A new era for small-x physics

Highlights and ongoing efforts

California EIC Consortium Collaboration Meeting

UC Davis
July 19th, 2022

Farid Salazar

in collaboration with many people!

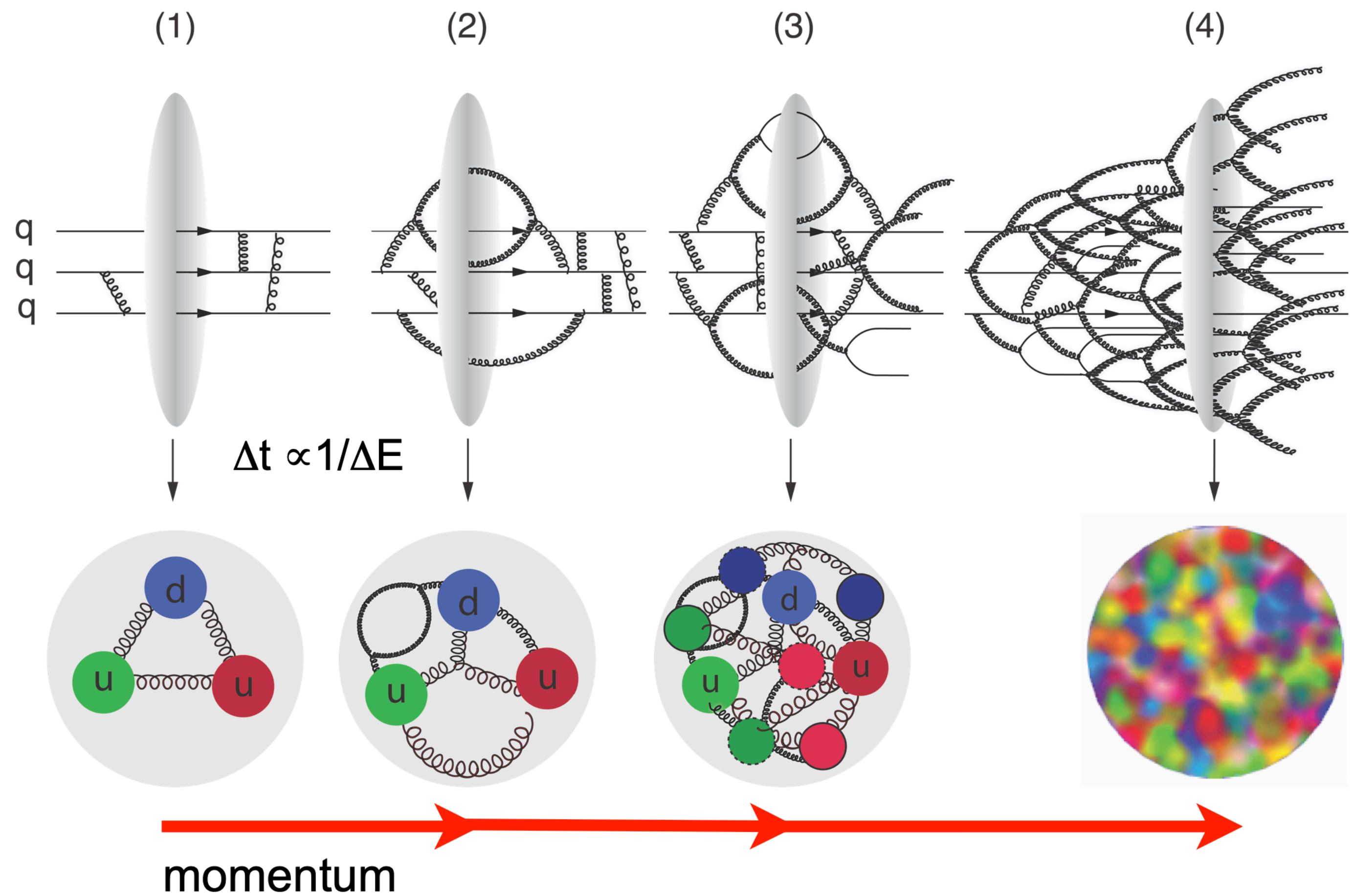
Outline

- Uplifting saturation physics to NLO

- A unified framework for dilute and dense dynamics

- Further ongoing projects

Nuclear matter in the high-energy limit



Artwork: T. Ullrich

Emergence of an energy and nuclear species dependent momentum scale

$$Q_s^2 \propto \left(\frac{A}{x}\right)^{1/3}$$

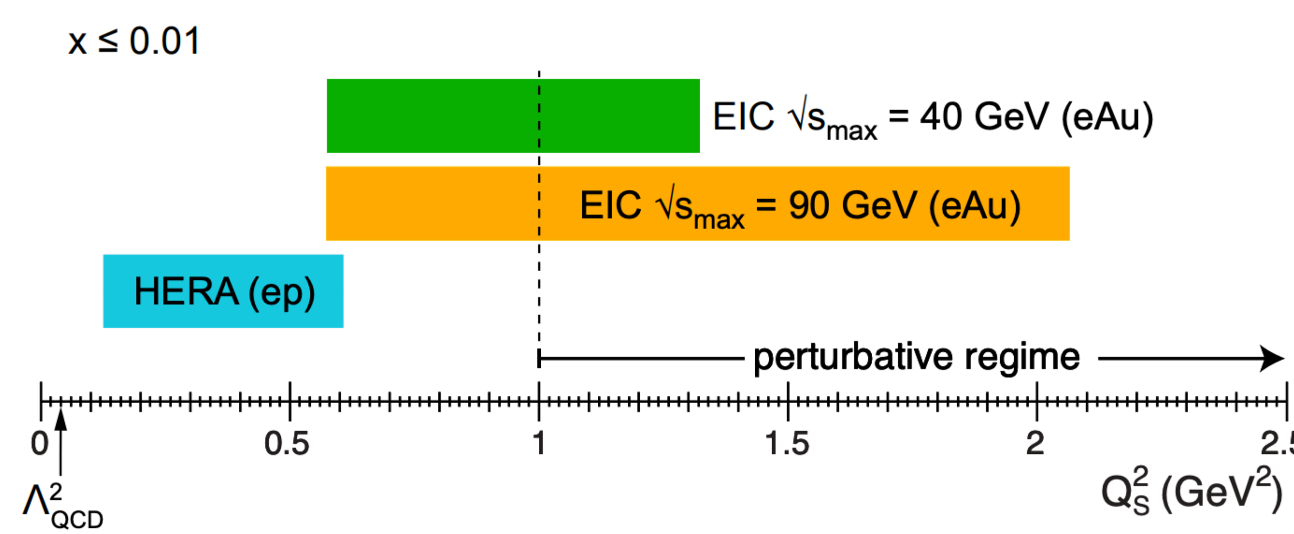
Multiple scattering (higher twist effects)

Non-linear evolution equations (BK/JIMWLK)

Nuclear "Oomph factor" $A^{1/3}$

One of the major objectives of the EIC is the search for a new type of state composed of dense gluon matter

<u>*See Barbara and Barak talks*</u>



Aschenauer et al *(2017)*

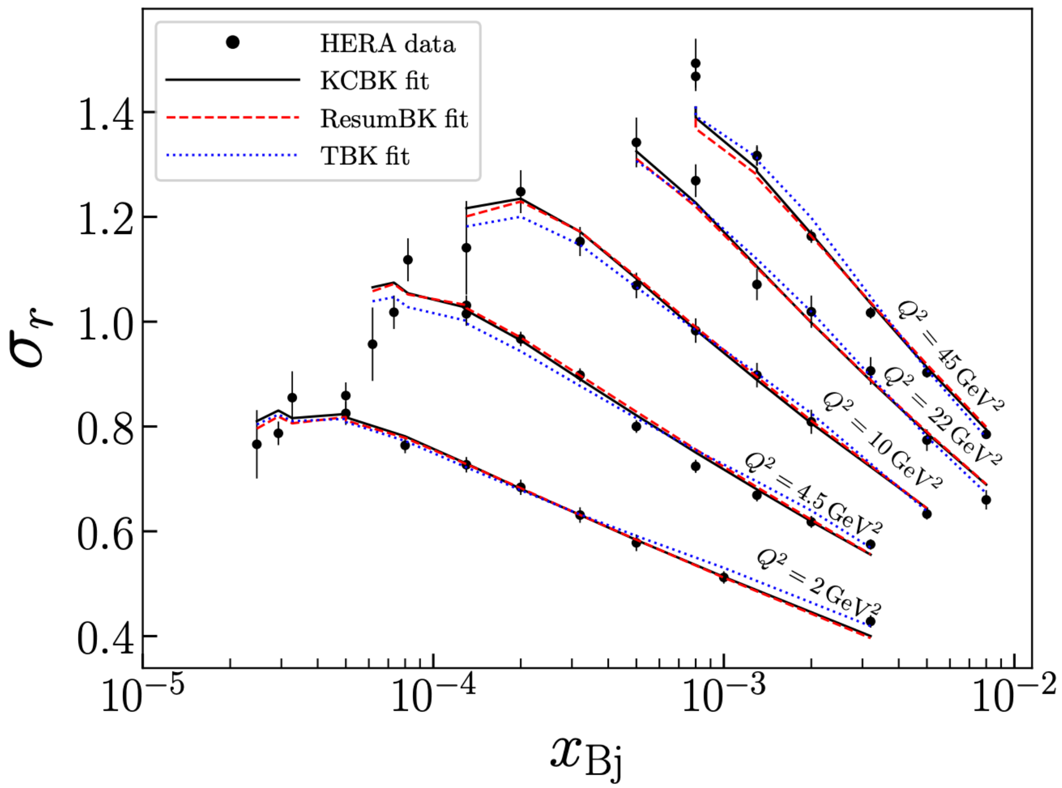
For a recent review see

Mining for gluon saturation at colliders
Astrid Morreale, FS (2021)

Uplifting saturation physics to NLO

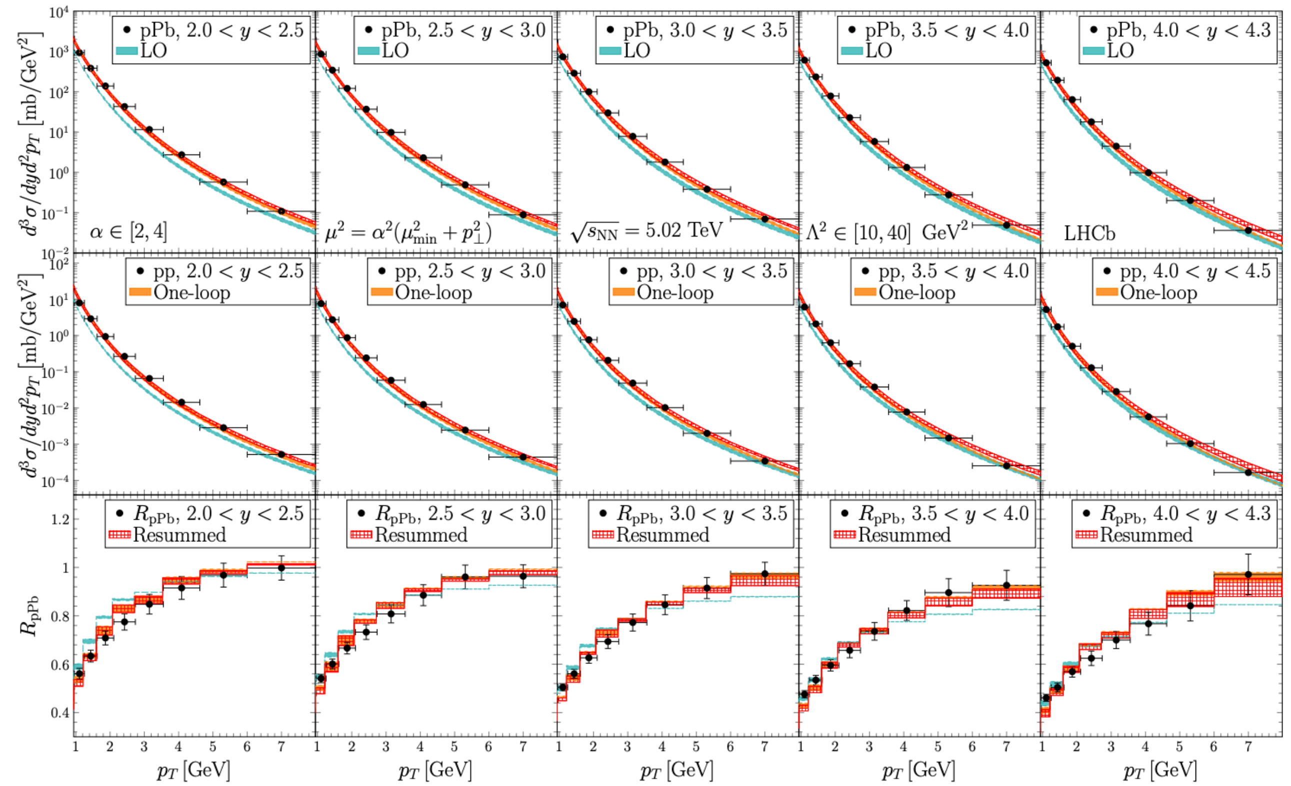
Recent developments

DIS structure functions



Beuf, Lappi, Hänninen, Mäntysaari (2020)

Hadron production in pp (pA)



Shi, Wang, Wei, Xiao (2021)

Many recent developments pushing saturations physics to NLO

Diffractive structure functions

Massive structure functions

Exclusive vector meson production in DIS

Jyväskylä group (Lappi et al, 2020-2022)

Dijet production in DIS *Caucal, FS, Venugopalan (2021)*

Jet production in pA *Liu, Xie, Kang, Liu (2022)*

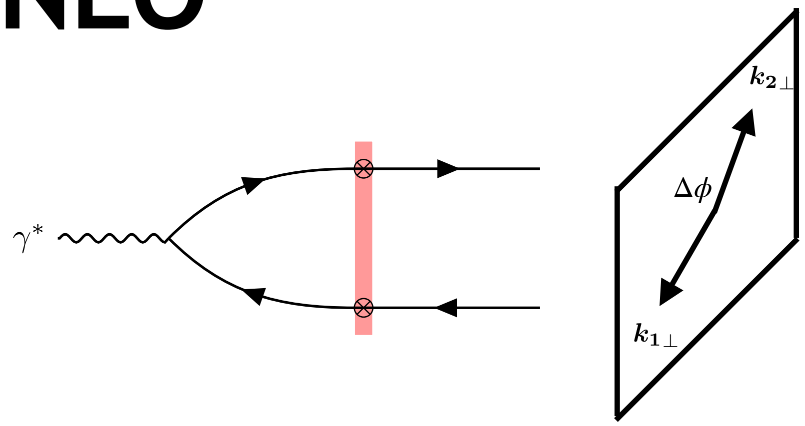
Dijet production in photo-production *Taels et al (2022)*

Dihadron production in DIS *Bergabo, Jalilian-Marian(2022)*

Uplifting saturation physics to NLO

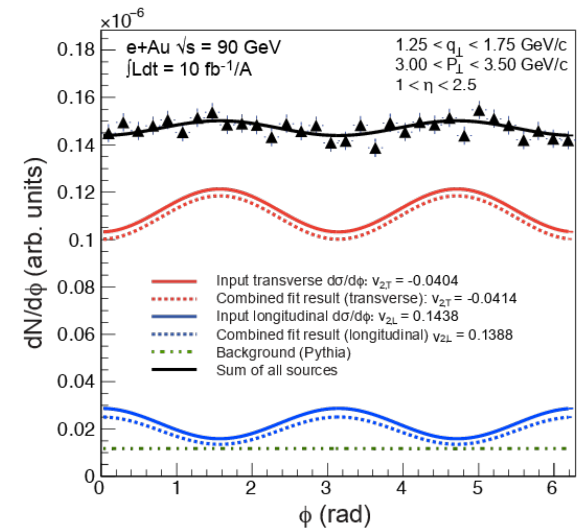
Why dijet production?

Complementary process to fully inclusive



$$Q_Y(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp; \boldsymbol{y}'_\perp, \boldsymbol{x}'_\perp) = \frac{1}{N_c}\langle \mathrm{Tr}\left[V(\boldsymbol{x}_\perp)V^\dagger(\boldsymbol{y}_\perp)V(\boldsymbol{y}'_\perp)V^\dagger(\boldsymbol{x}'_\perp)\right]\rangle_Y$$

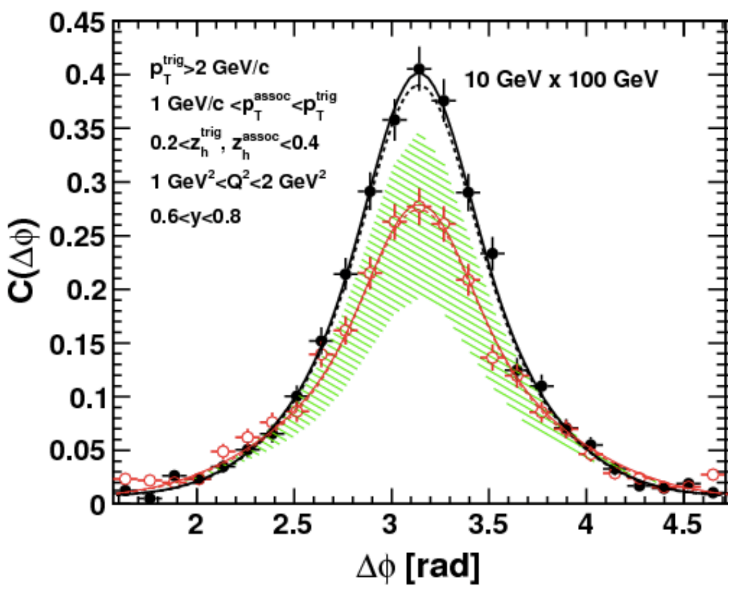
Simplest observable featuring the quadrupole.
JIMWLK factorization beyond the dipole



Dumitru, Skokov, Ullrich (2019)

In the back-to-back limit contact with the (transverse momentum dependent) TMD formalism

Dominguez, Marquet, Xiao, Yuan (2011)



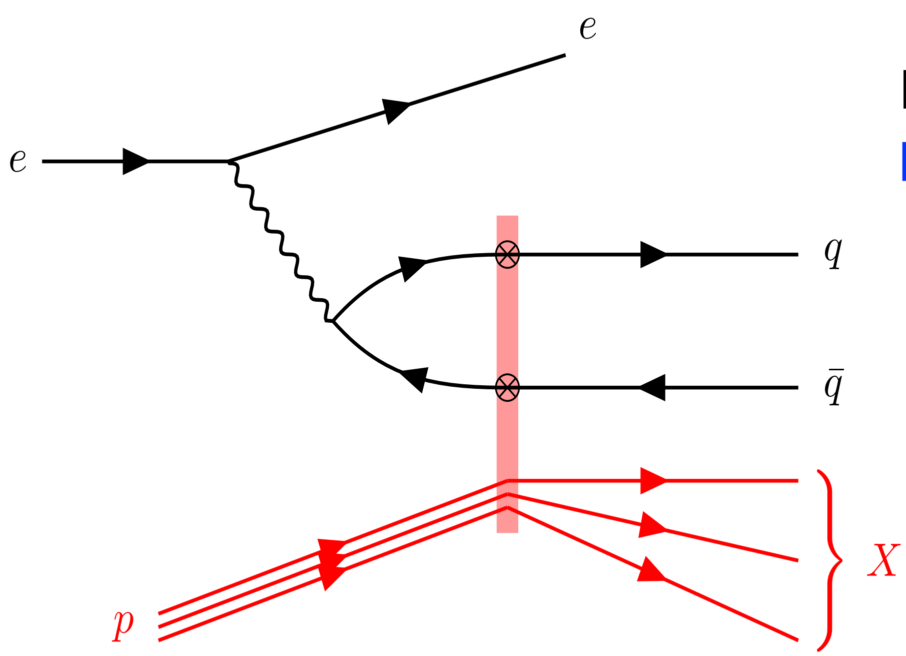
Suppression of back-to-back peak potential signature of gluon saturation (dihadrons)

Zheng, Aschenauer, Lee, Xiao (2014)

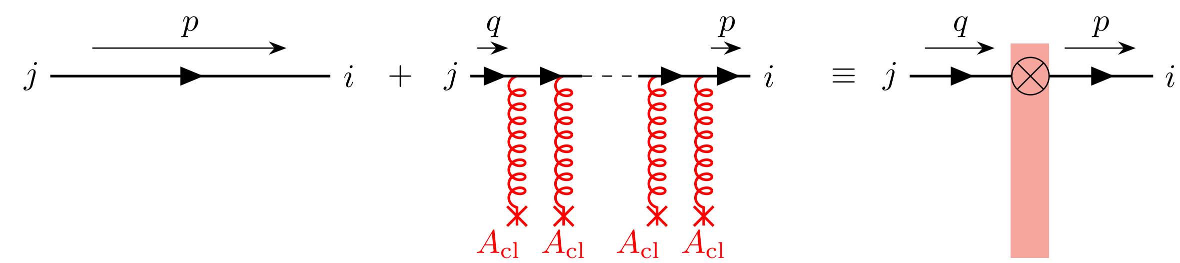
Jets are better proxies of hard partons (than hadrons)

Uplifting saturation physics to NLO

Dijet production: from CGC to TMD



In the CGC the differential cross-section is a convolution of a perturbative factor and correlators of products of Wilson lines



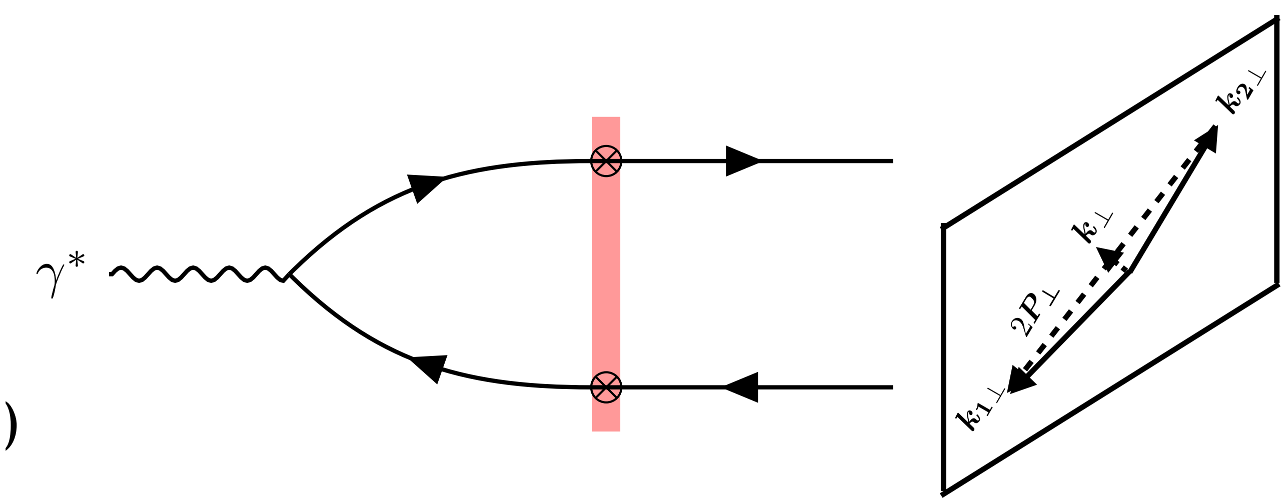
Wilson line resums multiple scatterings

$$V_{ij}(\boldsymbol{x}) = P \exp\left\{ ig \int dx^- A_{cl}^{+,a}(\boldsymbol{x}, x^-) t^a \right\}$$

In the back-to-back dijet configuration, the result can be cast as a product of a hard factor and the WW gluon TMD

Dominguez, Marquet, Xiao, Yuan (2011)

See also Boussarie, Mäntysaari, FS, Schenke (2021)

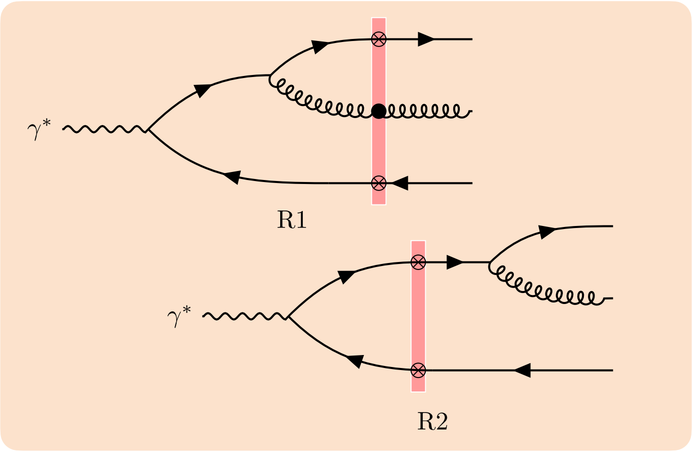


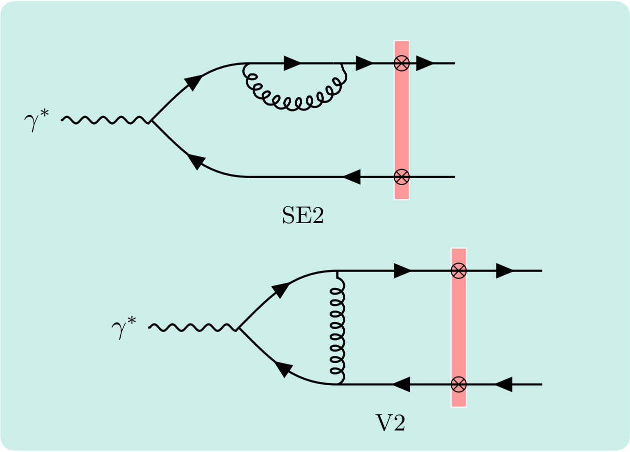
Does this CGC-TMD correspondence hold at NLO?

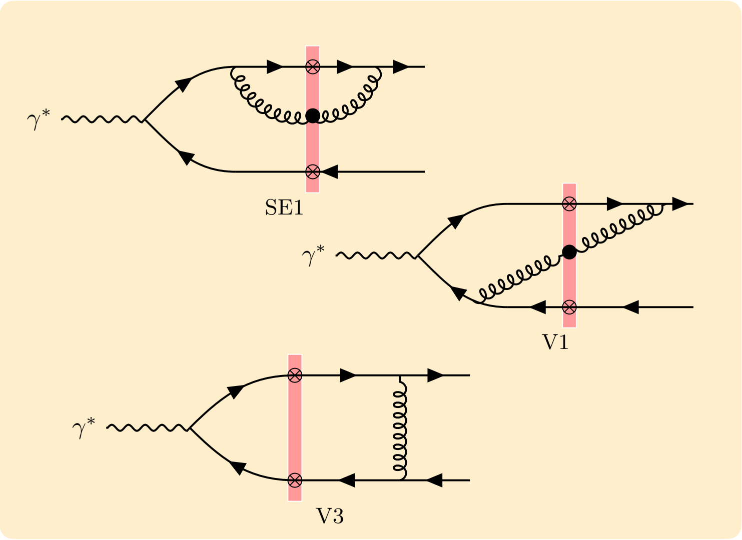
Uplifting saturation physics to NLO

Dijet production in the CGC at NLO

Computed one-loop corrections







Highlights of our results

- Cancellation of UV, soft and collinear divergences
- Large energy (rapidity) logs factorize, and can be resumed via JIMWLK evolution
- Impact factor (free of large energy logs) is finite and can be numerically computed

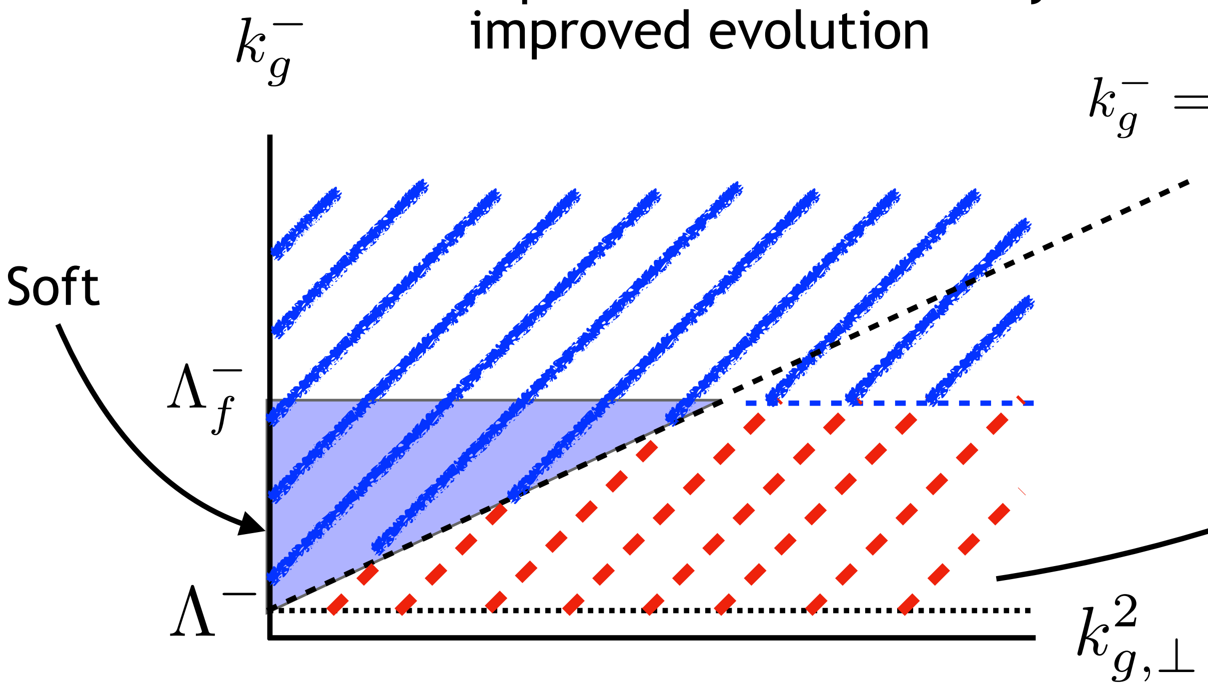
In collaboration with Paul Caucal, and Raju Venugopalan. *2108.06347* *[JHEP 11 (2021) 222]*

Uplifting saturation physics to NLO

From CGC at NLO to TMDs

Sudakov logs in collinear/TMD obtained by Mueller, Xiao, Yuan (2013)

Phase space for kinematically improved evolution



Kinematic constraint:
ordering in + and - momenta

$$k_g^+ \geq \Lambda_f^+ \quad \& \quad k_g^- \leq \Lambda_f^-$$

Taels, Altinoluk, Marquet, Beuf (2022) for photo-production (focused on double logs and large Nc).

$$\mathrm{d}\sigma \sim \mathcal{H}^{ij}(\boldsymbol{P}_\perp, Q, z_1) \int \mathrm{d}^2\boldsymbol{b}_\perp \mathrm{d}^2\boldsymbol{b}'_\perp e^{-i\boldsymbol{k}_\perp\cdot(\boldsymbol{b}_\perp - \boldsymbol{b}'_\perp)} \mathcal{S}(\boldsymbol{P}_\perp^2, \boldsymbol{b}_\perp - \boldsymbol{b}'_\perp) S_{\mathrm{WW}}^{ij}(\boldsymbol{b}_\perp, \boldsymbol{b}'_\perp; Y_f)$$

$$\mathcal{S}(\boldsymbol{P}_\perp^2, \boldsymbol{R}_\perp^2) = \exp\left(-\int_{c_0^2/\boldsymbol{R}_\perp^2}^{\boldsymbol{P}_\perp^2} \frac{\mathrm{d}\mu^2}{\mu^2} \frac{\alpha_s(\mu^2) N_c}{\pi} \left[\underbrace{\frac{1}{2}\ln\left(\frac{\boldsymbol{P}_\perp^2}{\mu^2}\right)}_{\text{Double log}} + \underbrace{\frac{C_F}{N_c} A_0 - A_f}_{\text{Single log}}\right]\right)$$

+ NLO pieces that break TMD factorization

work in preparation (2208.XXXX) with Paul Caucal, Björn Schenke, and Raju Venugopalan

Uplifting saturation physics to NLO

From CGC at NLO to TMDs (next steps)

- Numerical predictions for dijets at NLO

  Implementing kinematically constrained small-x evolution

  Double and single Sudakov log resummation

  Impact on azimuthal asymmetries (extraction of linearly pol gluons)

  Estimate the size of factorization breaking terms (enhanced in nuclei)

  work in progress with Caucal, Schenke, Venugopalan

- Distinguish soft/rapidity divergences using SCET

  A systematic treatment of soft and collinear regions, and rapidity divergences following *Liu, Xie, Kang, Liu (2022)*

  Establish factorization at small-x ala SCET

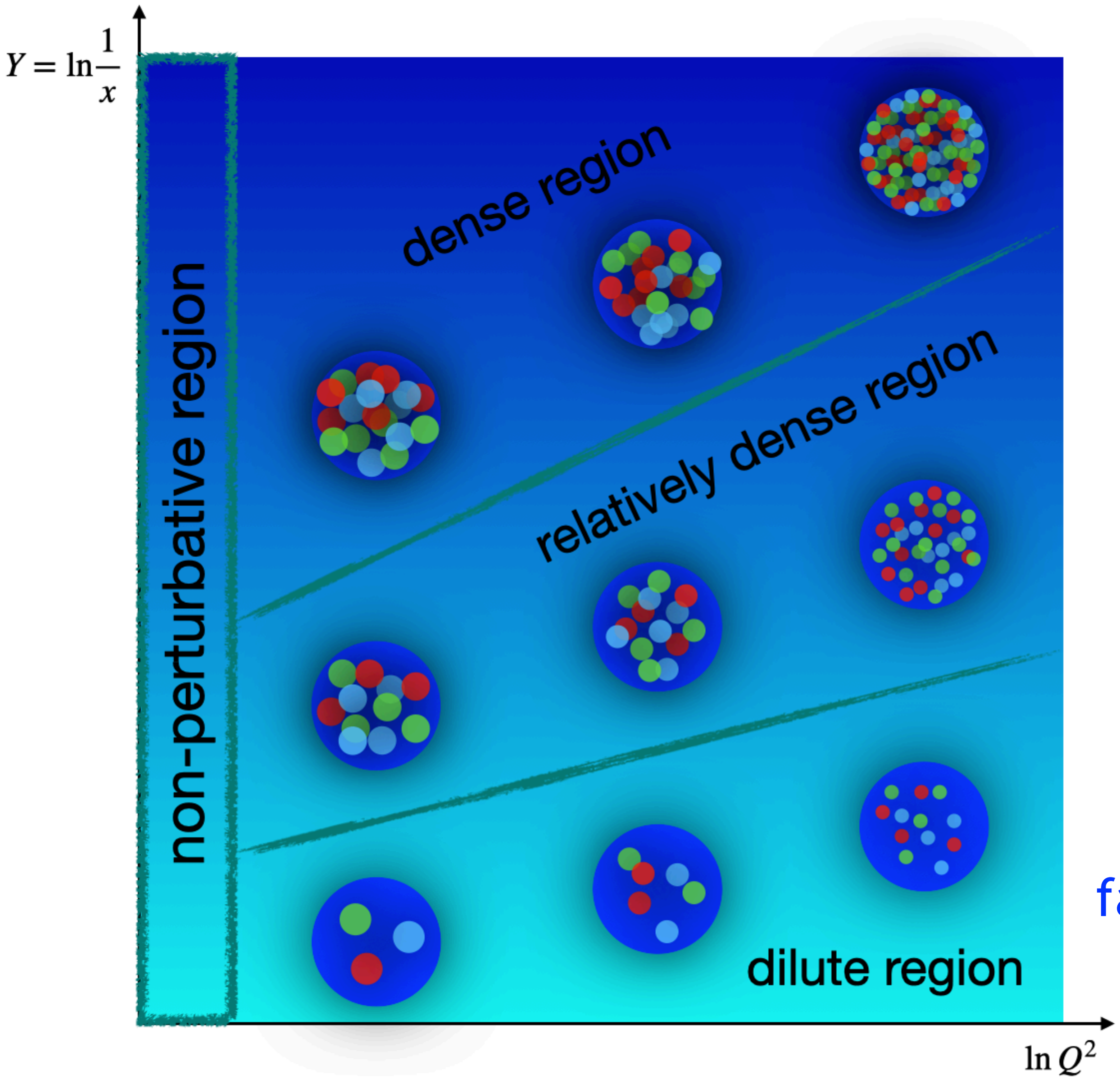
  work in progress with Zhongbo Kang and Xiaohui Liu

see also Zhongbo's talk

A unified framework for dilute-dense dynamics

Anatomy of hadronic matter

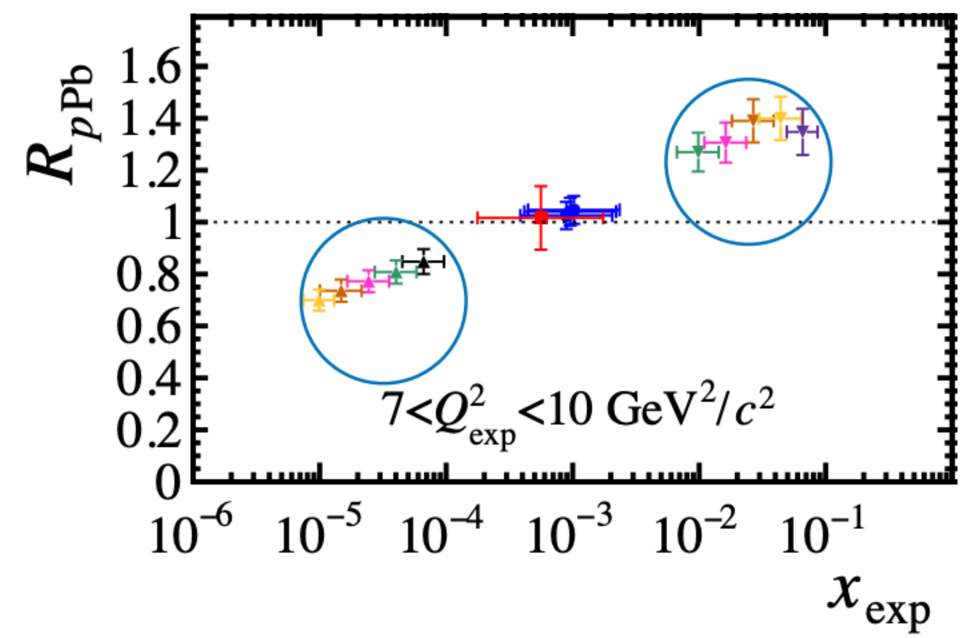
CGC/shock-wave formalism



High-twist formalism

Collinear factorization

Nuclear modification of charged particle production



Enhancement (backward region) vs suppression (forward region)

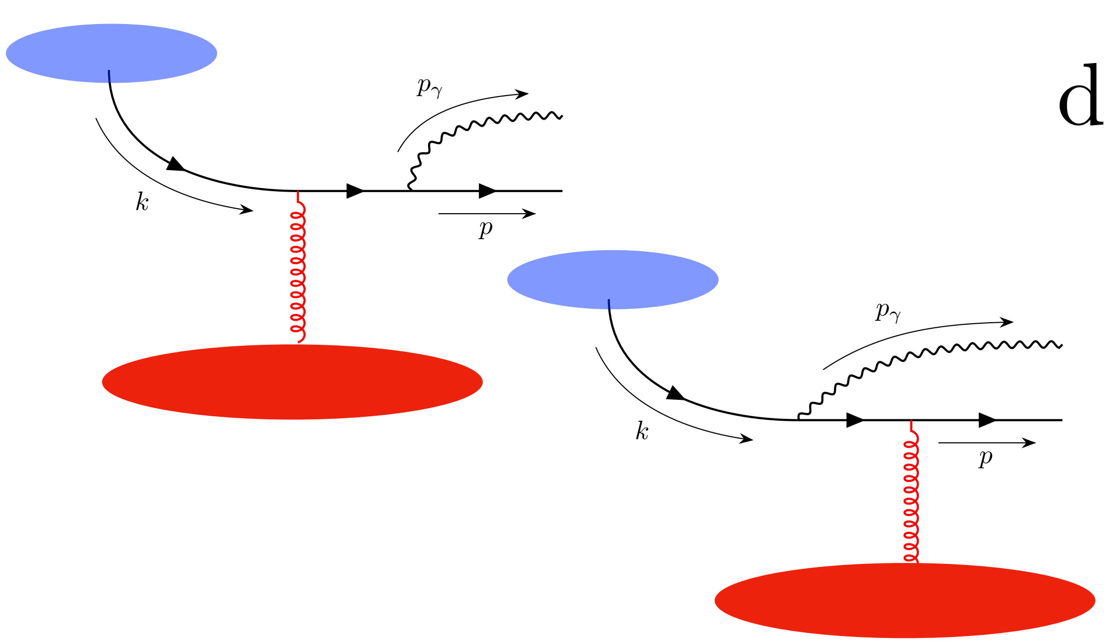
LHCb Collaboration.
Phys. Rev. Lett. 128, 142004

Can we establish a framework that simultaneously describes both regions?

A unified framework for dilute-dense dynamics

Beyond leading twist in collinear factorization

A simple example:
direct photon production in pA



$$\mathrm{d}\sigma \sim \frac{1}{p_{\gamma\perp}^4}\left[A + B\frac{\langle k_\perp^2\rangle}{p_{\gamma\perp}^2} + C\frac{\langle k_\perp^2\rangle^2}{p_{\gamma\perp}^4}\ldots\right]$$

leading twist
(twist-2)

Higher twist
(twist-4 and twist-6)

Higher twist become important at moderate $p_{\gamma\perp}^2$!

What is the intrinsic momentum $\langle k_\perp^2\rangle$ of the nucleus ?

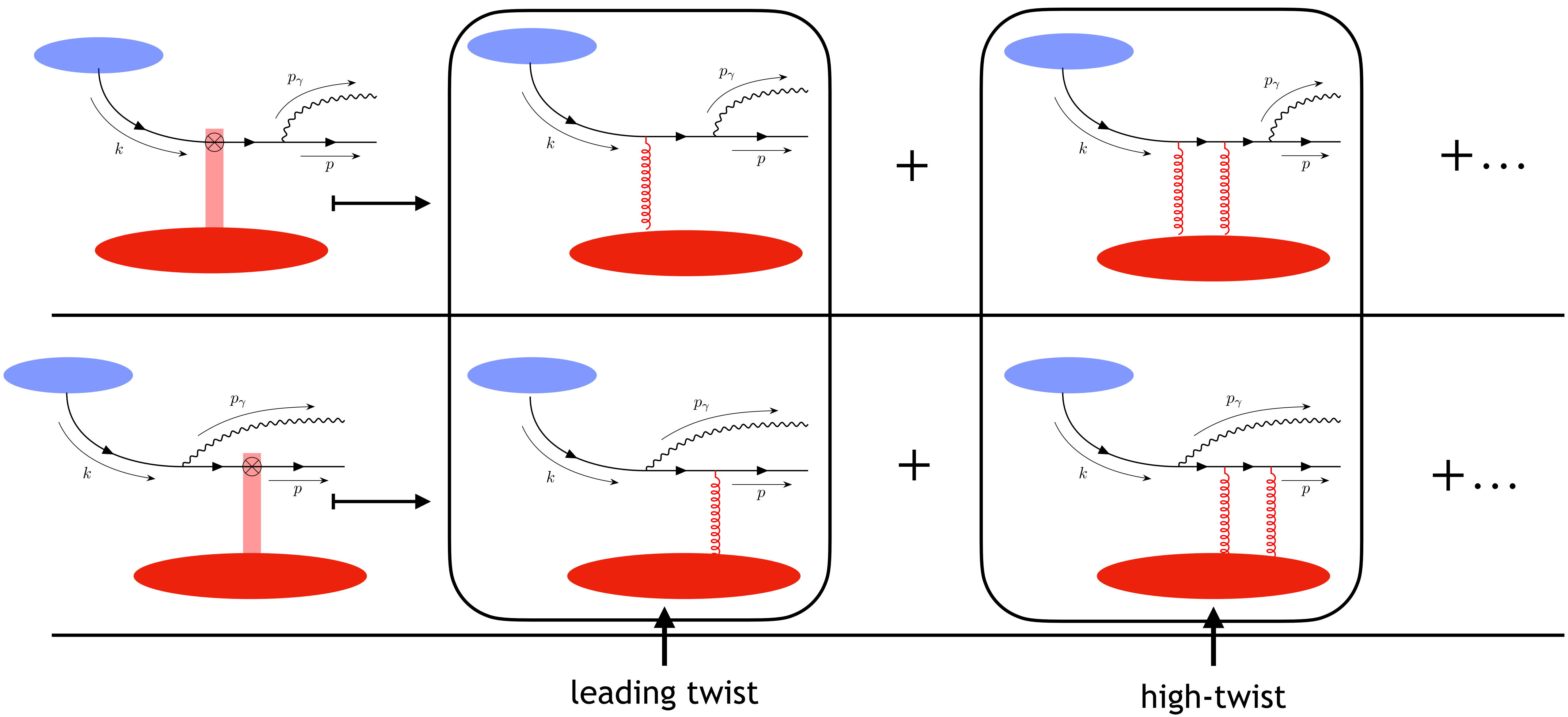
Λ_{QCD}^2?

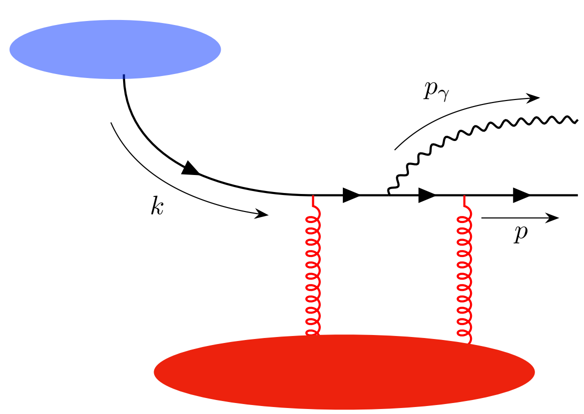
Q_s^2?

Saturation scale?
grows with energy and
nuclear number?

A unified framework for dilute-dense dynamics

Matching between high-twist and CGC formalism: open up shock-wave





CGC missing diagram
to match to high-twist → Can be recovered by keeping "sub-eikonal" phase

in preparation (2208.XXXX) with Yu Fu, Zhongbo Kang, Xin-Nian Wang, Hongxi Xing

A unified framework for dilute-dense dynamics

Matching between high-twist and CGC formalism in the collinear limit

- Twist-2

$$p_\gamma^- \frac{\mathrm{d}\sigma^{p+A\to\gamma+X}}{\mathrm{d}p_\gamma^- \mathrm{d}^2\boldsymbol{p_\gamma}_\perp} = \int \mathrm{d}x_p f(x_p) \frac{\alpha_{\mathrm{em}}\alpha_s}{N_c} \frac{\xi^2\left[1+(1-\xi)^2\right]}{\boldsymbol{p_\gamma}_\perp^4} T_{\mathrm{LT}}(x)$$

$$T_{\mathrm{LT}}(x) = \frac{1}{P_A^+}\int \frac{\mathrm{d}w^-}{2\pi} e^{ixP_A^+ w^-} \left\langle P_A \middle| F_a^{\alpha+}(w^-,\mathbf{0}_\perp) F_a^{\beta+}(0^-,\mathbf{0}_\perp) \middle| P_A \right\rangle \delta_{\perp\alpha\beta}$$

- Twist-4 contributions

$$p_\gamma^- \frac{\mathrm{d}\sigma^{p+A\to\gamma+X}}{\mathrm{d}p_\gamma^- \mathrm{d}^2\boldsymbol{p_\gamma}_\perp}\Bigg|_{\mathrm{C,I}} = \frac{(2\pi)^3\alpha_{\mathrm{em}}\alpha_{\mathrm{s}}^2}{N_c^2} \int \mathrm{d}x_p f(x_p) \frac{\left[1+(1-\xi)^2\right]}{\boldsymbol{p_\gamma}_\perp^6}$$

$$\times\left[4\xi^4 T_{\mathrm{C,I}}(x,0) + \xi^3(1-\xi)\frac{\partial(T_{\mathrm{C,I}}(x,x_2))}{\partial x_2}\Bigg|_{x_2=0} - 3\xi^4 x \frac{\partial(T_{\mathrm{C,I}}(x_1,0))}{\partial x_1}\Bigg|_{x_1=x} + \xi^4 x^2 \frac{\partial^2(T_{\mathrm{C,I}}(x_1,0))}{\partial x_1^2}\Bigg|_{x_1=x}\right]$$

$$T_{\mathrm{C,I}}(x_1,x_2) = \frac{1}{P_A^+}\int\frac{\mathrm{d}w^-}{2\pi}\int\frac{\mathrm{d}z^-}{2\pi}\int\frac{\mathrm{d}z'^-}{2\pi} e^{ix_1P_A^+w^-} e^{ix_2P_A^+(z^--z'^-)} \Theta(w^--z^-)\Theta(-z'^-)$$
$$\left\langle P_A \middle| F_a^{\alpha+}(w^-,\mathbf{0}_\perp) F_b^{\rho+}(z^-,\mathbf{0}_\perp) F_b^{\delta+}(z'^-,\mathbf{0}_\perp) F_a^{\beta+}(0^-,\mathbf{0}_\perp) \middle| P_A \right\rangle \delta_{\alpha\beta}\delta_{\rho\delta}$$

+ contributions from final state, interference, and asymmetric cut

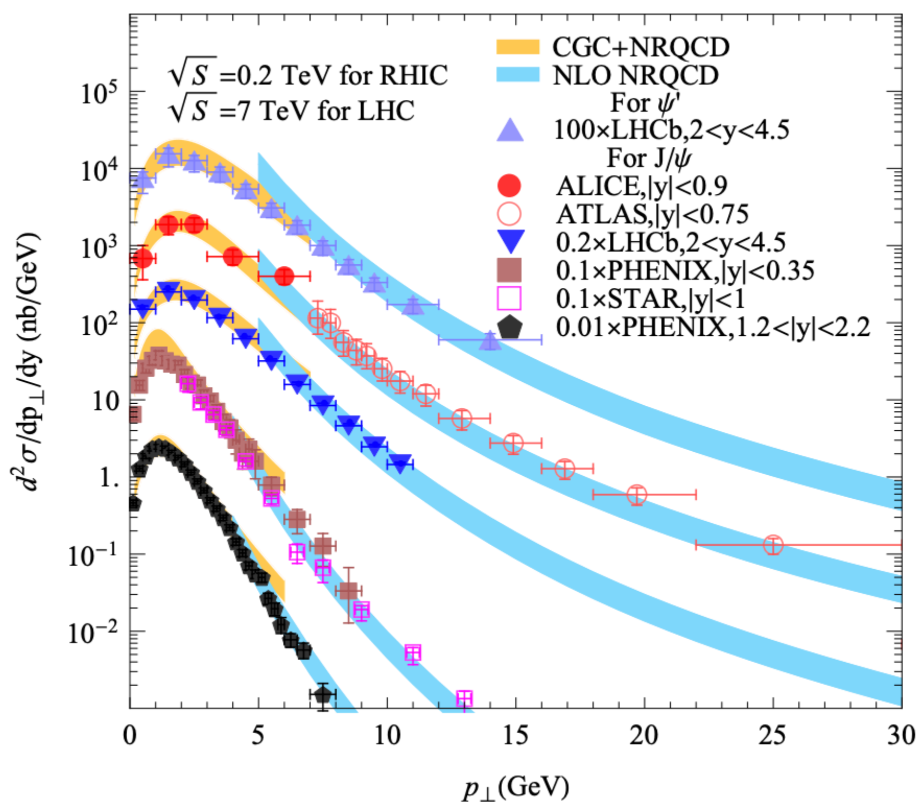
in preparation (2208.XXXX) with Yu Fu, Zhongbo Kang, Xin-Nian Wang, Hongxi Xing

Quarkonium production at small-x

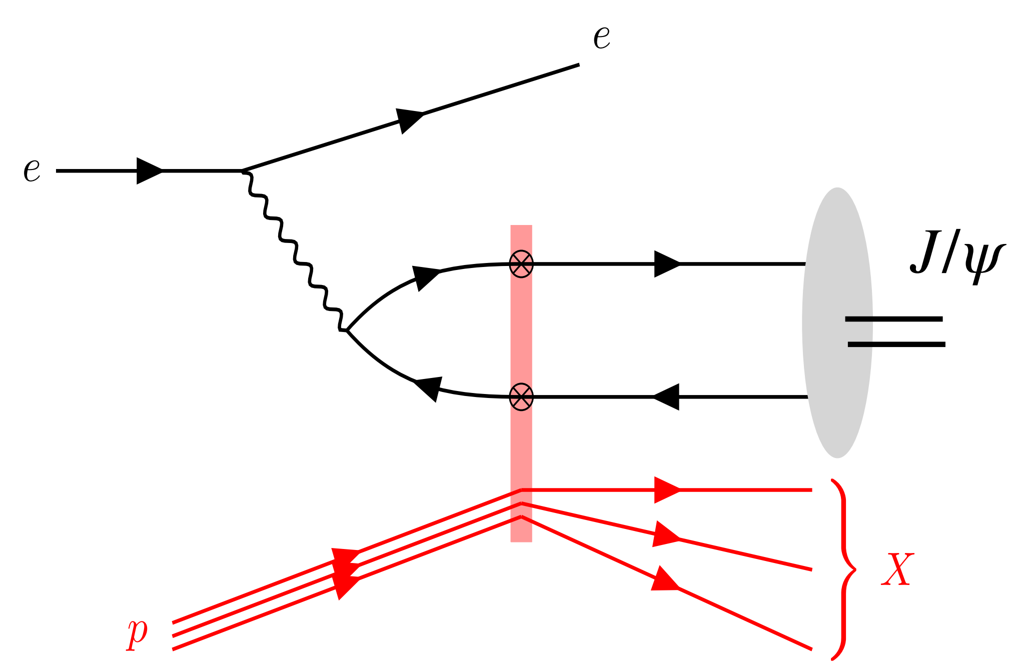
- Studies of quarkonium production in DIS at small-x have focused mostly on diffraction, and employ NP model for LCWF of quarkonium

- Employ CGC + NRQCD or CGC+ICEM to study nuclear modification factor in DIS

Good description of experimental data at low $p_\perp$ at RHIC and LHC



Ma, Venugopalan (2014)
based on Kang, Ma, Venugopalan (2014)



Quarkonium production in DIS and small-x

in progress with Vincent Cheung, Zhongbo Kang, and Ramona Vogt

For more about ICEM see Vincent's talk

Energy-energy correlators at small-x

- Jets ideal to access parton dynamics at low-x
- Due to limited center of mass energy at EIC, difficult to measure jets in low-x kinematics (see Barbara's talk)
- Hadrons measurements introduce some uncertainty due to fragmentation functions

Energy-energy correlator

$$\mathrm{EEC}_{\mathrm{EIC}}(\tau) = \sum_a \int \mathrm{d}\theta_a z_a \mathrm{d}z_a \frac{1}{\sigma} \frac{\mathrm{d}\sigma^{\gamma^* + A \to a + X}}{\mathrm{d}\theta_{ap} \mathrm{d}z_a} \delta\left(\tau - \left(\frac{1+\cos\theta_{ap}}{2}\right)\right)$$

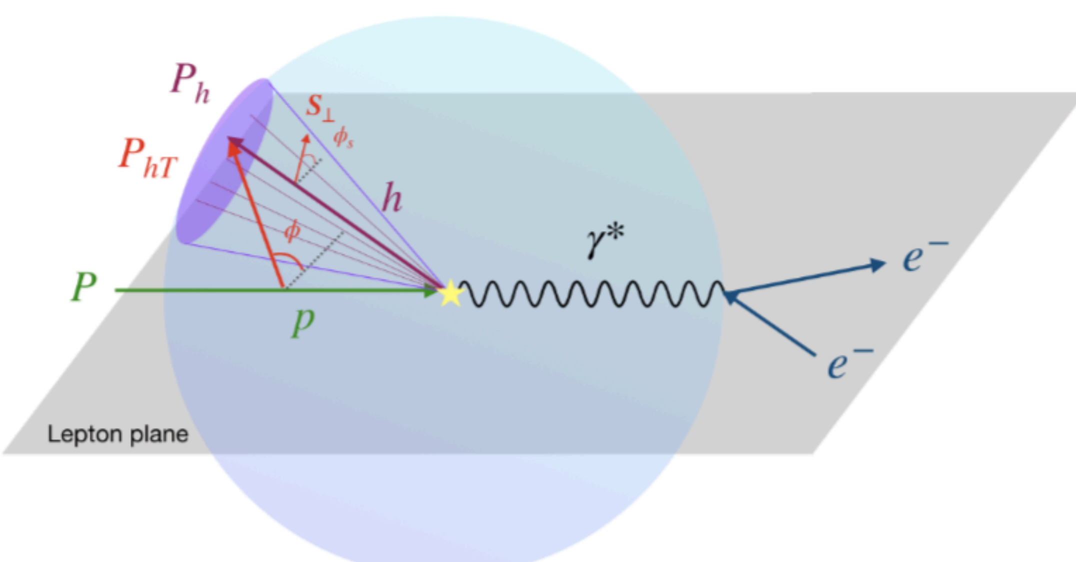


Figure from Fanyi Zhao

- Due to sum rule reduce uncertainties due to fragmentation
- Study nuclear modification factor of EEC near $\tau \sim 0$

in progress with Haotian Cao, Zhongbo Kang, Xiaohui Liu, and Fanyi Zhao

For more about EEC see Kyle's talk

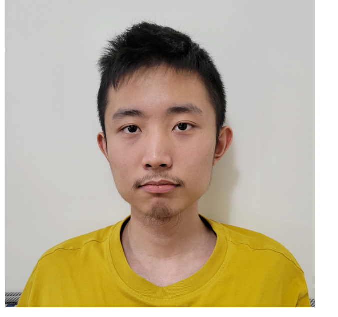
Ongoing projects with undergrads at UCLA

- Global analysis of DIS and pp/pA data

  with Amanda Wei and ZK (Miranda Li recently joined)*

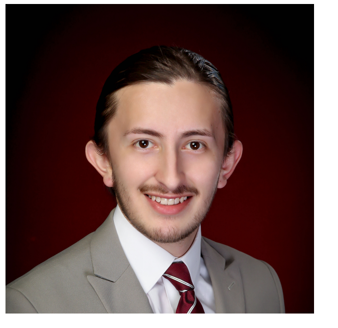
- Isolated photon+hadron(jet) production

  with Sky Shi and ZK*



- Leveraging the LHAPDF framework for efficient small-x computations

  *with Jeisson Pulido** (Cal Bridge), ZK, and John Terry*



- Diffractive J/ψ + photon production in DIS

  *with Philip Velie** (U. Virginia) and ZK*

*graduated recently

**visiting students

Summary

- Uplifting saturation physics to NLO

  Dijet production in DIS interplay between small-x resummation and TMD evolution

- A unified framework for dilute and dense dynamics

  Possibility to generalize the CGC formalism to admit a simultaneous description of small-x and moderate-x

- Further ongoing projects

  Promising observables at the EIC: energy-energy correlators, and quarkonium production in DIS at small-x

  Undergrads are actively engaged, hope they will join this meeting in the future!