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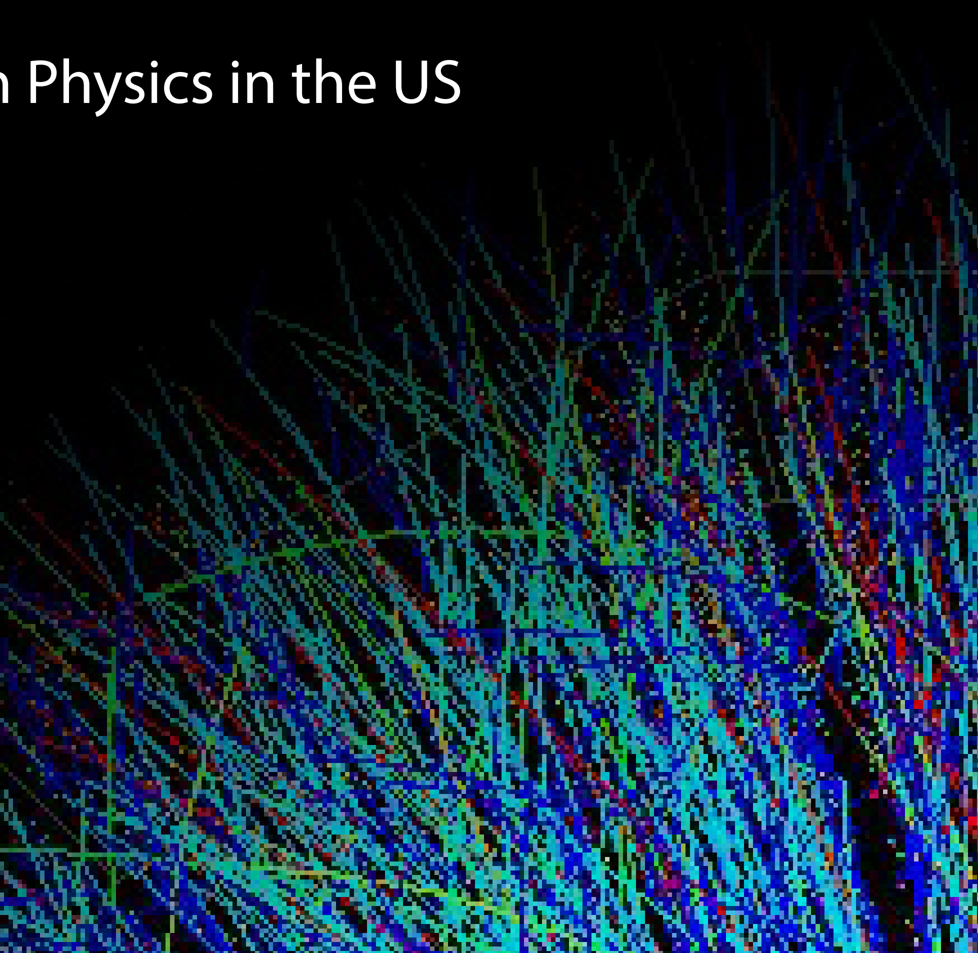
Hot and Dense QCD Matter

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

A Community White Paper on the Future of Relativistic Heavy-Ion Physics in the US



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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 and make a compelling case for its continuing support in an objective way that emphasizes the unique strengths of the program
- the very future of our field in the US may depend on how we present our case

Basic Outline of the White Paper

- **Introduction**
- **Success of the RHI Program**
- **“Standard 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

Discoveries made over the last 12 years cover a broad range of phenomena and multiple properties of hot & dense QCD

- high-momentum hadron suppression
- away-side jet modification (tomography)
- elliptic flow at the hydrodynamic 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

Theoretical & Phenomenological Advances

Discoveries made at RHIC and more recently at LHC have necessitated broad advances in theory and phenomenology to aid in our understanding and interpretation of the data.

- Relativistic Viscous Hydrodynamics
- AdS/CFT Modeling of Strongly-Coupled Media
- Statistical Hadronization Model
- Parton Recombination
- Parton Energy Loss Formalisms
- Parton Shower Evolution in Medium
- advances in Lattice QCD
- small-x Physics and the Color Glass Condensate

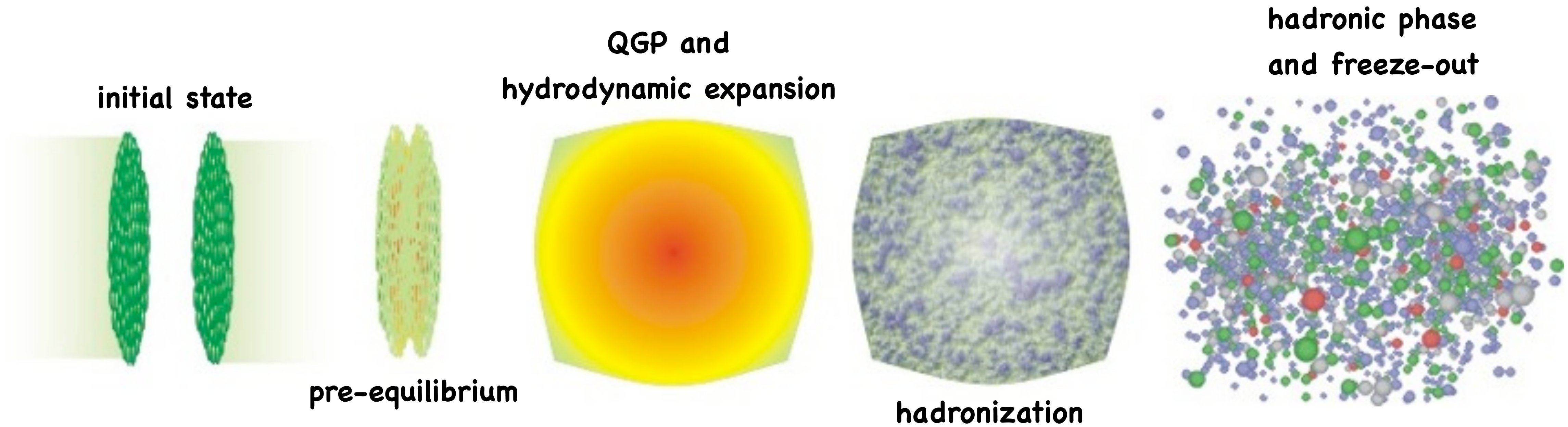
Quantitative Estimates of QGP Properties

Phenomenological analysis in conjunction with precision data and theoretical advances have lead to quantitative estimates for some of the most important quantities characterizing the formation and transport properties of the QGP:

- Initial State Characterization:
  - initial temperature: 300 MeV < T_{init} < 600 MeV
  - thermalization time: 0.2 fm/c < τ_0 < 1.2 fm/c
- Shear Viscosity / Entropy Density:
  - $1/(4\pi) < \eta/s \; 2/(4\pi)$
- Jet Energy-Loss Coefficients:
  - 2 GeV^2/fm < q-hat < 10 GeV^2/fm

These estimates lay the groundwork for the precision measurement of the QGP transport properties and their temperature dependence!

"Standard Model" of Heavy-Ion Collisions



- **Initial State:**
  - fluctuates event-by-event
  - classical color-field dynamics

- **QGP and hydrodynamic expansion:**
  - proceeds via 3D viscous RFD
  - EoS from Lattice QCD

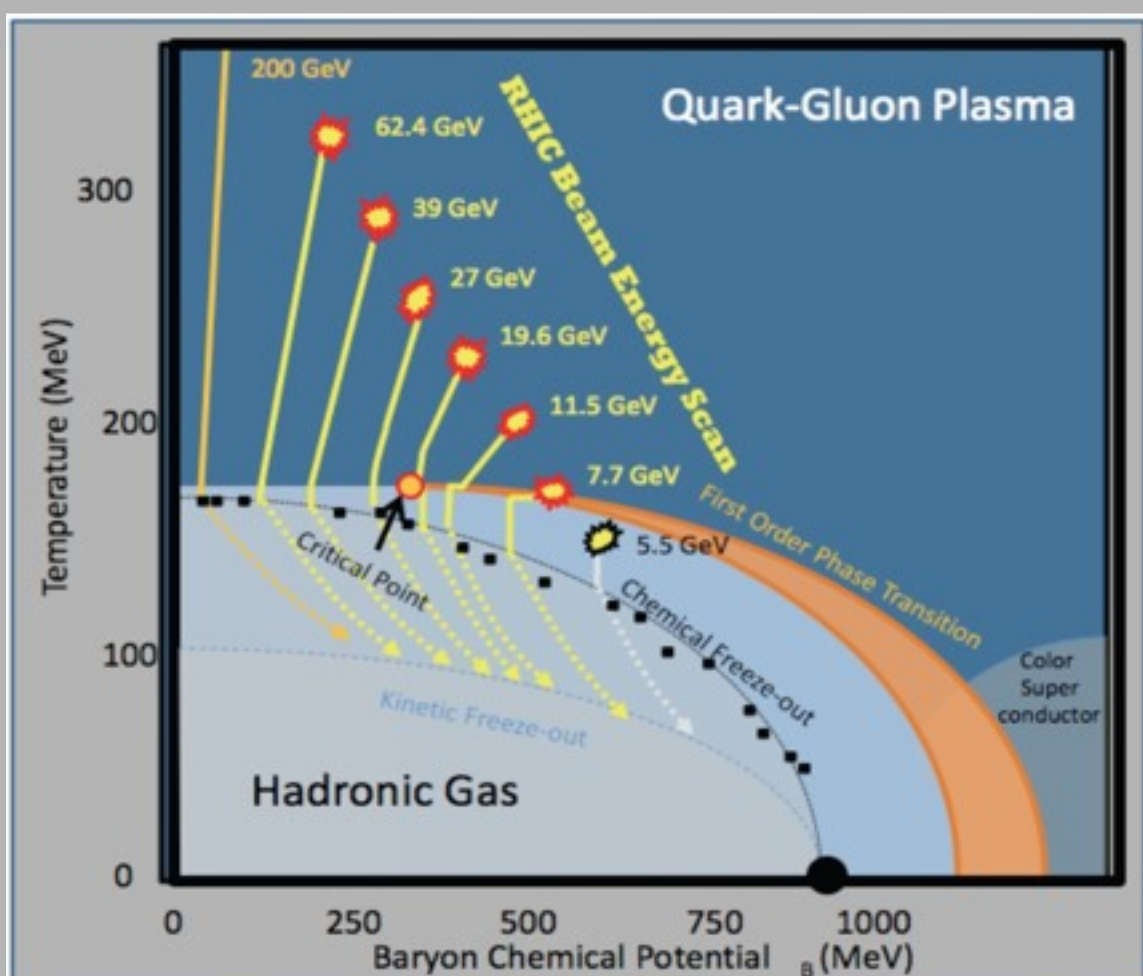
- **Pre-equilibrium:**
  - rapid change-over from glue-field dominated initial state to thermalized QGP
  - time scale: 0.15 to 2 fm/c in duration
  - build-up of transverse velocity fields?

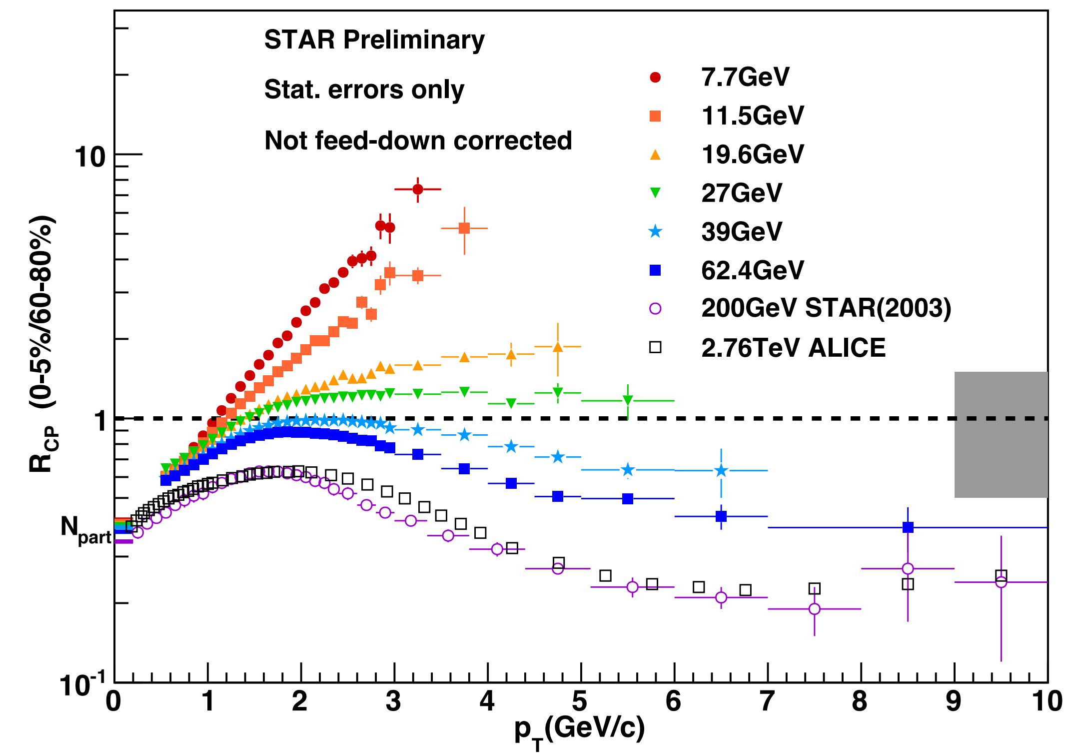
- **hadronic phase & freeze-out**
  - interacting hadron gas
  - separation of chemical and kinetic freeze-out

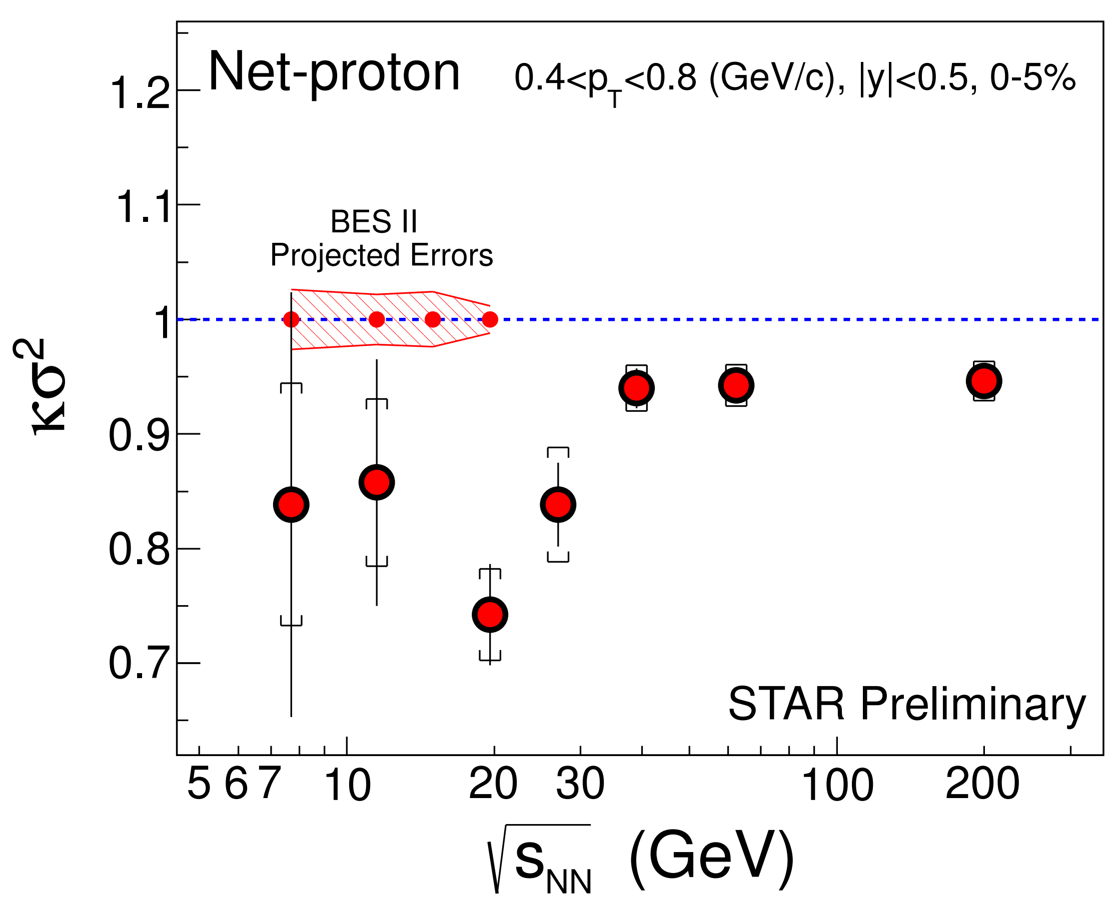
Discovery Potential: Charting the QCD Phase-Diagram

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 search for signatures of the CEP

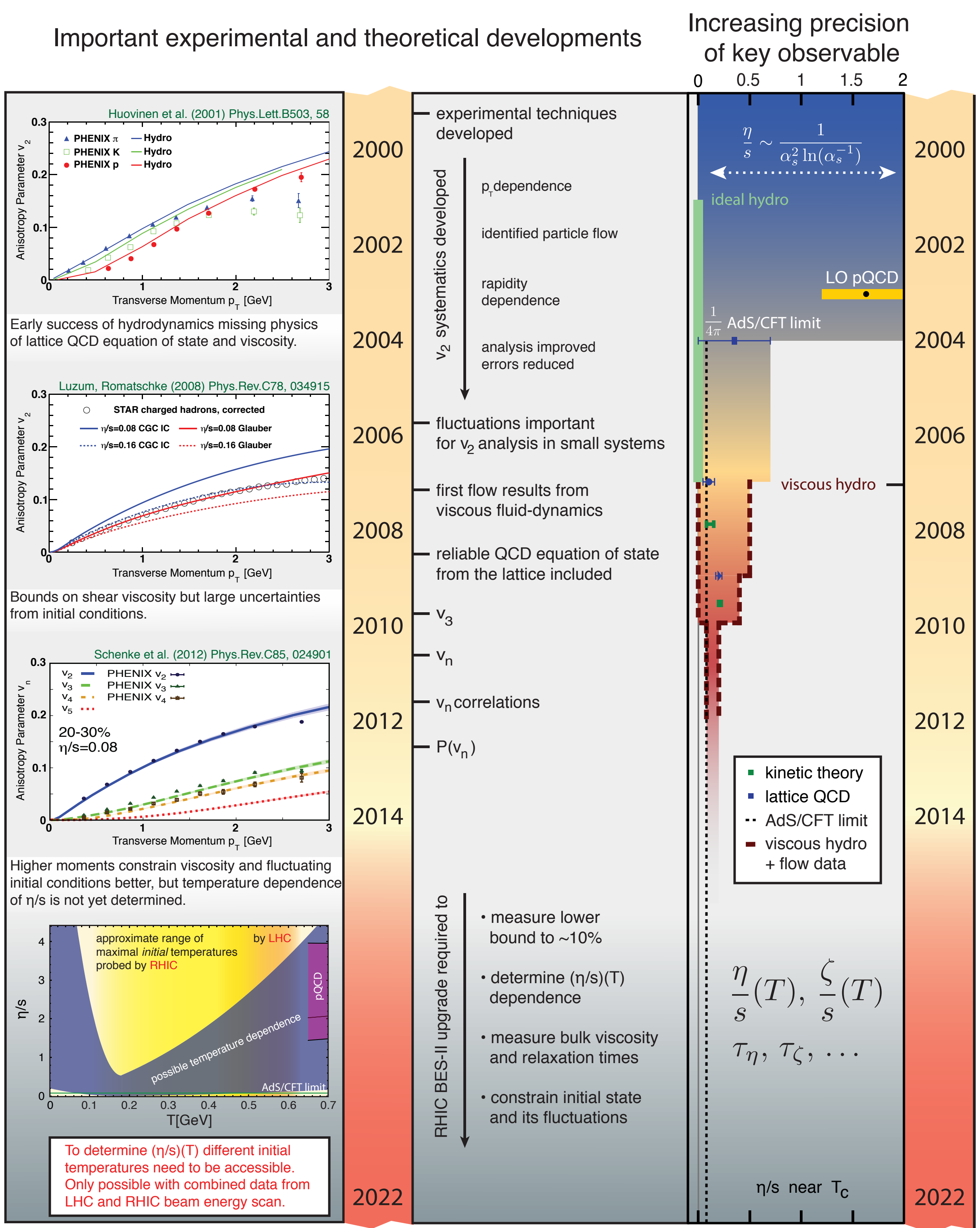


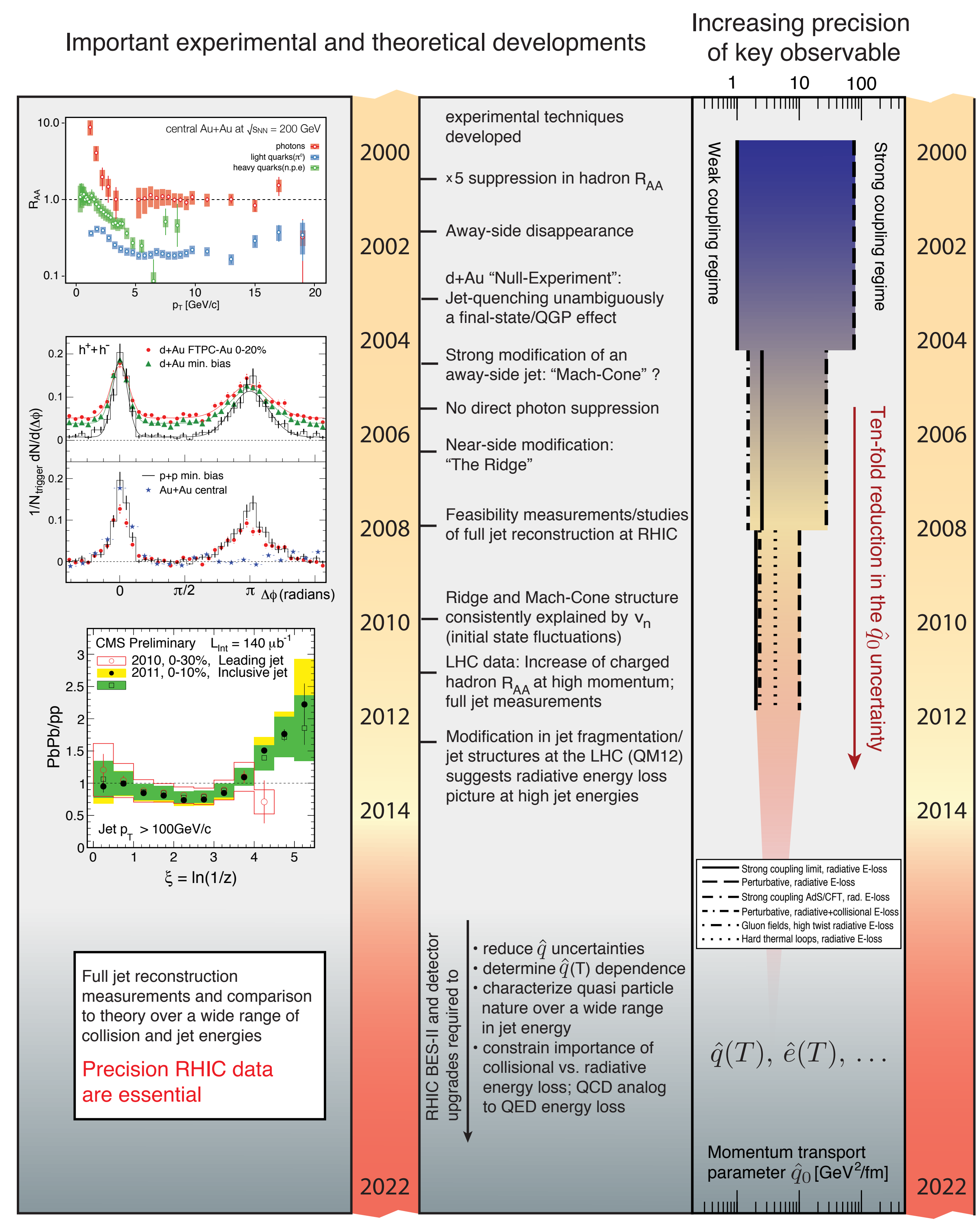




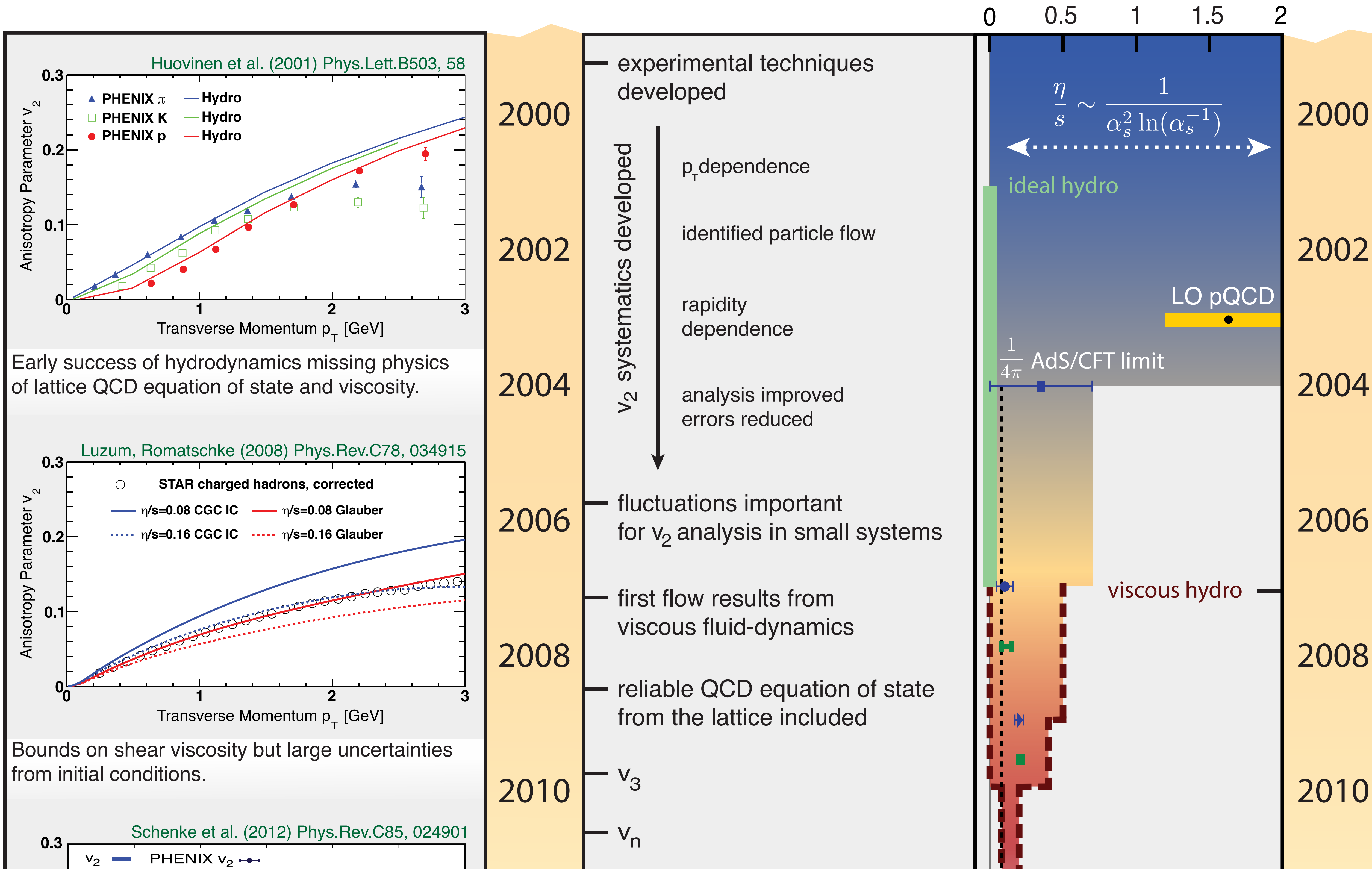
The Path to an Understanding of QGP Transport Coefficients

A large number of diverse measurements and theory insights contributed towards the improvement of our understanding of the QGP transport coefficients!



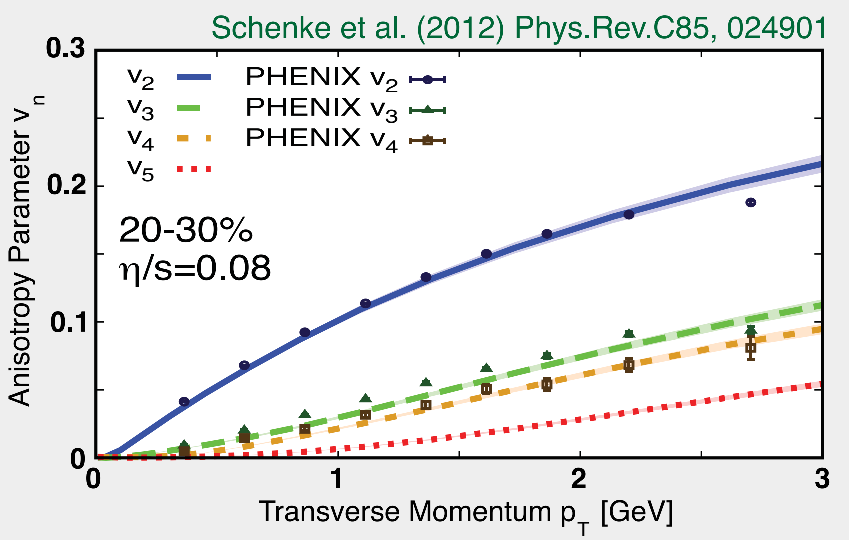


Towards a Precision Measurement of η/s

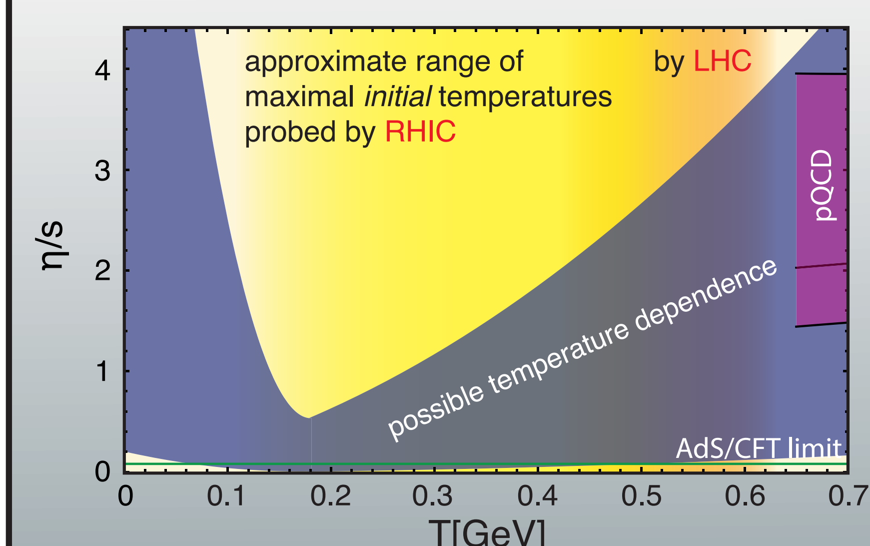


Quantifiable Deliverables:

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.

2012

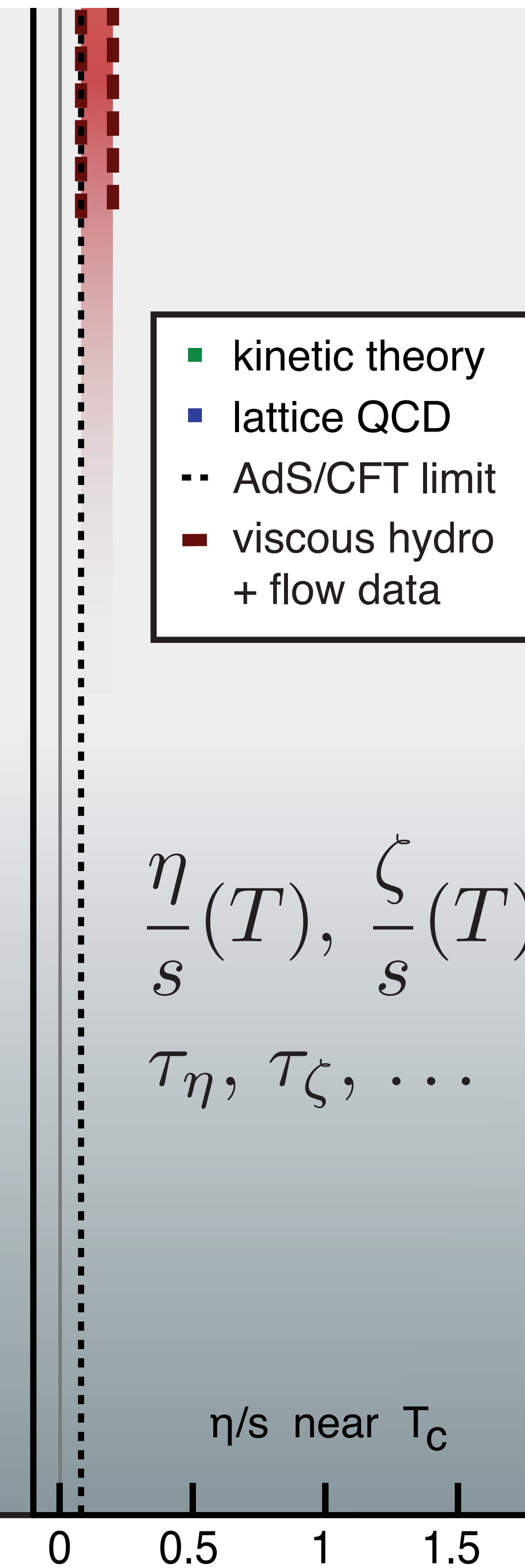
2014

2022

- v_n
- v_n correlations
- $P(v_n)$

RHIC BES-II upgrade required to

- measure lower bound to ~10%
- determine (η/s)(T) dependence
- measure bulk viscosity and relaxation times
- constrain initial state and its fluctuations



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

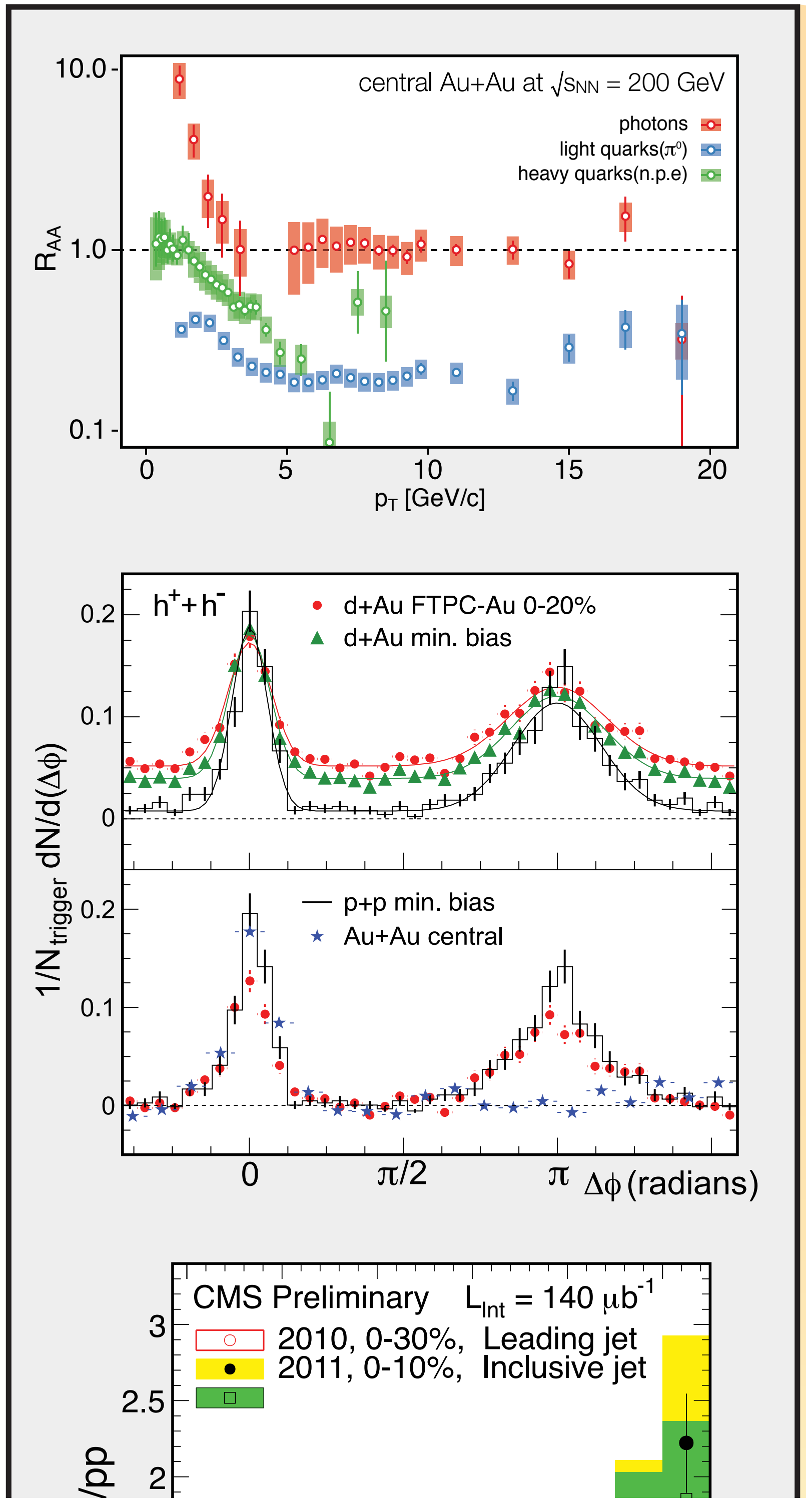
$$\tau_\eta,\ \tau_\zeta,\ \ldots$$

2012

2014

2022

Constraining Energy Loss Transport Coefficients



2000

- experimental techniques developed
- ×5 suppression in hadron R_{AA}
- Away-side disappearance

2002

- d+Au "Null-Experiment": Jet-quenching unambiguously a final-state/QGP effect

2004

- Strong modification of an away-side jet: "Mach-Cone" ?
- No direct photon suppression

2006

- Near-side modification: "The Ridge"

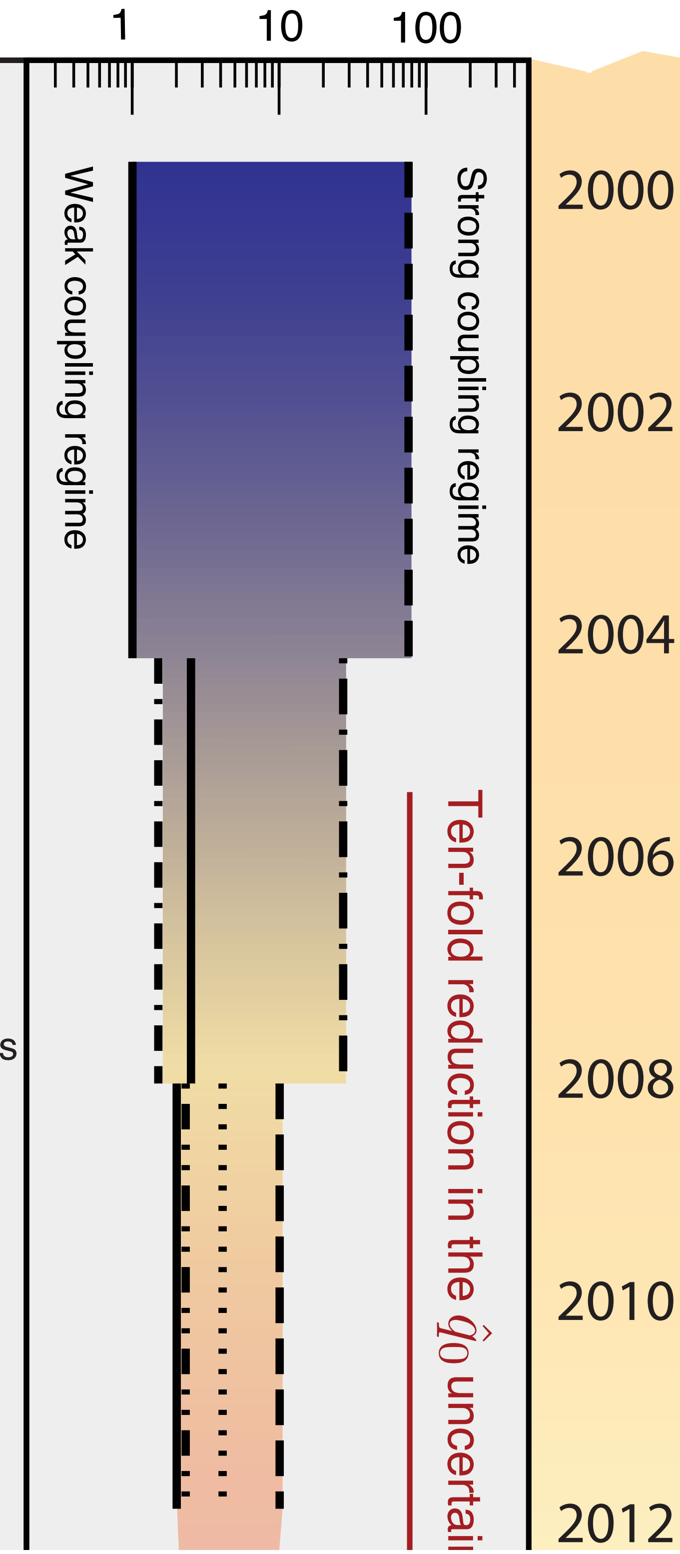
2008

- Feasibility measurements/studies of full jet reconstruction at RHIC

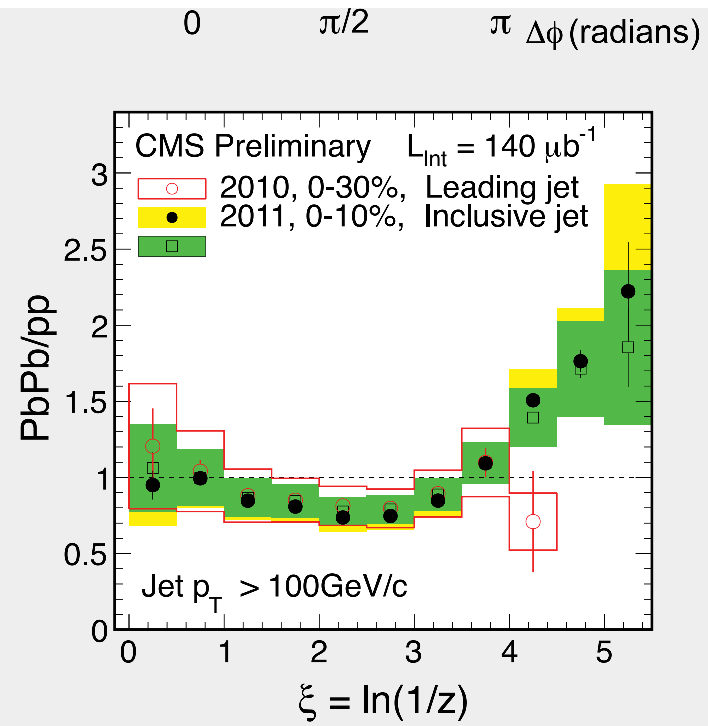
2010

- Ridge and Mach-Cone structure consistently explained by v_n (initial state fluctuations)
- LHC data: Increase of charged hadron R_{AA} at high momentum; full jet measurements

2012



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 — Ridge and Mach-Cone structure consistently explained by v_n (initial state fluctuations)

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

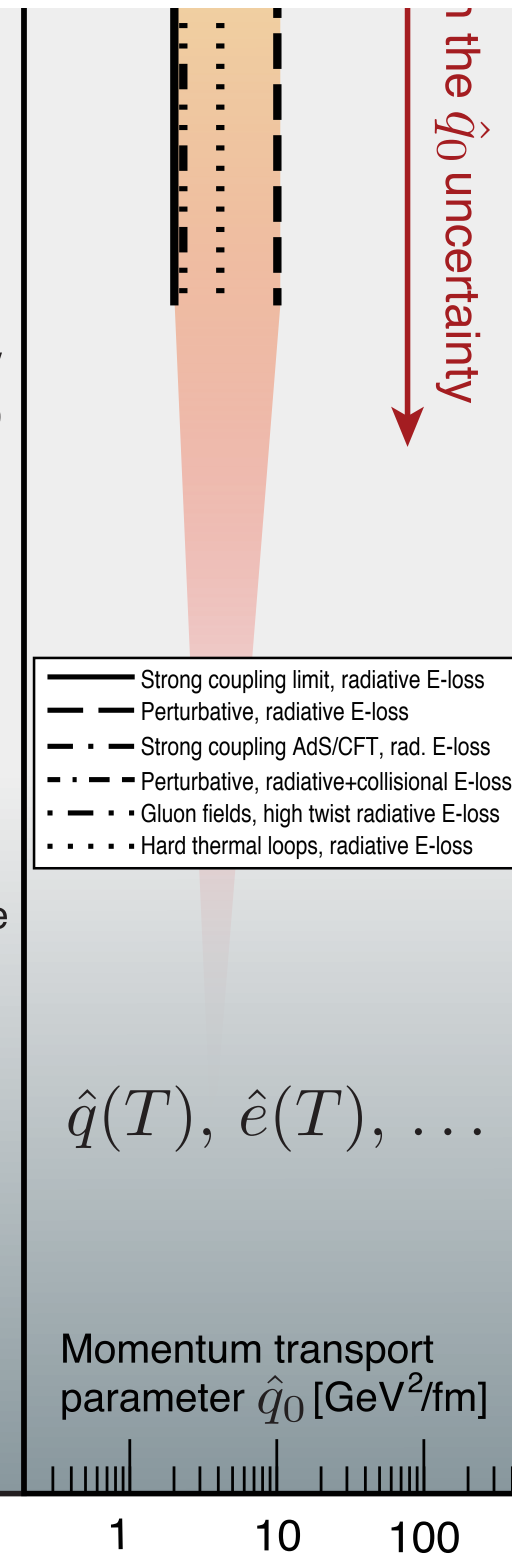
2012 — Modification in jet fragmentation/ jet structures at the LHC (QM12) suggests radiative energy loss picture at high jet energies

2014

RHIC BES-II and detector upgrades required to

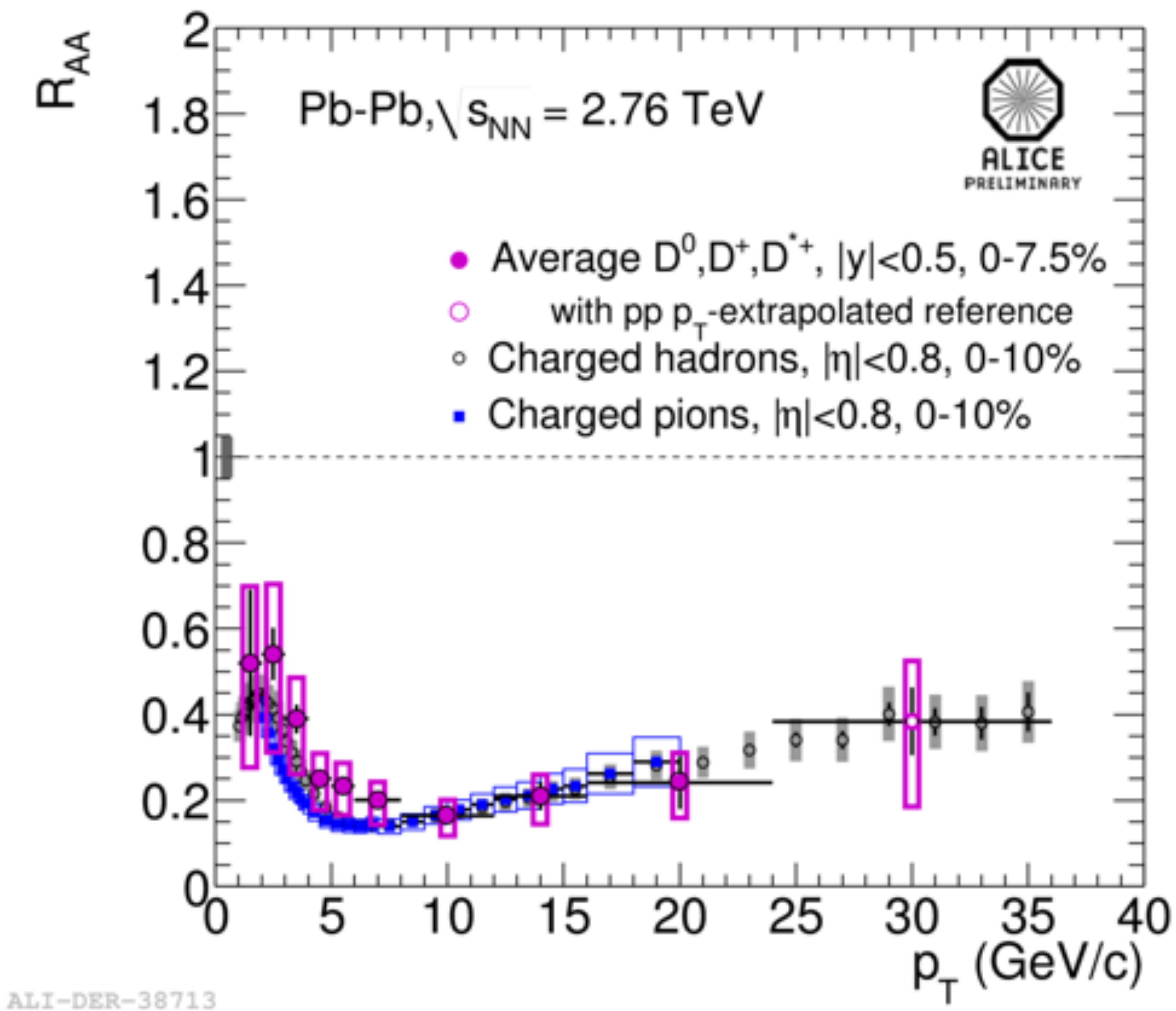
- reduce $\hat{q}$ uncertainties
- determine $\hat{q}$(T) dependence
- characterize quasi particle nature over a wide range in jet energy
- constrain importance of collisional vs. radiative energy loss; QCD analog to QED energy loss

2022



2010
2012
2014
2022

Open Questions: Heavy Quark Puzzle



Expectation:

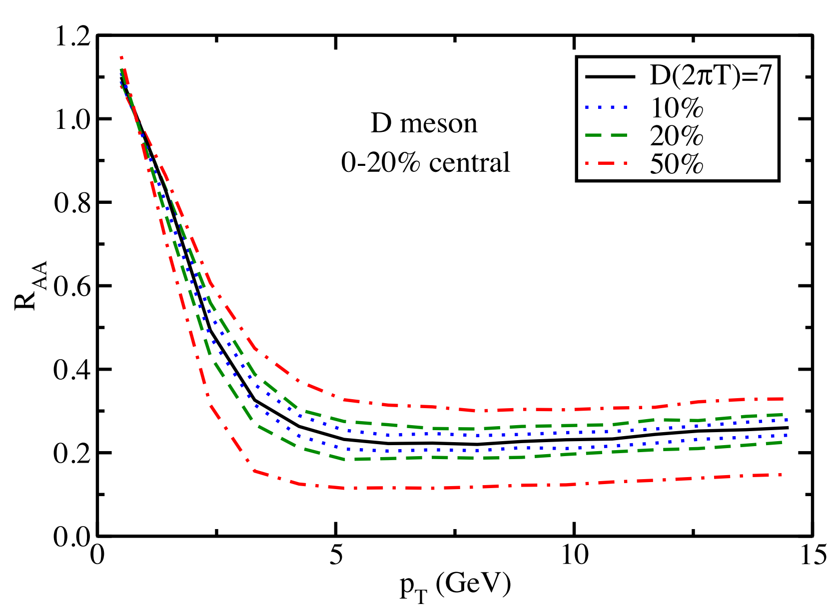
- Heavy Quarks should show significantly less energy-loss, due to their large mass vs. light quarks & gluons

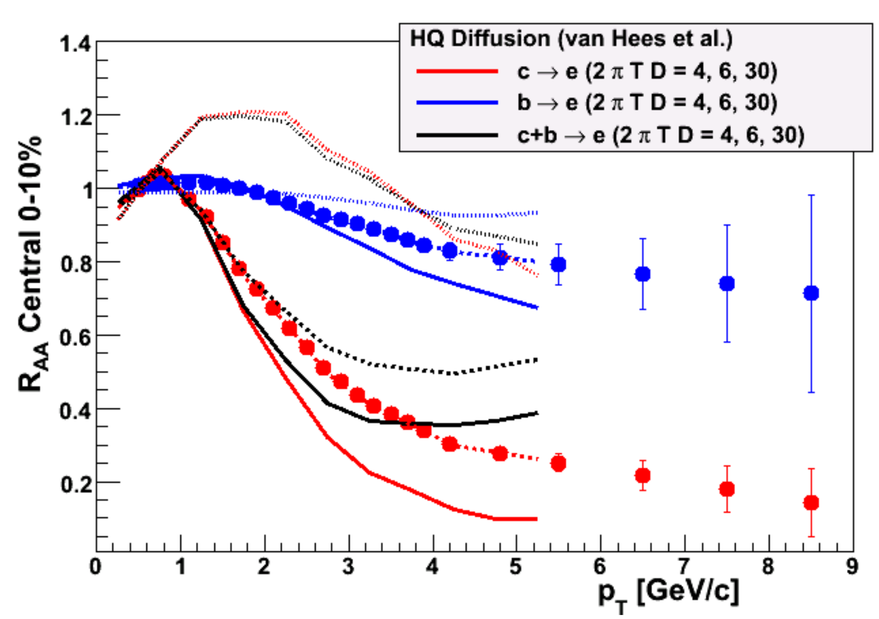
Discovery:

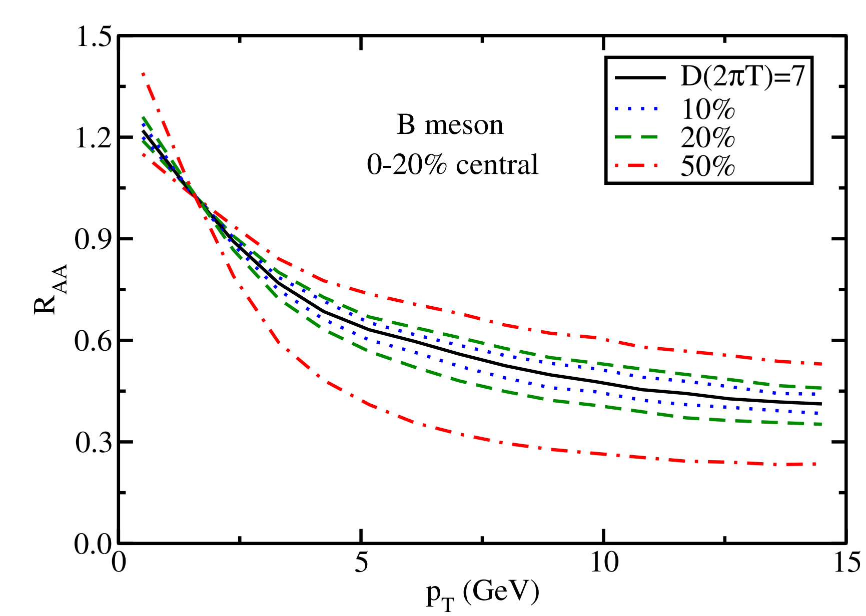
- Heavy Quarks exhibit nearly as much energy-loss as light quarks!
  - strong interaction with the medium
  - what drives the physics of HQ dynamics?

Measuring HQ Diffusion Constant:

- precision measurement will require <10% uncertainty in 5 GeV < p_T < 10 GeV range



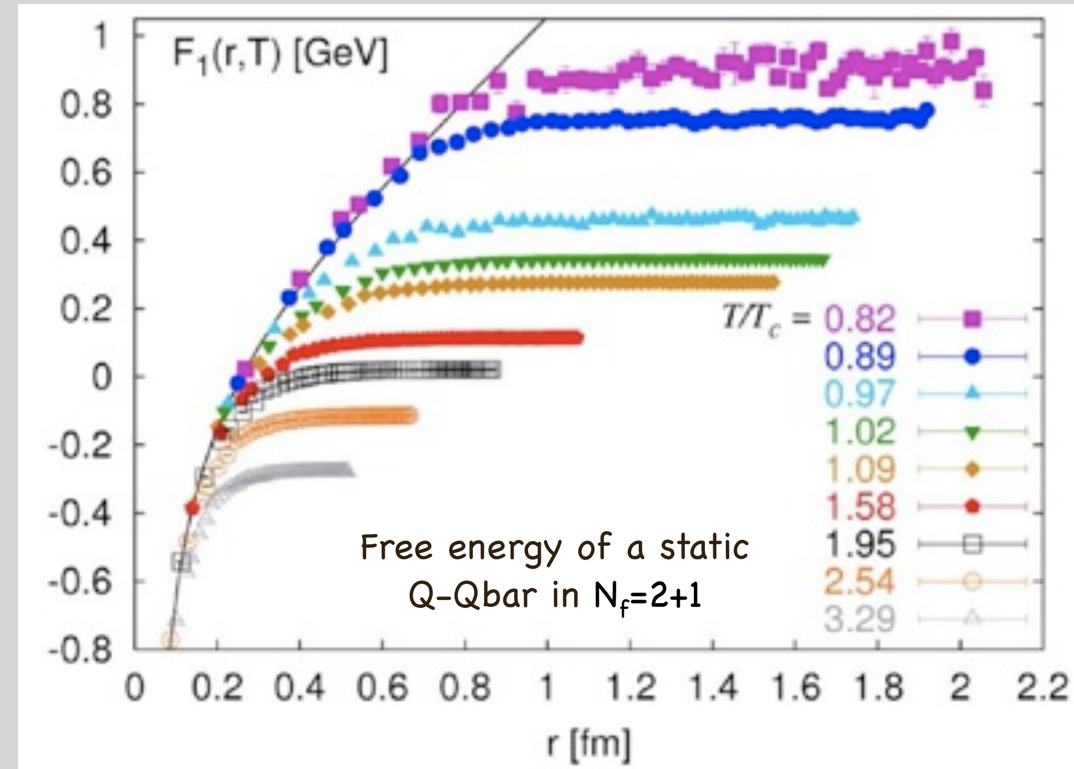


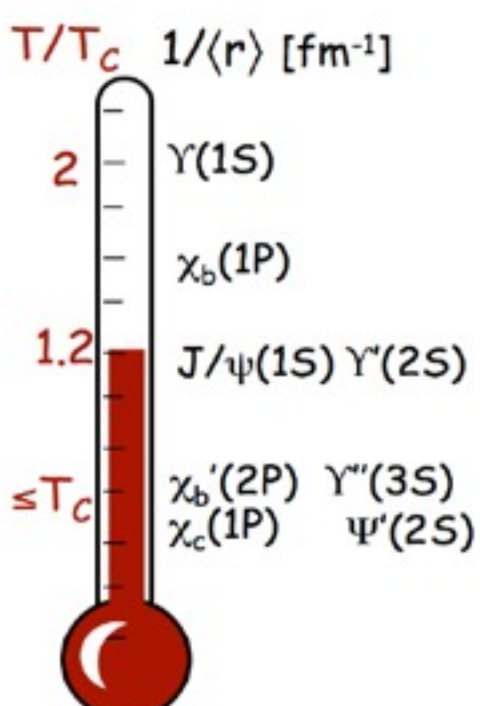


Quarkonium Suppression

Basic Idea:

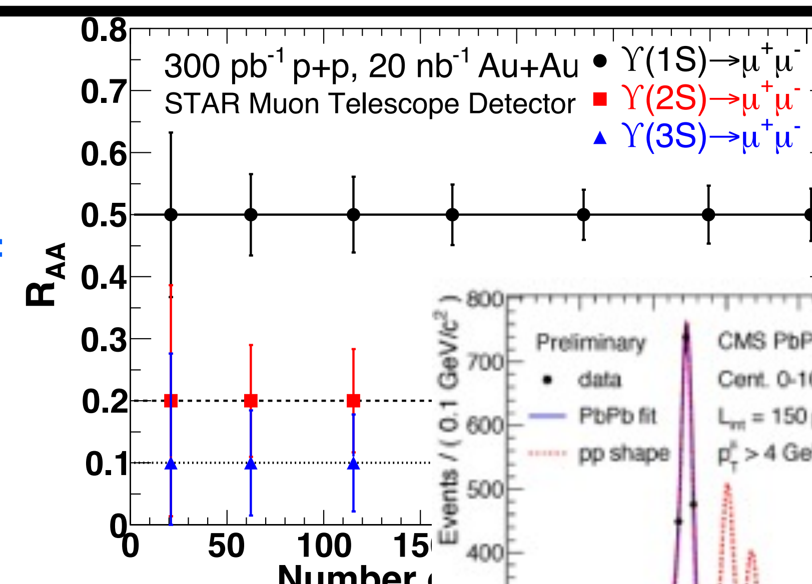
- color screening in deconfined matter weakens potential (force) between heavy quark and antiquark.
- strong screening seen in Lattice calculations
- screening sets in at shorter and shorter distances as T increases

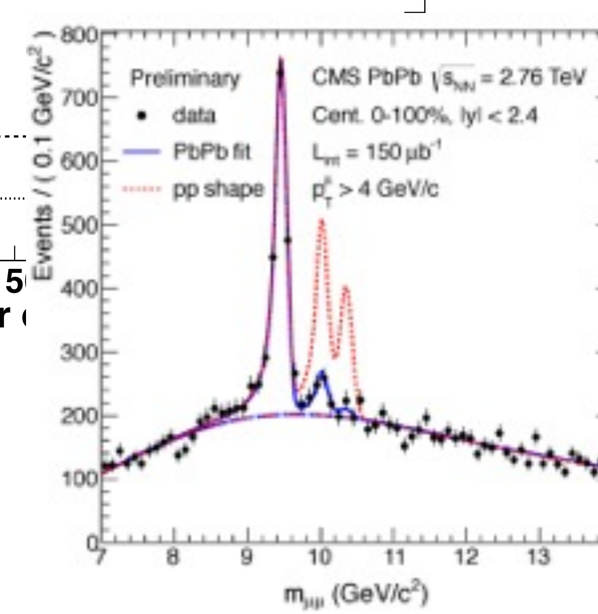




Υ(1S), Υ(2S) & J/ψ:

- three Quarkonium states relatively close in mass, but of significantly different radius
- ➢ expect sequential dissociation
- measurement of suppression pattern: standard candles for temperature achieved in collision





A. Mocsy & P. Petreczky: PRL **99** (2007) 211602

Open Questions: Thermalization

A hydrodynamic analysis of RHIC & LHC data indicates that the system must have thermalized on a timescale of $\leq$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**

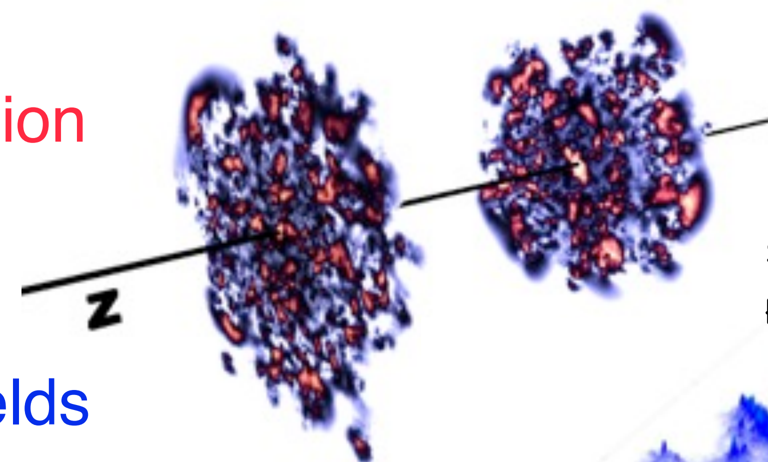
Initial State & Gluon Saturation: towards the EIC

Fundamental Challenge:

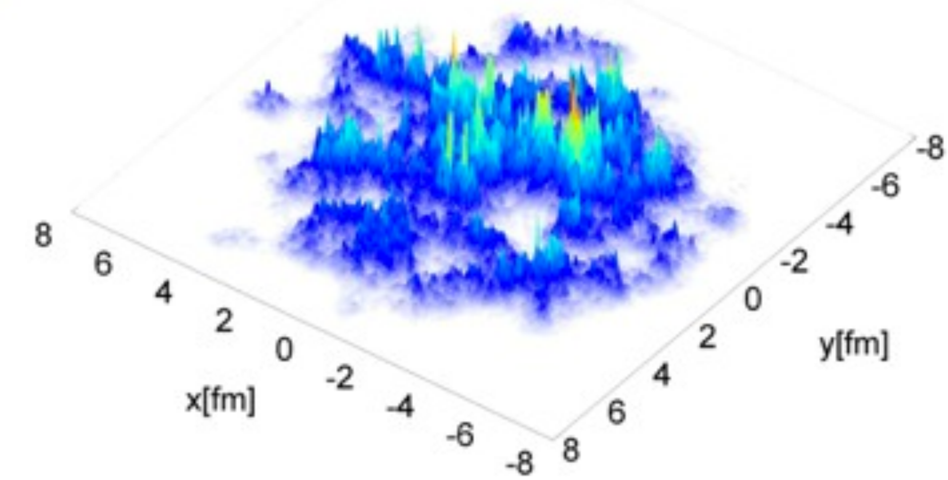
- how to describe the small-x gluon wave function of the incident nuclei?

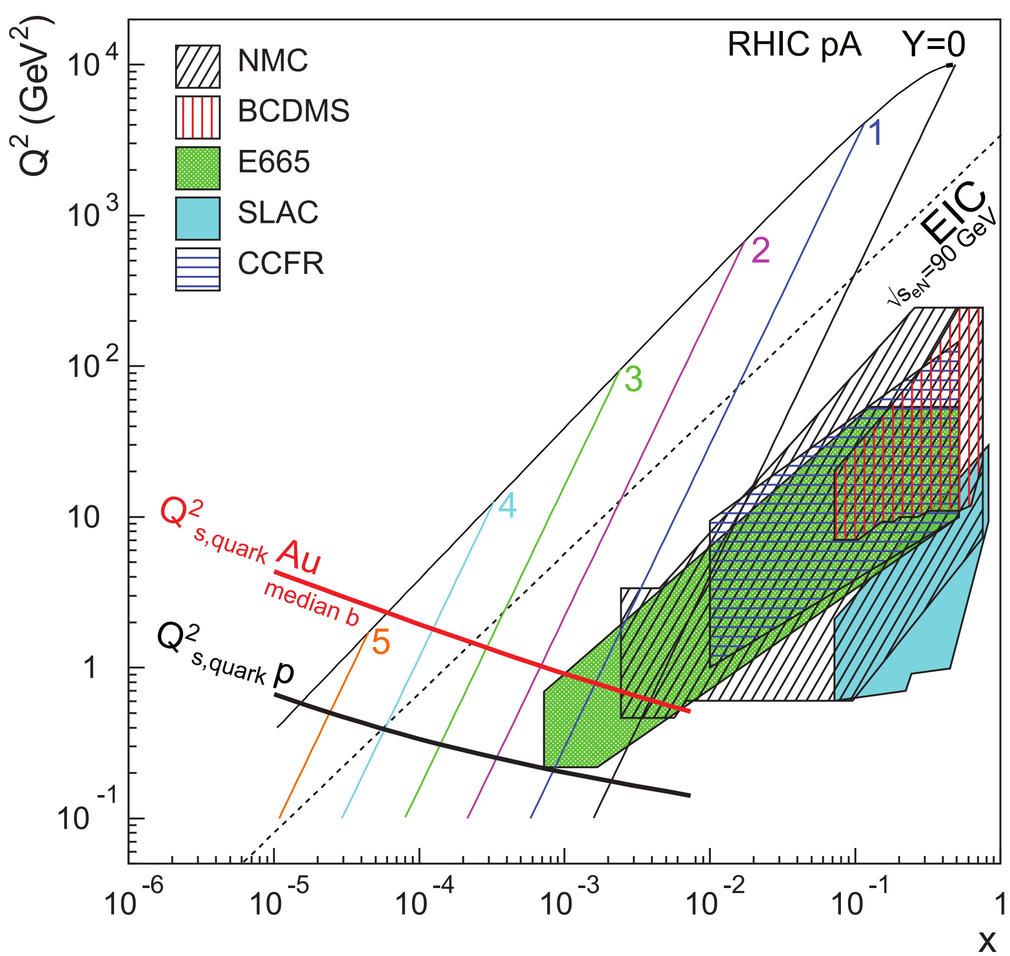
IP Glasma Model:

- correlations & fluctuations in the inital glue fields lead to a characteristic energy deposition, that can be probed via measurement of the distribution of flow coefficients v_n



Schenke, Tribedy & Venugopalan: PRL **108** (2012) 252301





- determination of the small-x gluon wave function will require measurement of Drell-Yan electrons in p+A reactions at forward rapidity
- best level of precision first obtainable in e+A reactions at the EIC

Complementarity of RHIC & LHC

- LHC provides prolific access to high energy probes (quarkonia, high energy jets, W/Z/γ) at rates beyond that obtainable at RHIC
- RHIC also accesses high energy probes (lower energy kinematical regime), and can leverage longer heavy-ion beam times in its favor, given sufficient luminosity.
- 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

RHIC and LHC are fully complementary to each other - the outlined research program cannot be accomplished by either facility alone!

The Future of the US Heavy-Ion Program

The next 5-10 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.
- the quantitive determination of the transport coefficients of the Quark Gluon Plasma, such as the temperature dependence of the shear-viscosity to entropy-density ratio, and that of the energy loss transport coefficients q-hat and e-hat.
- a jet physics program to study the nature of parton energy loss and the quasi-particle nature of the QGP.
- a heavy-flavor physics program to probe the nature of the surprisingly strong interactions of heavy quarks with the surrounding medium, as well as Quarkonia measurements that 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.