Exclusive Vector Meson Production in eA Collisions

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based on:

V.P. Gonçalves, M.S. Kugeratski, M.V.T. Machado and F.S. Navarra,

arXiv:0905.1143

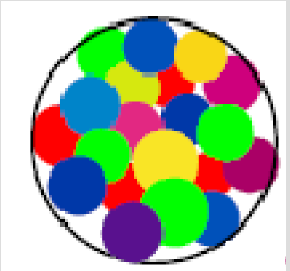
Introduction

The Electron-Ion Collider (EIC) :

A. Deshpande, R. Milner, R. Venugopalan and W. Vogelsang,
Ann. Rev. Nucl. Part. Sci. 55 165 (2005)

eA collisions : good place to look for the Color Glass Condensate

Saturation scale is large : $$Q_s^2 = A^{1/3} Q_0^2 \left(\frac{x_0}{x} \right)^{\lambda}$$



Observables to be measured at eRHIC

F_2 is reduced with respect to the linear case by up to 50 %

$\sigma_{diff} / \sigma_{tot}$ falls with x and Q^2 grows with W and A up to 0.30

$|q\bar{q}g>$ changed by saturation effects

$x_P \, F_2^{D(3)}$ becomes flat in β, x_P with increasing A

$R = F_{2,A_1}^{D(3)} / F_{2,A_2}^{D(3)}$ very flat in β, x_P

Kugeratski, Gonçalves, Navarra , EPJC (2005) , EPJC (2006)

Cazaroto, Carvalho, Gonçalves, Navarra, PLB (2008) , PLB (2009)

No "smoking gun" !

F_L and F_2^c

With dipoles:

$$F_2(x,Q^2) = \frac{Q^2}{4\pi^2\alpha_{em}}(\sigma_T + \sigma_L).$$

$$\sigma_{T,L}^{\gamma^* p}(x,Q) = \sum_f \int d^2\vec{r} \int_0^1 \frac{dz}{4\pi} (\Psi^*\Psi)_{T,L}^f \, \sigma_{q\bar{q}}(x,r).$$

With nuclear PDF´s:

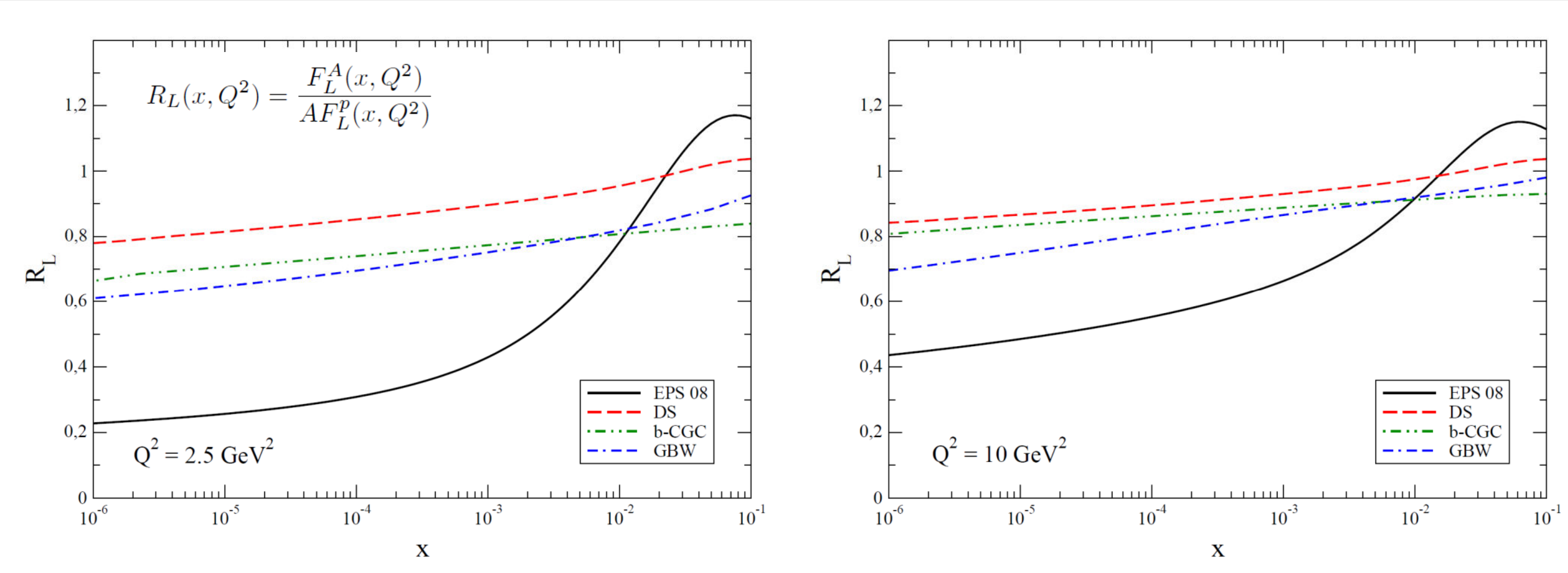
$$F_L(x,Q^2) = \frac{\alpha_s(Q^2)}{2\pi} x^2 \int_x^1 \frac{dy}{y^3}\left[\frac{8}{3} F_2(y,Q^2) + 4\sum_q e_q^2 (1-\frac{x}{y}) y g(y,Q^2)\right]$$

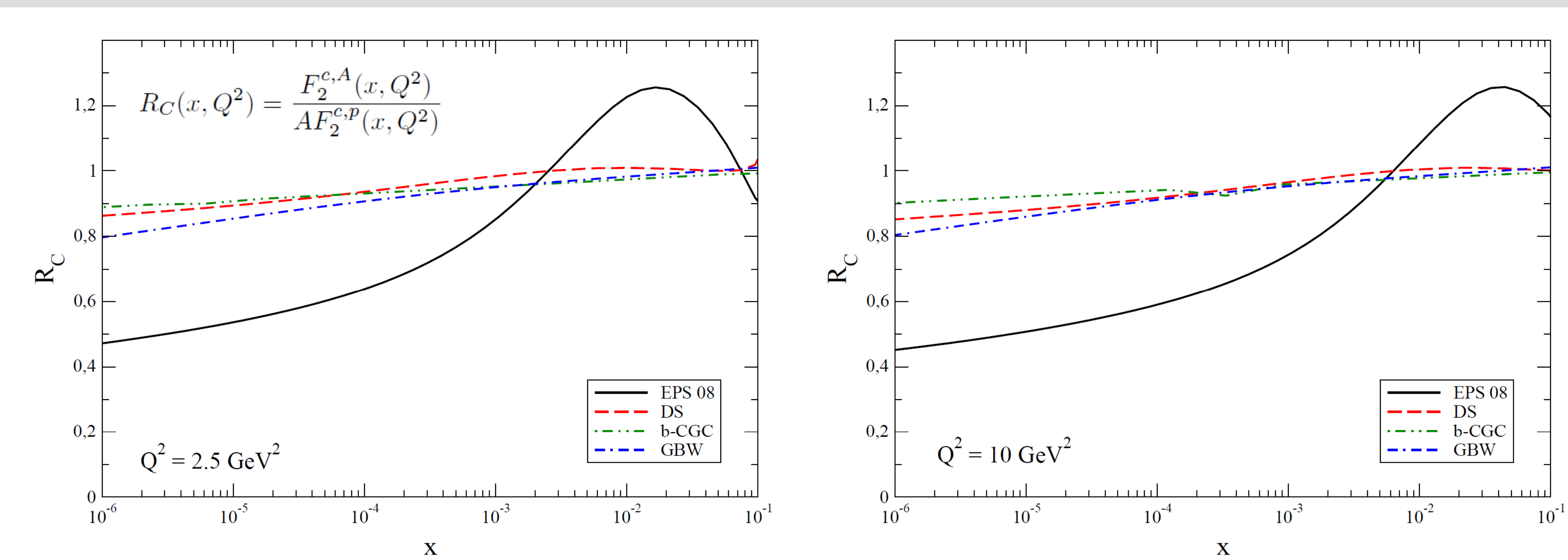
Altarelli Martinelli (1978)

$$\frac{1}{x} F_2^c(x,Q^2,m_c^2) = 2e_c^2 \frac{\alpha_s(\mu'^2)}{2\pi} \int_{ax}^1 \frac{dy}{y} C_{g,2}^c(\frac{x}{y}, \frac{m_c^2}{Q^2})\, g(y,\mu'^2)$$

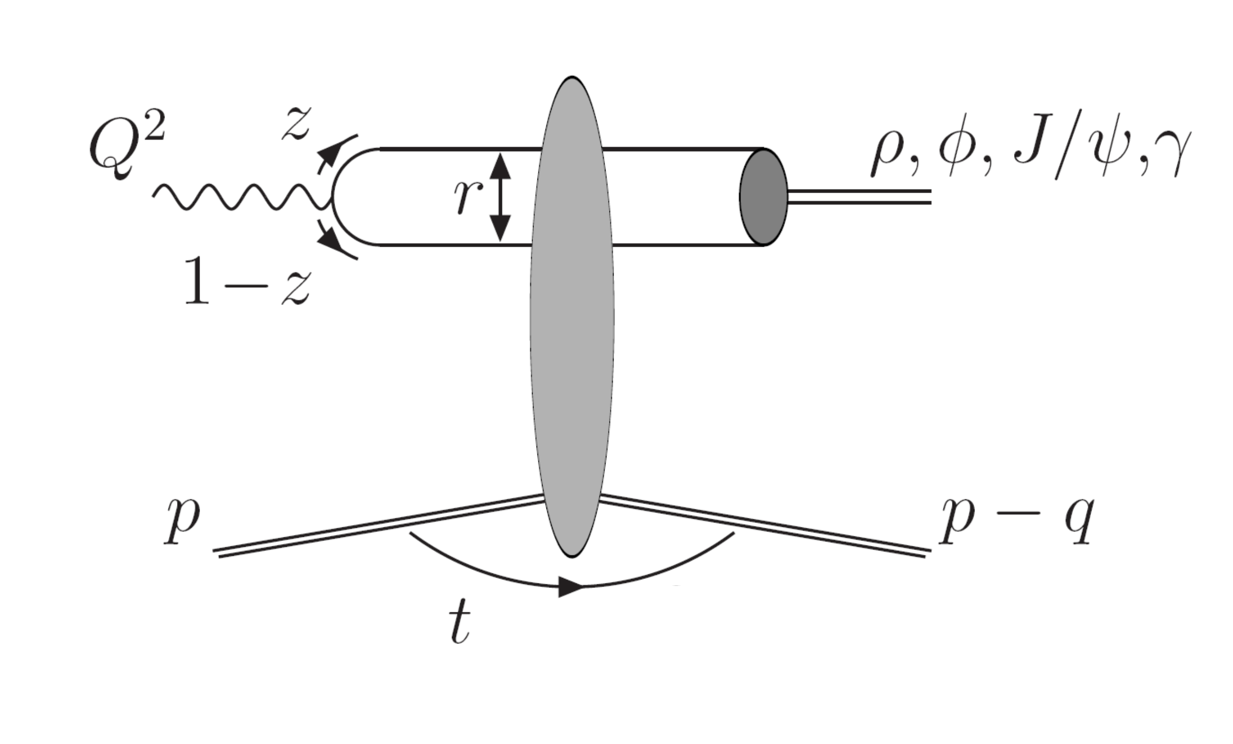
$$\begin{aligned} C_{g,2}^c(z, \frac{m_c^2}{Q^2}) &= \frac{1}{2}\{[z^2 + (1-z)^2 + z(1-3z)\frac{4m_c^2}{Q^2} - z^2\frac{8m_c^4}{Q^4}]ln\frac{1+\beta}{1-\beta} \\ &+ \beta[-1 + 8z(1-z) - z(1-z)\frac{4m_c^2}{Q^2}]\}, \end{aligned}$$

$$\beta = 1 - \frac{4m_c^2 z}{Q^2(1-z)} \qquad \mu'^2 = 4m_c^2 \qquad a = 1 + \frac{4m_c^2}{Q^2}$$


$R_L(x,Q^2) = \frac{F_L^A(x,Q^2)}{AF_L^p(x,Q^2)}$
R_L
EPS 08
DS
b-CGC
GBW
$Q^2 = 2.5$ GeV^2
$Q^2 = 10$ GeV^2
x
0
0,2
0,4
0,6
0,8
1
1,2
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}


$R_C(x,Q^2) = \frac{F_2^{c,A}(x,Q^2)}{AF_2^{c,p}(x,Q^2)}$
R_C
EPS 08
DS
b-CGC
GBW
$Q^2 = 2.5$ GeV^2
$Q^2 = 10$ GeV^2
x
0
0,2
0,4
0,6
0,8
1
1,2
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

Vector meson production in the dipole approach



Proportional to the square of the dipole cross section :

more sensitive to non-linear effects !

Vector meson production off nuclei :

Kopeliovich, Nemchik. Schmidt, Phys. Rev. **C76** 025210 (2007)

Kopeliovich, Nemchik. Schäfer, Tarasov, Phys. Rev. **C65** 035201 (2002)

Ivanov, Kopeliovich, Tarasov, Hüfner, Phys. Rev. **C66** 024903 (2002)

Coherent and incoherent nuclear diffraction :

Coherent : $\gamma^* A \to V A$

Incoherent : $\gamma^* A \to V X$

Light cone Green function formalism

High energy limit : large coherent length $l_c >> R_A$

$$l_c = \frac{2\nu}{Q^2 + m_V^2}$$

Not too large dipoles...

Coherent Production

$$\sigma^{coh}\left(\gamma^* A \to V A\right) = \int d^2 b \{ | \int d^2 r \int dz \Psi_V^*(r,z)$$

$$\times \quad \left[2 \left(1 - \exp[-\frac{1}{2} \sigma_{dp} T_A(b)] \right) \right] \Psi_{\gamma^*}(r,z,Q^2) |^2 \}$$

Compare with the Glauber approach : K. Tuchin, arXiv:0812.1519

$\Psi_{\gamma^*}(r,z,Q^2)$ Photon wave function: QED (back-up slide)

Barone , Predazzi (2002), Nikolaev, Zakharov (1991)

$\Psi_V(r,z,M_V^2)$ Meson wave function: Boosted gaussian (back-up slide)

C. Marquet, R. Peschanski, G. Soyez, hep/ph/0702171

σ_{dp} Dipole-nucleon cross section

Incoherent Production

$$\sigma^{inc}(\gamma^* A \rightarrow V X) = \frac{|\mathcal{I}m\,\mathcal{A}(s,\,t=0)|^2}{16\pi\,B_V}$$

$$|\mathcal{I}m\,\mathcal{A}(s,\,t=0)|^2 = \int d^2b T_A(b)$$

$$\times \quad \left[|\int d^2r \int dz \Psi_V^*(r,z)\sigma_{dp} \exp[-\frac{1}{2}\sigma_{dp} T_A(b)] \Psi_{\gamma^*}(r,z,Q^2)|^2 \right]$$

$$B_V \;=\; 0.6 \;\times \left(\frac{14}{(Q^2 + M_V^2)^{0.26}} + 1 \right)$$

GeV^{-2}

A. Caldwell, M. Soares, Nucl. Phys. 696 (2001)

Dipole cross section

$$\sigma_{dip}(x, \boldsymbol{r}) = 2 \int d^2\boldsymbol{b}\, \mathcal{N}(x = e^{-Y}, \boldsymbol{r}, \boldsymbol{b})$$

$$Y \equiv ln(1/x)$$

$$\mathcal{N}(x, \boldsymbol{r}) = \left[1 - \exp\left(-\frac{(Q_s(\tilde{x})\, \boldsymbol{r})^2}{4}\right)\right]$$

$$Q_s^2(\tilde{x}) = Q_0^2 \left(\frac{x_0}{\tilde{x}}\right)^{\lambda} \mathrm{GeV}^2$$

$$\tilde{x} = \frac{Q^2 + 4\, m_f^2}{Q^2 + W_{\gamma N}^2}$$

GBW

K. Golec-Biernat, M. Wüstoff, Phys. Rev. D59, 014017 (1998)

Parameters: $\sigma_0 = 23$ mb, $\lambda = 0.288$ $\quad x_0 = 3.04 \times 10^{-4}$

$$\mathcal{N}(x, \boldsymbol{r}) = \mathcal{N}_0 \left(\frac{\boldsymbol{r}Q_s}{2}\right)^{2\left(\gamma_s + \frac{\ln(2/\boldsymbol{r}Q_s)}{\kappa\lambda y}\right)} \qquad \boldsymbol{r}Q_s \leq 2$$

$$\mathcal{N}(x, \boldsymbol{r}) = 1 - e^{-a \ln^2(b\,\boldsymbol{r}Q_s)} \qquad \boldsymbol{r}Q_s > 2$$

IIM

$$Q_s \equiv Q_s(x) = Q_0(x_0/x)^{\lambda/2}$$

E. Iancu, K. Itakura, S. Munier, Phys. Lett. B590, 199 (2004)

Parameters: $\mathcal{N}_0 = 0.7$, $Q_0 = 1$GeV, $\sigma_0 = 2\pi R^2$ $R = 0.641$ fm, $\lambda = 0.253$, $x_0 = 0.267 \times 10^{-4}$, $\gamma_s = 0.63$ $\kappa = 9.9.$

$$Q_{s,p} \equiv Q_{s,p}(x, \overline{\mathbf{b}}) = \left(\frac{x_0}{x}\right)^{\lambda/2} \left[\exp\left(-\frac{\overline{b^2}}{2B_{CGC}}\right)\right]^{\frac{1}{2\gamma_s}}$$

bCGC

Parameters: $\mathcal{N}_0 = 0.558$, $\gamma_s = 0.46$, $\lambda = 0.119$, $x_0 = 1.84 \times 10^{-6}$ $B_{CGC} = 7.5$GeV^{-2}.

G. Watt, H. Kowalski, Phys. Rev. D78, 014016 (2008)

Linear limit

GBW, IIM and bCGC cross sections include non-linear effects

To define signatures of saturation we need to know the linear background

$r \to 0$ $Q^2 \to \infty$ $JIMWLK\ ,\ BK \to DGLAP$

- $r \to 0$ $\sigma_{dp}^{GBW} \to \sigma_0 \frac{Q_s(\tilde{x})\boldsymbol{r}^2}{4}$
- $rQ_s \leq 2$ $\sigma_{dp}^{bCGC} \to \mathcal{N}_0 \left(\frac{\boldsymbol{r}Q_s}{2}\right)^{2\left(\gamma_s + \frac{\ln(2/\boldsymbol{r}Q_s)}{\kappa\lambda y}\right)}$

Turn off non-linear effects in the nucleon

Results

We expect:

σ grows with W because σ_{dp} does

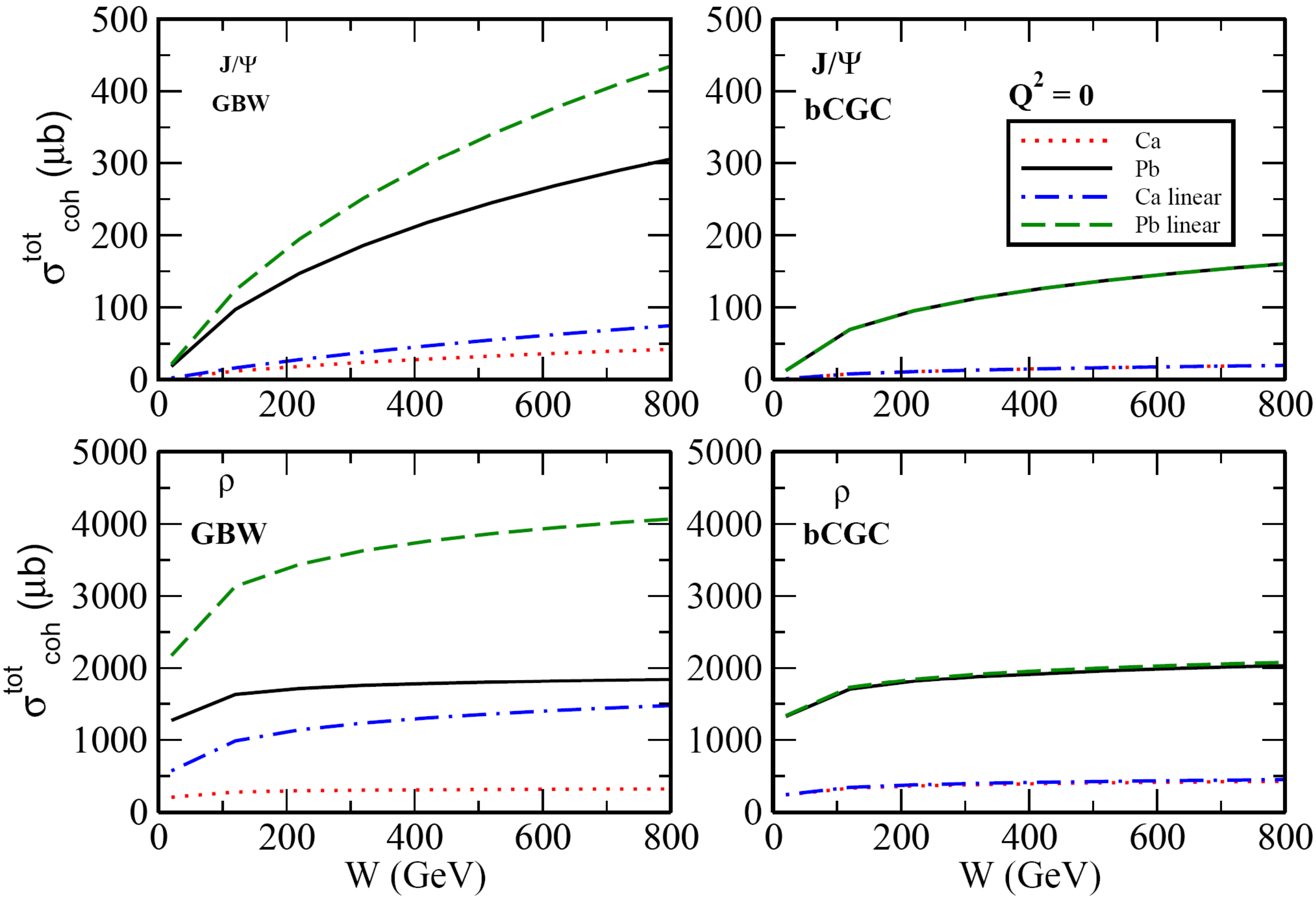
σ falls with Q because Ψ_{γ} does

σ grows with the size of the meson

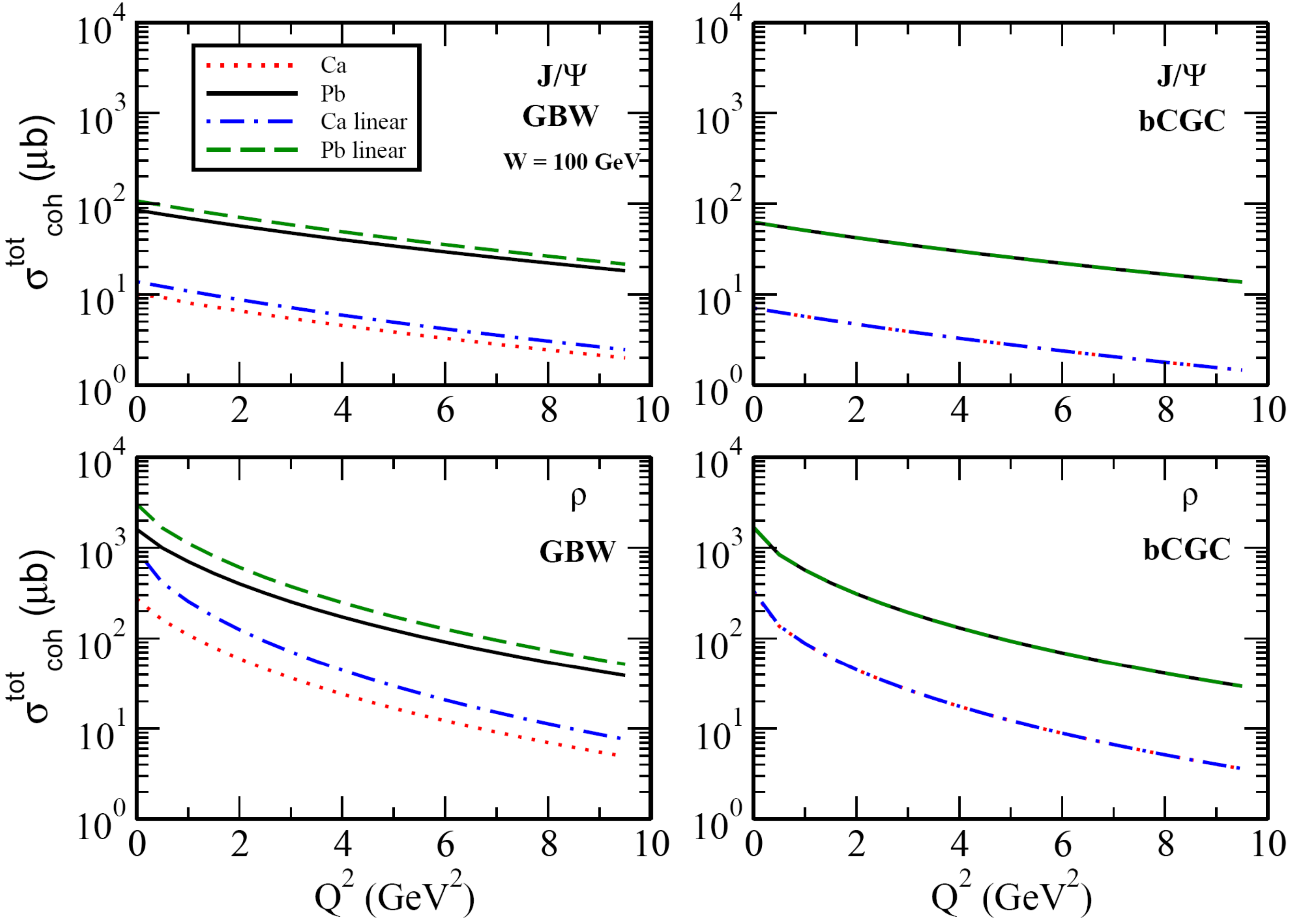
$\sigma_{coherent}$ grows with the size of the nucleus

$\sigma_{incoherent}$ grows weakly with the size of the nucleus

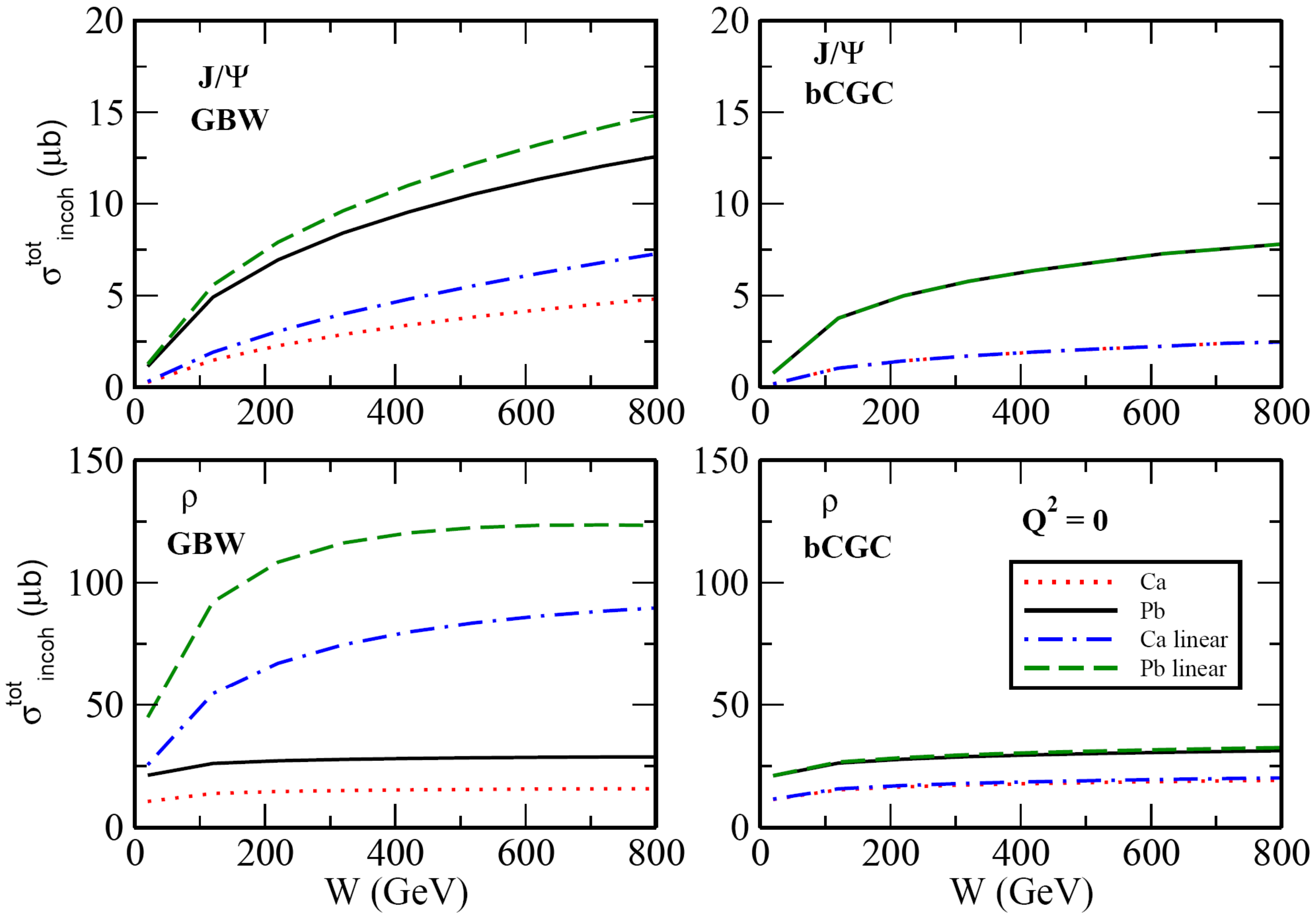
Coh. photoproduction



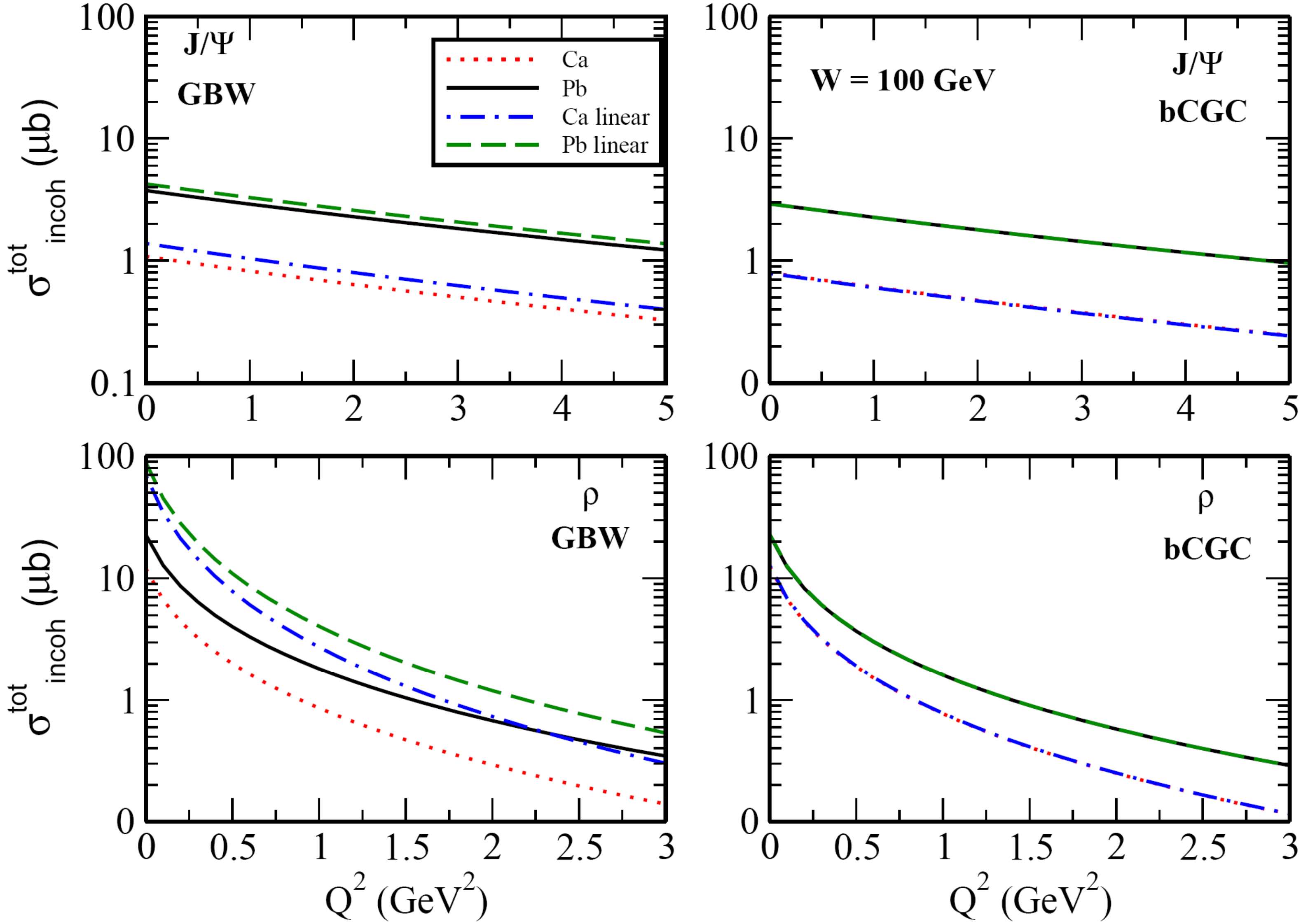
Coh. electroproduction



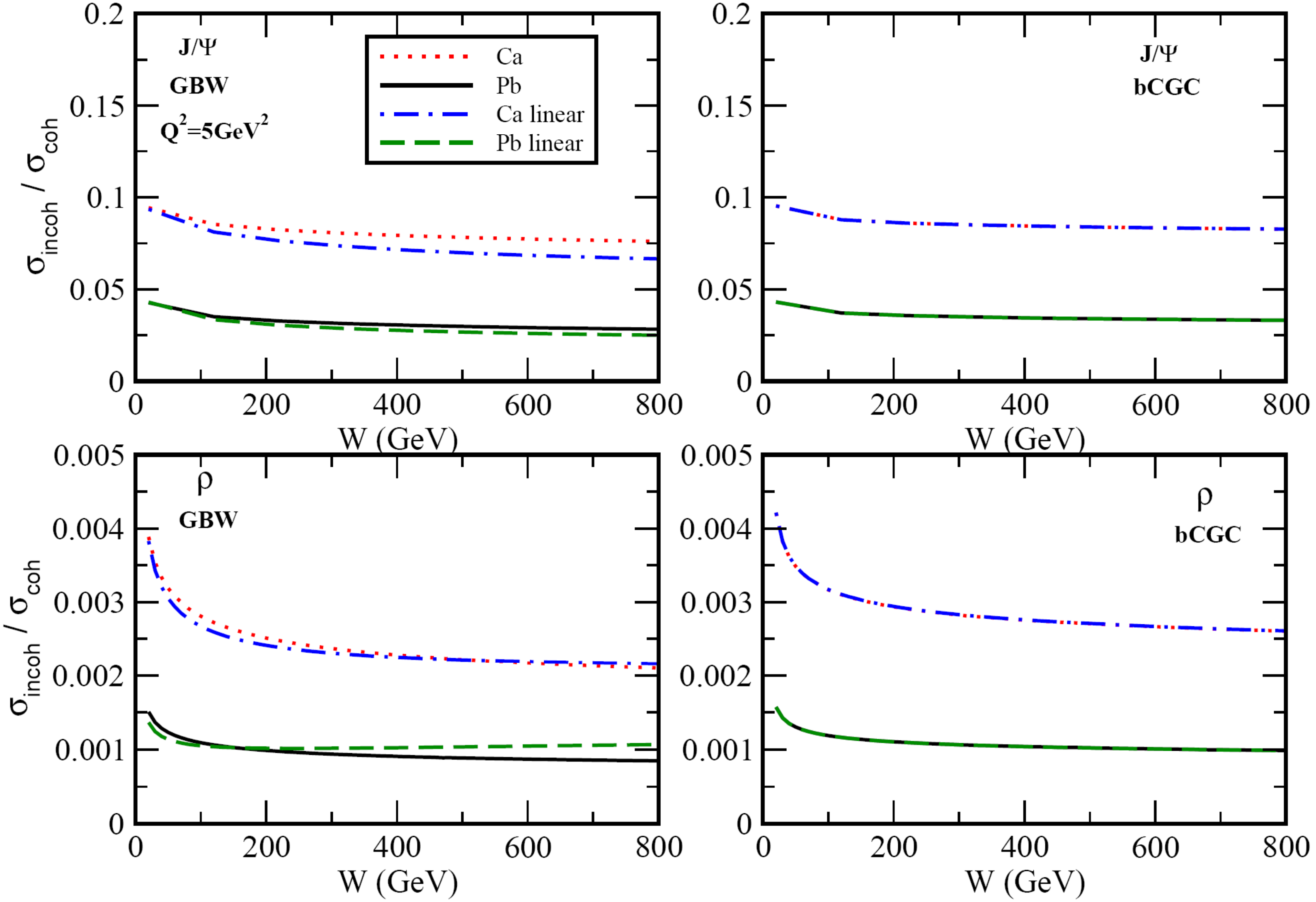
Incoh. photoproduction



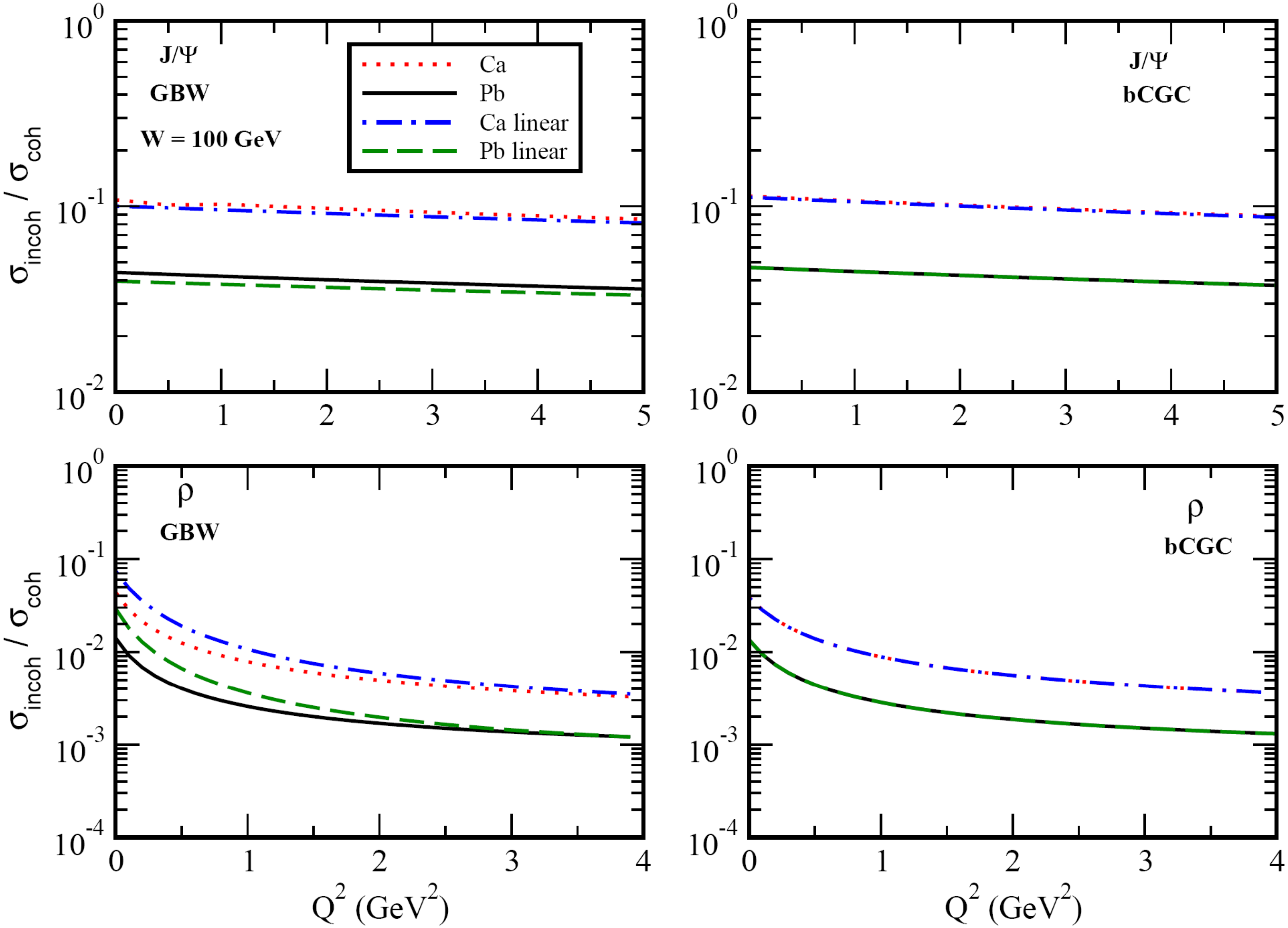
Incoh. electroproduction



$\sigma^{incoh}/\sigma^{coh}$



$\sigma^{incoh} / \sigma^{coh}$



Conclusions

Predictions for the coherent and incoherent cross sections

Update and improvement of previous estimates

V.P. Gonçalves, M.V. Machado, Eur. Phys. J. **C38**, 319 (2004)

Kopeliovich, Nemchik. Schmidt, Phys. Rev. **C76,** 025210 (2007)

Coherent cross sections are much larger in all cases

Ratio inc/coh weakly dependent on W, Q and dipole cross section

Ratio inc/coh strongly dependent on *A* and on the vector meson

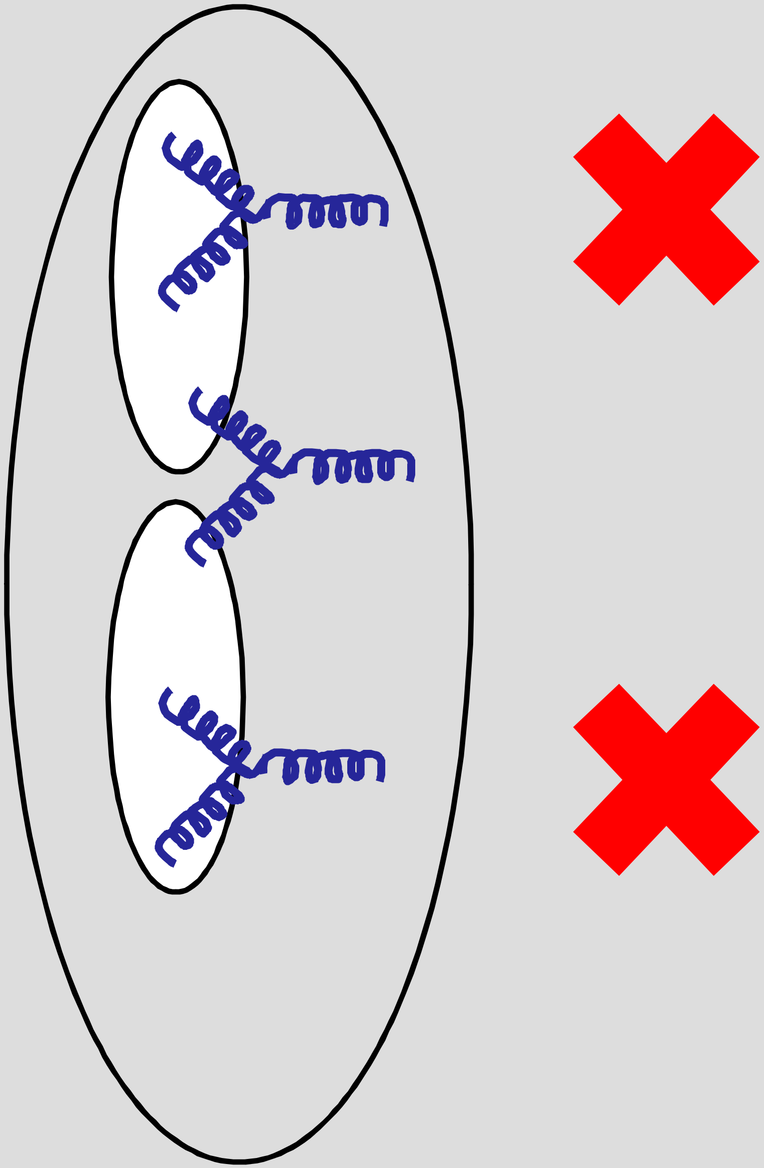
Nucleon non-linear effects are small

To be done: theoretical error bars, improve on the dipole cross section, compute the t dependence

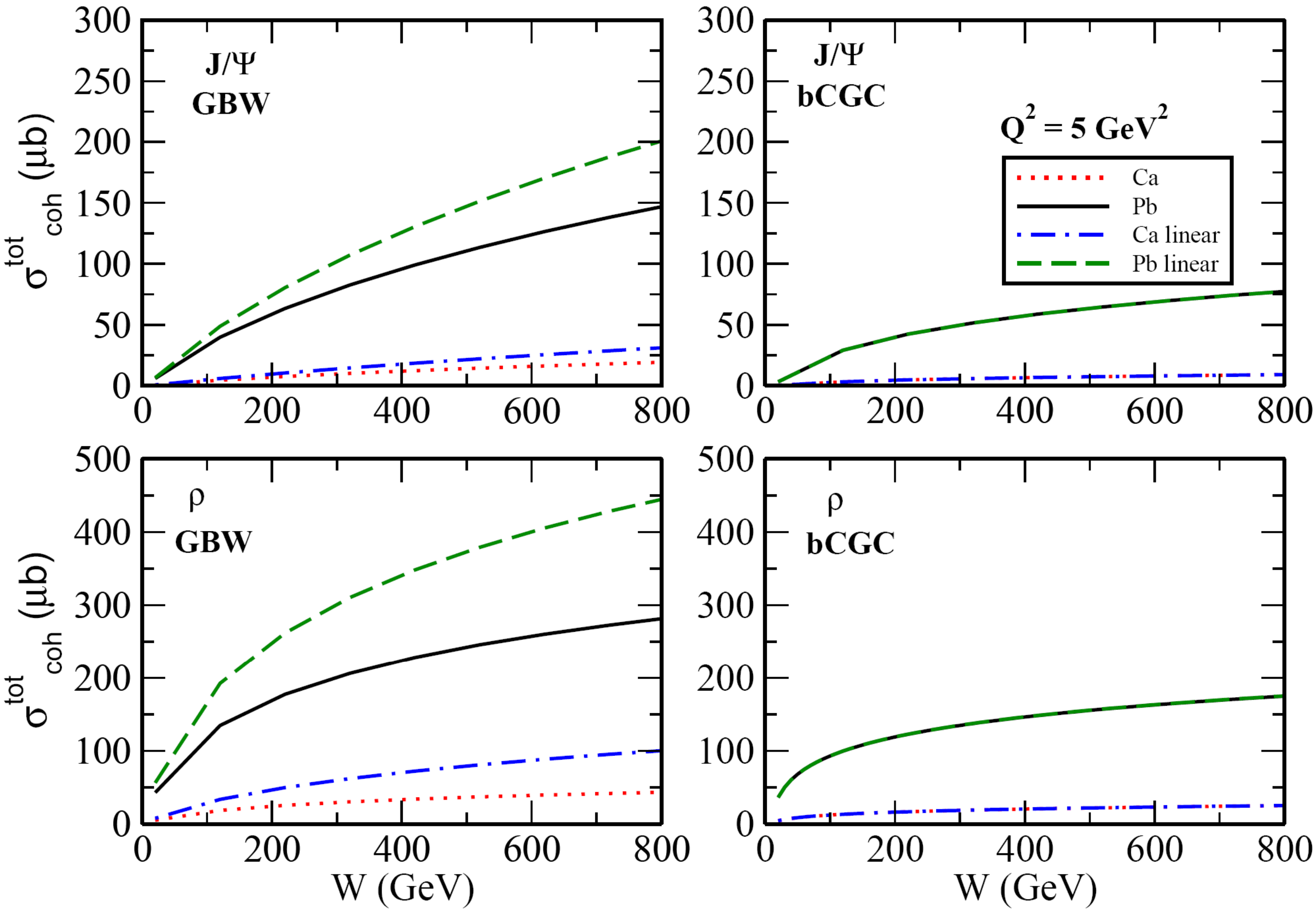
Our results agree qualitatively with other approaches

F. Dominguez, C. Marquet, B. Wu, Nucl. Phys. A823, 99 (2009)

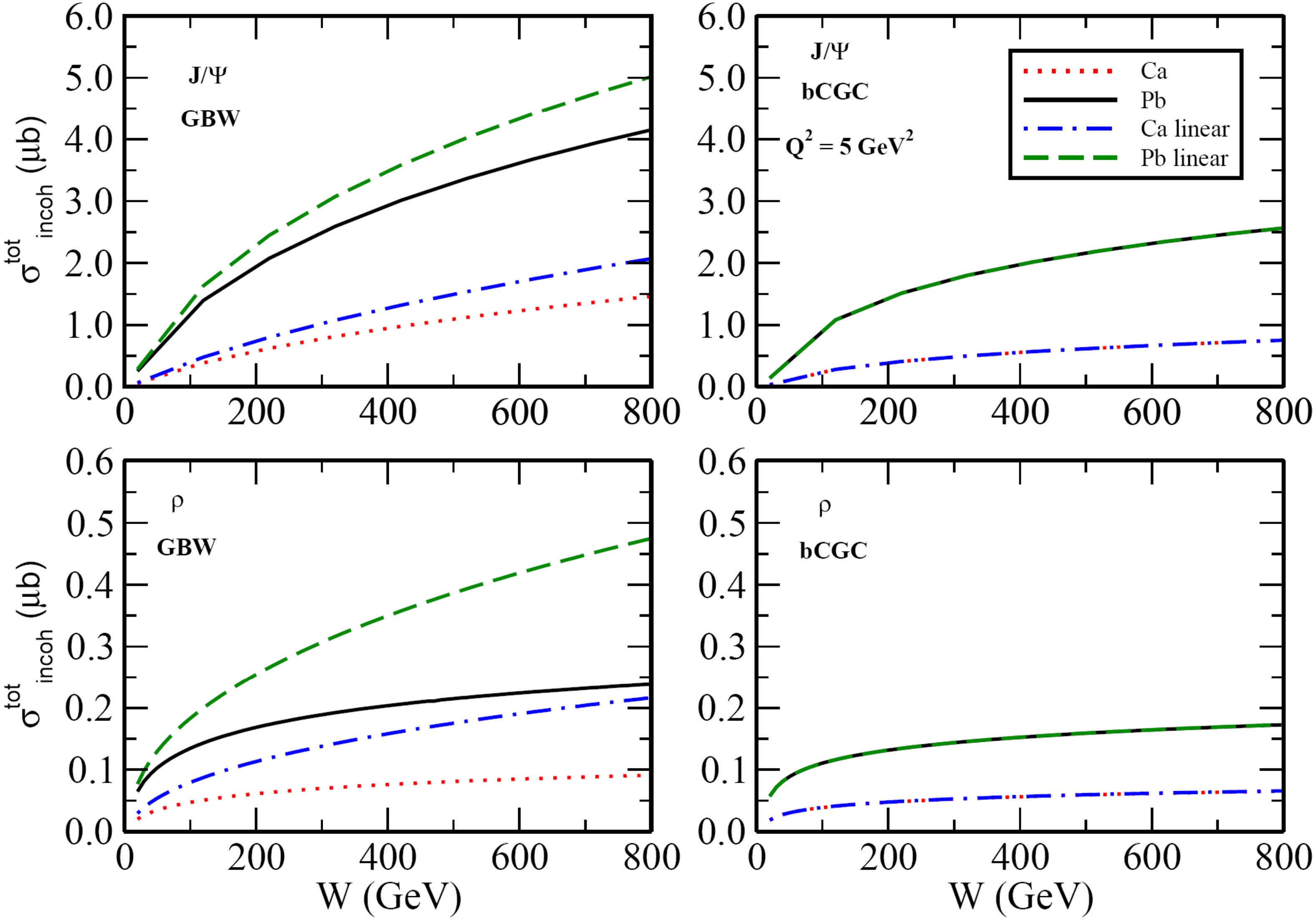
Nuclear X nucleon effects



Coh. electroproduction



Incoh. electroproduction



Meson wave functions

Boosted gaussian

J. Nemchik, N. N. Nikolaev, E. Predazzi and B. G. Zakharov, Phys. Lett. B **374**, 199 (1996)
J. Nemchik, N. N. Nikolaev, E. Predazzi and B. G. Zakharov, Z. Phys. C **75**, 71 (1997)

$$\Phi_\lambda^{\gamma^* V}(z, \boldsymbol{r}; Q^2, M_V^2) = \sum_{f h \bar{h}} \left[\Psi_{f,h,\bar{h}}^{V,\lambda}(z, \boldsymbol{r}; M_V^2) \right]^* \Psi_{f,h,\bar{h}}^{\gamma^*,\lambda}(z, \boldsymbol{r}; Q^2)$$

$$\Phi_L^{\gamma^* V}(z, \boldsymbol{r}, Q^2) \;=\; \hat{e}_f \sqrt{\frac{\alpha_e}{4\pi}} N_c \, 2Q K_0(\varepsilon r) \left[M_V z(1-z)\phi_L(\boldsymbol{r}, z) + \frac{m_f^2 - \nabla_r^2}{M_V} \phi_L(\boldsymbol{r}, z) \right],$$

$$\Phi_T^{\gamma^* V}(z, \boldsymbol{r}, Q^2) \;=\; \hat{e}_f \sqrt{\frac{\alpha_e}{4\pi}} N_c \frac{\alpha_e N_c}{2\pi^2} \left\{ m_f^2 K_0(\varepsilon r)\phi_T(r, z) - [z^2 + (1-z)^2]\varepsilon K_1(\varepsilon r))\partial_r \phi_T(r, z) \right\}$$

$$\phi_{L,T} = N_{L,T} \, \exp\left[-\frac{m_f^2 R^2}{8z(1-z)} + \frac{m_f^2 R^2}{2} - \frac{2z(1-z)r^2}{R^2} \right]$$

J. R. Forshaw, R. Sandapen and G. Shaw, Phys. Rev. D **69**, 094013 (2004).
H. Kowalski, L. Motyka and G. Watt, Phys. Rev. D **74**, 074016 (2006).
C. Marquet, R. B. Peschanski and G. Soyez, Phys. Rev. D **76**, 034011 (2007)

$V(m_V)$ (MeV)	m_f (GeV)	R^2 (GeV^{-2})	N_L	N_T	$\hat{e}_f$
$\rho\,(776)$	0.14	12.9	0.853	0.911	$1/\sqrt{2}$
$J/\Psi\,(3097)$	1.4	2.3	0.575	0.578	2/3

$$\varepsilon^2 = z(1-z)Q^2 + m_f^2$$

Photon wave function

J. R. Forshaw, R. Sandapen and G. Shaw, Phys. Rev. D **69**, 094013 (2004).
H. Kowalski, L. Motyka and G. Watt, Phys. Rev. D **74**, 074016 (2006).

$$\Psi^{L}_{h,\bar{h}}(z,\,\boldsymbol{r}) \;=\; \sqrt{\frac{N_c}{4\pi}}\,\delta_{h,-\bar{h}}\,e\,e_f\,2z(1-z)\,Q\,\frac{K_0(\varepsilon r)}{2\pi}\,,$$

$$\Psi^{T(\gamma=\pm)}_{h,\bar{h}}(z,\,\boldsymbol{r}) \;=\; \pm\sqrt{\frac{N_c}{2\pi}}\,e\,e_f\,\left[ie^{\pm i\theta_r}(z\delta_{h\pm,\bar{h}\mp}-(1-z)\delta_{h\mp,\bar{h}\pm})\partial_r + m_f\,\delta_{h\pm,\bar{h}\pm}\right]\frac{K_0(\varepsilon r)}{2\pi}$$

Spin and polarization are the same for the photon and the meson

F.~Dominguez, C.~Marquet and B.~Wu, %``On multiple scatterings of mesons in hot and cold QCD matter,'' Nucl.\ Phys.\ A {\bf 823}, 99 (2009) [arXiv:0812.3878 [nucl-th]].

Polarization and helicity

Normalization of wave function: not 1 for photons

$$Y \simeq -\frac{1}{4} Q_s^2 (x_\perp^2 + x_\perp'^2). \tag{69}$$

If the dipole interacts with the medium only through double-scatterings, that is, the target is not excited, we get the probability for the so-called elastic process

$$\begin{aligned} P_{el}^\lambda &= \int d^2x_\perp d^2x'_\perp \Phi_{fi}^\lambda(x_\perp) \Phi_{fi}^{\lambda *}(x'_\perp) \sum_{m_I, m_{II}=0}^{\infty} \frac{1}{m_I! m_{II}!} (-2\chi)^{m_I} (Y + 2\chi)^{m_{II}} \\ &= \int d^2x_\perp d^2x'_\perp \Phi_{fi}^\lambda(x_\perp) \Phi_{fi}^{\lambda *}(x'_\perp) e^{-\frac{1}{4} Q_s^2 (x_\perp^2 + x_\perp'^2)}. \end{aligned} \tag{70}$$

C. Diffractive vector meson production

An experimental situation where elastic and inelastic processes can be distinguished is the diffractive production of vector mesons in deep inelastic scattering: $\gamma^* A \to VY$, where A stands for the target nucleus and Y for the final state it has dissociated into. In this process, the $q\bar{q}$ pair that the virtual photon has fluctuated into scatters off the nucleus before recombining into a vector meson. While the scattering involves a color-singlet exchange, leaving a rapidity gap in the final state, the nucleus can still scatter elastically ($Y = A$, this is called coherent diffraction) or inelastically (*i.e.* break up, called incoherent diffraction). Kinematically, a low invariant mass of the system Y corresponds to a large rapidity gap between that system and the vector meson (this also implies that the longitudinal momentum of the meson is close to that of the photon, which justifies using the eikonal approximation for this process), which makes it possible in principle to keep track of the state of the target, and separate coherent and incoherent diffraction.

The cross-section is peaked at minimum momentum transfer where the elastic scattering dominates, but as the transfer of momentum gets larger, the role of the inelastic contribution increases and eventually it becomes dominant (typically for momenta bigger that the inverse nucleus size). The momentum transfer in this process is essentially the transverse momentum of the vector meson in the final state $P'_\perp$, and as a function of $|t| = P'^2_\perp$, the elastic contribution decreases exponentially while the inelastic contribution decreases only as a power law. This important difference was not discussed in this paper where only $P'_\perp-$integrated quantities are analyzed. It deserves detailed studies which are left for future work, such as for instance the numerical analysis of our results and a comparison with data from HERA on diffractive vector meson production, with or without proton breakup. The case of deep inelastic scattering off a large nucleus should also be studied, and in this case the MV model we considered provides a natural framework, and a good starting point to implement the high-energy QCD evolution. Inclusive and diffractive structure functions have been calculated [31], but vector-meson production has yet to be addressed. At an electron-ion collider, when the momentum transfer is small enough for the nucleus to stay intact, then it will escape too close to the beam to be detectable; therefore the whole diffractive program will rely on our understanding of incoherent diffraction.

Differential equation depends on the equation of state !

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla})\vec{v} = -\frac{1}{(\varepsilon + p)\gamma^2}\left(\vec{\nabla} p + \vec{v}\frac{\partial p}{\partial t}\right)$$

Euler

EOS: $p = {c_s}^2 \varepsilon$ ➡ $\vec{\nabla} p = {c_s}^2 \vec{\nabla} \varepsilon$

If: $\varepsilon \propto \ldots + \ldots \vec{\nabla}^2 \rho_B$ ➡ $\vec{\nabla} p \propto \ldots + \ldots \vec{\nabla}(\vec{\nabla}^2 \rho_B) \ldots$

$$\frac{\partial \rho_1}{\partial t} + \alpha \rho_1 \frac{\partial \rho_1}{\partial x} + \beta \frac{\partial^3 \rho_1}{\partial x^3} = 0$$

Korteweg - de Vries (KdV)

If: $\nabla^2 \ldots = 0$

$$\frac{\partial \hat{\rho}_1}{\partial t} + c_s \frac{\partial \hat{\rho}_1}{\partial x} + \frac{2}{3} c_s \hat{\rho}_1 \frac{\partial \hat{\rho}_1}{\partial x} = 0$$

Breaking wave equation

How to get the Laplacian $\vec{\nabla}^2 \rho_B$?

In nuclear matter mean field theory (non-linear Walecka) :

$$\mathcal{L}^* = \bar{\psi}[(i\gamma_\mu \partial^\mu - g_V \gamma_0 V_0) - (M - g_S \phi_0)]\psi + \frac{1}{2}\left(\partial_\mu \phi_0 \partial^\mu \phi_0 - {m_S}^2 {\phi_0}^2\right) +$$

$$+\frac{1}{2}(\vec{\nabla} V_0)^2 + \frac{1}{2}{m_V}^2 {V_0}^2 - \frac{b}{3}{\phi_0}^3 - \frac{c}{4}{\phi_0}^4$$

Mean field Lagrangian

$$-\vec{\nabla}^2 V_0 + {m_V}^2 V_0 = g_V \bar{\psi}\gamma^0 \psi$$

$$(\partial_\mu \partial^\mu + {m_S}^2)\phi_0 = g_S \bar{\psi}\psi - b{\phi_0}^2 - c{\phi_0}^3$$

$$\left[i\gamma_\mu \partial^\mu - g_V \gamma_0 V_0 - (M - g_S \phi_0)\right]\psi = 0$$

Equations of motion

Usually: $\nabla^2 V_0 = 0$ and $V_0 = \frac{g_V}{{m_V}^2}\rho_B$

But we can estimate the Laplacian :

$$V_0 = \frac{g_V}{m_V{}^2}\rho_B \rightarrow \nabla^2 V_0 = \frac{g_V}{m_V^2}\nabla^2\rho_B \rightarrow -\vec{\nabla}^2 V_0 + m_V{}^2 V_0 = g_V\bar{\psi}\gamma^0\psi$$

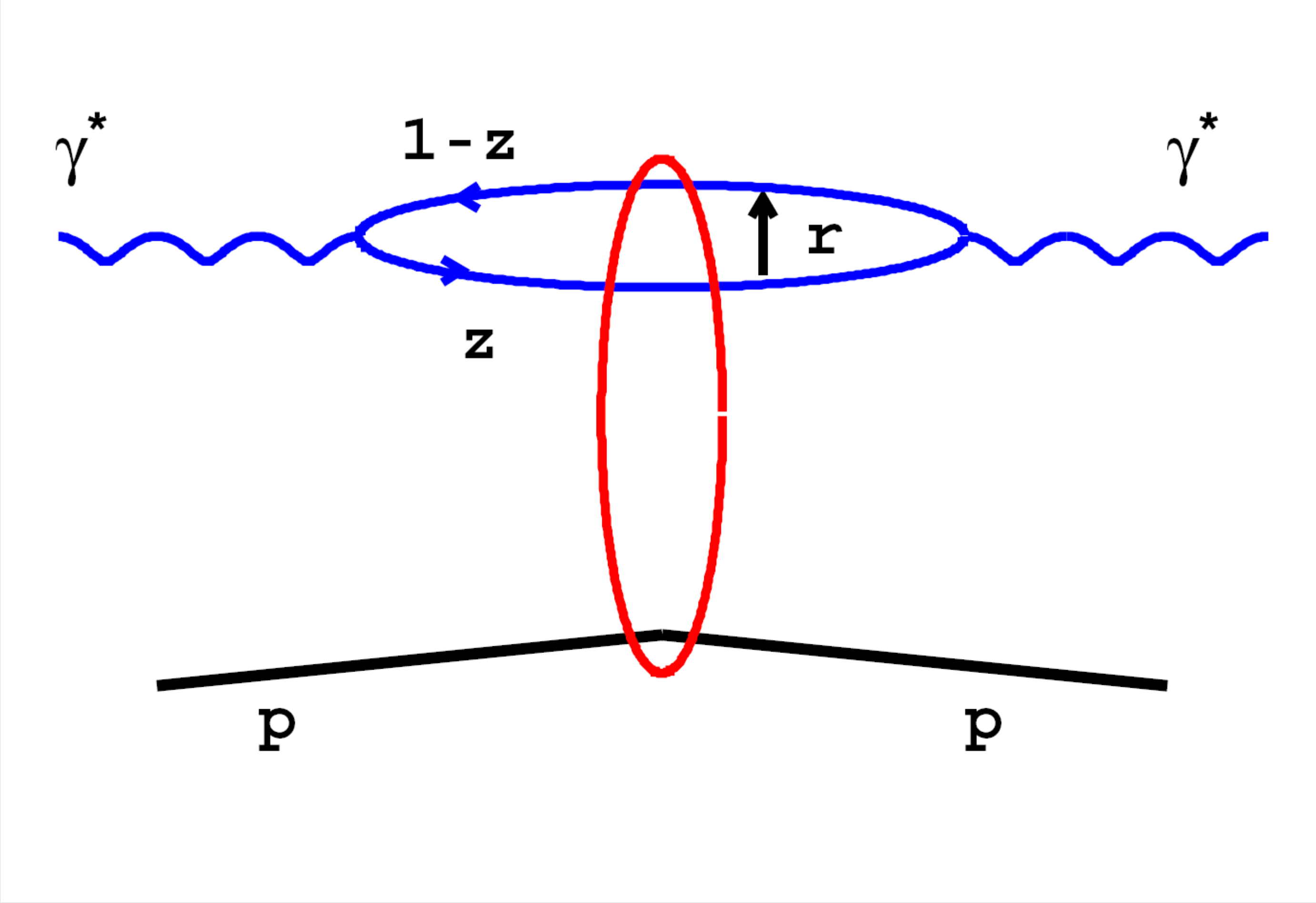
$$\downarrow$$

$$m_V{}^2 V_0 = \frac{g_V}{m_V{}^2}\vec{\nabla}^2\rho_B + g_V\rho_B \rightarrow V_0 = \frac{g_V}{m_V{}^2}\rho_B + \frac{g_V}{m_V{}^4}\vec{\nabla}^2\rho_B$$

Compute the Lagrangian, energy-momentum tensor and obtain the EOS :

$$\varepsilon = \frac{1}{2}\left\{\frac{\partial}{\partial t}\left[\frac{(M-M^*)}{g_S}\right]\right\}^2 + \frac{1}{2}\left\{\vec{\nabla}\left[\frac{(M-M^*)}{g_S}\right]\right\}^2 + \frac{m_S{}^2}{2g_S{}^2}(M-M^*)^2 +$$
$$+b\frac{(M-M^*)^3}{3g_S{}^3} + c\frac{(M-M^*)^4}{4g_S{}^4} + \frac{g_V{}^2}{2m_V{}^2}\rho_B{}^2 + \frac{g_V{}^2}{2m_V{}^4}\rho_B\vec{\nabla}^2\rho_B +$$
$$+\frac{\gamma_s}{(2\pi)^3}\int_0^{k_F} d^3k(\vec{k}^2 + M^{*2})^{1/2}$$

Dipole approach



- The scattering is mediated by a color singlet exchange, leaving a rapidity gap in the final state
- The nucleus can be scattered:
  1. Elastically → Y = A, coherent diffraction
  2. Inelastically → the nucleus breaks up, incoherent diffraction.

M.S. Kugeratski, V.P. Gonçalves, F.S. Navarra, Eur. Phys. J. **C44** 577 (2005)

M.S. Kugeratski, V.P. Gonçalves, F.S. Navarra, Eur. Phys. J. **C46** 413 (2006)

M.S. Kugeratski, V.P. Gonçalves, F.S. Navarra, Eur. Phys. J. **C46** 465 (2006)

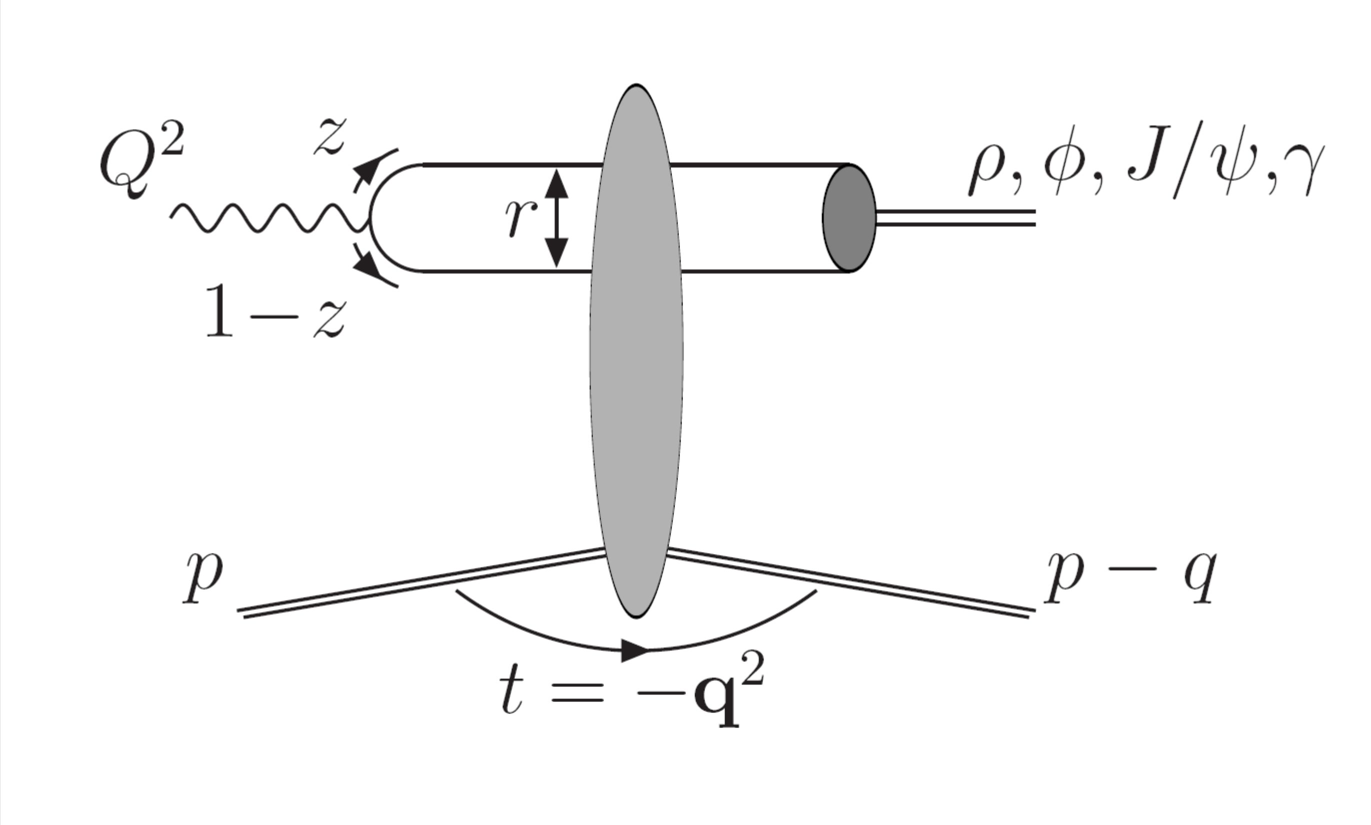
E.R. Cazaroto, F. Carvalho, V.P. Goncalves, F.S. Navarra, Phys. Lett. **B669** 331 (2008)

E.R. Cazaroto, F. Carvalho, V.P. Goncalves , F.S. Navarra, Phys. Lett. **B671** 233 (2009)

F. Carvalho, F.O. Durães, F.S. Navarra, S. Szpigel, Phys. Rev. **C79** 035211 (2009)

Dipole approach

$$\gamma^* A \to V A$$



M.S. Kugeratski, V.P. Gonçalves, M.V. Machado, F.S. Navarra, Phys. Lett. **B44** 577 (2006)


XI HADRON PHYSICS
March, 22 - 27, 2010, São Sebastião, Brazil


SCHWEIZERISCHE NATIONALBANK
BANCA NAZIUNALA SVIZRA
10
Zehn Franken
Dieci Franchi
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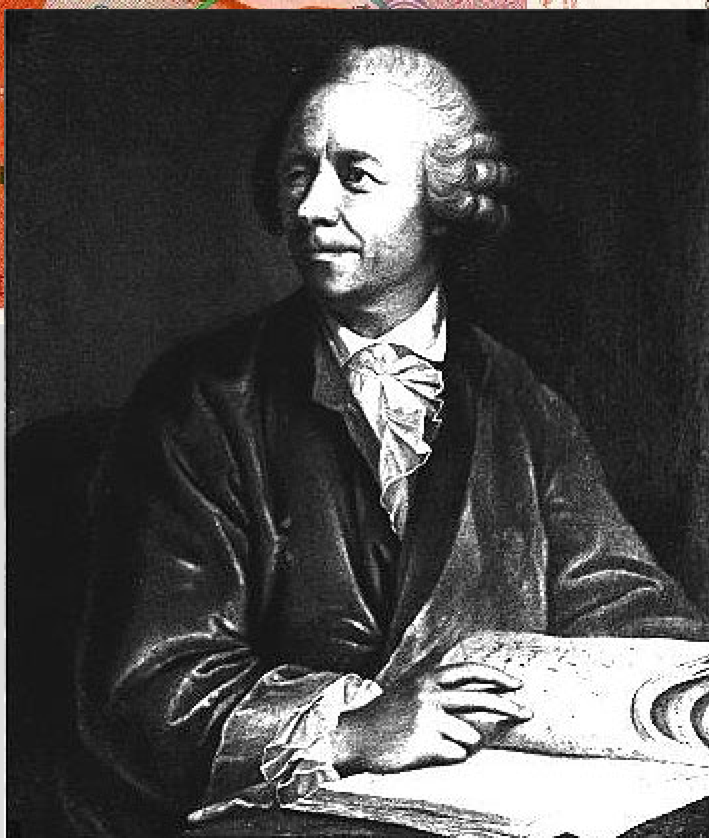
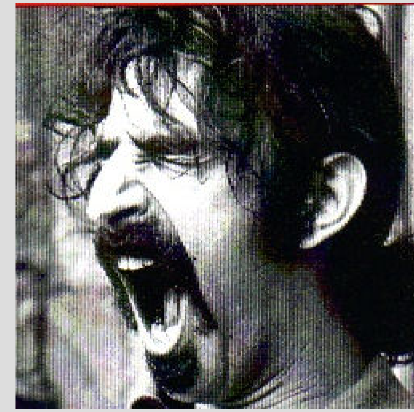
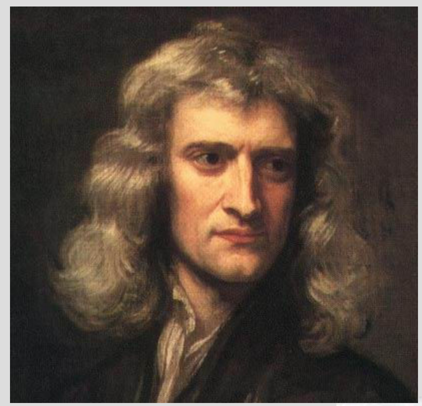
Dix Francs
BANQUE NATIONALE SUISSE




É difícil acreditar...