SEARCHING FOR SATURATION SIGNALS IN UPC

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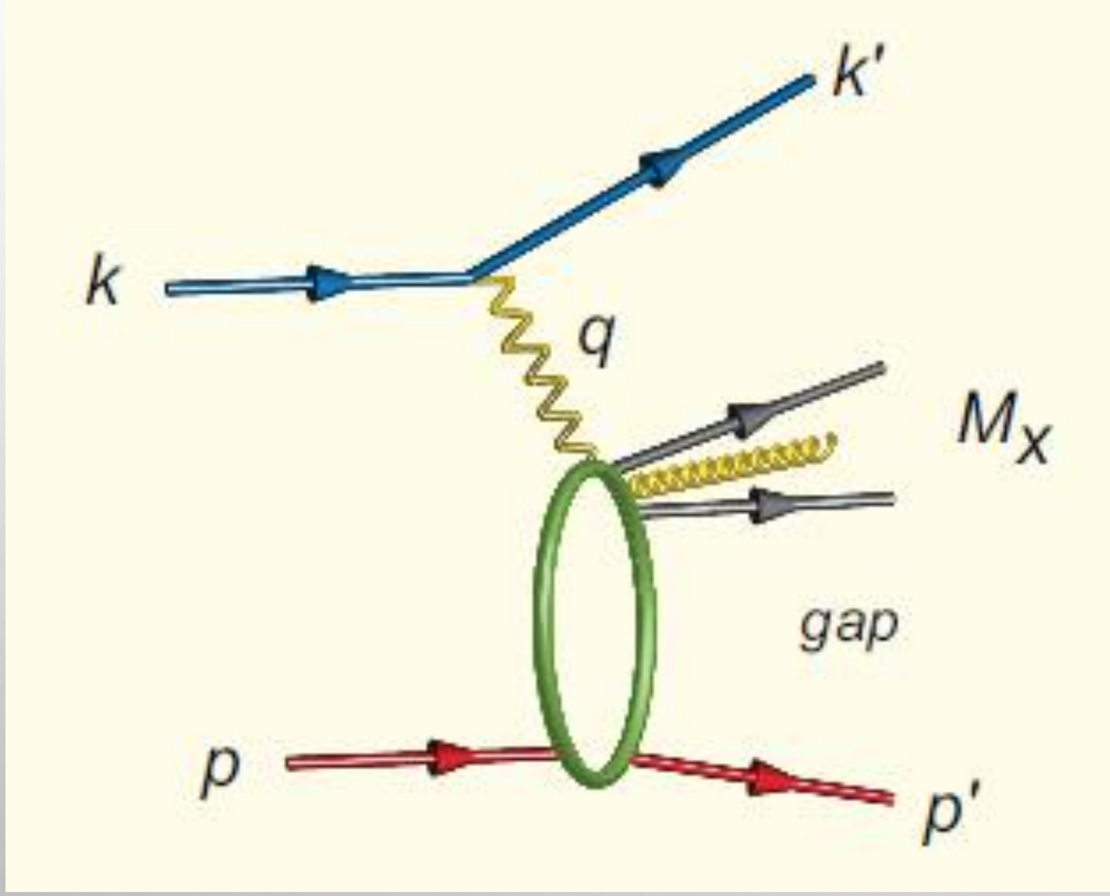
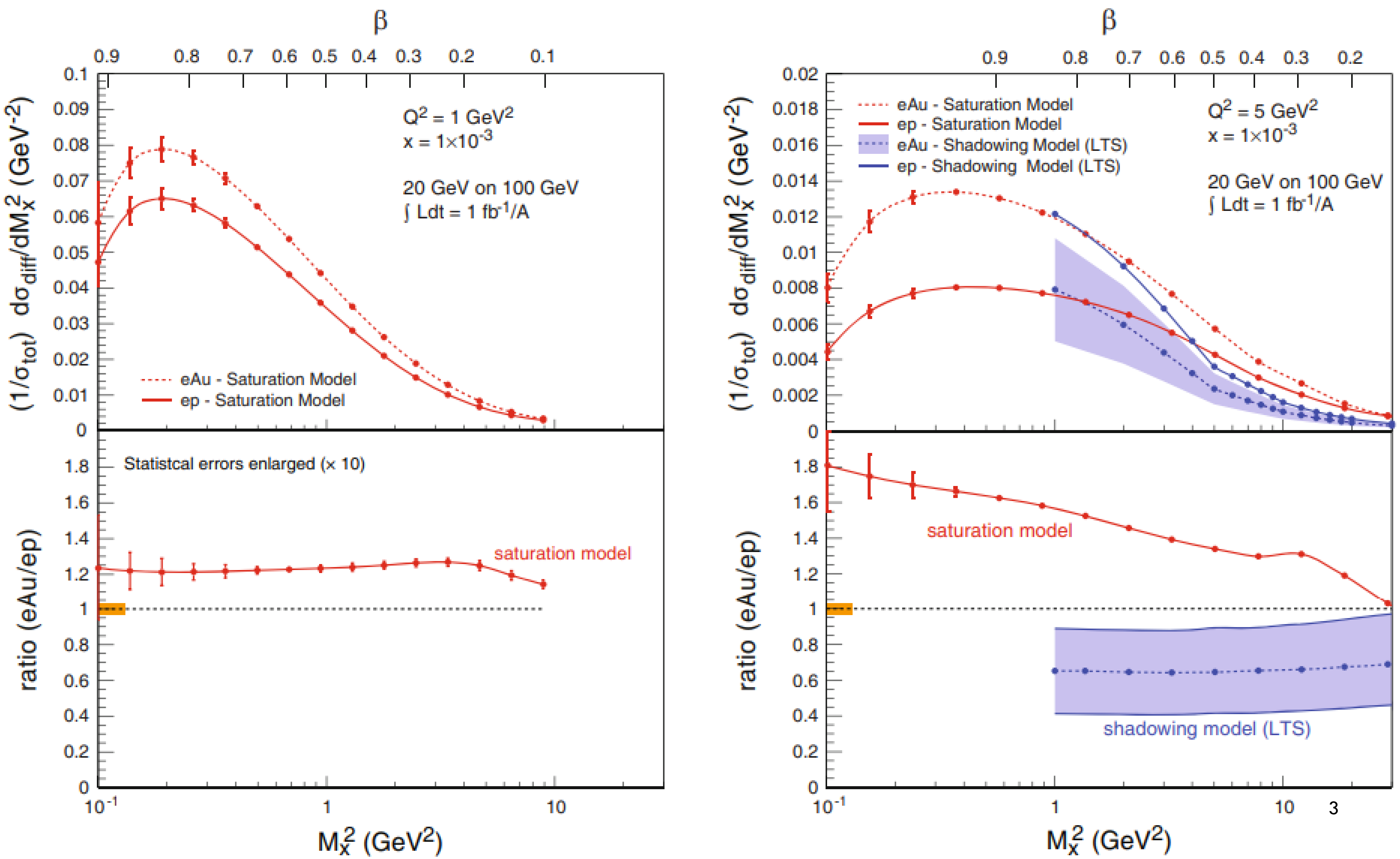
Diffractive scattering as a probe for saturation



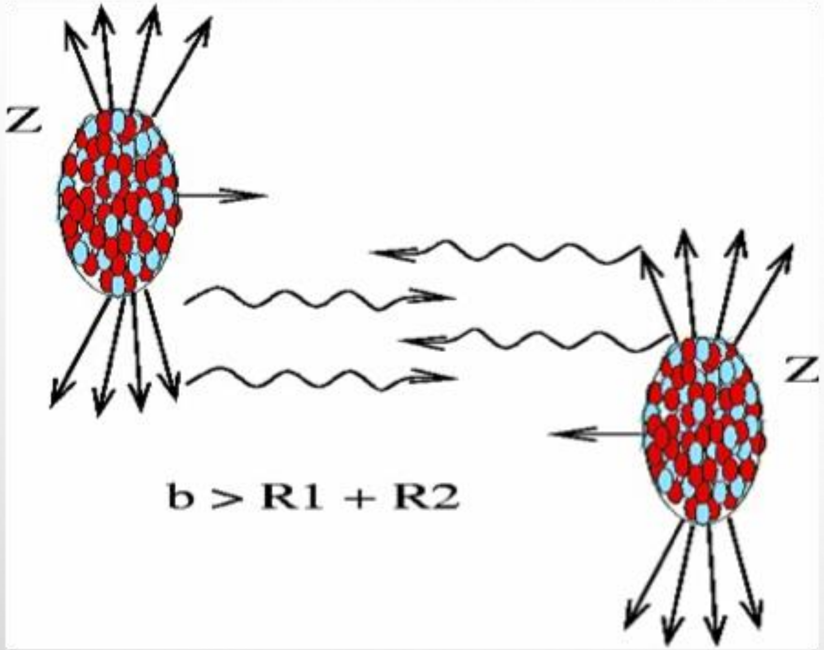
- Characterize by a rapidity gap between the produced hadron and the target
- Color neutral exchange in the t-channel (pomeron) between the virtual photon and the target proton
- Diffractive cross sections are more sensitive to saturation phenomena

Some measurements in diffractive scattering

$$\frac{d\sigma_{diff}/dM_X^2}{\sigma_{tot}}$$



Ultra peripheral collision (Ap or AA)



Fast moving highly-charged ions carry strong electromagnetic fields that act as a beam of photons.

$Q^2 \approx 20\ \mathrm{MeV}^2$ small virtuality

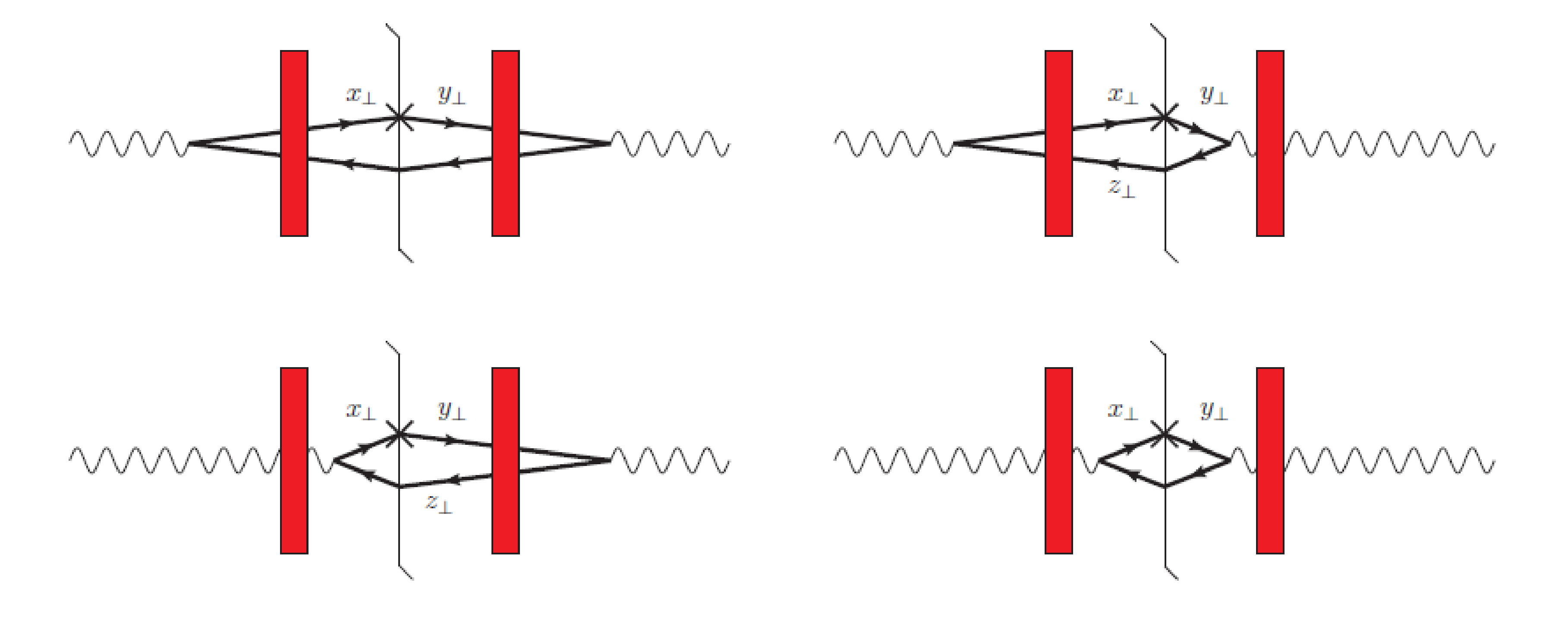
We define R_1, the ratio of elastic vector meson production cross section to the inelastic cross section

$$R_1 = \frac{\sigma^{\gamma^* A \to VA}}{\frac{d\sigma_{inel}}{d^2 p_T}}$$

and R_2, the double ratio between pA scattering and AA scattering,

$$R_2 = \frac{R_1(\gamma^* A)}{R_1(\gamma^* p)}$$

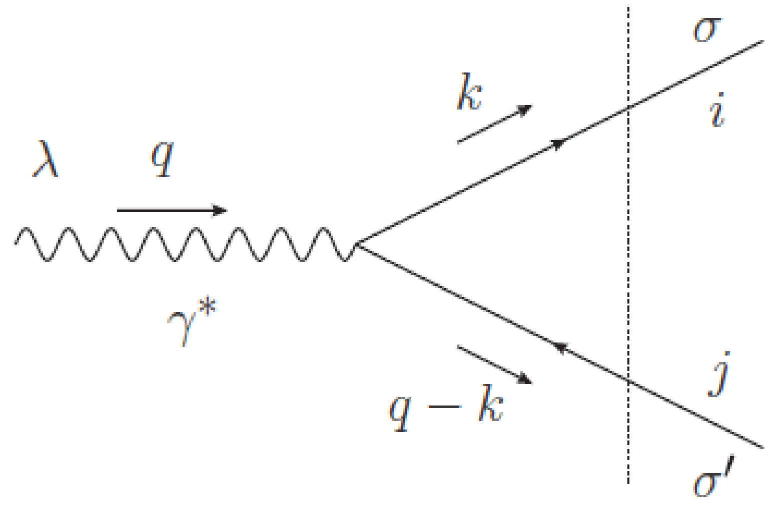
Inelastic cross section



$$\frac{d\sigma}{d^2 p_T} = \frac{1}{2(2\pi)^3} \int_0^1 \frac{dz}{z(1-z)} \int d^2\mathbf{x}\, d^2\mathbf{y}\, d^2\mathbf{z}\, e^{-i\mathbf{p}\cdot(\mathbf{x}-\mathbf{y})} \Psi_{\gamma\to q\bar{q}}(z, \mathbf{x}-\mathbf{z}) \Psi^*_{\gamma\to q\bar{q}}(z, \mathbf{y}-\mathbf{z})$$
$$\times \left[N(\mathbf{x},\mathbf{z}) + N(\mathbf{y},\mathbf{z}) - N(\mathbf{x},\mathbf{y})\right]$$

Kovchegov and Sievert (2015)

Virtual photon wave function



- Transversely polarized

$$\Psi_T^{\gamma\to q\bar{q}}(\mathbf{x},z) = \frac{eZ_f}{2\pi}\sqrt{z(1-z)}\delta_{ij}\left[(1-\delta_{\sigma\sigma'})(1-2z-\sigma\lambda)ia_f\frac{\epsilon^\lambda\cdot\mathbf{x}}{x_\perp}K_1(x_\perp a_f)+\delta_{\sigma\sigma'}\frac{m_f}{\sqrt{2}}(1+\sigma\lambda)K_0(x_\perp a_f)\right]$$

- Longitudinally polarized

$$\Psi_L^{\gamma^*\to q\bar{q}}(\mathbf{x},z) = \frac{eZ_f}{2\pi}[z(1-z)]^{\frac{3}{2}}\delta_{ij}2Q(1-\delta_{\sigma\sigma'})K_0(x_\perp a_f), \qquad a_f^2 = Q^2z(1-z)+m_f^2$$

$$\frac{d\sigma}{d^2p_T} = \frac{N_c}{(2\pi)^3}\alpha_{EM} Z_f^2 \int_0^1 \int d^2\mathbf{r}\, d^2\mathbf{b}\, e^{-i\mathbf{p}\cdot\mathbf{r}} \left\{ [z^2 + (1-z)^2] \left[4ia_f K_1(r_\perp a_f) \frac{\mathbf{p}\cdot\mathbf{r}}{(p_\perp^2 + a_f^2) r_\perp} - \frac{3}{2} K_0(r_\perp a_f) + \left(\frac{3}{4} r_\perp a_f + \frac{1}{r_\perp a_f}\right) K_1(r_\perp a_f) - \frac{3}{2} K_2(r_\perp a_f) + \frac{1}{4} r_\perp a_f K_3(r_\perp a_f) \right] + \frac{4m_f^2}{p_\perp^2 + a_f^2} K_0(r_\perp a_f) - \frac{m_f^2 r_\perp}{a_f} K_1(r_\perp a_f) \right\} N(\mathbf{r},\mathbf{b})$$

The dipole amplitude $N(\boldsymbol{r},\boldsymbol{b})$ is given by

$$N(\mathbf{r},\mathbf{b}) = 1 - \exp\left\{ -\frac{r_\perp^2 Q_s^2(\mathbf{b})}{4} \ln \frac{1}{r_\perp \lambda} \right\}$$

, leading order calculation, no small-x evolution included

(i) $p_T > Q_s$, i.e. transverse momentum of the produced quark is outside the saturation regime.

$$N(\mathbf{r},\mathbf{b}) \approx \frac{r_\perp^2 Q_s^2(\mathbf{b})}{4} \ln \frac{1}{r_\perp \lambda} = \frac{\pi \alpha_2^2 C_F}{N_c} r_\perp^2 T_A(\mathbf{b}) \ln \frac{1}{r_\perp \lambda}$$

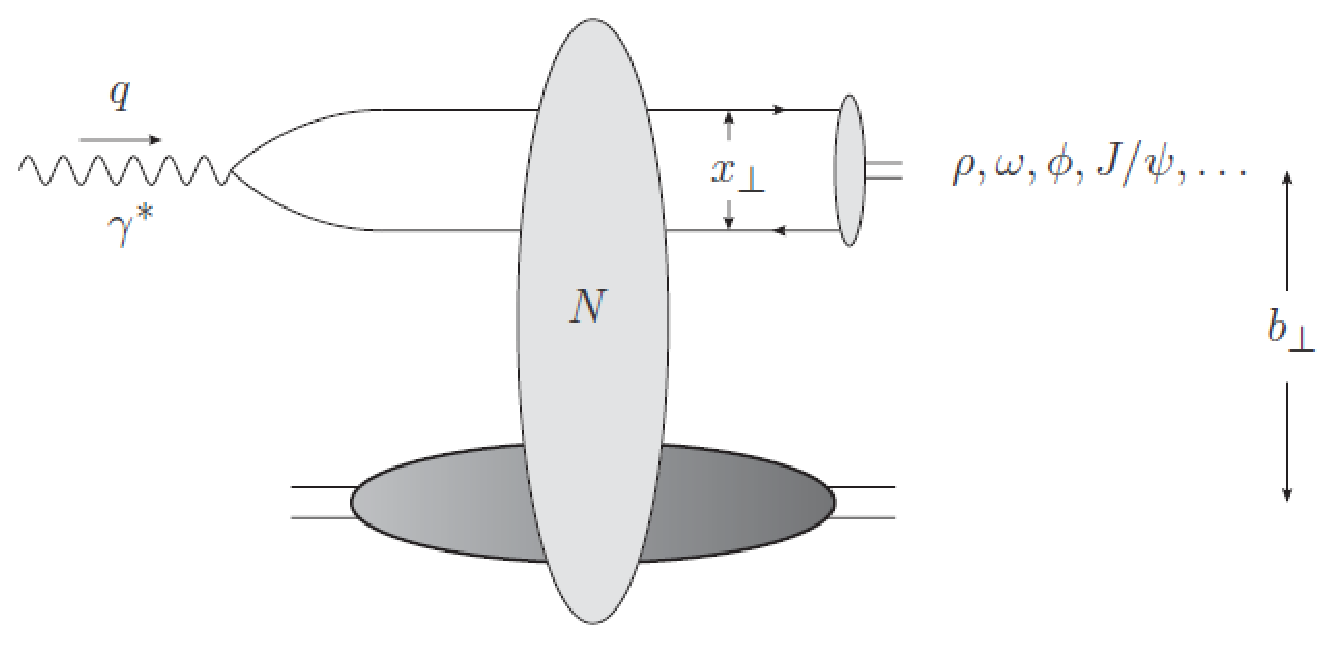
$$\Rightarrow \frac{d\sigma}{d^2p_T} \approx \frac{\alpha_{EM}\alpha_s^2}{8\pi^2} Z_f^2 C_F A \int_0^1 \{[z^2+(1-z)^2][-\frac{4\pi(5-6\gamma_E)}{p_\perp^4} + \frac{12\pi}{p_\perp^4} \ln \frac{p_\perp^2}{4\lambda a_f}] + \frac{8\pi}{p_\perp^4} \frac{m_f^2}{a_f^2}\} \sim \frac{A}{p_\perp^4} \ln \frac{p_\perp}{\lambda a_f}$$

(ii) $p_T < Q_s$, i.e. transverse momentum of the produced quark is inside the saturation regime.

$$N(\mathbf{r},\mathbf{b}) \approx 1$$

$$\Rightarrow \frac{d\sigma}{d^2p_T} \approx \frac{5N_c \alpha_{EM} Z_f^2 S_\perp}{12\pi^2} \frac{1}{p_\perp^2} \sim \frac{A^{\frac{2}{3}}}{p_\perp^2}$$

Elastic vector meson production



$$\sigma^{\gamma^* A \to V A} = \int d^2\mathbf{b} \left| \int \frac{d^2\mathbf{r}}{4\pi} \int_0^1 \frac{dz}{z(1-z)} \Psi^{\gamma^* \to q\bar{q}}(\mathbf{r}, z) N(\mathbf{r}, \mathbf{b}) \Psi^V(\mathbf{r}, z)^* \right|^2$$

Vector meson wave function (Kowalski, Motyka, Watt 2006)

The simplest approach is to assume that the vector meson is predominantly a quark-antiquark state that has the same spin and polarization structure as the virtual photon.

1. Start with a wave function that is Gaussian distributed in transverse momentum in the rest frame of the vector meson.
2. Assume that the wave function is Lorentz invariant, so we can boost the vector meson to a frame with large longitudinal momentum.
3. Fourier transform into transverse coordinate space.

$$\Psi^V_\lambda(\mathbf{r}, z) = N_T \sqrt{z(1-z)}\delta_{ij}\left[i(1-\delta_{\sigma\sigma'})(1-2z-\sigma\lambda)\frac{4z(1-z)}{R^2}\epsilon\cdot\mathbf{r} + \delta_{\sigma\sigma'}\frac{m_f}{\sqrt{2}}(1+\sigma\lambda)\right]\exp\left[-\frac{2z(1-z)r_\perp^2}{R^2} - \frac{m_f^2 R^2}{8z(1-z)}\right]$$

Transversely polarized photons can only produce transversely polarized vector mesons, assuming they have the same spin and polarization structures.

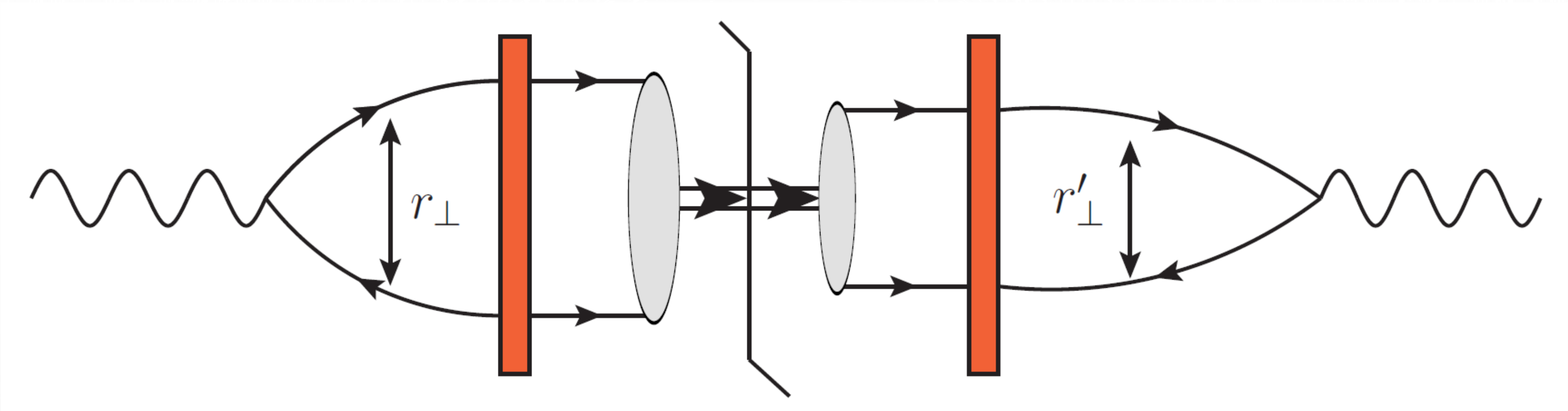
Cross section for exclusive vector production

$$\sigma^{\gamma^* A\to VA} = \frac{\alpha_{EM} Z_f^2}{2\pi^2} N_c^2 N_T^2 \int_0^1 dz dz' \int dr_\perp dr'_\perp \{\frac{2a_f}{R^2} z(1-z)((1+2z)^2+1) r_\perp K_1(r_\perp a_f) + m_f^2 K_0(r_\perp a_f)\}$$

$$\times\exp[-\frac{2z(1-z)r_\perp^2}{R^2} - \frac{m_f^2 R^2}{8z(1-z)}]\{\frac{2a_f^{'}}{R^2} z'(1-z')((1+2z')^2+1) r'_\perp K_1(r'_\perp a'_f) + m_f^2 K_0(r'_\perp a'_f)\}$$

$$\times \exp[-\frac{2z'(1-z')r'^2_\perp}{R^2} - \frac{m_f^2 R^2}{8z'(1-z')}] \int d^2\mathbf{b} N(\mathbf{r},\mathbf{b}) N(\mathbf{r}',\mathbf{b})$$

The integral is hard to evaluate analytically. However, the *A*-dependence lies completely in the expression following the $b_\perp$-integral, since it is the transverse area of the target and the nuclear profile function from which the *A*-dependence come.



Divide the $r_\perp, r'_\perp$-integral into 4 regions

i. $r_\perp, r'_\perp < \frac{1}{Q_s}$, both dipole sizes outside saturation regime.

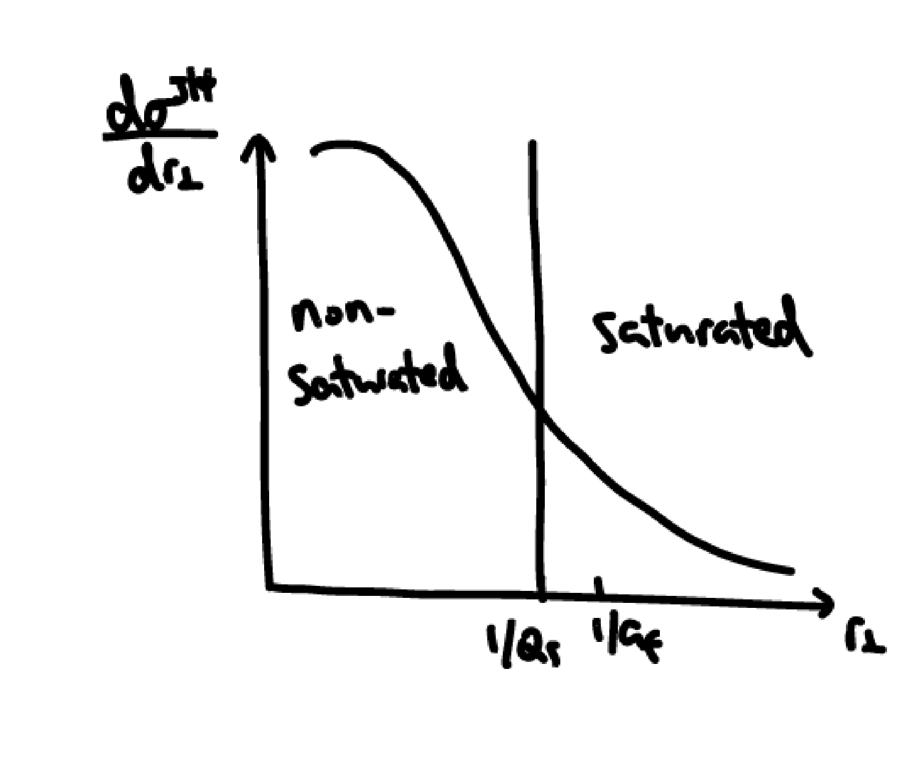
ii. $r_\perp, r'_\perp > \frac{1}{Q_s}$, both dipole sizes inside saturation regime.

iii. $r_\perp < \frac{1}{Q_s}, r'_\perp > \frac{1}{Q_s}$ or vice versa, one dipole outside and one inside.

In each region, we can use the approximation for $N(\boldsymbol{r}, \boldsymbol{b})$ accordingly.

Exclusive J/ψ production

- The contribution from the $r_\perp, r'_\perp$-integral mainly comes from $r_\perp \leq \frac{1}{m_c} \approx 0.79\ \mathrm{GeV}^{-1}$.
- The inverse of saturation scale at $x = 10^{-3}$ for a gold nucleus at medium impact parameter is about $\frac{1}{Q_s} \approx 1.12\ \mathrm{GeV}^{-1}$, and at $x = 10^{-4}$ is about $\frac{1}{Q_s} \approx 0.79\ \mathrm{GeV}^{-1}$.
- Therefore, we can say that the contribution to $\sigma^{J/\psi}$ mainly comes from non-saturated regime. $\sigma_{el}^{J/\psi} \propto A^{\frac{4}{3}}$.



Double ratio for Au+p and Au+Au for J/ψ production

Inelastic quark production

$$\frac{d\sigma}{d^2p_T} \sim A \text{ for } p_T > Q_s; \qquad \frac{d\sigma}{d^2p_T} \sim A^{2/3} \text{ for } p_T < Q_s$$

Elastic J/ψ production

$$\sigma_{el}^{J/\psi} \propto A^{4/3}$$

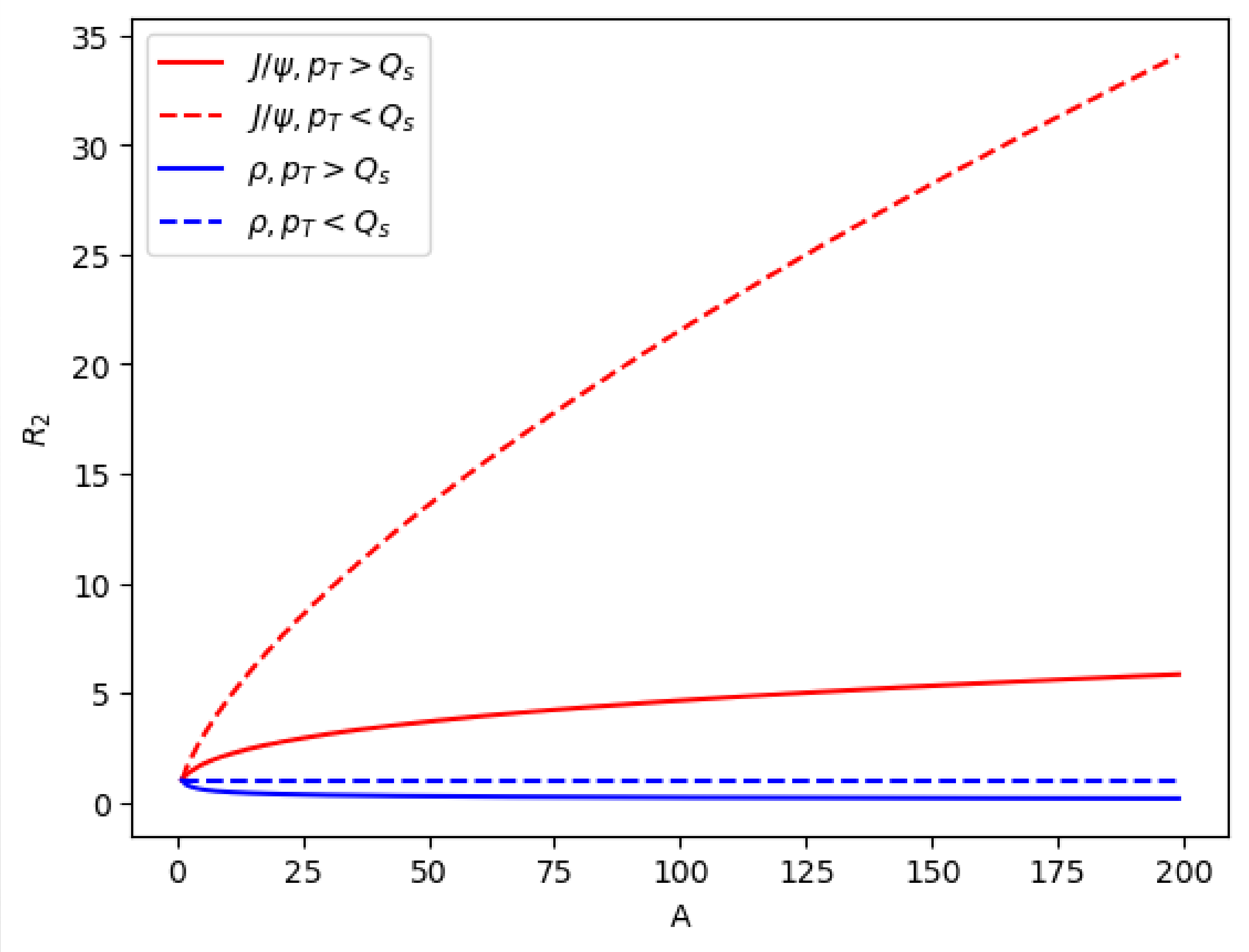
- $R_1(J/\psi) = \frac{\sigma^{\gamma^* A \to J/\psi\, A}}{\frac{d\sigma_{inel}}{d^2p_T}} = \begin{cases} f_1(p_T)A^{\frac{1}{3}} & , \quad p_T > Q_s \\ f_2(p_T)A^{\frac{2}{3}} & , \quad p_T < Q_s \end{cases}$

- $R_2(J/\psi) = \frac{R_1(\gamma^* A)}{R_1(\gamma^* p)} = \begin{cases} A^{\frac{1}{3}} \approx 6 & , \quad p_T > Q_s \\ A^{\frac{2}{3}} \approx 34 & , \quad p_T < Q_s \end{cases}$

Double ratio for Au+p and Au+Au for ρ meson production

- $R_1(\rho) = \frac{\sigma^{\gamma^* A \to J/\psi\, A}}{\frac{d\sigma_{inel}}{d^2 p_T}} = \begin{cases} f_1(p_T) A^{-\frac{1}{3}} & , \quad p_T > Q_s \\ f_2(p_T) A^0 & , \quad p_T < Q_s \end{cases}$

- $R_2(\rho) = \frac{R_1(\gamma^* A)}{R_1(\gamma^* p)} = \begin{cases} A^{-\frac{1}{3}} \approx 0.17 & , \quad p_T > Q_s \\ A^0 \approx 0 & , \quad p_T < Q_s \end{cases}$


$J/\psi, p_T > Q_s$
$J/\psi, p_T < Q_s$
$\rho, p_T > Q_s$
$\rho, p_T < Q_s$
R_2
A
0
5
10
15
20
25
30
35
0
25
50
75
100
125
150
175
200

Summary

- Saturation effects are more sensitive to elastic diffractions than inelastic processes, and saturation scale Q_S depends on the atomic number A.
- We look at the differential cross sections for inelastic processes and the cross section for exclusive J/ψ production.
- Based on the saturation model the ratio of the two cross sections has an $A^{\frac{1}{3}}$ dependence for $p_T > Q_S$ and $A^{\frac{2}{3}}$ dependence for $p_T < Q_S$.

Saturation scale Qs vs. x