Rapportuer -II (Theory)

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ICPAQGP Series:

- 7^{th} ICPAQGP - 2015 (Kolkata)
- 6^{th} ICPAQGP - 2010 (Goa)
- 5^{th} ICPAQGP - 2006 (Kolkata)
- 4^{th} ICPAQGP - 2001 (Jaipur)
- 3^{rd} ICPAQGP - 1997 (Jaipur)
- 2^{nd} ICPAQGP - 1993 (Calcutta-Then)
- 1^{st} ICPAQGP - 1988 (Bombay - Then)

Beginning

- In the beginning, the search for QGP in high energy nuclear collision was very much like an exploratory endeavor

  - ☛ As in most explorations, the enthusiasm of the explorers was greater than their knowledge of what to expect or look for!!

  - ☛ General feeling was that if QGP would be produced by any mechanism, it would manifest in a variety of unknown but dramatic ways!!!

  - ☛ Something like an order parameter, which doesn't change over a period but changes suddenly at a point!

Aim of Heavy-Ion Collisions Experiments:

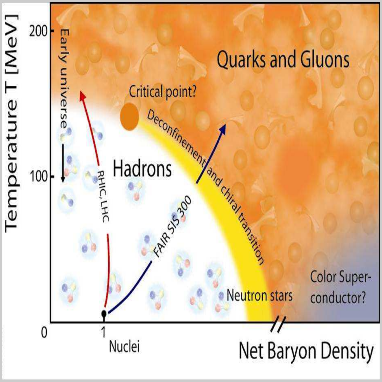
- Accelerate heavy stable ions with energy as much as one can and then collide them travelling at relativistic speed
- Not to focus on energy but on energy density created
- Not to focus on fine/precision physics but on collective physics

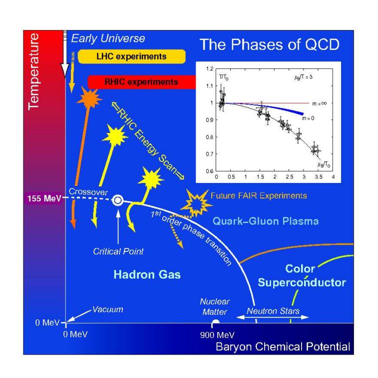
  - **Explores properties of matter under extreme conditions**
  - **Much focus on Quark-Gluon Plasma formation: the primordial form of matter that existed in the universe shortly after the Big Bang**
  - **Study how QCD works in unusual conditions**

Heavy-ion Collisions Experiments

- AGS (1986-1996): Si, Au; $\sqrt{s} = 2.5 - 5.5$ GeV/A;
  Barely reached the energy density required for QGP formation
- SPS: O, Si, Pb; 158 GeV, 200GeV
  Indication of a possible onset of deconfinement!
- RHIC (2000-$\cdots$): d, 3He, Cu, Au, U, d; $\sqrt{s} = 7.7 - 200$ GeV/A
  Evidence of Deconfinement or partonic degrees
- LHC(2010-$\cdots$): Pb-Pb, p-Pb; $\sqrt{s} = 2.76, 5.5$ ATeV
  Evidence of Deconfinement or partonic degrees
- FAIR: Expected in 2018 !! ; $E_{\rm lab} = 10(35)$ GeV/A
  ($\sqrt{s} < 4.5(8.4)$ GeV for Au/U

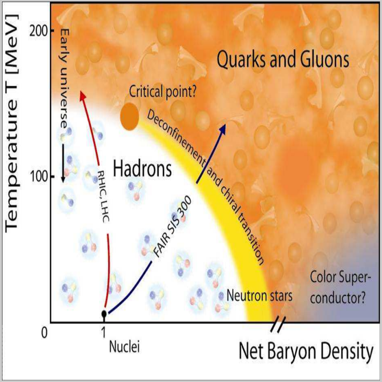
Present-day understanding of the QCD phase diagram

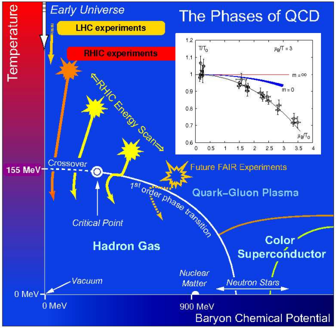




- Theory (QCD and models based on it)
- Numerical Experiments (LQCD)
- Astrophysical observations
- Mini Bang (Laboratory Expt.)

Present-day understanding of the QCD phase diagram





- Theory (QCD and models based on it)
- Numerical Experiments (LQCD)
- Astrophysical observations
- Mini Bang (Laboratory Expt.)

☛ Complex: Difficult to span the whole PD by a single effort !

Present-day understanding of the QCD phase and/or diagram

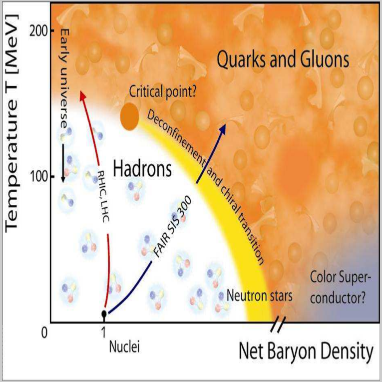
- Higher the collision energy the closer is the created system located near temperature axis
- A crossover at RHIC and LHC; No true phase transition; LQCD also exhibited.
- Preliminary to attribute a definite position for critical point in phase diagram (BES-I at RHIC and LQCD)
- Data appear to demand an explanation beyond a purely hadronic scenario $\Rightarrow$ non-hadronic source (partonic degrees)
- Collective behaviours $\Rightarrow$ Circumstantial evidences

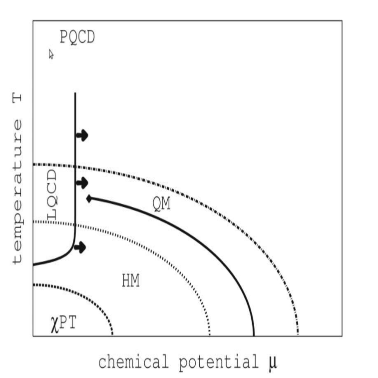
Evidences of Partonic Degrees of Freedom at RHIC and LHC

- Hot and dense matter produced is a liquid (with low η/s) in which partons flow individually; strogly coupled near perfect fluid
- QGP produced in RHIC is (on average) closer to perfection than the that at LHC.

  Large opacity caused energy-loss that led to supression of R_{AA} (for both Light Heavy hadrons)
- Light quarks (u, d, s) completely thermalize and recombine to hadrons
- Melting of Quarkonia States and regeneration.
- New data is a joy to experimentalists but a hard task for Theoreticians to explain them!

Theoretical Approaches



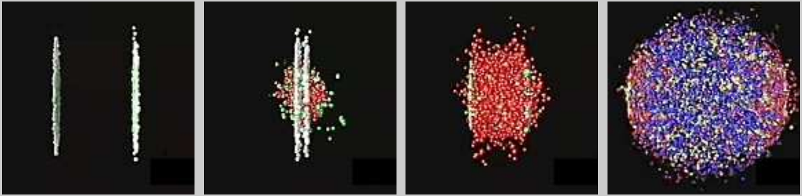


- All regions of the PD by the first principle QCD calculations !
  Not Yet!!
- Interface of Nuclear Physics and Particle Physics

Interface of particle physics & high-energy nuclear physics

- Draws heavily from QCD: pert, non-pert, semiclassical
- Overlaps with:
  - ☛ Thermal Field Theory
  - ☛ Relativistic Fluid Dynamics
  - ☛ Kinetic or Transport theory
  - ☛ Quantum Collision Theory
  - ☛ String Theory
  - ☛ Statistical Mechanics & Thermodynamics

Quark-Gluon Plasma: A new phase of QCD



- QGP ➤ Expands ➤ Hadronizes **(Detector)**
- Expansion: Hydrodynamics (idel, viscous) + Initial Conditions

- Two Aspects
  - **Snap Shot properties** (Given Temp. & Chem. Pot^{l})
  - **Experimental Information**

Quark-Gluon Plasma: A new phase of QCD

- Snap Shot:
- Exptl. Data:

- Thermodynamic Quantities } Hydro inputs
  $(F, P, \cdots,$ EoS$)$
- Transport Coefficients } Hydro/FP Eq. inputs
  $(\ \sigma,\ \ \gamma_d,\ \ \mathcal{D},\ \ \eta/s)$
- Various Susceptibilities ➥ Fluctuations, Critical Point
  $(\ \chi_c, \chi_q, \cdots,$ response$)$
- Screening of Plasma ➥ Binary states: J/ψ, Υ
- Interactions ➥ Hadron spectra; R_{AA}, v_n
  (Coll., Rad., E-loss)
- Particle Production Rates ➥ l^+l^-, γ spectra
  $(l^+l^-, \gamma, \cdots)$

ICPAQGP-2015

- Stdents' Day (1/2/2014)
- Overview talks: 4
- Plenary Talks: 30
- Parallel sessions: 65
- Posters: 40

⇒ ICPAQGP2015 has provided extensively the field's history and developments until date

Rapportuer-I

Rapportuer-I by Raju Venugopalan

- Initial States (pp, pA, AA)
- Hydrodynamics
- Thermalization
- Final states of (pp $\&$ pA)
- Flow coefficients $\&$ extraction of η/s
- Quarkonic Phase
- Photons (!)

Rapportuer-II

Rapportuer-II by M G. Mustafa

- Thermodynamics, Susceptibilities & CP
- Transport Coefficients
- Energy Loss and Jets
- Dileptons
- Quarkonia Melting
- Astrophysical aspects

Students' Day

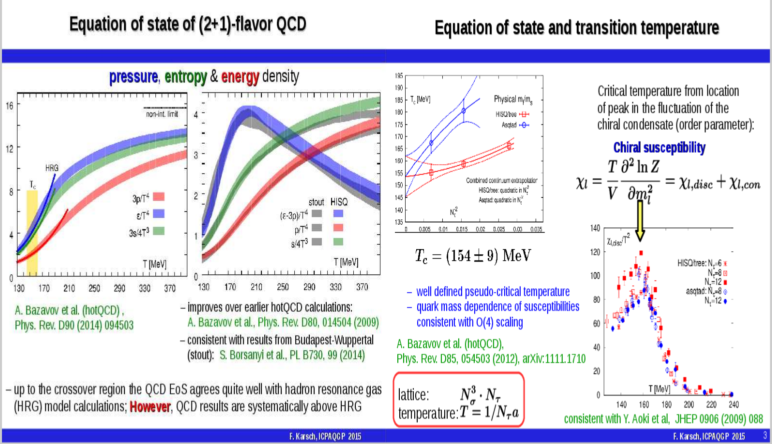
- Stage for this conference was set by a series of pedagogical lectures
  - ☛ Signals of Quark-Gluon Plasma by Jan-e Alam
  - ☛ QGP in the Universe - from the early univese to the present by Ajit M Srivastava
  - ☛ Relativistic Fluid Dynamics and Collective Flow in HIC by Rajeev Bhalerao
  - ☛ Thermal Model by Jean Cleymans
  - ☛ Heavy-ion Physics (past/present/future) by Jurgen Schukraft
  - ☛ Compressed Baryonic Matter by Subhasis Chattopadhyay
  - ☛ Physics with Electron-Ion Collider by Abhay Deshpande

Thermodynamics, Cumulant and Critical Point

- Precise knowledge of equation of state (pressure) of QCD at high density and temperature has important significance for the analysis of HIC experiments.

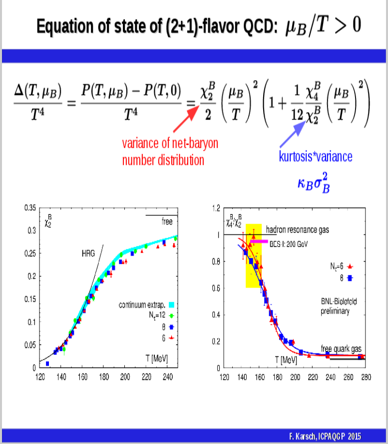
Thermodynamics, Cumulant and Critical Point

- LQCD EOS at $\mu = 0$ [**F. Karsch, P. Hegde**]



Thermodynamics, Cumulant and Critical Point

- LQCD at $\mu \neq 0$ [**F. Karsch, P. Hegde**]



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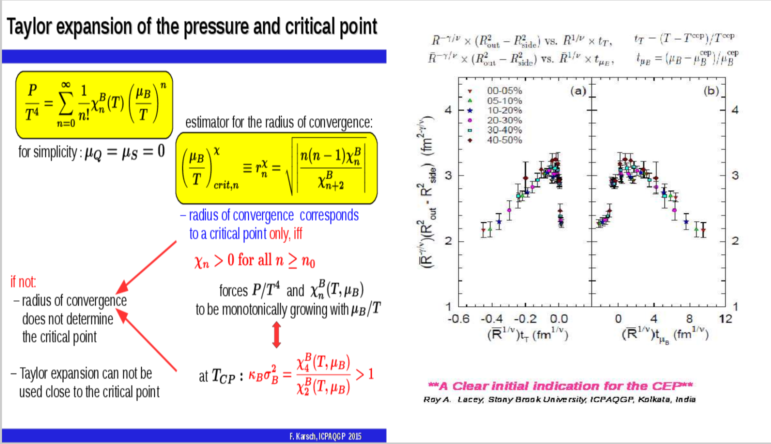
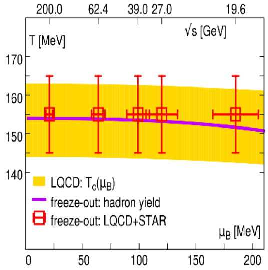


Thermodynamics, Cumulant and Freeze out

- LQCD [**S. Mukherjee**]; Model Calculation [**K. Redlich**]

Freeze-out at RHIC



freeze-out in RHIC takes place close to the phase boundary

need better T^f determination

freeze-out from hadron yield parametrization:
Andronic et.al., J. Phys. G38, 124081 (2011),
with $T^f(\sqrt{s}\to\infty)=154$ MeV

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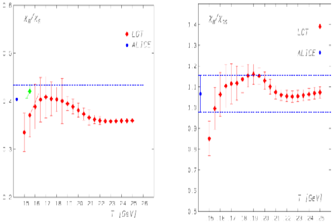
Consider T-dependent LQCD ratios and compare with ALICE data



- The LQCD susceptibilities ratios are weakly T-dependent for $T \geq T_c$
- We can reject $T \leq 0.15$ GeV for saturation of χ_B, χ_S and χ_{QS} at LHC and fixed to be in the range $0.15 < T \leq 0.21$ GeV, however
- LQCD => for $T > 0.163$ GeV thermodynamics cannot be anymore described by the hadronic degrees of freedom

Take Home from LQCD

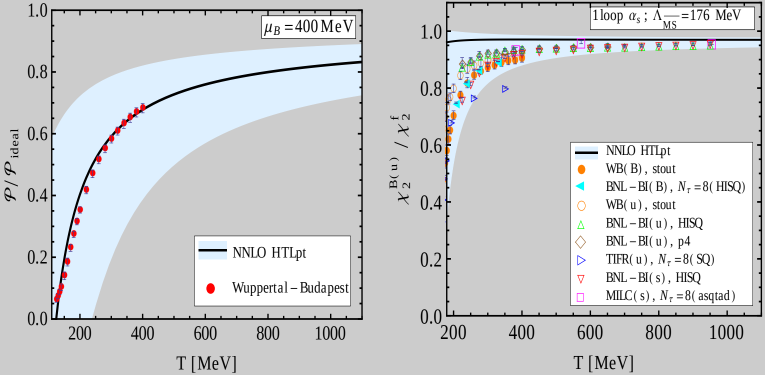
- Lattice gauge theory has made impressive progress on the calculation of static thermodynamic properties of baryon symmetric QCD matter
- The equation of state at $\mu_B = 0$ for physical quark masses is now known with a precision that far exceeds that required in (viscous) hydrodynamics calculations
- By Taylor expansion pressure for $\mu_B \neq 0$ is also computed
- The quasi-critical temperature where chiral suscept. related to chiral symmetry peak has been determined to lie at $T_c = 155$MeV

Scope

- CP requires further precision in calculation
- Freeze out has been estimated with a band, requires improvement
- Dilepton rate and transport coefficients have been computed!

Thermodynamics and susceptibility in HTLpt

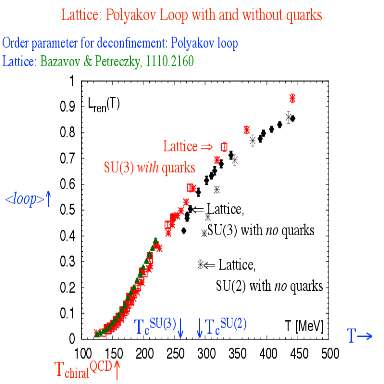
- 3-loop Pressure and susceptibility [**N. Haque**];

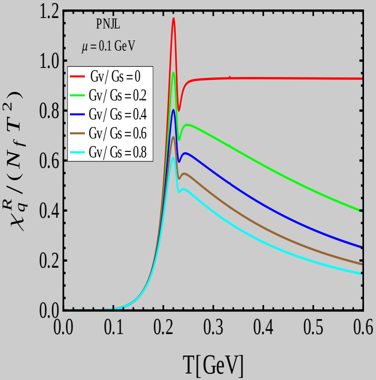


- Trace anomaly, speed of sound and higer order QNS have been computed and agree well with LQCD $T \geq 250$ MeV
- Scope: Pressure at large μ_B and very small T for FAIR and Stars; informative to LQCD

Thermodynamics in Polyakov-Loop-NJL Model

- Pressure and susceptibility [**Aminul& Sarbani; Stefan Schramm**]





- With(out) Vector interaction (G_V) with coupling that doesn't depend on T and μ_B
- With vector interaction, pressure and susceptibilites deviate from

Some more works based on Polyakov Loop

- Finite volume study of thermodynamics [Subrata Sur]
- Evolution of Polyakov loop fields in heavy-ion collisions [P S Saumia]
- Isospin symmetry breaking and baryon-isospin correlation [Sarbani Majumder]
- Phase diagram and CP [Abhijit Bhattacharya; Rajarshi Ray, Sanjay Ghosh]

Scope

- Temperature dependent vector coupling G_V is required to match with LQCD data
- $D = 4$ Gluon Condensates in quark and gluon props. [Purnendu Chakraborty: JHEP 1303 (2013) 120]
- Gribov Term in props. [Kharzeev and Levin, arXiv:1501.04622; Su and Tywoniuk, arXiv:1409.3203]

Last two items in above: probably marring the perturbative and nonperturbative approach in $T_c \leq T \leq 2T_c$

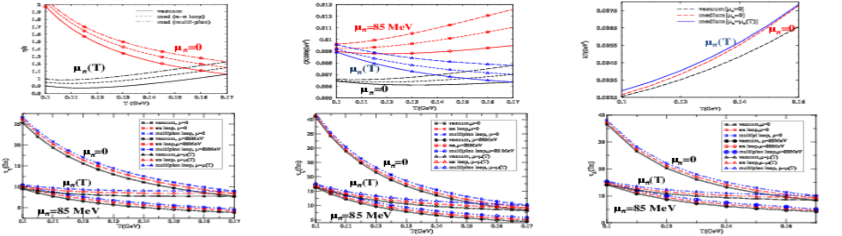
Transport Coefficients

- They are extracted through vHydro by fitting flow coeffs.
- Also calculated in two ways: Boltzmann Equation $\&$ Kubo Formula
- Fitting to data doesn't give T and μ dependence
- Since these are properties of a medium, should T and μ depanendence
- So one should use Boltzmann Eq $\&$ Kubo formula

Transport Coefficients

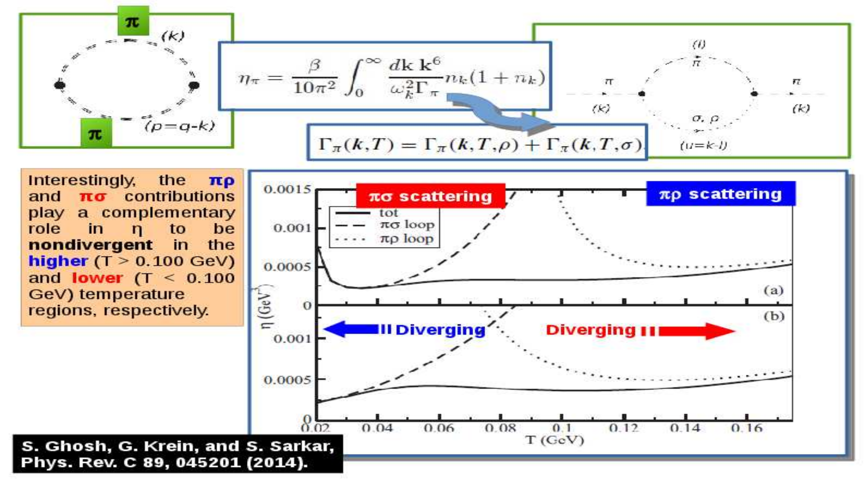
- Bulk and Shear [**Sukanya Mitra**]

- The transport coefficients and relaxation time of dissipative flows have been evaluated from microscopic transport theory for a hot pion gas.
- The effects of a thermal medium have been introduced through the dynamical interaction cross section that has been estimated from effective theory at finite temperature.
- The medium modified interaction cross section gets suppressed which in turn enhances the temperature dependence of the first and second order transport coefficients.
- A temperature dependent pion chemical potential has been used indicating the early chemical freeze out of pion gas which also affects the temperature dependence of transport coefficients.
- Being important inputs of the hydrodynamic evolution equations the medium modified transport coefficients are expected to affect the signals extracted from hydrodynamic simulations.



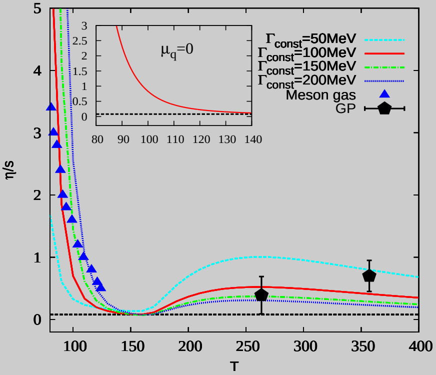
Transport Coefficients

- η **[Sabyasachi Ghosh]**



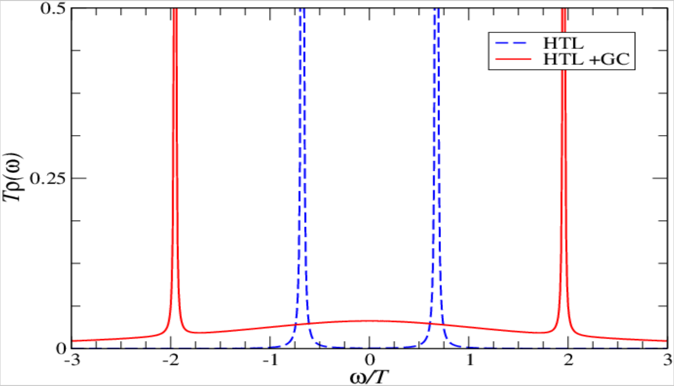
Transport Coefficients

- η/s in PNJL but considering some width in quark propagator **[Sudipa and Kinkar]**



Scope in Transport Coefficients

- $D = 4$ Gluondensates in Quark Propagator [Purnendu Chakraborty: JHEP 1303 (2013) 120]



- May be with Gribov term too, but not sure at the moment!

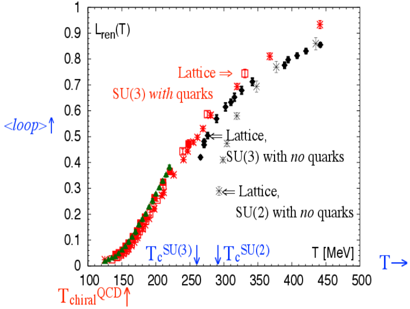
Dileptons

- Rob Pisarski

Lattice: Polyakov Loop with and without quarks

Order parameter for deconfinement: Polyakov loop

Lattice: Bazavov & Petreczky, 1110.2160



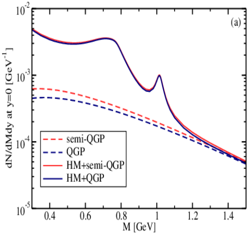
Hydrodynamics: # dileptons

MUSIC: 3+1 hydro @ RHIC: $\sqrt{s}$ = 200 GeV/A, central collisions

Preliminary analysis: only ideal hydro.

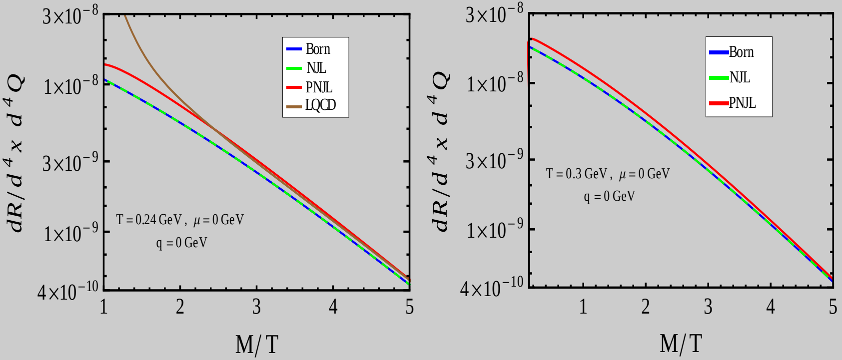
Small enhancement of dileptons in semi-QGP, swamped by hadronic phase.

No matching of semi-QGP to hadronic phase: clearly essential.



Dileptons

- Aminul and Sarbani



- Dilepton rate with gluon condensates [Aritra & Purnendu]

Message

- Dilepton Rate is computed in LQCD but bias dependent spectral function
- pQCD (HTL) rate is available for more than a decade
- Nonperturbative rates (with Polyakov Loop, Gluon Condensates) have been computed

☛ No match to the enhancement of low mass dilepton spectra

☛ At low mass Dileptons from Hadrons essential [Rolf Rapp& H van Hees; Sourav Sarkar]

Energy Loss and Jet quenching [Abhijit Majumdar, Ivan Vitev]

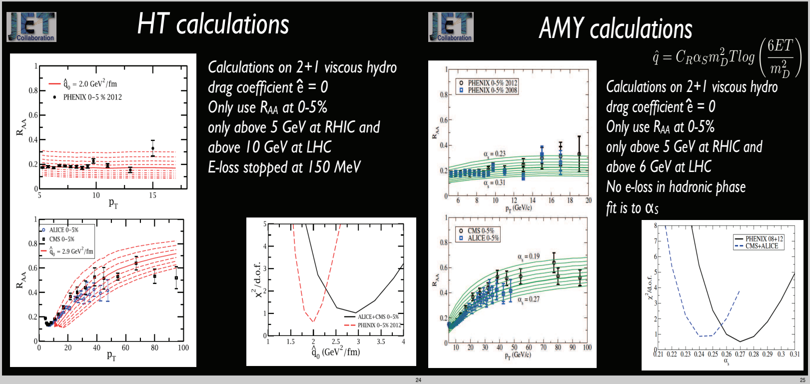
- Significant Assumptions in E-loss Model:
  - ☛ The virtuality and splitting of hard parton and how to reduce its virtuality
  - ☛ The nature of the medium through which the energy parton propagates
  - ☛ Kinematic approximations for the interaction between medium partons and projectile partons: Eikonal approximation, soft gluon emission, small angle/colinear emission

  Some extensively used models: BDMPS-Z, GLV, AMY, HT

- Modeling the medium:
  - ☛ Collection of static scattering centers with specified density distributions
  - ☛ Thermally equilibrated perturbative medium
  - ☛ Multigluon exchange between projectile and spatially extended medium in terms of expectation values of higher field operators ⇒ Higher Twist

Energy Loss and Jet quenching

- Abhijit Mazumdar



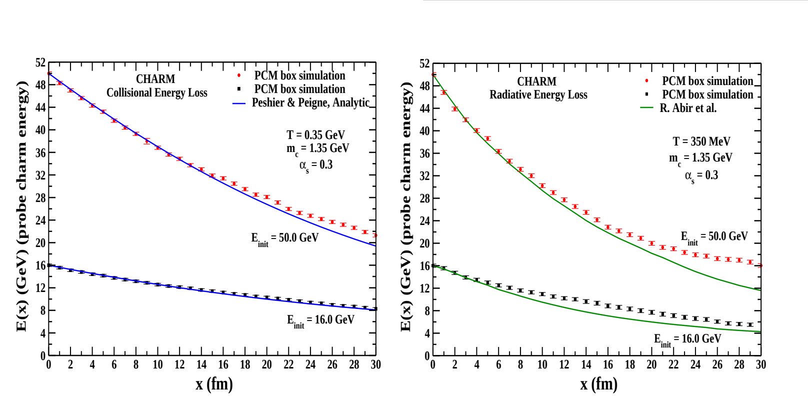
- No collisonal $\hat{e}$ in above; discussed uncertainities in IC of hydro and also in modeling
- Emphasized Importance on collision $\hat{e}$; can be taken into account consistently in a given model!

Heavy Quark Quenching

- LHC
  - ☛ Charm: LHC $\sim$ 10 $\times$ RHIC
  - ☛ Bottom: LHC $\sim$ 100 $\times$ RHIC
- Produced at early time ($\tau_Q < \tau_{th}$); No production at later time
- Produced in pairs (QQ) at early times $\Rightarrow$ pQCD
- Total no. of HQ gets frozen very early in the history of collisions
- Immediately upon their production they will propagate through QGP
- One is left with the task of determining the HQ distribution
- Details of the distribution may reflect the characteristics and development of QGP
- Generalized Dead-Cone formula for radiative E-loss
- Fokker-Planck Eq. distribution for collisional & radiative loss
- R_{AA}: D-meson spectra; semileptonic decay of Charmed and Bottomed Meson
- HQ and LQ lose energy in similar fashion

Heavy Quark Quenching

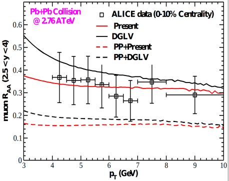
- Charm Evolution: Analytic model vs PCM(VNI/BMS) [Md. Younus]



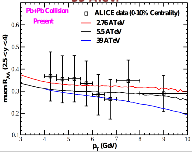
Heavy Quark Quenching

- U. Jamil

R_{AA} of muons at forward rapidity at 2.76 ATeV.



Comparison of R_{AA} of muons at forward rapidity at 2.76, 5.5 and 39 ATeV.



ALICE Collaboration, Phys. Rev. Lett. 109, 112301 (2012).

- K. Saraswat; Souvik P Addya

Quarkonia Melting

- Color Screening

Quarkonia and the concept of suppression

Charmonia: J/ψ, Ψ', χ_c **Bottomonia**: Υ (1S), Υ(2S), Υ(3S)

Heavy quarks carry the information of early stage of collisions:

- Charm and bottom quarks are massive.
- Formation takes place early only in the collision.

Proposed Signature : **QCD phase transition**

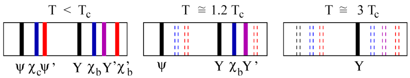
Color screening of static potential between heavy quarks:

J/ψ suppression: Matsui and Satz, *Phys. Lett. B* **178** (1986) 416

– Suppression of states is determined by T_C and their binding energy

Lattice QCD: Evaluation of spectral functions $\Rightarrow T_{melting}$

Deconfinement → Color screening → heavy quarkonia states "dissolved"



H. Satz, HP2006

$T_{diss}(\psi') \approx T_{diss}(\chi_c) < T_{diss}(\Upsilon(3S)) < T_{diss}(J/\psi) \approx T_{diss}(\Upsilon(2S)) < T_{diss}(\Upsilon(1S))$

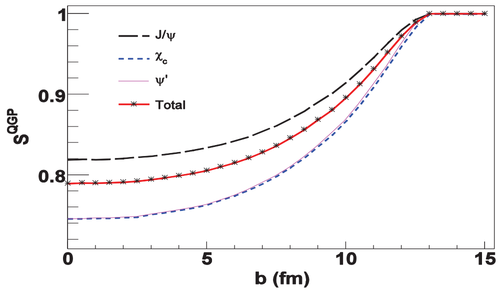
2/17

Their suppression pattern is a **thermometer** of the QCD matter

Quarkonia Melting

- P. Bhaduri
- Color screening
- Described pA with cold nuclear effects
- Prediction for FAIR

Centrality dependence of inclusive survival probability

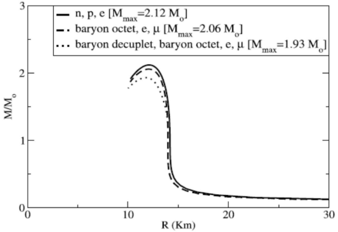


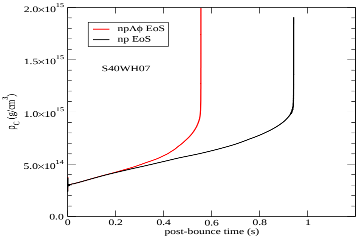
Effects of feed down is included: 30 % from χ and 10 % from ψ'

$S_{tot}=0.6S_{J/\psi} + 0.3\ S_{\chi} + 0.1S_{\psi'}$

Does exotic matter exist in 2 $M_\odot$ Neutron Stars?

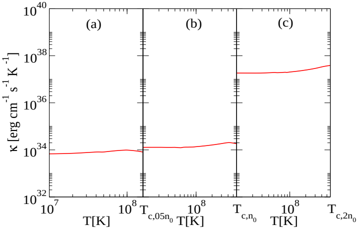
Accurately measured highest Neutron Star of $2.01\pm0.04\ M_\odot$ puts stringent conditions on the EoS. [J. Antoniadis et al., Science 340 (2013)]

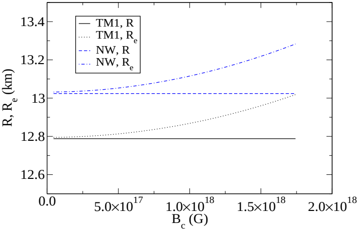




- Hyperon puzzle - Softer EoS, smaller maximum mass (S. Schramm's talk)
- Chiral EoS including hyperons, Δ resonances (V. Dexheimer, S. Schramm, ApJ683 (2008))
- Vector meson repulsion makes the EoS stiffer resulting in higher maximum mass
- Hadron look-alike quark matter EoS leads to heavy neutron stars. (M. Alford et al. ApJ 629 (2005))
- First Λ hyperon SN EoS compatible with 2 $M_\odot$ NS (S. Banik, M. Hempel, D. Bandyopadhyay, ApJS 214 (2014))
- The supernova simulation with this hyperon EoS leads to early collapse of the protoneutron star to a black hole (P. Char's talk)

Superfluidity and Strong Magnetic Fields in NS





- Rapid cooling of the Neutron Star in Cas A is attributed to the neutron superfluidity in the core [D. Page et al., PRL106 (2011)]
- The contribution of superfluid phonons to the thermal conductivity computed solving Boltzmann equation are shown here (S. Sarkar's talk)
- Neutron Stars are laboratories of dense matter under extreme physical conditions. The surface magnetic field could be as high as 10^{16} G.
- Such high magnetic fields influence the EoS through Landau quantization
- Anisotropic magnetic pressure deforms the neutron star (R. Mallick's talk)

Quark Nuggets with $Z(3)$ Symmetry

- Abhishek Atreya
  quarks may be trapped in $Z(3)$ domain