Strong Interaction Theory in India: a Snapshot

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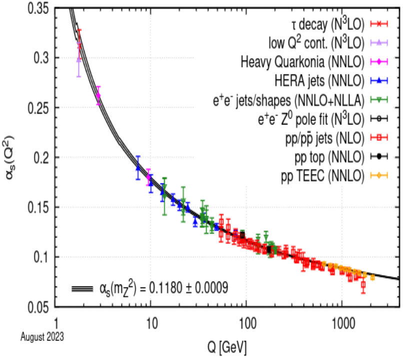
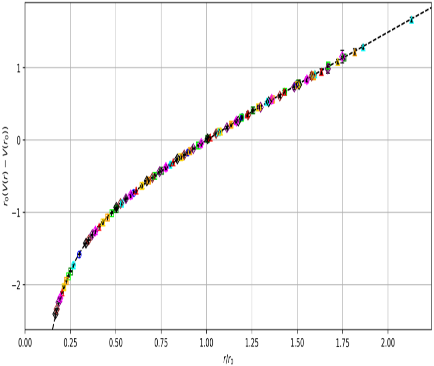
November 11, 2025

Strong interaction

QCD, the theory of strong interactions: SU(3) gauge theory, gauge mediators: gluons.
Leads to asymptotic freedom and confinement.

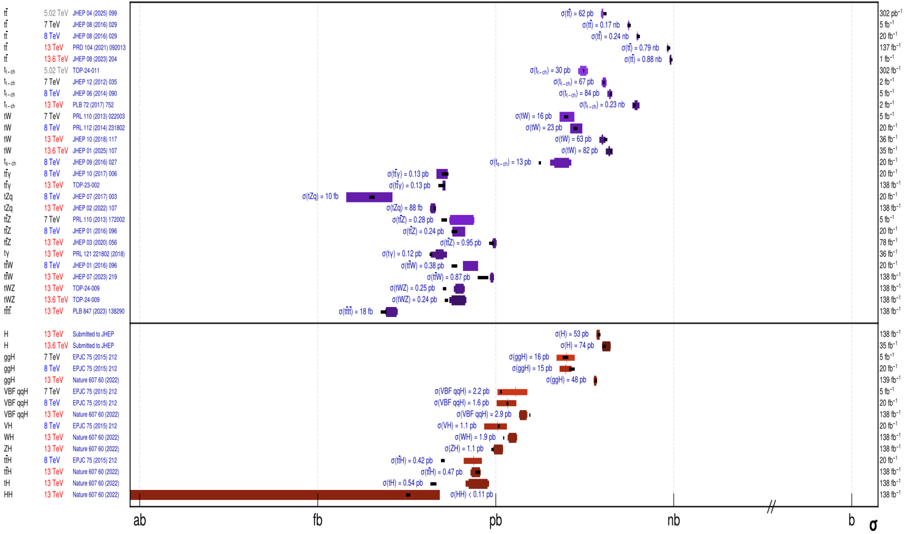




PDG

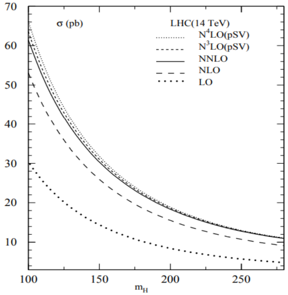
Urs Wenger, Lattice 2025 plenary

Perturbative QCD



CMS, summary of Higgs and $t\bar{t}$ data (public page)

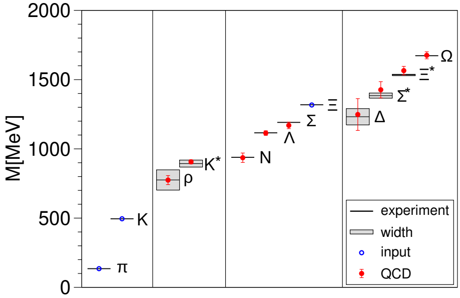
- Important contribution of Indian physicists to higher order perturbative calculations of processes relevant for LHC.
  V. Ravindran(IMSc, Chennai), P. Mathews(SINP, Kolkata), N. Rana(NISER), ...
- Higgs production through *gg* fusion in LHC: perturbative calculation.



V. Ravindran, Nucl.Phys.B752 (2006) 173

Spectrum calculation

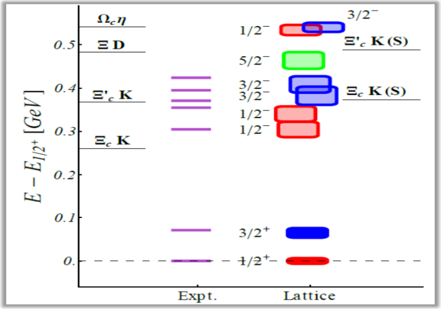
- Confinement and chiral symmetry breaking in QCD: determine the spectrum of the states, which are singlets of the SU(3) gauge group.
- Nonperturbative physics.
  Numerical Monte Carlo calculations using Lattice QCD allows a calculation of the spectrum of states.



BMW collab., Science 322 (2008) 1224

Spectrum calculation

- **N. Mathur(TIFR, Mumbai), M. Padmanath(IMSc), S. Basak (NISER):** lattice calculation of baryons and tetraquarks, in particular those with heavy quarks (c, b).
- Lattice helps in identifying the spin of the Ω_c^0 states.



Mathur & Padmanath, PRL 119 (2017) 042001

- Various tetraquark and dibaryon states with one or more heavy quarks.

Other nonperturbative approaches

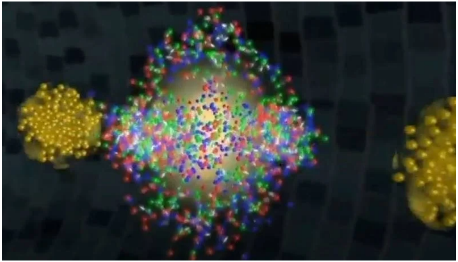
- QCD dispersion relations, which use analyticity properties of scattering amplitudes to connect low energy and high energy regimes.
- Chiral perturbation theory: effective theory for pions, the Goldstone bosons of chiral symmetry breaking.
- **B. Ananthanarayan (IISc, Bangalore), Udit Raha (IIT Guwahati)**
- Use of the Roy equations (S.M. Roy, 1972) to extract the s wave $\pi\pi$ scattering lengths and using them to determine other low energy experimental data.

  B. Ananthanarayan, G. Colangelo, J. Gasser, H. Leutwyler, Phys. Rept. 353 (2001) 207
- Spectrum, decay width, form factors from QCD based potential/models: **H. Dahiya (NIT Jalandhar), A.K. Rai (SVNIT, Surat), ...**
- Light cone QCD

  A. Mukherjee (IIT Mumbai), D. Chakrabarti (IIT Kanpur), ...

Physics goals of NICA

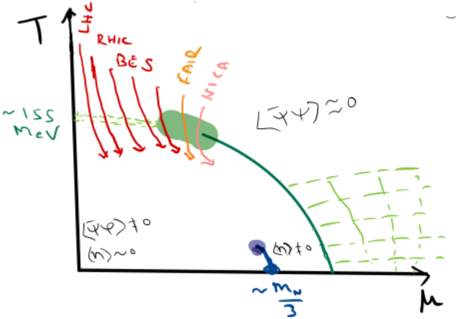
- NICA in JINR: collision of heavy ions to study the transition of nuclear matter into quark-gluon plasma.



- Collision of polarized beams: study of spin physics.
- EDM of light nuclei.
- Beam species: protons and polarized deuterons to very massive gold ions.

Phase diagram of QCD

- At high temperature and densities, strongly interacting matter is expected to manifest in a deconfined, chiral symmetry restored phase: Quark Gluon Plasma (QGP).
  Explored by relativistic heavy ion collision experiments.



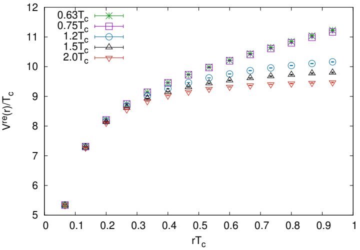
- The system is highly nonperturbative at temperatures reached in the collider experiments.

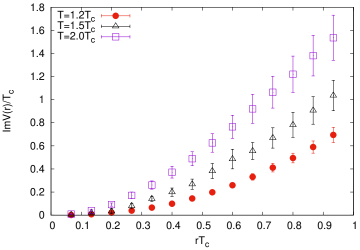
Study of the nonperturbative QGP

- Lattice study of the QGP: properties of the equilibrium plasma in the thermodynamic limit. **R. Gavai, S. Gupta, S. Datta (TIFR), S. Digal, S. Sharma (IMSc), P. Hegde (IISc)**
- At $\mu_b = 0$: chiral symmetry restoring transition at ~ 156 MeV

HotQCD, BMW

- Nature of confining $\bar{Q}Q$ potential changes.





D. Bala & S. Datta, PRD 101 (2020) 034507

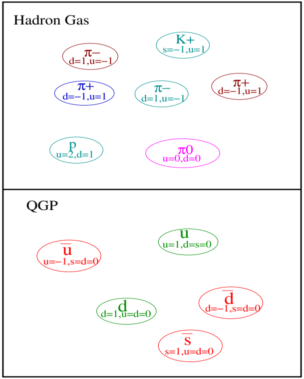
This is for gluonic plasma. Similar figure for 2+1 flavor QGP.

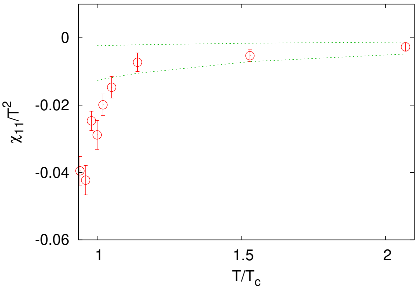
HotQCD, PRD 112 (2025) 054510

χ_{ud} and deconfining nature of the plasma

Quantities like χ_{ud} probe correlations between quantum numbers: very different between bound state phase and free quarks.

Koch, Majumdar & Randrup, PRL 95(05) 182301; R. Gavai & S. Gupta (2006)





Datta, Gavai, Gupta, PRD(2017)
PT: Andersen, et al., JHEP (2013)

Leading contribution at $g^6 \log g$

Study of nonperturbative plasma

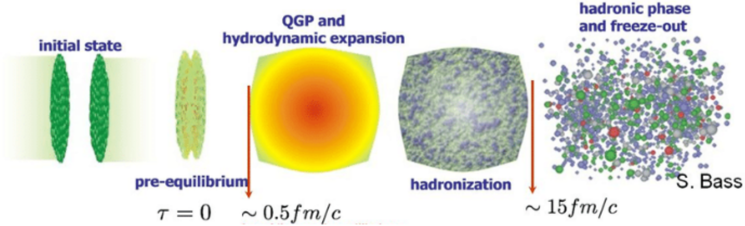
- Resummed perturbation theory has been shown to work till quite low temperatures in the plasma.
  M.G. Mustafa (SINP, Kolkata), N. Haque (NISER), ...
- "Modified perturbation theory" to explain some features at small T.

  see the poster of Manas Debnath

- QCD based study with some simplifying assumptions, as well as QCD inspired models, have also been used for the study of the QGP.
  Chiral symmetry: NJL, PNJL, quark-meson model.
  Quasiparticle models: in particular, effective fugacity model.
  H. Mishra (NISER), A. Mishra (IIT Delhi), B. Patra (IIT Roorkee), V. Chandra (IIT Gandhinagar), M. Kurian (IIT Dhanbad),C.R. singh (IIT Indore), S. Ghosh (IIT Bhilai), ...
- Transport coefficients have been calculated.

Phenomenology of the medium in URHIC

- Good control over thermodynamics of static,equilibriated plasma at μ_B=0.
- The medium created in the heavy ion collisions is very different.

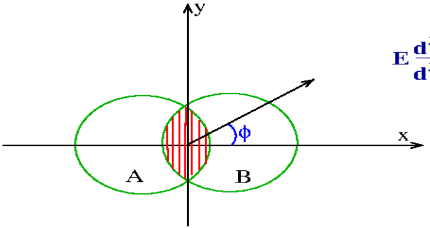


- Pre-equilibrium phase: partonic transport, e.g., AMPT (**Subrata Pal (TIFR) and collaborators**), or models like color glass condensate (L. McLerran & R. Venugopalan), which use the high gluon density to argue for an effective classicalization.
- The classical model has been studied using classical lattice gauge theory, and thermalization investigated.

S. Sharma, S. Guin, H. Pandey, S. Sharma, PLB 866(2025)139490

Relativistic hydrodynamics

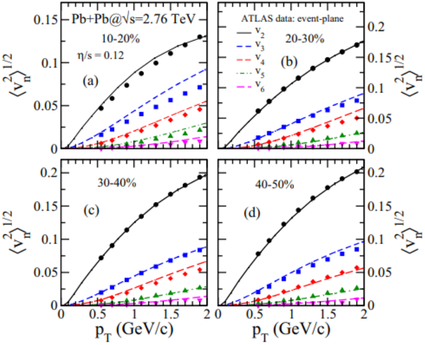
- Once local thermalization reached, the evolution of the system can be described by relativistic hydrodynamics.
- Lattice calculations provide inputs.
- In the development of relativistic hydrodynamics for the medium in relativistic heavy ion collisions, various Indian groups played an important role. **R. Bhalerao, S. Pal (TIFR), A. Chaudhuri (VECC, Kolkata), A. Jaiswal, S. Mitra, V. Roy (NISER), V. Sreekanth (Coimbatore), ...**
- One of the major successes of relativistic hydrodynamics in RHIC phenomenology is the explanation of anisotropic flow.



$$E\frac{d^3n}{d^3p} \propto 1 + \Sigma_n\, v_n \cos(n\ \phi)$$

Anisotropic flow

- v_n: AMPT initial stage, switch to relativistic hydrodynamics.



R. Bhalerao, A. Jaiswal, S. Pal, PRC 92(2015)014903

- Physics of the higher coefficients $v_{n>5}$, and their connection to CMBR physics.

A. Mishra, R. Mohapatra, P.S. Saumia, A. Srivastava, PRC77(2008)064902

Angular momentum, magnetic field

- Further, the system can have a finite (large) angular momentum, which leads to polarization of vector mesons and baryons.

  B. Mohanty's talk, Monday

- The extension of relativistic hydrodynamics to include finite angular momentum, and in the presence of finite magnetic field **A. Jaiswal, S. Bhadury, V. Roy, S. Mitra (NISER)**.
- Some interesting effects of rotation discussed in the posters.

  S. Dey, Lakshmi Naik, B. Sahoo

- Lattice study difficult.
  Some development: V. Bragutta and A. Roenko's talk, Wednesday

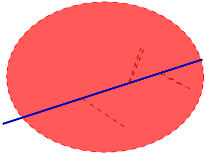
Hard probes

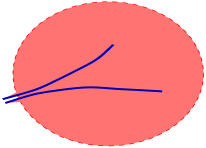
- Jets provide a probe of the medium. Energetic parton created early, interacts with medium to lose energy.

  N. Sahoo's talk, Monday

  Theoretical work on jet structure and energy loss in QGP.

  R. Sharma (TIFR), S. Prasad (Bose Inst., Kolkata), ...

- Heavy quarks also form in early hard collisions.
  Their energy loss can be parametrized by a transport coefficient, which can be calculated, e.g., from lattice QCD, or from QCD-based models.
- Quarkonia. Interactions with the thermal gluons in a medium can lead to dissociation: Υ suppression. For J/Ψ in LHC, interplay of suppression and recombination.

Hard probes

- The heavy scale of the quark mass allows an effective field theory formulation of the dynamics of heavy quark and quarkonia in medium.
- The heavy quark energy loss can be understood in a Langevin framework. The diffusion coefficient can be calculated from lattice QCD.
- The interaction of quarkonia in QGP can also be worked out in terms of a few parameters, which can be calculated using lattice QCD.
- The QCD based models can also be used for the calculation of these coefficients.

S. Das (IIT Goa), S. Datta, R. Sharma (TIFR), B. Patra (IIT Roorkee), V. Chandra (IIT Gandhinagar), M. Kurian(IIT Dhanbad), C.R. Singh (IIT Indore), P. Bhaduri (VECC), ...

QCD at finite μ_B

- In NICA, we are interested in the physics at finite μ_B, T.
- The QCD model based calculations can easily be generalized to finite μ_B.
- Lattice: Monte Carlo calculations cannot be performed at finite μ_B (**Sign Problem!**)
- The Taylor expansion method, pioneered in TIFR (**R. Gavai, S. Gupta**), allows calculation of equation of state at not-too-large μ_B.

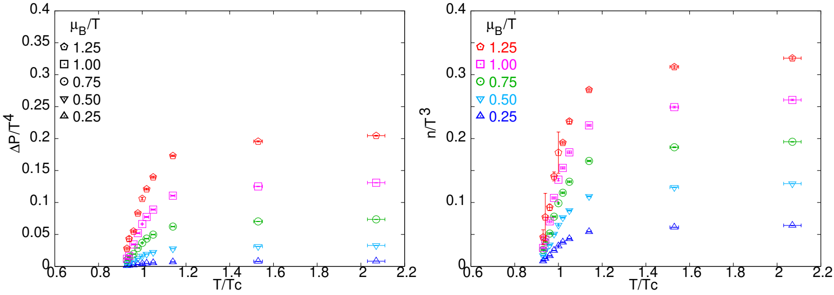
$$P(\mu_B, T) \;=\; P(0, T) + \sum_n \frac{\mu_B^n}{n!}\chi_n^B, \qquad \chi_n^B = \frac{\partial^n P}{\partial \mu_B^n}|_{\mu_B=0}$$

R. gavai & S. Gupta, PRD 68(2003) 034506; C. Allton, et al., PRD 68(2003) 014507

- The other thermodynamic quantities can be obtained from P.

$$\frac{n_B}{T^3} \;=\; \frac{\partial\left(P/T^4\right)}{\partial(\mu_B/T)}, \qquad \frac{\epsilon}{T^4} = \left(T\frac{\partial}{\partial T} + 3\right)\frac{P}{T^4}$$

QCD at finite μ_B



S. Datta, R. Gavai, S. Gupta, PRD 95(2017)054512

- Alternate discretization of the chemical potential term (**S. Sharma, R. Gavai (2015)**): allows more accurate calculation of higher order susceptibilities.

HotQCD, PRD 105(2022)074511

- χ_n^B from simulations at imaginary μ_B.

D'Elia, Gagliardi, Sanfilippo (2017)

- EoS till $\mu_B/T \approx 2.5$.

Critical point of QCD

- An examination of the χ_n^B allows one to find the critical point T_c, μ_B^c in the QCD phase diagram.

  R. Gavai & S. Gupta, PRD 71(2005)114014

- A recent estimate, based on simulation at imaginary μ_B and a multipoint Pade search: $(T_c, \mu_B^c) \approx \left(105^{+8}_{-18}, 422^{+80}_{-35}\right)$ MeV.

  D.A. Clarke, et al., arXiv:2405.10196

- This will be very much in the reach of NICA.
- Finite size of fireball.

  Effect studied with QCD based models.
  P. Deb, A. Bhattacharya, R. Mohapatra,...

  Talk of R. Mohapatra, Wednesday

- System evolution. Critical slowing down: correlation length cannot increase sufficiently in fast evolving medium.

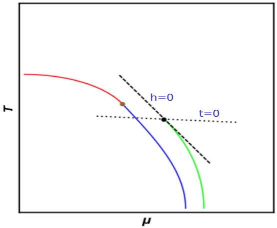
  On to hydrodynamics with critical fluctuations.

  Chandrodoy Chattopadhyay (PRL, Ahmedabad), Maneesha Pradeep (IISc)

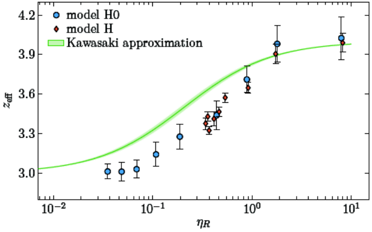
Study of critical dynamics

- Same static universality class as 3D Ising Model.
- Need to know the mapping between the Ising $(h, t = T - T_c)$ and the QCD(μ_B, T) variables.
- $\angle(h, t)$ axes $\propto m_q^{2/5}$.

M. Pradeep & M. Stephanov, PRD 100(2019) 056003



- Dynamical universlity class: model H.
- The critical slowing down time $\tau \sim \xi^z$ dependent on viscosity.

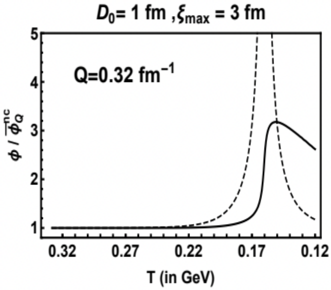


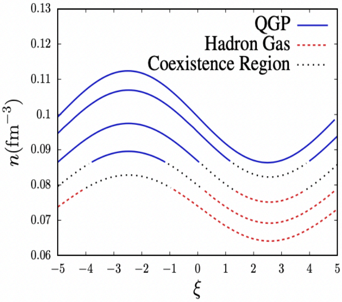
C. Chattopadhyay, J. Ott, T. Schäfer, V. Skokov, PRL 133(2024) 032301

Dynamics near critical points and first-order phase transitions in HICs

- Deterministic dynamical description of critical modes and freeze-out *Maneesha Pradeep*

M Pradeep, Rajagopal, Stephanov, Yin, PRD, 22





Kapusta, M Singh, Welle, PRC 24

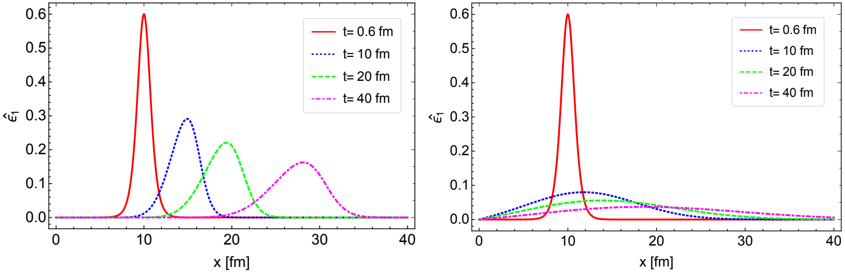
- Spinodal decomposition in rapidly expanding quark gluon plasma

Mayank Singh

Critical slowing down

- The evolution of energy density perturbations: very different in the presence of CEP.

  G. Sarwar, M. Hasanujjaman, M. Rahman, A. Bhattacharya, J. Alam, PLB 820 (2021) 136583

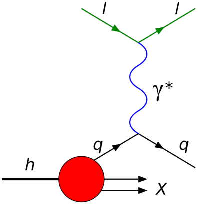


- Phase trajectories in the presence of CP different.

  S. Singh & J. Alam, PRD 107(2023)074702

Spin physics

Perturbative calculations involving hadrons require structure functions.



$$\frac{d^2\sigma}{dx\,dy} \equiv \frac{d^2\sigma^{\uparrow\Uparrow}}{dx\,dy} + \frac{d^2\sigma^{\uparrow\Downarrow}}{dx\,dy} \qquad : F_1, F_2$$

$$F_1 = \frac{1}{2}\sum_q e_q^2\, q(x), \qquad q(x) = q^{\uparrow}(x) + q^{\downarrow}(x)$$

$$\frac{d^2\sigma^p}{dx\,dy} \equiv \frac{d^2\sigma^{\uparrow\Uparrow}}{dx\,dy} - \frac{d^2\sigma^{\uparrow\Downarrow}}{dx\,dy} \qquad : G_1, G_2$$

$$G_1 = \frac{1}{2}\sum_q e_q^2\, \Delta q(x), \qquad \Delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$$

- $\Delta q(x), \Delta g(x)$ are the polarized pdfs, required for polarized cross section calculations.
- $\Delta q = \int_0^1 dx\, \Delta q(x)$ is interpreted as the fraction of proton spin carried by the flavor q.

Spin physics

- The proton spin can be decomposed into $\Delta q, \Delta g$ and terms which can be interpreted as quark and gluon angular momentum.

  X. Ji, PRL 78(1997)610

- They can be connected to gravitational form factors (matrix elements of $T^{\mu\nu}$), which are in turn related to the GPDs $H(x, \xi, t), E(x, \xi, t)$.
- The GFFs and the GPDs have been studied by **A. Mukherjee (IIT Mumbai), D. Chakrabarti(IIT Kanpur), R. Abir (AMU, Aligarh).**
- Gauge invariant definition of Gluon angular momentum.

  K. Banu, N. Vasim, R. Abir, PRD 105(2022)114033

- Calculation of gluon gravitational form factors of the proton using light front QCD.

  A. Sain,P. Choudhary,B.Gurjar,C.Mondal,D.Chakrabarti,A.Mukherjee, PRD 111(2025)094011

Concluding remarks

- There is a large community of theoreticians in India working in the topics of interest for NICA.
- For the QGP and QCD critical point search, the theoretical expertise cover most aspects of interest, including LQCD, hydodynamics, model based studies.
- The spin physics community is comparatively small, but growing, with EIC physics groups.
- I did not cover topics like neutron stars and dense matter EoS. See the talks in Monday session (H. Mishra, M. Bhuyan, V. Sreekanth, D. Kumar) and J. Pathak, Wednesday.
  Other experts: D. Chatterjee (IUCAA), R. Mallick (IISER Bhopal), R. Nandi (IIT Delhi), A. Srivastava (IOP)

Thanks to Chandrodoy Chattopadhyay, Maneesha Pradeep, M. Hasanujjaman, Dipankar Chakrabarti for help.