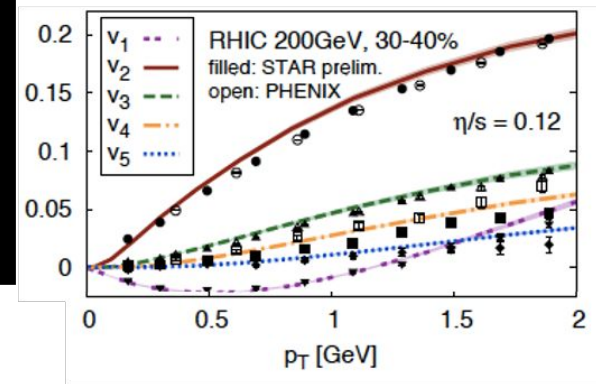
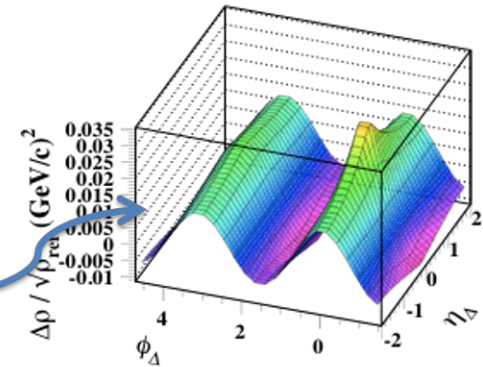
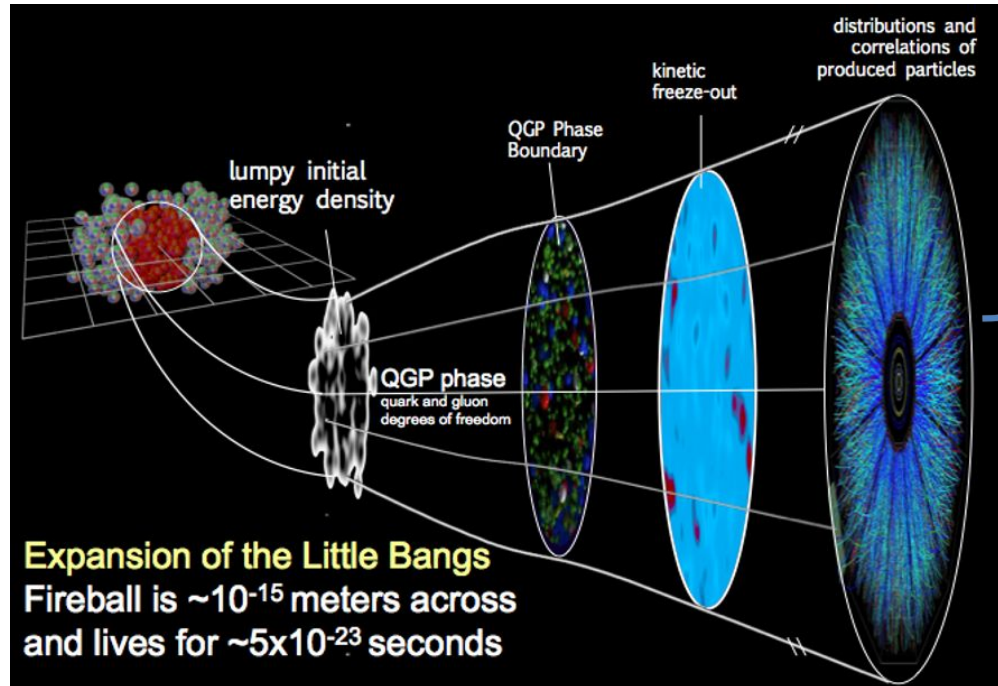


Flow in the Collider Region

Lipei Du, Huan Huang, Iurii Karpenko, Richard Seto, Mayank Singh



- At lower p_T , multi-phase, hydro models describe intricate details of flow and correlations providing estimates of η/s and the EOS near $\mu_B=0$.
- At intermediate p_T , NCQ scaling of flow is interpreted as a sign of hadronization of deconfined quarks by coalescence.

How far down in energy can this paradigm be taken? What does the data tell us?
What model adjustments are needed at lower energies?

Progress on Applying Hydro at Lower Energy

Bottom line (on top of the slide): **it is possible to construct a hydro model reproducing most of the basic observables in the RHIC BES region.** The densest part of the fireball is still dense enough for hydro to make sense. [Nonaka&Bass showed it as early as 2006].

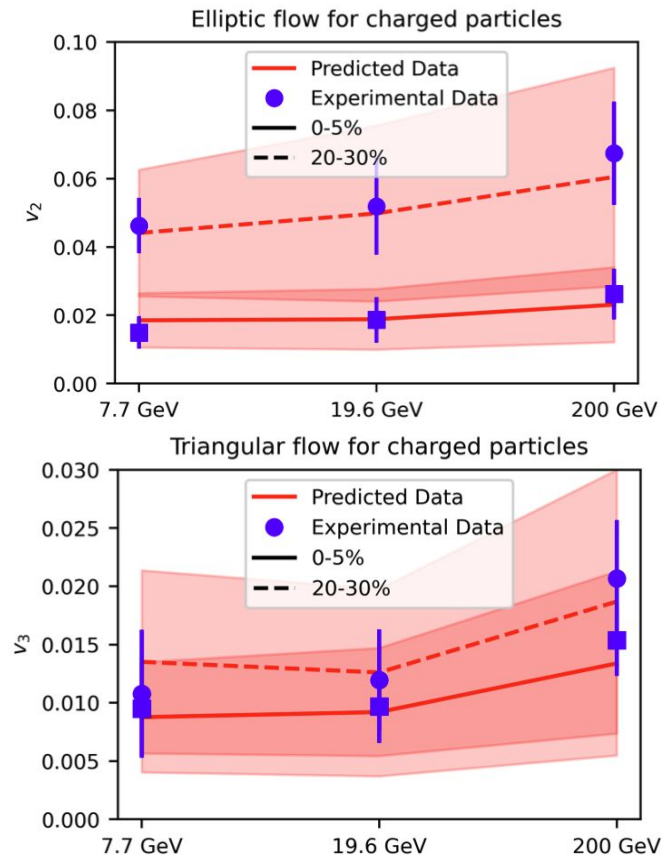
Hydro-based models for RHIC BES region include: UrQMD+vHLLE (2015), SMASH+vHLLE (2022), EPOS4, 3D Glauber+MUSIC (2018?), SMASH+MUSIC (a.k.a. JETSCAPE)

The recipe is mostly imported from higher energies:

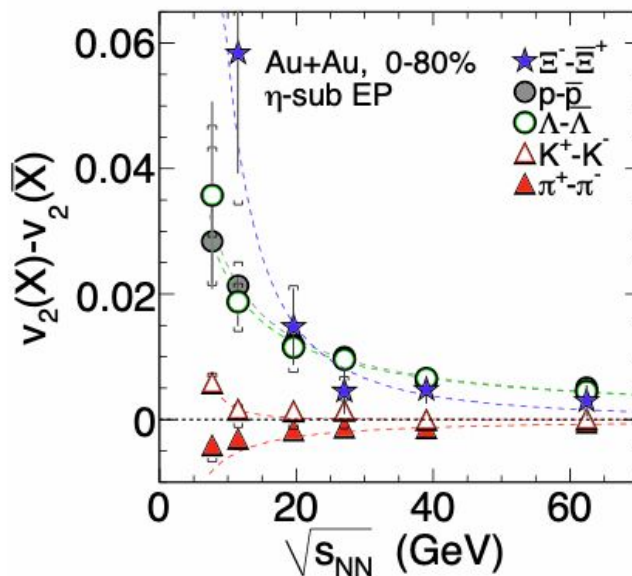
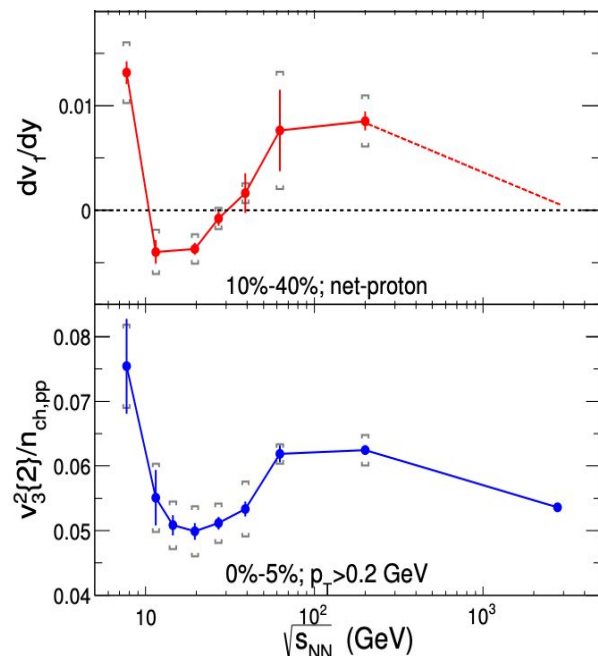
- 3D initial state: from transport (UrQMD, SMASH, JAM, EPOS) or parametrized (3D Glauber)
- 3D hydro with finite viscosity (not a challenge) and conserved charges (not a challenge either)
- EoS at finite μ_B (e.g. Chiral model EoS)
- Same or slightly adapted Cooper-Frye
- final-state hadronic cascade

Work in progress includes (see simulations WG eg.):

- Persevering fluctuations through the evolution and hadronization
- Better understanding of baryon stopping and the initial state



Notable Deviations from Smooth Trends



Most flow-related observables vary smoothly down to 7.7 GeV, showing no evidence for QGP disappearance: little happens to challenge the usual multiphase hydro models.

There are three notable exceptions:

1. Net proton dv_1/dy exhibits a minimum near 15-20 GeV
2. Charged hadron v_3 /multiplicity exhibits a very similar minimum
3. A difference between particle and anti-particle flow increases at lower energies

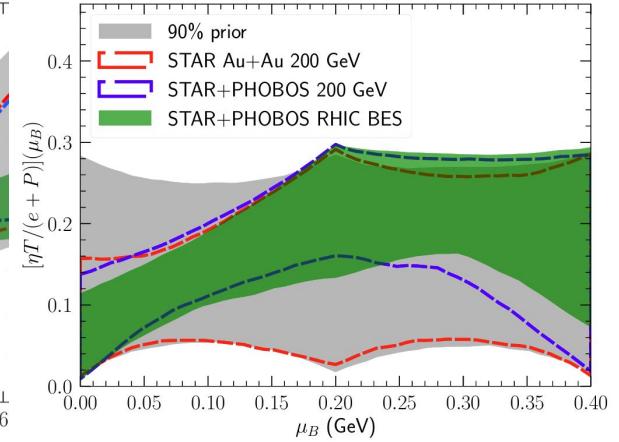
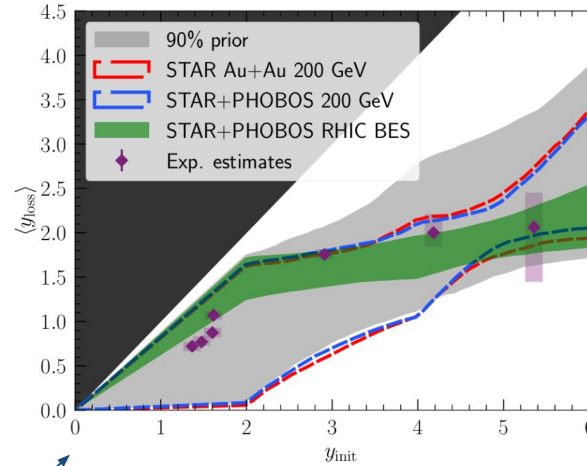
Implications: The minimum in dv_1/dy was a predicted signal for a softening in the EOS. The splitting between particles and antiparticles obscures NCQ scaling.

Model Findings for v_3

Models correctly describe v_3 . Some analyses only using yields, mean p_T , v_2 , and v_3 indicate a change in stopping at near 20 GeV and perhaps a kink in the viscosity.

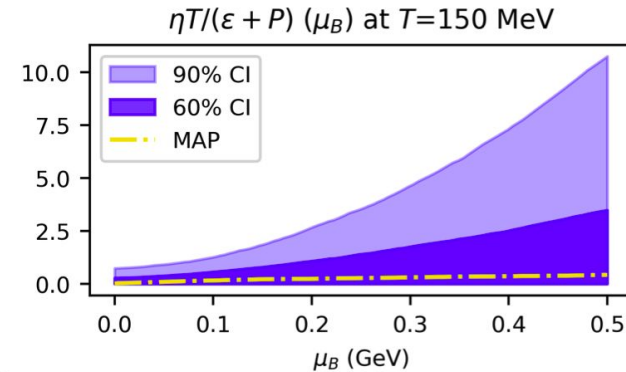
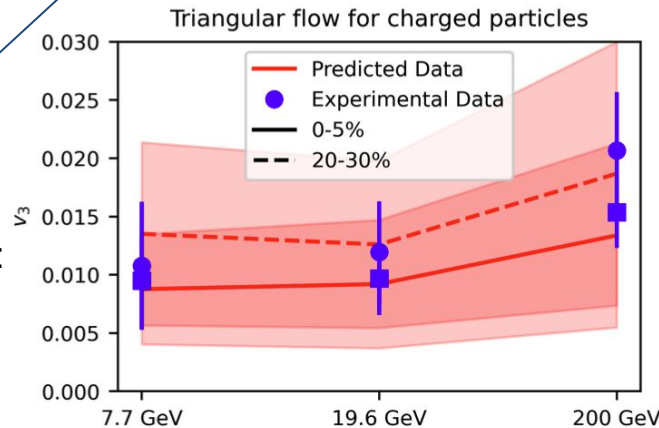
TABLE II. The experimental measurements in Au+Au collisions used in this Bayesian inference study.

$\sqrt{s_{NN}}$ (GeV)	STAR	PHOBOS
200	$dN/dy(\pi^+, K^+, p, \bar{p})$ [54] $\langle p_T \rangle(\pi^+, K^+, p, \bar{p})$ [54] $v_2^{\text{ch}}\{2\}$ [57], $v_3^{\text{ch}}\{2\}$ [58]	$dN^{\text{ch}}/d\eta$ [55] $v_2^{\text{ch}}(\eta)$ [56]
19.6	$dN/dy(\pi^+, K^+, p)$ [59] $\langle p_T \rangle(\pi^+, K^+, p, \bar{p})$ [59] $v_2^{\text{ch}}\{2\}$ [57], $v_3^{\text{ch}}\{2\}$ [58]	$dN^{\text{ch}}/d\eta$ [55]
7.7	$dN/dy(\pi^+, K^+, p)$ [59] $\langle p_T \rangle(\pi^+, K^+, p, \bar{p})$ [59] $v_2^{\text{ch}}\{2\}$ [57], $v_3^{\text{ch}}\{2\}$ [58]	



Some hint of discontinuity in viscosity and baryon stopping near 20 GeV when factoring in v_3 :
<https://arxiv.org/pdf/2310.10787>,

but this doesn't seem to show up in:
<https://arxiv.org/pdf/2503.10181>
where v_3 doesn't seem to strongly constrain the extracted viscosity.



Summary of Model findings for dv_1/dy

v_1 seems to be a greater challenge than v_3 with a breakdown between expectation and reality

Expectation: “ dv_1/dy is sensitive to a softening in the EoS”

Reality: results from the zoo of existing models are ambiguous:

- 3-fluid models: EoS applies to the early (compression?) stage, but at the end the v_1 is sensitive to both the initial and the final state.
More precisely, THESEUS: at $\sqrt{s}=3$ GeV, pion v_1 is affected, proton v_1 is not. MUFFIN at $\sqrt{s}\sim 10$ GeV: other way round.
THESEUS: incomplete merging to final state UrQMD may be contributing to “wrong” pion/parton v_1 . The same may be true for MUFFIN, which is new 3FH+SMASH.
- Initial state from transport (UrQMD+hydro, SMASH+hydro, etc):
The early stage is modelled with transport, so EoS does not apply there.
UrQMD+ideal hydro suggests that final state affects v_1 a lot.
- Parametrized initial state for hydro: parametrization tuned to reproduce v_1 .
Only run with one EoS (correct?) so the EoS sensitivity is unclear.
- Full transport: works generally better for v_1 , and if EoS is emulated by properly chosen mean fields (yes?), the v_1 is sensitive to the EoS.
But the DOF are always hadrons, so the phase transition is only reflected in the EOS without explicit change in DOF. Very challenging computationally in the collider region.
- Parton cascades? AMPT, PHSD.

TABLE II: Summary of model approaches to the proton directed flow dv_1/dy , their main results, and whether a minimum in dv_1/dy is found to be related to a softening in the equation of state (EOS).

Model Class	Reference(s)	Main Findings / Features	Sensitivity of dip in dv_1/dy to Softening
First hydro prediction	nucl-th/9908010	Non-monotonic dp_x/dy proposed as a phase-transition signal (late 1990s); later work 1402.7236 argues against a unique connection.	Sensitive: Sensitivity to “Softest-point” though later study showed interpretation is not unique.
Hydro with parametrized initial state	2003.05852 (Shen, Alzhrani)	Pion v_1 reproduced reasonably; proton v_1 overestimated.	Not Sensitive: Strong sensitivity to initial-state geometry.
	2211.16408 (Du, Shen, Jeon, Gale)	Sign of baryon dv_1/dy governed by misalignment between energy and baryon densities in the initial state. Reproduces slope sign change with beam energy.	Not Sensitive: Parameterization of densities in the initial state controls slope sign.
Hydro with dynamic initial states	1402.7236 (UrQMD + ideal hydro)	Hybrid “sandwich” approach with fixed-time fluidization; directed flow is very sensitive to particlization and final-state treatment.	Not Sensitive: EOS dependence obscured by final-state treatment and particlization which strongly influence v_1 .
	Multi-fluid (3FD) 1601.03902 (Ivanov et al.)	Models collisions from $t = 0$ with two baryon-rich fluids exchanging energy-momentum via friction and forming a third “fireball” fluid. Pion flow reproduced better than proton flow; crossover EOS preferred. Neither species matches data across full $\sqrt{s_{NN}}$ range.	Not Sensitive: Direct EOS sensitivity partially obscured by afterburner and particlization effects.
	Multi-fluid with afterburner (THESEUS) 2403.02787v1	Adds UrQMD hadronic afterburner. In the FXT region, pion flow strongly modified, proton flow insensitive to EOS. Λ flow shows enhanced EOS sensitivity in baryon-rich regime; kaon flow proposed as a complementary probe.	Not Sensitive: Strange-hadron flow (Λ , K) sensitive to EOS in baryon-rich matter.
	Multi-fluid with fluctuation initial conditions (MUFFIN) 2312.11325	Contrasts with THESEUS results: proton v_1 significantly altered by SMASH afterburner, while pion v_1 remains largely unchanged. Focused on $\sqrt{s_{NN}} > 10$ GeV, where incomplete hadron-spectator coupling may limit accuracy.	Not Sensitive: EOS obscured by afterburner effects which depend on collision energy and spectator interactions.
Hybrid Parton Cascade	AMPT	Text	Text
Hadronic cascade	JAM 1601.07692	Pion and proton v_1 both consistent with data at 11.5–27 GeV when using a soft EoS with attractive mean-field interactions, but the model fails at 7.7 GeV.	Sensitive: Demonstrates sensitivity to effective mean-field potential; low-energy behavior problematic.
	JAM2 Mean-field with Skyrme-type potential as Lorentz vector 2109.07594 (Nara, Ohnishi)	Energy dependence arises from competition between compression (positive flow at low $\sqrt{s_{NN}}$) and expansion (negative flow at higher $\sqrt{s_{NN}}$). Reproduces proton v_1 from 2–20 GeV but fails to match rapidity-dependent net-proton yields near 20 GeV.	Not Sensitive: Minimum in dv_1/dy driven by competition between compression and expansion; dominated by duration of phases not the EOS.
	SMASH	Text	Text
	UrQMD	Text	Text

Tabulated Overview of Model implications for dv_1/dy

good match to minimum in dv_1/dy :
but not from softening in EOS

not sure if it reproduces the minimum...

→ sensitive to EoS but far from the data

softening in EOS doesn't create a
good match to minimum in dv_1/dy

only pion v_1 is sensitive

good match to minimum in dv_1/dy :
but not from softening in EOS

...from momentum-dependent hadronic MF

Big Picture Takeaway for dv_1/dy

Not all models with a softening produce a minimum in dv_1/dy , and not all models that produce a minimum in dv_1/dy do so with a softening.

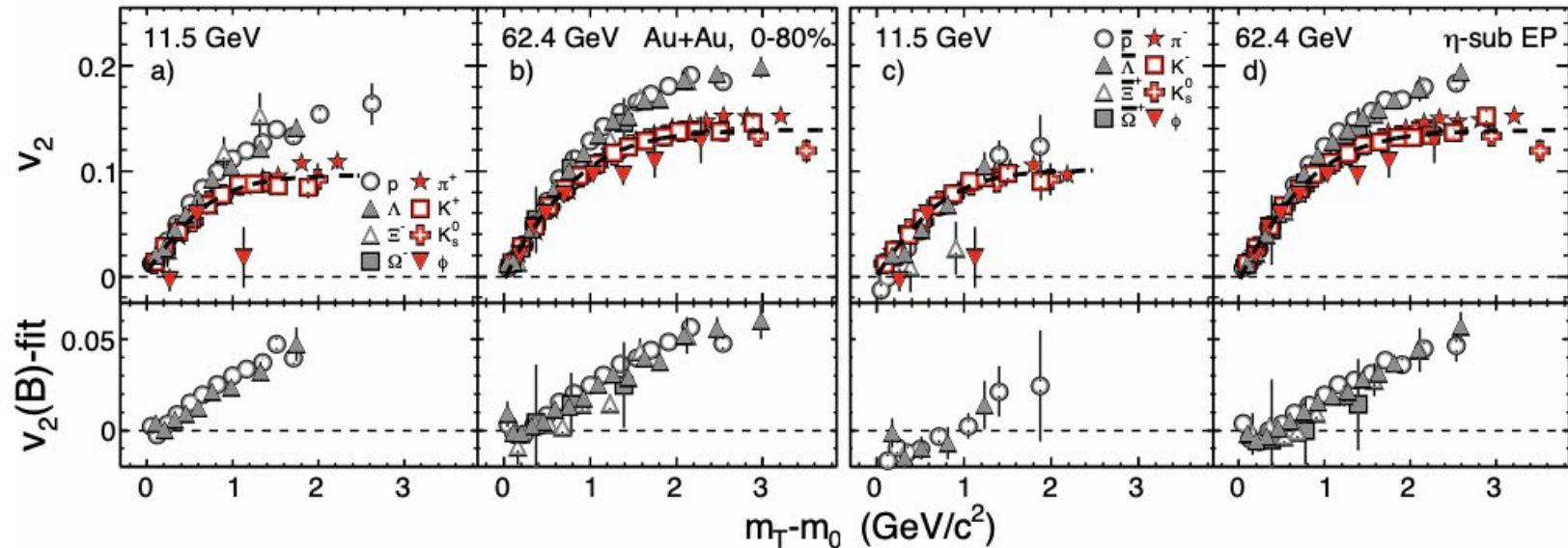
We conclude therefore that **the non-monotonic behavior of dv_1/dy cannot, at the moment, be linked to a softening in the EOS; other plausible explanations need to be considered.** Model space needs to be narrowed, including by constraining baryon stopping and initial distributions (hydro with a tuned initial state can explain the dip). Perhaps these modifications will also explain v_3 and HBT.

Non-monotonic behavior can be observed even in models with a boring EOS (for example from a transition from compression at low energy to expansion at higher energy): the hope that experiments could observe a non-monotonic trend and declare an EOS discovery seems too naive.

Models also suggest that some of the lore related to v_1 (established very early) may need to be revisited.

We recommend that 1) experiments prioritize measurements that elucidate baryon stopping dynamics including but not limited to the proton and anti-proton spectra across the widest rapidity and energy range possible and 2) dynamic models be modified to study baryon transport more robustly.

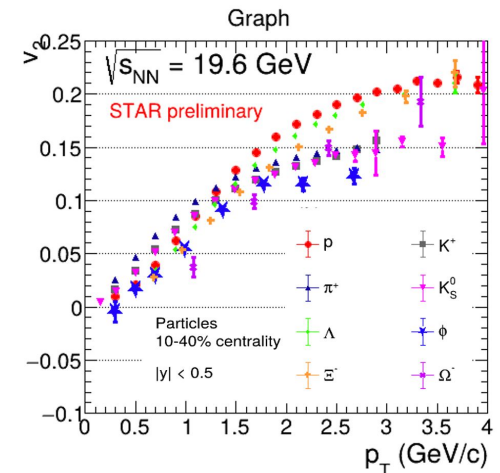
NCQ Scaling in the Collider Region



At intermediate p_T , meson and baryon v_2 and R_{CP} group together based on their NCQ instead of mass (see phi especially). We know of three interpretations: 1) hadronization by coalescence of flowing quarks, 2) relaxation time effects in viscous corrections, and 3) additive quark model for hadronic x-sections.

NCQ scaling from coalescence of flowing quarks is a “smoking gun” signal for QGP. Is that the correct interpretation?

At lower energies, splitting between particles and antiparticles obscures NCQ-scaling. As far as we can tell, scaling persists throughout the collider region. Can the splitting be understood based on coalescence from produced and transported quarks with different flows?



Additional Tests of NCQ Scaling

Is flow data consistent with coalescence from two pools of quarks: transported with higher flow (v_t) and produced with smaller flow (v_p)?

NCQ-scaling says

$$v_{q\bar{q}} = v_q + v_{\bar{q}}$$

$$v_{uud} = v_u + v_u + v_d$$

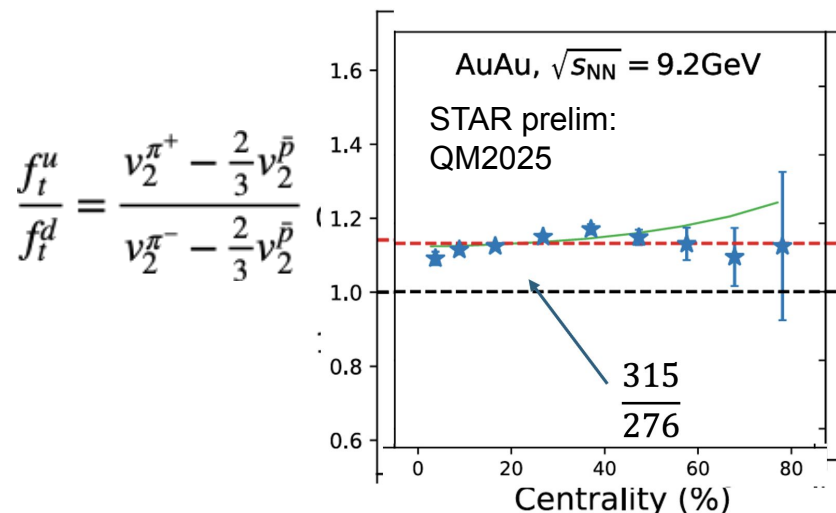
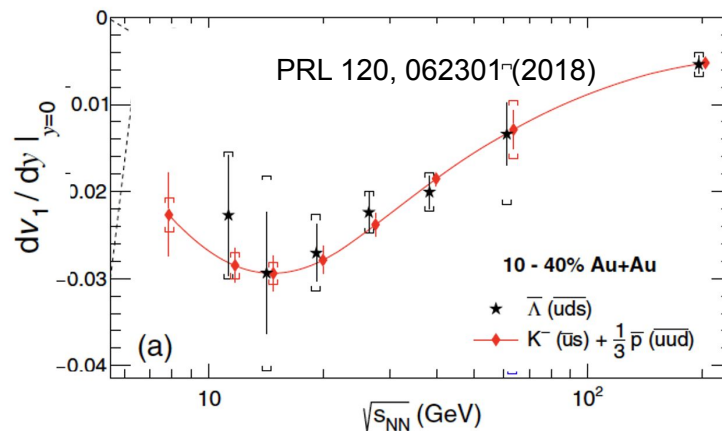
So we should be able to relate particle flows like:

$$v_{\bar{\Lambda}} = v_{\bar{u}\bar{u}\bar{d}} = v_{\bar{u}s} + \frac{1}{3}v_{\bar{u}\bar{u}\bar{d}} = v_{K^-} + \frac{1}{3}v_{\bar{p}}$$

where we've used $v_s = v_{\text{ubar}}$.

Some fraction of u's and d's are transported to mid-rapidity. The u/d ratio of transported quarks should match that of the incoming nucleus. If NCQ scaling applies, you can calculate the ratio of the fraction of transported u's and d's per pion (f_t^u/f_t^d) from the flow of pions and protons.

It matches the ratio of u/d in a Au nucleus.

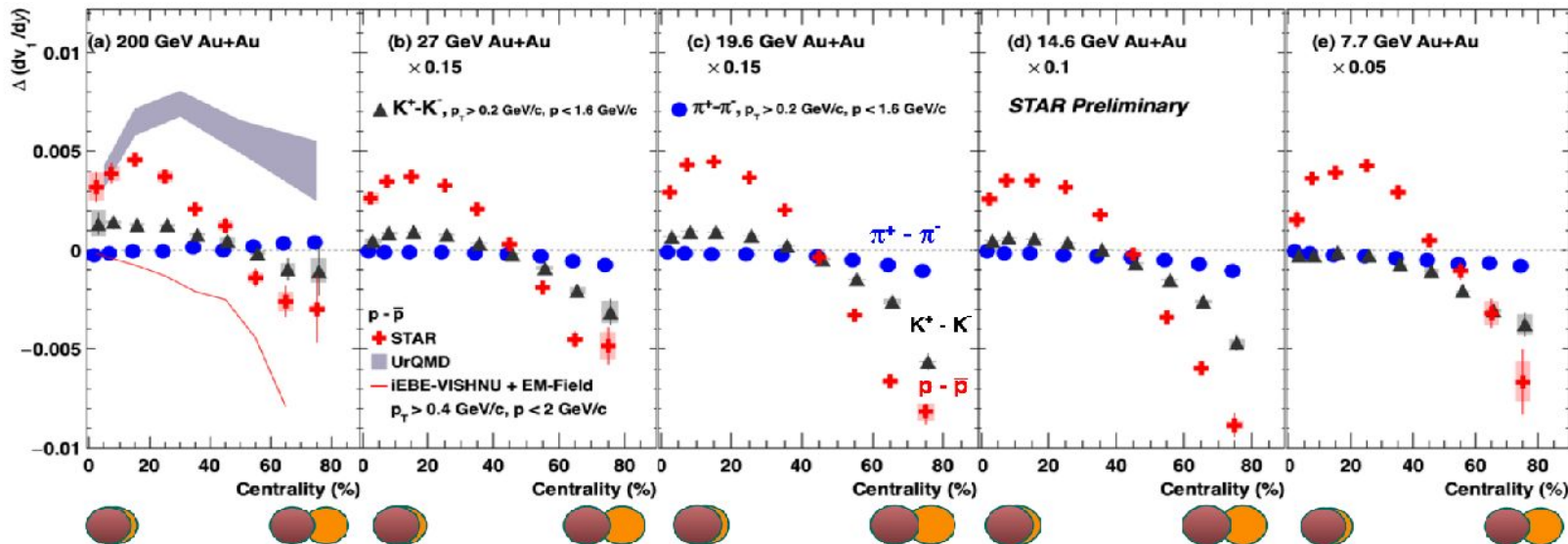


The coalescence picture seems to hold. Are there alternative explanations?

Splitting and E&M Fields?

The effect of E&M fields has been investigated to understand the splitting between particle and anti-particle v_1 .

So far, model comparisons are inconclusive and more investigation is needed. Especially if model predictions for this observable vary as much as dv_1/dy .



- **BES-II results of negative $d(\Delta v_1)/dy$ in peripheral collisions as expected from electromagnetic effects**
- Suggests dominance of Faraday+Coulomb effect in peripheral collisions
- Comparison to IEBE-VISHNU+EM field calculations indicates that the used **conductivity $\sigma = 0.023 \text{ fm}^{-1}$ falls within a reasonable range**

[PRC 98,055201, PRC 89 054905]

Major Recommendations

To better understand the non-monotonic behavior of dv_1/dy and $v_3/mult$ we recommend

- 1) experiments prioritize measurements that elucidate baryon stopping dynamics including but not limited to the proton and anti-proton spectra across the widest rapidity and energy range possible, and
- 2) dynamic models be modified to study baryon transport more robustly.

To arrive at more robust conclusions from NCQ-scaling studies,

- 1) model calculations need to be performed to provide a picture of what coalescence from a deconfined medium would look like in data at lower energies, and
- 2) a method needs to be devised to disambiguate the NCQ-scaling explanations: finite relaxation time effects, hadronic cross sections, and quark coalescence. Are we there?

We need a better understand of the splitting between particle and anti-particle flows, the role of transported vs produced quarks, and E&M fields. Calls for

- 1) extensive model comparisons (with mean-fields or chemical potentials) need to be made, esp with high stats data sets. Can models reproduce this? AMPT?

Discussion topic: A host of non-monotonic trends show up at 15-20 GeV. Are they a red-herring? A discovery (of what)? How do we come to a conclusion?

The end

Produced/transported quarks (Iurii):

I did a shallow googling, which led me to this STAR paper:

<https://doi.org/10.1016/j.physletb.2025.139245>

which includes a statement “Transported quarks undergo more interactions” and there refers to a study in UrQMD (not by UrQMD authors though)

<https://journals.aps.org/prc/abstract/10.1103/PhysRevC.86.044901> , so it might be the study that coined the term (?).

What the study does is not really produced or transported quarks, but rather produced or transported hadrons (after all, quarks are not DOF in UrQMD). The main point is only about the initial scatterings, which are treated by PYTHIA6, and hadrons with quarks from the ends of Lund strings are tagged as “transported”, the rest are tagged as produced. Then all hadrons do what hadrons usually do - they rescatter and decay if they should. At a high enough collision energy such procedure would indeed link transported hadrons to transported quarks, but at lower energies I feel that the link is not really accurate, and what it does is more like looking at hadrons with larger p_z versus hadrons with smaller p_z .

If there are other theory/pheno studies that would somehow demonstrate the picture, I’d be happy to see it.

Discussion of Models

TABLE I: Internal machinery of models.

Model type	Initial state	Dense phase	Final state
1-fluid hydro	At $t = 0$, two blobs of the same fluid smash into each other. Each fluid represents an incoming nucleus.	All evolution is compression and expansion of a single fluid	I would say - does not matter, because what is computed is not dv_i/dy but a proxy for it, dp_x/dy of fluid. There are no particles DOF in the final state.
Caveat: no baryon transparency - leads to Landau hydro picture.			
3-fluid hydro	Two blobs of baryon-rich fluids (incoming nuclei) pass through each other and lose energy and momentum via friction. The lost energy and momentum goes into creation of a third fluid.	There is no separation into initial and hydro stage, because hydro applies from $t = 0$. EoS in the fluid(s) can be EoS with PT or purely hadronic EoS - both were tried by Ivanov.	Once energy density is low enough locally in space-time, switch to particle DOF via Cooper-Frye. The standard argument to apply Cooper-Frye: mean free path (see note 1 below).
Caveat: initial NN scatterings = inter-penetration of nuclear fluids; friction is not computable from kinetic theory, so it is one dominant free parameter.			
Transport + hydro	Initial scatterings are handled by hadronic transport. If a scattering has $\sqrt{s} > \text{several GeV}$, it is handled by PYTHIA (therefore string decay). At a fixed $\tau = \tau_0$ or $t = t_0$, the hadrons and pre-hadrons are suddenly melted together to form a fluid (a forced) fluidisation).	Fluid with a relation $p(e)$, $T(e)$, ... that correspond to a medium one chooses to model.	Same: once energy density is low enough locally in space-time, switch to particle DOF via Cooper-Frye (see note 1 below). Final-state hadrons are fed to hadronic cascade (at different times!) to rescatter and decay.
Caveat: applicability of forced fluidisation; medium may not look like fluid when fluidised [3], [4]			
Parametrized initial state	initial state is parametrised (no dynamics)	Same as above	Same as above
Dynamic fluidisation	Same as in transport + hydro, but fluidisation happens dynamically once the system is dense enough locally, cell-by-cell.	Same as above	Same as above
Same caveat as in transport+hydro models.			
Pure hadronic transport	Same as in transport+hydro, but with no fluidisation. Note that the initial "hard" scatterings are modelled with PYTHIA - which defines the baryon stopping to a big degree (am I right here?).	No separation into initial, intermediate dense and late dilute phases. Effectively the DOF are hadronic particles at all times.	No separation here as well. The entirety of evolution is modelled with one approach.
Caveat: only hadronic DOF. One can emulate softening of the EoS as if there was a transition to QGP.			
Parton + hadron transport (AMPT, PHSD)	Initial state strings (representing each initial NN scattering) produce partons. Partons re-scatter with a certain (fixed or not) cross section σ .	Partonic scatterings, on-shell (AMPT) or off-shell (PHSD). σ can be adjusted to generate enough flow.	Coalescence into hadrons (when?). Then hadrons re-scatter and decay.

Presentation Outline

Big picture lessons from flow in the collider region: NCQ, EOS extraction, Bayesian analysis, Initial-state fluctuations and v_n , Reaction plane correlators/longitudinal decoherence, Multi-phase hydro. What else?

Deviations from the simple picture:

dv_1/dy : minimum, v_3 /mult minimum

ncq: obscured by splitting between particles and antiparticles

Major recommendations

I would like a discussion of the general outline of how a model works. We speak of transport. - what does this mean? To an experimentalist, it means a hadronic transport “afterburner” like the hadronic pieces of URQMD, JAM, SMASH (to name a few). In the same vein - what is “hydro”. Hydro equations representing the behaviour of what fluid? To an experimentalist, this means a QGP. The typical chain (for an experimentalist) is 1) initial condition often given by Glauber or a “glasma”, then hydro (where the fluid is understood to be a QGP), then a hadronization via Cooper-Frye or ISS etc, to a hadronic transport (URQMD...) giving the hadrons that experimentalists measure. I have now learned that in some models the hadronic phase can (and is) described via hydro. I think the experimental community gets this, as this is done for neutron stars etc, but we did not know that this is true in our community, since it is thought that the above chain is what is being done. Clearly we need to be educated. There is a nice table of models later in these slides - but I needed to understand this, to understand the table. Am I the only one who is confused?

Q&A (1) for the questions from the first slide

We speak of transport. - what does this mean? To an experimentalist, it means a hadronic transport “afterburner” like the hadronic pieces of URQMD, JAM, SMASH (to name a few).

Transport solves Boltzmann equation (roughly speaking). Which has two limitations:

i) it is applicable when the system is dilute, and ii) it typically includes only hadronic DOF.

At top RHIC/LHC, both i) and ii) fail.

Therefore we employ hydro, and switch to transport only when the system is dilute enough and is in hadronic phase (according to fluid-dynamic EoS).

But, one can run transport alone, keeping in mind the limitations. The limitations are less broken at lower energies.

Hydro equations representing the behaviour of what fluid? To an experimentalist, this means a QGP.

Hydro equations represent the behaviour of dense medium. What the medium is, depends on the equation of state that one imports into the hydro. It can be dense hadronic medium or a two-phase medium which is QGP above some temperature and hadronic matter below.

Allow me for a remark: simulation codes (in heavy ions) are typically not equipped with checks and warnings telling you explicitly “you should not run this model for this system or that $\sqrt{s}$ ” or “the simulation does not appear to be consistent; I quit”.

Therefore, for example, you may encounter someone running pure hadronic cascade for $\sqrt{s}=200$ GeV. The code will run and will produce you some results. It is essentially on the user to judge whether the simulation makes sense (inconsistent or not) and how valid the results are.

Q&A (2)

The typical chain (for an experimentalist) is 1) initial condition often given by glauber or a “glasma”, then hydro (where the fluid is understood to be a QGP, then a hadronization via Cooper-Frye or ISS etc, to a hadronic transport (URQMD...) giving the hadrons that experimentalists measure. I have now learned that in some models the hadronic phase can (and is) described via hydro.

Yes, what you’ve described is a typical simulation chain for high energies. How does it change for lower energies - see a next slide “Progress on Extending Hydro to Lower Energy”

The hadronic phase can be described by hydro in most models (because the EoS extends down to low temperatures) but the validity of such description breaks down. Therefore, typically, hydro is stopped somewhere when the system is already in hadronic phase but is not very dilute yet. It happens like that in **all hydro models**. It may be a subtle thing, so theory colleagues might not have had time or opportunity to explain it carefully - it happens, no worries. Modern simulation chains are complex.

In fact, I am not aware if anyone switches QGP-level hydro straight into particle-level hadronic system. It isn’t even clear how to do it.

Q&A (3)

I think the experimental community gets this, as this is done for neutron stars etc, but we did not know that this is true in our community, since it is thought that the above chain is what is being done.

I am not sure what neutron star simulations have to do with this.
But, as I was saying - it is common knowledge among hydro practitioners in heavy ions - you switch to particle degrees of freedom (stop the fluid description) when the supposed particles are already hadrons. Otherwise, it gets more complicated.

Q&A (4)

is it clear how to propagate and preserve fluctuations through the evolution and freezeout?

It is actually a topic (maybe *the* topic) for the Simulations WG, so I'd put only a brief answer: It depends how the critical dynamics is modelled. If it is Hydro+, then I would say it is WIP (Misha, Maneesha) how to transfer such non-hydro modes into fluctuations after particlization, the rest of evolution is a business of hadronic cascade. If it is a conventional hydro with stochastic noise (Tomas Schaefer et al), then it is more straightforward to do so.

Are any of the models UrQMD, SMASH, JAM, ~~EPOS~~, reliable enough to carry the heavy load at lower energies where more of the evolution and more of the system is out of equilibrium?

UrQMD, SMASH, JAM are actually designed to work better at (much) lower energies, where there's no equilibrium. The longer the mean free path is, the more dilute system is, the better is the applicability of Boltzmann equation. I rather hear concerned voices regularly asking why does it make sense to use hydro there.

Can a BUU code with hadronic DoF but with an EOS with a QGP be reliably used in the QGP phase?

I think not - mainly because it doesn't work well for dense system. A good example would be to run a hadronic cascade for top RHIC energy, or even for top SPS - it will fail the radial and elliptic flows (there are plots/references I can dig up to support this). Whereas if one does a curious exercise and runs a hydro with fully hadronic EoS, because the EoS will be quite stiff, the radial flow will even overshoot the data :D But, such exercise would be meaningless because we know (Lattice QCD, etc) that at high densities hadrons are supposed to melt, and hadronic EoS at $T=200$ MeV is a nonsense.

Is it obvious that hydro, with no DoF and assuming equilibrium, is preferred for modeling a QGP phase over a BUU code which doesn't assume equilibrium but propagates hadronic DoF?

At $\sqrt{s} > 20$ GeV I would say yes, definitely it is. A BUU code won't describe most of the observables. Maybe it will get dN/dy and maybe $dN_{\text{net proton}}/dy$ and somehow maybe $v_1(y)$ but not anything else (flow).

Hydro can be derived from BUU: with computational advances, can't we push BUU further so that we are less reliant on hydro at low energy?

... A quick response (may be incorrect): Yes it can be derived, with a specific RTA approximation for the collision kernel, (not what the codes like UrQMD/SMASH/... have, but it may be not crucial). Well, there are examples of using transport for quark-and-gluon system: AMPT, BAMPS (orphaned?), PHSD. They may have their own caveats. Out of the tip of my head - having a properly working hadronization is tricky (e.g. there will be runaway free quarks, one has to deal with that). There may be other caveats - here my knowledge ends.

BTW, most of the above should be (hopefully will be) discussed in the Simulations WG. We did a bit of write-up on Overleaf, but it may look quite condensed.

Those are very good questions for the Simulations WG, I think. Do you agree?

Summary of Model findings for dv_1/dy

Big picture: Not all models with a softening produce a minimum in dv_1/dy , and not all models that produce a minimum in dv_1/dy do so with a softening.

We conclude therefore that **the non-monotonic behavior of dv_1/dy cannot, at the moment, be linked to a softening in the EOS; other plausible explanations need to be considered.** Model space needs to be narrowed, including by better constraining baryon stopping and the initial baryon distributions.

Non-monotonic behavior can be observed even in models with a boring EOS: the hope that experiments could observe a non-monotonic trend and declare a discovery was too naive.

Models also suggest that some of the lore related to v_1 (established very early) may need to be revisited.

We recommend that 1) experiments prioritize measurements that elucidate baryon stopping dynamics including the proton and anti-proton spectra across the widest rapidity and energy range possible and 2) dynamic models be modified to study baryon transport more robustly.

When you say that v_1 (or dv_1/dy) is not sensitive in a model to the EOS, what does this mean? For instance, in JAM - v_1 in general is very sensitive to the potential. Doesn't the potential affect the EOS (EOS is the relationship between the

Overview of the Big Picture in the Collider Region

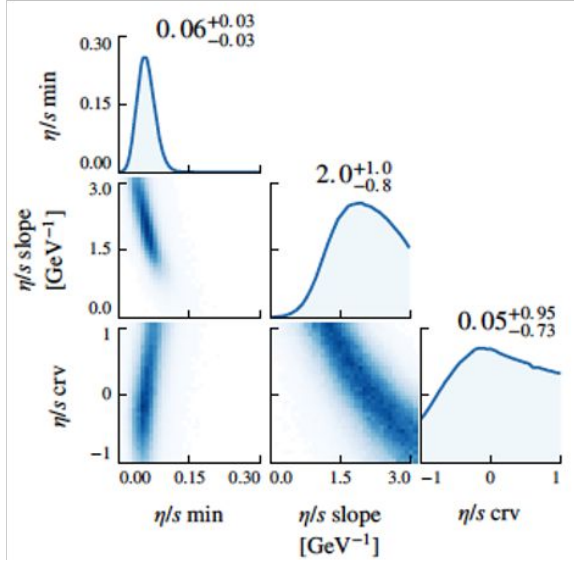
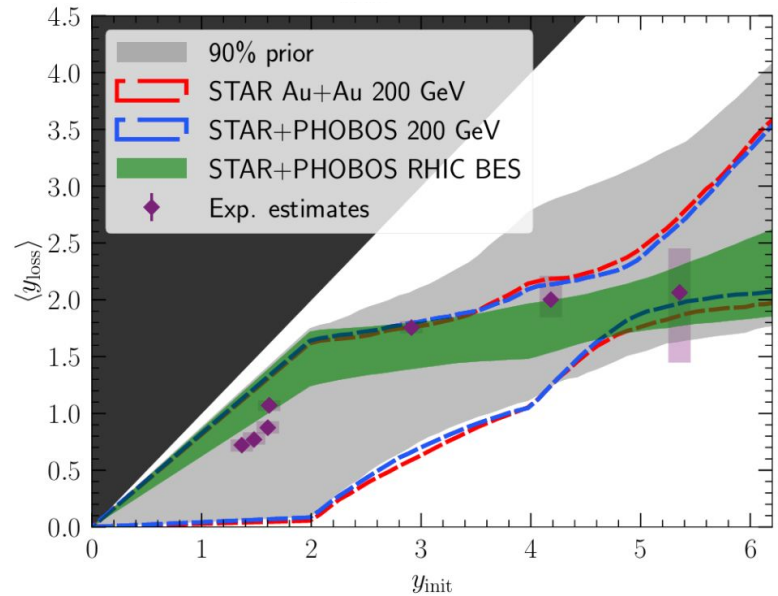
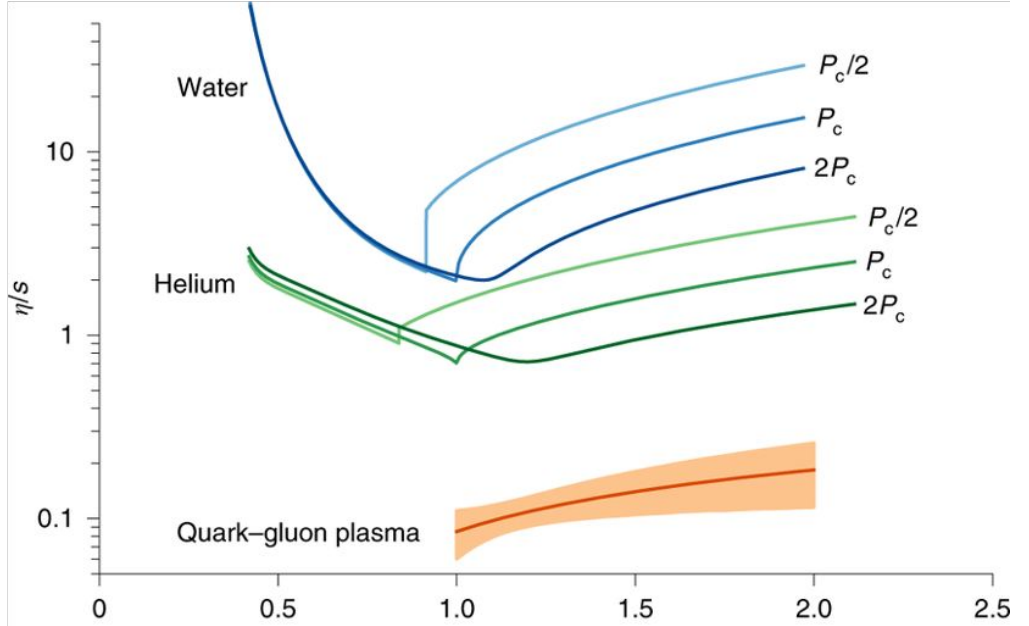


TABLE II. The experimental measurements in Au+Au collisions used in this Bayesian inference study.

$\sqrt{s_{NN}}$ (GeV)	STAR	PHOBOS
200	$dN/dy(\pi^+, K^+, p, \bar{p})$ [54] $\langle p_T \rangle(\pi^+, K^+, p, \bar{p})$ [54] $v_2^{\text{ch}}\{2\}$ [57], $v_3^{\text{ch}}\{2\}$ [58]	$dN^{\text{ch}}/d\eta$ [55] $v_2^{\text{ch}}(\eta)$ [56]
19.6	$dN/dy(\pi^+, K^+, p)$ [59] $\langle p_T \rangle(\pi^+, K^+, p, \bar{p})$ [59] $v_2^{\text{ch}}\{2\}$ [57], $v_3^{\text{ch}}\{2\}$ [58]	$dN^{\text{ch}}/d\eta$ [55]
7.7	$dN/dy(\pi^+, K^+, p)$ [59] $\langle p_T \rangle(\pi^+, K^+, p, \bar{p})$ [59] $v_2^{\text{ch}}\{2\}$ [57], $v_3^{\text{ch}}\{2\}$ [58]	



Backups

Summary of NCQ in the Collider Region

Testing Coalescence 1 :
transported-produced/quark-flavors – v2
(Xiaotong)

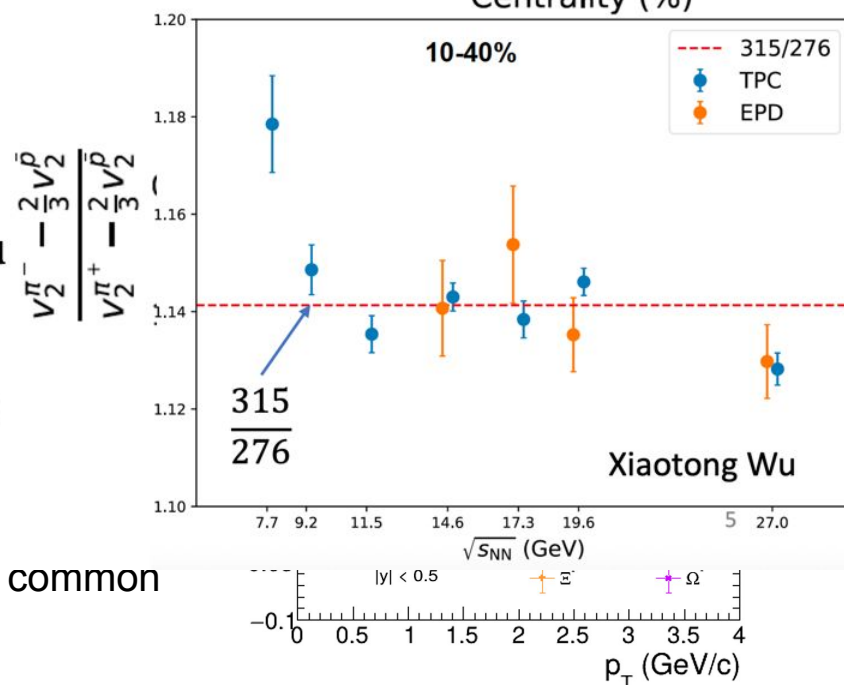
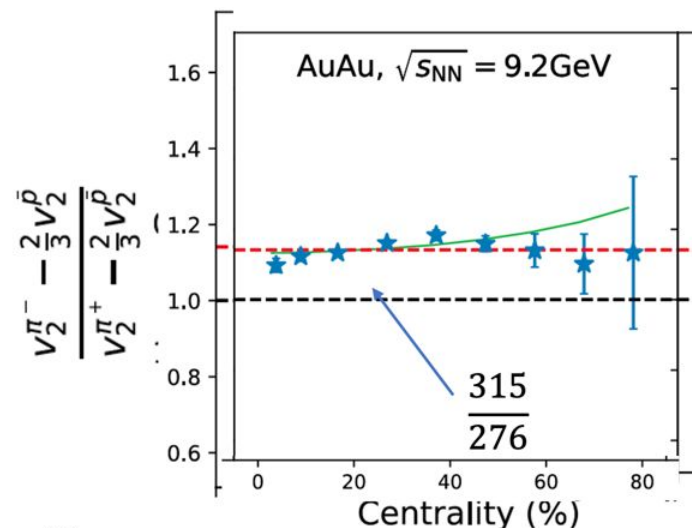
- ❑ NCQ scaling assumes the constituent quarks have the same p_T and the same v_n
- ❑ If we further differentiate between
 - Transported and produced quarks
 - Different quark flavors

$$\pi^- : d\bar{u} \quad \pi^+ : u\bar{d} \rightarrow$$

$$\frac{N_{\text{trans},d}^{\pi^-}}{N_{\text{trans},u}^{\pi^+}} = \frac{v_2^{\pi^-} - 2v_2^{\bar{u}}}{v_2^{\pi^+} - 2v_2^{\bar{d}}} = \frac{315}{276} = 1.14 \text{ for Au}$$

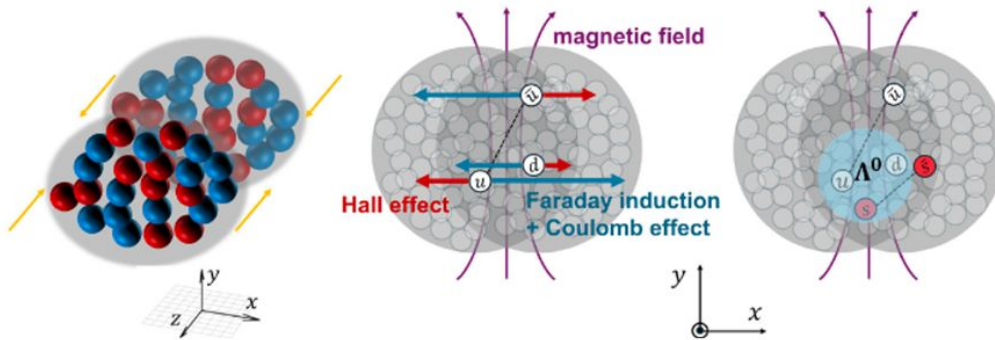
If quark coalescence holds (partonic system)

that plotted vs $m_T - m_u$, the picture holds for the more common meson and baryons.



Testing Coalescence 2, searching for the EM field - v1

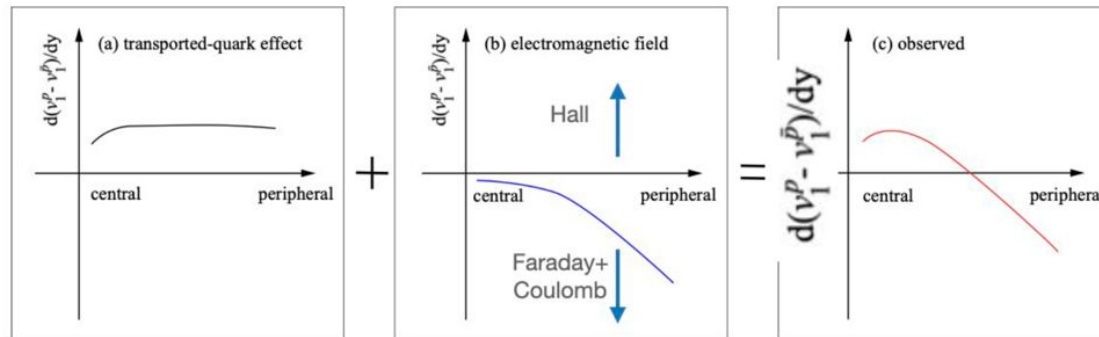
(Gang Wang, Aditya Dash)



Previous PRX paper reported the effect in Peripheral events for protons (charged)

What about for Λ^0 (uncharged)?

Invoke coalescence



[STAR, Phys. Rev. X 14, 011028]

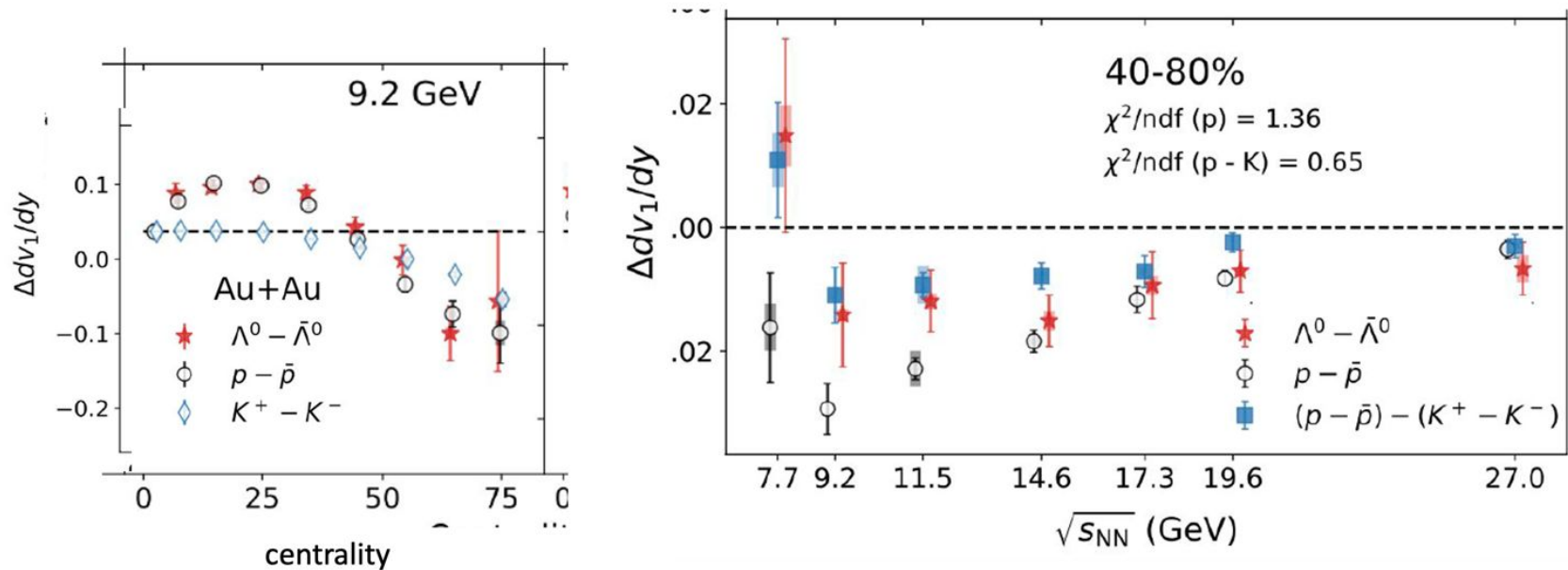
- EM effects act on quarks before hadronization.
- Coalescence: $v_1(\text{hadron}) = \sum v_1(\text{quarks})$
- Λ behaves like charged particles,

To test coalescence

$$\Lambda^0 - \bar{\Lambda}^0 = (p - \bar{p}) - (K^+ - K^-)$$

???

Testing Coalescence in v1, searching for the EM field

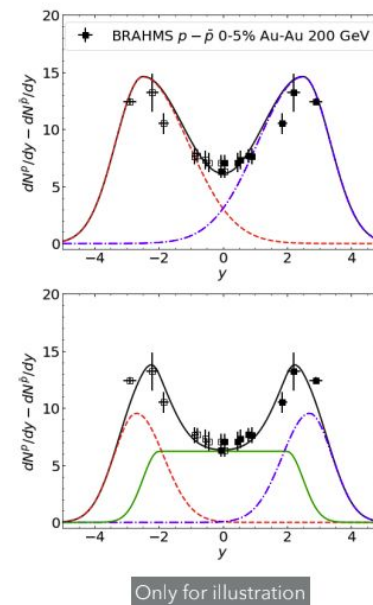
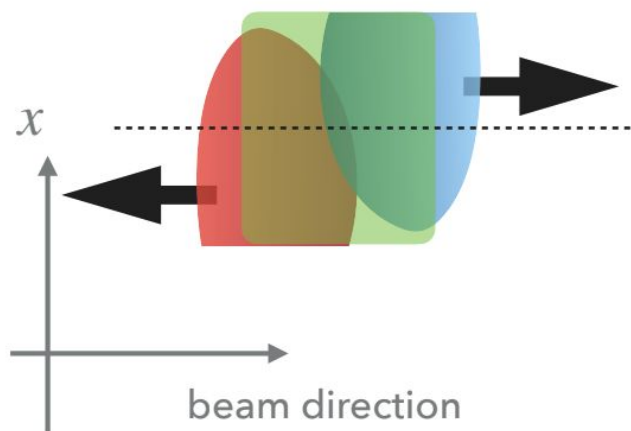
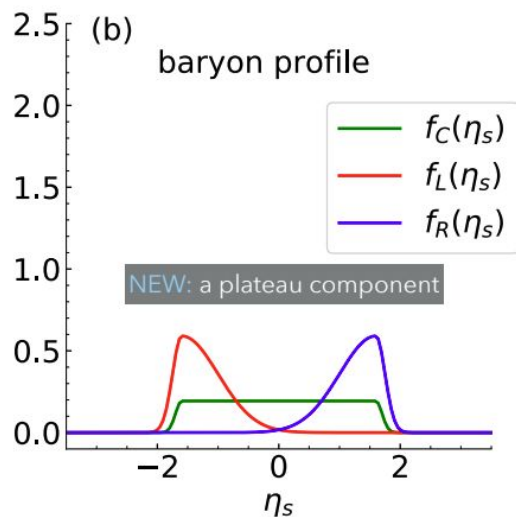


Conclusions (with caveats/concerns)

- ✓ Coalescence test for Lambda v1 works
- ✓ EM field effect like protons (Faraday+Coulomb)
(in peripheral collisions)

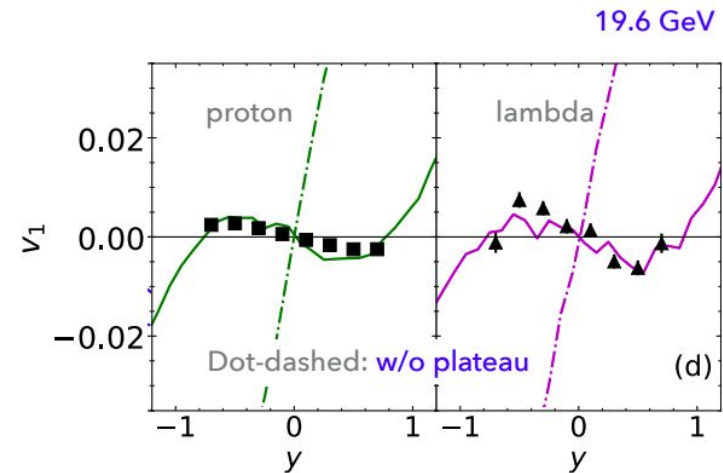
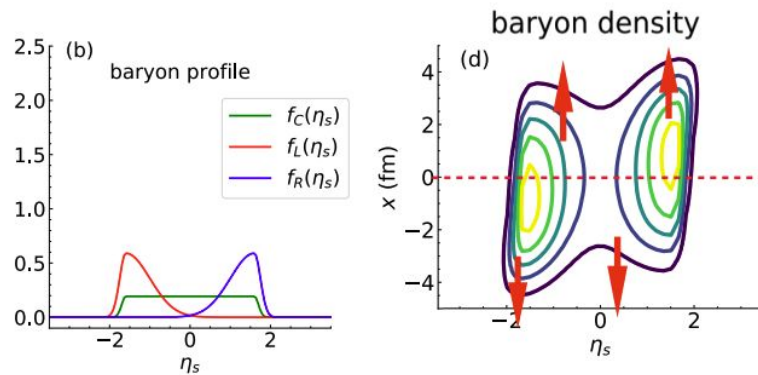
NEW PARAMETRIC BARYON INITIAL CONDITION

9



- To explain the rapidity distributions of net proton yields and baryons' directed flows simultaneously, a plateau component is favored

String junction: Kharzeev, PLB 378, 238 (1996); Sjostrand & Skands, NPB 659, 243 (2003)



LD, C. Shen, S. Jeon & C. Gale, PRC 108 (2023) L041901

- ▶ Transverse expansion + asymmetric distribution of baryon density along $x \Rightarrow$ double sign change in the slope of $v_1(y)$ for baryons at 19.6 GeV, and positive slope at 7.7 GeV
- ▶ The sign change of $dv_1(y)/dy|_{y=0}$ is naturally reproduced without a 1st-order phase transition.