Hot & Dense QCD Matter White Paper

- Unraveling the Mysteries of the Strongly Interacting Quark-Gluon-Plasma -

Steffen A. Bass (Coordinator)
Duke University

Helen Caines
Yale University

Brian A. Cole
Columbia University

Jamie Dunlop
Brookhaven Nat. Lab.

Thomas K. Hemmick
Stonybrook University

David Morrison
Brookhaven Nat. Lab.

Joern Putschke
Wayne State Univ.

Sevil Salur
Rutgers University

Bjoern Schenke
Brookhaven Nat. Lab.

Ron A. Soltz
Lawrence Livermore N.L.

Peter Steinberg
Brookhaven Nat. Lab.

Michael Strickland
Kent State University

Derek Teaney
Stonybrook University

Ivan Vitev
Los Alamos Nat. Lab.

Bolek Wyslouch
MIT

Nu Xu
Lawrence Berkeley N.L.

The Task

Charge to the Tribble NSAC sub-committee:

describe how to optimize the overall Nuclear Science Program over the next 5 years (FY2014 - 2018) under at least 2 budget scenarios:

1. flat funding at the FY2013 level
2. modest increases over the next 5 years

purpose of the White Paper:

- inform the NSAC subcommittee on the status and outlook of the US Relativistic Heavy Ion program
- present the future potential of that program in an objective, yet maximally positive way
- convince the committee members to issue a recommendation in favor of vigorously continuing (or possibly even strengthening) the funding for the RHI program.
  - the very future of our field in the US may depend on how compelling we present our case

Basic Outline of the White Paper

- Introduction
- Success of the RHI Program
- "Concordance Model" of Heavy-Ion Collisions
- Discovery Potential, Quantifiable Deliverables & Open Questions
- The Future of the US Relativistic Heavy-Ion Program

- WP has to emphasize key messages
- selective, not comprehensive

Discoveries: 2000-2012

- high-momentum hadron suppression
- away-side jet modification (tomography)
- elliptic flow at the hydro limit
- constituent quark number scaling of elliptic flow
- density fluctuation driven higher order flow moments
- suppression & flow of heavy quarks
- sequential melting of heavy quarkonia
- charge correlations suggesting a Chiral Magnetic Effect
- suppression of particle production in the low-x coherent regime
- new anti-nuclei and hyper-nuclei created
- determination of gluon contribution to nucleon spin

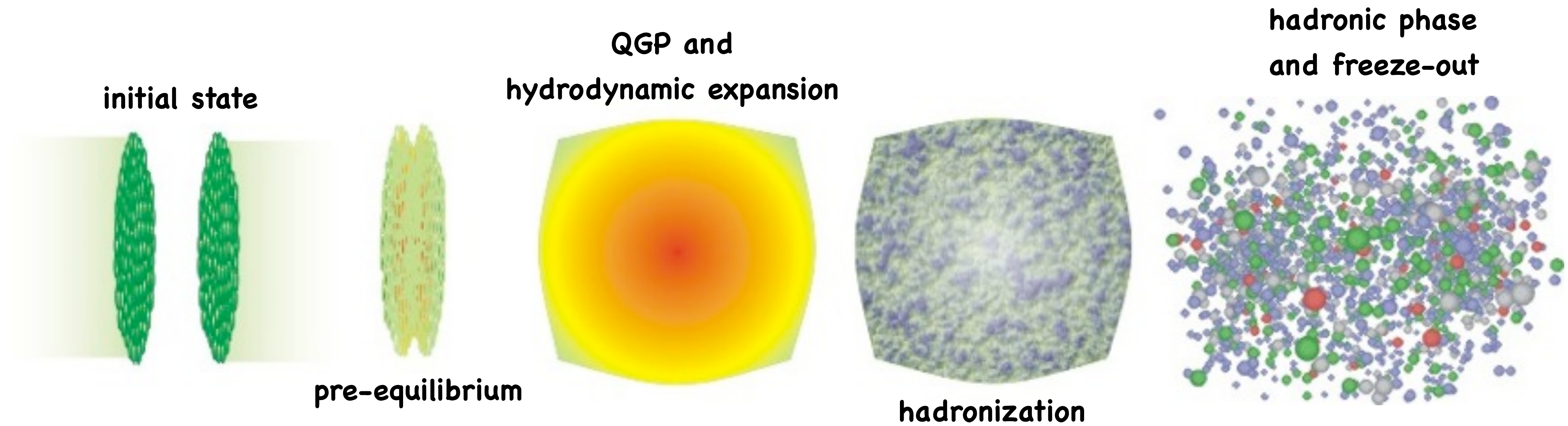
Theoretical & Phenomenological Advances

- Statistical Hadronization Model
- Parton Recombination
- Relativistic Viscous Hydrodynamics
- Blast Wave Model
- AdS/CFT Modeling of Strongly-Coupled Media
- advances in Lattice QCD
- small-x Physics and the Color Glass Condensate

Quantitative Estimates of QGP Properties

- Initial State Characterization:
  - …
- Shear Viscosity / Entropy Density:
  - …
- Jet Energy-Loss Coefficients:
  - …

"Concordance Model" of Heavy-Ion Collisions

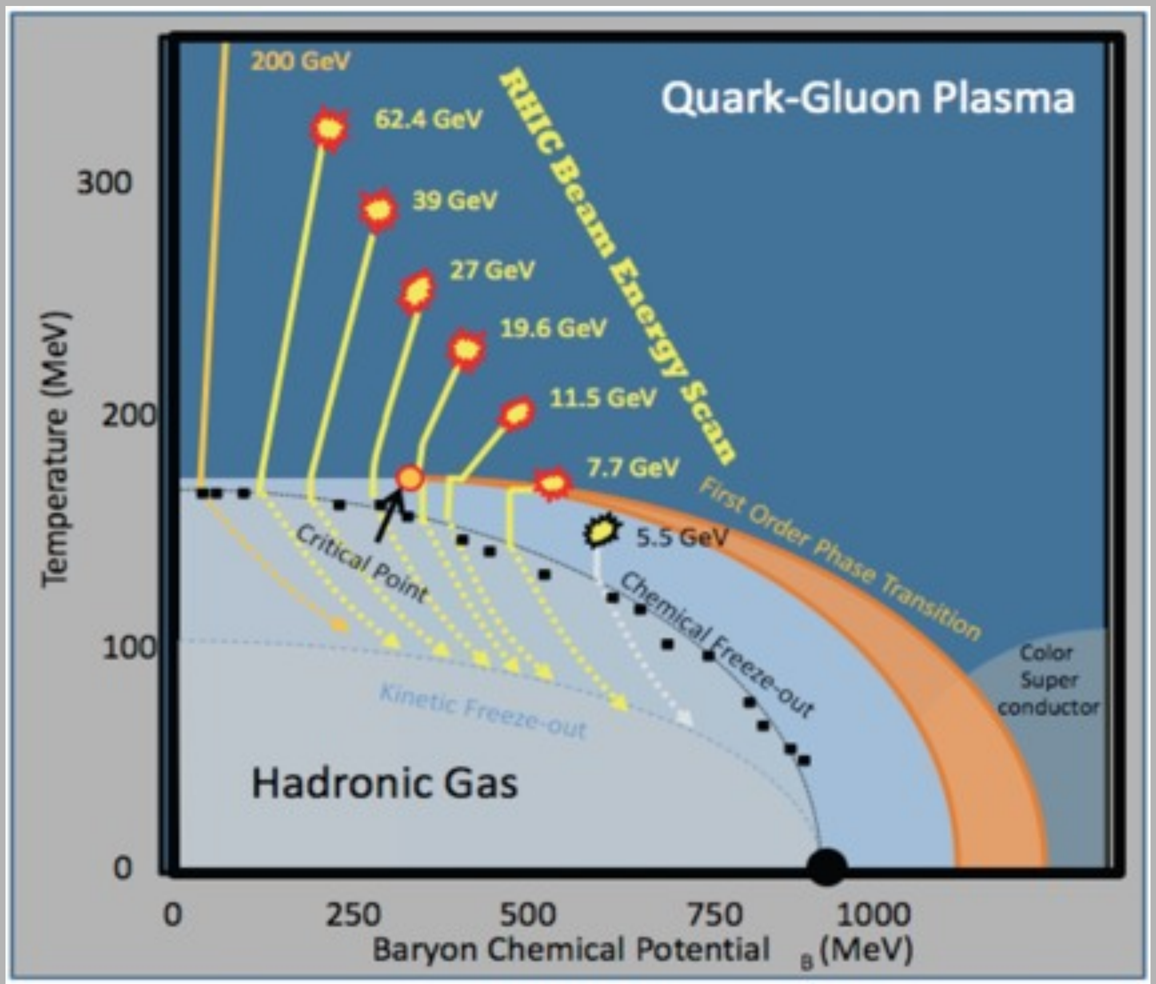


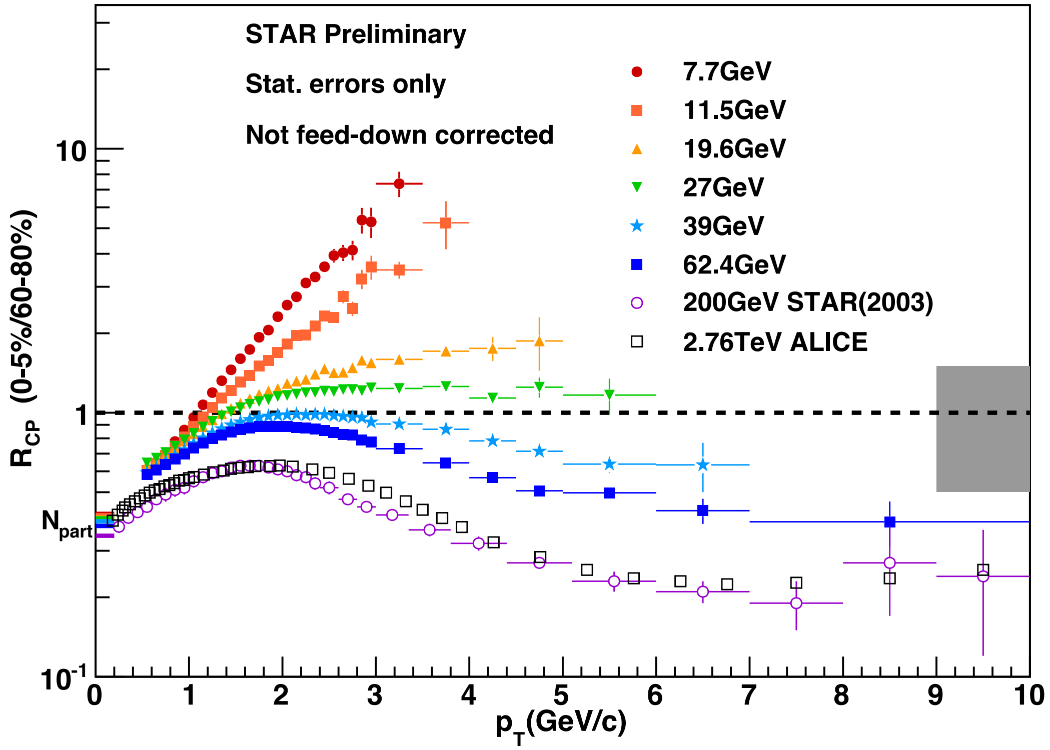
- Initial State:
  - fluctuates event-by-event
  - classical color-field dynamics
- Pre-equilibrium:
  - rapid change-over from glue-field dominated initial state to thermalized QGP
  - time scale: 0.15 to 2 fm/c in duration
  - build-up of transverse velocity fields?
- QGP and hydrodynamic expansion:
  - proceeds via 3D viscous RFD
  - EoS from Lattice QCD
- hadronic phase & freeze-out
  - interacting hadron gas
  - separation of chemical and kinetic freeze-out

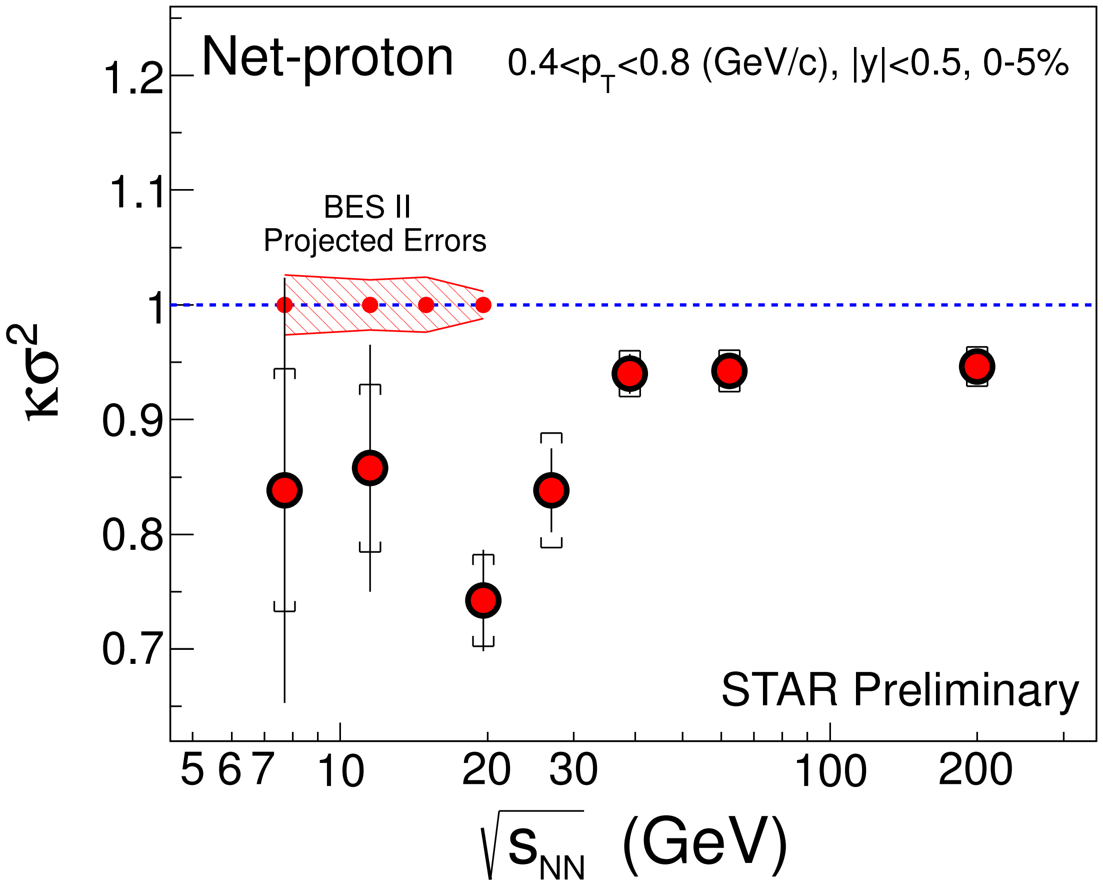
Discovery Potential: Charting the QCD Phase-Diagram

Probing the QCD Phase-Diagram

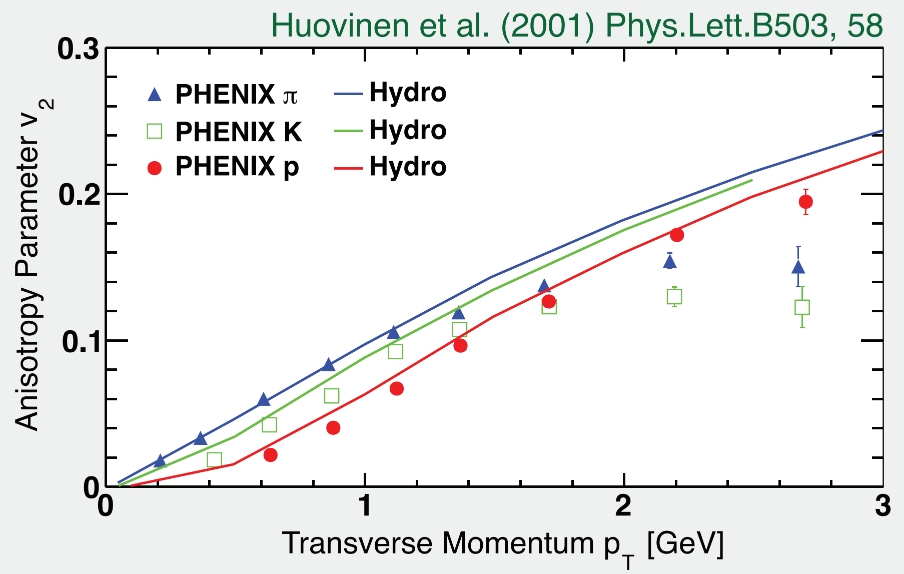
- RHIC Beam-Energy-Scan: use beam energy as control parameter to vary initial temperature and chem. potential
- beam energy range in area of relevance is unique to RHIC!
- BES-II will deliver precision required to probe for signatures of the CEP



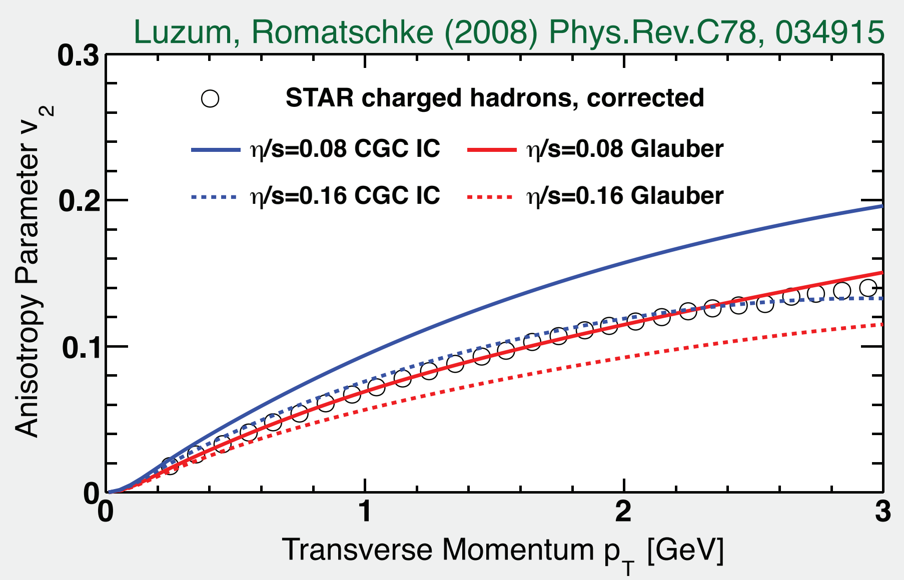




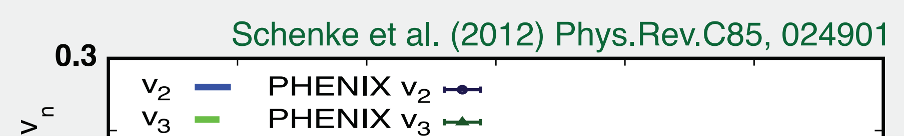
Towards a Precision Measurement of η/s

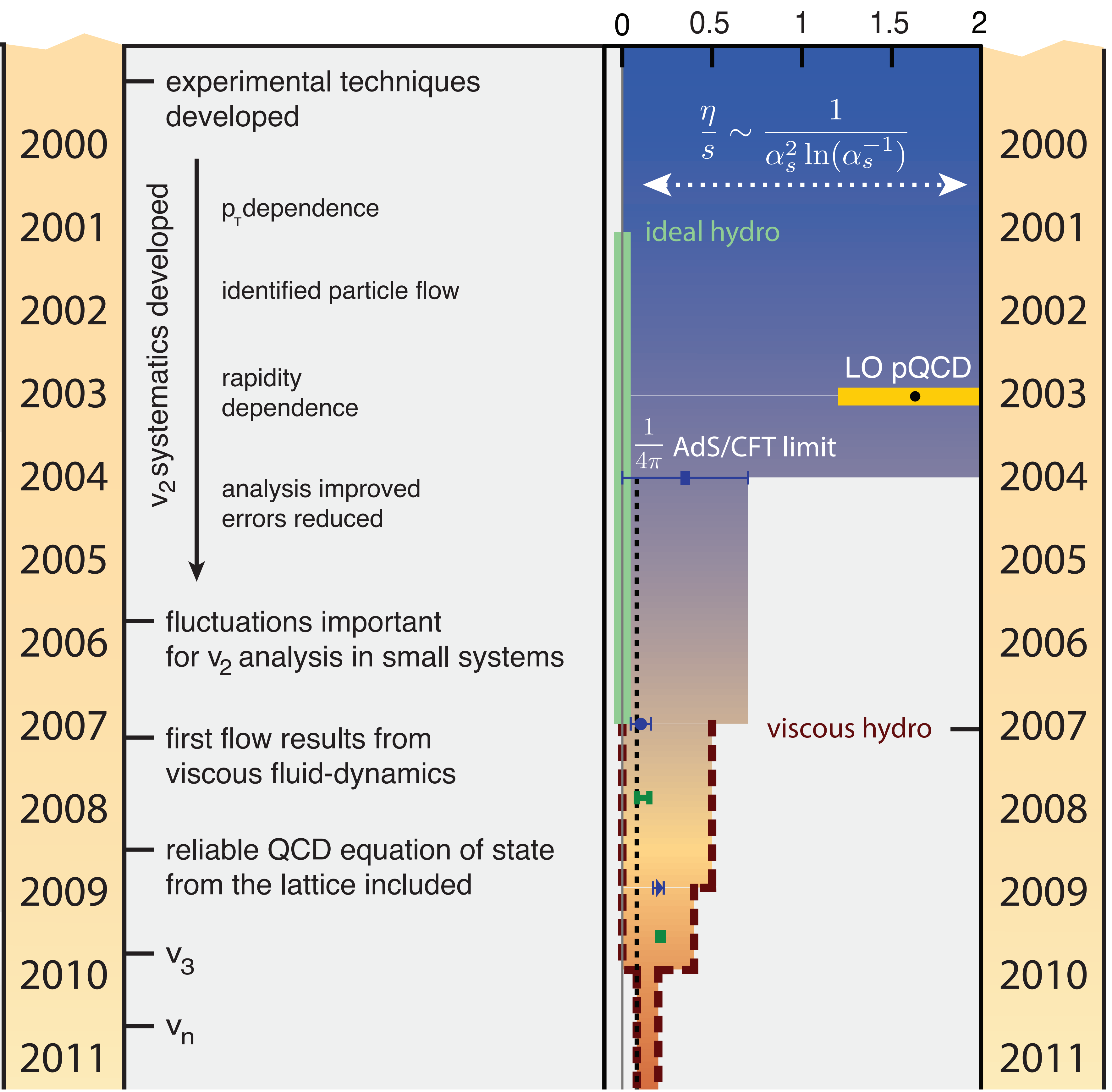


Early success of hydrodynamics missing physics of lattice QCD equation of state and viscosity.



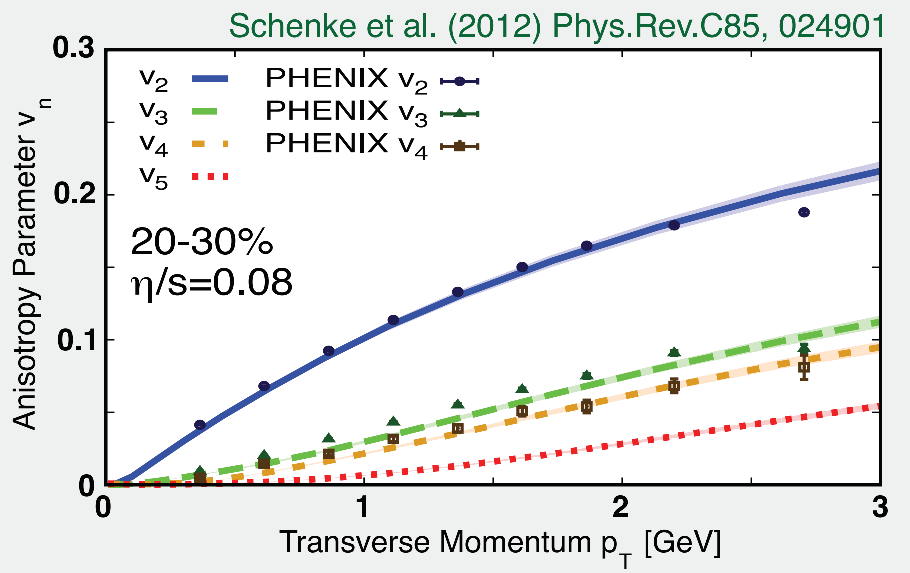
Bounds on shear viscosity but large uncertainties from initial conditions.



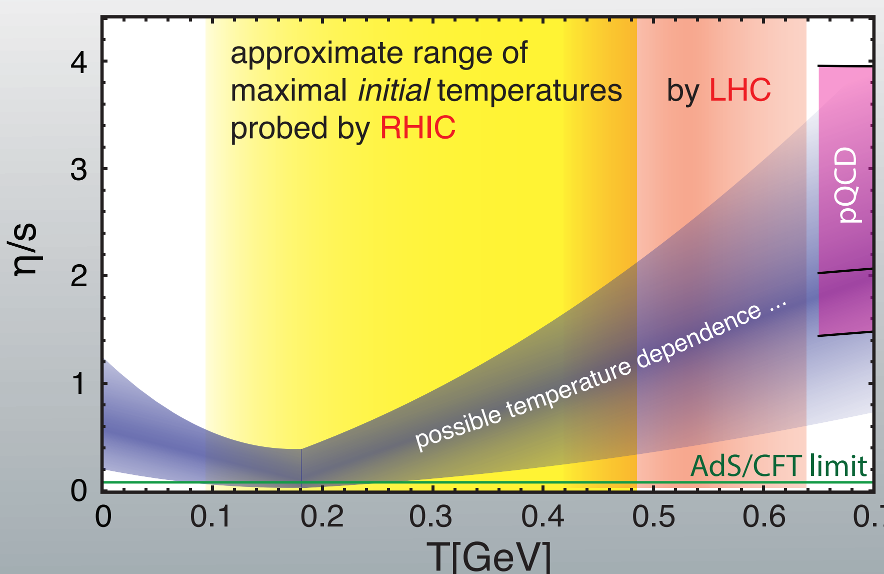


Quantifiable Deliverables:

Temperature Dependence of η/s



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.

2011

v_n

2012

v_n correlations

2013

$P(v_n)$

2014

2015

2016

~6 years RHIC program required to:

- determine (η/s)(T) dependence
- measure lower bound to ~5%
- measure bulk viscosity and relaxation times
- constrain initial gluon distributions and their fluctuations

2017

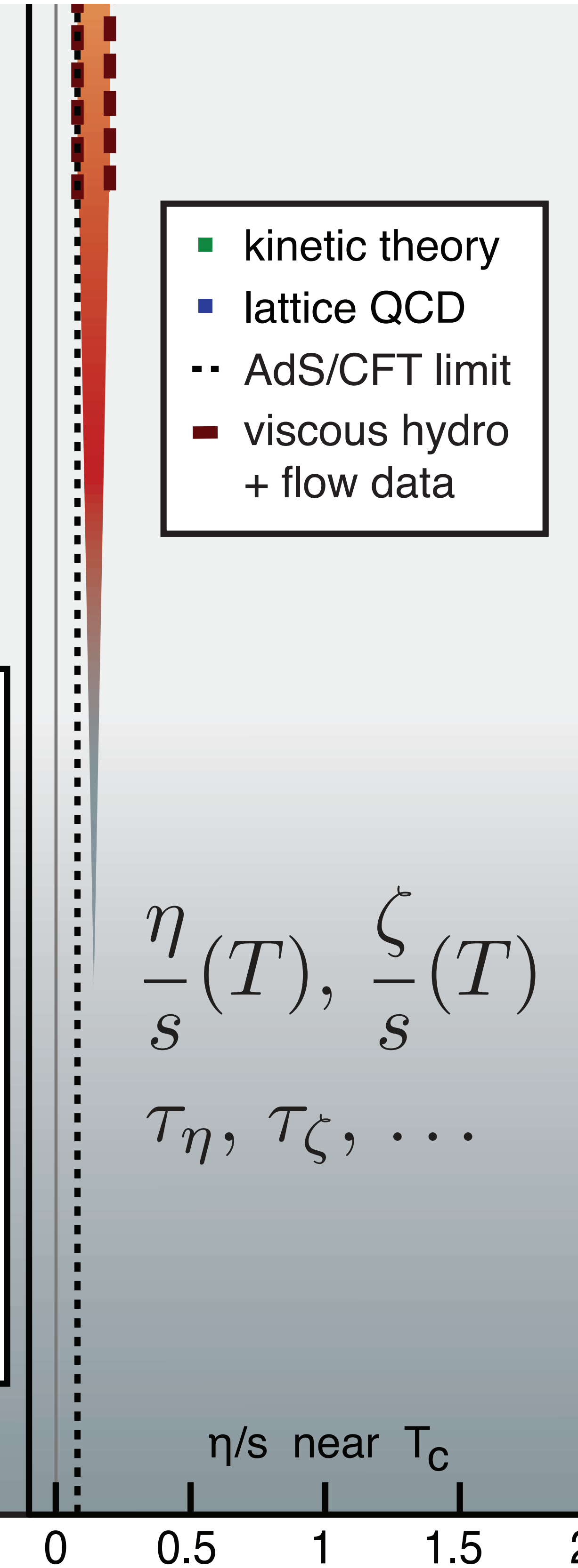
2018

2019

2020

2021

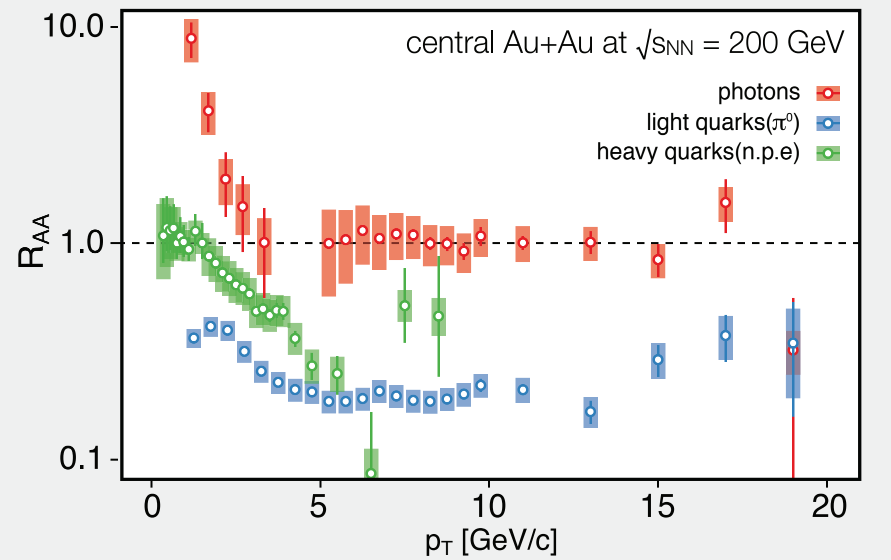
2022

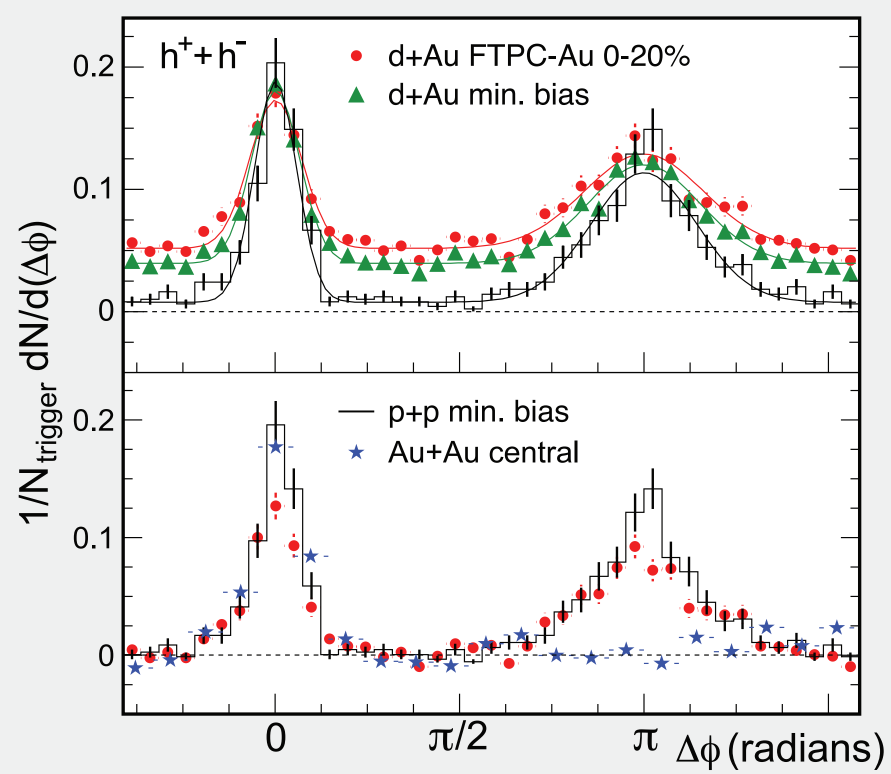


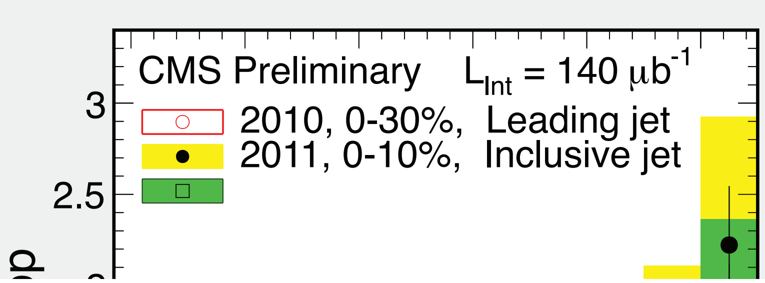
$$\frac{\eta}{s}(T),\ \frac{\zeta}{s}(T)$$

$$\tau_\eta,\ \tau_\zeta,\ \ldots$$

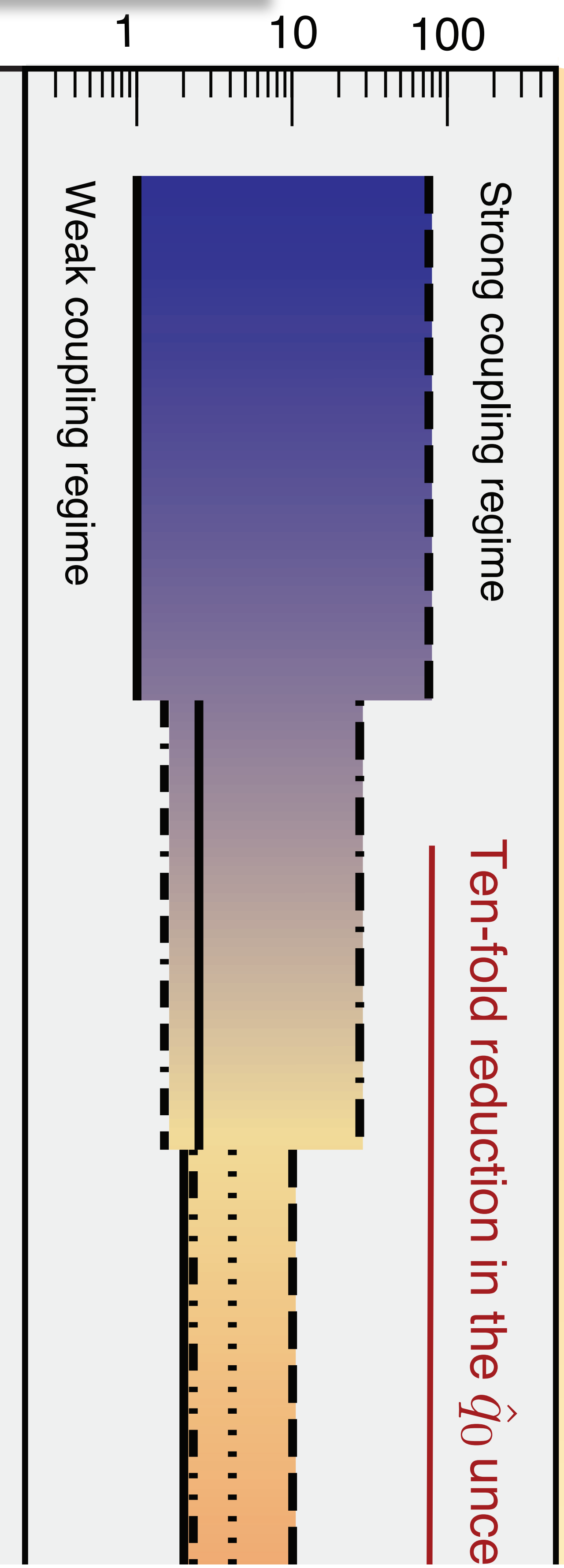
Energy Loss Transport Coefficients





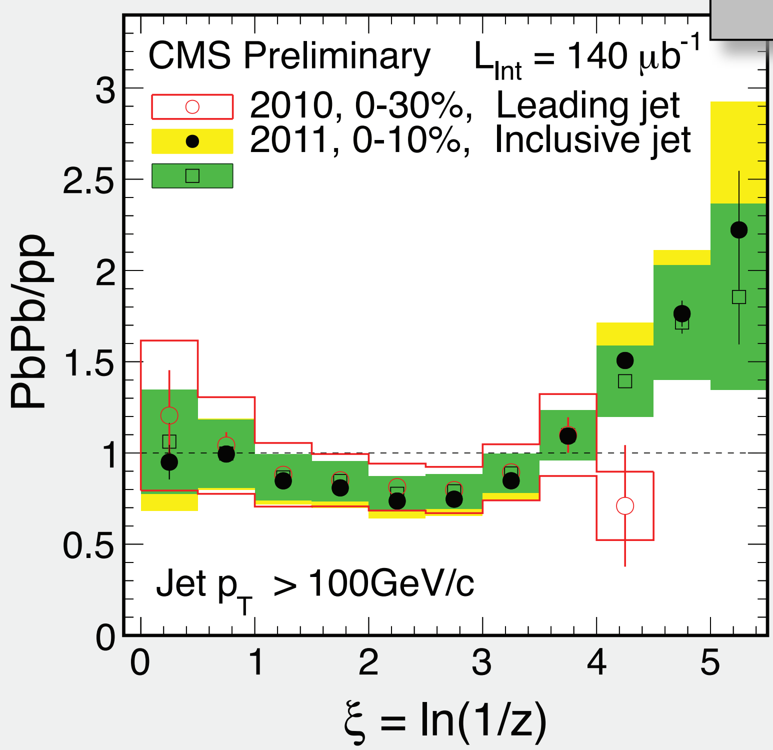


	experimental techniques developed
2000	
2001	×5 suppression in hadron R_{AA}
2002	Away-side disappearance
2003	d+Au "Null-Experiment": Jet-quenching unambiguously a final-state/QGP effect
2004	Strong modification of an away-side jet: "Mach-Cone" ?
2005	No direct photon suppression
2006	Near-side modification: "The Ridge"
2007	
2008	First (preliminary) full jet reconstruction measurements in HI Collisions at RHIC
2009	
2010	Ridge and Mach-Cone structure consistently explained by v_n (initial state fluctuations)
2011	LHC data: Increase of charged hadron R_{AA} at high momentum;



Quantifiable Deliverables:

Energy Loss Transport Coefficients



Full jet reconstruction measurements and comparison to theory over a wide range of collision and jet energies

Precision RHIC data are essential

2010 – consistently explained by v_n (initial state fluctuations)

2011 – LHC data: Increase of charged hadron R_{AA} at high momentum; full jet measurements

2012 – Modification in jet fragmentation/ jet structures at the LHC (QM12) suggests radiative energy loss picture

2013

2014

2015

2016

2017

2018

2019

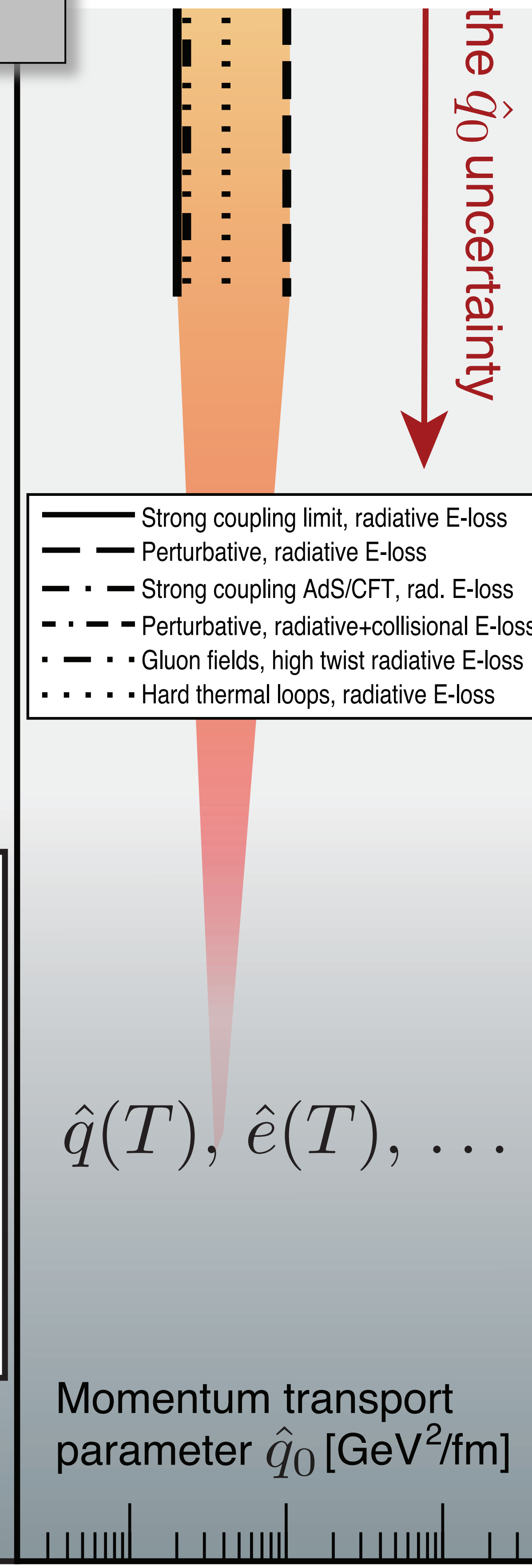
2020

2021

2022

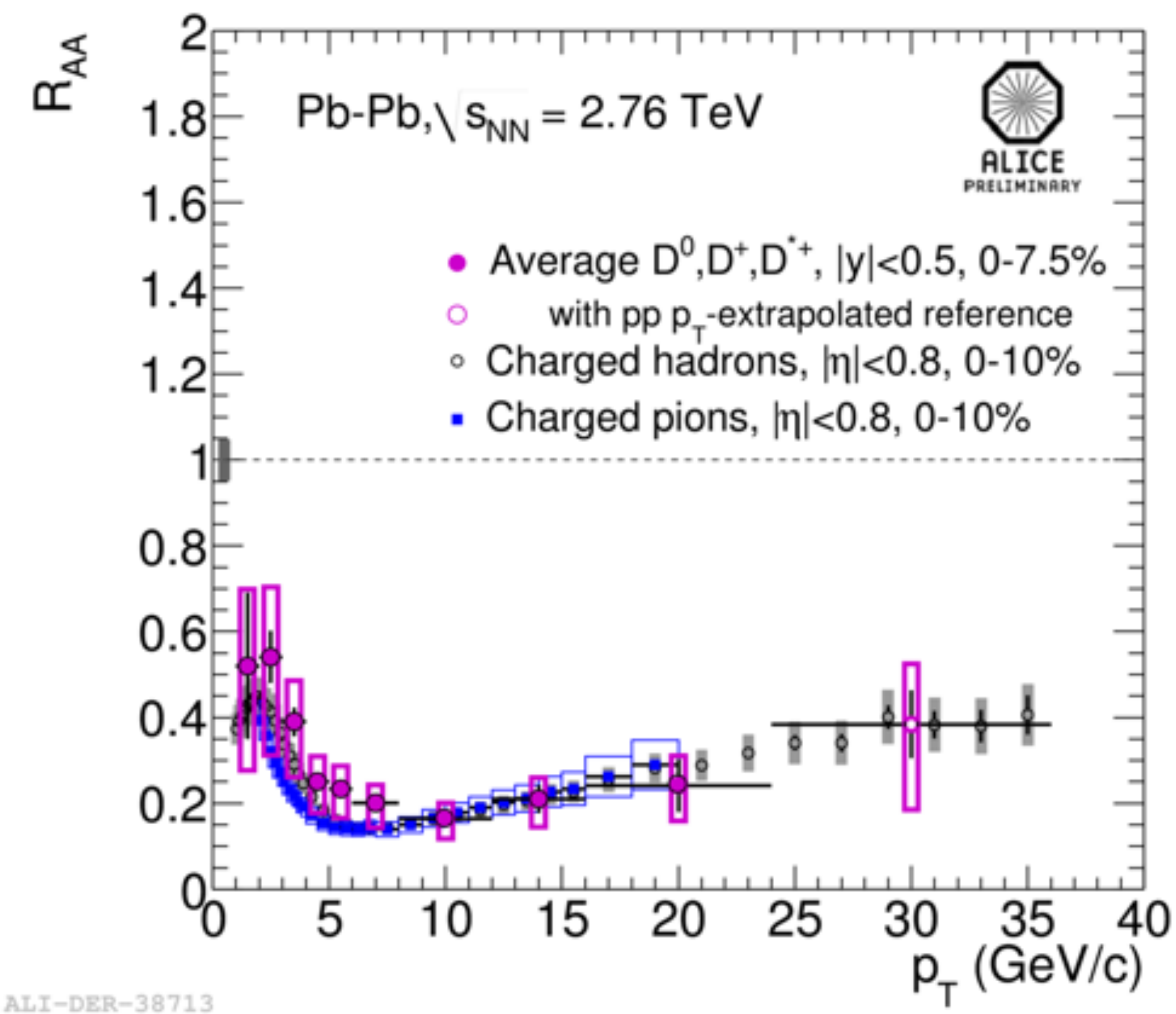
6+ years RHIC program and upgrades required to:

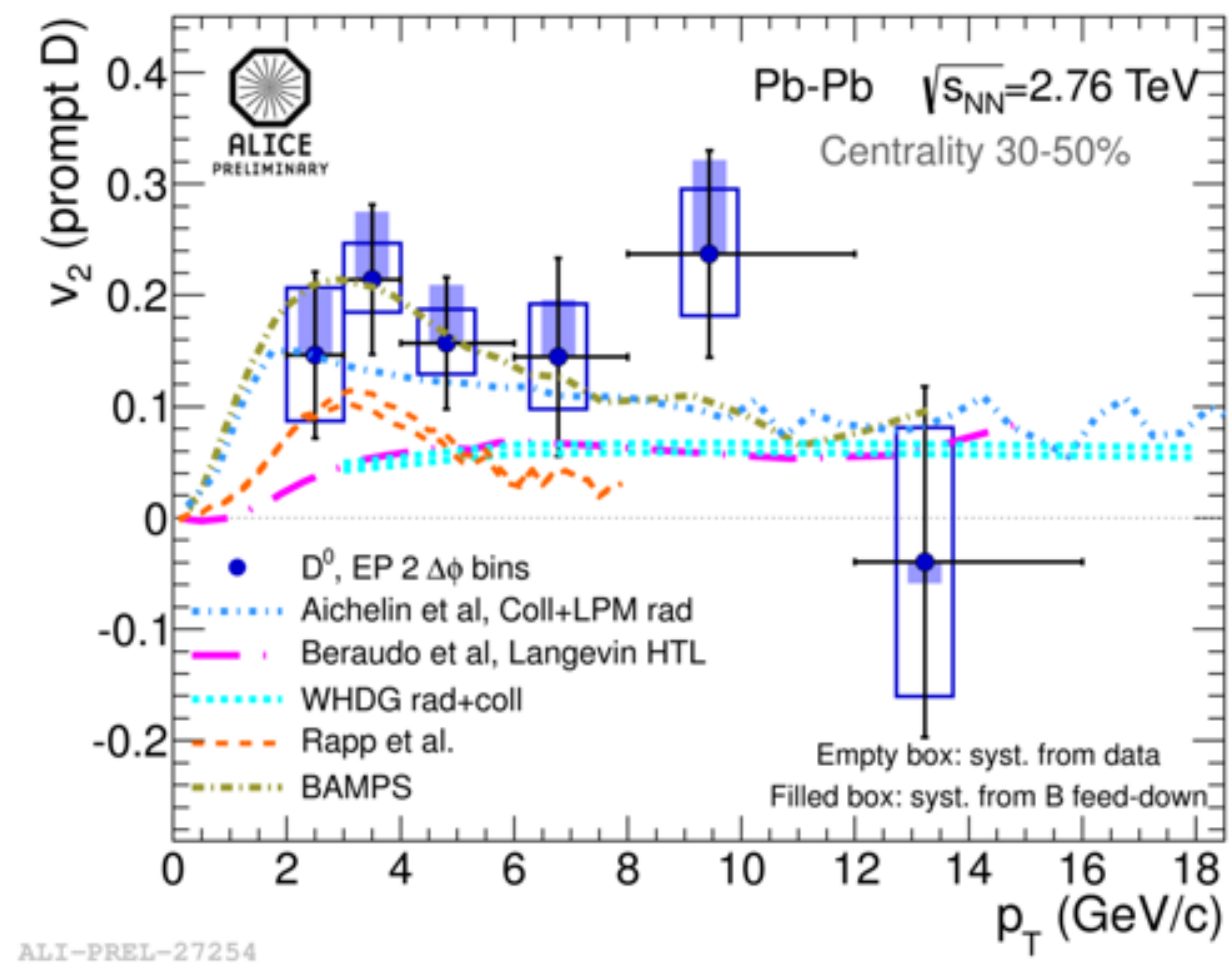
- reduce $\hat{q}$ uncertainties
- determine $\hat{q}$(T) dependence
- characterize quasi particle nature over a wide range in jet energy
- constrain importance of collisional vs. radiative energy loss; QCD analog to QED energy loss



2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022

Open Questions: Heavy Quark Puzzle





Open Questions: Thermalization

A hydrodynamic analysis of RHIC & LHC data indicates that the system must have thermalized on a timescale of ≤1 fm/c in order to account for the observed collective flow

- **how does the system transition from a coherent multi-particle gluonic initial state with maximally anisotropic $T^{\mu\nu}$ to a quasi-isotropic $T^{\mu\nu}$ over such a short time-scale?**

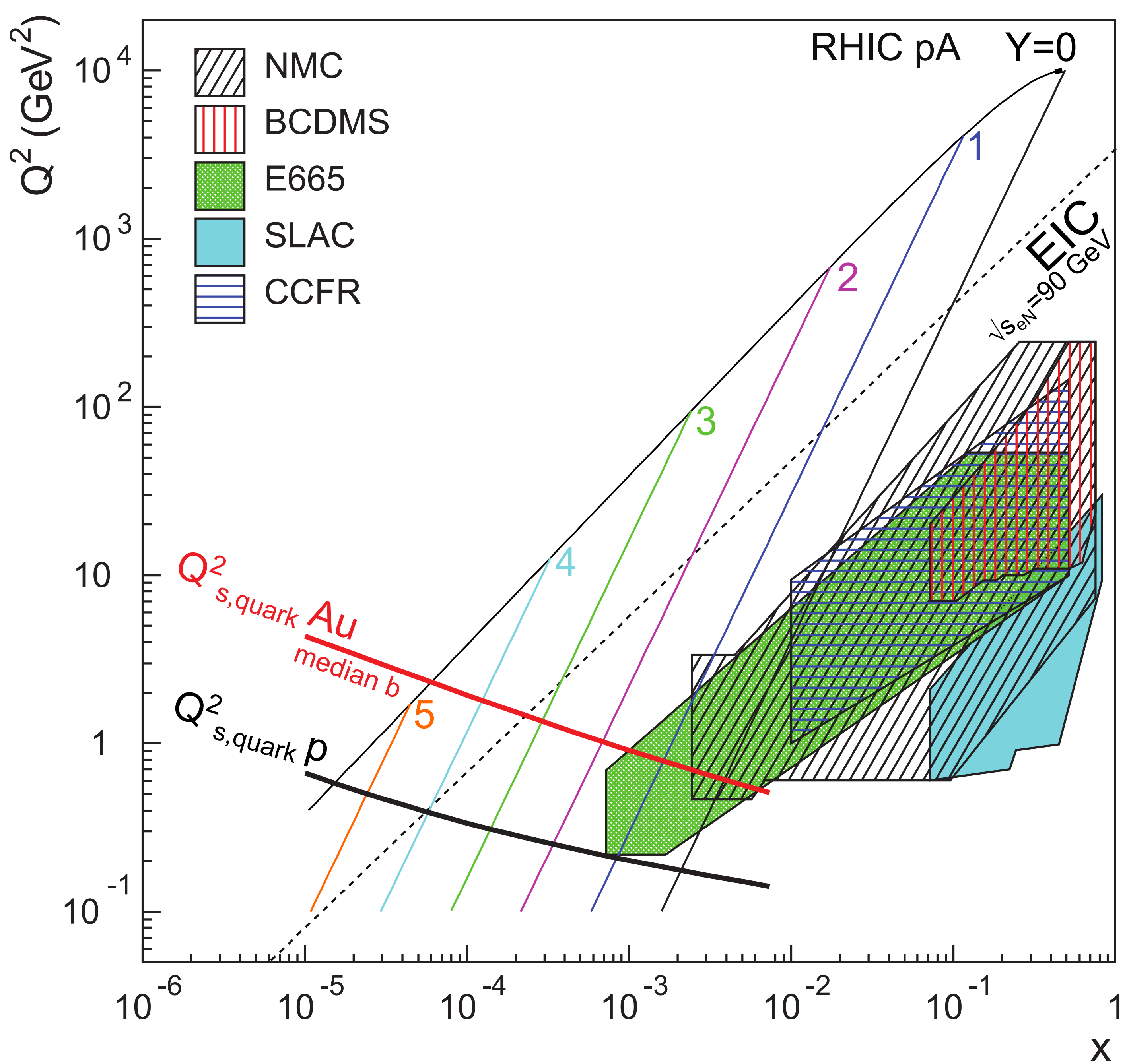
CGC and/or weak coupling approaches:

- Boltzmann transport of partons: inconclusive, depend on details of multi-parton interactions and LPM effect
- quantum fluctuations in a system with strong fields: may speed up thermalization, but currently toy-model only
- turbulent color fields: significant progress in this area, time to get quantitative?

Strong coupling approaches:

- AdS/CFT studies suggest rapid thermalization, but provide poor understanding of underlying mechanisms and initial state
    - **no compelling/rigorous explanation of thermalization to date!**
    - **data on lepton & photon radiation as discriminator**

Initial State & Gluon Saturation: towards the EIC



Complimentarity of RHIC & LHC

- LHC provides access to high energy probes (quarkonia, high energy jets, W/Z/gamma) in the baryon free regime beyond the reach of RHIC
- RHIC also accesses high energy probes, given sufficient luminosity, and can leverage longer heavy-ion beam times in its favor.
- Jets of similar energy and characteristics produced at RHIC and LHC will be sensitive to different aspects of the system evolution.
- RHIC can explore a much wider region of the QCD phase diagram (critical point, phase structure, baryon density) than is possible at the LHC

The Future of the US Heavy-Ion Program

the next ten years of the US relativistic heavy-ion program will deliver:

- a beam-energy scan program with unparalleled discovery potential to establish the properties and location of the QCD critical point and to chart out the transition region from hadronic to deconfined matter.
- a hard probes program, compromising of jet and heavy-flavor physics to provide precision values for the QGP transport coeffcients q^ and e^, as well as a solution to the heavy-flavor puzzle. The planned quarkonia measurements will provide standard candles for the temperatures obtained in the early stages of a heavy-ion reaction.
- a systematic forward physics program to study the nature of gluon saturation. This program will build the foundation for the future EIC research program and facility.