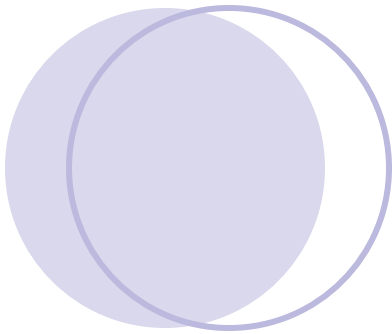


# Recent Results From **RHIC**

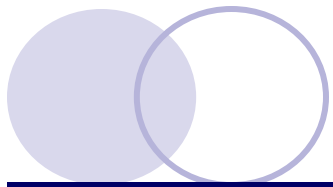


Olga Evdokimov

University of Illinois at Chicago

## Outline:

- HI @ RHIC - Data & Detectors
- Selected recent results
  - Jets, jet-like correlations and medium properties
- Summary and outlook

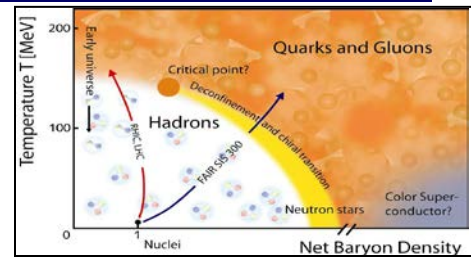
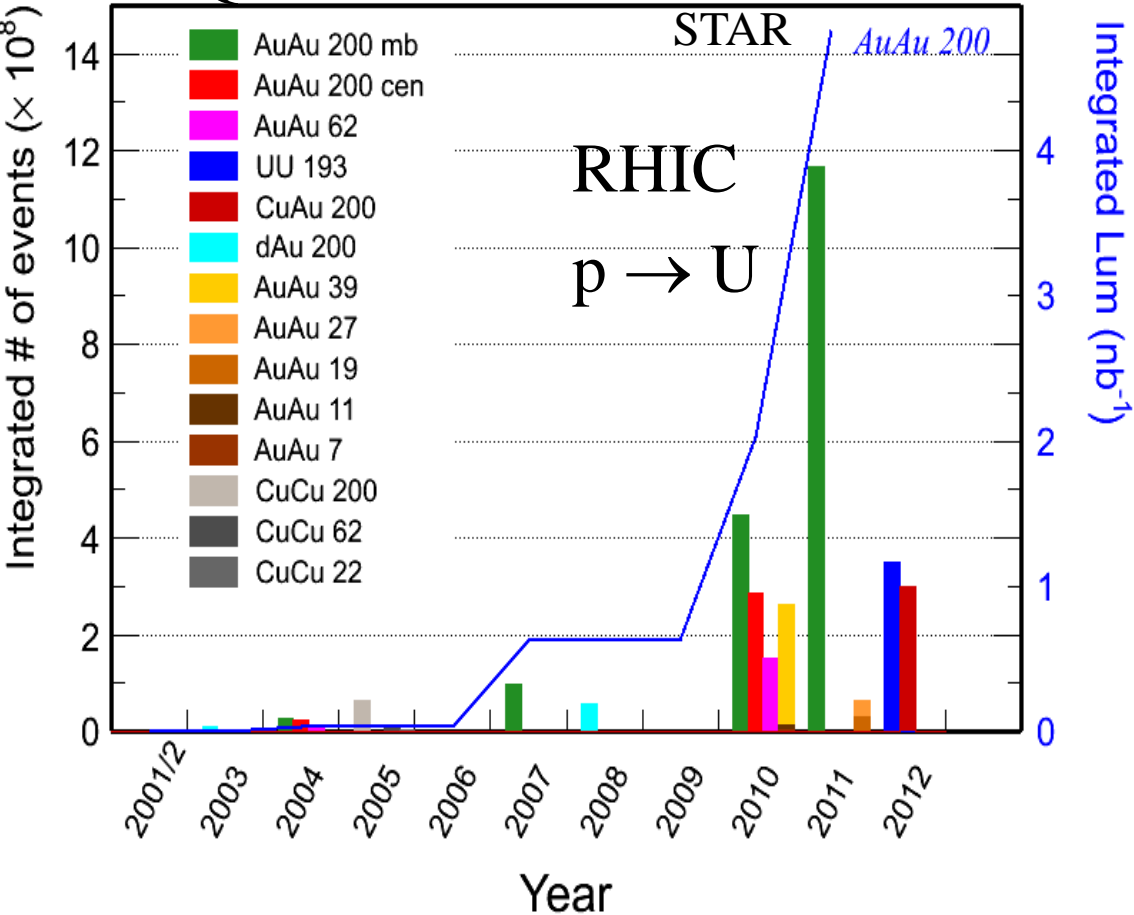


# A+A Data Collection

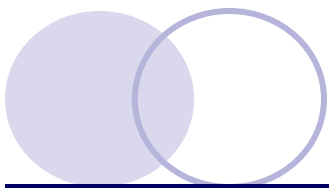


- HI Program:

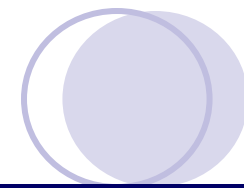
## QCD matter under Extreme Conditions



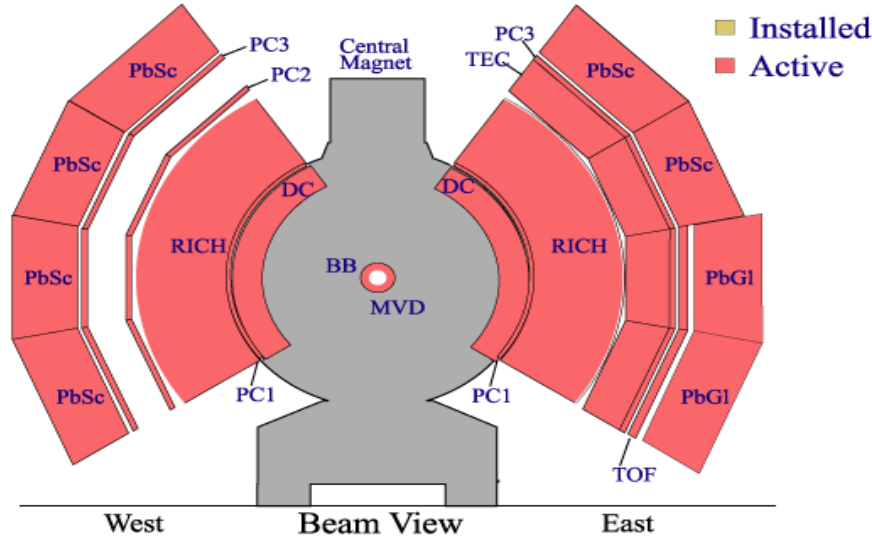
- sQGP Studies
  - EoS,
  - $E_{loss}$  in QCD medium
  - ....
- Beam Energy Scan
  - QCD critical point search,
  - Onset of deconfinement,
  - Chiral symmetry restoration
  - ...



# PHENIX Detector



## PHENIX Detector - Second Year Physics Run



## Central Arm Detectors

Drift, Pad, Time-Extension Chambers

RICH, EMCal

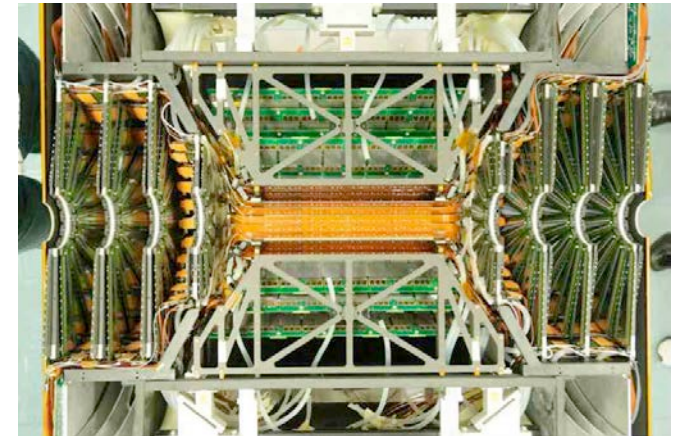
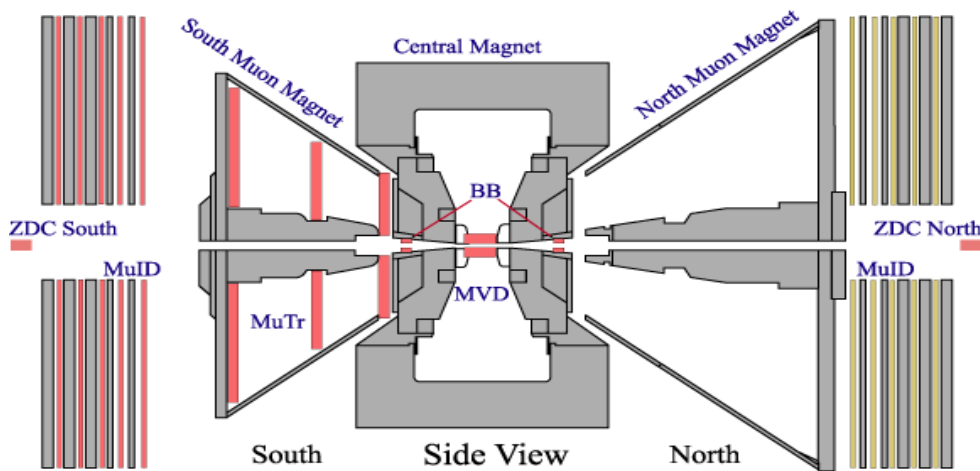
- 2 arms  $90^\circ$  in  $\phi$
- 0.7 units of  $\eta$

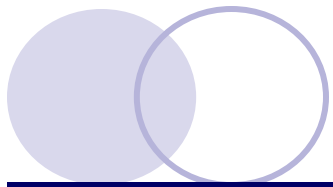
## Muon Arms Detectors

MuTr, MuID, MPC

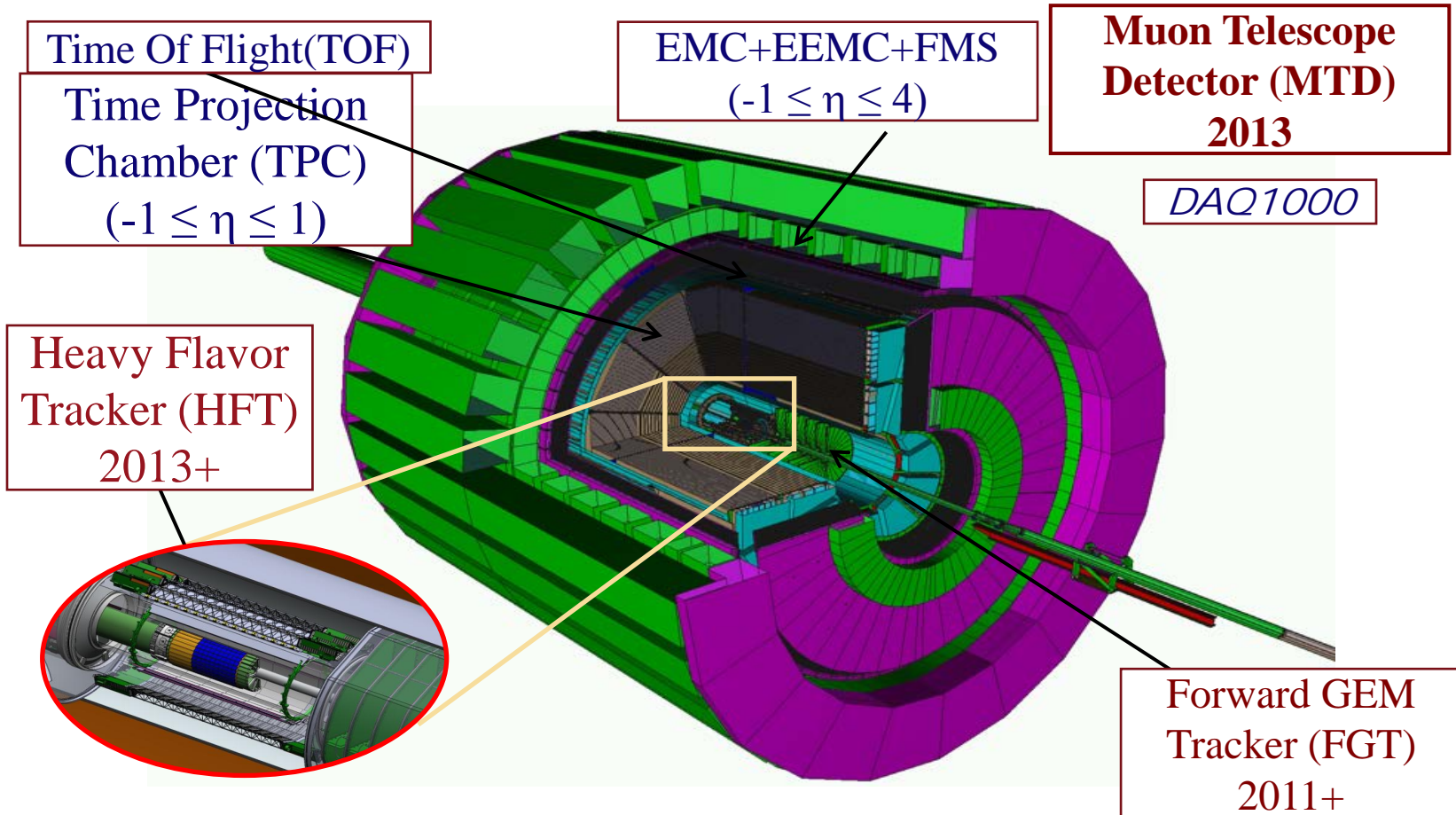
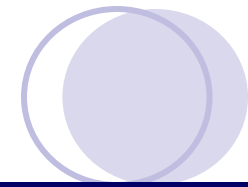
- $1.2 < |\eta| < 2.2(2.4)$
- $3 < |\eta| < 4$

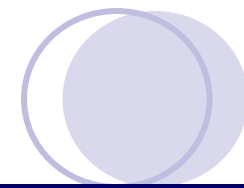
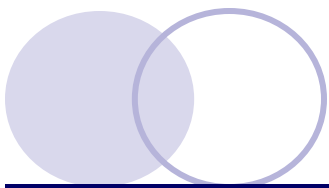
## Upgrade (HF physics): VTX, FVTX





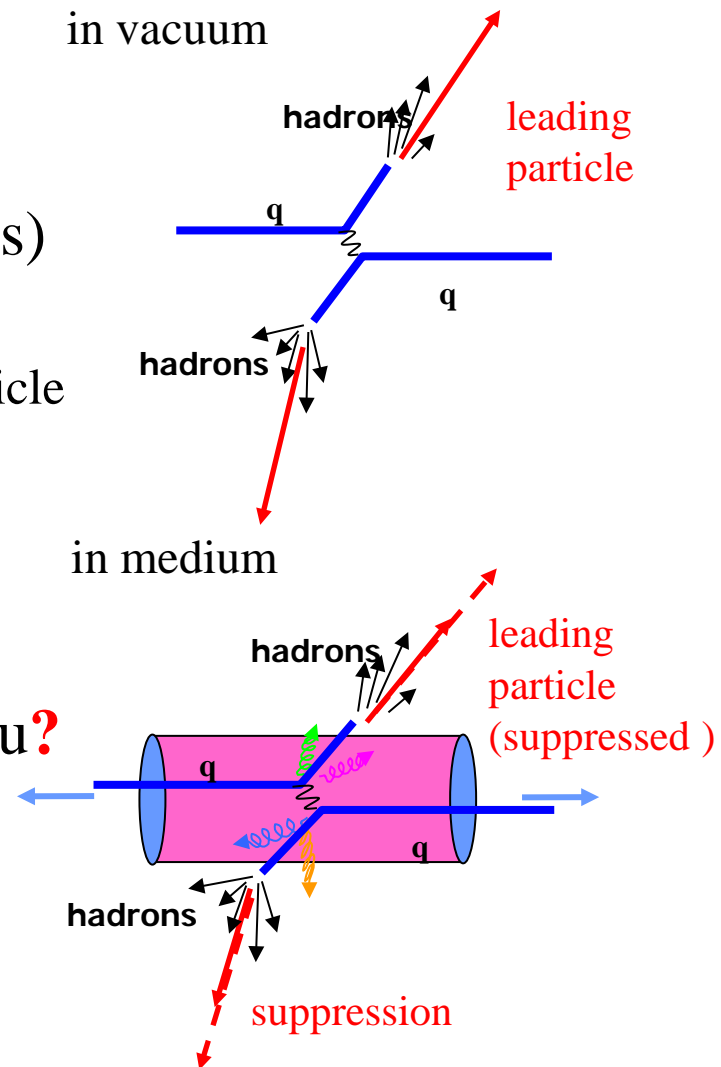
# STAR Detector



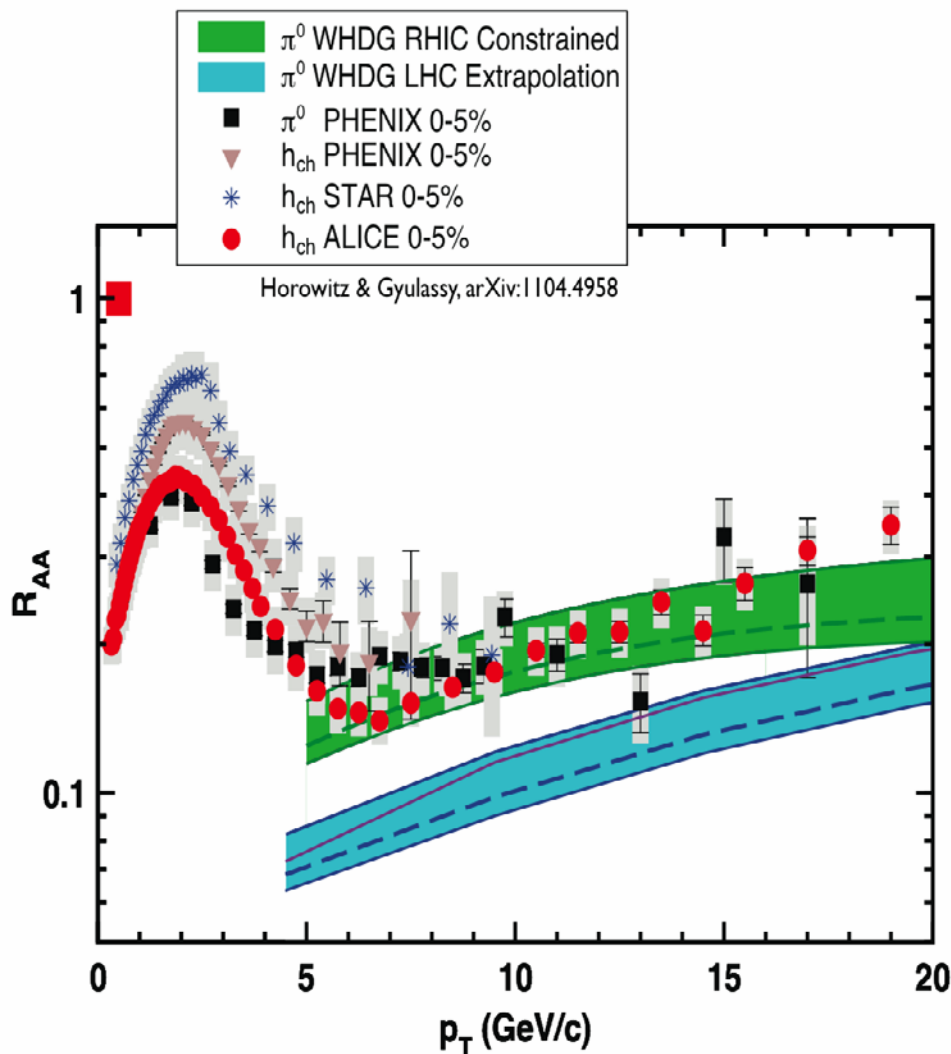


## Jet Quenching

- Angular correlations (with high  $p_T$  probes)
  - Early stage (pQCD) probes
  - Interactions of created matter with passing particle
    - Jet quenching
    - Azimuthal anisotropy
  - Long range correlations
- Control over cold matter effects via d+Au?
- **Initial vs. Final state effects?**



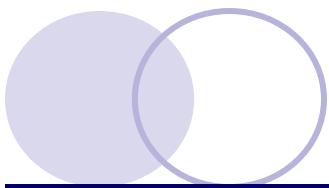
# Early Quenching Sightings - $R_{AA}$



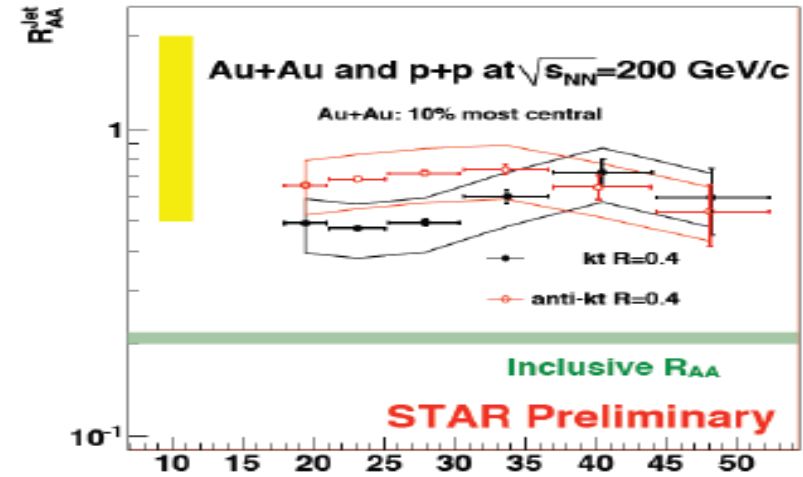
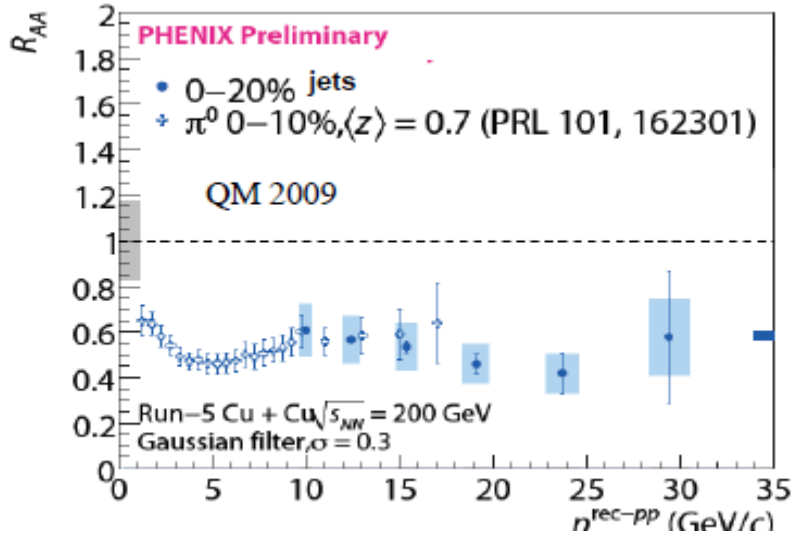
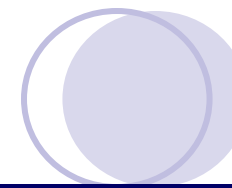
- $R_{AA}$  – the first tool for jet quenching studies

$$R_{AA}(p_T) = \frac{d^2 N^{AA} / dp_T d\eta}{T_{AA} d^2 \sigma^{NN} / dp_T d\eta}$$

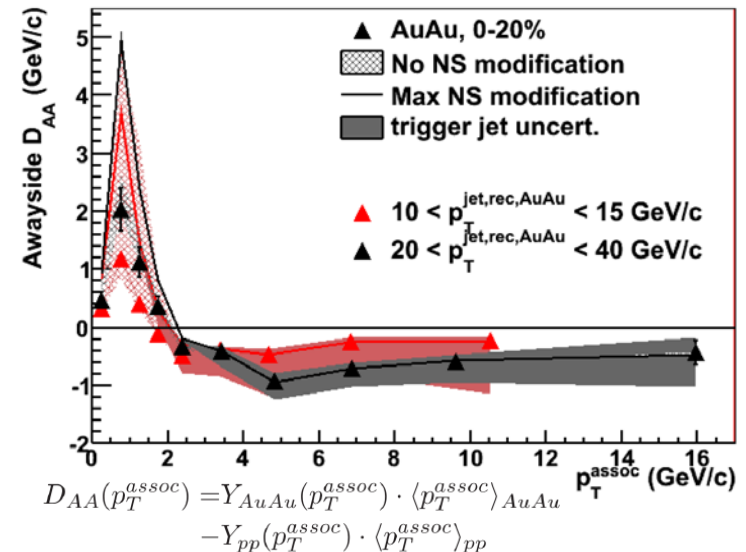
- Colorless probes check  $N_{coll}$  scaling: Direct photons
- High  $p_T$  hadron suppression:
  - Final state effect in Au+Au collisions
  - Observation extends to all accessible  $p_T$  range
- High density opaque medium

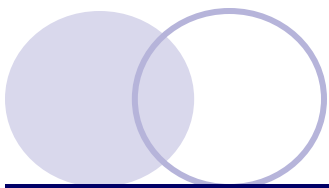


# Now –Jet $R_{AA}$



- Jet  $R_{AA}$  shows suppression, but the level is dependent on the method used
- Redistribution of jet momenta is shifted towards soft hadrons [note the difference in the crossing point with LHC]
- Still under construction





# Jet Quenching

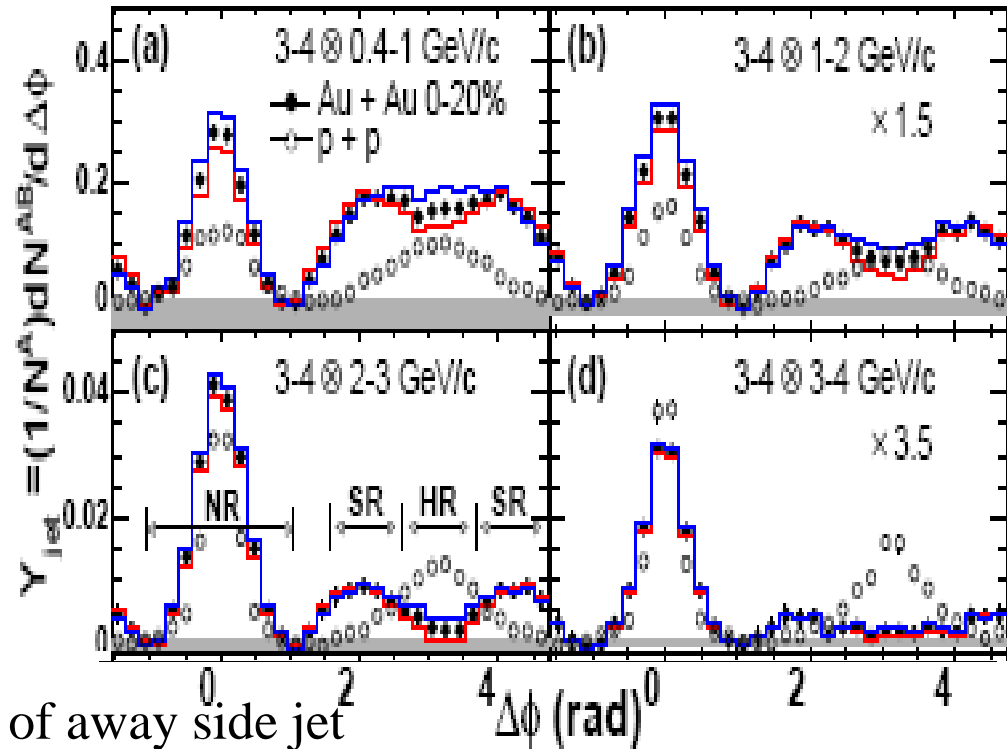
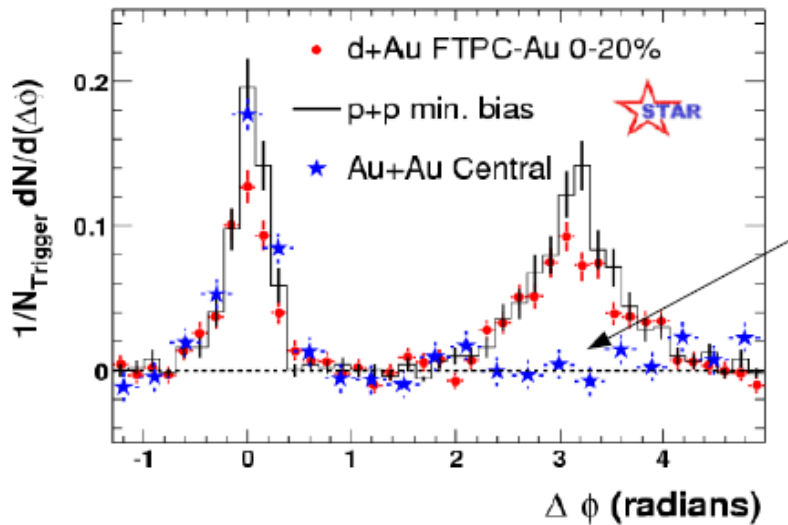


trigger:  $4 < p_T(\text{trig}) < 6 \text{ GeV}$   
 associated:  $2 < p_T < p_T(\text{trig})$

STAR:  
*PRL 90, 082302 (2003)*

PHENIX

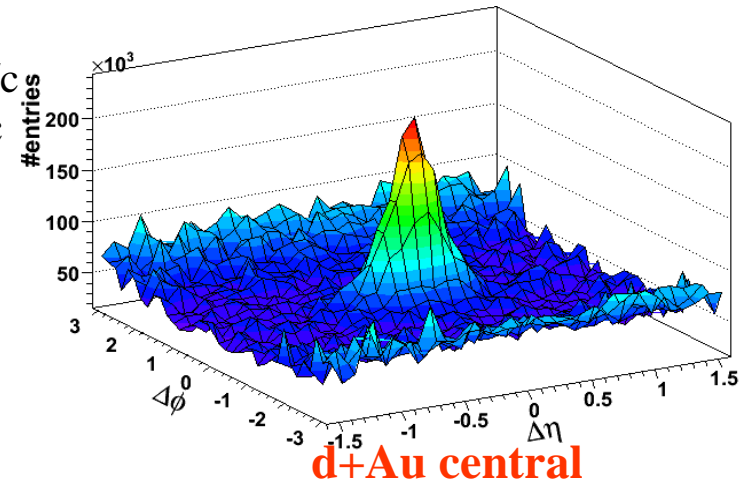
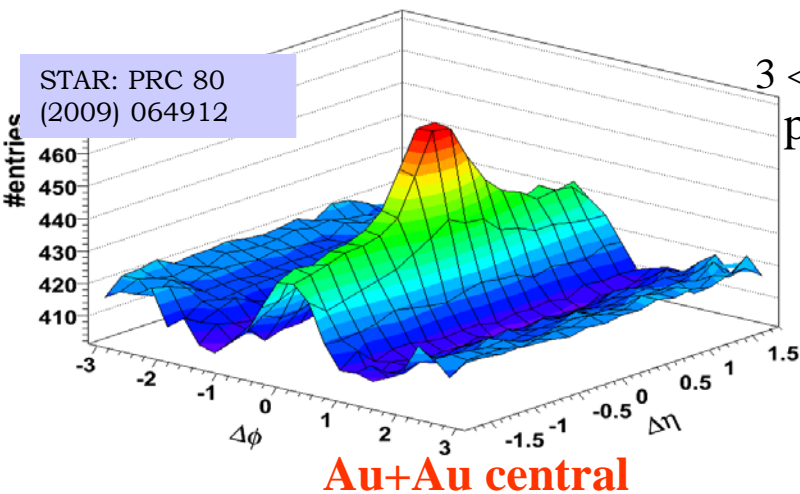
*PRC 78, 014901 (2008)*



- The discovery plot: disappearance of away side jet
- Associated  $p_T$  dependence:
  - Recovering the away side
  - Development of “double-humps” or “shoulders”



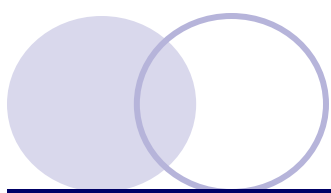
# Correlations in 2D – The Ridge



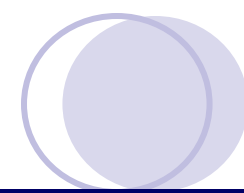
From not-so-recent results:

- Ridge correlated with jet direction
- Approximately independent of  $\Delta\eta$  and trigger  $p_T$
- Extends to acceptance boundary and to the highest trigger  $p_T$  measured
- Production mechanisms for jet and ridge differ

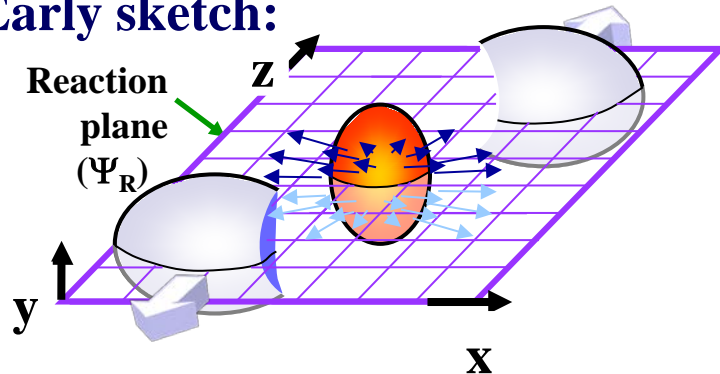
Until recent, the ridge open question:  
manifestation of the jet quenching or coincidental nuisance?



# Azimuthal Anisotropy



## Early sketch:

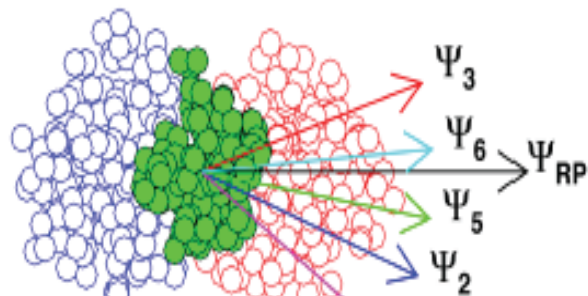


$$\frac{d^3N}{p_T dp_T d\eta d\phi} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T d\eta} \left( 1 + \sum_{k=1}^{\infty} 2v_{n=km}(p_T, \eta) \cos[n(\phi - \Psi_m)] \right)$$

## Motivation for “ $v_n$ fit” :

- Cross-talk between data and theory - transport model predictions

## Glauber-based picture:



$$\Psi_m^{pp} = \frac{1}{m} \tan^{-1} \left\{ \frac{\sum_{i=1}^{N_{part}} r_i^m \sin(m\phi_i)}{\sum_{i=1}^{N_{part}} r_i^m \cos(m\phi_i)} \right\} - \frac{\pi}{m}$$

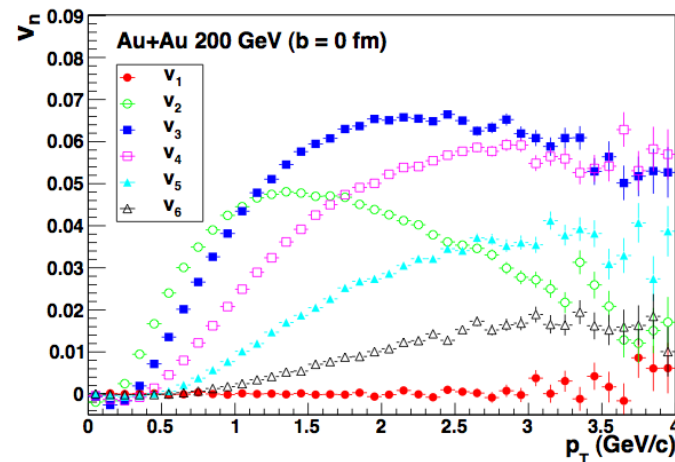
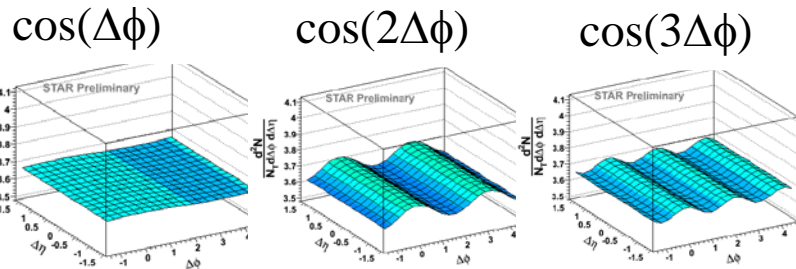


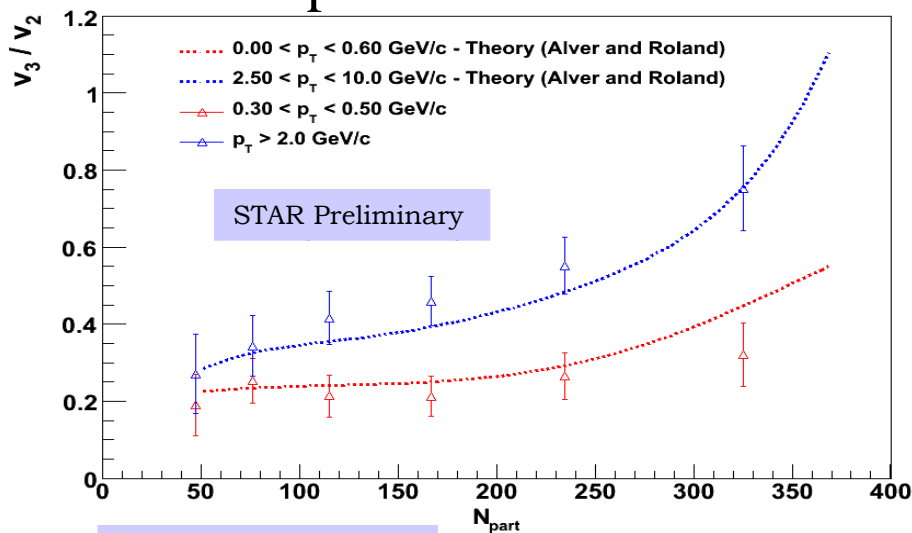
FIG. 2: (Color online) Azimuthal anisotropies of hadron spectra  $v_n(p_T)$  ( $n = 1 - 6$ ) in central ( $b = 0$ ) Au + Au collisions at  $\sqrt{s} = 200$  GeV from AMPT model calculation.

# Long Range Correlation – Fourier Fits



- Long range correlations near- and away from the trigger could be simultaneously described via higher order  $v_n$  terms

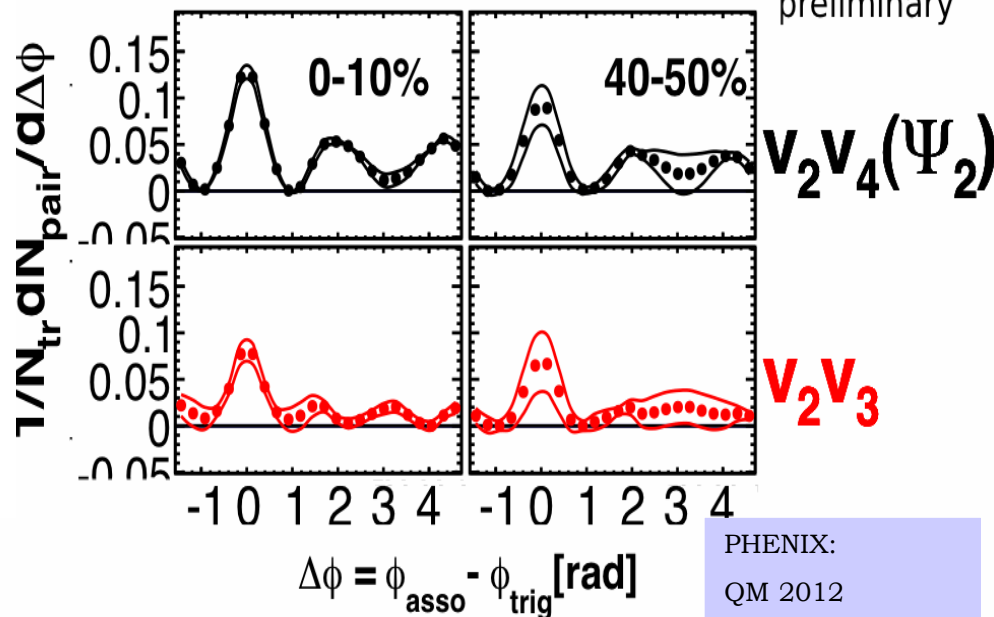
## ○ Comparison with flow:

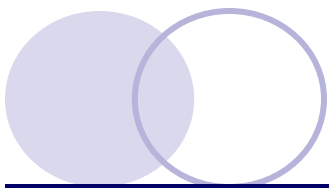


Alver and Roland,  
*PRC 81, 054905 (2010)*

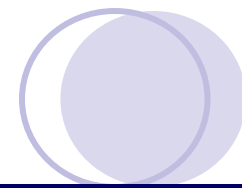
Au+Au 200GeV,  $p_T^t \otimes p_T^a = 2-4 \otimes 1-2$  GeV, ZYAM

**PHENIX**  
preliminary





# All in Hydro?



## 200 GeV Au+Au collisions

Excellent agreement for PHENIX and STAR:

$v_3 \sim v_2$  in central events

$v_3$  and higher harmonics  $\sim$  centrality independent  $\rightarrow$  origin in fluctuations

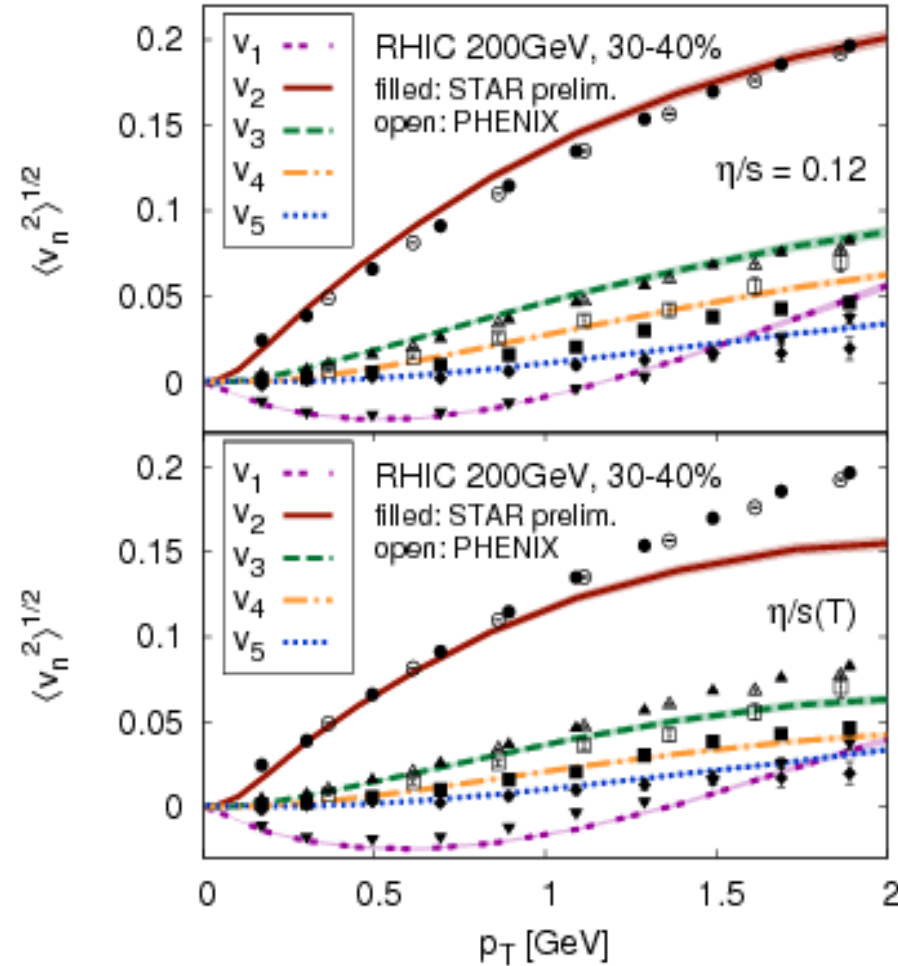
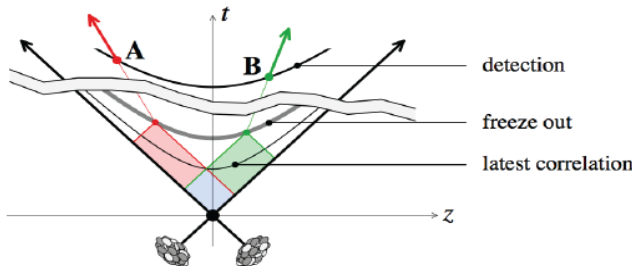
Centrality and  $p_T$  dependences of  $v_n$  well reproduced by hydro calculations

Precision measurements constrain  $\eta/s$

### What's the catch?

Unresolved issue of fast thermalization

Long range correlations probe  $\sim 10^{-24}$ s

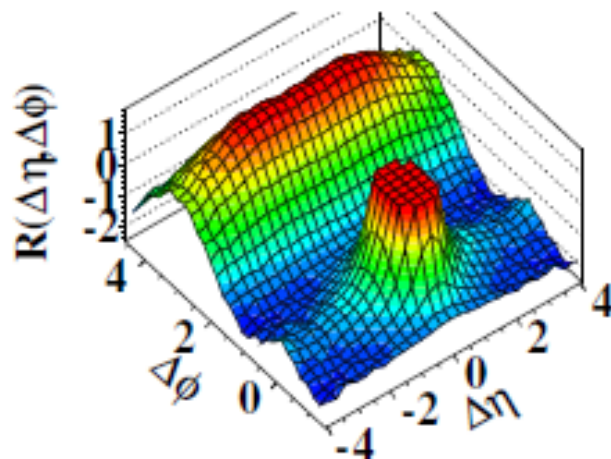


PRL 110, 012302 (2013)

# Hot Topic: dA (pA) Collisions

- Renewed attention to the “reference”
  - Understanding cold nuclear effects
  - Understanding initial state in HI collisions

(d) CMS  $N \geq 110$ ,  $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$

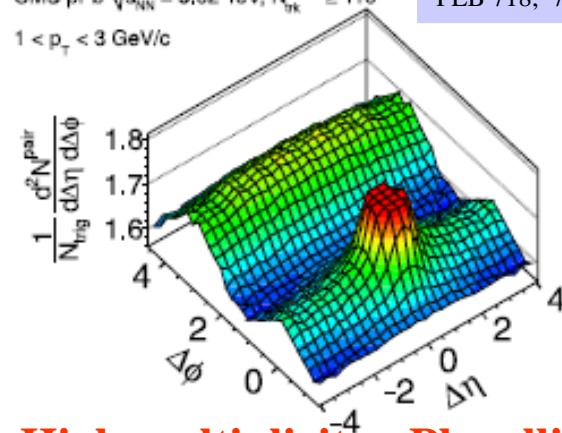


**High multiplicity pp collisions**

CMS

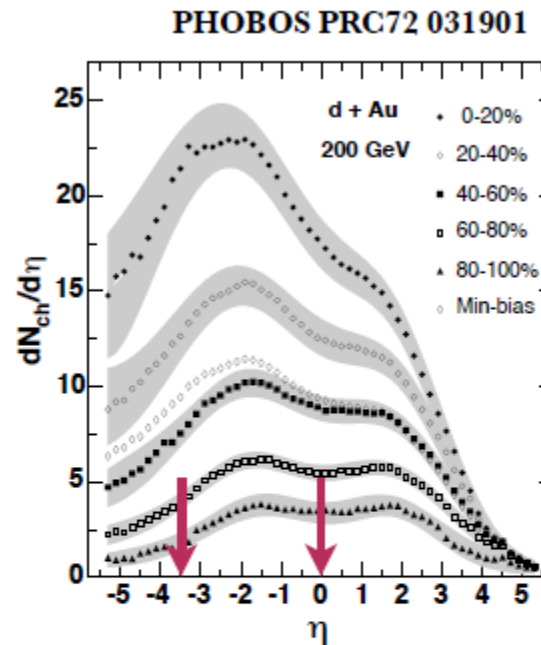
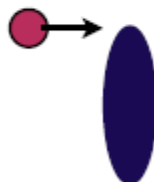
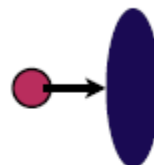
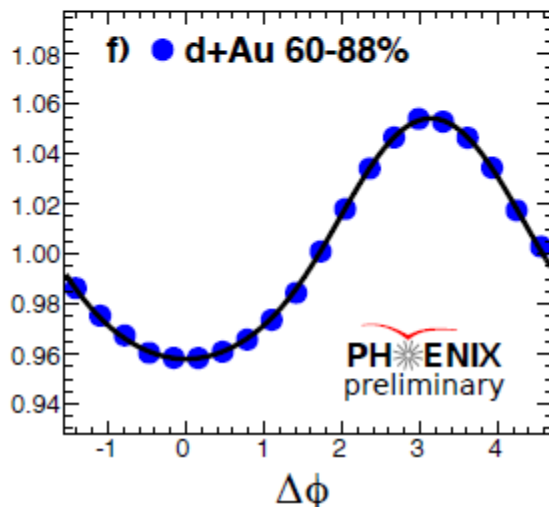
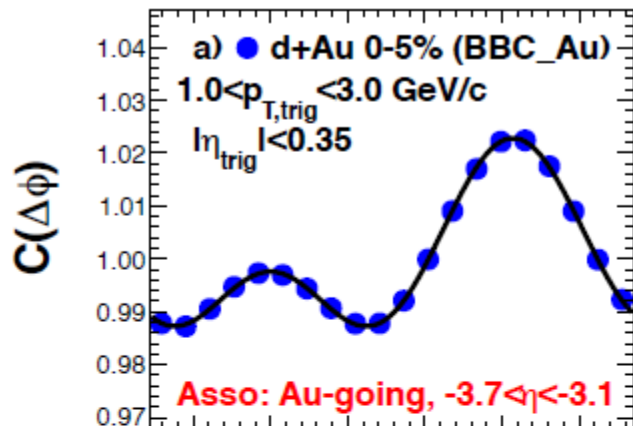
PLB 718, 795 (2013)

CMS pPb  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ ,  $N_{ch}^{0.4 < \eta < 0.8} \geq 110$   
 $1 < p_T < 3 \text{ GeV}/c$



**High multiplicity pPb collisions**

# PHENIX: d+Au Correlations

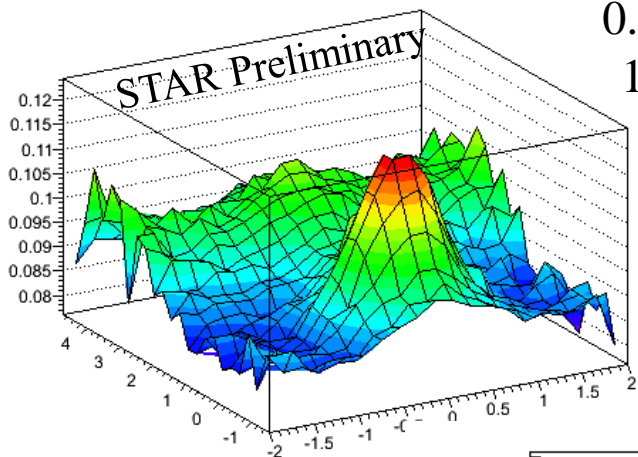


A. Sickles  
MIT pA Workshop

**Ridge in high multiplicity d+Au collisions!**

# STAR: d+Au Correlations

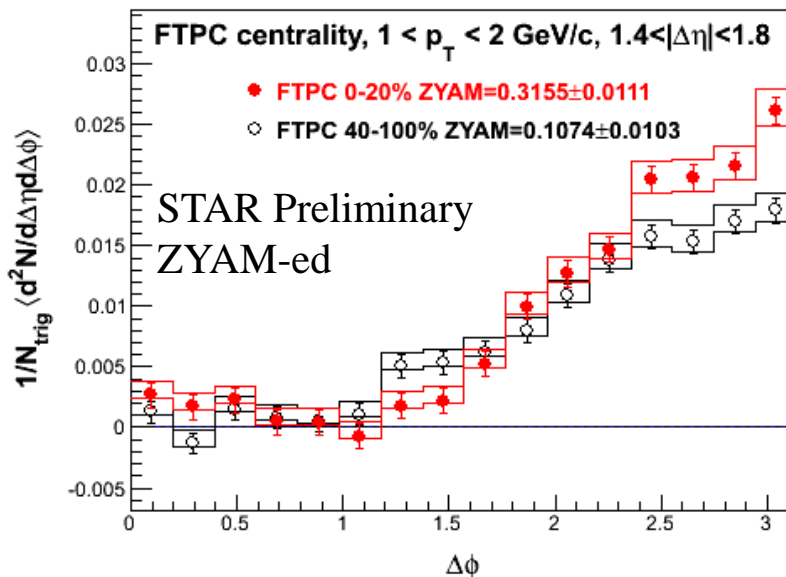
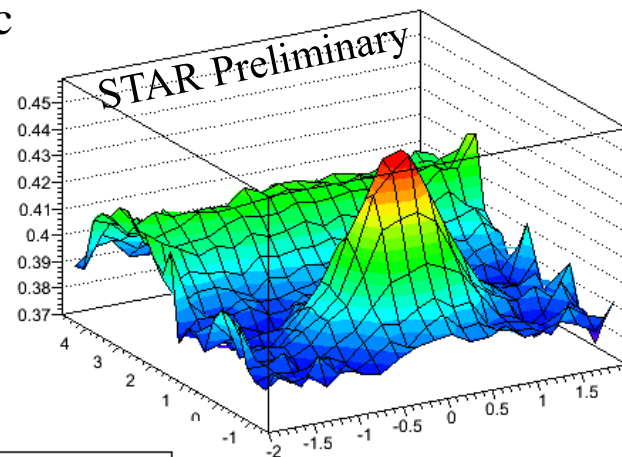
TPC 50-80%,  $1 < p_T < 2$  GeV/c



$0.15 < p_T^{\text{trig}} < 3$  GeV/c  
 $1 < p_T^{\text{assoc}} < 2$  GeV/c

TPC mult.  
 $|\eta| < 1$   
as centrality

TPC 0-20%,  $1 < p_T < 2$  GeV/c

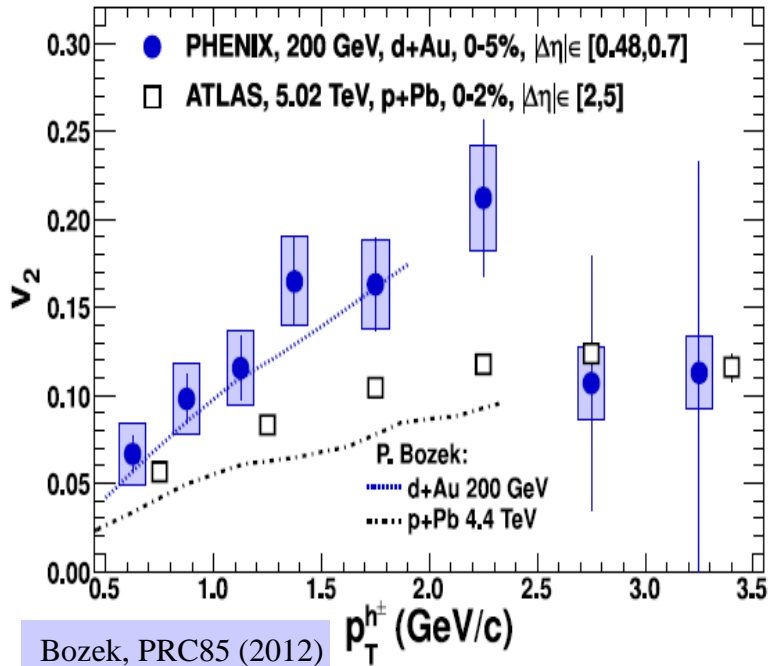


F. Wang  
RBRC Workshop

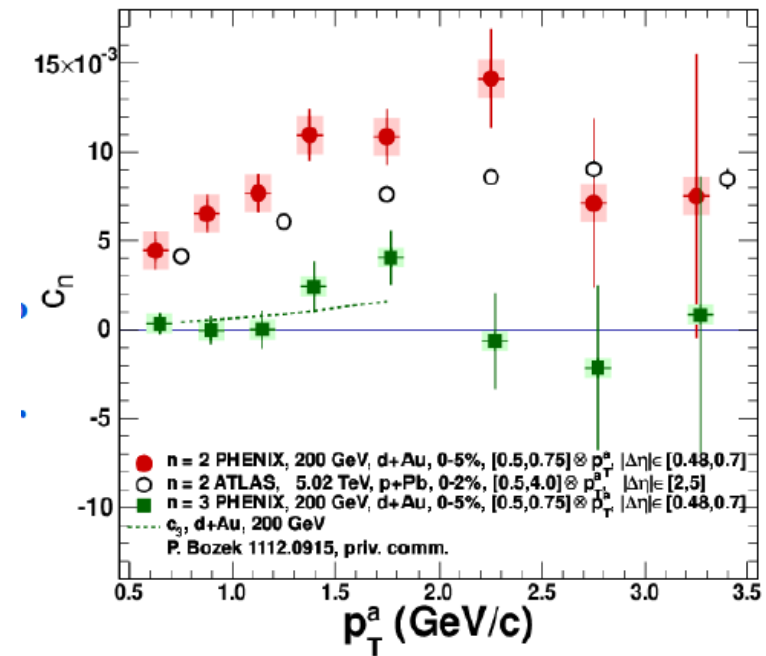
Ridge in high multiplicity d+Au collisions?

# What is Ridge in d+Au?

PHENIX, arXiv:1303.1794



Bozek, PRC85 (2012)



- d+Au ridge consistent with hydro predictions?
- $v_2/v_3$  depend strongly on initial state

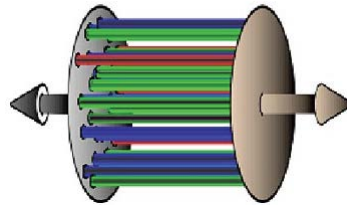


# Initial vs. Final State Effects

- Are we back to the drawing board?

- **CGC/Glasma:**

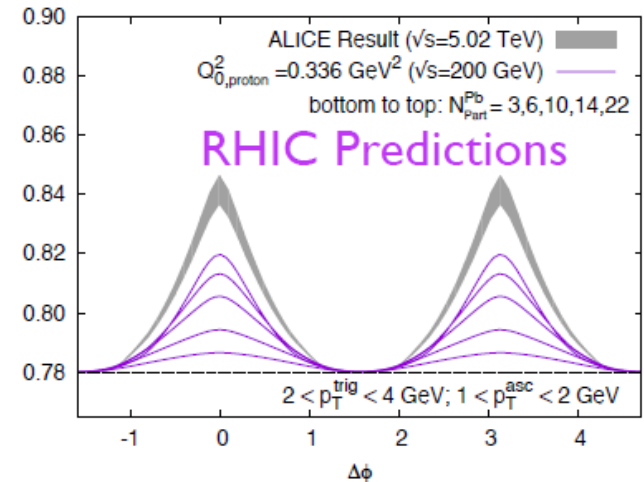
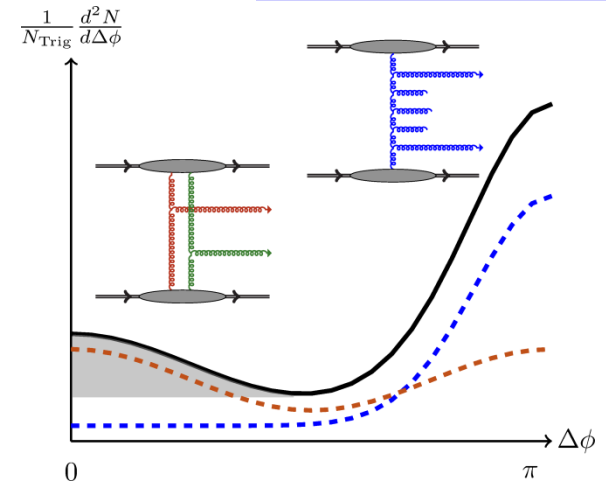
Weak coupling, high intensity color fields

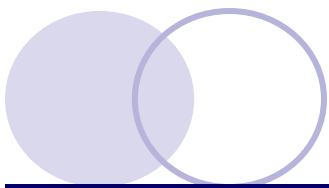


- Long-range correlations – induced by color fluctuations
- High multiplicity events probe rare gluon configurations

- Describes multiplicity in pA, dA, AA
- Describes  $v_n$  for different AA centralities at RHIC and LHC
- A factor of 2 below data on  $v_n$  in pPb(?)

Dusling and Venugopalan, arXiv:1302.7018





# Summary



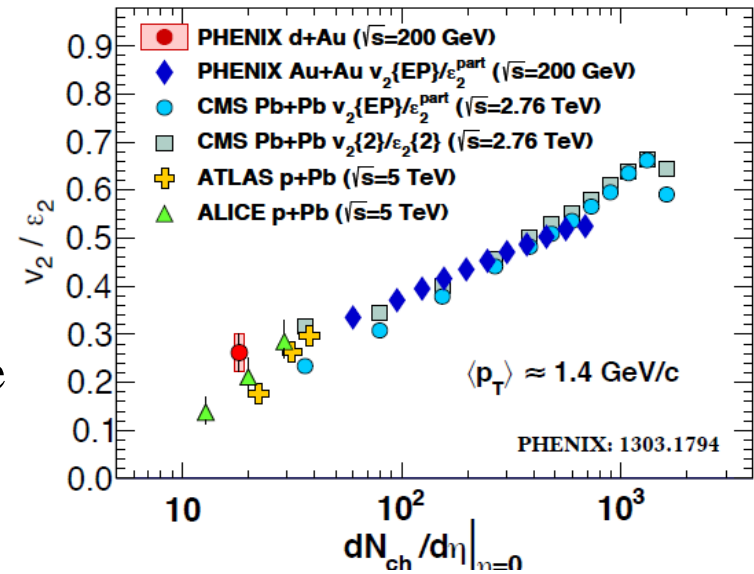
- PHENIX and STAR Au+Au results:

- Quantitative studies of jet quenching
- Higher order anisotropies from initial state fluctuations

- Ridge correlations in d+Au

(needs resolution between the experiments)

- Systematic measurements of  $v_2/v_3$   $p_T$ , energy and centrality dependence should address the relevance of initial and/or final state effects



**Common trend for different systems?**