Mapping the Phase Structure of Cold Nuclei -- Gluon Saturation at small-x

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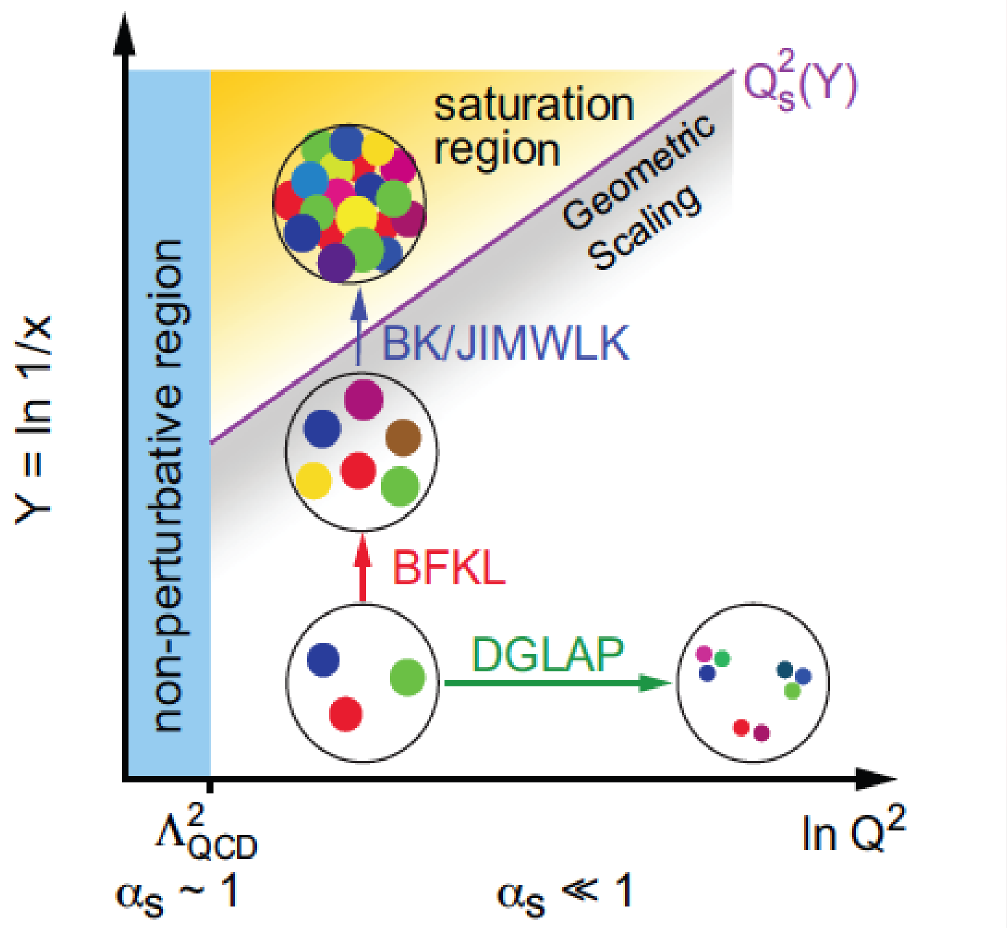
Refs: Mueller, Xiao, Yuan, to be published;
Stasto, Xiao, Yuan, arXiv:1109.1817;
Dominguiz, Xiao, Yuan, PRL 106, 022301 (2011);
Marquet, Dominguiz,Xiao,Yuan, PRD83, 105005 (2011)

Outlines

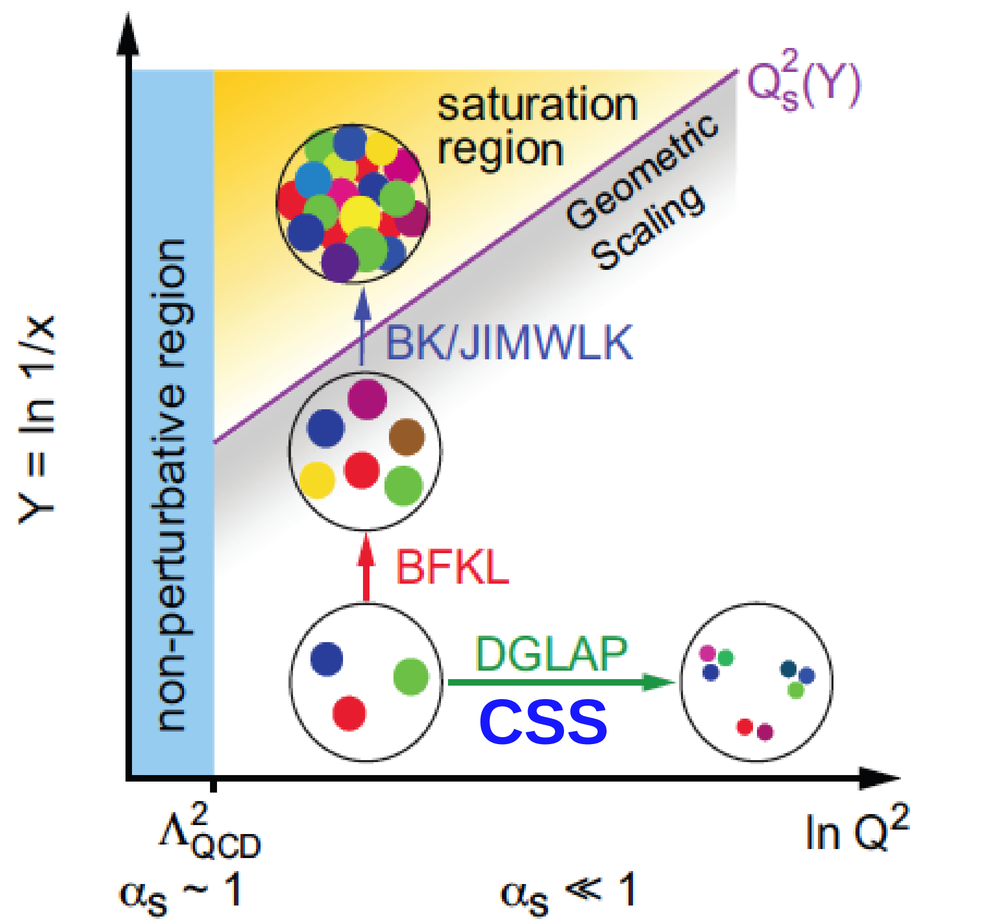
- Introduction
- Sudakov double logarithms in hard processes
- Two-particle correlations as probe for the phase structure of cold nuclei

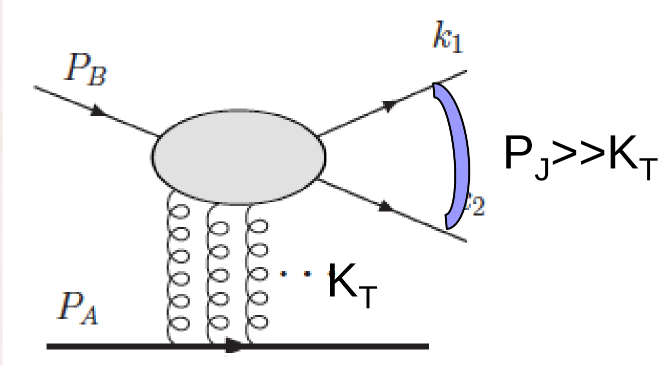
QCD dynamics in cold nuclei



- Inclusive observables
  - DIS structure functions
  - P+A→h+x
- Gluon density in integral form or limited access to the kt-dependence
- Full exploration of the dynamics needs kt-dependence in hard processes

Kt-dependent observables





- Hard processes probe the kt-dependent gluon distributions directly
- Saturation phenomena manifest in the observables

Sudakov Double Logarithms

- Differential cross section depends on Q_1, where $Q^2 \gg Q_1^2 \gg \Lambda^2_{QCD}$

$$\frac{d\sigma}{dQ_1^2} = \frac{1}{Q_1^2} f_1 \otimes f_2 \otimes \sum_i \alpha_s^i \ln^{2i-1} \frac{Q^2}{Q_1^2} + \cdots$$

- We have to resum these large logs to make reliable predictions
  - Q_T: Dokshitzer, Diakonov, Troian, 78; Parisi Petronzio, 79; Collins, Soper, Sterman, 85
  - Threshold: Sterman 87; Catani and Trentadue 89

Collins-Soper-Sterman Resummation

- Large Logs are re-summed by solving the energy evolution equation of the TMDs

$$\frac{\partial}{\partial \ln Q} f(k_\perp, Q) = (K(q_\perp, \mu) + G(Q, \mu)) \otimes f(k_\perp, Q)$$

- K and G obey the renormalization group eq.

$$\frac{\partial}{\partial \ln \mu} K = -\gamma_K = \frac{\partial}{\partial \ln \mu} G$$

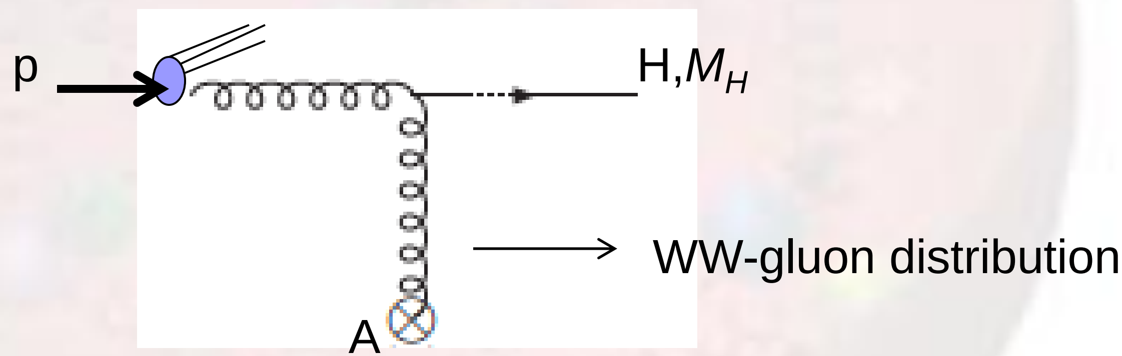
- The large logs will be resummed into the exponential form factor

$$W(Q, b) = e^{-\int_{1/b}^{Q} \frac{d\mu}{\mu}\left(\ln \frac{Q}{\mu} A + B\right)} C \otimes f_1 C \otimes f_2$$

  - A,B,C functions are perturbative calculable.

Sudakov resummation at small-x

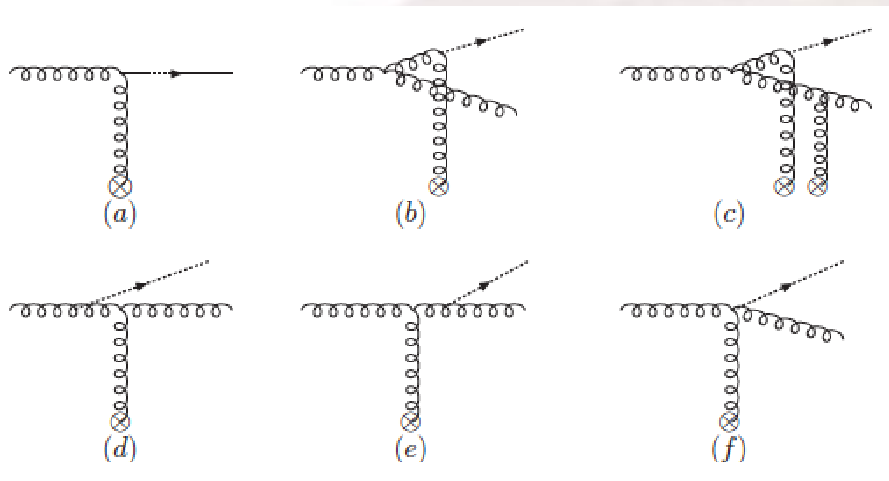
- Take massive scalar particle production p+A->H+X as an example to demonstrate the double logarithms, and resummation



$$\frac{d\sigma^{(\mathrm{LO})}}{dyd^2k_\perp}=\sigma_0\int\frac{d^2x_\perp d^2x'_\perp}{(2\pi)^2}e^{ik_\perp\cdot r_\perp}x_0g_p(x_0)S^{(WW)}(x_\perp,x'_\perp)$$

$$S_Y^{WW}(x_\perp,y_\perp)=-\left\langle\mathrm{Tr}\left[\partial_\perp^\beta U(x_\perp)U^\dagger(y_\perp)\partial_\perp^\beta U(y_\perp)U^\dagger(x_\perp)\right]\right\rangle_Y$$

Explicit one-loop calculations



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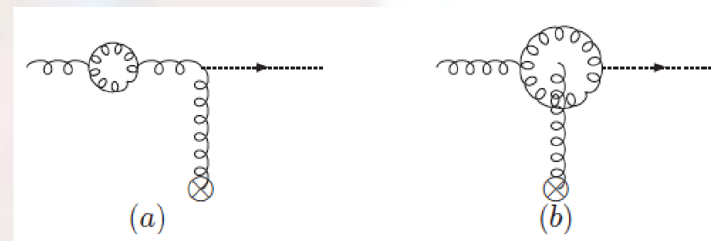


$$x_0 g_p(x_0) \int \frac{d\xi}{\xi} \mathbf{K}_{DMMX} \otimes S^{WW}(x_\perp, y_\perp) + \left(-\frac{1}{\epsilon}\right) S^{WW}(x_\perp, y_\perp) \mathcal{P}_{g/g} \otimes x_0 g(x_0) \ ,$$

- Collinear divergence ➔ DGLAP evolution
- Small-x divergence ➔ BK-type evolution

Dominguiz-Mueller-Munier-Xiao, 2011

Final result

- Double logs at one-loop order

$$\frac{d\sigma^{(\mathrm{LO+NLO})}}{dyd^2k_\perp}|_{k_\perp\ll Q} = \sigma_0 \int \frac{d^2x_\perp d^2x'_\perp}{(2\pi)^2} e^{ik_\perp\cdot r_\perp} S^{WW}_{Y=\ln 1/x_a}(x_\perp, x'_\perp) xg_p(x, \mu^2 = \frac{c_0^2}{r_\perp^2}) \left\{1 + \frac{\alpha_s}{\pi} C_A \left[\beta_0 \ln\frac{Q^2 r_\perp^2}{c_0^2} - \frac{1}{2}\left(\ln\frac{Q^2 r_\perp^2}{c_0^2}\right)^2 + \frac{\pi^2}{2}\right]\right\} ,$$

- Collins-Soper-Sterman resummation

$$\frac{d\sigma^{(\mathrm{resum})}}{dyd^2k_\perp}|_{k_\perp\ll Q} = \sigma_0 \int \frac{d^2x_\perp d^2x'_\perp}{(2\pi)^2} e^{ik_\perp\cdot r_\perp} e^{-S_{sud}(Q^2, r_\perp^2)} S^{WW}_{Y=\ln 1/x_a}(x_\perp, x'_\perp) \times xg_p(x, \mu^2 = c_0^2/r_\perp^2) \left[1 + \frac{\alpha_s}{\pi}\frac{\pi^2}{2} N_c\right] ,$$

Comments

- Sudakov double logs can be re-summed consistently in the small-x formalism
- Kinematics of double logs and small-x evolution are well separated
  - Soft vs collinear gluons
- If Q_s is small, back to dilute region
- If Q_s is large ($\sim Q$), we can safely neglect the Sudakov effects

Di-jet correlations in pA

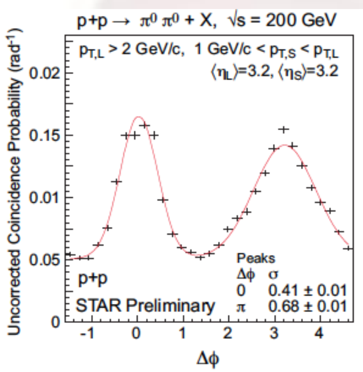
- Effective kt-factorization is formulated

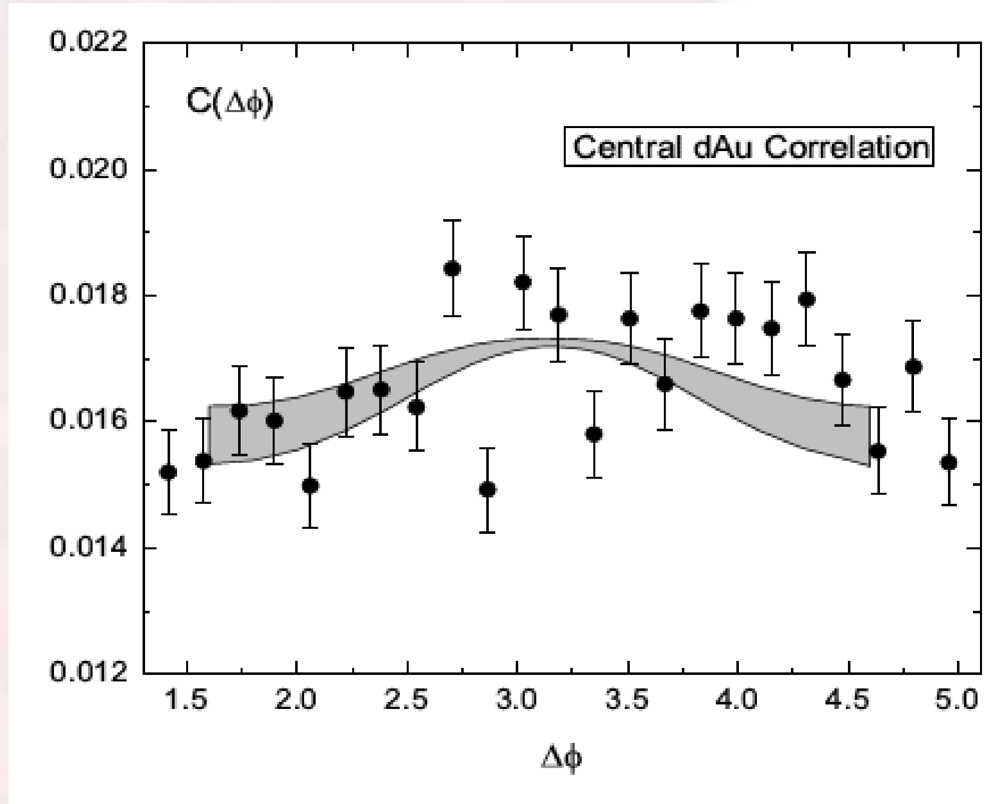
$$\frac{d\sigma^{(pA\to \text{Dijet}+X)}}{d\mathcal{P.S.}}$$
$$=\sum_q x_1 q(x_1)\frac{\alpha_s^2}{\hat{s}^2}\left[\mathcal{F}_{qg}^{(1)}H_{qg\to qg}^{(1)}+\mathcal{F}_{qg}^{(2)}H_{qg\to qg}^{(2)}\right]$$
$$+x_1 g(x_1)\frac{\alpha_s^2}{\hat{s}^2}\Big[\mathcal{F}_{gg}^{(1)}\left(H_{gg\to q\bar{q}}^{(1)}+H_{gg\to gg}^{(1)}\right)$$
$$+\mathcal{F}_{gg}^{(2)}\left(H_{gg\to q\bar{q}}^{(2)}+H_{gg\to gg}^{(2)}\right)+\mathcal{F}_{gg}^{(3)}H_{gg\to gg}^{(3)}\Big]\ ,$$

- In forward region of dAu collisions at RHIC and pA at LHC, Qs is large enough to neglect the Sudakov effects

Central dAu collisions

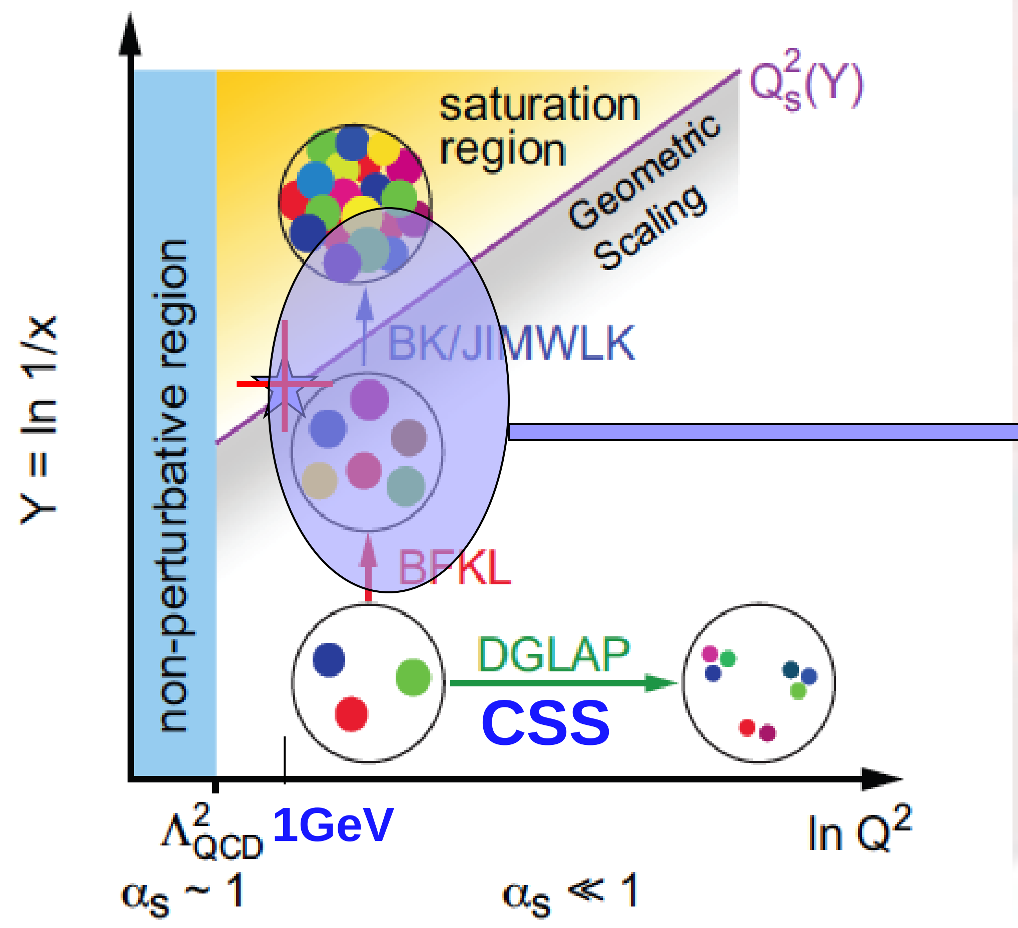
- $\eta_1 \sim \eta_2 \sim 3.2$
- $Q^2_{sA} \sim 0.85 A^{(1/3)} Q_{sp}^{\ 2}$
- GBW model





- No Sudakov effects
  No-BK evolution
  Geometric scaling

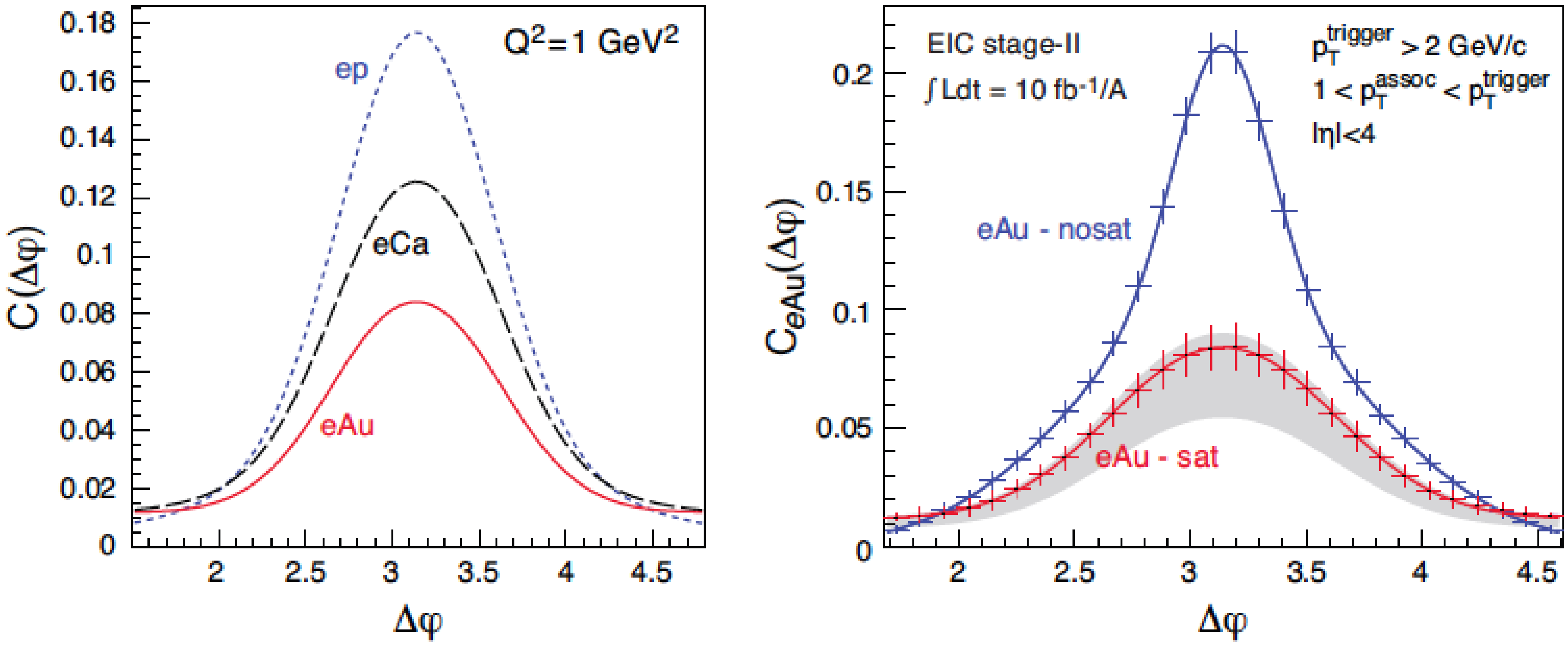
Mapping the phase structure



- RHIC
- pA at LHC

Universality of UGD

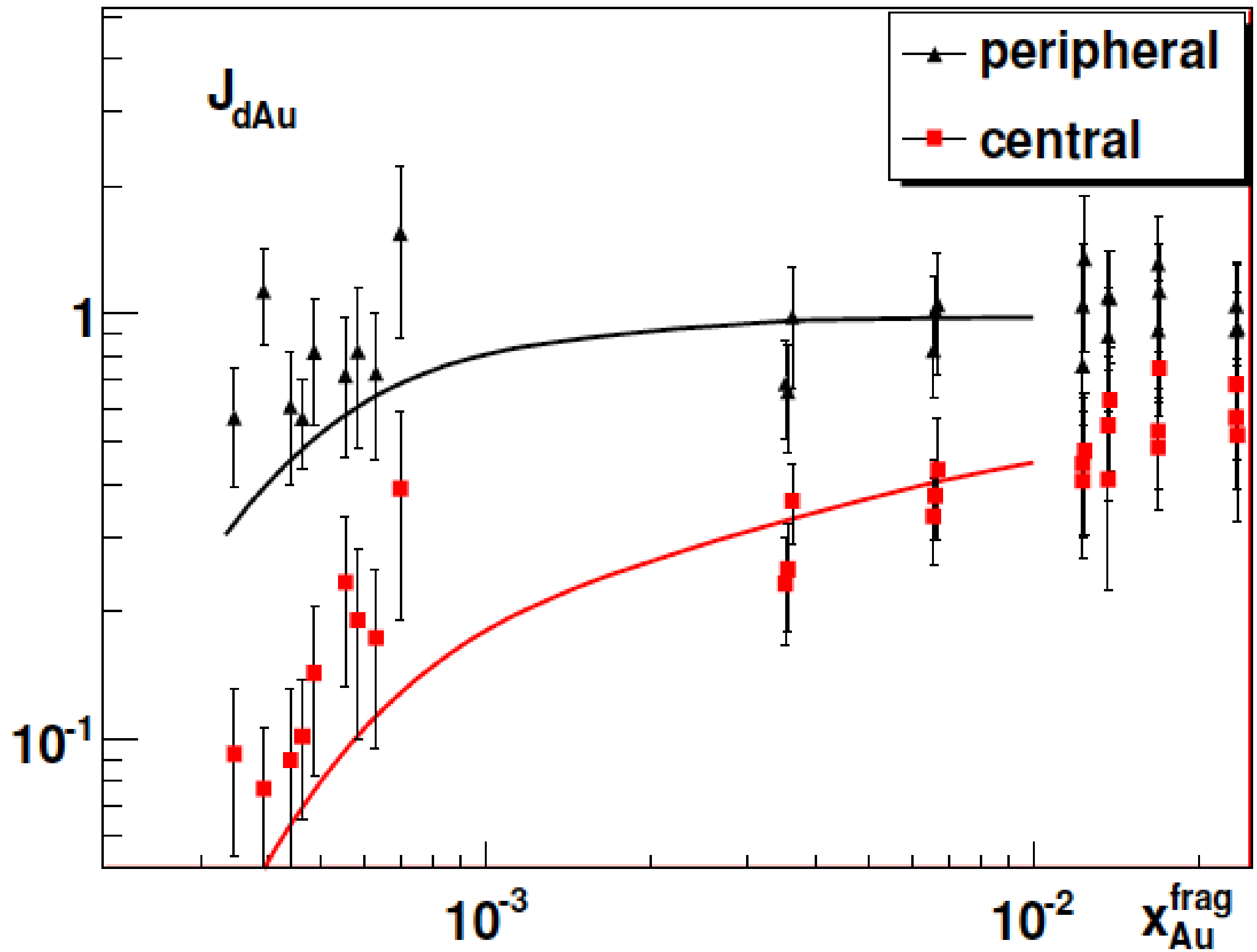
- Un-ambiguously study at the EIC



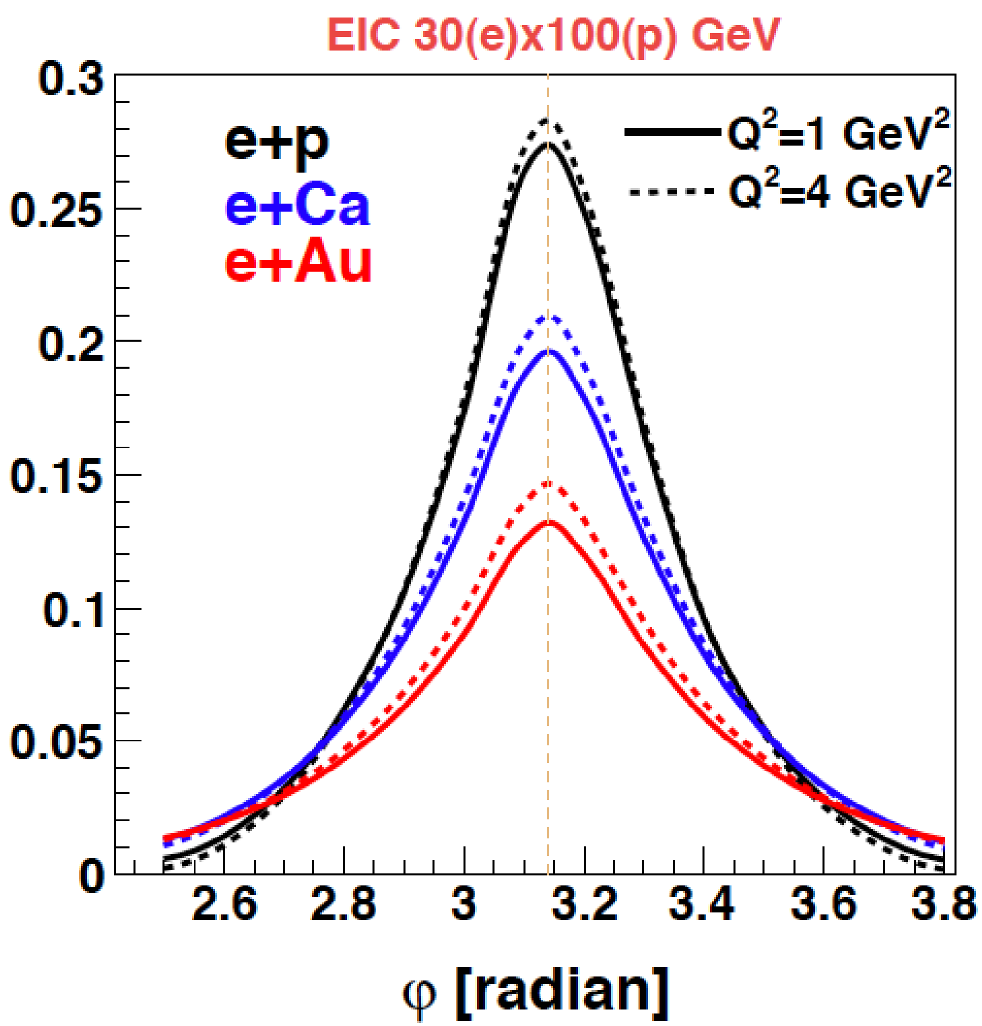
Conclusion

- Sudakov double logs are re-summed in the small-x saturation formalism
- Hard processes are used to map the phase structure of cold nuclei at small-x
- Further developments shall follow to fully investigate the QCD dynamics at small-x in dense medium

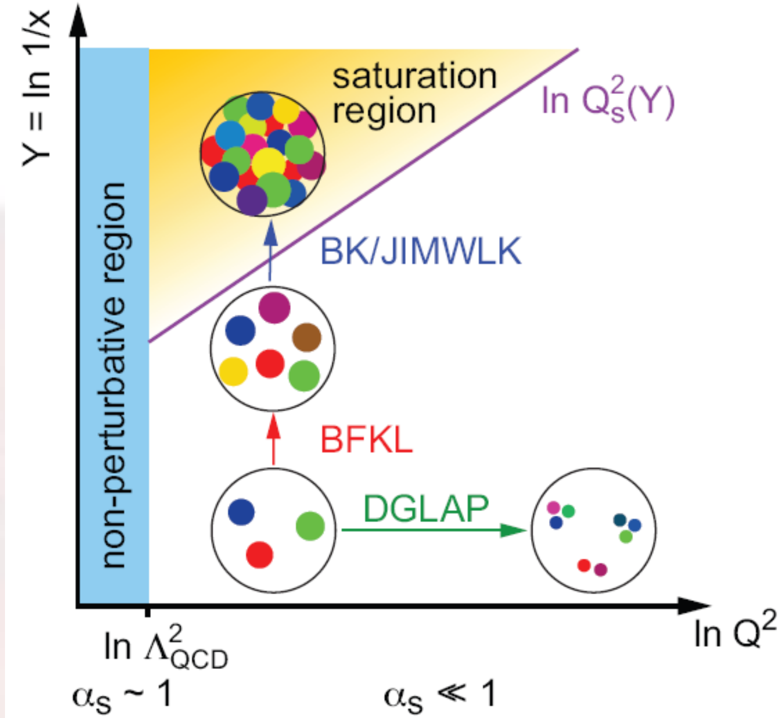
PHENIX J_{dA}

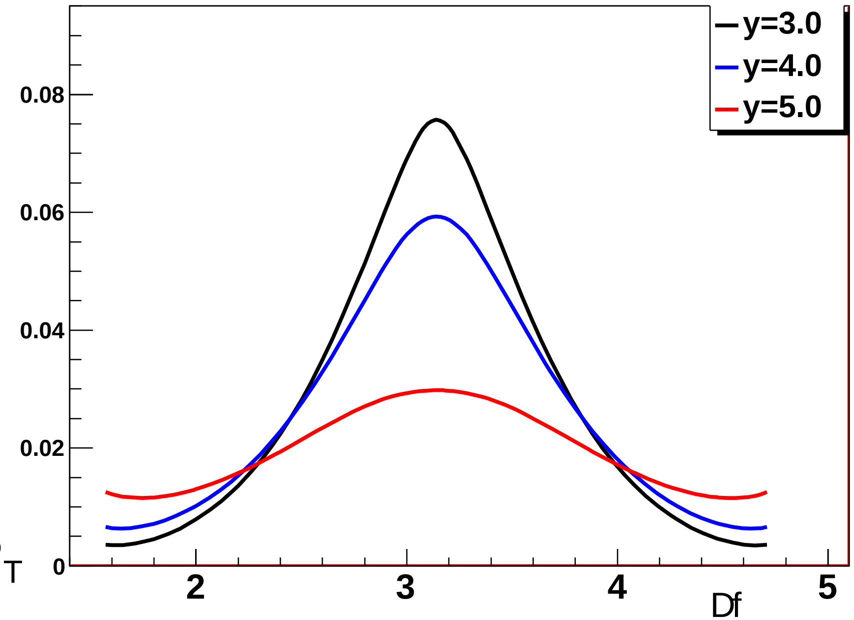


EIC predictions

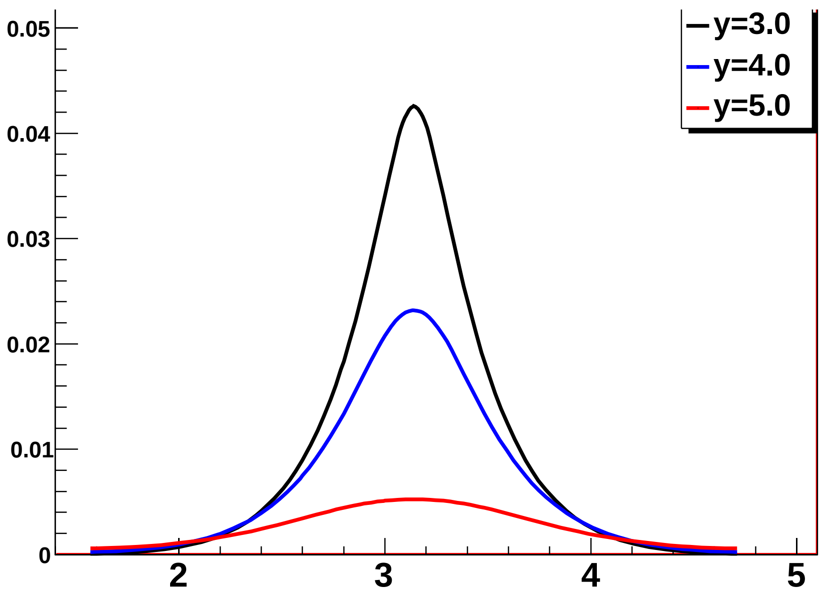


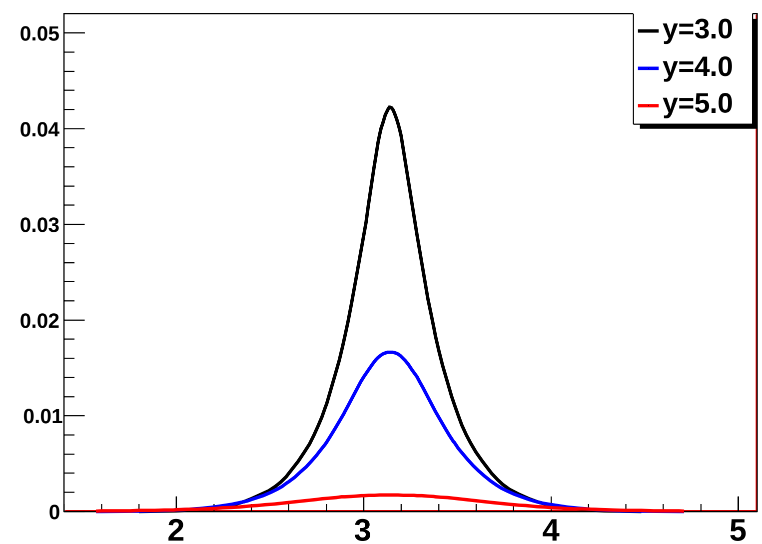
pA at the LHC



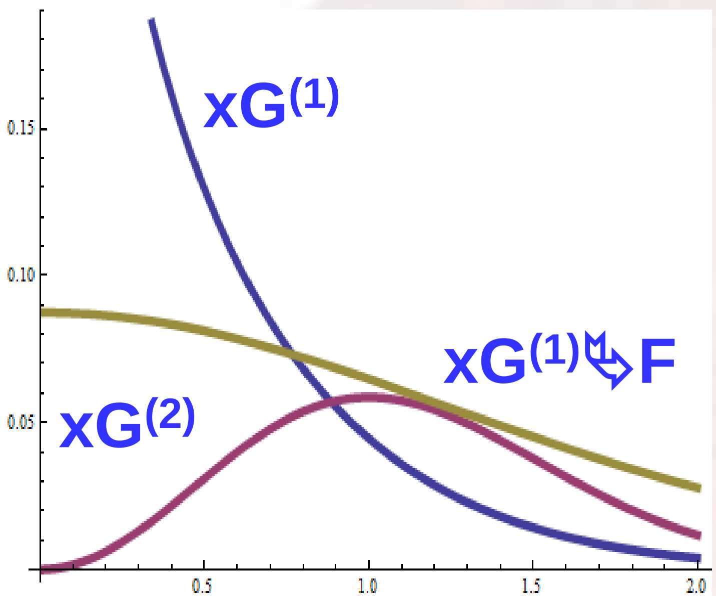


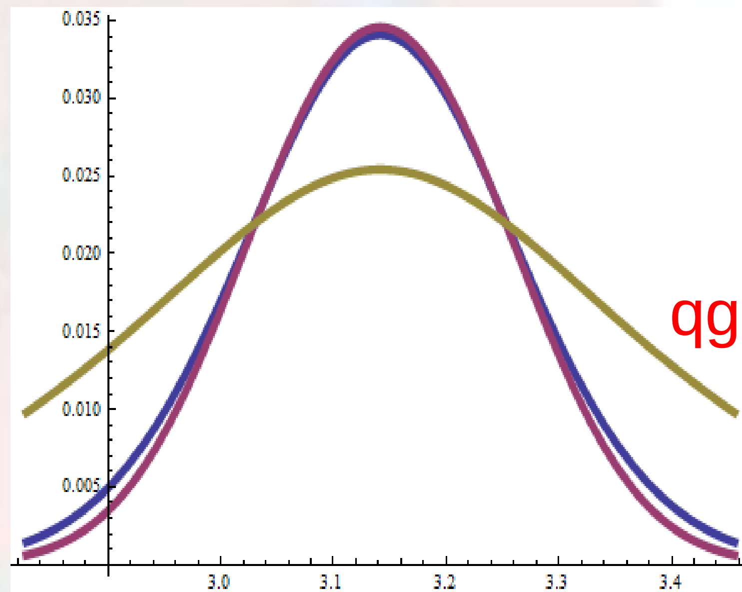
P_T





Violation effects

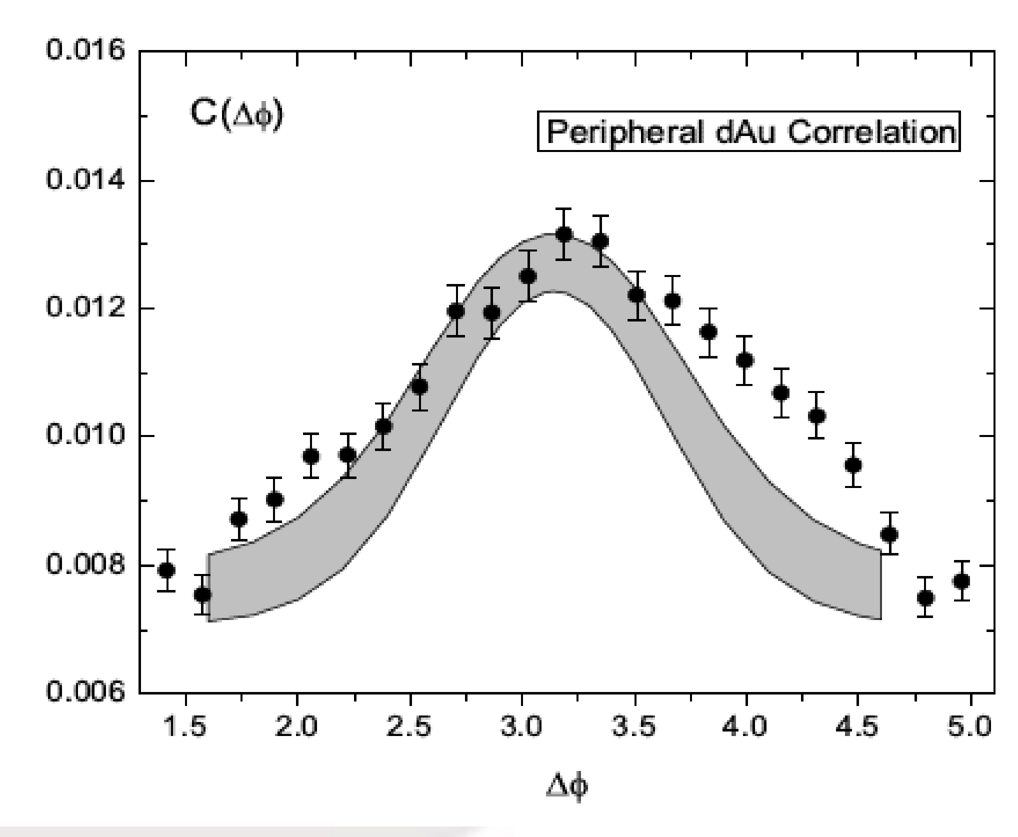




qg→qg

Compare to the STAR data

- $\eta_1 \sim \eta_2 \sim 3.1$
- GBW model for UGDs
- $Q_s^2 \sim (3.10^{-4}/x)^{0.28} GeV^2$
- $Q^2_{sA} \sim 0.45 A^{(1/3)} Q_{sp}^2$



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