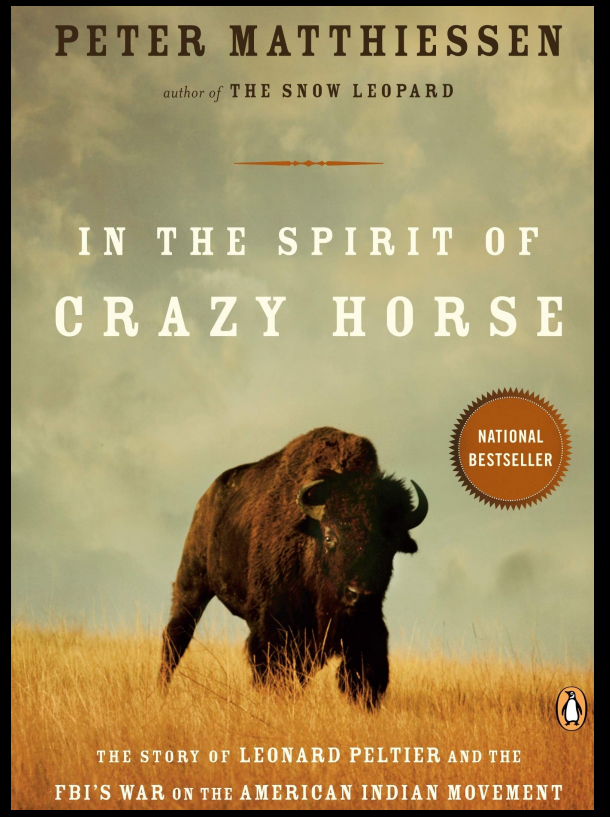
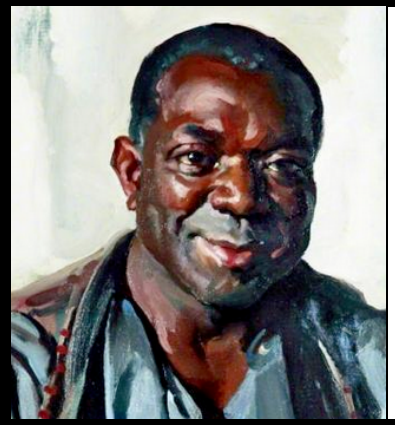
Today

See Rev. Al Sharpton Eulogy for George Floyd!

Today



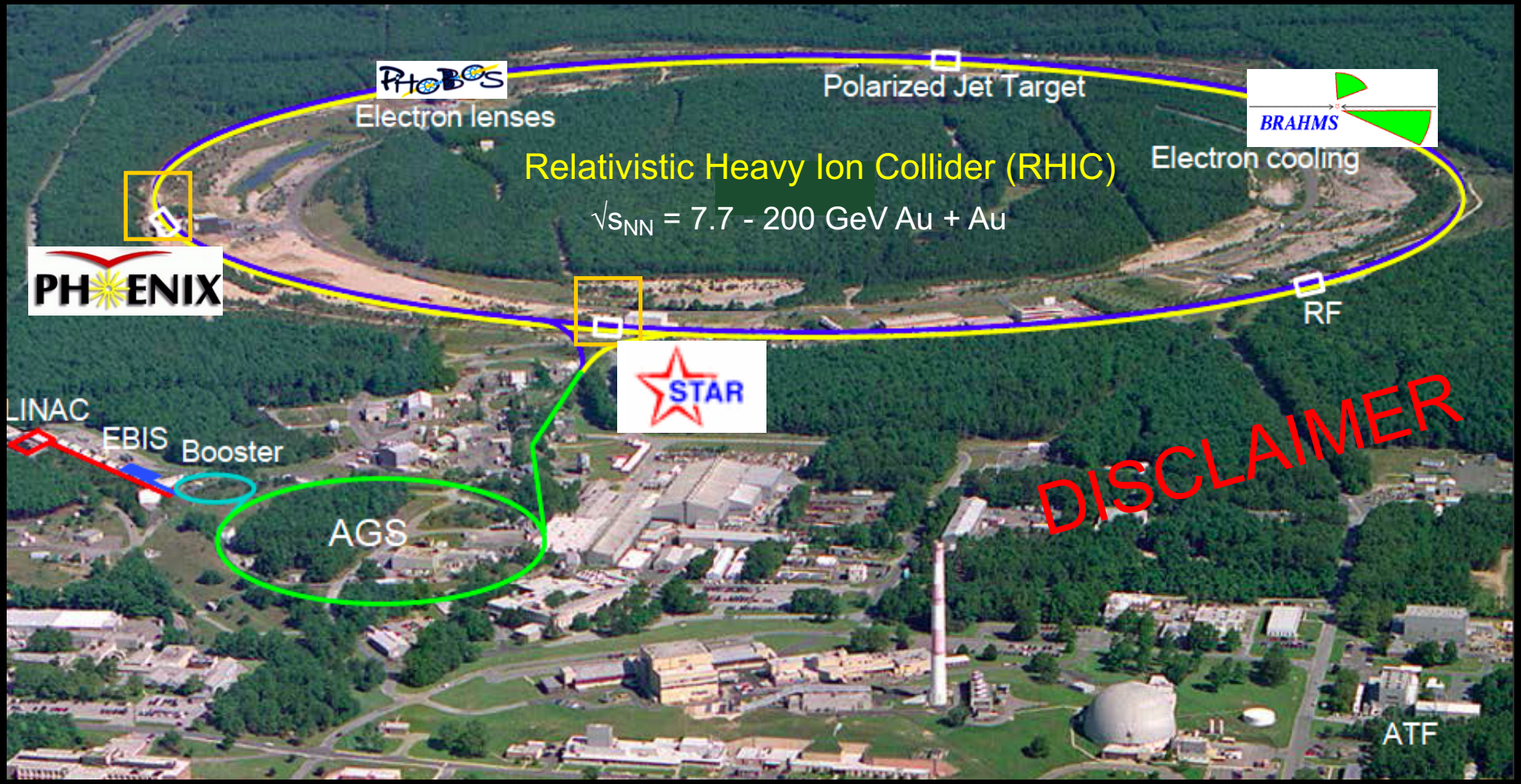


"A mind that is stretched by new experience can never go back to its old dimensions."
Oliver Wendall Holmes Sr., Supreme Court Justice

Brookhaven Laboratory Pre-RHIC

Brookhaven Laboratory Post-RHIC

20 Years of Heavy Ion Physics at RHIC



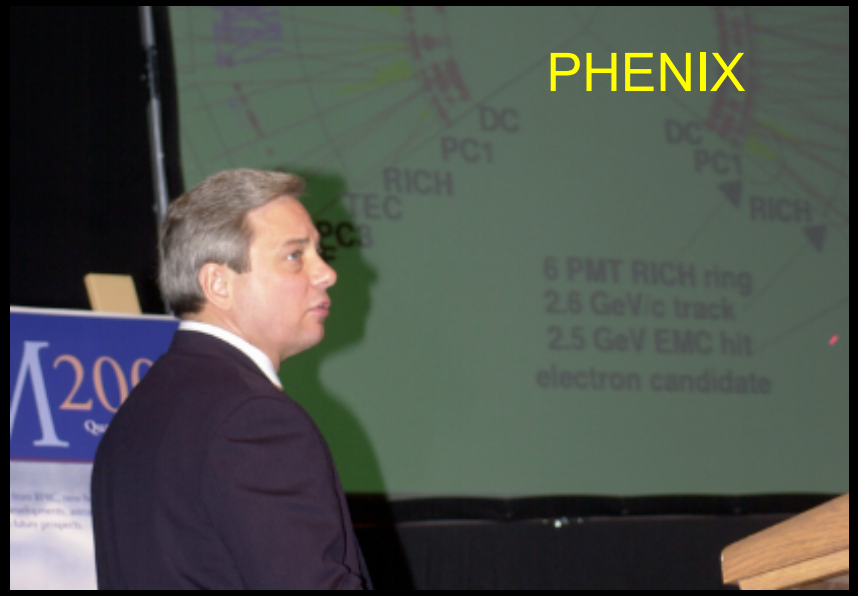
The Holy Grail – Quark-Gluon Plasma

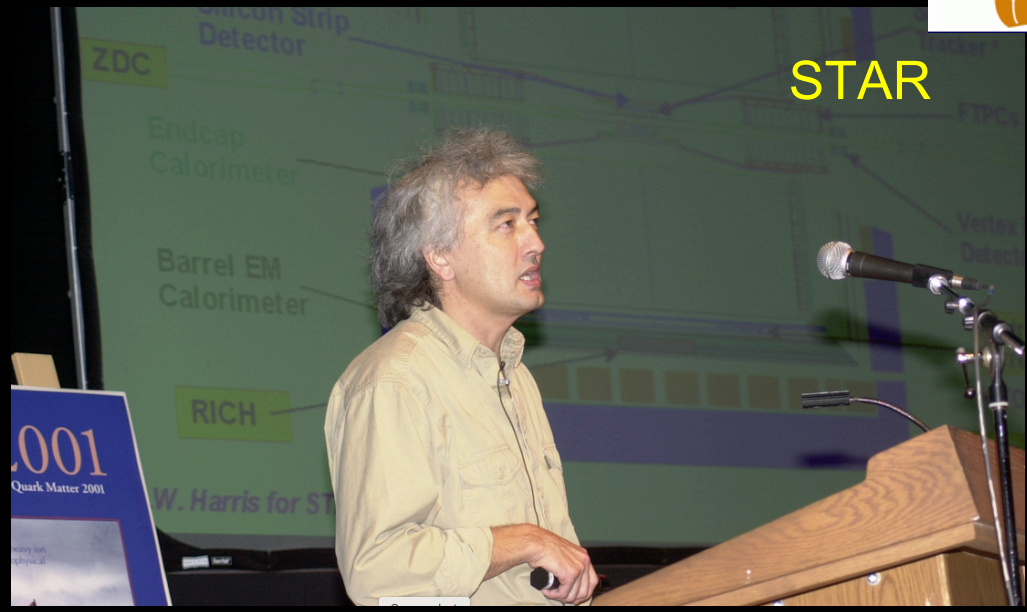
- The Standard Model (QCD) predicts at high temperature & density
  → Quark-hadron phase transition at T ~ 170 – 190 MeV
- Cosmology → Quark-hadron phase transition in early Universe
- Astrophysics → Cores of dense stars, neutron-star mergers!
- Can we make it in the lab? Establish its properties at high T!

The Dawn of RHIC Physics (2001)

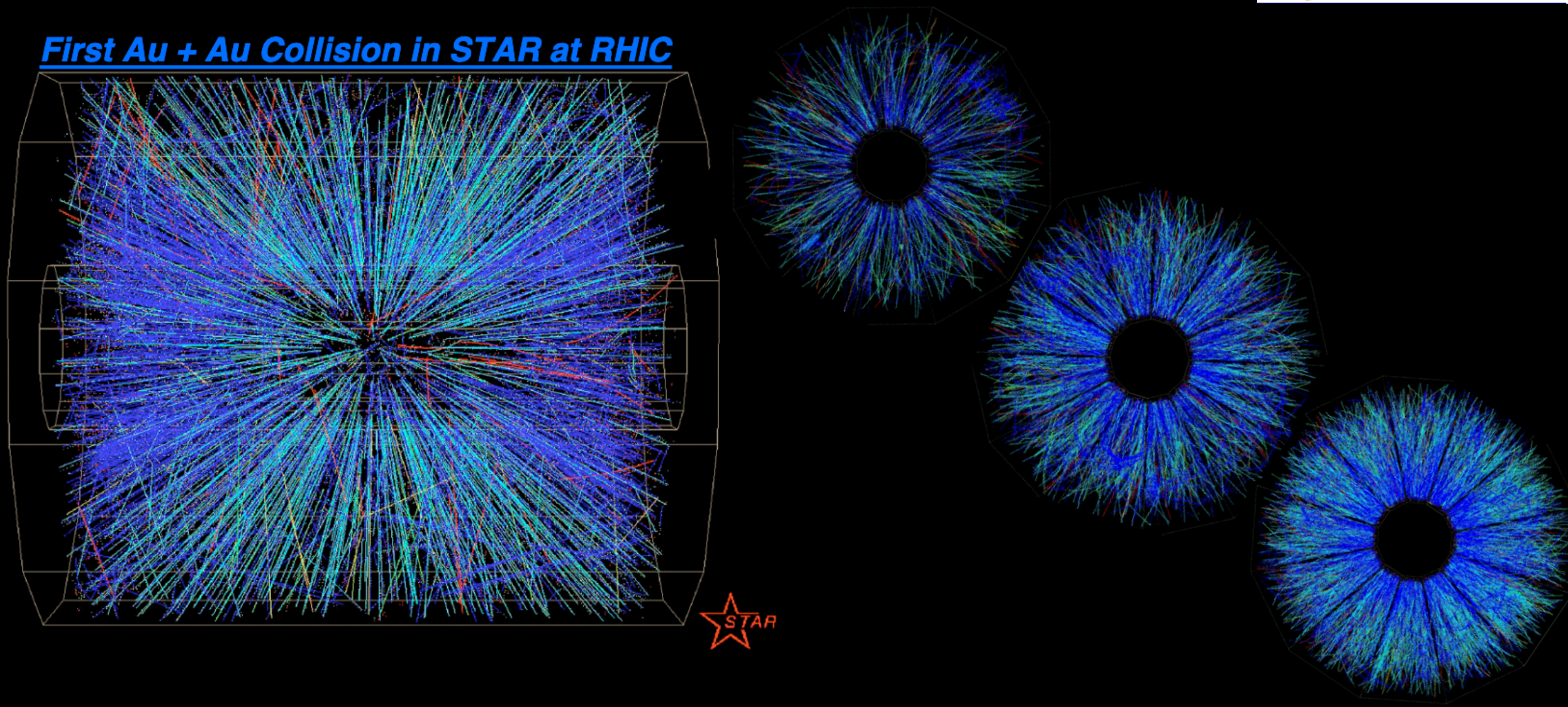
(a real scramble)

The Dawn of RHIC Physics



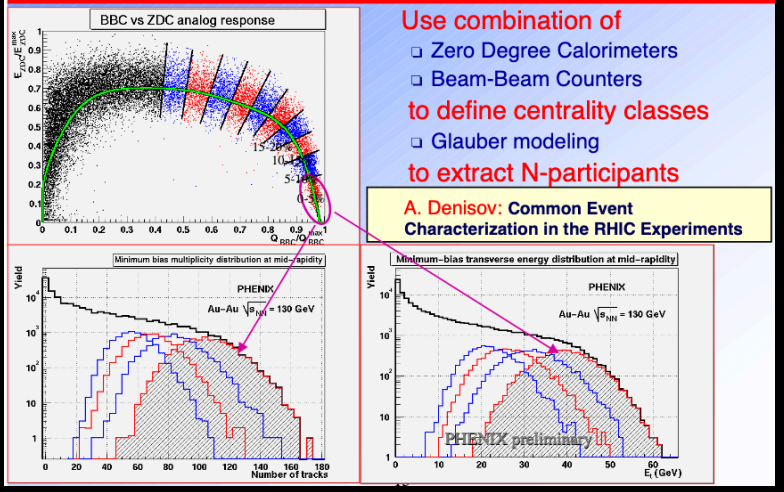


Collision Geometry (QM2001)



Collision Geometry (QM2001)

PHENIX Determining N(participants)



Use combination of
- Zero Degree Calorimeters
- Beam-Beam Counters

to define centrality classes
- Glauber modeling

to extract N-participants

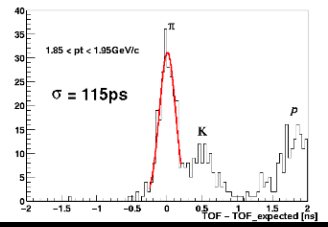
A. Denisov: **Common Event Characterization in the RHIC Experiments**

Examples –
4 experiments did these studies!

PHENIX Hadron Identification

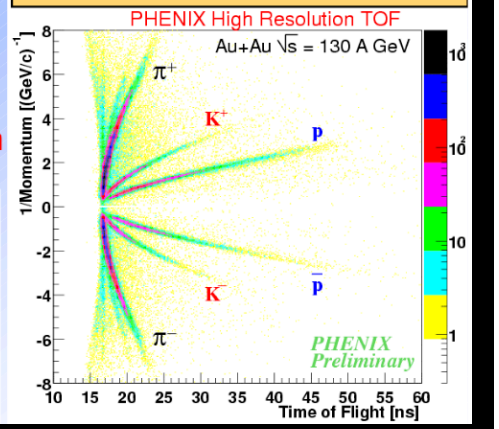
Combined
- Tracking
- Beam-Beam Counter
- Time-of-Flight array

provides excellent hadron identification over broad momentum band:



Tuesday, Parallel Session I

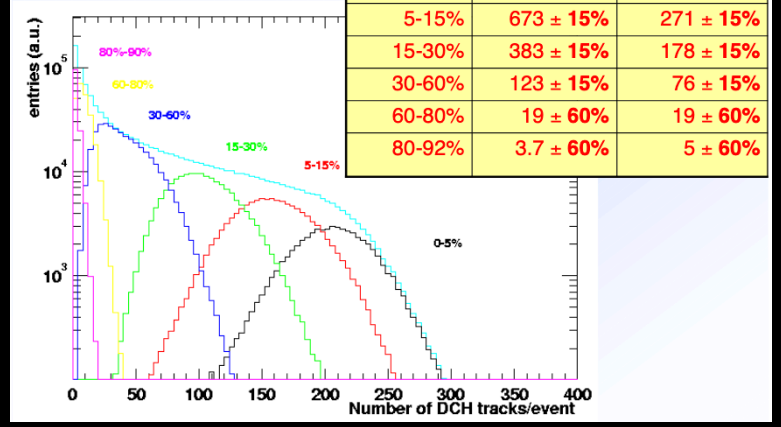
H. Hamagaki: Particle identification capability of the PHENIX experiment



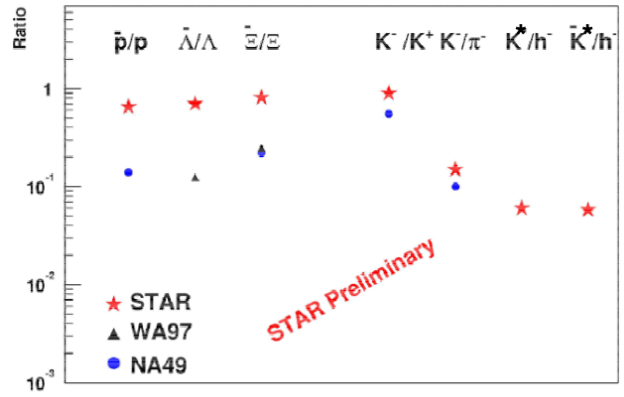
PHENIX Centrality Selections

Conversion to Ncollisions and Nparticpants

Centrality	Collisions	Participants
0-5%	945 ± 15%	347 ± 15%
5-15%	673 ± 15%	271 ± 15%
15-30%	383 ± 15%	178 ± 15%
30-60%	123 ± 15%	76 ± 15%
60-80%	19 ± 60%	19 ± 60%
80-92%	3.7 ± 60%	5 ± 60%



STAR Ratios Compared to SPS



$\bar{p}/p$ = 0.61 ± 0.03 (stat.) ± 0.06 (sys.)

$\bar{\Lambda}/\Lambda$ = 0.73 ± 0.03 (stat.)

$\bar{\Xi}/\Xi$ = 0.82 ± 0.08 (stat.)

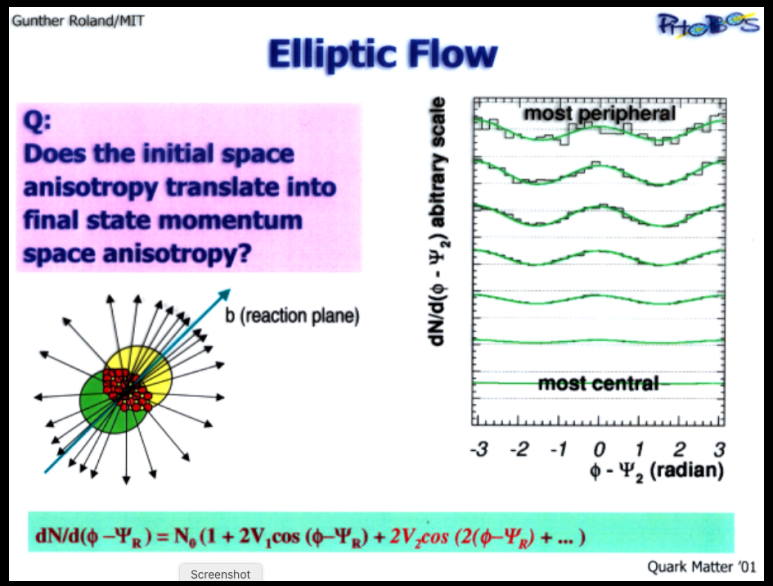
K^+/K^- = 1.12 ± 0.01 ± 0.06

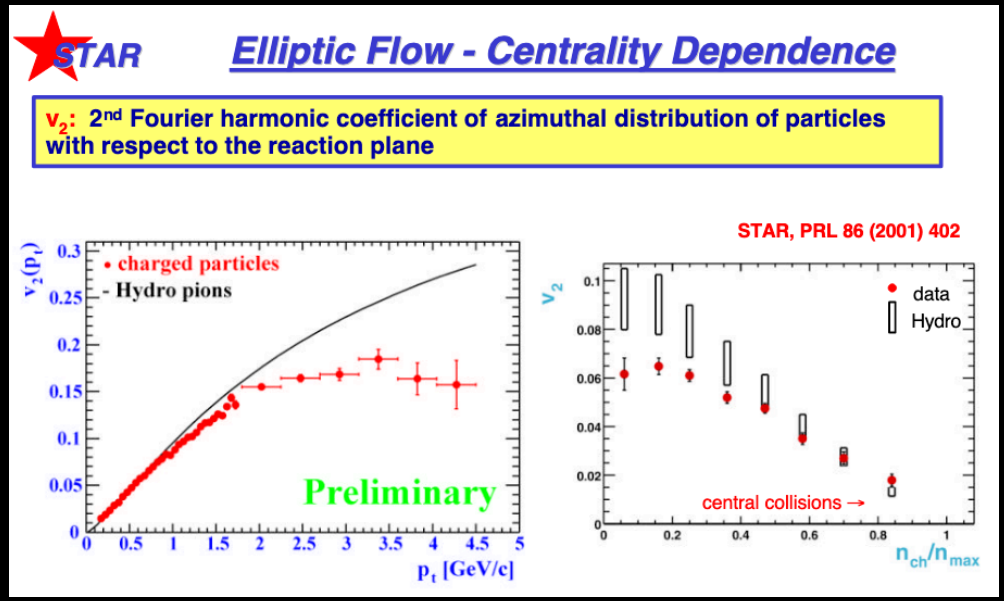
→ **Quark Coalescence**

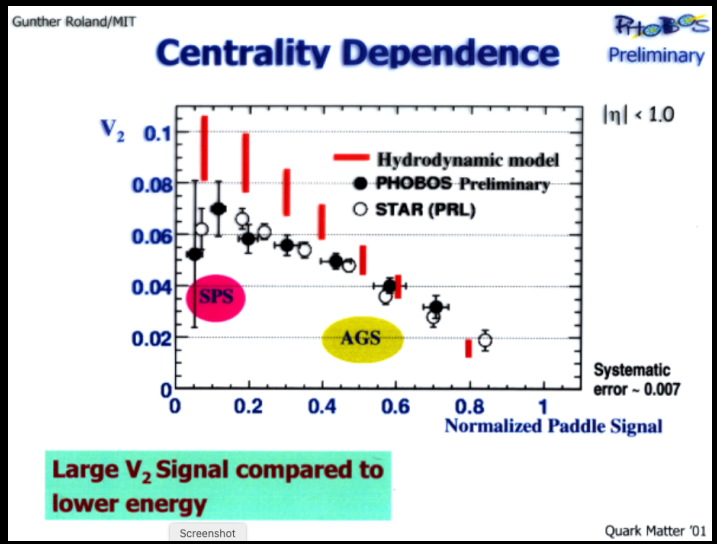
T_{ch} (RHIC) = 190 MeV ≥ T_{ch} (SPS/AGS)

μ_q (RHIC) = 15 MeV << μ_q (SPS/AGS)

Collective Flow (QM2001)







High p_T Particle Suppression (QM2001)

QM2001 Quark Matter 2001

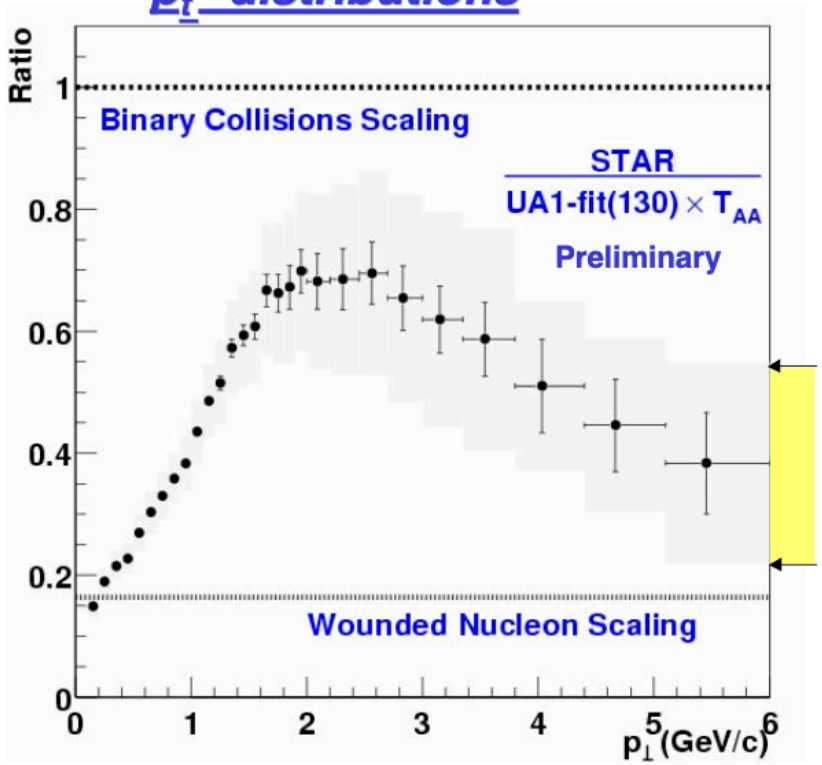
STAR — Negative Hadrons: Compare with $\bar{p}p$ p_t - distributions

UA1 $\sqrt{s}$ = 200
⇒ R (130/200)

From power law scaling
R = 0.92 at 0.2 GeV/c
R = 0.70 at 2 GeV/c

"Hard" Scaling
Nuclear Overlap Integral
T_{AA} = 26 mb^{-1} for 5% most central
$N_{AA} / N_{pp} = N_{bin\ coll} = 1050$

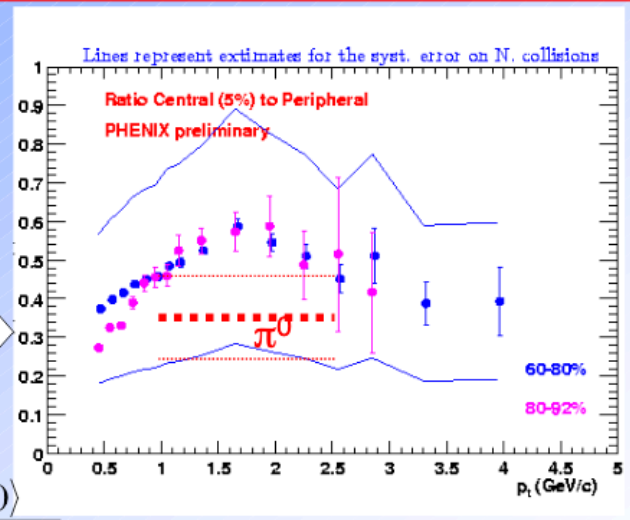
"Soft" Scaling
$N_{AA} / N_{pp} = (344 / 2)$



J.W. Harris for STAR at QM2001

PHENIX — Central vs. Peripheral Yields

- Can study relative yields within the data set:
  - Compare central to peripheral spectra vs. p_T
  - Scale by the average number of collisions

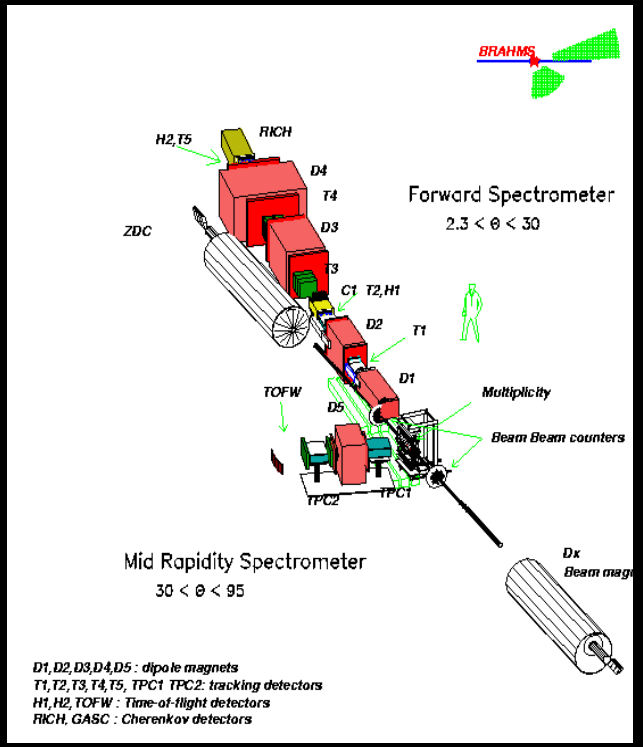


$$\text{Ratio} = \frac{\text{Yield(Central)} / \langle N_{COLL}(\text{Central}) \rangle}{\text{Yield(Peripheral)} / \langle N_{COLL}(\text{Peripheral}) \rangle}$$

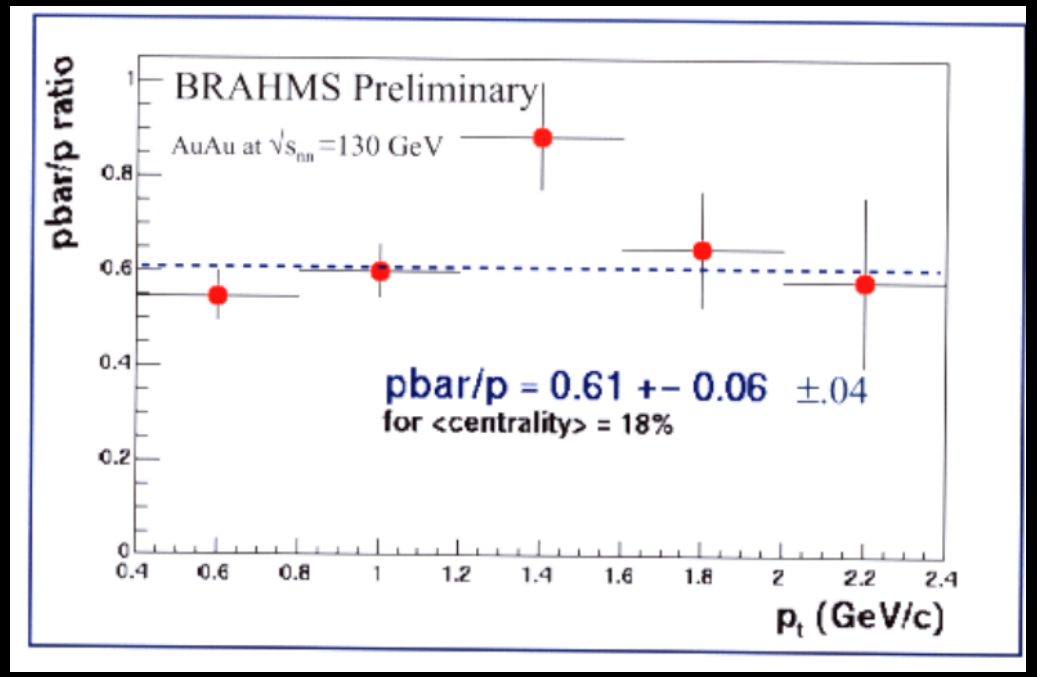
- Ratio unity if yields scale as number of collisions
- Ratio found to be less than 1, decreasing for $p_T > 2$ GeV/c
- Same is observed in π^0 analysis (very different sytematics)

31

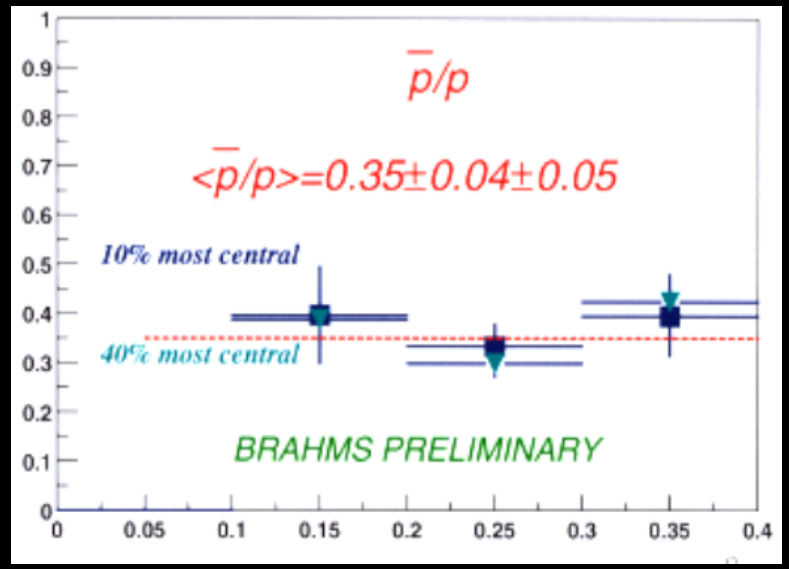
P-bar/p at Midrapidity & Forward (QM2001)



$\bar{p}/p$ ratio at $\eta \sim 0$

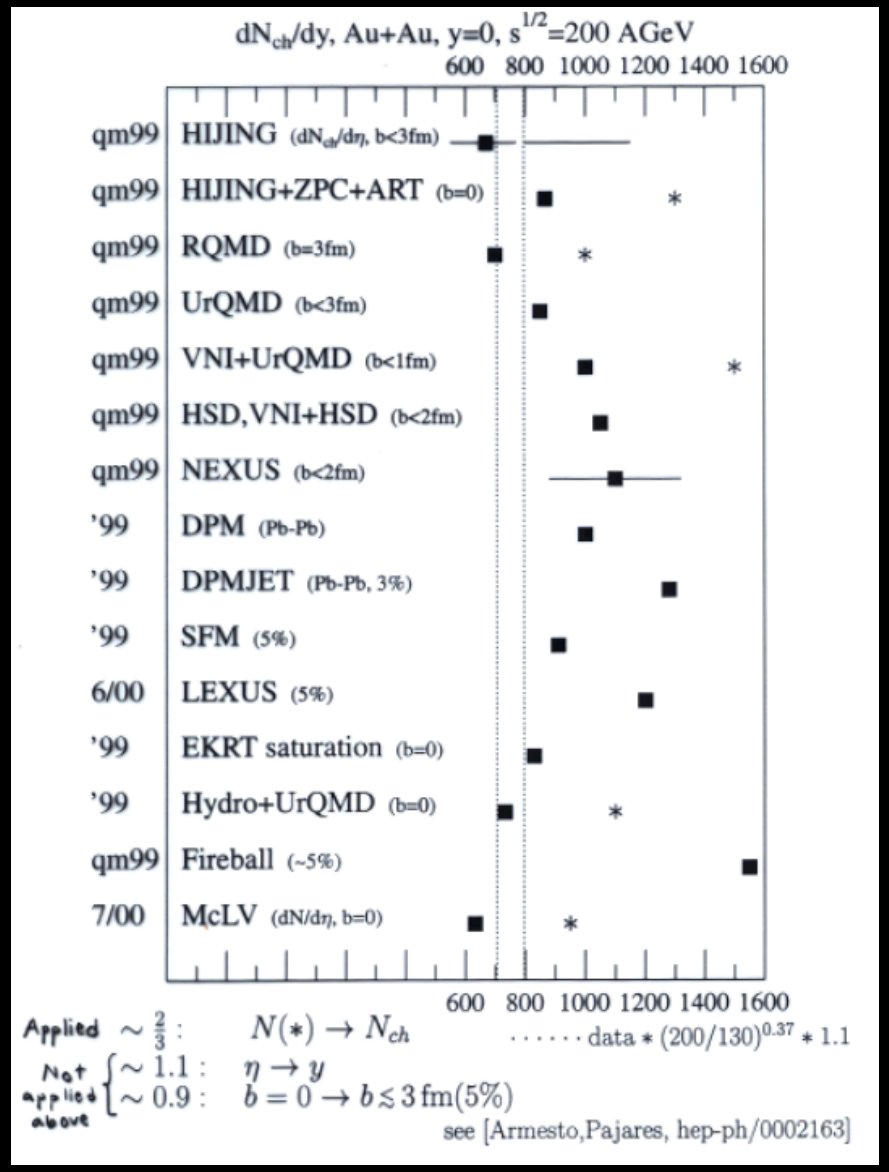


$\bar{p}/p$ ratio at $\eta \sim 3$



Theory Predictions & Summary

K. Eskola



Some quotations :

" Theoretical uncertainties are bigger than exp^al error bars "

(K. ESKOLA)

" We have to be more concerned about the theoretical content of models : an ill-defined model which fits the data is quite useless "

(K. WERNER)

JP Blaizot

RHIC Physics (QM2001)

Brief Summary

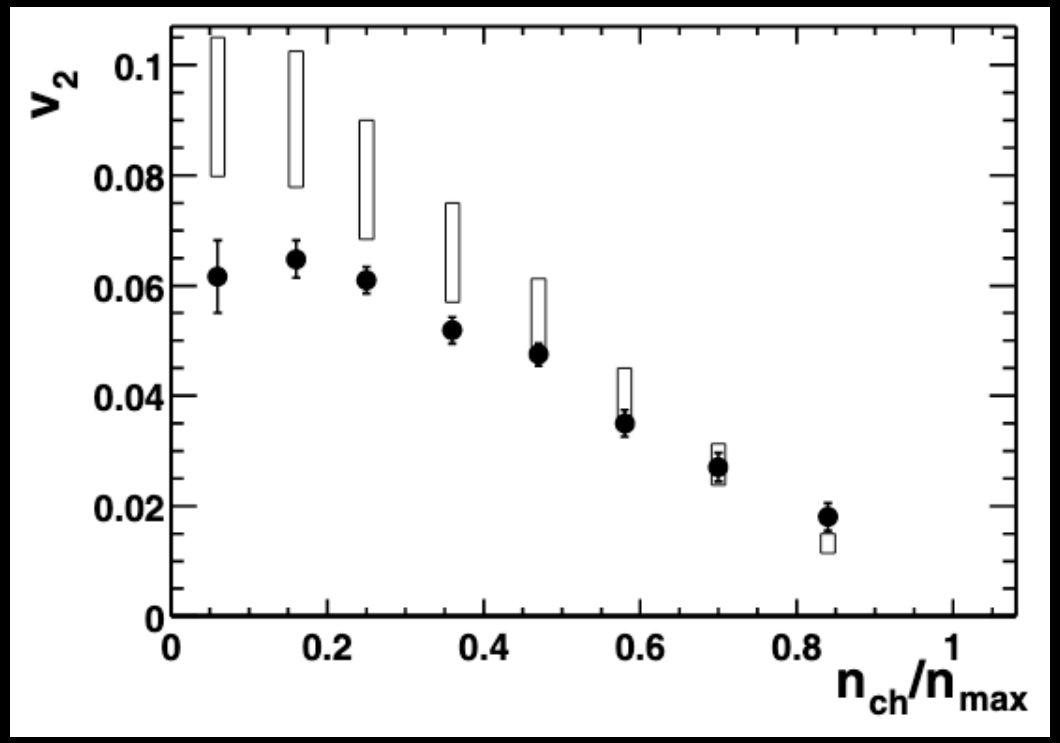
- Mapped out "Soft Physics" Regime
  - Particle production increased by 43% relative to SPS
  - Midrapidity spectral slopes increase with centrality & particle mass
    - → Strong transverse flow
  - Strong elliptic flow measured to high p_t (4.5 GeV/c)
  - Anti-particle and strange particle production increase rel. to SPS
    - → low net baryon density (but mid-rapidity not yet baryon free)
    - → consistent with quark coalescence
  - HBT (freeze-out) sizes similar to SPS
  - Substantial excess in mean p_t fluctuations
- "Hard Physics"
  - h- spectra never reach hard-scattering limit,
    diverge from it at $2 < p_t < 6$ GeV/c

RHIC Discovery Physics (2001– 2003)

(serious excitement)

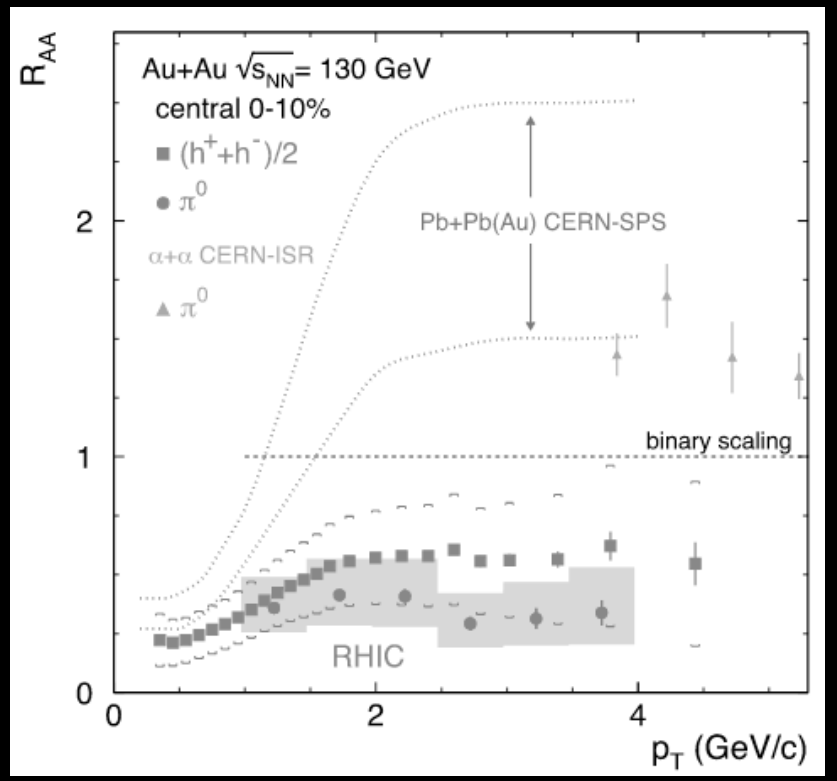
RHIC Physics Discovery Papers (2001 - 2003)

Strong Elliptic Flow in RHIC Collisions



"Elliptic flow in Au+Au Collisions at $\sqrt{s_{NN}}$ = 130 GeV,"
STAR, Phys. Rev. Lett. 86 (2001) 402.

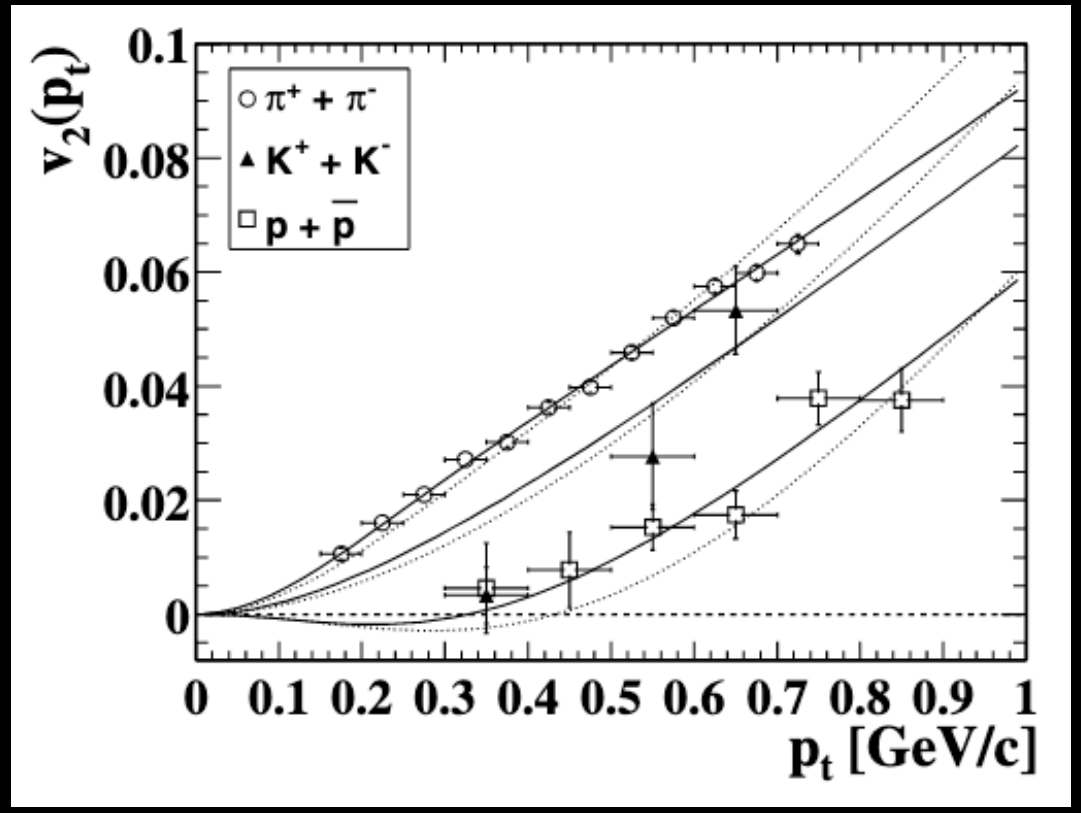
Suppression of High p_T Hadrons in RHIC Collisions



"Suppression of Hadrons with Large Transverse Momentum in Central Au+Au Collisions at $\sqrt{s_{NN}}$ = 130 GeV,"
PHENIX, Phys. Rev. Lett. 88 (2002) 022301.

RHIC Physics Discovery Papers (2001 - 2003)

Identified Particle Elliptic Flow



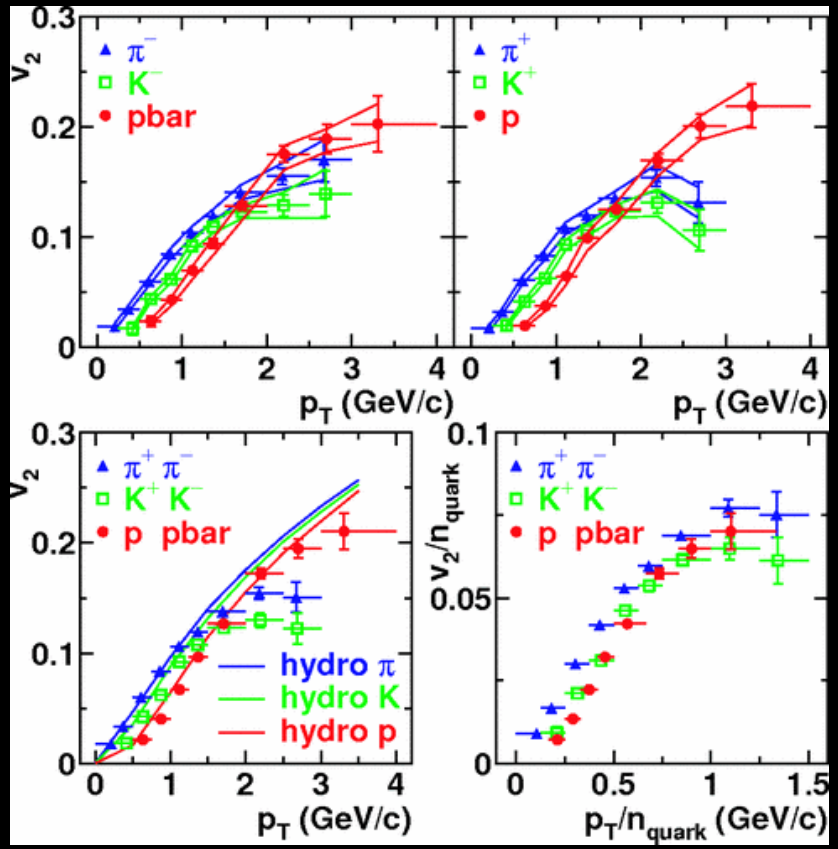
"Identified particle elliptic flow in Au + Au collisions at $\sqrt{s_{NN}}$ = 130 GeV,"

STAR, PRL 87 (2001) 182301.

Fine Structure in Elliptic Flow

"Elliptic flow of Identified Hadrons in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV,"

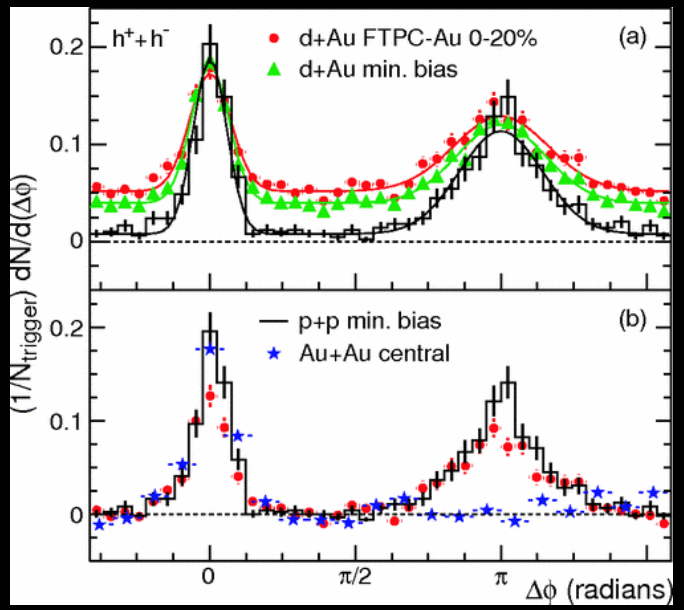
PHENIX, PRL 91 (2003) 182301.



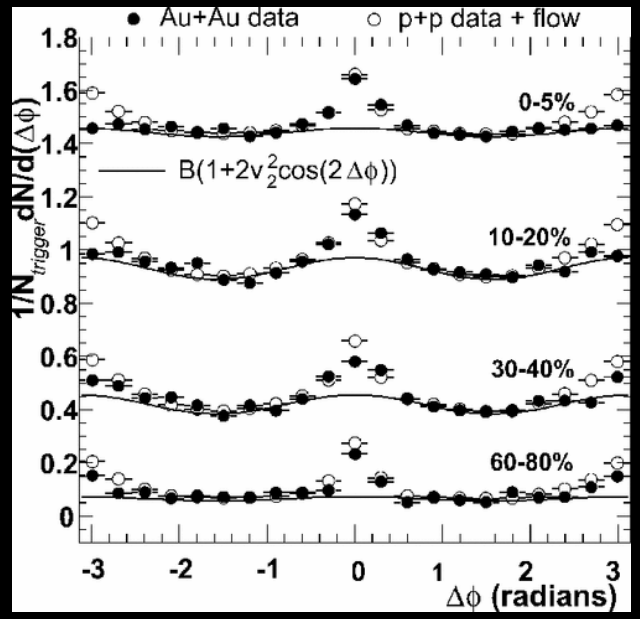
RHIC Physics Discovery Papers (2001 - 2003)

Suppression of High-p_T Hadrons is Final-State

"Evidence from d+Au Measurements for Final-State Suppression of High-p_T Hadrons in Au+Au Collisions at RHIC," STAR, PRL 91 (2003) 072304.



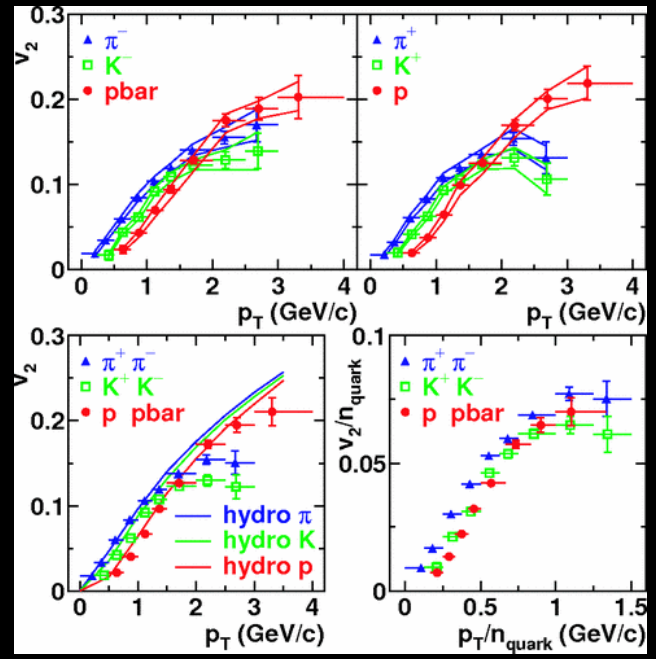
Disappearance of the Away-side Jet



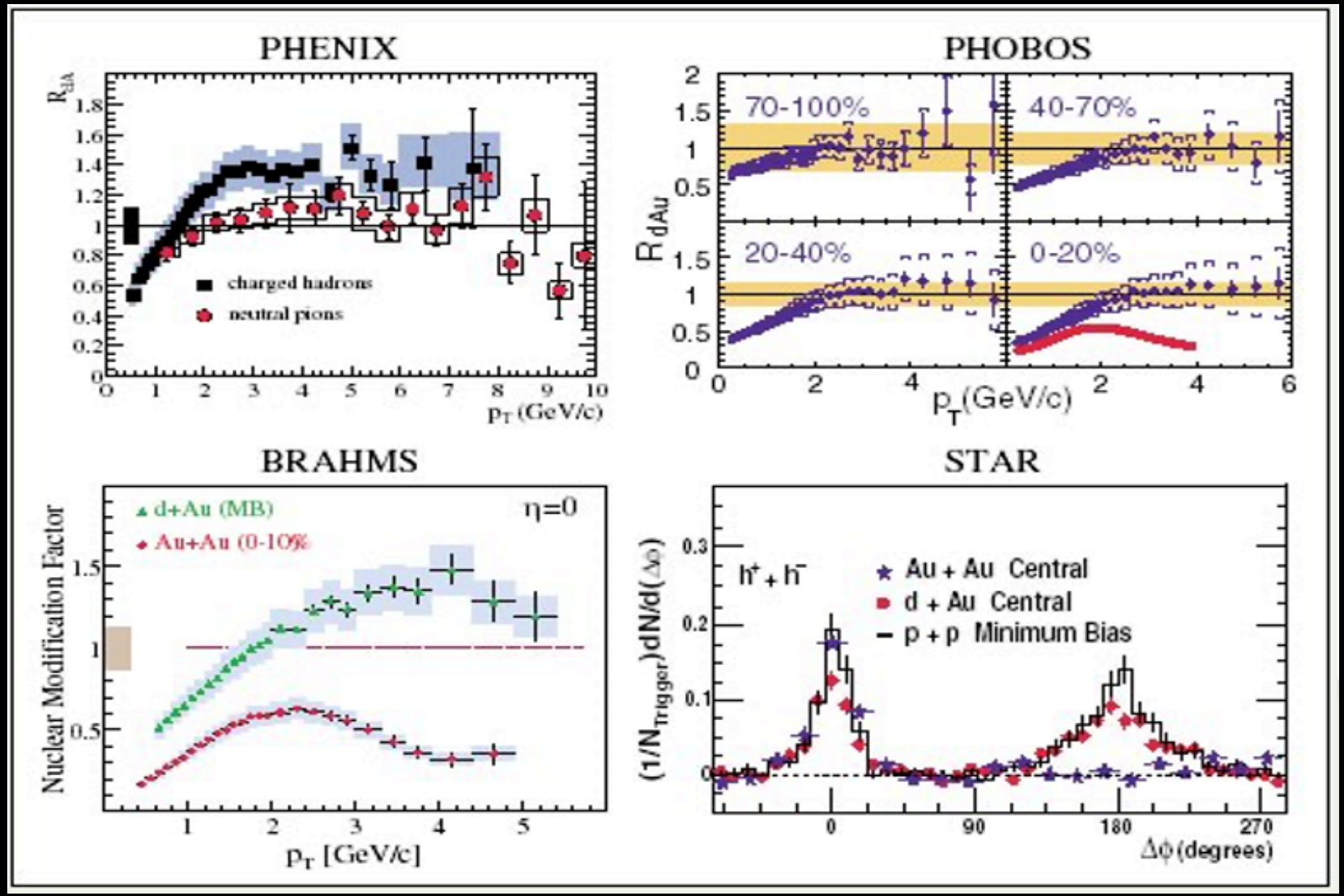
"Disappearance of Back-to-Back High p_T Correlations in Central Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV," STAR, PRL 91 (2003) 082302.

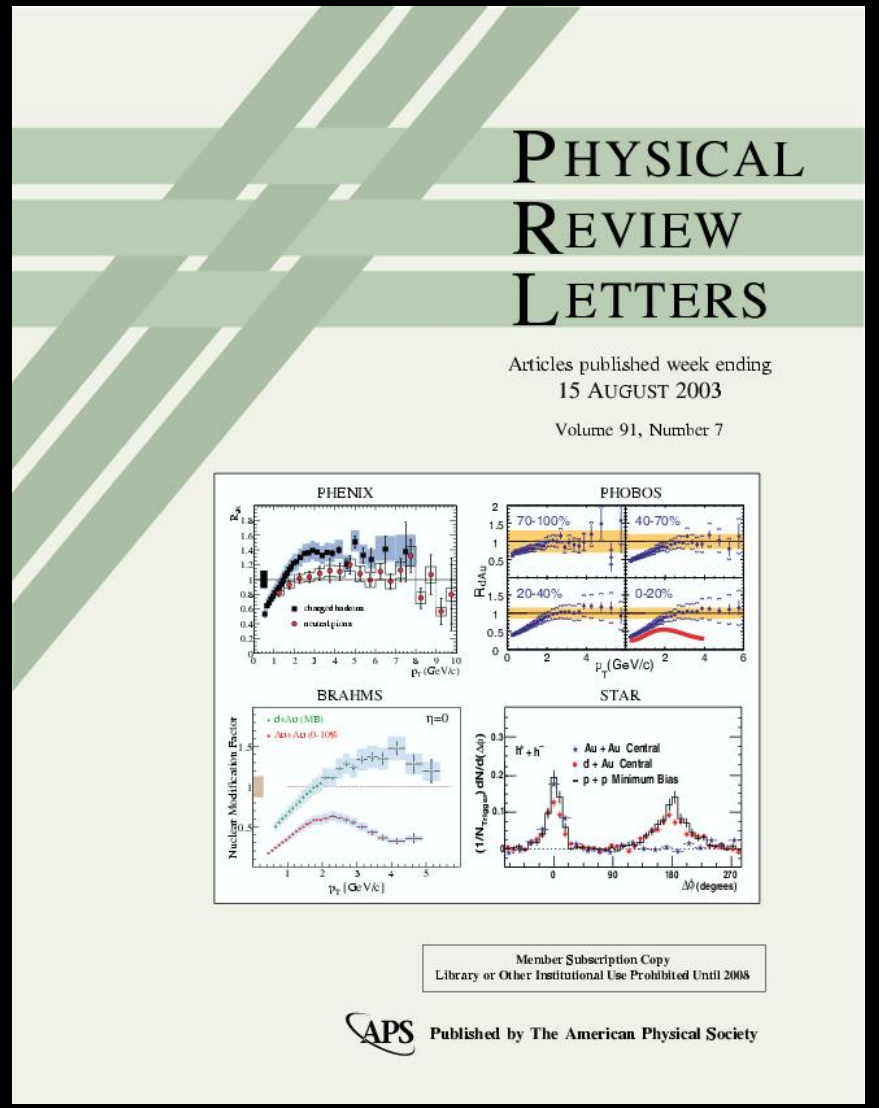
Appearance of Fine Structure in Elliptic Flow

"Elliptic flow of Identified Hadrons in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV," PHENIX, PRL 91 (2003) 182301.



Iconic RHIC Physics Figures (2003)





Suppression in Au+Au is a Final-State Effect!

RHIC White Papers (2005)

(a Tour de Force)

RHIC White Papers (2005)

- *"Quark gluon plasma and color glass condensate at RHIC? The Perspective from the BRAHMS experiment,"* Nucl.Phys. **A757** (2005) 1-27, nucl-ex/0410020

  2171 citations

- *"Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration,"* Nucl.Phys. **A757** (2005) 184-283, nucl-ex/0410003

  2886 citations

- *"The PHOBOS perspective on discoveries at RHIC,"* Nucl.Phys. **A757** (2005) 28-101, nucl-ex/0410022

  2207 citations

- *"Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions,"* Nucl.Phys. **A757** (2005) 102-183, nucl-ex/0501009

  3117 citations

RHIC Theory (2005)

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Available online at www.sciencedirect.com
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Nuclear Physics A 750 (2005) 30–63

NUCLEAR PHYSICS A

New forms of QCD matter discovered at RHIC

Miklos Gyulassy [a], Larry McLerran [b,*]

1097 citations

7. Conclusions

Our criteria for the discovery of the quark–gluon plasma at RHIC are:

- Matter at energy densities so large that the simple degrees of freedom are quarks and gluons. This energy density is that predicted by lattice gauge theory for the existence of a QGP in thermal systems, and is about 2 GeV/fm^3.
- The matter must be to a good approximation thermalized.
- The properties of the matter associated with the matter while it is hot and dense must follow from QCD computations based on hydrodynamics, lattice gauge theory results, and perturbative QCD for hard processes such as jets.

All of the above are satisfied from the published data at RHIC. A surprise is the degree to which the computations based on ideal fluid hydrodynamics agree so well with elliptic flow data. This leads us to conclude that the matter produced at RHIC is a strongly coupled quark–gluon plasma (sQGP) contrary to original expectations that were based on weakly coupled plasma estimates.

The case for the color glass condensate is rapidly evolving into a compelling case. Much

Although in our opinion, the case for the sQGP at RHIC is now overwhelming, there are of course many important scientific issues not yet addressed in the first three years of data. The experiments have demonstrated that a new form of matter, the sQGP, exists. The harder long term task of mapping out more of its novel properties can now confidently proceed at RHIC.

RHIC & the QGP "Nearly Perfect Liquid"

SHARE Print

Contacts: Karen McNulty Walsh, (631) 344-8350 or Peter Genzer, (631) 344-3174

RHIC Scientists Serve Up 'Perfect' Liquid

New state of matter more remarkable than predicted — raising many new questions

Monday, April 18, 2005

TAMPA, FL — The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) — a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory — say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

SCIENTIFIC AMERICAN 175 YEARS

THE SCIENCES

New State of Matter Is 'Nearly Perfect' Liquid

By Sarah Graham on April 18, 2005

CERNCOURIER | Reporting on international high-energy physics

Physics ▾ | Technology ▾ | Community ▾ | In focus | Magazine

NEWS

RHIC groups serve up 'perfect' liquid

5 May 2005

APS physics

Publications | Meetings & Events | Programs | Membership

APS NEWS

June 2005 (Volume 14, Number 6)

RHIC Detects Liquid State of Quark-Gluon Matter

By Ernie Tretkoff

The News of the QGP Hit the Streets

Universe May Have Begun as Liquid, Not Gas

Associated Press
Tuesday, April 19, 2005; Page A05

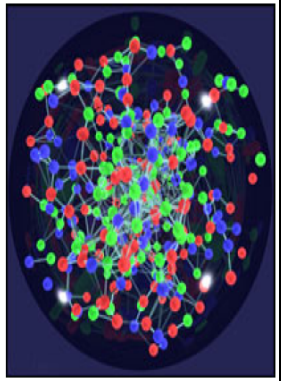
The Washington Post

New results from a particle collider suggest that the universe behaved like a liquid in its earliest moments, not the fiery gas that was thought to have pervaded the first microseconds of existence.

Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.

BBC NEWS



The impression is of matter that is more strongly interacting than predicted

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

Early Universe was a liquid

Quark-gluon blob surprises particle physicists.

by Mark Peplow
news@nature.com

nature

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.

DISCOVER
Science, Technology, and The Future

THE BIG BANG MACHINE
A Long Island Particle Smasher Re-creates The Moment Of Creation

An atom smasher on Long Island re-creates the particle soup that gave rise to the universe

"Here is where the action takes place. This is where we effectively try to turn the clock back 14 billion years. Right above your head, about 13½ feet in the air."

Looking up, I try to imagine the events Tim Hallman is describing—atoms of gold colliding at 99.99 percent the speed of light; temperatures instantly soaring to 1 trillion degrees, 150,000 times hotter than the core of the sun. Then I try to picture a minuscule five-dimensional black hole, which, depending on your point of view, may or may not have formed at that same spot over my head. It's all a little much for an imagination that sometimes struggles with the plot of *Battlestar Galactica*.

SCIENTIFIC AMERICAN

Bringing DNA Computers to Life

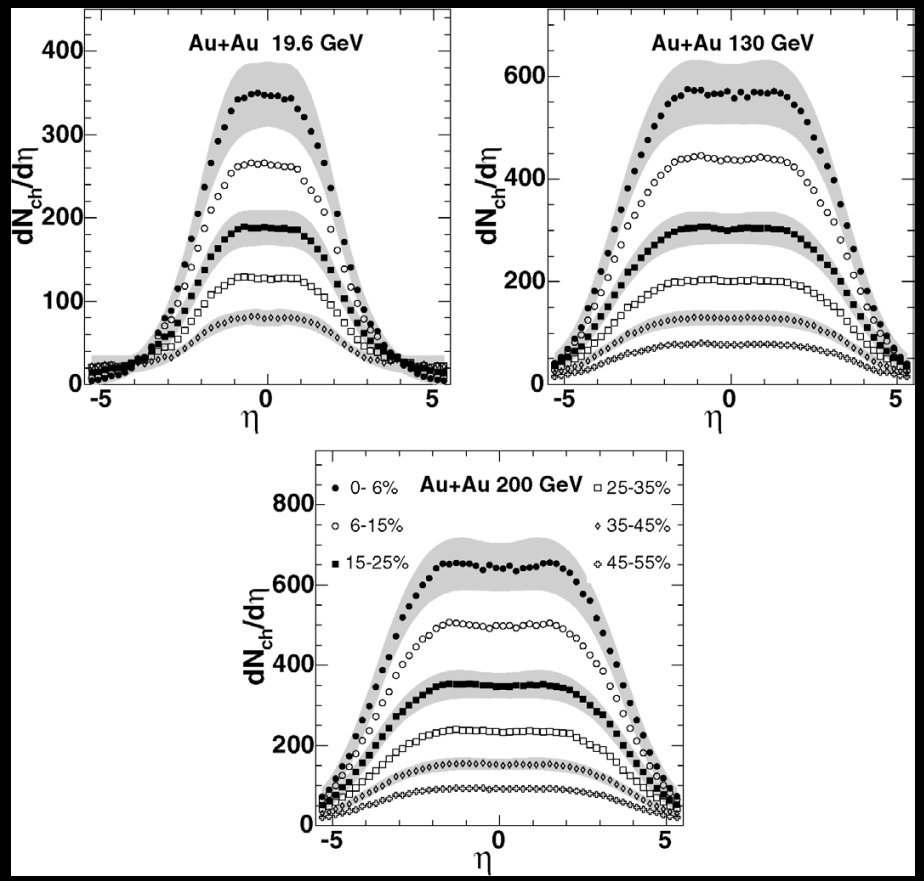
MAY 2006
WWW.SCIAM.COM

Quark Soup

PHYSICISTS RE-CREATE THE LIQUID STUFF OF **THE EARLIEST UNIVERSE**

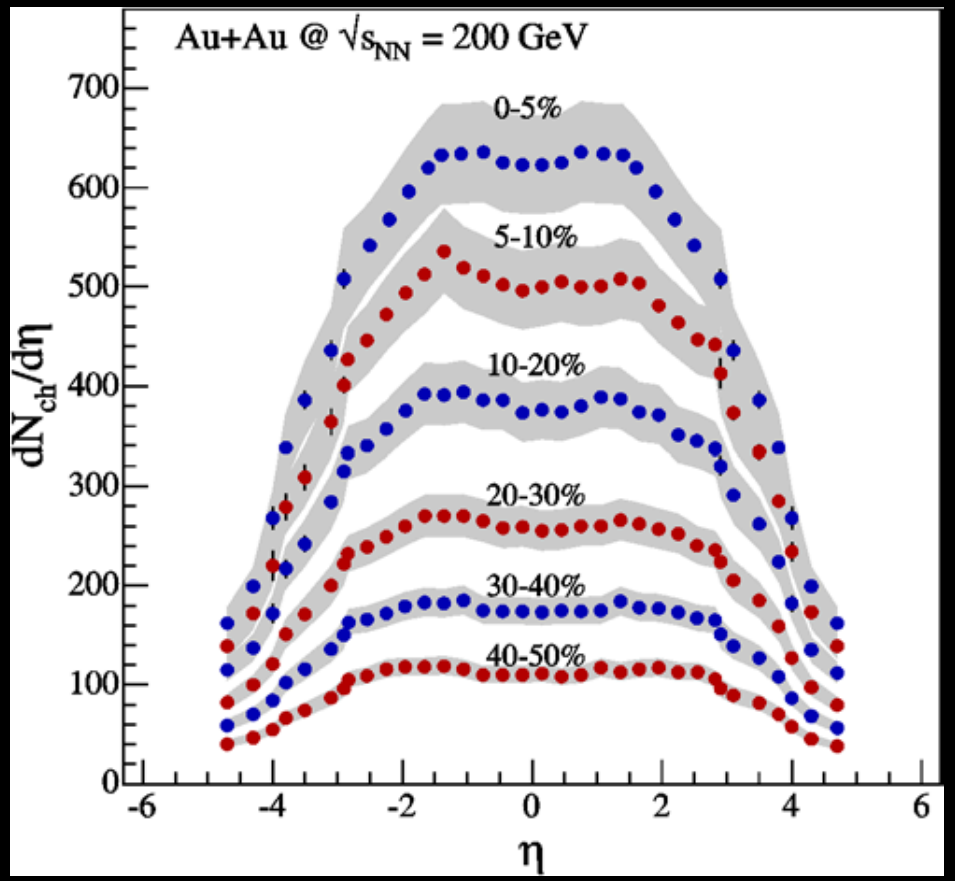
Pseudorapidity Densities(2005): $dn_{ch}/d\eta$ vs $\sqrt{s}$ & Centrality

PHOBOS



$dn_{ch}/d\eta$

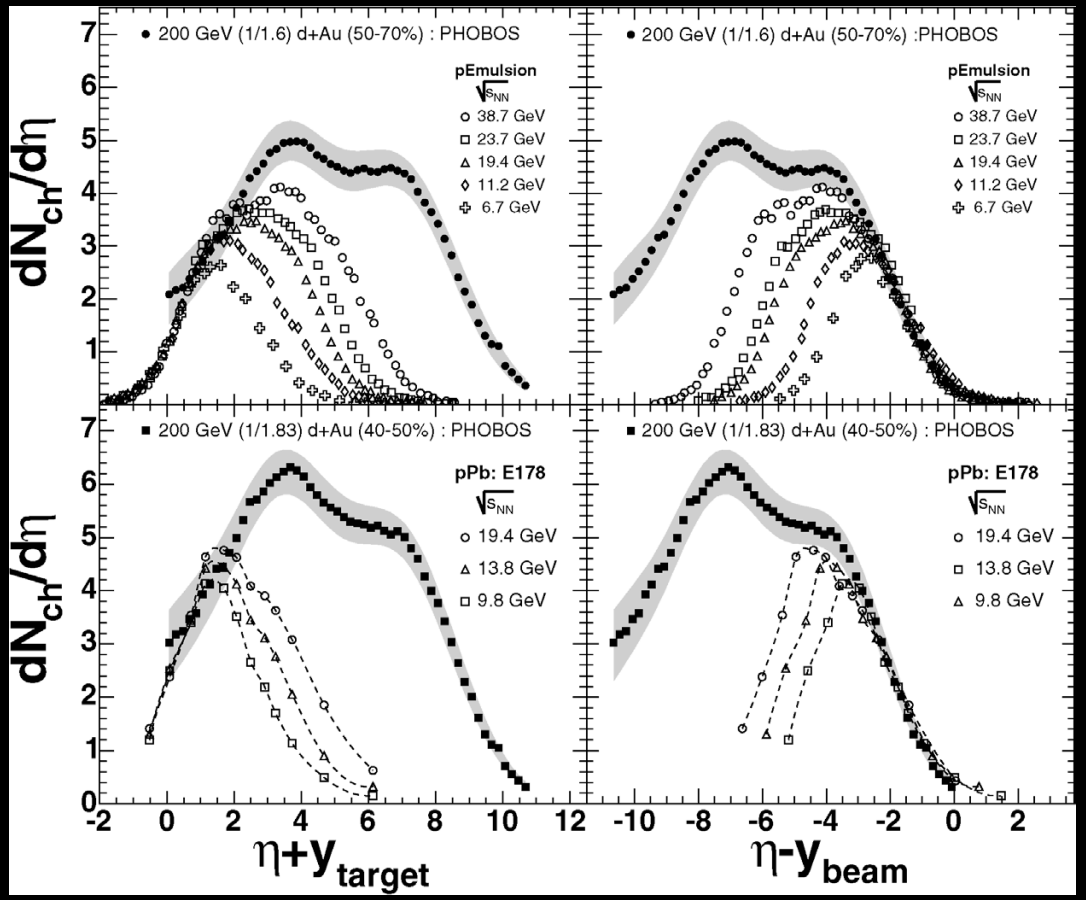
BRAHMS

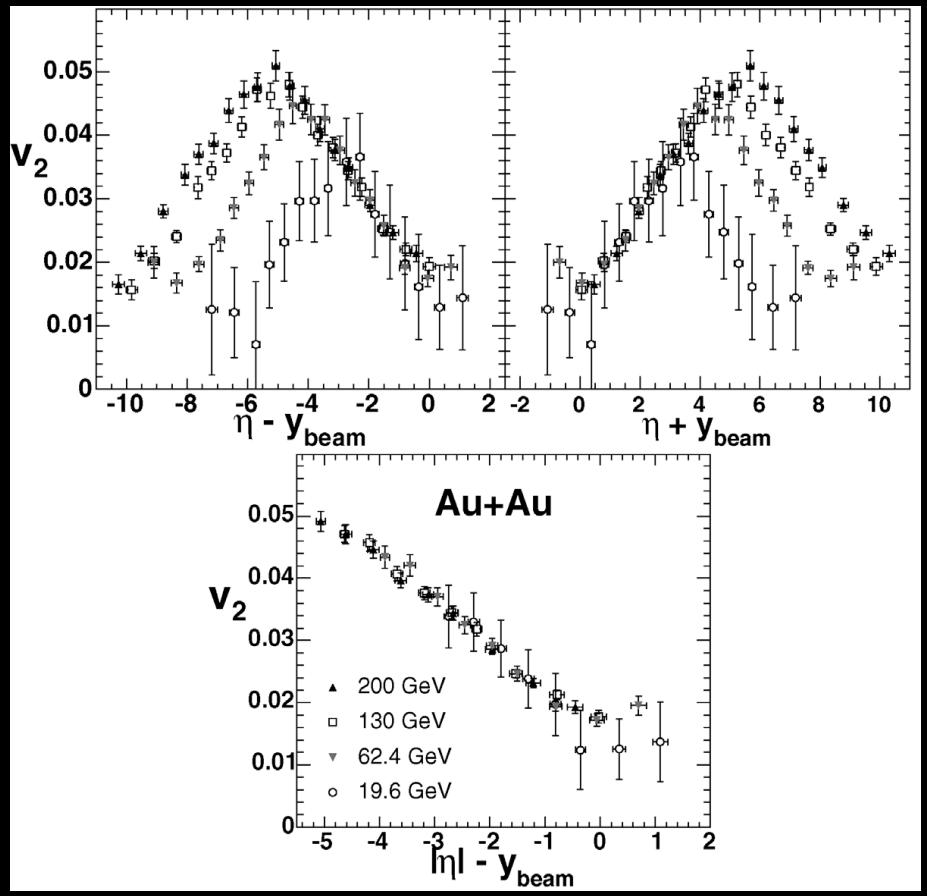


As a function of centrality, the total number of charged particles scales with the number of participating nucleons.

"Extended Longitudinal Scaling" (2005): dn/dy vs √s

PHOBOS





$dn_{ch}/d\eta$ and v_2 independent of energy over a broad range of pseudorapidities

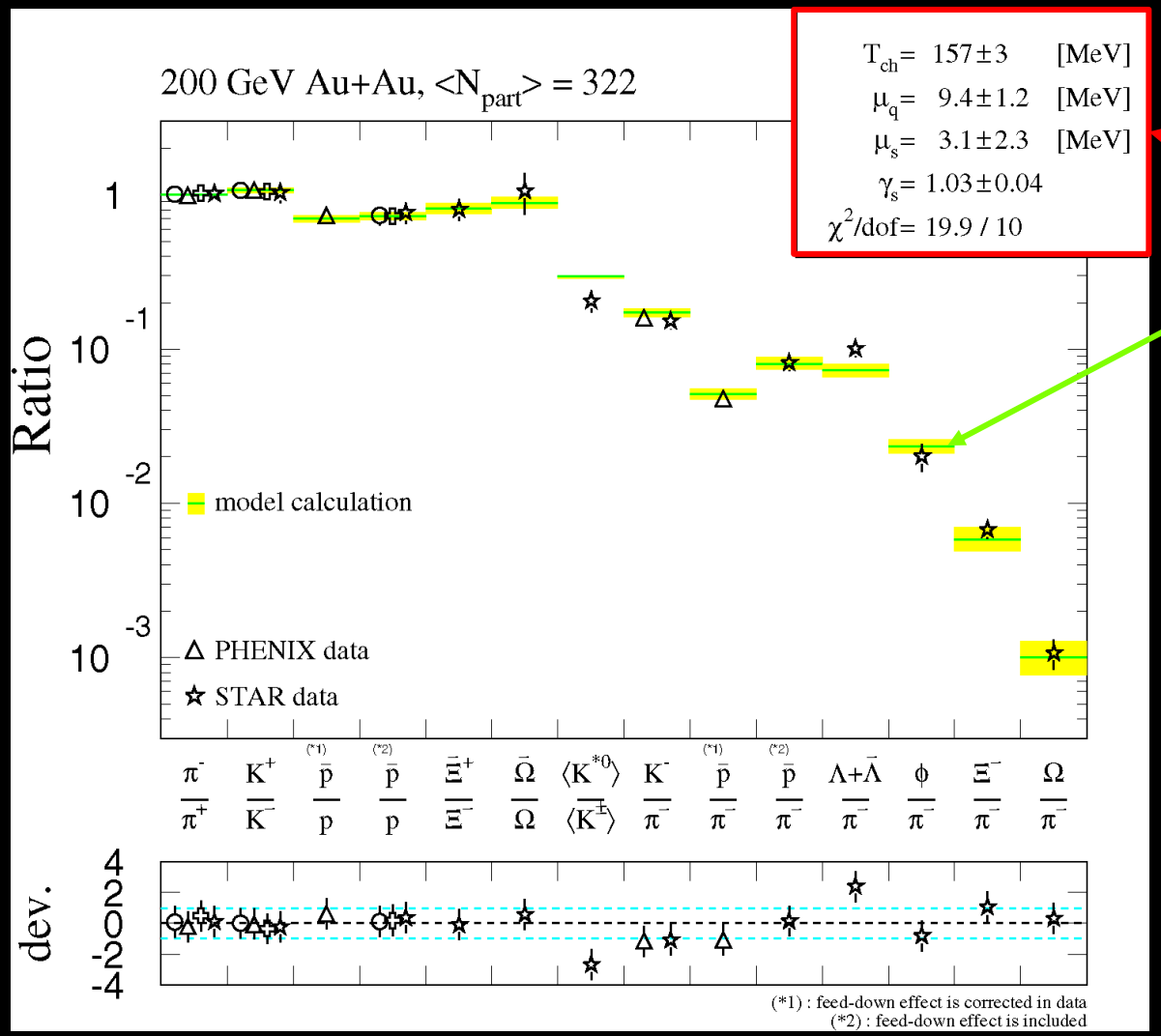
as viewed in rest frame of one of colliding nuclei → "extended longitudinal scaling"

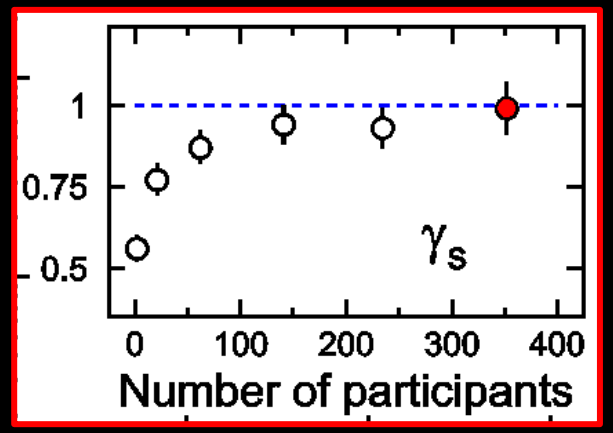
→ Geometry & early evolution important in determining properties of final state observables

Particle Ratios and Statistical Model Fits (2005)

PHENIX & STAR

Thermal Model Fits to Ratios



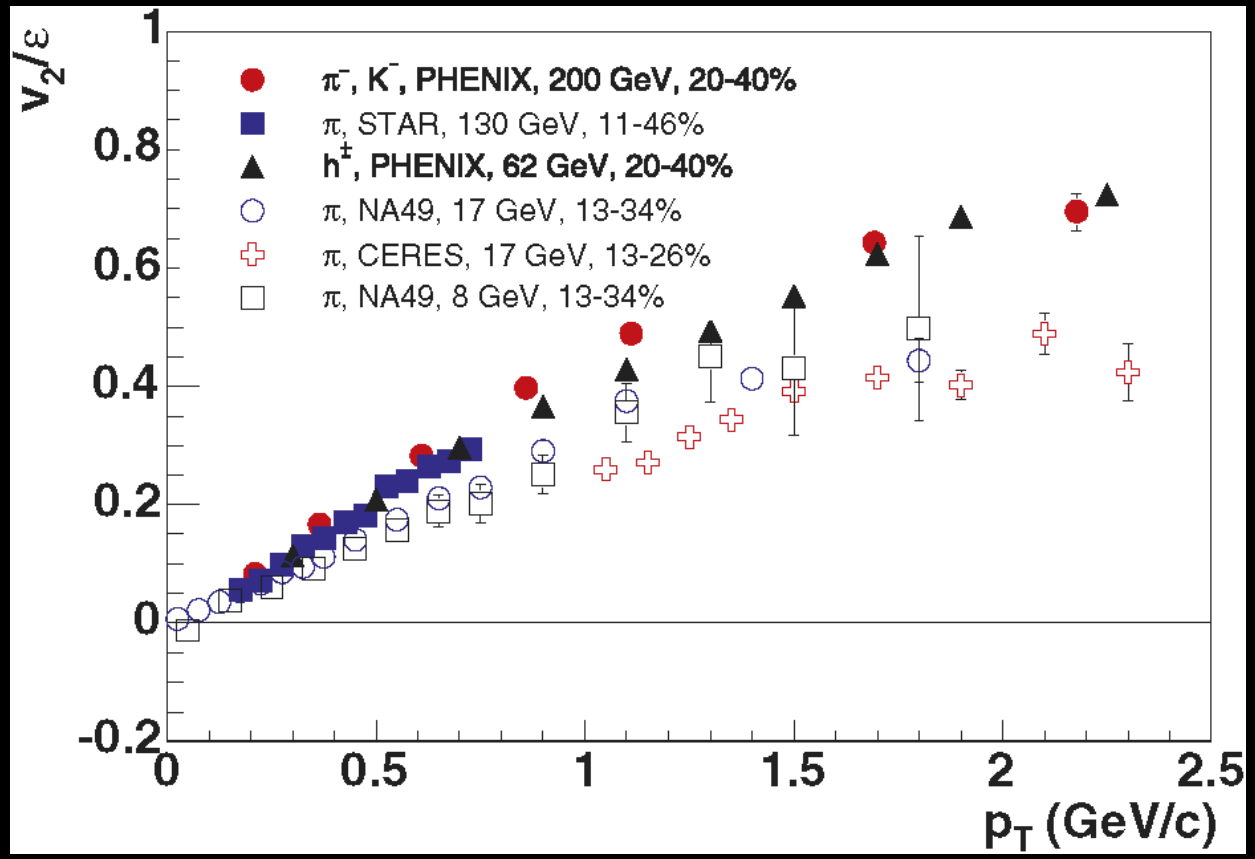


Strangeness saturates with multiplicity

Elliptic Flow v_2/ε (2005)

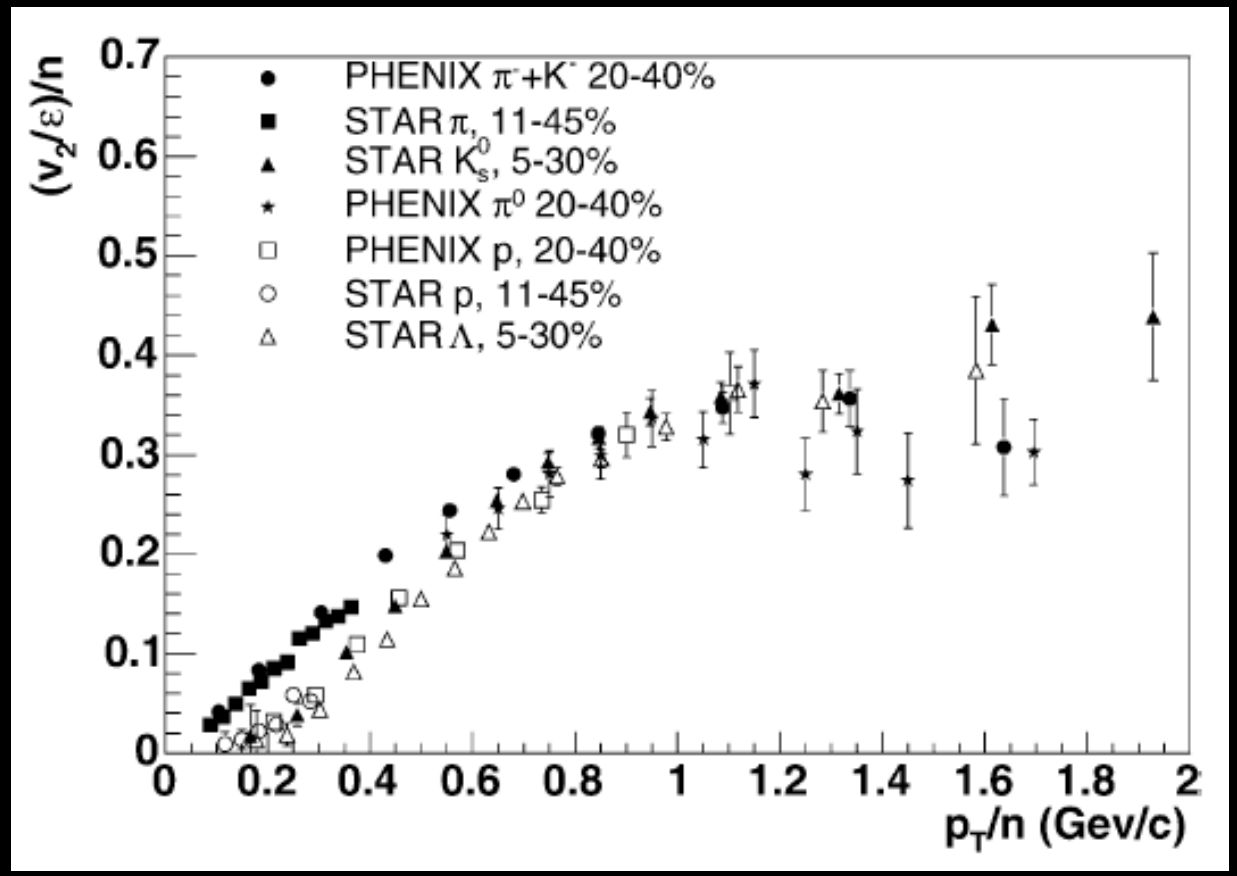
PHENIX & STAR

v_2/ε at different $\sqrt{s}$



v_2/ε increases with $\sqrt{s}$

$(v_2/\varepsilon)/n$ for different particles



v_2 follows ncq scaling up to 1 GeV

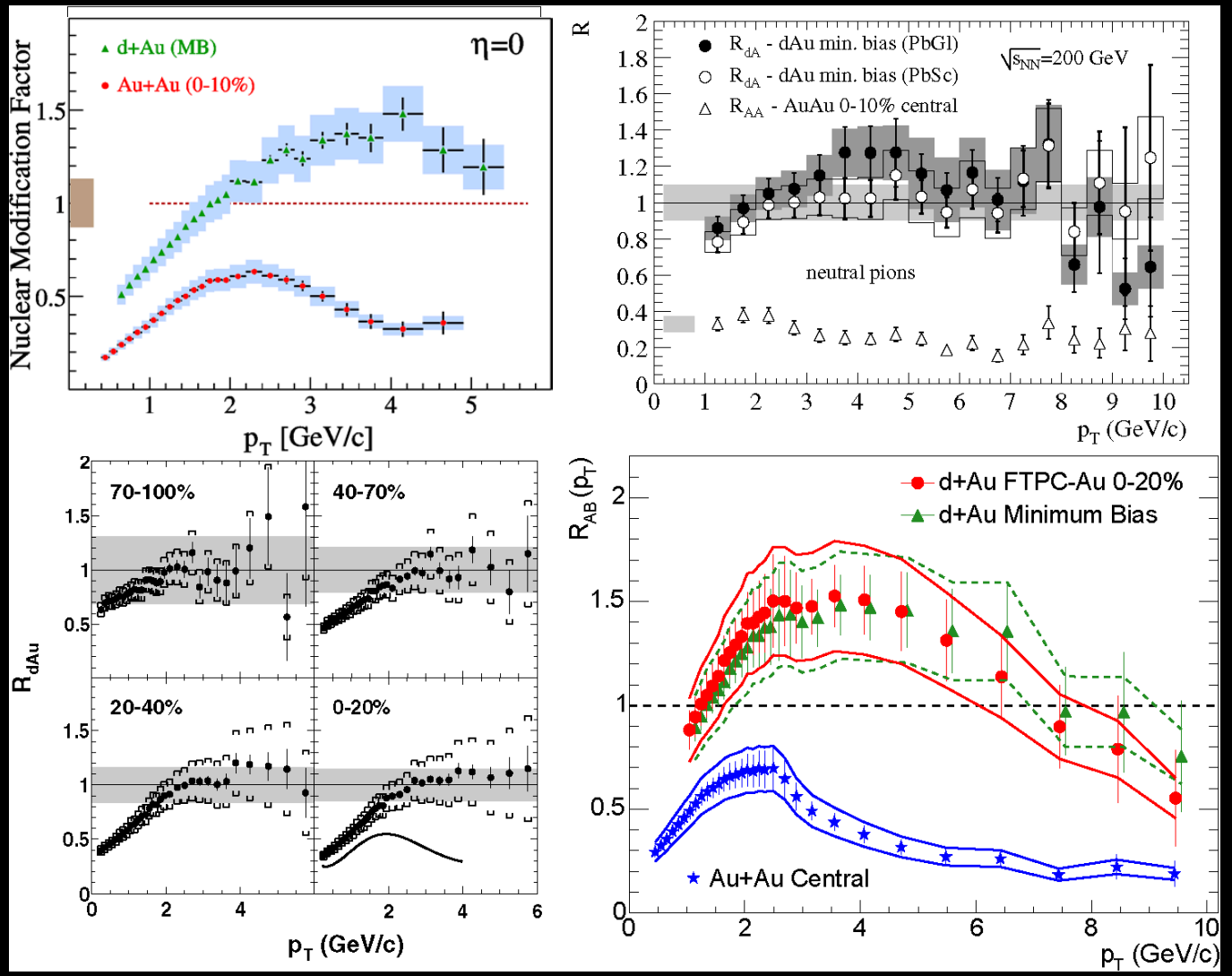
R_{AuAu} and R_{dAu} to High p_T (2005)

BRAHMS

PHENIX

PHOBOS

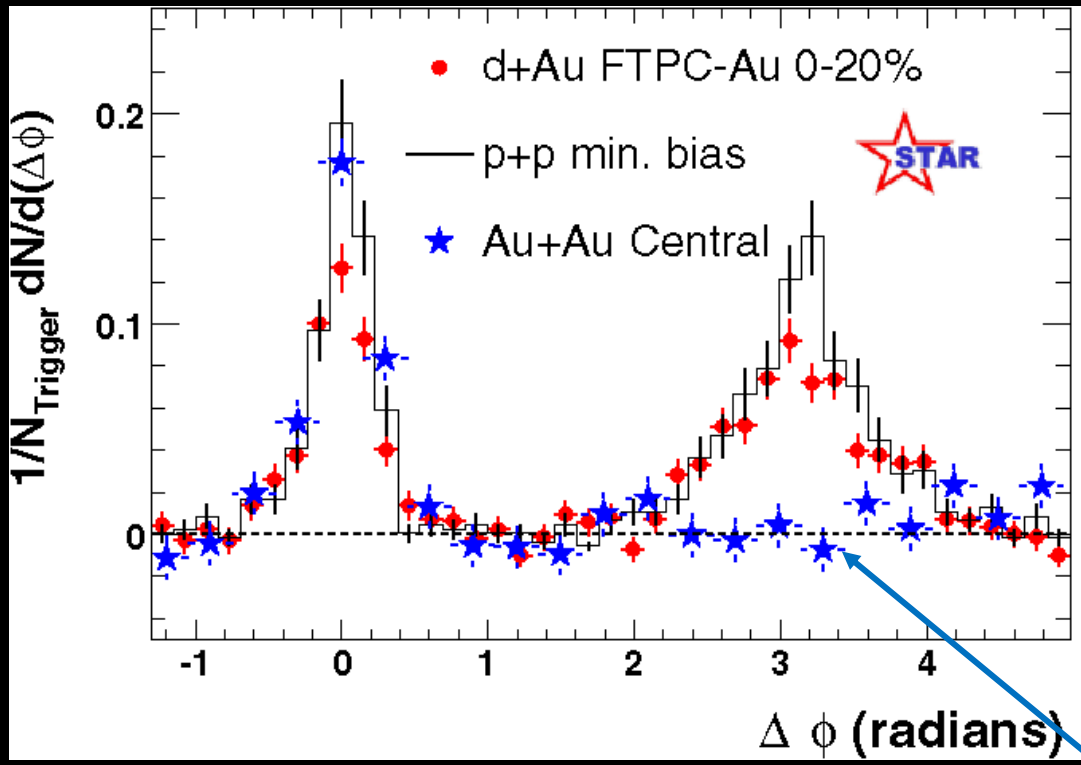
STAR

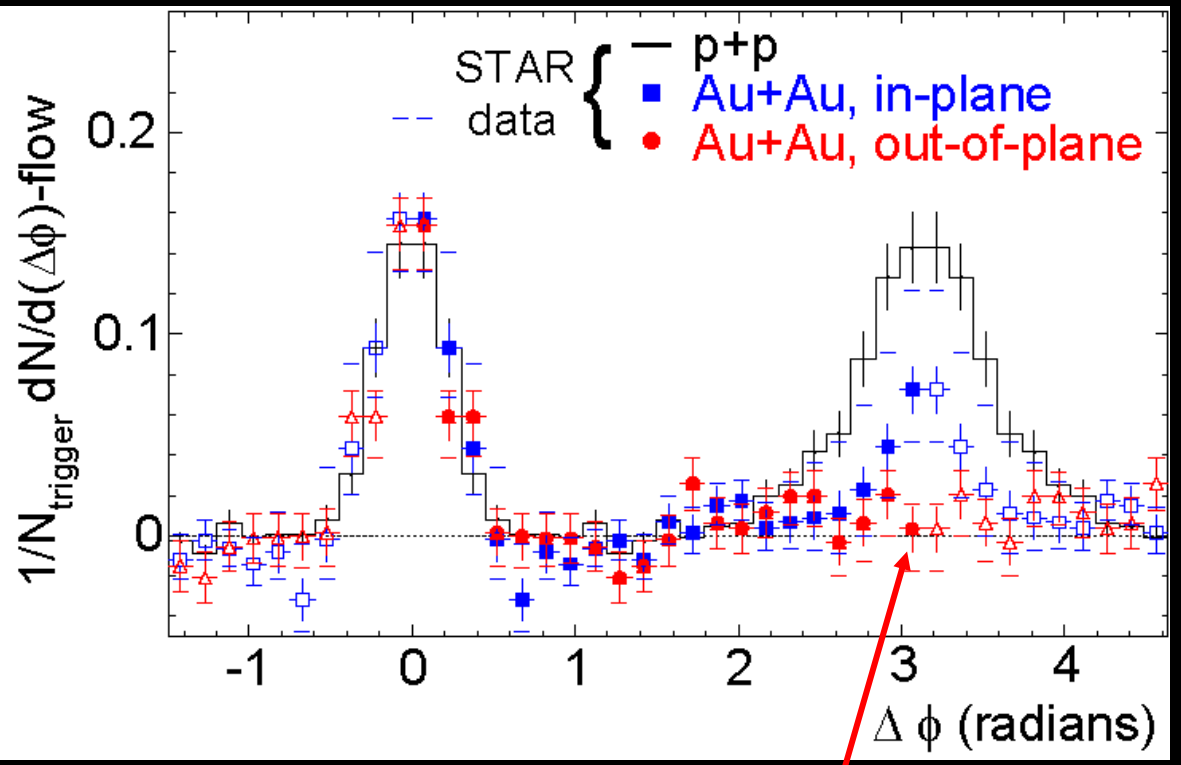


Update from 2003 PRL (cover articles) already shown!

Away-side Jet In-Plane and Out-of-Plane (2005)

STAR

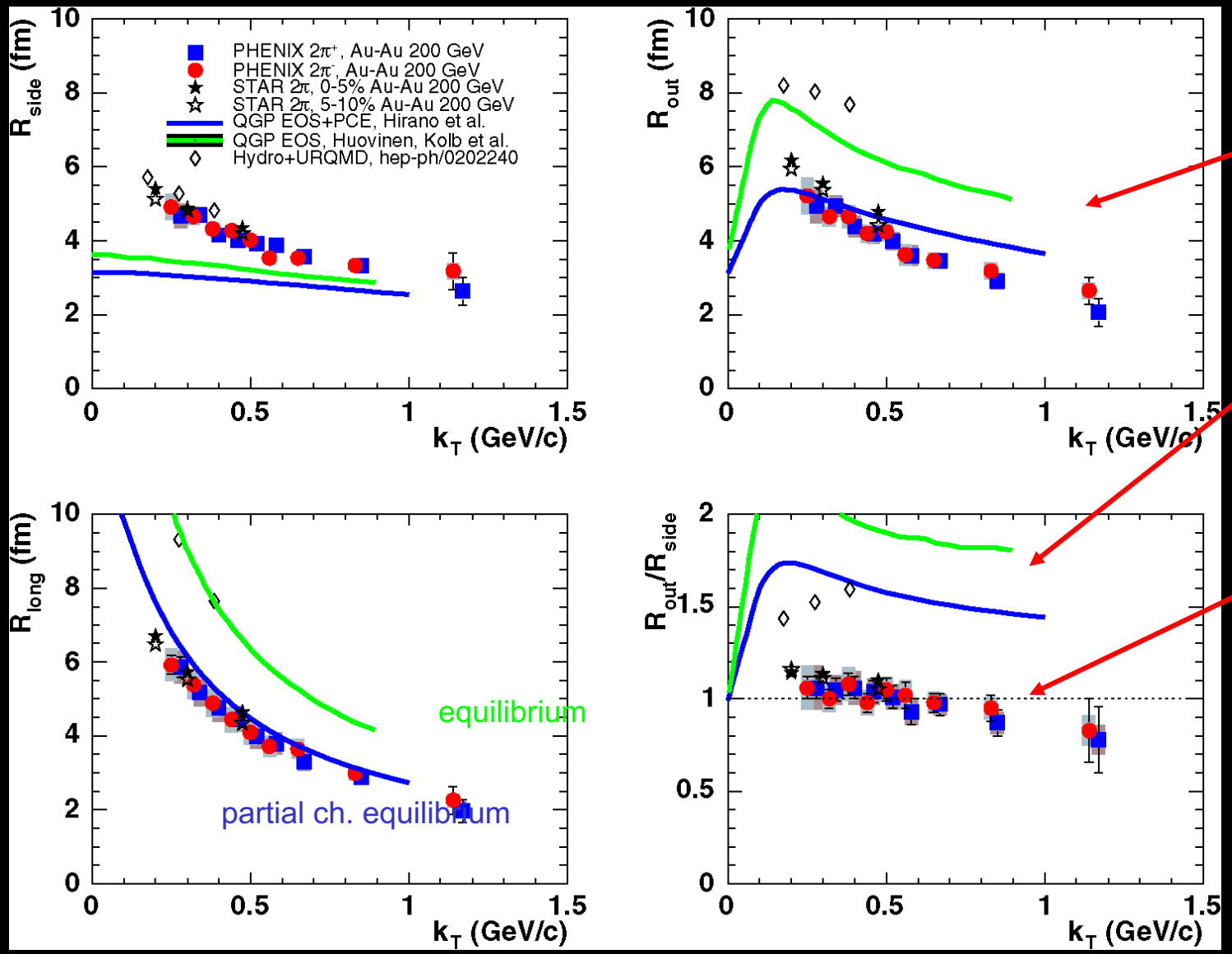




Central Au+Au Away-side Jet Quenched, More Quenched Out-of-Plane

An HBT Puzzle? (2005)

PHENIX & STAR



For rapidly expanding sources :

R_{out} , R_{side} , R_{long} decrease with increasing k_T

For sources emitting particles over long time:

$R_{out} / R_{side} > 1$

$R_{out} \approx R_{side}$

→ "HBT Puzzle!"

Equilibrium hydro overpredicts

R_{long} (collision duration)

R_{out}/R_{side} (emission time)

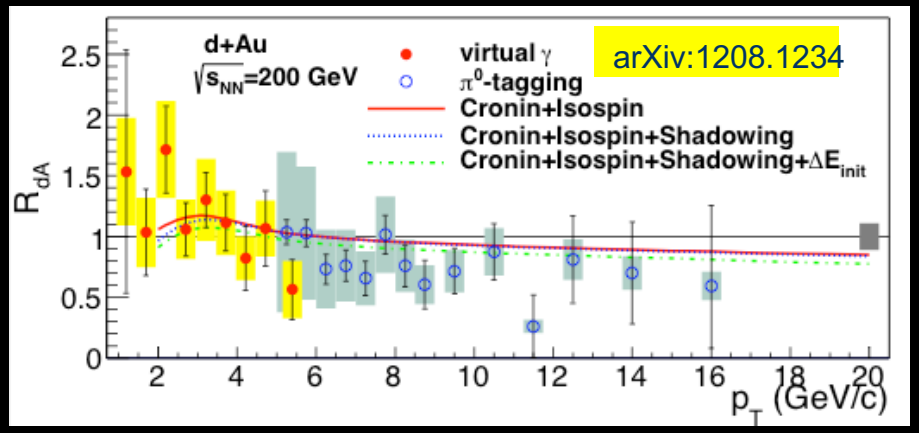
→ the mixed-phase is too long!

not a 1st order transition?

Start of a New Era (2010)

(a BIGGER younger brother arrives….serious competition!)

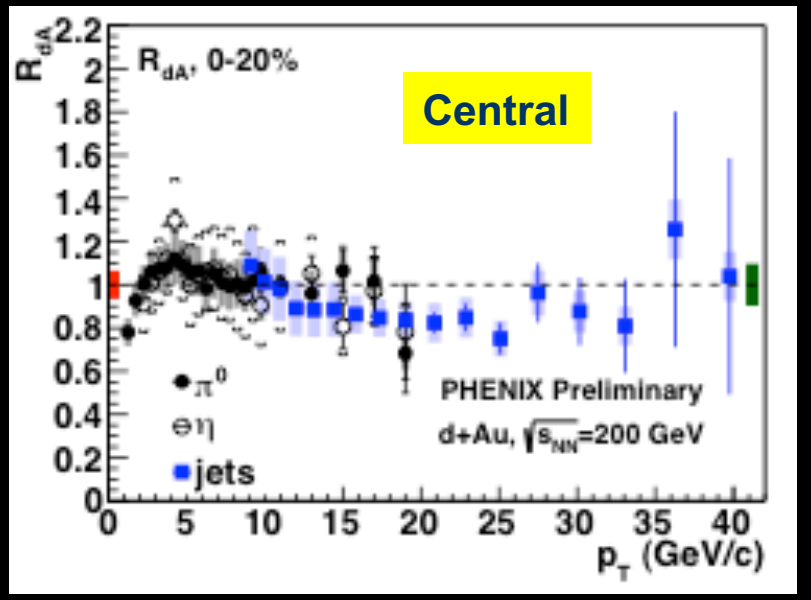
RHIC 2012: Initial State – Photons, Particles, Jets

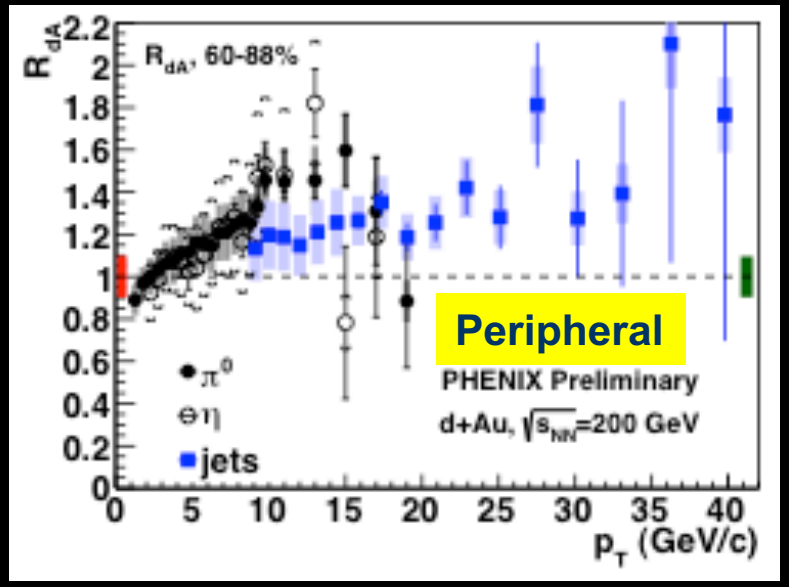


arXiv:1208.1234

d+Au

No modification in initial hard scattering at mid-rapidity



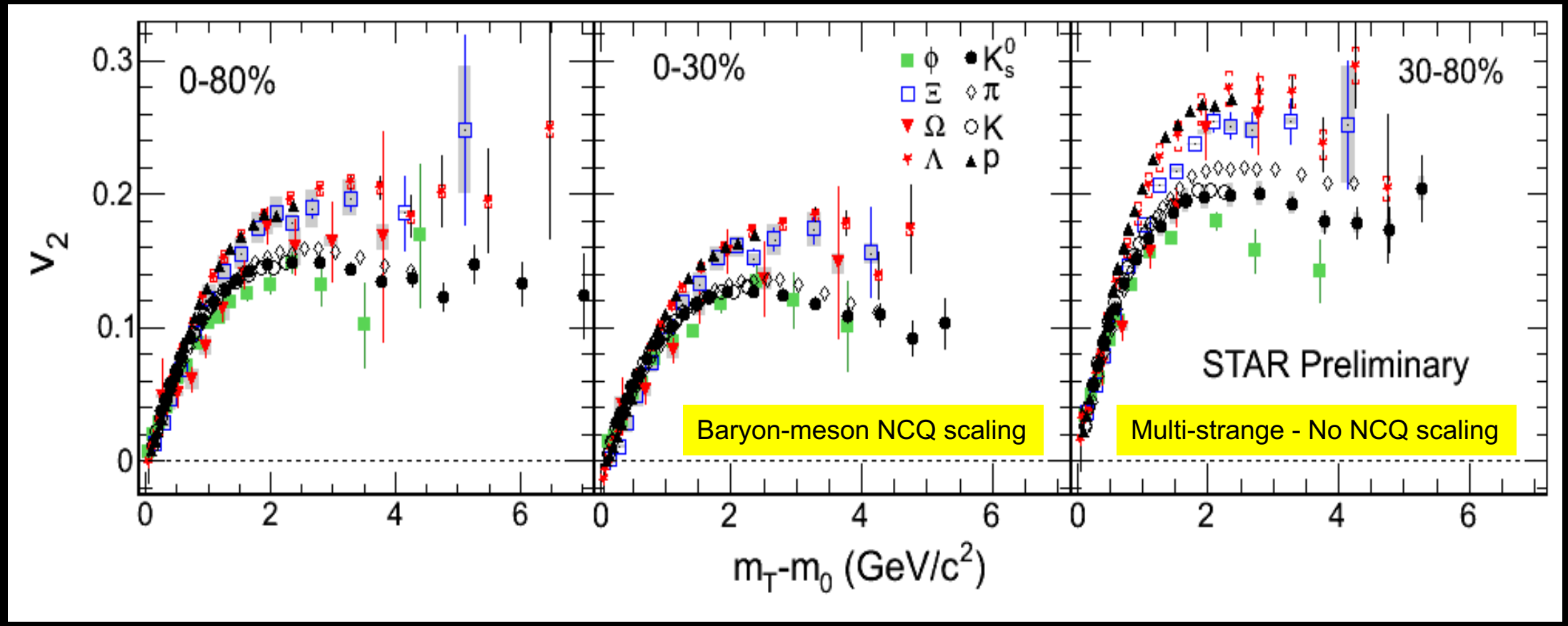


Jets are reconstructed in d+Au at RHIC up to 40 GeV/c !

Slight increase in peripheral collision R_{dA} at high p_T (?)

RHIC 2012: Collective Flow

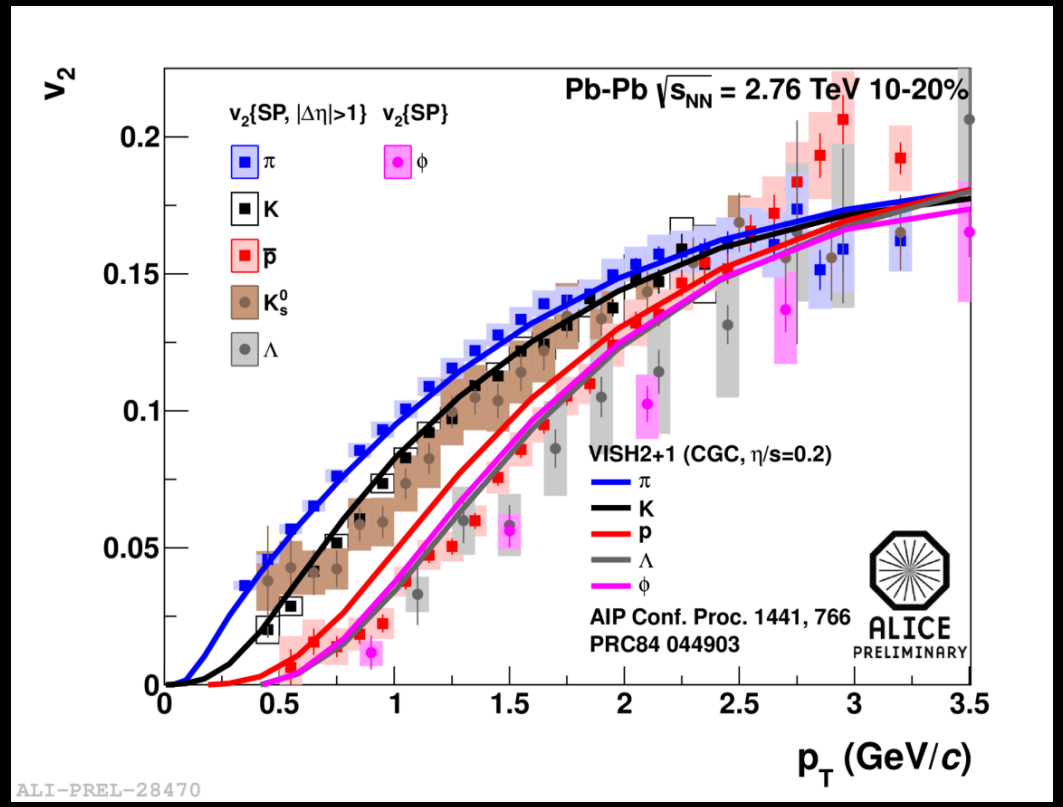
Identified Particle Elliptic Flow in 200 GeV Au+Au

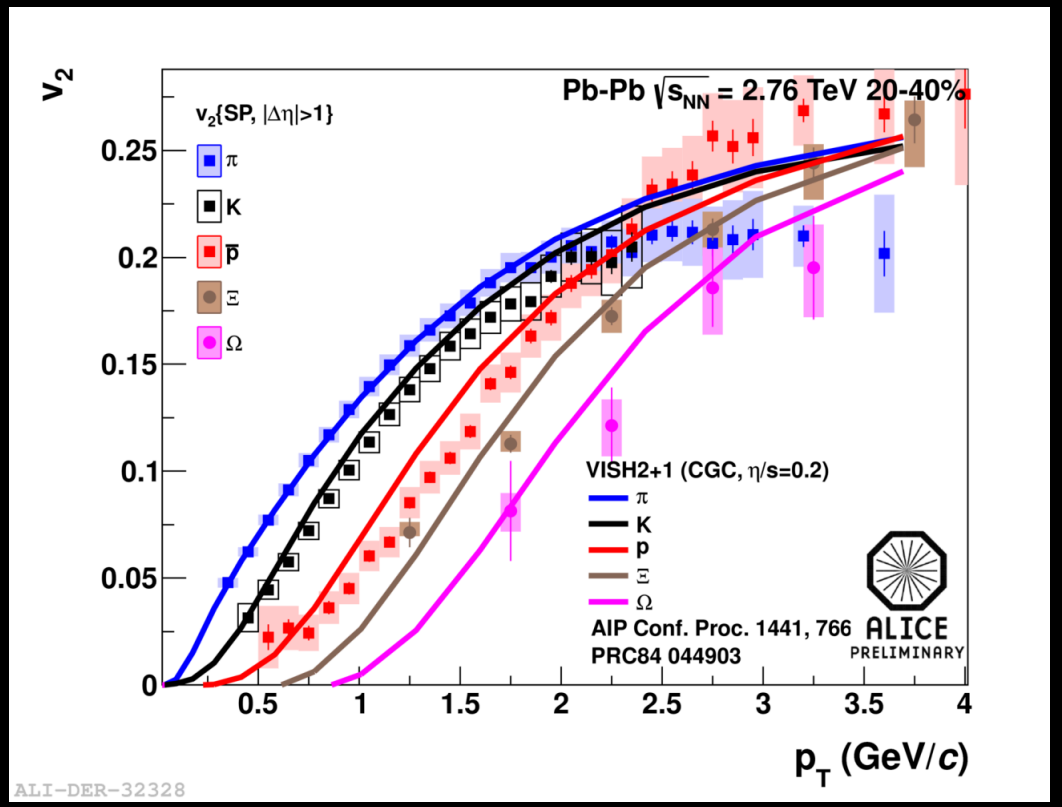


Identified particle v_2 can provide constraints for properties of the sQGP

RHIC 2012: Collective Flow at LHC Energies

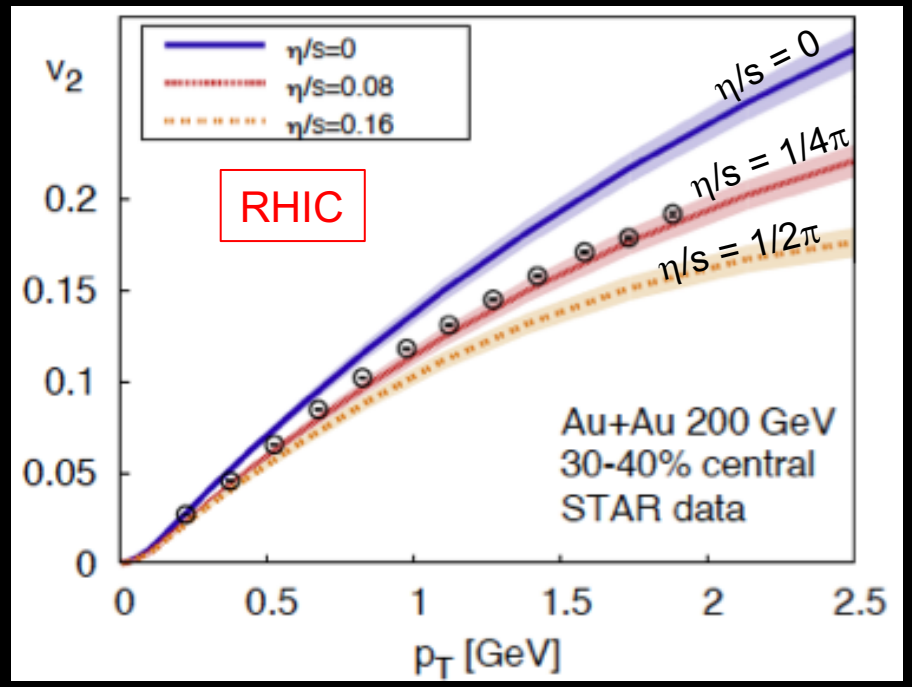
Identified Particle Elliptic Flow in 2.76 TeV Pb+Pb

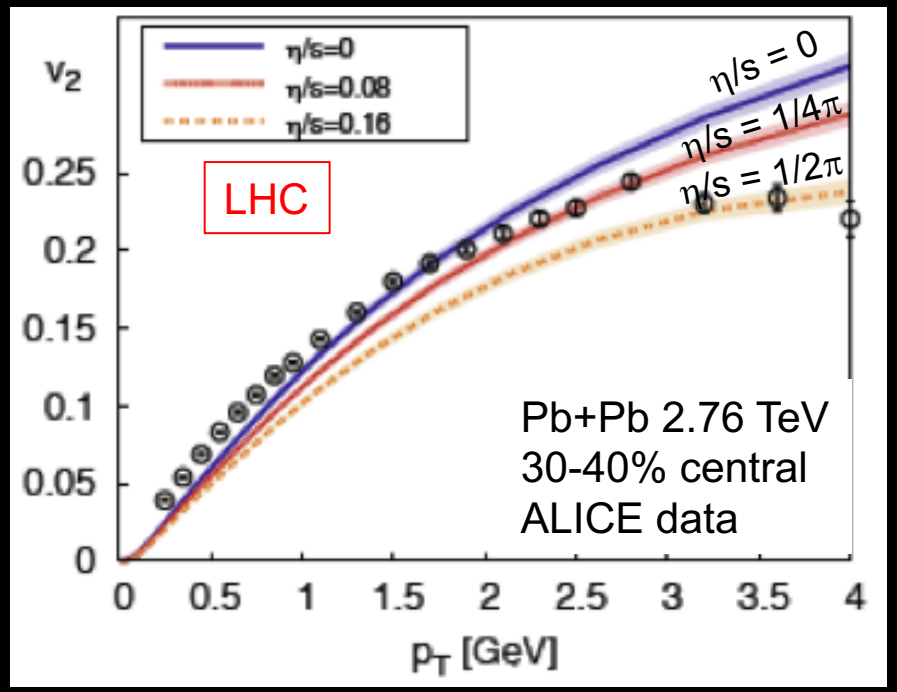




Precise measurements from π to Ω leave little (no) room for ncq scaling at LHC!

RHIC 2012: a Strongly-Coupled Medium with Ultra-low η/s





Viscous hydrodynamics calculations: Schenke, et al. PRL 106 (2011) 042301

$\rightarrow 1/4\pi < \eta/s < 1/2\pi$

Universal lower bound on shear viscosity / entropy ratio (η/s)

$\rightarrow$ $\eta/s = 1/4\pi$ for a "perfect liquid"

from strong-coupling limit of non-Abelian gauge theories with a gravity dual

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

RHIC 2012: Collective Flow Perspective & Summary

Perspective

2000: Ideal Hydro describes elliptic flow

2010: Hydro might also describe other harmonics

2012: starting to investigate and understand all correlations

QM12 Summary

Viscosity of hot QCD still unknown!

Higher harmonics more sensitive to shear viscosity η

but depend on initial conditions!

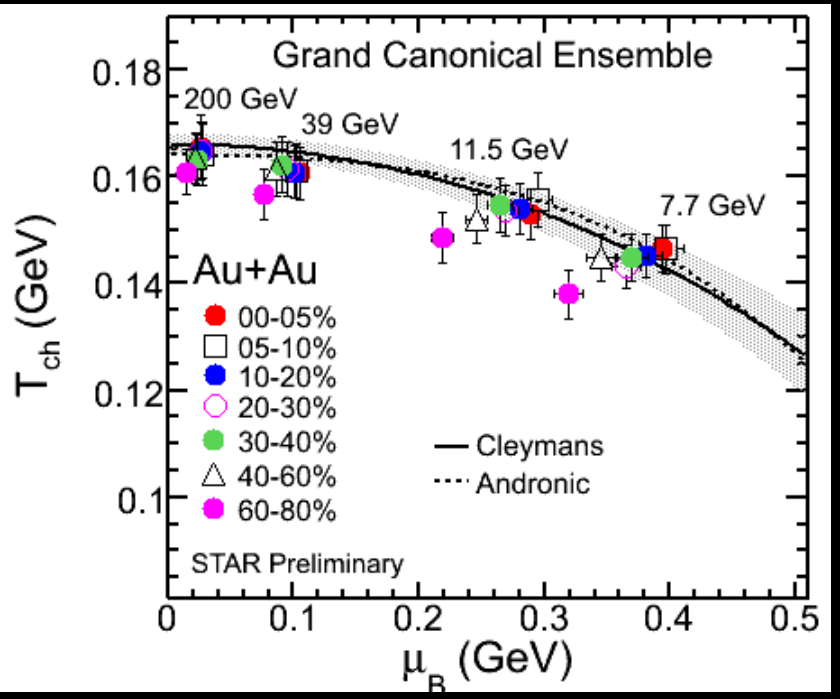
That a model matches data does not mean it has correct η/s

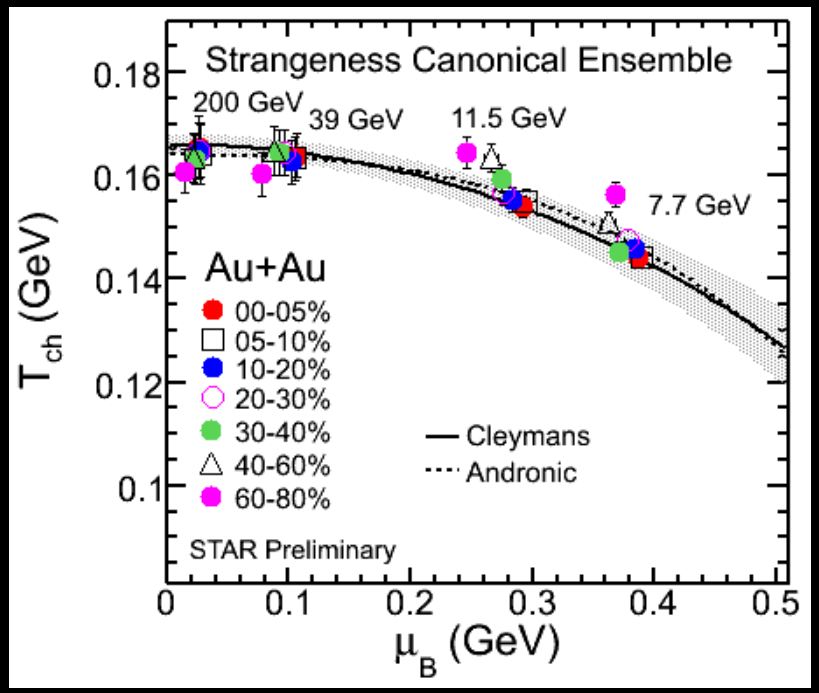
Bulk viscosity?

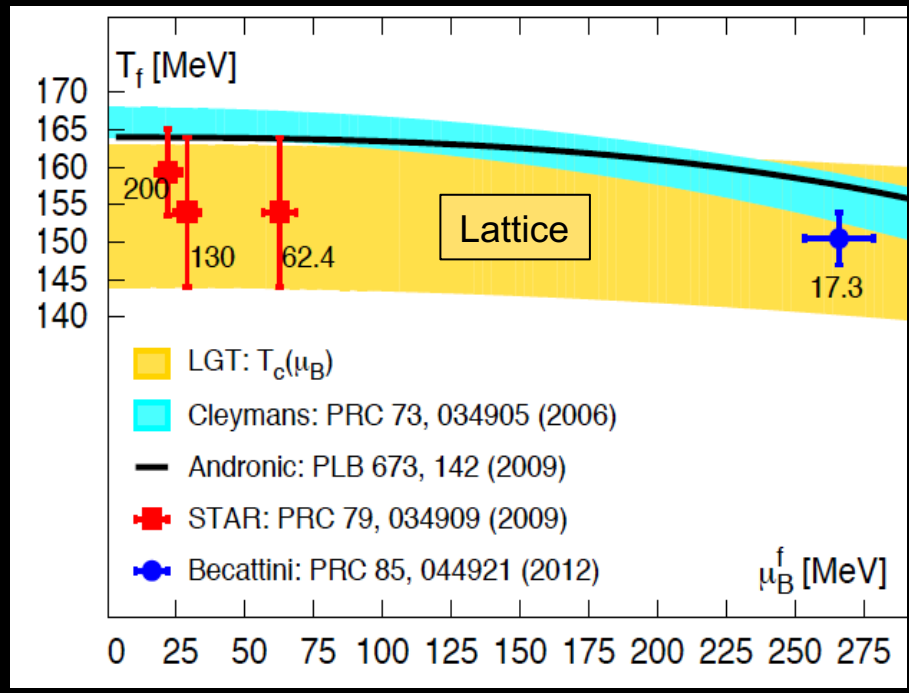
J-Y Ollitraut

RHIC 2012: QCD Phase Diagram

BES





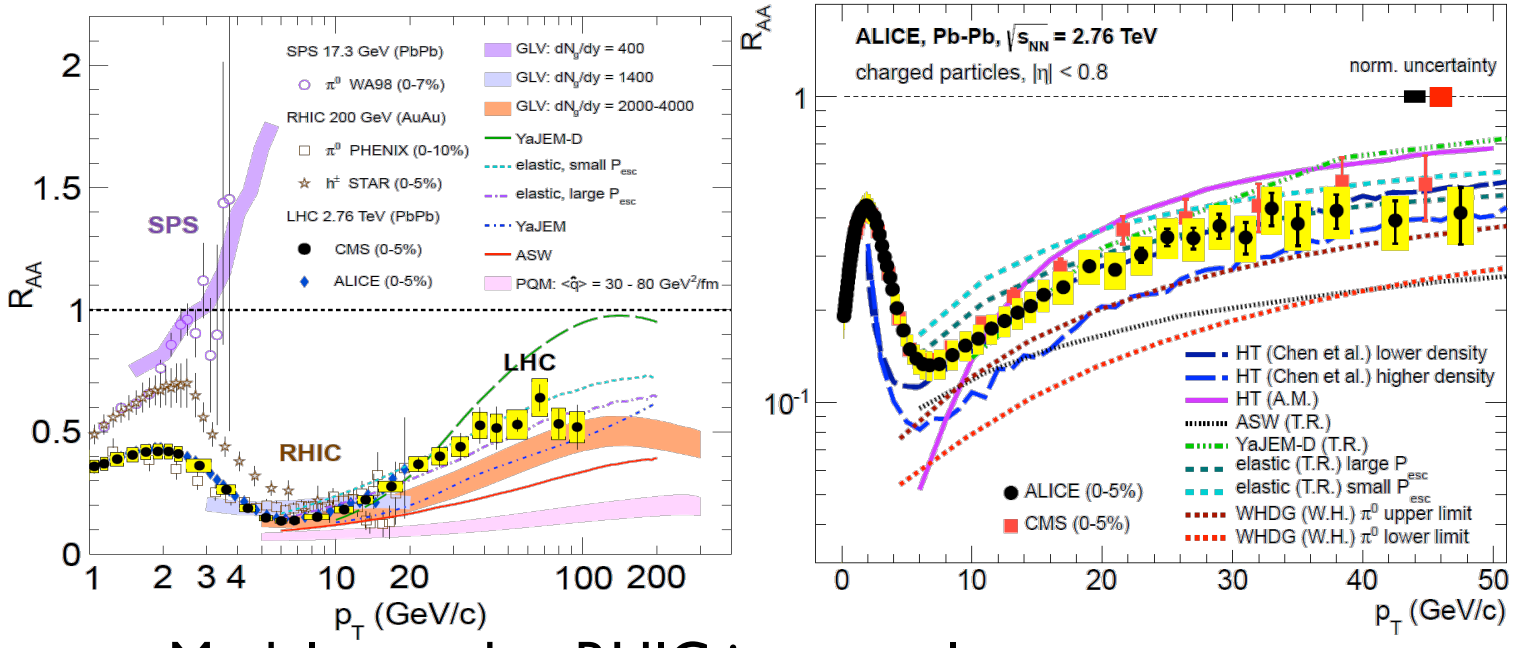


Centrality Dependence of T_{ch} Observed!

Chemical Freeze-out near Cross-over Line

RHIC 2012: R_{AA} & High p_T Suppression

Theory Status QM12



- Models tuned at RHIC in general:
  - Describe qualitatively the trend of the data
  - Fail in the quantitative description
- Can this be fixed with small re-tuning?

or?

- Do we understand the E/L dependence of E-loss?

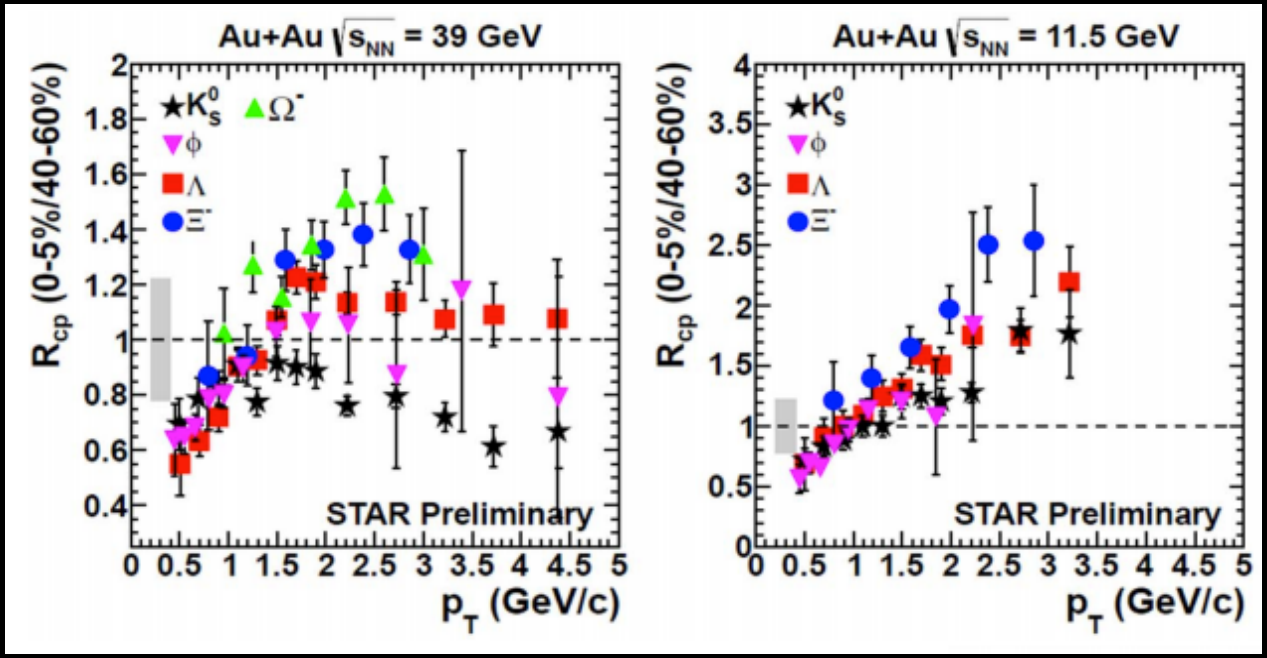
Interaction of jet soft-sector and medium is crucial to understanding jet energy loss!

QM12 Rapporteur Talk –
J Casalderry Solana, S. Milov

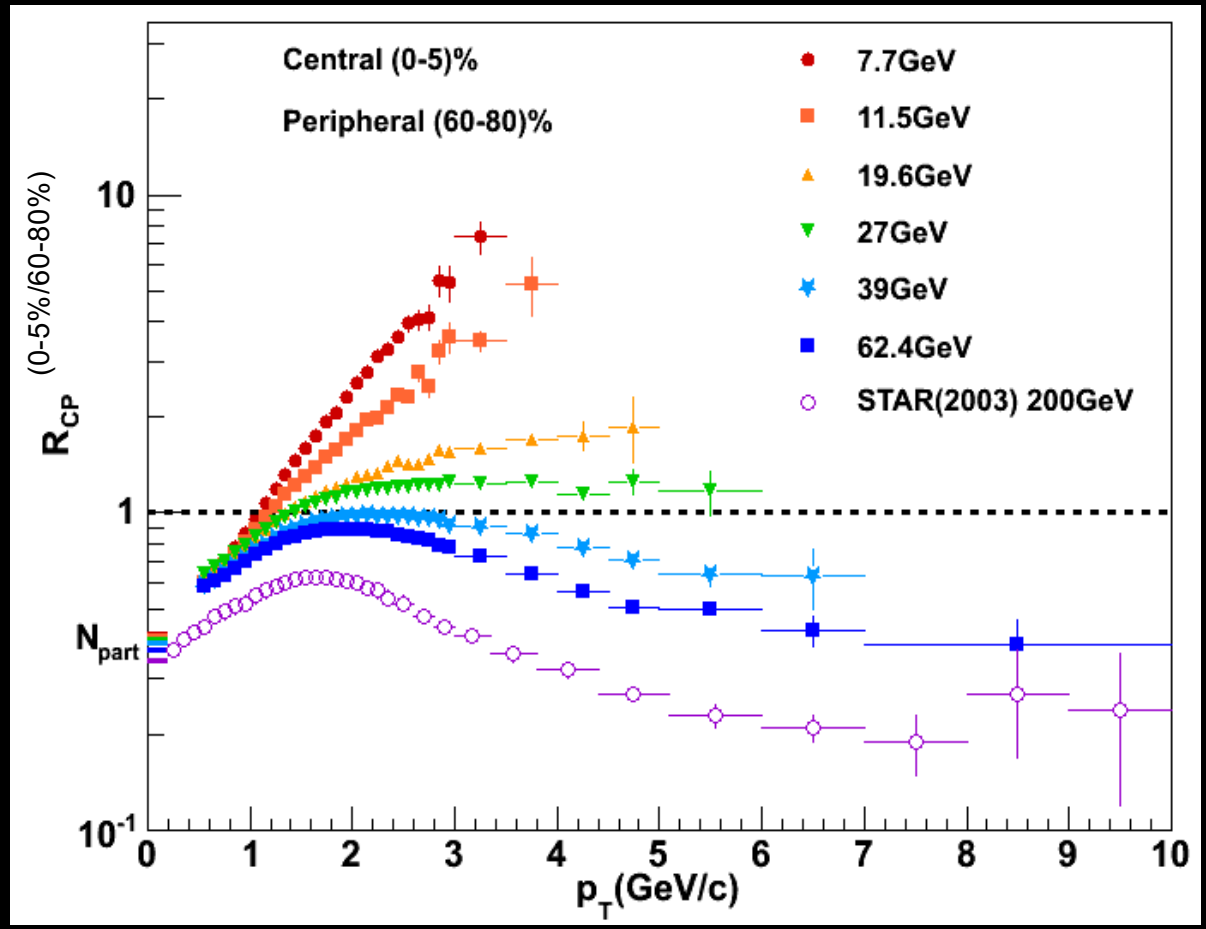
Better understanding of in-medium effects is needed!

RHIC 2012: R_{CP} Suppression to Enhancement

BES



Baryon-meson differences converge at lower √s to an enhancement

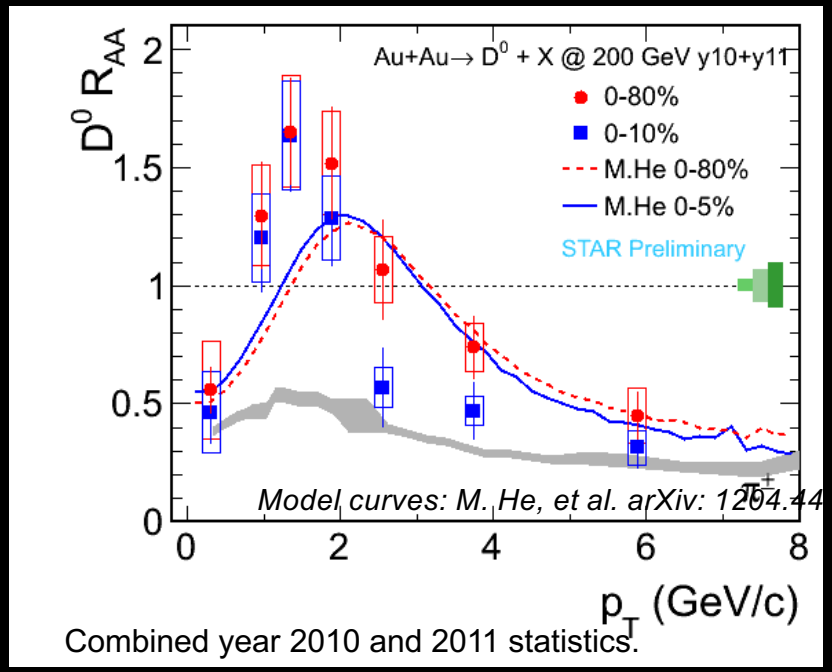


R_{cp} suppression NOT observed at lower energies!

Suppression decreases to where Cronin effect dominates

RHIC 2012: Open Charm & Bottom, Charmonium

Au+Au Open Charm

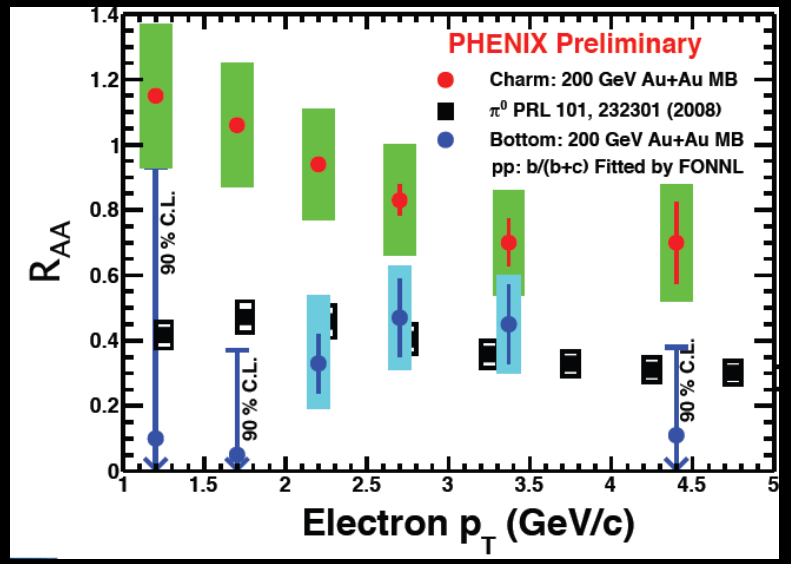


$R_{AA}(D^0)$ suppressed at $p_T > 3$ GeV/c.

$R_{AA}(D^0) \sim R_{AA}(\pi)$ at $p_T > 6$ GeV/c.

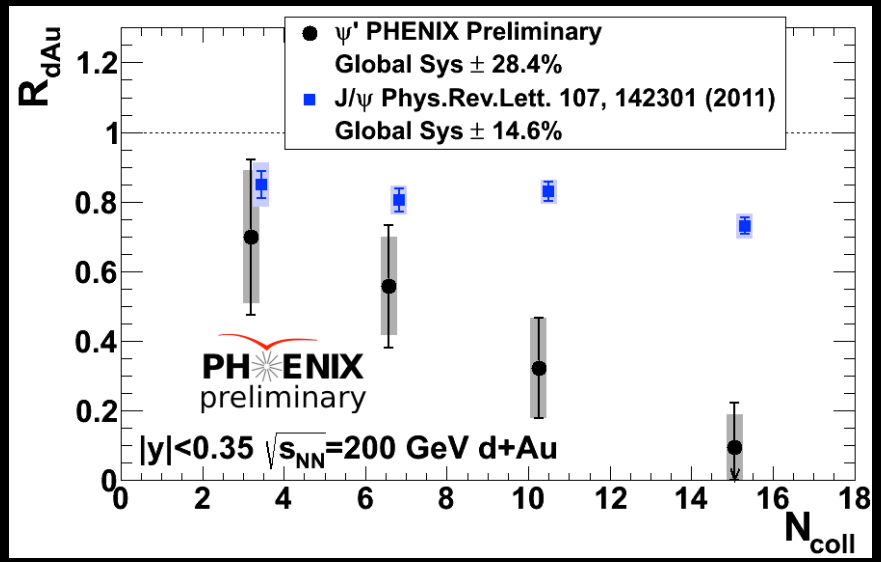
Low p_T $R_{AA}(D^0)$ ~ theory
(enhancement due to flow in calculation)

Au+Au Open Charm & Bottom



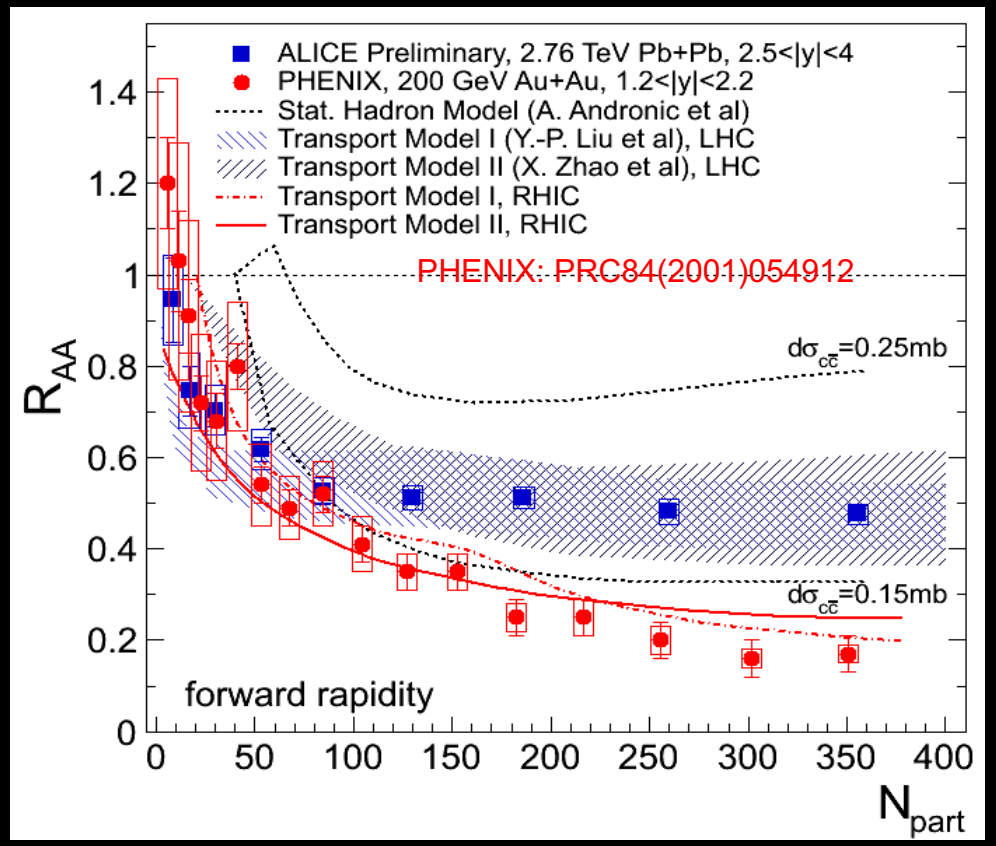
R_{AA}(Bottom) suppressed

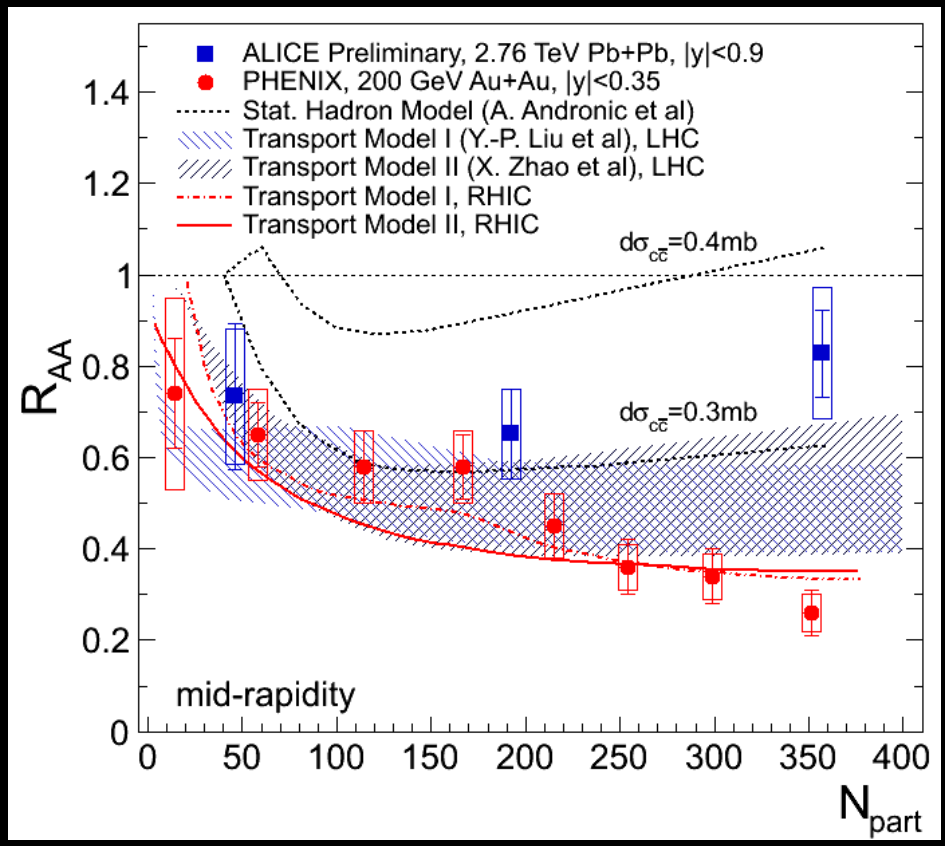
d+Au J/ψ and ψ'



ψ' < J/ψ
(factor 5 at highest multiplicity)

RHIC 2012: N_{part} dependence of J/ψ R_{AA}



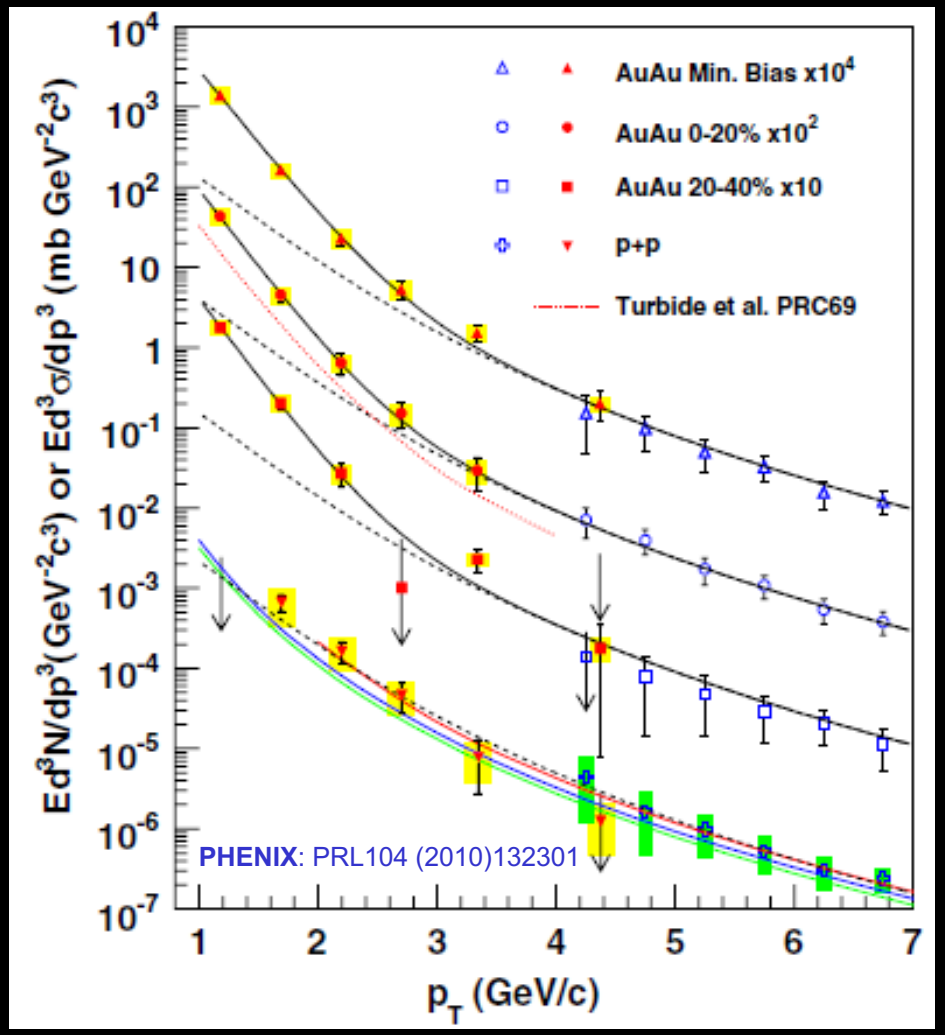


Less suppression at LHC compared to RHIC in central collisions!

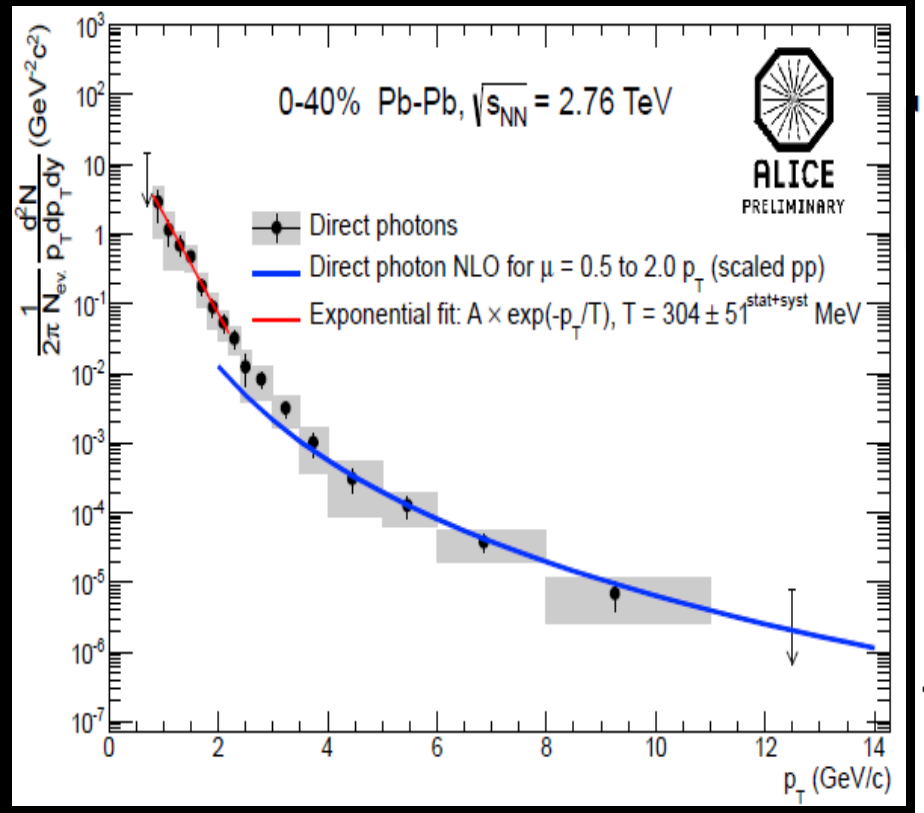
Interplay between CNM, color screening and charm recombination

More significant contribution from charm recombination at LHC energies(?...!)

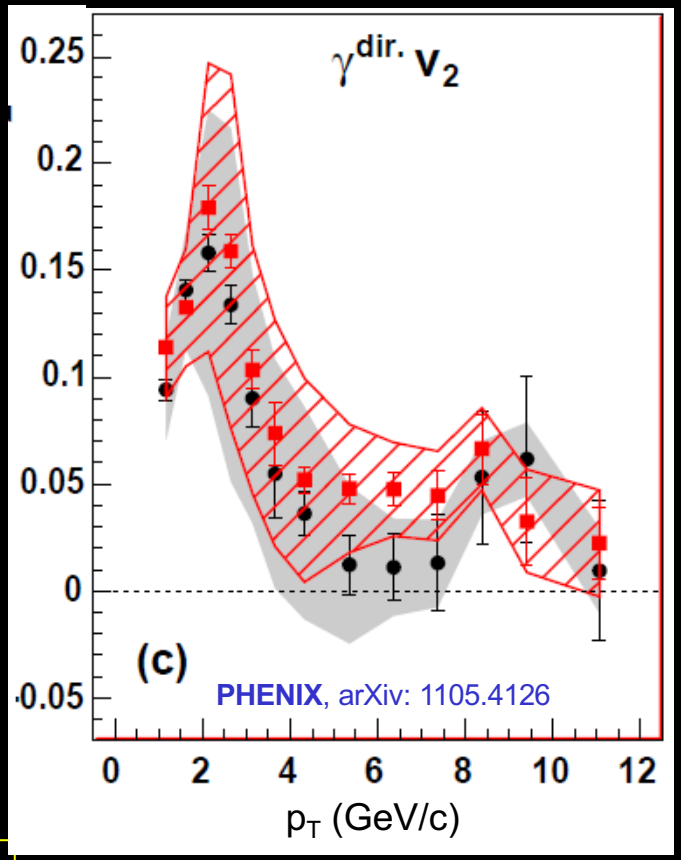
RHIC 2012: Electromagnetic Probes – γ



Excess of direct photons in 0-20% Au+Au
RHIC: T_{eff}=221 ± 19 ± 19 MeV



Excess of direct photons in 0-40% Pb+Pb
LHC: T_{eff}=304 ± 51 MeV



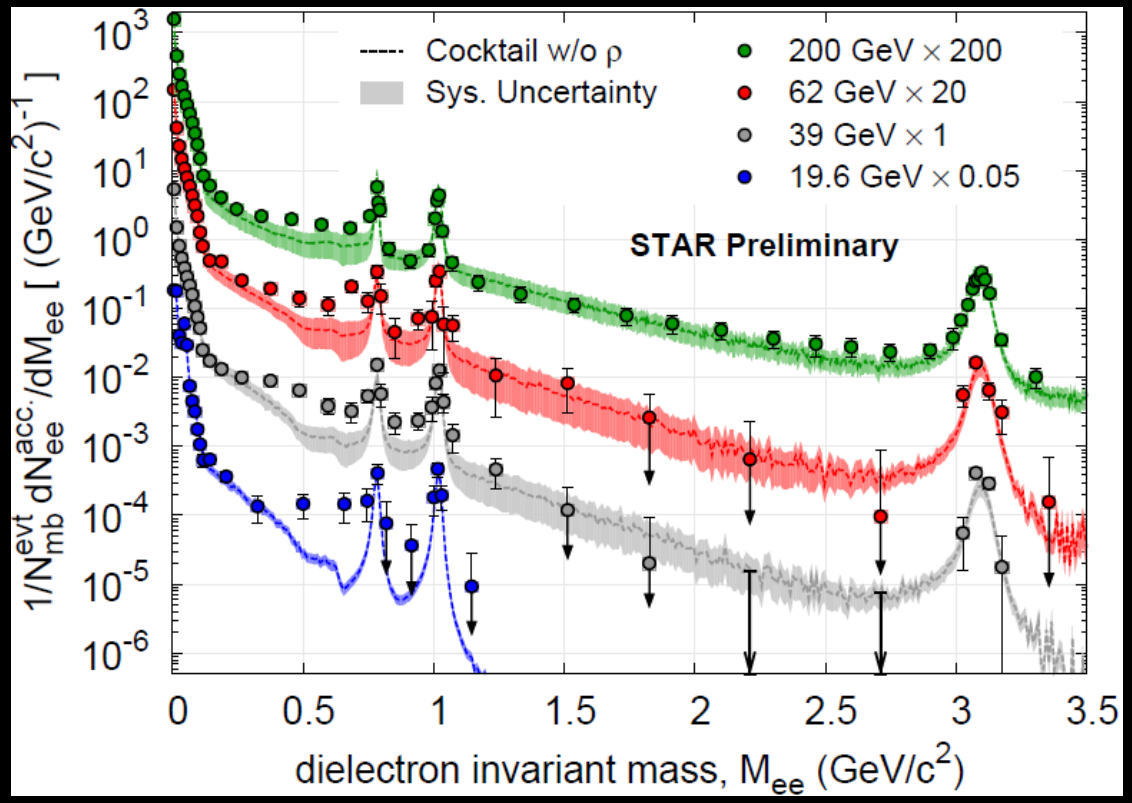
Photon v_2 observed
p_T < 4 GeV/c

Probe the properties of the medium from QGP to hadron-gas

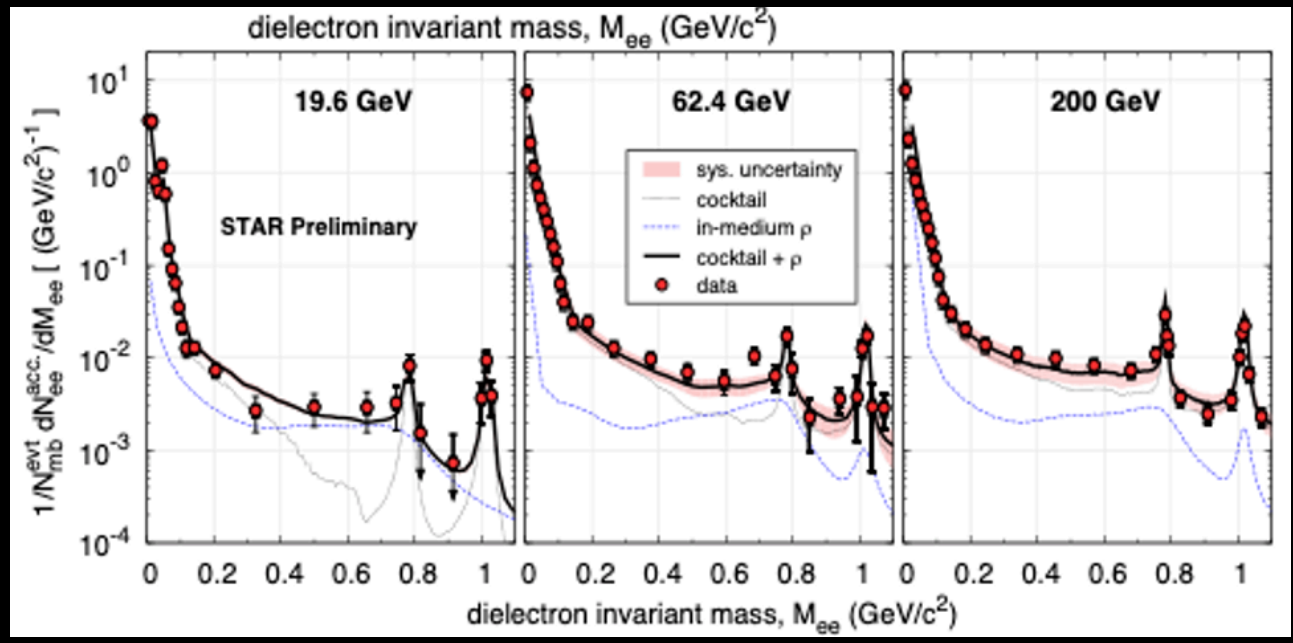
R. Chatterjee, D. K. Srivastava, U. Heinz, C. Gale, PRC75(2007)054909

BES

RHIC 2012: Dielectrons

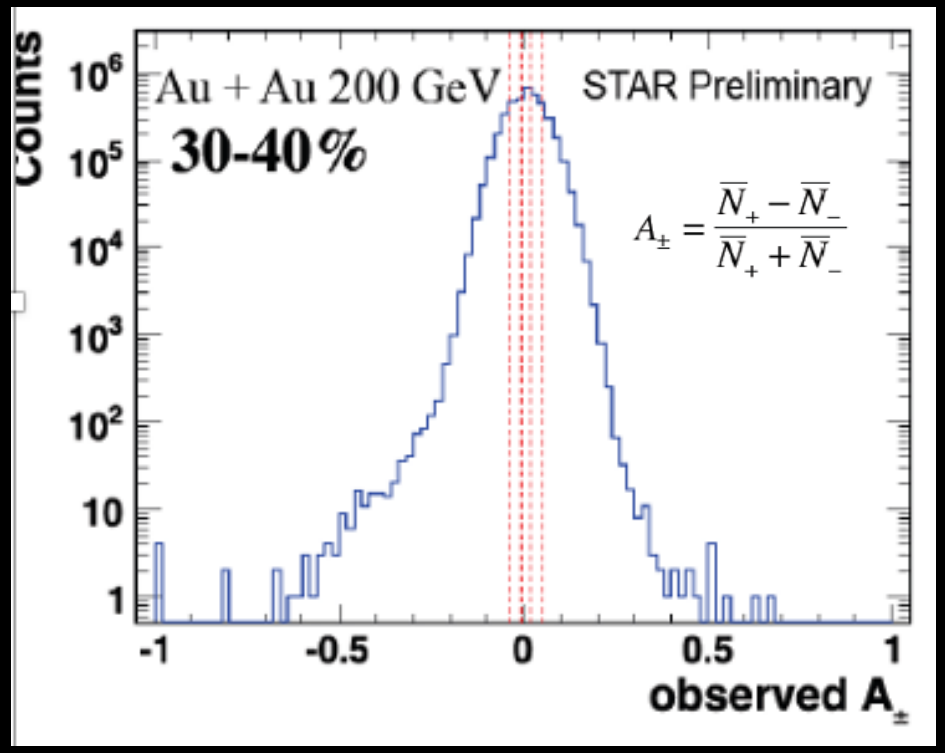


Low Mass Enhancement from RHIC to SPS energy

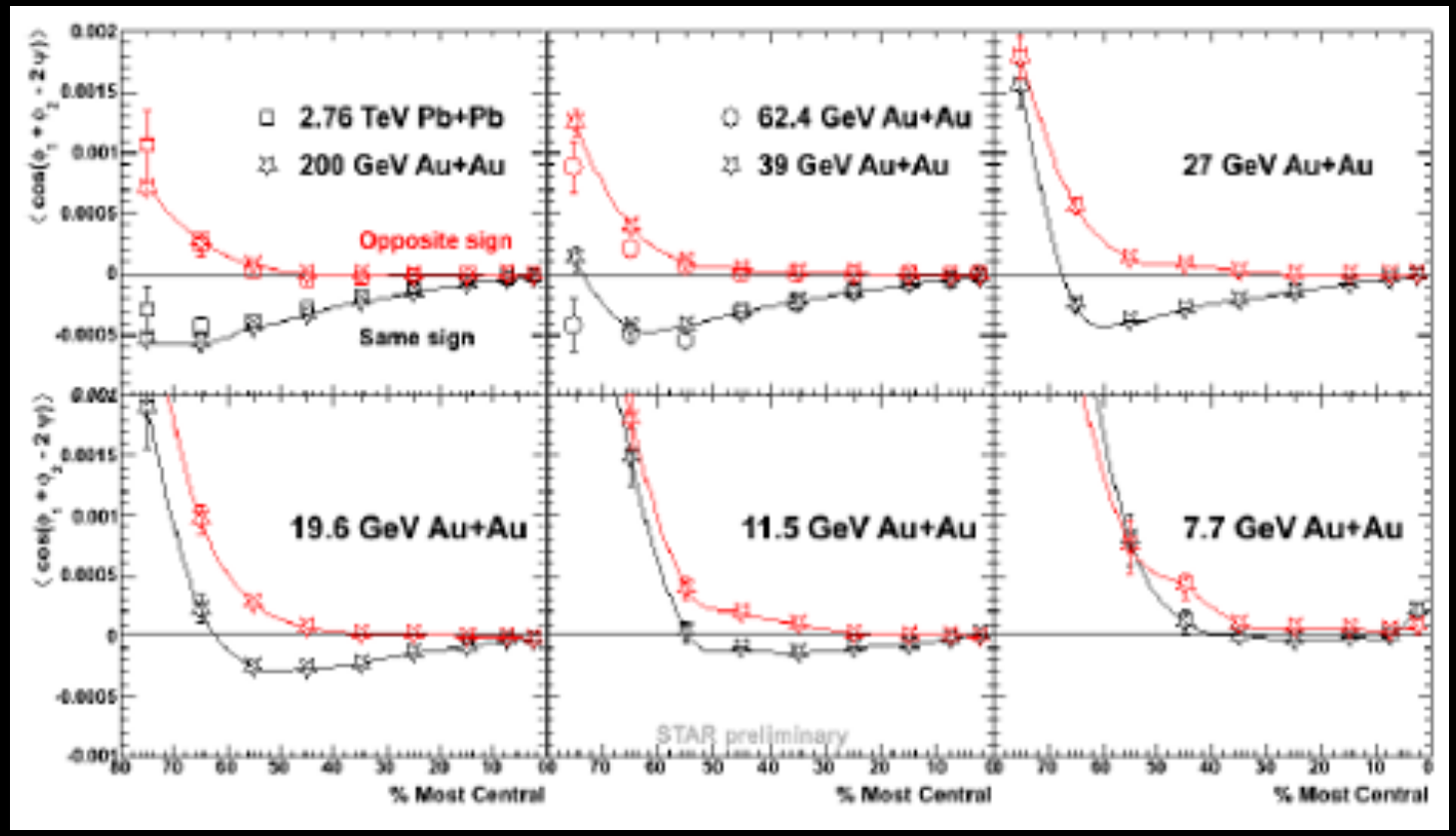


In-medium ρ broadening – R. Rapp et al
Spectral function from measurements consistently broadens.

RHIC 2012: Unexpected Charge Correlations



Events with Charge Asymmetry Exist



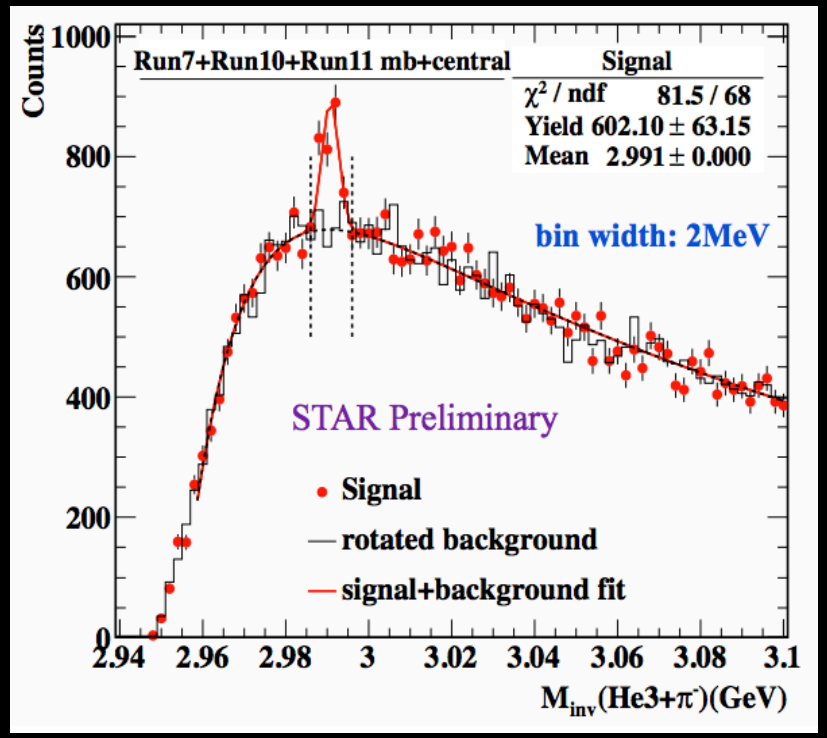
Similarities at LHC and RHIC
Differences at Different RHIC Energies

Chiral Magnetic Effect?

Models with local charge conservation may describe data!

RHIC 2012: Exotic Nuclei

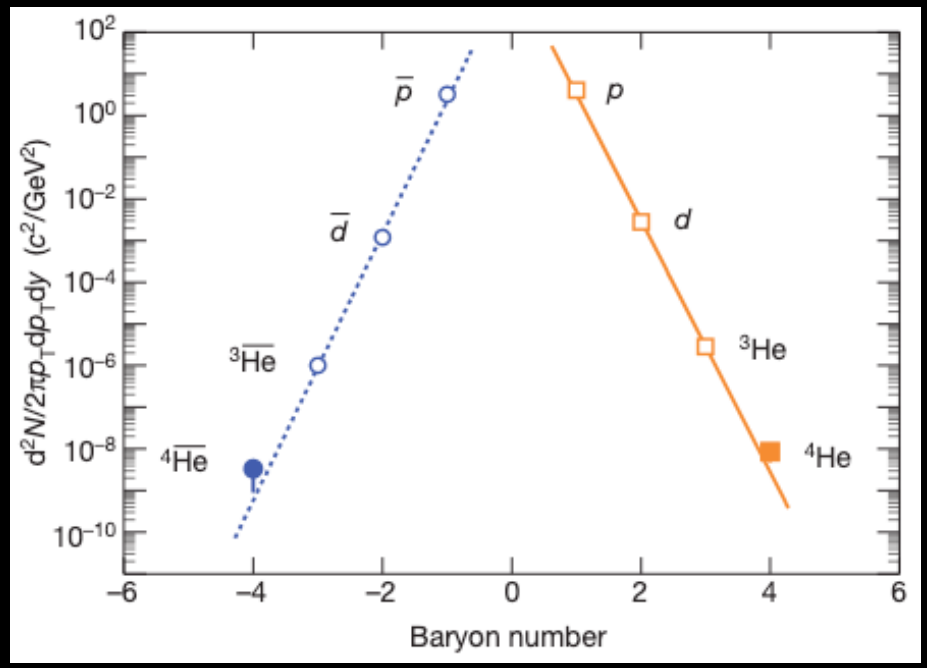
Hyper-triton observed



STAR Coll., Science 328 (2010) 58

$^{3}_{\Lambda}\mathrm{H}+^{3}_{\Lambda}\overline{\mathrm{H}}$ produced: 602 ± 63 significance: 9.6σ

1st Observation of anti-matter He^4



STAR Coll., Nature 473 (2011) 353

Consistent with coalescence & thermal models

RHIC HI Physics – QM 2012

"We are rapidly entering an era of detailed investigation of the properties of dense QCD matter"

Yesterday's Discovery → Baseline for tomorrow's investigation and understanding

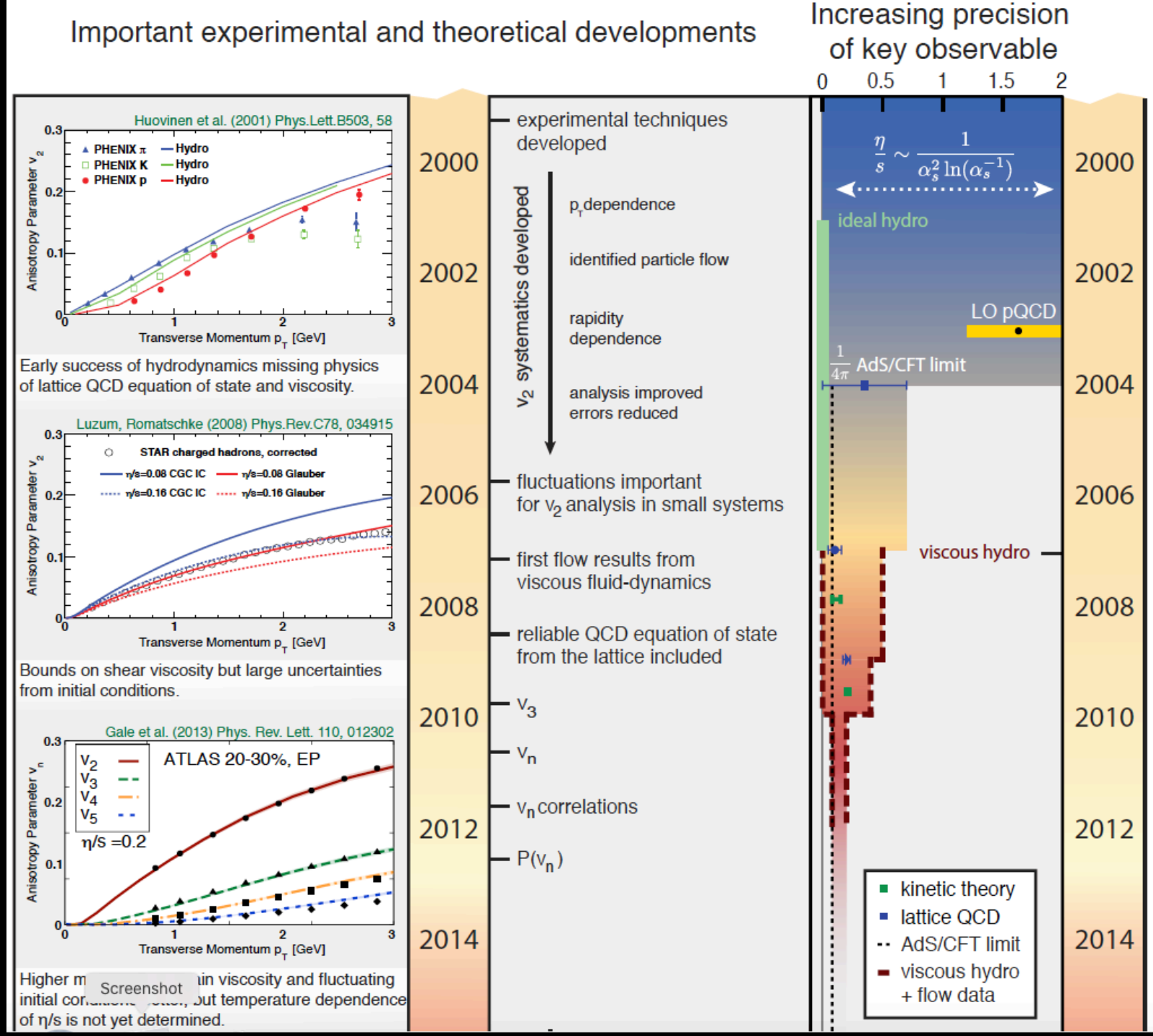
* Quoted at QM 2012

Adolescence (2013 – 2020)

(new discoveries & new approaches … an evolution)

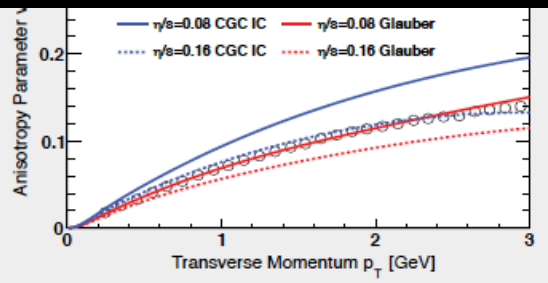
RHIC HI Physics (2000 – 2013)

According to:
C. Gale, S. Jeon, B. Schenke
Int. J. of Mod. Phys. A, Vol. 28, 1340011 (2013)

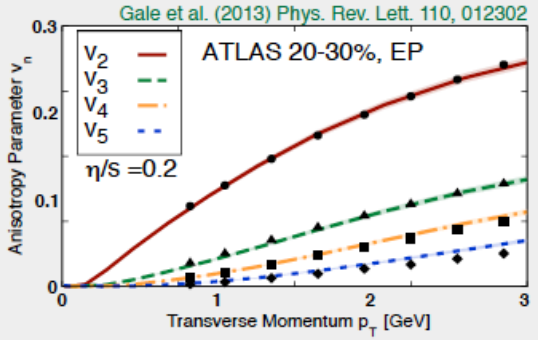


RHIC HI Physics (2013 – 2022)

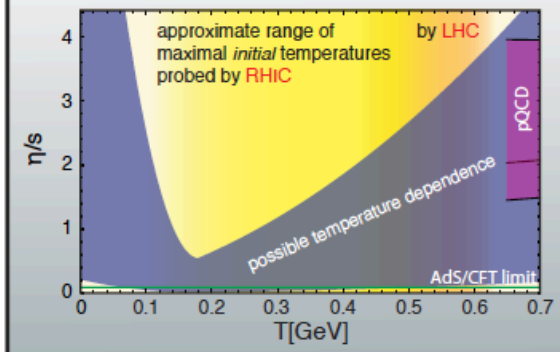
According to:
C. Gale, S. Jeon, B. Schenke
Int. J. of Mod. Phys. A, Vol. 28, 1340011 (2013)



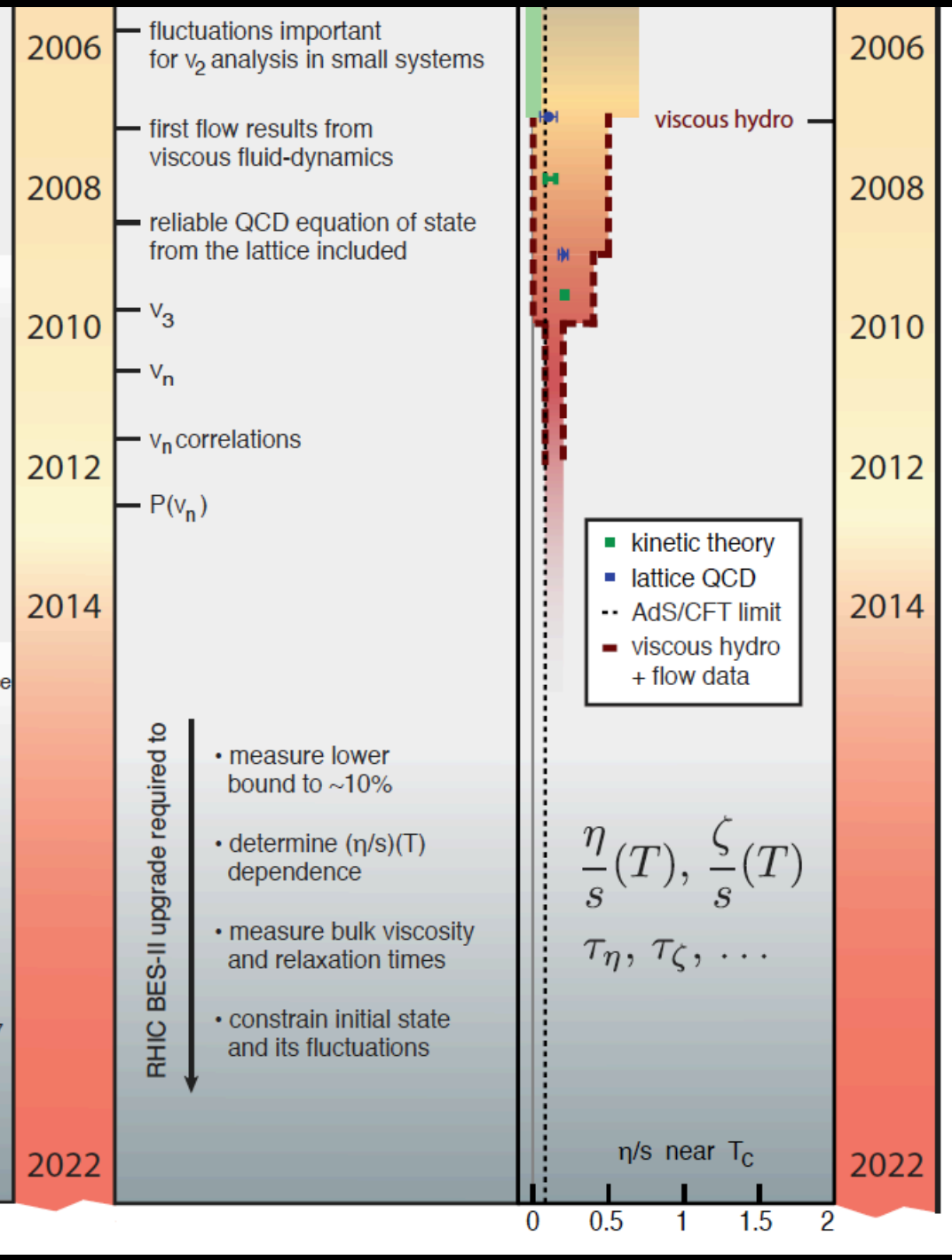
Bounds on shear viscosity but large uncertainties from initial conditions.



Higher moments constrain viscosity and fluctuating initial conditions better, but temperature dependence of η/s is not yet determined.



To determine (η/s)(T) different initial temperatures need to be accessible. Only possible with combined data from LHC and RHIC beam energy scan.



RHIC HI Physics and Developments 2013 – 2020

- CERN LHC Heavy Ions had started in 2010
- RHIC Beam-Energy Scan I was completed in 2011
- STAR installing Muon Telescope Detector (MTD) 2012 – 2014

PHENIX completed data-taking in 2016

- RHIC Beam-Energy Scan II (2017 – 2020) including fixed-target
  STAR Upgrades (iTPC, EPD, eTOF)

- Notable events between 2005 – 2010
  PHOBOS & BRAHMS completed data-taking in 2006

  STAR installs TOF (RPC) detector in 2009

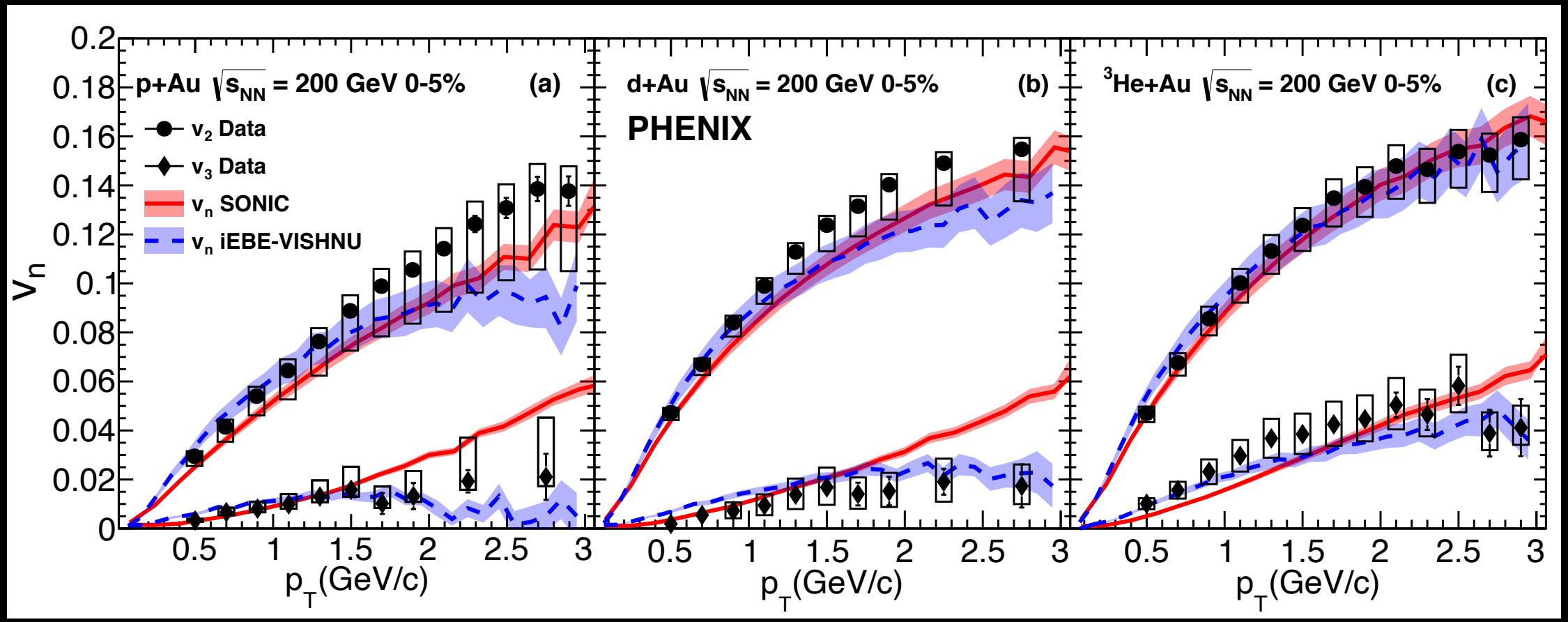
(Must) Fast Forward → RHIC Physics Now

→ Just A Few Selected "New" Topics & Results ←

Small Systems Scan at RHIC

Some Model Comparisons

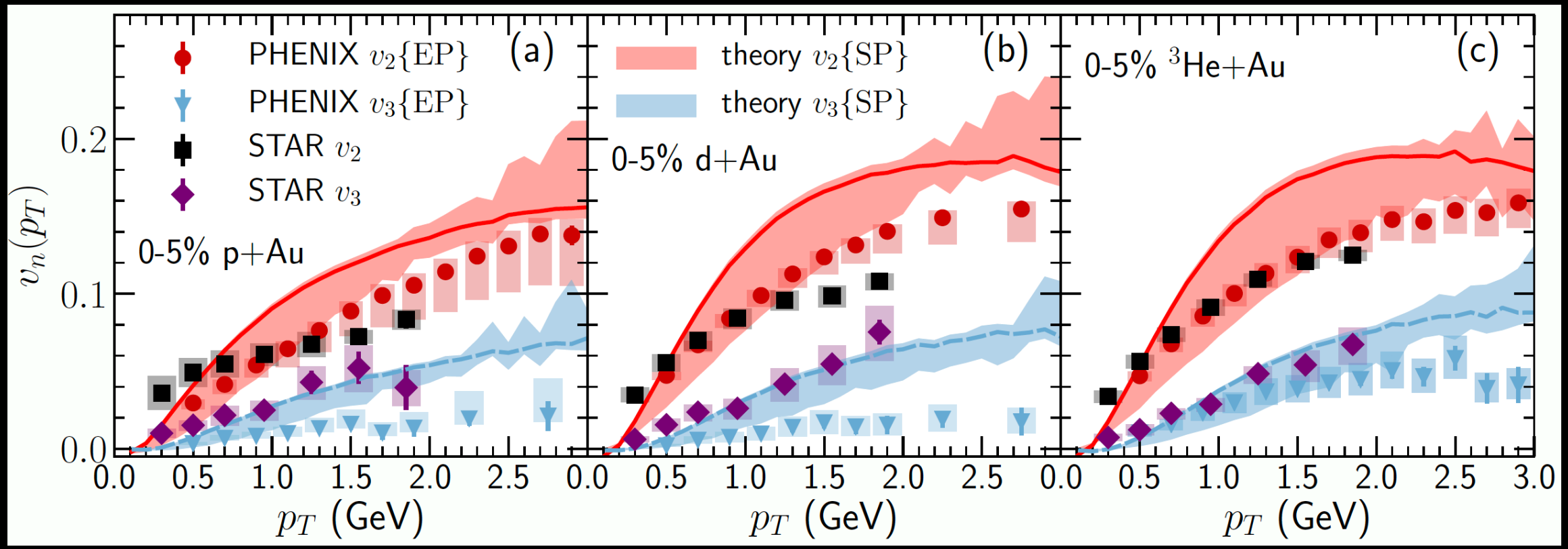
PHENIX, Nature Physics 15 (2019) 214-220



"Hydrodynamical models, which include the formation of a short-lived QGP droplet, provide a simultaneous description of these measurements."

Small Systems Scan at RHIC

B. Schenke, C. Shen, P. Tribedy, arXiv: 1908.06212

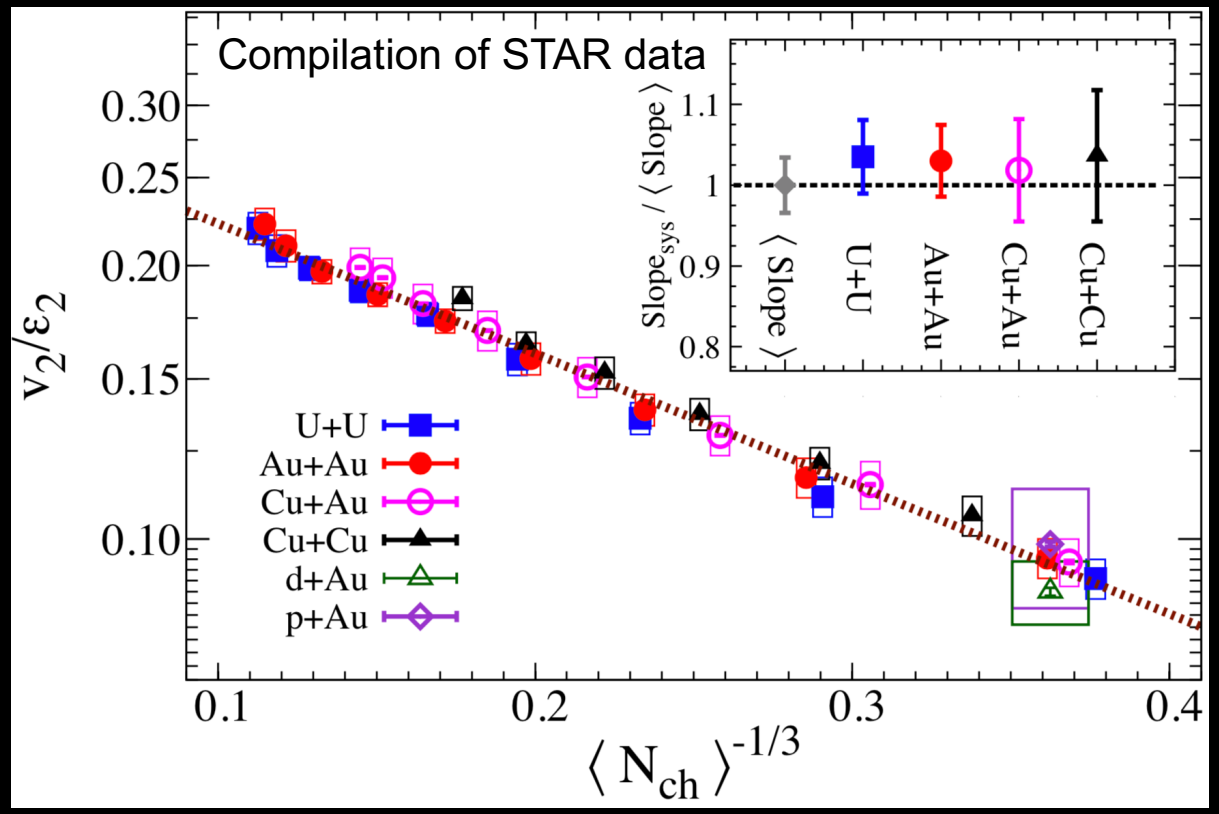


STAR measurements of v_3 ~ system independent
Need to understand the large difference in v_3 measurements!

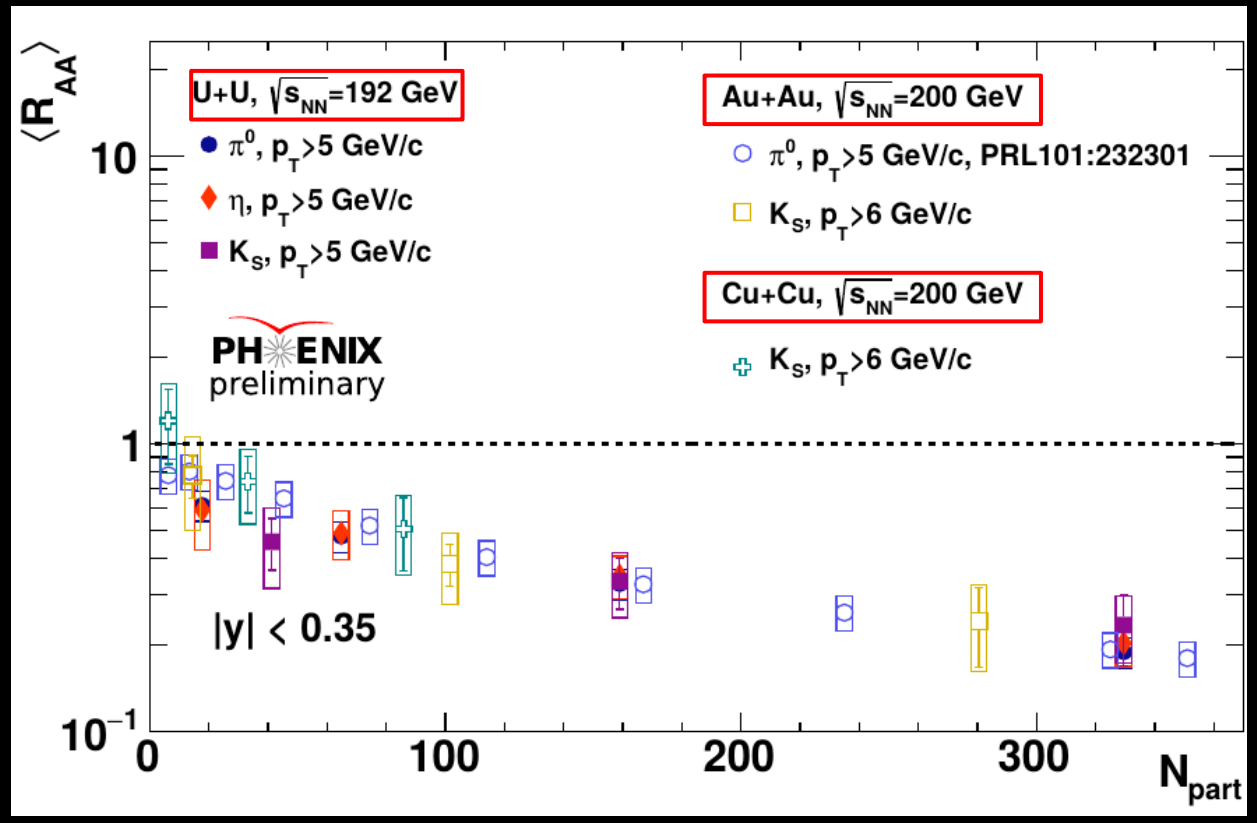
B. Schenke, C. Shen, P. Tribedy, arXiv: 1908.06212
"Initial state momentum anisotropy and final state response are necessary to describe the data."

Universal Scaling with Size?

Does Size really matter on the overall scale of things?

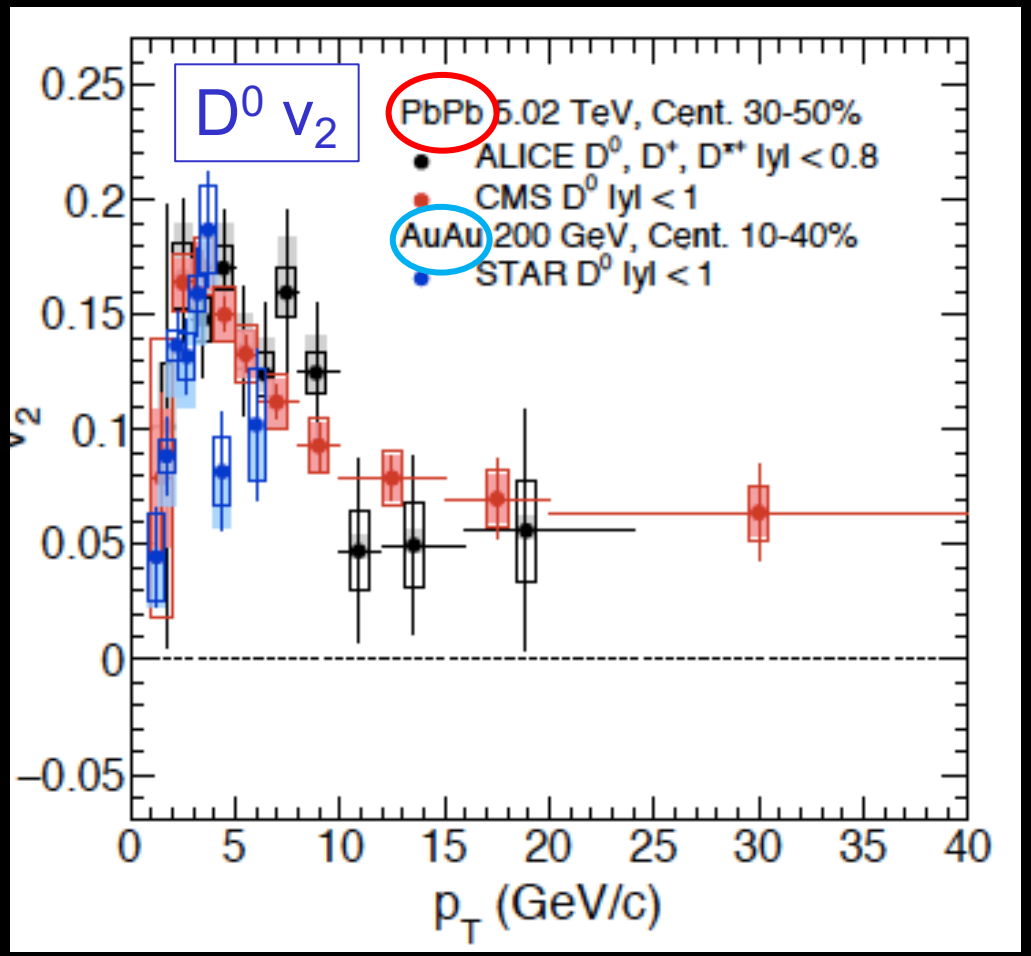


Multiplicity matters!

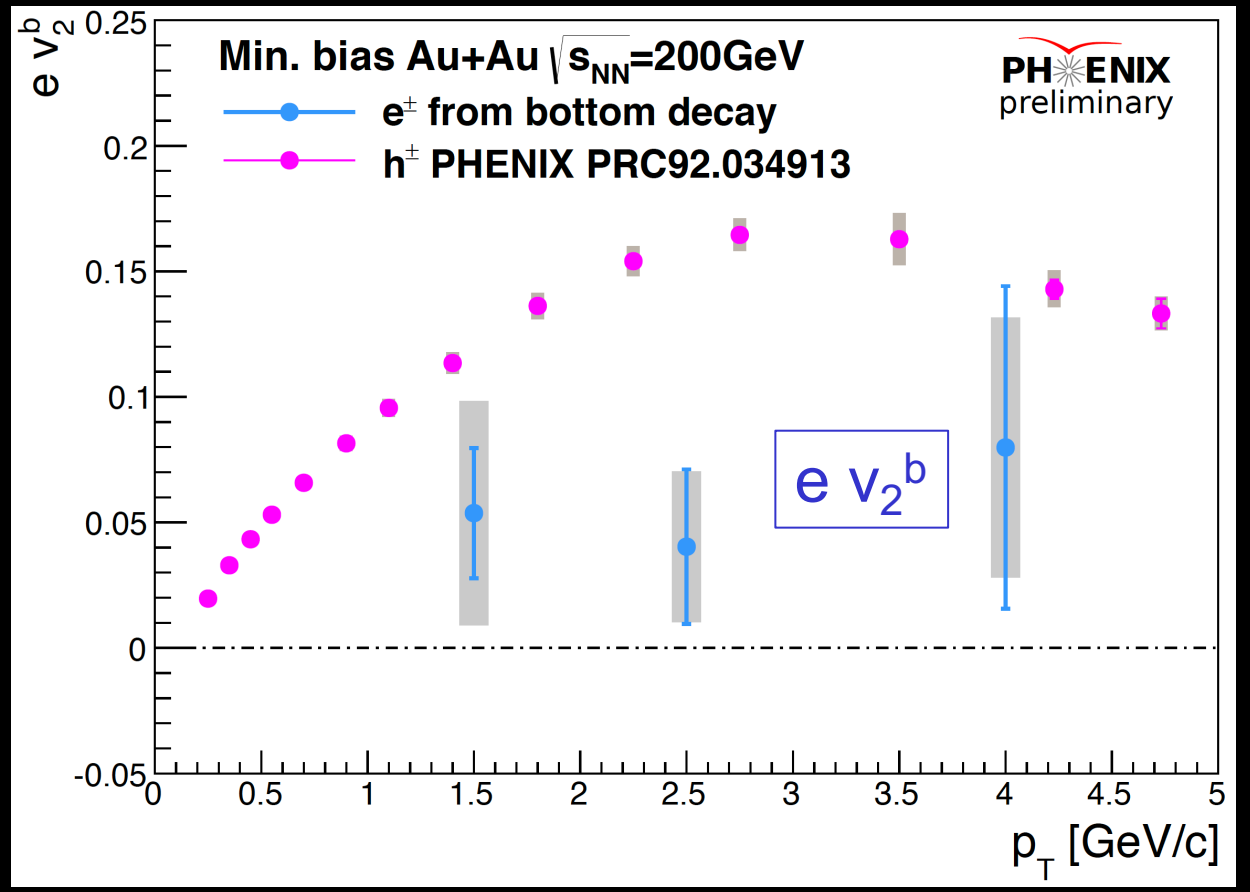


RHIC central R_{AA} depends on N_{part} not system

Open Heavy Flavor Flow at RHIC



D^0 results consistent over energy & experiments



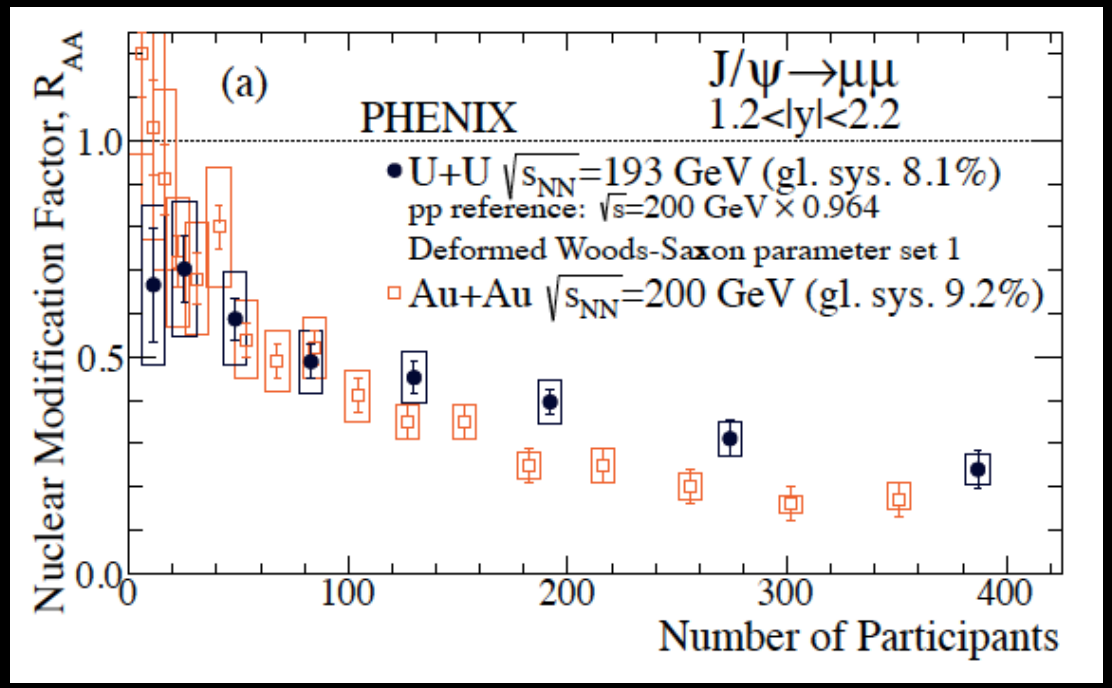
Heavy quark b->e flows
(~ALICE, ATLAS, STAR observations)

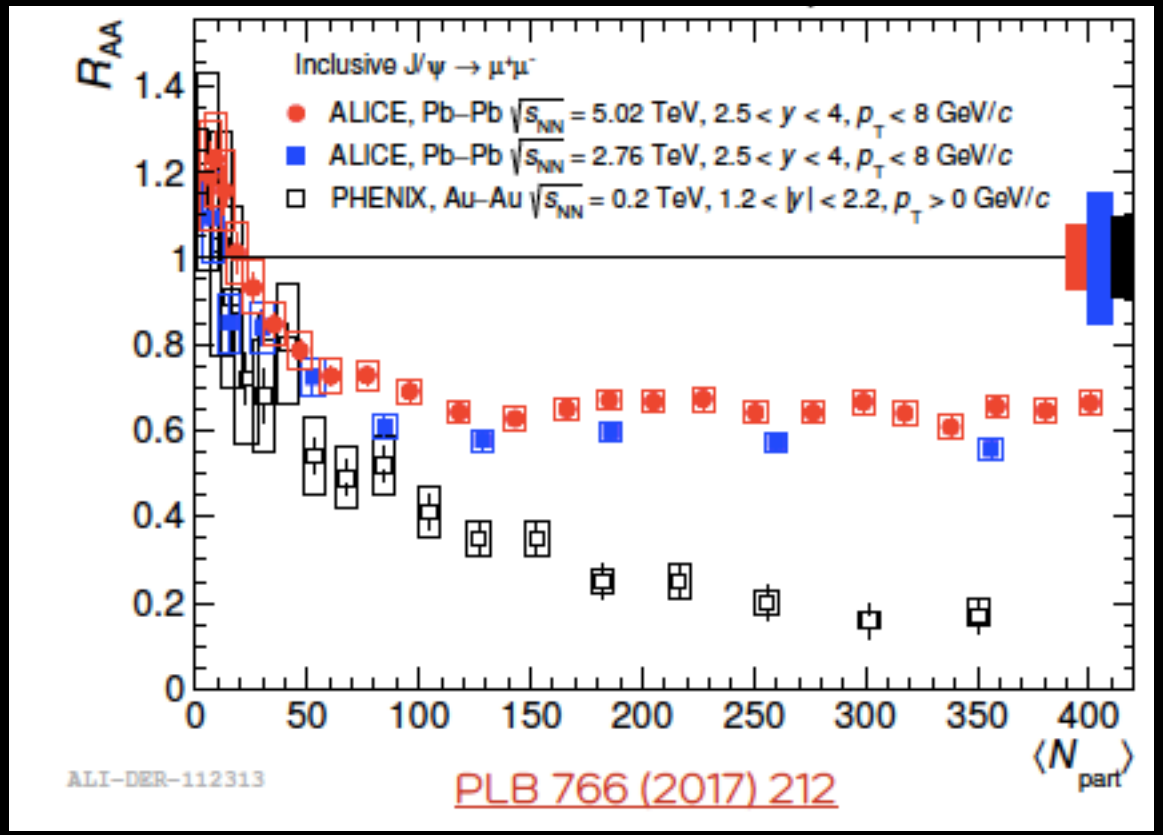
Flow of charm > flow of beauty

New data at QM19 on B flow at RHIC!

J/ψ Results: Comparison RHIC and LHC

PHENIX, Phys. Rev. C 93, 034903 (2016)

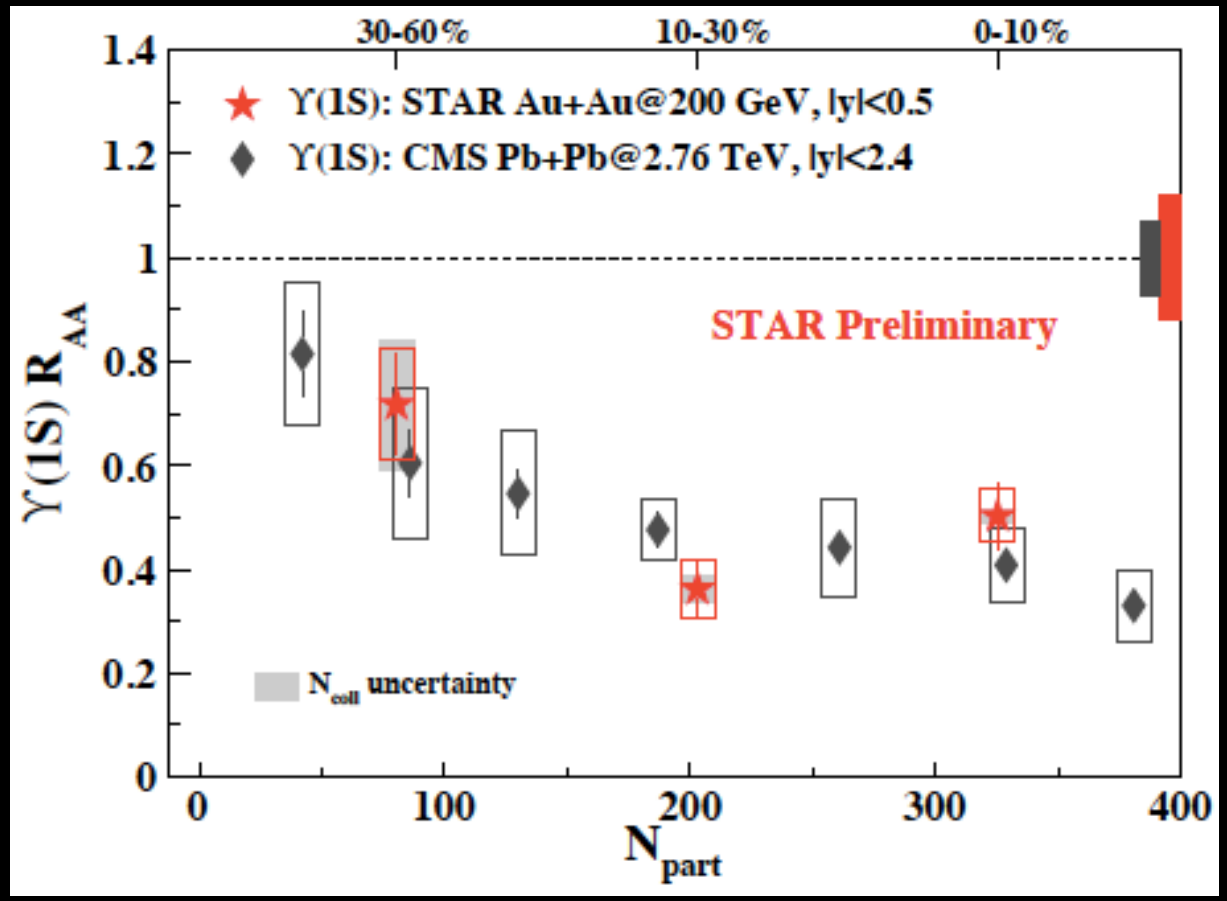


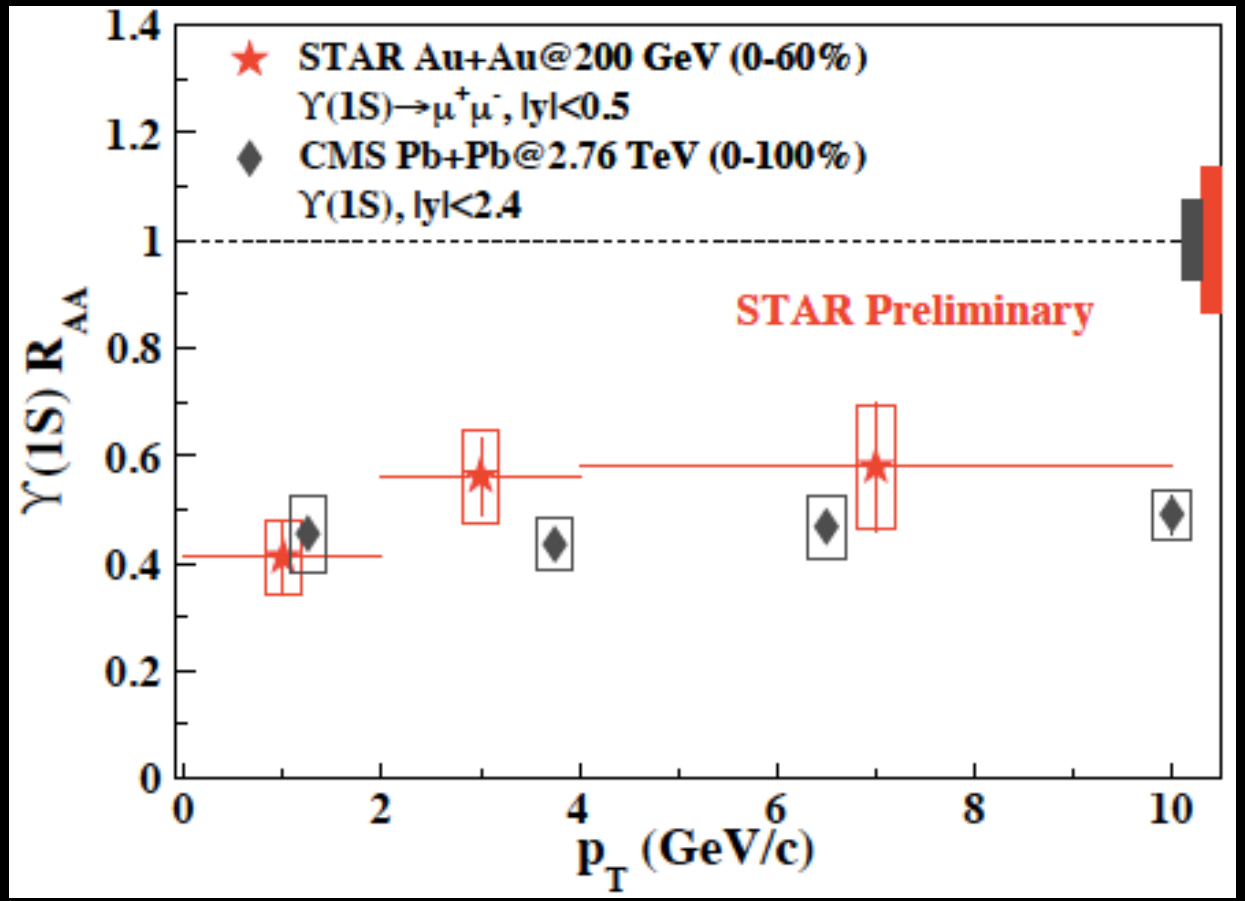


Forward results: Suppression stronger at RHIC

Υ(1S) Comparison RHIC and LHC

CMS, PLB 770 (2017) 357.
STAR preliminary (RHIC Users Mtg 2019)

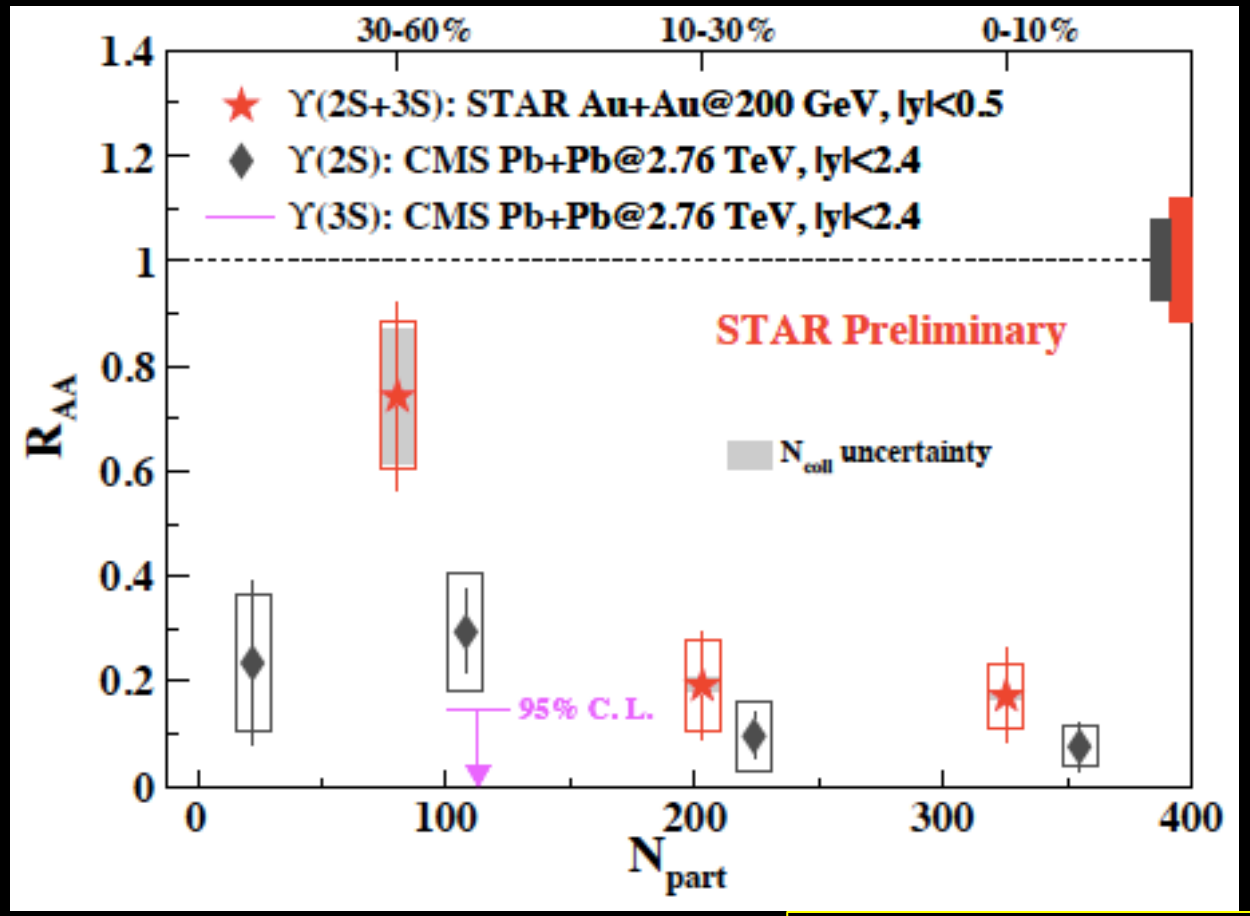


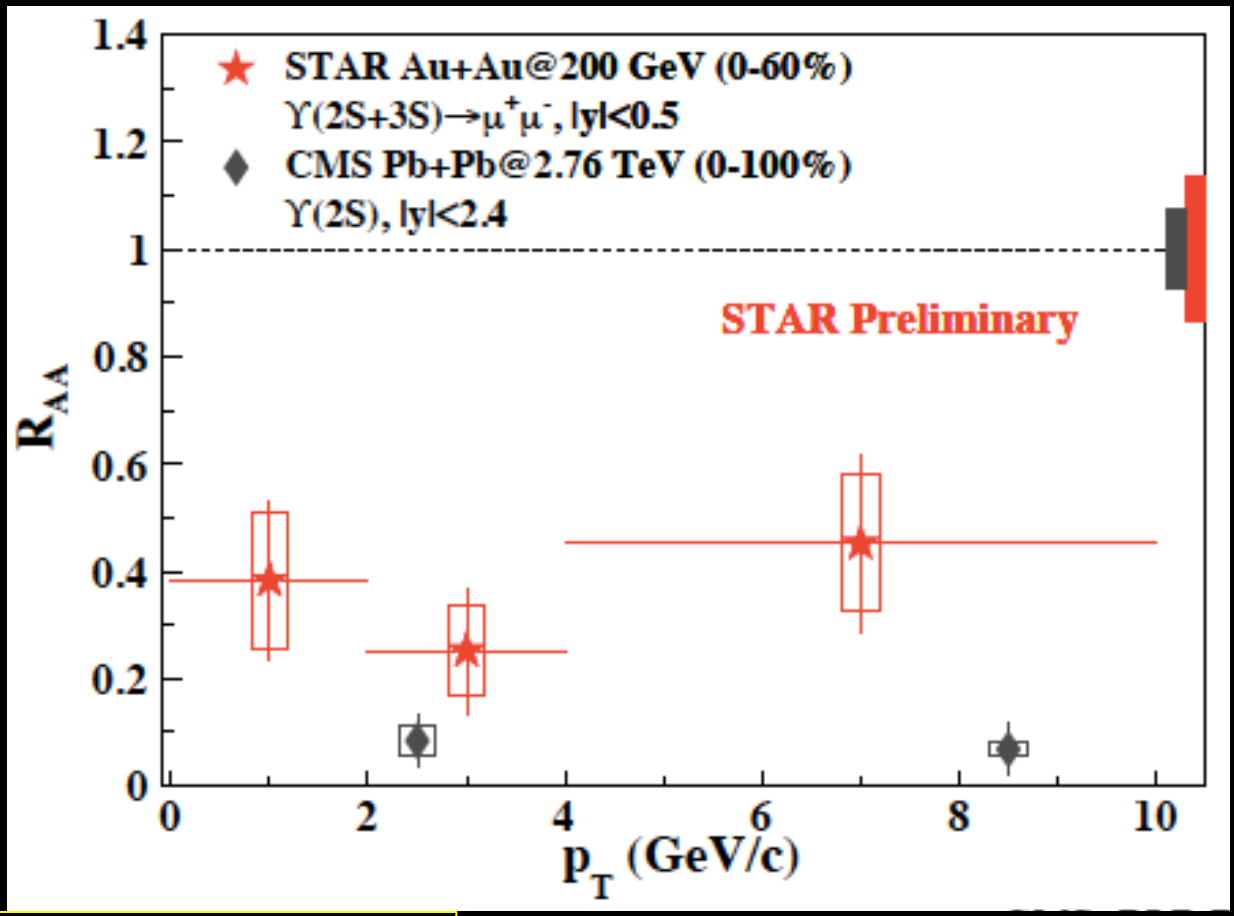


Υ(1S) suppression similar for RHIC and LHC

Υ(2S) and Υ(3S) Comparison RHIC and LHC

CMS, PLB 770 (2017) 357.
STAR preliminary (RHIC Users Mtg 2019)

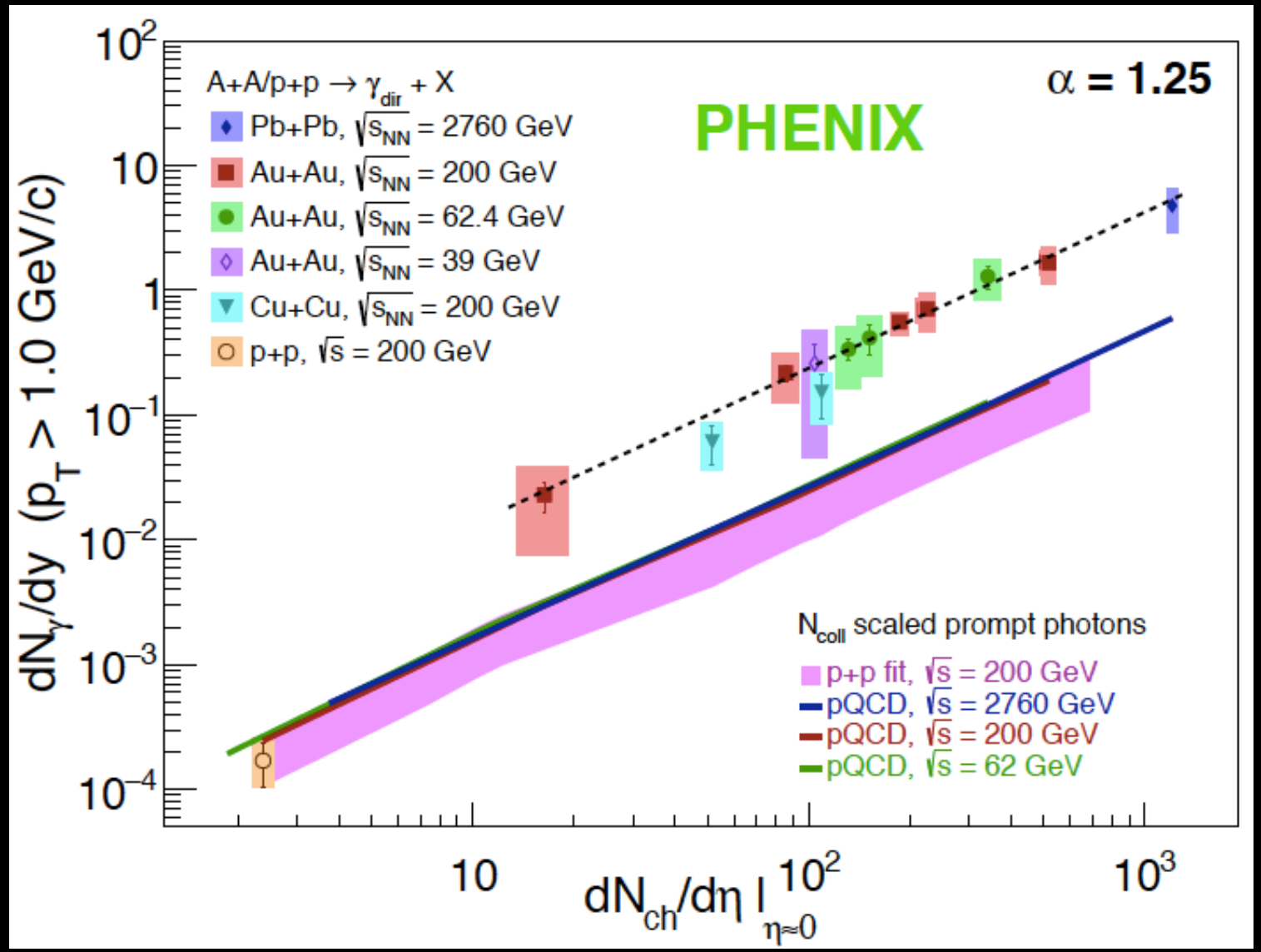




Υ(2S) and Υ(3S) strongly suppressed

Less suppression at RHIC than LHC in peripheral collisions
Low cross yields & statistics!

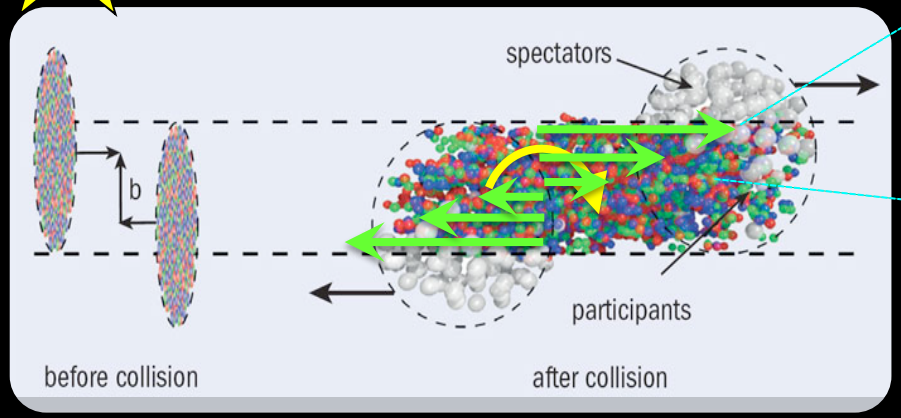
RHIC & LHC Photon Yields for Different Systems



PHENIX arXiv:1805.04.084 (in PRL)

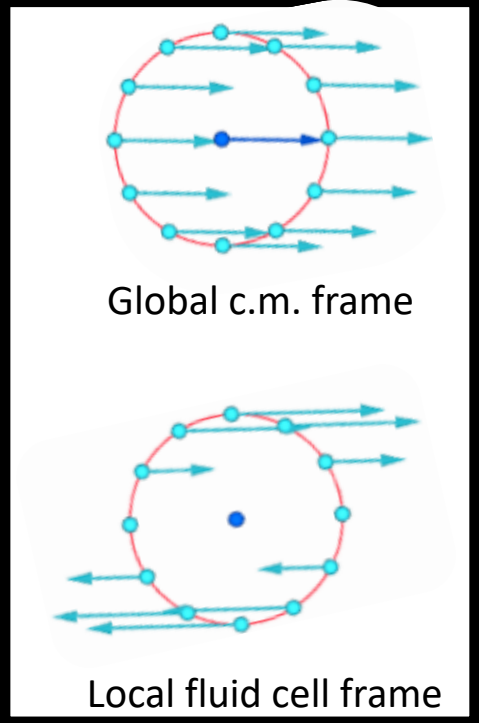
Common Scaling at RHIC and LHC
N_{coll}-scaled pp much lower!

A Spinning QGP Fluid!



Non-central collisions
angular momentum ~ 1000 ħ

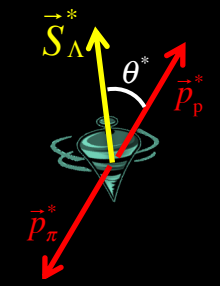
Vorticity: $\vec{\omega} = \frac{1}{2}\vec{\nabla} \times \vec{v}$



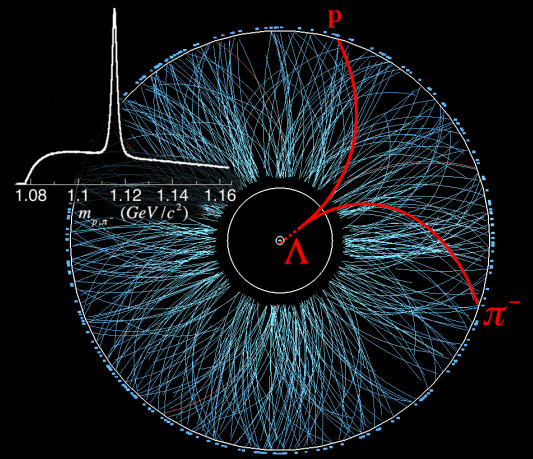
Collision generates a "spinning QGP"

Large vortical flow measured! Also new data at lower energies!

Local orbital angular momentum (vorticity), transferred to spin degree of freedom of final-state hadrons, is measured!



$\Lambda \rightarrow p + \pi^-$



Nature 548, 62–65 (2017), STAR Collaboration

+ new STAR paper arXiv:1905.11917v1

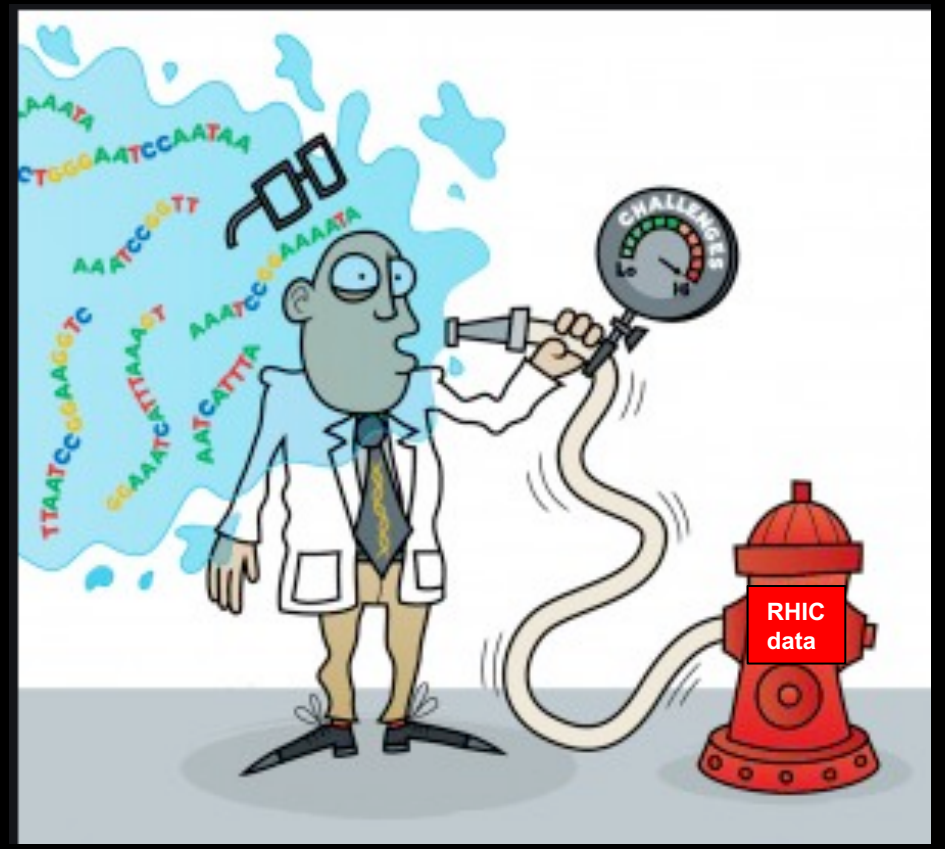
Correlate $\vec{p}^*_p$ and $\hat{J}_{sys}$

Graphics courtesy M. Lisa and Wikipedia

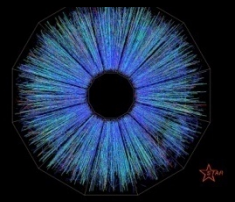
Many Topics & Results Not Presented (or not in detail)

At RHIC:

- Directed Flow and link of Net-proton BES data to EOS
- Ultra-Peripheral Collisions
- Chiral Magnetic Effect
- Cold Nuclear Matter studies
- Higher order flow harmonics
- Fluctuations, correlation lengths and susceptibilities
- Fragmentation Function studies
- Jet (sub-)structure
- New STAR birefringence studies
- Various theoretical approaches
- and others …



Big Picture Summary – What We've Learned about Heavy Ion Collisions

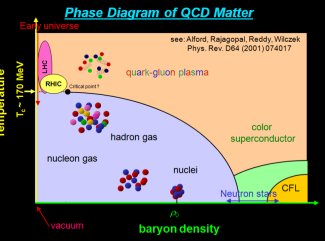


System evolves rapidly from the initial collision to a thermalized state

"With characteristics of a hot quark-gluon liquid"

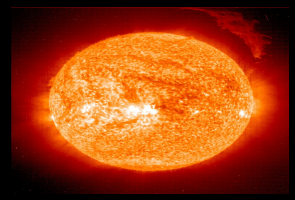
Particles Formed at Universal Hadronization T

Particles yields → equilibrium abundances → universal hadronization $T_{critical}$



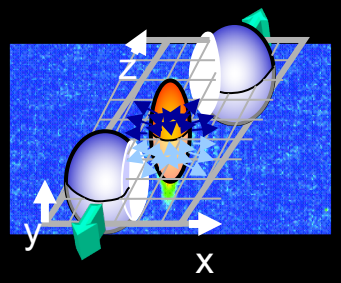
"Hottest matter ever on Earth ($T > 2 \times 10^{12}$ K)"

There is a thermal component of direct photon spectra



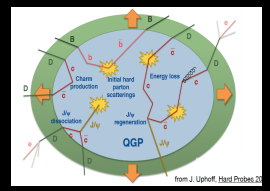
Thermal radiation from the QGP

Collective flow observed



A Strongly-Coupled liquid with ultra-low shear viscosity / entropy

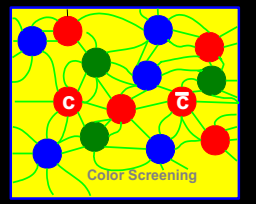
High transverse momentum (p_T) hadrons are suppressed, jets quenched



QGP "opaque" to energetic probes → parton energy loss in the QGP

J/Ψ and Υ (quarkonia) suppressed

Indicates color screening of $c\bar{c}$ and $b\bar{b}$ quarks resulting in quarkonium suppression



Maturity after 20 Years ?

More discoveries & new approaches ahead …..

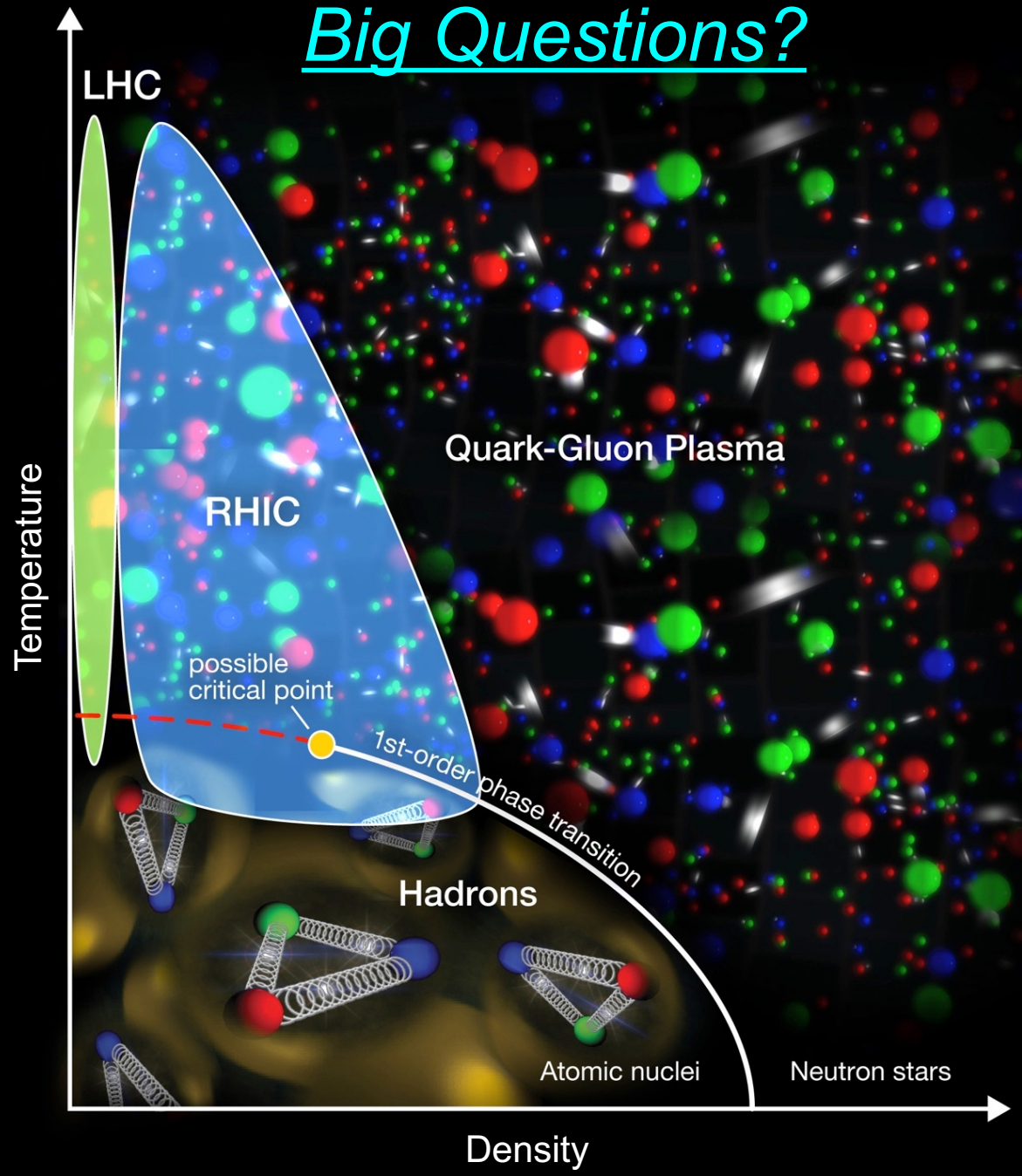
a new generation!

Acknowledgements

I'd like to acknowledge and thank the innumerable people and vision that made RHIC, its experiments and its physics an incredibly successful endeavor.

Two more slides!

Big Questions?



Some of the BIG Questions

What are the properties & states of matter that exist at high T & density?

- Can we explore the phase structure of a fundamental gauge (QCD) theory?
  → Can we use this to understand other gauge theories (like gravity!)?
- Is the Phase Diagram of QCD featureless above Tc?
  → What are the constituents (are there quasi-particles, exotic states, others)?
  → When does the "quark-gluon soup" become resolvable into quarks / gluons?
  → Is there a critical point (scan in energy)?

What is the smallest size & density of a QCD droplet that behaves like a liquid?"

What are the properties of the QGP?

transport properties, α_s (T), sound attenuation length,
sheer viscosity/entropy density, formation time (τ_f),
excited modes, ….EOS?

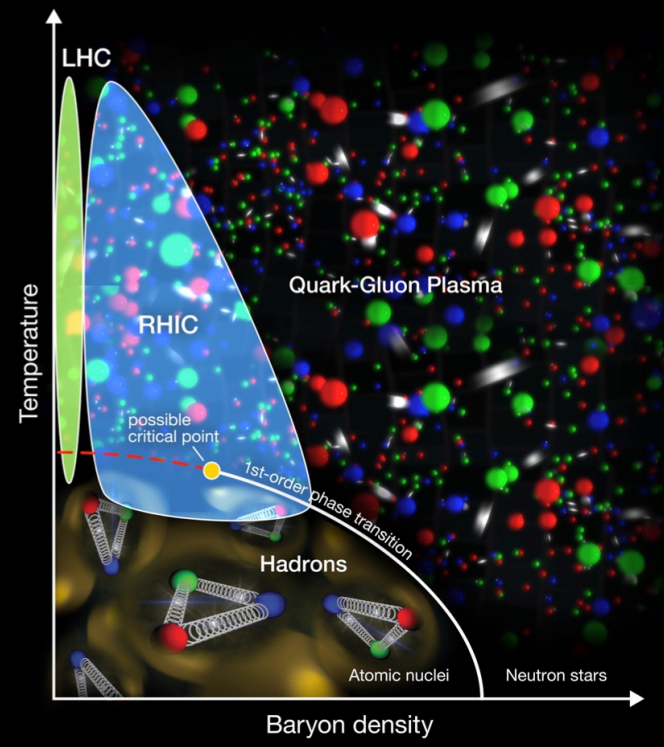
How does the system evolve and thermalize from its initial state?

What is the initial state (Shadowing / Color-Glass Condensate?)

Can we understand parton propagation & energy loss at a fundamental level?

What can we learn about the response of the QGP?

Are there new phenomena, new states of matter?



Thanks for your patience & attention!