The standard model for QGP evolution: Theoretical status and future

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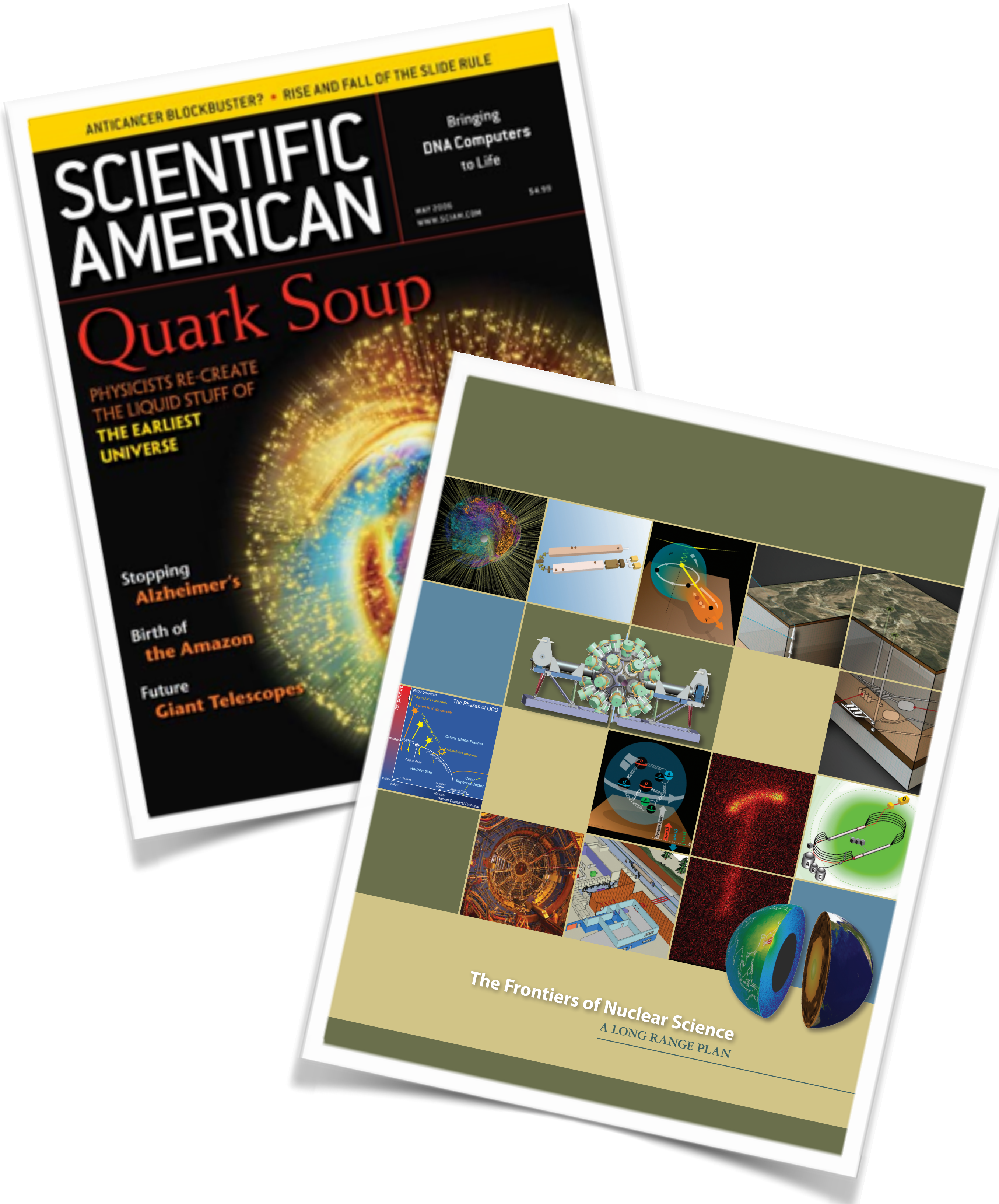
Nuclear matter under extreme conditions



- 2005 Fluid nature of Quark Gluon Plasma (QGP) created in Heavy Ion Collisions at RHIC established
- 2007 Long Range Plan recommends broad quantitative study of QGP properties

Long Range Plan 2007

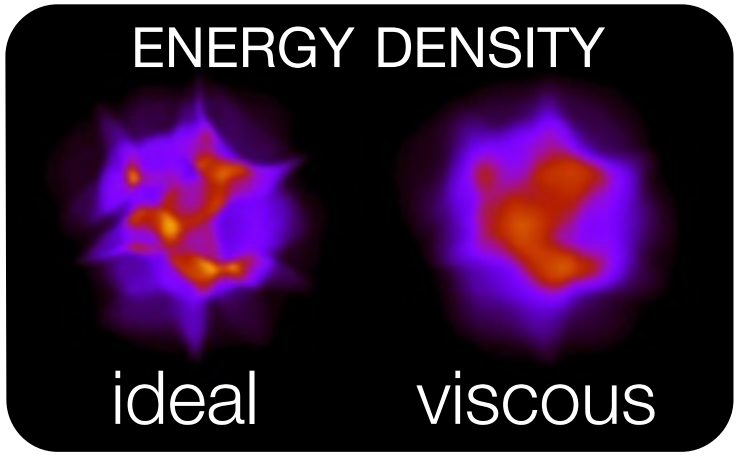
Recommendation IV:

- The major discoveries in the first five years at RHIC must be followed by a broad, quantitative study of the fundamental properties of the quark-gluon-plasma.

- Achieving a quantitative understanding of the quark-gluon-plasma also requires new investments in modeling of heavy-ion collisions, in analytic approaches, and in large-scale computing.

Continuous theory progress since the LRP 2007

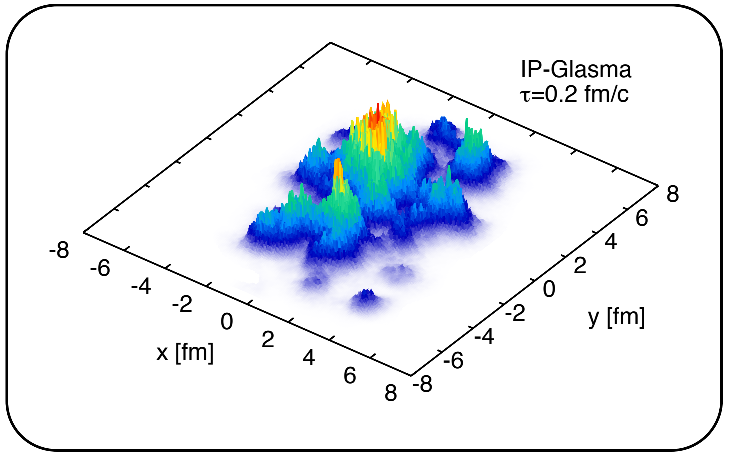
- Viscous relativistic fluid dynamics:
  2+1 dimensions (2007)
  3+1 dimensions (2011)



- Importance of fluctuations broadly realized (2005-2010)

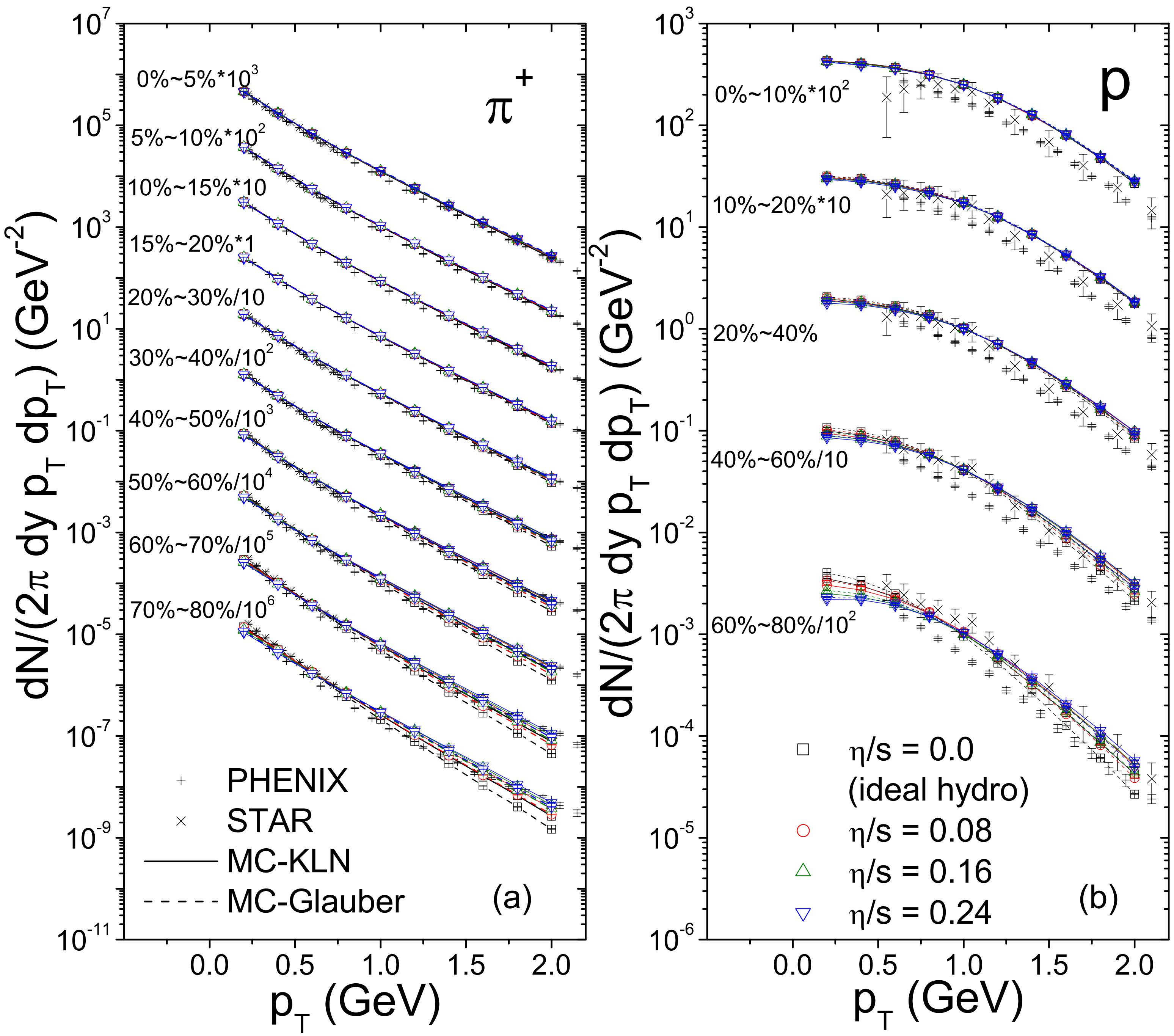
- Sophisticated equation of state from the lattice (2010)

- At high energies Color Glass Condensate effective theory of QCD provides framework to compute the fluctuating initial state (2012)

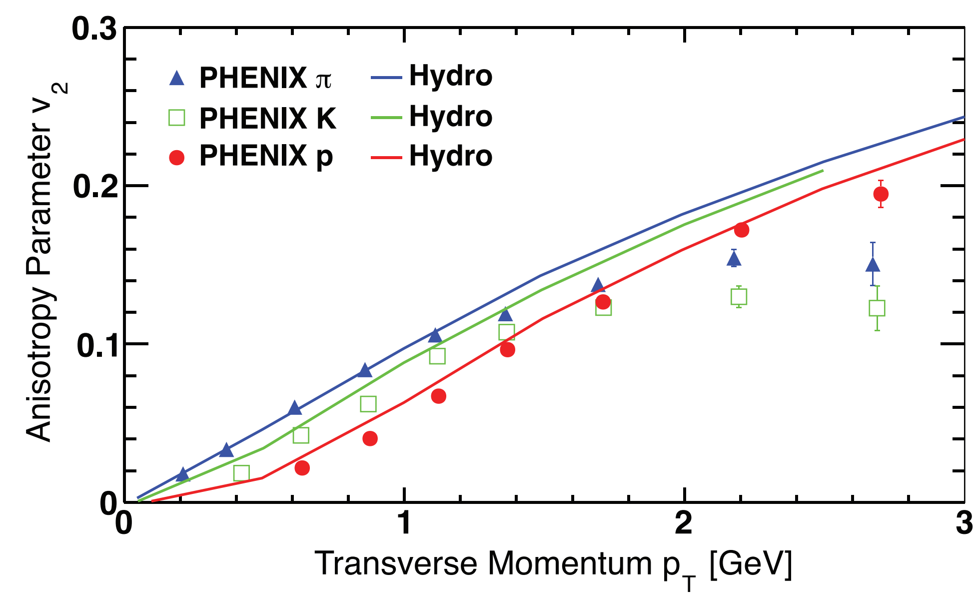


Validation: Hydrodynamics describes the data

hadron spectra



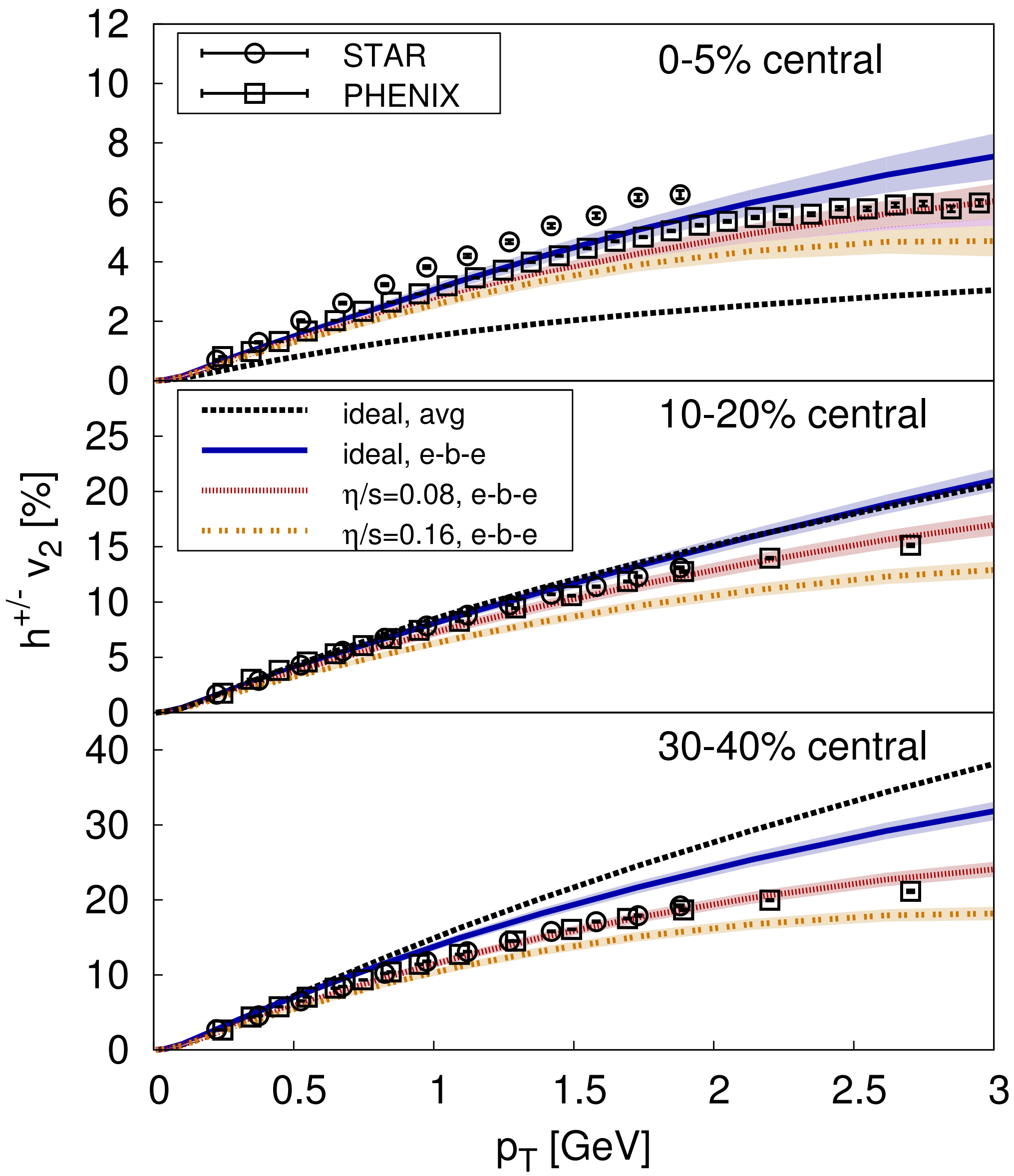
anisotropic flow

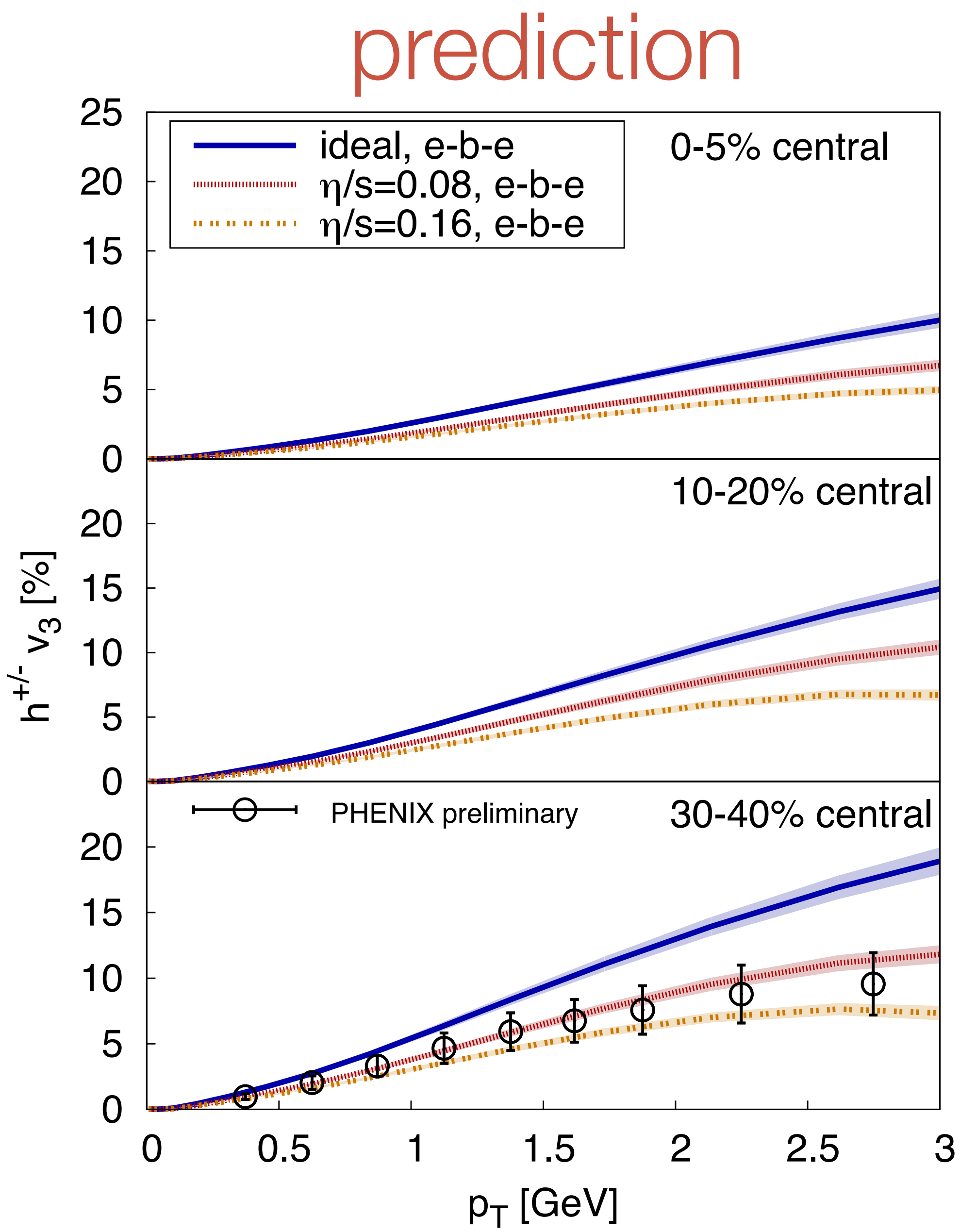


Huovinen et al. (2001) Phys.Lett.B503, 58

H. Song, S. Bass, U. Heinz, T. Hirano, C. Shen, Phys.Rev. C83 (2011) 054910

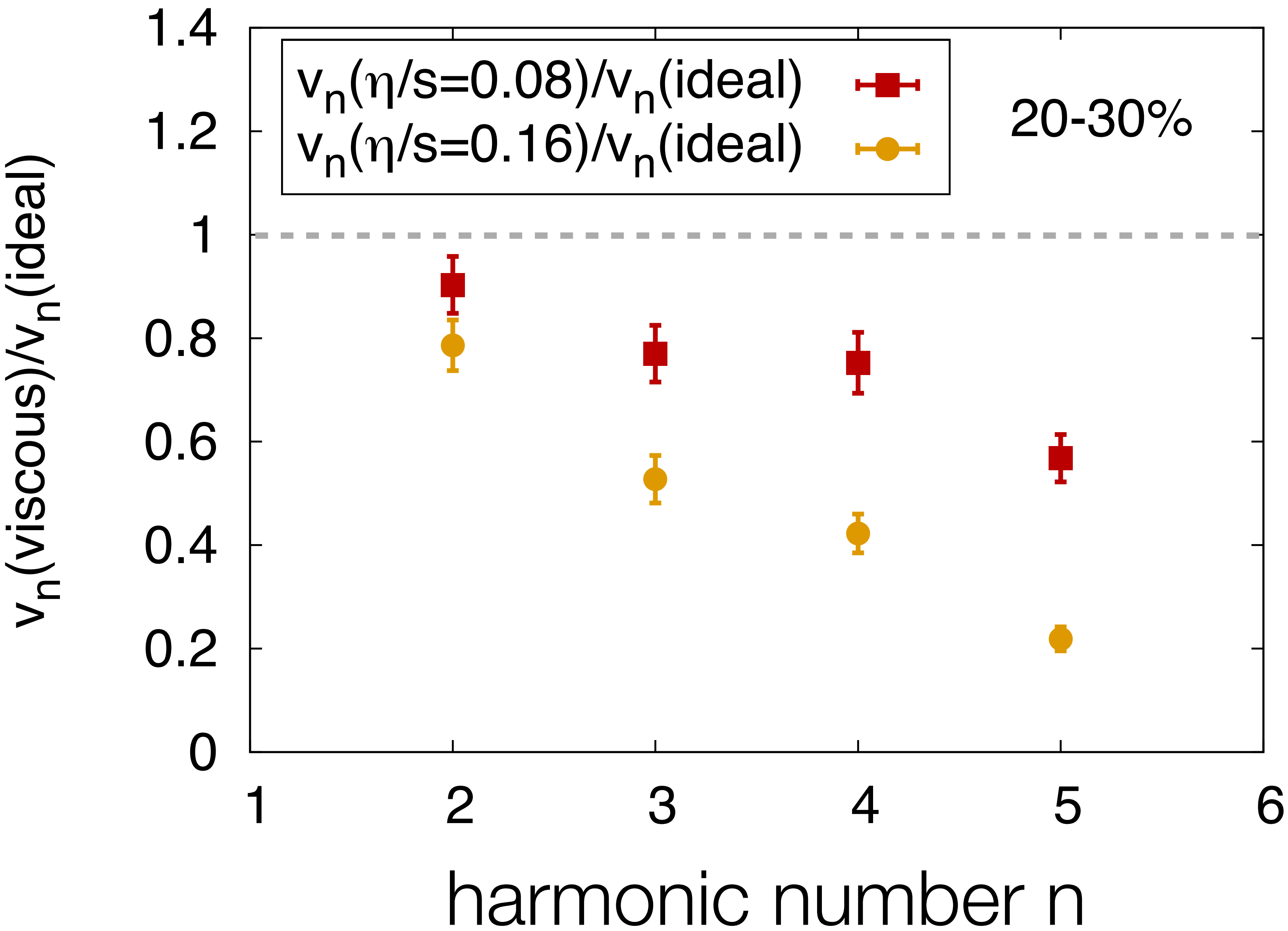
Event-by-event calculations predict flow harmonics





B. Schenke, S. Jeon, C. Gale, Phys. Rev. Lett. 106, 042301 (2011)
J. Adams et al. (STAR), Phys. Rev. C72, 014904 (2005)
A. Adare et al. (PHENIX), Phys. Rev. Lett. 105, 062301 (2010)
A. Adare et al. (PHENIX), Phys.Rev.Lett. 107, 252301 (2011)

Sensitivity of observables to transport properties

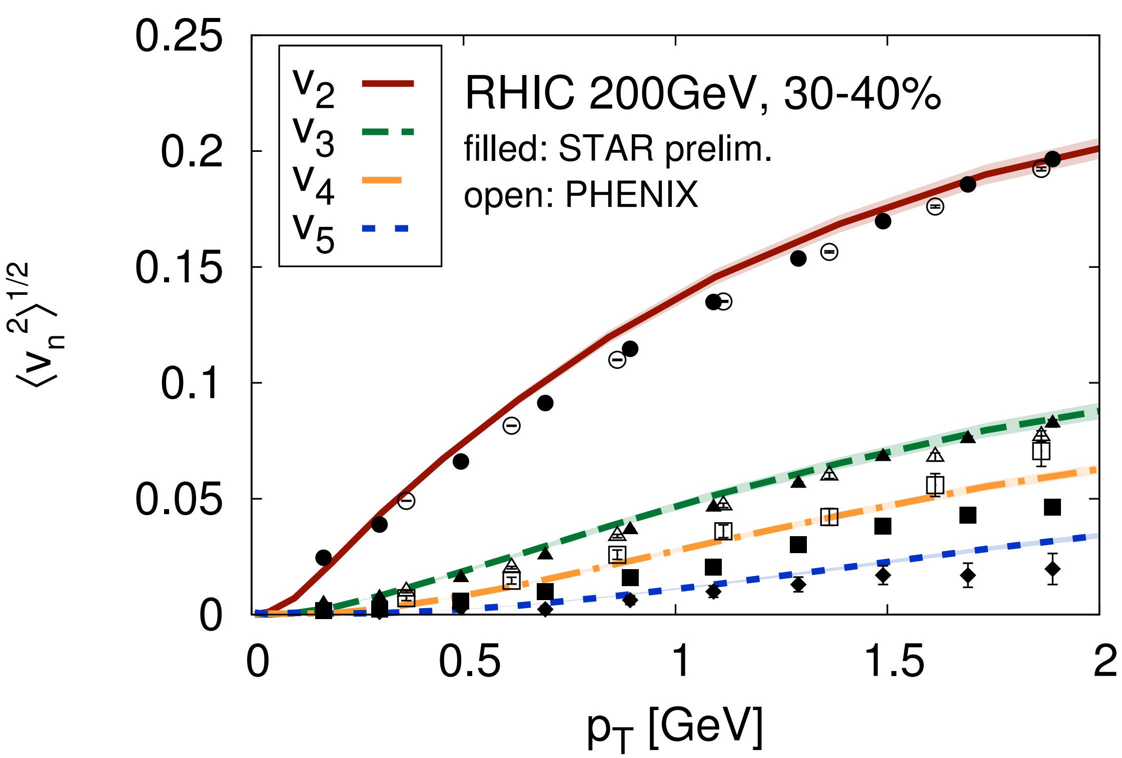


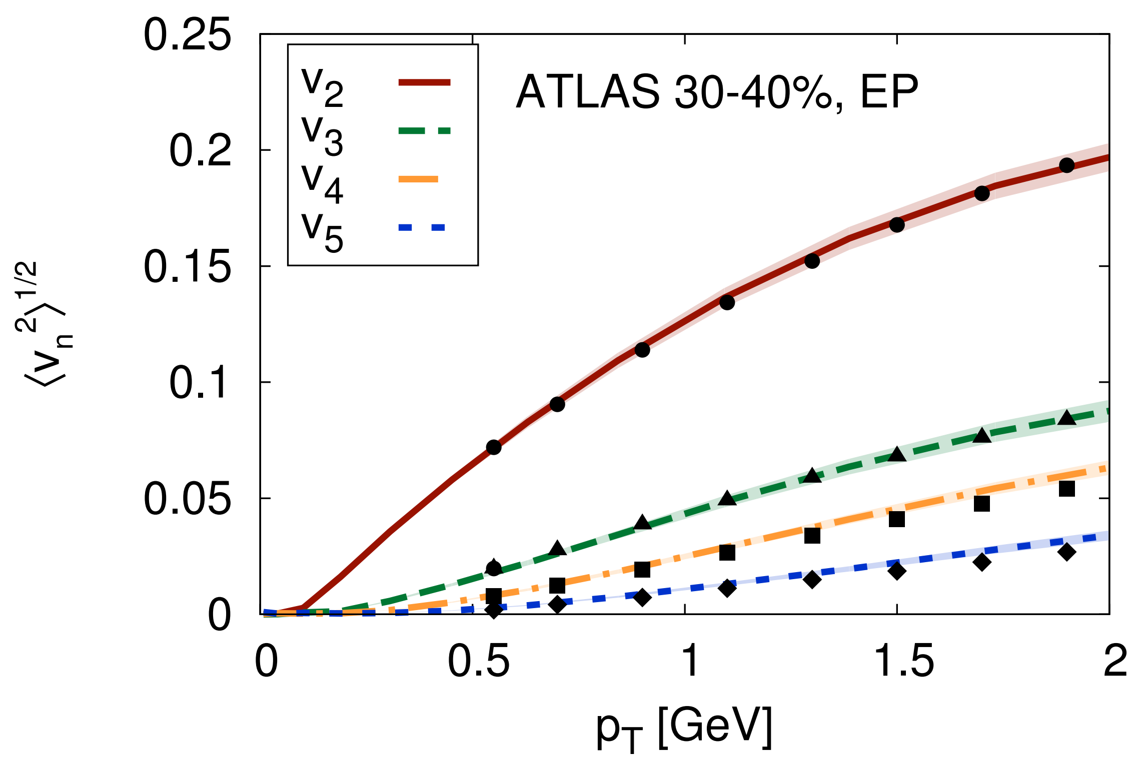
viscosity affects higher harmonics more

B. Schenke, S. Jeon, C. Gale, Phys. Rev. C85, 024901 (2012)

IP-Glasma fluctuating initial state

Include more QCD dynamics and reduce free parameters
Consistently describes all flow harmonics for a given η/s





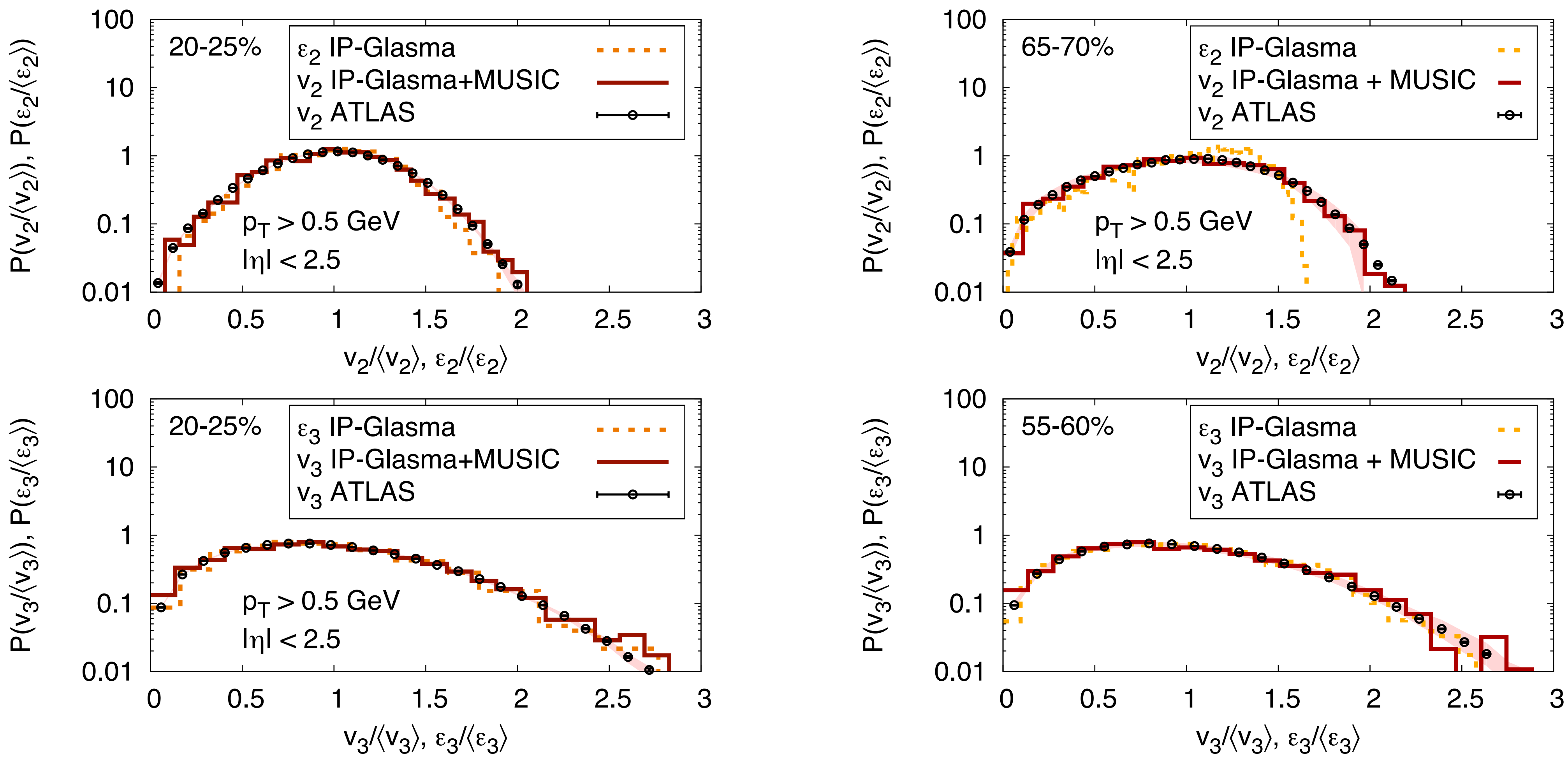
$\eta/s \approx 0.12$ at $\sqrt{s} = 0.2$ TeV

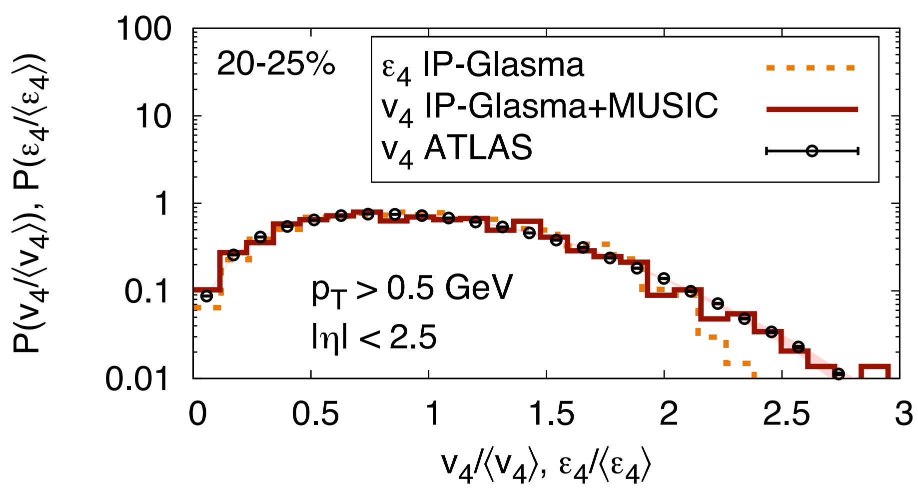
$\eta/s \approx 0.2$ at $\sqrt{s} = 2.76$ TeV

C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 110, 012302 (2013)
Experimental data:
A. Adare et al. (PHENIX Collaboration), Phys.Rev.Lett. 107, 252301 (2011)
Y. Pandit [for the STAR collaboration], Quark Matter 2012; Phys. Rev. C 88, 14904 (2013)
G. Aad et al. (ATLAS Collaboration), Phys.Rev. C86, 014907 (2012).

Event-by-event fluctuations of flow coefficients

C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 110, 012302 (2013)
Experimental Data: ATLAS Collaboration, JHEP 1311, 183 (2013)

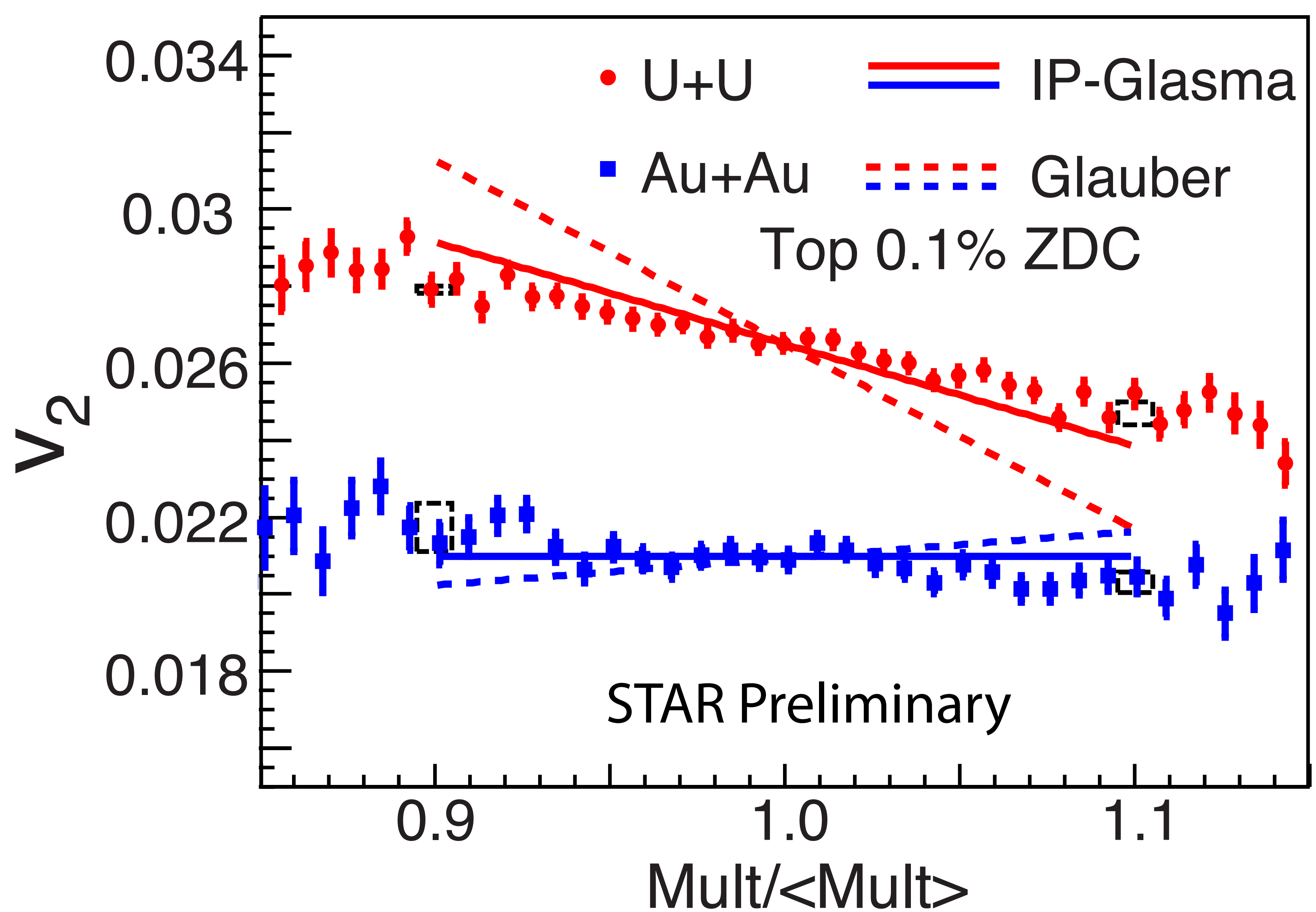




- Flow fluctuations reflect initial state fluctuations
- Support collectivity interpretation

Testing the initial state model in U+U collisions

B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. C89, 064908 (2014)
Experimental Data: STAR Collaboration, H. Wang, Nucl. Phys. A (in press, 10.1016/j.nuclphysa.2014.08.086)

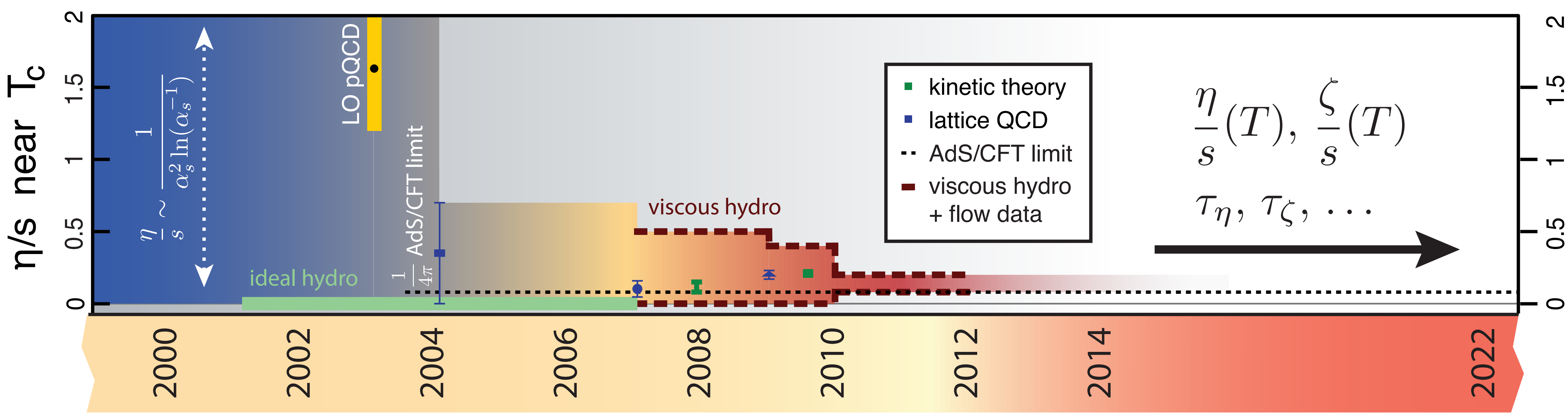


Ultra-central collisions of deformed nuclei distinguish between different models of particle production - IP-Glasma preferred

Extracting quantitative information

Example: Shear viscosity to entropy density ratio η/s

Broad theoretical efforts and experimental advances lead to increasingly precise determination of η/s



LO pQCD: P. Arnold, G. D. Moore, L. G. Yaffe, JHEP 0305 (2003) 051
AdS/CFT: P. Kovtun, D. T. Son, A. O. Starinets, Phys.Rev.Lett. 94 (2005) 111601
Lattice QCD: A. Nakamura, S. Sakai, Phys.Rev.Lett. 94 (2005) 072305
H. B. Meyer, Phys.Rev. D76 (2007) 101701; Nucl.Phys. A830 (2009) 641C-648C
Ideal hydro: P. F. Kolb, J. Sollfrank, U. W. Heinz, Phys.Rev. C62 (2000) 054909
P. F. Kolb, P. Huovinen, U. W. Heinz, H. Heiselberg, Phys.Lett. B500 (2001) 232-240
pQCD/kin. theory: Z. Xu, C. Greiner, H. Stöcker, Phys.Rev.Lett. 101 (2008) 082302
J.-W. Chen, H. Dong, K. Ohnishi, Q. Wang, Phys.Lett. B685 (2010) 277-282
Viscous hydro: P. Romatschke, U. Romatschke, Phys.Rev.Lett. 99 (2007) 172301
M. Luzum, P. Romatschke, Phys.Rev. C78 (2008) 034915
H. Song, U. W. Heinz, J.Phys. G36 (2009) 064033
H. Song, S. A. Bass, U. Heinz, T. Hirano, C. Shen, Phys.Rev.Lett. 106 (2011) 192301

What we have learned

- All observations are consistent with the creation of a strongly interacting **quark gluon plasma** in heavy ion collisions at highest RHIC energies and the LHC
- The created matter behaves like an **almost perfect fluid** with shear viscosity to entropy density close to the lower bound
- Initial state **fluctuations** are recovered in the observed particles' momentum distributions
- Direct photons indicate that **temperatures** exceed 300 MeV
- The created matter is nearly **opaque** to traversing partons

The Standard Model of Heavy Ion Collisions

- Initial state fluctuations of nucleon positions
  and sub-nucleonic color charges

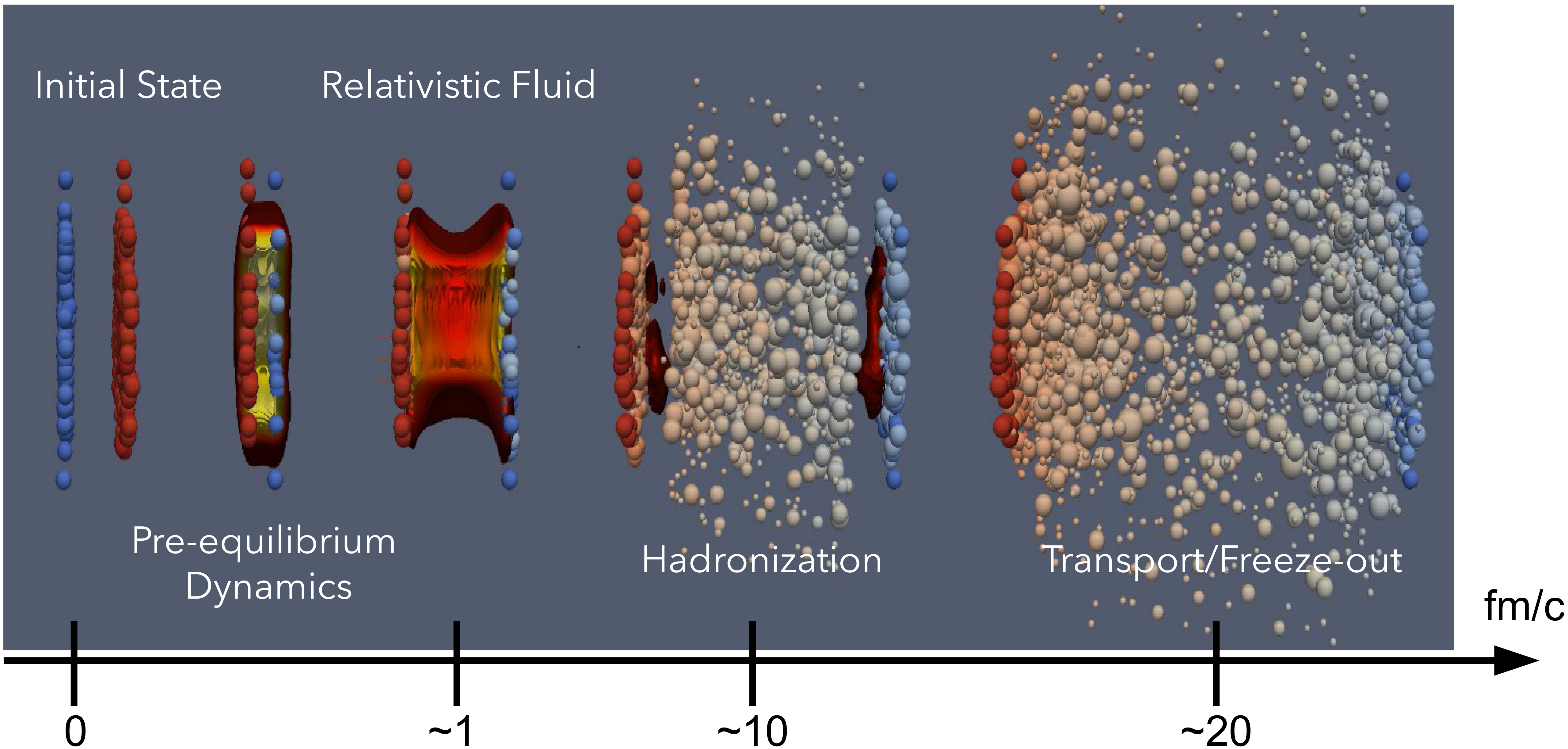
- Rapid transition to applicability of viscous fluid dynamics

- Second order viscous relativistic fluid dynamics describes the bulk of the evolution

- Equation of state is provided by lattice QCD calculations
  Hadronic phase shows chemical freeze-out before kinetic

- Kinetic freeze-out occurs in hadronic phase - late stage can be described by microscopic transport calculations

Evolution of a Heavy Ion Collision



Visualization: madai.us

Going forward: Necessary improvements

We have achieved **good control** over initial state,
equation of state, fluid dynamics **at high collision energies**

Still need significant work on:

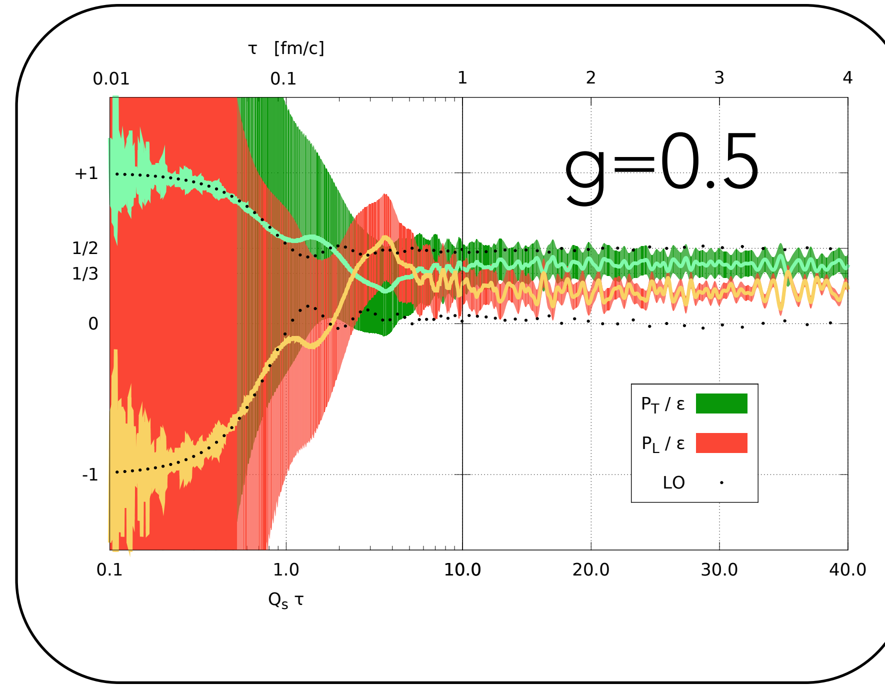
- Pre-equilibrium dynamics
- Temperature dependent transport parameters
- Initial conditions at lower collision energies
- Finite baryon densities
- Hydrodynamic fluctuations
- Freeze-out / transition to transport, especially viscous corrections

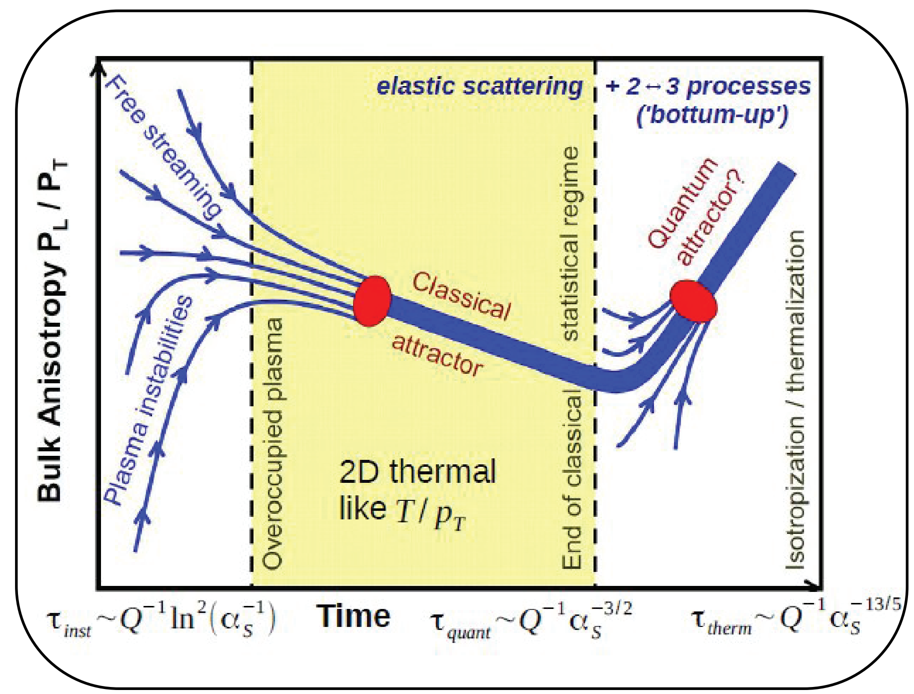
Pre-equilibrium dynamics - thermalization?

More sophisticated first principles computations of non-equilibrium early time dynamics

- Addressing the still open issue of rapid isotropization and thermalization

- Field has advanced significantly but issue is still under debate

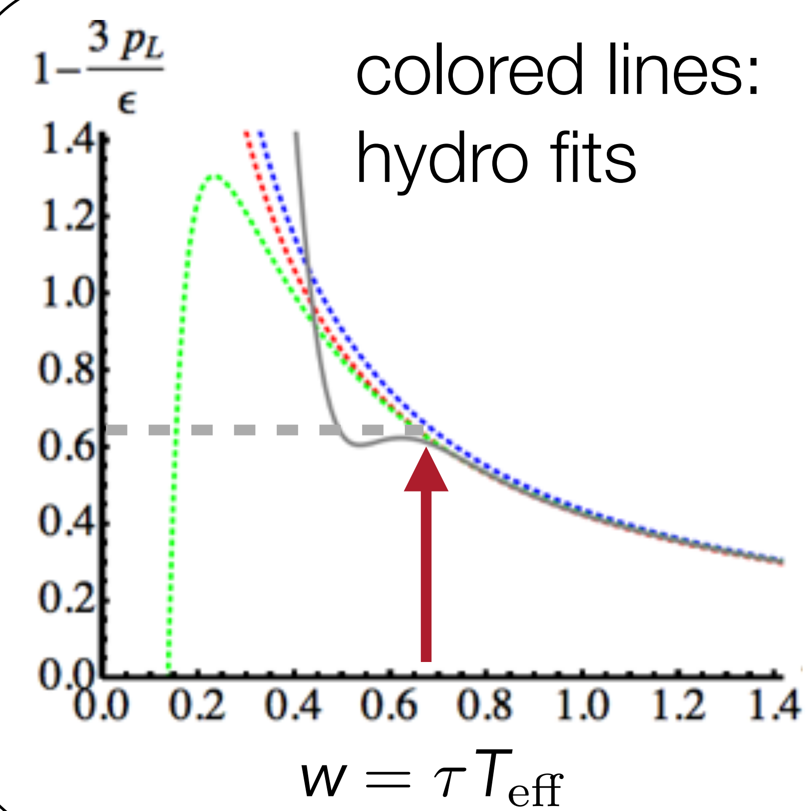




T. Epelbaum, F. Gelis, Phys.Rev.Lett. 111 (2013) 232301
J. Berges, K. Boguslavski, S. Schlichting, R. Venugopalan Phys.Rev. D89 (2014) 074011
M. Attems, A. Rebhan, M. Strickland, Phys.Rev. D87 (2013) 025010

Pre-equilibrium dynamics - thermalization?

Strong coupling limit:



AdS/CFT calculation shows "hydrodynamization" but no pressure isotropization at early times τ≈0.25 fm/c

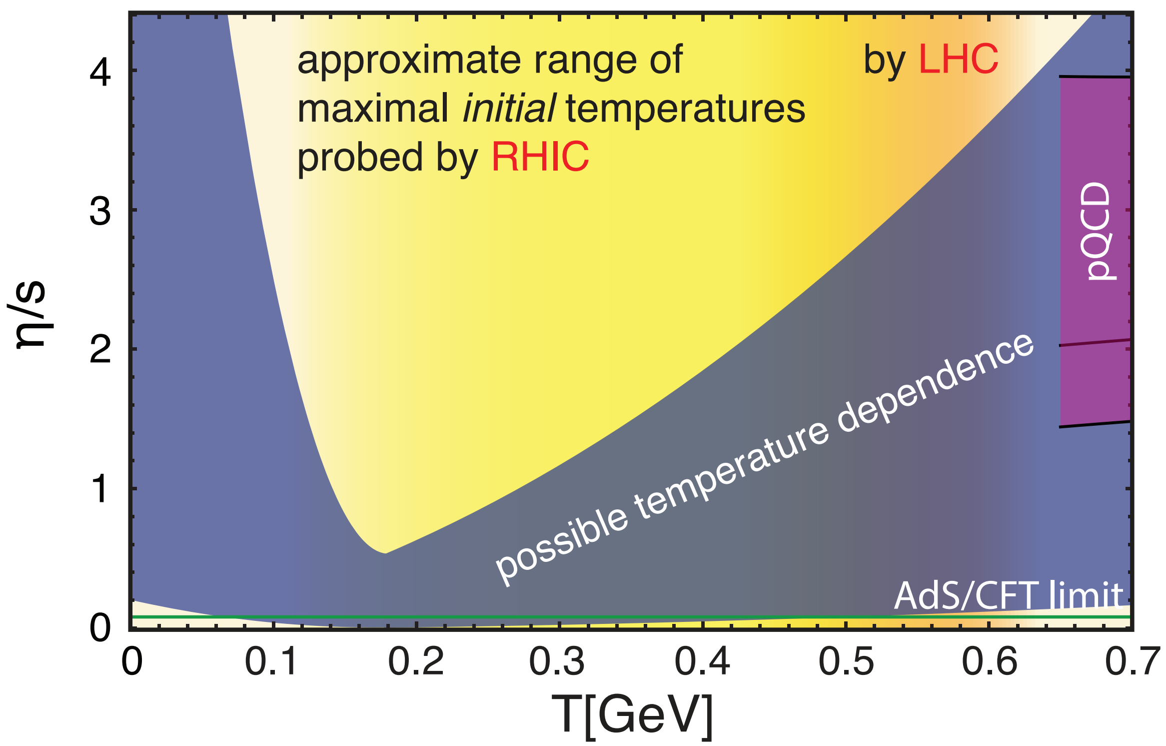
The pressure anisotropy is completely explained by dissipative hydrodynamics for τ≳0.25 fm/c

Before that non-equilibrium effects are large

M. P. Heller, R. Janik, P. Witaszczyk, Phys.Rev.Lett. 108 (2012) 201602

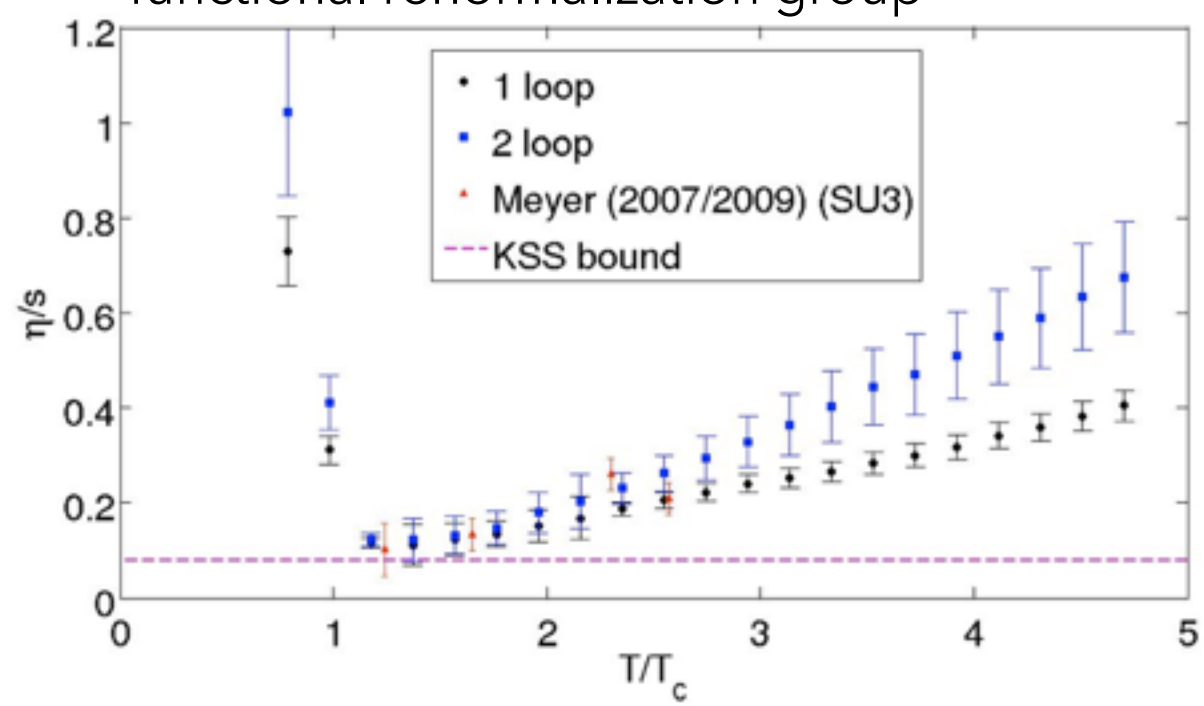
Temperature dependent transport parameters

Extract information on (η/s)(T) from experimental data



- Need to vary collision energy over wide range

Maximum entropy method and functional renormalization group



J. Pawlowski at Quark Matter 2014
(Christiansen, Haas, Pawlowski, Strodthoff)

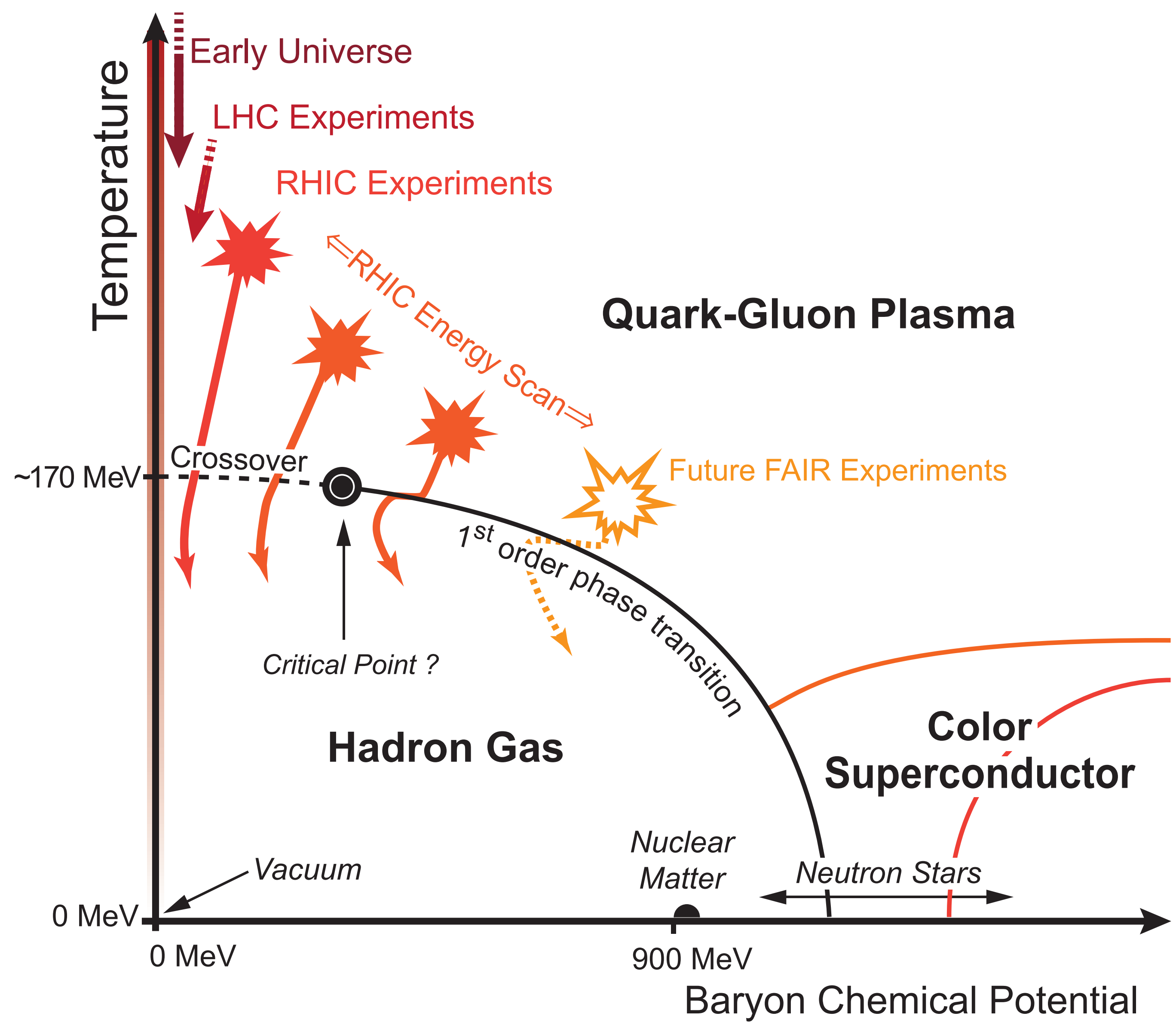
- Compare to non-perturbative QCD approaches (Lattice, FRG)

- Detailed simulations needed

Beam Energy Scan - Lower collision energies

Goal: Determine the detailed Phase Structure of QCD

- Is there a critical point?
- Need detailed simulations taking into account all sources of fluctuations
- Fluid dynamics: Include thermal conductivity, baryon diffusion, hydrodynamic fluctuations, appropriate initial state, equation of state at finite μ_B

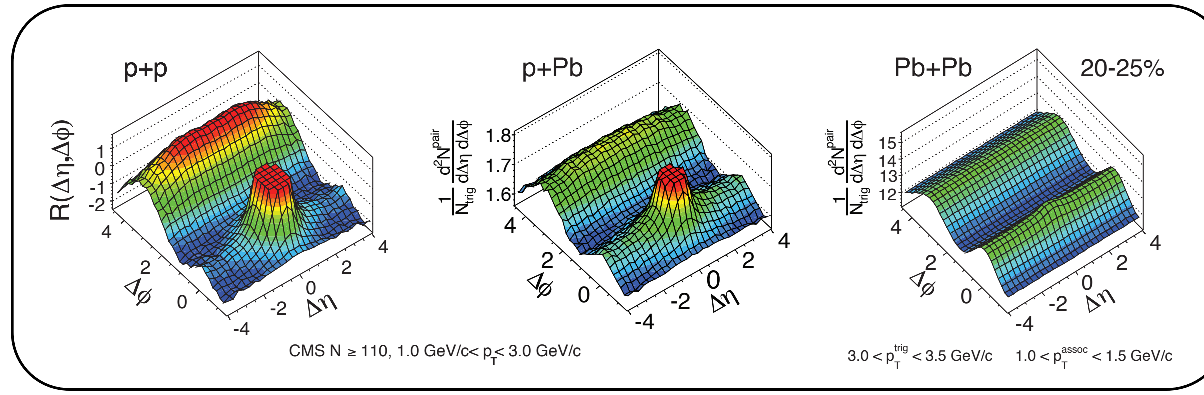


Beam Energy Scan - Lower collision energies

- Hybrid models of transport and fluid dynamics are applicable at low beam energies (talk by H. Petersen)
- Modeling requires significant theoretical investments due to the importance of non-zero baryon density and the complex nature of the initial state
- Need more detailed measurements (BESII) with higher statistics to constrain model parameter space, extract information on the phase transition, critical point, and transport parameters as functions of T and μ_B

Small systems: New questions, new opportunities

- High multiplicity p+p and p+Pb collisions at LHC show similar features as Pb+Pb collisions (ridge, v_n)
- d+Au at RHIC also seems to show similar features



- Interpretation not yet clear:
  - Initial geometry + collective effects? Fluid dynamics?
  - Initial correlations? Theory on this is developing: new insights on particle production mechanism

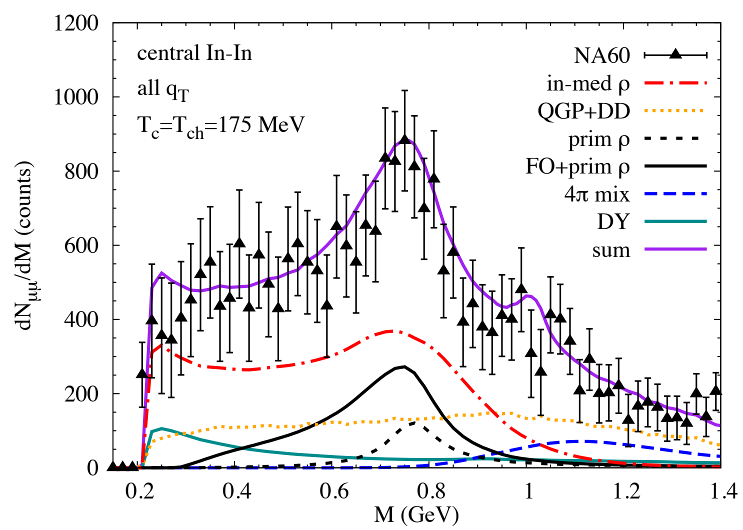
CMS: JHEP 1009 (2010) 091, Phys.Lett. B718 (2013) 795-814, JHEP 1107 (2011) 076 , Eur.Phys.J. C72 (2012)

Small systems: New questions, new opportunities

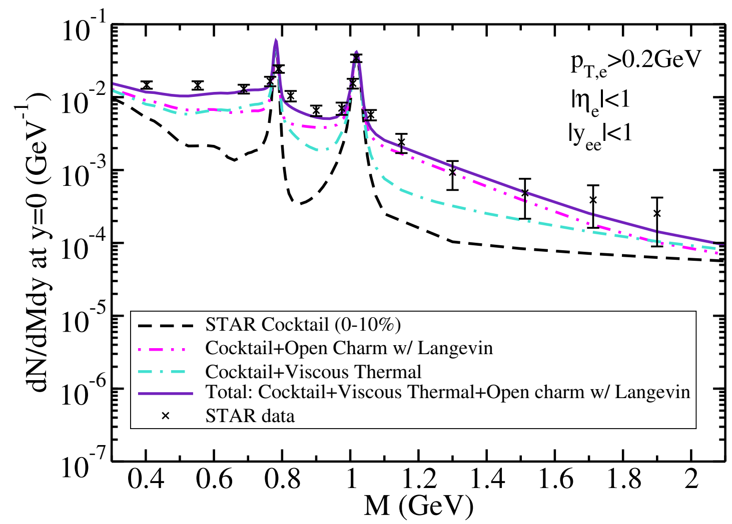
- Versatility of RHIC helps to address these questions
- Running p+A at RHIC is essential
  Is there a ridge? At what multiplicity? Any collectivity?
- $^{3}He+Au$ collisions (different geometry) - larger v_3?
- Understand the origin of correlations measured
  in small collision systems at LHC

Electromagnetic probes: Status

- Thermal photon and dilepton production + fluid dynamic evolution is very successful

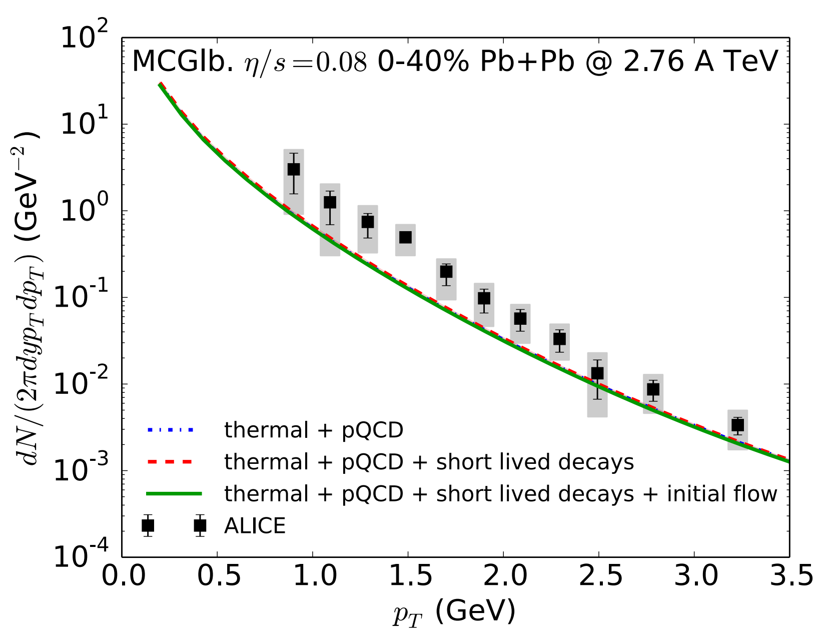


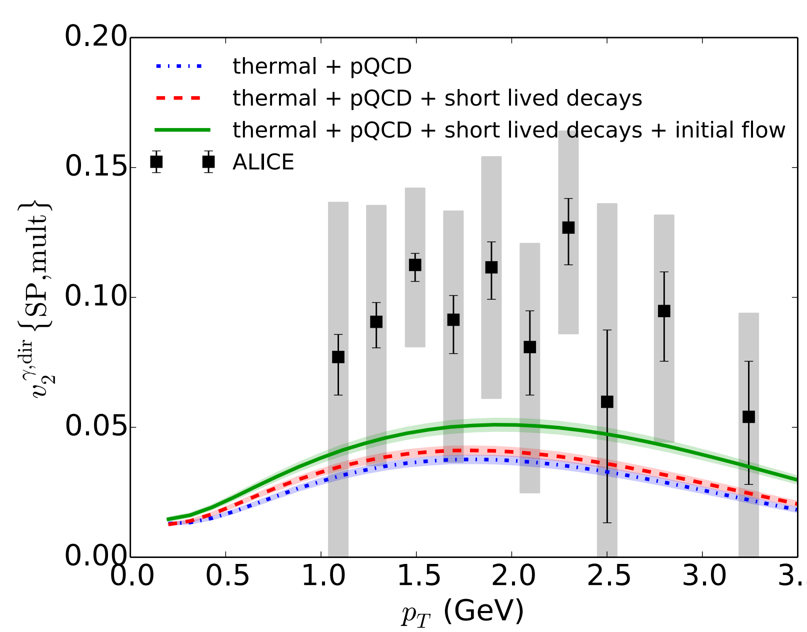
H. van Hees, R. Rapp
Nucl.Phys. A806 (2008) 339-387



G. Vujanovic, C. Young
B. Schenke, R. Rapp
S. Jeon, C. Gale
Phys.Rev. C89 (2014) 034904

- Photon yield and v_2 is under-predicted at RHIC and LHC





C. Shen, J.-F. Paquet, J. Liu, G. Denicol, U. Heinz, C. Gale
arXiv:1407.8533

Electromagnetic probes: To do

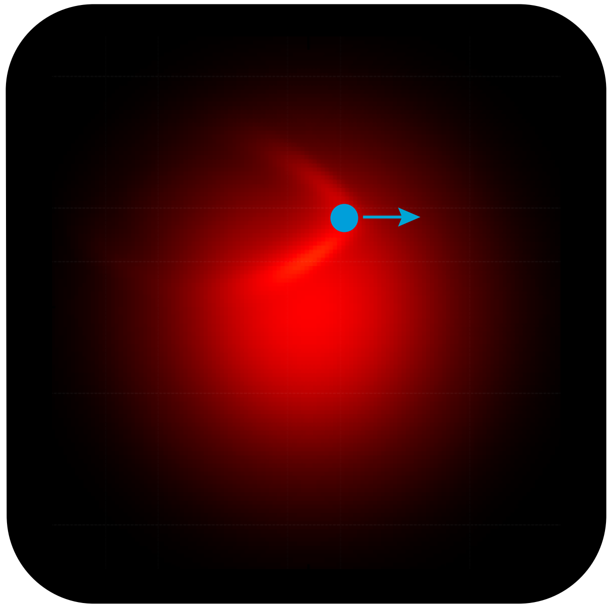
- Solve photon v_2 puzzle: Possible contributions: Rates enhanced in transition region? Magnetic field? Glasma/Semi-QGP? pQCD photons? Jet-fragmentation?

- Map **lifetime** via low mass excess yield of dileptons and **temperature** from p_T slopes of intermediate mass dileptons as function of $\sqrt{s}$

- Chiral restoration (see L. Ruan and P. Hohler's presentations)

- Determine in-medium rho-spectral function with precision at all energies (FAIR, SPS, RHIC, LHC)

Jet-Medium interaction



Are there jet observables sensitive to the short distance structure of the medium?

Extract energy loss and transport parameter $\hat{q}$

Perform detailed Monte-Carlo calculations
using the constrained background and experimental measurements of jet fragmentation functions - where does the “lost” energy go, why?

Compare weak coupling and hybrid (weak+strong coupling) methods

Obtain detailed information on the QCD processes in the medium, color decoherence, perturbative vs. non-perturbative effects

Model - Data comparison

Models are reaching a level of sophistication that makes systematic model to data comparisons useful, necessary

- Simultaneous study of many observables
- Simultaneous variation of all parameters
- Very computing intensive
- Model emulators

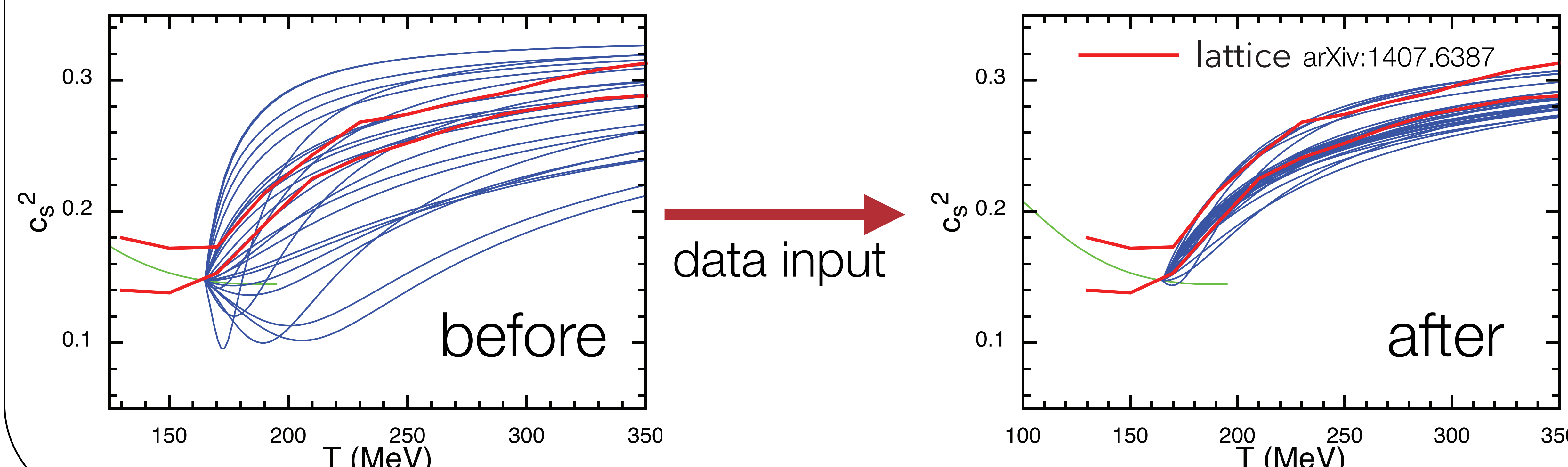
Extract quantitative information on fundamental properties of nuclear matter under extreme conditions

Model - Data comparison

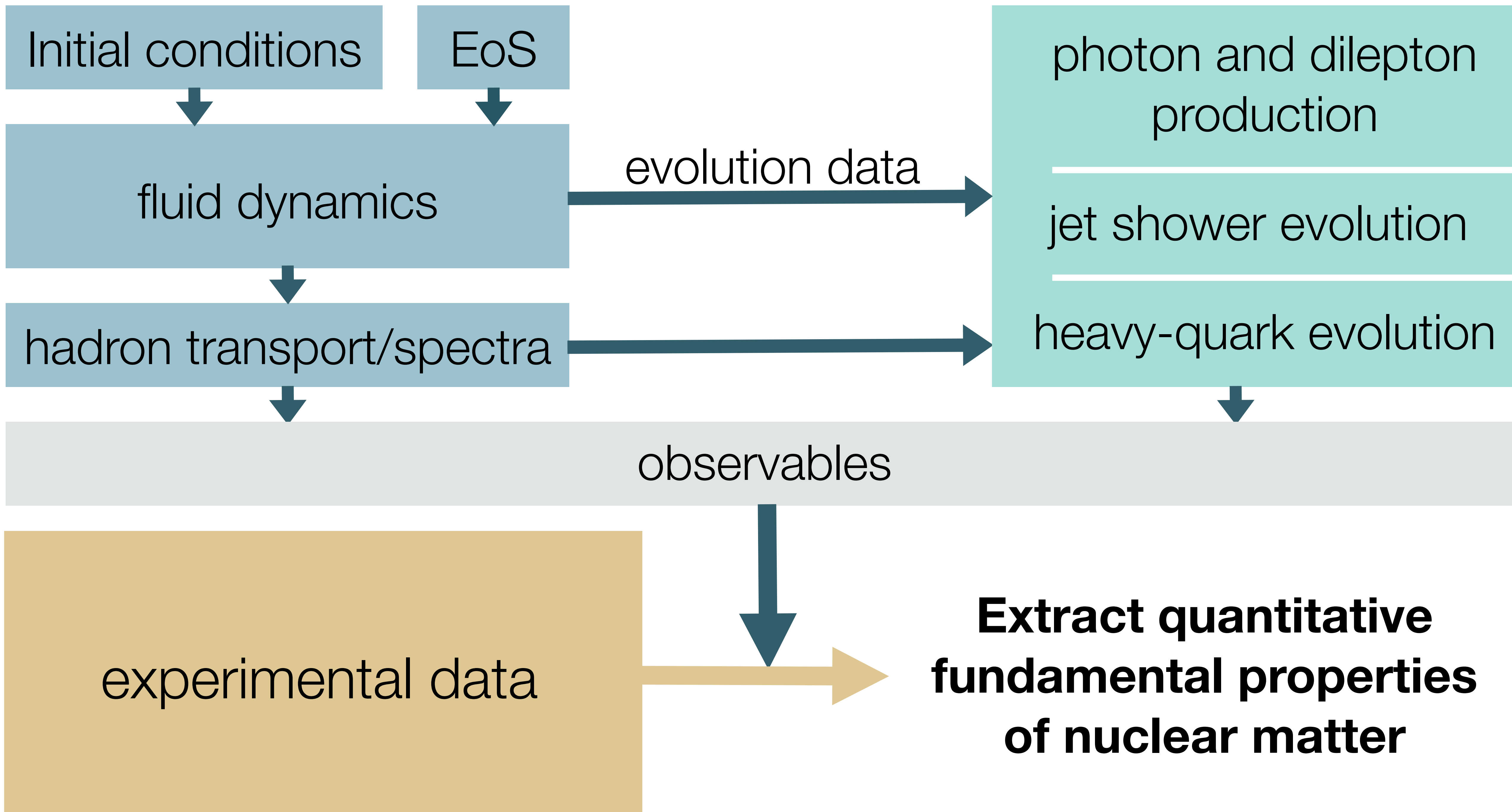
Detailed model to experimental data comparisons via model emulators allows to **constrain** transport properties and the equation of state

Constraining parameters in a parametrization of the EoS

S. Pratt, E. Sangaline



Establish modular framework and standard interfaces



What continued RHIC operations, results from LHC and theory developments will deliver

- A beam energy scan program to establish the properties of the phase diagram and the existence/location of the critical point
- Determination of the transport properties of hot QCD including temperature dependent η/s and $\hat{q}$, and heavy quark diffusion constant
- A jet physics program to study the QGP on a variety of length scales
- Information about the transition from weak to strong coupling by studying jet quenching and QGP response as a function of jet and collision energy
- Insight into the role and behavior of heavier quarks in the medium
- Deeper insight into how the matter thermalizes so quickly
- Deeper understanding of the nature of correlations in p+p and p+A collisions
- A QCD thermometer via the sequential melting of quarkonia

Conclusions

- We have established a working description of the evolving strongly interacting system created in high energy heavy ion collisions

- Now is the time to use it to extract detailed information on the properties of QCD at high temperature

- Next focus work on topics where further understanding is needed to complete the picture:
  lower collision energies, jet physics, heavy flavor,
  pre-equilibrium dynamics, correlations in small systems

- Preserving US leadership in our field will require sustained investment and support of new theory and phenomenology developments, tools for collaboration between all parts of the community, and resources for large-scale computing