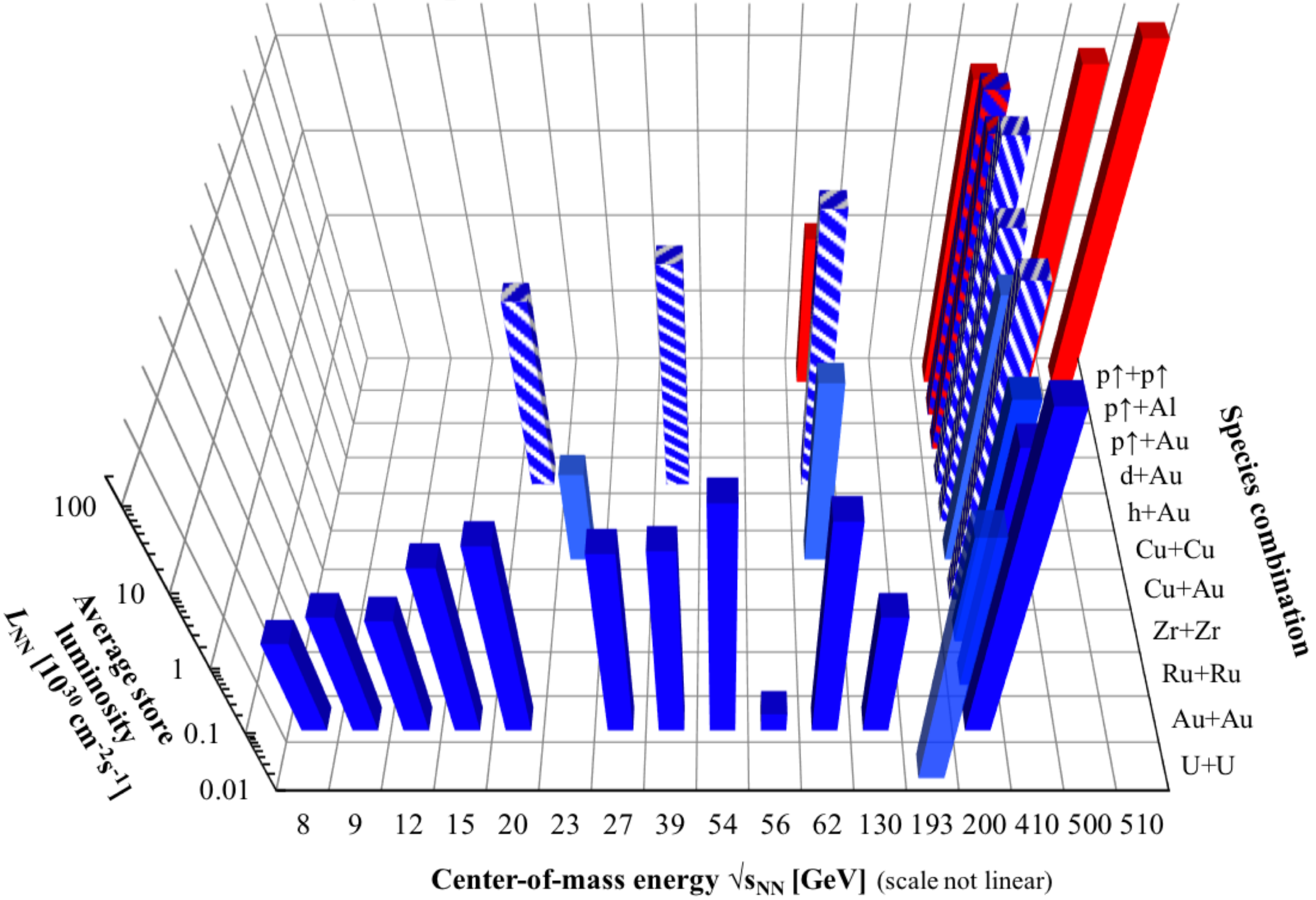
Study of QGP at RHIC

Zhangbu Xu
许长补

RHIC energies, species combinations and luminosities (Run-1 to 19)



- **Early days of RHIC discoveries and the topics that continue**
  - Gluon Saturation
  - Jet Quench
  - Flow
- **Intensive thermodynamics parameters**
  - Temperature
  - Temperature
  - Temperature
  - How we turn extensive measures into intensive physics quantities
- **Degree of Freedoms**
  - Free quarks
  - Symmetries
  - Fields
- **What to remember**

In part supported by

Outline

- **Early days of RHIC discoveries and the topics that continue**
  - Gluon Saturation
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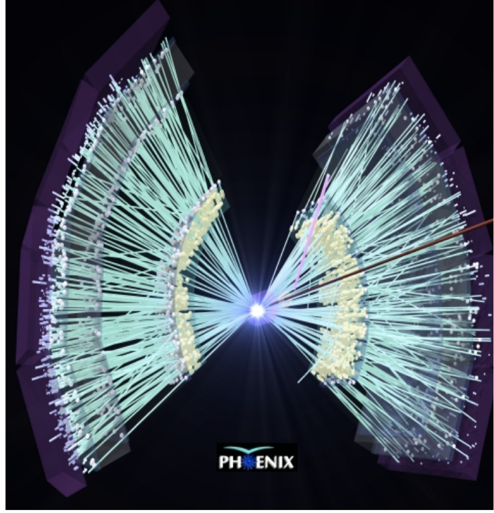
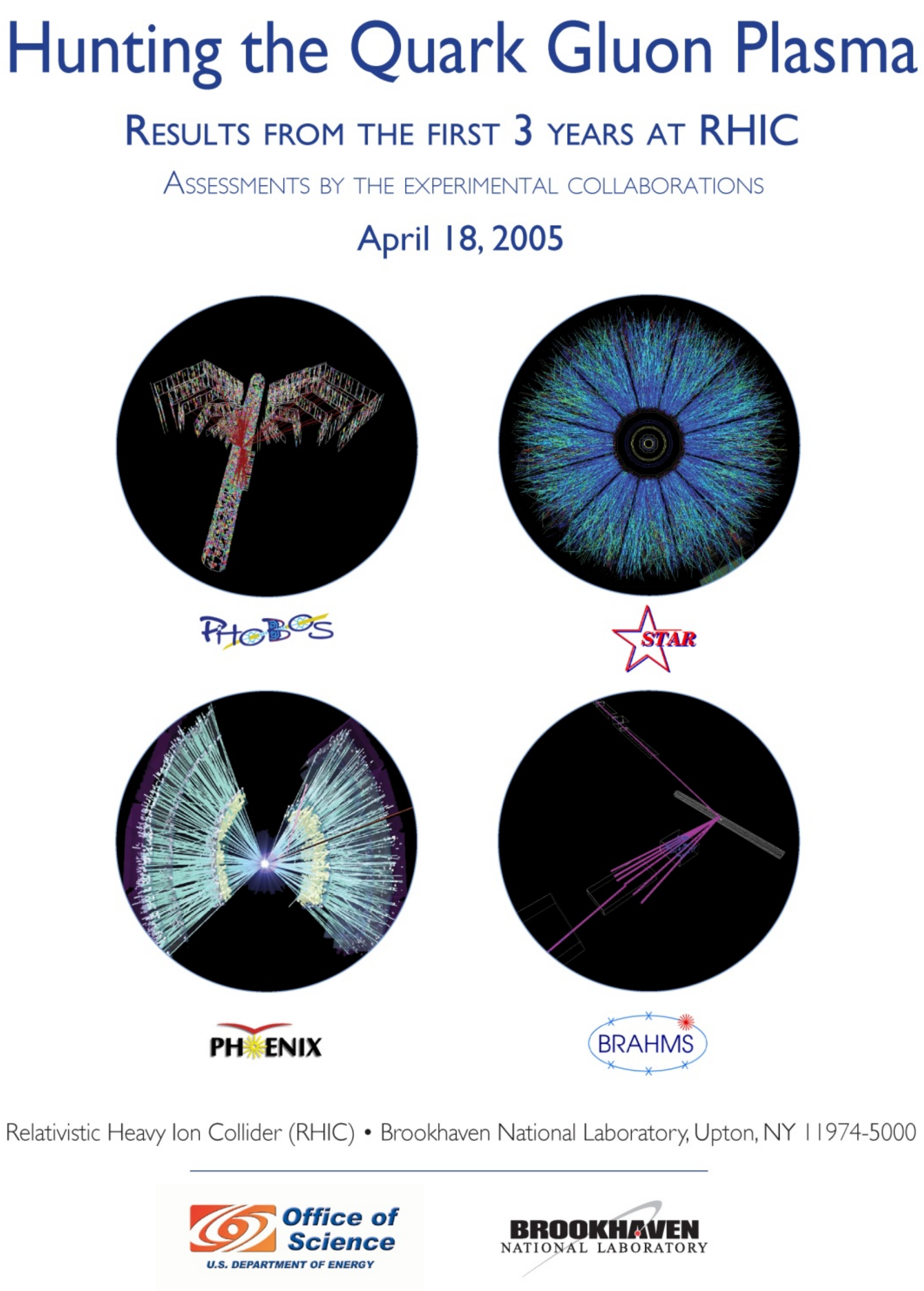


PHENIX

A Physics Experiment at RHIC


Hunting the Quark Gluon Plasma

RESULTS FROM THE FIRST 3 YEARS AT RHIC

ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

April 18, 2005

Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

Experimental and Theoretical Challenges in the Search for the Quark Gluon Plasma

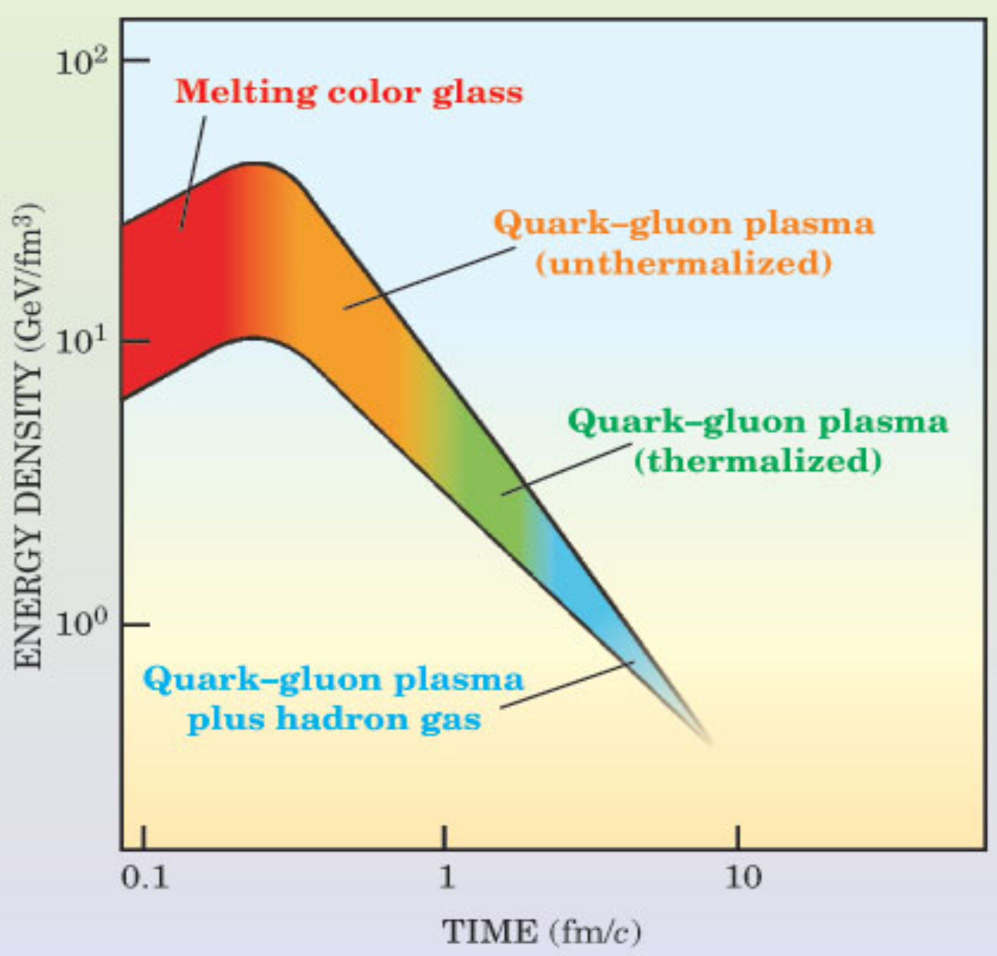
The STAR Collaboration's Critical Assessment of the Evidence from RHIC Collisions,

Nucl. Phys. A 757 (2005) 102

Strong evidences pointing to a "dense, opaque, **low-viscous**, pre-hadronic liquid state of matter **not anticipated** before RHIC"

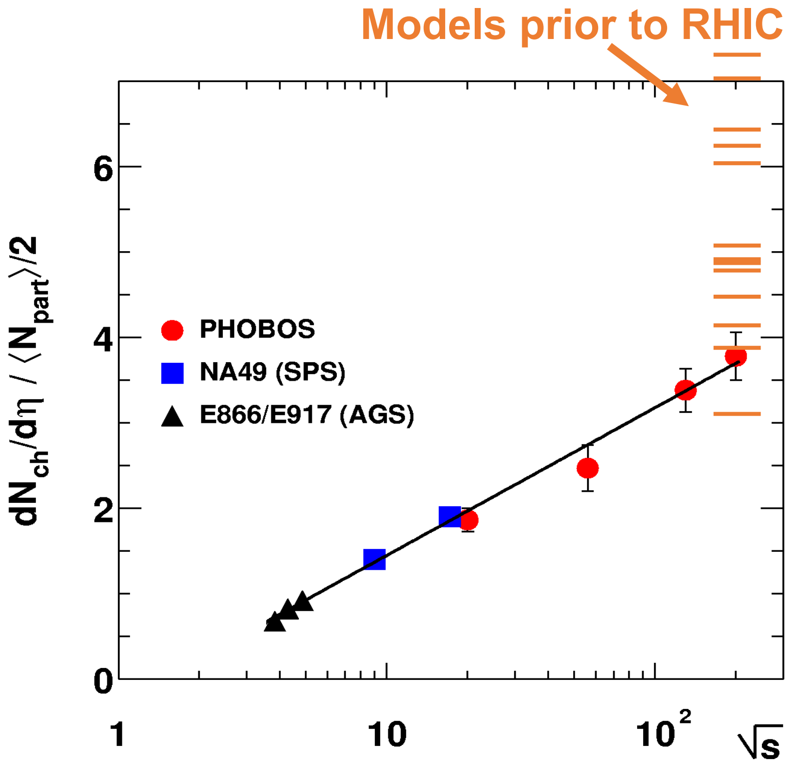
Color Glass Condensate

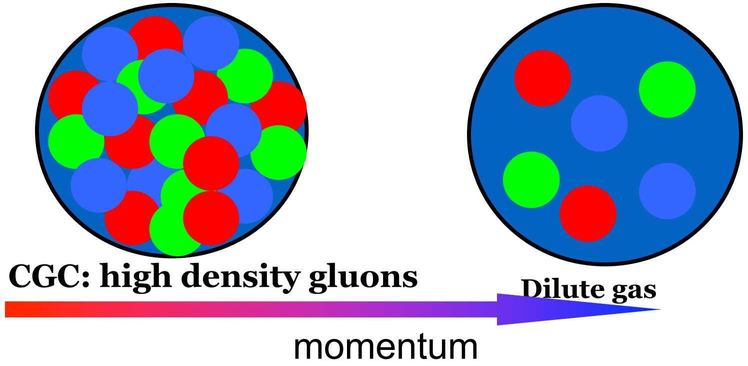
Initial condition: high density gluons
DIS: ep, eA (eRHIC)



Physics Today, Ludlam/McLerran

Simple Counting





First RHIC scientific journal paper by PHOBOS

Extend to high p_T and high rapidity

STAR, Phys. Rev. C **70** (2004) 64907

22 BRAHMS *I. Arsene et al. / Nuclear Physics A 757 (2005) 1–27*

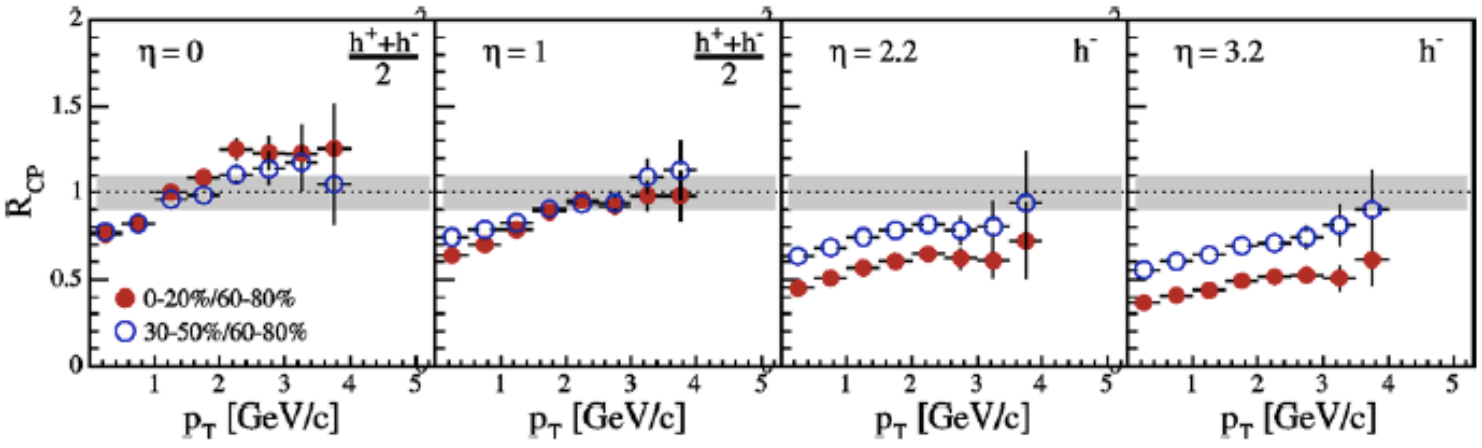
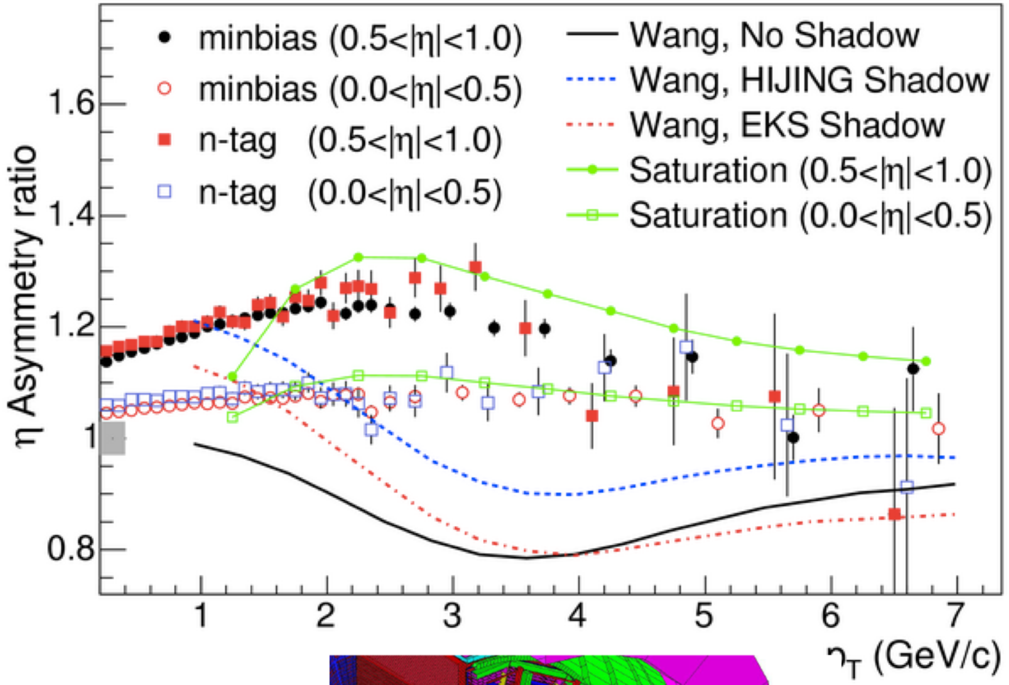
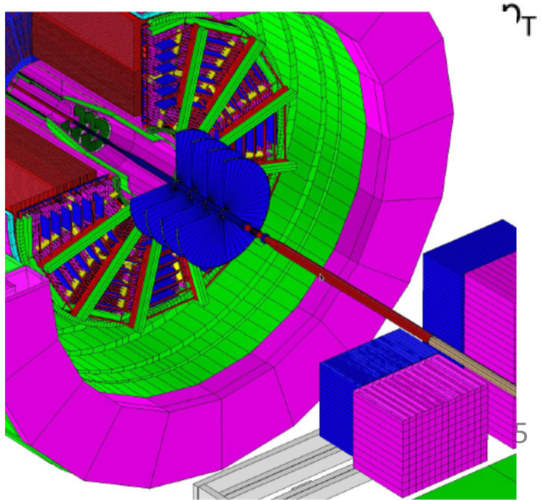


Fig. 18. Central to peripheral ratios R_{CP} as a function of pseudorapidity measured by BRAHMS for d + Au collisions at the RHIC top energy [76]. The filled circles represent the central-to-peripheral (0–20% over 60–80%) ratio. The open circles the semicentral-to-peripheral (30–50% over 60–80%) ratio. The shaded band around unity indicates the uncertainty associated with the values of the number of binary collisions at the different centralities.



Becomes one of the most debated topics in the field:
Are the observed effects in small systems from initial or final-state effects?

STAR Forward upgrade (2021+) is a large acceptance version of BRAHMS

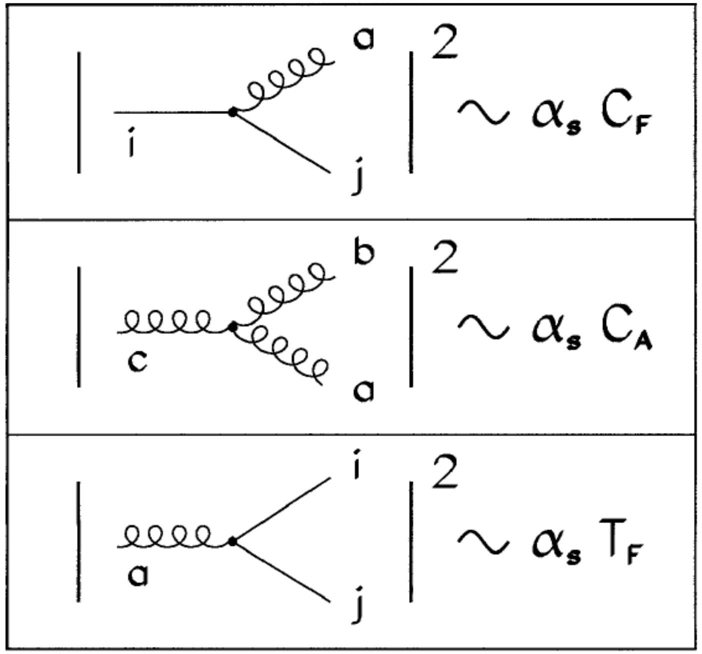


Jet Quenching

- Color factor and coupling constant
- Pathlength L^2 dependence
- Deadcone (mass hierarchy)
- Jet chemistry and Jet Conversion
- Mach Cone
- Jet imbalance
- Jet structures
- Jet Splitting

$$dP = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{k_\perp^2 dk_\perp^2}{(k_\perp^2 + \omega^2\theta_0^2)^2} = \frac{dP_0}{(1+\theta_0^2/\theta^2)^2}$$

$$\theta_0 \equiv \frac{M}{E}, \theta \equiv \frac{k_\perp}{\omega}$$



1982: J. D. Bjoken: Fermilab-pub-82/59-THY
Energy loss in elastic scattering

1992/1995: X.-N. Wang, M. Gyulassy:
PRL68(92) 148, PRD45 (92)844, NPB420(94)583, PRD51(95)3436
Energy loss is dominated by gluon radiation

1995/1997: BDMPS (R. Baier, Yu. L. Dokshitzer, A. Mueller, S. Peigue, D.Schiff) :PLB345(95) 277, NPB478(96)577,NPB483(97)291,NPB484(97)265
Gluon multiple scattering and gluon radiation

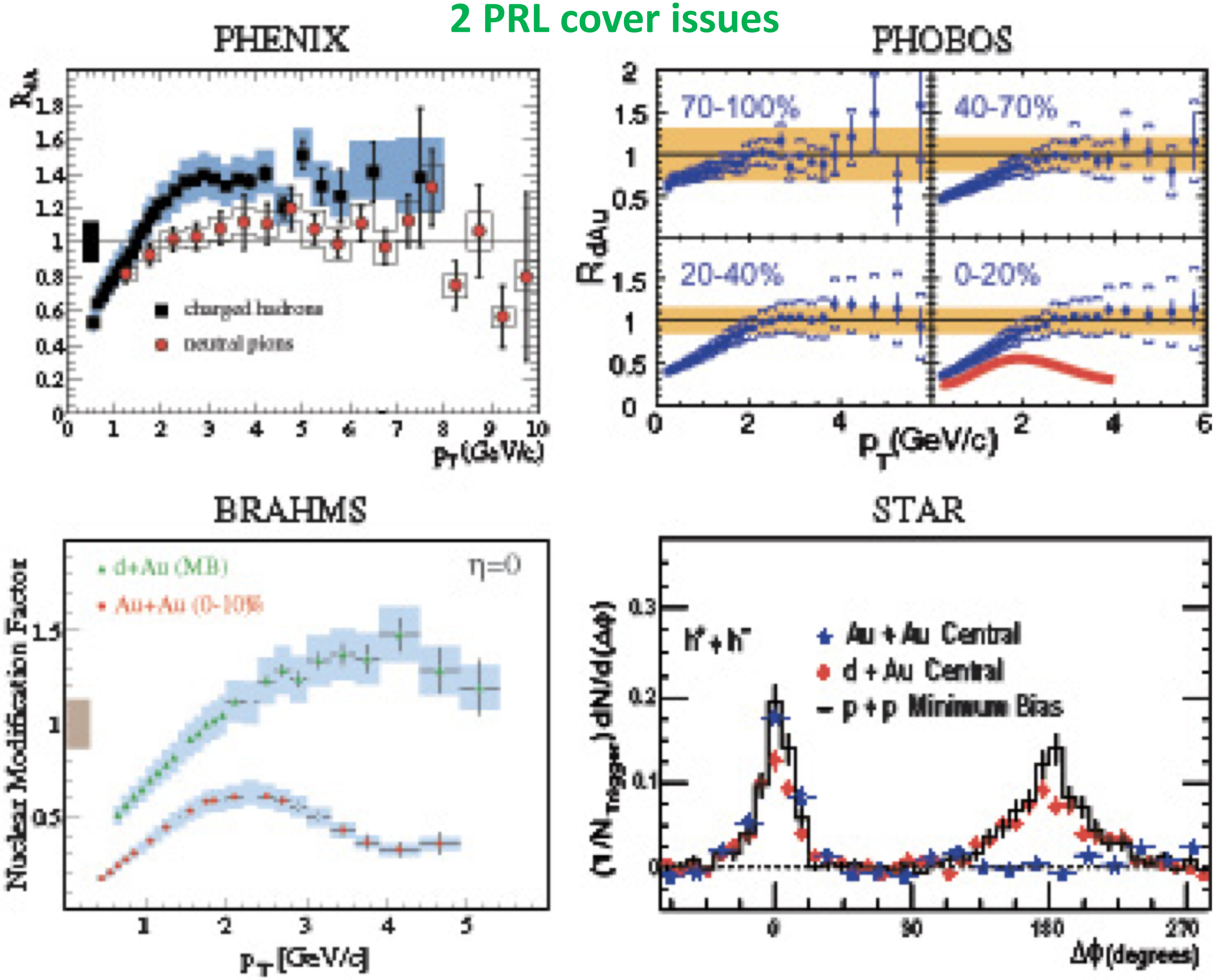
2000: GLV(M. Gyulassy, P. Levai, I. Vitev): PRL85(00)5535, NPB594(01)371, U. Wiedemann: NPB588(2000)303
Opacity expansion

2001/2002: E. Wang, X.-N. Wang: PRL87(01)142301, PRL89(02)162301
Detailed Balance; Jet Tomography

2001/2009
Y. Dokshitzer & D. Kharzeev *PLB 519(2001)199;* S. Wicks et al, nucl-th/0512076

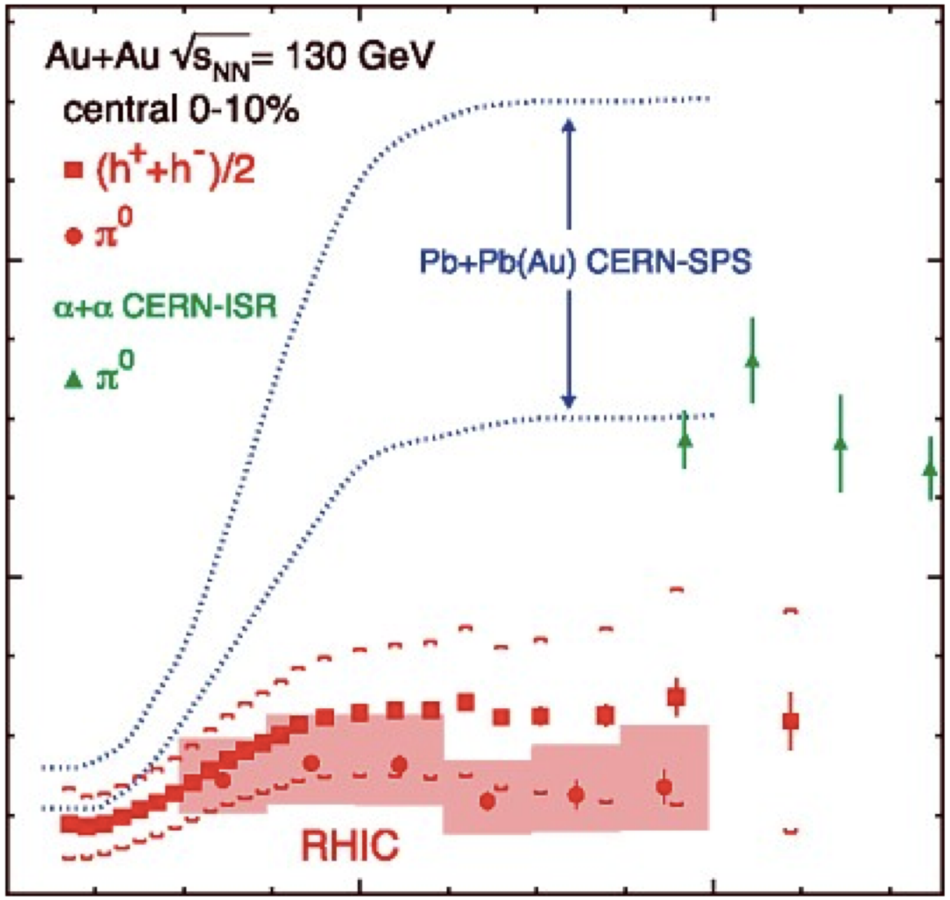
RHIC Discovery of Jet Quench

2 PRL cover issues



4 RHIC collaborations, PRL 90 (2003)

Cover Image: Phys. Rev. Lett.



PHENIX paper, PRL 88 (2001)

PHYSICAL REVIEW C **90**, 014909 (2014)

Extracting the jet transport coefficient from jet quenching in high-energy heavy-ion collisions

Karen M. Burke,[1] Alessandro Buzzatti,[2] Ningbo Chang,[3] Charles Gale,[4] Miklos Gyulassy,[5] Ulrich Heinz,[6] Sangyong Jeon,[4] Abhijit Majumder,[1] Berndt Müller,[7] Guang-You Qin,[1,3] Björn Schenke,[7] Chun Shen,[6] Xin-Nian Wang,[2,3,*] Jiechen Xu,[5] Clint Young,[8] and Hanzhong Zhang[3]
(JET Collaboration)

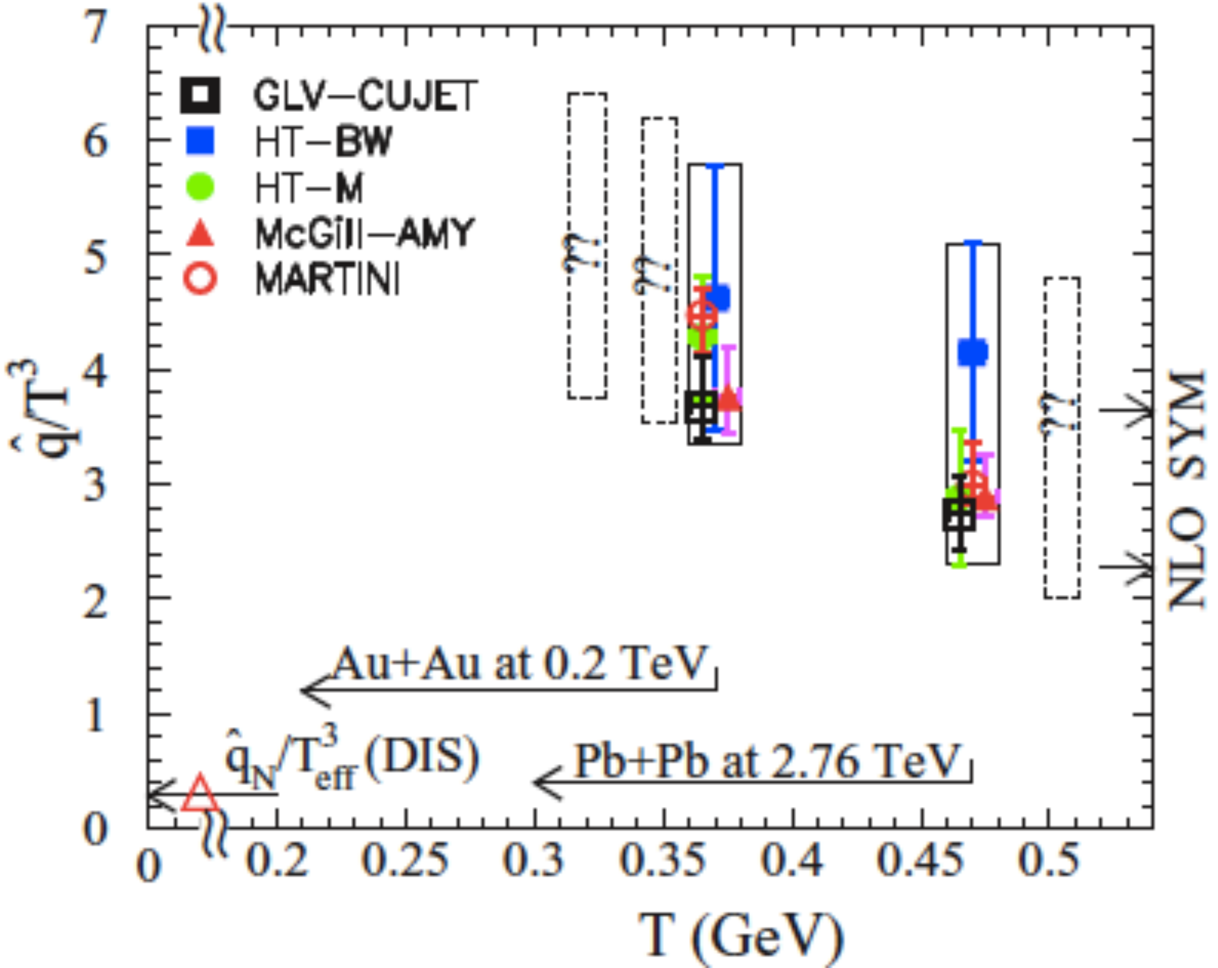


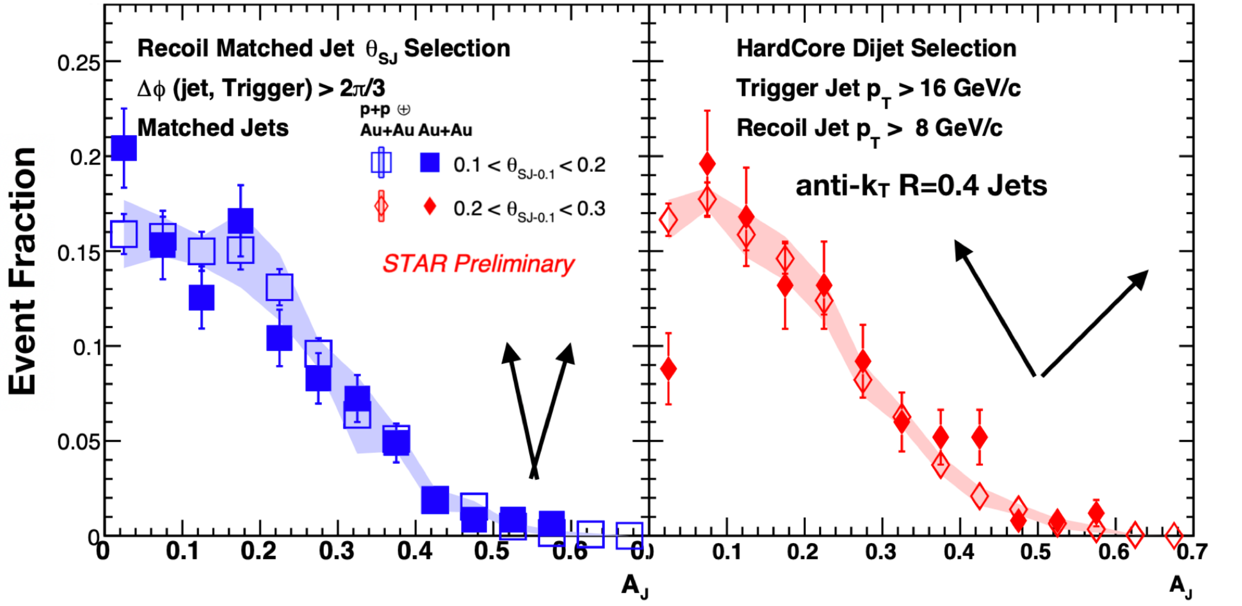
FIG. 11. (Color online) Values of scaled jet transport parameter $\hat{q}/T^3$ for an initial quark jet with energy $E = 10$ GeV at the center of the most central $A + A$ collisions at an initial time $\tau_0 = 0.6$ fm/c constrained by experimental data on hadron suppression factor R_{AA} at both RHIC and LHC. The dashed boxes indicate expected values in $A + A$ collisions at $\sqrt{s} = 0.063, 0.130$, and 5.5 TeV/n, assuming the initial entropy is proportional to the final measured charged hadron rapidity density [85]. The triangle indicates the value of $\hat{q}_N/T^3_{\rm eff}$ in cold nuclei from DIS experiments. Values of $\hat{q}^{\rm NLO}_{\rm SYM}/T^3$ from NLO SYM theory are indicated by two arrows on the right axis.

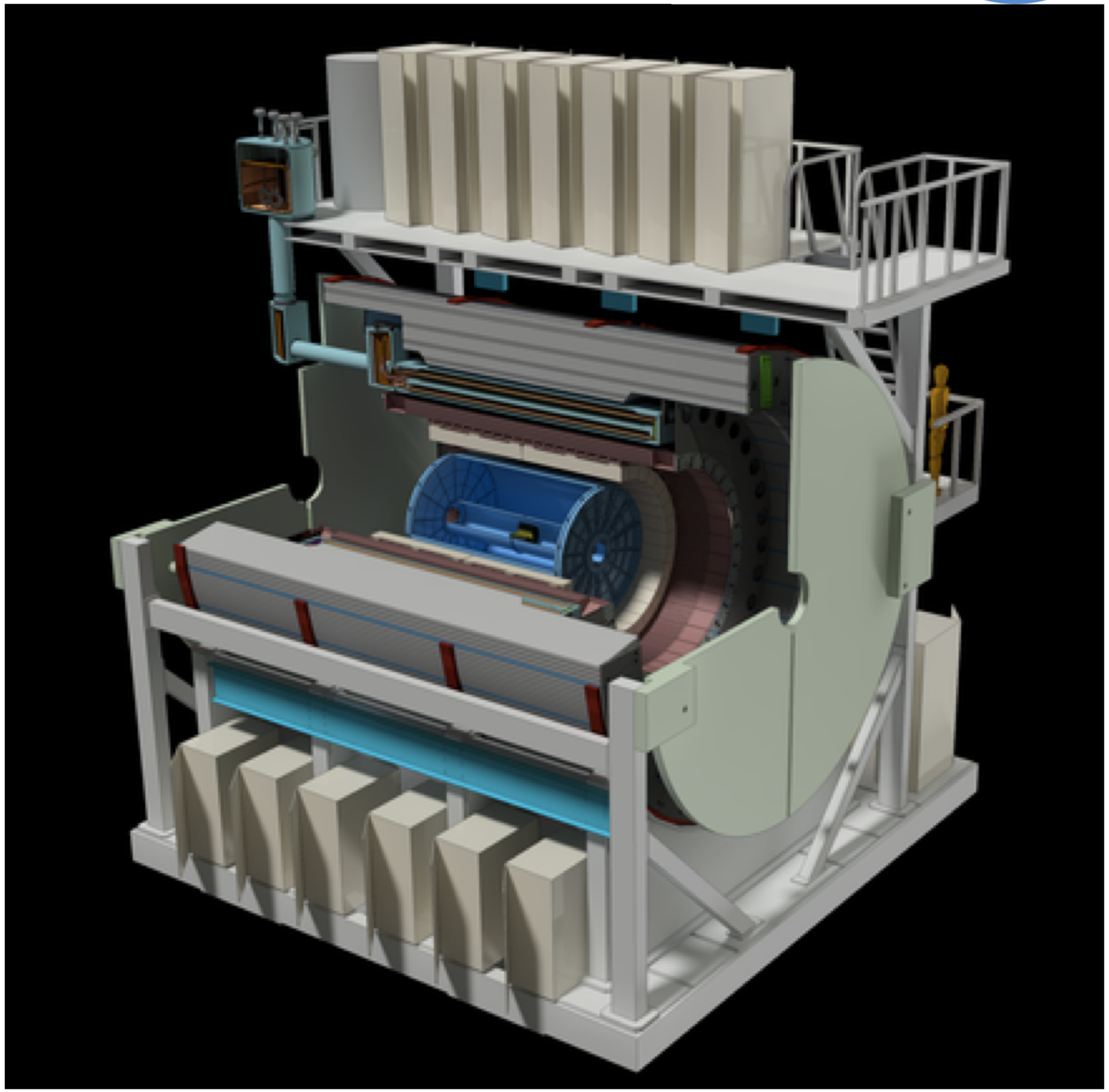
Where do we go from here?

Under construction,
a brand new jet detector

Raghav Kunnawalkam Elayavalli for the STAR Collaboration at QM2019

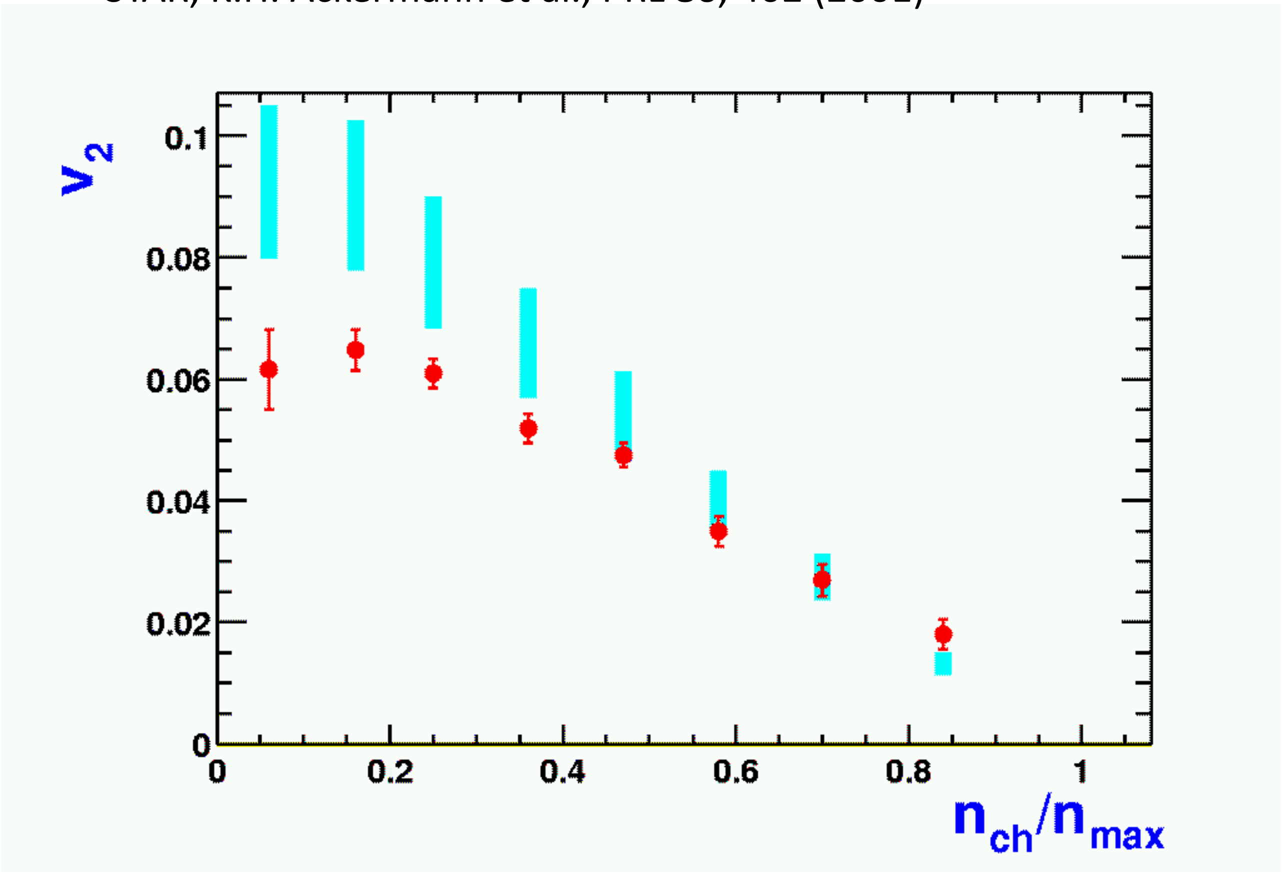
These jets lose energy as single color jet and split outside medium





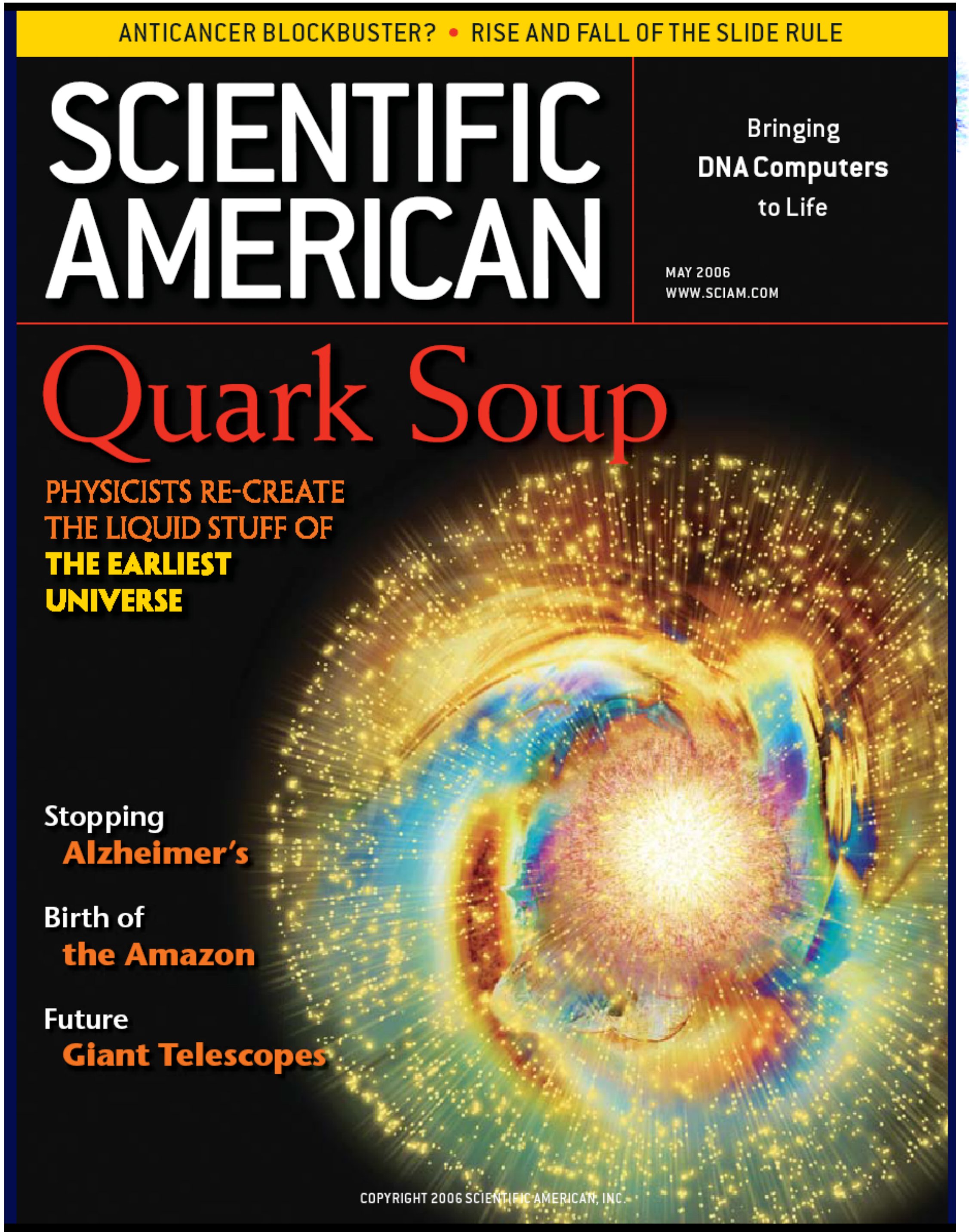
First RHIC Elliptic Flow

STAR, K.H. Ackermann et al., PRL **86**, 402 (2001)



Data approach hydro for central collisions

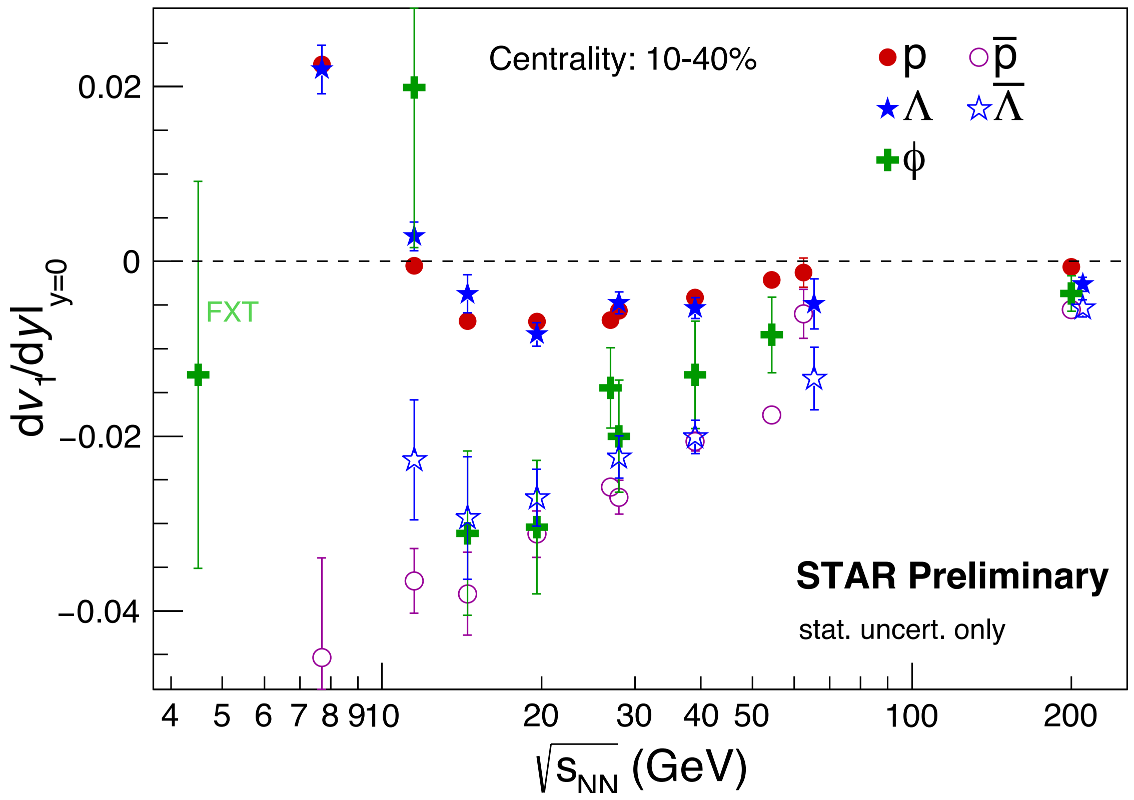
First paper from STAR with 22k events

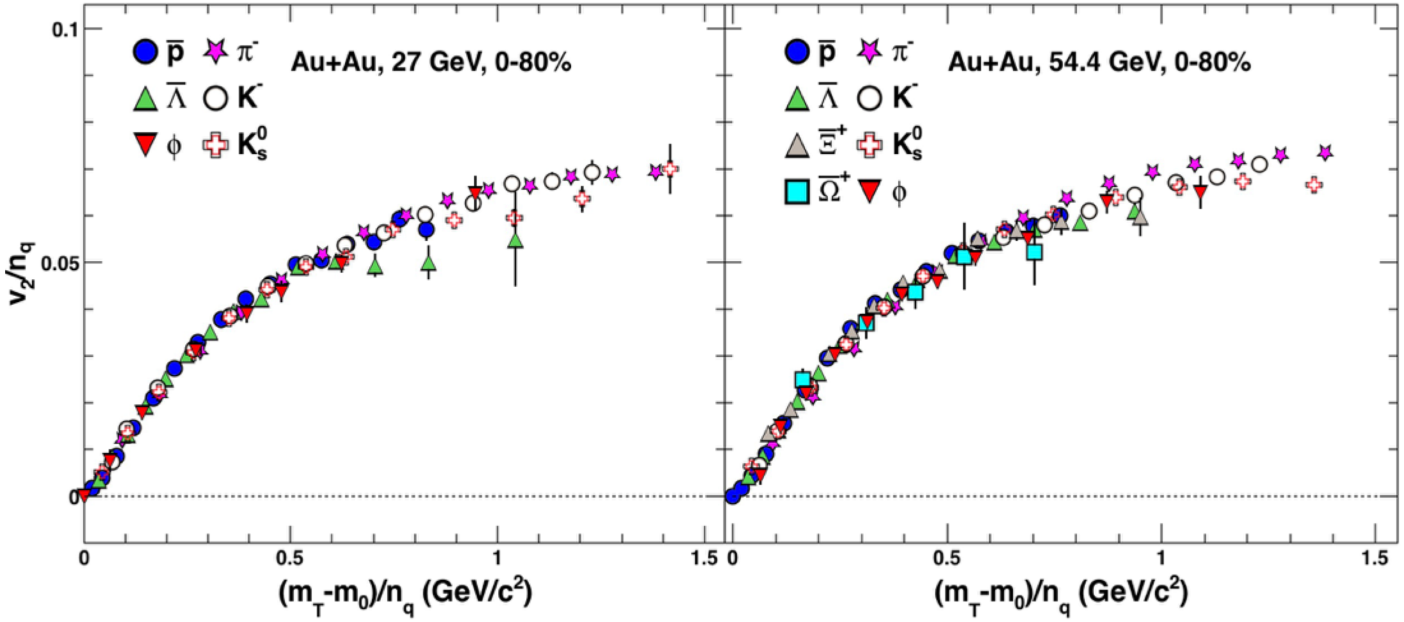


Excitation functions of v_1 slope and v_2

New data at FXT, 27 and 54.4 GeV

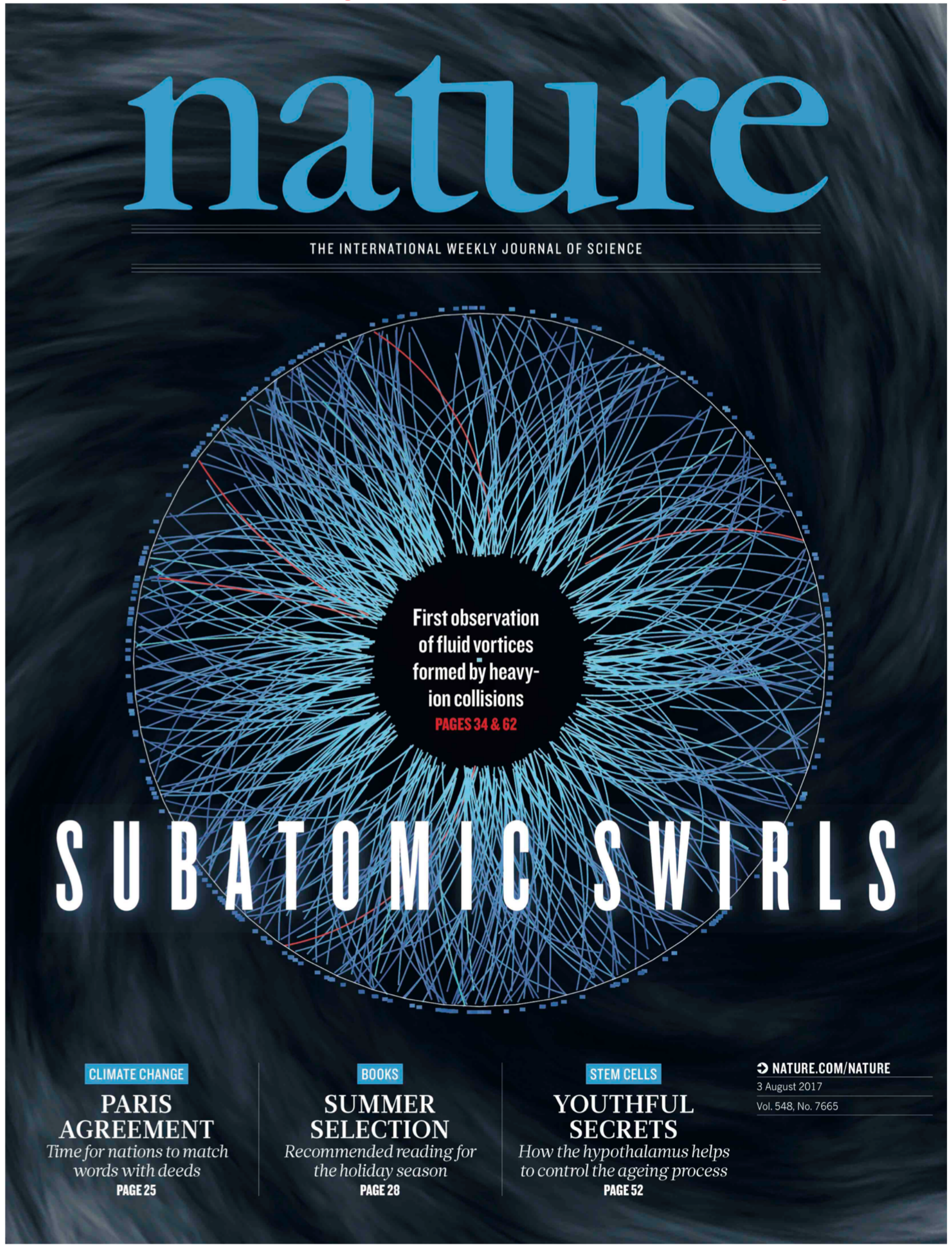
Kishora Nayak, QM2019



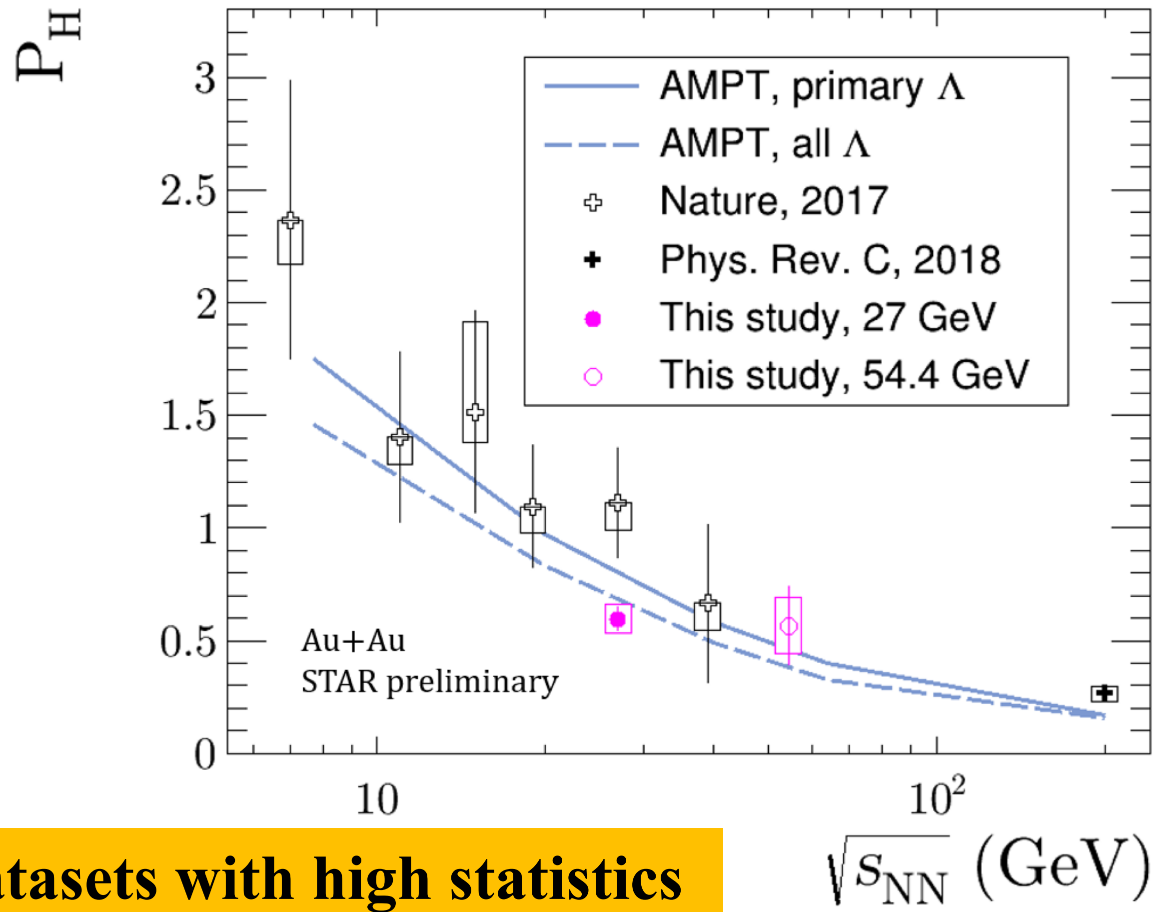


Mesons and produced baryons: negative v_1 slope
NCQ scaling for produced particles

Put spin and hydrodynamics together



Global and local hyperon polarization
(pt, rapidity, centrality dependence)
Vector meson spin alignment

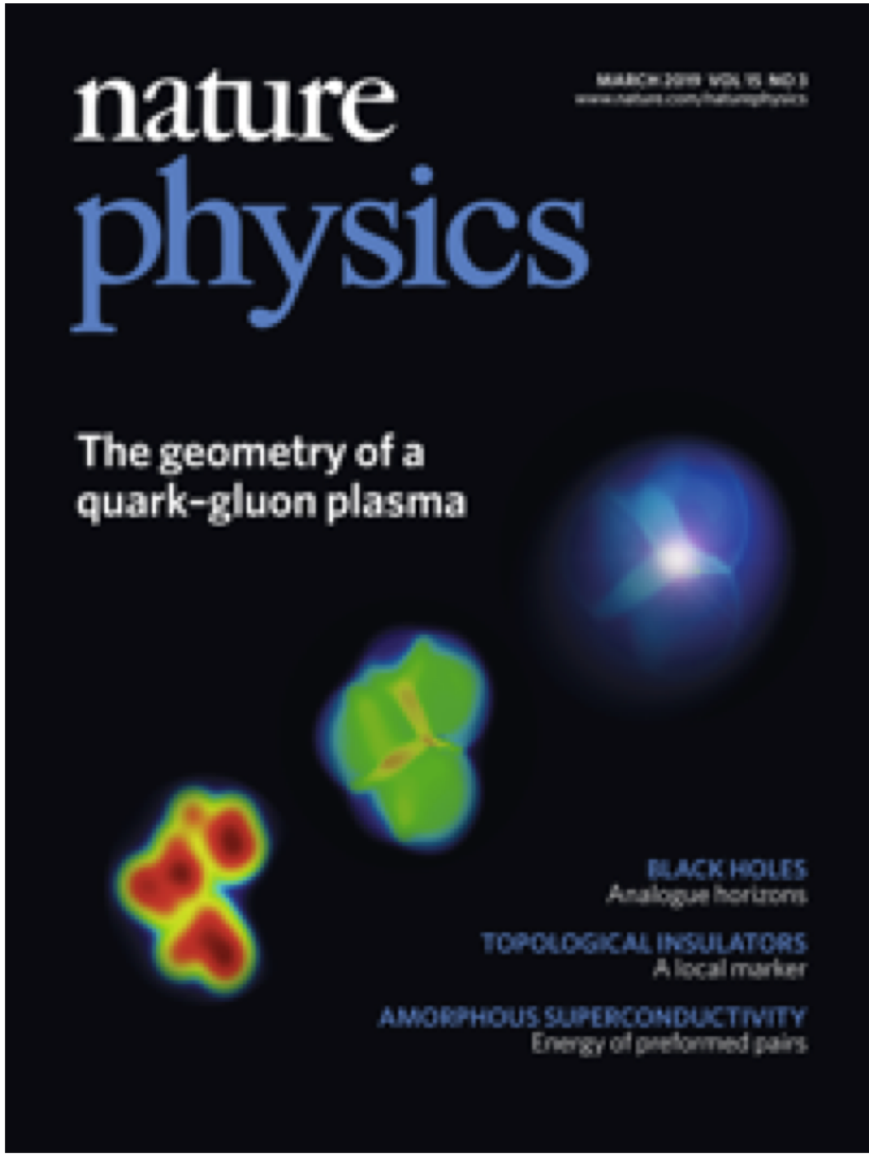


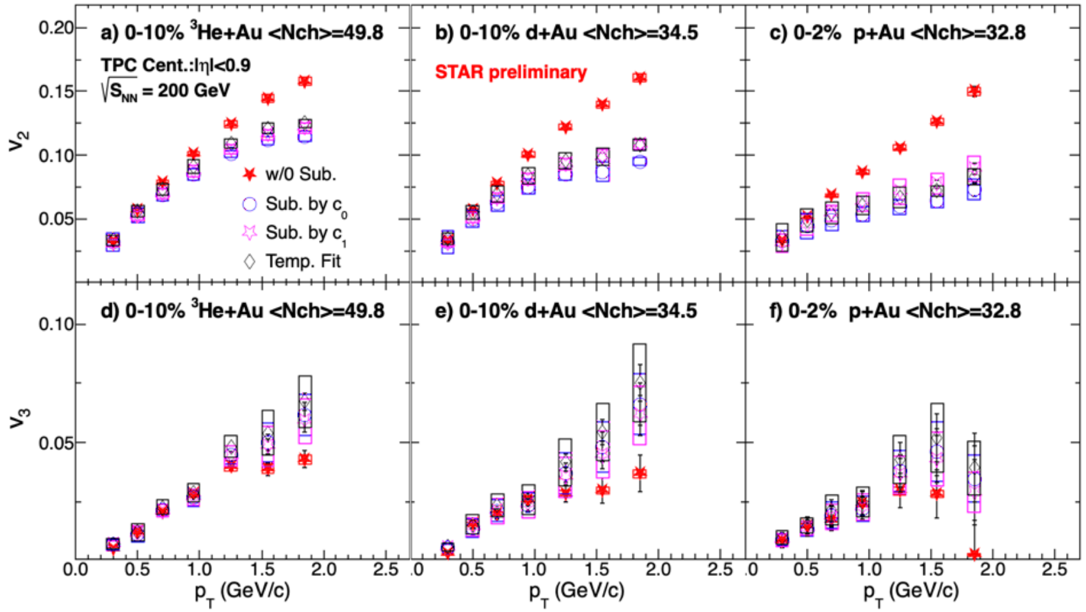
New datasets with high statistics follow previous measured trend

Hydrodynamics with small systems

Roy Lacey, QM2019

PHENIX, NATURE Physics 2018





PHENIX measurements:

- QGP flow effects
- Dominated by nucleon geometry

STAR measurements:

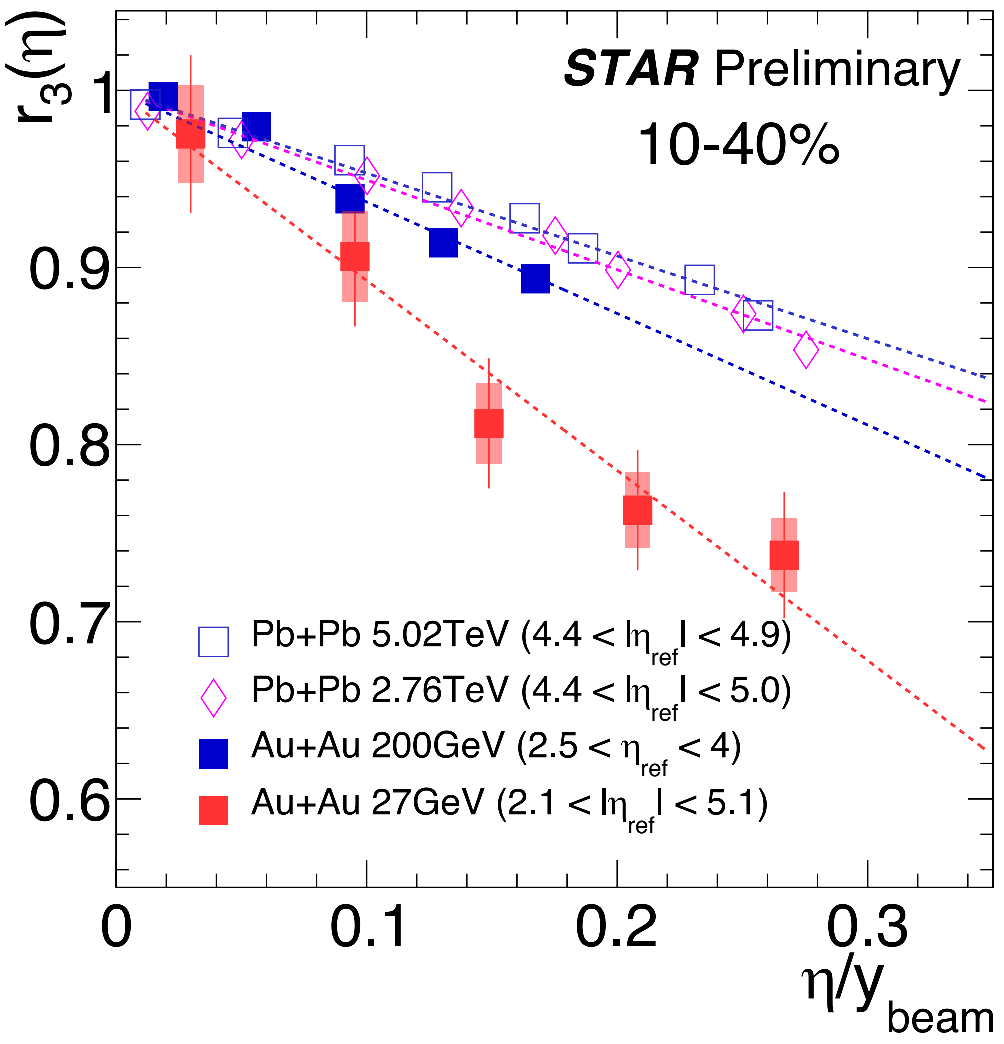
- Flow correlation beyond other known effects
- consistent with dominant roles of multiplicity
- Consistent with fluctuation-driven partonic shape (ε_n)

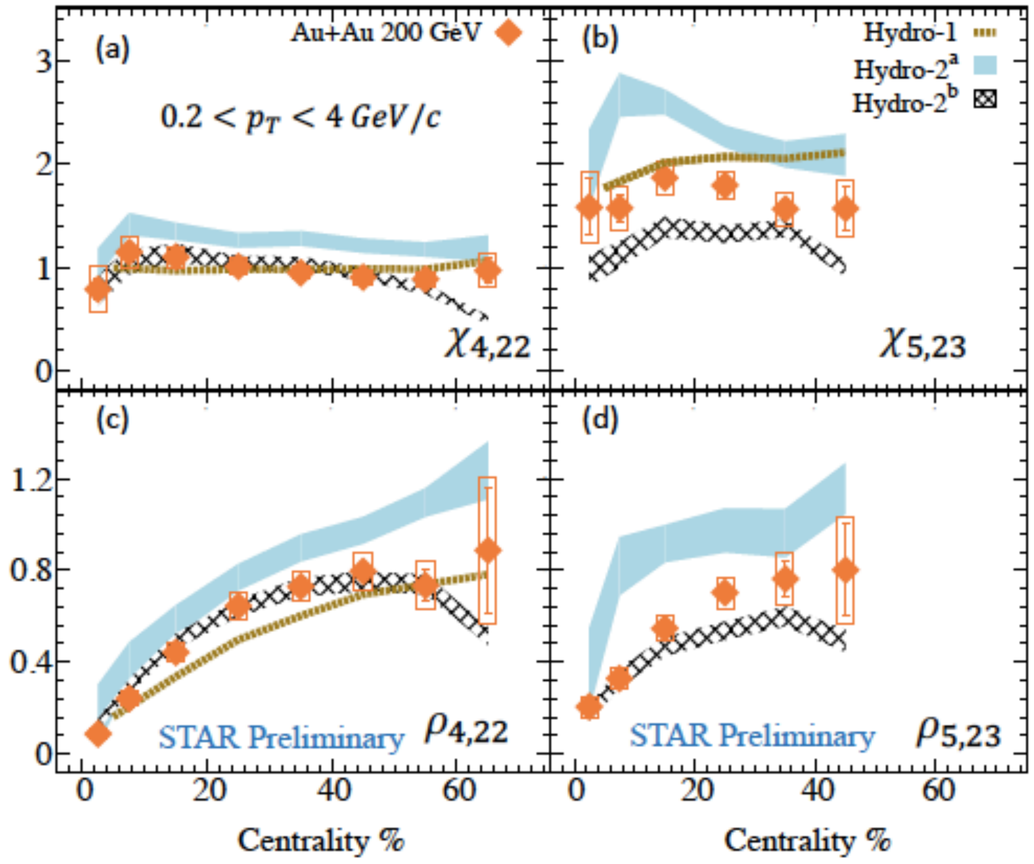
Flow harmonics and rapidity correlations

If there is doubt whether there is flow in large A+A systems, it will be hard to explain the rapidity and phase correlations

Next step: going toward smaller systems: O+O before assessing small systems

Niseem Magdy, Maowu Nie, QM2019

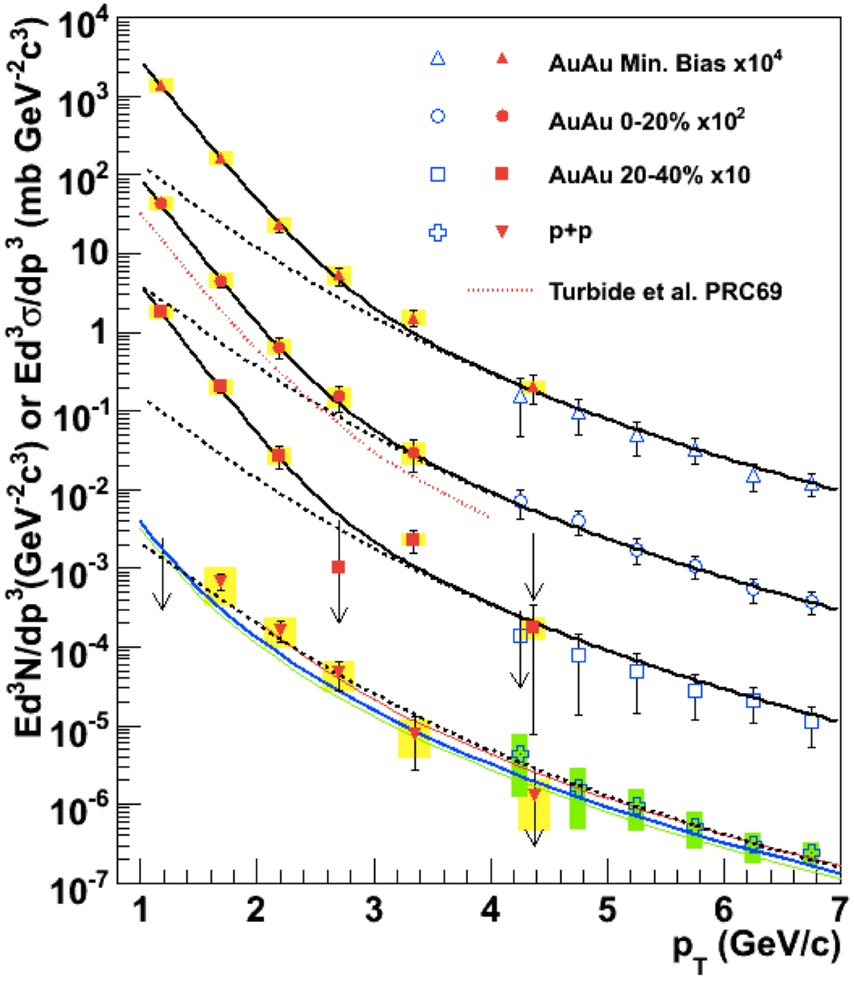




- $\chi_{k,nm}$ shows a weak centrality dependence
- $\rho_{k,nm}$ shows a strong centrality dependence

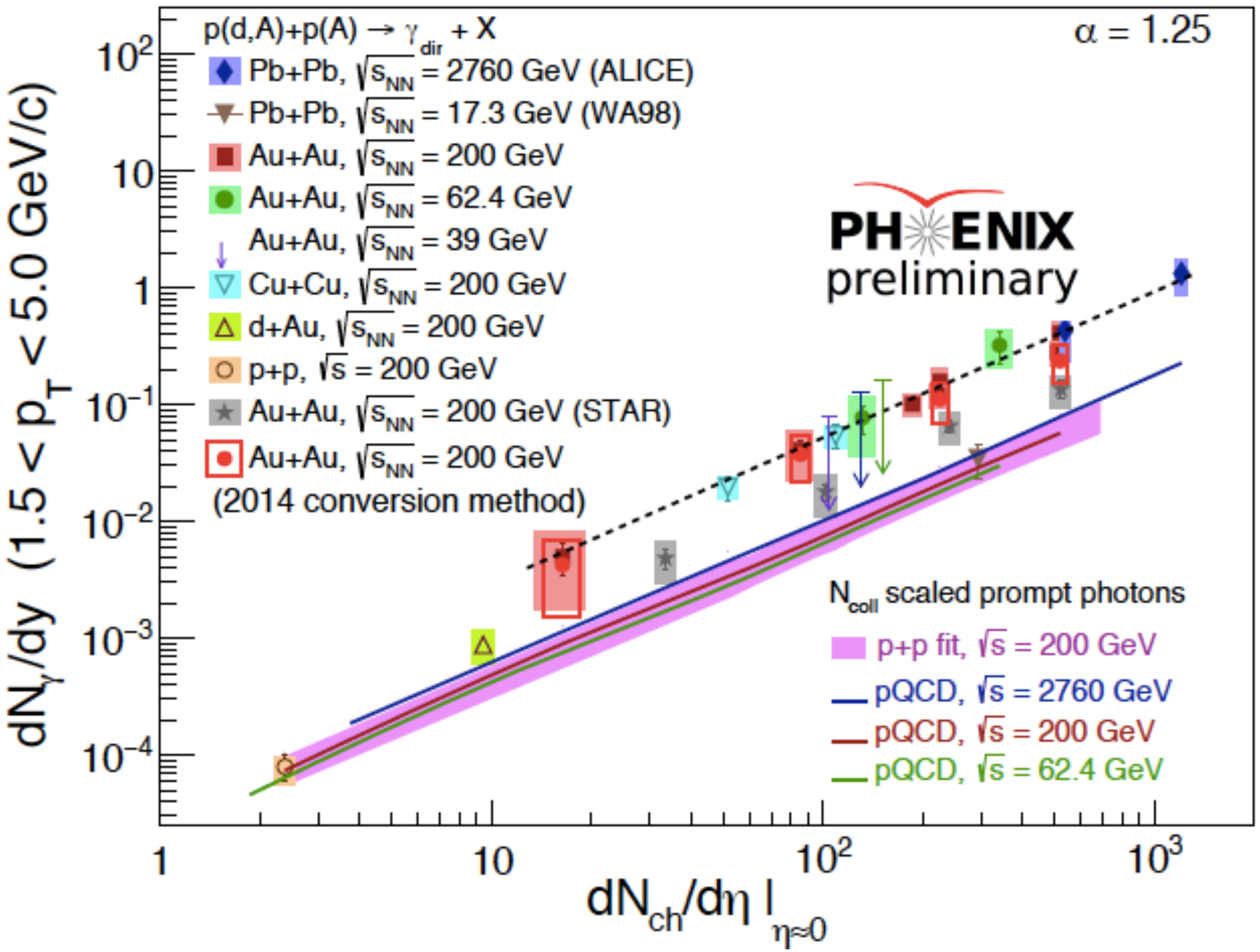
Temperatures from radiation

Fundamental parameter of thermodynamics



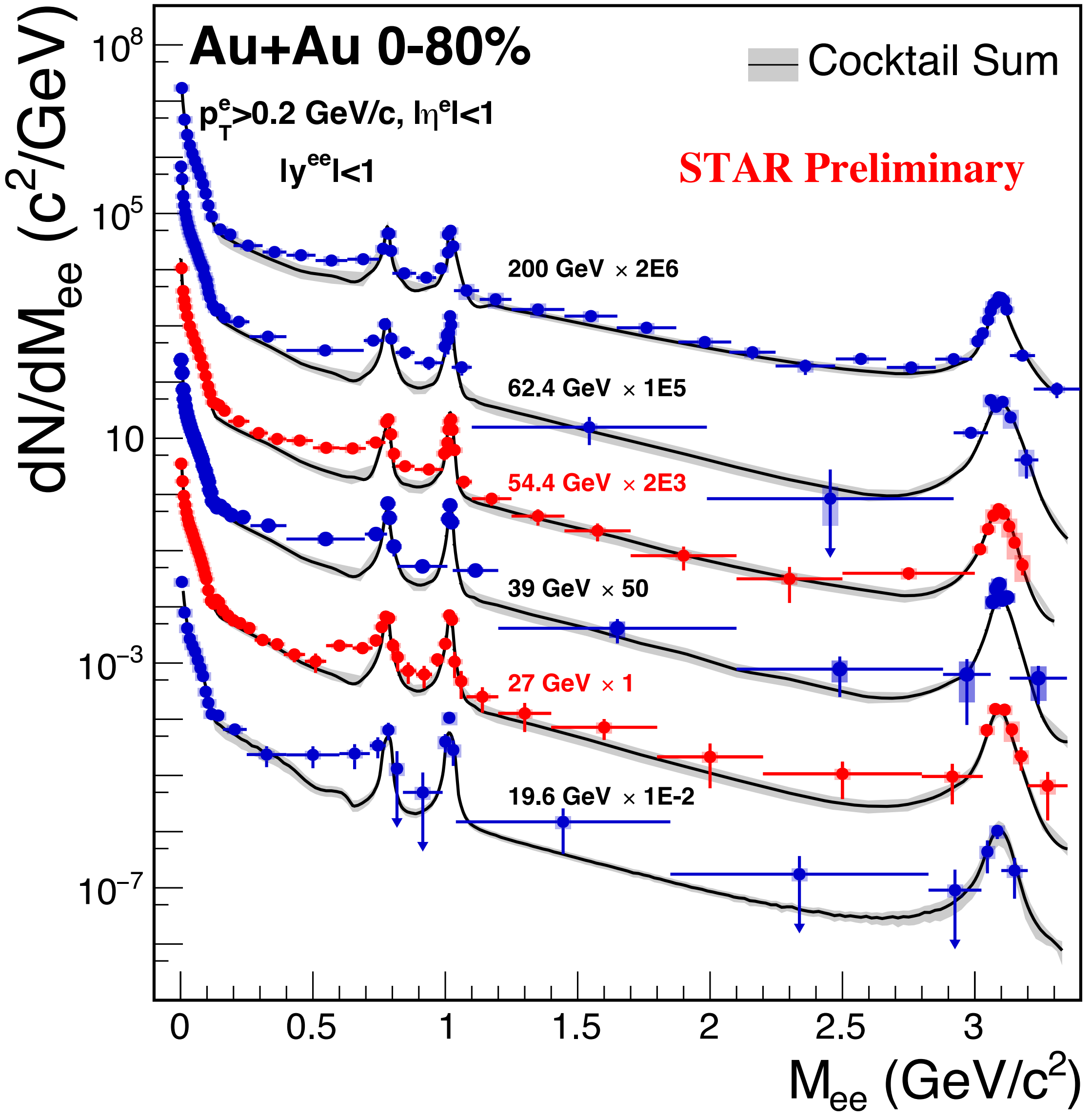
T=221+-19+-19 MeV
PRL 104, 2010

Wenqing Fan (PHENIX), QM2019



Temperatures from IMR dilepton

Florian Seck, QM2019



Enough statistics to perform (multi-)differential measurements

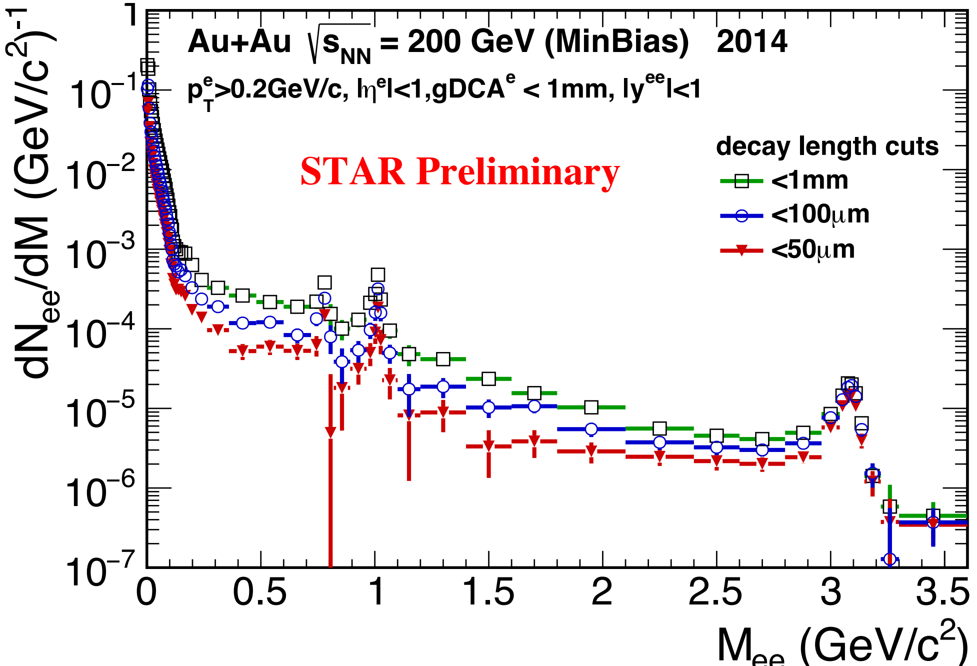
Temperatures from other methods are subjective to interpretation:

- **Photon slopes influenced by flow**
- **Hadron chemistry at freeze-out only**
- **Intermediate mass range dileptons is boost-invariant and true temperature**

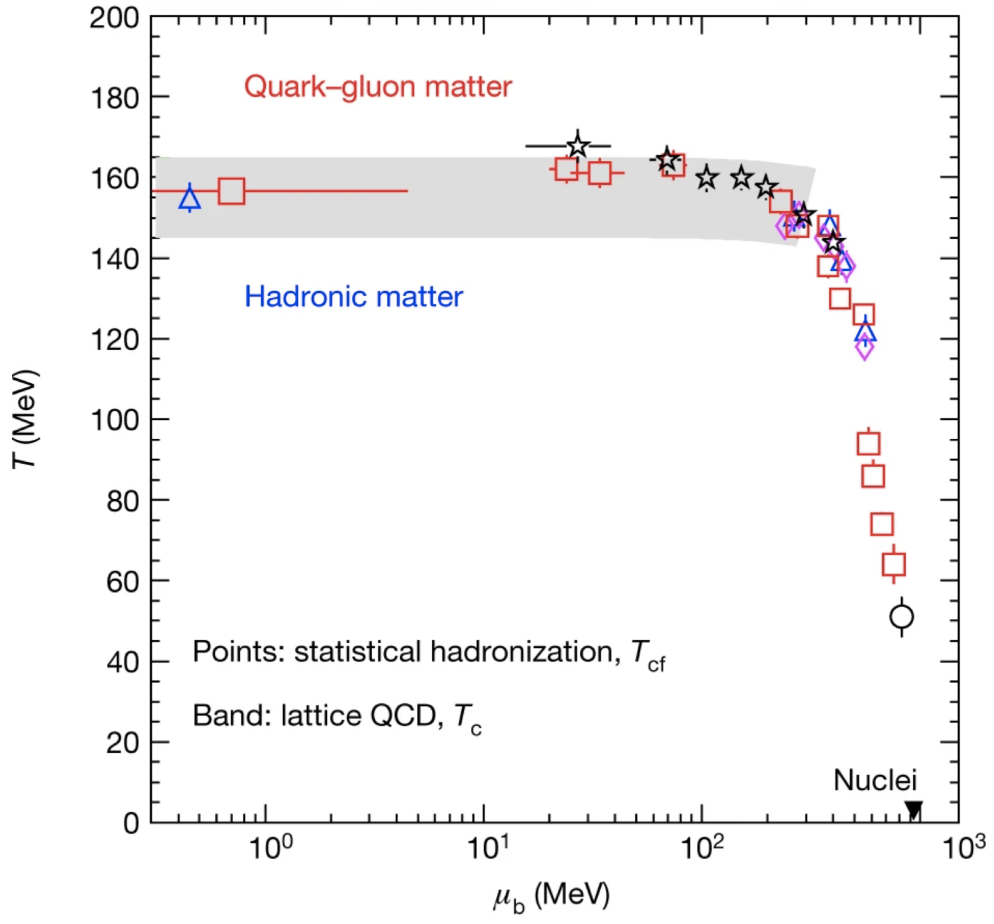
New data and future BES-II:

- **Consistent with published data**
- **Hints of excess at IMR**

Use HFT capability to disentangle thermal and charm contributions at IMR



Temperature from chemistry



A. Andronic et al., NATURE 561 (2018)

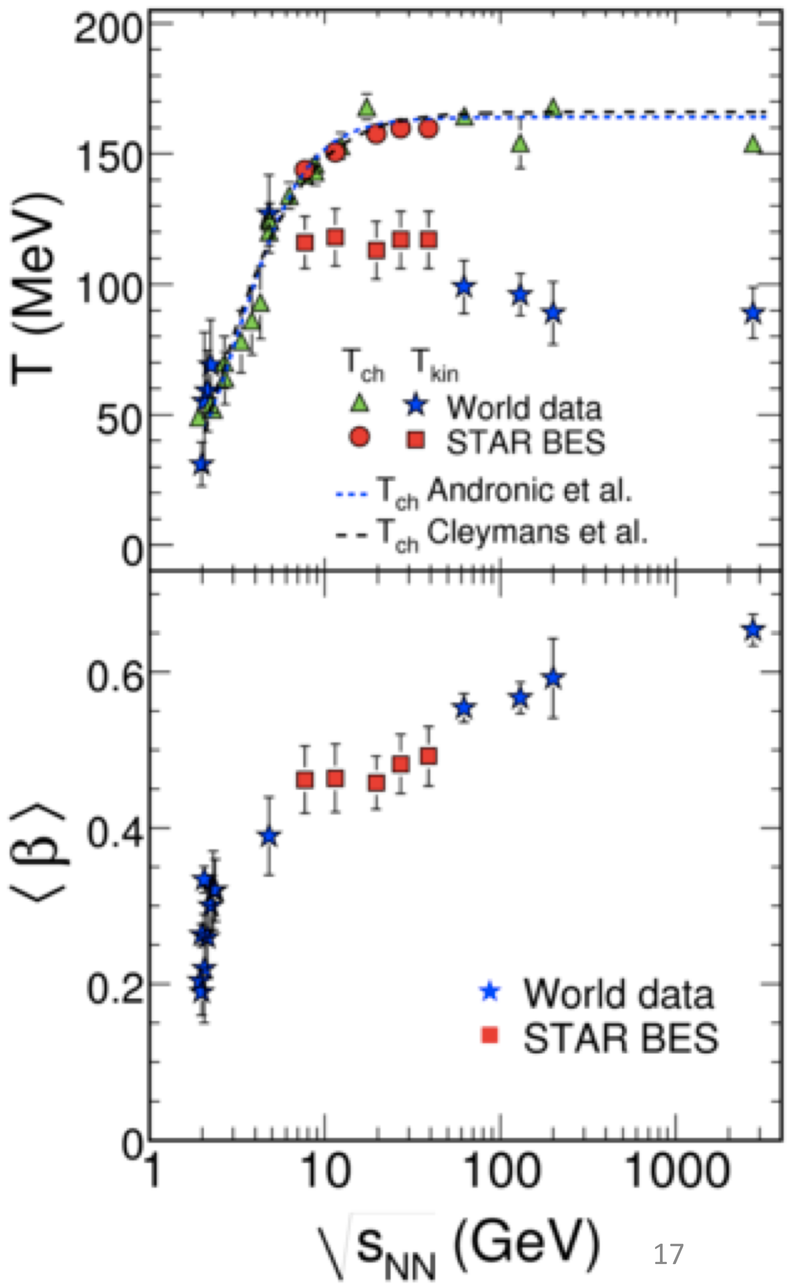
From particle yields and momentum spectra, obtain temperatures and chemical potentials at freeze-out

Whether the chemical freeze-out is at the phase transition boundary is still in debate.

Regardless, STAR data cover a large range from
μ_B = 20MeV to 700MeV
with large PID coverage over rapidity-azimuthal-p_T

A foundation to search for Critical Point

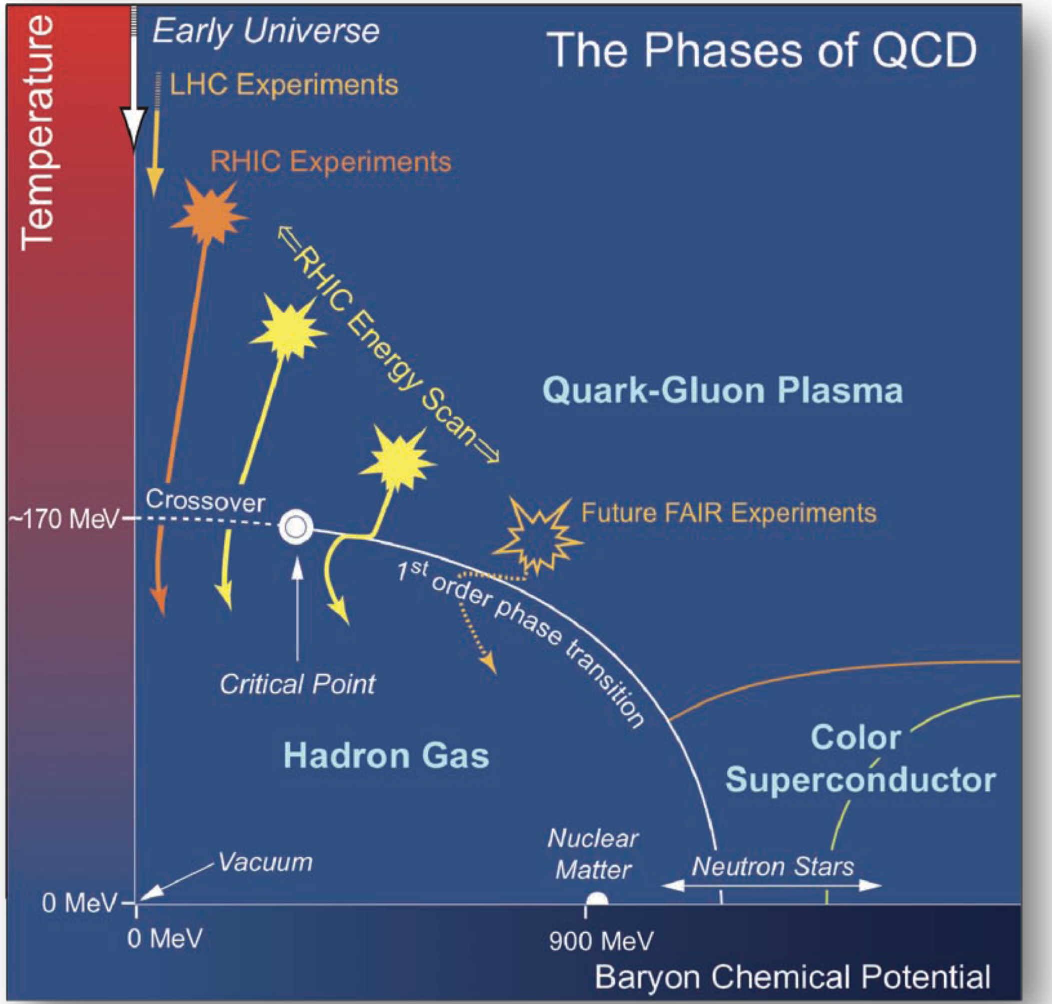
STAR, PRC 96 (2017)



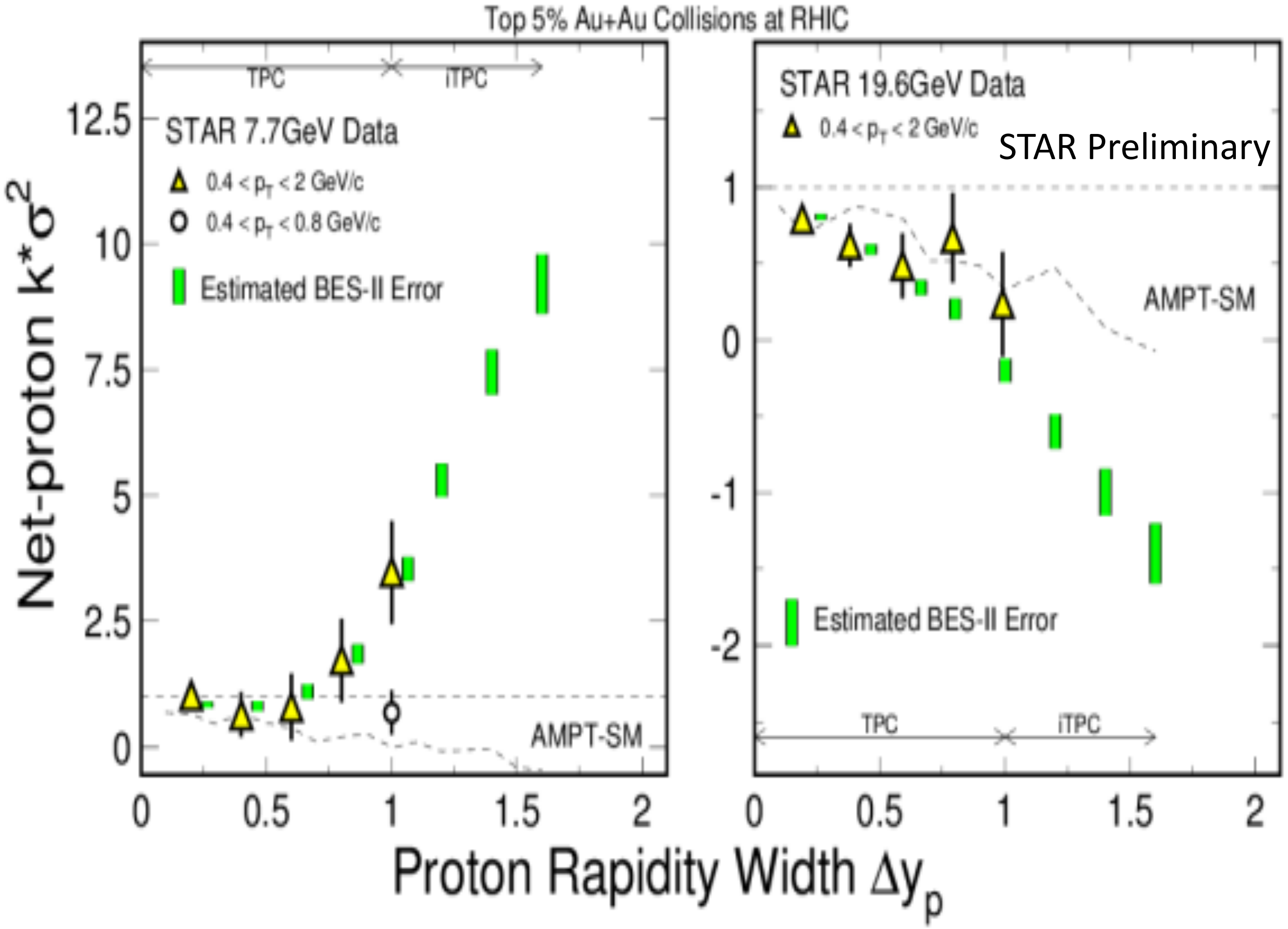
Turn proton numbers into correlation strength

Run 10-14 BES-I, run 19-21 BES-II

US Long Range Plan 2007

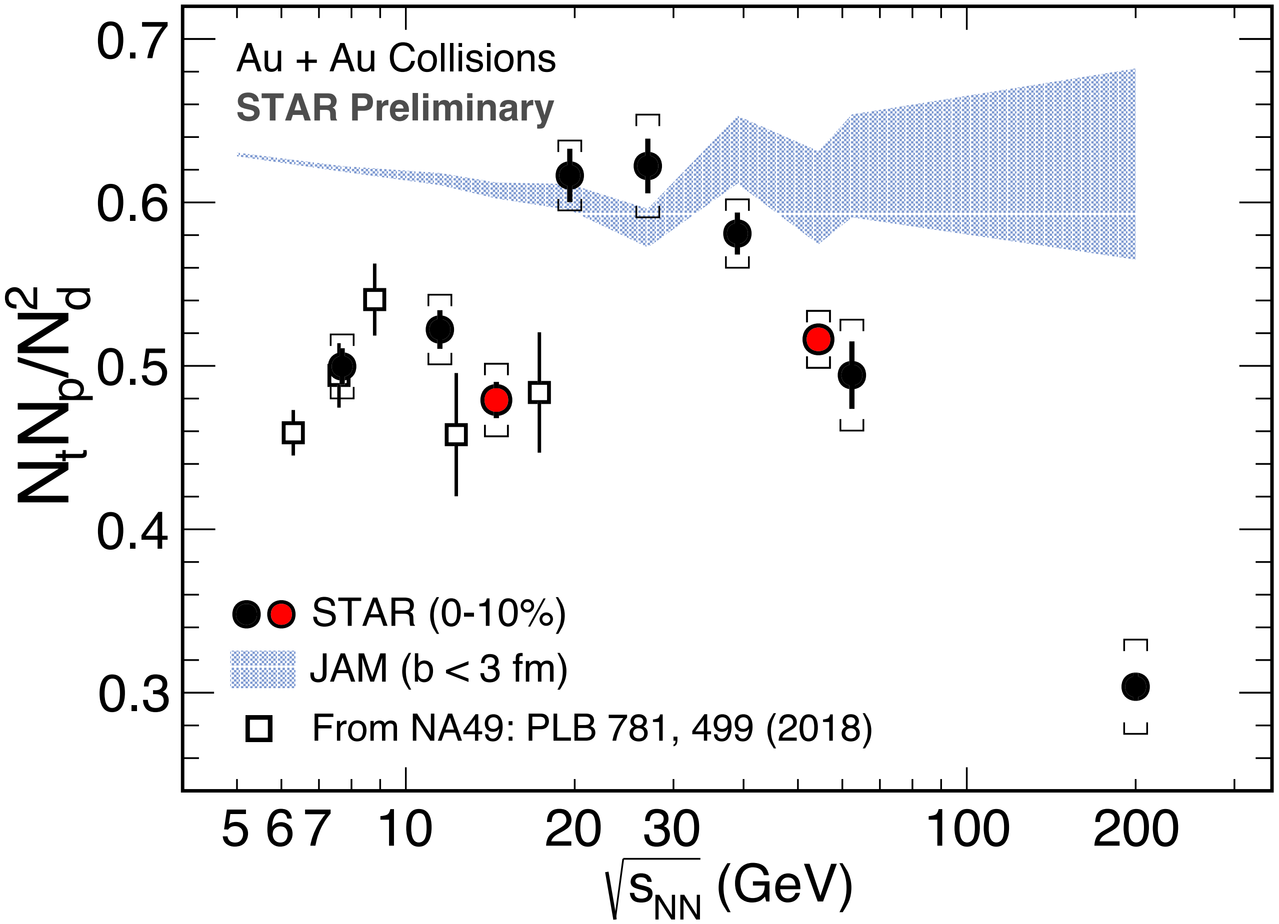


STAR: Phys. Rev. Lett. **112** (2014) 32302; Phys. Rev. Lett. **113** (2014) 92301; arXiv: 2001.02852



C2,C4,C6 for Critical Point Search and crossover assessment

Turn nucleus yield into nucleon density fluctuations



Dingwei Zhang, QM2019

$$N_t \cdot N_p / N_d^2 = g(1 + \Delta n),$$

$$with\ g = 0.29$$

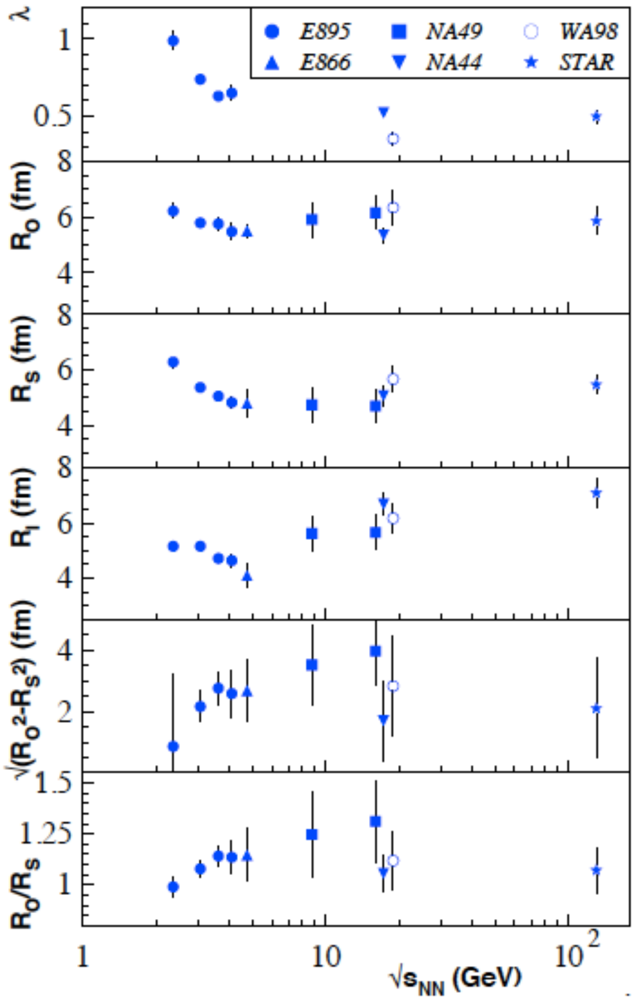
Yield ratio is related to neutron density fluctuations.

Yield ratio shows non-monotonic behavior on collision energy in 0-10% Au+Au collisions.

Flat energy dependence of yield ratio observed in JAM model - does not describe data.

Turn source size into critical exponents

Two-pion correlation functions in Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV have been measured by the STAR (Solenoidal Tracker at RHIC) detector. The source size extracted by fitting the correlations grows with event multiplicity and decreases with transverse momentum. Anomalously large sizes or emission durations, which have been suggested as signals of quark-gluon plasma formation and rehadronization, are not observed. The HBT parameters display a weak energy dependence over a broad range in $\sqrt{s_{NN}}$.



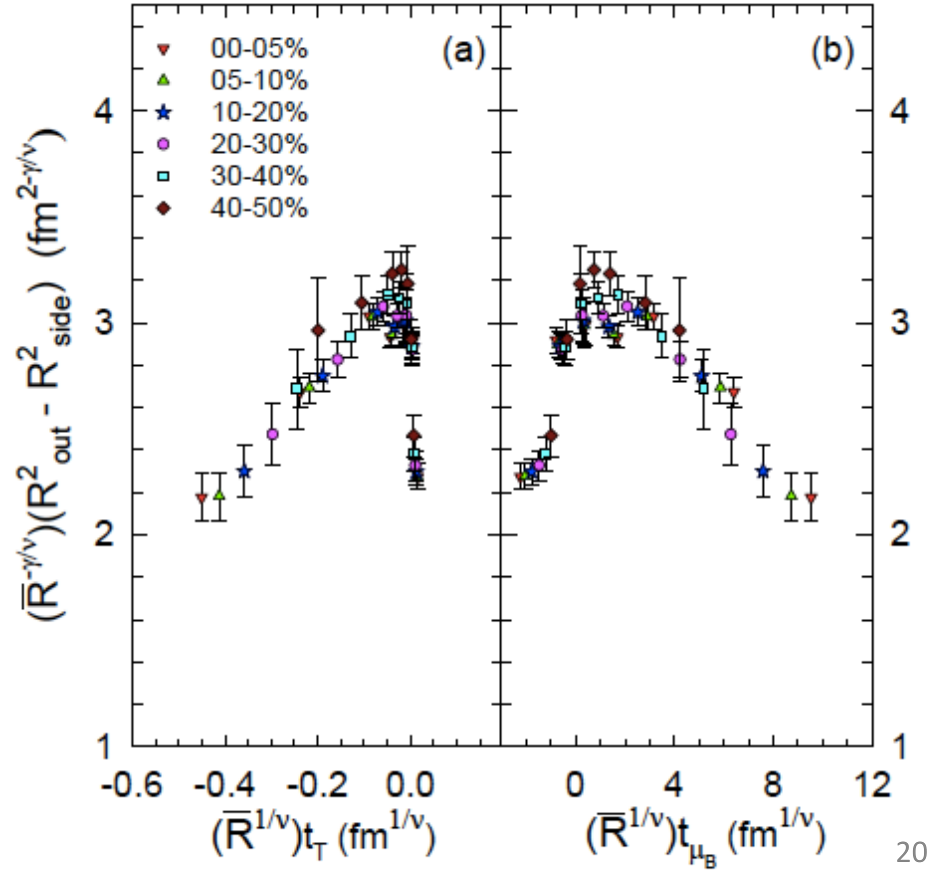
STAR, PRL 2001

Theory prediction before RHIC order of magnitude difference in source size

After more than a decade, And detailed study (operation) difference in the difference is 50% but is as striking

Excitation functions for the Gaussian emission source radii difference ($R^2_{\rm out} - R^2_{\rm side}$) obtained from two-pion interferometry measurements in Au+Au ($\sqrt{s_{NN}}$ = 7.7 – 200 GeV) and Pb+Pb ($\sqrt{s_{NN}}$ = 2.76 TeV) collisions, are studied for a broad range of collision centralities. The observed non-monotonic excitation functions validate the finite-size scaling patterns expected for the deconfinement phase transition and the critical end point (CEP), in the temperature vs. baryon chemical potential (T, μ_B) plane of the nuclear matter phase diagram. A Finite-Size Scaling (FSS) analysis of these data indicate a second order phase transition with the estimates $T^{\rm cep} \sim 165$ MeV and $\mu_B^{\rm cep} \sim 95$ MeV for the location of the critical end point. The critical exponents ($\nu \sim 0.66$ and $\gamma \sim 1.2$) extracted via the same FSS analysis, places the CEP in the 3D Ising model universality class.

R. Lacey, PRL 2014



1. FREE QUARKS 自由夸克
2. EXCITED VACUUM 真空激发态

Quark Matter 1995

Nobel Prize 1957

1. TWO PUZZLES OF MODERN PHYSICS

The status of our present theoretical structure can be summarized as follo

QCD (strong interaction)

$SU(2) \times U(1)$ **Theory** (electroweak)

General Relativity (gravitation).

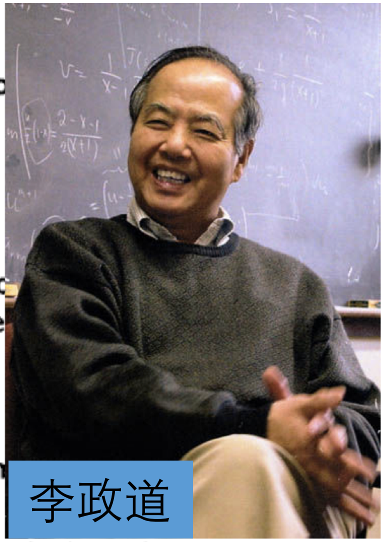
However, in order to apply these theories to the real world, we need a set o parameters, all of unknown origins. Thus, this theoretical edifice cannot be complete.

The two outstanding puzzles that confront us today are:

i) **Missing symmetries** - All present theories are based on sym most symmetry quantum numbers are *not* conserved.

ii) **Unseen quarks** - All hadrons are made of quarks; yet, no individual quark can be seen.

These two puzzles have been with us for several decades, beginning with parity nonconservation in the fifties and CP and time reversal violations in the sixties. They are perhaps of an equal profundity as the puzzles which faced our predecessors around the turn of the century.



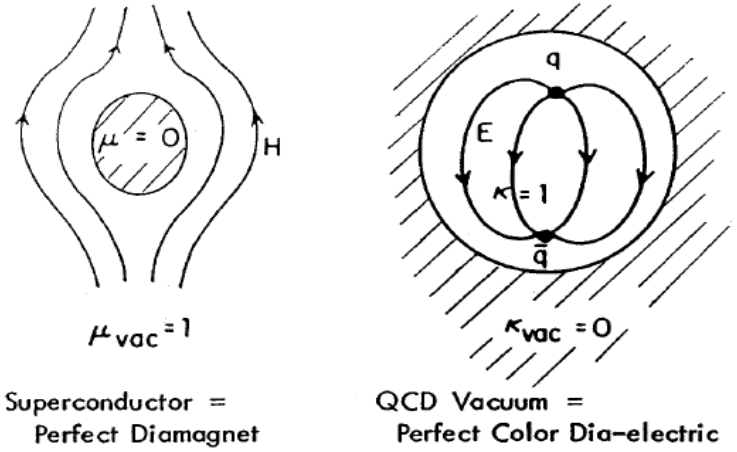


Figure 1. Superconductivity in QED vs. quark confinement in QCD.

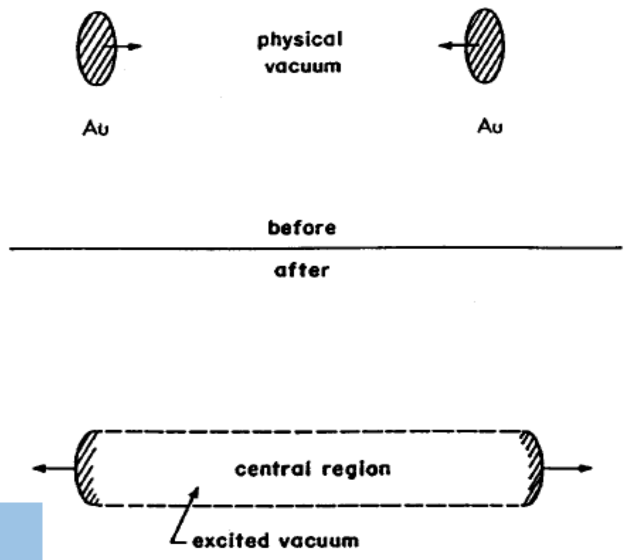


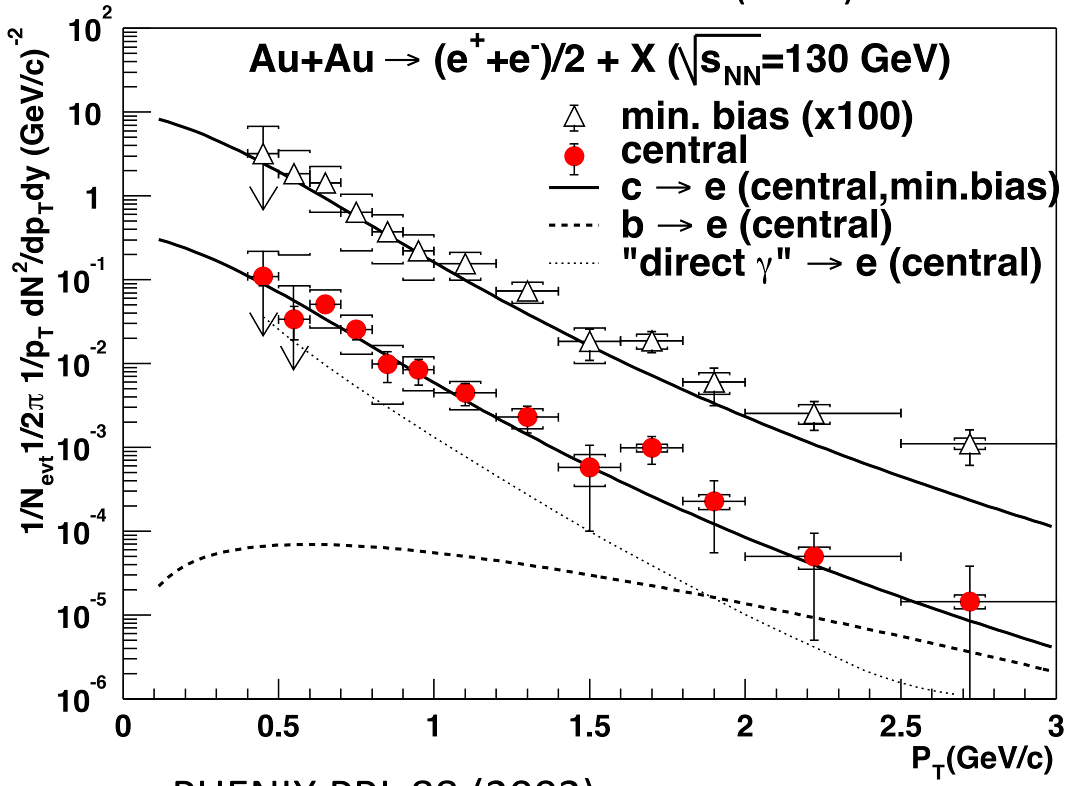
Figure 2. Vacuum excitation through relativistic heavy ion collisions.

1. Color Screening of Quarkonia, Charm Quark Flow
2. In-medium ρ spectral function, thermal radiation, Chiral Magnetic Effect

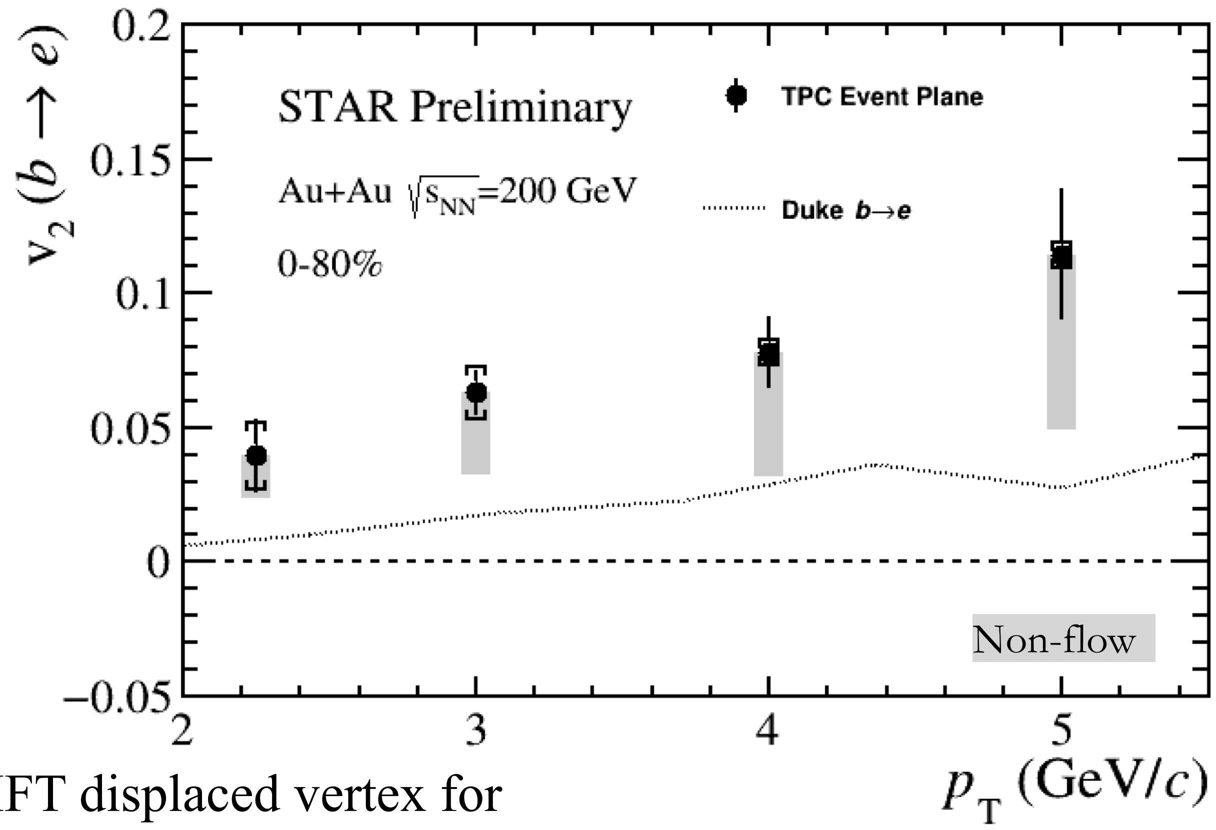
Open charm and bottom

Matthew Kelsey, QM19

From first paper by PHENIX in 2002 to current measurements of displaced secondary vertex (both PHENIX and STAR), full charm reconstructions (STAR)



PHENIX PRL 88 (2002)

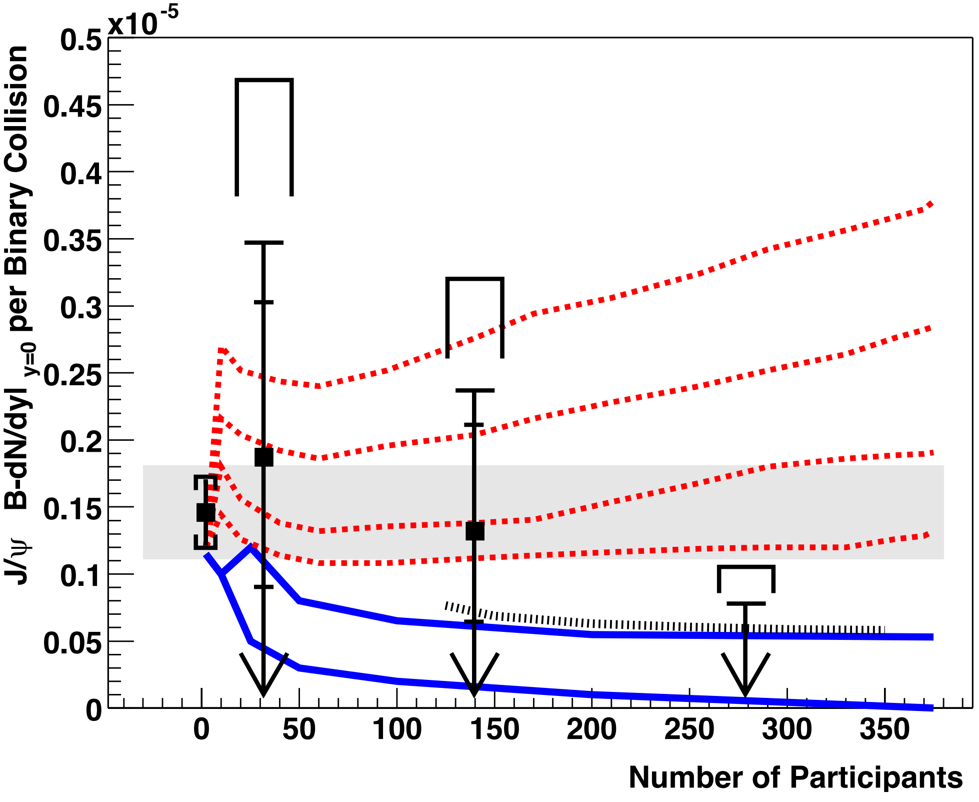


- Using HFT displaced vertex for heavy-flavor decay topology
- Observation of Λ_c/D enhancement: arXiv:1910.14628, PRL
- New charmed electron $v_{1,2}$ are consistent with D^0 measurements

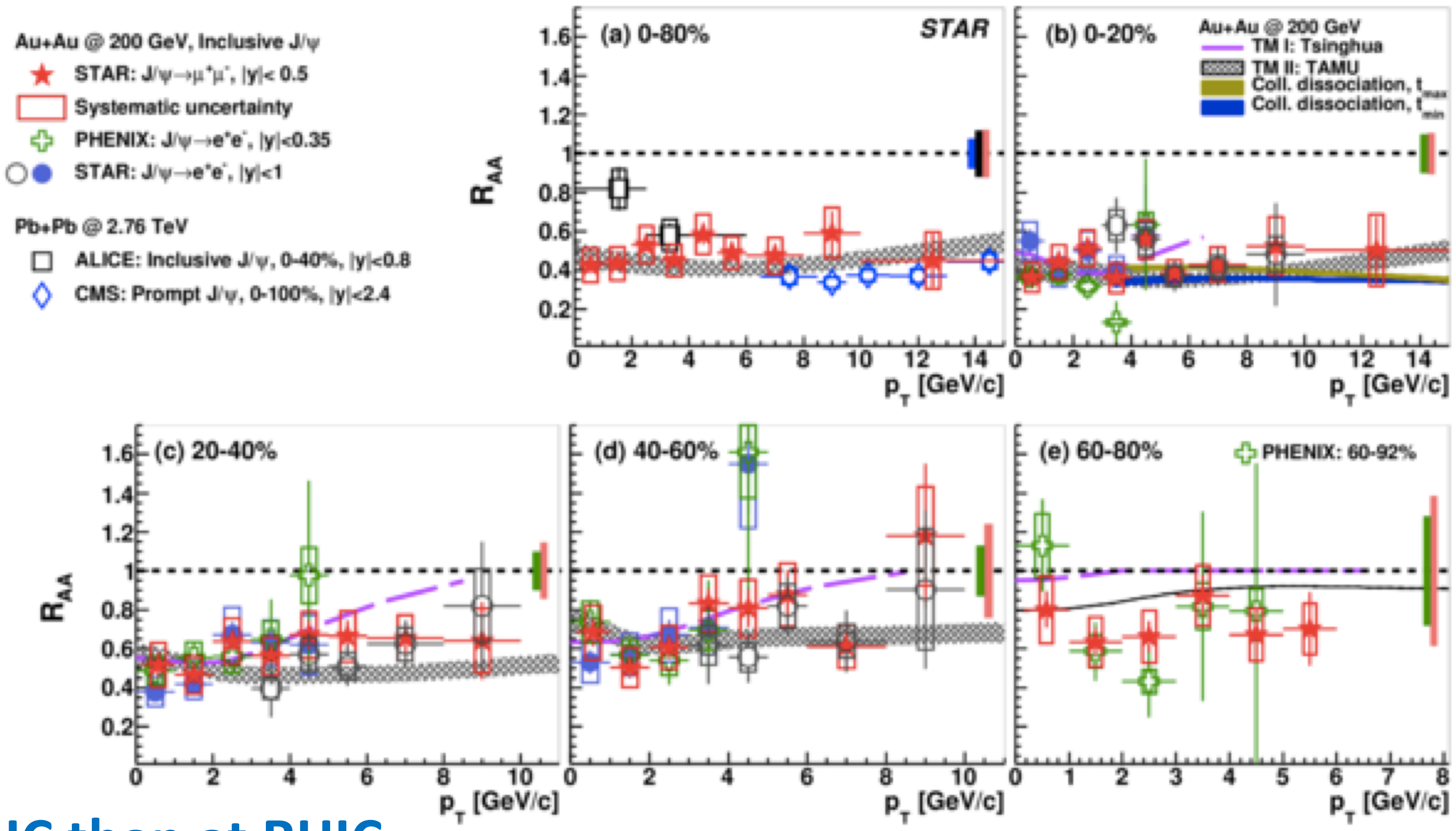
- **First observation of significant non-zero bottom hadron flow (>3σ) at RHIC**
- **Observation of bottom suppression less than charm at RHIC (>3σ)**

Quarkonia, best probes of free quarks

PHENIX, PRL (2002)



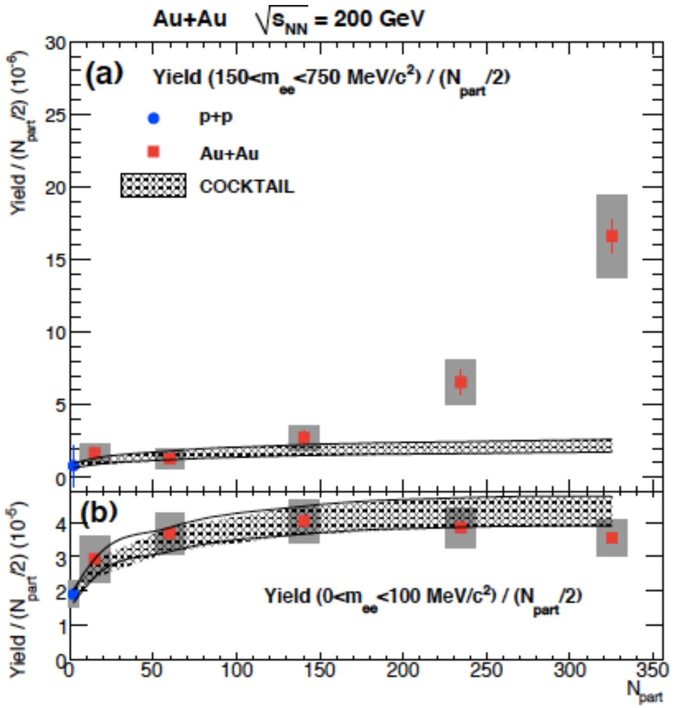
STAR, PLB 797 (2019)



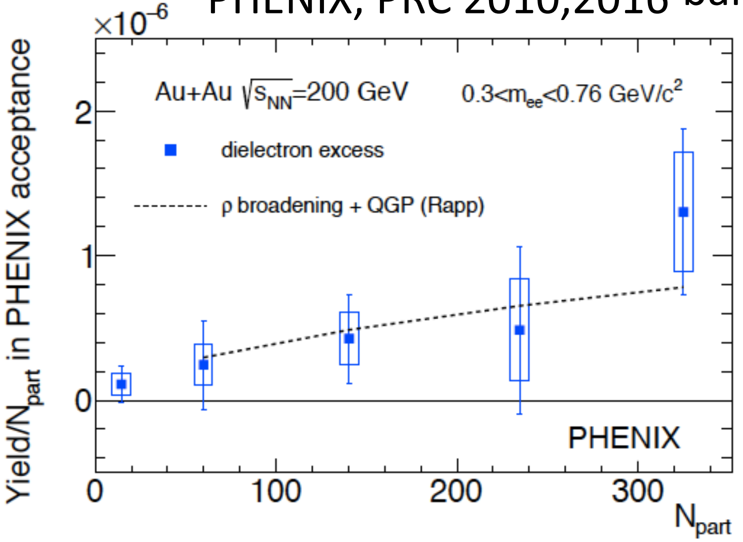
- **Less suppression at low p_T at LHC than at RHIC**
- **Similar suppression at high p_T**
- **Consistent with color screening, quark coalescence**

Upsilon states with STAR MTD and sPHENIX

Chiral Symmetry Restoration



PHENIX, PRC 2010,2016

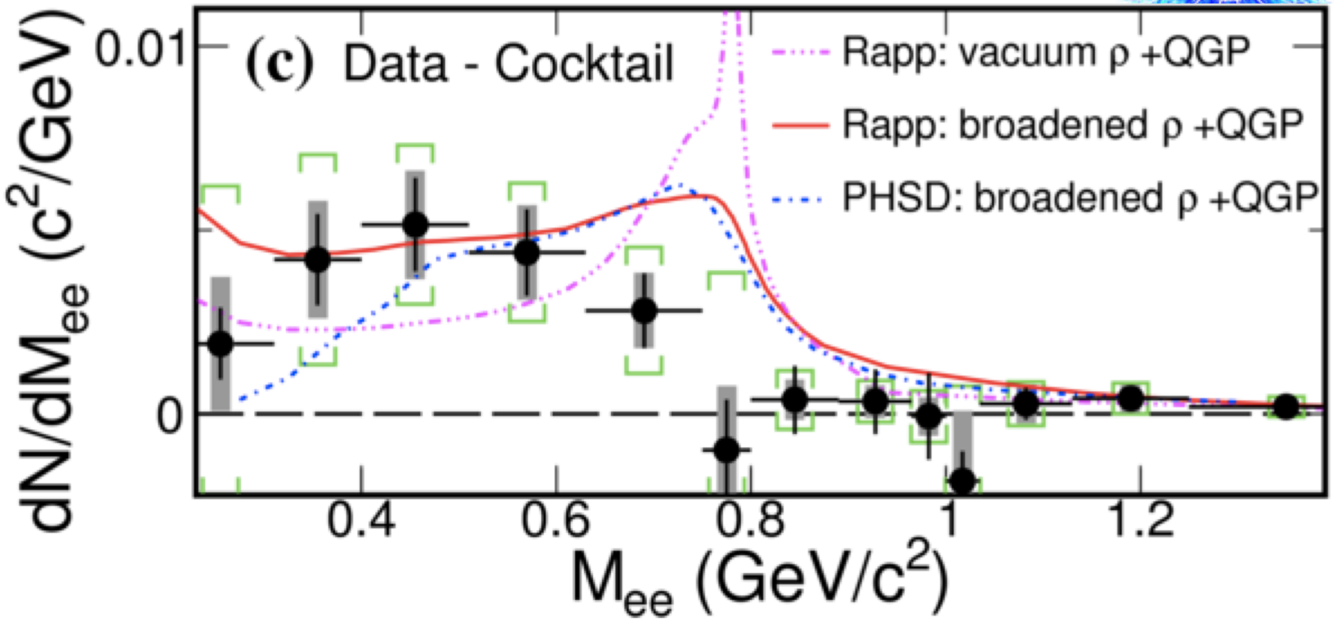


When hadron structure disappears, we are achieving symmetry restoration

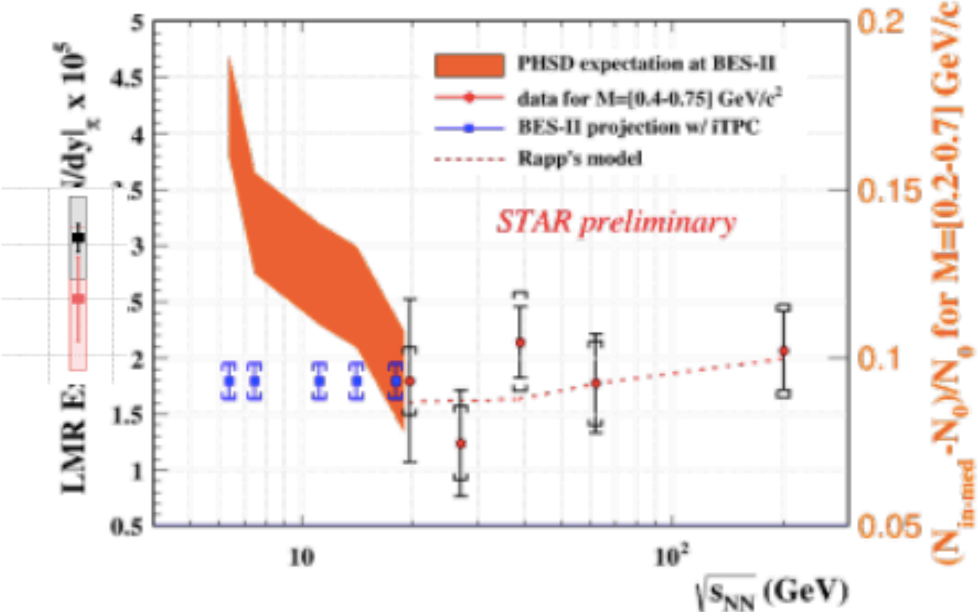
Best way to study this is rho vector meson in-medium effect

That effect depends on temperature (high energy), baryon density (low energy)

STAR, PRL 113 (2014)



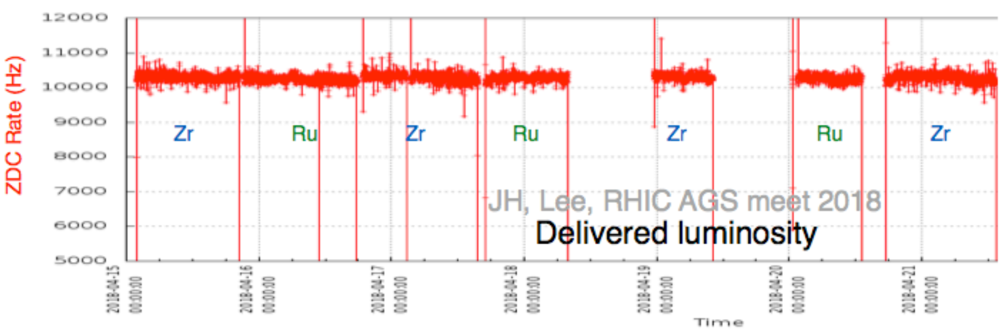
0.3<M_{ee}<0.7 GeV/c^2

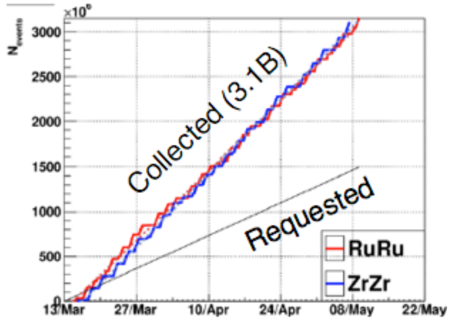


Chiral Magnetic Effect

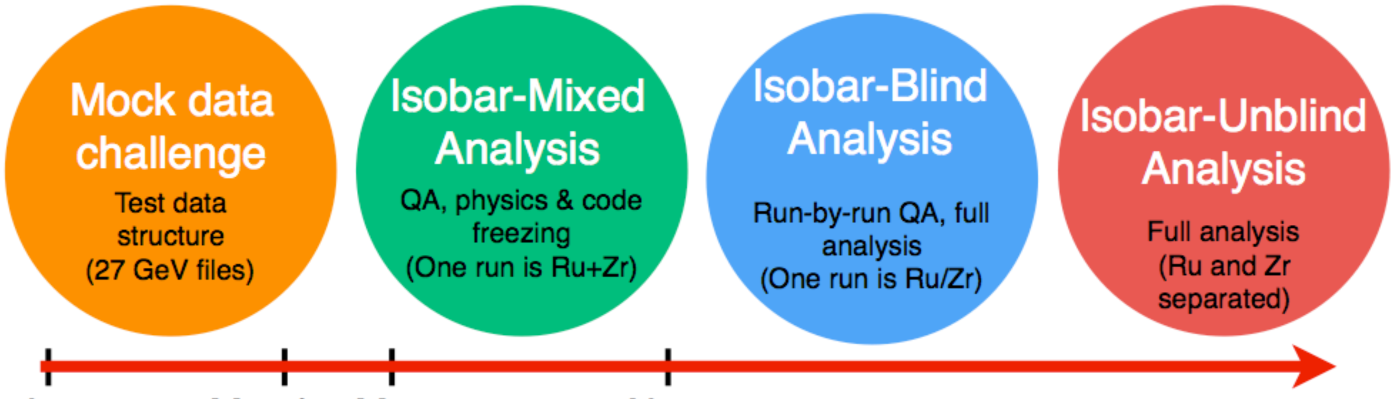
Chiral Symmetry Restoration + Magnetic Field + QCD Topological Charge

Jie Zhao, QM2019

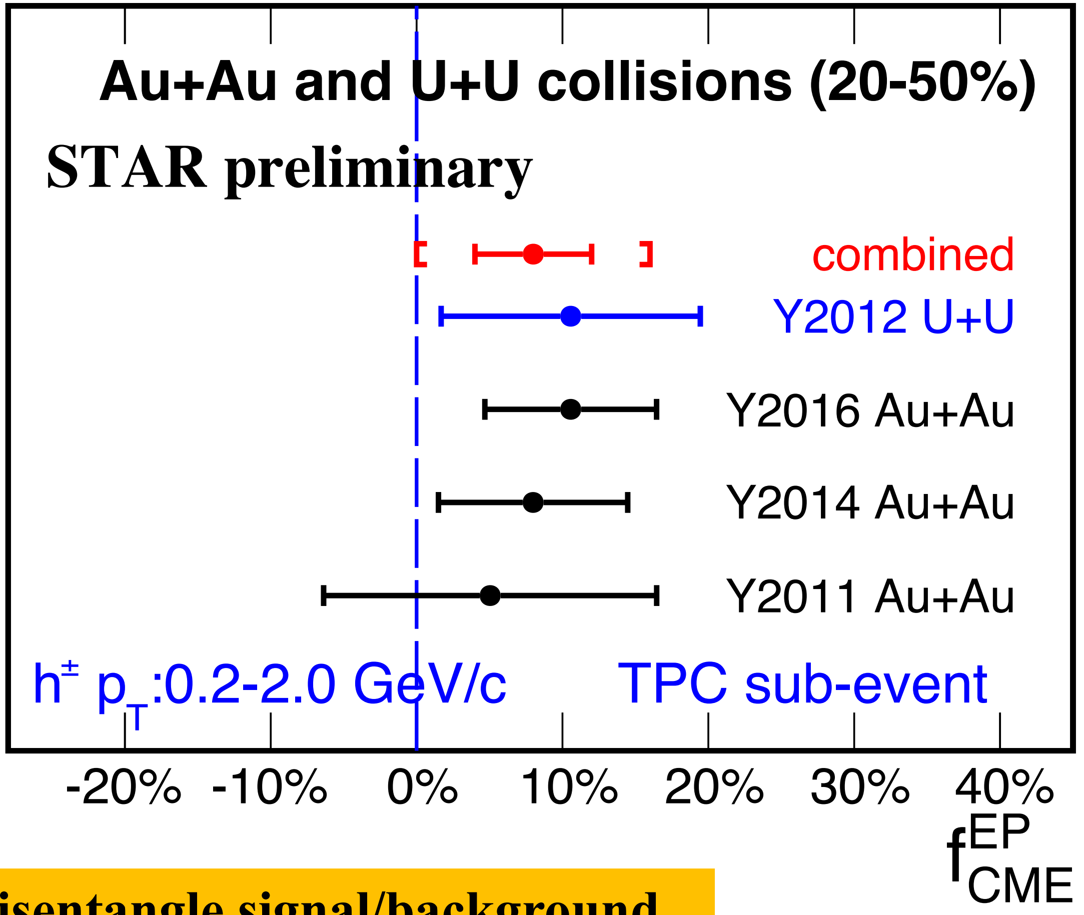




3.1B events for both Ru+Ru, Zr+Zr collected over 8 weeks
Plans for blind analyses of the data was laid down from the beginning



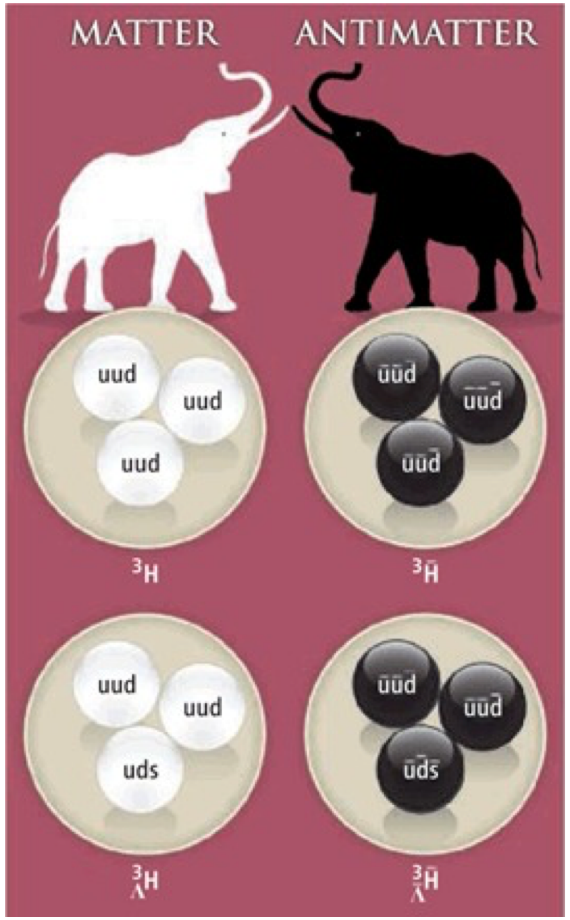
Blinding method document
in arXiv: 1911.00596



Ψ_{PP} and Ψ_{RP} to disentangle signal/background.
Fractions are extracted in U+U and Au+Au,
Averaged CME fraction = (8±4±8)%

Many other important discoveries

- Discovery of first antimatter hypernucleus (SCIENCE 2010)
- Discovery of heaviest antimatter nucleus (NATURE 2011)
- Interactions of antimatter protons (NATURE 2015)
- Binding energy of hypertriton (NATURE Physics 2020)
- Vacuum Birefringence (in process)
- …

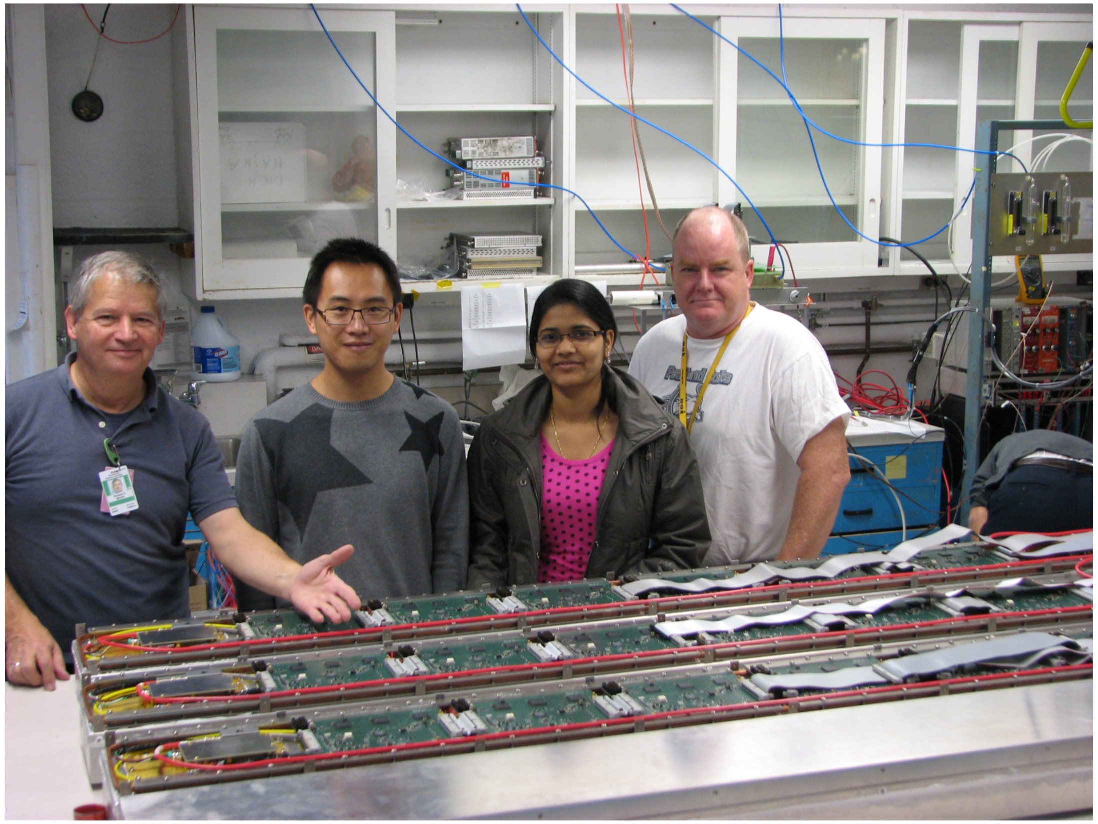


Many made this endeavor possible

My heroes:
Leadership and Service to the community
From beginning, work behind the scene
Promote generations of scientists

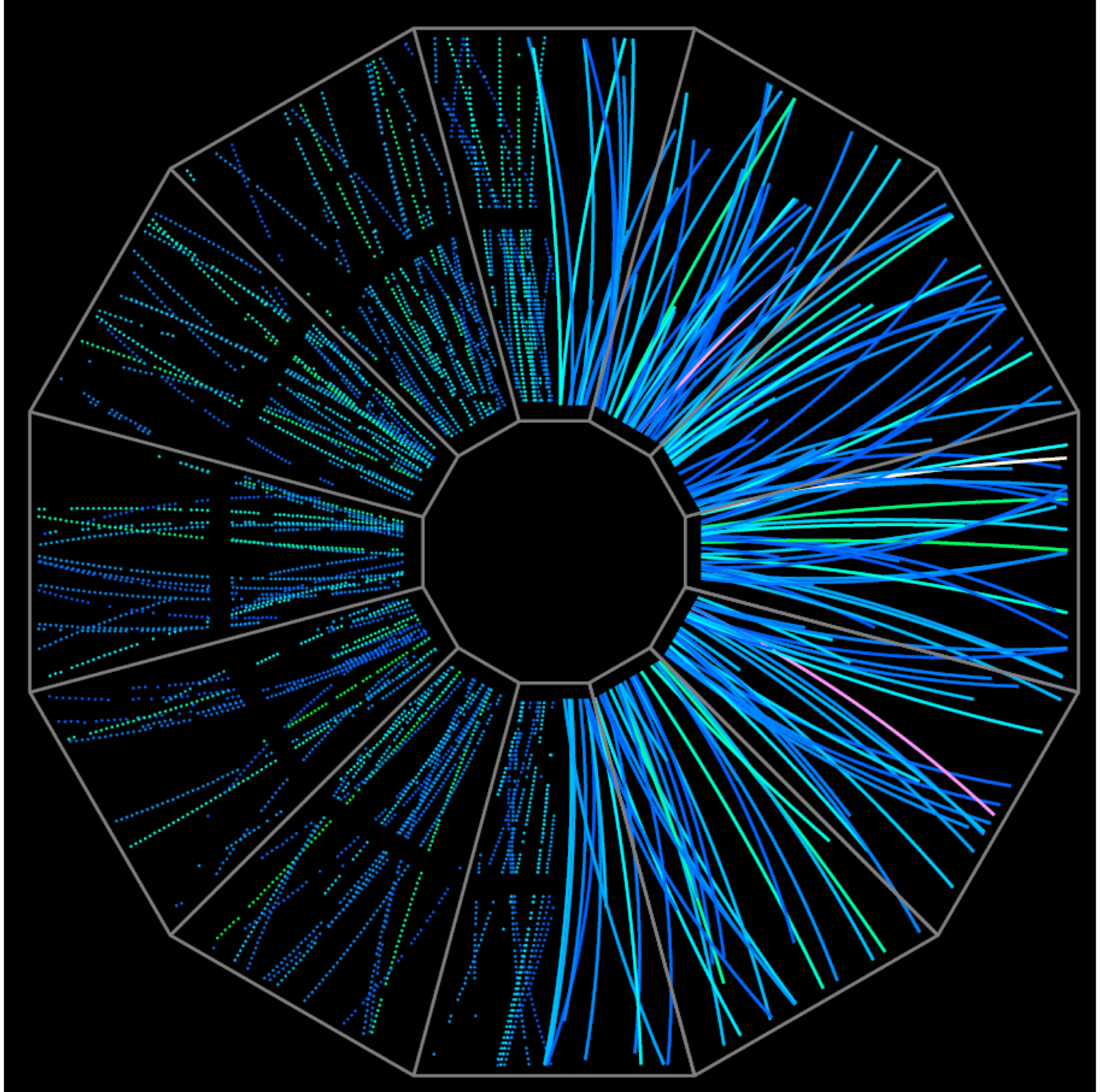
Dr. Richard (Dick) Majka 1946-2020 (Yale University)

陈宏芳教授 1938-2017（中国科学技术大学）



DOE iTPC project
Closeout Review (05/02/19):
Panel:
Howard Fenker (Jlab)
Hendrik Schatz (MSU)
Richard Van Berg (UPenn)
Elizabeth Bartosz (DOE)

First-line comment:
"This is a success story!"



It has been an incredible 6-year run
ending on a happy note.

I wouldn't trade for anything else.