Physics at Heavy Ion Colliders
Theory Drivers & View from LHC

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NSAC Implementation Subcommittee Hearings
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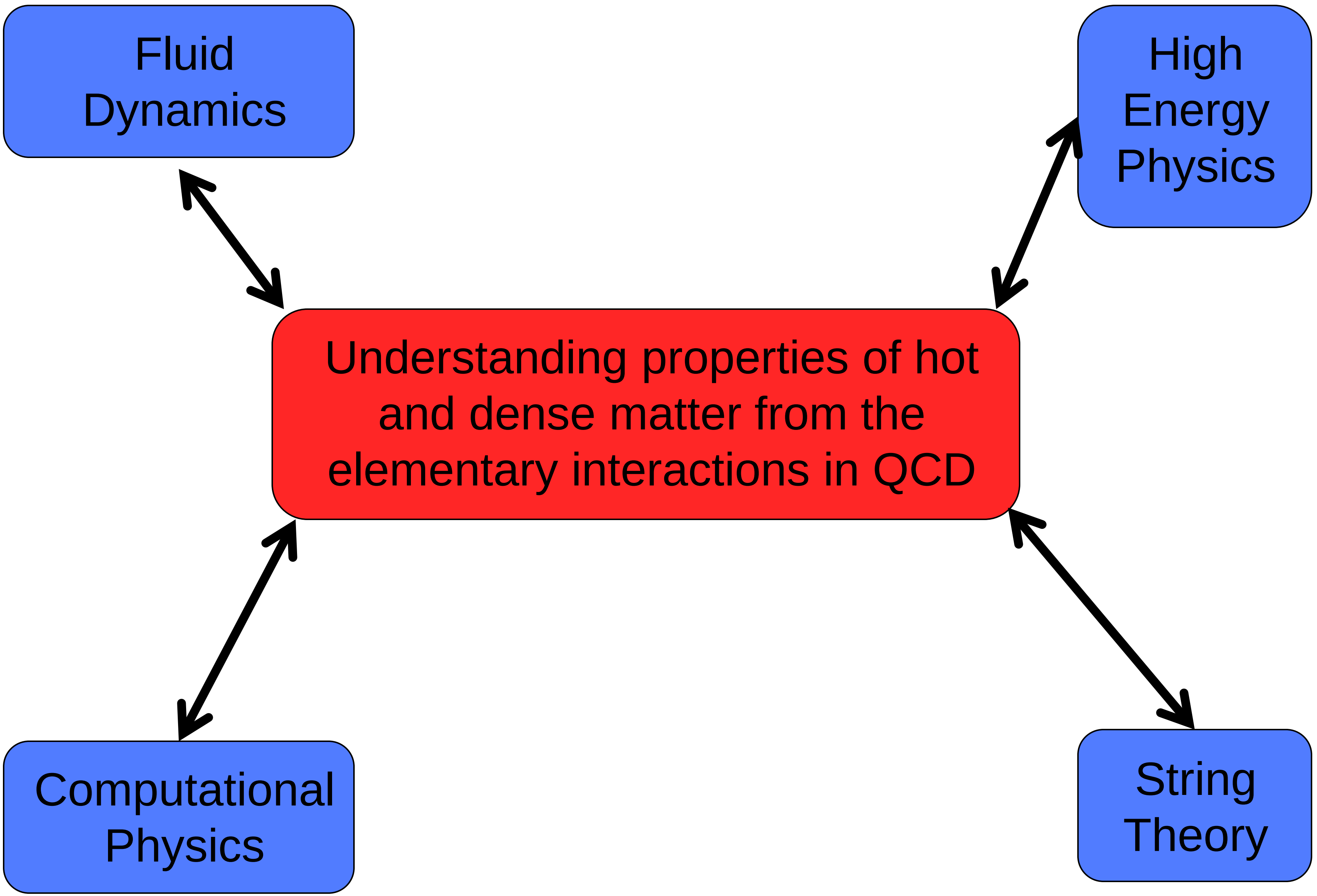
Heavy Ion Physics – Main Tools of Theorists



Dissipative fluid dynamic description

- Based on: E-p conservation: $\partial_\mu T^{\mu\nu} = 0$

  2nd law of thermodynamics: $\partial_\mu S^\mu(x) \geq 0$

- Sensitive to properties of matter that are

calculated from first principles in quantum field theory

Lattice QCD ==>

Finite Temp pQCD ==>

AdS/CFT ==>

EOS: $\varepsilon = \varepsilon(p, n)$ and **sound velocity** $c_s = \partial p / \partial \varepsilon$

transport coefficients: shear η bulk ξ viscosity, conductivities …

$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt\, dx\, e^{i\omega t} \left\langle \left[T^{xy}(x,t), T^{xy}(0,0) \right] \right\rangle_{eq}$$

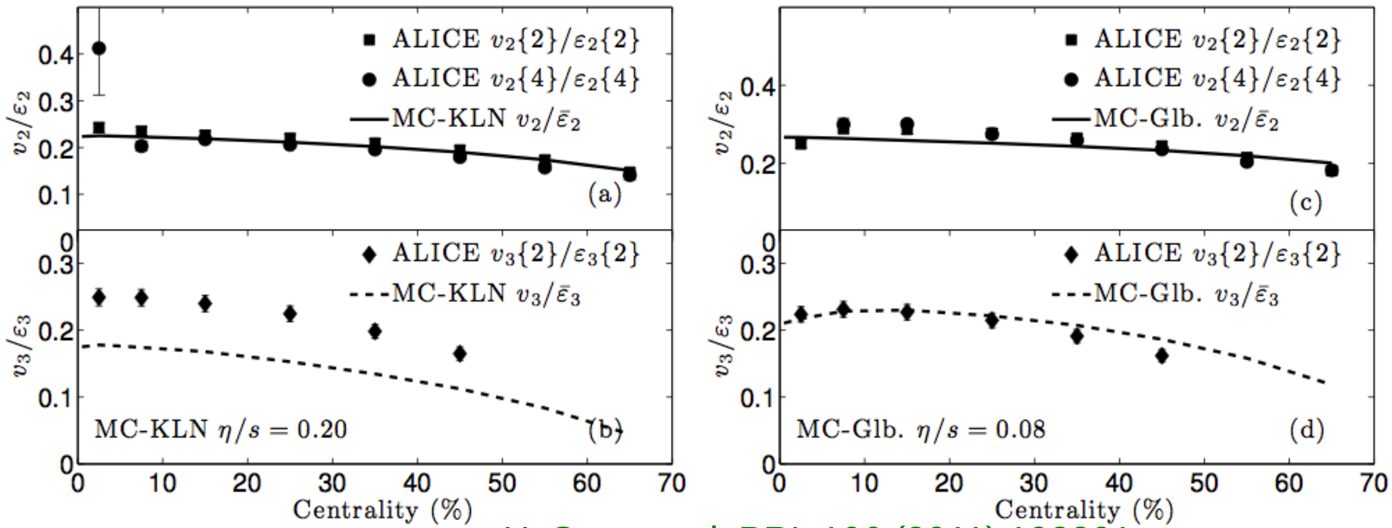
relaxation times: τ_π, τ_Π, …

What we conclude from fluid dynamics

- Recent data & recent analyses yield tight constraints

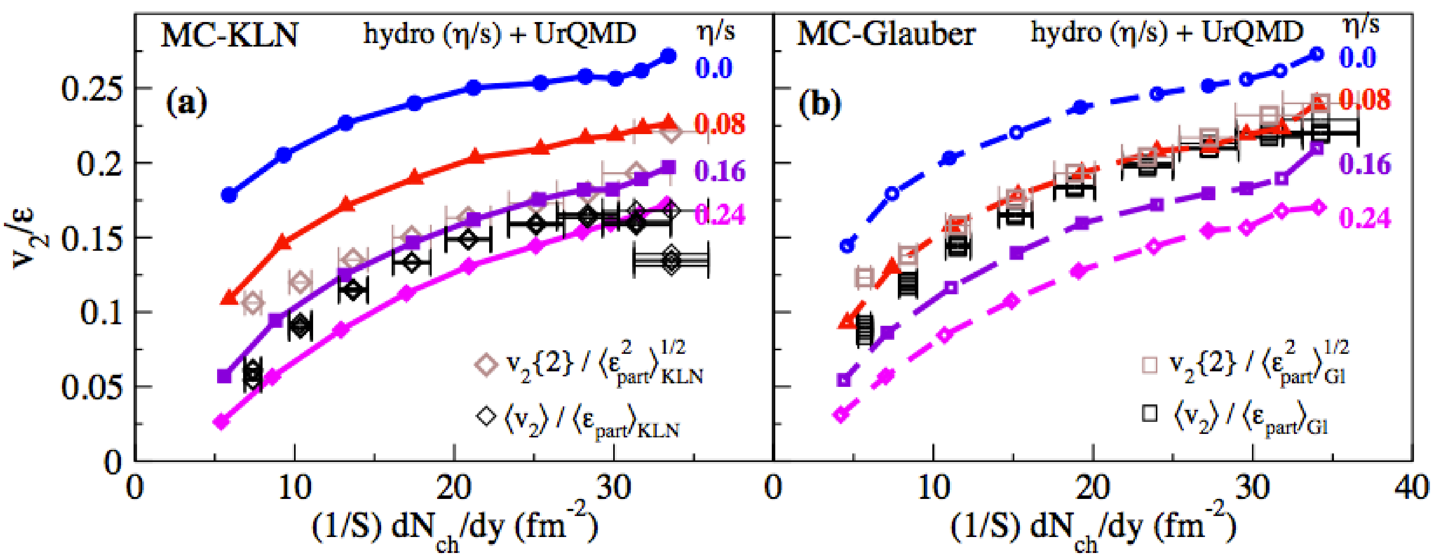
$$1 \le 4\pi\left(\eta/s\right) \le 2$$

LHC



H. Song et al. PRL 106 (2011) 192301
Z. Qiu et al., Phys.Lett.B 707 (2012) 151

RHIC



Main TH conclusions from current analysis

- Value of shear viscosity minimal,
  => perfect liquid, strongly coupled plasma

- Fluid dynamics applies at $\tau_0 < 1\, fm$
  In perturbative scenario: hydro valid if

  but $\underbrace{\alpha_s^2 T_0}_{collision\ rate} >> \underbrace{1/\tau_0}_{espansion\ rate}$

  => non-perturbative thermalization

  $\alpha_s >> 1 \quad \Rightarrow 0.65 \leq \tau_0\, T_0$

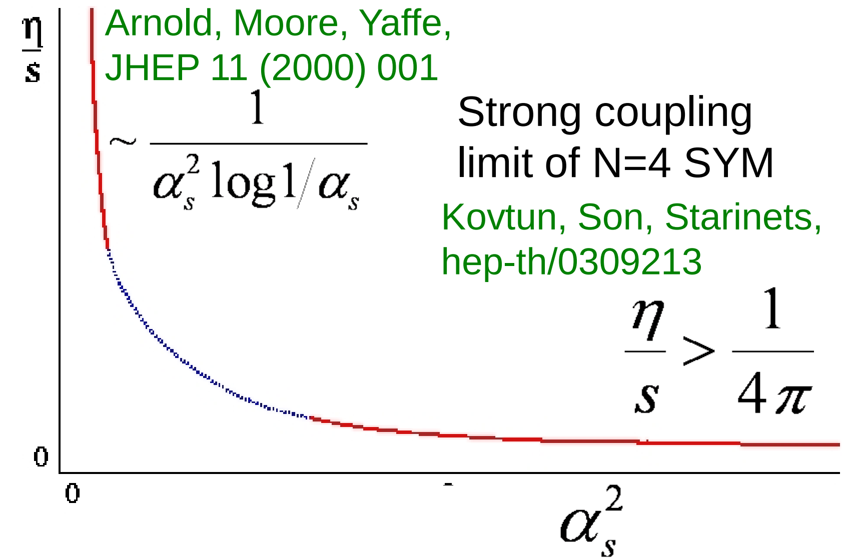
  Heller, Janik Witaszczyk, PRL 108 (2012) 201602 Chesler, Yaffe, PRL 102 (2009) 211601

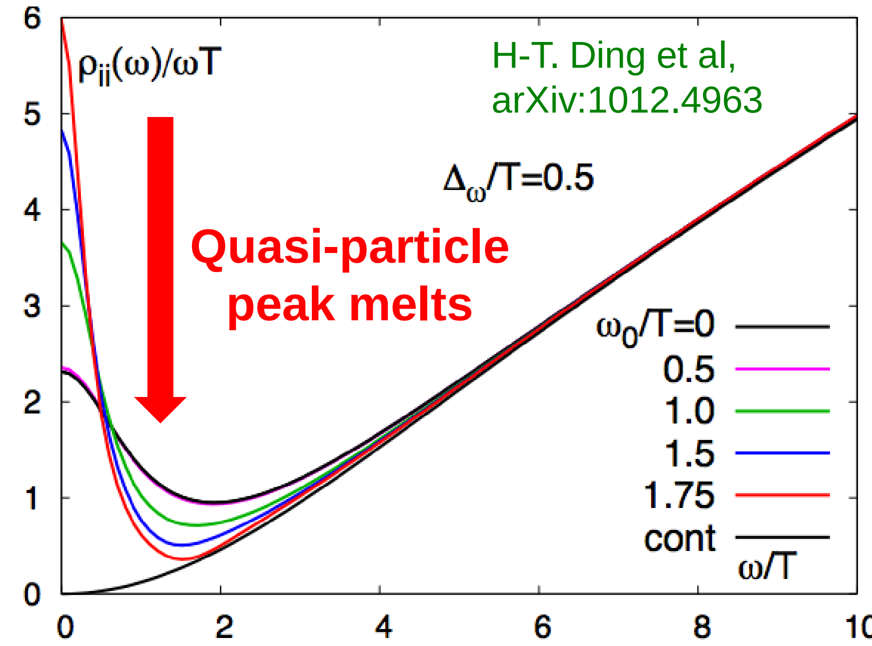
- Perturbatively require $\tau_{quasi} \sim \frac{1}{\alpha_s^2 T} >> \frac{1}{T}$

  but $\tau_{quasi} \approx \frac{const}{T} \frac{\eta}{s}$

  Such a plasma is unique in that it does **not carry quasi-particle excitations**

Establishing this conjecture is one of the main drivers for future EXP&TH





Precision enables discovery

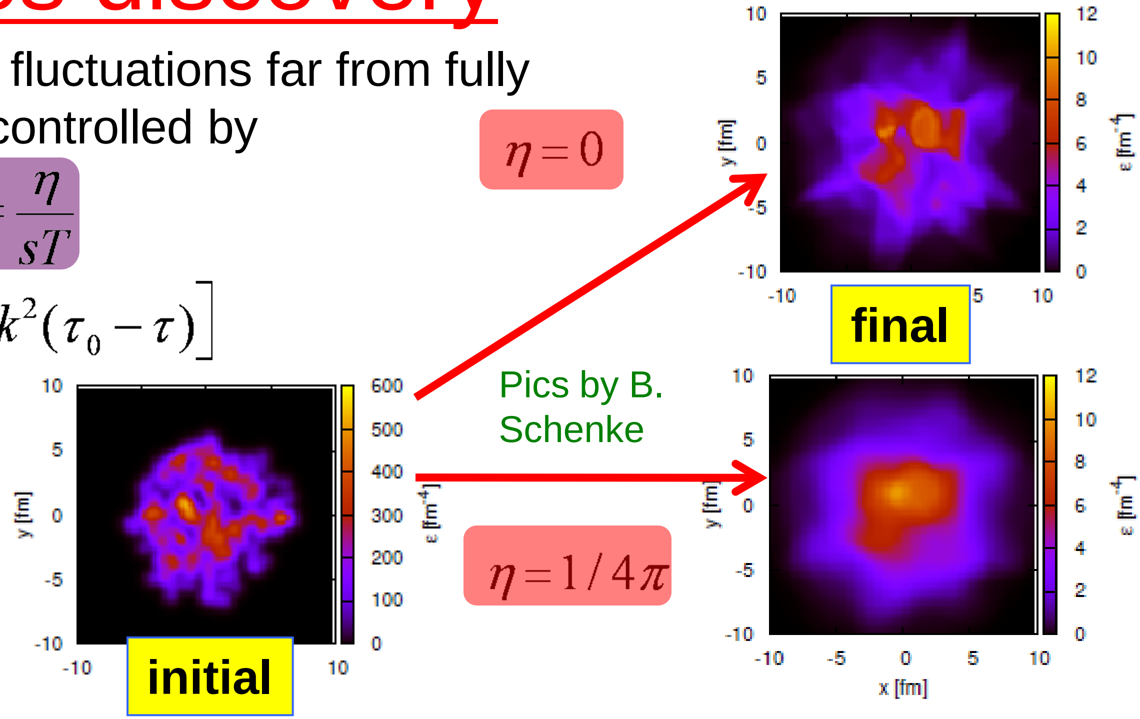
- Precision how? Event-by-event fluctuations far from fully explored. Fluctuation damping controlled by **sound attenuation length** $\Gamma_s = \frac{\eta}{sT}$

$$\delta v(\tau,k) = \delta v(\tau_0,k)\left(\frac{\tau_0}{\tau}\right)^* \exp\left[-\Gamma_s k^2(\tau_0-\tau)\right]$$

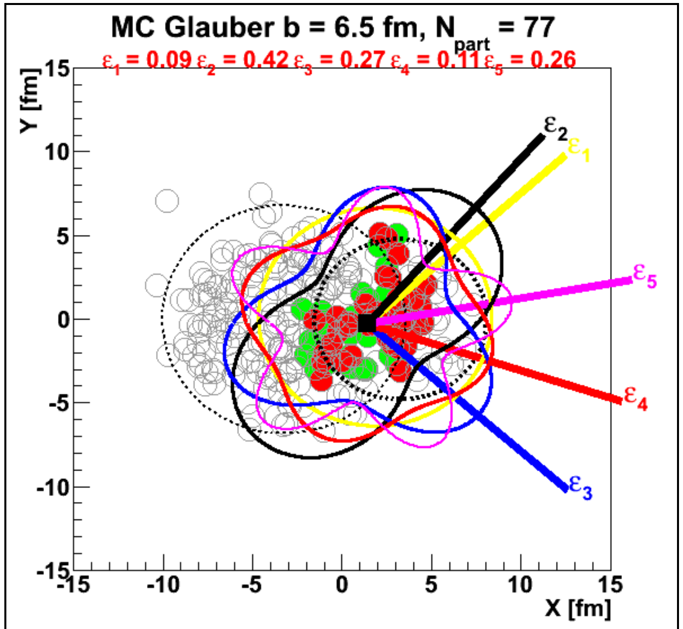
Much to be learnt from varying scale of fluctuation

e.g. $\tau_{1/e}(k) = \frac{1}{\Gamma_s k^2}$

$$\tau_{1/e}(k=1\,fm^{-1}) \approx 10-20\,fm$$
$$\tau_{1/e}\left(k=(0.5\,fm)^{-1}\right) \approx 2.5-5\,fm$$



- Experimental tools to vary initial fluctuations:
  - colliding different beam species



opportunity for RHIC to continue contributing substantially in the soft sector

LHC Heavy-Ion Program up to 2022

- So far two 4-week-long Pb-Pb runs (2010, 2011), p-Pb in Feb 2013
  6 further runs (Pb-Pb, p-Pb, Ar-Ar) scheduled,
- No further beam species (at least till 2023)
- At injection energy ($\sqrt{s_{PbPb}} = 350\ GeV$), luminosity $O(10^{-3})$ lower than at RHIC
- Approved plan after 1st long shutdown (LS1) is

John Jowett, CERN Beam Department
Submission to Cracow Open Symposium of European Strategy Preparatory Group,
https://indico.cern.ch/contributionDisplay.py?contribId=164&confId=175067

Year	Colliding species	Remarks
2015-16	**Pb-Pb**	Design luminosity, ~ 250 μb^{-1}/year, Luminosity levelling if required.
2017	**p-Pb *or* Pb-Pb**	p-Pb to enhance 2015-16 data. Pb-Pb if luminosity still needed
2018		LS2: install DS collimators around ALICE to protect magnets, injector upgrades* (ALICE upgrade for 6 × design luminosity)
2019	**Pb-Pb**	2-3×design luminosity in ALICE (or more with, eg, reduced bunch spacing*).
2020	**p-Pb**	
2021	**Ar-Ar**	Intensity to be seen from injector commissioning for SPS fixed target and collimation requirements.
2022		LS3, Possible upgrades such as cooling systems.

Table 1: LHC heavy ion programme from the end of Long Shutdown 1 to the start of Long Shutdown

Which discoveries with increased precision?

- Shear viscosity with 50 % precision

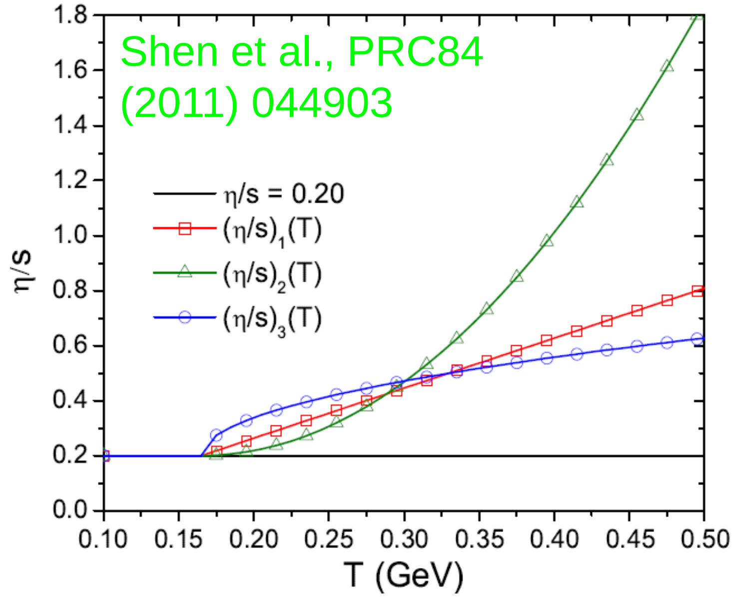
  T-dependence of eta/s comes into reach

  only if measured **at RHIC & LHC** with this precision

  Aim: establish expected deviations from the 'perfect' limit $\lambda \to \infty$ $\qquad \lambda = \lambda(T) \equiv g^2 N_c$

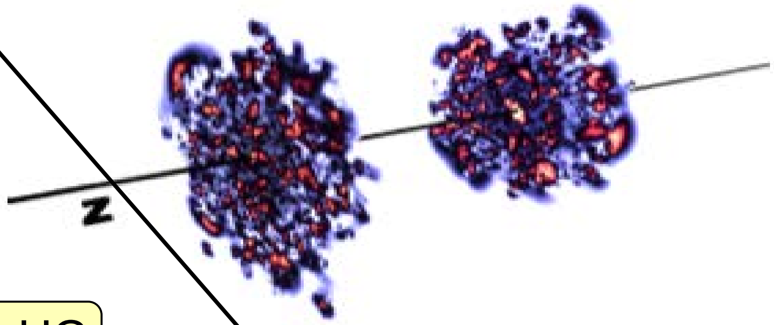
  A. Buchel et al., NPB707 (2005) 56

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 + \frac{15\,\zeta(3)}{\lambda^{3/2}} + \ldots + O\left(N_c^{-2}\right)\right)$$



- **Access to initial quantum fluctuations**
  - better characterization possible if η/s more precisely known
  - expected to evolve in $\sqrt{s}$ from RHIC to LHC
  - this quantum evolution is accessible

  if measured with sufficient precision at RHIC & LHC



- Shear viscosity with 10 % precision (possibly earlier)

  Bulk viscosity and relaxation times come into reach

High priority for European Heavy Ion Community

Recommendations of CERN town meeting

Conclusions from the Town Meeting on Relativistic Heavy Ion Physics
Submission to European Strategy Preparatory Group,
https://indico.cern.ch/userAbstracts.py?confId=175067

1. *The top priority for future quark matter research in Europe is the full exploitation of the physics potential of colliding heavy ions in the LHC.*

2. **At lower center of mass energies where the highest baryon densities are reached, advances in accelerator and detector technologies provide opportunities for a new generation of precision measurements that address central questions about the QCD phase diagram.**

3. **The complementarity of LHC and RHIC is an essential resource in efforts to quantify properties of the Quark-Gluon Plasma.**

4. **Dedicated investments in theoretical research are needed to fully exploit the opportunities arising from the upcoming precision era of nuclear research at collider and fixed target energies.**

Search for critical point in QCD phase diagram

- Fundamental question of QCD thermodynamics
- Not the subject of this talk and clearly not in reach of LHC
- Recognized as high priority by European physics community with long-term plans for a dedicated accelerator [SIS300 @ FAIR]
- RHIC beam energy scan uniquely positioned to map out transition from hadron gas to perfect liquid

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Hard Probes

- Light high-momentum hadrons
  $\pi, K, p, \Lambda, \ldots$
- Heavy flavors
  $D^0, D^+, D^{*+}, \ldots$
- Quarkonia
  $J/\psi, \psi', \Upsilon(1s), \Upsilon(2s)\ldots$
- Jets,

- created at $\tau_{init} \approx 1/Q_{hard} << 1\,fm$
- propagate up to $\tau_{final} \approx 10\,fm$

➡ Hard probes test the conjecture that the plasma does not carry quasi-particle excitations.

Open heavy flavor at low pt

- 'No-quasiparticle conjecture' implies that light low-momentum dressed quarks do not exist (i.e. do not propagate beyond $L \approx 1/T$)

  In contrast, charm & bottom propagate (consequence of flavor conservation). How?

- At low pt, Langevin dynamics determines how charm & beauty quarks move: The perfect liquid is source of **random forces**

$$\frac{dp_L}{dt} = \xi_L(t) - \mu(p_L)\,p_L, \qquad \langle \xi_L(t)\,\xi_L(t') \rangle \equiv \kappa_L(p_L)\,\delta(t-t')$$

$$\frac{dp_T}{dt} = \xi_L(t) \qquad\qquad \langle \xi_{Ti}(t)\,\xi_{Tj}(t') \rangle \equiv \kappa_T(p_L)\,\delta_{ij}\,\delta(t-t')$$

calculable from 1st principles in quantum field theory, e.g. in strong coupling limit:

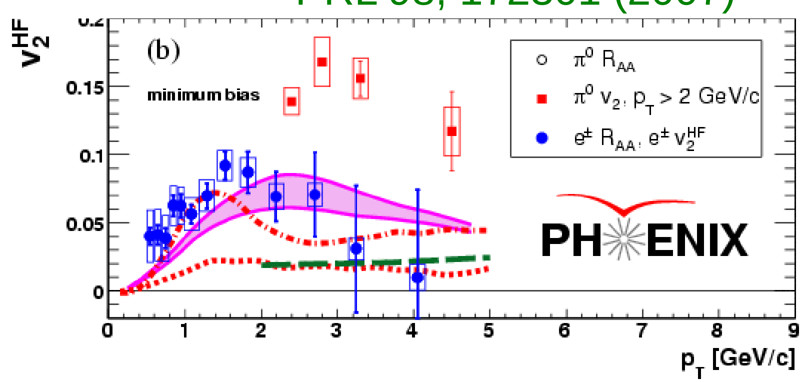
$$\kappa_T = \pi\sqrt{\lambda}T^3\sqrt{\gamma} \qquad \kappa_L = \pi\sqrt{\lambda}T^3\gamma^{5/2}$$

- This hard probe is unique in that we know already that it is moved by the flow.

  In coming years: establish T-dependence and separate flow of b and c to constrain κ_T, κ_L, μ

  RHIC&LHC needed

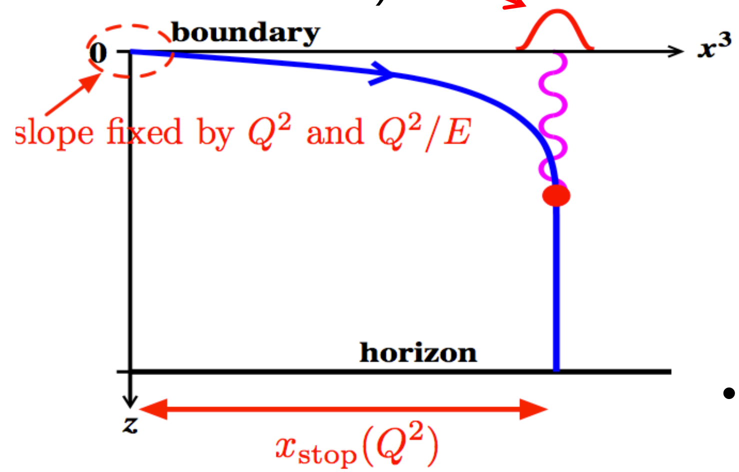
PRL 98, 172301 (2007)



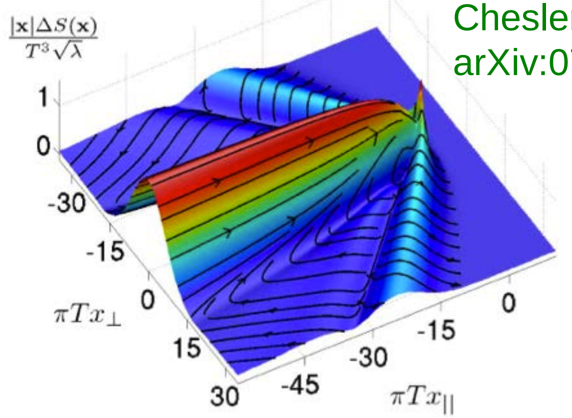
How do high-momentum partons propagate?- theory

In a perfect liquid (AdS/CFT view)

- Light partons/jets **thermalize** (no collinear structure remains)



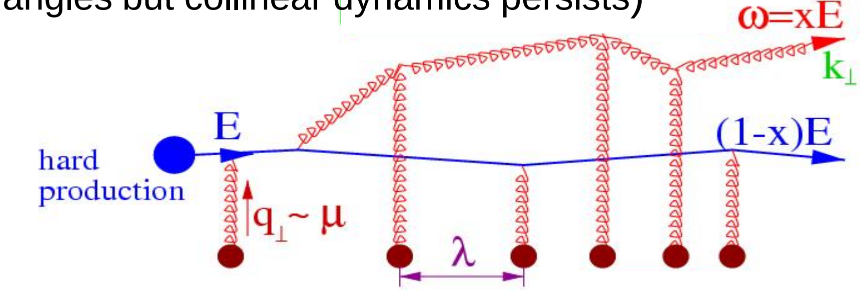
- Heavy quarks loose momentum via sound modes and wake



Chesler, Yaffe
arXiv:0712.0050

In system with finite mean free path

- Light hard partons **fragment** in medium
  (Energy moved to softer scales/larger angles but collinear dynamics persists)



- Heavy quarks **fragment** with smaller branching probabilities (*dead-cone effect*)

$$\frac{1}{k_T^2} \Rightarrow \frac{k_T^2}{\left(k_T^2 + \frac{M^2}{E^2}\omega^2\right)^2}$$

testable hierarchy in mass and color charge

$$\Delta E_{gluon} > \Delta E_{quark,\,m=0} > \Delta E_c > \Delta E_b$$

- For $M \ll E$, mass unimportant.
  In high energy limit (eikonal limit)
  ΔE determined by $\hat{q}$
  (calculable as short distance limit of the expectation value of two eikonal Wilson lines)

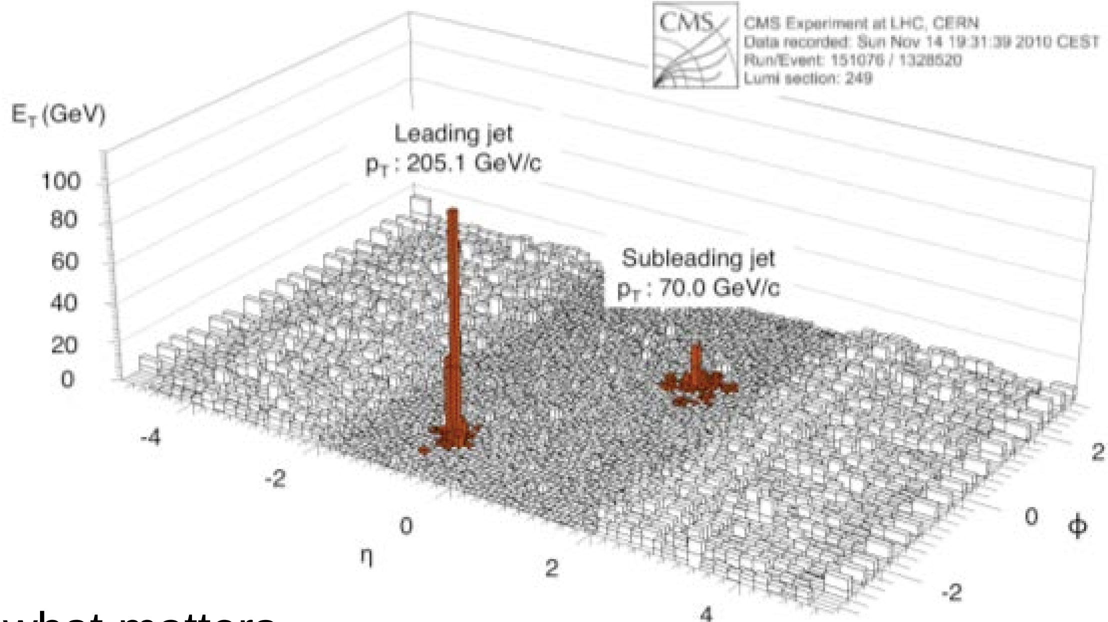
Motivates experimental study of medium-dependent jet fragmentation

Jets at RHIC & LHC

Beware of naïve arguments that compare kinematic reach of RHIC and LHC

Bullet plowing through some material

Jets plowing through QCD medium



For jets as a probe of the medium, what matters

- **calibration**: experimental control over amount of energy ΔE put into medium
- **access to medium dynamics**:
  i.e. experimental ability to characterize dissipation of ΔE in medium

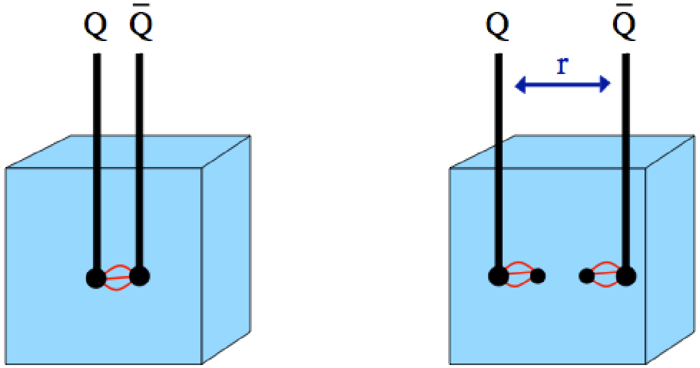
… and what does not matter:

- to punch as forcefully as possible through the medium

→ Sample of 20-50 GeV jets can address central questions of previous slides if sufficiently abundant for detailed analysis!

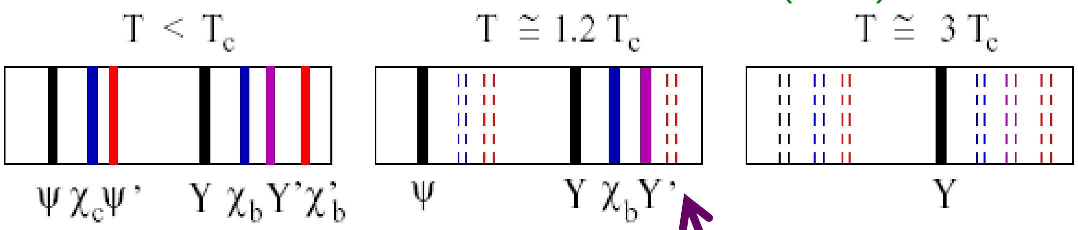
Quarkonia

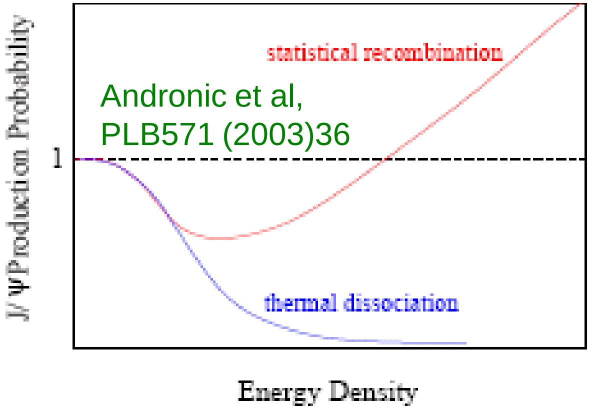
- Dissociation is litmus test for deconfinement, calculable from 1st principles in QFT



Sequential suppression

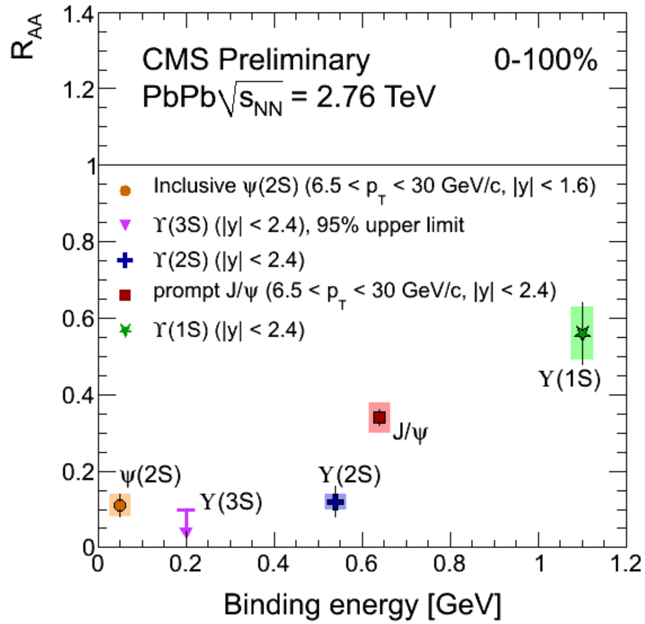
Digal, Petreczky, Satz, PRD 64 (2001) 0940150





Tasks:

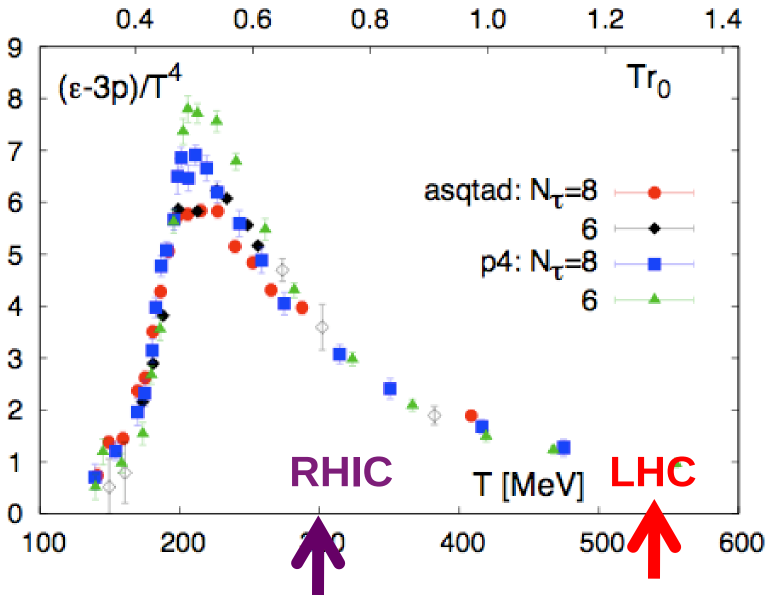
- locate RHIC & LHC on this gluodensimeter
  => measure bottomonium hierarchy at RHIC.
- are quarkonia at low pt enhanced as consequence of regeneration?

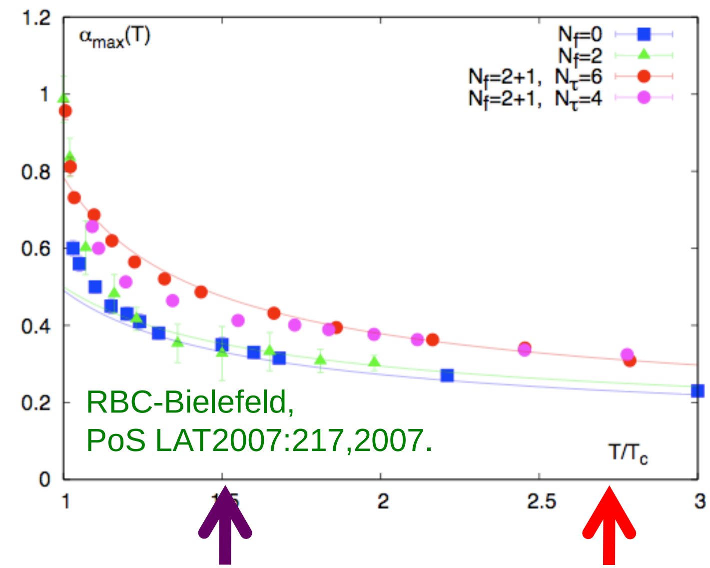


- Physics conclusions significantly stronger if T ($\sqrt{s}$) –dependence known. Requires further measurements at RHIC and LHC.

Theory provides firm arguments that the properties of the QCD liquid change with center of mass energy from RHIC to LHC.

See e.g. interaction measures from lattice QCD:





Aim: turn the perfect liquid discovery into a chapter in the ultimate QCD textbook:

by understanding how minimal dissipation is realized in a strongly coupled non-abelian medium without quasi-particles.

To achieve this aim, a period of simultaneous experimentation at RHIC and LHC is needed.