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

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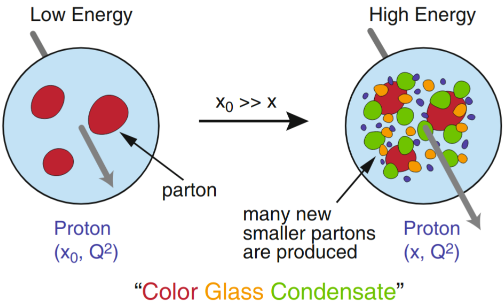
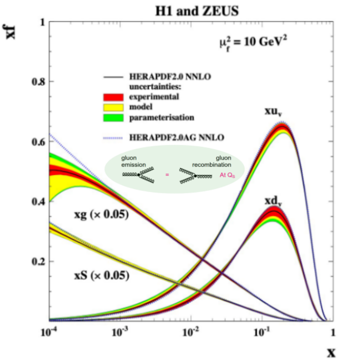
Light-Cone 2024 : Hadron Physics in the EIC era

Outline

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



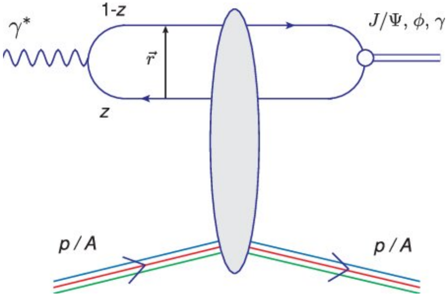


• Color glass condensate (CGC) is a popular effective field theory for explaining physical phenomena in the proton saturation region.

— 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

- Dipole approach :



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

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

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

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

β_λ being the ratio of the real to imaginary components of the scattering amplitude and B_D is diffractive slope parameter.

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

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 :

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

Using the matrix method $\Rightarrow$ $\chi(x) \simeq x^{\beta_1}(1-x)^{\beta_2}$, with

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

- Total Holographic vector meson light-front wavefunction :

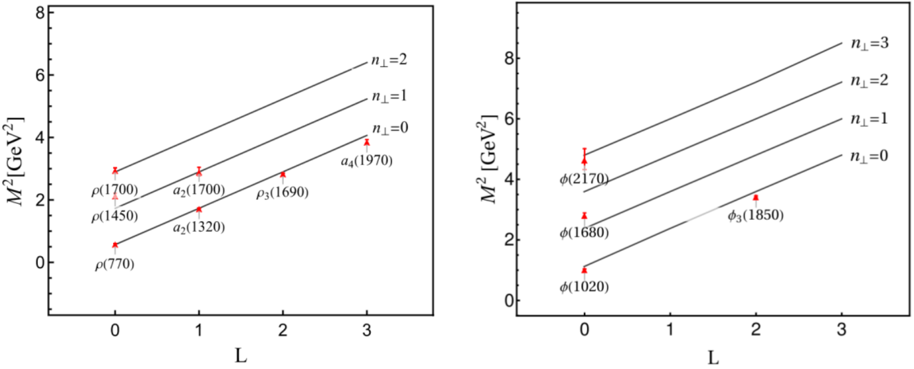
$$\Psi_\lambda(x,\zeta) = \mathcal{N}_\lambda\sqrt{x(1-x)}x^{\beta_1}(1-x)^{\beta_2}\exp\left[-\frac{\kappa^2\zeta^2}{2}\right]$$

— Teramond, S.J. Brodsky PRD, 104 (2021), C. Mondal et al. PLB, 823 (2021), J.R. Hiller, Ann. Phys. 337 (2013)

Model predictions : Mass spectrum

- Using both the holographic Schrödinger Equation together with the 't Hooft Equation ρ and ϕ meson mass spectra :

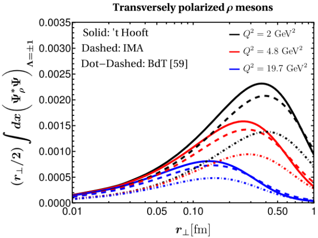
$$M^2(n_\perp, n_\parallel, J, L) = 4\kappa^2\left(n_\perp + \frac{J+L}{2}\right) + M_\parallel^2(n_\parallel, m_q, m_{\bar{q}}, g)\ ,$$

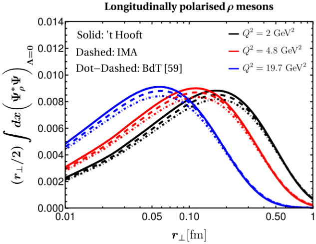


— BG, C. Mondal, S. Kaur PRD, 109 (2024), BG, C. Mondal, S. Kaur (manuscript in prepration), C. Mondal et al. PLB, 823 (2021)

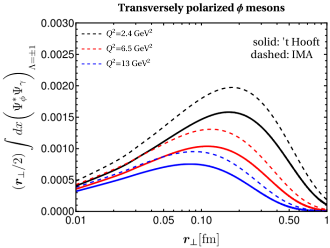
LFWFs overlap

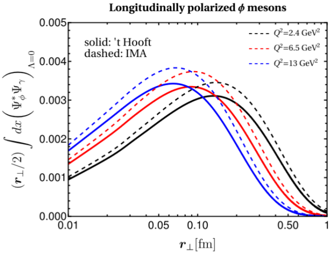
- ρ-meson production scattering amplitude $\propto \Psi^{\gamma^*,\lambda}_{h,\bar{h}}(r,x;Q^2) \otimes \Psi^{\rho,\lambda}_{h,\bar{h}}(r,x)$





- ϕ-meson production scattering amplitude $\propto \Psi^{\gamma^*,\lambda}_{h,\bar{h}}(r,x;Q^2) \otimes \Psi^{\phi,\lambda}_{h,\bar{h}}(r,x)$





— BG, C. Mondal, S. Kaur PRD, 109 (2024), Teramond and S. J. Brodsky, PRD 104 (2021), M. Ahmady et

Dipole cross section

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

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

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

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

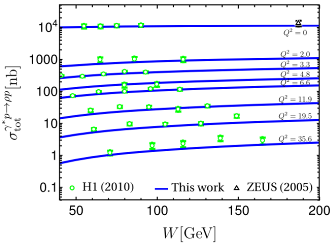
• CGC dipole model free parameters σ_0, λ, x_0 and γ_s fitted from recent H1 and ZEUS (2015) structure function F_2 data (with $x_Bj \le 0.01$ and $Q^2 \in [0.045, 45]$ GeV^2) for $m_{u,d} \sim 0.046$.

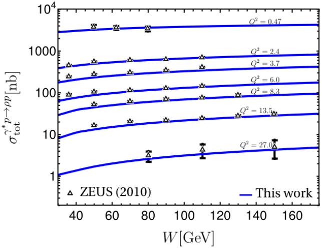
$$F_2(Q^2, x_{Bj}) = \frac{Q^2}{4\pi^2\alpha_{em}} \left(\sigma_L^{\gamma^* p}(Q^2, x_{Bj}) + \sigma_T^{\gamma^* p}(Q^2, x_{Bj})\right)$$

• 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 $\chi^2/\text{d.o.f} = 1.03$.

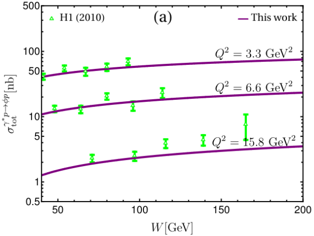
— E. Iancu, et al. B 590, 199 (2004), Ahmady, Sandapen, and Sharma PRD 94, (2016)

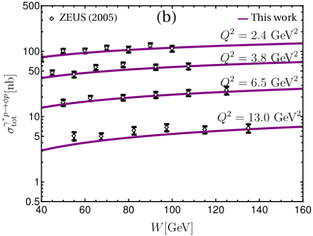
- ρ meson cross-section as a function of COM energy W in different Q^2 bins :





- ϕ meson cross-section as a function of COM energy W in different Q^2 bins :

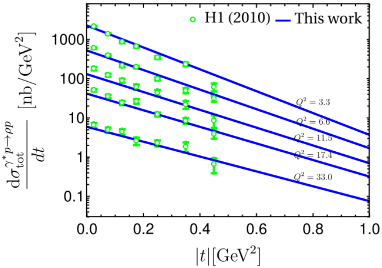


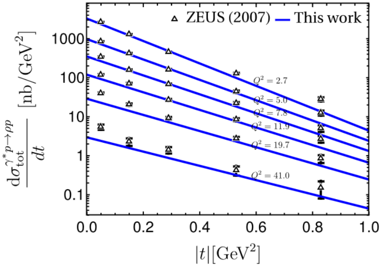


— BG, C. Mondal et al. PRD(2024) ; H1 Collaboration : NPB 463 (1996), JHEP (2010) ; ZEUS Collaboration : NPB 718 (2005)

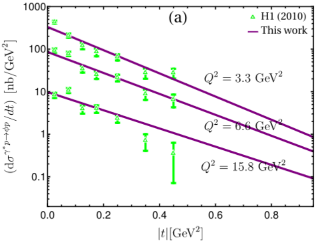
Dependence on t : $\mathrm{d}\sigma \propto e^{-B_D t}$

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





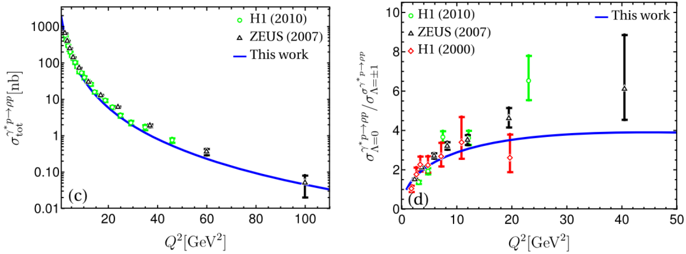
- ϕ vector meson production differential cross-section with $|t|$:



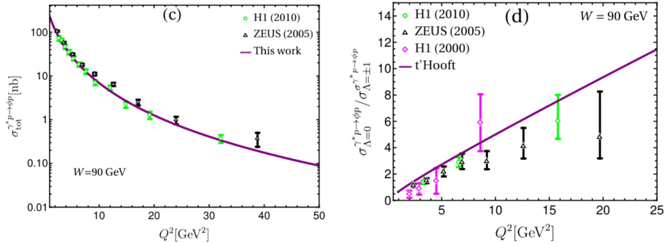
— BG, C. Mondal et al. PRD(2024) ; H1 Collaboration : JHEP (2010) ; ZEUS Collaboration (2007)

Dependence on Q^2

- ρ vector meson production total cros-section as a function of Q^2 at fixed $W = 75$ GeV :



- ϕ vector meson production total cros-section as a function of Q^2 at fixed $W = 90$ GeV :

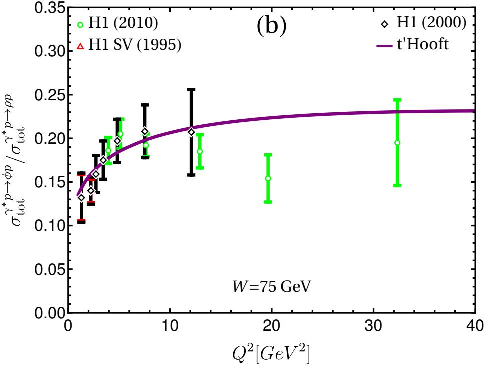


— BG, C. Mondal et al. PRD(2024) ; H1 Collaboration JHEP (2010) ; ZEUS Collaboration : NPB 718 (2005) ;

ϕ to ρ meson cross section ratio

- ϕ to ρ cross-section ratio is simply given by the squared ratio of the effective electric charges of the quark-antiquark coupling to the photon :

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



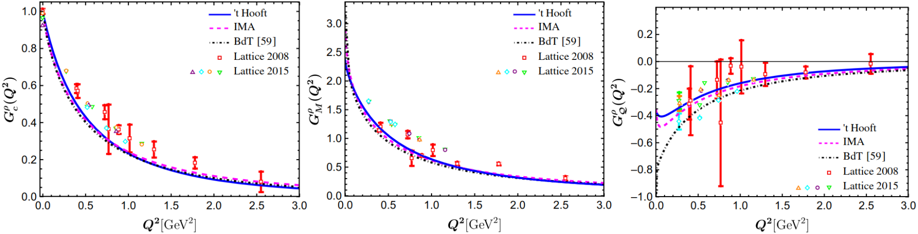
- H1 : $\frac{\sigma(\phi)}{\sigma(\rho)} = 0.191 \pm 0.007$ (stat.)$^{+0.008}_{-0.006}$ (syst.) for $\left(Q^2 + M_V^2 \geq 2 \text{ GeV}^2\right)$.

— BG, C. Mondal, S. Kaur (manuscript in prepration) ; H1 Collaboration JHEP (2010) ; H1 Collaboration : Physics Letters B 483 (2000)

Electromagnetic Form Factors : ρ meson

- The EM FFs : plus component of the electromagnetic current, $J^+(0)$:

$$I^+_{\Lambda',\Lambda}(Q^2) \triangleq \langle V(P',\Lambda')|\frac{J^+(0)}{2P^+}|V(P,\Lambda)\rangle = \sum_{h,\bar{h}} \int_0^1 \int_0^\infty \frac{dx d^2\mathbf{k}_\perp}{16\pi^3} \Psi^{\Lambda' *}_{h\bar{h}}(x, \mathbf{k}_\perp + (1-x)\mathbf{q}_\perp) \Psi^{\Lambda}_{h\bar{h}}(x, \mathbf{k}_\perp)$$

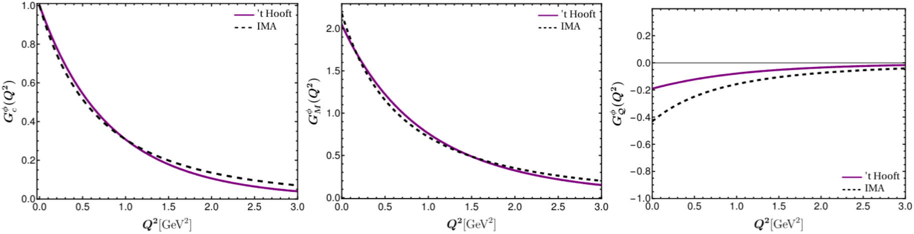


- The static properties : rms charge radius, magnetic moment, and quadrupole moment :

$$\langle r^2_\rho \rangle = -\frac{6}{G_C(0)} \frac{\partial G_C(Q^2)}{\partial Q^2}|_{Q^2\to 0}, \quad \boxed{eG_C(0) = e, \quad eG_M(0) = 2M_V\mu, \quad eG_Q = M_V^2 \mathcal{Q}}.$$

	This work			BLFQ	BSE	Lattice QCD	Lattice QCD	LFQM	NJL model
	't Hooft	IMA	BdT	[111]	[118]	[119]	[121]	[108]	[120]
$\sqrt{\langle r^2_\rho \rangle}$	0.75	0.94	0.91	0.44	0.73	0.819(42)	0.55(5)	0.52	0.82
μ_ρ	2.40	2.90	3.30	2.15	2.01	2.067(76)	2.17(10)	1.92	2.48
$\mathcal{Q}_\rho$	−0.027	−0.023	−0.066	−0.063	−0.026	−0.0452(61)	−0.035	−0.028	−0.070

- Eectric, magnetic, and quadrupole form factors of ϕ mesons :



- The static properties : rms charge radius, magnetic moment, and quadrupole moment :

	This work	LFH-IMA	BdT	Ref. [52]	Ref. [45]
$\sqrt{\langle r_\phi^2 \rangle}$	0.54	0.60	0.58	0.472	0.52
μ_ϕ	2.04	2.18	2.32	2.09	2.08
$\mathcal{Q}_\phi$	−0.006	−0.013	−0.015	−0.830	−0.32

— S. J. Brodsky and J. R. Hiller, PRD(1992) ; H.M. Choi and C.R. Ji, PRD(2004) ; BG et al. (manuscript in prepration) ; Y.-Z. Xu, D. Binosi, et al. (2019) ; R. J. Hern ́andez-Pinto, et al. (2024), 2410.23813.

Conclusion

- Color glass condensate (CGC) is a theoretical framework widely used to explain physical phenomena occurring within proton saturation region.
- Light-Front Holographic AdS/QCD predictions along with 't Hooft 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, $\phi : \rho = 2 : 9$.
- Electromagnetic Form factors and static properties are also consistent with the available predictions in litreture.
- The study of VM production at HERA thus provides new insights for the understanding of QCD.

Thanks for your attentation ! !