# 3rd International Conference on New Frontiers in Physics
# Kolymbari, Crete, Greece

## Recent Highlights from the PHENIX Heavy Ion Program

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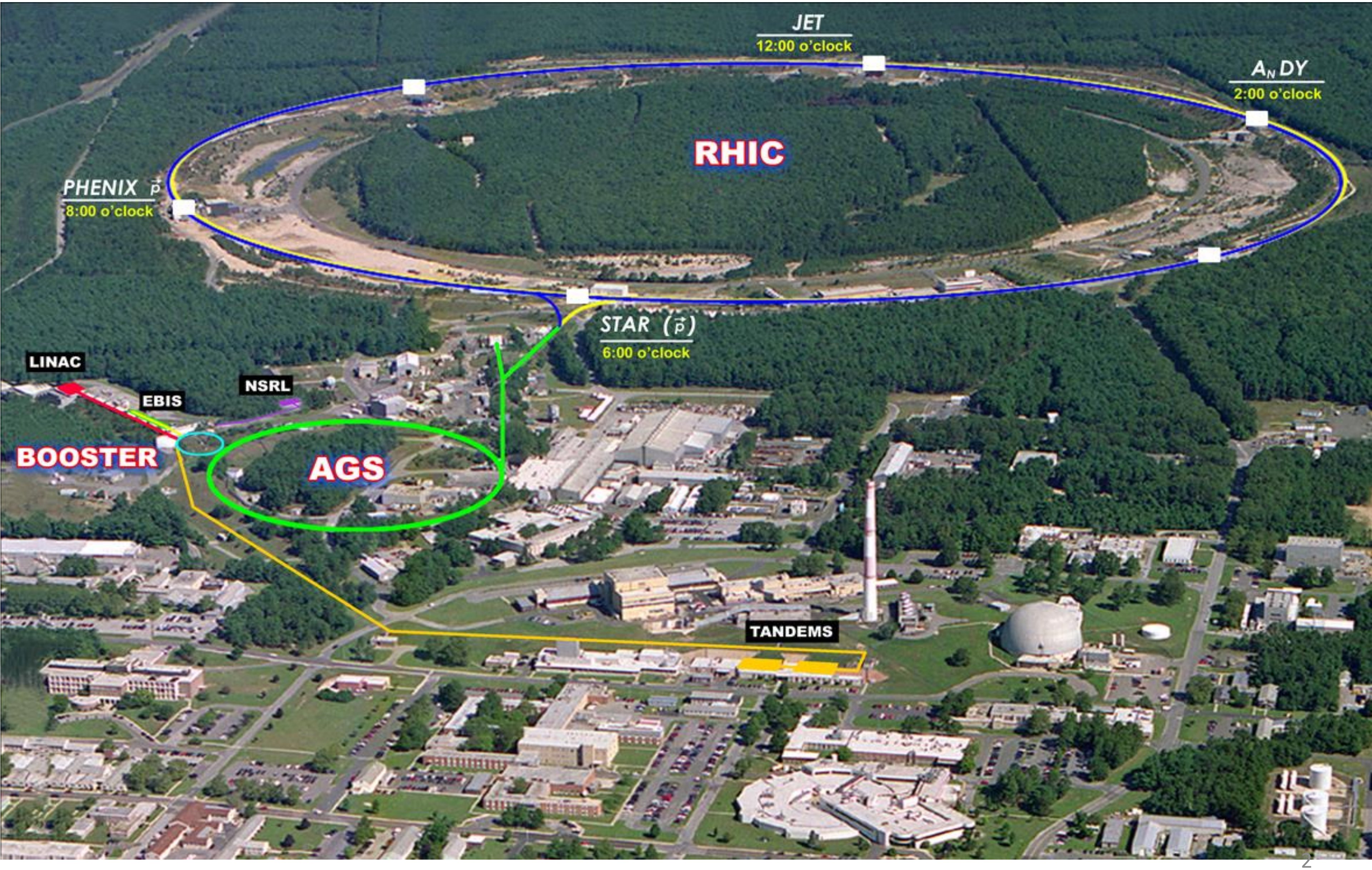
PHENIX

Iowa State CYCLONES

# PHENIX


JET
12:00 o'clock
A$_N$ DY
2:00 o'clock
RHIC
PHENIX $\vec{p}$
8:00 o'clock
STAR ($\vec{p}$)
6:00 o'clock
LINAC
EBIS
NSRL
BOOSTER
AGS
TANDEMS

# PHENIX Talks at ICNFP 2014

1. Highlights from the PHENIX Heavy Ion Program (this talk)
   (dAu, BES, dark photons)

1. Studies on Nuclear Spin at PHENIX
   (Kiyoshi Tanida) Next talk!

3. Probing Properties of Hot Dense QCD Matter with Heavy Flavor at PHENIX
   (Rachid Nouicer) This afternoon: 16:15 Parallel 5

4. The Future of PHENIX: Upgrading to sPHENIX and Beyond
   (Eric Mannel) 5-8-14 (Tuesday) Parallel 5

5. Direct Photon Measurements with PHENIX Experiment at RHIC
   (Ilia Ravinovich) 5-8-14 (Tuesday) Parallel 4

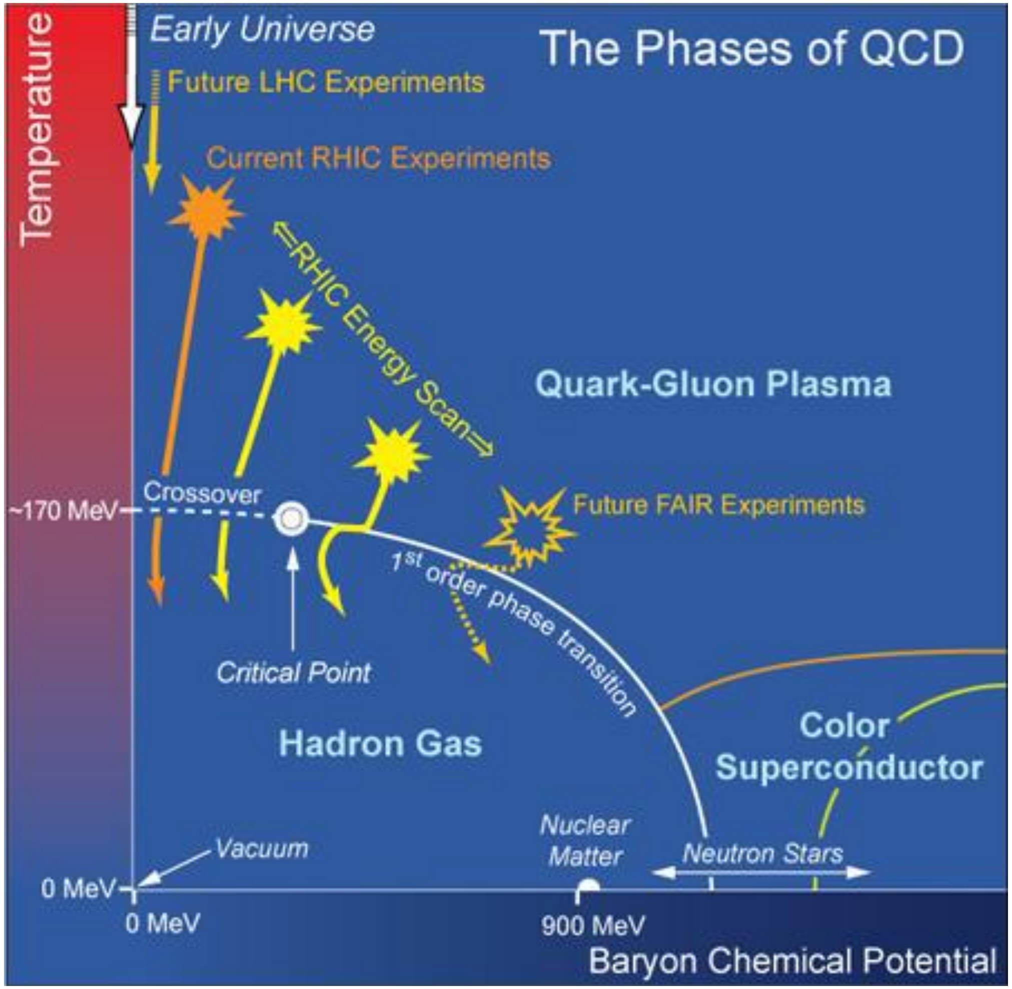
# Results of Study of Quark-Gluon Plasma with Heavy Nuclei

1. Hot dense medium created in Au+Au collisions. Evidence is nuclear modification factor $R_{AA} < 1.0$.

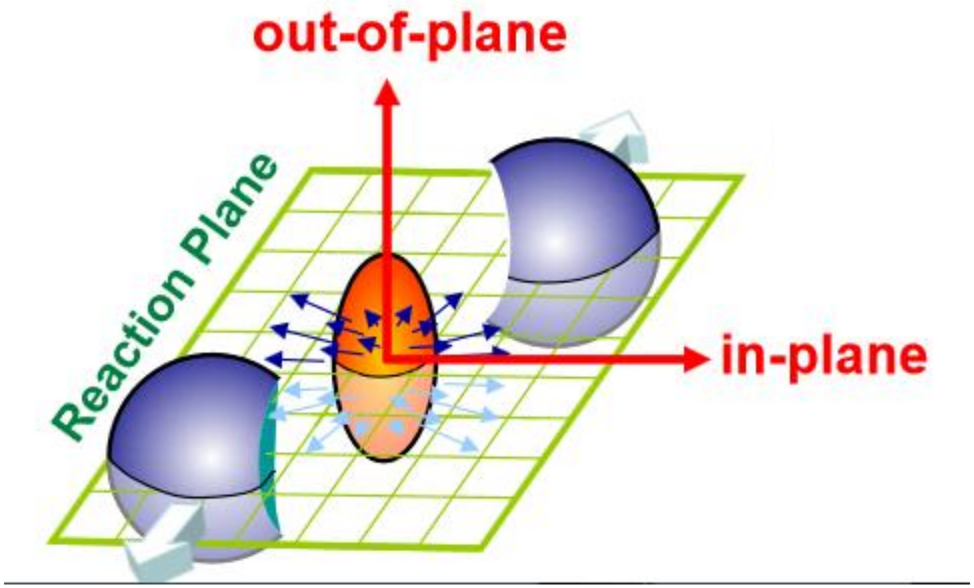
2. The hot dense medium flows with low viscosity. Evidence is $v_2 > 0$ and observation of ridge.

3. The quark-gluon actually created. Evidence is quark scaling of $v_2$ for mesons (q=2) and baryons (q=3).

4. No phase transition observed implies crossover from plasma to hadron gas.



# How Study Flow




1. Reaction geometry produces almond shaped interaction region.

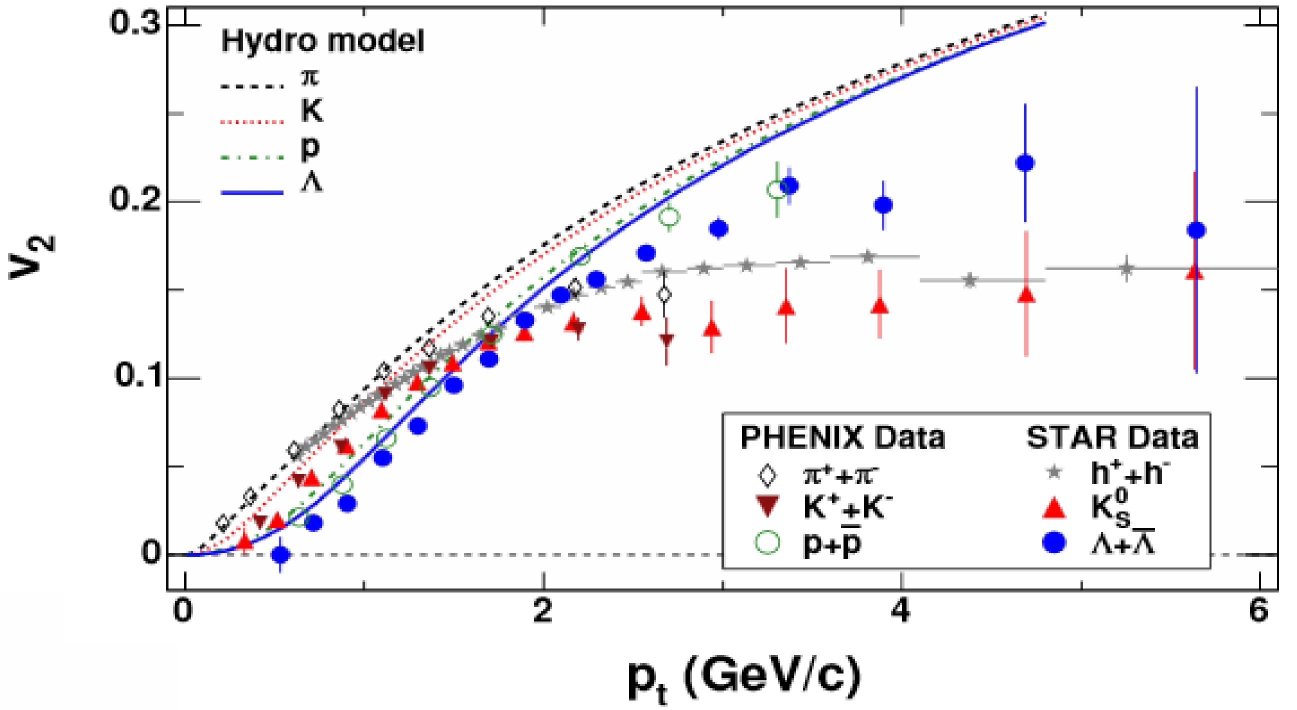
2. Compression of mass in center produces anisotropic $p_T$ distribution.

3. Resulting $p_T$ distribution described in terms $\left[1 + \sum_{n=1}^{\infty} \left\{ 2v_n \cos\left[n(\phi - \Psi_R)\right] \right\} \right]$

4. A finite $v_2$ is termed elliptic flow. $\Psi_R$ in plane of beam and impact parameter.

# Data for $v_2$ for 200 GeV Au+Au Collisions

STAR [Phys. Rev. C72 014904 (2005)]




1. Flow evident for 200 GeV Au+Au collisions.

2. Relativistic hydro good fit to the data for $p_t < 2.0$ GeV/c

# Are Long Range Correlations and Flow Present in Small Systems?

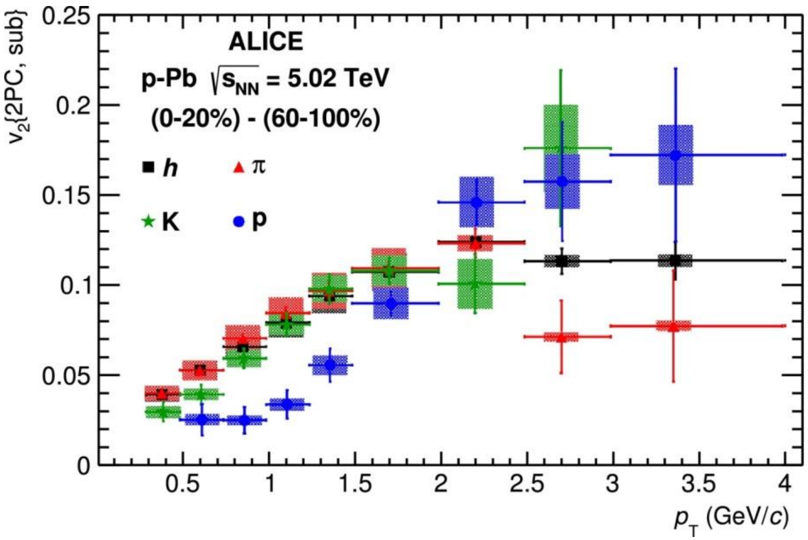
In relativistic A-A collisions a QGP medium is formed which signals its presence through long range correlations and finite flow ($v_2$).

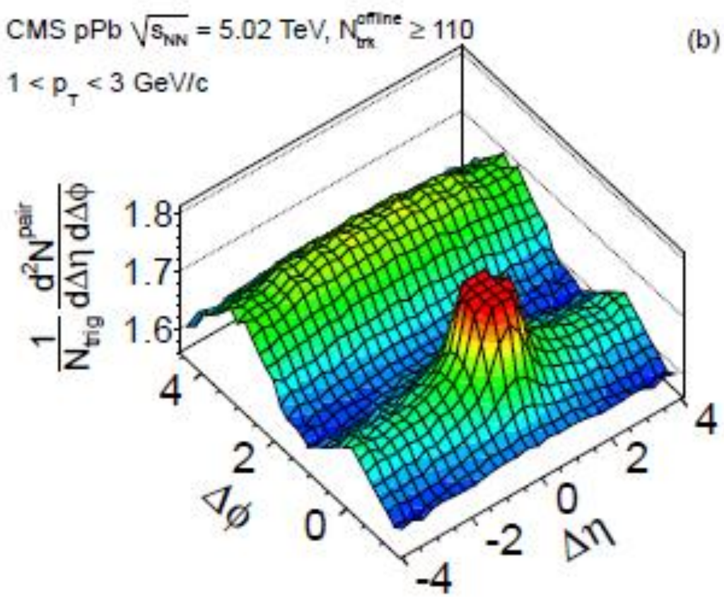
It was thought that p+p and p+A collisions could not form such a medium because of the small system size.

Recent results from p+Pb at LHC indicate presence of long range correlations.

# Flow and the Ridge in p+Pb at the LHC

For p+Pb at 5.02 TeV at LHC, $v_2$ and a ridge observed.



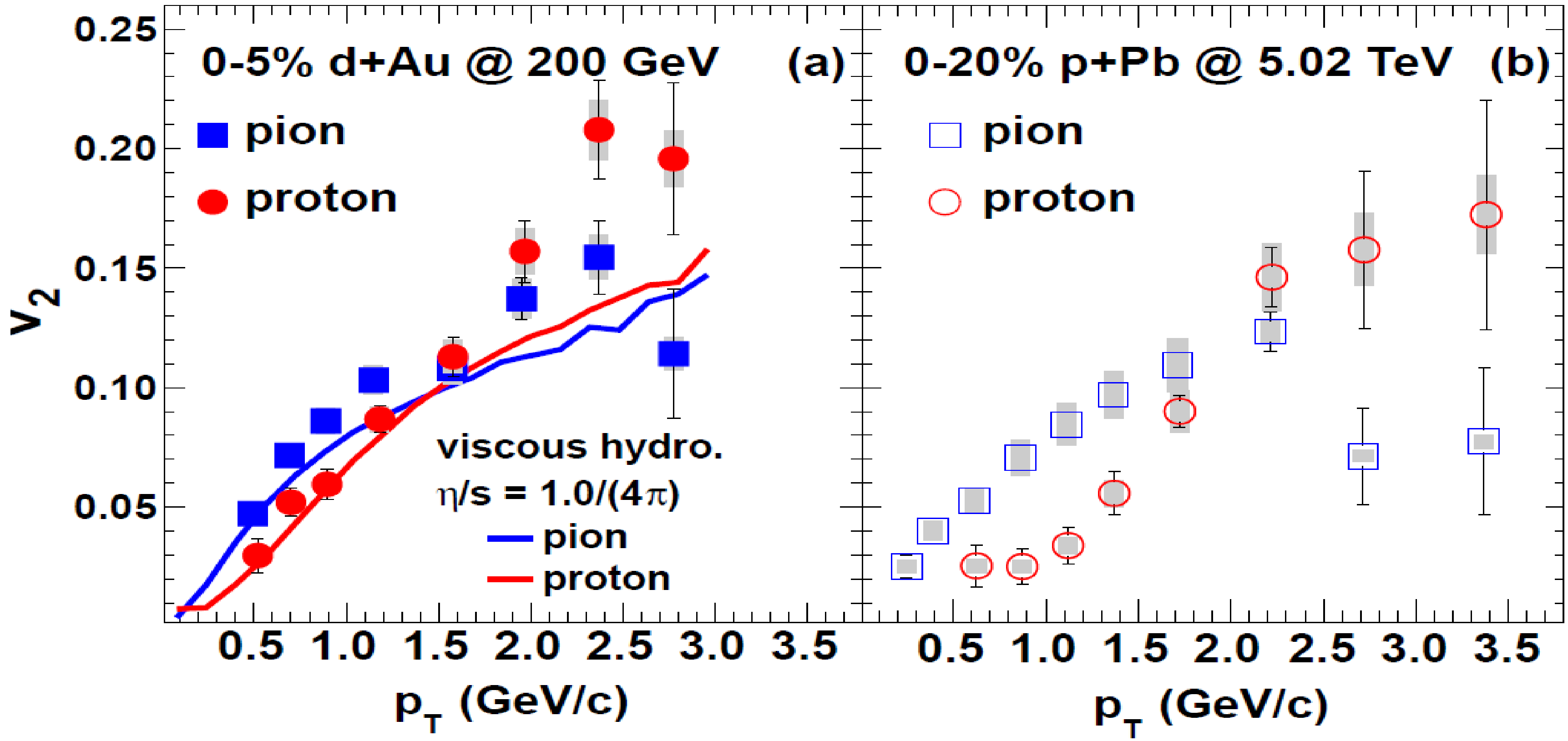

ALICE: Physics Letters B 726 (2013)
ATLAS: Phys. Rev. Lett. 110(2013)
CMS: Phys. Lett. B 7198(2013

Evidence for long range correlations and flow for p+Pb.

Do we observe $v_2$ and a ridge with d+Au at RHIC?

# $v_2$ Observed for d+Au at 200 GeV

Measured $v_2$ of identified hadrons using event-plane method.

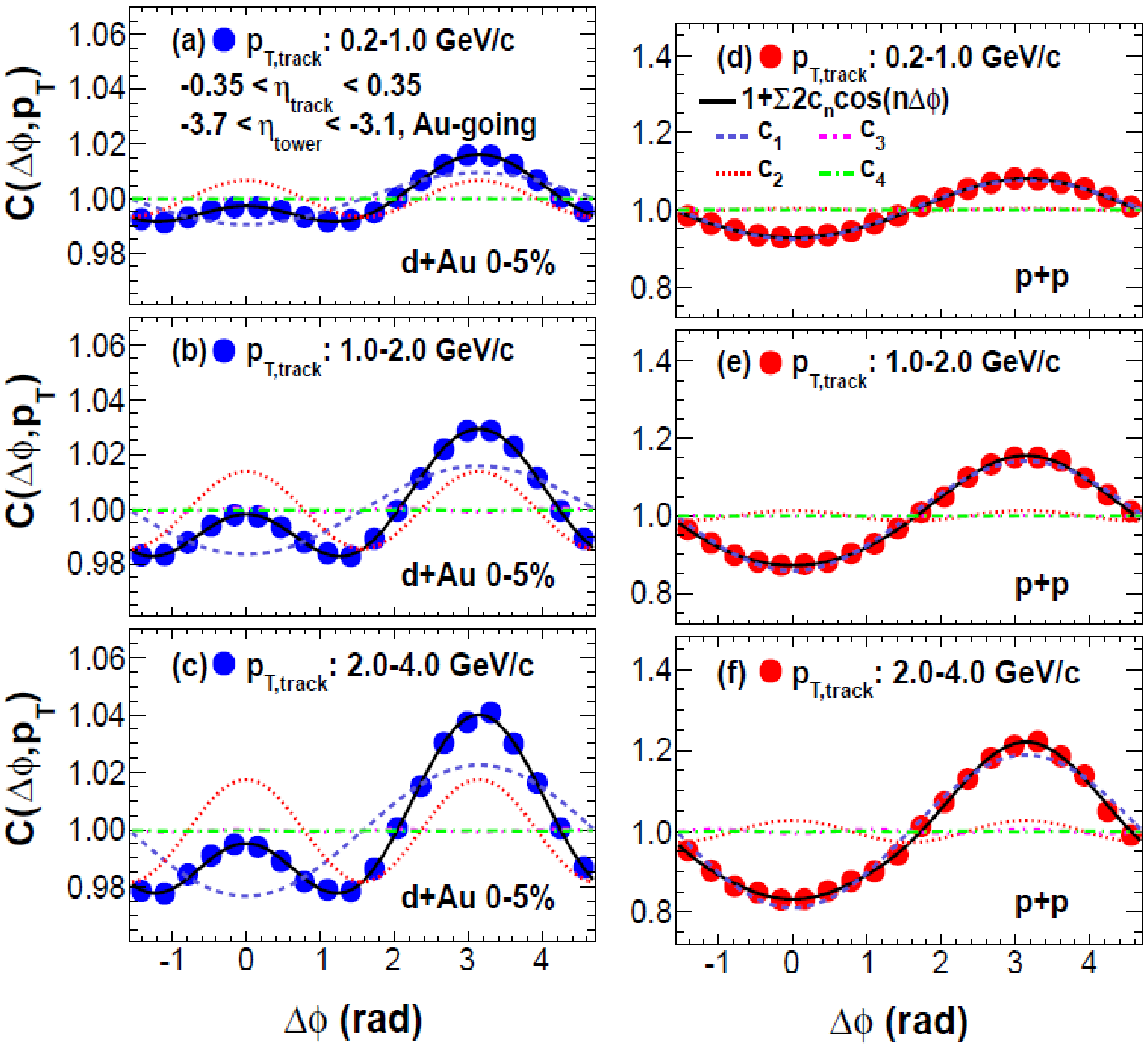



1. Mass splitting of $v_2$ seen for both d+Au and p+Pb with pion larger $v_2$.
2. Viscous hydrodynamics describes d+Au below $p_T$ = 2.0 GeV/c.
3. Note larger mass splitting for p+Pb below $p_T$ = 2.0 GeV/c.
4. May indicate stronger radial flow for p+Pb.

# Do We See a Ridge with d+Au at RHIC?

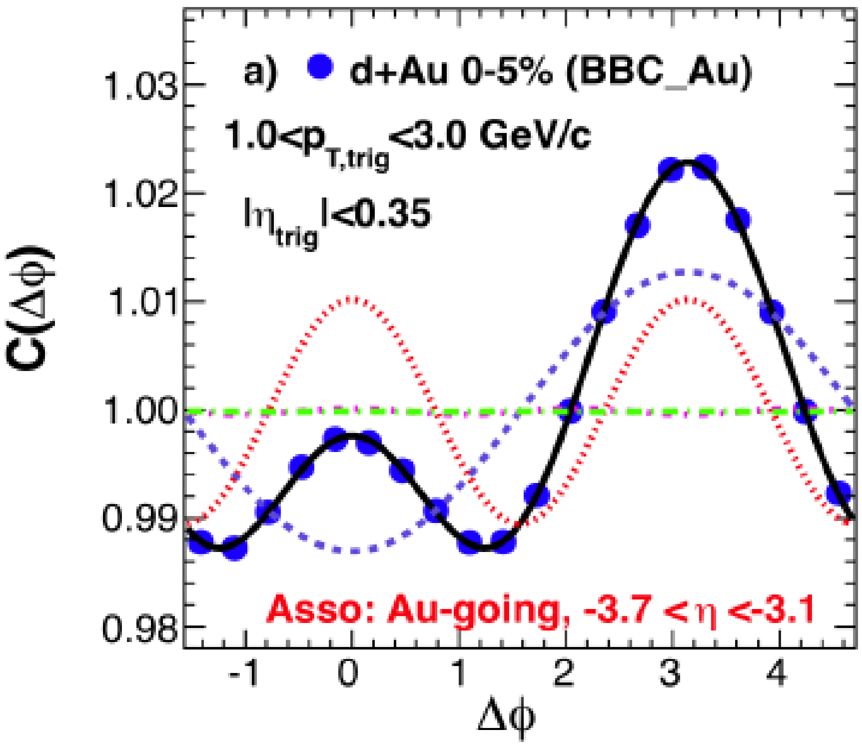
1. Construct correlation function $C(\Delta\phi, p_T)$.
2. Constructed from one track in central arm and one in the forward muon piston calorimeter (MPC).
3. Construct signal distribution $S(\Delta\phi, p_T)$ where $\Delta\phi = \phi_{track} - \phi_{tower}$.
4. Construct mixed-event distribution $M(\Delta\phi, p_T)$ from different events.
5. Construct normalized correlation function $C(\Delta\phi, p_T)$.

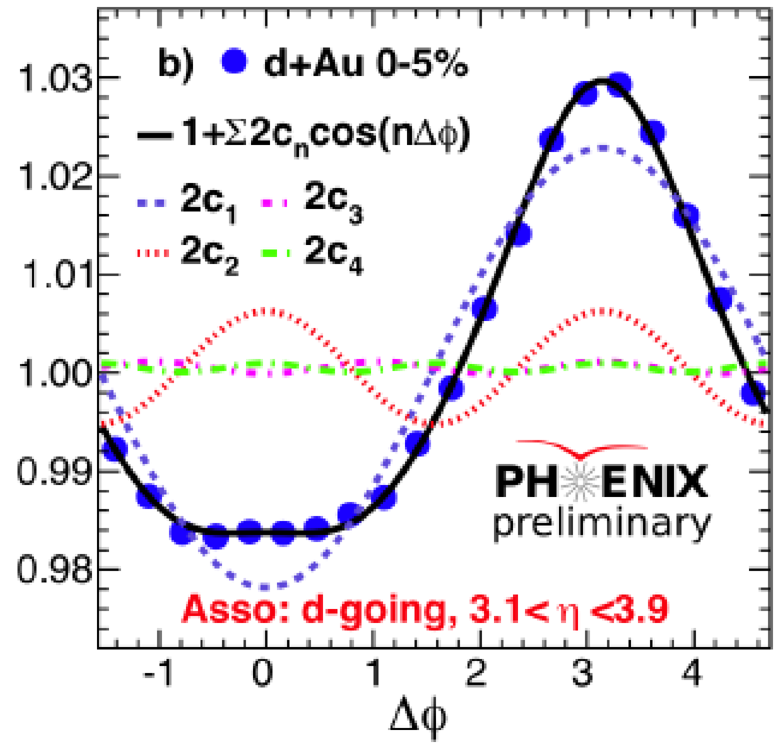
# Correlation Functions for d+Au (0-5%) and p+p (MB)

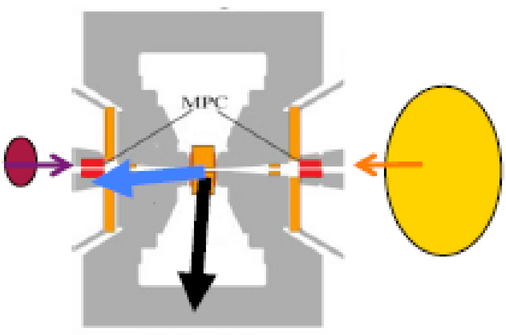


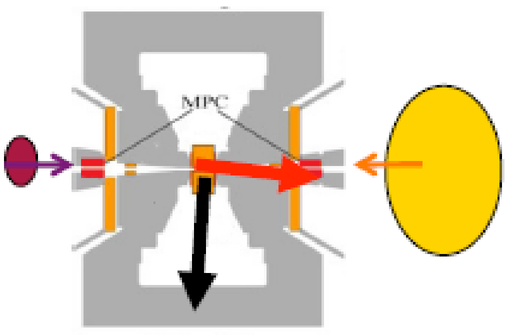

1. Fits to c1 to c4 in $\cos(n\Delta\phi)$.
2. p+p dominated by dipole.
3. d+Au shows a near side peak (ridge).

# Comparison d going and Au going sides.



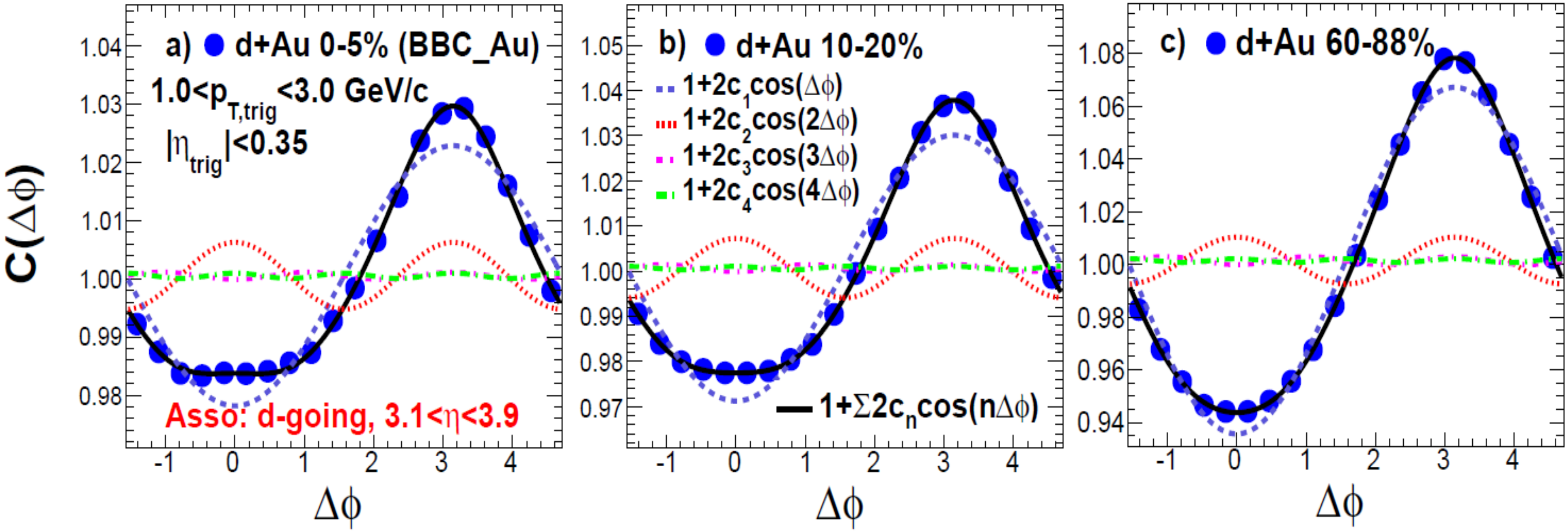



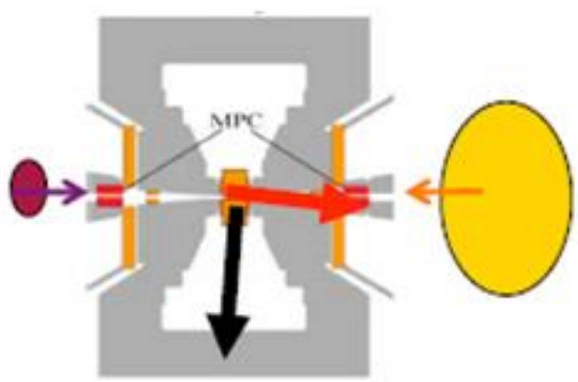




Note ridge in Au but not d going side.

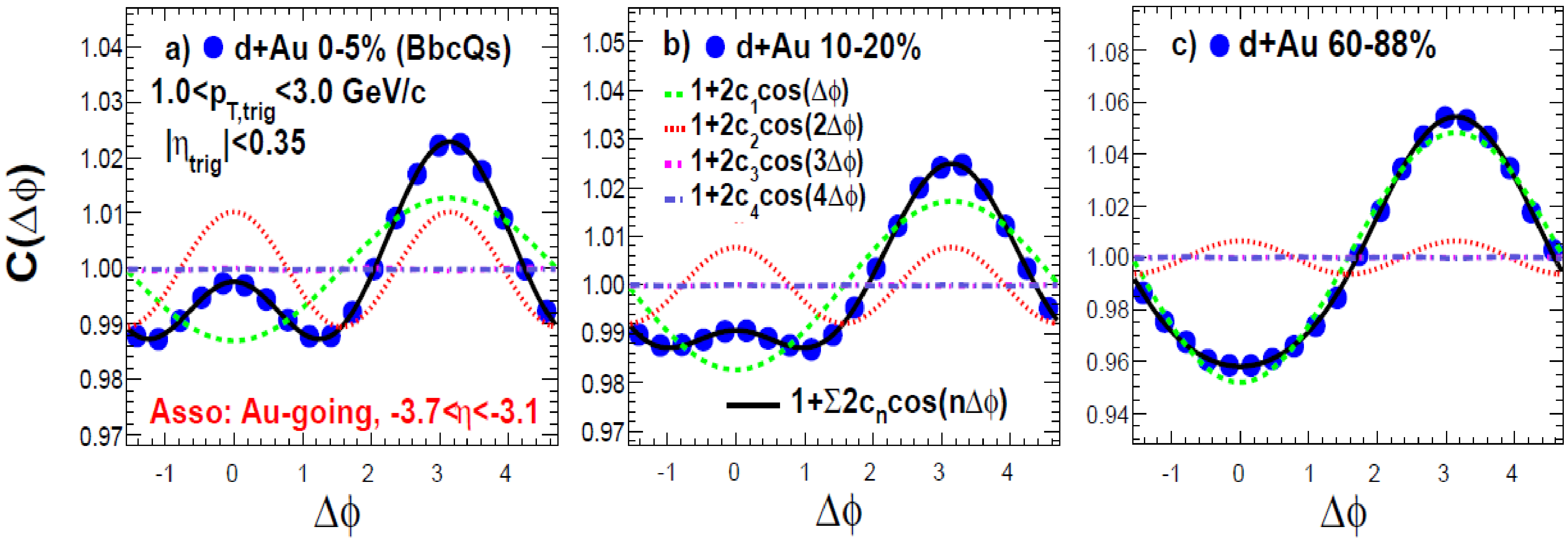
# Details of d Going Correlation

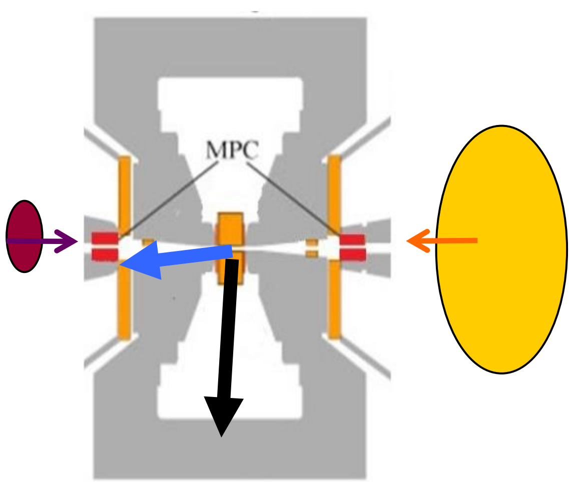



No ridge observed but correlations change with rapidity.

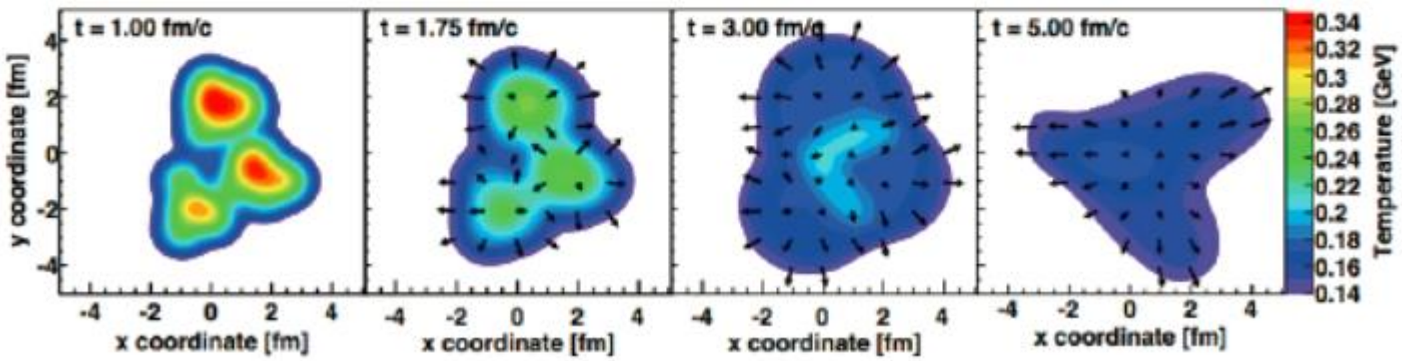
# Details of Au Going Correlation




1. Clear ridge and increases with centrality.
2. Peripheral collision pattern similar for d side and Au side.

# Recent $^{3}$He + Au RHIC run




Results of hydro calculation. Note 3 hot spots.

1. We took $^{3}$He + Au collision data for two weeks this year at RHIC.
2. We collected a data sample of 2.2B events in MB.
3. Eager to see if the odd geometry of $^{3}$He gives us a significant $n_3$ component and more flow.

# C. Beam Energy Scan Results

Table shows all particle species and collision energies run at RHIC

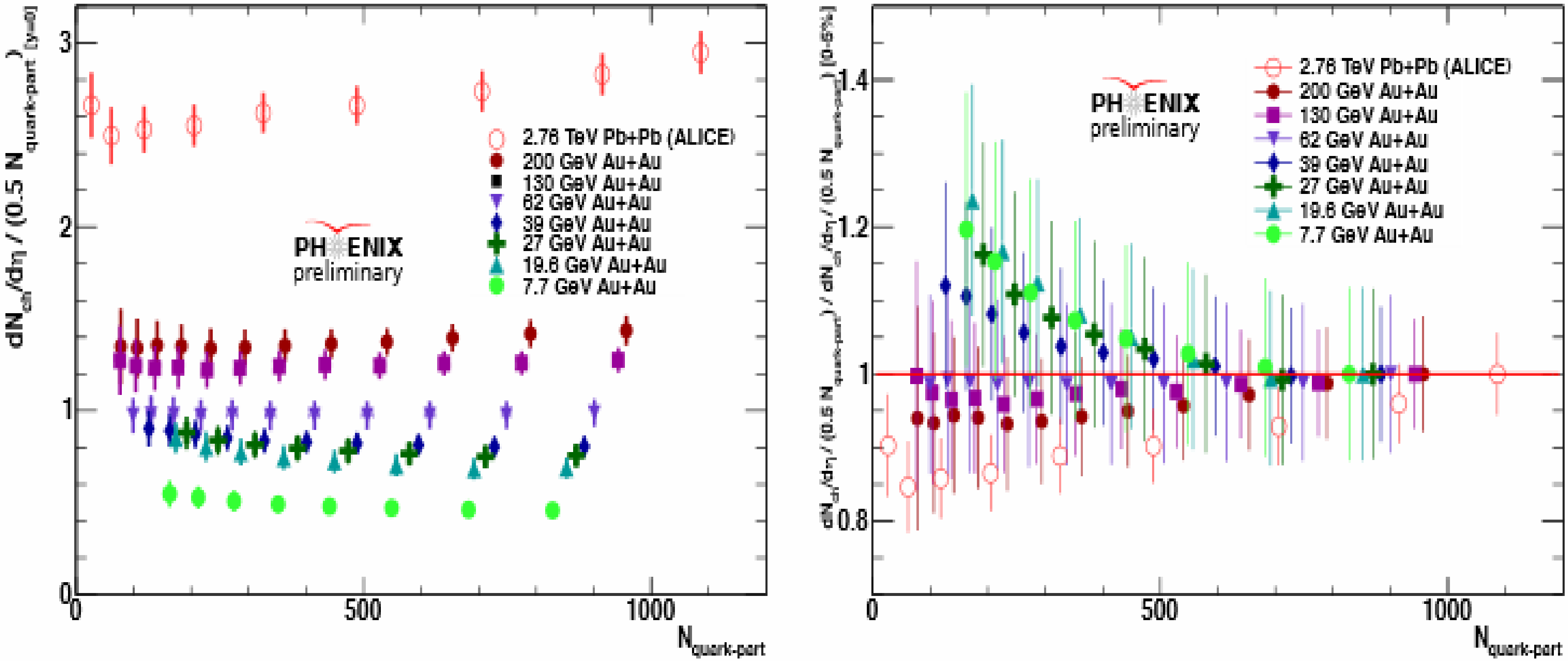
RHIC accelerates particles from p to U and at energies from 7.7 to 200 GeV (510 GeV for p+p).

Next look at scaling results for Au+Au at energies 7.7, 19.6, 27, 39, 62.4, 130 and 200 GeV.

| RHIC Run | Year | Species | Energy | Ldt |
|---|---|---|---|---|
| Run-1 | 2000 | Au+Au | 130 GeV | 1 μb-1 |
| Run-2 | 2001-2 | Au+Au | 200 GeV | 24 μb-1 |
| Run-2 | | Au+Au | 19 GeV | 0.4 μb-1 |
| | | p+p | 200 Gev | 150 nb-1 |
| Run-3 | 2002/3 | d+Au | 200 GeV | 2.74 nb-1 |
| | | p+p | 200 GeV | 0.35 nb-1 |
| Run-4 | 2003/4 | Au+Au | 200 GeV | 241 μb-1 |
| | | Au+Au | 62.4 GeV | 9 μb-1 |
| Run-5 | 2005 | Cu+Cu | 200 GeV | 3 nb-1 |
| | | Cu+Cu | 62.4 GeV | 0.19 nb-1 |
| | | Cu+Cu | 22.4 GeV | 2.7 μb-1 |
| Run-6 | 2006 | p+p | 200 GeV | 10.7 pb-1 |
| | | p+p | 62.4 GeV | 100 nb-1 |
| Run-7 | 2007 | Au+Au | 200 GeV | 813 μb-1 |
| Run-8 | 2007/2008 | d+Au | 200 GeV | 80 nb-1 |
| | | p+p | 200 GeV | 5.2 pb-1 |
| | | Au+Au | 9.2 GeV | |
| Run-9 | 2009 | p+p | 200 GeV | 16 pb-1 |
| | | p+p | 500 GeV | 14 pb-1 |
| Run-10 | 2010 | Au+Au | 200 GeV | 1.3 nb-1 |
| | | Au+Au | 62.4 GeV | 100 μb-1 |
| | | Au+Au | 39 GeV | 40 μb-1 |
| | | Au+Au | 7.7 GeV | 260 mb-1 |
| Run-11 | 2011 | p+p | 500 GeV | 27 pb-1 |
| | | Au+Au | 200 GeV | 915 μb-1 |
| | | Au+Au | 27 GeV | 5.2 μb-1 |
| | | Au+Au | 19.6 GeV | 13.7 M events |
| Run-12 | 2012 | p+p | 200 GeV | 9.2 pb-1 |
| | | p+p | 510 GeV | 30 pb-1 |
| | | U+U | 193 GeV | 171 μb-1 |
| | | Cu+Au | 200 GeV | 4.96 nb-1 |
| Run-13 | 2013 | p+p | 510 GeV | 156 pb-1 |
| Run-14 | 2014 | Au+Au | 15 GeV | 44.2 μb-1 |
| | | Au+Au | 200 GeV | >1.5 nb-1 |

r PHENIX - Quark Matter 2014 3

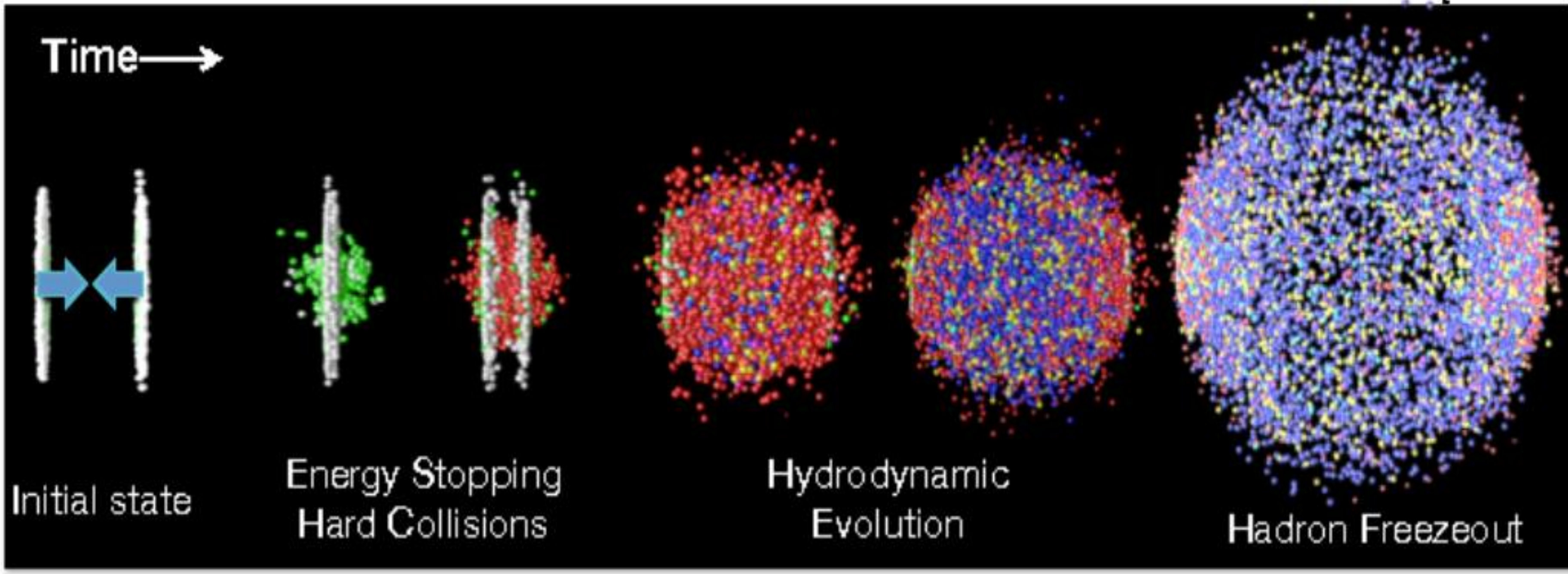
# Beam Energy Scan Q Scaling Results




1. Plot on left shows yield of Au+Au collisions from 7.7 to 200 GeV as a function of centrality but divided by number of valence quarks.
2. Plot on right shows same data but with highest centrality points for each beam energy normalized to 1.0 to show trends.
3. Quark scaling works well from 200 to 62 GeV but breaks down at lower energies.
4. Nucleon scaling works well for energies below 40 GeV.

# HBT as Tool to Study Nuclear Fireball

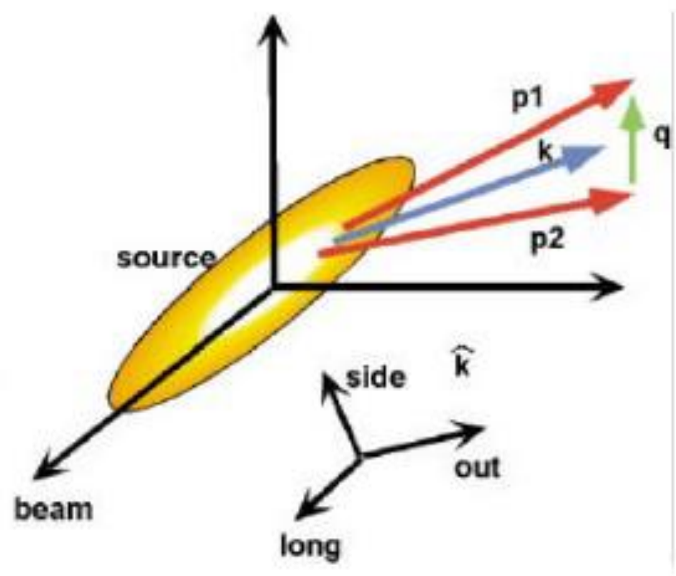
arXiv:1201.4264 [nucl-ex]




1. In 1956 Hanbury Brown and Twiss (HBT) measured angular diameter of Sirius from light.
2. In 1960 Goldhaber et al. measured correlation functions between pions in $p+p_{bar}$ reactions.
3. It is possible to use HBT to determine correlation functions for the nuclear fireball at kinetic freeze out.

# Construction of 2 Pion Correlation Function

1. Determine 2 pion correlation function $C_2(q) = A(q)/B(q)$.
2. $A(q)$ is measured distribution momentum difference $q = p_2 - p_1$.
3. $B(q)$ is pair uncorrelated distribution from different events.
4. $C_2(q) = N[(\lambda(1+G(q)))F_c + (1-\lambda)]$
5. $G(q) = \exp(-R^2_{side}q^2_{side} - R^2_{out}q^2_{out} - R^2_{long}q^2_{long})$
6. Measured $C_2(q)$ can be used to determine R.




N = normalization factor

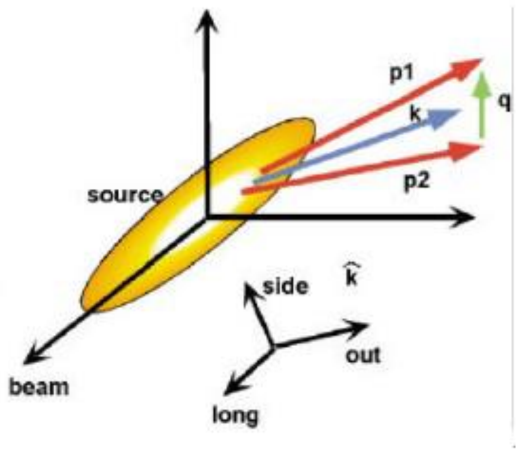
$\lambda$= correlation strength

$F_c$ = Coulomb correction factor

R's = Gaussian HBT radii

$R_{long}$ measured in $q_{long}$ = 0 frame

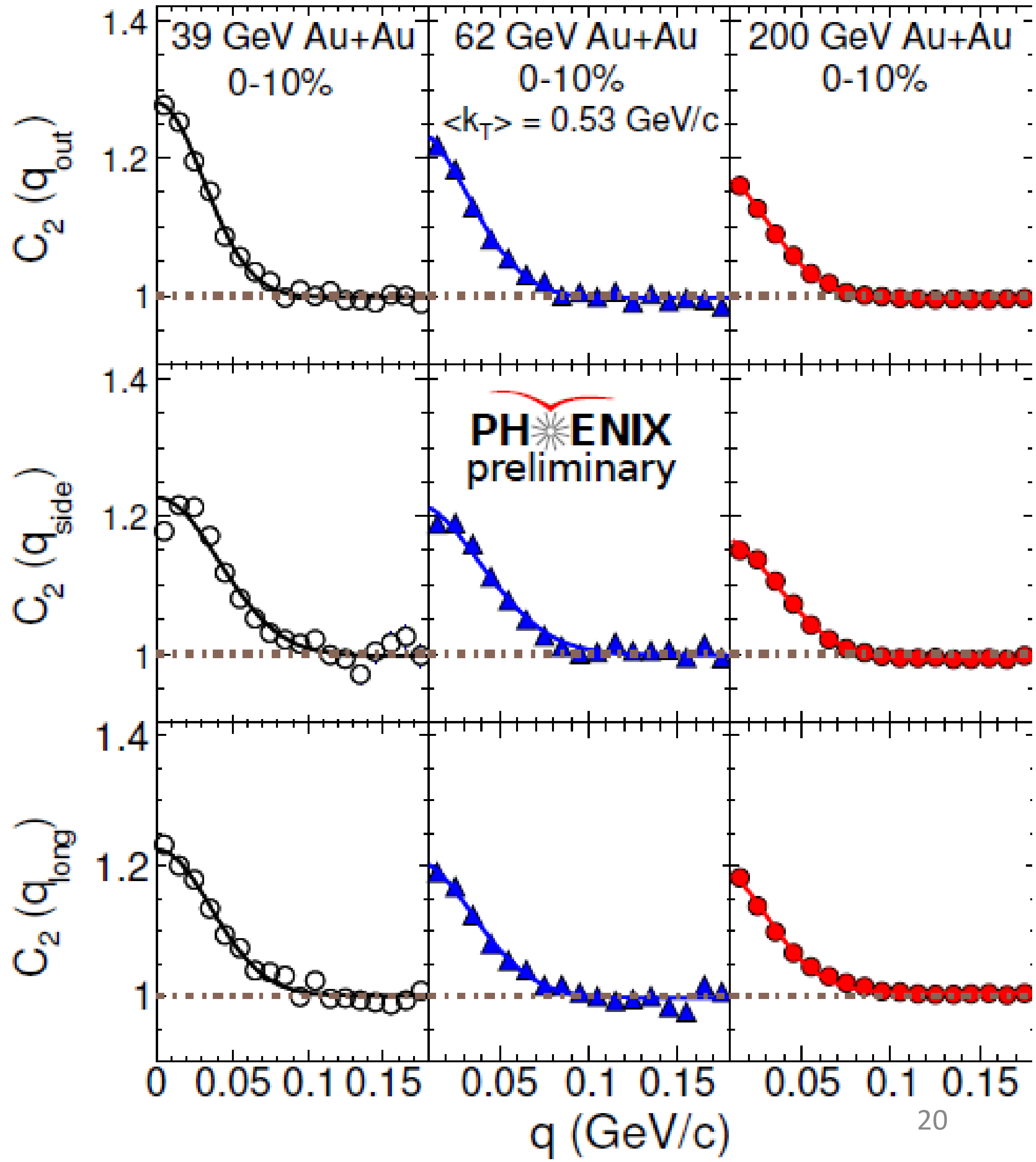
# C's for 39, 62 and 200 GeV Au+Au




$q_{long}$ along beam direction

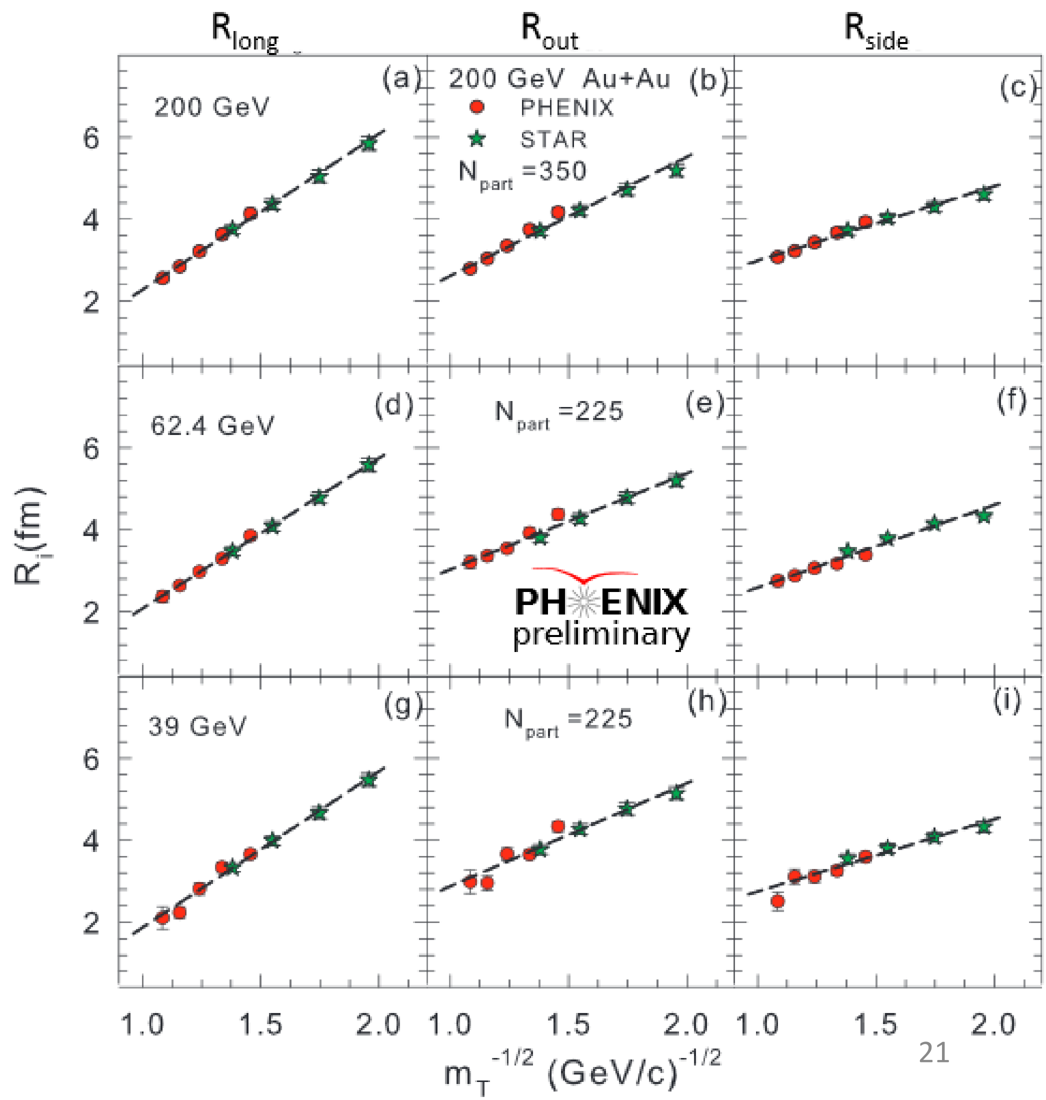
$q_{out}$ parallel to $k_T$ of pair

$q_{side}$ perpendicular to beam and $k_T$ of pair

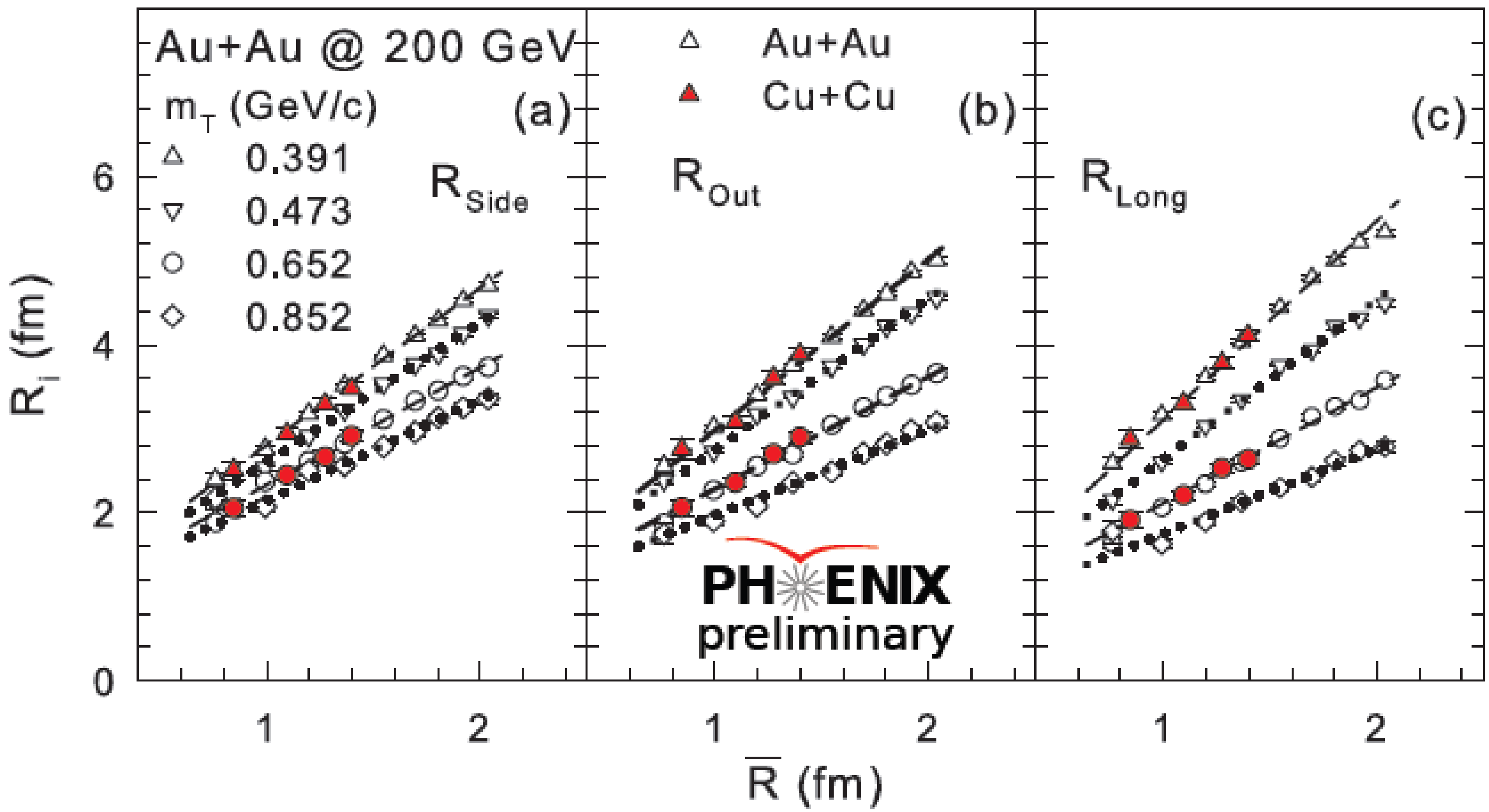


# $m_T$ Scaling is Valid.

1. HBT radii scale linearly with $m_T^{-1/2}$.
2. Star and PHENIX agree.



# Geometric Scaling is Valid.

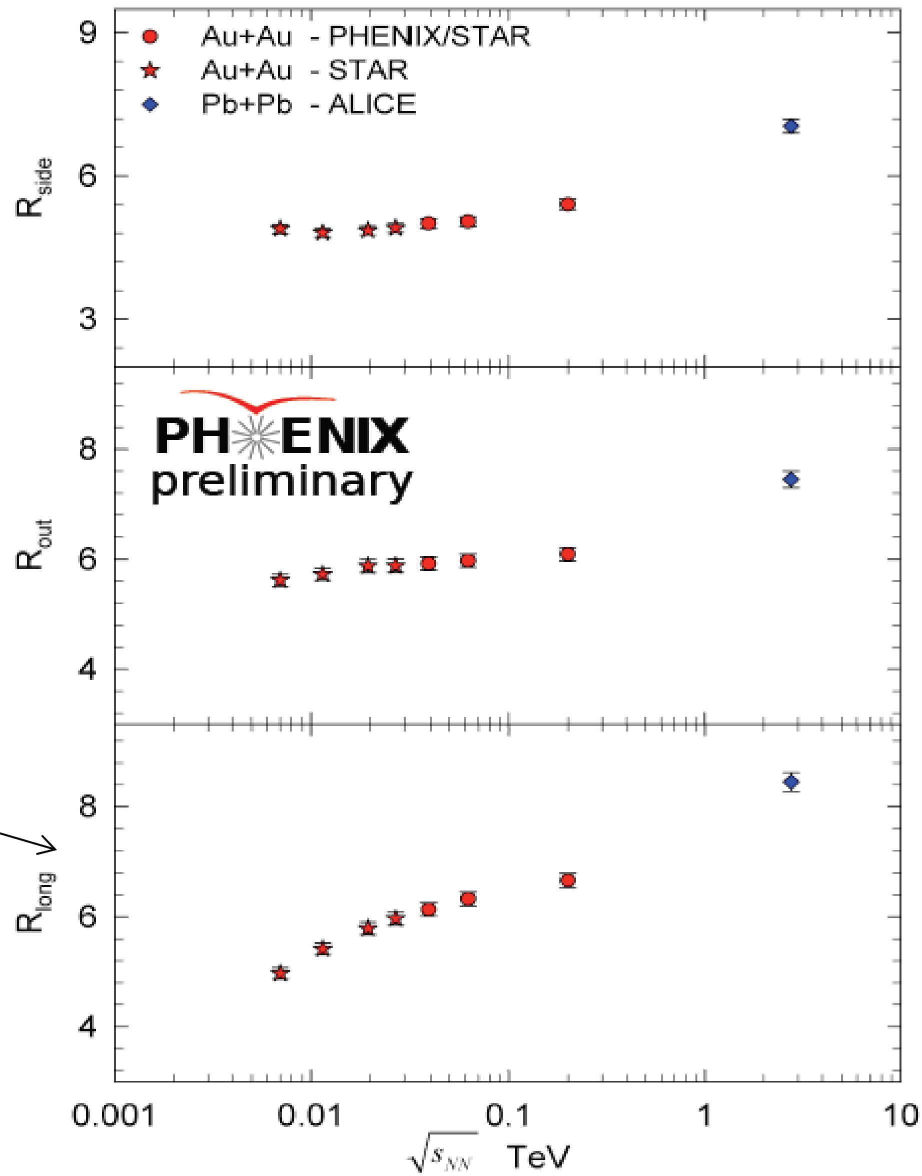



1. HBT pion radii scale linearly with initial radius.

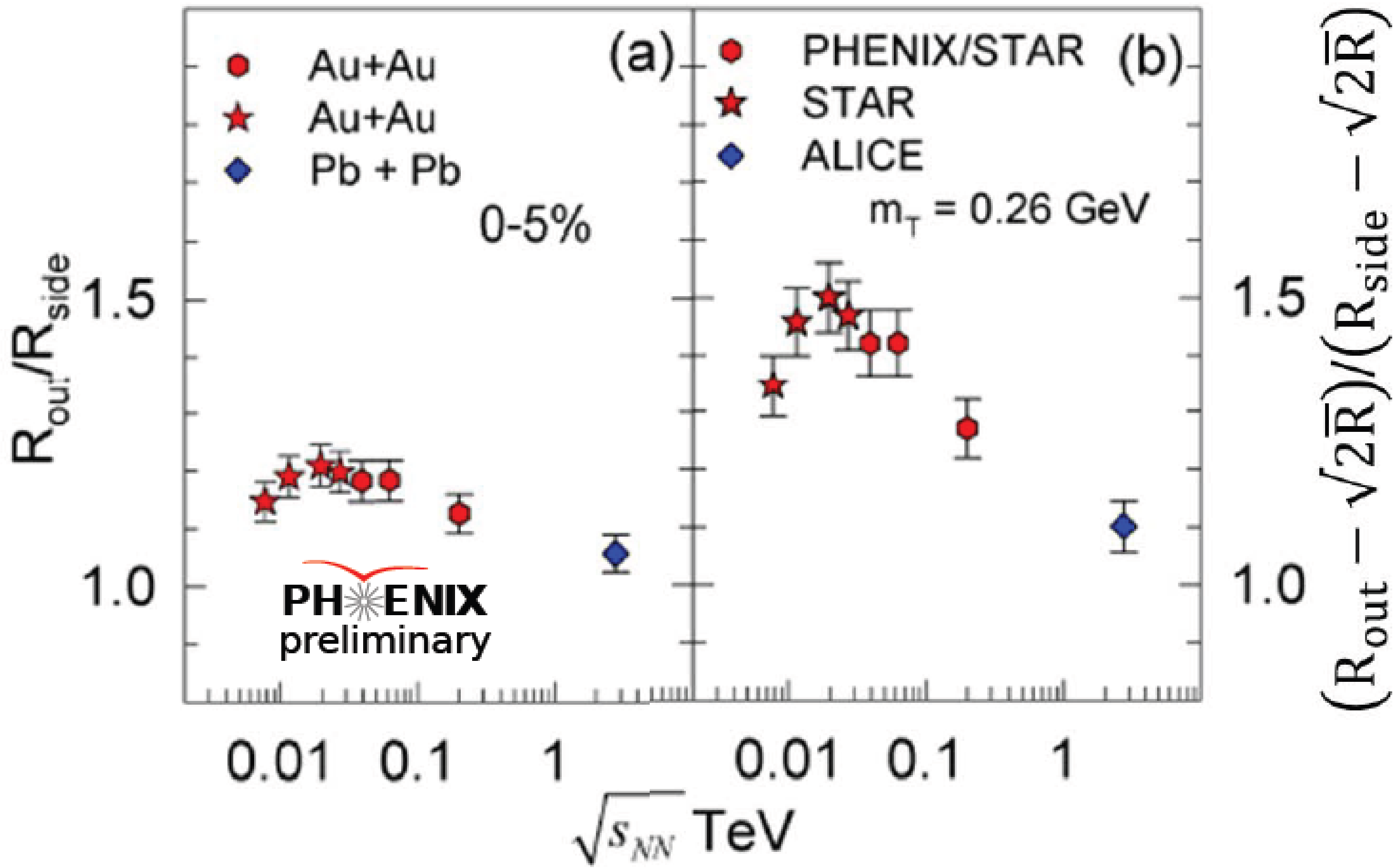
2. Hydro associates larger expansion time with larger size.

# Results HBT Radii vs Collision Energy

1. PHENIX, STAR and ALICE data.
2. Interpolation to $m_T = 0.26$ GeV.
3. $R_{long}$ is a proxy for $\tau$. Note increase with energy.
4. Construct ratios and differences.

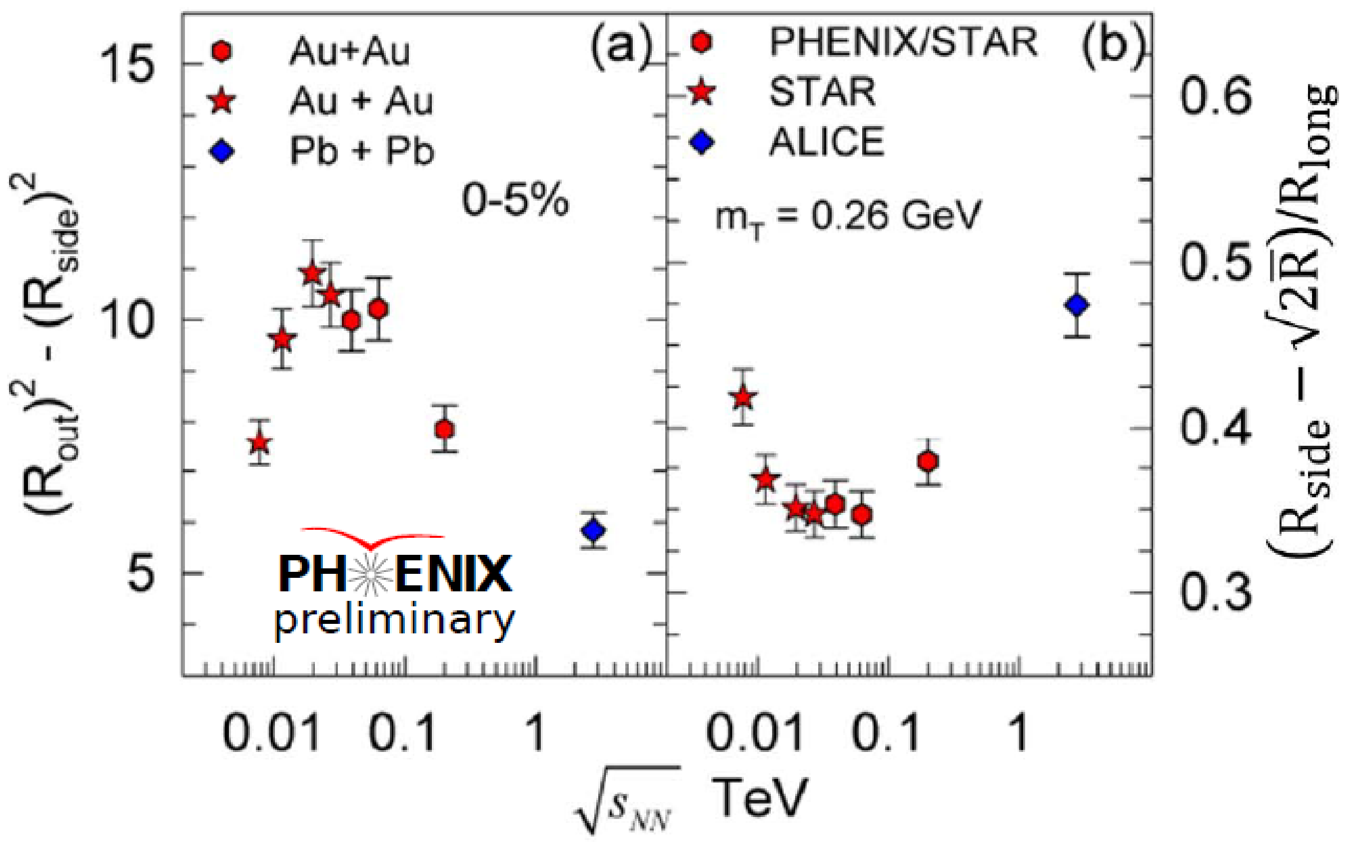


# Trends of Radii Results with Energy




1. $R_{out}/R_{side}$ shows maximum around 30 GeV.
2. $R_{out}/R_{side}$ sensitive to emission duration $\Delta\tau$.

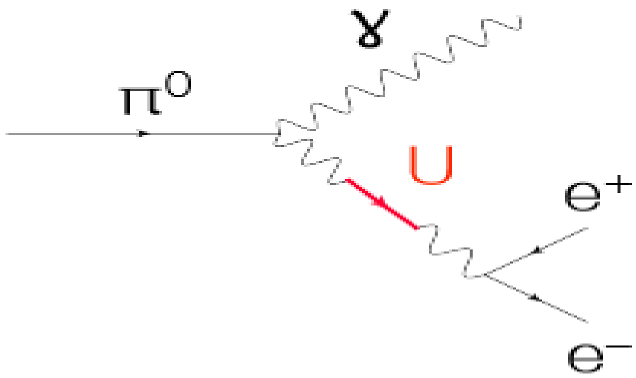
# More Trends of Radii Results with Energy

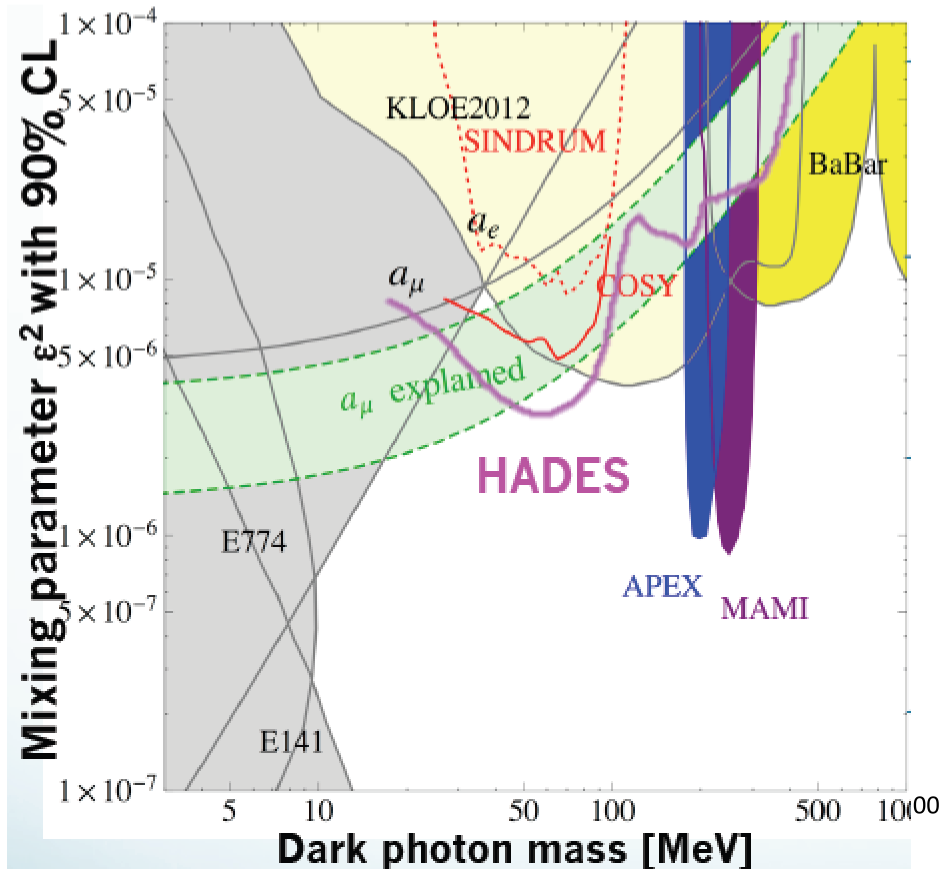



1. $(R_{out})^2$ - $(R_{side})^2$ is also a proxy for emission duration $\Delta\tau$ with maximum at around 30 GeV
2. $R_{side}$ / $R_{long}$ is a proxy for expansion speed and the speed of sound $c_s$ in the medium and has minimum at around 30 GeV.

# Dark Photons and Muon g-2 SM Discrepancy

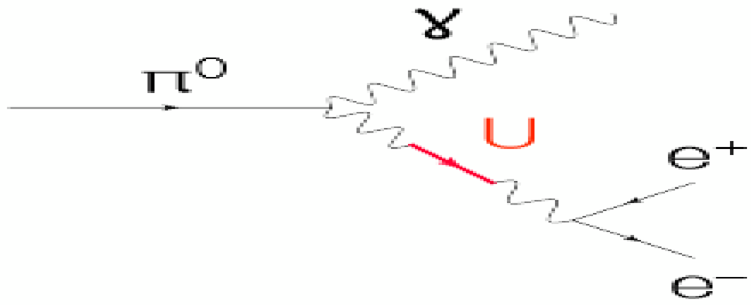
1. Muon g-2 measured 3.6σ discrepancy from SM.
2. Dark photons U can explain discrepancy.
3. Many experiments limit U range.
4. Muon g-2 explainable band (90% CL) still survives for 30-50 MeV.



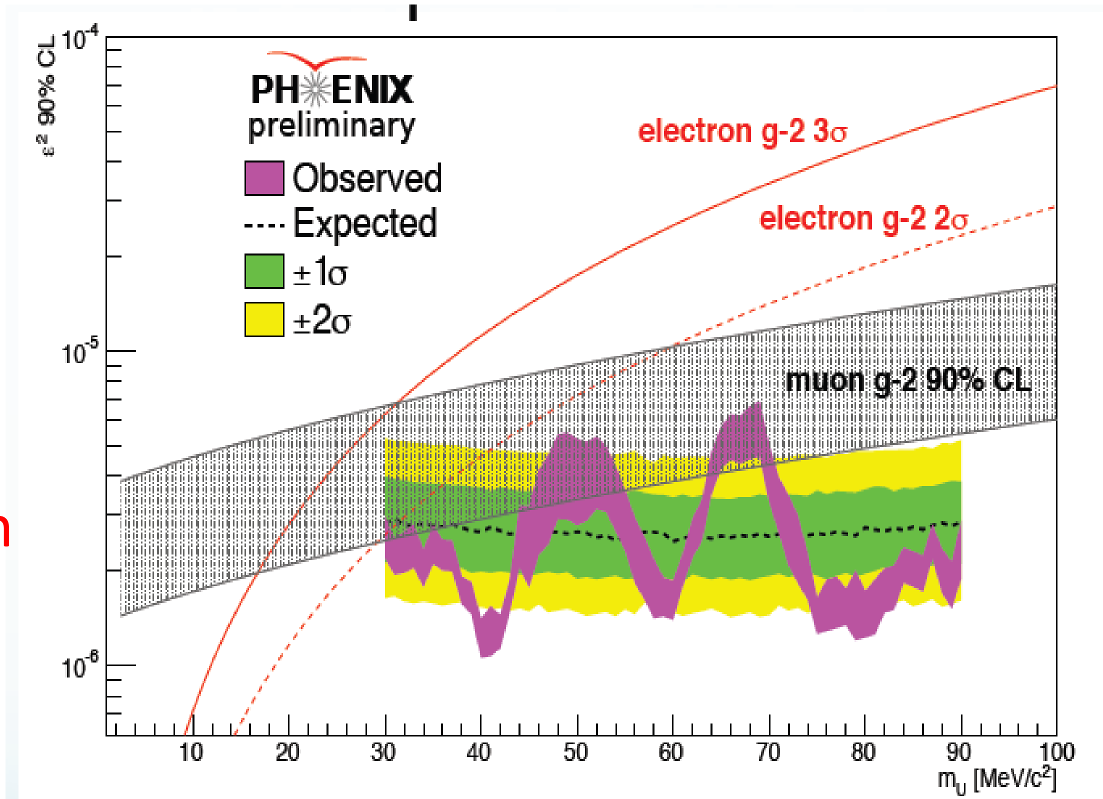



# PHENIX Limits for Dark Photons

1. PHENIX has large sample of $\pi^0$s and history of $e^+e^-$ analysis.




2. Measured Dalitz pairs $\pi^0/\eta \rightarrow \gamma U \rightarrow \gamma e^+e^-$
3. 1.4 million $e^+e^-$ pairs from p+p and d+Au collisions.
4. Region from 30 to 45 MeV eliminated but small region survives.
5. Will add pairs from p+p (2009).



# Summary

1. Evidence for long range correlations and flow observed in 200 GeV d+Au $v_2$ and ridge measurements at RHIC.

2. The RHIC beam energy scan (BES) shows break down in quark scaling below 62 GeV.

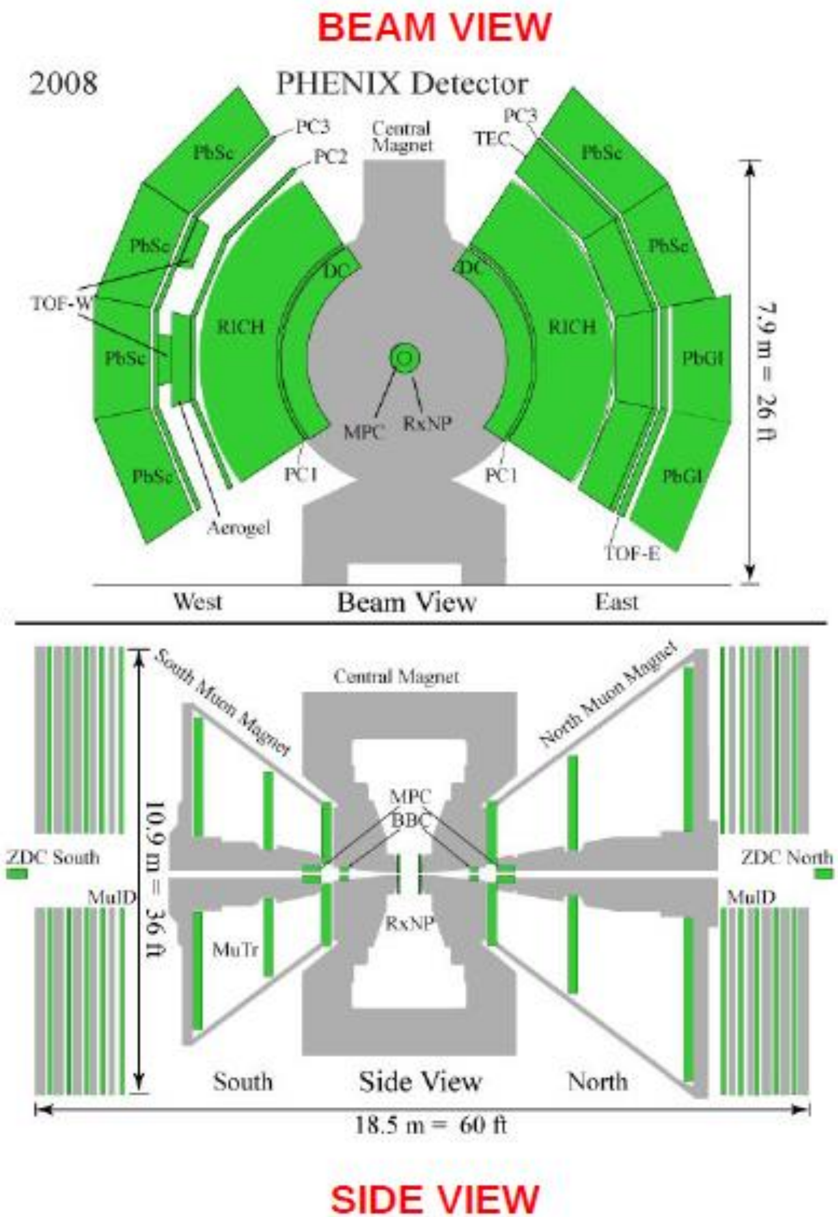
3. HBT measurements have determined fireball radii for Au+Au collisions at kinetic freeze out which suggests possible softening of the nuclear matter equation of state in the vicinity of 30 GeV.

4. Dalitz electron pair measurements have limited the range of dark-photon masses as an explanation of the muon g-2 anamoly.

Thank you for your attention!!

# Backup Slides

# A. PHENIX




**Zero Degree Calorimeter (ZDC) & Beam Beam Counter (BBC)**
Vertex and centrality determination

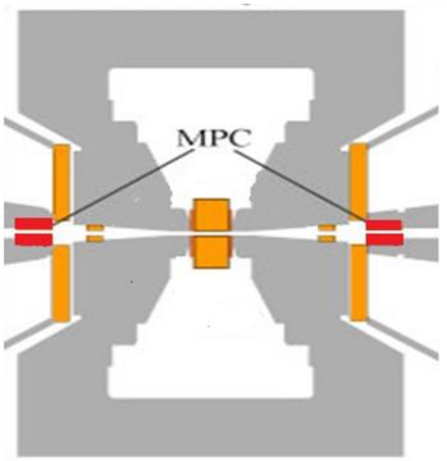
**Drift Chamber (DC) & Pad Chamber (PC)**
Tracking information

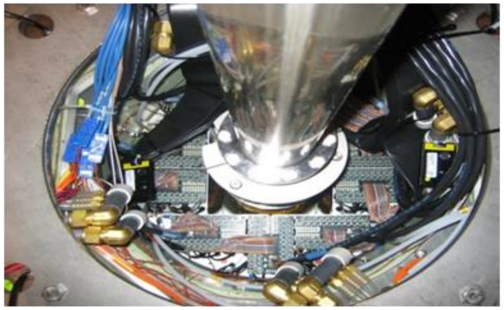
**Electromagnetic Calorimeter (EMC) Lead Scintillator Sectors (Six Total)**
PID information

**Time-of-Flight Detector (TOF)**
PID information

With their good timing resolution, the EMC and TOF detectors provide for very good PID capabilities

# Muon Piston Calorimeter (MPC)



Forward/backward-rapidity $3<|\eta|<4$

Extend the rapidity range by measuring the correlation between tracks with $|\eta|<0.35$)

For MPC towers: $|\Delta\eta|>2.75$!

Makes correlation studies possible over wide $\eta$ range.

6

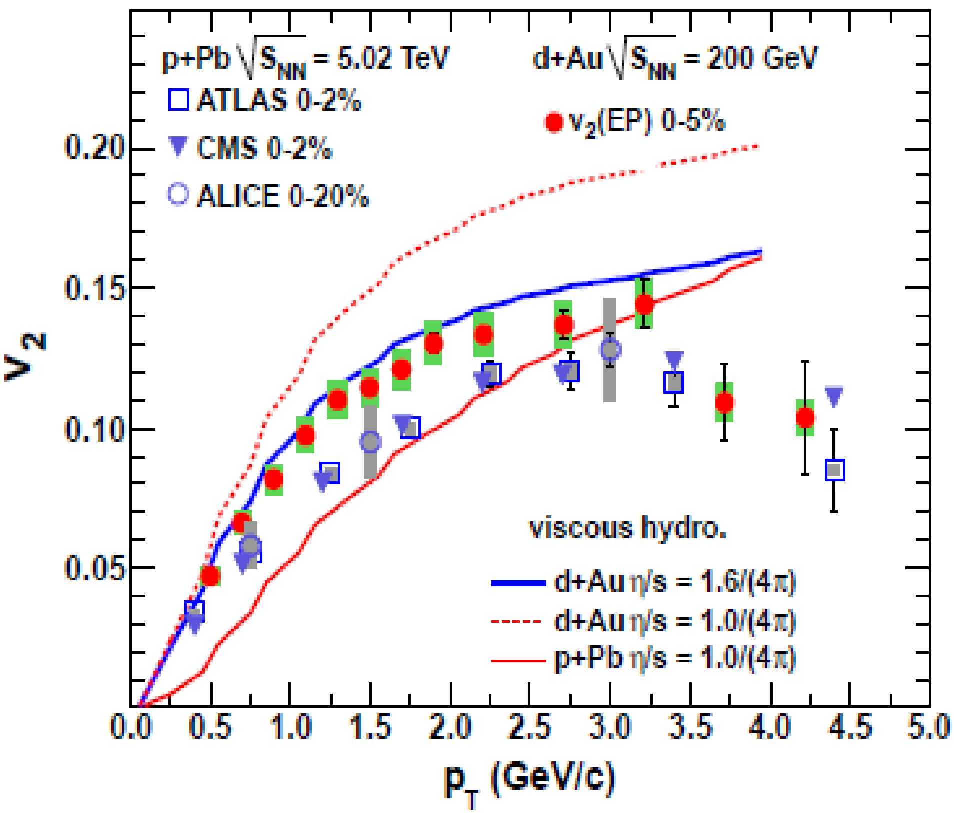
# d+Au and Flow in Small Systems

We observe $v_2$ and flow in d+Au at 200 GeV for charged hadrons at RHIC. Compare with 5.02 TeV p+Pb at LHC.

1. $v_2$ calculated for charged tracks using the event plane method.

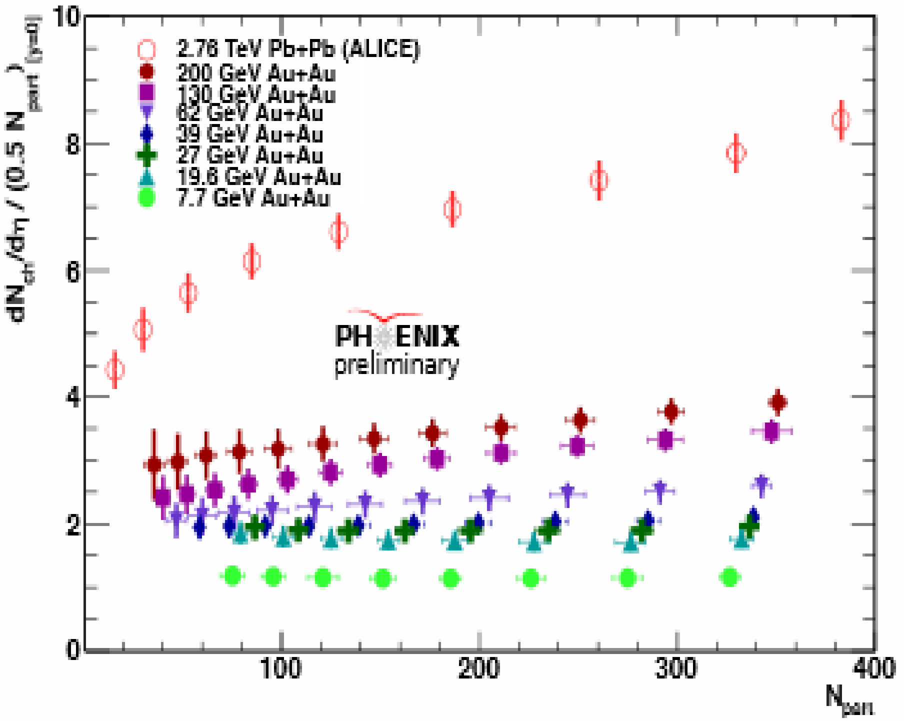
2. $v_2$ for d+Au generally higher than p+Pb for $p_T < 3$ GeV/c.

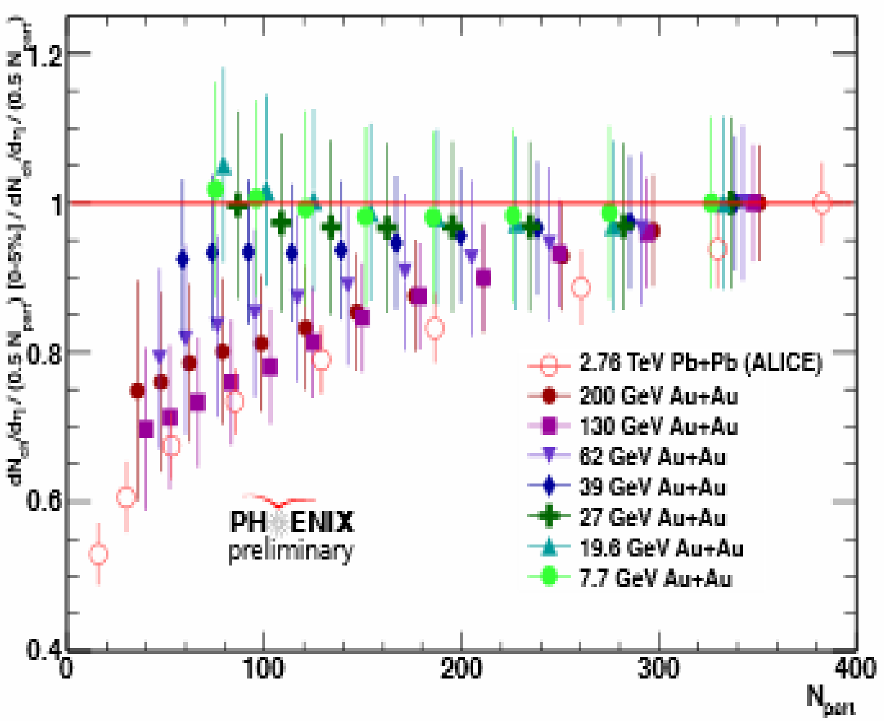
3. Hydrodynamic model predictions good with $\eta/s$ best at $1.6(4\pi)$ for d+Au but $1.0(4\pi)$ for p+Pb.



# C. Beam Energy Scan Results

## Nucleon scaling results




1. Plot on left shows yield of Au+Au collisions from 7.7 to 200 GeV as a function of centrality but divided by the number of nucleons. Note ALICE Pb+Pb results.
2. Plot on right shows same data but with highest centrality points for each beam energy normalized to 1.0 to show trends.
3. Nucleon scaling works well from 7.7 to 39 GeV, breaks down at higher energies.