Collective Behaviors in Small Collision Systems

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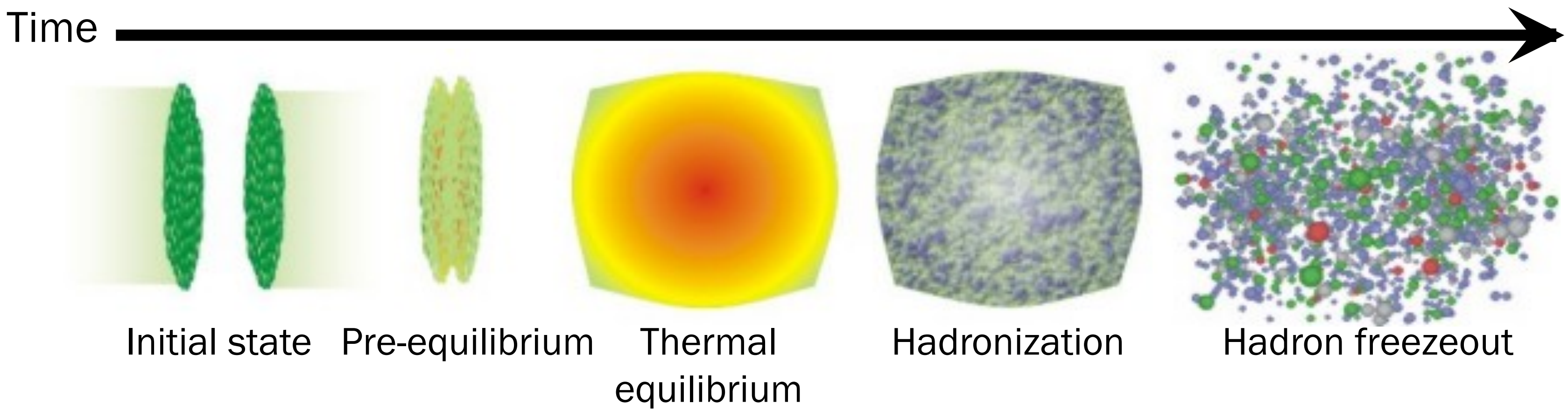
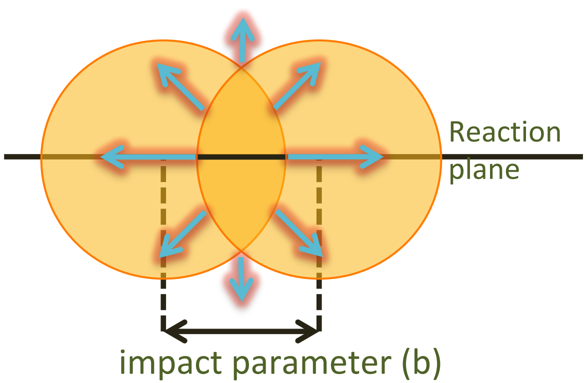
Korea University

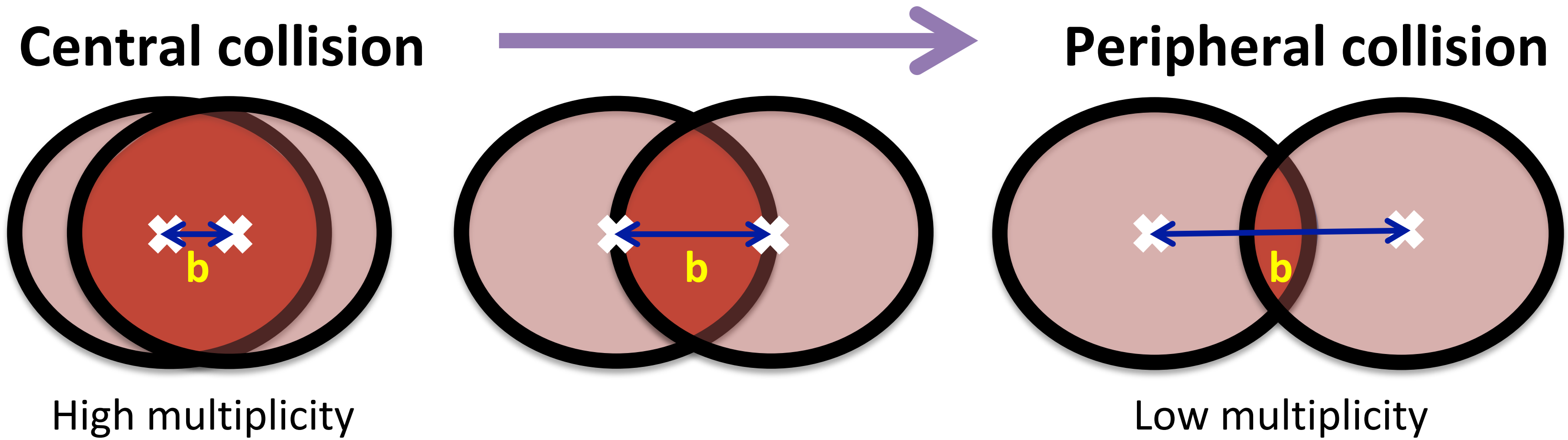
Collective behavior in heavy ion collision





- Common understanding of A+A collisions
- Nearly ideal fluid with low viscosity created – sQGP.
- Multi-particle correlations among rapidities which originated from a common source.
- In dihadron correlations, Fourier harmonics v_n are commonly attributed to hydrodynamic flow.
- **Nonflow** : Non-collective originated correlation also exists; jet, particle decays, EP decorrelations, HBT etc.

Centrality



- The size and shape of the overlap area have huge dependence on the ‘b’
- The strong force is mediated within the short distance.
- Only the partons within the overlap area can interact with each other and generate QGP.

The multiplicity is, therefore, showing the centrality which is related to the impact parameter, “b”.

The multiplicity dependence is one of the evidence of the QGP.

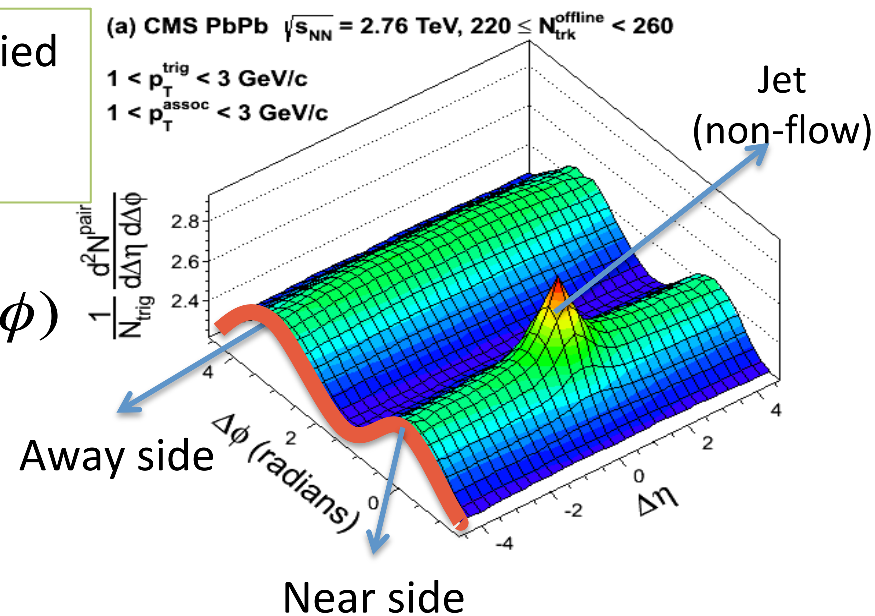
QGP flow

From the two-particle correlation, multiplied value shown at the near-side ridge:

$v_2(p_T^A)\, v_2(p_T^B) = c_2^{AB}$

$$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2(v_2)^2\cos(2\Delta\phi)$$

<u>Non-zero!</u>



"Elliptic flow"

The non-zero v_2 explains the near-side long-range ridge structure which corresponds to the elliptical shape of the QGP.

Generated QGP behaves like the almost ideal fluid with small viscosity.

Link the "shape" and "size(mult.)"

QGP flow

From the two-particle correlation, multiplied value shown at the near-side ridge:

$v_2(p_T^A)\, v_2(p_T^B) = c_2^{AB}$

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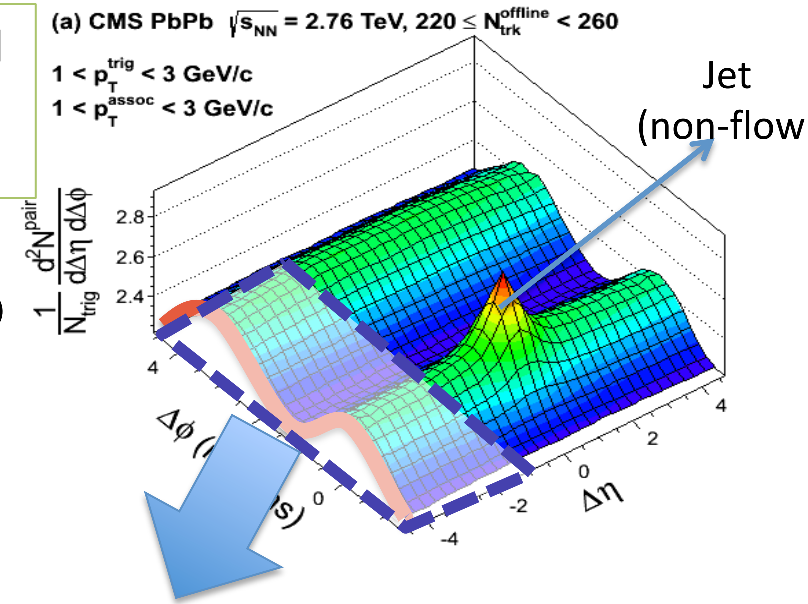

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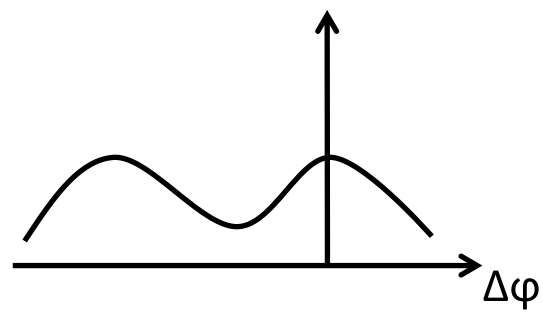
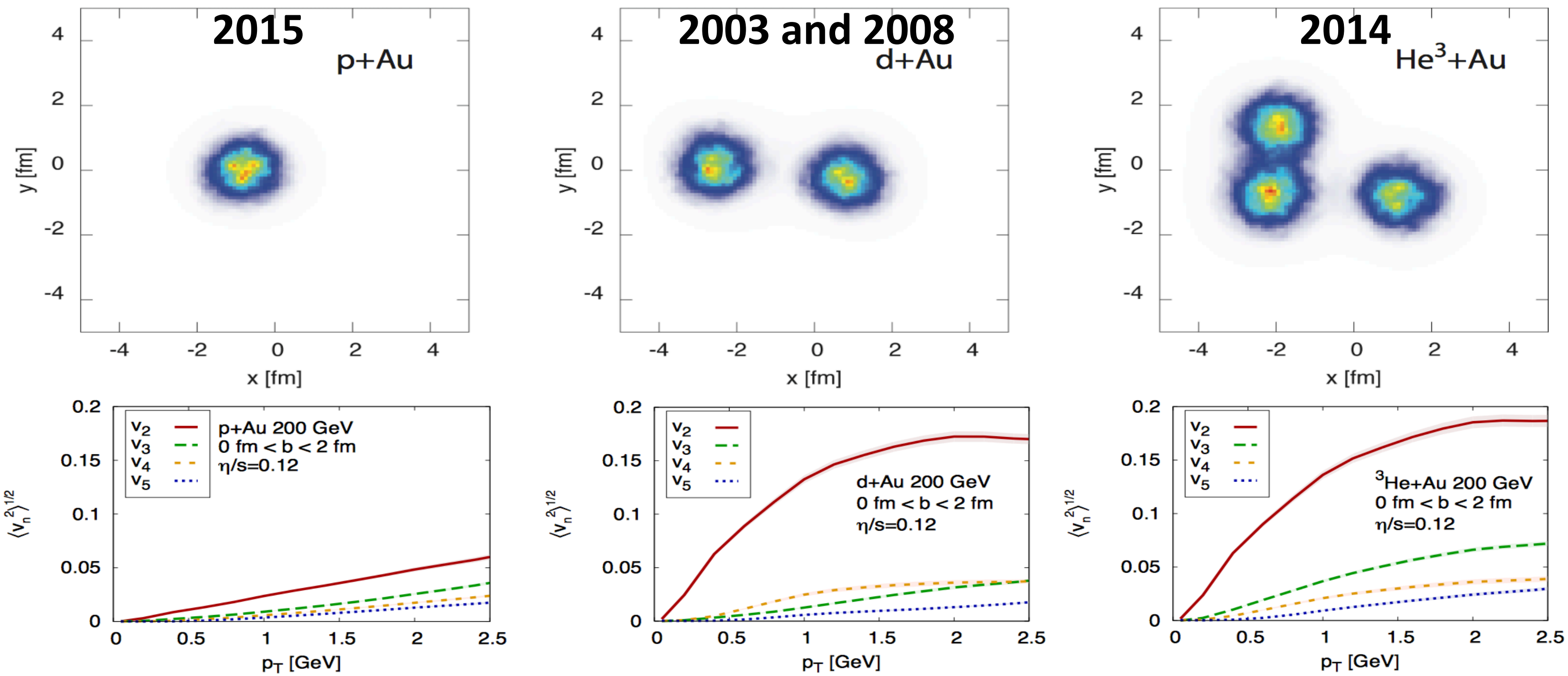


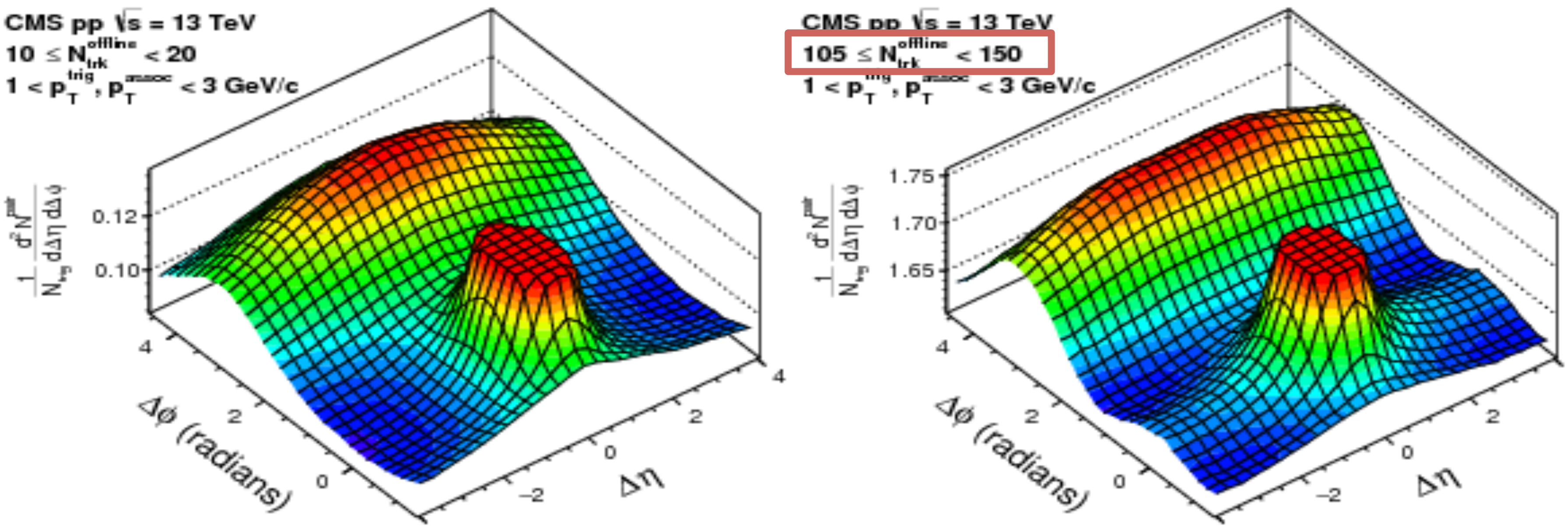
Schenke & Venugopalan arXiv:1407.7557

Small systems collision

- At first the small system collisions were considered as control measurement for "cold" nuclear matter effect – no QGP is created
- Recently, the high multiplicity collisions with small systems gained interest. It may not be as "cold".



The CMS experiments found ridge



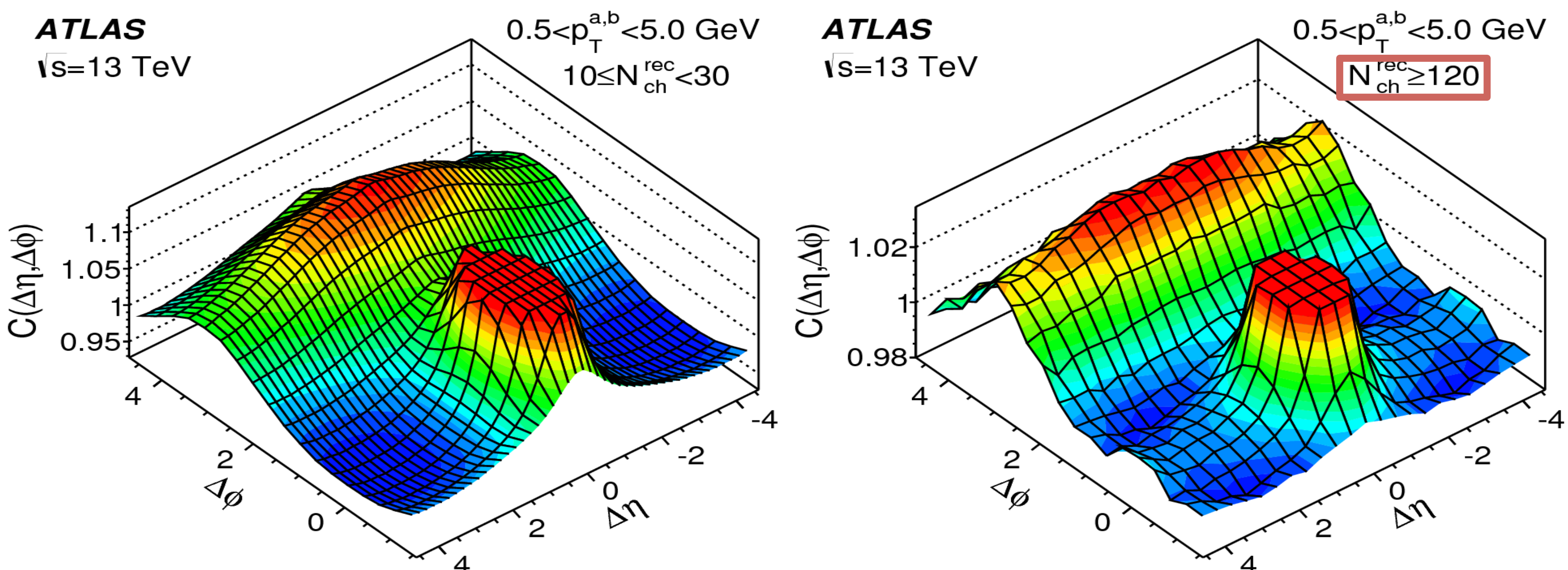
low multiplicity

high multiplicity

The CMS experiments founds near-side long-range ridge structure at the p+p 13 TeV collisions in the high-multiplicity events.

Multiplicity dependence: QGP

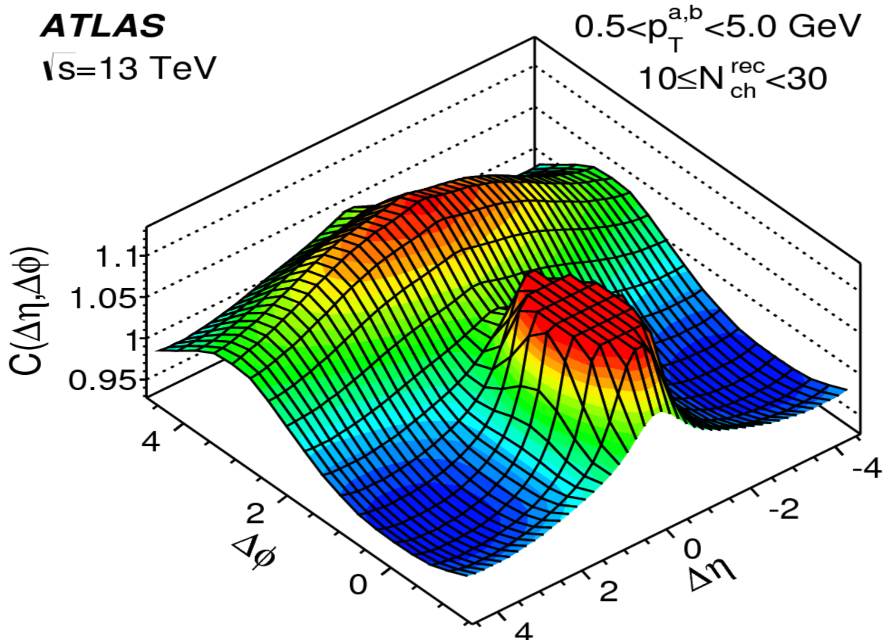
The ATLAS experiments found ridge



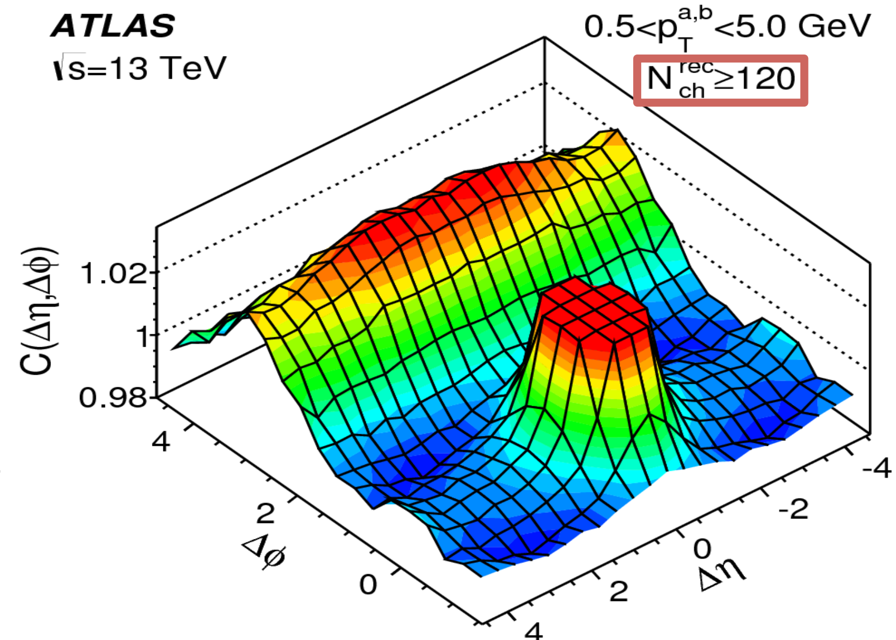
low multiplicity high multiplicity

The ATLAS experiments also founds near-side long-range ridge structure at the p+p 13 TeV collisions in the high-multiplicity events.

The ATLAS experiments found ridge



low multiplicity

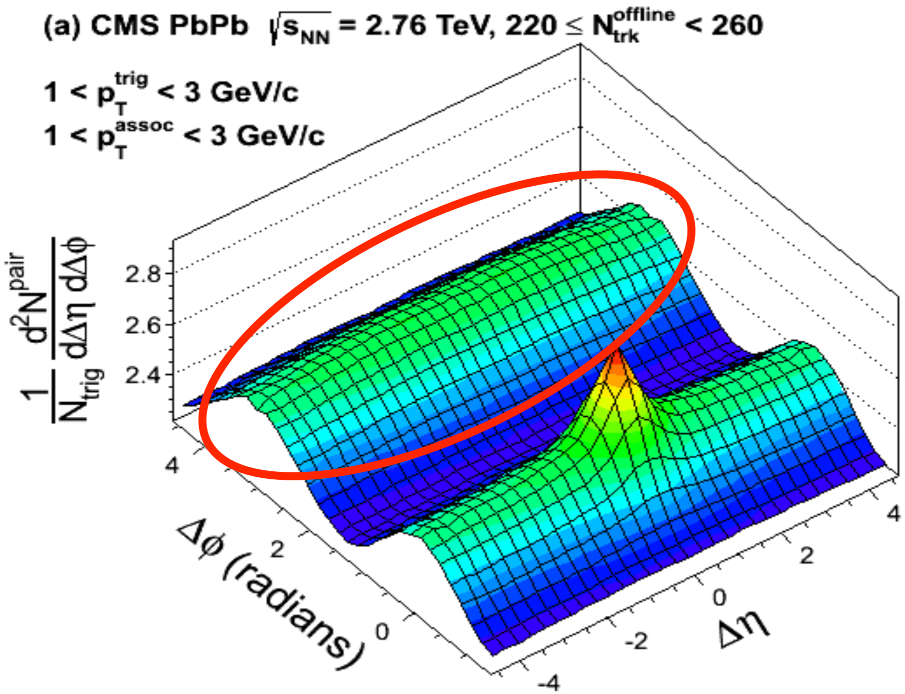


high multiplicity

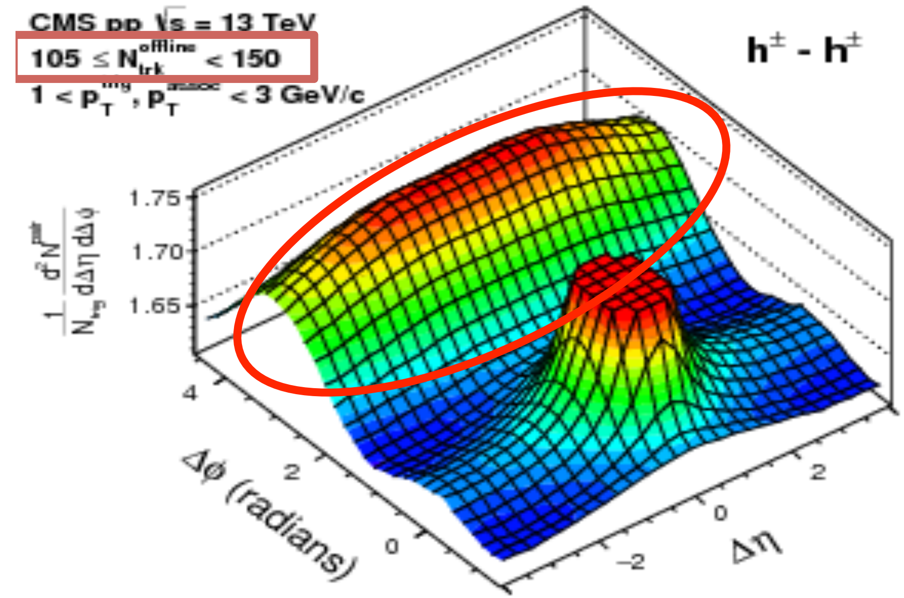
The ATLAS experiments also founds near-side long-range ridge structure at the p+p 13 TeV collisions in the high-multiplicity events.

Did you find the differences between small systems and heavy ion collisions?

Nuclear modification factor

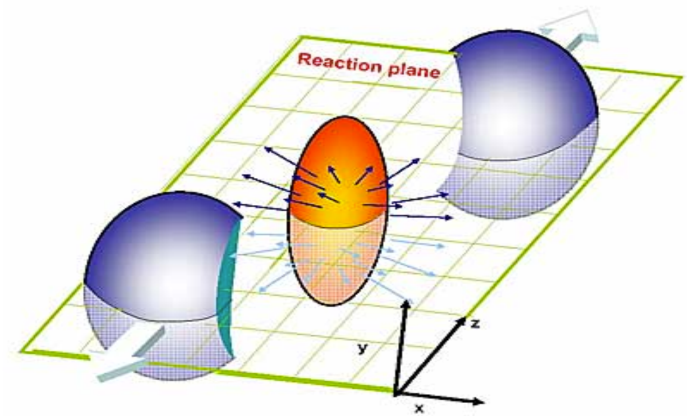


Nuclear modification factor(R_{AA})
suppress the away-side jet (no peak)



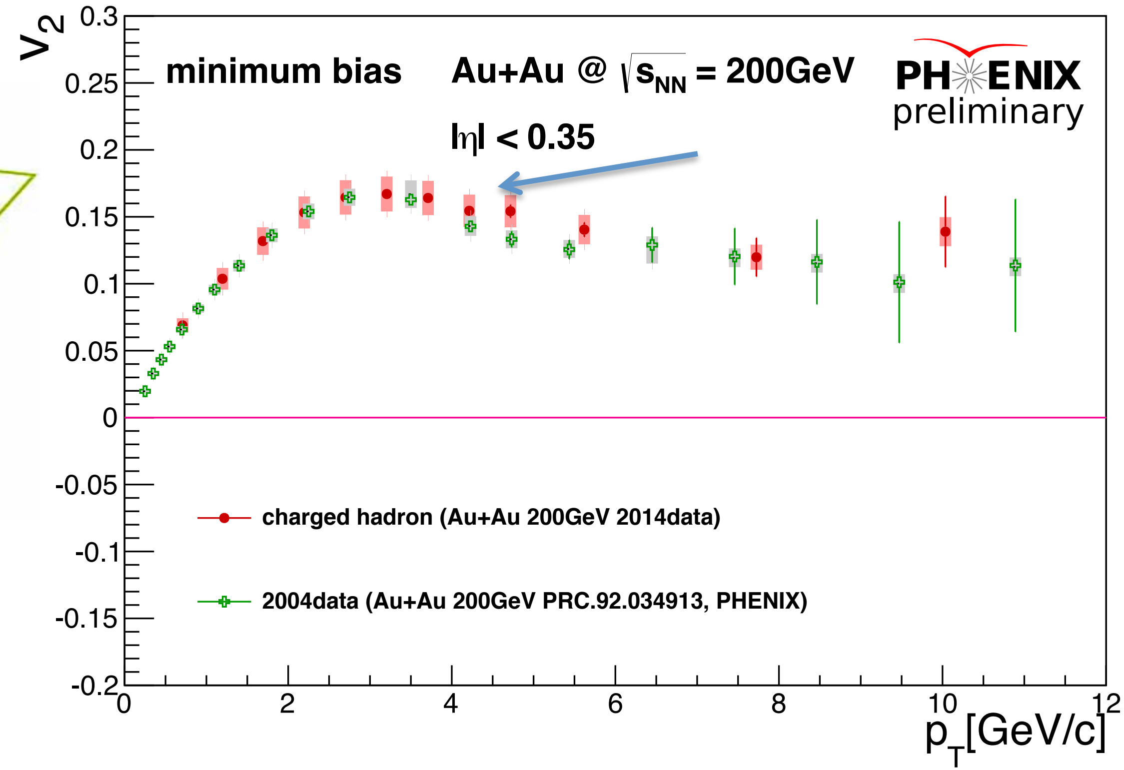
Intrinsic transverse momentum;
the partons within the proton smear
the away-side jet

Elliptic flow in heavy ion collisions



$$p_T = \sqrt{p_x^2 + p_y^2}$$

Turn-on at >~3GeV/c

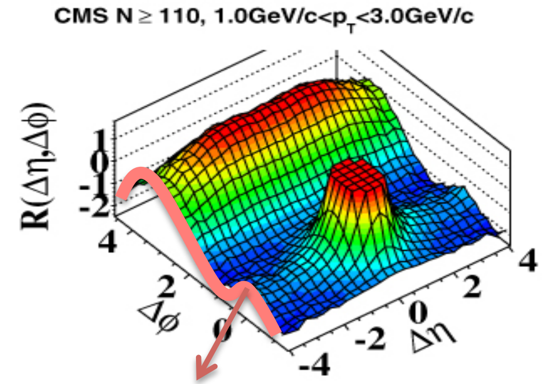


Jet starts to be dominant at the higher p_T because of the intrinsic transverse momentum starts to be dominated >~3GeV/c (RHIC energy, and LHC energy)

Collective dynamics of the small systems

- What is the smallest system size that can create a QGP?
- What is the role of the initial geometry?
- How important are the contributions from the initial state and the hadronization process?
- How do we quantify the long range ridge structure?
- What is the physics behind?

JHEP09(2010)091

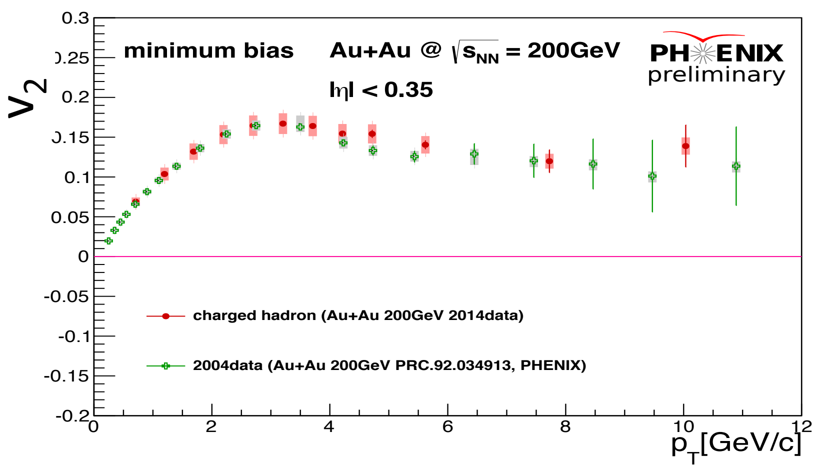


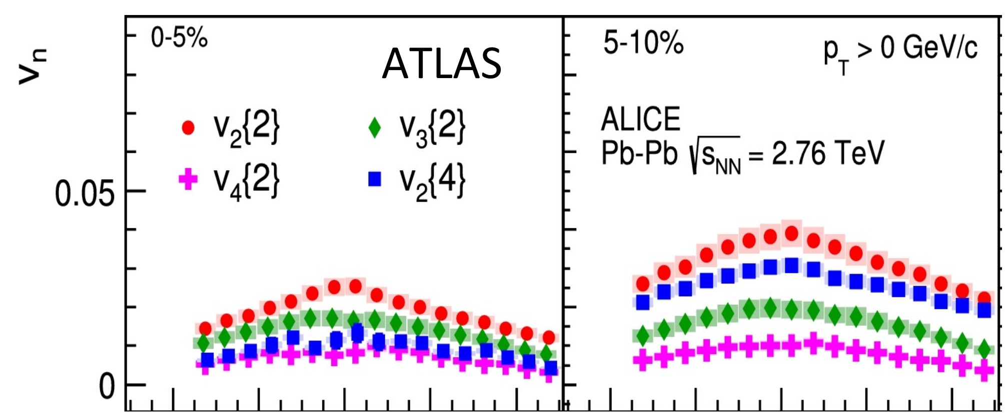
QGP-originated elliptic flow?

Considerable size of near-side long-range ridge structure measured at p+p 7TeV(CMS) at the very high multiplicity events.

PHENIX datasets

$\sqrt{s_{NN}}$ [GeV]	U+U	Au+Au	Cu+Au	Cu+Cu	^{3}He+Au	d+Au	p+Au	p+p
510								✔
200	✔	✔	✔	✔	✔	✔	✔	✔
62.4		✔		✔		✔		✔
39		✔				✔		
19.6		✔		✔		✔		





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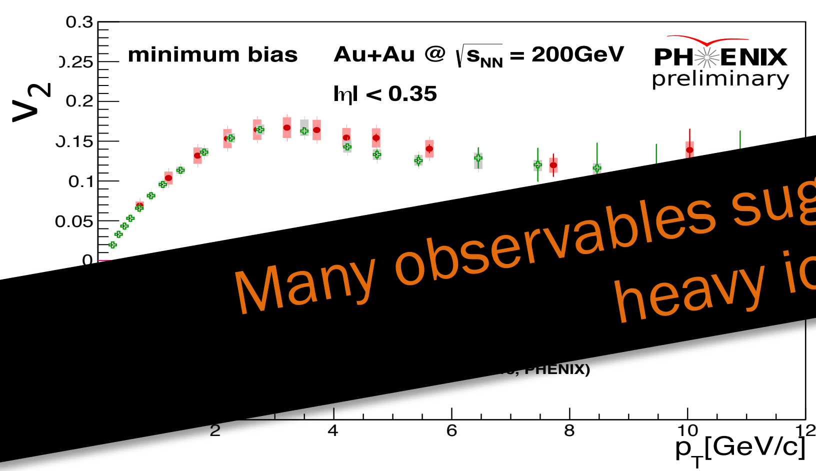

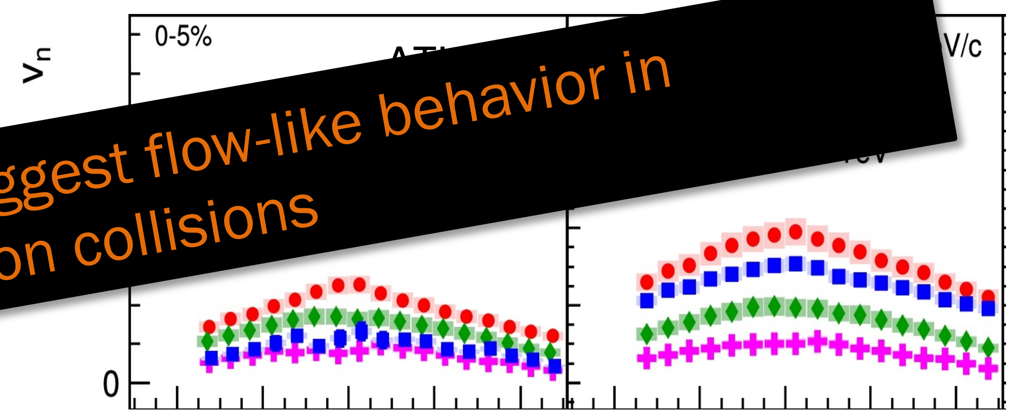

Many observables suggest flow-like behavior in heavy ion collisions

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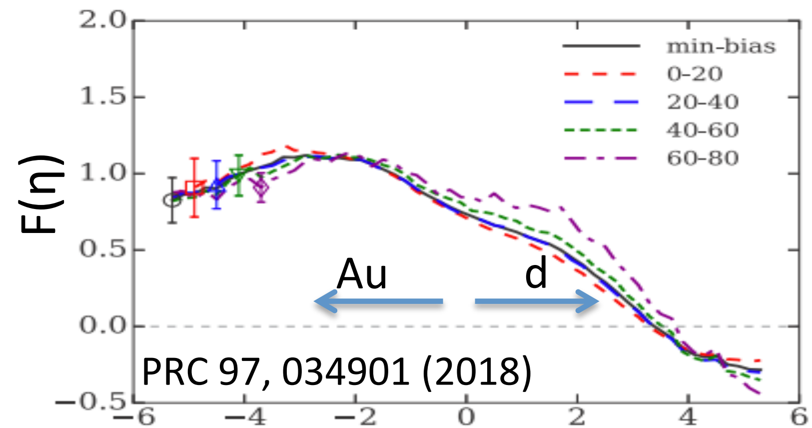
19.6		✔		✔		✔		

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

PRL **120**, 062302 (2018)
PRC **96**, 064905 (2017)

- In small collision systems, can we find some similar features of the heavy ion collisions case?
- Do these features indicate QGP formation?
- How can we interpret them based on our present understanding of the QGP?



small systems F(η) of wounded quark model using PHOBOS d+Au 200GeV

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PRL **120**, 062302 (2018)
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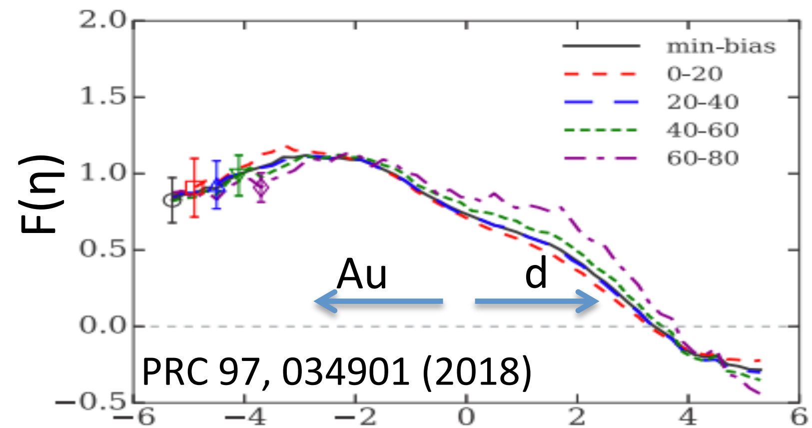
What about small systems?

- Beam-energy scan data of d+Au



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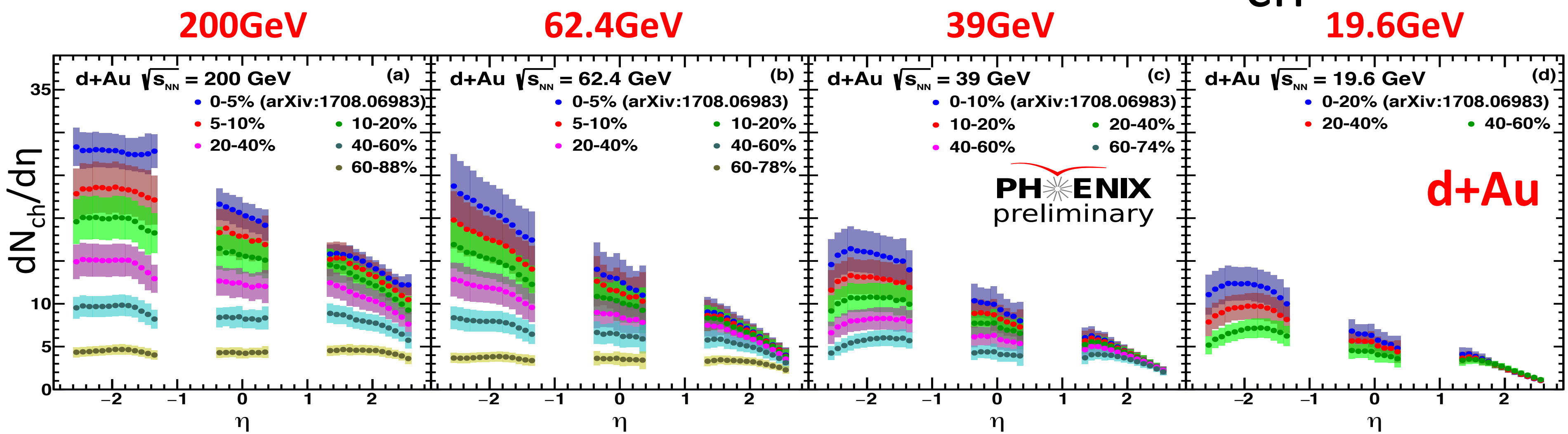
d+Au Beam Energy Scan : $dN_{ch}/d\eta$

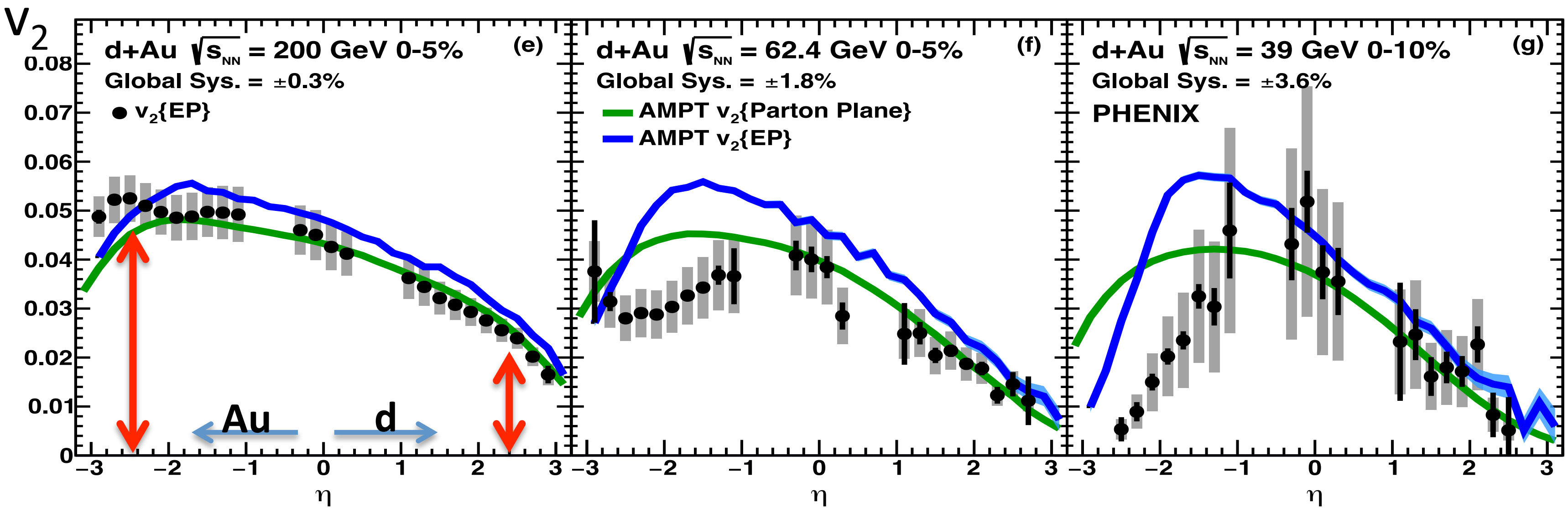


Collision energy gets to be smaller by
a factor of about ~10

$dN_{ch}/d\eta$ decreases by a factor of ~3

PRC 96, 064905 (2017)

d+Au Beam Energy Scan : v_2 vs η



Larger v_2 in Au-going direction, but this asymmetry becomes smaller in lower energies.

d-going, η>0

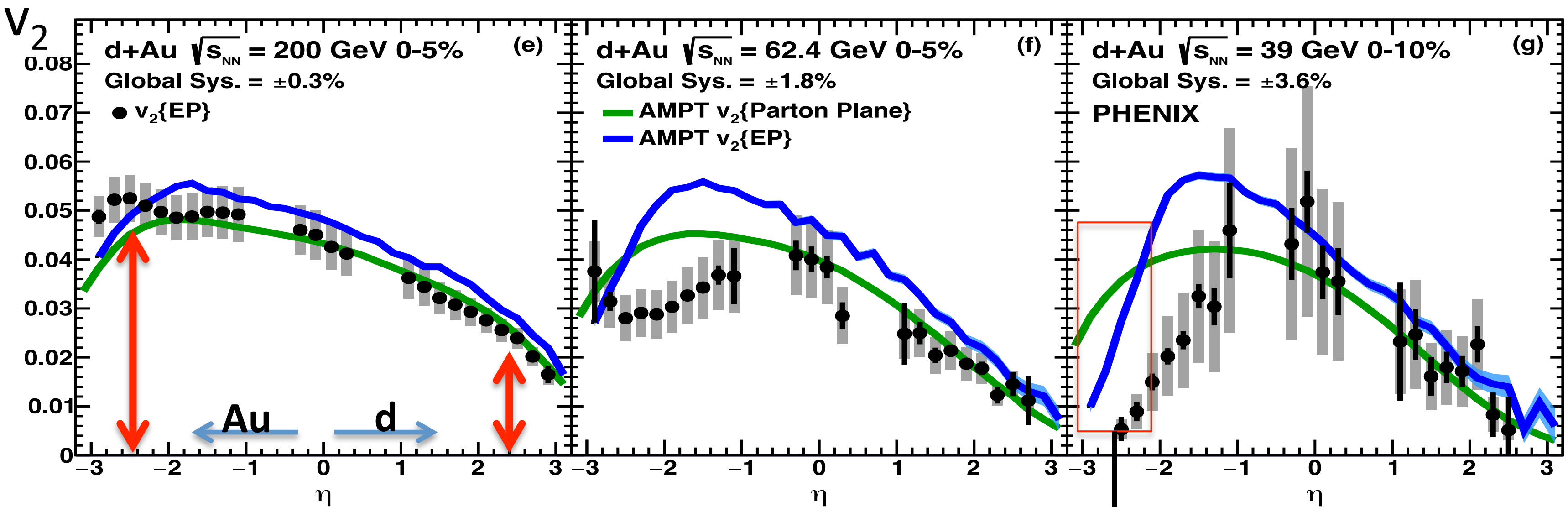
- 3 energies have similar size of v_2
- AMPT $v_2^{\{EP\}}$ describes the data quite well in all three collision energies with small non-flow contribution.

Au-going, η<0

- v_2 decreasing at the lower energy
- AMPT $v_2^{\{EP\}}$ described data points well, but tends to overshoot in lower energies.

PRC 96, 064905 (2017)

d+Au Beam Energy Scan : v_2 vs η



Larger v_2 in Au-going direction, but this asymmetry becomes smaller in lower energies.

Nonflow is not additive!

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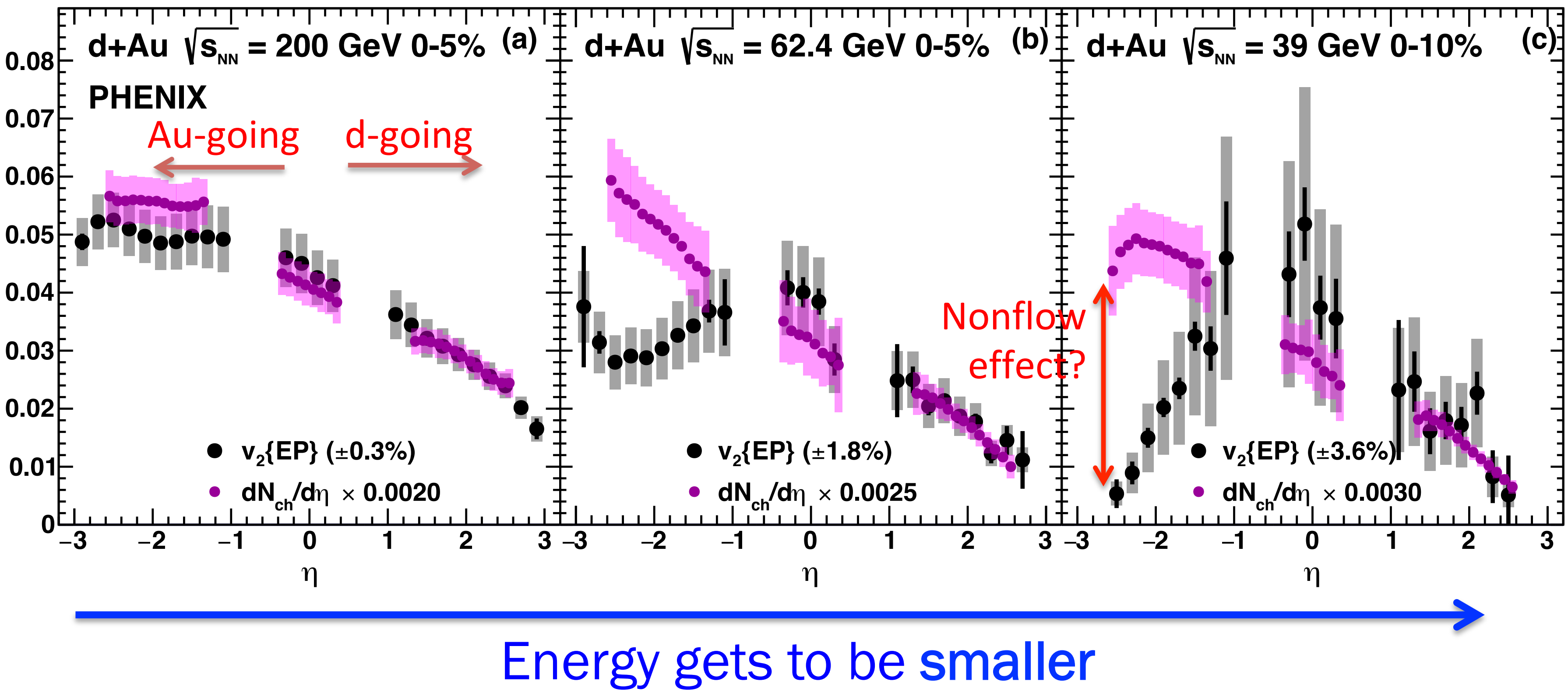
PRC 96, 064905 (2017)

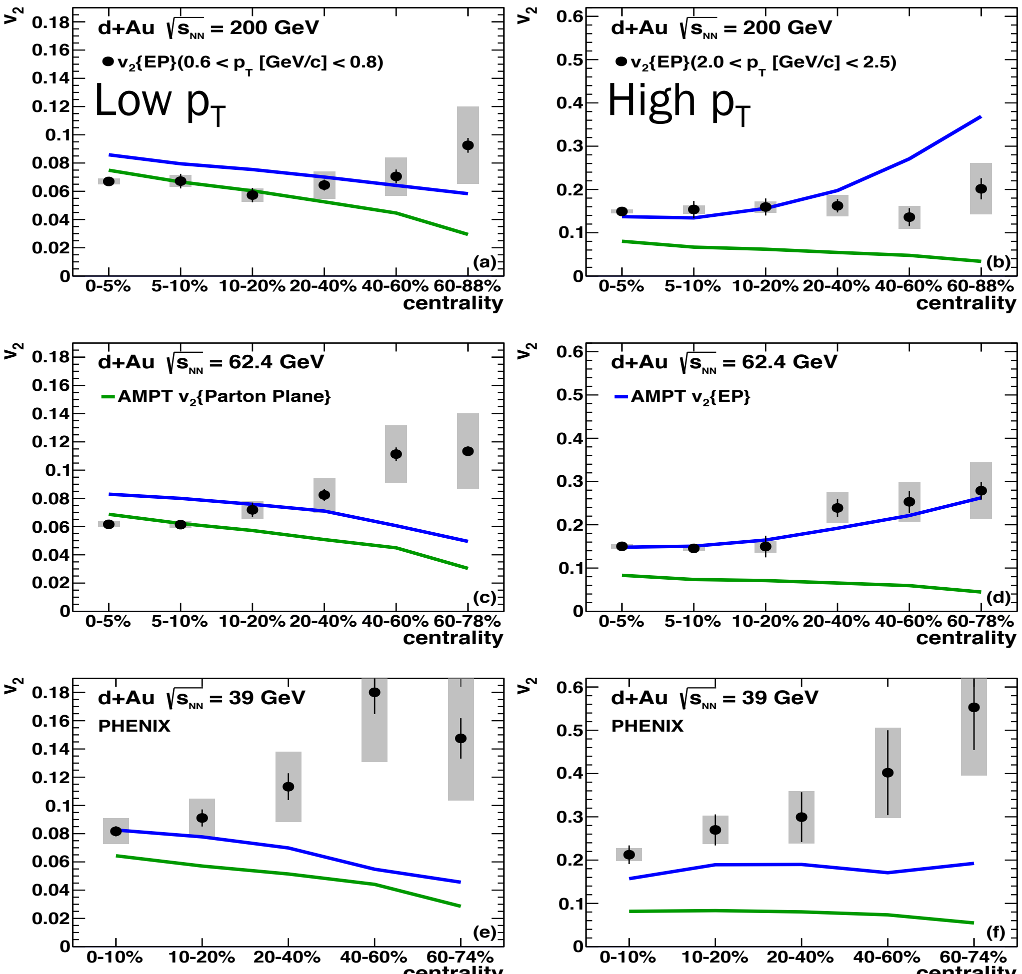
d+Au v_2 and the scaling $dN_{ch}/d\eta$



- One interesting feature of v_2 and the $dN_{ch}/d\eta$

PRC 96, 064905 (2017)

v_2 vs. centrality



v_2 increases: low multiplicity

-As the collisions become more peripheral.

-As the collision energy decreases.

AMPT predicts

-$v_2^{PartonP}$ decrease as centrality

-At lower p_T, two curves more in agreement.

-At high p_T, v_2^{EP} is significantly larger than v_2^{ParonP} where non-flow effects may dominant.

There would be additional nonflow effect which are not included.

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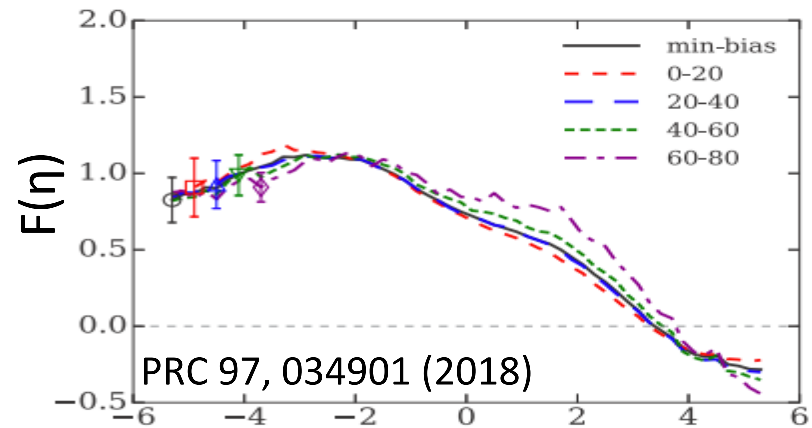
What about small systems?

- System-size, and initial geometry dependence for small systems



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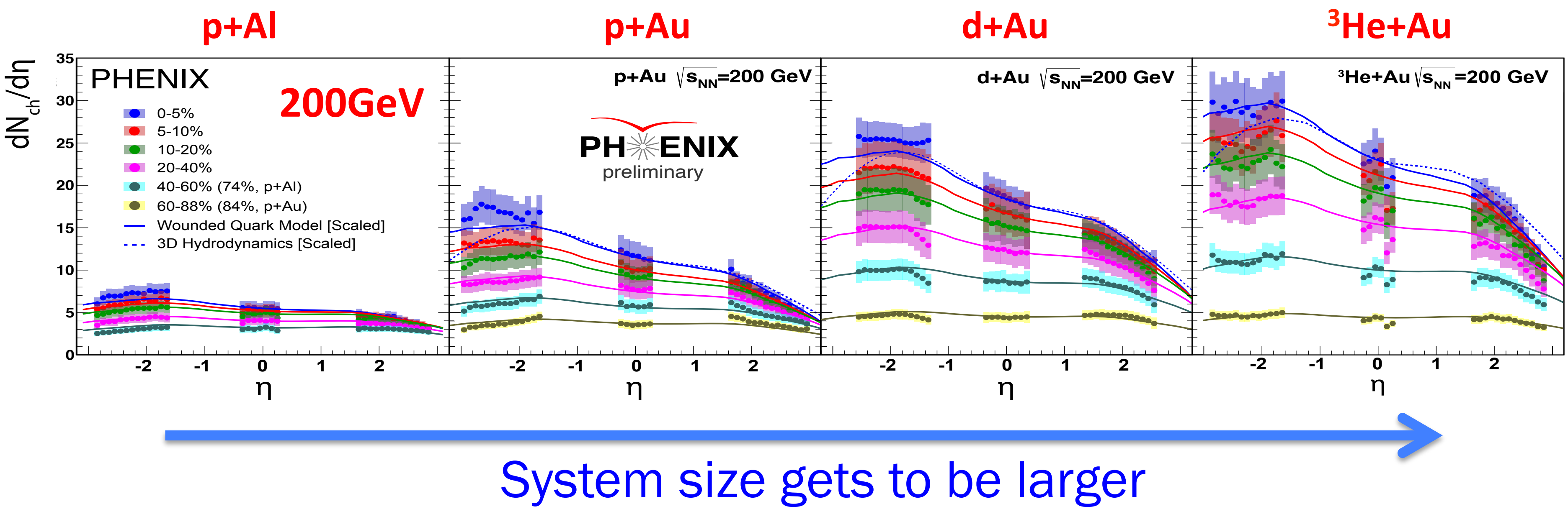
PRL 212, 22301 (2018)

Collision system size dependence



PRL 212, 22301 (2018)

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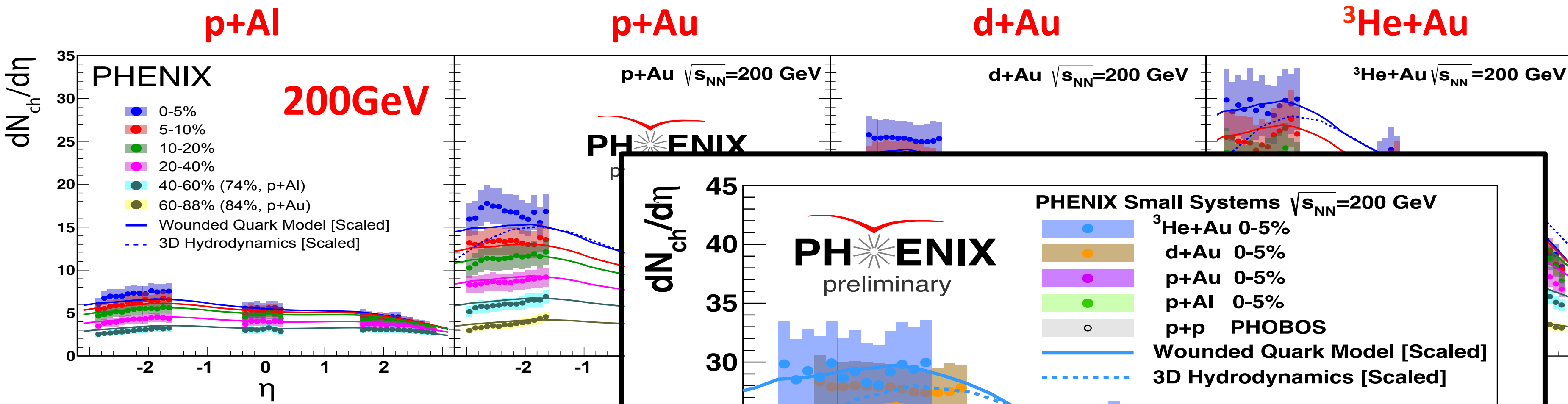
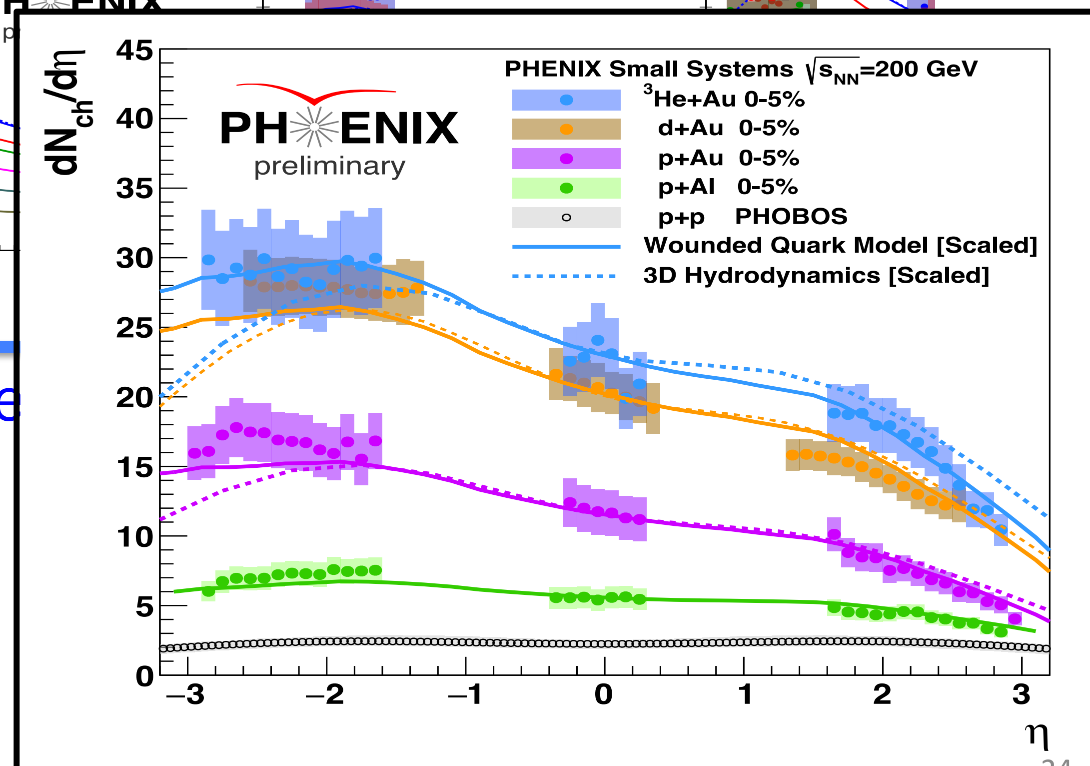


Syste

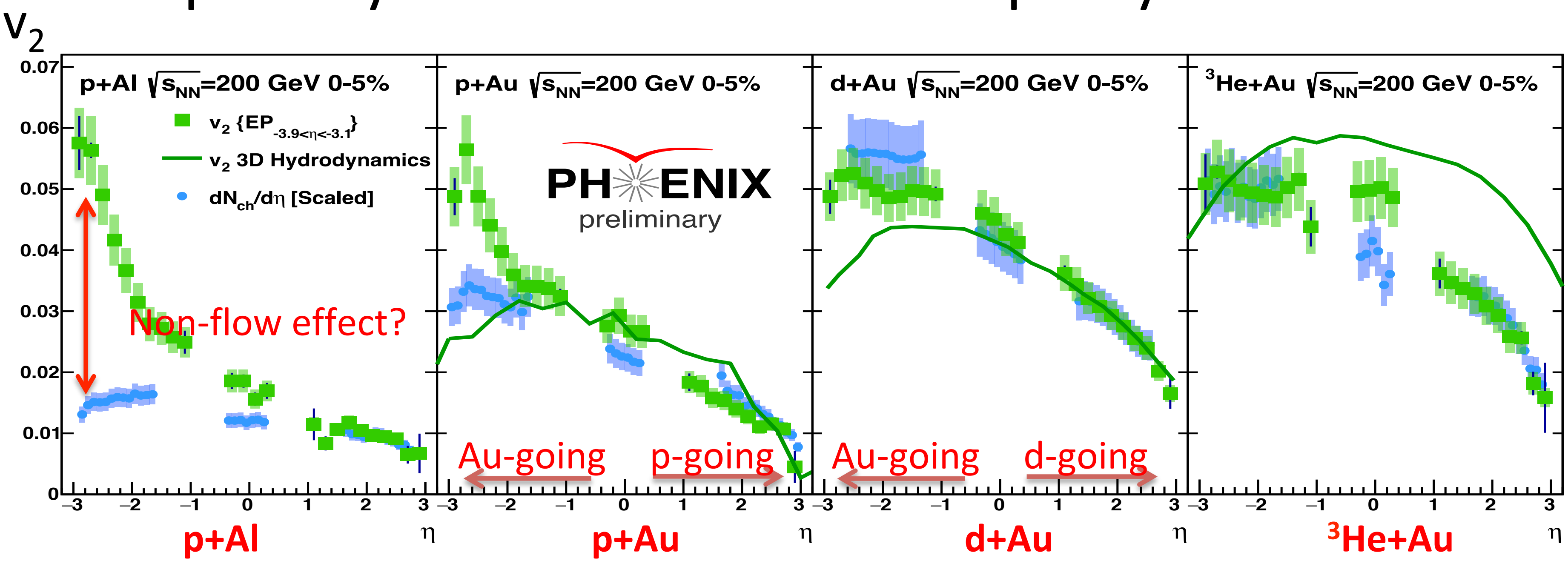


$dN_{ch}/d\eta$ reasonably well-described by wounded quark model

PRL 121, 222301 (2018)

v_2 and the scaling $dN_{ch}/d\eta$

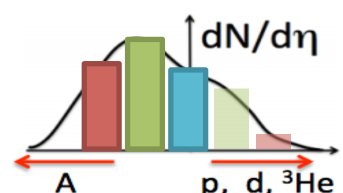
- Different systems are also shown similar shape especially at the mid-forward rapidity



3D hydrodynamics gives

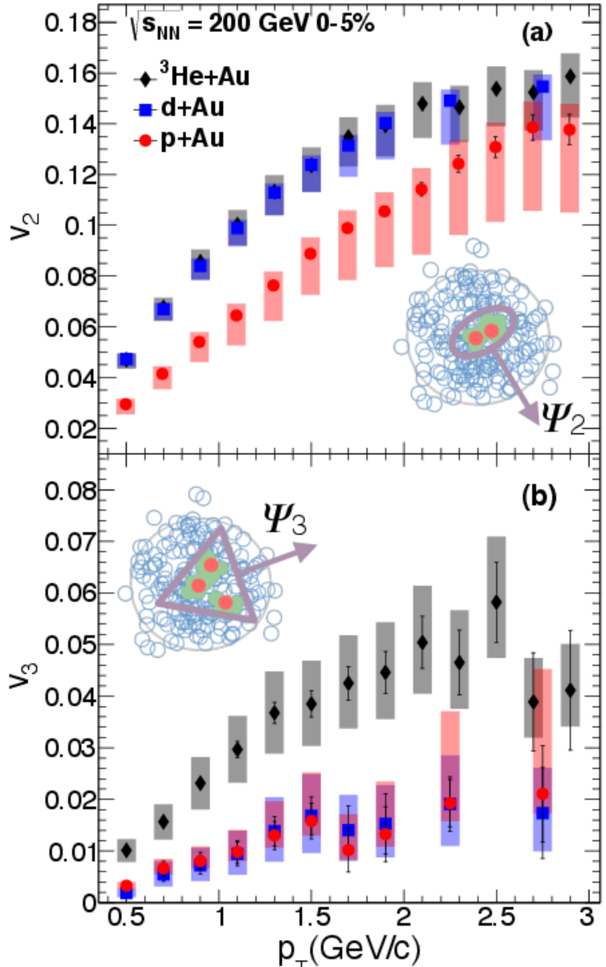
- reasonably describe the rapidity dependence of v_2

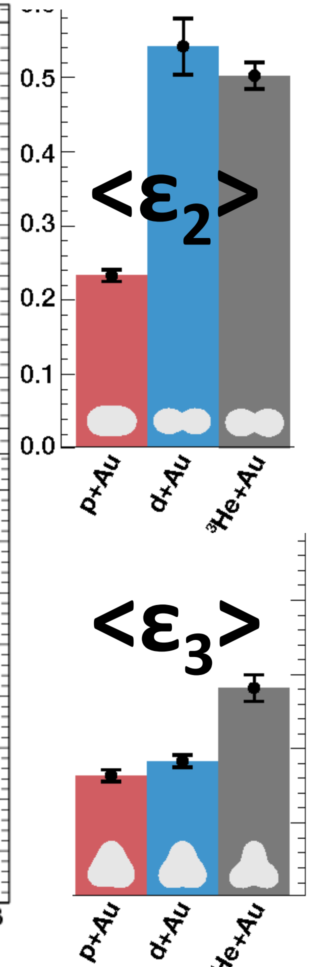
- larger differences at the Au(Al)-going side.



Nature Phys. 15, 214 (2019)

Initial geometry and the v_n





v_2[p+Au] < v_2[d+Au] ≈ v_2[^{3}He+Au]

ε_2[p+Au] < ε_2[d+Au] ≈ ε_2[^{3}He+Au]

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Initial geometry dependence of v_2 is studied using different collision systems.

The hierarchy of v_2 and v_3 consistent with that of ε_n.

Summary

- Collective-like behavior was observed in small systems by the PHENIX experiment.
  - Measured v_n are well described by viscous hydro model.
  - $dN_{ch}/d\eta$ is described by the wounded quark model.
  - Confirmed initial geometry effect in the medium formed in small systems (p/d/^{3}He + Au)
  - 3D hydrodynamics reasonably well describe the rapidity(η) dependence of the v_2.
  - Measured centrality dependence but it is not described by AMPT.
- Nonflow contribution needs to be studied for the better understanding of small collision systems.

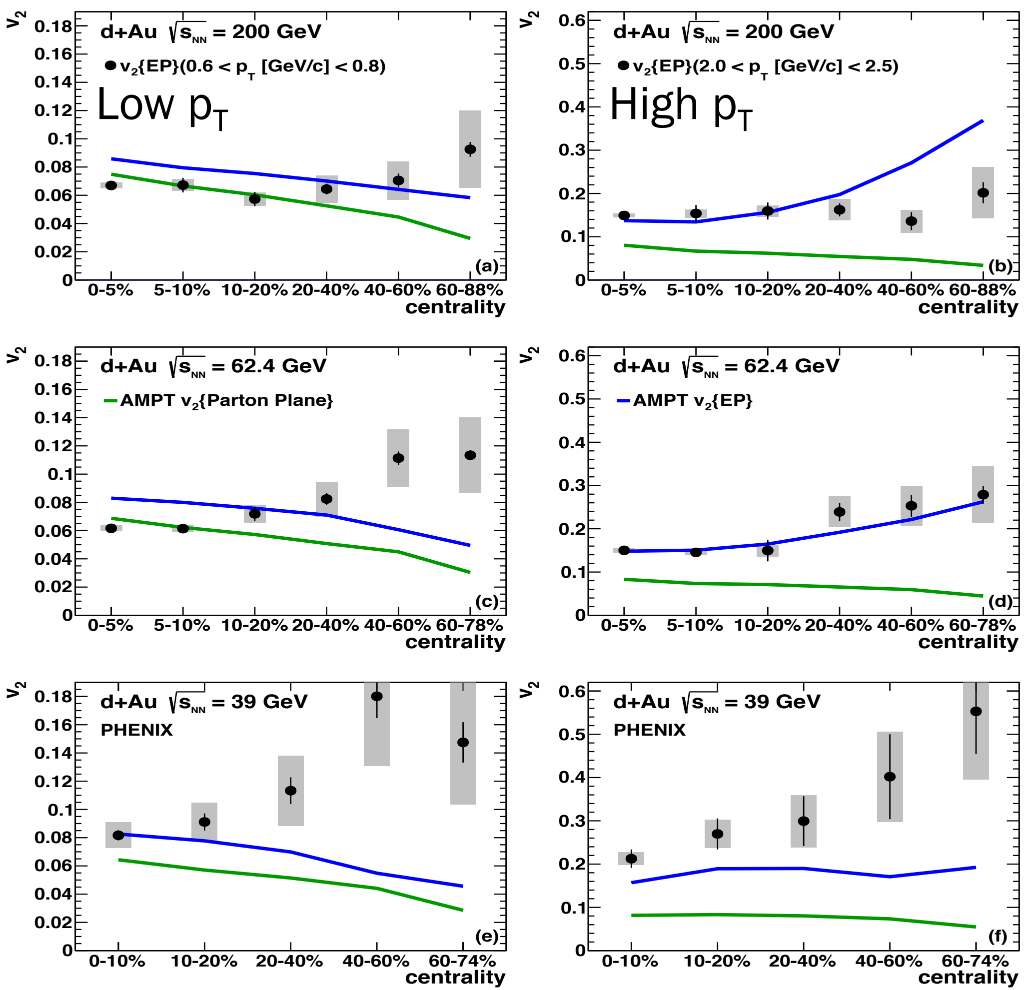
BACKUP

QCD and QGP

- Quantum chromo-dynamics(QCD)
  - Giving color charge to quarks
    - r(red), g(green), b(blue)
  - Hadron satisfied color confinement “white”
  - Asymptotic freedom
    - “Quark gluon plasma(QGP)” predicted
    - Early stage of the universe
- Relativistic heavy ion collider
  - Accelerate the ions to generate QGP

PRC 96, 064905 (2017)

v_2 vs. centrality



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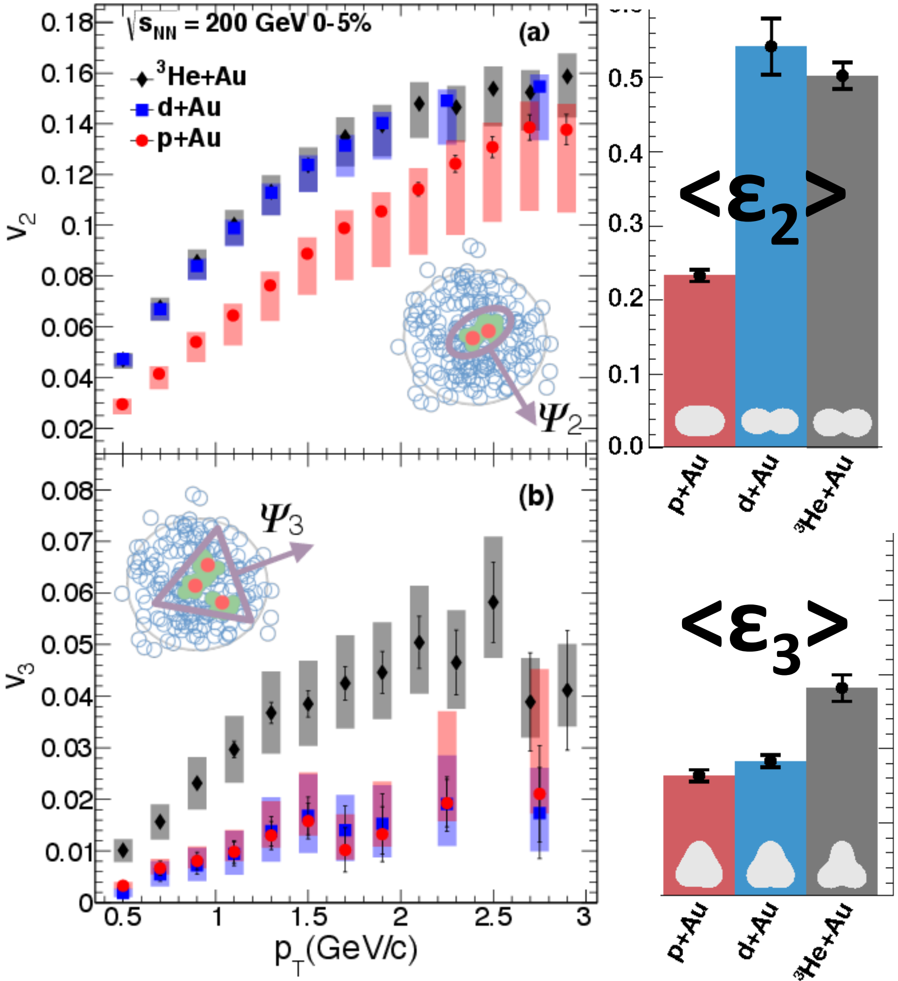

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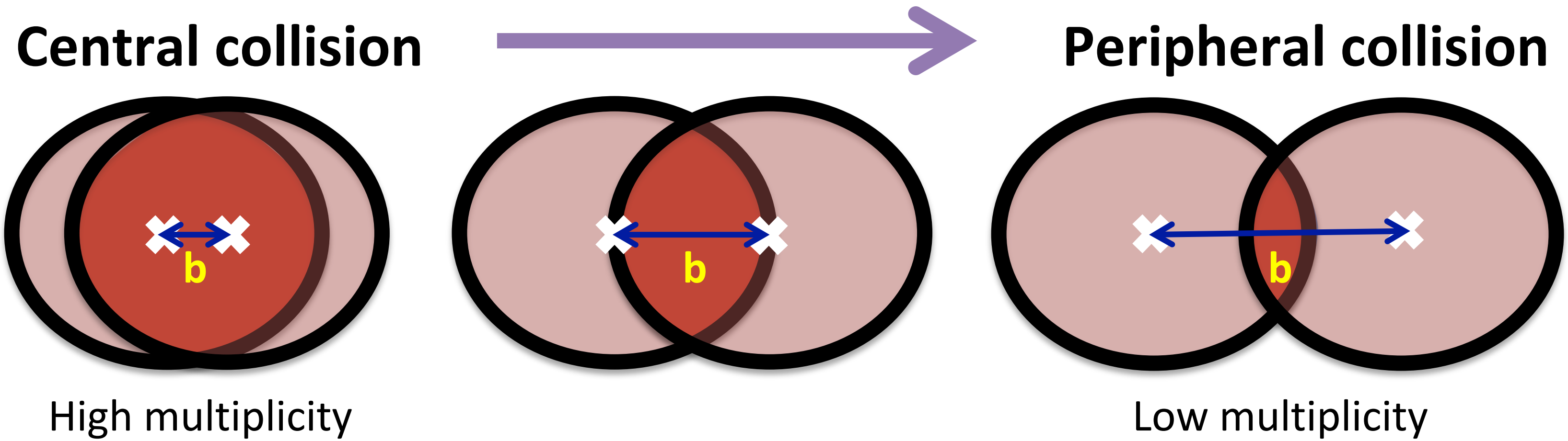

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- Only the partons within the overlap area can interact with each other and generate QGP.

The multiplicity is, therefore, showing the centrality which is related to the impact parameter, “b”.

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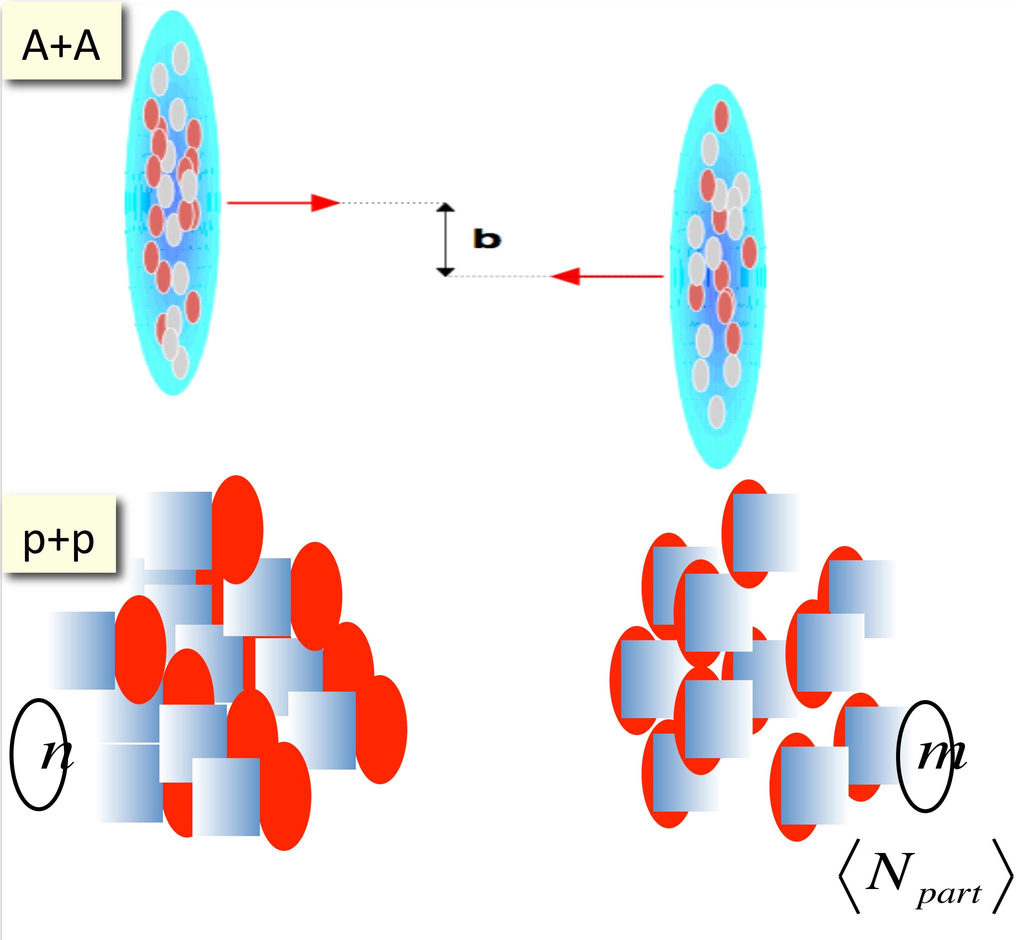
Nuclear modification factor

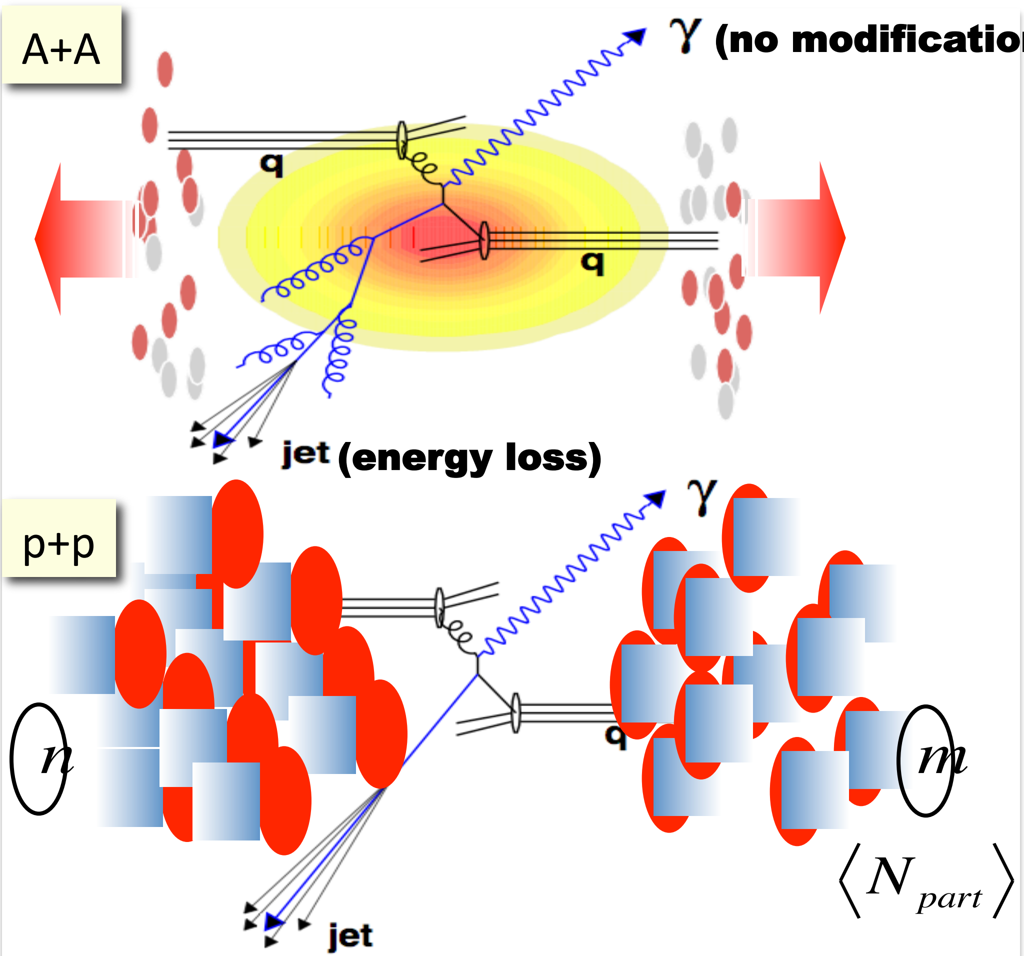


$\propto \langle N_{binary} \rangle$

$\langle N_{part} \rangle \approx n + m$

varies with impact parameter ***b*** ***(centrality %)***

Nuclear modification factor



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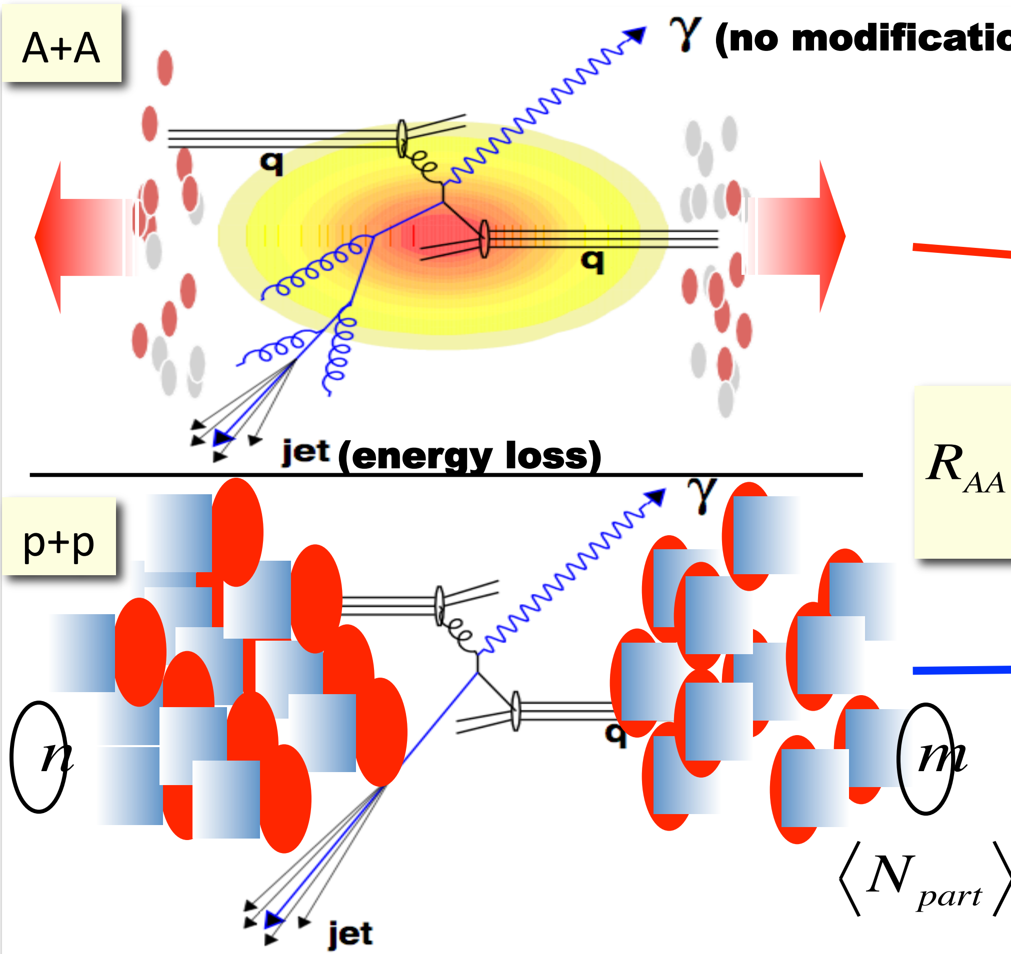

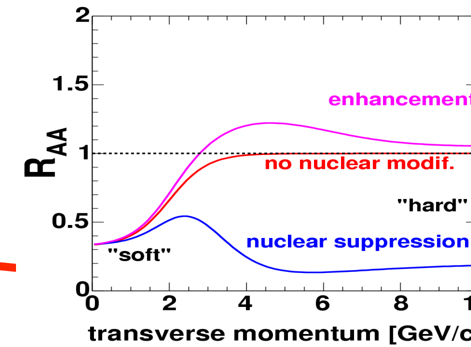

$$R_{AA}(p_T) = \frac{d^2N^{AA} / dp_T d\eta}{\langle N_{binary} \rangle d^2N^{pp} / dp_T d\eta}$$

$$\propto \langle N_{binary} \rangle$$

$$\langle N_{part} \rangle \approx n + m$$

varies with impact parameter ***b***
(centrality %)