Event-by-event hydrodynamics + jet energy loss: A solution to the $R_{AA} \times v_2$ puzzle

JORGE NORONHA

University of São Paulo

arXiv:1602.03788 [nucl-th] Phys. Rev. Lett. 116, 252301 (2016)

in collaboration with **J. Noronha-Hostler,** M. Gyulassy, B. Betz

Hot Quarks 2016, South Padre Island, TX, USA

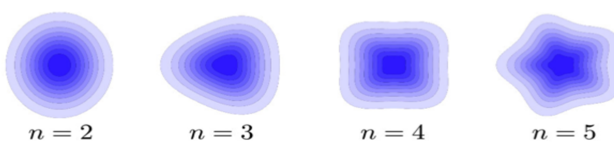
QGP

Lattice QCD ??? ???

Perfect fluidity: an emerging property of QCD

Behavior consistent with a strongly interacting fluid !!!

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + \sum_n 2v_n \cos\left[n\left(\phi - \psi_n\right)\right]\right]$$

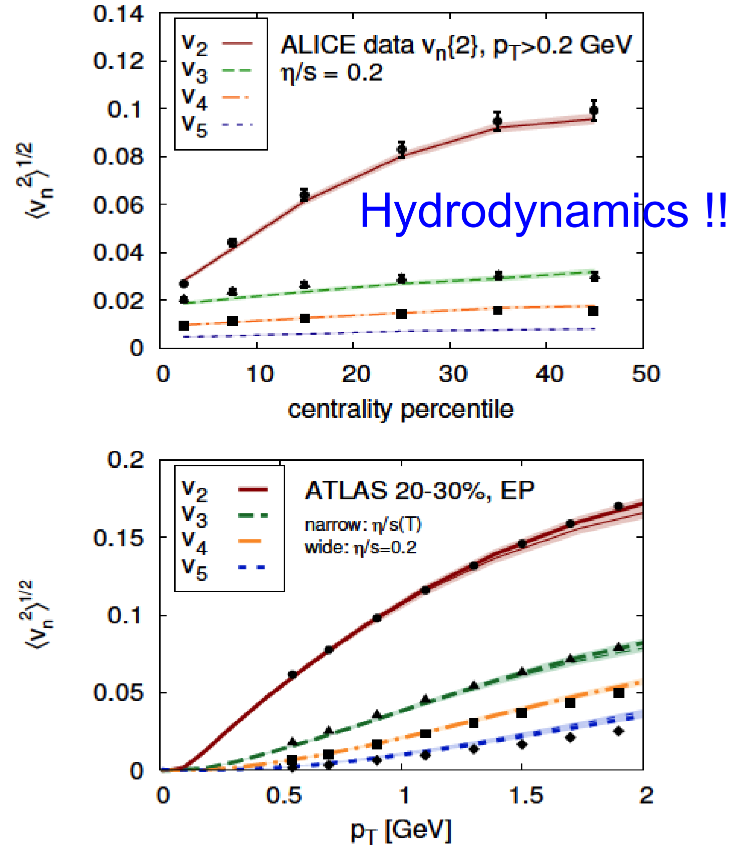


QGP as the world's “smallest fluid”

QGP is a strongly interacting relativistic fluid

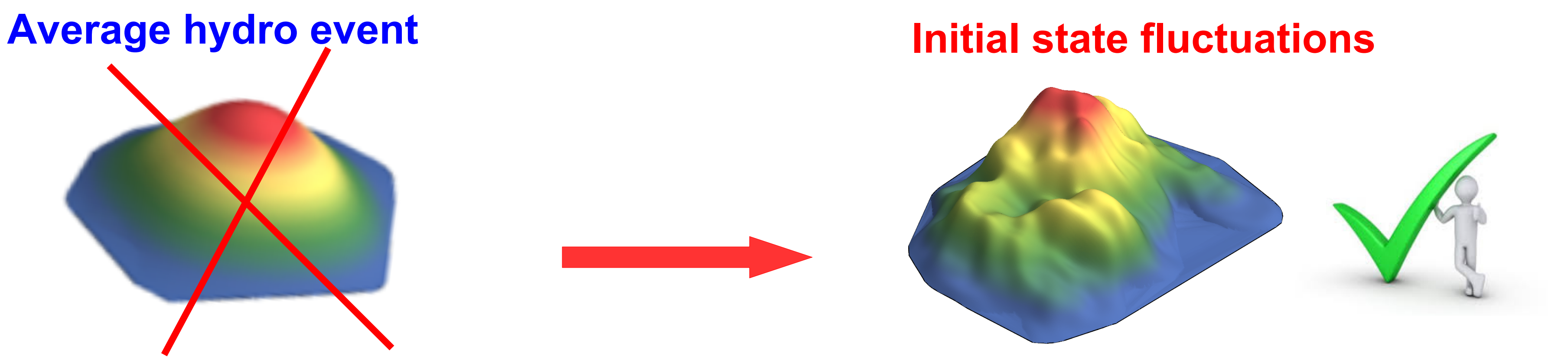
$$\eta/s \lesssim 0.2$$

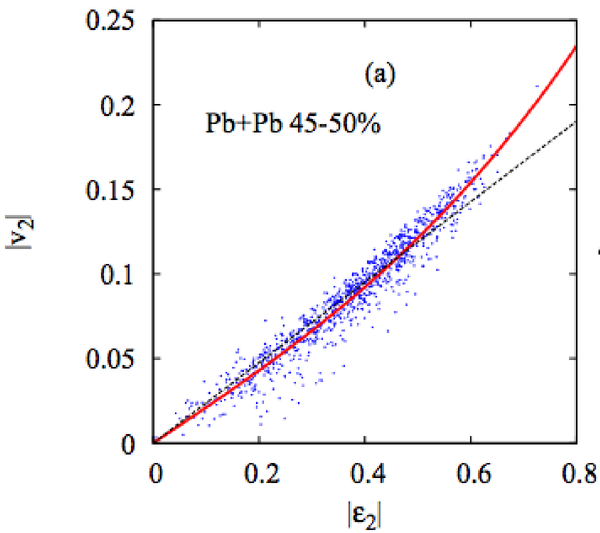
2.76 TeV, Pb+Pb at LHC



Gale et al, PRL 110, 012302 (2013)

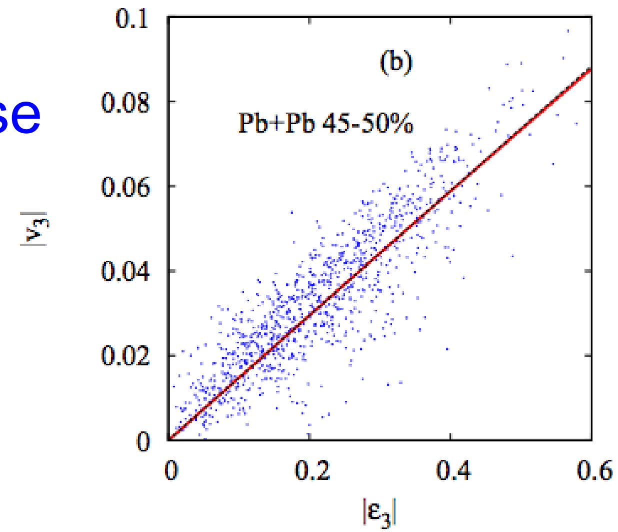
Event-by-event viscous hydrodynamics





Linear + cubic response

$$v_n = \kappa_n \varepsilon_n + \kappa'_n |\varepsilon_n|^2 \varepsilon_n$$



See, for instance, J. Noronha-Hostler et al., PRC 93, 014909 (2016)

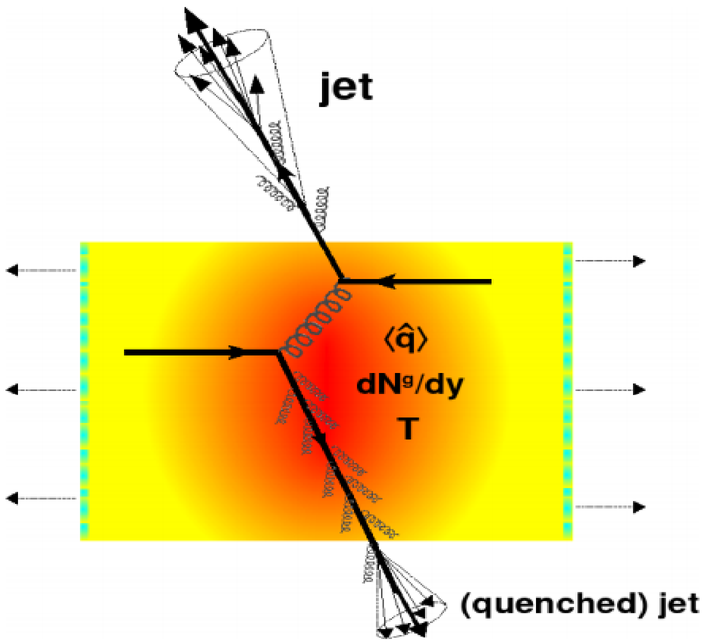
QGP

Lattice QCD **Anisotropic f bw** **???**

Jet Quenching

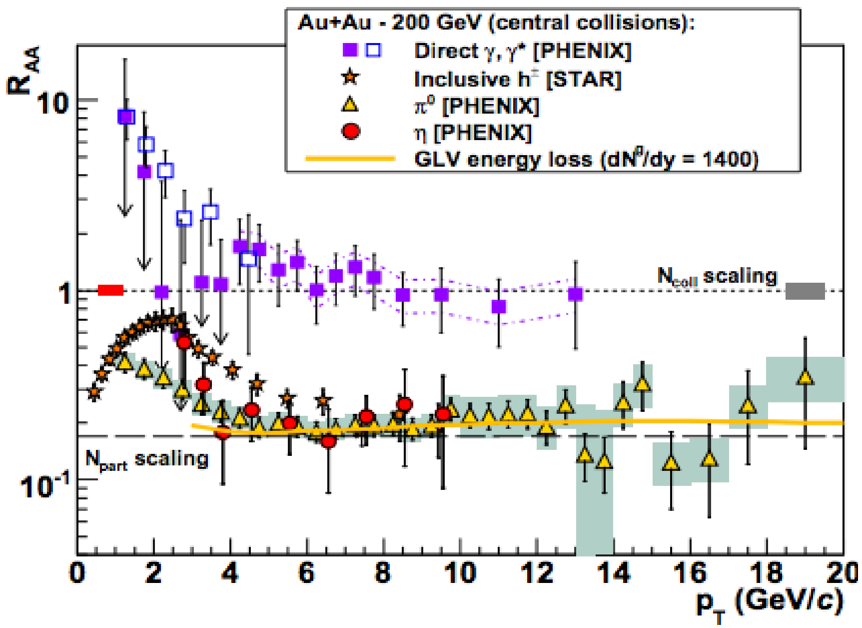
Nuclear modification factor

$$R_{AA}(p_T, y; b) = \frac{d^2N_{AA}/dydp_T}{\langle T_{AA}(b)\rangle \times d^2\sigma_{pp}/dydp_T}$$



D. d'Enterria, Nucl.Phys. A827 (2009)

Signature of QGP formation

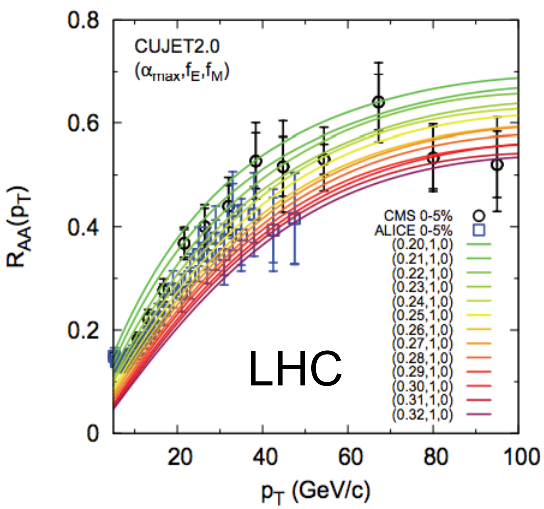


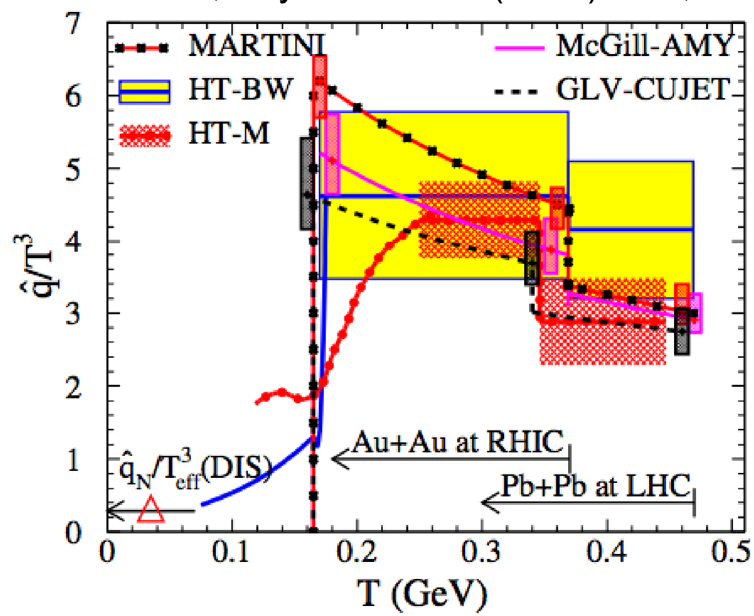
Jet quenching parameter $\hat{q}$

Better control of theory parameters through the JET collaboration

R_{AA} can be well described

Burke et al., Phys.Rev. C90 (2014) no.1, 014909





$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \;\; \text{at} \;\; \begin{matrix} T{=}370 \text{ MeV} \\ T{=}470 \text{ MeV} \end{matrix}$$

Peak near phase transition

QGP

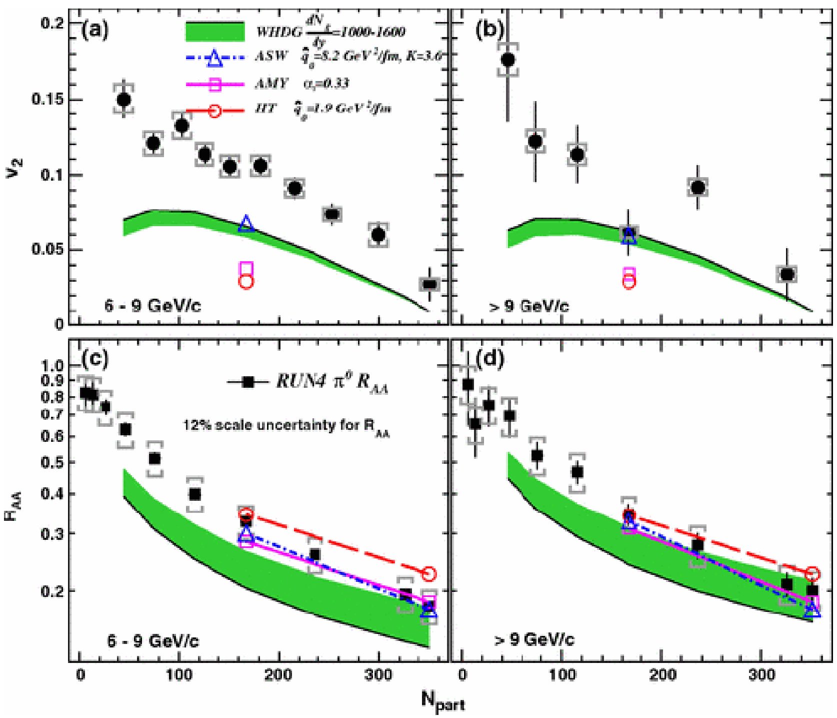
Lattice QCD **Anisotropic f bw** **Jet quenching**

All seemed fine … BUT WAIT !!!!

$R_{AA} \times v_2$: A decade long puzzle

Puzzle: $R_{AA} \times v_2$ at high pT not described simultaneously

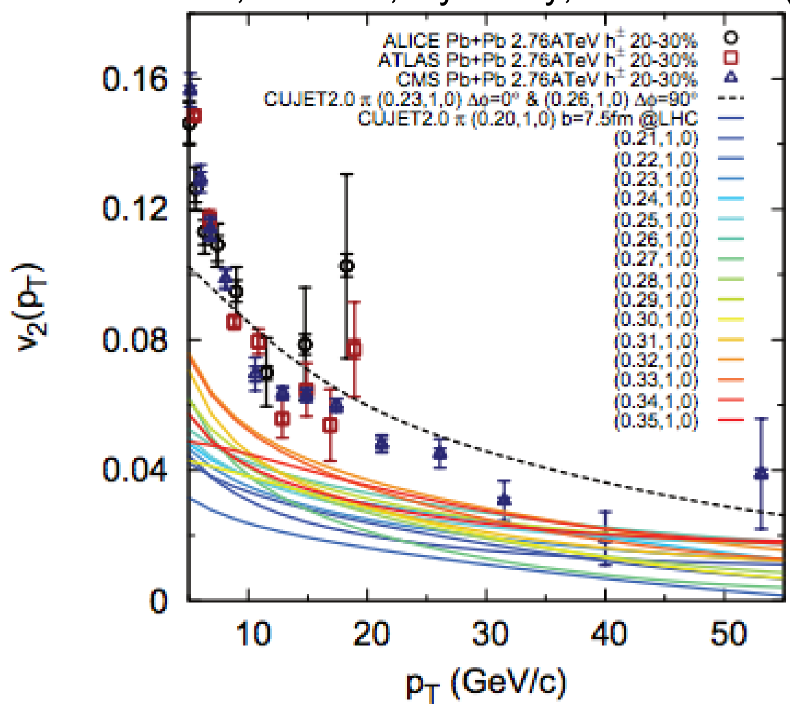
RHIC



[PHENIX] Phys. Rev. Lett. 105, 142301

LHC

See Xu, Buzzatti, Gyulassy, JHEP 1408 (2014) 063

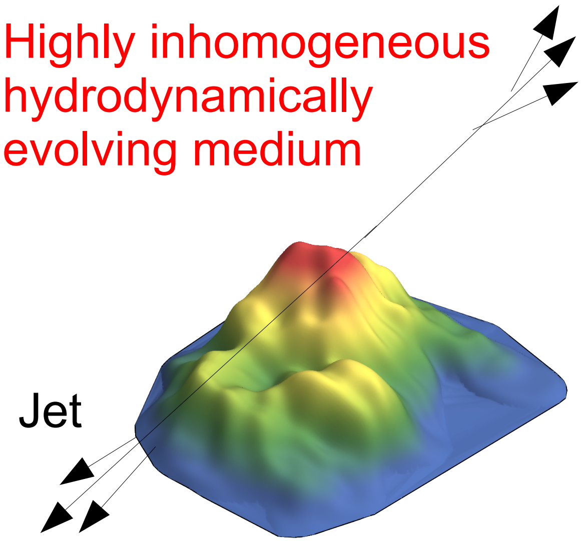


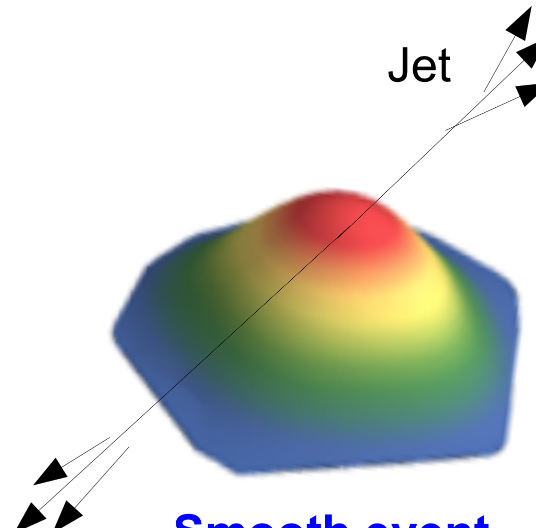
\+ many other papers

Previous model calculations did not produce enough high pT v2

In Phys. Rev. Lett. 116, 252301 (2016) we showed that the main problem was

Highly inhomogeneous hydrodynamically evolving medium





Smooth event

Previous model calculations did not use <u>event-by-event hydrodynamics</u>

Previous calculations compared (mostly driven by energy loss)

$$v_n^{hard}(p_T) = \frac{\frac{1}{2\pi}\int_0^{2\pi} d\phi \, \cos\left[n\phi - n\psi_n^{hard}(p_T)\right] \, R_{AA}(p_T,\phi)}{R_{AA}(p_T)}$$

$$\psi_n^{hard}(p_T) = \frac{1}{n}\tan^{-1}\left(\frac{\int_0^{2\pi} d\phi \, \sin(n\phi) \, R_{AA}(p_T,\phi)}{\int_0^{2\pi} d\phi \, \cos(n\phi) \, R_{AA}(p_T,\phi)}\right).$$

directly to data (using a smooth hydro event)

We computed, for the first time, the soft-hard correlation $v_2\{2\}(p_T)$

$$v_2\{2\}(p_T) = \frac{\left\langle v_2^{soft} \, v_2^{hard}(p_T) \cos\left[2\left(\psi_2^{soft} - \psi_2^{hard}(p_T)\right]\right)\right\rangle}{v_2^{soft}\{2\}}$$

Event-by-event !!!

Without fluctuations

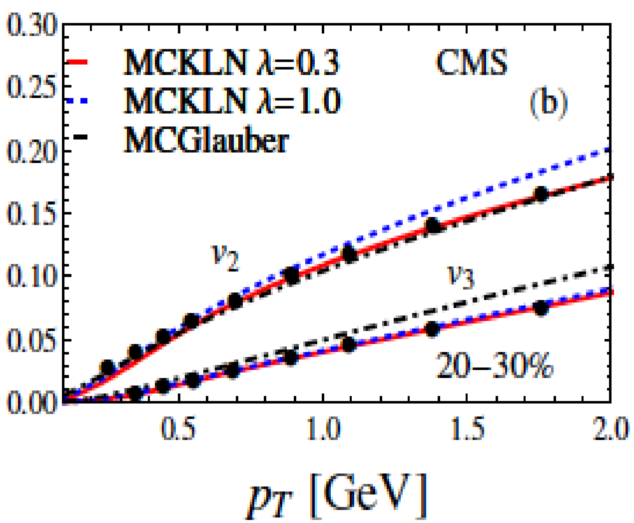
$$v_2\{2\}(p_T \gtrsim 10\,\mathrm{GeV}) \to v_2^{hard}(p_T)$$

Soft sector: Viscous hydrodynamic model

Event-by-event relativistic viscous hydrodynamical calculations*.

Parameters: $\tau_0 = 0.6$ fm, $T_{FO} = 120$ MeV

"Old" lattice EOS



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

*V-USPhydro Lagrangian code: J. Noronha-Hostler et al., PRC 88 (2013); PRC 90 (2014) 3, 034907

Hard sector: BBMG jet energy loss model

Betz, Gyulassy and Torrieri,PRC 84, 024913 (2011); B. Betz and M. Gyulassy, PRC 86, 024903 (2012) ; JHEP 1408, 090 (2014)

Full event-by-event viscous hydro + jet energy loss model

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

- 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
- $\Gamma_{\rm flow} = \Gamma_{\rm f} = \gamma\left[1 - v\cos\left(\phi_{\rm jet} - \phi_{\rm flow}\right)\right]$ is the flow factor defined using the local flow velocities of the medium

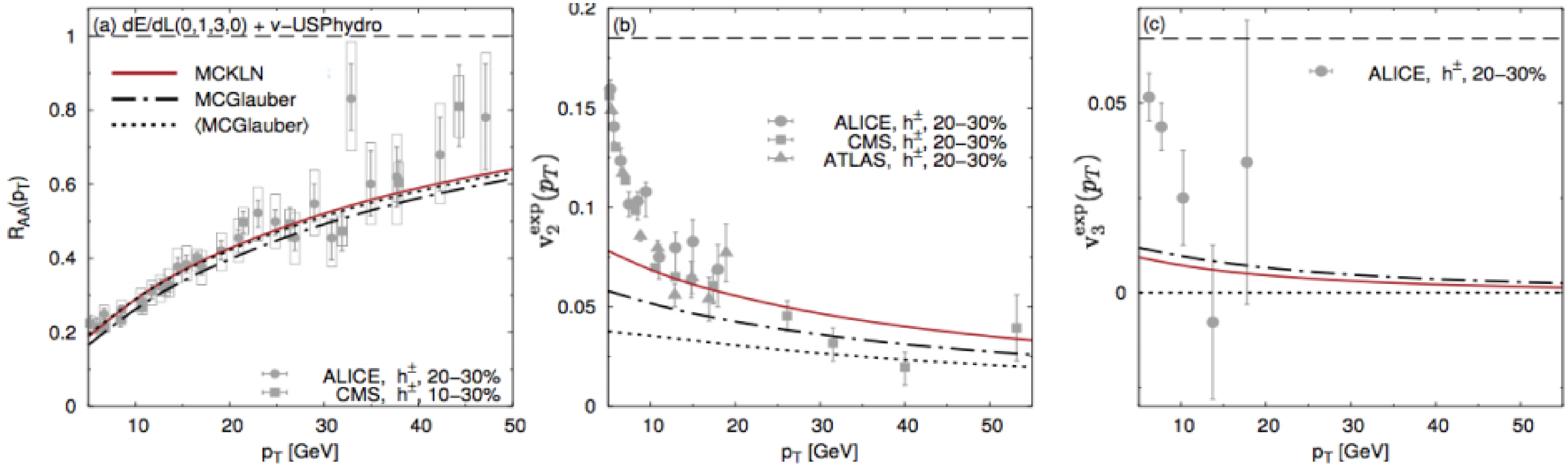
"pQCD" scenario (a=0, z=1, c=3, q=0) → $dE/dL \sim L$

Other energy loss models can be easily implemented

$R_{AA} \times v_2$ puzzle is solved (+ 1st calculation of v3)

arXiv:1602.03788 [nucl-th] PRL 116, 252301 (2016)

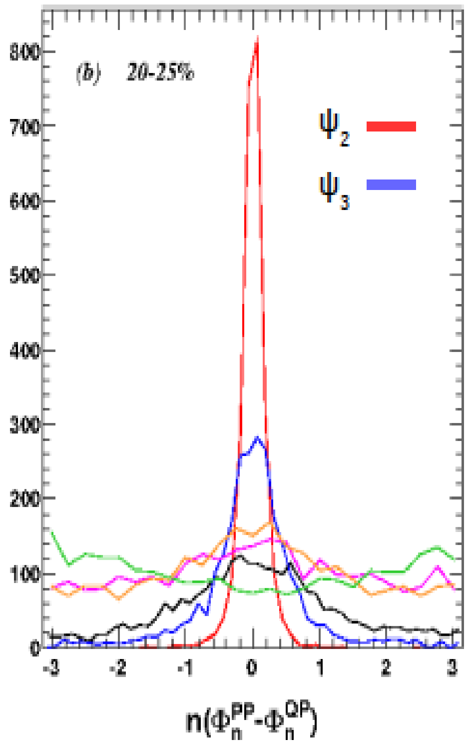
PbPb $\sqrt{s} = 2.76\,\mathrm{TeV}$



- **Consistent event-by-event hydro + jet energy loss gives enough v2 at high pT**
- Event-by-event hydrodynamics needed to generate triangular flow at high pT
- Harmonic flow at high pT strongly depend on the choice of initial conditions

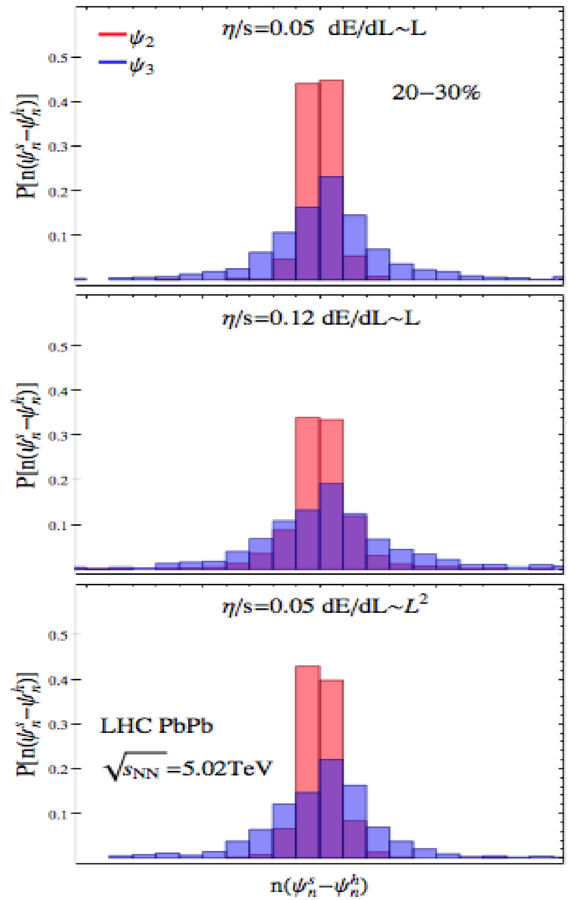
Soft-hard event plane correlation

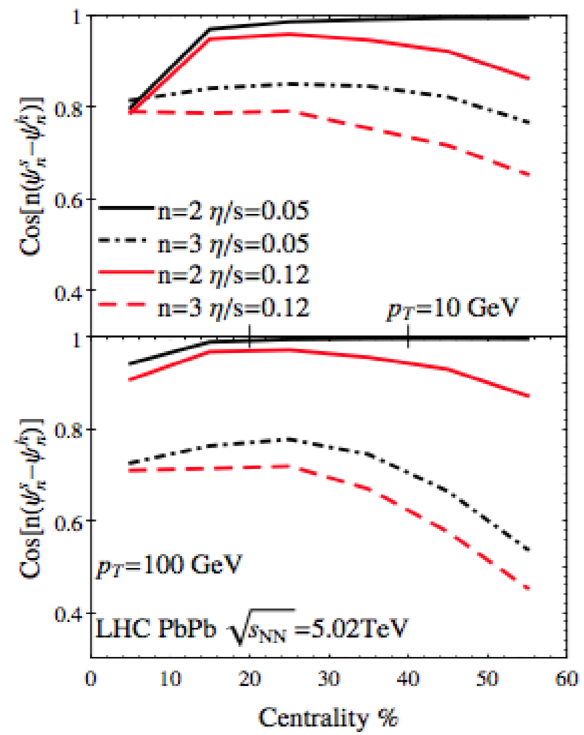
Expectation



Jia PRC87,no. 6,061901(2013)

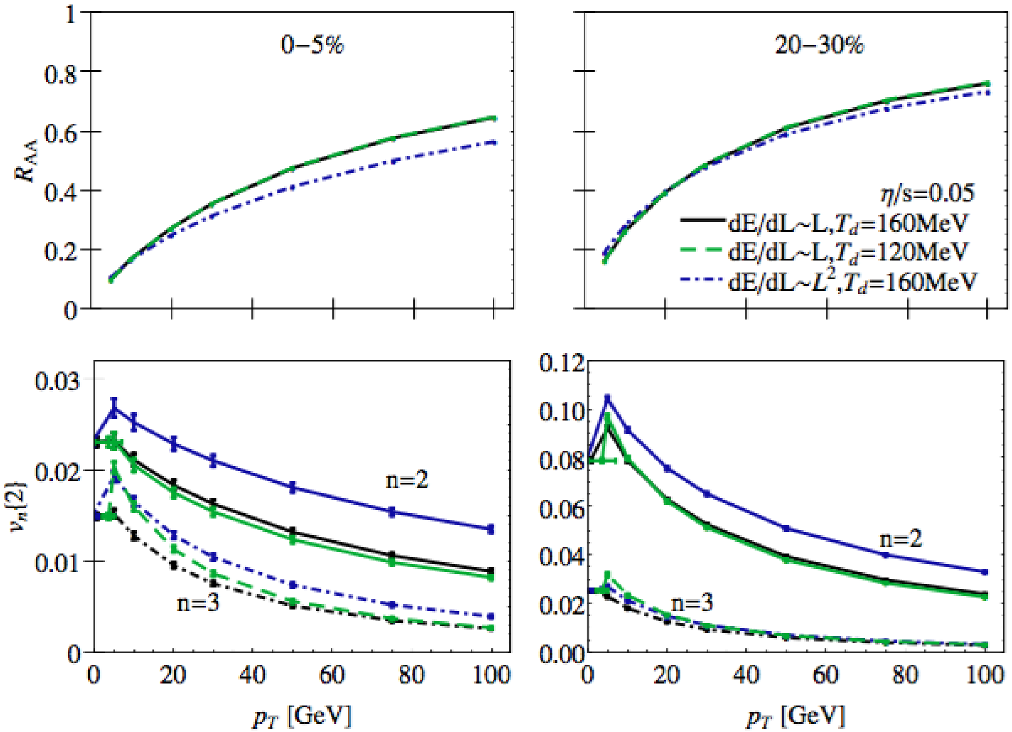
Our new PbPb results at $\sqrt{s} = 5.02\,\mathrm{TeV}$

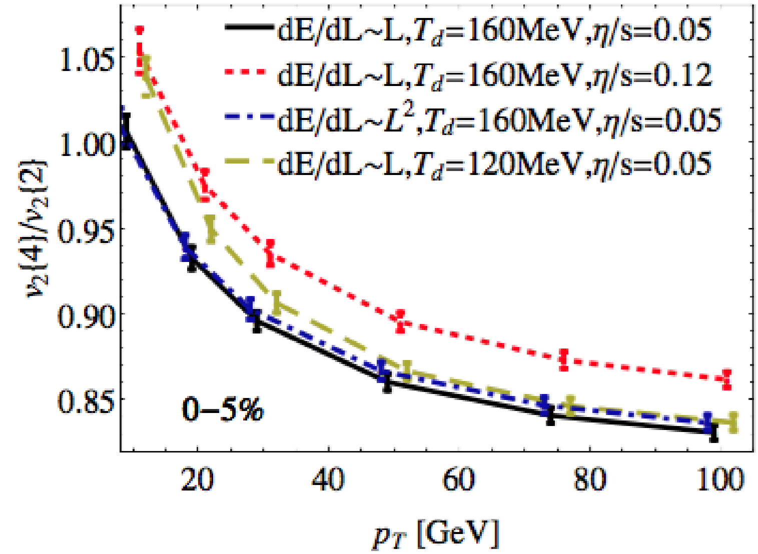




Elliptic flow angle = correlated
Triangular flow angle = poorly correlated

Predictions for LHC run 2





First calculation of 4-particle cumulant at high pT !!!!

Checked effects from:

- Path length and centrality dependence, viscosity, and decoupling temperature.

- LHC run 2 data should greatly constrain path length dependence of energy loss !!!

Conclusions

- All the previous calculations of v2 at high pT did not include event-by-event hydrodynamic effects.

- Event-by-event approach using viscous hydrodynamics + jet energy loss provides a natural solution for the R_AA x v2 puzzle.

- This approach produced the first theoretical calculation of high pT v3{2} and v2{4}. Predictions for LHC run 2 will be out soon!

- Soft and hard elliptic flow event planes are strongly correlated – not true for triangular flow.

- Theoretical calculations of high pT anisotropic flow require simultaneous description of both soft and hard sectors of heavy ion collisions.