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

Presented by: Scott McDonald
In Collaboration with: Chun Shen, Francois Fillion-Gourdeau, Sangyong Jeon, and Charles Gale
McGill University

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 η-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:

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

- 2+1D boost invariant initial gauge fields

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

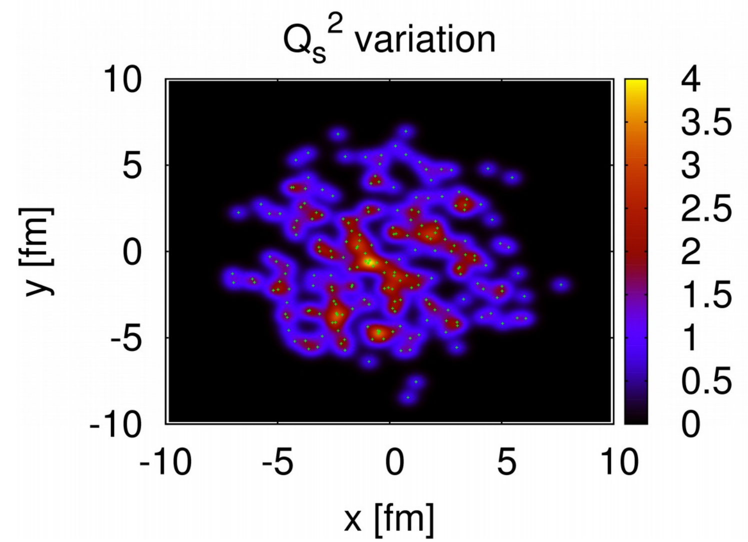
- Classical Yang-Mills evolution

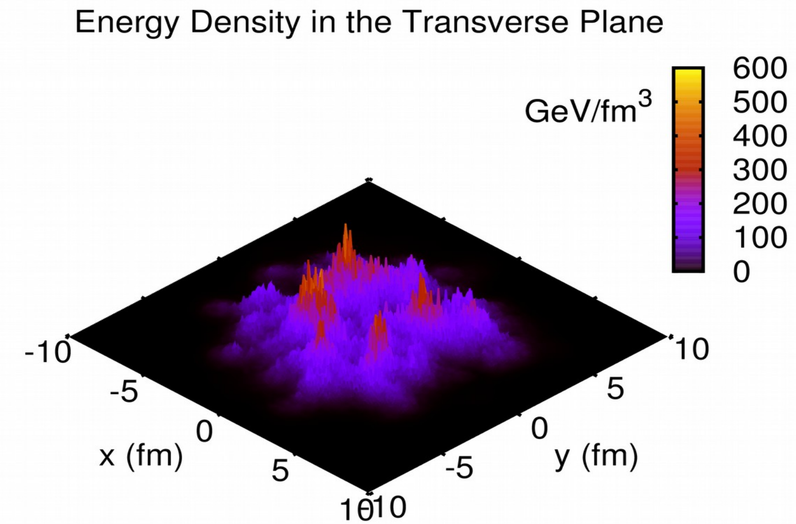
$$[D_\mu, F^{\mu\nu}] = 0$$

- 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

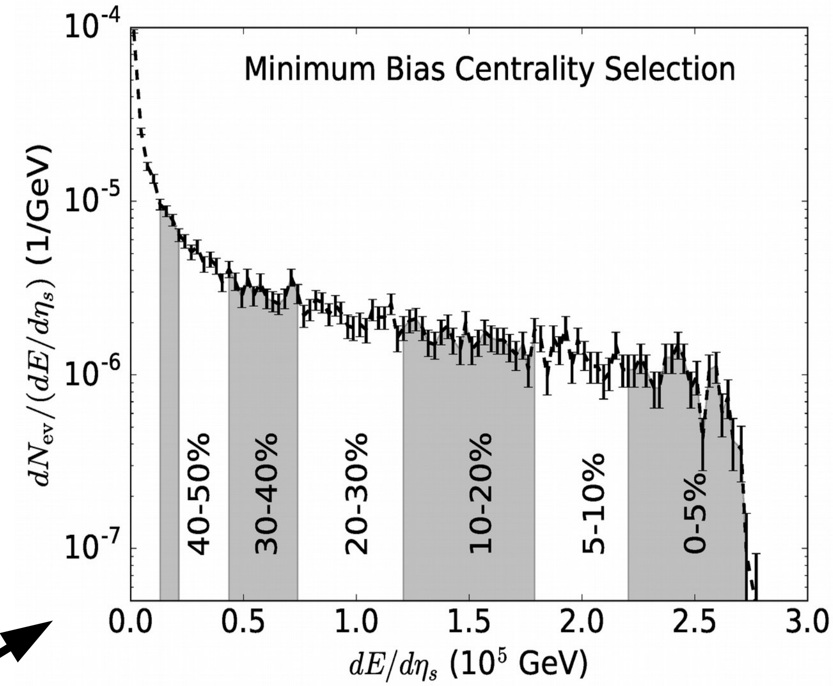
- ~25k IP-Glasma events per collision energy

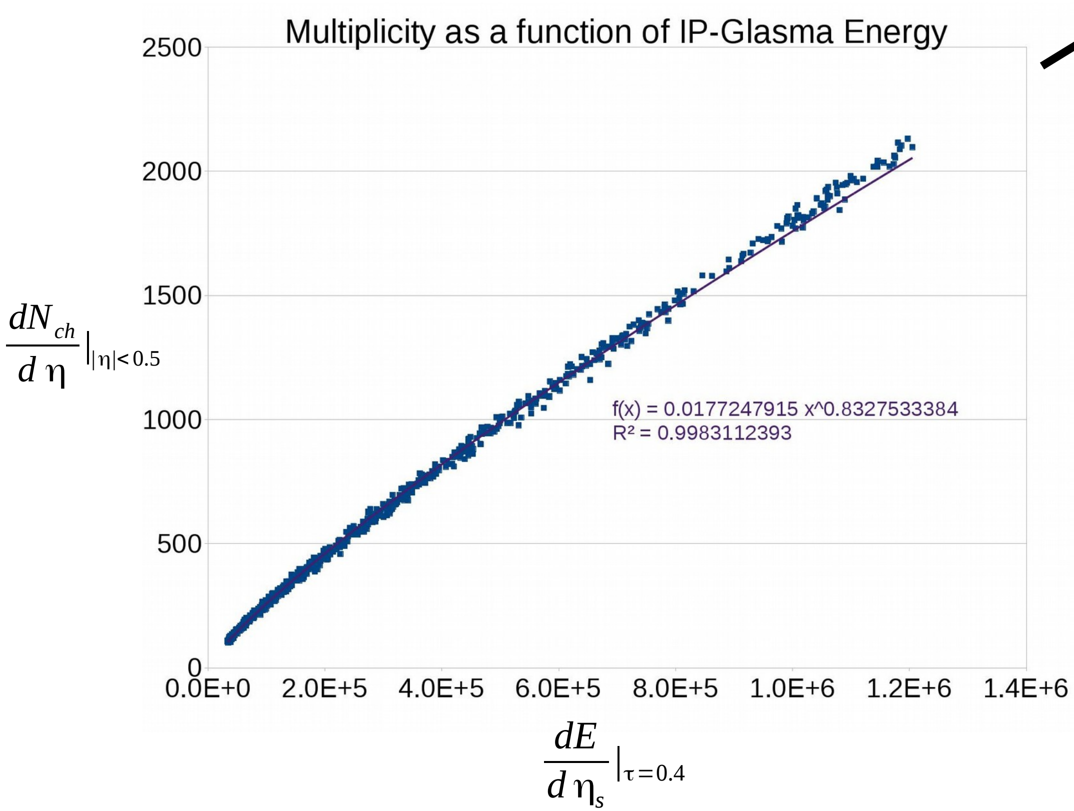
$$0 \;\; fm \leq b \leq 20 \;\; fm$$

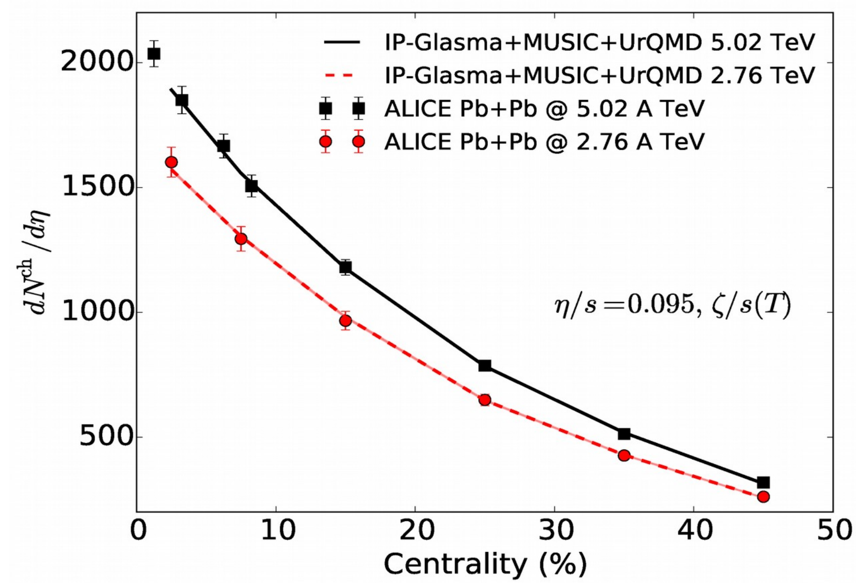
- Fed a subset (~2k) into MUSIC to determine

$$\frac{dN_{ch}}{d\eta}\Big|_{|\eta|<0.5} = 0.018\left(\frac{dE}{d\eta_s}\Big|_{\tau=0.4}\right)^{0.833}$$

- 100% boundary corresponded to a total energy of ~4 GeV, or ~2 gluons at the saturation scale.



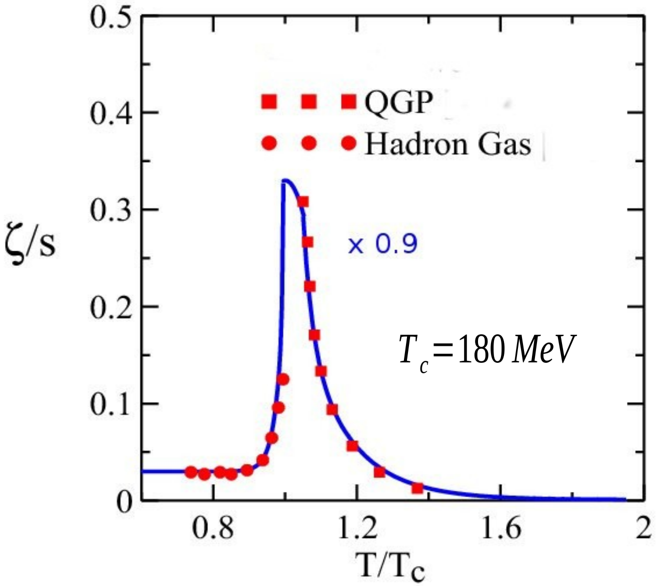




MUSIC+UrQMD

- **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*)
    - $\tau_{sw} = 0.4\, fm$
    - Equation of state: s95p-v1
    - Constant $\eta/s = 0.095$
    - Temperature dependent bulk viscosity

      (peak reduced by 10%)
    - $T_{sw} = 145\, MeV$

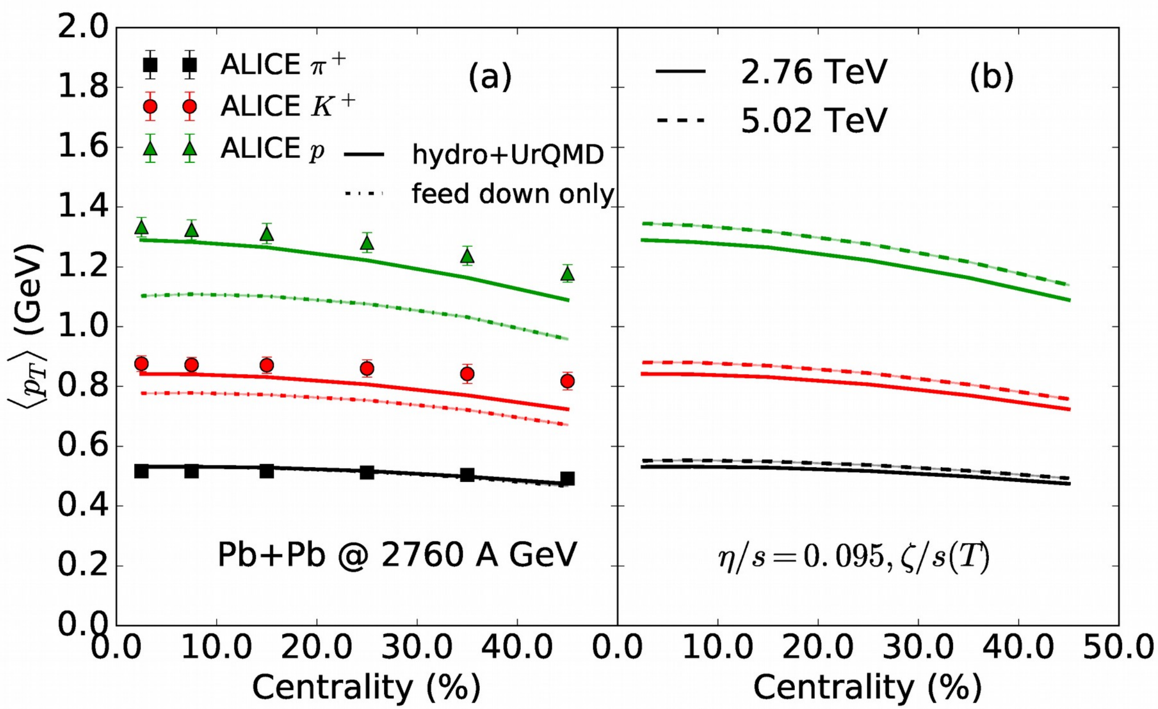


- **UrQMD** is a hadronic cascade model that includes hadronic re-scatterings and resonance decays
  - Default parametrization

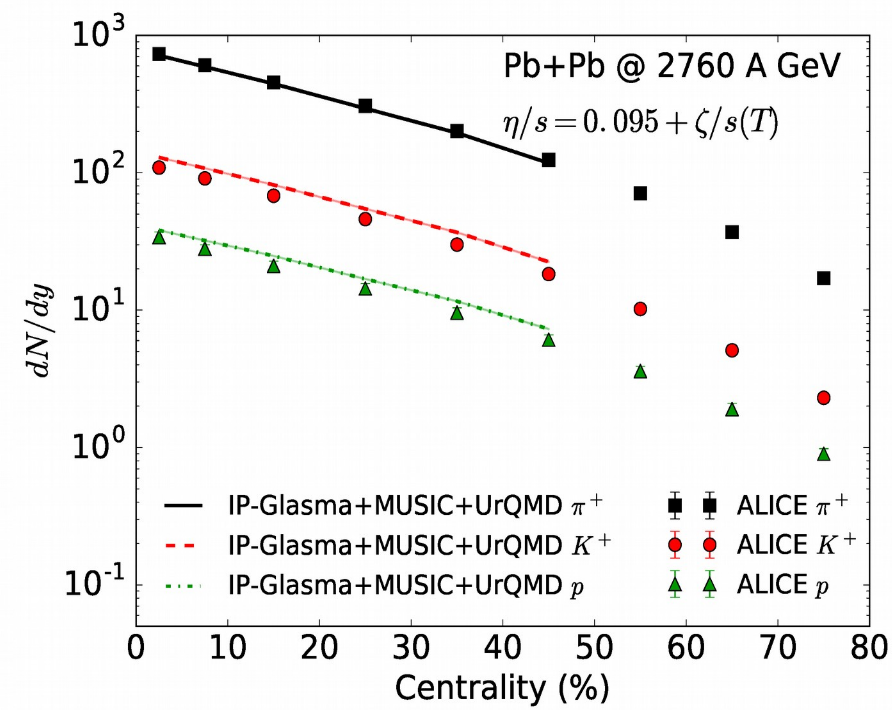
Same parametrization used at 2.76 TeV and 5.02 TeV

Testing the Model and Making Predictions

Identifed Particle $\langle p_T \rangle$



Identifed Particle dN/dy



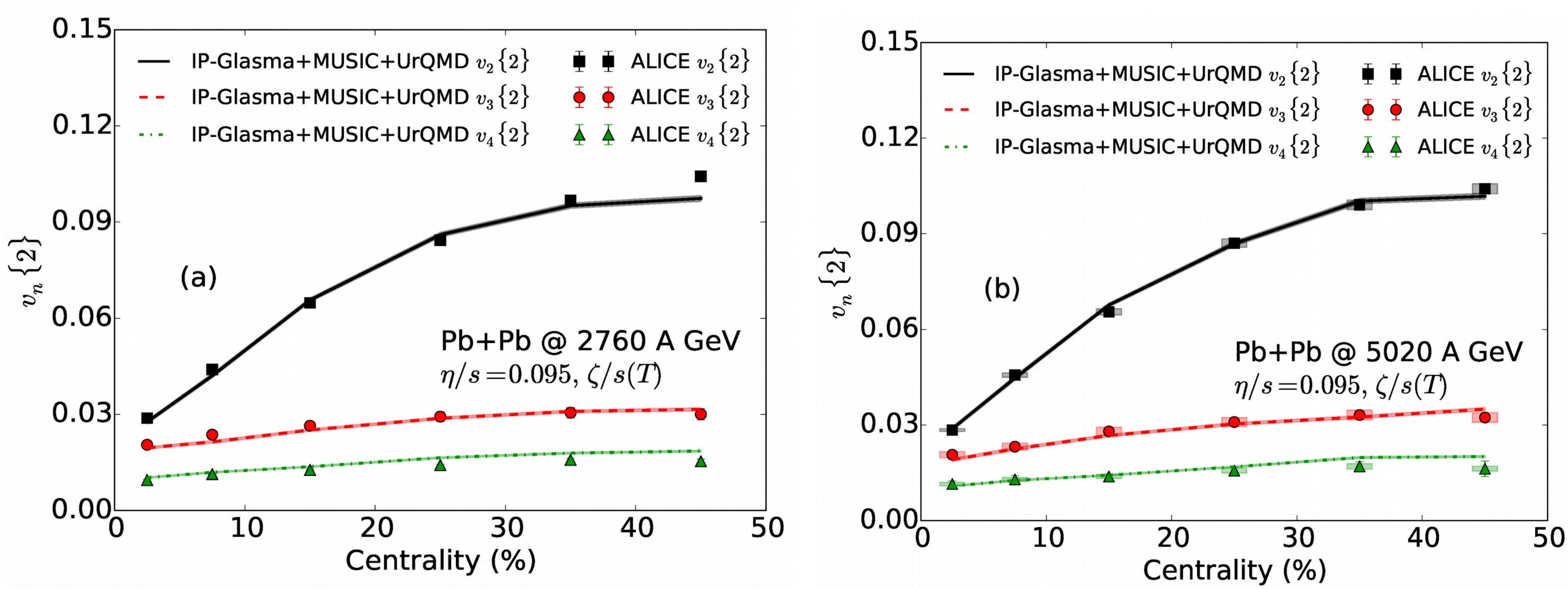
- *Effects of hadronic re-scatterings and bulk viscosity*
- *Prediction for 5.02 TeV shows slight increase over 2.76 TeV*

- *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 η/s

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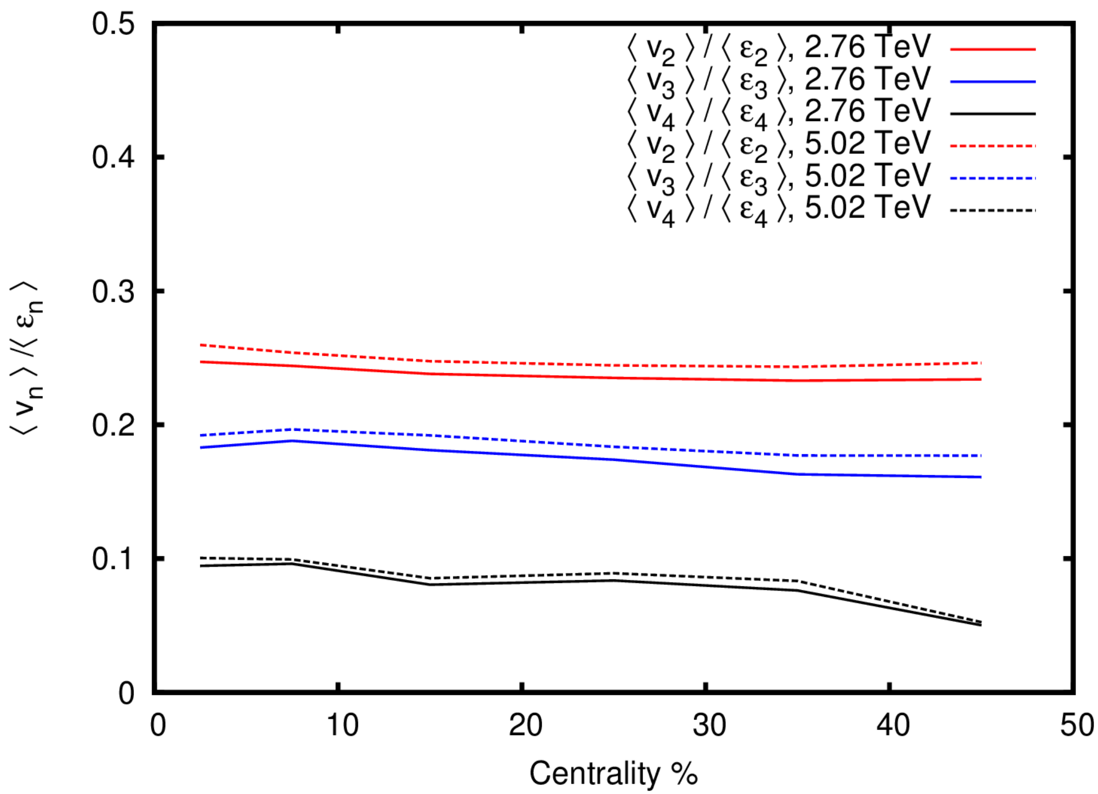
Percent Increase of v_n's at 5.02 TeV

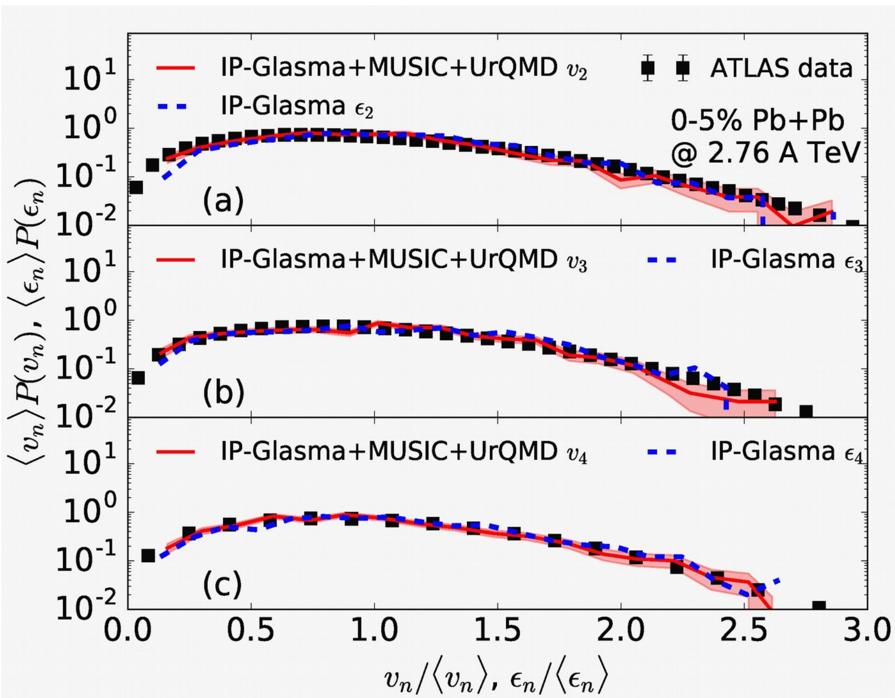
	v_2	v_3	v_4
ALICE (arXiv:1602.01119)	(3.0 ± 0.6)	(4.3 ± 1.4)	(10.2 ± 3.8)
IP-Glasma+MUSIC+UrQMD (arXiv:1609.02958)	(4.1 ± 1.7)	(5.1 ± 2.2)	(6.2 ± 2.3)

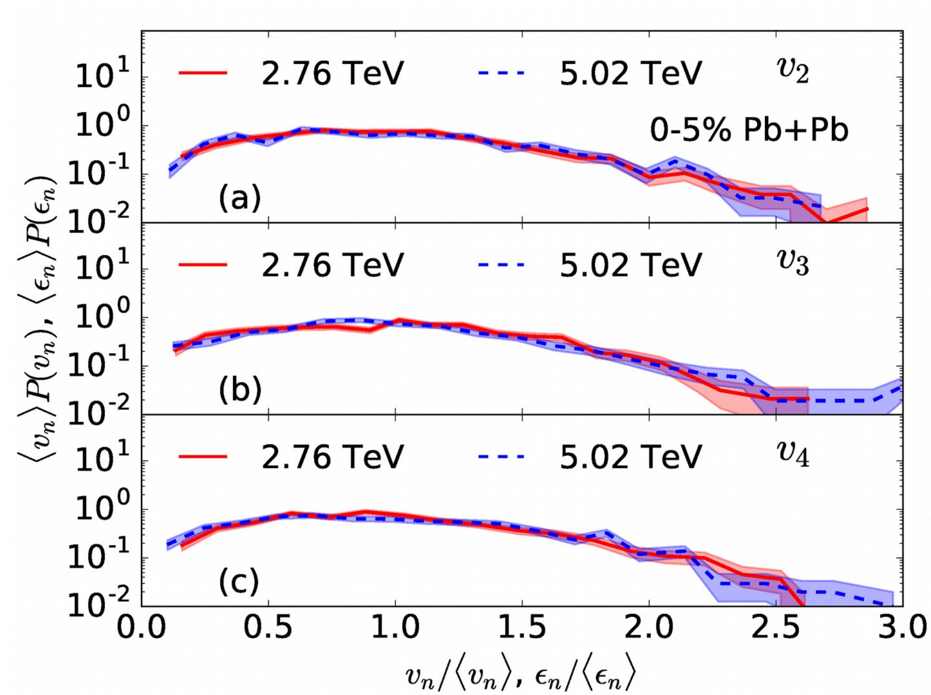


✔Due to increased lifetime of the fireball

Event by Event Fluctuations

- IP-Glasma provides good description of EbyE v_n distributions





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- Other observables to further constrain the initial state?

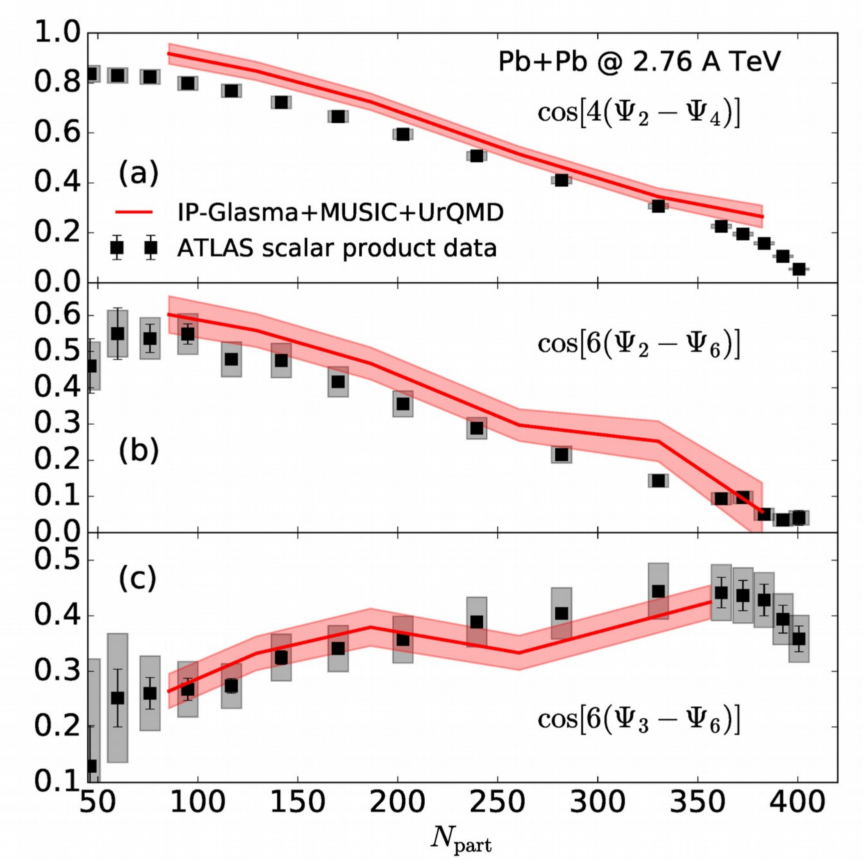
- v_n correlations give insight into non-trivial physics beyond v_n's

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)

$$V_n = k_n \epsilon_n + \sum_{quadratic} k_{pq} \epsilon_p \epsilon_q + \dots \qquad \epsilon_n = |\epsilon_n| e^{in\Phi_n} = \frac{-\int d^2 r_\perp r^m e^{in\varphi} e(r,\varphi)}{\int d^2 r_\perp r^m e(r,\varphi)}$$



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

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

✔ Good agreement with data

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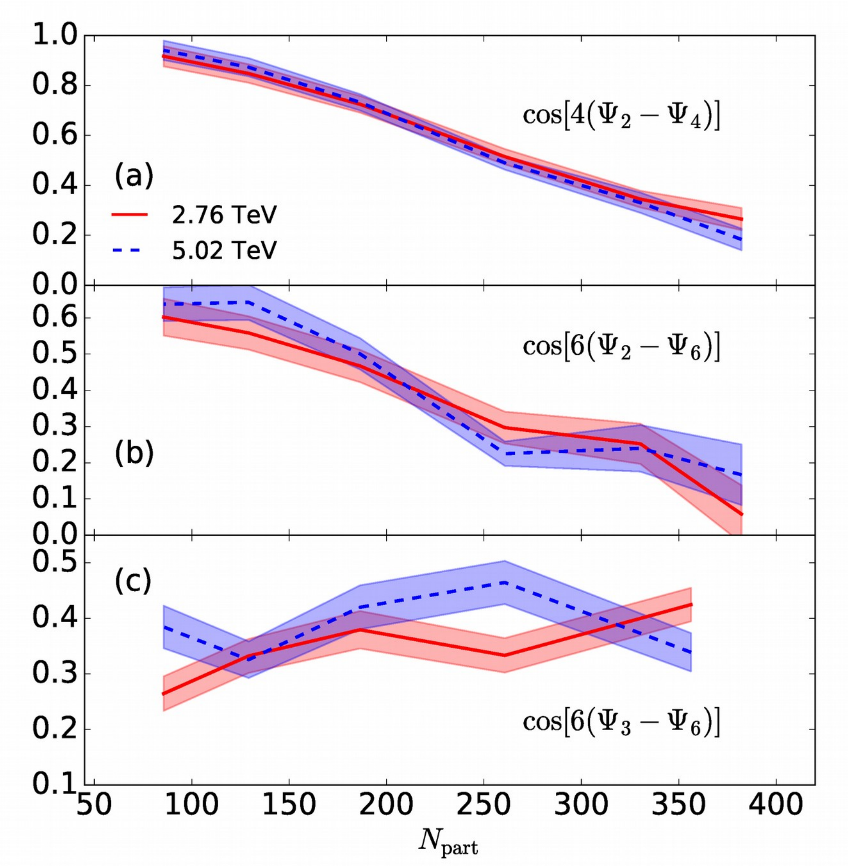

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✔ Similar response at 2.76 and 5.02 TeV

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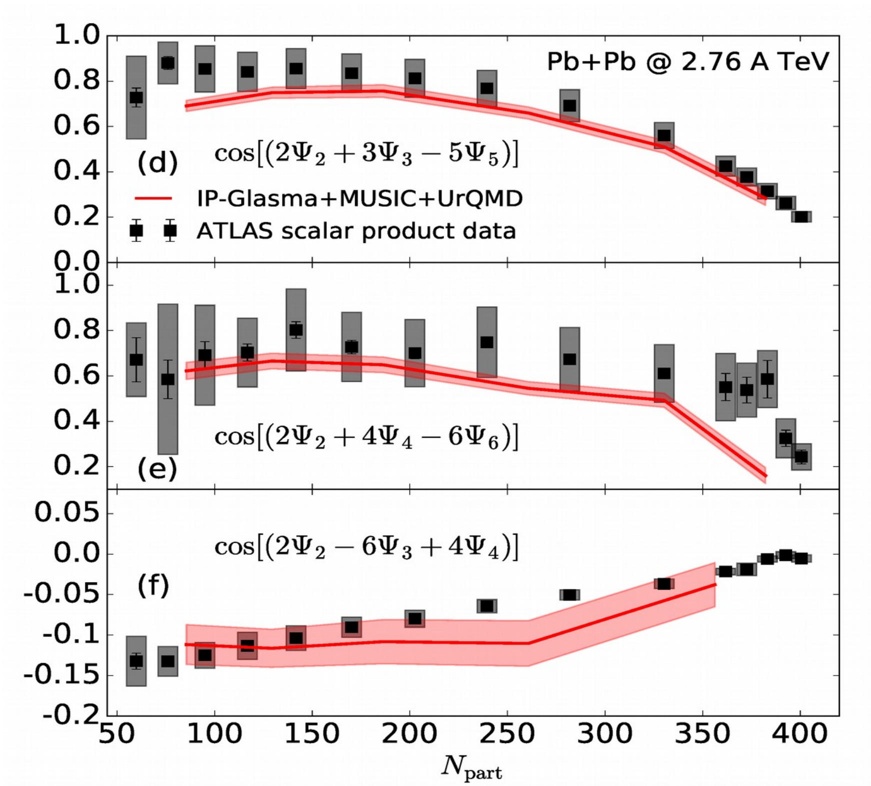

$$v_5 e^{5i\psi_5} = k_5 \epsilon_5 e^{5i\Phi_5} + k_{23} \epsilon_2 e^{2i\Phi_2} \epsilon_3 e^{3i\Phi_3}$$

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Teaney, Yan (arxiv:1210.5026)

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

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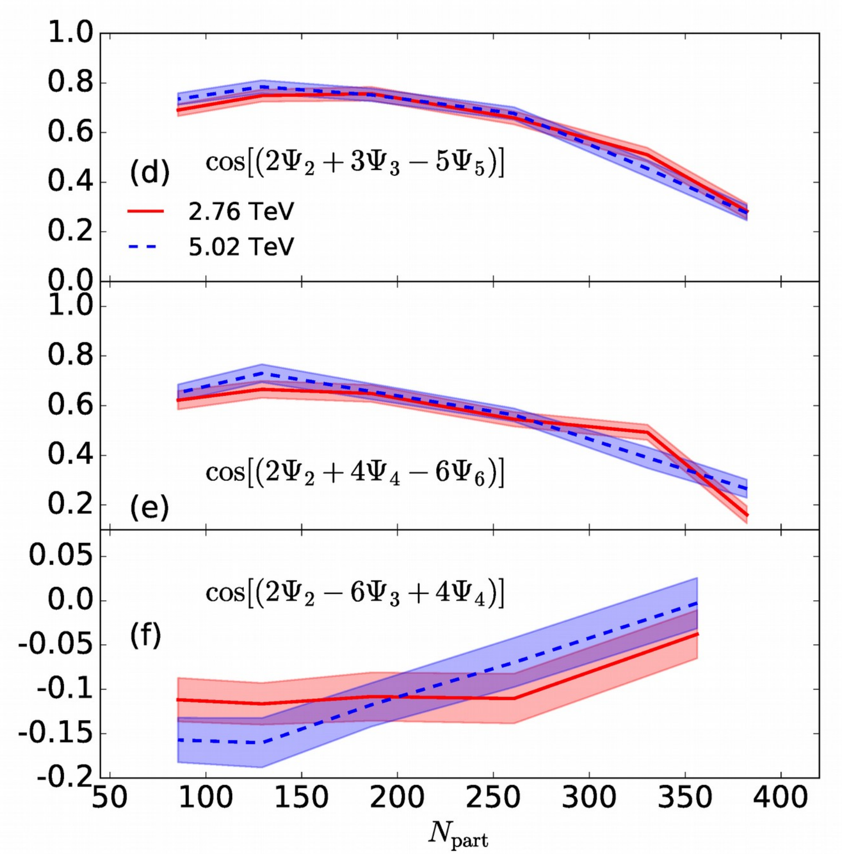

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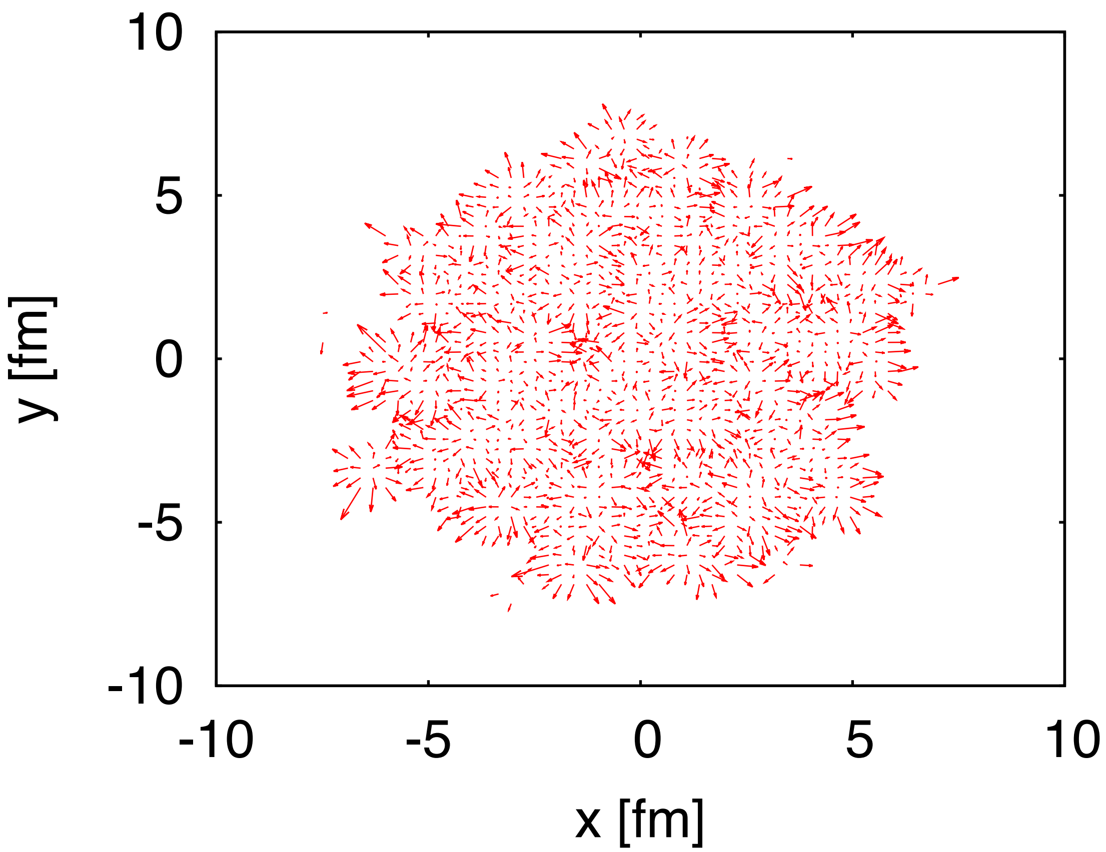
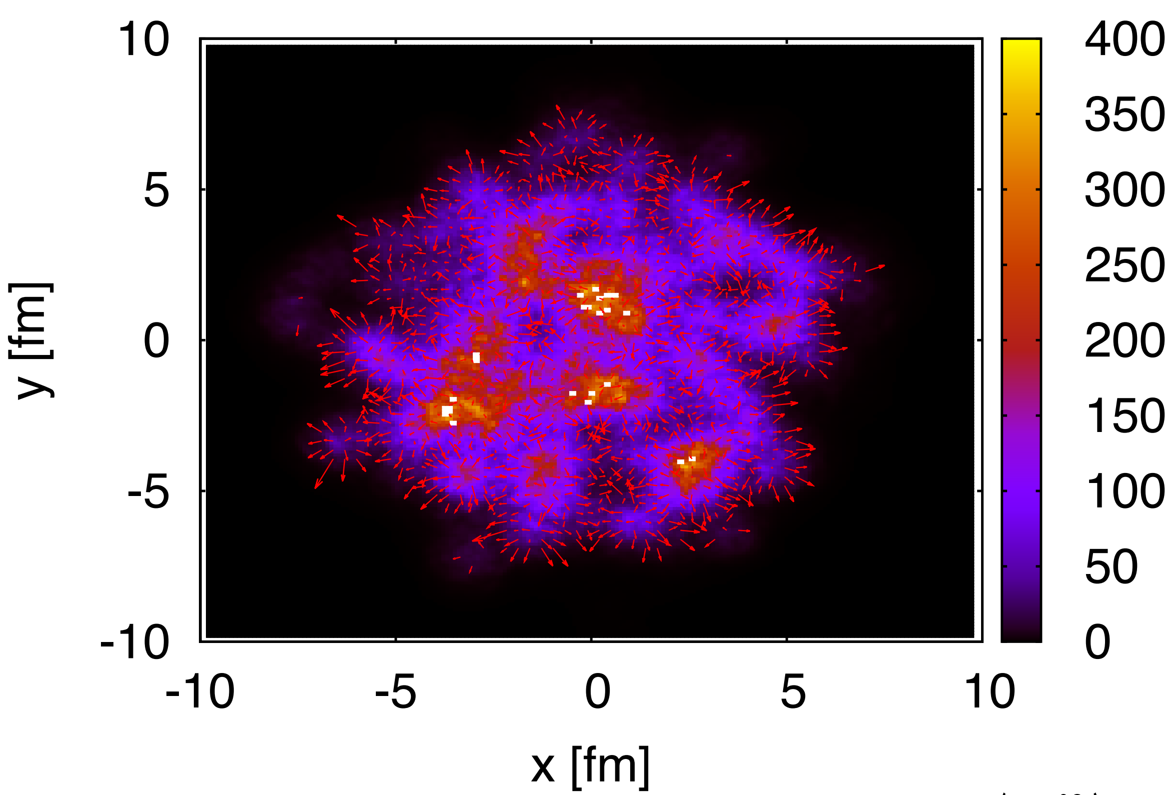
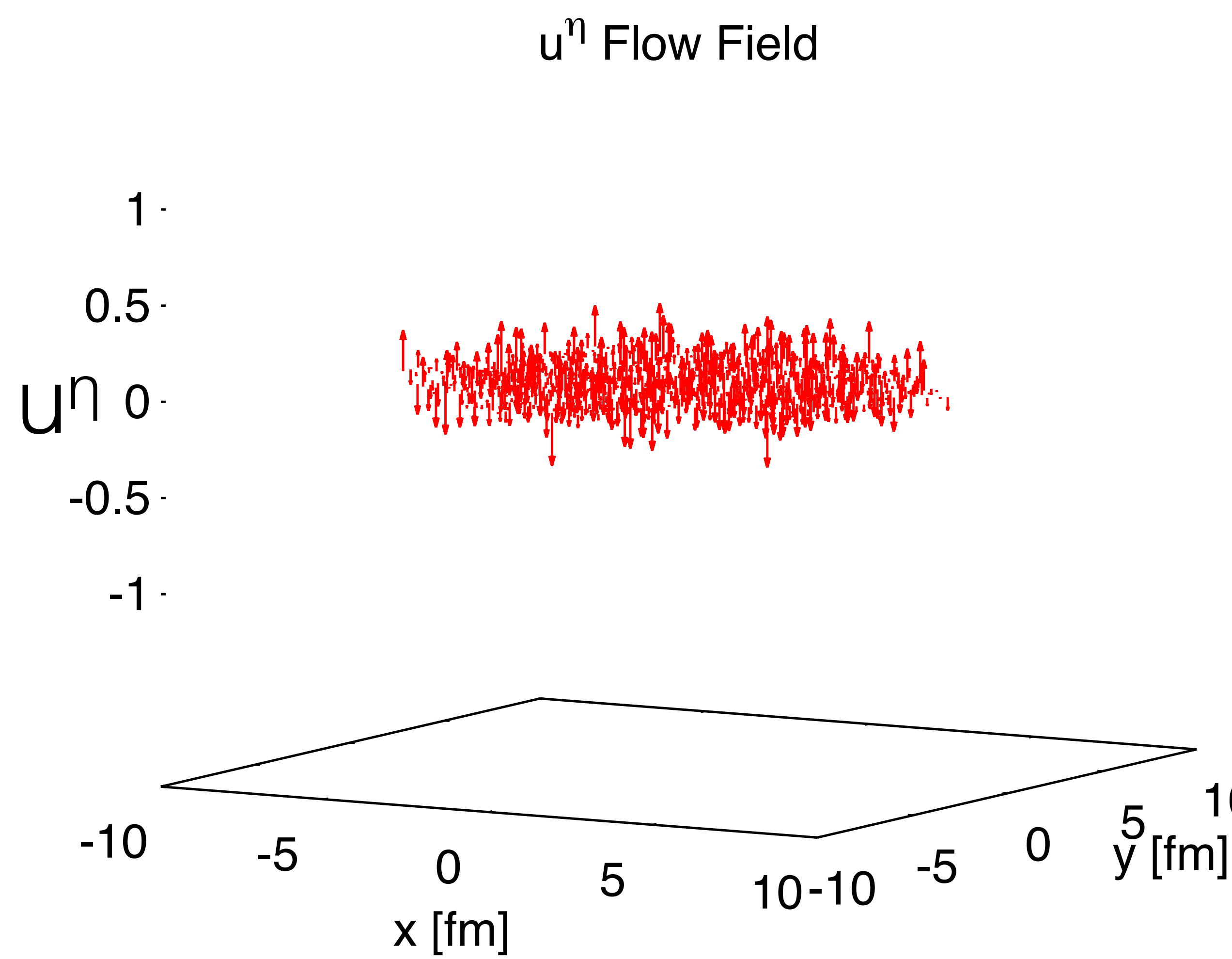
How we think about initial flow





On average, $\langle u^{\eta} \rangle \approx 0.5 \langle u^{\perp} \rangle$

How we should think about initial flow

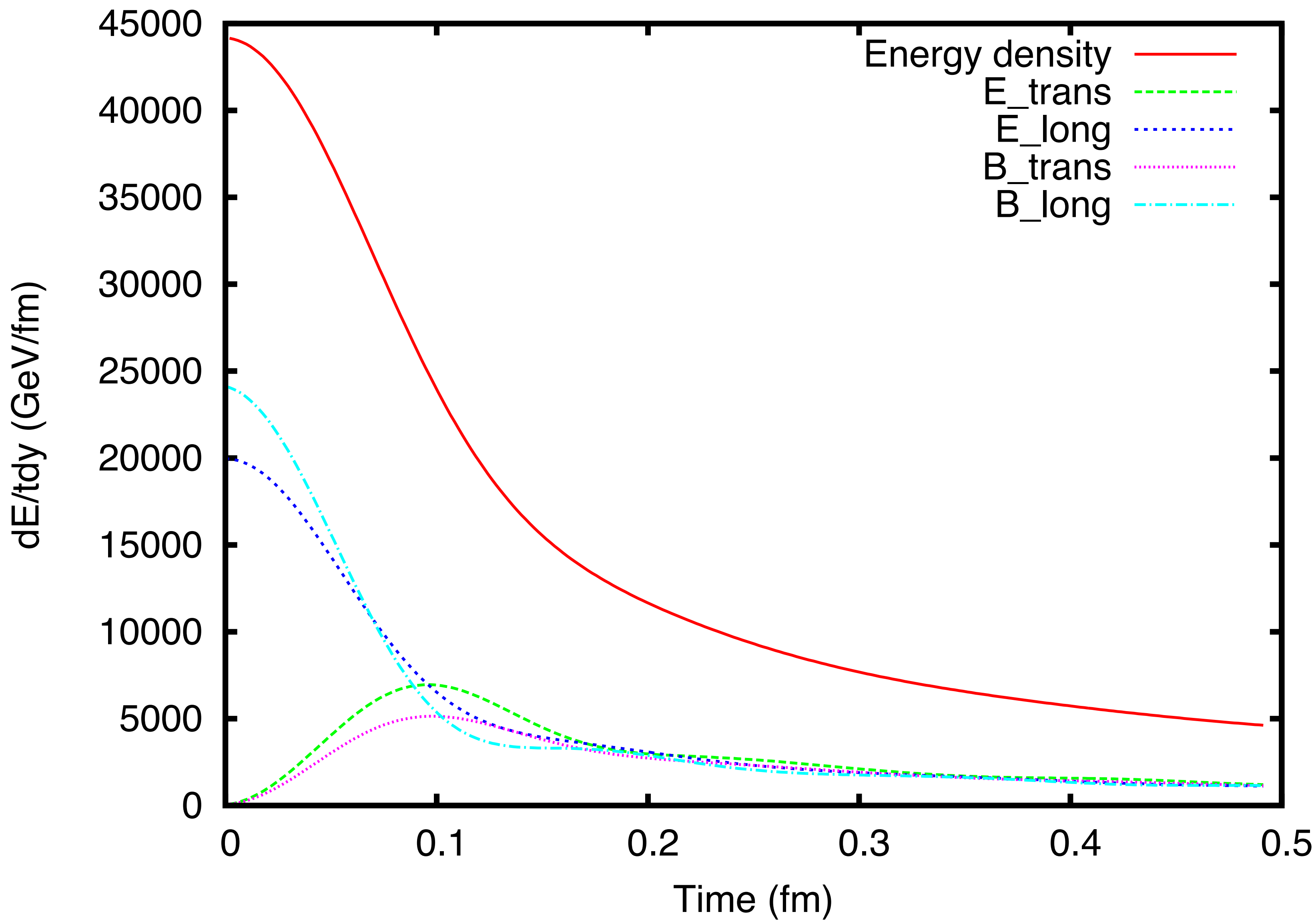


$$\langle u^{\mu} \rangle = \sqrt{\frac{\int (u^{\mu})^2 \epsilon\, d^2 x}{\int \epsilon\, d^2 x}}$$

Where does u^η come from?

- Even in the boost invariant case, non-zero chromo-electric and magnetic fields lead to non-zero η 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^η

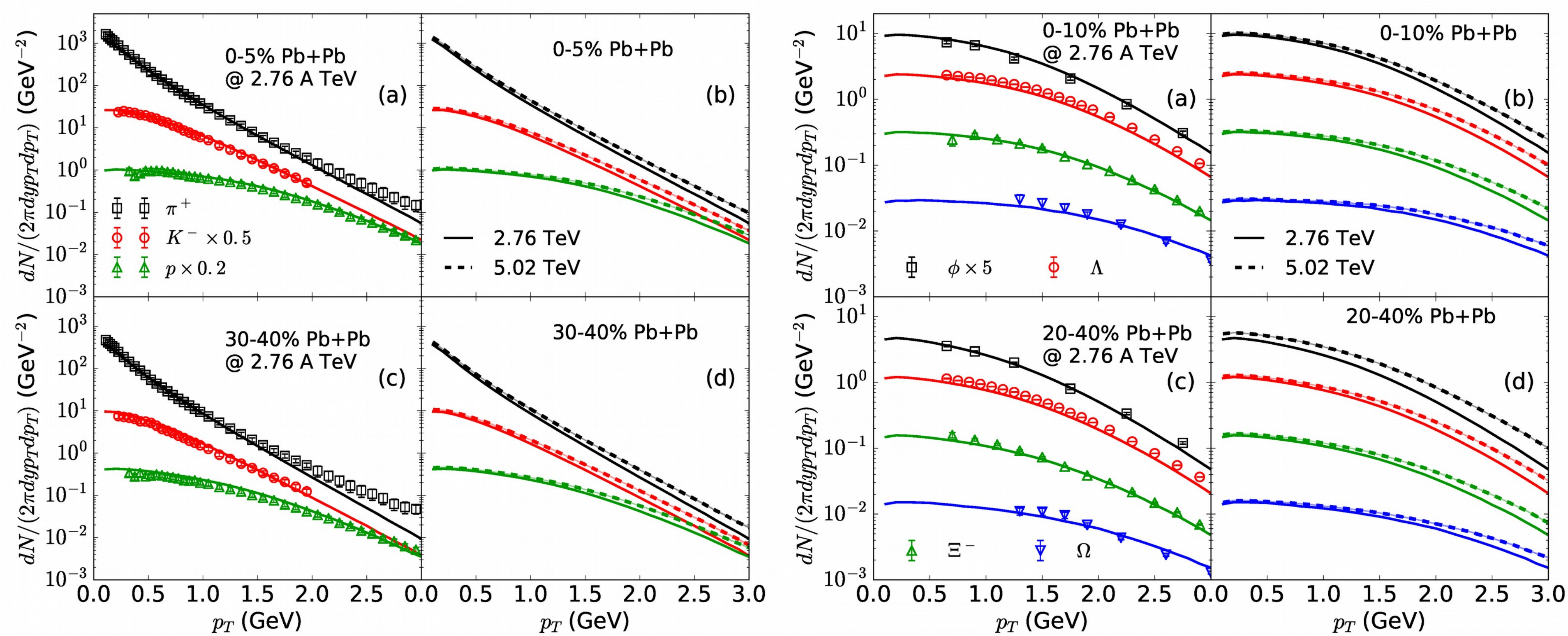
Conclusions

- ✔ **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^η 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

Identifed Particle Spectra



Particle spectra increase due to larger particle yield, but are also flatter. This suggests larger radial flow. Effects of bulk viscosity are important.

v_n Correlations

Two plane corelations

$$\cos(c_1 n_1 \Psi_{n_1} - c_2 n_2 \Psi_{n_2}) = \frac{\Re[\langle Q_{n_1}^{c_1}(Q_{n_2}^{c_2})^* \rangle]}{\sqrt{\langle Q_{n_1}^{c_1}(Q_{n_1}^{c_1})^* \rangle}\sqrt{\langle Q_{n_2}^{c_2}(Q_{n_2}^{c_2})^* \rangle}}$$

Three plane correlations

$$\cos(c_1 n_1 \Psi_{n_1} + c_2 n_2 \Psi_{n_2} - c_3 n_3 \Psi_{n_3}) = \frac{\Re[\langle Q_{n_1}^{c_1} Q_{n_1}^{c_2}(Q_{n_3}^{c_3})^* \rangle]}{\sqrt{\langle Q_{n_1}^{c_1}(Q_{n_1}^{c_1})^* \rangle}\sqrt{\langle Q_{n_2}^{c_2}(Q_{n_2}^{c_2})^* \rangle}\sqrt{\langle Q_{n_3}^{c_3}(Q_{n_3}^{c_3})^* \rangle}}$$

$$Q_n = \sum_i e^{in\varphi_i} \qquad \sum_i c_i n_i = 0$$

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

Event average

Average over
m particles

$$\begin{aligned}\langle\langle e^{in_1\varphi_1} e^{in_2\varphi_2} \dots e^{in_m\varphi_m}\rangle\rangle &= \langle v_{n_1}^{obs} e^{in_1\psi_1} v_{n_2}^{obs} e^{in_2\psi 2} \dots v_{n_m}^{obs} e^{in_m\psi_m}\rangle \\ &= \langle v_{n_1} e^{in_1\Phi_1} v_{n_2} e^{in_2\Phi_2} \dots v_{n_m} e^{in_m\Phi_m}\rangle \text{ + non-flow} \\ &= \langle v_{n_1} v_{n_2} \dots v_{n_m} \cos(n_1\Phi_1 + n_2\Phi_2 \dots + n_m\Phi_m)\rangle \text{ + non-flow}\end{aligned}$$

$$\langle \cos(n_1\varphi_1 + n_2\varphi_2 \dots + n_m\varphi_m)\rangle = \langle v_{n_1} v_{n_2} \dots v_{n_m} \cos(n_1\Phi_1 + n_2\Phi_2 \dots + n_m\Phi_m)\rangle \text{ + non-flow}$$