Probing gluon saturation through precision studies of inclusive photon+(di)jet production in e+A DIS at small x

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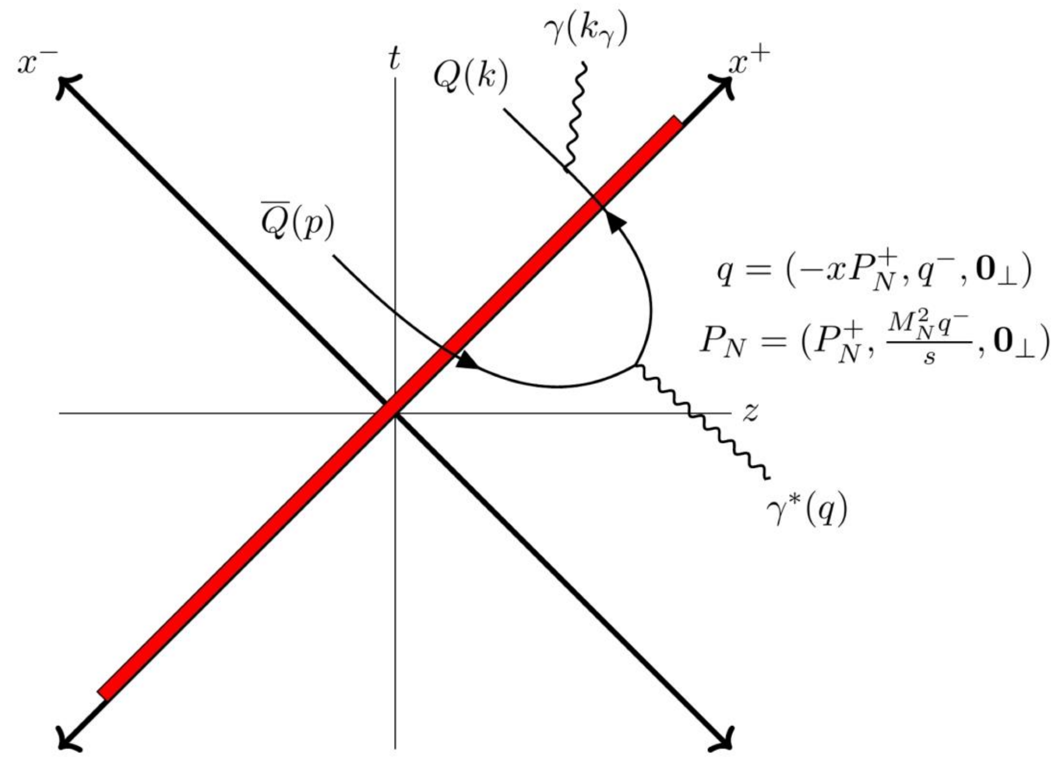
KR, Venugopalan, JHEP 1805 (2018) 013 [arXiv: 1802.09550] ,
Phys. Rev. D 101 (2020) 3, 034028 [arXiv: 1911.04530] , Phys. Rev. D 101 (2020) 7, 071505 [arXiv: 1911.04519]

Kolbe, KR, Salazar, Schenke, Venugopalan, in preparation .

The process: $e + A \to e + q\bar{q} + \gamma + X$ (inclusive)

KR, Venugopalan, arXiv: 1802.09550, 1911.04530, 1911.04519



The right moving nucleus with large P_N^+ has its x^- extent Lorentz contracted

$$\text{fixed } Q^2 \gg \Lambda_{QCD}^2\,,\;\; s \to \infty\,,\;\; x_{Bj} \to 0$$

Regge-Gribov small-x kinematics

Complements similar computations for pA collisions

Gelis, Jalilian-Marian, hep-ph/0205037
Dominguez, Marquet, Xiao, Yuan, arXiv:1101.0715
Benic, Fukushima, arXiv:1602.01989;
Benic, Fukushima, Garcia-Montero, Venugopalan, arXiv:1609.09424, 1807.03806

- **Clean** initial and final states
- Can be measured at a future **E**lectron **I**on **C**ollider (**EIC**)

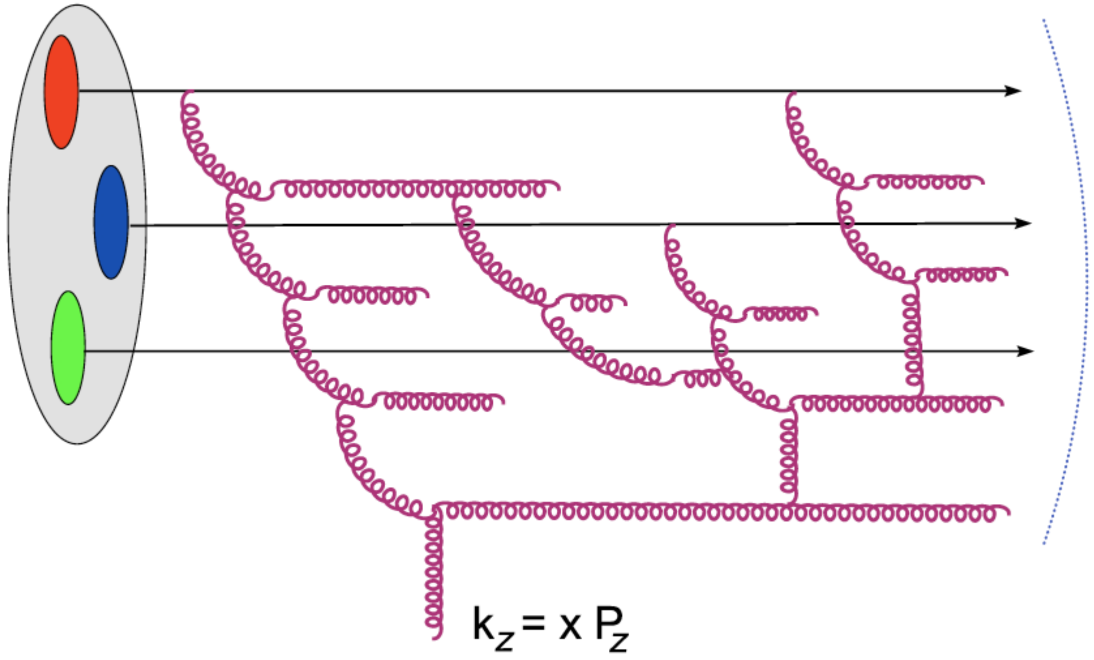
Measured at HERA at higher energies but lower luminosities

Inclusive γ arXiv: 0711.4578, 0909.4223

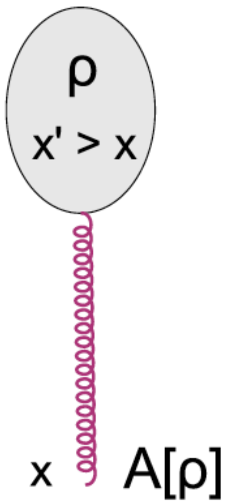
Inclusive γ +jet arXiv: 1206.2270

- Computed for the **first time** in the **Color Glass Condensate (CGC)** effective field theory

McLerran, Venugopalan, hep-ph/9309289
Iancu, Leonidov, McLerran, hep-ph/0011241
Iancu, Venugopalan, hep-ph/0303204



Born-Oppenheimer separation of modes



Static color sources (large x)

$$D_\nu F^{\nu\mu,a}(x) = \delta^{\mu+}\rho_A^a(x^-, \boldsymbol{x}_\perp)$$

Dynamical gluon fields (small x)

CGC EFT provides a framework in QCD to systematically discuss

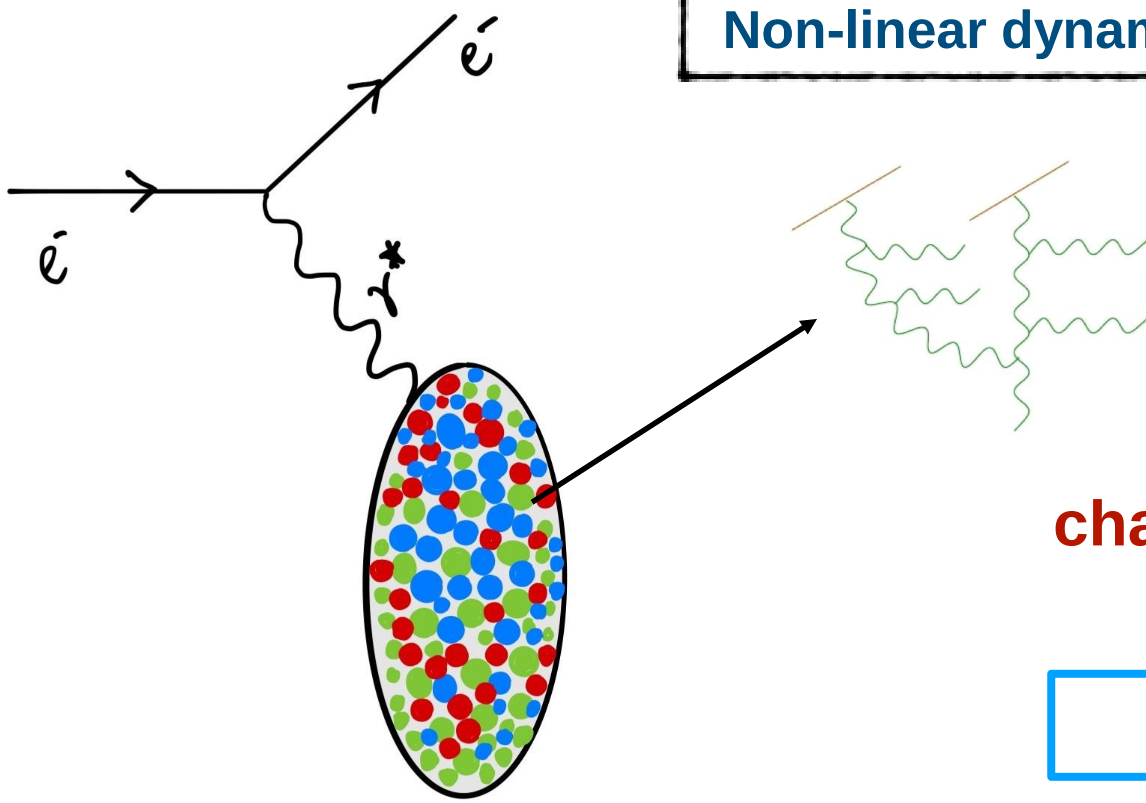
“classical” (multiple scattering) gluon radiation in the presence of sources
and
“quantum” evolution (shadowing) of the strong sources: JIMWLK RGE

Why is it interesting?

See Matt Sievert's talk (Tue) for a review

γ^* probe responds to strongly correlated gluonic matter

Non-linear dynamics !!!



Recombination vs. gluon bremsstrahlung

generates a resolution scale growing with energy

$$Q_s^2 \sim A^{1/3} s^{\lambda}$$

characteristic "semi-hard" scale in Regge limit

Weak coupling: $\alpha_S(Q_s) \ll 1$, ***for*** $Q_s(x) \gg \Lambda_{QCD}$

Allows perturbative methods to compute

- **"hard" coefficient functions – "impact factors"**
- **Energy evolution of "soft" non-perturbative component – JIMLWK RGE**

$\gamma + q\bar{q}$ in DIS at NLO contains a wealth of information…

- Dijets+photon to NLO accuracy

$k_\gamma \to 0$ → **Inclusive dijet**

Integrate out $q/\bar{q}$ → **Inclusive photon + jet**

Integrate out $q\bar{q}$ → **Inclusive photon**

$k_\gamma \to 0$ and Integrate out $q\bar{q}$ → **Fully inclusive DIS**

Real gluon emissions → $q\bar{q}g + \gamma$ **at LO**

Real gluon emissions$+k_\gamma \to 0$ → $q\bar{q}g$ **at LO**

Differential measurements are sensitive to non-trivial many-body gluon correlations

Extant NLO results for DIS only for fully inclusive or diffractive measurements

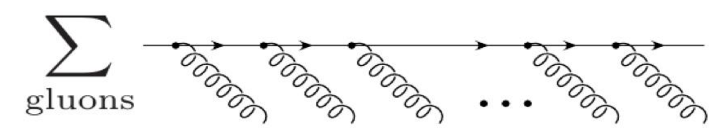
Fully Inclusive DIS
- Balitsky, Chirilli, arXiv: 1009.4729
- Beuf, arXiv: 1606.00777, 1708.06557
- Hanninen, Lappi, Paatelainen, arXiv: 1711.08207

Diffractive DIS dijet → Boussarie, Grabovsky, Szymanowski, Wallon, arXiv:1606.00419

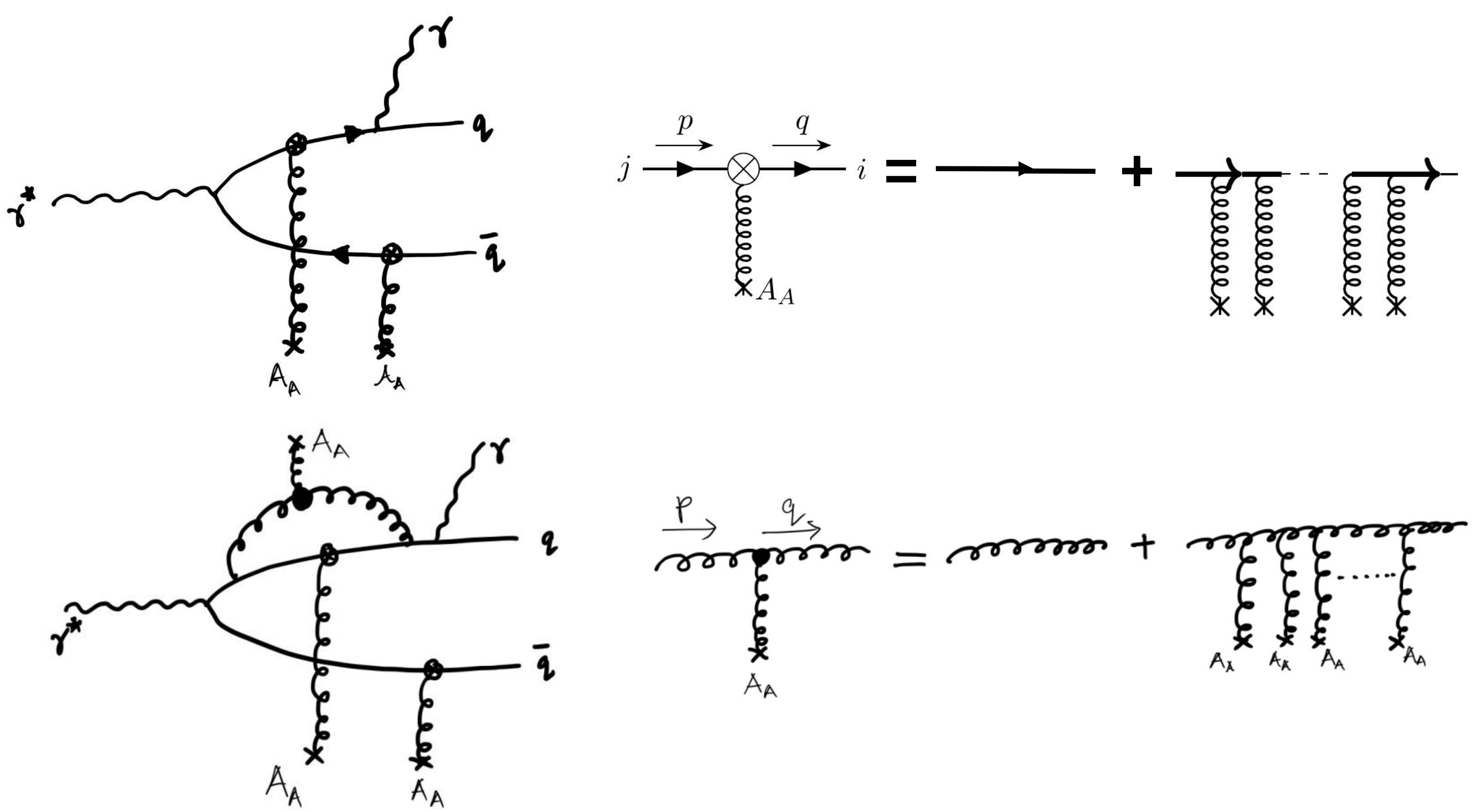
Systematic power counting in the CGC

At each order in α_s , higher twist (multiple scattering) contributions are resummed to all orders

Observable: $\mathrm{O} = \sum_{n=0} c_n \alpha_S^n$ **where** $c_n = \sum_{j=1}^{\infty} d_{nj} (g\rho_A)^j$



In the momentum space computation, these are incorporated into "dressed" quark and gluon propagators



These exponentiate into Wilson lines

CGC EFT also allows for a resummation of $\alpha_s ln(^1/_x)$ enhancements in loop computations, thanks to the JIMWLK Wilsonian RG equation

$$O = \sum_n A_n(\alpha_s L_x)^n + \alpha_s\, B_n(\alpha_s L_x)^n + \ldots \qquad A_n = \sum_j a_{nm}\,(g\rho_A)^m \text{ etc.}$$

$$L_x = \ln(1/x)$$

Fixed order →

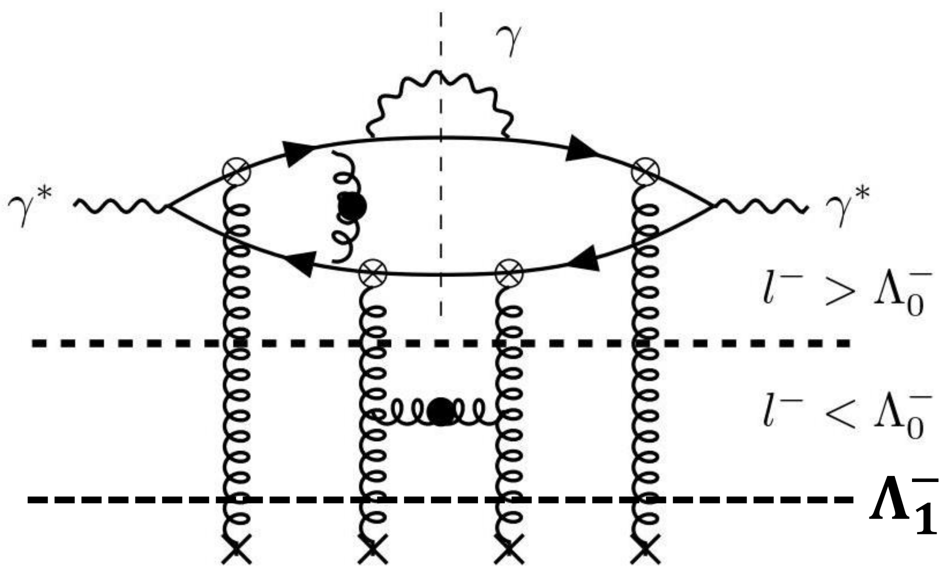
Resummation ↓

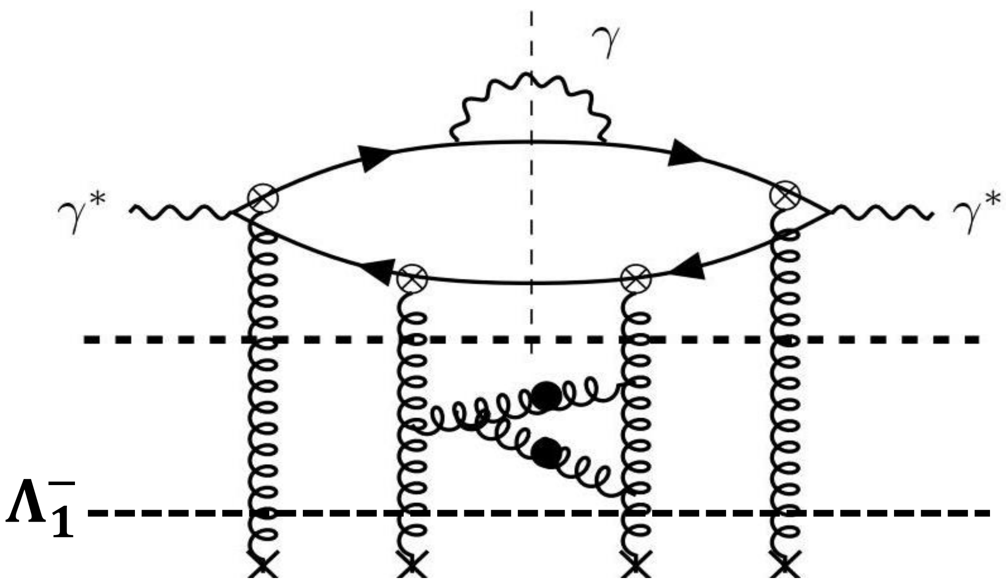
LO	$\boxed{\alpha_S^0}$	**What we have computed**					
NLO	$\alpha_S L_x$	$\boxed{\alpha_S}$					
N^2LO	$\alpha_S^2 L_x^2$	$\alpha_S^2 L_x$	α_S^2				
N^3LO	$\alpha_S^3 L_x^3$	$\alpha_S^3 L_x^2$	$\alpha_S^3 L_x$	α_S^3			
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
N^kLO	$\alpha_S^k L_x^k$	$\alpha_S^k L_x^{k-1}$	……	……	……		α_S^k
	↓ LLx	↓ $NLLx$	↓ N^2LLx				↓ N^kLLx

The NLO impact factor is crucial to attain NLO+NLLx accuracy

DIS photon+dijet at NLO+NLLx

KR, Venugopalan, arXiv: 1911.04530, 1911.04519





Collect leading log (LL) pieces $\alpha_s\, ln\,(\frac{\Lambda_1^-}{\Lambda_0^-})$

+

NLO pieces~α_s in the photon+dijet impact factor

Collect next-to-leading-log (NLL) pieces $\alpha_s^2\, ln\,(\frac{\Lambda_1^-}{\Lambda_0^-})$

+

LO pieces~α_s^0 in the photon+dijet impact factor

By combining the NLO impact factor with the NLL resummed evolution kernel (NLO BK/JIMWLK), we can obtain $\alpha_s^3\, ln\,(1/x)$ accuracy.

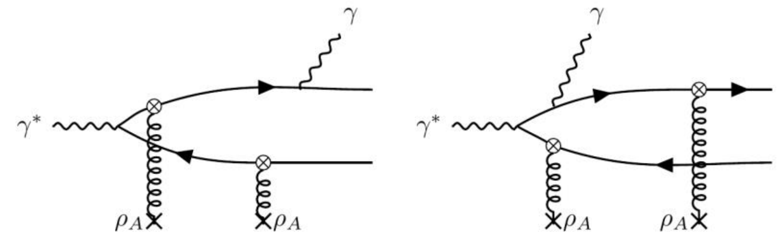
NLO BK
- Balitsky, Chirilli, arXiv: 0710.4330
- Kovchegov, Weigert, hep-ph/0609090

NLO JIMWLK
- Kovner, Lublinsky, Mulian, arXiv:1310.0378
- Grabovsky, arXiv:1307.5414
- Caron-Huot, arXiv:1309.6521
- Balitsky, Chirilli, arXiv: 1309.7644
- Balitsky, Grabovsky, arXiv: 1405.0443
- Lublinksy, Mulian, arXiv: 1610.03453

LO impact factor results

KR, Venugopalan, arXiv: 1802.09550

$$\mathcal{M}_{LO}^{hadron} =$$



$$+q \leftrightarrow \bar{q}$$

Triple differential cross-section

$$\frac{\mathrm{d}^3\sigma^{\mathrm{LO}}}{\mathrm{d}x\,\mathrm{d}Q^2\mathrm{d}^6K_\perp\mathrm{d}^3\eta_K} = \frac{\alpha_{em}^2 q_f^4 y^2 N_c}{512\pi^5 Q^2}\,\frac{1}{(2\pi)^4}\,\frac{1}{2}\,L^{\mu\nu}\tilde{X}_{\mu\nu}^{\mathrm{LO}}$$

Lepton tensor

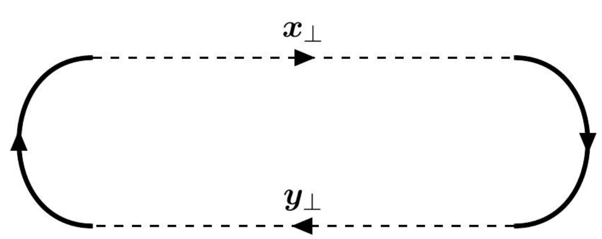
Hadron tensor

$$\tilde{X}_{\mu\nu}^{\mathrm{LO}} \propto \Xi(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp; \boldsymbol{y}'_\perp, \boldsymbol{x}'_\perp) \longrightarrow$$ **Non-perturbative input on strongly correlated gluons**

$$\boxed{\Xi(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp; \boldsymbol{y}'_\perp, \boldsymbol{x}'_\perp) = 1 - D_{xy} - D_{y'x'} + Q_{y'x';xy}}$$

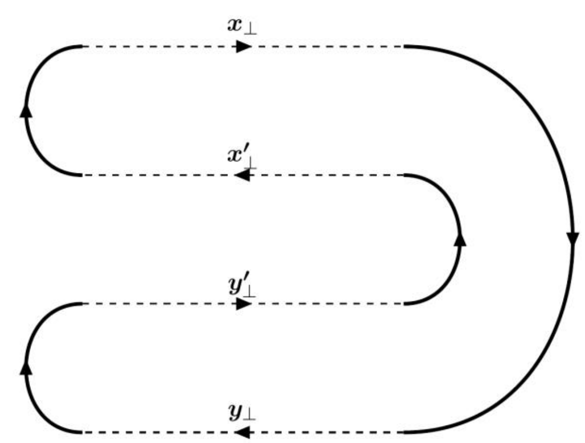
Dipole Wilson line correlator

$$D_{xy} = \frac{1}{N_c}\left\langle \mathrm{Tr}\left(\tilde{U}(\boldsymbol{x}_\perp)\tilde{U}^\dagger(\boldsymbol{y}_\perp)\right)\right\rangle$$



Quadrupole Wilson line correlator

$$Q_{xy;zw} = \frac{1}{N_c}\left\langle \mathrm{Tr}\left(\tilde{U}(\boldsymbol{x}_\perp)\tilde{U}^\dagger(\boldsymbol{y}_\perp)\tilde{U}(\boldsymbol{z}_\perp)\tilde{U}^\dagger(\boldsymbol{w}_\perp)\right)\right\rangle = Q_{zw;xy}$$



Ubiquitous many-body correlators/building blocks of high energy QCD

NLO impact factor results

KR, Venugopalan, arXiv: 1911.04530, 1911.04519

Triple differential cross-section to NLO+NLLx

$$\frac{\mathrm{d}^3\sigma^{\mathrm{LO+NLO+NLL}x;\mathrm{jet}}}{\mathrm{d}x\mathrm{d}Q^2\mathrm{d}^6K_\perp\mathrm{d}^3\eta_K} = \frac{\alpha_{em}^2 q_f^4 y^2 N_c}{512\pi^5 Q^2}\frac{1}{(2\pi)^4}\frac{1}{2}L^{\mu\nu}\tilde{X}_{\mu\nu}^{\mathrm{LO+NLO+NLL}x;\mathrm{jet}}$$

Hadron tensor to NLO+NLLx

Jets were defined using a cone algorithm and we used small cone approximation

$$\tilde{X}_{\mu\nu}^{\mathrm{LO+NLO+NLL}x;\mathrm{jet}} = \int[\mathcal{D}\rho_A]\,W_{x_{\mathrm{Bj}}}^{NLLx}[\rho_A]\Bigg[\Bigg(1+\frac{2\alpha_S C_F}{\pi}\Bigg\{-\frac{3}{4}\ln\left(\frac{R^2|\boldsymbol{p}_{J\perp}|\,|\boldsymbol{p}_{K\perp}|}{4z_J z_K Q^2 e^{\gamma_E}}\right)+\frac{7}{4}-\frac{\pi^2}{6}\Bigg\}\Bigg)\tilde{X}_{\mu\nu}^{\mathrm{LO;jet}}[\rho_A] + \tilde{X}_{\mu\nu;\mathrm{finite}}^{\mathrm{NLO;jet}}[\rho_A]\Bigg]$$

$\alpha_s^2\, ln\,(1/x)$ enhanced contributions are absorbed into the redefinition of large x source distribution

We are missing terms of $O(\alpha_s^3\, ln\,(1/x))$ which are formally part of an NNLO calculation

Work in progress

Obtain results for the sub channels

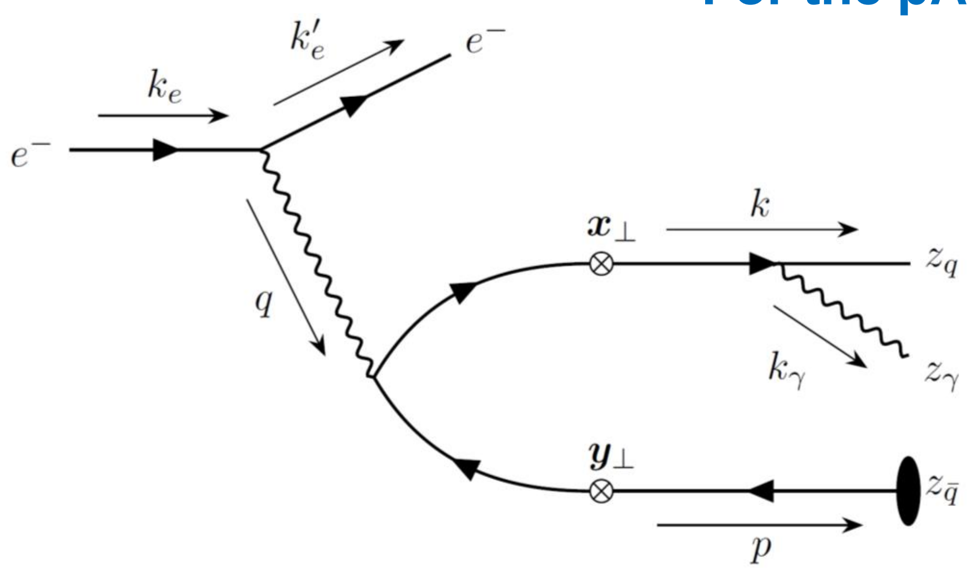
- Inclusive dijet
- Inclusive photon + jet
- Inclusive photon

First CGC results to NLO+NLL accuracy

Inclusive prompt photon+quark(jet) production at LO

Kolbe, KR, Salazar, Schenke, Venugopalan, in preparation

For the pA case, see Jamal's talk (Thursday)



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Start from photon+dijet cross-section

KR, Venugopalan, arXiv: 1802.09550

3 more graphs

Integrate over the antiquark phase space

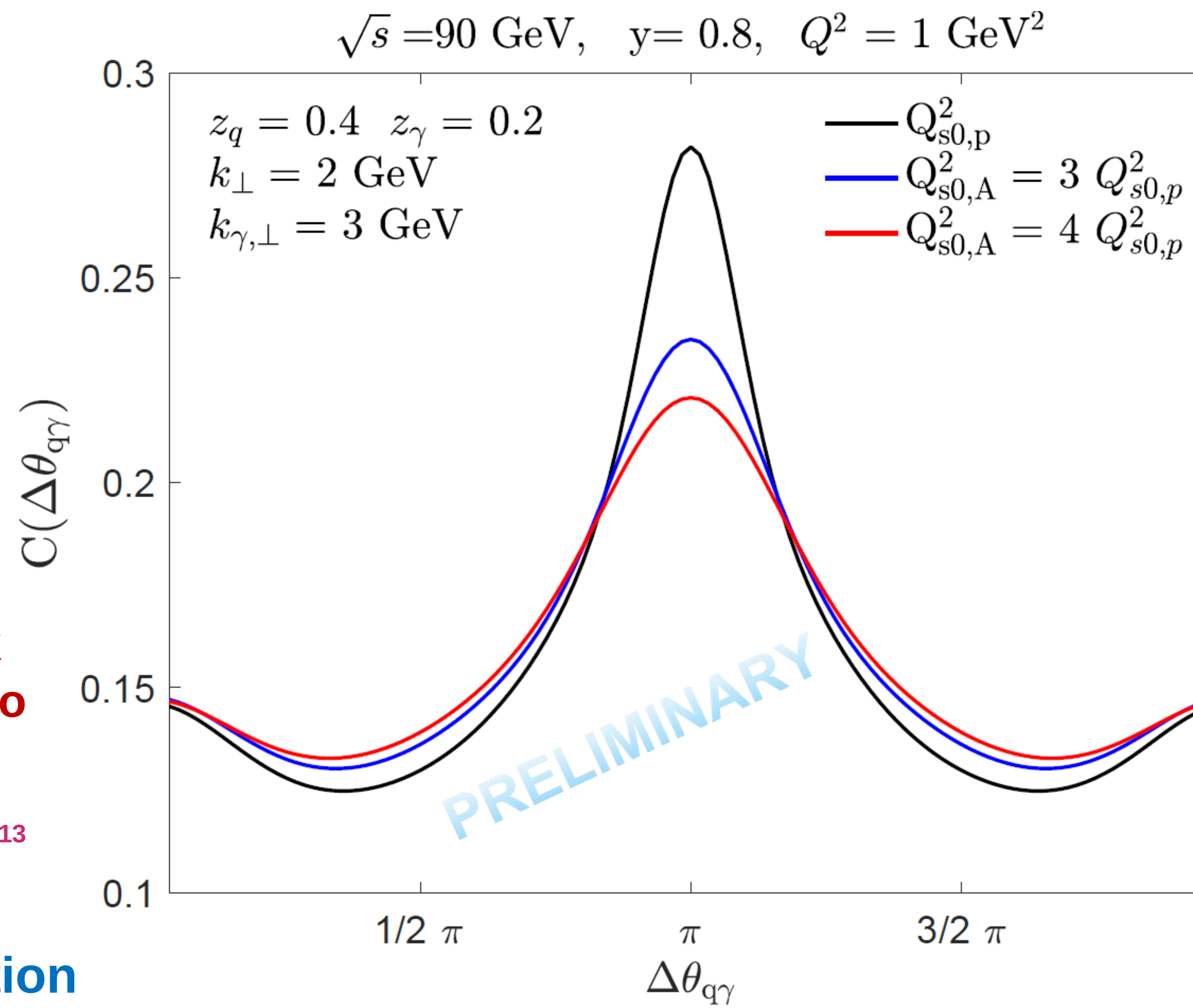
- Fully analytical expressions obtained for the “direct” photon+jet cross-section.
- Color structure mostly contains dipoles, and some quadrupoles (numerics challenging but possible)

See for eg. LO inclusive dijet numerics including the quadrupole

Mäntysaari, Mueller, Salazar, Schenke, arXiv: 1912.05586

Study qualitative features in a limit, $\mathbf{k}_{\gamma\perp} \gtrsim Q_s$ where the color structure contains only dipoles

$$C(\Delta\theta_{q\lambda}) = \frac{\frac{d\sigma_D^{eA\to e'+\gamma+q+X}}{d^2\mathbf{k}_\perp d^2\mathbf{k}_{\gamma\perp} dz_q dz_\gamma}}{\int d(\Delta\theta_{q\lambda}) \frac{d\sigma_D^{eA\to e'+\gamma+q+X}}{d^2\mathbf{k}_\perp d^2\mathbf{k}_{\gamma\perp} dz_q dz_\gamma}}$$



Suppression of the back-to-back peak with increasing Q_s^2 similar to dihadrons in DIS

Zheng, Aschenaeur, Lee, Xiao, arXiv: 1403.2413

Signature of gluon saturation

Generic caveat for EIC kinematics: Small-x constraint $(x < 0.01)$ severely restricts transverse momenta of produced particles in differential measurements.

See Shu-Yi Wei's talk (Monday) for dihadrons

Summary

- **We performed a first computation of inclusive photon+dijet production in e+A DIS at small x in the CGC framework to NLO in α_S .**

- **The simple structure of the dressed quark and gluon propagators in the "wrong" light cone gauge enables higher order computations in momentum space using otherwise standard covariant perturbation theory (pQCD) techniques.**

- **The NLO impact factor in combination with extant results on NLO JIMWLK provide the ingredients towards extending the precision to $\mathcal{O}(\alpha_S^3 \ln(1/x))$ accuracy.**

- **These results can be used to compute up to the same accuracy a number of particle production channels. The LO results for inclusive photon+jet are complete and will be available soon.**

- **Within simple limits, we see a suppression of the back-to-back peak in γ +jet with Q_s similar to diharons.**

Outlook

One of the main goals of the EIC program

The physics of the saturation regime is novel and non-trivial

The semihard $k_{\perp} \sim Q_s$ from the target generalizes functional forms in the collinear framework to nontrivial integrals that in many instances have to be performed numerically

Much more complicated than their collinear counterparts

It needs to progress to where perturbative QCD is - higher order computations, tests of universality, factorization, global analyses etc.

The momentum space methods developed in our work are general and can be implemented in higher order CGC computations for p+A collisions

A systematic comparison between e+A and p+A data will enhance discovery potential of saturation

This will also help shed light on profound questions such as:

What is truly universal at small x?

Thank you and stay safe…