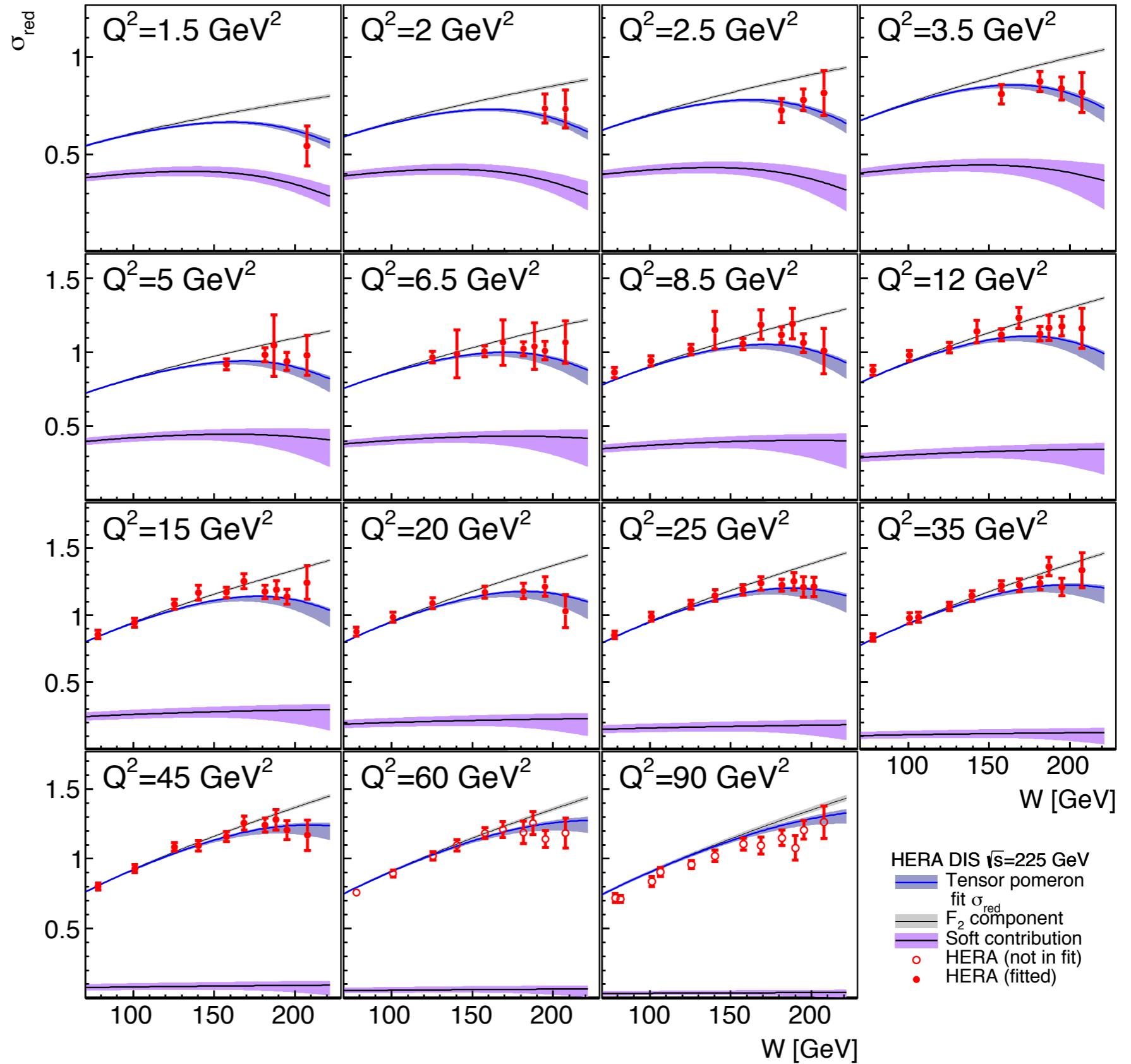
- Real photoabsorption cross section **dominated by soft pomeron**, hard pomeron contribution compatible with zero:
at $W = 200 \text{ GeV}$:

$170.4^{+4.2}_{-4.0} \mu\text{b}$	for the soft pomeron \mathbb{P}_1 ,
$0.002^{+0.086}_{-0.002} \mu\text{b}$	for the hard pomeron \mathbb{P}_0 ,
$0.84^{+0.99}_{-0.58} \mu\text{b}$	for the f_{2R} reggeon.
- Reggeon contribution important at low W
- Vector pomeron would give zero!

Fit results: DIS (I)

$\sqrt{s} = 225 \text{ GeV}$

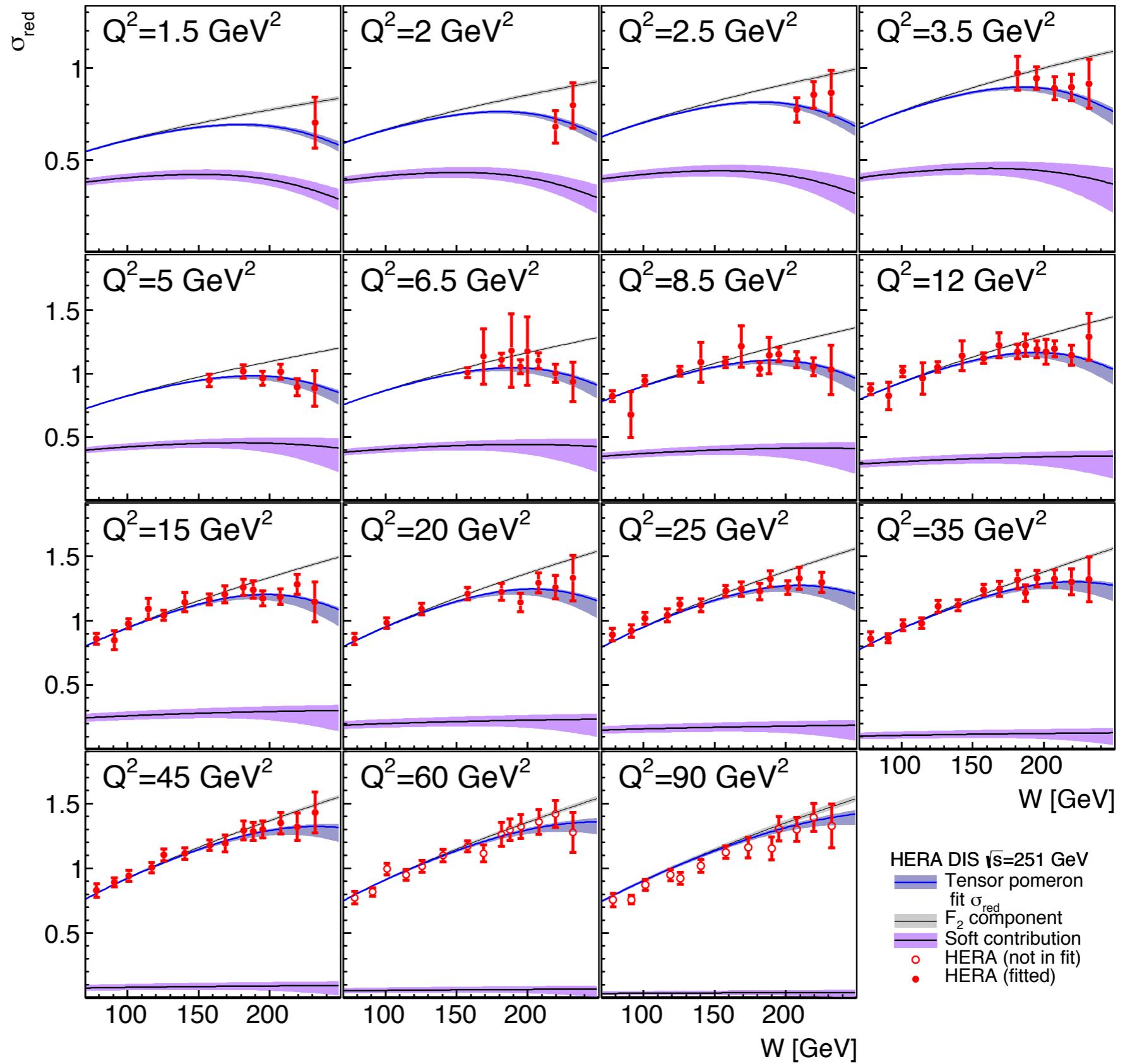
reduced cross section



Fit results: DIS (2)

$\sqrt{s} = 251 \text{ GeV}$

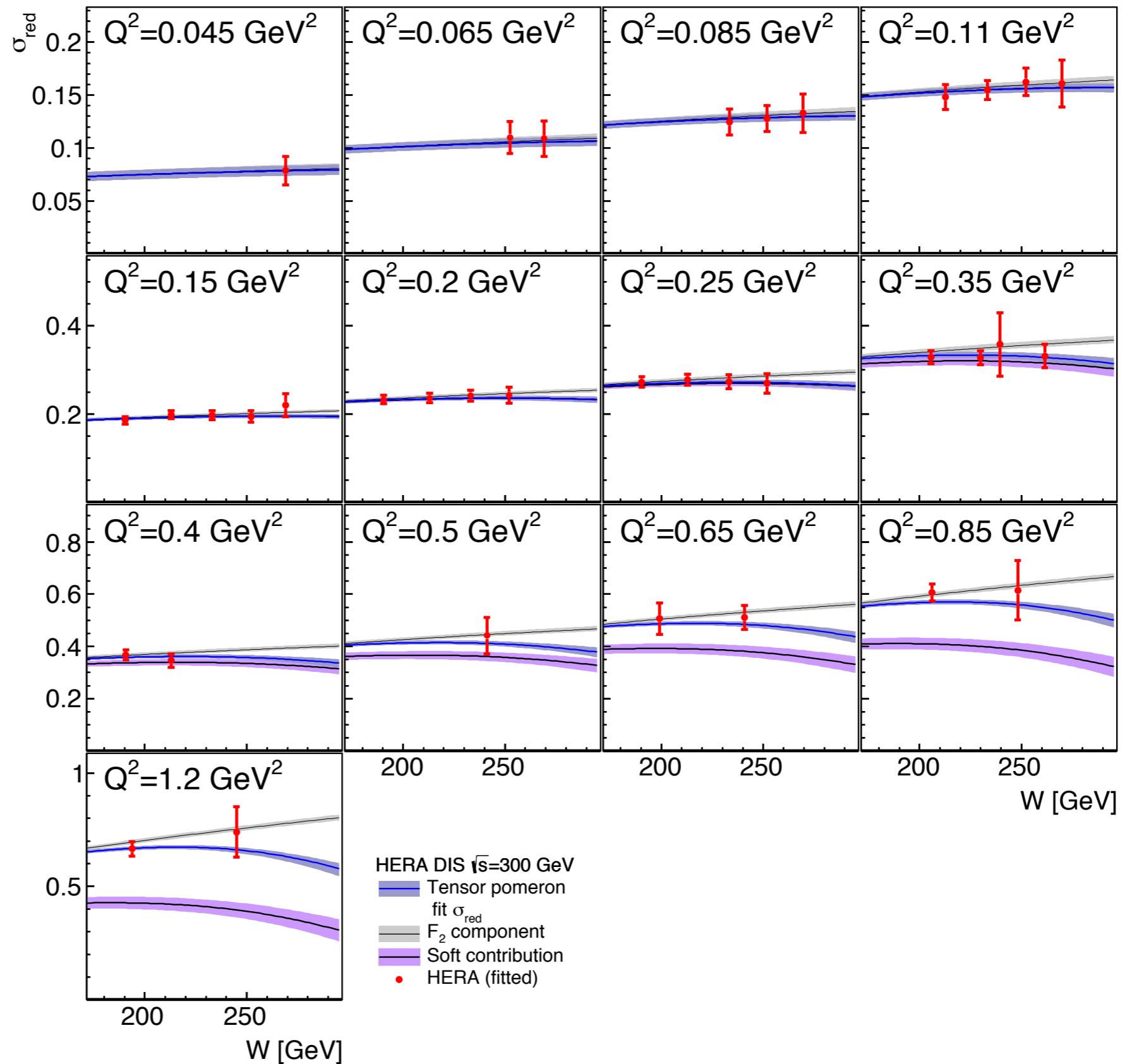
reduced cross section



Fit results: DIS (3)

$\sqrt{s} = 300 \text{ GeV}$

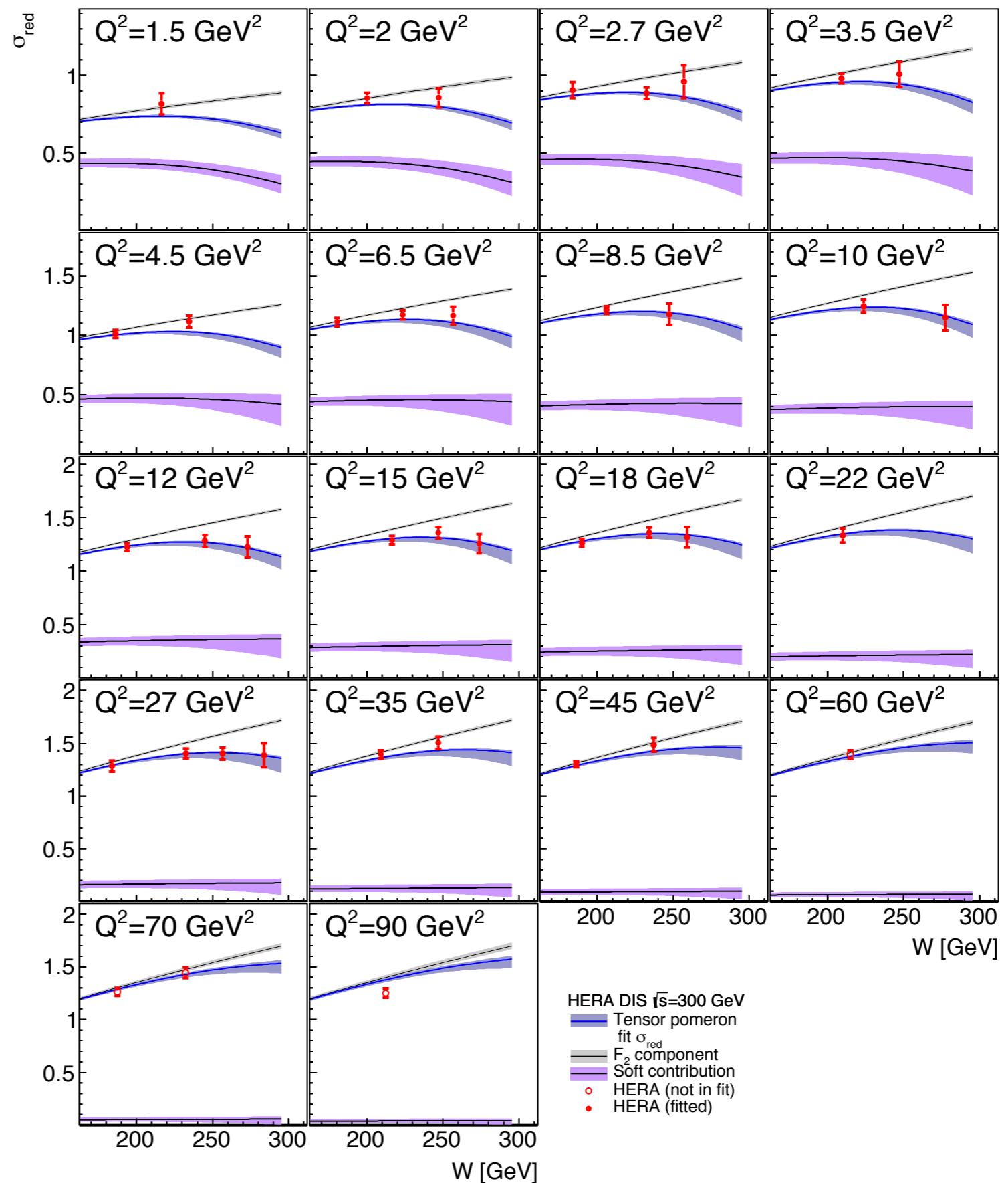
reduced cross
section



Fit results: DIS (4)

$\sqrt{s} = 300 \text{ GeV}$

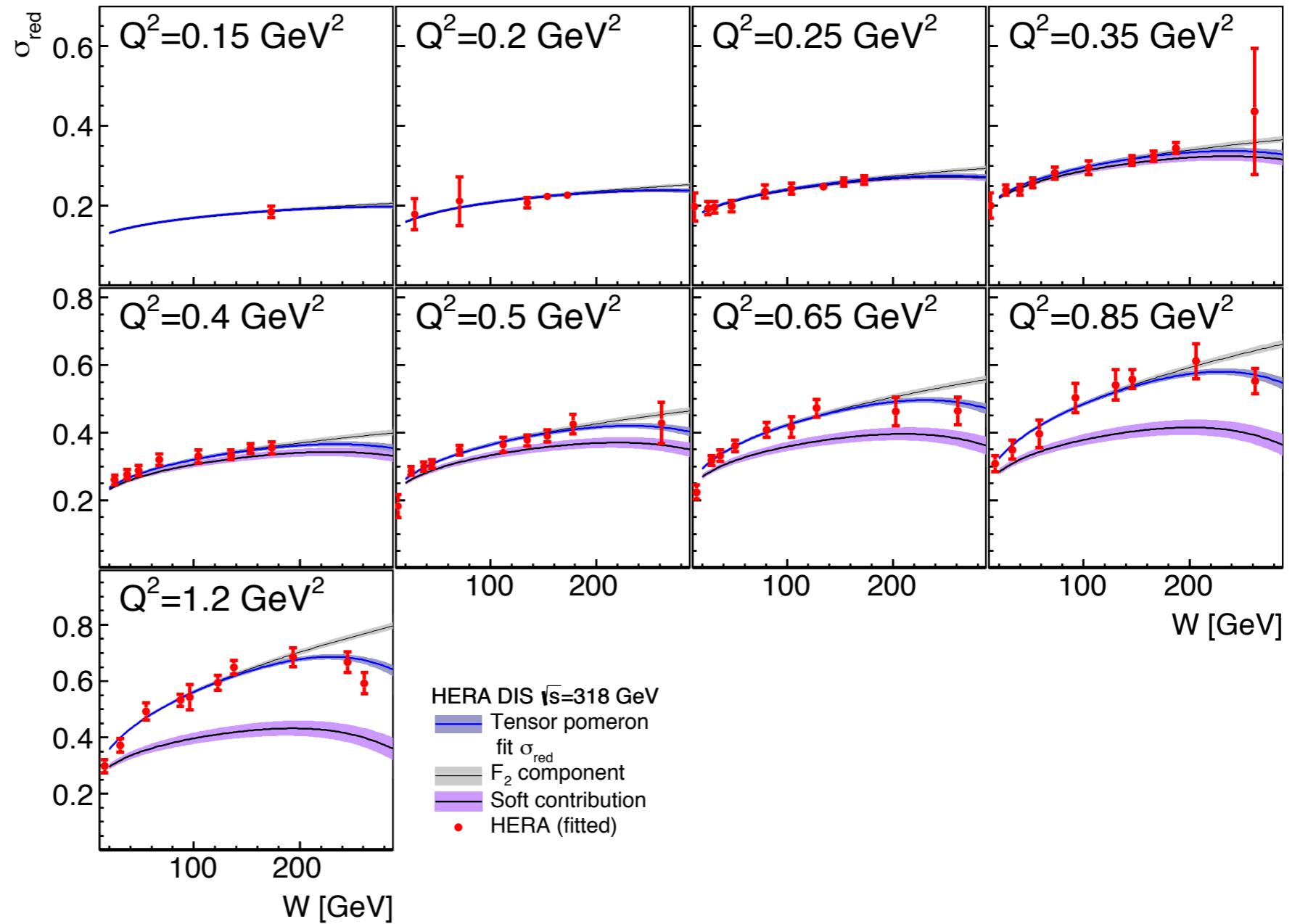
reduced cross
section



Fit results: DIS (5)

$\sqrt{s} = 318 \text{ GeV}$

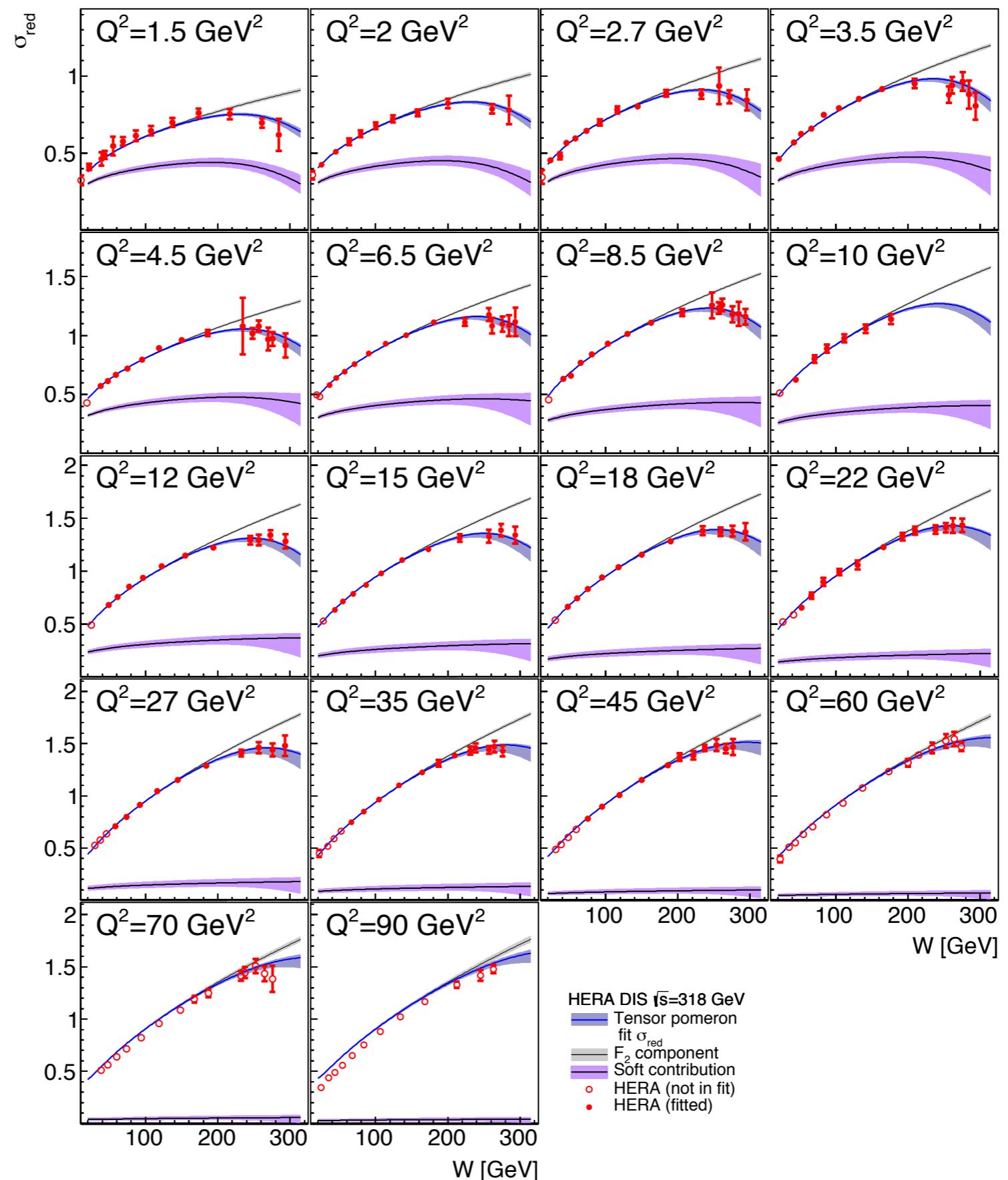
reduced cross
section



Fit results: DIS (6)

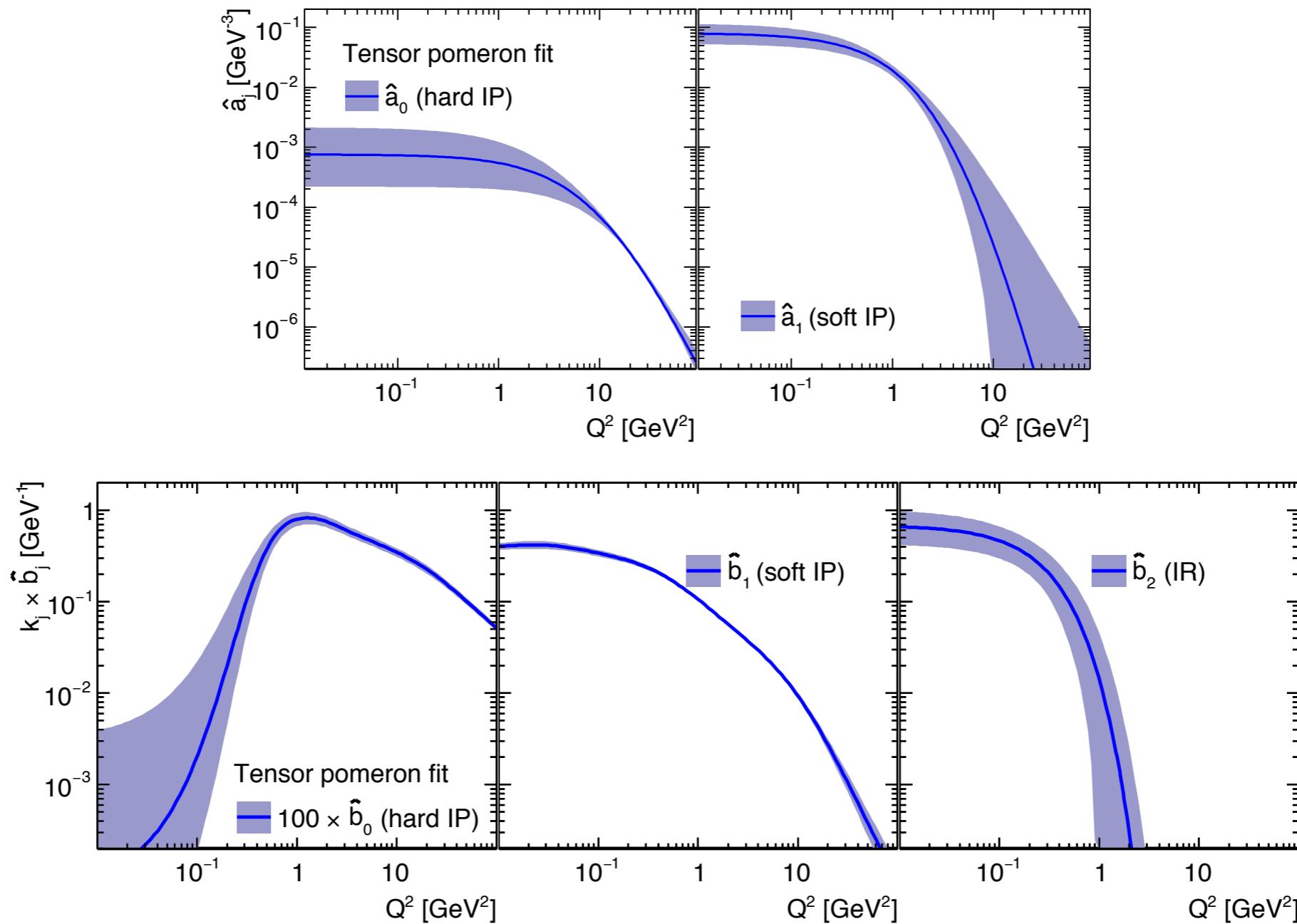
$\sqrt{s} = 318 \text{ GeV}$

reduced cross
section



Fit results: coupling functions

- pomeron and reggeon couplings to $\gamma^*\gamma^*$



Observations: DIS

- Hard contribution increases with Q^2 .
Hard and soft pomeron contributions of equal size at about 5 GeV^2 , but soft contribution still clearly visible at 20 GeV^2
- σ_L clearly visible
- Reggeon contribution very small at high W

Observations: DIS

- We do not see any particular sign of saturation in our fit. Saturation could be in the DIS data, but it would not be due to unitarity.

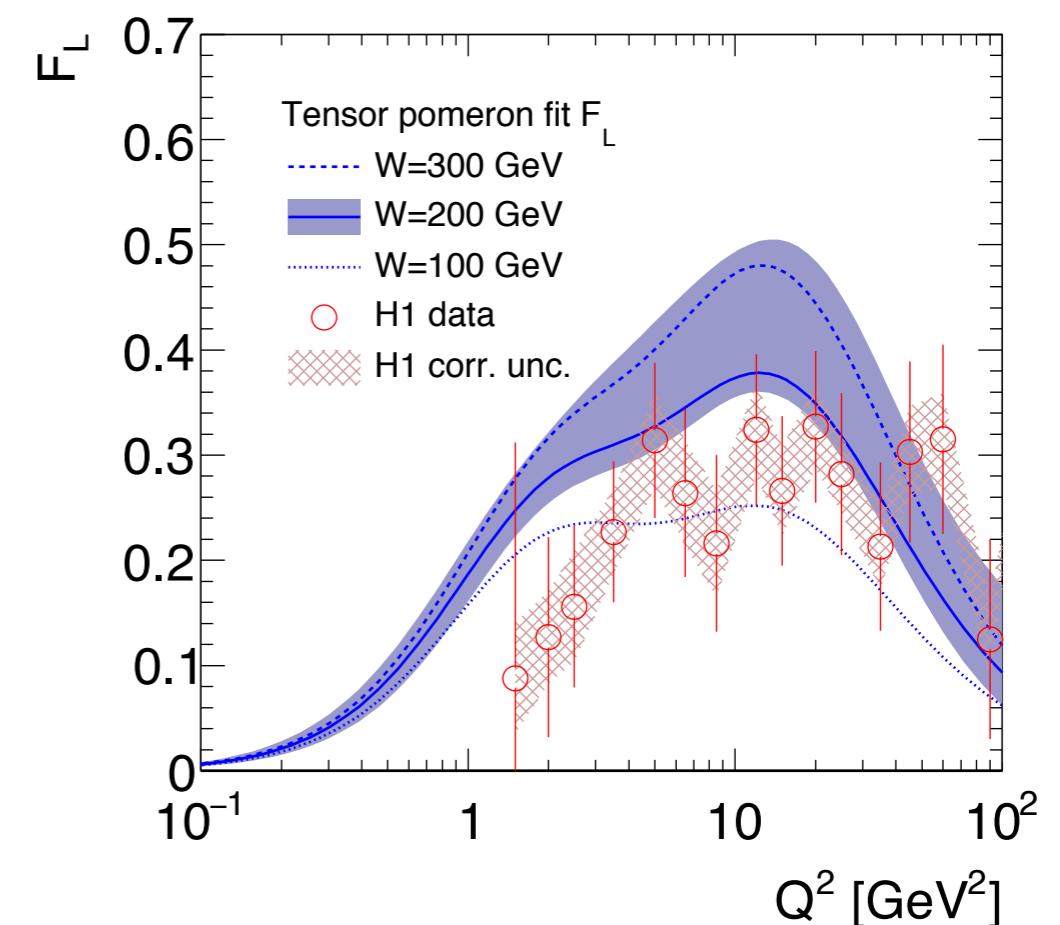
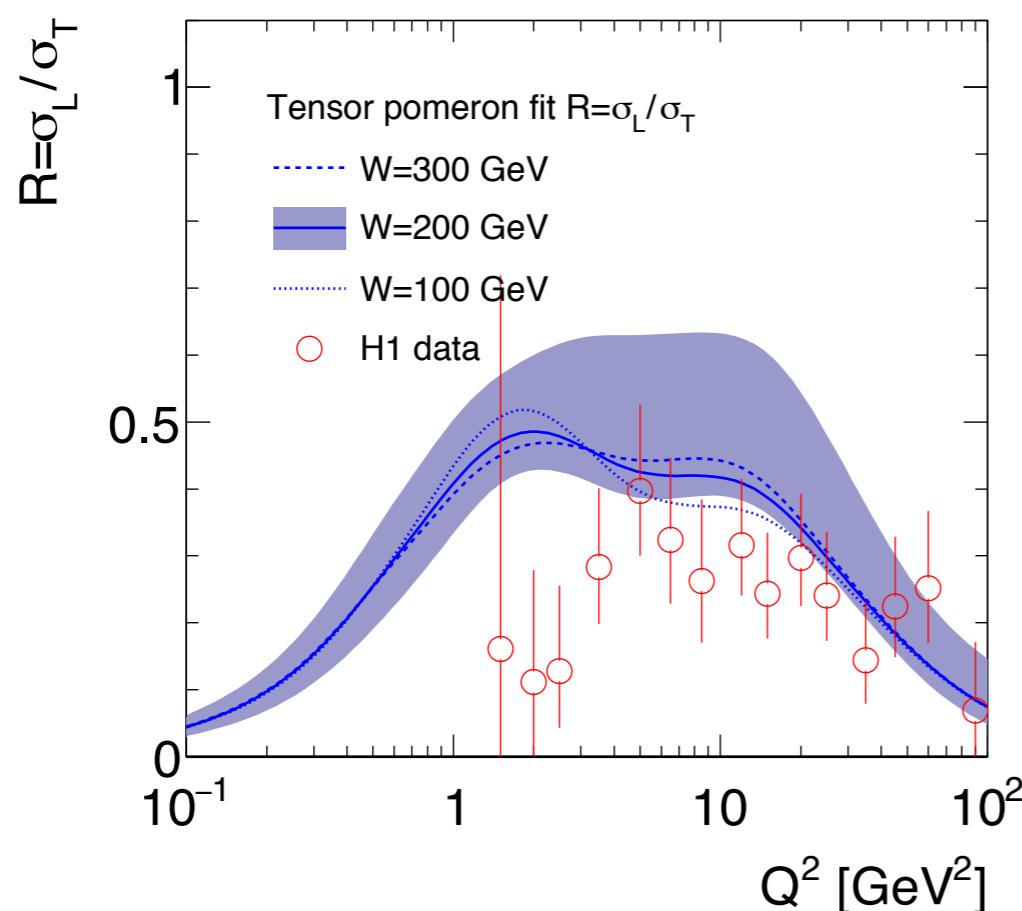
There is no Froissart bound for photon-proton cross sections / structure functions! They might rise like powers indefinitely.

In this case, the exponents might be related to critical phenomena.

Nachtmann

$$R = \sigma_L/\sigma_T \text{ and } F_L$$

- comparison to F_L extraction by H1 (not in fit): fit prefers relatively large R



- Future measurements of σ_L and R at an EIC would be very interesting.

Observations: R and the dipole model

- R close to upper bound from dipole model,
 $R_{\max} = 0.37248$.
This might indicate problems with the dipole model in the corresponding kinematical regime.
- Speaking of the dipole model ... (and since we discussed photoproduction):
One should use W instead of x_{Bj} in the dipole cross section - because of QFT, and since otherwise photoproduction is constant in energy.

Summary (I)

- We have developed a 2-tensor-pomeron model and have made a fit to photoproduction and low- x DIS data from HERA.
- We obtain a very satisfactory fit and determine in particular the intercepts of the two pomerons and the f_2 reggeon.
- For DIS, the soft contribution is still clearly visible up to about $Q^2 = 20 \text{ GeV}^2$. The transition from low to high Q^2 is nicely described.

Summary (2)

- We find strong support for the tensor pomeron picture:

A vector pomeron would not give any contribution to the real photoabsorption cross section, while the tensor pomeron gives an excellent description.