Soft-Hard Event Engineering (SHEE) at RHIC and LHC

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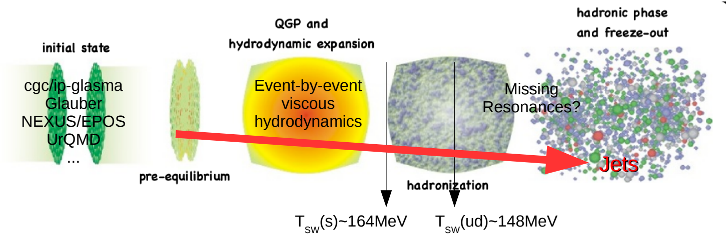
Outline

Current understanding of heavy-ion collisions

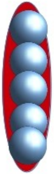


- Event-by-event calculations needed for soft physics (low p_T)
- Statistical analysis techniques developed to understand the large number of events
- Hard physics (highp_T) affected by initial conditions, the medium, and the energy loss model
- Can soft physics techniques be applied to hard physics?

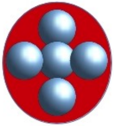
Same density (centrality), different shapes

Centrality bins by the density, but for the same density..

“**Event-by-Event**” Holding the number of partons (density) constant for the same types of collisions, different shapes can be formed.



For the same 5 participants



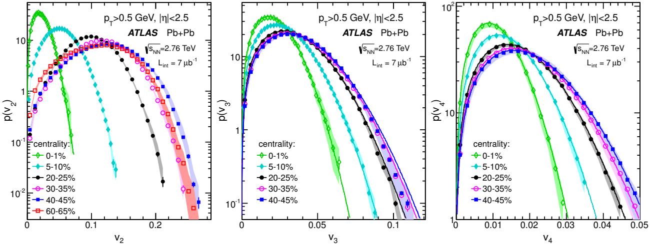
Ellipsoid= Large eccentricity (ε_2)

Circle= Small eccentricity (ε_2)

Triangles, squares etc can even appear...

Elliptical flow distributions

Event-by-event calculations are necessary to describe the v_n distributions

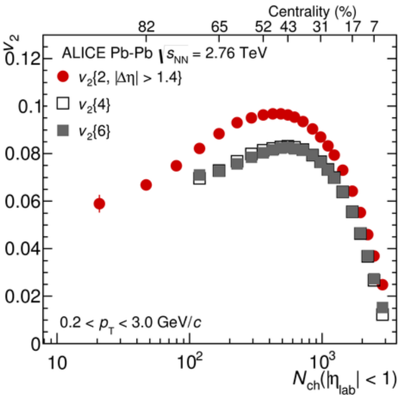


From [Atlas] JHEP **1311**, 183 (2013) [arXiv:1305.2942 [hep-ex]]

v_n distributions place a new constraint on initial conditions

Cumulants calculate the moments of the distributions

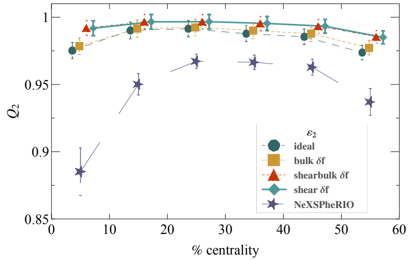
- $v_n\{2\} \equiv \sqrt{\langle v_n^2 \rangle} > \langle v_n \rangle$
- $v_n\{4\} \equiv \left(2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle\right)^{0.25}$
- Higher order cumulants converge $\rightarrow$ sign of collective behavior!
- Higher order cumulants eliminate non-flow effects



[ALICE] Phys. Rev. C 90 (2014) 054901

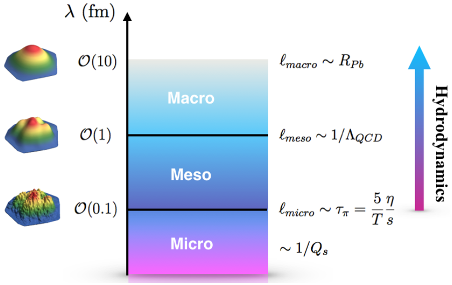
Shape, not small scale fluctuations→ flow harmonics

Eccentricities drive the final flow harmonics



Gardim et al, PRC85(2012)024908,
Gardim,JNH,Luzum,Grassi PRC91(2015)3,034902

Smoothing scale (λ) probes energy scales

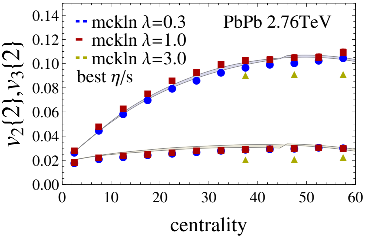


JNH, Noronha, Gylassy, Phys.Rev. C93 (2016) 2, 024909

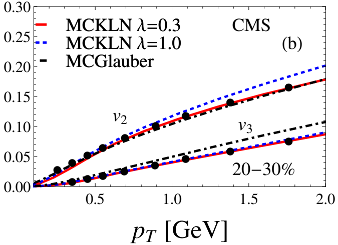
However, λ has almost no effect on the flow harmonics (PbPb)

SHEE=Soft Hard Event Engineering

Use the best fit hydro models for low p_T



JNH to appear shortly (other cumulants also fit well)



JNH, Betz, Noronha and M. Gyulassy, arXiv:1602.03788 [nucl-th].

- mckln (fluctuations smoothed out to $\lambda = 0.3$ fm): $\eta/s = 0.11$
- mckln (fluctuations smoothed out to $\lambda = 1$ fm): $\eta/s = 0.1128$
- mcglauber: $\eta/s = 0.08$

Model: event-by-event v-USPhydro+energy loss

Full Hydro in v-USPhydro [1] into BBMG energy loss model [2]:

$$\frac{dE}{dL} = -\kappa\, E^a(L)\, L^z\, T^c\, \zeta_q\, \Gamma_{\text{flow}}$$

- κ is the jet-medium coupling
- T is the local temperature along the jet trajectory
  $c = 2 + z - a$
- ζ_q describes energy loss fluctuations
- $\Gamma_{\text{flow}} = \Gamma_{\text{f}} = \gamma\left[1 - v\cos\left(\phi_{\text{jet}} - \phi_{\text{flow}}\right)\right]$ is the flow factor defined using the local flow velocities of the medium

[1] JNH et al, PRC88 (2013) 044916 ; PRC90 (2014) 3, 034907
[2] Betz, Gyulassy and Torrieri,PRC 84, 024913 (2011); B. Betz and M. Gyulassy, PRC 86, 024903 (2012) ; JHEP 1408, 090 (2014)

Wasn't this done already?

No.

Here's what people have looked at already:

- Fluctuating initial conditions but not full hydrodynamics temperature profiles
  Zhang,Liao Phys.Rev. C87 (2013) 044910
- Smoothed hydrodynamical/parton cascade/URQMD backgrounds (many groups)
- Jets effects (as a source term) on soft physics
  Andrade, Noronha, and Denicol PRC90 (2014) 2, 024914 ; Pang et al PRC86 (2012) 024911

Correlated *vn* calculation

Experimentally, high and low particles are correlated to calculate the flow.
Theoretically, high p_T flow harmonic are calculated via:

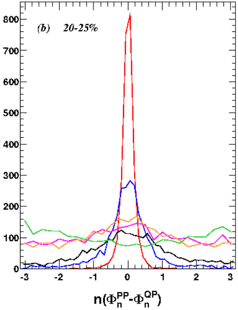
$$v_n^{\mathrm{high}}(p_T \gtrsim 10\,\mathrm{GeV}) = \frac{\langle v_n^s\, v_n(p_T) \cos\left[n\left(\psi_n^s - \psi_n(p_T)\right)\right]\rangle}{\sqrt{\langle (v_n^s)^2\rangle}}, \quad (1)$$

where the soft flow harmonic is v_n^s and the high p_T flow harmonic is $v_n(p_T)$
$v_n^{\mathrm{high}}(p_T \gtrsim 10\,\mathrm{GeV})$ is largest when the jet angle is aligned with the low p_T event plane angle

Correlated event plane angles

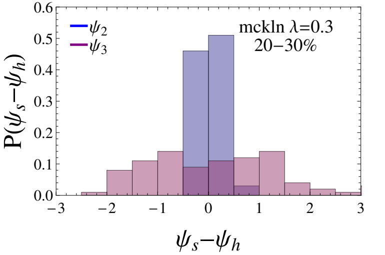
Elliptical flow angle highly correlated between soft and hard physics, triangular flow angle is not

Experiment



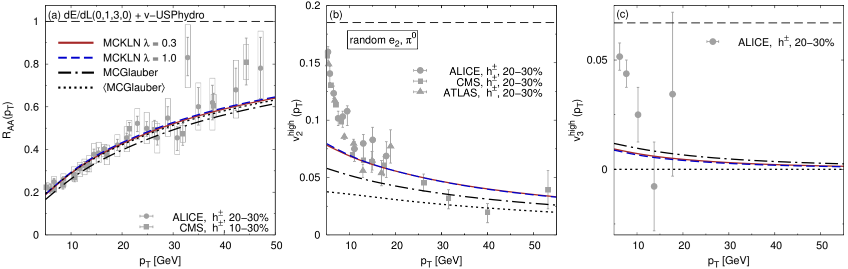
Jia PRC**87**,no. 6,061901(2013)

Theory



JNH, Betz, Noronha, Gyulassy, arXiv:1602.03788 [nucl-th]

Results: R_{AA}, v_2, and v_3

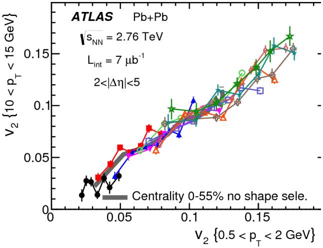


JNH, Betz, Noronha, Gyulassy, arXiv:1602.03788 [nucl-th]

- mckln provides the best fit at both low and high p_T
- R_{AA} not as sensitive as v_n's to eccentricities/event-by-event calculations
- v_2 is more sensitive to the initial conditions due to the correlated high/low angles. First calculation of high p_T v_3.

Results: v_2 low-high correlations

Experiment



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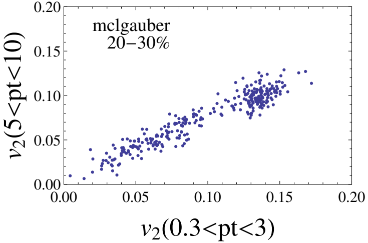


JNH, Betz, Noronha, Gyulassy, to appear shortly

- Clear correlation between high and low v_2
- Note differences in pt bins (only qualitative comparison)

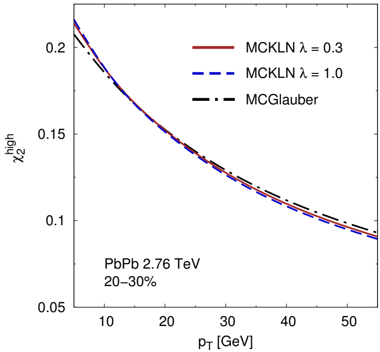
Assuming linear response..

Then $v_n^s \approx c\,\varepsilon_n$, $v_n \approx \chi_n(p_T)\,\varepsilon_n$, and $n\,(\psi_n^s - \psi_n(p_T)) \approx 0$

$$
\begin{aligned}
v_n^{\text{high}}(p_T \gtrsim 10\,\text{GeV}) &= \frac{\langle v_n^s\, v_n(p_T) \cos\left[n\,(\psi_n^s - \psi_n(p_T))\right]\rangle}{\sqrt{\langle (v_n^s)^2\rangle}} \\
v_n^{\text{high}}(p_T \gtrsim 10\,\text{GeV}) &\approx \frac{c\chi_n(p_T)\langle\varepsilon_n^2\rangle}{c\sqrt{\langle\varepsilon_n^2\rangle}} \\
&\approx \chi_n(p_T)\sqrt{\langle\varepsilon_n^2\rangle}
\end{aligned}
$$

Energy loss susceptibility

$\chi_n(p_T) = v_n^{\mathrm{high}} / \sqrt{\langle \varepsilon_n^2 \rangle}$

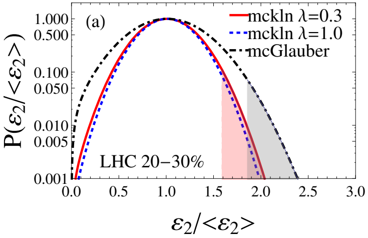


- For current energy loss set-up linear response holds
- Slight differences most likely due to differences in η/s
- Independent of the initial conditions

Event Shape Engineering

Picking events out of the low p_T v_2 distribution ($\frac{v_2}{\langle v_2 \rangle}$)

- ebe Random ε_2: random ε_2 within the same centrality class
- ebe top 1% ε_2: top 1% of ε_2 within the centrality class (shaded)

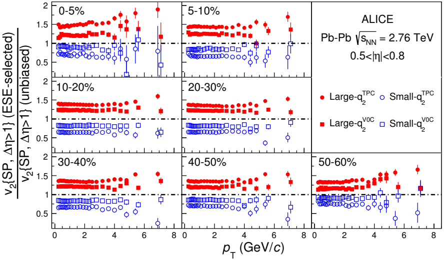


JNH, Betz, Noronha, Gyulassy, arXiv:1602.03788 [nucl-th]

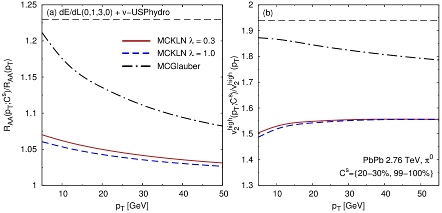
Smaller scale fluctuations lead to slightly wider distributions (10% effect)

Event Shape Engineering

$v_2^{\text{high}}(p_T;\mathcal{C}^s)/v_2^{\text{high}}(p_T)$



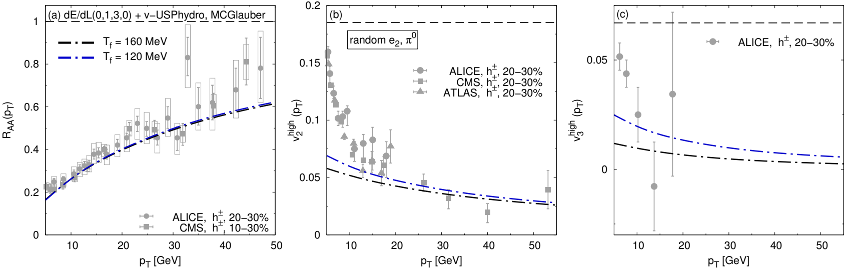
[ALICE] arXiv:1507.06194 [nucl-ex].



JNH, Betz, Noronha, Gyulassy, arXiv:1602.03788 [nucl-th]

- Differences in initial conditions are more pronounced
- R_{AA} slight dependence on the smoothing scale
- Effect of Glauber's wider distribution very clear at high p_T

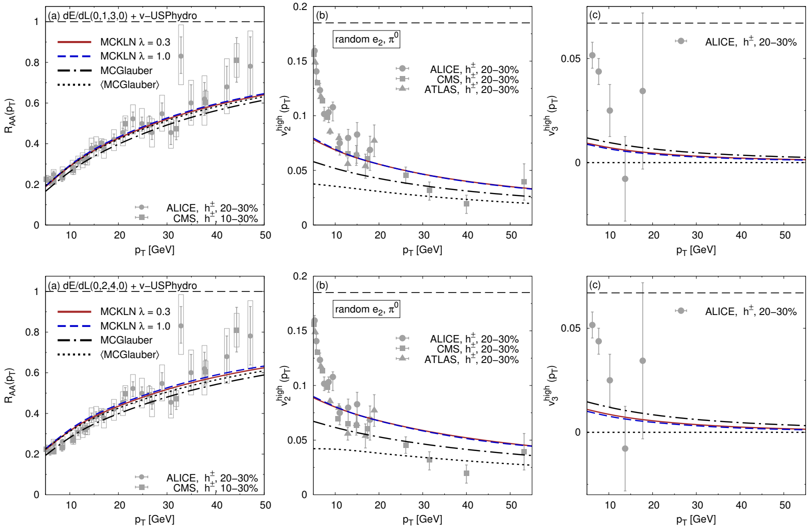
Freeze-out temperature



JNH, Betz, Noronha, Gyulassy, to appear shortly

- Decreasing the freeze-out Temperature allows more time to build up flow

Path Length Dependence (linear vs. squared)



JNH, Betz, Noronha, Gyulassy, to appear shortly

My experimental wish list

- Percentages of events (compared to all events) triggered on that which produce high p_T jets
- Comparison of v_n distributions and cumulants in the low p_T region of events that produce jets
- Event shape engineering extended up to higher p_T ranges
- Cumulants at high p_T??
- Improved statistics on v_3 of high p_T
- v_n's of π_0

My theoretical wish list

- Full integration of jets into hydrodynamics (jets included in the equations of motion with energy loss calculations as well)
- More statistics, centralities, energies, systems sizes (pPb) etc
- Full analysis of effects of hydrodynamic parameters (shear + bulk viscosity, Equation of State)
- Mapping of eccentricities onto high p_T flow harmonics
- Flavor dependence
- Variation in the energy loss model
- Beam Energy Scan

Conclusions

- Soft-hard Event Engineering (SHEE) reproduces both R_{AA} as well as high p_T v_2
- First theoretical calculation of high p_T v_3 (only possible with event-by-event calculations)
- ψ_2 high/low more strongly correlated than ψ_3
- Indications of linear response at v_n^{high}
- Event-shape-engineering shows clear differences between initial state models