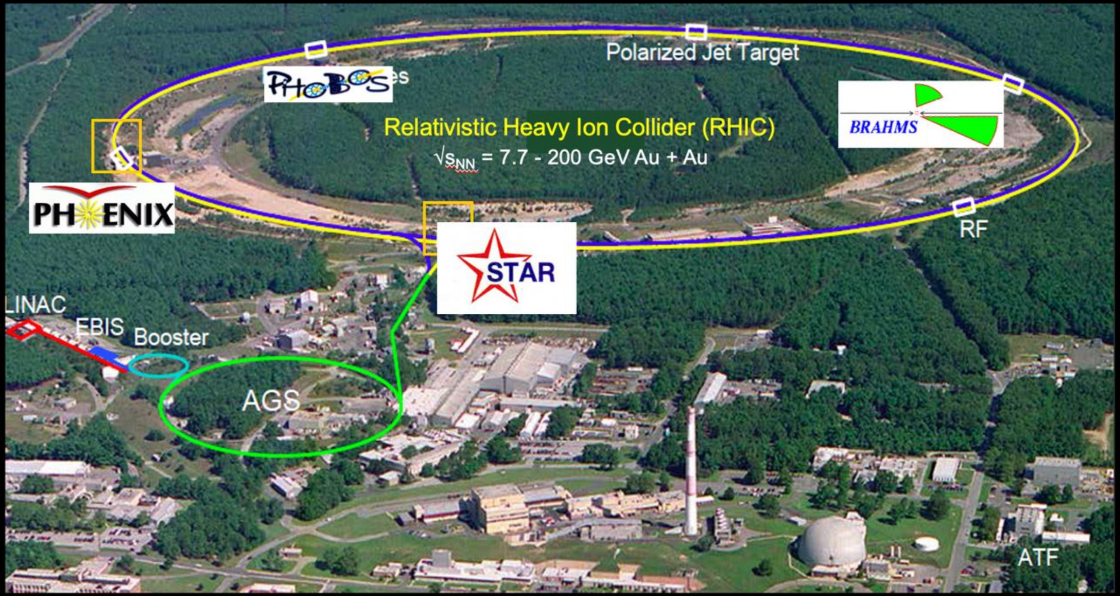
Impact of RHIC on the LHC Heavy-ion Program

Early RHIC

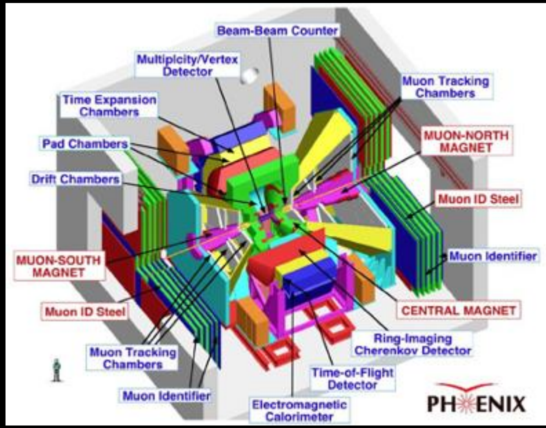


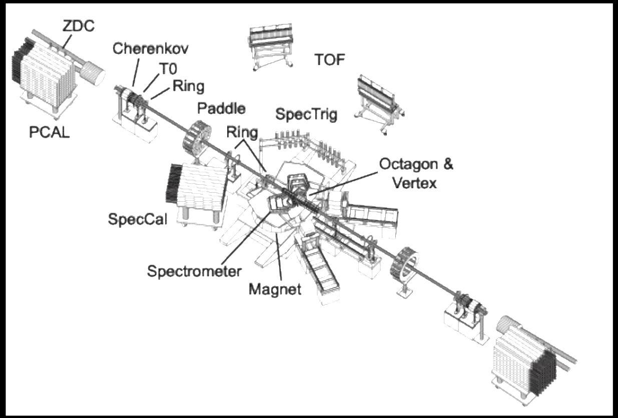
Cover 4 decades
of energy
in center-of-mass

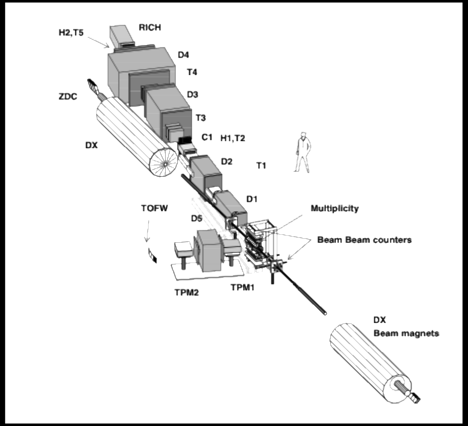
RHIC Important to the LHC!

Scientific Legacy of RHIC

- science
- experiments
- methodologies

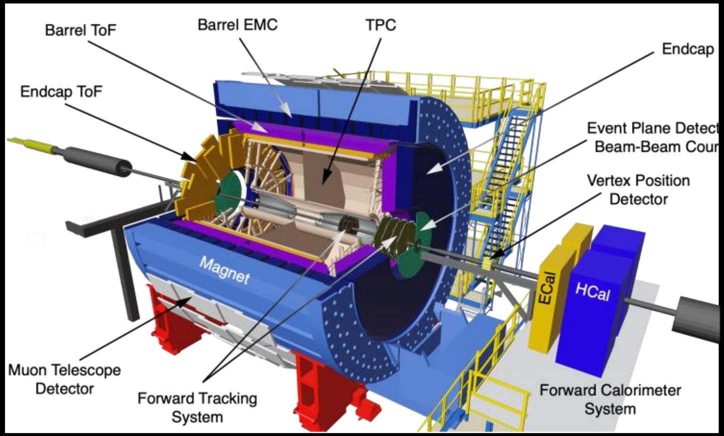


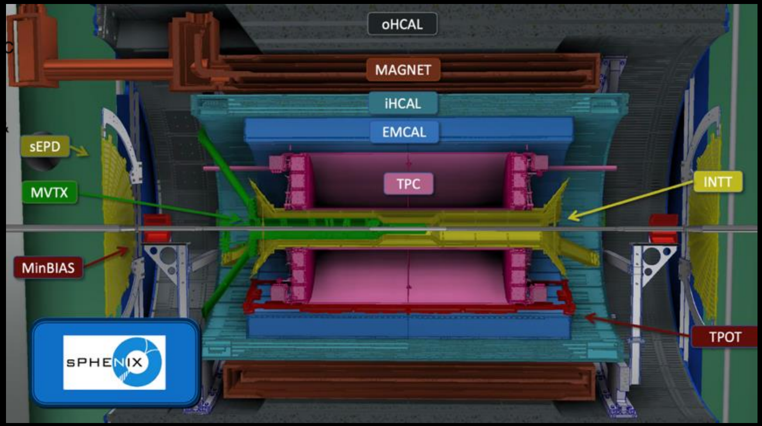




Sociological Culture from RHIC

- collaborative culture & values
- community structure & attitudes
- leadership principles & organization





RHIC Launched & Defined the Field -> sQGP Discovery!

RHIC established the sQGP paradigm

overturned any expectations or misconceptions of weak coupling

QGP is strongly-coupled -> sQGP

Collective flow dominates

Large v_2 (elliptic flow) –> Near-perfect fluid

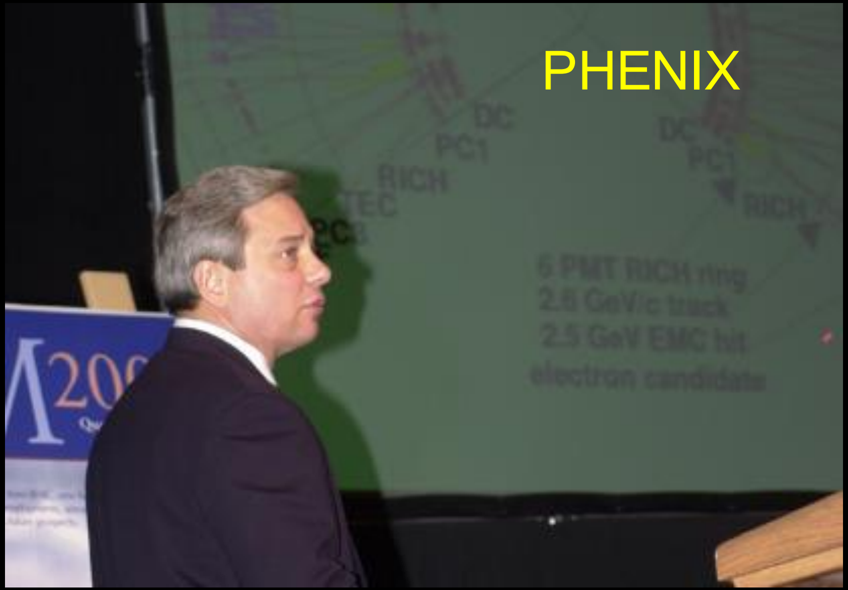
Rapid thermalization ~1 fm/c

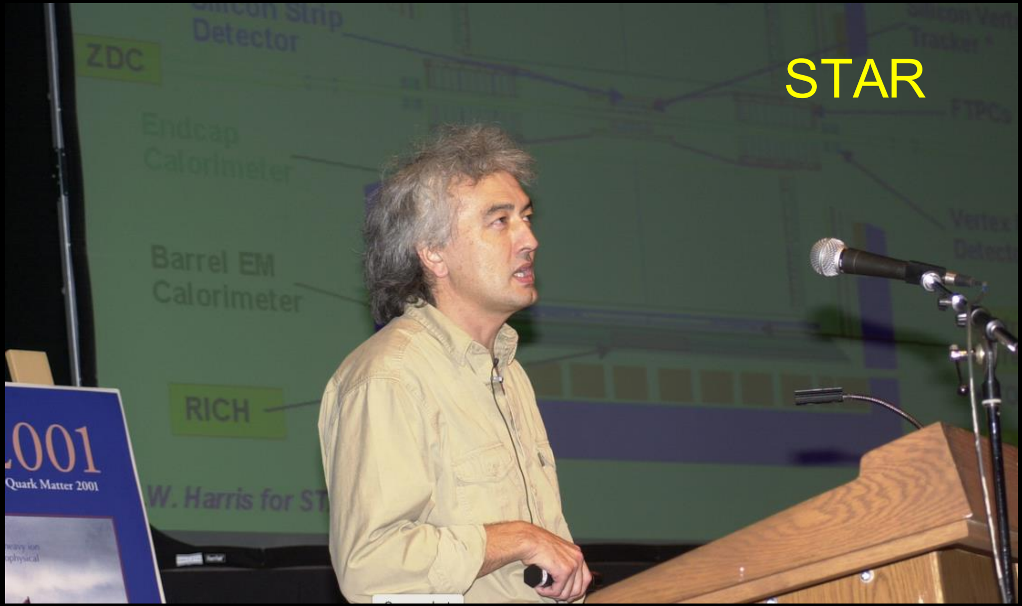
Hard probes interact strongly

High-p_T particles are suppressed

Jets are quenched

The Dawn of RHIC Physics





PHOBOS

The Dawn of RHIC Physics (2001)

Welcome to the Quark Matter 2001 Home Page

QM2001 In The News

- Quark Matter 2001 Features First RHIC Results - *Brookhaven Bulletin, Feb. 2, 2001 (PDF Format)*
- New Collider Sees Hints of Quark-Gluon Plasma - *Science. Jan. 2001*
- On the Verge of Re-Creating Creation. Then What? - *New York Times Week In Review, Jan. 28, 2001*
- Lab Heralds a New Era - *New York Newsday Discovery Section, Jan. 30, 2001*
- Trying to Cook a Soup of Free-Range Quarks - *New York Times Science Section, Jan. 23, 2001*
- Big Bang Scientists Get Dense - *Wired News, Jan. 23, 2001*
- A Coming-Out Party for a Particle Collider - *New York Times Long Island Section, Jan. 21, 2001*
- Experiments on Dense Matter Evoke Big Bang - *New York Times, Jan. 16, 2001*
- Optimism About Ion Collider - *New York Newsday, Jan. 16, 2001*
- Highest Density of Matter Created - *Yahoo! News (AP), Jan. 16, 2001*

Key Measurements/Observables behind RHIC Discoveries!

Collective Flow Dominates –> reaches hydrodynamic limit

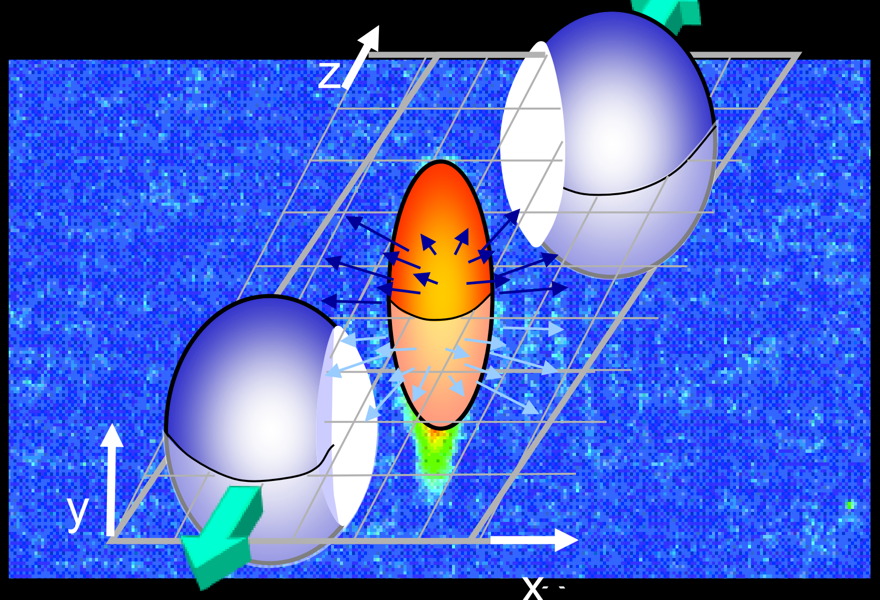
- Elliptic flow large v_2 (p_T)
- Flow harmonics v_2 (p_T), v_3 (p_T), v_4 (p_T),…..

Rapid thermalization ~1 fm/c

- Elliptic flow / eccentricity –> v_2 (p_T) / ε
- Constituent quark scaling & mass ordering of collective flow –> v_2 (p_T/q) and v_2 (E_T/q)
- Identified hadron spectra & integrated yield ratios at mid-rapidity –> γ_s -> 1

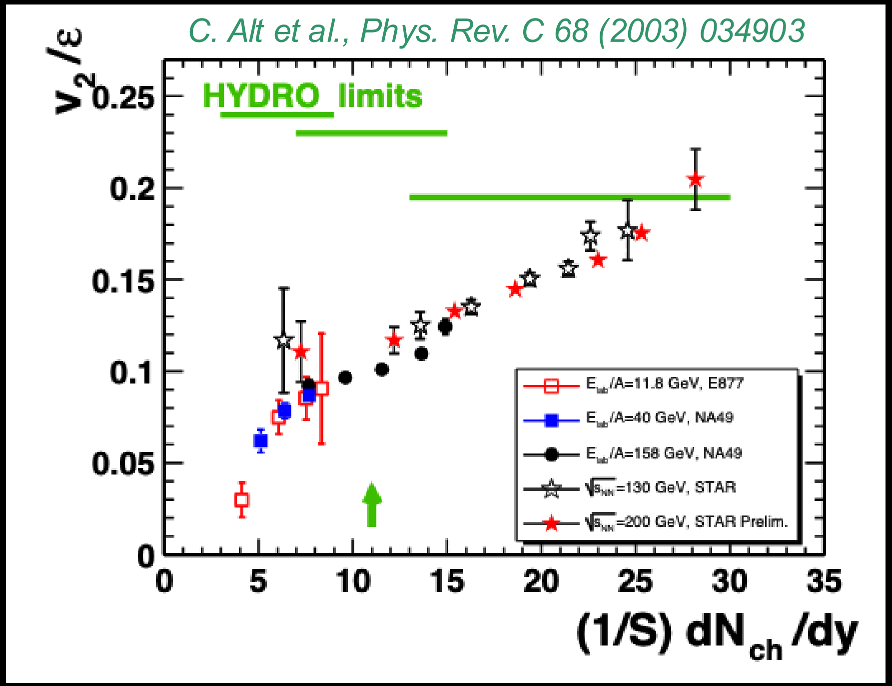
Hard Probes Interact Strongly

- High-p_T particles are suppressed –> R_{AA} (p_T)
- Jets are quenched –> R_{AA} (p_T, flavor, r_{jet})

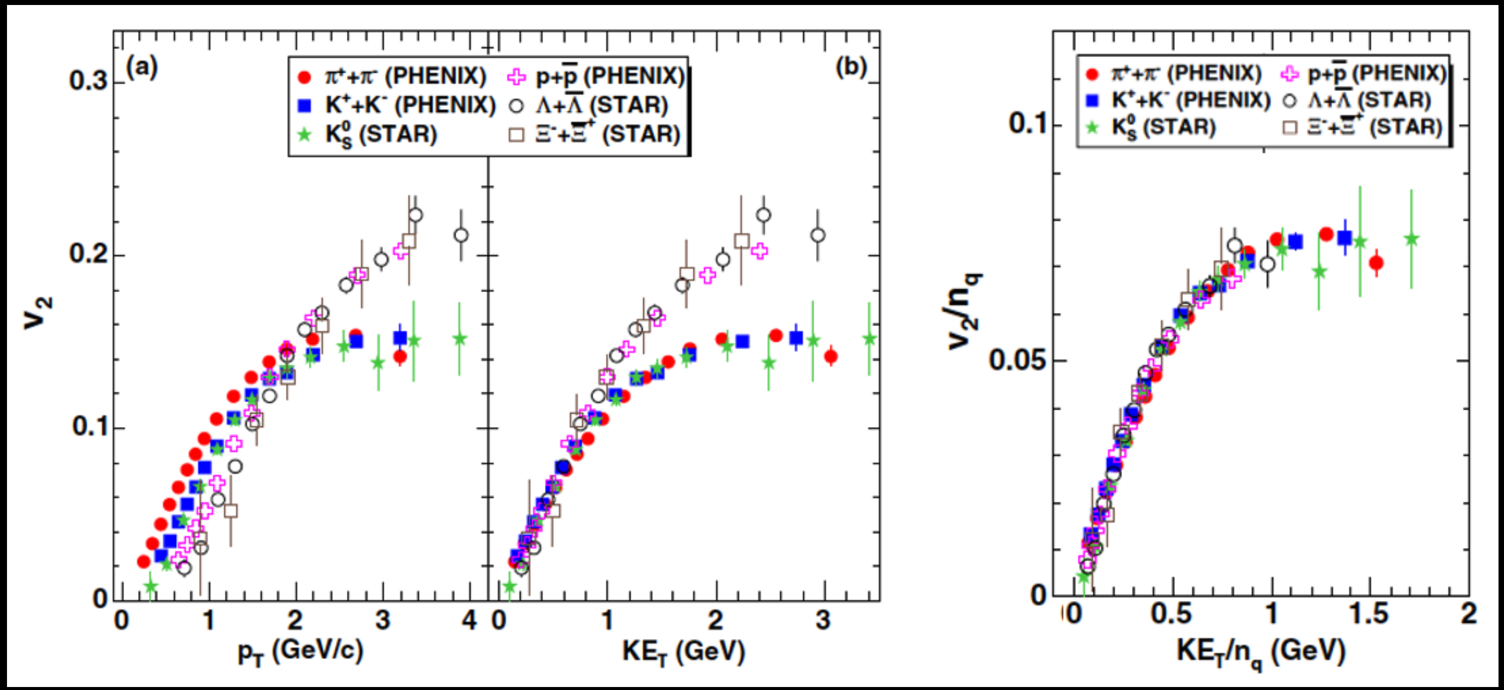


Elliptic Flow

- Reaches hydrodynamic limit
- Rapid thermalization

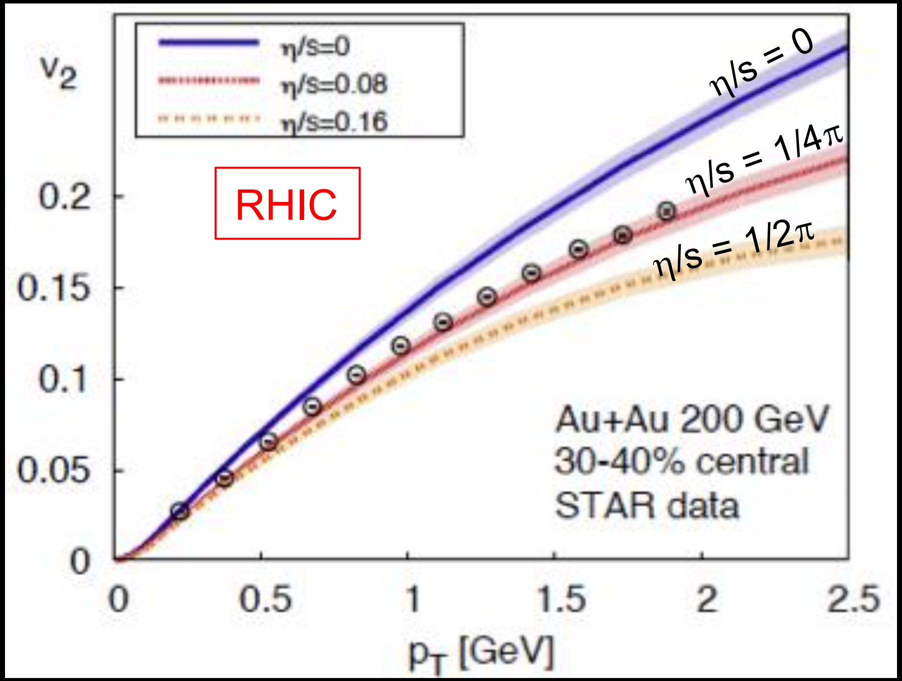


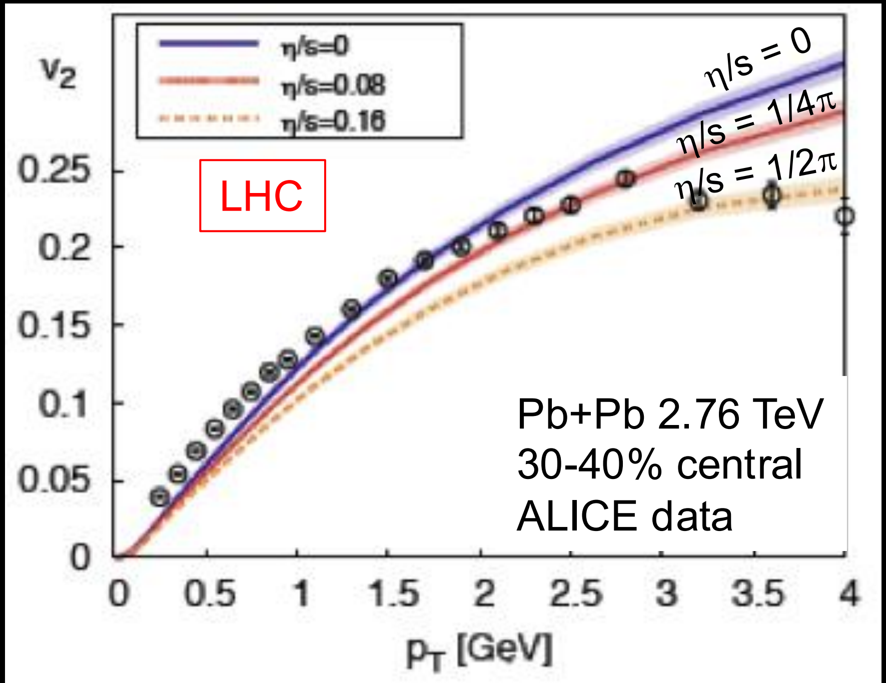
K. H. Ackermann et al., STAR, PRL 86 (2001) 402



A. Adare et al. PHENIX, PRL 98 (2007) 162301

Flow Consequences:
A Strongly-Coupled Medium with Ultra-low η/s (shear viscosity / entropy)





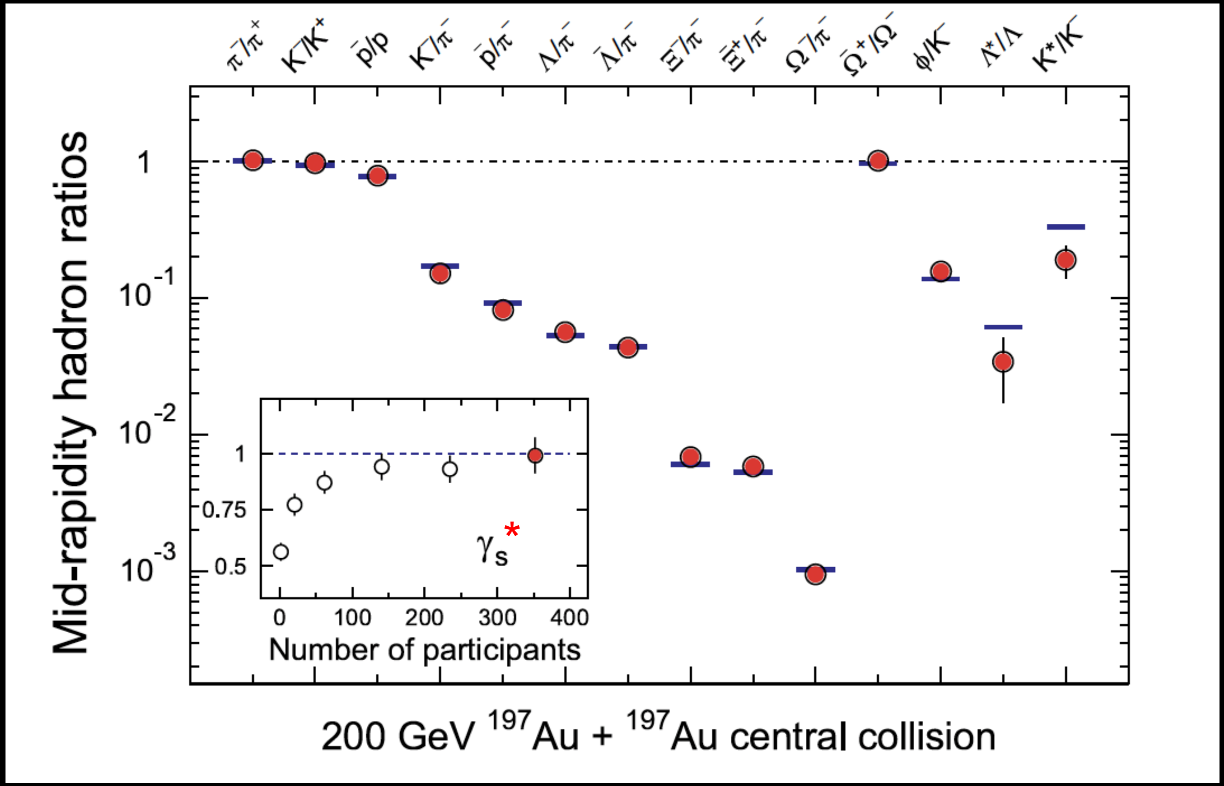
Viscous hydrodynamics calculations: Schenke, et al. PRL 106 (2011) 042301 → $1/4\pi < \eta/s < 1/2\pi$

Universal lower bound on shear viscosity / entropy ratio $\eta/s \rightarrow 1/4\pi$ for a "perfect liquid"

from strong-coupling limit of non-Abelian gauge theories with a gravity dual
(Kovtun, Son, Starinets, PRL 94, 111601 (2005))

Thermalization and Strangeness Saturation

Identified hadron spectra & integrated yield ratios supported thermalization –> γ_s -> 1



STAR Collaboration, J. Adams et al. Nucl. Phys. A 757 (2005) 102–183

- Thermal model gives particle ratios
- * ***S**trangeness is saturated*

* *see B. Muller, "Strangeness and quark gluon plasma" in Hadronic Matter in Collision: HADRON88, pp. 739, 1988*

Key Measurements/Observables behind RHIC Discoveries!

Collective Flow Dominates –> reaches hydrodynamic limit

- Elliptic flow large v_2 (p_T)
- Flow harmonics v_2 (p_T), v_3 (p_T), v_4 (p_T),…..

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- Identified hadron spectra & integrated yield ratios at mid-rapidity -> γ_s -> 1

Hard Probes Interact Strongly

- High-p_T particles are suppressed –> R_{AA} (p_T)
- High-p_T EM-probes NOT suppressed
- Jets are quenched –> R_{AA} (p_T, flavor, r_{jet})

High p_T Particles Suppressed at RHIC!

PRL Cover - Phys. Rev. Lett. 91 (7), 070401
15 August 2003.

PHENIX Collaboration, *"Suppression of hadrons with large transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV,"* Phys. Rev. Lett. 88, 022301

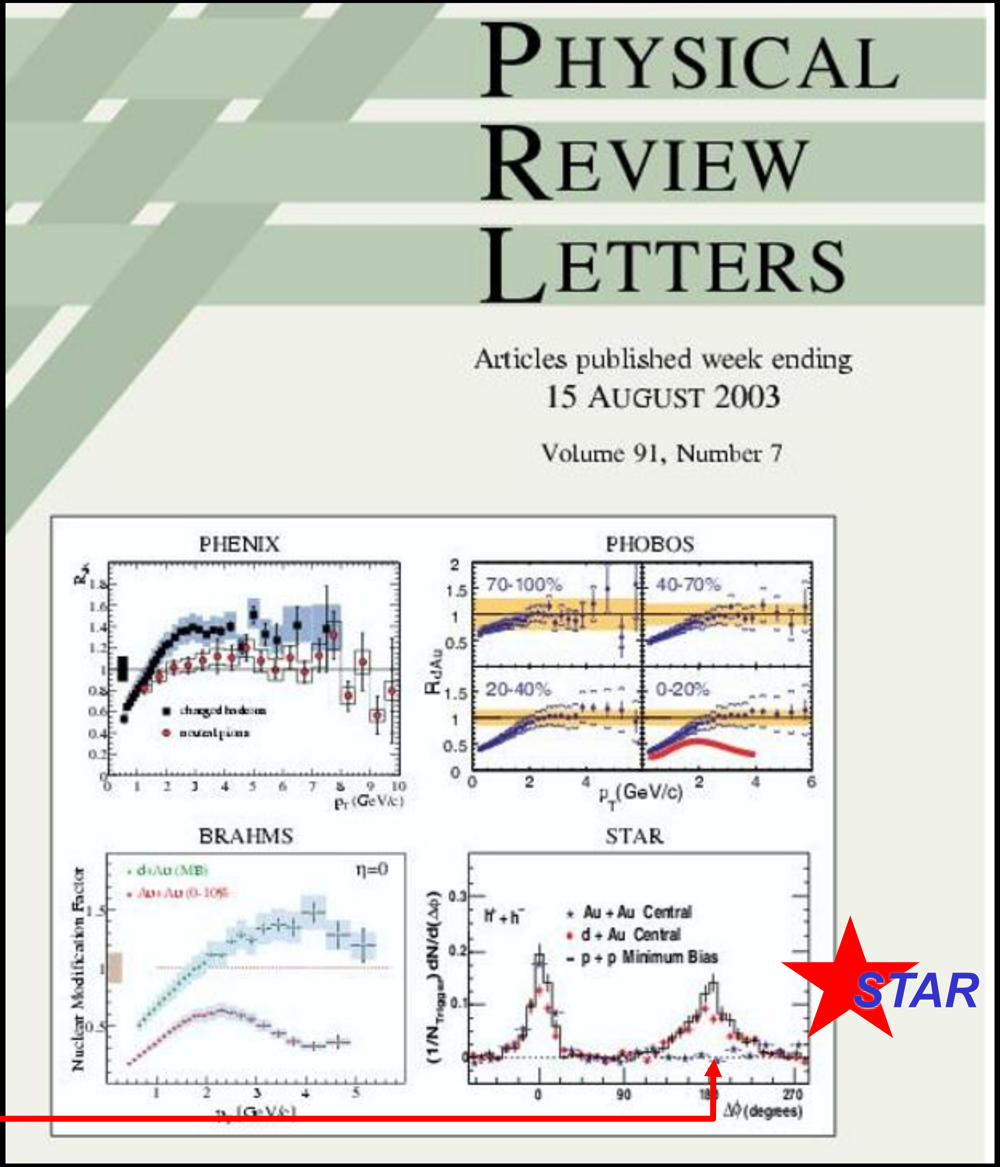
STAR Collaboration, *"Suppression of charged hadron yields at large transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV,"* Phys. Rev. Lett. 89, 202301 (2002).

PHOBOS Collaboration, *"Centrality dependence of charged hadron transverse momentum spectra in d+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV,"* Phys.Rev.Lett. 91 (2003) 072302.

BRAHMS Collaboration, *"Transverse momentum spectra in Au+Au and d+Au collisions at at $\sqrt{s_{NN}}$ = 200 GeV and the pseudorapidity dependence of high p(T) suppression,"* Phys.Rev.Lett. 91 (2003) 072305.

STAR Collaboration, "*Evidence from d+Au Measurements for Final-State Suppression of High-p_T Hadrons in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV* ", Phys.Rev.Lett. 91 (2003) 072304.

Away-side jet quenched



Hard Probes - Jets

Hard Probes Interact Strongly – Jets at RHIC

Jets are quenched –> R_{AA} (p_T)

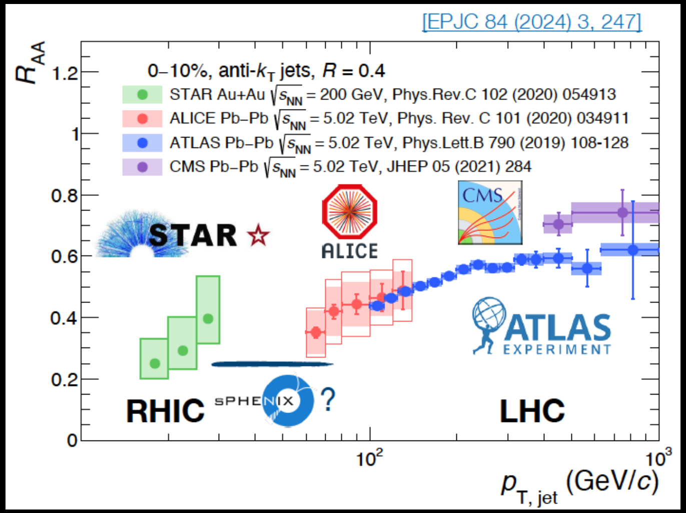
Di-jets imbalanced –> Angular correlations

Disappearance of the away-side jet –> Di-hadron correlations

Jet substructure –> Substructure variables

Energy-energy correlations in jets

-> sPHENIX and STAR continue RHIC data production!



H. Bossi, 2026 RHIC-AGS Jet Workshop

Jets at LHC –> See the comprehensive talk by H. Bossi on

"Recent Jet Measurements at the LHC" at Monday's RHIC-AGS Jet Workshop

LHC is extending our understanding, e.g. R_{AA} (p_T, flavor, r_{jet})

–> Precision characterization –> jet tomography!

–> How does the jet structure evolve (pQCD, npQCD)? Medium response?

Advances in Theory (and Our Understanding) during RHIC

RHIC results motivated the development of models

- Relativistic Viscous Hydrodynamics
- Jet Quenching
- Initial State

Brought about introduction of AdS/CFT into the field

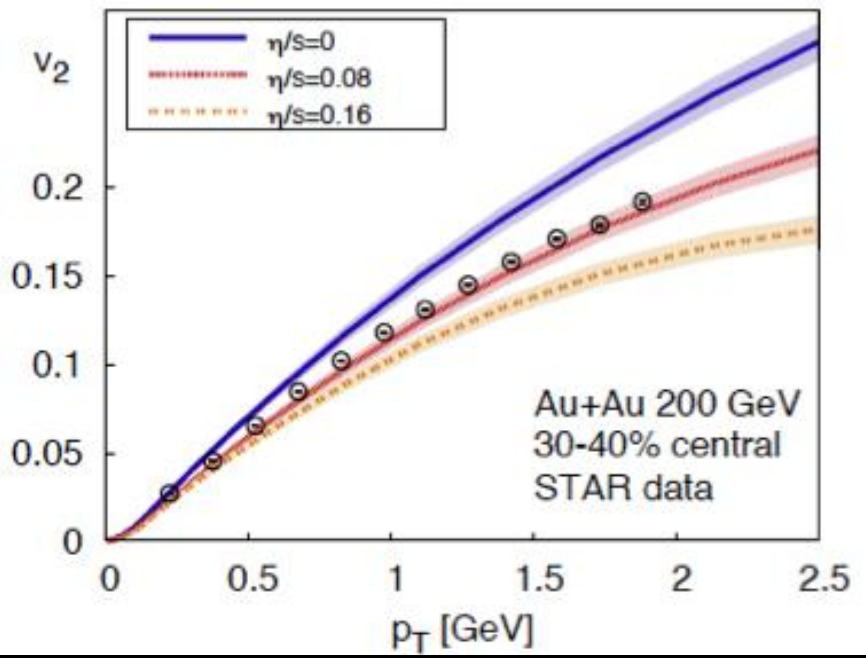
Stimulated cross-disciplinary interest in the sQGP

Advances in Relativistic Hydrodynamics during RHIC

Relativistic Viscous Hydrodynamics

- event-by-event hydrodynamics
- fluctuating initial conditions
- -> Bayesian extraction of transport coefficients

- -> First quantitative extraction of:
  - shear viscosity η/s
  - bulk viscosity
  - diffusion coefficients
  - freezeout properties



Advances in Theory during RHIC -> AdS/CFT

RHIC collective flow (perfect-fluid) results -> catalyzed new cross-disciplinary development in *QCD matter*

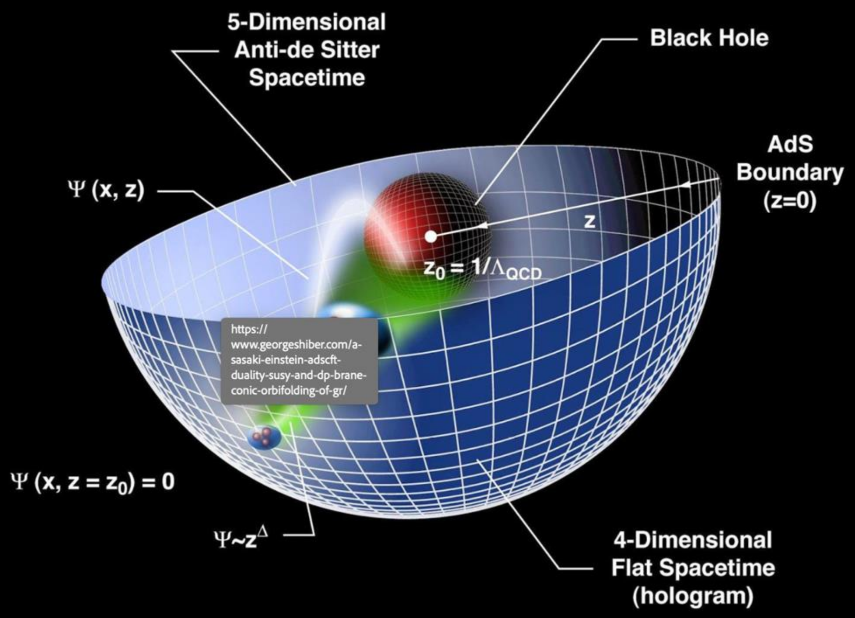
-> AdS/CFT and Gauge–Gravity Duality entered the field as a result of RHIC results

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

string-theory-inspired gauge/gravity dual to QCD-like matter

-> The AdS/CFT correspondence has provided or contributed to:

- strongly-coupled plasma calculations
- viscosity bounds
- thermalization estimates
- heavy-quark drag
- jet-energy-loss models



-> AdS/CFT provides analytic control over strongly-coupled gauge theories (where pQCD fails)

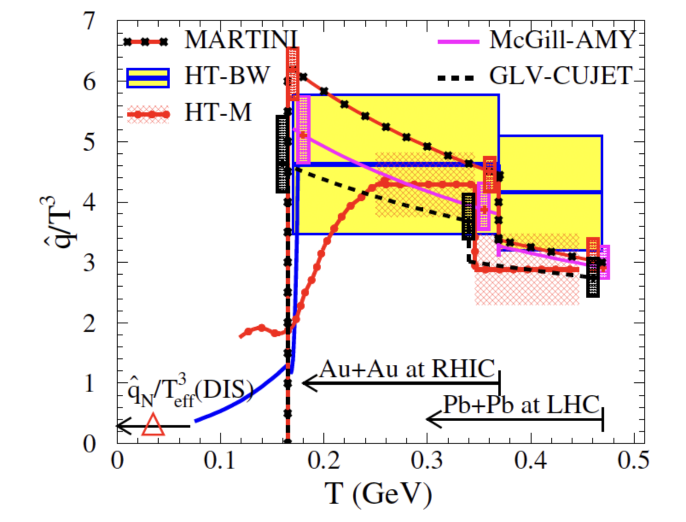
Advances in Jet Quenching during RHIC

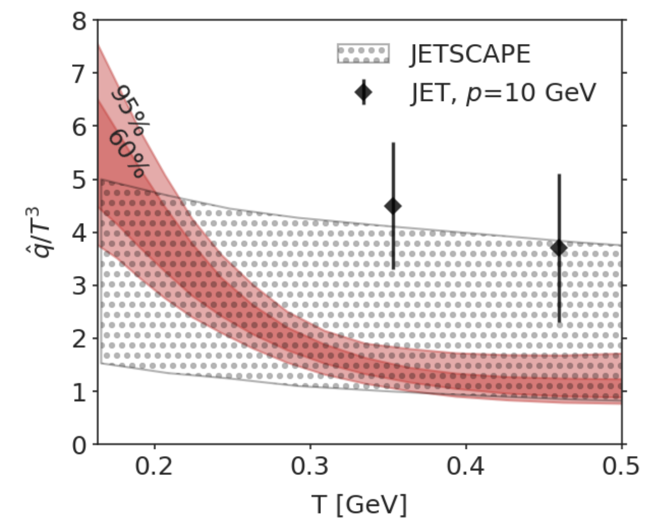
RHIC results established partons lose energy in QCD matter

-> a precision tool to probe the sQGP

Jet Quenching Models have included, advanced, improved:

- radiative energy loss
- collisional energy loss
- medium-induced gluon radiation
- coherence effects
- path-length dependence
- in-medium parton showers





Wang & Wiedemann, https://arxiv.org/abs/2508.18794

Advances in Initial-State during RHIC

RHIC data indicate details of initial geometry & fluctuations strongly impact the final observables

-> forced major advances in initial-state theory

Initial-state Models

-> Modified for event-by-event geometric fluctuations

-> Suppression of forward hadron d+Au & forward scaling data supported CGC & saturation

-> Rapid thermalization reinforced "Glasma" picture

-> Small-system collectivity required rethinking of the origin of collectivity in models

RHIC results required inclusion of initial conditions

-> Bayesian extraction of initial-state parameters made possible by precision of RHIC data

RHIC Was a New Era for Nuclear Physics Experiments

1990

Technological and Detector Developments

New Detector Techniques

- TPC
- RICH
- Photon Detectors
- CCD's
- Smart Calorimeters
- Scintillating Fibers
- ...

Data Acquisition

- Large Event Sizes
- Fast High Density Electronics
- Rapid Online Data Reduction
- Large Scale Data Storage
- ...

multiple

Integration of Complex Detector Systems into Experiments

Technological Developments

- Data Storage Devices and Media
- Integrated Electronics
- ...

NOTE:

ARPANET (started 1966-69 until 1990)

- UCLA, Stanford Research Institute, UC Santa Barbara, University of Utah

INTERNET

- became connected in 1980's

World Wide Web

- invented in 1989
- implemented at CERN 1990

RHIC Detector, Integration & Experimental Advances

RHIC drove major advances in experimental nuclear and particle physics

- Pushed detector technologies to unparalleled scales & levels of integration
- Detectors to handle extreme particle multiplicities, strong collective flow and detect rare events
- Integrated large-acceptance tracking, particle identification (PID), calorimetry, and triggering
- Large acceptance and complete event reconstruction
- Measurement of global collision properties and sQGP dynamics

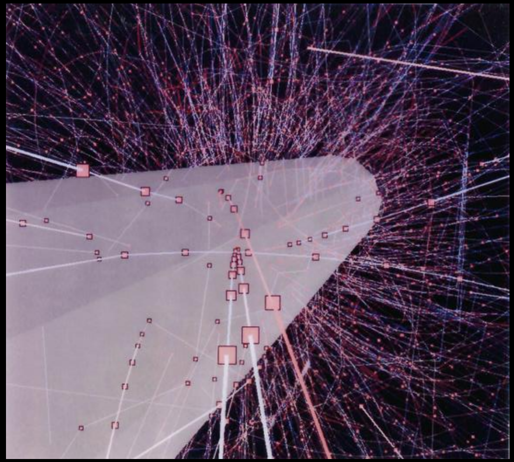
Major technological advances driven by RHIC

- Advances in tracking, vertex tracking, PID, calorimetry, triggering, and high-rate data acquisition
- Development of sophisticated background-subtraction and analysis techniques

Established technologies and methodologies later adopted at the LHC and future facilities

RHIC Advances in Large-Acceptance Tracking & Event Reconstruction

RHIC drove major advances in detector technology



Breakthroughs in high-multiplicity tracking with STAR TPC *(Ackermann et al., 2003)*

- Reconstructed thousands of charged tracks in a single heavy-ion collision
- Enabled precision 3D tracking in extreme high-particle-density environments

Key technological innovations

- Precise drift-field uniformity and gas-handling systems
- Advanced detector calibration techniques
- Sophisticated real-time pattern-recognition and tracking algorithms for very large data volumes

Physics impact - Essential for quantitative characterization of the sQGP

- Enabled detailed event-by-event measurements of global observables:
  - Collective flow
  - $\langle E_T \rangle$
  - Collision centrality
  - Strangeness content

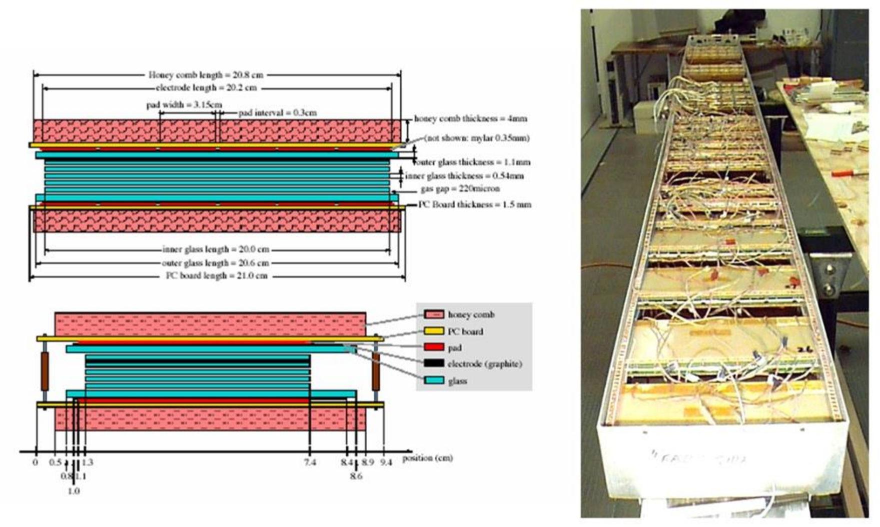
RHIC Advances in Particle Identification (PID)

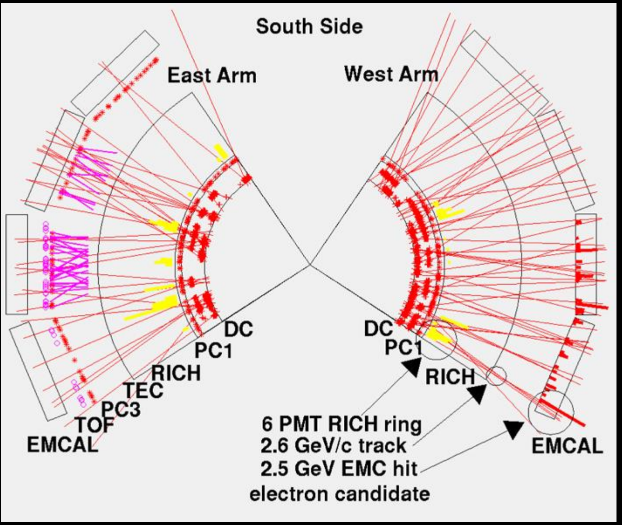
Precision particle identification (PID) through complementary detector technologies

- High-resolution dE/dx enabled robust π/K/p separation (STAR)
- MRPC-based Time-of-Flight (TOF) systems ~50–100 ps timing, extended PID to several GeV/c
- PHENIX RICH detectors provided efficient electron identification in high-background environments

Global impact of RHIC detector technologies

- MRPC technology became the worldwide standard for modern TOF systems
- Adopted in later experiments and facilities including the LHC and FAIR



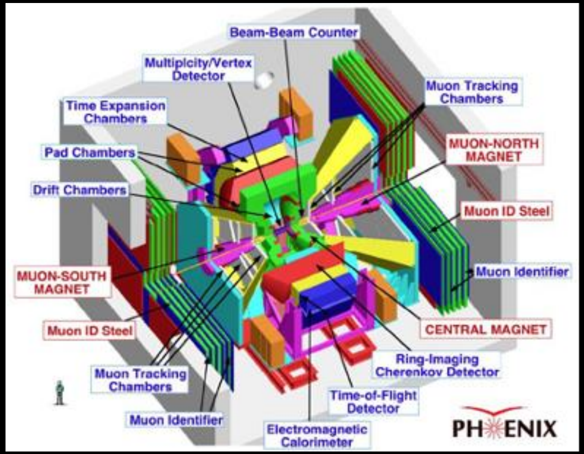


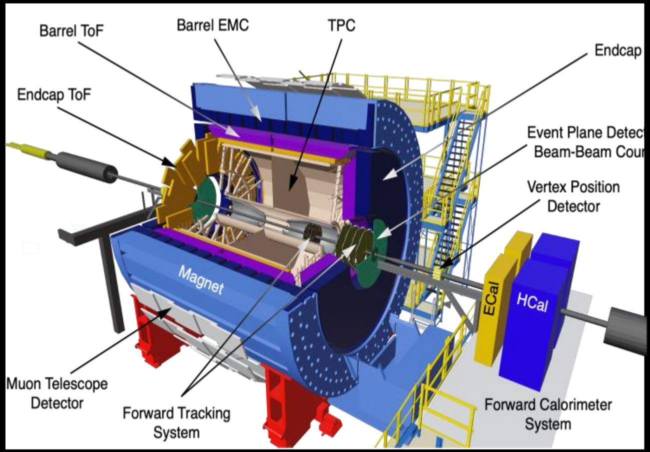
Combined systems delivered high-precision PID over a broad kinematic range

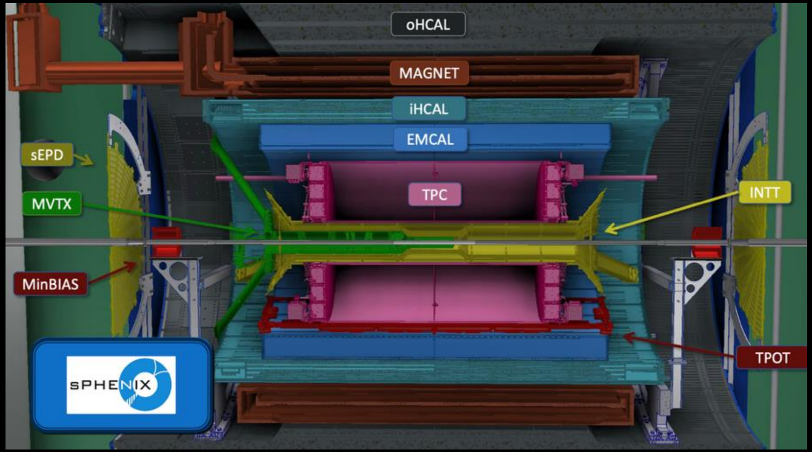
RHIC Advances in Calorimetry

Advances in calorimetry and jet measurements

- High-resolution electromagnetic calorimeters enabled precision measurements of:
  - Direct photons, Dileptons, Neutral mesons (e.g. $\pi^0 \rightarrow \gamma\gamma$)
- Heavy-ion jet studies required:
  - Advanced jet-finding algorithms
  - Sophisticated background-subtraction techniques
  - Precision calorimeter calibration in high-multiplicity environments







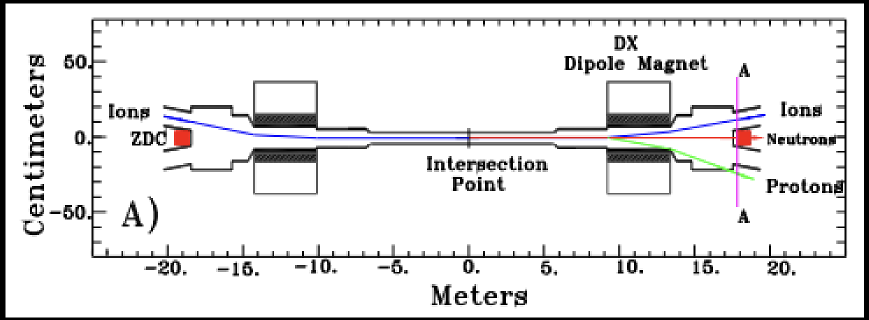
- Machine-learning methods have further enhanced the precision of recent jet measurements

These technical advances, pioneered at RHIC, continue to be refined at RHIC & the LHC

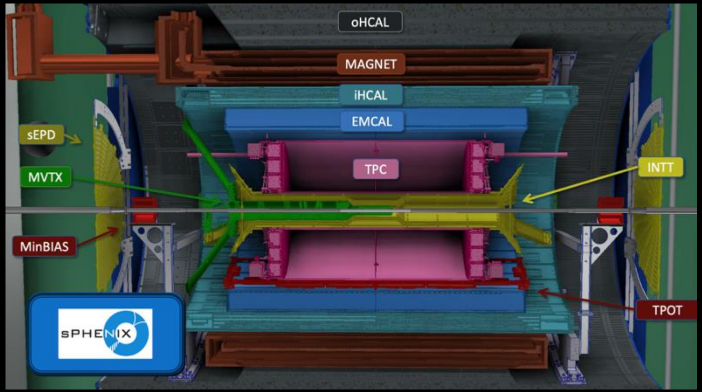
RHIC Advances in Calorimetry

Zero-Degree Calorimeters (ZDCs) Adler et al. (2001) designed, developed for RHIC, now at LHC

C. Adler et. al, NIM Physics Research A 461 (2001) 337



- Fast triggering on collision centrality
- Provide luminosity monitoring (especially in p+p)
- Segmented versions
  - Contribute to event-plane and global event characterization



On to sPHENIX

- sPHENIX extended RHIC calorimetry program:
  - High-rate DAQ
  - High-granularity EM & hadronic calorimetry
- sPHENIX combined calorimetry, silicon vertexing, streaming electronics
- -> Enabling precision jet and hard-probe measurements in heavy-ion collisions

Evolution of High-Resolution Vertex Tracking at RHIC

Key advance: Precision silicon vertex tracking for heavy flavor physics

Enabled topological reconstruction of displaced vertices from charm and beauty decays

Essential for measurements of heavy-flavor production, flow, and energy loss in the sQGP

Evolution of early microvertex systems to modern MAPS-based detectors used at RHIC & LHC

STAR Silicon Vertex Tracker (SVT) *(2001–2007)* – 1st generation precision vertex tracking at RHIC

Three-barrel silicon drift detector (SDD) microvertex system ~20 μm 2D spatial resolution with dE/dx capability

STAR Heavy Flavor Tracker (HFT) *(2014–2016)*

Low-material, high-precision tracker using monolithic active pixel sensors (MAPS)

Micron-scale spatial resolution near the interaction point optimized for precision charm and beauty

PHENIX VTX and FVTX *(2011–2016)*

VTX: four-layer silicon pixel detector for high-precision heavy-flavor vertexing

FVTX: forward silicon tracker extending heavy-flavor acceptance

On to *sPHENIX MVTX (2023-2026)*

Employs advanced MAPS technology from the ALICE ITS -> low material budget and micron-scale tracking

RHIC Advances: Triggering, DAQ, & High-Throughput Computing

Pioneered fast triggering and DAQ systems for heavy-ion collisions

- In extreme particle multiplicities with rare-probe selection in real time
- Triggering on rare signatures (jets, photons, heavy flavor, and others)
- Developed Level-0/Level-1 trigger, fast front-end electronics & parallelized data streams
- Triggering & DAQ systems isolated rare physics signals in large backgrounds

STAR: evolution into a multi-petabyte, high-throughput experiment

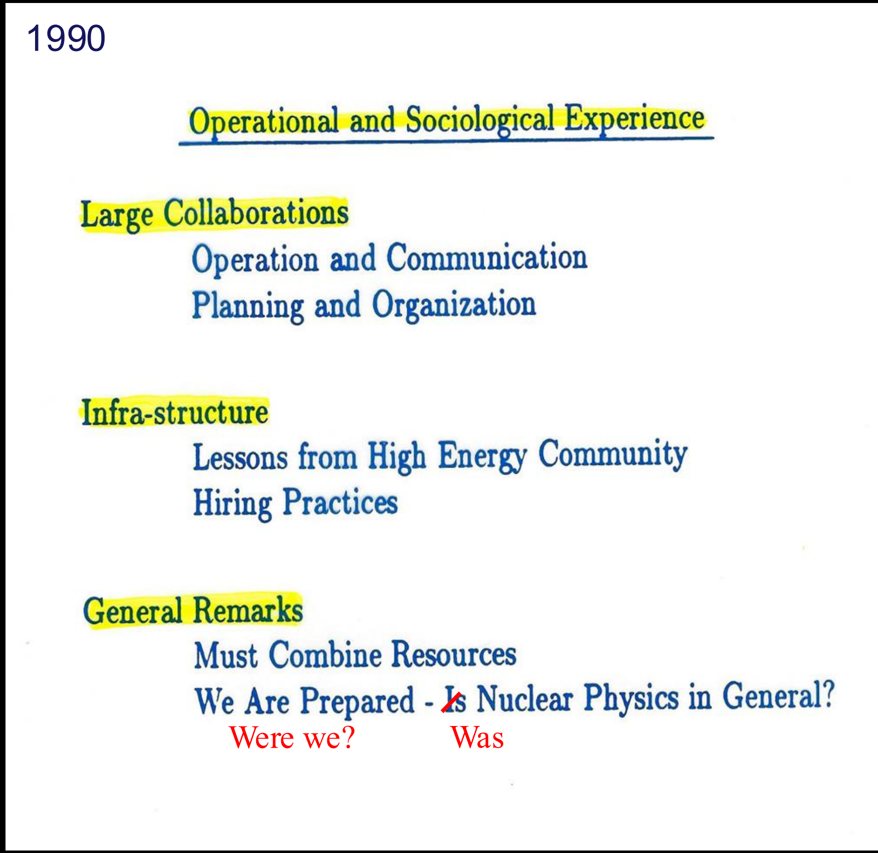
- Early: ~100–200 kB event sizes, recording rates ~50–100 Hz
- After DAQ/trigger upgrades event sizes up to ~0.5–1 MB
  - Rates to few hundred Hz to kHz scale with sustained throughput O(100 MB/s)
- Annual stored data volumes reached several PB

PHENIX: precision rare-probe strategy

- More selective triggering and smaller event sizes (~10–30 kB)
- High-rate rare-probe measurements in lower total data volumes
- Annual data storage generally below ~1 PB

RHIC established modern high-rate triggering, DAQ, & large-scale data-processing paradigms, later adopted at the LHC and future collider experiments

RHIC – Sociological and Operational Experience


1990

Operational and Sociological Experience

Large Collaborations
- Operation and Communication
- Planning and Organization

Infra-structure
- Lessons from High Energy Community
- Hiring Practices

General Remarks
- Must Combine Resources
- We Are Prepared - ~~Is~~ Nuclear Physics in General?

Were we? Was

Sociological
- Large collaboration – culture & operation
- Distributed leadership
- Working Group & Project structures & operation

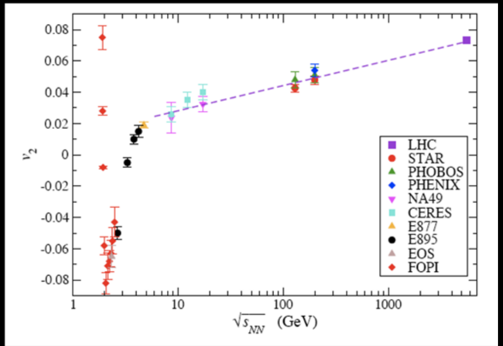
RHIC-trained next generation

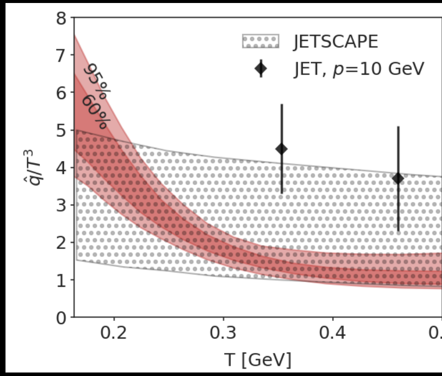
RHIC scientists -> LHC leadership

Continuity of
- Science
- Sociology
- Expertise & ideas
- Approach
- Analysis and interpretation

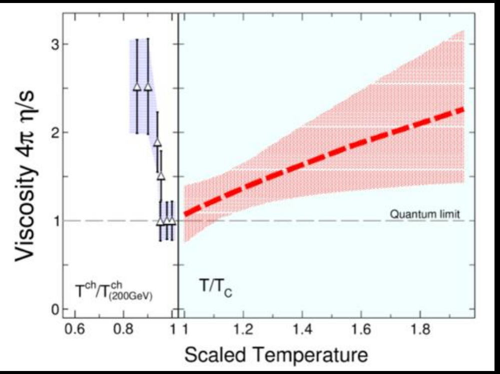
Continuity RHIC → LHC

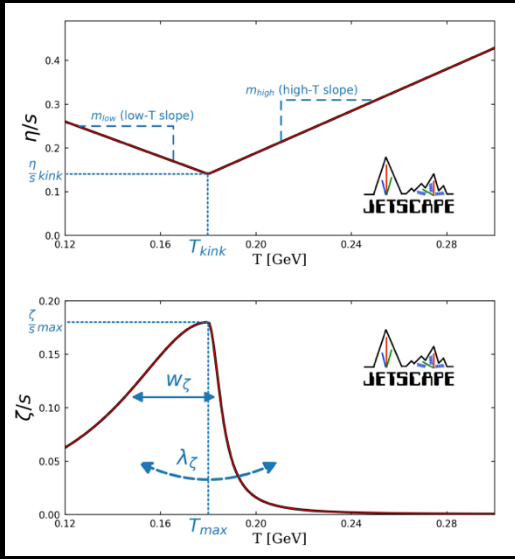
Extended energy and temperature range
- Same observables & methods
- Consistent picture across energies
- Energy scaling
  - (RHIC 10-200 GeV) (LHC up to 5 TeV)





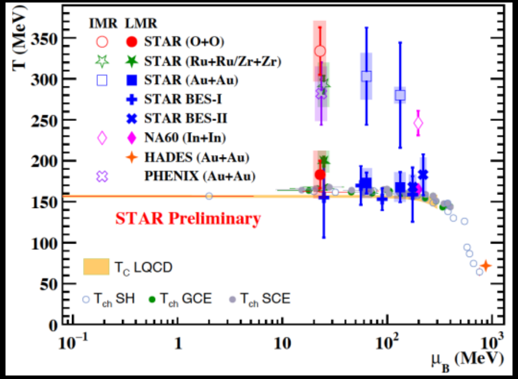
Transport coefficients now constrained





Studying T dependence of variables (q-hat, η/s,..)

Models extend range of energies & temperature



Developing new techniques

RHIC Legacy – Impact on LHC RHI Physics

RHIC established the sQGP paradigm & defined the relativistic heavy-ion program

LHC is extending our understanding

With precision characterization, especially in hard probes, high-p_T & jet regime

New analysis and detector techniques still to be developed

New additions to be added to theoretical models

I thank all RHIC Collaborators over the last ~~26~~ 36 years!

&

I thank the organizers for this opportunity to speak.