Exploring Longitudinal Observables with 3+1D IP-Glasma

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Part of JETSCAPE and BEST. Many alumni.

Plan

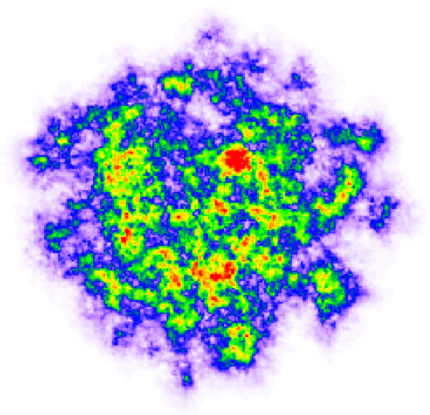
- Going 3D

Why 3D?

- The world is 3D!
- Midrapidity observables are exhaustively studied
- Average observables – The same
- Transverse fluctuations – The same
- A lot of important physics in longitudinal dynamics (e.g. JIMWLK evolution) and correlations
- Understanding the whole picture

Before the collision (2D)

Single nucleus

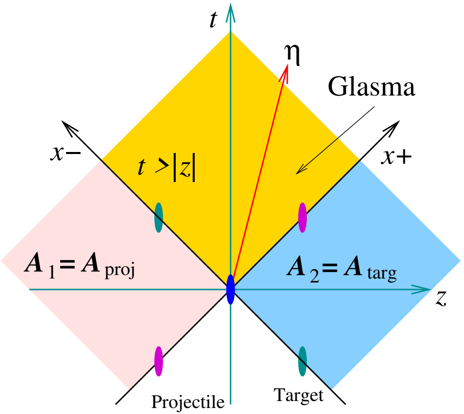


McLerran-Venugopalana picture

- Large x partons $\approx$ Lorentz contracted colour source on the light cone $t = \pm z$
- Small x partons $\approx$ Classical gluon field
- Most of multiplicity is in the soft gluon field
  $\Longrightarrow$ Becomes the QGP medium
- Gluon field scale: $Q_s \sim A^{1/6}\Lambda_{\rm QCD}\sqrt{s}^{\lambda/2}$ for $\lambda \ll 1$

McLerran & Venugopalan, PRD49 (1994) 2233, PRD49 (1994) 3352, PRD50 (1994) 2225

2D Glasma



- In the forward light-cone region:

$$[\mathcal{D}_\mu, \mathcal{G}^{\mu\nu}] = 0$$

Initial conditions at $\tau = 0^+$

- $\mathcal{A}_i = \mathcal{A}_i^1 + \mathcal{A}_i^2$
- $\mathcal{E}^\eta = ig[\mathcal{A}_i^1, \mathcal{A}_i^2]$
- $\mathcal{E}^i = 0$, $\mathcal{B}^i = 0$, $\mathcal{A}_\eta = 0$
- Boost-invariant $\Longrightarrow$ Relevant mostly for the mid-rapidity dynamics

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Dumitru & McLerran, NPA700 (2002) 492, Schenke, Tribedy & Venugpalan, PRL108 (2012) 252301 (2012),

Gale, Jeon, Schenke, Tribedy & Venugopalan, PRL110 (2013) 012302,

McDonald, Shen, Fillion-Gourdeau, Jeon & Gale, PRC95 (2017) 064913

Going 3D

What we need

- Retain the good features of the 2D IP-Glasma model
- Add the rapidity direction
- 3 different rapidities
  - Space-time rapidity: $\eta = \tanh^{-1}(z/t)$: This is what we need
  - Kinematic rapidity: $y = \tanh^{-1}(p^z/E_p)$: JIMWLK evolution is in y
  - Pseudo-rapidity: $\eta_s = \tanh^{-1}(p^z/|\mathbf{p}|)$: Massless particles

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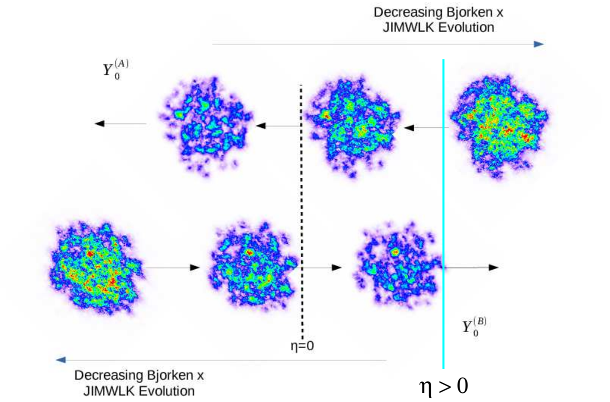
Initial condition: Idea



- JIMWLK: How the gluon field appears in a moving frame
- Finite $\eta \neq 0 \Longrightarrow$ Moving frame with $v^z = \tanh\eta$
- In this frame, the projectile has $\gamma_p = \cosh(y_{\rm beam} - \eta)$ and the target has $\gamma_t = \cosh(y_{\rm beam} + \eta)$
- The target appears much denser than the projectile (for $\eta > 0$)

This idea originally by Schenke and Schlichting, Phys. Rev. C 94, 044907 (2016). The JIMWLK solution by Lappi and Mäntysaari, NPA932 (2014) 69. CGC & JIMWLK: Work by Iancu, Jalilian-Marian, Kovner, Leonidov, McLerran, Venugopalan, Weigert, and many others.

The 3D Initial conditions

- Stay as close to the 2D initial conditions as possible
- Energy deposition only when there is overlap
- Evolution by $[\mathcal{D}_\mu, \mathcal{G}^{\mu\nu}] = 0$

2D Initial conditions

- $\mathcal{A}_i^{1,2} = (i/g) V_{1,2} \partial_i V_{1,2}^\dagger$
- $\mathcal{A}_\eta^{1,2} = 0$
- $\mathcal{A}_i = \mathcal{A}_i^1 + \mathcal{A}_i^2$
- $\mathcal{A}_\eta = 0$
- $\mathcal{E}^\eta = ig[\mathcal{A}_i^1, \mathcal{A}_i^2]$
- $\mathcal{E}^i = 0$

3D Initial conditions

- $\mathcal{A}_i^{1,2} = (i/g) V_{1,2} \partial_i V_{1,2}^\dagger$
- $\mathcal{A}_\eta^{1,2} = (i/g) V_{1,2} \partial_\eta V_{1,2}^\dagger$
- $\mathcal{A}_i = \mathcal{A}_i^1 + \mathcal{A}_i^2$
- $\mathcal{A}_\eta = \mathcal{A}_\eta^1 + \mathcal{A}_\eta^2$
- $\mathcal{E}^\eta = ig[\mathcal{A}_i^1, \mathcal{A}_i^2]$
- $[\mathcal{D}_\eta, \mathcal{E}^\eta] + [\mathcal{D}_i, \mathcal{E}^i] = 0$

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3D-Glasma Results

A bit of technical detail

- New implementation of 3D SU(3) real-time CYM in $\tau, \eta, \mathbf{x}_\perp$
- Fully in-house code
- Running coupling JIMWLK following Lappi and Mäntysaari
- Initial y for JIMWLK: ± 4.25
- Hydro: MUSIC in 3+1D mode with full initial $T^{\mu\nu}$
- Hadronic afterburner: UrQMD
- Preliminary: Going 3D also means two orders of magnitude more compute time... More statistics coming soon (S. McDonald's thesis work)

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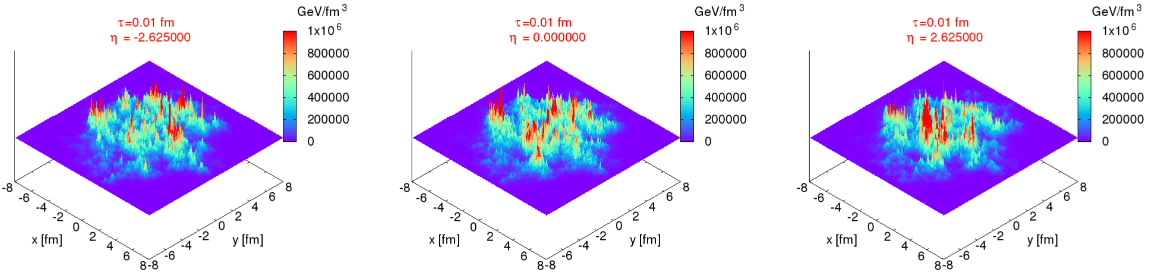
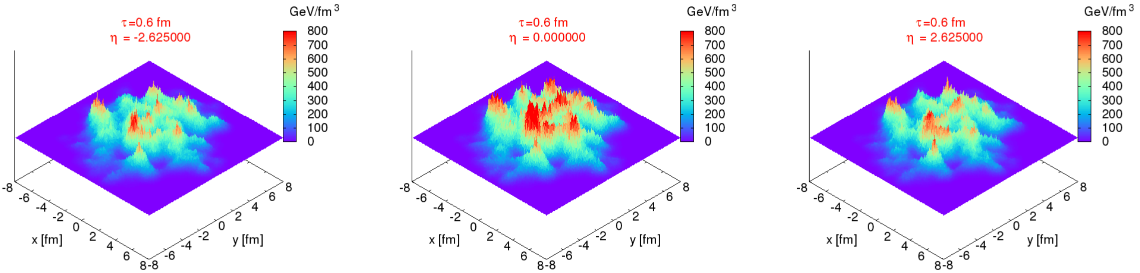
Energy density evolution



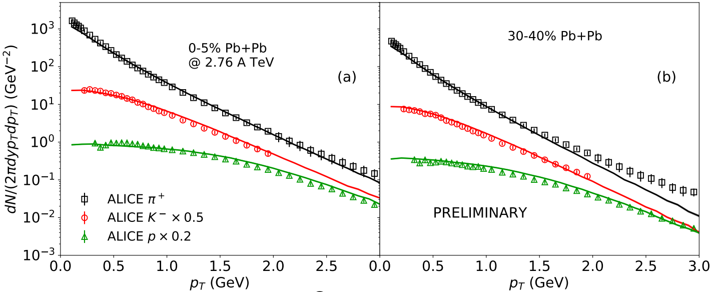
- $\sqrt{s_{NN}} = 2.76\,\text{TeV}$
- This is within the “plateau”
- Right after the collision
- $1/\tau$ in the transverse part

Energy density evolution

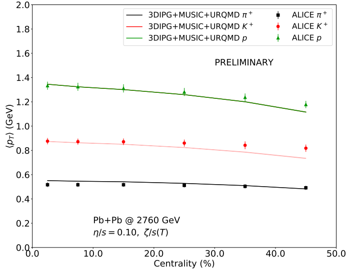


- $\sqrt{s_{NN}} = 2.76\,\text{TeV}$
- This is within the “plateau”
- $\tau = 0.6\,\text{fm}$: Energy density reasonable for hydro
- Decorrelation visible

New Results – Transverse dynamics

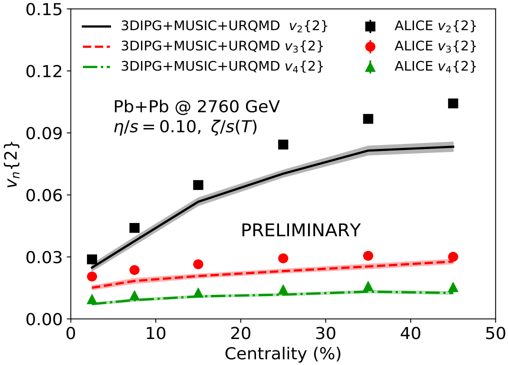


Spectra

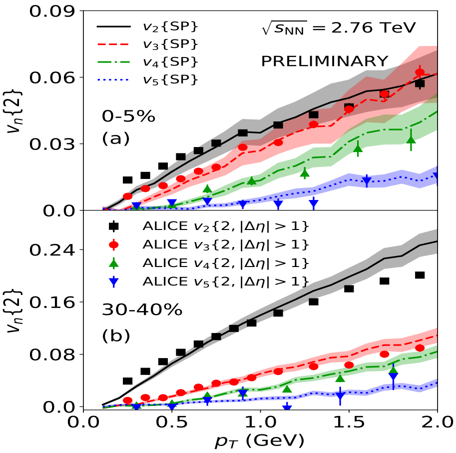


Mean p_T

- Similar level of description as 2D IP-Glasma results



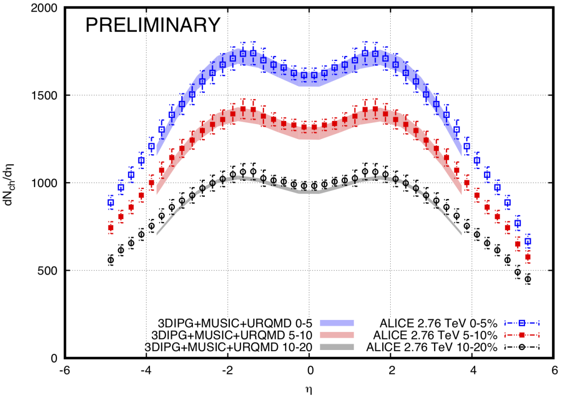
Integrated v_n



Differential v_n

- Similar level of description as 2D IP-Glasma results

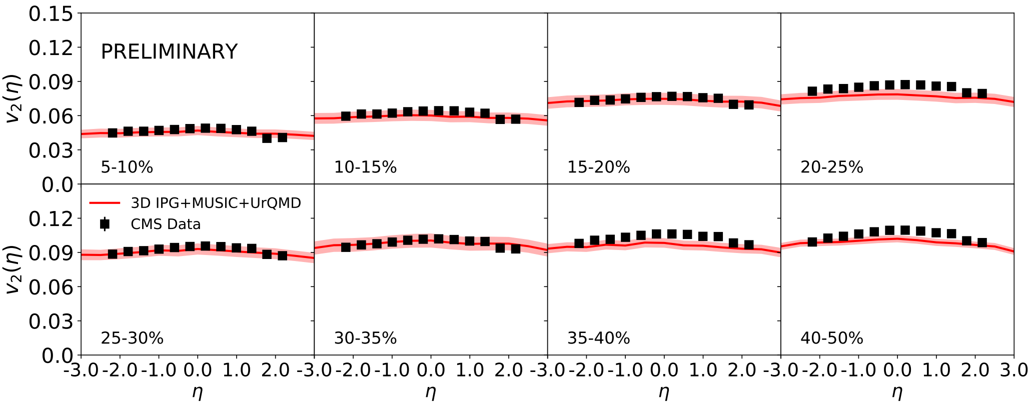
New Results – Longitudinal dynamics



- Global longitudinal dynamics is being well captured

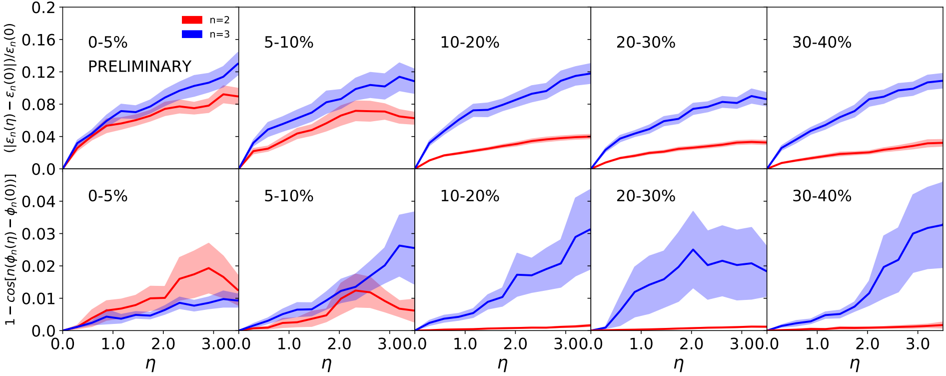
Initial hydro condition beyond $y = \pm 4.25$: Smooth fall-off

New Results – Longitudinal dynamics



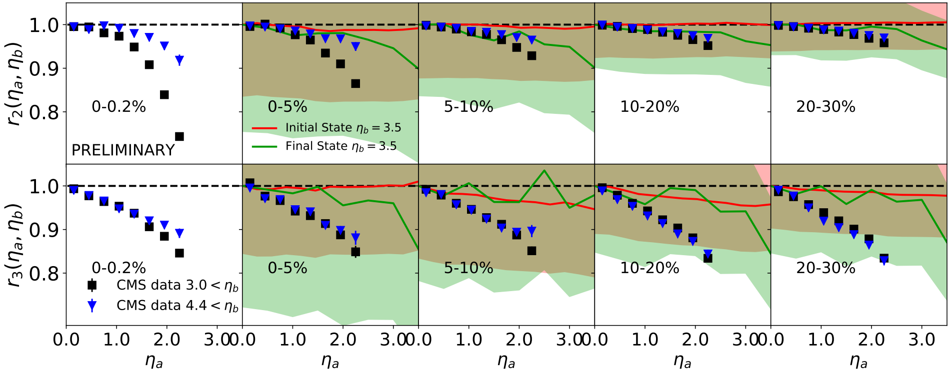
- Global longitudinal dynamics is being well captured

New Results – ε_n decorrelation



- ε_2 decorrelation: Decreases as the system becomes more *geometry* driven
- ε_3 decorrelation: Does not change much as they are mostly *fluctuation* driven

New Results – Longitudinal dynamics



- Note: Correlation measured from $\eta = 3.5$

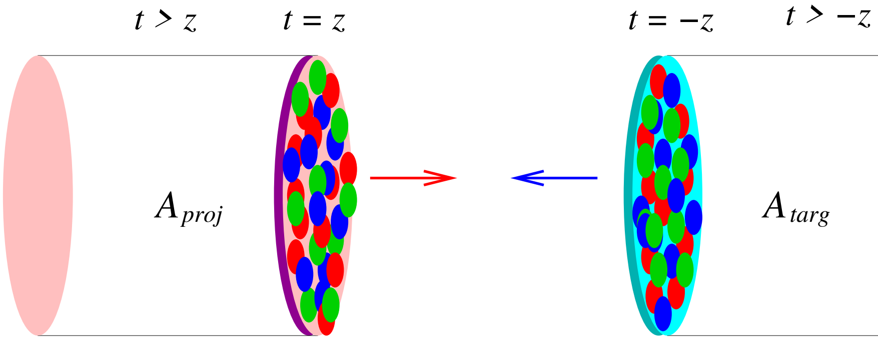
Summary & Perspectives

- Saturation physics provides good picture of initial interactions
- Going 3D is non-trivial but doable
- 3D IP-Glasma Phenomenology – First time
- A lot of physics to learn: Saturation physics, JIMWLK, ...
- Thermal fluctuations to be included (Mayank Singh)
- Simulated events are being accumulated

Backup Slides

Before the collision (2D)

$\boxed{t < 0}$



- Two nuclei approach each other accompanied by trailing gluon fields

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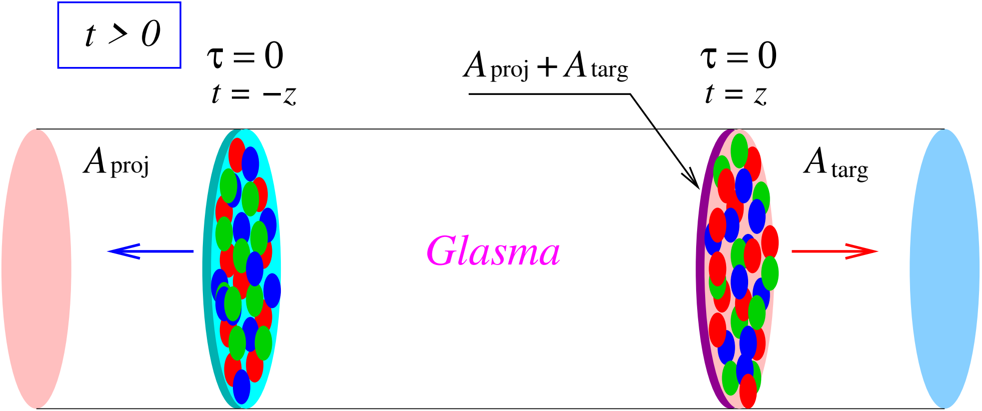
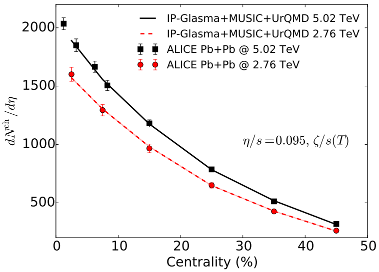
After the collision (2D)



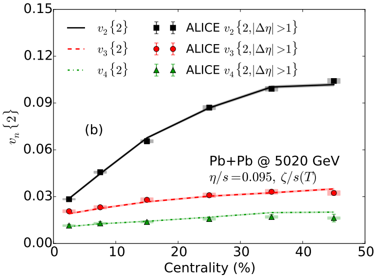
- Middle: Glasma - Result of interaction between A_{proj} and A_{targ}
- Boundary condition: $A_i = A_i^{\text{proj}} + A_i^{\text{targ}}$ and $E^\eta = ig[A_i^{\text{proj}}, A_i^{\text{targ}}]$

2D IP-Glasma has been successful

[Phys. Rev. C 95, 064913 (2017), McDonald, Shen, Fillion-Gourdeau, Jeon, Gale]



Centrality selection

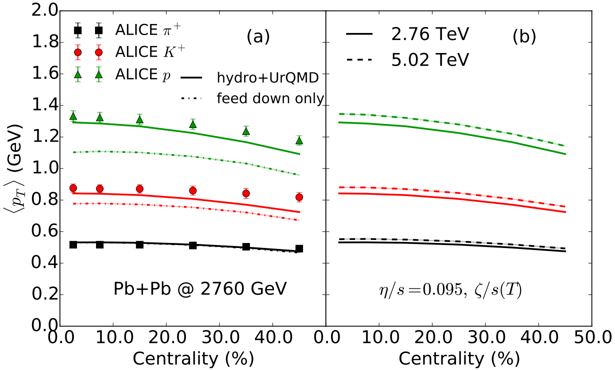


Integrated v_n

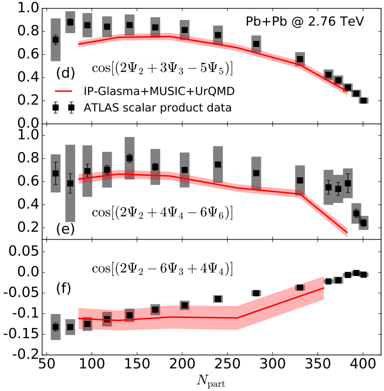
- Centrality selections done by generating sample min-bias events and binning them – Turned out to be crucial
- Shear viscosity fixed by fitting the integrated v_2

2D IP-Glasma has been successful

[Phys. Rev. C 95, 064913 (2017), McDonald, Shen, Fillion-Gourdeau, Jeon, Gale]



PID'ed mean p_T



v_n correlation results: Prediction

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Going 3D – Early attempts

[Phys.Lett.B424:15-24,1998, McLerran & Venugopalan]

- MV's definition of space-time rapidity

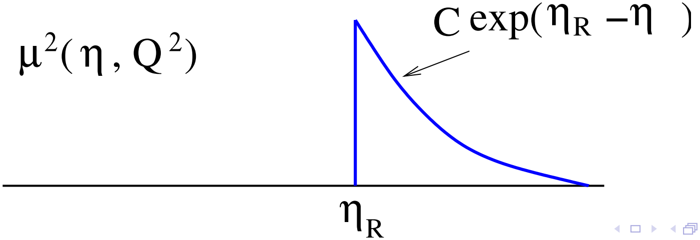
$$\eta = \eta_R + \ln(x_R^- / x^-)$$

with $x_R^- = \sqrt{2}R/\gamma$. The Gauss law

$$[\mathcal{D}_i, \mathcal{G}^{i+}] = g\rho(x^-, \mathbf{x}_\perp) \text{ becomes } [\mathcal{D}_i, \partial_\eta \mathcal{A}_i] = g\rho(\eta, \mathbf{x}_\perp)$$

with $\rho(\eta, \mathbf{x}_\perp) = x^- \rho(x^-, \mathbf{x}_\perp)$

- Color fluctuation scale per unit rapidity: Color sources exist only at high rapidity



JIMWLK sources

[Phys.Rev.D78:054019,2008, Gelis, Lappi, Venugopalan.

Also see Annals of Physics 340, No. 1, 119-170, S. Jeon]

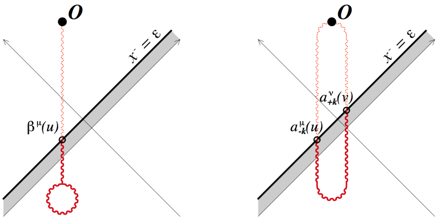


Figure 3: NLO corrections in the single nucleus case, seen as an initial value problem on the surface $x^- = \epsilon$. The shaded area represents the domain where the nuclear color sources live ($0 \le x^- \le \epsilon$). The field fluctuations represented in red continue to evolve in the region $x^- > \epsilon$ until they hit the operator we want to evaluate. However, this evolution is entirely hidden in the dependence of the classical field upon its initial value at $x^- = \epsilon$, and we do not need to consider it explicitly.

- The *classical* JIMWLK color sources are spatially located at or below $x^- = \epsilon$.
- The origin of the JIMWLK evolution: *Vacuum fluctuations*
- Trade the gluon propagator $\langle aa \rangle$ with the equivalent source correlator $G\langle \rho\rho \rangle G$
- Is there any *real* color source at η?

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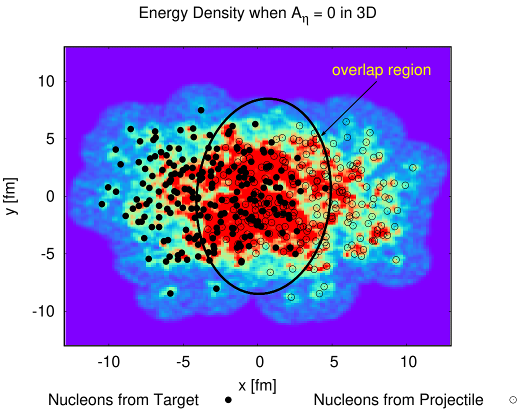
Finding the 3D Initial conditions



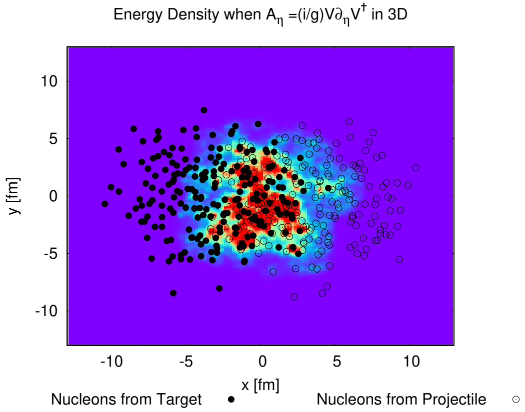
- If 2D conditions are used at each η without modification,

$$\mathcal{G}_{i\eta} = (i/g)[\mathcal{D}_i, \mathcal{D}_\eta] \neq 0$$

even when there is no overlap

- This is because $\partial_\eta \mathcal{A}_i \neq 0$
- Leads to energy deposites where there shouldn't be

Finding the 3D Initial conditions



- Need: $\mathcal{A}_\eta^{1,2} = (i/g) V_{1,2} \partial_\eta V_{1,2}^\dagger$ and $\mathcal{A}_\eta = \mathcal{A}_\eta^1 + \mathcal{A}_\eta^2$ so that $\mathcal{G}_{i\eta} = 0$
- $\mathcal{E}^\eta = 0$ when no overlap $\Longrightarrow [\mathcal{D}_\eta, \mathcal{E}^\eta] + [\mathcal{D}_i, \mathcal{E}^i] = 0$ forces $\mathcal{E}^i = 0$
- Energy deposites only in the overlap region

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Rapidity Dependence

- Comes from JIMWLK

$$V_{\mathbf{x}_\perp}(y+dy) = \exp\left(-i\frac{\sqrt{dy}}{\pi}\int_{\mathbf{z}_\perp}\sqrt{\alpha_S}\,\mathbf{K}_{\mathbf{x}_\perp-\mathbf{z}_\perp}\cdot\tilde{\xi}_{\mathbf{z}_\perp}\right)$$

$$\times\, V_{\mathbf{x}_\perp}(y)\exp\left(i\frac{\sqrt{dy}}{\pi}\int_{\mathbf{z}_\perp}\sqrt{\alpha_S}\,\mathbf{K}_{\mathbf{x}_\perp-\mathbf{z}_\perp}\cdot\left(V^\dagger_{\mathbf{z}_\perp}\tilde{\xi}_{\mathbf{z}_\perp}V_{\mathbf{z}_\perp}\right)\right)$$

with

$$\langle\tilde{\xi}^{a,i}_{\mathbf{x}_\perp}\tilde{\xi}^{b,j}_{\mathbf{y}_\perp}\rangle = \delta^{ab}\delta^{ij}\delta(\mathbf{x}_\perp-\mathbf{y}_\perp)$$

- Running coupling:

$$\alpha_S(\mathbf{k}_\perp) = \frac{4\pi}{\beta\ln\left[\left(\left(\frac{\mu_0^2}{\Lambda^2_{\mathrm{QCD}}}\right)^{1/c}+\left(\frac{\mathbf{k}_\perp^2}{\Lambda^2_{\mathrm{QCD}}}\right)^{1/c}\right)^c\right]}$$

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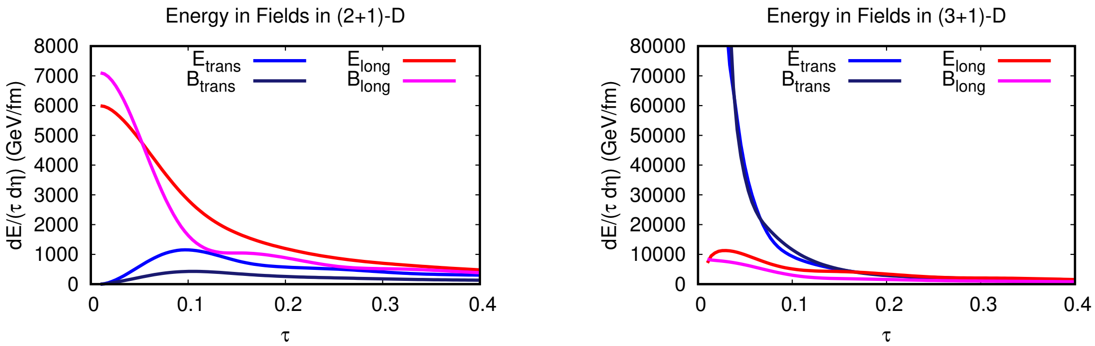
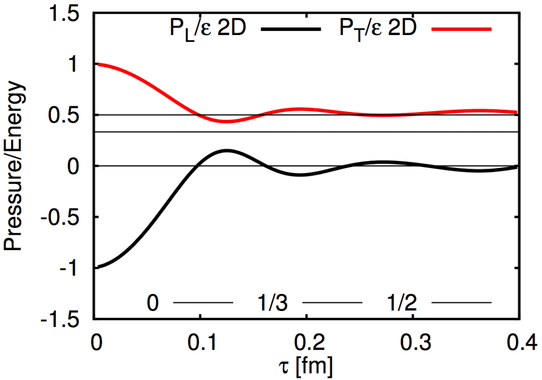
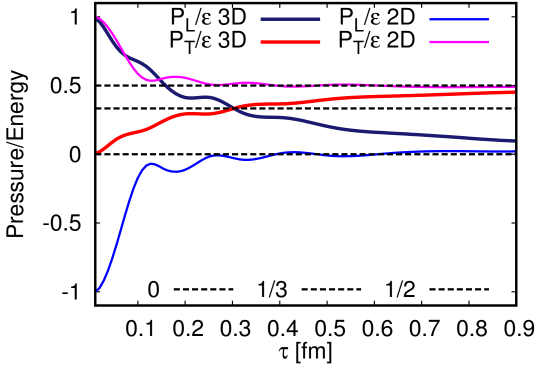
Field Evolution (S. McDonald, Last QM)



- Note the scale – 3D initial energy is *much* higher
- This is because $E = \int d\eta d^2x_\perp \, \tau \left(\frac{1}{2}\left((\mathcal{E}^\eta)^2 + (\mathcal{B}^\eta)^2 \right) + \frac{1}{2\tau^2}\left(\mathbf{E}_\perp^2 + \mathbf{B}_\perp^2 \right) \right)$
- In 3D, one *cannot* set $\mathbf{E}_\perp = 0$ and $\mathbf{B}_\perp = 0$

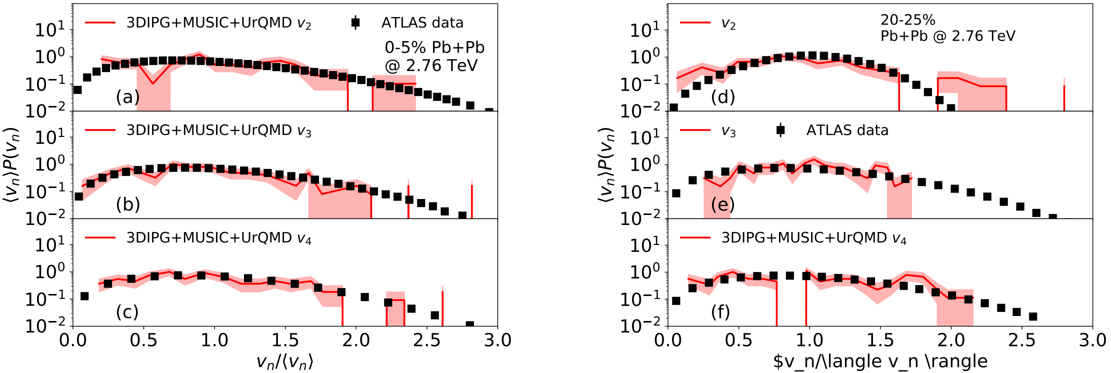
Pressure Evolution (S. McDonald, Last QM)





- In 2D, $P_L = \epsilon_\eta$ and $P_L = -\epsilon_\eta$ at τ_0
- In 3D, $P_L \approx \epsilon_x + \epsilon_y$ and $P_L \approx \epsilon_x - \epsilon_y$ at τ_0
- Note the crossing at the isotropic point $P_T = P_L = 1/3$
- Large τ behaviours are similar

v_n distributions with 3D IP-Glasma



Initial conditions in other approaches

- Phys. Rev. D 74, 045011 (2006), Romatschke and Venugopalan: 2D initial condition plus η dependent factorized random noise
- Phys. Rev. Lett. 111, 232301 (2013), Epelbaum and Gelis: 2D initial condition plus random initial field for the quantum fluctuations
- Phys. Rev. C 89, 034902 (2014), Ozonder and Fries based on Lam and Mahlon: 2D-like initial condition with boosted Coulomb field for η dependence
- Phys. Rev. D 94, 014020 (2016), Gelfand, Ipp and Müller: 2D MV model performed in (t, z). The sources move with $v = \pm c$
- Phys. Rev. C 94, 044907 (2016), Schenke and Schlichting: 2D initial conditions & 2D evolution for each η slice