Non-linear QCD dynamics and exclusive production in *ep* collisions*

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* Based on: V.P. Gonçalves, MVTM and A.R. Meneses, Eur. Phys. J. C68, 133 (2010)

Outline

- ✓Motivation: non-linear dynamics on exclusive processes
- ✓BK equation with running coupling (RC BK)
- ✓Fits to inclusive structure functions at small-x
- ✓New results for exclusive vector meson production
- ✓New results for Deeply Virtual Compton Scattering
- ✓Summary

Motivation

- ✓ Exclusive processes are quite sensitive to the gluon content at high energies (cross-section proportional to gluon PDF squared!)

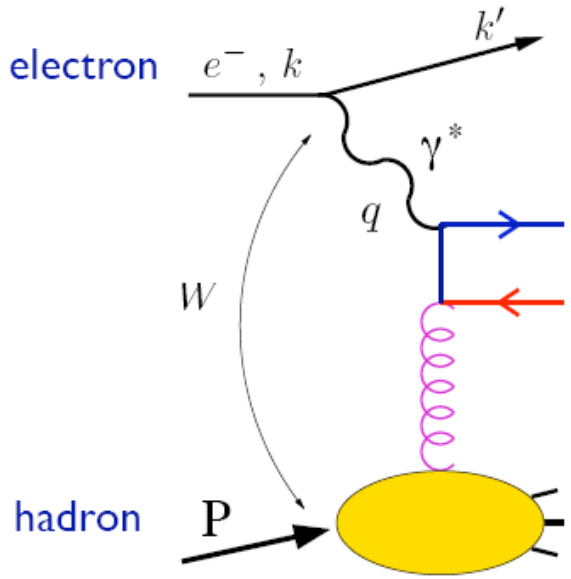
- ✓ Therefore, they are good candidates for searching signals of non-linear QCD dynamics (non-linear evolution equations)

- ✓ Non-linear effects are amplified in processes characterized by a scale near and/or below saturation scale (around 1 GeV at HERA)

- ✓ Very nice data for exclusive quarkonium production at DESY-HERA and accurated DVCS measurements as well

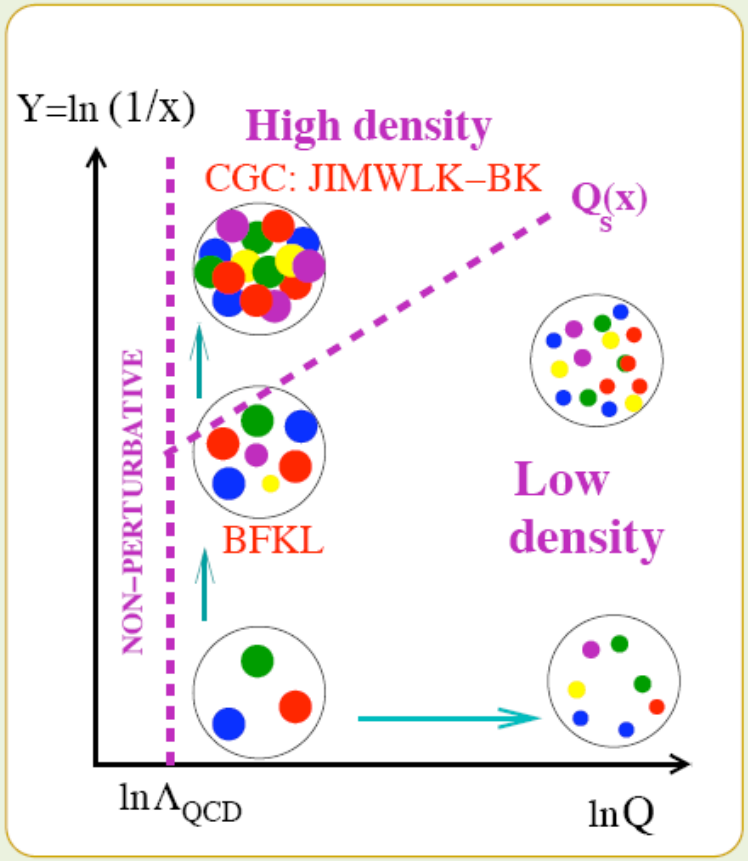
DIS kinematics

⇒ Measuring hadron structure: Deep Inelastic Scattering (DIS)



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

$$x = \frac{Q^2}{2\,P \cdot q} \approx \frac{Q^2}{W^2}$$

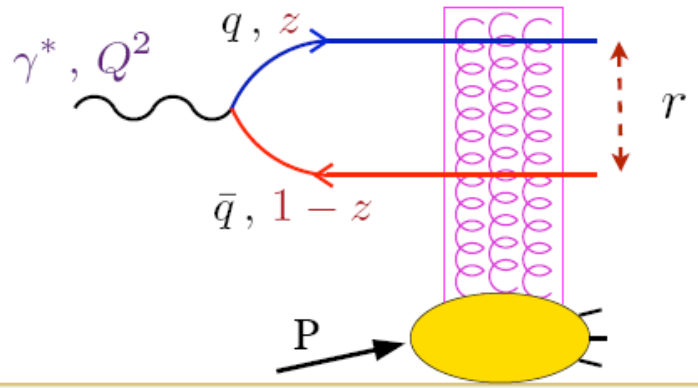


⇒ Saturation: At small-x the hadron wave function gets denser and non-linear, recombination processes become relevant

Adapted from J.L. Albacete et al., Phys.Rev. D80, 034031 (2009)

Color dipole picture

DIS in the dipole frame



Splitting of virtual photon in a qq pair. Perturbatively calculable within QED.

Dipole-target scattering amplitude. All the strong interactions and x-dependence are here

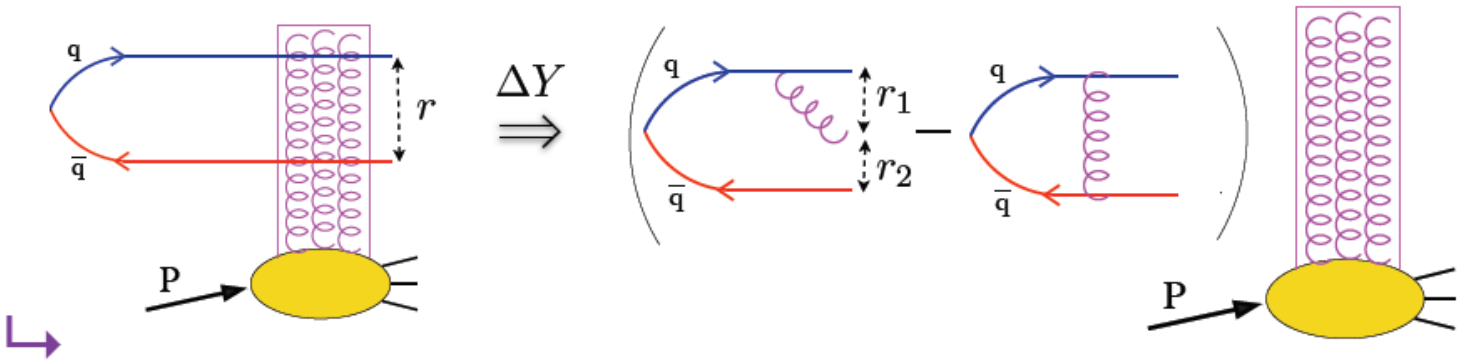
$$\sigma_{T,L}(x,Q^2) = \sigma_0 \int_0^1 dz \int d^2\mathbf{r} \left| \Psi_{T,L}^{\gamma^* \to q\bar{q}}(z,Q,r) \right|^2 \mathcal{N}(x,r)$$

The small-x evolution of the dipole scattering amplitude can be calculated by means of the BK equation

Adapted from J.L. Albacete et al., Phys. Rev. D80, 034031 (2009)

BK equation for small-x evolution

⇒ Balitsky-Kovchegov equation for small-x evolution of the dipole amplitude

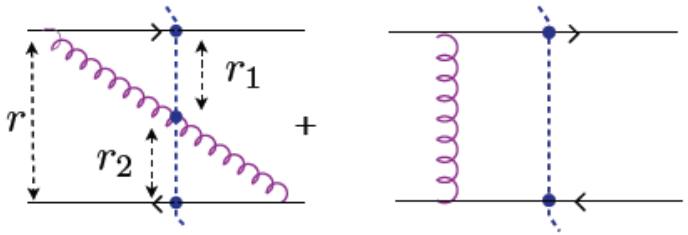


$$\frac{\partial \mathcal{N}(x,r)}{\partial \ln(x_0/x)} = \int d^2 r_1 \, K^{LO}(\mathbf{r},\mathbf{r_1},\mathbf{r_2}) \left[\mathcal{N}(x,r_1) + \mathcal{N}(x,r_2) - \mathcal{N}(x,r) - \mathcal{N}(x,r_1)\mathcal{N}(x,r_2)\right]$$

Non-linear term

⇒ The LO kernel: probability of small-x gluon emission at leading-logarithmic accuracy in $\alpha_s \ln 1/x$

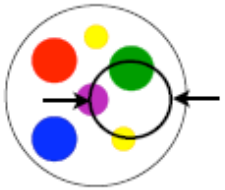
$$K^{L0}(\mathbf{r},\mathbf{r_1},\mathbf{r_2}) = \frac{\alpha_s N_c}{2\pi^2} \frac{r^2}{r_1^2 r_2^2} =$$



Adapted from J.L. Albacete et al., Phys. Rev. D80, 034031 (2009)

BK equation for small-x evolution

⇒ Phenomenology vs LO-BK (fixed coupling)



$$\begin{cases} Q_s^2(Y) = Q_0^2 \exp \lambda Y \\ \lambda = \dfrac{d \ln Q_s^2(Y)}{dY} \end{cases}$$

evolution speed

⇒ Golec-Biernat Wusthoff fit to inclusive and diffractive DIS data:

$$\mathcal{N}^{GBW}(x,r) = 1 - \exp\left[-\frac{r^2 Q_s^2(x)}{4}\right] \longrightarrow \lambda^{GBW} \sim 0.288$$

⇒Energy dependence of multiplicities in gold-gold collisions at RHIC:

$$\left.\frac{dN}{dy}\right|_{y=0} \propto Q_s^2 \sim \sqrt{s}^{\lambda} \longrightarrow \lambda \sim 0.2 \div 0.3$$

⇒ LO-BK evolution yields $\longrightarrow \lambda^{LO} \sim 4.8\,\alpha_s$

Adapted from J.L. Albacete et al., Phys. Rev. D80, 034031 (2009)

Fits to DIS structure function with BK@NLO

⇒ Fits to inclusive DIS structure function for $x \leq 10^{-2}$ $\quad F_2(x,Q^2) = \dfrac{Q^2}{4\,\pi^2\,\alpha_{em}}\,(\sigma_T + \sigma_L)$

$$\sigma_{T,L}(x,Q^2) = \sigma_0 \int_0^1 dz \int d^2\mathbf{r} \left|\Psi_{T,L}^{\gamma^* \to q\bar{q}}(z,Q,r)\right|^2 \mathcal{N}(x,r)$$

⇒ x-dependence: (only) running coupling BK using Balitsky's prescription

$$\frac{\partial \mathcal{N}(x,r)}{\partial \ln(x_0/x)} = \int d^2 r_1\, K^{Bal}(\mathbf{r},\mathbf{r_1},\mathbf{r_2})\,[\mathcal{N}(x,r_1) + \mathcal{N}(x,r_2) - \mathcal{N}(x,r) - \mathcal{N}(x,r_1)\mathcal{N}(x,r_2)]$$

$$K^{Bal}(\mathbf{r},\mathbf{r_1},\mathbf{r_2}) = \frac{N_c\,\alpha_s(r^2)}{2\,\pi^2}\left[\frac{r^2}{r_1^2\,r_2^2} + \frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1\right) + \frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1\right)\right]$$

⇒ Regularization of the coupling: We freeze to a constant, α_{fr}=0.7 in the IR:

$$\alpha_s(r^2) = \frac{12\,\pi}{(11\,N_c - 2\,N_f)\ln\left(\frac{4\,C^2}{r^2\,\Lambda_{QCD}}\right)} \quad \text{for } r < r_{fr},\ \text{with } \alpha_s(r_{fr}^2) \equiv \alpha_{fr} = 0.7$$

$$\alpha_s(r^2) = \alpha_{fr} = 0.7 \qquad \text{for } r > r_{fr} \qquad\qquad \Lambda_{QCD} = 0.241\,\text{GeV}$$

Adapted from J.L. Albacete et al., Phys. Rev. D80, 034031 (2009)

Exclusive vector meson production

- **The amplitude for the exclusive production of a final state, *E,* is:**

$$\mathcal{A}_{T,L}^{\gamma^* p \to Ep}(x, Q^2, \Delta) = i \int dz\, d^2\boldsymbol{r}\, d^2\boldsymbol{b} e^{-i[\boldsymbol{b}-(1-z)\boldsymbol{r}].\boldsymbol{\Delta}} \times (\Psi_E^* \Psi)_T 2\mathcal{N}(x, \boldsymbol{r}, \boldsymbol{b})$$

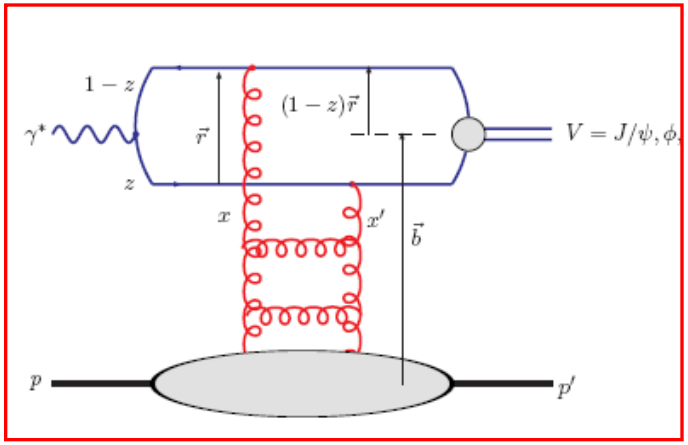
- **The diffrential cross section for the exclusive production is given by**

$$\frac{d\sigma_{T,L}}{dt}(\gamma^* p \to Ep) = \frac{1}{16\pi} |\mathcal{A}_{T,L}^{\gamma^* p \to Ep}(x, Q^2, \Delta)|^2 (1 + \beta^2)$$

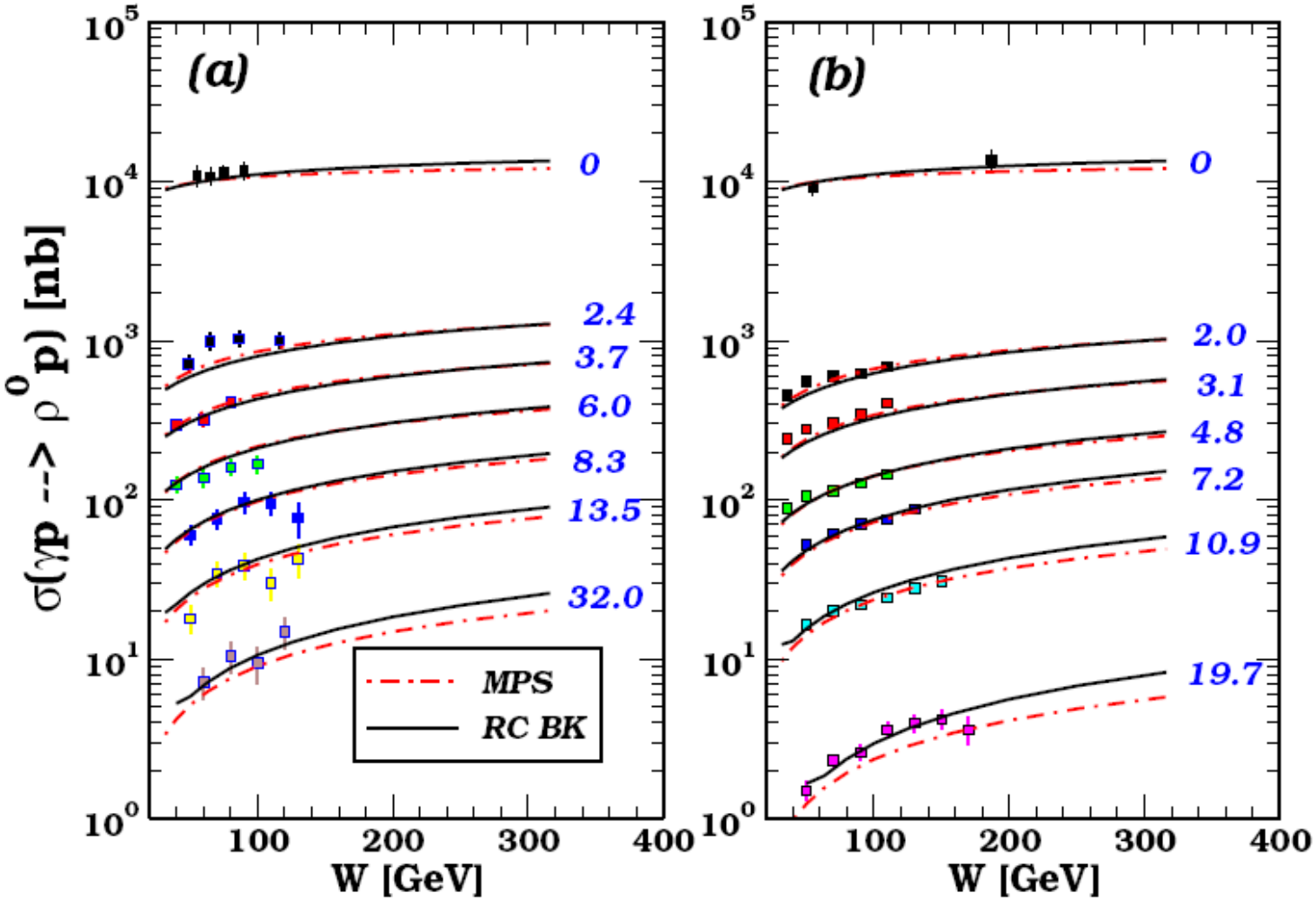
- **BK@NLO has no impact parameter dependence, so:**

$$\sigma_{tot}(\gamma^* p \to Vp) = \frac{1}{B_V} \left[\left. \frac{d\sigma_T}{dt} \right|_{t=0} + \left. \frac{d\sigma_L}{dt} \right|_{t=0} \right]$$

$$B_V\,(Q^2) = 0.60 \left[\frac{14}{(Q^2 + M_V^2)^{0.26}} + 1 \right]$$

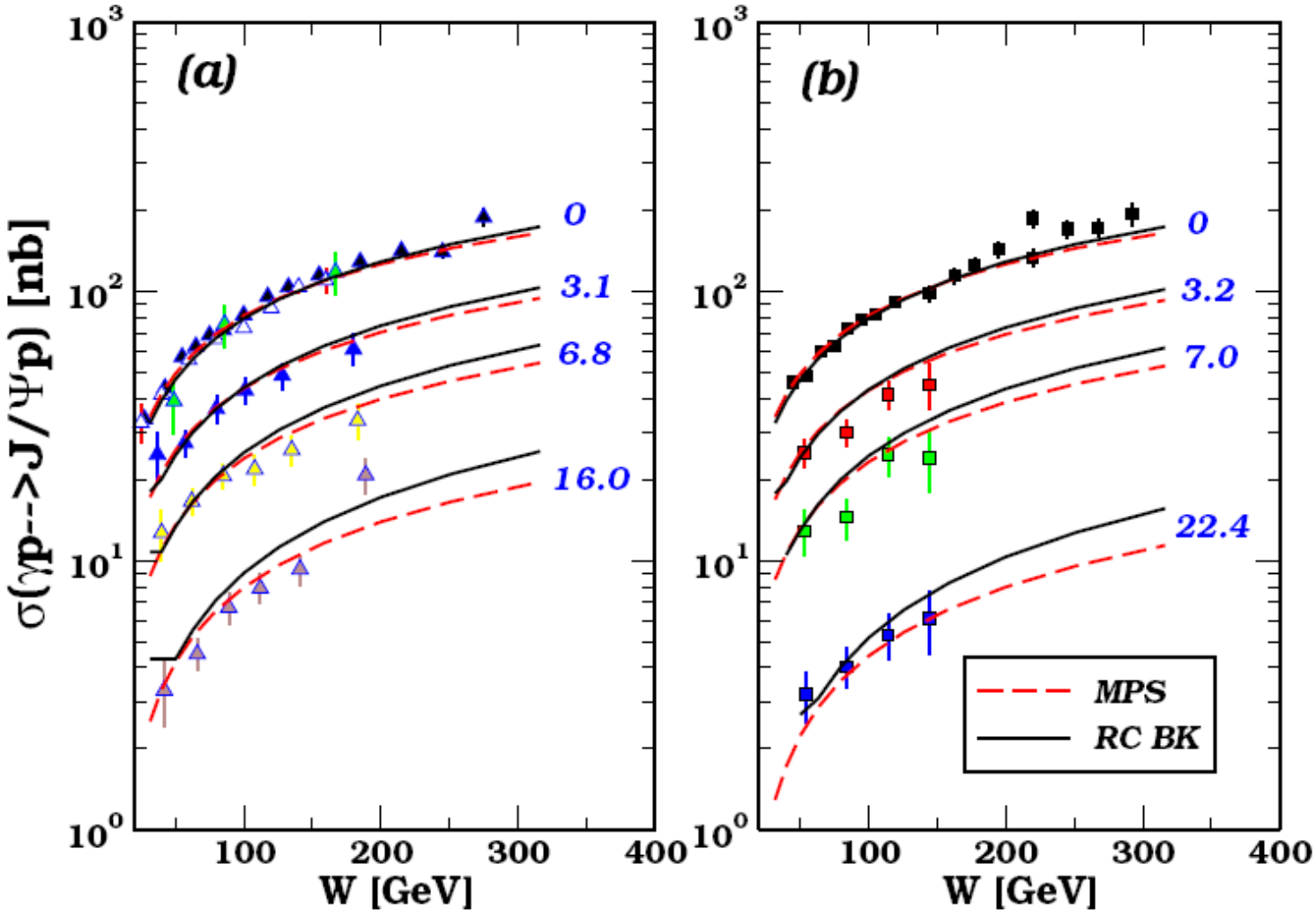


Results: exclusive rho production



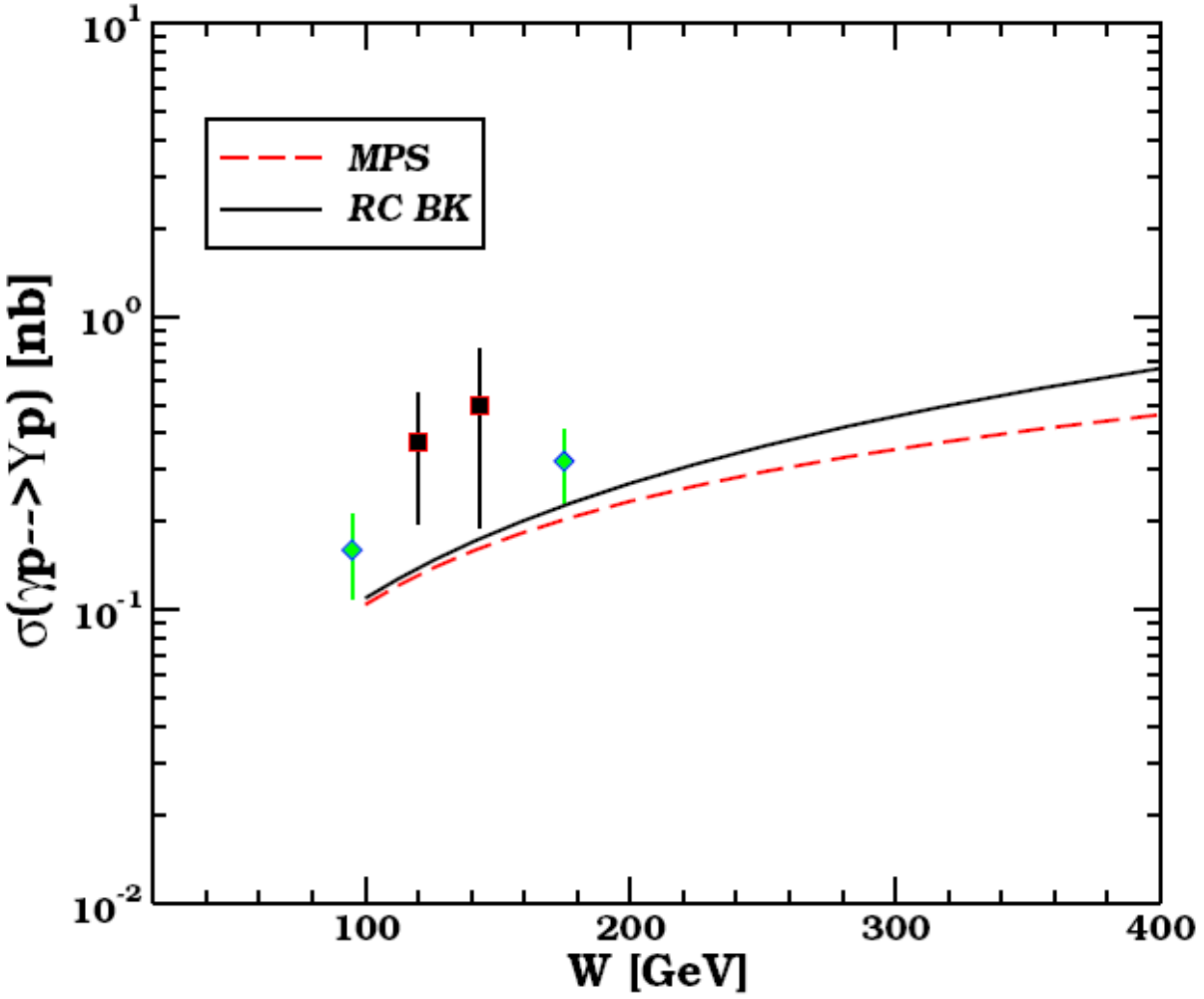
✓ ***MPS:*** C. Marquet, R. Peschanski and G. Soyez, Phys.Rev.D76, 034011 (2007)

Results: exclusive J/ψ production



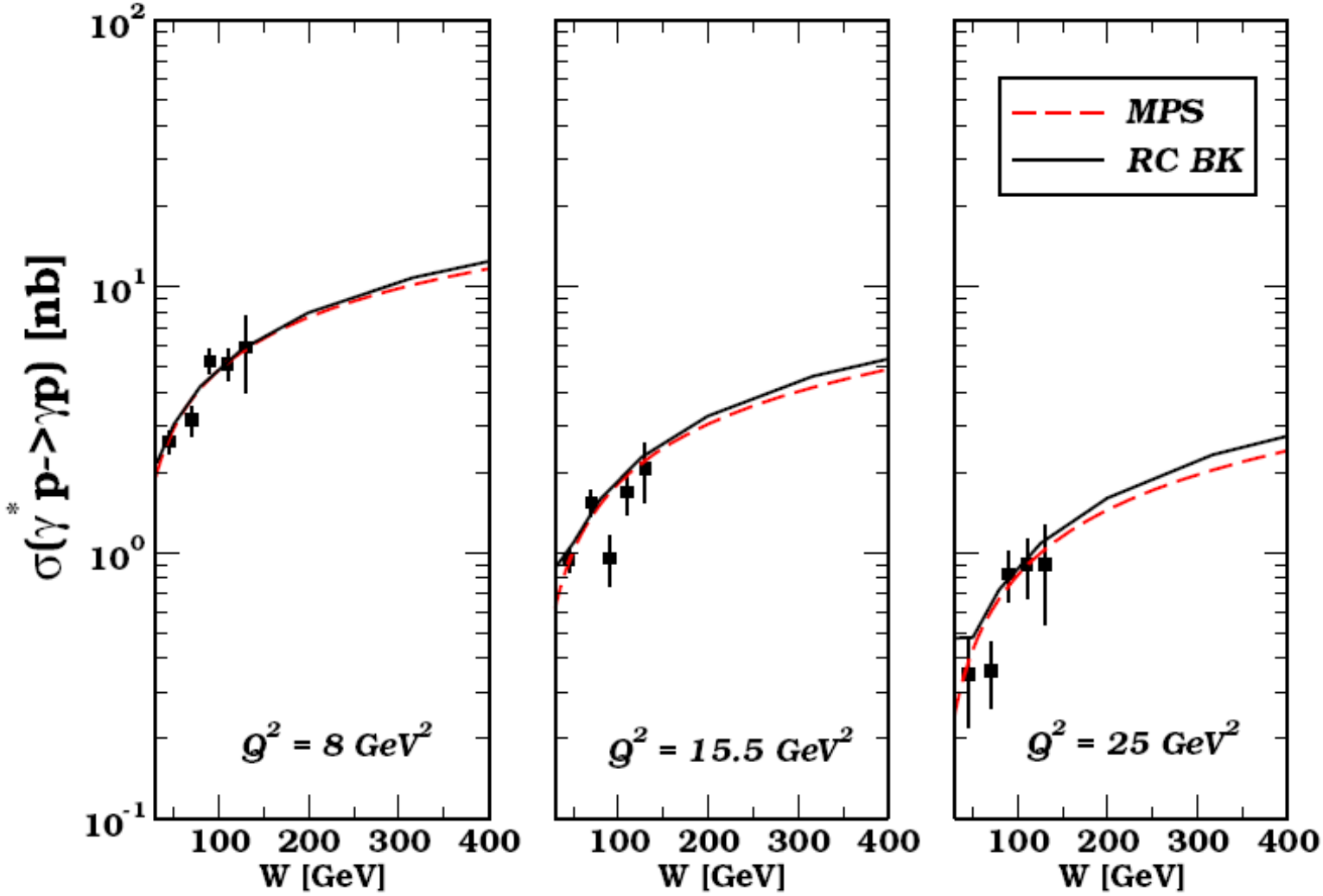
✓ Skewedness has also been introduced in RC BK result.

Results: exclusive Upsilon production



✓ Skewedness has also been introduced in RC BK result.

Results: BK@NLO and DVCS



Summary

- ✓ Analysis of exclusive production in DIS is performed using the numerical solution of BK evolution equation at NLO accuracy in small-x region

- ✓ The results are obtained from solution obtained from a fit (initial condictions) of inclusive structure function without any new adjusted parameter

- ✓ The data description is fairly good and it is compatible with phenomenological models inspired in assymptotic analytical solution of non-linear evolution equations