Azimuthal multigluon correlations in the glasma initial state

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UNIVERSITY OF JYVÄSKYLÄ

HELSINKI INSTITUTE OF PHYSICS

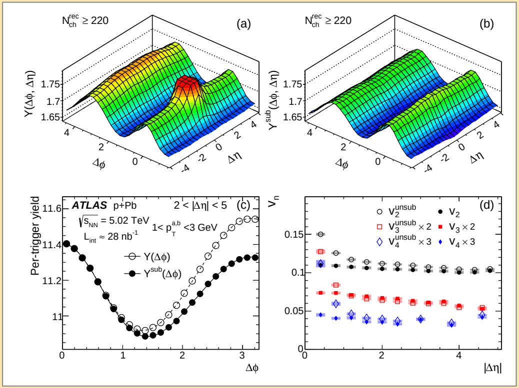
Outline

- Experimental observation: azimuthal correlations
- CGC and glasma
- How the CGC picture leads to azimuthal correlations
  - Dilute-dense case: Wilson line correlators
  - Dense-dense case: Classical Yang-Mills
- Relating different recent approaches

Azimuthal correlations in small systems

Experimental observation

- AA, high N_{ch} pA & pp
- Azimuthal anisotropy in particle production
  (especially $\sim \cos 2\varphi$)
- LHC and also RHIC

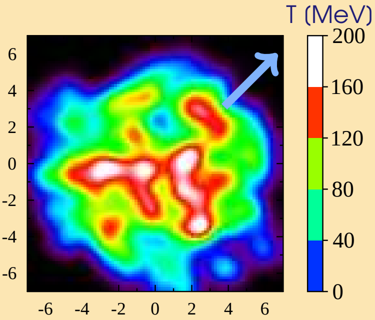


Analyzed as yield/trigger or as v_n:
ATLAS, Phys. Rev. C **90** (2014) 4, 044906 [arXiv:1409.1792 [hep-ex]].

What is the origin of the effect?

- Collective flow as in AA?
- Initial state gluon correlations?

Azimuthal correlations from flow



- Interactions/collectivity
- \+ Temperature/pressure gradients
- ⟹ Anisotropic force, acceleration
  - anisotropy in momentum

Large system:

⟹ details of MC Glauber matter little

⟹ initial geometry under control

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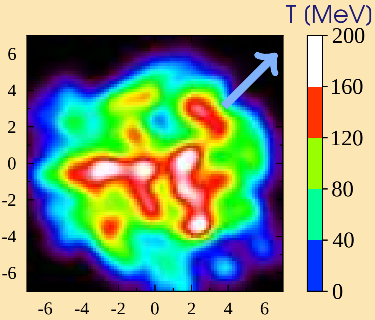

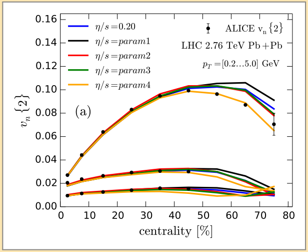

Works well in AA Niemi et al

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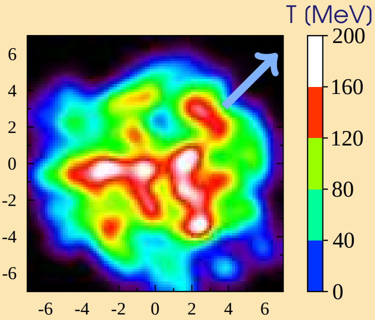

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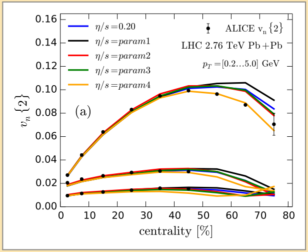

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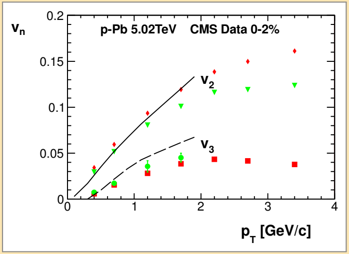
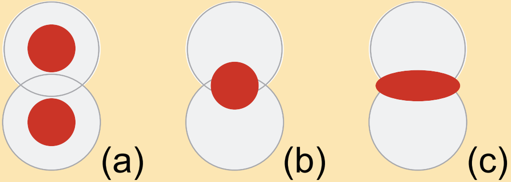


But also in small systems? Bozek, Broniowski

Flow in small systems

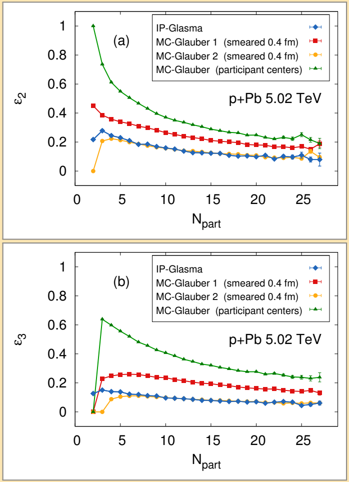
Want to do MC Glauber for pA & pp
How is the energy distributed?



Eccentricities very model-dependent

"Hydro prediction for flow" in small systems: large initial state theory uncertainty.

Hydro calculations for v_n in pA
what about pp at similar N_{ch}?

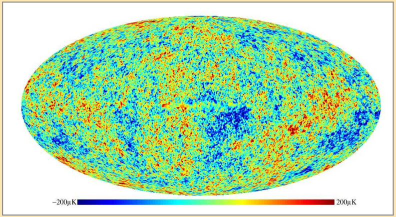


(Green: (a), red: (a) smeared, yellow: (b) smeared)

Bzdak, Schenke, Tribedy Venugopalan,

Long range in rapidity: early time

- Long range rapidity correlations: early time
  - Analogous to CMB
- v_n= multiparticle correlation
  (usually long range in rapidity)
  - Some particles determine reaction plane
  - Other particles correlated with this plane
- Geometry is the ultimate infinite-range correlation
  - All rapidities sensitive to $\perp$ geometry
  - Hydro translates *x*-space correlations into *p*-space



T of universe very homogenous:
early time causal connection

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

Gluon saturation, Glass and Glasma

Small x: the hadron/nucleus wavefunction is characterized by **saturation scale** $Q_s \gg \Lambda_{QCD}$.

Gluon saturation, Glass and Glasma

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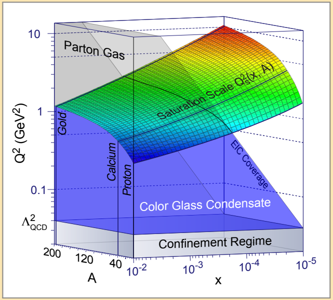
▼

$\mathbf{p}_T \sim Q_s$: strong fields $A_\mu \sim 1/g$

- occupation numbers $\sim 1/\alpha_s$
- classical field approximation.
- small α_s, but nonperturbative



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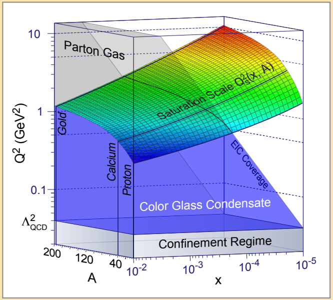

CGC: Effective theory for wavefunction of nucleus

- Large x = source ρ, **probability** distribution $W_y[\rho]$
- Small x = classical gluon field A_μ + quantum flucts.

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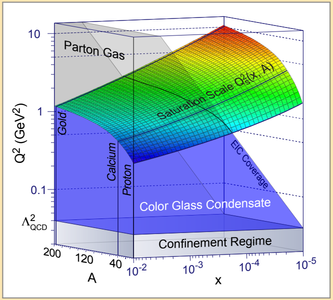

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Glasma: field configuration of two colliding sheets of CGC.
JIMWLK: y-dependence of $W_y[\rho]$

Wilson line

Classical color field described as Wilson line

In practice degree of freedom is not ρ but Wilson line:

$$V(\mathbf{x}_T) = P \exp\left\{ ig \int \mathrm{d}x^- A^+_{\mathrm{cov}}(\mathbf{x}_T, x^-) \right\} \quad \in \quad \mathrm{SU}(3)$$

$$\text{Color charge } \rho: \quad \boldsymbol{\nabla}_T{}^2 A^+_{\mathrm{cov}}(\mathbf{x}_T, x^-) = -g\rho(\mathbf{x}_T, x^-)$$

Physical interpretation:

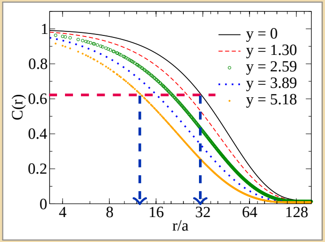
Eikonal propagation of parton through target color field

Q_s is characteristic momentum/distance scale

Precise definition used here:

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

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



JIMWLK evolution

Classical color field described as Wilson line

$$V(\mathbf{x}_T) = P\exp\left\{ig\int \mathrm{d}x^- A^+(\mathbf{x}_T, x^-)\right\} \in \mathrm{SU}(3)$$

- Energy dependent **probability** distribution $W_y[V]$ $\quad (y \sim \ln\sqrt{s})$
- Energy/rapidity dependence of $W_y[V]$ given by JIMWLK renormalization group equation

$$\partial_y W_y[V(\mathbf{x}_T)] = \mathcal{H} W_y[V(\mathbf{x}_T)]$$

- Then get all expectation values $\langle V \cdots V^\dagger \rangle$

$$\mathcal{H} \equiv \frac{1}{2}\alpha_s \int_{\mathbf{x}_T\mathbf{y}_T\mathbf{z}_T} \frac{\delta}{\delta A_c^+(\mathbf{y}_T)} \mathbf{e}_T^{ba}(\mathbf{x}_T, \mathbf{z}_T) \cdot \mathbf{e}_T^{ca}(\mathbf{y}_T, \mathbf{z}_T) \frac{\delta}{\delta A_b^+(\mathbf{x}_T)},$$

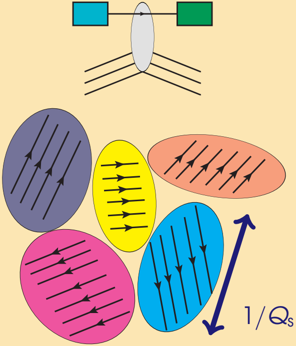
$$\mathbf{e}_T^{ba}(\mathbf{x}_T, \mathbf{z}_T) = \frac{1}{\sqrt{4\pi^3}} \frac{\mathbf{x}_T - \mathbf{z}_T}{(\mathbf{x}_T - \mathbf{z}_T)^2} \Big(1 - U^\dagger(\mathbf{x}_T) U(\mathbf{z}_T)\Big)^{ba}$$

(Here U is adjoint reps of V)

In practice solve as a Monte Carlo Langevin process

Domains in the target color field

Initial state CGC correlations in dilute-dense limit



- $\sim$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 $\frac{1}{{N_c}^2 Q_s^2 S_\perp}$ $\Longrightarrow$ relatively stronger in small systems

Explicit setup for dilute-dense

TL Phys. Lett. B **744** (2015) 315 (arXiv:1501.05505 (hep-ph))

- Passage of probe particle through color field: eikonal Wilson line in target color field

$$V(\mathbf{x}_T) = P\exp\left\{ig\int \mathrm{d}x^- A^+_{\mathrm{cov}}(\mathbf{x}_T, x^-)\right\}$$

- Localize quarks in Gaussian wave packet in probe:

$$\frac{\mathrm{d}N}{\mathrm{d}^2\mathbf{p}_T} \propto \int_{\mathbf{x}_T,\mathbf{y}_T} e^{-i\mathbf{p}_T\cdot(\mathbf{x}_T-\mathbf{y}_T)} e^{\frac{-(\mathbf{x}_T-\mathbf{b}_T)^2}{2B}} e^{\frac{-(\mathbf{y}_T-\mathbf{b}_T)^2}{2B}} \frac{1}{N_c}\operatorname{Tr} V^\dagger_{\mathbf{x}_T} V_{\mathbf{y}_T}.$$

- Two particle correlation

$$\frac{\mathrm{d}N}{\mathrm{d}^2\mathbf{p}_T\,\mathrm{d}^2\mathbf{q}_T} = \int \ldots \left\langle \frac{1}{N_c}\operatorname{Tr} V^\dagger_{\mathbf{x}_T} V_{\mathbf{y}_T} \frac{1}{N_c}\operatorname{Tr} V^\dagger_{\mathbf{u}_T} V_{\mathbf{v}_T}\right\rangle \quad\Longrightarrow\quad v_n\{2\}$$

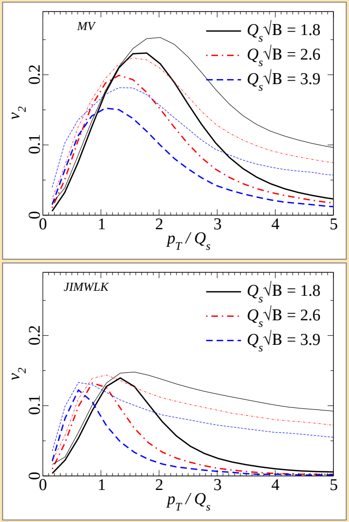
- Need distribution of Wilson lines V for Monte Carlo: MV or JIMWLK (in Langevin method)

Anisotropy coefficients from JIMWLK and MV

TL Phys. Lett. B **744** (2015) 315 (arXiv:1501.05505 (hep-ph))

- p_T-structure like data, but peak at lower p_T
- Depends on probe size B
- Stronger for larger x (MV)

v_2



- Thick line: correlate p_T vs all
- Thin line: p_T vs p_T

Here target homogenous & isotropic

$\Longrightarrow$ v_n purely from field fluctuations

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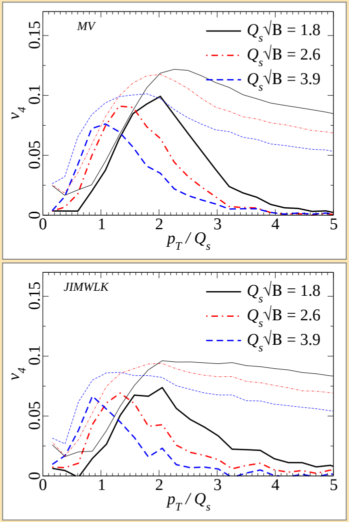
- v_4 peaks at higher p_T

v_4



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- p_T-structure like data, but peak at lower p_T
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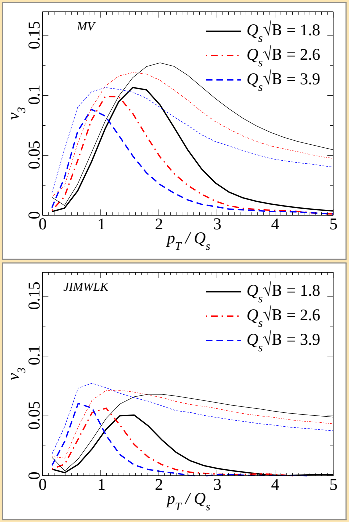
- Stronger for larger x (MV)
- v_4 peaks at higher p_T
- Odd v_n only for quark probe

v_3



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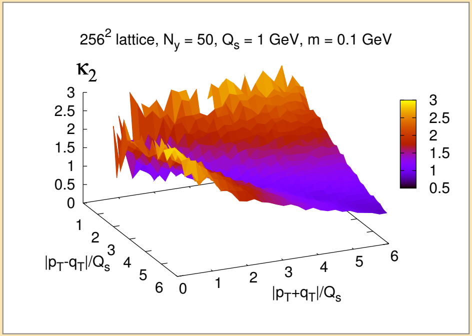
What about the glasma, dense-dense case?

The same azimuthal correlation was seen already many years ago:

T.L., Srednyak, Venugopalan, 2009

...it was just not Fourier-decomposed into v_n's.

$$\kappa_2(\mathbf{p}_T,\mathbf{q}_T) = \overbrace{S_\perp Q_s^2}^{\#\text{ of independent regions}} \left[\frac{\left\langle \frac{d^2 N_2}{dy_p\, d^2\mathbf{p}_T\, dy_q\, d^2\mathbf{q}_T} \right\rangle}{\left\langle \frac{dN}{dy_p\, d^2\mathbf{p}_T} \right\rangle \left\langle \frac{dN}{dy_q\, d^2\mathbf{q}_T} \right\rangle} - 1 \right]$$

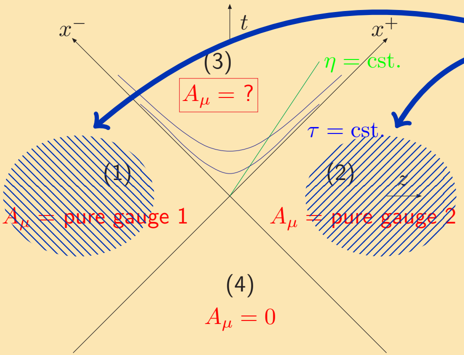


Newer developments Schenke, Schlichting, Venugopalan 2015 :

Finite nucleus, decompose in v_n's ...

How is the dense-dense calculation performed?

Classical **Y**ang-**M**ills



Change to LC gauge:

$$A^i_{(1,2)} = \frac{i}{g} U_{(1,2)}(\mathbf{x}_T)\partial_i U^\dagger_{(1,2)}(\mathbf{x}_T)$$

$U(\mathbf{x}_T)$ is the same Wilson line

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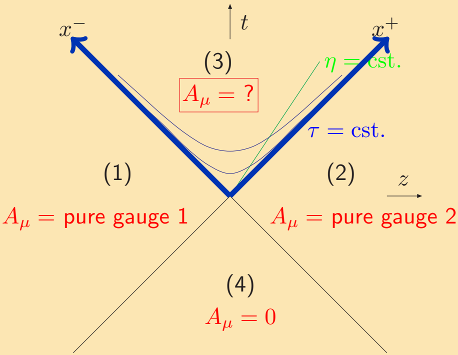

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At $\boldsymbol{\tau = 0}$:

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

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

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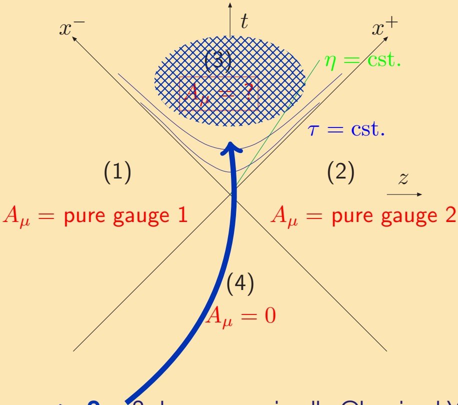

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$\tau > 0$ Solve numerically Classical Yang-Mills **CYM** equations.
This is the **glasma** field $\Longrightarrow$ Then average over initial Wilson lines.

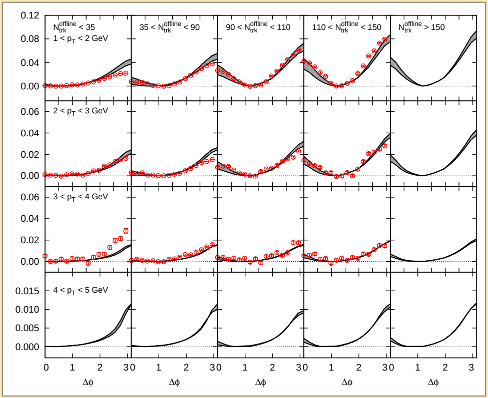
Fix gauge, Fourier-decompose: gluon spectrum

- Gluons with $p_T \sim Q_s$ — strings of size $R \sim 1/Q_s$
- Same domain structure is built into the calculation

Recent calculations in the literature

Azimuthal correlations analyzed in terms of the

- “Glasma graph” ridge correlation



Dusling, Venugopalan, Phys. Rev. D **87** (2013) 9, 094034 [arXiv:1302.7018 [hep-ph]].

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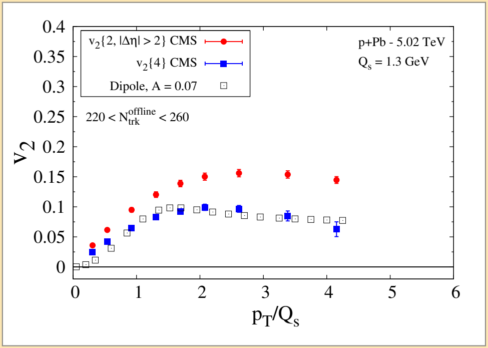

Dumitru, Giannini, Nucl. Phys. A **933** (2014) 212
[arXiv:1406.5781 [hep-ph]].

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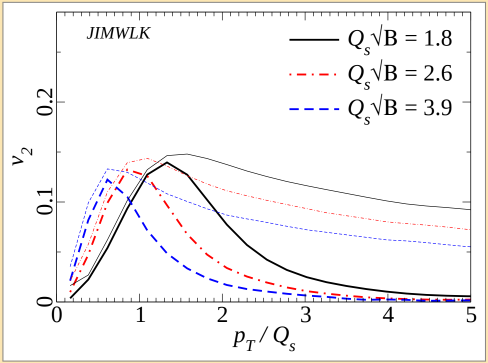

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[arXiv:1501.05505 [hep-ph]].

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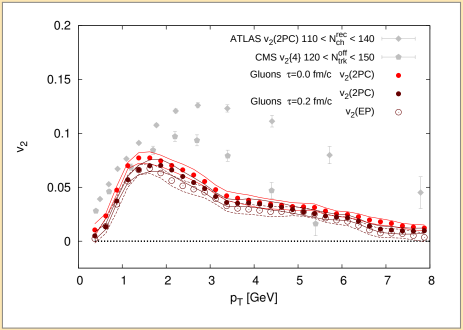

Schenke, Schlichting, Venugopalan, Phys. Lett. B **747** (2015) 76 `[arXiv:1502.01331 [hep-ph]]`.

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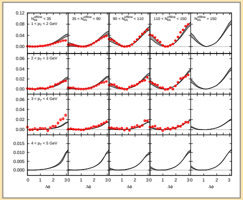
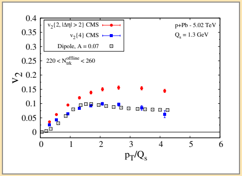
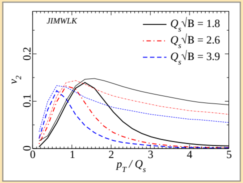
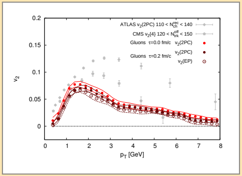








Physics of color field domains same; approximations different

Difference between approximations

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

need $\left\langle \mathrm{Tr}\, V^\dagger(\mathbf{x}_T) V(\mathbf{y}_T)\, \mathrm{Tr}\, V^\dagger(\mathbf{u}_T) V(\mathbf{v}_T) \right\rangle$

Different approximations used

- JIMWLK: Langevin equation for $V(\mathbf{x}_T)$.
  Close to Gaussian in ρ, but nonlinear ("nonlinear Gaussian")
- "Glasma graph": linearize in ρ, Gaussian ρ
- "E-field domain model", small dipole limit

$$\frac{1}{N_c} V^\dagger(\mathbf{b}_T + \mathbf{r}_T/2) V(\mathbf{b}_T - \mathbf{r}_T/2) \approx 1 - \frac{r^i r^j}{4N_c} E_i^a(\mathbf{b}_T) E_j^a(\mathbf{b}_T)$$

  + non-Gaussian 4-point correlation with extra parameter $\mathcal{A}$
- CYM: nonlinear with Gaussian ρ for **both** nuclei
  + final state evolution

Comparing approximations for Wilson line correlator

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

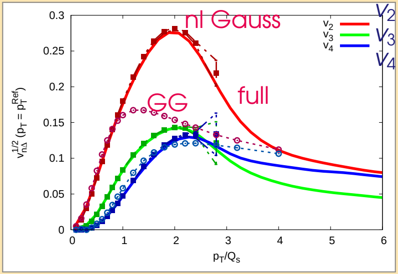
Compare full MV or JIMWLK $v_n\{2\}$ to

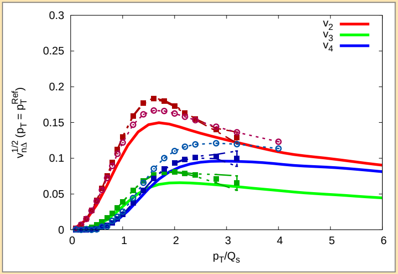
- Nonlinear Gaussian (Gaussian ρ, do not linearize) :

  accurate within 10%

- "Glasma graph" (Gaussian + linearized)

  differs by factor 2 at most





MV JIMWLK

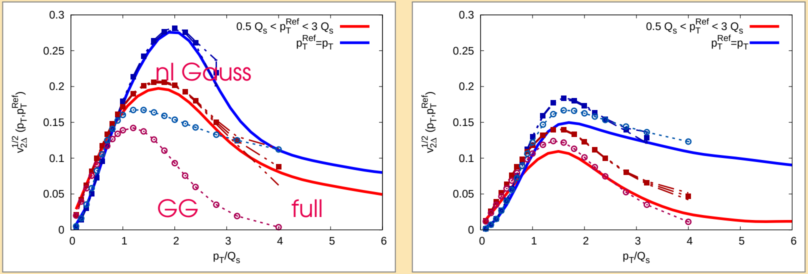
Remarkable consistency between approximations

Effect of reference p_T

$p_{T\,\mathrm{ref}} = \mathrm{all}$

$p_{T\,\mathrm{ref}} = p_T$

MV JIMWLK



- MV
  - Correlation more localized in p_T than experimental data (Hadronization will change this, but how much?)
  - GG decorrelates paricularly fast
- JIMWLK:
  - Little difference between approximations

For the future: rapidity structure

- All of these neglect decorrelation in rapidity due to gluon emissions, parametrically true only for $\Delta y \lesssim 1/\alpha_s$
- Rapidity decorrelation formulated
  Iancu, Triantafyllopoulos, JHEP **1311** (2013) 067 `[arXiv:1307.1559 [hep-ph]]`
  but not implemented

Color field domain model

A. Dumitru and A. V. Giannini, Nucl. Phys. A **933** (2014) 212 [arXiv:1406.5781 [hep-ph]]

$$\left\langle E^i E^j \right\rangle \sim \left[\delta^{ij}(1-\mathcal{A}) + 2\mathcal{A}\hat{a}^i\hat{a}^j\right]$$

Then average over color field direction $\hat{a}$.
Result: non-Gaussianity with unknown parameter $\mathcal{A}$:

$$\langle EEEE\rangle = (\overbrace{3}^{\text{Gaussian}} + \overbrace{\mathcal{A}^2}^{\text{from } \hat{a}})\,\langle EE\rangle\,\langle EE\rangle$$

What does $\mathcal{A}$ represent?

1. Effect of nonlinearities?
   "Glasma graph" linearization is factor $\sim$2 effect.
2. Nongaussianities in JIMWLK?
   $\sim$10% effect, but interesting for theorist.
3. New structure beyond conventional CGC (MV+JIMWLK)?
   Origin? Timescales? N_c-counting?

Conclusions

- Strong multiparticle azimuthal correlations seen even in small systems
- Interpretation as initial vs. final state collectivity still open
- Initial gluon field can be a significant source of correlation
  - Especially for small systems
  - Hadronization, p_T-dependence?