Pre-equilibrium Longitudinal Flow in the IP-Glasma Framework for Pb+Pb Collisions at the LHC

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Outline

➢ Model: New Implementation of IP-Glasma (+MUSIC+UrQMD)

➢ Testing at 2.76 TeV and Predicting at 5.02 TeV

➢ Newly investigated observables in the IP-Glasma framework: $v_n$ correlations

➢ Novel non-zero initial flow in the $\eta$-direction: where does it come from and what are its effects?

➢ Conclusions
IP-Glasma: New Implementation, Same Physics

- Small-x gluon saturation from the IP-Sat model (*PhysRevD.68.114005*)
  \[ Q_s^2 \approx 0.5 \, g^2 \mu^2 \]
- Sub-nucleonic color charge fluctuations:
  \[ \langle \rho^a_{A(B)}(x_\perp) \rho^b_{A(B)}(y_\perp) \rangle = g^2 \mu^2_{A(B)}(x, x_\perp) \delta^{ab} \delta(x_\perp - y_\perp) \]
- 2+1D boost invariant initial gauge fields
  \[ A^i = A^i_{(A)} + A^i_{(B)} \quad A^\eta = \frac{ig}{2} [ A^i_{(A)}, A^i_{(B)} ] \]
- Classical Yang-Mills evolution
  \[ [D_\mu, F^{\mu\nu}] = 0 \]
- Pre-equilibrium flow
  \[ T^\mu_\nu u^\nu = \epsilon u^\mu \]

- Same underlying physics as the original IP-Glasma
- New opportunities to explore parameter space, interesting physics.
Centrality Selection

- ~25k IP-Glasma events per collision energy
  \[ 0 \text{ fm} \leq b \leq 20 \text{ fm} \]
- Fed a subset (~2k) into MUSIC to determine
  \[
  \frac{dN_{ch}}{d\eta} \big|_{|\eta|<0.5} = 0.018 \left( \frac{dE}{d\eta_s} \big|_{\tau=0.4} \right)^{0.833}
  \]
- 100% boundary corresponded to a total energy of ~4 GeV, or ~2 gluons at the saturation scale.
MUSIC+UrQMD

- **MUSIC** is a 2nd order relativistic viscous hydrodynamics code
  - 1500 IP-Glasma+MUSIC events per 10% centrality
  - Parametrization based on previous work (*Ryu et. al. PRL 115, 132301*)
    - $T_{sw} = 0.4 \text{ fm}$
    - Equation of state: s95p-v1
    - Constant $\eta/s = 0.095$
    - Temperature dependent bulk viscosity (peak reduced by 10%)
      - $T_{sw} = 145 \text{ MeV}$

- **UrQMD** is a hadronic cascade model that includes hadronic re-scatterings and resonance decays
  - Default parametrization

*Same parametrization used at 2.76 TeV and 5.02 TeV*
Testing the Model and Making Predictions

Identified Particle $\langle p_T \rangle$

➢ Effects of hadronic re-scatterings and bulk viscosity
➢ Prediction for 5.02 TeV shows slight increase over 2.76 TeV

Identified Particle $dN/dy$

➢ Particle sampling is able to reproduce particle multiplicities.

McDonald, et. al. (arXiv:1609.02958)
Testing the Model and Making Predictions

*Integrated $v_n$ (n=2,3,4)*

- Same parametrization achieves good agreement for both energies
- Suggests only slight temperature dependence of $\eta/s$

*McDonald, et. al. (arXiv:1609.02958)*
**Percent Increase of $v_n$'s at 5.02 TeV**

|                | $v_2$      | $v_3$      | $v_4$      |
|----------------|------------|------------|------------|
| **ALICE**      | $(3.0 \pm 0.6)$ | $(4.3 \pm 1.4)$ | $(10.2 \pm 3.8)$ |
| (arXiv:1602.01119) |            |            |            |
| **IP-Glasma+MUSIC+UrQMD** | $(4.1 \pm 1.7)$ | $(5.1 \pm 2.2)$ | $(6.2 \pm 2.3)$ |
| (arXiv:1609.02958) |            |            |            |

✔ Due to increased lifetime of the fireball
Event by Event Fluctuations

➢ IP-Glasma provides good description of EbyE $v_n$ distributions

➢ Other observables to further constrain the initial state?

➢ $v_n$ correlations give insight into non-trivial physics beyond $v_n$'s

*McDonald, et. al. (arXiv:1609.02958)*
$v_n$ Correlations with IP-Glasma Initial Conditions

- First order physical interpretation:
  - Central collisions dominated by fluctuations, peripheral collisions dominated by geometry
- Better: non-linear response formalism (Gardim et. al. Phys. Rev. C 85, 024908)

\[
V_n = k_n \epsilon_n + \sum_{\text{quadratic}} k_{pq} \epsilon_p \epsilon_q + \ldots
\]

\[
\epsilon_n = |\epsilon_n| e^{i \Phi_n} = \frac{-\int d^2 r_{\perp} r_m e^{in\psi} e(r, \varphi)}{\int d^2 r_{\perp} r_m e(r, \varphi)}
\]

\[
v_4 e^{4i\psi_4} = k_{44} \epsilon_4 e^{4i\Phi_4} + k_{22} (\epsilon_2 e^{2i\Phi_2})^2
\]

\[
v_6 e^{6i\psi_6} = k_{222} (\epsilon_2 e^{2i\Phi_2})^3 + k_{33} (\epsilon_3 e^{3i\Phi_3})^2
\]

☑ Good agreement with data

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v_4 e^{4i \Psi_4} = k_4 \epsilon_4 e^{4i \Phi_4} + k_{22} (\epsilon_2 e^{2i \Phi_2})^2
\]

\[
v_6 e^{6i \Psi_6} = k_{222} (\epsilon_2 e^{2i \Phi_2})^3 + k_{33} (\epsilon_3 e^{3i \Phi_3})^2
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✔ Similar response at 2.76 and 5.02 TeV

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\epsilon_n = |\epsilon_n| e^{i \Phi_n} = -\int d^2 r_\perp r^m e^{i n \varphi} e(r, \varphi) \int d^2 r_\perp r^m e(r, \varphi)
\]

\[
\begin{align*}
 v_5 e^{5i \psi_5} &= k_5 \epsilon_5 e^{5i \Phi_5} + k_{23} \epsilon_2 e^{2i \Phi_2} \epsilon_3 e^{3i \Phi_3} \\
 v_4 e^{4i \psi_4} &= k_4 \epsilon_4 e^{4i \Phi_4} + k_{22} \left( \epsilon_2 e^{2i \Phi_2} \right)^2 \\
 v_6 e^{6i \psi_6} &= k_{222} \left( \epsilon_2 e^{2i \Phi_2} \right)^3 + k_{33} \left( \epsilon_3 e^{3i \Phi_3} \right)^2 + \ldots
\end{align*}
\]

Teaney, Yan (arxiv:1210.5026)

- Good agreement with data

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$v_n$ Correlations with IP-Glasma Initial Conditions

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\[ V_n = k_n \epsilon_n + \sum_{\text{quadratic}} k_{pq} \epsilon_p \epsilon_q + \ldots \]

\[ \epsilon_n = |\epsilon_n| e^{i n \Phi_n} = -\int d^2 r \int d^2 r' \epsilon_n e(r, \varphi) \]

\[ v_5 e^{5 i \psi_5} = k_5 \epsilon_5 e^{5 i \Phi_5} + k_{23} \epsilon_2 e^{2 i \Phi_2} \epsilon_3 e^{3 i \Phi_3} \]

\[ v_4 e^{4 i \psi_4} = k_4 \epsilon_4 e^{4 i \Phi_4} + k_{22} (\epsilon_2 e^{2 i \Phi_2})^2 \]

\[ v_6 e^{6 i \psi_6} = k_{222} (\epsilon_2 e^{2 i \Phi_2})^3 + k_{33} (\epsilon_3 e^{3 i \Phi_3})^2 + \ldots \]

- Similar response at 2.76 and 5.02 TeV

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McDonald et. al. (arxiv:1609.02958)
How we think about initial flow

On average, $\langle u^n \rangle \approx 0.5 \langle u^\perp \rangle$

How we should think about initial flow

$\langle u^\mu \rangle = \sqrt{\frac{\int (u^\mu)^2 \epsilon \, d^2x}{\int \epsilon \, d^2x}}$
Where does $u^\eta$ come from?

- Even in the boost invariant case, non-zero chromo-electric and magnetic fields lead to non-zero $\eta$ components of the energy-momentum tensor, i.e.,

$$T^{\tau\eta} = F^{\tau x} F^{\eta x} + F^{\tau y} F^{\eta y} = \frac{2}{\tau^3} \left( E^x D_x A_\eta + E^y D_y A_\eta \right) \neq 0$$

- Thus, solving the eigenvalue problem yields a non-zero $U^\eta$
Conclusions

- **New** IP-Glasma – describes data quite well at the LHC
- Same parametrization at both LHC energies
- **New** Observable (in the IP-Glasma framework): $v_n$ correlations – good agreement further validates the model
- **New** Feature: Inclusion of $u^n$ in initial flow – phenomenological study in progress
- Need to explore observables that reflect the longitudinal and rotational (vorticity, angular momentum, etc) dynamics.
Backup Slides
Particle spectra increase due to larger particle yield, but are also flatter. This suggests larger radial flow. Effects of bulk viscosity are important.
\[ \mathbf{v}_n \text{ Correlations} \]

Two plane correlations

\[
\cos(c_{1n_1} \Psi_{n_1} - c_{2n_2} \Psi_{n_2}) = \frac{\Re \left[ \langle Q_{n_1}^c (Q_{n_2}^c)^* \rangle \right]}{\sqrt{\langle Q_{n_1}^c (Q_{n_1}^c)^* \rangle \langle Q_{n_2}^c (Q_{n_2}^c)^* \rangle}}
\]

Three plane correlations

\[
\cos(c_{1n_1} \Psi_{n_1} + c_{2n_2} \Psi_{n_2} - c_{3n_3} \Psi_{n_3}) = \frac{\Re \left[ \langle Q_{n_1}^c Q_{n_2}^c (Q_{n_3}^c)^* \rangle \right]}{\sqrt{\langle Q_{n_1}^c (Q_{n_1}^c)^* \rangle \langle Q_{n_2}^c (Q_{n_2}^c)^* \rangle \langle Q_{n_3}^c (Q_{n_3}^c)^* \rangle}}
\]

\[
Q_n = \sum_i e^{in \varphi_i} \quad \sum_i c_i n_i = 0
\]

The m-particle azimuthal correlation can be written (Jiangyong Jia arxiv:1407.6057)

Event average

\[
\langle \langle e^{in_1 \varphi_1} e^{in_2 \varphi_2} \ldots e^{in_m \varphi_m} \rangle \rangle = \langle \mathbf{v}_{n_1}^{\text{obs}} e^{in_1 \psi_1} \mathbf{v}_{n_2}^{\text{obs}} e^{in_2 \psi_2} \ldots \mathbf{v}_{n_m}^{\text{obs}} e^{in_m \psi_m} \rangle
\]

\[
= \langle \mathbf{v}_{n_1}^{\text{obs}} e^{in_1 \Phi_1} \mathbf{v}_{n_2}^{\text{obs}} e^{in_2 \Phi_2} \ldots \mathbf{v}_{n_m}^{\text{obs}} e^{in_m \Phi_m} \rangle + \text{non-flow}
\]

\[
= \langle \mathbf{v}_{n_1} \mathbf{v}_{n_2} \ldots \mathbf{v}_{n_m} \cos(n_1 \Phi_1 + n_2 \Phi_2 + \ldots + n_m \Phi_m) \rangle + \text{non-flow}
\]

\[
\langle \cos(n_1 \varphi_1 + n_2 \varphi_2 + \ldots + n_m \varphi_m) \rangle = \langle \mathbf{v}_{n_1} \mathbf{v}_{n_2} \ldots \mathbf{v}_{n_m} \cos(n_1 \Phi_1 + n_2 \Phi_2 + \ldots + n_m \Phi_m) \rangle + \text{non-flow}
\]