9th International Workshop
on Multiple Partonic Interactions at the LHC
@Shimla India

System size dependence of high pT hadron production at RHIC-PHENIX

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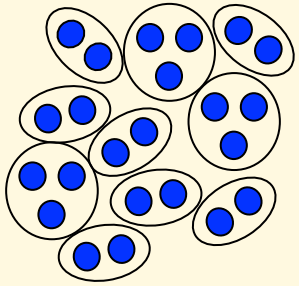
Quark gluon plasma (QGP)

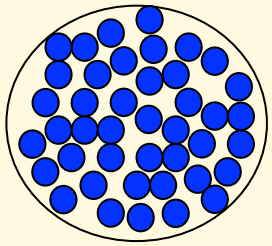
The purpose of our experiment
（1）Create QGP by HIC – done
（2）Understand the QGP – on going

Heavy “Nucleus – Nucleus” collisions

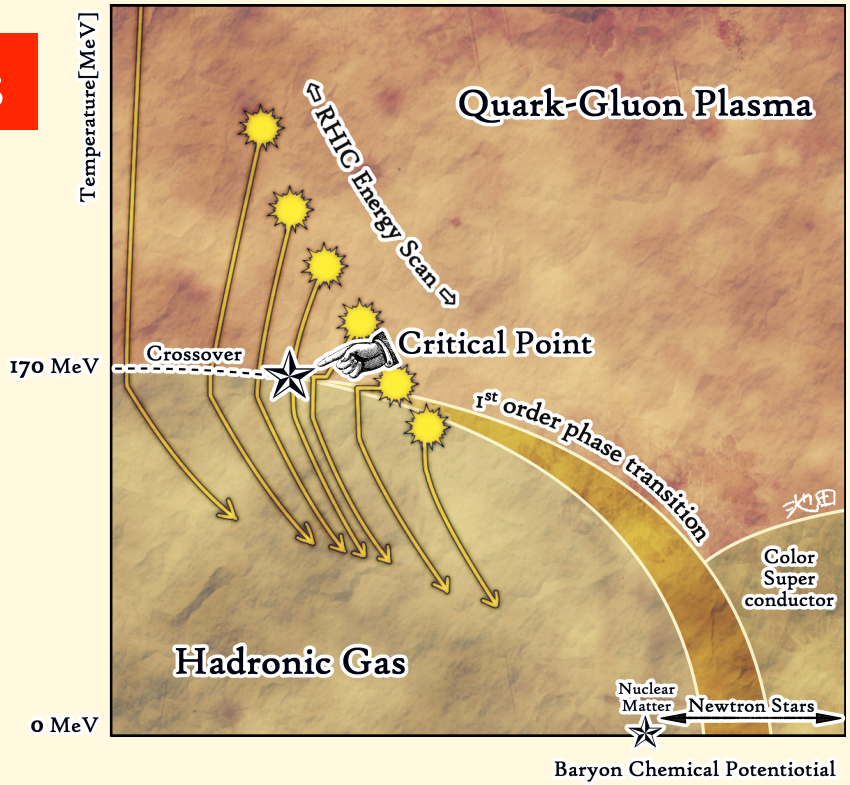
hadron phase



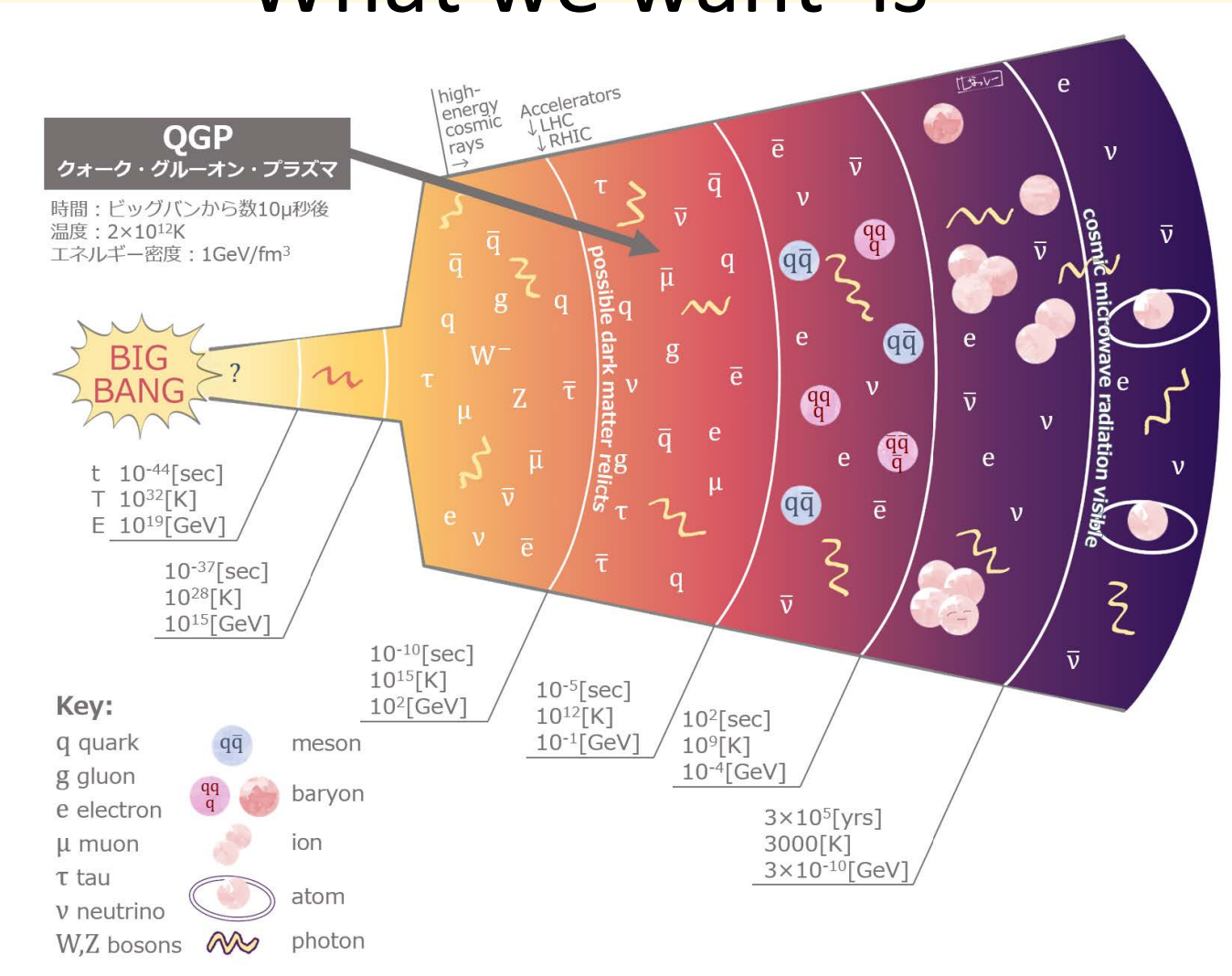
QGP phase



Expectation : weakly interacted like gas
RHIC results : strongly coupled like liquid



What we want is



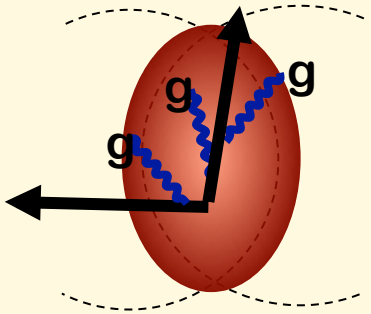
Understanding of the early universe.

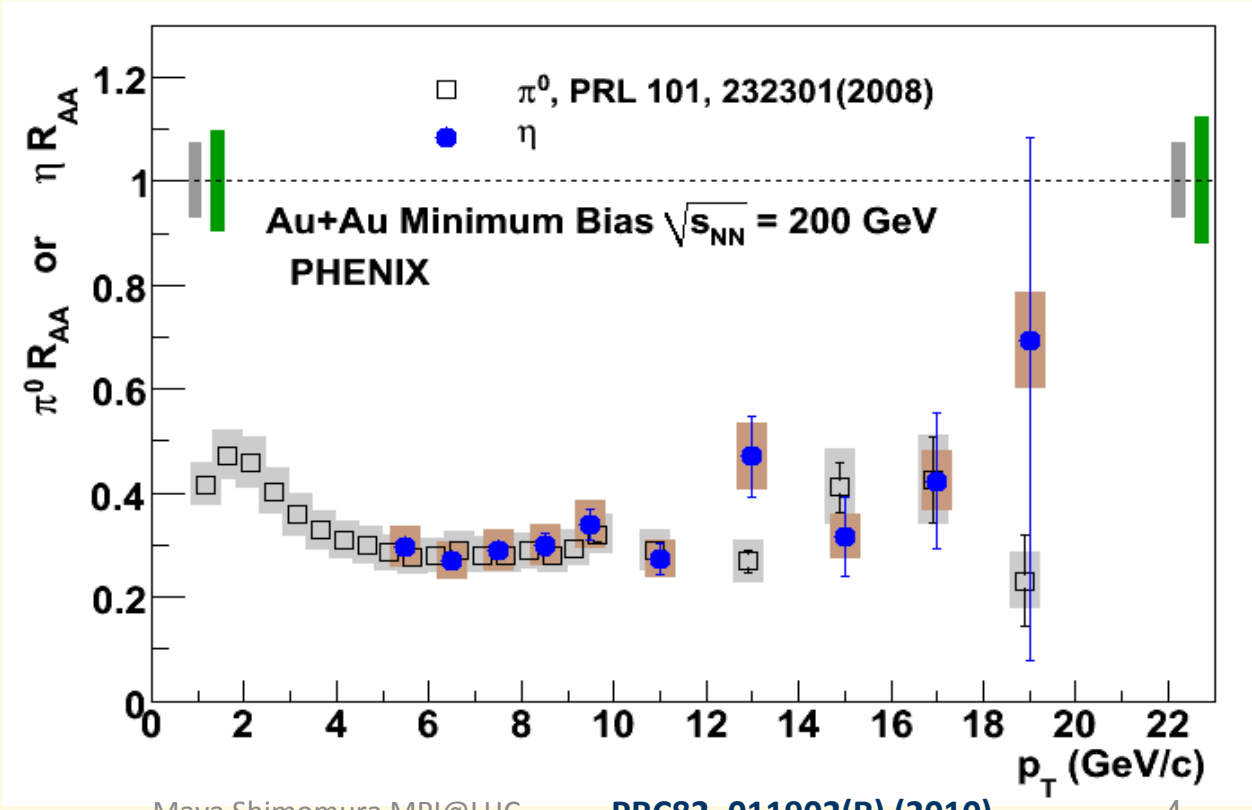
Evidences of QGP

- Suppression of hadron productions due to parton energy loss in QGP.

Ncoll : Number of binary collisions

$$R_{AA}(p_T) = \frac{yield(AuAu)/N_{coll}}{yield(pp)}$$



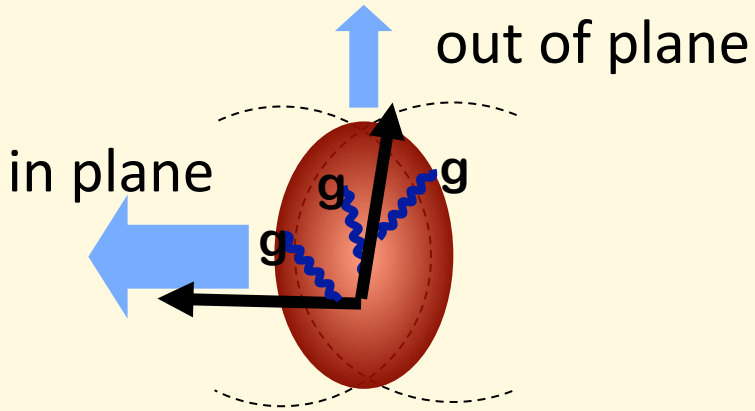


PRC82, 011902(R) (2010)

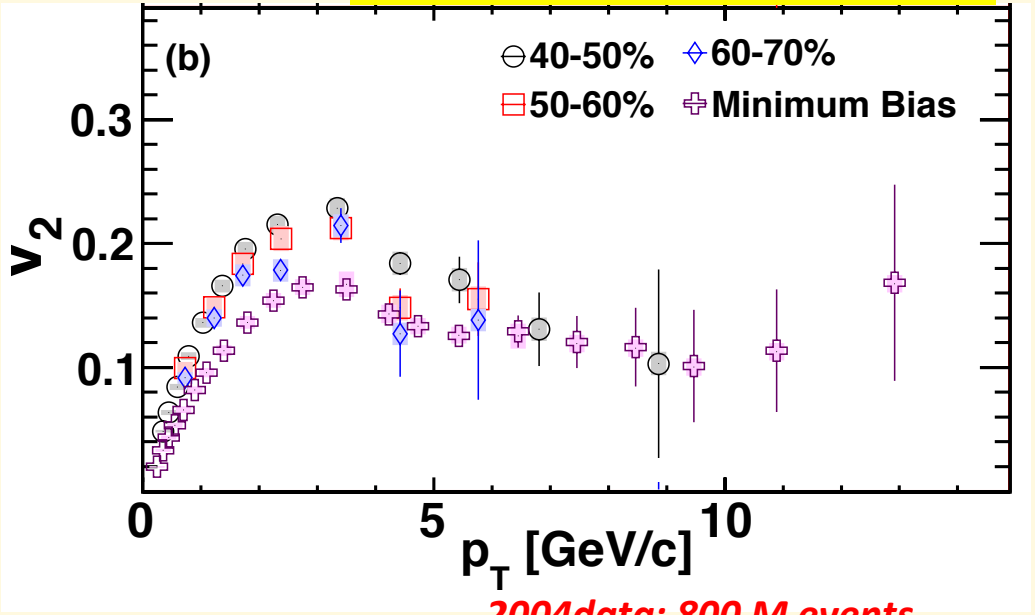
Evidences of QGP

- **Positive v_2 at high p_T is due to initial anisotropy and parton energy loss.**

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos(2\phi)$$



[PHENIX: PRC.92.034913 (2015)]

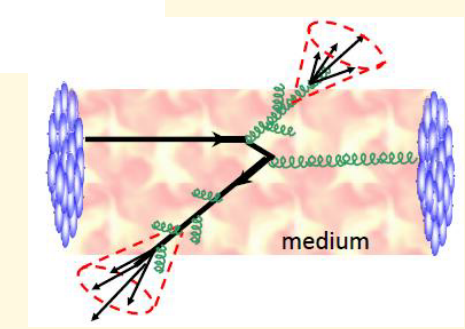


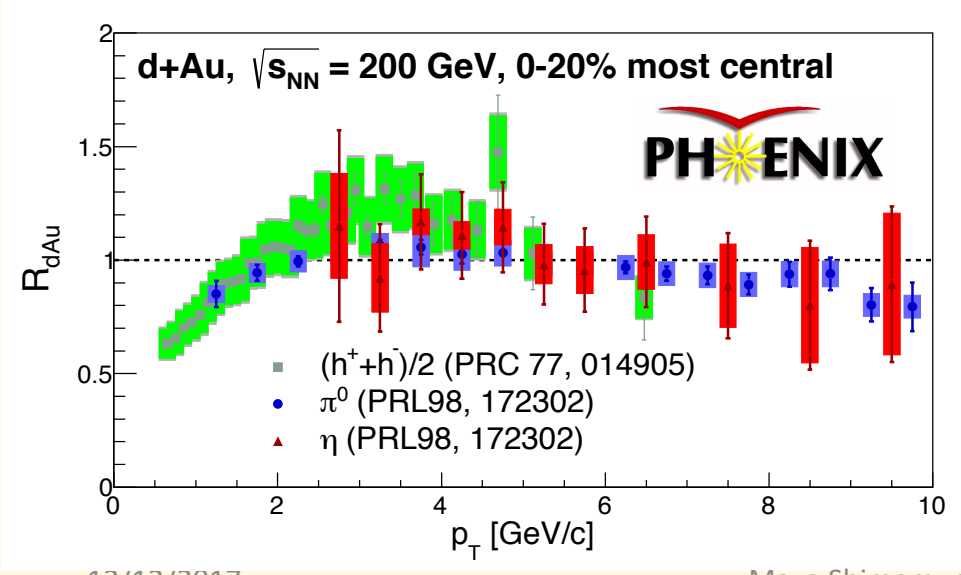
2004data: 800 M events

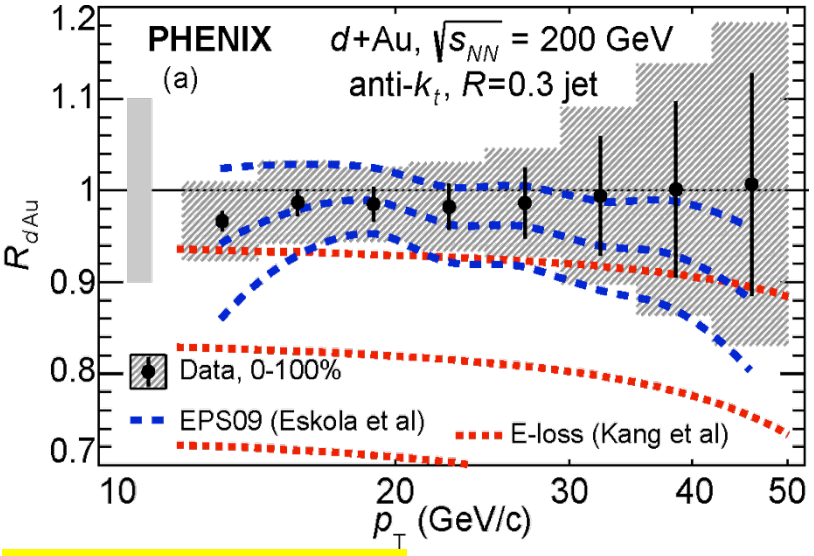
Small system (pp/dAu)

Why were we interested in small system collisions (i.e., $p/d/^3$He+Au) ?

- Baseline for AuAu
  - the system known **not to** form QGP
  - R_{dAu} of jets and hadrons in MB are consistent with unity at high-p_T







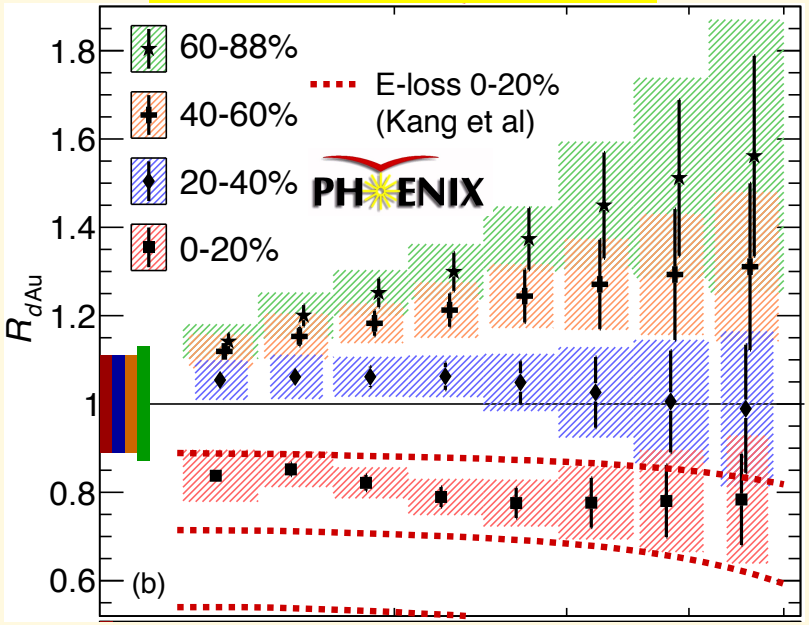
PRL 116, 1223011 (2016)

Small system is no longer baseline.

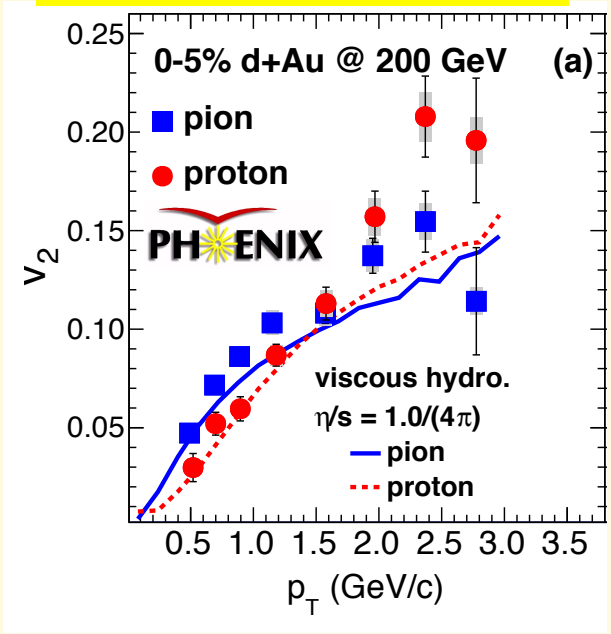
- Jets R_{dA} shows suppression in most central, enhancement in most peripheral
- Hydrodynamic flow in most central
- Multi parton interaction may make larger multiplicity and may creat the small but hot&dense matter.

See the talk by Prakhar on Thursday

PRL 116, 122301 (2016)



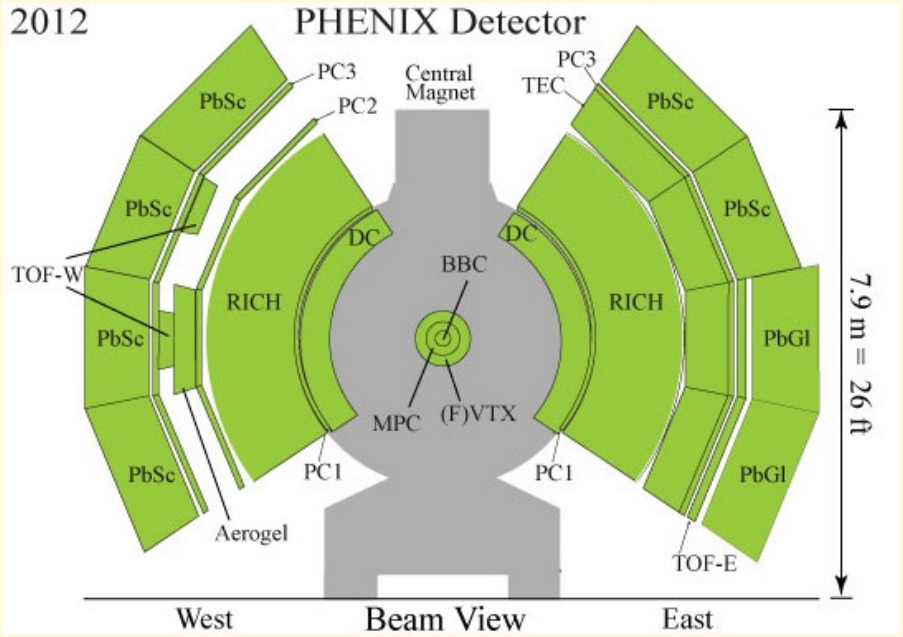
PRL 114, 192301 (2015)

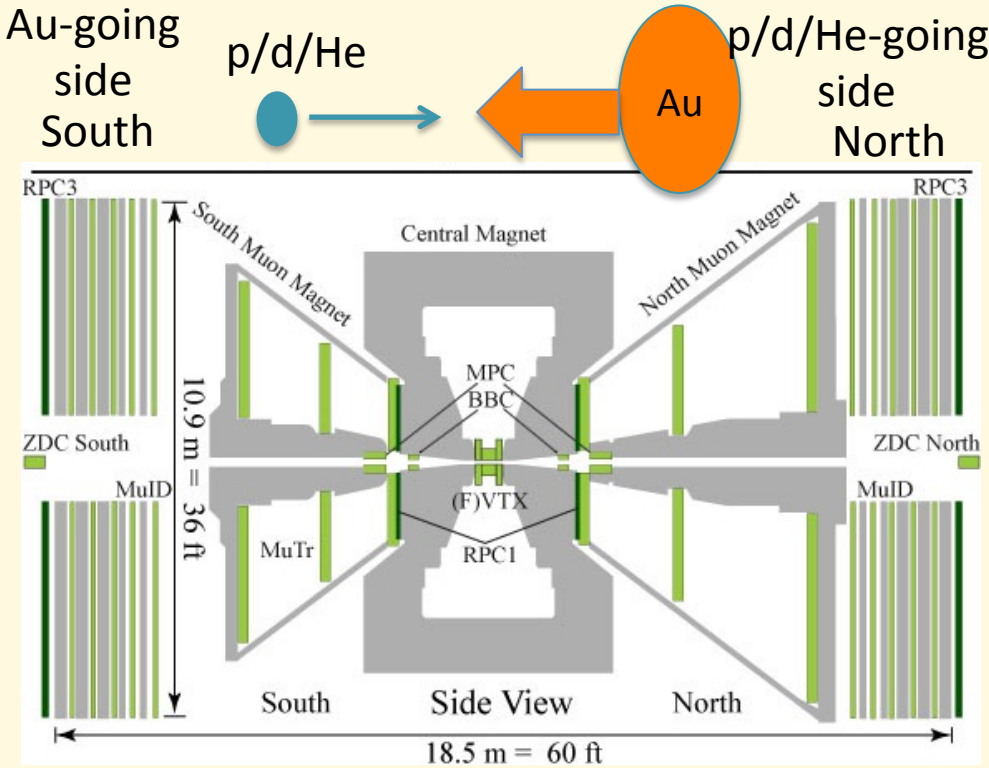


Check hadron R_{dA} to see if there is suppression at high pT in small systems.

PHENIX Detector

- Particle identification and tracking:
  - π^0 by EMC in central arm ($|\eta|<0.35$)
  - momentum measured by DC in central arm
  - Hadrons by muon arms ($3.1<|\eta|<3.9$)

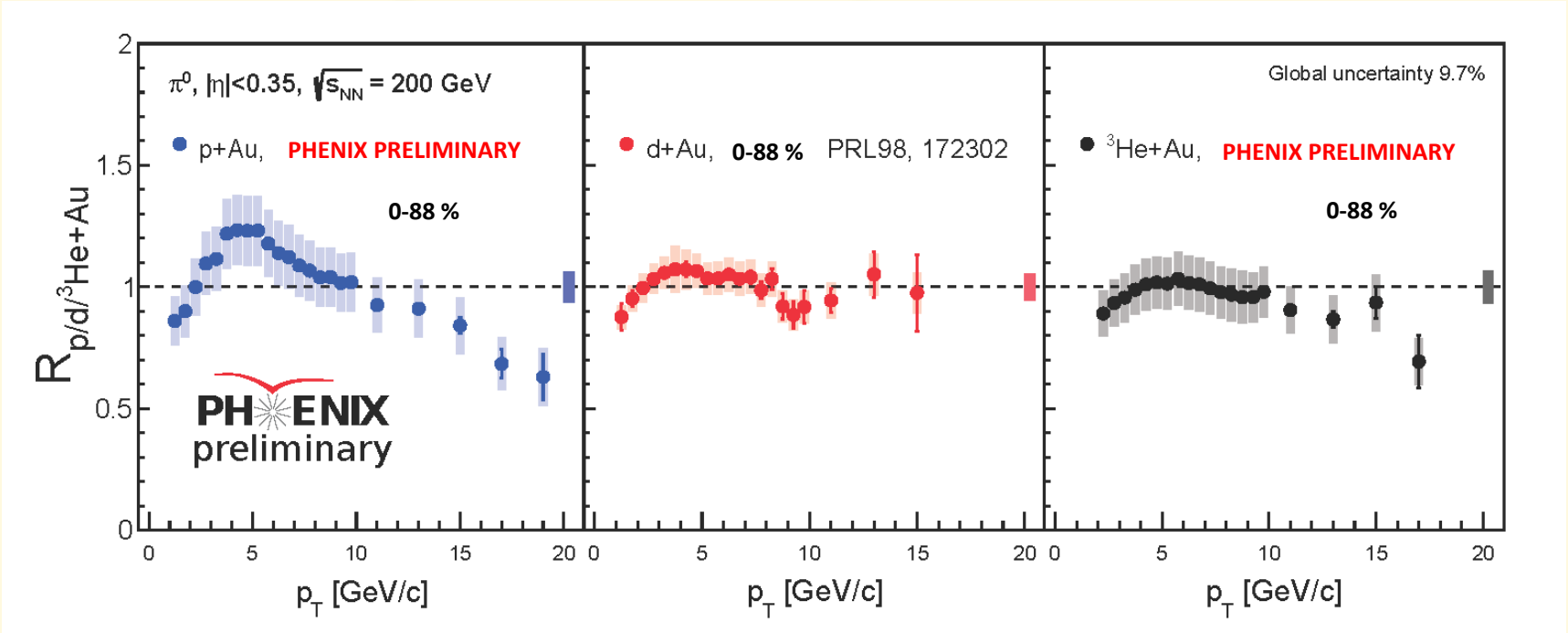




Nuclear modification factors for MB

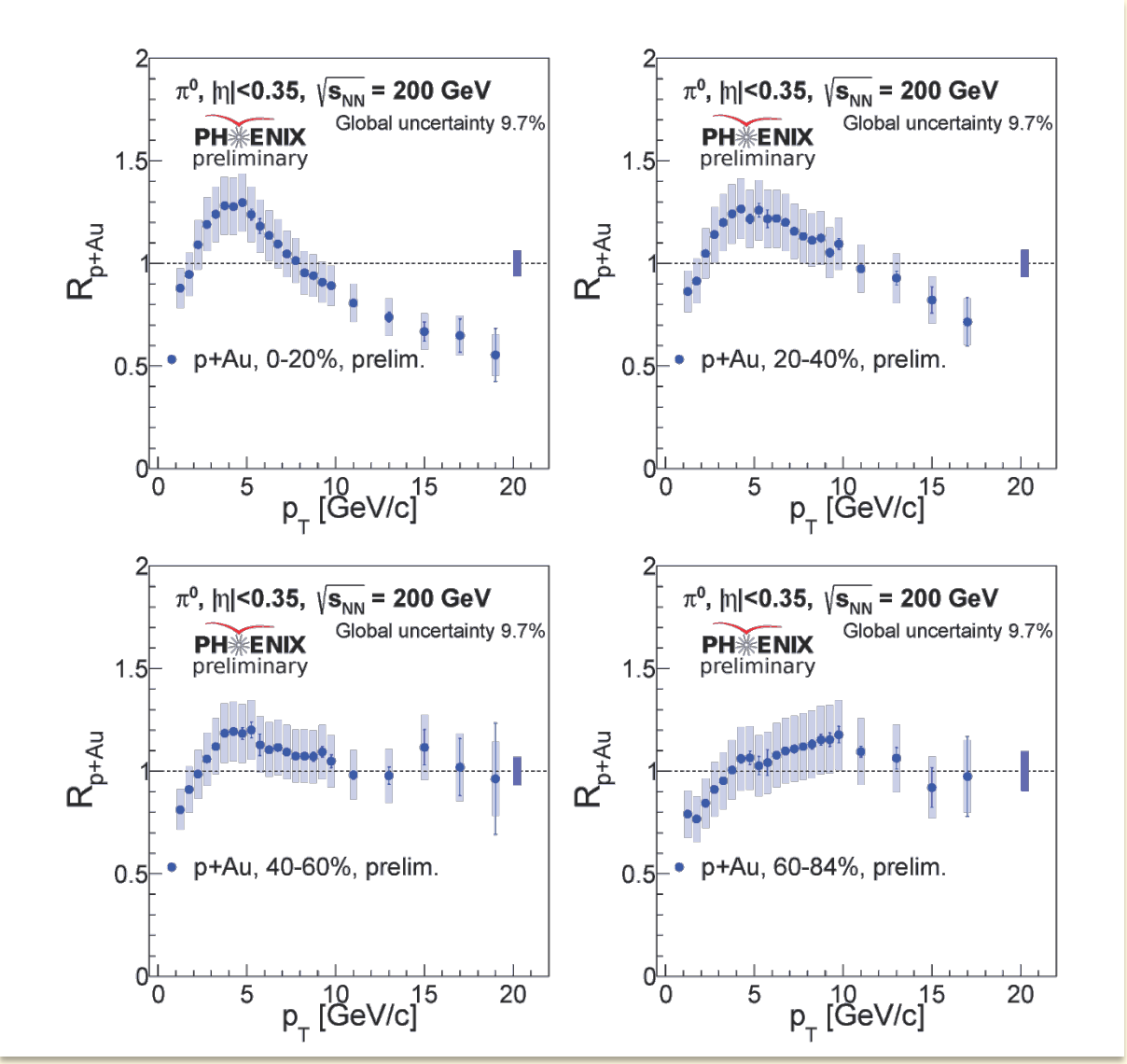
- Minimum bias events triggered by BBC
  - Centrality 0-88 % (MB)

Year-3 and -8 *d*+Au
Year-14 ^{3}He+Au, Au+Au
Year-15 *p*+Au, *p*+Al



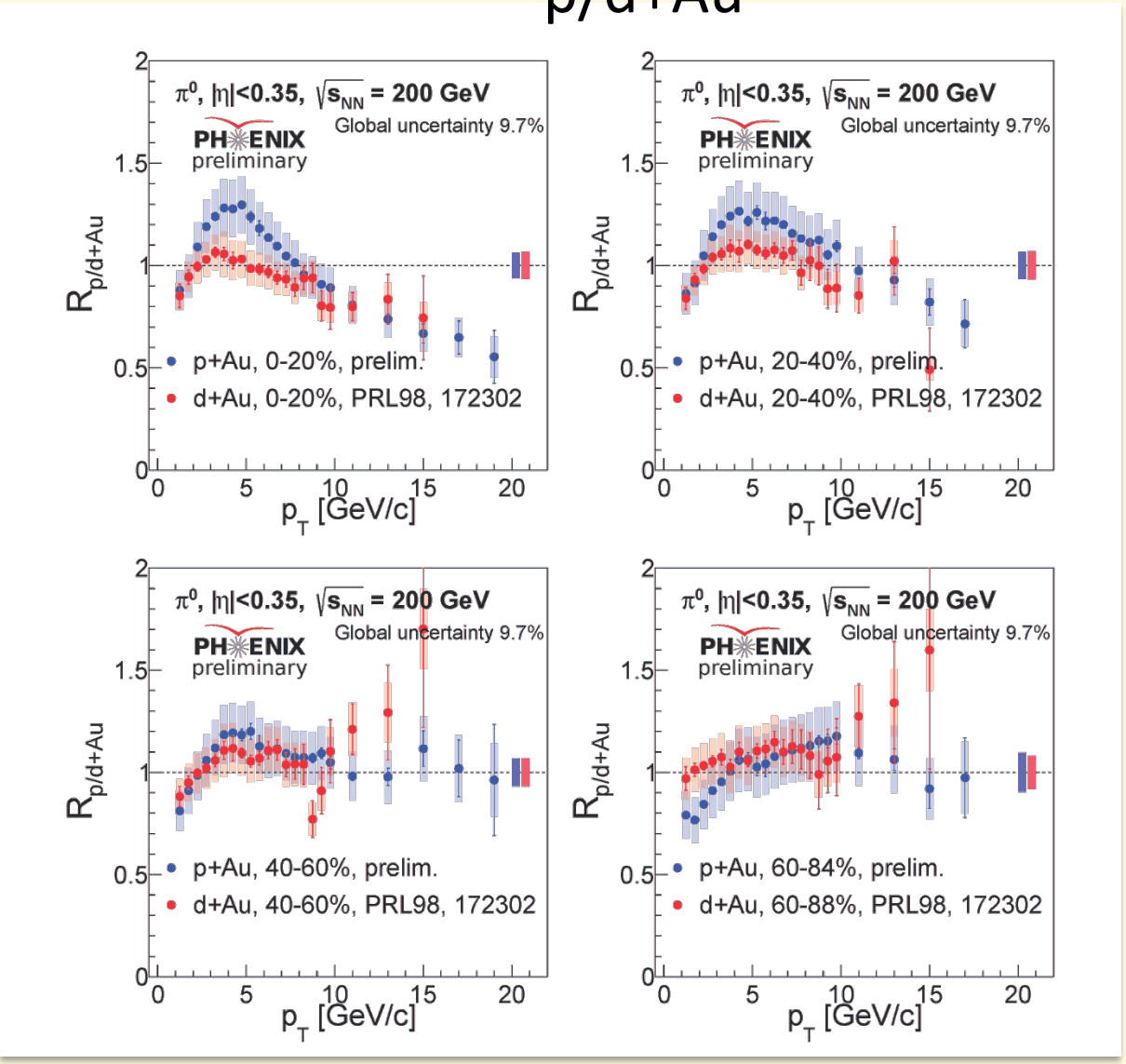
Mostly consistent to 1. At high pT , RpA seems to be suppressed in p+Au.

R_{p+Au} vs centralities



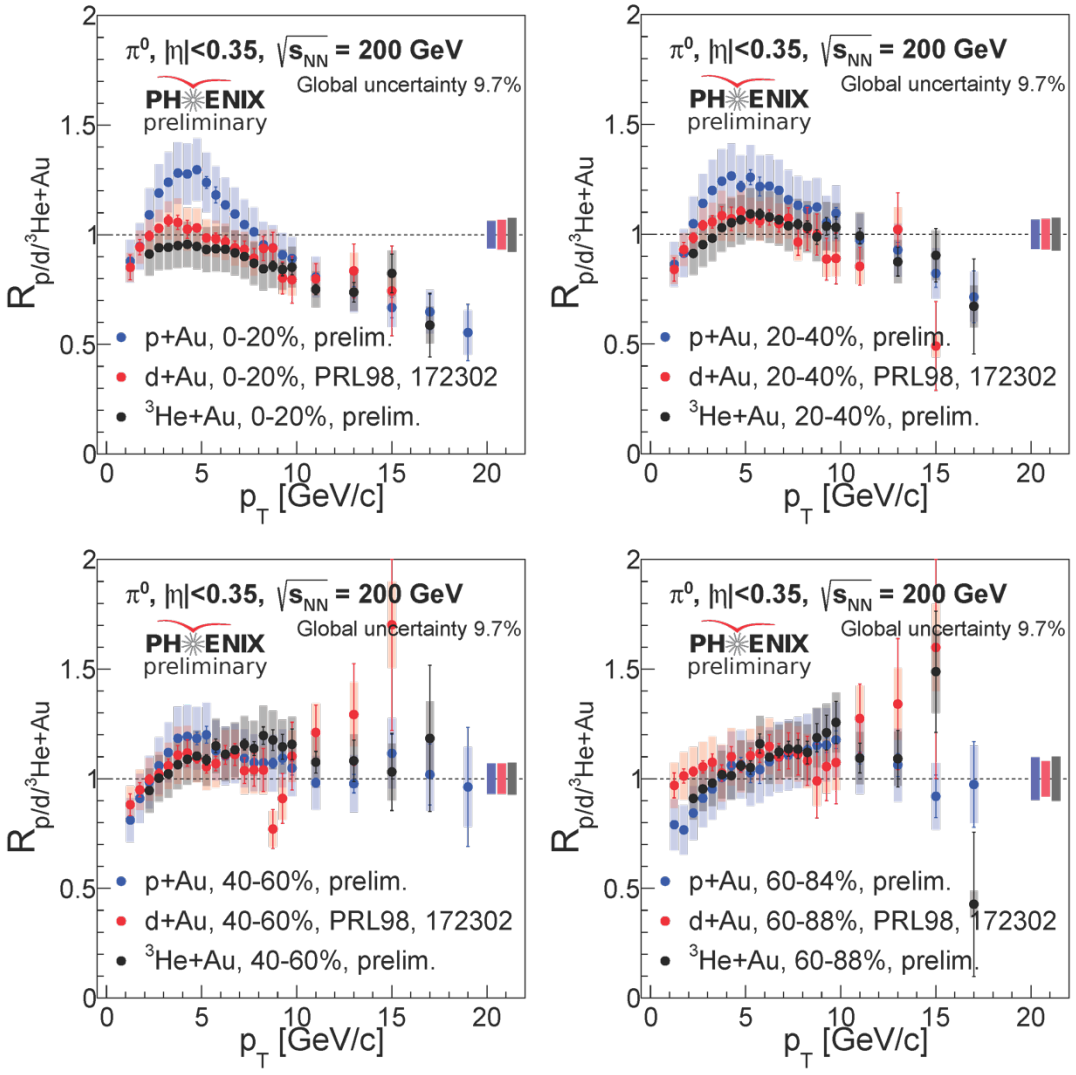
- ***p*+Au results show large centrality dependence**

$R_{p/d+Au}$ vs centralities



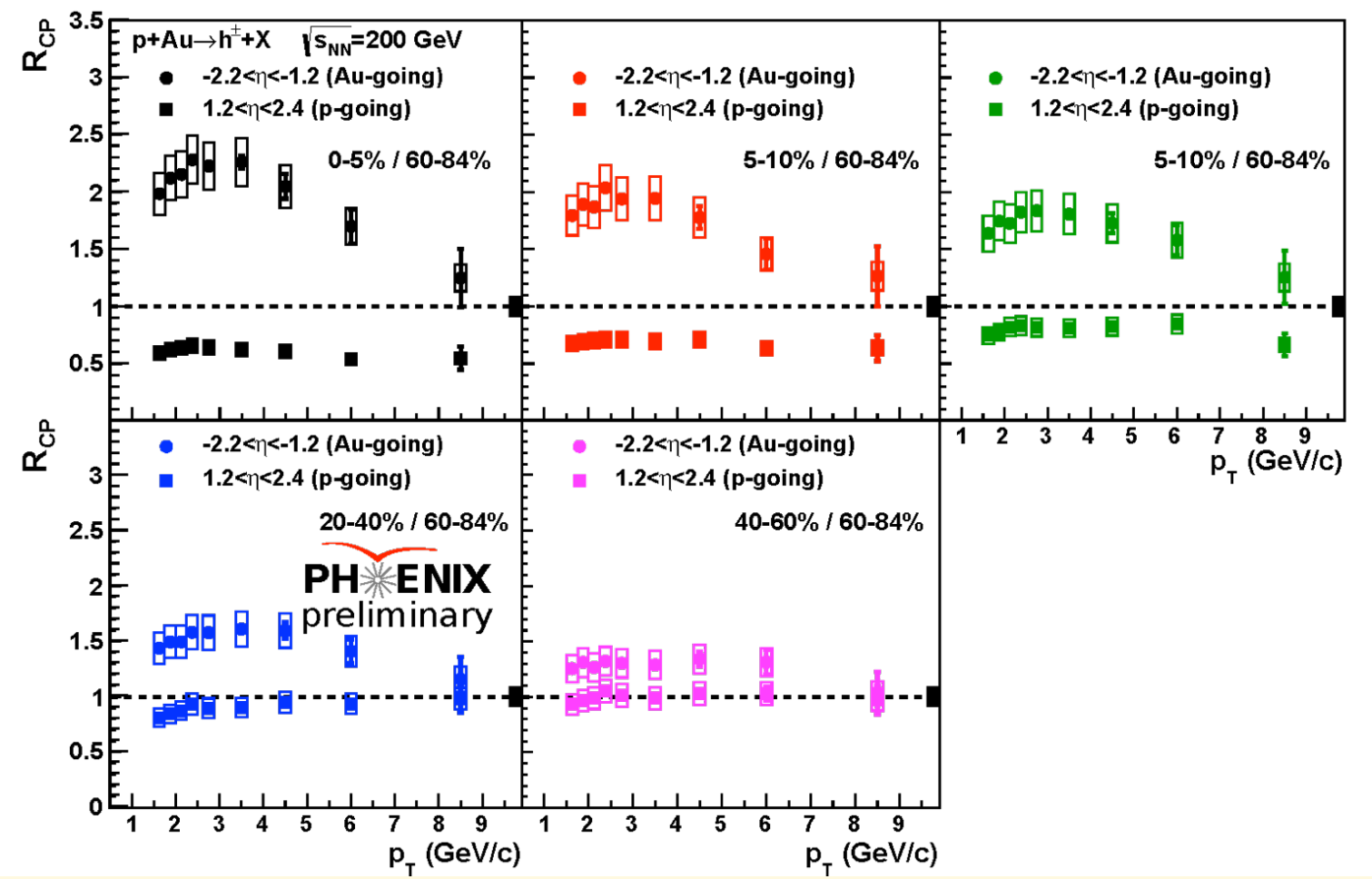
- ***p*+Au results show large centrality dependence**
- ***d*+Au results agree with *p*+Au at high-p_T**

Centrality dependence of $R_{p/d/^3He+Au}$



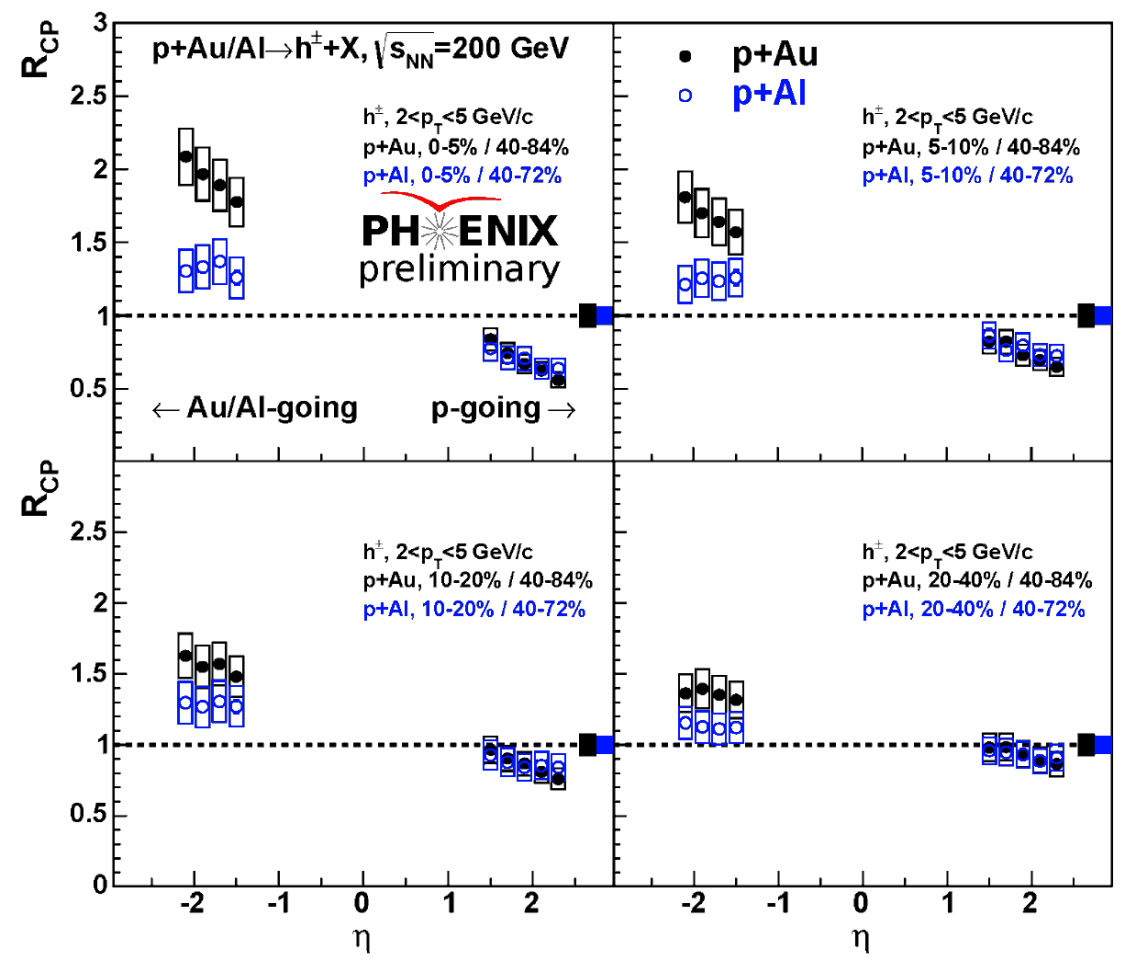
- ***p*+Au results show large centrality dependence**
- ***d*+Au results agree with *p*+Au at high-p_T**
- **^{3}He+Au results agree with *p*+Au and *d*+Au at high-p_T**
- **At moderate p_T an ordering is seen as a function of systems**

R_{cp} at Au-going and p-going



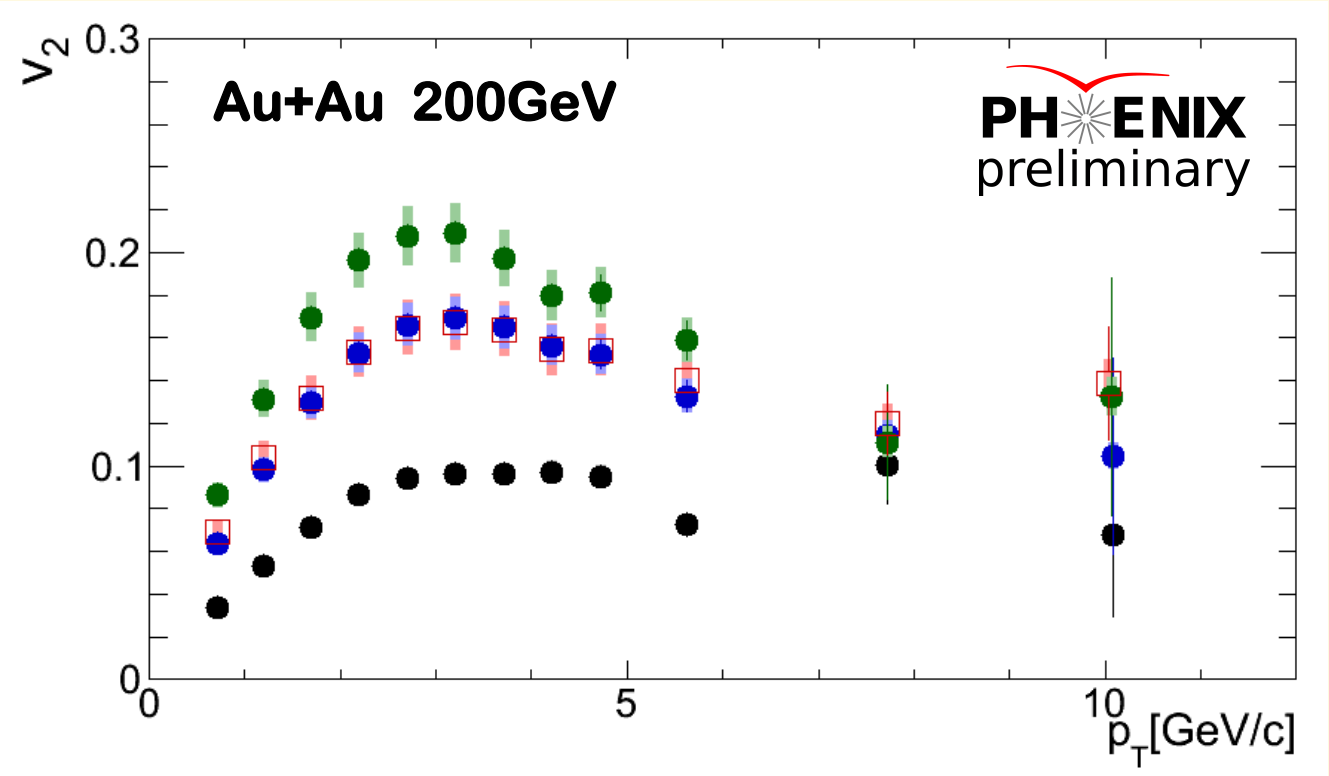
p-going side is suppressed.
Au-going side is enhanced.

η dependence in p+Au and *p*+Al



- Comparison of R_{CP} in same centralities in p+Au and *p*+Al collisions:
- **Forward** hadrons shows **same suppression**
- **Backward** hadron production show smaller **enhancement** in *p*+Al than in *p*+Au collisions
- EPS09 tells that the nuclear PDFs are not very different for Au and Al

High p_T v_2 at Au+Au



2014data: 3 B events

20%-30%

10%-20%

0%-10%

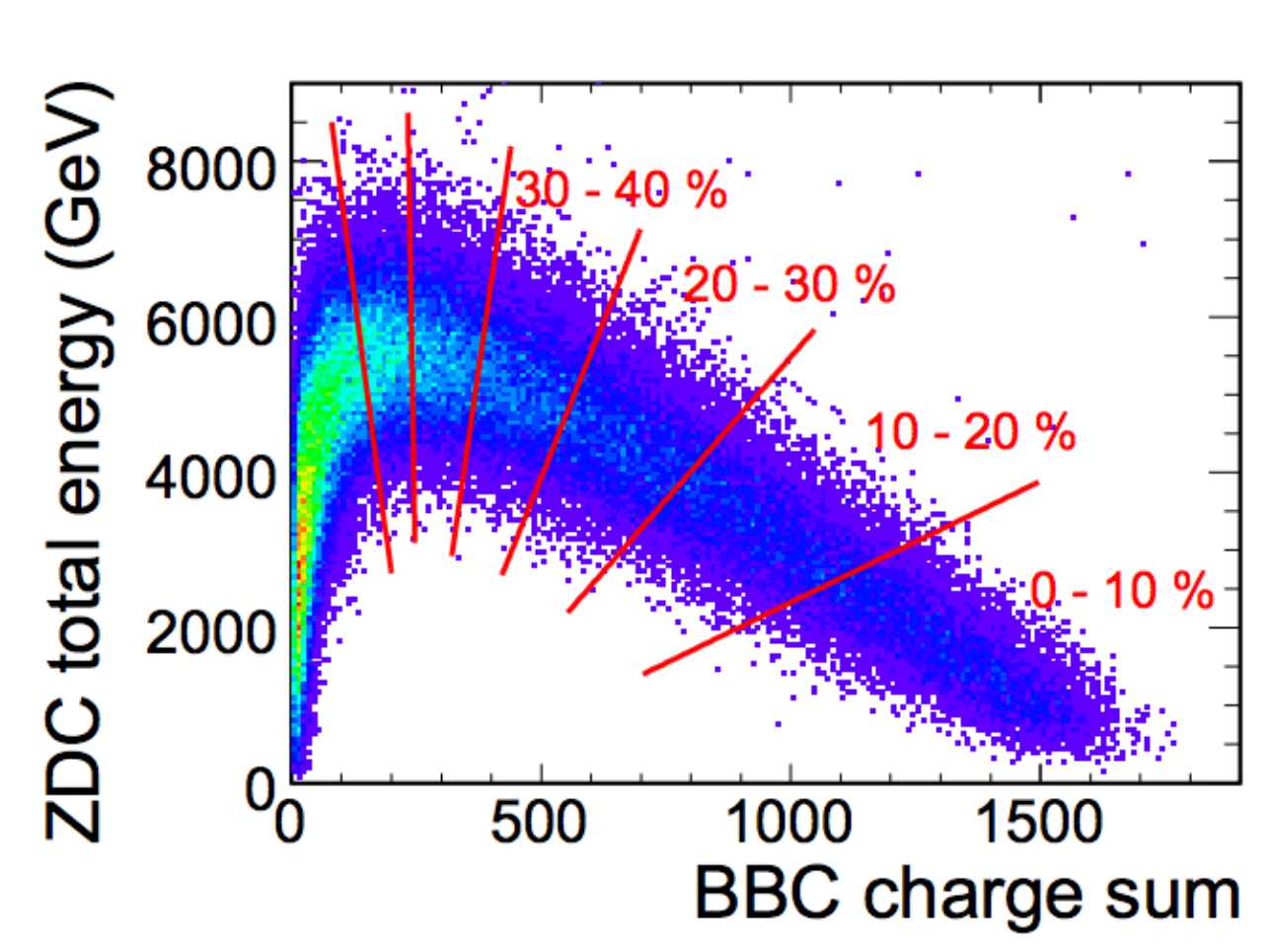
minimum bias

- At p_T > 6GeV/c, v_2s of different centralities converge.
- This is not consistent with path-length dependent energy loss, large uncertainties notwithstanding.
- Next : We may calculate spectator dependence.

Summary

- *p*/*d*+Au system is no longer a baseline.
  - Same observables can be seen in small system as Au+Au.
- $R_{p/d/3HeAu}$ are mostly consistent to 1.
  - At high pT , RpA seems to be suppressed in p+Au.
- $R_{p/d/3HeAu}$ has large centrality dependence
  - agree with each other.
- R_{cp} has also strong large centrality dependence.
  - p-going side is suppressed.
  - Au-going side is enhanced.

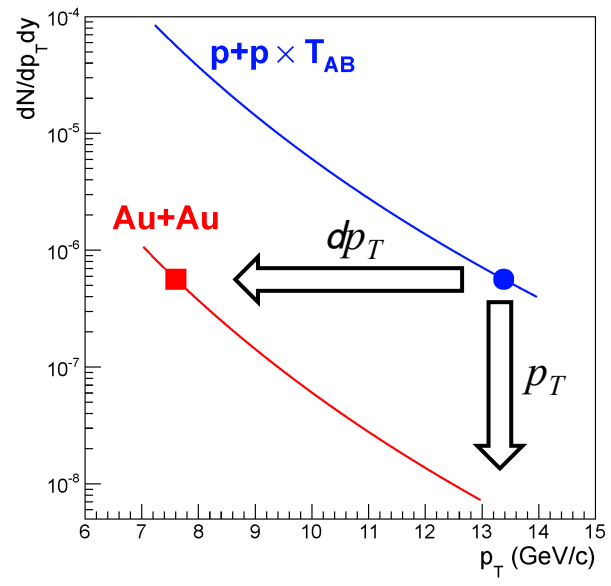
participant(BBC) −spectator(ZDC)



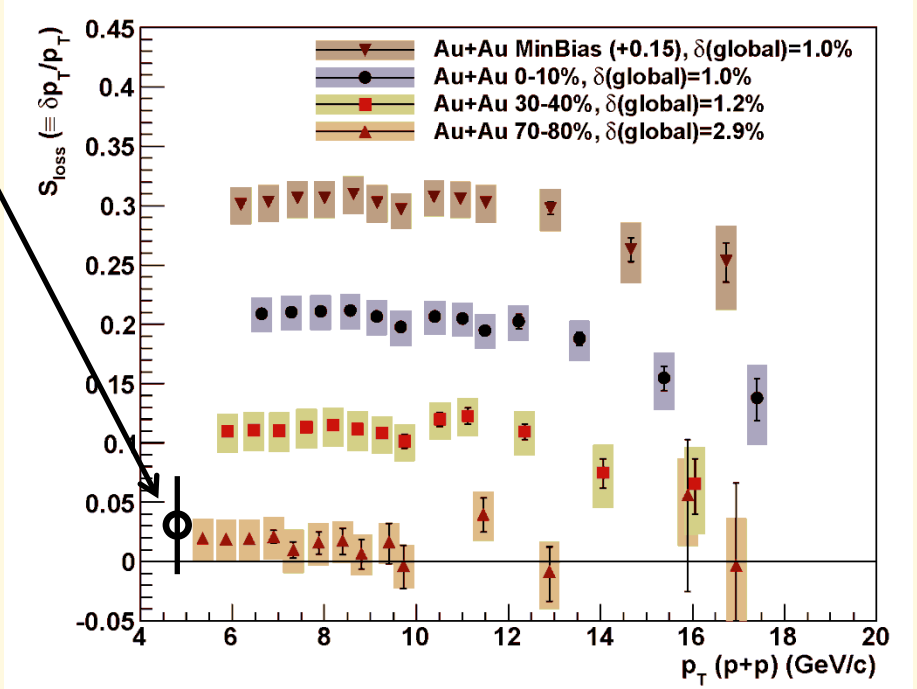
Fractional momentum loss in ^{3}He+Au

- R_{AA} can be rewritten in the form of fractional momentum loss (dp_T/p_T).
  - Instead of taking ratio of spectra, one can directly measure the spectra shift (dp_T)
- Most central (0-10%) ^{3}He+Au collisions shows similar R_{AA} as 60-70% Au+Au
  - At same cms energy, same R_{AA} implies same dp_T/p_T
- ***dp_T/p_T = ~0.03*** in most central ^{3}He+Au collisions

$$p_T : p_T(p+p)$$
$$\delta p_T = p_T(p+p) - p_T(A+A)$$



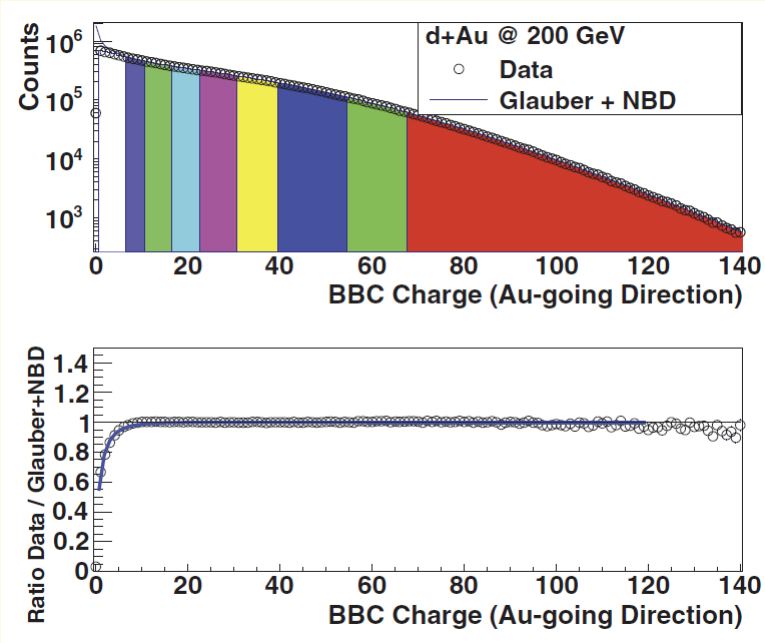
PHENIX, PRC87, 034911(2013), PRC93, 024911 (2016)

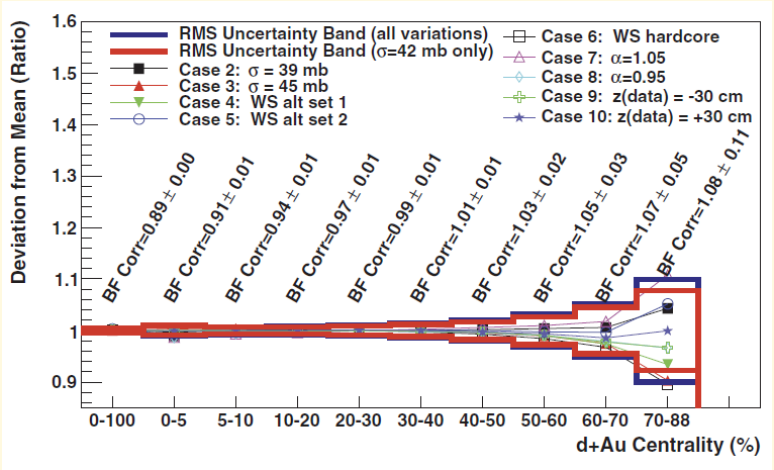


Event trigger and bias

PRC 90, 034902 (2014)

- Min. Bias trigger has inefficiency
  - Measured BBC charge distribution was compared with a Glauber Monte Carlo simulation folded with a negative binomial distribution (NBD)
- Trigger efficiency is determined as **88%**.
  - Same for *p*/*d*/^{3}He+Au
- Bias factors (BF) for centrality selection are calculated
  - Bias is coming from auto-correlation between high p_T particle in mid-rapidity and backward multiplicity (where centrality is determined)

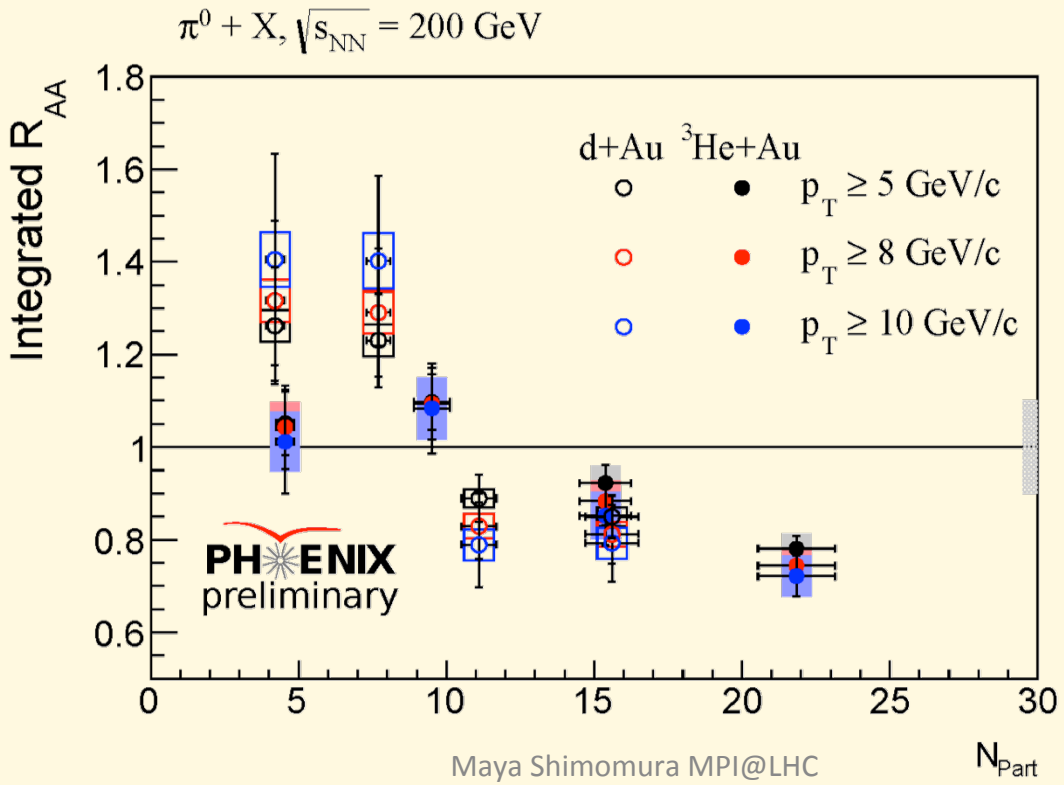




Cent (%)	0-20	20-40	40-60	60-88	0-100
p+Au BF	0.90	0.98	1.02	1.00	0.86
d+Au BF	0.94	1.00	1.03	1.03	0.89
^{3}He+Au BF	0.95	1.02	1.02	1.03	0.89

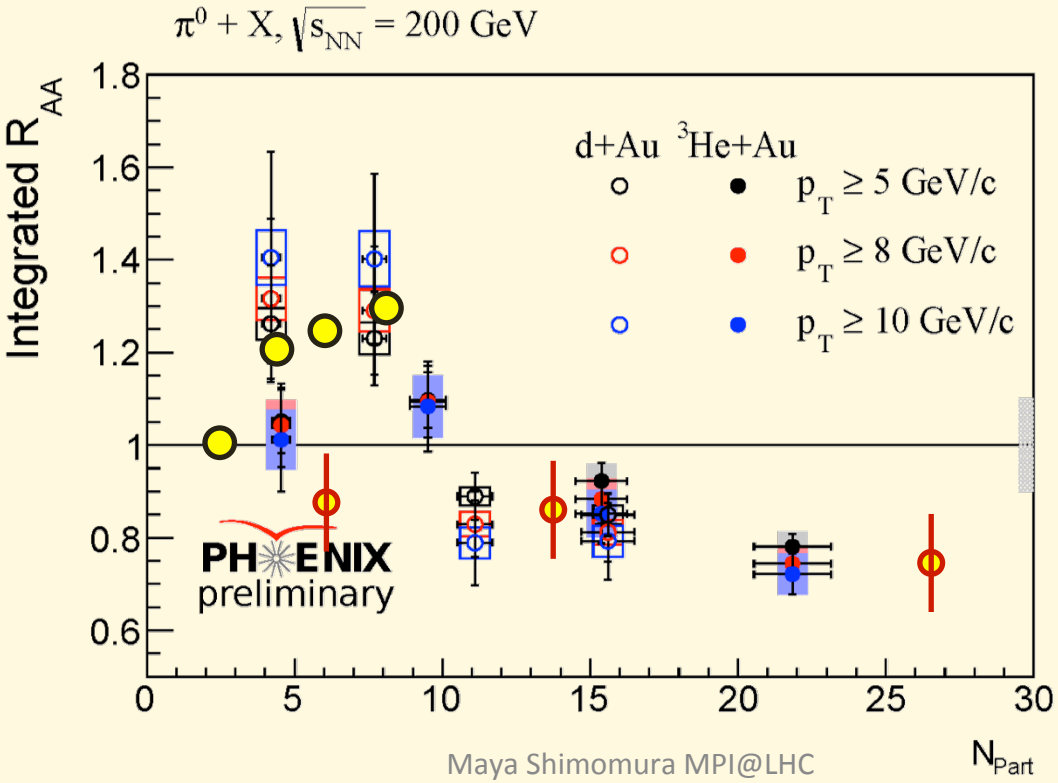
Integrated R_{AA} in *d*+Au and ^{3}He+Au

- At higher N_{part}, *d*+Au and ^{3}He+Au show very similar N_{part} dependence
- At lower N_{part}, *d*+Au collisions show more enhancement
  - More Cronin effect, or less suppression (energy loss)



Integrated R_{AA} in $p/d/^3$He/Au+Au

- Integrated R_{AA} for $p/d/^3$He/Au+Au
- R_{AA} from all three systems converge for N_{part}>~12
  - Similar ***hot*** matter is produced?
- System ordering of R_{AA} is seen for N_{part}<12 is seen; R_{pAu}~R_{dAu}>R_{HeAu}>R_{AuAu}



p+Au @ p_T=5GeV/c (0-20, 20-40, 40-60, 60-88%)

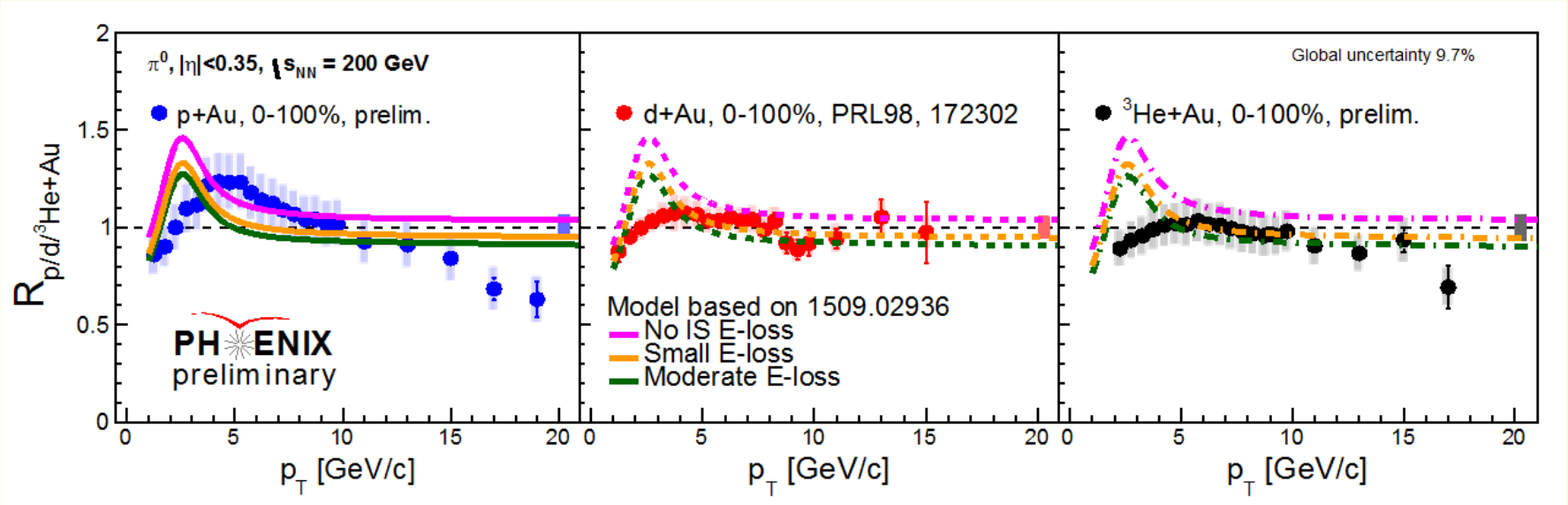
Au+Au @ p_T=5GeV/c (80-93, 70-80, 60-70%)

Cold nuclear energy loss?

- Different energy loss scenarios (no, small or moderate) are comparable to the data at high-p_T

- System dependent enhancement change at low-p_T is not reproduced
  - The peak positions are also different
  - Additional parameters to be tuned?

PRD 93, 074030, and priv. comm. with I. Vitev



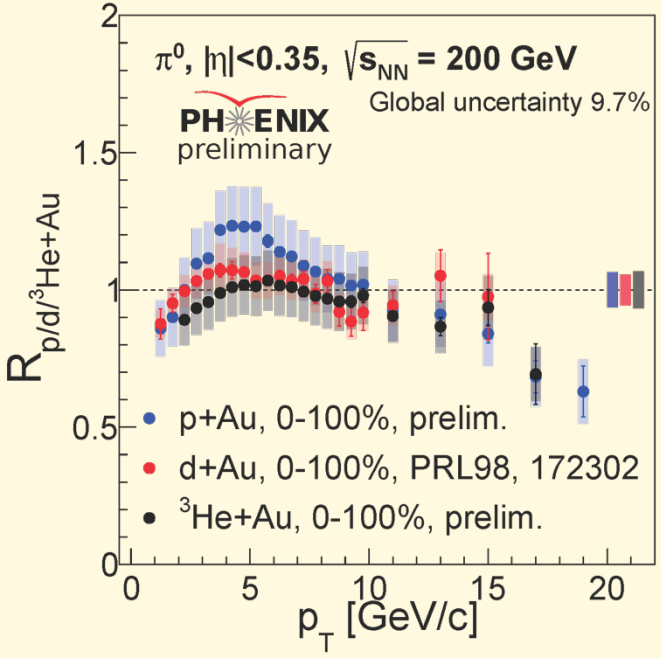
Multiple scattering ?

- HIJING++ simulation shows similar trend between collision systems
  - Ingredient: multiple scattering + shadowing effect

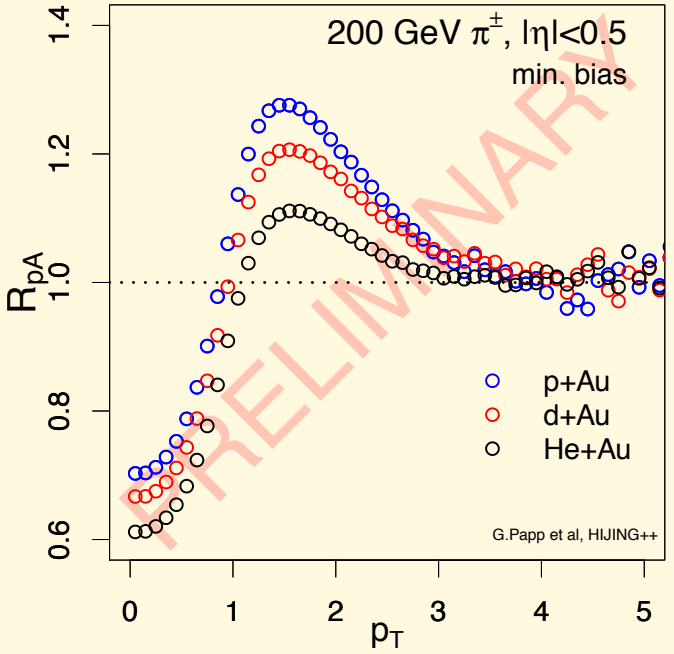
- HIJING++ predicts the Cronin peak around p_T = 1.5-2GeV/c
  - Much lower than in the data (p_T ~ 5 GeV/c)

based on 1701.08496
private comm. with G. Papp

PHENIX Data



HIJING++ simulation

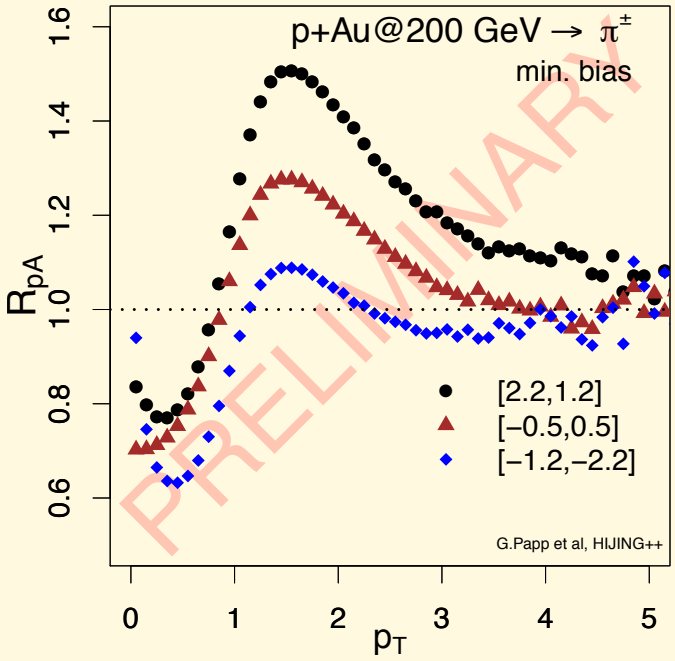


Lessons from model comparison

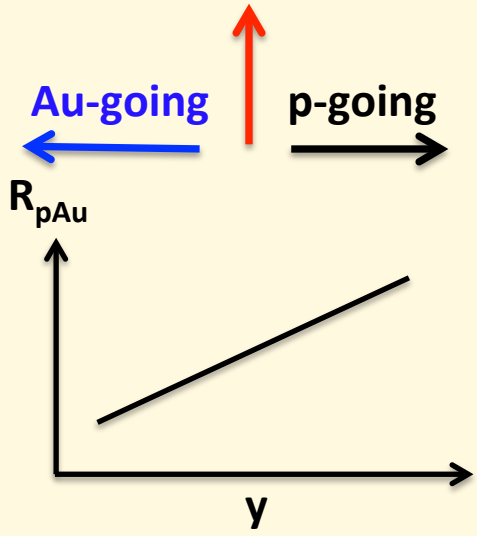
- Cold nuclear energy loss alone can't describe the trend of nuclear modification factors for $p/d/^3$He+Au collisions

- Multiple scattering + shadowing scenario seems to describe the spectra
  - This scenario predicts **larger** (**smaller**) enhancement in the **forward** (**backward**) in comparison to **mid-rapidity**

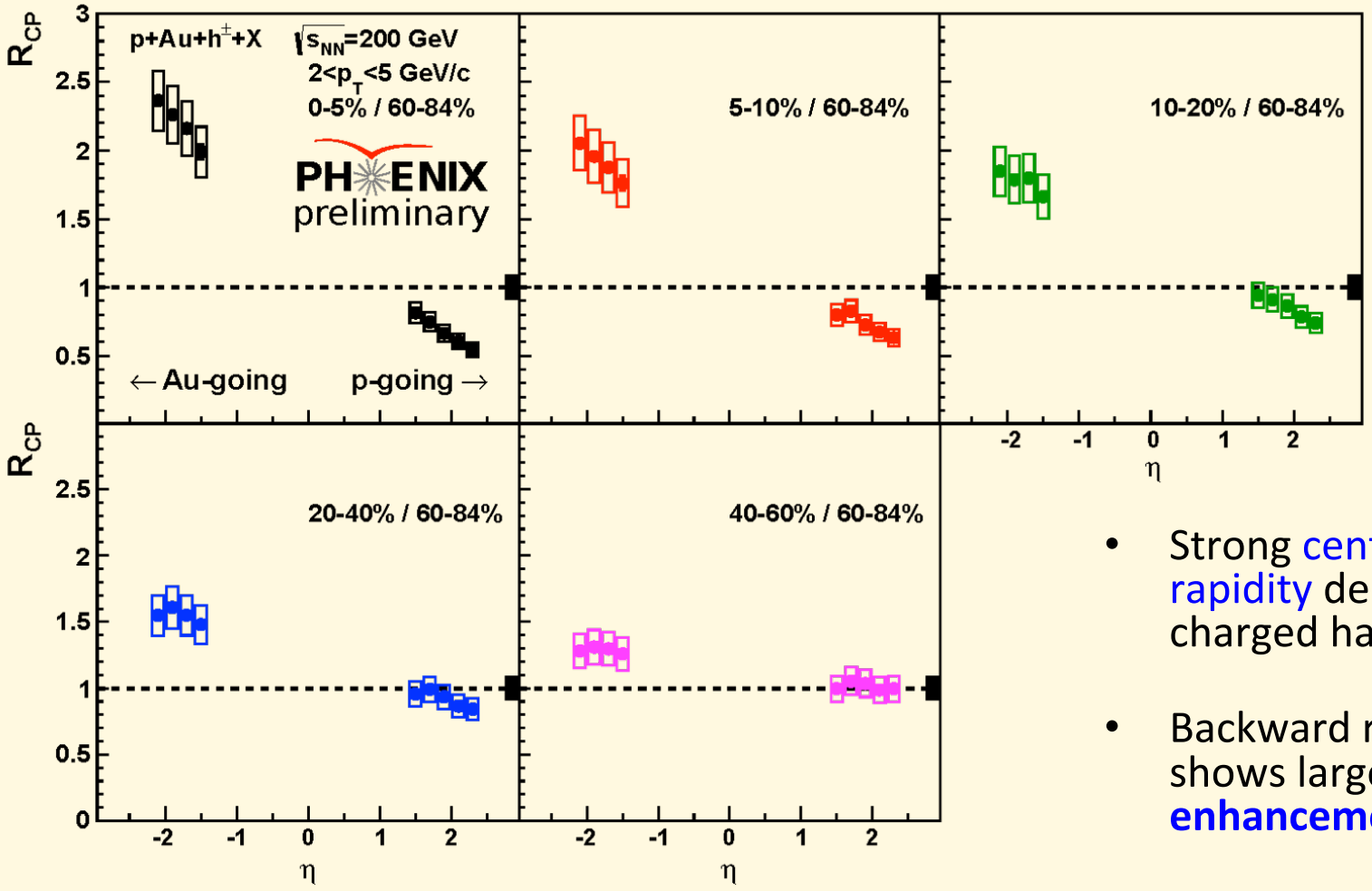
HIJING++ simulation



based on 1701.08496
private comm. with G. Papp



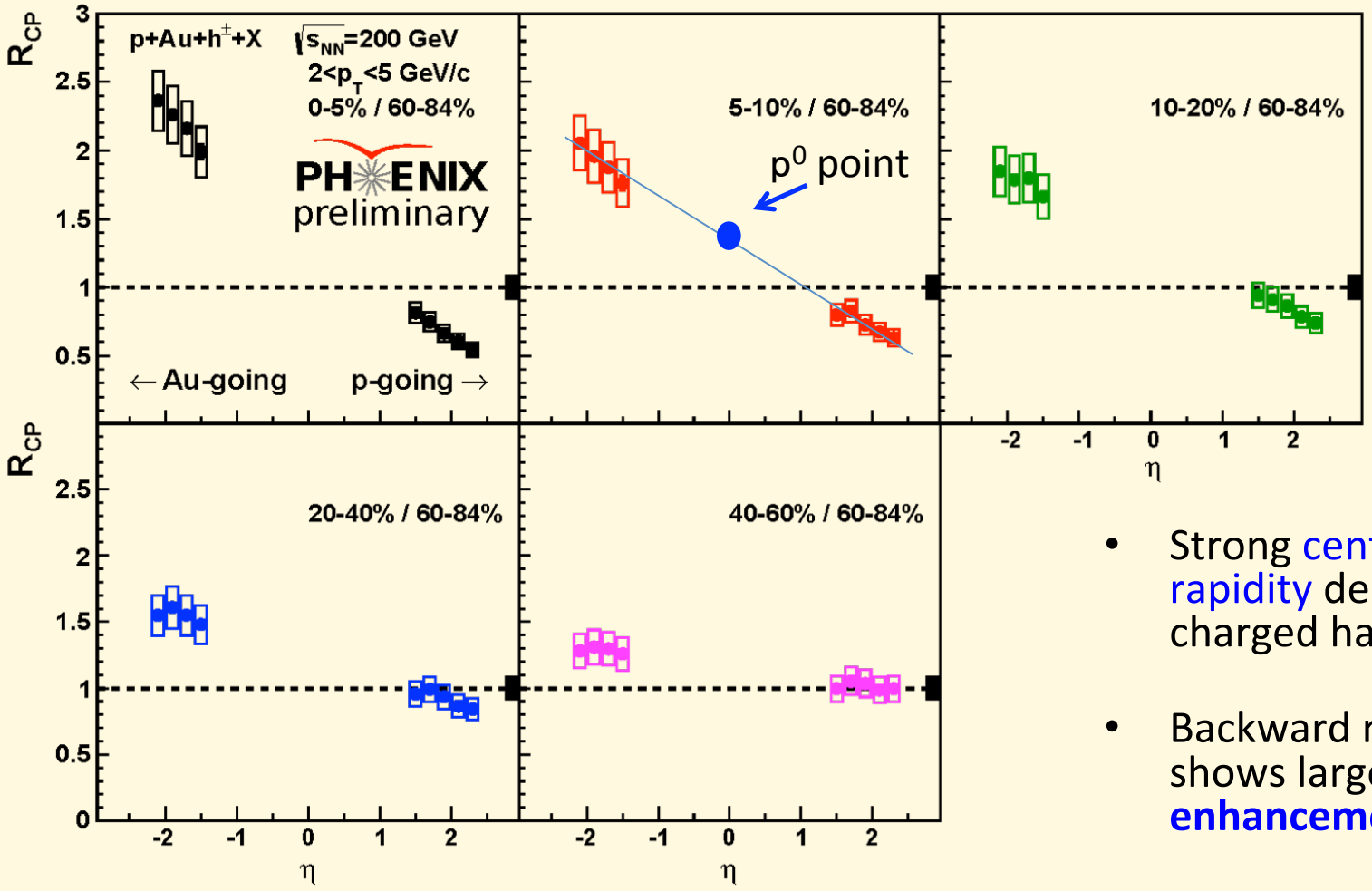
Looking forward and backward



- Strong centrality and rapidity dependence of charged hadrons
- Backward rapidity shows large **enhancement**
- Forward rapidity shows **suppression**

Opposite trend compared to HIJING++ prediction

Looking forward and backward



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Opposite trend compared to HIJING++ prediction

Dataset collected by PHENIX