HEAVY ION PHYSICS AT RHIC: EXPEPRIMENTAL STATUS & OUTLOOK

Baruch COLLEGE The City University of New York
RIKEN BNL Research Center

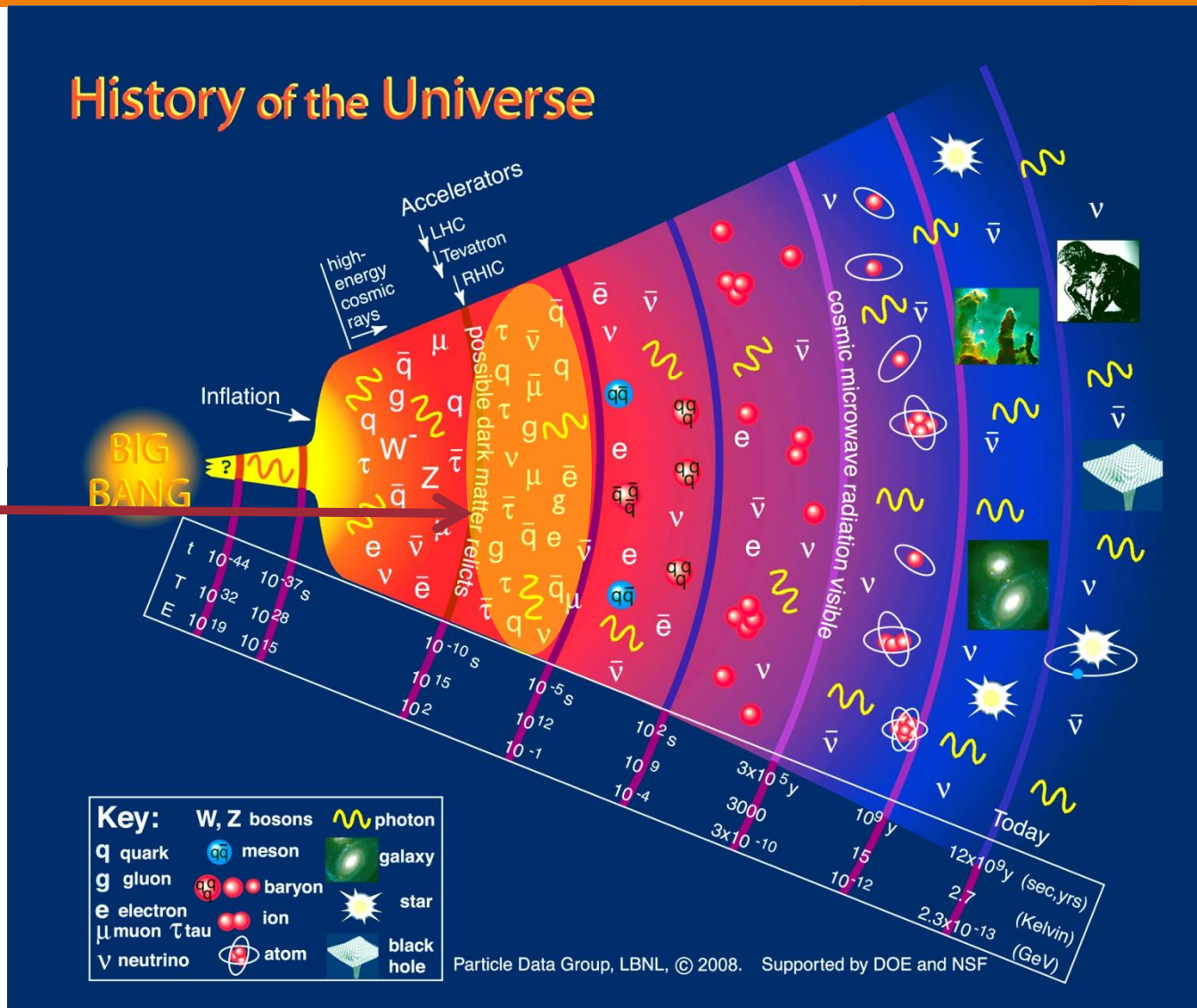
History of the Universe

Time
few μs after Big Bang

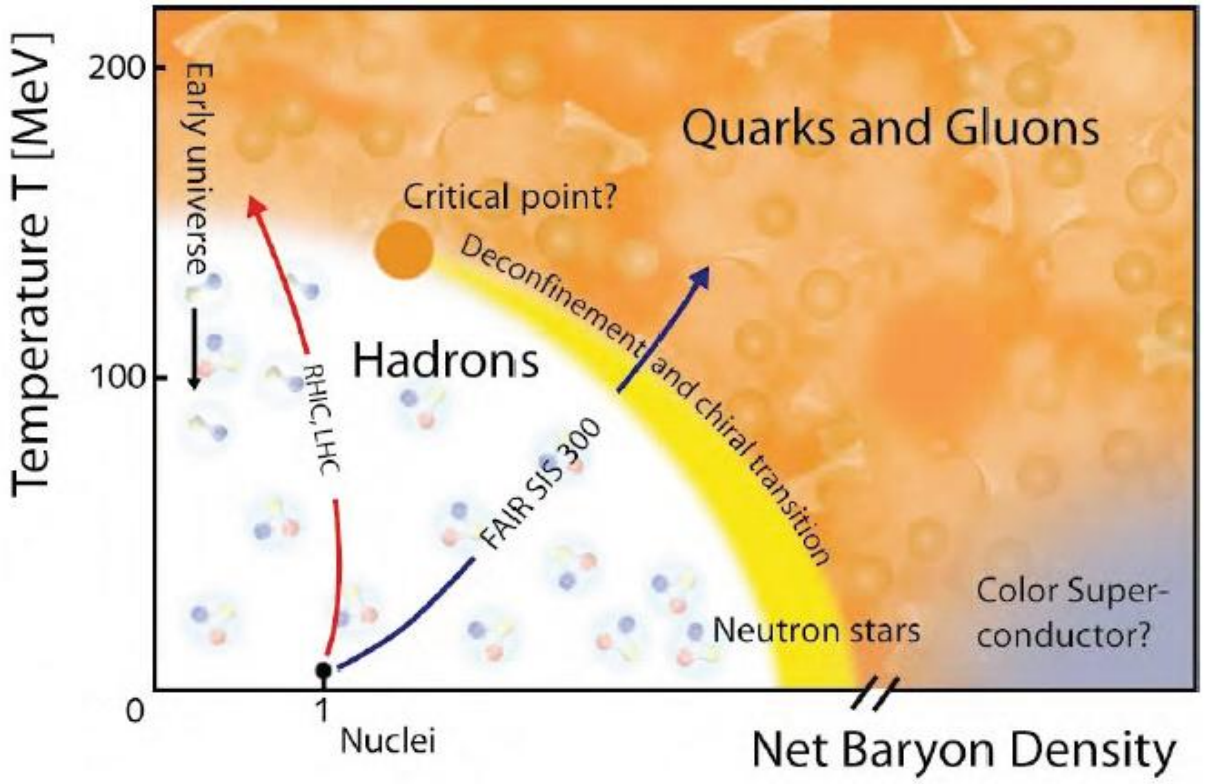
Energy density
$\varepsilon \sim 1$ GeV/fm^3

QGP

Temperature:
T=170 MeV



Exploring the QCD Phase Diagram

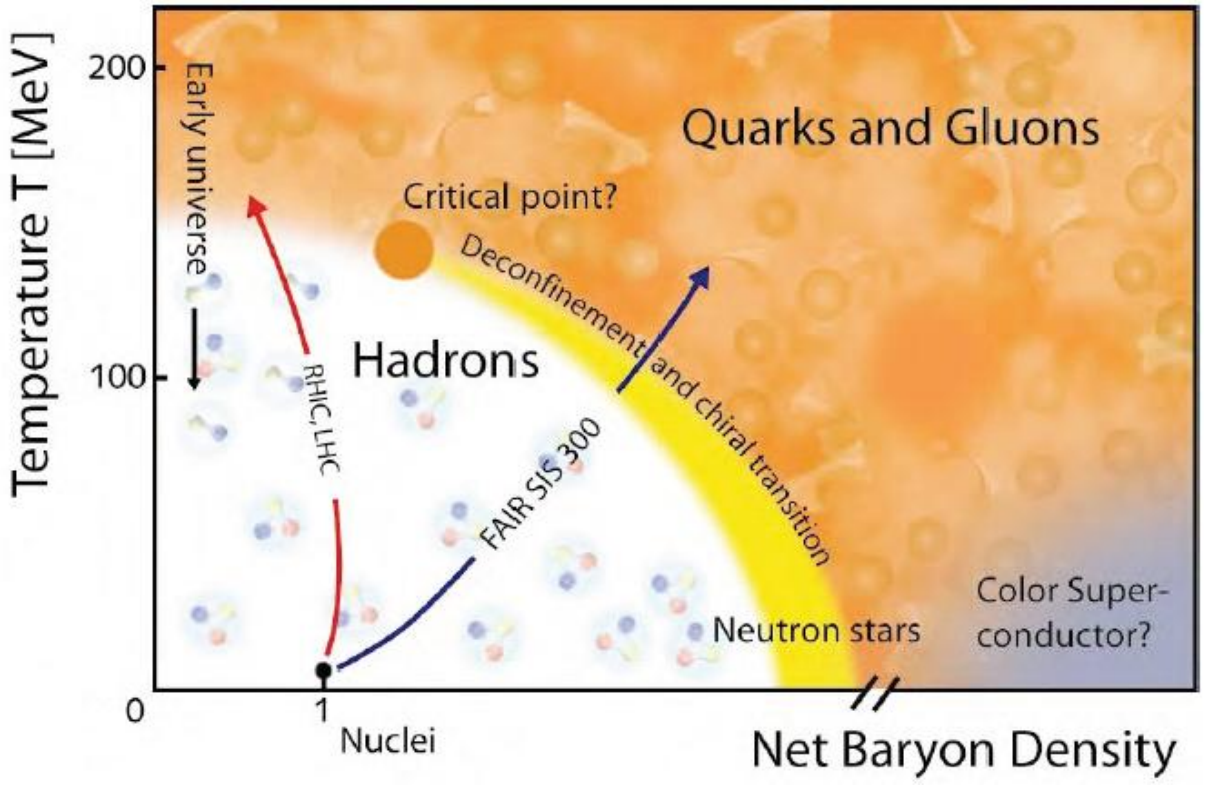


How to explore the QCD phase diagram **experimentally?**

Collide heaviest nuclei at highest energies

Stefan Bathe, Heavy Ion Physics at RHIC

Exploring the QCD Phase Diagram



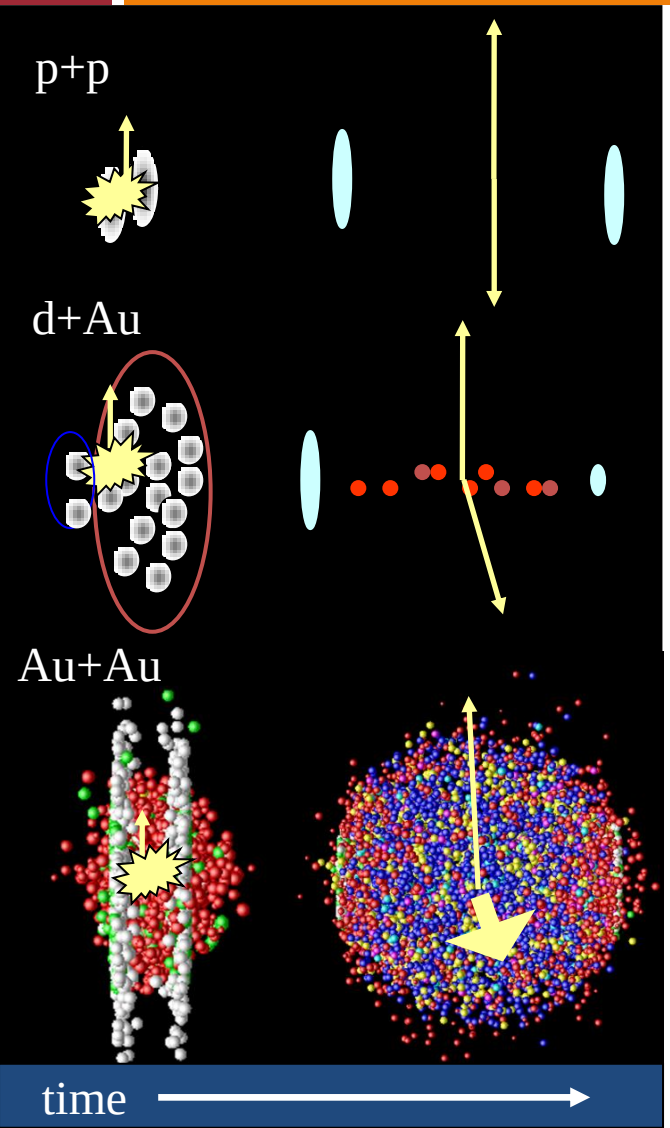
How to explore the QCD phase diagram **experimentally?**

Collide heaviest nuclei at highest energies

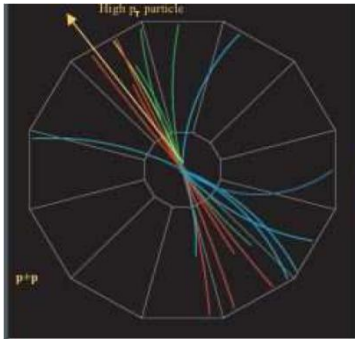
RHIC's original mission:
- Find QGP phase transition
- Established

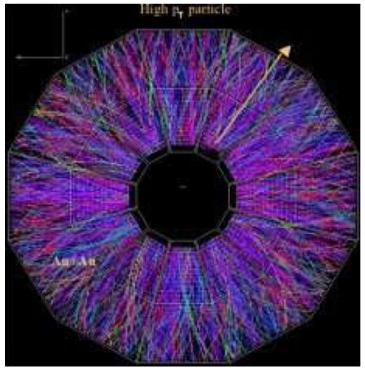
Now:
- understand QGP properties quantitatively

Baseline And Control

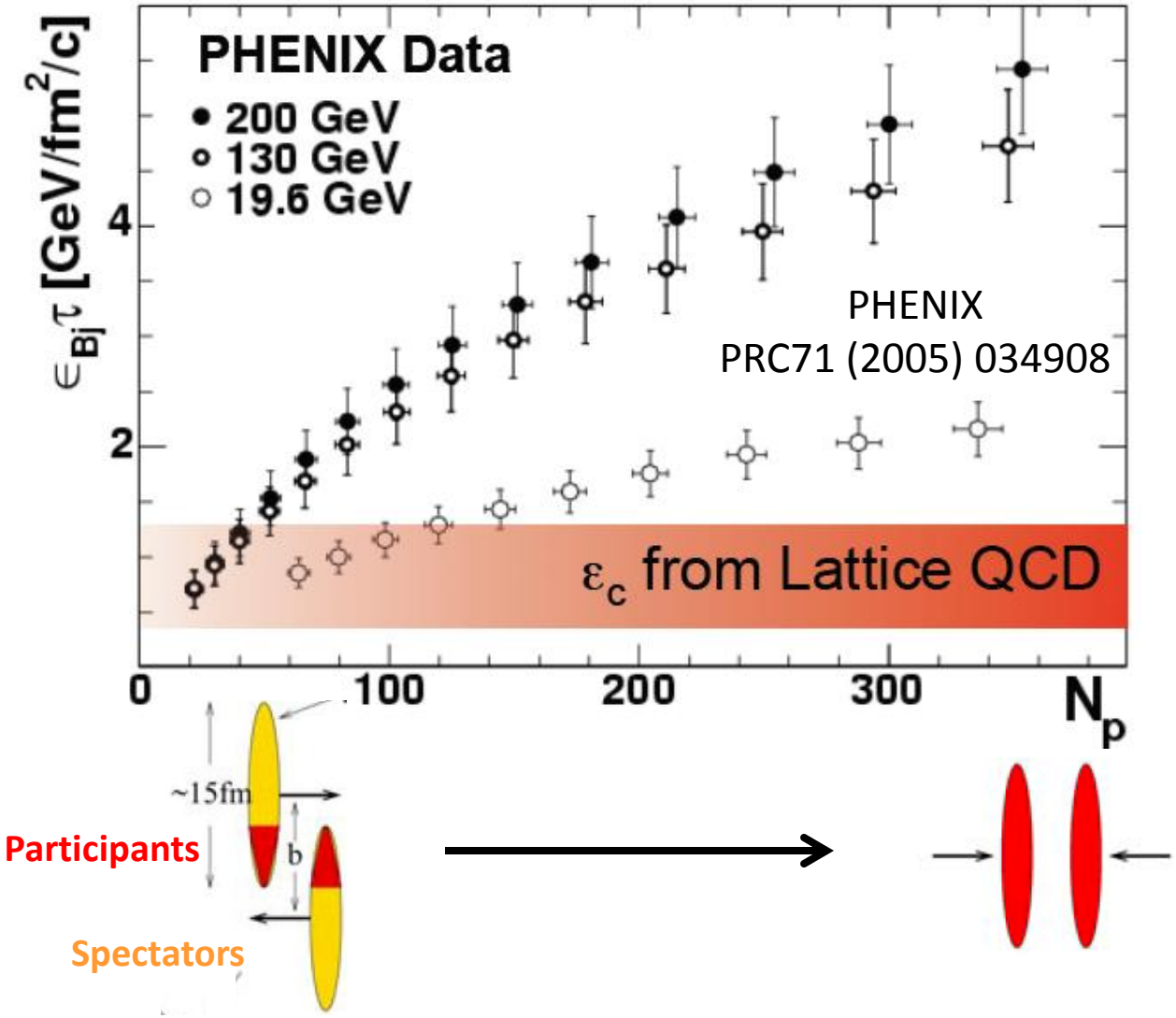


- Systematic Approach
  - p+p: baseline
  - d+A: control
  - Au+Au: new effects





Energy Density: a Pre-requisite



from $dE_T/d\eta$ measurement

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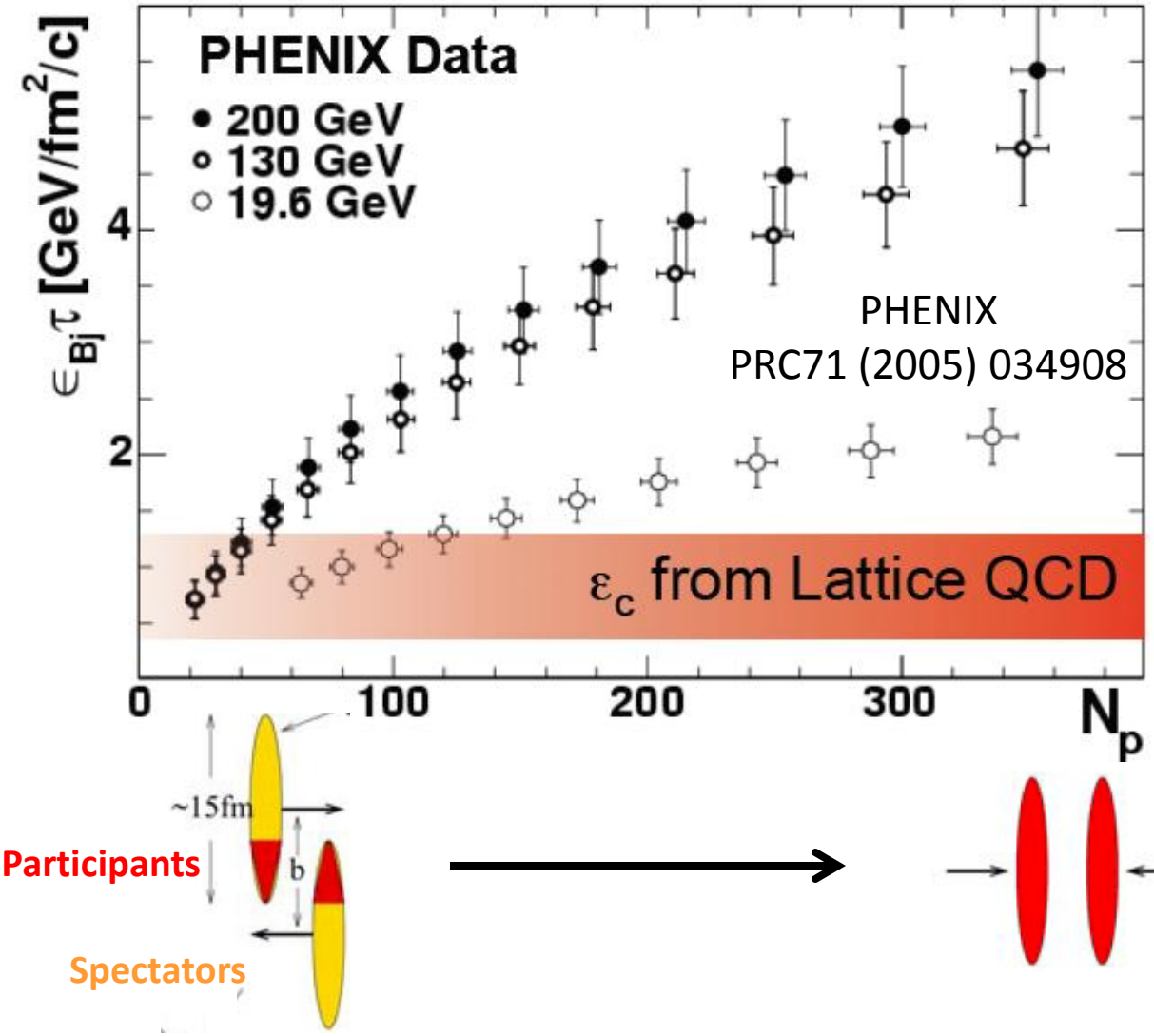
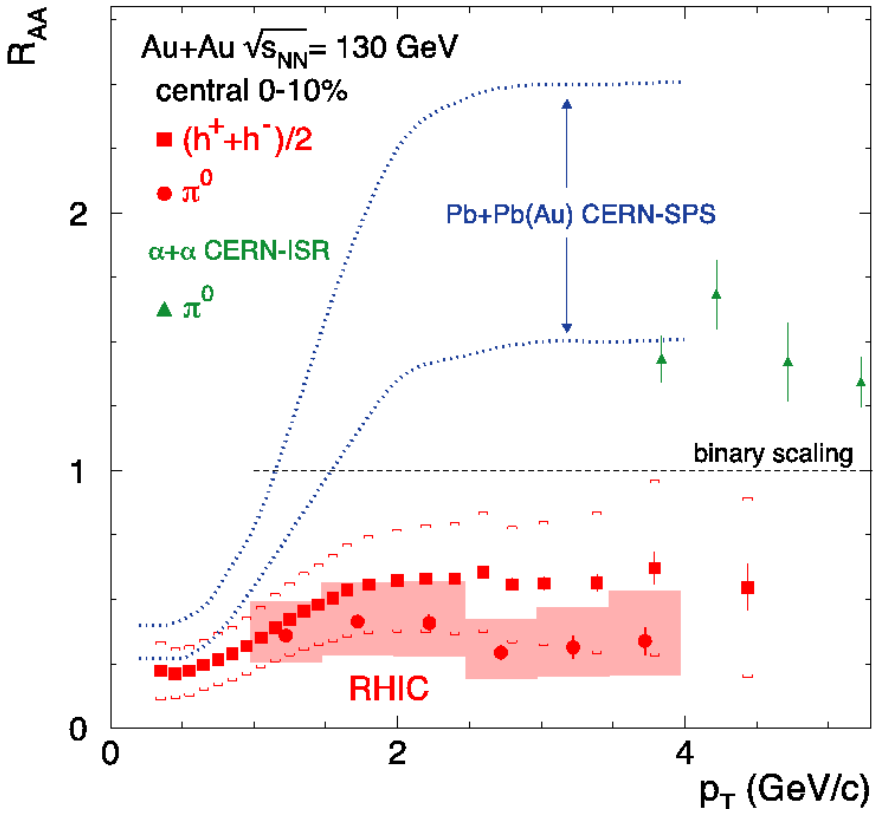


from $dE_T/d\eta$ measurement

– $\varepsilon >> \varepsilon_c$
- Hadronic picture difficult to maintain

RHIC's Two Major Discoveries: 1

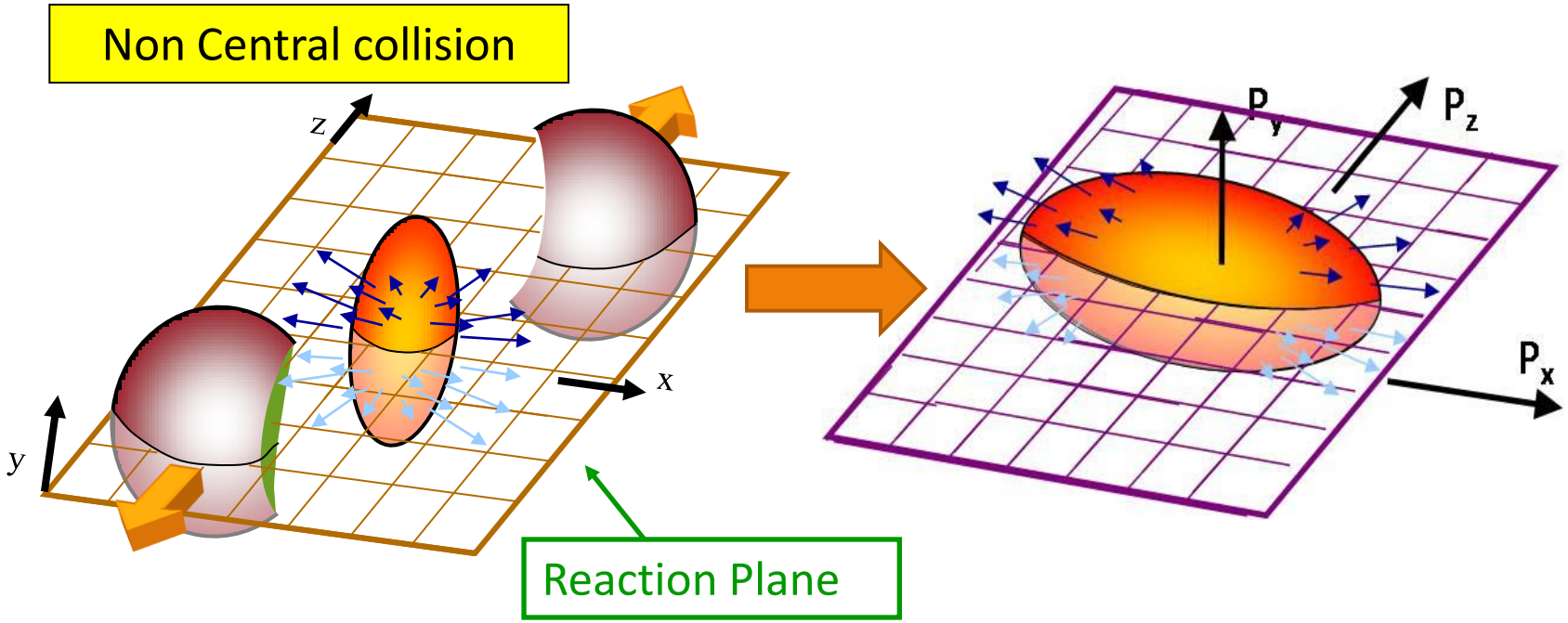
PHENIX PRL88,022301(2002)



$$R_{AA} = \frac{\text{Yield}_{AA}}{N_{coll}\text{Yield}_{pp}}$$

High p_T suppression
→Energy loss of quark/gluon
→Very dense matter

Elliptic Flow



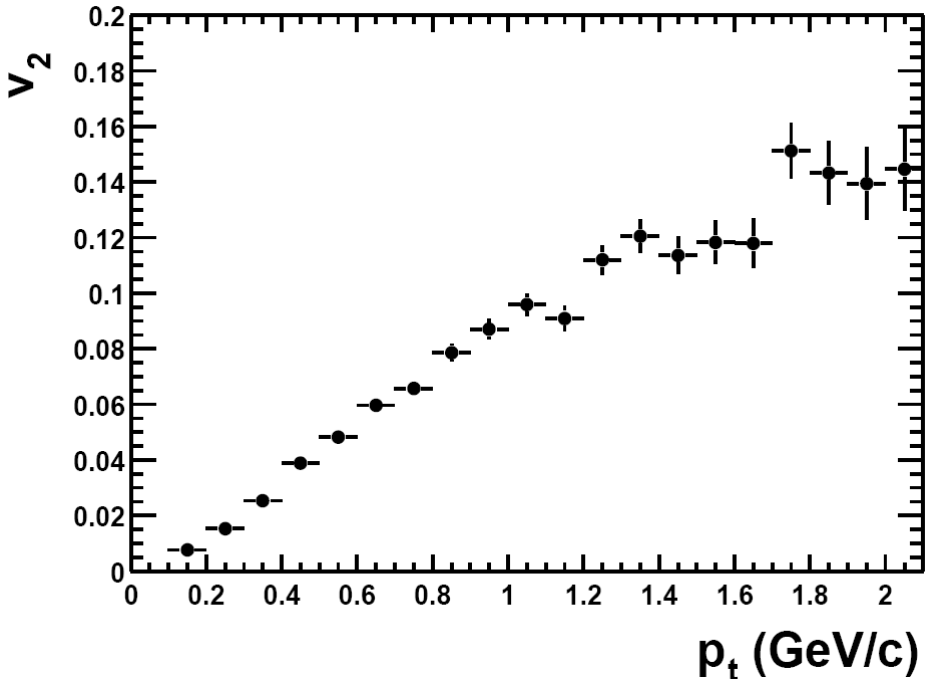
In non-central collisions, high density matter with elliptic shape is formed

➔Expansion towards reaction plane

→ *Elliptic Flow*

RHIC's Two Major Discoveries: 2

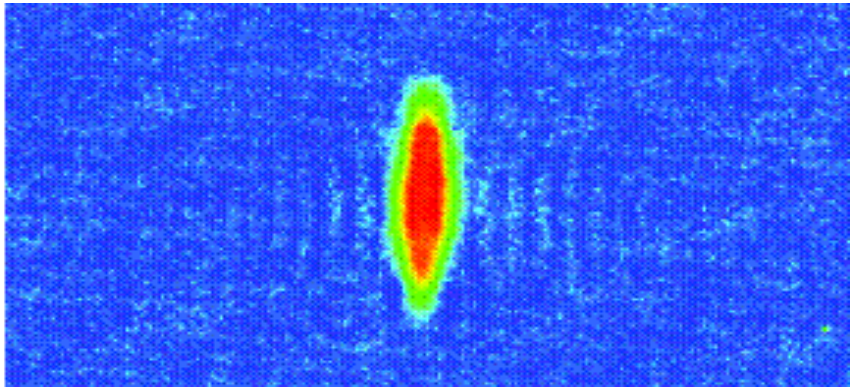
STAR PRL86,402 (2001)



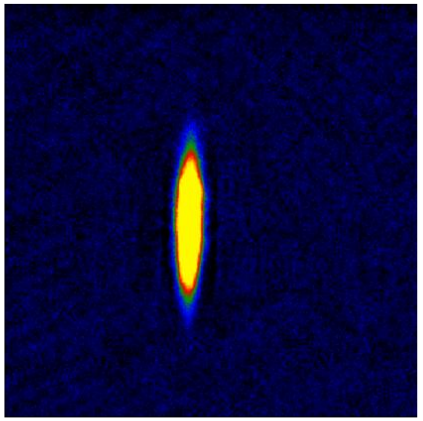
Strong Elliptic flow
→Agrees with ideal hydrodynamics
→Low viscosity/entropy (η/s)

Strongly vs. weakly coupled

strongly-coupled
small η/s



weakly-coupled
large η/s



(Almost) Perfect Fluid

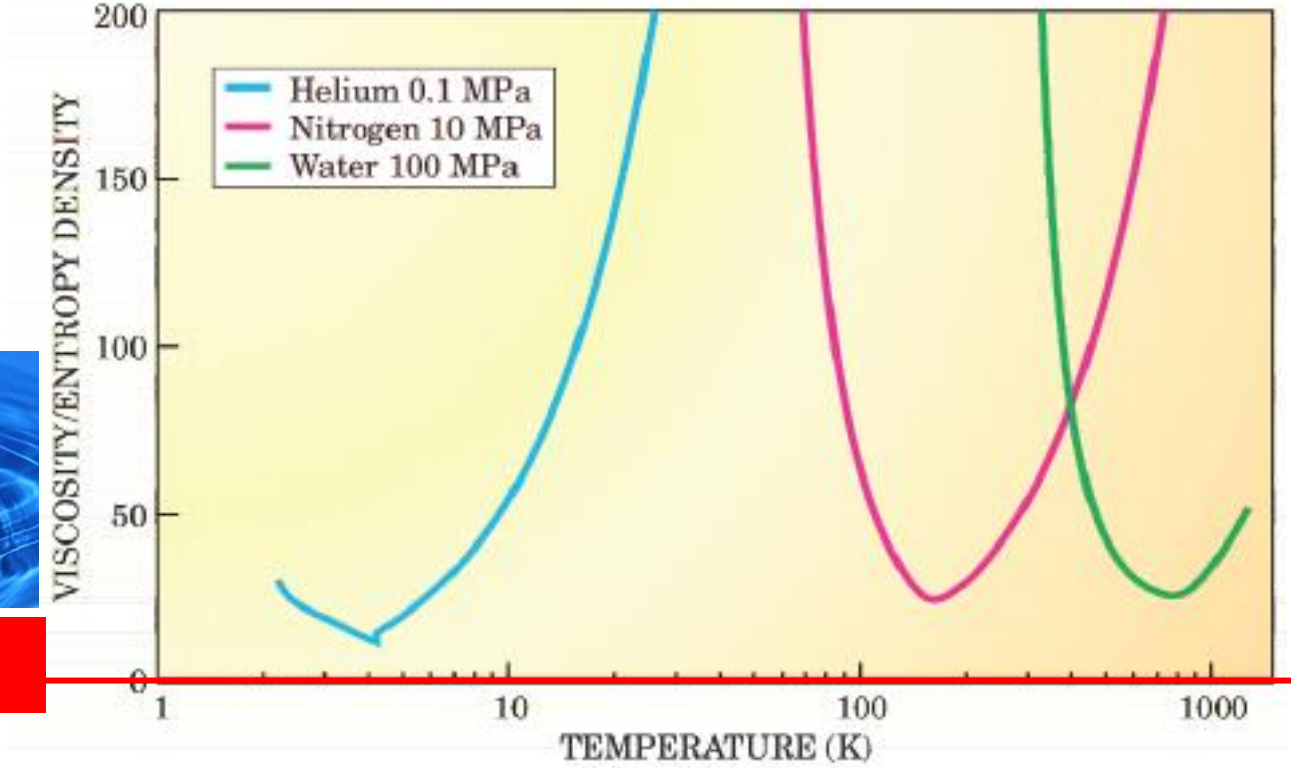
v_2 data indicates that matter has very small $\eta/s \sim 0.1$

< 1/10 that of any known matter

close to conjectured lower bound of $1/4\pi$: AdS/CFT

Kovtun, Son, Starinets
PRL 94 (2005) 111601)

RHIC matter



10^{12} ^{0}C

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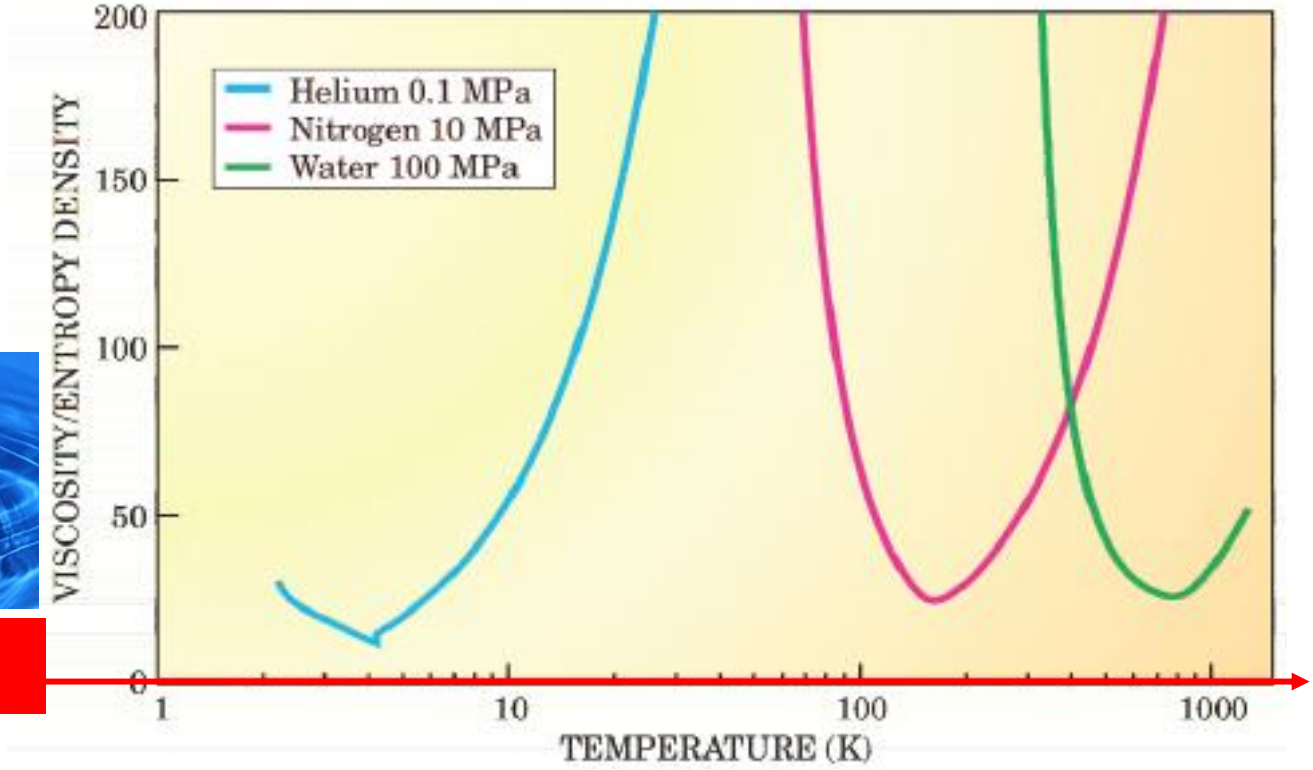


10^{12} ^{0}C

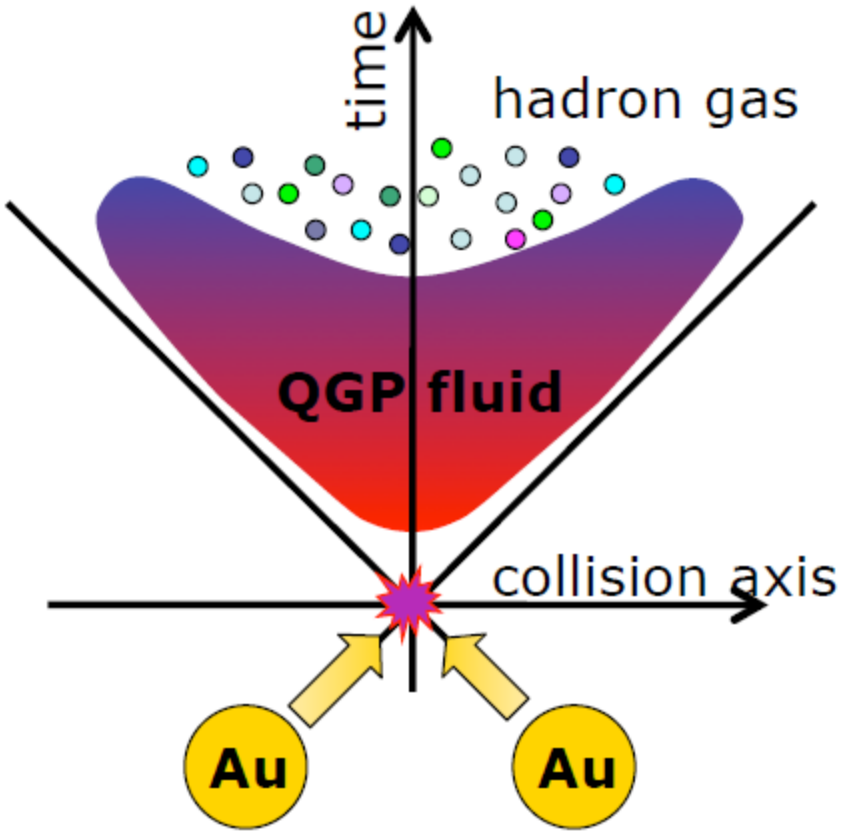
$\eta/s \approx 1/4\pi$
Connections to fields outside of NP

sQGP Paradigm

- sQGP: strongly-coupled QGP
  - i.e. nearly perfect fluid (ideal hydrodynamics)

- as opposed to weakly-coupled
  - deconfined state predicted before RHIC program

Space-Time Evolution of HI Collision



hadronization

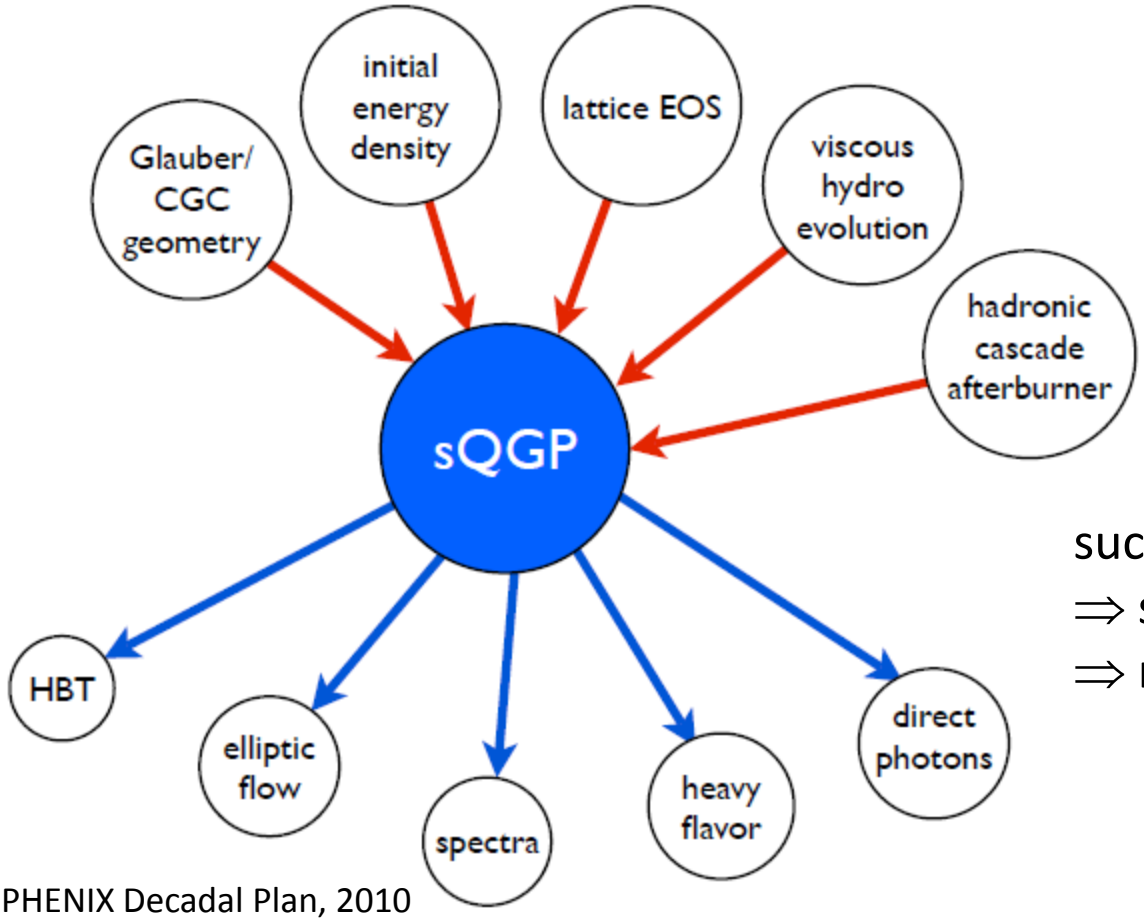
quark-gluon fluid:
hydrodynamic evolution

rapid thermalization

high initial energy density

Figure from PHENIX Decadal Plan 2011-2020
http://www.phenix.bnl.gov/phenix/WWW/docs/decadal/2010/phenix_decadal10_full_refs.pdf

sQGP I/O

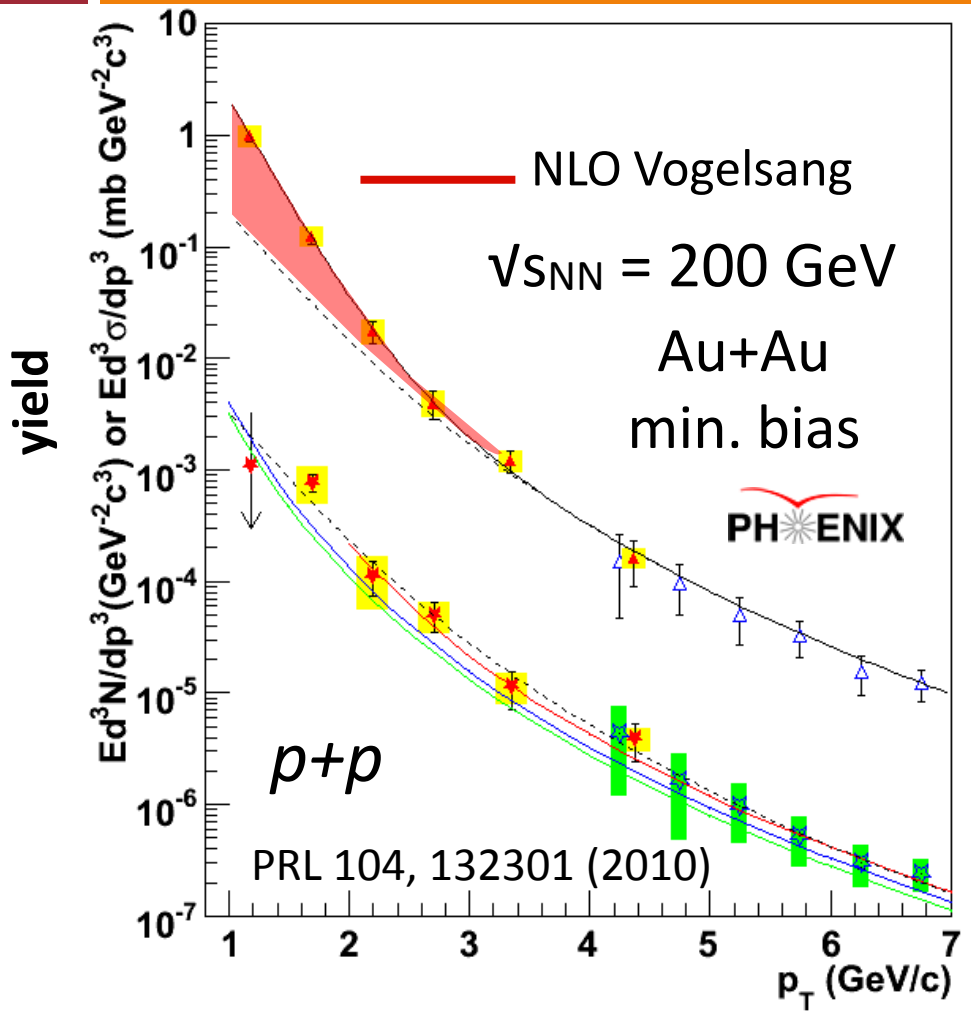


PHENIX Decadal Plan, 2010

success of hydrodynamics
⇒ single physics scenario
⇒ reconciles inputs
(theoretical and experimental)
with outputs
(predictions vs. observations)

Puzzles & Recent Progress

Temperature from Direct Photons



- Direct photon excess in Au+Au above *p*+*p* spectrum
- Exponential (consistent with thermal)
- Inverse slope = 220 ± 20 MeV
- T_i from hydro
  - 300 . . . 600 MeV
  - Depending on thermalization time

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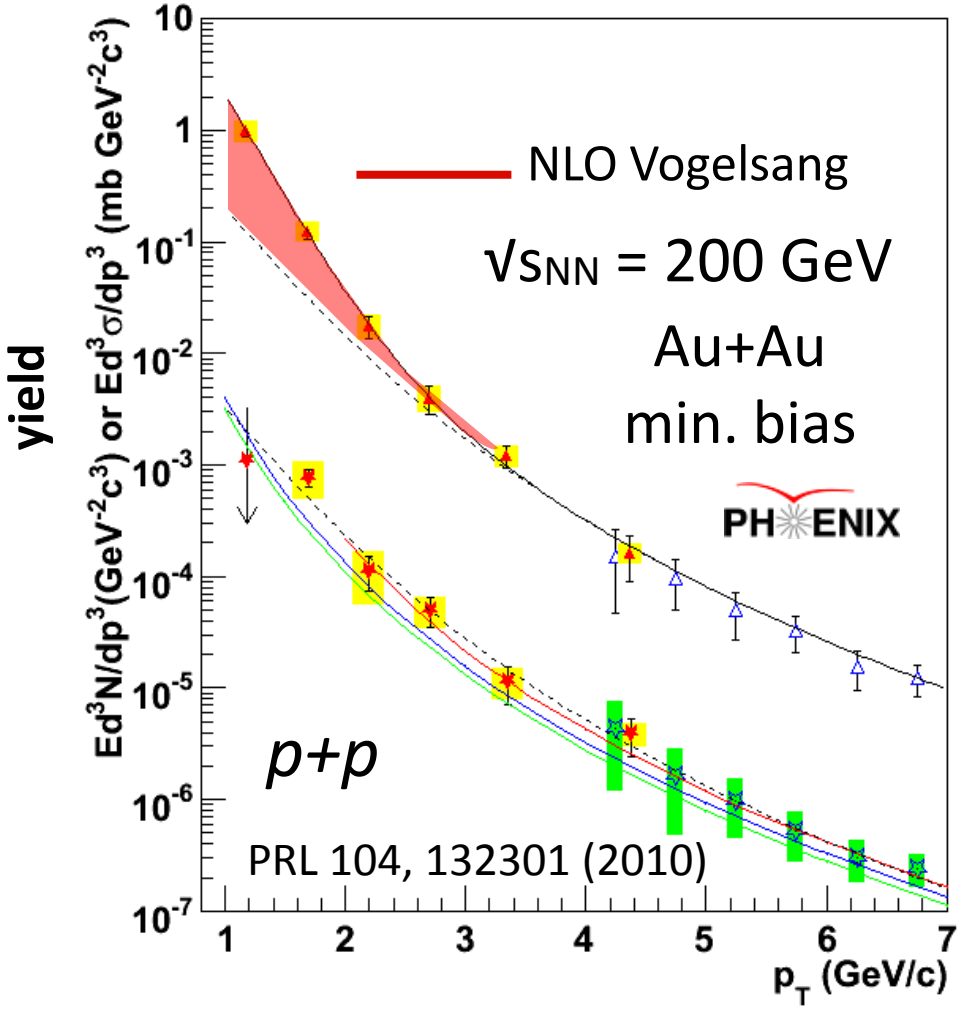

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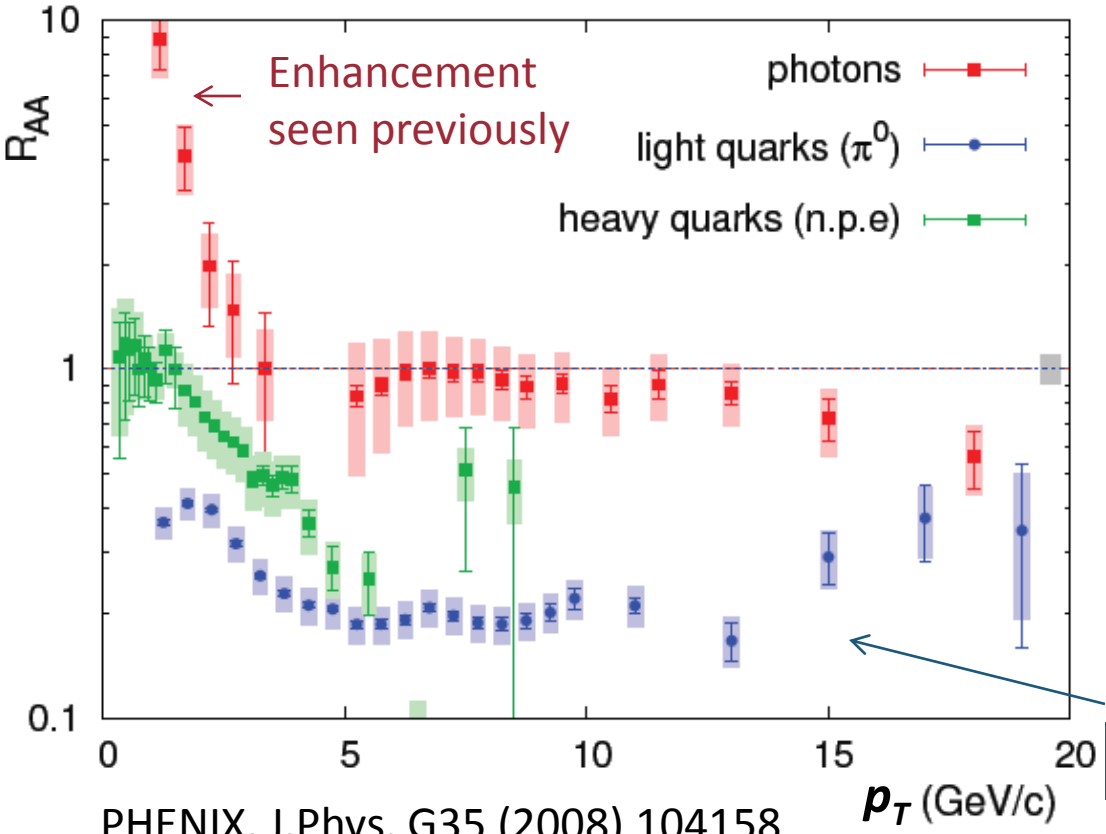
$T >> T_{Hagedorn} = 170$ MeV *
(from hadronic resonance gas)

Hadronic picture difficult to maintain

*Hagedorn Nuovo Cim. Suppl. 3 (1965) 147

Jet Quenching: Single Particles



PHENIX, J.Phys. G35 (2008) 104158

Strong suppression of light quarks

Expected from radiative (gluon) E loss

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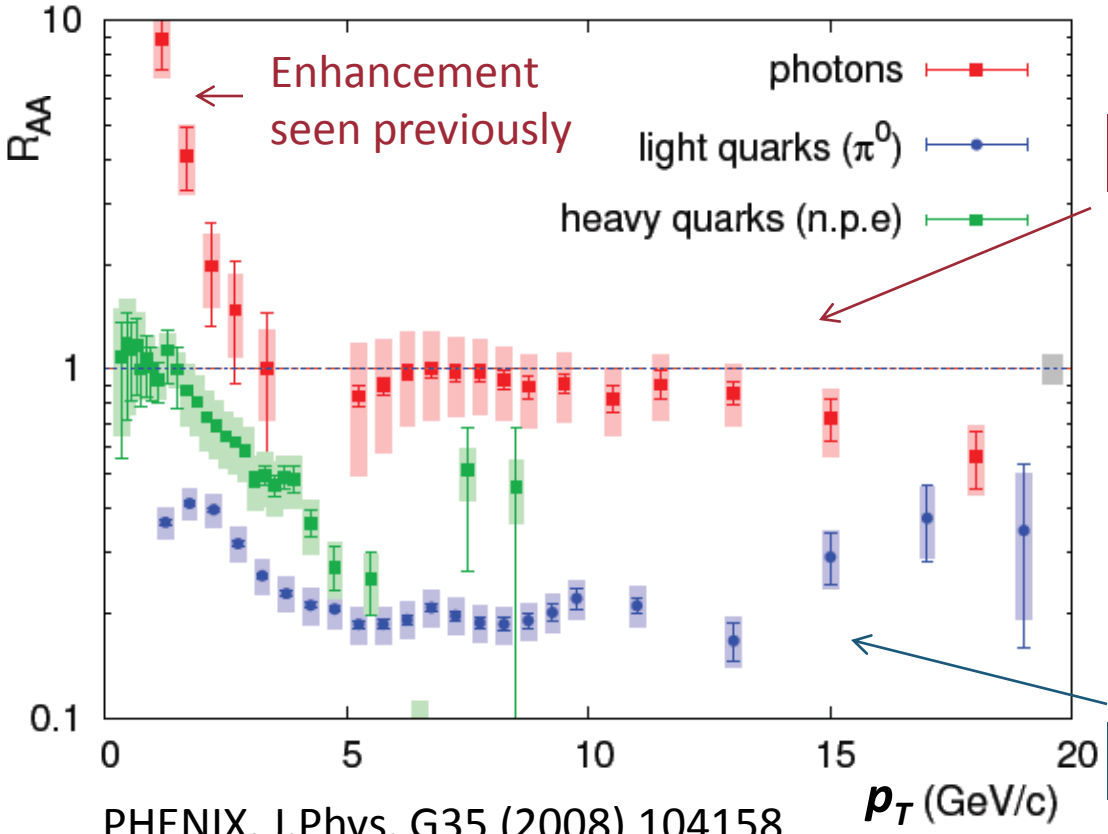

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Direct photons not suppressed

No depletion of partons in initial state

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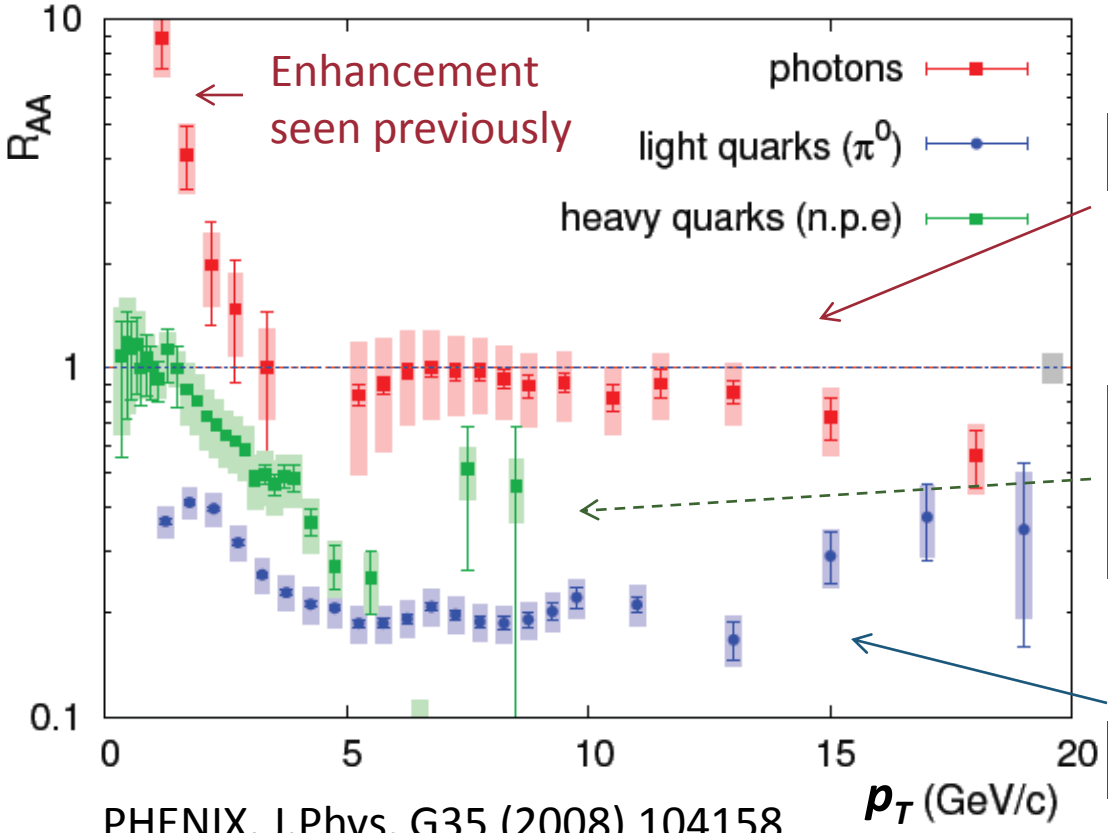

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Significant suppression of light quarks (single non-photonic electrons)

Unxpected
Collisional E loss?
AdS/CFT? Gyulassi, Physics 2 (2009) 107

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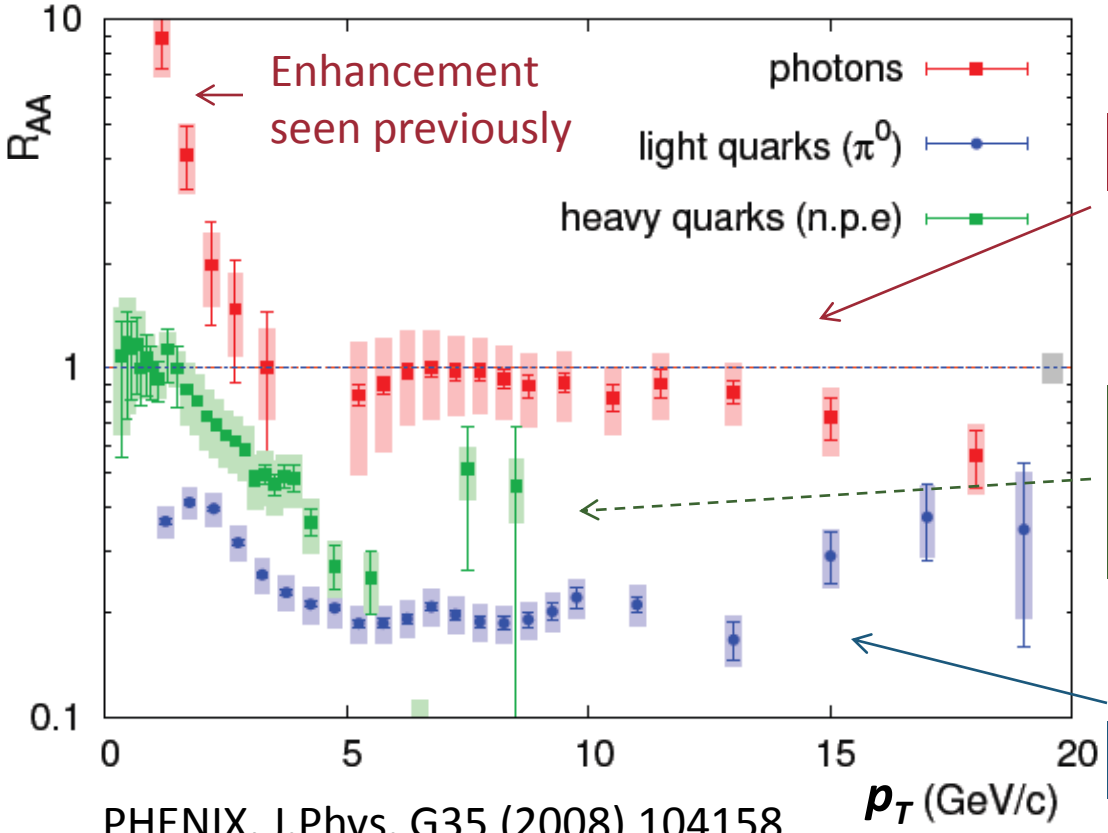

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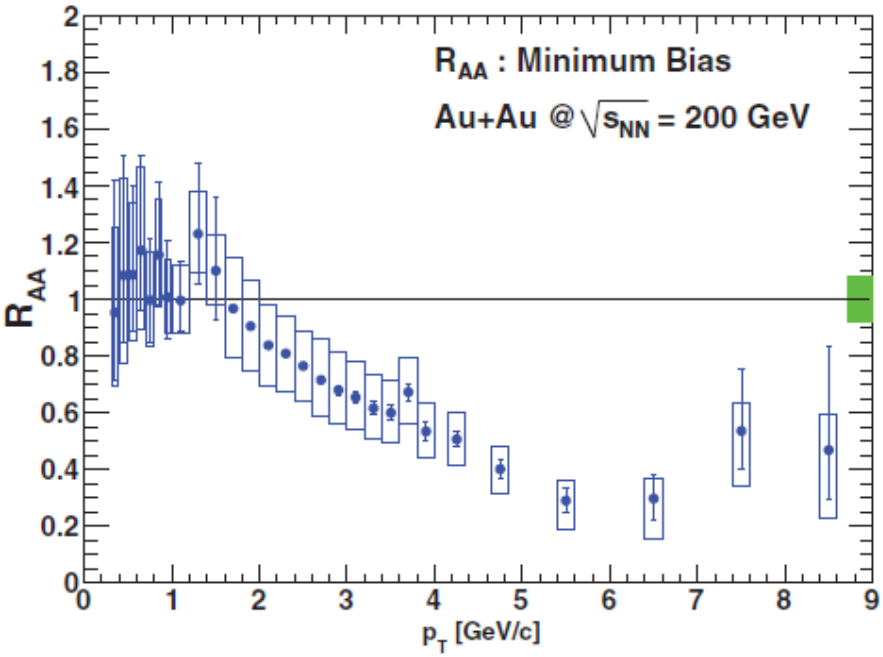
Expected from radiative (gluon) E loss

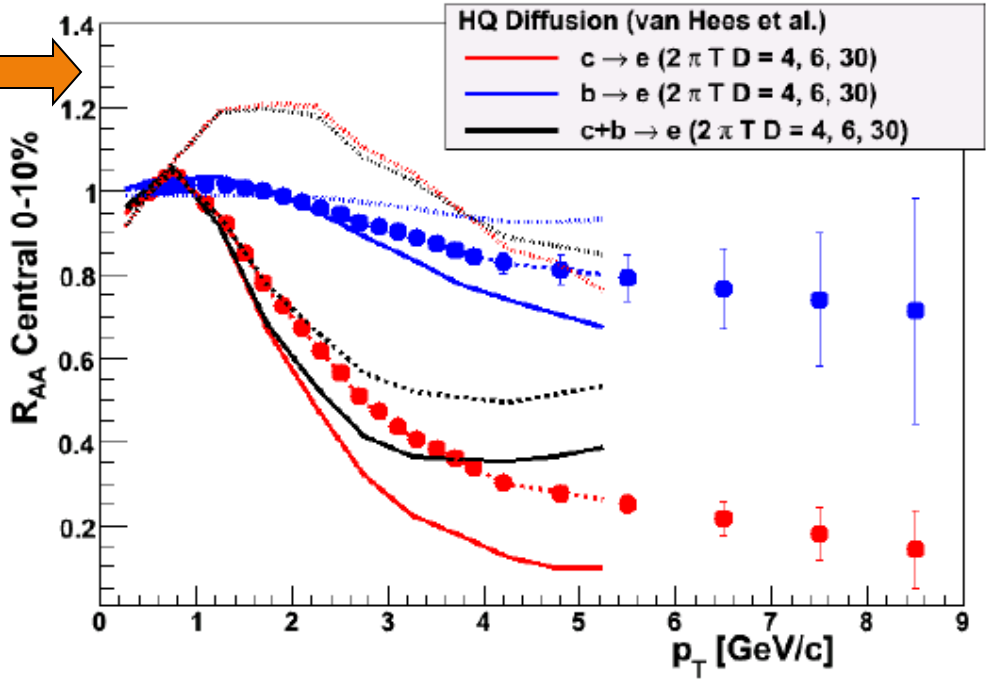
Needed:
-Measure c, b quarks separately
$\Rightarrow$ VTX detector

Heavy Quark R_{AA}



PHENIX PRCC.84 (2011) 044905

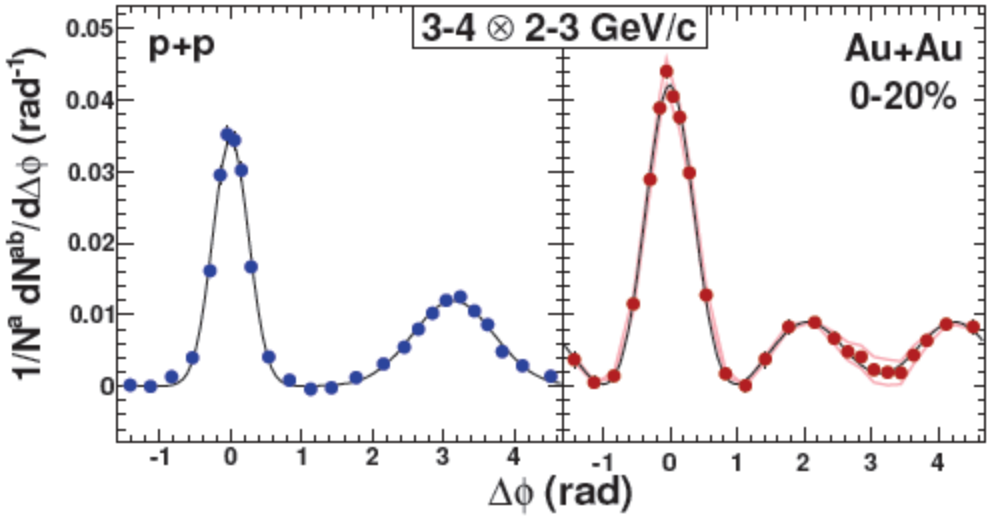
Projected data by 2015

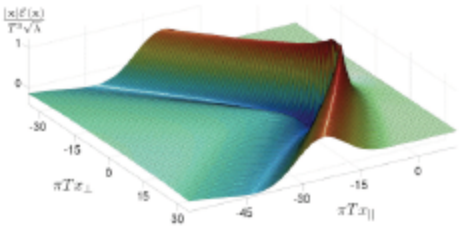


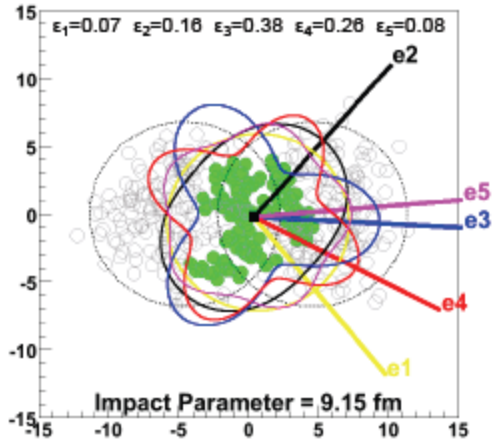
Sensitive to diffusion coefficient, D (related to η/s)
elastic collisions only

Needed:
-Measure c, b quarks separately
⇒ VTX detector

2-Particle Correlations, moderate p_T







PHENIX Decadal Plan, 2010

Double hump on away-side
Two scenarios

1: Mach cone (both pQCD, AdS/CFT)

Chesler, Yaffe, PRL99 (2007)152001

2: initial state fluctuations, triangular component

Alver, Roland, PRC81 (2010) 054905
Sorensen, J.Phys.G G37 (2010) 094011

Stefan Bathe, Heavy Ion Physics at RHIC

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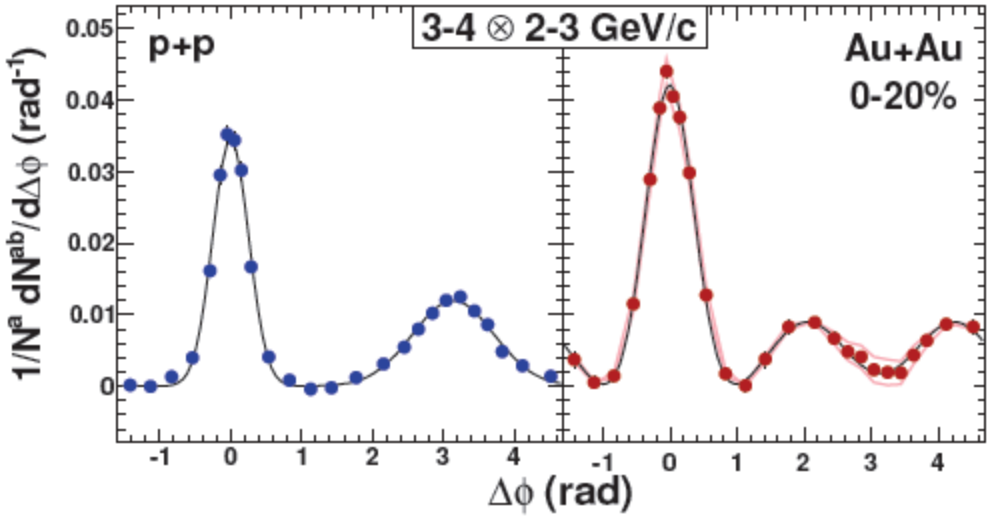

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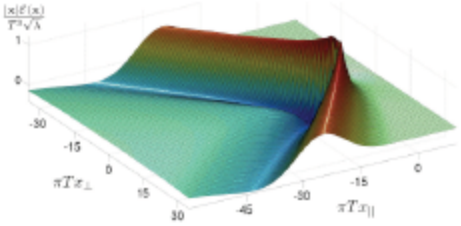

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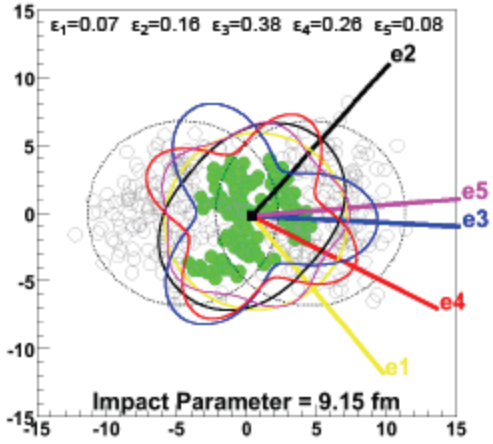
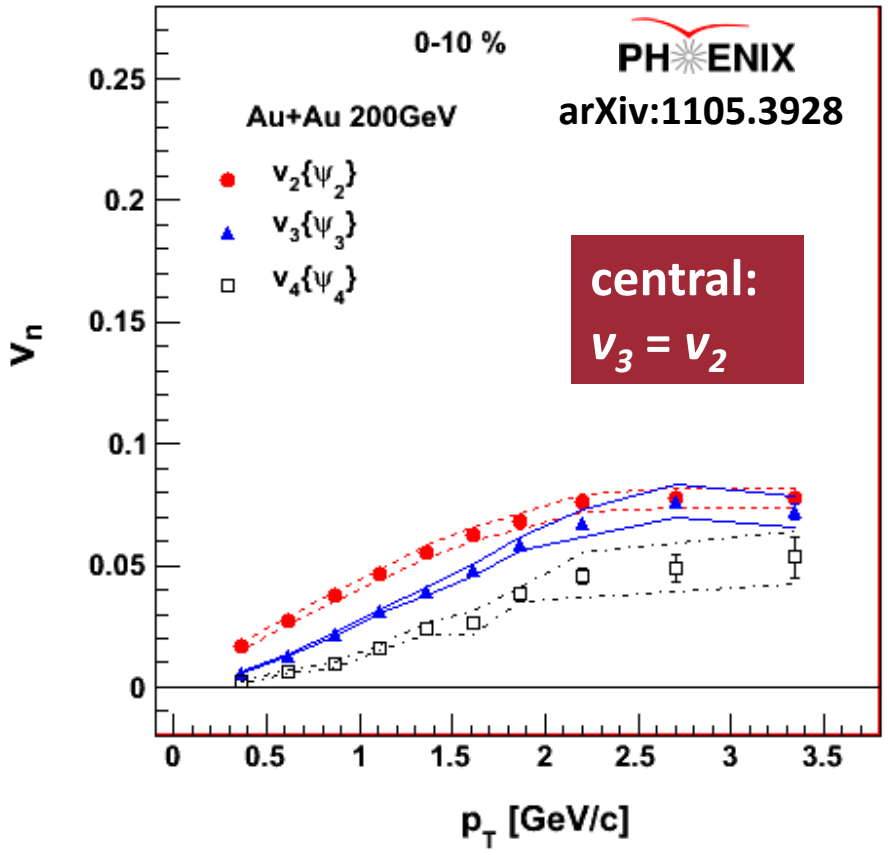
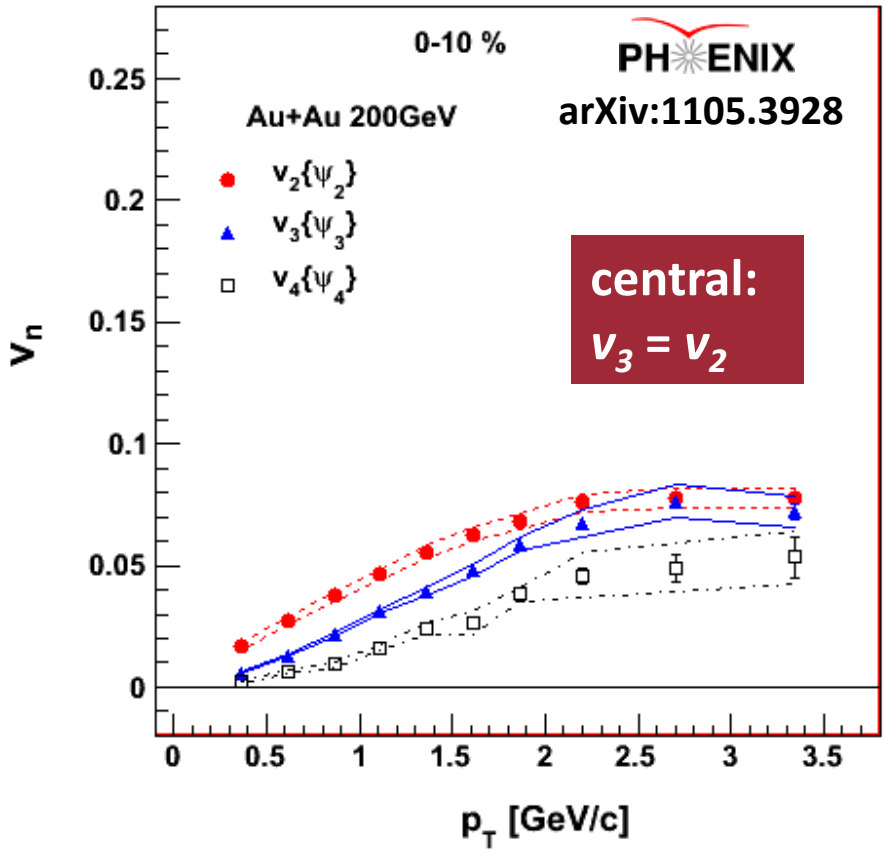


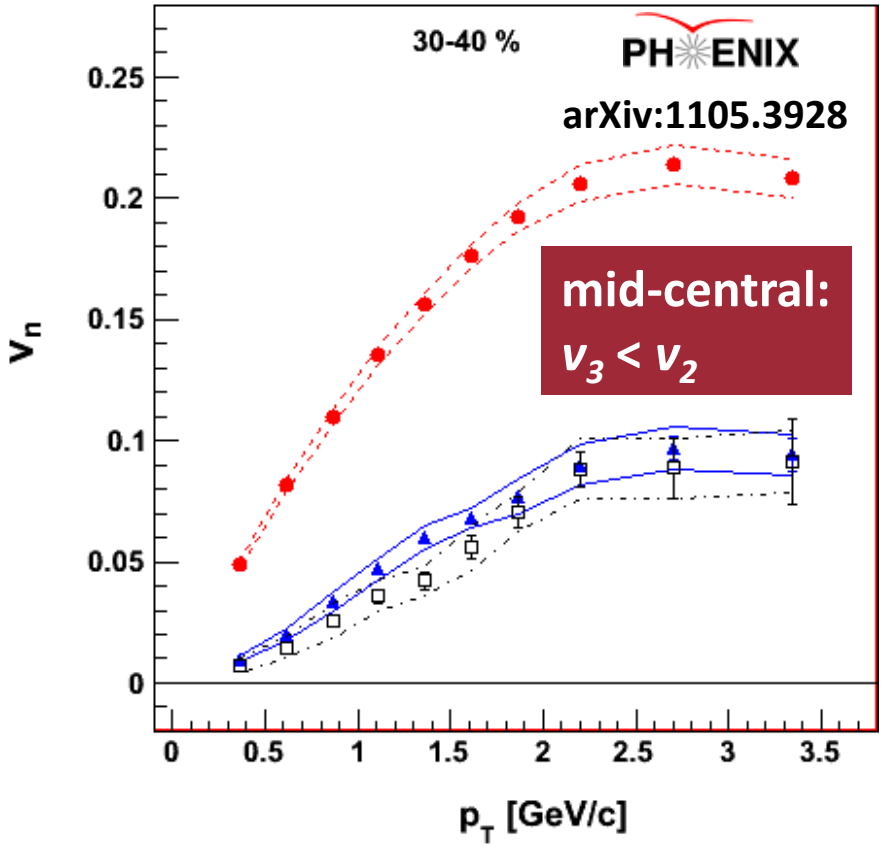
Stefan Bathe, Heavy Ion Physics at RHIC

v_3 measured


0-10 %
PHENIX
Au+Au 200GeV
arXiv:1105.3928
$v_2\{\psi_2\}$
$v_3\{\psi_3\}$
$v_4\{\psi_4\}$
central:
$v_3 = v_2$
v_n
p_T [GeV/c]
0
0.05
0.1
0.15
0.2
0.25
0.5
1
1.5
2
2.5
3
3.5

v_3 measured

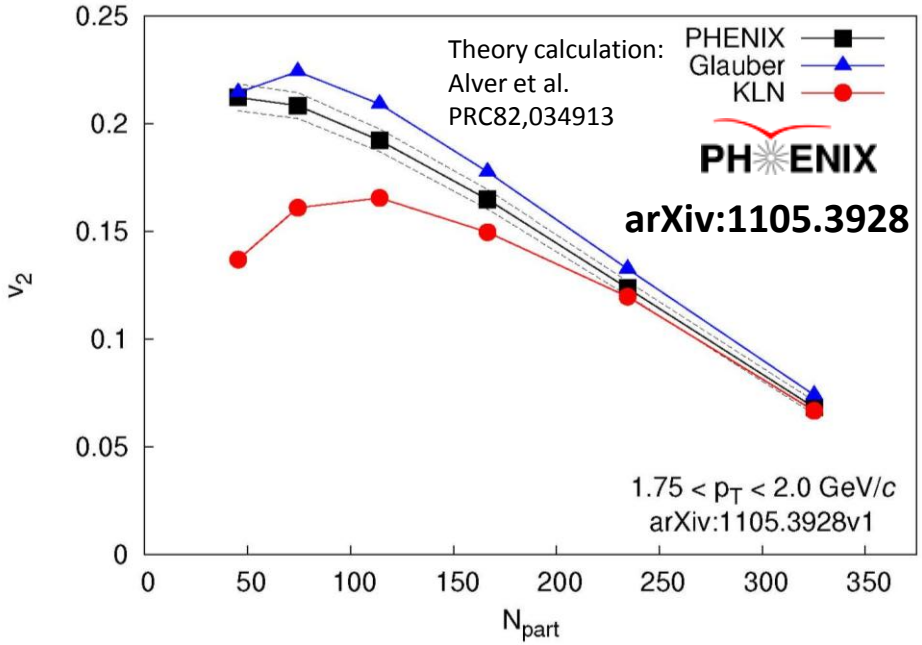




weak centrality dependence of v_3 => fluctuations origin

v_3 disentangles initial state and η/s

v_2 described by Glauber and CGC



- Glauber
  - Glauber initial state
  - $\eta/s = 1/4\pi$

← Two models →

- KLN
  - CGC initial state
  - $\eta/s = 2/4\pi$

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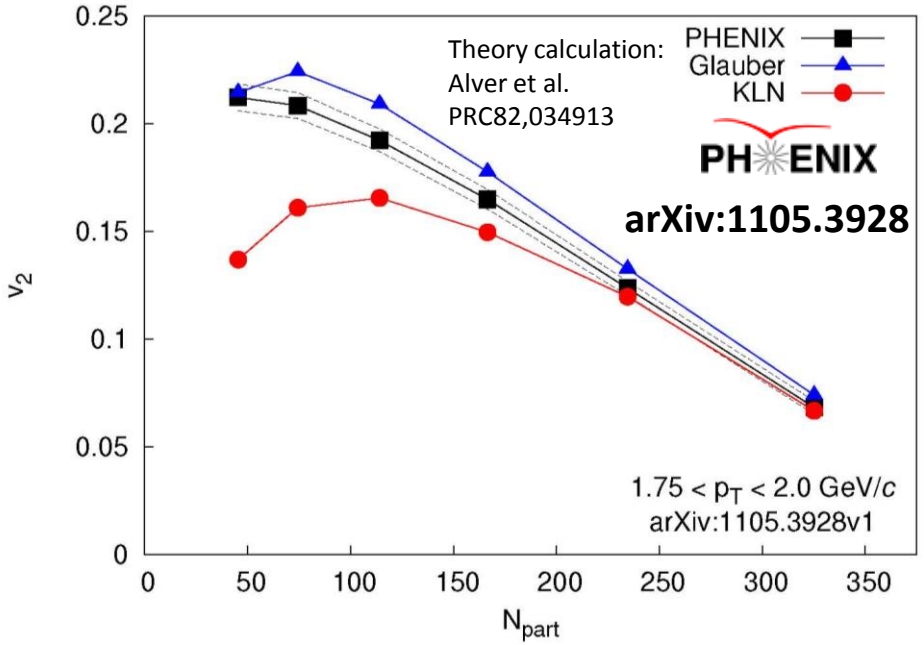
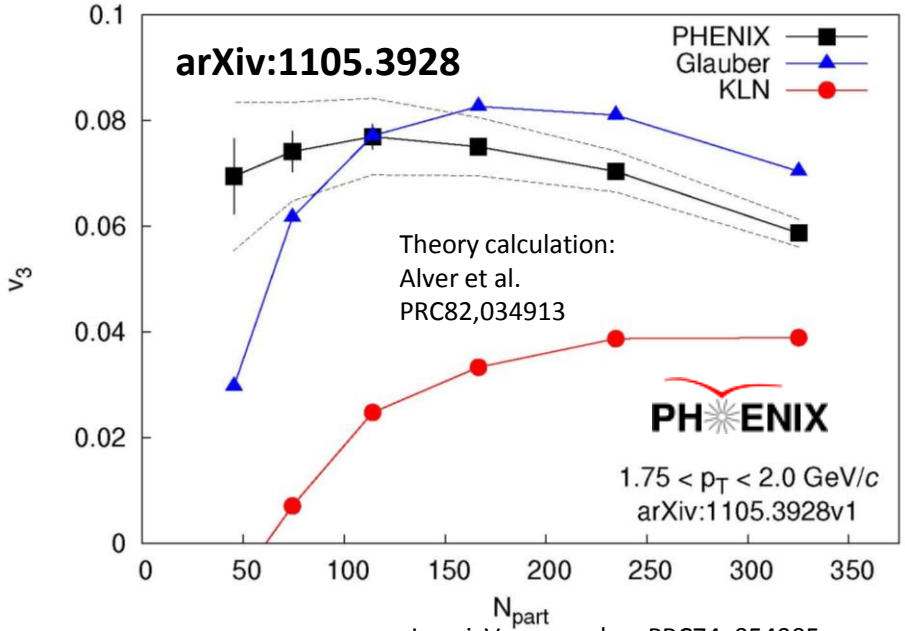


v_3 described only by Glauber



Lappi, Venugopalan, PRC74, 054905
Drescher, Nara, PRC76, 041903

- Glauber
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⟵ Two models ⟶

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  - CGC initial state
  - $\eta/s = 2/4\pi$

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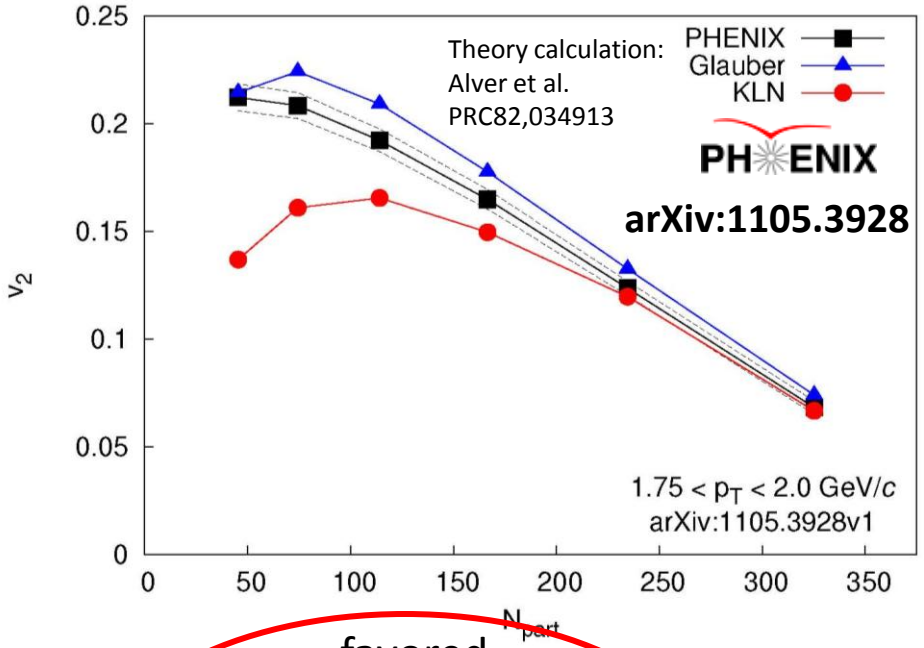

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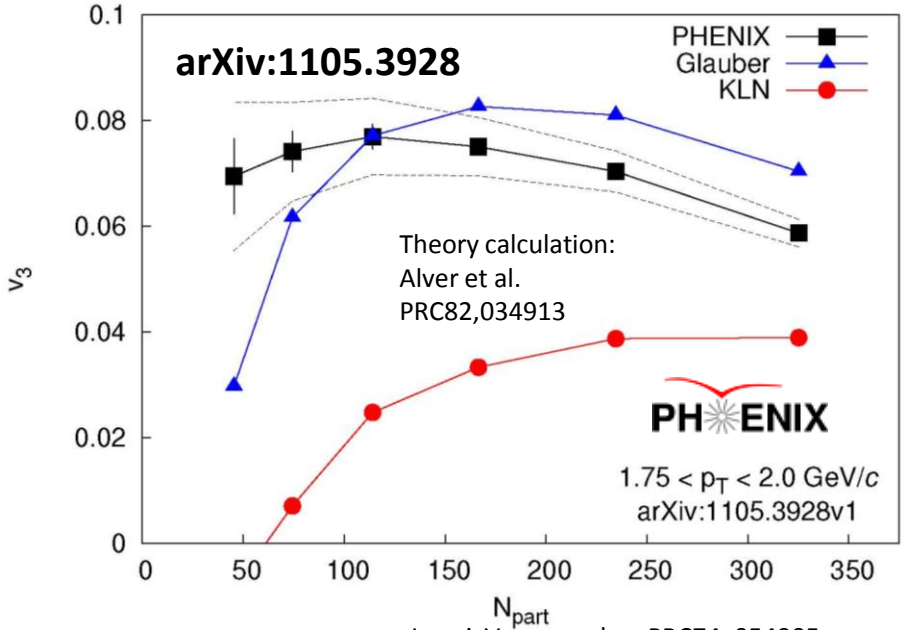

Lappi, Venugopalan, PRC74, 054905
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favored

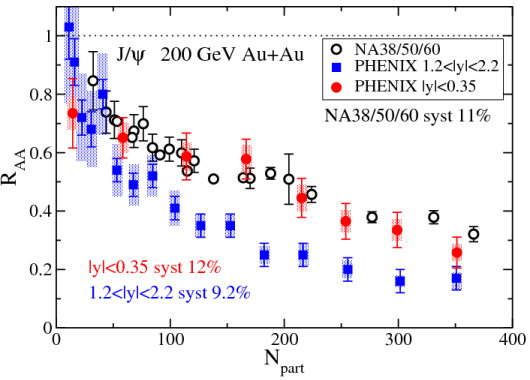
- Glauber
  - Glauber initial state
  - $\eta/s = 1/4\pi$

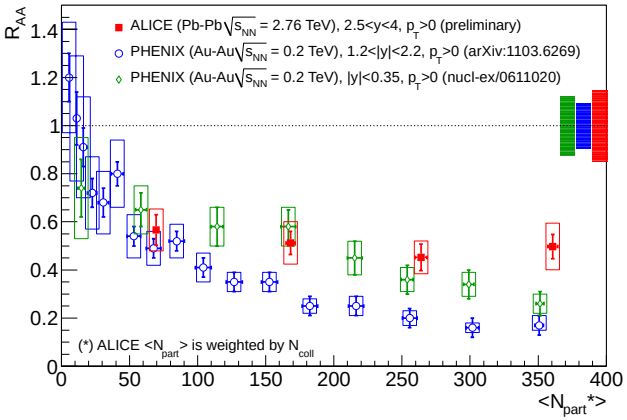
← Two models →

- MC-KLN
  - CGC initial state
  - $\eta/s = 2/4\pi$

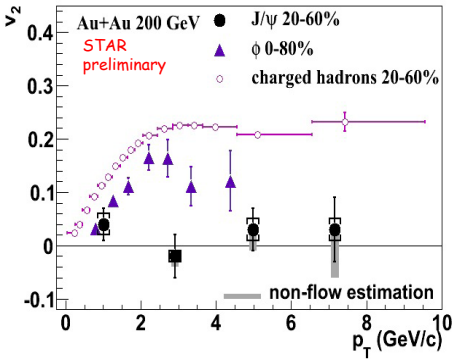
CGC not excluded
Details of MC implementation matter

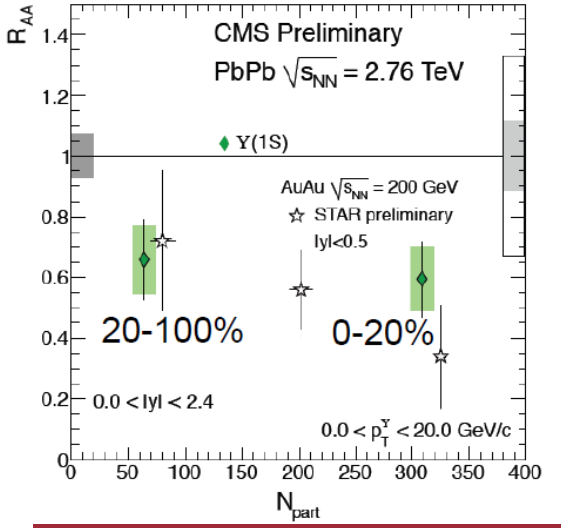
Quarkonia

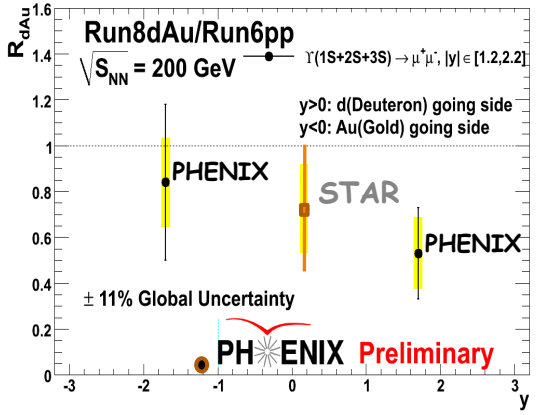




- J/ψ suppression almost same at all energies
- Stronger at forward rapidity!
- Regeneration?







- But: flow very small at RHIC
- Regeneration dead?

Upsilon suppression at RHIC & LHC similar

Strong CNM effects for Upsilon too

CNM measurements needed FVTX upgrade

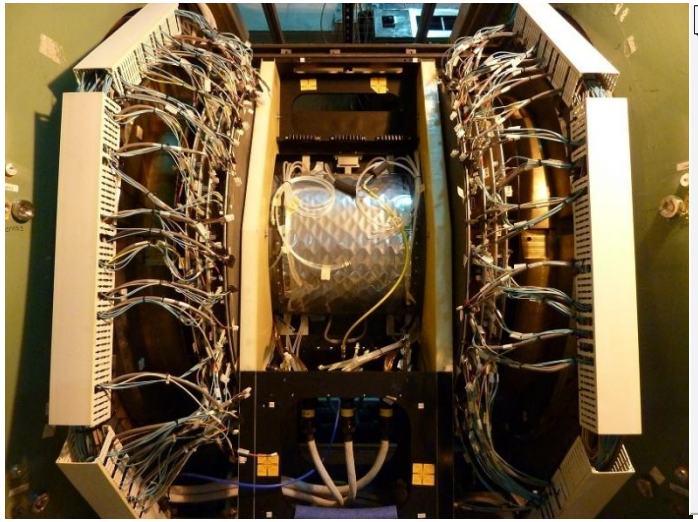
Outlook

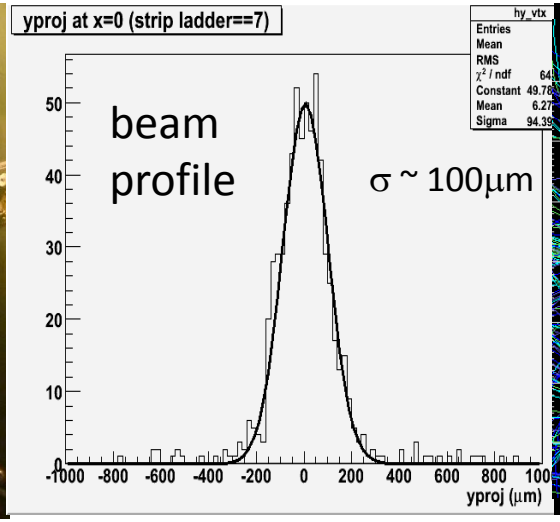
Near-Term Future: Silicon Vertex Detector

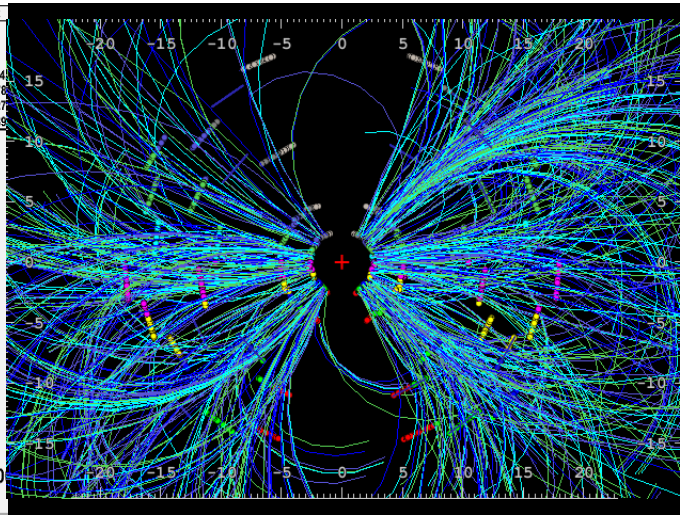
Status

- VTX successfully took data in 2011 Au+Au run

Data: Au+Au@200 GeV, 2011



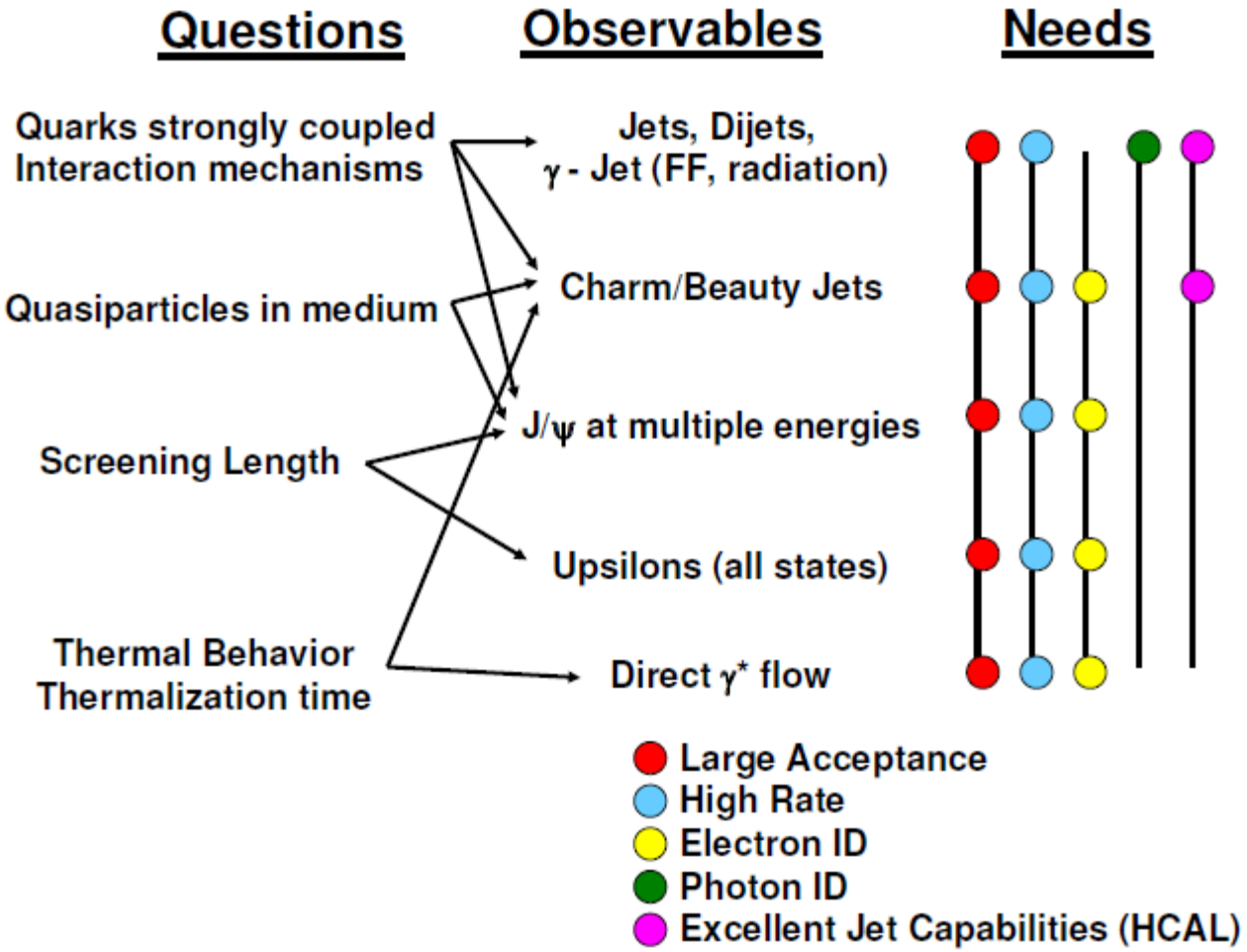




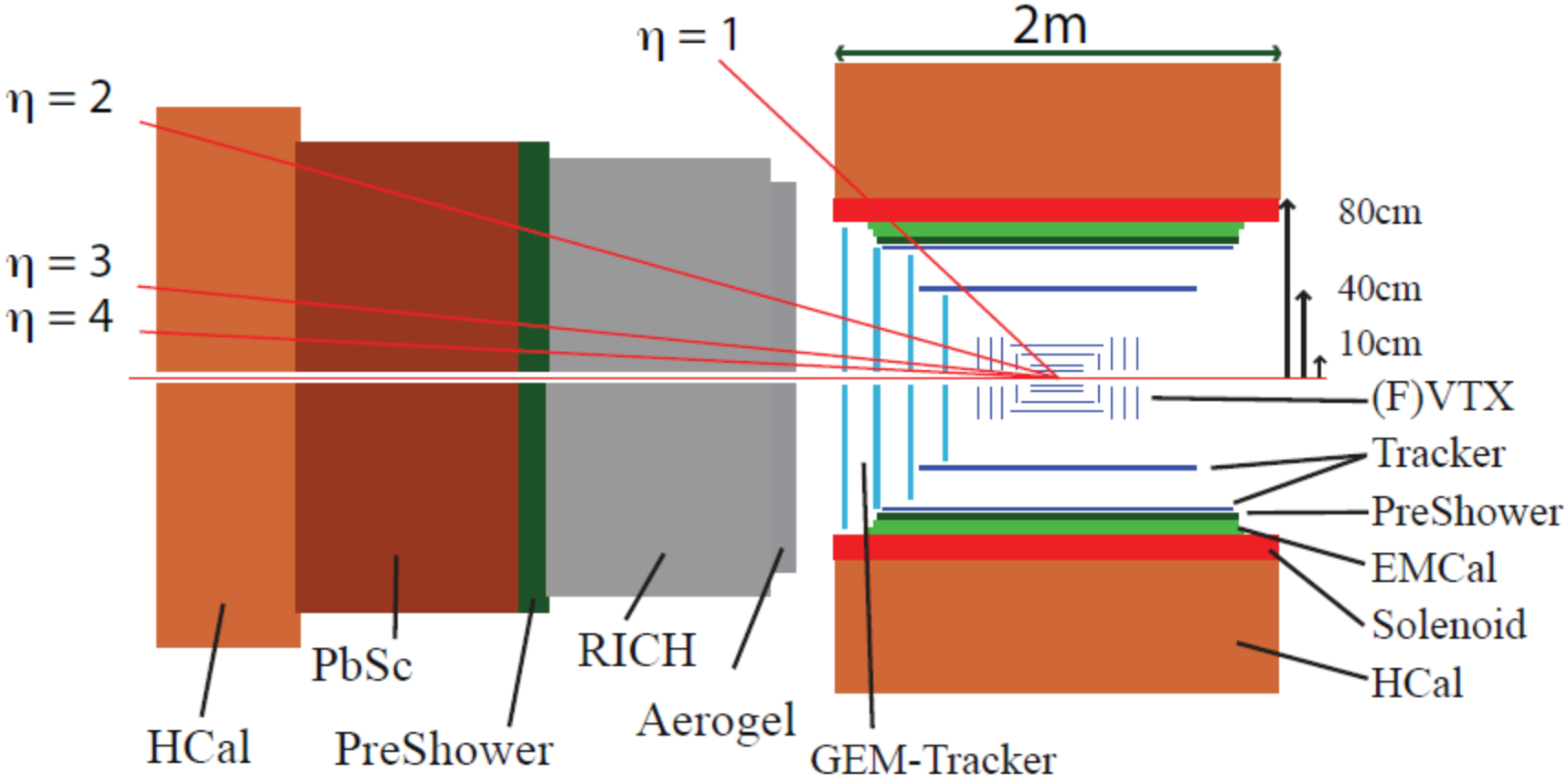
Physics

- R_{AA} of *c*, *b* separately
- v_2 of *c*, *b* separately
- Jet tomography (di-hadron, γ-*h*, *c*-*h*, *c*-$\bar{c}$)

sPHENIX Physics Question and Needs



sPHENIX/ePHENIX



Measuring the Properties of the QGP

Conditions ⟹ Properties

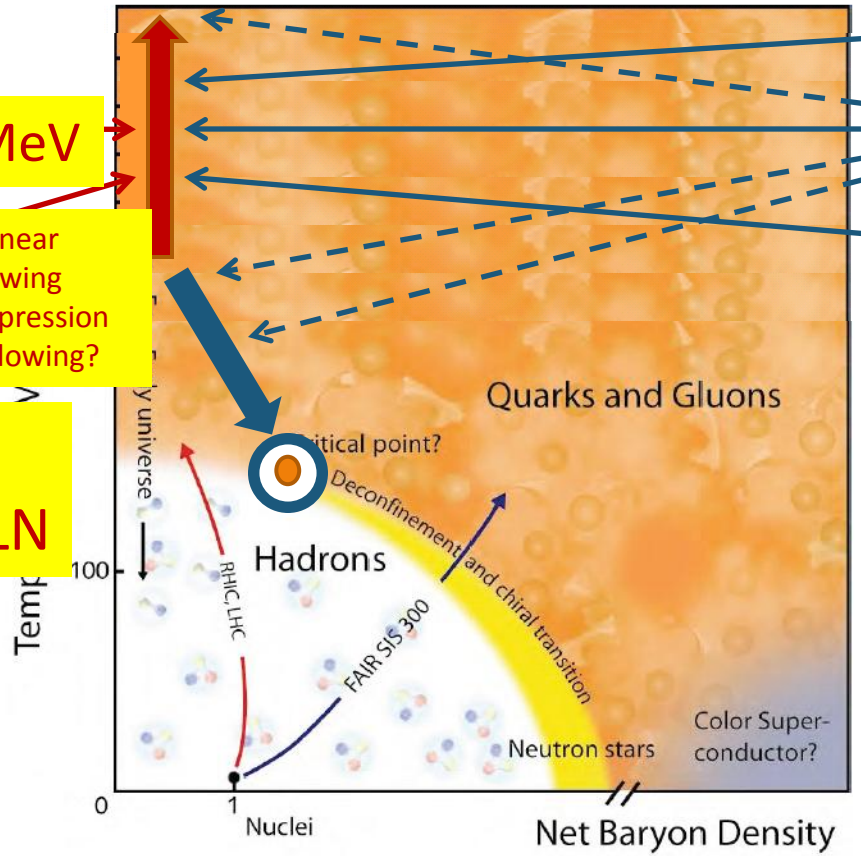
$\mu \sim 0$

T_i =300-600 MeV

CNM effects

non-linear shadowing
low-x suppression
anti-shadowing?

Initial State
→not MC-KLN



Screening length

$\eta/s \rightarrow (1—3)x1/4\pi$

$dE/dx \rightarrow l^3$

Stefan Bathe for PHENIX, QM2011