Center for Frontiers in Nuclear Science

Transverse momentum dependent distributions and the hadron as a many-body parton system

Andrey Tarasov

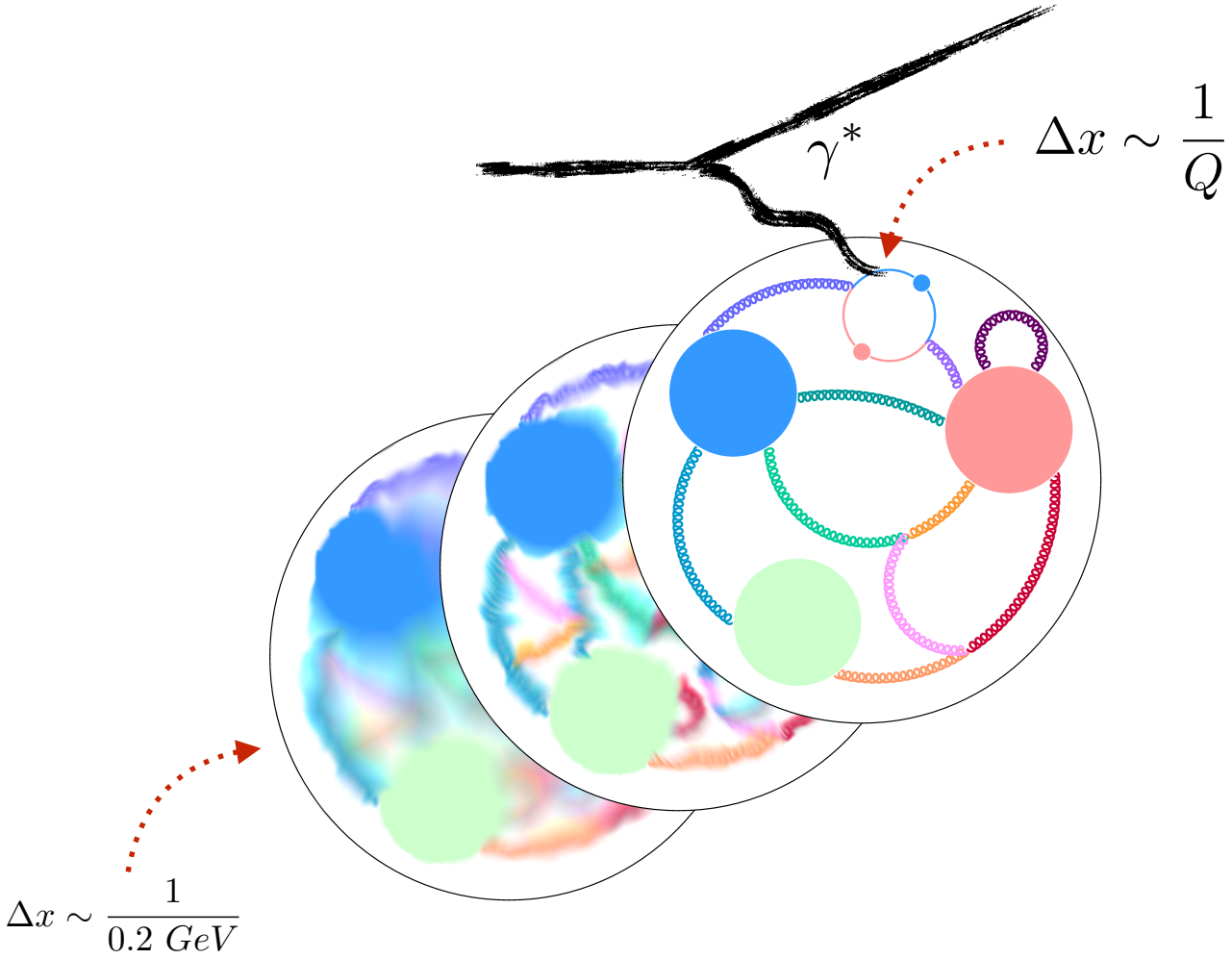
CFNS joining date: 10/14/2019

Amongst the Senior Physicists at CFNS: Yuri Kovchegov

The Ohio State University

Hadron as a many-body parton system

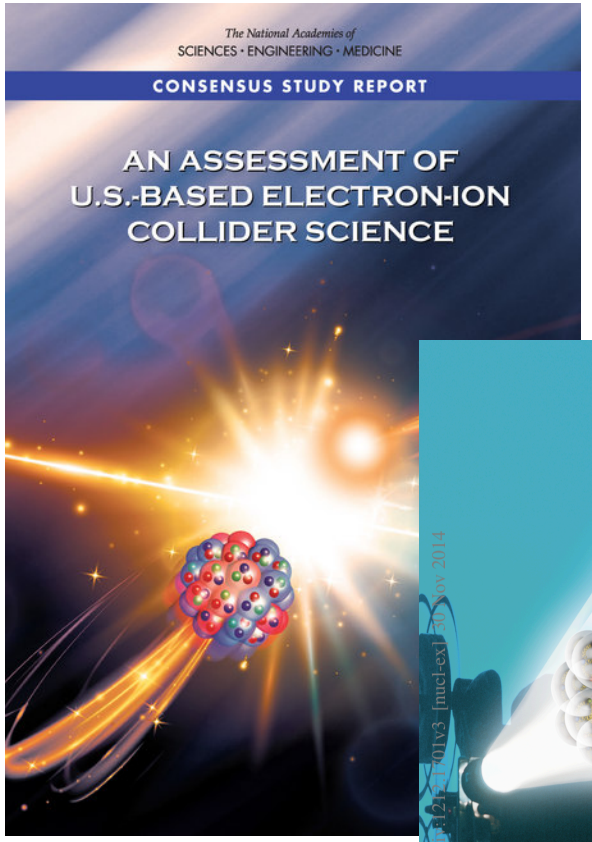
- In DIS a dense QCD medium strongly interacts with the probe
- Interacting with external probe the hadron reveals different types of parton dynamics. Separation of different scales
- There is a strong correlation between different phases, e.g. perturbative and non-perturbative components
- If we study perturbative phase at a large energy scale, we can extract information about the non-perturbative structure of hadrons

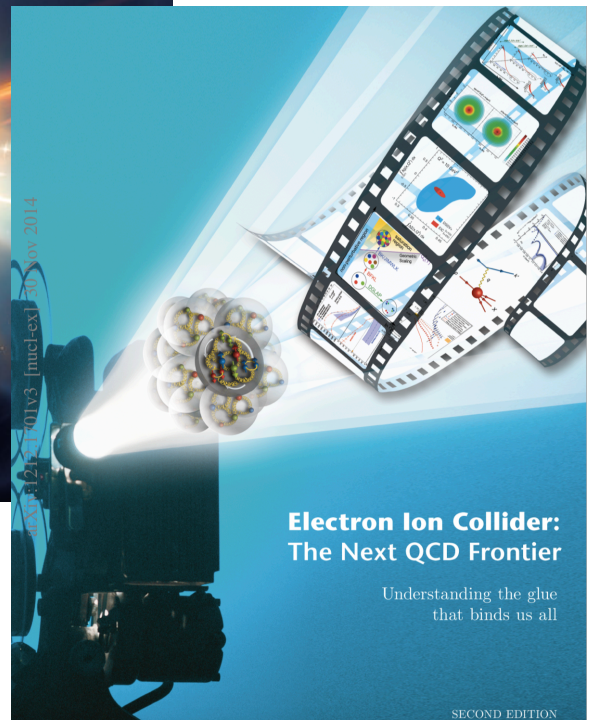


Center for Frontiers in Nuclear Science

Hadron as a many-body parton system

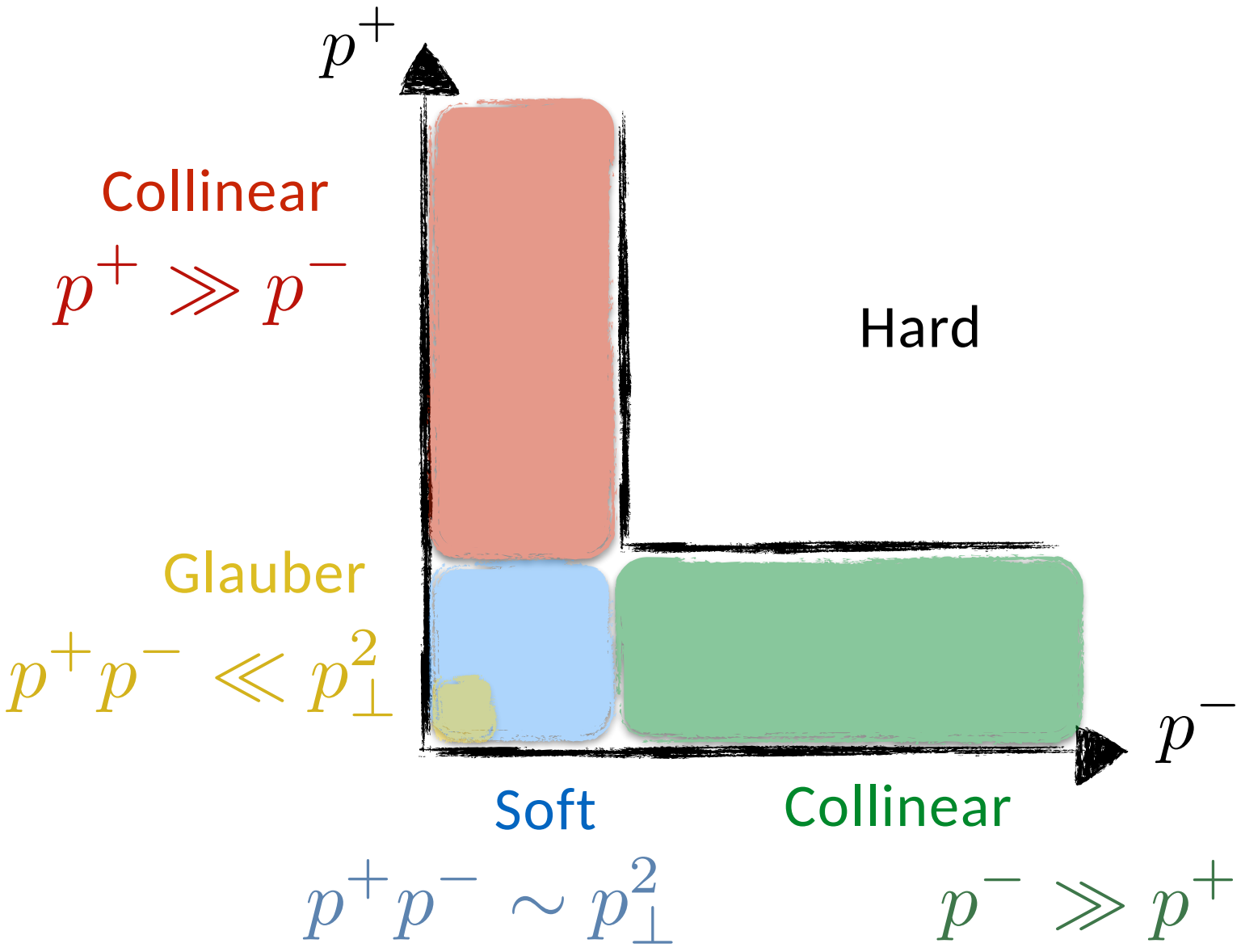
- We have tools to study this system of connected phases, which is very non-trivial
- The phases interact with each other in a dynamical way
- Using methods of perturbative QCD we can obtain very precise information on the hadron structure as a multi-phase many-body parton system





Kinematical phases in the TMD factorization

- There are different kinematical phases in the many-body parton system
- EIC will make possible to reveal these phases and understand interaction between them

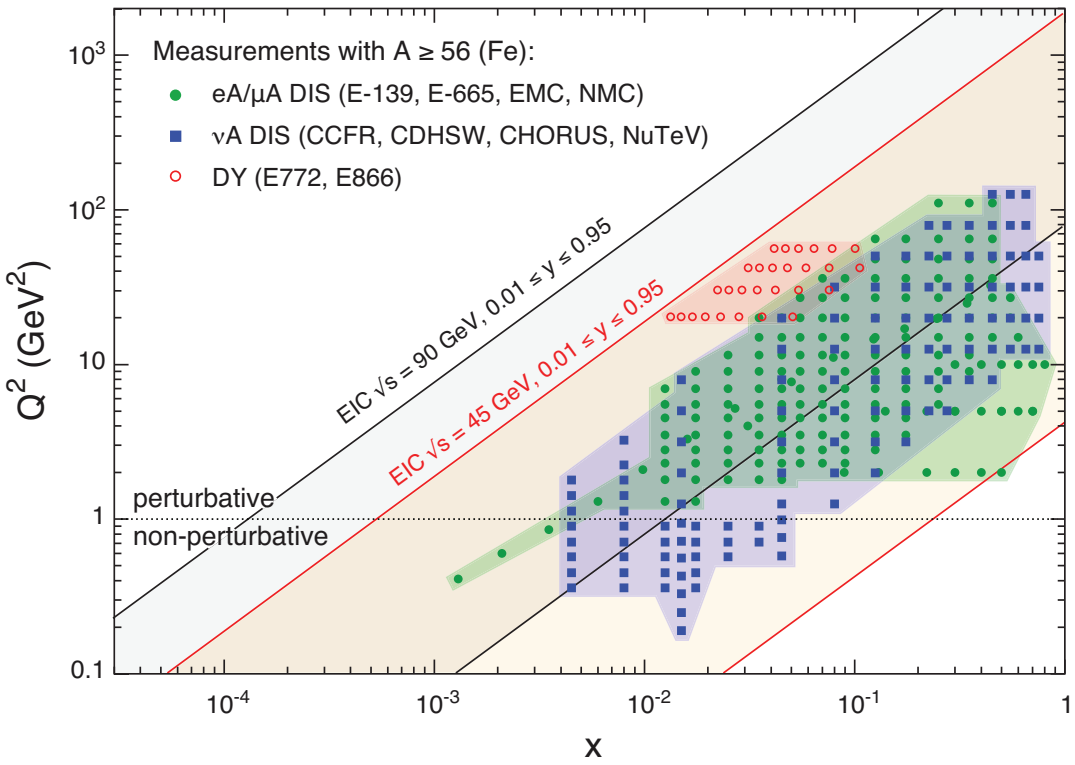


EIC and the precision test of QCD

- EIC will have a broad kinematic coverage
- Different kinematical phases will be involved
- Complex dynamics of interacting phases. Precision test of QCD

Factorization breaking

PDFs



Matching

EIC white paper

Small-x

TMDs

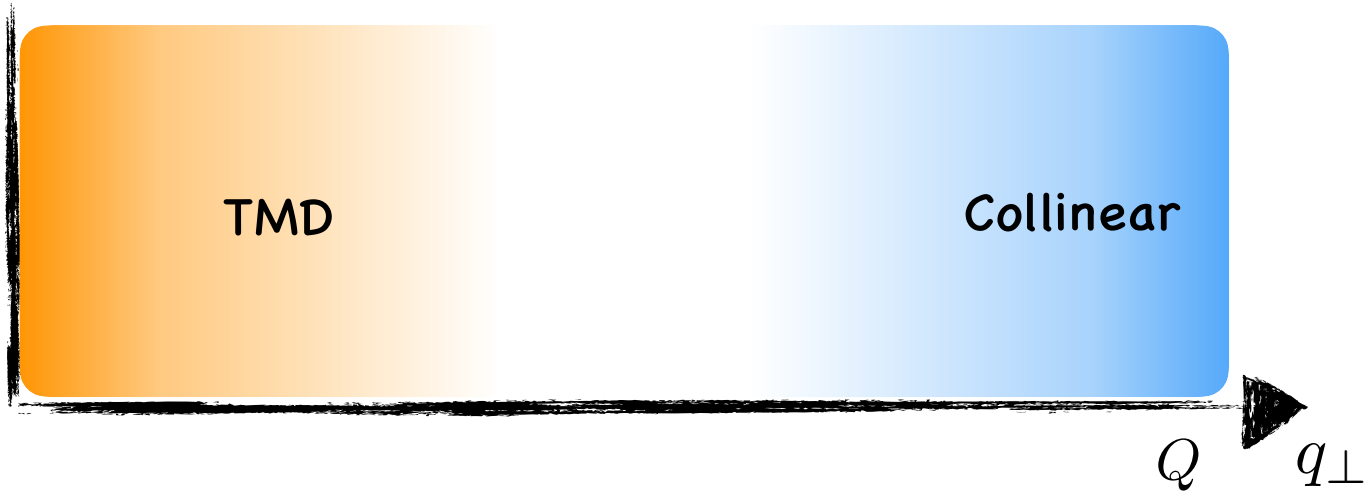
Background field method

- We can separate different phases of the many-body parton system at the level of the QCD Lagrangian
- The method provides a consistent way to take into account interaction between phases using an expansion in the background field
- We can consider different types of interaction

$$S_{bQCD}(A, B) = S_{QCD}(A + B) - S_{QCD}(B)$$

TMD vs. collinear factorization

- There is a correlation between transverse momenta of partons and factorization properties of the system
- The many-body parton system can generate different factorization properties
- The TMD factorization is valid in the limit of very small transverse momenta
- Collinear factorization is valid at large transverse momenta
- The transition region is not well understood. EIC will be able to measure it



Factorization breaking

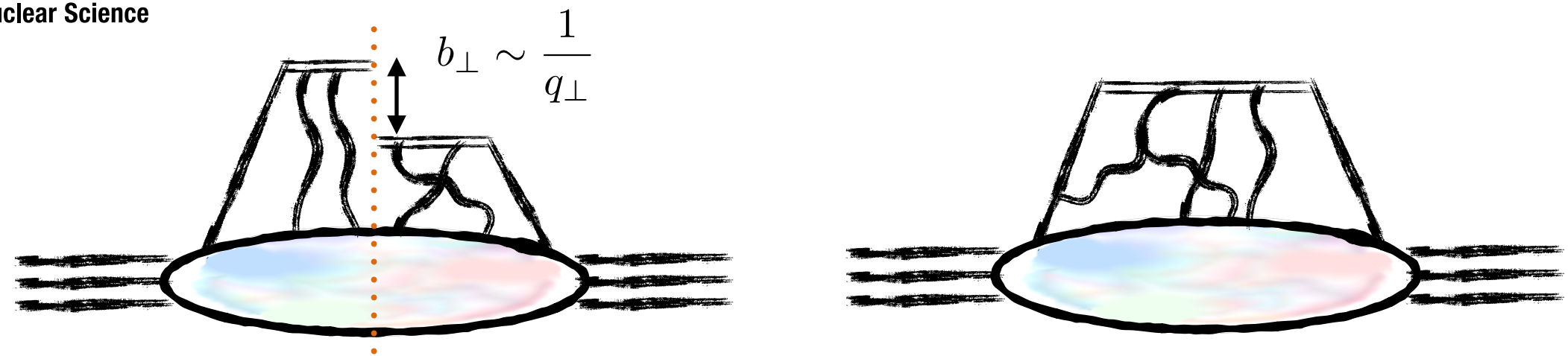
$$W(\alpha_z, \beta_z, q_\perp) \simeq -\frac{e^2}{8 s_W^2 c_W^2 N_c} \int d^2 k_\perp \frac{1}{k_\perp^2 (q-k)_\perp^2} \left[1 - 2\frac{(k, q-k)_\perp}{Q^2}\right]$$
$$\times \left[\left\{(1+a_u^2)[f_u(\alpha_z)\bar{f}_u(\beta_z) + \bar{f}_u(\alpha_z) f_u(\beta_z)]\right\} + \left\{u \leftrightarrow c\right\} + \left\{u \leftrightarrow d\right\} + \left\{u \leftrightarrow s\right\}\right]$$

I. Balitsky, A.T., JHEP 05, 150 (2018)

- We have obtained a quantitative estimation of the factorization breaking effect
- With certain approximations the structure of corrections gets a very simple form
- We estimate that effects become important at $q_\perp \sim \frac{1}{4} Q$
- This result is in agreement with phenomenological studies

Center for Frontiers in Nuclear Science

TMD vs. collinear distributions



$$F(x,b;\zeta_f,\mu_f) = F(x,b;\zeta_i,\mu_i)\exp\left\{\int_{\mu_i}^{\mu_f}\frac{d\mu}{\mu}\gamma\left(\alpha_s(\mu),\ln\frac{\zeta_f}{\mu^2}\right)\right\}\left(\frac{\zeta_f}{\zeta_i}\right)^{-\mathcal{D}(\mu_i,b)}$$

- Collinear distributions can be used as an initial condition for the TMD evolution
- In the region of small transverse separation TMDs and PDFs should coincide
- Using calculations in the background field we can construct projection of TMDs onto collinear distributions

J.C. Collins, D.E. Soper and G. Sterman, Phys. Lett. B 109 (1982) 388;
J.C. Collins, D.E. Soper and G.F. Sterman, Nucl. Phys. B 250 (1985) 199;
X.-d. Ji, J.-p. Ma and F. Yuan, Phys. Rev. D 71 (2005) 034005;
M.G. Echevarria, A. Idilbi and I. Scimemi, JHEP 07 (2012) 002

Center for Frontiers in Nuclear Science

TMD vs. collinear distributions

$$f^{\perp}_{1T;q\leftarrow h;\mathrm{DY}}(x,\boldsymbol{b};\mu,\zeta) = \pi T(-x,0,x) + \pi a_s(\mu)\Big\{$$
$$-2\mathbf{L}_\mu P\otimes T + C_F\left(-\mathbf{L}_\mu^2 + 2\mathbf{l}_\zeta\mathbf{L}_\mu + 3\mathbf{L}_\mu - \frac{\pi^2}{6}\right)T(-x,0,x)$$
$$+\int d\xi\int_0^1 dy\,\delta(x-y\xi)\Big[\left(C_F-\frac{C_A}{2}\right)2\bar{y}T(-\xi,0,\xi)+\frac{3y\bar{y}}{2}\frac{G_+(-\xi,0,\xi)+G_-(-\xi,0,\xi)}{\xi}\Big]\Big\}$$

I. Scimemi, A.T., A. Vladimirov, JHEP 05 (2019) 125

- We derive matching coefficient for the Sivers function at the next-to-leading order
- We use background field method to calculate emission in the many-body parton background
- The structure of the result is dictated by strong interaction between phases
- It is easy to generalize calculation to other operators and matrix elements (Collins function)
- The results will be implemented in extraction of the Sivers function

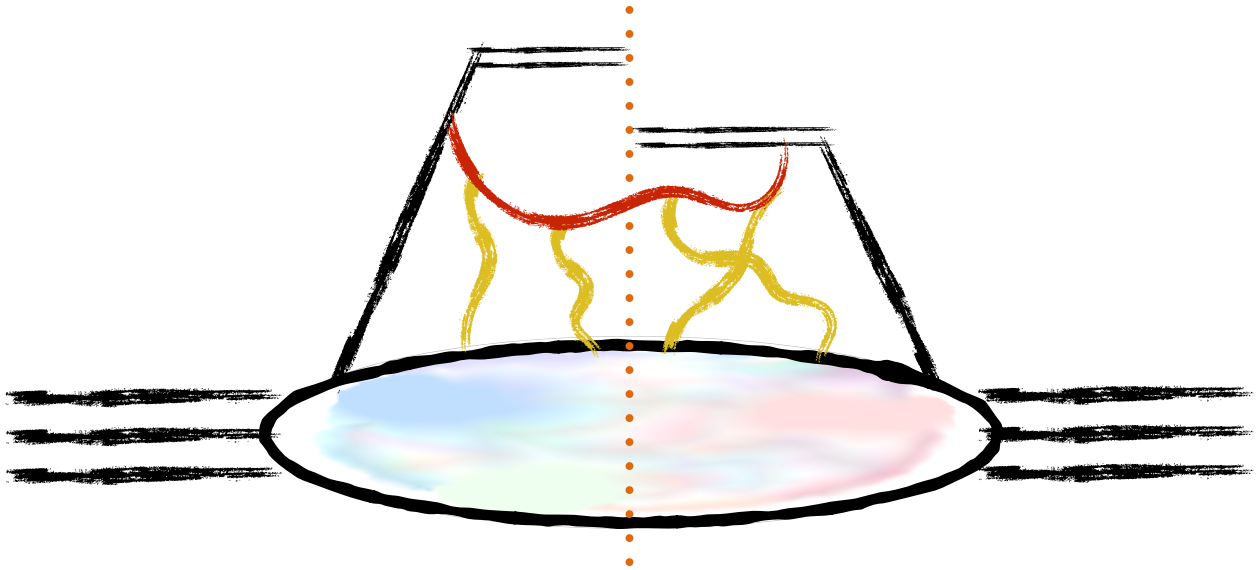
Center for Frontiers in Nuclear Science

Glauber gluons in TMDs

- We want to understand properties of the Glauber phase and quantitatively estimate its contribution to the TMD evolution
- It is possible to take into account Glauber background in the background field method
- Contribution of all phases can be calculated with the same technique
- There is a smooth transition between large and small-x limits

$$\frac{d}{d\ln\sigma}\tilde{U}_i^a(z_1)U_j^a(z_2) = -\frac{g^2}{8\pi^3}\mathrm{Tr}\{(-i\partial_i^{z_1}+\tilde{U}_i^{z_1})[\int d^2z_3(\tilde{U}_{z_1}\tilde{U}_{z_3}^\dagger-1)\frac{z_{12}^2}{z_{13}^2z_{23}^2}(U_{z_3}U_{z_2}^\dagger-1)](i\overleftarrow{\partial}_j^{z_2}+U_j^{z_2})\}$$

I. Balitsky, A.T., JHEP 10, 017 (2015)

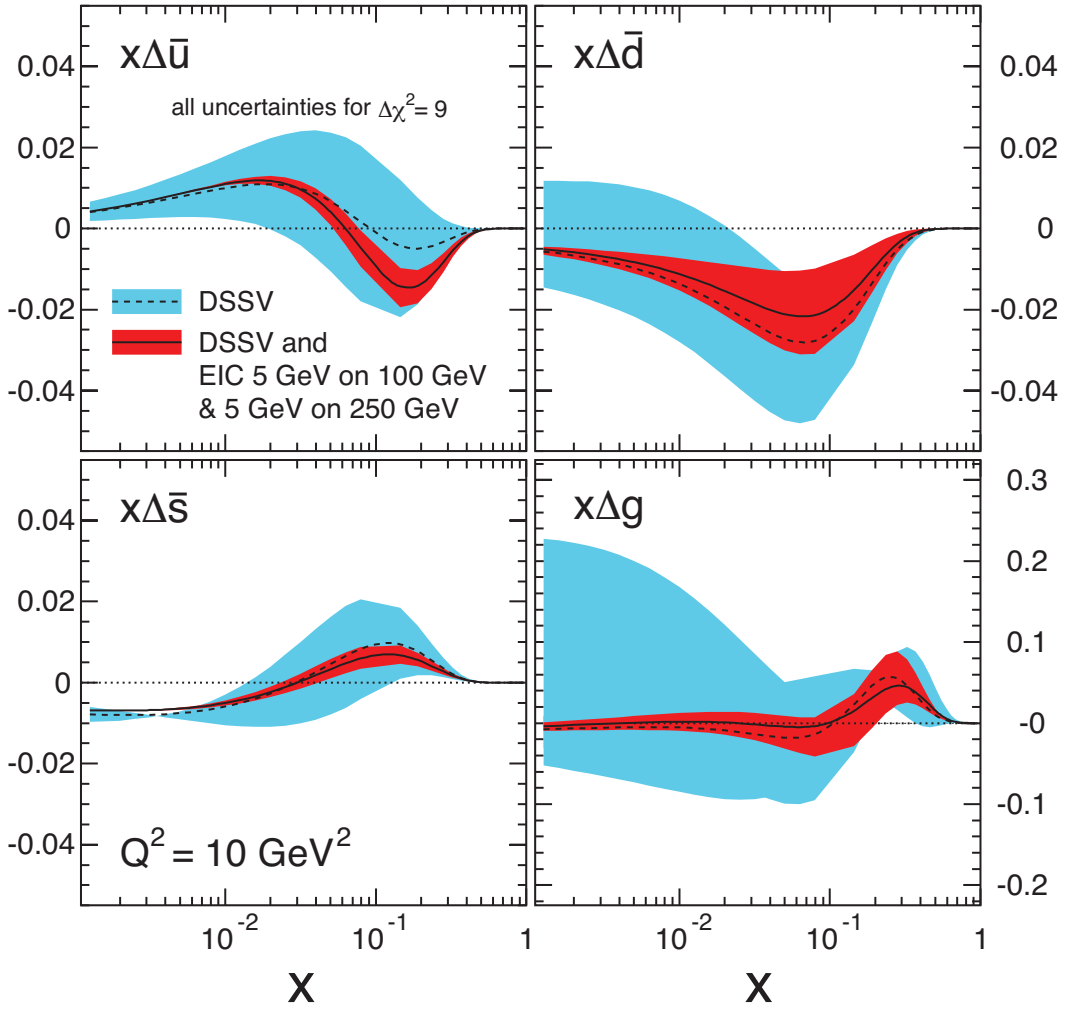


Center for Frontiers in Nuclear Science

Glauber gluons in TMD

- Many surprises from small x region for spin physics
- We do not know where the hadron spin comes from (spin crises, dark spin)
- One of the main problem we are going to solve with EIC
- Significant contribution comes from the region of small x
- Current project at OSU: single log evolution at small-x (connection with large x)
- Collaboration with BNL: spin in the worldline approach

Y.V. Kovchegov, D. Pitonyak and M.D. Sievert, 15-18;
A.T., R. Venugopalan, Phys. Rev. D100 (2019) 054007



D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, PRL 101, 072001 (2008); EIC white paper

DIS on a hybrid quantum computer

- Structure of proton via real-time correlation functions

$$W^{\mu\nu}(q,P,S) = \frac{1}{2\pi}\int d^4x e^{iq\cdot x}\langle P,S|\hat{j}^\mu(x)\hat{j}^\nu(0)|P,S\rangle$$

- Proton state

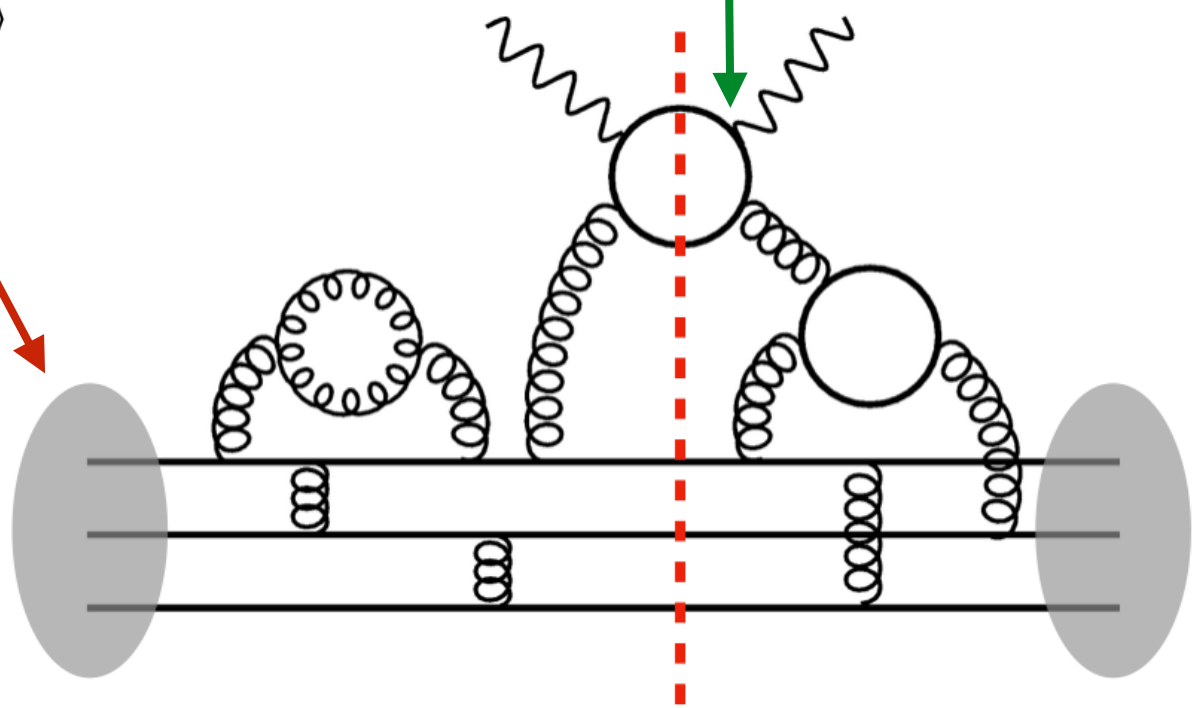
$$|P,S\rangle = \hat{\mathcal{U}}_{(0,-\infty)}\,\hat{\Phi}_{P,S}|0\rangle$$

$$\hat{\rho}_{P,S} = |P,S\rangle\langle P,S|$$

- Partition function

$$Z = Tr\left[\hat{\mathcal{U}}_{(0,-\infty)}\hat{\rho}_{\text{init}}\hat{\mathcal{U}}_{(-\infty,0)}\right]$$

- Construct evolution of a proton state on a quantum computer



N. Mueller, A.T., R. Venugopalan, arXiv:1908.07051

Center for Frontiers in Nuclear Science

Recent talks and presentations

- N. Mueller, A.Tarasov, R. Venugopalan, “Deeply inelastic scattering structure functions on a hybrid quantum computer,” arXiv:1908.07051;
- A.Tarasov, R. Venugopalan, “Structure functions at small x from worldlines: Unpolarized distributions,” Phys. Rev. D100 (2019) 054007;
- I.Scimemi, A.Tarasov, A.Vladimirov, “Collinear matching for Sivers function at next-to-leading order,” JHEP 05 (2019) 125;
- Balitsky, I., and Tarasov, A., “Power corrections to TMD factorization for Z-boson production,” JHEP 05 (2018), 150;

- “Deeply inelastic scattering structure functions on a hybrid quantum computer”, 9th International Conference on Physics Opportunities at an ElecTron-Ion-Collider
- “Collinear matching for TMD distributions in the background field method”, 9th International Conference on Physics Opportunities at an ElecTron-Ion-Collider
- “Collinear matching of TMD distributions”, QCD Evolution 2019
- “Calculation of structure functions at small x”, TMD Collaboration Workshop