Experiment ↔ Lattice QCD: understanding high temperature QCD matter

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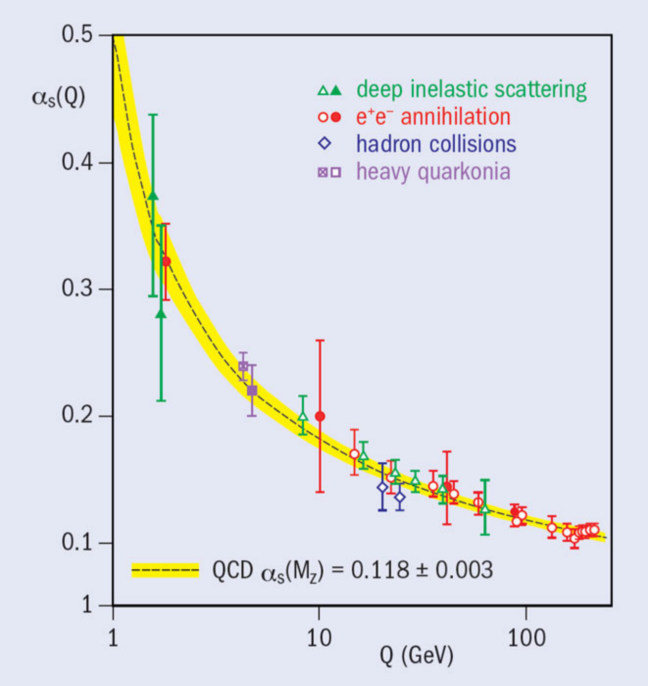
4th November 2025

Quantum chromodynamics – theory of strong interactions

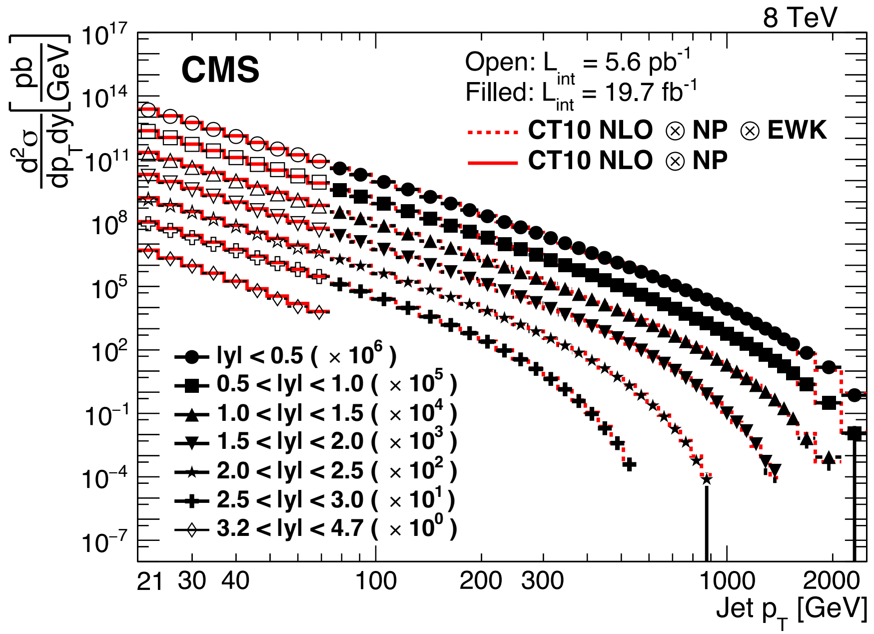
Strong coupling constant
1. Perturbative regime
2. Non-perturbative regime

Test of QCD in perturbative regime.

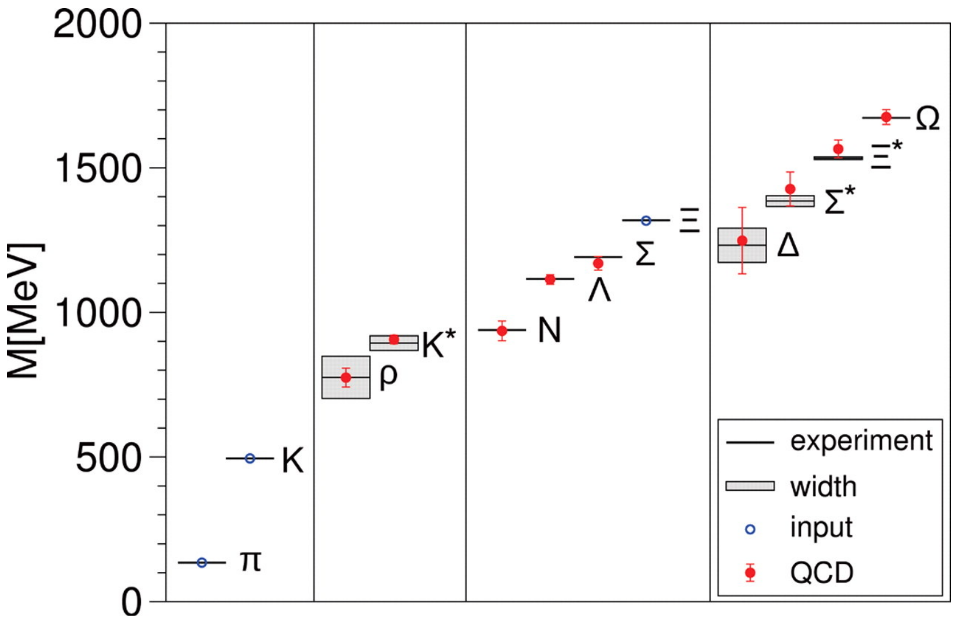
Test of QCD in non-perturbative regime (T=0).



https://cerncourier.com/a/the-history-of-qcd/



CMS: JHEP 03 (2017) 156



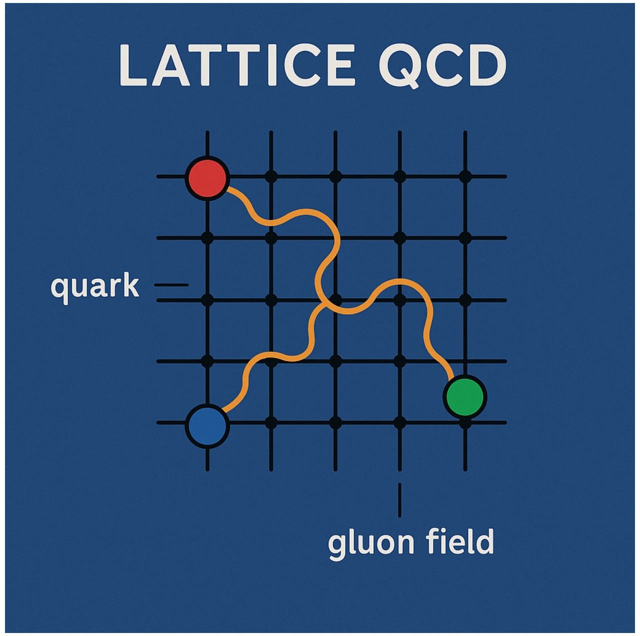
BMW: Science 322 (2008) 1224-1227

Theory tested by comparing to experimental measurements: QCD successful theory of strong interactions

What about non-perturbative and finite temperature ?

Theory and Experiment

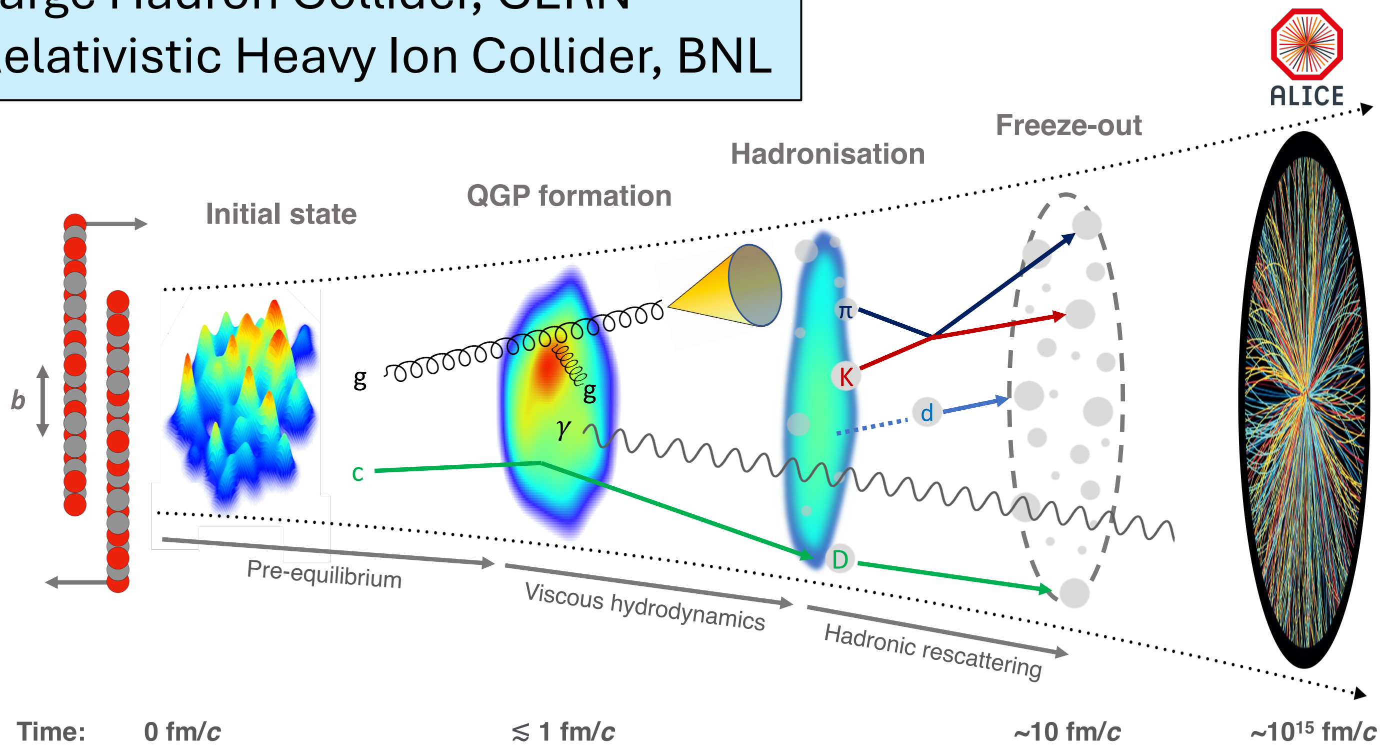
Lattice QCD



Discretizing spacetime into a 4-dimensional lattice. Quarks live on the lattice sites, while gluons are represented by link variables connecting sites. The path integral is then transformed into a very high-dimensional integral that can be evaluated by Monte Carlo simulations.

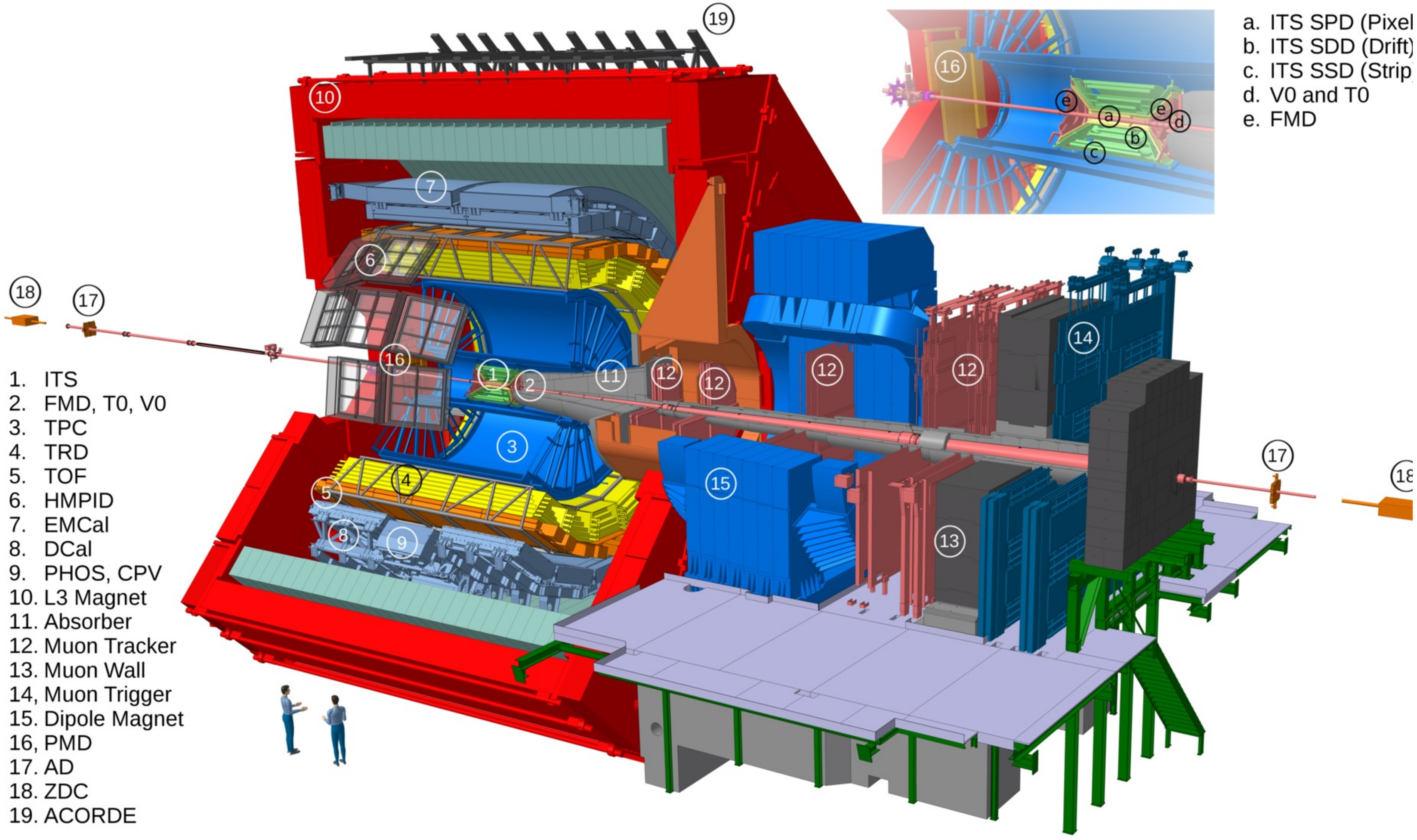
Relativistic heavy-ion collisions

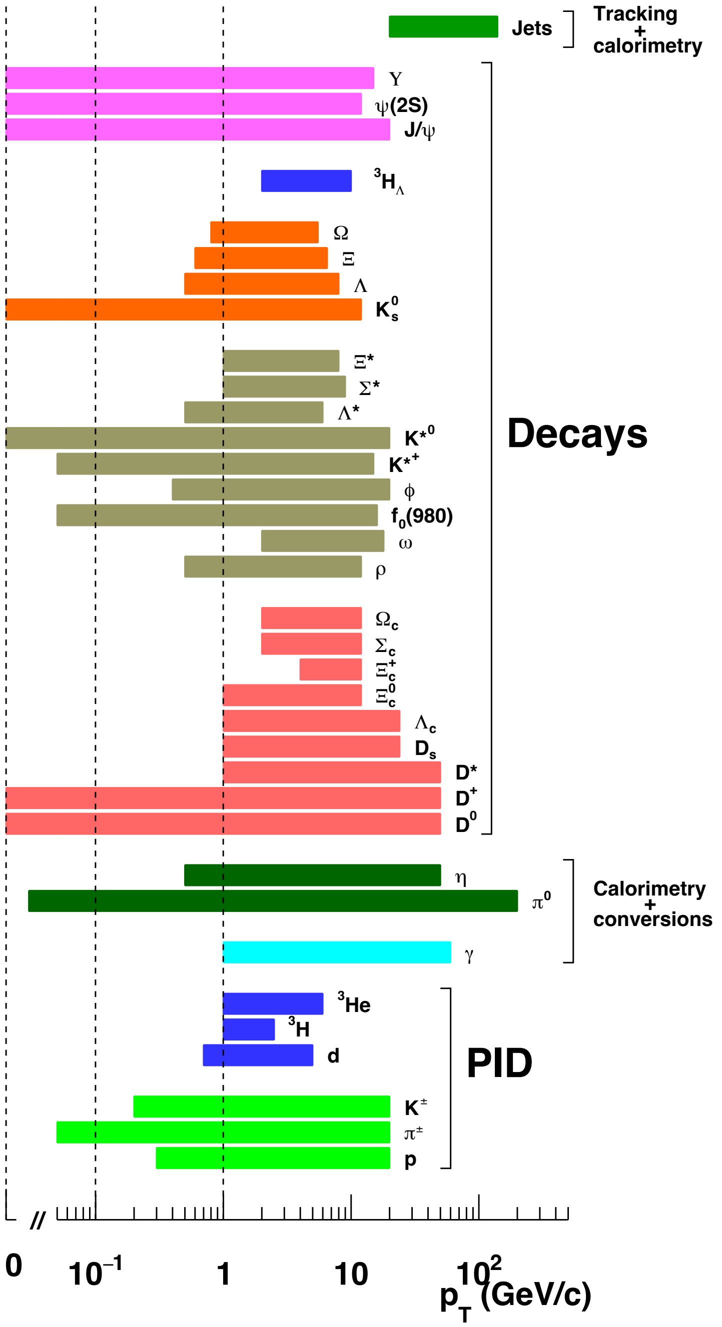
Running facilities
1. Large Hadron Collider, CERN
2. Relativistic Heavy Ion Collider, BNL



We can test QCD in non-perturbative regime and finite temperature.

Typical experiment – ALICE @ LHC





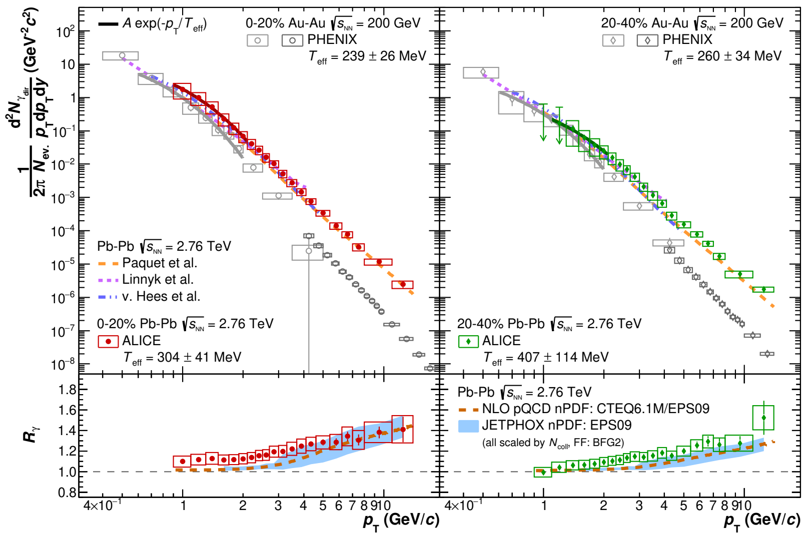
Probes: T ~ 90-800 MeV, μ_B ~ 0 MeV and $\alpha_s \approx 1 \rightarrow 0.1$.

Using $Q \sim 2\pi T$:
Near $T_c \approx 155$ MeV: $Q \sim 1$ GeV $\Rightarrow \alpha_s \sim 0.4$–$0.5$ (strongly coupled QGP).
At LHC mid-rapidity, $T \sim 400$–500 MeV: $Q \sim 2.5$–3 GeV $\Rightarrow \alpha_s \sim 0.25$–$0.3$.

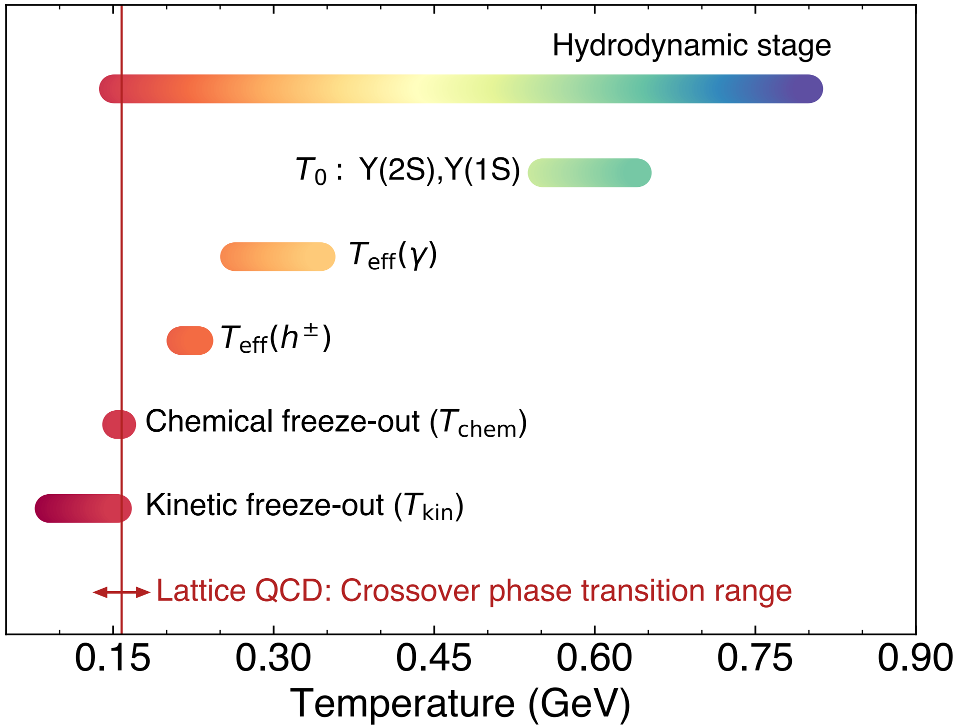
ALICE: Eur.Phys.J.C 84 (2024) 8, 813

Quark Gluon Plasma

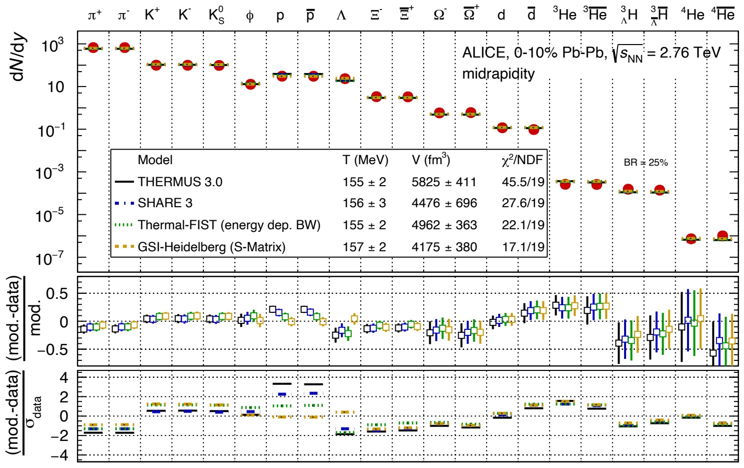
Direct photon measurements:
Initial temperatures ~ 800 MeV at LHC

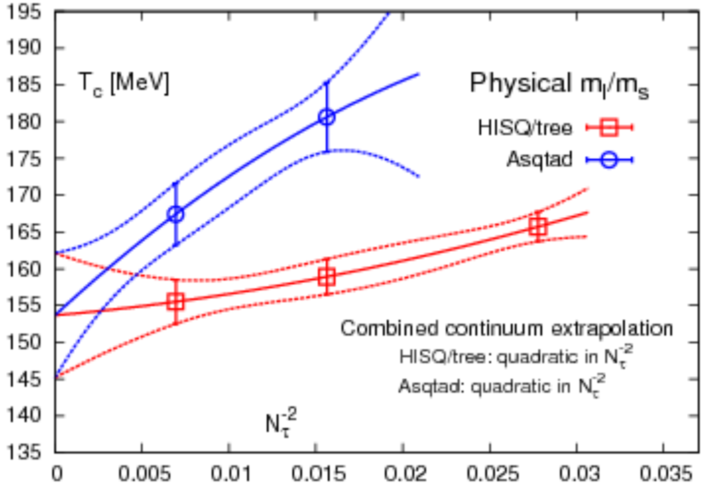


ALICE: Eur.Phys.J.C 84 (2024) 8, 813



Hadronization temperatures ~ 150 MeV

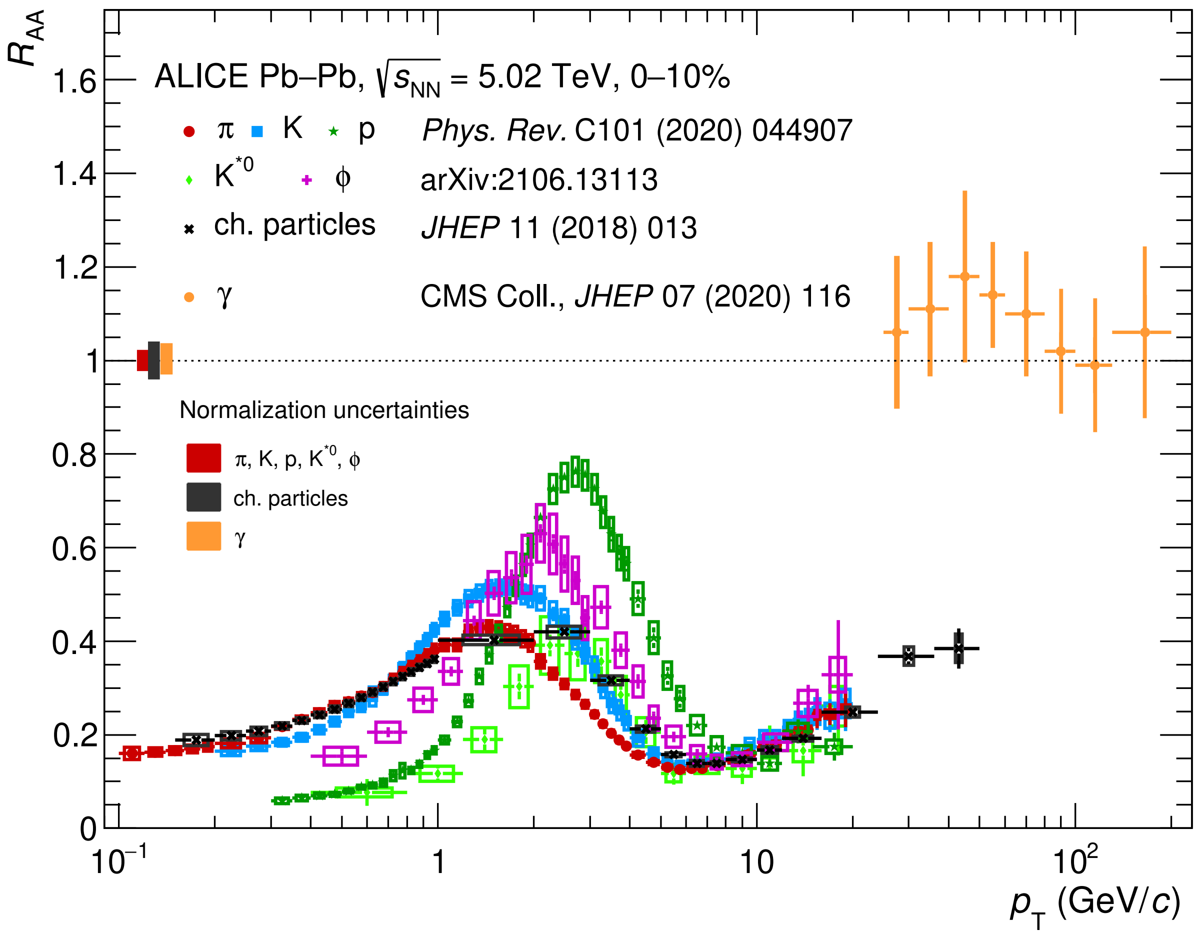




HotQCD: Phys. Rev. D 90 (2014) 094503
HotyQCD: Phys.Rev.D 85 (2012) 054503

Lattice QCD – transition temperature, T_c=156.5 ± 1.5 MeV – relevant degrees of freedom quarks and gluons

Experimental signature of QGP



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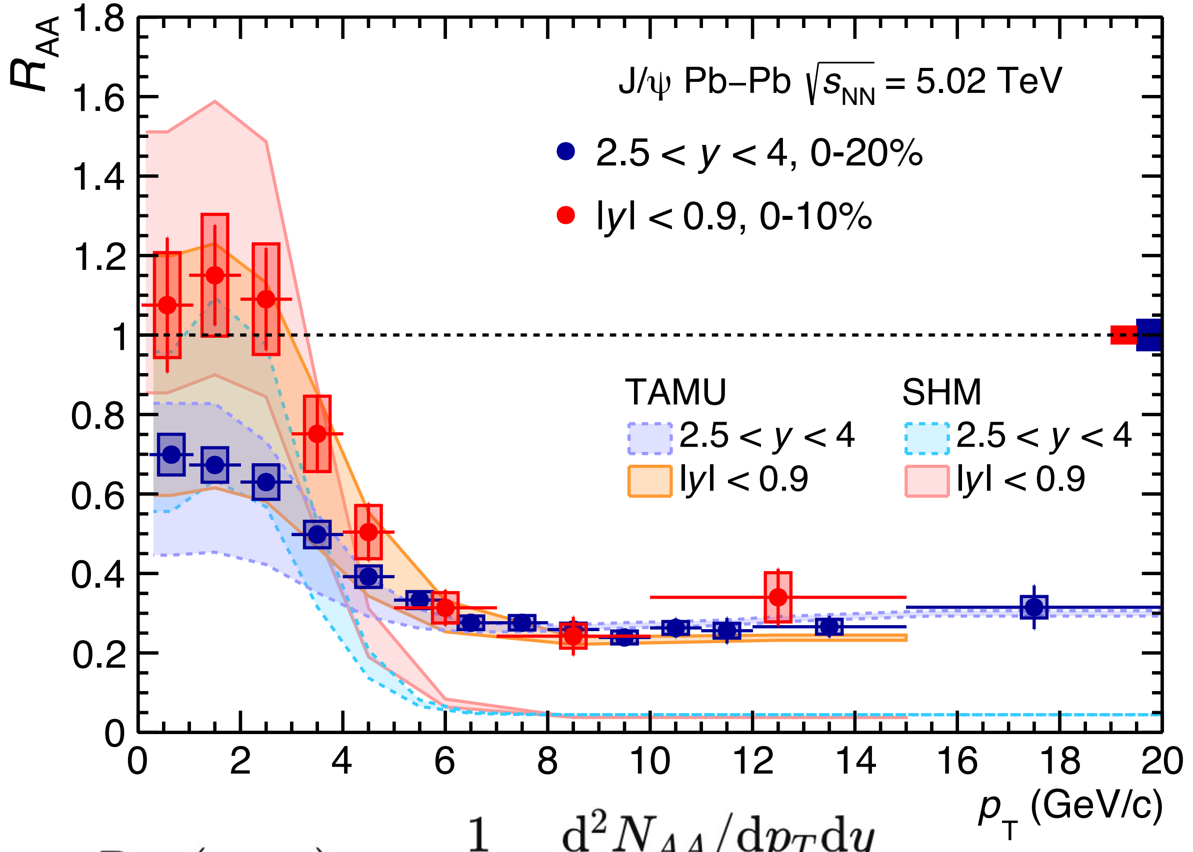


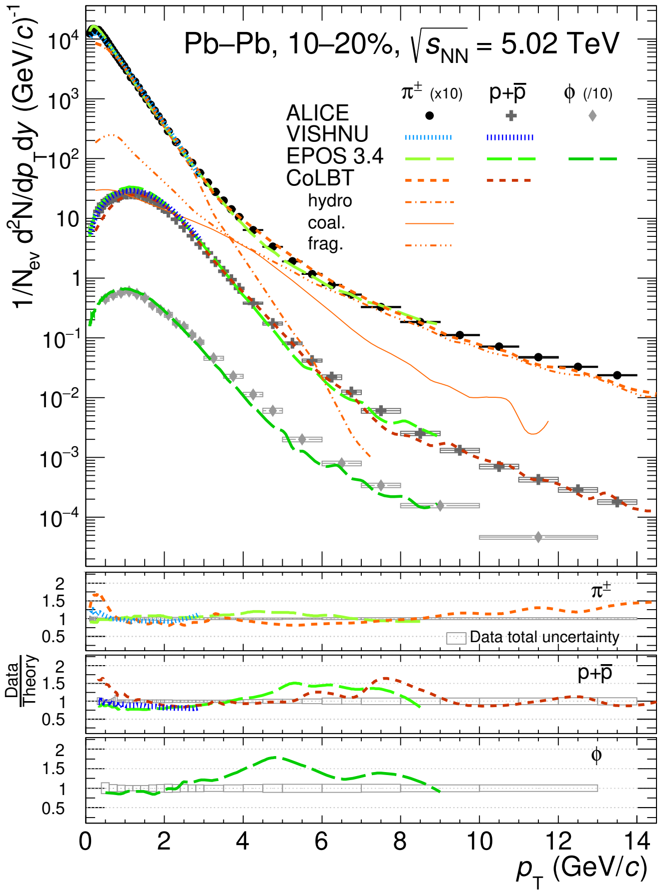
$$R_{AA}(p_T, y) = \frac{1}{\langle N_{\rm coll} \rangle} \frac{{\rm d}^2 N_{AA}/{\rm d}p_T{\rm d}y}{{\rm d}^2 N_{pp}/{\rm d}p_T{\rm d}y}$$

Data can only be explained by invoking quark gluon degrees of freedom at high temperatures

Testing QCD – Lattice vs. rel. heavy-ion collisions

Indirect comparison with experimental observables and inferences

(near) Direct comparison with experiment and inferences



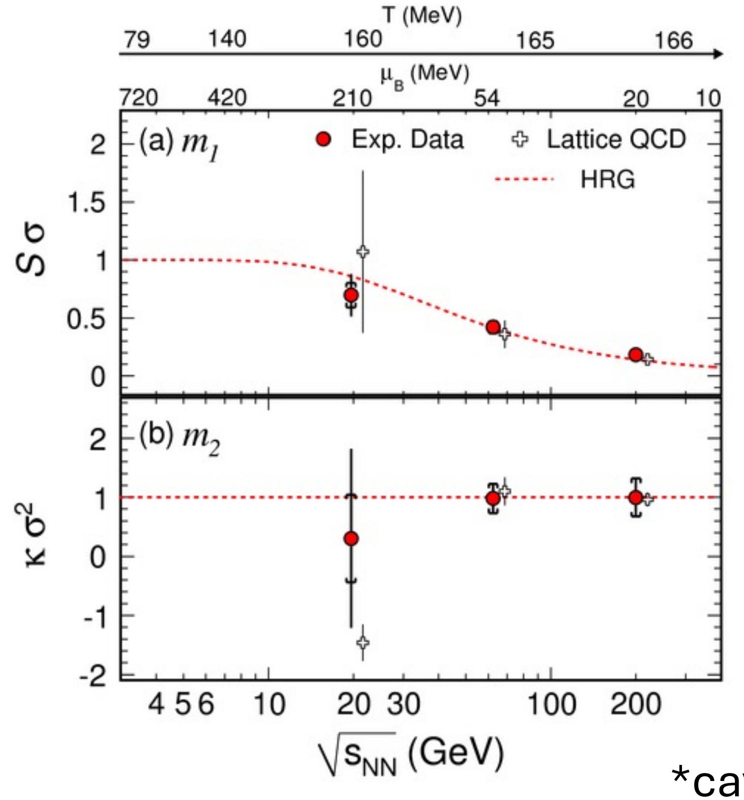
ALICE: Eur.Phys.J.C 84 (2024) 8, 813

Example:

Multi-stage evolution involving hydrodynamics -

Equation of State (EoS) is taken from lattice QCD calculations

Experiment



Theory: QCD

*caveats

Science, *332*, 1525(2011)
Gavai-Gupta: Phys.Lett.B 696 (2011) 459-463

Caveats: theory and experiment comparison

Theory side

1. Discretization and continuum extrapolation
2. Finite-volume effects
3. Unphysical quark masses (Chiral extrapolation)
4. Renormalization and scale setting
5. Euclidean vs. Minkowski observables (only static or equilibrium quantities accessible.
6. Finite-Temperature and Chemical Potential Issues (sign problem)
7. Statistical noise and autocorrelations
8. Choice of lattice action and discretization scheme
9. Observable matching and interpretation

Experiment side

1. Non-equilibrium and finite lifetime
2. Finite size and volume fluctuations
3. Freeze-out vs. Lattice temperature
4. Experimental acceptance and kinematic cuts
5. Baryon stopping and finite μ_B
6. Time averaging over cooling trajectory
7. Hadronic afterburner and final-state interactions
8. Critical fluctuations and event-by-event noise (finite size and lifetime, critical slowing down)
9. Experimental limitations to measure net-baryon and net-strangeness (need proxies)

Several aspects can be controlled, and uncertainties can be estimated.

Measurements and Lattice QCD

HIC Measurement	Needed Lattice Quantity	Status / Uncertainty (lattice)
Bulk spectra & flow (hydro closure)	QCD EoS: $p(T)$, $\epsilon(T)$, $s(T)$, $c_s^2(T)$at $\mu_B \approx 0$ (+ Taylor to $\mu_B > 0$)	Mature at $\mu_B = 0$; controlled Taylor up to $\mu_B/T \lesssim 2.5$
Hadrochemistry (yields/ratios)	Conserved-charge susceptibilities $\chi_n^{B,Q,S}(T, \mu_B)$	Precise at $\mu_B = 0$; Taylor/imaginary-μ extensions with sys.
Freeze-out via cumulants	Ratios: χ_1/χ_2, χ_3/χ_2, χ_4/χ_2along freeze-out lines	Active; comparisons with BES data possible with caveats.
Critical-point search (BES)	Higher-order coefficients/Taylor radius; cumulants at finite μ_B	Constraining bounds improving; direct location still uncertain
Flow systematics v_n	η/s(T), $\zeta/s(T)$ via Kubo (energy-momentum correlators)	Estimates with sizable sys.; trends near $T_c$could be /are used as priors.
Soft EM probes (photons/dileptons)	Vector spectral function; electrical conductivity $\sigma(T)$	σ/T known within factors $\sim$ 2; full spectra under study
Open heavy flavor R_{AA}, v_2	Heavy-quark diffusion $D_s(T)$, momentum diffusion $\kappa(T)$	Non-perturbative values with $\mathcal{O}(30–50\%)$sys.; improving

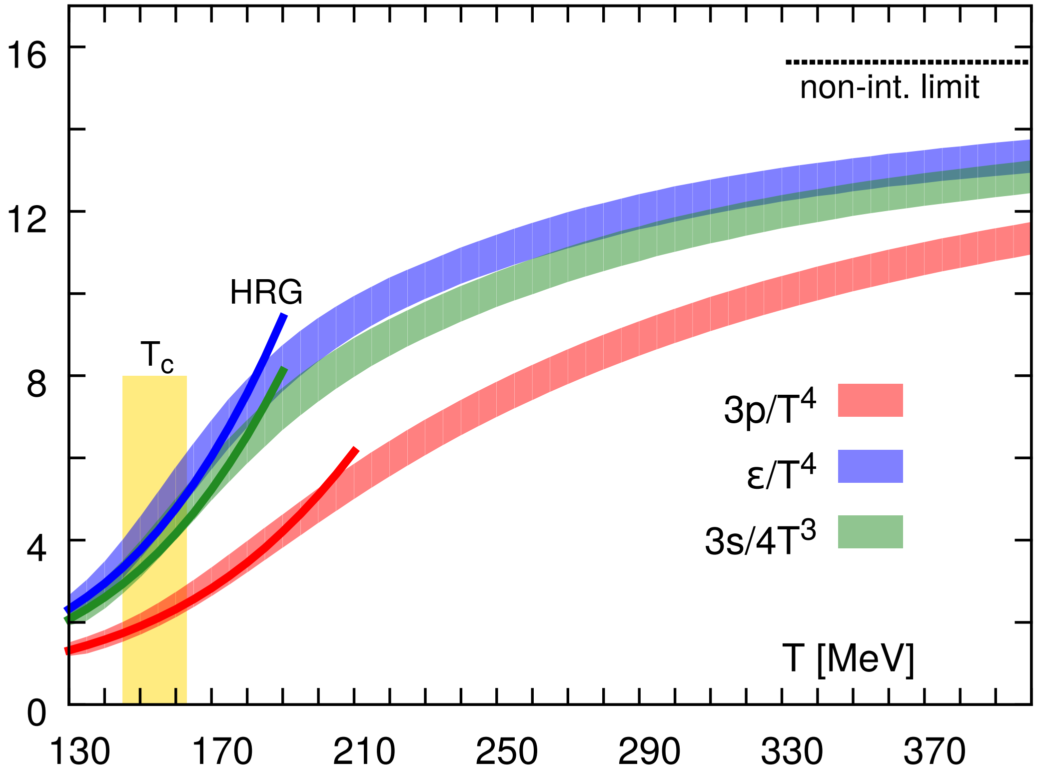
Measurements and Lattice QCD

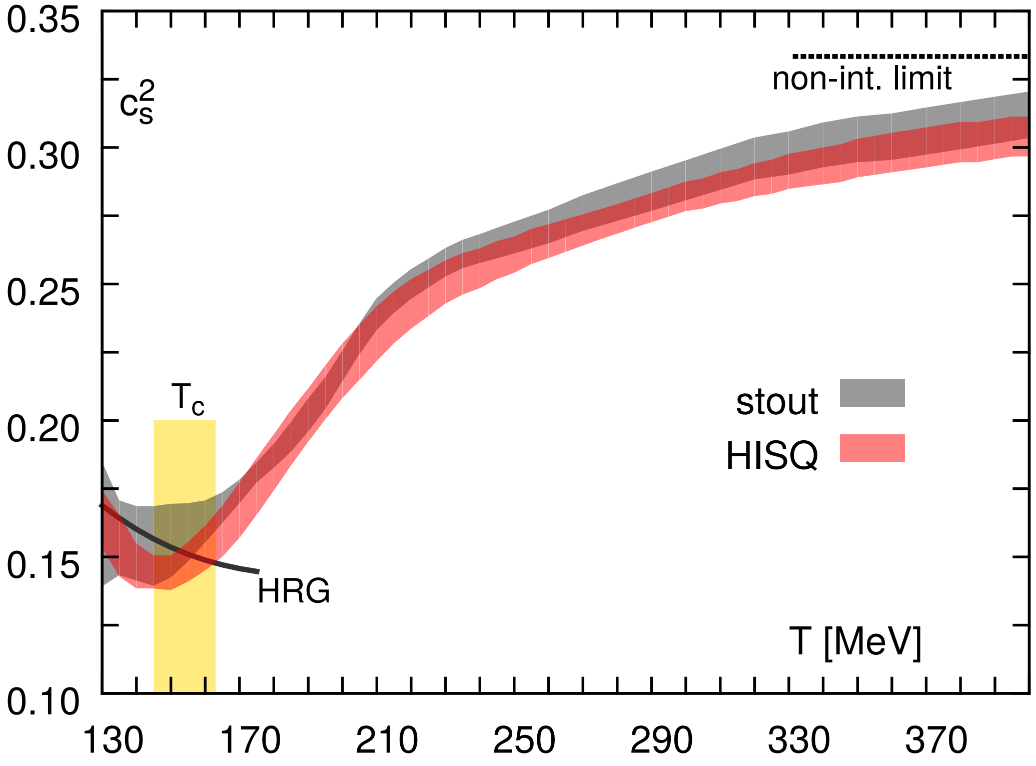
HIC Measurement	Needed Lattice Quantity	Status / Uncertainty (lattice)
Quarkonium suppression/regeneration	In-medium $Q\bar{Q}$ potential & spectral functions (NRQCD/pNRQCD)	Sequential melting scales constrained; widths still model-dependent
Jet quenching & substructure	Jet transport coefficient $\hat{q}(T)$ (soft part, EQCD/LQCD)	EQCD-matched results with uncertainties; T-dependence used in fits
Chiral & $U_A(1)$ restoration	Topological susceptibility $\chi_t(T)$; $U_A(1)$ breaking indicators	χ_t(T) well mapped; fate of $U_A(1)$ near T_c debated
CME/CVE related modeling	Sphaleron (Chern–Simons) rate; axial-charge diffusion	Hot, active topic; only bounds/estimates so far
Magneto-hydro effects	EoS & susceptibilities at $B \neq 0$; magnetization $M(T, B)$ - Heng-Tong Ding	Several continuum results; full dynamical-QCD with B advancing
Strangeness/charm freeze-out	Mixed susceptibilities $\chi_{11}^{BS}, \chi_{11}^{QS}$; charm EoS at high T	Good precision for S sector; charm thermodynamics emerging
Low-mass dileptons (chiral)	Vector/axial spectral functions & Weinberg-type sum rules at T	Reconstructions exist; quantitative systematics still large

High energy heavy-ion collisions and Lattice QCD need each other – test QCD

Equation of state – crucial ingredient for QGP phenomenology ($\mu_B \sim 0$ MeV)

HotQCD: Phys. Rev. D 90 (2014) 094503



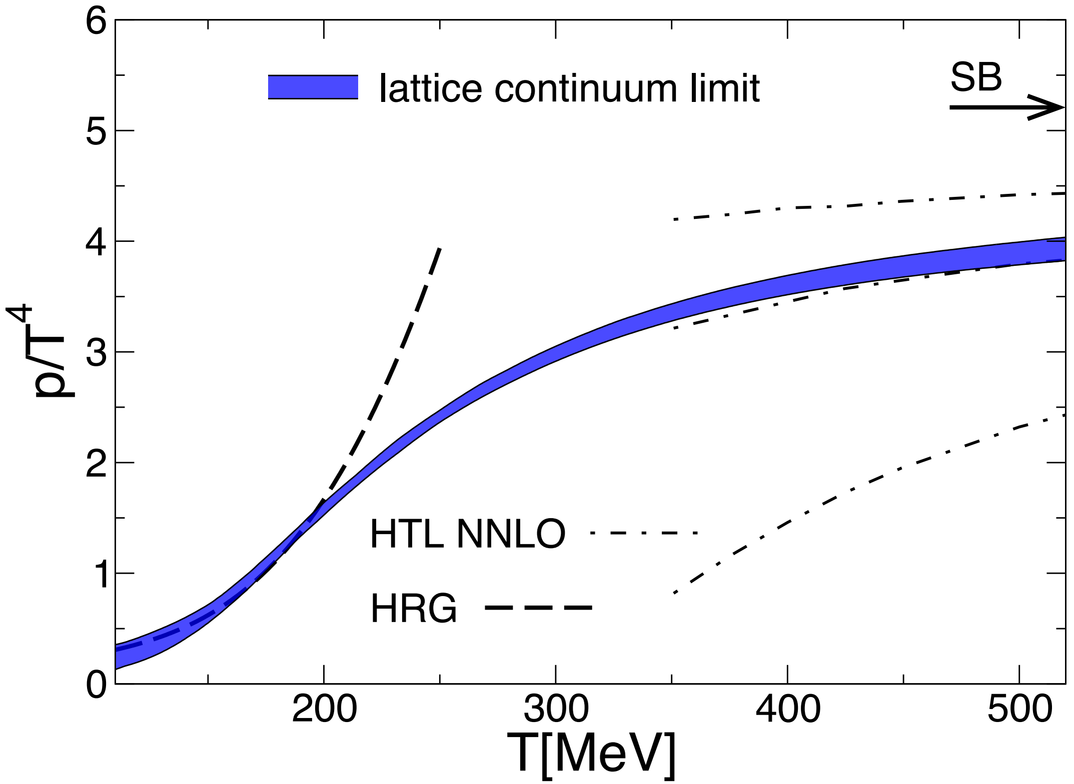


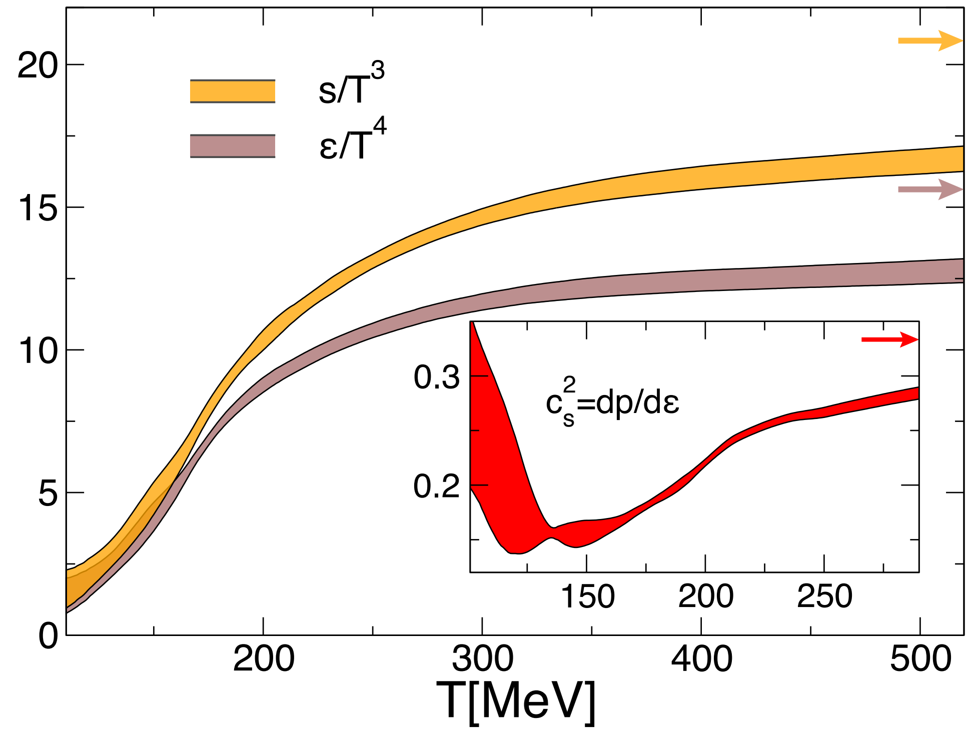
1. The EoS is a critical input to relativistic hydrodynamic simulations.
2. Softest point of the QCD EoS at $T \simeq 145–155\,MeV, c_s^2 \simeq 0.15$ (still non – zero).
3. The crossover region energy density $\varepsilon_c = (0.18–0.5)\ GeV/fm^3$.
4. Agreement with phenomenological estimates from RHIC and LHC freeze-out systematics. Anchors the onset of deconfinement observed experimentally.

1. Improved Lattice Action - Highly Improved Staggered Quark
2. Continuum extrapolation and Scale setting
3. Cross-checks and error control

Equation of state – Important ingredient for QGP phenomenology ($\mu_B \sim 0$ MeV)

Wuppertal-Budapest: Phys. Lett. B 730 (2014) 99–104
Crossover- WB: *Nature* 443 (2006) 675-678



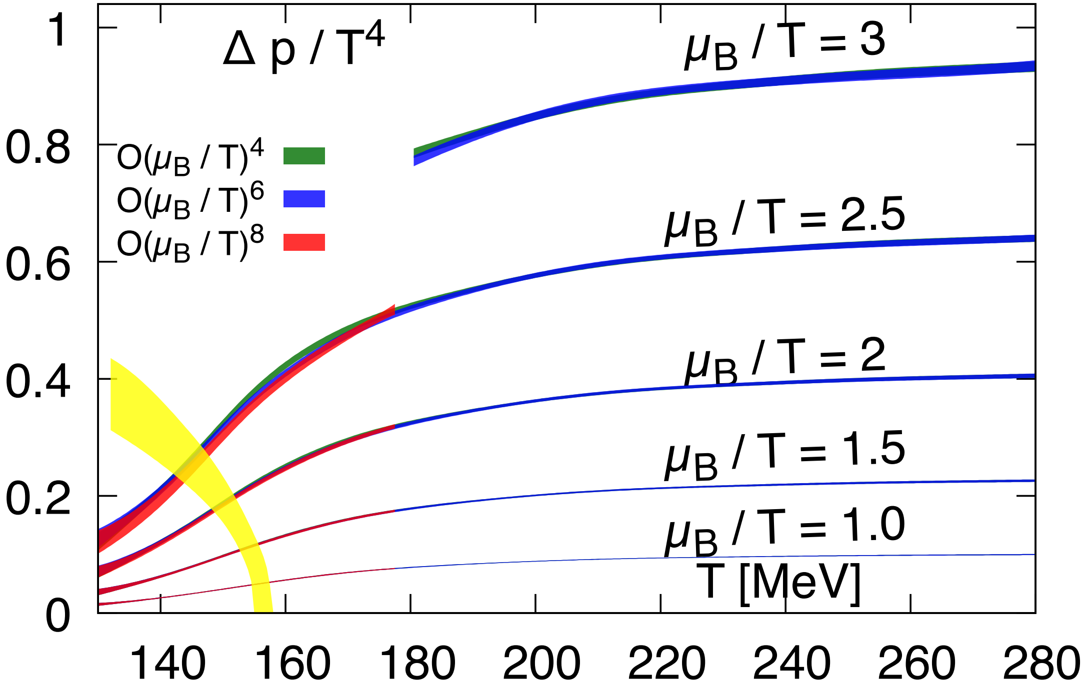


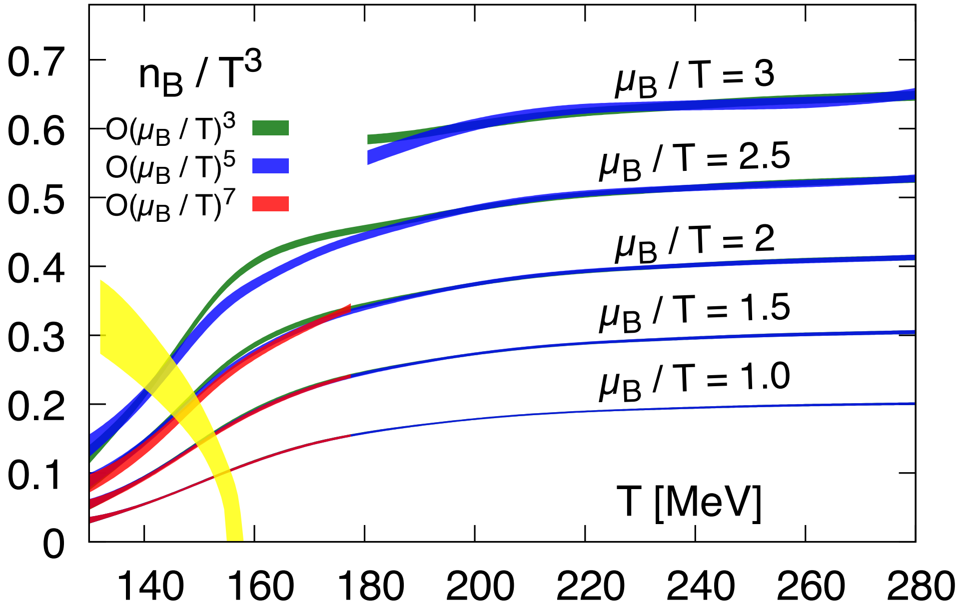
The collaboration's analytic parameterization has been adopted in widely used codes such as VISHNU and MUSIC, influencing flow and femtoscopic observables.

1. Physical Quark Masses & Continuum Limit
2. Improved Lattice Action: tree-level Symanzik-improved gauge action + two-step stout-link improved staggered fermions
3. Comprehensive Error Analysis; Cross-Checks and Validation

Equation of state – RHIC – BES and FAIR/NICA

HotQCD: Phys.Rev.D 108 (2023) 1, 014510





1. Extended the QCD EoS for (2 + 1) flavors to eighth-order in a Taylor expansion in μ_B / T.
2. Second- and fourth-order terms are fully continuum-extrapolated.
3. Used Padé resummation to improve convergence and estimate the range of validity of the series.

1. Provides the most precise lattice-QCD EoS at finite baryon density to date, essential for:Hydrodynamic modeling of RHIC and LHC heavy-ion collisions.
2. Constraining QCD phase-diagram trajectories.
3. Benchmarking future low-energy experiments (RHIC BES-II, FAIR, NICA).

Transport properties of QCD matter

1. Shear viscosity (η)
2. Bulk viscosity (ζ)
3. Diffusion coefficient(D)
4. Electrical conductivity (σ)

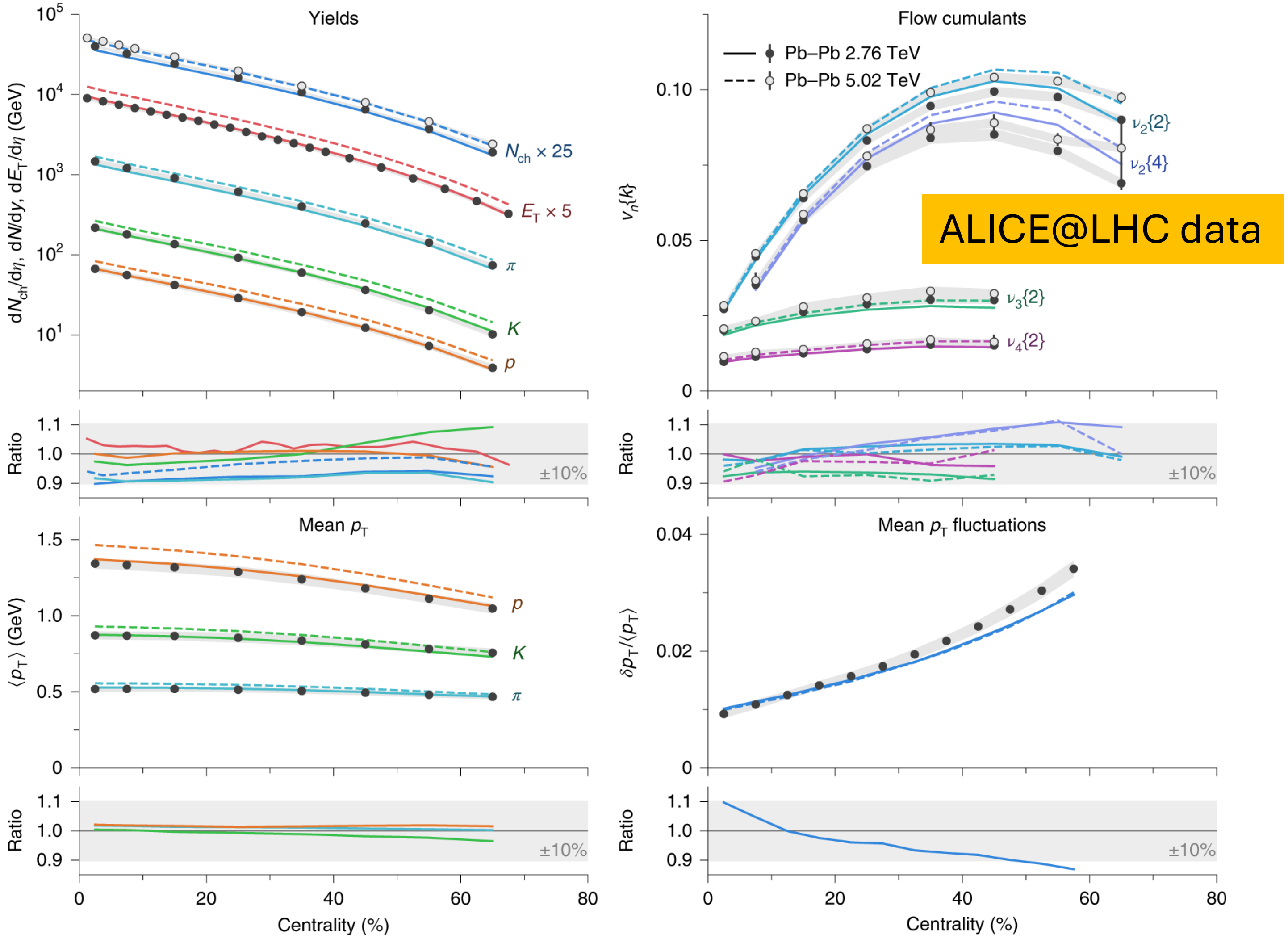
a) **Shear viscosity:** Measures a fluid's resistance to flow. The KSS bound ($\eta/s \geq 1/4\pi$) defines the limit for a *perfect fluid*.
b) **Bulk viscosity:** Quantifies resistance to volume change — the entropy produced when the fluid is compressed or expanded. In a conformally invariant system (trace of the energy–momentum tensor = 0), there's no resistance to expansion or compression, so $\zeta = 0$. The degree of conformal-symmetry breaking is reflected in the magnitude of ζ.
c) **Diffusion coefficient:** A transition in D(T) from an exponential (thermally activated) to a weaker, kinetic-energy–dominated temperature dependence signals a crossover from strongly to weakly coupled regimes.
d) **Electrical conductivity:** Determines how much of the intense electromagnetic fields generated in heavy-ion collisions are sustained by the QCD medium and for how long.

Equation of state – Hydrodynamics – constraining the transport properties (data + Hydro model)

Heavy-ion collisions (Pb–Pb at the LHC) are modelled as a multi-stage evolution:

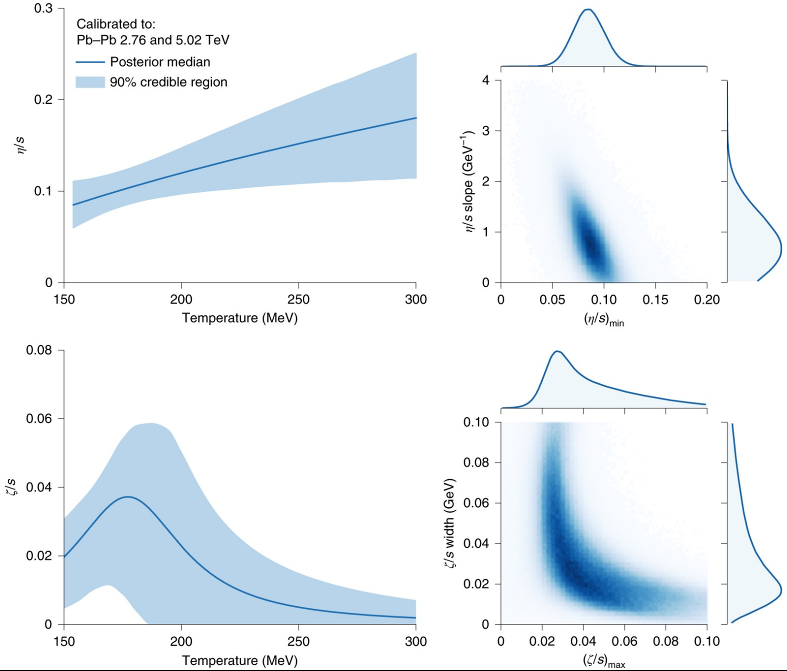
1. Initial conditions
2. Pre-equilibrium stage
3. Hydrodynamic evolution: relativistic viscous hydrodynamics is used to evolve the hot QGP fluid. The Equation of State (EoS) is taken from (2 + 1)-flavor lattice QCD calculations.
4. Hadronization ("particlization").
5. Hadronic transport

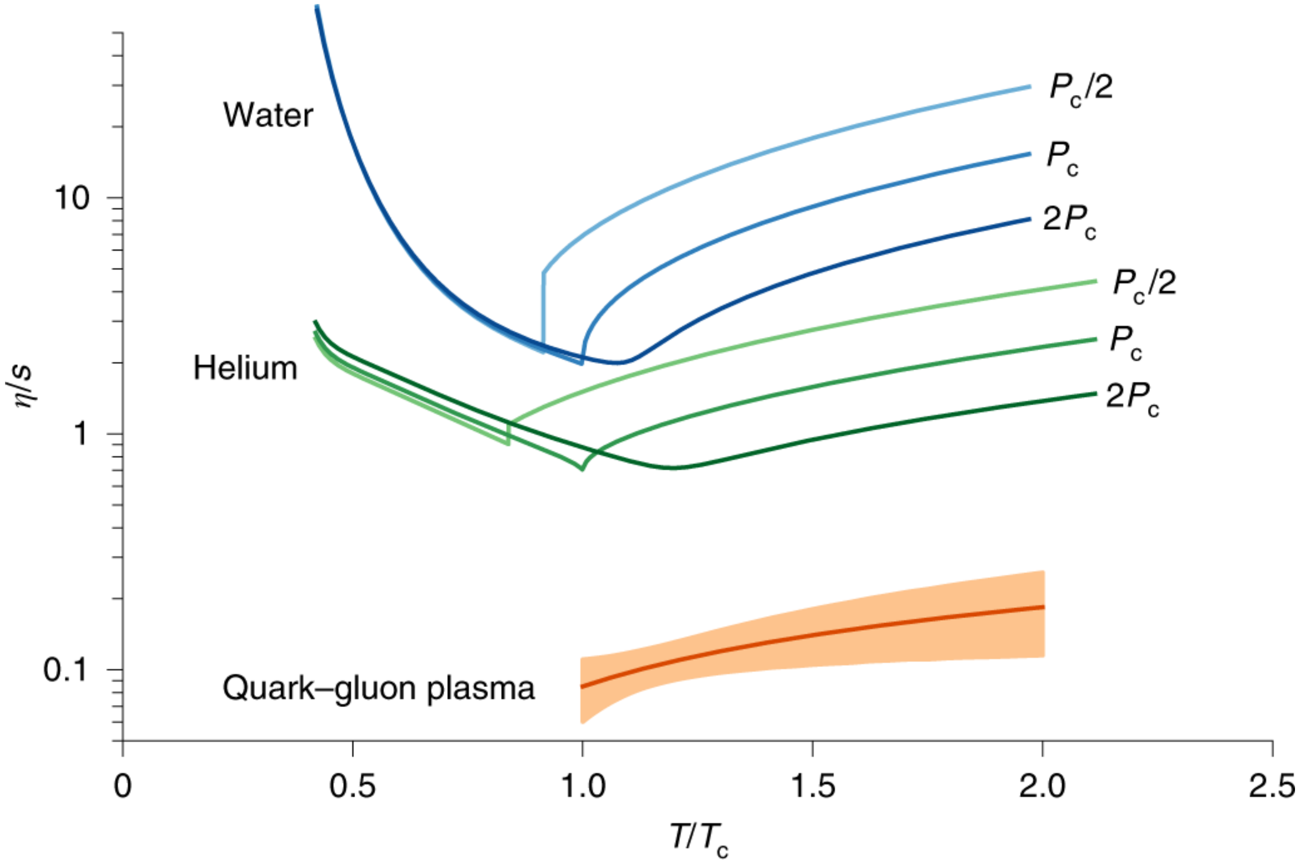
Thus the model connects early geometry → QGP fluid → final hadron spectra.



Nature Physics volume 15, 1113–1117 (2019)

Equation of state – Hydrodynamics – constraining the transport properties (data + Hydro model)

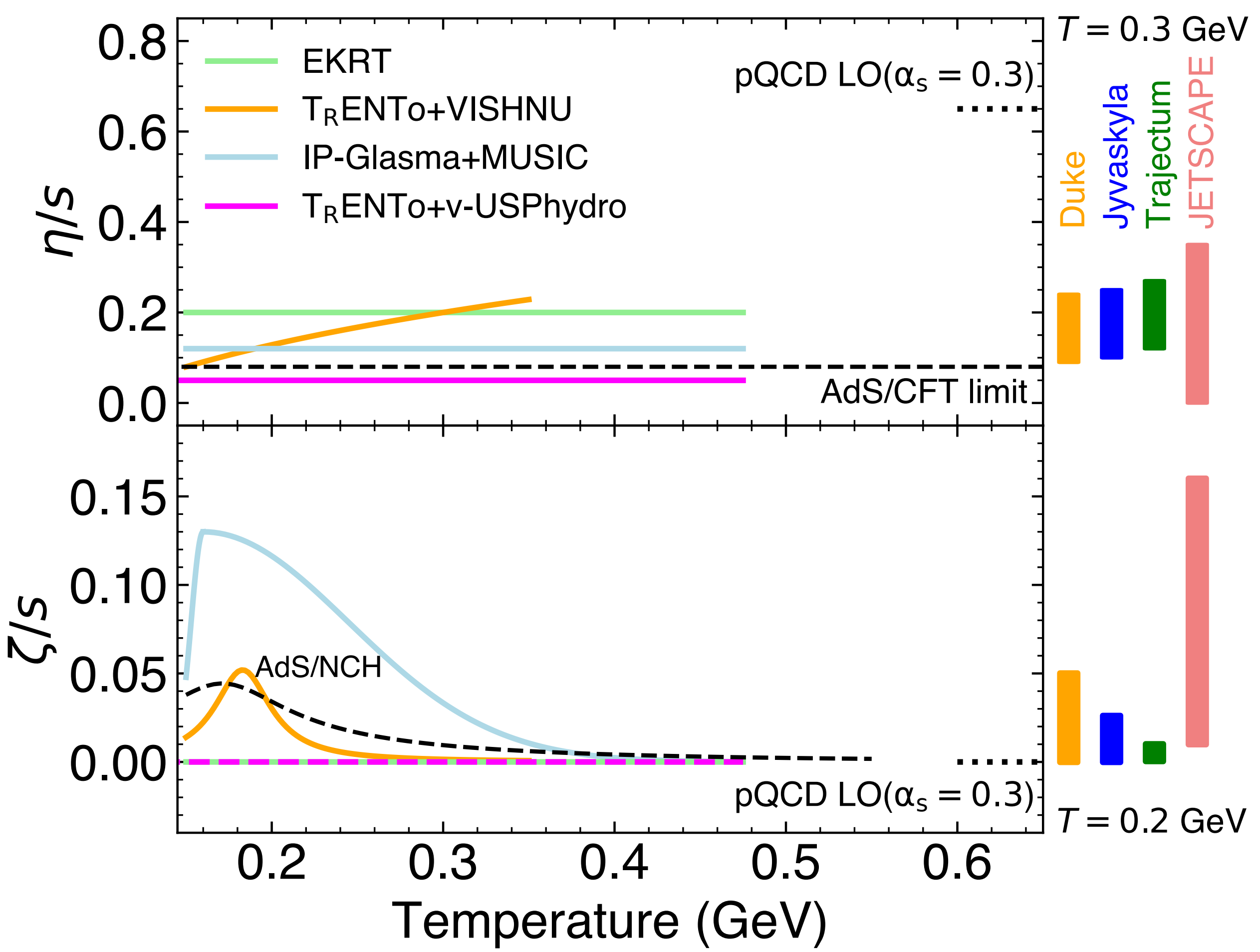


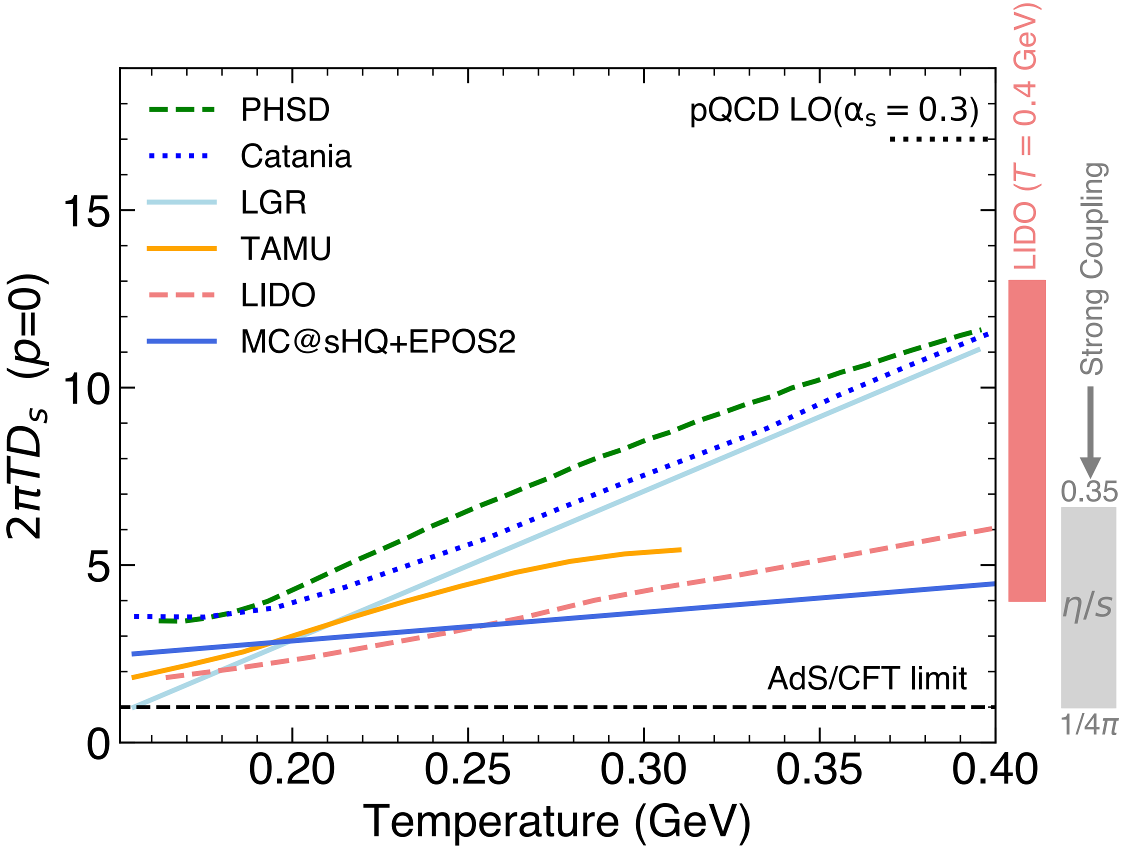


Nature Physics volume 15, 1113–1117 (2019)

Physical Picture: QGP created at RHIC/LHC behaves as an almost perfect fluid with η/s ≈ 0.08–0.2. Bulk viscosity peaks near the crossover temperature, indicating strong resistance to compression near the transition.

Equation of state – Hydrodynamics – constraining the transport properties of QCD matter



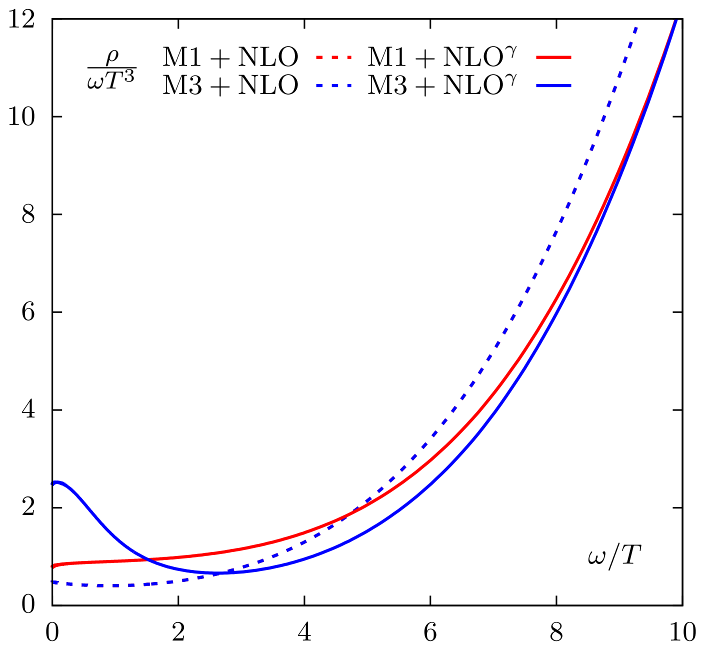


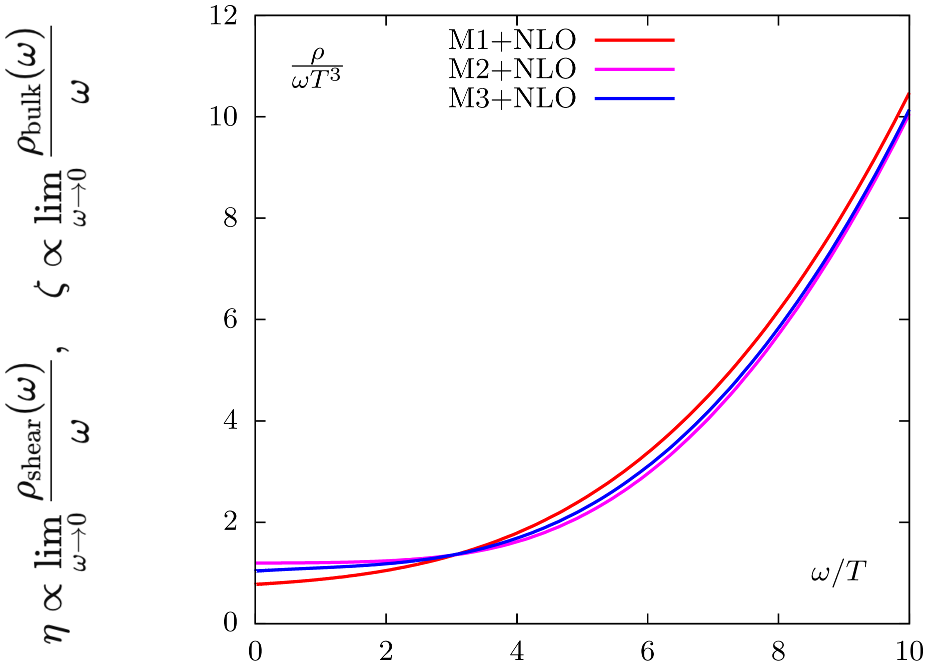
ALICE: Eur.Phys.J.C 84 (2024) 8, 813

LQCD: transport properties of QCD matter – pure glue

Methods:

1. Energy–momentum tensor (EMT) correlators.
2. Techniques to reduce noise and renormalization uncertainties.
3. Continuum and zero-flow-time extrapolations.
4. Extracted viscosities via Kubo relations.





Luis Altenkort et al., Phys.Rev.D 108 (2023) 014503

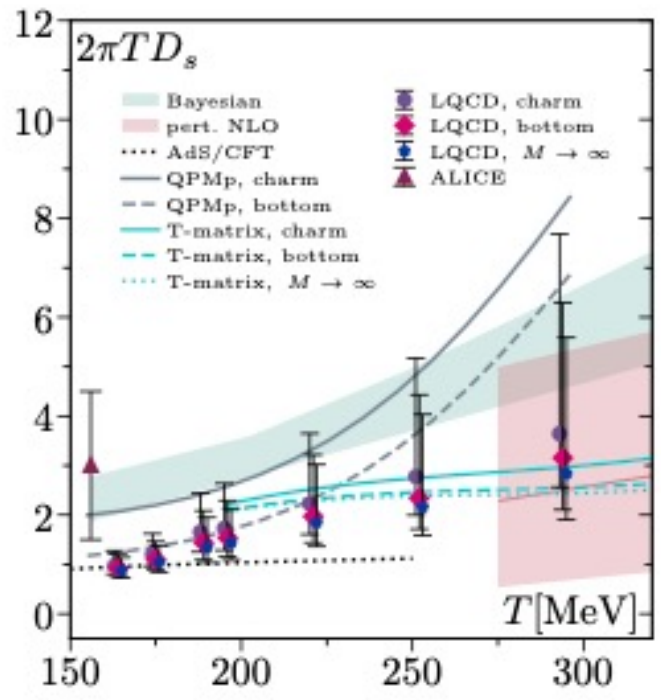
1. Shear viscosity to entropy ratio: η/s=0.15–0.48 → consistent with the "nearly perfect fluid" picture from heavy-ion data.
2. Bulk viscosity to entropy ratio: ζ/s=0.017–0.059 → small but nonzero, as expected for non-conformal QCD near Tc

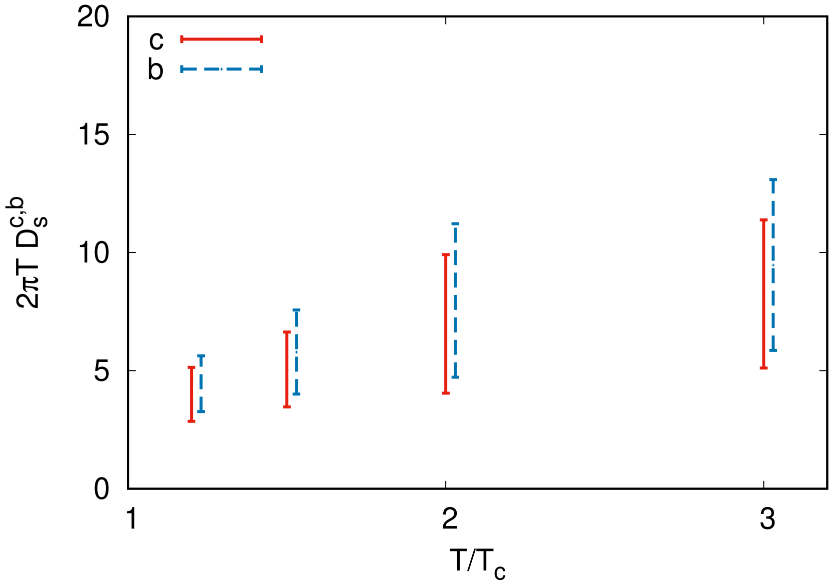
Confirms that the quark-gluon plasma behaves as a strongly coupled, low-viscosity fluid, validating interpretations from RHIC/LHC hydrodynamic analyses.

LQCD: transport properties of QCD matter – diffusion coefficient

HotQCD: JHEP09(2025)180

Method:
1. Lattice setup: (2+1)-flavor QCD with HISQ action, light-quark masses corresponding to $m_\pi \approx 160$MeV; extensive continuum and gradient-flow extrapolations to control UV and lattice artifacts.
2. Extraction method: Computed chromo-electric and chromo-magnetic correlators;

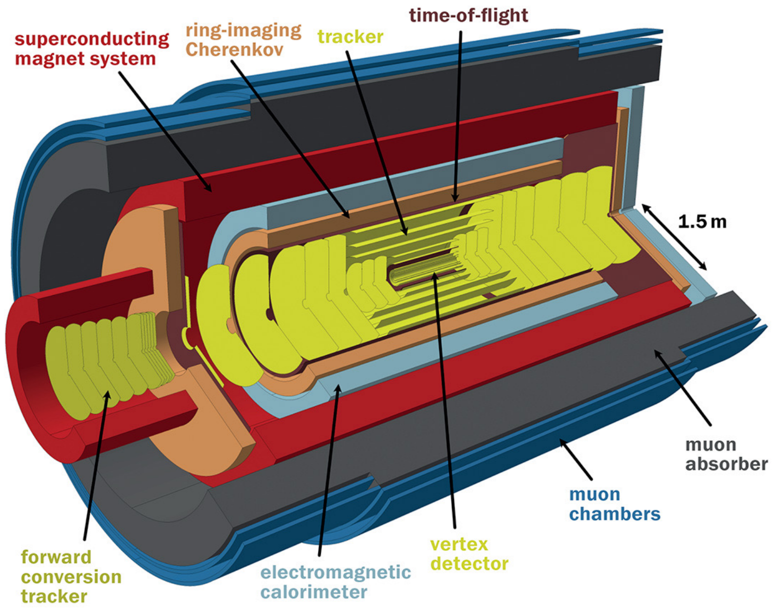


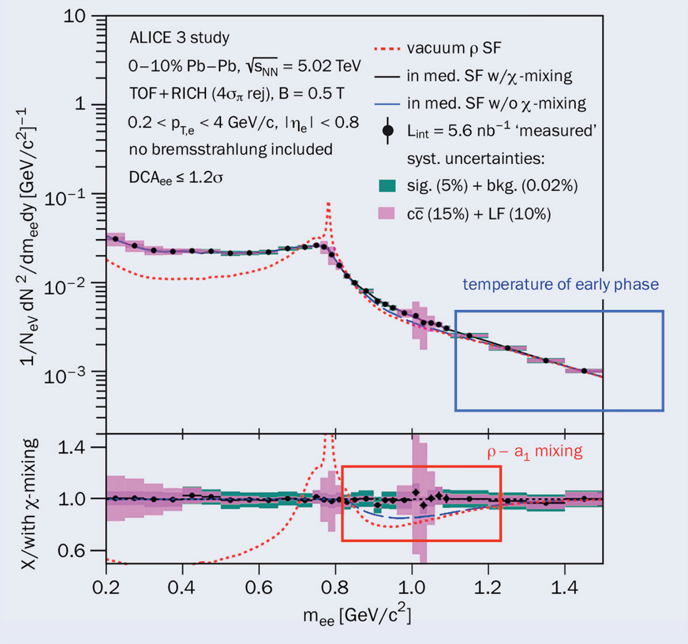


Debasish Banerjee et al., Nuclear Physics A 1038 (2023) 122721

1. The diffusion coefficient increases with temperature, consistent with a transition from a strongly to weakly coupled QGP.
2. Physical implication: Heavy quarks (charm, may be bottom) equilibrate rapidly in the QGP — confirming the strongly interacting, nearly perfect-fluid nature of the medium.

Transport properties – ALICE 3 - Conductivity





ALICE Collab. 2022 [arXiv:2211.02491.](arXiv:2211.02491)

1. Electrical conductivity of the QGP **determines the time evolution of electromagnetic fields** generated by spectator protons in non-central heavy-ion collisions.
2. Knowledge of the electrical conductivity is **important for the understanding of phenomena like the Chiral Magnetic Effect** related to the presence of these strong magnetic fields.
3. Major experimental challenge in measuring the electrical conductivity are accurate photons and dielectron spectra, may be accessible with ALICE 3

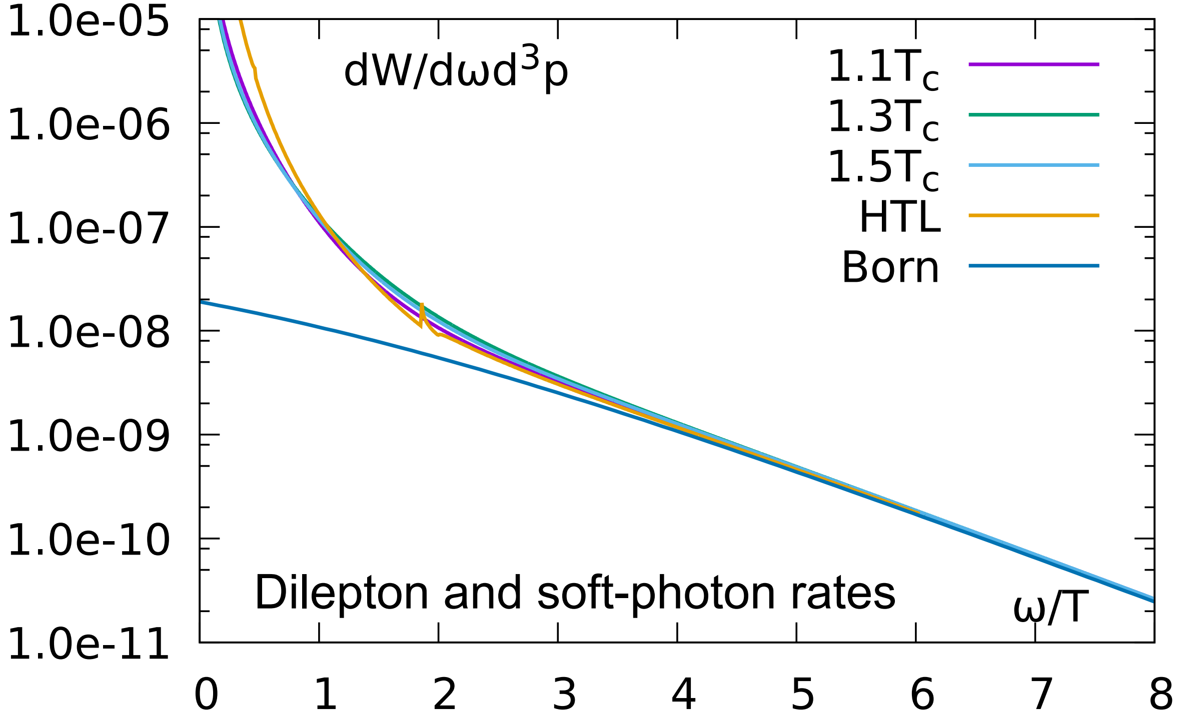
Dileptons are emitted via virtual photons coupling to quark currents, making their spectra sensitive to the QGP's electromagnetic response.

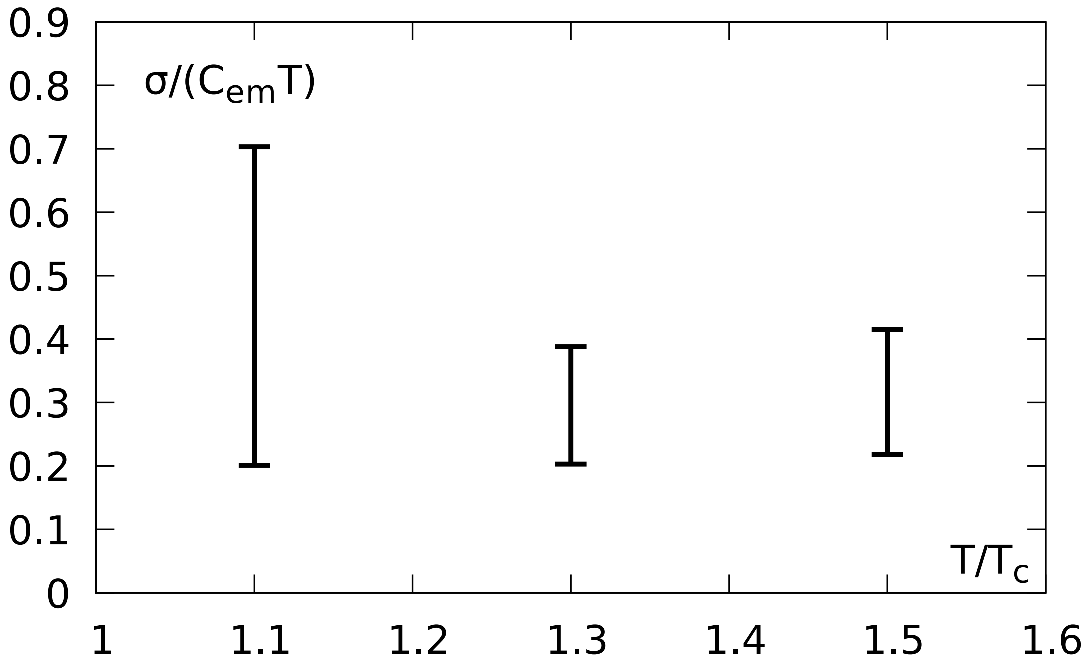
The low-mass dilepton yield probes the vector current spectral function, whose low-frequency limit defines the electrical conductivity (σ).

Thus, enhanced soft dilepton emission signals higher σ and longer-lived electromagnetic currents in the plasma.

LQCD: transport properties of QCD matter – conductivity

H.T. Ding et al., Phys. Rev. D 94, 034504 (2016)





Lattice-QCD study determines the vector spectral function, thermal dilepton rate, and electrical conductivity (σ/T) of QGP in quenched QCD at T = 1.1 Tc, 1.3 Tc, 1.5 Tc. Using continuum-extrapolated vector correlators with clover-improved Wilson fermions.

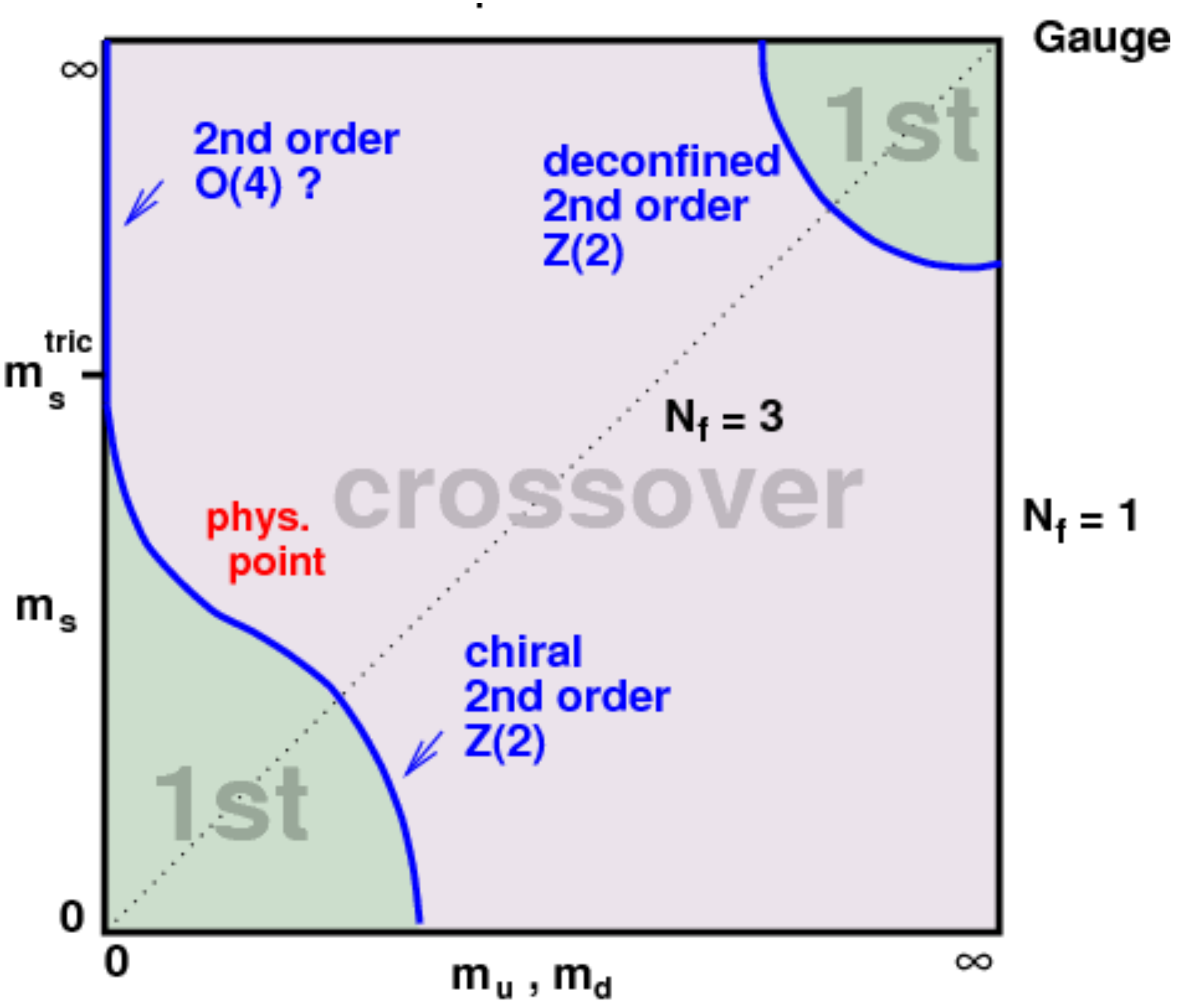
Extracted **electrical conductivity** lies in the range σ/T ≈ (0.2 – 0.7) C_{em} at 1.1 T_c. and ≈ (0.2 – 0.4) C_{em} at 1.3–1.5 T_c.

O(3−10) fm/c electromagnetic lifetimes in the QGP

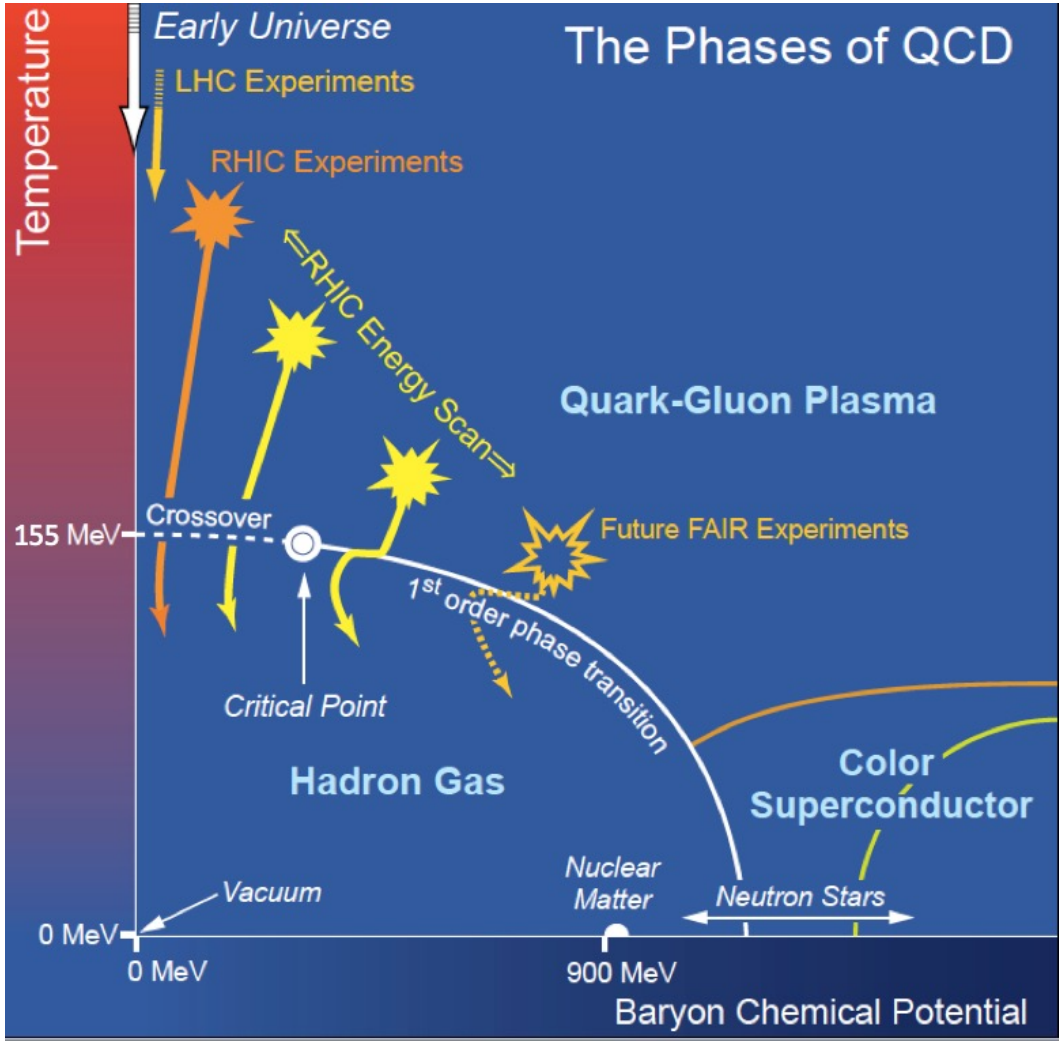
Uniform **E** decays with $\tau_E \simeq \frac{1}{\sigma}$ Magnetic-field diffusion time $\tau_B \simeq \sigma L^2 \quad (\mu \simeq 1)$

QCD Phase diagram

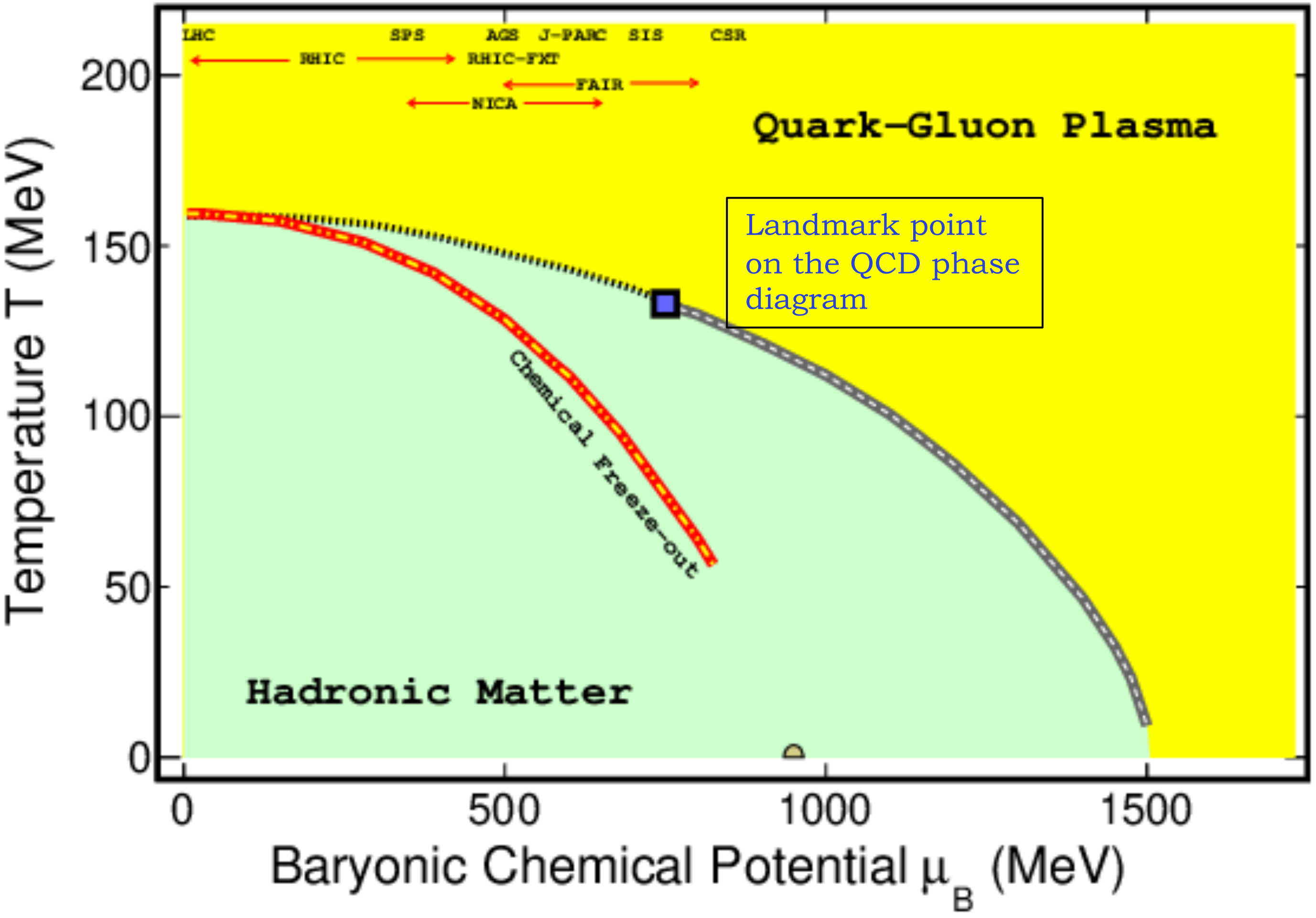
What theory would also like to pursue

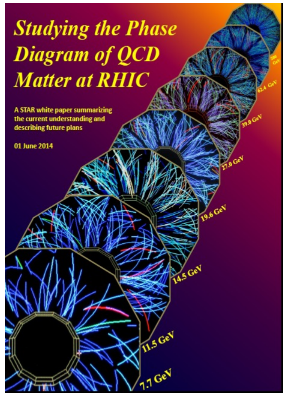


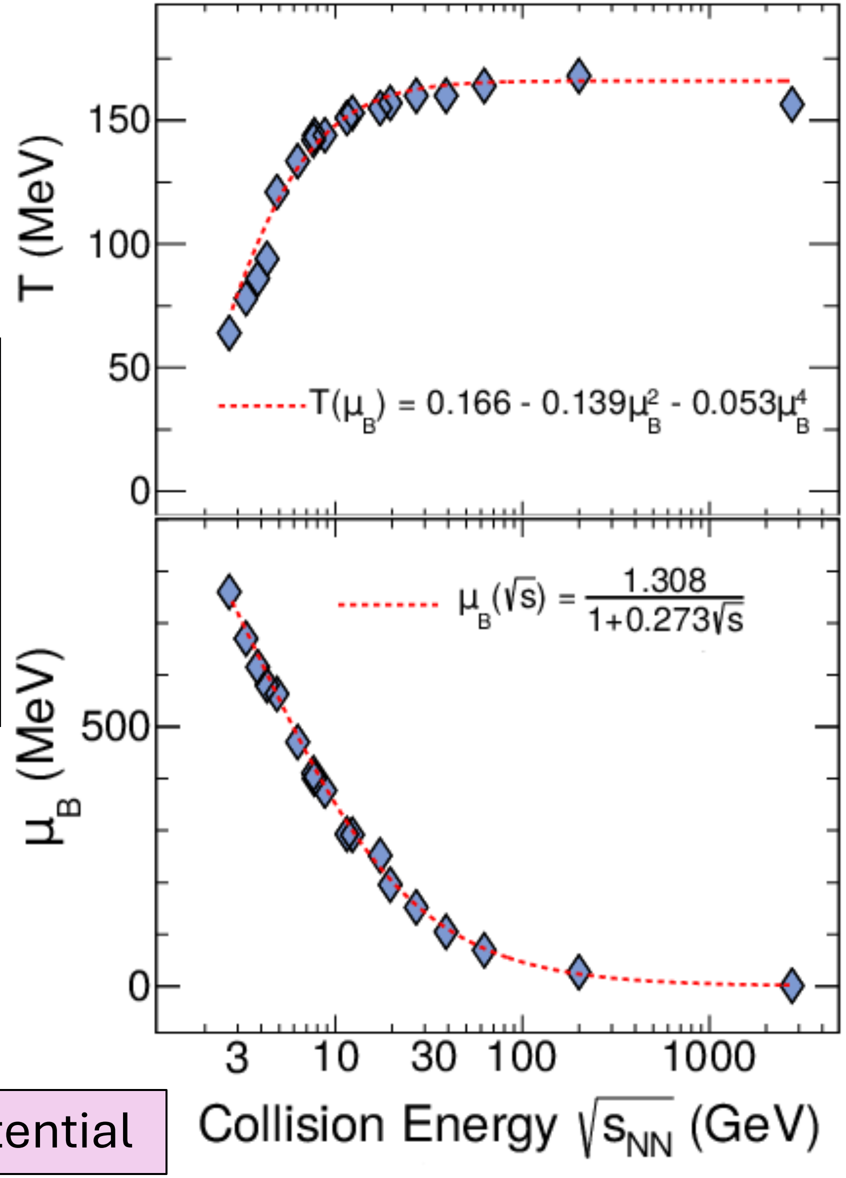
What is experimentally possible



QCD Phase Diagram and Critical Point Search

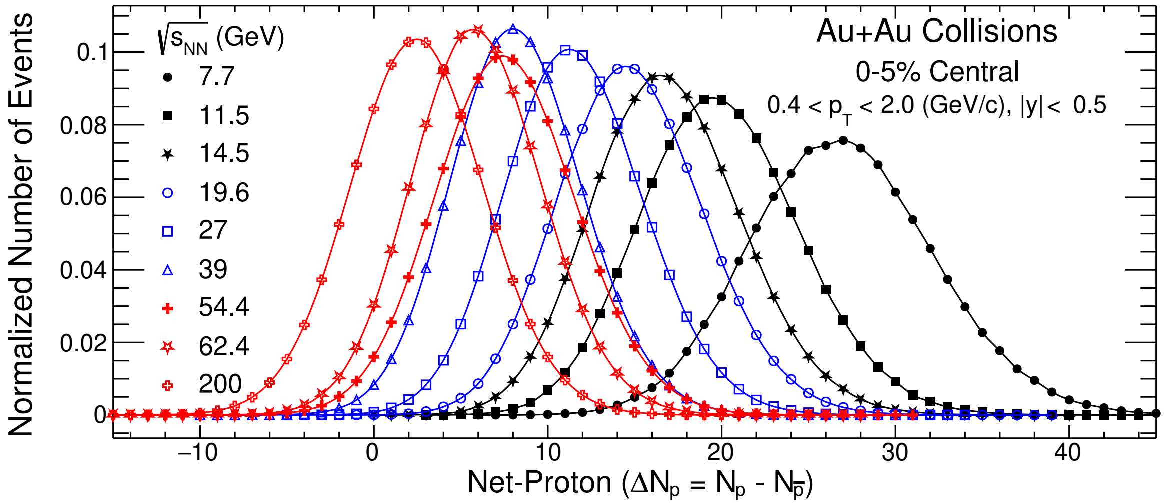


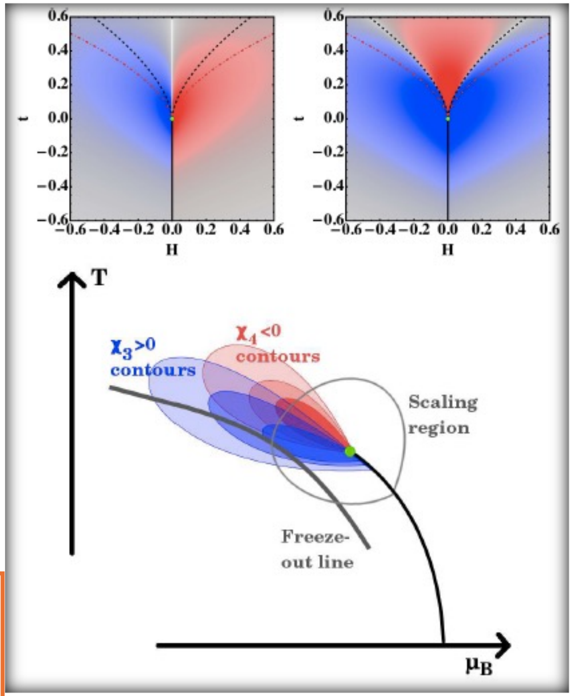




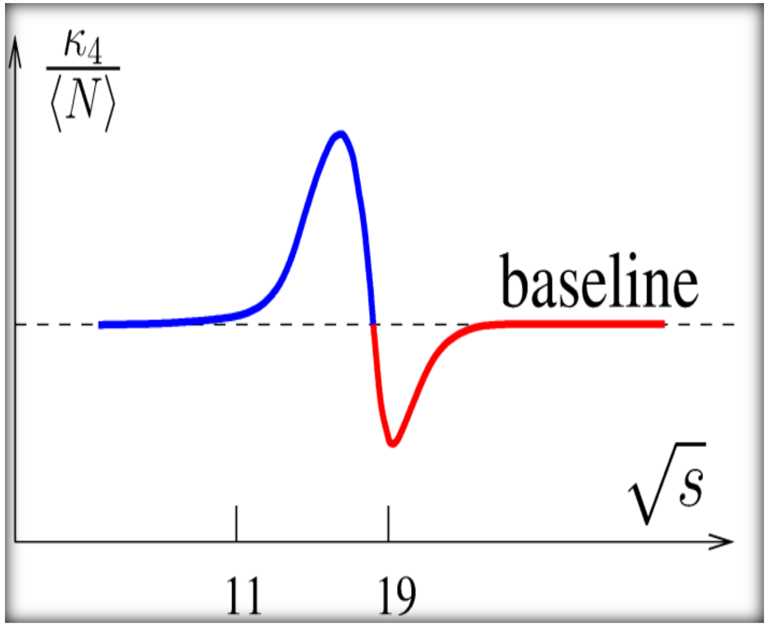
Varying collision energy varies the temperature and baryon chemical potential

QCD Phase Diagram : Observable





PRL 102, 032301 (2009)



PRL 107, 052301 (2011)

- $C_2 \sim \xi^2 \qquad C_4 \sim \xi^7$
- $\frac{\chi_q^{(4)}}{\chi_q^{(2)}} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^{(3)}}{\chi_q^{(2)}} = S\sigma = \frac{C_{3,q}}{C_{2,q}}$

Caveats: Lattice and experiments

(1)QCD critical point:non-monotonic variations

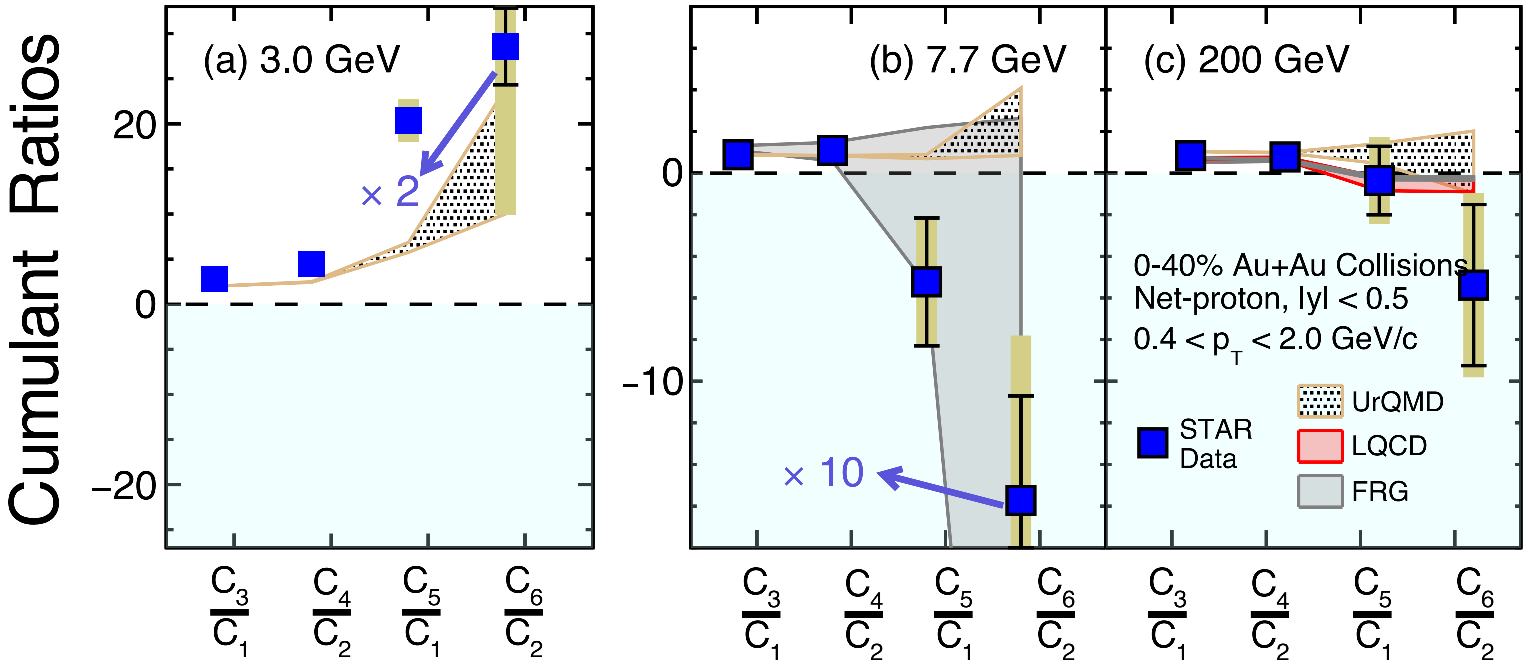
(2) Exact shape depends on the location of freeze-out with respect to the location of CP - Critical Region

Experimental data and QCD thermodynamics

LQCD: Ordering of susceptibility ratios (Net-baryon)

$$\frac{\chi_6^B(T,\vec{\mu})}{\chi_2^B(T,\vec{\mu})} < \frac{\chi_5^B(T,\vec{\mu})}{\chi_1^B(T,\vec{\mu})} < \frac{\chi_4^B(T,\vec{\mu})}{\chi_2^B(T,\vec{\mu})} < \frac{\chi_3^B(T,\vec{\mu})}{\chi_1^B(T,\vec{\mu})}$$

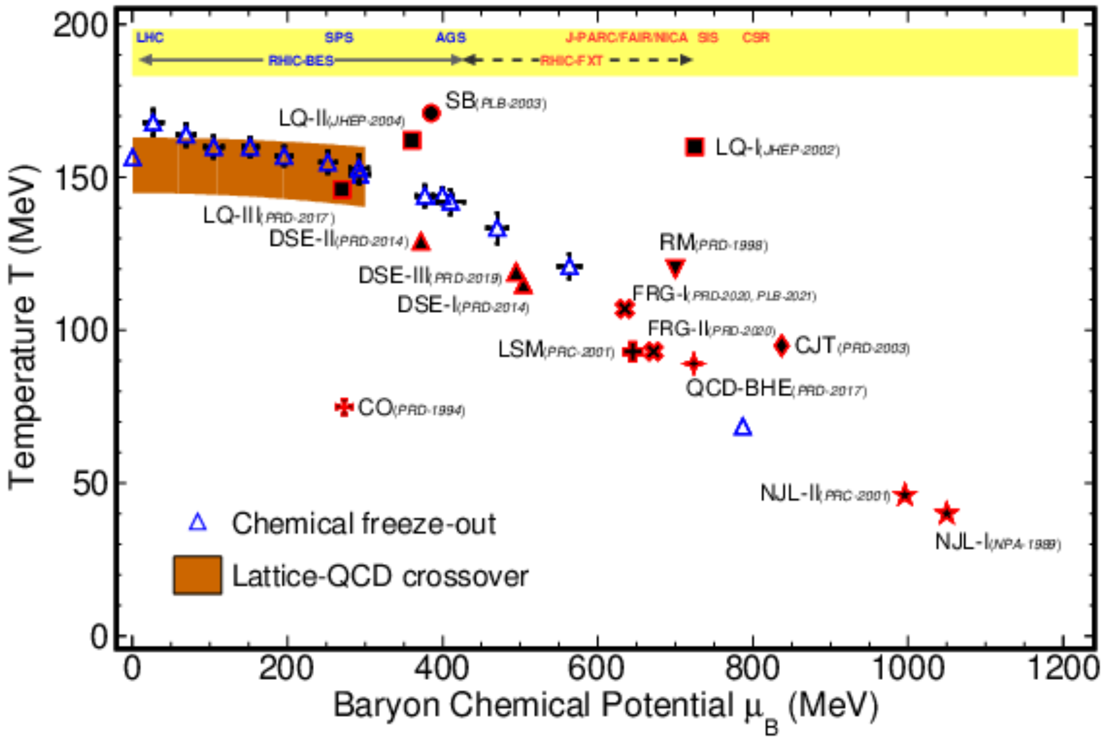
HotQCD: PHYS. REV. D 101, 074502 (2020)



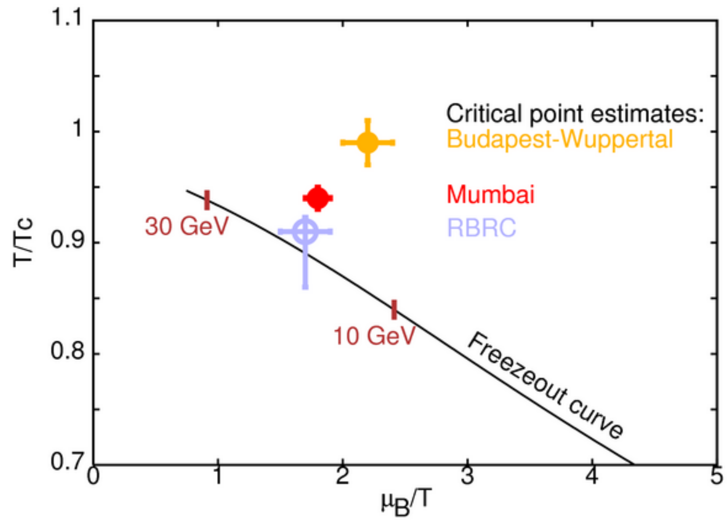
STAR: PRL 130 , 82301 (2023)
STAR: PRL128, 202303 (2022)
STAR: PRL 127, 262301 (2021)
STAR: PRL 126, 092301 (2021)
STAR: PRC 104, 024902 (2021)

- Ordering of ratios as per LQCD thermodynamics observed for collision energies > 7 GeV
- Reverse ordering observed for collision energy of 3.0 GeV.

Critical point search – some years back



Prog.Part.Nucl.Phys. 125 (2022) 103960



STAR: PRL 130 , 82301 (2023)
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STAR: PRL 127, 262301 (2021)
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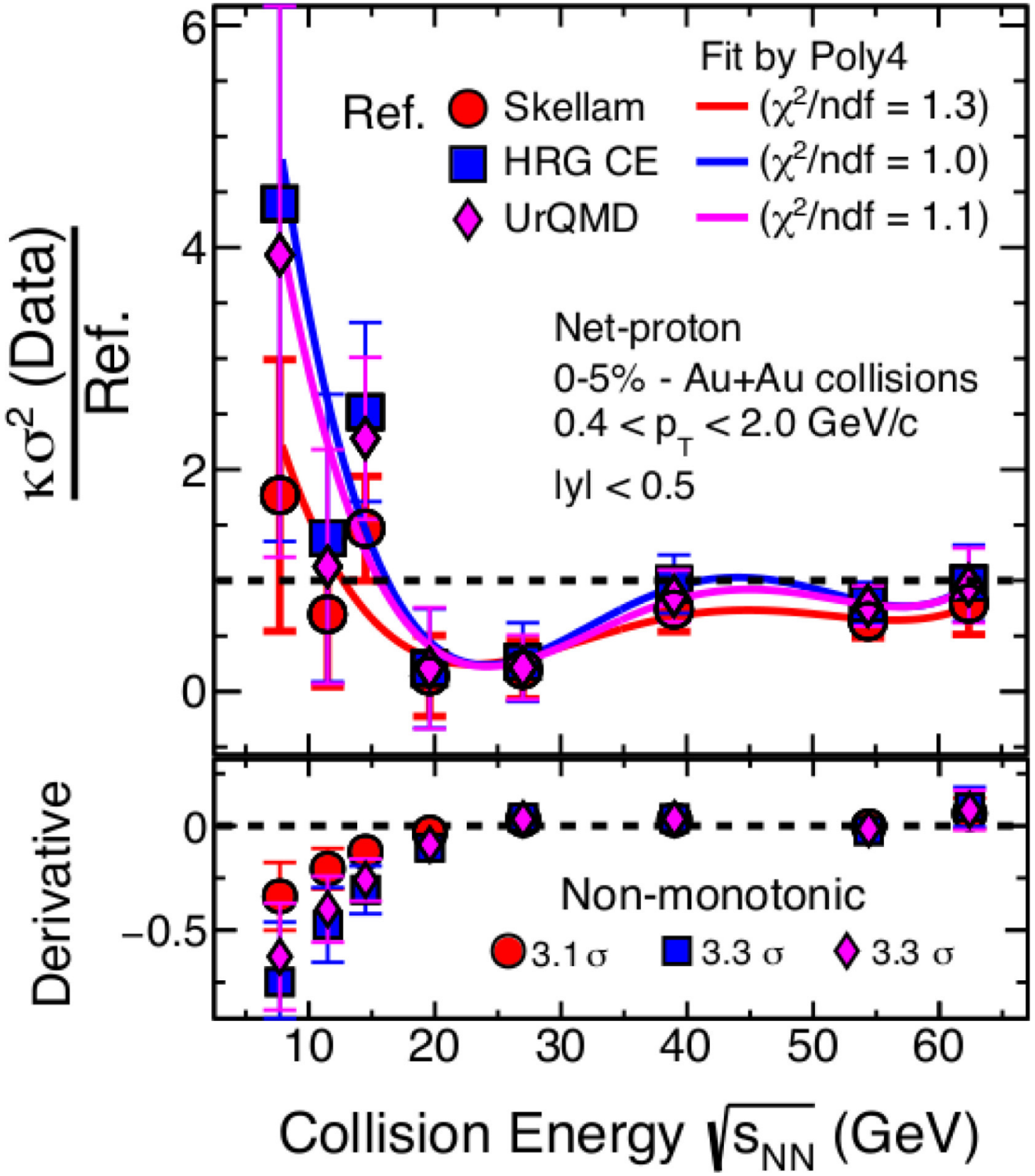
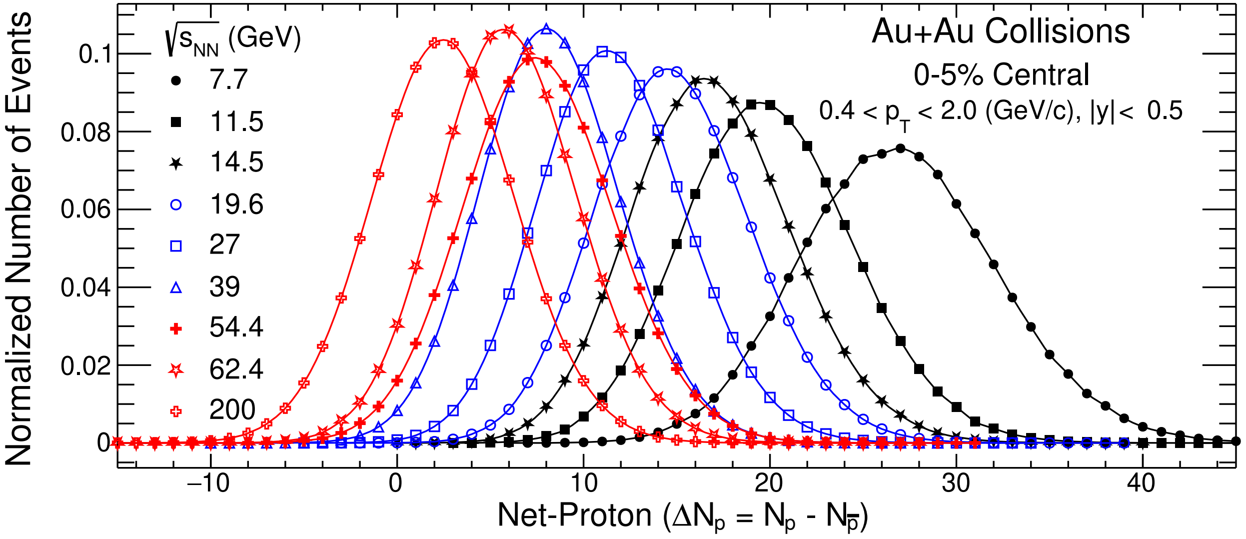
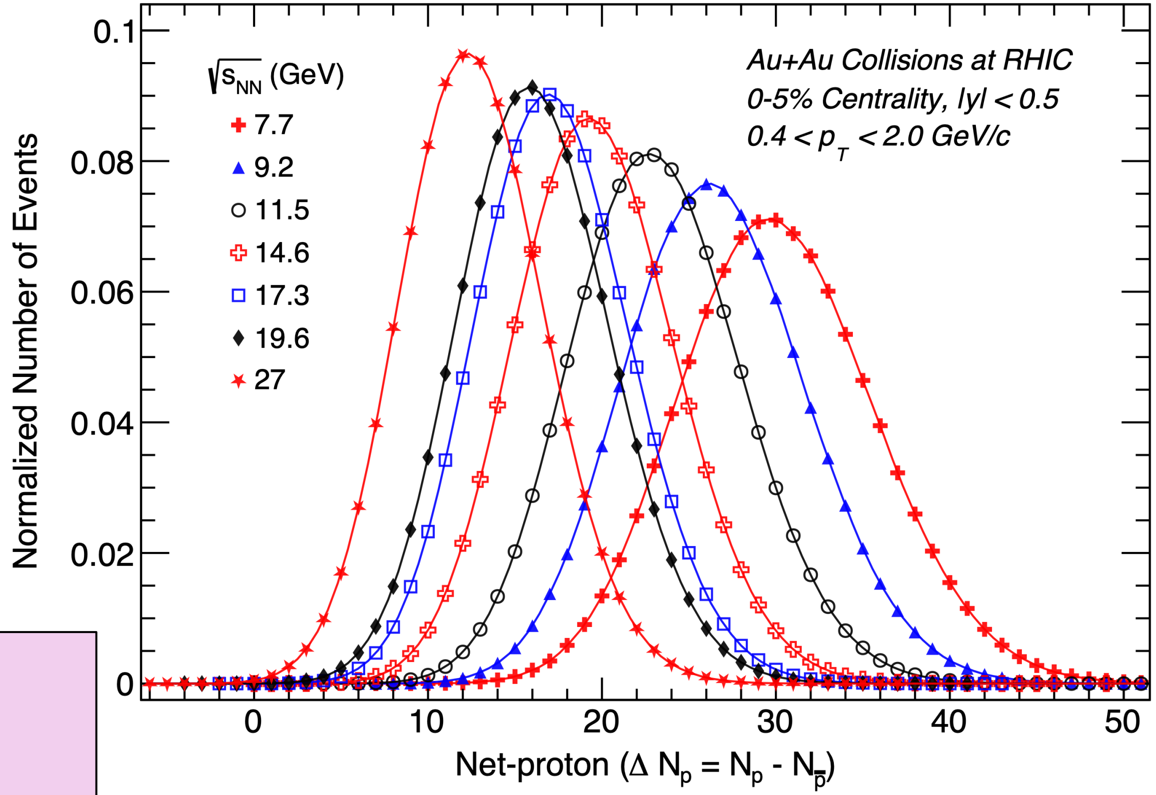
STAR: PRC 104, 024902 (2021)



Beam Energy Scan Phase-I vs. Phase-II



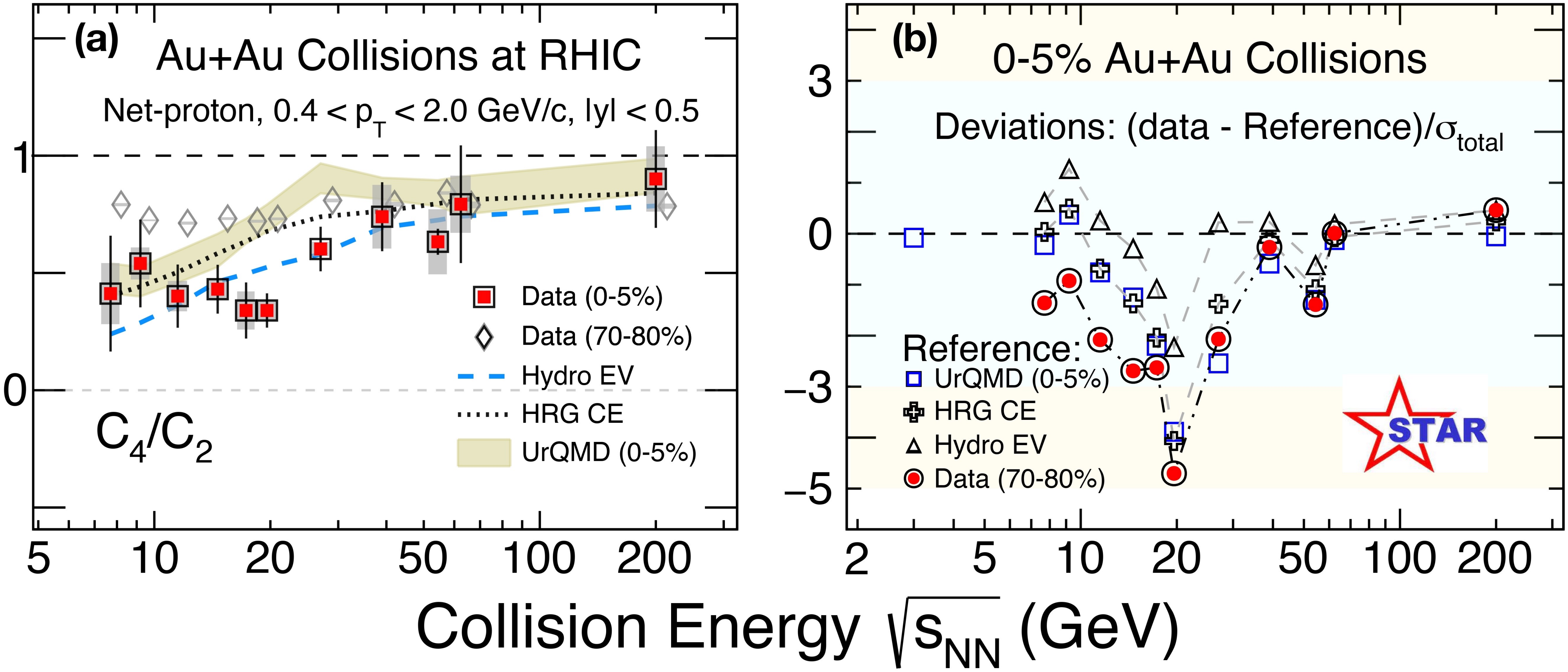
STAR: Physical Review Letters 2010 & 2014



STAR: PRL 135, 142301 (2025)

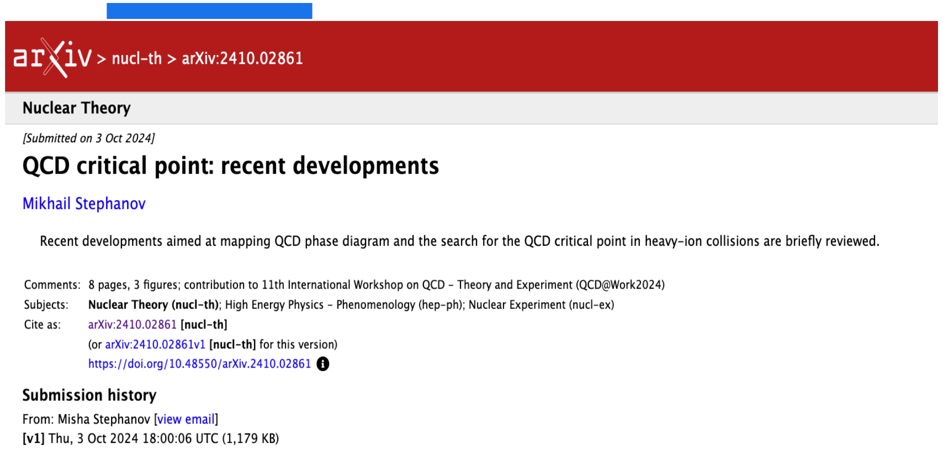
- 10-18-fold increase in statistics
- Two new collision energies
- Detector upgrades in STAR: Better control on centrality resolution and volume fluctuations

QCD critical point search



STAR: PRL 135, 142301 (2025)

Establishing the QCD critical point


arXiv > nucl-th > arXiv:2410.02861

Nuclear Theory

[Submitted on 3 Oct 2024]

QCD critical point: recent developments

Mikhail Stephanov

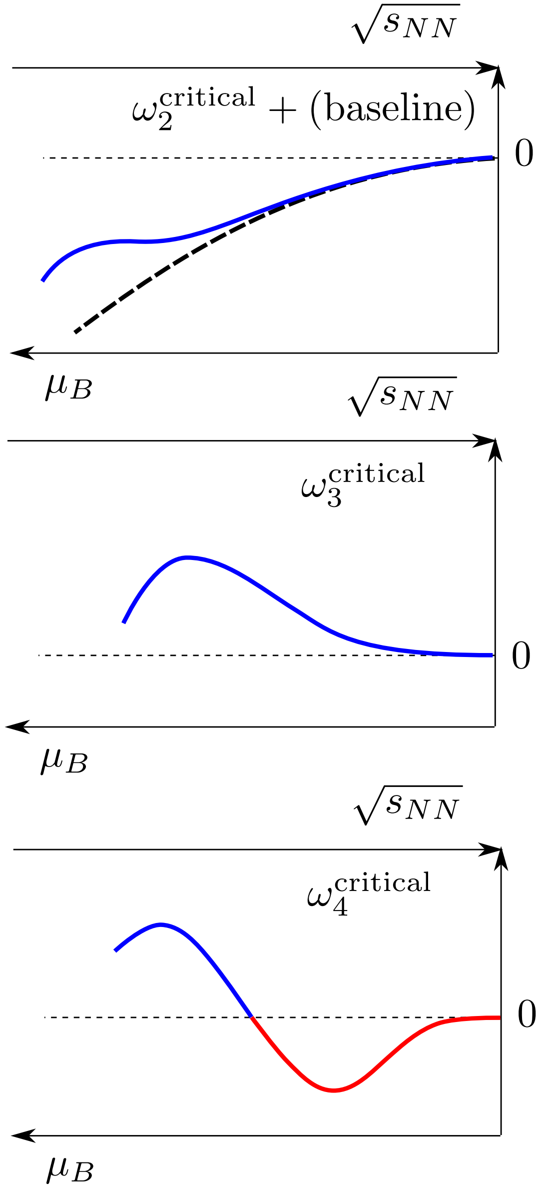
Recent developments aimed at mapping QCD phase diagram and the search for the QCD critical point in heavy-ion collisions are briefly reviewed.

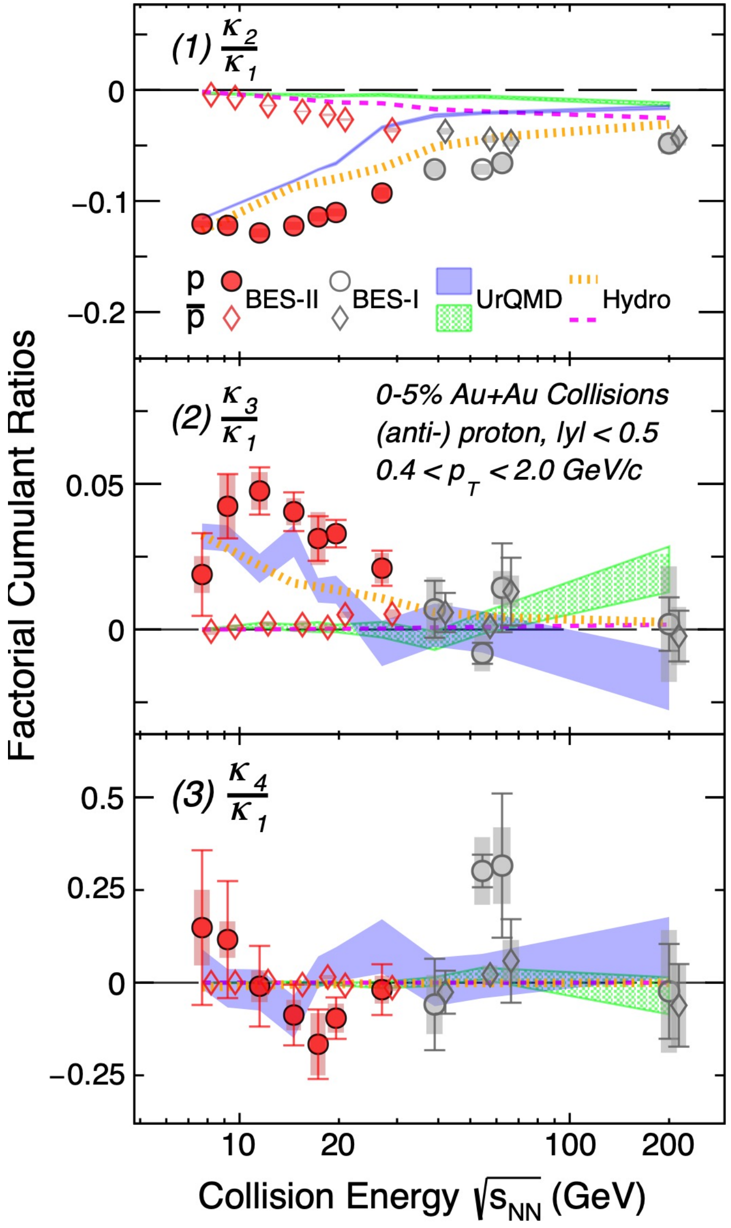
Comments: 8 pages, 3 figures; contribution to 11th International Workshop on QCD - Theory and Experiment (QCD@Work2024)
Subjects: Nuclear Theory (nucl-th); High Energy Physics - Phenomenology (hep-ph); Nuclear Experiment (nucl-ex)
Cite as: arXiv:2410.02861 [nucl-th]
(or arXiv:2410.02861v1 [nucl-th] for this version)
https://doi.org/10.48550/arXiv.2410.02861

Submission history
From: Misha Stephanov [view email]
[v1] Thu, 3 Oct 2024 18:00:06 UTC (1,179 KB)

CP based model in qualitative agreement with measurements

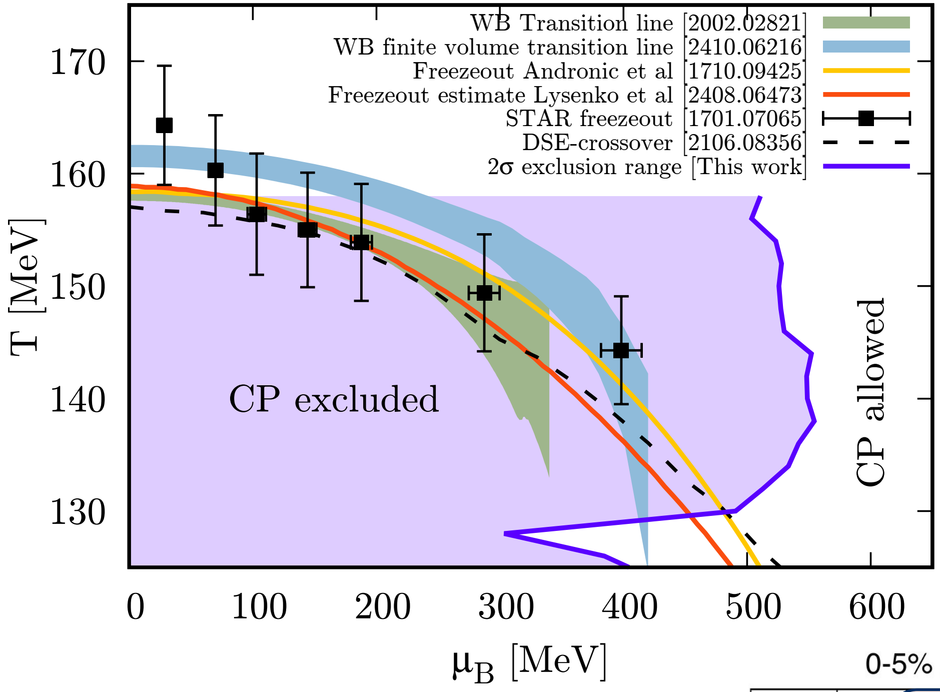
Caveats
1. Choice of the baseline
2. Based on Ising model (singular & regular)
3. Does not tell the location of CP





QCD phase diagram and critical point search

Szabolcs Borsanyi, arXiv:2502.10267

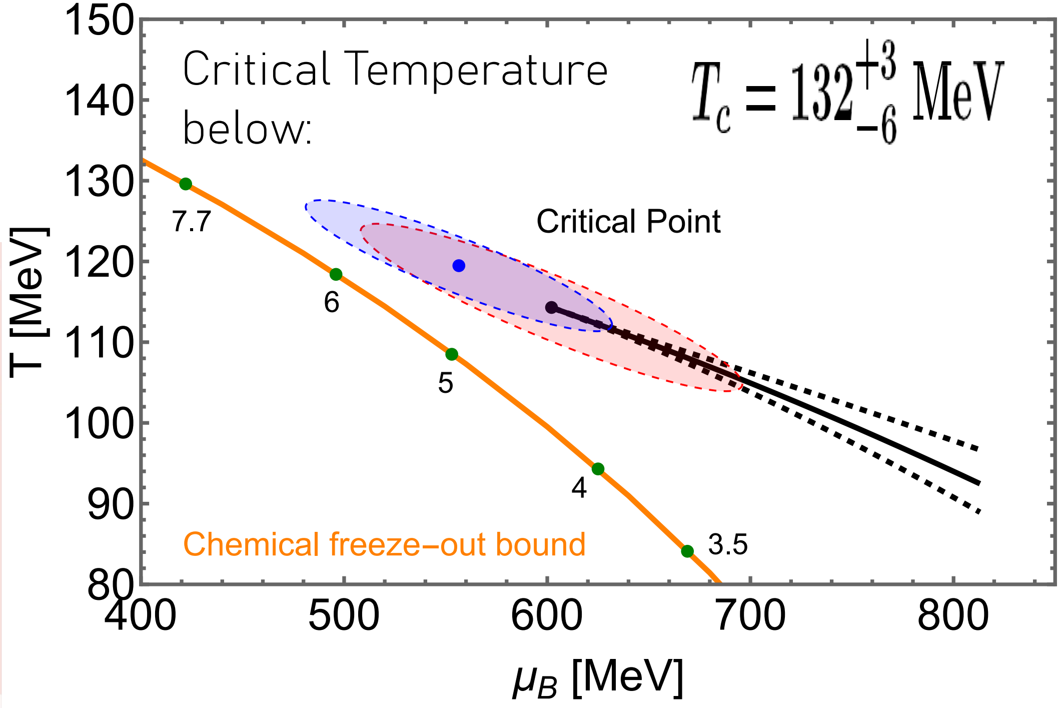


Indicates no CP:

$$\mu_B/T \lesssim 2.5$$

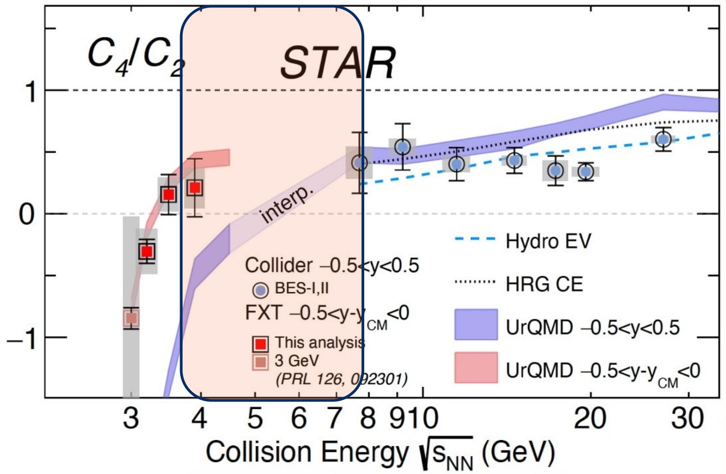
Idea: If multiple constant-entropy contours meet or cross, it means the entropy becomes multi-valued — a thermodynamic signal of a first-order transition. The location where contours start to merge corresponds to the critical endpoint.

Hitansh Shah et al., arXiv:2410.16206 [hep-ph]



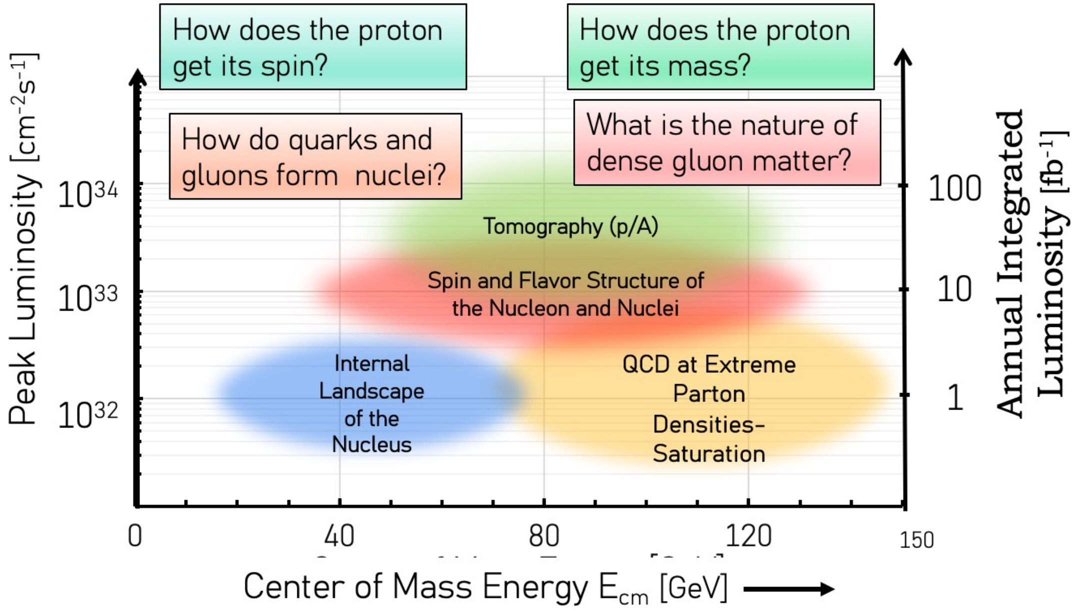
20 GeV deviation not understood. Experiments also focusing on the region 4-7 GeV

0-5% Au+Au Collisions at RHIC



Electron ion collider – exotic hadron studies

1. EIC provides a new environment to study non-conventional hadrons (tetraquarks, pentaquarks, hybrids, glueballs) via photo- and electro-production with unprecedented luminosity ($\sim 10^{34}$ cm^{-2} s^{-1}).
2. Builds on discoveries at LHCb, BESIII, Belle II, and complements hadron-beam programs (PANDA, JLab12).
3. Probes QCD confinement and gluonic excitations in a clean lepton–hadron environment.



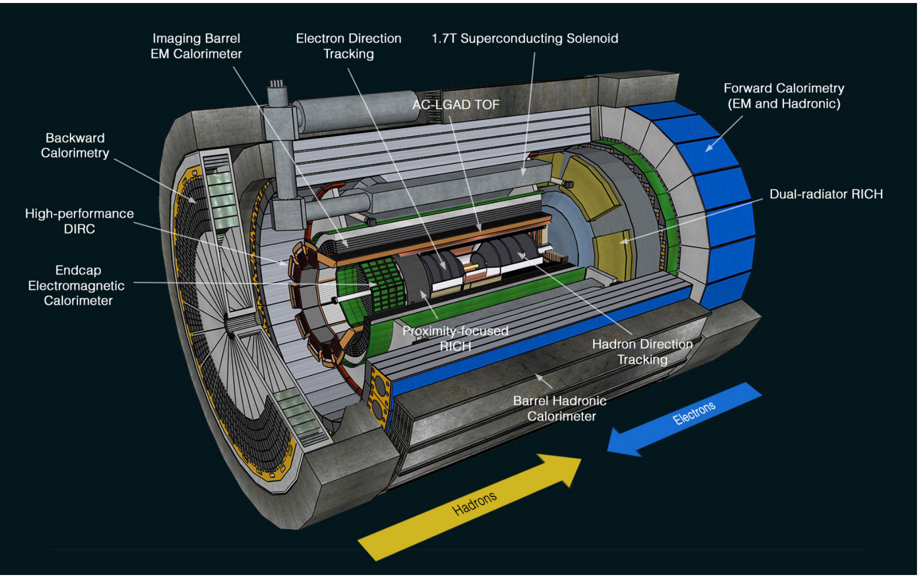
"Precision Studies of QCD in the Low-Energy Domain of the EIC," arXiv:2211.15746 (2023).

Production Channels & Methods:

1. Photoproduction: quasi-real photons via electron scattering at small angles (tagged electrons).
2. Electroproduction: virtual-photon processes accessing Q^2-dependence and transition form factors.
3. JPAC amplitude modeling and other frameworks used for cross-section estimates.
4. Expected production cross-sections comparable to J/ψ photoproduction; feasibility studies ongoing.

State	J^PC	Mass (GeV)	Typical decay modes	Experimental Status
$\pi_1(1400)$, $\pi_1(1600)$	1^{-+}	1.4 – 1.7	ηπ, η'π, ρπ	light hybrid candidates
X(3872)	1^{++}	3.872	J/ψ ππ	charmonium-like
Z_c(3900)	1^{+-}	3.9	J/ψ π	charged exotic
Y(4260)	1^{--}	4.26	J/ψ ππ	vector exotic
Glueball candidates	0^{++}, 2^{++}	1.7 – 2.4	multi-hadron	lattice-motivated

Electron ion collider – Indian participation



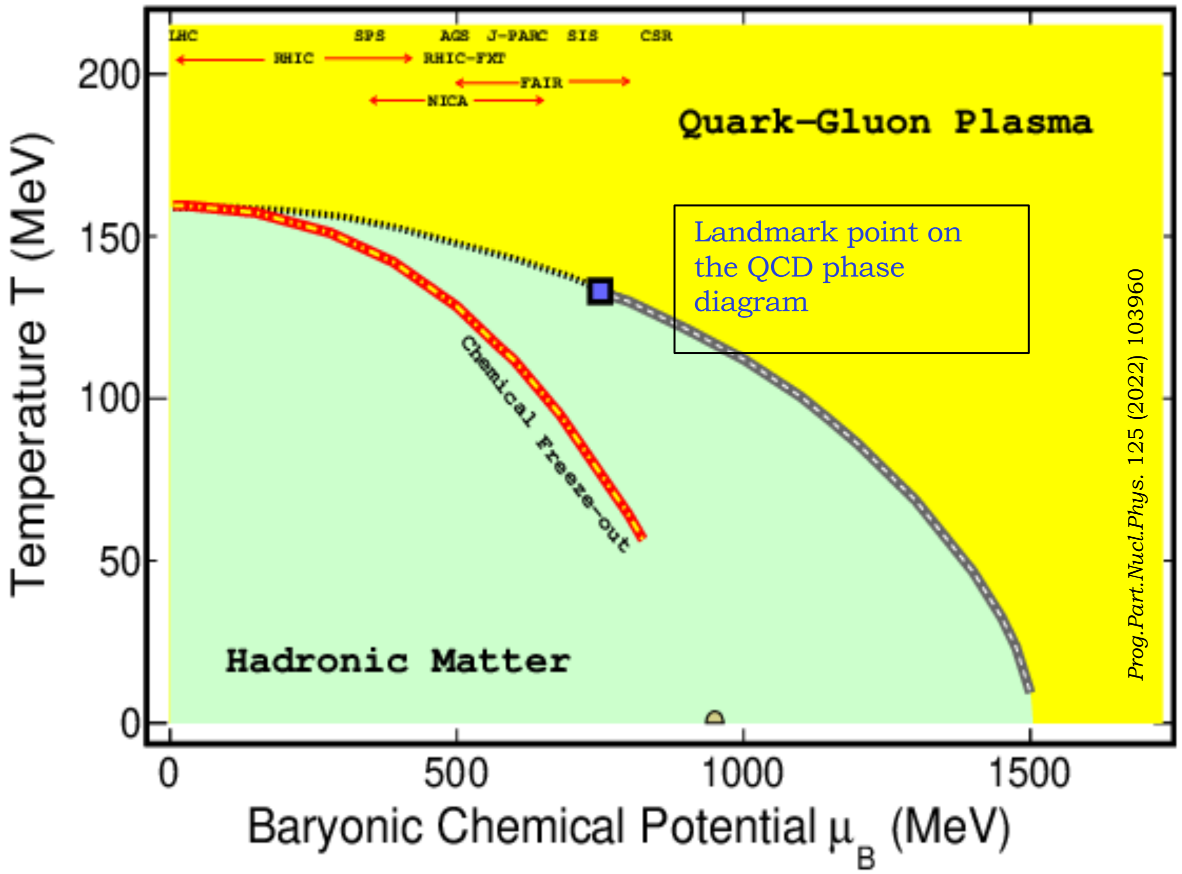
ePIC now has 171 institutions from 24+ countries

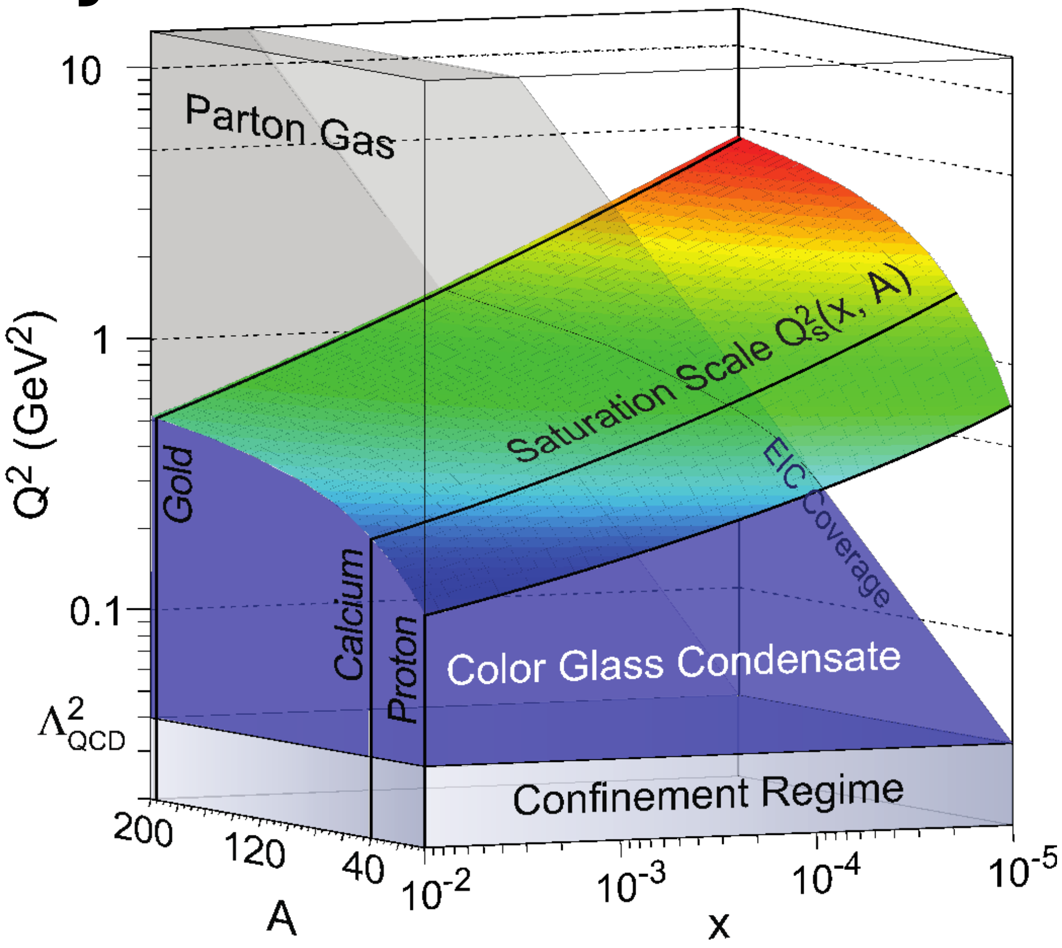
India has now formed an **India–EIC collaboration** to participate in the scientific program of the Electron–Ion Collider. In parallel, our **lattice QCD colleagues in India** have strong expertise in **studying exotic hadrons**, and they will contribute significantly to this effort, complementing the experimental initiatives.

EIC-India-Experiment
Aligarh Muslim University
Banaras Hindu University
Central University of Karnataka
Central University of Tamil Nadu
NIT Jalandhar
Indian Institute of Technology (IIT) Madras
IISER, Berhampur
IISER Tirupati
Indian Institute of Technology (IIT) Bombay
Indian Institute of Technology (IIT) Delhi
Indian Institute of Technology (IIT) Indore
Indian Institute of Technology (IIT) Patna
Institute of Physics, Bhubaneswar
MNIT Jaipur
NISER
Panjab University Chandigarh
Ramaiah University of Applied Sciences

EIC-India-Theory
Aligarh Muslim University
Indian Institute of Technology (IIT), Bombay
Indian Institute of Technology (IIT), Kanpur
Indian Institute of Science Education and Research (IISER), Berhampur
National Institute of Science Education and Research (NISER), Jatni
National Institute of Technology (NIT), Kurukshetra
National Institute of Technology (NIT), Jalandhar
Tata Institute of Fundamental Research (TIFR), Mumbai
The Institute of Mathematical Sciences (IMSc), Chennai
Vellore Institute of Technology (VIT), Vellore

Summary





Quest to establish the phase diagrams of cold and hot-dense QCD continues. It is testing QCD as a theory of strong interactions at extremes. Lattice QCD and Experiments have to work closely.

Acknowledgements

Dibyendu Bala, Frithjof Karsch, Heng-Tong Ding, Jean-Yves Ollitrault, Krishna Rajagopal, Misha Stephanov, Nilmani Mathur, Rajiv Gavai, Sourendu Gupta and Volker Koch.

Thanks for this opportunity

Acknowledgements