

Onium production from the Color Glass Condensate

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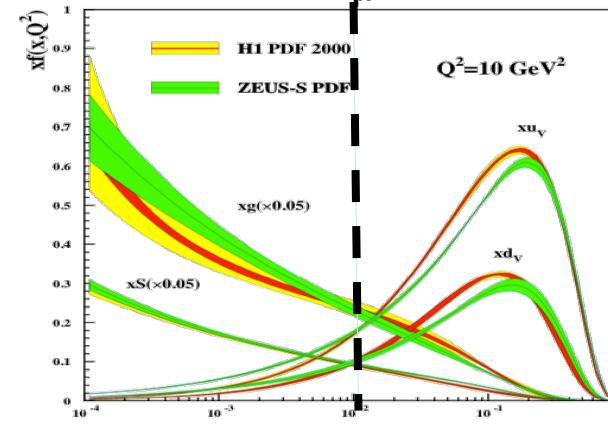
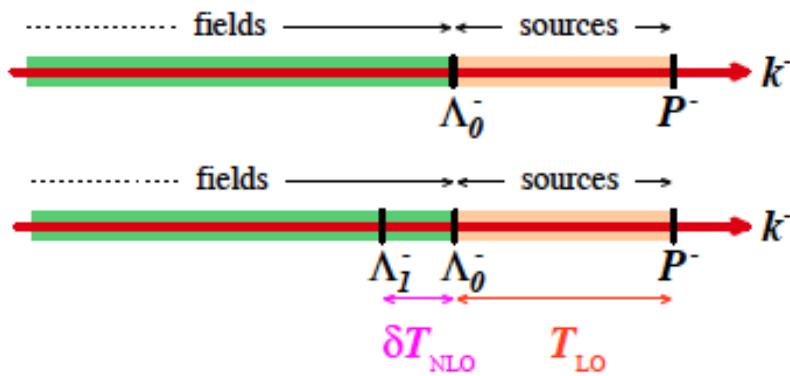
Talk Outline

- ❖ The Color Glass Condensate EFT
- ❖ Quark pair production in the CGC
- ❖ Matching: to pQCD at large momenta and NRQCD at large distances
- ❖ Sensitivity of Color Singlet and Color Octet channels to novel, universal multi-parton correlators
- ❖ Results for p+p collisions
 - '
- ❖ Expectations for p+A collisions
- ❖ Outlook (A+A collisions, ...)

Color Glass Condensate EFT

Gelis,Iancu,Jalilian-Marian, RV: Ann. Rev. Nucl. Part. Sci. (2010)

- ◆ QCD light front EFT framework of static light front (**large x**) color sources ρ^a coupled to dynamical (**small x**) gauge fields A_μ^a



- ◆ Wilsonian procedure in x (or rapidity) whereby fields are successively absorbed into sources- at each step, one has a **classical EFT**
- whereby A 's are functionals of ρ

$$\langle \mathcal{O} \rangle_Y = \int [d\rho] W_Y[\rho] \mathcal{O} \quad \text{where} \quad \frac{\partial W_Y[\rho]}{\partial Y} = \mathcal{H}[\rho] W_Y[\rho]$$

- ◆ Hamiltonian-describes functional “Fokker-Planck” –like evolution (in rapidity) of hierarchy of Balitsky-JIMWLK multi-parton (Wilson line) correlators

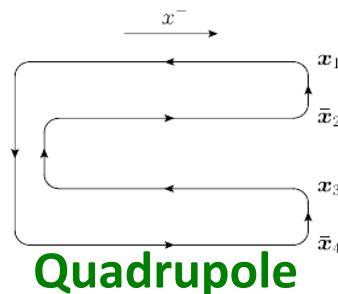
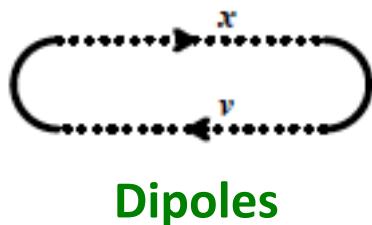
Color Glass Condensate EFT

Gelis, Iancu, Jalilian-Marian, RV: Ann. Rev. Nucl. Part. Sci. (2010)

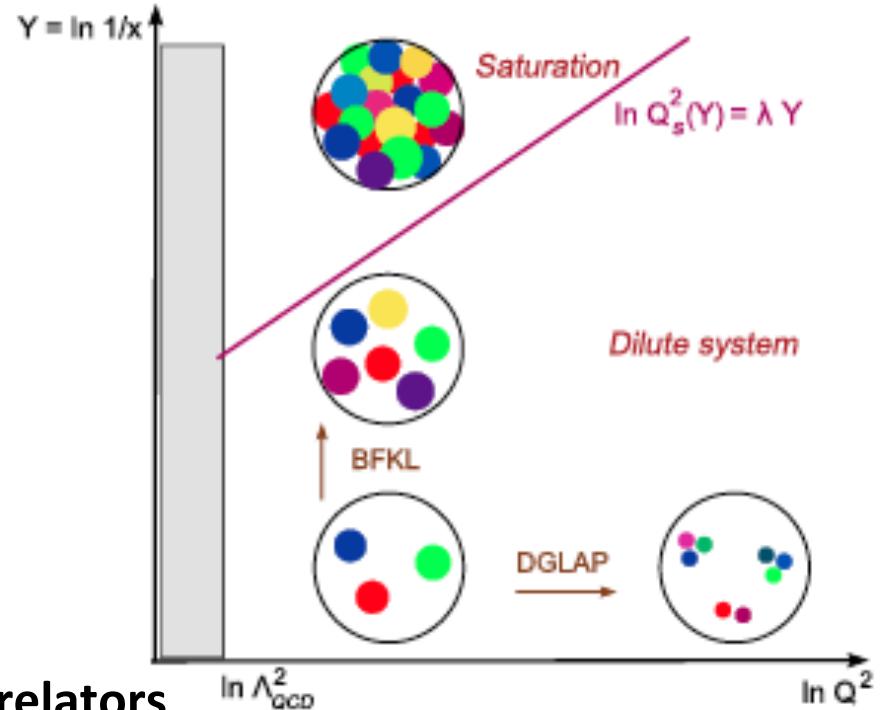
- Dynamically generated semi-hard scale Q_s controls multi-parton dynamics in the saturation regime

$k_T >> Q_s$, recover perturbative dynamics
 $k_T \leq Q_s$, classical high occupancy regime

- In nuclei, the saturation scale is enhanced: $Q_s^2 \sim A^{1/3} \Lambda_{\text{QCD}}^2 e^{\lambda Y}$
- Multi-parton dynamics encoded in energy evolution of light-like Wilson line correlators



$$D(x, y) = \frac{1}{N_c} \langle \text{Tr}(V_x V_y^\dagger) \rangle_Y \quad Q(x, y; \bar{y}, \bar{x}) = \frac{1}{N_c} \langle \text{Tr}(V_x V_{\bar{x}}^\dagger V_{\bar{y}} V_y^\dagger) \rangle_Y$$



These objects appear in a number of final states in DIS and hadron collisions

Heavy quark pair production in the CGC

Blaizot, Gelis, RV, NPA743 (2004) 57

Fujii, Gelis, RV, PRL95 (2005) 16202 ; NPA780 (2006) 146

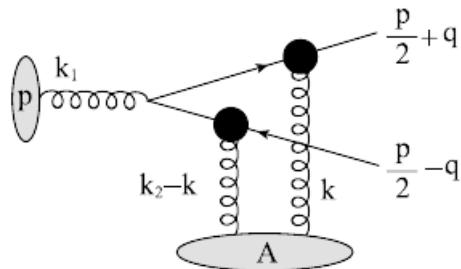
p+A collisions in the CGC:

i) Solution of Yang-Mills equations $[D_\mu, F^{\mu\nu}] = J^\nu$ with

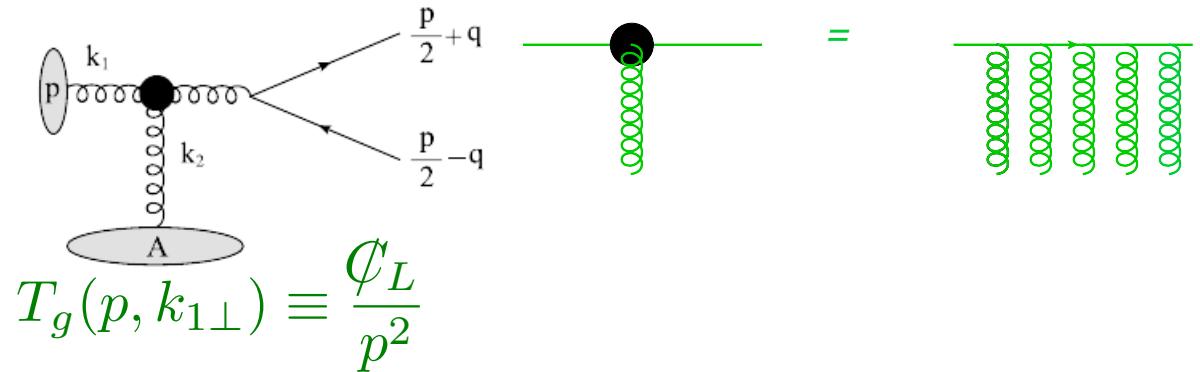
$$J_a^\nu = g\delta^{\nu+}\delta(x^-)\rho_{p,a}(x_{\perp\perp}) + g\delta^{\nu-}\delta(x^+)\rho_{A,a}(x_{\perp\perp})$$

LF proton color charge density LF nuclear color charge density

ii) Compute pair production amplitude in this background field



$$T_{q\bar{q}}(p, q, k_{1\perp}, k_{\perp})$$



$$T_g(p, k_{1\perp}) \equiv \frac{\mathcal{G}_L}{p^2}$$

are effective vertices, where

\mathcal{G}_L is the Lipatov vertex

Heavy quark pair production in the CGC

ii) Compute pair production amplitude in this background field

$$M_{s\bar{s};i\bar{i}}^F(p, q) = \frac{g_s^2}{(2\pi)^4} \int_{k_{1\perp}, k_\perp} \frac{\rho_{p,a}(x_p, k_{1\perp})}{k_{1\perp}^2} \int_{x_\perp, y_\perp} e^{ik_\perp \cdot x_\perp} e^{i(p_\perp - k_\perp - k_{1\perp}) \cdot y_\perp}$$

$$\times \bar{u}_{s;i} \left(\frac{p}{2} + q \right) \left[T_{q\bar{q}}(p, q, k_{1\perp}, k_\perp) V_F(x_\perp) t^a V_F^\dagger(y_\perp) + T_g(p, k_{1\perp}) t^b V_A^{ba}(x_\perp) \right] v_{\bar{s};\bar{i}} \left(\frac{p}{2} - q \right)$$

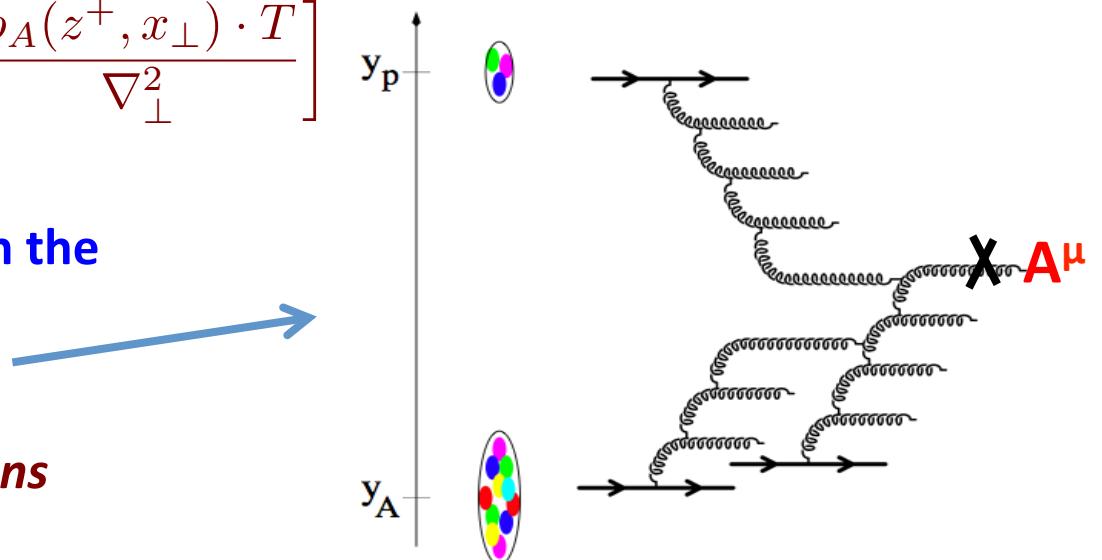
$$V_F(x_\perp) \equiv \mathcal{P}_+ \exp \left[-ig^2 \int_{-\infty}^{\infty} dz^+ \frac{\rho_A(z^+, x_\perp) \cdot t}{\nabla_\perp^2} \right]$$

$$V_A(x_\perp) \equiv \mathcal{P}_+ \exp \left[-ig^2 \int_{-\infty}^{\infty} dz^+ \frac{\rho_A(z^+, x_\perp) \cdot T}{\nabla_\perp^2} \right]$$

Analytical expressions derived in the
“dilute-dense” limit:

$$\rho_p/k_{T1}^2 \ll 1 \text{ and } \rho_A/k_{T2}^2 \approx 1$$

Forward p+p and/or p+A collisions

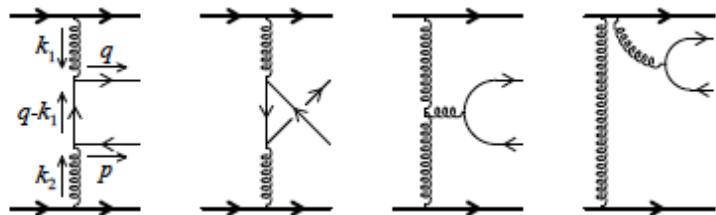


Heavy quark pair production in the CGC

iii) Average over color sources with RG-evolved weight functionals

$$\frac{d\sigma}{dy_p dy_q d^2 p_\perp d^2 q_\perp} \propto \int d^2 b_\perp \int [D\rho_p][D\rho_A] W_p[x_p, \rho_p] W_A[x_A, \rho_A] |\mathcal{M}_F(p_\perp, q_\perp)|^2 [\rho_p, \rho_A]$$

❖ In the “dilute-dilute” limit of $\rho_p/k_{T1}^2, \rho_A/k_{T2}^2 \ll 1$, recover k_T factorization results



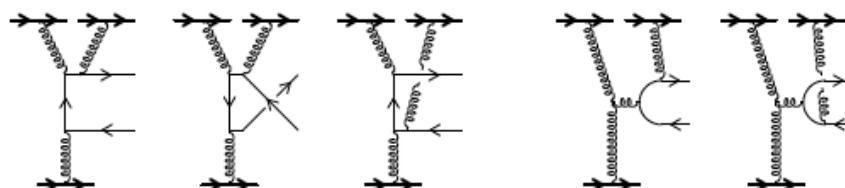
Collins, Ellis, NPB360 (1991) 3

Catani,Ciafaloni, Hautmann, NPB366 (1991) 135

Levin,Ryskin, Shuvaev,Shabelski, Sov.J. Nucl. Phys 53 (1991) 657
See also

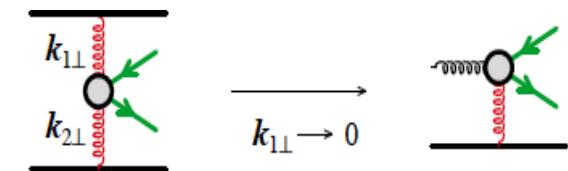
Catani,Ciafaloni,Hautmann, PLB242 (1990) 97

❖ k_T factorization breaks down at first non-trivial order in sources

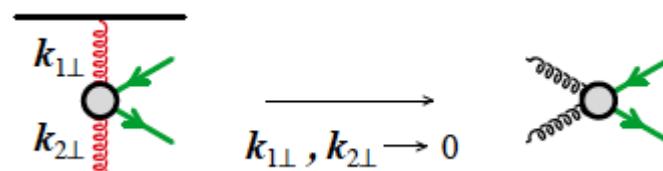


Gelis, RV, PRD69 (2004) 014019

❖ Perturbative (collinear) limits:



$$\frac{dN}{dM^2 d^2 P_\perp dY} \underset{P_\perp \rightarrow \infty}{\underset{M=\text{const}}{\sim}} \frac{\ln(P_\perp^2)}{P_\perp^4}$$



$$\frac{dN}{dM^2 d^2 P_\perp dY} \underset{P_\perp \rightarrow \infty}{\underset{M=\text{const}}{\sim}} \frac{\ln^2(M^2)}{M^4}$$

CGC meets NRQCD

$$p + A \longrightarrow H + X$$

$$d\sigma_H = \sum_{\kappa} d\hat{\sigma}^{\kappa} \langle \mathcal{O}_{\kappa}^H \rangle$$

**Short distance dynamics
computed in the CGC**

Kang, Ma, RV, JHEP1401 (2014) 056
Ma, RV, PRL113 (2014) 192301

$\kappa = {}^{2S+1}\mathbf{L}_J^{[c]}$ quantum
numbers of the intermediate
heavy quark pair

**Long distance matrix elements (LDME)
from NRQCD**

Quarkonium	contributing states
$J/\psi, \psi', \Upsilon(nS)$	${}^3S_1^{[1]}, {}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[8]}$
η_c, η_b	${}^1S_0^{[1]}$
h_c, h_b	${}^1P_1^{[1]}, {}^1S_0^{[8]}$
χ_{cJ}, χ_{bJ}	${}^3P_J^{[1]}, {}^3S_1^{[8]}$

❖ CGC amplitude projected on state with quantum #'s κ

$$M^{\kappa, J_z, (1,8c)}(p) = \sqrt{\frac{1}{m}} \sum_{L_z, S_z} \sum_{s, \bar{s}} \sum_{i, \bar{i}} \langle LL_z; SS_z | JJ_z \rangle \left\langle \frac{1}{2}s; \frac{1}{2}\bar{s} | SS_z \right\rangle \langle 3i; \bar{3}\bar{i} | (1, 8c) \rangle$$

$$\times \begin{cases} M_{s\bar{s}; i\bar{i}}^F(p, 0), & \text{if } \kappa \text{ is } S\text{-wave,} \\ \epsilon_{\beta}^*(L_z) M_{s\bar{s}; i\bar{i}}^{F, \beta}(p, 0), & \text{if } \kappa \text{ is } P\text{-wave} \end{cases}$$

$$M_{s\bar{s}; i\bar{i}}^{F, \beta}(p, 0) = \frac{\partial}{\partial q^{\beta}} M_{s\bar{s}; i\bar{i}}^F(p, q) \Big|_{q=0}$$

CGC meets NRQCD

$$\frac{d\hat{\sigma}^\kappa}{d^2 p_\perp dy} \stackrel{\text{CO}}{=} \frac{\alpha_s(\pi R_p^2)}{(2\pi)^7(N_c^2 - 1)} \int_{\mathbf{k}_{1\perp}, \mathbf{k}_\perp} \frac{\varphi_{p,y_p}(\mathbf{k}_{1\perp})}{k_{1\perp}^2} \\ \times \mathcal{N}_Y(\mathbf{k}_\perp) \mathcal{N}_Y(p_\perp - \mathbf{k}_{1\perp} - \mathbf{k}_\perp) \Gamma_8^\kappa$$

$$\phi_{p,y_p}(k_{1\perp}) = \pi R_p^2 \frac{N_c k_{1\perp}^2}{4\alpha_S} \tilde{\mathcal{N}}_{y_p}^A(k_{1\perp})$$

$$\mathcal{N}_Y(k_\perp) = \int_{r_\perp} e^{ik_\perp \cdot r_\perp} D_{Y,r_\perp}$$

Dipole correlator

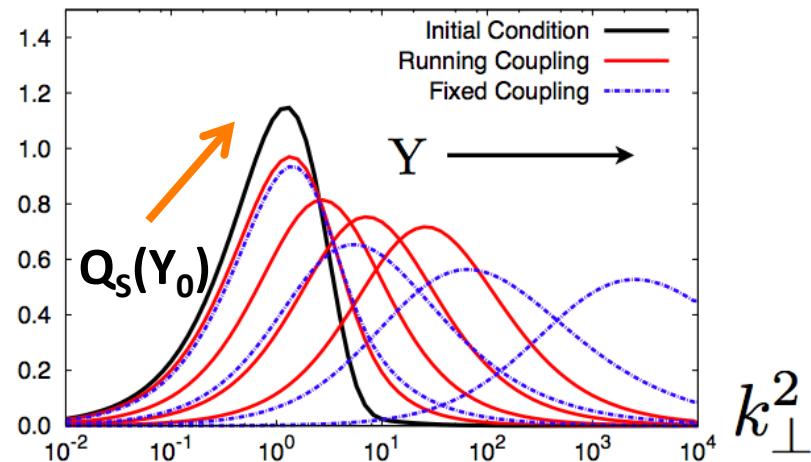
$$\frac{d\hat{\sigma}^\kappa}{d^2 p_\perp dy} \stackrel{\text{CS}}{=} \frac{\alpha_s(\pi R_p^2)}{(2\pi)^9(N_c^2 - 1)} \int_{\mathbf{k}_{1\perp}, \mathbf{k}_\perp, \mathbf{k}'_\perp} \frac{\varphi_{p,y_p}(\mathbf{k}_{1\perp})}{k_{1\perp}^2} \\ \times \mathcal{N}_Y(\mathbf{k}_\perp) \mathcal{N}_Y(\mathbf{k}'_\perp) \mathcal{N}_Y(p_\perp - \mathbf{k}_{1\perp} - \mathbf{k}_\perp - \mathbf{k}'_\perp) \mathcal{G}_1^\kappa$$

Previously only derived in a
quasi-classical approximation
Dominguez et al., PLB710 (2012) 182

Good approx. to expression involving both
quadrupole and dipole correlators

RG evolution of
the Balitsky-Kovchegov (JIMWLK)

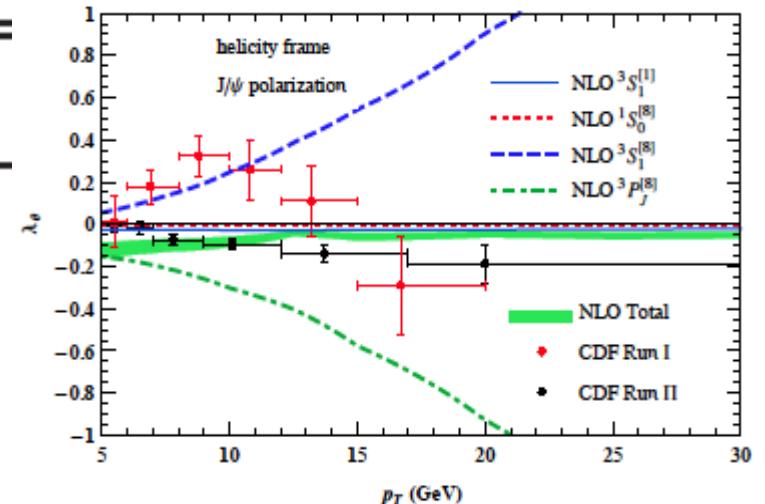
$\Phi(\mathbf{k}_T),$



Parameters from NRQCD and pdf fits

$\langle \mathcal{O}(\bar{S}_1^{[1]}) \rangle$	$\langle \mathcal{O}(S_0^{[8]}) \rangle$	$\langle \mathcal{O}(\bar{S}_1^{[8]}) \rangle$	$\langle \mathcal{O}(P_0^{[8]}) \rangle / m_c^2$
GeV ³	10 ⁻² GeV ³	10 ⁻² GeV ³	10 ⁻² GeV ³
1.16	8.9 ± 0.98	0.30 ± 0.12	0.56 ± 0.21

❖ LDME fit from differential cross-sections & polarization of J/ψ to Tevatron data in NLO pQCD+NRQCD K.-T. Chao et al., PRL108 (2012) 2420



❖ Unintegrated gluon distributions at large x > 0.01 (at large rapidities and p_T) determined from matching to the CTEQ6M pdf set

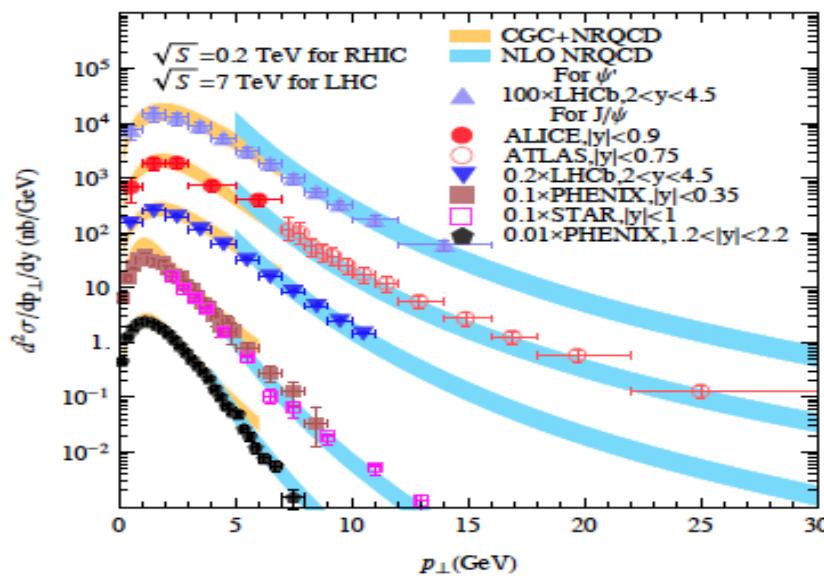
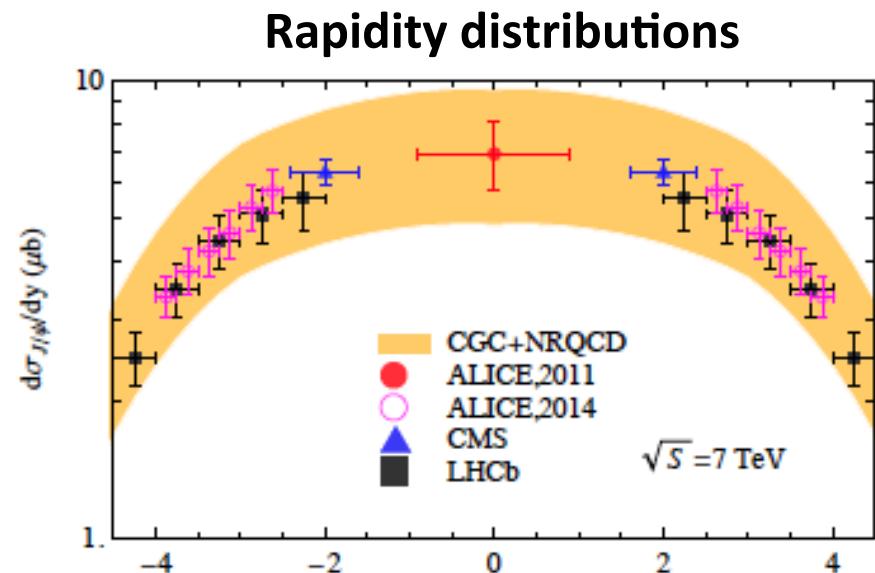
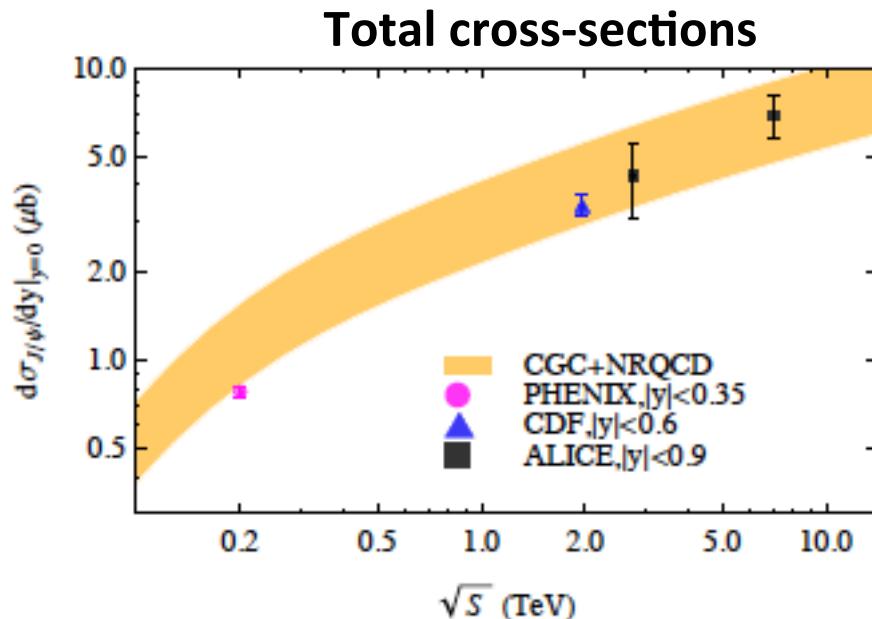
$$\text{For } x > x_0, \quad \tilde{\mathcal{N}}_{y_p}^A(k_{1\perp}) = a(x_p) \tilde{\mathcal{N}}_{Y_0}^A(k_{1\perp})$$

$$a(x_p) = x_p f_{p/g}(x_p, Q_0^2) \left[\frac{\pi R_p^2 N_c}{4\pi^3 4\alpha_S} \int^{Q_0^2} dk_{1\perp}^2 k_{1\perp}^2 \tilde{\mathcal{N}}_{Y_0}^A(k_{1\perp}) \right]^{-1}$$

From matching of function and its derivative at x₀, determine R_p=0.48 fm and Q₀=5.1 GeV

Results for p+p collisions

Ma, RV, PRL113 (2014) 192301



- ❖ p_T distributions match CGC+NRQCD at low p_T to NLO pQCD+NRQCD at large p_T
- ❖ Color singlet contribution at most 10%
Estimate this to be 15-20% for p+A
- ❖ Qualitative & quantitative differences with other approaches

Brodsky,Lansberg, PRD81 (2010)051502

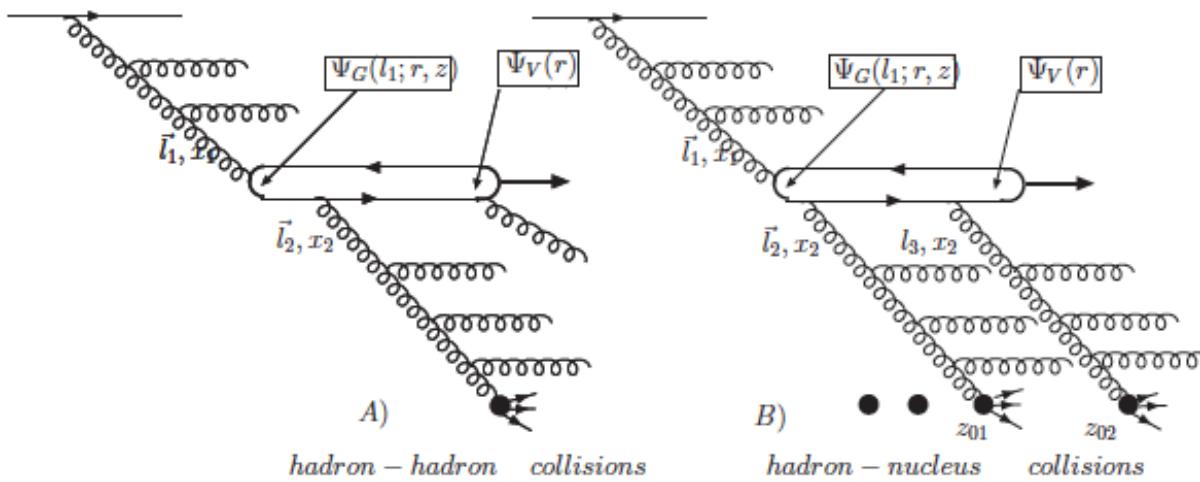
Fujii,Watanabe, NPA915 (2013) 1

Nelson,Vogt,Frawley, PRC87 (2013)014908

Quarkonia in p+A collisions

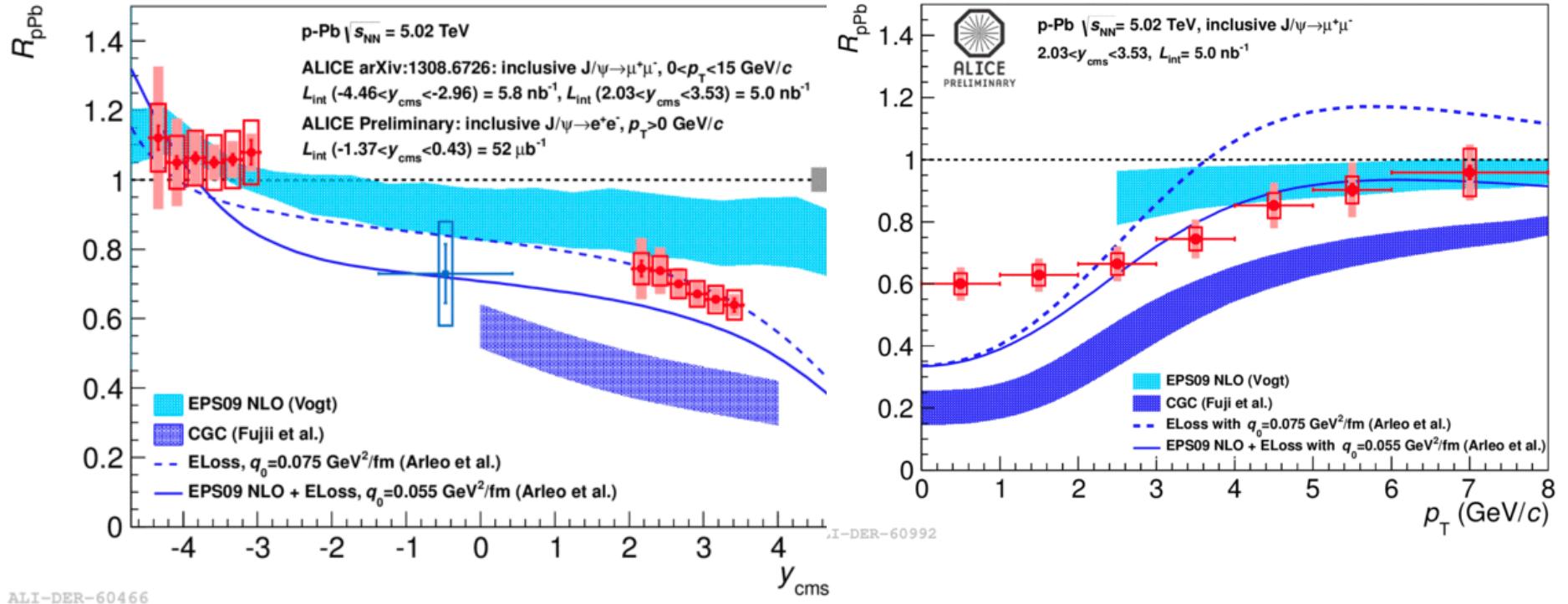
- ❖ The relative contribution of color singlet and color octet mechanisms can be modified in nuclei – in the CGC, multiple semi-hard scattering is not suppressed

Kharzeev, Levin, Nardi, Tuchin, NPA826 (2009) 230
Dominguez, Mueller, Kharzeev, Levin, Tuchin, PLB710 (2012) 182



- ❖ We recover the results of Dominguez et al in a semi-classical approximation of our expressions
- ❖ Obtain in our CGC+NRQCD approach, color singlet enhancement of ~ factor of 2 -- 15-20% of the cross-section

Quarkonia in p+A collisions

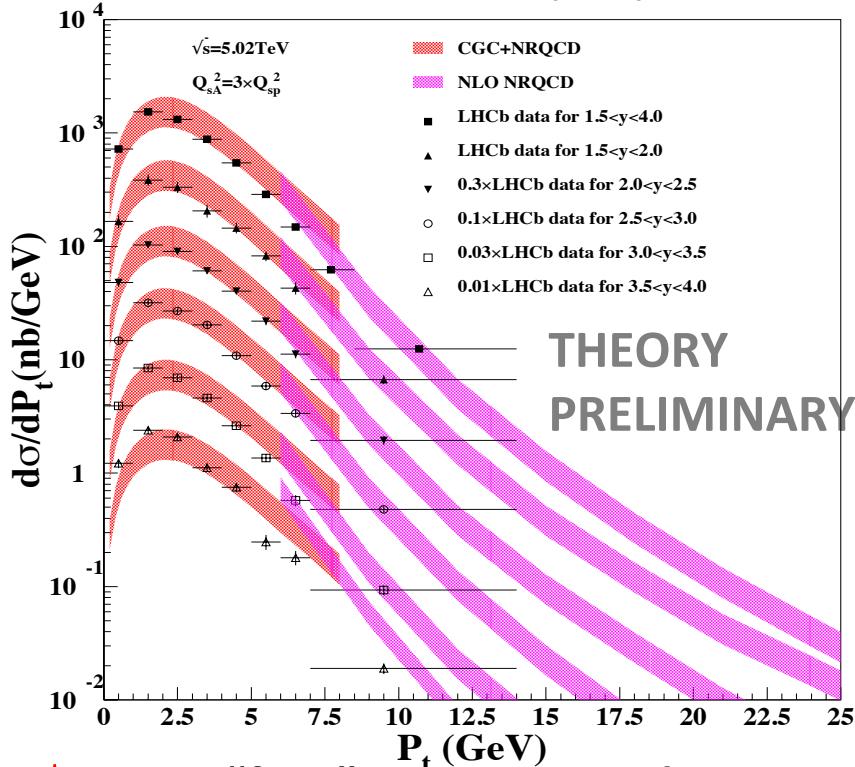


Experimentally, ALICE $R_{p\text{Pb}}$ shows patterns of suppression, also seen in LHCb and RHIC experiments

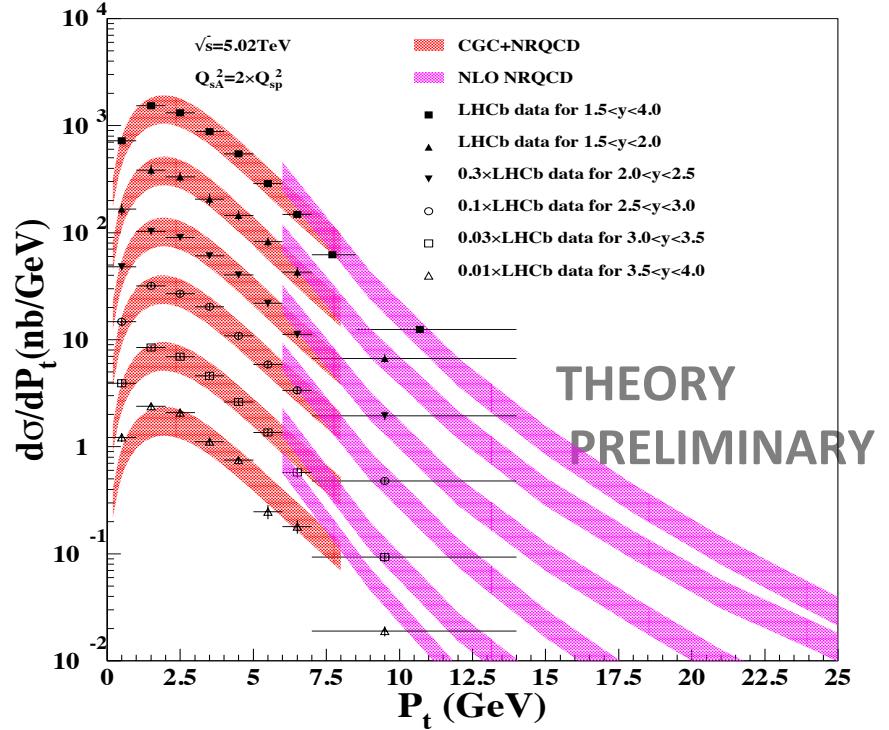
The CGC calculation of Fujii and Watanabe shows too much suppression:
 a) not matched to pQCD at large p_T ,
 b) fragmentation via color evaporation model

Quarkonia in p+A collisions

LHCb data. JHEP 02 (2014) 072



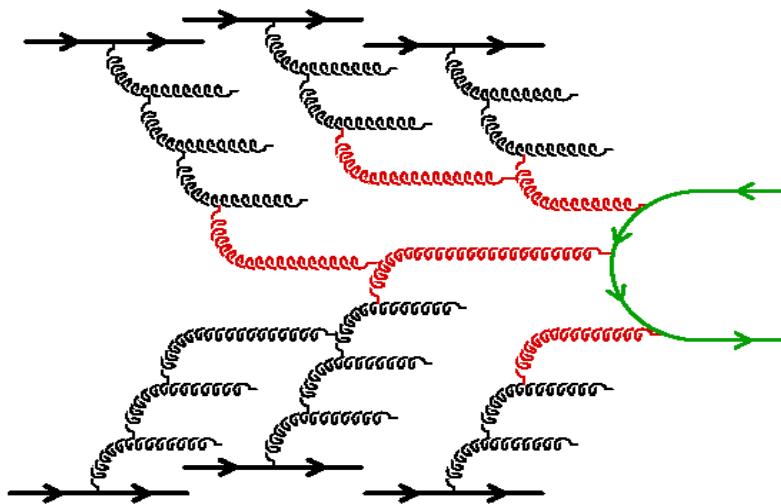
Yan-qing Ma, Hong-fei Zhang, RV, in preparation



- ❖ Two “free” parameters—the transverse overlap area and saturation scale at initial rapidities -- both are reasonable
- ❖ The matching to NLO pQCD ensures (modulo small shadowing corrections) that R_{pA} will go to unity – as seen in the data.
- ❖ This will ensure better agreement with data relative to previous CGC calculations

First principles computation of Onium production in A+A collisions

- ❖ Too challenging for analytical computations – but can be computed using real time lattice simulations of the classical EFT



Early attempt,
Gelis, Lappi, Kajantie, PRL96 (2006) 032304

- ❖ Significant recent progress in classical statistical lattice simulations in the CGC – heavy quark pair-production feasible now

Gelis, Epelbaum, PRD88 (2013) 085015
Berges, Schenke, Schlichting, RV, arXiv:1409.1638
Berges, Gelfand, Sexty, PRD89 (2014) 025001

Outlook

- ◆ Very promising CGC/NLO pQCD + NRQCD approach gives good agreement with p+p (and p+A) cross-sections in the entire p_T range.
- ◆ Very promising for quantitative studies – a wealth of data from RHIC and LHC to compare to.
- ◆ Include refinements to the approach (Sudakov logs for instance, see Jianwei Qiu's talk on Thursday).
- ◆ Extension of framework to compute Onium production in the initial stages of A+A collisions is feasible, if challenging.