Diffractive vector meson production at HERA using holographic light-front QCD

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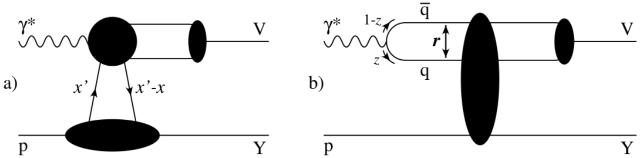
Outline

Introduction : Vector meson production

• Exclusive and dissociative vector meson production can be an excellent probe to the gluon structure of the target.



(a) The approach based on collinear factorisation which describes VM production using the parton content of the proton, in the presence of a hard scale $(W^2 \gg M_V^2, Q^2 \gg \Lambda_{QCD}^2)$.

$$T_L^{\gamma^* p \to Vp}(x,t) = \sum_{i,j} \int_0^1 dz \int dx' \; f_{i/p}(x', x'-x, \mu) \; H_{ij}(Q^2 x'/x, Q^2, z; \mu) \; \psi_j^V(z;\mu)$$

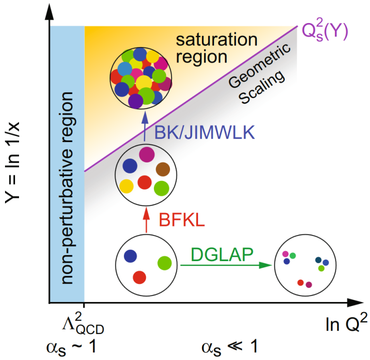
• Collinear factorisation holds for heavy VMs, and its validity is extended to transverse amplitudes at sufficiently high Q^2.

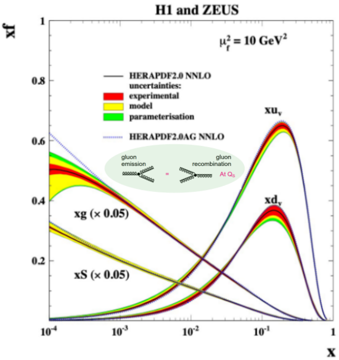
(b) High energy, low x colour dipole approach :

$$T^{\gamma^* p \to Vp}(x,t) = \int_0^1 dz \int d^2\mathbf{r} \; \psi^{\gamma^*}(z,\mathbf{r}) \; \sigma^{q\bar{q}-p}(x,\mathbf{r};t) \; \psi^V(z,\mathbf{r})$$

— J.C. Collins, PRD 56 (1997), A.H. Mueller Nucl. Phys. B 335 (1990)

Gluon saturation



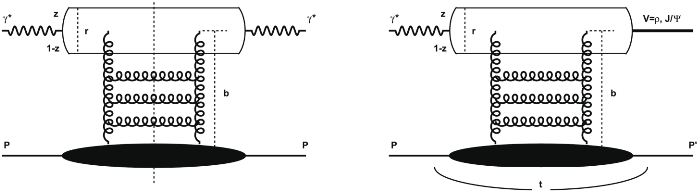


- Linear evolution of the gluon density below the saturation scale (dilute regime)
- Non-linear evolution above the saturation scale (dense regime) → gluon saturation
- Moving to smaller x one can reach and go beyond the saturation scale $Q_s(x)$
- At small x gluon recombination and multiple scattering balance

— Y.V. Kovchegov, PRD 61, (2000), L.V. Gribov, E.M. Levin, M.G. Ryskin, Phys. Rep. 100, 1 (1983), HERA Collaboration, Eur.Phys.J.C 81 (2021)

The CGC dipole model

• Colour glass condensate (CGC) is a popular effective field theory for explaining physical phenomena in the proton saturation region.



• The forward scattering amplitude for the diffractive process : $\gamma^* p \rightarrow Vp$

$$\Im\mathrm{m}\,\mathcal{A}_\lambda^{\gamma^* p \rightarrow Vp}(s,t;Q^2) \quad = \quad \sum_{h,\bar{h}} \int \mathrm{d}^2\mathbf{r}\,\mathrm{d}x\,\Psi_{h,\bar{h}}^{\gamma^*,\lambda}(r,x;Q^2)\Psi_{h,\bar{h}}^{V,\lambda}(r,x)^* e^{-ix\mathrm{r}\cdot\boldsymbol{\Delta}}\mathcal{N}(x_{\mathrm{m}},\mathrm{r},\boldsymbol{\Delta})$$

• The high energy QCD dynamics of the dipole-proton interaction are all encoded in the scattering amplitude, $\mathcal{N}(x_m, r, \Delta)$.

• To compare with experiment, we compute the differential cross section :

$$\frac{d\sigma_\lambda^{\gamma^* p \rightarrow Vp}}{dt} = \frac{1}{16\pi}[\Im\mathrm{m}\mathcal{A}_\lambda^{\gamma^* p \rightarrow Vp}(s,t=0)]^2\ (1+\beta_\lambda^2)\exp(-B_D t)$$

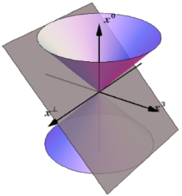
— G. Watt and H. Kowalski, PRD 78, (2008), E. Iancu, et al. B 590, 199(2004)

Light-Front QCD

• Light-Front is a three-dimensional surface in space-time formed by a plane wave front advancing with the velocity of light. —Dirac (1949)

• Light-front QCD is a valuable approach that is particularly useful for high-energy QCD processes and the exploration of Parton Distribution Functions (PDFs).

• Its advantages lie in its manifest Lorentz symmetry and natural separation of longitudinal and transverse degrees of freedom.



- Light-Front coordinates : $x^\mu = (x^+, x^-, x^\perp)$
  $x^\pm = x^0 \pm x^3$ & $x^\perp = (x^1, x^2)$
- Light-Front coordinates : $k^\mu = (k^+, k^-, k^\perp)$
  $k^\pm = k^0 \pm k^3$ & $k^\perp = (k^1, k^2)$

• Dispersion relations for a free massive particle $k^2 = m^2$: $k^- = \frac{(k^\perp)^2 + m^2}{k^+}$

(1) There is no square root factor. (2) The dependence of the energy k^- on the transverse momentum $k^\perp$ is just like in the nonrelativistic dispersion relation.
(3) Simple vacuum structure : Vacuum expectation value is zero as all ground state fluctutions are absent. — A. Harindranath (1996) ; Stanley J. Brodsky (2009)

Light-Front wavefunction

Photon LFWFs : LF QED

- The photon light-front wavefunctions can be computed perturbatively in QED.

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

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

Where $\epsilon^2 = x(1-x)Q^2 + m_f^2$

In $Q \to 0$ or $x \to (0,1)$ limit : m_f acts as infrared regulator.

— G. P. Lepage and S. J. Brodsky PRD22 (1980)

Meson LFWFs : LF Holographic QCD

- The longitudinal and transversely polarized vector meson light-front wave functions :

$$\Psi^{V,L}_{h,\bar{h}}(r,x) = \frac{1}{2}\delta_{h,-\bar{h}}\left[1 + \frac{m_f^2 - \nabla_r^2}{x(1-x)M_V^2}\right]\Psi_L(r,x)\,.$$

$$\Psi^{V,T}_{h,\bar{h}}(r,x) = \pm\left[ie^{\pm i\theta_r}(x\delta_{h\pm,\bar{h}\mp} - (1-x)\delta_{h\mp,\bar{h}\pm})\partial_r + m_f\delta_{h\pm,\bar{h}\pm}\right]\frac{\Psi_T(r,x)}{2x(1-x)}\,.$$

— J. R. Forshaw and R. Sandapen, PRL109 (2012)

The holographic vector meson LFWFs $\Psi_\lambda(r,x) = \mathcal{N}_\lambda \phi(\zeta) \times \chi(x)$

- Transverse mode : Can obtained by solving the LF Schrödinger equation :

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + U_\perp(\zeta)\right)\phi(\zeta) = M_\perp^2 \phi(\zeta);$$

with $U_\perp(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(J-1)$ and $\zeta = \sqrt{x(1-x)}r_\perp$.

$$\Psi(x,\zeta) = \frac{\kappa}{\sqrt{\pi}}\sqrt{x(1-x)}\exp\left[-\frac{\kappa^2\zeta^2}{2}\right].$$

- Longitudinal mode : 't Hooft equation which can be derived by using the QCD lagrangian in (1+1) dimension with large N_c approximations

$$\left(\frac{m_q^2}{x} + \frac{m_{\bar{q}}^2}{1-x}\right)\chi(x) + \frac{g^2}{\pi}\mathcal{P}\int dy \frac{|\chi(x)-\chi(y)|}{(x-y)^2} = M_\parallel \chi(x);$$

$$\Rightarrow \chi(x) \simeq x^{\beta_1}(1-x)^{\beta_2}$$

In the chiral limit,

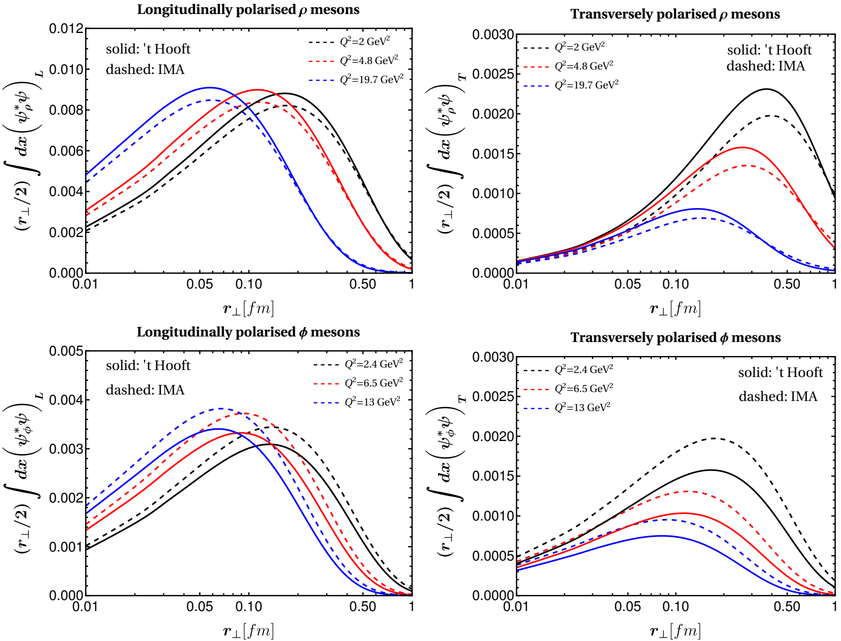
$$\beta_1 = (3m_q^2/\pi g^2)^{1/2}, \qquad \text{and} \qquad \beta_2 = (3m_{\bar{q}}^2/\pi g^2)^{1/2}$$

- Total Holographic vector meson light-front wavefunction :

$$\Psi_\lambda(x,\zeta) = \mathcal{N}_\lambda\sqrt{x(1-x)}x^{\beta_1}(1-x)^{\beta_2}\exp\left[-\frac{\kappa^2\zeta^2}{2}\right]$$

— Teramond, S.J. Brodsky PRD, 104 (2021), C. Mondal et al. PLB, 823 (2021)

ρ and ϕ vector meson LFWF overlap with γ^* LFWFs



Dipole cross section

- Dipole-proton scattering amplitude $\mathcal{N}(x_m, r, b)$ can be obtained by solving the Balitsky-Kovchegov (BK) equation.

- $\hat{\sigma}(x_{\mathrm{m}}, r) = \sigma_0 \mathcal{N}(x_{\mathrm{m}}, rQ_s, 0)$

$$\mathcal{N}(x_{\mathrm{m}}, rQ_s, 0) = \begin{cases} \mathcal{N}_0 \left(\frac{rQ_s}{2}\right)^{2\left[\gamma_s + \frac{\ln(2/rQ_s)}{\kappa\,\lambda\,\ln(1/x_{\mathrm{m}})}\right]} & \text{for} \quad rQ_s \leq 2 \\ 1 - \exp[-\mathcal{A}\ln^2(\mathcal{B}\,rQ_s)] & \text{for} \quad rQ_s > 2 \end{cases}$$

- Q_s is the saturation scale which is given as, $Q_s = (x_0/x_m)^{\lambda/2}$ GeV, $x_m = \frac{Q^2 + 4m_f^2}{W^2}$

- $\mathcal{A}$ and $\mathcal{B}$ determined from the condition that $\mathcal{N}(x_m, rQ_s, 0)$, and its derivative with respect to rQ_s, are continuous at $rQ_s = 2$.

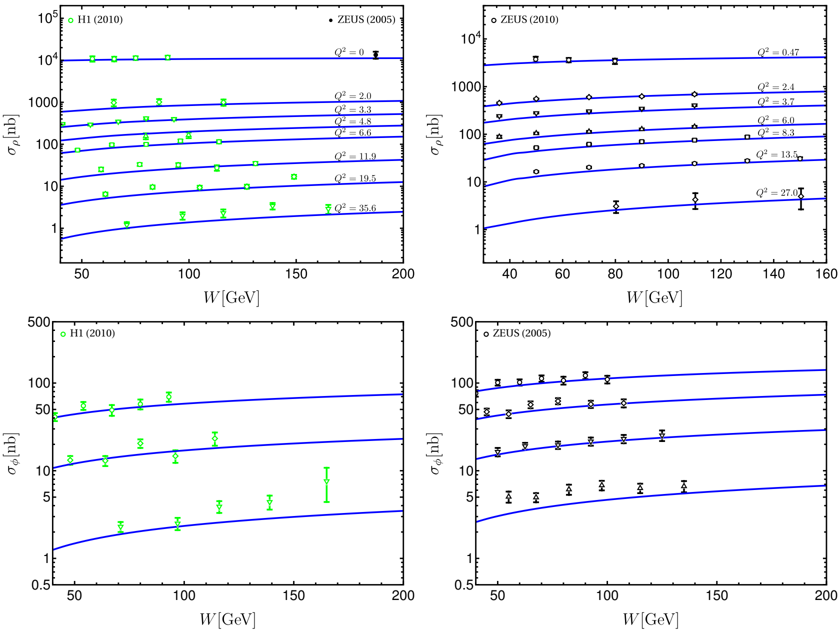
- CGC dipole model free parameters σ_0, λ, x_0 and γ_s fitted from recent H1 and ZEUS (2015) structure function F_2 data (with $x_Bj \leq 0.01$ and $Q^2 \in [0.045, 45]$ GeV^2) for $m_{u,d} \sim 0.046$.

$$F_2(Q^2, x_{Bj}) = \frac{Q^2}{4\pi^2\alpha_{em}} \left(\sigma_L^{\gamma^* p}(Q^2, x_{Bj}) + \sigma_T^{\gamma^* p}(Q^2, x_{Bj})\right)$$

- The fitted parameters are $\sigma_0 = 26.3$ mb, $\gamma_s = 0.741, \lambda = 0.219, x_0 = 1.81 \times 10^{-5}$ with a χ^2/d.o.f $= 1.03$.

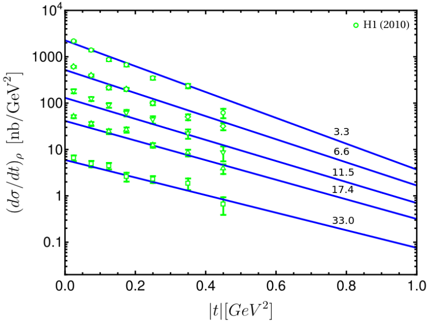
— E. Iancu, et al. B 590, 199 (2004), Ahmady, Sandapen, and Sharma PRD 94, (2016)

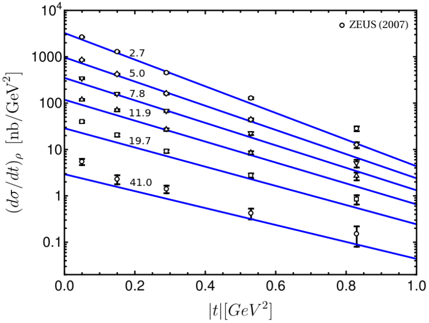
• Cross section as a function of COM energy W in different Q^2 bins : HERA

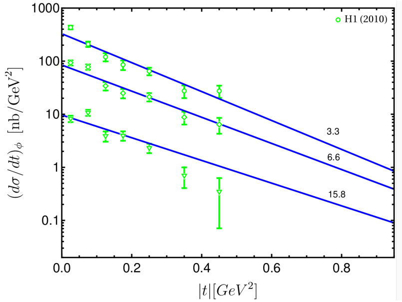


— H1 Collaboration : NPB 463 (1996), JHEP (2010), ZEUS Collaboration : NPB 718 (2005)

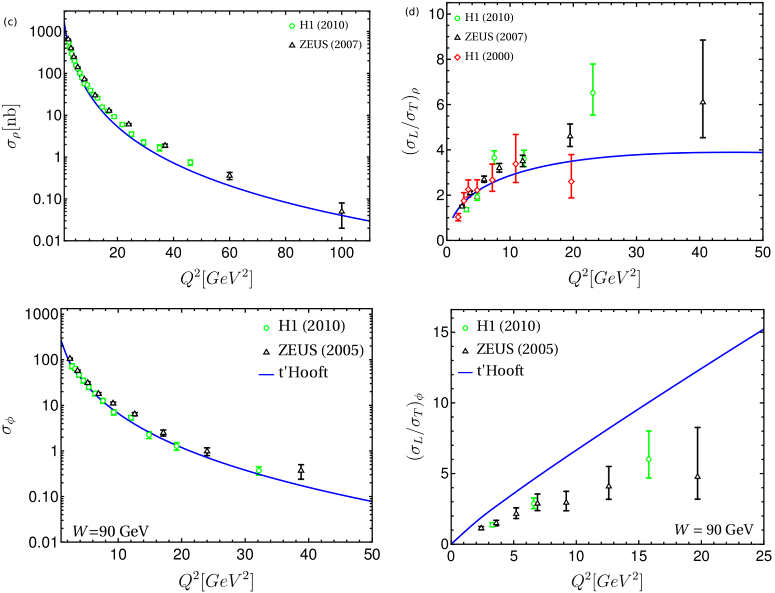
- ρ and ϕ vector meson production differential cross-section with $|t|$:







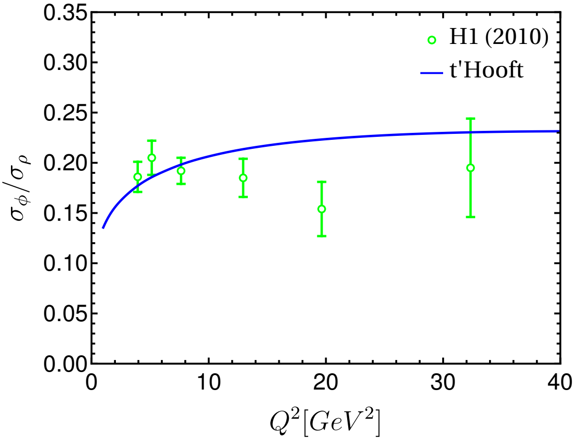
- ρ and ϕ vector meson production total cros-section as a function of Q^2 at fixed W,



— H1 Collaboration JHEP (2010), ZEUS Collaboration : NPB 718 (2005), PMC Phys. A1,(2007).

- If the ρ and the ϕ had identical masses and holographic wave functions, this ratio is simply given by the squared ratio of the effective electric charges of the quark-antiquark coupling to the photon :

$$\lim_{Q^2\to\infty} \frac{\sigma_\phi}{\sigma_\rho} = \frac{e_s^2}{e_{u/d}^2} = \left(\frac{1/3}{1/\sqrt{2}}\right)^2 = 0.22$$



— H1 Collaboration JHEP (2010)

Conclusion

- Color glass condensate (CGC) is a theoretical framework widely used to explain physical phenomena occurring within proton saturation region.
- CGC dipole model provides a good fit to 2015 HERA combined data on F_2
- Light-Front Holographic AdS/QCD predictions for diffractive ρ and ϕ production are in good agreement with the HERA data
- The ϕ to ρ total cross section ratios are found to be independent of $(Q^2 + M_V^2)$ and consistent with ratio expected from quark charge counting, $\phi : \rho = 2 : 9$.
- The study of VM production at HERA thus provides new insights for the understanding of QCD.

Thanks for your attentation ! !