Dipole model analysis of HERA data and investigation of exclusive $J/\psi, \rho, \phi$ production at the LHC

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Introduction

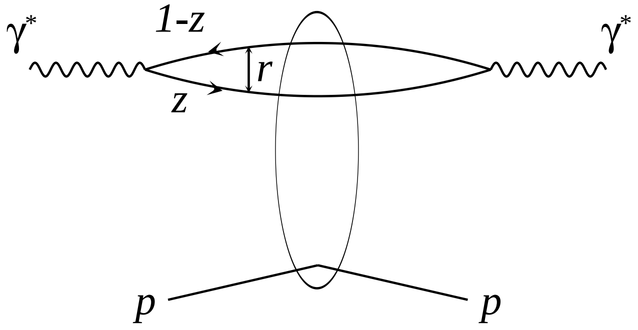
- Motivation: We analyse, within a dipole model, the final, inclusive HERA DIS cross section data in the low x region, using fully correlated errors.
- We show, that these highest precision data are very well described within the dipole model framework starting from very low Q^2 values of 0.3 GeV^2 to the highest values of $Q^2 =$ 250 GeV^2.
- We discuss the saturation question and the properties of the gluon density obtained in this way.
- We discuss exclusive production for $J/\psi, \rho, \phi$ at the HERA and LHC.
- The analysis was done in the xFitter framework.

Outline

- Dipole model approach.
- Results of the fits from BGK dipole model.
- Gluon density.
- Comparision with HERA data.
- Color dipole formulas for diffractive processes.
- Exclusive production for $J/\psi, \rho, \phi$ at the HERA and LHC.
- Summary.

Dipole model of DIS

- Dipole picture of DIS at small x in the proton rest frame



r - dipole size

z - longitudinal momentum fraction of the quark/antiquark

- Factorization: dipole formation + dipole interaction

$$\sigma^{\gamma p} = \frac{4\pi^2\alpha_{em}}{Q^2} F_2 = \sum_f \int d^2r \int_0^1 dz \, |\Psi^\gamma(r, z, Q^2, m_f)|^2 \;\; \hat{\sigma}(r, x)$$

- Dipole-proton interaction

$$\hat{\sigma}(r, x) = \sigma_0 \left(1 - \exp\{-\hat{r}^2\}\right) \qquad \hat{r} = r/R_s(x)$$

Dipole cross section

- BGK (Bartels-Golec-Kowalski) parametrization

$$\hat{\sigma}(r,x) = \sigma_0 \left\{1 - \exp\left[-\pi^2 r^2 \alpha_s(\mu^2) xg(x,\mu^2)/(3\sigma_0)\right]\right\}$$

- $\mu^2 = C/r^2 + \mu_0^2$ is the scale of the gluon density
- μ_0^2 is a starting scale of the QCD evolution. $\mu_0^2 = Q_0^2$
- gluon density is evolved according to the LO or NLO DGLAP eq.
- soft gluon:

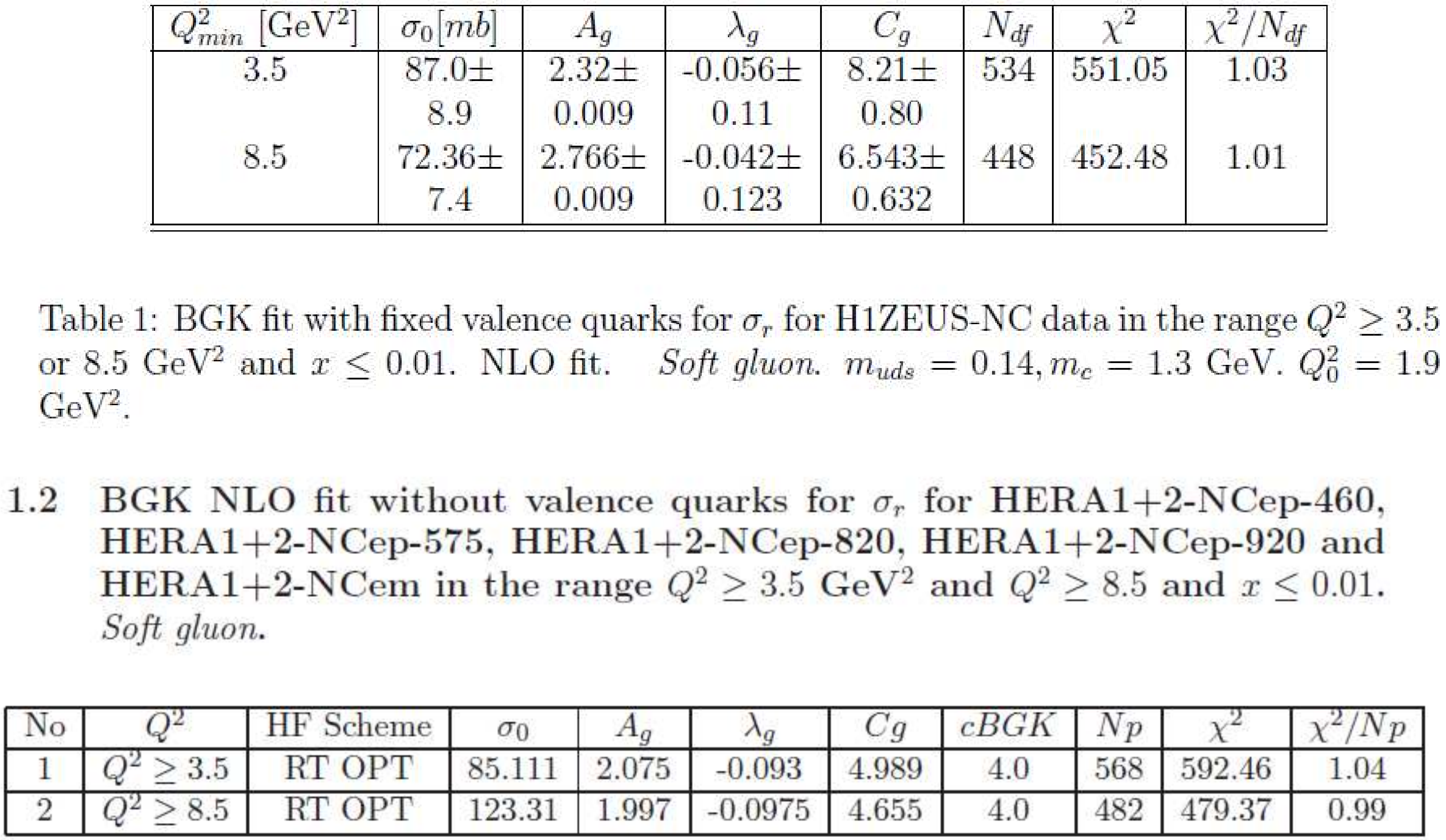
$$xg(x,\mu_0^2) = A_g\, x^{\lambda_g}\, (1-x)^{C_g}$$

- soft + hard gluon:

$$xg(x,\mu_0^2) = A_g\, x^{\lambda_g}\, (1-x)^{C_g} (1 + D_g x + E_g x^2)$$

Results of the Fits

- Dipole model BGK fit with fix valence quarks and without



Q^2_{min} [GeV^2]	$\sigma_0 [mb]$	A_g	λ_g	C_g	N_{df}	χ^2	χ^2/N_{df}
3.5	87.0$\pm$ 8.9	2.32$\pm$ 0.009	-0.056$\pm$ 0.11	8.21$\pm$ 0.80	534	551.05	1.03
8.5	72.36$\pm$ 7.4	2.766$\pm$ 0.009	-0.042$\pm$ 0.123	6.543$\pm$ 0.632	448	452.48	1.01

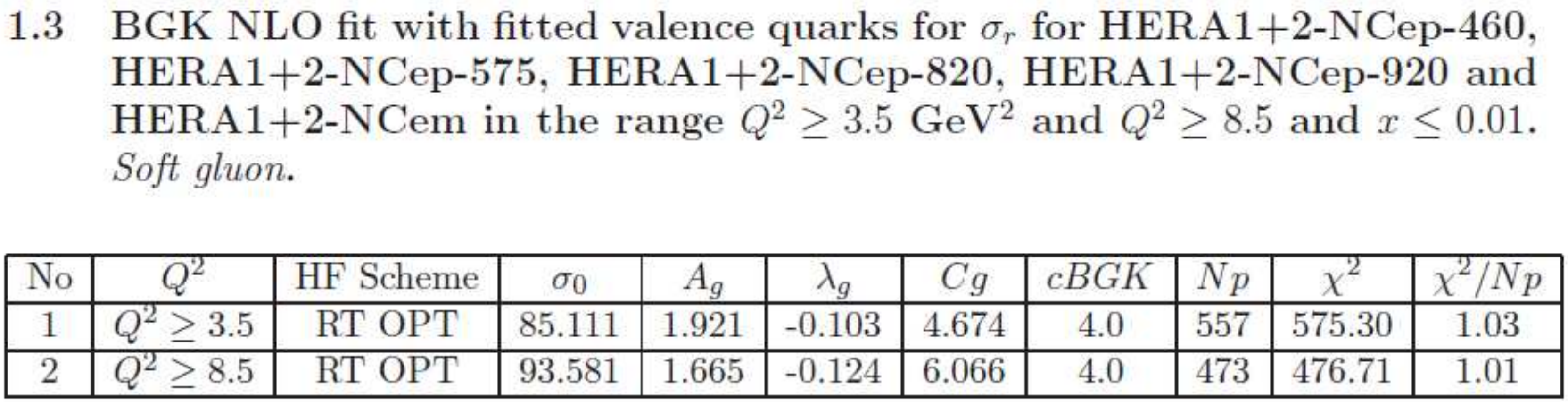
Table 1: BGK fit with fixed valence quarks for σ_r for H1ZEUS-NC data in the range $Q^2 \geq 3.5$ or 8.5 GeV^2 and $x \leq 0.01$. NLO fit. *Soft gluon.* $m_{uds} = 0.14, m_c = 1.3$ GeV. $Q_0^2 = 1.9$ GeV^2.

1.2 BGK NLO fit without valence quarks for σ_r for HERA1+2-NCep-460, HERA1+2-NCep-575, HERA1+2-NCep-820, HERA1+2-NCep-920 and HERA1+2-NCem in the range $Q^2 \geq 3.5$ GeV^2 and $Q^2 \geq 8.5$ and $x \leq 0.01$. *Soft gluon.*

No	Q^2	HF Scheme	σ_0	A_g	λ_g	Cg	$cBGK$	Np	χ^2	χ^2/Np
1	$Q^2 \geq 3.5$	RT OPT	85.111	2.075	-0.093	4.989	4.0	568	592.46	1.04
2	$Q^2 \geq 8.5$	RT OPT	123.31	1.997	-0.0975	4.655	4.0	482	479.37	0.99

Results of the Fits

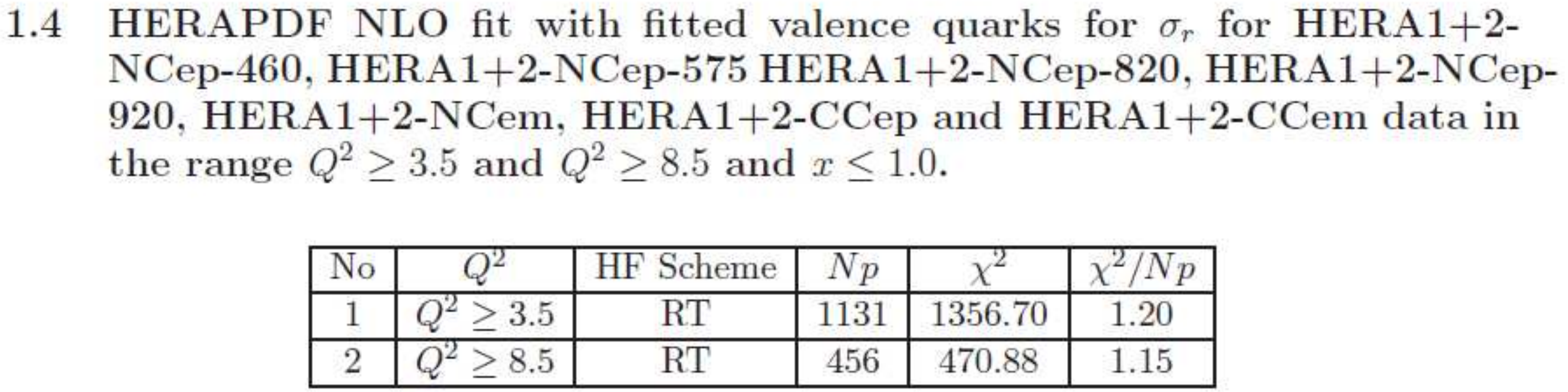
- Dipole model BGK fit with fitted valence quarks



1.3 BGK NLO fit with fitted valence quarks for σ_r for HERA1+2-NCep-460, HERA1+2-NCep-575, HERA1+2-NCep-820, HERA1+2-NCep-920 and HERA1+2-NCem in the range $Q^2 \geq 3.5$ GeV^2 and $Q^2 \geq 8.5$ and $x \leq 0.01$. *Soft gluon.*

No	Q^2	HF Scheme	σ_0	A_g	λ_g	Cg	$cBGK$	Np	χ^2	χ^2/Np
1	$Q^2 \geq 3.5$	RT OPT	85.111	1.921	-0.103	4.674	4.0	557	575.30	1.03
2	$Q^2 \geq 8.5$	RT OPT	93.581	1.665	-0.124	6.066	4.0	473	476.71	1.01

- HERAPDF fit with fitted valence quarks

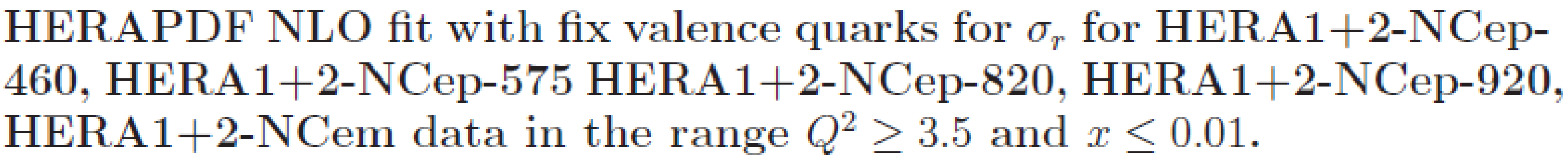


1.4 HERAPDF NLO fit with fitted valence quarks for σ_r for HERA1+2-NCep-460, HERA1+2-NCep-575 HERA1+2-NCep-820, HERA1+2-NCep-920, HERA1+2-NCem, HERA1+2-CCep and HERA1+2-CCem data in the range $Q^2 \geq 3.5$ and $Q^2 \geq 8.5$ and $x \leq 1.0$.

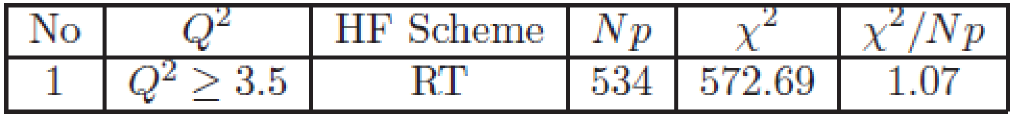
No	Q^2	HF Scheme	Np	χ^2	χ^2/Np
1	$Q^2 \geq 3.5$	RT	1131	1356.70	1.20
2	$Q^2 \geq 8.5$	RT	456	470.88	1.15

Results of the Fits

- HERAPDF fit with fix valence quarks, soft gluon

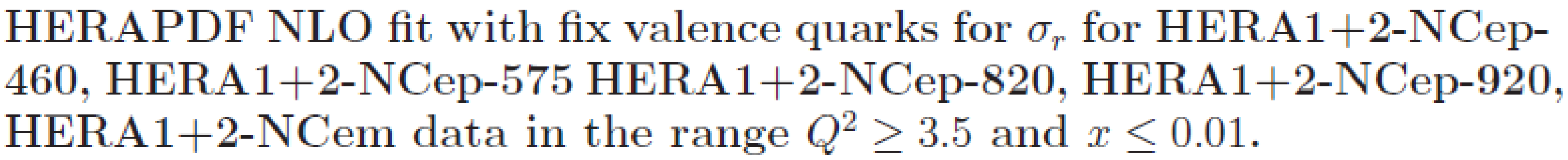


HERAPDF NLO fit with fix valence quarks for σ_r for HERA1+2-NCep-460, HERA1+2-NCep-575 HERA1+2-NCep-820, HERA1+2-NCep-920, HERA1+2-NCem data in the range $Q^2 \geq 3.5$ and $x \leq 0.01$.

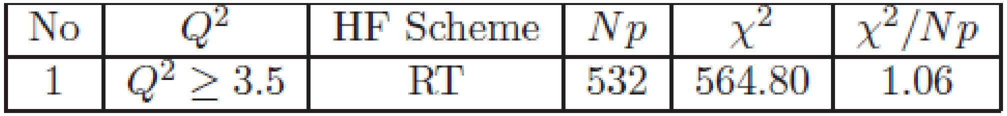


No	Q^2	HF Scheme	Np	χ^2	χ^2/Np
1	$Q^2 \geq 3.5$	RT	534	572.69	1.07

- HERAPDF fit with fix valence quarks, soft + hard gluon



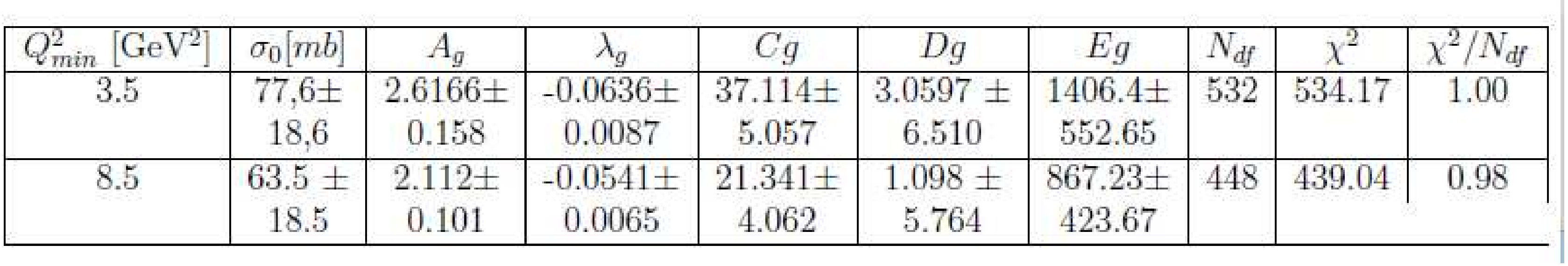
HERAPDF NLO fit with fix valence quarks for σ_r for HERA1+2-NCep-460, HERA1+2-NCep-575 HERA1+2-NCep-820, HERA1+2-NCep-920, HERA1+2-NCem data in the range $Q^2 \geq 3.5$ and $x \leq 0.01$.



No	Q^2	HF Scheme	Np	χ^2	χ^2/Np
1	$Q^2 \geq 3.5$	RT	532	564.80	1.06

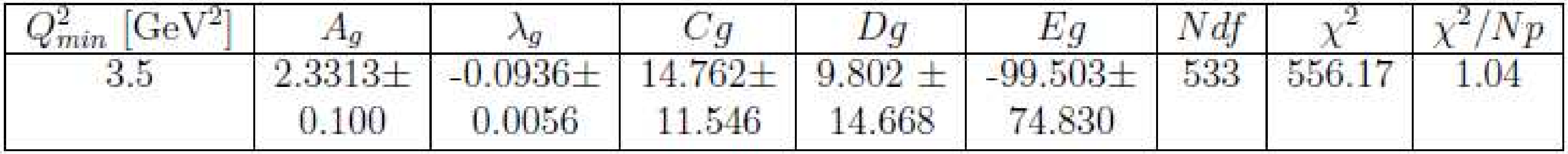
Results of the Fits

- $m_{u,d,s} = 140\ MeV$, $m_c = 1.3\ GeV$
- $\hat{\sigma}(r,x) = \sigma_0 \left\{1 - \exp\left[-\pi^2 r^2 \alpha_s(\mu^2) x g(x,\mu^2)/(3\sigma_0)\right]\right\}$ with saturation



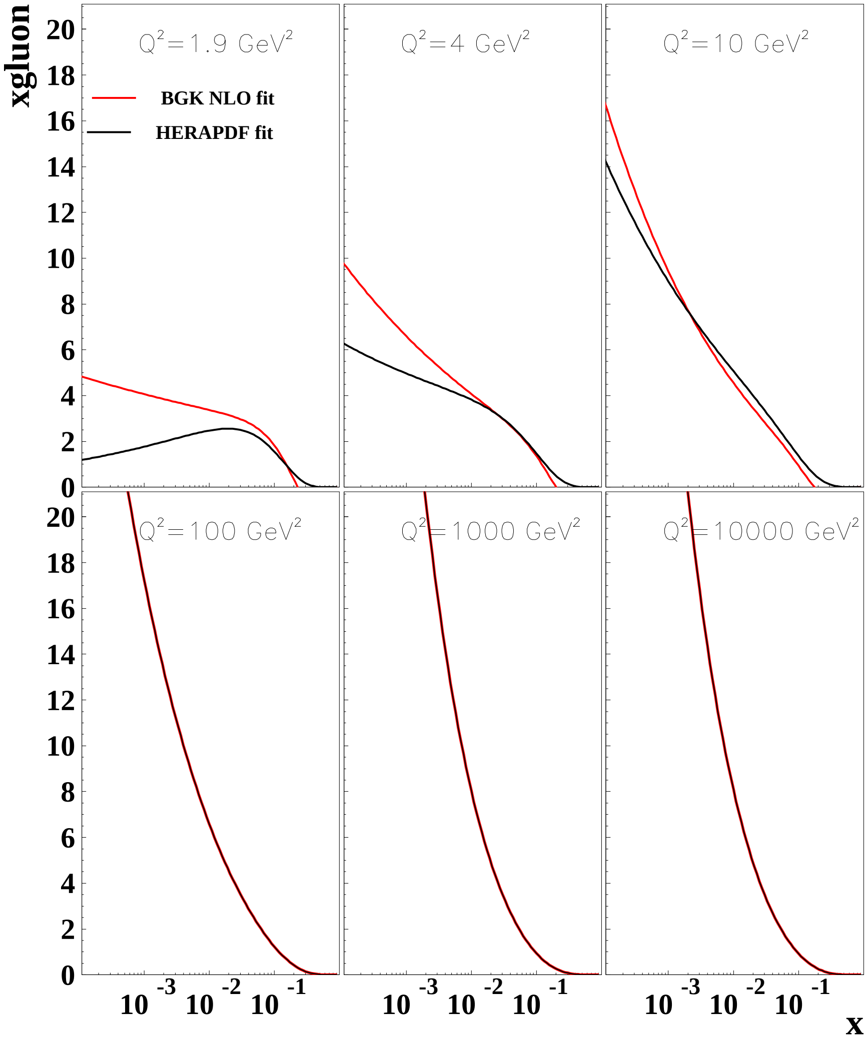
Q^2_{min} [GeV^2]	$\sigma_0[mb]$	A_g	λ_g	Cg	Dg	Eg	N_{df}	χ^2	χ^2/N_{df}
3.5	77,6± 18,6	2.6166± 0.158	-0.0636± 0.0087	37.114± 5.057	3.0597 ± 6.510	1406.4± 552.65	532	534.17	1.00
8.5	63.5 ± 18.5	2.112± 0.101	-0.0541± 0.0065	21.341± 4.062	1.098 ± 5.764	867.23± 423.67	448	439.04	0.98

- $\hat{\sigma}(r,x) = \sigma_0 \left[\pi^2 r^2 \alpha_s(\mu^2) x g(x,\mu^2)/(3\sigma_0)\right]$ without saturation

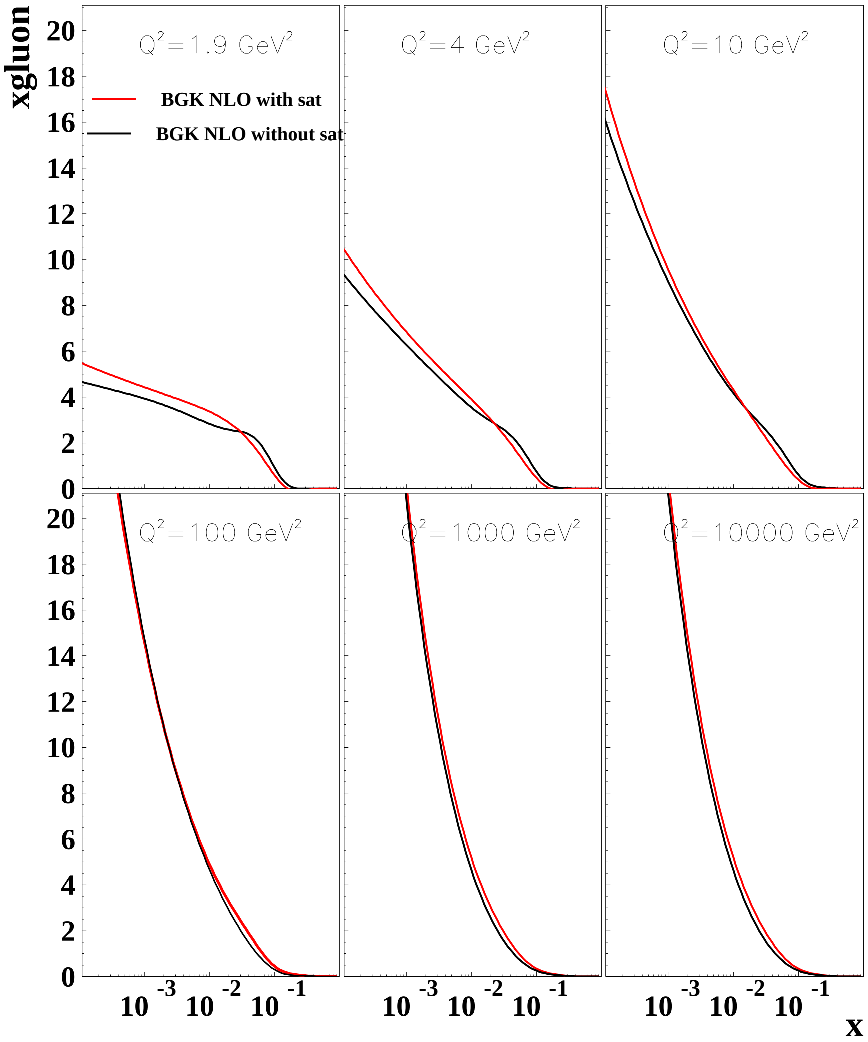


Q^2_{min} [GeV^2]	A_g	λ_g	Cg	Dg	Eg	Ndf	χ^2	χ^2/Np
3.5	2.3313± 0.100	-0.0936± 0.0056	14.762± 11.546	9.802 ± 14.668	-99.503± 74.830	533	556.17	1.04

Gluon density

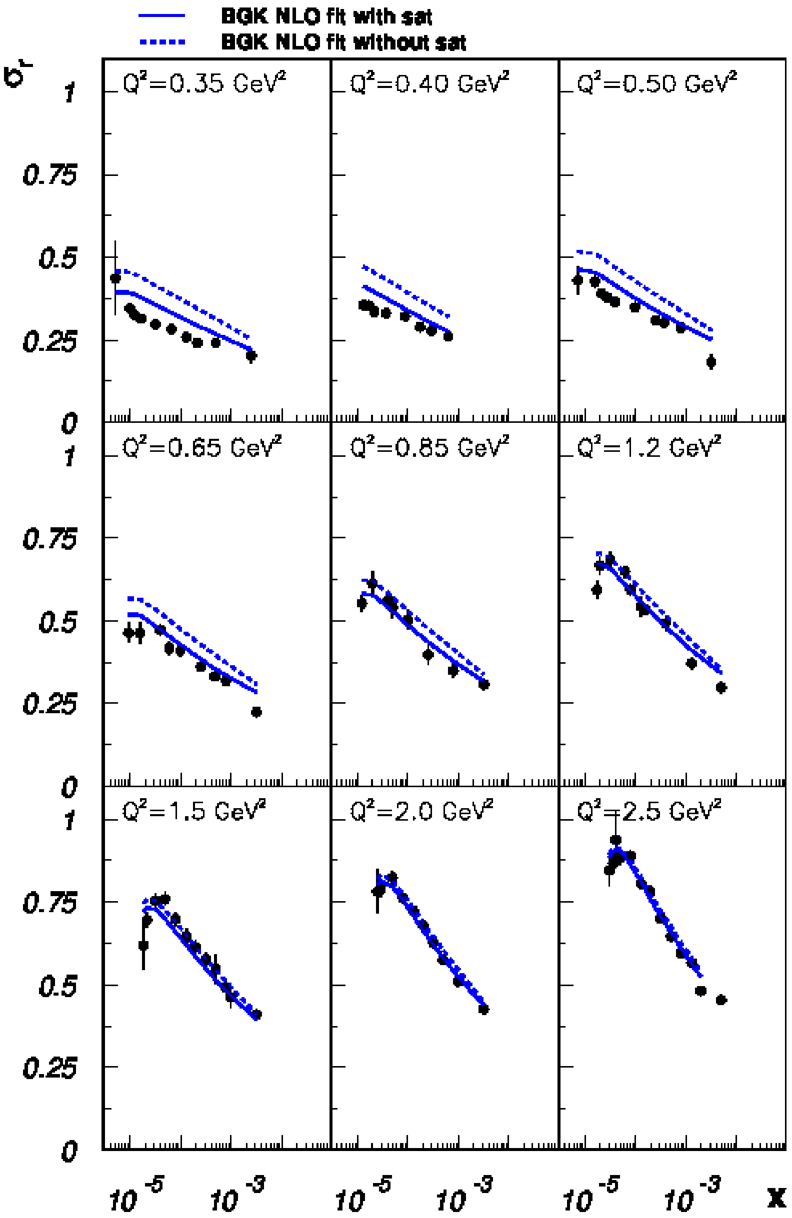


Gluon density

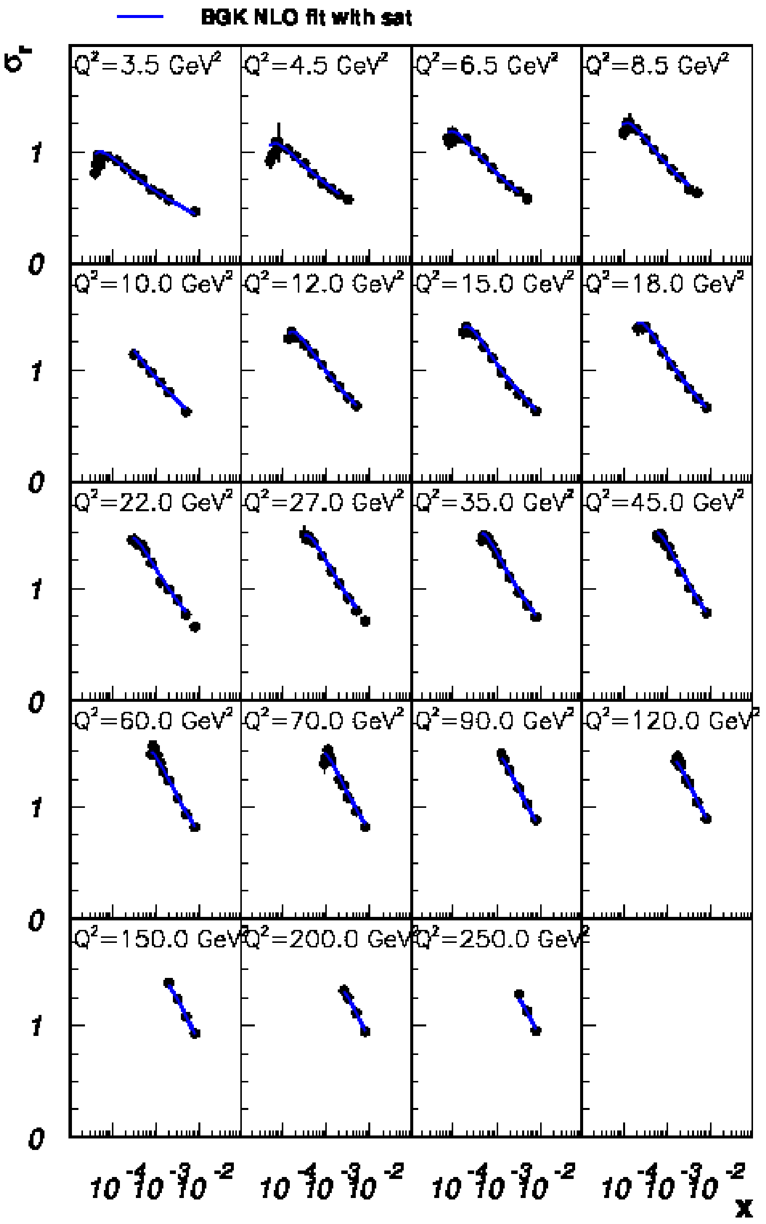


- The differences are disappearing at larger Q^2.

Comparision with HERAI+II data



Comparision with HERAI+II data



Color dipole formulas for diffractive processes

- Up to now we have determined the dipole cross section from the total photoabsorption cross section/proton structure function.
- The same dipole cross section enters also the forward amplitude for the diffractive process $\gamma^* p \to V p$:
- For heavy quarkonia, like $J/\psi, \psi', \Upsilon$, the large quark mass ensures that small dipoles of size dominate.

$$r \sim r_S \approx \frac{6}{\sqrt{Q^2 + M_V^2}}$$

- for small dipoles the dipole cross section is related to the gluon density of the proton:

$$\sigma(x, r) = \frac{\pi^2}{3} r^2 \alpha_S(q^2) x g(x, q^2)\, ,\; q^2 \approx \frac{10}{r^2}$$

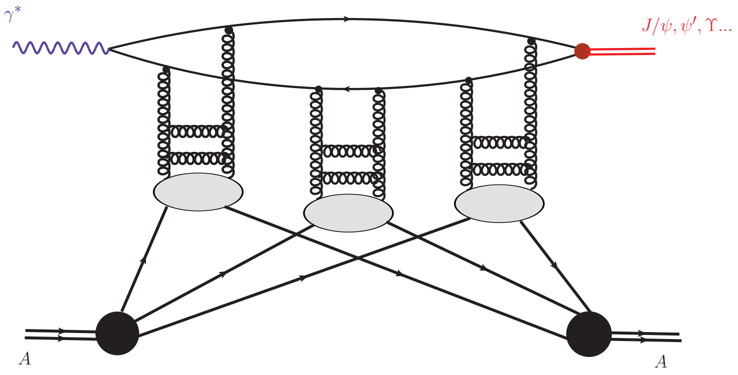
Color dipole formulas for diffractive processes

- Cross sections in the color dipole approach:

$$\sigma_{\rm tot}(\gamma^* p) = \int_0^1 dz \int d^2\boldsymbol{r} |\psi_{q\bar q}(z,\boldsymbol{r})|^2 \sigma(x,\boldsymbol{r})$$

$$\frac{d\sigma(\gamma^* p \to Vp; t=0)}{dt} = \frac{1}{16\pi}\left| \int_0^1 dz d^2\boldsymbol{r} \psi_V^*(z,\boldsymbol{r})\psi_{q\bar q}(z,\boldsymbol{r})\sigma(x,\boldsymbol{r})\right|^2$$

- Color dipoles: the nuclear target



Color dipole formulas for nuclear targets

- For the case of the nuclear target, we have to take into account multiple scatterings of the color dipole.
- Nuclear cross section in the color dipole approach:

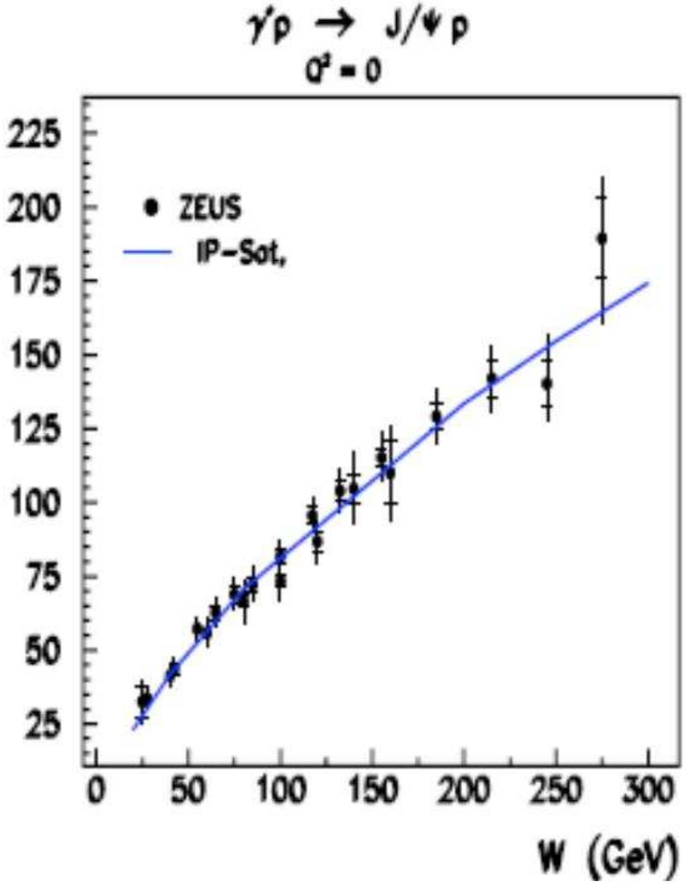
$$\sigma_A(x,\boldsymbol{r}) \quad = \quad 2\int d^2\boldsymbol{b}\Gamma_A(\boldsymbol{b},x,\boldsymbol{r}) = 2\int d^2\boldsymbol{b}(1-\exp[-\frac{1}{2}\sigma(x,\boldsymbol{r})T_A(\boldsymbol{b})])$$

- together with the light-cone wavefunctions of photon and vector meson that is all the input we need to evaluate observables for DIS or diffractive vector meson production on nuclear targets.
- similarly, one can calculate incoherent diffraction on a nucleus (with nuclear breakup).

Exclusive J/ψ production

- J/ψ cross-sections grows almost like $\sigma \propto (xg(x,\mu^2))^2$

H.Kowalski, D.Teaney, Phys. Rev. D 68, 2003

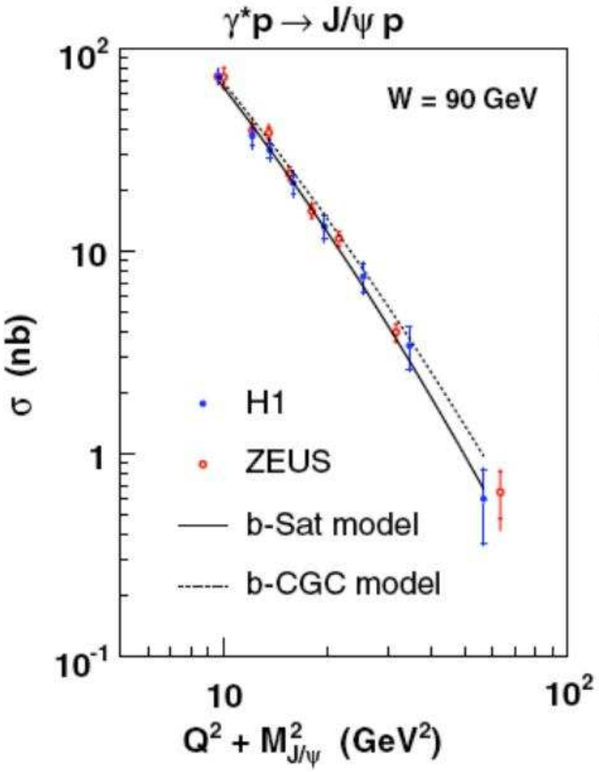


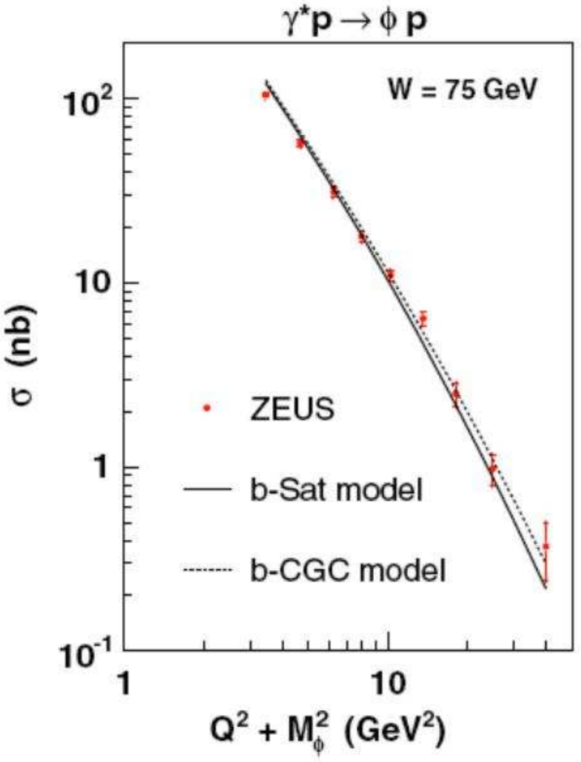
- The determination of gluon density with J/ψ would be more precise than by $F2$ or FL if J/ψ measurements would have small systematic errors

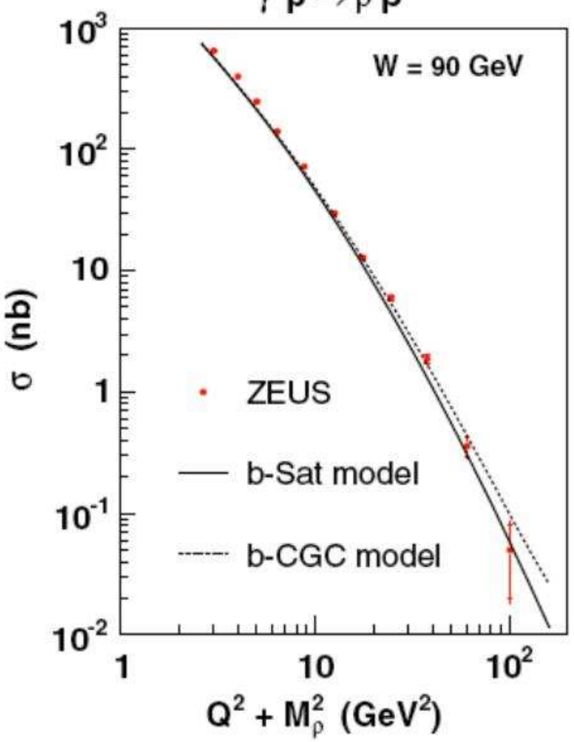
Total vector Meson (VM) cross sections from dipole model

- Predictions from b-Sat and b-CGC models for vector mesons

A.Caldwell, H.Kowalski, Phys.Rev.C81, 2010

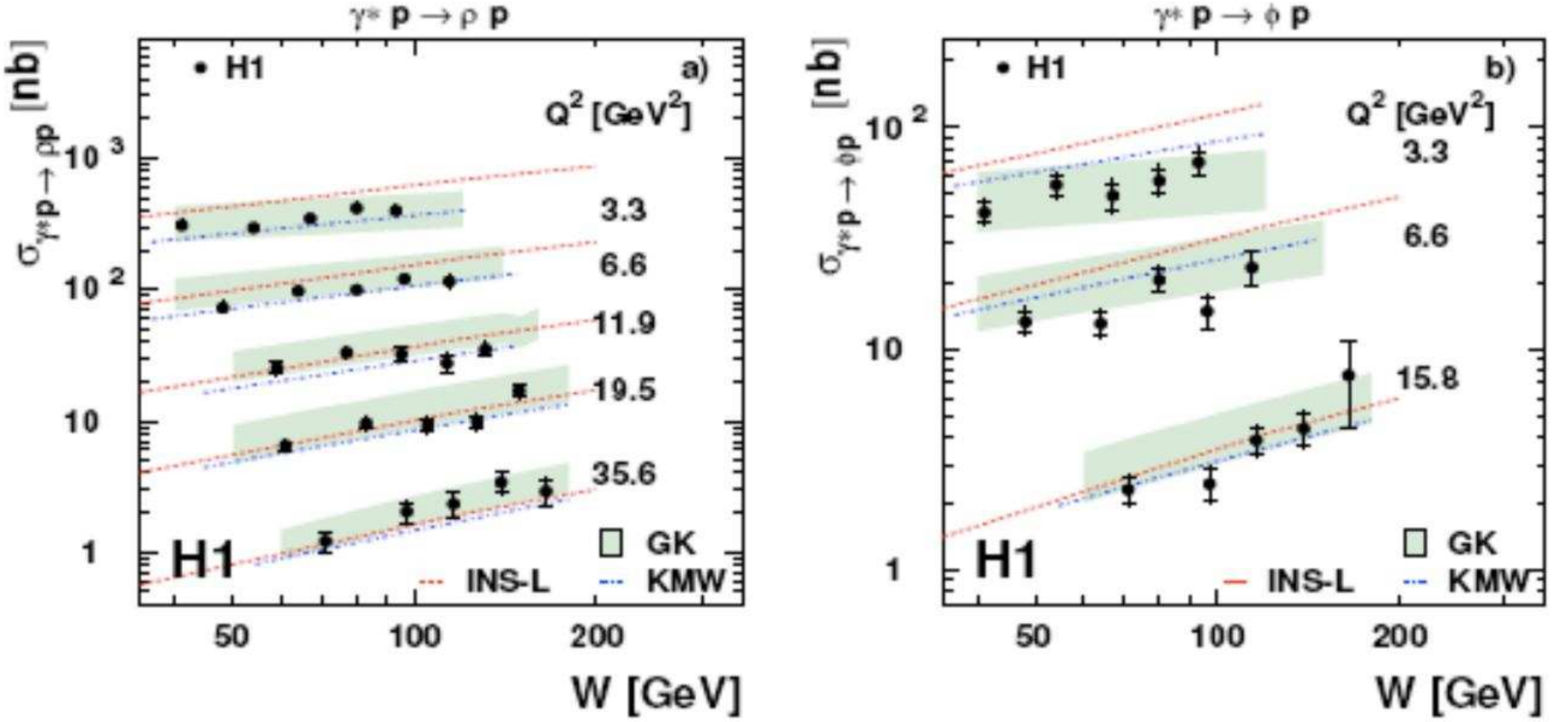






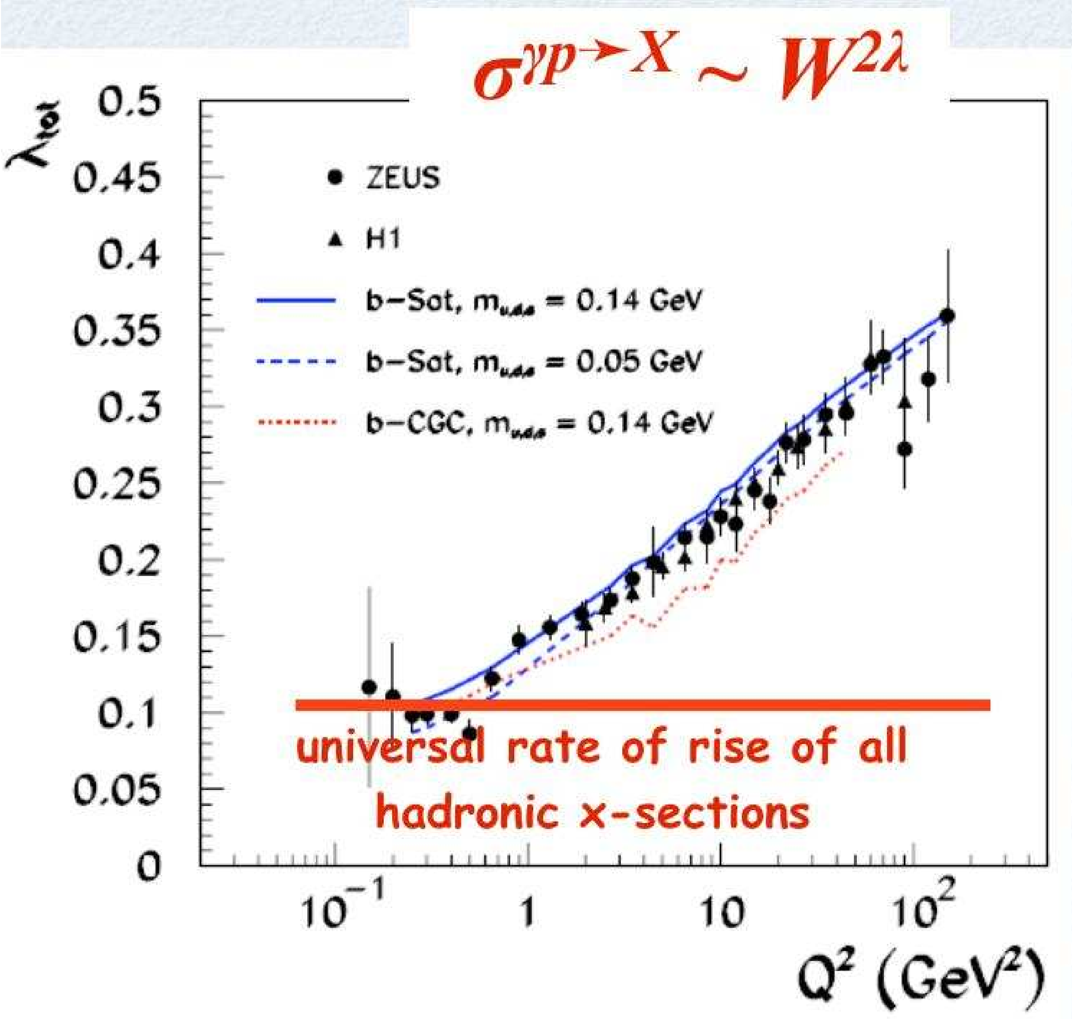
- These are absolute predictions obtained from the gluon density determined from F2

W dependence of exclusive Vector Mesons cross sections

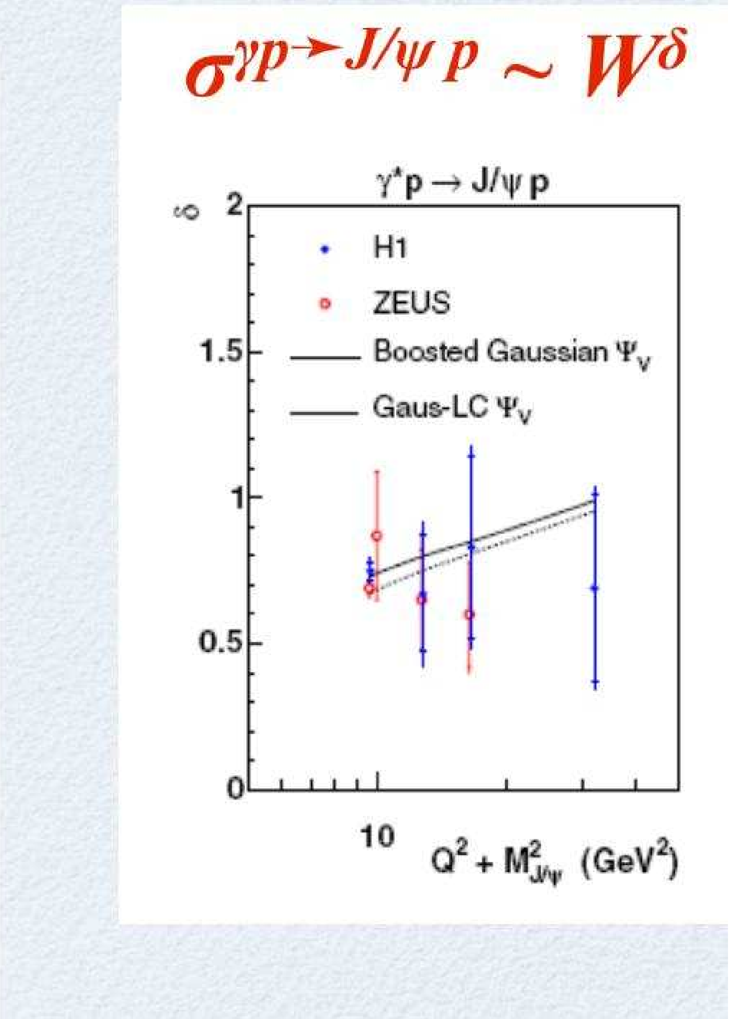


- Dipole model with the DGLAP evolution of gluon density predicts well the rise with W of the ρ and ϕ VM cross sections

HERA -$F2$ is dominated by the gluon density at low x



$\sigma^{\gamma p \to X} \sim W^{2\lambda}$



$\sigma^{\gamma p \to J/\psi\, p} \sim W^{\delta}$

- The same universal gluon density describes different interactions:$\gamma^* p \to X$, $\gamma^* p \to J/\psi p$, $\gamma^* p \to \rho p$..

Summary I

- BGK dipole fits (with saturation) describe the final, high precision HERA data with $x < 0.01$, very well: $\chi^2/Np \to 1$.
- Little sensitivity to valence quarks contribution observed.
- Gluon density from the dipole models is higher than the PDFs gluon at low Q^2.
- The extrapolation to the very low Q^2 region shows a sizable overshoot. This indicates that at very low Q^2 saturation effects of the eikonal aproximation are too small.
- The fit in the whole Q^2 region, $0.3 < Q^2 < 250$ GeV^2 is only slightly better than in the extrapolated case. The systematic overshoot of the fits over data remains.
- The χ^2/N_{df} in the region: $0.3 < Q^2 < 250$ GeV^2 is sizably higher than in the fits in the region $3.5 < Q^2 < 250$ GeV^2, $\chi^2/N_{df} = 1.21$, with the saturation ansatz and $\chi^2/N_{df} = 1.52$ without the saturation ansatz.
- In the lower $Q^2 < 3.5$ GeV^2 range the saturated ansatz of the gluon density seems to be prefered.

Summary II

- Dipole model b-Sat can be used to investigate the gluonic structure of nuclei via J/ψ scattering.
- Predictions for the exclusive J/ψ and ρ at HERA will be provided using dipole model.
- The data indicate that the transverse gluon shape observed in the various exclusive processes is compatible with the same proton-gluon distribution, i.e. it is independent of a specific projectile, J/ψ, ρ or ϕ.
- Using the gained experience in first point in the next step we planned to extend our studies to nuclei.
- Predictions for the exclusive J/ψ and ρ at RHIC and LHC data on heavy ion-ion and heavy ion-proton scattering are investigated
- The above experiments observe the diffractive, exclusive J/ψ and ρ production, which is described by a very similar dipole formation as in the electro-production at HERA.

Summary II

- The main properties of a nucleus, like radius and skin depth, are known from e.g. the low energy electoproduction. However, these properties, measured in low energy experiments, reflect the charge structure of nuclei, whereas the high energy experiments at RHIC and the LHC will reveal the gluonic structures.

Dipole scattering amplitude with GBW parametrization

- GBW parametrization with heavy quarks $f = u, d, s, c$

$$\hat{\sigma}(r,x) = \sigma_0 \left(1 - \exp(-r^2/R_s^2)\right), \qquad R_s^2 = 4 \cdot (x/x_0)^{\lambda} \text{ GeV}^2$$

- The dipole scattering amplitude in such a case reads

$$\hat{N}(\mathbf{r},\mathbf{b},x) = \theta(b_0 - b)\left(1 - \exp(-r^2/R_s^2)\right)$$

where

$$\hat{\sigma}(r,x) = 2\int d^2b\, \hat{N}(\mathbf{r},\mathbf{b},x)$$

- Parameters b_0, x_0 and λ from fits of $\hat{N}$ to F_2 data

$$\lambda = 0.288 \qquad x_0 = 4 \cdot 10^{-5} \qquad 2\pi b_0^2 = \sigma_0 = 29 \text{ mb}$$