

Initial conditions in AA and pA collisions

T. Lappi

University of Jyväskylä, Finland

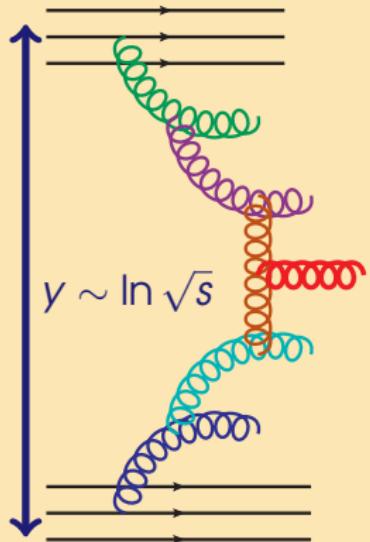
Confinement XII, Thessaloniki



Outline

- ▶ From nuclear wavefunction to collision
 - ▶ Small x and saturation
 - ▶ Classical Yang-Mills
- ▶ Control experiments: probing small x
- ▶ Long range correlations:
direct signs of initial state in data?

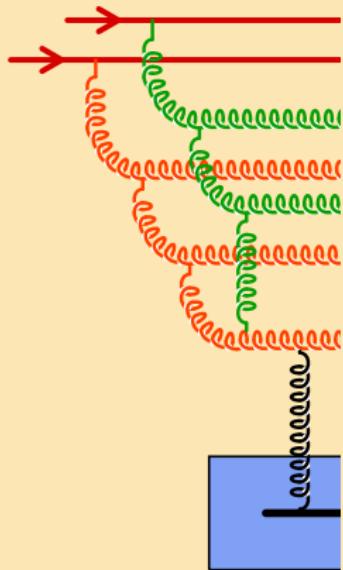
Initial state is small x



- ▶ Gluons ending in central rapidity region: multiple splittings from valence quarks
- ▶ Emission probability $\alpha_s dx/x$
⇒ rapidity plateau for $\Delta y \ll / \alpha_s$
- ▶ Many gluons, in fact

$$N \sim \sum_n \frac{1}{n!} (\alpha_s \ln \sqrt{s})^n \sim \sqrt{s}^{\alpha_s}$$

Small x and saturation



- ▶ Eventually gluons in cascade overlap
- ▶ YM covariant derivative
 $-iD_\mu = -i\partial_\mu + gA_\mu = p_\mu + gA_\mu$
- ▶ Nonlinearities when $p_T \sim gA_\perp \sim Q_s$
 $\implies A_\perp \sim Q_s/g$
(LC gauge gluons have $\mu \rightarrow \perp$)

Weak coupling, but nonperturbative

- ▶ α_s small
- ▶ $f(k) \sim A_\mu A_\mu \sim 1/\alpha_s$ large

True when $Q_s \gg \Lambda_{\text{QCD}}$

\implies gets better at large \sqrt{s}

Wilson line

Classical color field described as Wilson line

$$V(\mathbf{x}_T) = P \exp \left\{ ig \int dx^- A_{\text{cov}}^+(\mathbf{x}_T, x^-) \right\} \in \text{SU}(3)$$

Physical interpretation:

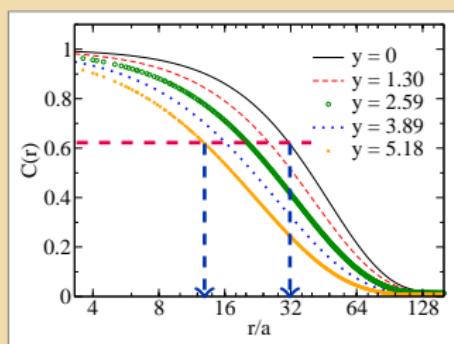
Eikonal propagation of parton through target color field

Q_s is characteristic momentum/distance scale

Precise definition used here:

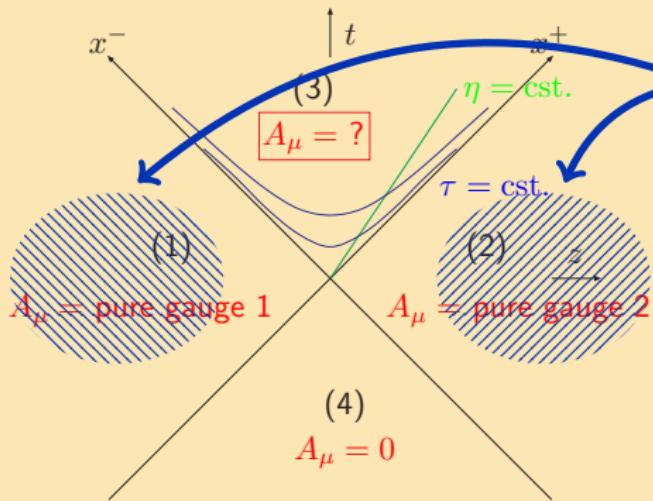
$$\frac{1}{N_c} \left\langle \text{Tr } V^\dagger(\mathbf{0}_T) V(\mathbf{x}_T) \right\rangle = e^{-\frac{1}{2}}$$

$$\iff \mathbf{x}_T^2 = \frac{2}{Q_s^2}$$



Classical Yang-Mills initial state

Classical Yang-Mills



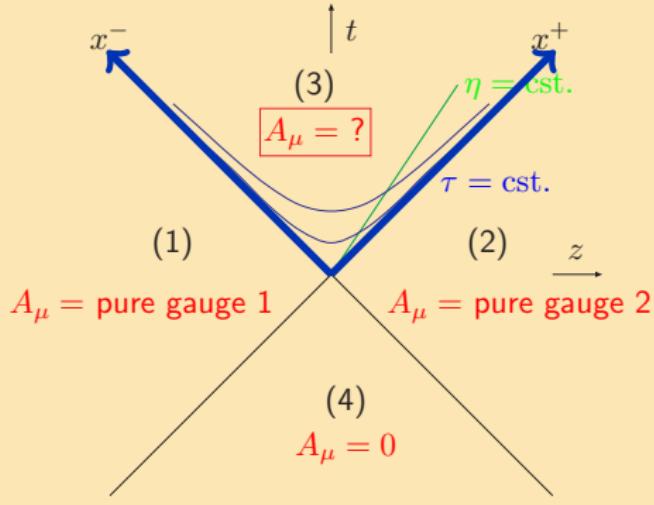
Change to LC gauge:

$$A_{(1,2)}^i = \frac{i}{g} U_{(1,2)}(\mathbf{x}_T) \partial_i U_{(1,2)}^\dagger(\mathbf{x}_T)$$

Same Wilson line $U(\mathbf{x}_T)$

Classical Yang-Mills initial state

Classical Yang-Mills



Change to LC gauge:

$$A_{(1,2)}^i = \frac{i}{g} U_{(1,2)}(\mathbf{x}_T) \partial_i U_{(1,2)}^\dagger(\mathbf{x}_T)$$

Same Wilson line $U(\mathbf{x}_T)$

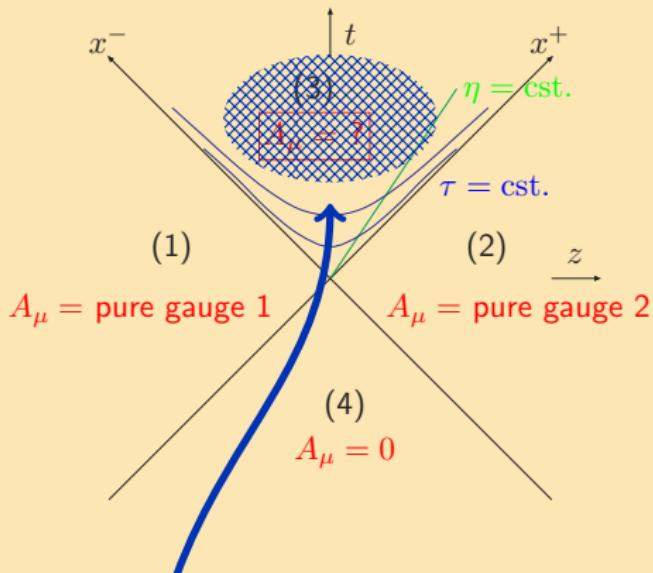
At $\tau = 0$:

$$A^i|_{\tau=0} = A_{(1)}^i + A_{(2)}^i$$

$$A^\eta|_{\tau=0} = \frac{ig}{2} [A_{(1)}^i, A_{(2)}^i]$$

Classical Yang-Mills initial state

Classical Yang-Mills



$\tau > 0$ Solve Classical Yang-Mills **CYM** equations.

This is the **glasma** field \implies Then average over $U(\mathbf{x}_T)$.
In dilute limit reduces to k_T -factorization.

Change to LC gauge:

$$A_{(1,2)}^i = \frac{i}{g} U_{(1,2)}(\mathbf{x}_T) \partial_i U_{(1,2)}^\dagger(\mathbf{x}_T)$$

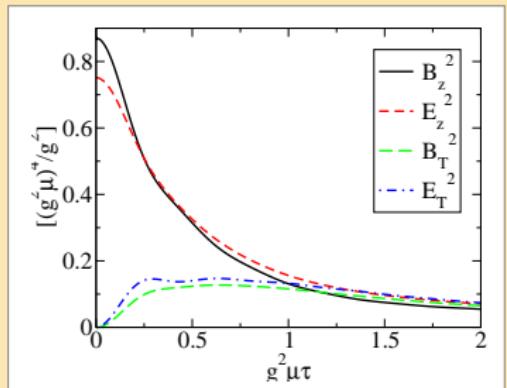
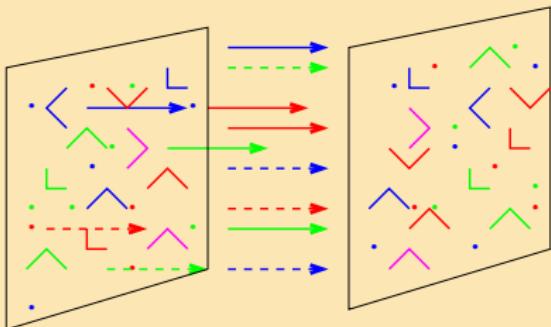
Same Wilson line $U(\mathbf{x}_T)$

At $\tau = 0$:

$$A^i|_{\tau=0} = A_{(1)}^i + A_{(2)}^i$$

$$A^\eta|_{\tau=0} = \frac{ig}{2} [A_{(1)}^i, A_{(2)}^i]$$

Properties of the plasma initial state



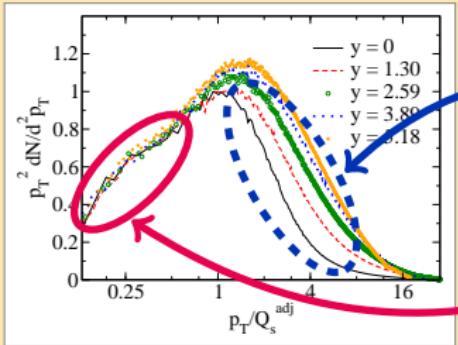
- $\tau = 0$: longitudinal E and B field,
- At $\tau \gtrsim 1/Q_s$:
gluons with $p_T \sim Q_s$
— strings of size $R \sim 1/Q_s$
- Correlation length $1/Q_s$

Pressure components:

$$\begin{aligned} P_\perp &= \frac{1}{2} (E_L^2 + B_L^2) \sim \frac{1}{\tau} \\ P_L &= \frac{1}{2} (E_\perp^2 + B_\perp^2 - E_L^2 - B_L^2) \\ &\ll P_\perp \implies \text{anisotropy} \end{aligned}$$

Universality in the IR

Dumitru, T.L., Nara 2014



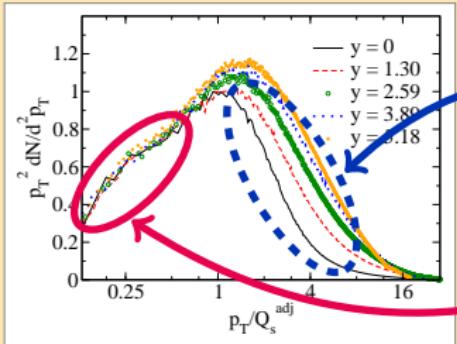
Gluon spectrum:

- UV depends on initial condition
- IR scales, close to

$$\frac{dN}{d^2 p_T} \sim \frac{1}{p_T}$$

Universality in the IR

Dumitru, T.L., Nara 2014



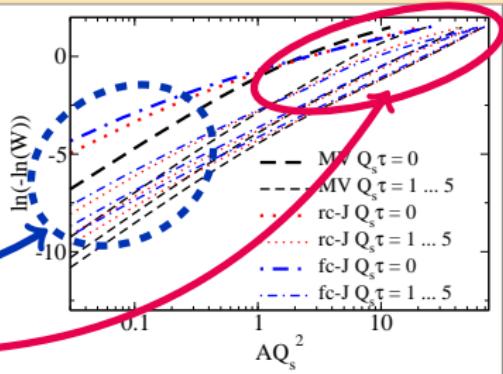
Gluon spectrum:

- UV depends on initial condition
- IR scales, close to

$$\frac{dN}{d^2 p_T} \sim \frac{1}{p_T}$$

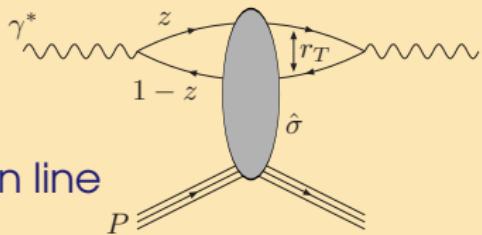
Spatial Wilson loop:

- $W = \exp \{ -(\sigma A)^\gamma \}$
- UV (small loop): initial slope γ stays
 - IR (big loop): universal area law



Dilute-dense control measurements

DIS at small x : dipole picture



- ▶ CGC: dipole cross section is Wilson line correlator

$$\sigma_{q\bar{q}}(\mathbf{r}_T) = \int d^2\mathbf{b}_T \frac{1}{N_c} \text{Tr} \left\langle 1 - U^\dagger \left(\mathbf{b}_T + \frac{\mathbf{r}_T}{2} \right) U \left(\mathbf{b}_T - \frac{\mathbf{r}_T}{2} \right) \right\rangle$$

$$U(\mathbf{x}_T) = P \exp \left\{ ig \int dx^- A_{\text{cov}}^+(\mathbf{x}_T, x^-) \right\}$$

- ▶ High energy: energy dependence from JIMWLK (for U) or BK (for $\sigma_{q\bar{q}}$) equations

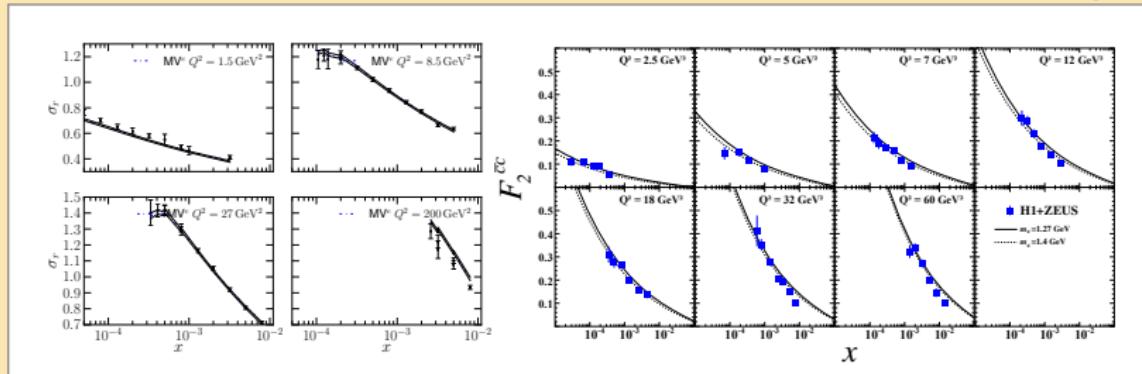
Total DIS cross section $\sigma_{\text{tot}}^{\gamma^* H} = |\Psi(\gamma^* \rightarrow q\bar{q})|^2 \otimes \sigma_{q\bar{q}}$

Same Wilson line $U(\mathbf{x}_T)$ as in initial glasma color field.

Control measurement 1: DIS

Initial state description should:

- ▶ Be consistent with DIS measurements from HERA, e.g.



Proton F_2 rcBK

T.L., Mäntysaari

Proton F_2^C IPsat

Rezaeian et al

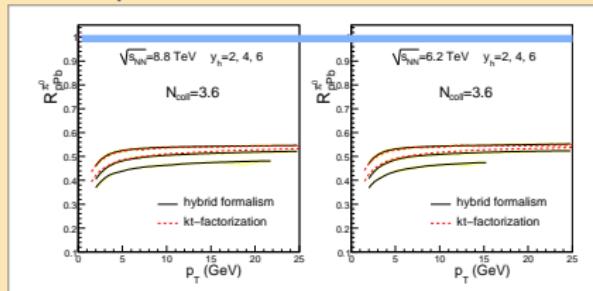
- ▶ Give testable predictions for EIC.

Control measurement 2: R_{pA}

R_{pA} = Cross section ratio between $p p$ and $p A$ collisions

- ▶ Need **unintegrated** gluon distribution
 - Fourier transform of dipole cross section
- ▶ Normalization corrected with “K-factor” (Cancels in R_{pA})
- ▶ Nuclear geometry

Compare with state of the art BK evolution in 2010:

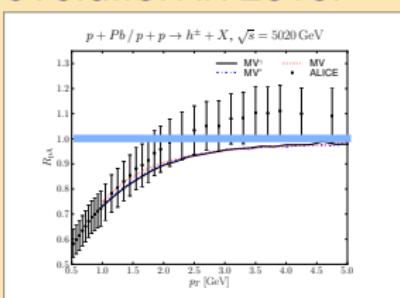


Albacete, Marquet arXiv:1001.1378

T.L., Mäntysaari, arXiv:1309.6963

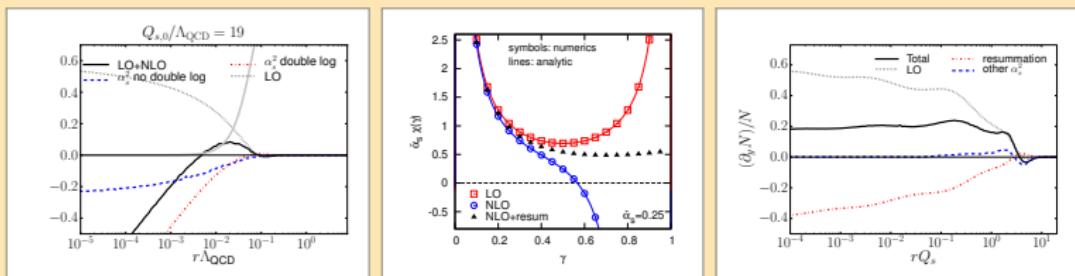
Similar rcBK — main difference is nuclear geometry

Similarly: $J/\Psi R_{pA}$: Ducloué., T.L., Mäntysaari 2015



Moving to NLO: BK evolution

- ▶ Balitsky-Kovchegov equation: energy dependence of dipole cross section.
- ▶ LO (~ 1995): used routinely
- ▶ NLO equation: Balitsky, Chirilli 2008



Equation unstable Plot here: T.L., Mäntysaari 2015

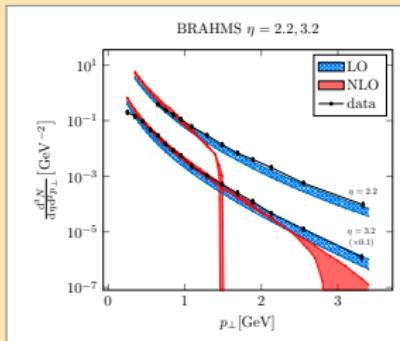
Resummation of double logs logs Iancu et al

Resummation & finite NLO T.L., Mäntysaari 2016

With suitable scale choice: finite NLO part small

See also previous talk: Triantafyllopoulos: first actual fit to HERA DIS data

Single inclusive particle production at NLO



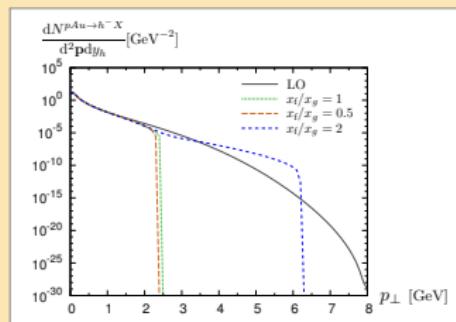
- ▶ NLO calculation Chirilli, Xiao, Yuan 2012
- ▶ Cross section negative Stasto, Xiao, Zaslavsky 2013
- ▶ Many suggestions: Beuf et al 2014, Kang et al 2014, Watanabe, et al 2015

Ducloué, T.L., Zhu arXiv:1604.00225:

Problem is subtraction in BK-factorization:

- ▶ Identify from color factor ($N_c < \infty$!)
- ▶ Solution: probe \rightarrow target momentum ordering

Iancu, Mueller, Triantafyllopoulos arXiv:1608.05293 :



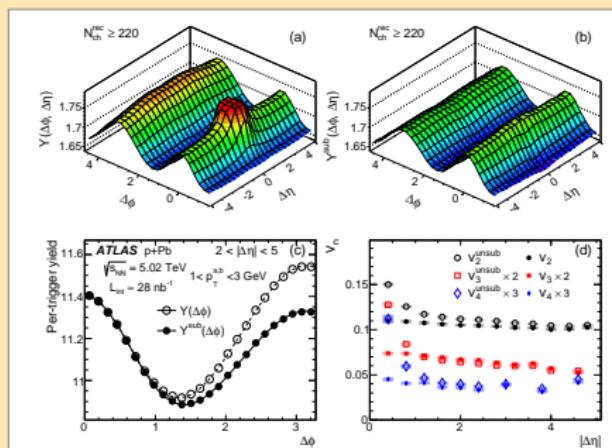
new manifestly positive formulation 13/19

Correlations:
direct signals of initial state?

Long range in rapidity: early time

See also talk by S. Schlichting

- ▶ Long range rapidity correlations: early time
 - ▶ Analogous to CMB
- ▶ v_n = multiparticle correlation (usually long range in rapidity)
- ▶ Geometry is the ultimate infinite-range correlation
 - ▶ All rapidities sensitive to \perp geometry
 - ▶ Hydro translates x -space correlations into p -space

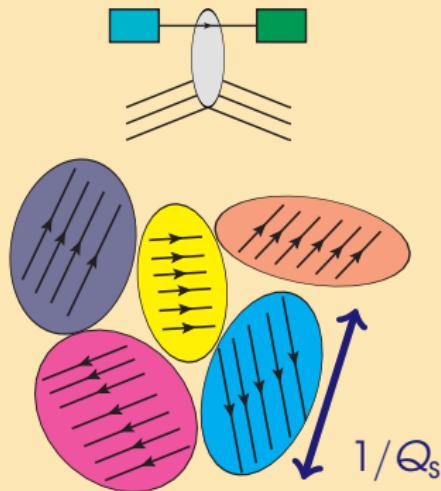


Seen as yield/trigger or as v_n :
ATLAS arXiv:1409.1792

Initial state QCD long range effects:
non-geometry correlations directly in momentum space

Domains in the target color field

Initial state CGC correlations in dilute-dense limit



- ▶ ~collinear high- x q/g
- ▶ Momentum transfer from target E -field
- ▶ Domains of size $\sim 1/Q_s$
- ▶ Several particle see same domain: multiparticle azimuthal correlations.

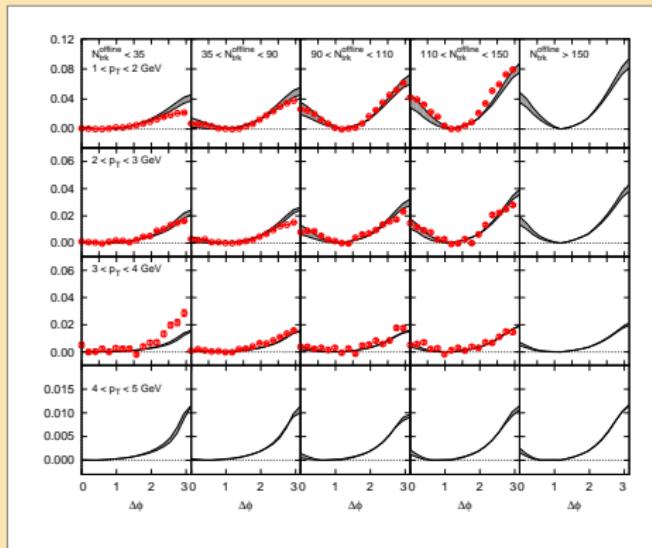
- ▶ $\sim Q_s^2 S_\perp$ domains (S_\perp = size of interaction area, πR_A^2 , πR_p^2)
- ▶ $\sim N_c^2$ colors

Correlation $\frac{1}{N_c^2 Q_s^2 S_\perp}$ \implies relatively stronger in small systems

Initial state angular correlation calculations

Analyzed in terms of the

- ▶ Ridge correlation

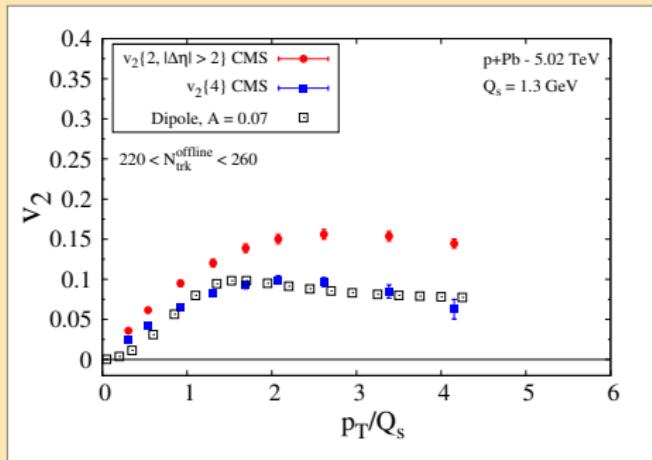


Dusling, Venugopalan, arXiv:1302.7018

Initial state angular correlation calculations

Analyzed in terms of the

- ▶ Ridge correlation
- ▶ E-field domain model

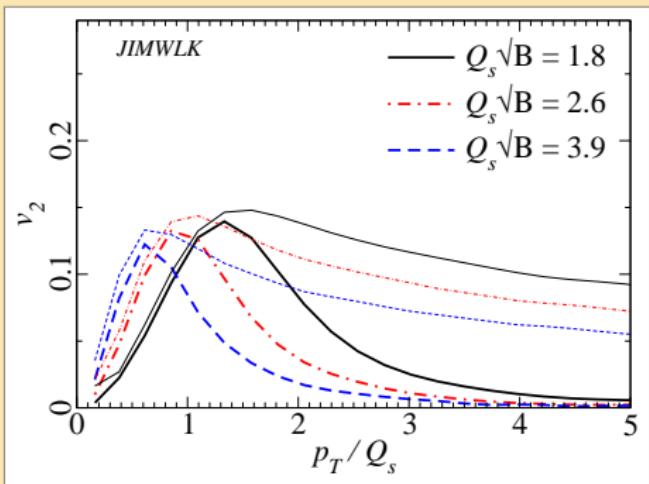


Dumitru, Giannini arXiv:1406.5781

Initial state angular correlation calculations

Analyzed in terms of the

- ▶ Ridge correlation
- ▶ E-field domain model
- ▶ Dilute dense with full nonlinear JIMWLK

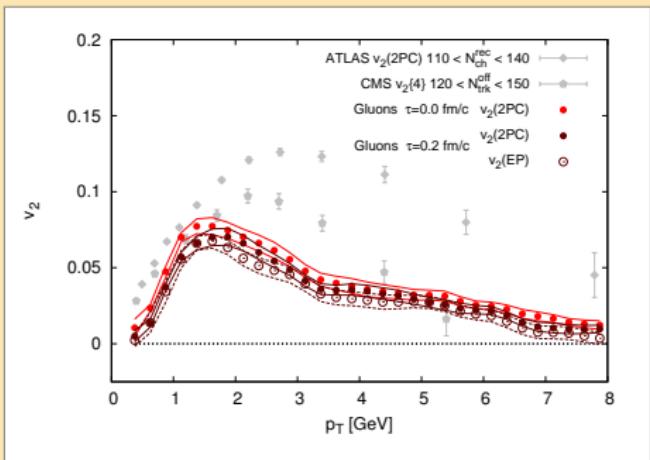


T.L., arXiv:1501.05505

Initial state angular correlation calculations

Analyzed in terms of the

- ▶ Ridge correlation
- ▶ E-field domain model
- ▶ Dilute dense with full nonlinear JIMWLK
- ▶ Dense-dense with CYM



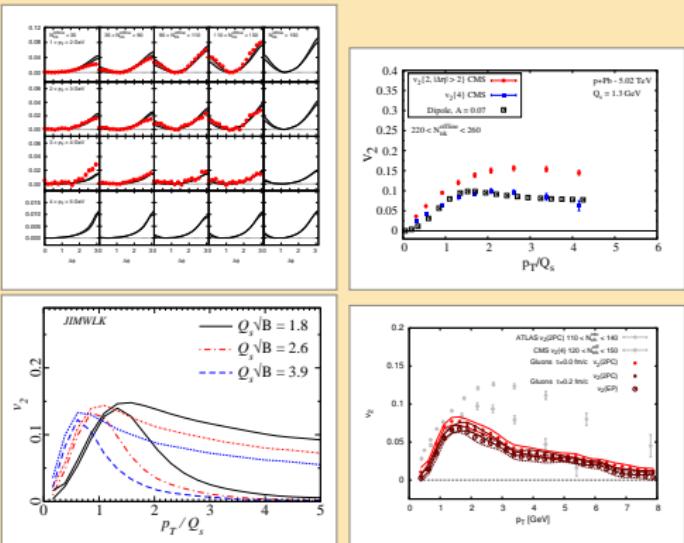
Schenke, Schlichting, Venugopalan

arXiv:1502:01331

Initial state angular correlation calculations

Analyzed in terms of the

- ▶ Ridge correlation
- ▶ E-field domain model
- ▶ Dilute dense with full nonlinear JIMWLK
- ▶ Dense-dense with CYM



Main physics idea in these is the same;
approximations in the calculations different

Difference between approximations

For $V(\mathbf{x}_T) = P \exp \left\{ ig \int d\mathbf{x}^- \frac{\rho(\mathbf{x}_T, \mathbf{x}^-)}{\nabla_T^2} \right\}$,

need $\langle \text{Tr } V^\dagger(\mathbf{x}_T) V(\mathbf{y}_T) \text{Tr } V^\dagger(\mathbf{u}_T) V(\mathbf{v}_T) \rangle$

Different approximations used

- ▶ “Nonlinear Gaussian”: Gaussian in ρ + nonlinear $\rho \rightarrow V$
- ▶ “Glasma graph”: linearize in ρ , Gaussian ρ
- ▶ “E-field domain model”, small dipole limit + intrinsic non-Gaussianity
- ▶ CYM: nonlinear with Gaussian ρ for **both** nuclei
+ final state evolution

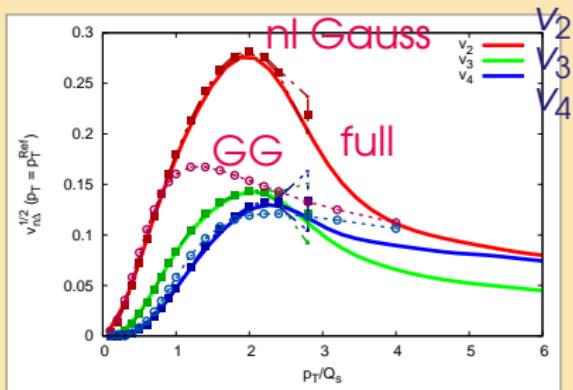
More recent focus: decorrelations for parametrically large rapidity separations. See talk by S. Schlichting

Approximations for Wilson line correlator

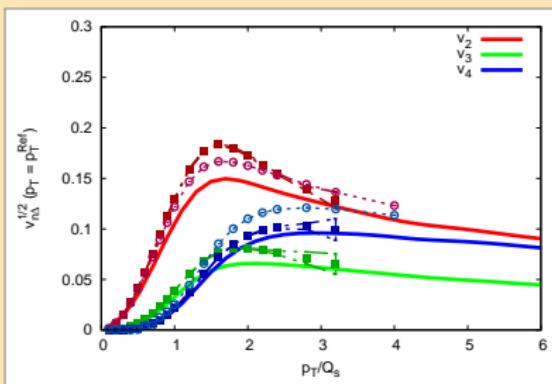
T. L., B. Schenke, S. Schlichting and R. Venugopalan, arXiv:1509.03499 [hep-ph]

Compare full MV or JIMWLK $v_n\{2\}$ to

- ▶ Nonlinear Gaussian (Gaussian ρ , do not linearize) :
accurate within 10%
- ▶ “Glasma graph” (Gaussian + linearized)
differs by factor 2 at most



MV



JIMWLK

Conclusions

- ▶ CGC picture of initial stage of an AA collision:
nonperturbatively strong, classical gauge fields
⇒ anisotropic system of gluons
- ▶ Dilute-dense control processes: moving to NLO accuracy
- ▶ Correlations (v_n) in small systems: interplay between initial and final state collective effects

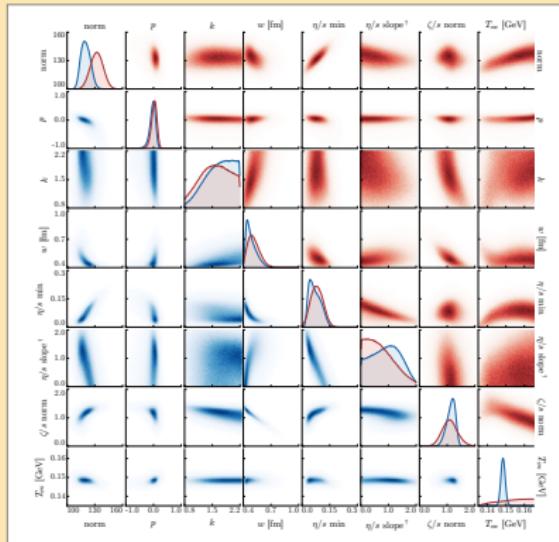
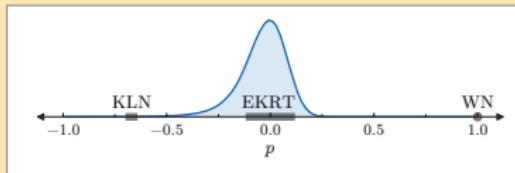
Initial state extraction from hydro?

Hydro, Bayesian global fit Bernhard et al arXiv:1605.03954

Initial entropy density
parametrized as

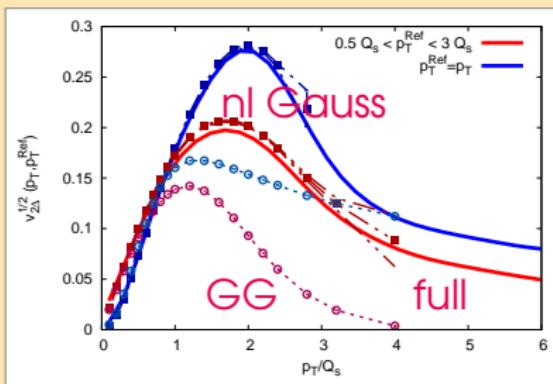
$$s(\mathbf{x}_T) \sim \left(\frac{(T_A(\mathbf{x}_T))^p + (T_B(\mathbf{x}_T))^p}{2} \right)^{\frac{1}{p}}$$

Heavy ion data favors particle
production from gluon
saturation ($p \approx 0$) :



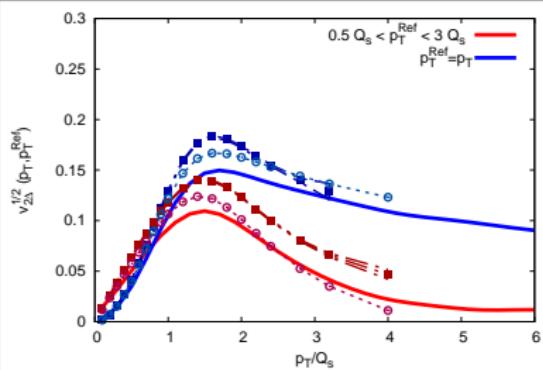
Effect of reference p_T

MV



$p_{T\text{ref}} = \text{all}$
 $p_{T\text{ref}} = p_T$

JIMWLK



Correlation more localized in p_T than experimental data
(Hadronization will change this, but how much?)

- ▶ MV: GG decorrelates particularly fast
- ▶ JIMWLK: Little difference between approximations