One Fluid to Rule Them All

Hydrodynamics from Mid-Central p+p to Central Pb+Pb

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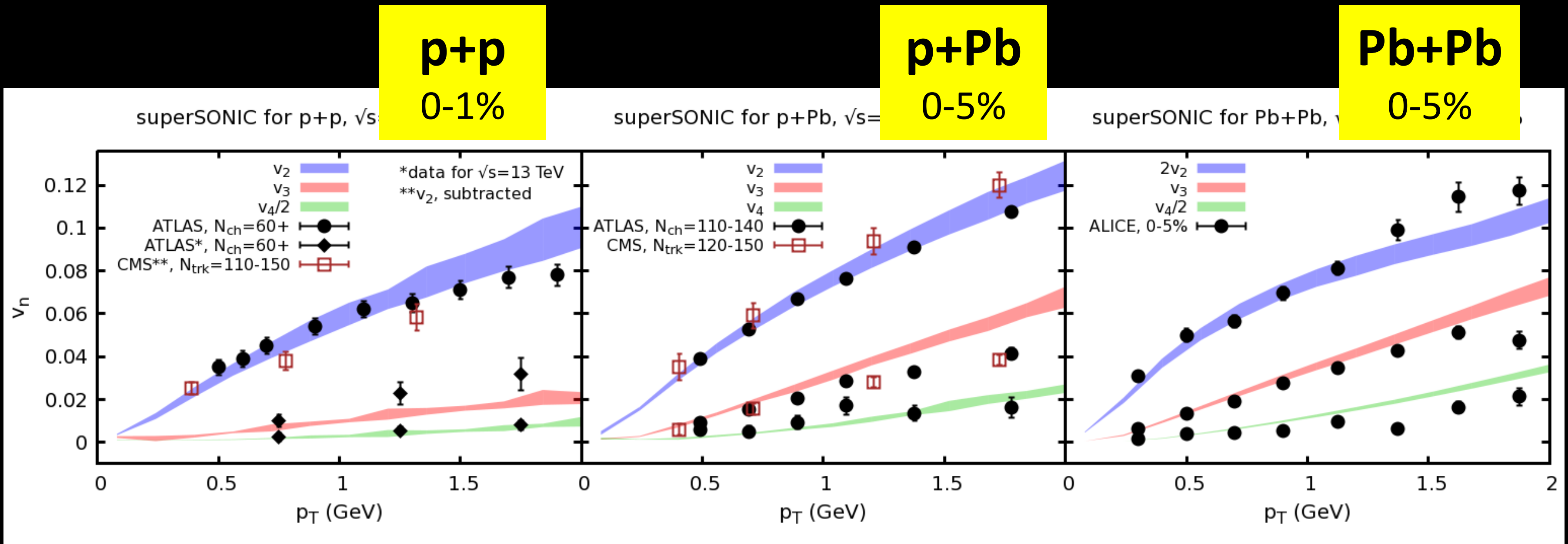
ONE FLUID TO RULE THEM ALL

Claim: Hydrodynamics can consistently describe the soft particle data in ALL hadronic collisions.

Evidence:



RW and Romatschke, 1701.07145

Hydrodynamic Gradient Expansion

Hydro is an effective field theory describing a system when

<u>system size</u> >> <u>scale of microscopic interactions</u>

i.e. the gradients are "small" and we can perform a gradient expansion:

$$T^{\mu\nu} = \underbrace{\epsilon u^\mu u^\nu + P\Delta^{\mu\nu}}_{\text{0th-order terms}} - \underbrace{\eta\nabla^{\langle\mu}u^{\nu\rangle} - \zeta\Delta^{\mu\nu}\nabla_\alpha u^\alpha}_{\text{1st-order terms}} - \underbrace{\tau_\pi\left({}^{\langle}D\pi^{\alpha\beta\rangle} + \frac{4}{3}\pi^{\mu\nu}\nabla_\alpha u^\alpha\right) + \cdots}_{\text{2nd- and higher-order terms}}$$

Breakdown of Hydrodynamics

Non-hydrodynamic modes signal breakdown of the gradient expansion as a good effective description

$$\delta T \sim \exp\left(-i(\omega t - \mathbf{k}\cdot\mathbf{x})\right), \quad \delta u^{\mu} \sim \exp\left(-i(\omega t - \mathbf{k}\cdot\mathbf{x})\right)$$

modes with $\lim_{\vec{\mathbf{k}}\to 0} \omega(\vec{\mathbf{k}}) = 0$ — hydro modes

$\lim_{\vec{\mathbf{k}}\to 0} \omega(\vec{\mathbf{k}}) \neq 0$ — non-hydro modes

Hydro modes have a universal structure

Non-hydro modes are specific to the microscopic theory at hand (e.g. QCD)

When Does Breakdown Happen?

In some effective/toy theories of hot QCD (AdS/CFT, kinetic theory), the hydro modes become subdominant to the non-hydro modes at length scales of around ~0.15 fm
[Romatschke, Eur. Phys. J. C 77, 21 (2017)]

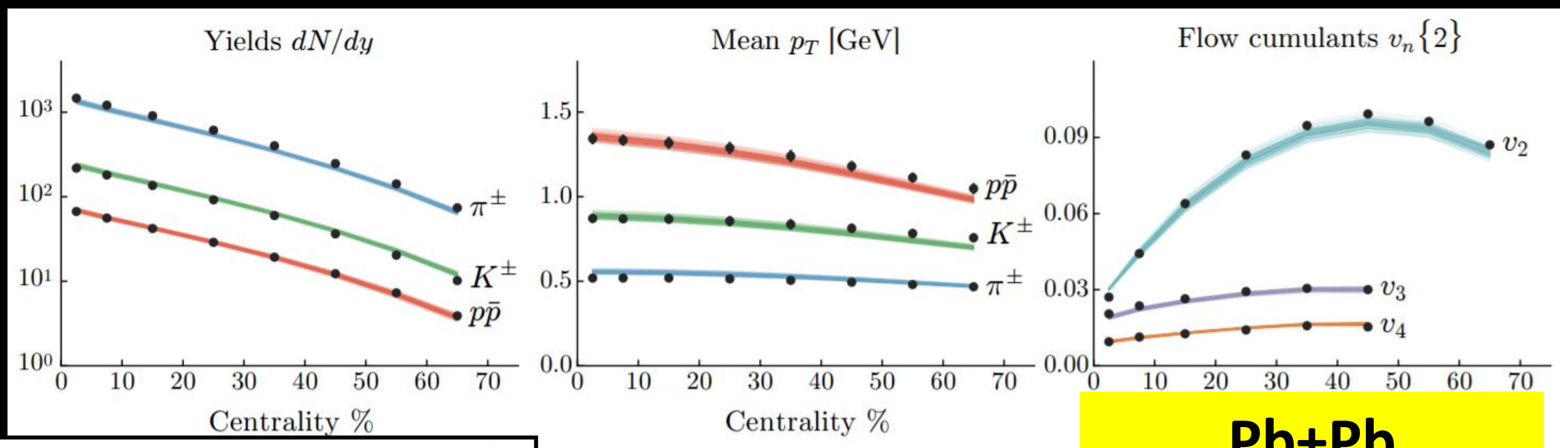
Suggests a reason that hydro *could* (but doesn't necessarily have to) apply on the length scales of p/d/^{3}He+A collisions

Could even apply to p+p, where gradients are of $\mathcal{O}(1\ \mathrm{fm}^{-1})$

Far-from equilibrium hydrodynamics?

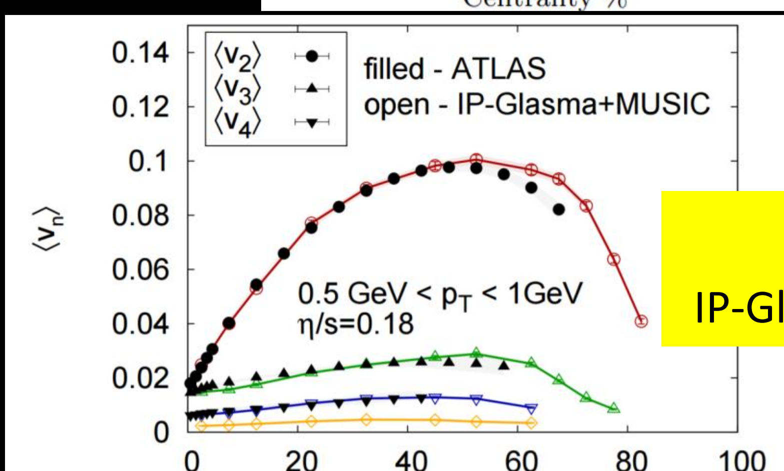
HYDRO IN LARGE SYSTEMS

Hydro+cascade models account for experimental soft particle (low-p_T) data, flow, etc. in A+A collisions



Pb+Pb
TRENTo+iEBE-VISHNU

Bass et al., PRC 94, 024907 (2016)



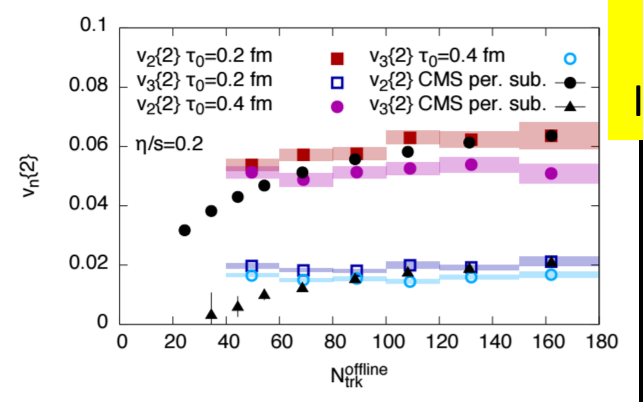
Pb+Pb
IP-Glasma+MUSIC

Schenke and Venugopalan, PRL 113, 102301 (2014)

HYDRO IN SMALL SYSTEMS

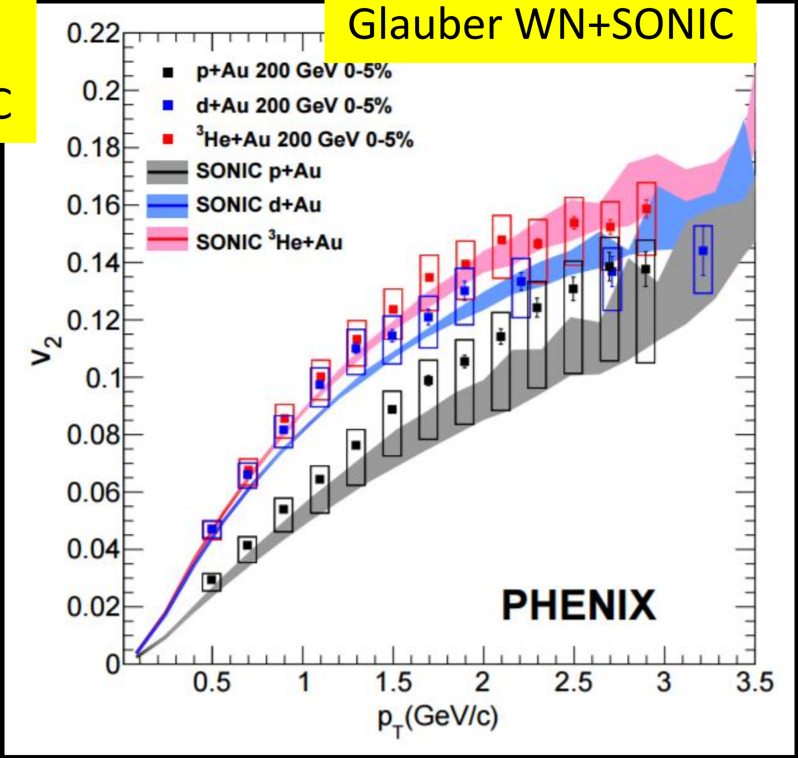
Hydro(+cascade) models also used to extensively study p+A, d+Au, and ^{3}He+Au collisions

p+Pb
IP-Glasma+MUSIC

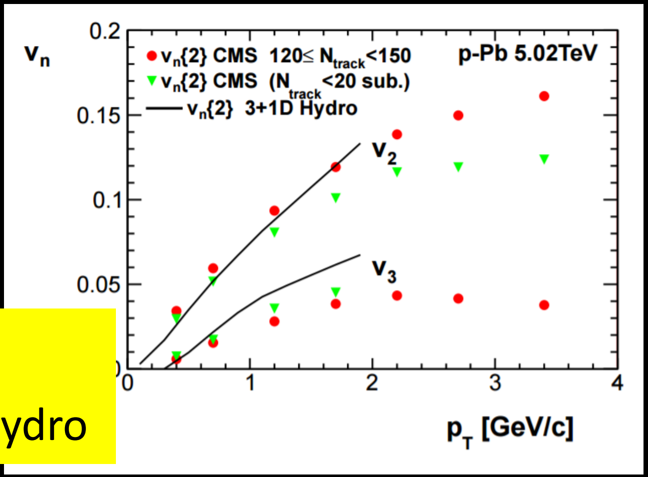


Mäntysaari et al., 1705.03177

p/d/^{3}He+Au
Glauber WN+SONIC



Aidala et al., PRC 95, 034910 (2017)

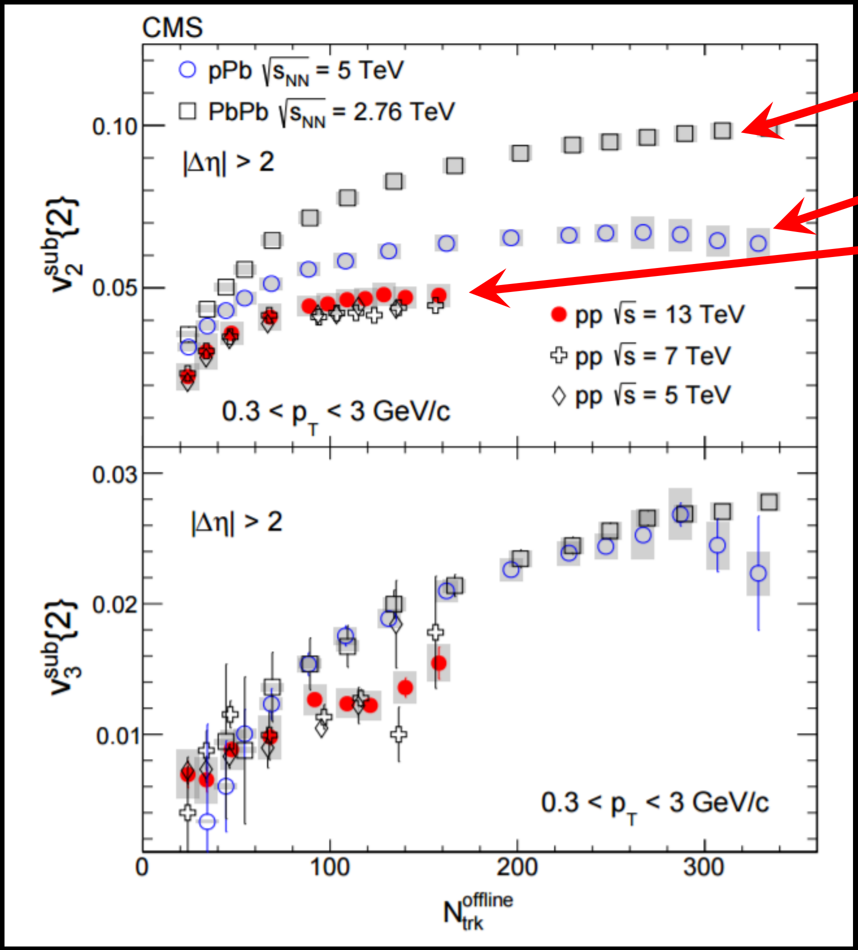


p+Pb
Glauber BC+3D Hydro

Bozek et al., PRL 111, 172303 (2013)

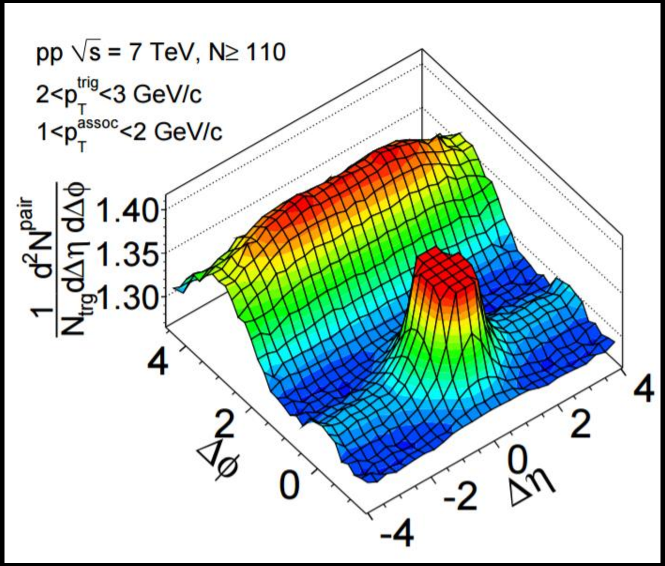
What About p+p?

Anisotropic flow comparable to p+A and A+A:



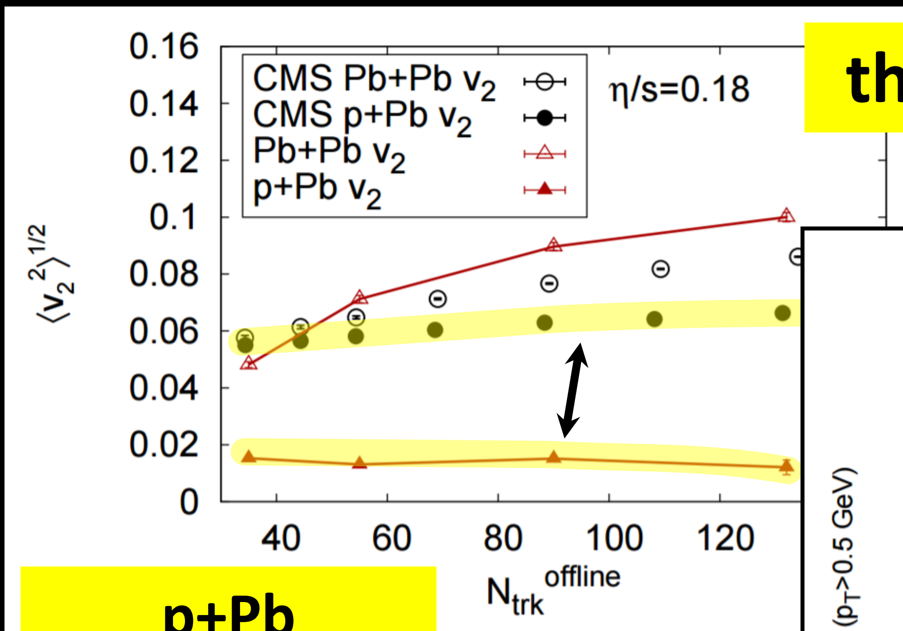
CMS Collaboration, PLB 765, 193-220 (2017)

The infamous "ridge":

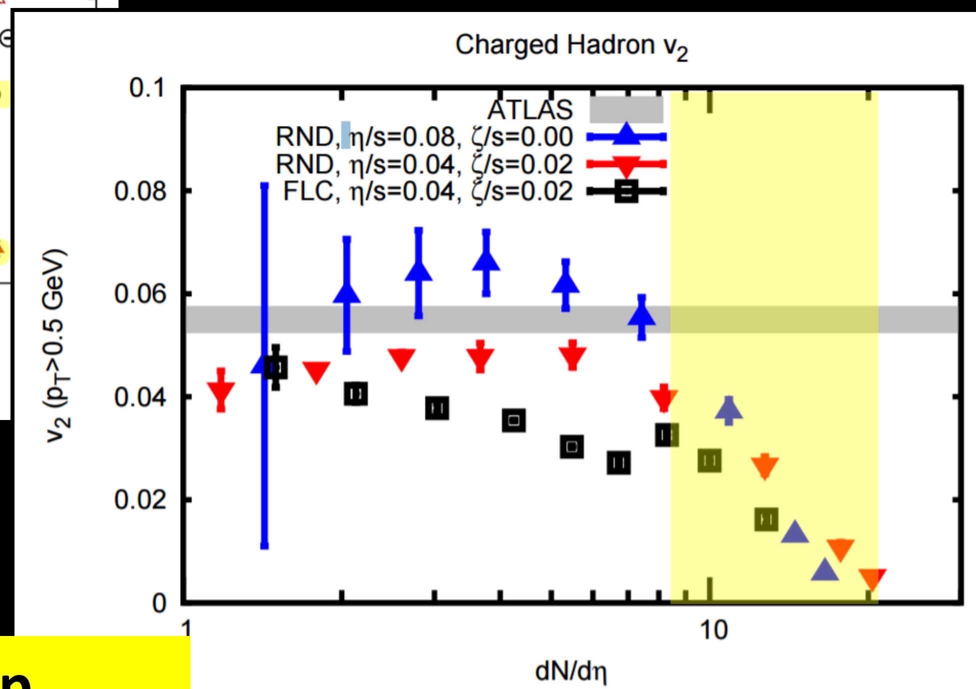


Velicanu, J. Phys. G 38, 124051 (2011)

NEED FOR NUCLEON SUBSTRUCTURE



these used ROUND protons



p+Pb
IP-Glasma+MUSIC

Schenke and Venugopalan, PRL 113, 102301 (2014)

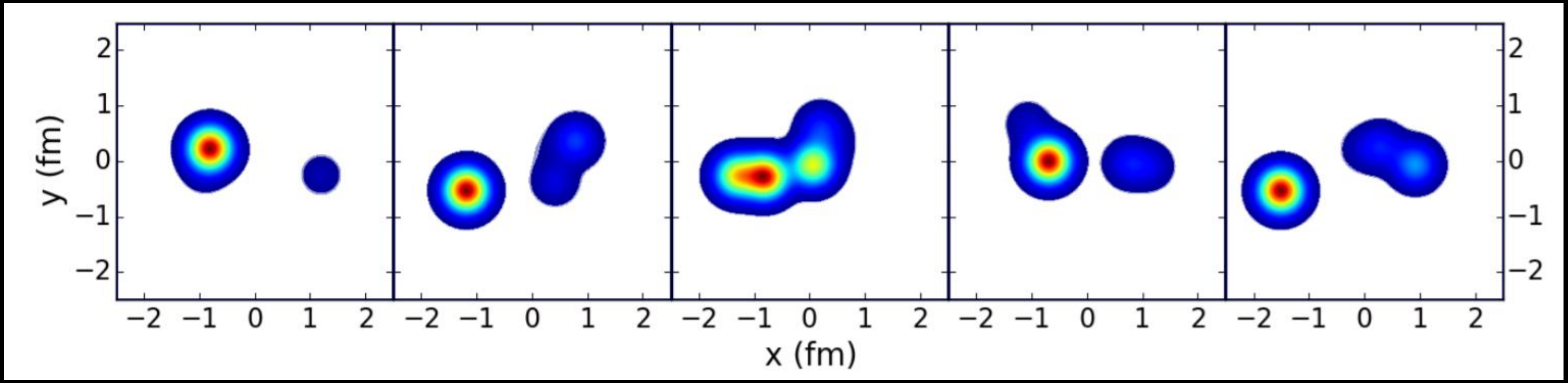
p+p
Optical+SONIC

Habich et al., Eur. Phys. J. C 76, 408 (2016)

OSU I.C. FOR NUCLEON SUBSTRUCTURE

Round protons → not enough anisotropic flow

OSU initial conditions model (Welsh, Singer, Heinz):
low-x gluons surrounding 3 high-x valence quarks



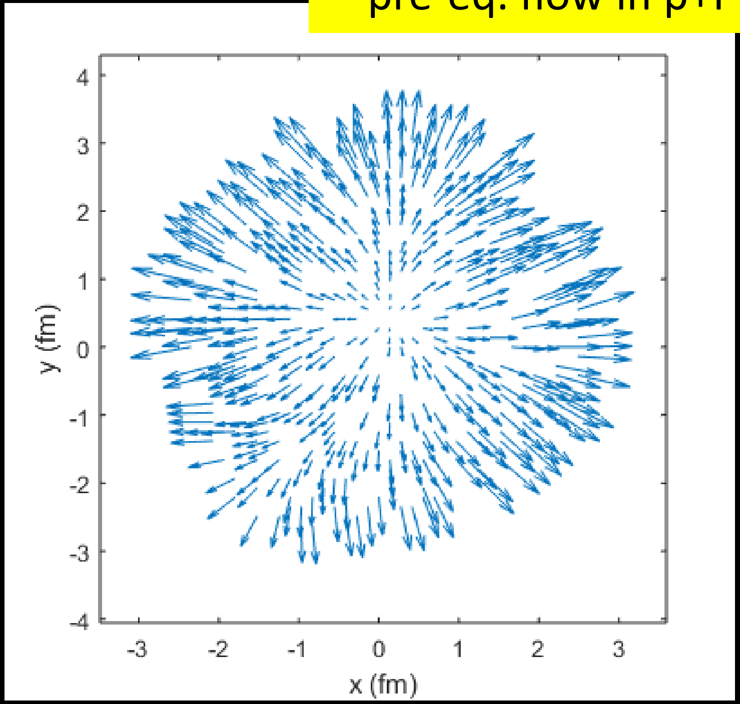
Welsh, Singer, Heinz, PRC 94, 024919 (2016)

MC Glauber model with a tunable parameter w_q(=quark size) to control nucleon substructure

EVOLUTION WITH SUPERSONIC

Use superSONIC model for evolution of profiles:
van der Schee, Romatschke, Pratt, PRL 111, 222302 (2013)

pre-eq. flow in p+Pb



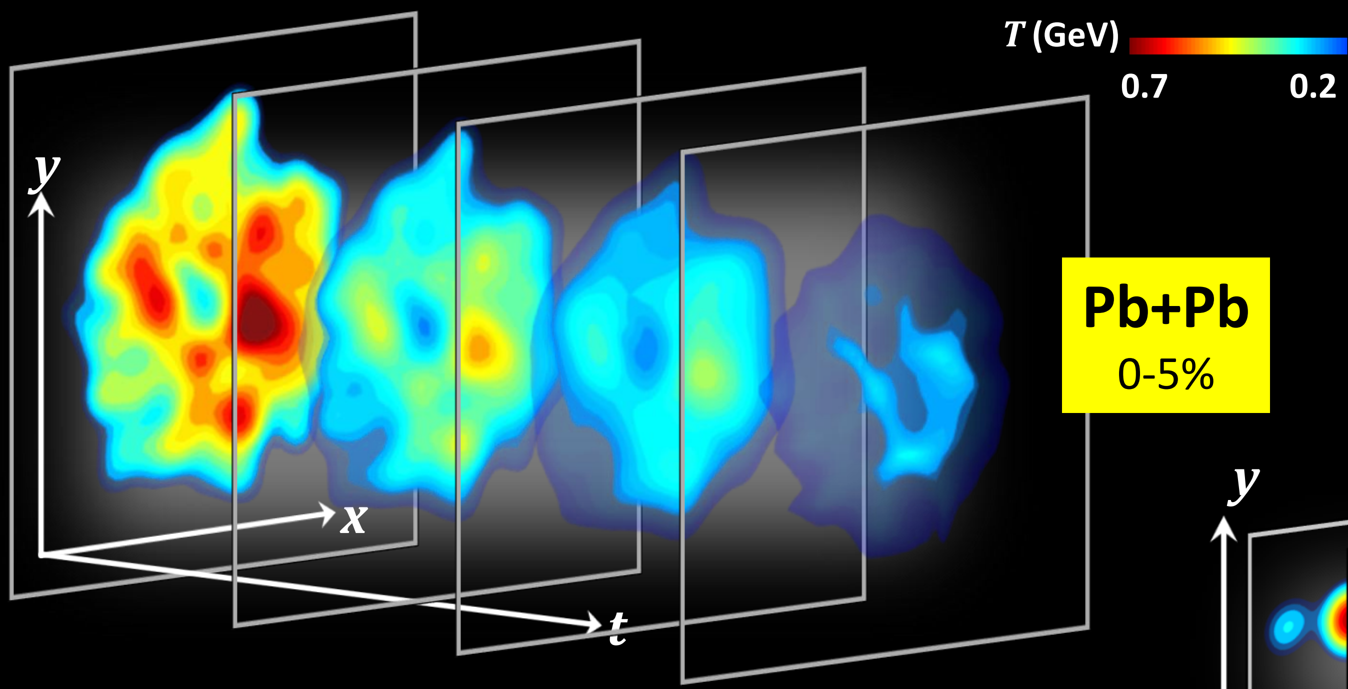
pre-equilibrium flow +
2+1D viscous hydro +
B3D hadron cascade

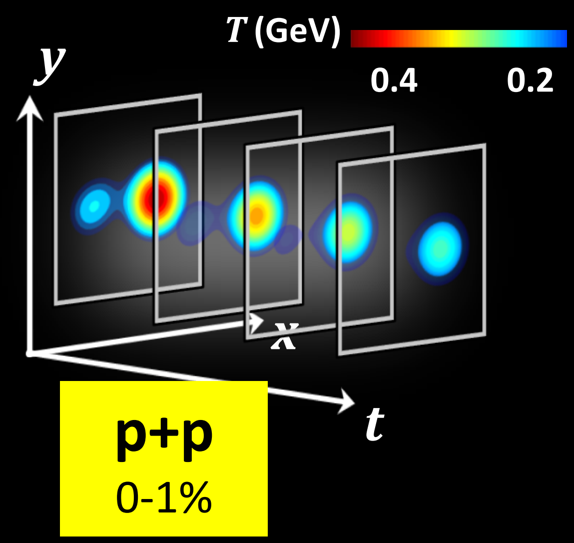
Params same for all 3 systems:

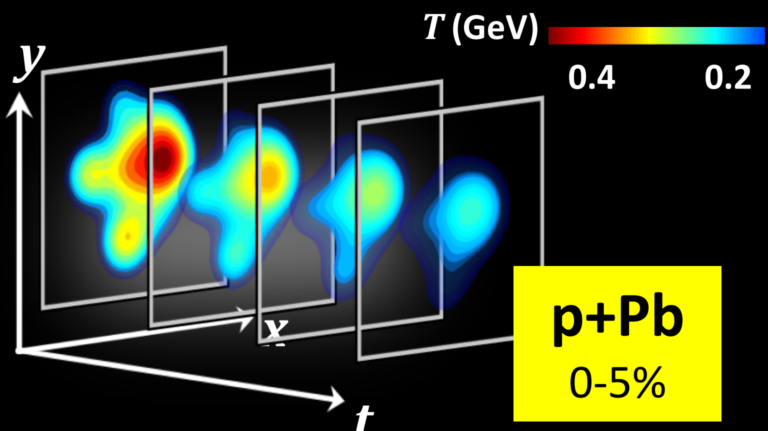
$\eta/s=0.08$ (KSS)
$\zeta/s=0.01$
$\tau_0=0.25$ fm/c
$T_C=170$ MeV
$w_N=0.52$ fm, $w_q=0.46$ fm

No attempt at precision fitting or fine-tuning

Temperature Profiles with OSU I.C.

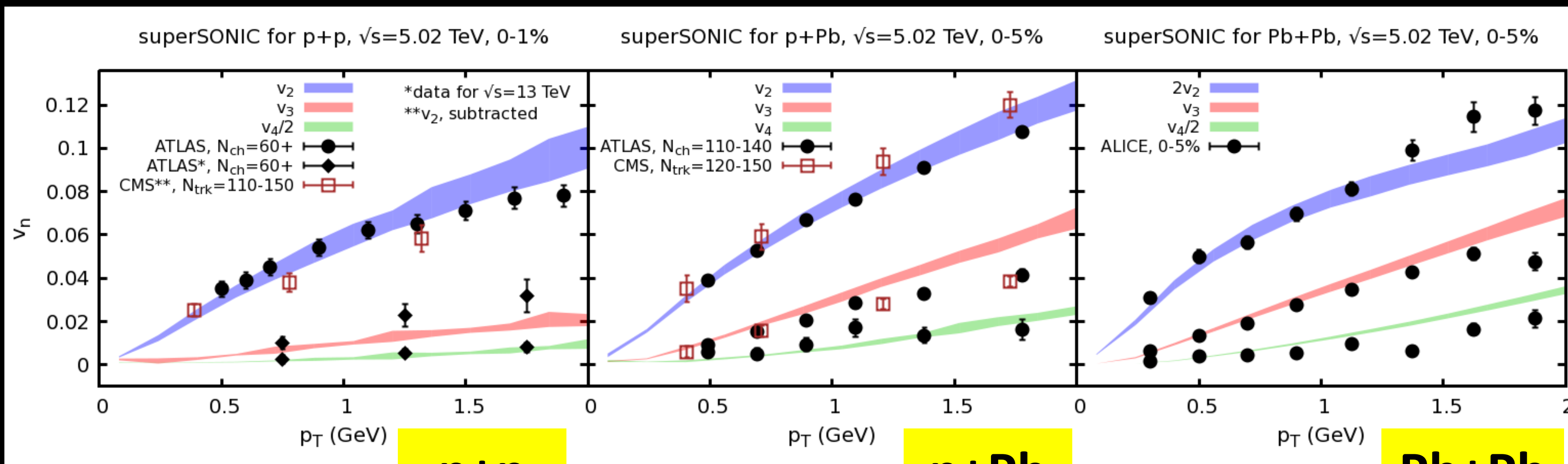






Similar temperatures
in central p+p and p+Pb

Anisotropic Flow v_2, v_3, and v_4



p+p
0-1%

p+Pb
0-5%

Pb+Pb
0-5%

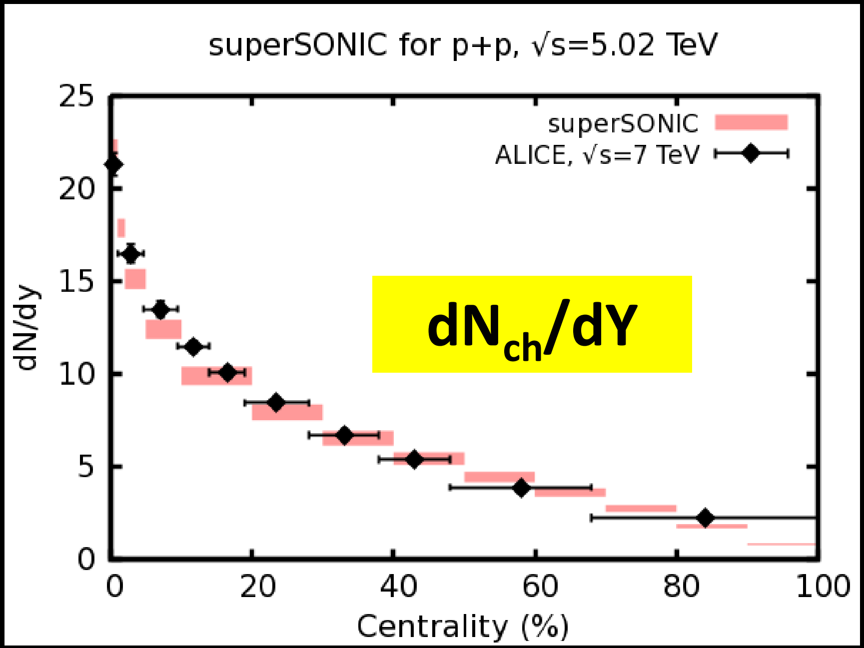
Agreement across all three systems, despite their differences!

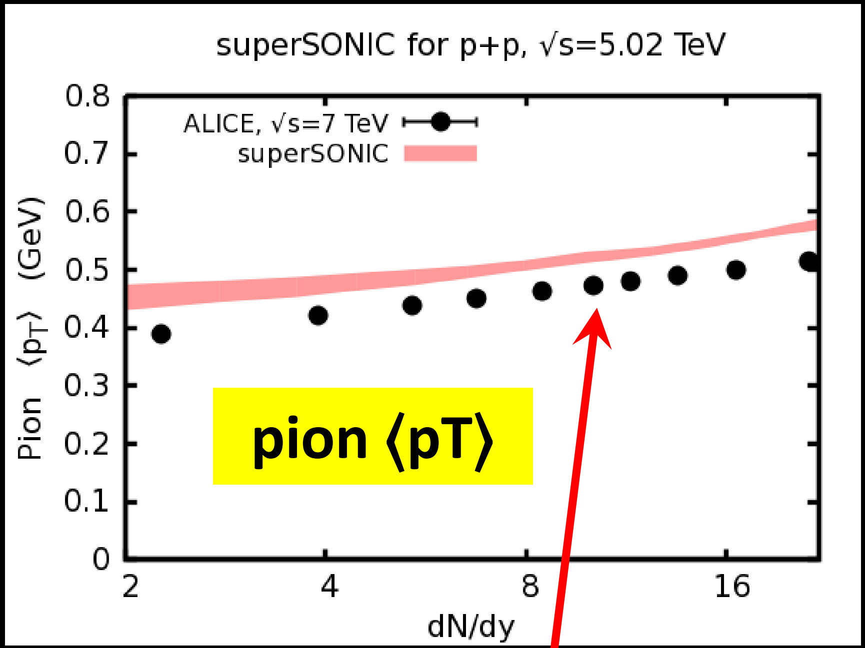
At √s=5.02 TeV:

$dN/d\eta \approx 20$ in 0-1% p+p

$dN/d\eta \approx 2000$ in 0-5% Pb+Pb

N_{ch}-DEPENDENT OBSERVABLES IN p+p

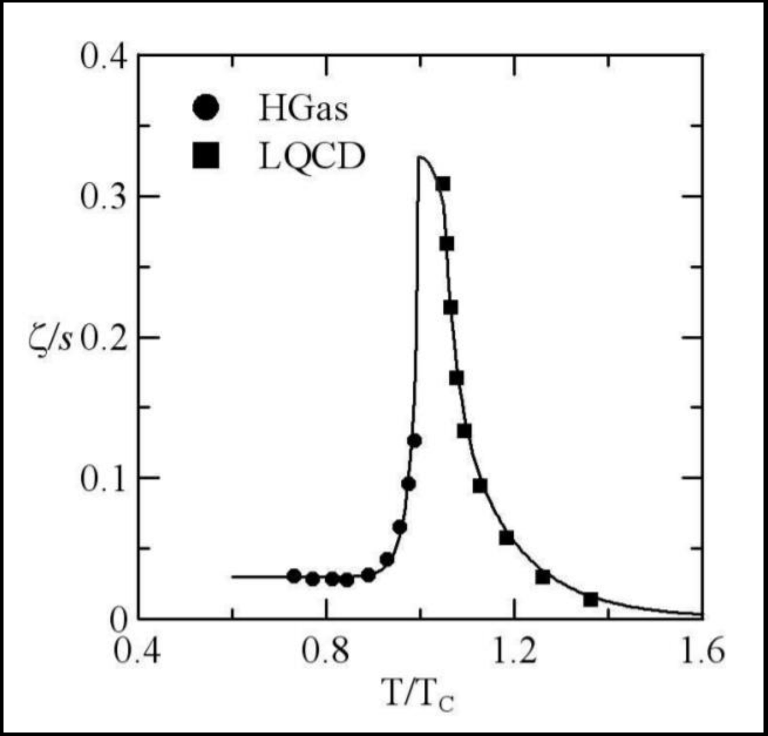




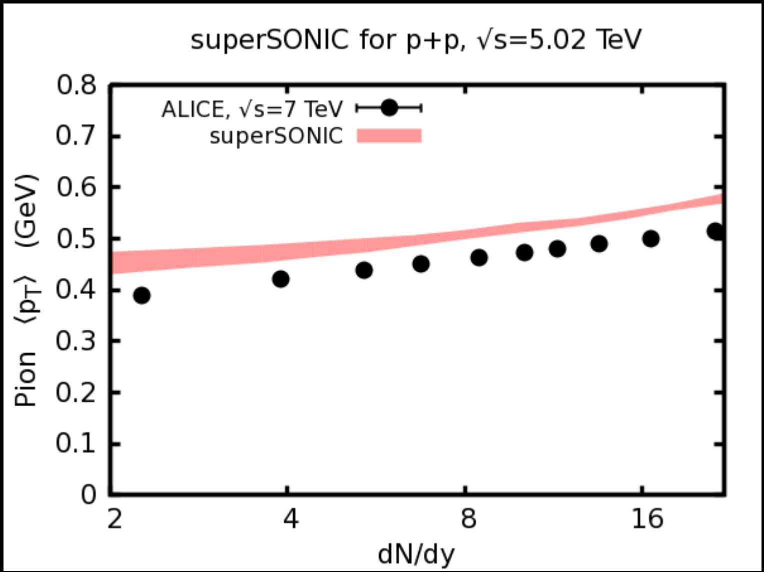
Need consistent bulk viscosity at freeze-out

Bulk Viscosity and Pion $\langle p_T \rangle$

There are reasons to believe that ζ/s is large near freeze-out:



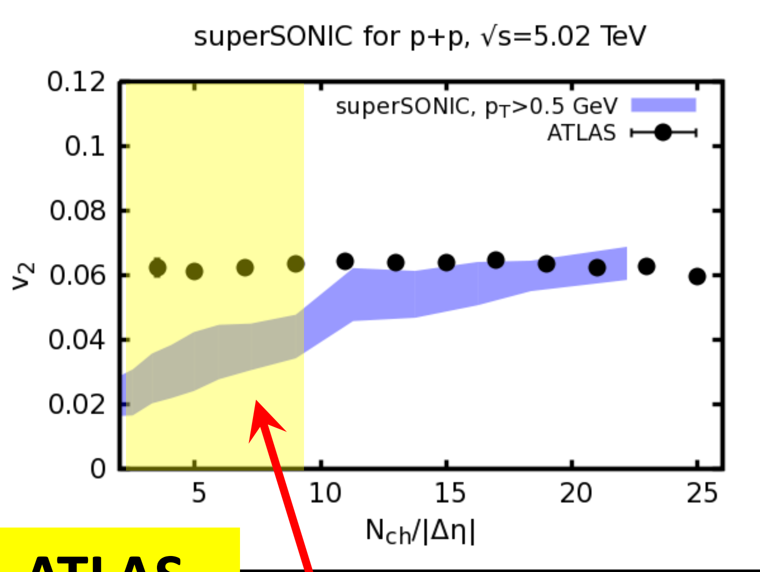
Denicol et al., PRC 80, 064901 (2009)



Standard freeze-out procedures rely on assumption of small ζ/s:

$$f = f_{\text{eq}} + \delta f, \quad \delta f \sim \mathcal{O}(\zeta)$$

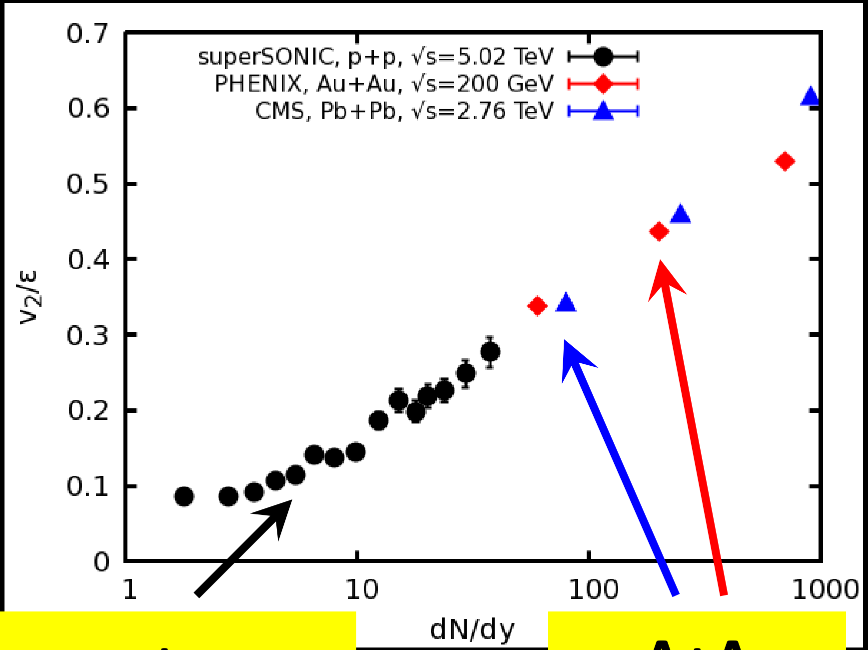
Elliptic Flow v_2 in p+p



ATLAS
pT>0.5 GeV

Lifetime of system is short

Response to ε_2:



p+p
OSU+superSONIC

A+A
PHENIX & CMS

Applicability of Hydrodynamics

Standard Mueller-Israel-Stewart theory of 2nd-order viscous hydro has a built-in non-hydro mode:

$$\omega_H^{(\pm)} = \frac{k}{\sqrt{3}} - \frac{2i}{3T}\frac{\eta}{s}k^2 + \ldots$$

Hydro (e.g. sound) modes

$$\omega_{NH} = -i\left(\frac{1}{\tau_\Pi} - \frac{4}{3T}\frac{\eta}{s}k^2\right) + \ldots$$

Non-hydro mode

Spalinski, Phys. Rev. D 94, 085002 (2016)

Governed by a transport parameter τ_π which in "realistic" microscopic theories (AdS/CFT, kinetic theory, etc.) takes on values between $2(2-\ln 2)\eta/sT \lesssim \tau_\pi \lesssim 6\eta/sT$

Hydro gradient expansion is valid when sensitivity to this non-hydro mode is minimal

Quantifying Hydro Applicability

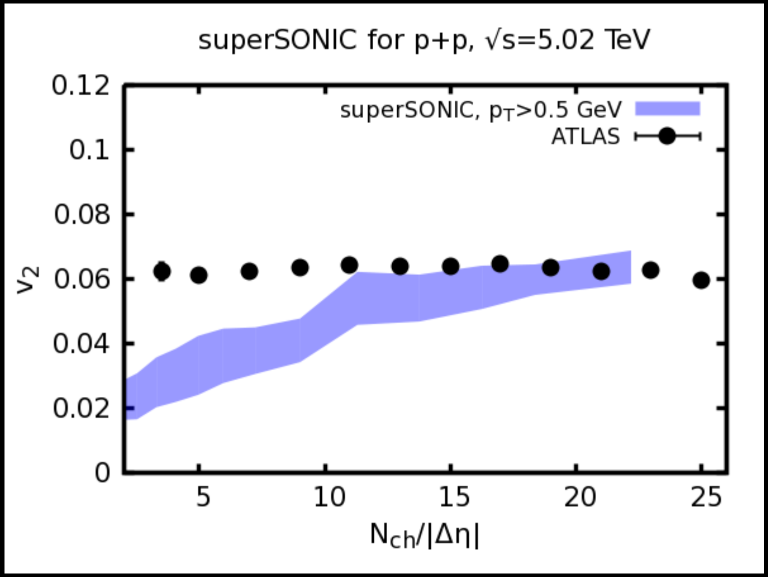
How do we get a handle on the applicability of hydrodynamics? e.g. see Spalinski, Phys. Rev. D 94, 085002 (2016)

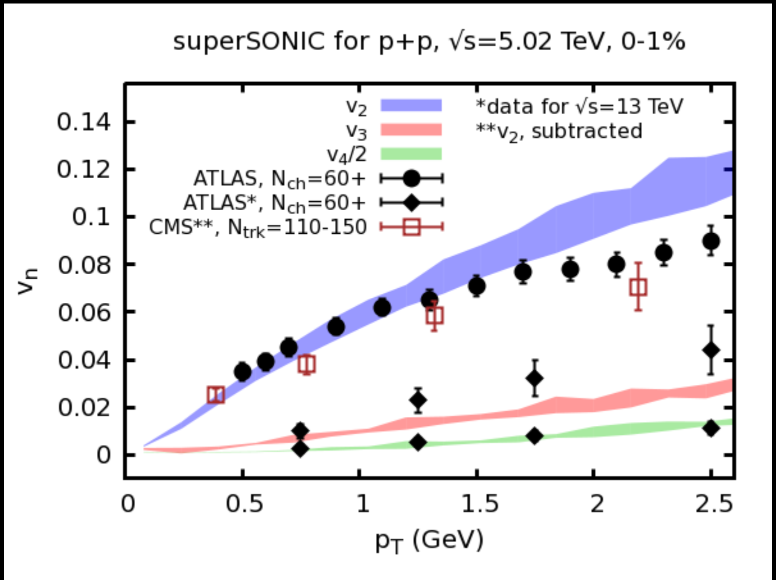
Vary τ_π within the range

$$2(2-\ln 2)\eta/sT \le \tau_\pi \le 6\eta/sT$$

and estimate the systematic uncertainty induced by our lack of knowledge of the underlying microscopic dynamics

QUANTIFYING HYDRO APPLICABILITY





→ Uncertainties (systematic + statistical) are small; description of p+p is NOT sensitive to microscopic details

Hydro applies down to ~1 fm!

REMAINING QUESTION

So, hydro is applicable at least down to mid-central p+p (dN/dY≈5), even though the gradients are not “small”

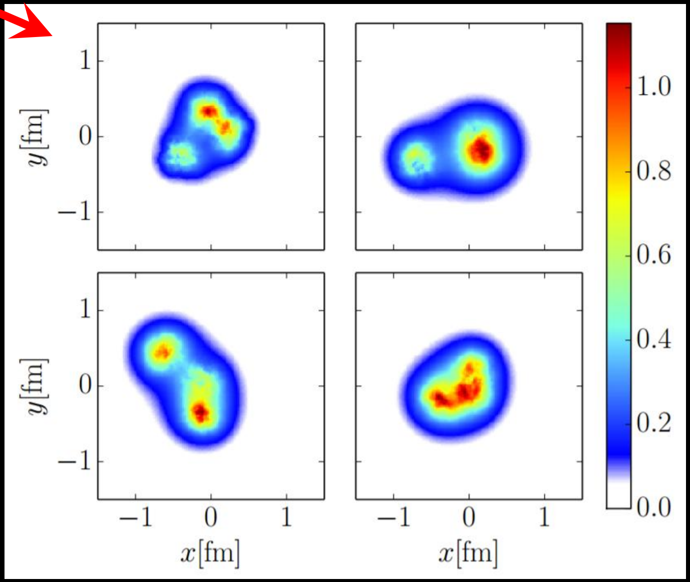
Question remaining: How much is the observed v_n the result of hydrodynamic response to initial geometry vs. initial state correlations?

ENOUGH SUBSTRUCTURE?

Running with OSU initial conditions and η/s≈0.08 seems to favor a small-ish amount of nucleon substructure

$w_q = 0.46\ \mathrm{fm} \lesssim w_N$

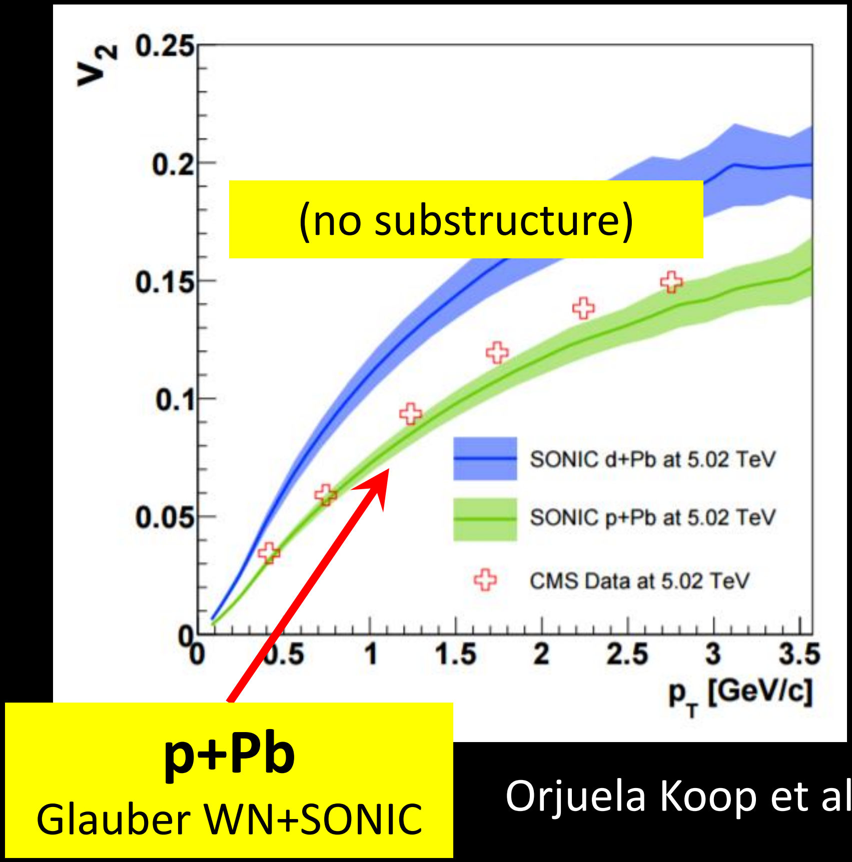
Param values at conflict with recent analyses of HERA diffractive data (see plenary talk by Mäntysaari)



Mäntysaari and Schenke, PRD 94, 034042 (2016)

Enough Substructure?

Why?? MC Glauber models can get eccentricities in p+p, p+A even *without* nucleon substructure



Without substructure, eccentricities are already a reasonable size for p+A

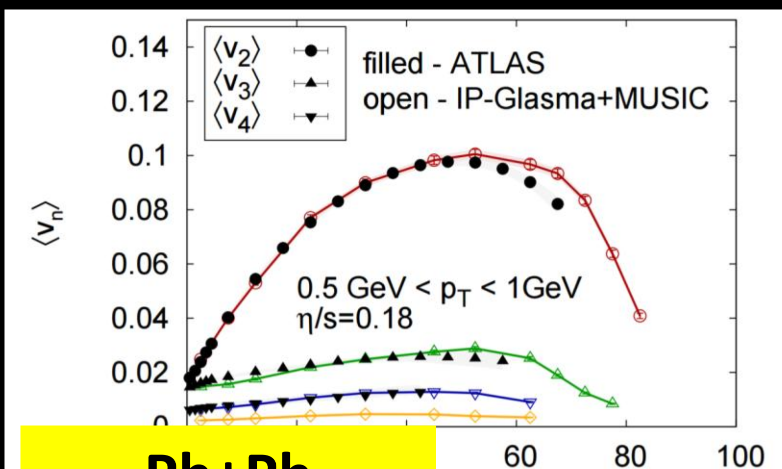
(still need substructure in p+p though)

Orjuela Koop et al., PRC 93, 044910 (2016)

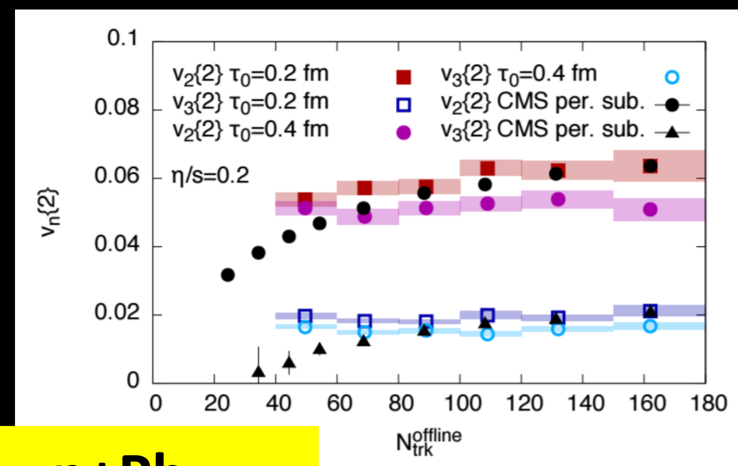
SENSITIVITY TO CHOICE OF I.C. MODEL

Probably should improve model of the initial state (e.g. use HERA constraints on nucleon substructure parameter, question assumptions of Glauber I.C. model)

Schenke and Venugopalan, PRL 113, 102301 (2014)



Pb+Pb
IP-Glasma+MUSIC



p+Pb
IP-Glasma+MUSIC

Mäntysaari et al., 1705.03177

See if I.C. models like IP-Glasma, EKRT, & TRENTo work in small systems too?

What is the Goal Here?

Lots of work has been done to get the flow and e-by-e flow distributions right in large systems

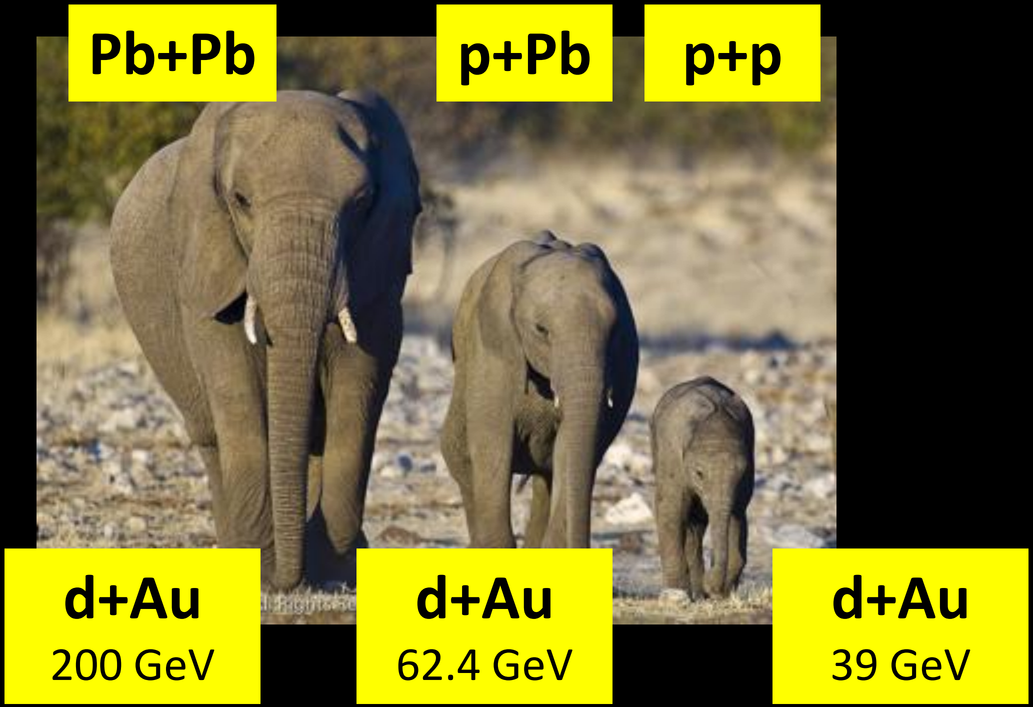
Focus should NOT merely be on precision fits of one or two systems, but global descriptions of ALL systems (ion type, beam energy)

> "With four parameters I can fit an elephant, and with five I can make him wiggle his trunk."
> – John von Neumann

Relation to d+Au AND THE BES

"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk." – John von Neumann

Ok, fine, but can we make all the elephants wiggle their trunks at the same time??



Conclusion

Hydro can adequately describe the flow results down from central Pb+Pb to mid-central p+p, at least

→ "The unreasonable effectiveness of hydrodynamics"

This is appealing, suggests a universal model for soft particle production particle production and flow in all high-energy hadronic collisions

However, it surely does NOT resolve the hydro/initial correlations debate… More work to be done!!!!

Supplemental Material

Far-from-Equilibrium Hydro

Hydro gradient series is typically divergent!

$$T^{\mu\nu} = \underbrace{\epsilon u^\mu u^\nu + P\Delta^{\mu\nu}}_{\text{0th-order terms}} - \underbrace{\eta\nabla^{\langle\mu}u^{\nu\rangle} - \zeta\Delta^{\mu\nu}\nabla_\alpha u^\alpha}_{\text{1st-order terms}} - \underbrace{\tau_\pi\left({}^{\langle}D\pi^{\alpha\beta\rangle} + \frac{4}{3}\pi^{\mu\nu}\nabla_\alpha u^\alpha\right) + \cdots}_{\text{2nd- and higher-order terms}}$$

$+\ n!\,\mathcal{O}(\partial^n) + \ldots$

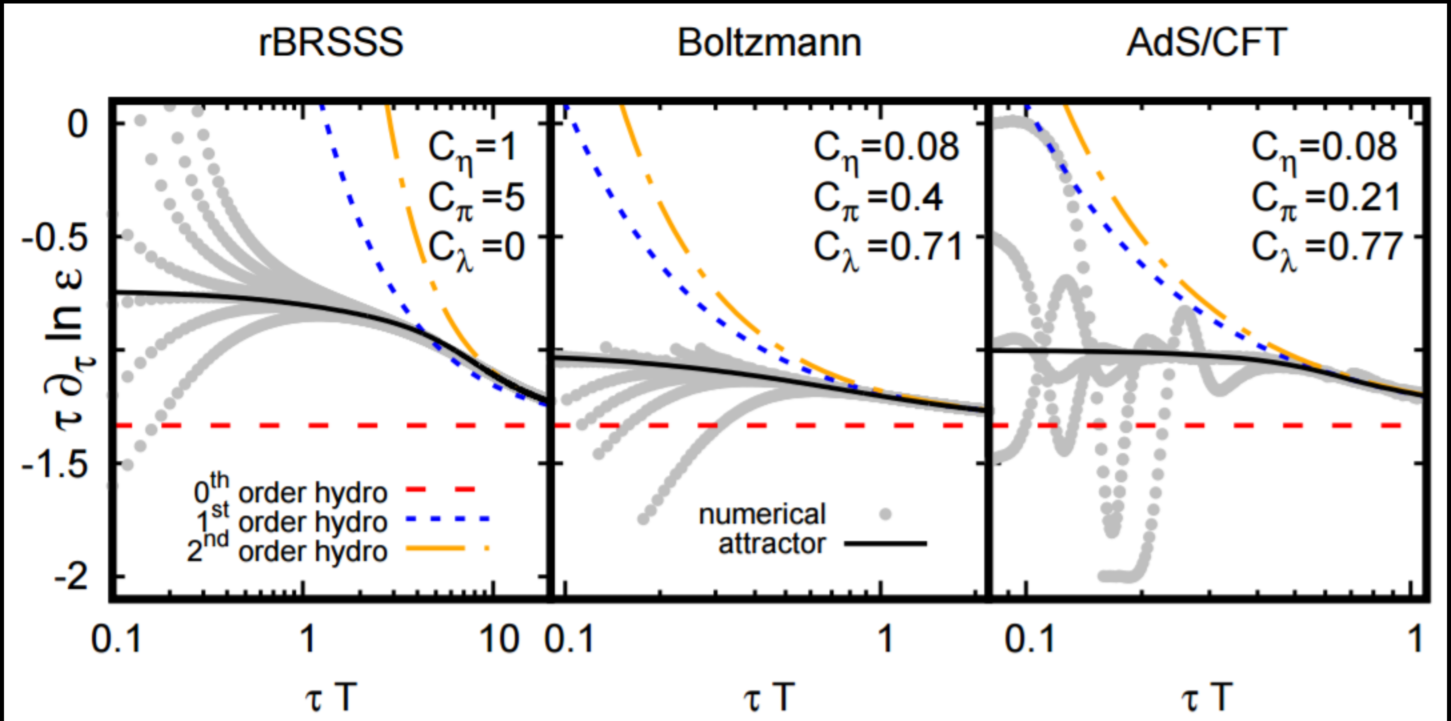
Can Borel-resum the series to make it finite

→ In doing so, you pick up a contribution non-analytic in the gradients that is due to the non-hydro modes

Romatschke, 1704.08699

Hydrodynamic Attractors

Borel-resummed solutions quickly relax to a hydrodynamic attractor solution, that agrees with small-order hydro for small gradients

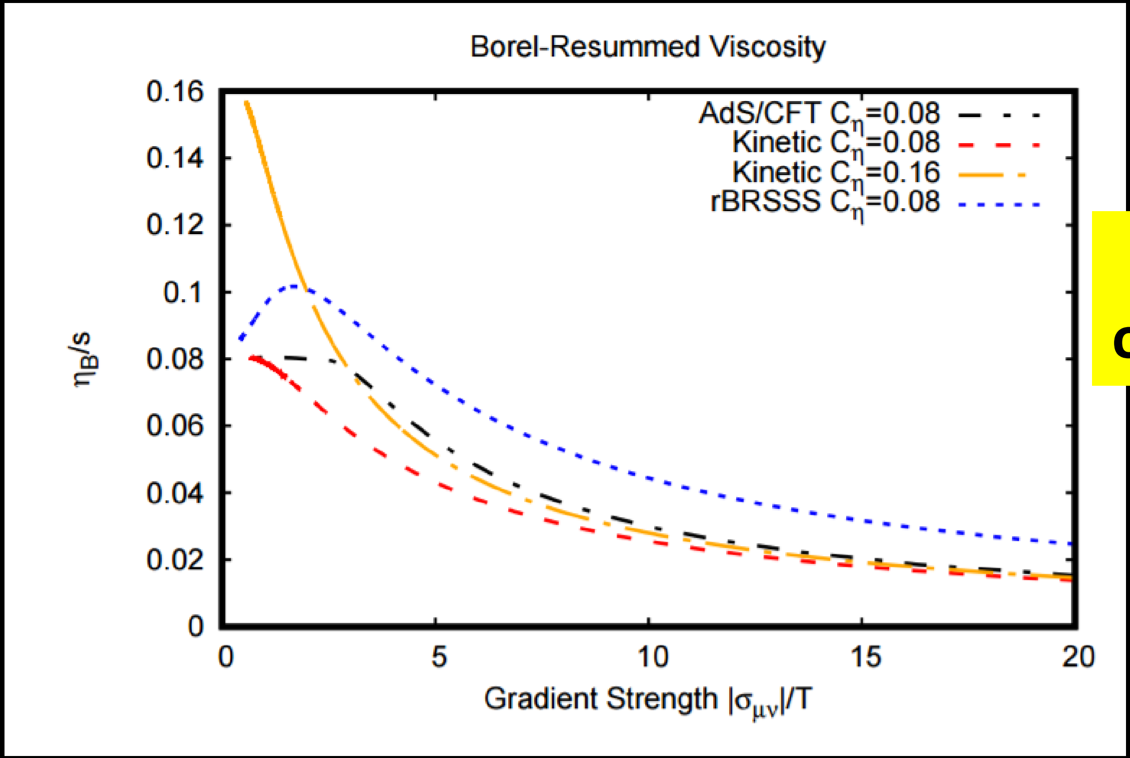


Romatschke, 1704.08699

System-Size-Dependent Viscosity?

The stress tensor of the hydro attractor looks like that of a fluid, except with an effective EoS and effective shear/bulk viscosity

$$T^{\mu\nu}_{\rm hydro} = (\epsilon + P_B) u^\mu u^\nu + P_B g^{\mu\nu} - \eta_B \sigma^{\mu\nu}$$



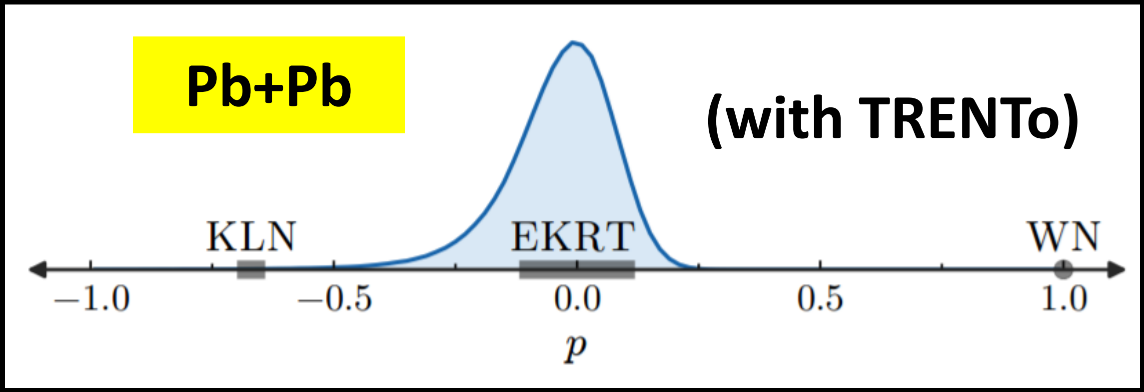
Romatschke, 1704.08699

"Viscosity" depends on gradient strength??

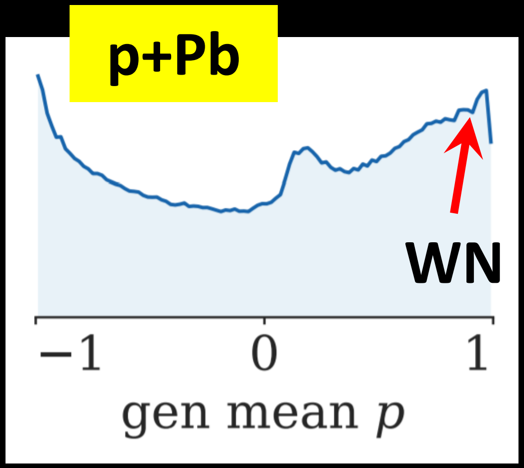
MC Glauber vs. Other I.C. Models

Large systems seem to disfavor MC Glauber wounded nucleon approach for precision description of flow across all centralities. Saturation-type models (EKRT, IP-Glasma) work better

However, Bayesian analysis of p+Pb somewhat favors a Glauber WN method of entropy scaling over sat-type models



Bass et al., PRC 94, 024907 (2016)

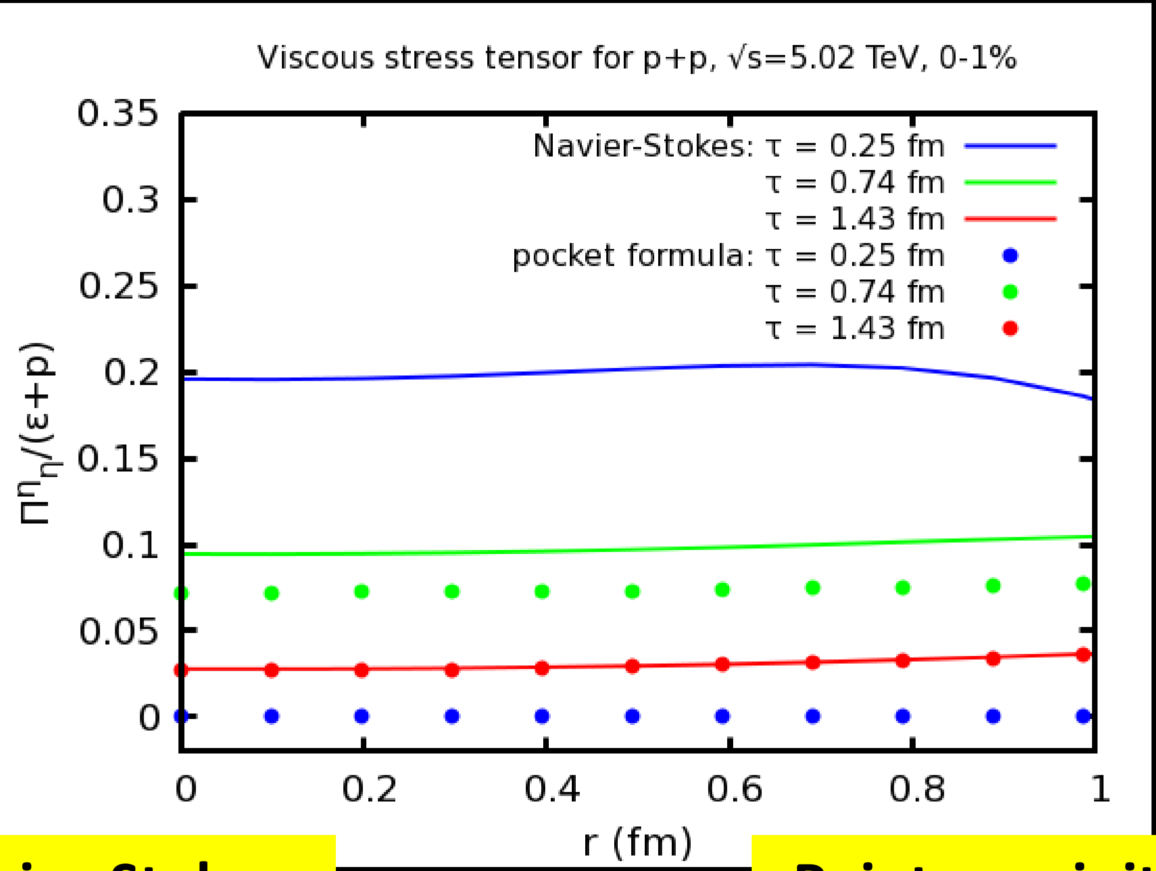


S. Moreland, talk at QM2017

There is a little tension here

Initial Viscous Stress Tensor

Do results in p+p depend heavily on initial value of $\Pi^{\mu\nu}$?

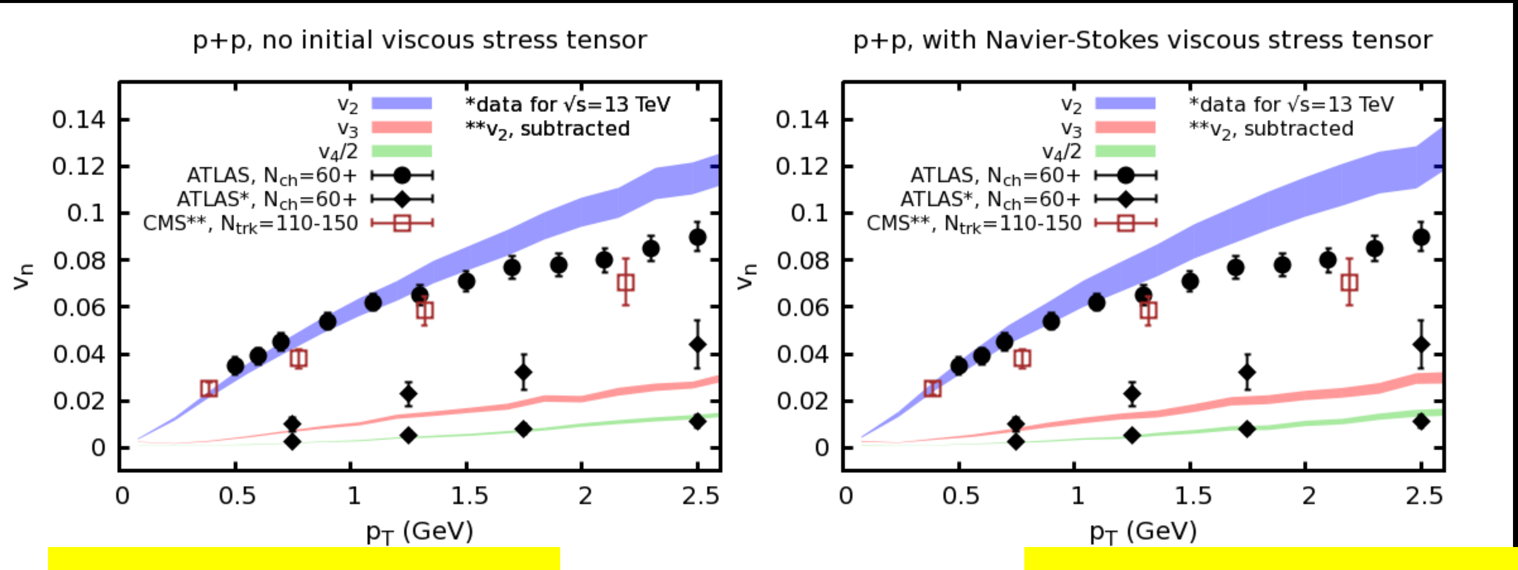


Lines: Navier-Stokes initialization

Points: no initial viscous tensor

Initial Viscous Stress Tensor

Results on p+p are not terribly sensitive to initial value of $\Pi^{\mu\nu}$:



No initial viscous stress tensor

Navier-Stokes initialization