SUMMARY OF RECENT RHIC RESULTS

THEODORE KOBLESKY
UNIVERSITY OF COLORADO BOULDER

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BROOKHAVEN NATIONAL LABORATORY

University of Colorado Boulder

PHENIX

HEAVY ION COLLISION TOPICS

JETS QUENCHING

COLLECTIVE FLOW

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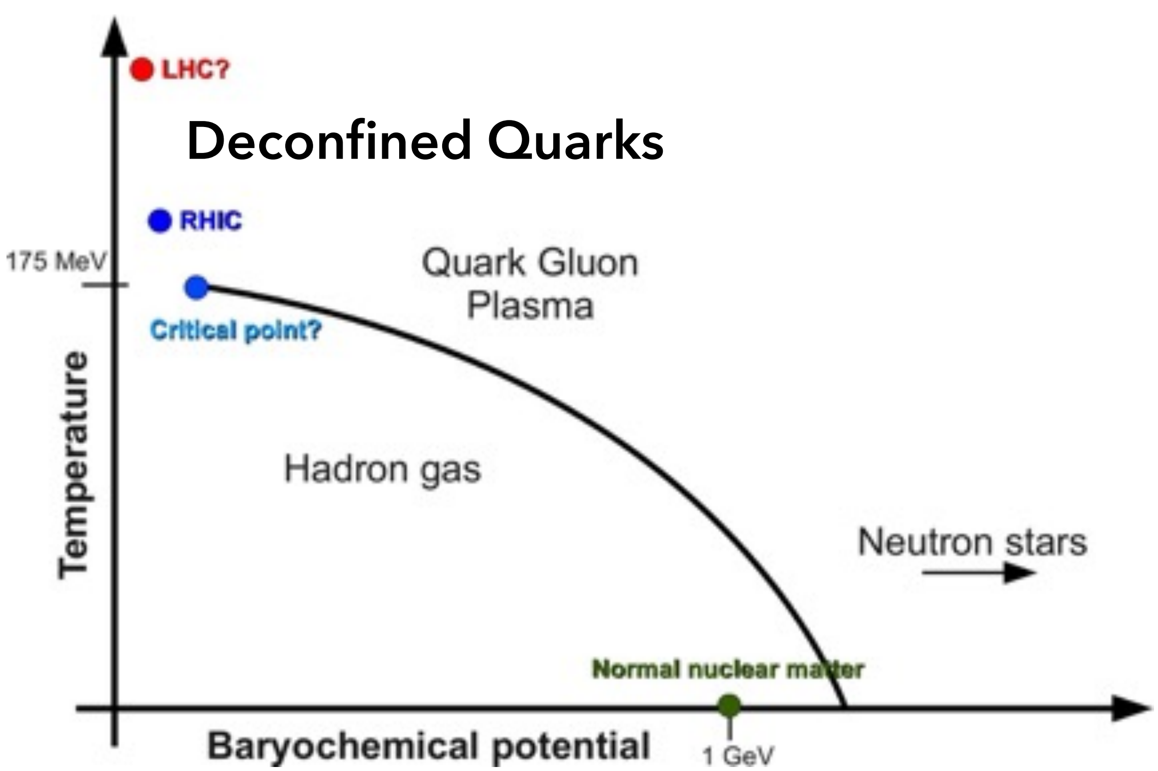
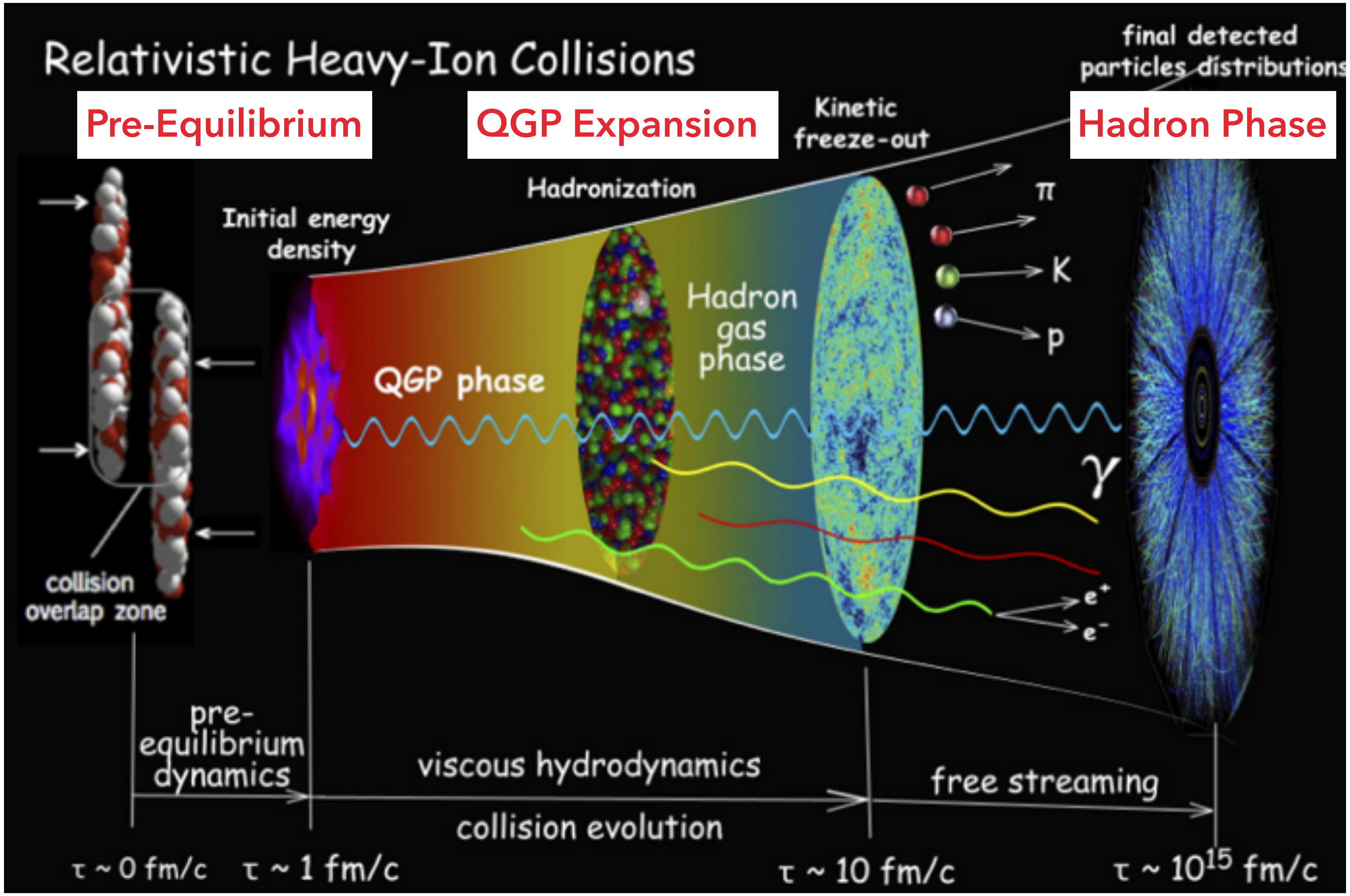
COLLECTIVE FLOW

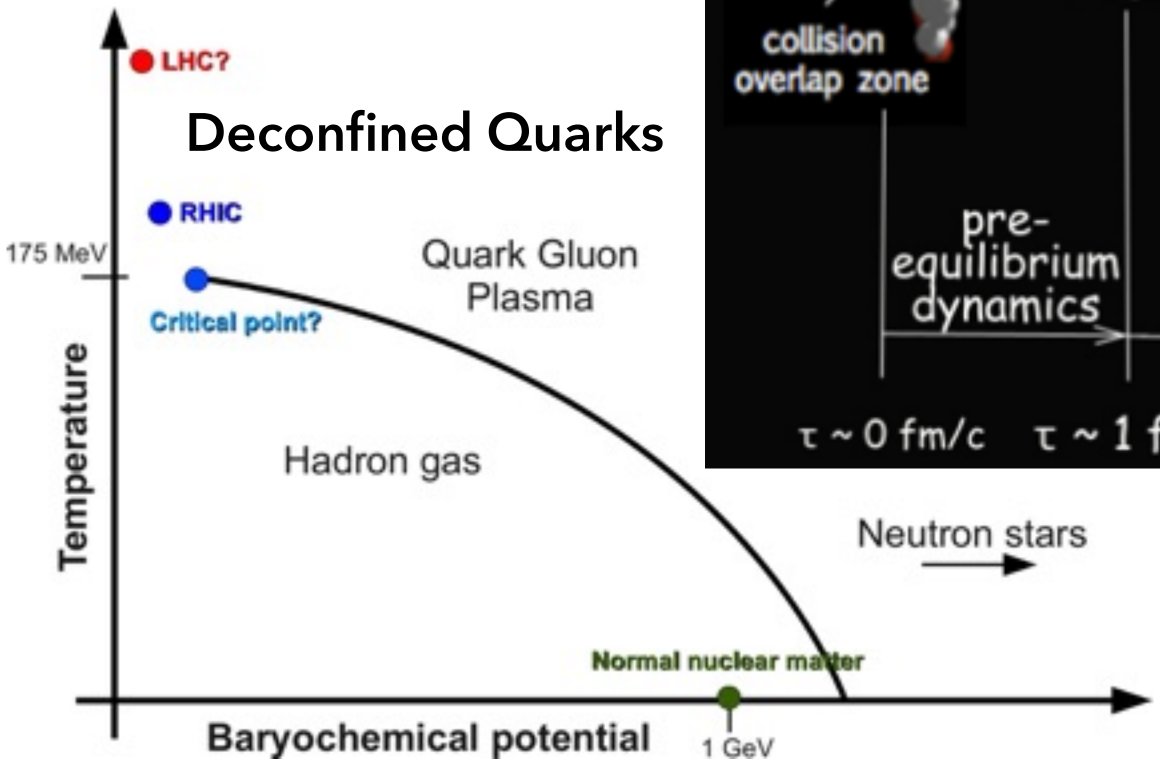
A+A COLLISIONS → SMALL SYSTEM

QUARK GLUON PLASMA (QGP)



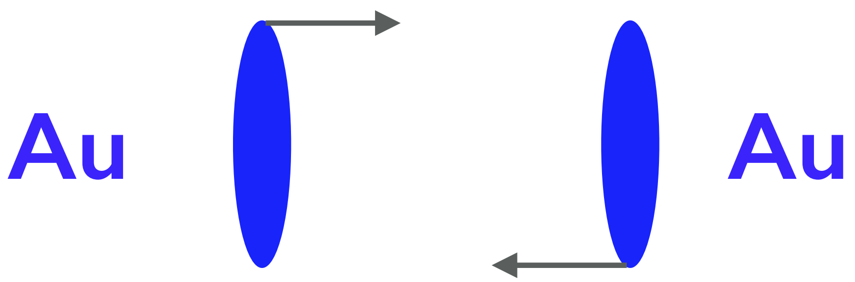
QUARK GLUON PLASMA EVOLUTION



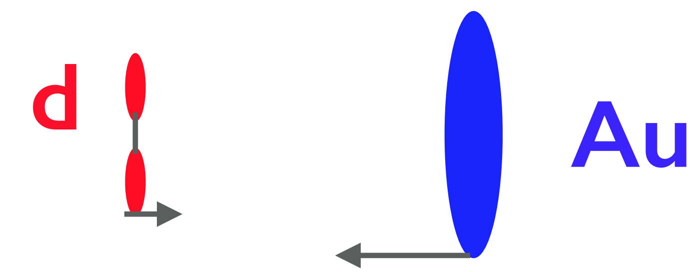


WHY ARE SMALL SYSTEMS INTERESTING?

Au+Au collisions were thought to be the necessary for the generation of **QGP**



Small systems like **d+Au** were thought of as the **control test** to measure cold nuclear matter effects.



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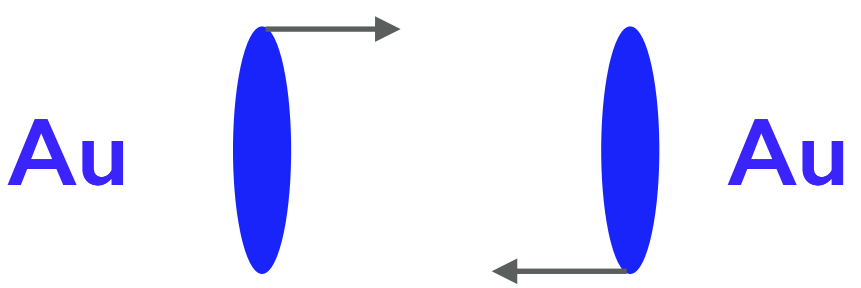
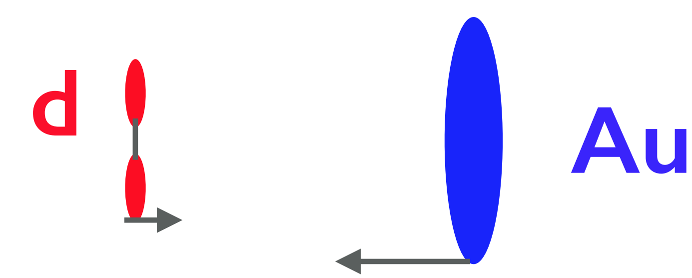
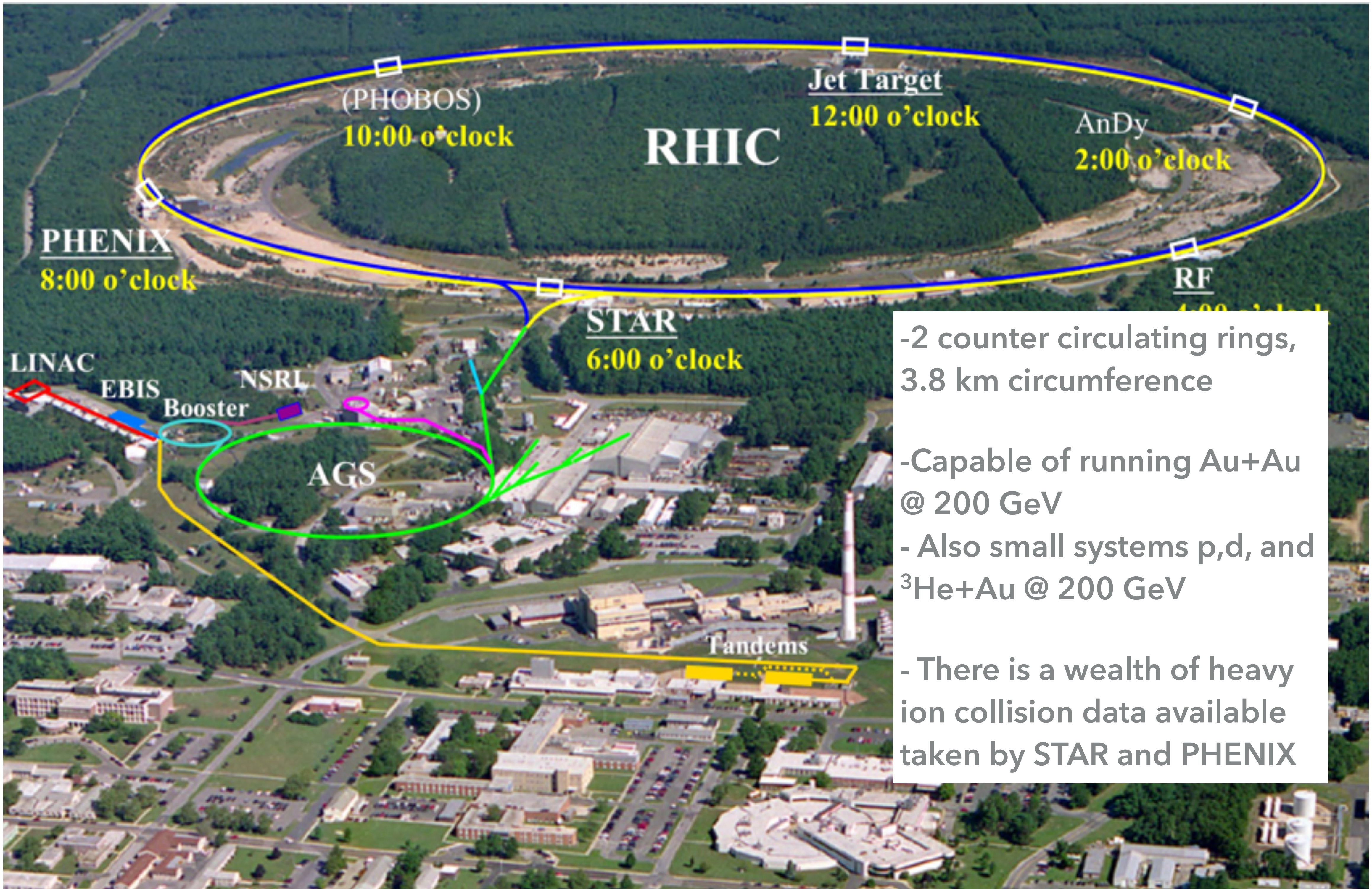




However, recent measurements of flow and jet quenching in small systems have yielded surprising results.

Small systems allow for control over the initial collision geometry.

RELATIVISTIC HEAVY ION COLLIDER AT BNL



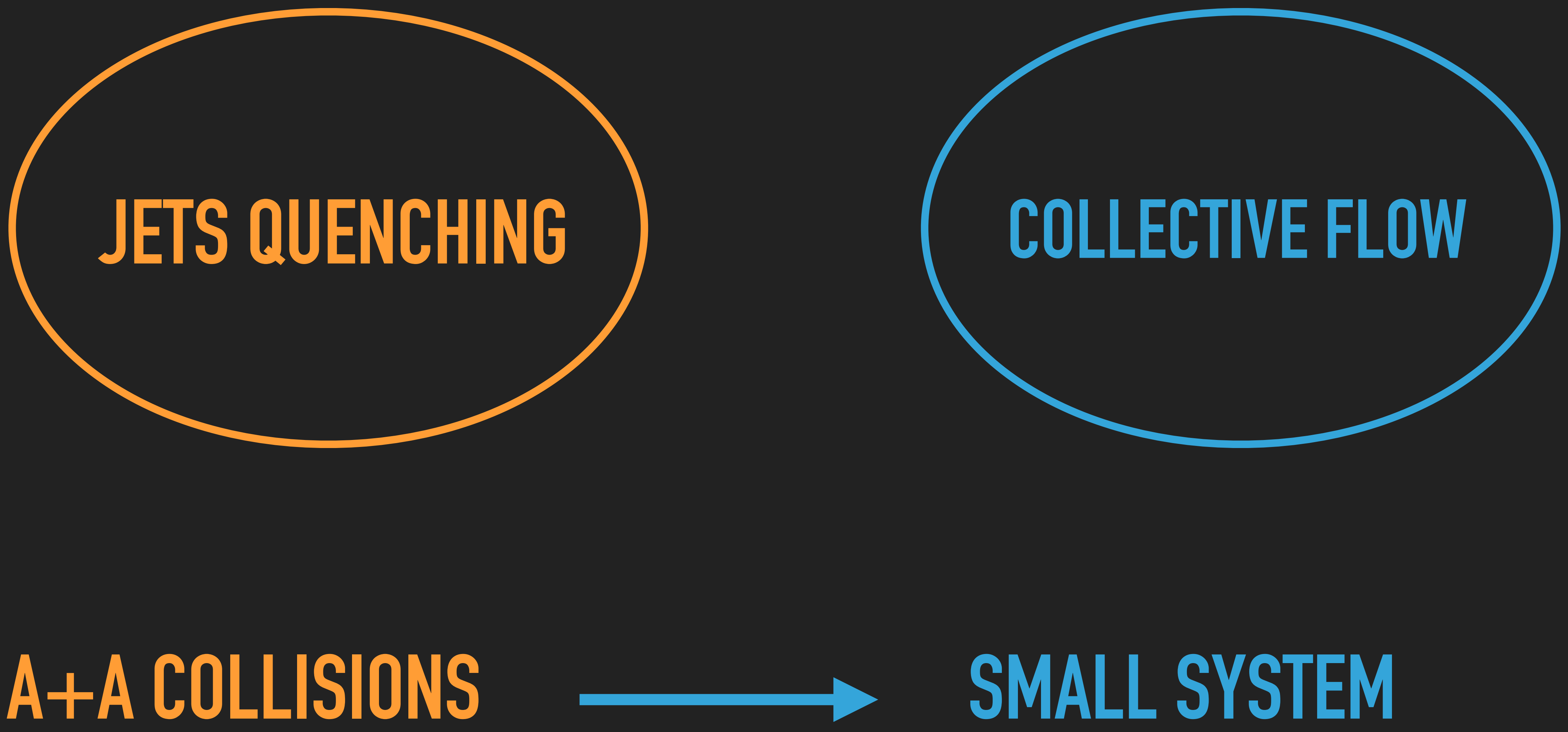
-2 counter circulating rings, 3.8 km circumference

-Capable of running Au+Au @ 200 GeV

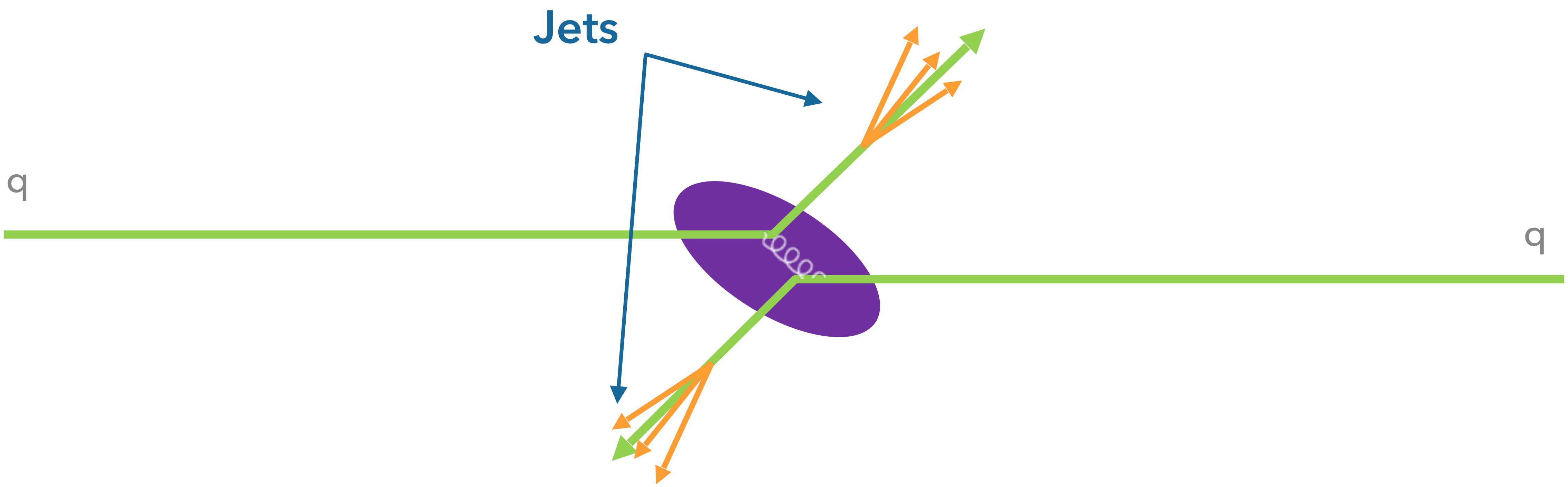
- Also small systems p,d, and ^{3}He+Au @ 200 GeV

- There is a wealth of heavy ion collision data available taken by STAR and PHENIX

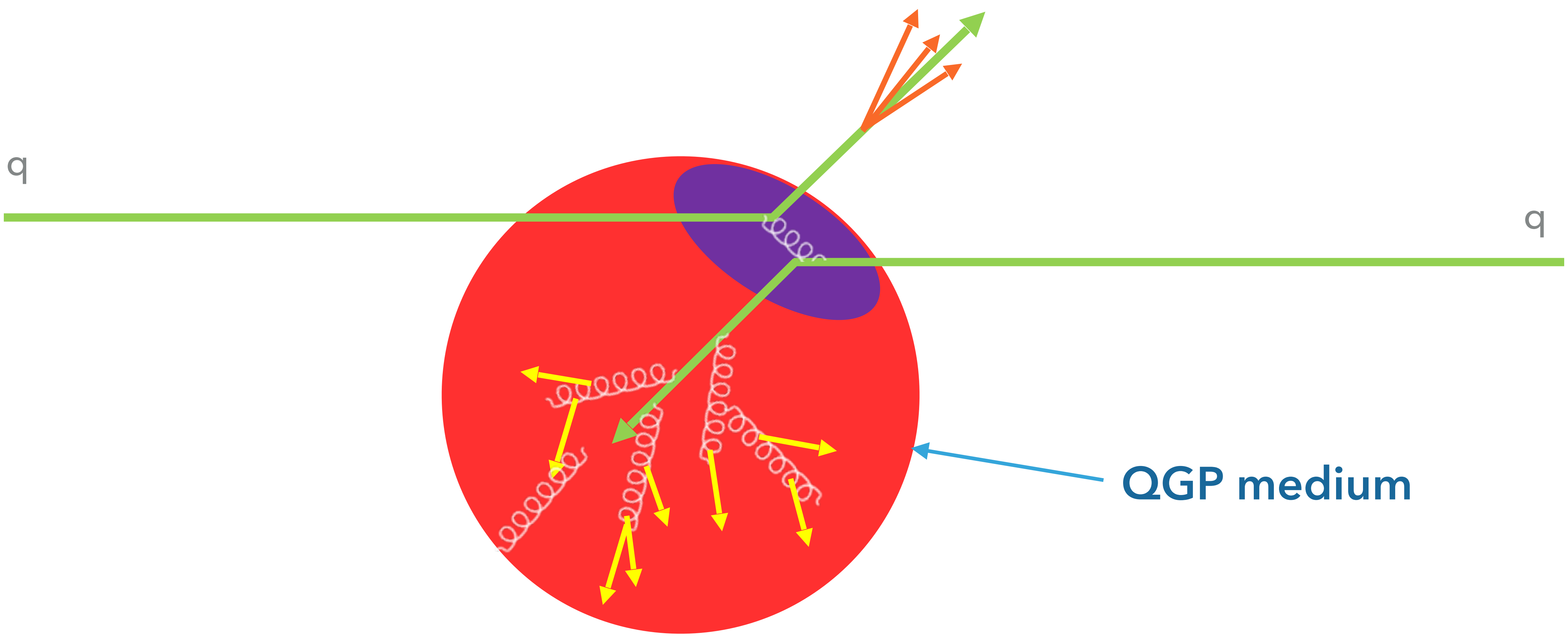
HEAVY ION COLLISION TOPICS



HARD SCATTERING



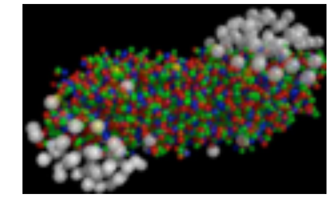
THE QGP IS OPAQUE



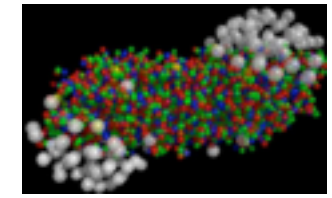
Energy loss via Gluon Bremsstrahlung

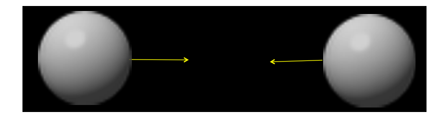
Suppression in jets.

$$\frac{\text{Physics in the Medium}}{\text{Physics in the Vacuum}}$$



$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} \sim \frac{\text{Physics in the Medium}}{\text{Physics in the Vacuum}}$$





Number of binary collisions

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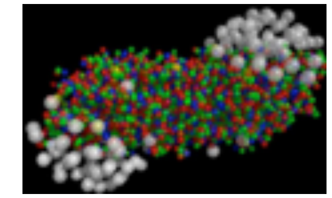
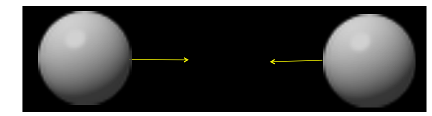
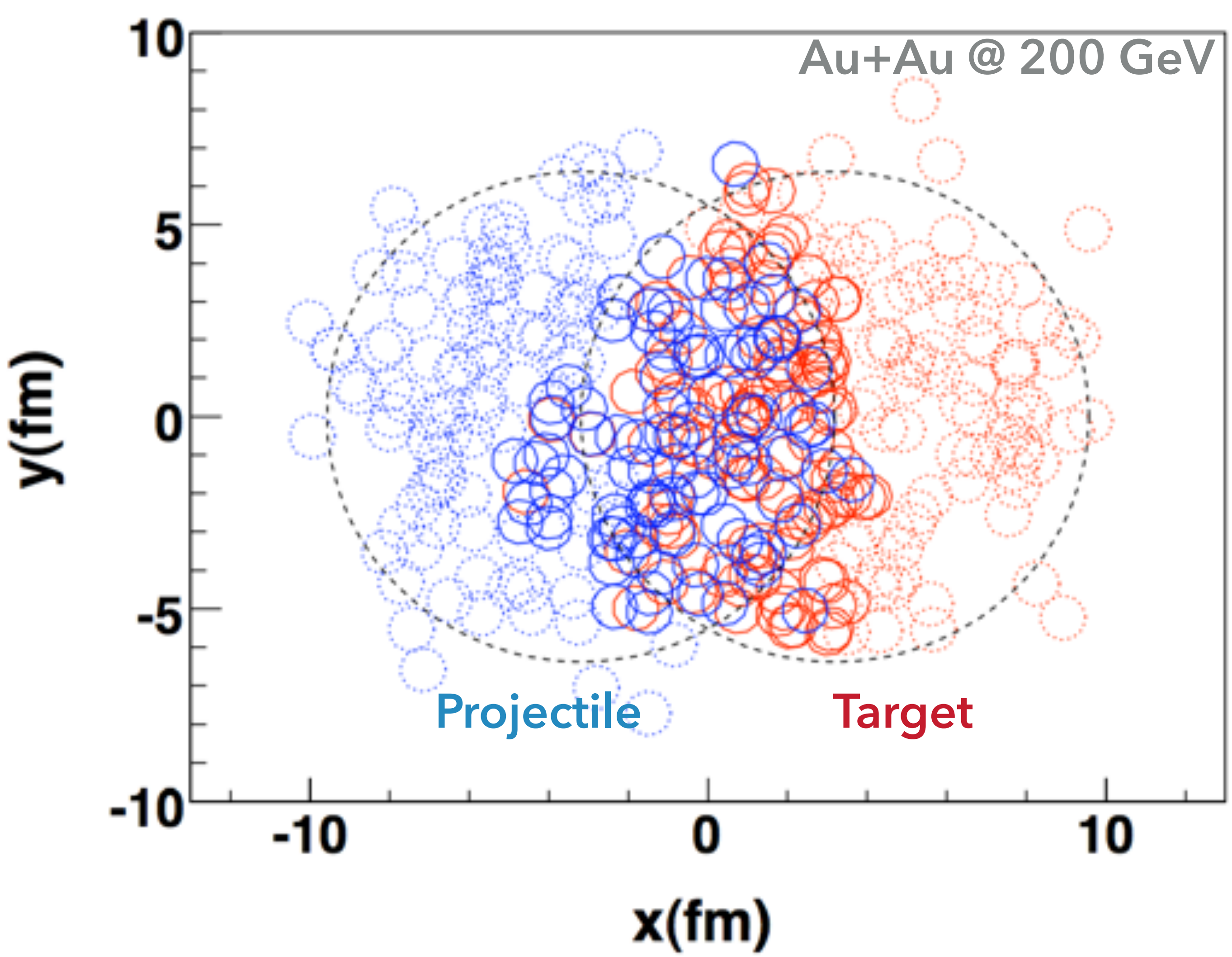




Number of binary collisions

Glauber Monte Carlo



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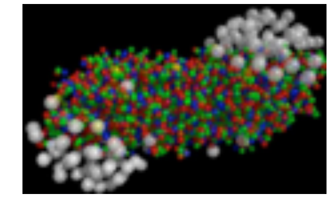

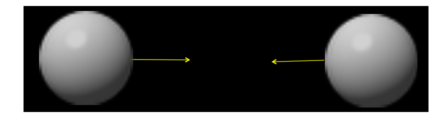

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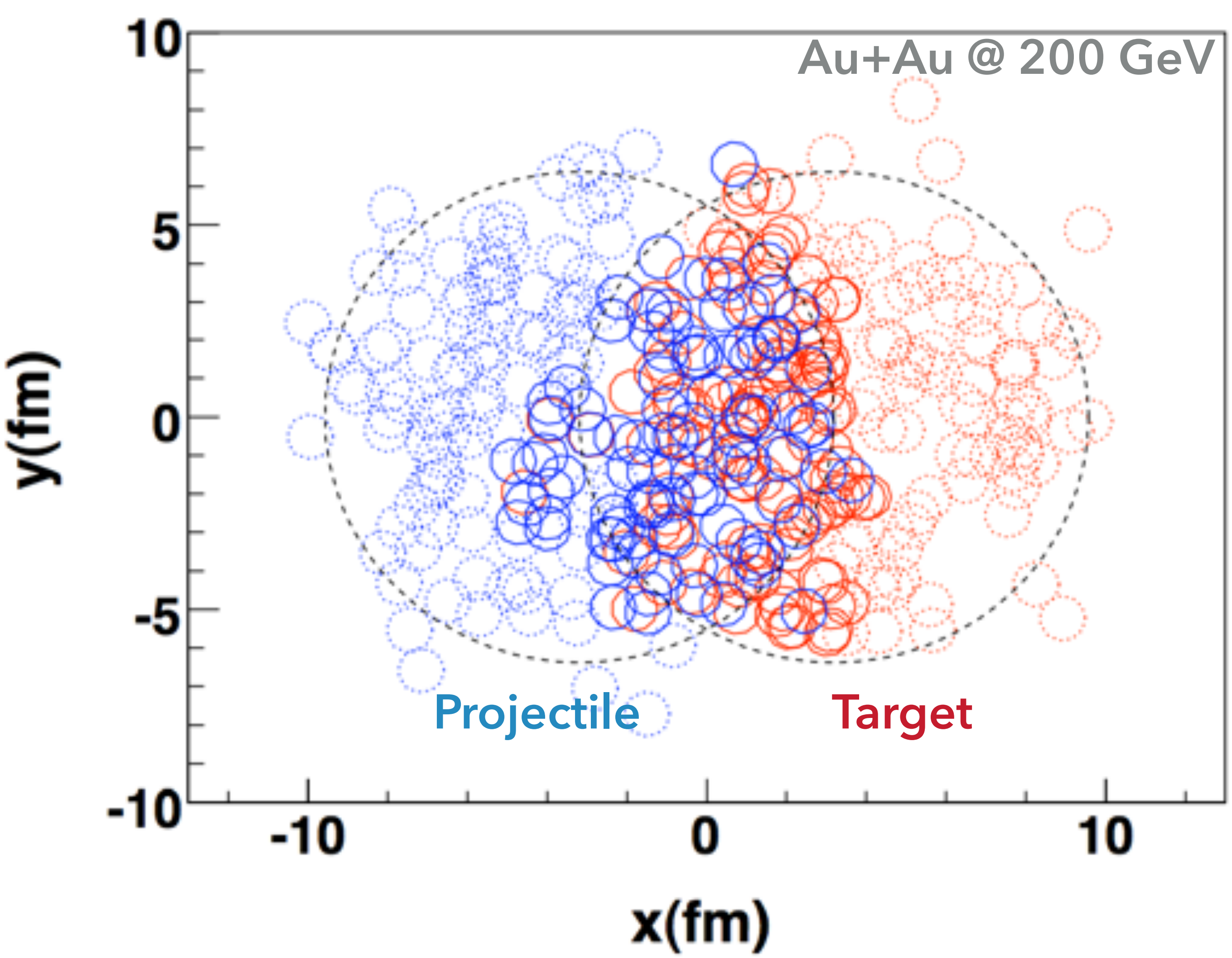
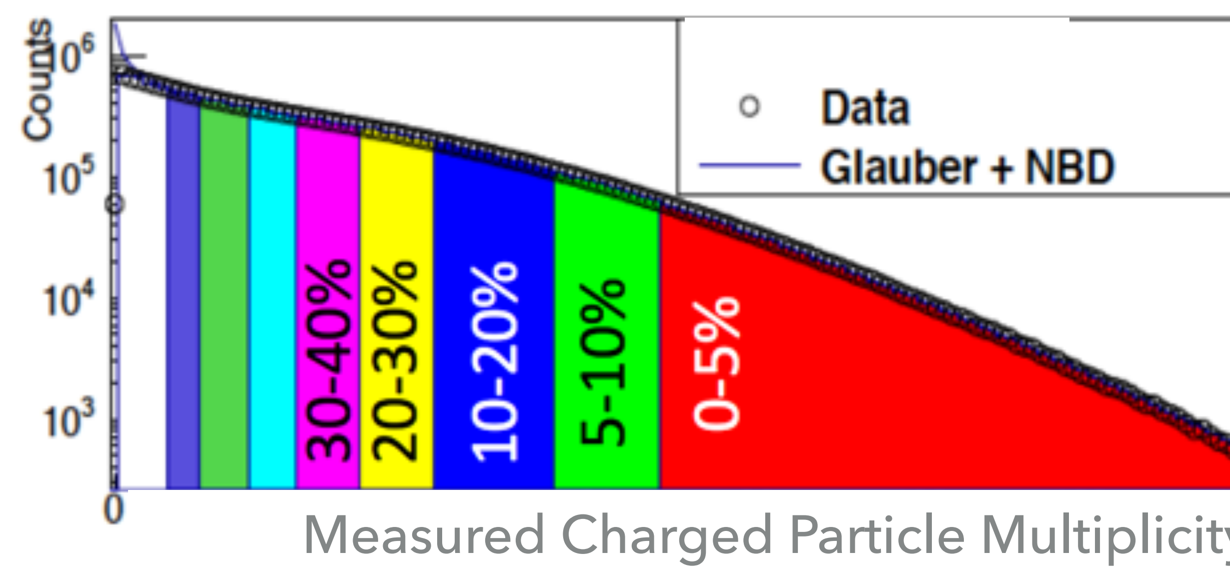
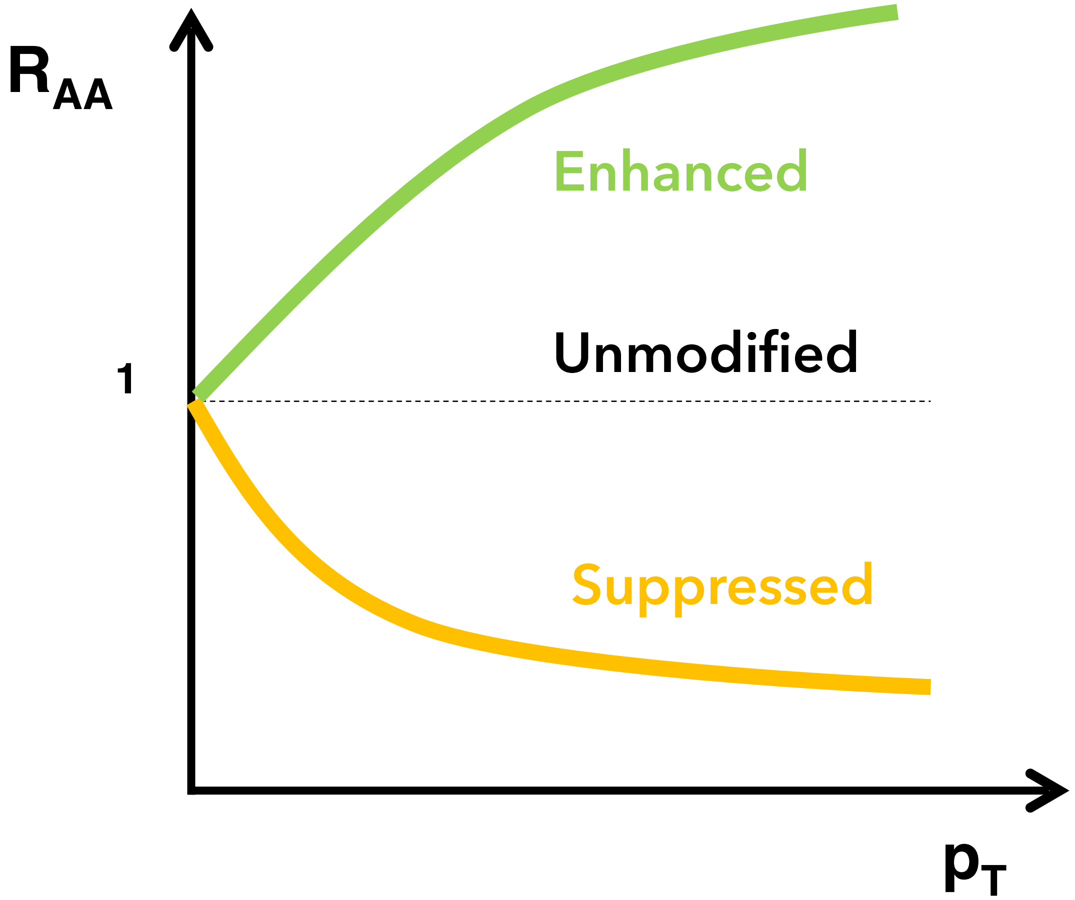
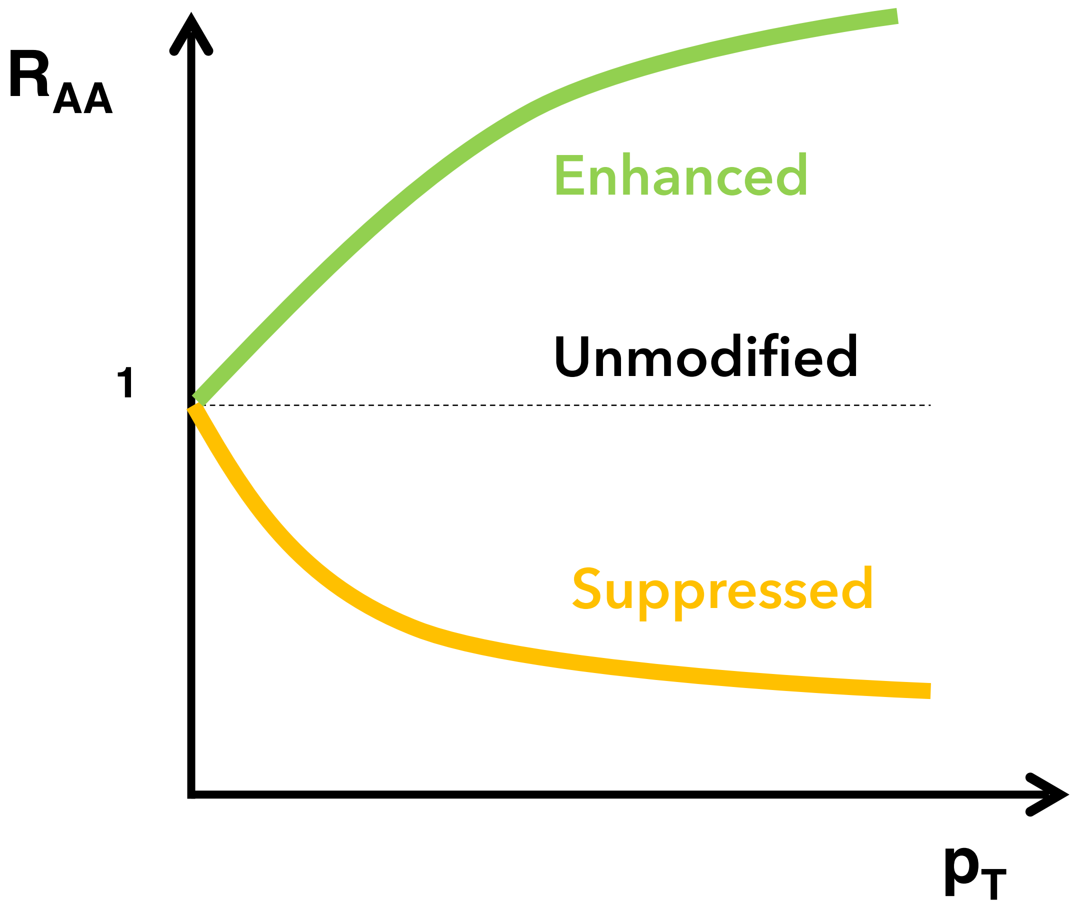


And we can relate Ncoll to charged particle multiplicity to determine centrality classes: 0 - 100% (0% is most central)





$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



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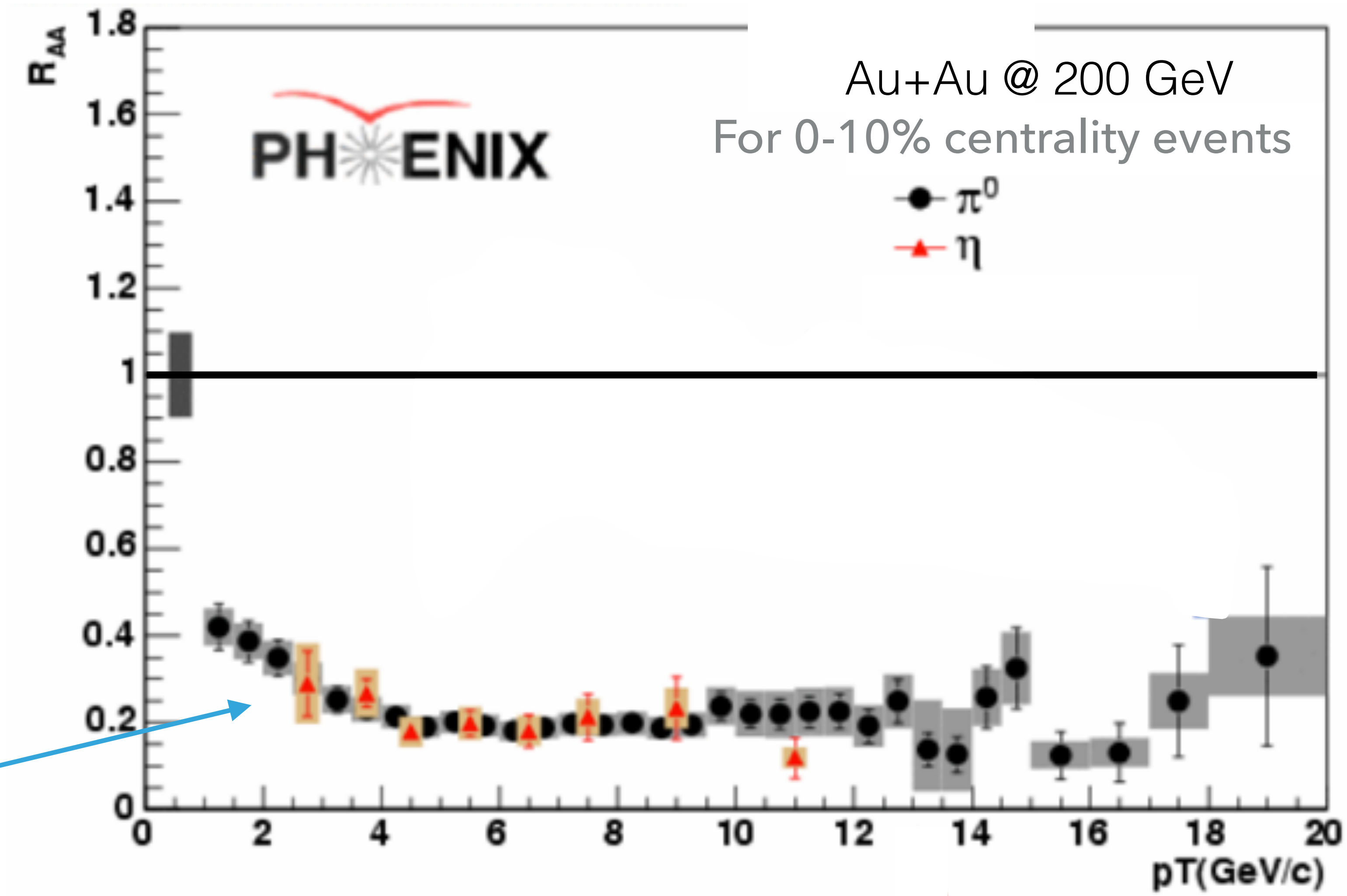


Substantial suppression across p_T of hadrons

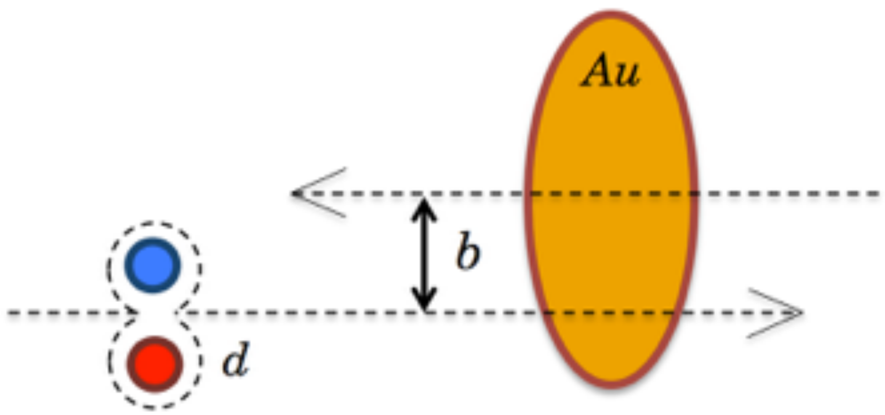
This measurement is consistent with jet quenching due to the medium.

HEAVY ION COLLISION TOPICS

JETS QUENCHING

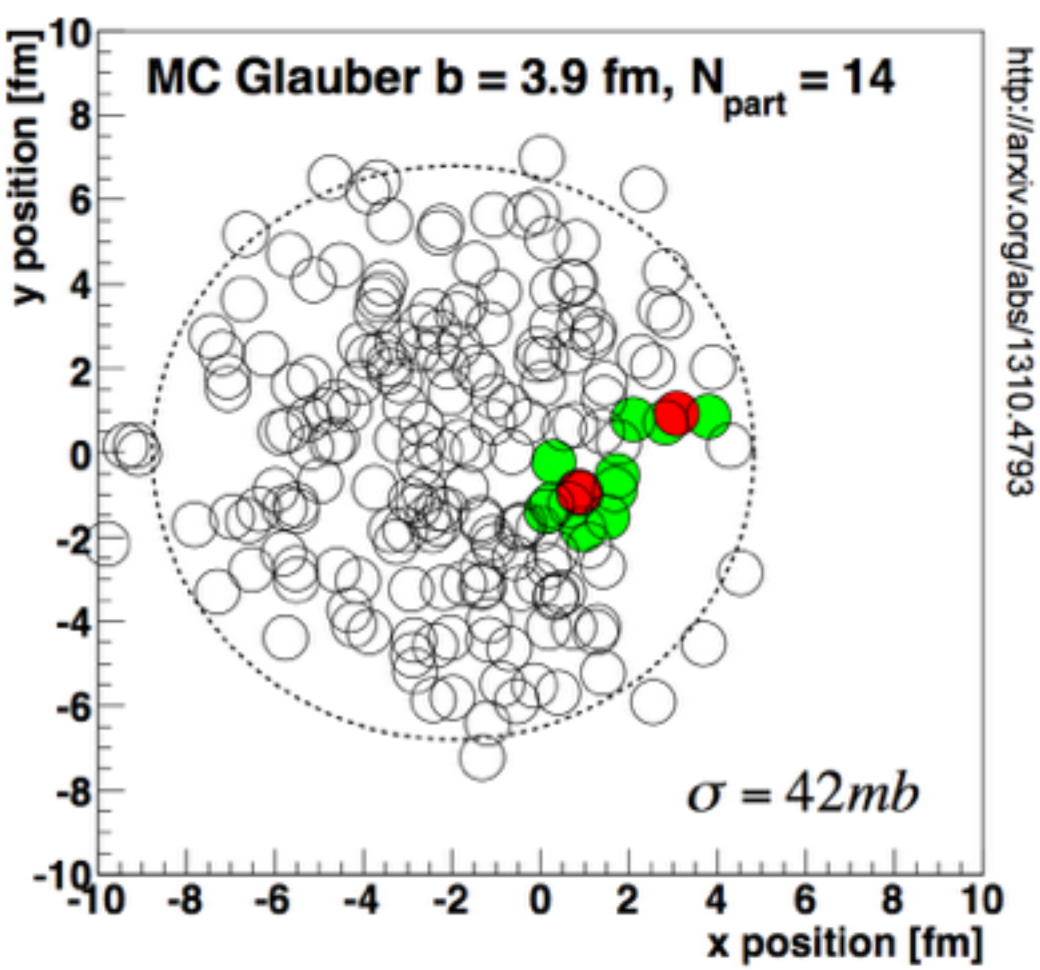
COLLECTIVE FLOW

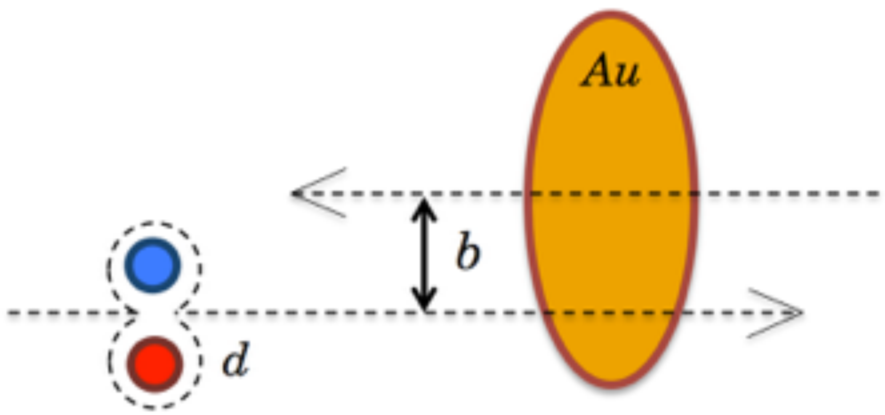
A+A COLLISIONS → SMALL SYSTEM



$$R_{\mathsf{d}A} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{\mathsf{d}A}/dp_T}{dN_{pp}/dp_T}$$

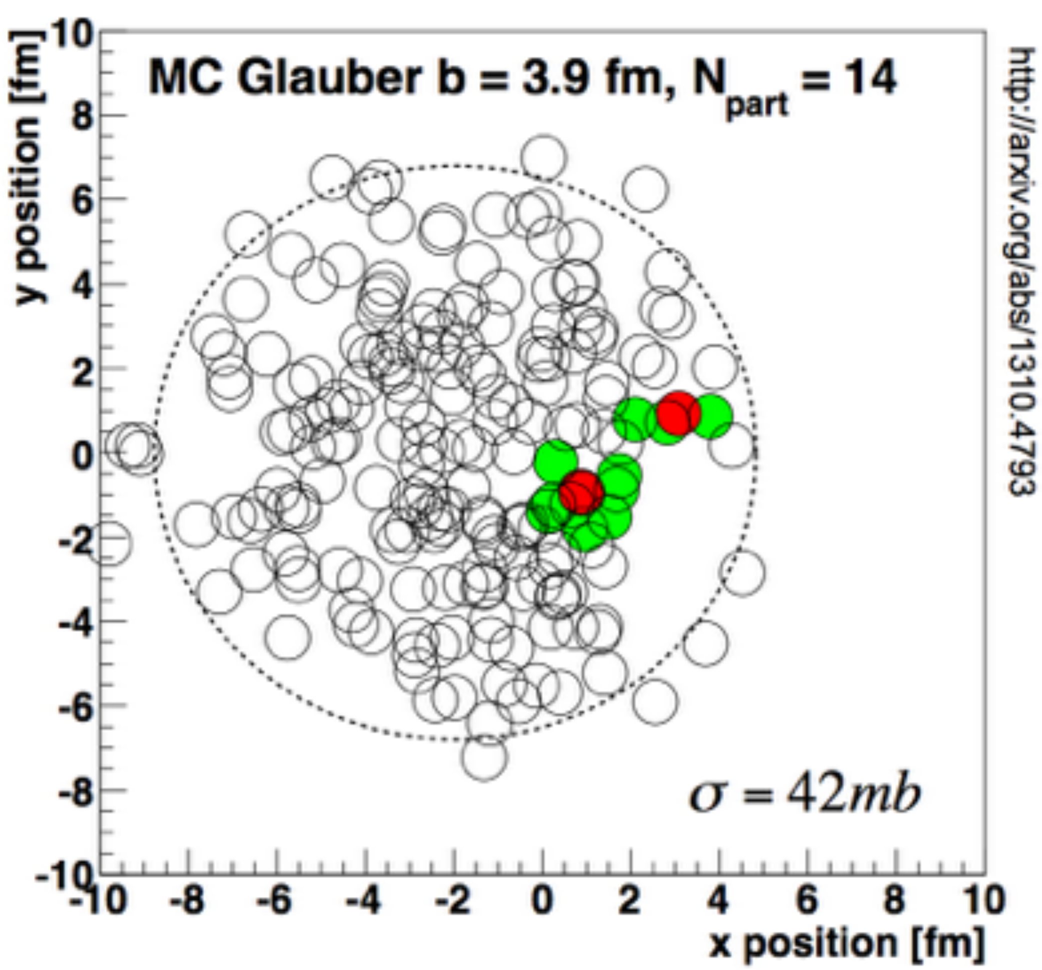
The number of binary collisions in d+Au is much lower than in Au+Au.





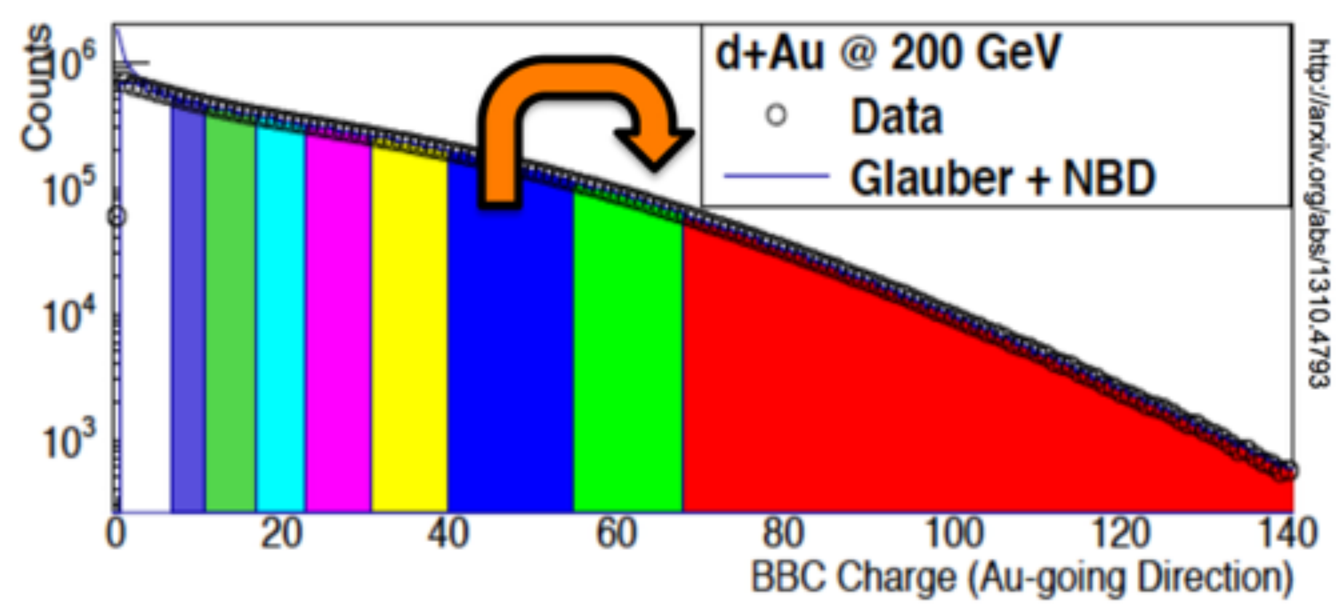
$$R_{dA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{dA}/dp_T}{dN_{pp}/dp_T}$$

The number of binary collisions in d+Au is much lower than in Au+Au.



NOT ALL BINARY COLLISIONS ARE CREATED EQUAL

Hard scattering collisions will bias the centrality of events upwards.



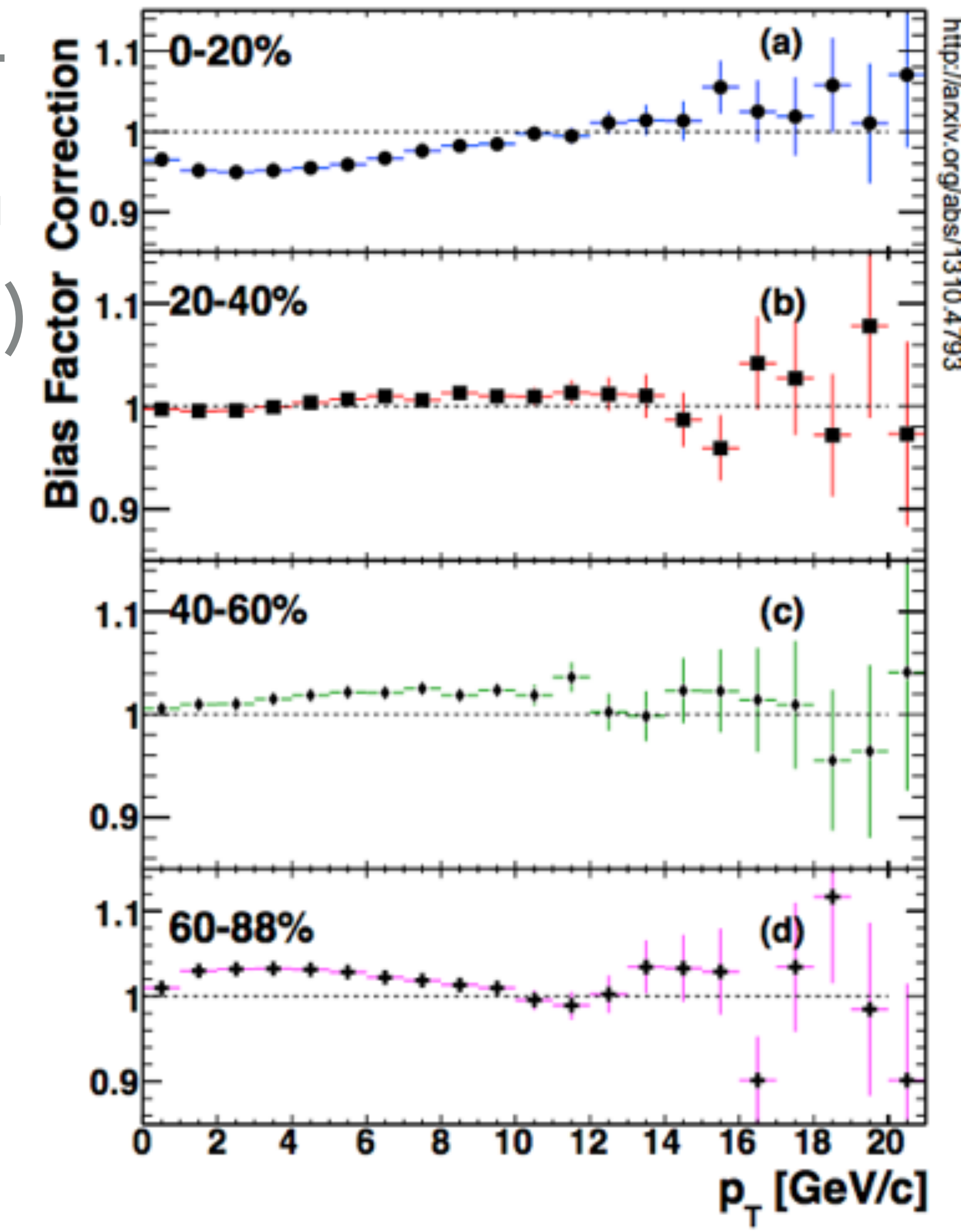
- Using the MC Glauber, we can calculate the centrality dependent bias factors

	Glauber Model
Centrality	**Bias Correction Factor**
0-20%	0.94 ± 0.01
20-40%	1.00 ± 0.01
40-60%	1.03 ± 0.02
60-88%	1.03 ± 0.06

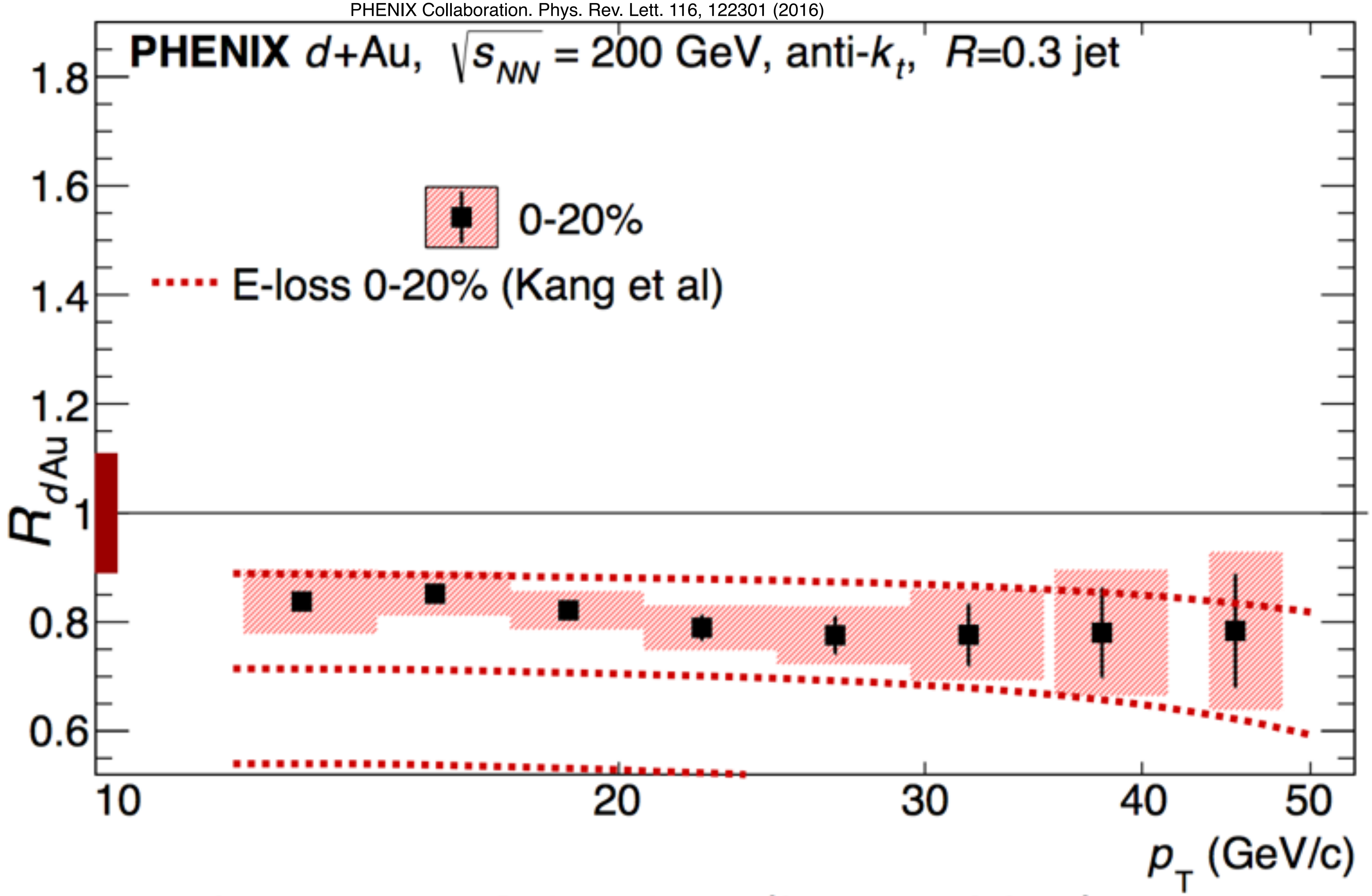
- Using the MC Glauber, we can calculate the centrality dependent bias factors
- We can go farther to calculate the pT dependent bias factors using HIJING (Heavy Ion Jet INteraction Generator)

	Glauber Model	HIJING
Centrality	**Bias Correction Factor**	**Mean Bias Factor 1< p_T <5 GeV/c**
0-20%	0.94 ± 0.01	0.951 ± 0.001
20-40%	1.00 ± 0.01	0.996 ± 0.001
40-60%	1.03 ± 0.02	1.010 ± 0.001
60-88%	1.03 ± 0.06	1.030 ± 0.001

for d+Au @ 200 GeV



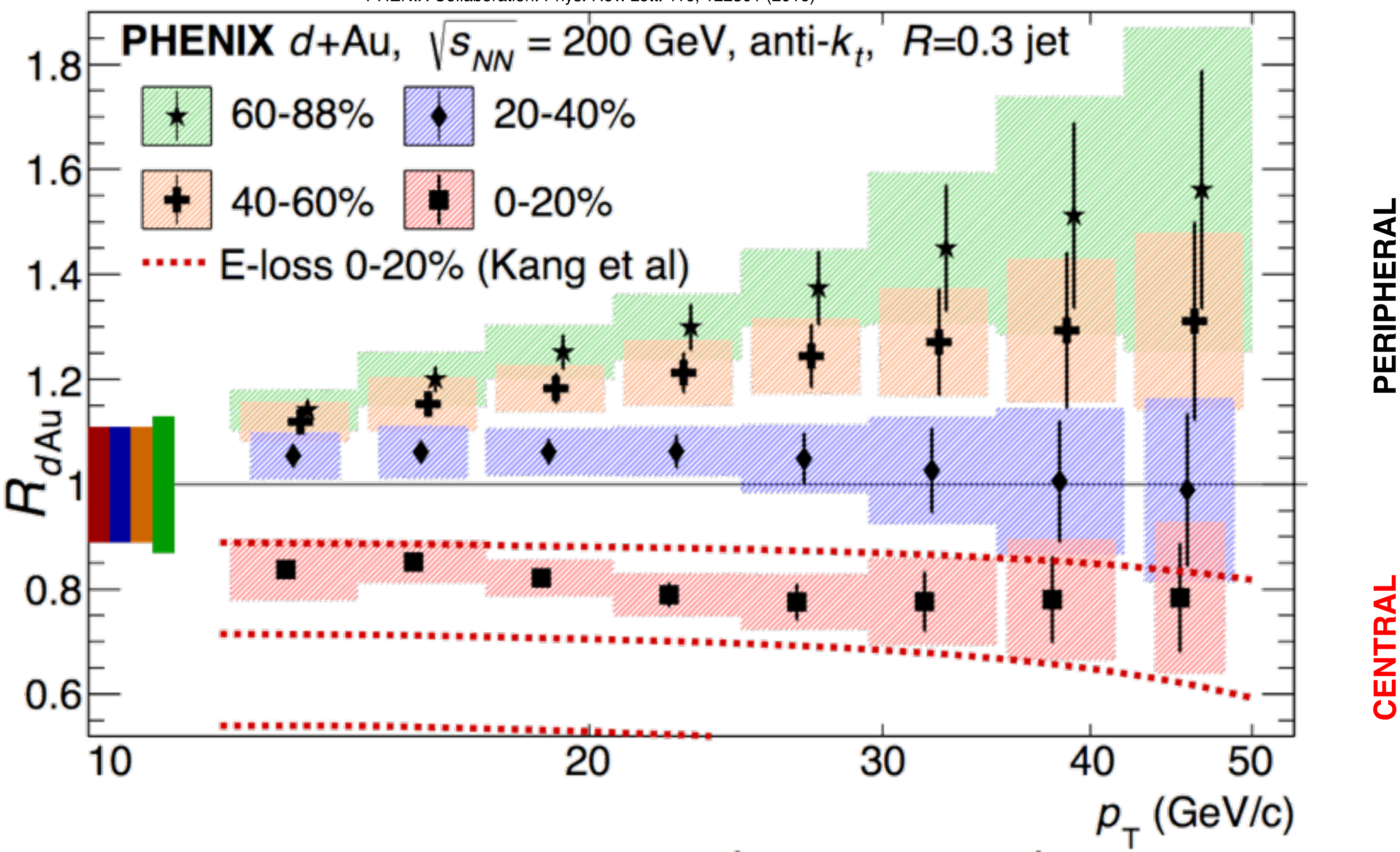
PHENIX Collaboration. Phys. Rev. Lett. 116, 122301 (2016)



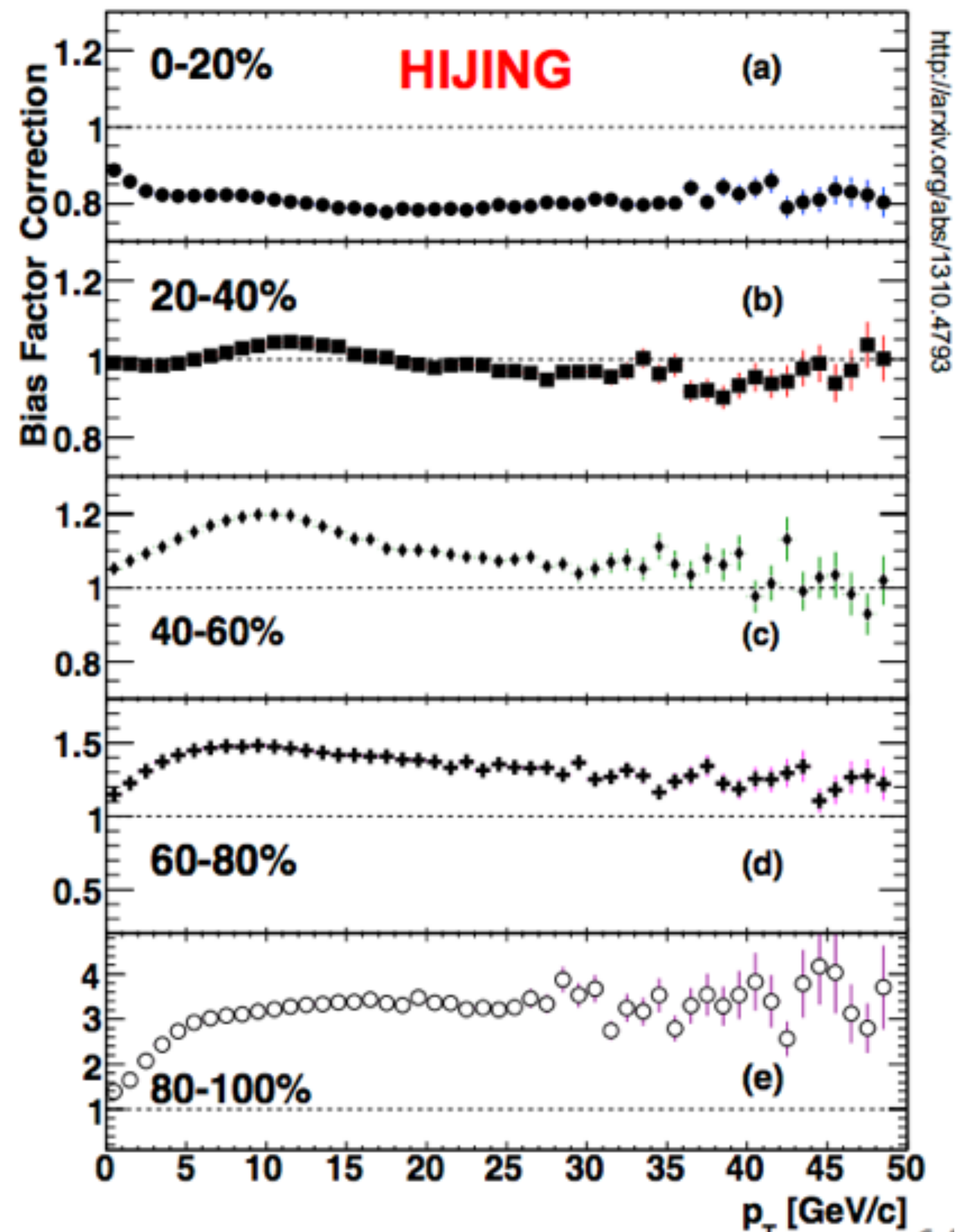
CENTRAL

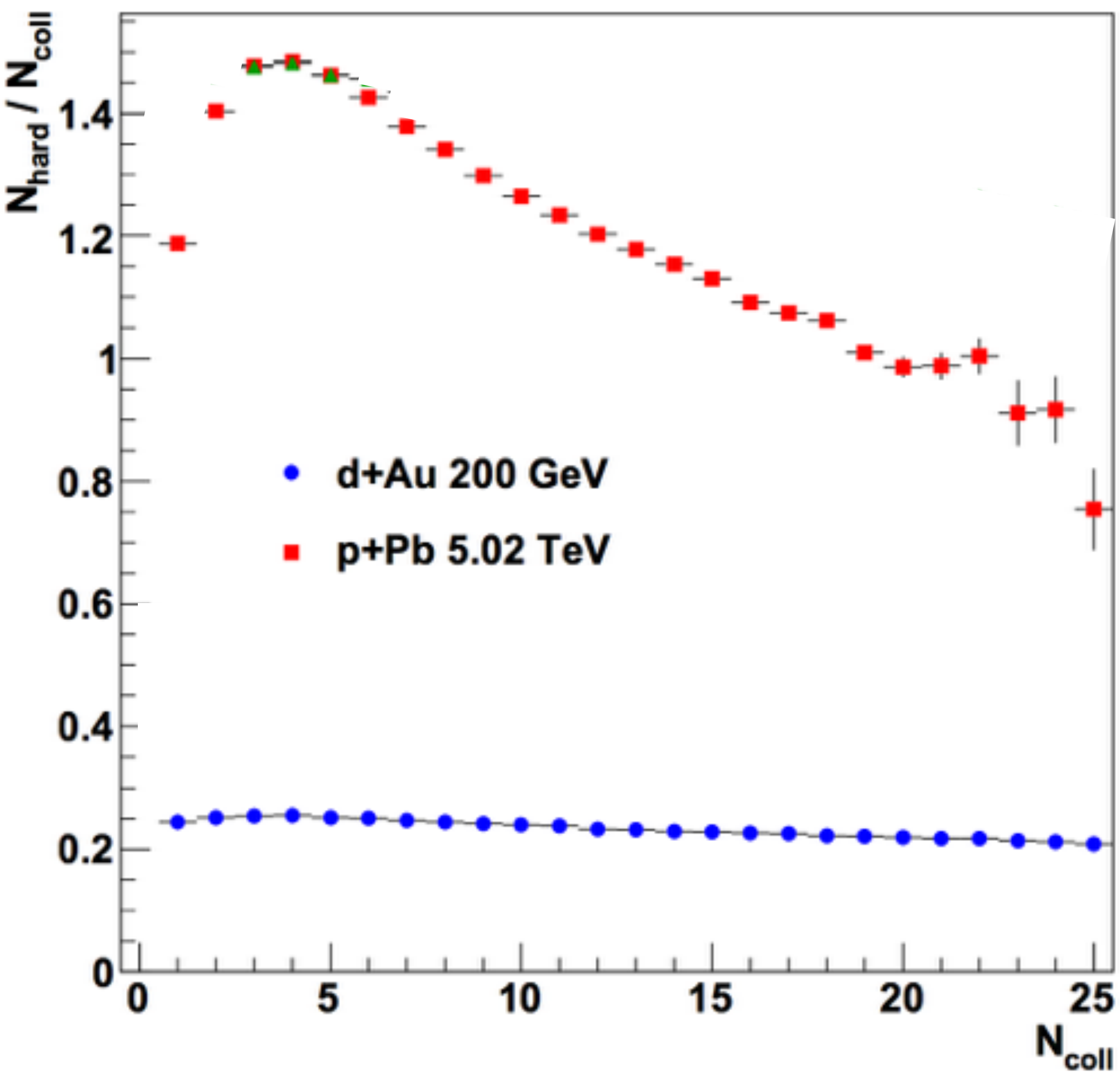
Central suppression consistent with energy loss models

PHENIX Collaboration. Phys. Rev. Lett. 116, 122301 (2016)



- We can calculate the bias factors for LHC p+Pb 5.02 TeV events.
- The centrality bias effect is much larger at LHC energies, MPI could play a role.





- Using HIJING, we can compute the number of hard scatterings per nucleon nucleon collision
- There is nearly an order of magnitude difference between the LHC and RHIC.

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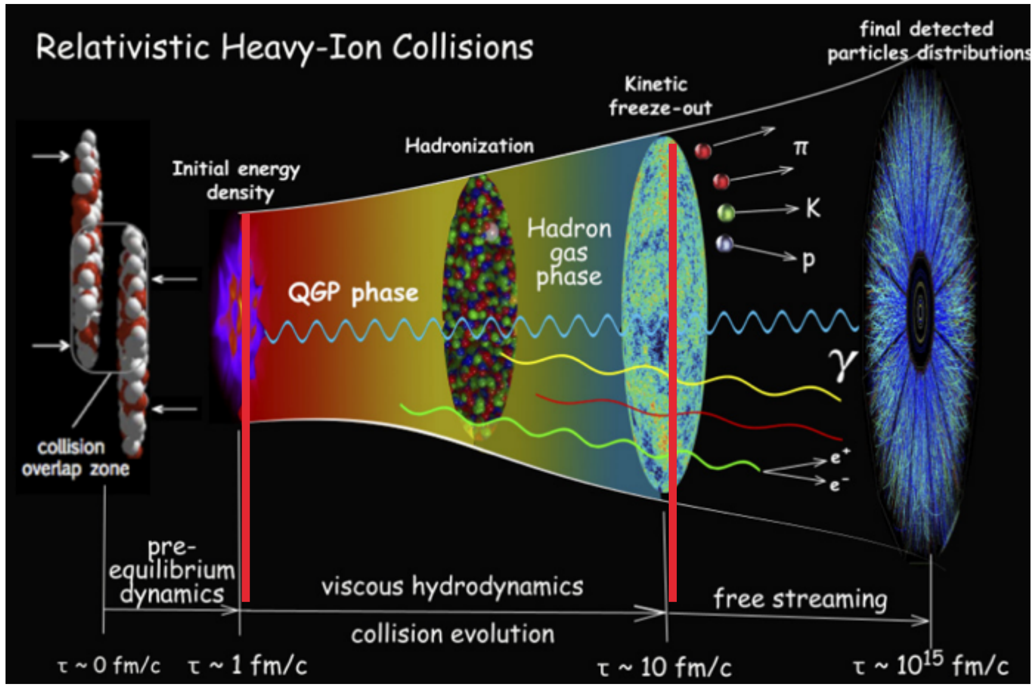

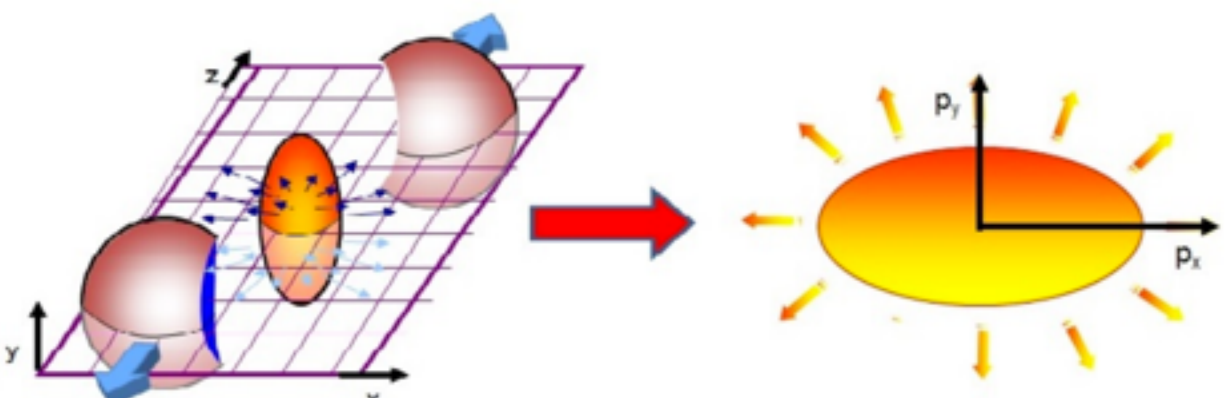

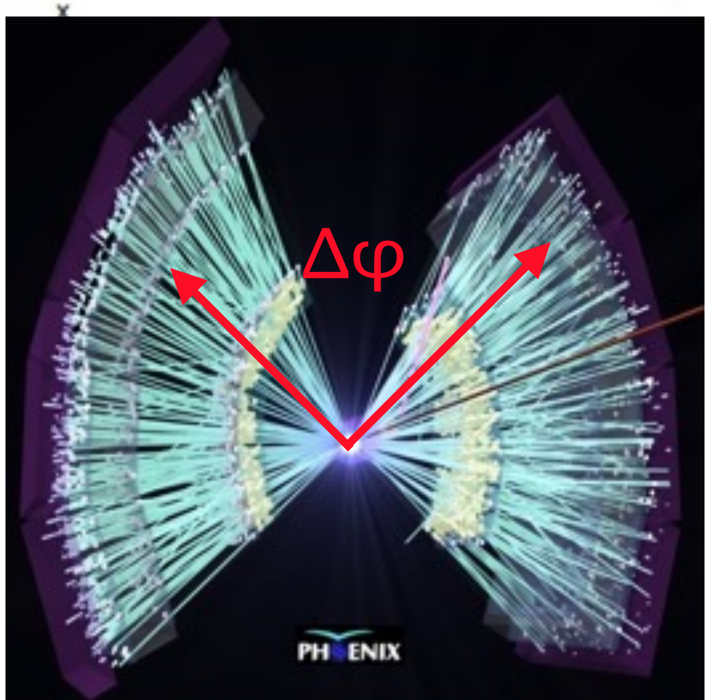

- The medium becomes locally equilibrated
- Initial state geometric anisotropy gets translated into final state momentum anisotropy.
- We can measure flow by looking at the long range angular correlations in the spray of particles

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1} 2\, v_n \cos(n[\phi - \Psi_n]),$$

v_N are Flow Coefficients

$$v_N = \frac{\langle \sum \cos N(\phi - \Psi_N) \rangle}{\mathrm{Res}(\Psi_N)}$$

Ψ_N is the generalized participant Event Plane

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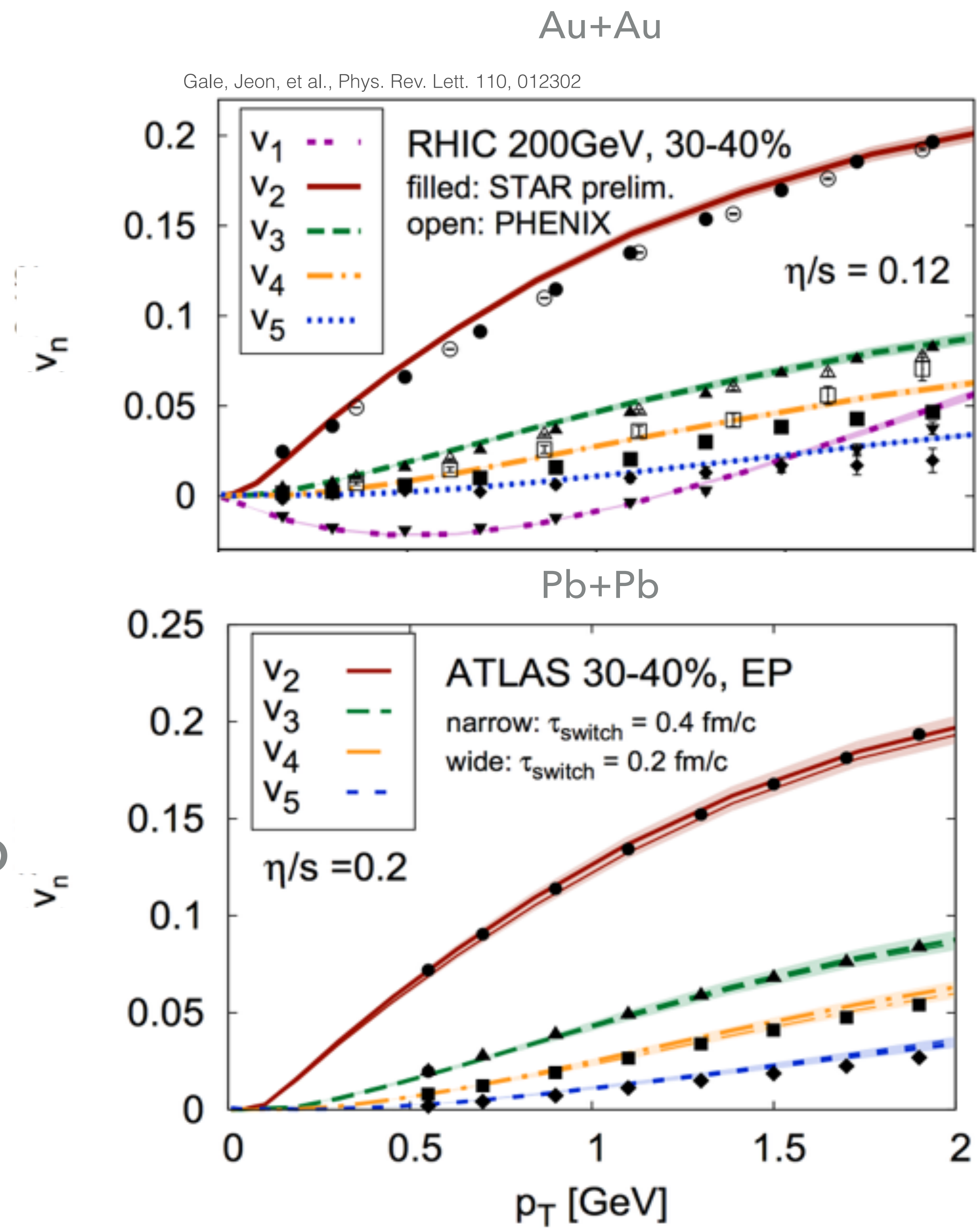
Ψ_N is the generalized participant Event Plane

- Hydrodynamics describes the data at both energies up to the 5th harmonic order.



HEAVY ION COLLISION TOPICS

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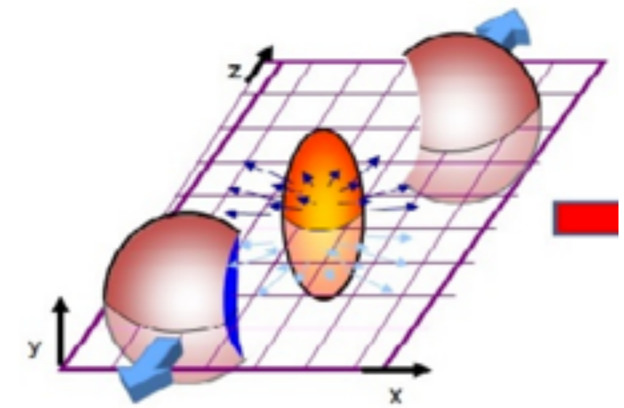
p+Au d+Au ^{3}He+Au 200 GeV

0-5% central p+Au d+Au ^{3}He+Au 200 GeV

	p+Au	d+Au	^{3}He+Au
$\langle N_{coll} \rangle$	9.7 ± 0.6	18.1 ± 1.2	26.1 ± 2.0
$\langle N_{part} \rangle$	10.7 ± 0.6	17.8 ± 1.2	25.1 ± 1.6
Glauber $\langle \varepsilon_2 \rangle$	0.23 ± 0.01	0.54 ± 0.04	0.50 ± 0.02

ε_2 is the second order initial collision eccentricity



For ideal hydrodynamics:

$v_N \propto \varepsilon_N$

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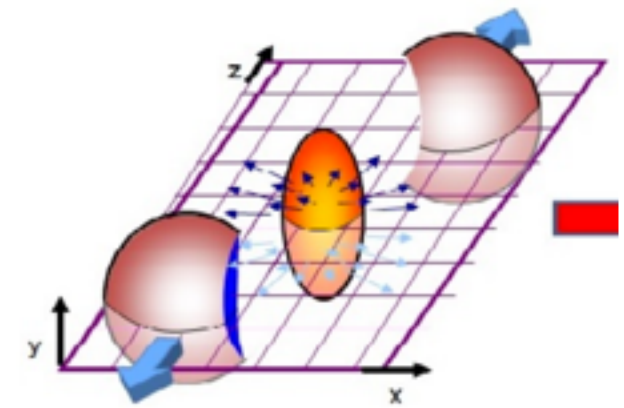

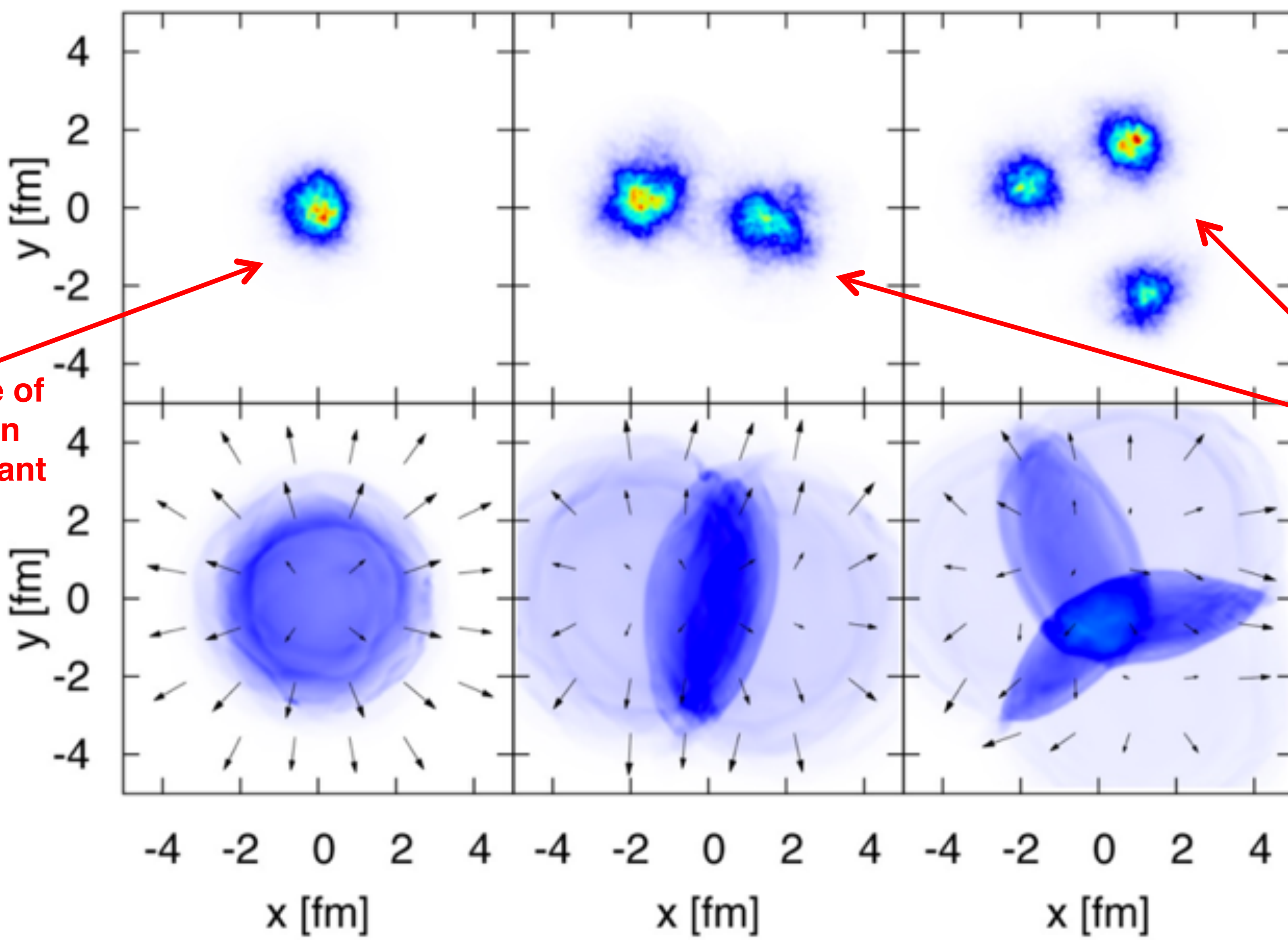

Structure of the proton is important

Geometry dominated by elliptic/triangular shape.

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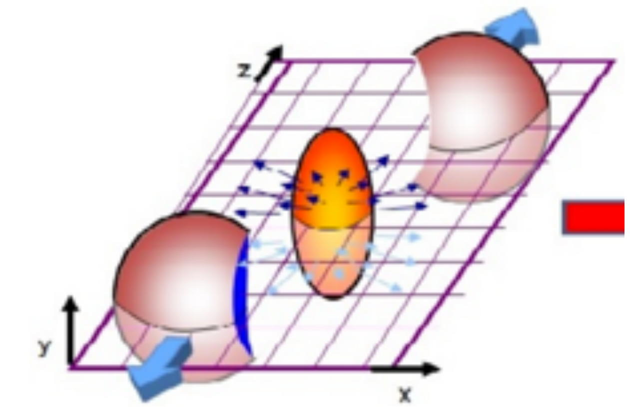

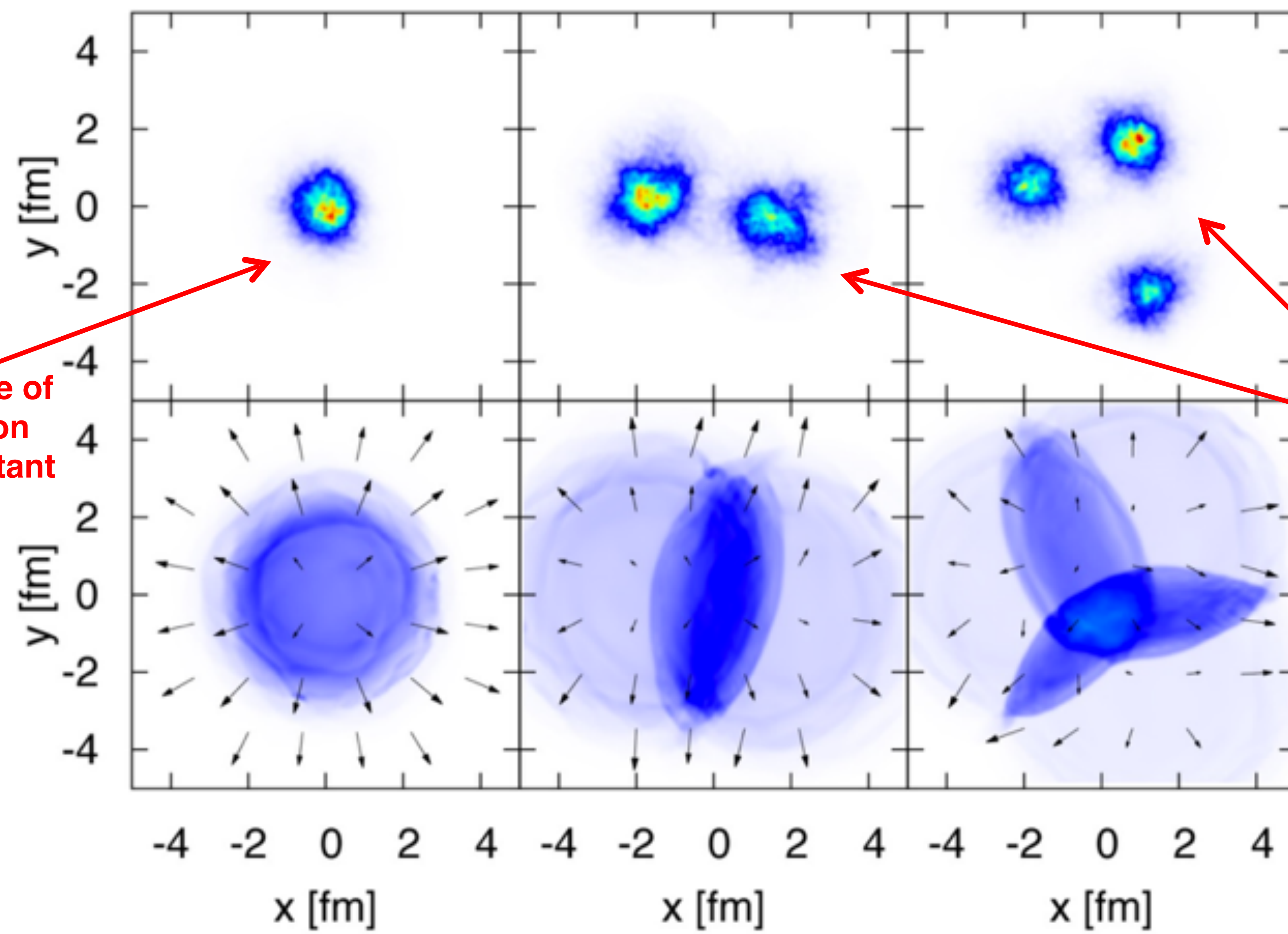

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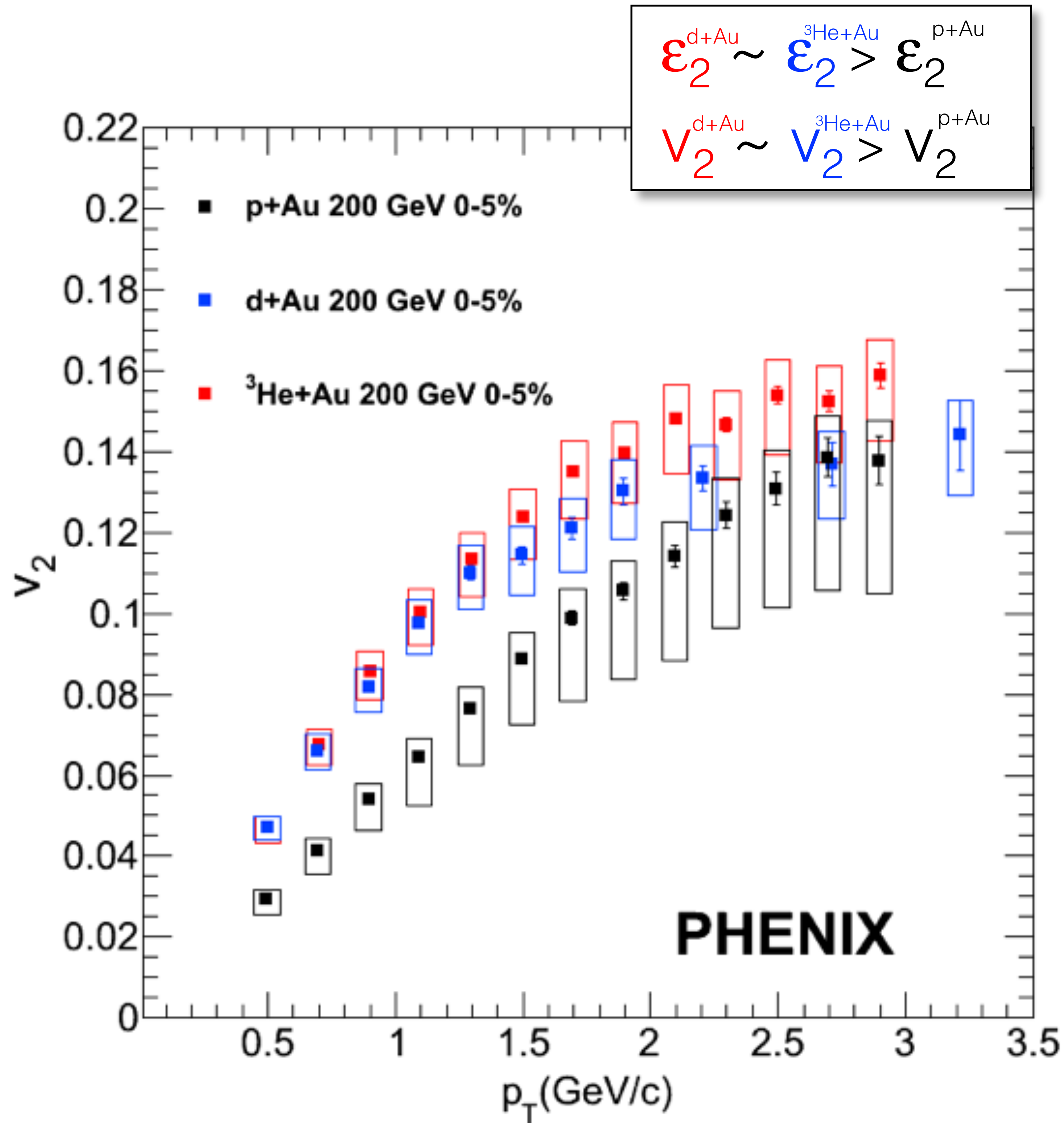
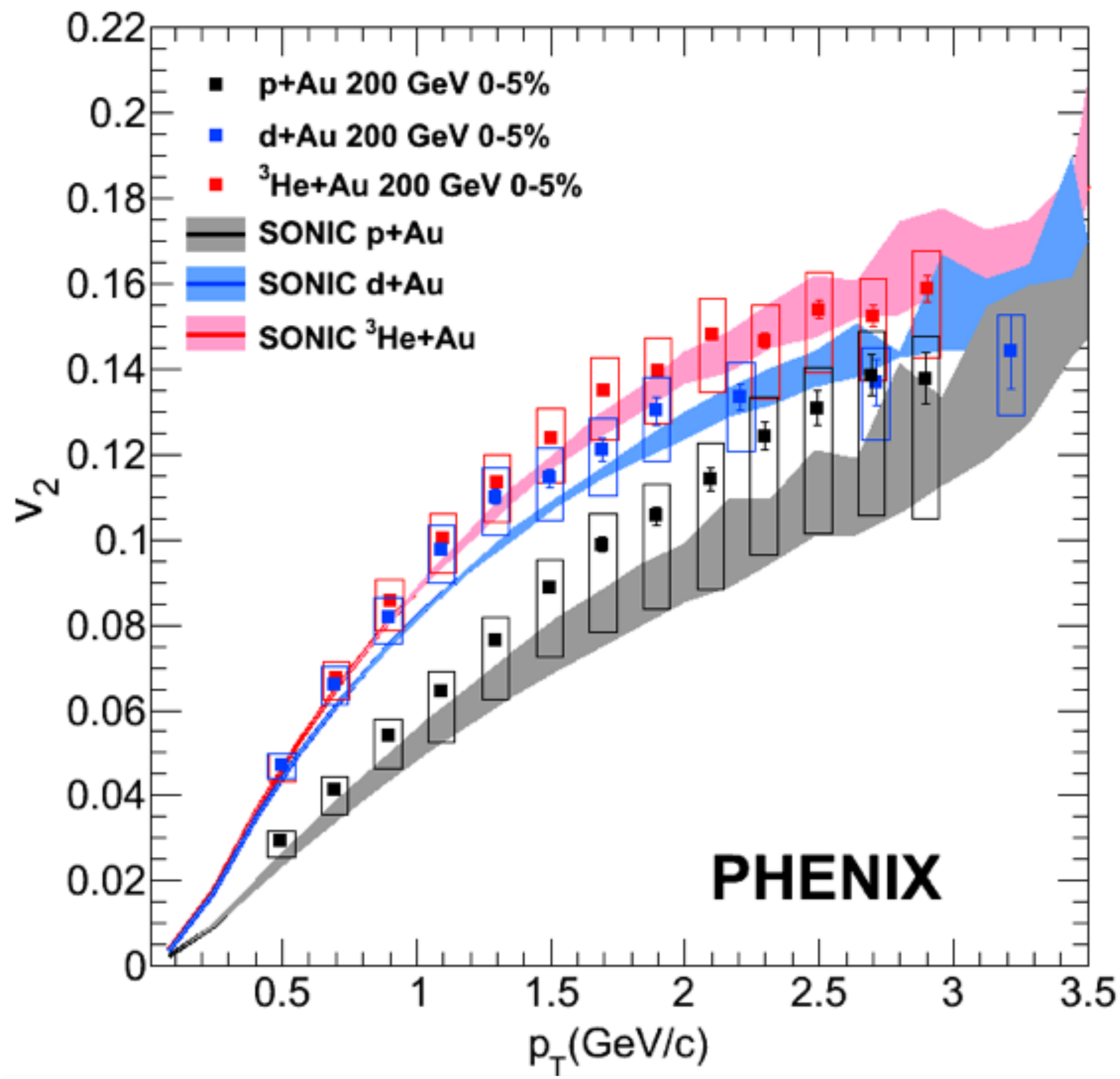
New 2016 d+Au Beam Energy Scan (200, 62, 39, 20 GeV) dataset (not in this talk)

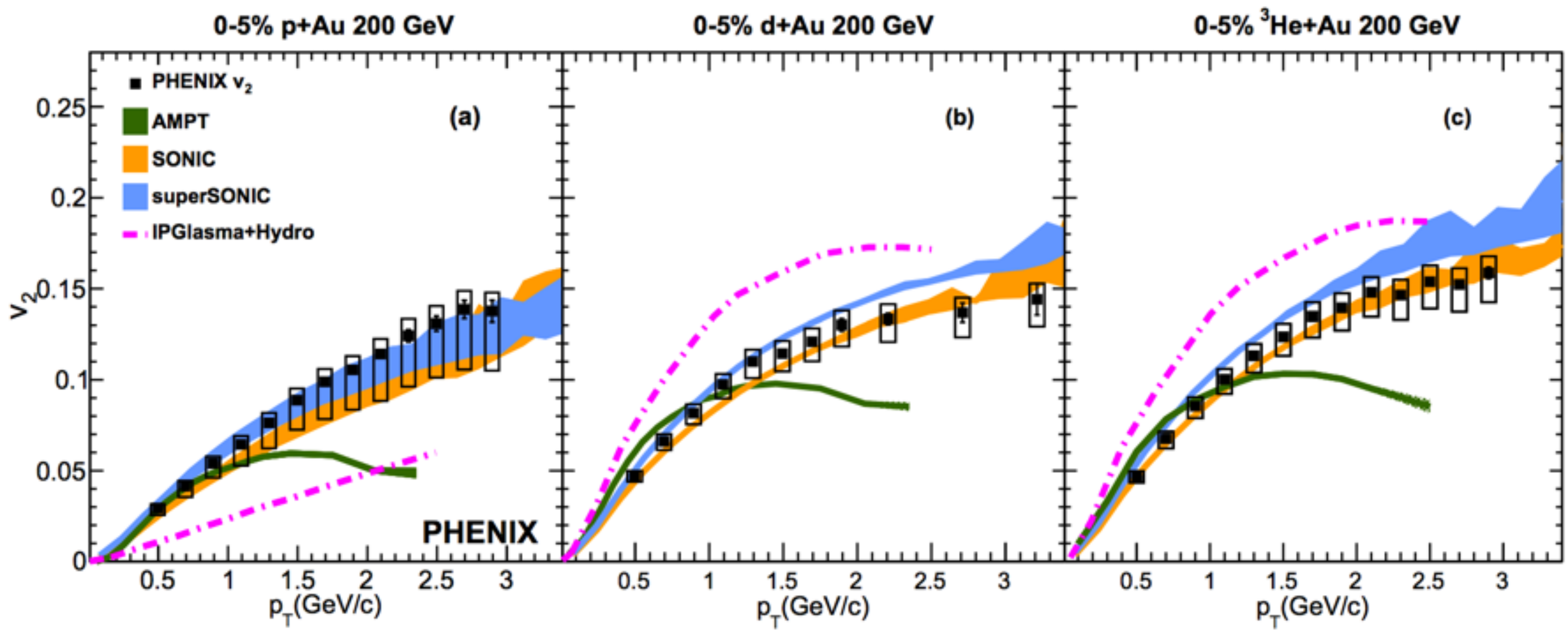
- v2 measured across three distinct small systems roughly follows Glauber ε2 scaling.
- The large non-flow systematic error on the p +Au points gives it the largest errors of all 3 systems.



- SONIC is a model which includes:
  -MC Glauber
  -Viscous Hydrodynamics
  - eta/s = 0.08
  - Hadronic cascade at T = 170 MeV
  - Centrality matching
- The data is consistent with a viscous hydrodynamic model
- The epsilon scaling is not perfect.



SONIC HAS THE LARGEST AGREEMENT

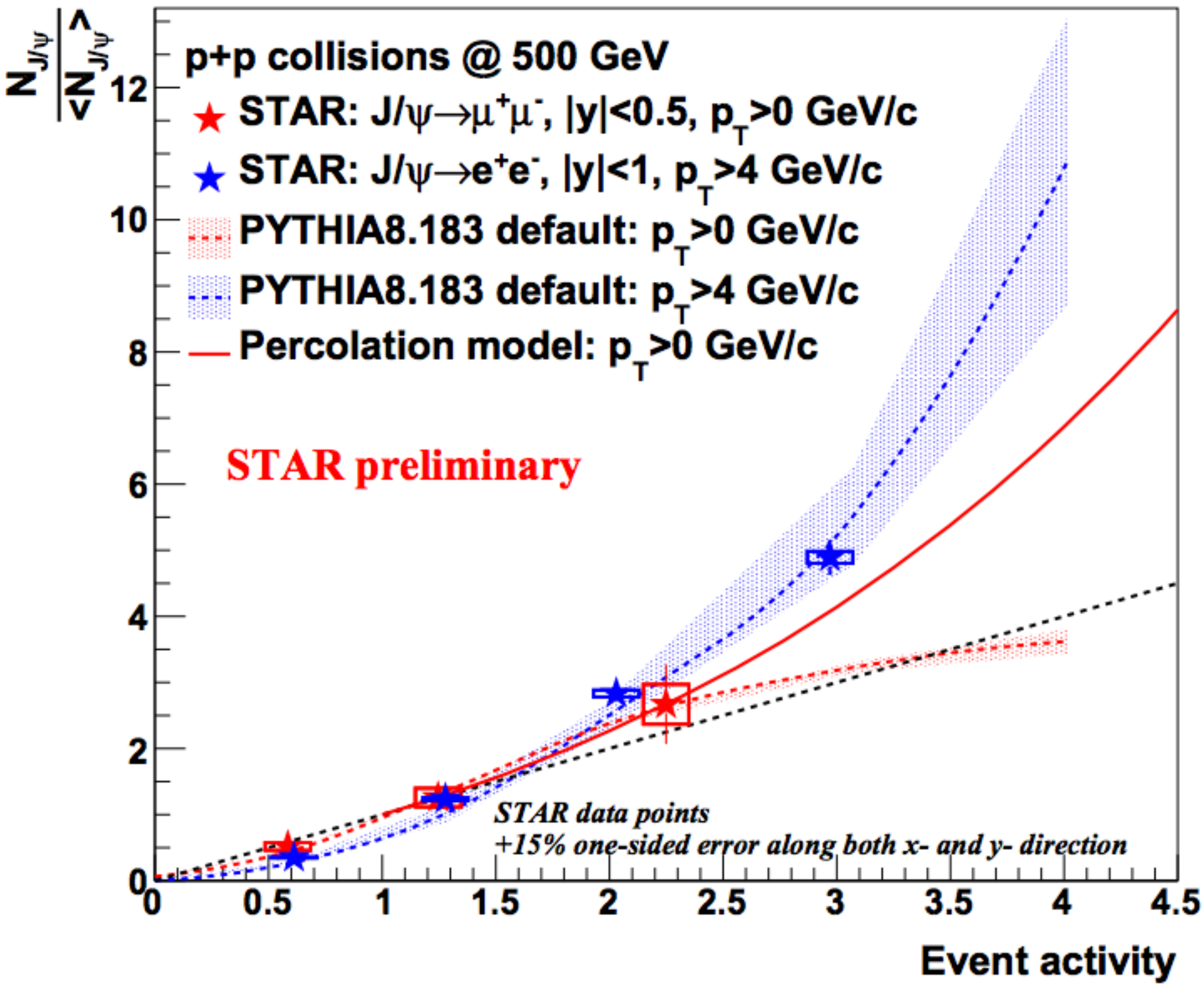


- IP Glasma (initial conditions) + Hydro can not simultaneously agree with all three systems.
- AMPT (a multi transport model) uses string-melty and a tunable parton scattering cross section.
  - Is in agreement with all three systems up to ~ 1.5 GeV
  - Does not use viscous hydrodynamics

- Centrality bias factors due to hard scattering must be calculated in small systems.
  - MPI probably plays a role in the centrality bias factors difference at the LHC in comparison to RHIC

- Substantial flow coefficients are observed in p+Au, d+Au, and He3+Au at RHIC.
  - These observations are consistent with hydrodynamic models.
  - Could be evidence of QGP

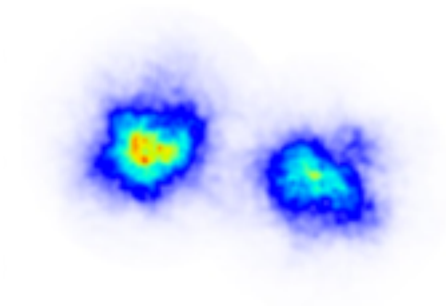
THANK YOU


p+p collisions @ 500 GeV
STAR: J/ψ→μ⁺μ⁻, |y|<0.5, p_T>0 GeV/c
STAR: J/ψ→e⁺e⁻, |y|<1, p_T>4 GeV/c
PYTHIA8.183 default: p_T>0 GeV/c
PYTHIA8.183 default: p_T>4 GeV/c
Percolation model: p_T>0 GeV/c
STAR preliminary
STAR data points
+15% one-sided error along both x- and y- direction
N_J/ψ / <N_J/ψ>
Event activity
0
2
4
6
8
10
12
0.5
1
1.5
2
2.5
3
3.5
4
4.5

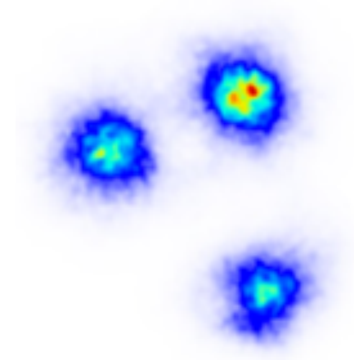
DATASET INFORMATION

- 2008 d+Au 200 GeV
  - delivered luminosity: 437 nb^{-1}
- 2014 He3+Au 200 GeV
  - delivered luminosity: 134 nb^{-1}
- 2015 p+Au 200 GeV
  - delivered luminosity: 1270 nb^{-1}
- New 2016 d+Au Beam Energy Scan (200, 62, 39, 20 GeV) dataset (not in this talk)
  - delivered luminosity: (289, 44, 7.2, 19.5) nb^{-1}

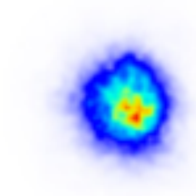
d+Au



^{3}He+Au

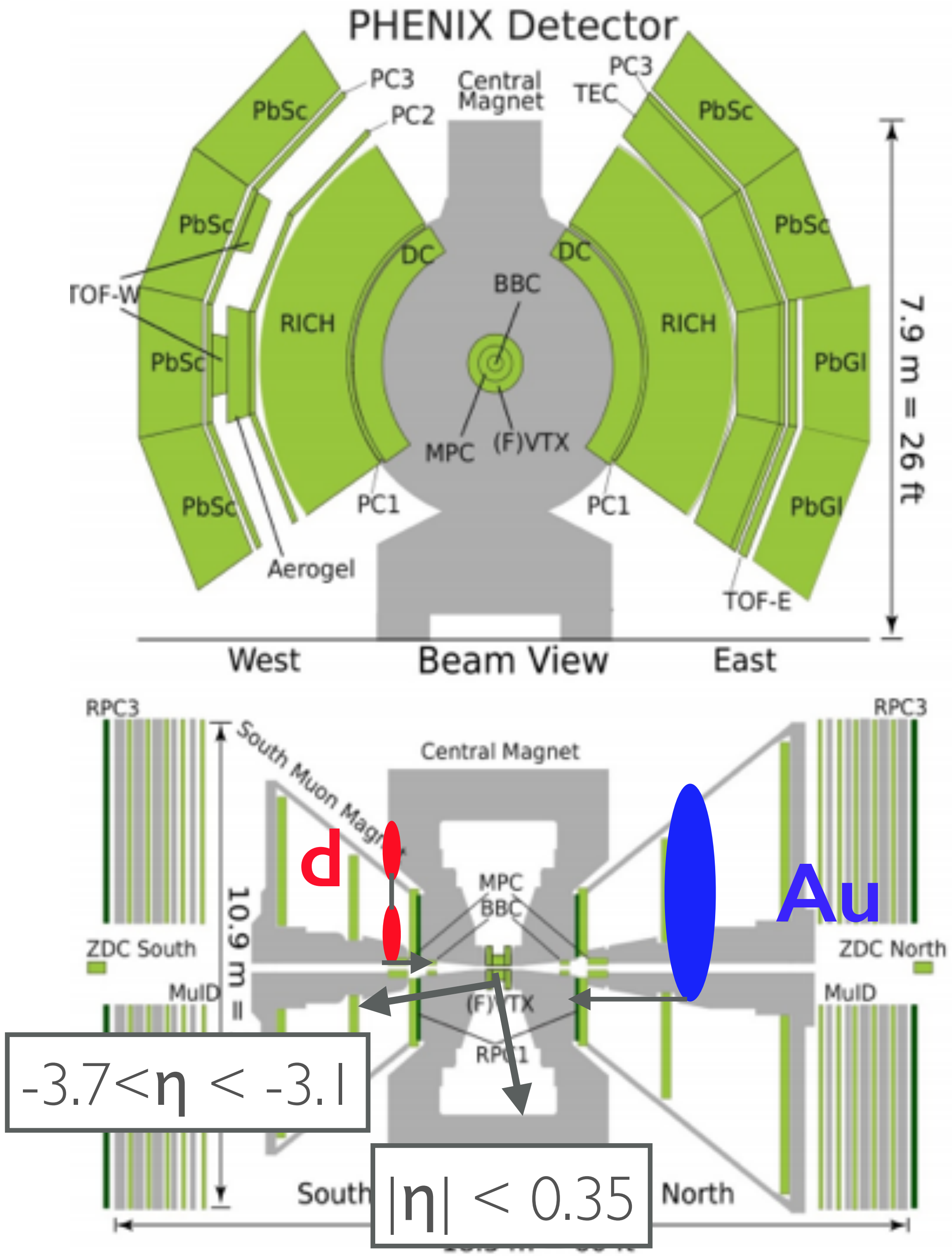


p+Au



RELEVANT DETECTORS

- Beam Beam Counter (BBC): 3.1< |η| < 3.7
  -Does minimum bias event triggering and centrality characterization
- Forward Silicon Vertex Detector (FVTX): 1< |η| < 3
  - Does precision charged particle measurements near the collision vertex
- Drift Chamber (DC): |η| < 0.35
  - Does precision charged particle tracking and momentum measurement in mid-rapiditiy

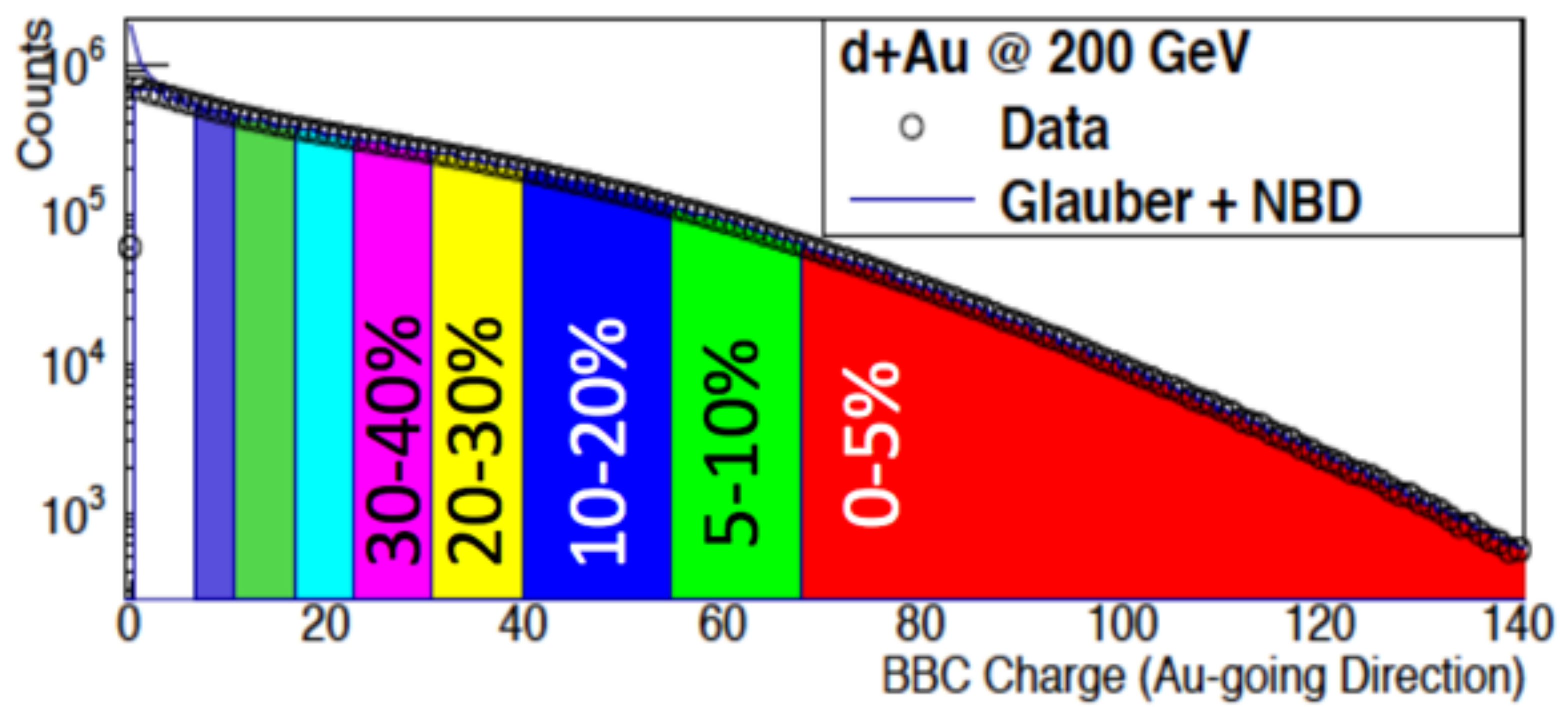


CENTRALITY RELATED TO NUMBER OF BINARY COLLISIONS

Using Negative Binomial Distribution (to model charge fluctuations):

$$NBD(x;\mu,\kappa) = \left(1+\frac{\mu}{\kappa}\right)\frac{(\kappa+x-1)!}{x!(\kappa-1)!}\left(\frac{\mu}{\mu+\kappa}\right)^x$$

And fold in the MC Glauber: $P(x) = \sum_{n=1}^{N_{binary}(max)} Gl(n) \times NBD(x;n\mu,n\kappa)$



CENTRALITY BIAS FROM HARD SCATTERING

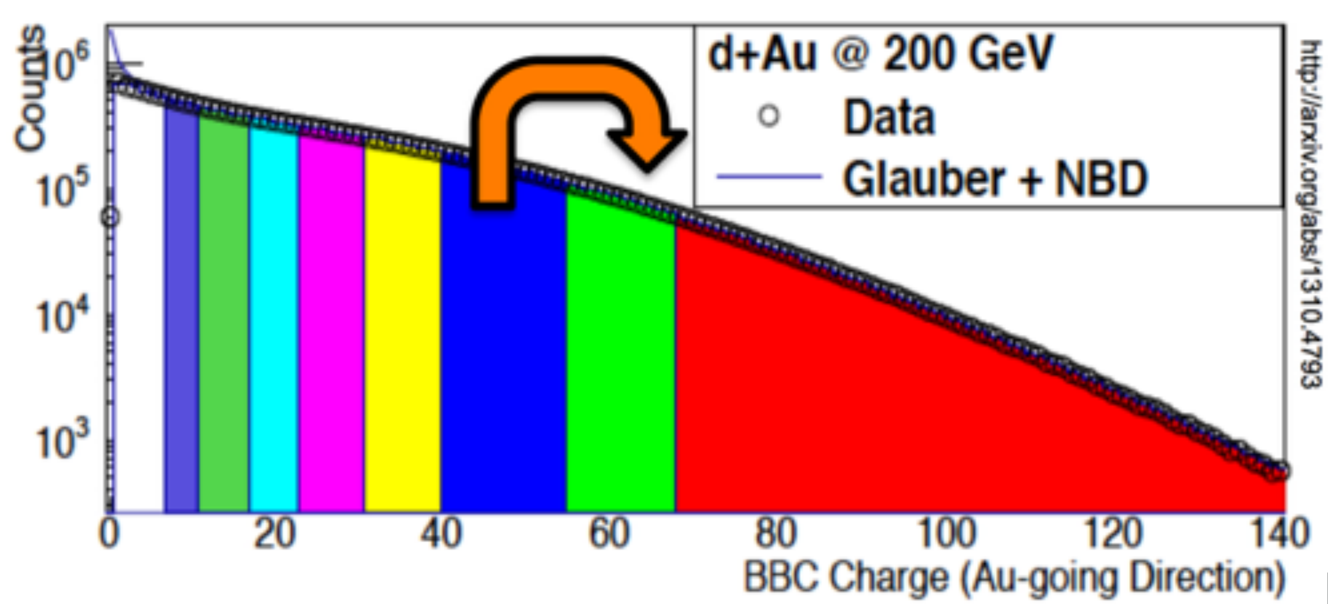
- In p+p 200 GeV, the BBC Minbias trigger fires 23% more often if there is a charged particle in mid-rapidity.
- Consider the inelastic cross section:

$$\sigma_{inel} = \sigma_{non-diff} + \sigma_{s-diff} + \sigma_{d-diff}$$

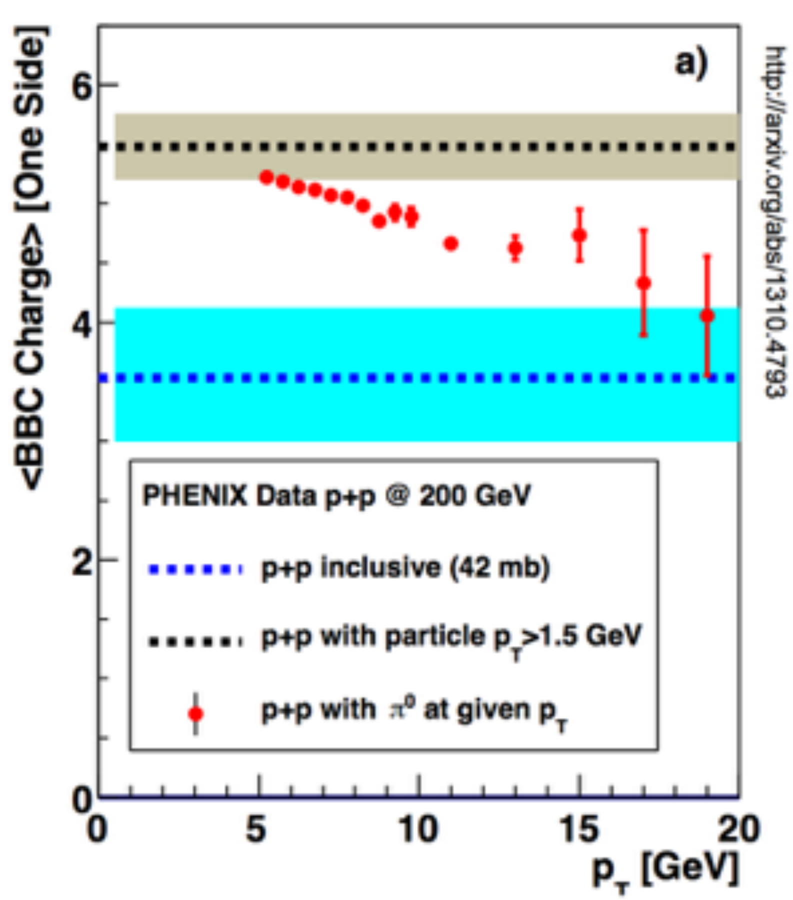
get rid of

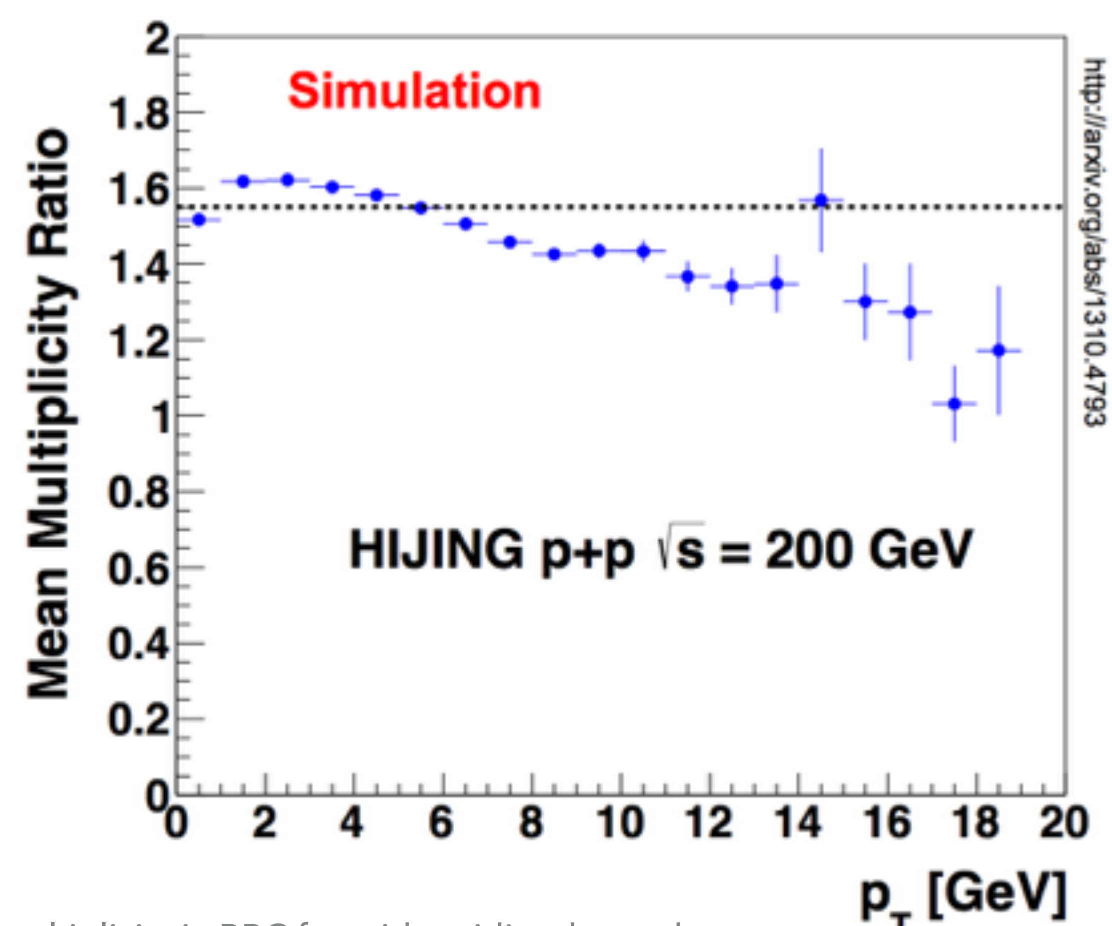
non-diffractive single-diffractive double-diffractive

- Hard scatterings tend to bias the charge into higher centrality classes.



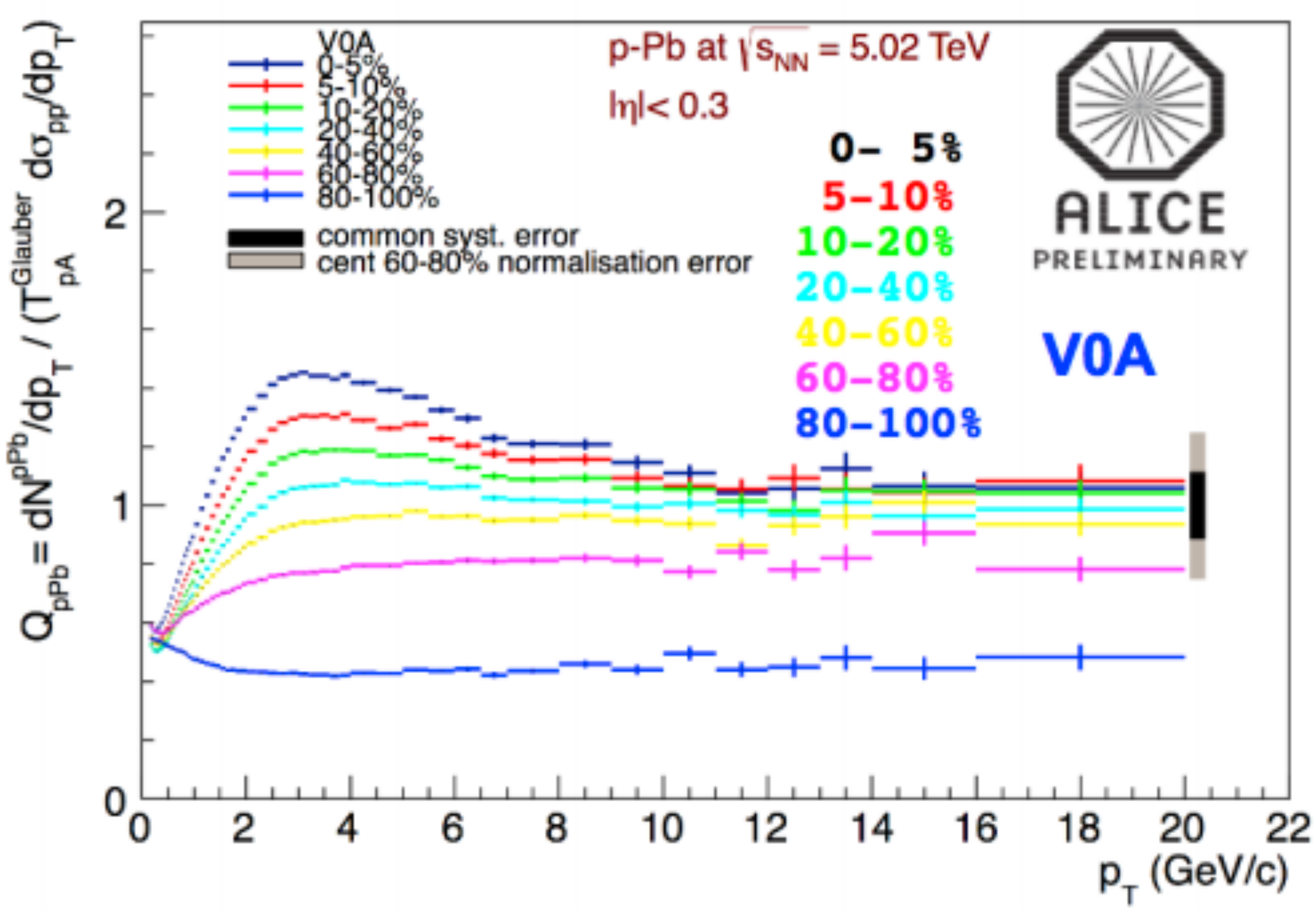
- Use HIJING (Heavy Ion Jet INteraction Generator),
  - A is a successful MC for heavy ion and p+p collisions.
- HIJING is able to reproduce a p+p bias and general pT dependence.

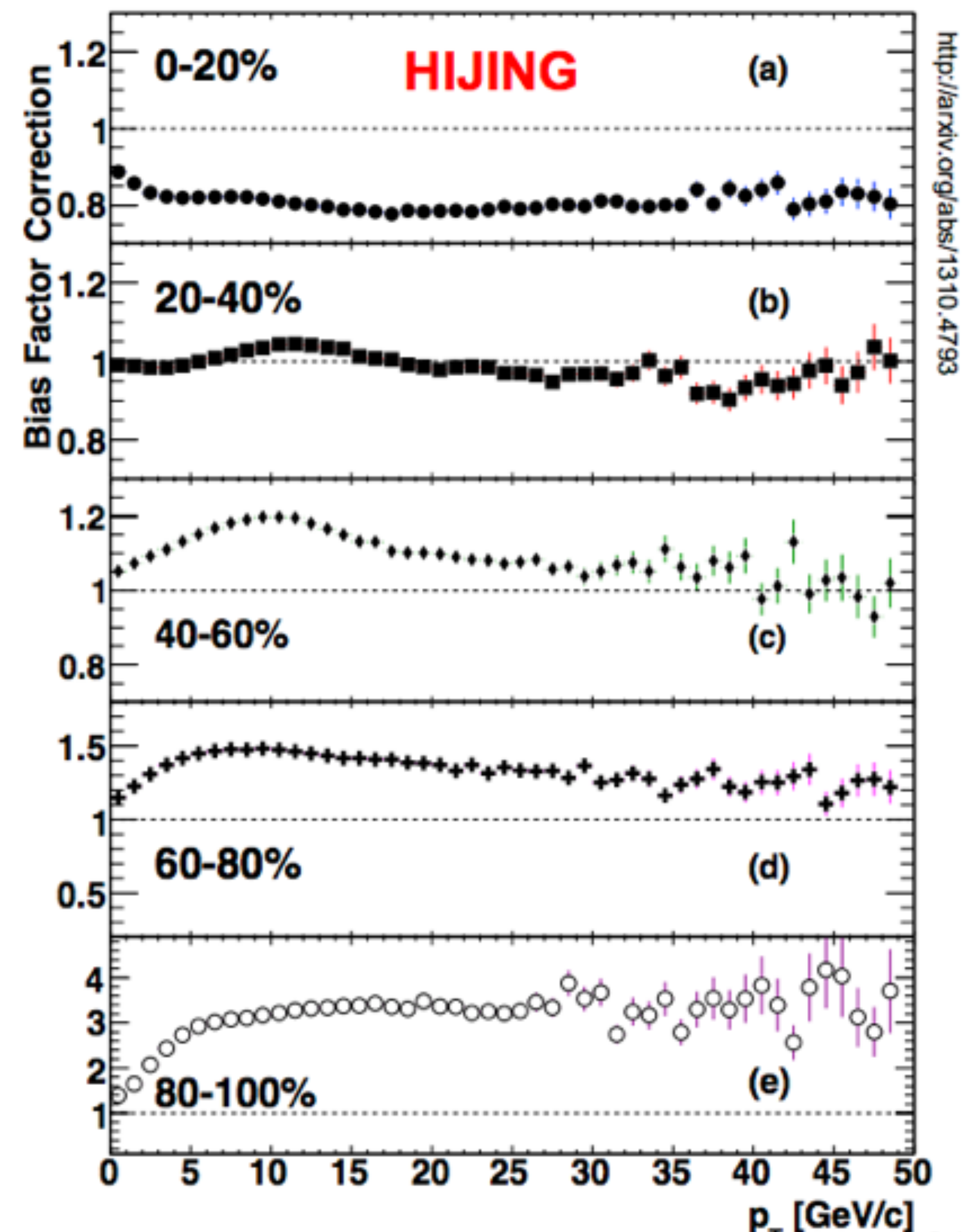




(ratio of mean multiplicity in BBC for mid rapidity charged particle triggered events to all inelastic collision events)

- Because the HIJING simulation is successful, we can apply it to LHC p+Pb 5.02 TeV events using simulated p+p 5.02 TeV events
- The centrality bias effect is larger at LHC energies, MPI could play a role.



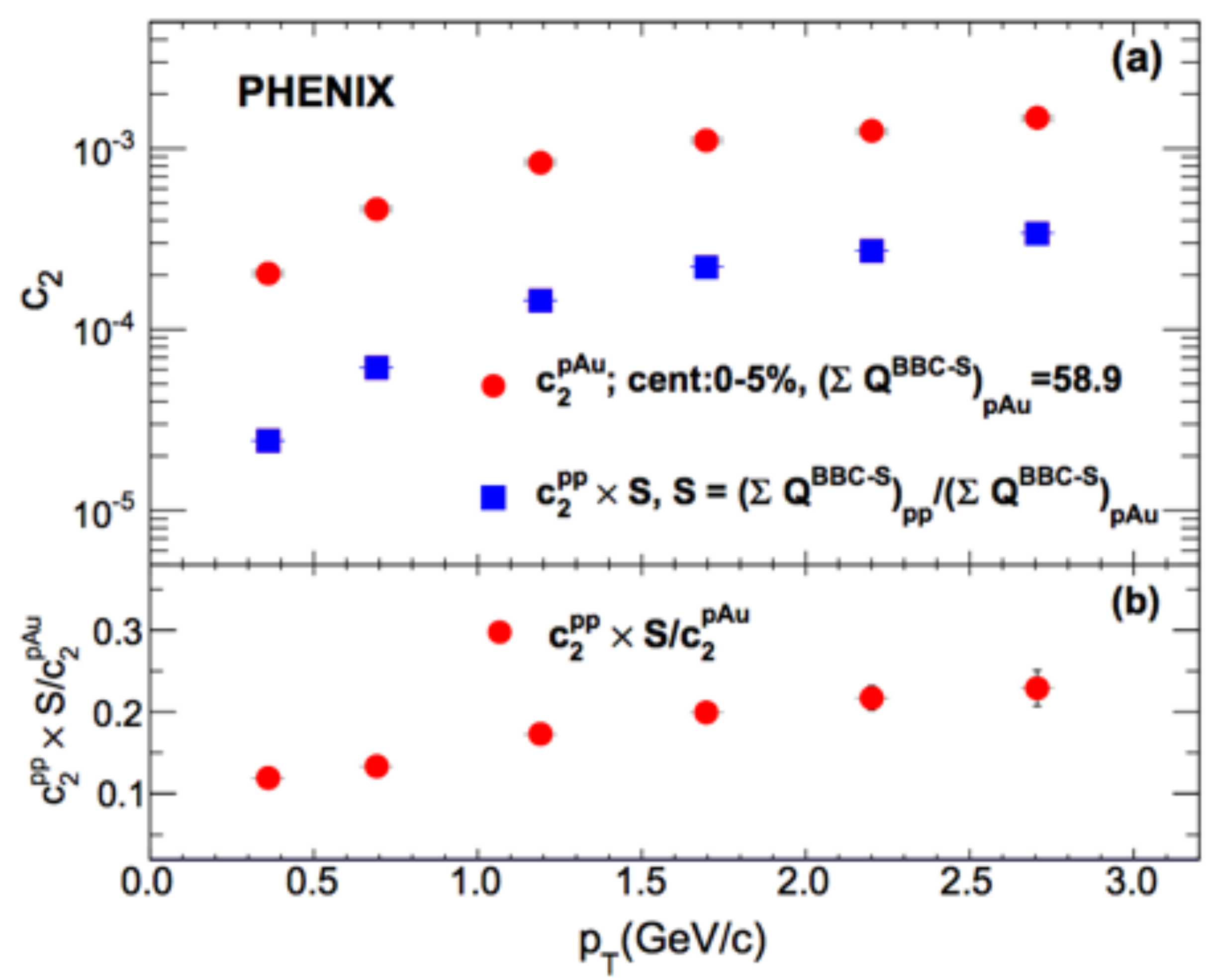


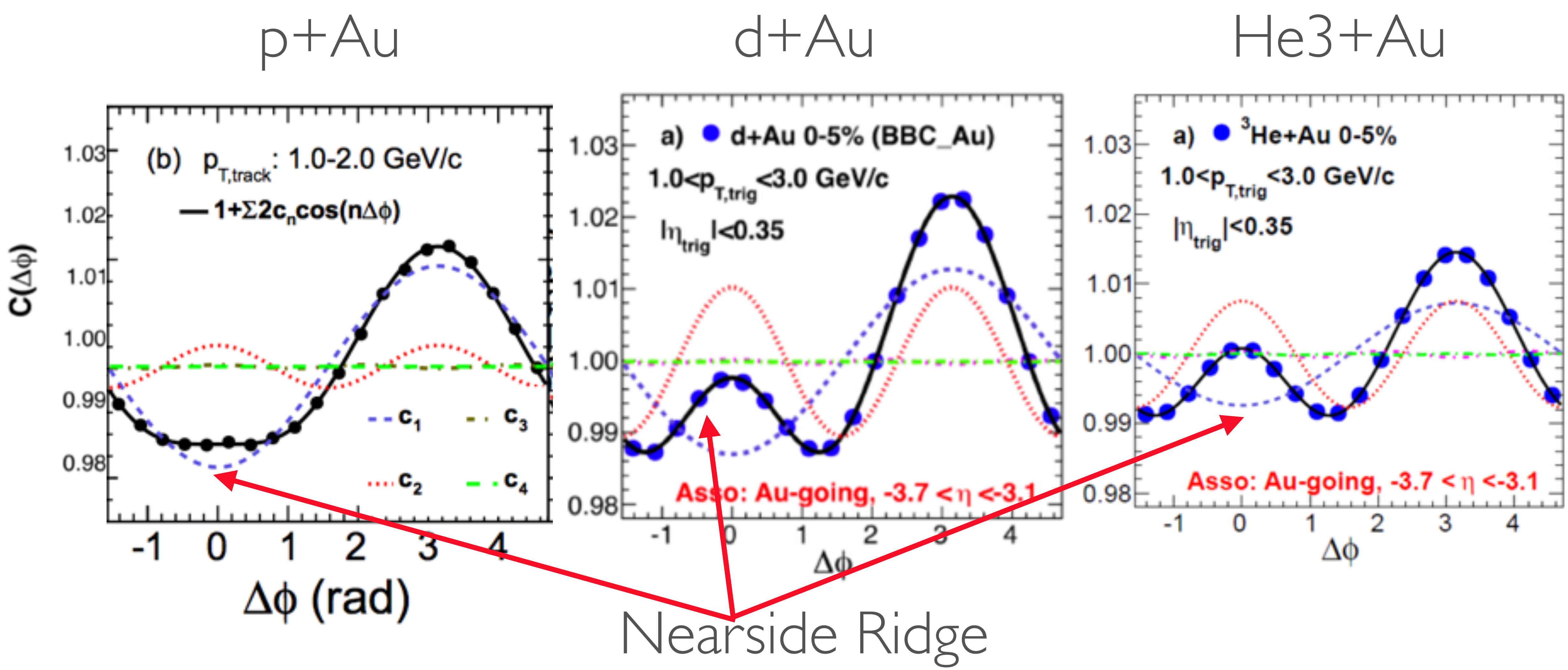
NON-FLOW IS THE DOMINANT SYSTEMATIC SOURCE

Source	Systematic Uncertainty	Type
Track Background	2.0%	A
Event Pile-up	$^{+4}_{-0}\%$	B
Non-Flow	$^{+0}_{-23}\%$	B
Beam Angle	5.0%	C
Event-Plane Detectors	3%	C

- Systematic types:
  - Type A: point-to-point uncorrelated between pT bins
  - Type B: point-to-point correlated
  - Type C: overall normalization uncertainty
- Non-flow is estimated using p+p 200 GeV c2 measurements scaled down by the mean BBC south (Au going direction) charge ratio.
- There are other methods of estimating non-flow contributions, but it's not clear which is preferable.

p+Au @ 200 GeV




p+Au
d+Au
He3+Au
(b) $p_{T,track}$: 1.0-2.0 GeV/c
— $1+\Sigma 2c_n\cos(n\Delta\phi)$
c_1
c_2
c_3
c_4
$C(\Delta\phi)$
$\Delta\phi$ (rad)
a) d+Au 0-5% (BBC_Au)
$1.0<p_{T,trig}<3.0$ GeV/c
$|\eta_{trig}|<0.35$
Asso: Au-going, $-3.7<\eta<-3.1$
$\Delta\phi$
a) ^{3}He+Au 0-5%
$1.0<p_{T,trig}<3.0$ GeV/c
$|\eta_{trig}|<0.35$
Asso: Au-going, $-3.7<\eta<-3.1$
$\Delta\phi$
Nearside Ridge