

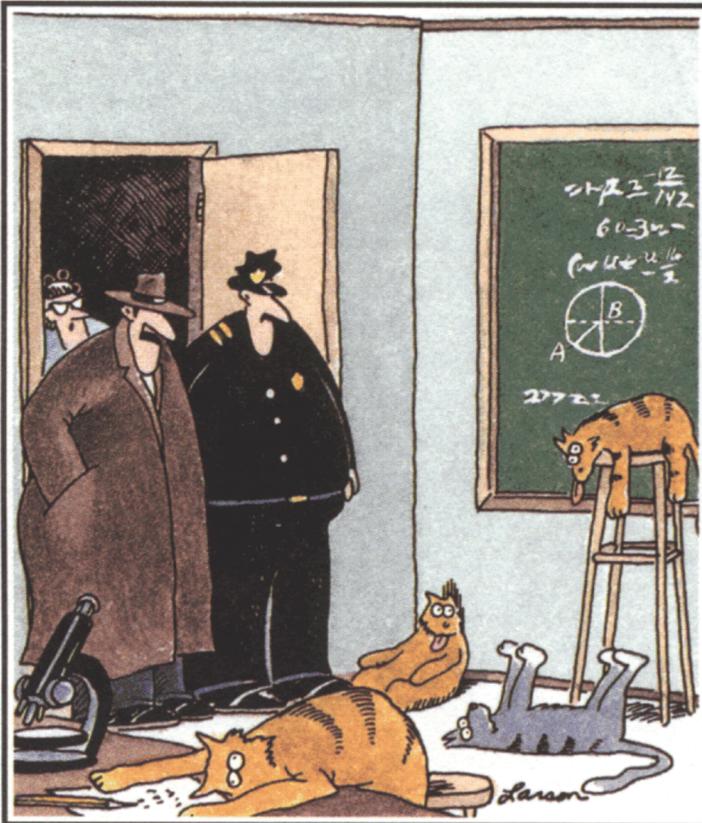
Small system studies: A theory overview

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Kent, OH USA

May 17, 2018



Plan of attack



"Notice all the computations, theoretical scribblings, and lab equipment, Norm. ...
Yes, curiosity killed these cats."

I. Soft probes

- Viscous hydrodynamics
- Kinetic theory vs hydrodynamics
- Initial state correlations
- Putting the pieces together
- Even smaller systems

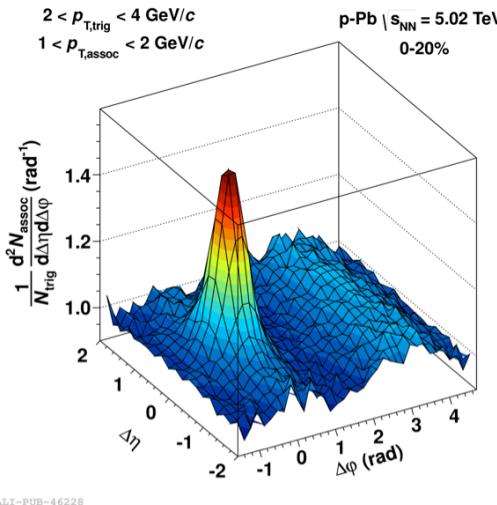
II. Hard probes

- Jet quenching
- Heavy quarkonium production

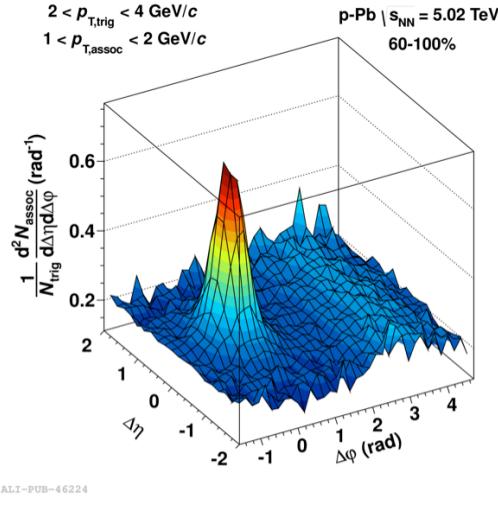
III. Conclusions

Definitions: Azimuthal anisotropy vs flow

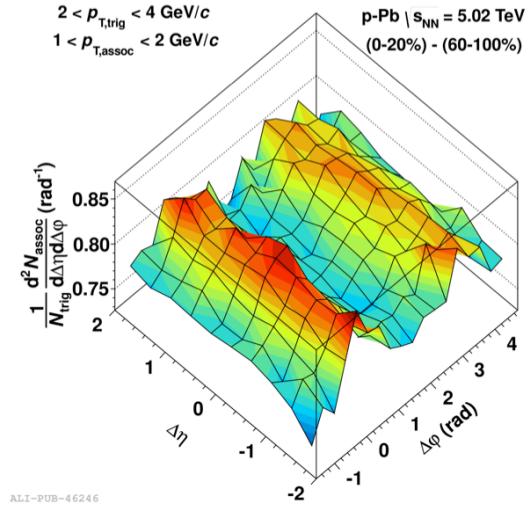
- **Azimuthal anisotropy** = experimental observations without reference to a specific physical interpretation [‘double hump’ after jet subtraction which is long range in rapidity]
- **Collective flow** = azimuthal anisotropies established during the hydrodynamic stage in response to initial geometry (final state interactions).



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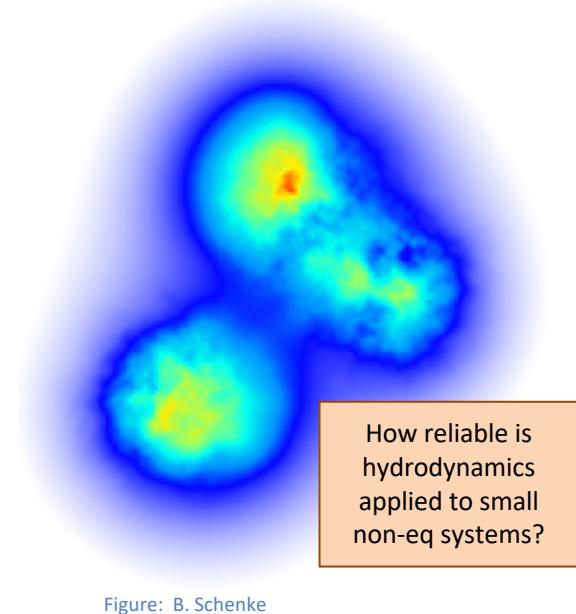
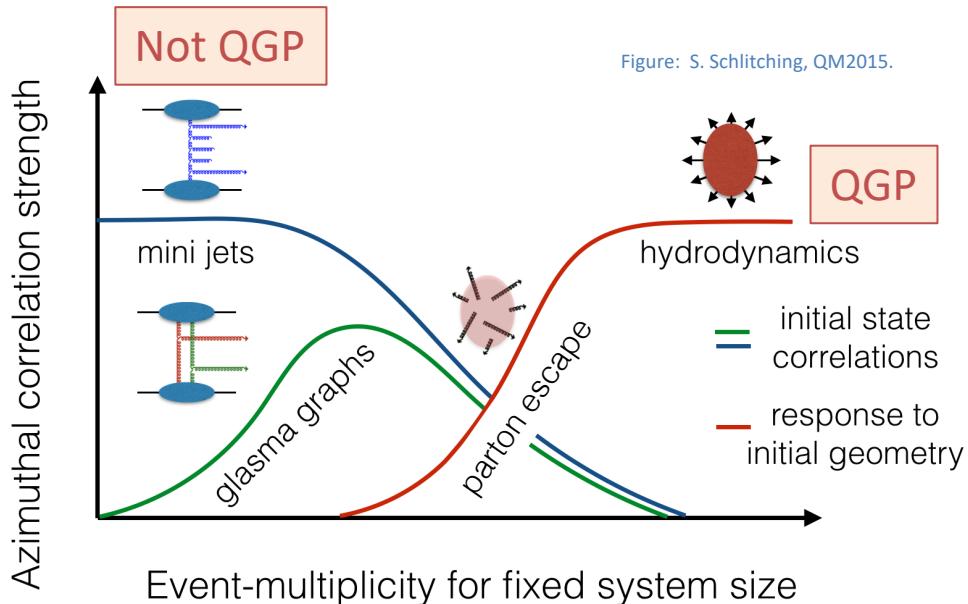


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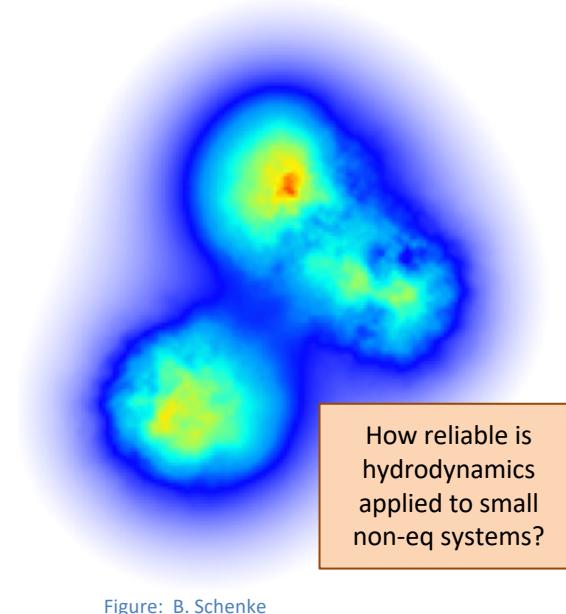
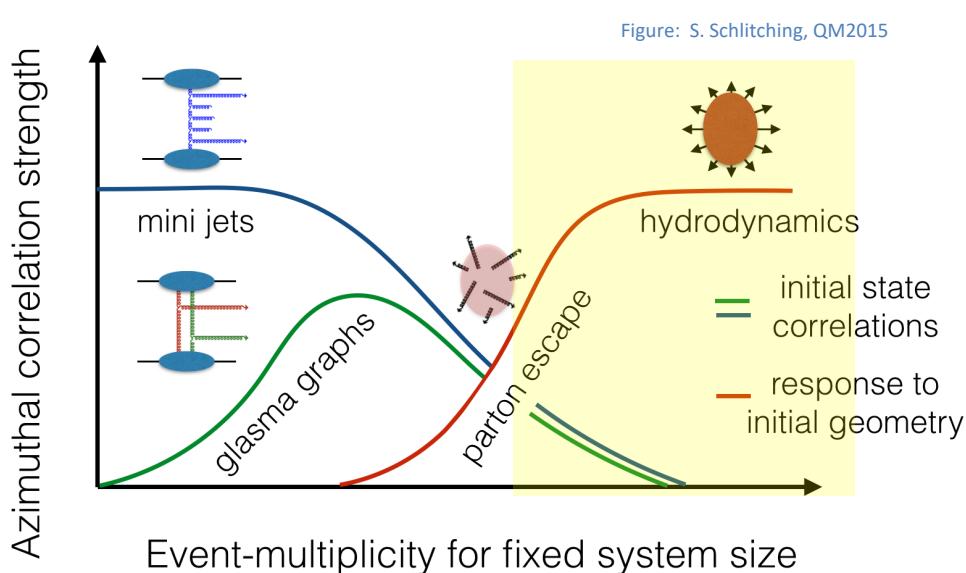
Sources of azimuthal anisotropy

- Hydrodynamical simulations of high-multiplicity events generate azimuthal anisotropies due to geometry-induced **collective flow**.
- Consistent with experimental observations; but not parameter free (!).



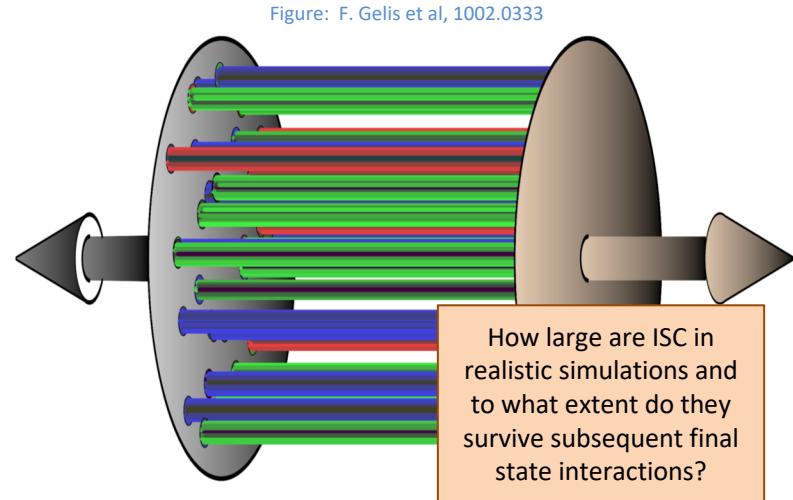
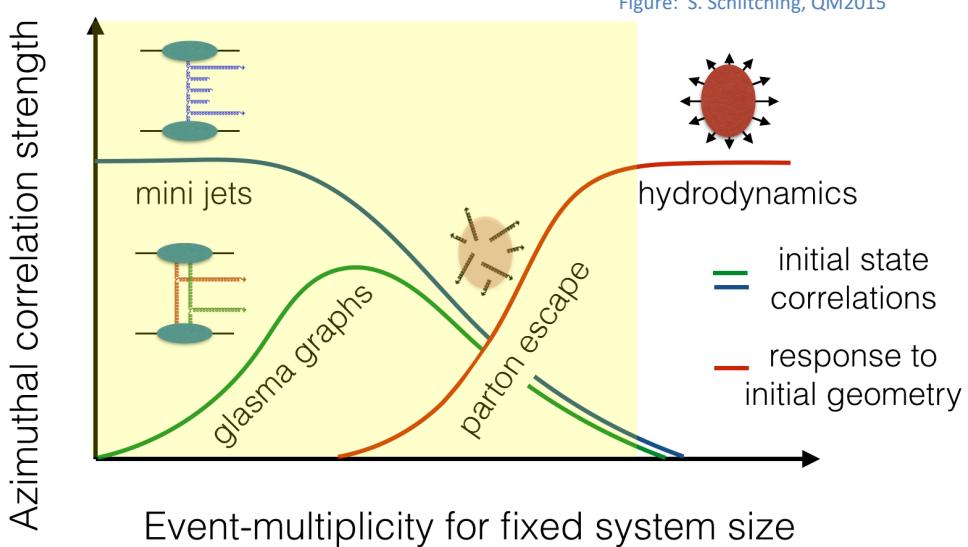
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Sources of azimuthal anisotropy

- At lower event multiplicity, **initial state correlations (ISC)** and **parton escape** generate azimuthal anisotropies in particle production.
- Now understood that one can generate non-zero **even and odd** azimuthal anisotropies from initial state effects (mini jet, glasma diagrams, etc.). [More later]

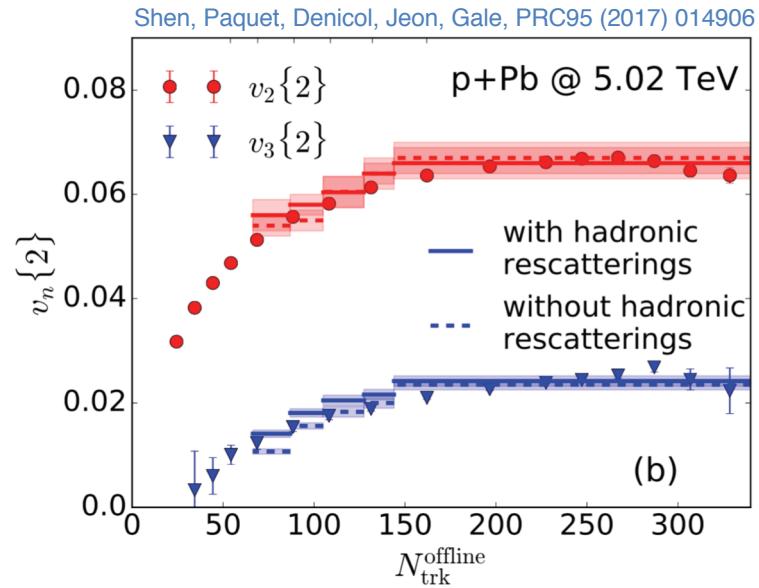
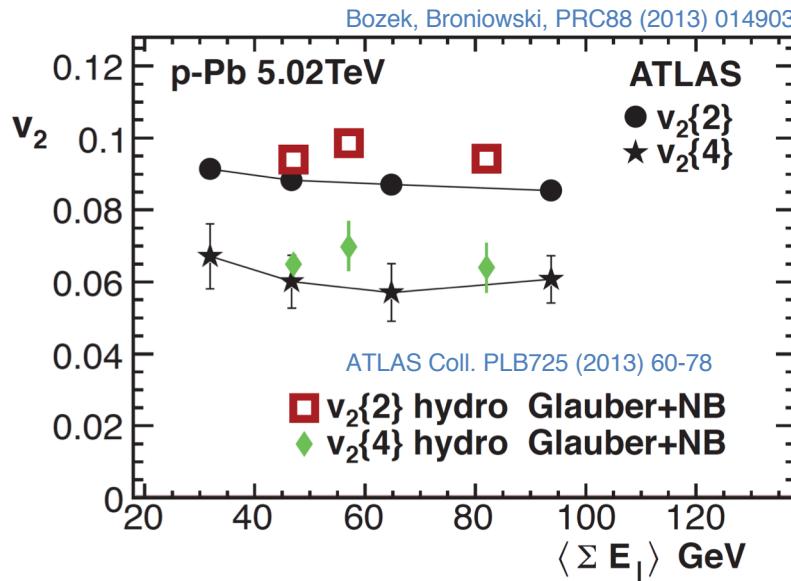


Azimuthal anisotropy from hydrodynamics

Azimuthal anisotropy from hydrodynamics

- Hydrodynamics results strongly suggest that the **observed azimuthal anisotropies can be understood in terms of collective response to the initial geometry**, aka hydrodynamic flow.
- Pioneering work done by the Krakow group.
- Anisotropies well-reproduced including mass ordering, approx. equal $v_2\{2m\}$ for all $m \gtrsim 4$

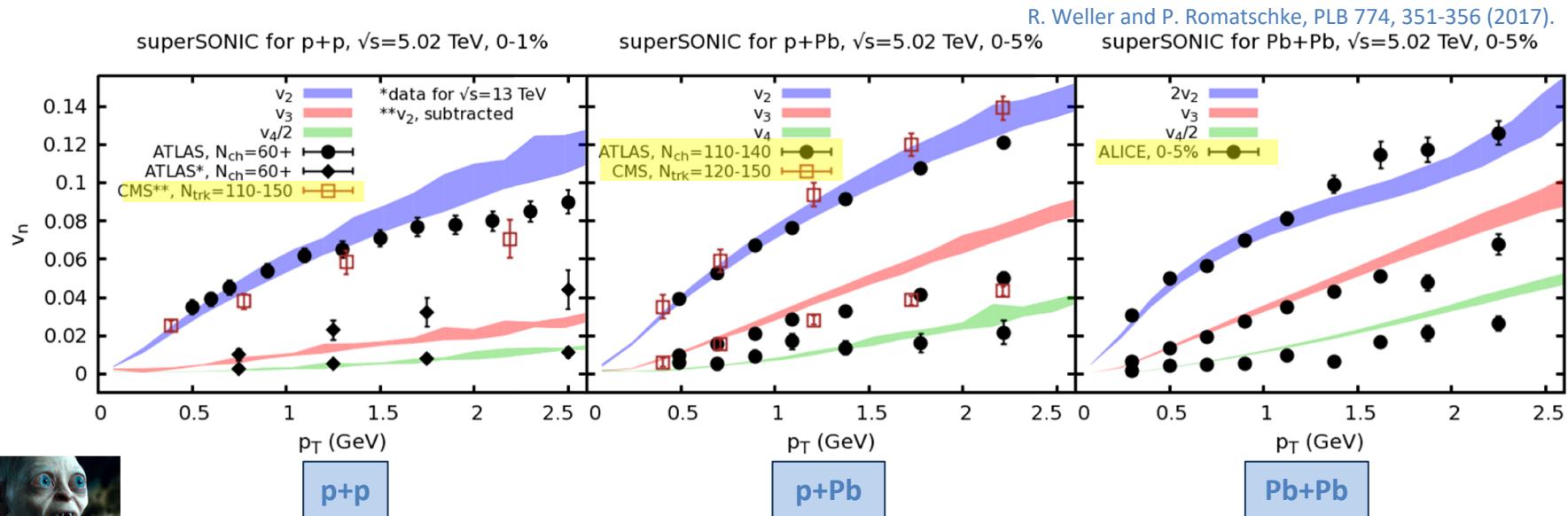
L. Yan, J.-Y. Ollitrault, PRL 112, 082301 (2014)



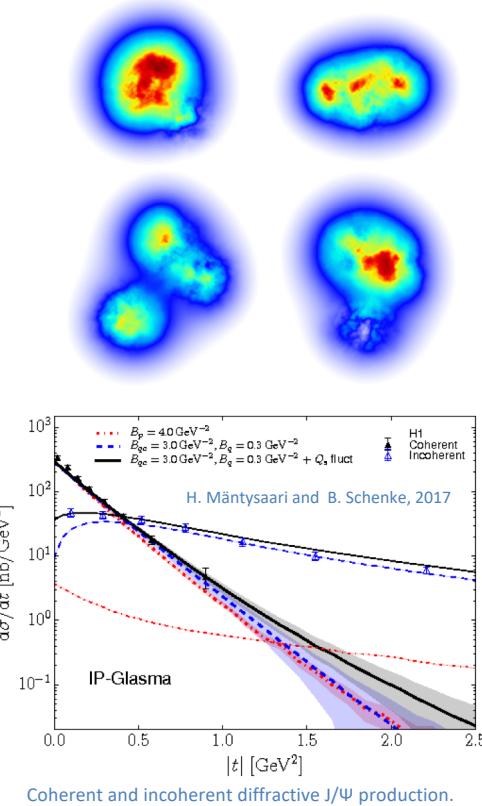
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Sub-nucleonic fluctuations

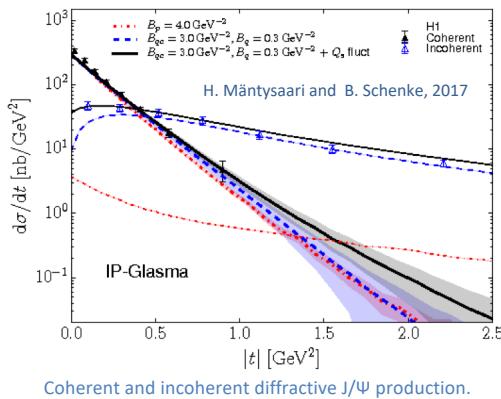
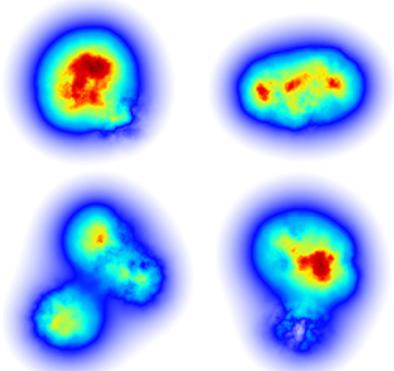


- A crucial ingredient in all successful hydrodynamical descriptions is the inclusion of **sub-nucleonic fluctuations**.
- Without them, initial eccentricities generated are too small to produce the observed azimuthal anisotropy.
- For some works on wounded quarks and shape fluctuations, see e.g.

- P. Bozek, W. Broniowski, M. Rybczynski, Phys. Rev. C94 014902 (2016)
K. Welsh, J. Singer, U.W. Heinz, Phys. Rev. C94 024919 (2016)
R. Weller and P. Romatschke, PLB 774, 351-356 (2017)
P. Bozek, W. Broniowski, Phys. Rev. C 96, 014904 (2017)
H. Mäntysaari and B. Schenke, Nucl. Part. Phys. Proc. 289-290 457 (2017)
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, PLB 772, 681 (2017)
J. Albacete, H. Petersen, and A. Soto-Ontoso, Phys.Lett. B778, 128 (2018)

QM18 talks
S. Moreland
H. Mäntysaari

Sub-nucleonic fluctuations

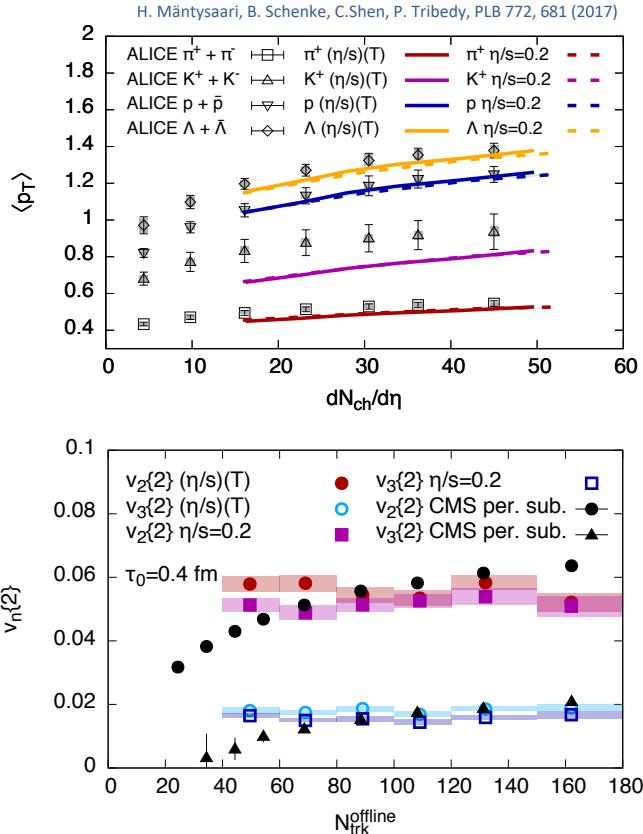


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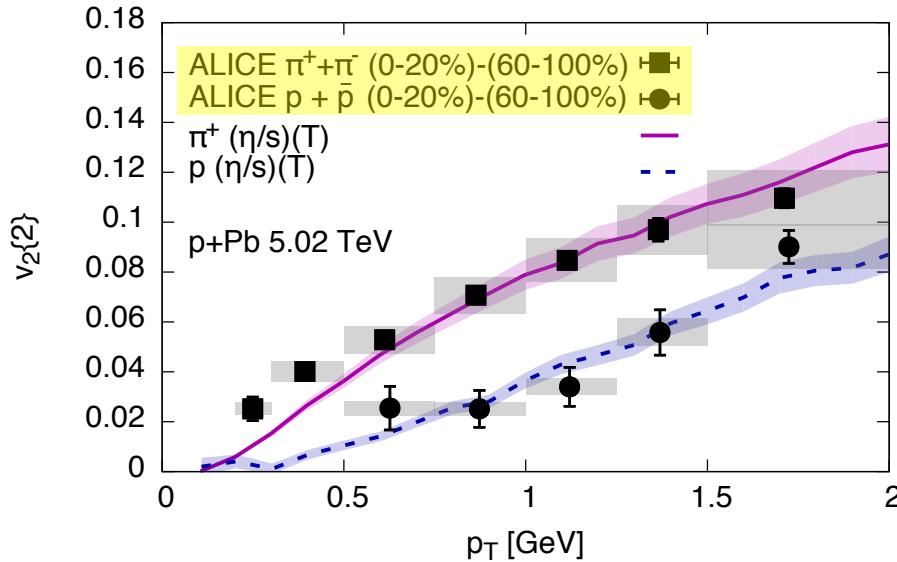
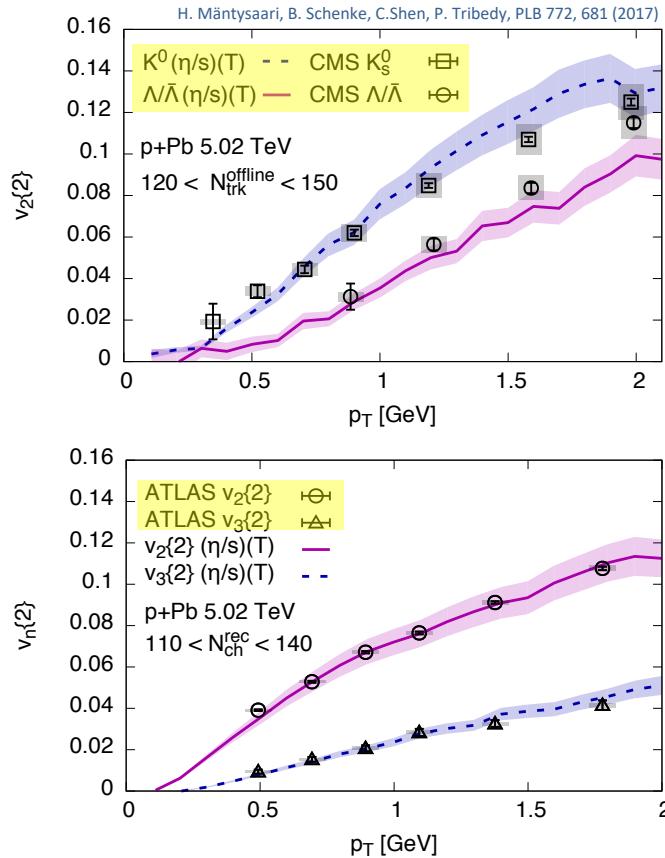
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p-Pb with IP-Glasma + 3+1d MUSIC + URQMD



- IP-Glasma + sub-nucleonic “bumps”
- 3+1d event-by-event viscous hydrodynamics with **shear and bulk viscosity**
- URQMD afterburner
- Average transverse momentum well-reproduced (Kaons?); inclusion of bulk viscosity key in not over-predicting $\langle p_T \rangle$.
- **Elliptical and triangular anisotropy start to agree with data at approximately $N_{trk}^{offline} \sim 70$**

p-Pb with IP-Glasma + 3+1d MUSIC + URQMD



- Very good agreement with azimuthal anisotropy observed by ALICE, CMS, and ATLAS.
- Mass ordering reproduced as in Pb-Pb.

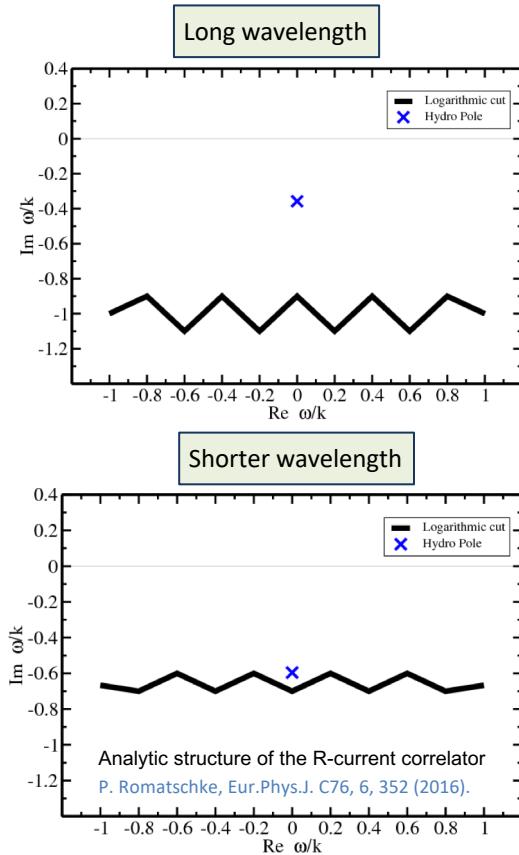
Should we trust hydro simulations in this case?

- If spatiotemporal gradients are large, the **gradient expansion** underpinning hydrodynamics becomes suspect.
- One expects to have trouble when the size of the gradients becomes comparable to the inverse temperature of the system

$$TL \sim 1$$

- If the initial temperatures are on the order of 1 GeV, then the “**smallest size**” will be approximately $L \sim 0.2$ fm.

How to formalize this with correlators



- The “**hydro pole**” governs the evolution of the **slowest mode**. Poles/cuts further down in the complex plane map to **non-hydrodynamic modes**.
- Ideally, non-hydrodynamic modes decay on a much shorter time scale than the hydro mode evolves.
- The analytic structure of the correlators changes with k : **hydro pole at high-momentum can be “eaten by the branch cut”**.
- Implies existence of “smallest scale” for conventional hydro

$$L \sim 0.15 \text{ fm}$$

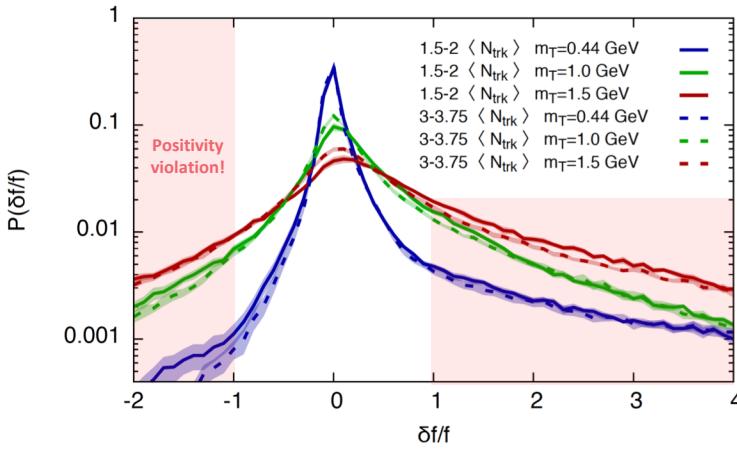
- Also see a similar (but qualitatively different) story AdS/CFT as the coupling is reduced from ∞ :
[S. Grozdanov, N. Kaplis, and A. Starinets, JHEP 1607 151 \(2016\)](#).

Are the viscous corrections under control?

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, PLB 772, 681 (2017)

$v_n(p_T)$, however, studying the distribution of corrections relative to the thermal distribution from all freeze-out surface cells, we find a significant share (10% for $p_T \sim 0.45$ GeV, 25% for $p_T \sim 1$ GeV, 45% for $p_T \sim 1.5$ GeV for pions) of large (shear) corrections ($|\delta f|/f \gtrsim 100\%$).

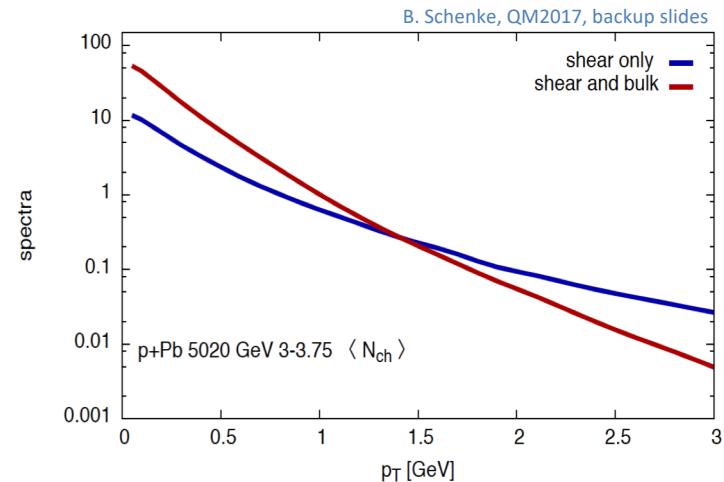
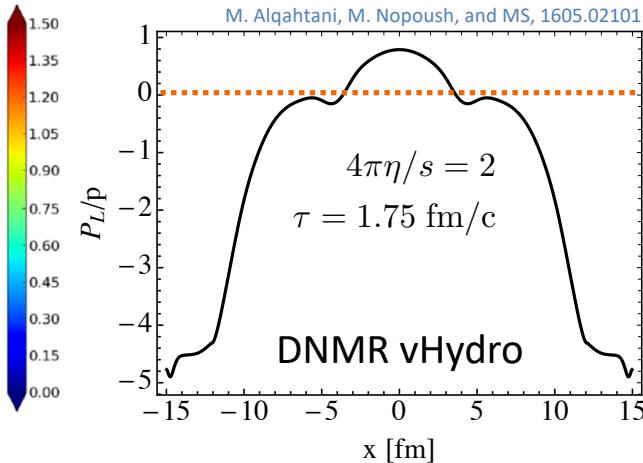
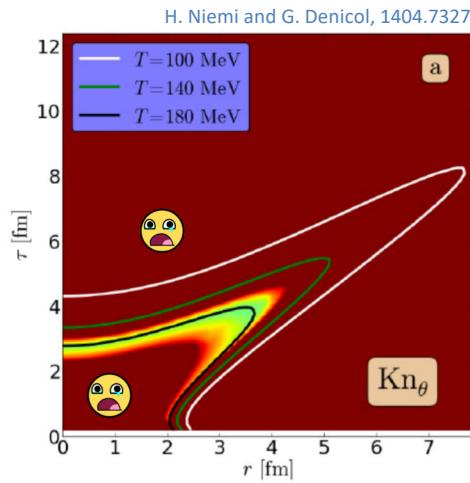
This demonstrates that our results are plagued by large viscous corrections, in particular for $p_T \gtrsim 1$ GeV. Nevertheless, p_T -integrated quantities are dominated by low p_T contributions and less sensitive to these problems.

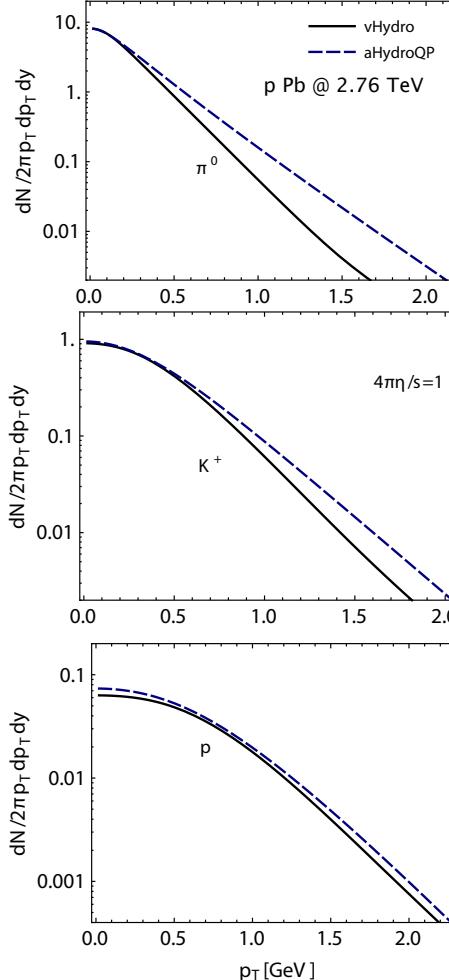


- Not really
- **Short lifetime + large momentum-space anisotropy + large isotropic (bulk) pressure correction**
- As a result, simulations suffers from negative effective pressures in a large hypervolume.
- **Large δf corrections on freeze-out hypersurface.**
- Groups deal with this differently. SONIC, for example, uses an “exponentiation trick” introduced by Pratt and Torreiri in PRC 82, 044901 (2010) to prevent $f < 0$ on the switching surface (still large correction though).

Are the viscous corrections under control?

- Short lifetime + large momentum-space anisotropy + large isotropic (bulk) pressure correction
- Bulk viscous effects are large
- Spectra change significantly when including the δf corrections

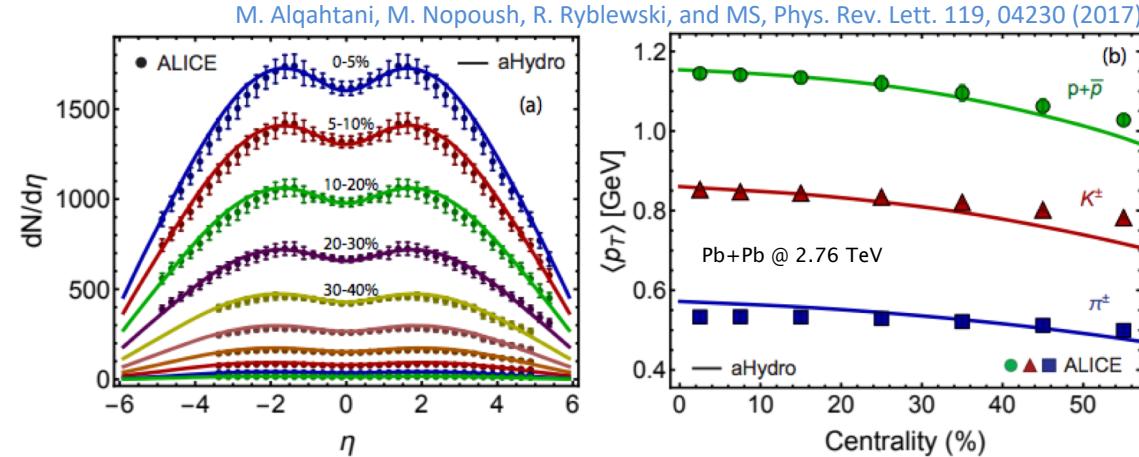


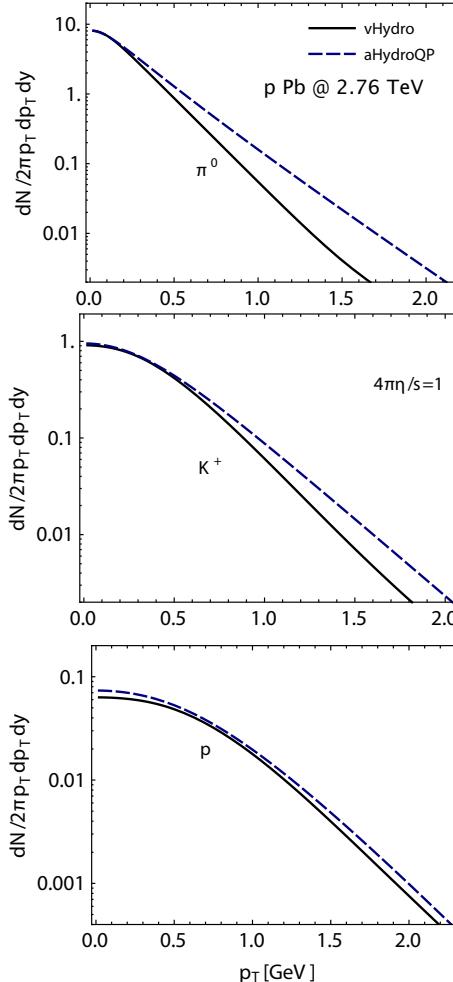


Can anisotropic hydrodynamics help?

- In anisotropic hydrodynamics (aHydro), large shear/bulk corrections are resumed (sums up corrections to all orders in inverse Reynolds number).
- Has been to more accurately reproduce kinetic theory evolution in far-from-equilibrium contexts.
- Pressures are guaranteed to be ≥ 0 .
- One-particle distribution function is guaranteed to be ≥ 0 at all times, including at freeze-out.

QM18 talk
M. Alqahtani

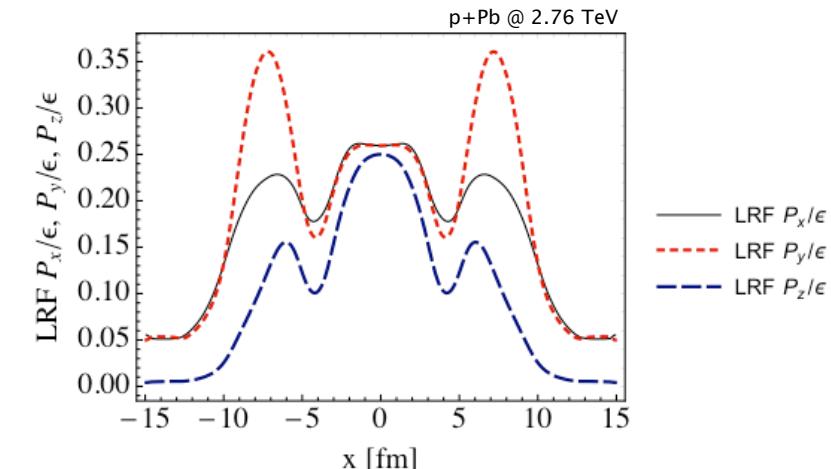
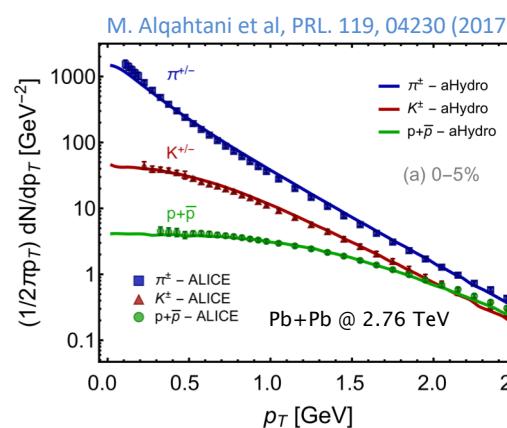




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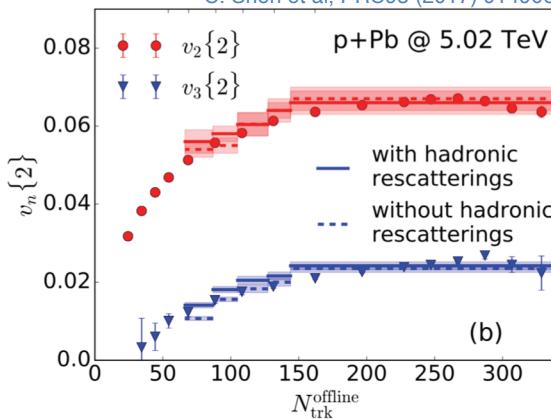
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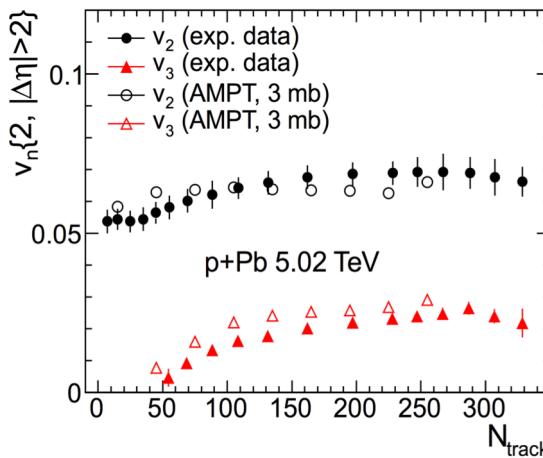
Kinetic theory vs viscous hydro - A paradigm shift?

Kinetic theory vs viscous hydro

C. Shen et al, PRC95 (2017) 014906



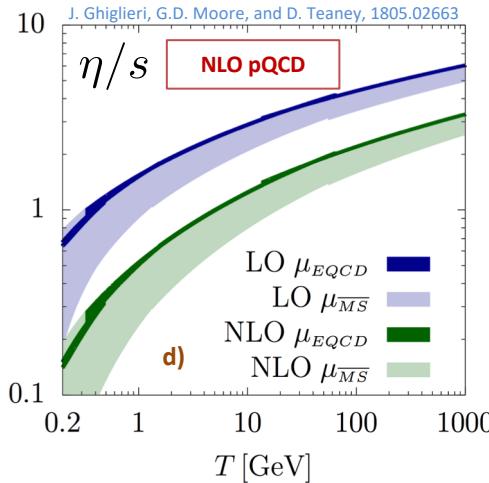
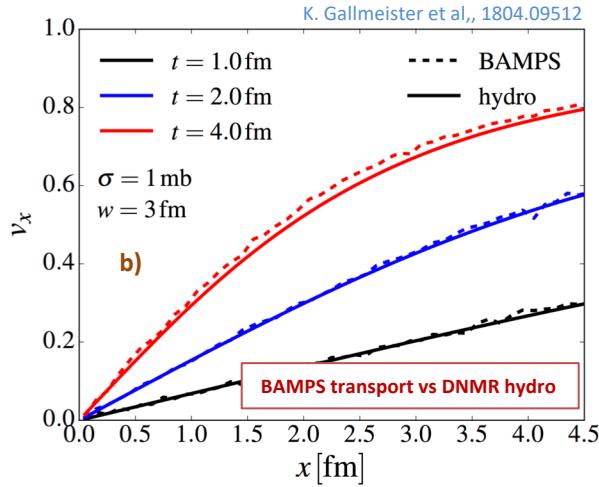
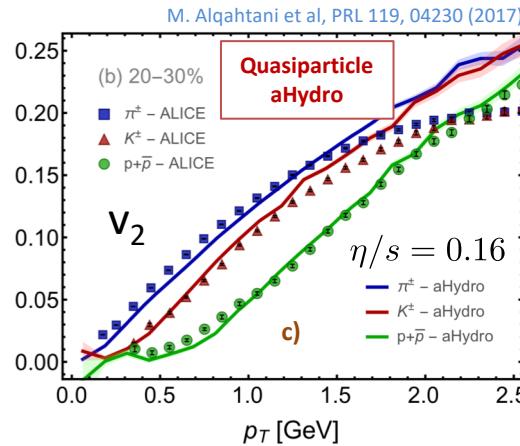
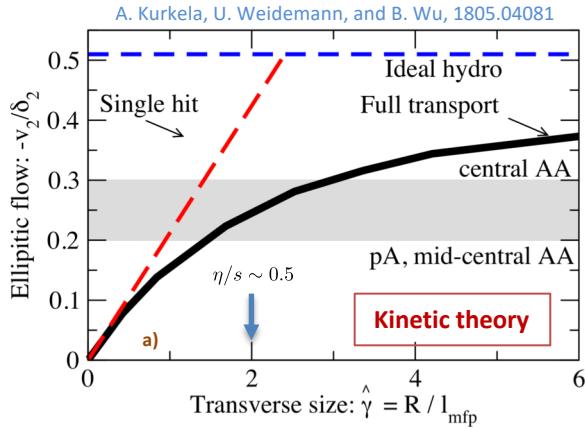
L. He et al 1502.05572; A.Bzdak, G.Ma, PRL 113 (2014) 252301



- Magnitude of v_2 and v_3 found using viscous hydro (top) and AMPT transport (bottom) are very similar.
- Somewhat heretical opinion: Hydro is just an efficient way to solve kinetic transport equations using only a few low-order moments of f .
- Many examples are accumulating which demonstrate that viscous hydro doesn't completely break when pushed far from equilibrium or when the scattering cross sections are small.
- Lots of work on the hydro front to push it further from equilibrium in a more quantitatively reliable manner (e.g. anisotropic hydrodynamics).

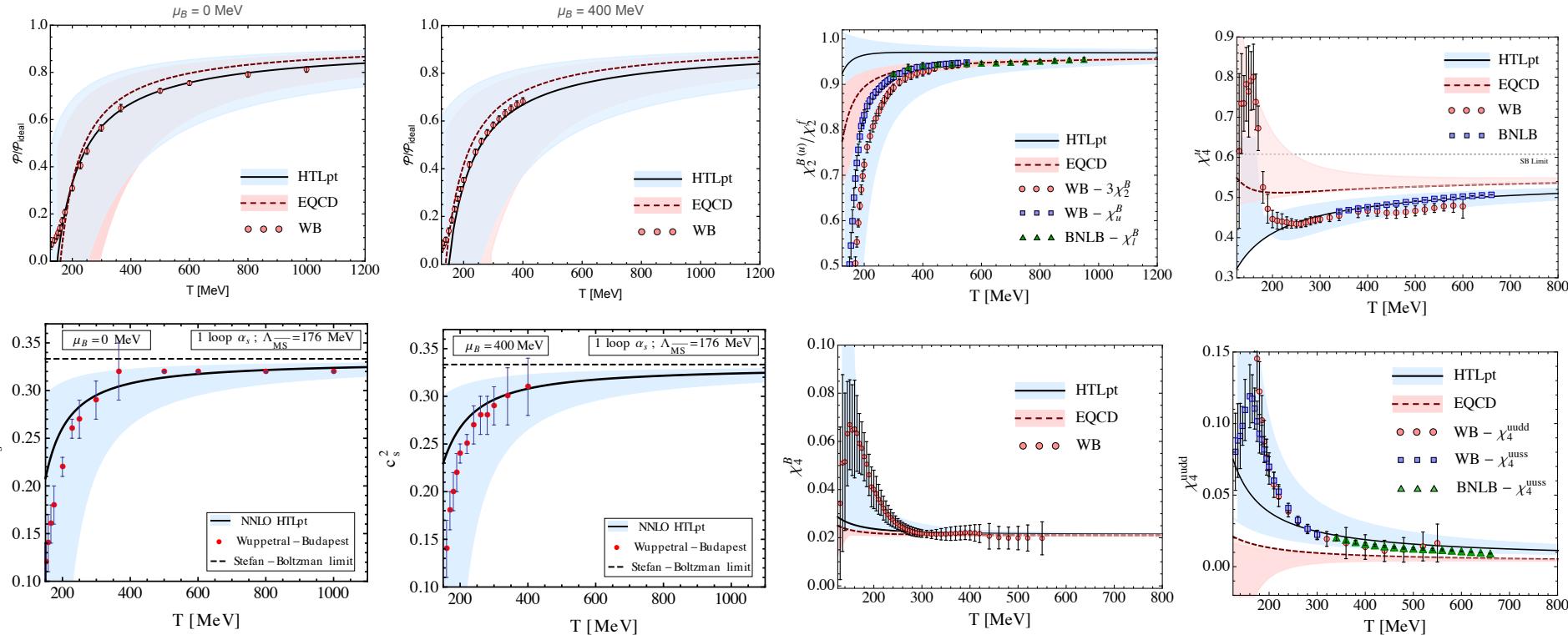
A paradigm shift?

- a) Magnitude of v_2 is consistent with “few hit” kinetic theory.
- b) Similar energy density and flow profiles obtained using transport and hydro.
- c) Hydro models that are based on quasiparticle transport describe elliptic flow.
- d) NLO pQCD calculation of η/s gives values which are consistent with phenomenologically extracted values.



New theory results presented at QM2018!

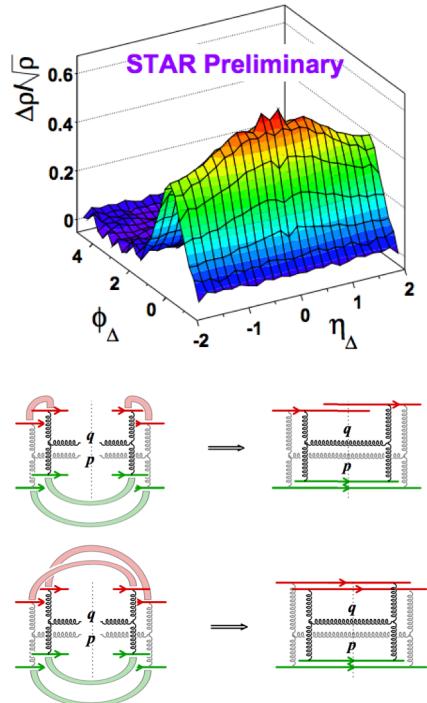
Not only transport, also thermodynamics



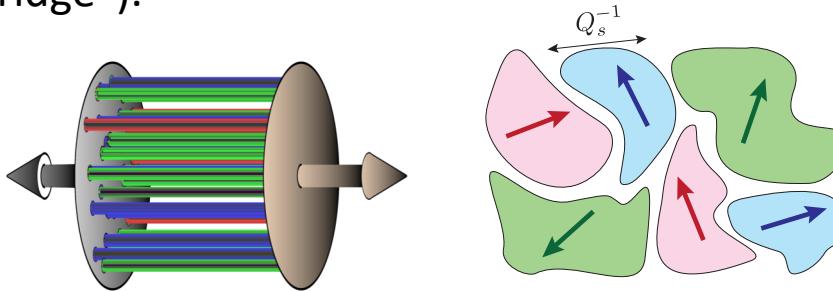
Resummation results based explicitly on a first principles quasiparticle picture

Azimuthal anisotropy from initial state correlations

CGC correlations - The plasma graphs



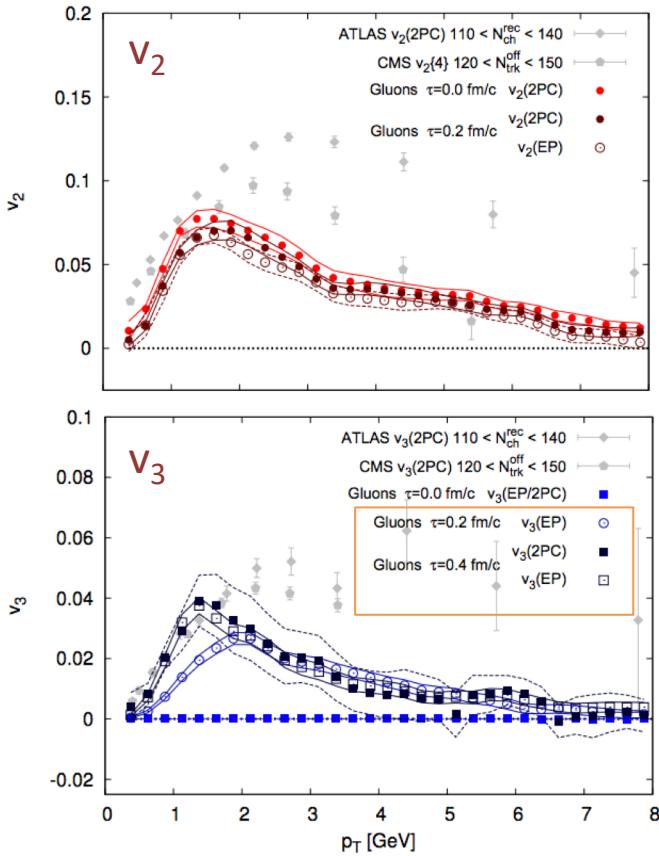
- Glasma flux tubes provide long range rapidity correlation (the “ridge”).



- In the CGC explanation for the ridge, long range rapidity correlations requires a double interaction in both the projectile and target → “**glasma graphs**”
- Quite successful phenomenology.
- Only even azimuthal harmonics generated by these graphs.

Dumitru et al, Nucl. Phys. A810, 91 (2008);
Dumitru et al, PLB 297,21 (2011);
Dusling and Venugopalan, PRL 108, 262001 (2012);
Dusling and Venugopalan, PRD 87, 093034 262001 (2013).

Beyond the plasma graphs I

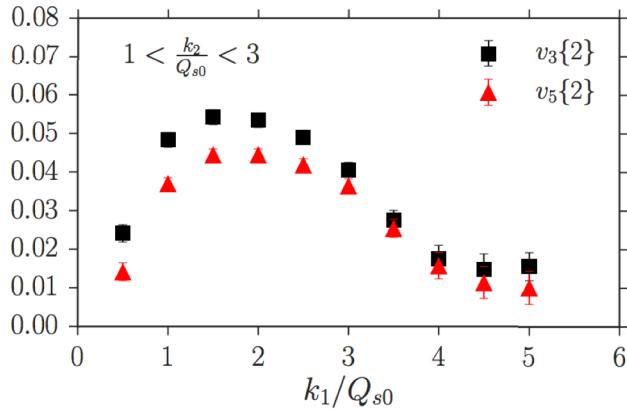


- Numerical simulations of classical gluon fields within the McLerran-Venugopalan model show that it is possible to generate odd harmonics from initial state effects.

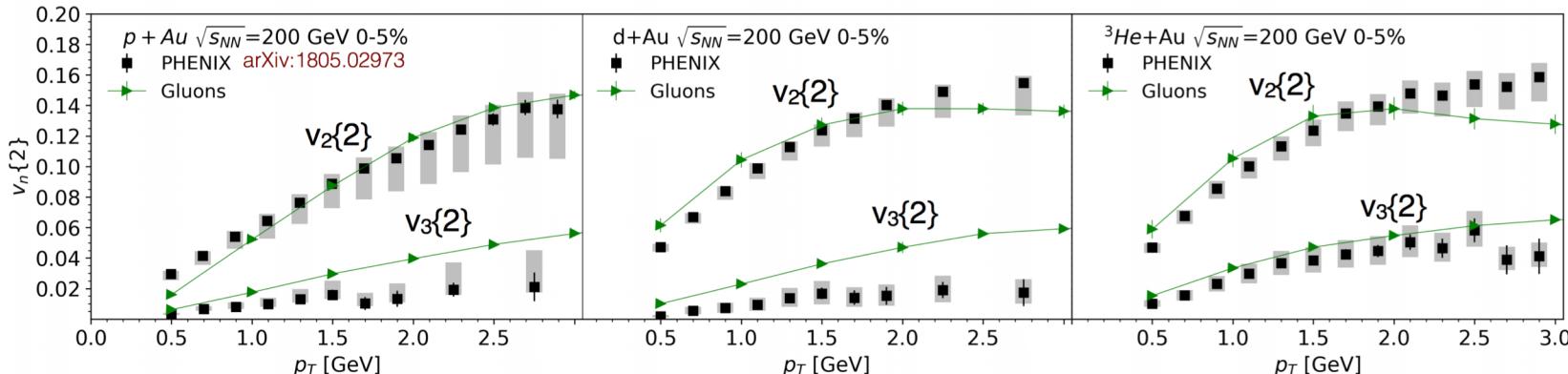
T. Lappi, S. Srednyak and R. Venugopalan, JHEP **1001**, 066 (2010);
B. Schenke, S. Schlichting and R. Venugopalan, PLB **747**, 76 (2015).

- The key difference between the numerical result and the original plasma graph analysis comes from the inclusion of saturation effects in the projectile.
- Natural to guess that odd harmonics originate in higher-order projectile interactions.

Beyond the glasma graphs II



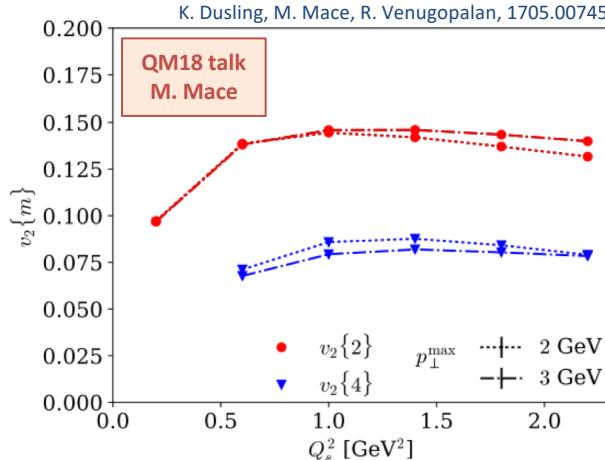
- Kovchegov and Skokov preprint (1802.08166) analytically demonstrates how classical gluon fields can generate odd azimuthal harmonics that are long-range in rapidity.
- **Generated by higher-order saturation corrections in the interactions with the projectile and the target.**
- Analytic understanding of a source of odd harmonics which comes solely from initial state correlations + pQCD.
- **Numerical realization and data comparison by M. Mace (below).**



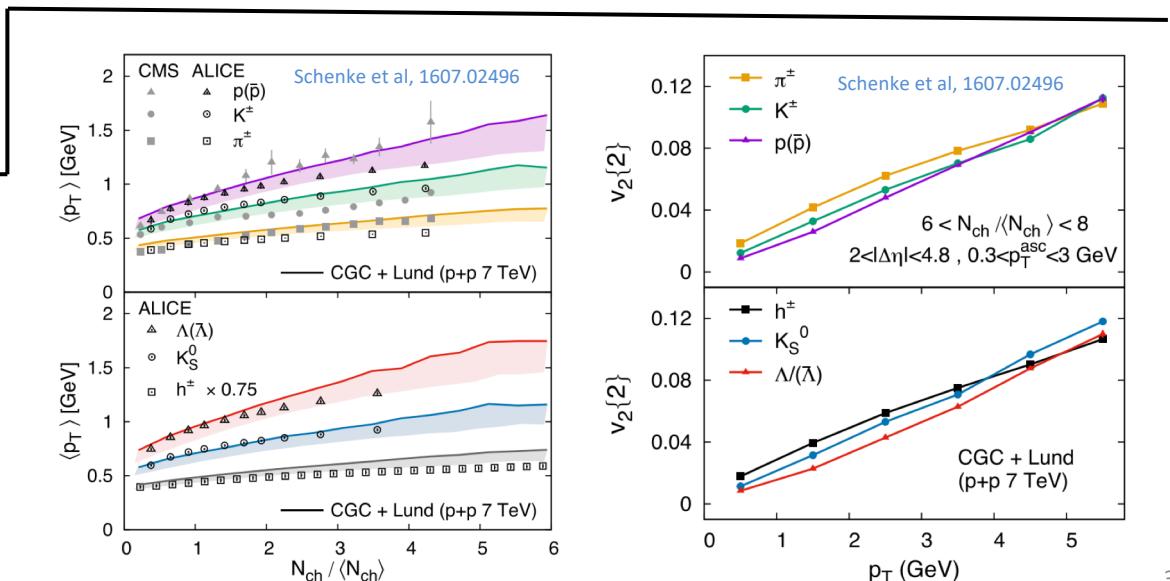
QM18 talk
M. Mace

Multiparticle correlations and mass ordering

K. Dusling, M. Mace, R. Venugopalan, 1705.00745



- In 1705.00745 and 1706.06260 Dusling, Mace, and Venugopalan demonstrated that qualitative features of multiparticle correlations in $p+A$ collisions can be reproduced by ISC:
 - Ordering of $v_n\{2\}$ emerges naturally
 - $v_2\{2\} > v_2\{4\}$ (abelian version has $v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$)

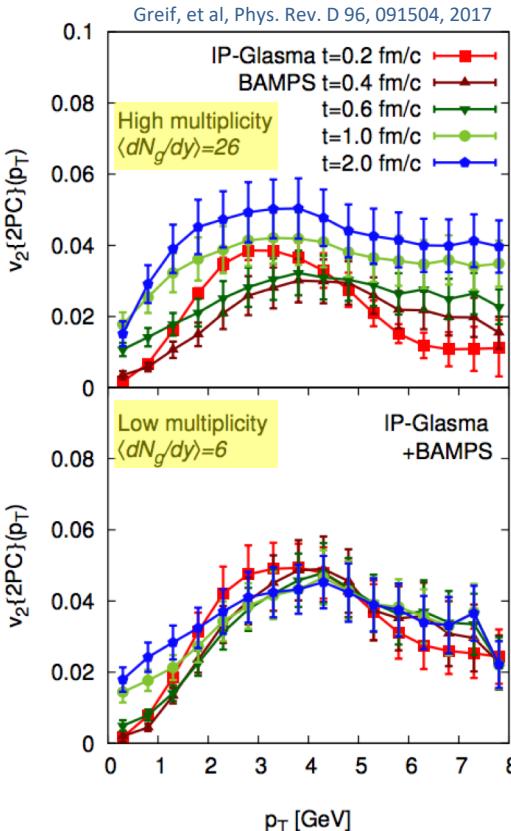


- ISC reproduce particle mass dependence of $\langle p_T \rangle$ and $v_2(p_T)$
- Gluons are fragmented into hadrons using the PYTHIA's Lund string fragmentation

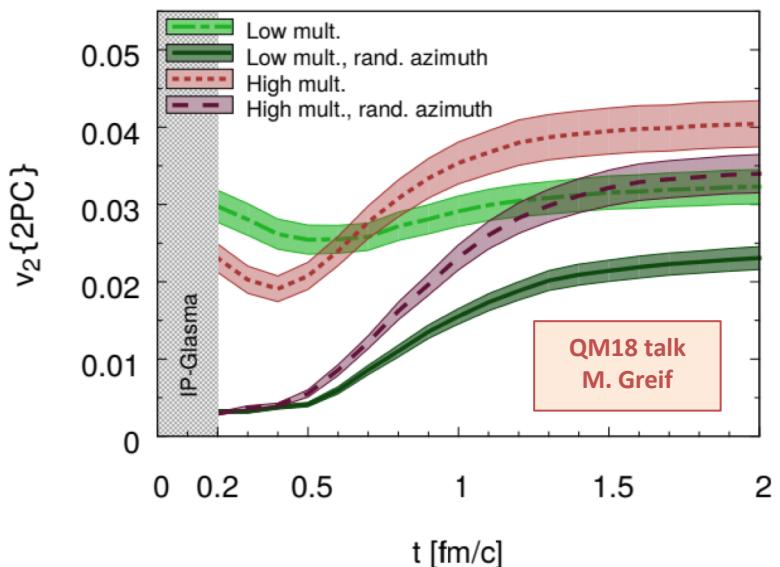
QM18 talk
P. Tribedy

Putting the pieces together

Putting the pieces together: IP-Glasma + BAMPS



- How large are ISC in a realistic simulations and to what extent do they survive subsequent final state interactions?
- Greif et al sampled IP-Glasma correlated gluons as the initial condition for the BAMPS parton cascade code.

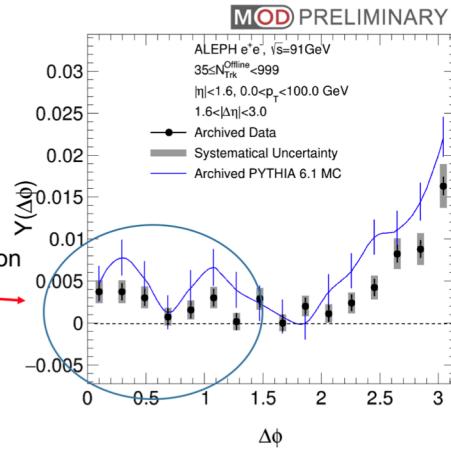
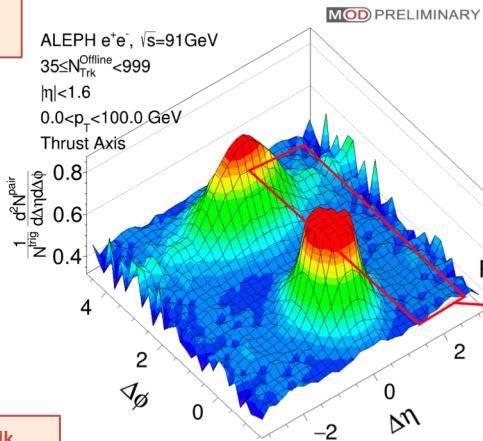


- Low multiplicity: ISC survive with only small modifications
- High multiplicity: final state interactions dominate
- 15% modification at high multiplicity
- Answer depends on momentum

Even smaller systems!

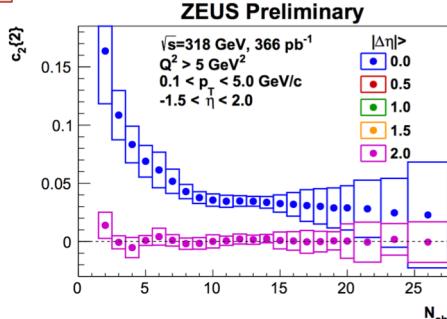
Azimuthal correlations in even smaller systems?

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Y.-J. Lee

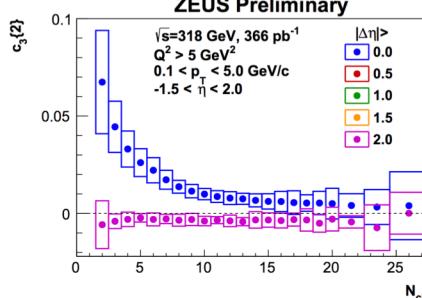


$e^+ + e^-$

QM18 talk
J. Onderwaater



$|\Delta\eta| > 2.0: c_2\{2\}$ consistent with zero.



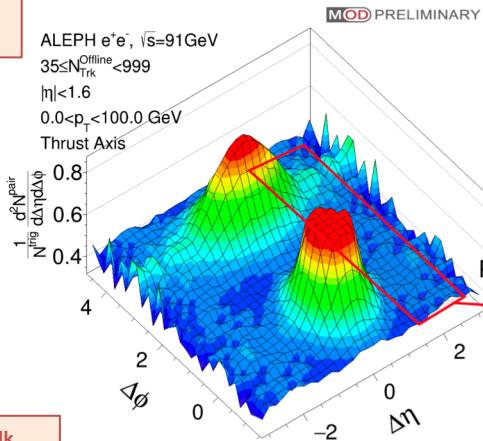
$c_3\{2\}$ and $c_4\{2\}$ are consistent with zero.

- No ridge found in $e^+ + e^-$ collisions! (ALEPH)
- Results well-explained by Pythia 6.1 without final state interactions
- $e^- + p$ collisions? (ZEUS)
- $c_{2,3,4}\{2\}$ consistent with zero.
- Results consistent with existing MC generators (Arriande and/or Lepto)
- Existential problem for ISC?

Azimuthal correlations in even smaller systems?

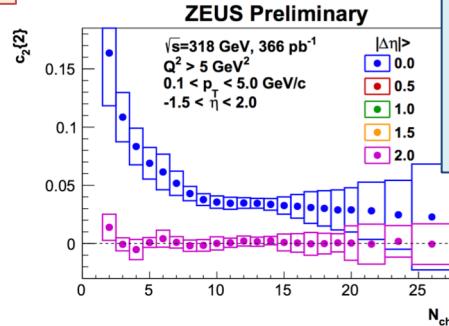
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e^+e^-

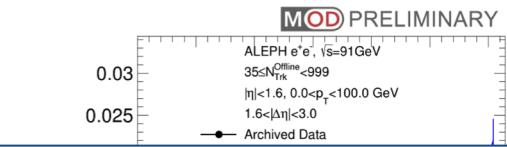


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$p + e$



$|\Delta\eta| > 2.0: c_2\{2\}$ consistent with zero.



- Does $|\Delta\eta| > 2$ push you in the BFKL ladder regime which decorrelates the gluons (Mueller-Navelet jets)?
- If this is the explanation why are the correlations not also killed in $p+p$ or $p+A$?

$c_3\{2\}$ and $c_4\{2\}$ are consistent with zero.

- No ridge found in e^+e^- collisions! (ALEPH)

Results well-explained by Pythia 6.1 without final state interactions

p collisions? (ZEUS)

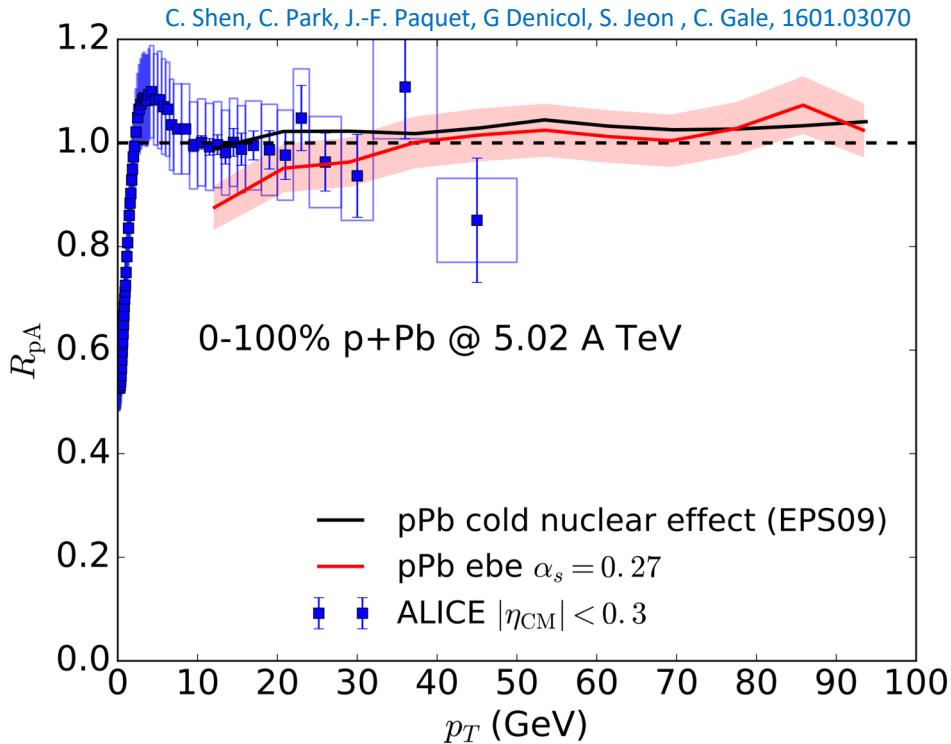
$c_2\{2\}$ consistent with zero.

Results consistent with existing MC generators (Arriande and/or Lepto)

- Existential problem for ISC?

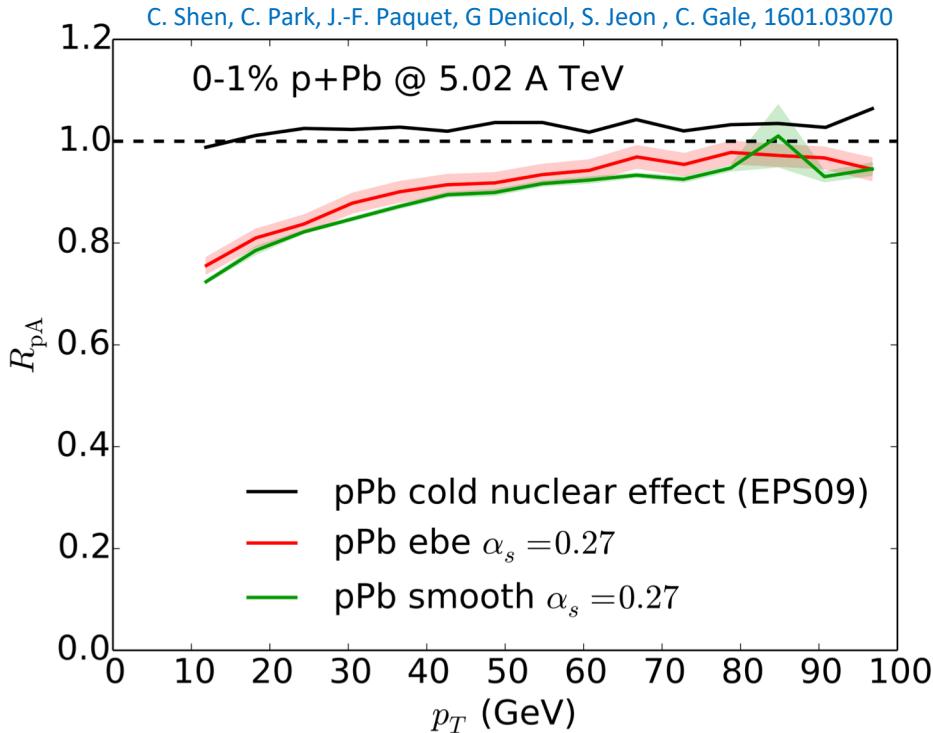
Hard probes

Jet quenching



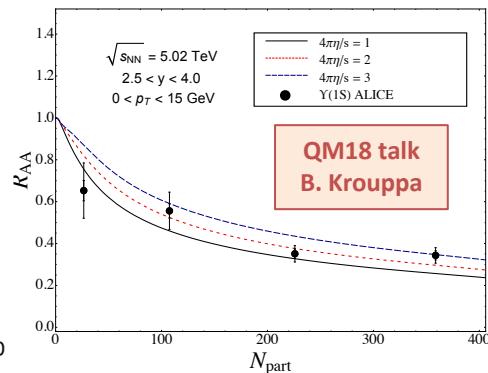
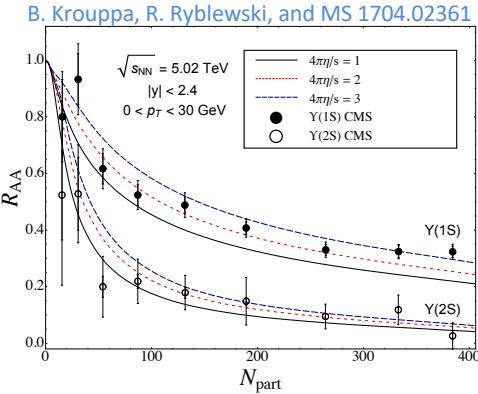
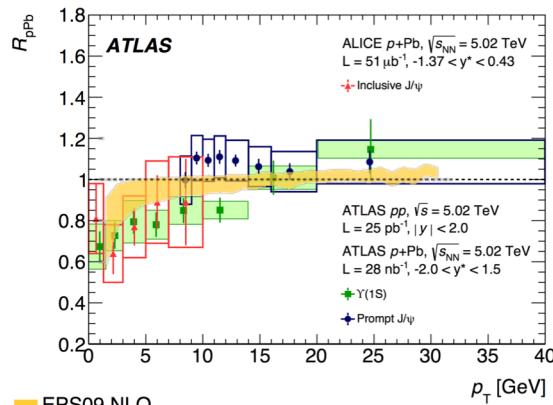
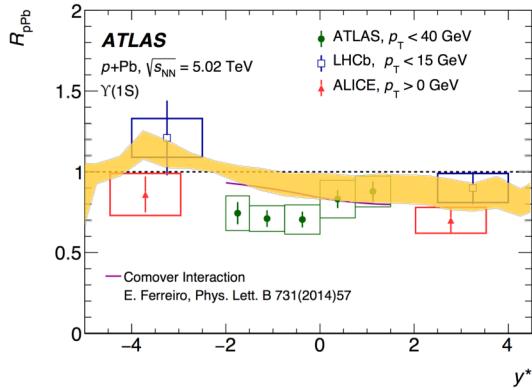
- Min-bias R_{pA} shows no signs of significant jet suppression
- Very different from what is seen in AA collisions.
- However, if one selects high multiplicity event (0-1%), then a sizable R_{pA} is predicted at 10 GeV.
- Suggestive of a small and short-lived QGP and seems to be consistent with measurements (p-Pb and peripheral Pb-Pb)

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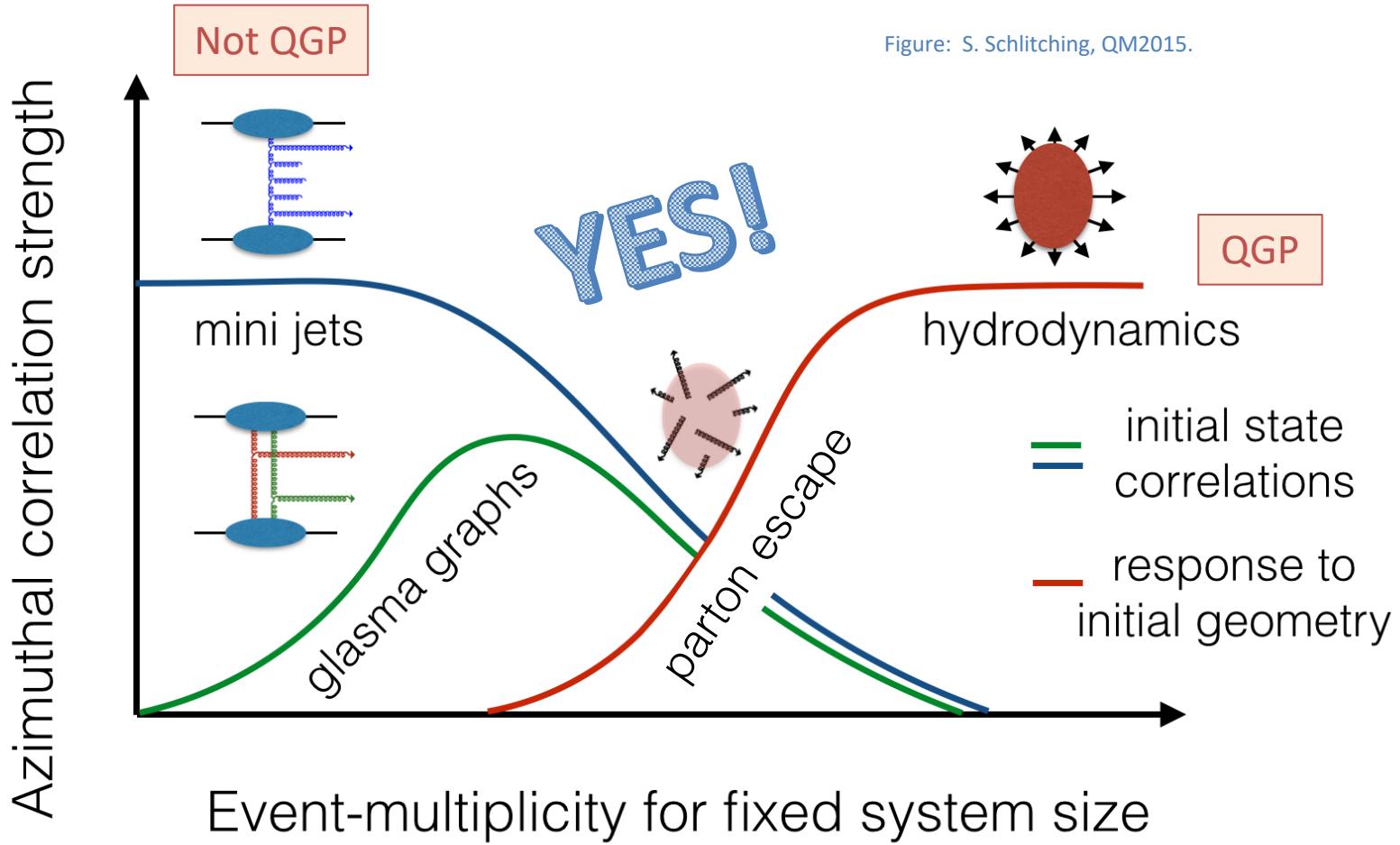
Heavy quarkonium production



- At the highest LHC energies a significant suppression of Υ 's is seen in Pb-Pb collisions.
 $R_{AA}(\Upsilon_{1S}) \sim 0.35$
- A much weaker suppression is seen in p-Pb collisions.
- Within error bars, the suppression ~ 0.7 - 0.8 @ avg p_T .
- A similar magnitude CNM effect is seen on low-momentum J/ψ 's; can be reduced by a low momentum cut $p_T > 5$ GeV.

CONCLUSIONS

**BASIC QUESTION:
CAN WE TURN THE QGP OFF?**



More conclusions

- More theory work needed on far-from-equilibrium extensions of dissipative hydrodynamics for both dynamical evolution and freezeout.
- Initial studies have been performed to assess the relative impact of the different mechanisms in a unified picture; more work is needed.
- For min-bias, jet quenching and bottomonium suppression are clear smoking guns for QGP creation (on/off).
- It would be interesting indeed to see data for “central events” in small systems; very hard because of limited statistics but we saw results here for jet quenching which are consistent with hydro expectations.

We're hiring a nuclear experimentalist!



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