Initial state azimuthal anisotropies in small collision systems

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Outline

This talk:

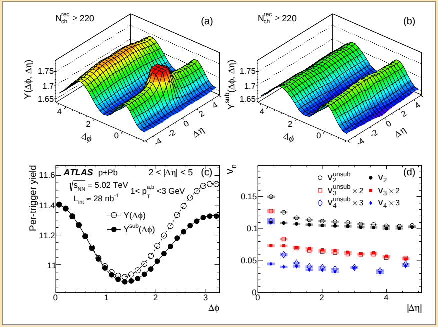
- Dilute probe scattering off CGC field:
  particle production and correlations
- Azimuthal correlations v_n from MV/JIMWLK target
- Relating different approximations for the dipole-dipole correlator

Based on:

- T. L., "Azimuthal harmonics of color fields in a high energy nucleus," Phys. Lett. B **744** (2015) 315 [arXiv:1501.05505 [hep-ph]].
- T. L., B. Schenke, S. Schlichting and R. Venugopalan, "Tracing the origin of azimuthal gluon correlations in the color glass condensate," arXiv:1509.03499 [hep-ph].

Long range in rapidity: early time

- 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

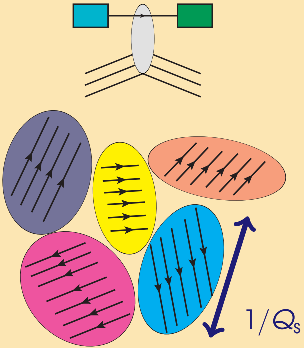


Seen as yield/trigger or as v_n:
ATLAS, Phys. Rev. C **90** (2014) 4, 044906
[arXiv:1409.1792 [hep-ex]].

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

Domains in the target color field

Initial state CGC correlations: dilute-dense limit



Particle production

- $\sim$collinear high-x q/g
- p_T transfer from target E-field

Correlations:

- Domains of size $\sim 1/Q_s$
- Several particles, same domain $\Longrightarrow$ 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

Dense-dense: domain structure same (details more complicated)

Explicit setup for dilute-dense

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

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

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

- Localize quarks in Gaussian wave packet in probe:

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

- Two particle correlation

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

- Need distribution of Wilson lines V for $\langle\rangle$: MV or JIMWLK (in Langevin method)

Anisotropy coefficients from JIMWLK and MV

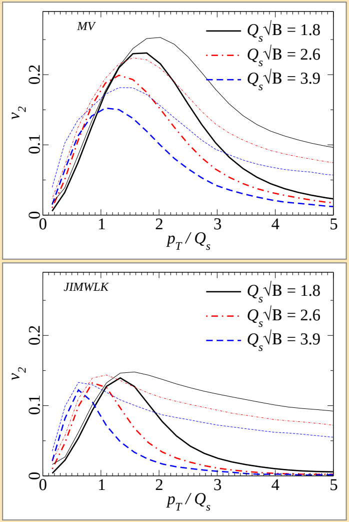
TL Phys. Lett. B **744** (2015) 315 (arXiv:1501.05505 (hep-ph))

- 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: reference is all p_T's
- Thin line: reference is same p_T bin

Target homogenous & isotropic
$\Longrightarrow$ v_n from fluctuations, not geometry



Anisotropy coefficients from JIMWLK and MV

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- p_T-structure like data, but peak at lower p_T
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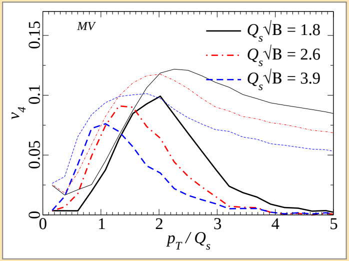
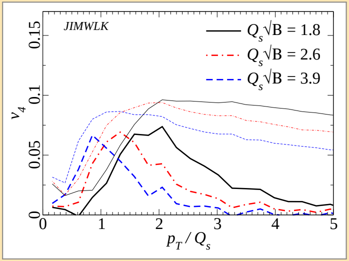
- v_4 at higher p_T

v_4





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Target homogenous & isotropic
$\Longrightarrow$ v_n from fluctuations, not geometry

Anisotropy coefficients from JIMWLK and MV

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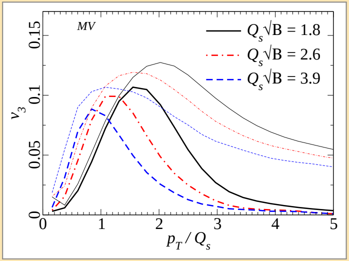
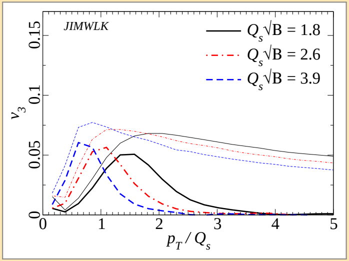
- p_T-structure like data, but peak at lower p_T
- Depends on probe size B
- Stronger for larger x (MV)
- v_4 at higher p_T
- Also odd v_n (only for quark probe)

v_3





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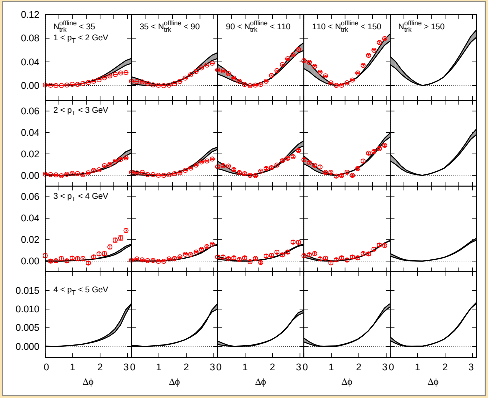
Calculations in the literature

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]].

Calculations in the literature

Azimuthal correlations analyzed in terms of the

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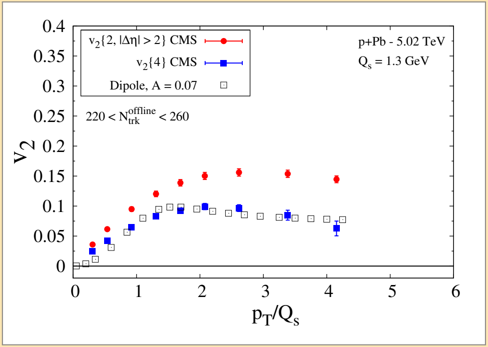
- E-field domain model



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

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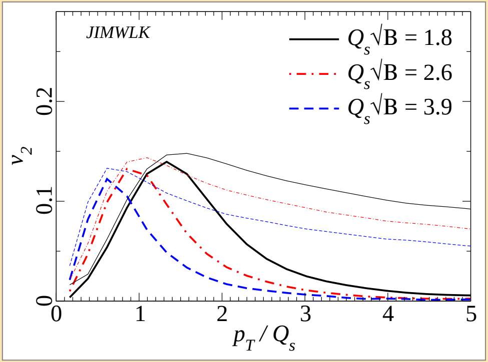

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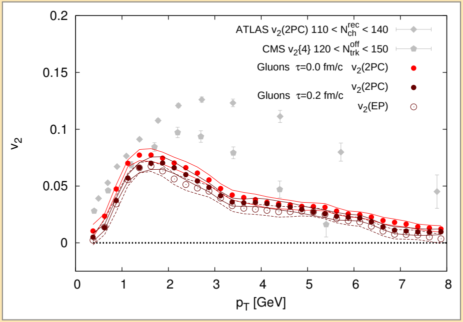
- Dilute dense with full nonlinear JIMWLK
- Dense-dense with Classical Yang-Mills



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

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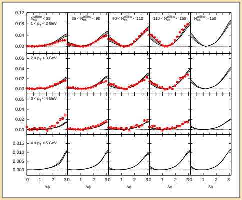
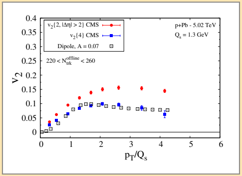
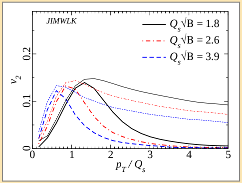
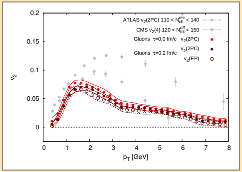








Physics of color field domains same; approximations different

Difference between approximations

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

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

Approximations in dilute-dense

- 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

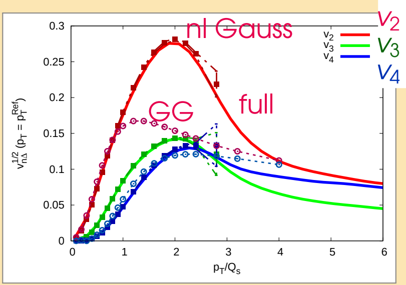
+ final state evolution

Numerical comparison of approzimations

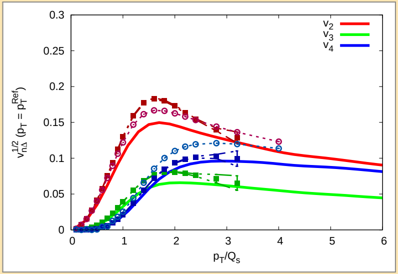
T. L., B. Schenke, S. Schlichting and R. Venugopalan, arXiv:1509.03499 [hep-ph]

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



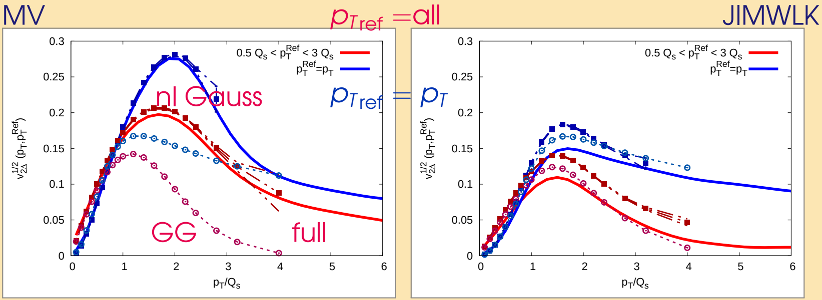
MV



JIMWLK

Remarkable consistency between approximations

Effect of reference p_T



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

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 $\mathcal{A}$:

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

What does $\mathcal{A}$ represent?

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

Conclusions

Initial gluon field contribution to v_n's

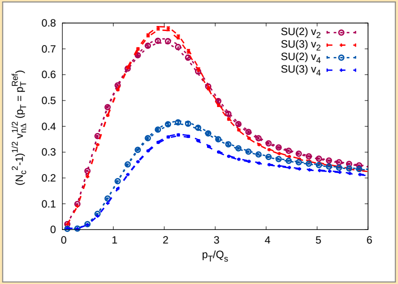
- Can be significant contribution to observed flow signal, especially for small systems
- ¿ Hadronization, p_T-dependence ?
- Calculated in different approximations of CGC
  Differences in terminology, but same physical picture

For the future: rapidity structure

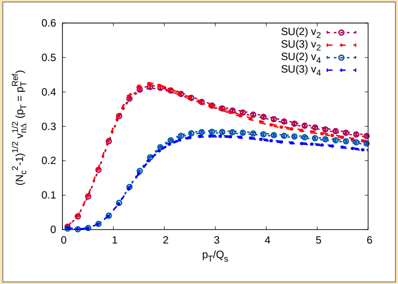
- All of these neglect decorrelation in rapidity due to gluon emissions, parametrically important for $\Delta y \gtrsim 1/\alpha_s$
- Rapidity decorrelation formulated
  Iancu, Triantafyllopoulos, JHEP **1311** (2013) 067 [arXiv:1307.1559 [hep-ph]]
  but not implemented

MV/JIMWLK: correlation is N_c-suppressed

MV



JIMWLK



$\sqrt{N_c{}^2 - 1}\, v_n$ independent of N_c $\Longrightarrow$ $v_n \sim 1/N_c$