

Exclusive vector meson production at high energies and gluon saturation

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- Motivation, introduction to saturation, confronting the saturation models with the recent H1+ZEUS combined data for σ_r .
- Exclusive diffractive & DVCS in the CGC approach
- The origin of dips in the t-distribution
- Conclusion

This talk is mainly based on:

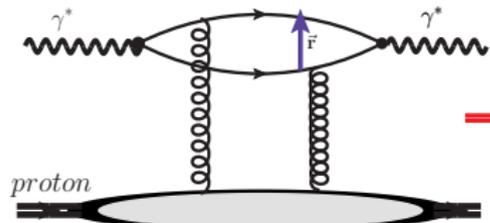
Armesto and Rezaeian, arXiv:1402.4831.

See also:

Rezaeian, Siddikov, Van de Klundert, Venugopalan, **PRD 87**, 034002 (2013) [arXiv:1212.2974]

Rezaeian and Schmidt, **PRD 88**, 074016 (2013) [arXiv:1307.0825].

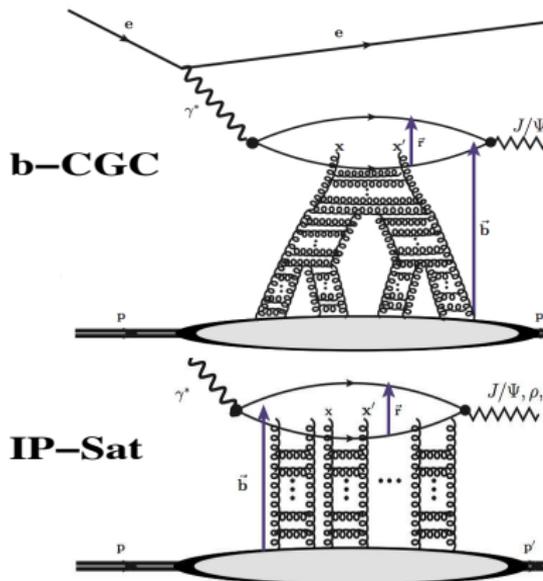
Connection between unitarization and saturation:



Unitarization



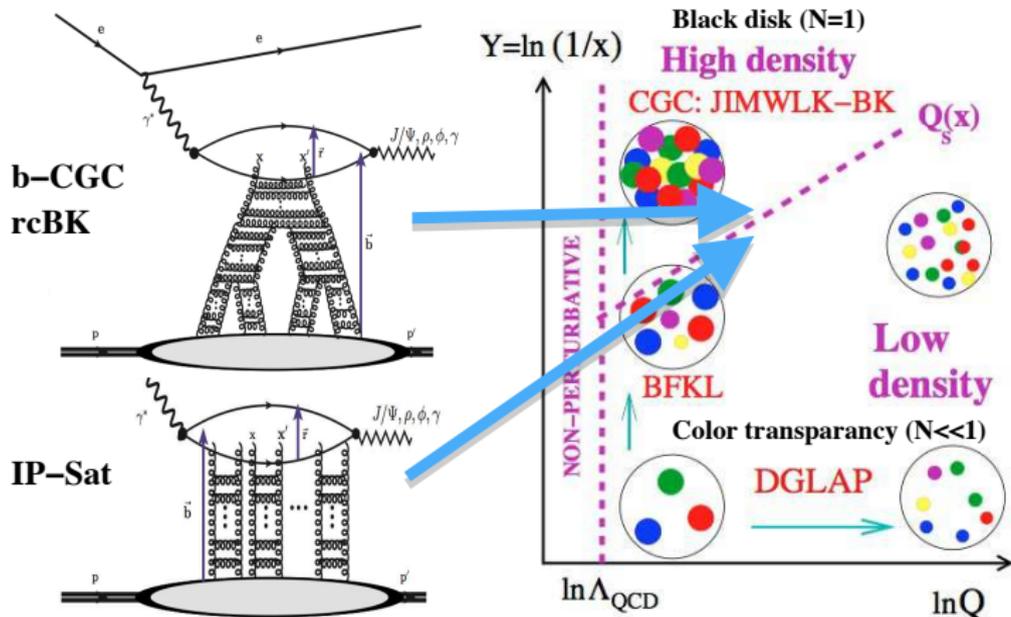
$$N(x, r, b) \approx \alpha_s r^2 \frac{xG(x, 1/r^2)}{\pi R^2} \equiv \alpha_s n(x, Q^2 \sim 1/r^2)$$



Strong scattering $N \sim 1 \iff$ High gluon density $n \sim 1/\alpha_s \implies$ gluon saturation

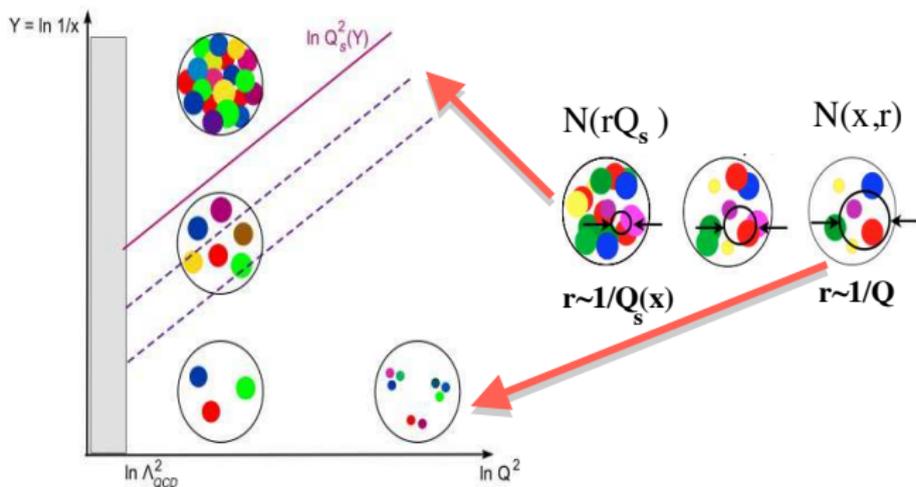
To preserve unitarity \iff Multiple scattering is important: $(\alpha_s n)^n \sim 1$

Road map of strong interaction



- **IP-Sat**: probing the saturation from DGLAP region.
- **b-CGC**: probing the saturation from BFKL region.
- Are there already any direct evidence of saturation phenomenon?

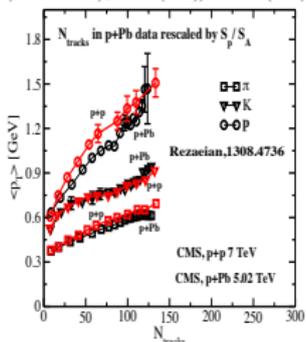
Physics is invariant along any line parallel to the saturation line:
Scattering amplitude is constant on these lines!



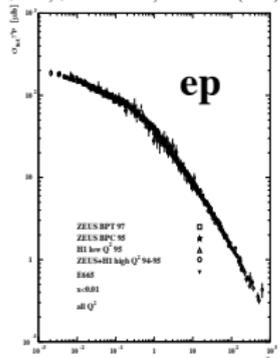
- **The observables scale as functions of the ratio $Q^2/Q_s^2(Y)$:** only depend on the difference $\ln Q^2 - \ln Q_s^2(Y) = \ln(Q^2/Q_s^2(Y))$
- The small-x evolution eq. (BK-JIMWLK eq.) has geometric scaling property.

Evidence of saturation: Geometric scaling in e+p, e+A, p+p, p+A

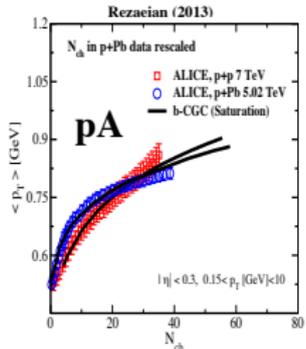
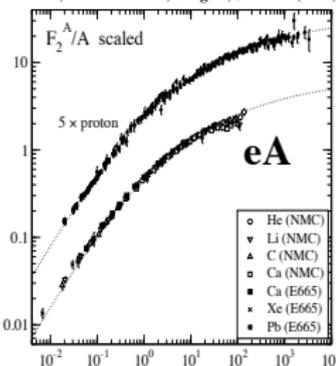
McLerran, Praszalowicz, Schenke (2013), Rezaeian (2013)



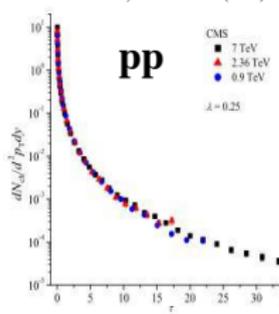
Stasto, Golec-Biernat, Kwiecinski (2000)



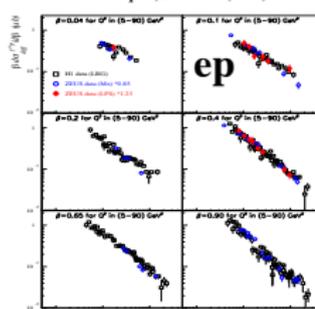
Freund, Rummukainen, Weigert, Schaefer (2002)



McLerran, Praszalowicz (2010)



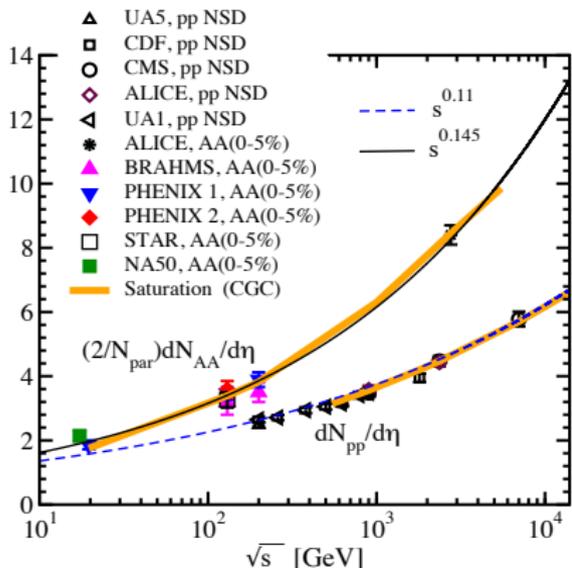
Marquet, Schoeffel (2006)



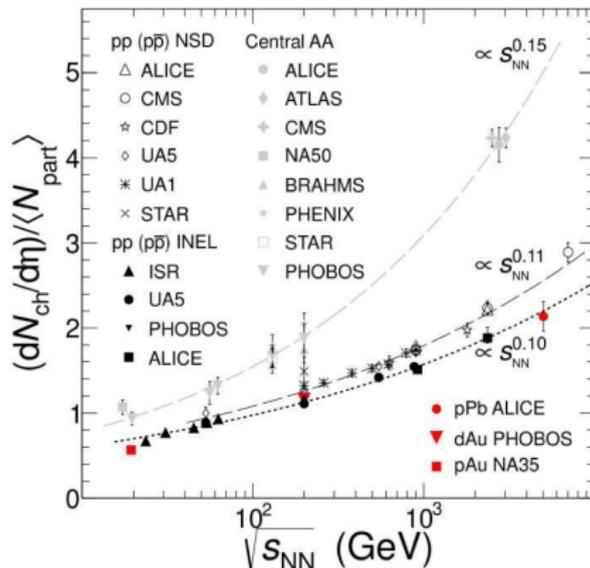
The geometric scaling observed in different reactions can be naturally (and only) explained in the CGC approach \rightarrow universality at small-x.

Universality of particle production at small-x at different energies: p+p, p+A, A+A

Levin, Rezaeian, arXiv:1102.2385

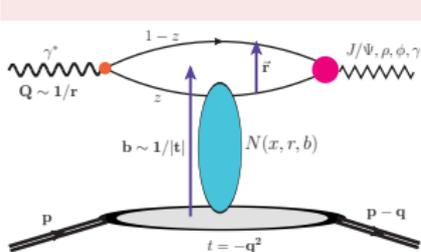


ALICE collaboration, arXiv:1210.3615



$$\frac{dN_h}{d\eta} \propto Q_s^2 \propto s^{\lambda/2} = s^{0.10 \div 0.145}$$

b-dependence of the saturation scale is crucial for a detailed understanding of above scaling properties \implies importance of exclusive diffractive processes.

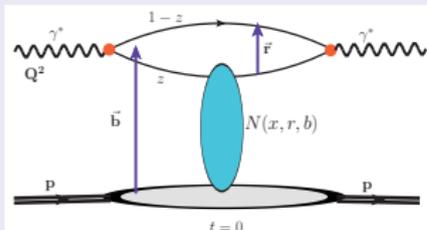
Exclusive diffractive process: $\psi_{q\bar{q}}^\gamma \otimes \phi_{q\bar{q}}^V \otimes \mathcal{N}^{q\bar{q}-p}$


$$\mathcal{A}_{T,L}^{\gamma^* P \rightarrow Vp}(x, Q, \Delta) = 2i \int d^2r \int_0^1 dz (\Psi_E^* \Psi)_{T,L} \int d^2b e^{-i[b-(1-z)r] \cdot \Delta} N(x, r, b)$$

$$\frac{d\sigma_{T,L}^{\gamma^* P \rightarrow Ep}}{dt} = \frac{1}{16\pi} \left| \mathcal{A}_{T,L}^{\gamma^* P \rightarrow Ep} \right|^2$$

$$t = -\Delta^2$$

- With corrections from the real part of the amplitude and skewedness effect $x \neq x'$
- $(b \rightarrow 1/|t|)$: t -distributions access impact-parameter distribution of interactions

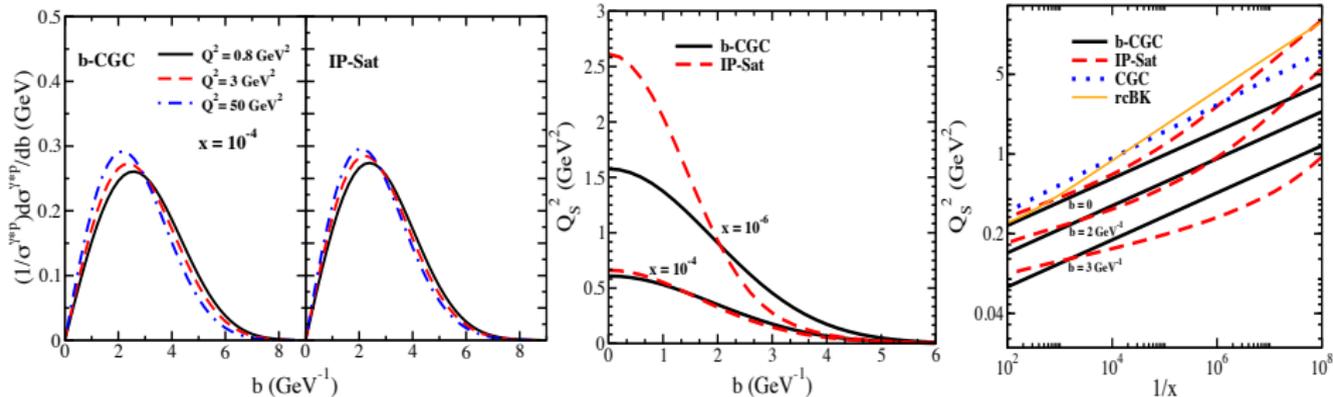
 Inclusive deep-inelastic scattering (DIS): $\psi_{q\bar{q}}^\gamma \otimes \psi_{q\bar{q}}^\gamma \otimes \mathcal{N}^{q\bar{q}-p}$


$$\sigma_{L,T}^{\gamma^* P}(Q^2, x) = \text{Im} \mathcal{A}_{T,L}^{\gamma^* P \rightarrow \gamma^* P}(x, Q, \Delta = 0)$$

$$= 2 \int d^2r \int_0^1 dz |\Psi_{L,T}(r, z; Q^2)|^2 \int d^2b N(x, r, b)$$

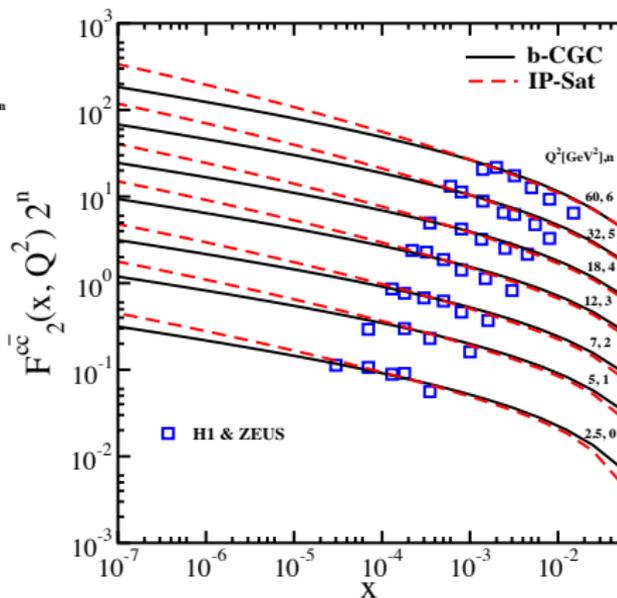
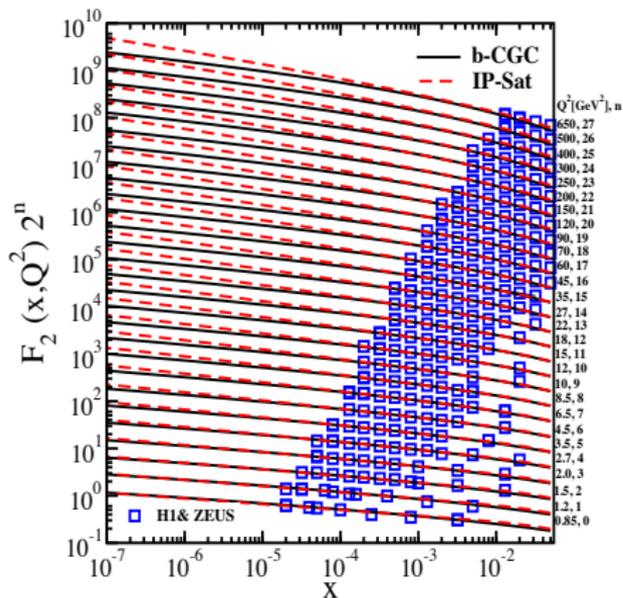
- DIS is less sensitive to the b -dependence compared to exclusive diffractive process.

Combined HERA data: constraining the b - and x - dependence of dipole amplitude



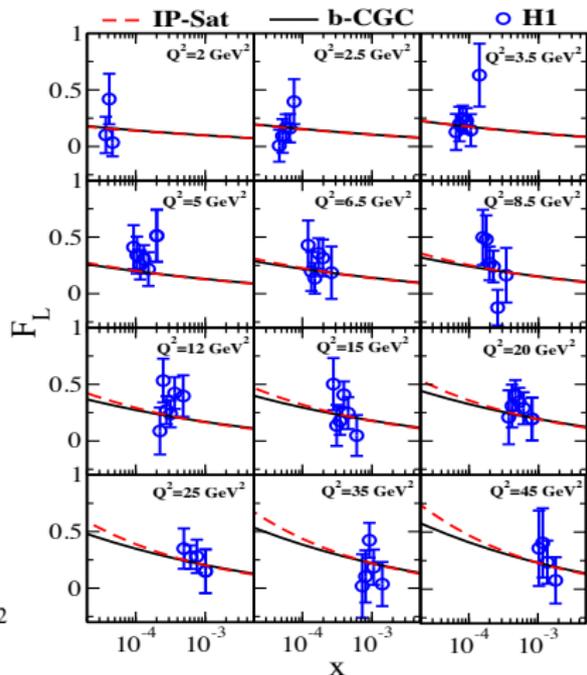
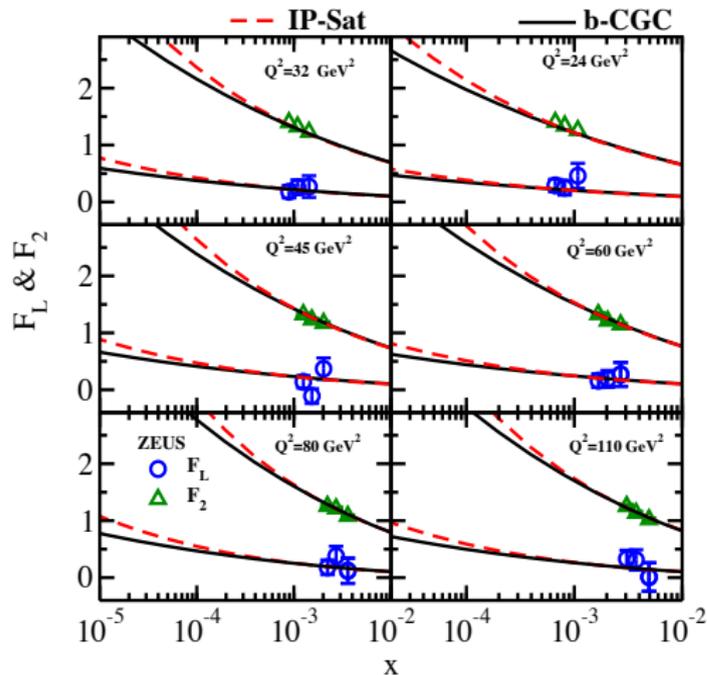
- The typical impact-parameter probed in the total $\gamma^* p$ cross-section is about $b \approx 2 \div 3 \text{ GeV}^{-1} \implies$ less constrain for $b \approx 0$ (large $|t|$ diffractive data are needed).
- Order of magnitude discrepancies in saturation scale extracted from different models \implies **sizable uncertainties in predictions of various observables.**
- Current small- x data do not put enough constraints on saturation models at $x < 10^{-5}$.

CGC (IP-Sat v. b-CGC) description of combined HERA data



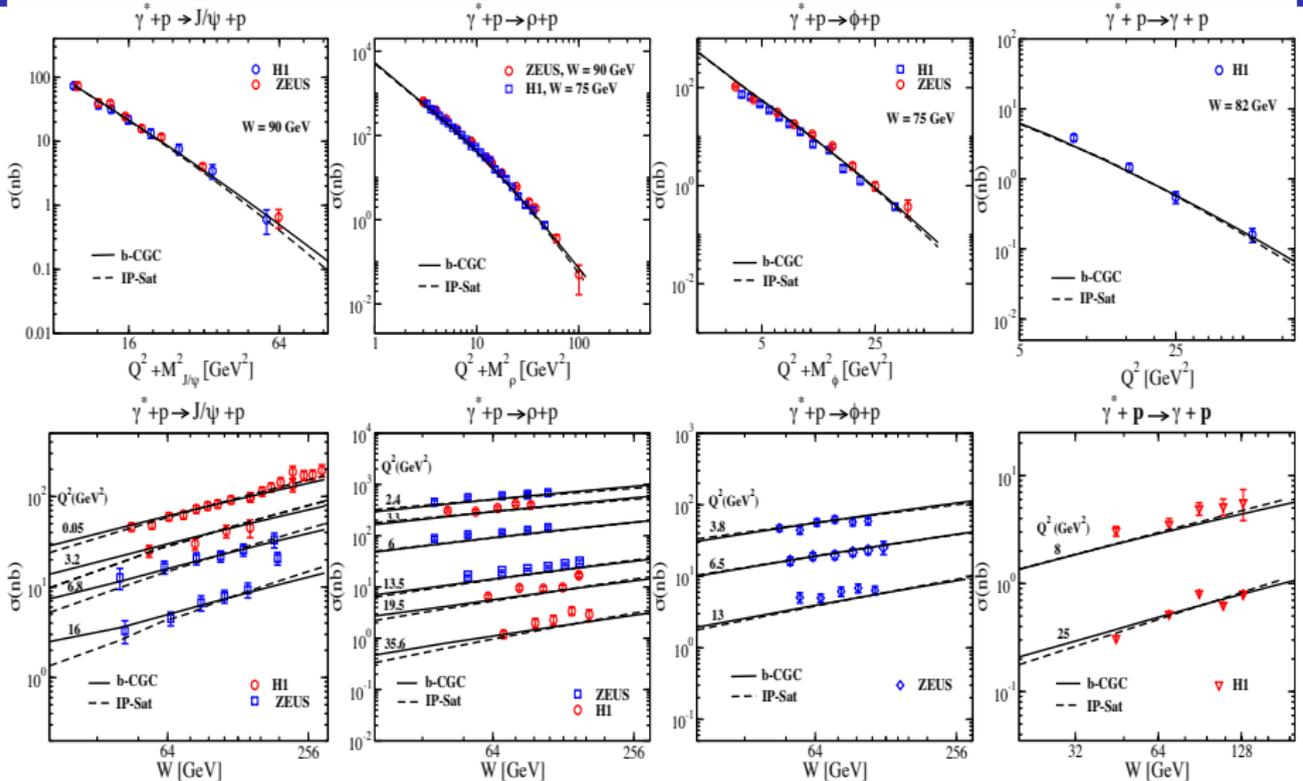
- $F_{c\bar{c}}$, F_2 data were not included in the fit.
- The difference among models can be considered as our current theoretical uncertainties \implies significant uncertainties at small- $x \implies$ Future expts with $x_B < 10^{-5}$ (LHeC, EIC) can constrain saturation models.

IP-Sat v. b-CGC description of HERA data



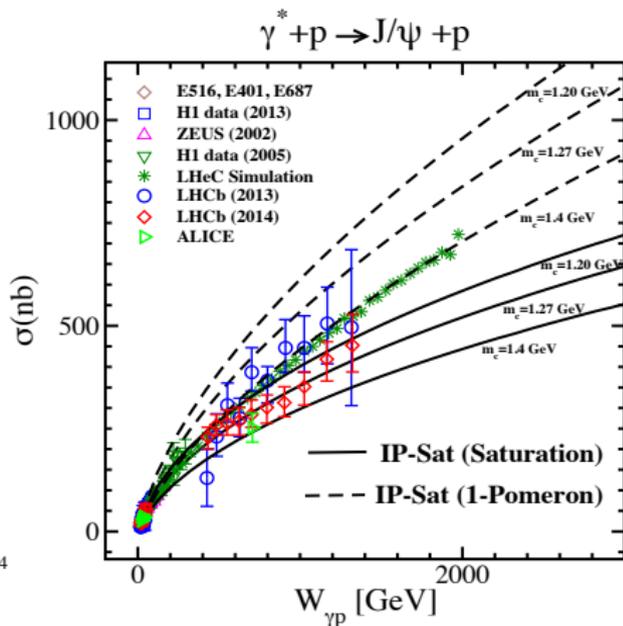
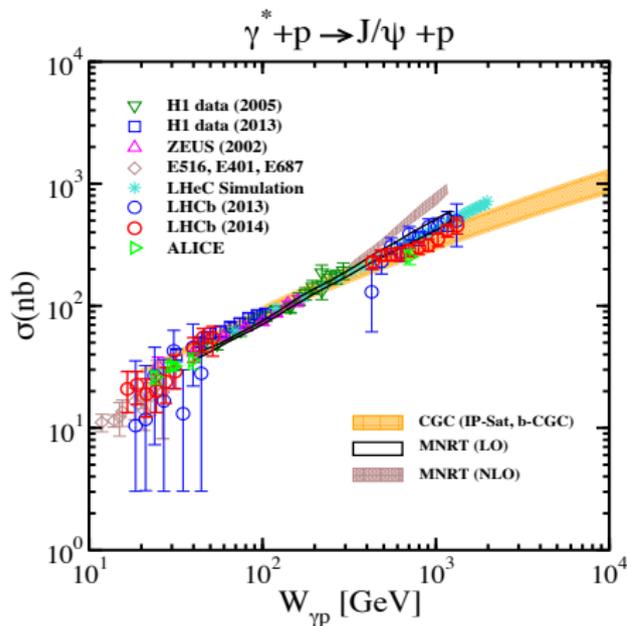
● F_L and F_2 data were not included in the fit.

Q^2 and W -dependence of exclusive processes in the CGC (for $Q^2 \neq 0$)



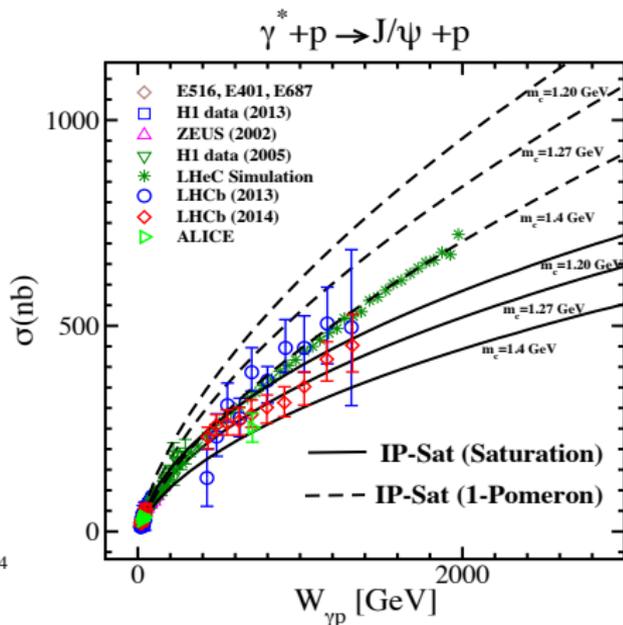
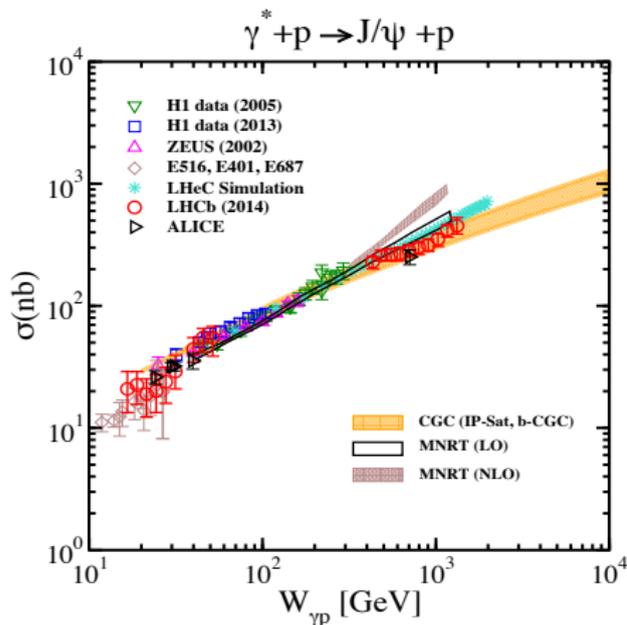
- The W -dependence of the cross-section follows a power-law behavior $\sigma \sim W^\delta \rightarrow$ Indication of geometric scaling in diffractive data.

Total J/ψ cross-section as a function of $W_{\gamma p}$

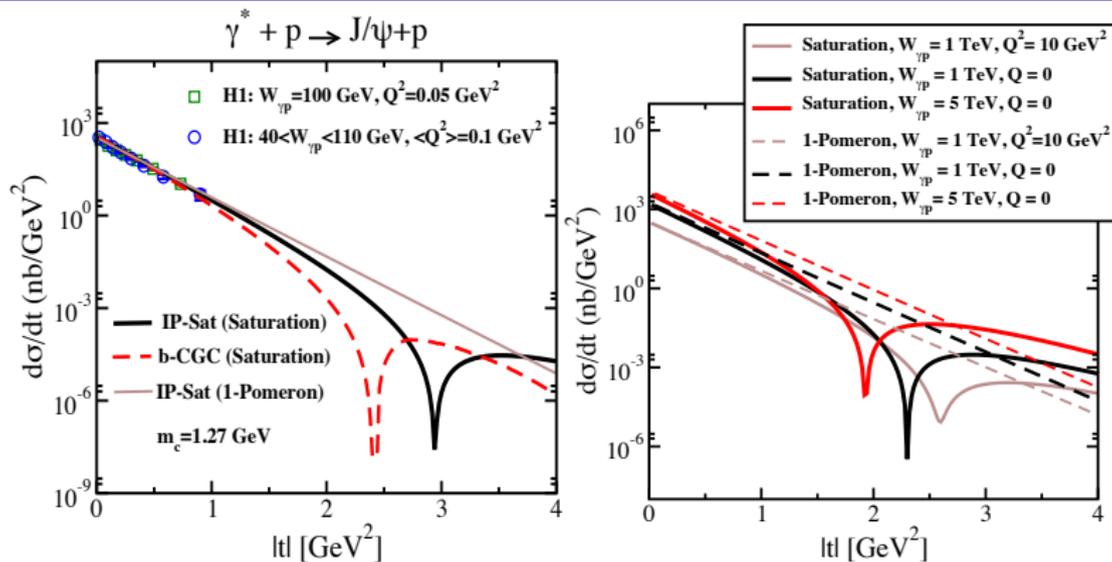


- The LHCb **2014** (compared to 2013) data seem to be more in favour of the CGC/Saturation predictions.
- The uncertainties related to the charm mass is very large for the total J/ψ cross-section.

Total J/ψ cross-section as a function of $W_{\gamma p}$

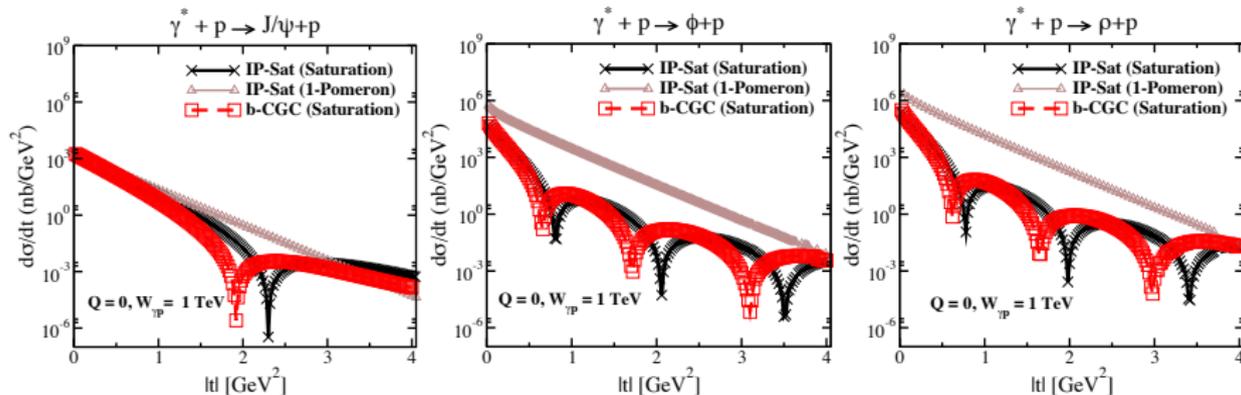


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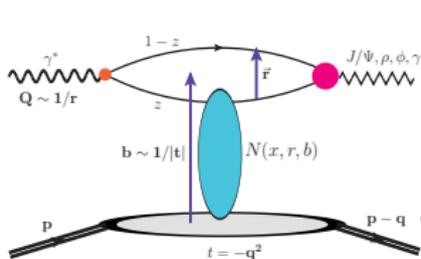


- Pronounced dip in the t -distribution of diffractive photoproduction of vector mesons at large $|t|$ in the **saturation models**.
- There is no dip in the non-saturation model (1-Pomeron). The dip moves toward lower $|t|$ at higher energies, accessible to LHeC kinematics.
- Saturation models are less constrained at very small x and $b \implies$ large uncertainties in t -distribution at large $|t|$.

J/ψ differential vector meson cross-sections as a function of $|t|$ at LHC/LHeC



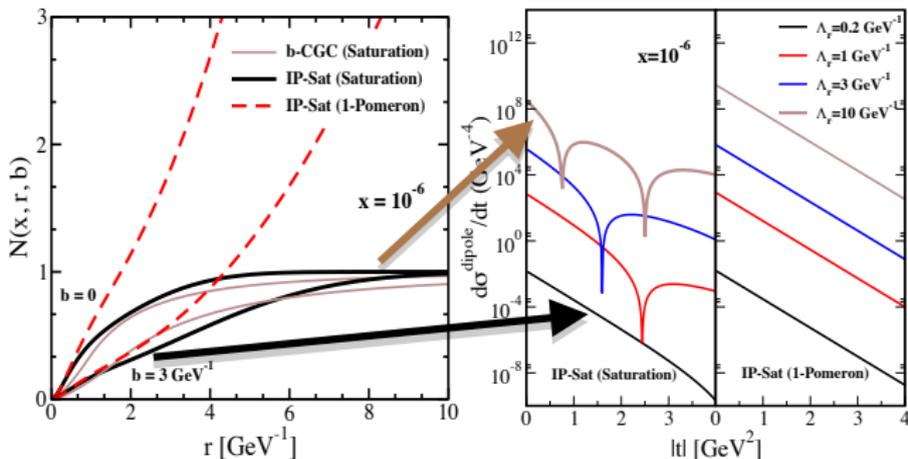
- The dip in the t -distribution recedes towards lower $|t|$ with going deeper to the saturation region:
 - increasing energy or decreasing Bjorken- x
 - decreasing virtuality Q .
 - decreasing mass of the vector meson
- The discrepancy between saturation and non-saturation models in diffractive processes is more obvious for lighter vector meson.



$$\frac{d\sigma_{T,L}^{\gamma^* p \rightarrow Ep}}{dt} = \left| \int d^2\mathbf{r} \int_0^1 dz (\Psi_E^* \Psi)_{T,L} \int d^2\mathbf{b} e^{-i[\mathbf{b} - (1-z)\mathbf{r}] \cdot \Delta} N(x, r, b) \right|^2$$

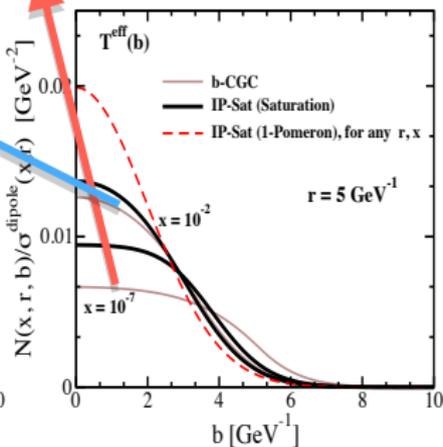
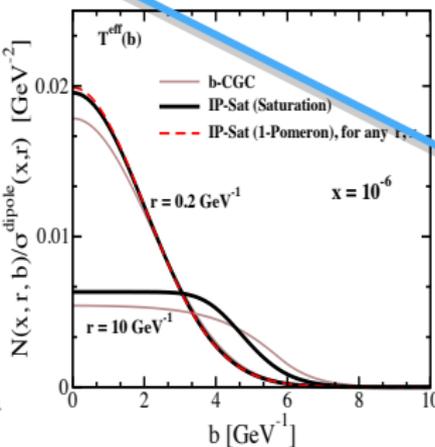
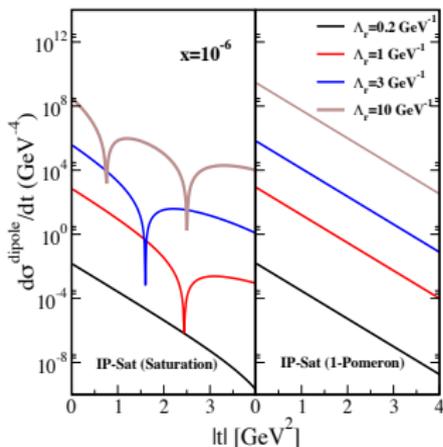
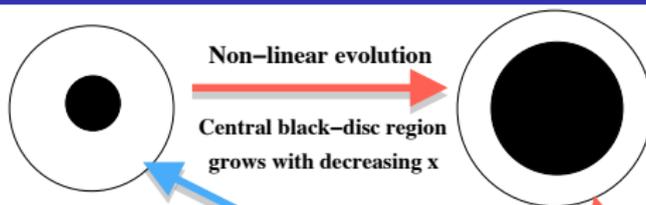
$$\frac{d\sigma^{\text{dipole}}}{dt} = 2\pi \left| \int_0^{\Lambda_r} r dr \int d^2\mathbf{b} e^{-i\mathbf{b} \cdot \Delta} N(x, r, b) \right|^2 \quad t = -\Delta^2$$

- Smaller Q^2 or/and smaller $x \iff$ Larger $\Lambda_r \iff$ More important saturation effects.
- t-dependences measure the Fourier transform of b -distribution of gluons.



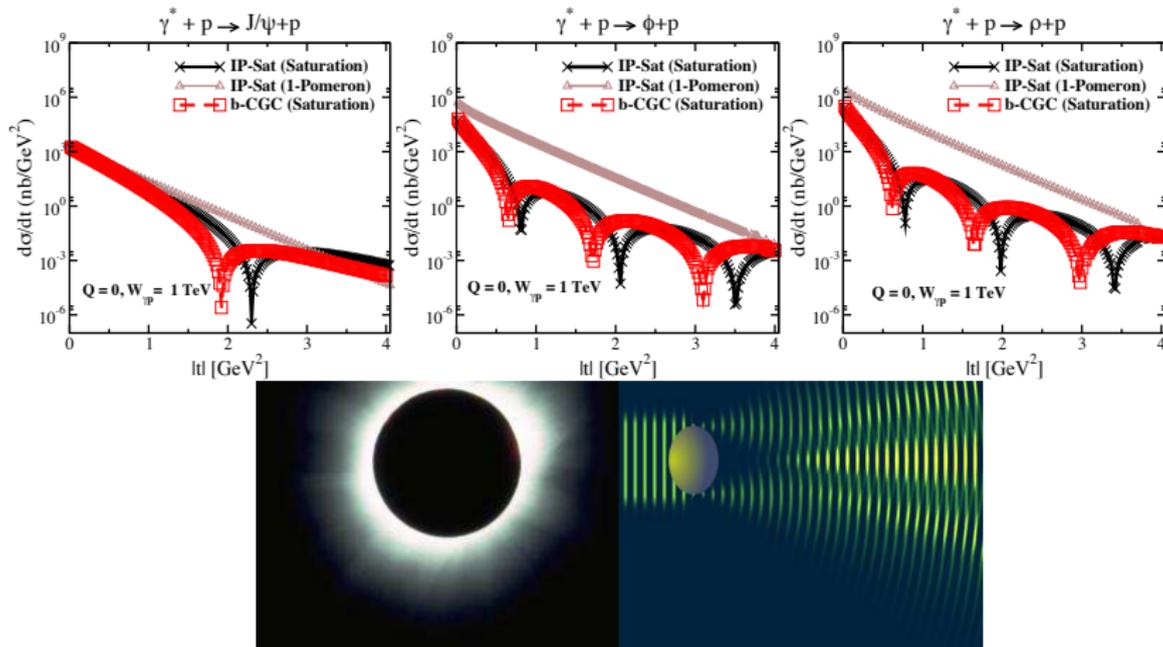
- In 1-Pomeron model: the b -dependence of the amplitude is a Gaussian for all values of $\Lambda_r \implies$ its Fourier transform is exponential \implies There is no dip.
- In Sat. models: a large Λ_r corresponds to the black-disk $N \rightarrow 1$ limit \implies The Fourier transform of the dipole amplitude leads to a dip or multi-dips.

The origin of diffractive dips: Non-linear evolution of black-disc region



- Non-linear evolution \implies evolves any realistic profile in b , like a Gaussian or Woods-Saxon distribution, and makes it closer to a step-like function in the b -space at black-disc limit.

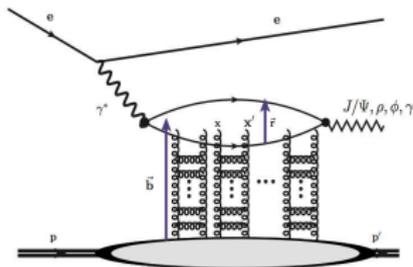
Where to look for the dips?



- The dips become more pronounced at smaller x region in the saturation regime: for a lighter vector meson at higher energies and lower virtualities.

Conclusion:

- Saturation models give generally good description of all HERA data at $x \leq 0.01$ including combined HERA data and exclusive diffractive data.
- The recent LHCb data (2014) in p+p collisions for exclusive diffractive photoproduction of J/ψ is in favour of CGC/saturation predictions.
- Saturation and non-saturation models are very different at very small x and large $|t|$ ($x < 10^{-5}$ and $|t| > 1$) \implies :
 - ▶ Emergence of dips in the t -distribution of diffractive photoproduction of vector mesons in γ^*p collisions at large $|t|$ in the saturation models.



- Kowalski, Teaney [hep-ph/0304189]
- Kowalski, Motyka, Watt [hep-ph/0606272]
- Rezaeian, Siddikov, Van de Klundert, Venugopalan [arXiv:1212.2974]

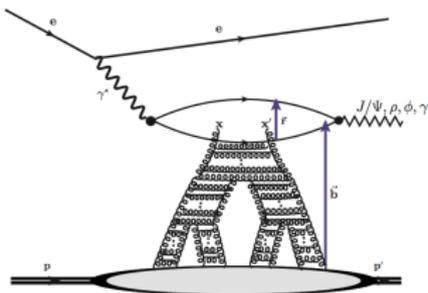
- Eikonalized DGLAP-evolved gluon density with Gaussian b dependence (Glauber-Mueller amplitude):

$$N(x, r, b) = 1 - \exp\left(-\frac{\pi^2 r^2}{2N_c} \alpha_s(\mu^2) xg(x, \mu^2) T_G(b)\right)$$

$$T_G(b) = \frac{1}{2\pi B_G} \exp(-b^2/2B_G)$$

- initial gluon distribution with a scale running with dipole size:

$$xg(x, \mu_0^2) = A_g x^{-\lambda_g} (1-x)^{5.6} \quad \mu^2 = C/r^2 + \mu_0^2$$



- [Watt, Kowalski](#) [arXiv:0712.2670]
- [Rezaeian, Schmidt](#) [arXiv:1307.0825]

- Approximate solution of the Balitsky-Kovchegov equation (Iancu, Itakura, Munier, hep-ph/0310338).

$$N(x, r, b) = \begin{cases} N_0 \left(\frac{rQ_s}{2}\right)^{2\gamma_{\text{eff}}} & rQ_s \leq 2, \\ 1 - \exp(-\mathcal{A} \ln^2(\mathcal{B}rQ_s)) & rQ_s > 2 \end{cases}$$

Effective anomalous dimension and the saturation scale are defined as

$$\gamma_{\text{eff}} = \gamma_s + \frac{1}{\kappa\lambda Y} \ln\left(\frac{2}{rQ_s}\right),$$

$$Q_s \rightarrow Q_s(x, b) = \left(\frac{x_0}{x}\right)^{\frac{\lambda}{2}} \exp\left\{-\frac{b^2}{4\gamma_s B_{\text{CGC}}}\right\} \text{ GeV}$$