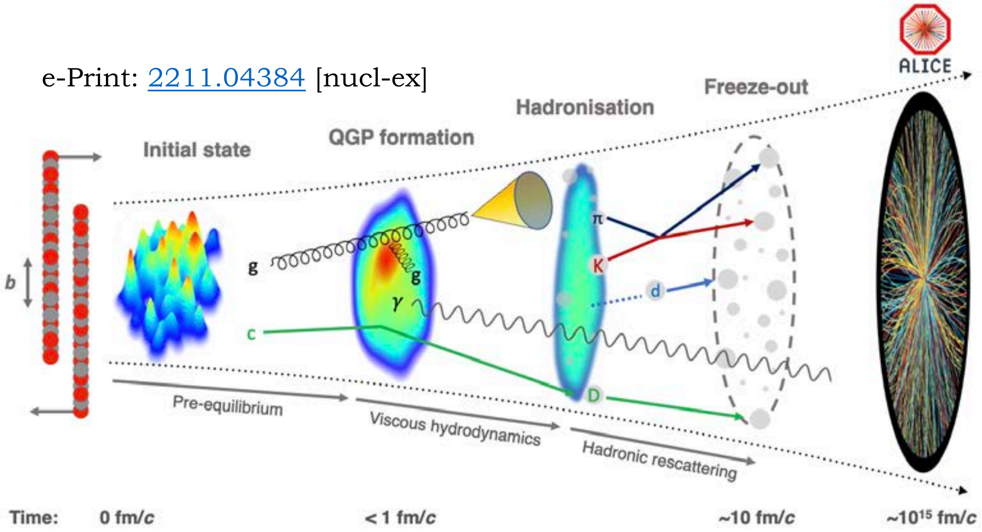
Heavy-Ion Physics (MSV2035)

Bedanga Mohanty
National Institute of Science Education and Research

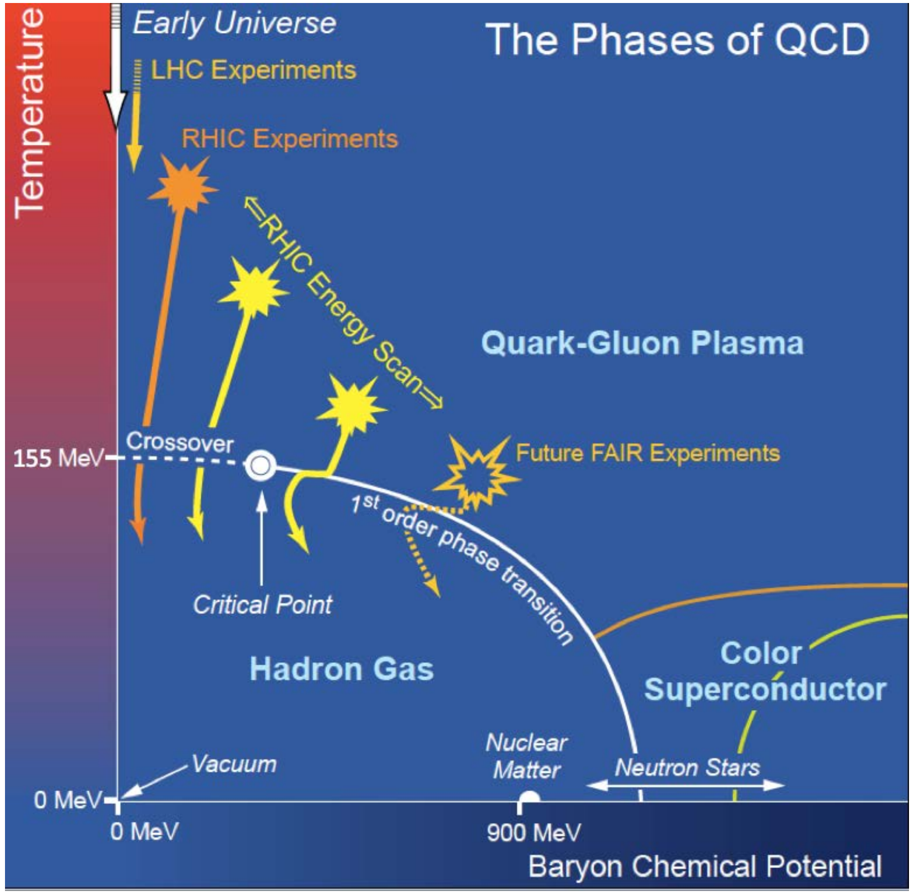
Studying emergent properties of strong interactions (QCD) using relativistic heavy-ion collisions

e-Print: 2211.04384 [nucl-ex]



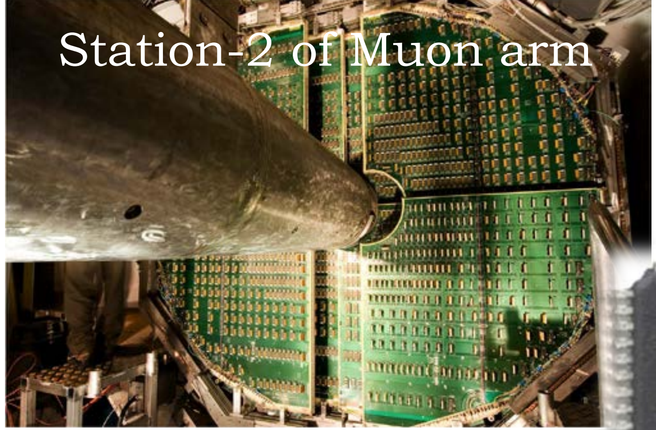
System

- Femto scale in time and
- Femto scale in size



US Long range plan

- QCD transitions: De-confinement & Chiral Symmetry restoration
- Deconfined state of quarks and gluons - Quark Gluon Plasma (QGP)
- Properties of QGP: viscosity, opacity, diffusion coefficient, conductivity, polarization and vorticity.
- Phase diagram of QCD – Thermalization, two phases, Crossover, first order and critical point.



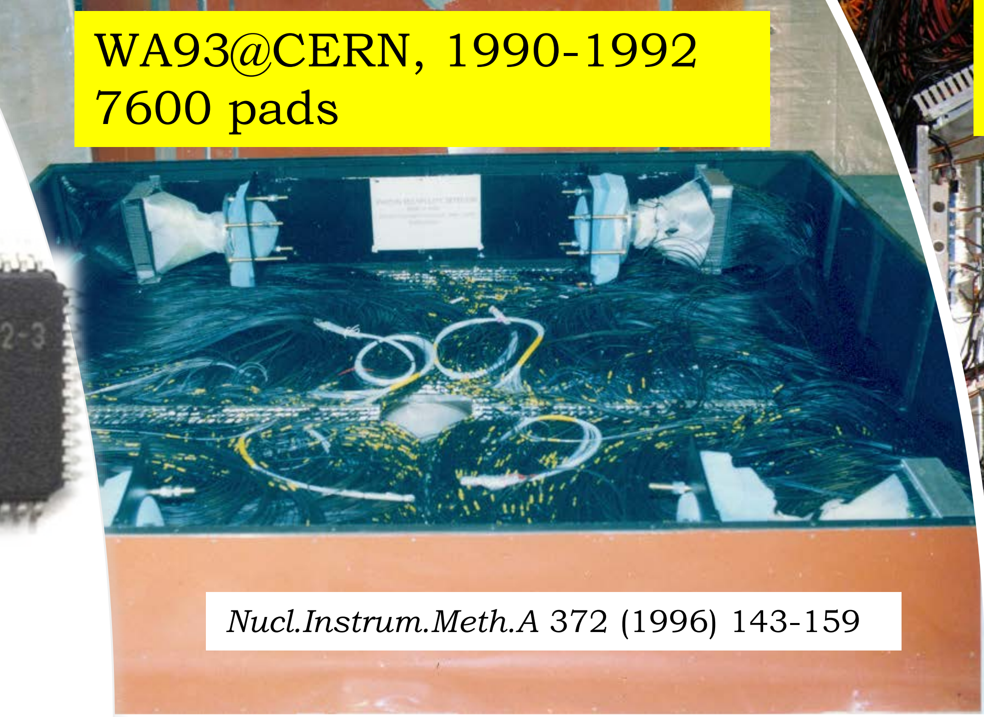
Station-2 of Muon arm

Indian Participation @CERN and BNL

Major contributions

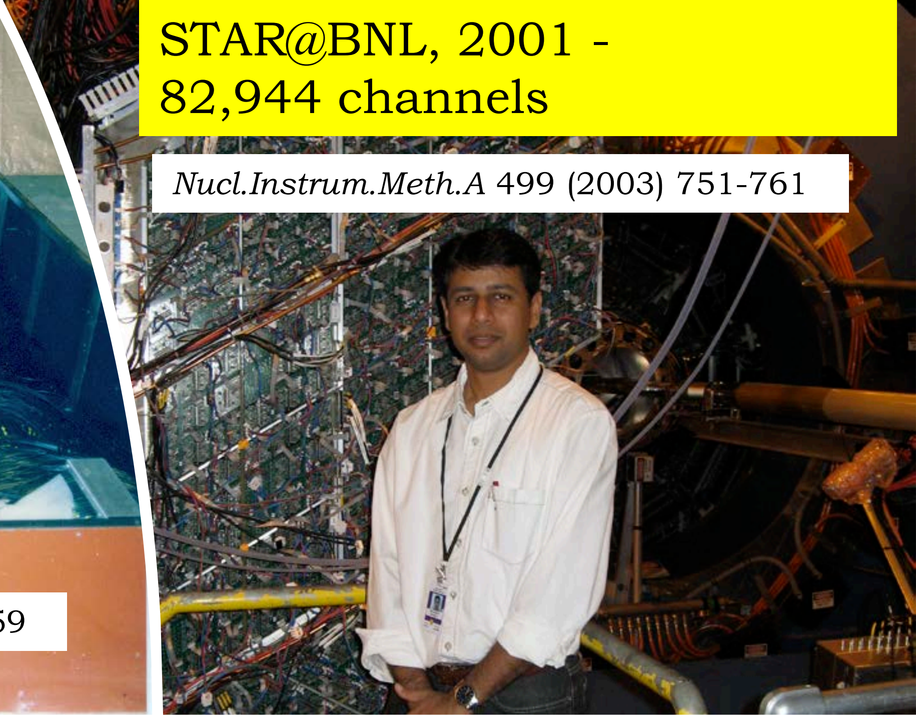
- Detectors and Electronics
- Physics analysis
- Theory

Photon multiplicity measurements: From SPS to RHIC and LHC, *Pramana* 60 (2003) 613-626



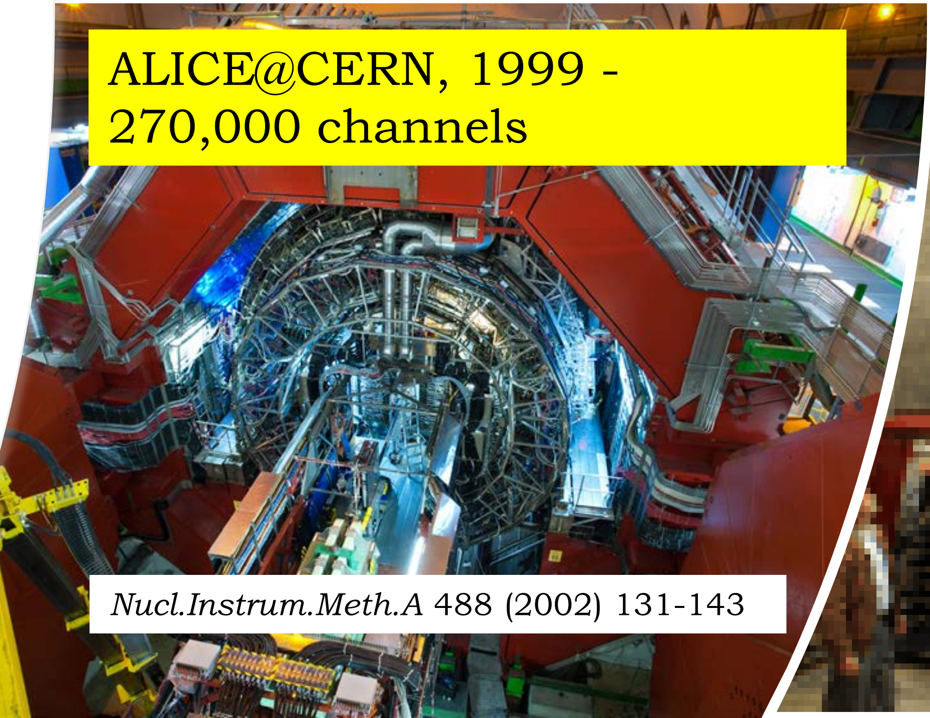
WA93@CERN, 1990-1992
7600 pads

Nucl.Instrum.Meth.A 372 (1996) 143-159



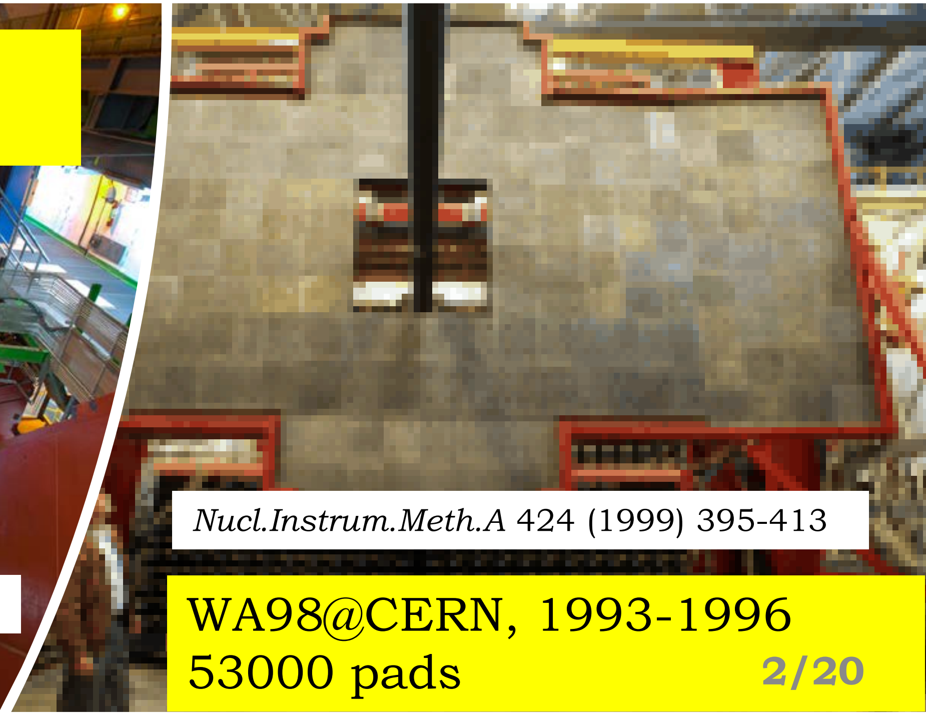
STAR@BNL, 2001 -
82,944 channels

Nucl.Instrum.Meth.A 499 (2003) 751-761



ALICE@CERN, 1999 -
270,000 channels

Nucl.Instrum.Meth.A 488 (2002) 131-143



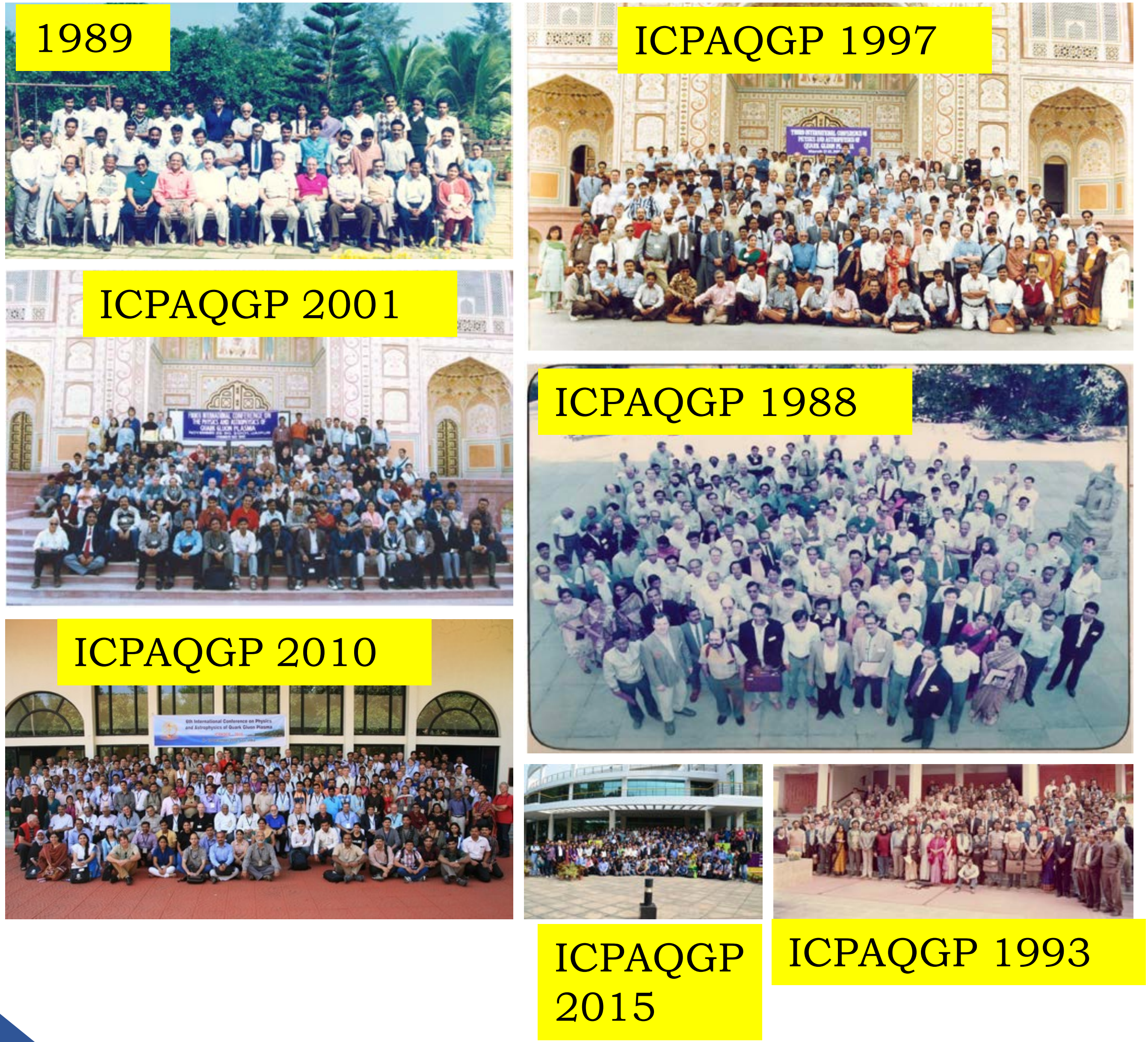
Nucl.Instrum.Meth.A 424 (1999) 395-413

WA98@CERN, 1993-1996
53000 pads

Community

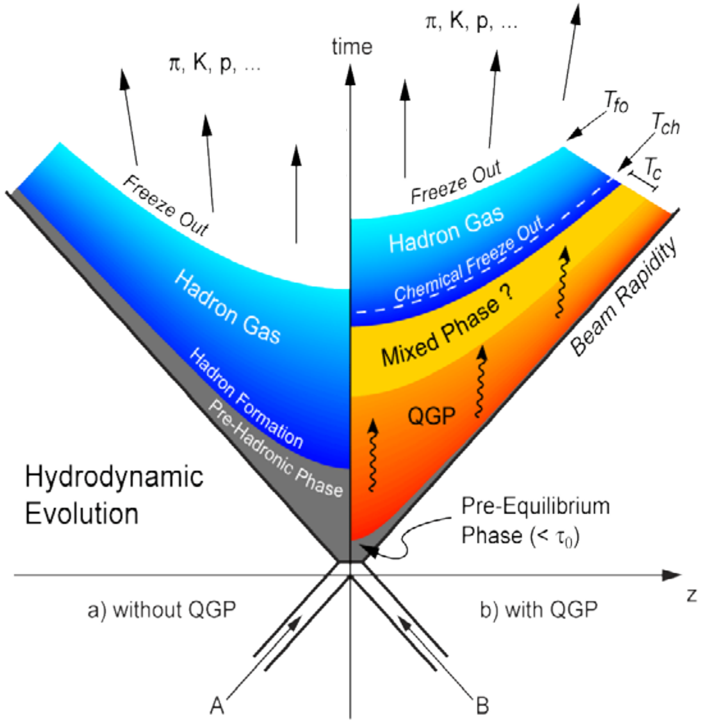
Growing with time

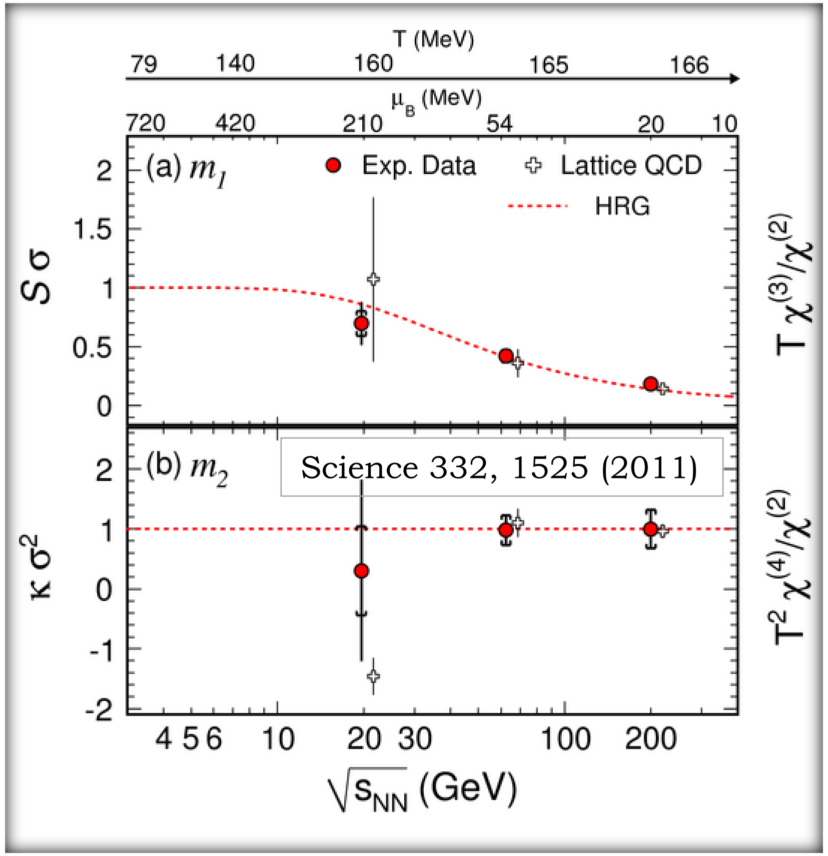
~ 120-150 experimental users at CERN

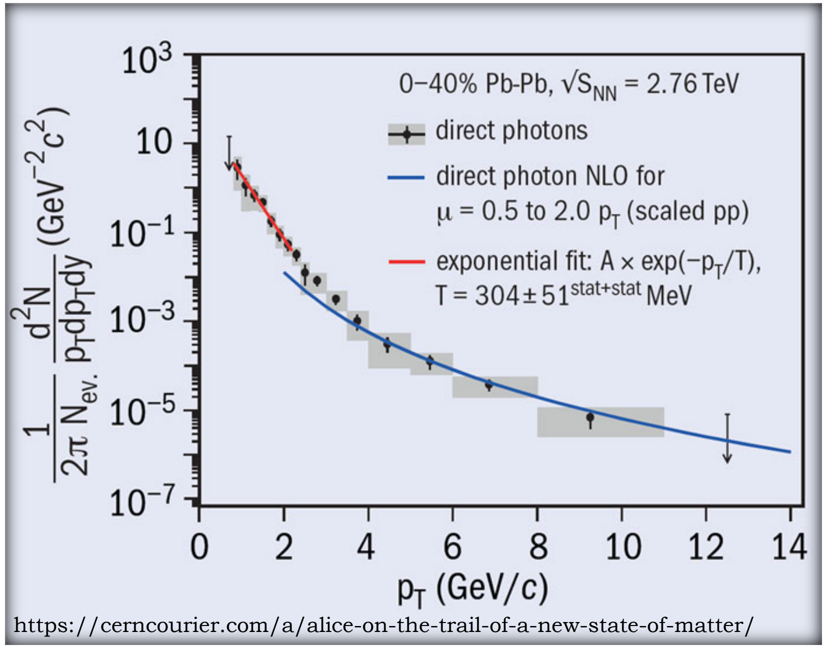


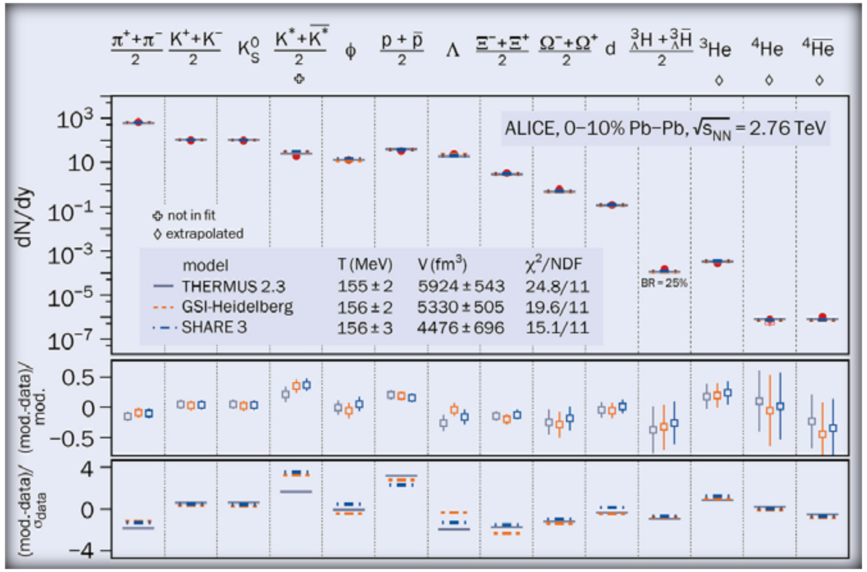
Relativistic Heavy-Ion Collisions and Temperature Scales

J. D. Bjorken Physical Review D 27 (1983) 140









Critical Temperature for QGP formation ~ 155 MeV

Universe:

QCD Phase Transition: T ~ 200 MeV

Electroweak Phase Transition: T ~ 150 GeV

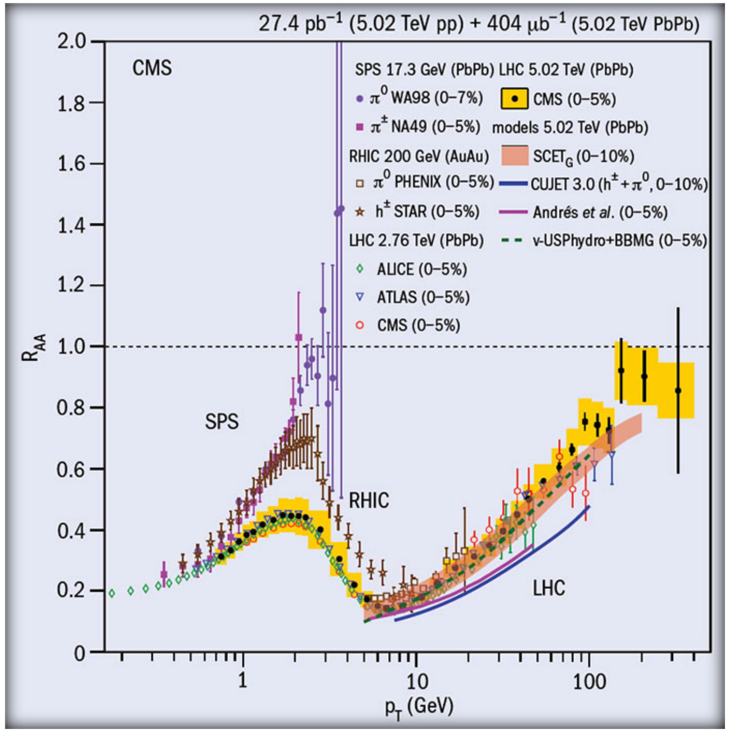
GUT phase Transition: T ~ 10^{16} GeV

JHEP 06, 088 (2009)
Phys. Rev. D 85, 054503 (2012)

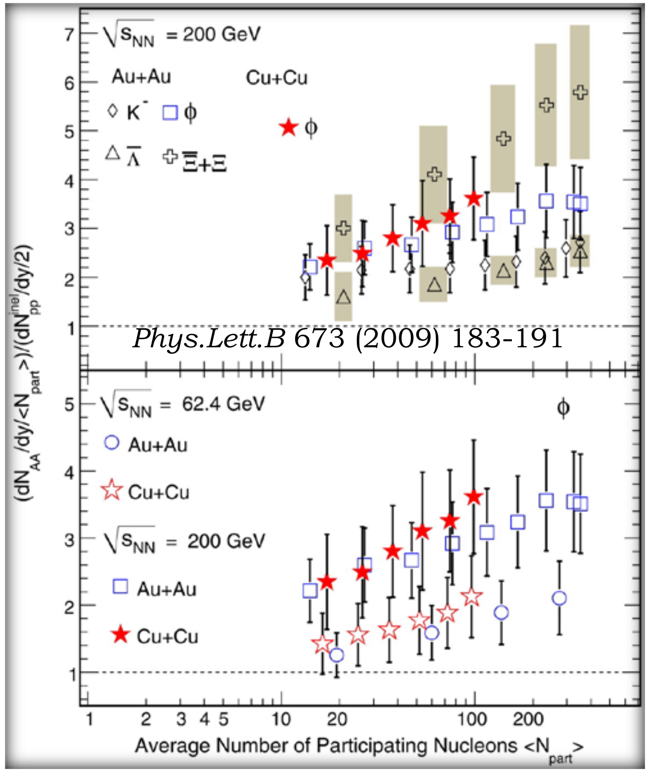
e-Print: 2211.04384 [nucl-ex]

Quark Gluon Plasma

Colour degrees of freedom essential to understand the measurements

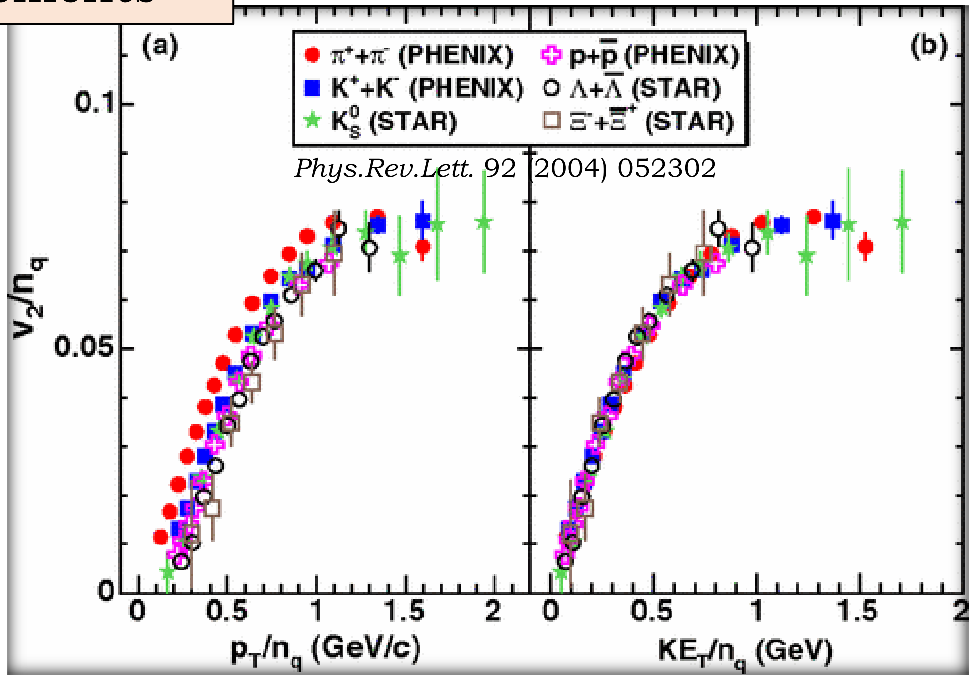


arXiv:1611.01664

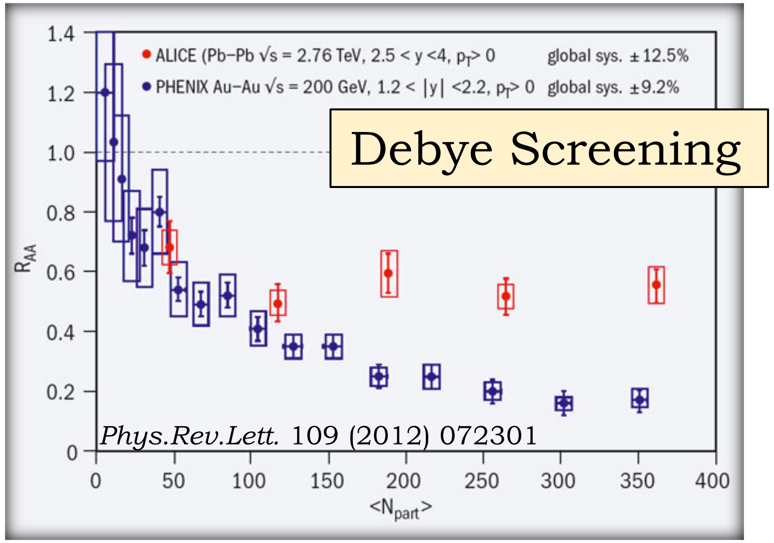


Phys.Lett.B 673 (2009) 183-191

Partonic Collectivity



Phys.Rev.Lett. 92 (2004) 052302



Debye Screening

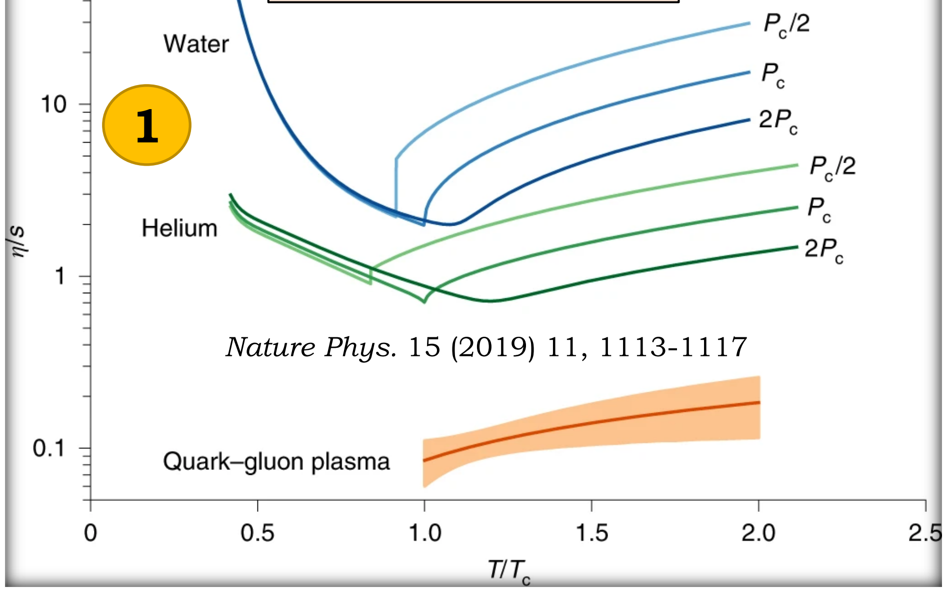
Phys.Rev.Lett. 109 (2012) 072301

- Relevant degrees of freedom : Quarks and Gluons.
- Collectivity present.
- Debye screening effect observed.

We have Quark-Gluon Plasma formed in the laboratory

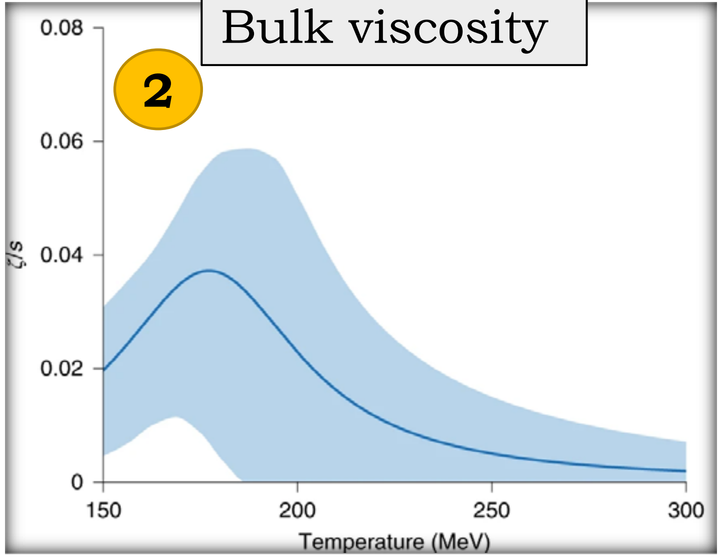
Properties of Quark Gluon Plasma

Shear viscosity

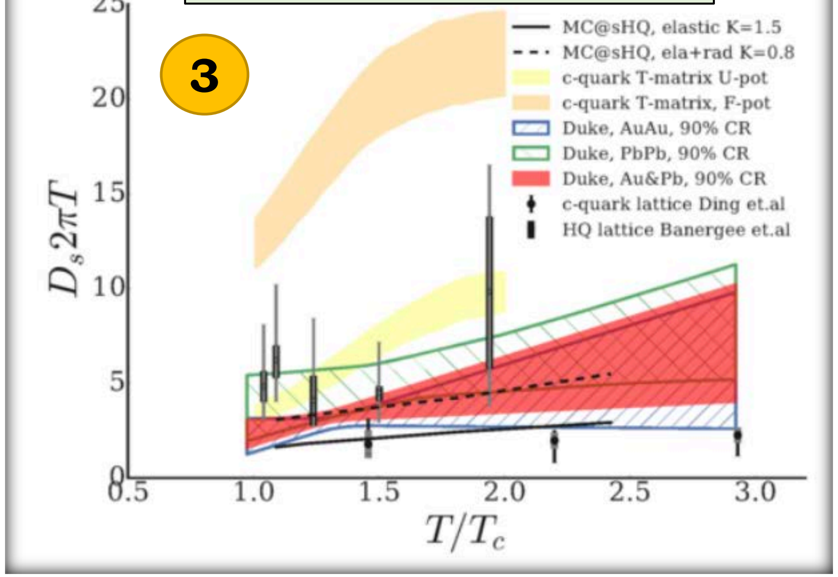


Nature Phys. 15 (2019) 11, 1113-1117

Bulk viscosity

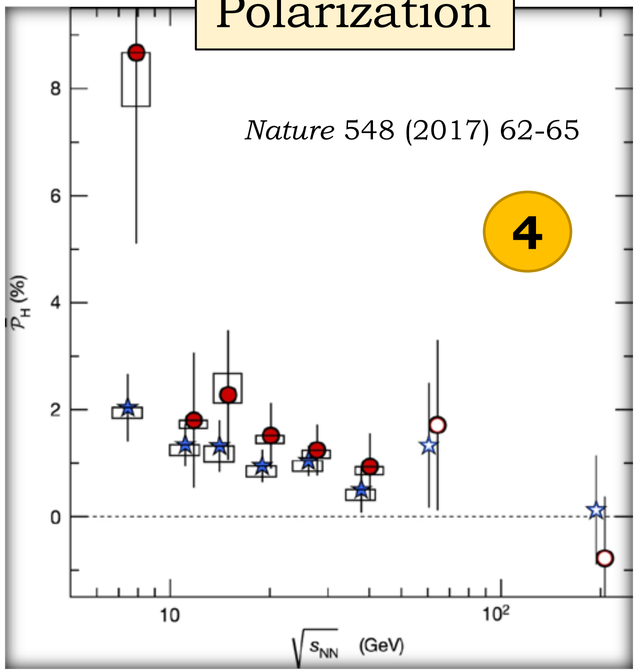


Diffusion co-efficient

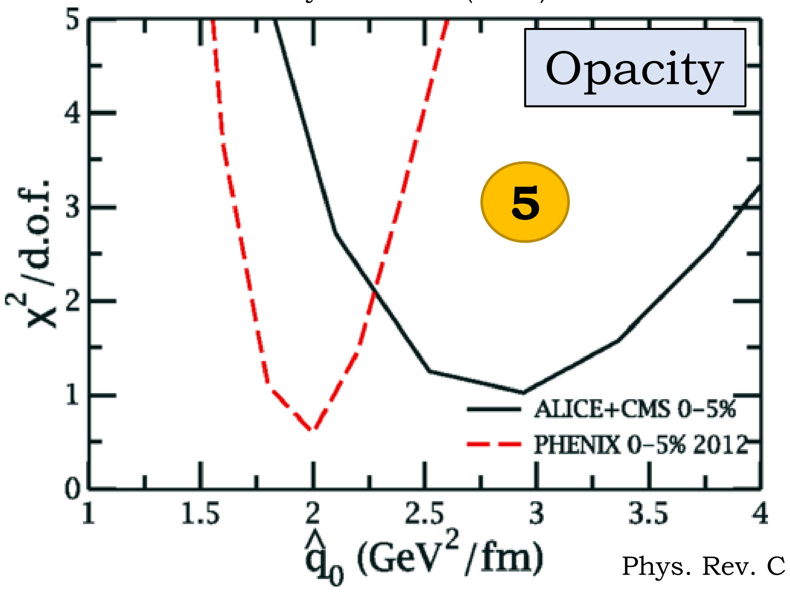


Nuclear Physics A 967 (2017) 668–671

Polarization



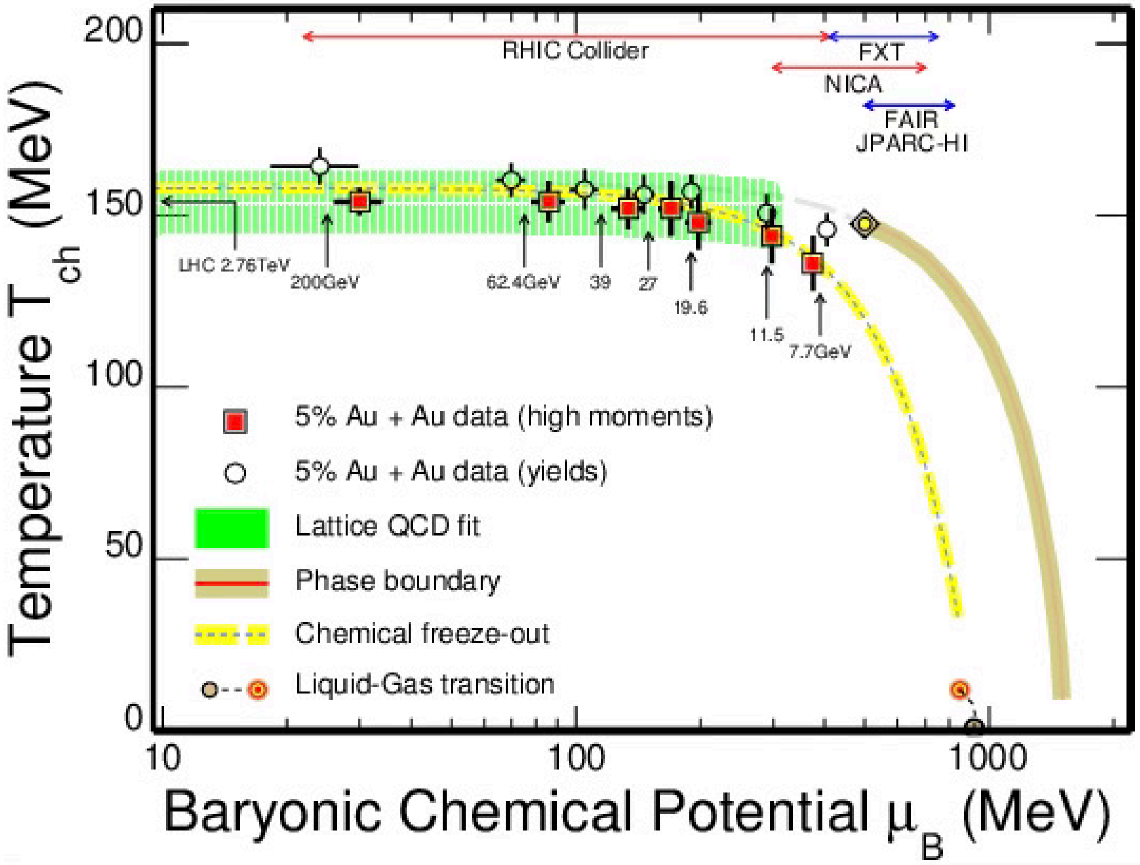
Opacity



Phys. Rev. C 90, 014909 (2014)

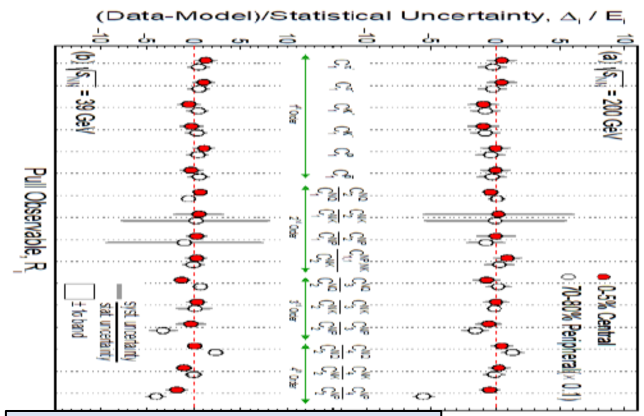
- Perfect fluid
- Brownian motion of heavy quarks in bath of light quarks
- Polarized plasma
- Dense medium

Status on the Phase Diagram of QCD



Phys.Lett.B 829 (2022) 137021

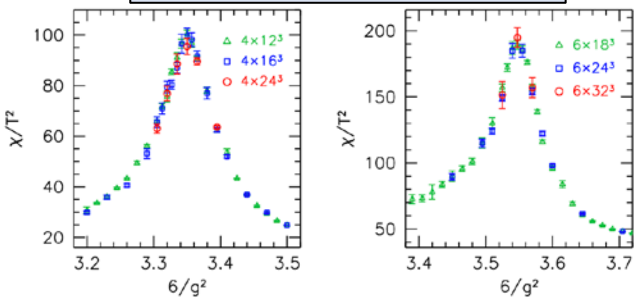
Thermalization μ_B < 140 MeV



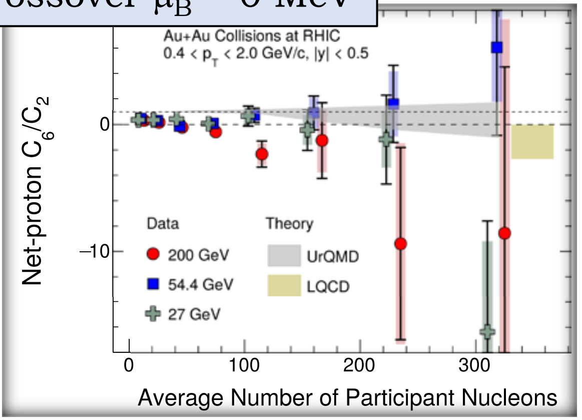
Phys.Rev.Lett. 127 (2021) 26, 262301

Nature 443 (2006) 675-678

Crossover μ_B ~ 0 MeV

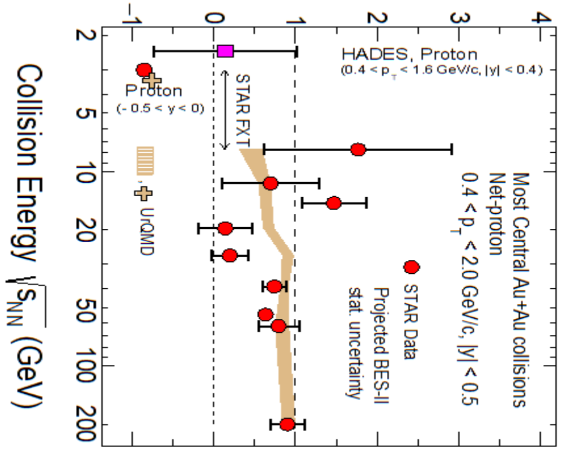


Crossover μ_B ~ 0 MeV



Phys.Rev.Lett. 126 (2021) 9, 092301

Net-proton $\kappa\sigma^2$



- Transition temperature ~ 150-170 MeV at small baryon chemical potential.
- Thermalization - clearer case for collision energies > 39 GeV / μ_B < 140 MeV
- Crossover at zero baryonic chemical potential
- Hadronic degrees of freedom relevant at collision energies ~ 3 GeV or μ_B ~ 750 MeV
- Intermediate energies interesting trends viz-viz cross over and Critical Point/First order

CP (if exists)
μ_B > 200 MeV
and < 750 MeV

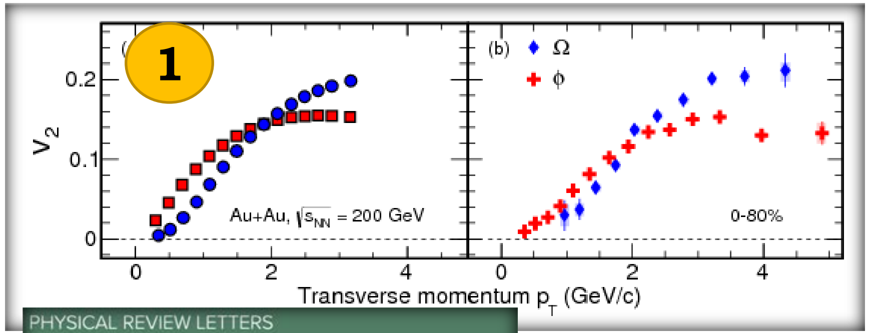
Phys.Rev.Lett. 128 (2022) 20, 202303

Selected Physics Results (India experimental groups)

6

Collectivity, first observation (WA93) and partonic collectivity

1



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Centrality and Transverse Momentum Dependence of Elliptic Flow of Multistrange Hadrons and ϕ Meson in Au + Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV

L. Adamczyk et al. (STAR Collaboration)
Phys. Rev. Lett. 116, 062301 – Published 10 February 2016

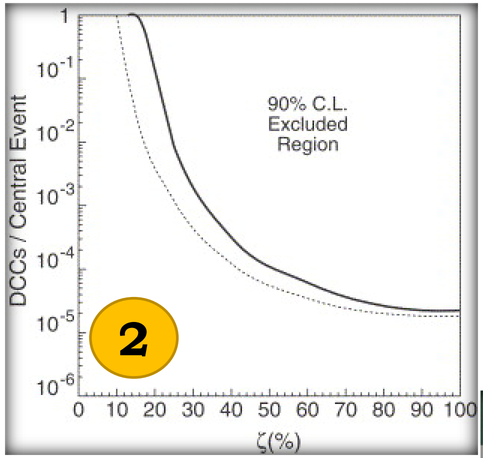
Limits on Disoriented Chiral Condensates

Physics Reports
Volume 414, Issue 6, August 2005, Pages 263-358

Disoriented chiral condensate: Theory and experiment

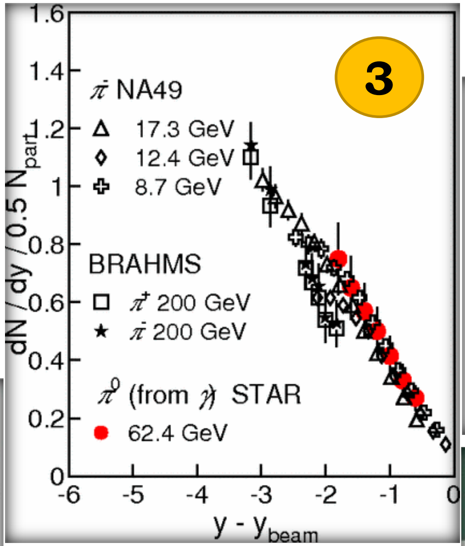
B. Mohanty, J. Serreau

2



Pioneered inclusive photon measurements and obs. of novel longitudinal scaling

3



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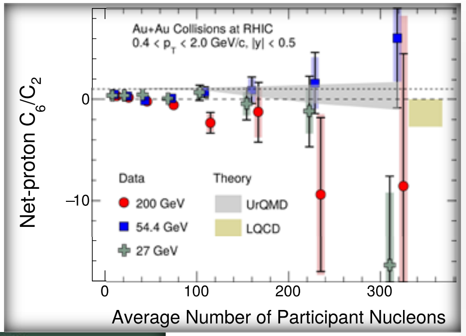
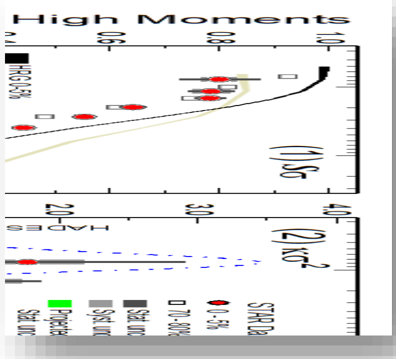
Multiplicity and Pseudorapidity Distributions of Photons in Au + Au Collisions at $\sqrt{s_{NN}}$ = 62.4 GeV

J. Adams et al. (STAR Collaboration)
Phys. Rev. Lett. 95, 062301 – Published 5 August 2005

QCD Critical Point and Phase Diagram





4

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Measurement of the Sixth-Order Cumulant of Net-Proton Multiplicity Distributions in Au + Au Collisions at $\sqrt{s_{NN}}$ = 27, 54.4, and 200 GeV at RHIC

M. S. Abdallah et al. (STAR Collaboration)
Phys. Rev. Lett. 127, 262301 – Published 20 December 2021

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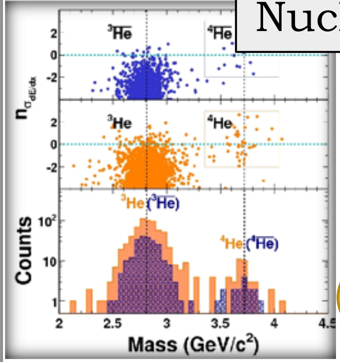
Nonmonotonic Energy Dependence of Net-Proton Number Fluctuations

J. Adam et al. (STAR Collaboration)
Phys. Rev. Lett. 126, 092301 – Published 5 March 2021

Nuclei production



nature

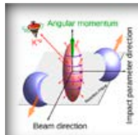
Observation of the antimatter helium-4 nucleus

The STAR Collaboration

Nature 473, 353–356 (2011)

5

Evidence: Spin-orbit effect

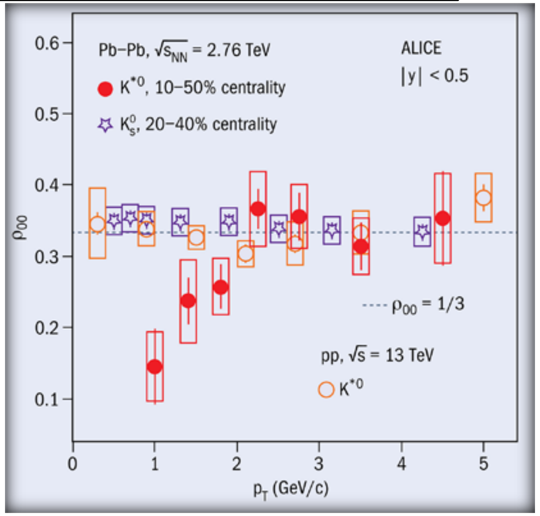


EDITORS' SUGGESTION

Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions

The measured spin alignment of vector mesons in heavy-ion collisions is consistent with that expected from the spin-orbit coupling of quarks with the large angular momentum of the collision.

S. Acharya et al. (The ALICE Collaboration)
Phys. Rev. Lett. 125, 012301 (2020)



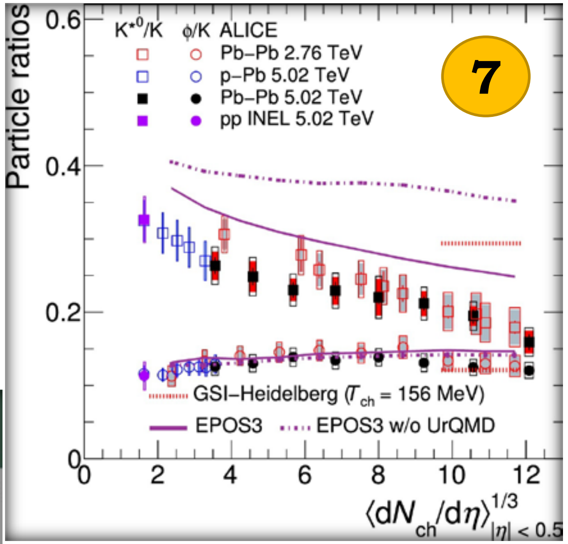
Evidence: rescattering effect

Physics Letters B

Evidence of rescattering effect in Pb-Pb collisions at the LHC through production of K*(892)^0 and ϕ(1020) mesons

ALICE Collaboration

7



Selected Physics Results (Indian theory groups)

LQCD: Diffusion Coefficient

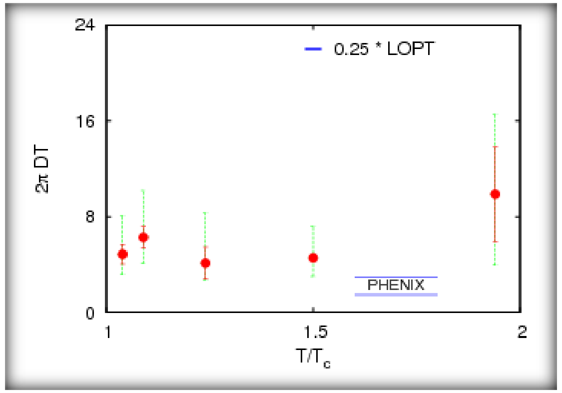
1

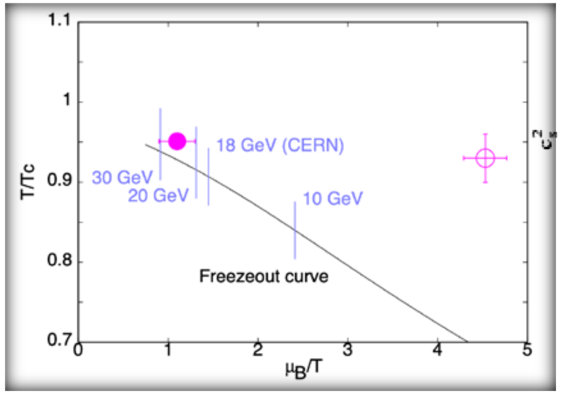
LQCD Critical Point

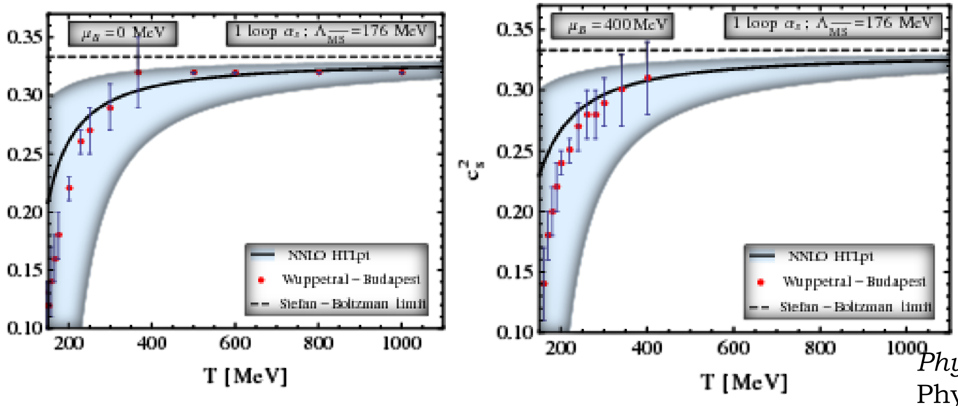
2

Equation of State

JHEP 05 (2014) 027
Phys.Rev.D 89 (2014) 6, 061701





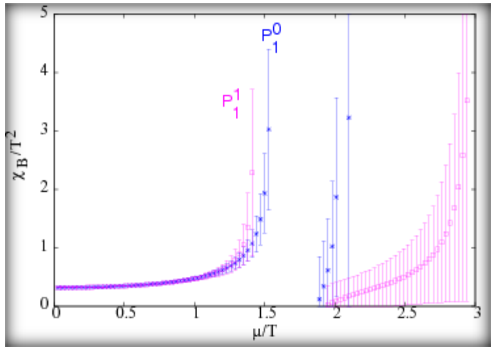


5

Heavy-quark propagation

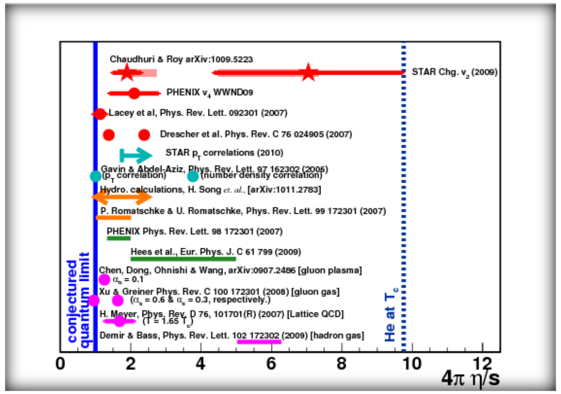
Phys.Rev.C 82 (2010) 024909
Phys.Rev.C 86 (2012) 014902

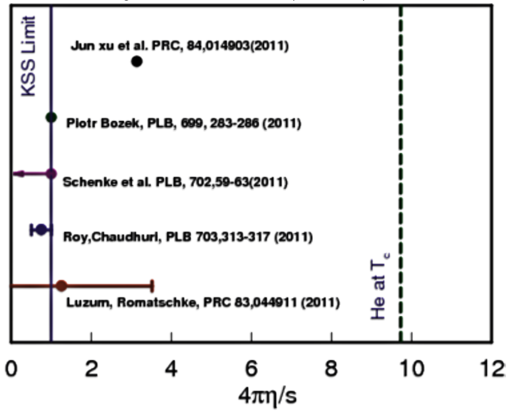
Phys.Rev.D 71 (2005) 114014
Phys.Rev.D 78 (2008) 114503
Phys.Lett.B 696 (2011) 459-463
Phys.Rev.D 85 (2012) 014510



Relativistic Hydrodynamics
- Magnetic field
- Spin

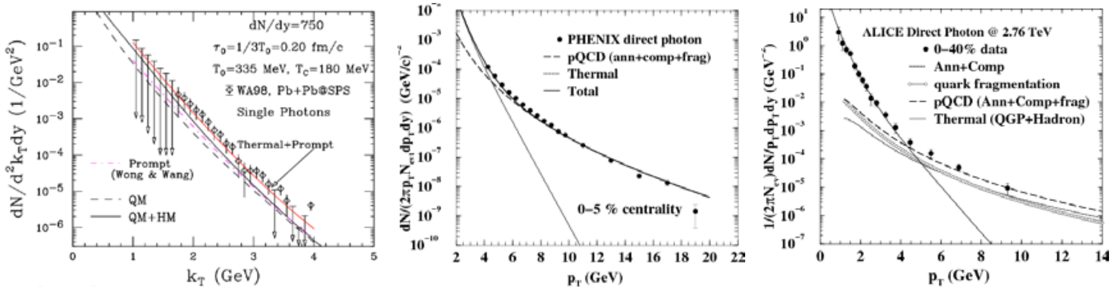
4

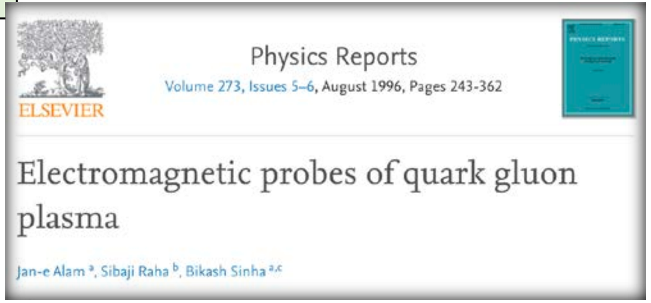




3

Electromagnetic probes of quark gluon plasma




Physics Reports
Volume 273, Issues 5–6, August 1996, Pages 243-362

Electromagnetic probes of quark gluon plasma

Jan-e Alam [a], Sibaji Raha [b], Bikash Sinha [a,c]


PHYSICAL REVIEW LETTERS

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Accepted Paper

Relativistic spin magnetohydrodynamics

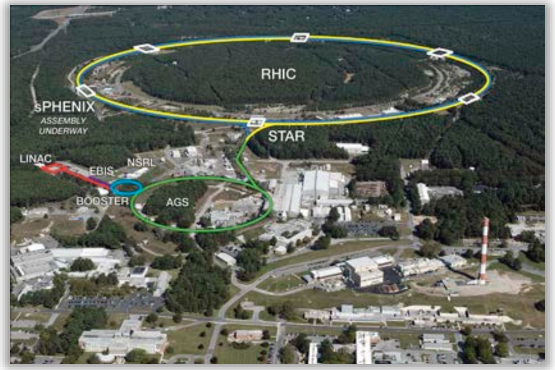
Phys. Rev. Lett.

Samapan Bhadury, Wojciech Florkowski, Amaresh Jaiswal, Avdhesh Kumar, and Radoslaw Ryblewski

Accepted 15 September 2022

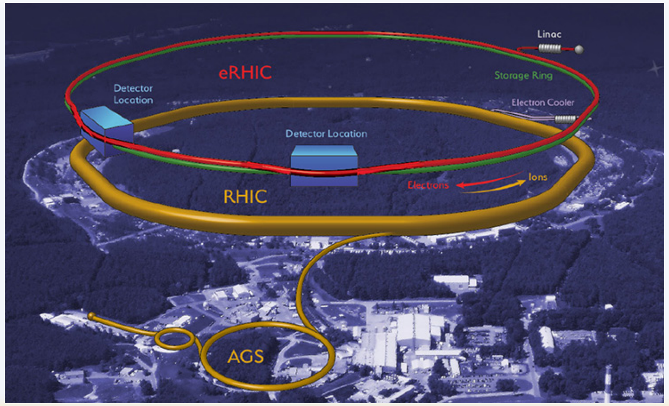
Future plans # 1

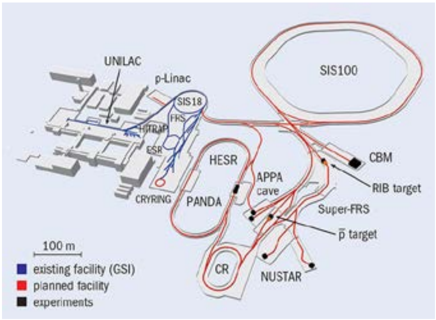
Relativistic Heavy Ion Collider, BNL



Operational till 2025

Electron Ion Collider at BNL - 2032

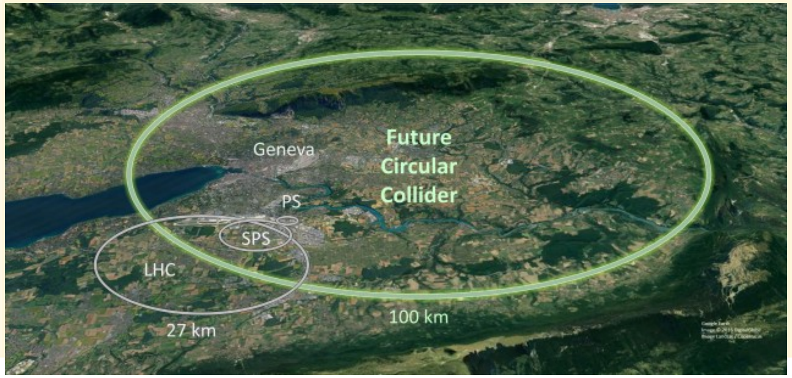


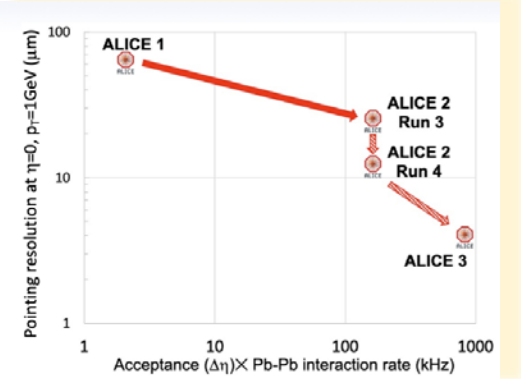


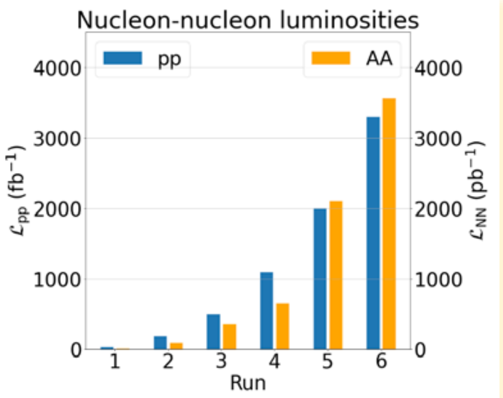
Facility for Anti-proton Ion Research

FAIR and CBM – Discussed by Prof. S. Chattopadhyay

Large Hadron Collider, CERN



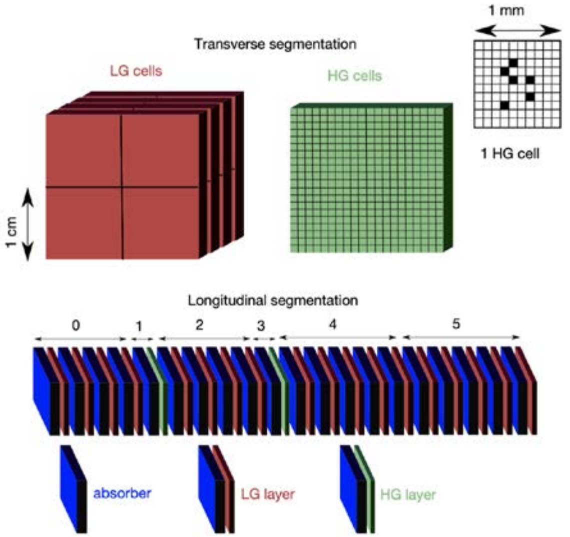


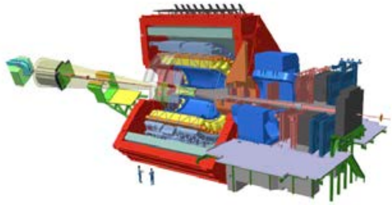


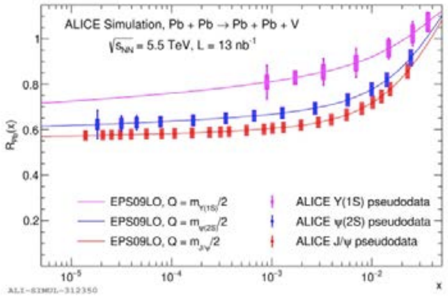
Future plans # 2

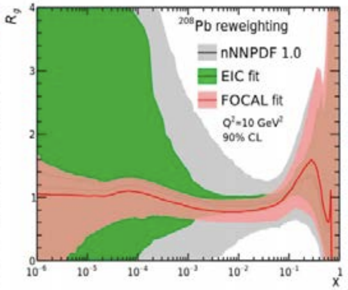
ALICE@LHC,CERN

FOCAL



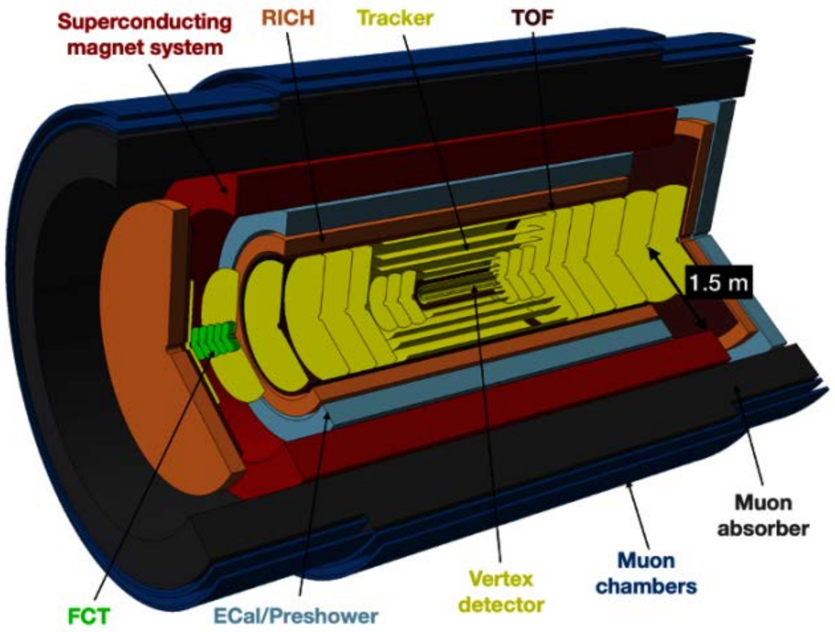




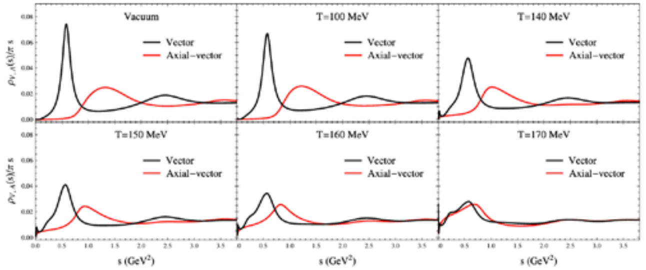


Probing initial-state nuclear parton densities

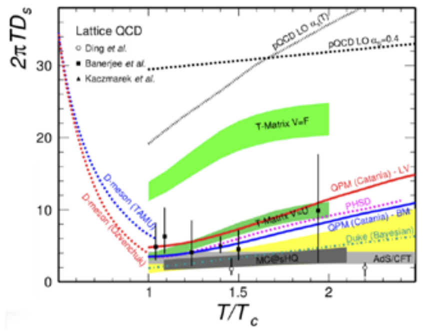
ALICE 3



arXiv:1902.01211

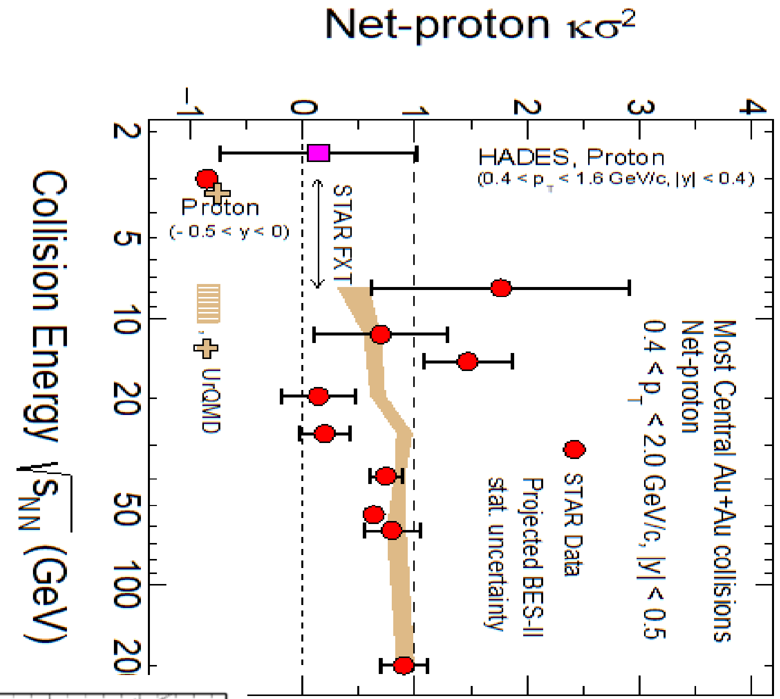


Chiral Symmetry Restoration



Transport Properties

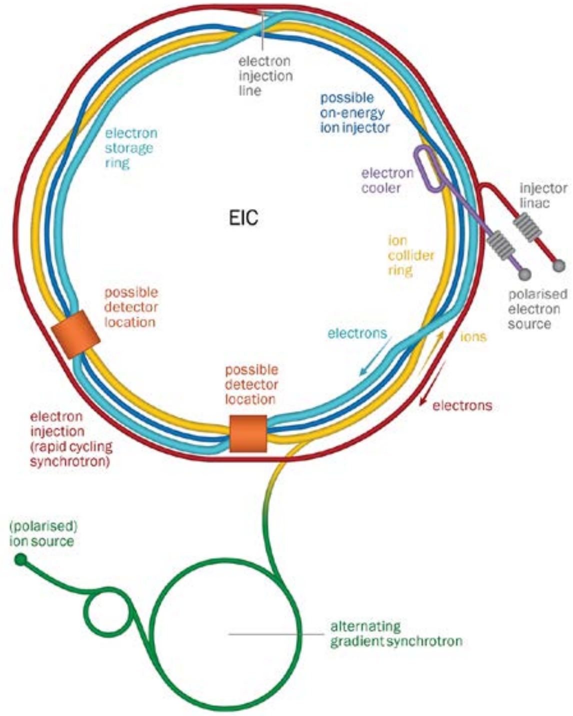
STAR@RHIC, BNL



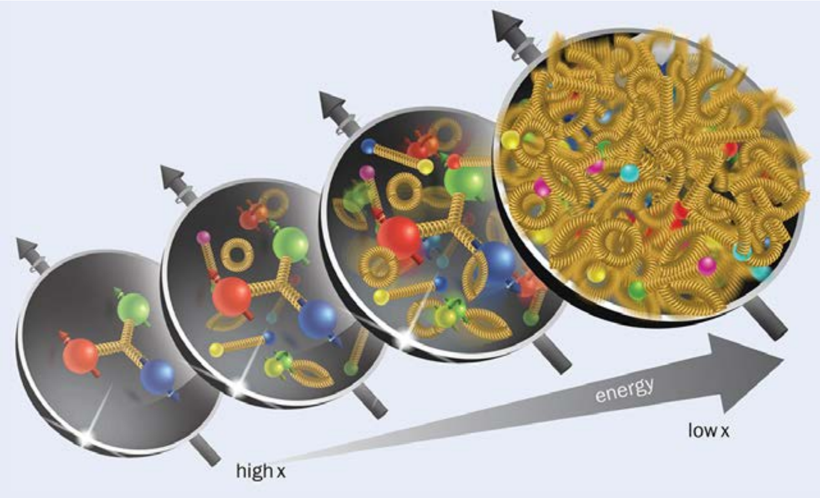
Physics Analysis of Phase II of Beam Energy Scan Program

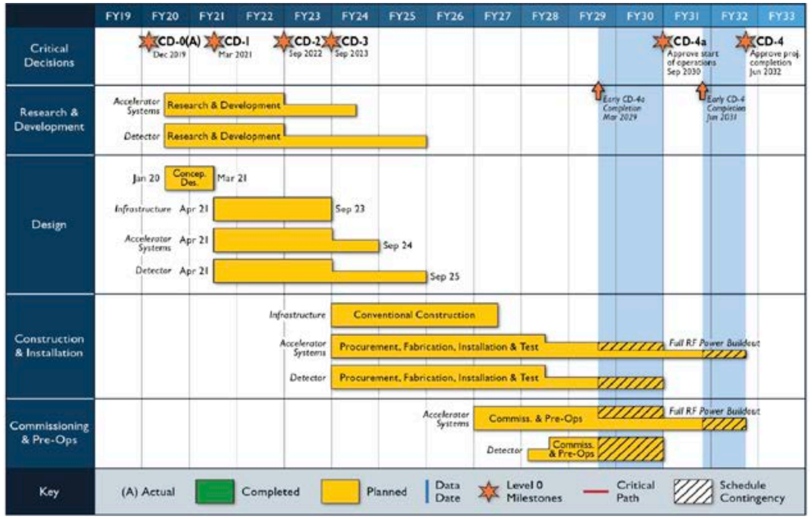
Future plans # 3

Electron Ion Collider

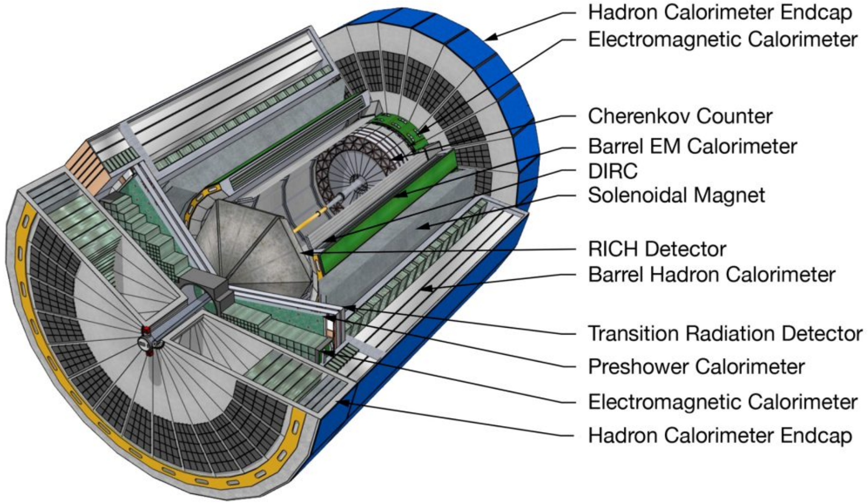


- First-ever accelerator to yield collisions of electrons and polarized-protons (and polarized light ions)
- First-ever accelerator to yield collisions of electrons and nuclei

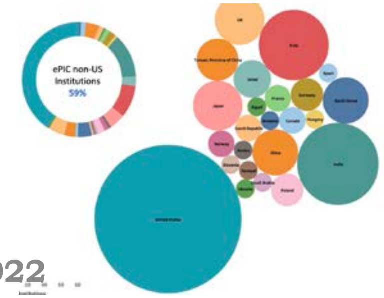




electron Proton Ion Collider (ePIC) Experiment

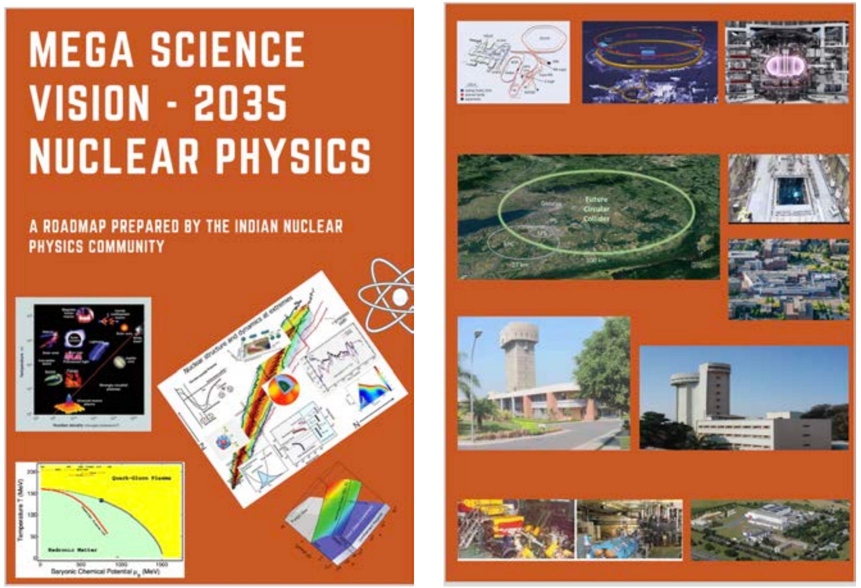


Indian Group (Experiment and Theory)
Experiment group part of ePIC



160+ institutions
24 countries
500+ participants

QCD (hot and cold)
Nuclear Physics (low energy)
Plasma physics



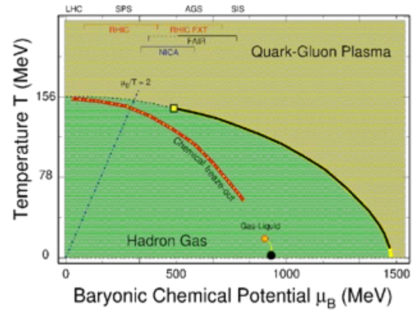
Team for MSV2035-NP

- *Drafting group met regularly for last 1.5 years.*
- *Regular consultations with working group.*
- *Inputs obtained from individual, institutes, facilities, collaborations.*
- *4000+ scientific members from across various areas contacted for inputs.*
- *National and International expert consultation.*
- *Consulted STIP document, Vision 2014 & LR-US-Eur.*
- *Professional editing work by Chandani Palshetkar.*

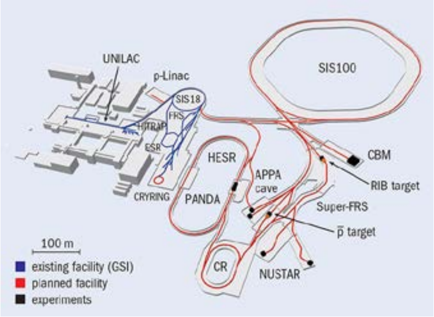
QCD: Recommendations

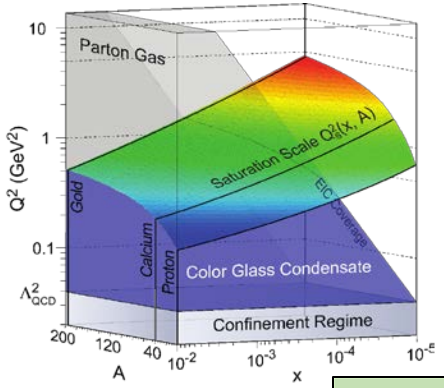
The study of the emergent properties of QCD matter is one of the most compelling science problems in nuclear physics. It includes mapping the phase diagram of the QCD matter, measuring the properties of the QCD matter subjected to extreme conditions of temperature, pressure, baryon density, electromagnetic fields and angular momentum, finding out the partonic content of a nucleus and the fundamental mechanisms behind the properties of nucleons, such as its mass and spin.

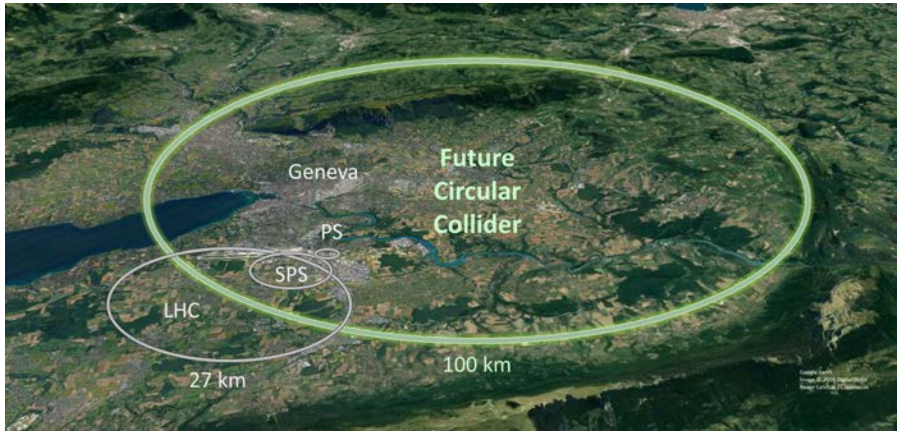
We recommend continued participation in heavy-ion programs at LHC, RHIC and FAIR, the collision energies of which, only when taken together, allow to map the QCD phase diagram. While the CBM experiment, which is under construction at FAIR, should be the focus for the high-energy nuclear collisions in the near future, we also recommend participation in the upcoming Electron-Ion Collider experiments to address the fundamental questions in nuclear physics.



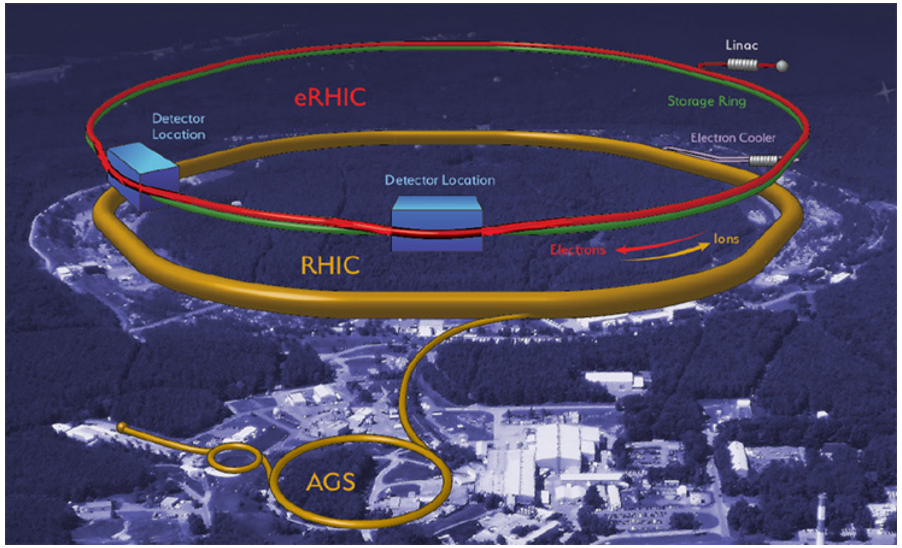
What are the phase structures of Quantum Chromodynamic (QCD) matter?







How do the strong interactions amongst quarks and gluons inside the nucleons result in confinement and collectively result in their properties such as mass and spin?



How does a nucleus look in terms of its partonic content? Does the gluon density saturate to gluonic matter of universal properties?

Industry participation MSP

Full list in the document

Industry	Nature of contribution	Project	Remarks
Gladstone Engineering Industries, Kolkata	Fabrication of honeycomb structures for Photon Multiplicity Detector (PMD) modules	ALICE and STAR	Cost-efficient product for a multi-channel detector
Micropack Private Limited, Bengaluru	Readout Printed Circuit Boards (PCB) for PMD, GEM foil	ALICE and CMS	New capacity for MPGDs and PCB for multichannel detectors
Hi_Q Electronics Pvt. Ltd., Bengaluru	Readout PCBs for muon station	ALICE	Cost-effective PCBs for gas-based detectors
SCL-ISRO, Chandigarh	Fabrication of MANAS ASIC	ALICE	New capacity developed for frond end electronics
Shogini Technoarts, Pune	Readout PCB	ALICE	Cost-effective PCBs
Graphite India Ltd., Bangalore	Fabrication and supply of a high-density graphite component of the front absorber of the ALICE muon system	ALICE	High quality product of international standards
BEL, Bangalore	Silicon sensors, Si-preshower	ALICE and CMS	Capacity building in silicon detector technology
Focustech Ltd., Gurgaon	CROCUS assembly	ALICE	New product line created
Steel Authority of India, Ranchi	Fabrication and supply of non-magnetic stainless-steel ingot for the front absorber of ALICE muon system.	ALICE	High quality product of international standards
FlexTech Ltd., Hyderabad	Fabrication of rigid and flexible PCBs for the Muon chambers of the 2nd tracking station	ALICE	High quality and cost-efficient product
Magnacon Pvt. Ltd., Kolkata	Machining of PEEK GF- 30 for the frames of the muon chambers	ALICE	High precision techniques
Narendra & Narendra, Howrah	Machining of stainless-steel ingots	ALICE	New product line developed
IGTR, Indore	Accelerator Equipment	CERN Accelerator	High quality products of international standards
Avasarala Industries, Bengaluru	Accelerator equipment	CERN Accelerator	High quality products of international standards

- ❖ Allow industry to directly be part of the MSPs.
- ❖ Foster industry-institute collaboration by granting the involved industry the rights to use the results of the research at the project-end.
- ❖ Develop avenues for undergraduate students, Ph.D. scholars and postdoctoral fellows to gain experience by working in an industrial setting.
- ❖ Provide support for a supplement to an existing grant for high-risk/high-gain research in order to develop a generic technology.

Common proposals (for MSV-WGs)

Computing

- Multiple data centres
- Peta Flop Level Machines
- Enhancement of Grid Computing infrastructure

National Detector Development and Training Centre

- Centre for R&D
- Collaboration with industry
- Remove a crucial bottle neck on hardware sector
- Seed for setting up mega experiments in India

New PG programs

- Related to Mega Science Programs (e.g Accelerator Physics, Medical Physics)
- Train required human resources

Outreach

International Particle Physics Outreach Group

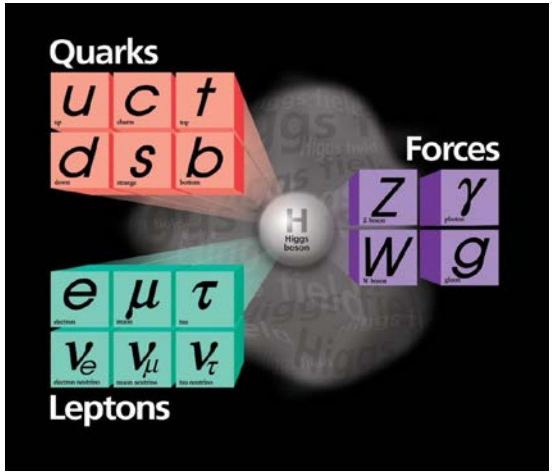
Timeline

Prog./ year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
STAR	Science Utilization Phase					Data available for physics analysis									
ALICE	Science Utilization Phase										Next generation heavy-ion experiment (ALICE 3)				
FAIR	Construction and Commissioning Phase					Science Utilization Phase									
EIC	Detector Design and R&D Phase				Construction and Commissioning Phase							Science Utilization Phase			
INGA	Science Utilization Phase														
ITER-India	Construction and Commissioning Phase														Science Utilization Phase
ELI-NP	Construction and Commissioning Phase					Science and Utilization Phase									
Tin.Tin	Planning and Conceptual Phase				Detector Design and R&D Phase		Construction and Commissioning Phase		Science and Utilization Phase						
ISMRAN	Construction and commissioning phase	Science Utilization Phase													

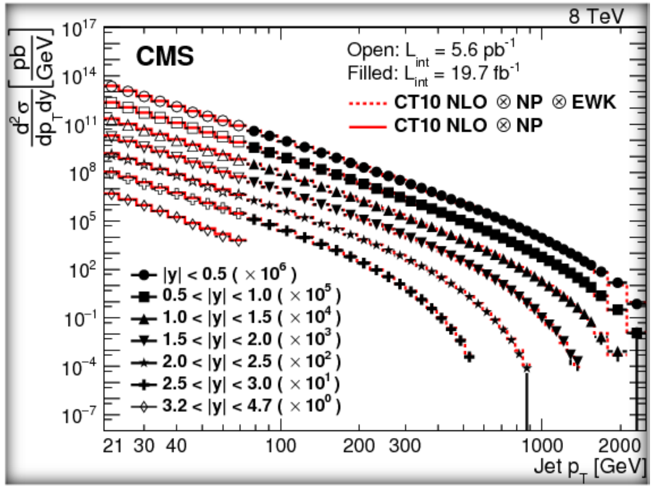
Projects nicely phase/spaced in time wise.

Towards a complete test of QCD as a theory

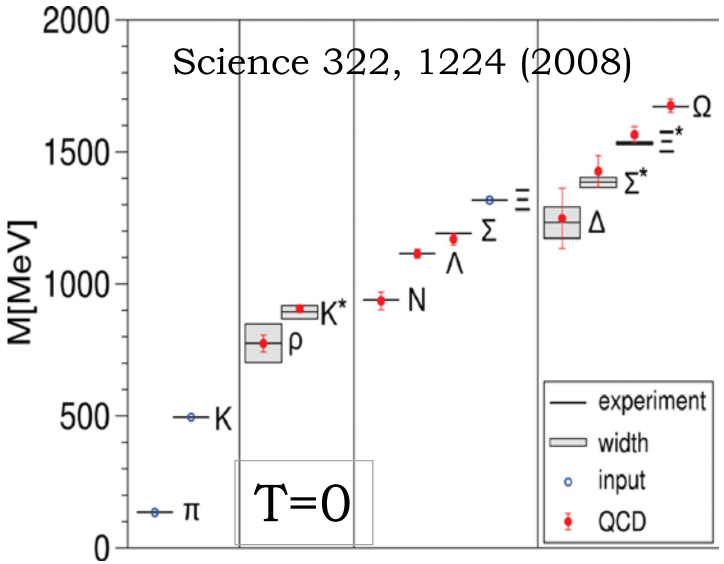
Standard Model & Origin of Mass

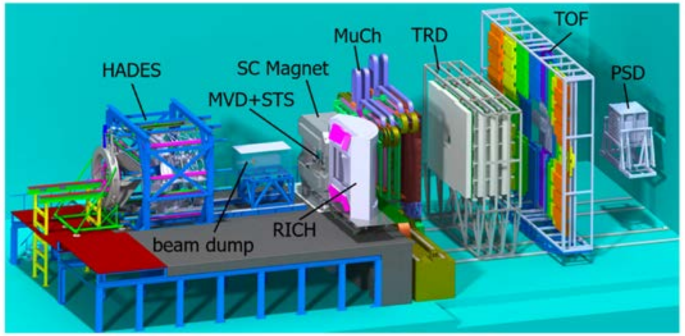


Test of QCD, Short distance scales, perturbative regime

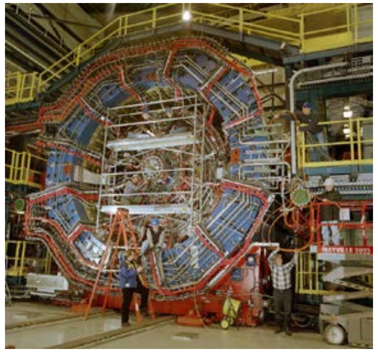


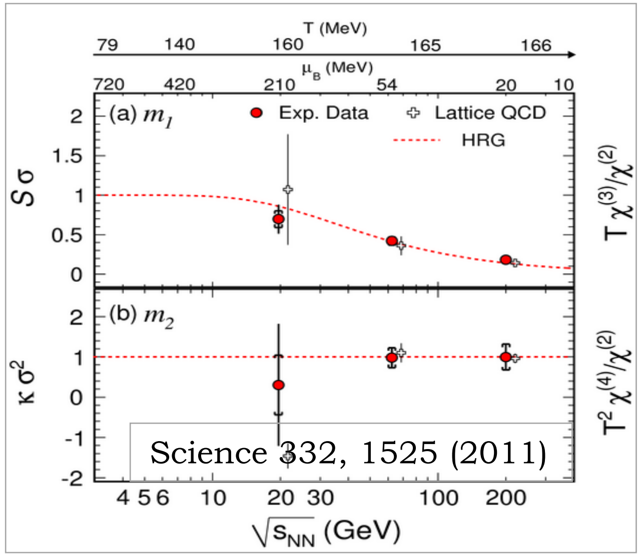
Test of QCD, Long distance scales, Non-perturbative regime

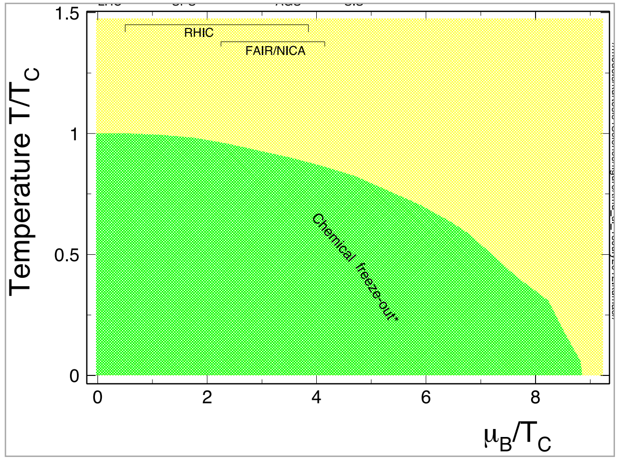




Test of QCD: Non-perturbative T>0
& Phase structure of QCD Phase diagram

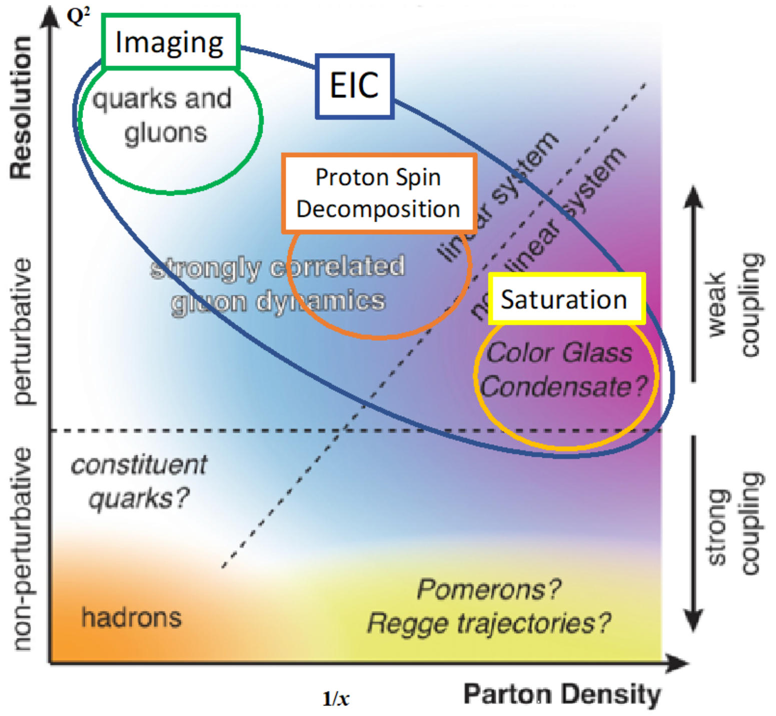




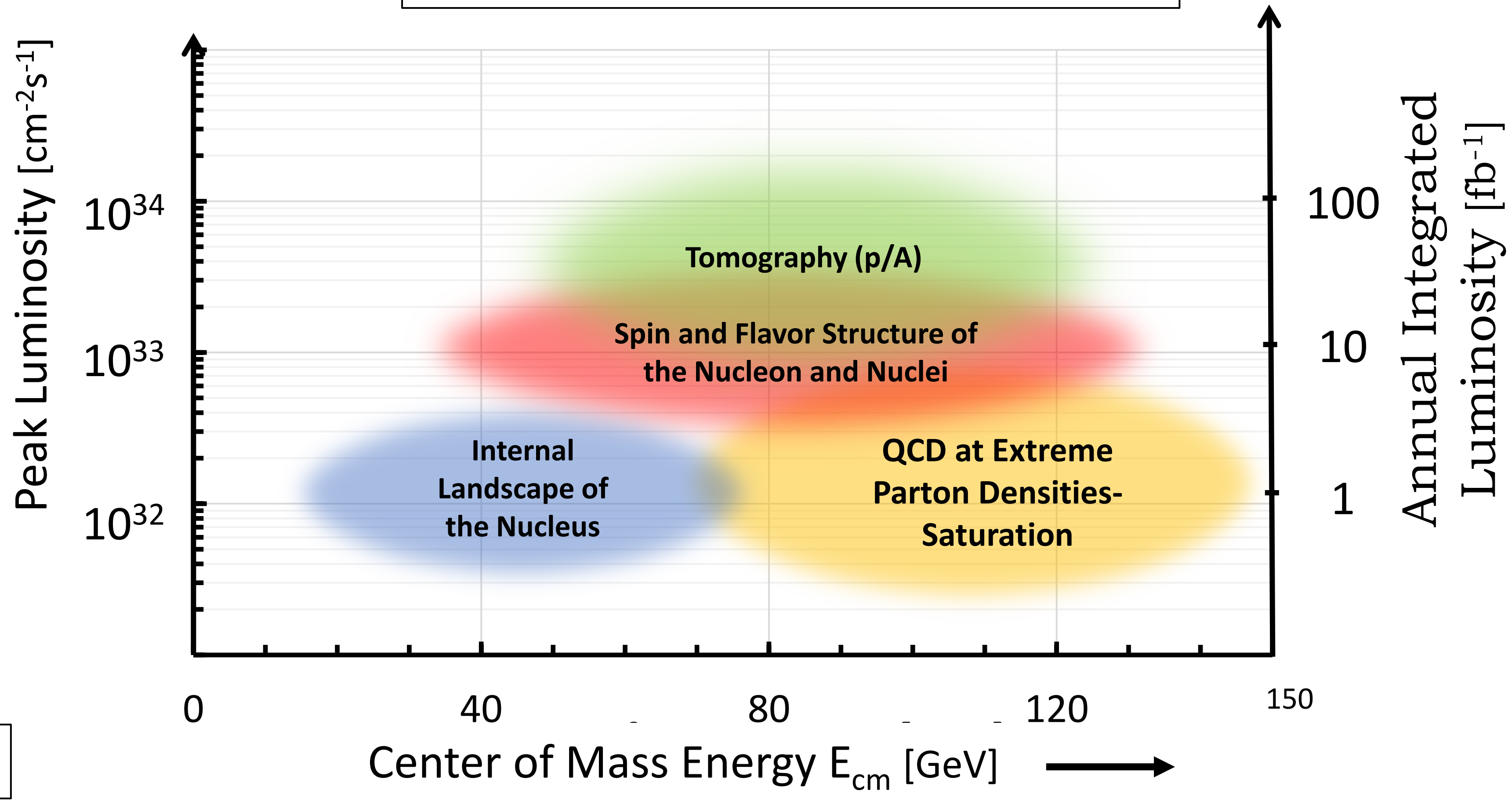


Electron Ion Collider – study QCD at new level

The next phase diagram



EIC @ BNL can address the physics



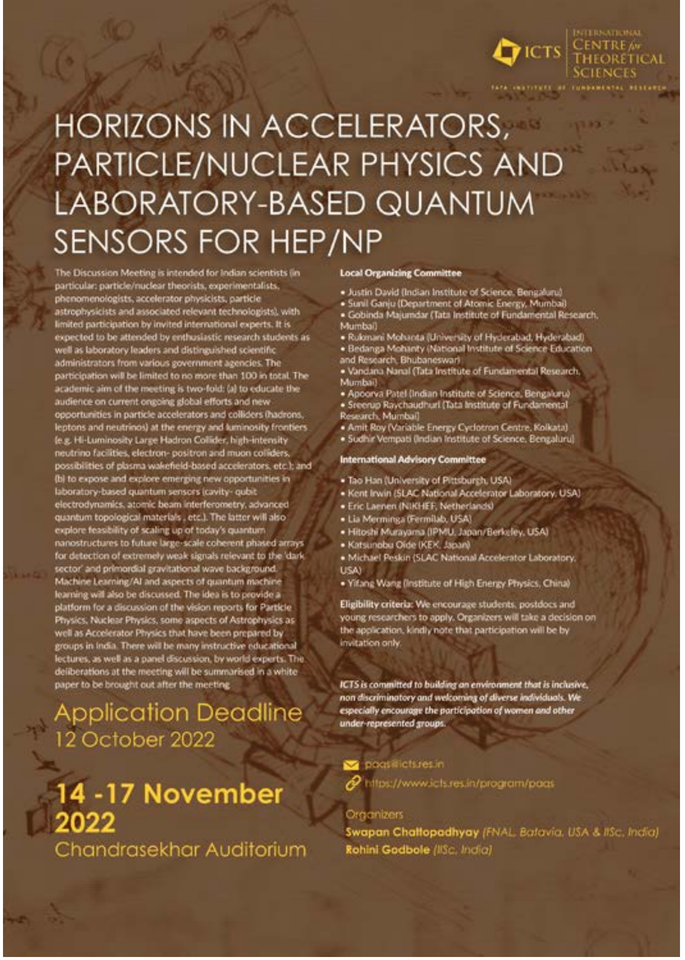
4 important questions - EIC

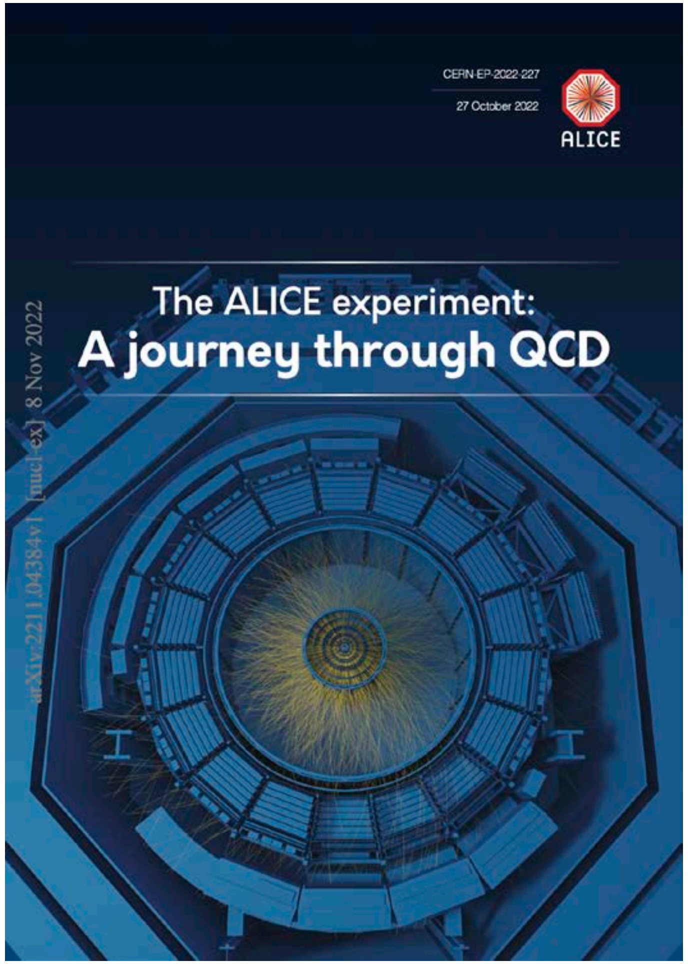
How do quarks and gluons form nuclei?

How does the proton get its spin?

How does the proton get its mass?

What is the nature of dense gluon matter?





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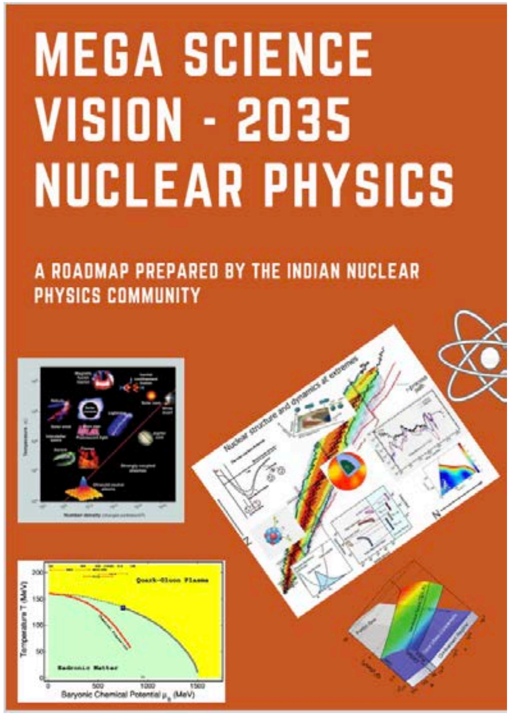

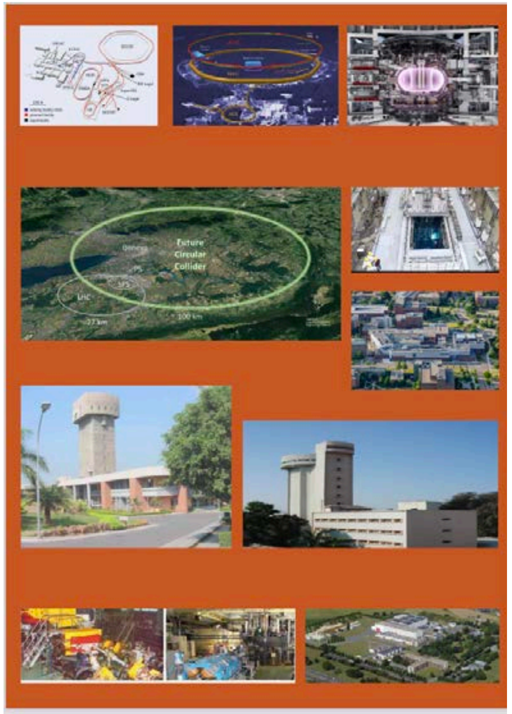

Acknowledgements

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