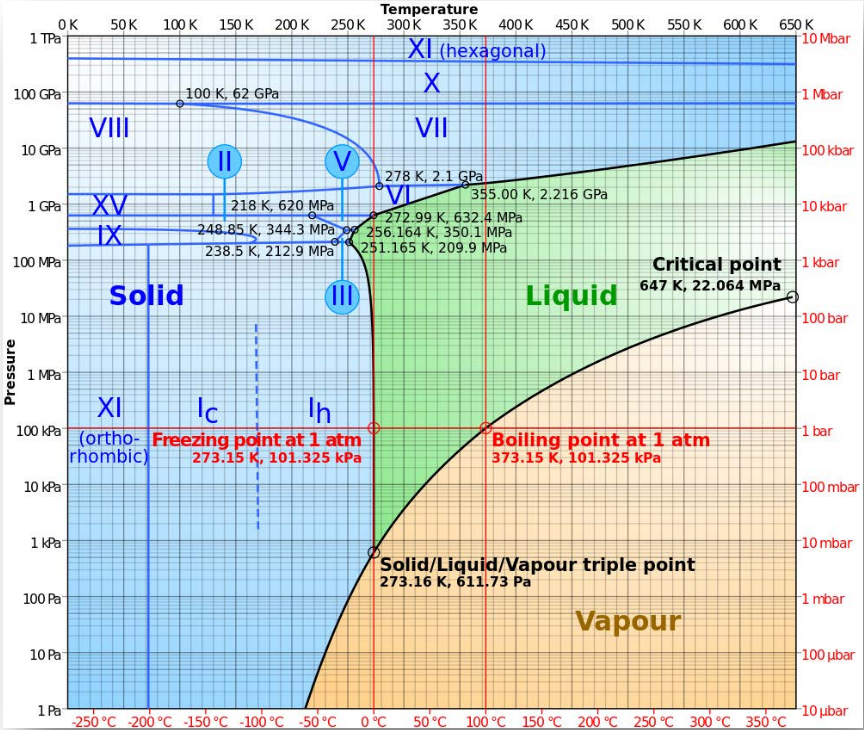
Search for the Possible Critical Point and Novel Symmetry in QCD Phase Diagram

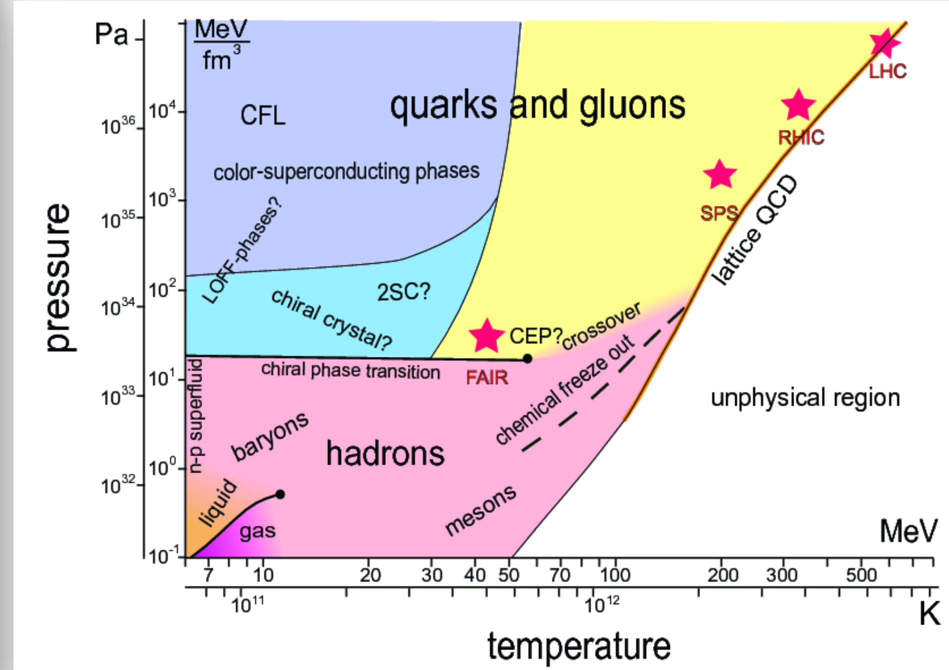
Outline:

- ✓ QCD Phase Diagram
- ✓ Signature and experimental search for Critical Point
- ✓ Chiral Symmetry Restoration and its probes
- ✓ Upgrades for BES II
- ✓ Future Plan
- ✓ Summary

Zhangbu Xu,
For the STAR Collaboration

Physics Goal: Establishing the QCD Phase Diagram





Phase diagram of water
Electromagnetic interaction
Precisely known

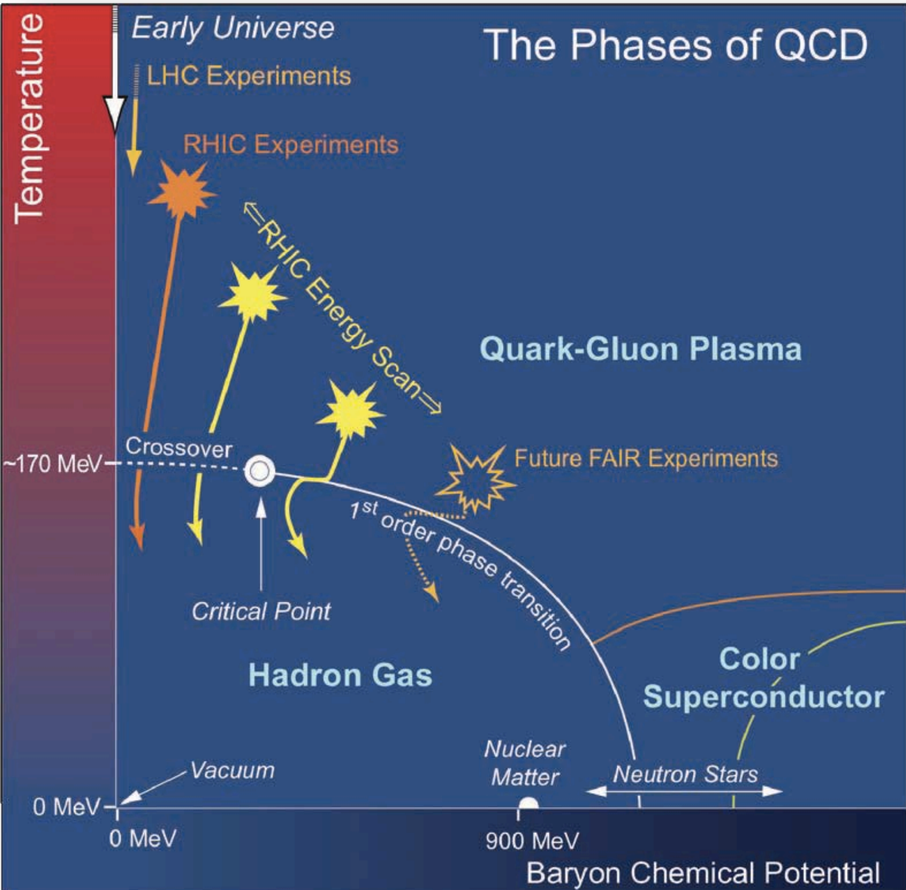
Phase diagram of strong interactions.

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)

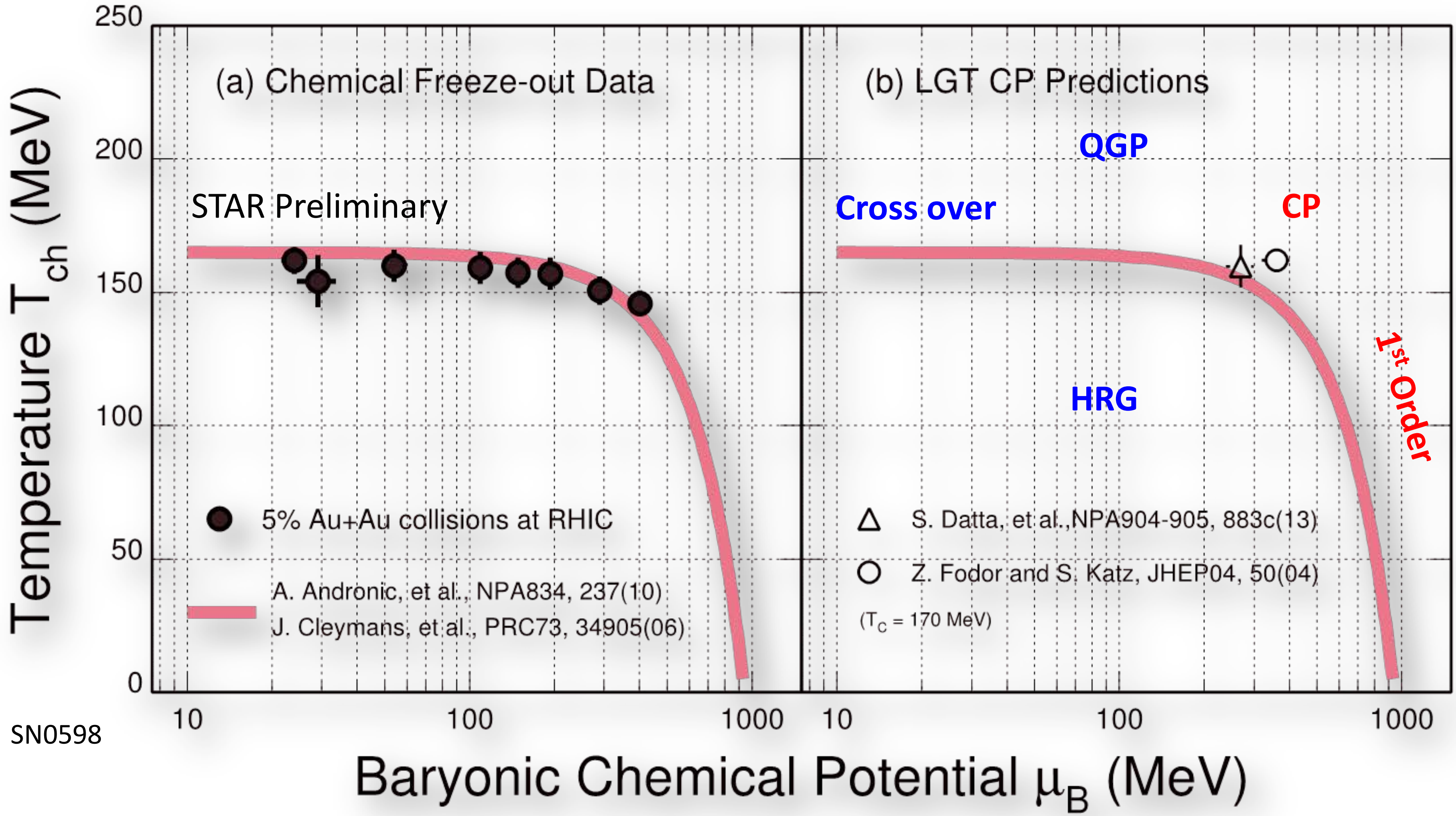
-- Strangeness (μ_S)

Vary: T, μ_B, μ_S, μ_Q

Baryon stopping is the reason that we can achieve finite baryon chemical potential

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

Phase Diagram: what remains to be done



Partonic Phase
Hadronic Phase

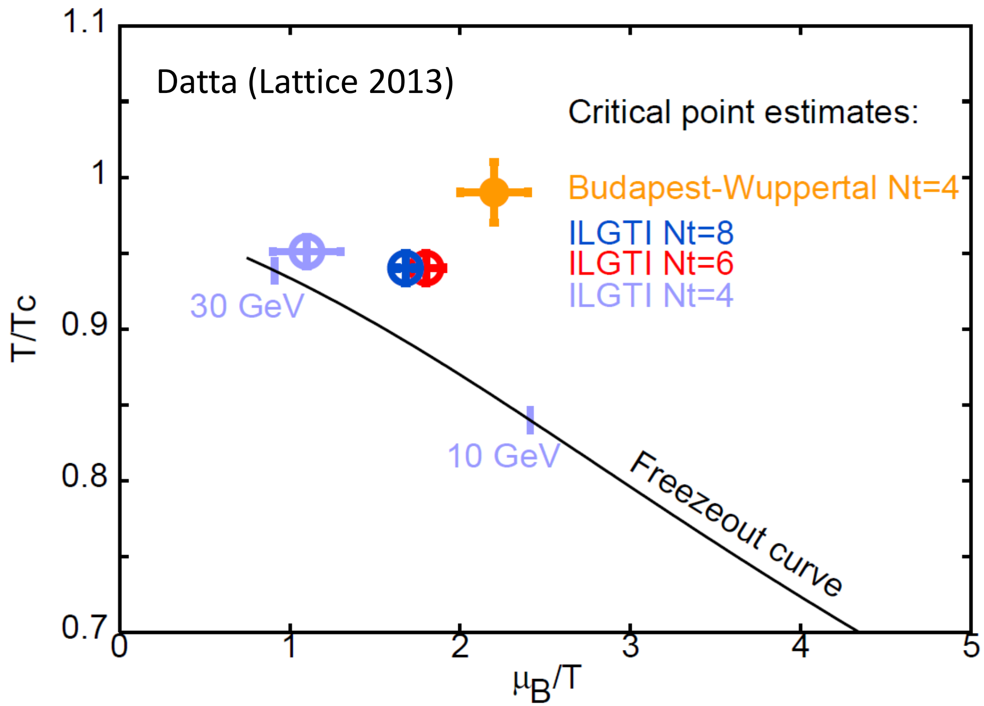
Cross Over
First Order

Critical region*

Search for Critical Point - Theory

Numerical QCD calculations at large μ_B – sign problem

Techniques: Reweighting, Taylor expansion & Imaginary μ_B



Phys. Rev. D 78, 14503 (2008)
Phys.Rev.D 71, 114014 (2005)

Acta Phys.Polon.Supp. 5 (2012) 825-835
JHEP 0404, 50 (2004)

Issues (not common to all) : lattice spacing, physical quark mass, continuum limit, Volume

Theory: Suggests CP may exist between 10 – 30 GeV C.M. beam energy

QCD Phase Diagram - Theory

At $\mu_B = 0$

Lattice QCD

- ❖Quark – hadron Transition – Cross-over
- ❖Transition temperature ~ 150 MeV (Observable dependent)
- ❖Robust continuum limit results: EOS and Thermodynamics

At μ_B non-zero

- ❖Efforts on to draw the transition line – large uncertainties
- ❖Efforts on to get EOS and thermodynamics
- ❖Critical point search progressing – positive results indicate CP region below Beam energy 30 GeV

Critical Point Observables

Necessity: Observable sensitive to correlation length and susceptibilities

Challenges: Finite system size effects, $\xi < 6$ fm
Finite time effects, $\xi \sim 2 - 3$ fm

Observable:

$< (\delta N)^2 > \sim \xi^2$

$< (\delta N)^3 > \sim \xi^{4.5}$

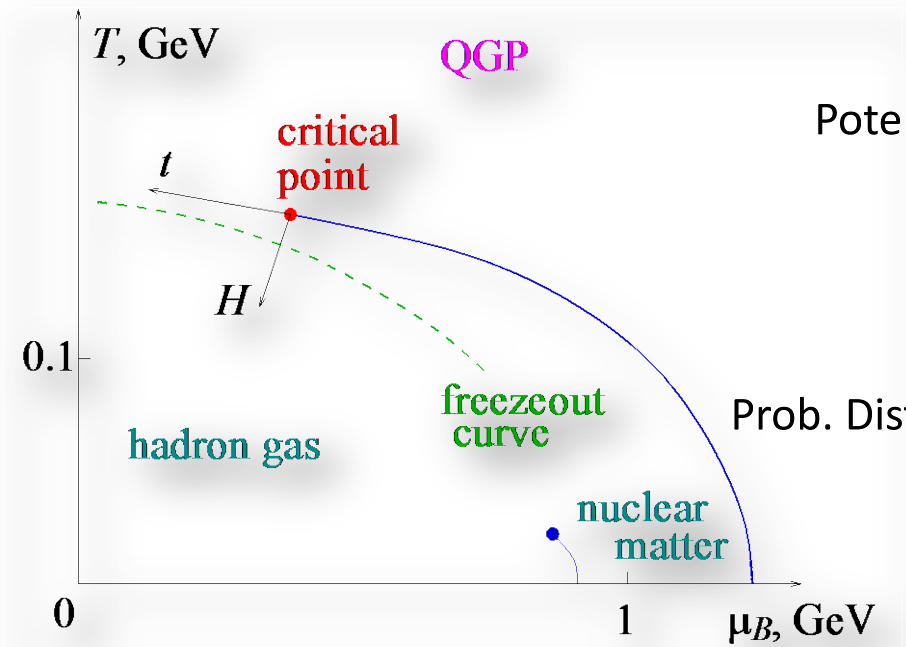
$< (\delta N)^4 > - 3 < (\delta N)^2 >^2 \sim \xi^7$

$S\sigma \sim \chi_B^{(3)}/\chi_B^{(2)}$

$\kappa\sigma^2 \sim \chi_B^{(4)}/\chi_B^{(2)}$

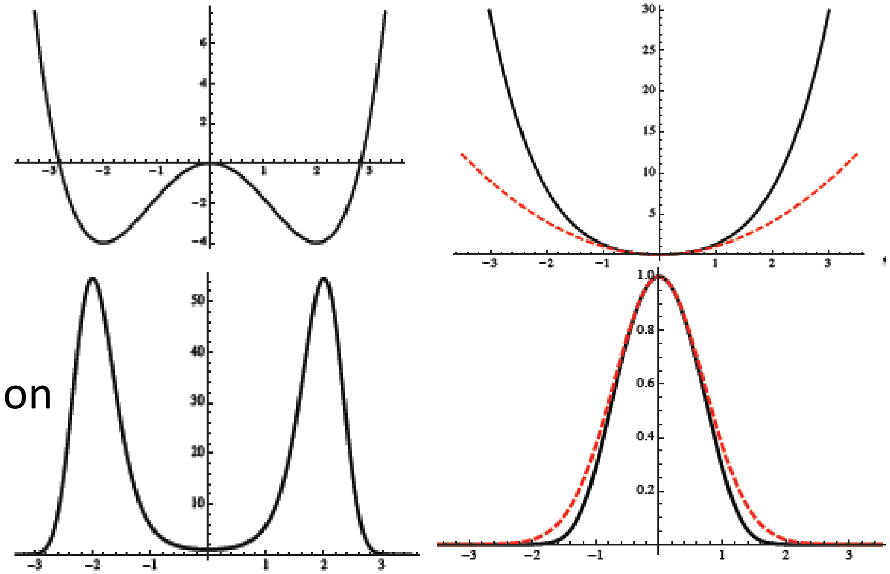
Phys.Rev.Lett. 107 (2011) 052301 Phys. Rev. Lett. 102, 032301 (2009) Phys.Lett. B696 (2011) 459
Phys. Rev. Lett. 91, 102003 (2003) Phys. Rev. D 61, 105017 (2000) Phys.Rev.Lett. 105 (2010) 022302

QCD based Model: CP Region and Kurtosis

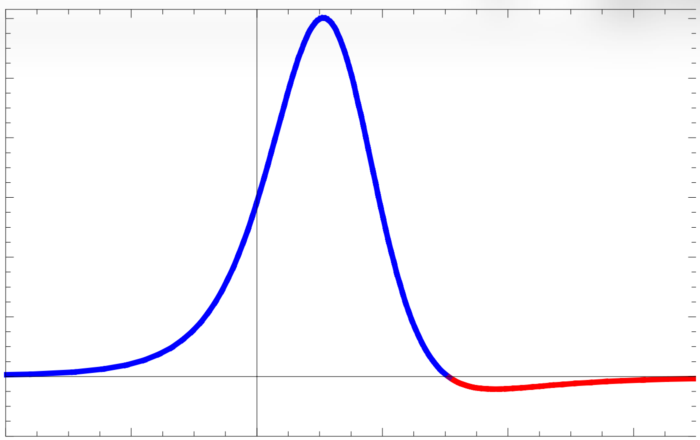


Potential

Prob. Distribution



J. Deng

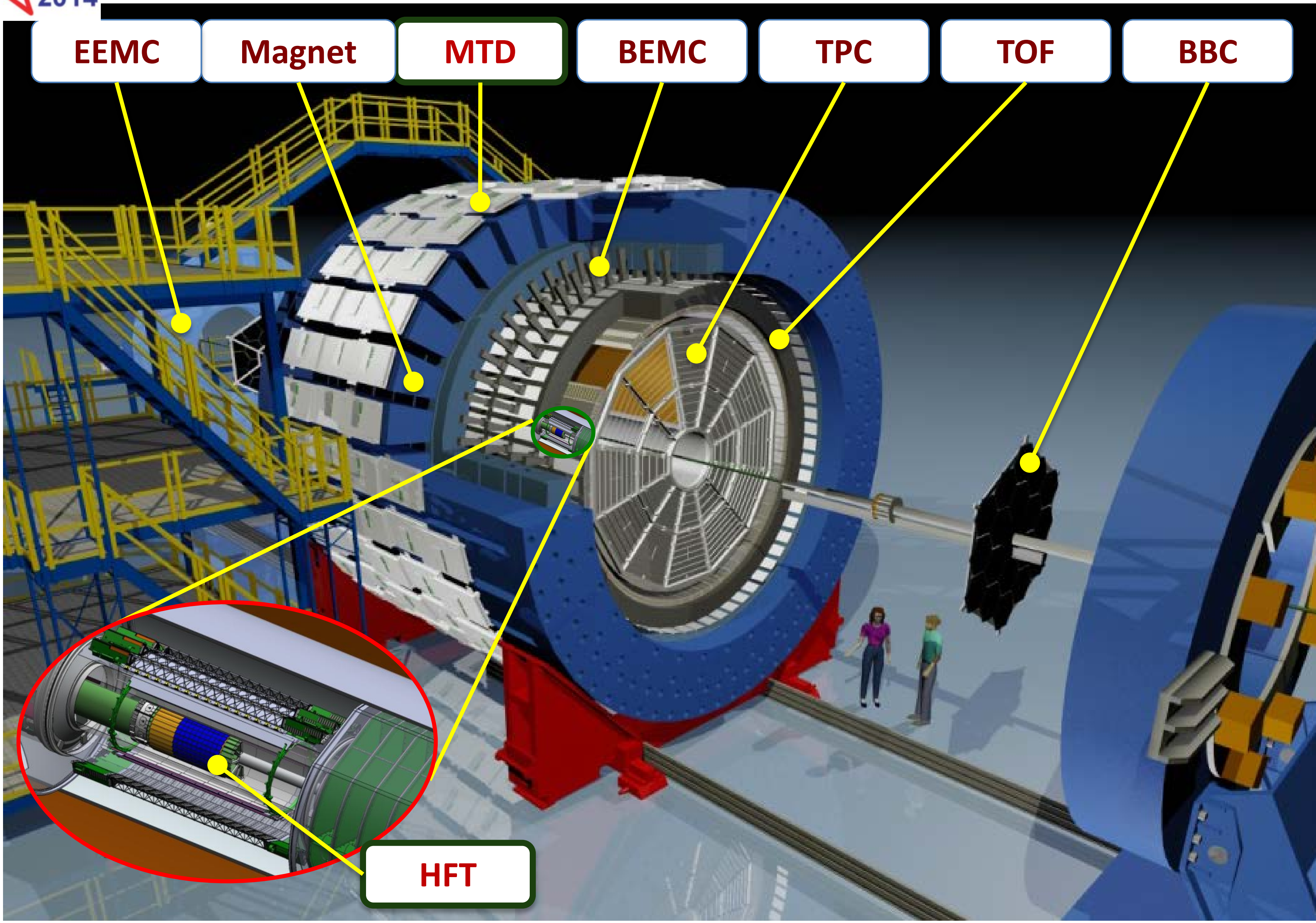


Poisson → Oscillation → Poisson

M. Stephanov: Phys.Rev.Lett. 107 (2011) 052301
M. Asakawa et al., Phys. Rev. Lett. 103 (2009) 262301

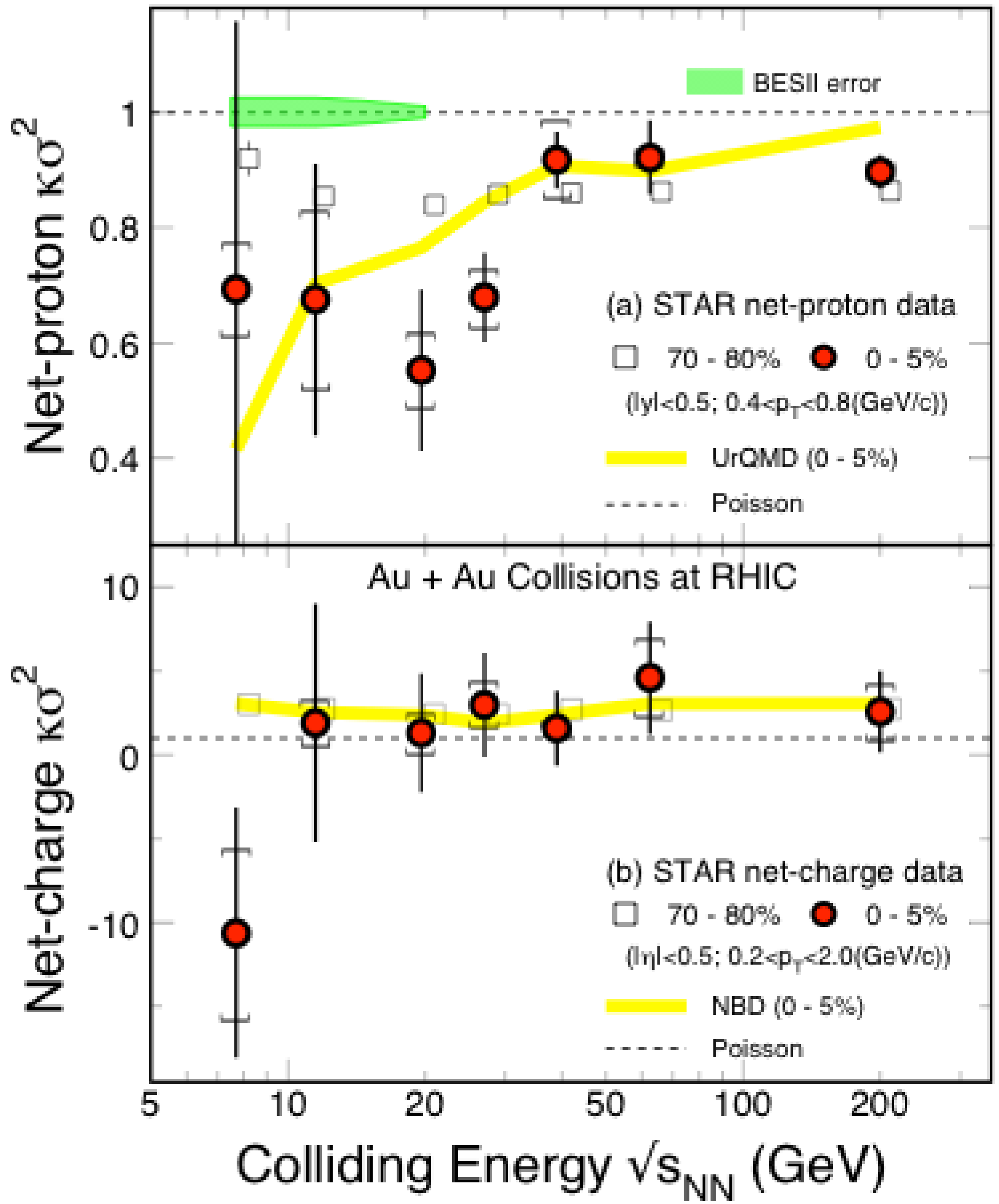
Collisions Energy → increasing

STAR Detector System



X10^3 increases in DAQ rate since 2000

Experimental Results from STAR



Physical Review Letters 112 (2014) 032302

Physical Review Letters 105 (2010) 022302

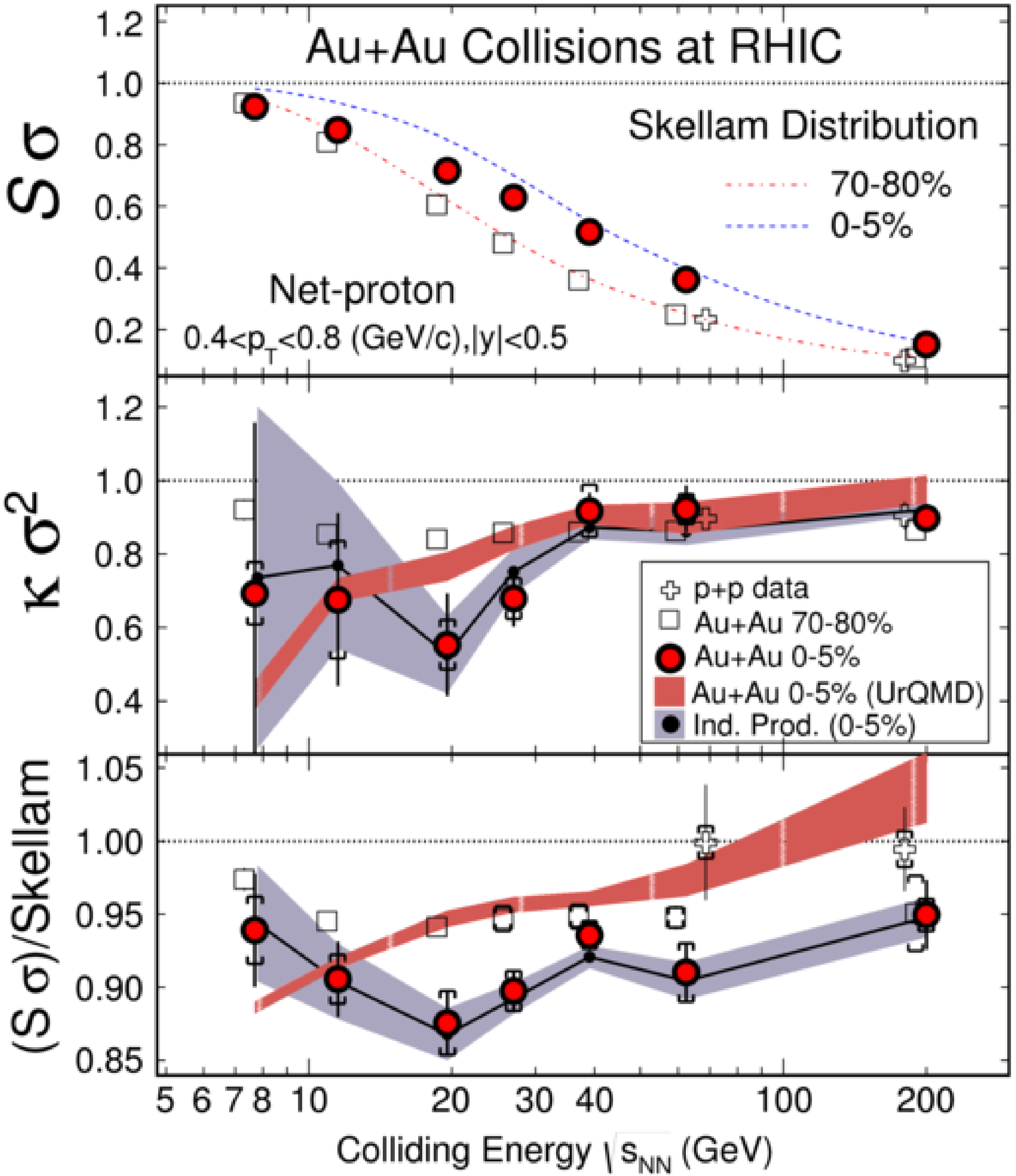
arXiv:1402.1558
Physical Review Letters 113 (2014)092301

Complimentary analysis ongoing in PHENIX experiment at RHIC

QCD Phase Structure: Below 39 GeV

Phys.Rev.Lett. 112 (2014) 032302; SN0598

How robust is this deviation from Poisson expectation?

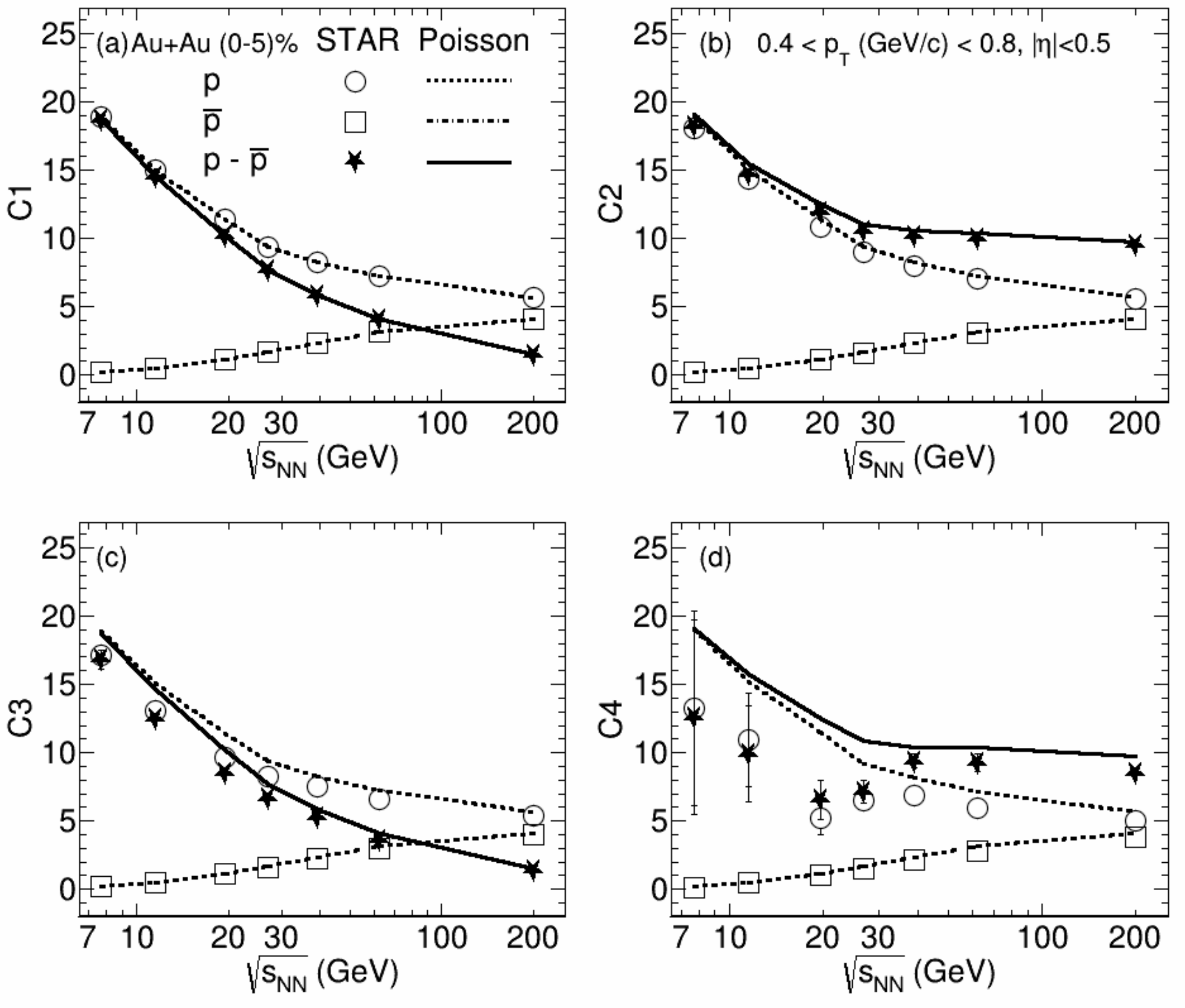


Net-proton
→ Net-baryon

Phys.Rev. C87 (2013) 041901

Phys.Rev. C86 (2012) 024904

Comparison to Poisson Expectation



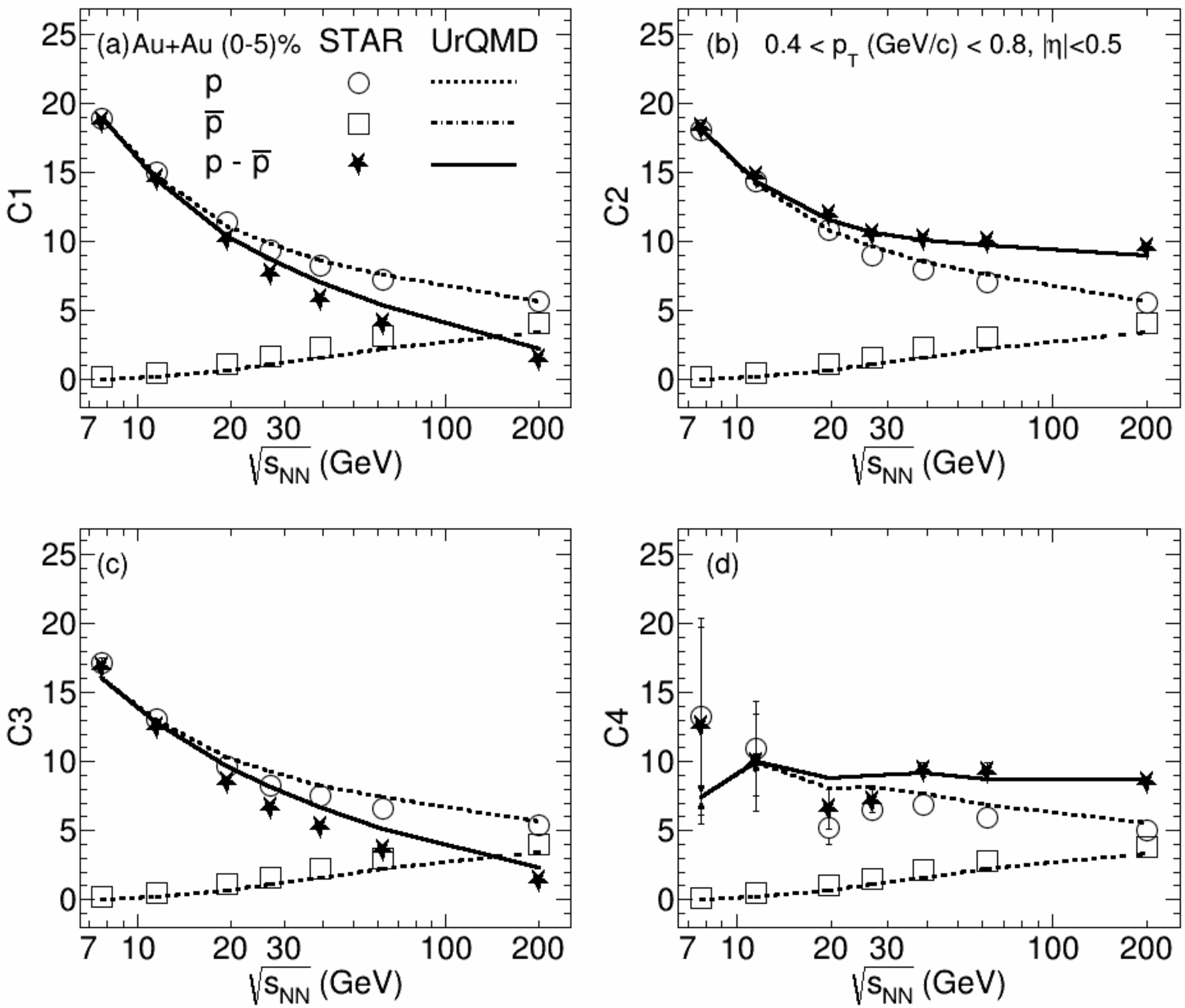
Uses mean from data

Incremental deviation with increase in Order of moments for Net-proton and proton

Reasonable agreement for anti-protons

Central collisions: Deviation from Poisson expectation observed below 39 GeV, errors large at 11.5 and 7.7 GeV

Comparison to UrQMD Expectation



Higher moments of Net-proton and proton data deviates from UrQMD at 19.6 and 27 GeV

Anti-proton data in reasonable agreement

Central collisions: Deviation from UrQMD expectation observed below 39 GeV, errors large at 11.5 and 7.7 GeV

Conclusions using available baselines

Data: Net-proton distributions in data dominated due to contribution from protons

Poisson: Net-proton and proton distributions shows deviation from Poisson while anti-proton proton distributions reasonably well described

Binomial: Net-proton and proton distributions at higher moments deviate at 19.6 anti-proton distributions well described

Hadron Resonance Gas Model: Deviations for net-proton and proton distributions at 19.6 and 27 GeV. Anti-proton distributions well described.

UrQMD: Net-proton and proton distributions deviate at 19.6 and 27 GeV. Anti-proton distributions reasonably well described

Independent production:

Continue to improve our understanding of this hypothesis, and extend coverage of rapidity range will definitely help

Endorsed by BNL NP Program Advisory Committee

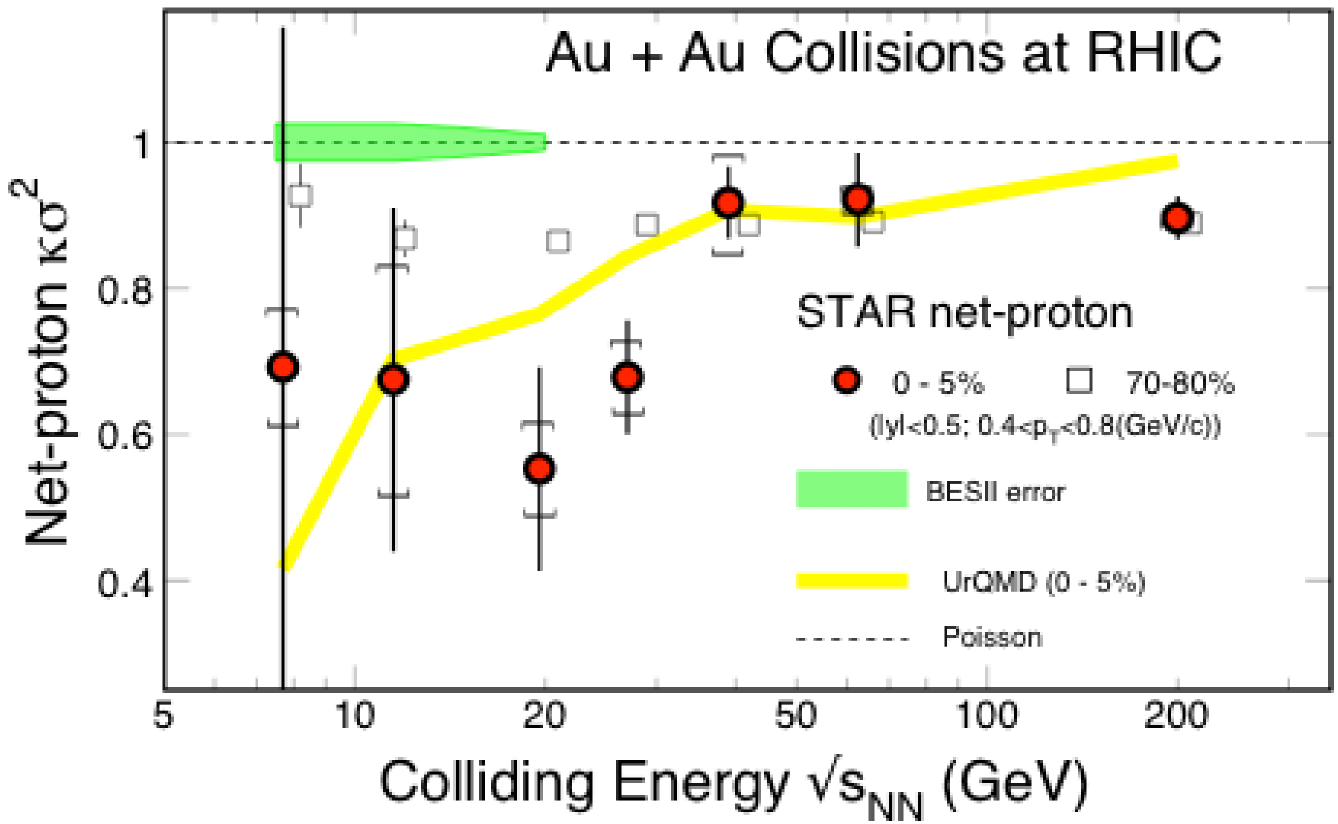
- "BES data, at present and in future from BES-II, together with the concerted theoretical response that present data motivates, will yield quantitative understanding of the properties of strongly coupled matter in the crossover region where QGP turns into hadrons, with quantitative connection between measured quantities and QCD. This, in and of itself, is an outstanding scientific goal."

- "If Nature puts a critical point in the region of the phase diagram with $\mu_B < 400$ MeV, with a first order phase transition starting at the critical point, BES-II data on fluctuation and flow observables at $\sqrt{s_{NN}}$=19.6 GeV and below together with the theoretical tools developed in response to BES-I data should yield evidence for both the critical point and the first order phase transition. This cannot be counted on, but if achieved it would constitute a landmark for the field as well as on the phase diagram."

- "We strongly support BNL and its C-AD in their plan to provide the electron cooling needed for the BES-II program, to run in 2018 and 2019."

Slides presented by Jamie Dunlop to the LEReC DOE review July 9, 2014

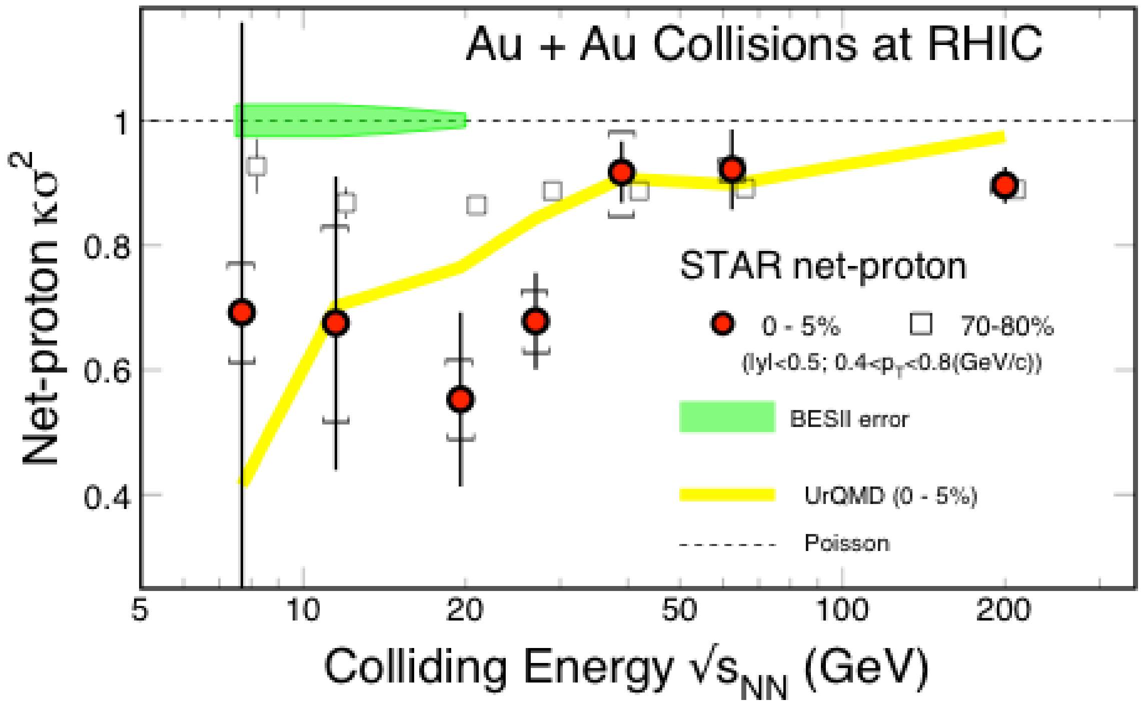
BNL PAC Recommendation

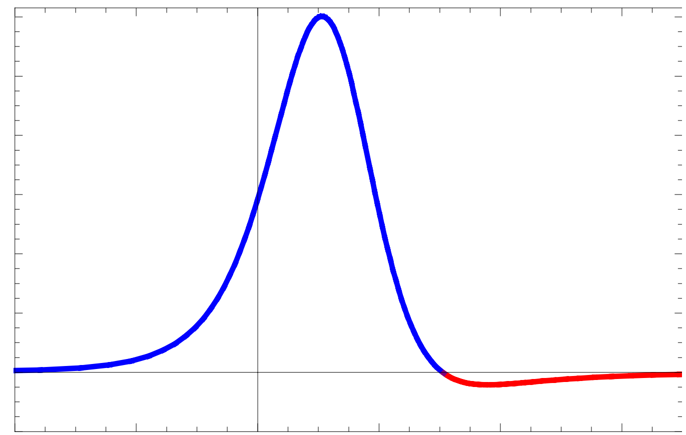


- Significant decrease in this measure at $\sqrt{s_{NN}}$ of 27 and 19.6 GeV

- "If this were to turn upward at lower $\sqrt{s_{NN}}$ this would be suggestive of a contribution from the fluctuations near a critical point. Determining whether this is so will require the higher statistics that BES-II can provide."

Complete the CP Measurement – Possible discovery





Phys.Rev.Lett. 107 (2011) 052301

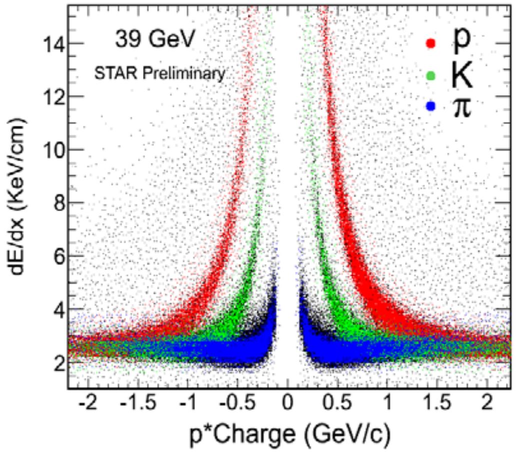
Phys.Rev.Lett. 102 (2009) 032301

High event statistics measurements of protons in narrow energy of collisions and large acceptance - RHIC BES-II
Lower energy collisions & measurement protons essential.

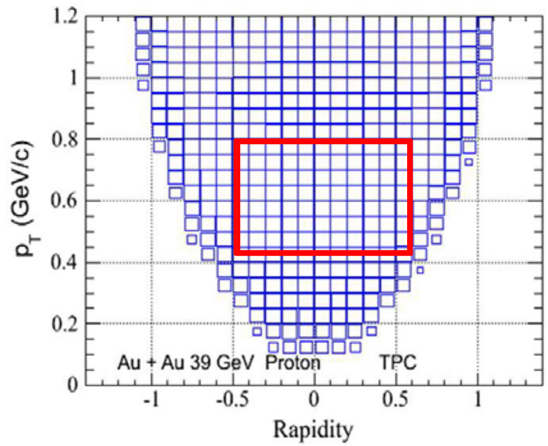
Extend Phase Space Coverage with TOF PID

Published Results: only TPC was used for proton/anti-proton PID. Currently, we use TOF detector to extend the phase space coverage for net-proton moment analysis.

TPC PID:



Proton Phase Space

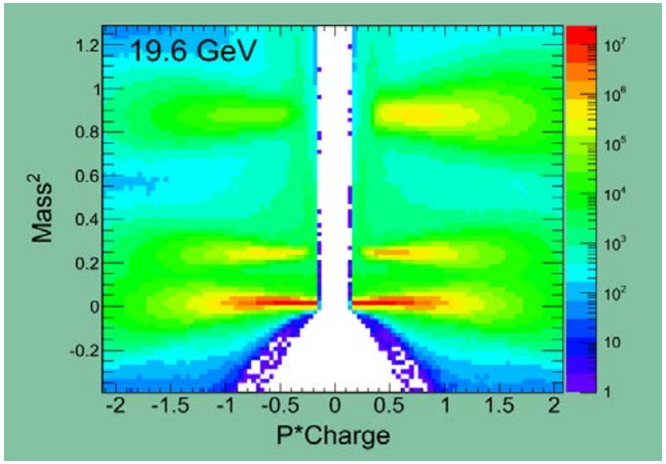


$0.4 < p_T < 0.8$ (GeV/c)

~ Doubled the accepted number of proton/anti-proton.

$0.4 < p_T < 2$ (GeV/c)

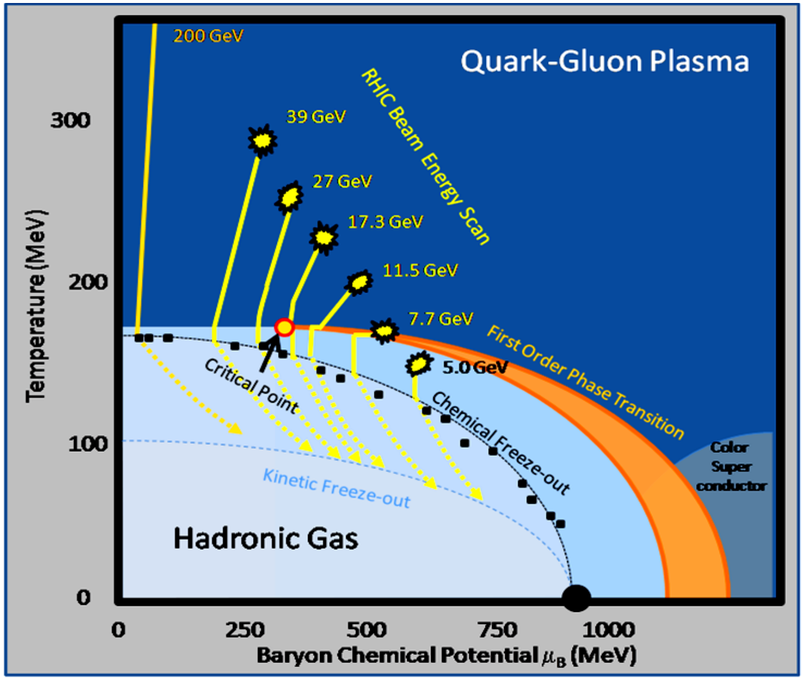
TOF PID:



Sufficiently large acceptance is crucial for fluctuati analysis and critical point search.

RHIC: eight key unanswered questions

Hot QCD Matter



1: Properties of the sQGP

2: Mechanism of energy loss:
weak or strong coupling?

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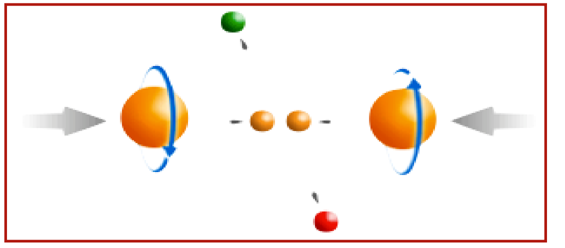
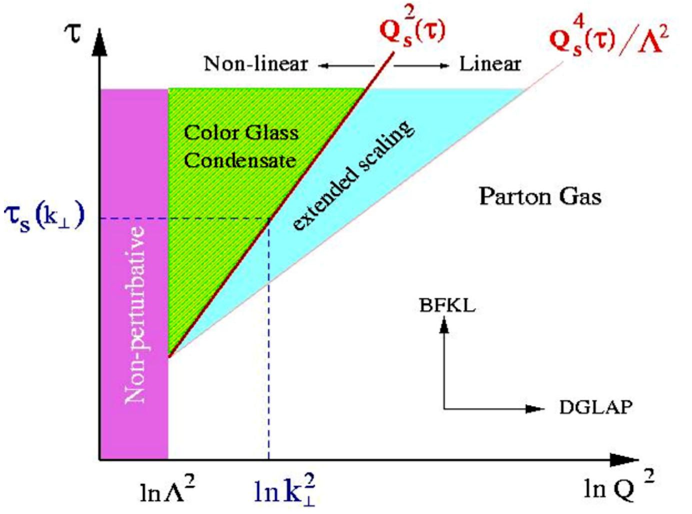
Partonic structure



6: Spin structure of the nucleon

7: How to go beyond leading twist and collinear factorization?

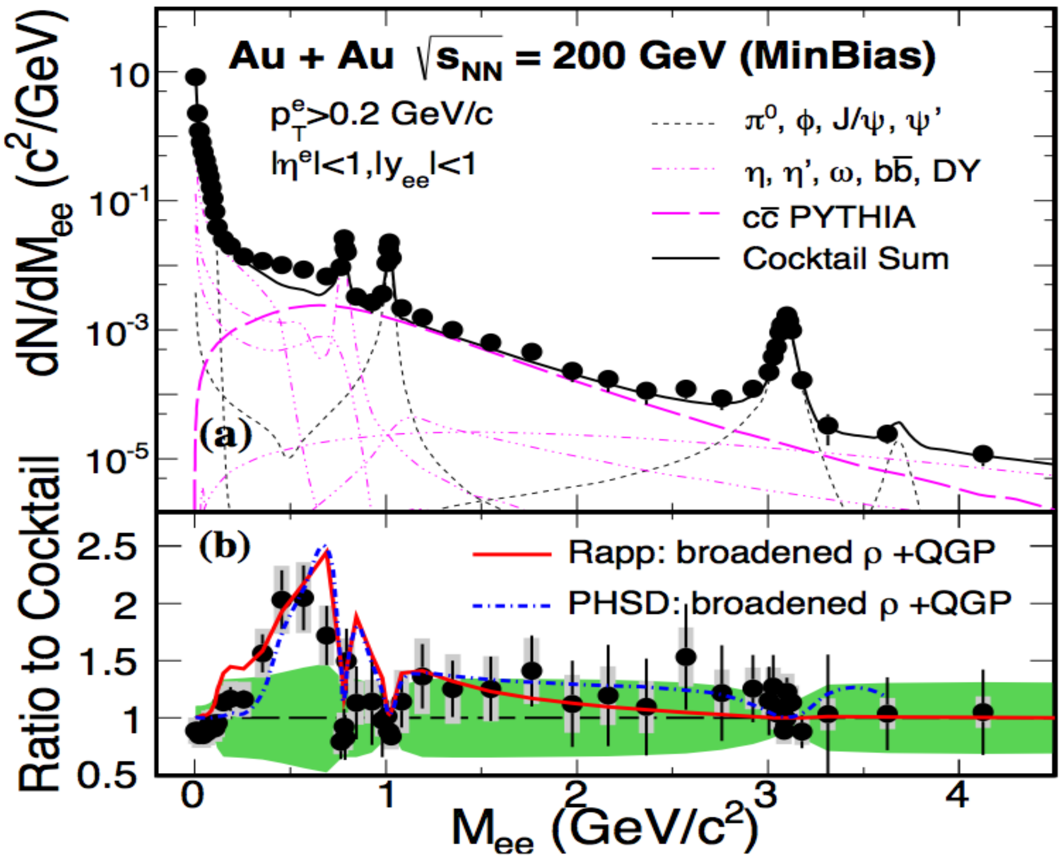


8: What are the properties of cold nuclear matter?

STAR DECADAL PLAN

http://www.bnl.gov/npp/docs/STAR_Decadal_Plan_Final%5b1%5d.pdf

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

LMR

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

πηφω

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

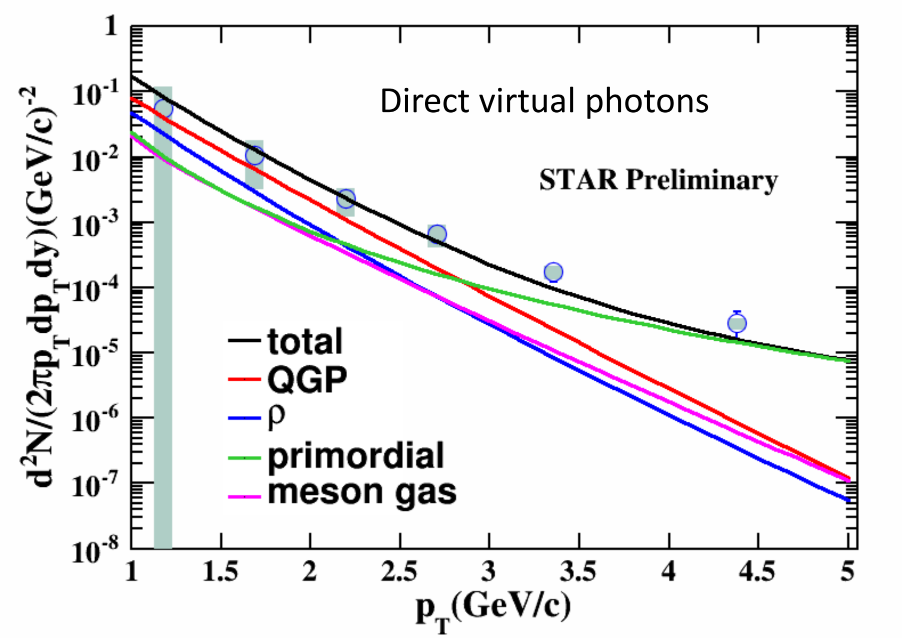
Quantify the Spectral Function

Temperature dependence of rho spectral function

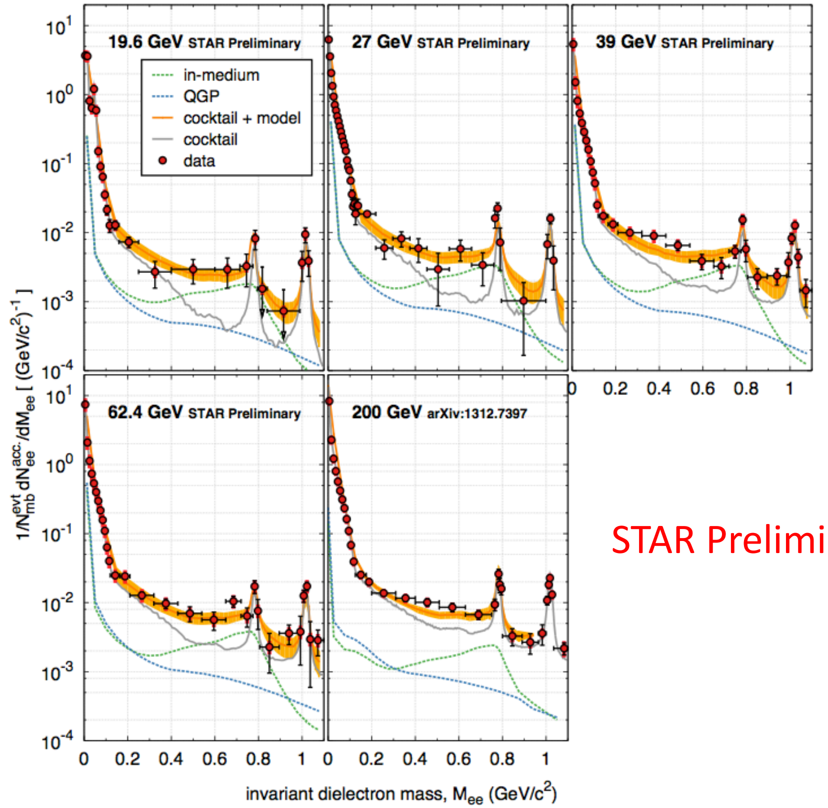
1. Beam energy range where final state is similar
2. Initial state and temperature evolution different
3. Density dependence by Azimuthal dependence (v_2)
4. Use centrality dependence as another knob
5. Direct photon results should match with extrapolation

Baryon dependence of rho spectral function

1. LMR excess expected to be consistent with total baryon density increase



QM14: Chi Yang, Patrick Huck

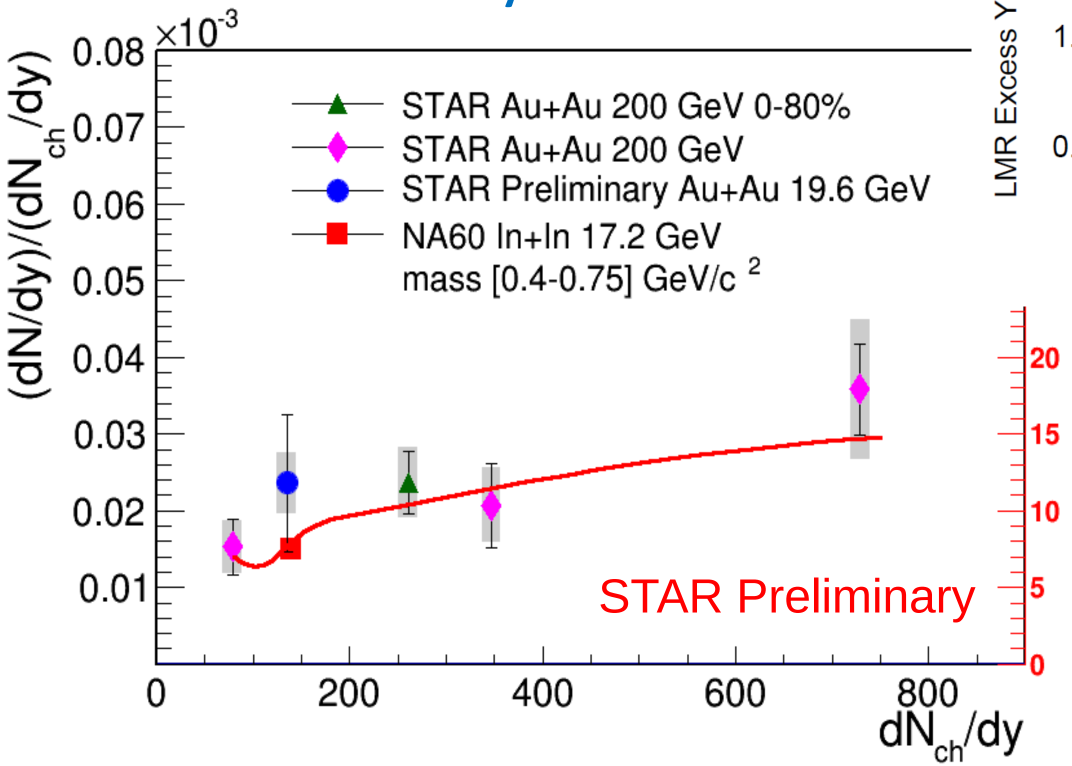


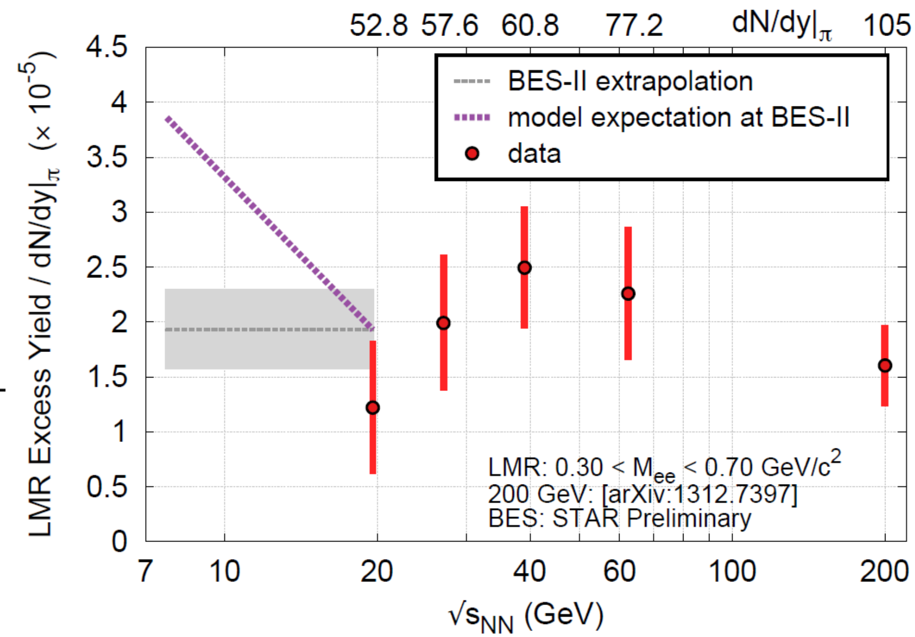
STAR Preliminary

Dilepton Measurements at BES II

Beam Energy

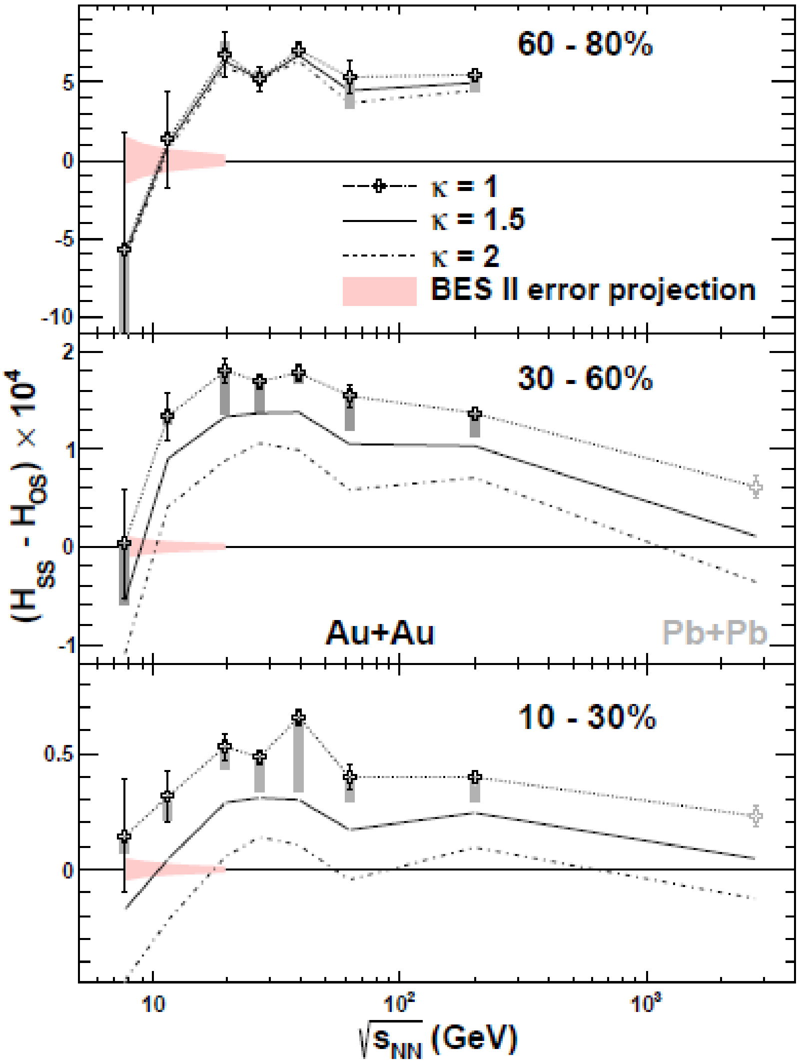
Centrality





BES II enables measurements at energy <20GeV

Chiral Magnetic Effects

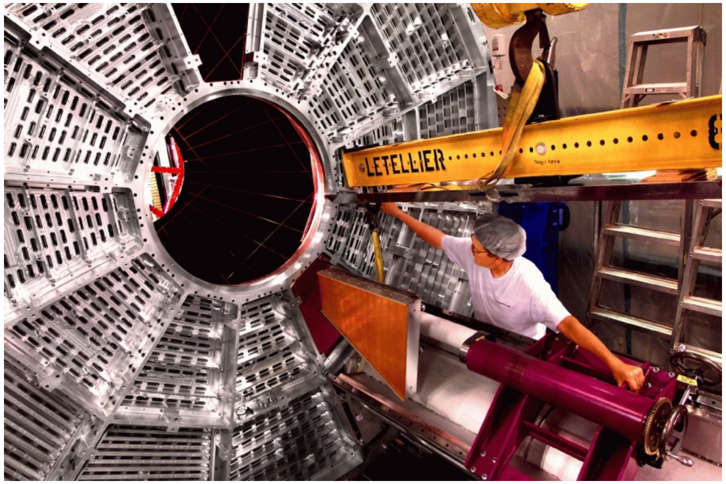


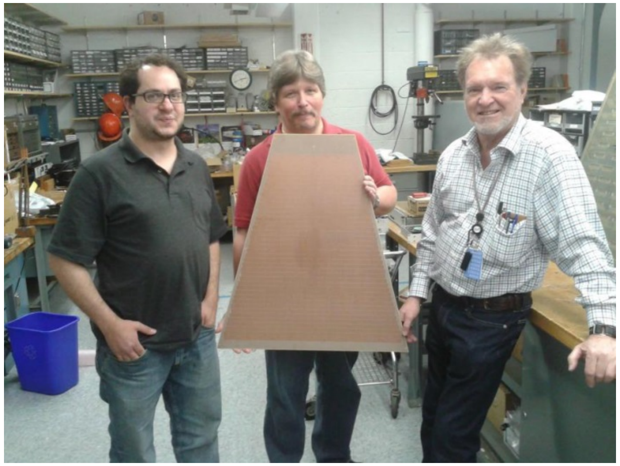
Phys. Rev. Lett. **113** (2014) 52302

- 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)

"Workshop on Quark Chirality Asymmetry, Fluid Vorticity and Strong Magnetic Field in Heavy Ion Collisions"
UCLA, January 21—23, 2015

Detector Upgrades: iTPC

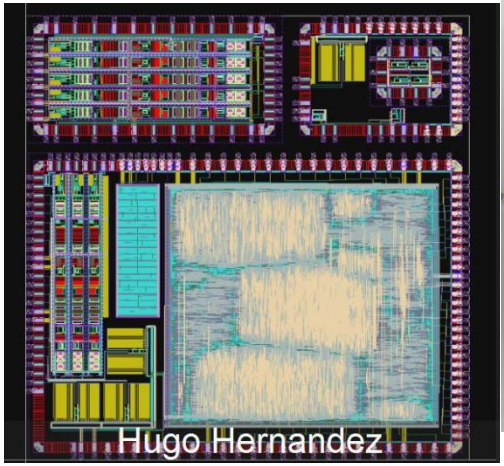




Replace inner Sectors

Progresses on R&D

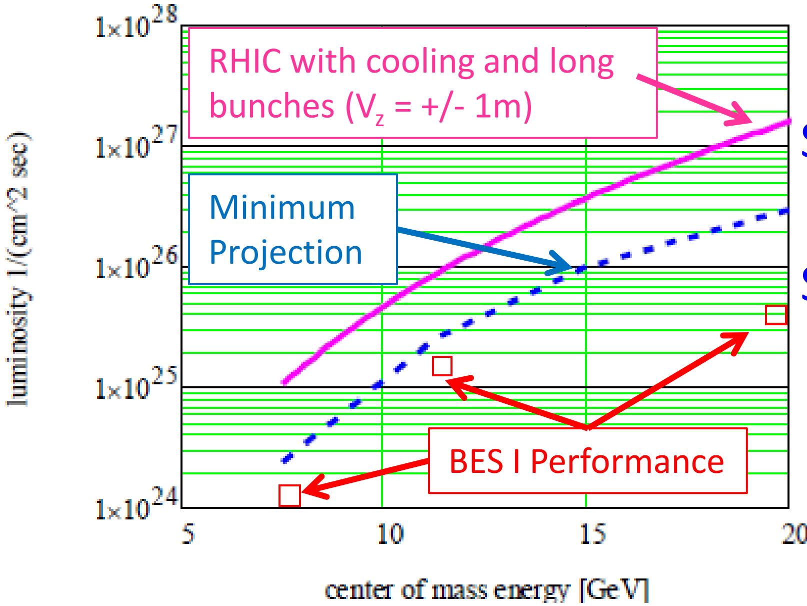
1. strongback produced at UT Austin
2. New padplane design at BNL
3. New ALICE TPC FEE
4. Wire chamber at SDU
5. Proposal and management plan to BNL next month



Low Energy Electron Cooling at RHIC

Electron Cooling can raise the luminosity by a factor of 3-10 in the range from 5 – 20 GeV

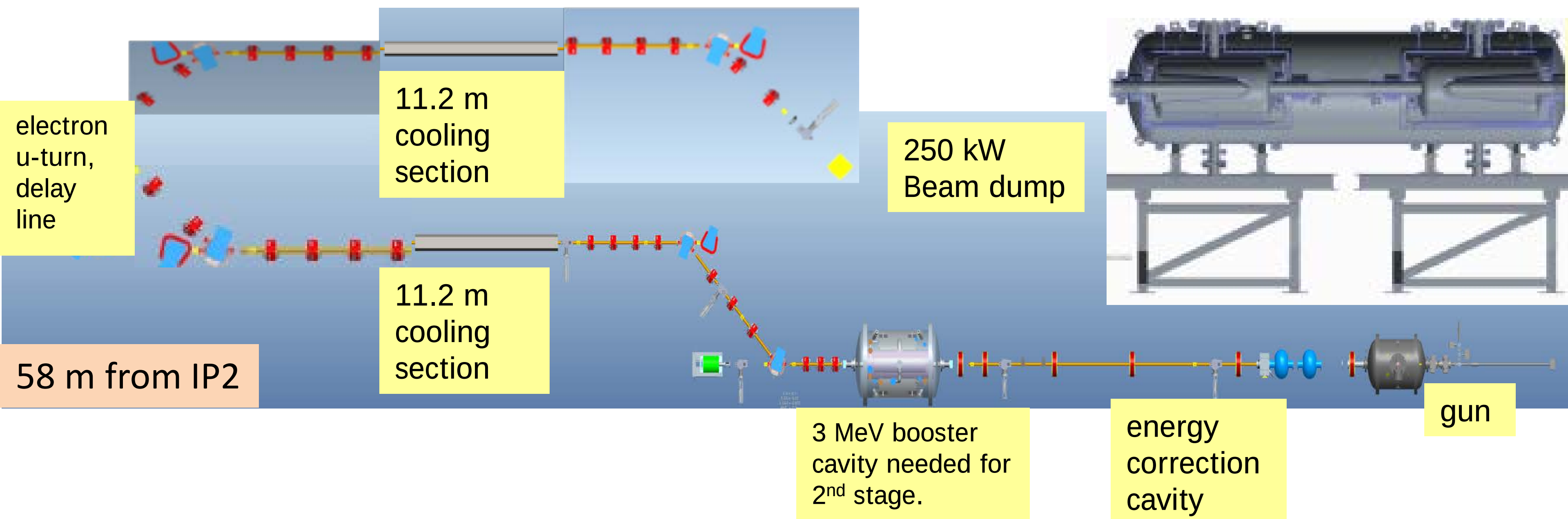
Long Bunches increase luminosity by factor of 2-5



Stage I
$\sqrt{s_{NN}}$ = 5-9 GeV

Stage II -- 3 MeV booster cavity
$\sqrt{s_{NN}}$ = 9-20 GeV

100 MHz SRF Gun



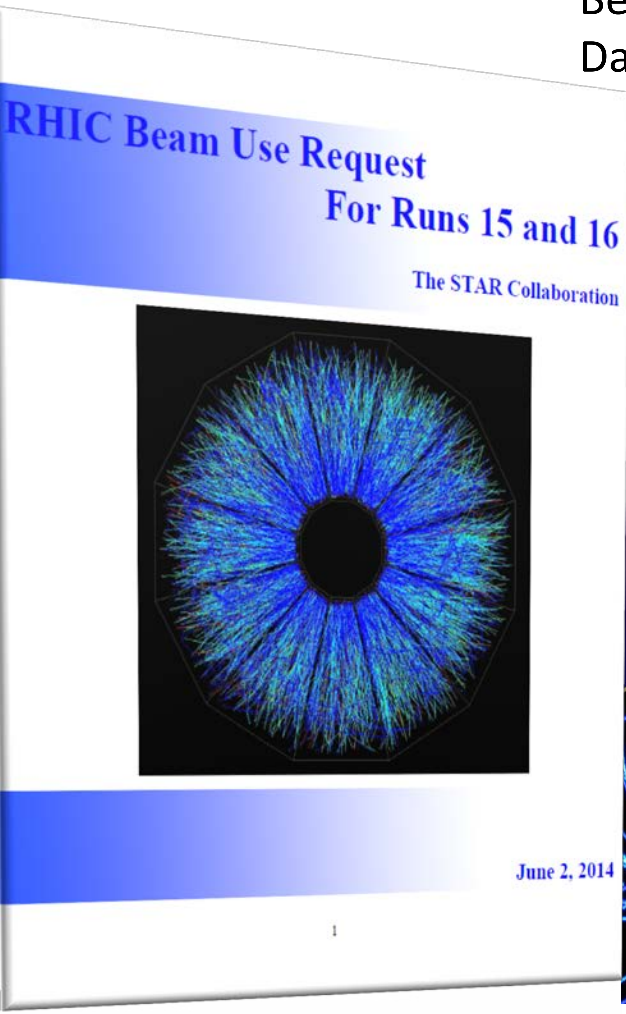
Statistics Needed in BES phase II

	Collision Energies (GeV):	**7.7**	**9.1**	**11.5**	**14.5**	**19.6**
	Chemical Potential (MeV):	**420**	**370**	**315**	**260**	**205**
	Observables	Millions of Events Needed				
QGP	R_{CP} up to p_T 4.5 GeV	NA	NA	160	92	22
QGP	Elliptic Flow of ϕ meson (v_2)	100	150	200	300	400
QGP	Local Parity Violation (CME)	50	50	50	50	50
1st P.T.	Directed Flow studies (v_1)	50	75	100	100	200
1st P.T.	asHBT (proton-proton)	35	40	50	65	80
C.P.	net-proton kurtosis ($\kappa\sigma^2$)	80	100	120	200	400
EM Probes	Dileptons	100	160	230	300	400
	Proposed Number of Events:	**100**	**160**	**230**	**300**	**400**

STAR Plan on BUR, BES II and pp/pA LoI

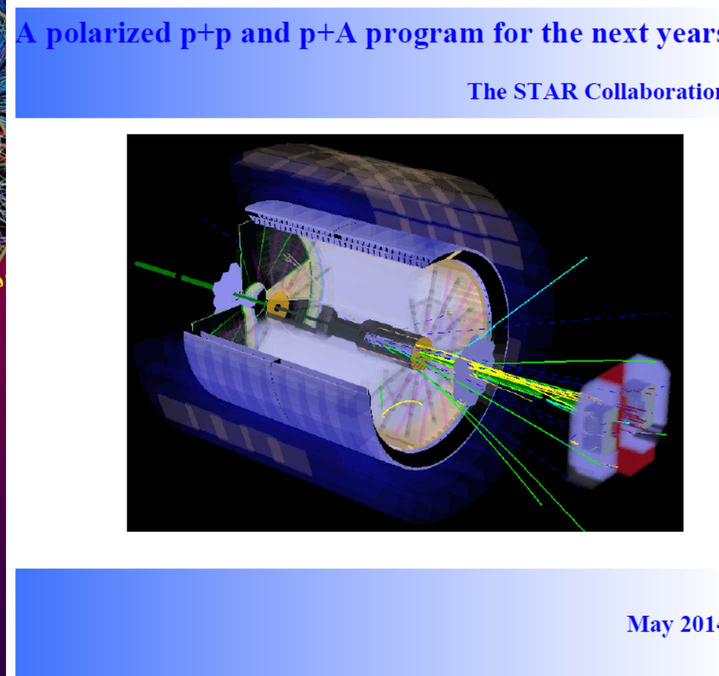
Committee co-chairs:
Bedanga Mohanty (NISER)
Dan Cebra (UC Davis)

Committee co-chairs:
Elke Aschenauer (BNL)
Ernst Sichtermann (LBL)
Huan Huang (UCLA)



https://drupal.star.bnl.gov/STAR/starnotes/public/sn0606

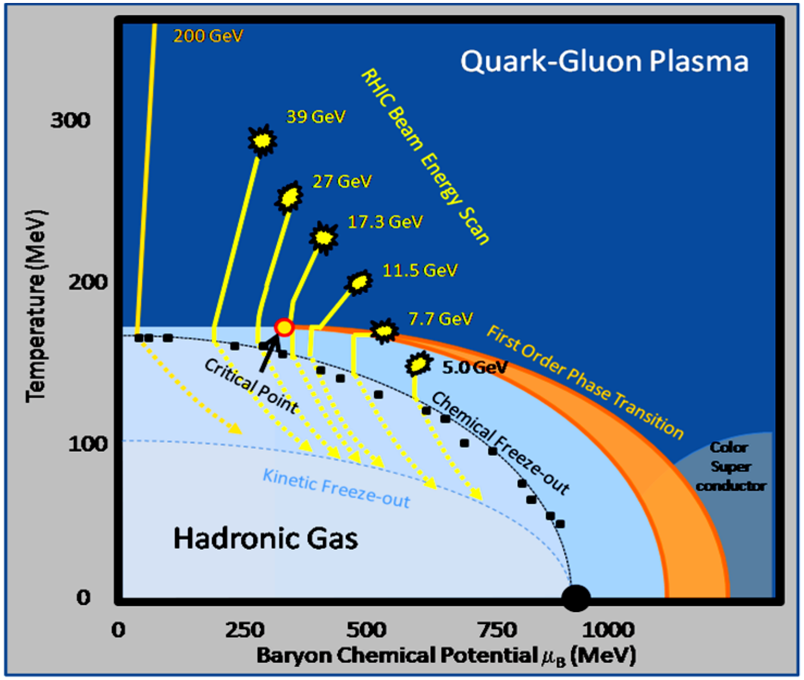
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598



https://drupal.star.bnl.gov/STAR/starnotes/public/sn0605

RHIC: eight key unanswered questions

Hot QCD Matter



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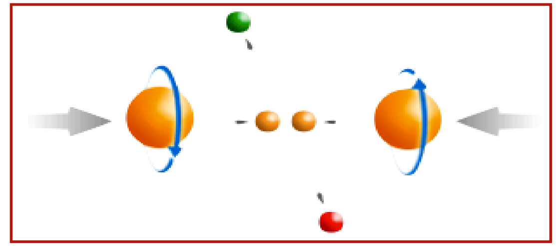

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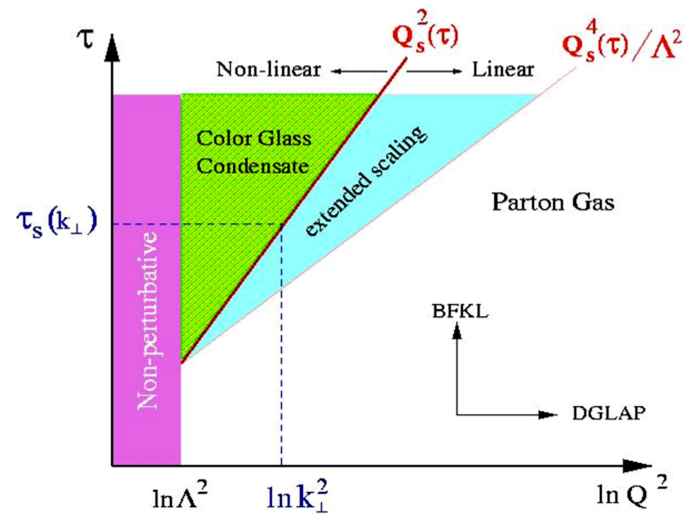

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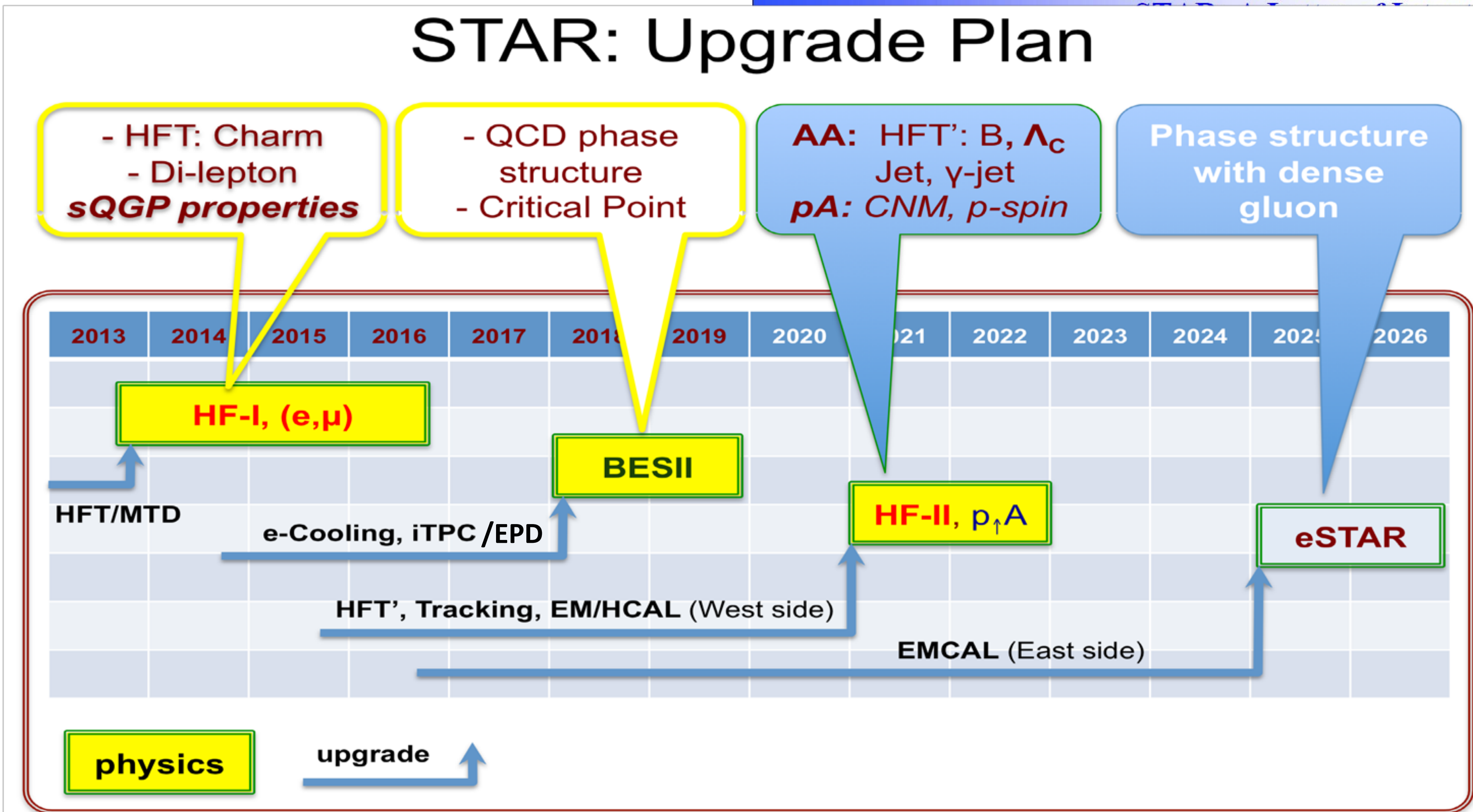
STAR DECADAL PLAN

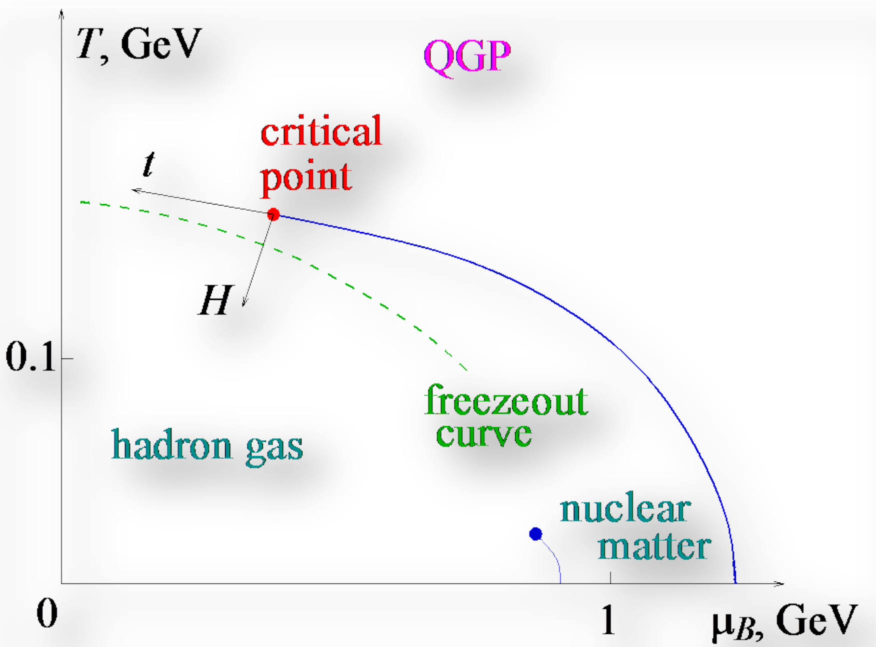
http://www.bnl.gov/npp/docs/STAR_Decadal_Plan_Final%5b1%5d.pdf

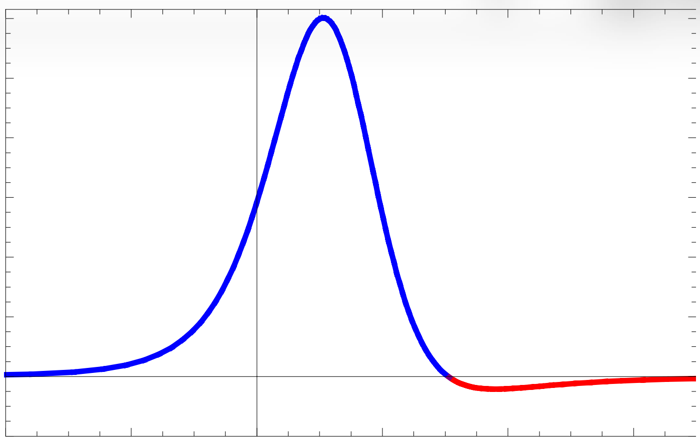
STAR Long-Term Plan

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0592



A system-size scan: freeze-out projection





Collisions Energy → increasing

What is your plan if Critical Point is discovered?
-- Roy Holt at the PAC Meeting

If we find first-order phase transition,
there has to be a critical point in-between.

it may be that central collisions are
the best and easiest to understand:
smaller N_{part} fluctuations, better η symmetry

A program to study very central A+A for nuclei
with A≈100 could turn out to be
a crucial follow-up to BESII

The most important discovery in our field
would warrant follow-up.

M. Stephanov: Phys.Rev.Lett. 107 (2011) 052301
M. Asakawa et al., Phys. Rev. Lett. 103 (2009) 262301

QCD Phase Structure

- ✧ Non-monotonic variations of v_1 slope for net-protons – *signature of softening of equation of state/1st Order Phase transition ?* -- *Declan Keane for STAR*

- ✧ Hints of non-monotonic variation of ks^2 for net-protons --- *Is there an oscillation* ? – BES- II / larger phase space acceptance needed. (Current presentation)

- ✧ A broadened spectral function describes di-lepton enhancement from SPS at 17.3 GeV to top RHIC energy from STAR.

Summary

Theory

Lattice QCD:

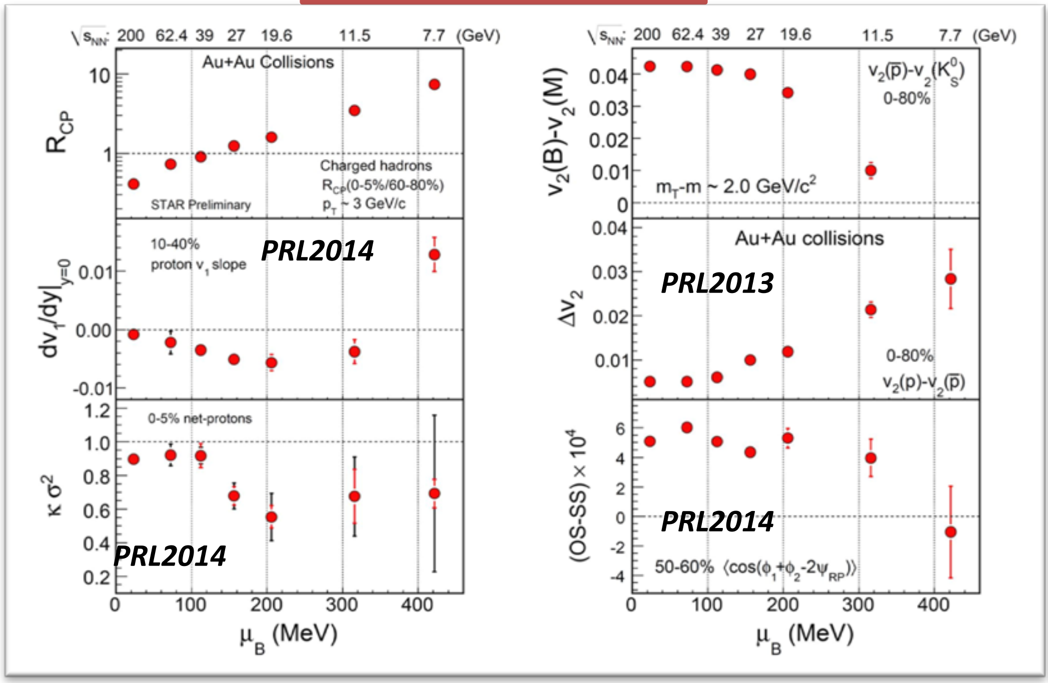
Solid results at zero μ_B

- ➢ Cross over
- ➢ EOS, Transition Temp.
- ➢ QCD Thermodynamics

Progress at large μ_B

- ➢ CP > μ_B = 300 MeV

Experiment



Success of BES@RHIC

Future

Increased statistics and phase space (centrality) in RHIC

Enable new measurements at BES II