A Detailed Study and Synthesis of Flow Observables in the IP-Glasma+MUSIC+UrQMD Framework

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February 8, 2017

Outline

Model Setup

- IP-Glasma Implementation
- MUSIC+UrQMD
- Centrality Determination

Results: Flow Observables

- Integrated/Global Observables
  - Identified Particle $\langle p_T \rangle$ and dN/dy
  - Integrated v_n
- EbyE Fluctuations and Correlations
  - v_n and ϵ_n Distributions
  - Event Shape Engineering
  - Event Plane Correlations
  - Non-Linear Response Formalism: χ_n, v_n^L

IP-Glasma: New Implementation, Same Physics

- Small-x gluon saturation from the IP-Sat model (PhysRevD.68.114005)

$$Q_s \approx 0.5 g^2 \mu$$

- Sub-nucleonic color charge fluctuations from MV model:

$$\langle \rho^a_{A(B)}(\mathbf{x}_\perp) \rho^b_{A(B)}(\mathbf{y}_\perp) \rangle = g^2 \mu^2_{A(B)}(x, \mathbf{x}_\perp) \delta^{ab} \delta^2(\mathbf{x}_\perp - \mathbf{y}_\perp)$$

- 2+1D boost invariant initial gauge fields

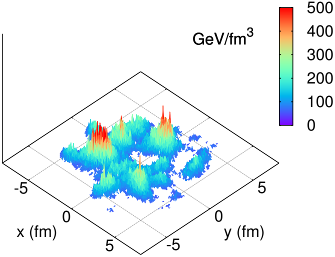
$$\mathrm{A}^\eta = \frac{ig}{2}[A^i_{(A)}, A^i_{(B)}] \qquad \mathrm{A}^i = A^i_{(A)} + A^i_{(B)}$$

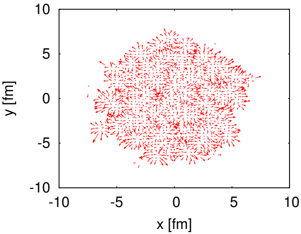
- Classical Yang-Mills evolution

$$[D_\mu, F^{\mu\nu}] = 0$$

- Pre-equilibrium flow

$$T^\mu_\nu u^\nu = \epsilon u^\mu$$





Same physics, new opportunities to explore parameter space

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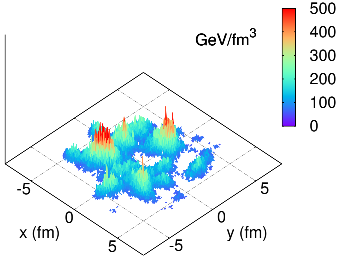

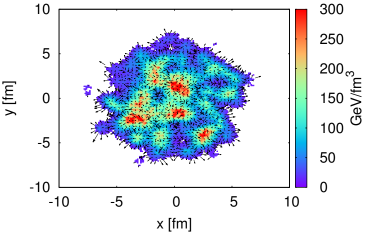

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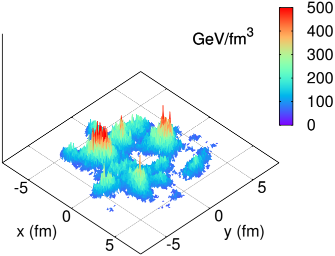

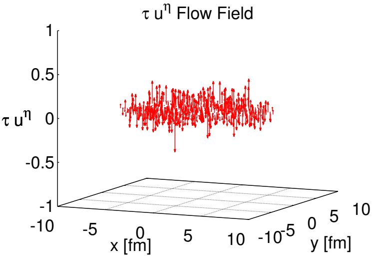

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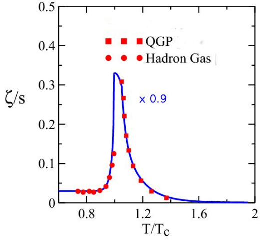
MUSIC+UrQMD

MUSIC is a 2^{nd} order relativistic hydrodynamics code

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



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

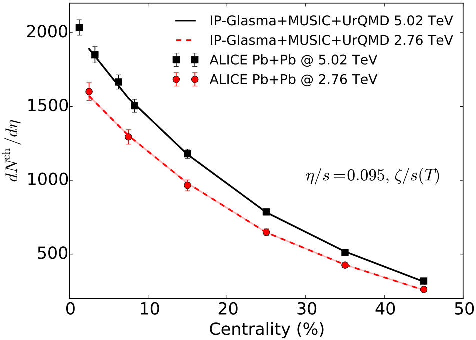
Centrality Determination

How do we determine if an event occurred?

Not so clear in IP-Glasma framework $\rightarrow$let data tell us

- Minimum bias sample $0 \leq b \leq 20$ fm
- Make the 100% centrality cut such that our results reproduce the exp. centrality dependence for $dN_{ch}/d\eta$, up to overall norm.
- Fix overall normalization to get $dN_{ch}/d\eta$ in 0-5 % bin

Charged Particle Multiplicity



McDonald, et. al. (arXiv:1609.02958)

Consistent with Pb-Pb cross section at 2.76 TeV, and system size applicability of hydro framework

Identified Particle $\langle p_T \rangle$ and dN/dy

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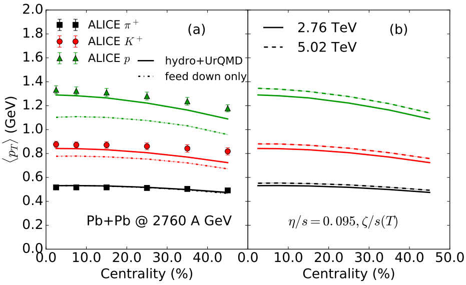

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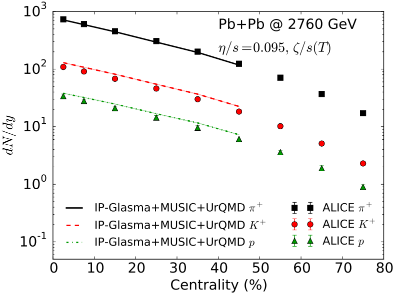
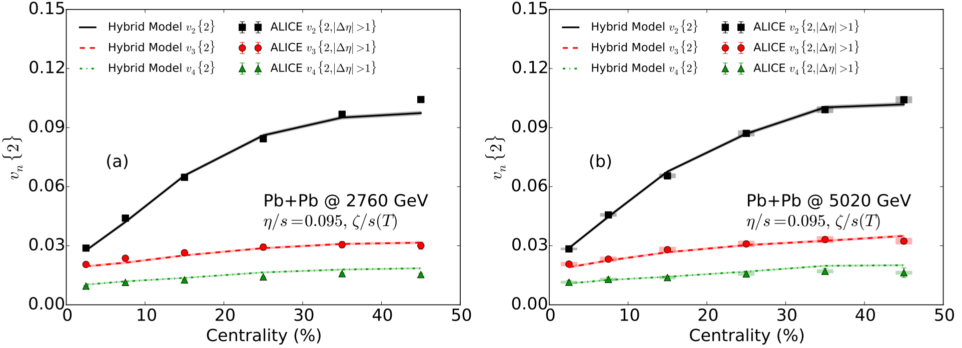
- Effects of **bulk viscosity** and hadronic re-scatterings
- Prediction for 5.02 TeV shows slight increase over 2.76 TeV

Identified Particle dN/dy



- PID dN/dy reproduces experimental data at 2.76 TeV quite well

Integrated v_n



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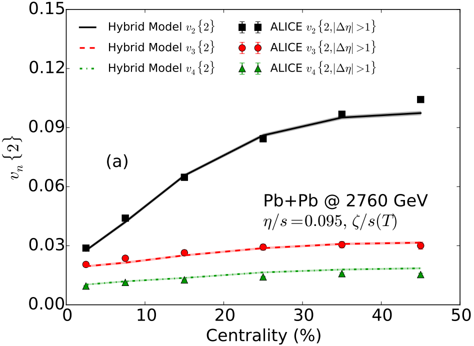
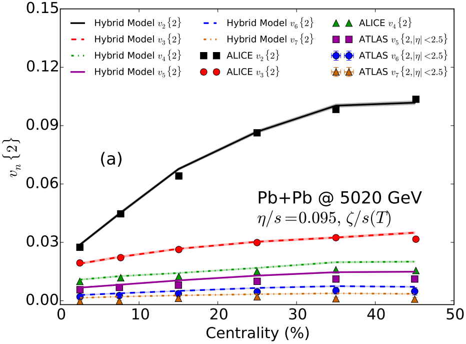
Percent Increase of v_n at 5.02 TeV

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

- Same parametrization achieves good agreement for both energies
- Nearly identical initial state eccentricities for two energies
  $\rightarrow$increased v_n's due to increased lifetime of fireball

Integrated v_n with Higher Harmonics





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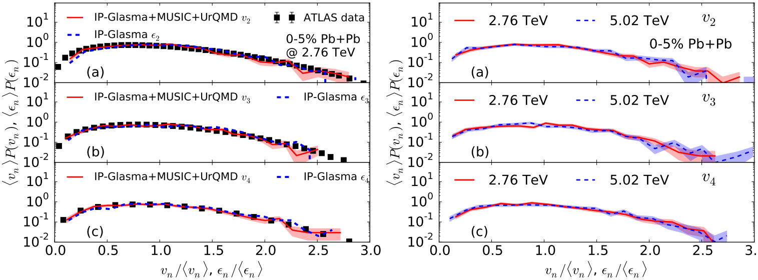
v_n and ϵ_n Distributions

- Fluctuations give rise to a large spread of values EbyE
- IP-Glasma's initial state fluctuations are able to describe the v_n distributions (Gale et. al, Phys. Rev. Lett. 110, 012302)



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- Correlations for different harmonics →for fixed system size, different p_T ranges, linear and non-linear response

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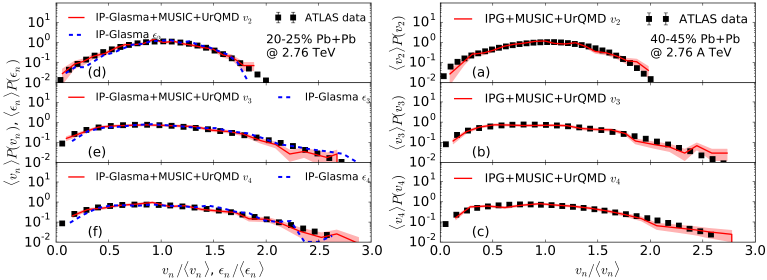

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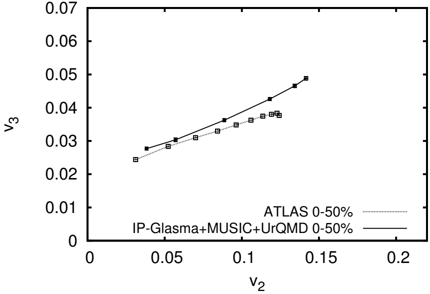
Event Shape Engineering

Bin events on reduced flow vector: q_2

$$q_n = \frac{Q_n}{\sqrt{N}} \qquad Q_n = \sum_{i=1}^{N} e^{in\phi_i}$$

This fixes the system size, isolates shape. Still see spread, now with some correlation.



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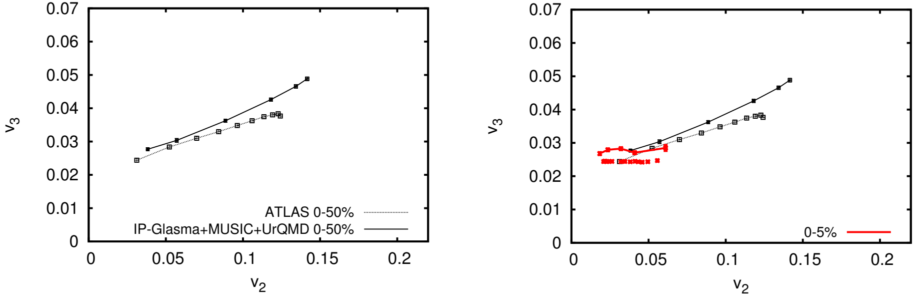

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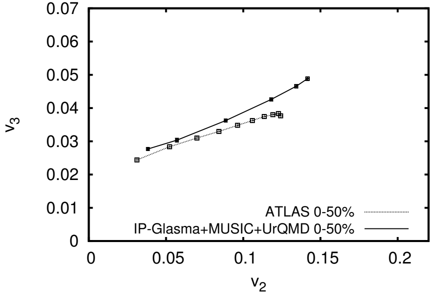

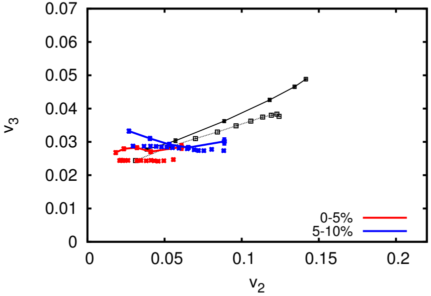

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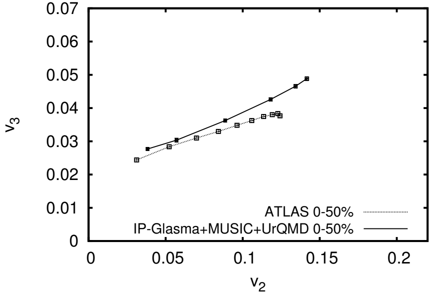

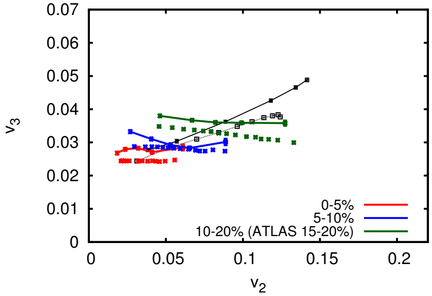

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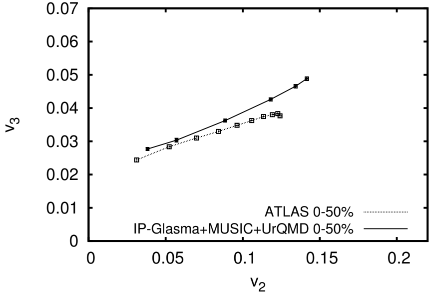

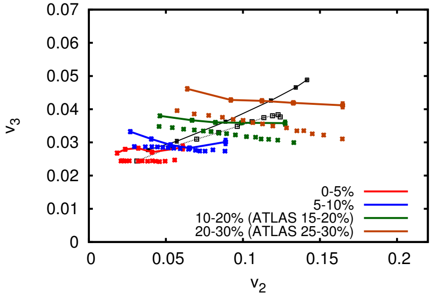

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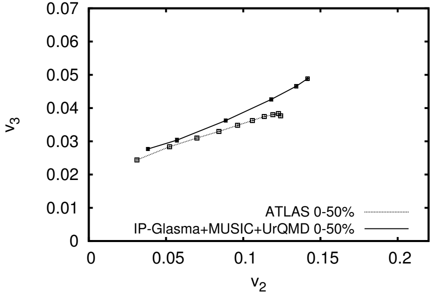

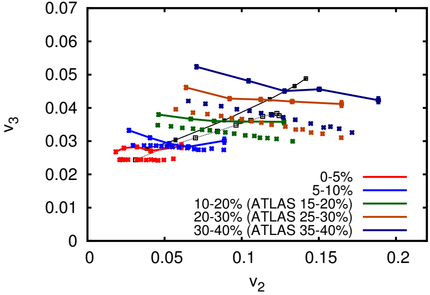

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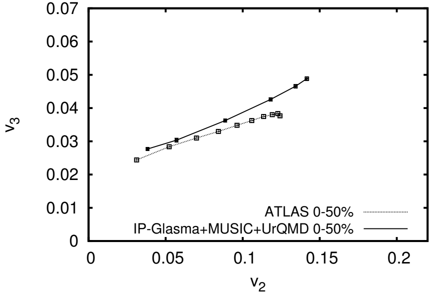

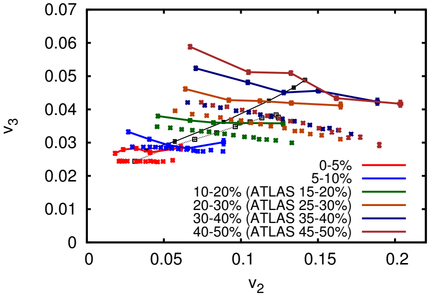

- The trends are reproduced but magnitudes are slightly off
- ESE provides rigorous constraint on QGP parameters

Event Plane Correlations

Two Plane Correlations

$$\cos\left[c_1 n_1 \Psi_{n_1} - c_2 n_2 \Psi_{n_2}\right] = \frac{\Re\{\langle Q_{n_1}^{c_1} (Q_{n_2}^{c_2})^* \rangle\}}{\sqrt{\langle Q_{n_1}^{c_1} (Q_{n_1}^{c_1})^* \rangle}\sqrt{\langle (Q_{n_2}^{c_2})(Q_{n_2}^{c_2})^* \rangle}}, \quad \sum_{i=1}^{N} c_i n_i = 0$$

First order physical interpretation: Central collisions dominated by fluctuations, peripheral collisions dominated by geometry

Intuitive Interpretation: Non-linear response formalism

$$\begin{aligned} V_n &= \kappa_n \epsilon_n + \sum_{n=p+q} \kappa'_{npq} \epsilon_p \epsilon_q + \ldots \\ &= V_n^L + \sum_{n=p+q} \chi_{npq} V_p V_q + \ldots \end{aligned}$$

$$\epsilon_n = \left|\epsilon_n\right| e^{in\Phi_n} = -\frac{\int d^2 r_\perp r^m e^{in\phi} e(r,\phi)}{\int d^2 r_\perp e^{in\phi} e(r,\phi)}$$

- ϵ_n represent initial state input to hydro
- κ_n, κ'_{npq} and χ_{npq} are functions of QGP transport coefficients

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$$V_4 = V_{4L} + \chi_{422}(V_2)^2$$

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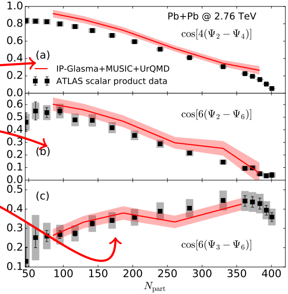

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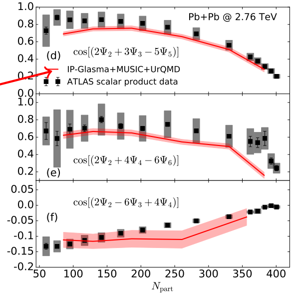

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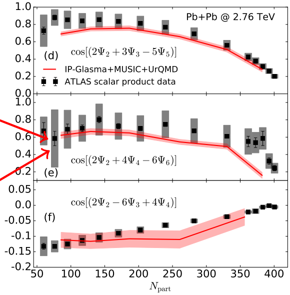

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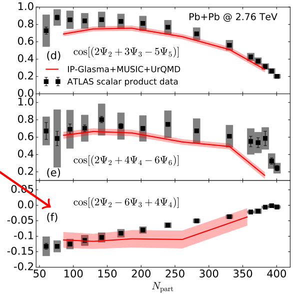

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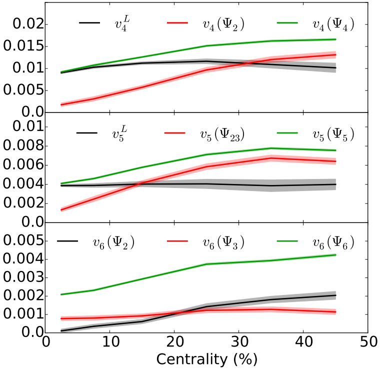

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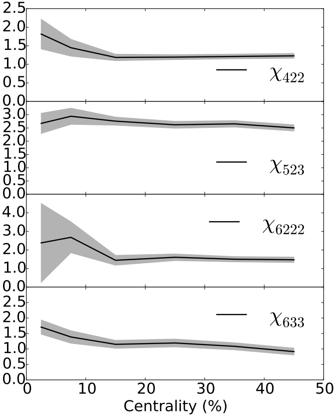
Not shown

- Disentangle initial state and hydrodynamic response
- Linear component for n=4,5 show little centrality dependence $\rightarrow$non-linear part defines shape of curve

Non-linear response formalism



$$\chi_{422} = \frac{\langle V_4 (V_2^*) \rangle}{\langle |V_2|^4 \rangle} = \frac{v_4\{\Psi_2\}}{\sqrt{\langle |V_2|^4 \rangle}}$$

$$\chi_{523} = \frac{\langle V_5 V_2^* V_3^* \rangle}{\langle |V_2|^2 \, |V_3^2| \rangle} = \frac{v_5\{\Psi_{23}\}}{\sqrt{\langle |V_2|^2 \, |V_3^2| \rangle}}$$

$$\chi_{6222} = \frac{\langle V_6 (V_2^*)^2 \rangle}{\langle |V_2|^6 \rangle} = \frac{v_6\{\Psi_2\}}{\sqrt{\langle |V_2|^6 \rangle}}$$

$$\chi_{633} = \frac{\langle V_6 (V_3^*)^2 \rangle}{\langle |V_3|^4 \rangle} = \frac{v_6\{\Psi_3\}}{\sqrt{\langle |V_3|^4 \rangle}}$$

- χ_n characterizes the strength of the non-linear response
- χ_n dependent on initial state? Sensitive to QGP parameters (η/S, ζ/S)?

Non-linear response formalism

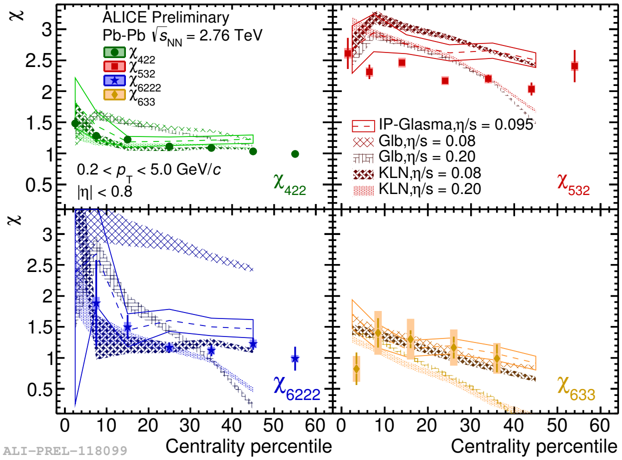
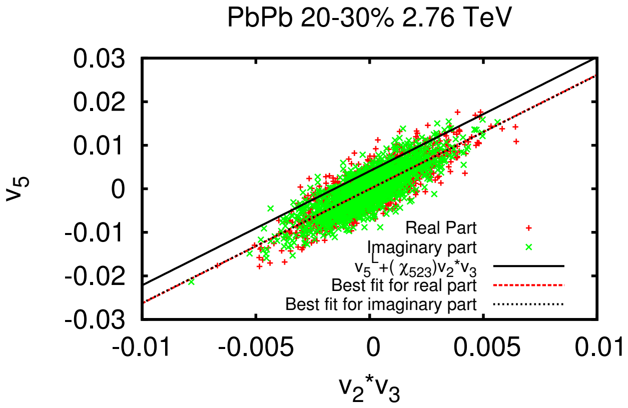


Figure courtesy of You Zhou and the ALICE collaboration
(Talk this morning at 8.30 Session 5.1)

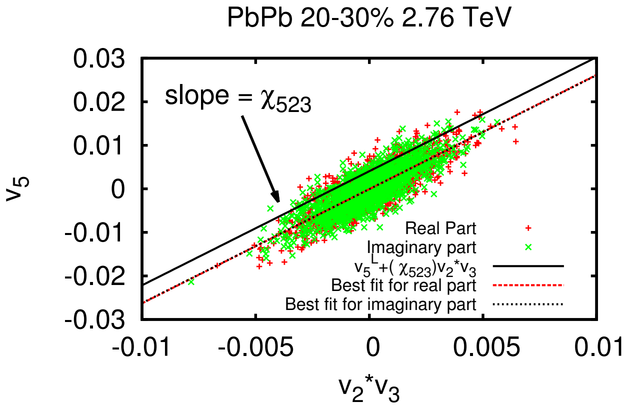
Verifying the non-linear response framework

We can look at scatter plots of EbyE theory to verify that the non-linear response is working



Verifying the non-linear response framework

We can look at scatter plots of EbyE theory to verify that the non-linear response is working



- Non-linear response formalism seems to be working
- Spread of values in v_5^L

Conclusion

- There are several key elements in our model:
  - initial state fluctuations
  - hydrodynamics with shear + bulk viscosities
  - hadronic afterburner
  - proper centrality selection.
- Our model achieves good agreement with many observables
- Clear opportunities to further constrain QGP parameters, initial state:
  - ESE, "boomerang", $\chi_n \rightarrow \eta/s$, ζ/s
  - higher order v_n's, linear response $\rightarrow$refine initial state
- Zooming out and looking at "totality" of flow observables simultaneously gives more rigorous constraints on initial state and QGP transport coefficients

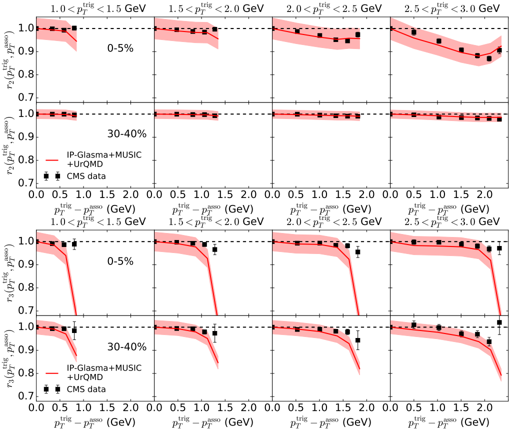
Backup

R_n Flow Factorization Breaking Ratios

Correlations over different p_T ranges

$$r_n(p_T^{\mathrm{trig}}, p_T^{\mathrm{asso}}) = \frac{\Re\{\langle Q_n(p_T^{\mathrm{trig}})(Q_n(p_T^{\mathrm{asso}}))^*\rangle\}}{\sqrt{\langle Q_n(p_T^{\mathrm{trig}})Q_n^*(p_T^{\mathrm{trig}})\rangle\langle Q_n(p_T^{\mathrm{asso}})Q_n^*(p_T^{\mathrm{asso}})\rangle}}$$

- R_n's are most sensitive to initial state (Shen et. al., Phys. Rev. C 92, 014901)
- For r_3 we see deviation from data →partially due to hadronic re-scatterings in UrQMD randomize v_3 flow angle for small p_T^{asso}.



R_n Flow Factorization Breaking Ratios

Correlations over different p_T ranges

$$r_n(p_T^{\rm trig}, p_T^{\rm asso}) = \frac{\Re\{\langle Q_n(p_T^{\rm trig})(Q_n(p_T^{\rm asso}))^*\rangle\}}{\sqrt{\langle Q_n(p_T^{\rm trig})Q_n^*(p_T^{\rm trig})\rangle\langle Q_n(p_T^{\rm asso})Q_n^*(p_T^{\rm asso})\rangle}}$$

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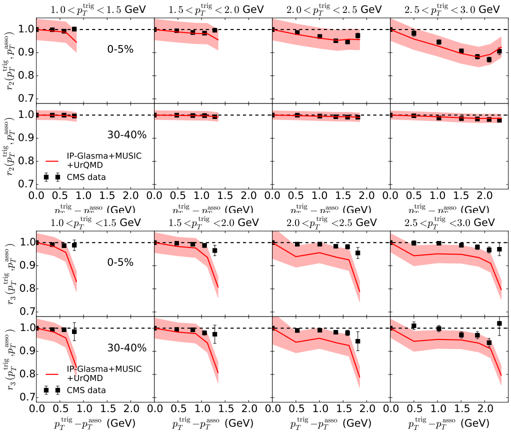
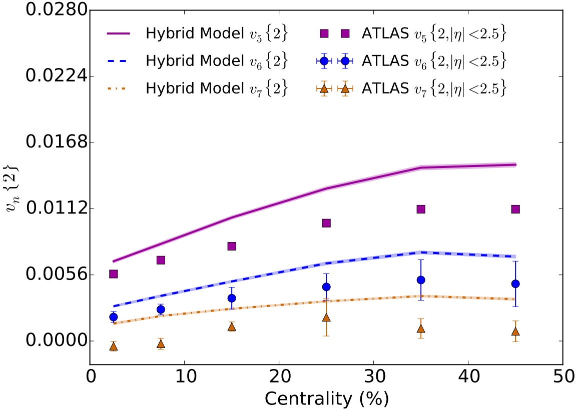


Integrated v_n (n=5, 6, 7)



Data extracted from Iwona Grabowska-Bold's ATLAS overview talk at HP2016

- Statistics increased to $\approx$ 2100 events per 10% centrality class
- Data: 0.5 GeV $\leq p_T \leq$ 25 GeV, Theory: 0.5 GeV $\leq p_T \leq$ 3 GeV
- Initial state $\rightarrow$shape of proton, nucleon-nucleon correlations become more important for higher v_n's

Verifying the non-linear response framework