# Opportunities for bulk physics with sPHENIX

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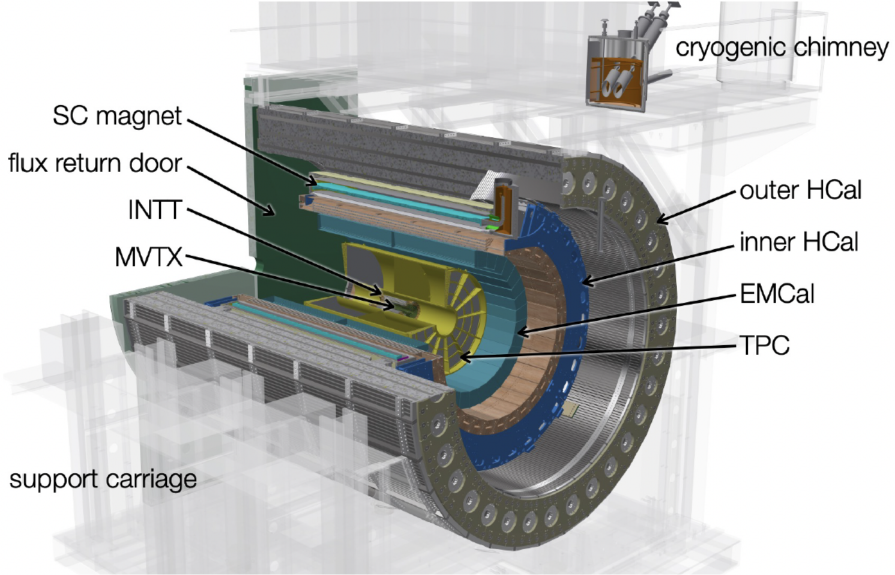
# Introduction

- What is bulk physics?
  —Event characterization
  —Hadron yields
  —Momentum spectroscopy (at low $p_T$)
  —Flow observables
  —Correlations (an overly broad category that means many different things)
- What is not bulk physics?
  —Heavy flavor production (both open and closed HF)
  —Jet spectroscopy
  —Jet structure measurements
  —Id est "the stuff that sPHENIX was built to measure"
- Where do the two meet?
  —Heavy flavor flow
  —Jet/bulk comparisons
  —Jet $v_n$
- NB none of these is meant to be an exhaustive list

# sPHENIX




Event characterization with MBD and sEPD

sPHENIX physics program requires excellent tracking for many key observables

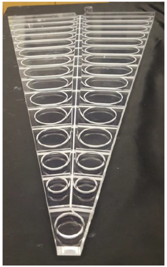
Key lesson from LHC for soft physics: great tracking means great physics

PID unlikely: primarily a physics problem (size) and maybe also a geopolitics problem (supply chain)

# MBD & sEPD

**Minimum Bias Detector (MBD) [3.51 < |η| < 4.61]**

- Reuse of the PHENIX Beam-Beam Counter
- 128 channels of 3 cm thick quartz radiator on mesh dynode PMT
- 120 ps timing resolution



**sPHENIX Event Plane Detector (sEPD) [2.0 < |η| < 4.9]**

- 1.2-cm-thick scintillator w/ wavelength shifting fibers
- 2 wheels of 12 sectors with 31 optically-isolated tiles = 744 channels
- Provides significant improvement in the event plane resolution

Hideki Okawa Strange Quark Matter 2022

# sPHENIX run plan

| Year | Species | $\sqrt{s_{NN}}$ [GeV] | Cryo Weeks | Physics Weeks | Rec. Lum. $\lvert z \rvert$ <10 cm | Samp. Lum. $\lvert z \rvert$ <10 cm |
|---|---|---|---|---|---|---|
| 2023 | Au+Au | 200 | 24 (28) | 9 (13) | 3.7 (5.7) $nb^{-1}$ | 4.5 (6.9) $nb^{-1}$ |
| 2024 | $p^{\uparrow}p^{\uparrow}$ | 200 | 24 (28) | 12 (16) | 0.3 (0.4) $pb^{-1}$ [5 kHz]<br>4.5 (6.2) $pb^{-1}$ [10%-$str$] | 45 (62) $pb^{-1}$ |
| 2024 | $p^{\uparrow}$+Au | 200 | – | 5 | 0.003 $pb^{-1}$ [5 kHz]<br>0.01 $pb^{-1}$ [10%-$str$] | 0.11 $pb^{-1}$ |
| 2025 | Au+Au | 200 | 24 (28) | 20.5 (24.5) | 13 (15) $nb^{-1}$ | 21 (25) $nb^{-1}$ |

- Year 1 provides >25 billion events of Au+Au
  —Year 1+3 provides > 114 billion events (and up to 141 billion)
- Year 2 provides >5 billion events of p+Au (hopefully 17 billion)

# Intermission

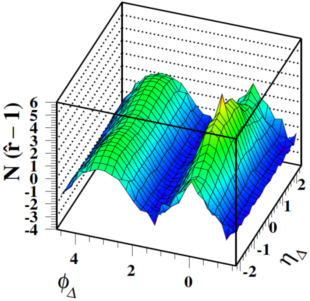
Correlations

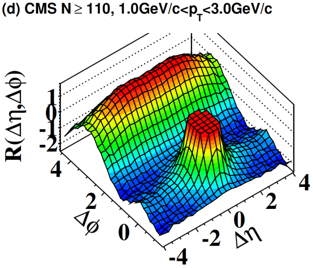
# Introduction

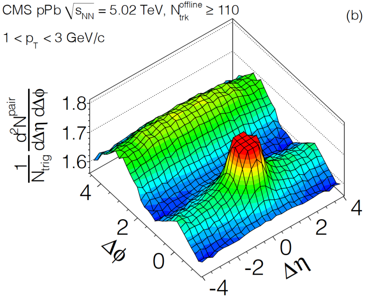
- There are many different kinds of correlations, including ones that are squarely in the realm of hard physics
- Very roughly, there are three categories
  —Multiplicity correlations
  —Momentum correlations
  —Angular correlations
- Since sPHENIX will probably not have PID certain kinds of correlations won't be possible, e.g. femtoscopy
- Most of the correlations that sPHENIX can do can also be done, and have been done, by STAR
- The main advantage with sPHENIX is the very high statistics; secondarily, different systematics because of different detector design may be of some benefit

# The ridge

STAR, PRC 73, 064907 (2006) CMS, JHEP 1009, 091 (2010) CMS, PLB 718, 795 (2013)



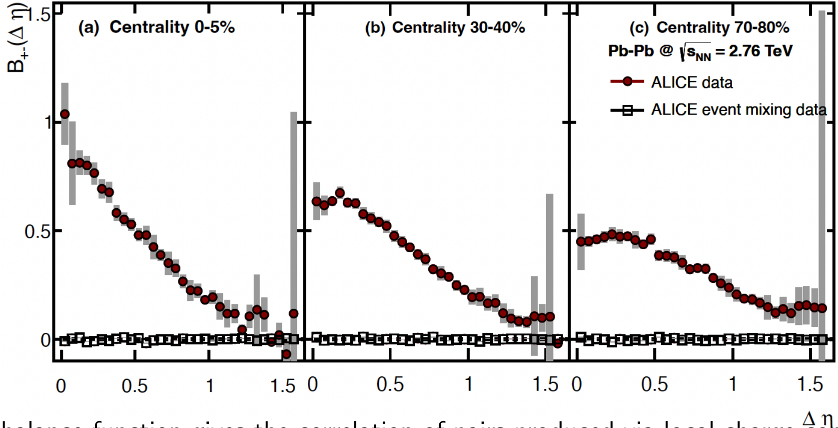




Extended structure away from near-side "jet" peak interpreted as collective effect due to presence of QGP

- First discovered by STAR in Au+Au in 2004 (PRC 73, 064907 (2006) and PRL 95, 152301 (2005))
- Realized by STAR to be flow in 2009 (PRL 105, 022301 (2010))
- First found in small systems by CMS (JHEP 1009, 091 (2010) and PLB 718, 795 (2013))

# Balance functions

ALICE, Phys. Lett. B 723, 267-279 (2013)



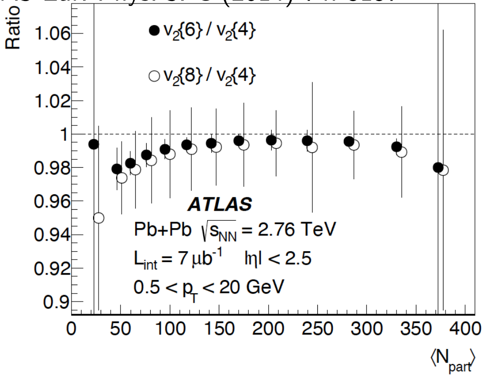

- The balance function gives the correlation of pairs produced via local charge conservation
- There are many different ways of measuring it, some of them “accidental”
  - —S. Schlichting and S. Pratt, Phys. Rev. C 83 (2011) 014913
  - —S.A. Voloshin and R. Belmont, Nucl. Phys. A 931 (2014) 992-996

# Intermission

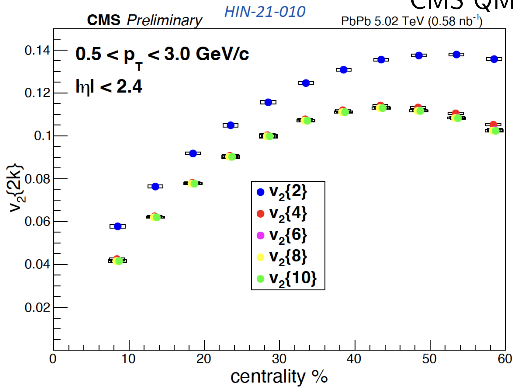
Flow observables

# Flow measurements in Au+Au

ATLAS Eur. Phys. J. C (2014) 74: 3157



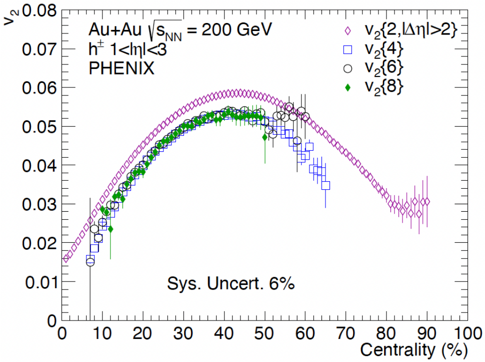

CMS QM2022

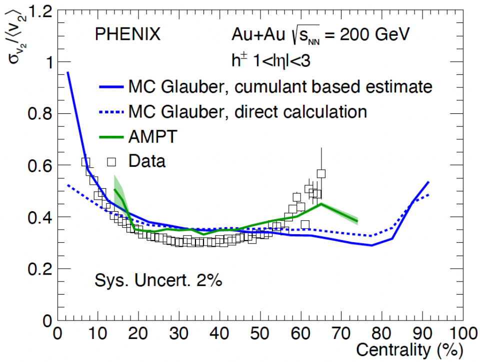



- sPHENIX can measure $v_2\{2,4,6,8\}$ with very high precision
  —Roughly, $v_2\{2\} = \sqrt{v_2^2 + \sigma^2}$ and $v_2\{4,6,8\} \approx \sqrt{v_2^2 - \sigma^2}$
  —Deviations of ratios from unity give insights into higher moments of $v_2$ distribution
- Can definitely measure $v_2\{10\}$, but not clear (yet) what level of sensitivity can be obtained

# Flow measurements in Au+Au

PHENIX, Phys. Rev. C 99, 024903 (2019)




- You can do a lot with ~1 billion events...
- ...so you can do a lot more with >25 billion events!

# Flow measurements in Au+Au

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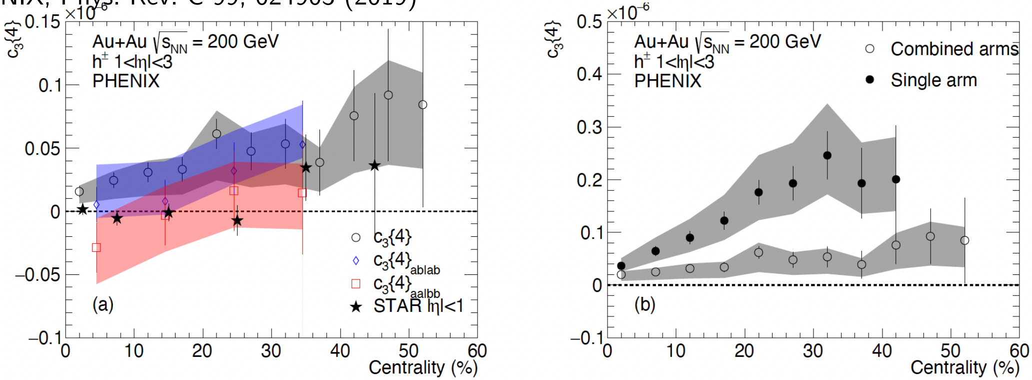
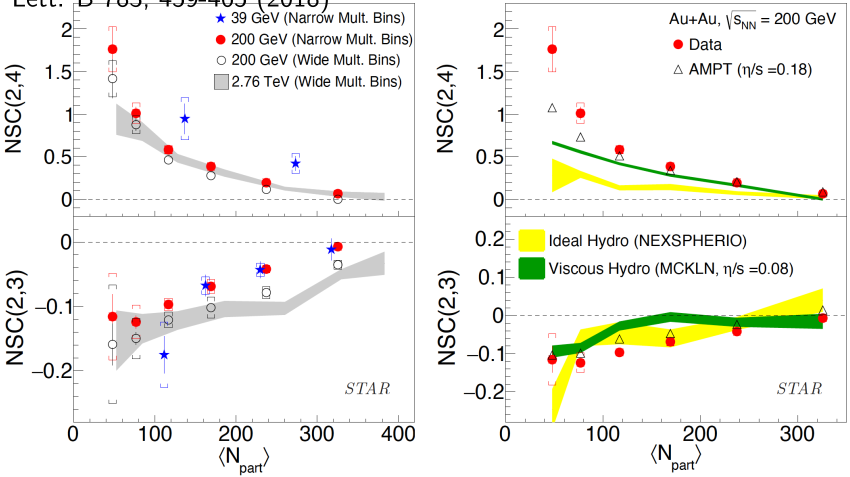



- Previous observation of interesting rapidity dependence of $v_3\{4\}$ comparing STAR $|\eta| < 1$ and PHENIX $1 < |\eta| < 3$
- Can obviously do measurement with central barrel $|\eta| < 1.1$, but maybe also with sEPD to get more information about rapidity dependence $2.0 < |\eta| < 4.9$

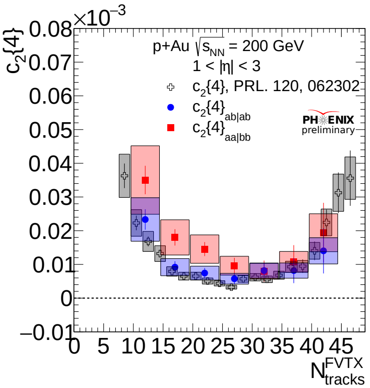
# Flow measurements in Au+Au

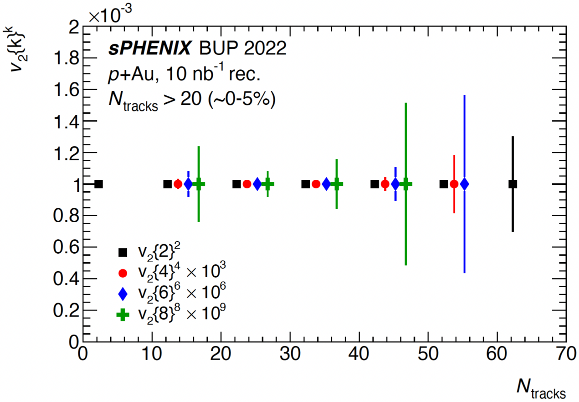
STAR, Phys. Lett. B 783, 459-465 (2018)




- NSC($n$,$m$) gives correlations between $n$-th and $m$-th harmonics
- sPHENIX can improve these with more statistics, add higher harmonics, etc

# Flow measurements in $p$+Au

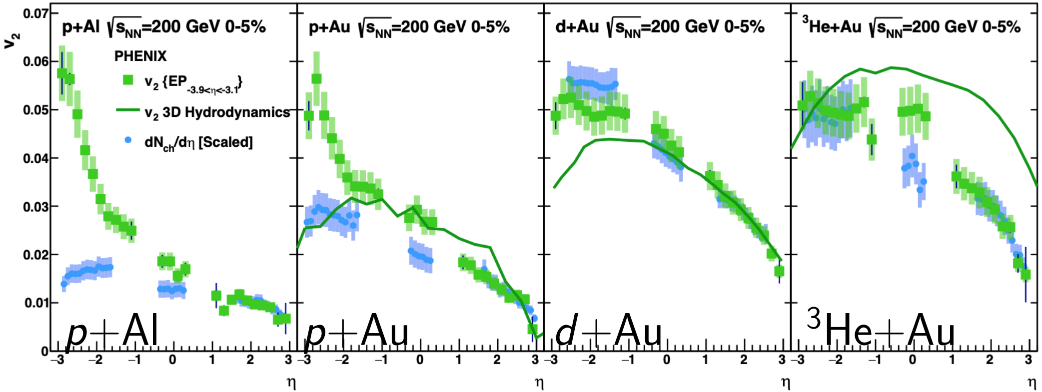



- Pretty big opportunity to get a really nice measurement of cumulant $v_2$ in $p$+Au
- In the PHENIX measurement ($1 < |\eta| < 3$) we see the higher moments swamp the mean, so that the cumulant is positive (and the $v_2\{4\}$ is complex-valued)
- The situation is different for sPHENIX, which will measure at midrapidity $|\eta| < 1.1$

# Flow measurements in $p$+Au

PHENIX, Phys. Rev. Lett. 121, 222301 (2018)




- $v_2$ vs $\eta$ in $p$+Al, $p$+Au, $d$+Au, and $^3$He+Au
- Good agreement with 3D hydro for $p$+Au and $d$+Au (Bozek et al, PLB 739, 308 (2014))

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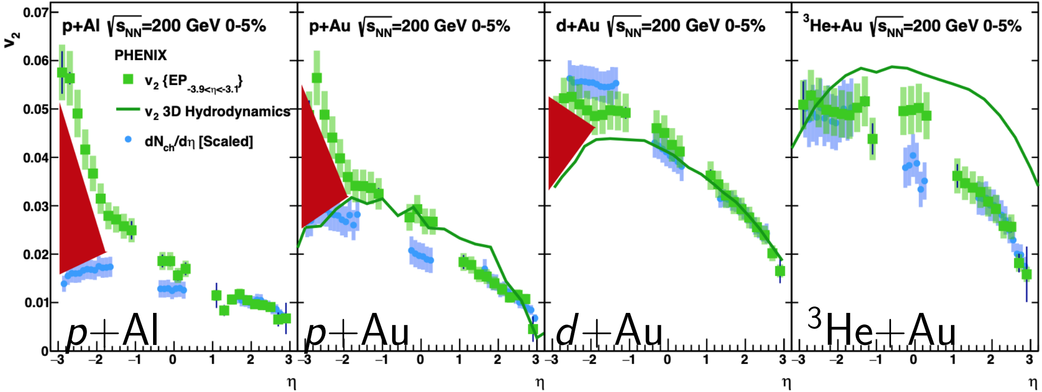


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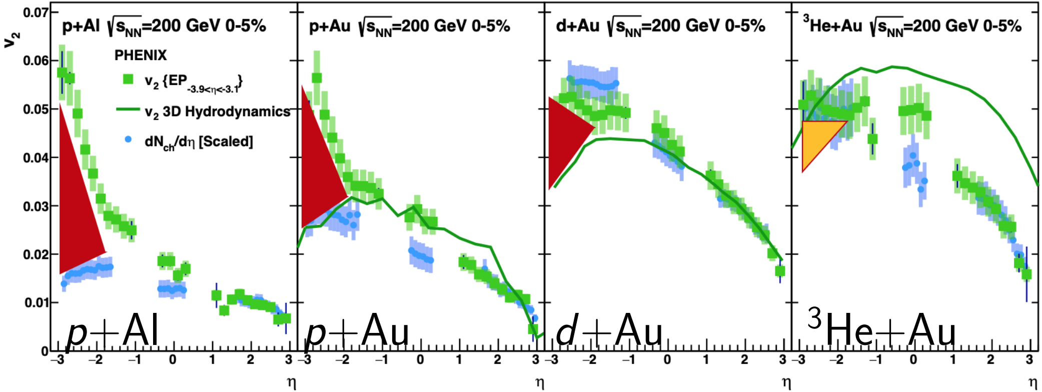


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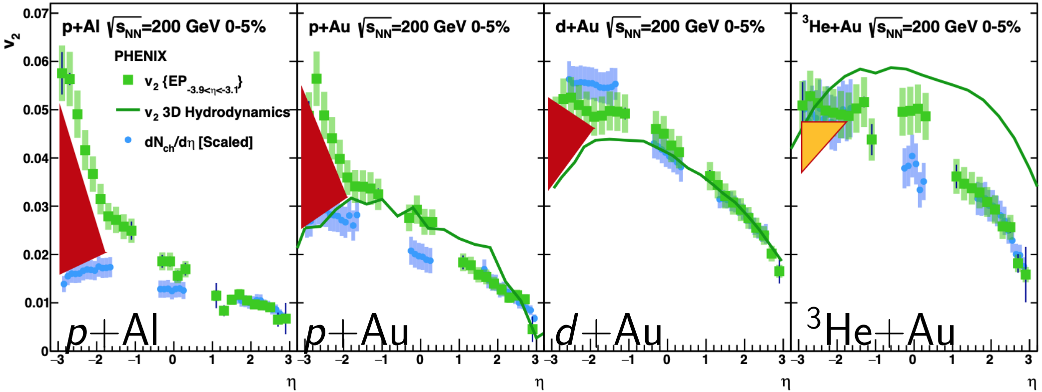


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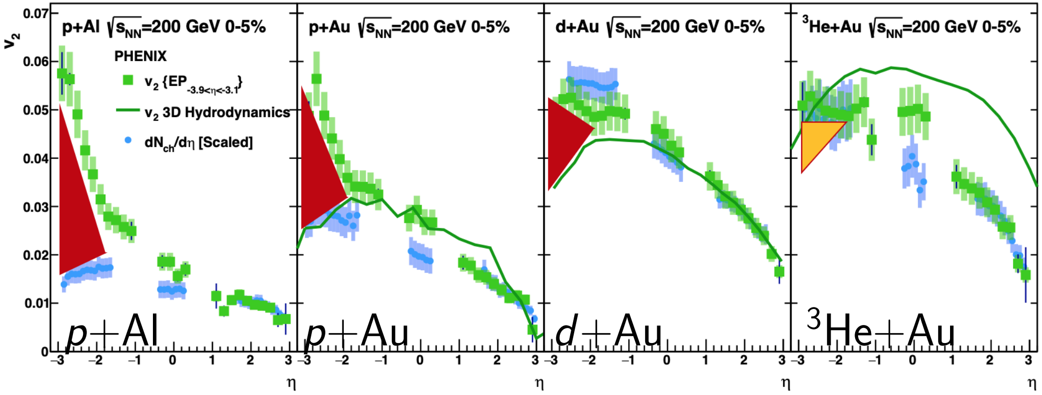
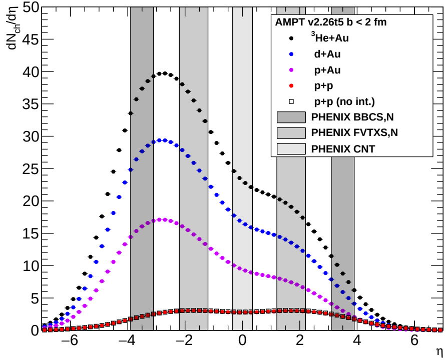
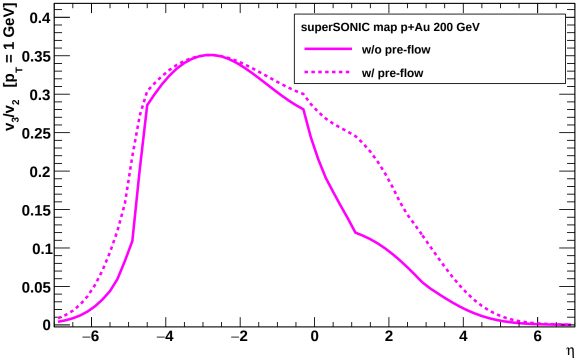



- Need to know $v_3(\eta)$ for a lot of reasons, but very hard to measure...
- However, combination of the sEPD and central barrel make this very promising for sPHENIX!

# Flow measurements in $p$+Au

J.L. Nagle et al, Phys. Rev. C 105, 024906 (2022)




- $dN_{ch}/d\eta$ from AMPT, $v_3(\eta)$ from (super)SONIC
- Can use the sPHENIX central barrel ($|\eta| < 1.1$) and sEPD ($2.0 < |\eta| < 4.9$, finely segmented into 16 rings) to make a broad measurement
  —Still very challenging, but too important to overlook

# Flow decorrelation measurements

ALICE, arXiv:2206.04574

- Detailed studies of "flow factorization" as a function of $p_T$ use reference particles in a broad $p_T$ range and associate particles in a specific $p_T$ bin
- Observable $A_n^f$ for angular decorrelation

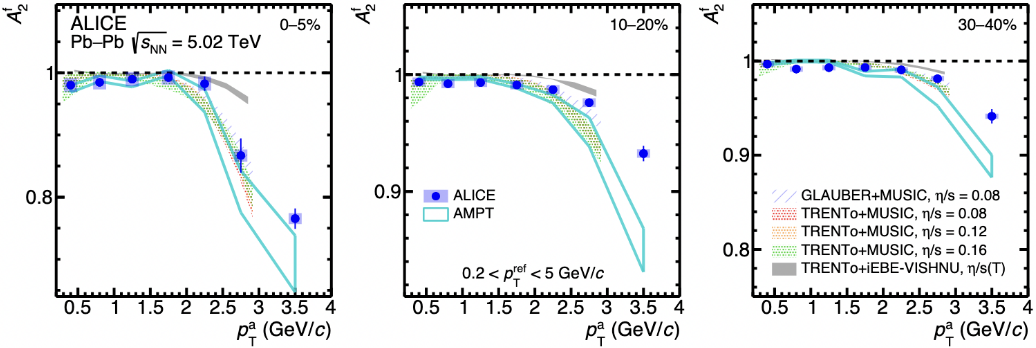
$$A_n^f = \frac{\langle\langle \cos(n(\phi_1^a + \phi_2^a - \phi_3 - \phi_4))\rangle\rangle}{\langle\langle \cos(n(\phi_1^a + \phi_2 - \phi_3^a - \phi_4))\rangle\rangle}$$
$$= \frac{\langle v_n^2(p_T^a) v_n^2 \cos(2n(\psi_n(p_T^a) - \psi_n))\rangle}{\langle v_n^2(p_T^a) v_n^2\rangle}$$
$$= \langle \cos(2n(\psi_n(p_T^a) - \psi_n))\rangle_{\text{weight}}$$

- The first order decorrelation can't be calculated directly, but there's an inequality

$$\sqrt{\frac{A_n^f + 1}{2}} \geq \langle \cos(n(\psi_n(p_T^a) - \psi_n))\rangle$$

# Flow decorrelation measurements

ALICE, arXiv:2206.04574

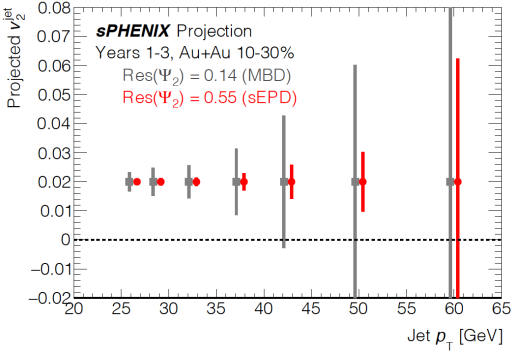


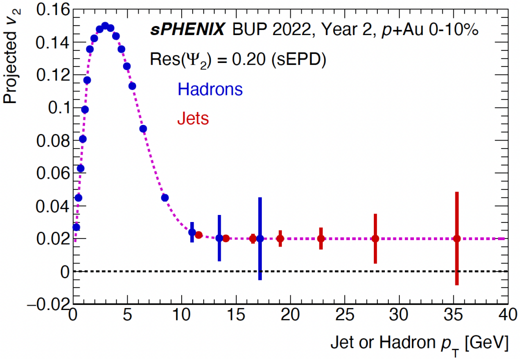

- Can see that "flow factorization" doesn't hold as a function of $p_T$
- A multi-differential four-particle correlation is extremely statistics-hungry
- The massive integrated luminosity in Au+Au to be collected by sPHENIX provides a huge opportunity to do this kind of study at RHIC energies

# Intermission

Where the hard and soft sectors meet

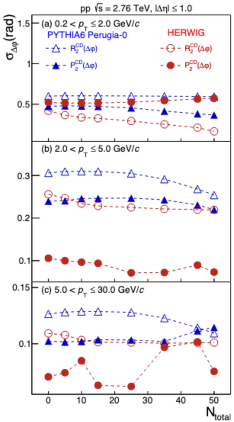
# Jet $v_n$




- Jet $v_n$ originates from path-dependent differential energy loss, which is not bulk physics
- But the global event shape, which *is* bulk physics, determines the path length
- Interesting potential caveat: how does $p_T$-dependent flow angle decorrelation affect our interpretation of jet $v_n$?

# Balance functions inside of jets

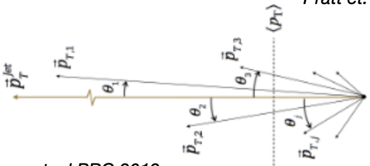



## Charge dependent balance functions in jets

$$R_2\left(\eta_1,\varphi_1,\eta_2,\varphi_2\right)=\frac{\rho_2\left(\eta_1,\varphi_1,\eta_2,\varphi_2\right)}{\rho_1\left(\eta_1,\varphi_1\right)\rho_1\left(\eta_2,\varphi_2\right)}-1$$

$$R_2^{CI}=R_2^{US}+R_2^{LS};\quad R_2^{CD}=R_2^{US}-R_2^{LS}$$

*Pratt et. al PRL 2000*

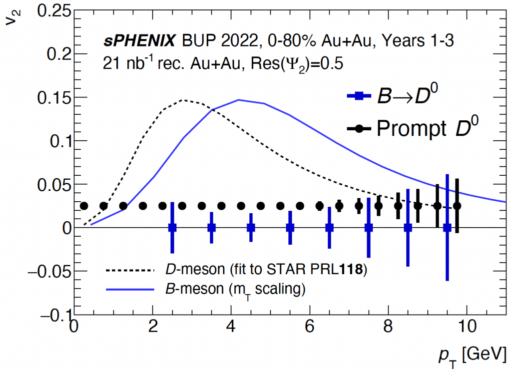


*Basu et. al PRC 2019*

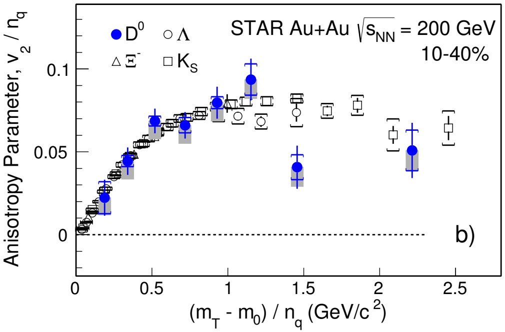
Thanks to Raghav Kunnawalkam Elayavalli

- Requirements - tracks, charge identification up to relatively high pT
- $p_T$ > 25 GeV jets at RHIC are mostly quark dominated and so start with a charge → charge dependent balance functions study the distribution of particles from the jet quenching wake around the jet

# Heavy flavor flow




STAR, Phys. Rev. Lett. 118, 212301 (2017)




- Charm seems to flow like light quarks
- What about bottom?
- Measurements of D- and B-meson flow in sPHENIX will yield key insights
  —$v_3$ may be particularly important (can use sEPD)

# Brief summary and outlook

- Plenty of opportunities for really interesting physics in the soft sector
- Some interesting cross-talk between the hard and soft sector, in "obvious" but also in potentially subtle ways
- Hard physics is the chocolate chips and soft physics is the batter: you need both to make the cookie