# RHIC Users Meeting

## 22-23 October 2020

Berndt Mueller

ALD for NPP

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# RHIC Begins World's Highest Energy Heavy-Ion Collisions

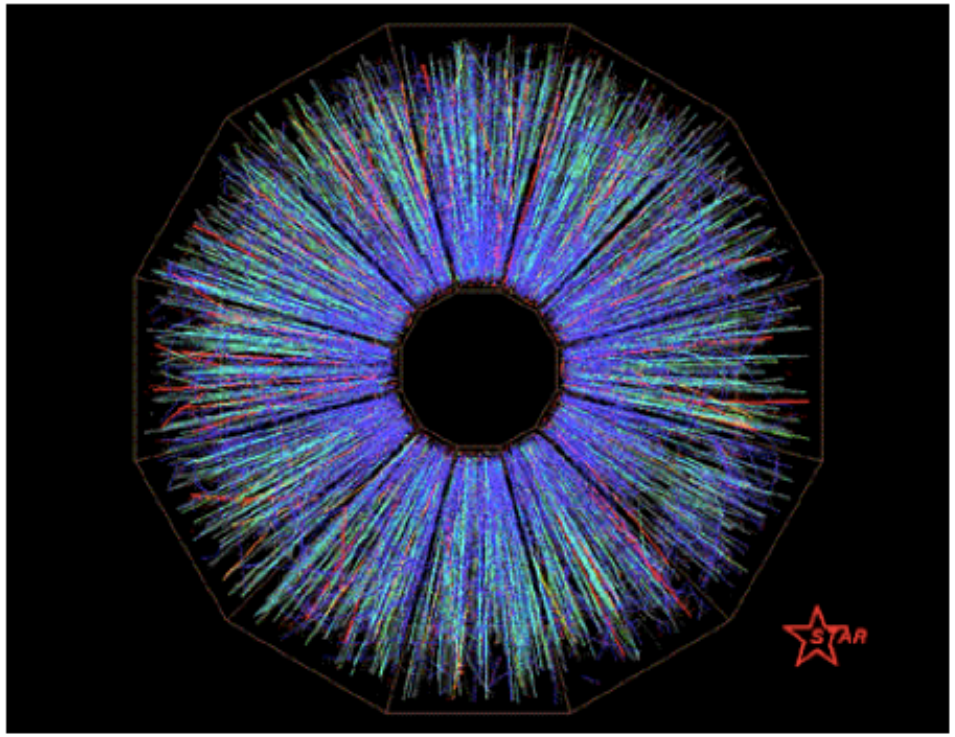
On the evening of Monday, June 12, operators in the main control room of the Relativistic Heavy Ion Collider (RHIC) watched control displays anxiously as the beams circulating in the collider's twin rings appeared to be colliding.

"The atmosphere was tense and very exciting," said Thomas Roser, head of the Accelerator Division and run coordinator for RHIC's first collision run. "We were operating at nearly 30 billion electron volts (GeV) per nucleon, our target energy for first collisions,

*"We are crossing into a new frontier of scientific inquiry."*

and we knew the beams were crossing at the collider's intersection points. But we couldn't say for sure that we'd had collisions until we got definitive, corroborative evidence from the detectors."

All four of RHIC's detectors — BRAHMS, PHENIX, PHOBOS and STAR — were poised and ready to take data as the accelerator physicists began to steer the beams into collision, necessarily one detector at a time.




A view of a RHIC collision seen in the STAR detector. "We knew immediately that we'd seen a true, beam-on-beam collision because all the particle tracks clearly originated at the center of the beam tube and sprayed out in all directions," said John Harris of Yale University and head of the STAR team. The symmetric pattern of particle tracks contrasts dramatically with so-called background events the team had witnessed, where collisions between ions and gas particles in the beam tube produce tracks going in only one direction.

est and biggest particle accelerator for studies in nuclear physics. "We are crossing into a new frontier of scientific inquiry," said Energy Secretary Bill Richardson upon hearing of the first collisions. "Scientists from around the world will use this facility to answer some of the most basic questions about the properties of matter and the evolution of our universe."

The collider aims to recreate the conditions of the early universe to gain insights into the fundamental nature of matter — and extend the boundaries of scientific understanding through the 21st century and beyond.

Scientists will use data collected during the collisions to explore the particles known as quarks and gluons

*The high temperatures and densities should allow a soup-like plasma, a state of matter believed to have last existed millionths of a second after the*

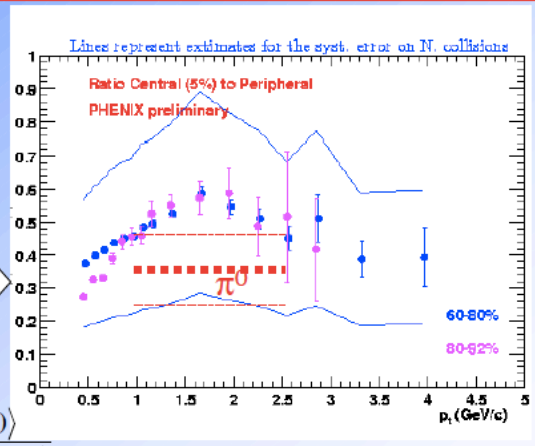
QM2001 Quark Matter 2001

# Jet Quenching

PHENIX

## Central vs. Peripheral Yields

- Can study relative yields within the data set:
  - Compare central to peripheral spectra vs. $p_T$
  - Scale by the average number of collisions




$$\text{Ratio} = \frac{\text{Yield(Central)} / \langle N_{COLL}(\text{Central}) \rangle}{\text{Yield(Peripheral)} / \langle N_{COLL}(\text{Peripheral}) \rangle}$$

- Ratio unity if yields scale as number of collisions
- Ratio found to be less than 1, decreasing for $p_T > 2$ GeV/c
- Same is observed in $\pi^0$ analysis (very different sytematics)

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STAR

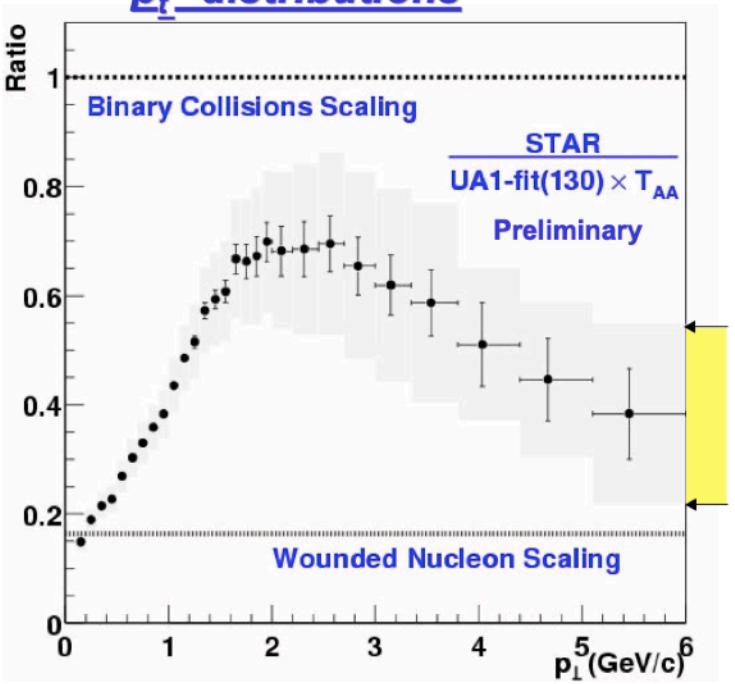
## Negative Hadrons: Compare with 'pp $p_t$- distributions

UA1 $\sqrt{s}$ = 200
⇒ R (130/200)

From power law scaling
R = 0.92 at 0.2 GeV/c
R = 0.70 at 2 GeV/c

"Hard" Scaling
Nuclear Overlap Integral
$T_{AA}$ = 26 mb$^{-1}$ for 5% most central
$N_{AA} / N_{pp} = N_{bin\ coll} = 1050$

"Soft" Scaling
$N_{AA} / N_{pp}$ = ( 344 / 2 )



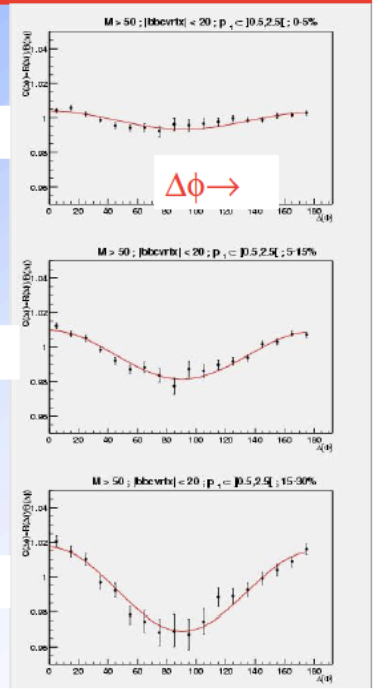

*J.W. Harris for STAR at QM2001*

## PHENIX — Elliptic Flow

- Determine via a correlation function method

$$C(\Delta\phi) = \frac{R(\Delta\phi)}{B(\Delta\phi)}$$

- Study versus
  - Centrality
  - $p_T$ (next slide)

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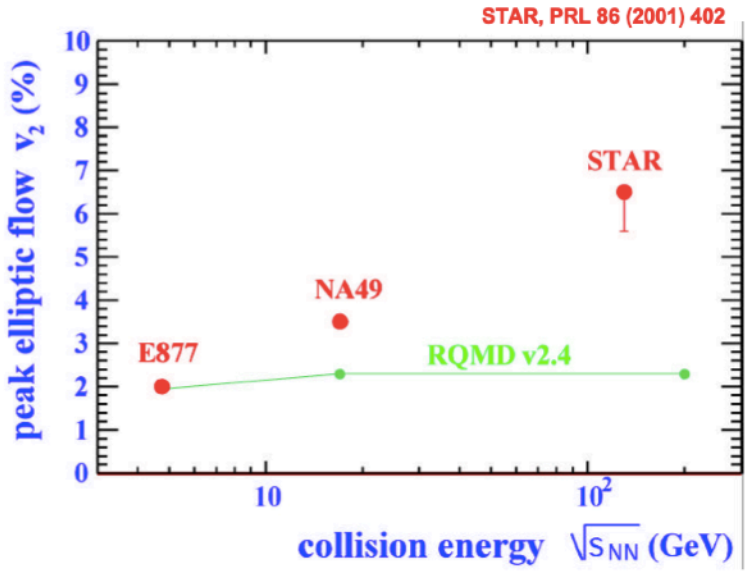
## STAR — Elliptic Flow Excitation function




*J.W. Harris for STAR at QM2001*

## On the Verge of Re-Creating Creation. Then What?

*New York Times - Week In Review, Jan. 28, 2001*

# RHIC's Answer (2005)

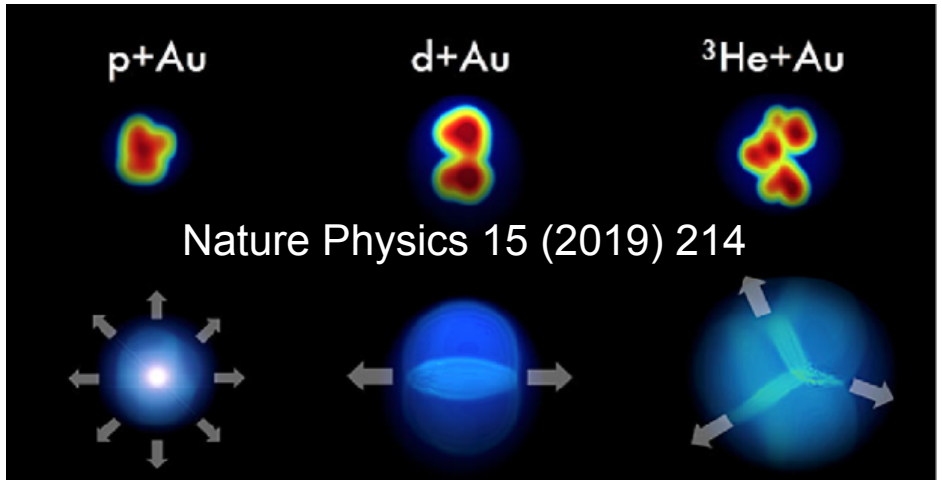
## RHIC Scientists Serve Up 'Perfect' Liquid

**New state of matter more remarkable than predicted — raising many new questions**

April 18, 2005

TAMPA, FL — The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) — a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory — say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

# Surprises keep coming

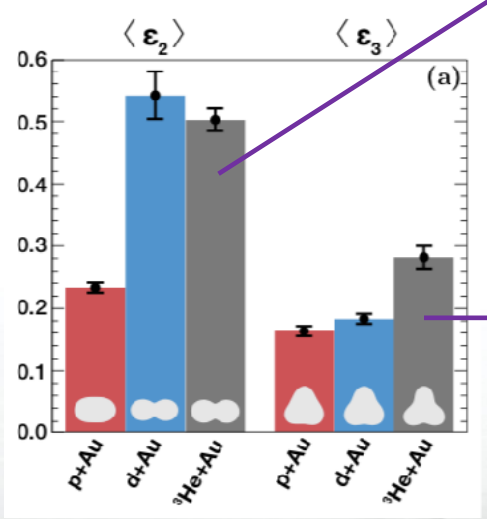


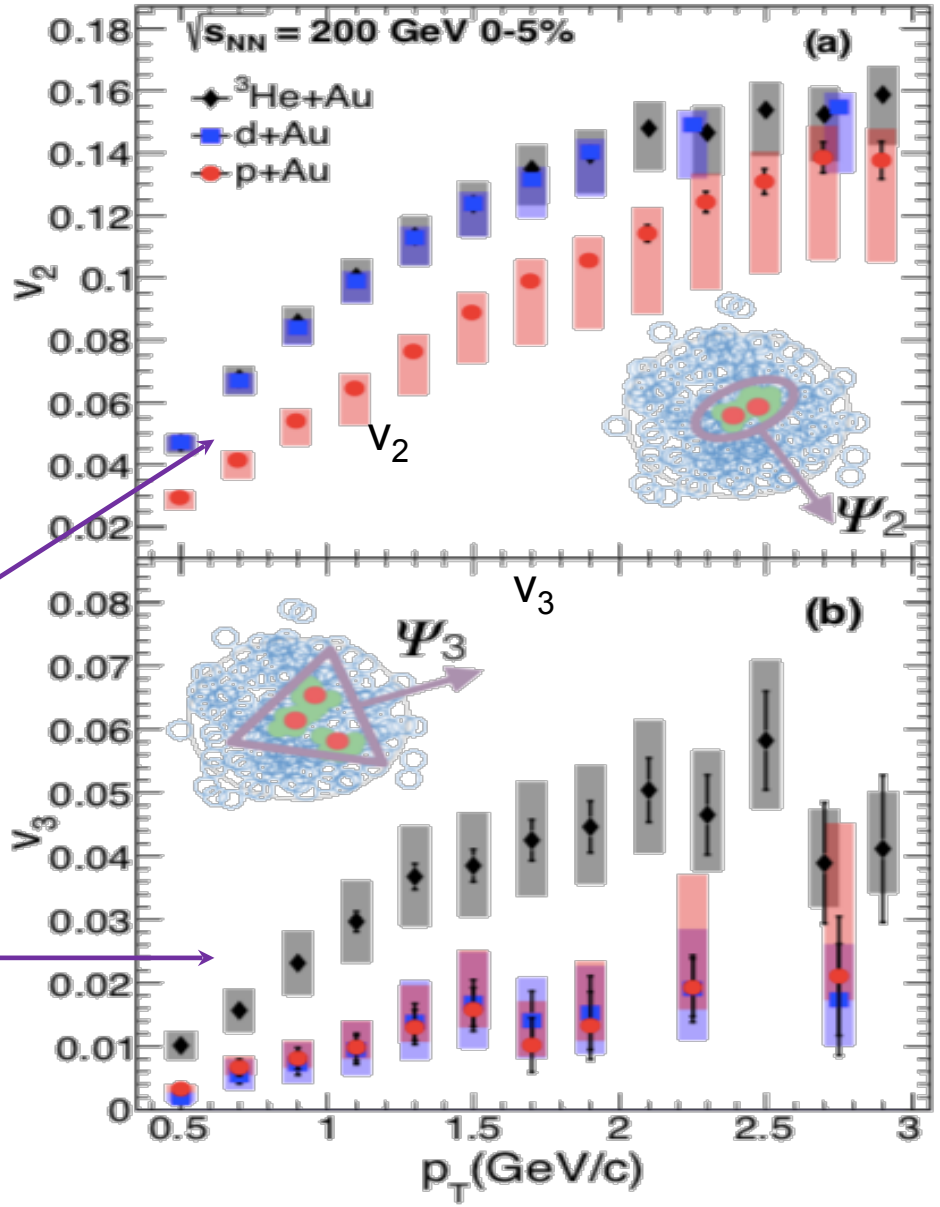

The QGP droplets created in collisions of p+Au, d+Au, $^3$He+Au have characteristically different shapes resulting in different emission patterns.

The ordering of flows follows the ordering of shapes ($\varepsilon_2$, $\varepsilon_3$)

$v_2$(d,$^3$He+Au) > $v_2$(p+Au)

$v_3$($^3$He+Au) > $v_3$(p,d+Au)

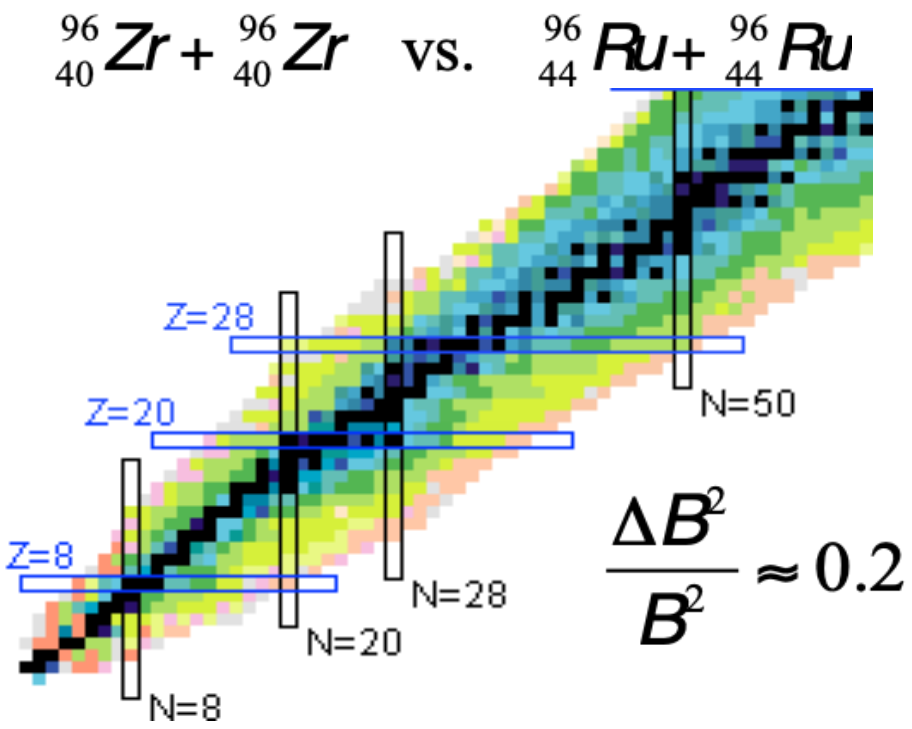


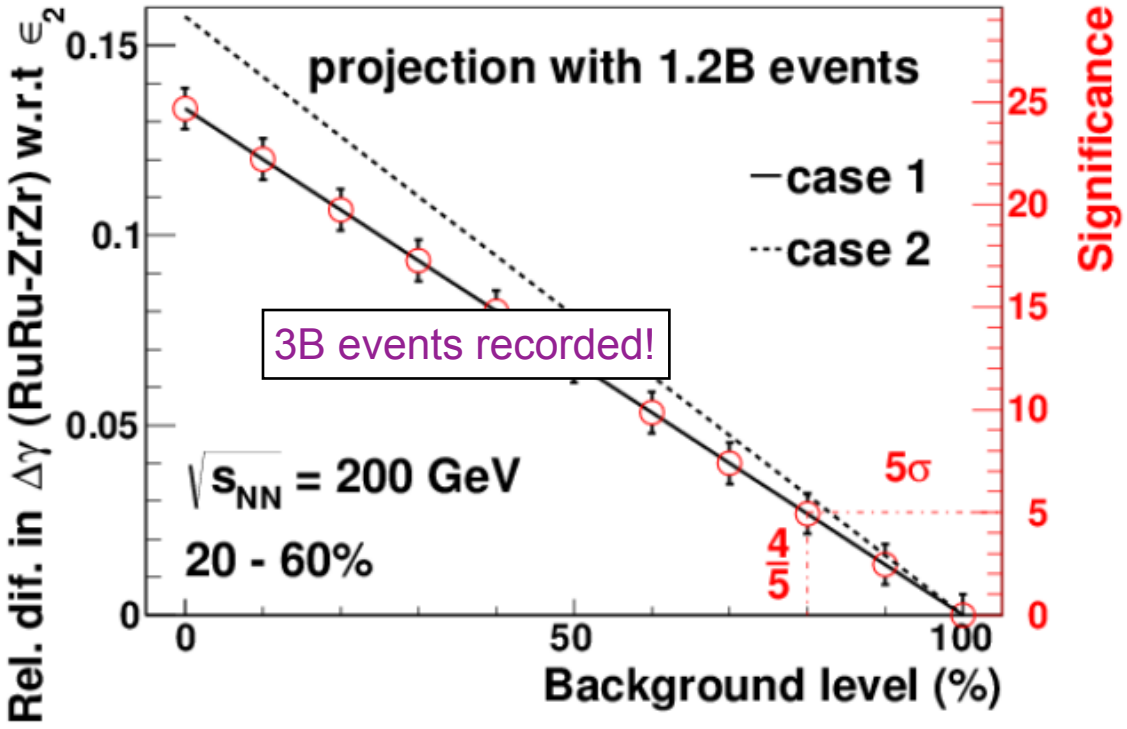




$^3$He+Au
d+Au
p+Au

$^3$He+Au
p+Au
d+Au

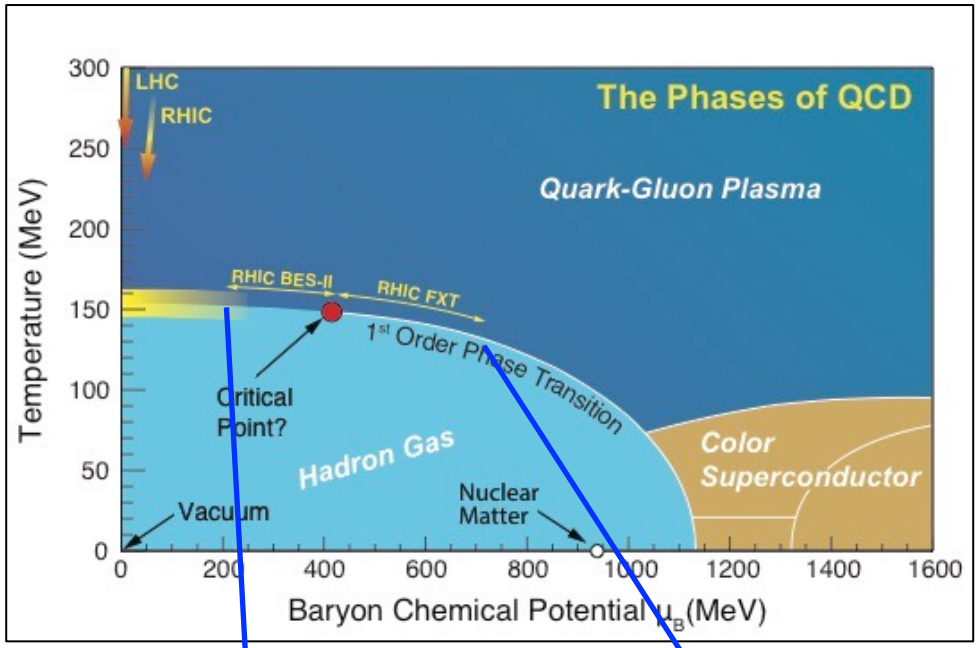
# More to come: 2018 Isobar Comparison Run

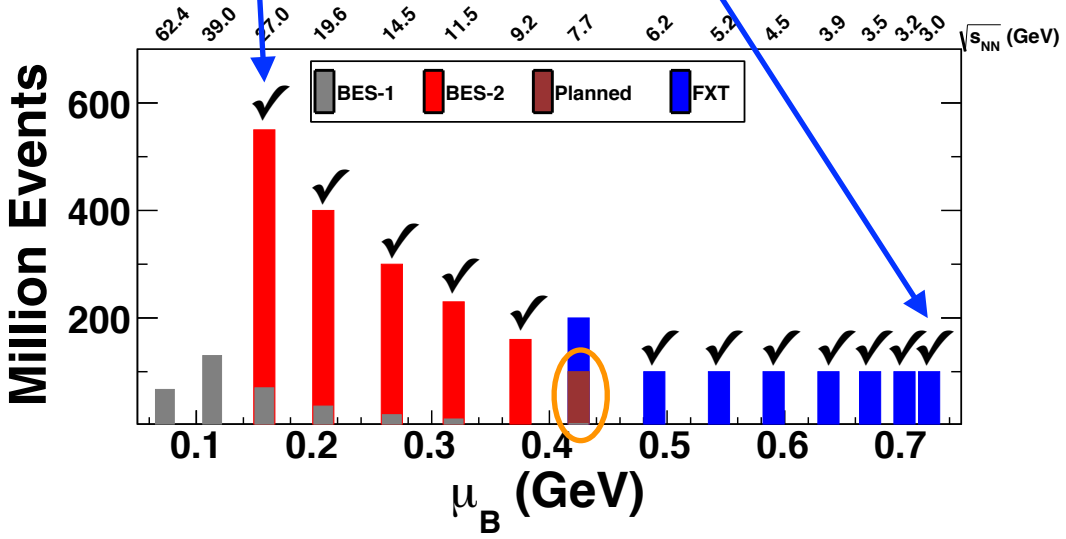


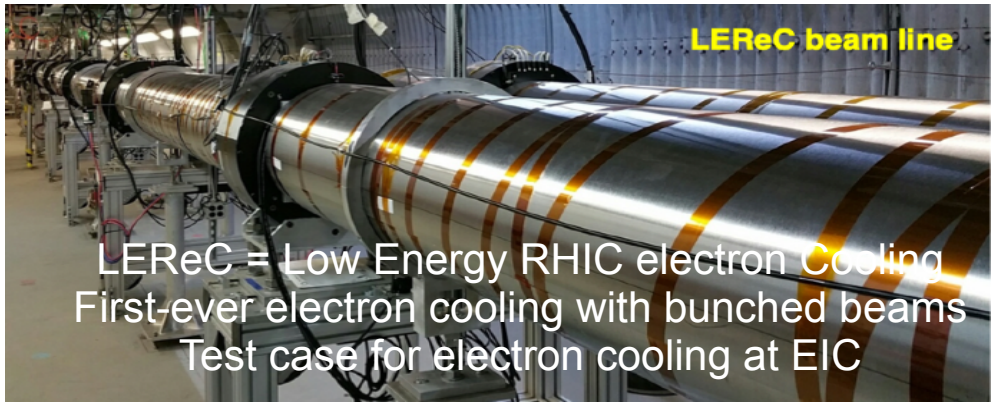




The isobar comparison run will tell us to with +/- 6% precision what fraction of the observed charge separation is due to the CME. Double blind analysis of several observables is in its final phase – results expected in late 2020 – unprecedented in heavy ion physics.

# More to come: Beam Energy Scan II



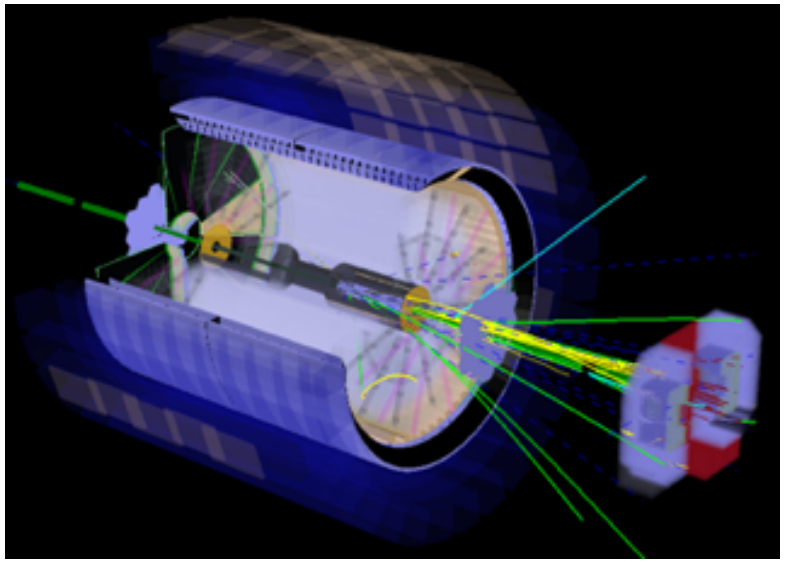




**Beam Energy Scan Goals**:

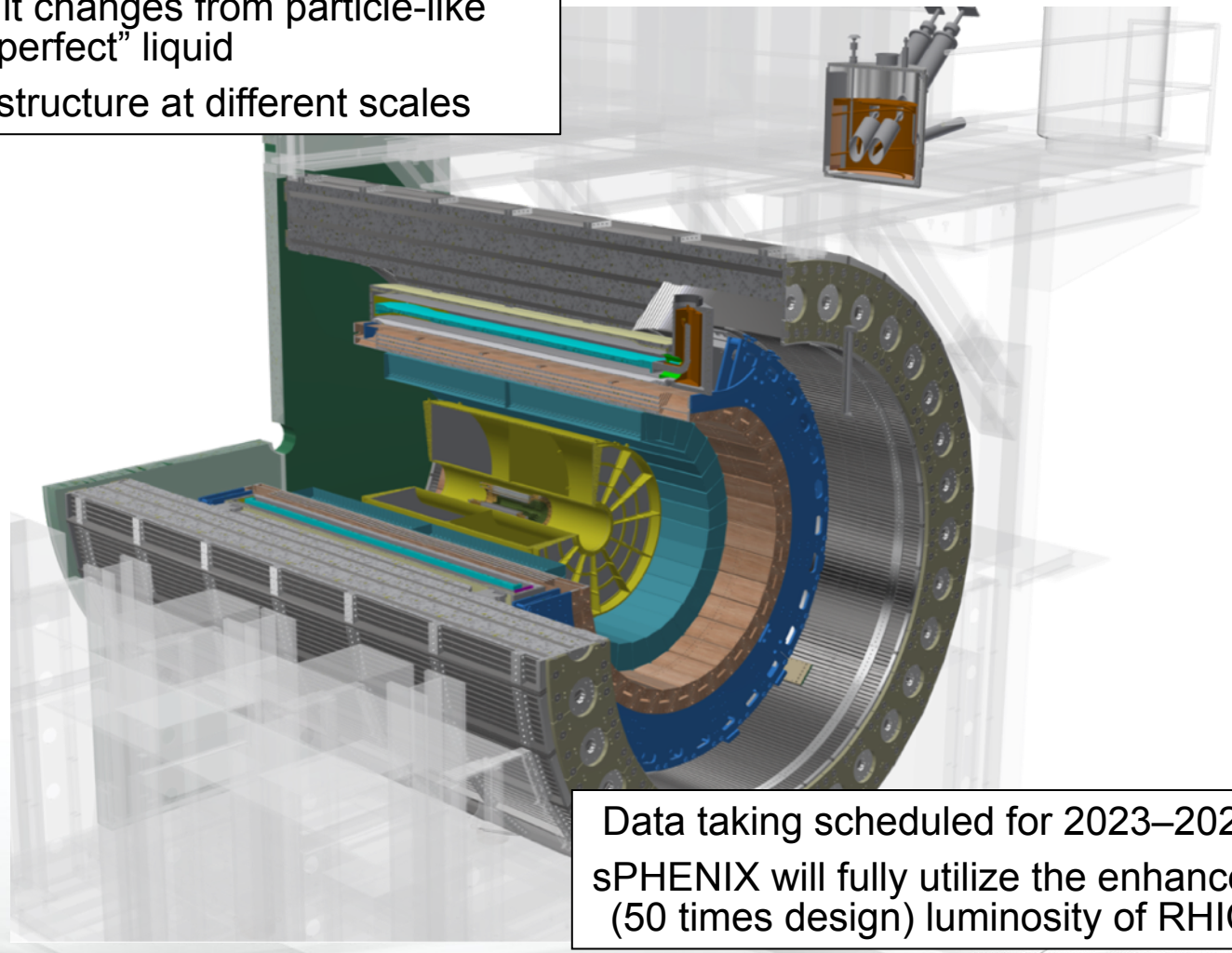
- What is the phase boundary of ordinary nuclear matter, i.e. matter composed of baryons and mesons?
- Is there a critical point in the QCD phase diagram and, if so, where is it located?
  - 3-year run program: 12 energies
  - 7 energies new (fixed target)
  - >10-fold statistics for all energies
  - 11 energy runs complete!

# More to come: sPHENIX & Forward STAR

- High energy jets probe the structure of the QGP on different length scales and determine where and how it changes from particle-like quarks and gluons to a structureless “perfect” liquid
- Heavy quark mesons probe the QGP structure at different scales



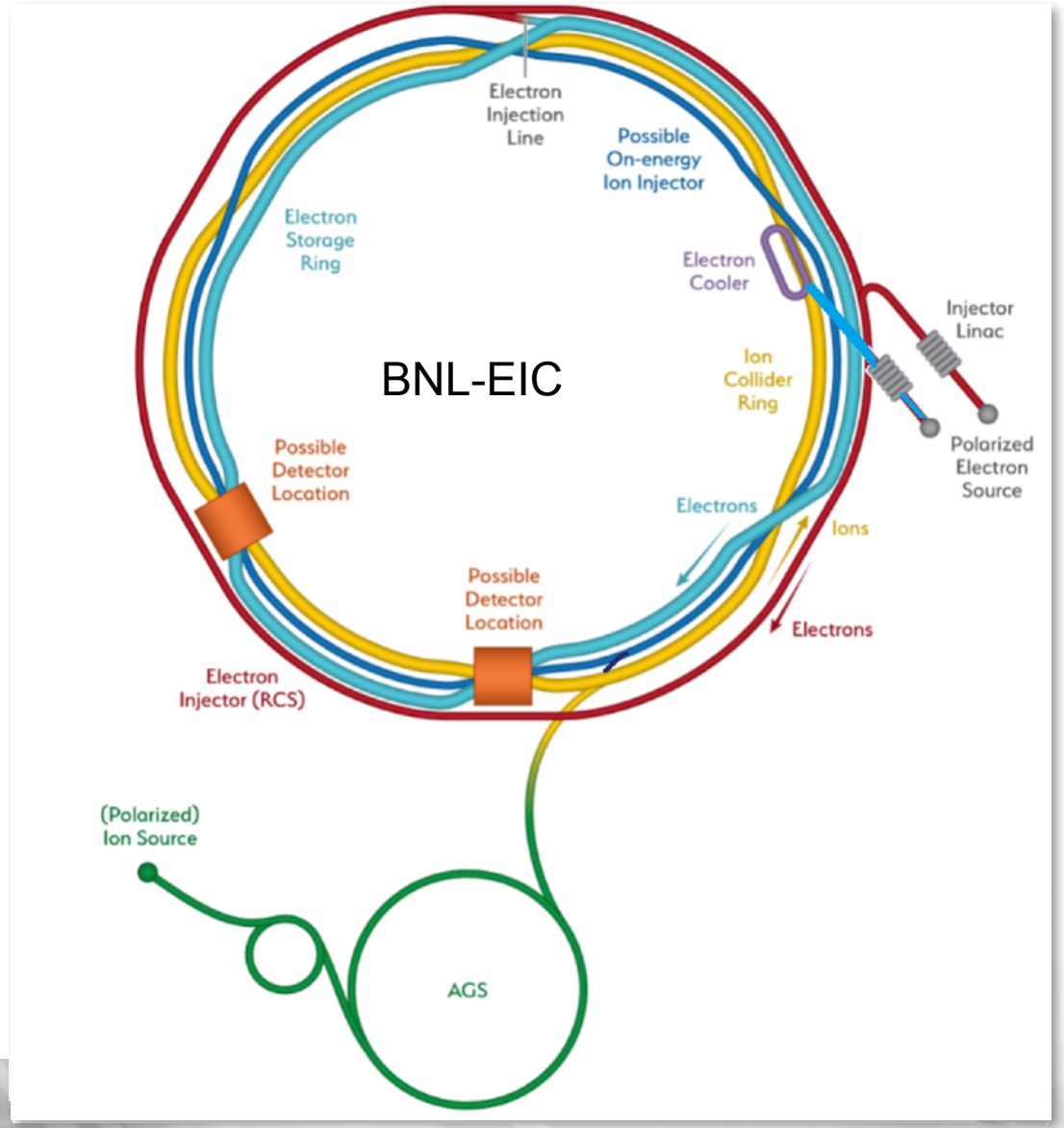
- New STAR forward detector systems in construction for FY 2022 RHIC run will enable measurements of physics important for EIC science program:
- Universality of 3-D Parton dynamics



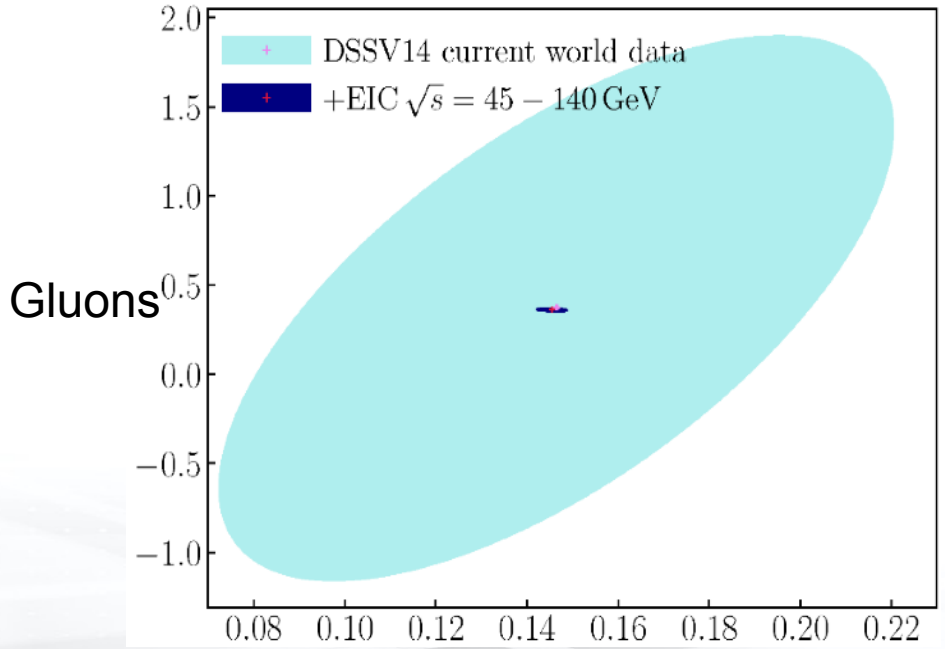
Data taking scheduled for 2023–2025

sPHENIX will fully utilize the enhanced (50 times design) luminosity of RHIC

# RHIC's Future "Reincarnation" as EIC

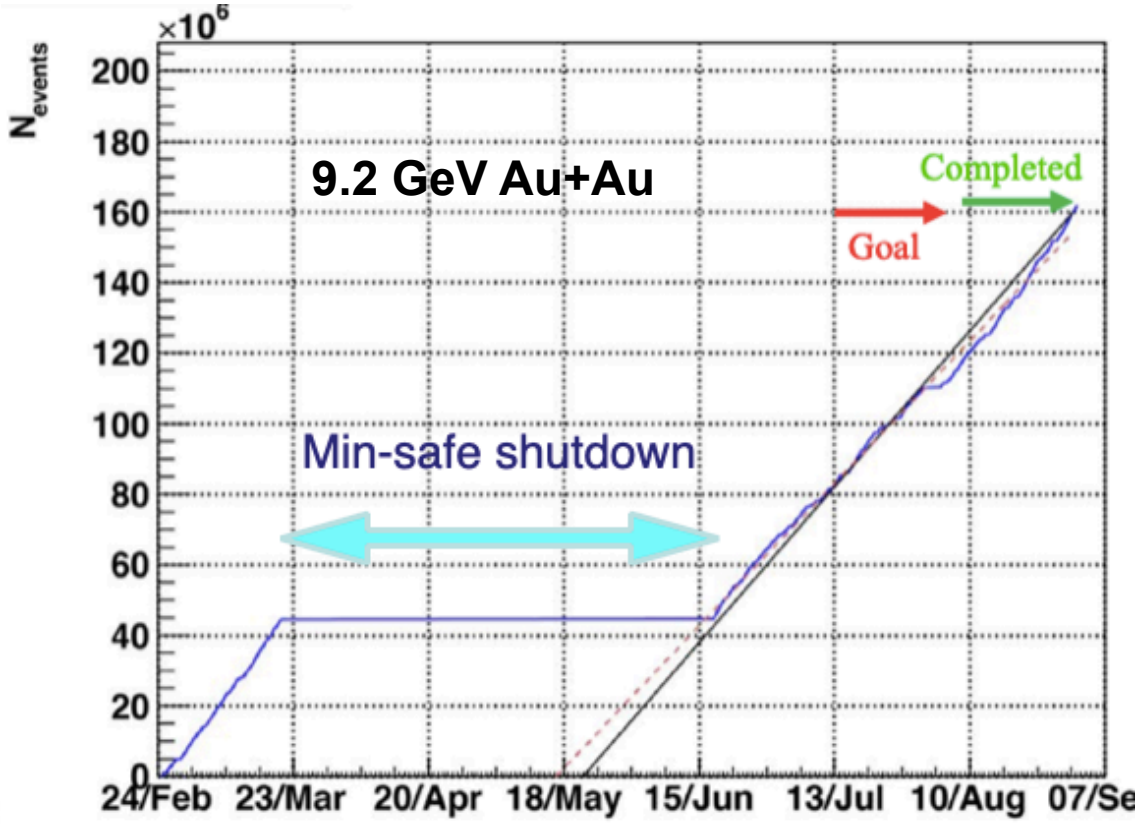



- Hadron Storage Ring
- Electron Storage Ring
- Electron Injector Synchrotron
- Possible on-energy Hadron injector ring
- Hadron injector complex



# The Run-20 Saga

- The 28 cryo-week Run-20 was interrupted on March 20 as part of the Lab's transition to Min-safe status with 12 weeks remaining (10 weeks for Au+Au at 9.2 GeV)
- We performed a cost/benefit analysis of keeping RHIC cold: Break-even point after 3 months shut-down, then $200k/month disadvantage
- Decision was made in mid-April to restart RHIC run at the earliest practical date
- RHIC/STAR physics running resumed on June 18 with excellent beam performance right from the start
- Weather related interruptions during July/August affected RHIC performance but less than anticipated
- Goal of 160 million events at 9.2 GeV was reached on August 31
- Run-20 ended on September 14 with all goals achieved



# RHIC Run Plans

- ***Beam Energy Scan II* (2019-21):**
  - Low energy ($\sqrt{s_{NN}}$ = **7.7**, 9.1, 11.5, 14.5, 19.6 GeV) Au+Au runs using electron cooling to increase luminosity
  - Fixed target runs at (3.0), 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV
  - Search for signs of critical phenomena in event-by-event fluctuations

- ***Forward spin run* (2022):**
  - 500 GeV p+p (enhanced by forward upgrades of STAR)
  - Spin physics measurements complementary to EIC

- ***Runs with sPHENIX* (2023-25) *and STAR* (2023-24):**
  - Full energy ($\sqrt{s_{NN}}$ = 200 GeV) Au+Au, p+p, p+Au
  - STAR taking "legacy data" with iTPC, forward detectors in 2023-24
  - Precision measurements of fully resolved jets, Upsilon states, heavy flavor

# COVID-19 modified schedule for Runs 21 + 22

- The end of Run-20 was delayed by approximately 3 months
- Much of the work on STAR Forward upgrade and sPHENIX could resume work in July 2020. Currently modest delays, mostly within schedule contingency.
- We developed a tentative schedule for Runs 21 and 22 with shutdowns and schedule for sPHENIX installation after Run 22. The plan will possibly require adjustments as work on sPHENIX proceeds.
- STAR: Concern about availability of contributed labor due to travel restrictions. Forward Si tracker has only 2 weeks of schedule float. (Forward tracking does not require Si tracker.)
- sPHENIX: 2 months delay in schedule (not an issue for MIE). Analysis of future impacts of social distancing underway - expected soon.
-
- 2020 PAC endorsed run plans through 2025.

# 2020 PAC recommendations: Run-21

- Accumulating the required data at 7.7 GeV (100M events) needed to complete the BES II program is the highest priority. We commend CAD for successfully improving the beam performance to enable the collection of the 7.7 GeV data within 15-20 weeks. Given the strong scientific motivations for other elements of the proposed Run 21 program, see below, we strongly encourage CAD to explore any further incremental improvements of the luminosity that they can envision.
- FXT measurements at 4 energies, 1 week in total, have been identified by STAR as their second priority for Run 21. We concur with this prioritization; these are important measurements and should be carried out if the beam time is available.
- In its BUR, STAR presented three different proposed runs as third priorities for Run 21, without providing a priority ordering. The PAC considers the proposed 1 week O+O run at 200 GeV (200M central events) and the proposed 2.5 week Au+Au run at 17.1 GeV (250M events) both to be important to the RHIC scientific program. At present, the PAC would rank the O+O run higher in priority.

# Summary

- FY 2020 was a very successful year in spite of the challenges of the COVID-19 pandemic.
- RHIC and STAR performed above expectations.
- RHIC Run-20 achieved all its objectives.
- We are confident that the high precision Beam Energy Scan (BES-II) will reach all its goals. It will be an accomplishment for the ages.
- STAR / sPHENIX upgrade projects remain on track, albeit with challenges.
- We have plans for an outstanding science program in 2021 - 2025 that promises to ensure RHIC's unique legacy.
- The plans are challenging, but realistic.
- CAVEAT: Additional pandemic related delays may require modifications of the run plans, especially in 2022, to assure readiness of sPHENIX for Run-23.