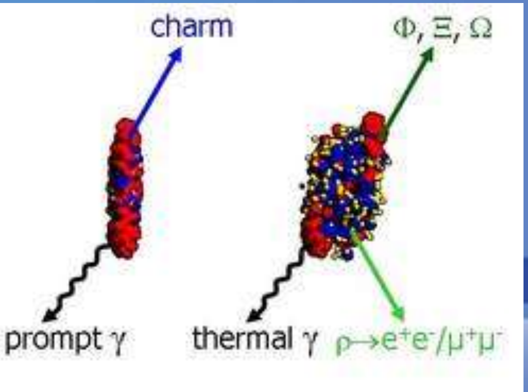
Dileptons in Ultra-relativisitic Heavy Ion Colliions

Free Quarks in Excited Vacuum

A tale of two programs

Zhangbu Xu
BNL

1. Introduction to Strong Force and QCD Phase Diagram
2. Heavy-Flavor in Quark Gluon Plasma
3. Mapping the QCD Phase Diagram
4. Chiral Symmetry Restoration
5. Summary



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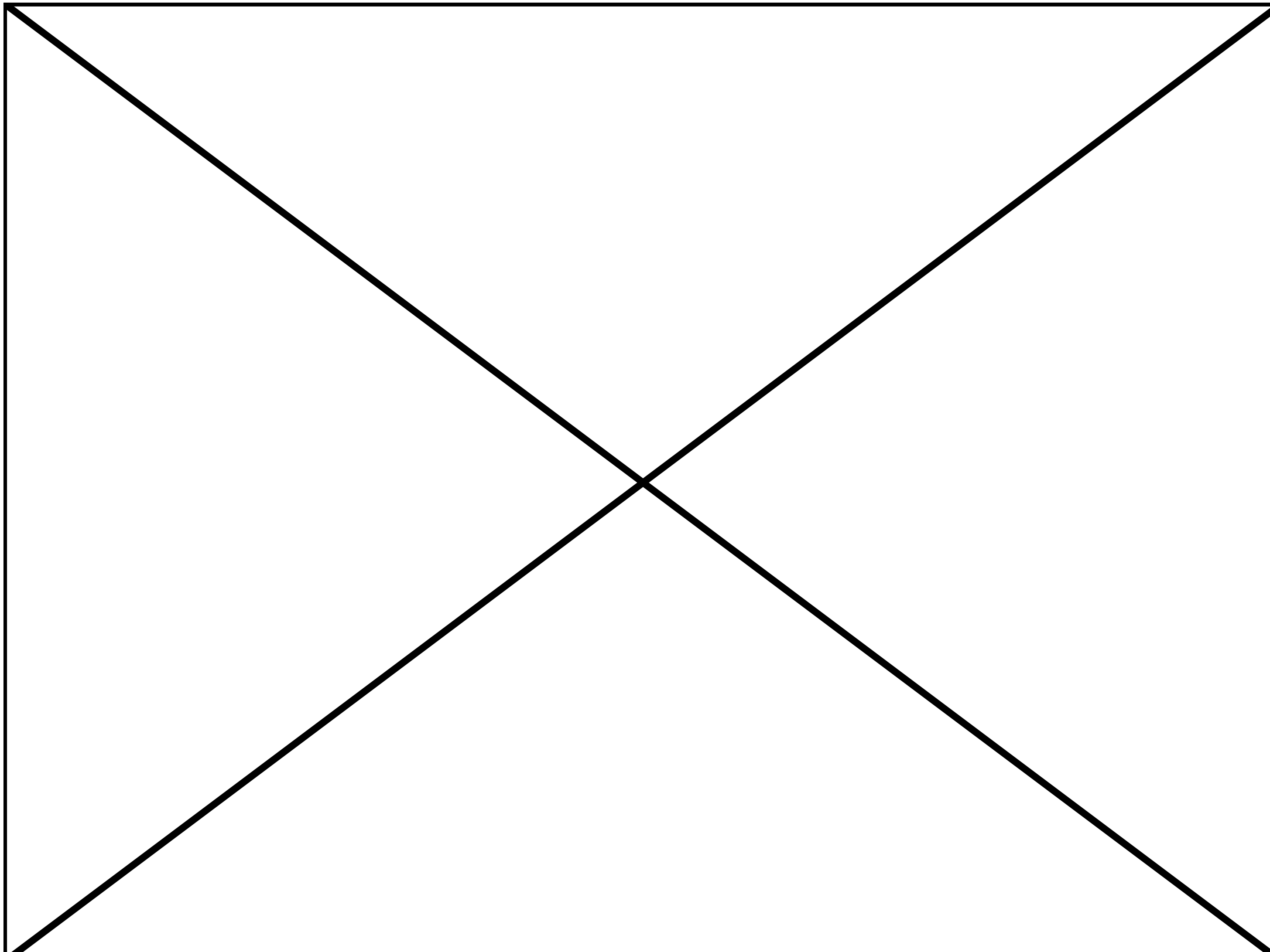
Office of Science

HOW THE UNIVERSE WORKS

http://www.bnl.gov/newsroom/news.php?a=25119 -- by science Channel Online



Strong Force, Confinement, 3 quarks into proton/neutron, BUT this matter has no mass!

Quantum Chromodynamics (QCD)

- QCD - “nearly perfect” fundamental quantum theory of quark and gluon fields **F.Wilczek, hep-ph/9907340 (Nobel Prize 2004)**

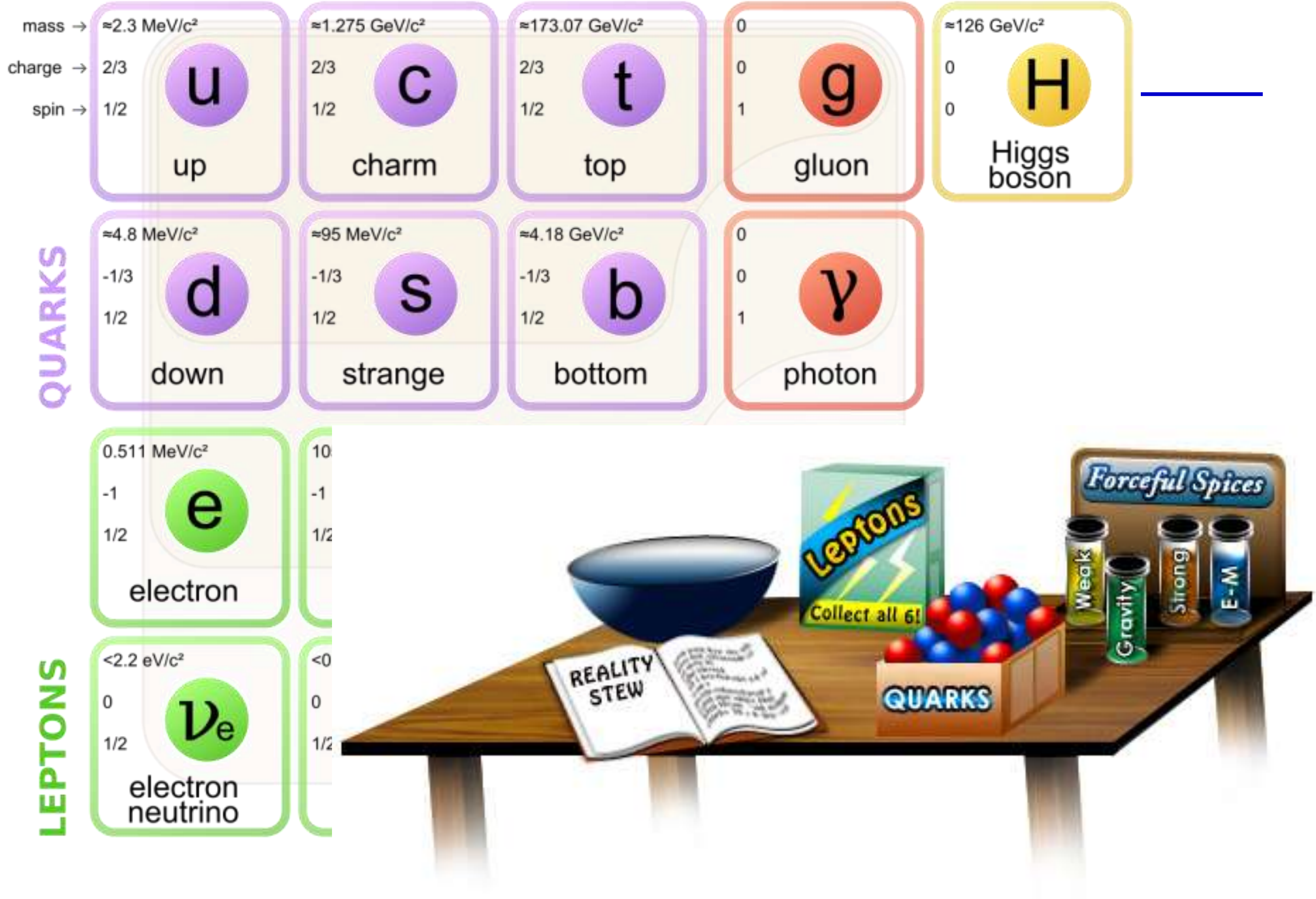
- Theory is rich in symmetries:

$$\underset{\text{i}}{SU(3)_c} \times \underbrace{SU(3)_L \times SU(3)_R}_{\text{ii}} \times \underbrace{U(1)_A \times U(1)_B}_{\text{iii}}$$

Gluons Left/Right Quarks Axial/Scale

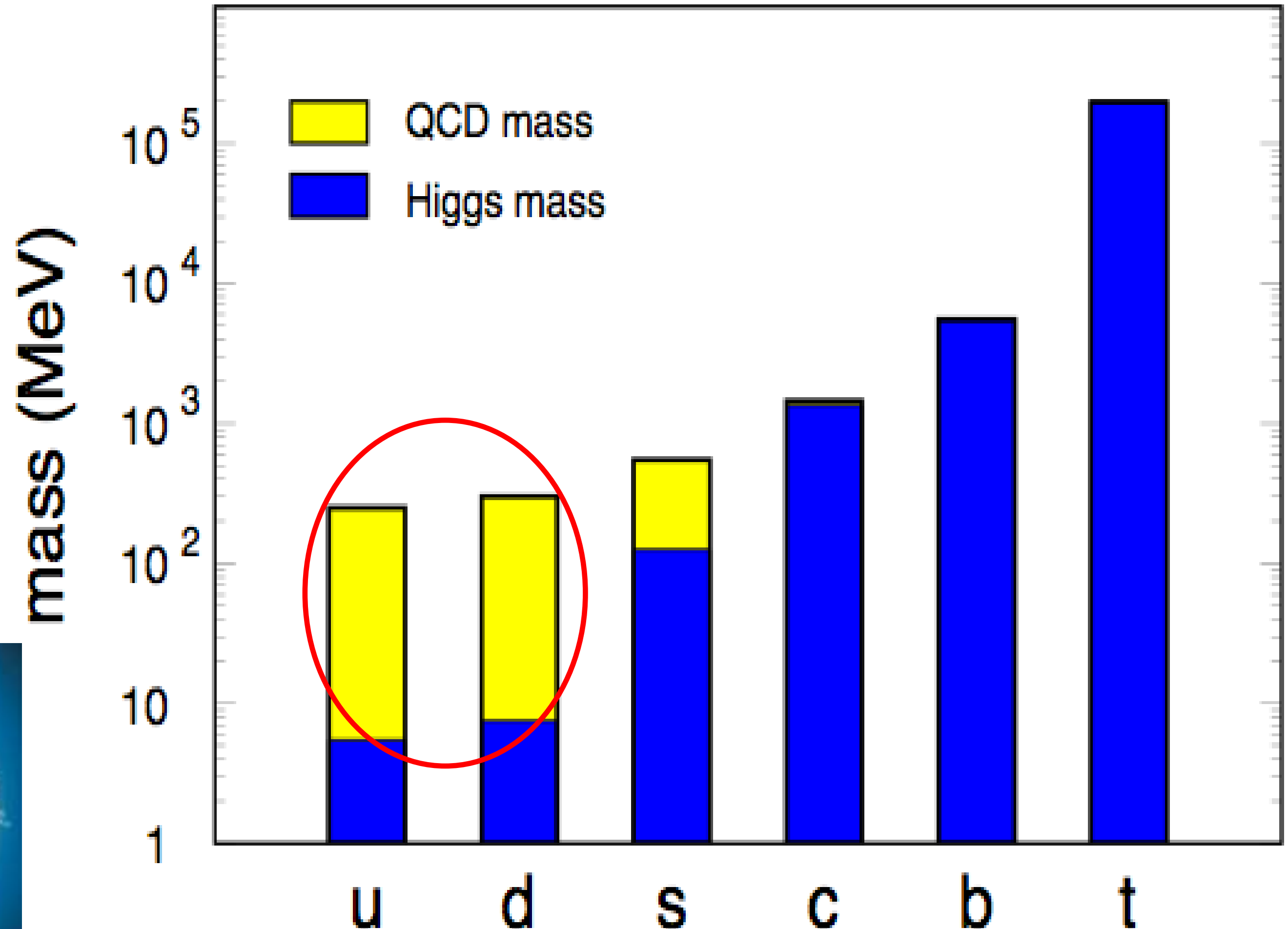
- Chiral, Axial, Scale and (in principle) P &T broken by vacuum/quantum effects - ”emergent” phenomena

- Inherent in QCD are the deepest aspects of relativistic Quantum Field Theories (confinement, asymptotic freedom, anomalies, spontaneous breaking of chiral symmetry) --Raju Venugopalan (BNL Theory Group)


mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
QUARKS
0.511 MeV/c²
-1
1/2
e
electron
<2.2 eV/c²
0
1/2
νe
electron neutrino
LEPTONS
Forceful Spices
Weak
Gravity
Strong
E-M
Leptons
Collect all 6!
QUARKS
REALITY STEW

Where is the mass from?

Muller *nucl-th/0404015*



Confinement and Chiral Symmetry Breaking

Free Quark Searches (Particle Data Book)

FREE QUARK SEARCHES

The basis for much of the theory of particle scattering and hadron spectroscopy is the construction of the hadrons from a set of fractionally charged constituents (quarks). A central but unproven hypothesis of this theory, Quantum Chromodynamics, is that quarks cannot be observed as free particles but are confined to mesons and baryons.

Experiments show that it is at best difficult to "unglue" quarks. Accelerator searches at increasing energies have produced no evidence for free quarks, while only a few cosmic-ray and matter searches have produced uncorroborated events.

This compilation is only a guide to the literature, since the quoted experimental limits are often only indicative. Reviews can be found in Refs. 1–4.

References

1. M.L. Perl, E.R. Lee, and D. Lomba, Mod. Phys. Lett. **A19**, 2595 (2004).
2. P.F. Smith, Ann. Rev. Nucl. and Part. Sci. **39**, 73 (1989).
3. L. Lyons, Phys. Reports **129**, 225 (1985).
4. M. Marinelli and G. Morpurgo, Phys. Reports **85**, 161 (1982).

1. FREE QUARKS
2. EXCITED VACUUM

Quark Matter 1995

T.D. Lee / Nuclear Physics A590 (1995) 11c-28c 13c

Nobel Prize 1957

1. TWO PUZZLES OF MODERN PHYSICS

The status of our present theoretical structure can be summarized as follows:

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$SU(2) \times U(1)$ **Theory** (electroweak)
General Relativity (gravitation).

However, in order to apply these theories to the real world, we need a set of about 18 parameters, all of unknown origins. Thus, this theoretical edifice cannot be considered complete.

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T.D. Lee / Nuclear Physics A590 (1995) 11c-28c 15c

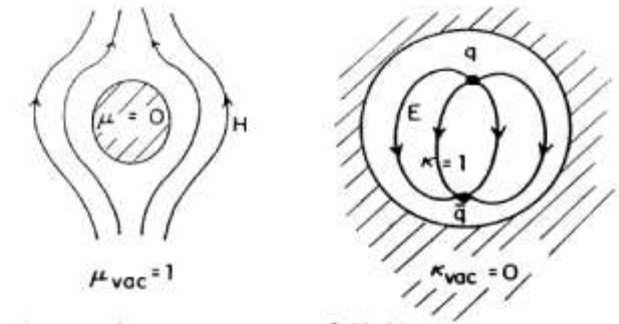


Figure 1. Superconductivity in QED vs. quark confinement in QCD.

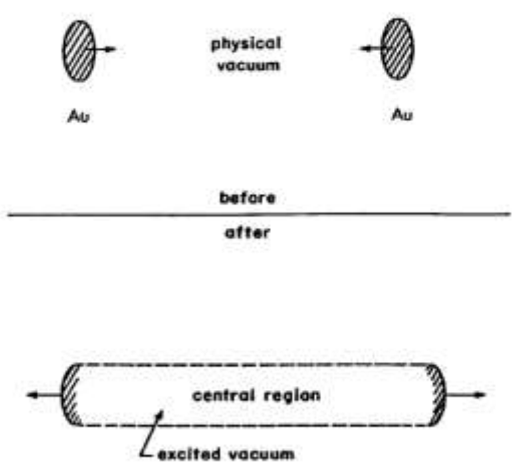


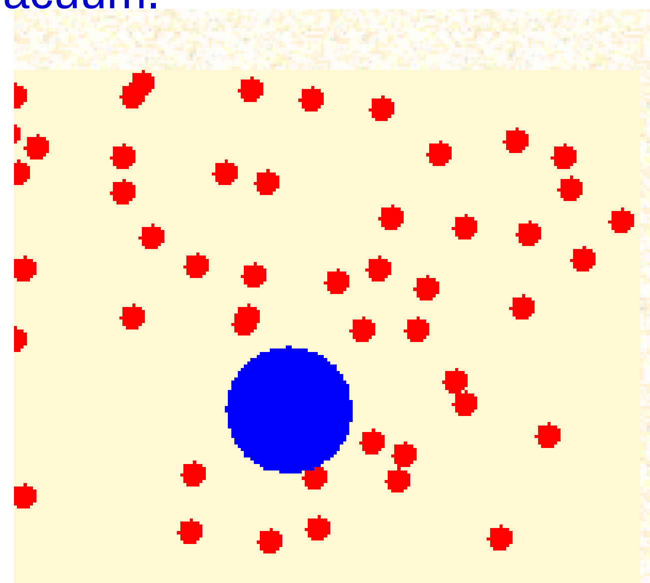
Figure 2. Vacuum excitation through relativistic heavy ion collisions.

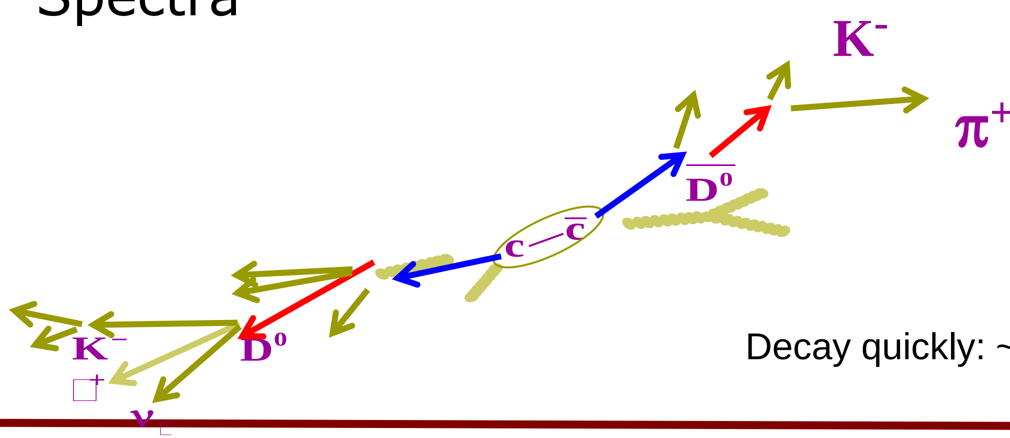
1. Color Screening of Quarkonia, Charm Quark Flow
2. In-medium ρ spectral function, thermal radiation, Chiral Magnetic Effect

Brownian motion of Heavy quarks

- Charm quarks
  m ~ 1275 MeV
  T ~ 160 MeV
- "drag" and diffusion of "solid" object
- Direct Reconstruction
  - Elliptic flow
  - Spectra

Einstein's famous theory in 1905 paper served as definitive confirmation that atoms and molecules actually exist.
Same should be true with free quarks in excited vacuum.

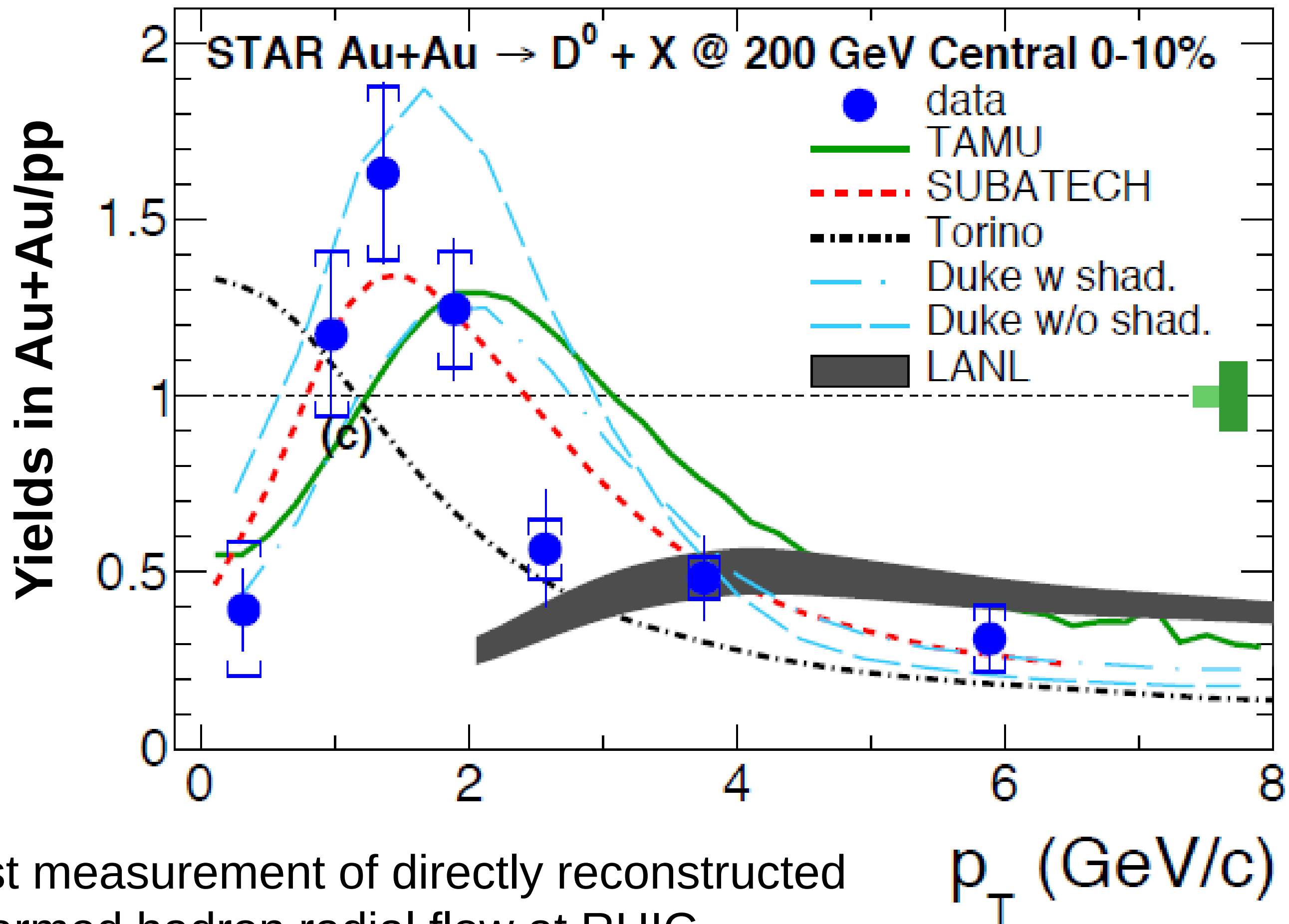




Decay quickly: ~120µm

8

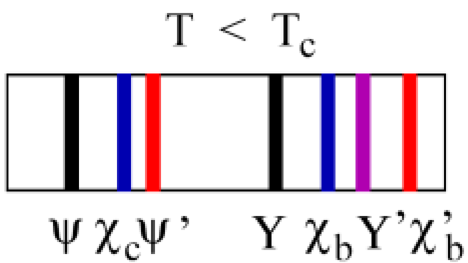
Flow and Quenching of Heavy Quarks

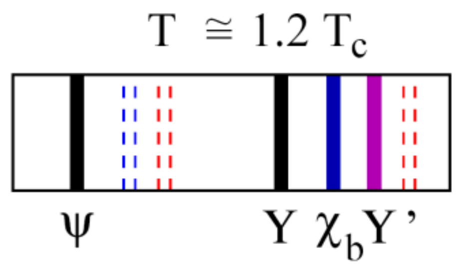


First measurement of directly reconstructed Charmed hadron radial flow at RHIC
arXiv: 1404.6185; PRL 113 (2014) 142301
Results in U+U Collisions (QM2014)

HFT/STAR and ALICE upgrades Crucial to moving forward the Program

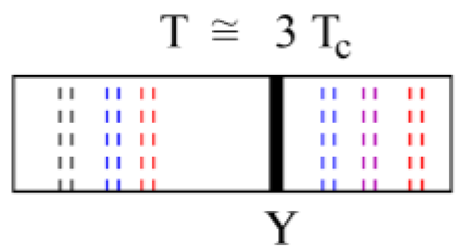
Color Screening of Quarkonium in QGP



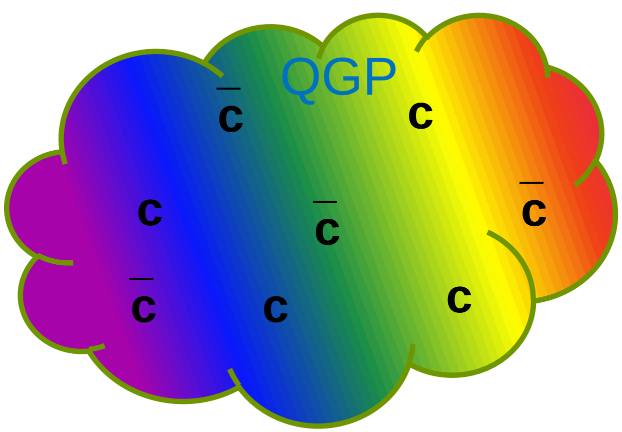


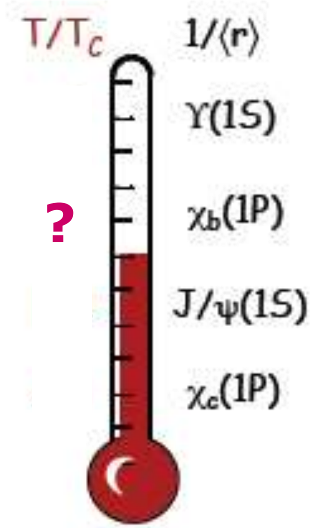
Melting

H. Satz, Nucl. Phys. A (783):249-260(2007)



J/Ψ → $\bar{c}$+c





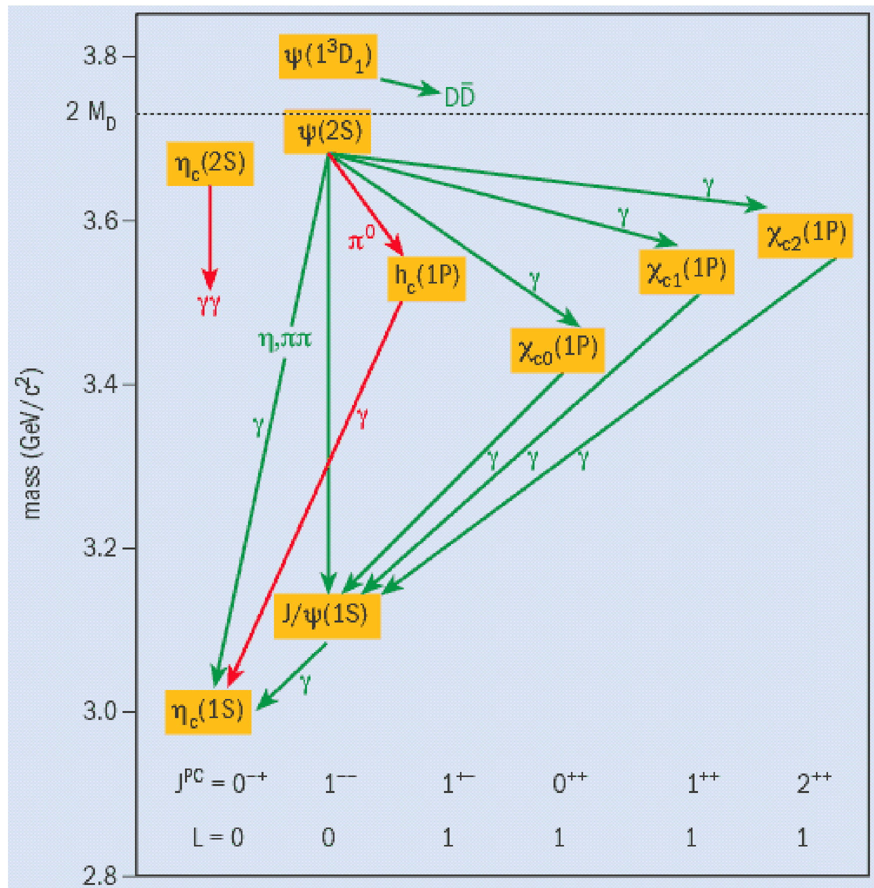
J/ψ (charm bound state)

SLAC/BNL

J/Ψ ($\bar{c}c$) → e^+e^-

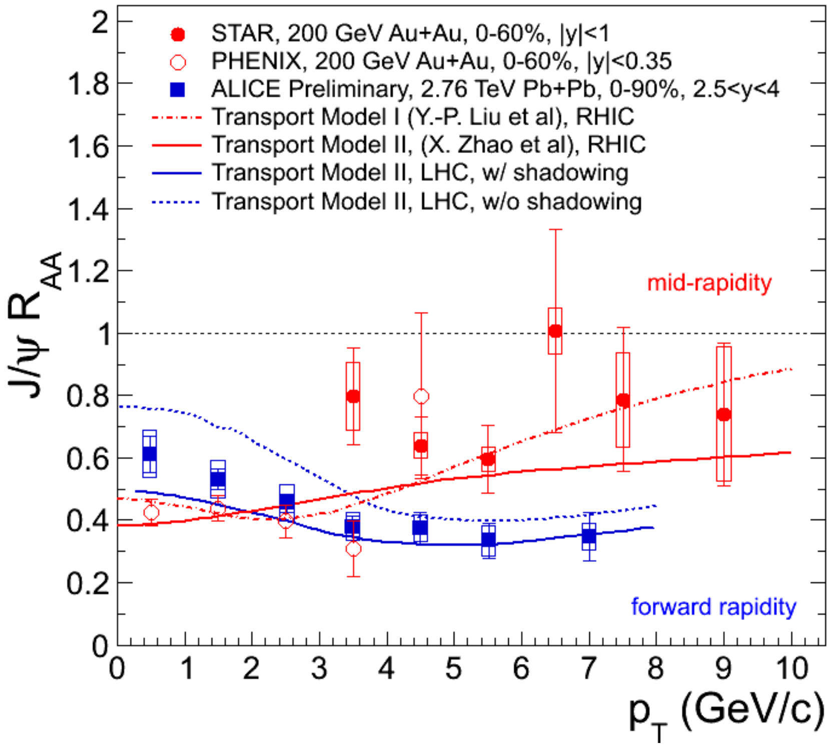
? → D+ $\bar{D}$

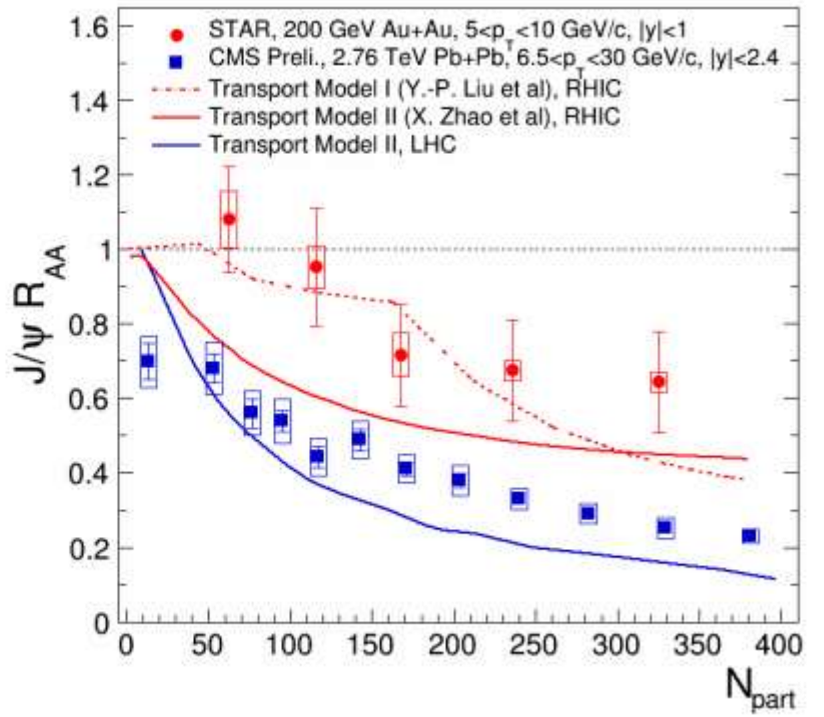
ϕ → K+ $\bar{K}$



J/ψ p_T dependence in A+A

PHENIX: PRL98(2007)232301;STAR: arXiv: 1208.2736, PLB (2013)





J/ψ R_{AA} decreases from low to high p_T at LHC.

J/ψ R_{AA} increases from low to high p_T at RHIC.

J/ψ R_{dA} reach unit at p_T>4GeV/c.

At high p_T, J/ψ more suppressed at LHC.

SPS/RHIC exhibits similar level of suppression.

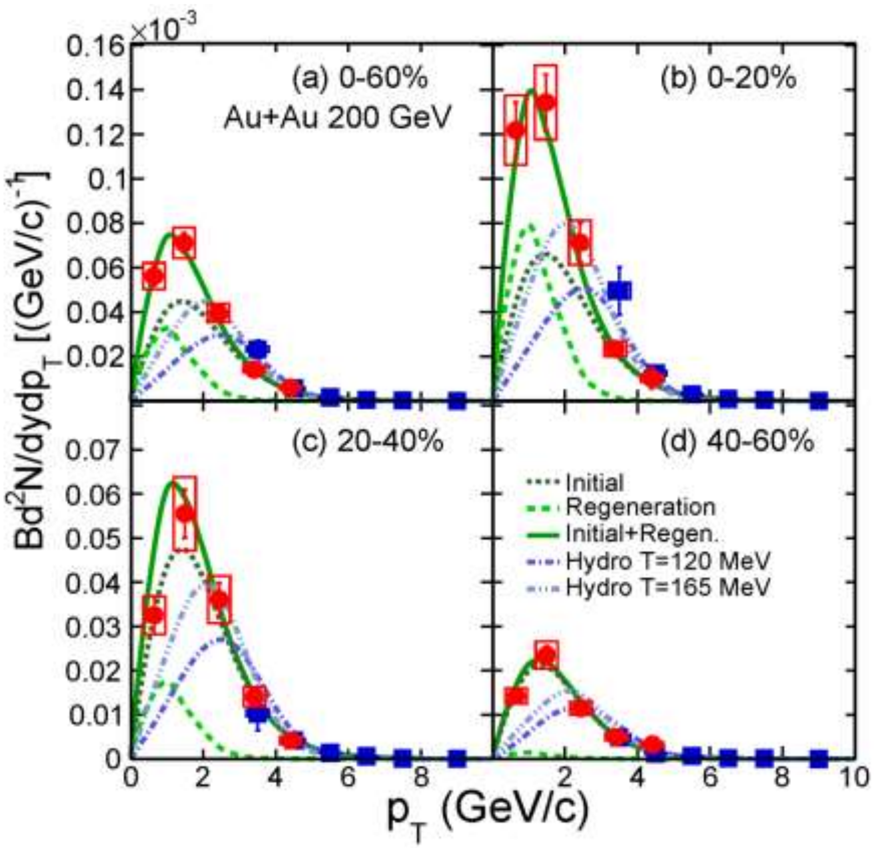
Substantial interaction (not just cold nuclear effect)

J/ψ Suppression without flow

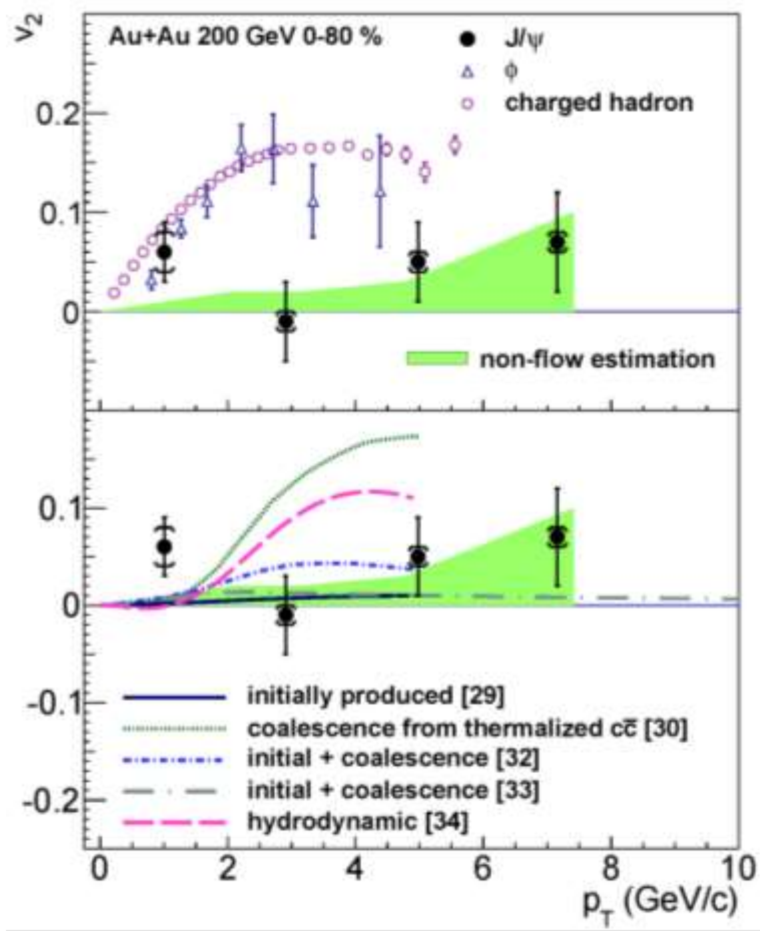
RHIC:
large suppression, zero flow
LHC:
less suppression, hints of flow

Color Screening and quark coalescence

STAR low-p_T Phys. Rev. C 90, 024906 ; high-p_T : Phys.Lett. B722 (2013)



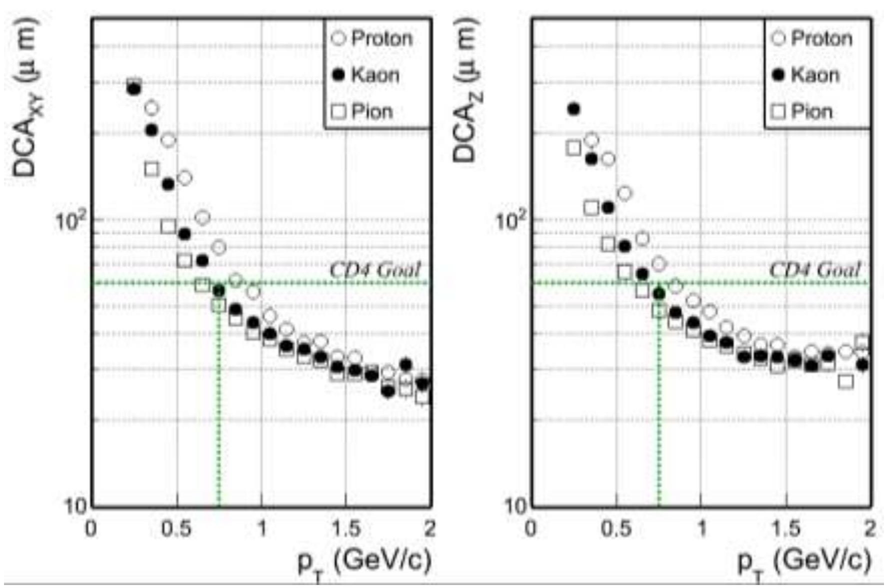
Phys. Rev. Lett. 111 (2013) 52301



Next step:
High-statistics J/Psi;
Separate three Upsilon States at RHIC

Heavy Flavor Tracker

$\sqrt{s_{NN}}$ = 200GeV Au+Au Collisions



Heavy Flavor Tracker (HFT)

Fully reconstruction of charm hadron with displaced vertex

Physics goal: **Precision measurement of heavy quark hadron production in heavy ion collisions**

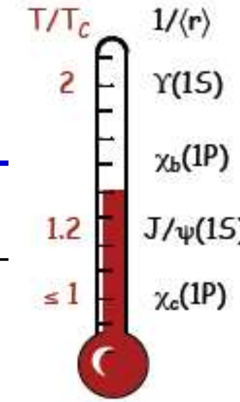
All 3 sub-detectors (PXL, IST, SSD) were completed, installed prior to Run14

PXL – heart of the HFT: state-of-art detector, MAPS technology, first time used at a collider experiment.

Taking data with STAR detector system, on track towards the physics goal

Reach Performance Requirement Goal:
With survey and preliminary alignment,
Kaons at 750 MeV/c: DCA < 60μm

To the future



To constrain η/s, D, and T …

Facility	Current measurements	Future measurements
RHIC heavy flavor	D R_{AA}, e from charm and bottom decays	e, muon from charm, e, muon from bottom, D with better precision, Λ_c, charm-charm correlation, heavy flavor tagged jet, B from non-prompt J/psi,
LHC heavy flavor	D, B from non-prompt J/psi, leptons from charm and bottom decays, B-tagged jet	Improve low and intermediate p_T measurements
RHIC quarkonia	ϒ(1S+2S+3S), J/ψ, ψ(2S) in dAu/pp	ϒ(1S), ϒ(2S), ϒ(3S), J/ψ with better precision at low and intermediate p_T, possible ψ(2S) and J/ψ tagged jet (away side)
LHC quarkonia	ϒ(1S), ϒ(2S), ϒ(3S), J/ψ, ψ(2S)	Improved precision

Beam Energy Close to Charm Threshold

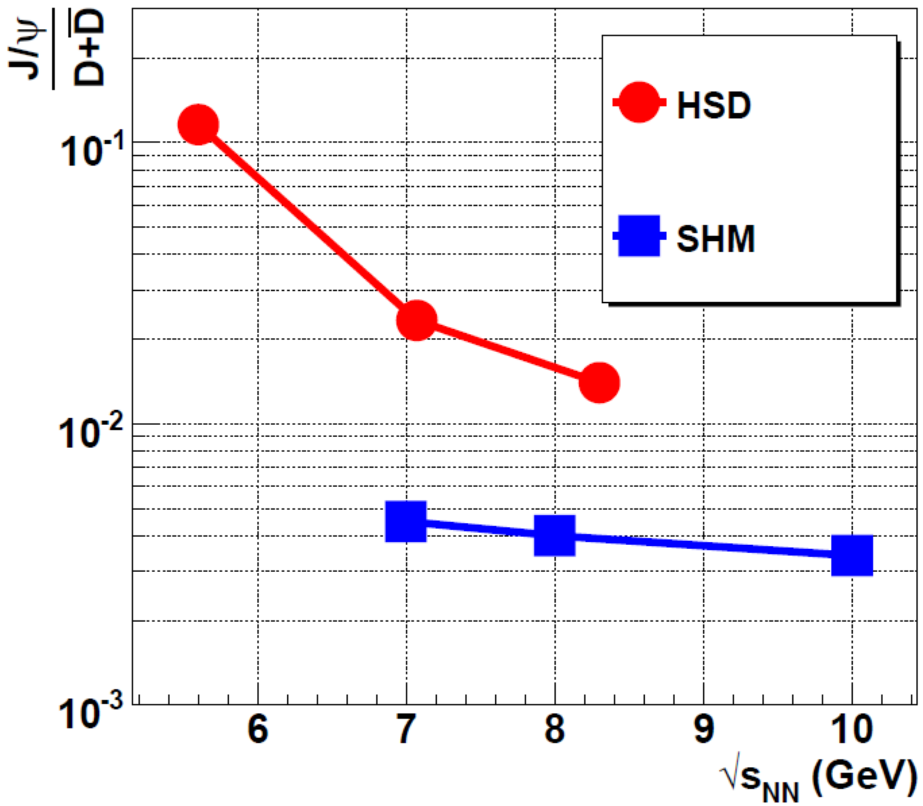


Fig. 8.17 Ratio of J/ψ over $D+\bar{D}$ mesons as a function of available energy in the nucleon-nucleon system predicted for central Au+Au collisions by the HSD hadronic transport model and by the statistical hadronization model SHM [19] which assumes a QGP initial state.

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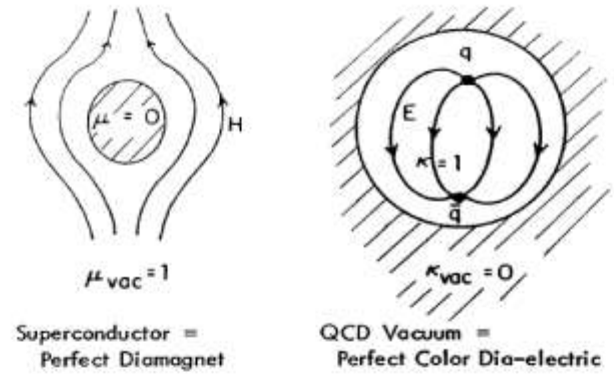


Figure 1. Superconductivity in QED vs. quark confinement in QCD.

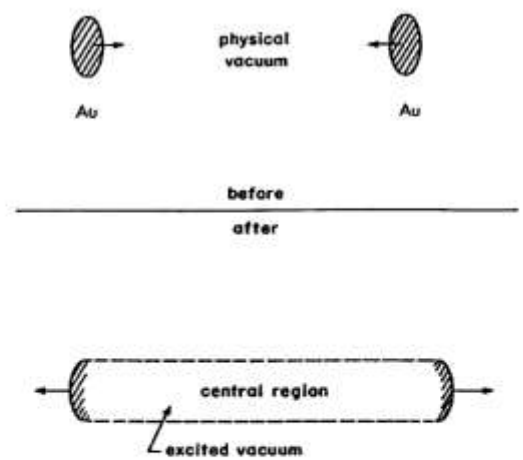
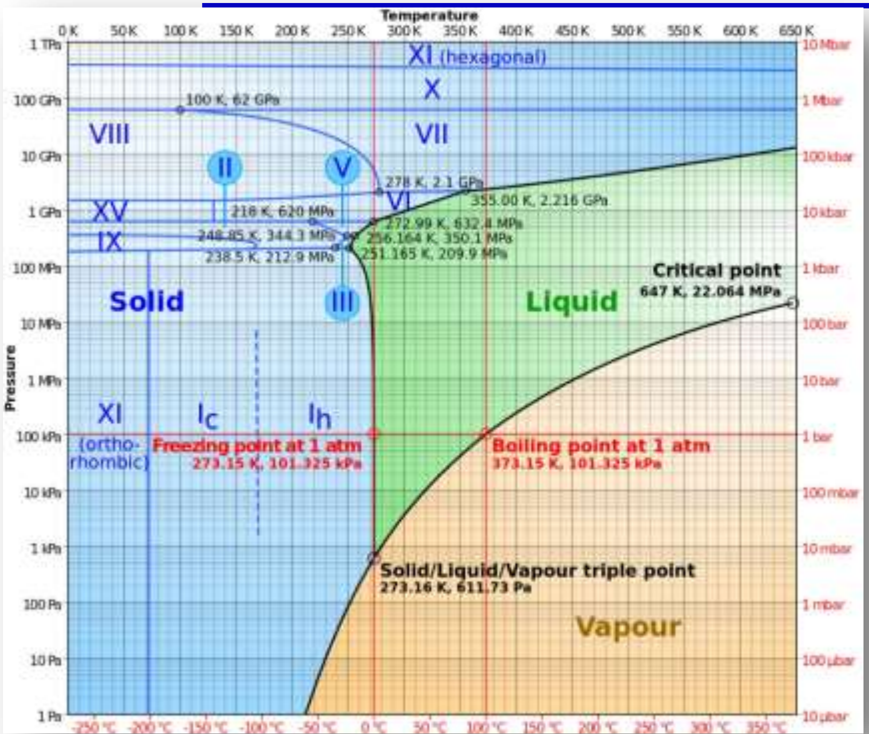
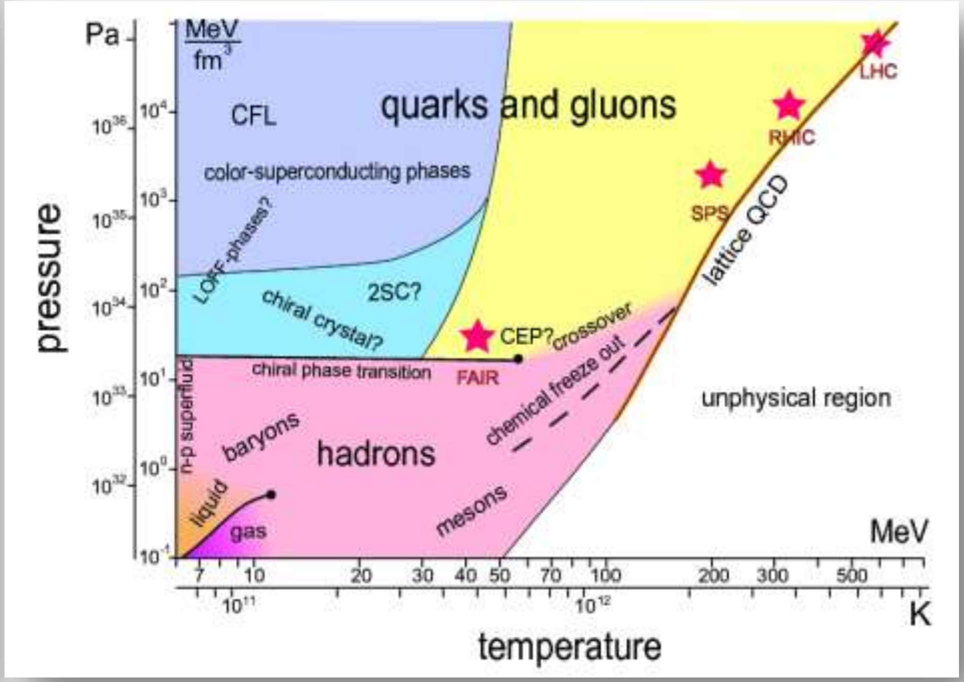


Figure 2. Vacuum excitation through relativistic heavy ion collisions.

1. Color Screening of Quarkonia, Charm Quark Flow
2. In-medium ρ spectral function, thermal radiation, Chiral Magnetic Effect

Physics Goal: Establishing the QCD Phase Diagram





Phase Diagram of Water
Electromagnetic Interaction
Precisely known

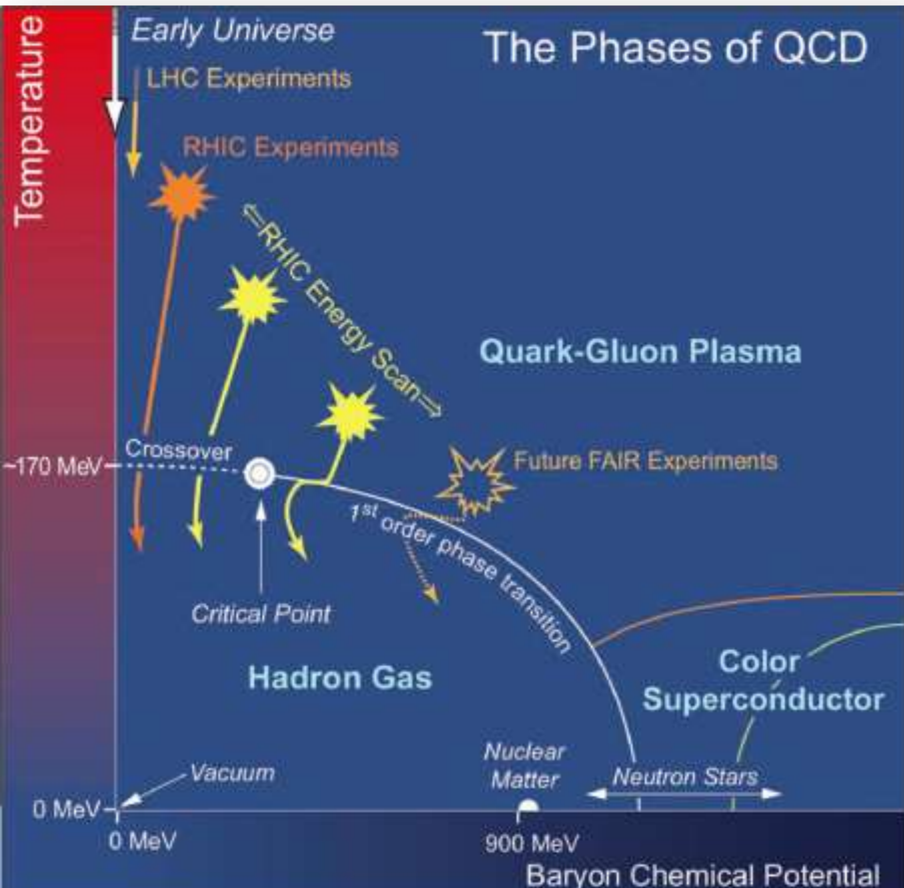
Phase Diagram of Strong Interactions.

arXiv:1111.5475 [hep-ph]

Goal: Establish the phase diagram of strong interactions to a comparable level as for Electromagnetic interactions.

Phase Diagram and Relativistic Heavy-Ion Collisions

US Long Range Plan 2007



Conservation in strong interactions

-- Charge (μ_Q)

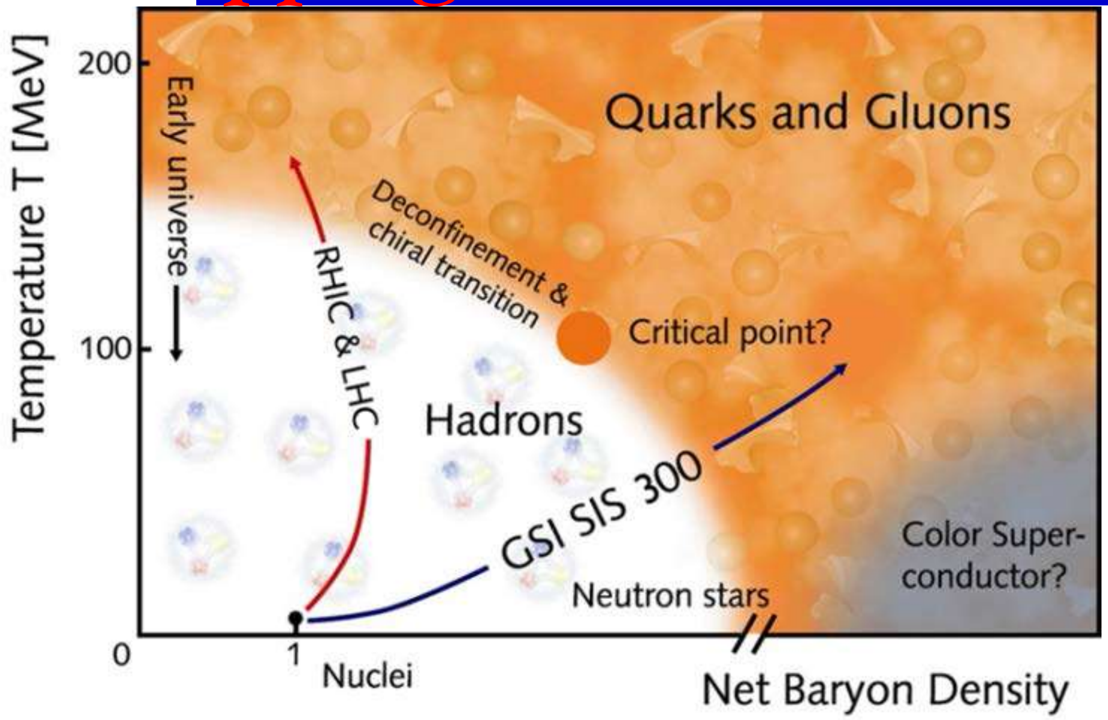
-- Baryon number (μ_B)

-- Strangeness (μ_S)

Vary: T, μ_B, μ_S, μ_Q

Collide heavy-ions and vary beam energy to change Temperature & Baryon Chemical Potential

Mapping the QCD Phase Diagram



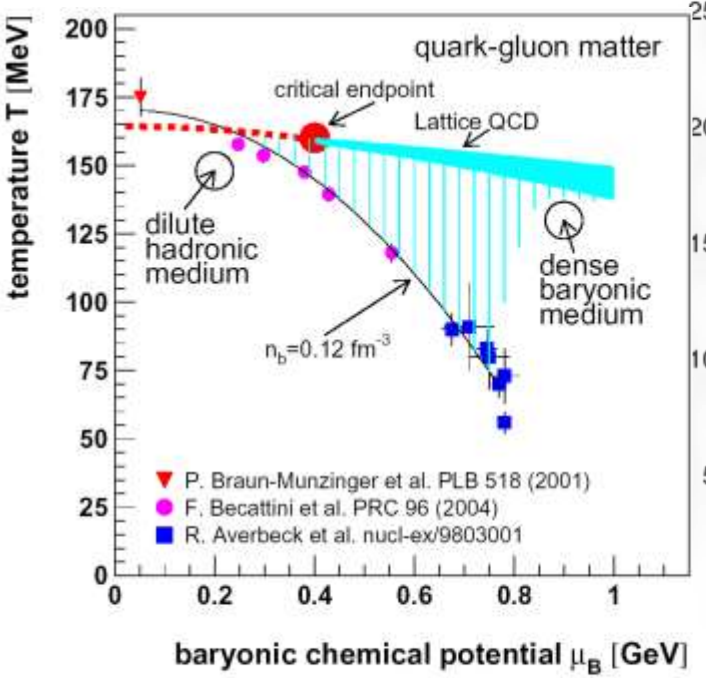
The predicted
QCD critical point
a landmark

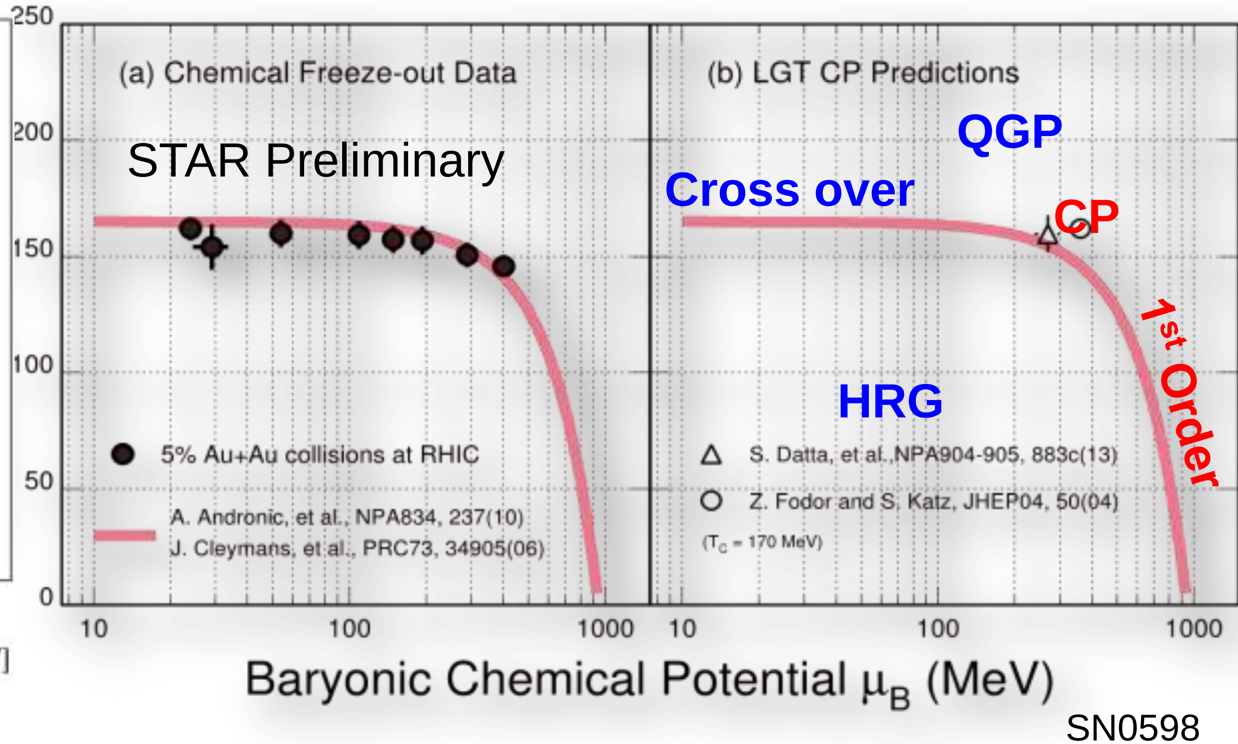
anchoring the crossover transition to the sQGP at low baryon density

first order phase boundary
and quarkyonic matter
at high baryon density.

RHIC:
Hints of new behavior in first Beam Energy Scan
Beam Energy Scan Phase 2 (BES II):
from hints to quantitative understanding
strive to reach high-statistics at lower energy
FAIR:
strive to reach high energy with unprecedented statistics

Phase Diagram: Experimental Points

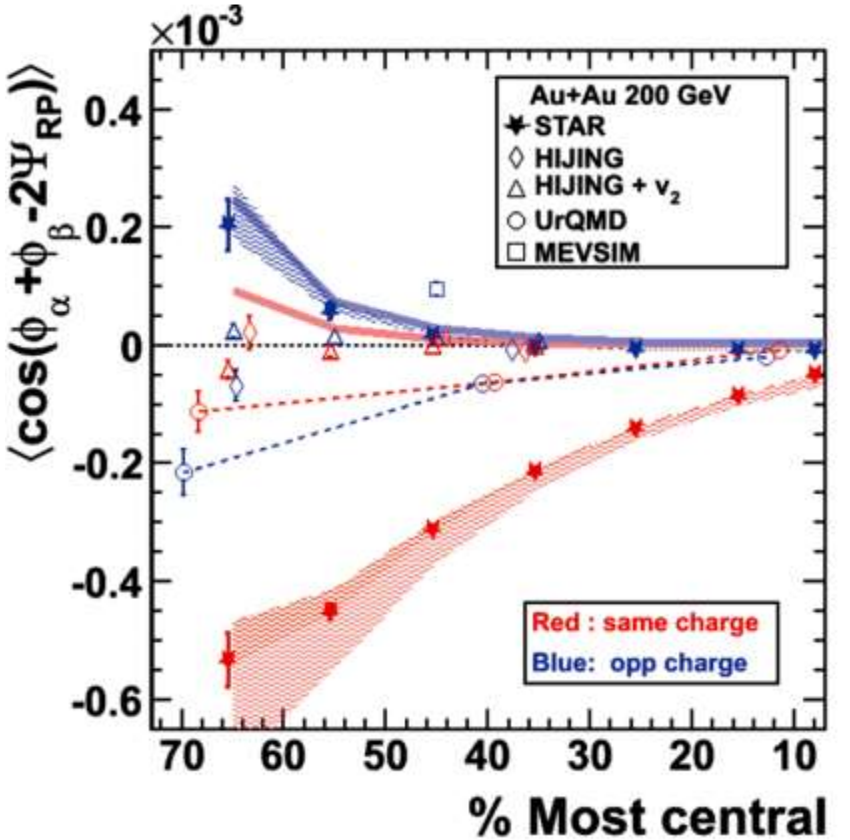




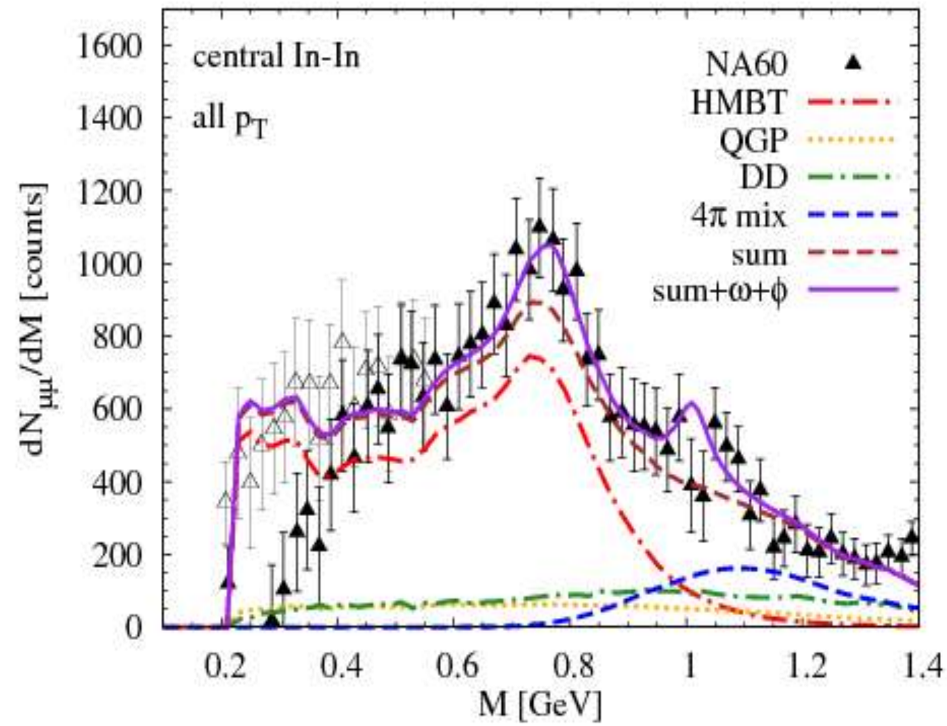
Partonic Phase Hadronic Phase	Cross Over First Order	Critical region*

Novel Symmetries

Chiral Magnetic Effect

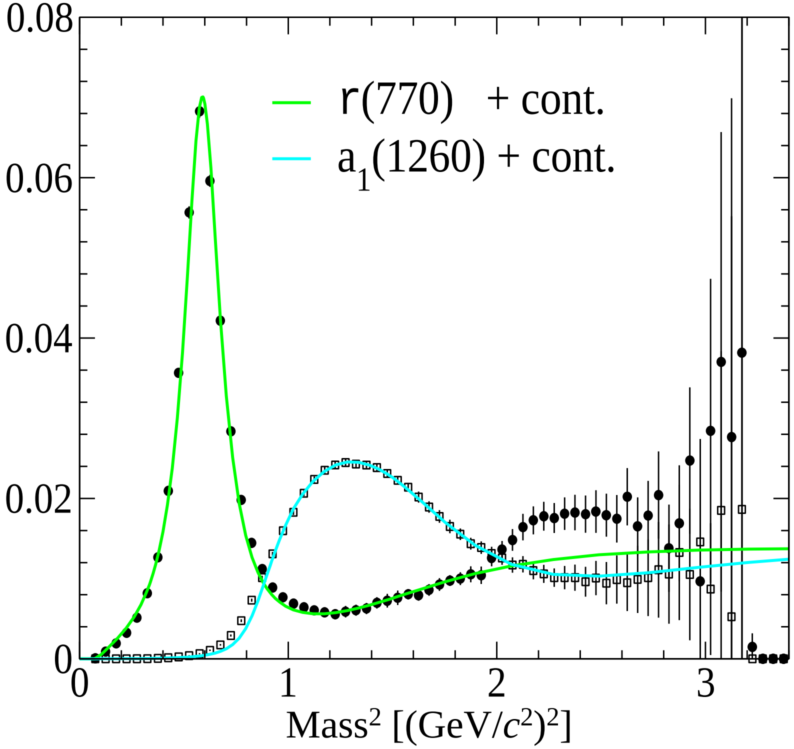


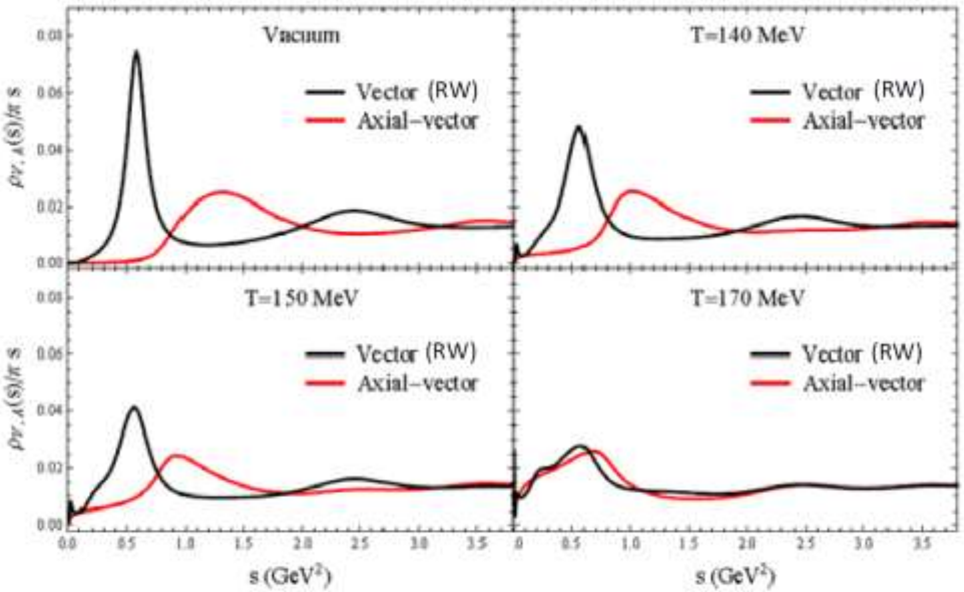
Vector Meson in-medium modification



Crucial to verify if Chiral Symmetry Restoration Effect is the **correct explanation**

ρ and a1 resonance (spectrum function) in (excited) vacuum





ALEPH: EPJC4 (1998) 409;

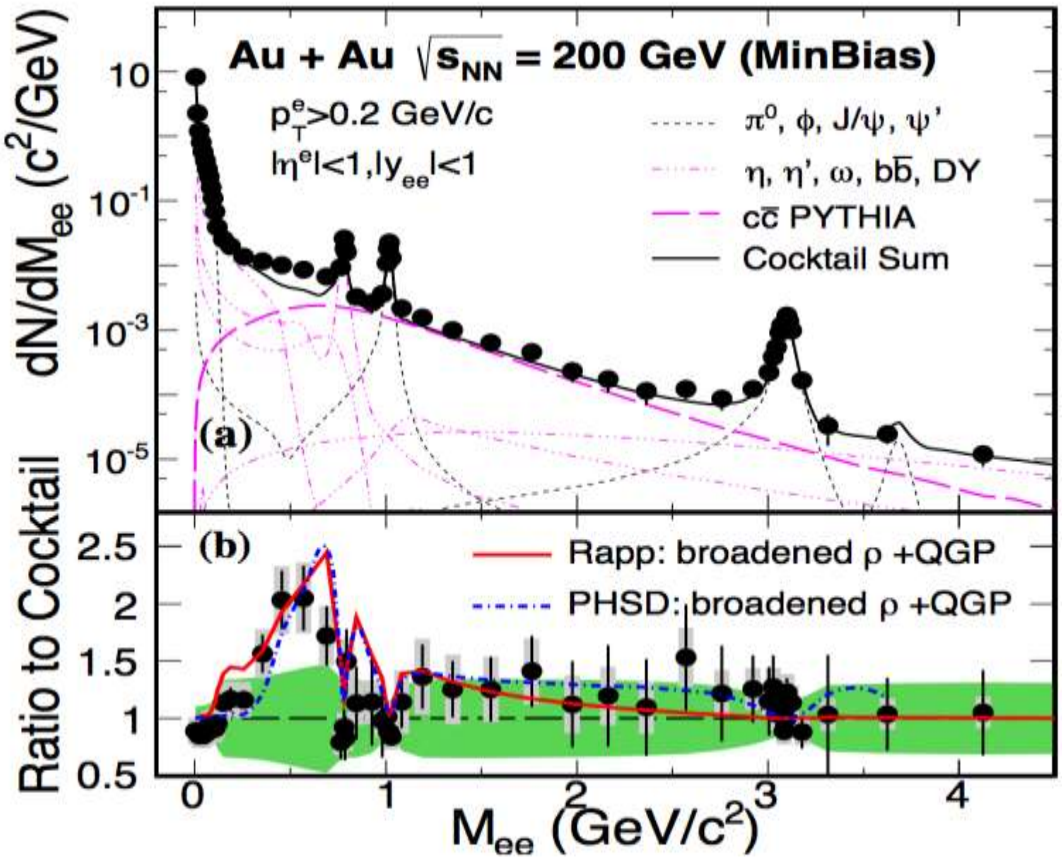
R. Rapp Pramana 60 (2003) 675.

Spontaneous chiral symmetry breaking:

mass distributions are different

Chiral symmetry restoration: mass difference disappears

Dilepton In-medium Effect



- Practical way of observing chiral symmetry restoration from dileptons:
  disappearance of hadronic structure (vector meson peaks) dissolve into continuous thermal distribution from LMR to IMR
- Subtract charm contributions at IMR
- Time-of-Flight (TOF) upgrade (2010+) enables this program; the most successful US-China collaboration in nuclear science
- Same groups are making TOF for CBM

LMR

$\rho \rightarrow e^+e^-$

$\pi\eta\phi\omega$

IMR

$q\,\bar{q} \rightarrow l^+l^-$

$c \rightarrow l$

HMR

J/Ψ, DY, Υ(1,2,3)

arXiv:1312.7397, PRL 113 (2014) 022301
published July 08, 2014

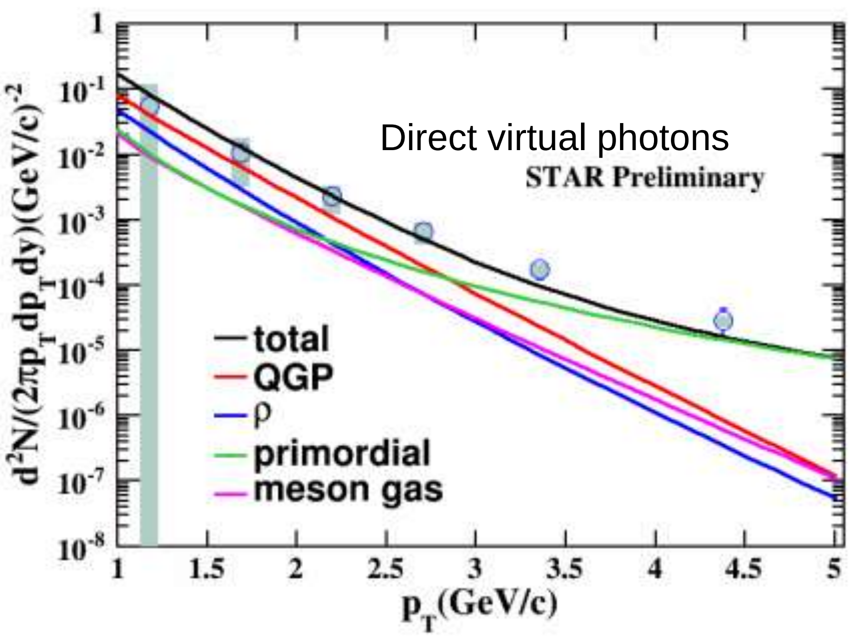
Quantify the Spectral Function

Temperature dependence of rho spectral function

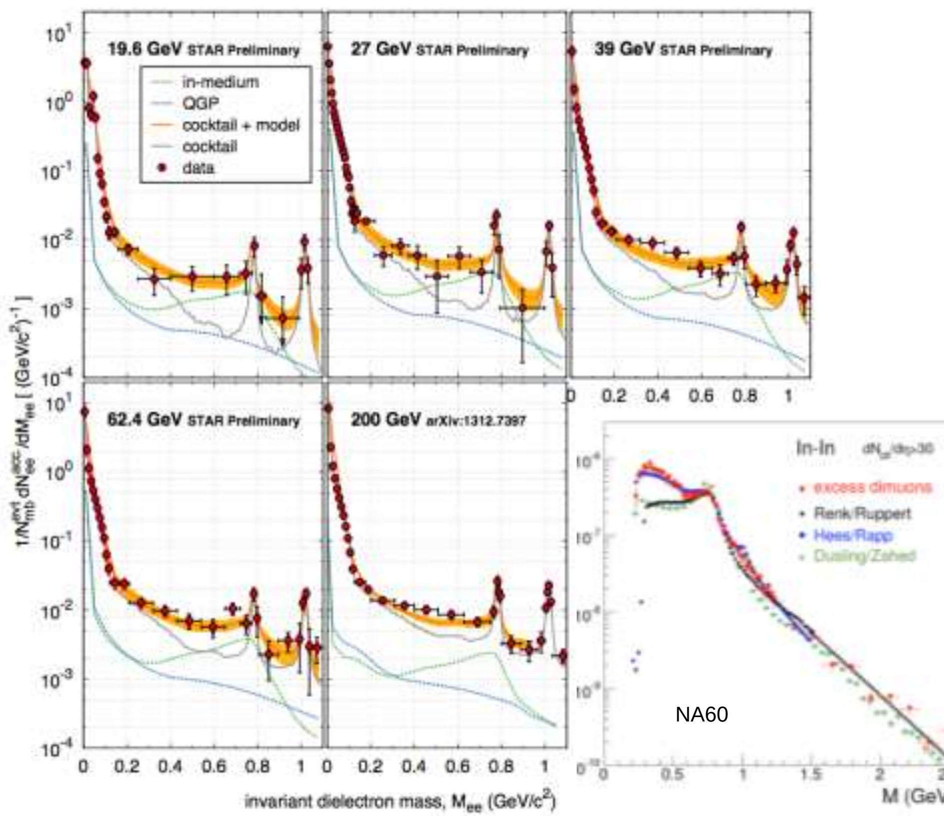
1. Use centrality dependence as another knob
2. Direct photon results should match with extrapolation

Baryon dependence of rho spectral function

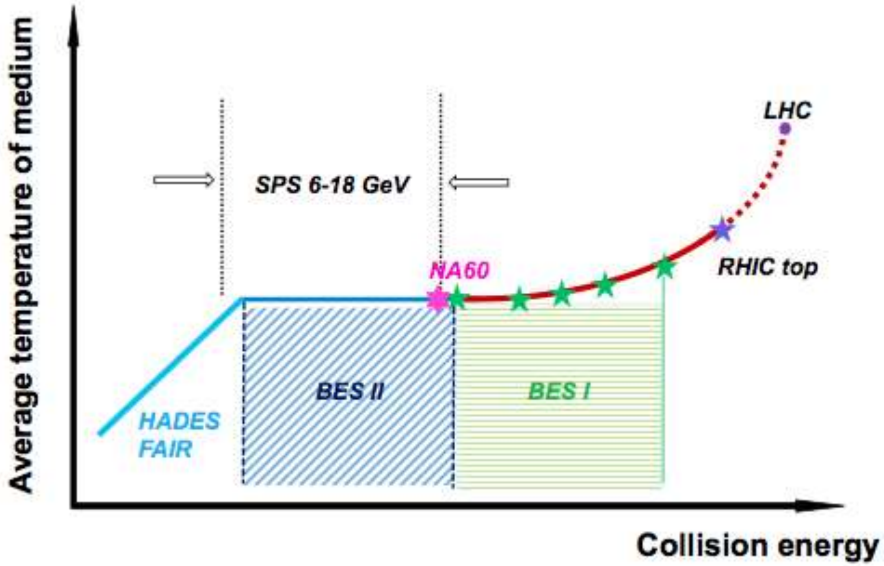
1. LMR excess expected to be consistent with total baryon density increase
2. Beam Energy with detectors capable of dilepton measurements: HADES, CBM, NA60+, STAR

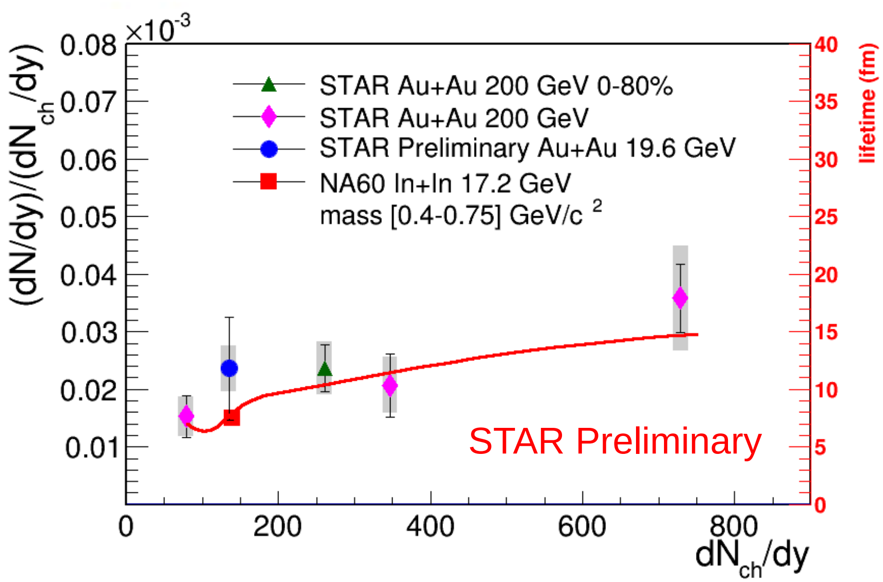


QM14: Chi Yang, Patrick Huck



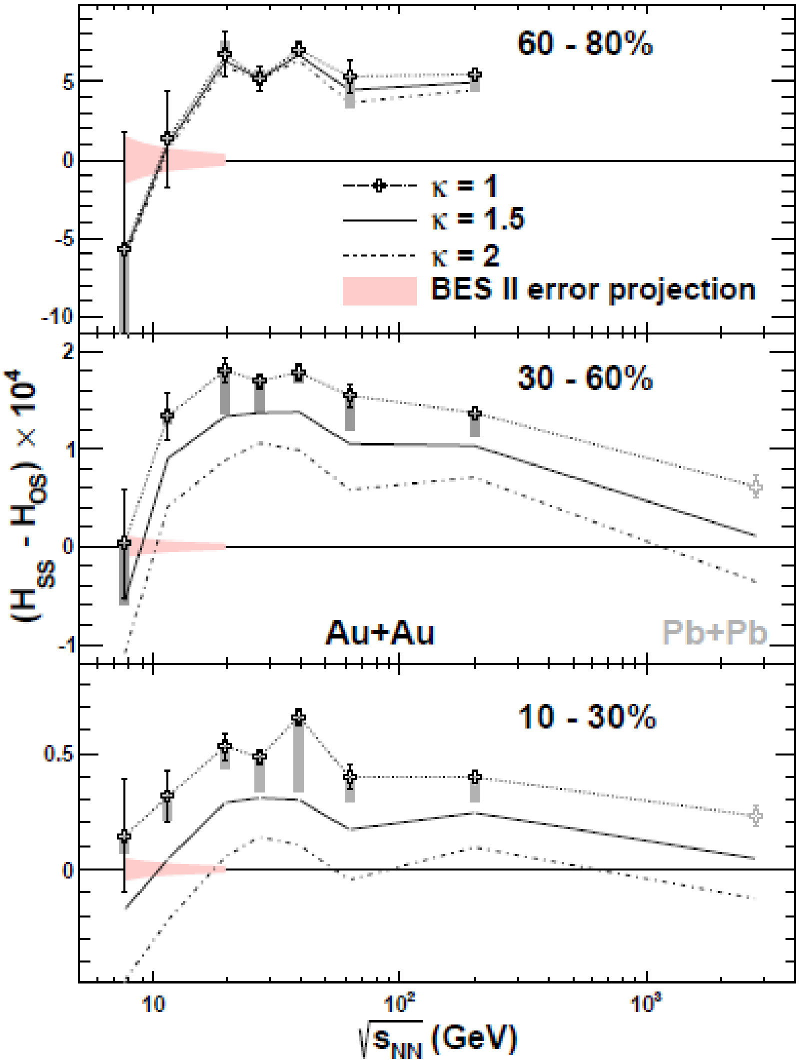
The future dilepton program





- **17.3 GeV to 200 GeV: the dilepton emission is in the T_c region, total baryon density is nearly a constant, therefore, the emission probes lifetime effect.**
- **RHIC beam energy scan phase II: probes the life time and total baryon density effect.**
- **NA60+ energies overlap with those at RHIC BESII and FAIR.**
- **Down to FAIR energies: probes the lifetime, total baryon density and temperature dependence.**

Chiral Magnetic Effects



STAR, Phys. Rev. Lett. **113** (2014) 052302
ALICE, Phys. Rev. Lett. 110 (2013) 012301

- Charge separation with respect to the reaction plane. Non-zero separation at high energies with a decreasing trend toward low energy
- Quarks (chiral) interact with gluonic fields (topologic change); produce such a charge separate with external magnetic field
- BES II determines if the effect disappears at low energy
- Similar effect with magnetic wave (CMW) and baryon vertices (CVE)
- Chiral Symmetry Restoration a necessary condition

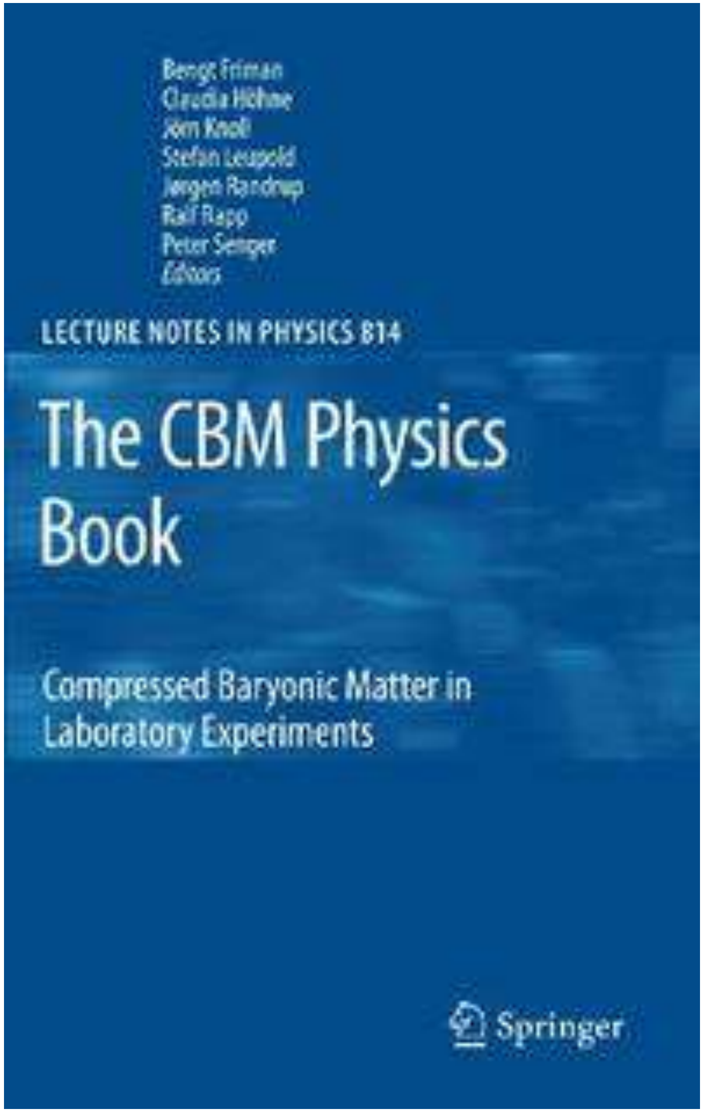
Two Strong Programs for the Future (2018+)

Scale of the Collaborations: ~10 countries, 50 institutions, 500 collaborators

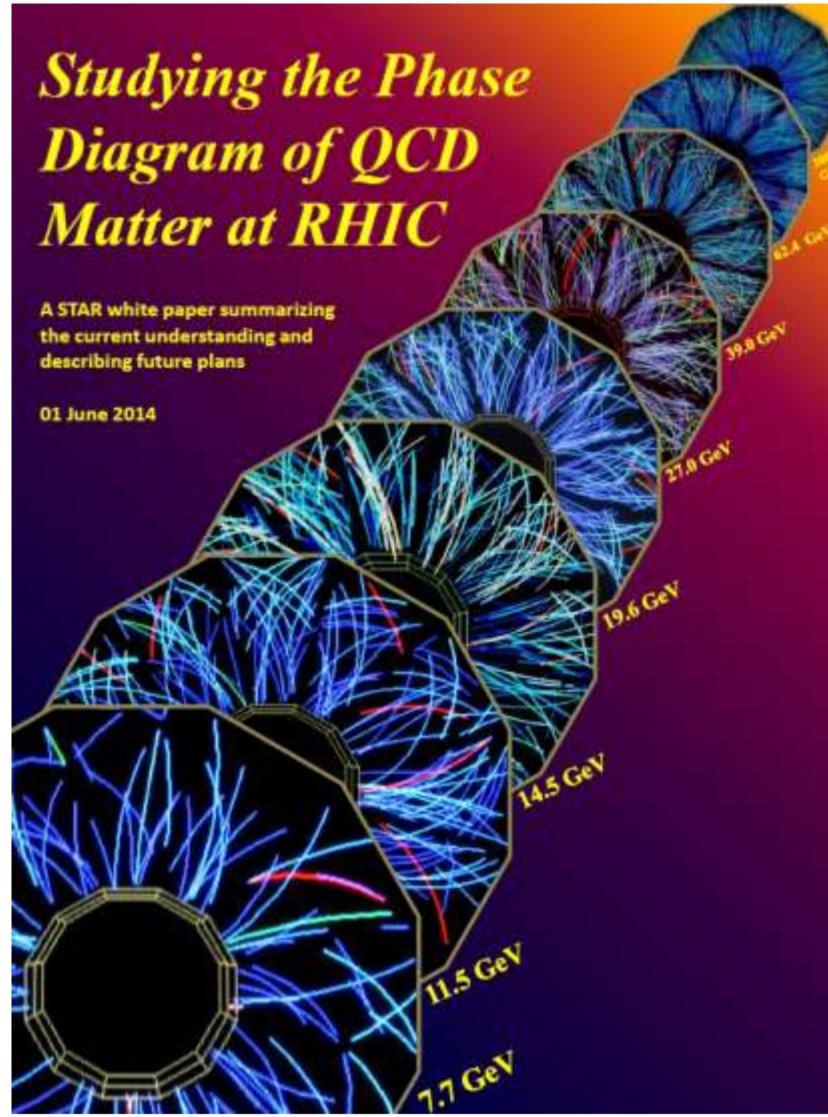
2000

23rd CBM Collaboration Meeting, GSI, April 2014

CBM Physics Book, STAR BES Whitepaper



http://www.fair-center.eu/for-users/experiments/cbm/the-cbm-physics-book.html



https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Summary

Effective use of penetrating probes (heavy-flavor, jet and dileptons) to study the properties of QCD

- Quantifying behavior of free heavy-quarks in-medium
- The role of color screen in quarkonium production
- Energy loss of energetic partons and quantifying medium properties
- Degree of Chiral Symmetry Restoration impacts on hadron spectral function

- Exciting results from **BES I narrowing regime of search window** for turn-off QGP signals; first-order phase transition; critical point
- proposes **BES II** to answer compelling questions about the phase structure of QCD matter;
  provide **precision data** for quantitative comparison with models on EOS at high-baryon density
- **Position ourselves in the frontiers of nuclear science**

Some of these developments have identified the regime of high baryon densities as a particularly interesting one. This is the main motivation for the proposed Compressed Baryonic Matter (CBM) experiment at the Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt. Closely related science will be pursued in a complementary fashion in an "energy scan" at the existing Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National

-- preface of the CBM Physics Book

Phase Diagram at high-baryonic density in 2018