Heavy Ion Collisions

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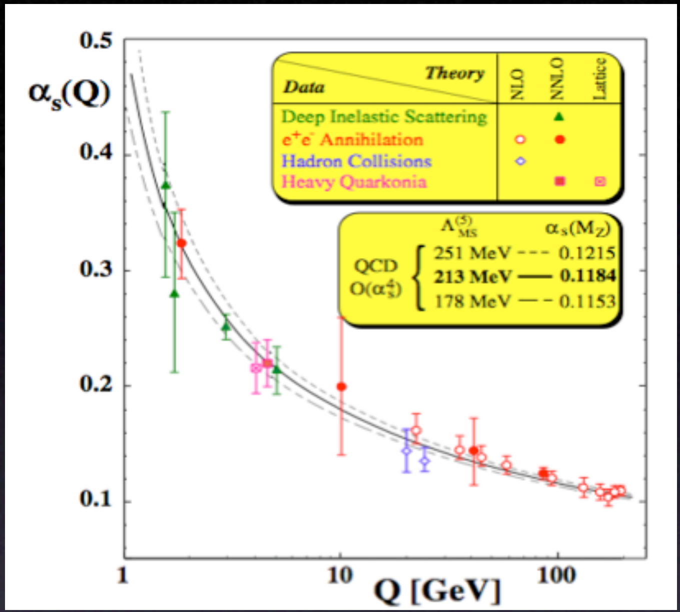
Experimental Overview

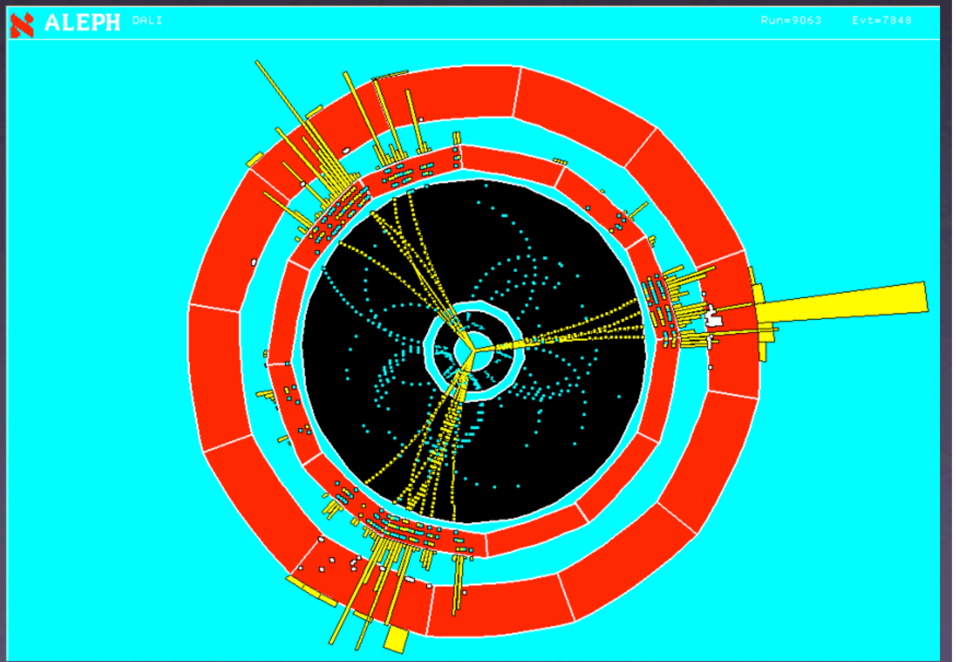
Physics at LHC 2006
Krakow
July 9 2006

Gunther Roland - MIT

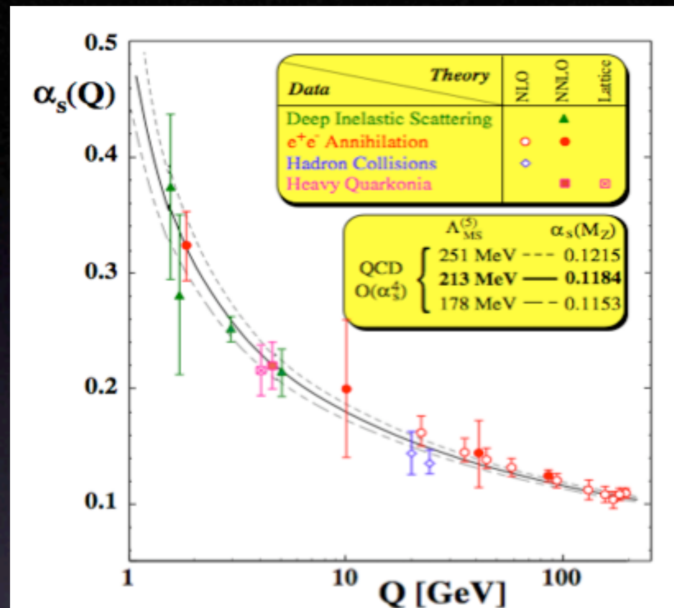
QCD



Point-like interactions of quarks and gluons at large momentum transfers



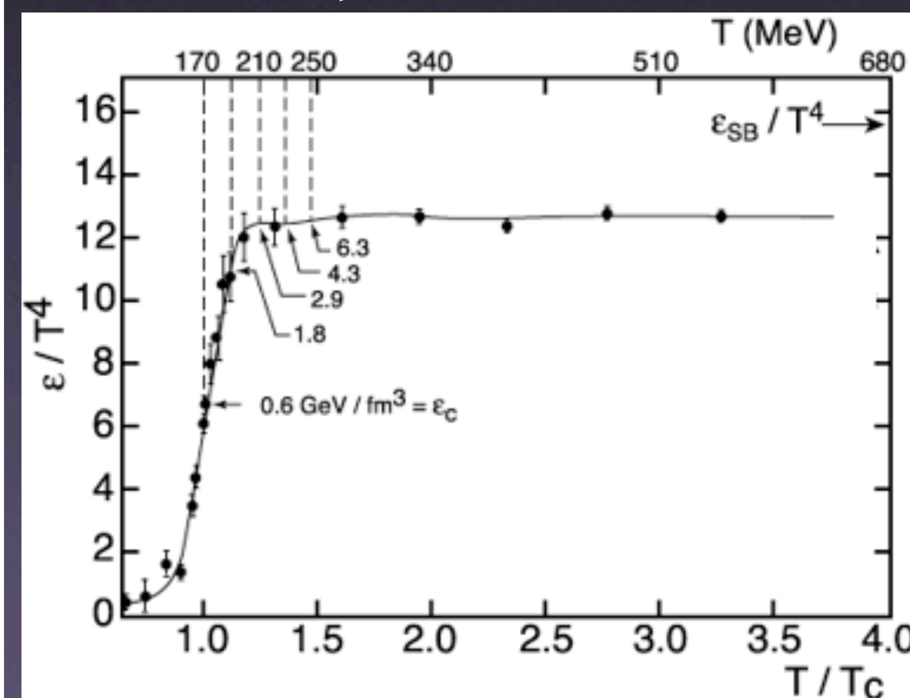
QCD

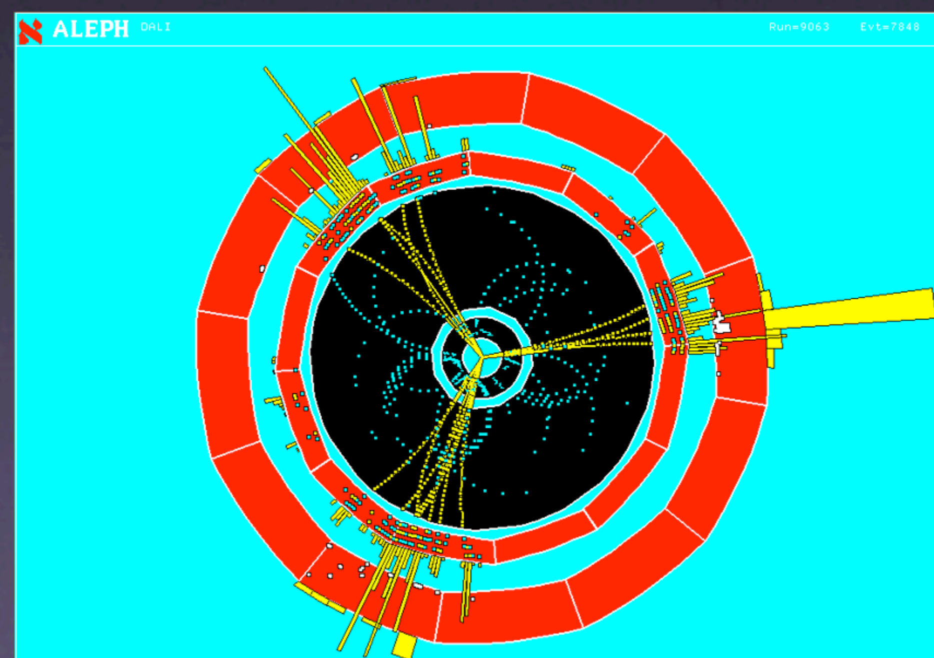


Bulk QCD Matter at "small" momentum scales?

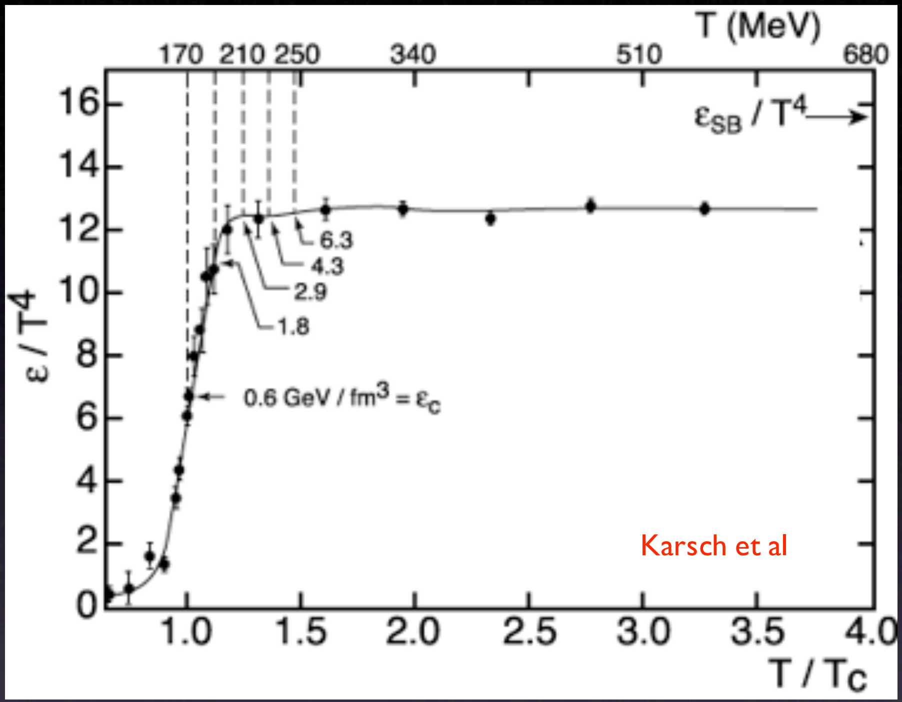
Point-like interactions of quarks and gluons at large momentum transfers

Lattice QCD





Bulk QCD Matter



Phase Transition at high T

~ 170 MeV

~ 0.6 GeV/fm^3

Deconfinement:

Quark-Gluon Plasma

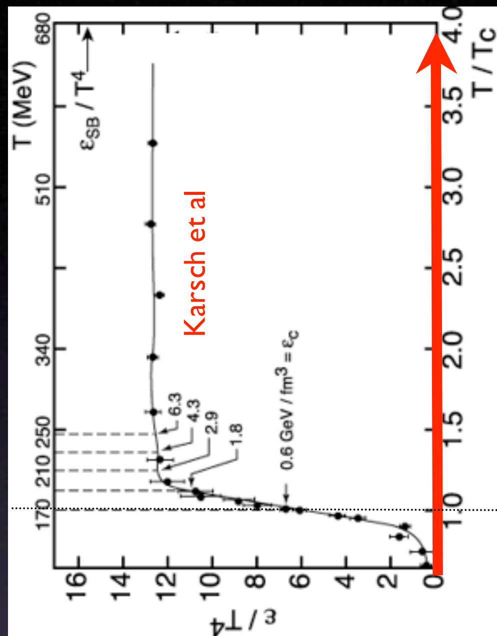
Theory:

Can we calculate **collective** properties of a **large**, **hot** Bulk QCD medium?

Experiment:

Can we <u>measure</u> **collective** properties of a **large**, **hot** Bulk QCD medium?

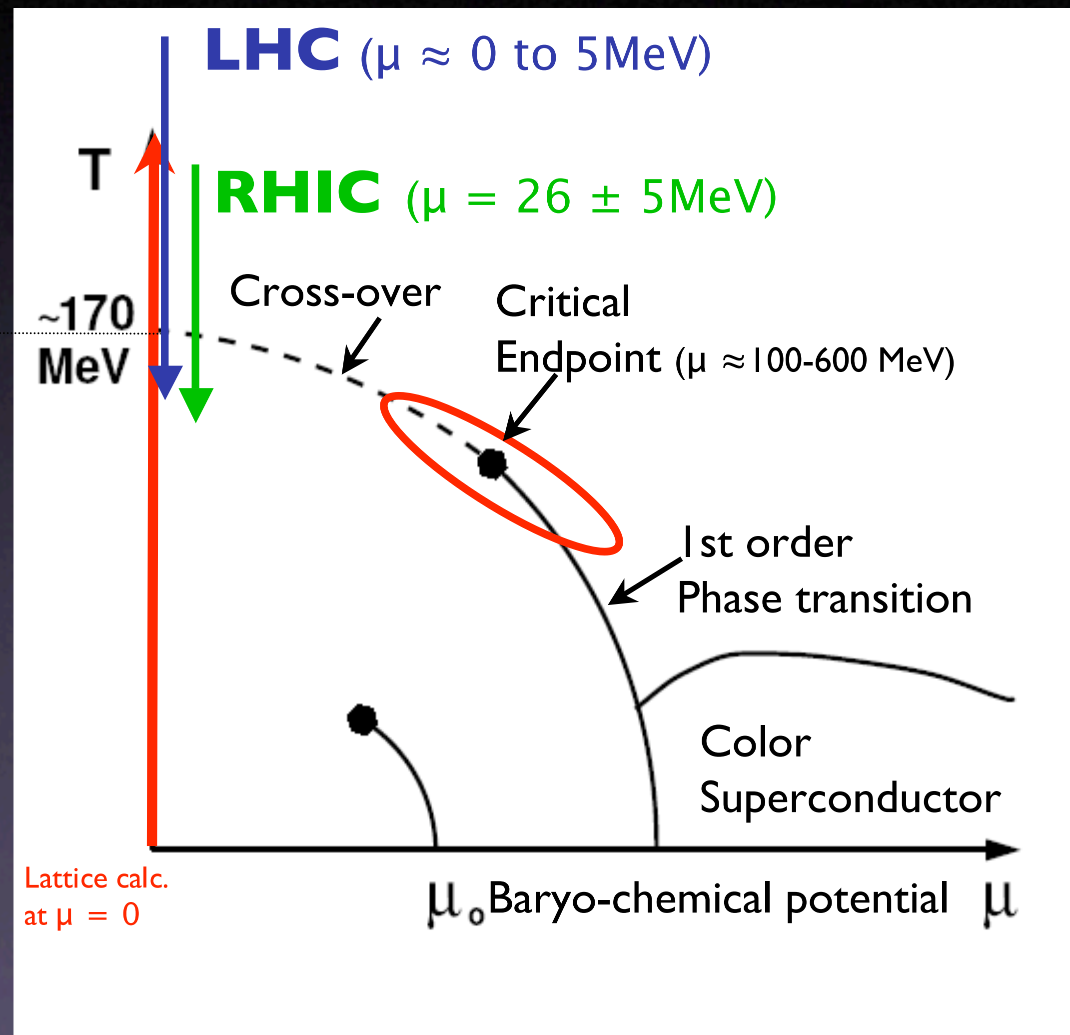
Entering the QGP Phase



LHC and RHIC:
 Live at small μ

Cross-over region of phase diagram

Properties of the vacuum at high temperature



Phase diagram is 2-dimensional

Bulk QCD Matter

Phase Transition at high T
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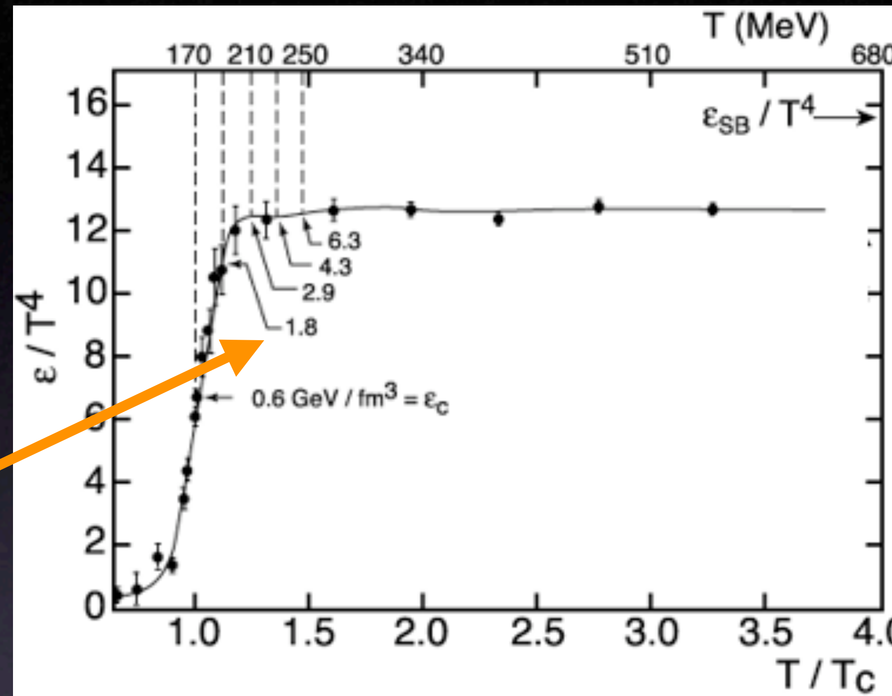
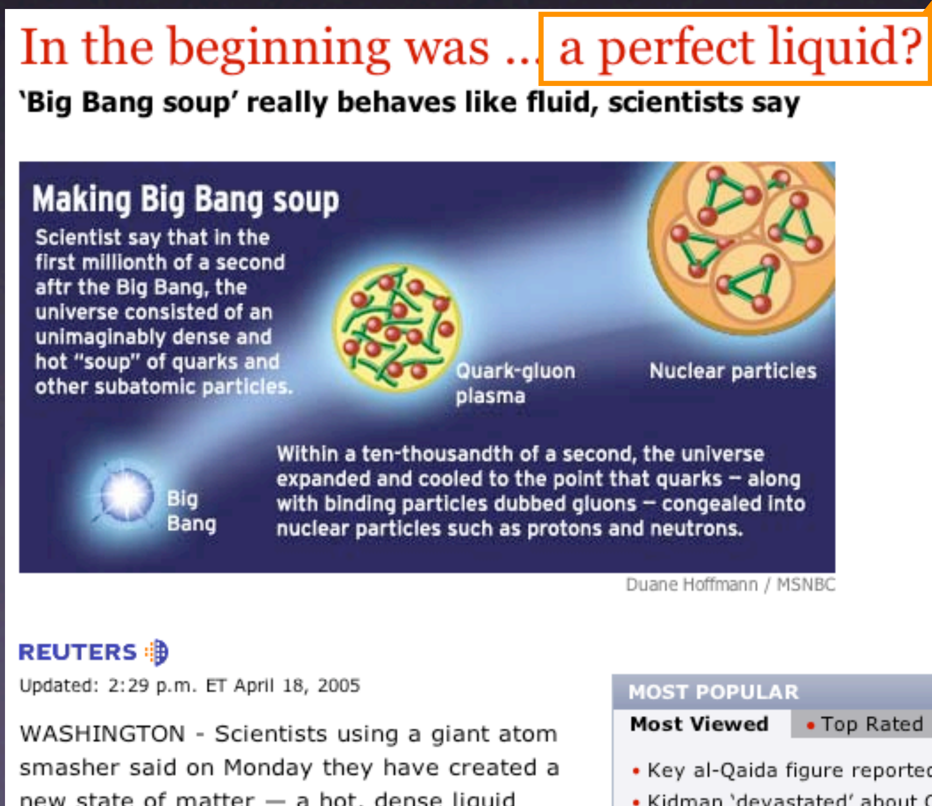
~ 0.6 GeV/fm^3
Deconfinement:
Quark-Gluon Plasma




In the beginning was ... a perfect liquid?

'Big Bang soup' really behaves like fluid, scientists say

Making Big Bang soup

Scientist say that in the first millionth of a second aftr the Big Bang, the universe consisted of an unimaginably dense and hot "soup" of quarks and other subatomic particles.

Quark-gluon plasma

Nuclear particles

Big Bang

Within a ten-thousandth of a second, the universe expanded and cooled to the point that quarks – along with binding particles dubbed gluons – congealed into nuclear particles such as protons and neutrons.

Duane Hoffmann / MSNBC

REUTERS

Updated: 2:29 p.m. ET April 18, 2005

WASHINGTON - Scientists using a giant atom smasher said on Monday they have created a new state of matter — a hot, dense liquid

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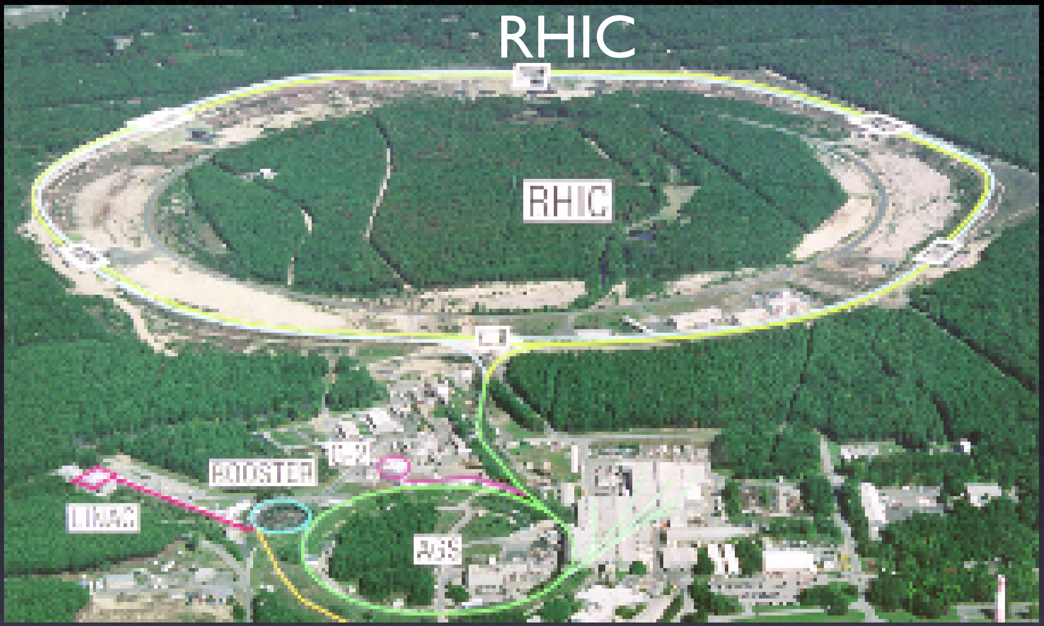
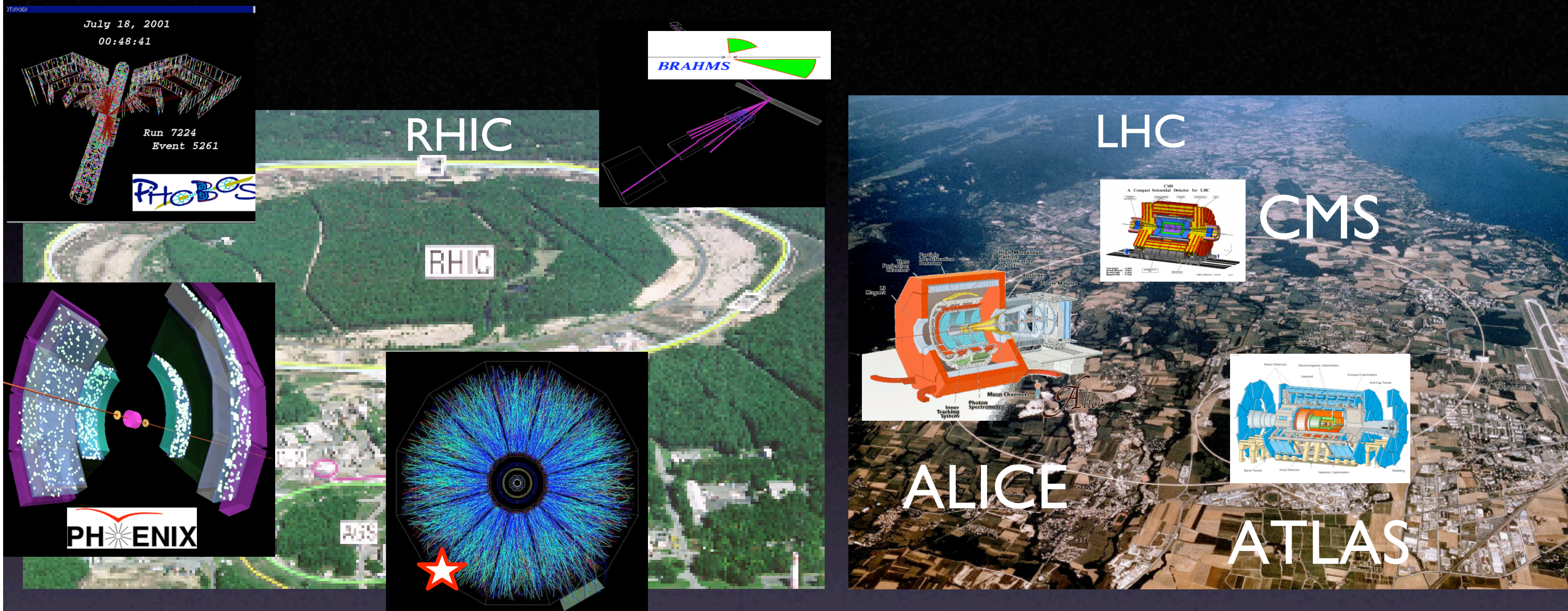
4 RHIC experiments

Heavy Ion Experiments at RHIC and LHC



	AGS	SPS	RHIC	LHC
$\sqrt{s_{NN}}$[GeV]	5	20	200	5500
E increase		x4	x10	x28
y range	±1.6	±3.0	±5.3	±8.6

Heavy Ion Experiments at RHIC and LHC



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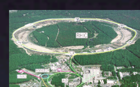
Heavy Ion Experiments at RHIC and LHC

RHIC



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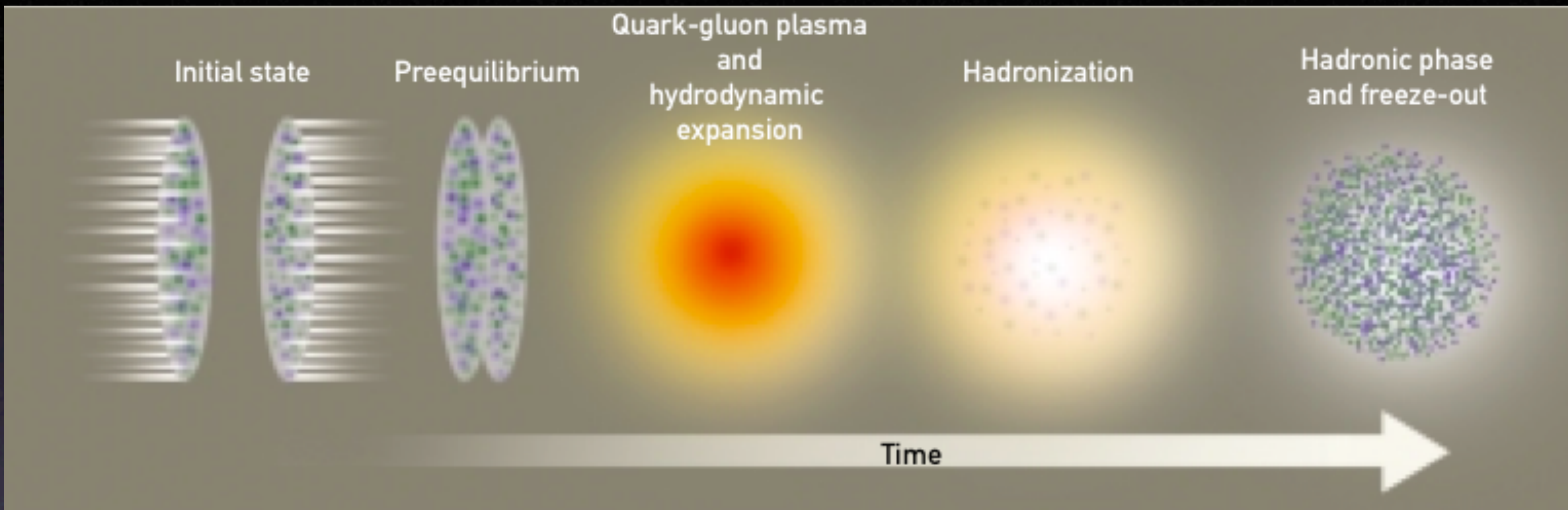
Bulk QCD Matter

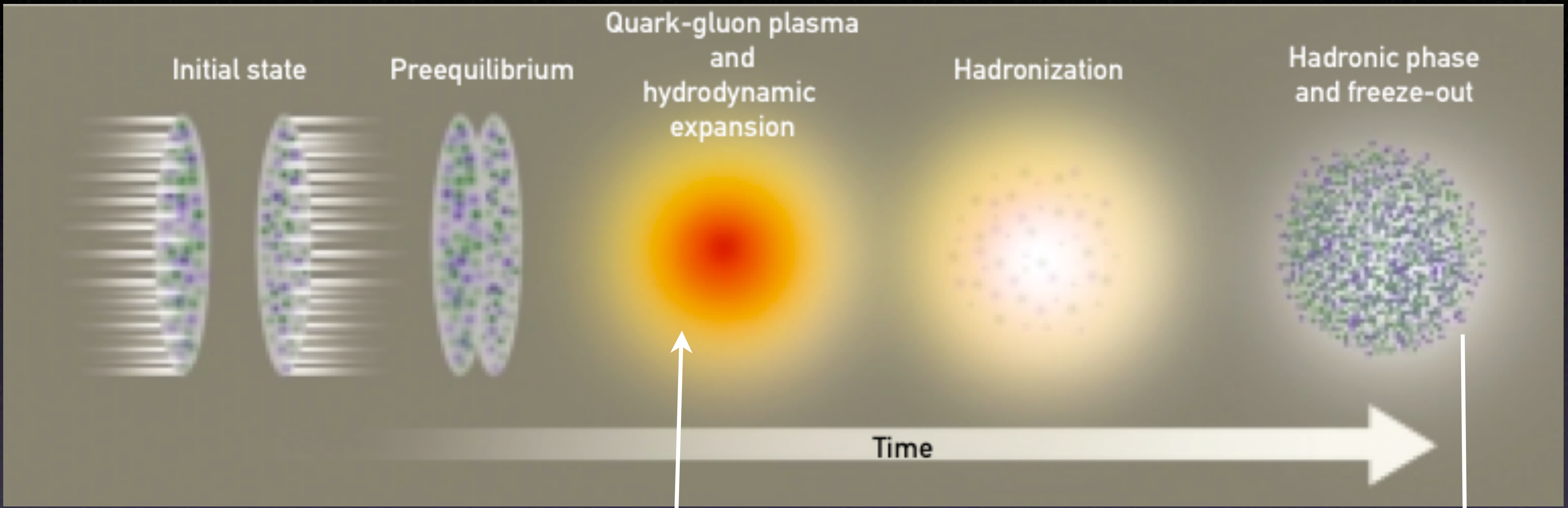


Examine different stages of the collision process

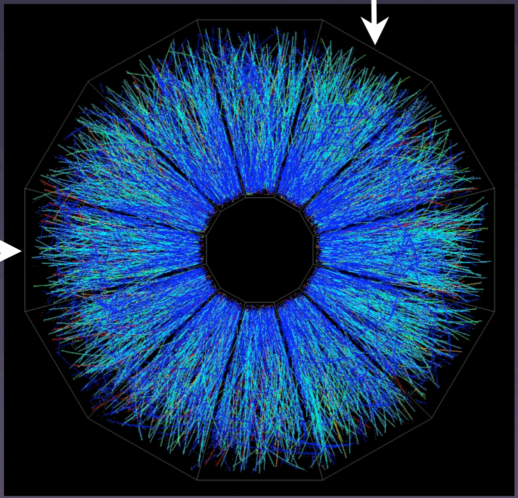
Look at key evidence for our current picture

Point out interesting puzzles

Bulk QCD Matter



Need to isolate contribution of hot medium to hadronic final state

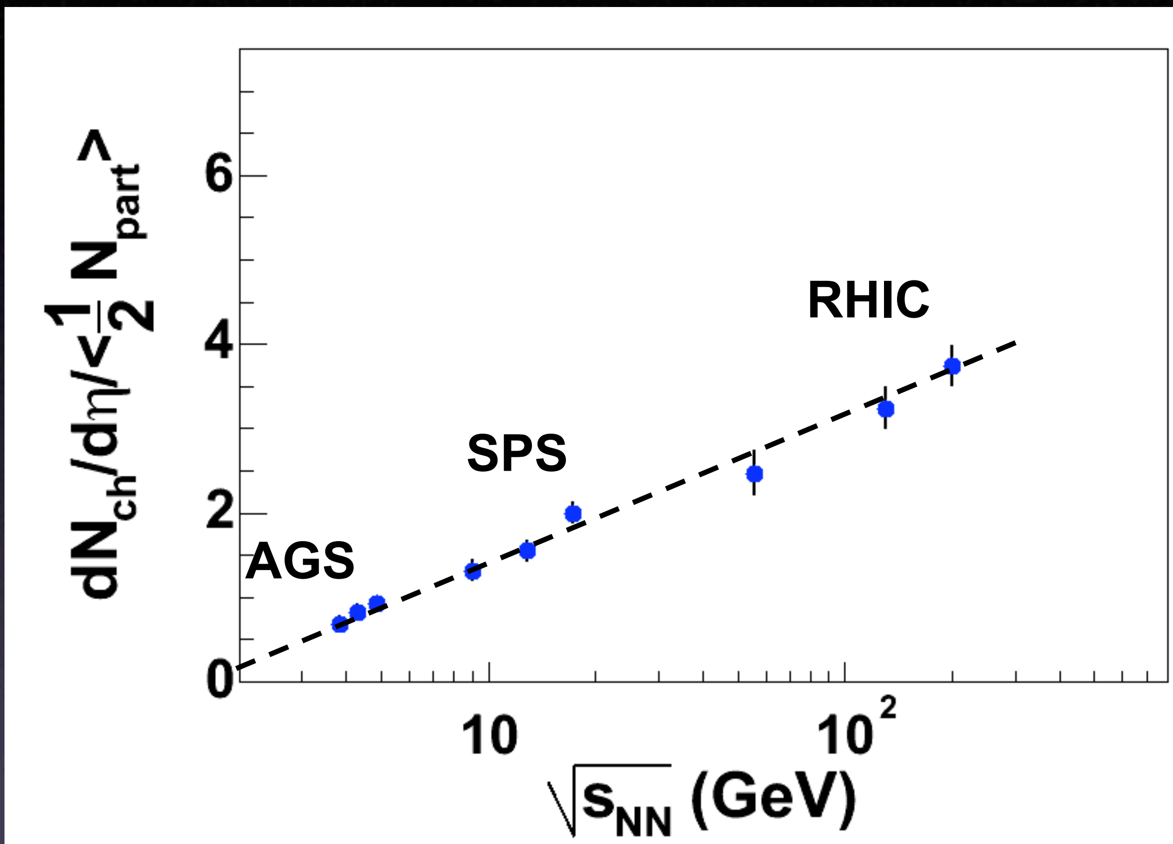


Single Au+Au at RHIC seen by STAR

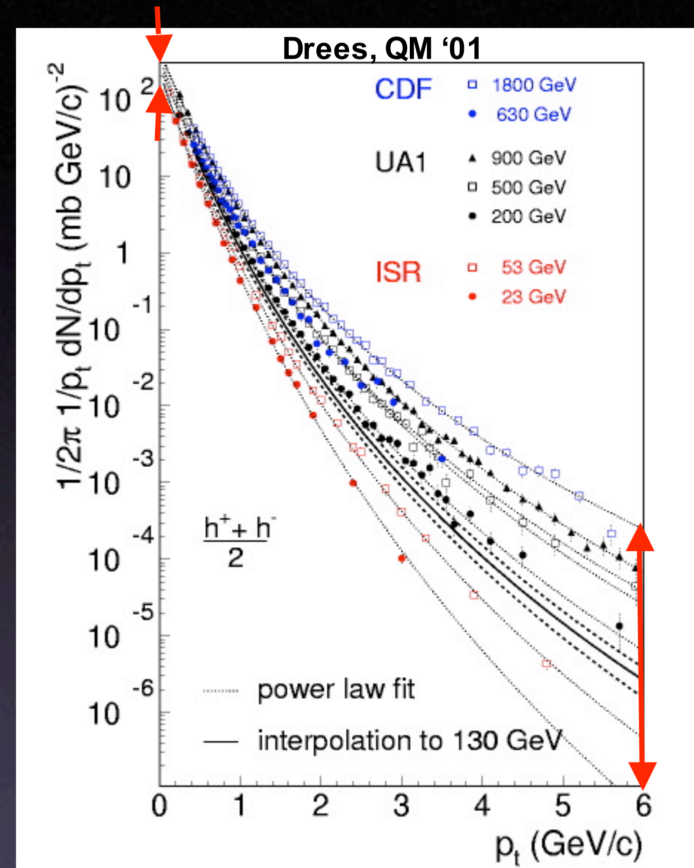
Vary initial state using control parameters:

Collision energy and **System Size**

Scanning Collision Energy

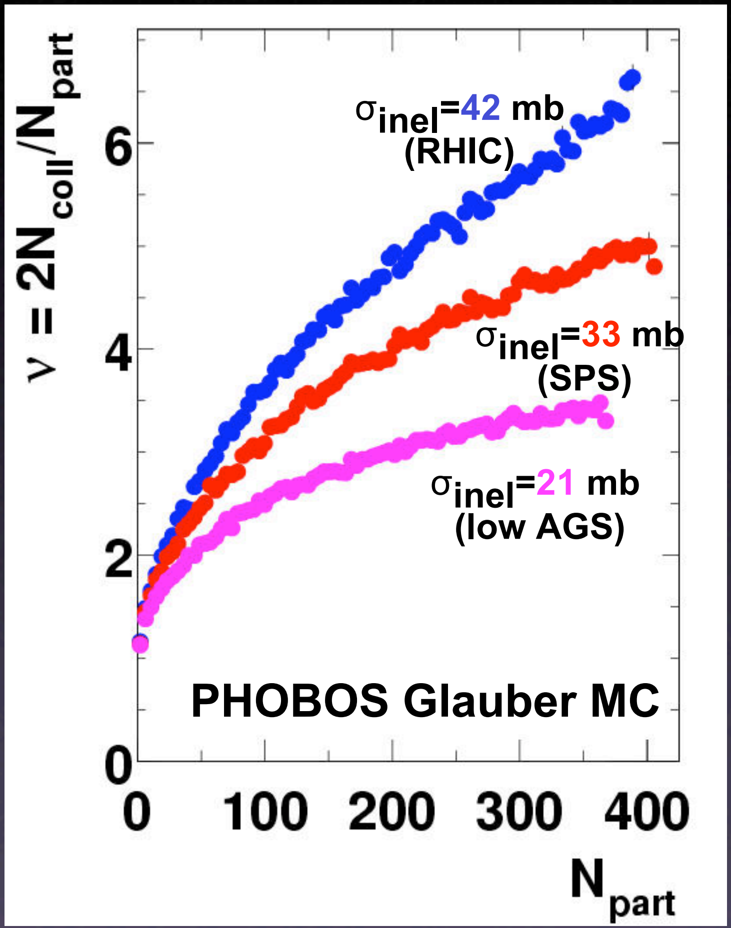


Changes energy density



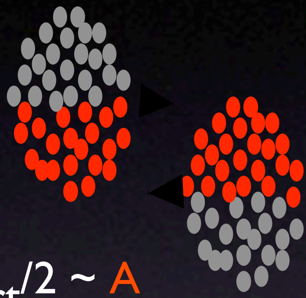
Changes balance of hard/soft particle production

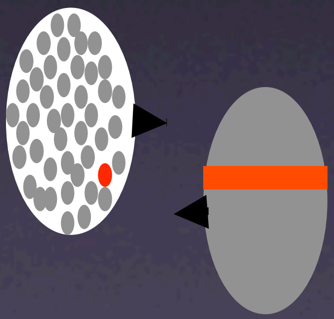
Scanning Collision Centrality



Changes number of collisions per participating nucleon

"Participants"

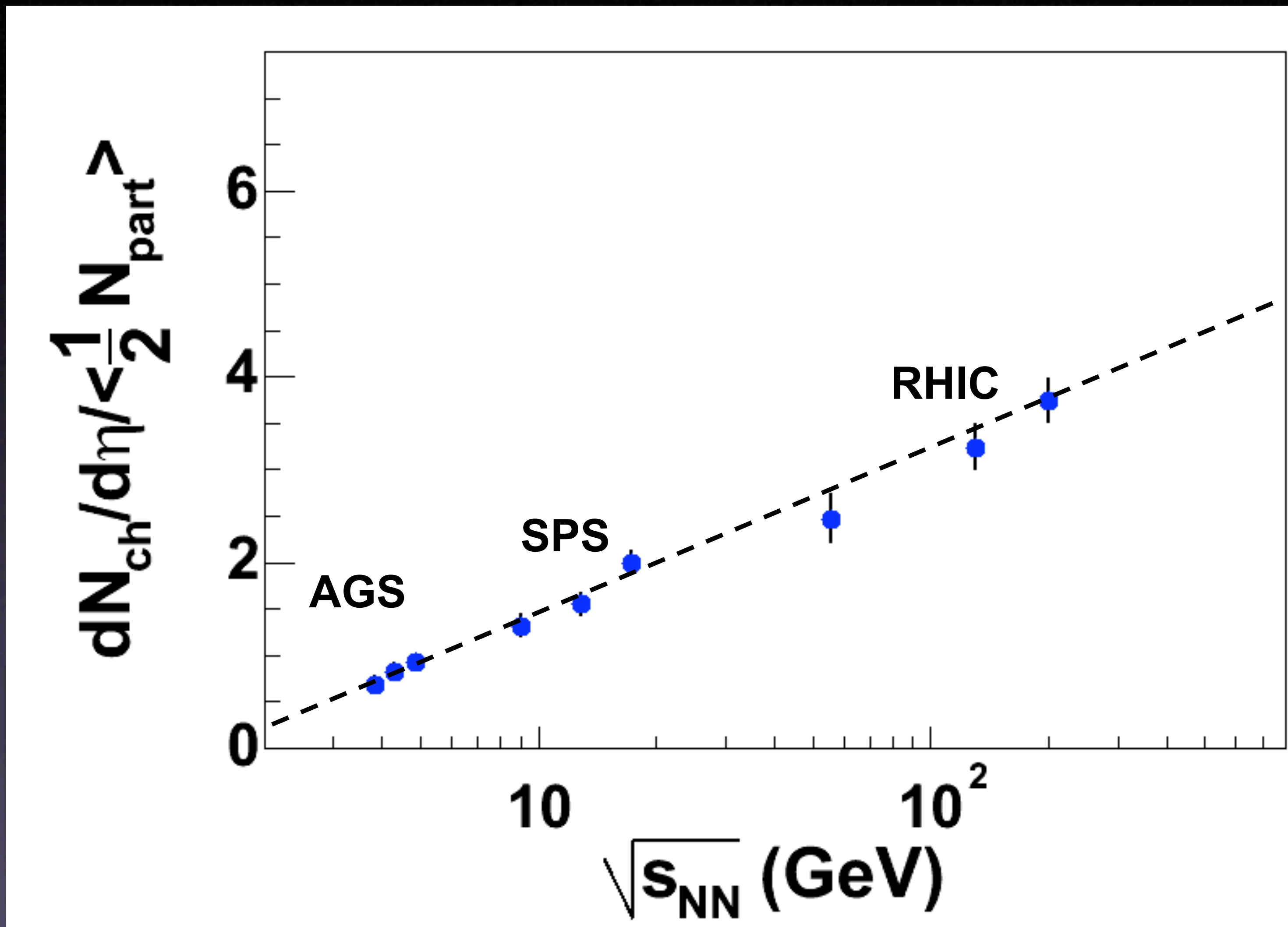




N_{coll}= # of NN collisions: $\sim A^{4/3}$

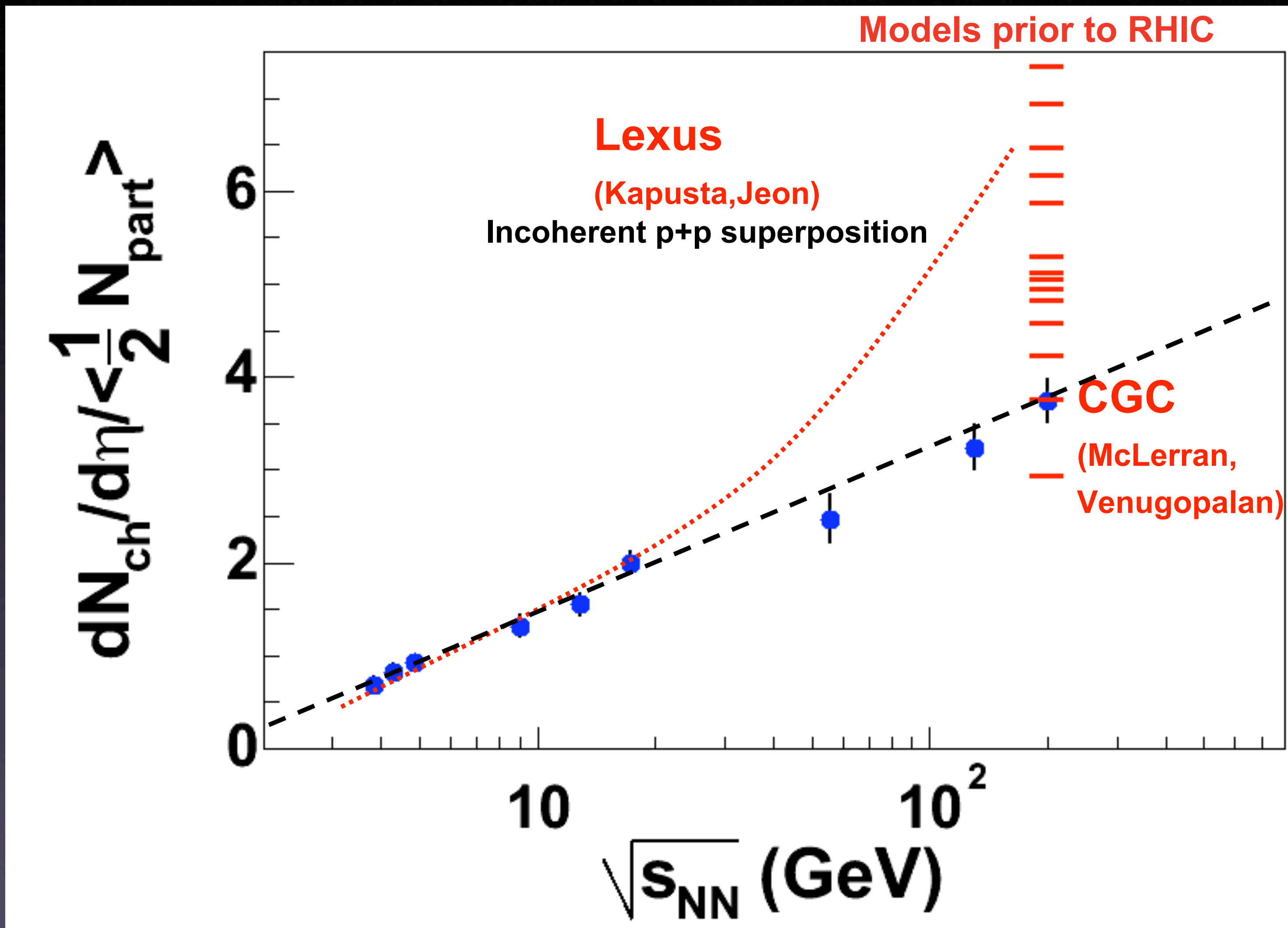
"Collisions"

Mid-rapidity particle density



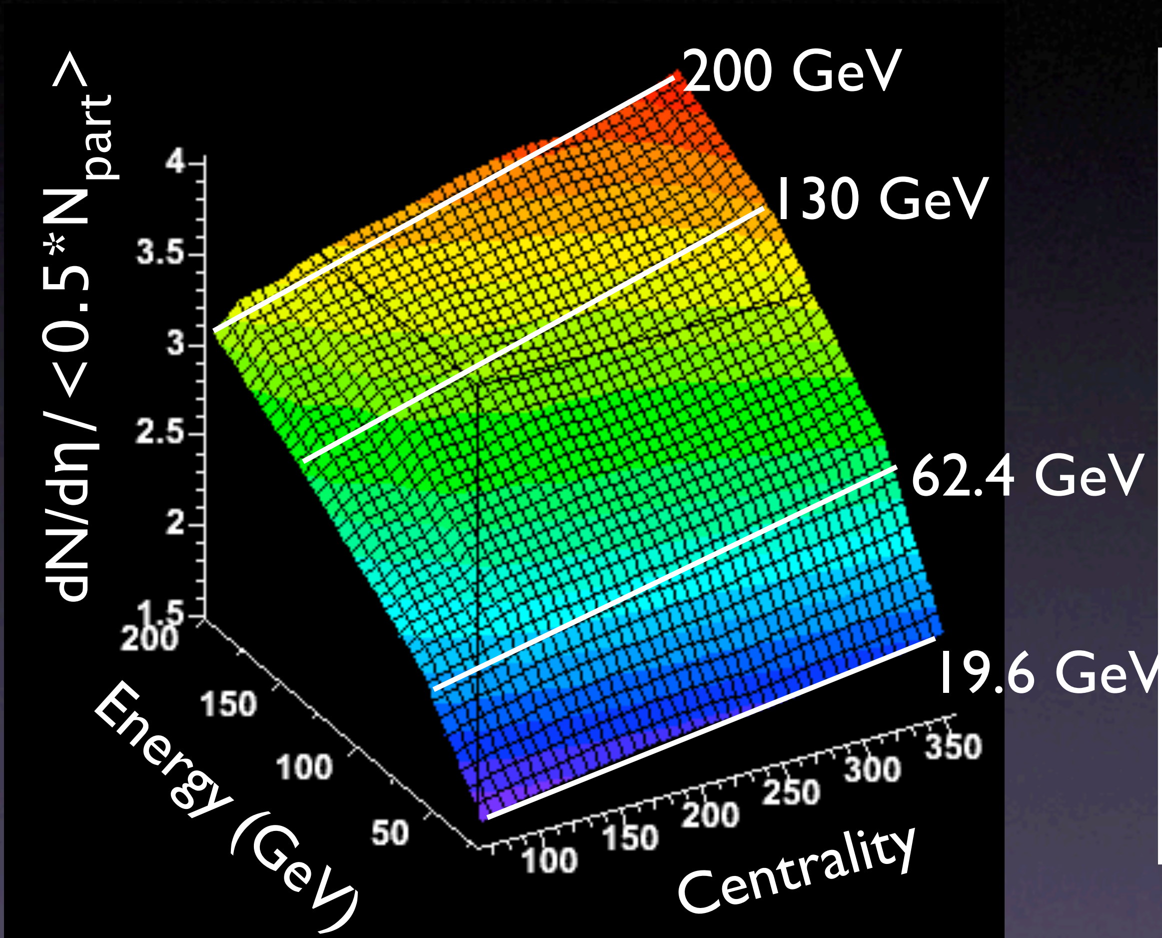
Observe slow logarithmic rise

Mid-rapidity particle density

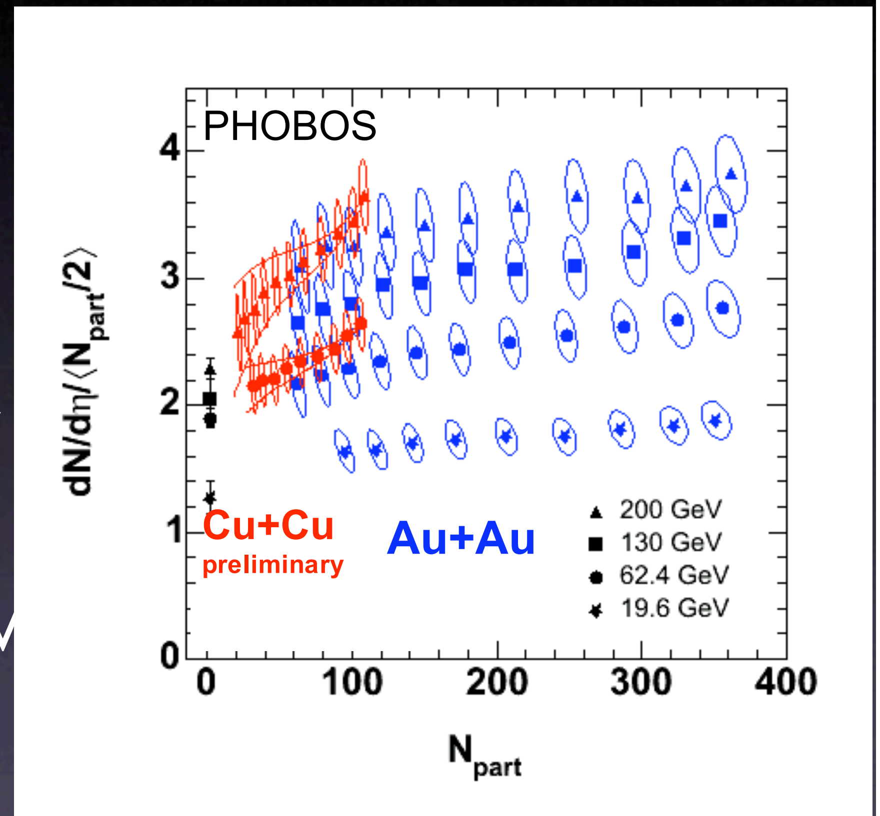


"Coherence" of initial state entropy production

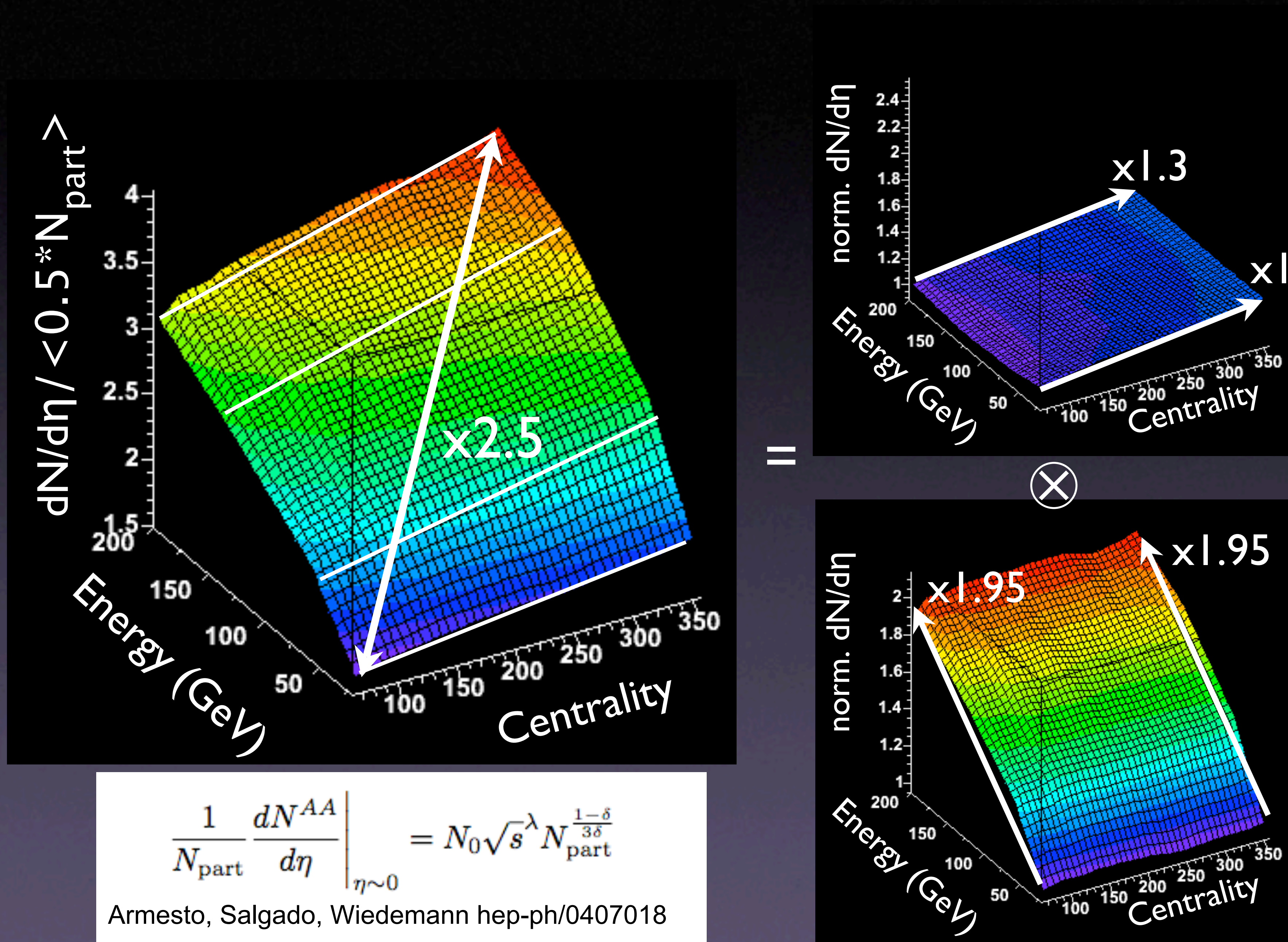
Mid-rapidity dN/dη vs √s and N_{part}



Au+Au : nucl-ex/0509034, submitted to PRC
Cu+Cu: QM 2005



Mid-rapidity dN/dη vs √s and N_{part}

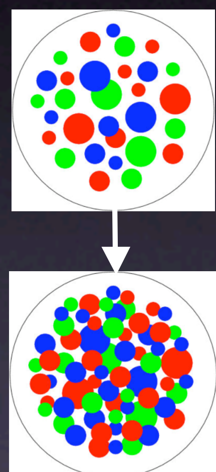


$$\frac{1}{N_{\rm part}} \frac{dN^{AA}}{d\eta}\bigg|_{\eta\sim 0} = N_0 \sqrt{s}^{\lambda} N_{\rm part}^{\frac{1-\delta}{3\delta}}$$

Armesto, Salgado, Wiedemann hep-ph/0407018

Mid-rapidity dN/dη vs √s and N_{part}

Initial State
Parton Saturation

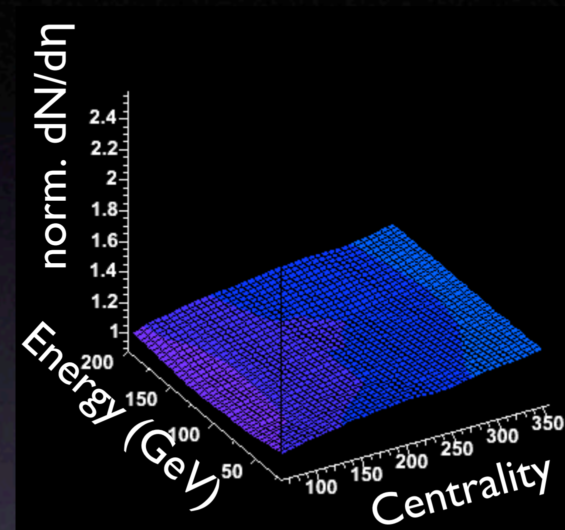


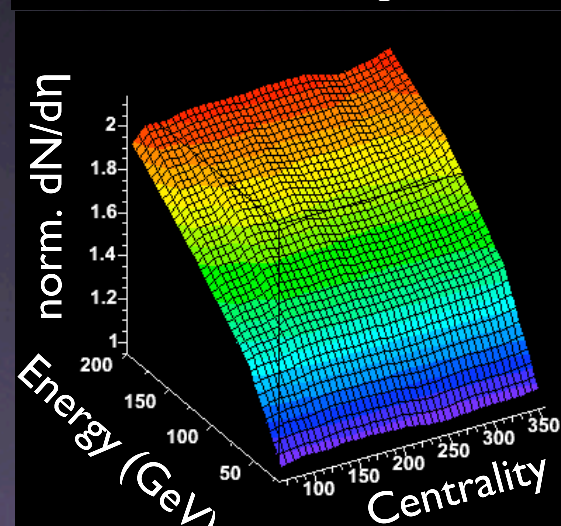
Low Energy

High Energy

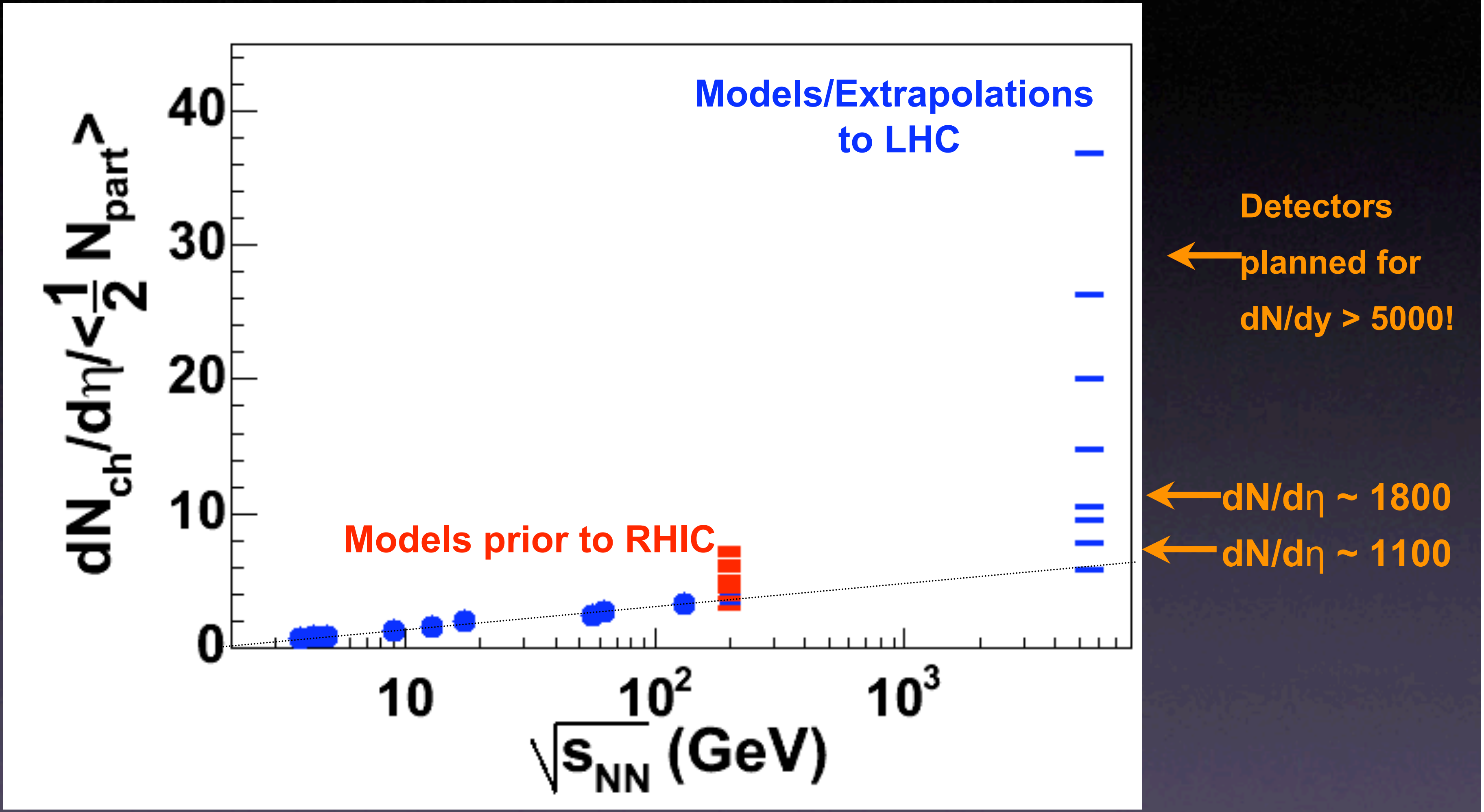
$$\frac{1}{N_{\rm part}}\frac{dN^{AA}}{d\eta}\bigg|_{\eta\sim 0} = N_0\sqrt{s}^{\lambda}N_{\rm part}^{\frac{1-\delta}{3\delta}}$$

Armesto, Salgado, Wiedemann hep-ph/0407018



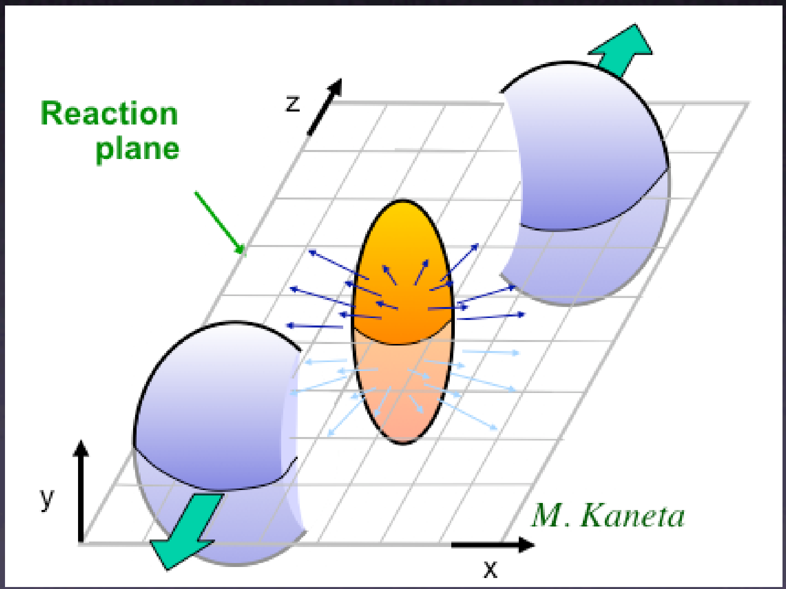


Hadron Multiplicities at LHC



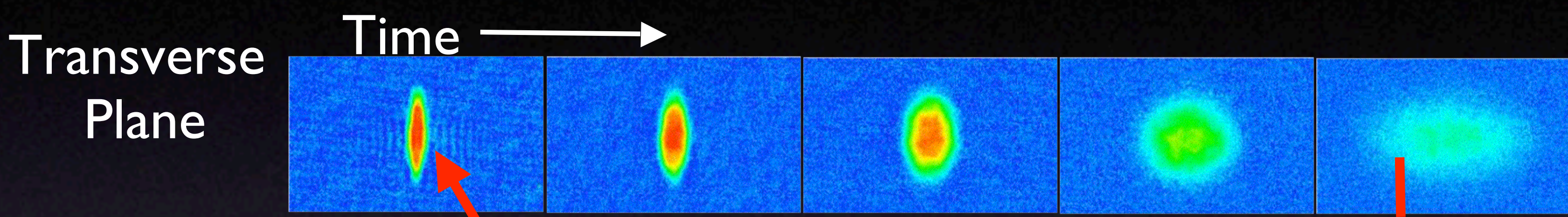
LHC will provide decisive test of saturation ideas

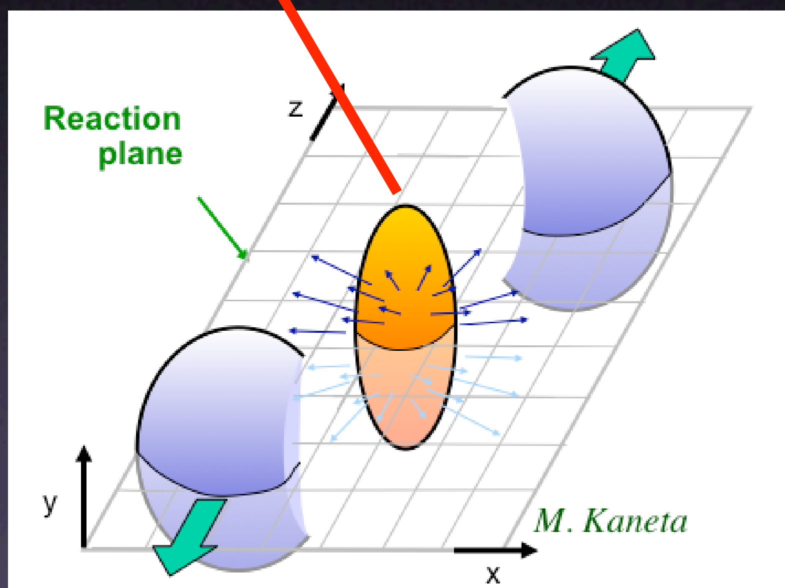
Hydrodynamic Evolution



Non-central collision:
Initial state eccentricity

Hydrodynamic Evolution





Non-central collision:
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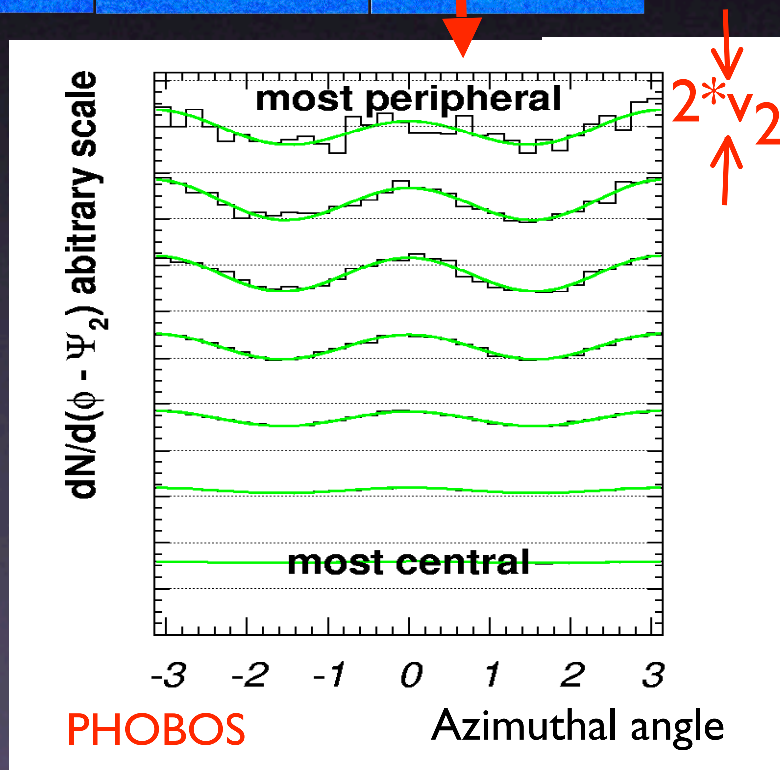
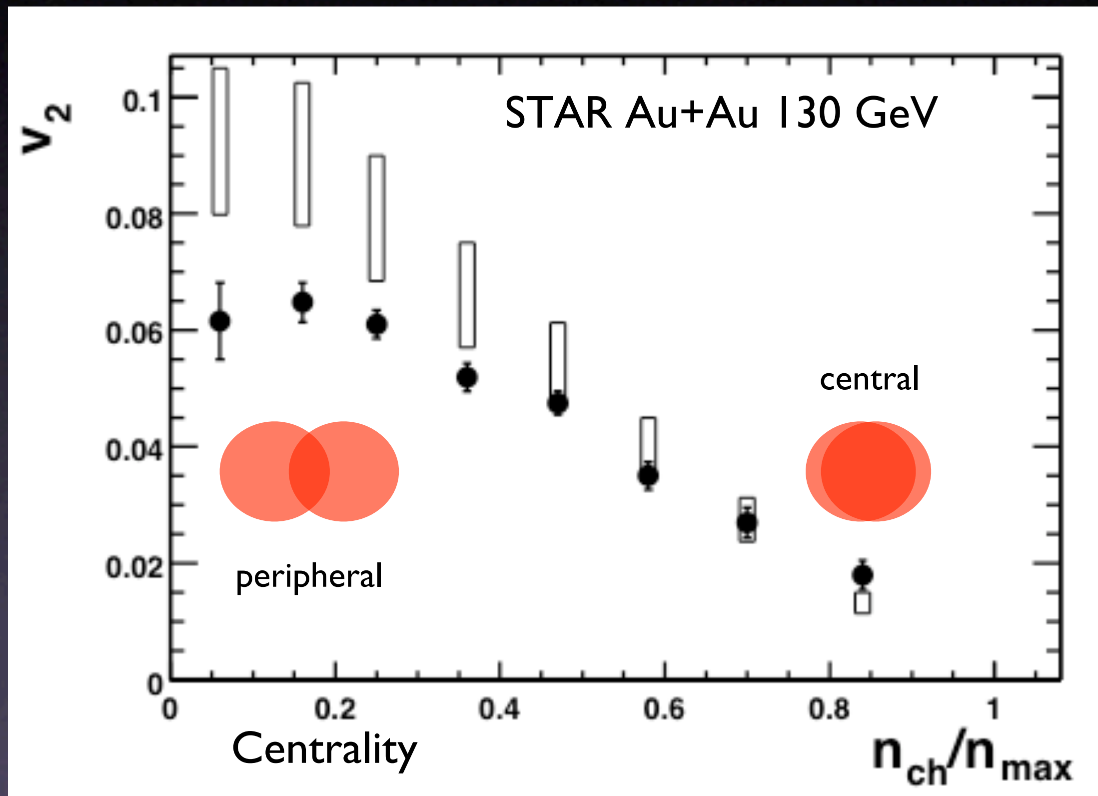


Momentum space
anisotropy

Hydrodynamic Evolution

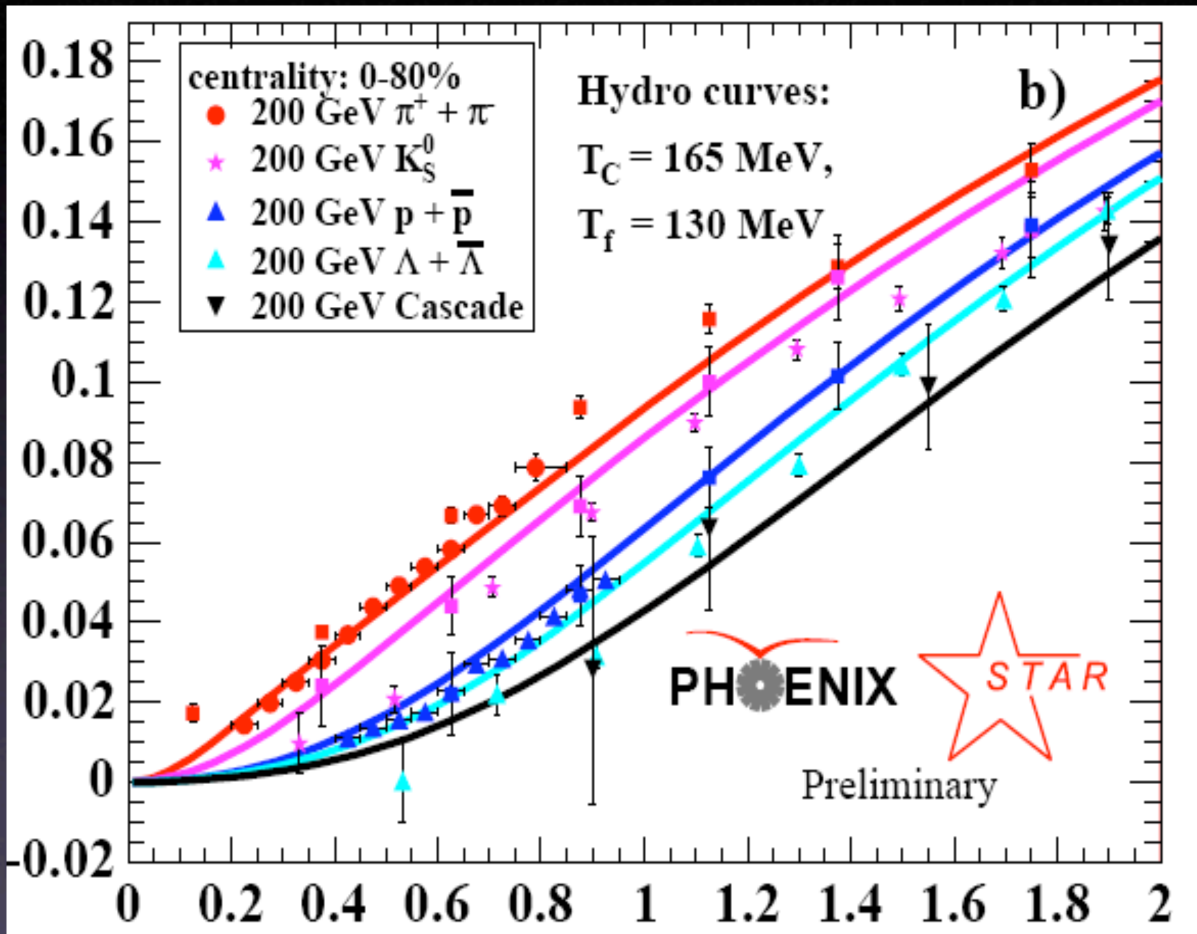
Azimuthal distribution

$dN/d\varphi = 1 + 2\, v_2 \cos(2(\varphi - \varphi 0))$



Elliptic Flow signal exhausts “hydro limit” for mid-central to central collisions

Hydrodynamic Evolution

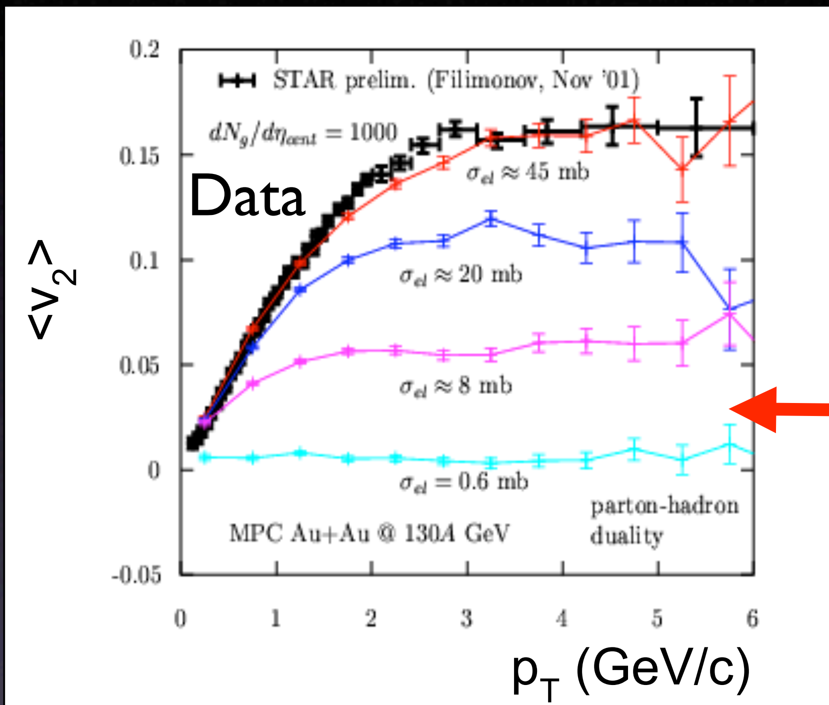


Huge signal at high p_T

Mass splitting of p_T dependence

Hydrodynamic Evolution

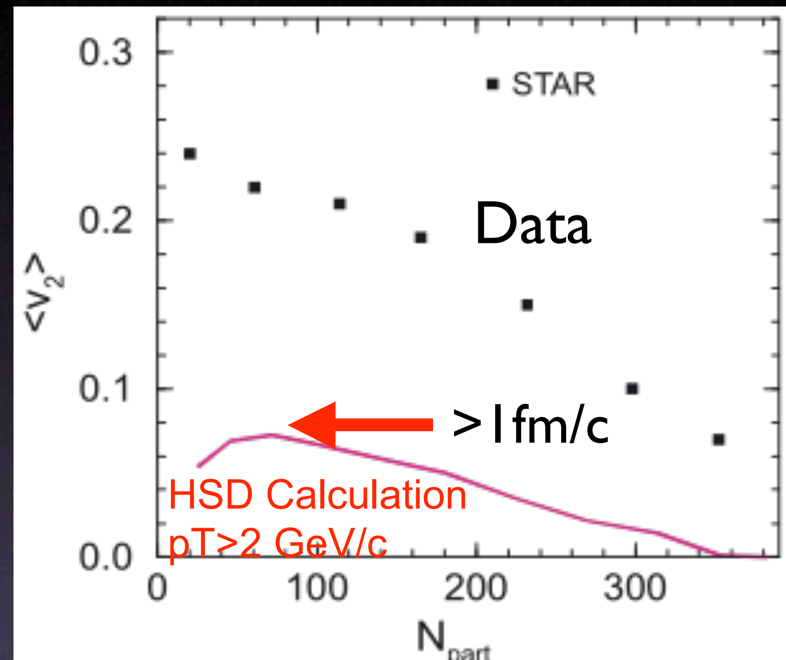
Parton Cascade



Molnar et al

Small x-section
Small formation time

Hadron Cascade



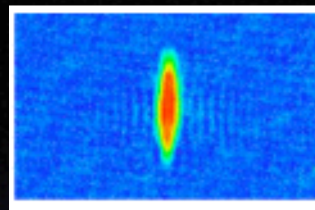
Cassing et al

Large x-section
Large formation time

Binary scattering of (small) partons or hadrons
(after formation time) can't explain data

Hydrodynamic Evolution

Initial State



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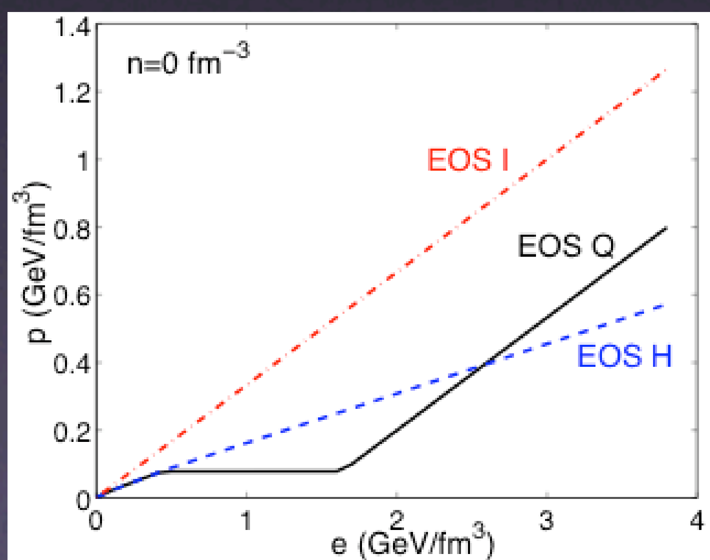
Energy/Momentum Conservation

$$\partial_\mu T^{\mu\nu} = 0$$
$$\partial_\mu j^\mu = 0$$

Baryon number Conservation

+

Equ. of State



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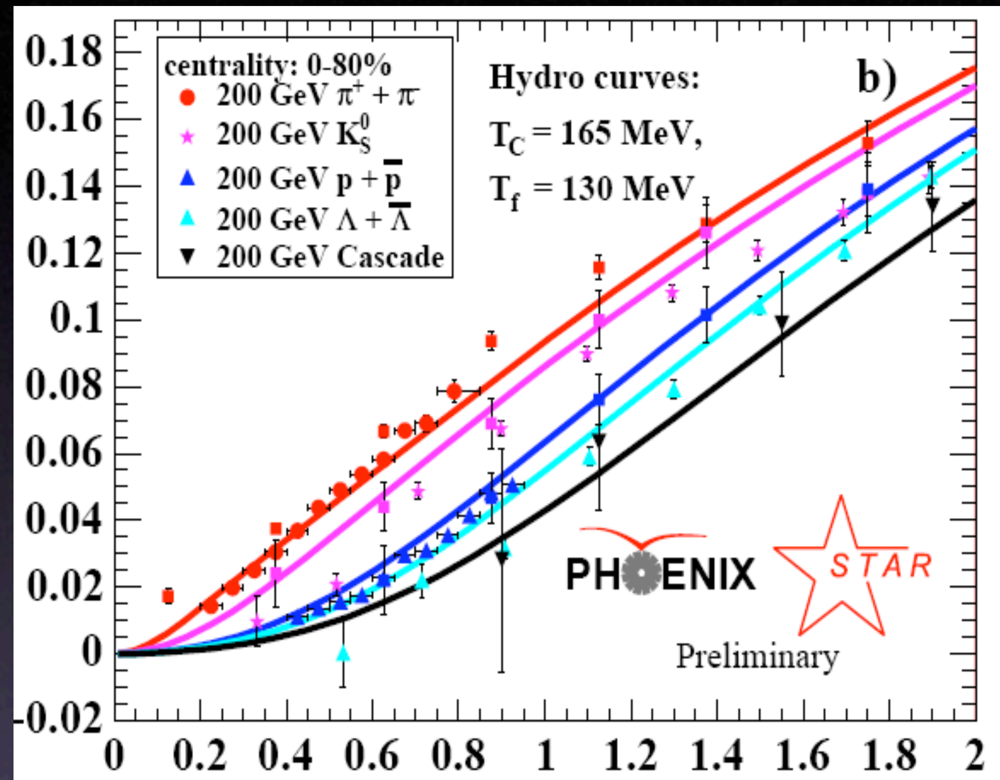
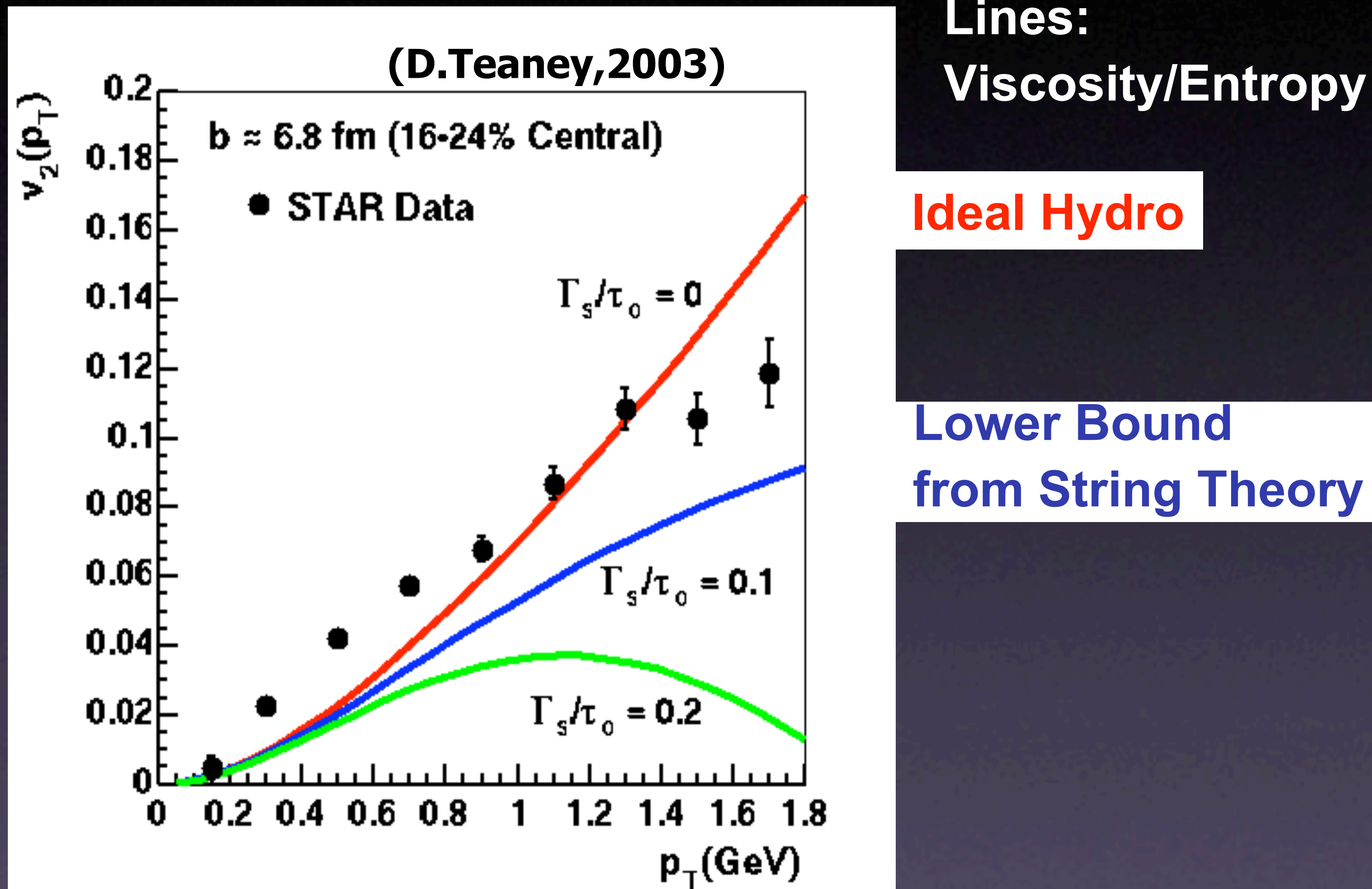


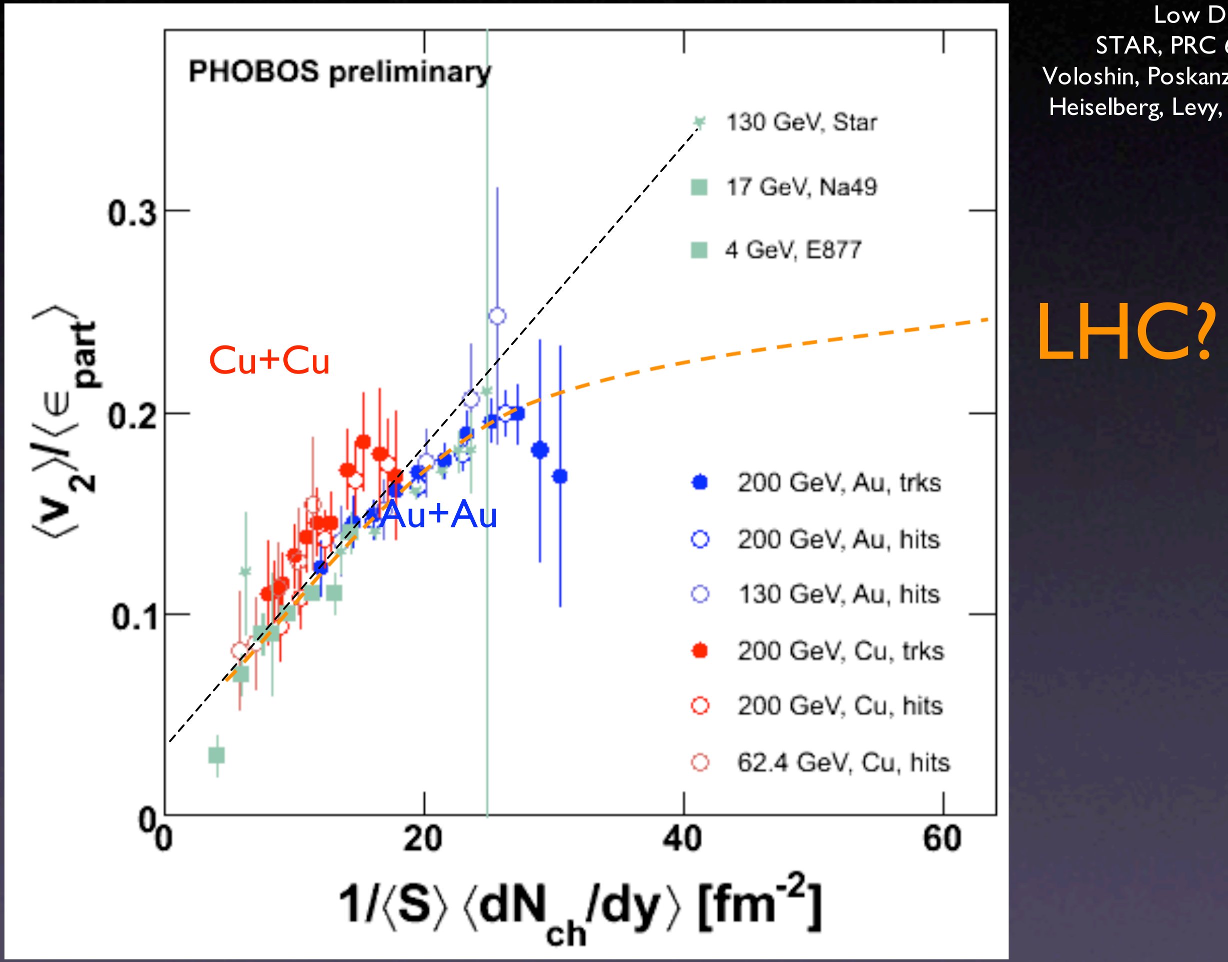
But: *no viscosity*

Perfect Liquid?



Elliptic Flow signal exhausts "hydro limit"

Hydrodynamic Evolution

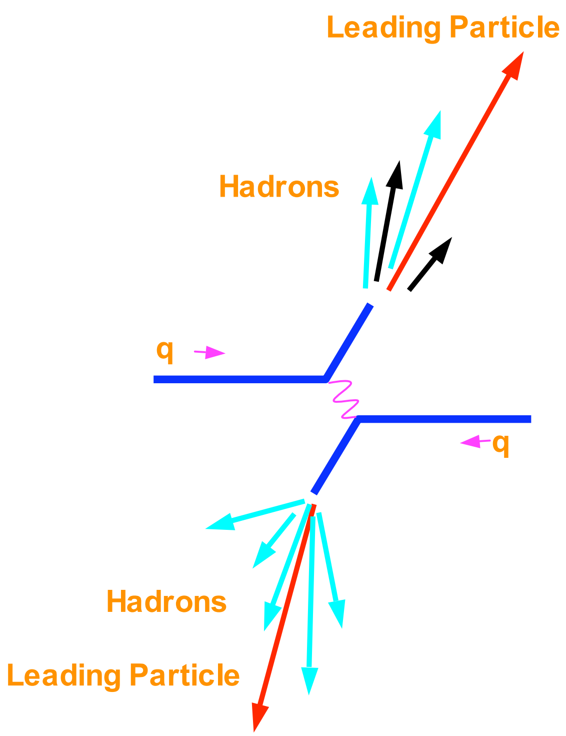


Low Density Limit:
STAR, PRC 66 034904 (2002)
Voloshin, Poskanzer, PLB 474 27 (2000)
Heiselberg, Levy, PRC 59 2716, (1999)

Will flow saturate at LHC
as thermalization is achieved?

Transport Properties of the Medium

p+p

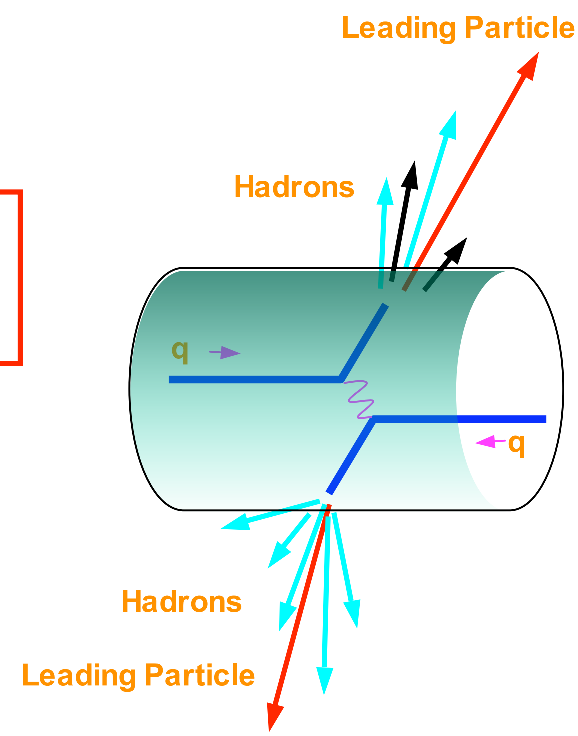


Jet-like high pT hadron production

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

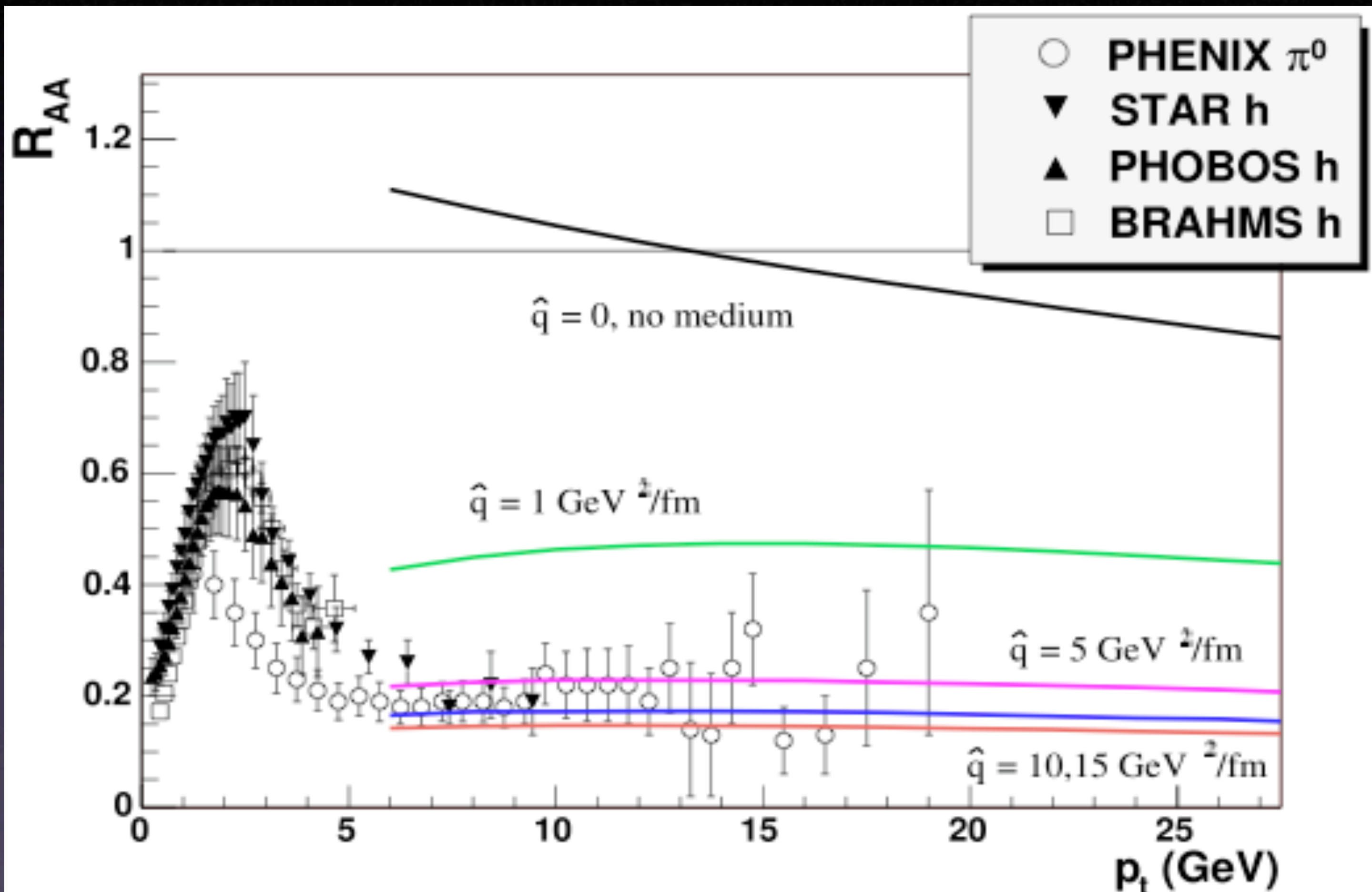
Ratio of AA/pp scaled by
# of binary NN collisions

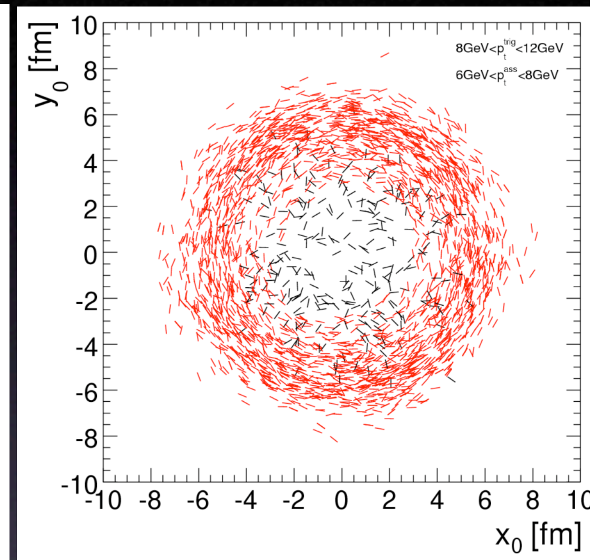
A+A



Partons propagate through medium
before fragmentation

Transport Properties of the Medium

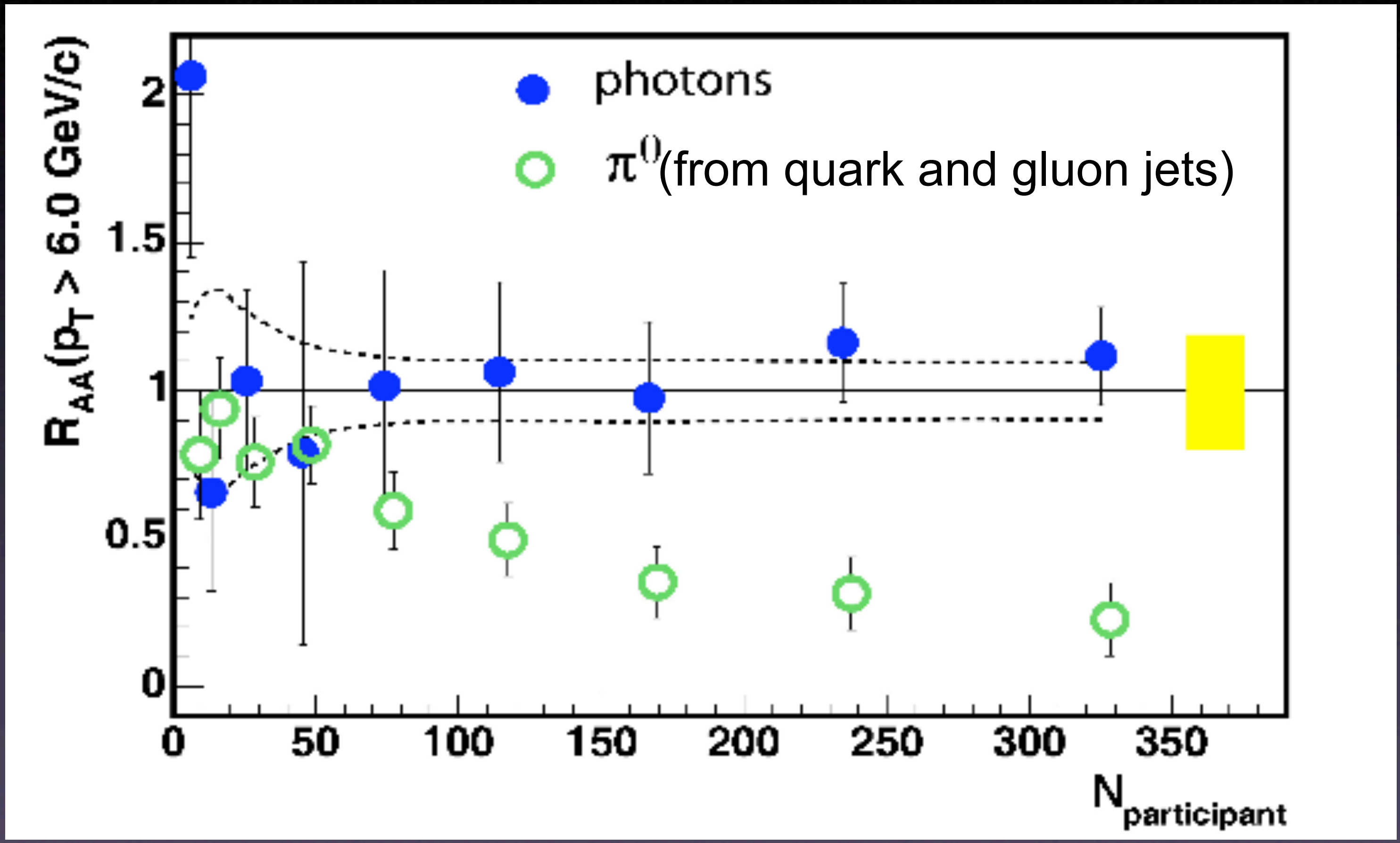




Surface emission?

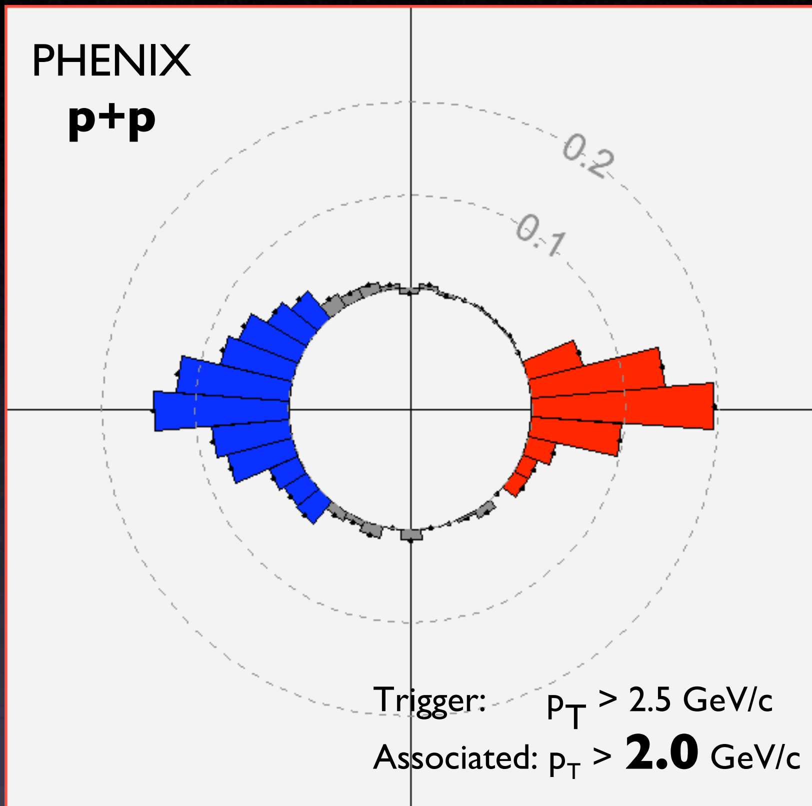
Suppression persists out to > 15 GeV/c

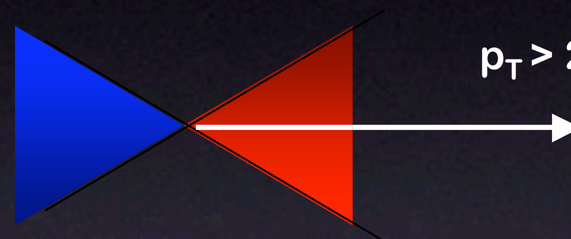
Binary Collision Scaling of Hard Processes



High p_T direct photons show expected scaling, while hadrons are suppressed

Jets and Angular Correlations



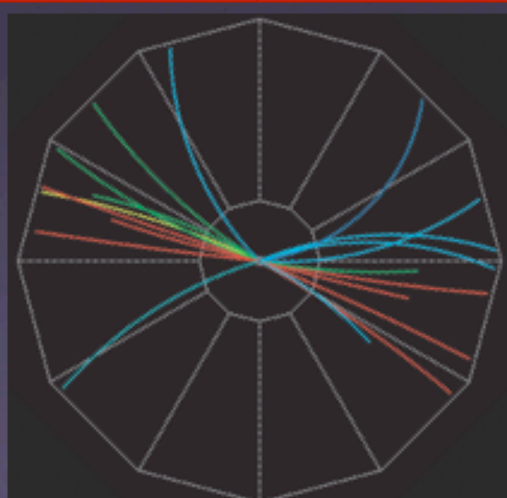


Trigger particle

p_T > 2.5 GeV

Associated particles

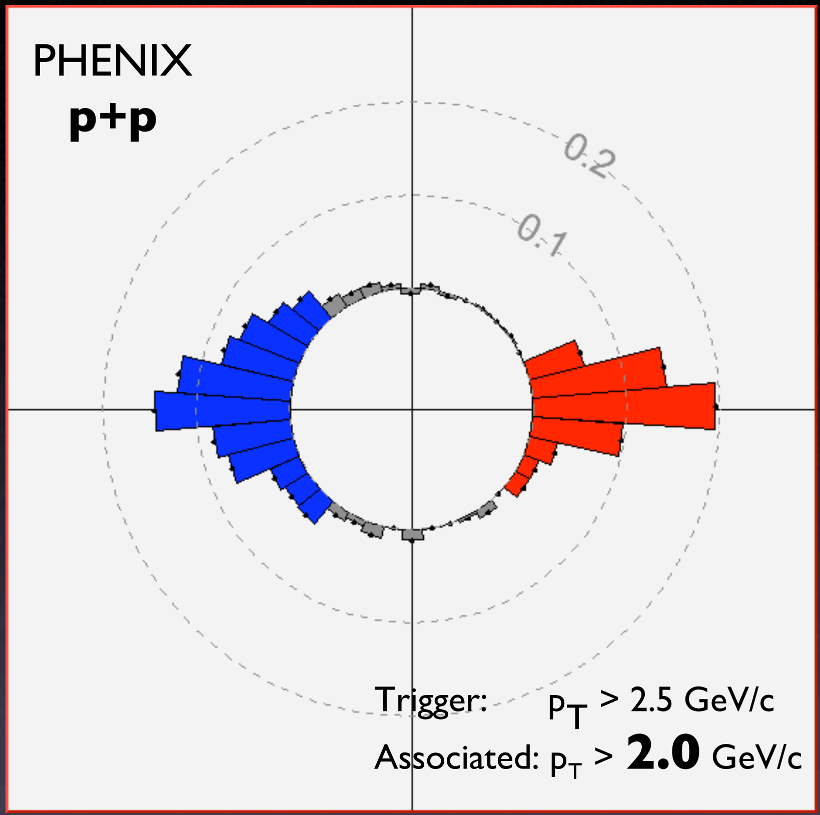
p_T > 2 GeV

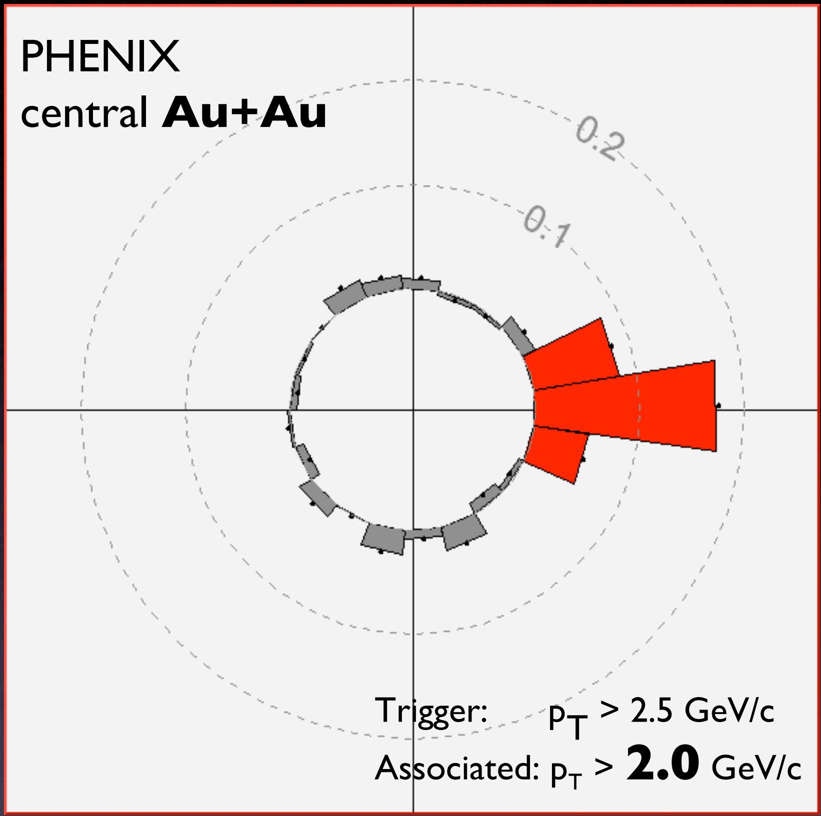


STAR
200 GeV p+p
p_T > 2.0 GeV/c

Plot angle of associated particles above p_T threshold relative to trigger

Jets and Angular Correlations





STAR
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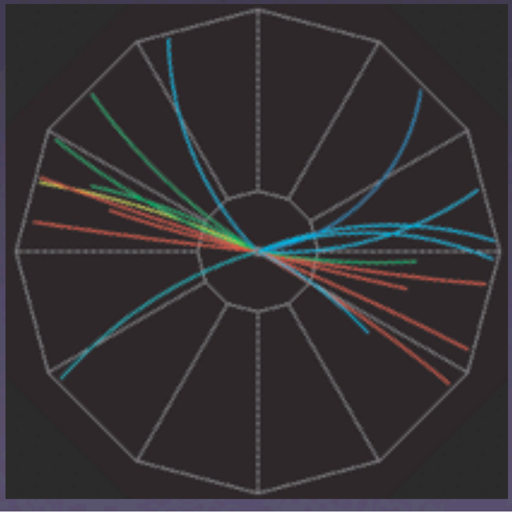
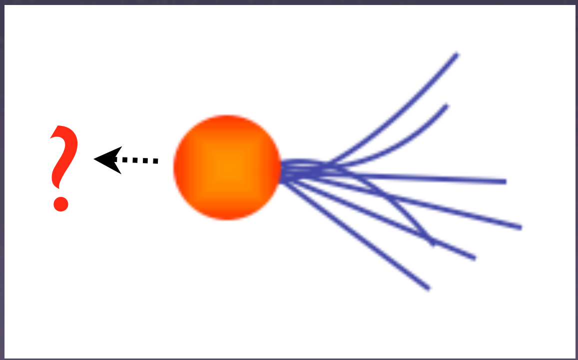
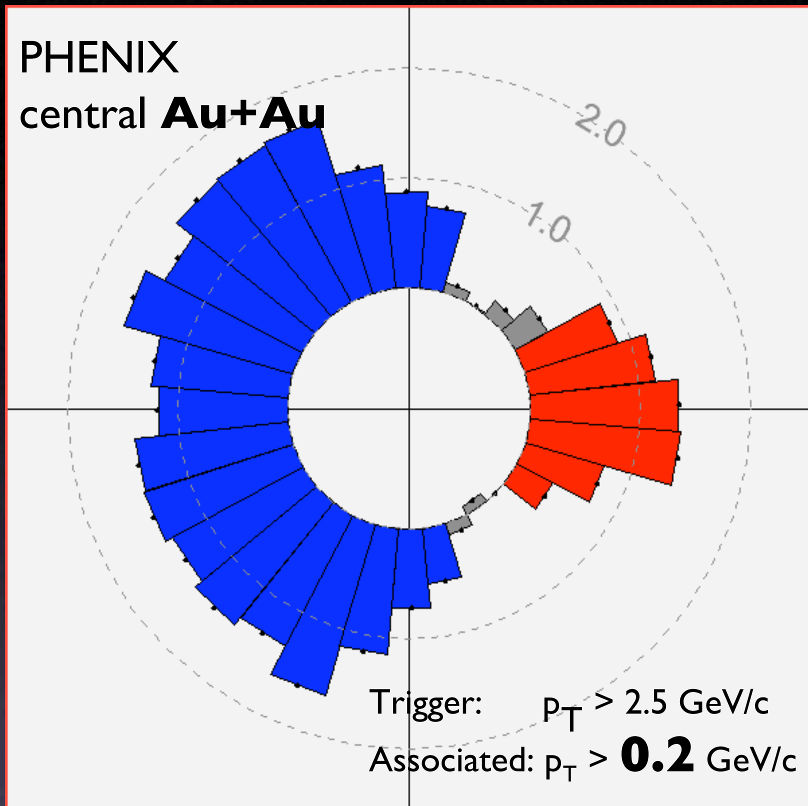
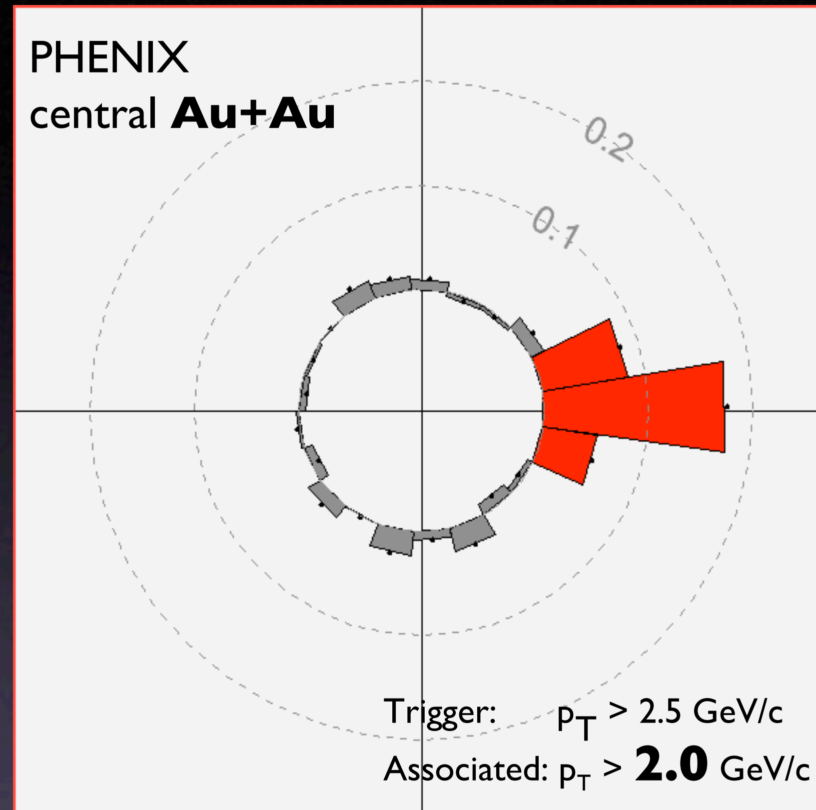
p_T > 2.0 GeV/c





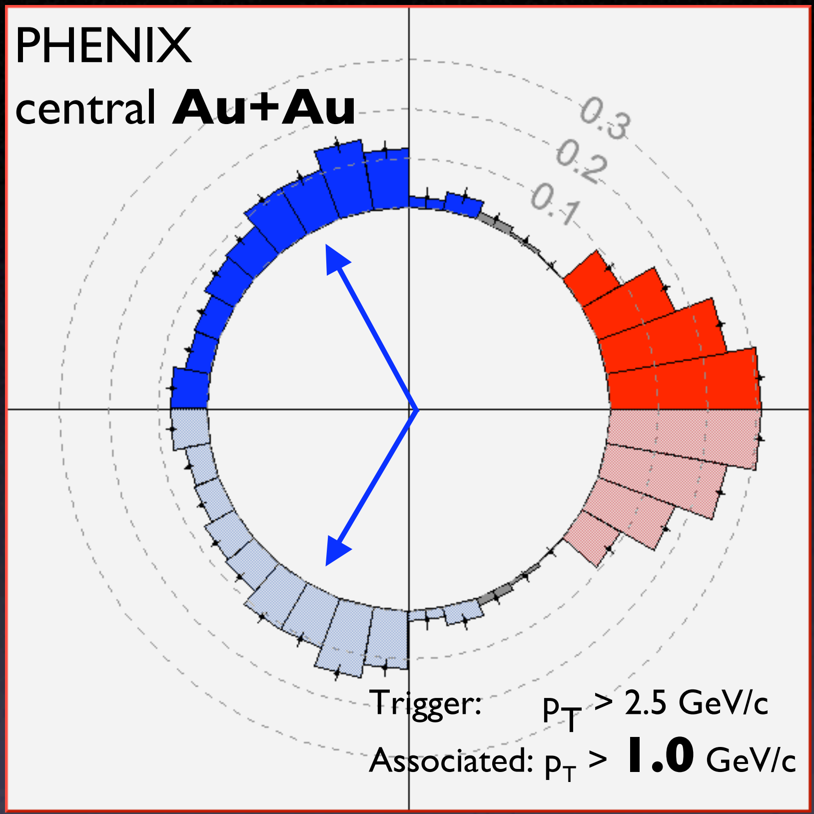
Jets and Angular Correlations

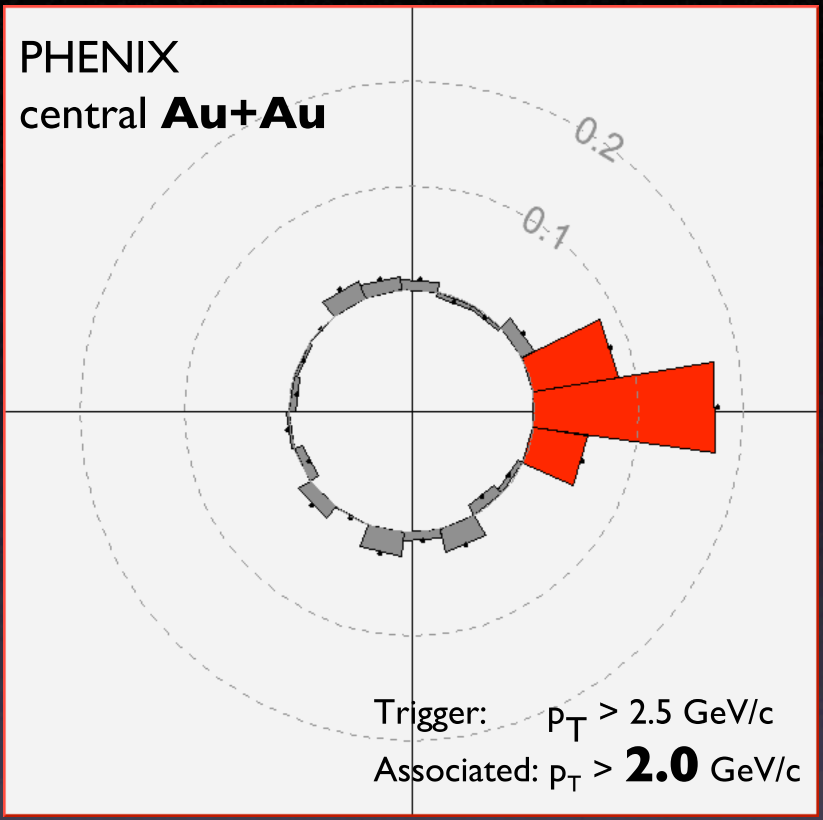




Away-side energy reappears in low p_T particles

Jets and Angular Correlations

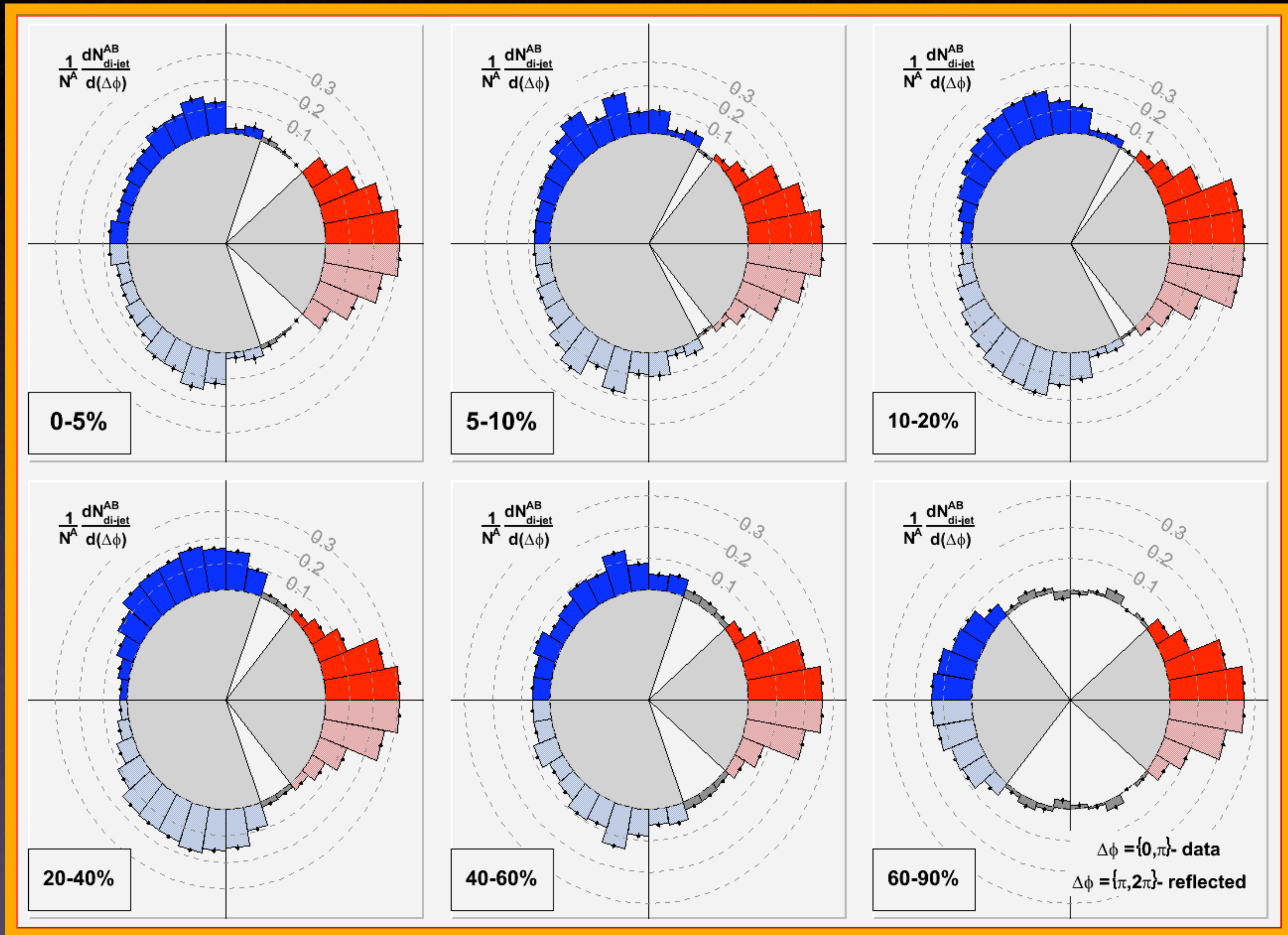




Structure in away-side distribution at intermediate p_T

Jets and Angular Correlations

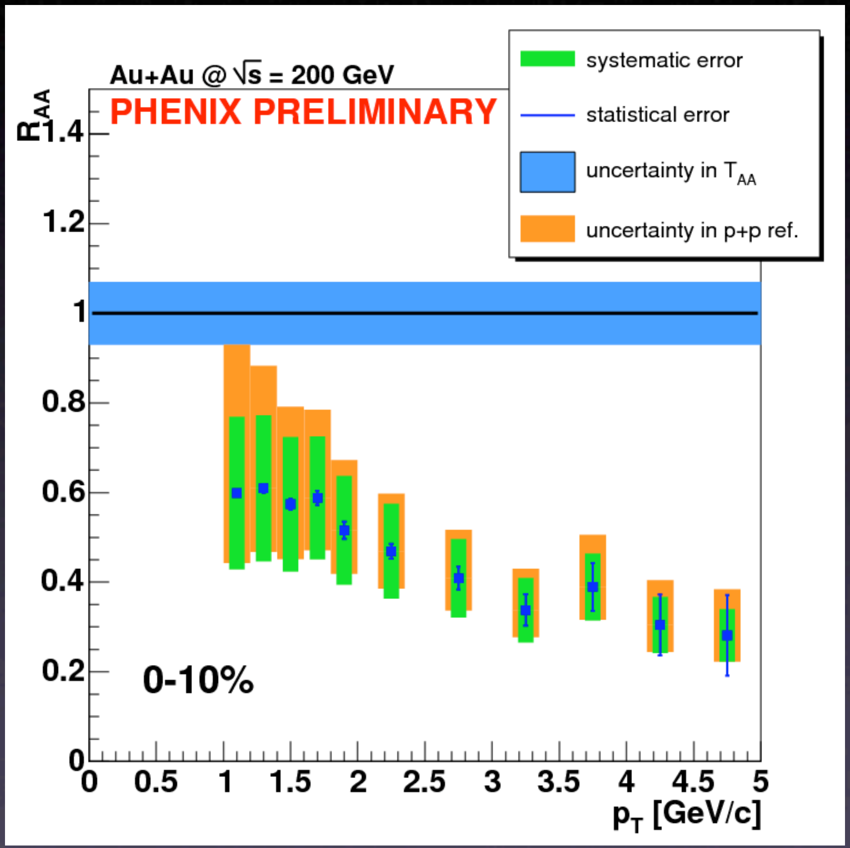
Trigger: $p_T > 2.5$ GeV/c
Associated: $p_T >$ **1.0** GeV/c



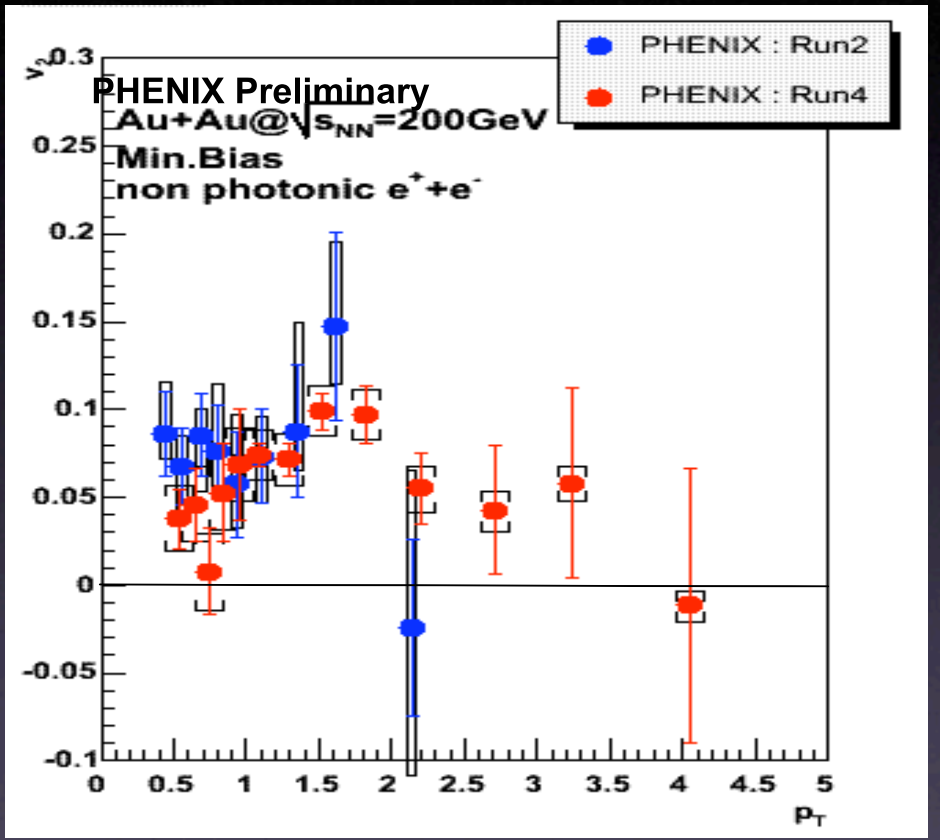
Rich phenomenology as a function of Trigger p_T, associated p_T and centrality

Heavy-Flavors and the Medium

Single electrons as proxies for heavy flavors (vertex detectors are being built)



Electron yields in A+A fall below N_{coll} scaling at higher p_T



Azimuthal asymmetry of electrons reflecting "flow" of heavy quarks?

Present

- System evolves out of "coherent" initial state
- Hydrodynamic evolution with small viscosity
- Medium is opaque to high p_T particles
- Heavy flavors feel "drag" of medium

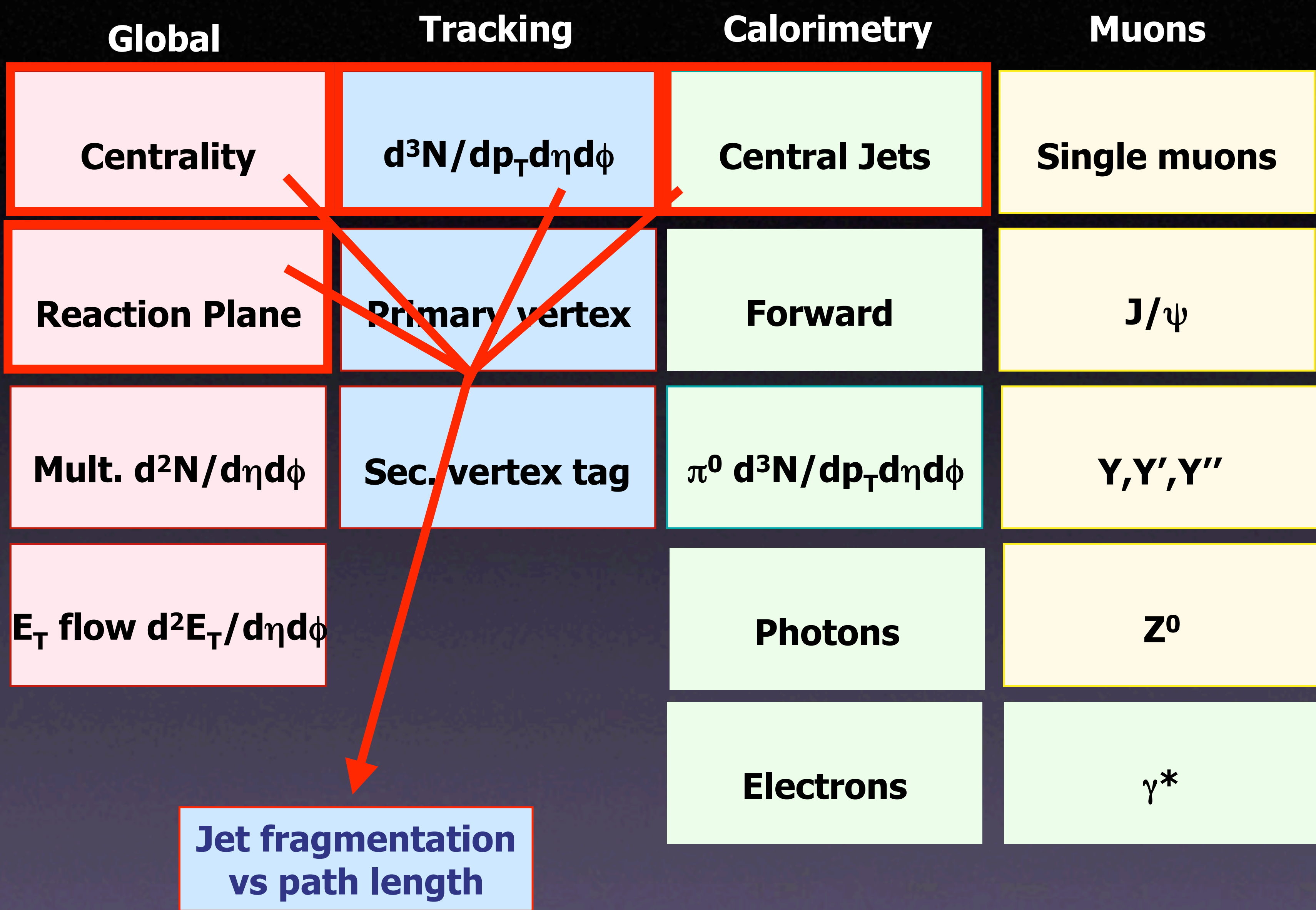
Future

- Measure viscosity, transport coefficients
- *Calculate* viscosity, transport coefficients
- Nature of DoF?
- Understand mechanism of thermalization
- Extract equation of state

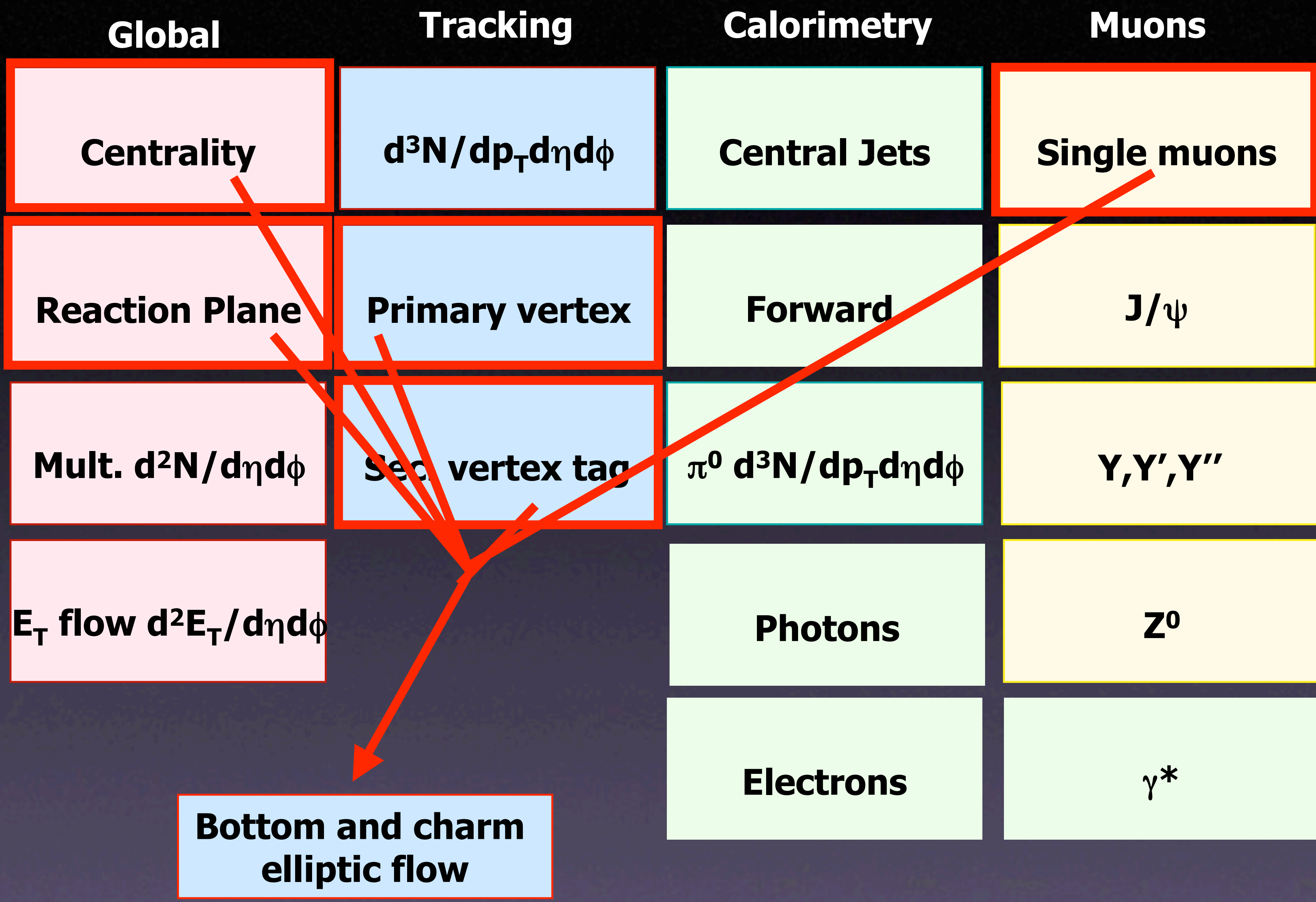
Heavy Ion Menu at the LHC

Global	Tracking	Calorimetry	Muons
Centrality	$d^3N/dp_Td\eta d\phi$	Central Jets	Single muons
Reaction Plane	Primary vertex	Forward	J/ψ
Mult. $d^2N/d\eta d\phi$	Sec. vertex tag	π^0 $d^3N/dp_Td\eta d\phi$	$\Upsilon, \Upsilon', \Upsilon''$
E_T flow $d^2E_T/d\eta d\phi$		Photons	Z^0
		Electrons	γ^*

Heavy Ion Menu at the LHC



Heavy Ion Menu at the LHC

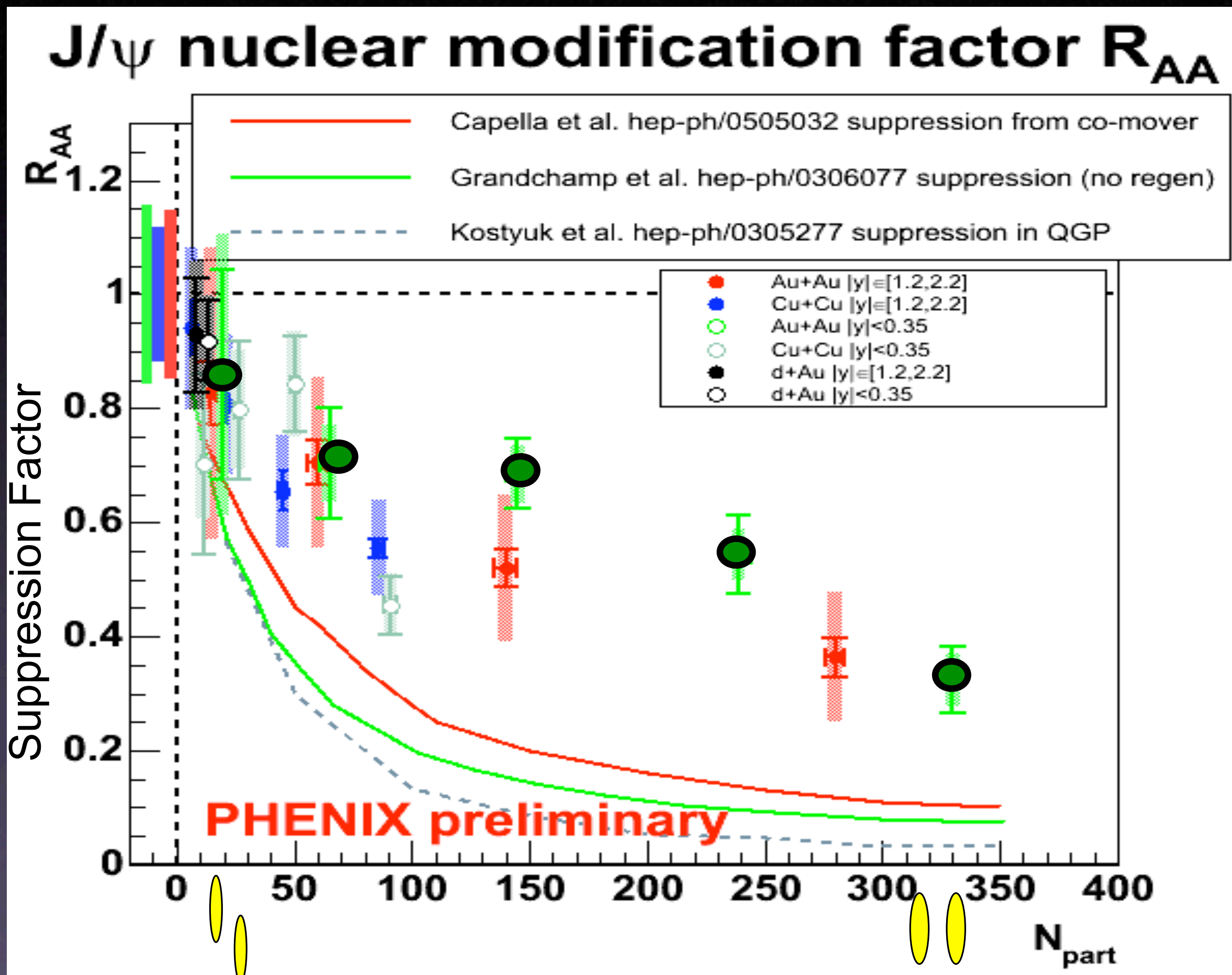


Heavy Ion Menu at the LHC

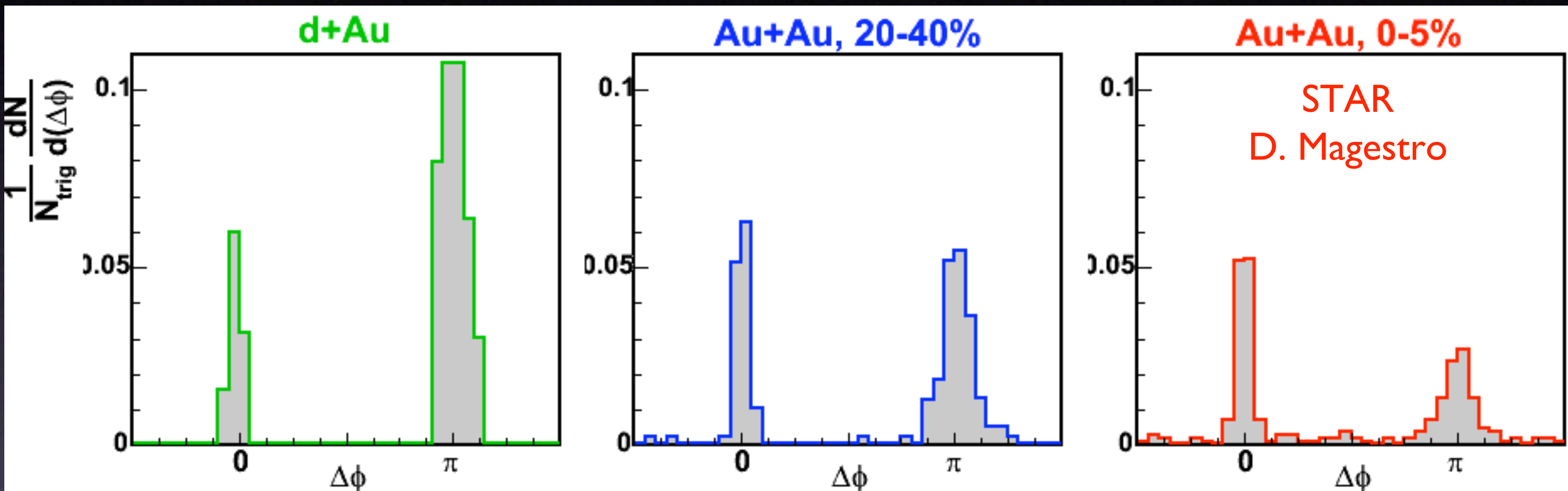
Global	Tracking	Calorimetry	Muons
Centrality	**$d^3N/dp_T d\eta d\phi$**	**Central Jets**	**Single muons**
Reaction Plane	**Primary vertex**	**Forward**	**J/ψ**
Mult. $d^2N/d\eta d\phi$	**Sec. vertex tag**	**π^0 $d^3N/dp_T d\eta d\phi$**	**$\Upsilon,\Upsilon',\Upsilon''$**
E_T flow $d^2E_T/d\eta d\phi$		**Photons**	**Z^0**
		Electrons	**γ^***

Heavy Ions @ LHC: Abundant, well-defined high p_T objects
Connected to identified partons in a well-characterized medium

Charmonium at RHIC



Properties of the Medium

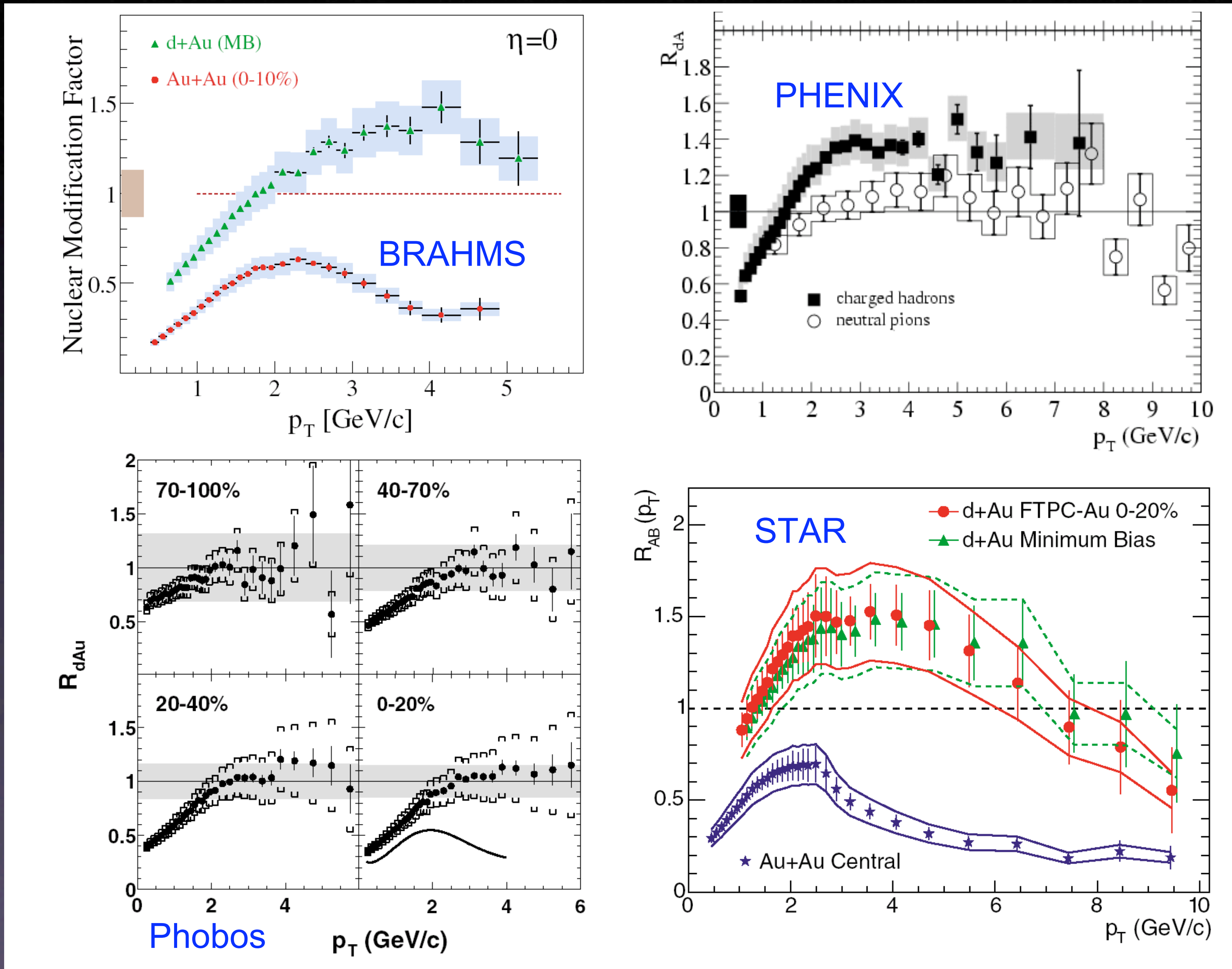


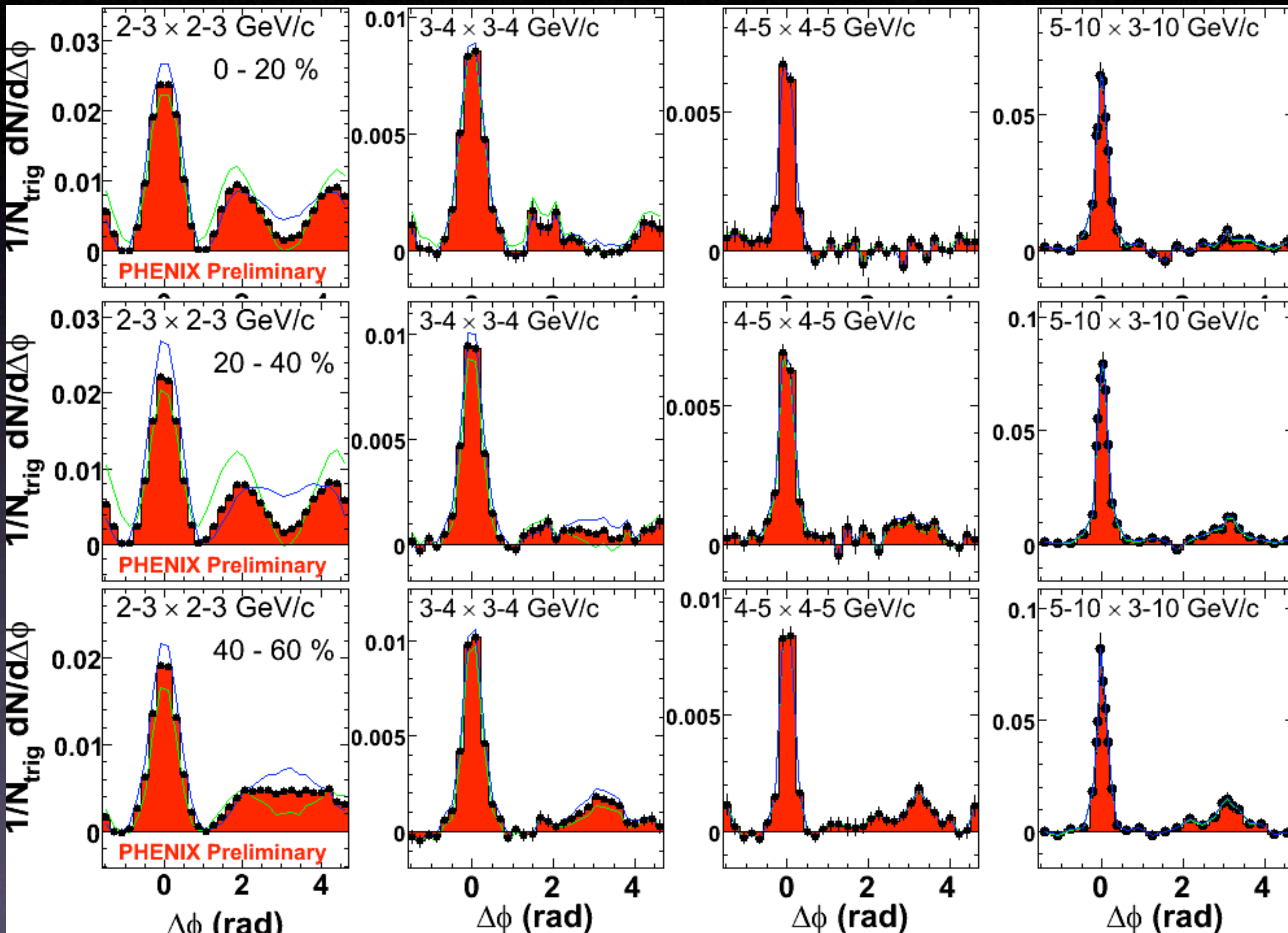
8 < p_T(trig) < 15 GeV/c
p_T(assoc) > 8 GeV/c

Back-to-back jets re-appear at sufficiently high p_T

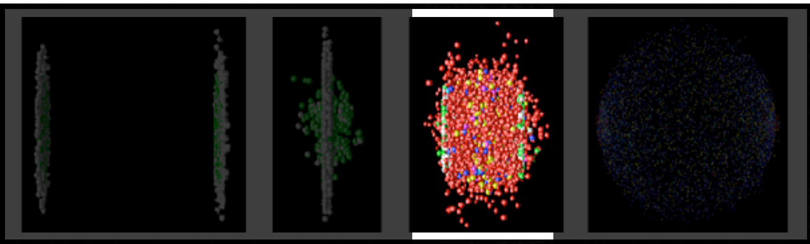
But: Reduced yield - tangential surface emission?

d+Au Control Experiment

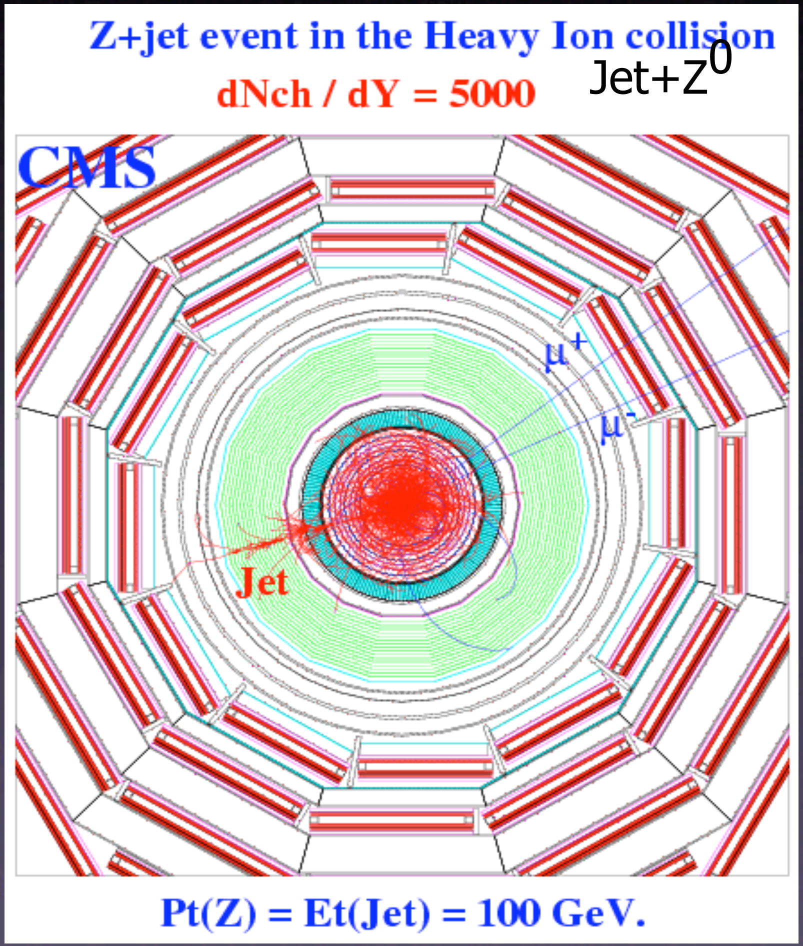


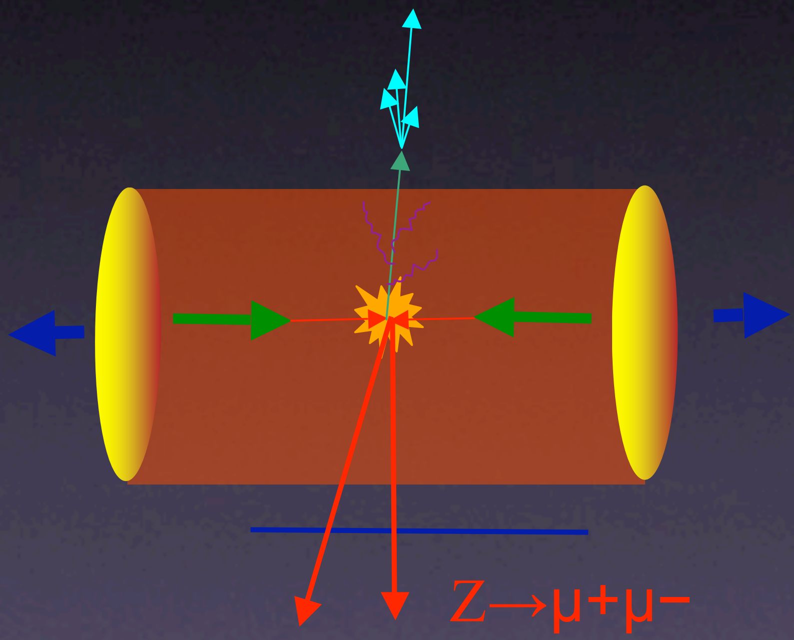


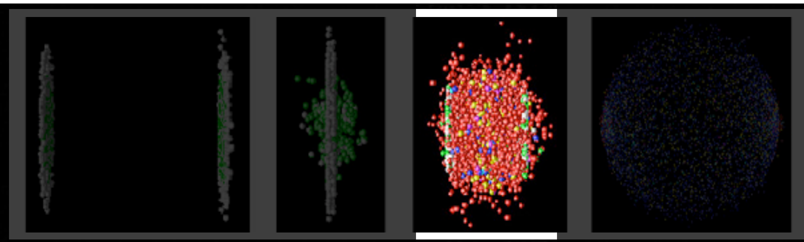
2-3 × 2-3 GeV/c
0 - 20 %
3-4 × 3-4 GeV/c
4-5 × 4-5 GeV/c
5-10 × 3-10 GeV/c
20 - 40 %
40 - 60 %
PHENIX Preliminary
$1/N_{trig}\ dN/d\Delta\phi$
$\Delta\phi$ (rad)



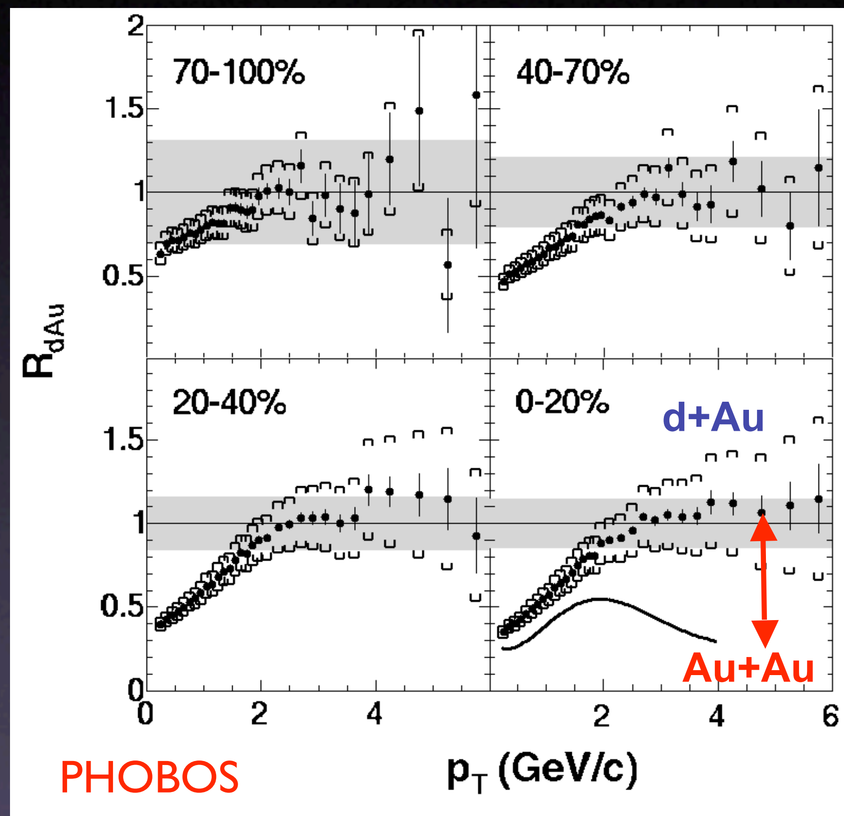
Properties of the Medium

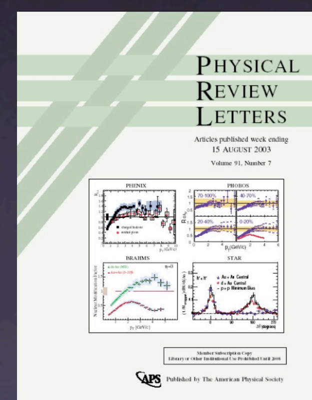






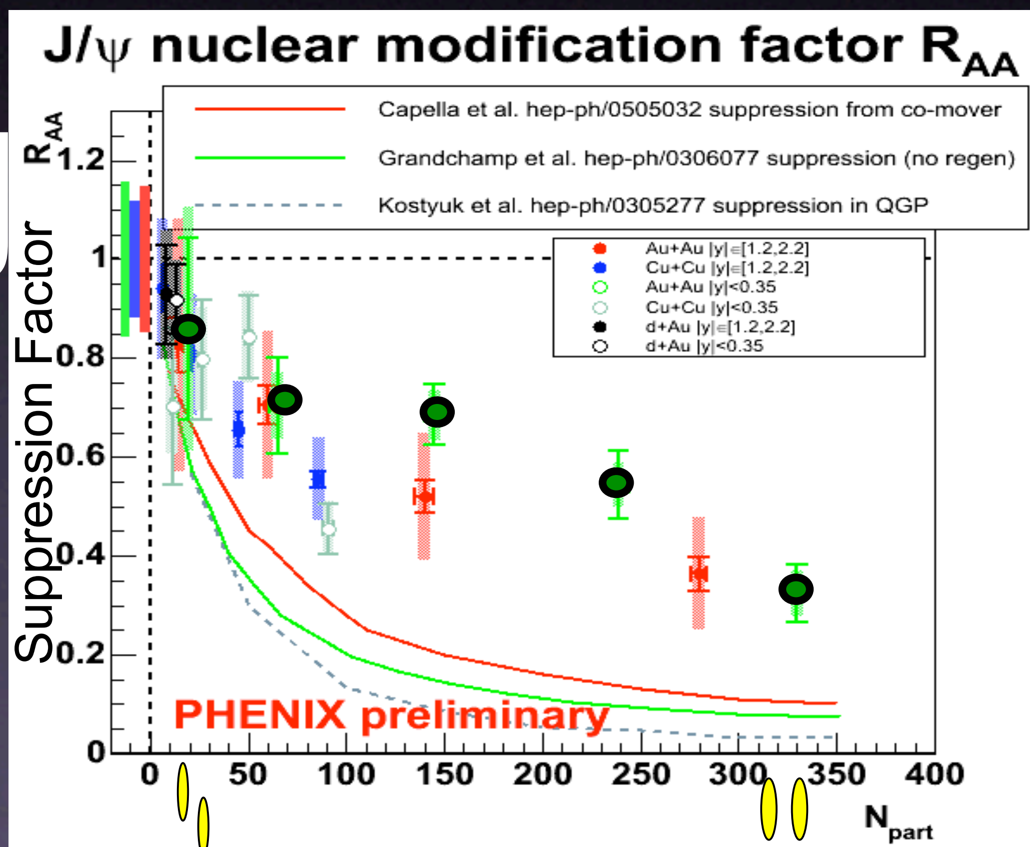
Properties of the Medium





Use high p_T hadron yield as “calibrated” probe

Strong (factor 5) suppression observed



J/ψ nuclear modification factor R_AA
Capella et al. hep-ph/0505032 suppression from co-mover
Grandchamp et al. hep-ph/0306077 suppression (no regen)
Kostyuk et al. hep-ph/0305277 suppression in QGP
Au+Au |y|∈[1.2,2.2]
Cu+Cu |y|∈[1.2,2.2]
Au+Au |y|<0.35
Cu+Cu |y|<0.35
d+Au |y|∈[1.2,2.2]
d+Au |y|<0.35
R_AA
Suppression Factor
1.2
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
350
400
N_part
PHENIX preliminary