Beam Energy Scan and Future Plans of RHIC

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XIIth Quark Confinement and the Hadron Spectrum
Thessaloniki, Greece
August 29th to September 3rd, 2016

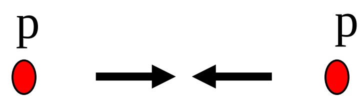
Many Thanks to:
- Berndt Mueller (ALD NP)
- David Morrison
- Wolfram Fischer
- Elke-Caroline Aschenauer

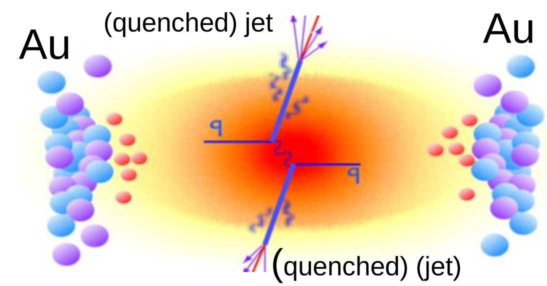
BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

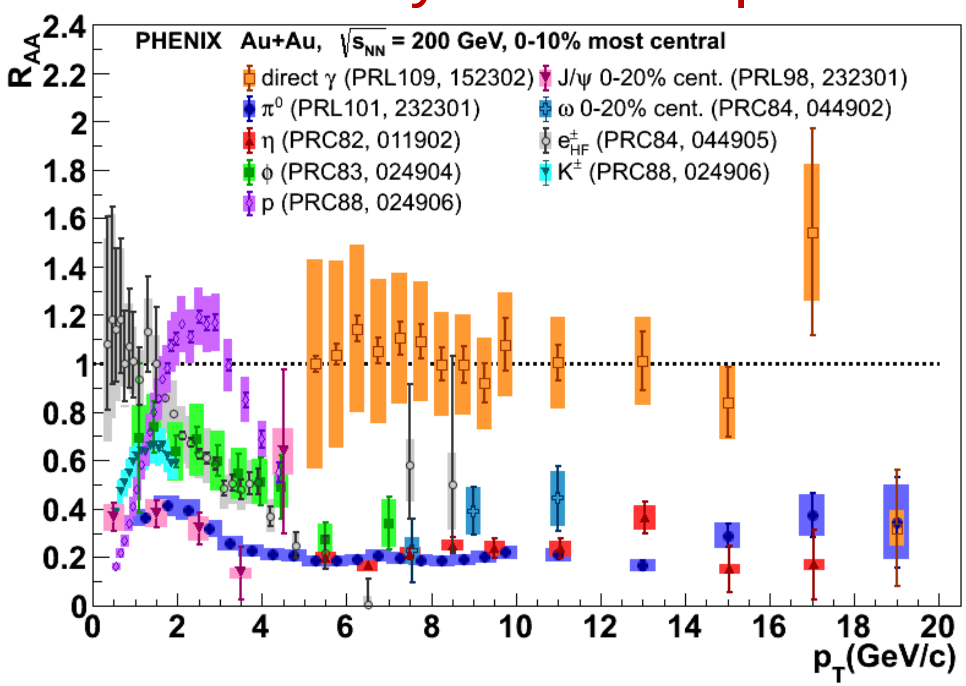
Motivation: Jet Quenching Major Discovery

$$R_{AA}(p_T, y, b) = \frac{d^2N^{AA}/dp_T d\eta}{\langle T_{AA}(b)\rangle\, d^2\sigma^{pp}/dp_T d\eta}$$

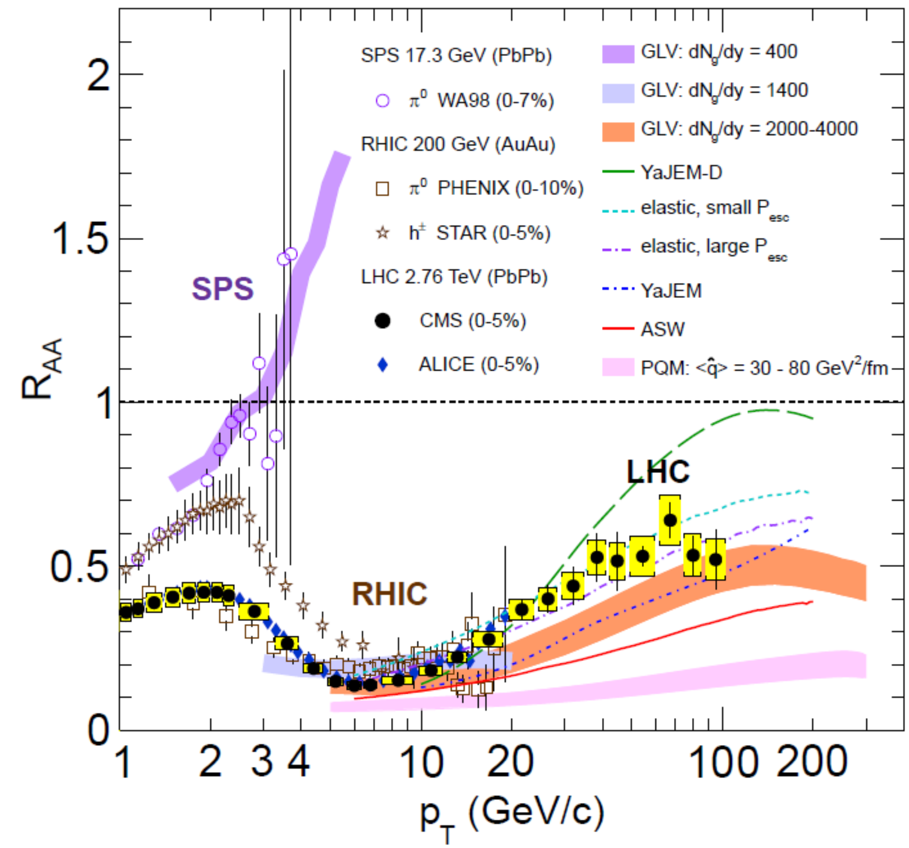




RHIC: Many Particle Species



SPS - RHIC - LHC



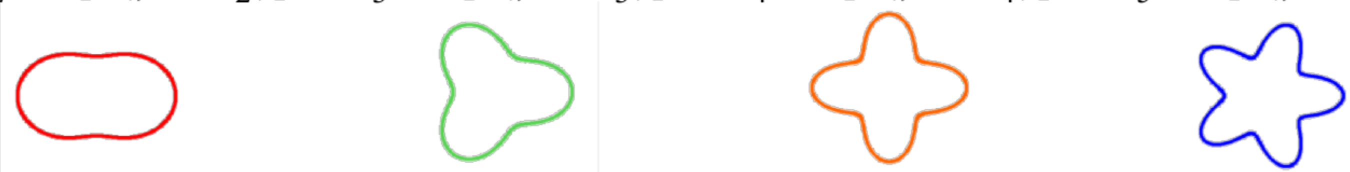
Eur. Phys. J. C (2012) 72:1945

Jet Quenching is the major discovery at RHIC as well at LHC

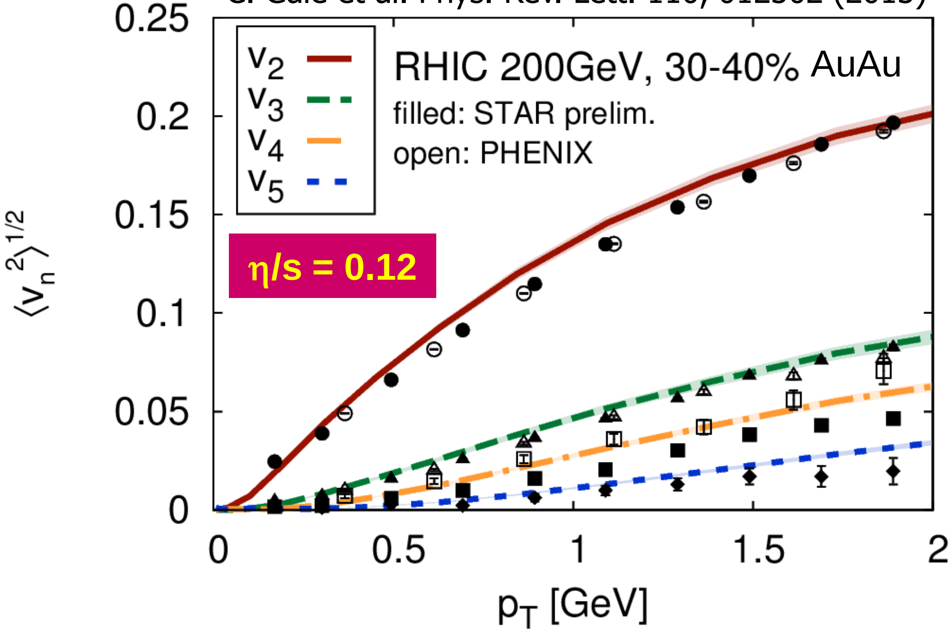
Motivation: Perfect Liquid Major Discovery

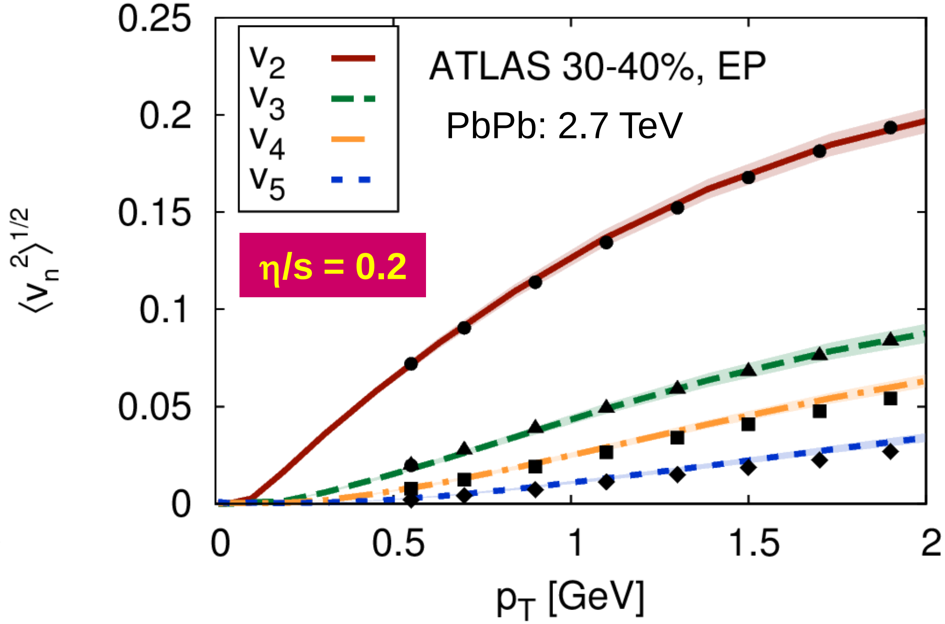
RHIC and LHC precision measures of higher moments

$$\frac{dN}{d\phi} = 1 + 2v_2\cos[2(\phi-\Psi_2)] + 2v_3\cos[3(\phi-\Psi_3)] + 2v_4\cos[4(\phi-\Psi_4)] + 2v_5\cos[5(\phi-\Psi_5)] + \ldots$$



C. Gale et al. Phys. Rev. Lett. 110, 012302 (2013)

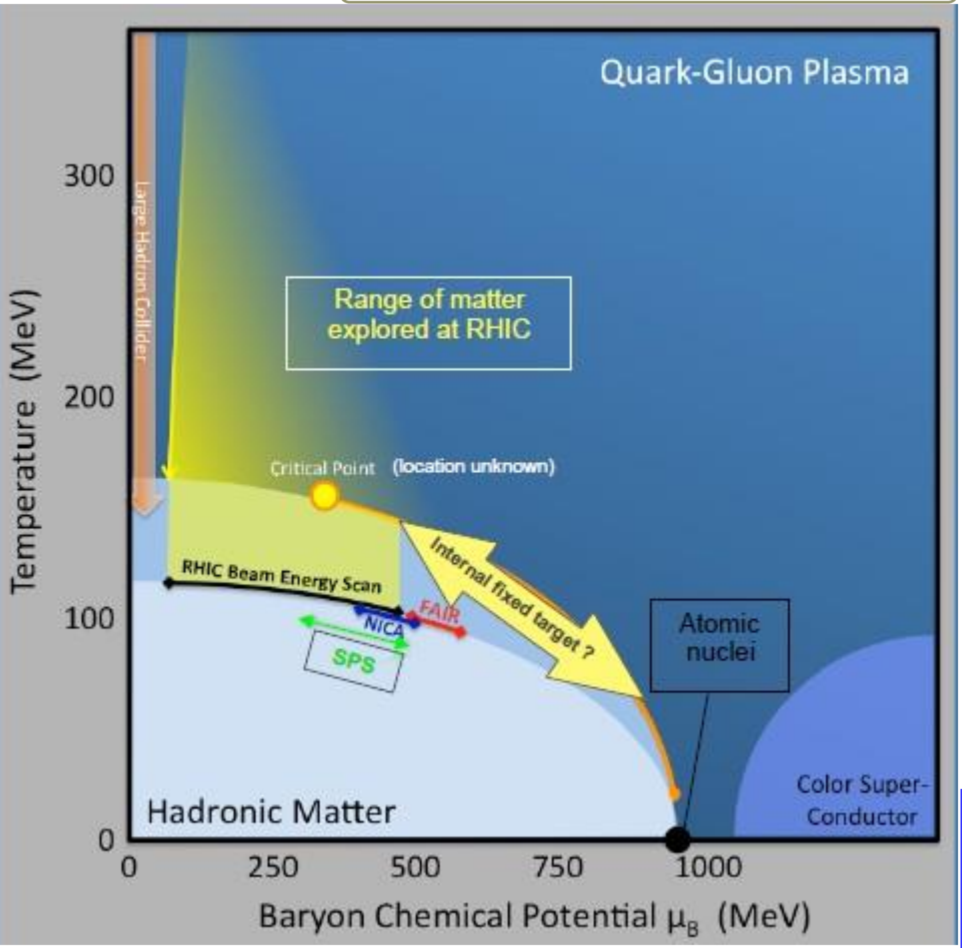




- **Medium is strongly interacting (the large amplitude of v_2)**
- Comparisons with models hydrodynamic viscous with RHIC and LHC data seem to support very small values for η/s. This implies that the nuclear matter created **is almost perfect fluid**.

Validation of the crossover transition leading to the QGP

Conjectured Phase Diagram



→ Necessary requirement for CEP
Strategy for RHIC BES-I

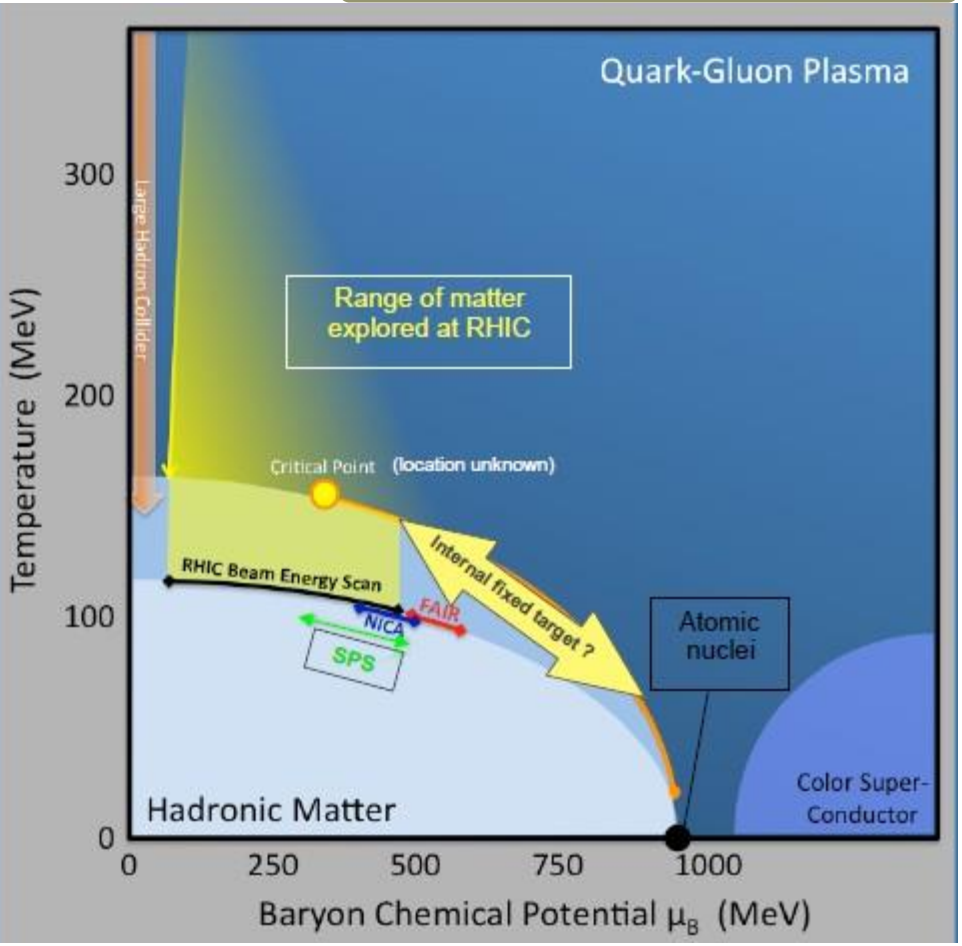
- Map turn-off of QGP signatures
- Location of the Critical End Point (CEP)?
- Location of phase coexistence regions?
- 1st order phase transition signs
- Detailed properties of each phase?

$$\frac{\eta}{s}(T,\mu),\ \frac{\zeta}{s}(T,\mu),\ c_s(T),\ \hat{q}(T),\ \alpha_s(T),\ \text{etc}$$

Phases of QCD matter

- How do we map the QCD phase diagram?

Conjectured Phase Diagram



RHIC has access to different collision systems and a broad domain of the (μ_B,T)-Plane

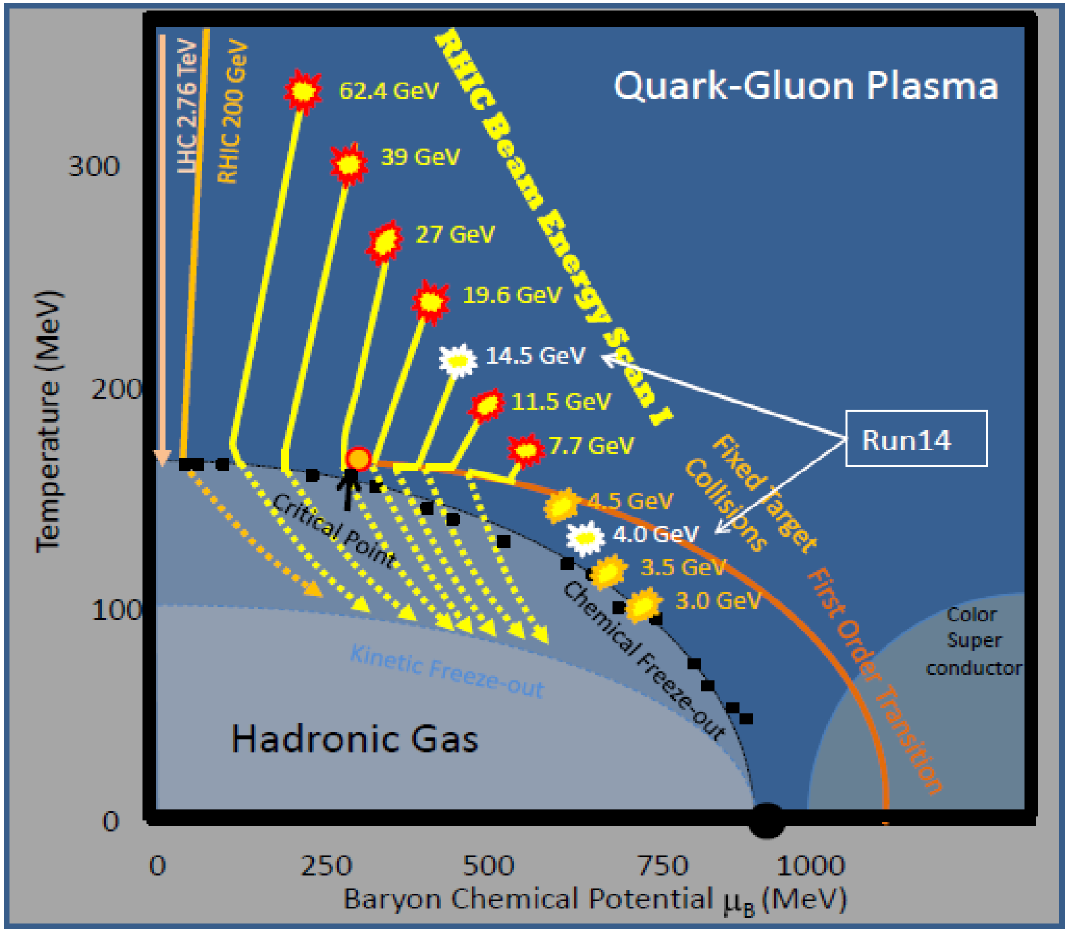
We can vary $\sqrt{S_{NN}}$ and explore the (μ_B,T) plane for experimental signatures.

RHIC established a physics program for Beam Energy Scan-I (BES-I):
7.7, 11.5, 14.5, 19.6, 27, 39, 62.4, 200 GeV

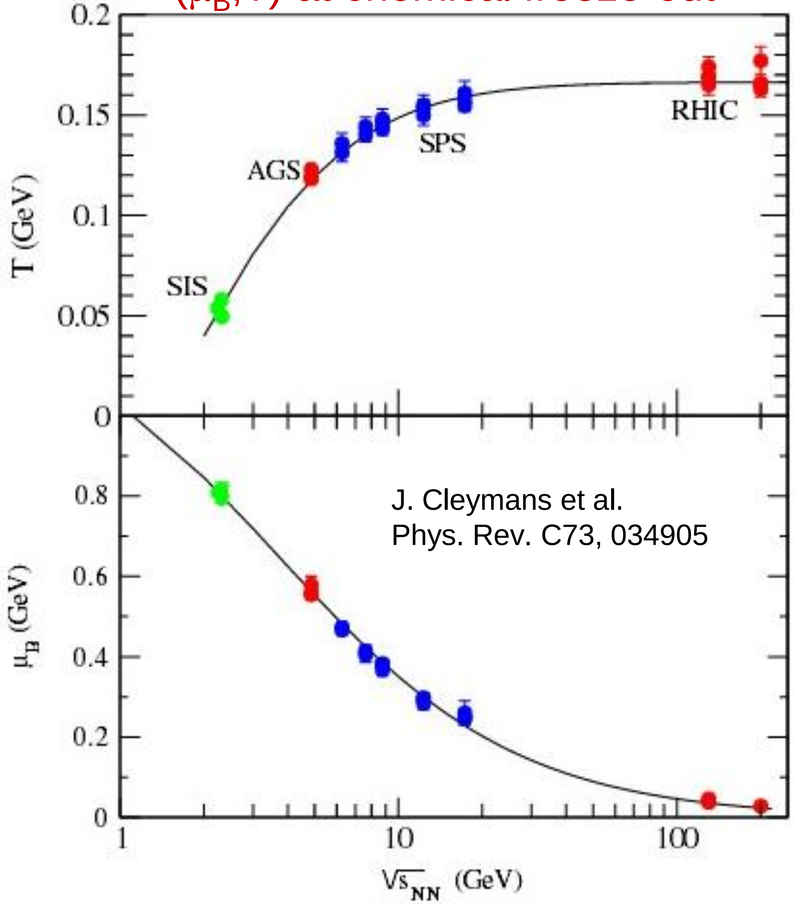
Phases of QCD matter

- How do we map the QCD phase diagram?

- Vary the collision energy over the full range accessible at RHIC



(μ_B,T) at chemical freeze-out

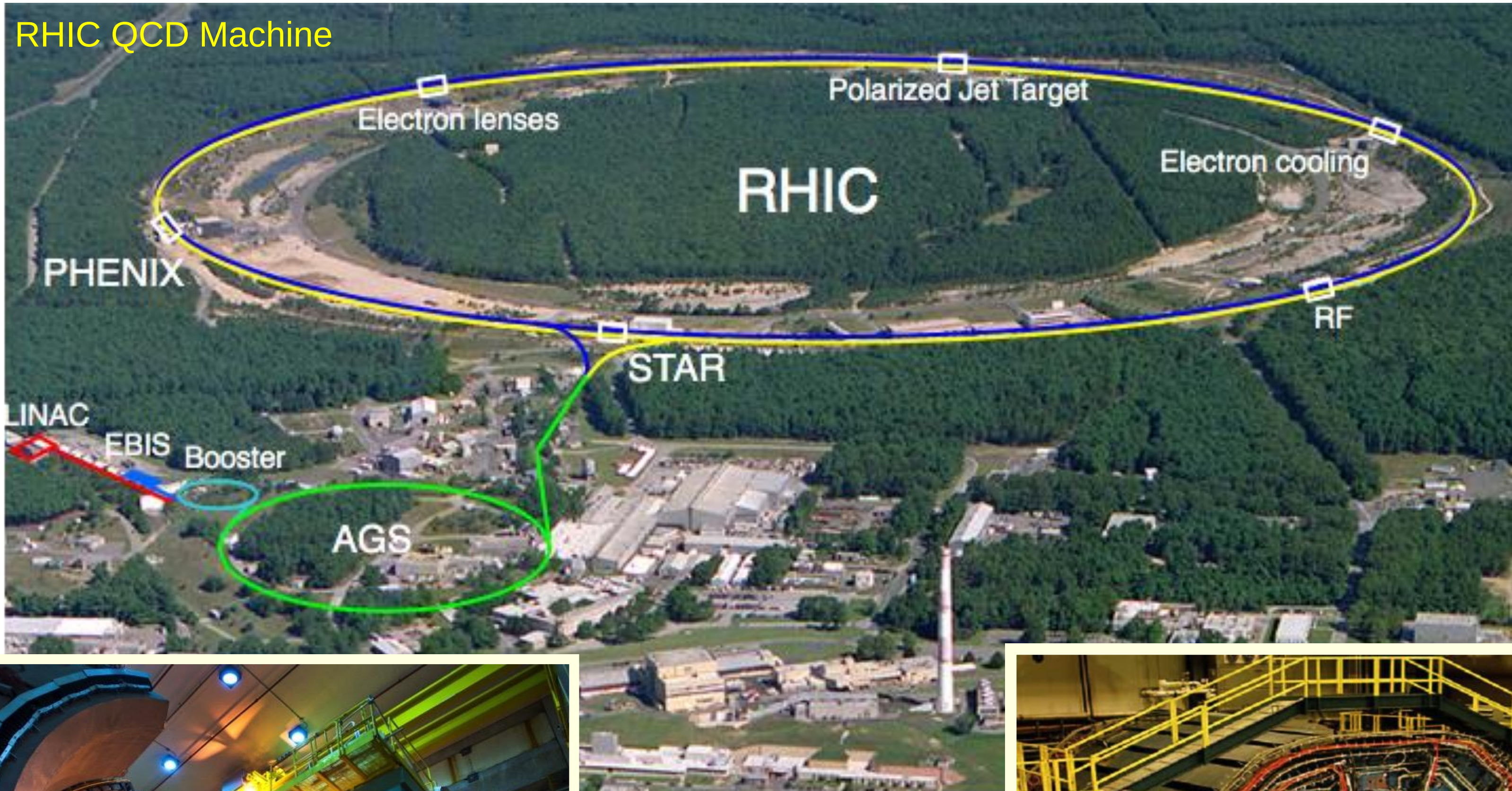


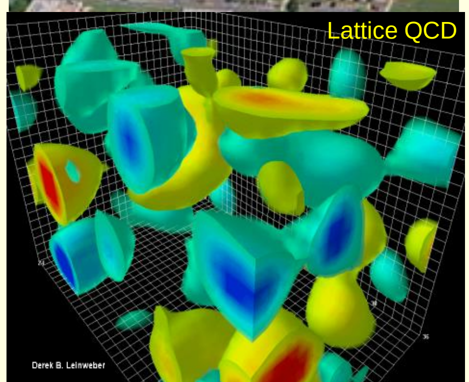
The RHIC Beam Energy Scan-I (BES-I)

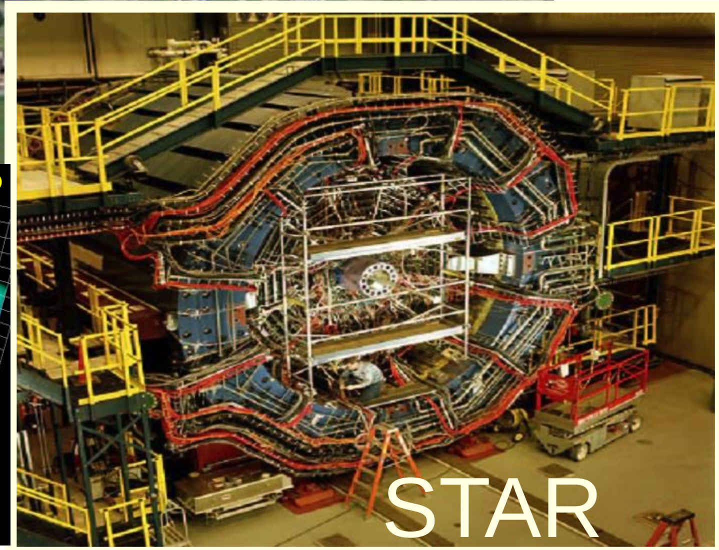
Phases of QCD matter

- How do we map the QCD phase diagram?
- Vary the collision energy over the full range accessible at RHIC
- Do we observe signatures of a phase transition and/or critical end point?
  - Elliptic and directed flow: indicators of the “softest point” in momentum space
  - Azimuthally-sensitive HBT: indicator of the “softest point” in coordinate space
- Do we observe turn off of the new phenomena that have been observed in full-energy RHIC collisions?
  - Jet quenching in central collisions

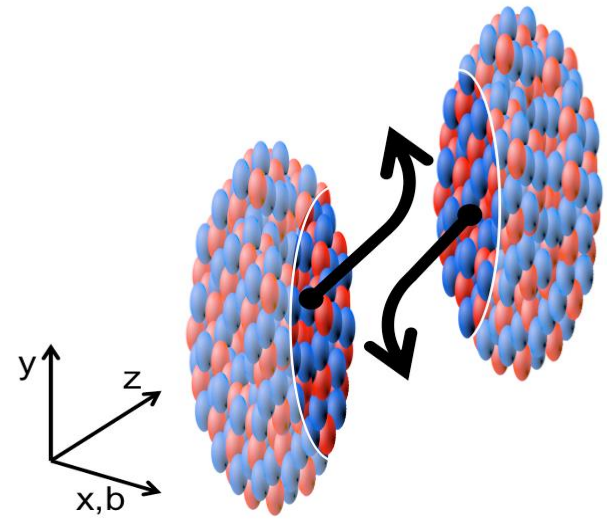
The RHIC Facility

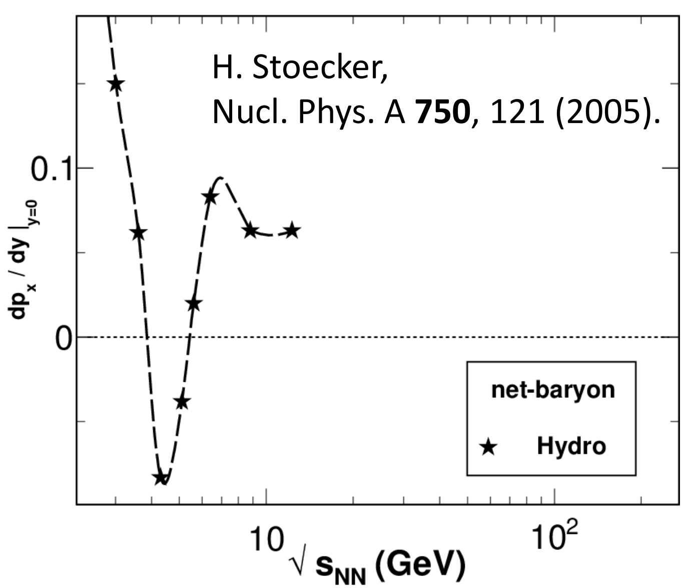






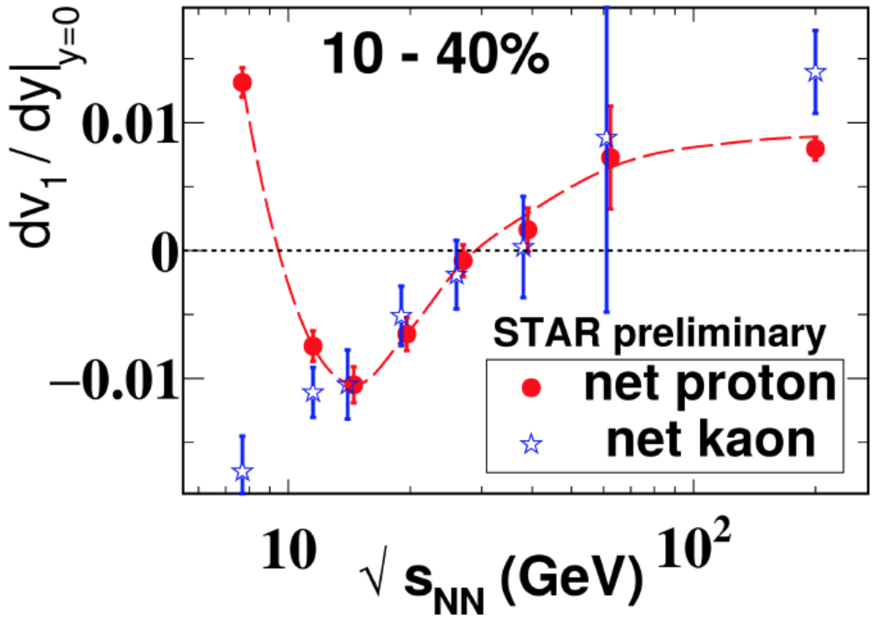
BES-I: Directed Flow (v_1)

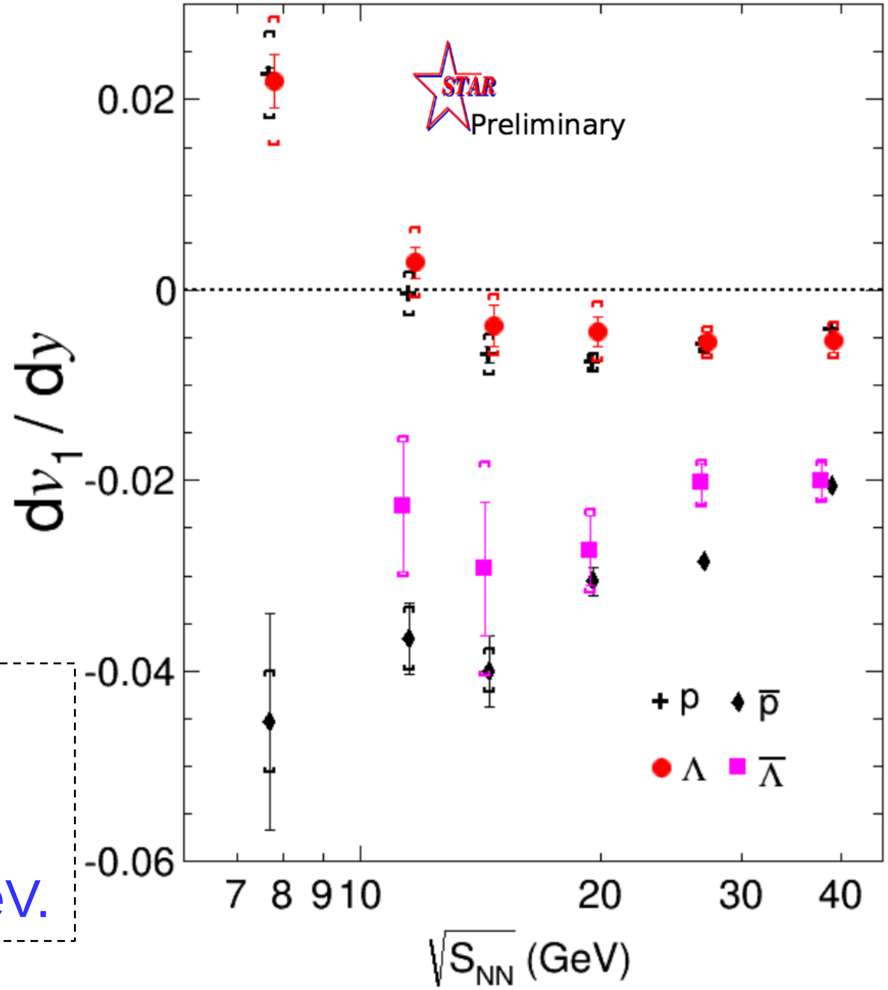




- Generated during the nuclear passage time ($2R/\gamma$) – sensitive to EOS
- Minimum in slope of directed flow (dv_1/dy) as a function of beam energy for baryons and double sign-change for net baryons suggest sudden softening of EOS - sign of the 1st order phase transition
- Proton v_1 probes interplay of baryon transport and hydro behavior

Net-proton v_1: STAR, PRL 112, 162301 (2014)





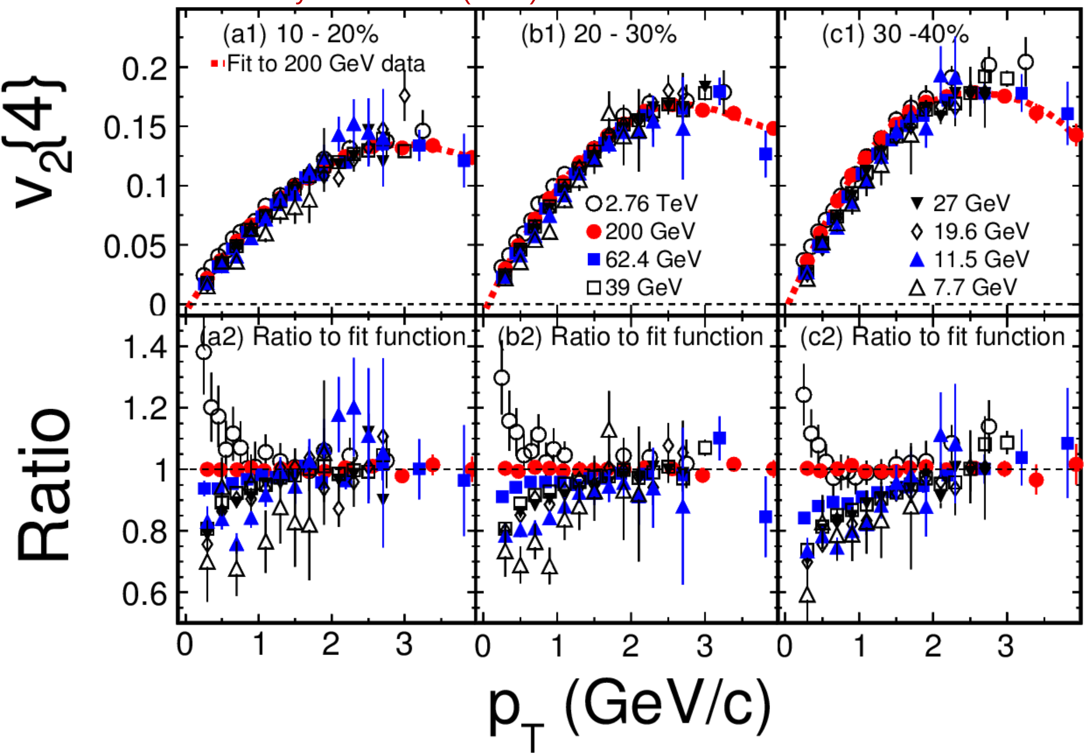
- Non-monotonic behavior in net-proton v_1 indicate 1st order phase transition?
- Split of net-p and net-K v_1 below 14.5 GeV.

H. Stoecker, Nucl. Phys. A 750, 121 (2005).
D.H. Rischke et al. HIP1, 309(1995)
J. Steinheimer et al., arXiv:1402.7236
P. Konchakovski et al., arXiv:1404.276

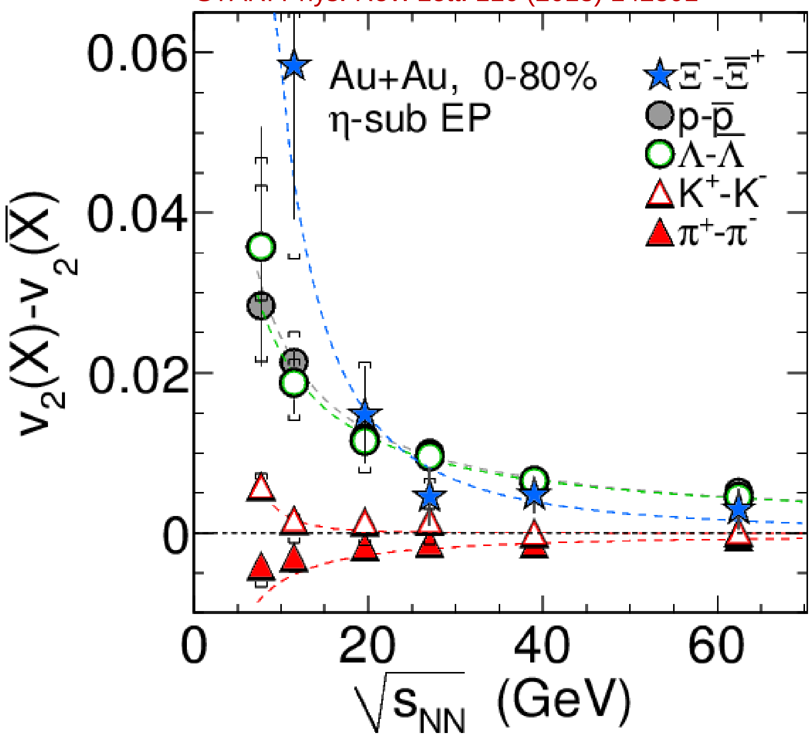
P. Shanmuganathan,
QM2015, RHIC/AGS 2016

BES-I: Elliptic Flow (v_2)

STAR: Phys. Rev. C 86 (2012) 054908



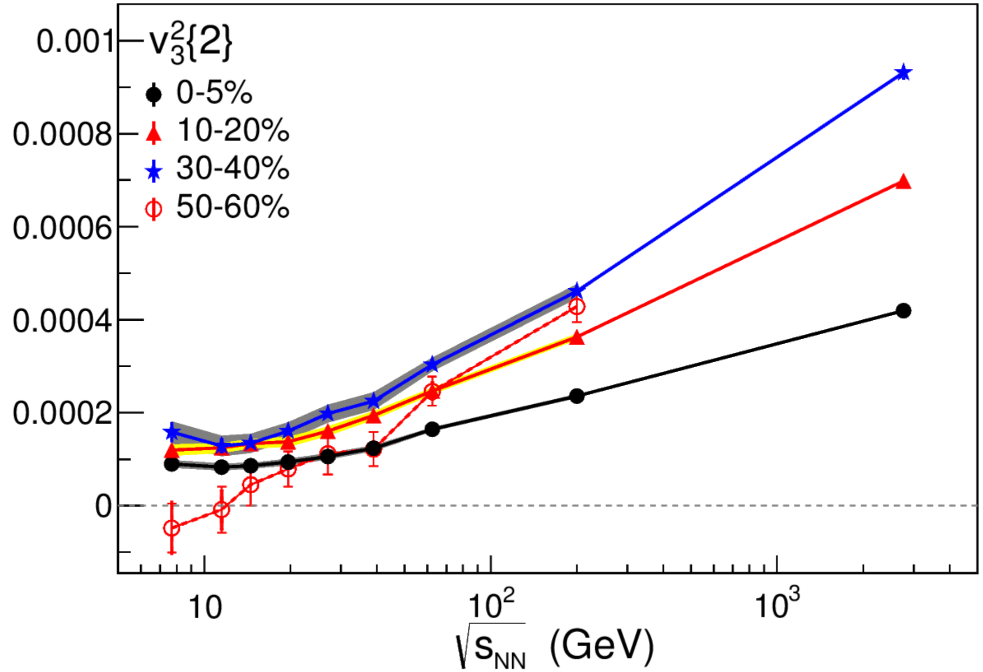
STAR: Phys. Rev. Lett. 110 (2013) 142301

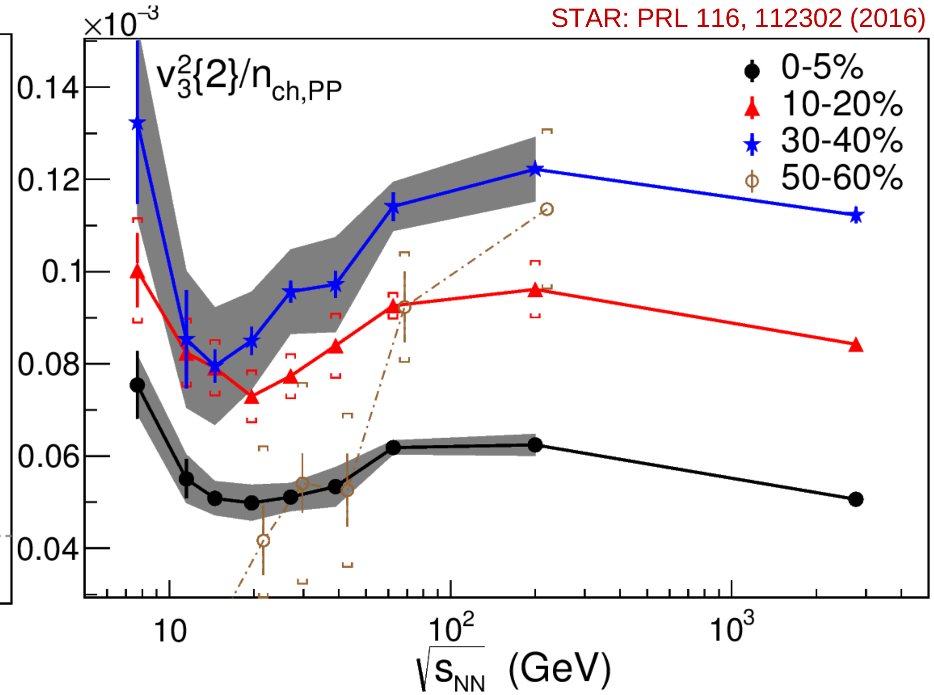


- Surprisingly consistent as the energy changes by a factor ~400
- Initial energy density changes by nearly a factor of 10
- No evidence from v_2 of charged hadrons for a turn off of the QGP

  How sensitive is v_2 to QGP?
- Substantial particle-antiparticle split at lower energies
- The number of quark scaling in elliptic flow is broken

BES-I: Triangle Flow (v_3)





- Models show that higher harmonic coefficients are more sensitive to the existence of a QGP phase. In models, v_3 goes away when the QGP phase disappears:

  J. Auvinen, H. Petersen, Phys. Rev. C 88, 64908, B. Schenke et.al., Phys. Rev. C 85, 024901

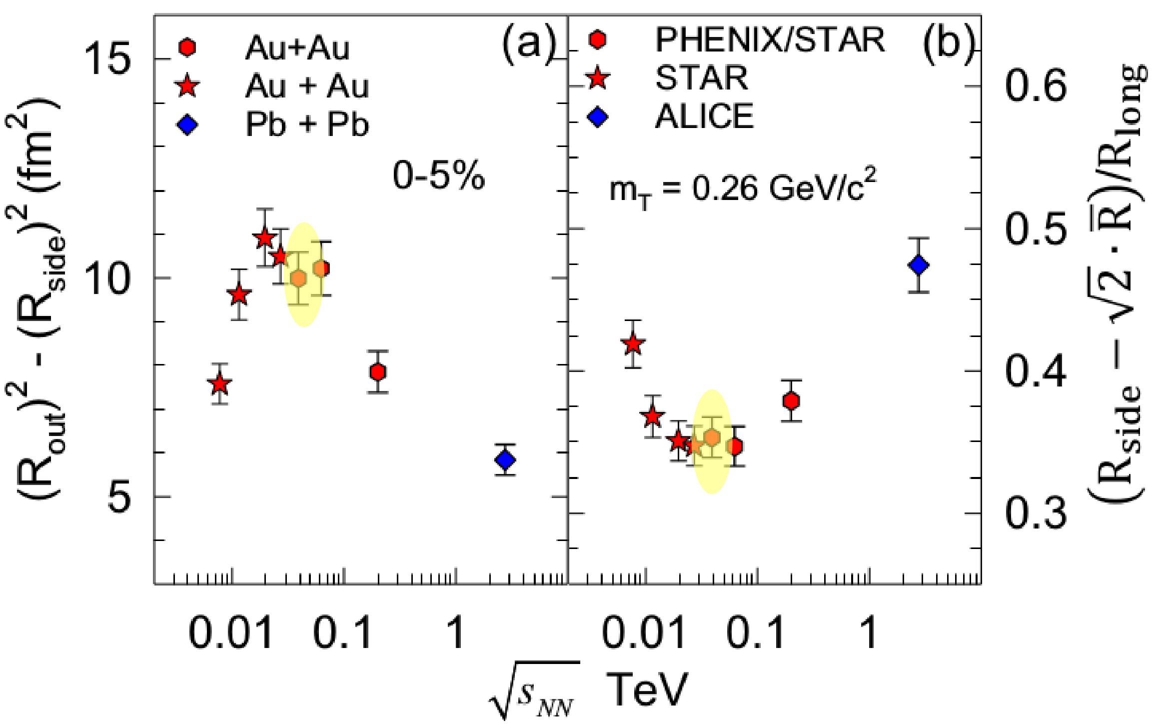
- STAR results show that v_3 vanishes for peripheral collisions at lowest RHIC BES energy. Minimum are observed for centralities bins in 0-50% collisions for $v_3^2/n_{ch,pp}$.

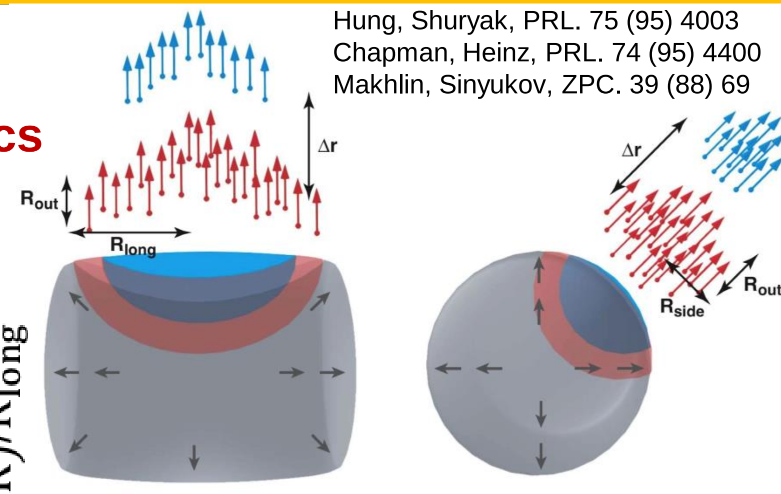
  STAR: PRL 116, 112302 (2016)

Energy Dependence of HBT signals

HBT radii are sensitive to the expansion dynamics

PHENIX: arXiv:1410.2559





Hung, Shuryak, PRL. 75 (95) 4003
Chapman, Heinz, PRL. 74 (95) 4400
Makhlin, Sinyukov, ZPC. 39 (88) 69

$$R^2_{side} = \frac{R^2_{geo}}{1+\frac{m_T}{T}b^2_T}$$

$$R^2_{out} = \frac{R^2_{geo}}{1+\frac{m_T}{T}b^2_T} + b^2_T(\Delta t)^2$$

$$R^2_{long} \approx \frac{T}{m_T}t^2$$

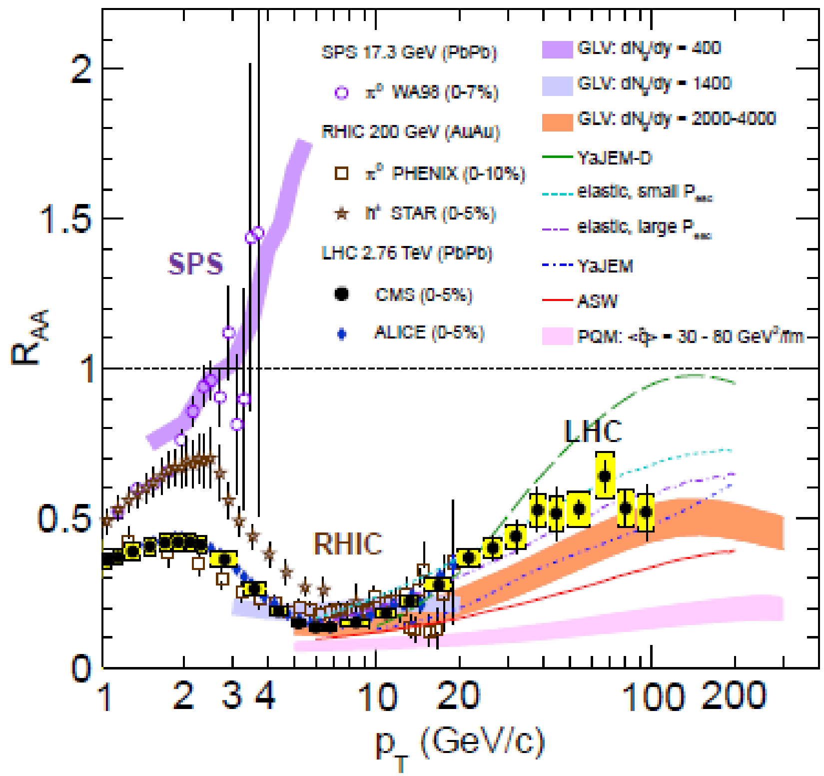
- These non-monotonic patterns signal an important change in the reaction dynamics; CEP?

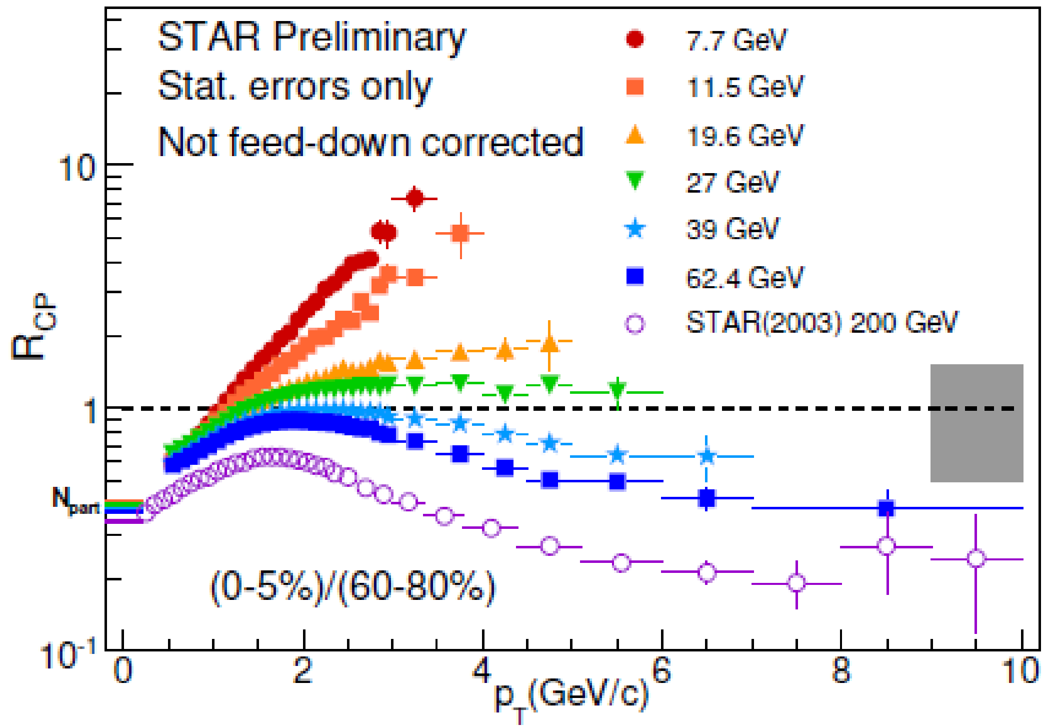
emission lifetime

$(R^2_{out} - R^2_{side})$ sensitive to emission duration

Jet quenching

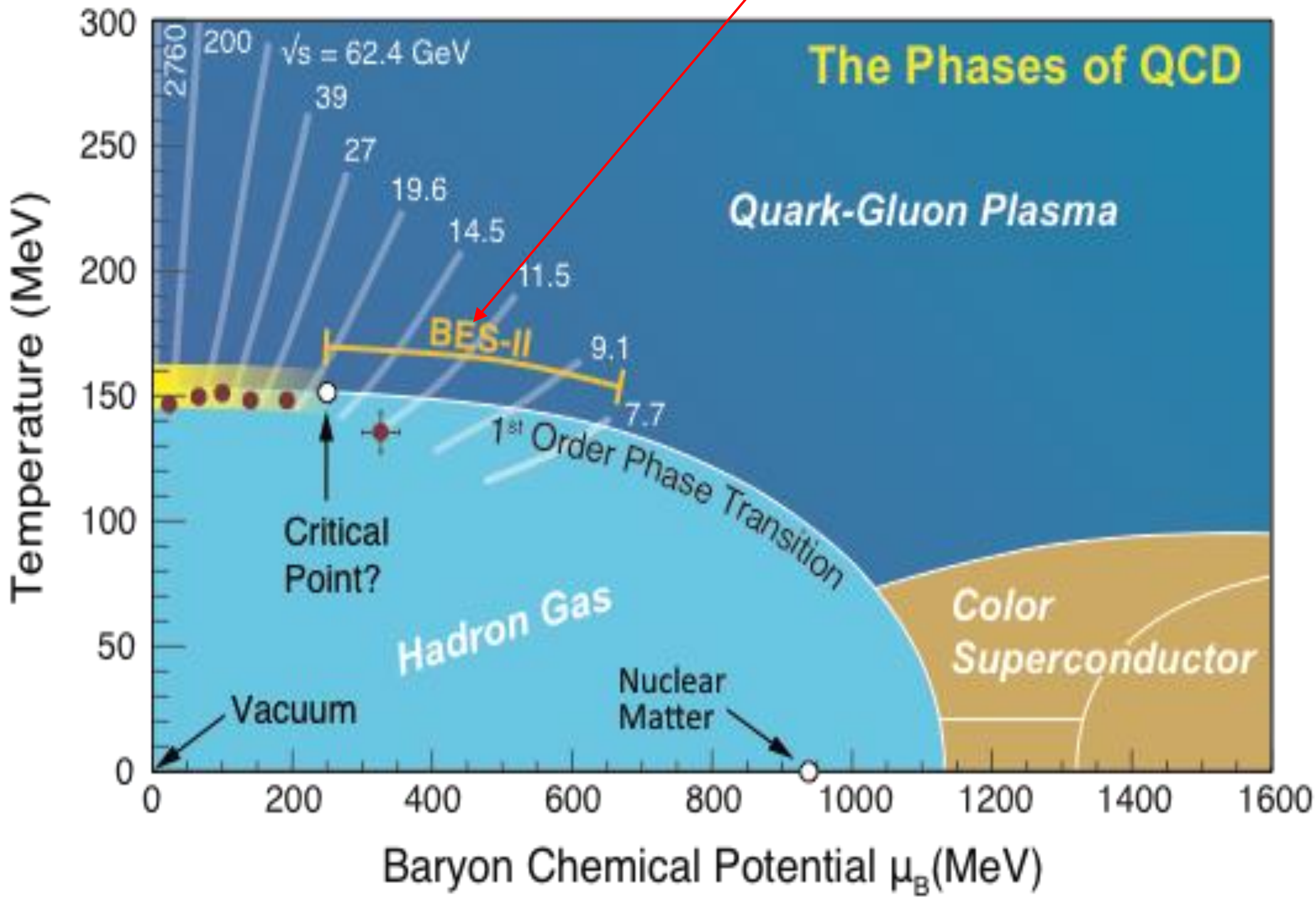
R_{CP} for hadrons can provide a measure of partonic energy loss in the medium





Insufficient reach to search for evidence of high p_T suppression below 19.6 GeV

Beam Energy Scan-I required more statistic and it is carried out by many interesting results. Beam Energy Scan-II (BES-II) is necessary.



Future Science Plan of RHIC 2017-2020

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2017	High statistics Pol. p+p at 510 GeV	**Transverse spin physics**	Coherent e-cooling test II
2018	$^{96}Zr+^{96}Ru$ at 200 GeV Au+Au at 27 GeV (?)	**Establish chiral magnetic effect**	**Low energy e-cooling upgrade**
2019-20	**7.7-20 GeV Au+Au (BES-2)**	**Search for QCD critical point and onset of deconfinement**	STAR iTPC upgrade EPD upgrade CBM TOF test

Strongly endorsed by 2016 RHIC PAC

Future Science Plan of RHIC 2017-2020

Also Endorsed by 2015 NSAC Long Range Plan

RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

- *Complete and run CEBAF 12 GeV upgrade*
- *Complete FRIB at MSU*
- *Targeted program in neutrinos and fundamental symmetries*
- *The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.*

Transverse Polarized p+p Collisions (Run-17)

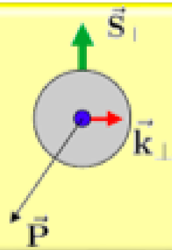
Talk by Elke-Caroline Aschenauer: "The RHIC Spin Program", Thursday at 17:00 PM

Visualize Color interactions in QCD

Sivers function

$\sin(\phi_h - \phi_s)$

modulation



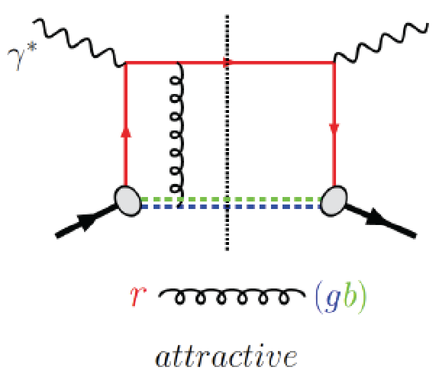
correlation of nucleon's transverse spin with the k_T of an unpolarized quark

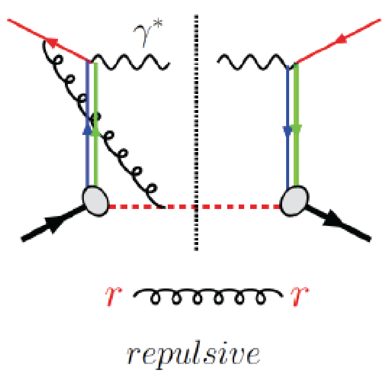
- measures spin-orbit correlations
- link to parton orbital motion (through models)
- reveals non-trivial aspects of QCD color gauge invariance

Measure non-universality of sivers-function

QCD:

DIS: γq-scattering **attractive FSI**	**pp:** qqbar-anhilation **repulsive ISI**



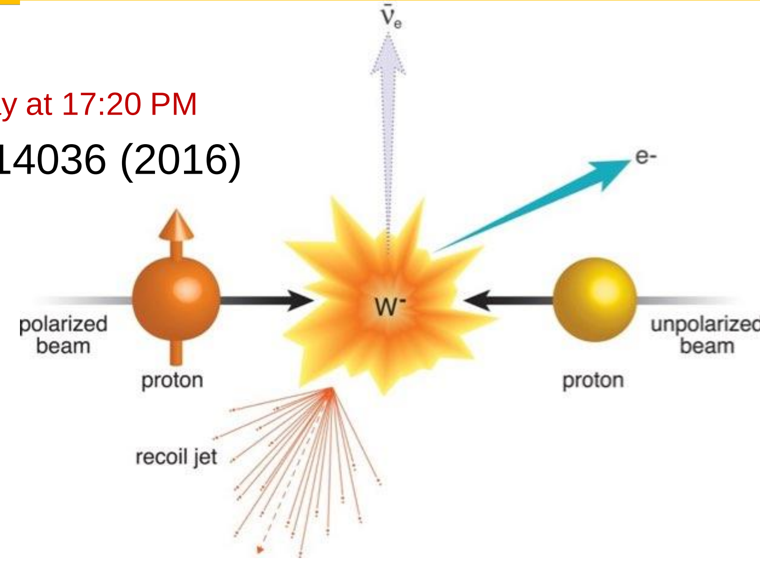


Sivers_{DIS} = − (Sivers_{DY} or Sivers_{W} or Sivers_{Z0})

W Sivers Function (Run-17)

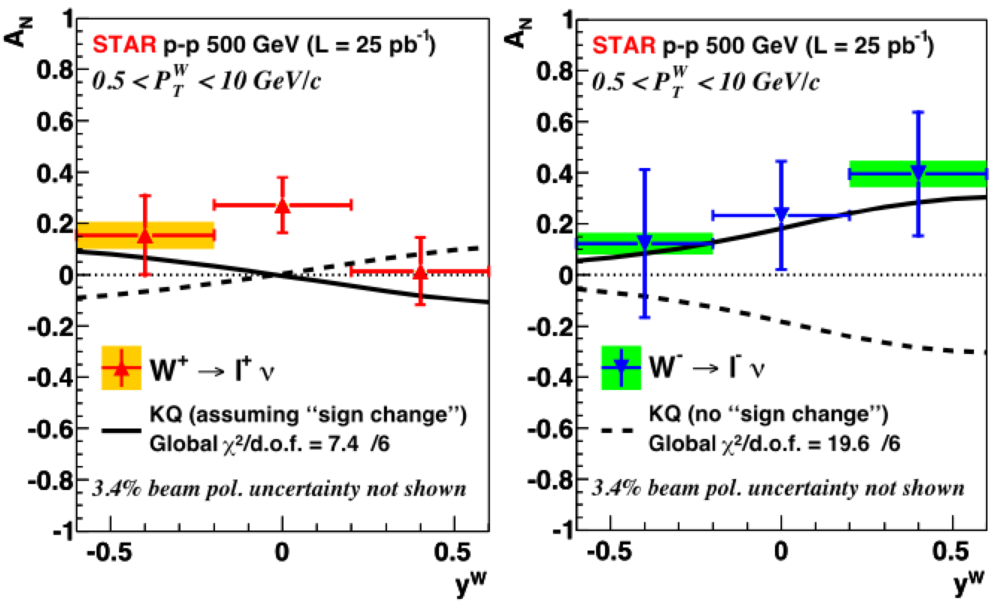
- Talk by Elke-Caroline Aschenauer:

  "The Spin structure of the Proton: What RHIC and EIC can teach us" Saturday at 17:20 PM
- Recent theory paper: Jin Huang et al. Phys. Rev. D 93, 014036 (2016)



Analysis of Run-15 data demonstrates viability of definitive measurement

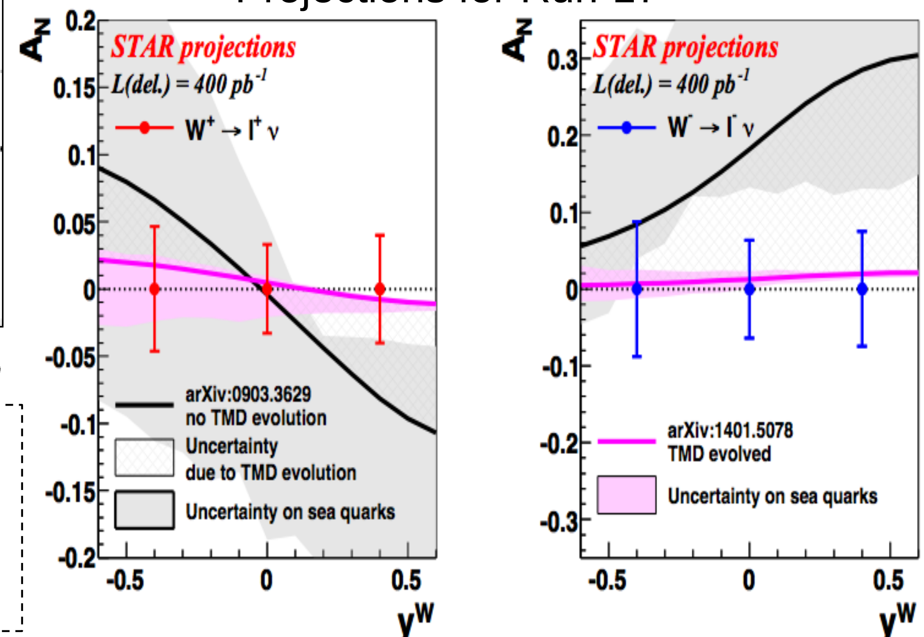
STAR: PRL 116 (2016) 132301



- Will provide data to constrain TMD evolution
- Sea-quark Sivers fct → y-dependence
- Test sign-change if TMD evolution ~ 5 or less.

Critical inputs for EIC!

Projections for Run-17



Probing Chiral Symmetry with Quantum Currents

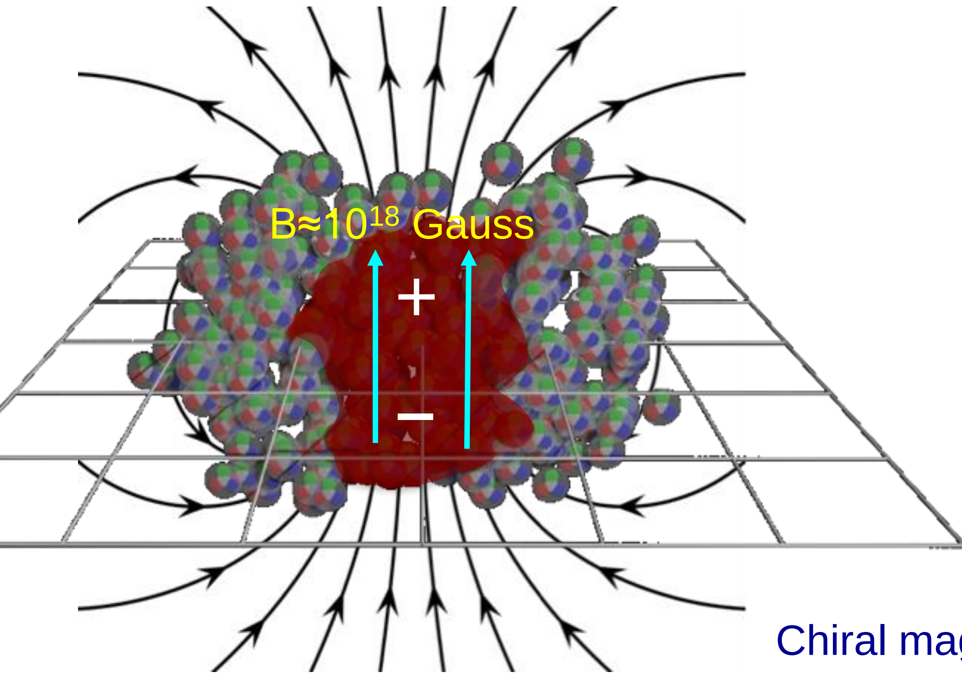
Talk by Dmitri Kharzeev :
"The Chiral Magnetic Effect from quark-gluon plasma ", Wednesday at 10:15 PM

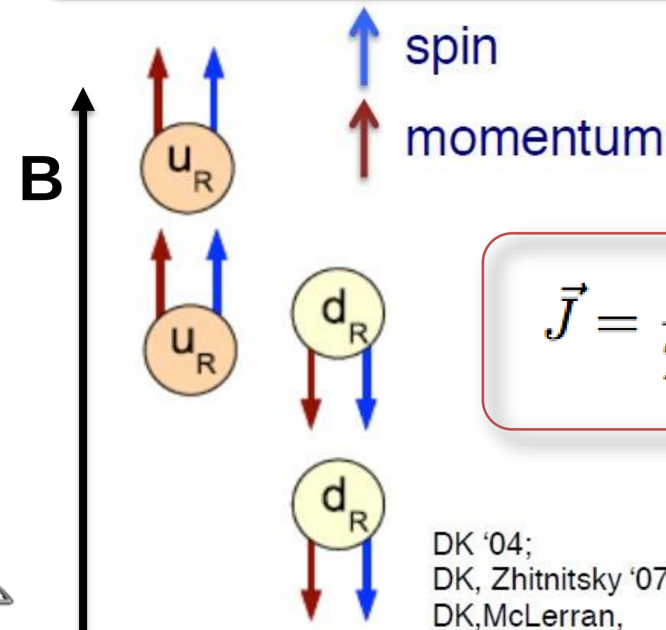
- The chiral anomaly of QCD creates fluctuating differences in the number of left and right handed quarks, characterized by a chiral chemical potential μ_5.

- In a chirally symmetric QGP, this imbalance generates an electric current along the magnetic field (chiral magnetic effect).

chirality + magnetic field = current

electric charge separation





$$\vec{J} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}$$

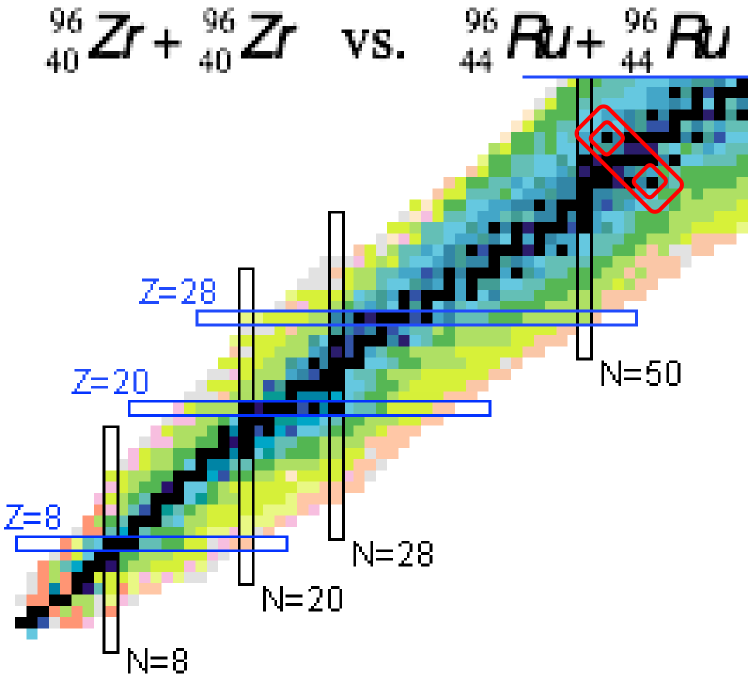
Chiral magnetic conductivity

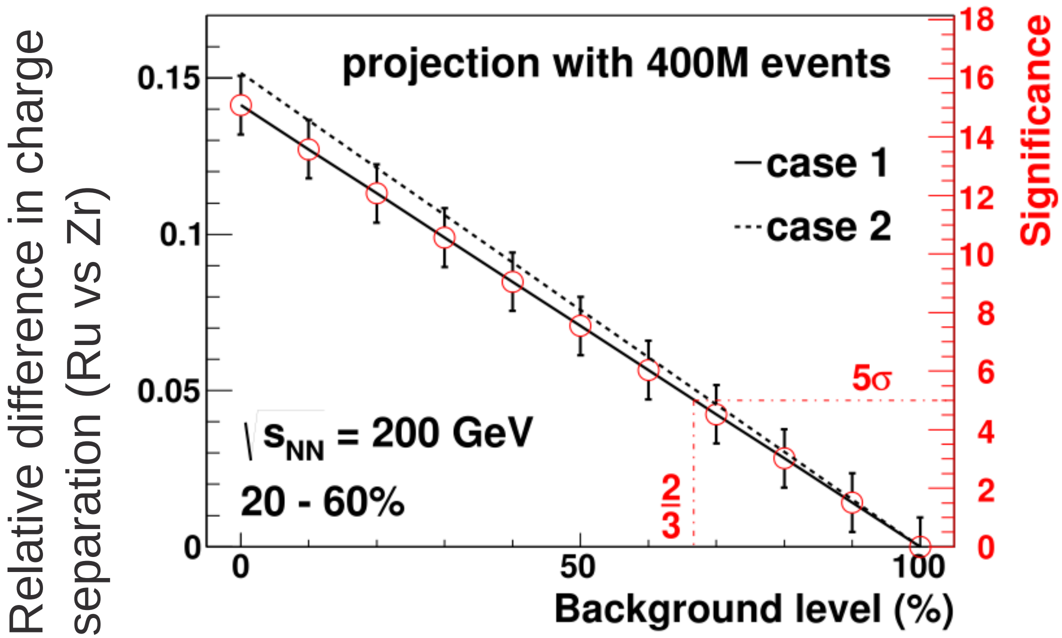
$\mu_5 > 0$

DK '04;
DK, Zhitnitsky '07
DK,McLerran, Warringa '07;
Fukushima, DK, Warringa '08

Probing Chiral Symmetry (Run-18)

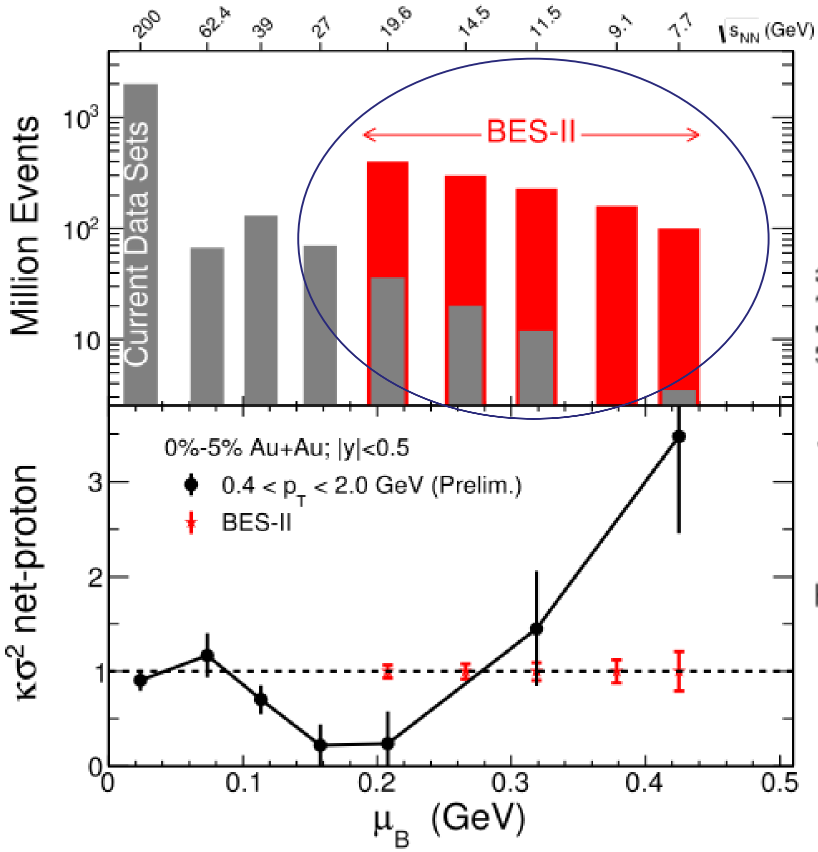
- Current understanding: backgrounds unrelated to the chiral magnetic effect may be able to explain the observed charge separation



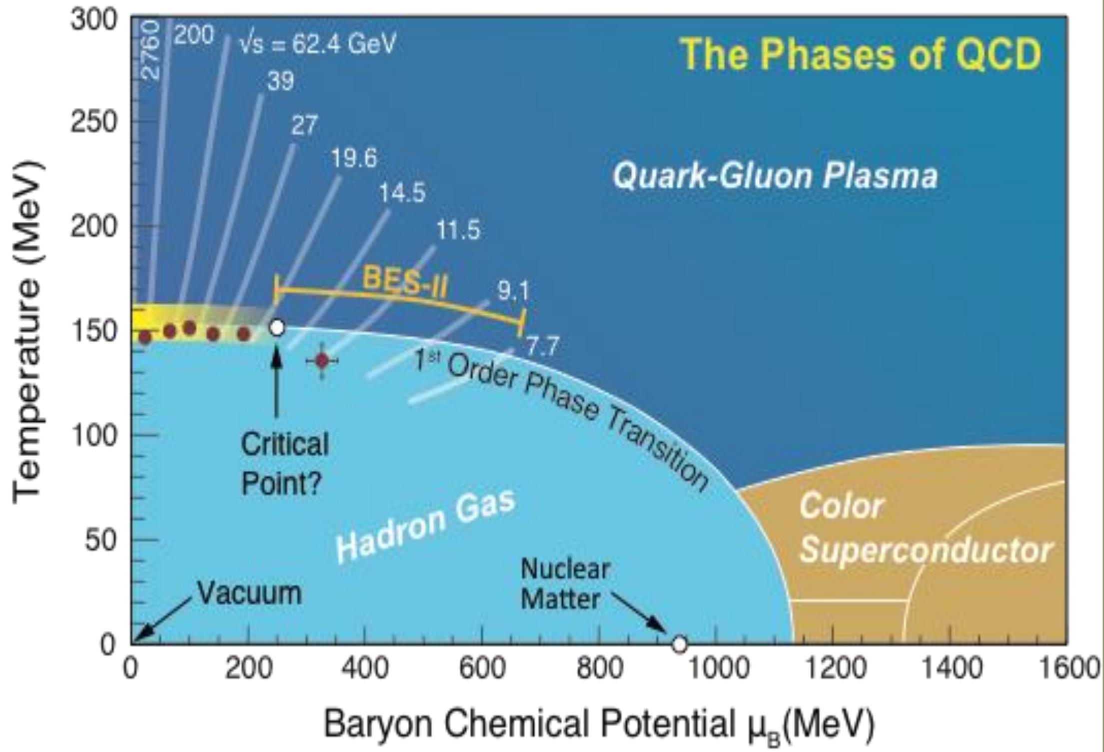


Isobar collisions will tell us what fraction of the charge separation is due to CME to within +/- 6% of the observed signal.

BES-II (Run-19-20)



A unique RHIC capability: a unique opportunity for U.S. science

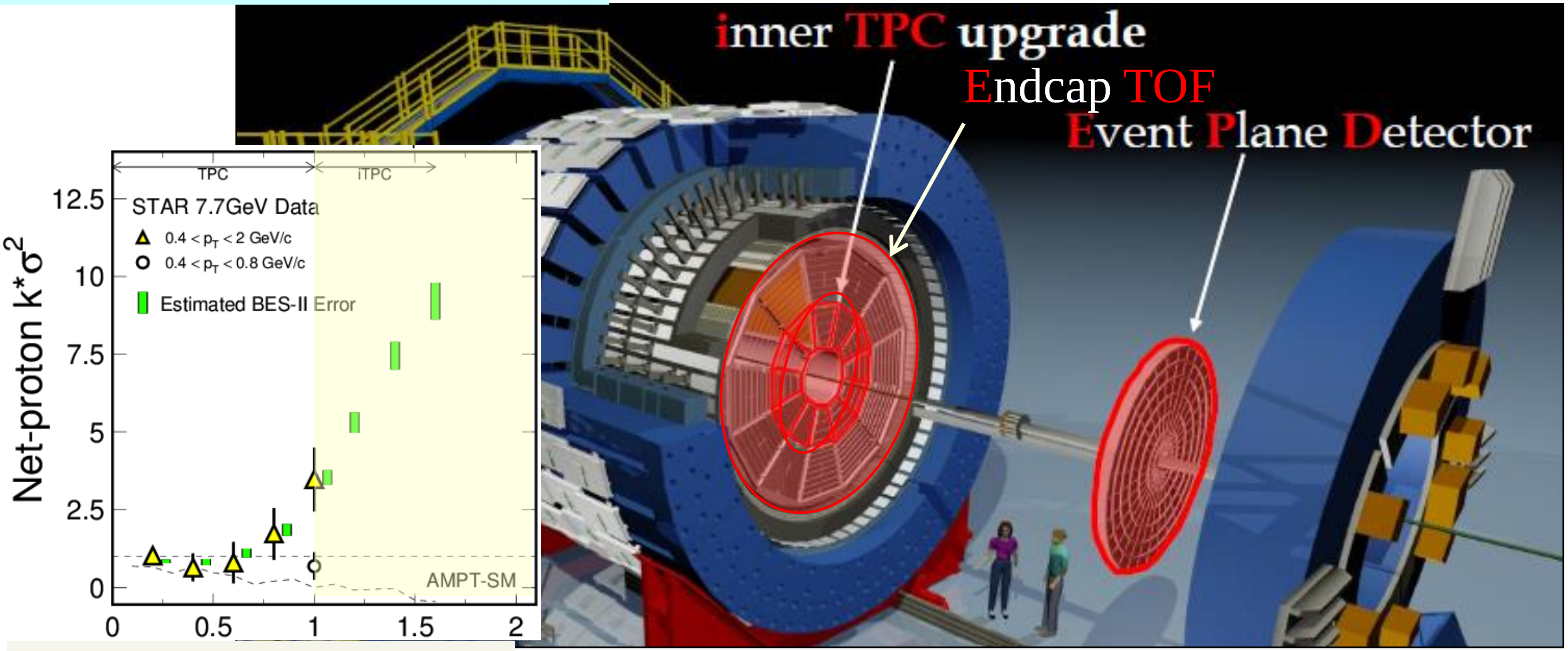


Breaking of chiral symmetry in QCD generates most of the visible mass of the universe.
Is chiral symmetry restored in these collisions?

At low density, the phase transition between QGP and hadrons is smooth.
Is there a 1st order transition and a critical point at higher density?

BES-II: The STAR Upgrades

Major improvements for BES-II



iTPC Upgrade:

- Rebuilds the inner sectors of the TPC
- Full (azimuth) coverage Improves dE/dx
- Extends η coverage from 1.0 to 1.7
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c

EndCap TOF Upgrade:

- Rapidity coverage is critical
- PID at forward rapidity
- Improves the fixed target program

EPD Upgrade:

- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

BES-II: Required Events and LEReC

LEReC: Low Energy RHIC electron Cooling   Talk by Wolfram Fischer: Sunday at 14:30 PM

➢ BES-II for search of critical point in QCD phase diagram

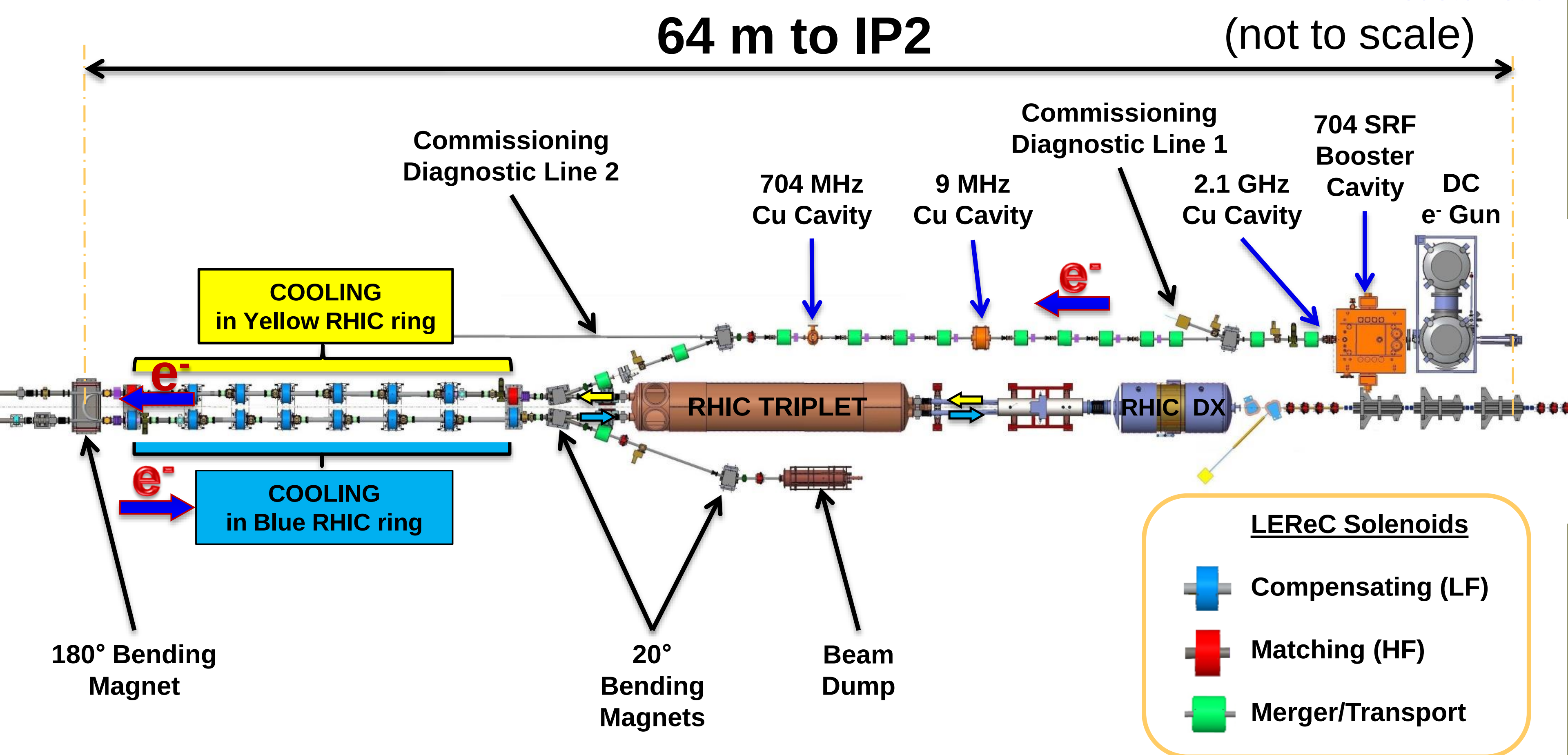
Center-of-mass energy $\sqrt{s_{NN}}$	GeV	7.7	9.1	11.5	14.6	19.6
Events BES-I, actual	M	4.3		11.7	24	36
Events BES-II, **min goal**	M	80	100	150	200	300
Events BES-II, **full goal**	M	100	160	230	300	400

➢ General strategy to maximize integrated luminosity is to use:

- Cooling at the 3 lowest energies (4x gain in L_{avg}),
- No cooling at the 2 highest energies (3x gain in L_{avg}): **demonstrated at 19.6 GeV in Run-16**
- Increase cryo-time from 22 to 24 weeks/year
- Start BES-II at highest energies (machine ready w/o cooling)
- Interleave cooling commissioning with physics operation
- Finish BES-II at lowest energies (largest gain in L_{avg} and time)

Talk by Wolfram Fischer: “RHIC upgrades for the next decade”, Sunday at 14:30 PM

A. Fedotov et al.

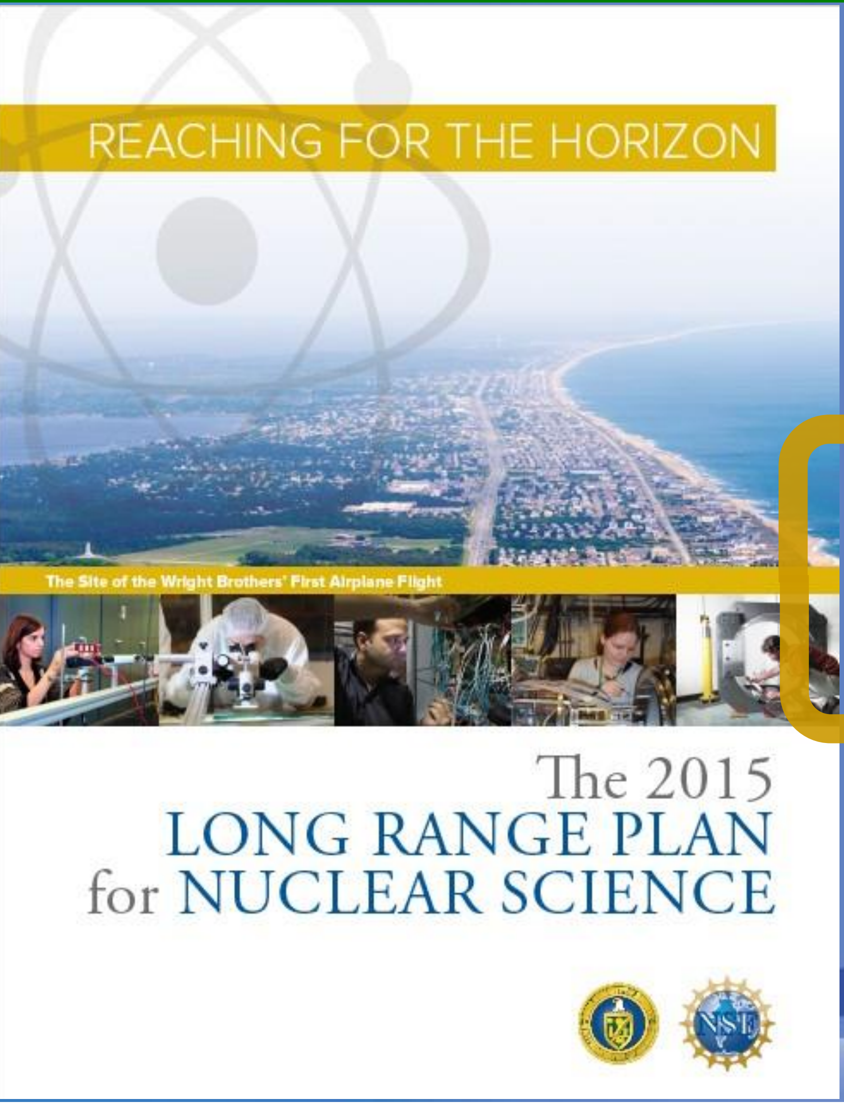


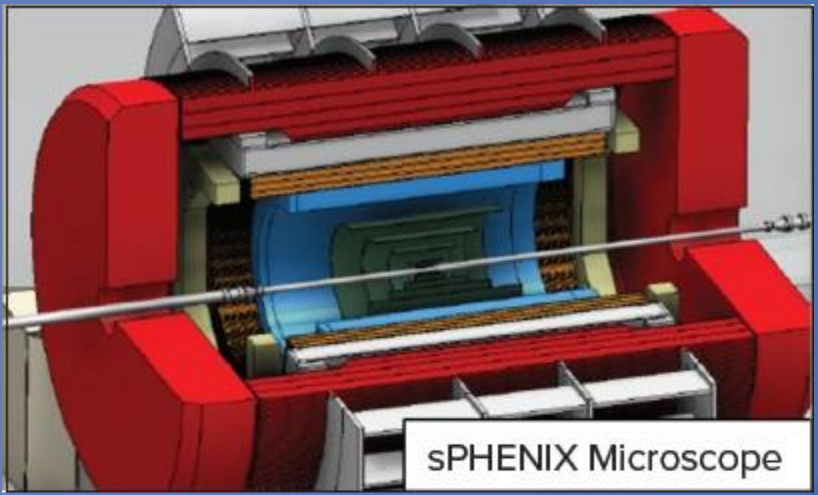
Energies : 1.6, 2.0 (2.65) MeV
Avg. current I_{avg} : 27 mA
Momentum dp/p : 5×10^{-4}
Luminosity gain : 4×

1st bunched beam electron cooler
planned operation in 2019/2020

Beyond 2020: sPHENIX

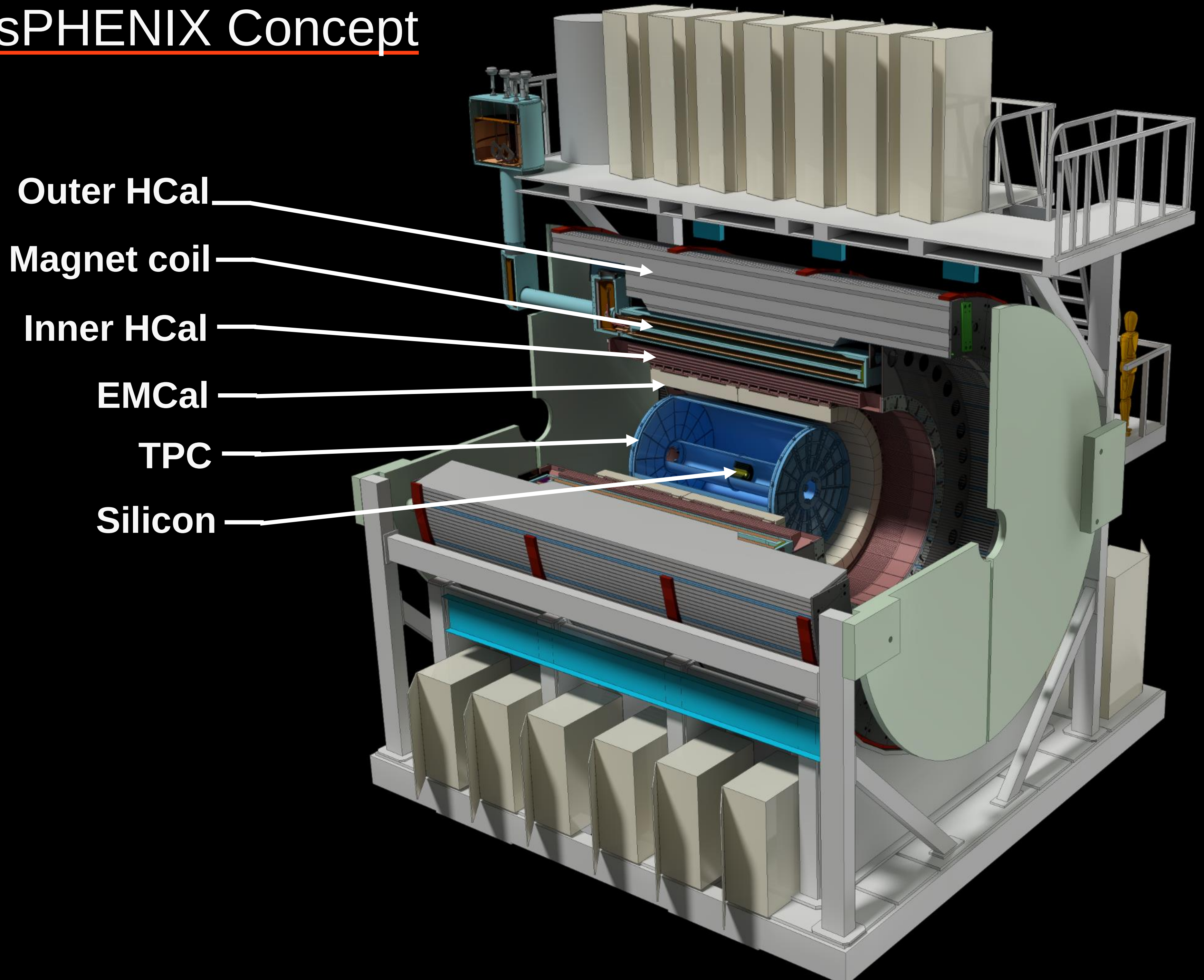
Endorsed by 2015 NSAC Long Range Plan





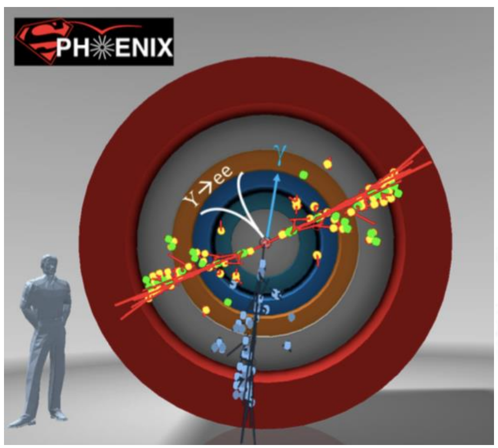
There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**

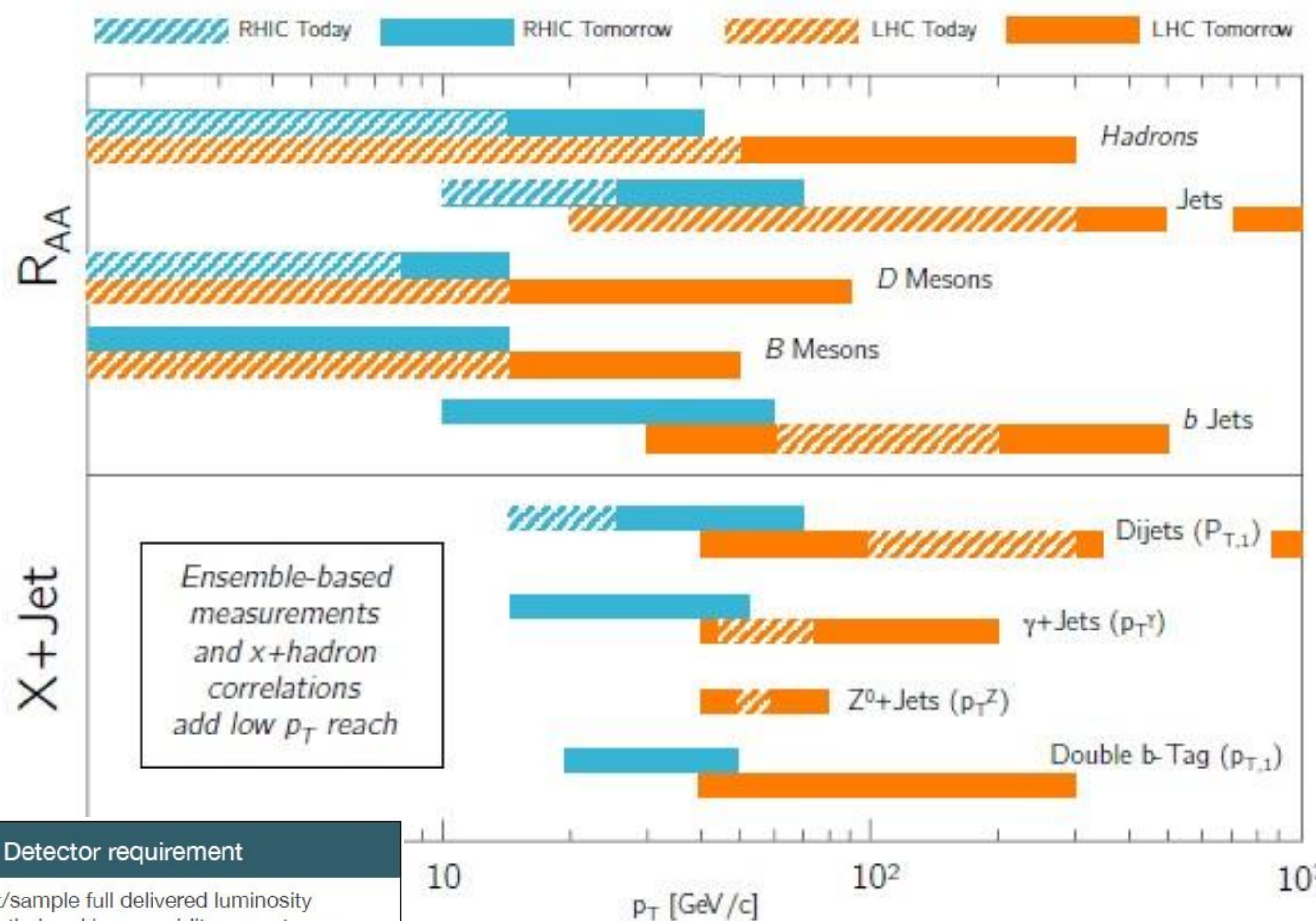
sPHENIX Concept



Complementarity of RHIC and LHC Measurements

Physics Requirements of sPHENIX at RHIC





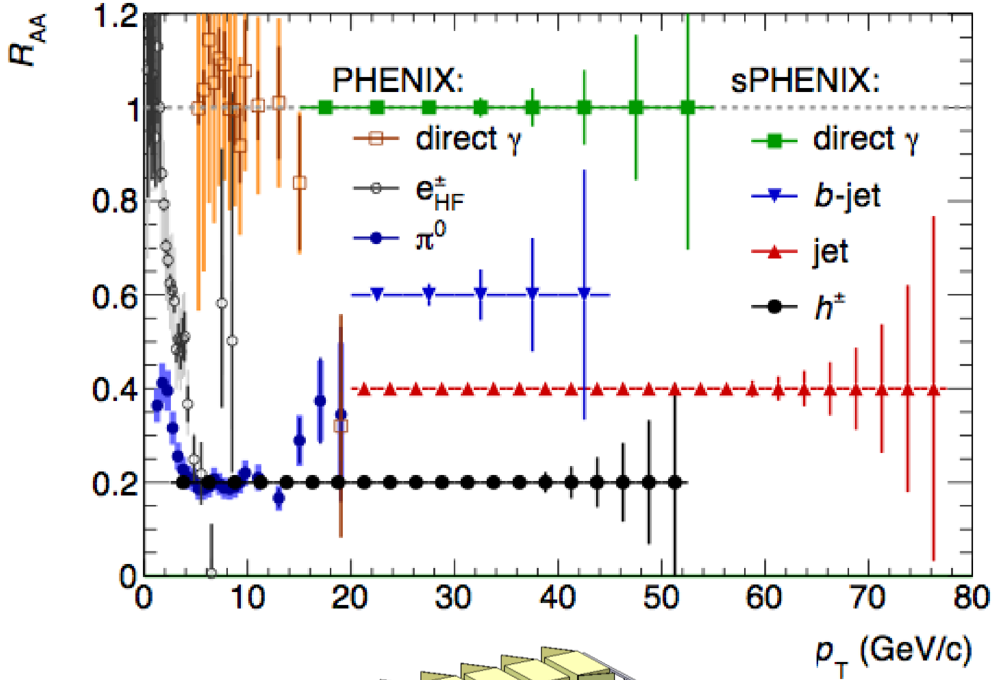
Physics goal	Detector requirement
High statistics for rare probes	Accept/sample full delivered luminosity Full azimuthal and large rapidity acceptance
Precision Upsilon spectroscopy	Hadron rejection > 99% with good $e^{+/-}$ acceptance Mass resolution 1% @ m_Υ
High jet efficiency and resolution	Full hadron and EM calorimetry Tracking from low to high pT
Control over parton mass	**Precision vertexing for heavy flavor ID**
Control over initial parton p_T	Large acceptance, high resolution photon ID
Full characterization of jet final state	High efficiency tracking for $0.2 < p_T < 40$GeV

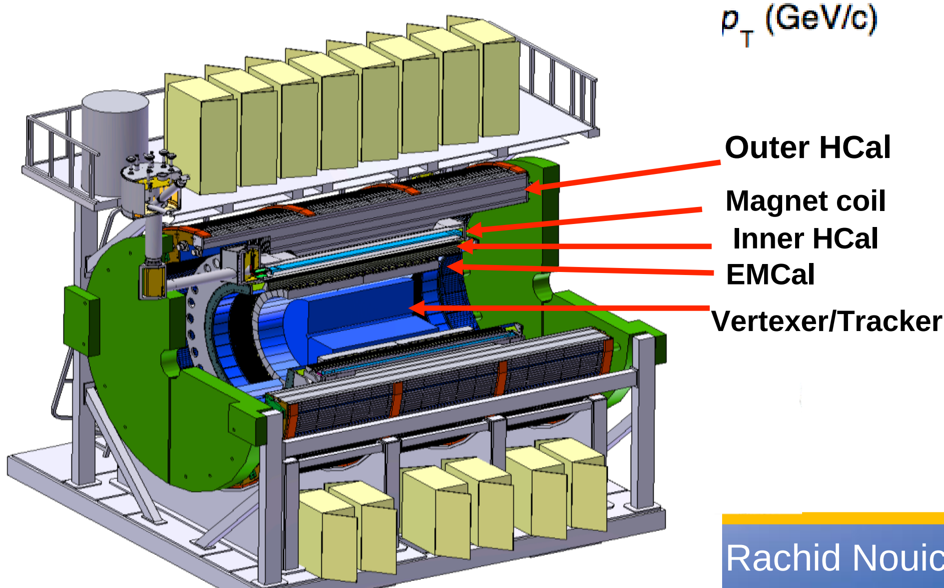
Talk by Gunther Roland (for sPHENIX S&T Review at BNL, August 2016 :

https://indico.bnl.gov/conferenceDisplay.py?confId=2238

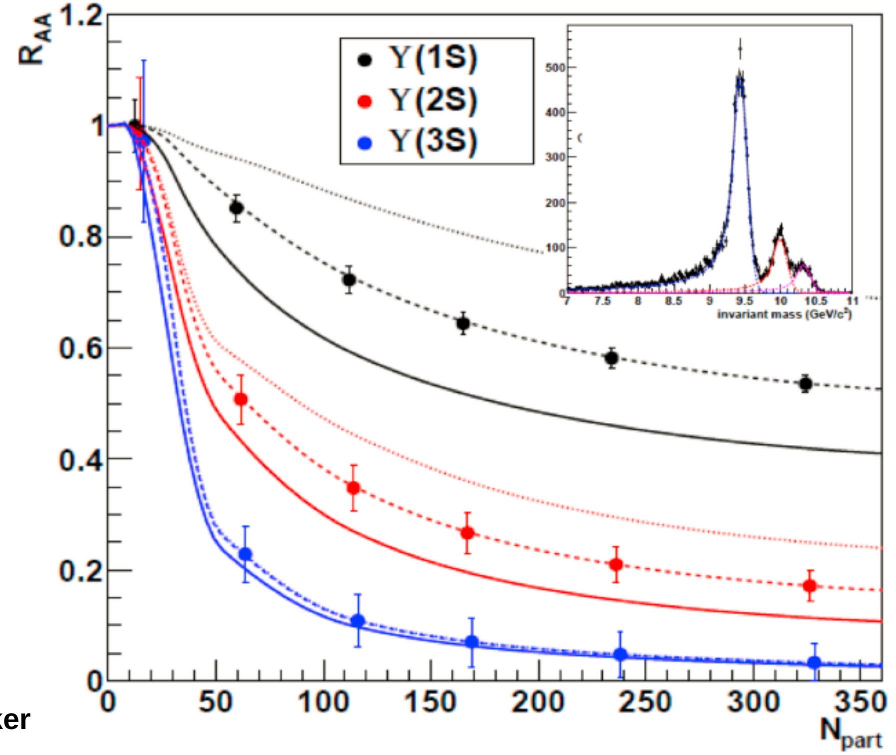
sPHENIX Capabilities: Jets & Upsilon states

Complete calorimetric jet spectroscopy





Completely resolved Upsilon spectroscopy



Beyond RHIC

2015 NSAC Long Range Plan

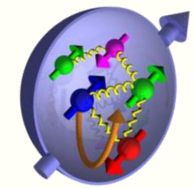
RECOMMENDATION **III**

We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

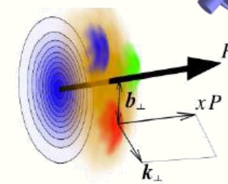
*The **EIC** will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new Quantum Chromodynamics (QCD) frontier of ultra-dense gluon fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei. This science will be made possible by the **EIC's unique capabilities** for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.*

Most compelling SCIENCE Questions

How are sea quarks and gluons and their spin distributed in space and momentum inside the nucleon?

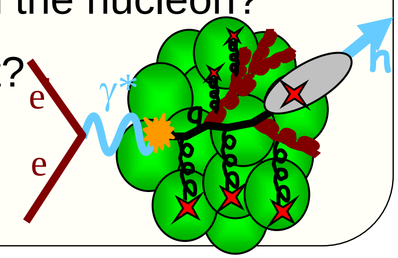


- How are these quark and gluon distributions correlated with the over all nucleon properties, such as spin direction?
- What is the role of the motion of sea quarks and gluons in building the nucleon spin?

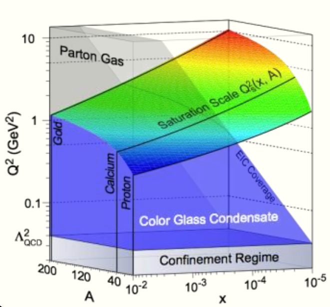


How does the nuclear environment affect the distribution of quarks and gluons and their interaction in nuclei?

- How does the transverse spatial distribution of gluons compare to that in the nucleon?
- How does matter respond to fast moving color charge passing through it? Is this response different for light and heavy quarks?



Where does the saturation of gluon densities set in?



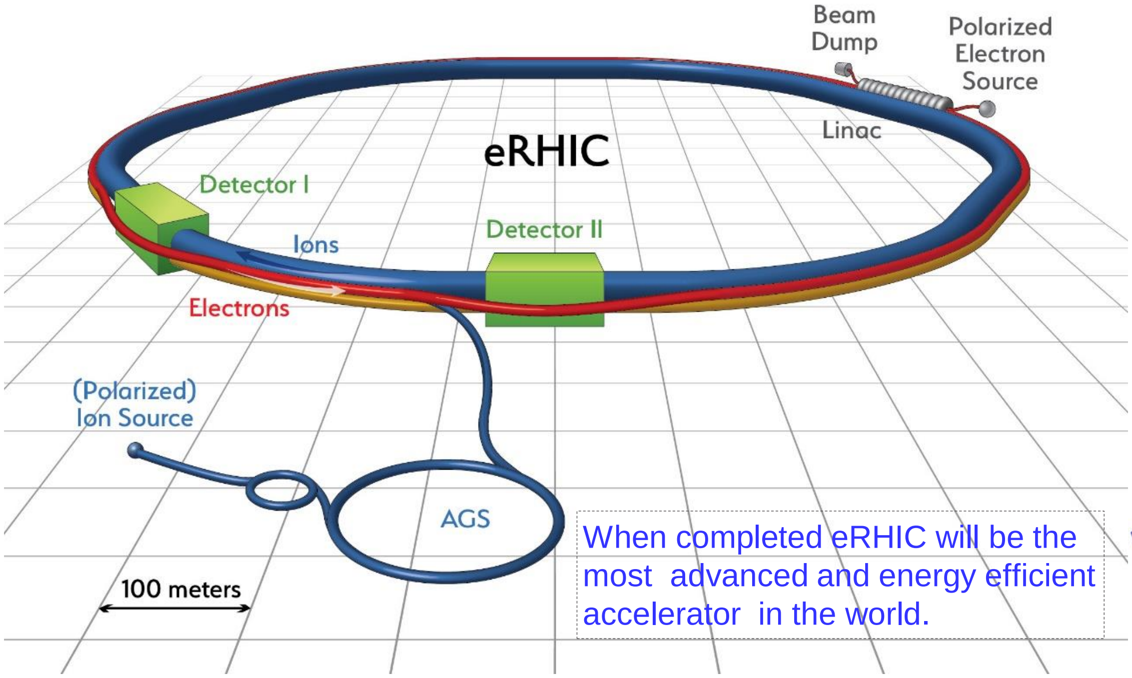
- Is there a simple boundary that separates the region from the more dilute quark gluon matter? If so how do the distributions of quarks and gluons change as one crosses the boundary?
- Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

BNL EIC Design: eRHIC

- Talk by Wolfram Fischer: “RHIC upgrades for the next decade”, Sunday at 14:30 PM
- Talk by Christoph Montag: “eRHIC Design Status and Plans”, Sunday at 15:15 PM

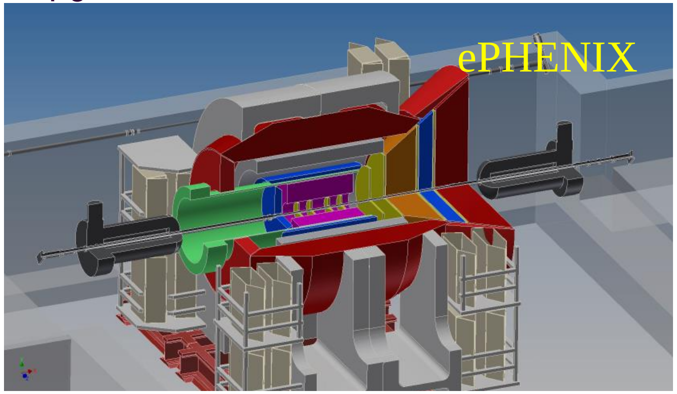
eRHIC ERL + FFAG ring design @ 10^{33}-10^{34}/cm^{2}s

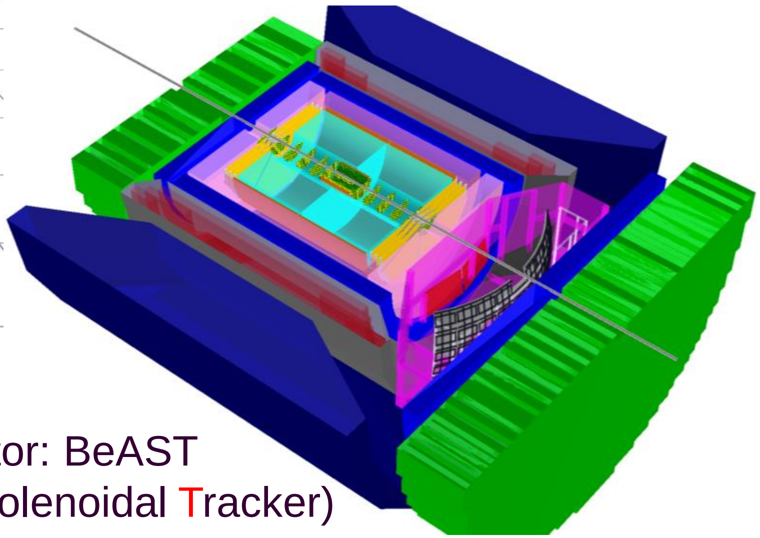
~20 GeV e^- + 255 GeV p or 100 GeV/u Au.



When completed eRHIC will be the most advanced and energy efficient accelerator in the world.

Upgrade sPHENIX to ePHENIX



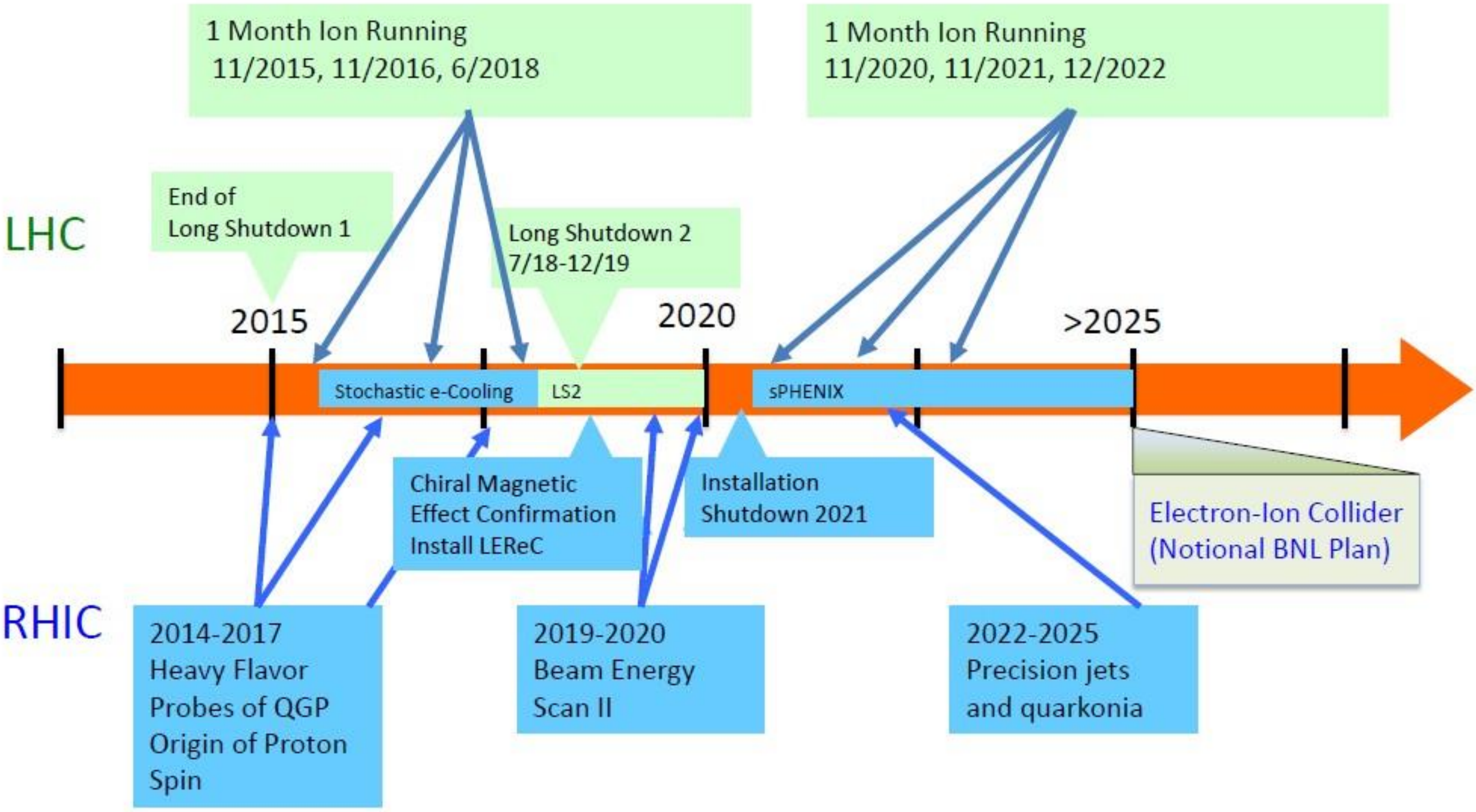


Note: new detectors for EIC fit in the existing RHIC tunnels.

Build a new detector: BeAST (Brookhaven eA Solenoidal Tracker)

RHIC / LHC Timeline

- Talk by Timothy J. Hallman Associate Director for Nuclear Physics DOE Office of Science
  RHIC User Meeting June 9, 2016: https://www.bnl.gov/aum2016/content/plenary/pdf/RHIC_User_Hallman_06092016.pdf



Summary

- ✓ RHIC is Amazing QCD Machine
  - Many Species, Many Energies, and High Luminosity and Stability

- ✓ RHIC is planning a unique forefront science program with continued discovery potential as laid out in NSAC LRP:
  - Quantify the transport properties of the QGP near T_c using heavy quarks as probes
  - Measure gluon and sea quark contributions to proton spin and explore transverse momentum-spin dynamics of QCD
  - High statistics map of the QCD phase diagram, including search for a possible critical point
  - Probe internal structure of the most liquid QGP using fully reconstructed jets and resolved Upsilon states as probes

- ✓ Important machine and detector upgrades underway for BES II (LEReC, iTPC, EPD)

- ✓ Major detector upgrade underway (sPHENIX)

- ✓ Transition from RHIC to eRHIC in mid-2020s