The Little Bang: A liquid tale of Heavy Ion collisions

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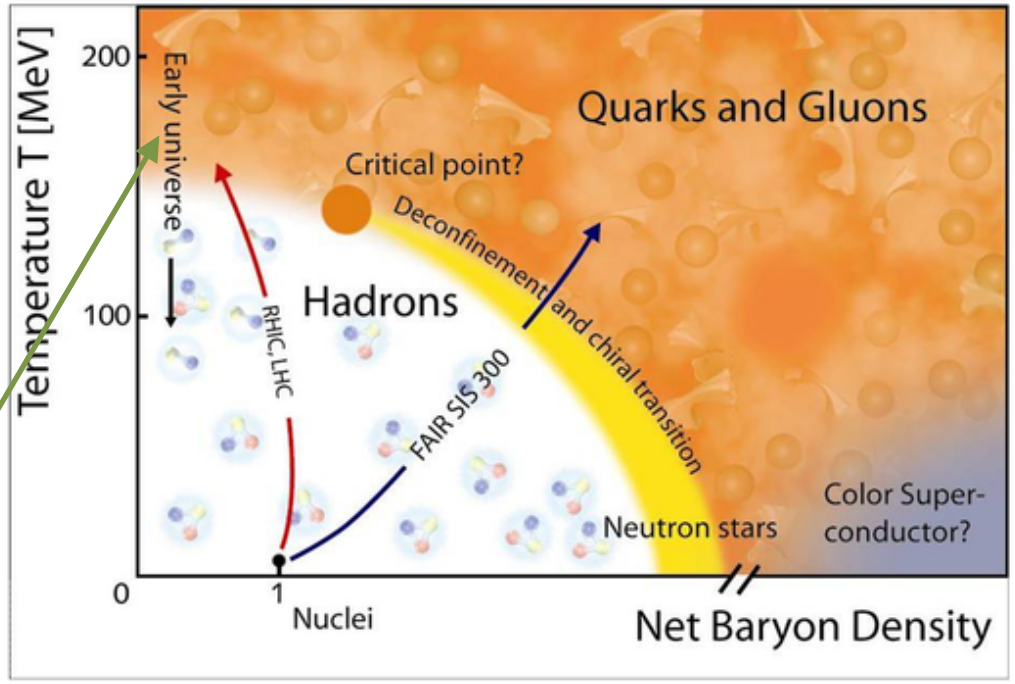
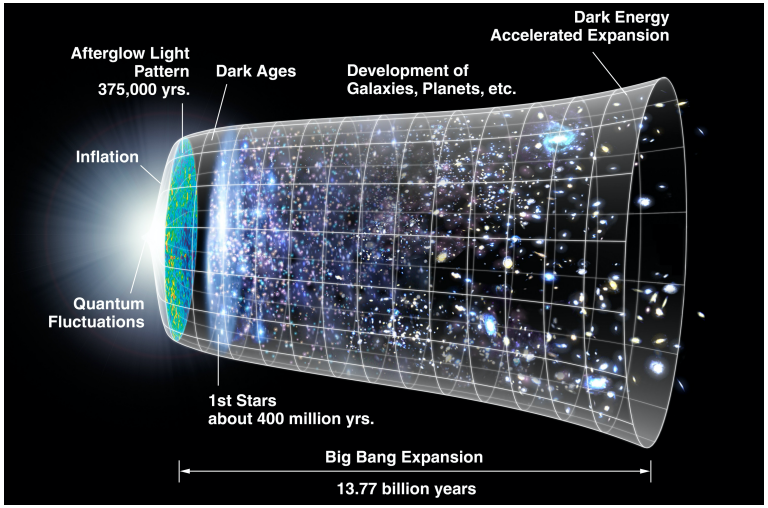
Heavy Ion Collisions

Region accesible through HIC

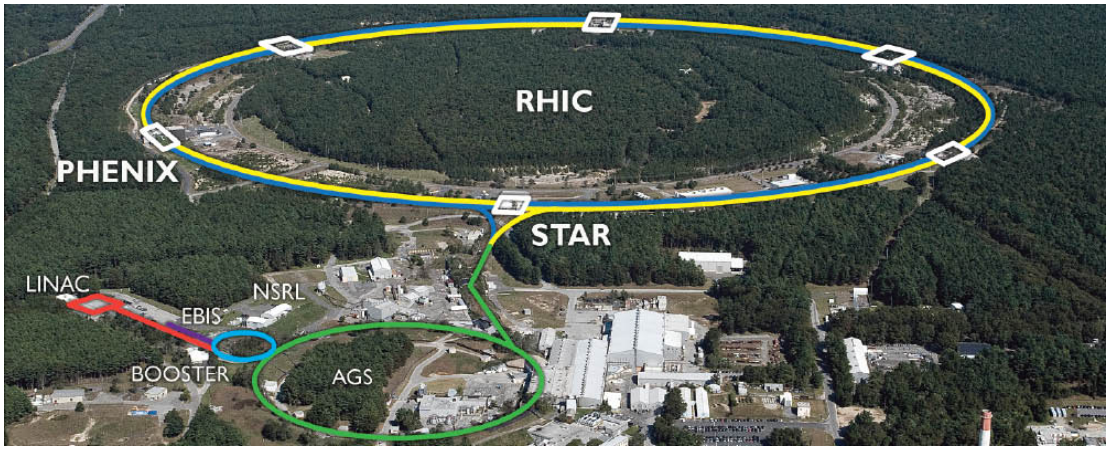
- Low Net Baryon density
- High Temperatures
- T_c ~ 160 MeV -> e_c ~ 0.5 GeV/fm^3
- RHIC AuAu @ 200GeV -> T ~ 349 MeV
- Similar conditions present in at t~10^{-6}s after Big Bang





- Systematic exploration and characterization of QCD matter under extreme conditions of temperature and pressure
- Unique controlled way to study deconfined QCD matter (Quark-Gluon Plasma)

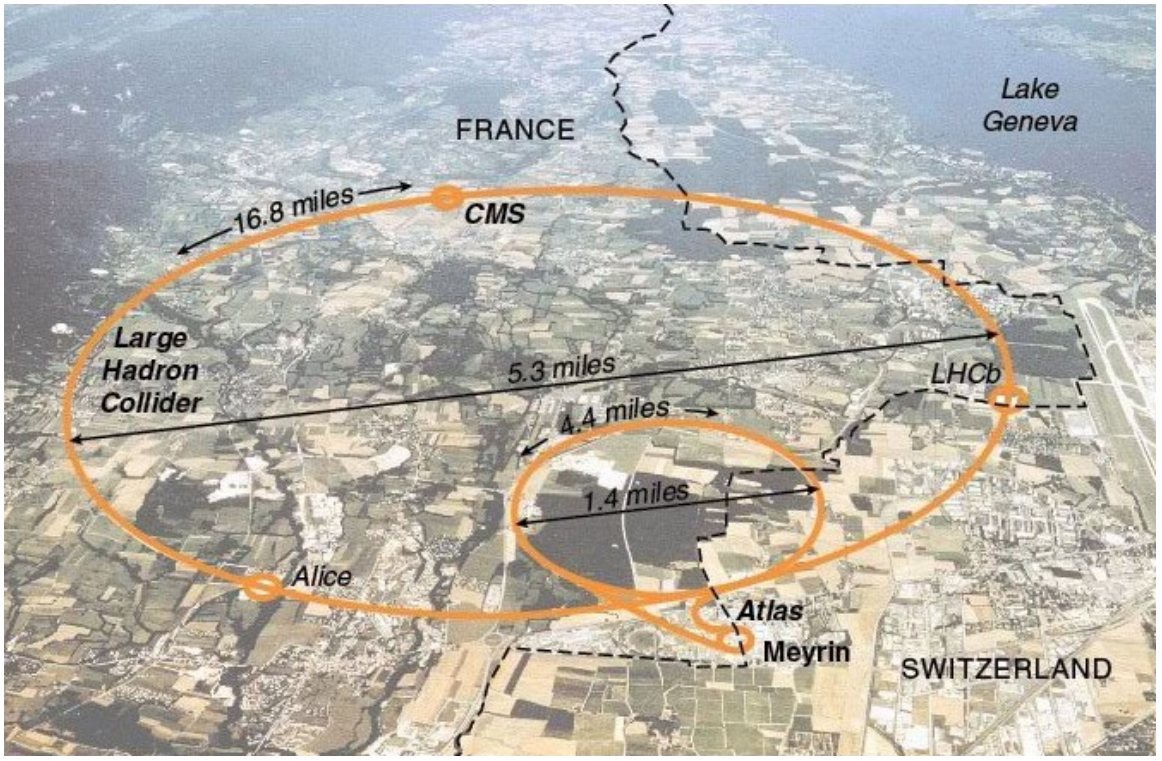
How dow we produce QGP?



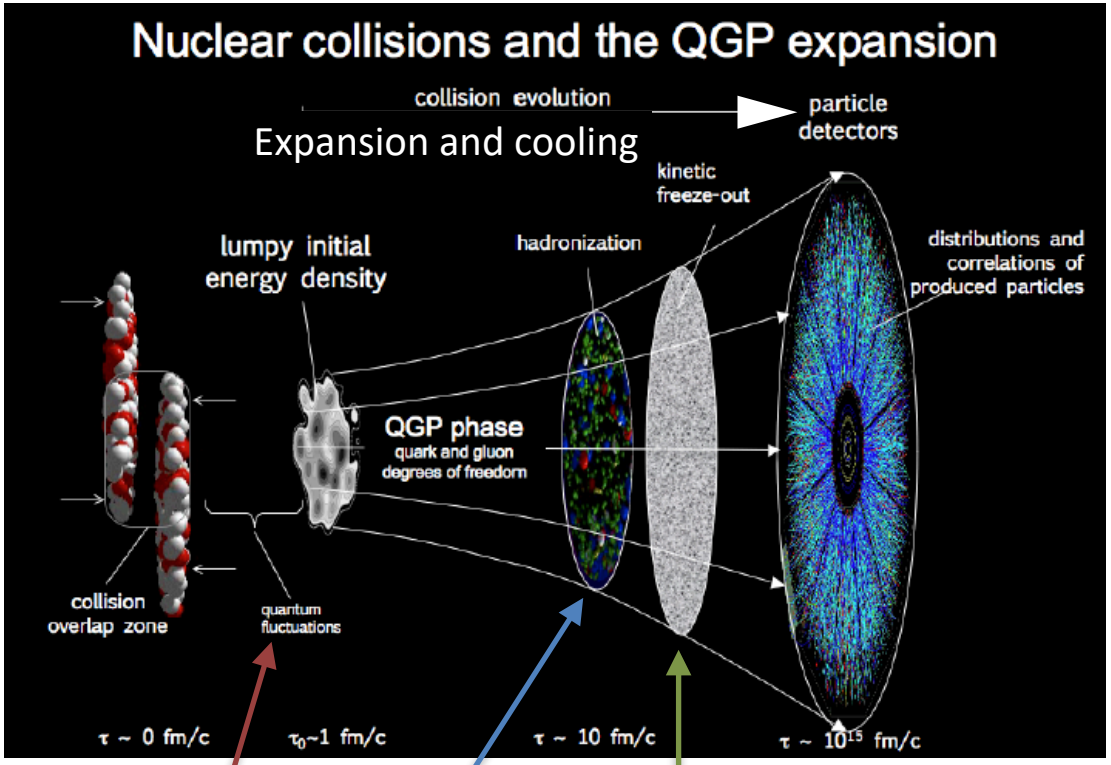
- First production of QGP ~20 years ago (SPS/RHIC)
- RHIC continues operations (STAR / sPHENIX) and will keep running for another 5 years

- LHC has four main experiments (ALICE/CMS/ATLAS/LHCb).
- All of them have a Heavy Ion program

RHIC	LHC
Low energies	High energies
Collision engineering	Large acceptance



Evolution of a Heavy-Ions Collision



Quite simplified model but very educative

- A lot happened already before hadronic matter arrives to our detectors
- However correlation analysis of the observables allow us to probe the evolution

Non-equilibrium stage

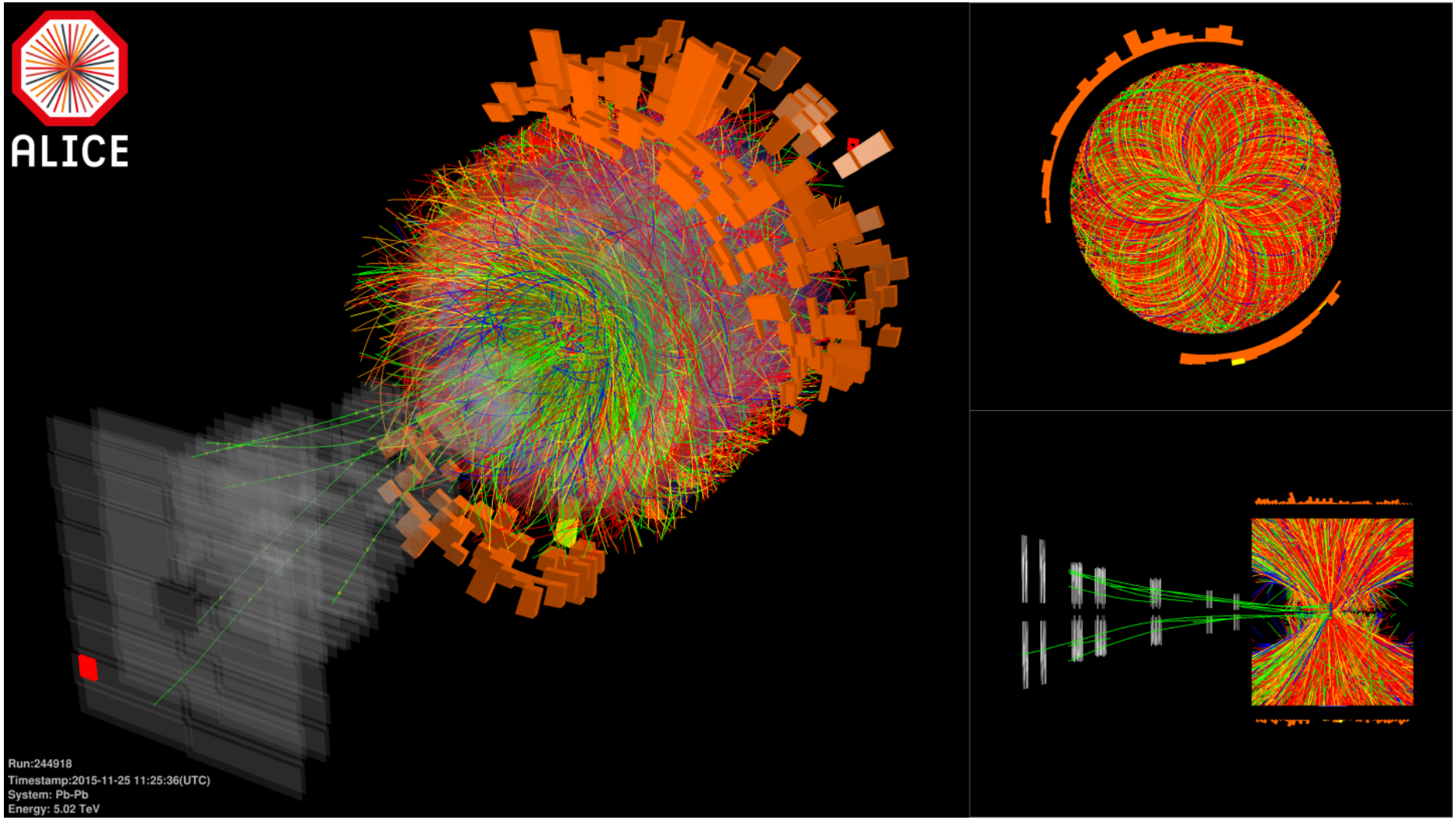
Close to critical Temperature for deconfinement

Hadronic gas phase

Hadrons mean free path is large enough that hadrons do not collide with each other anymore

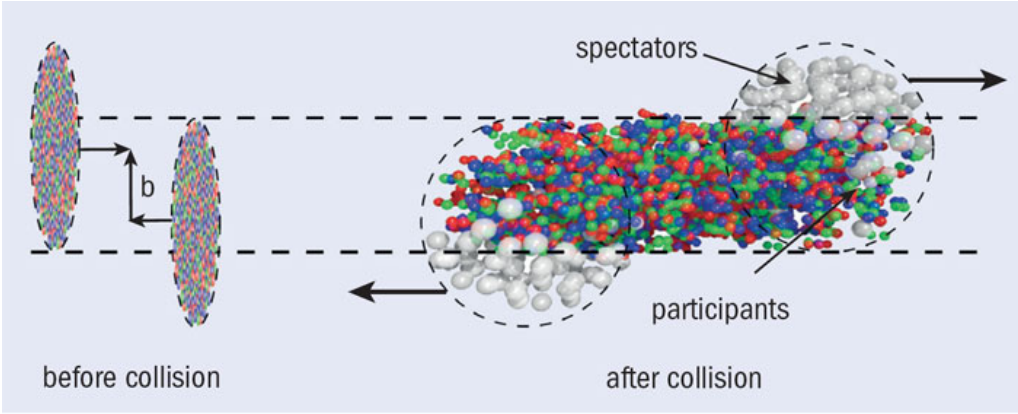
Free streaming towards detectors

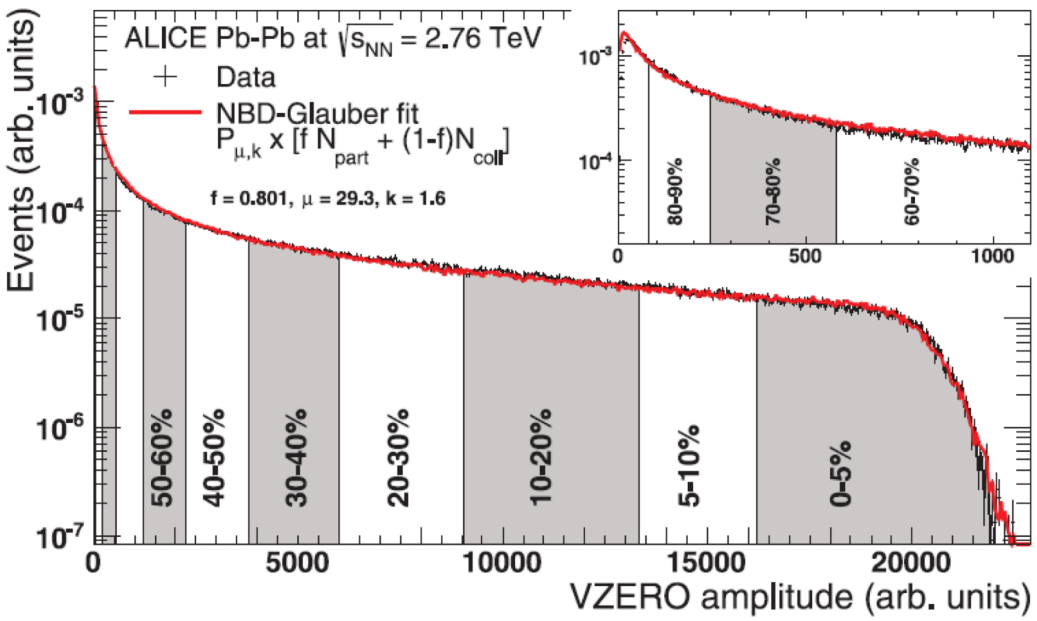
A single collision event for PbPb @ 5.72 TeV

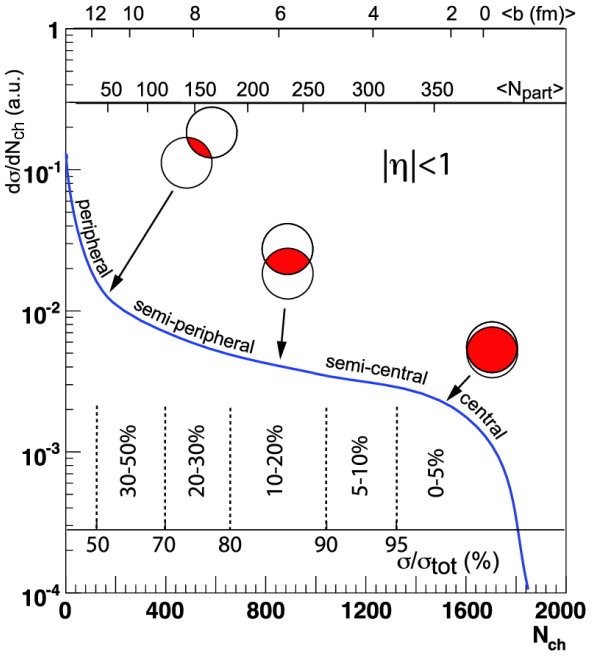


Centrality

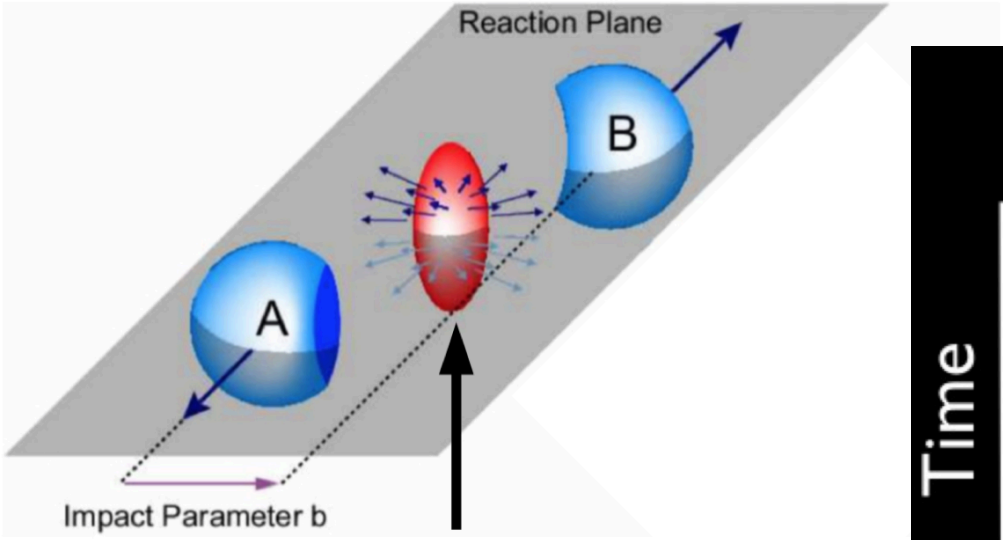
- Measures how big is the nuclear overlap in a collision
- Allows us to study effect of medium differentially

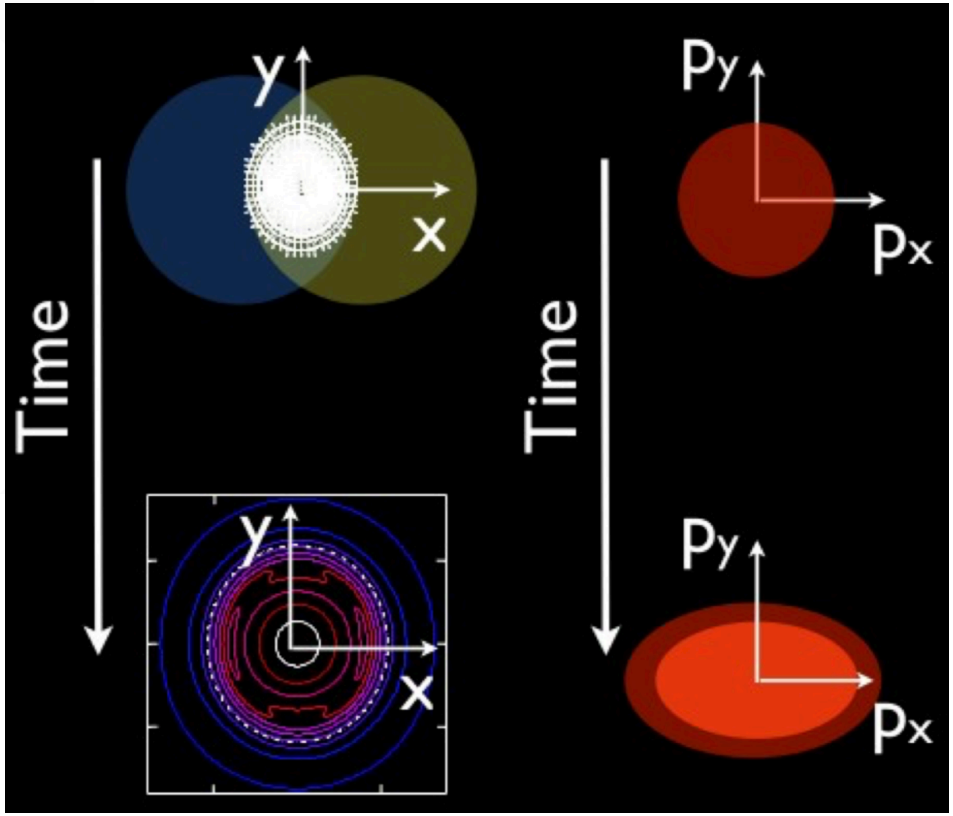






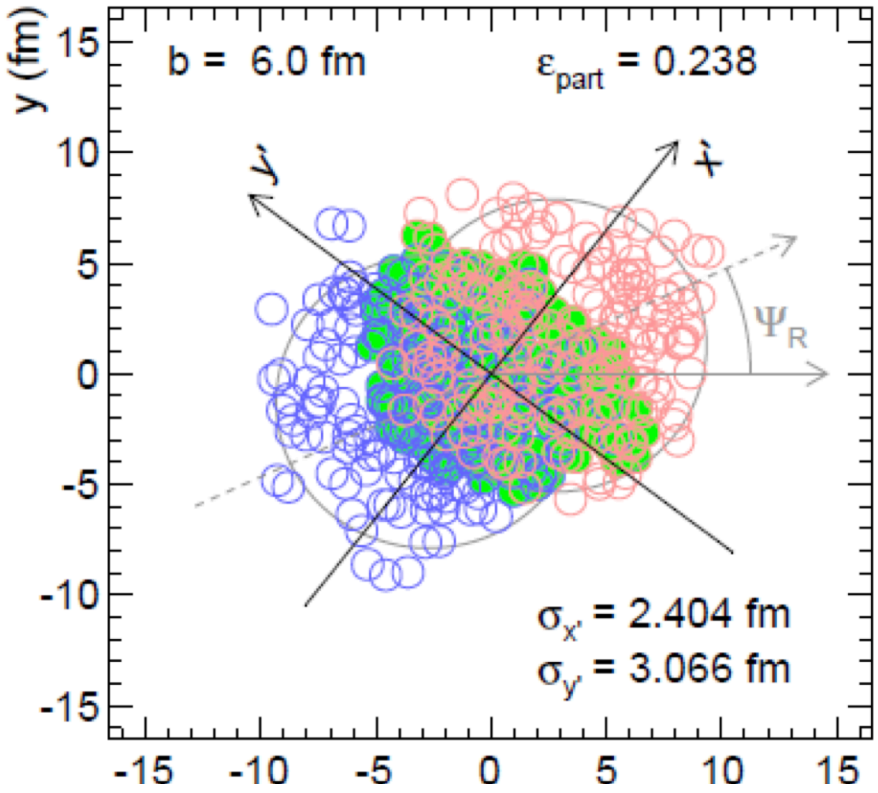
Collective effects: all particle correlation





- Initial spatial anisotropy => final momentum anisotropy
  - Pressure gradient and a medium-like expansion

Measuring azimuthal anisotropy



$$E\frac{\mathrm{d}^3N}{\mathrm{d}p^3} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_\mathrm{T}\,\mathrm{d}p_\mathrm{T}\,\mathrm{d}y}(1+2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_{RP})),$$

$$v_2 = \langle\langle \cos 2(\varphi - \Psi_2)\rangle\rangle = \langle\langle \mathrm{e}^{2i(\varphi-\Psi_2)}\rangle\rangle,$$

The strength of the Q-vector

$$Q_n \equiv \sum_i^M \exp \imath n \varphi_i$$

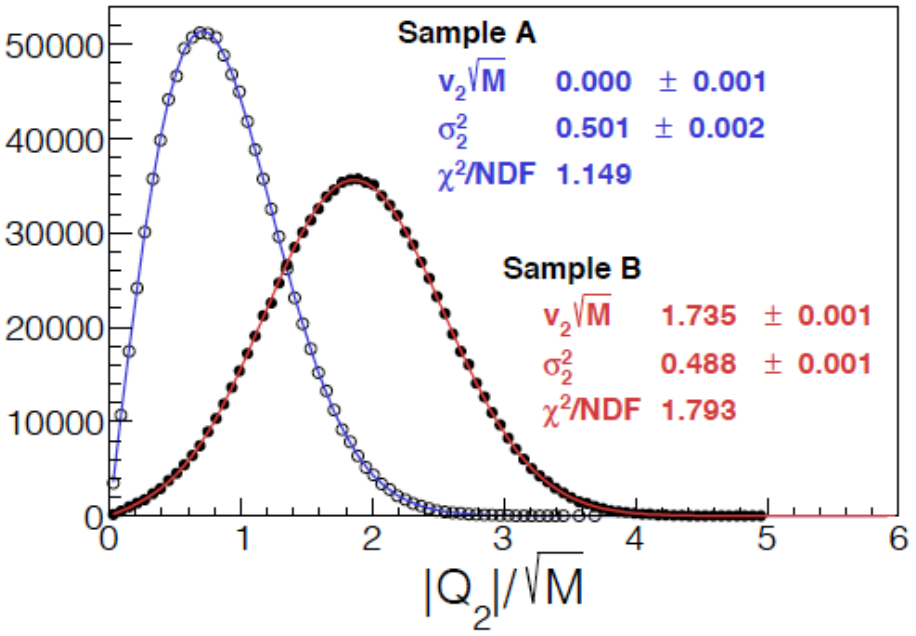
If particle momenta distribution is isotropic:
Underlying PDF would be that of a random walk

$$Q_n \equiv |Q_n| \exp \imath n \Psi_n.$$

MC simulation

Input:
SampleA: isotropic distribution
SampleB: v2=0.1 (no other harmonics)

In both cases multiplicity is 300 particles



A fairly good approximation of such distribution is given by:

$$\frac{dN}{dq_n} = \frac{q_n}{\sigma_n^2} \exp\left(-\frac{a^2+q_n^2}{2\sigma_n^2}\right) \mathrm{I}_0\left(\frac{q_n a}{\sigma_n^2}\right),$$

“Shape-analysis” for qn -> Cumulants

- Two particle correlator := second order cumulant

$$\langle\langle 2\rangle_n\rangle = \langle\langle \exp ni\left(\varphi_i - \Psi_n + \Psi_n - \varphi_j\right)\rangle\rangle$$
$$= \langle\langle \exp ni\left(\varphi - \Psi_n\right)\rangle\langle \exp ni\left(\Psi_n - \varphi\right)\rangle\rangle = \langle v_n^2\rangle.$$

Provided that factorization is allowed

This is the tricky part actually: You have to assumed that the only source of correlation is through the event plane

There are ways to diminish spurious correlation: introduction of rapidity gaps is the most popular one

- Four particle correlator:

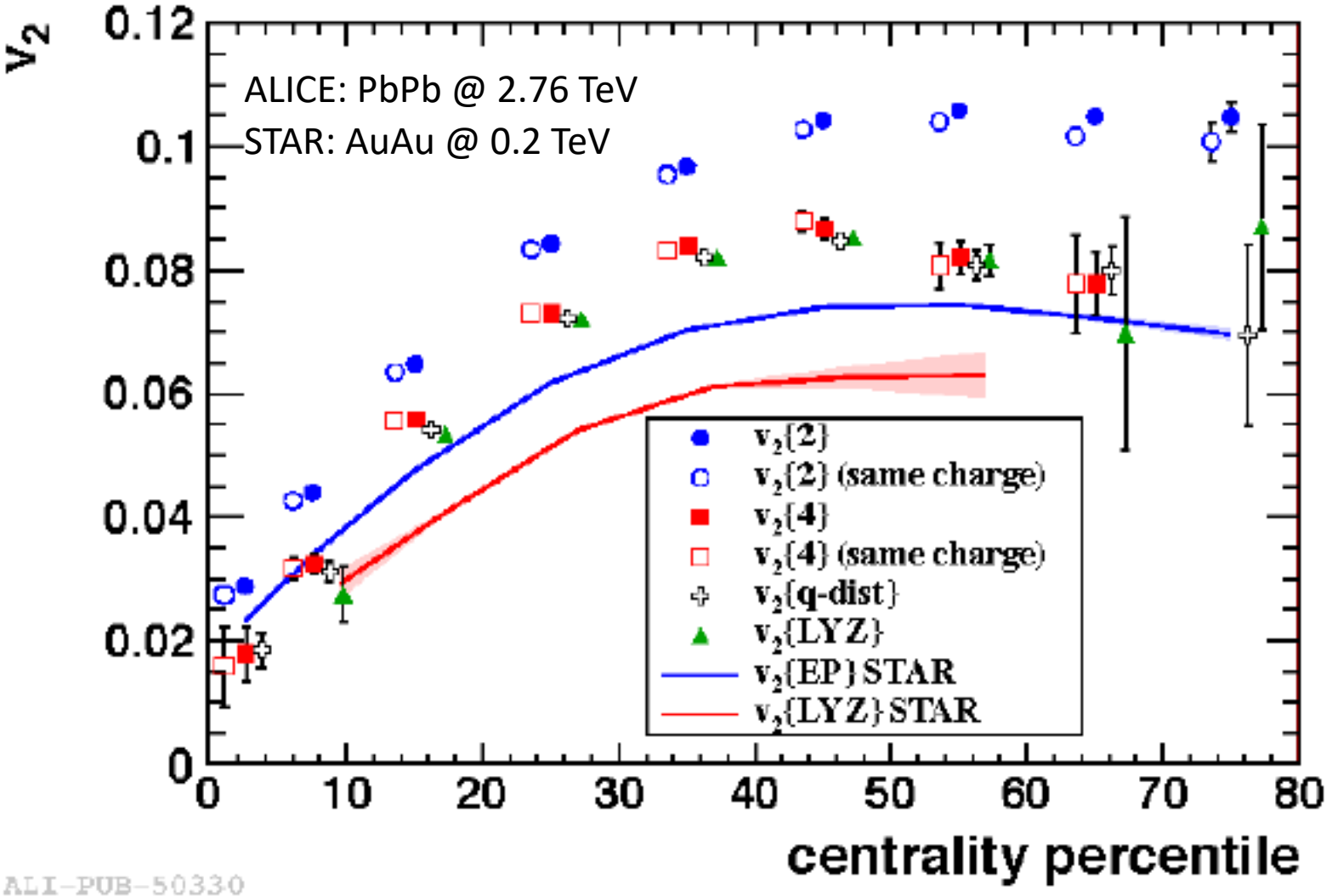
$$\langle 4\rangle_n \equiv \langle \exp ni\left(\varphi_i + \varphi_j - \varphi_k - \varphi_l\right)\rangle,$$

Allows for the construction of the 4th order cumulant

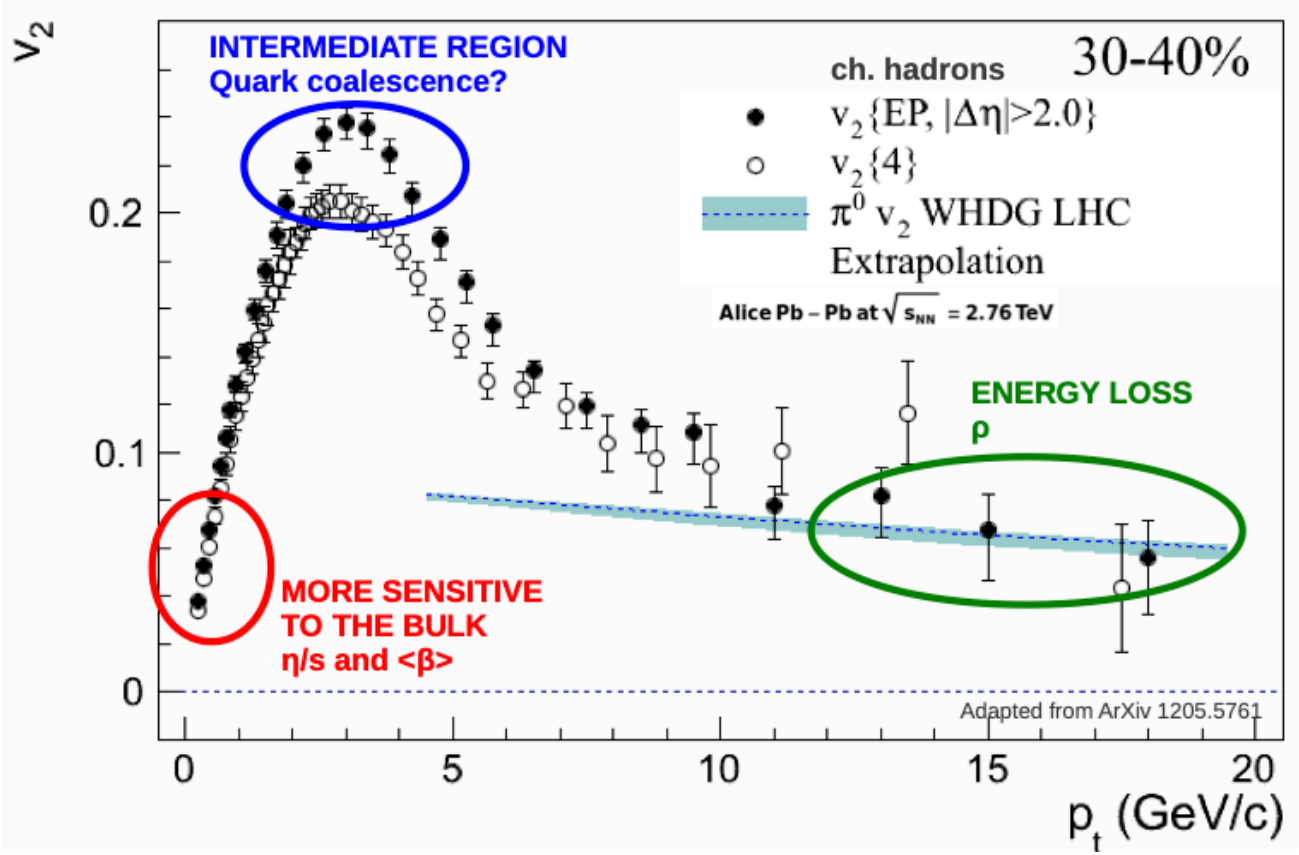
$$d_n\{4\} \equiv \langle\langle 4\rangle_{n;p,Q,q}\rangle - 2\langle\langle 2\rangle_{n;p,Q}\rangle\langle\langle 2\rangle_{n;Q,Q}\rangle,$$

$$v_n\{4\} = -\frac{d_n\{4\}}{\sqrt[4]{-r_n\{4\}^3}}$$

How do all these translate to medium expansion?



Looking at the Pt dependence

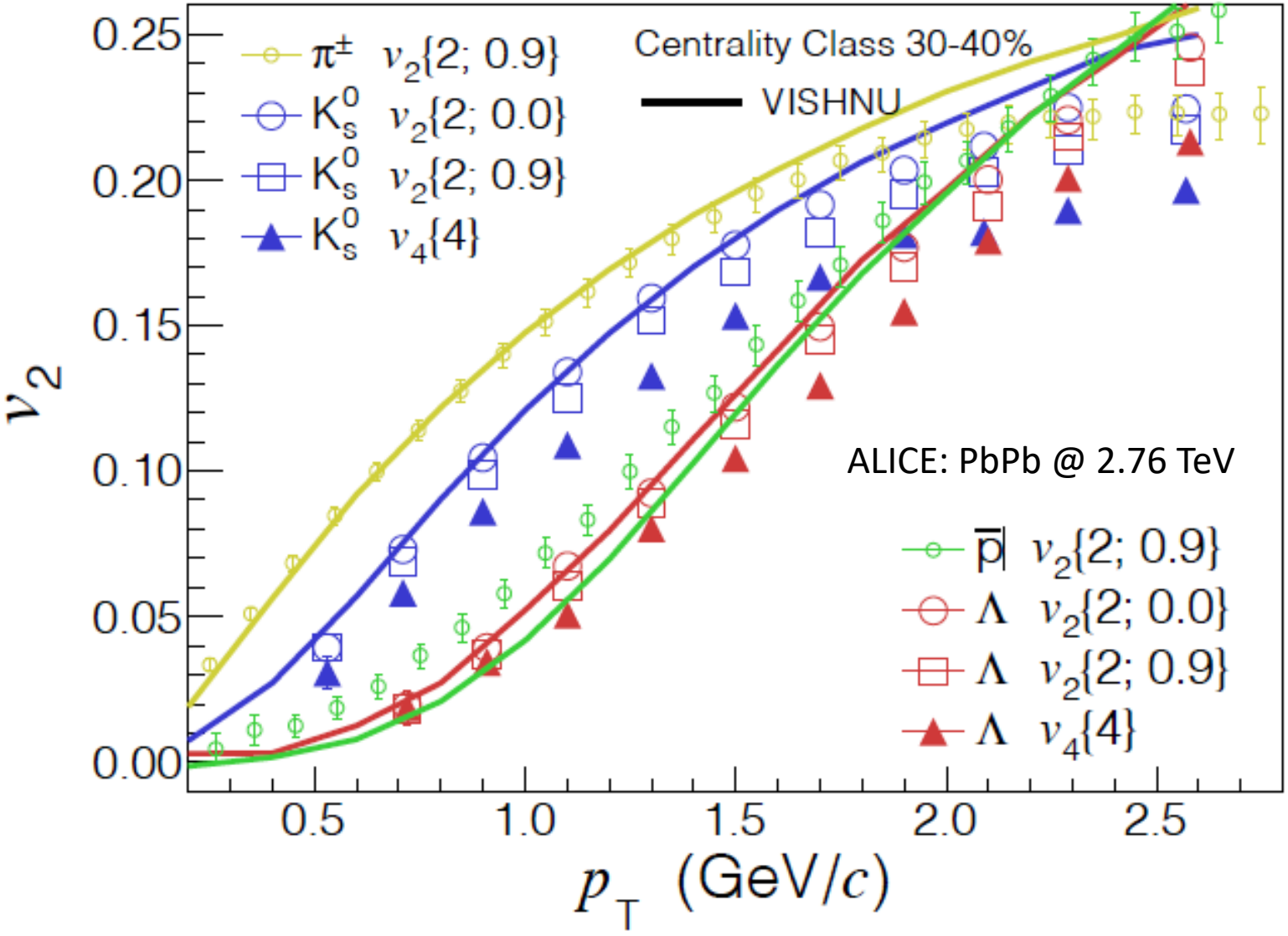


[low pt] measure the intensive properties of the medium (η/s and β)

[intermediate pt] give handle on the hadronization mechanism

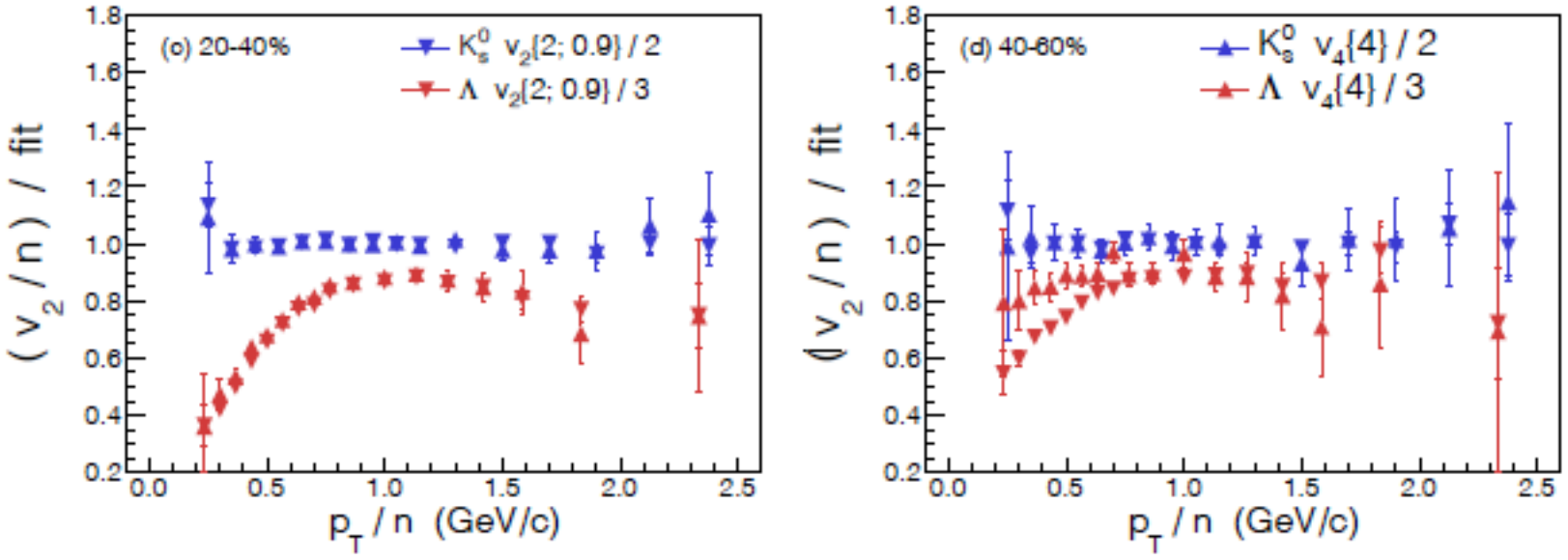
[high pt] measure the path length dependence in medium

A common velocity field: Hydro success!



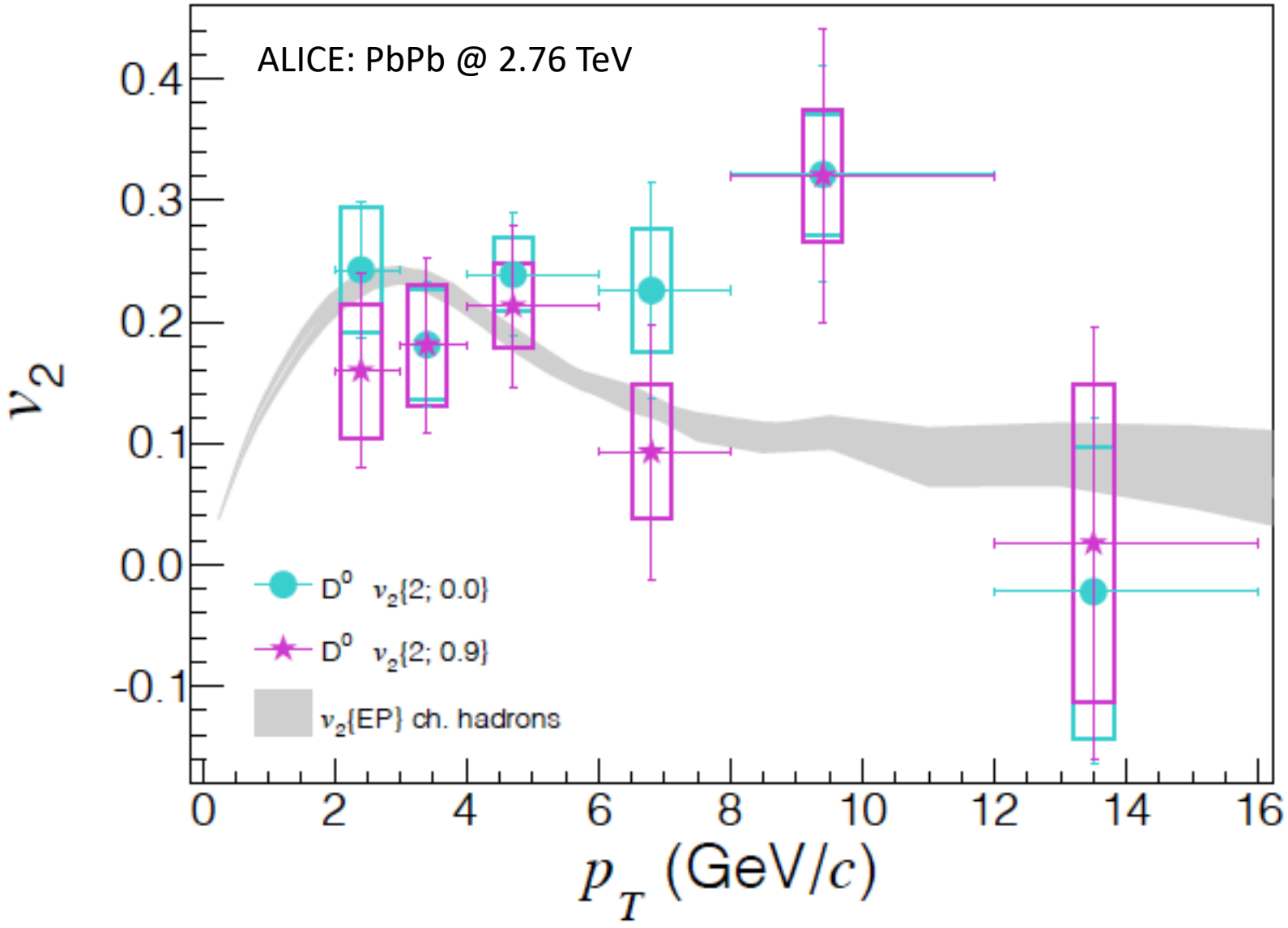
A smoking gun for deconfinement?

ALICE: PbPb @ 2.76 TeV



- Scaling holds partially within 15%
- Leading hadronization mechanism may be quark coalescence at intermediate Pt
- If so, clear signal that deconfined quarks suffered flow

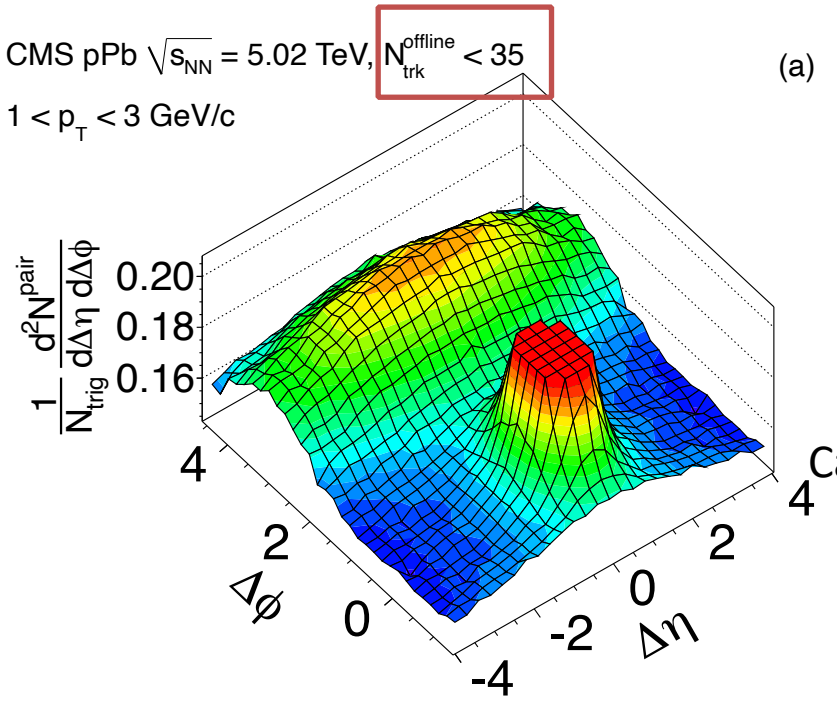
Or perhaps there is more about it?



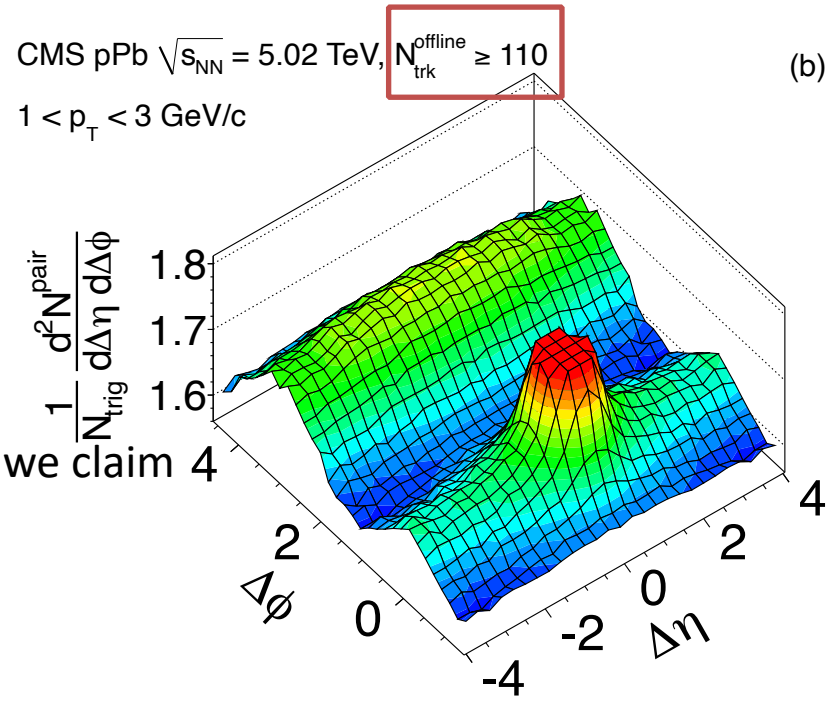
Things are way more interesting that we thought

The ridge in p-Pb at 5.02 TeV

Phys. Lett. B 718 (2013) 795

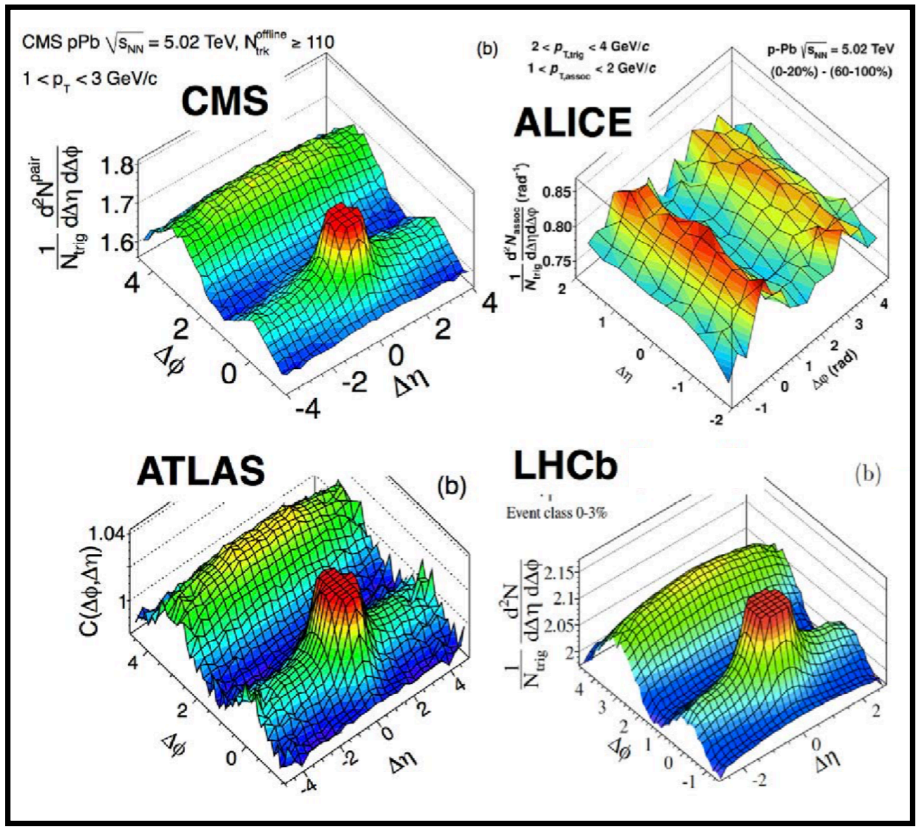


Can we claim



- In 2013, CMS published their results on the ridge structure found in high multiplicity p-Pb collisions at 5.02 TeV

The ridge in p-Pb at 5.02 TeV



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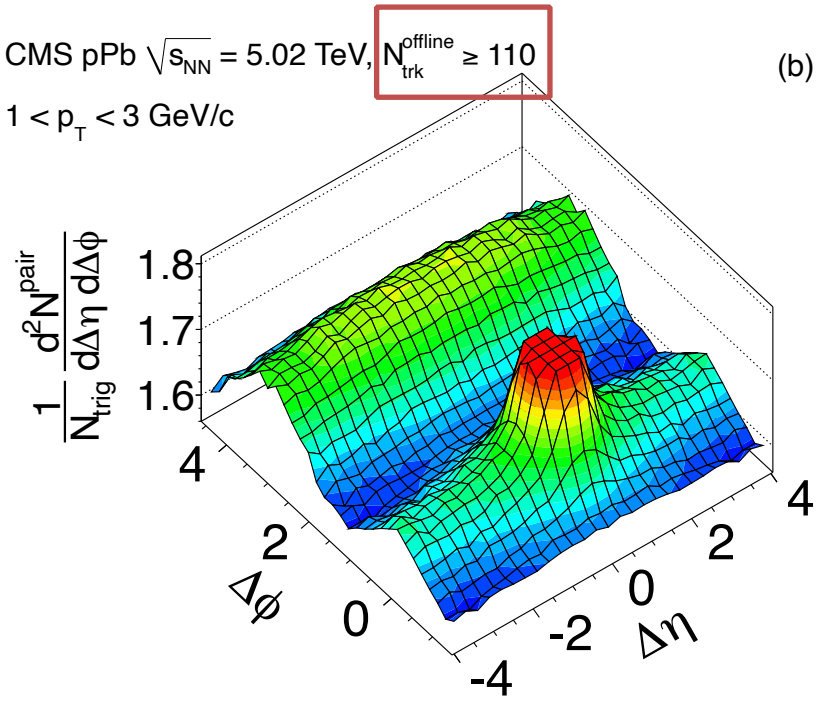

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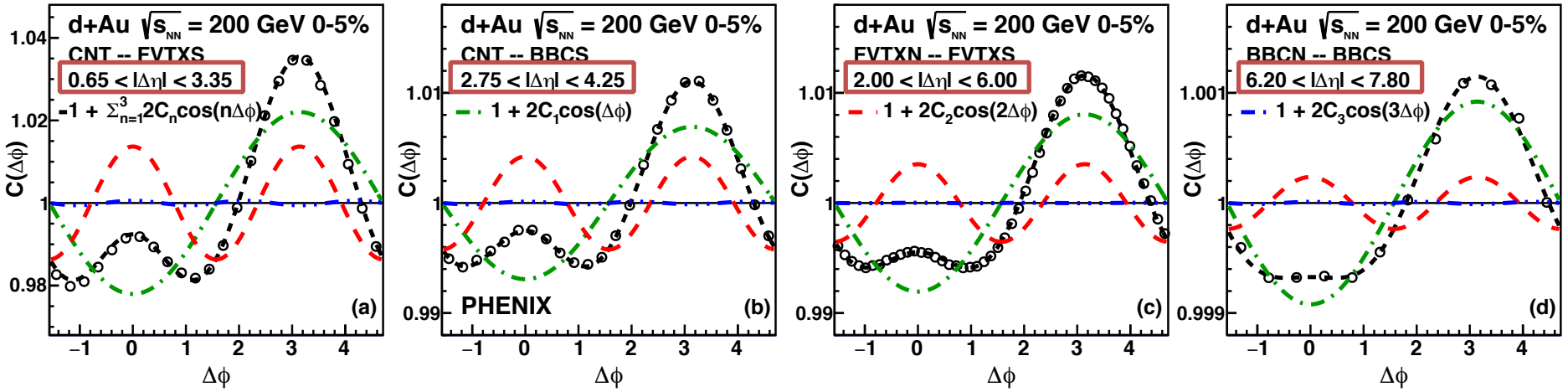
By 2015, confirmed by other experiments at LHC

Small Systems at RHIC Papers Published

- PRL 122, 172301 (**2019**) - (STAR) Azimuthal harmonics in small and large collision systems at RHIC top energies
- Nature Physics vol. 15, 214–220 (**2019**) - (PHENIX) Creation of quark–gluon plasma droplets with three distinct geometries
- PRL 121, 222301 (**2018**) - (PHENIX) Pseudorapidity Dependence of Particle Production and Elliptic Flow in Asymmetric Nuclear Collisions of pAl, pAu, dAu, HeAu at 200 GeV
- PRL 120, 062302 (**2018**) - (PHENIX) Measurements of Multiparticle Correlations in dAu Collisions at 200, 62.4, 39, and 19.6 GeV and p+Au Collisions at 200 GeV and Implications for Collective Behavior
- PRC 98,014912 (**2018**) - (PHENIX) Measurement of emission-angle anisotropy via long-range angular correlations with high-pT hadrons in dAu and pp collisions at 200 GeV
- PRC 97, 064904 (**2018**) - (PHENIX) Measurements of mass-dependent azimuthal anisotropy in central pAu, dAu, and HeAu collisions at 200 GeV
- PRC 96, 064905 (**2017**) - (PHENIX) Measurements of azimuthal anisotropy and charged-particle multiplicity in dAu collisions at 200, 62.4, 39, and 19.6 GeV
- PRC 95, 034910 (**2017**) - (PHENIX) Measurement of long-range angular correlations and azimuthal anisotropies in high-multiplicity pAu collisions at 200 GeV
- PRL 115,142301 (**2015**) - (PHENIX) Measurements of Elliptic and Triangular Flow in High-Multiplicity HeAu Collisions at 200GeV
- PRL 114,192301 (**2015**) - (PHENIX) - Measurement of Long-Range Angular Correlation and Quadrupole Anisotropy of Pions and (Anti)Protons in Central dAu Collisions at 200 GeV
- Phys. Lett. B 747 (**2015**) 265 - (STAR)- Long-range pseudorapidity dihadron correlations in dAu collisions at 200 GeV
- PRL 111, 212301 (**2013**)- (PHENIX) - Quadrupole Anisotropy in Dihadron Azimuthal Correlations in Central dAu Collisions at 200 GeV

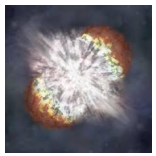
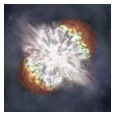
The ridge in d+Au at 200 GeV



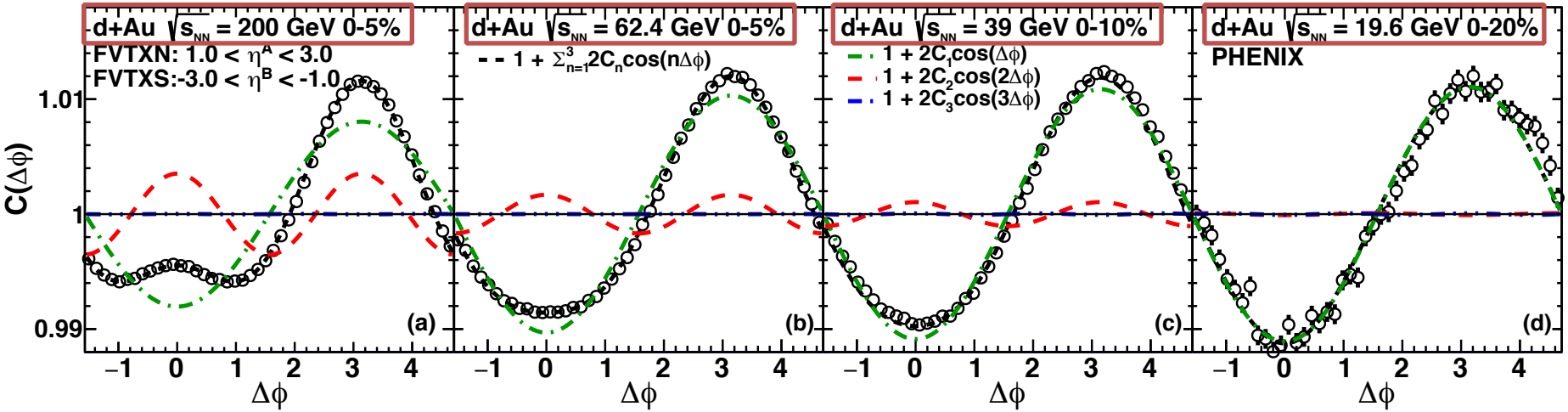
- In 2017, PHENIX published ridge-like structure for most central d-Au collisions
- Strong structure @ 200 GeV persists at large eta separation showing its long range nature

Phys. Rev. C 96 064905 (2017)

The ridge in d+Au even at lower energies


200 GeV



20 GeV



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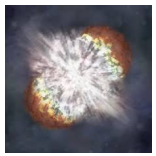
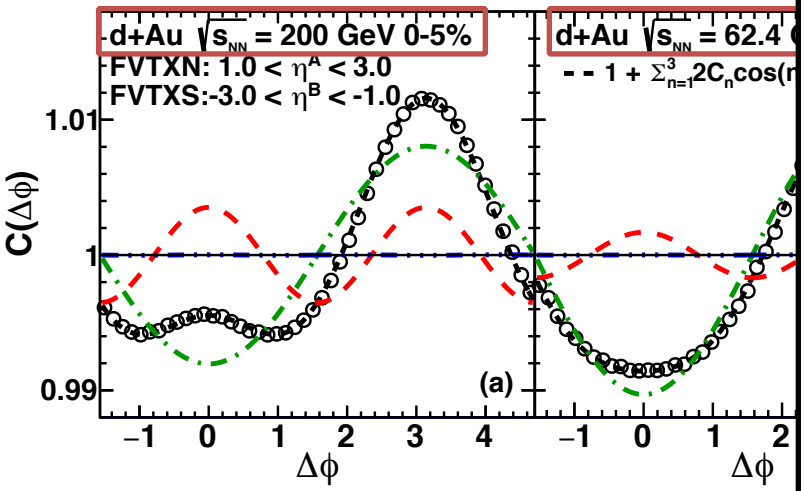
- Strong structure @ 200 GeV persists at large eta separation showing its long range nature
- Structure found also at smaller energies: 62, 39 GeV though gradually decreasing

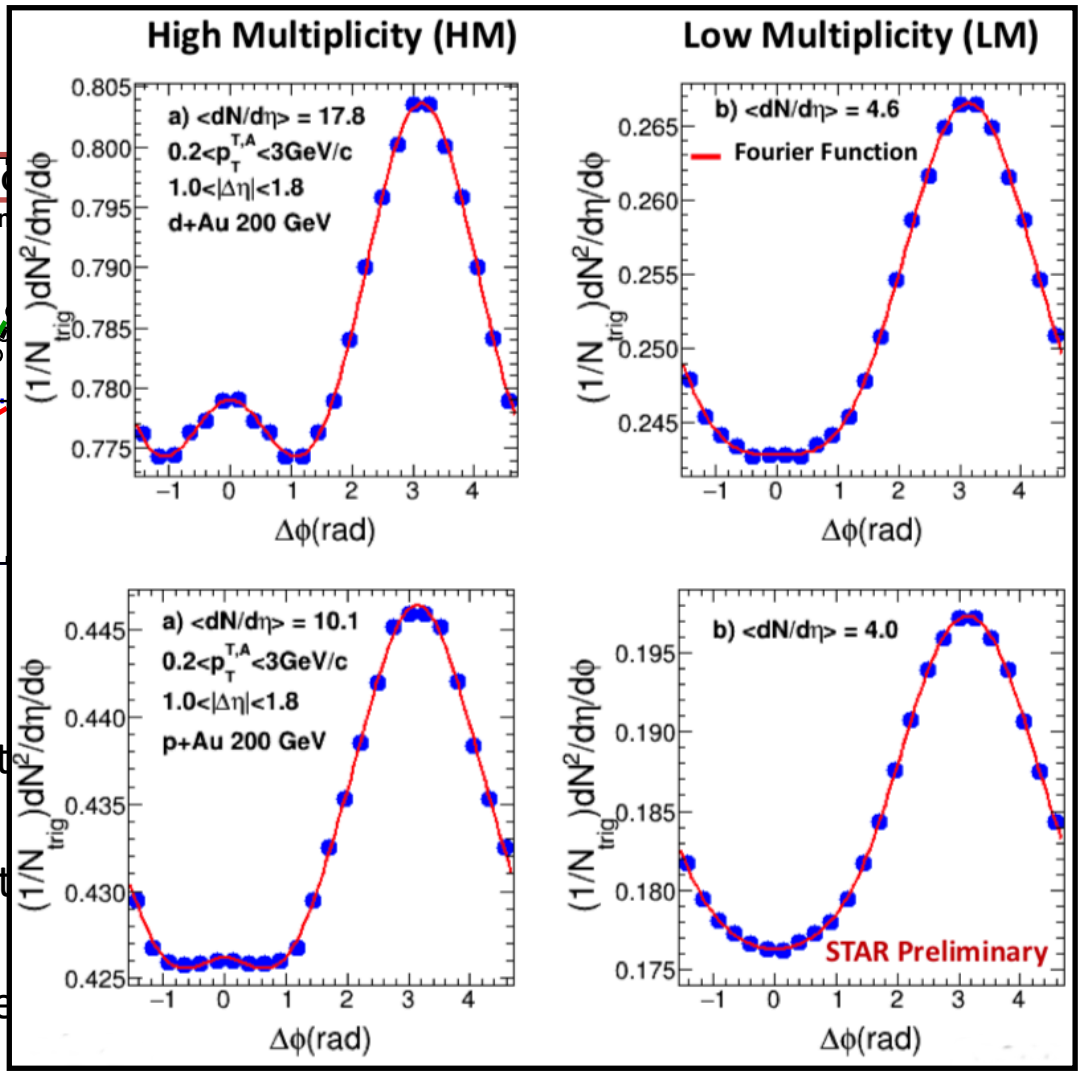
Phys. Rev. C 96 064905 (2017)

The ridge in d+Au even at lower energies



200 GeV





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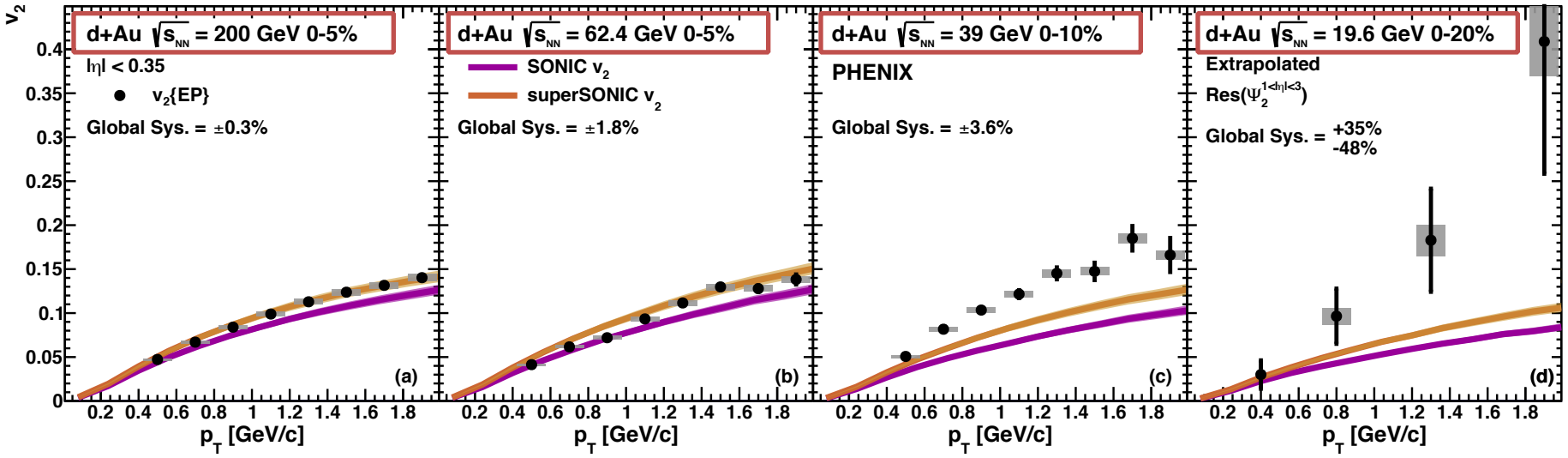
- Structure found also at smaller energie

Ridge confirmed by STAR

Phys. Rev. C 96 064905 (2017)

$v_2(p_T)$ in d+Au for various coll energies



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Phys. Rev. C 96 064905 (2017)

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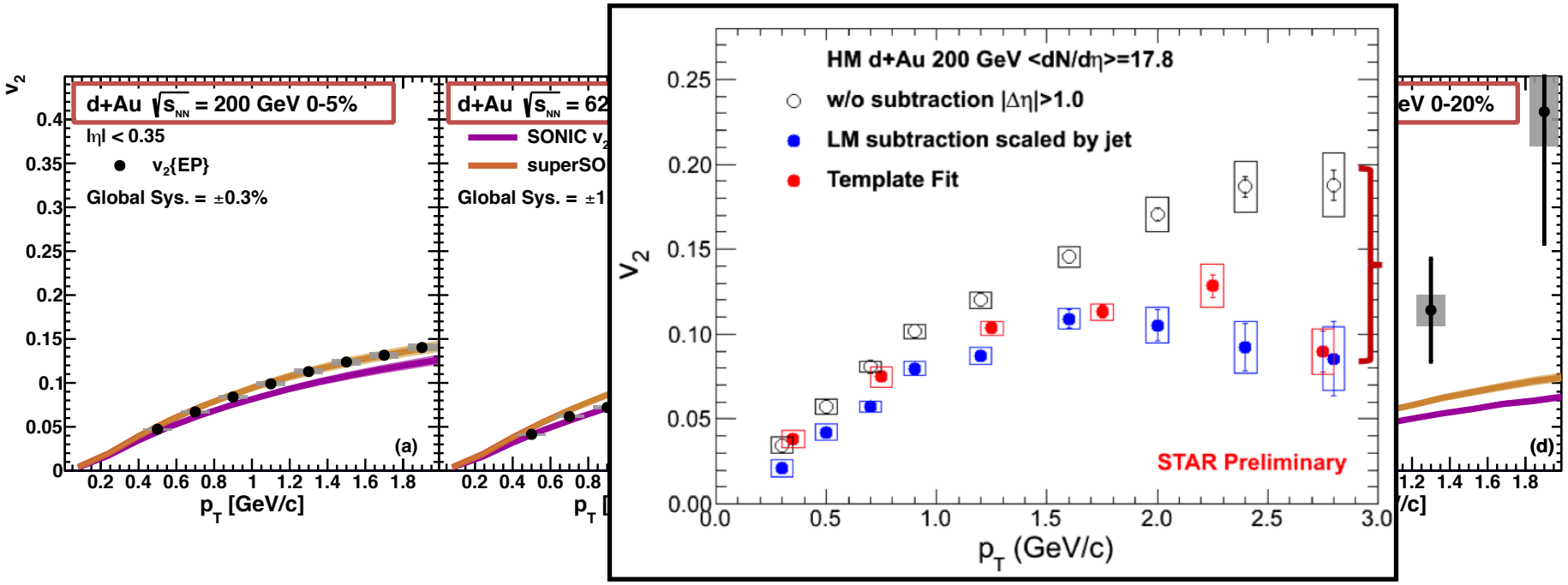

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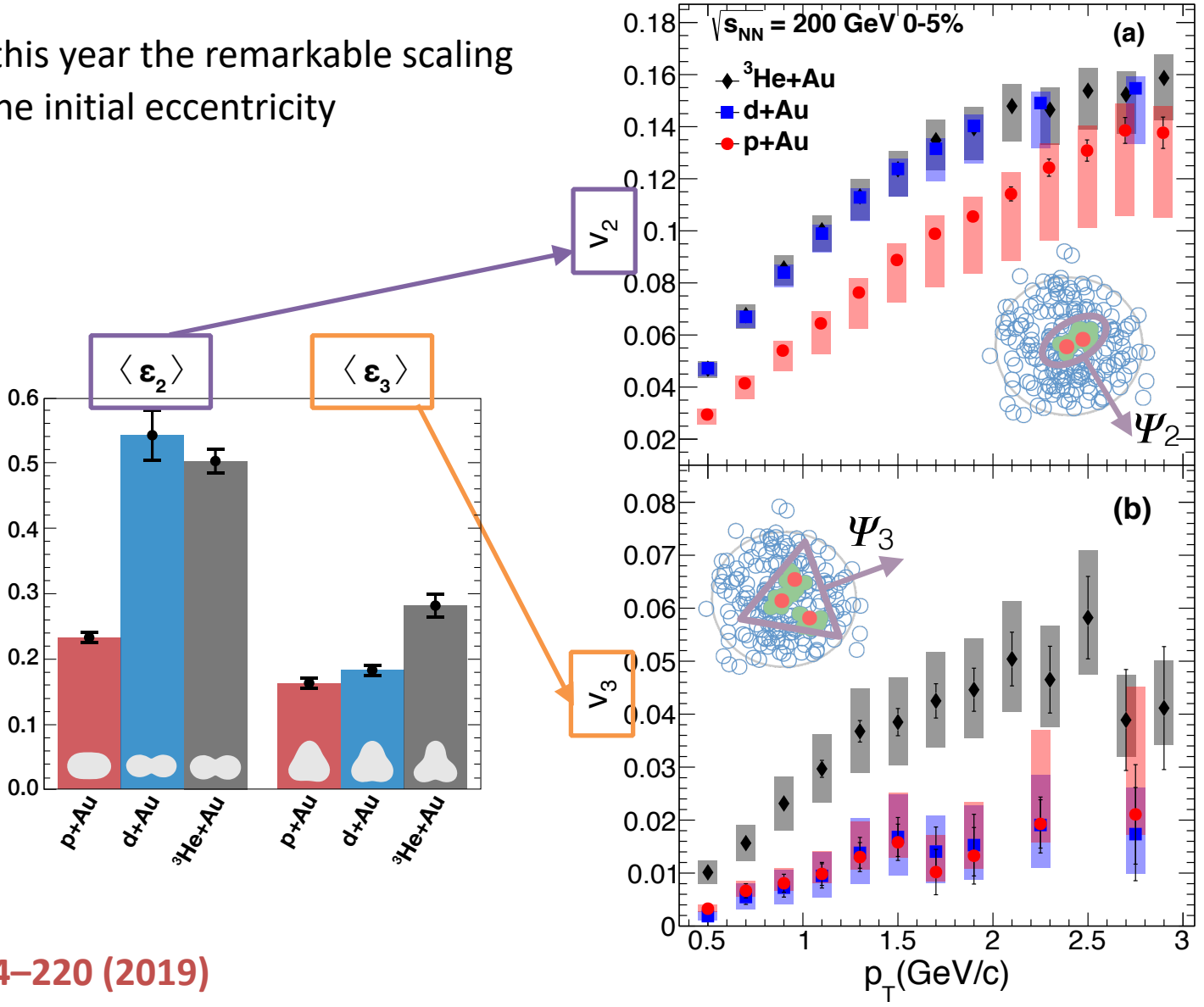
Large v_2 coefficient confirmed by STAR

Phys. Rev. C 96 064905 (2017)

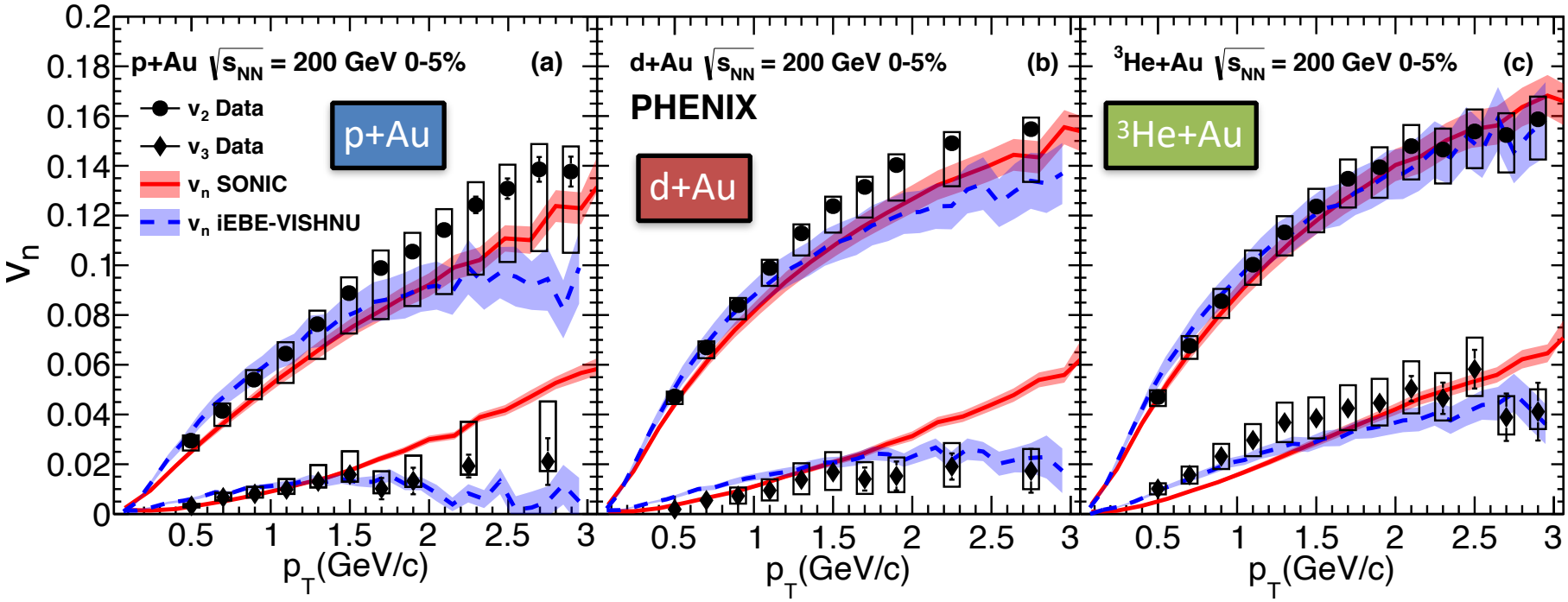
pAu, dAu, HeAu and a geometry stress tale

- PHENIX published this year the remarkable scaling of v2 and v3 with the initial eccentricity



Nature Physics 15, 214–220 (2019)

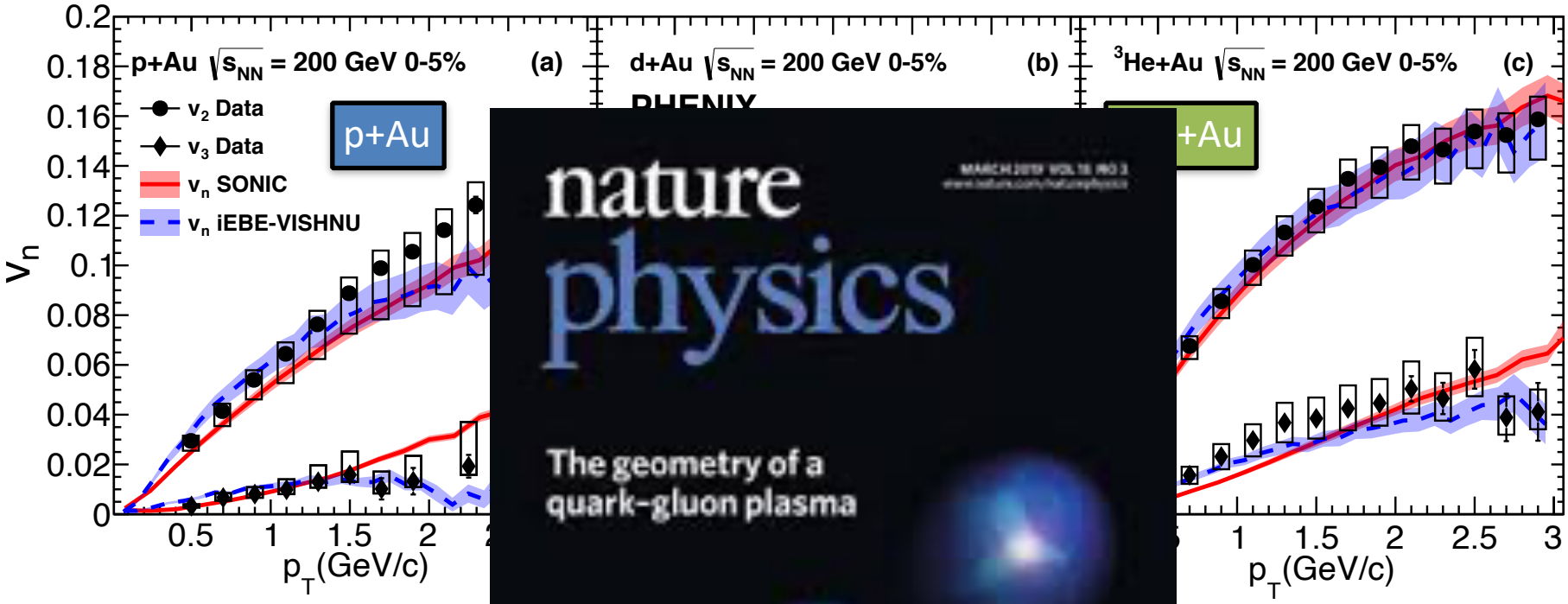
A small QGP droplet



- Hydro models reproduce the pT dependence quite well for all systems
- Supports that QGP droplet is created in these small systems
- Alternatives based on initial state effects alone fail to describe all data simultaneously

Nature Physics 15, 214–220 (2019)

A small QGP droplet



- Hydro models reproduce th ms
- Supports that QGP droplet
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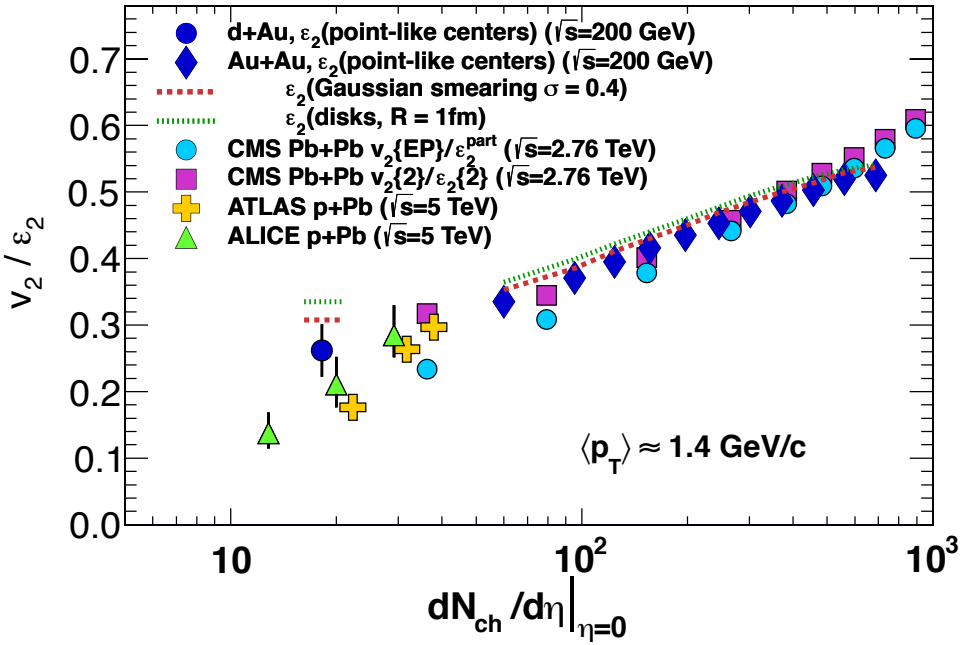
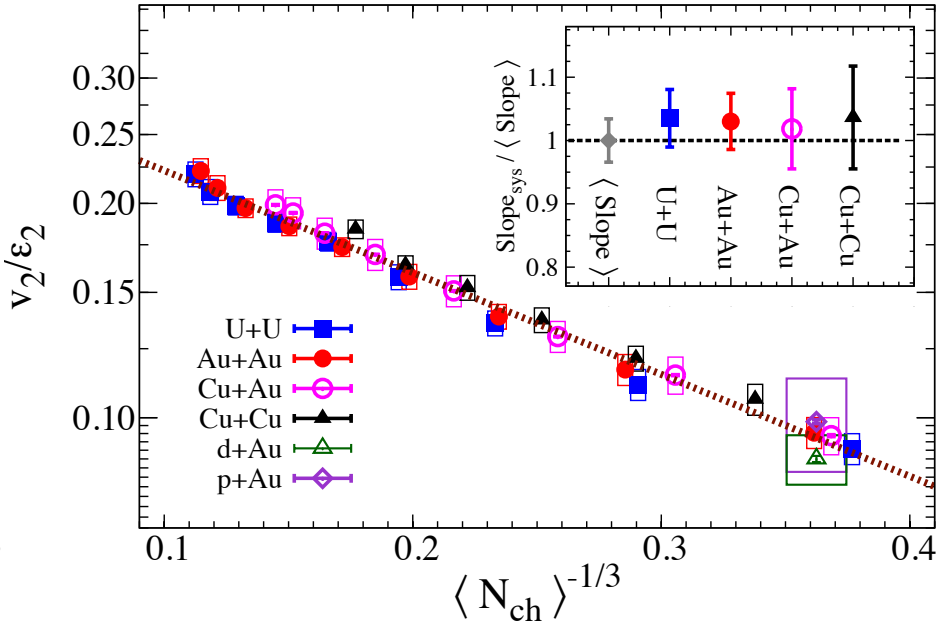
Nature Physics 15, 214–220 (2

Universal scaling from large to small systems

Phys. Rev. Lett. 111, 212301 (2013)



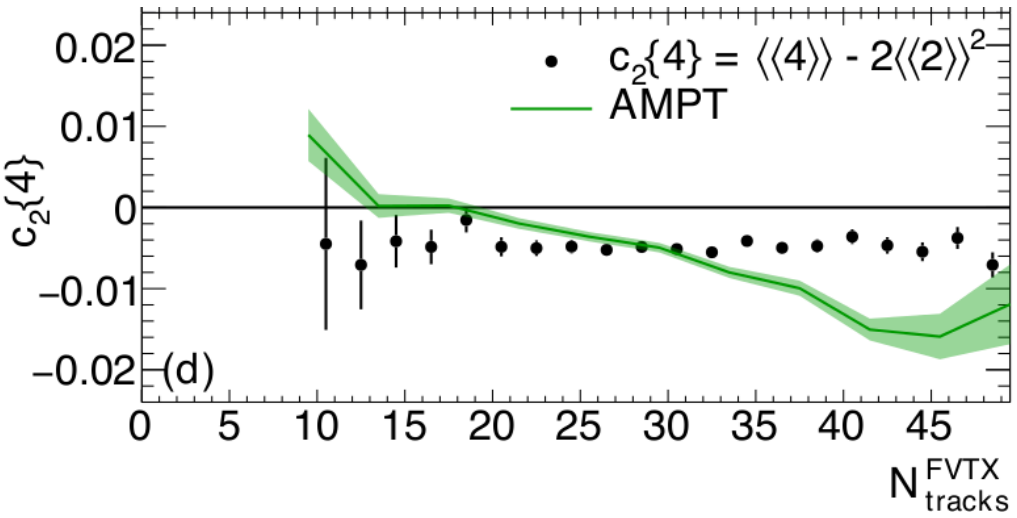
Phys. Rev. Lett. 122, 172301 (2019)



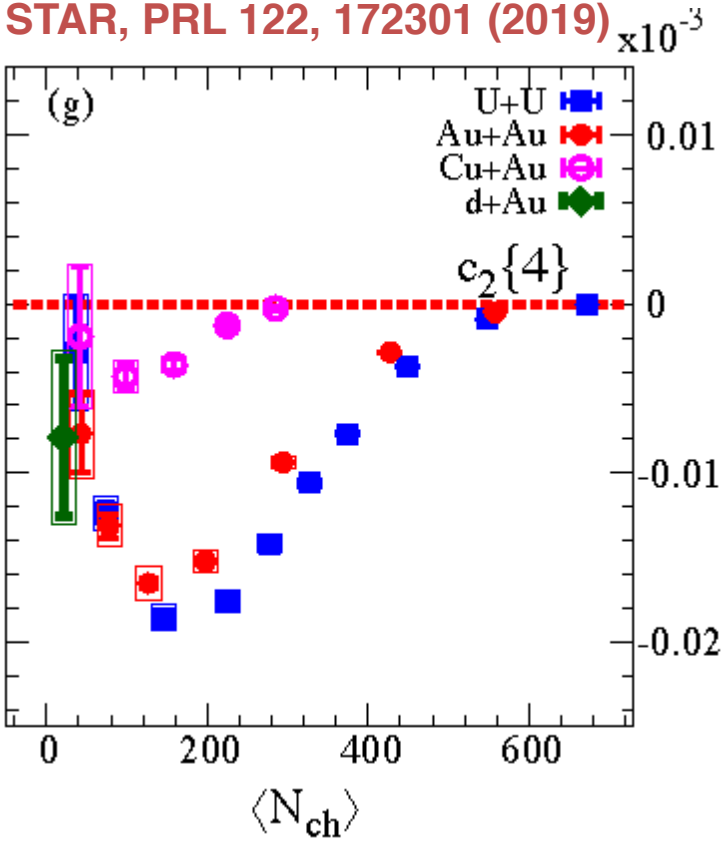
- Small systems fit nicely into trend for scaled v_2 as function of multiplicity in large systems

Multiparticle correlations

PHENIX, PRL 120, 062302 (2018)

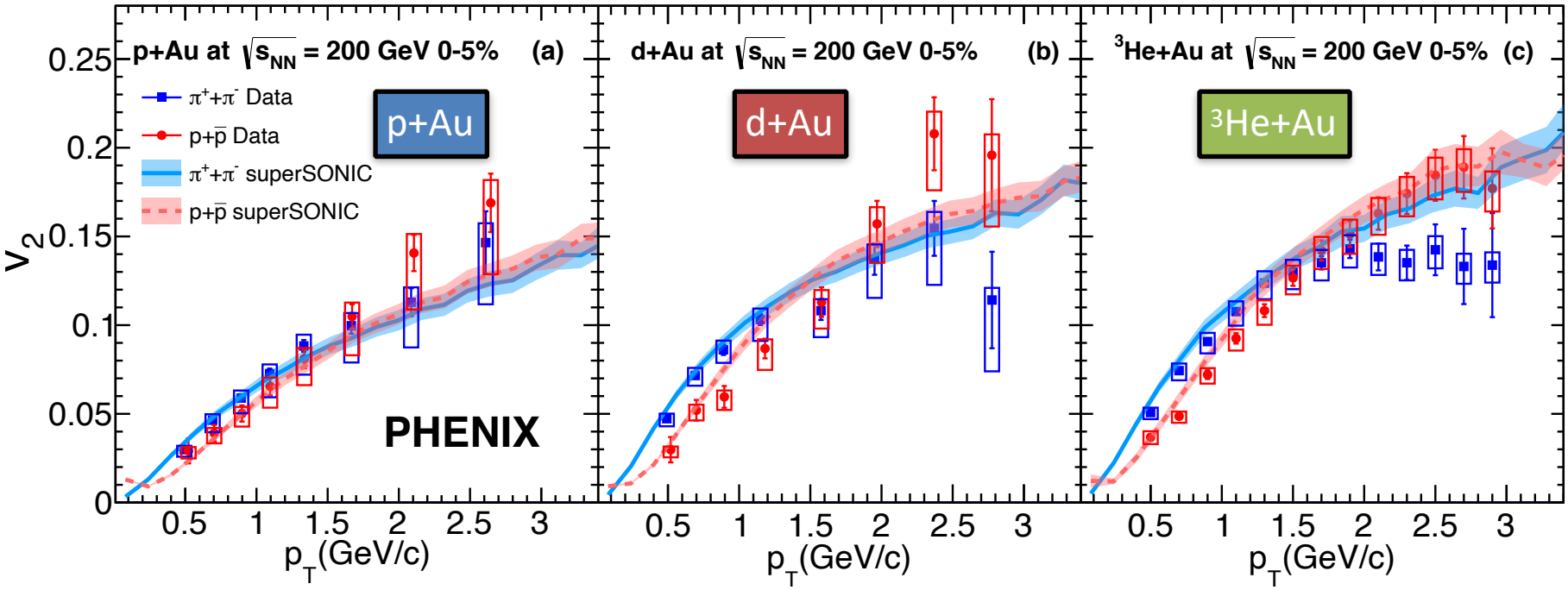


STAR, PRL 122, 172301 (2019)



- Fourth order cumulant of the Q distribution for d+Au is negative
- And it is compatible with the Nch dependance found in large systems too

$v_2(p_T)$ from common velocity field



- Large separation between pions and protons v_2 at low pt
- Split in v_2 well reproduced by hydrodynamics

Phys. Rev. C 97, 064904

Summary

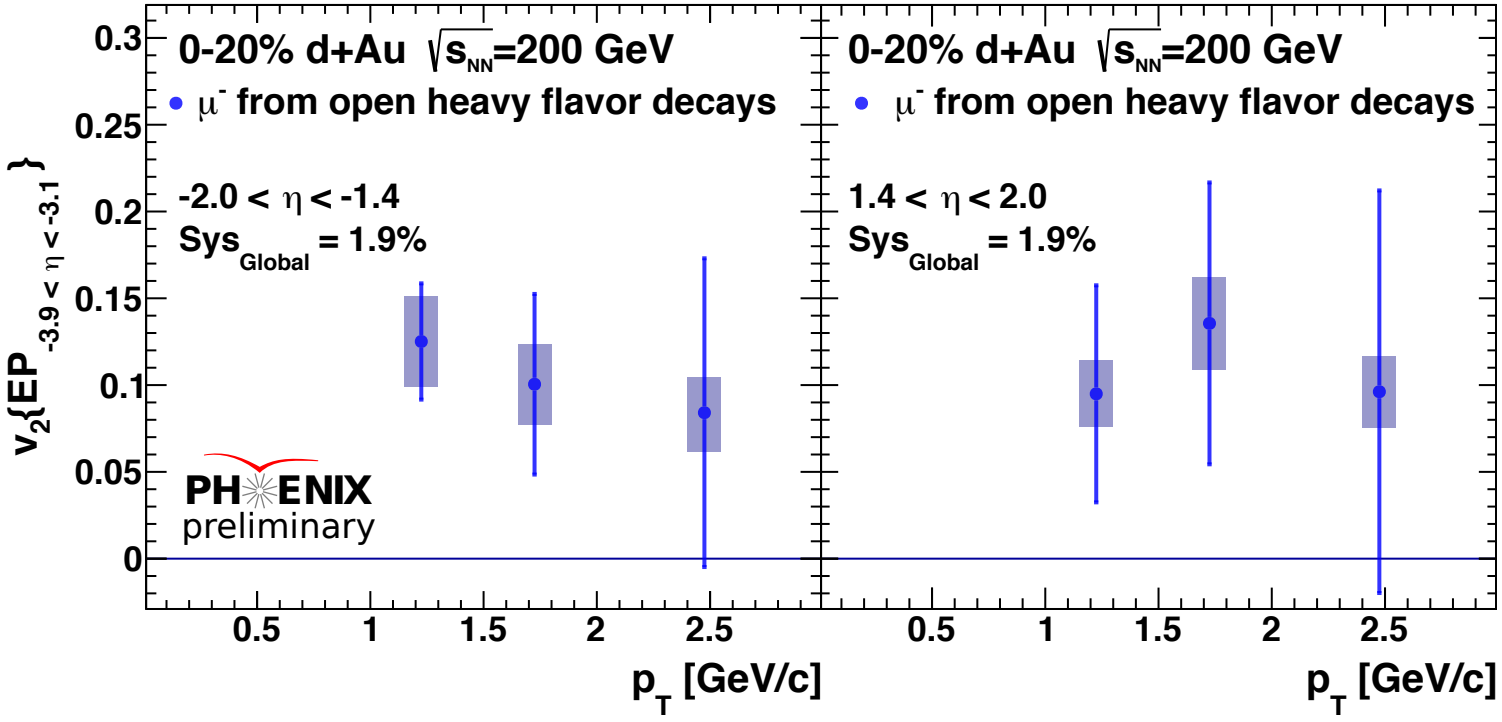
- A brief introduction to the importance of flow measurements in the understanding of the expanding QGP was presented

Smaller Systems

- Finite “flow-like” signals in Small Systems from 20 to 200 GeV and for different system geometries.
- Strong correlation between v_n and initial (spatial) anisotropy.
- Hydrodynamics models (quark-gluon droplets) are only models able to reproduced the large variety of small systems.

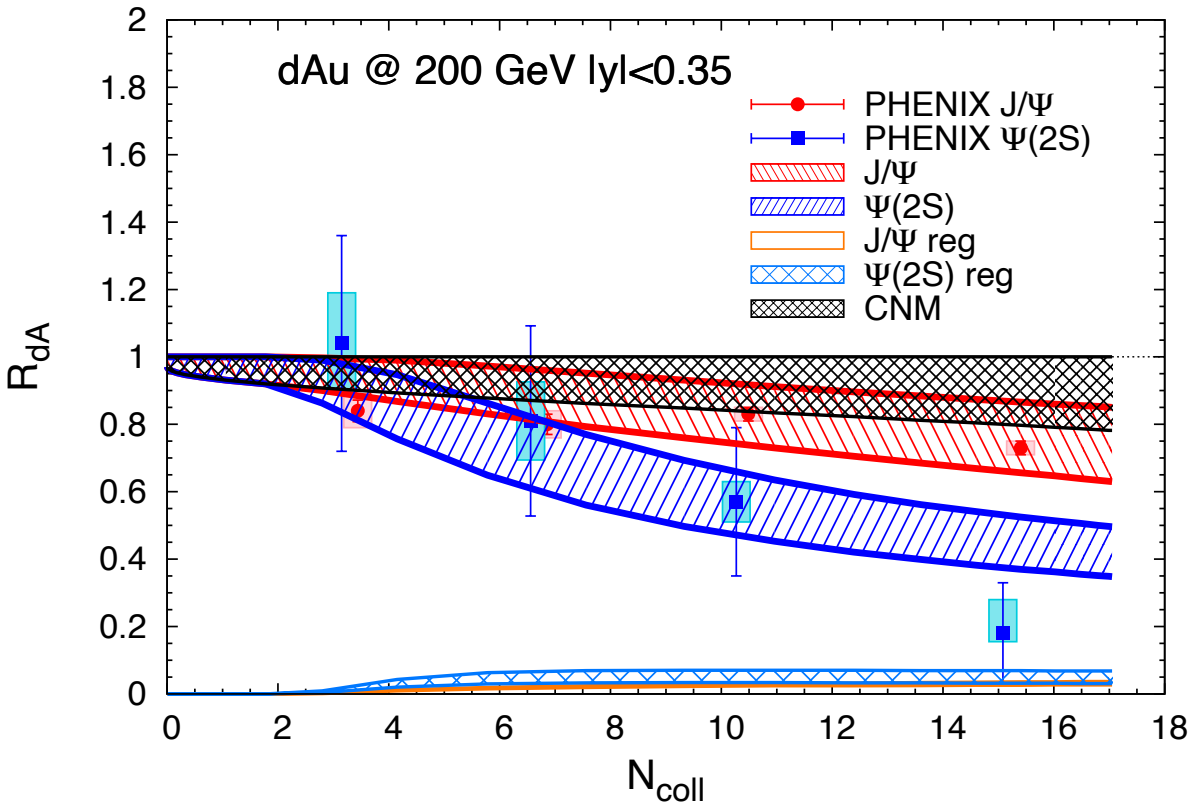
FEW OTHER RESULTS FROM SMALL SYSTEMS AT RHIC SKIPPED DUE TO TIME CONSTRAINS

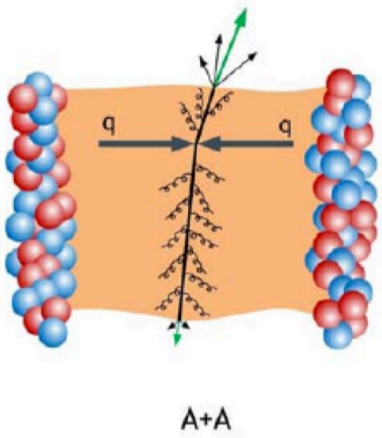
Heavy flavour hadrons in small systems



- Large v_2 for muons from decays show long range correlation imprint for heavy hadrons

Heavy flavour hadrons in small systems





- Large v_2 for muons from decays show long range correlation imprint for heavy hadrons
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Du, X. & Rapp, R. J. High Energ. Phys. (2019) 2019: 15

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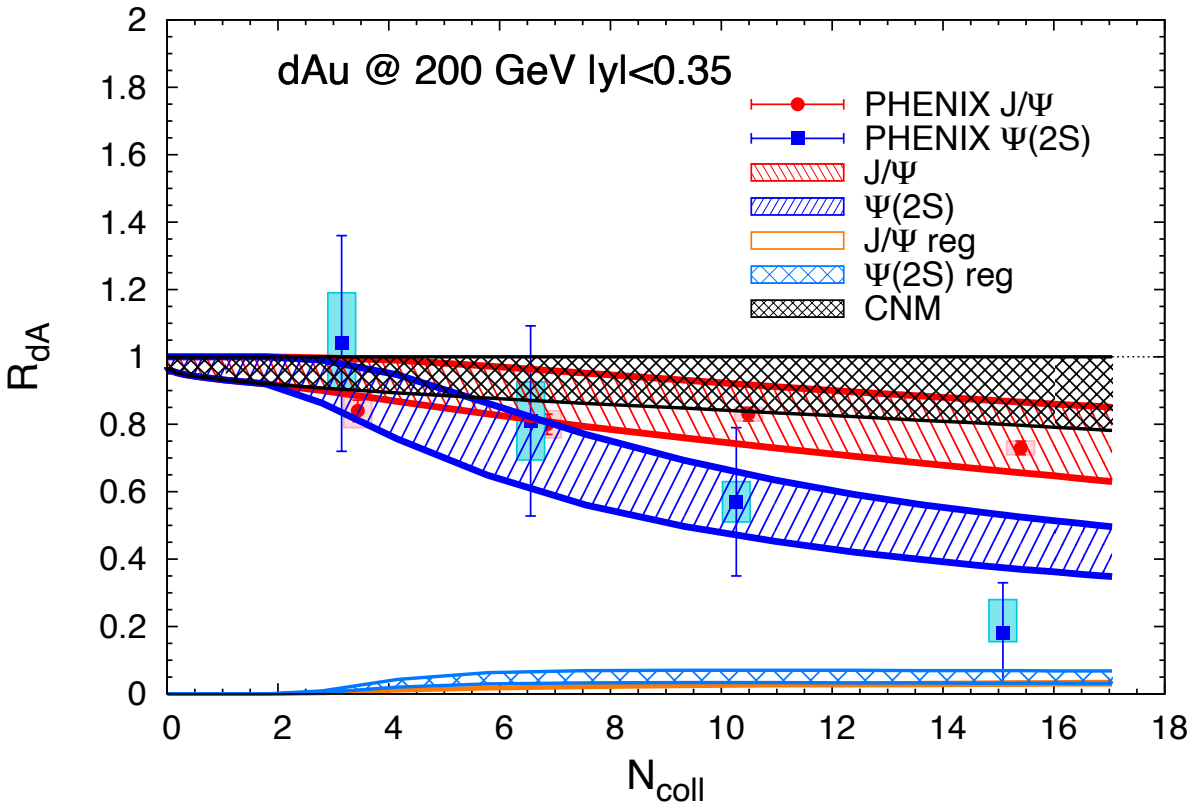

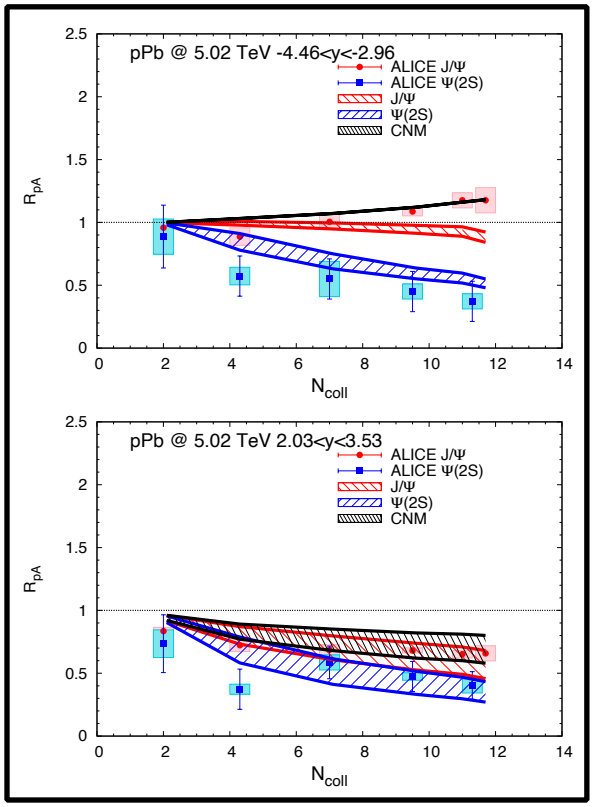

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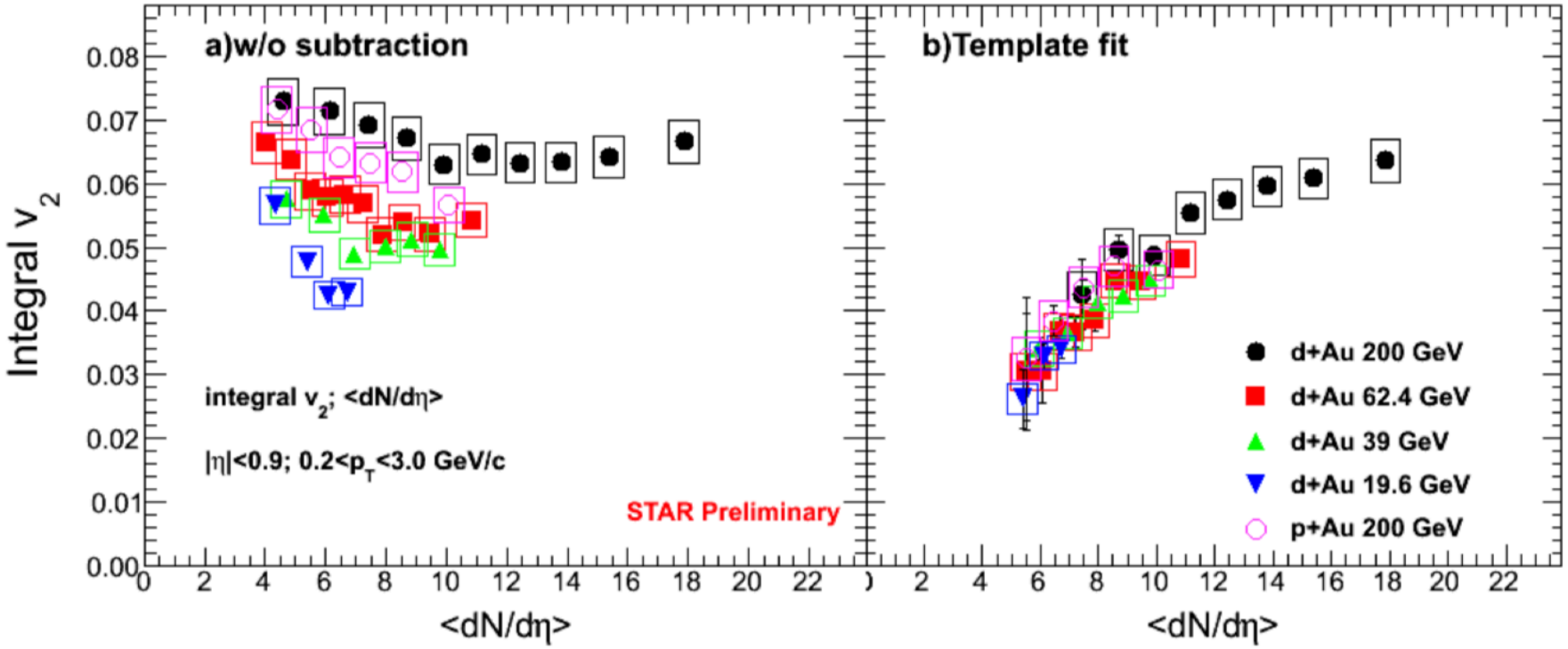
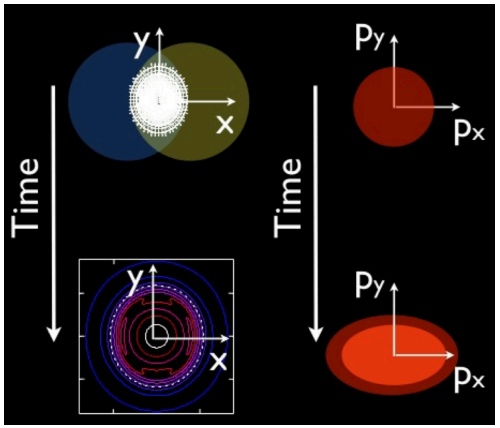
Universal trend in v_2 for small systems



Collective Phenomena



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- One of the main probes is anisotropic flow

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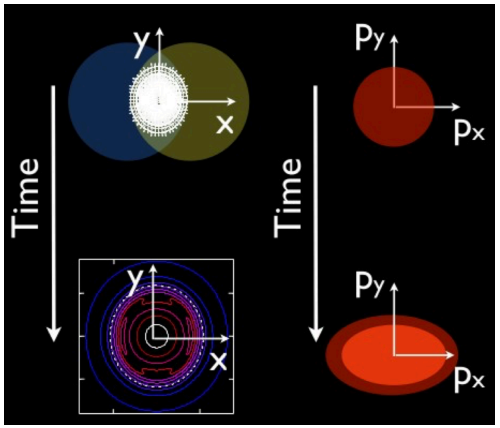

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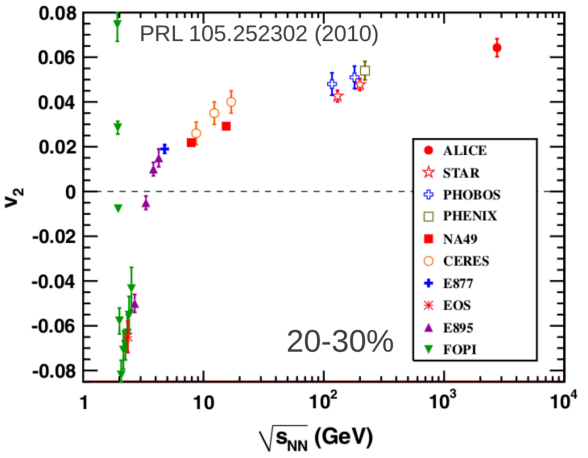
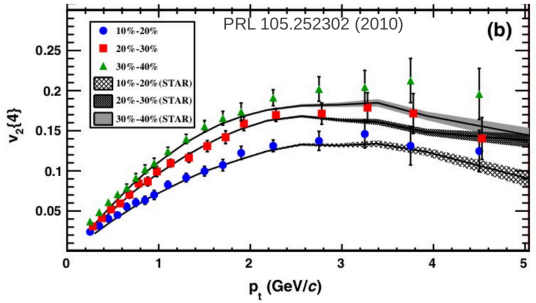
What do we learn from vn?

- Very low viscous fluid
- Increase with energy density
- Differential v2 similar between LHC and RHIC





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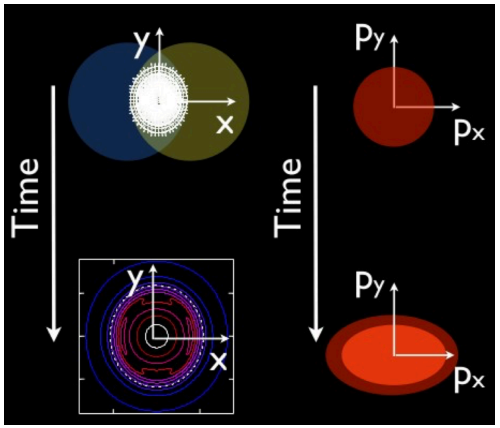

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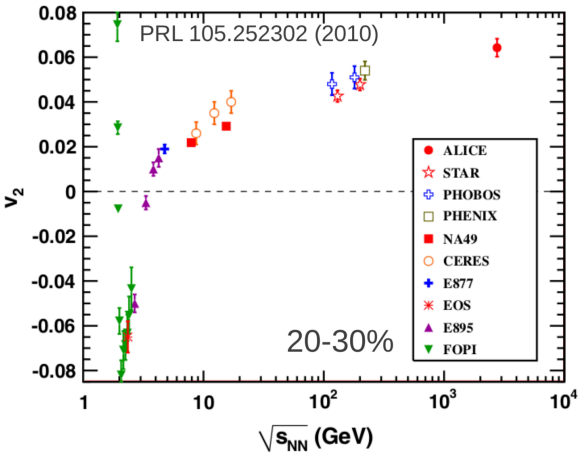

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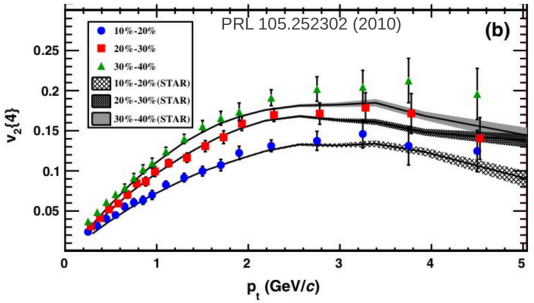
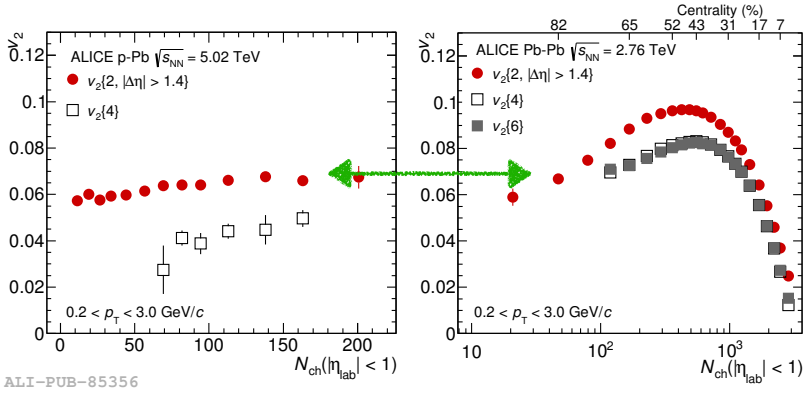


Properties hold even for smaller systems



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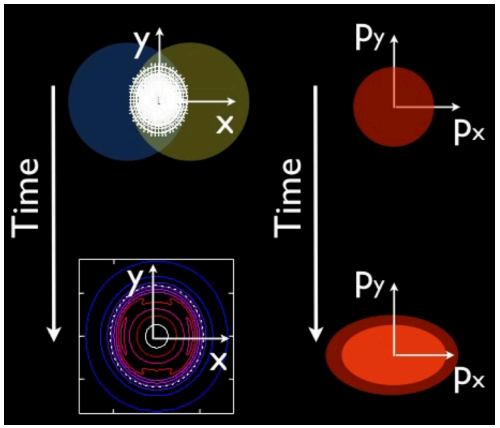

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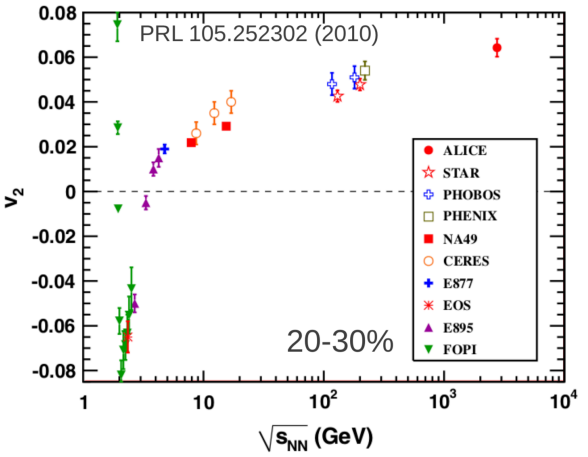

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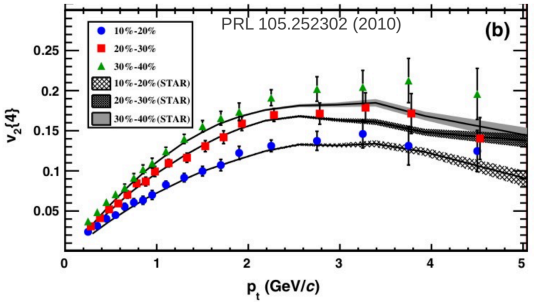
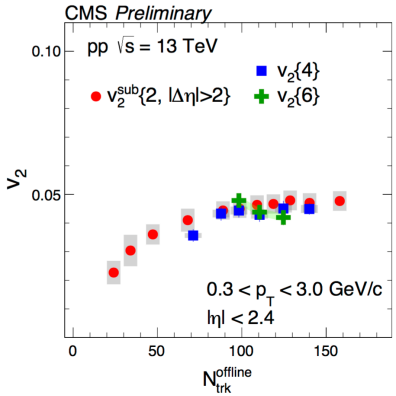
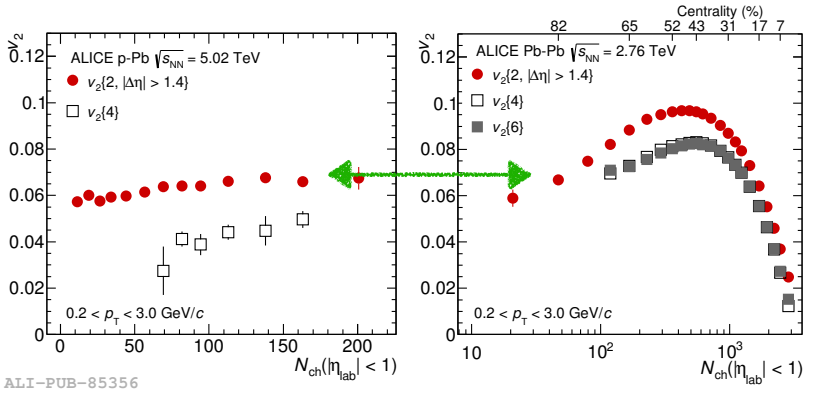


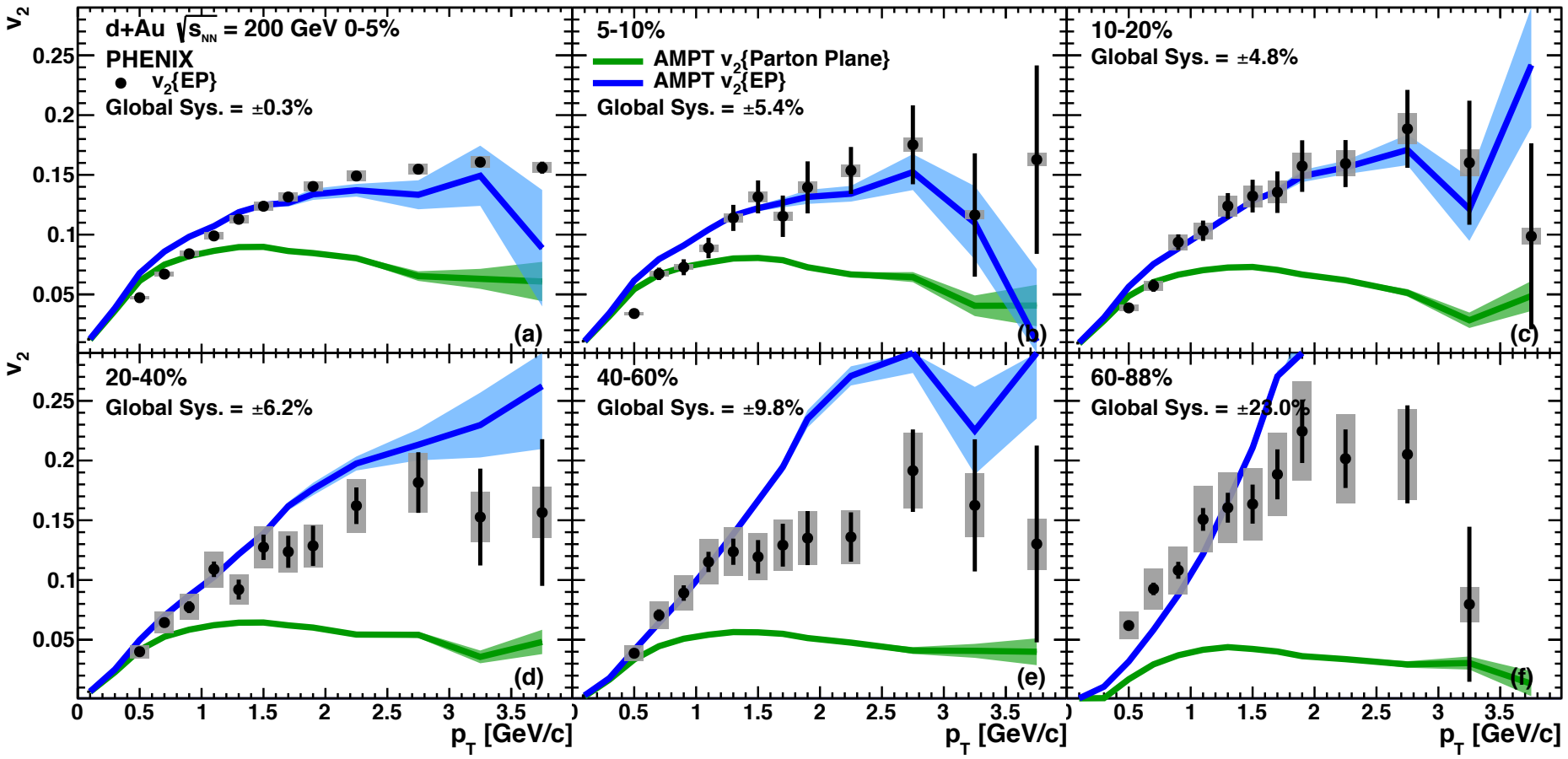
All particle correlation even for pp?

Truth is in the details





$v_2(p_T)$ for Charged Particles @ 200 GeV



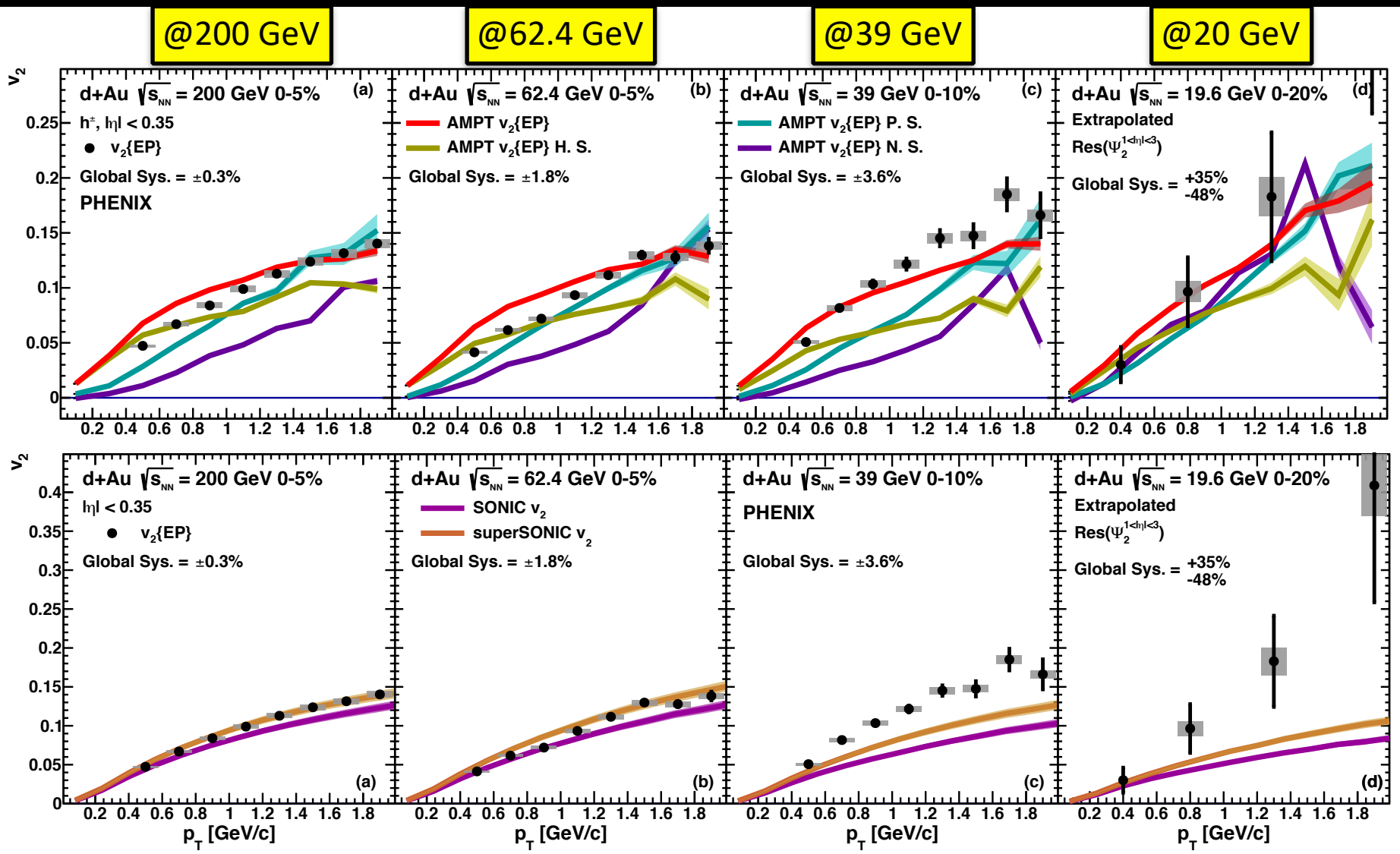
- v_2 signal present in all centralities
- v_2 reproduced by AMPT when simulating EP reconstruction. Difference nonflow?

Phys. Rev. C 96 064905 (2017)

d+Au

200

$v_2(p_T)$ for Most Central Low p_T

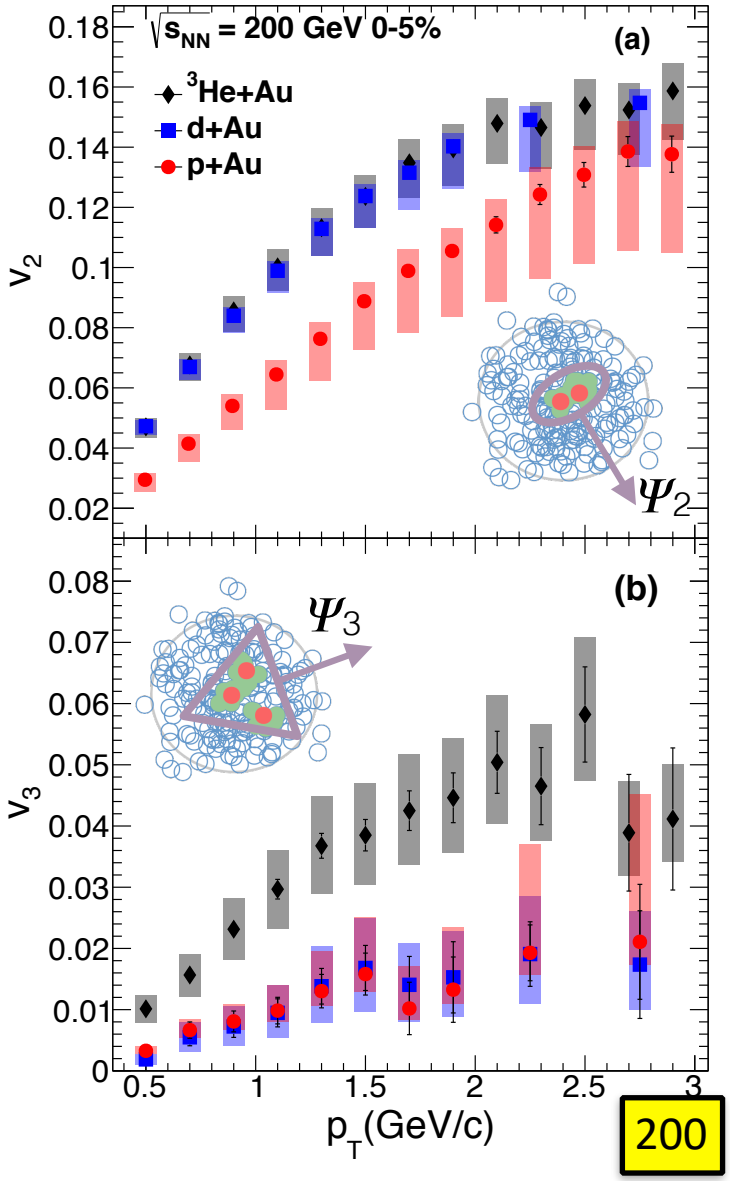


Phys. Rev. C 96 064905 (2017)

d+Au

v_2 and v_3 for Most Central Collisions

- Interesting scaling of v_2 and v_3 with system size
  - d+Au v_2 close to ^{3}He+Au
  - d+Au v_3 close to p+Au



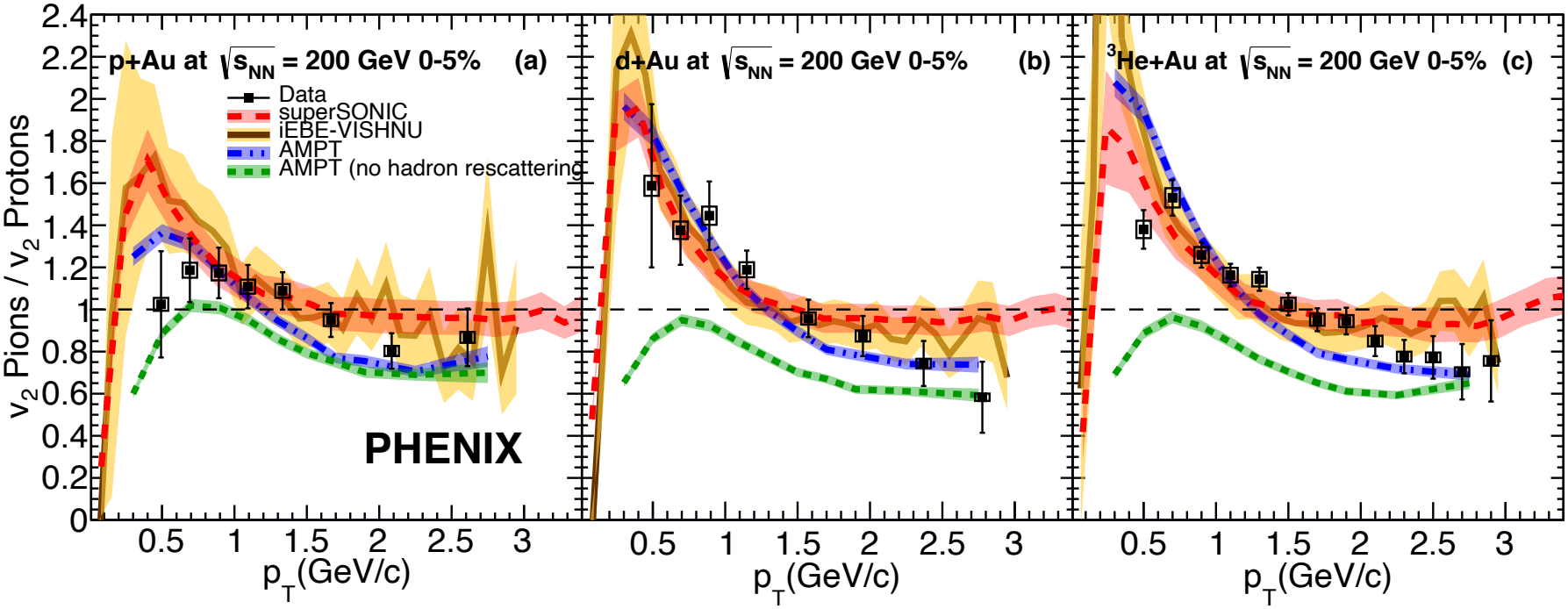
***Nature Physics* 15, 214–220 (2019)**

p+Au | d+Au | ^{3}He+Au

200

Particle Production Mechanism

$v_2(p_T)$ Mass Dependence



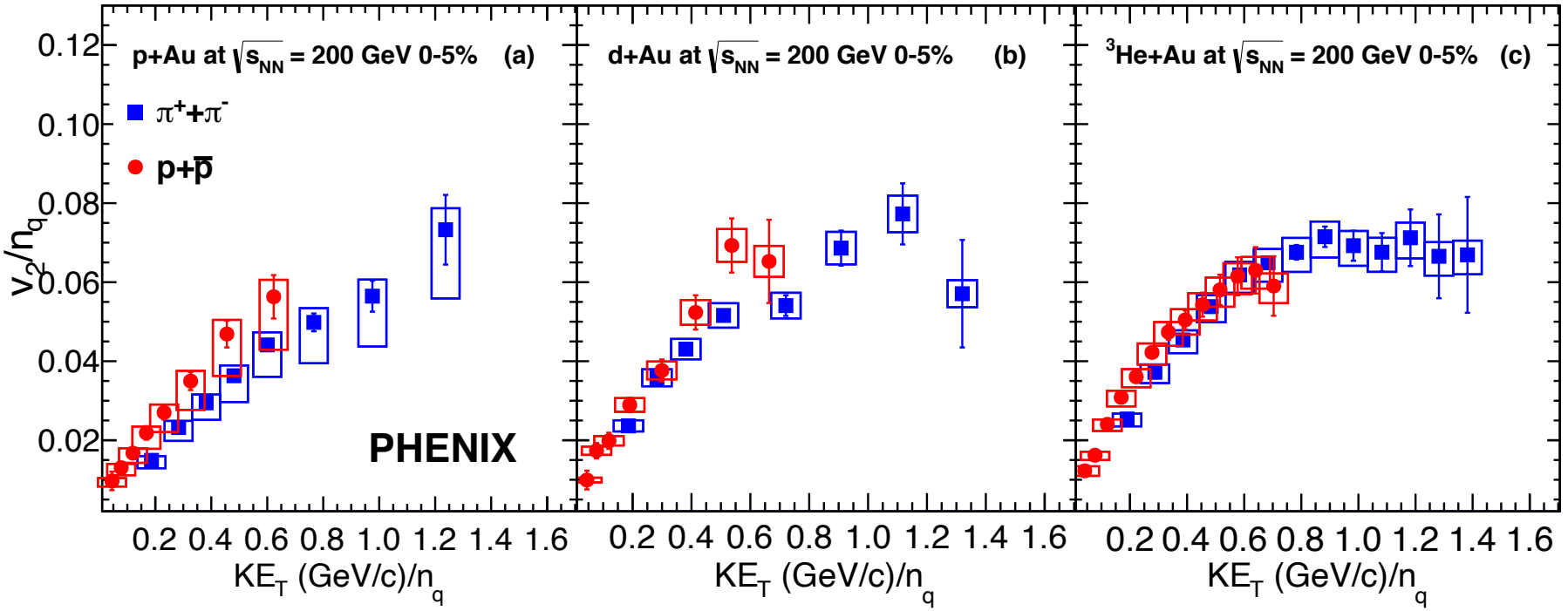
- Large difference in v_2 for pions and protons.
- Hydro reproduces quite well low p_T data. Radial Flow push?
- AMPT model suggests the difference could build up during hadronic scattering.

Phys. Rev. C 97, 064904

p+Au | d+Au | ^{3}He+Au

200

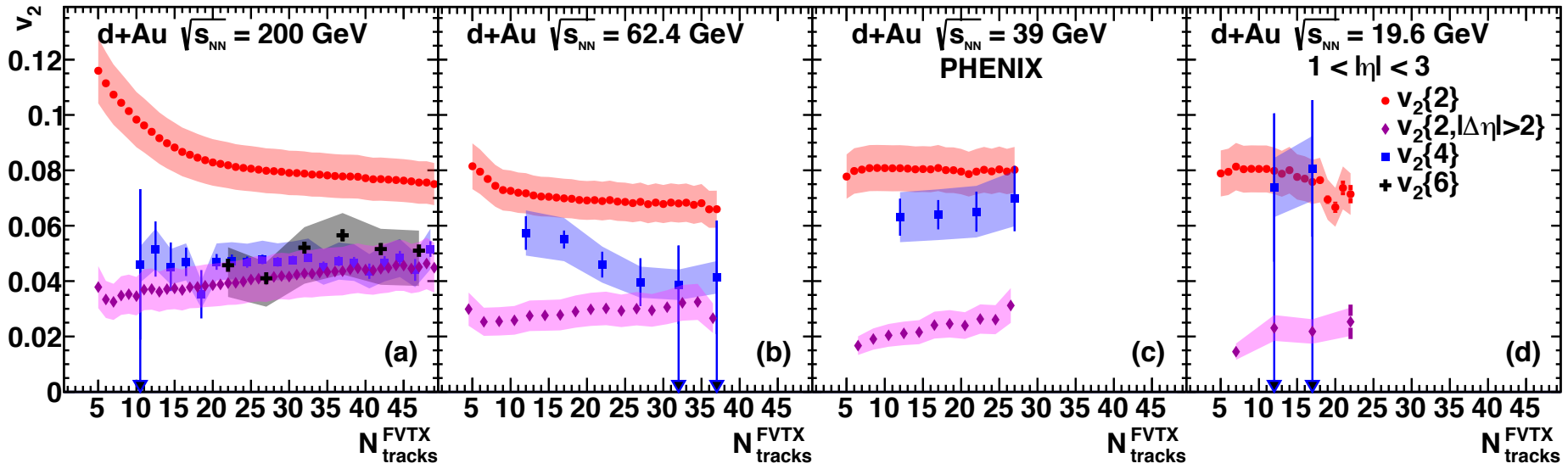
Partonic $v_2(p_T)$ Test



- Test of scaling with constituent quarks.
- Approximate quark scaling holds very well for the three different systems. Deconfinement?

Phys. Rev. C 97, 064904 p+Au d+Au ^{3}He+Au 200

MPC from 200 to 20 GeV

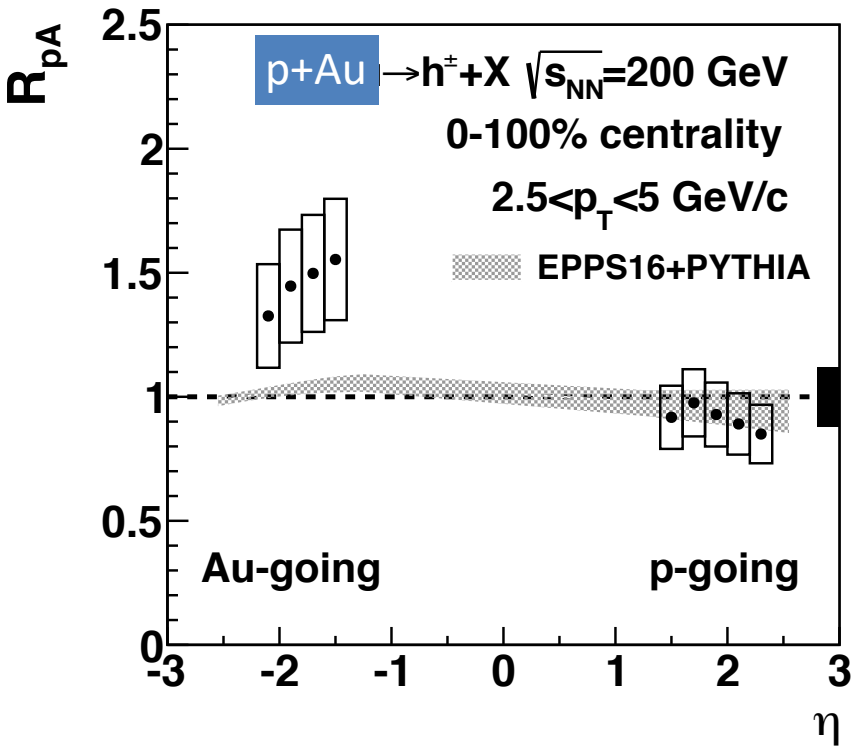


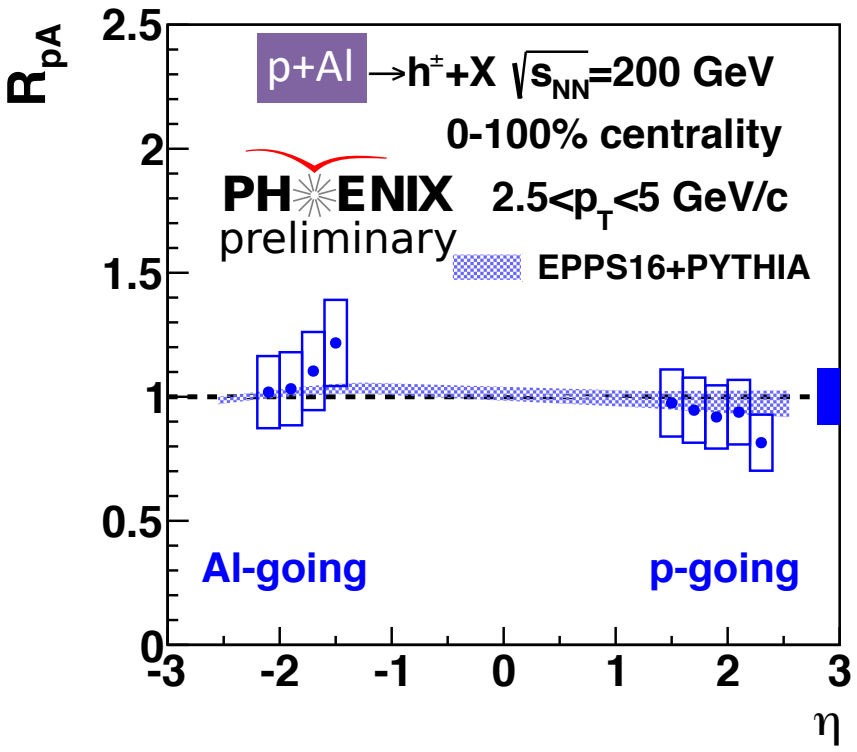
Phys. Rev. Lett. 120, 062302 (2018)

Forward Rapidities

NUCLEAR MODIFICATION FACTOR

R_{pA}(eta) for Charged Hadrons



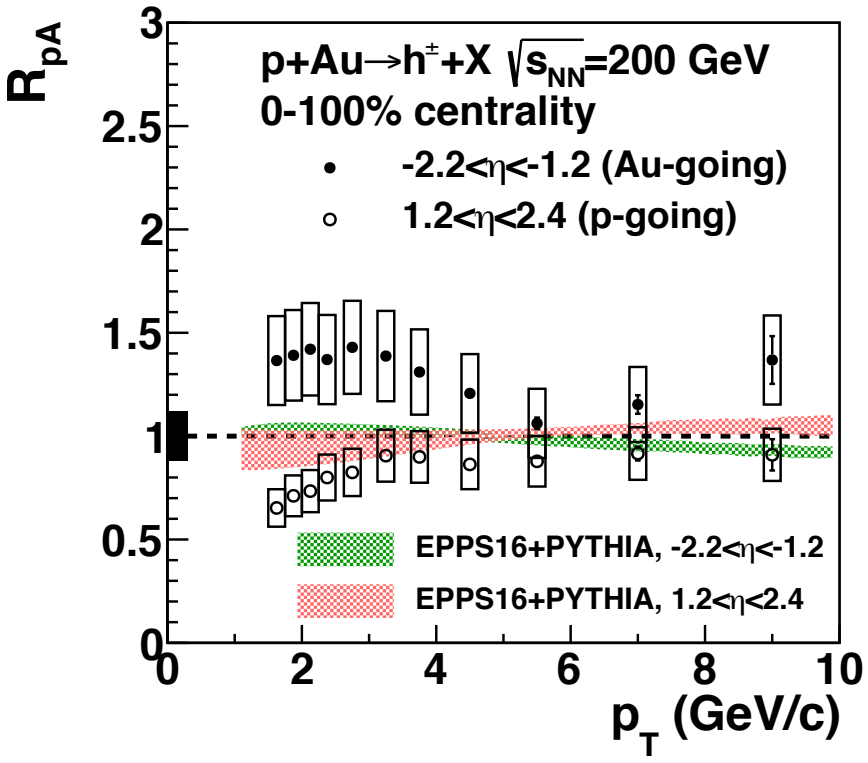


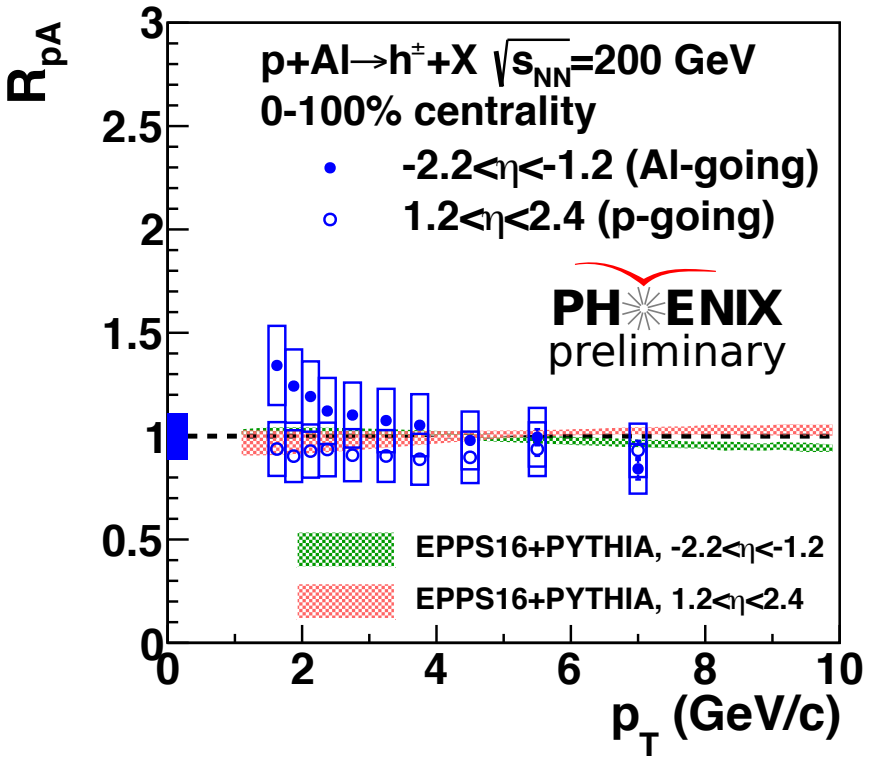
- Enhancement found in Au-going direction not reproducible by EPPS16.

p+Au p+Al

Where does it come from?

R_{pA}(pT) for Charged Hadrons





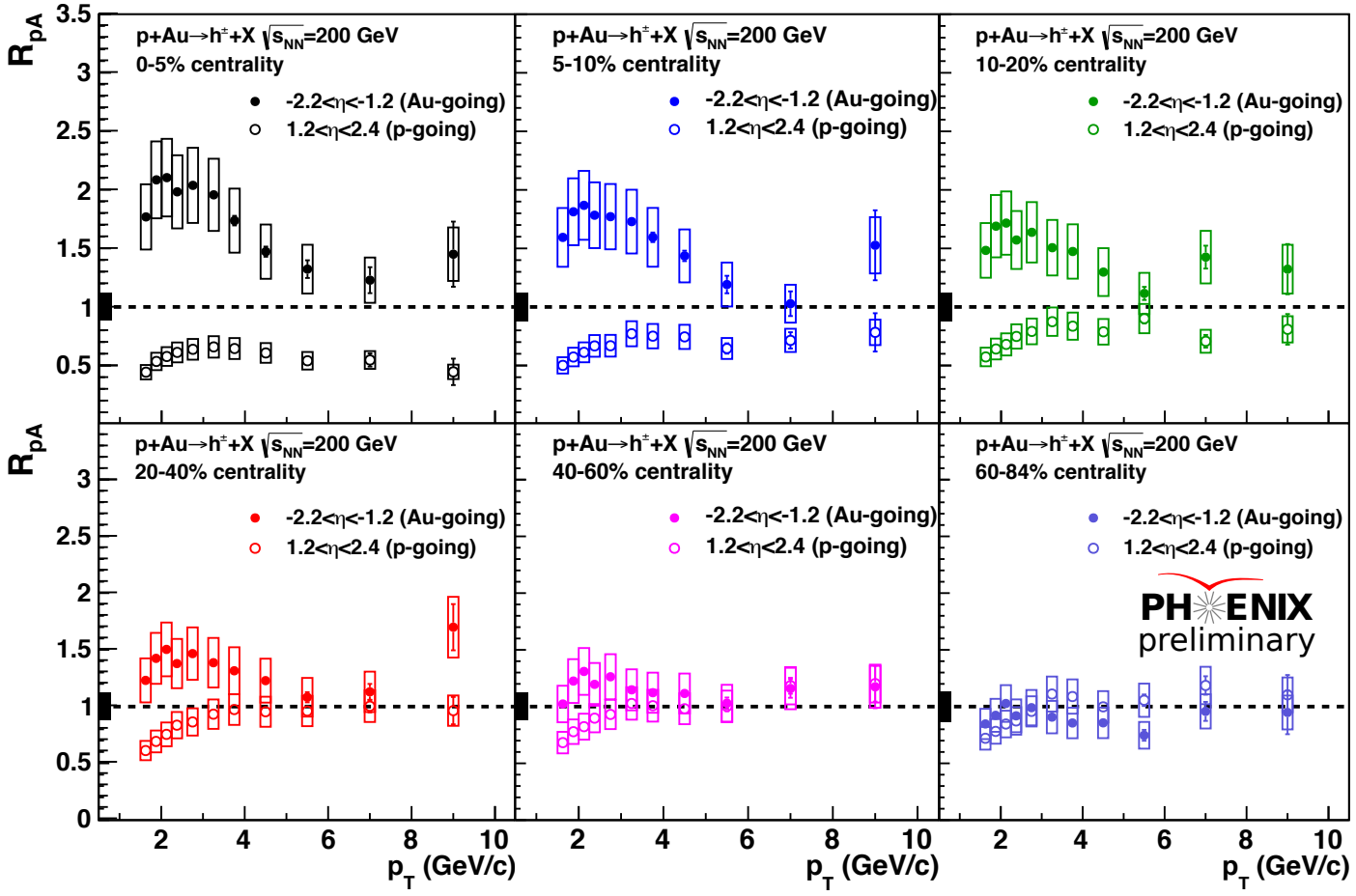
- Enhancement found in Au-going direction not reproducible by EPPS16.

- Enhancement mainly for p_T <5 GeV

p+Au p+Al

Where does it come from?

Centrality Dependence of $R_{pA}(pT)$



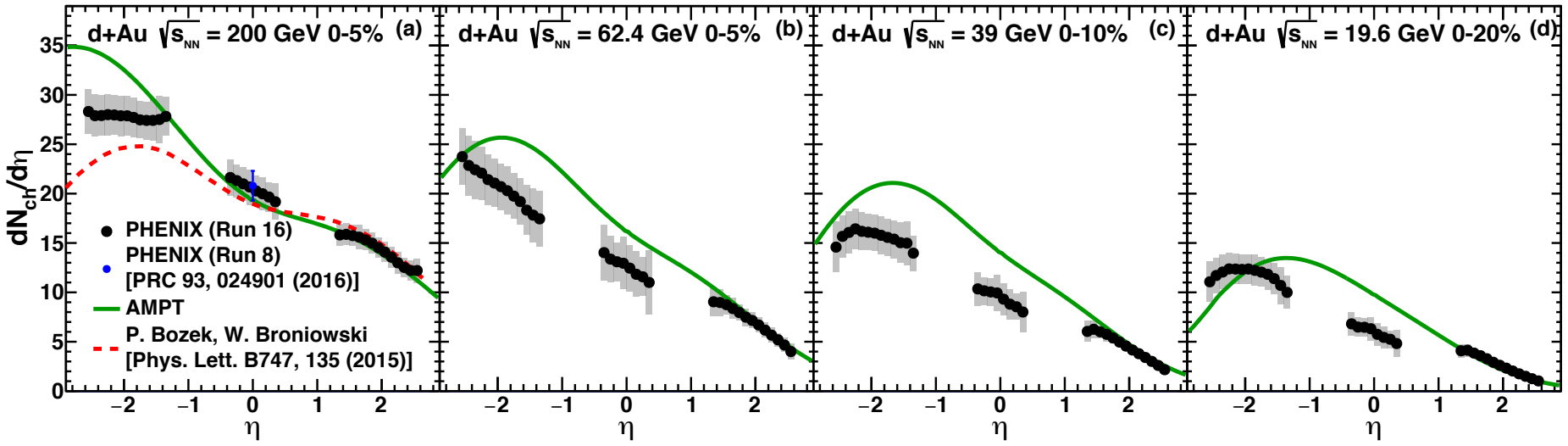
- Enhancement mainly for p_T <5 GeV and centrality dependent.

p+Au

Where does it come from?

Particle Production Mechanism

N_{ch} vs Eta



- Both AMP and Hydro qualitatively predict an enhancement in the Au-going direction.

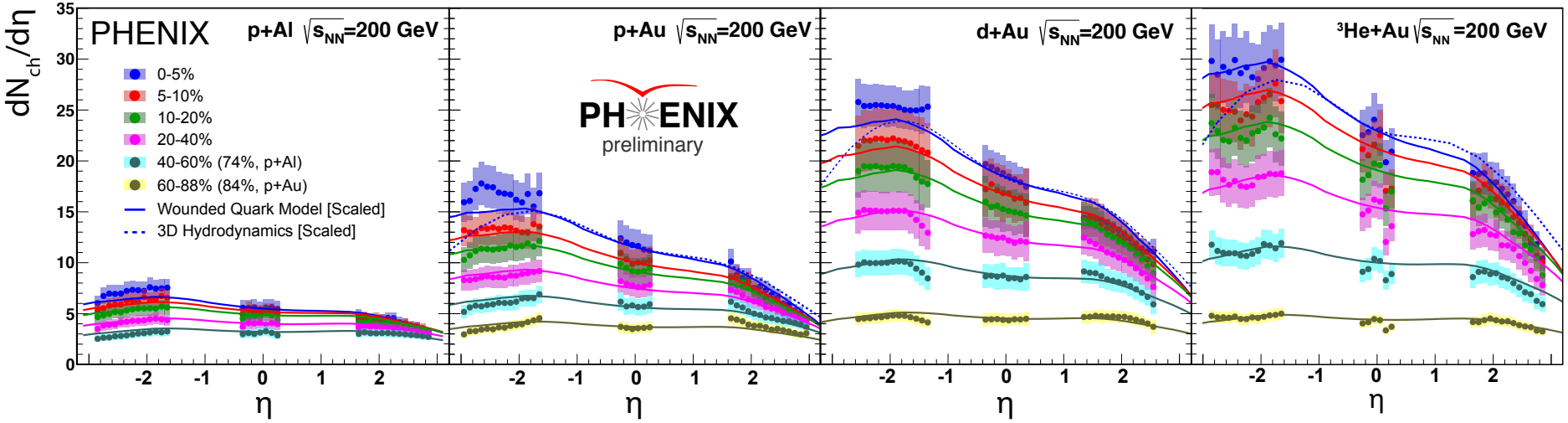
- AMPT describes also the measured trend in d+Au with collisional energy.

Phys. Rev. C 96 064905 (2017)

d+Au

20 39 62 200

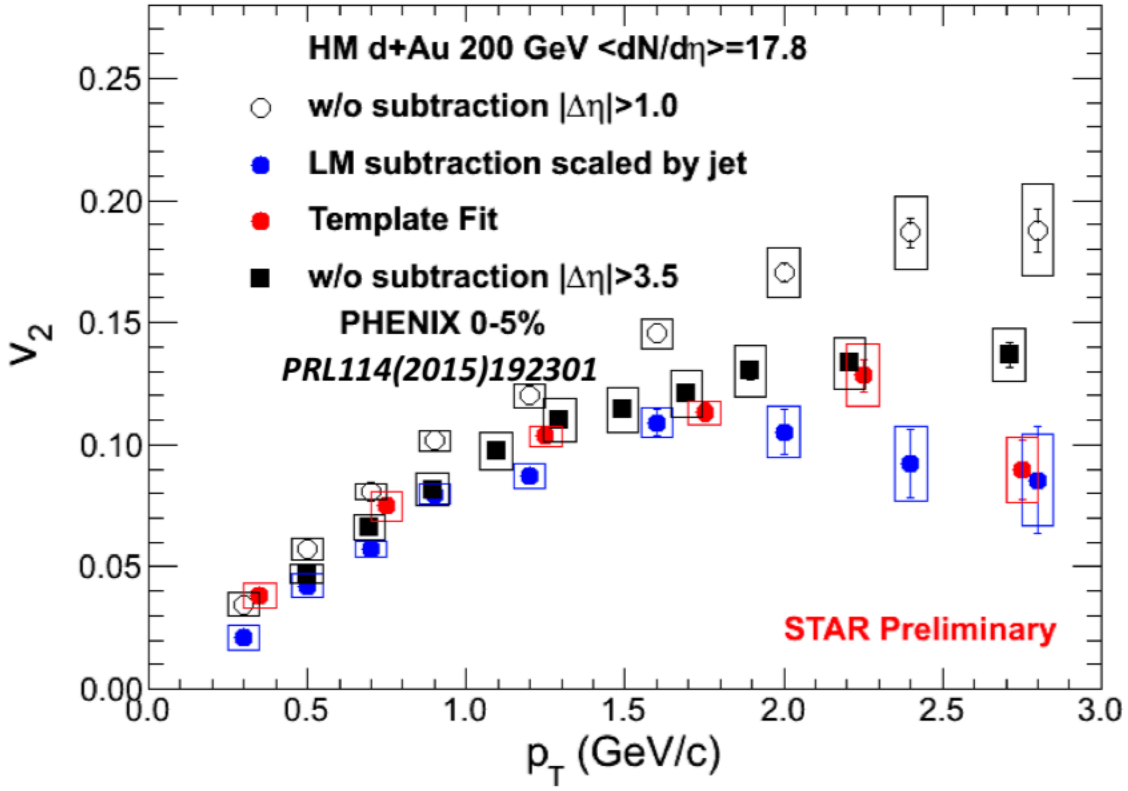
N_{ch} vs Eta



- Both AMP and Hydro qualitatively predict an enhancement in the Au-going direction.
- AMPT describes also the measured trend in d+Au with collisional energy.
- Hydro describes quite well the data from different systems at all centralities

Phys. Rev. C 96 064905 (2017) p+Al p+Au d+Au ^{3}He+Au 200

HEAVY FLAVOUR


HM d+Au 200 GeV <dN/dη>=17.8
w/o subtraction |Δη|>1.0
LM subtraction scaled by jet
Template Fit
w/o subtraction |Δη|>3.5
PHENIX 0-5%
PRL114(2015)192301
STAR Preliminary
v2
pT (GeV/c)
0.00
0.05
0.10
0.15
0.20
0.25
0.0
0.5
1.0
1.5
2.0
2.5
3.0

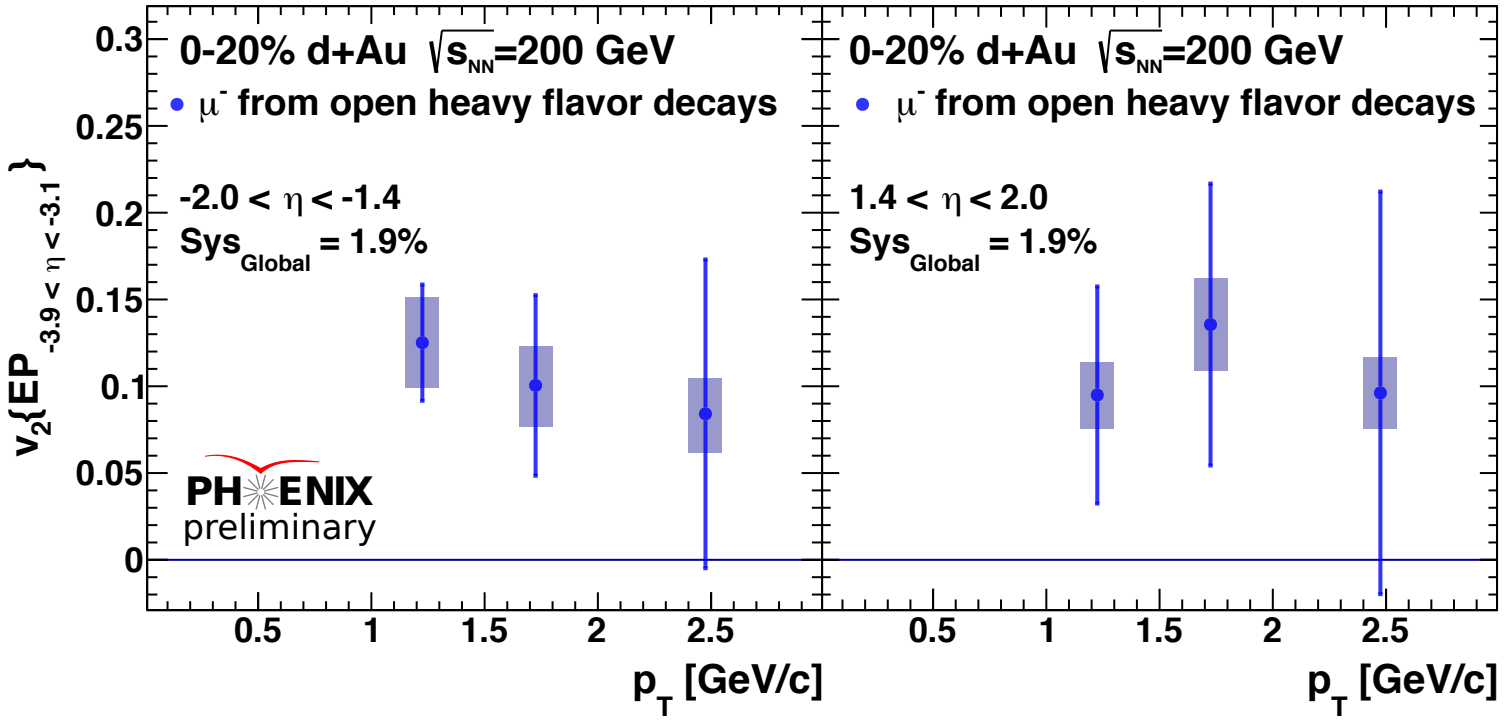
Heavy Flavour in Heavy Ion Collisions

- In Heavy Ion Collisions, heavy flavour particles are expected to be produced mainly in the hard scattering.

- A large (comparable to ch-particles) azimuthal anisotropy has been found for HF-particles in several experiments, species and energies, which suggests some degree of sensitivity to the collective expansion.

- How about small systems, low energies?

v_2 of Muons from Heavy Flavour Decays



- Muons from heavy flavour decays are obtained from MC templates.

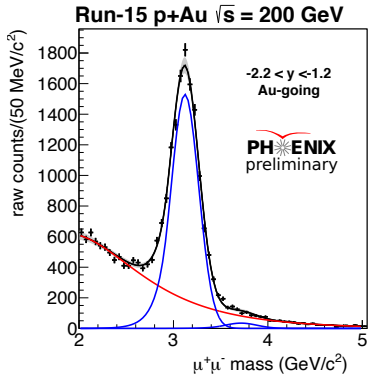
R_{AA} in Heavy Ion Collisions

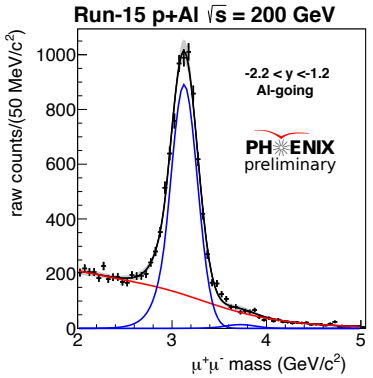
- RAA is one of the (oldest) golden experimental observables in studying the physics of heavy ion collisions.

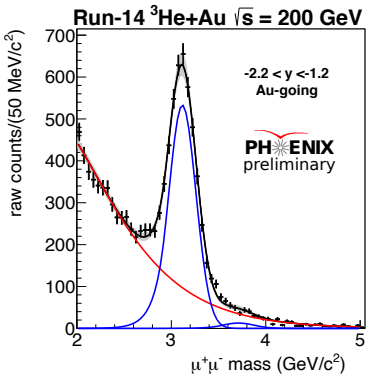
- It measures the relative yield found in AA to the respective scaled pp measurement, which helps characterise the role of in-medium modification.

- R_{pA} has been also used to study cold-matter effects, such as nuclear shadowing or gluon-saturation, specially at forward rapidities.

Inclusive J/Psi @ Forward Rapidities

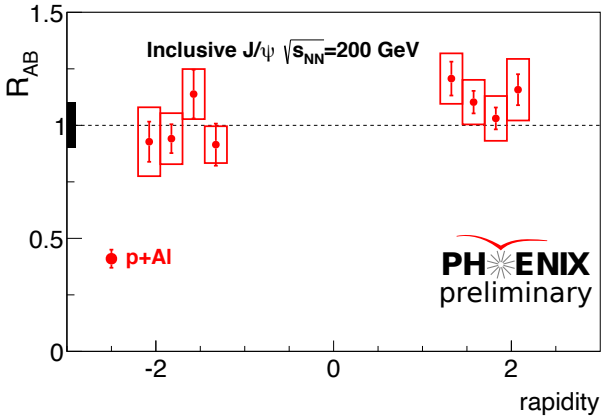


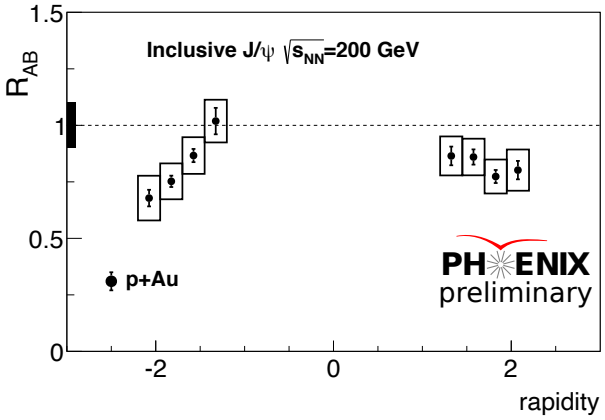


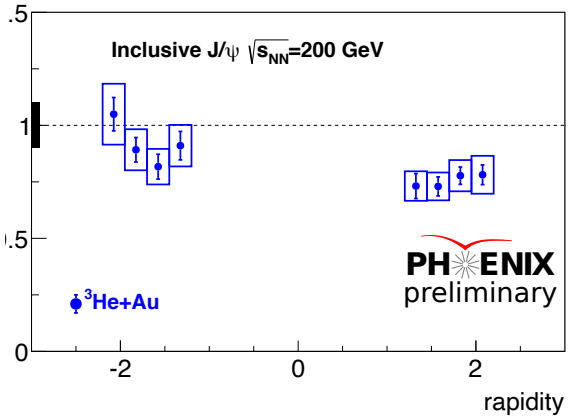


- Preliminary results for closed states hint to suppression even for Au-going direction.

- Are mechanisms responsible for enhancement of charged particles less effective with quarkonia?



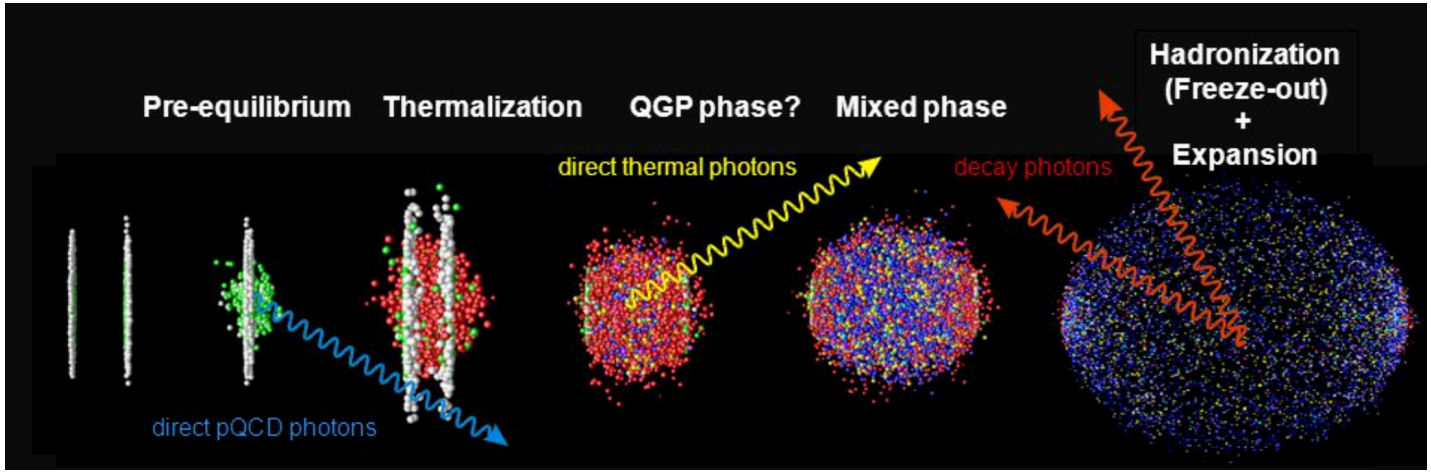




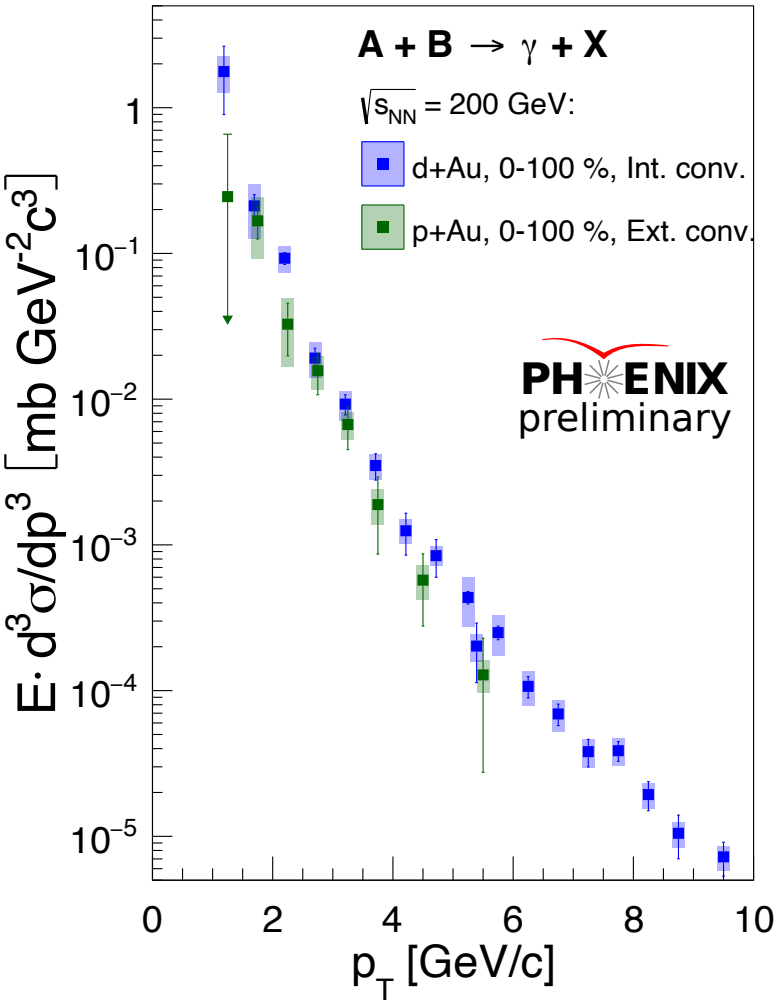
PHOTONS

Photons in Heavy Ion Collisions

- Photons from Heavy Ion Collisions
  - Direct Photons
    - Initial State hard scattering (prompt) pQCD
    - Thermal Temperature from Fireball (QGP)
  - Hadronic Photons
    - Decay products Underlying Event



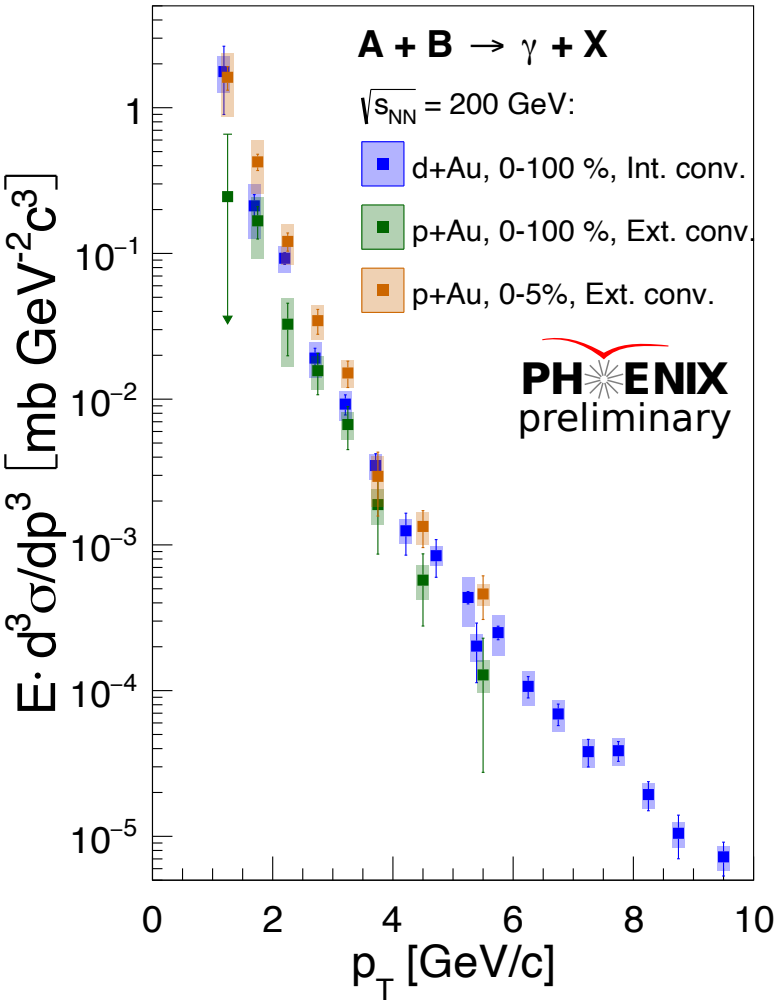
Direct Photon Yields @ 200 GeV in SS



- Small increase in photons production in d+Au wrt p+Au for minimum bias collisions

p+Au d+Au

Direct Photon Yields @ 200 GeV in SS



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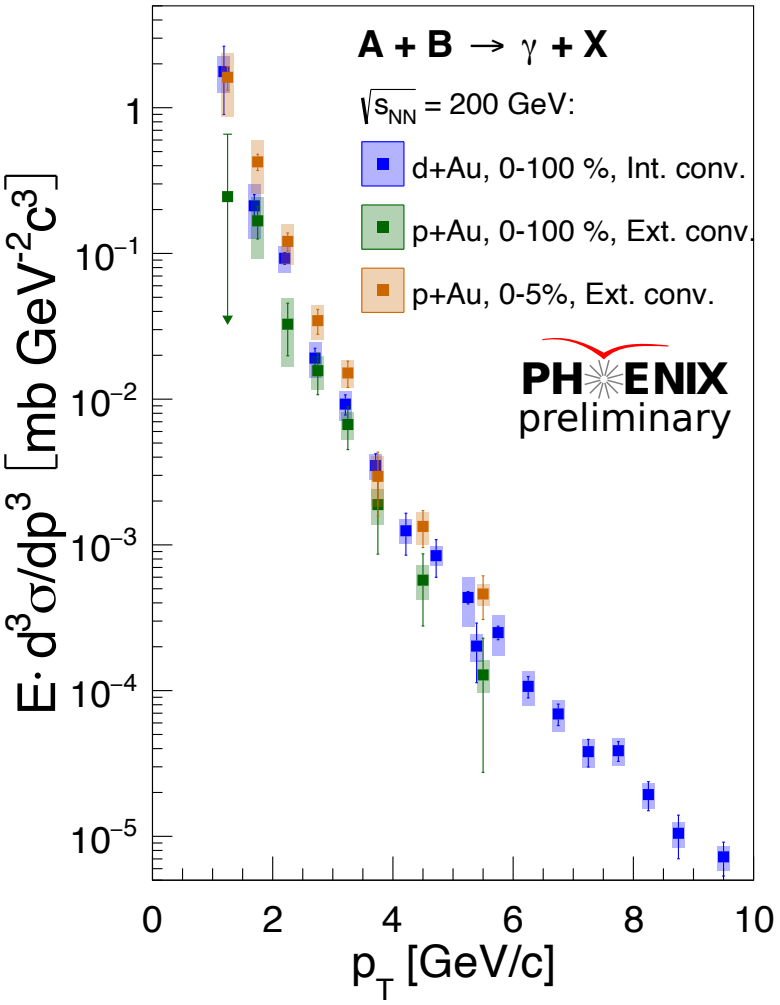
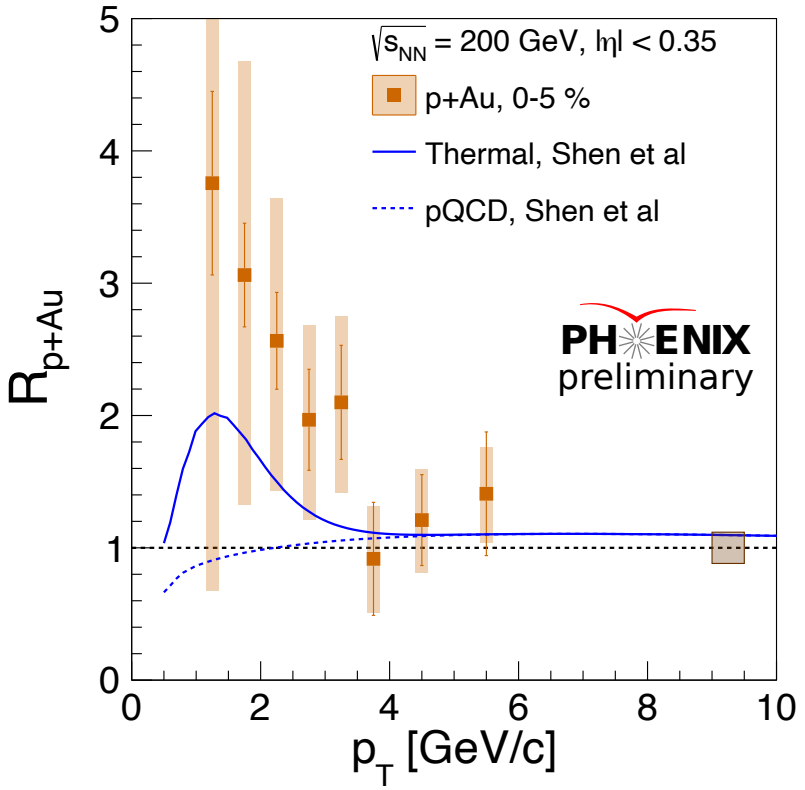
- Significant increase found at low p_T in most central p+Au Collisions wrt Minimum Bias

p+Au d+Au

Direct Photon Yields @ 200 GeV in SS





- Significant increase found at low p_T in most central p+Au Collisions wrt Minimum Bias

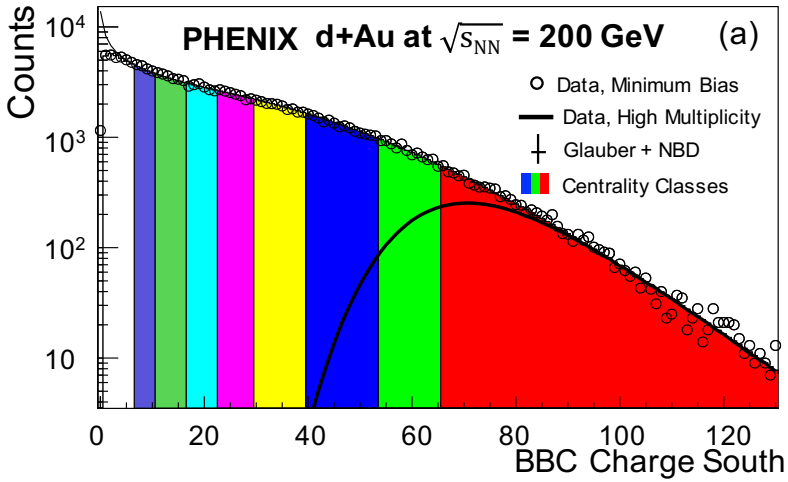
- Does it have a thermal origin?

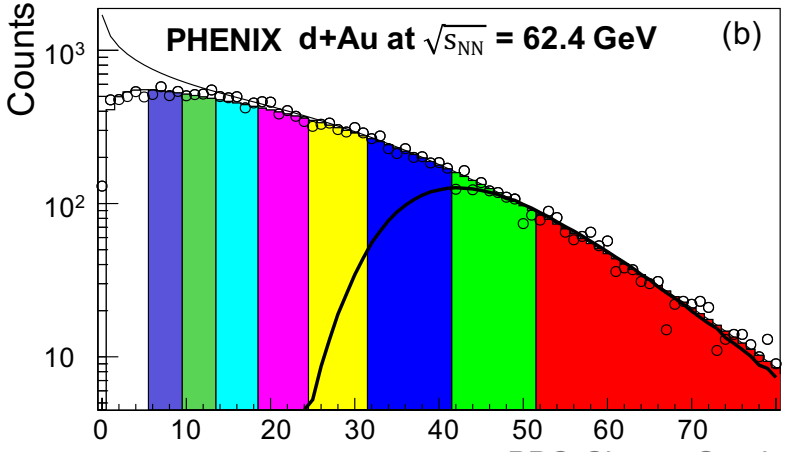
p+Au d+Au

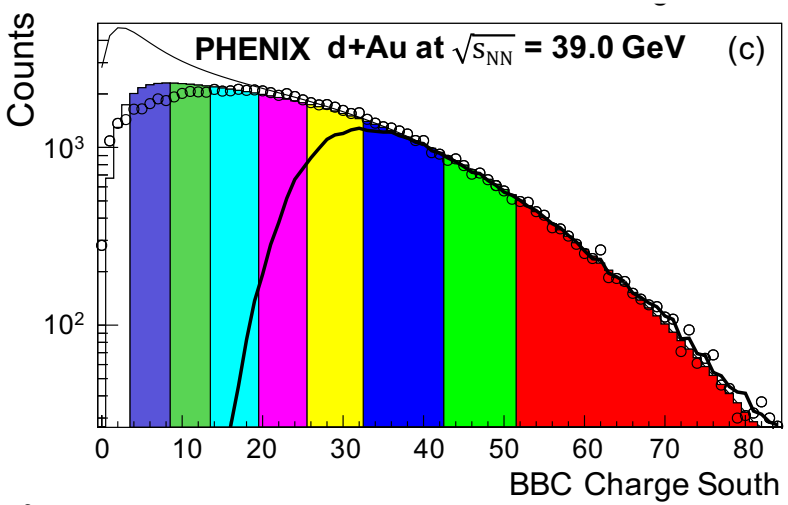
200

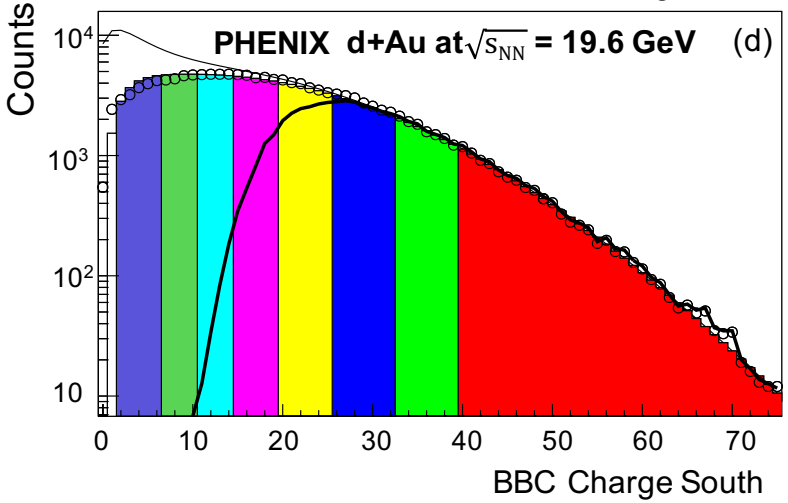
Centrality Classification

d+Au



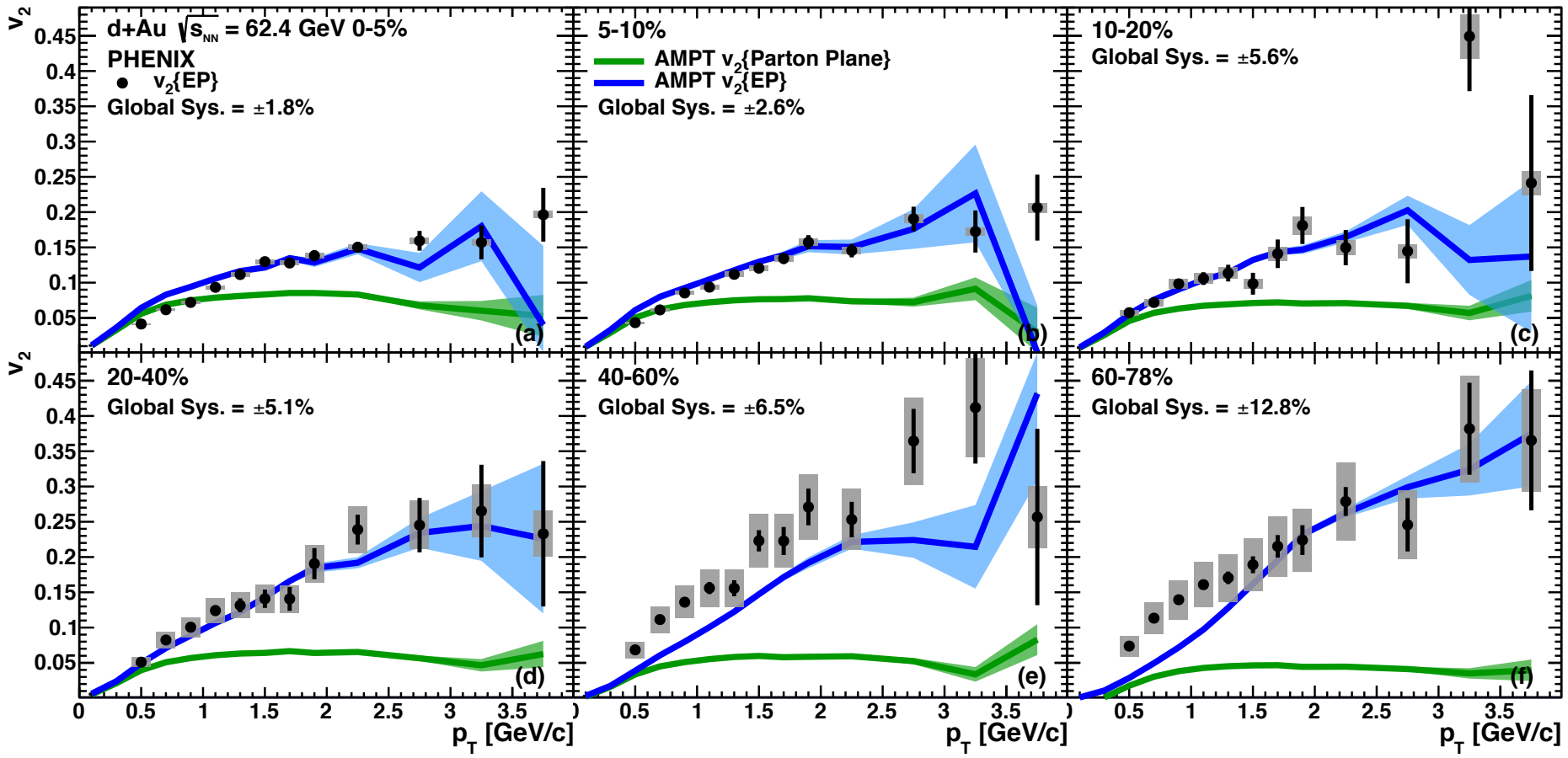






Phys. Rev. C 96 064905 (2017)

$v_2(p_T)$ for Charged Particles @ 62.4 GeV



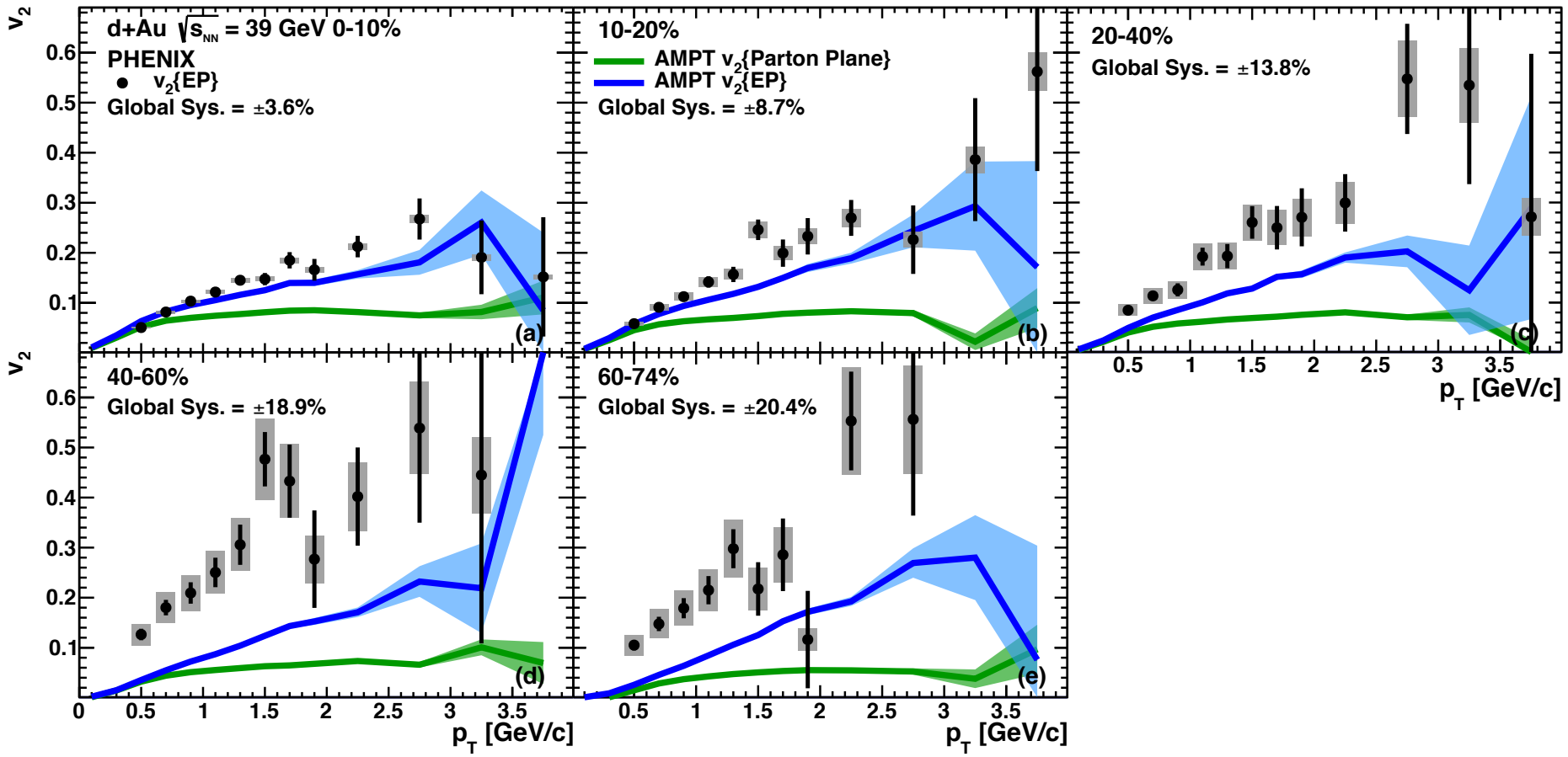
- v_2 signal present in all centralities. Also large for 62.4 GeV
- v_2 reproduced by AMPT when simulating EP reconstruction. Difference nonflow?

Phys. Rev. C 96 064905 (2017)

d+Au

62

$v_2(p_T)$ for Charged Particles @ 39 GeV



- v_2 signal present in all centralities. Also large for 62.4 and 39 GeV
- v_2 reproduced by AMPT when simulating EP reconstruction. Difference nonflow?

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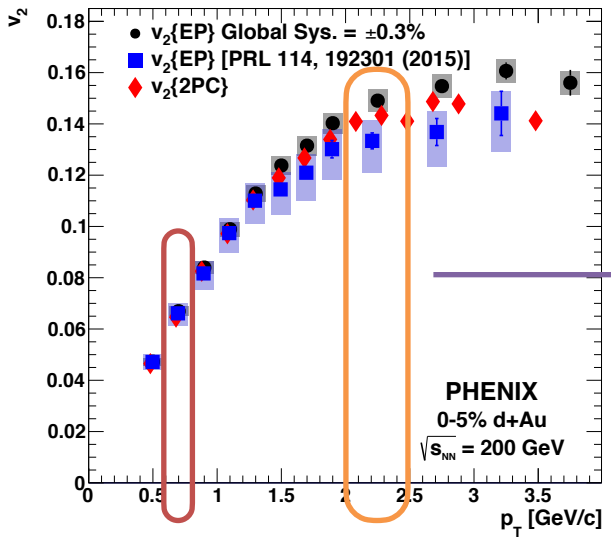
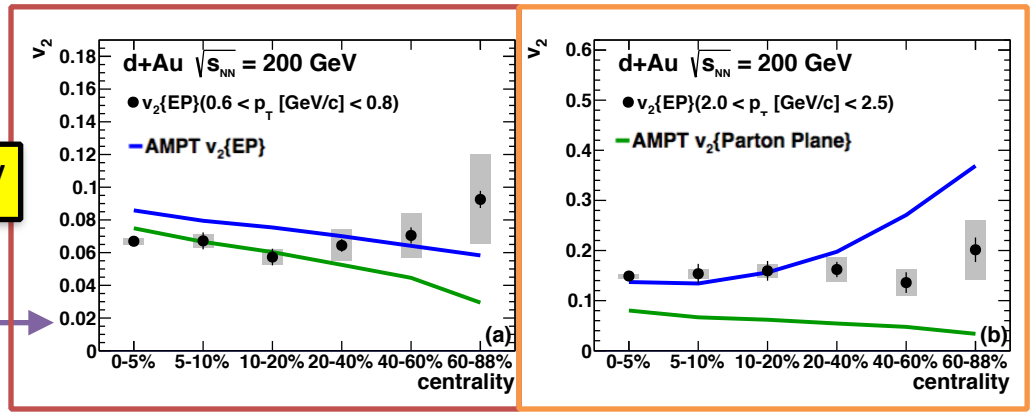
d+Au

39

v_2 vs Centrality



200 GeV

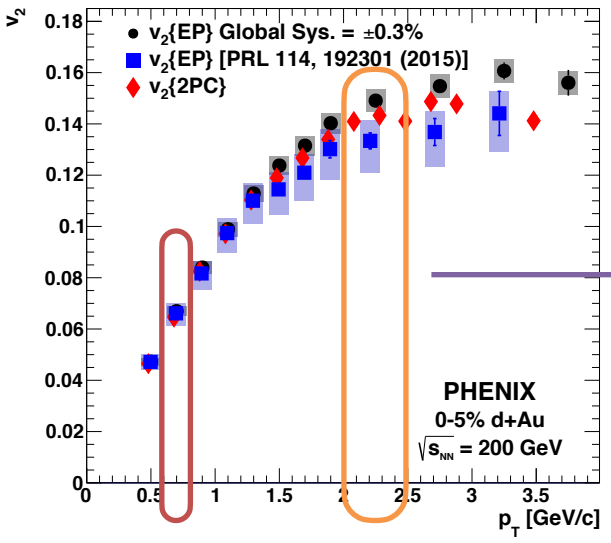


- Relative non-flow component higher for most peripheral centralities and higher p_T

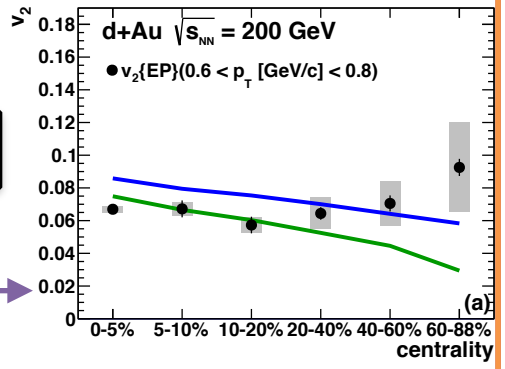
Phys. Rev. C 96 064905 (2017)

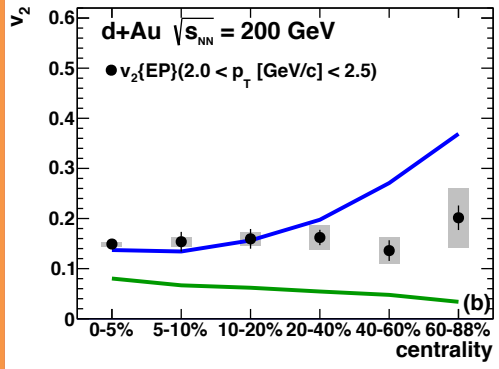
d+Au

v_2 vs Centrality

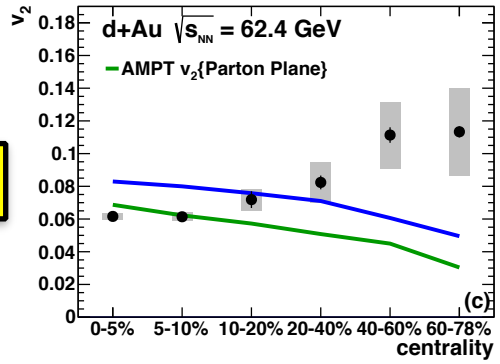


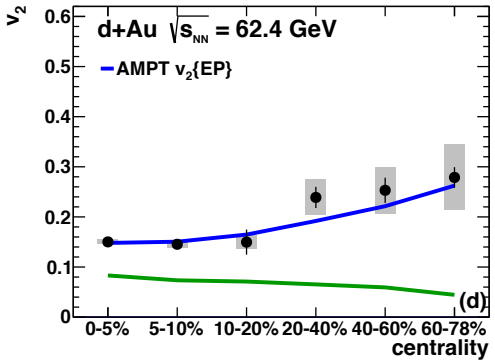
200 GeV



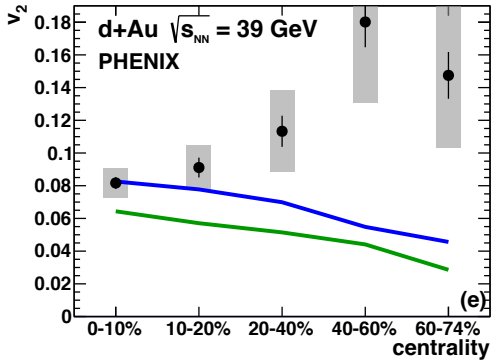


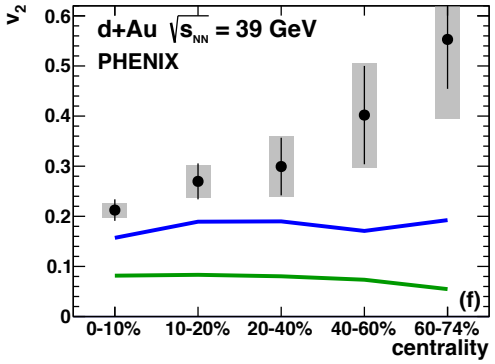
62.4 GeV





39 GeV



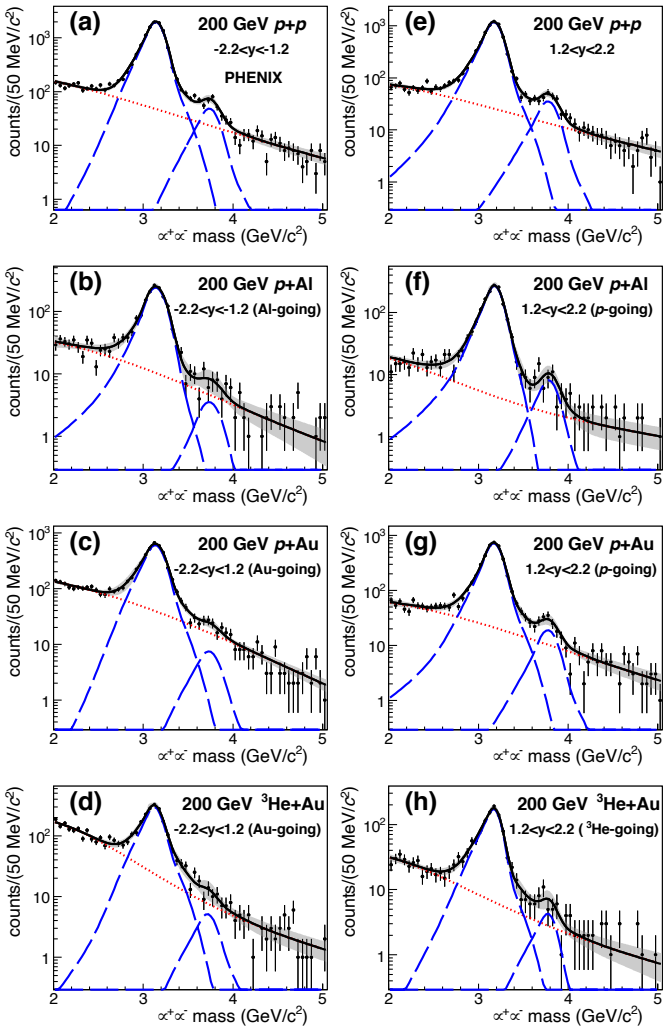


- Relative non-flow component higher for most peripheral centralities and higher p_T
- Same trend in all energies

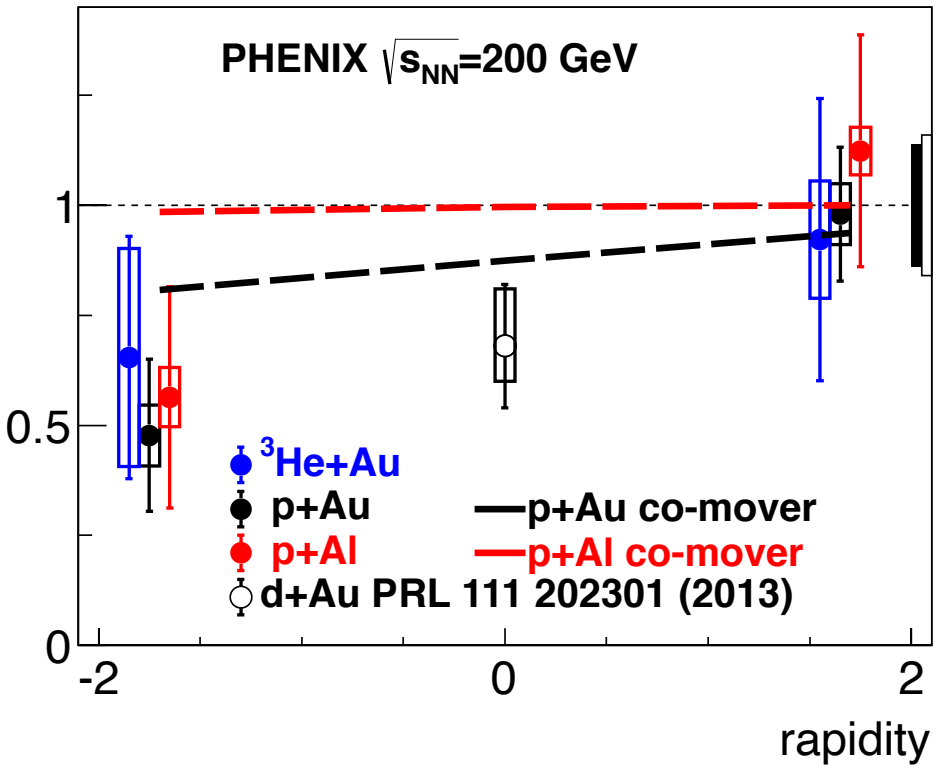
Phys. Rev. C 96 064905 (2017)

d+Au

Psi(2S) / Psi(1S) Ratios in SS



$$\left[\frac{\sigma_{\psi(2s)}}{\sigma_{\psi(1s)}}\right]^{p/^3He+A} \Big/ \left[\frac{\sigma_{\psi(2s)}}{\sigma_{\psi(1s)}}\right]^{p+p}$$



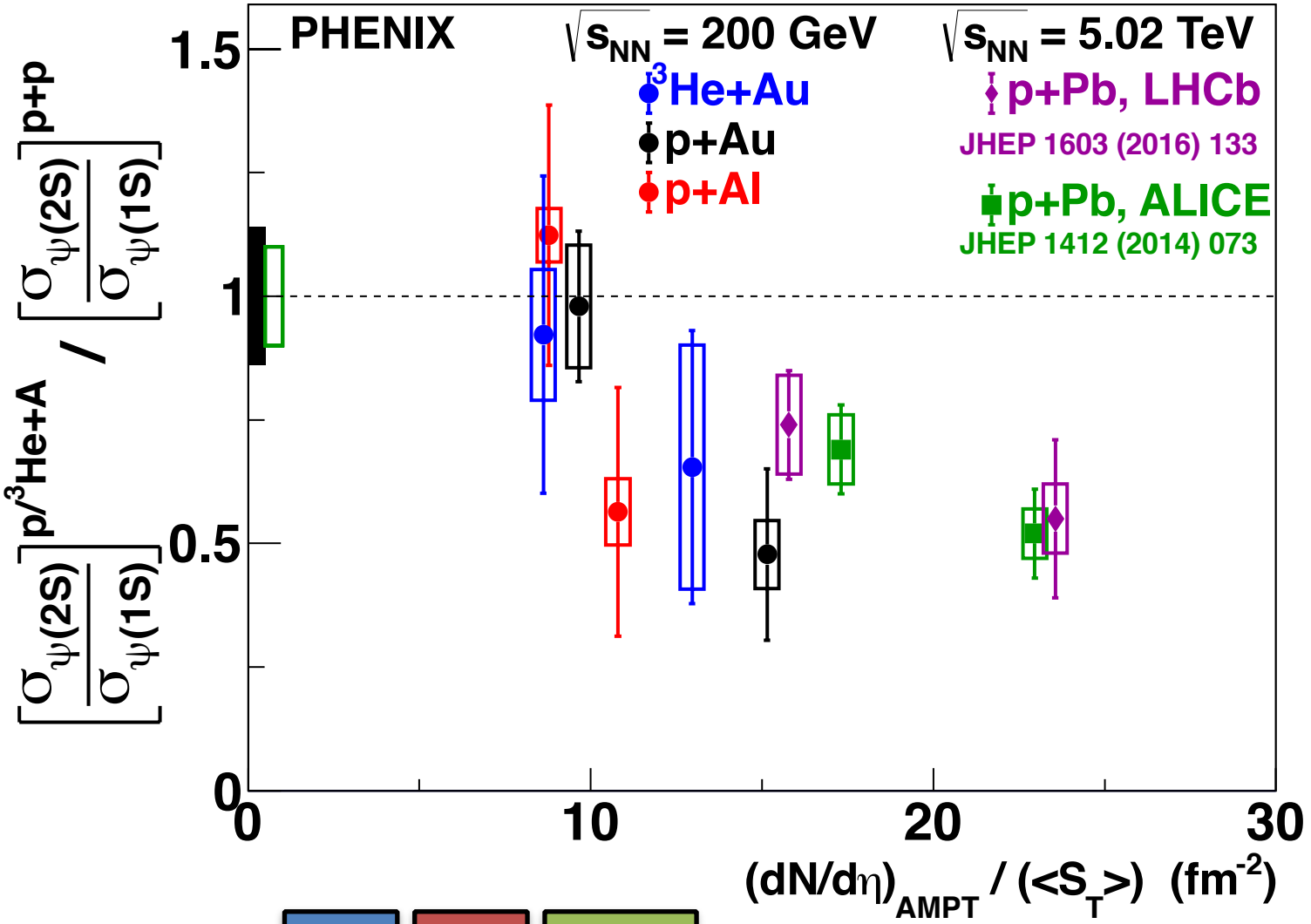
- Sequential suppression of exited states also present is small systems?

PRC 95, 034904 (2017)

p+Au | d+Au | ^{3}He+Au

200

A Transition?



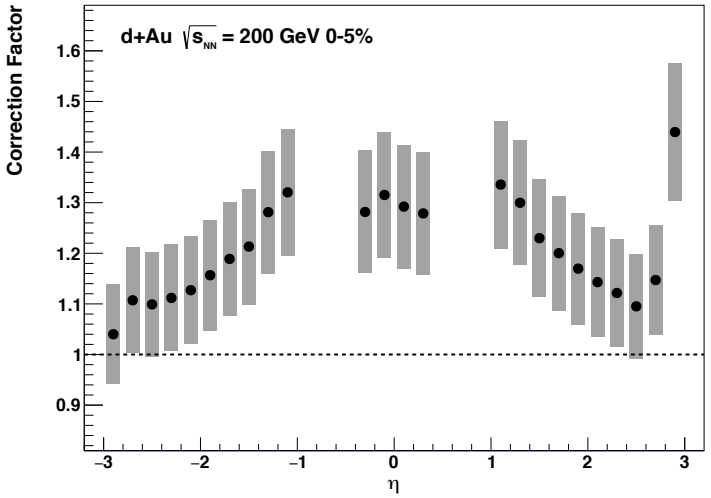
PRC 95, 034904 (2017)

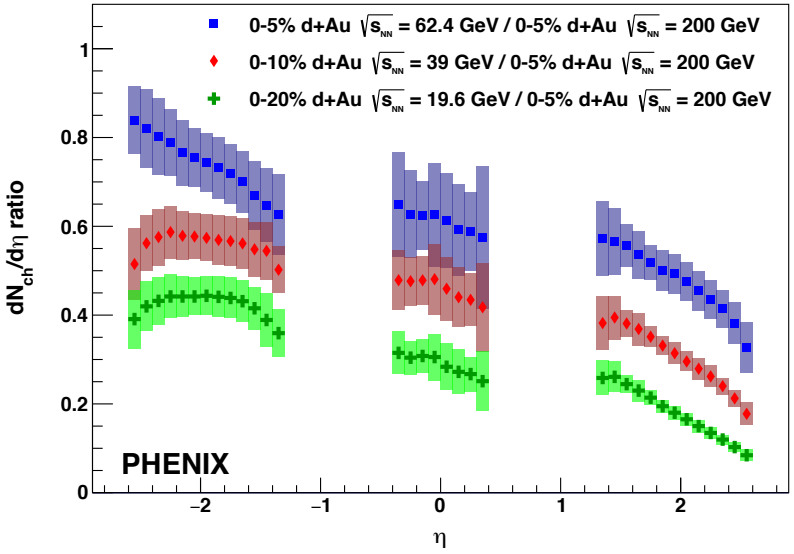
p+Au | d+Au | ^{3}He+Au

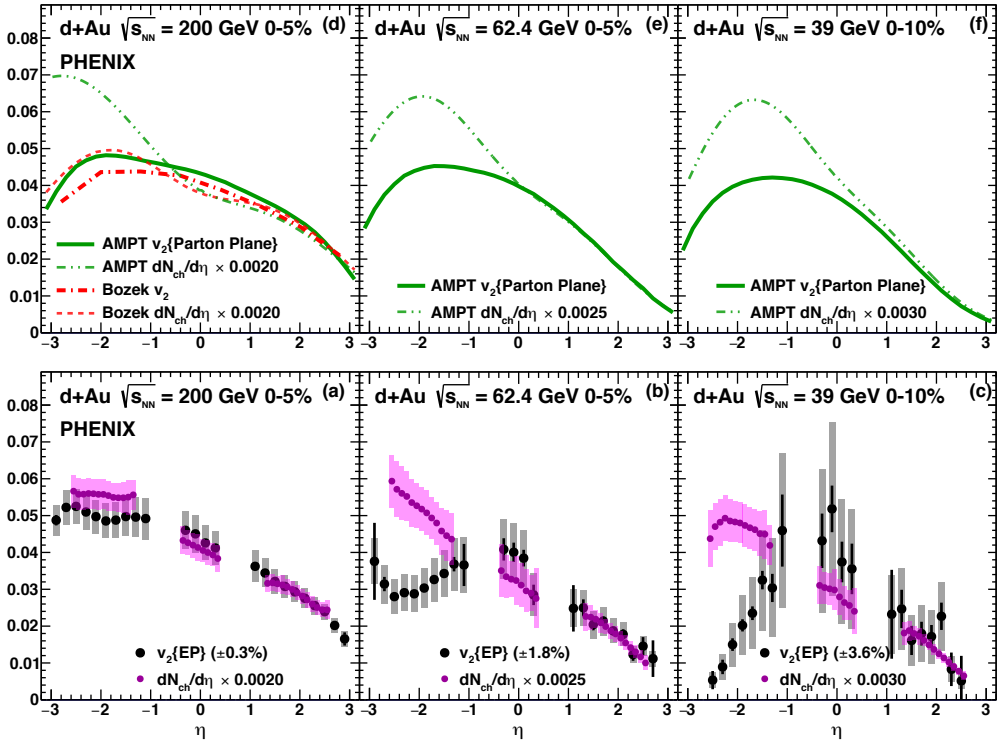
200

More on dNch/deta

d+Au

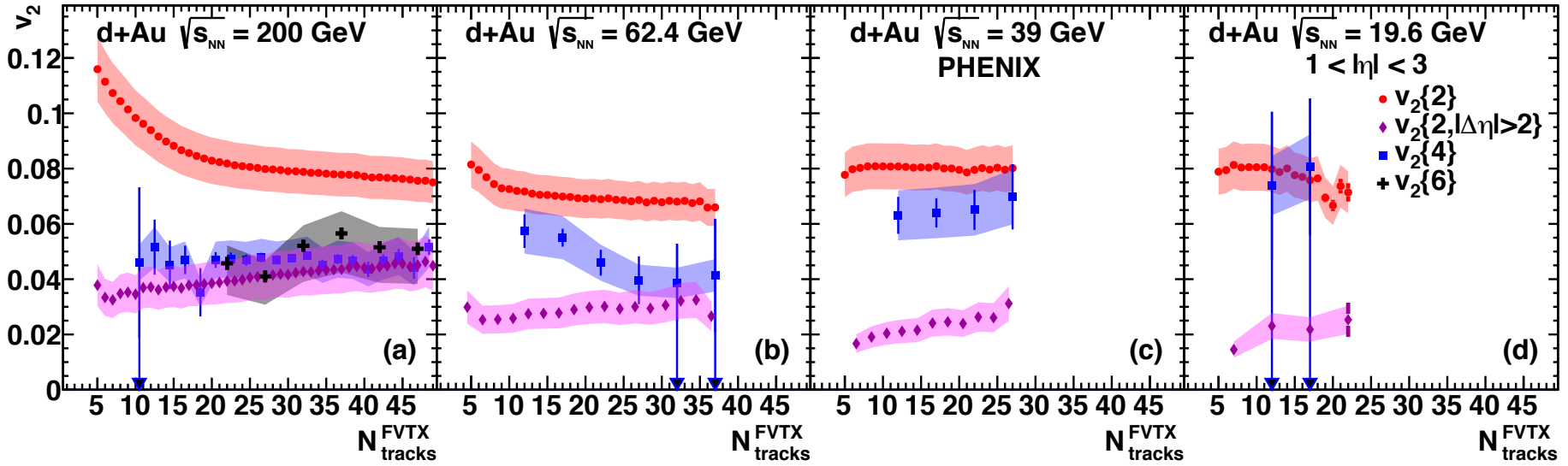






Phys. Rev. C 96 064905 (2017)

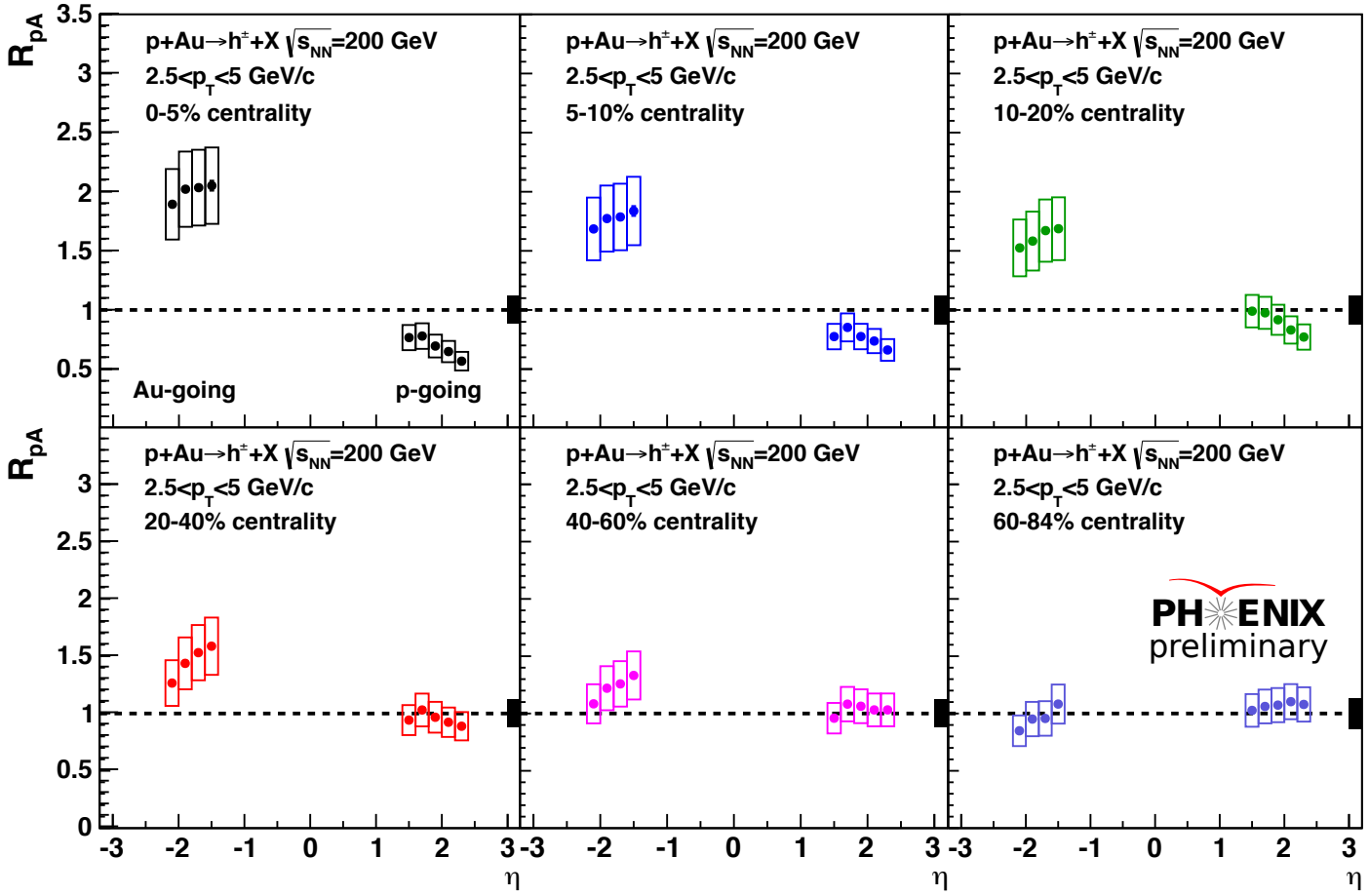
v_2 at Forward Rapidities via MPC



- Why? By increasing the number of particles in the correlation, a progressive suppression of non-flow can be achieved.

Phys. Rev. Lett. 120, 062302 (2018) d+Au 20 39 62 200

Centrality Dependence of R_{pA}(eta)

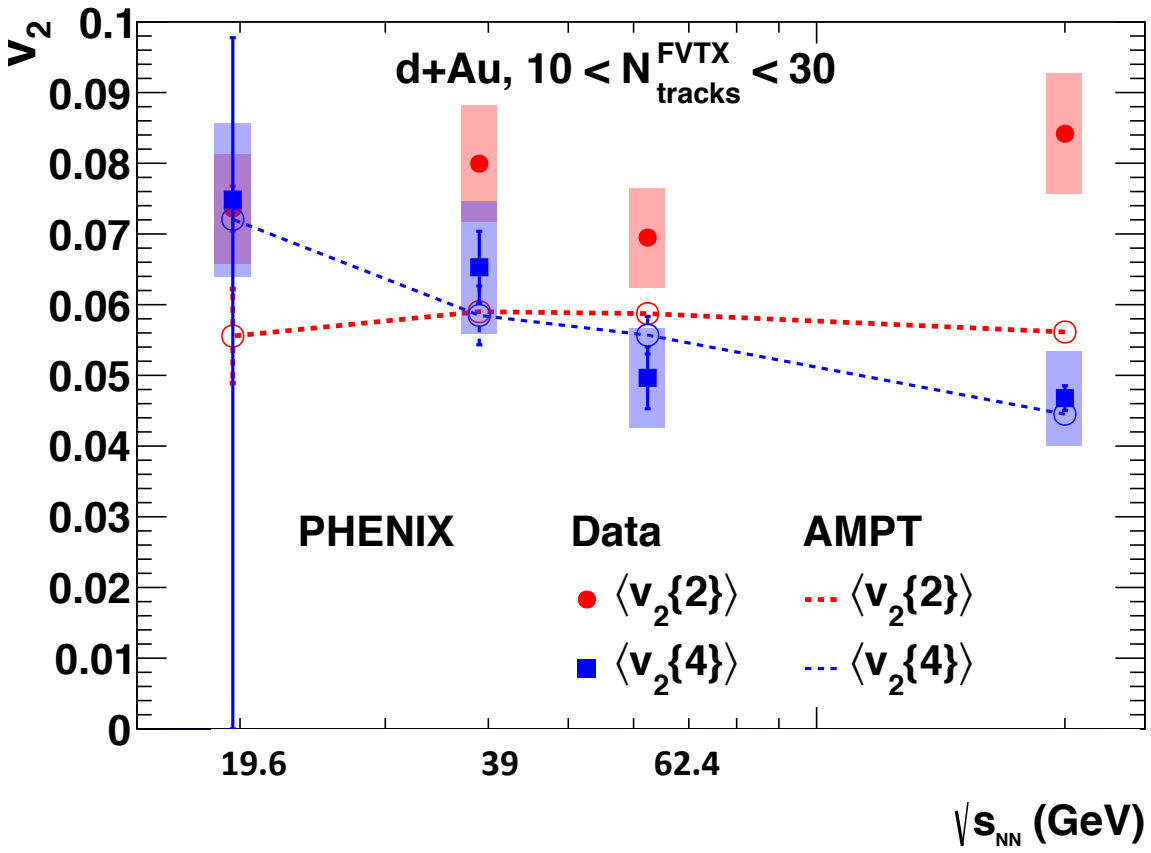


- Enhancement mainly for p_T <5 GeV and centrality dependent.

p+Au

Where does it come from?

$v_2\{2\}$, $v_2\{4\}$ at Different Energies



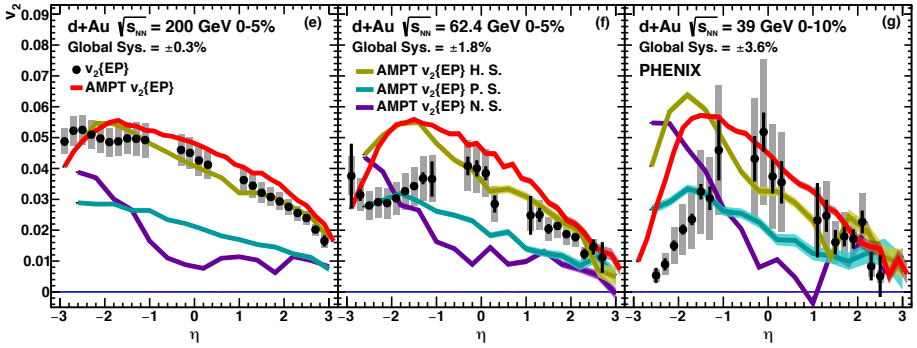
Phys. Rev. Lett. 120, 062302 (2018)

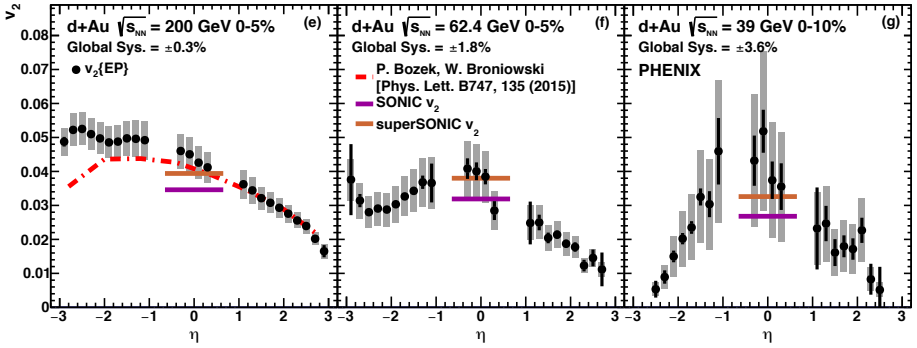
d+Au

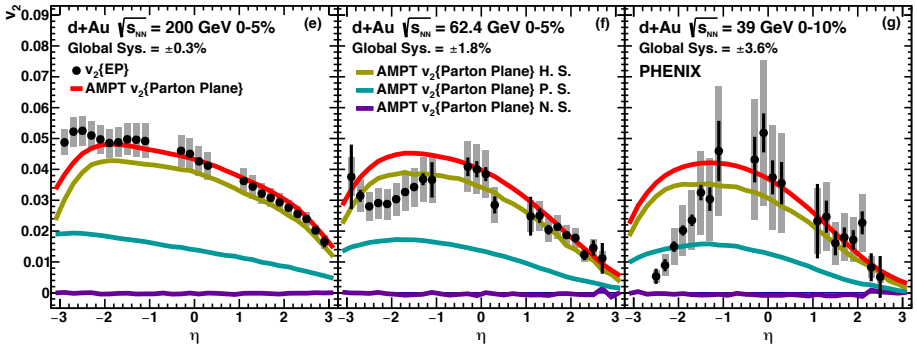
20 39 62 200

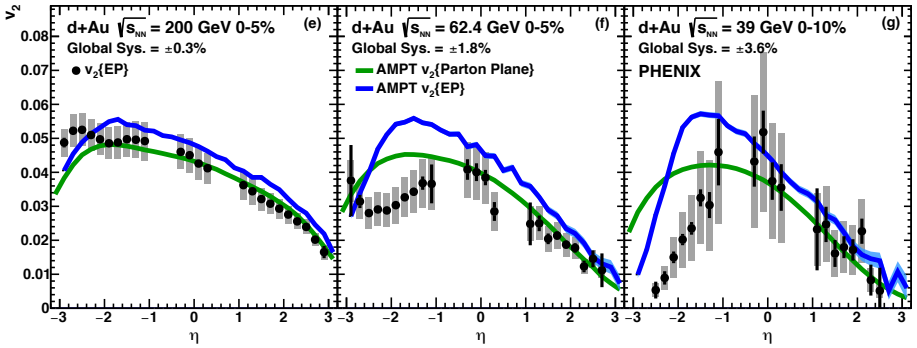
More on v2(eta)

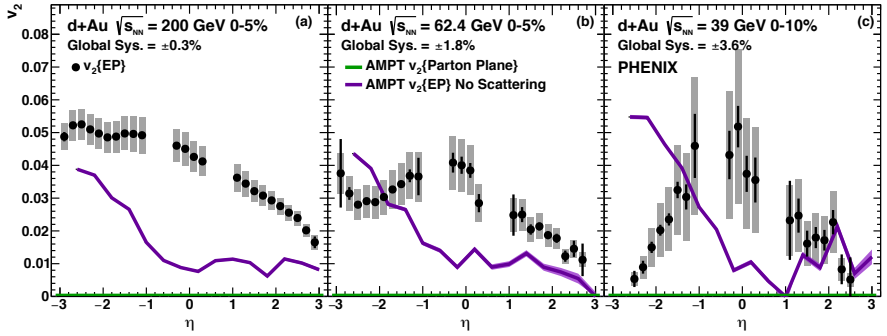
d+Au







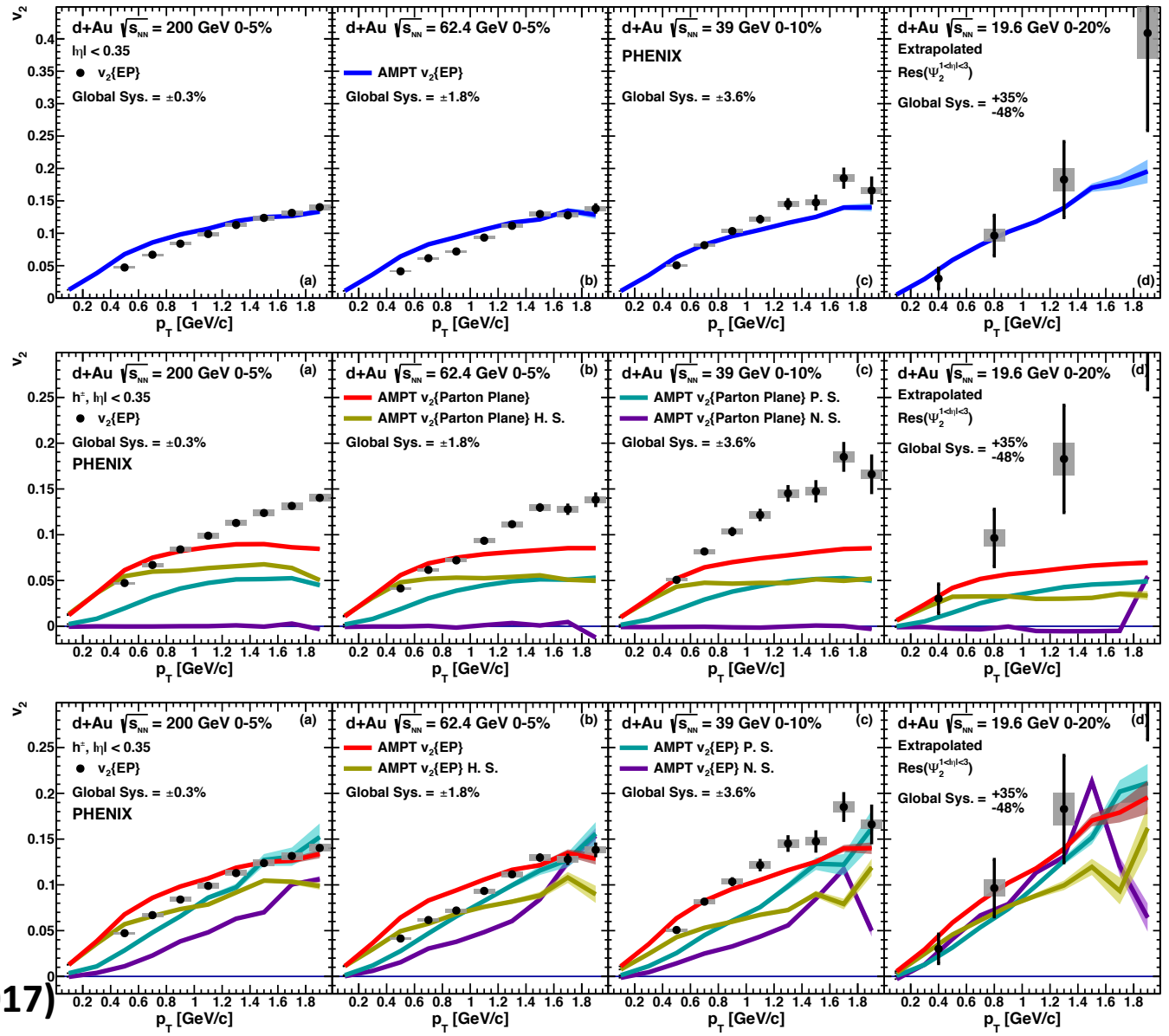




Phys. Rev. C 96 064905 (2017)

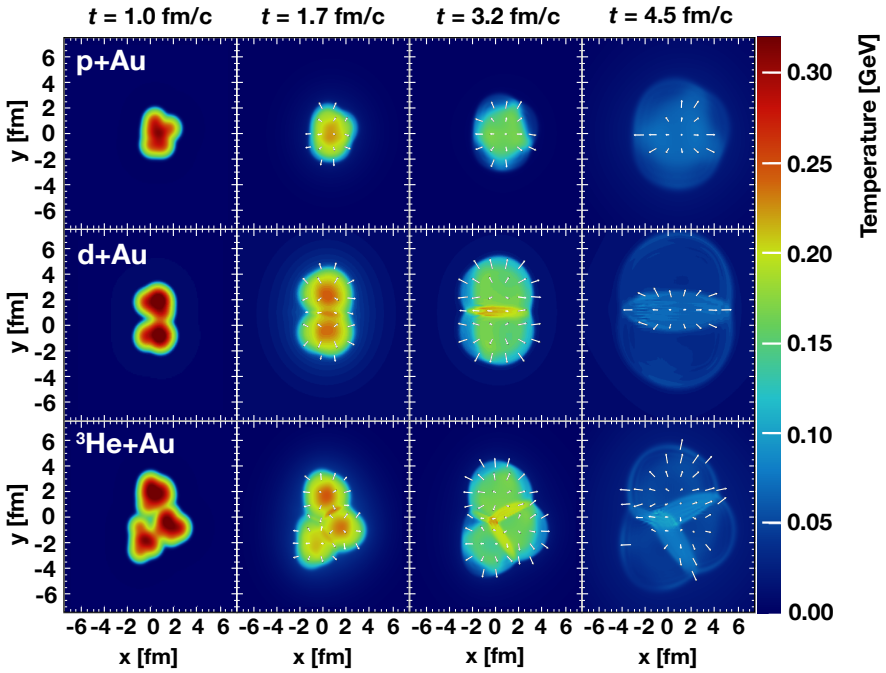
More on v2(pt)

d+Au



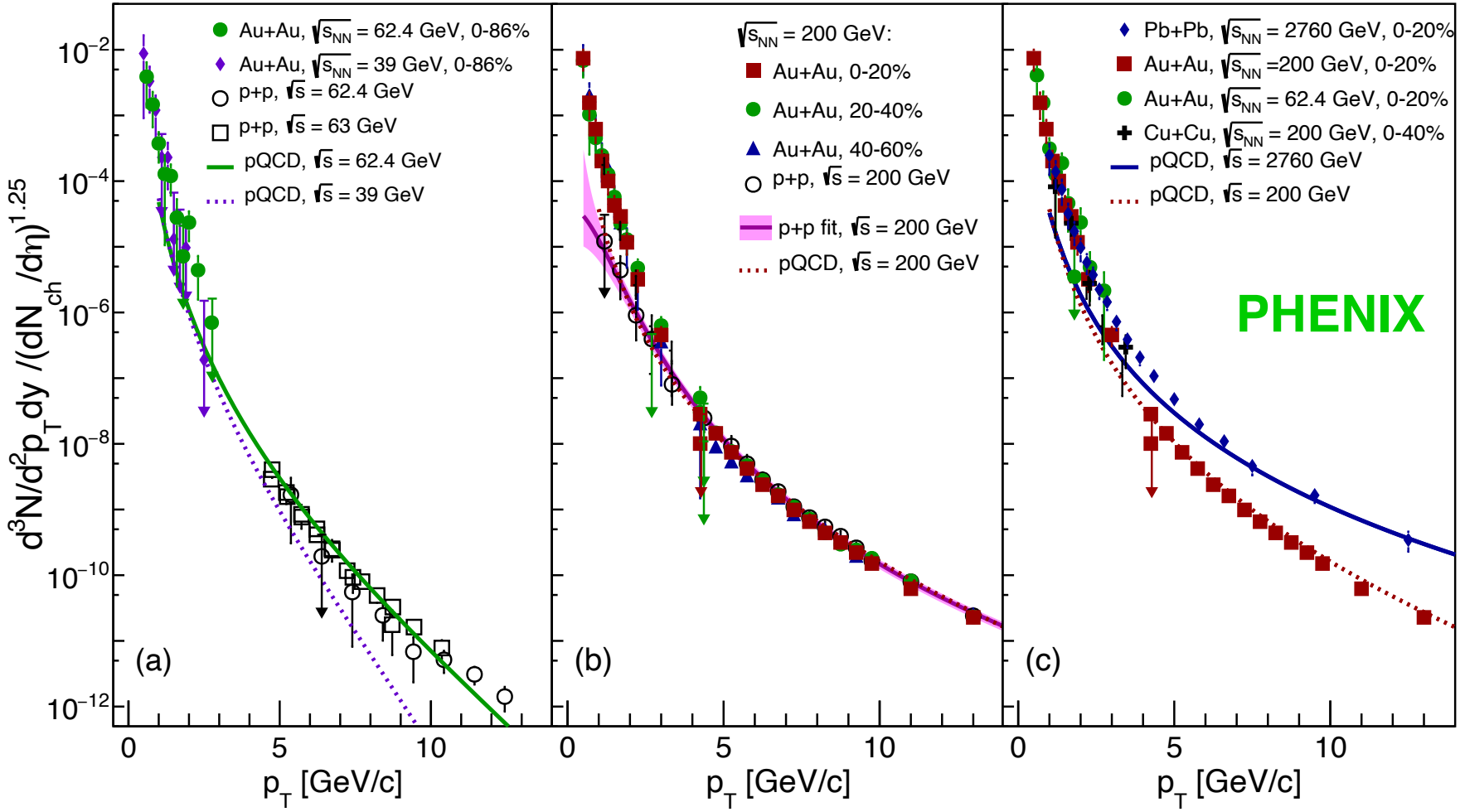
Phys. Rev. C 96 064905 (2017)

Hydro Evolution



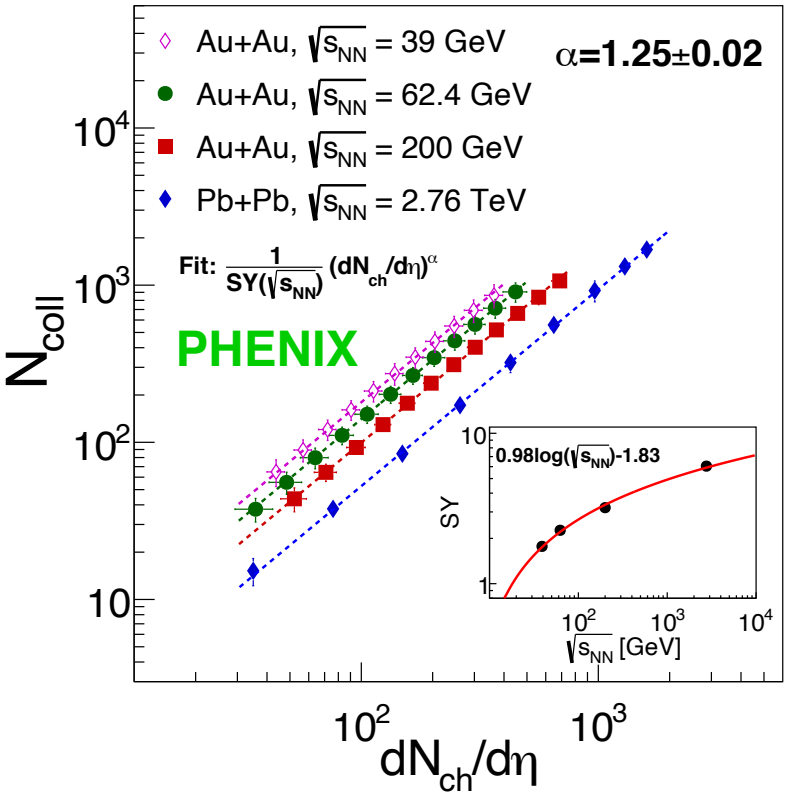
arXiv:1805.02973 (2018) p+Au d+Au ^{3}He+Au

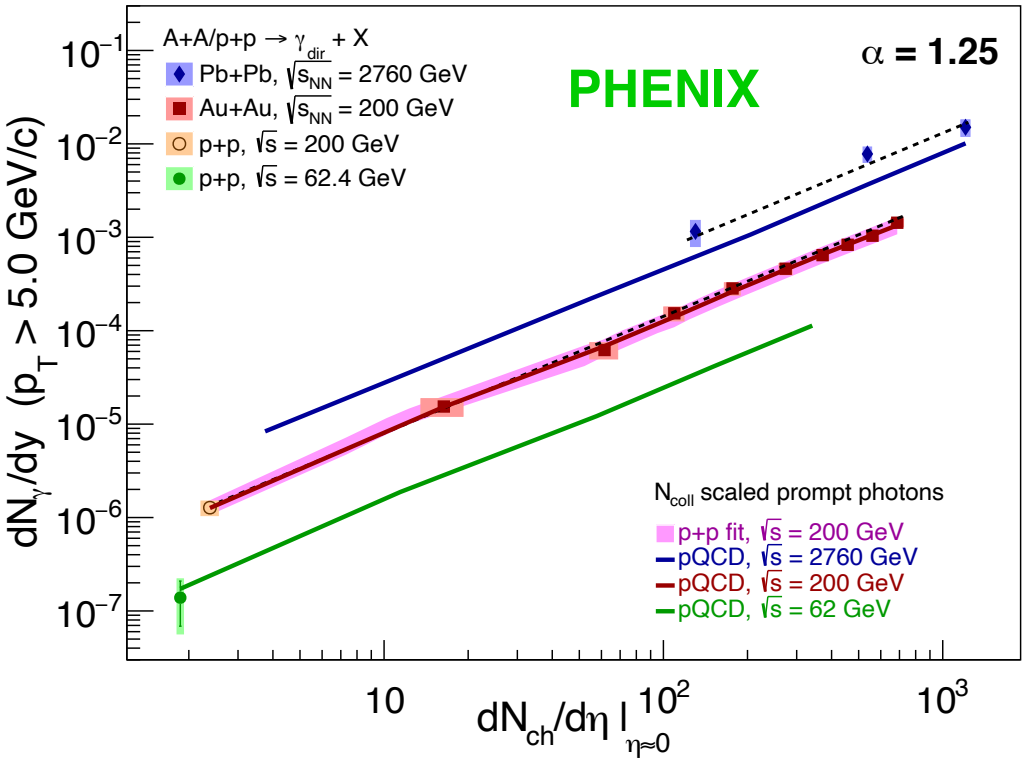
Photons in HIC



arXiv:1805.04084 (2018)

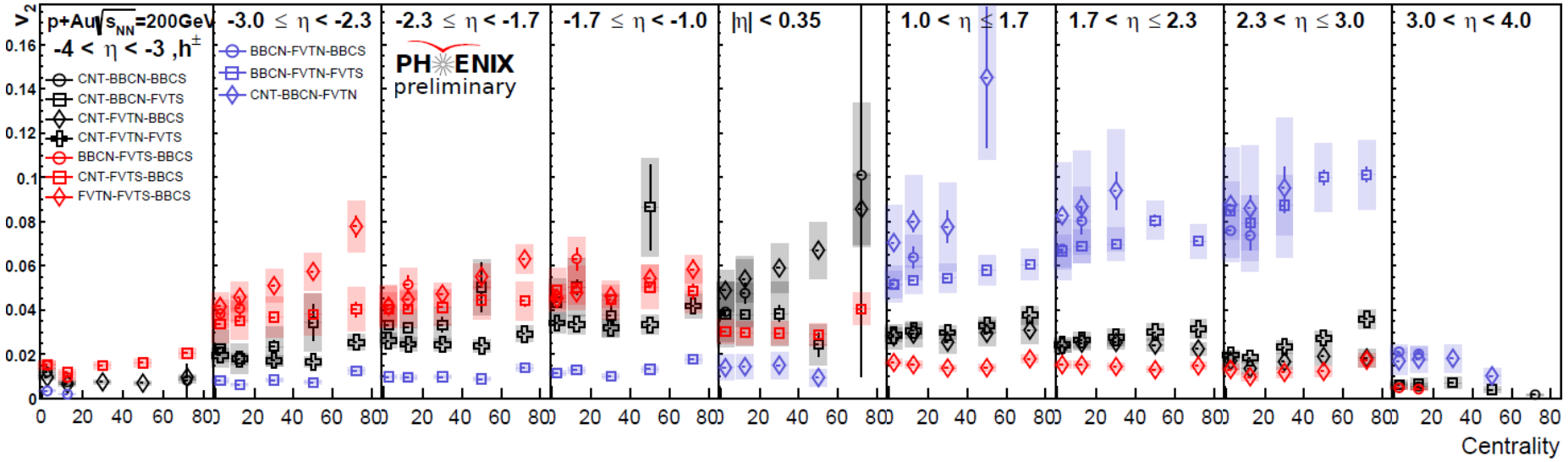
Photons in HIC



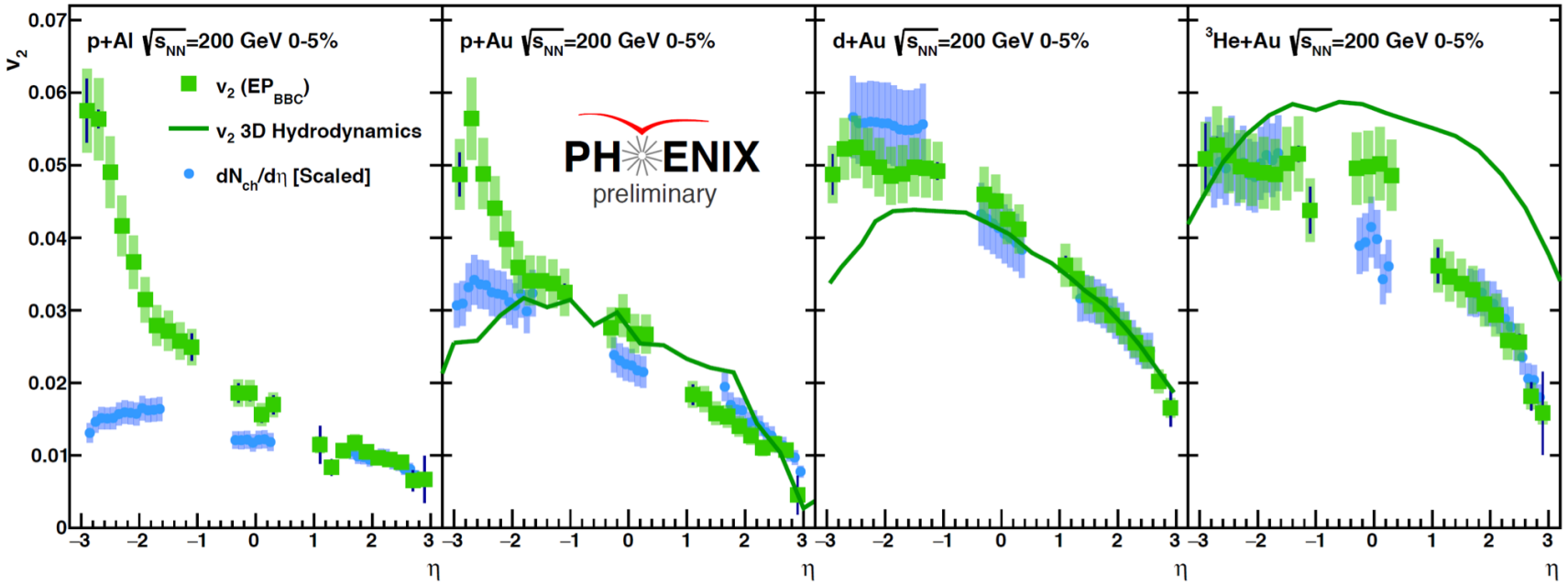


arXiv:1805.04084 (2018)

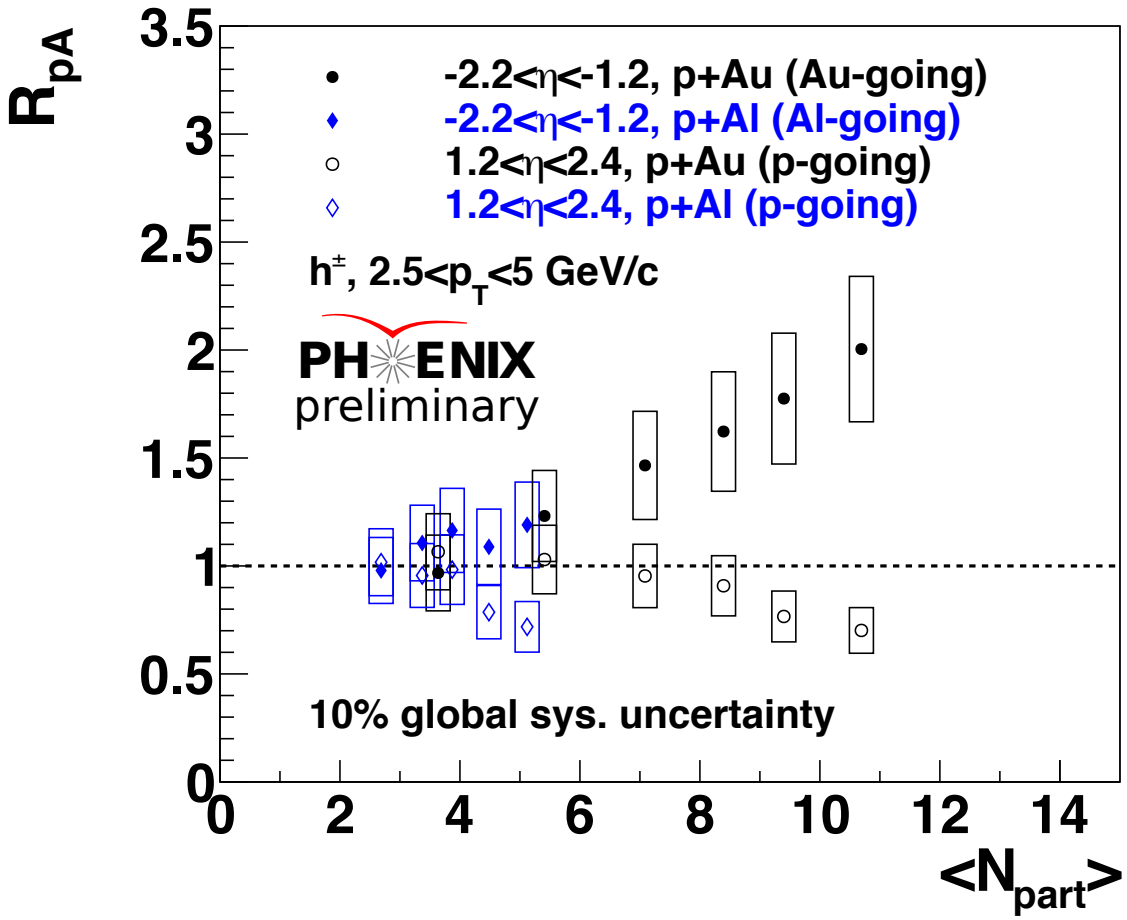
v2(eta) large rapidity coverage



v2(eta) system scan



RpA in SS

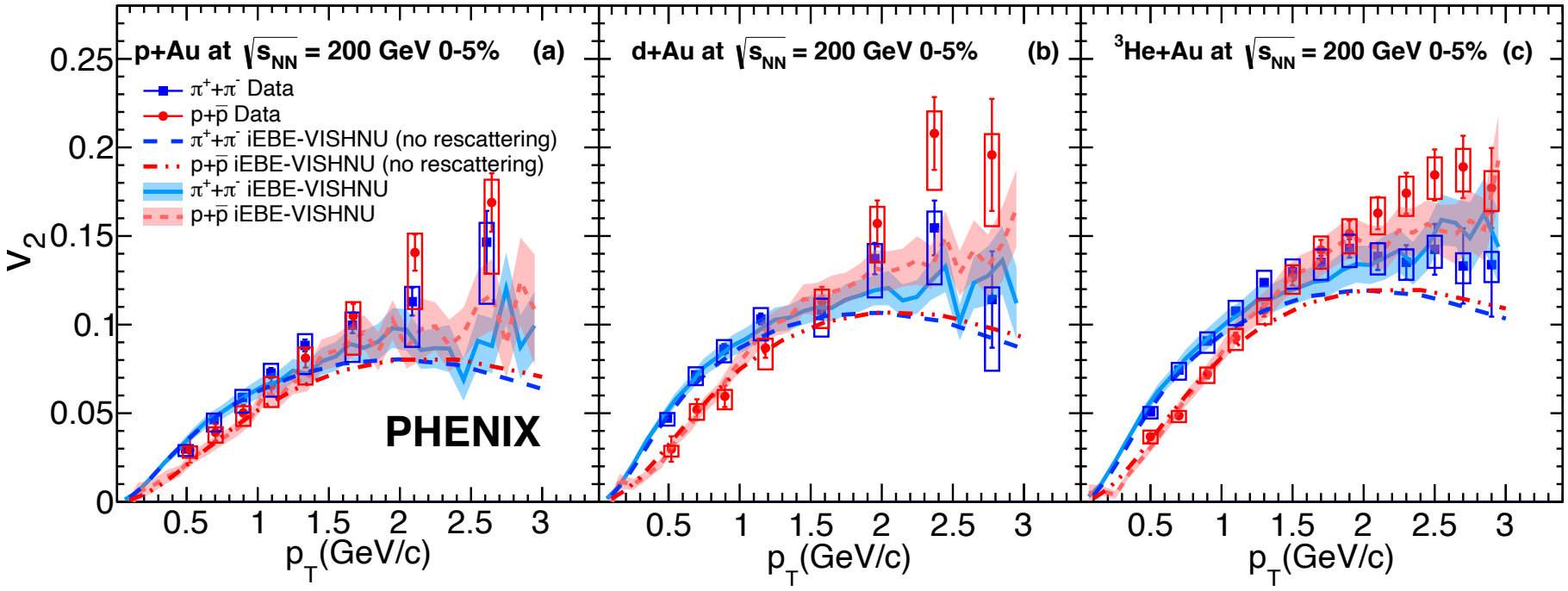


- Enhancement mainly from PT<5 GeV and centrality dependent.

p+Au p+Al

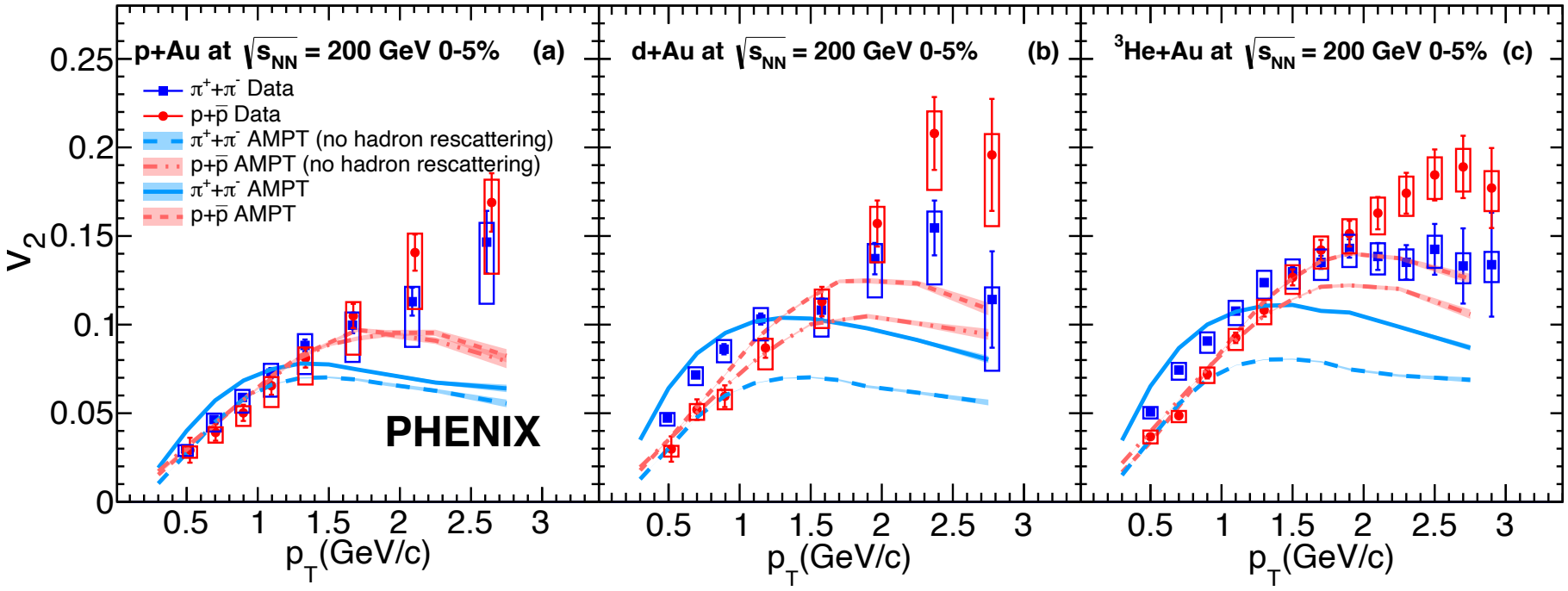
Where does it come from?

v2 Mass Dependence



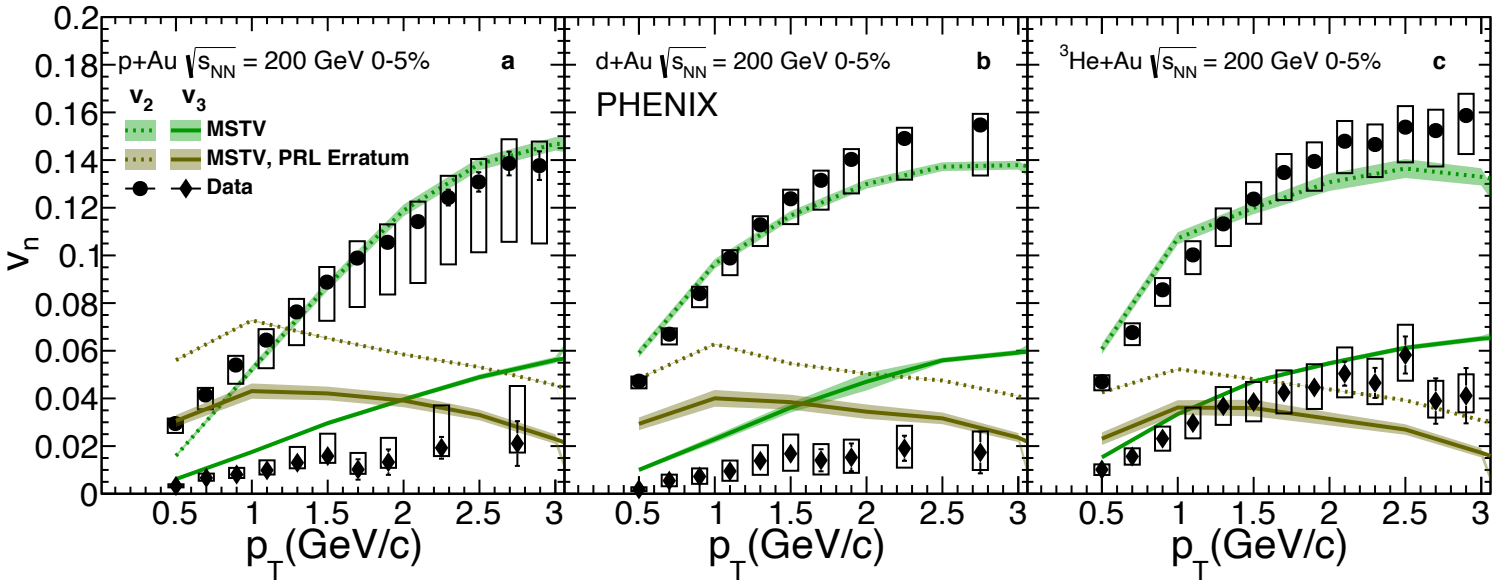
arXiv:1710.09736 (2017) p+Au d+Au ^{3}He+Au 200

v2 Mass Dependence



arXiv:1710.09736 (2017) p+Au d+Au ^{3}He+Au 200

v_2, v_3 <== CGC EFT == Initial State Correlations



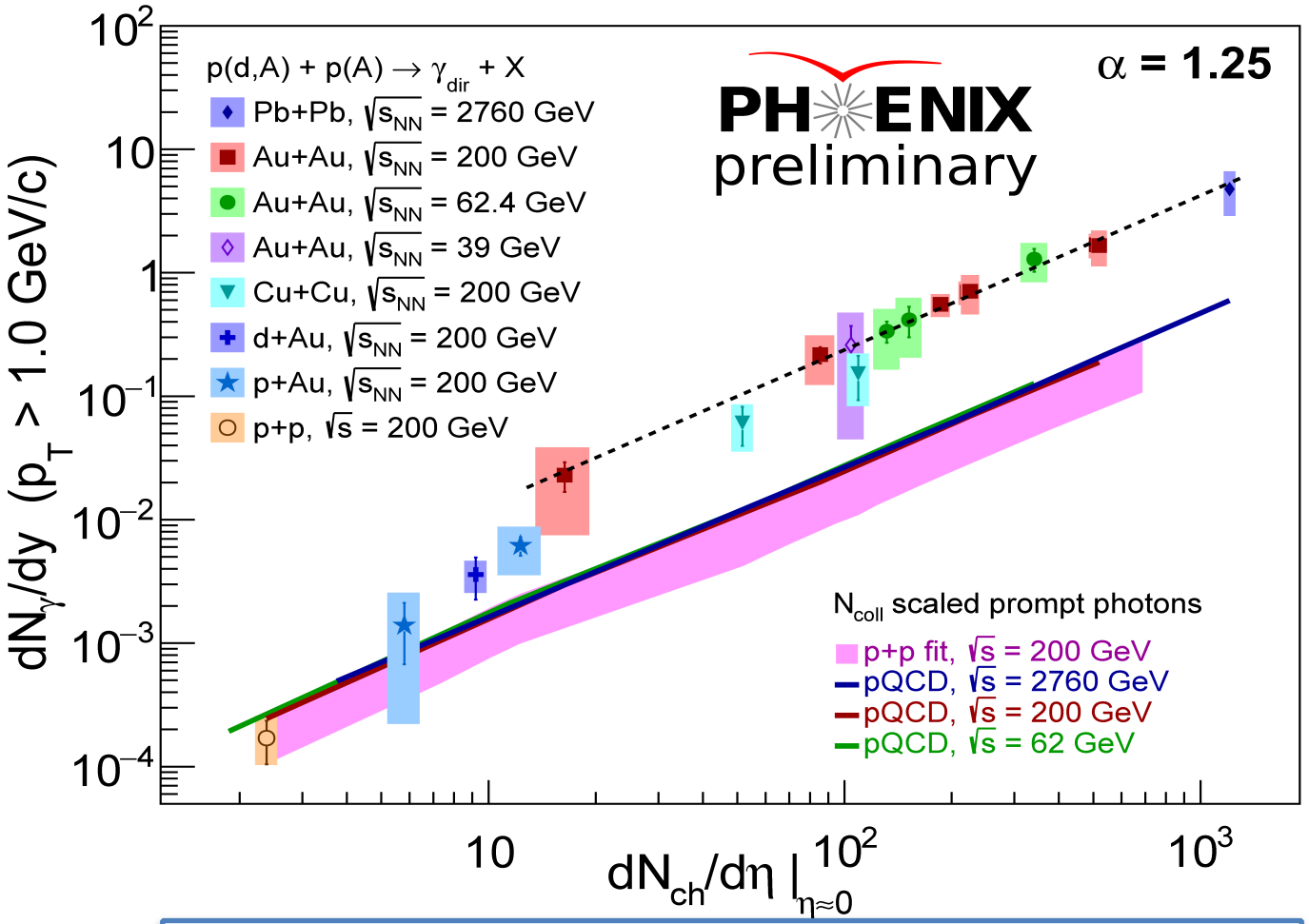
- Recent study extended the CFC effective theory to next to leading order couplings which also provide a scaling in the resulting v_2 and v_3 for asymmetric systems.

- CFC EFT also reproduces quite well the v_2 p_T trend for all systems, however overshoots v_3 in the smallest systems

detracted

arXiv:1805.09342 (2018) p+Au d+Au ^{3}He+Au 200

Direct Photon Scaling in HIC



- Yield scales with $(N_{ch}/deta)^{1.25}$
- Yield scaling holds over energies, systems, centralities.