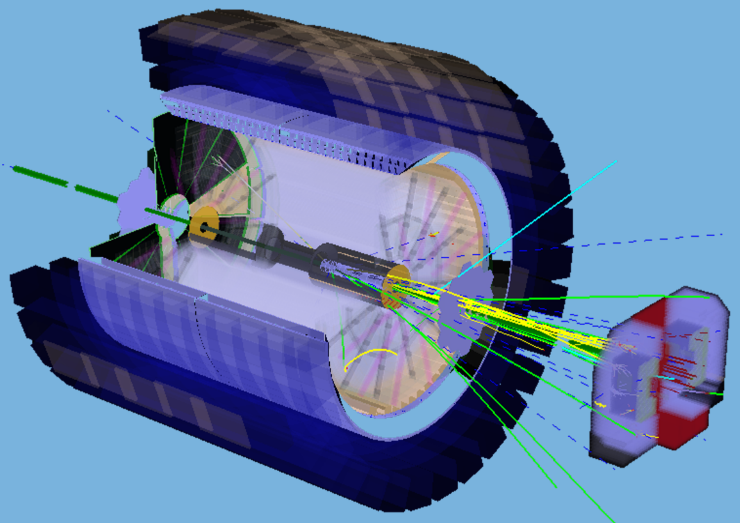
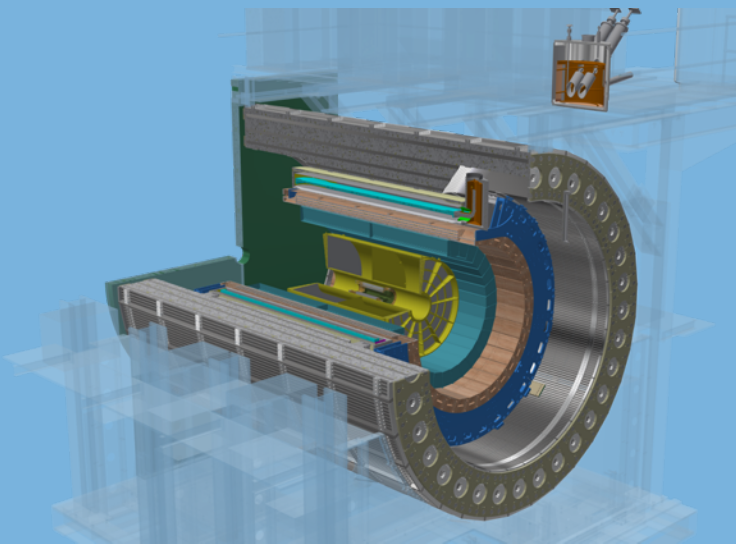
Future Physics Capabilities of RHIC

Rosi Reed

Lehigh University





The Big Picture: QCD @ RHIC

We have transitioned from asking, “Does the QGP exist?” to “Precisely how does QCD lead to the emergent phenomena we observe?”

- **Qualitative** observations (jets are quenched, nearly ideal fluid, fluctuations are important) to **quantitative** descriptions (qhat, η/S, σ, S, κ)

Major **upgrades** to the **STAR** experiment and the new **sPHENIX** experiment allow us to capitalize on the versatile RHIC accelerator and answer fundamental questions about QCD

- How do quarks and gluons form a strongly coupled, nearly perfect liquid?
    - What are its properties?
- How do the proton constituents lead to its spin?
- What is the initial state in nuclear collisions?

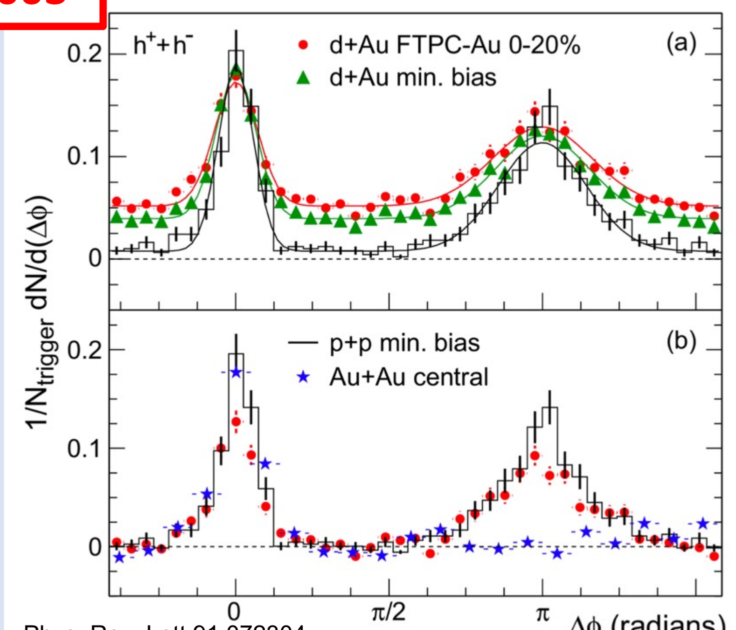
Goal of Jets in Heavy-ion Collisions

Address the important fundamental questions of **how** and **why** partons lose energy in the QGP? (What are the **properties of the QGP**?)

- What structures are the partons scattering off of?
    - Point-like jets at LHC —> lower energy jets at RHIC?
    - Quasi-particles, fields <=> **Microscopy of the QGP**
- Where does the “**lost**” energy go?
    - What is the response of the medium to the jet?
- What is the temperature/density dependence of the energy loss?
    - Quantifies the **Temperature** dependence of the coupling to the QGP

Era of Precision Measurements at RHIC

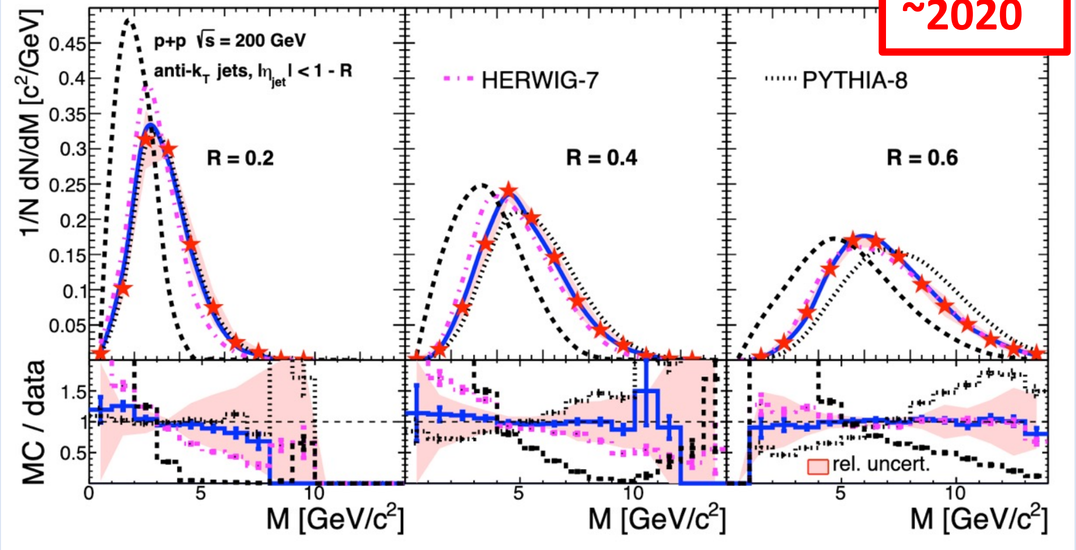
2003



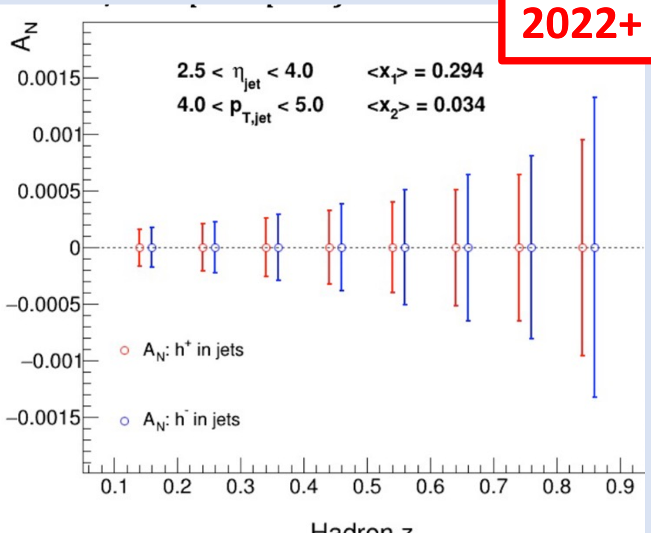
Phys. Rev. Lett.91,072304.

Arxiv:2103.13286

~2020

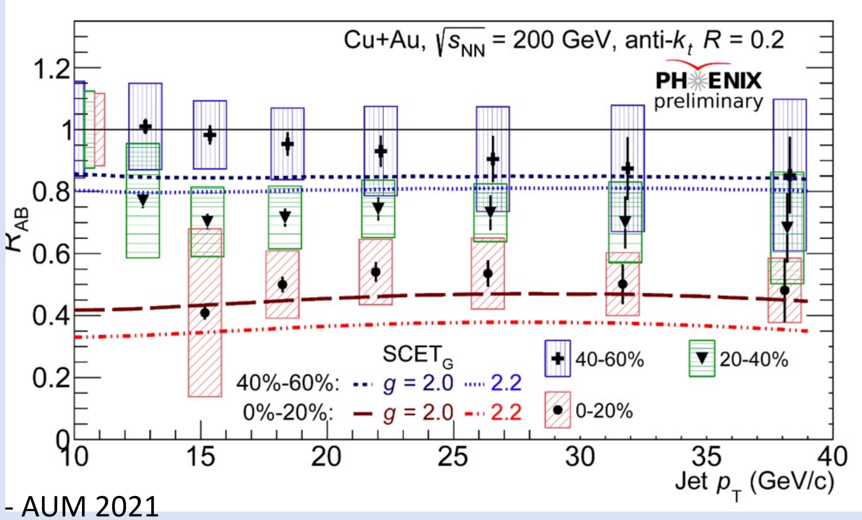


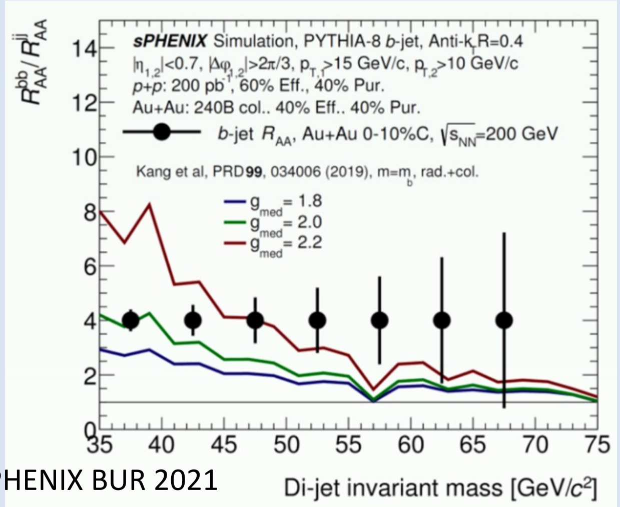
2022+



T. Lin Tues

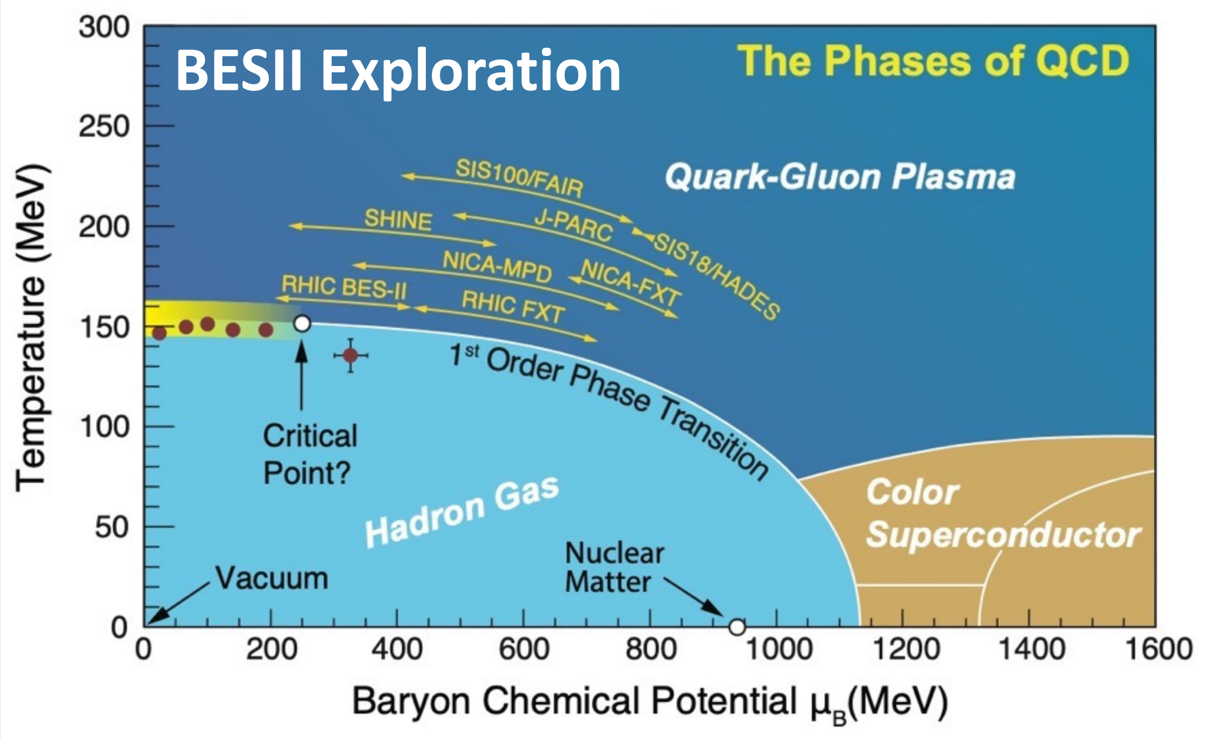
2 decades of jet physics @RHIC/LHC taught us that **precise tracking**, **hermetic calorimetry** and **well-developed correction** techniques are required to answer the big QCD questions

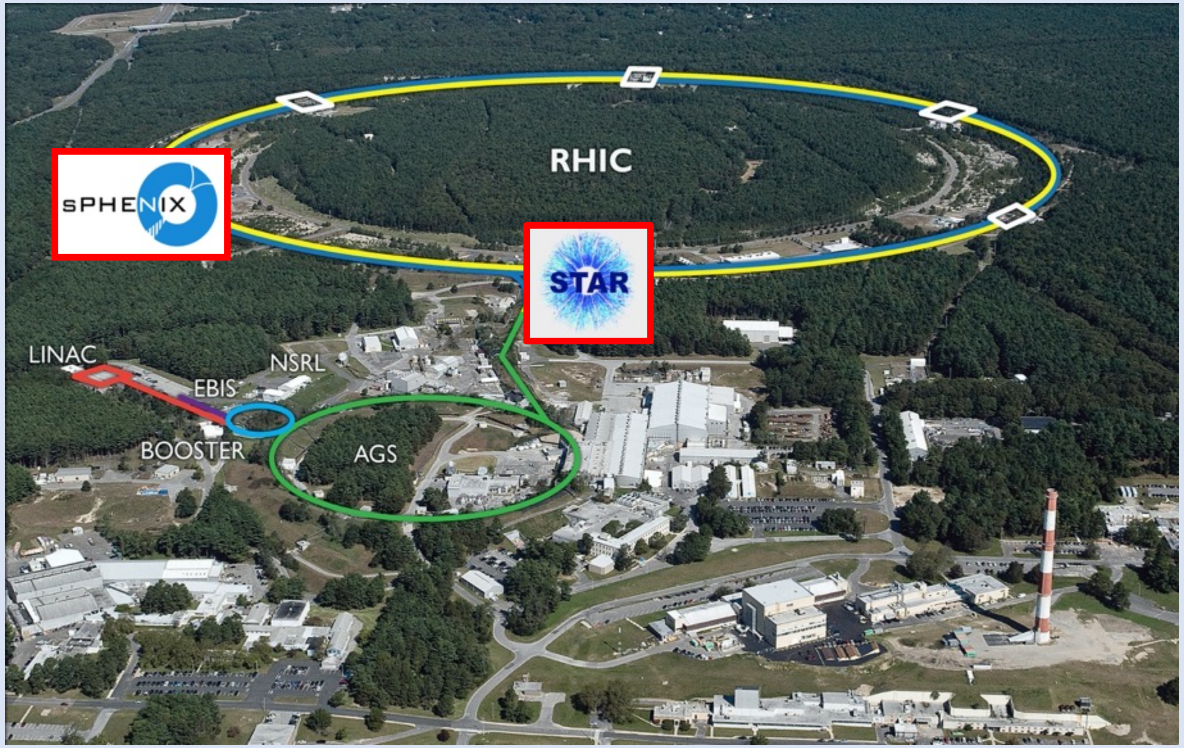




sPHENIX BUR 2021

RHIC Beyond BESII

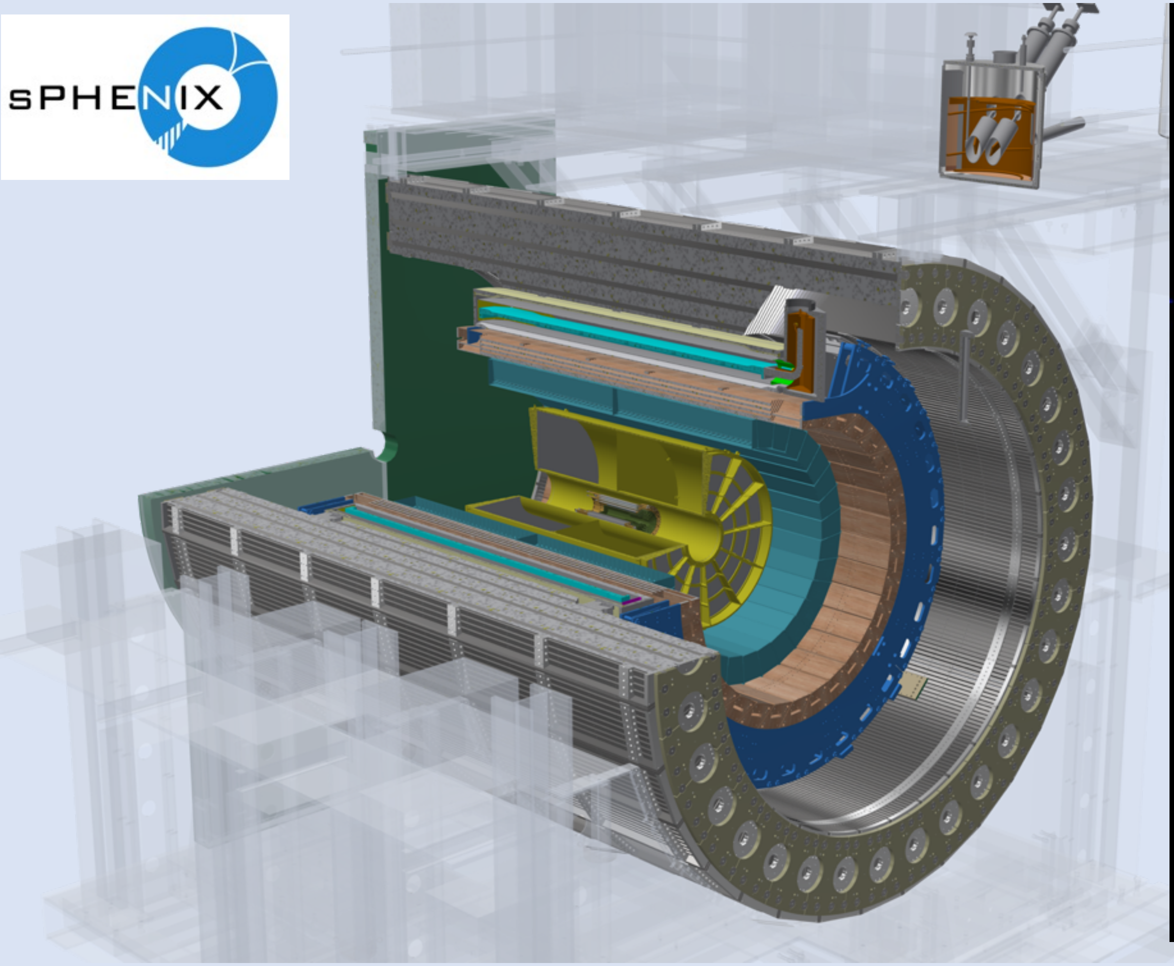


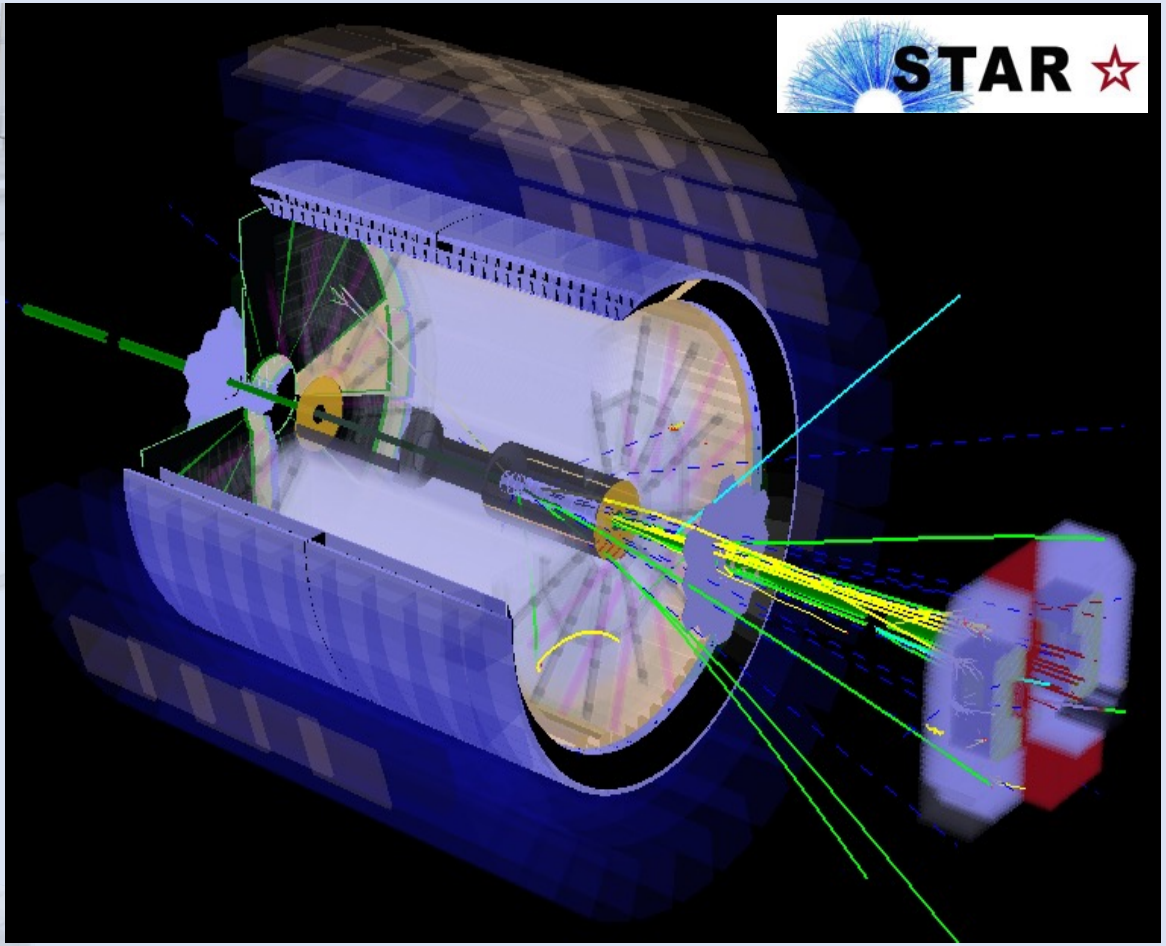


RHIC is an amazingly versatile machine, colliding **p+p, p+Al, p+Au, d+Au, He^3+Au, Cu+Cu, Cu+Au, Zr+Zr, Ru+Ru, Au+Au, U+U, O+O** from $\sqrt{s_{NN}}$ = 7.7 - 510 GeV

2 Detectors in the 2020+ era: **STAR, sPHENIX**

sPHENIX and STAR

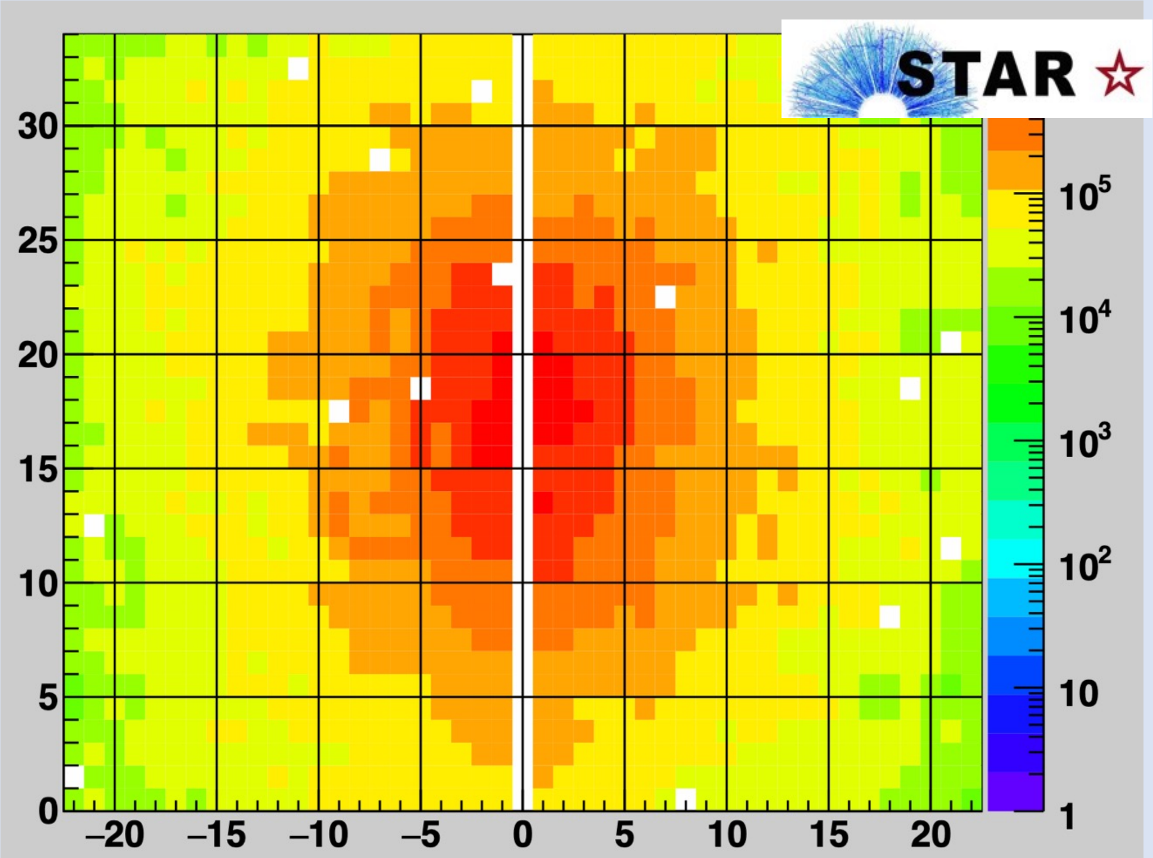




STAR Talks

For more information see STAR Talks:

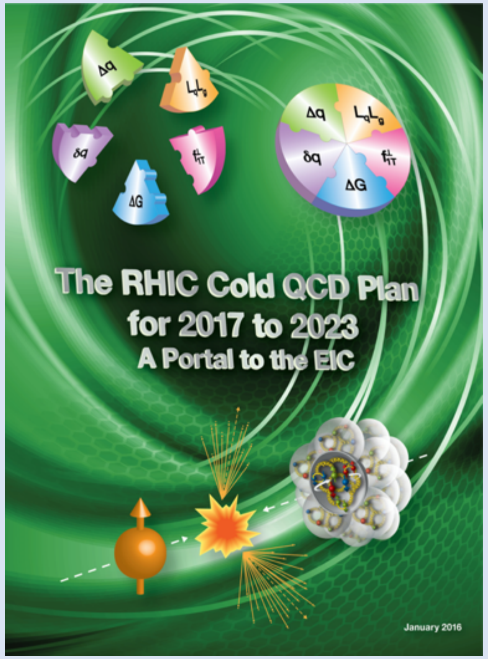
- X.Chu Tues 9:50
- T.Ling Tues 11:20
- I.Mooney Weds 1:45
- **L. Kosarzewski Thurs 11:20**

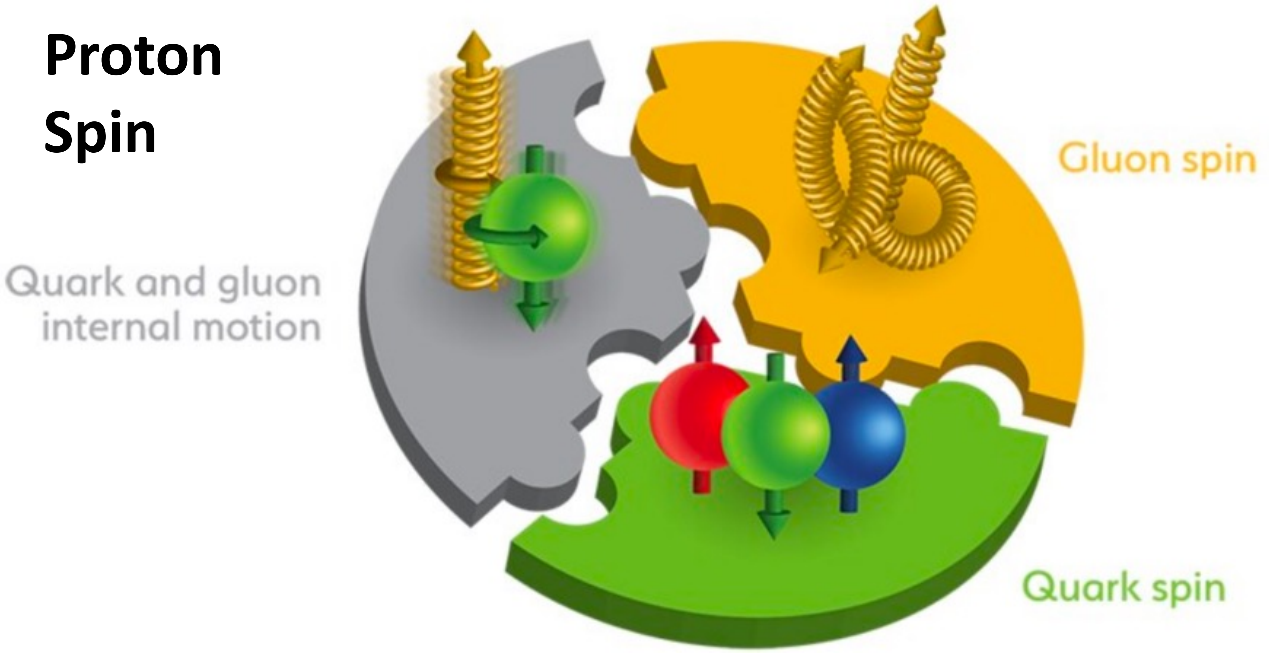


Run 21 FCS Ecal QA Data from virtual Shift Crew!

STAR Forward Upgrade Plan

Arxiv:1602.03922





Spin composition of the proton

Multidimensional landscape of proton

Initial state in nuclear collisions

We must complete p+p and p+A measurements prior to the EIC

- Lepton and purely hadronic probes are complementarity
- Necessary to establish the validity + limits of factorization+ universality

STAR Timeline

2015	2016	2017	2018	2019	2020	2021	2022
p+p	Au+Au/d+Au	p+p	BESII				p+p

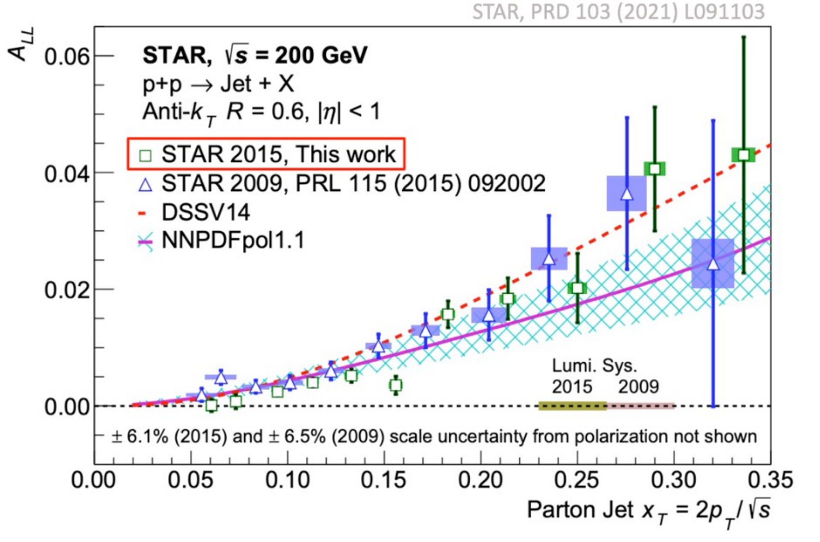
2023	2024	2025
Au+Au	p+p/p+Au	Au+Au

High Statics Polarized p+p Data

Electromagnetic Calorimeter Installed

Hadronic Calorimeter Installation

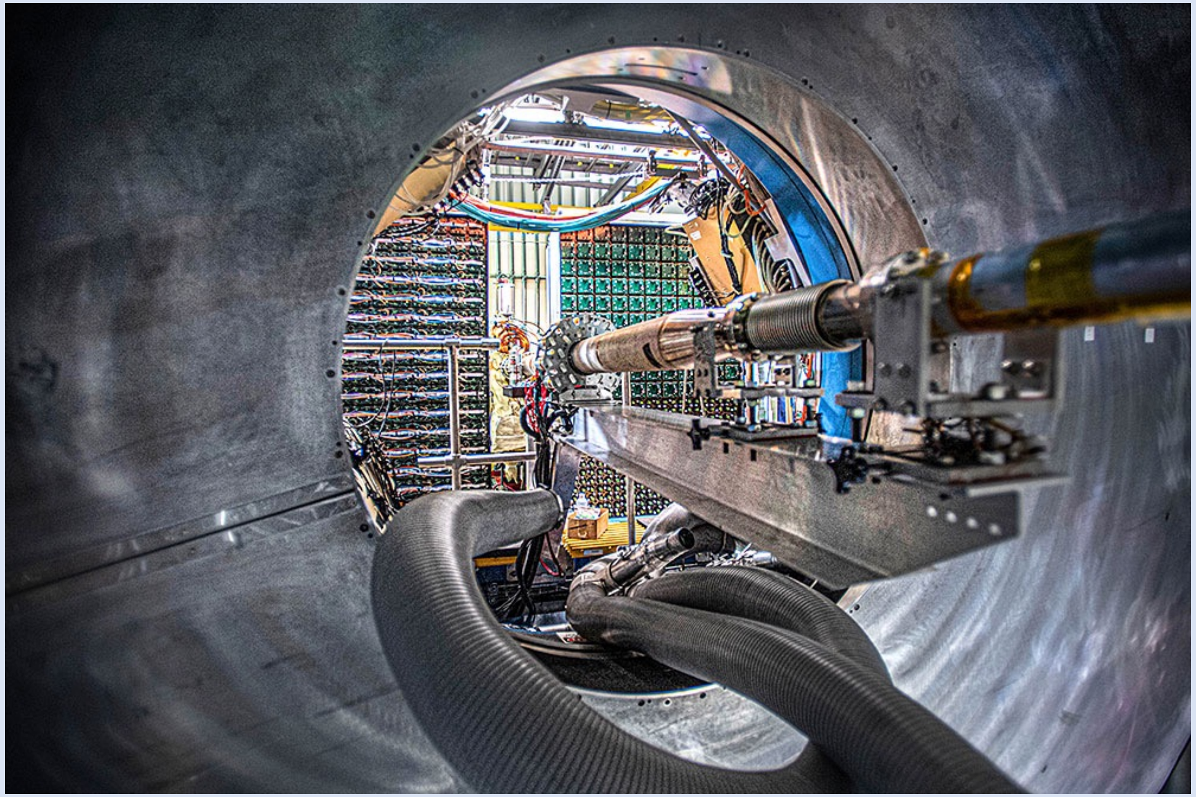
Tracking Installation



X. Chu Tuesday

STAR will run in parallel in the sPHENIX era with complementary RHIC programs

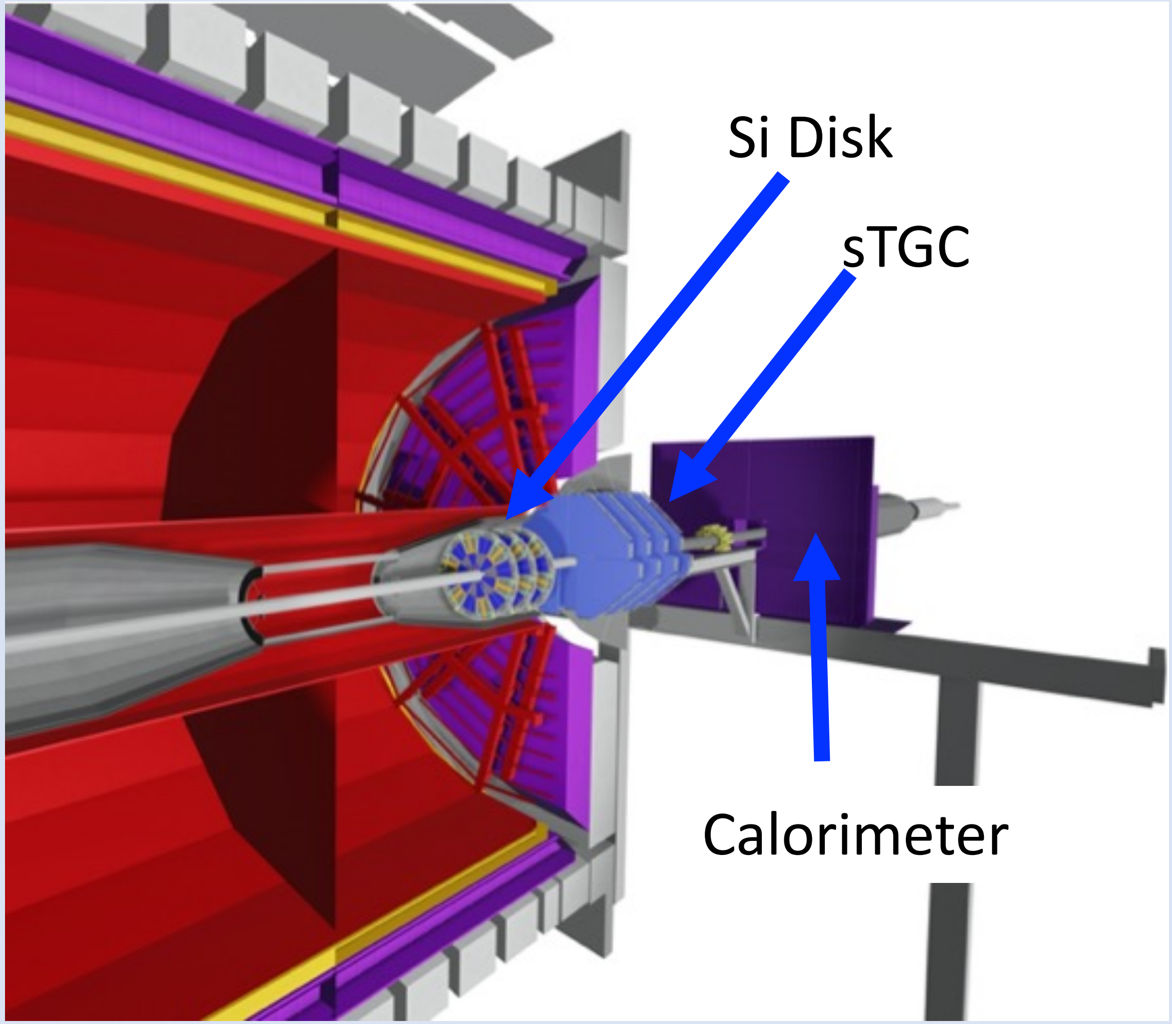
STAR Forward Upgrade Installation



See more pictures and full story at:
https://www.bnl.gov/newsroom/news.php?a=217681

Left to right: Edward Dabrowski, Adrian Timon, Matthew Ceglia, Travis Herbst, and Dennis Carlson

STAR Forward Upgrade



T.Lin Tuesday

Coverage: 2.5 < η < 4.0

- Mid-rapidity Emcal/Tracking coverage $|\eta| < 1.2$

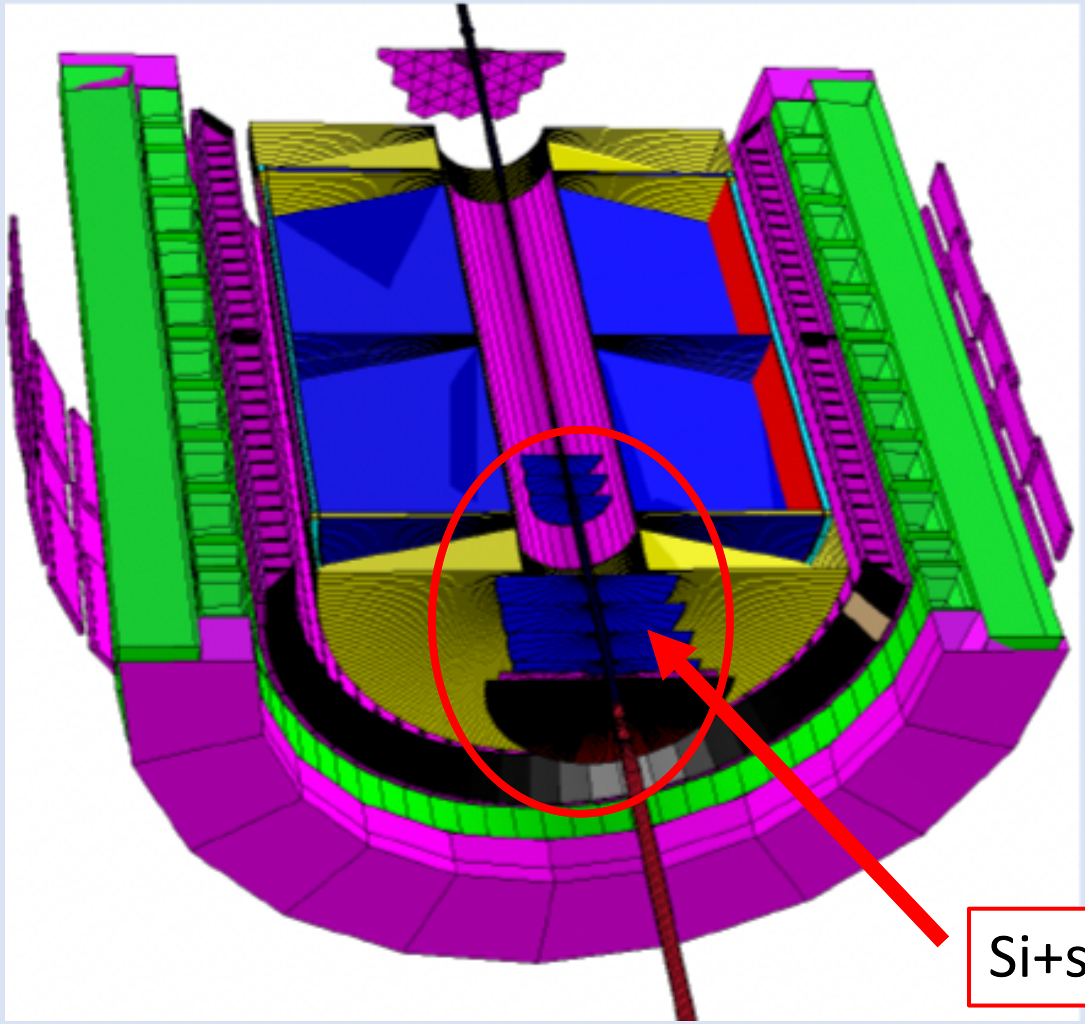
Forward Tracking System (FTS)

- Silicon microstrip sensors
- Small-Strip Thin Gap Chambers (sTGC)
- Momentum Resolution **< 30%**
- Tracking **Efficiency > 80%** @ 100 tracks / evt

Forward Calorimetry System (FCS)

- Hadronic Calorimeter
  - Resolution **~50%/$\sqrt{E}$+10%**
- Electromagnetic Calorimeter
  - Resolution **~10%/$\sqrt{E}$ p+p vs ~20%/$\sqrt{E}$ A+A**

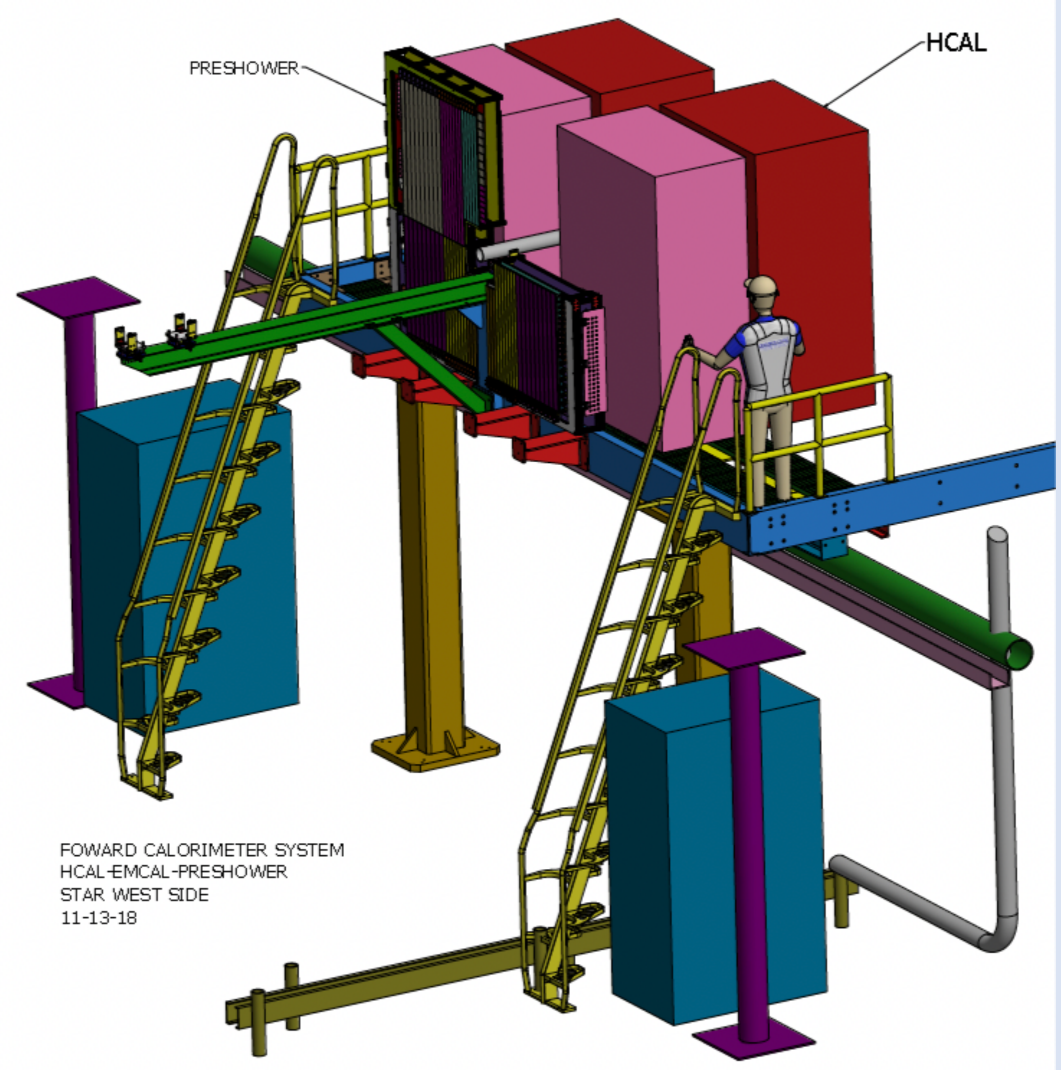
STAR Silicon and sTGC



Si+sTGC

- **3 Silicon disks**
  - Z = 139.9, 163.2, 186.5 cm (from IP)
  - Built on successful experience w/STAR Inner Silicon Tracker (IST)
  - Reuse IST DAQ system (FTS) + cooling system
- **4 sTGC disks**
  - Z = 273, 303, 333, 363 cm (from IP)
  - Inside Magnet pole tip opening Position resolution: ~100 μm
  - Material budget: ~0.5% per layer
  - 24,000 channels

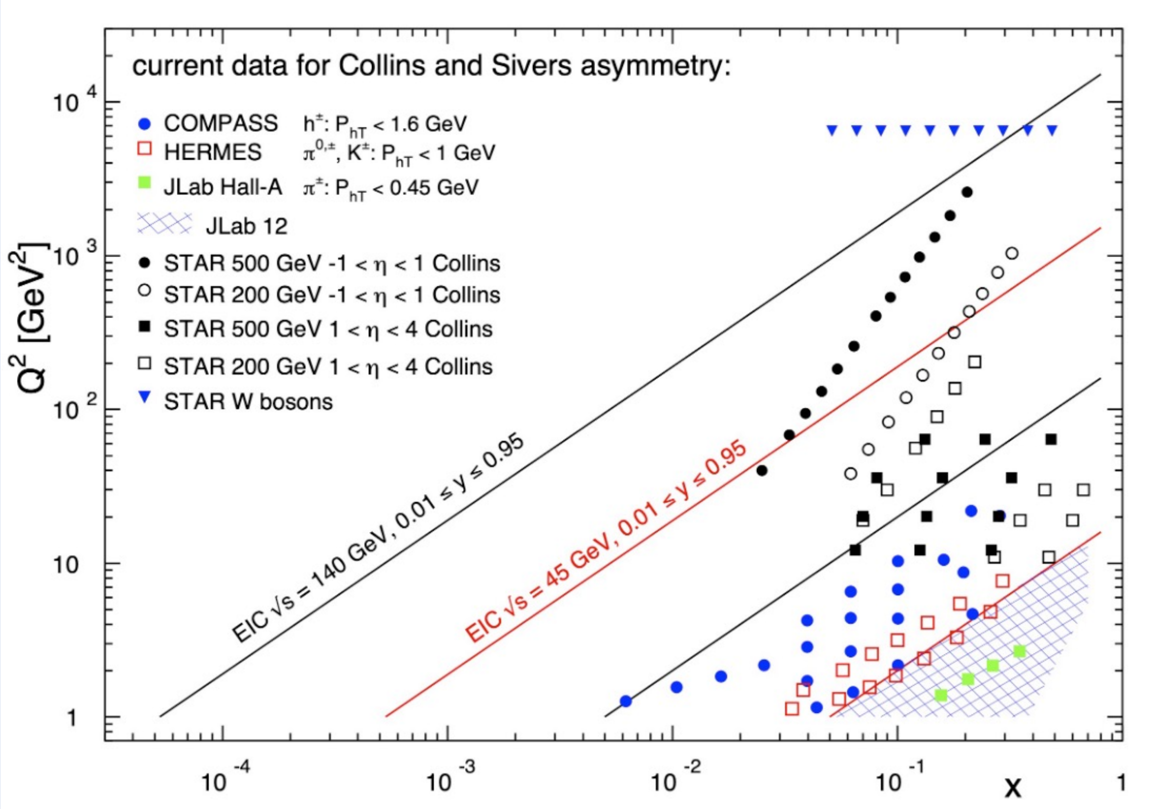
STAR ECal & HCal



- Location: Z = 7 m (from IP)
  - Readout: SiPMs
  - Will be used in the Trigger
  - Slightly projective
- **Ecal**
  - Reuse PHENIX PbSC calorimeter with new readout
  - ~18 X_0
- **Hcal**
  - First use of a hadronic calorimeter @ STAR!
  - Fe/Sc (20mm/3 mm) sandwich
  - 520 readout channels
  - Lateral tower size 10 x 10 cm^2
  - ~ 4.5λ
- EPD for improved triggering!

STAR Cold QCD Program w/Forward Upgrade

- STAR Forward Upgrade provides excellent charged-particle tracking for (2.5< η <4) +ECAL+HCAL.
  - Enables precise exploration of high-x (largely valence quark) and low-x (primarily gluon) partonic physics
- Complementary roles will be played by Run-22 at 510 GeV and Run-24 at 200 GeV
  - Allow measurement of fundamental proton properties over the range 0.005< x <0.5

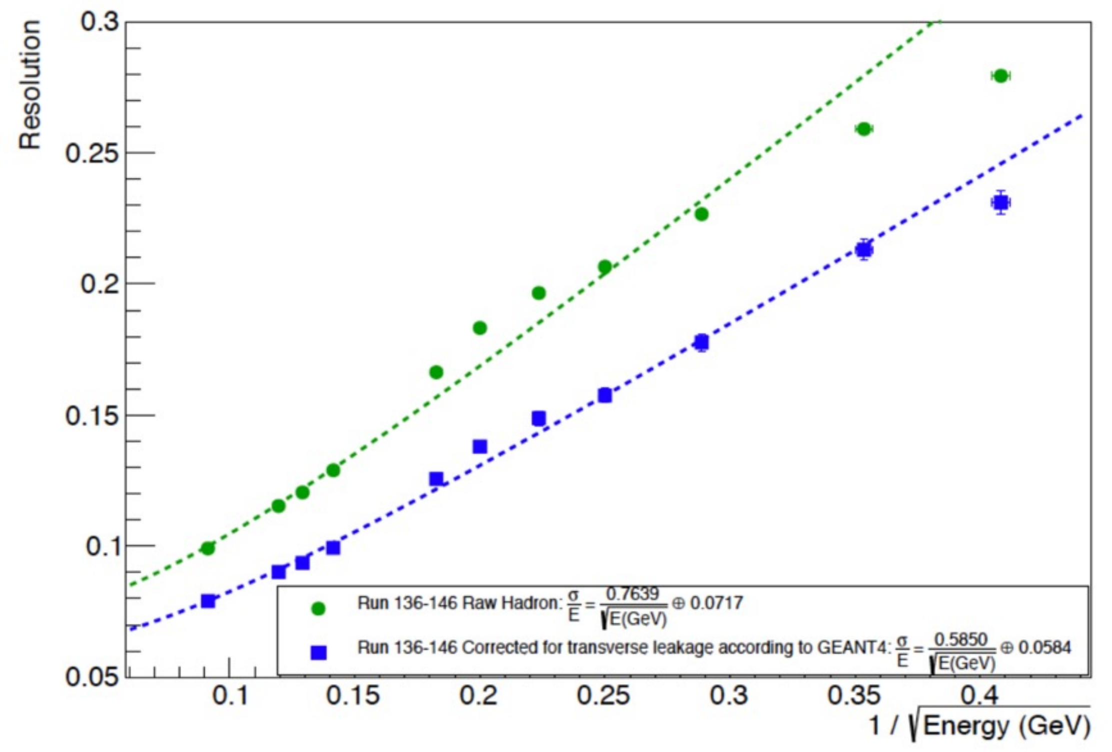


- T.Ling Tues 11:20

STAR Forward Upgrade Performance

Performance of HCAL @ FNAL

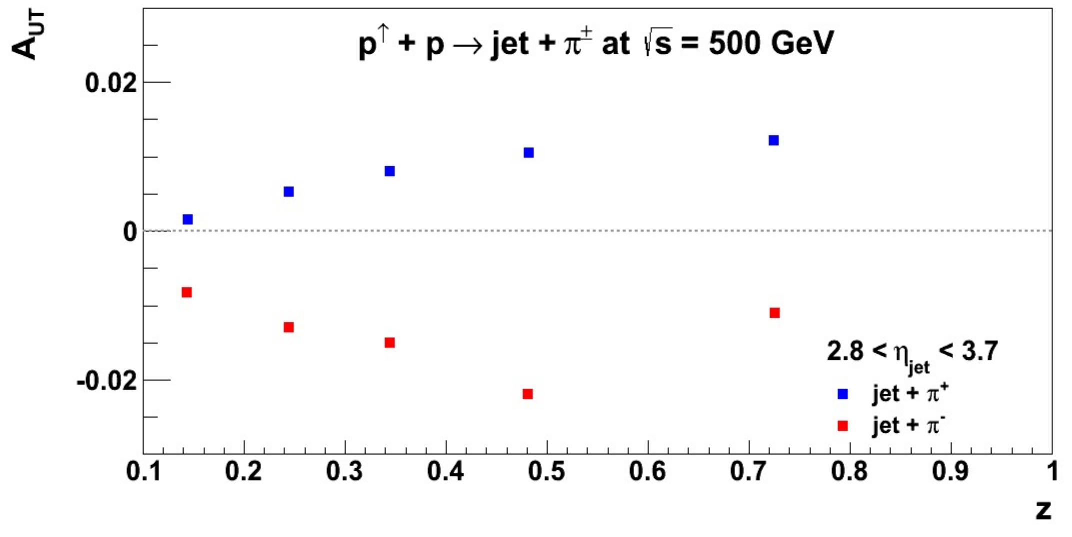
- ECAL+HCAL performance near requirements
- ~50%/$\sqrt{E}$+10%



Expected Collins asymmetries

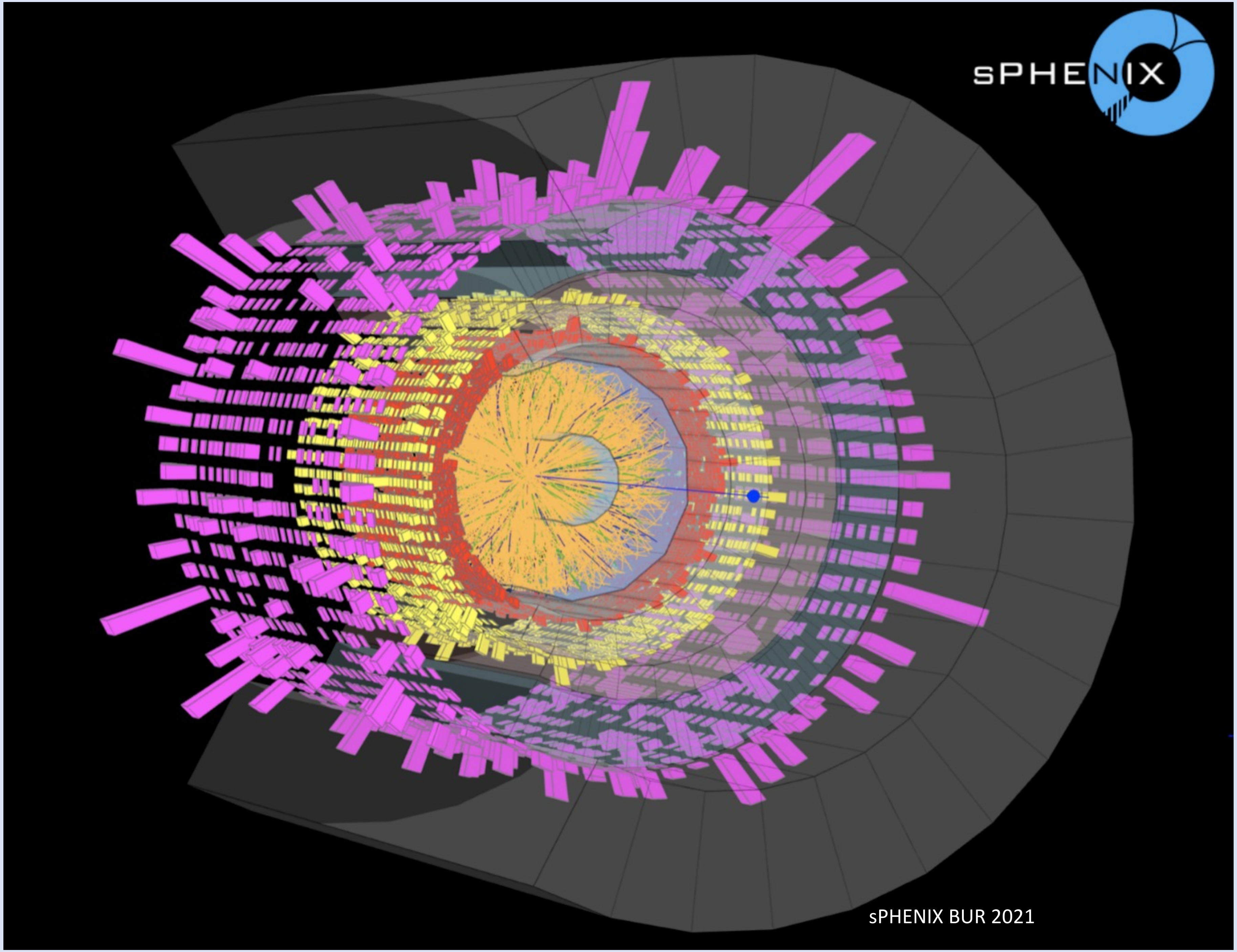
- Describes a transversely polarized quark fragmenting into an unpolarized hadron
- Single spin asymmetry (A_{UT}) → Asymmetry ~2% expected for both flavors of pion

$p_{T,jet}$ > 3 GeV/c
$\mathcal{L} = 1$ fb^{-1} w/ 60% polarization



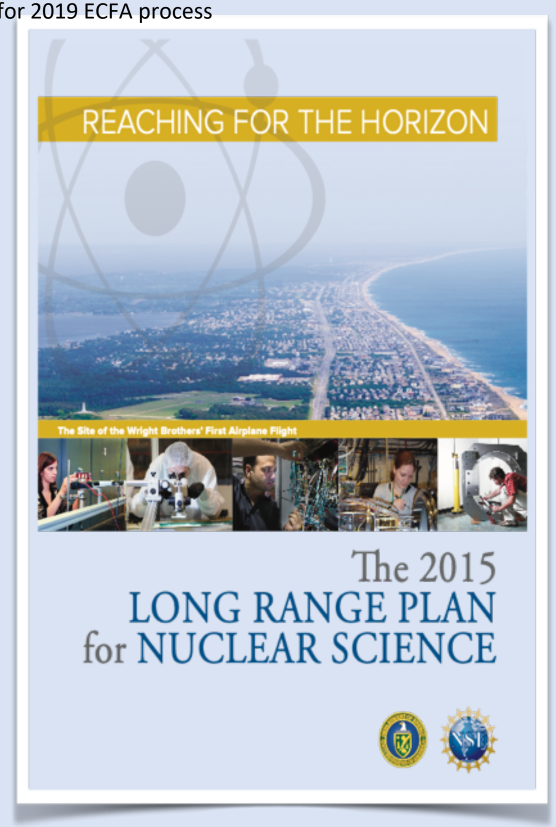
For more information see sPHENIX Talks:

- J.Huang Tues 10:55
- C.Dean Weds 1:05
- **E.Umaka Thurs 12:40**

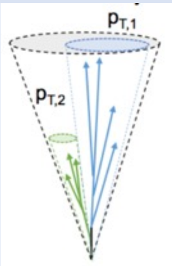


sPHENIX Science Mission

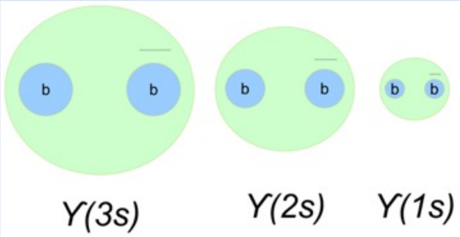
WG5 for 2019 ECFA process



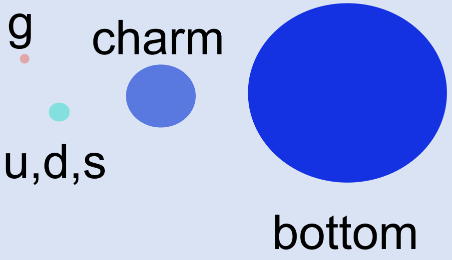
"Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of [RHIC and the LHC] is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX."



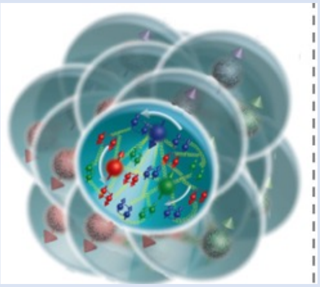
Jet structure
Vary momentum/angular scale of probe



Quarkonium spectroscopy
vary size of probe

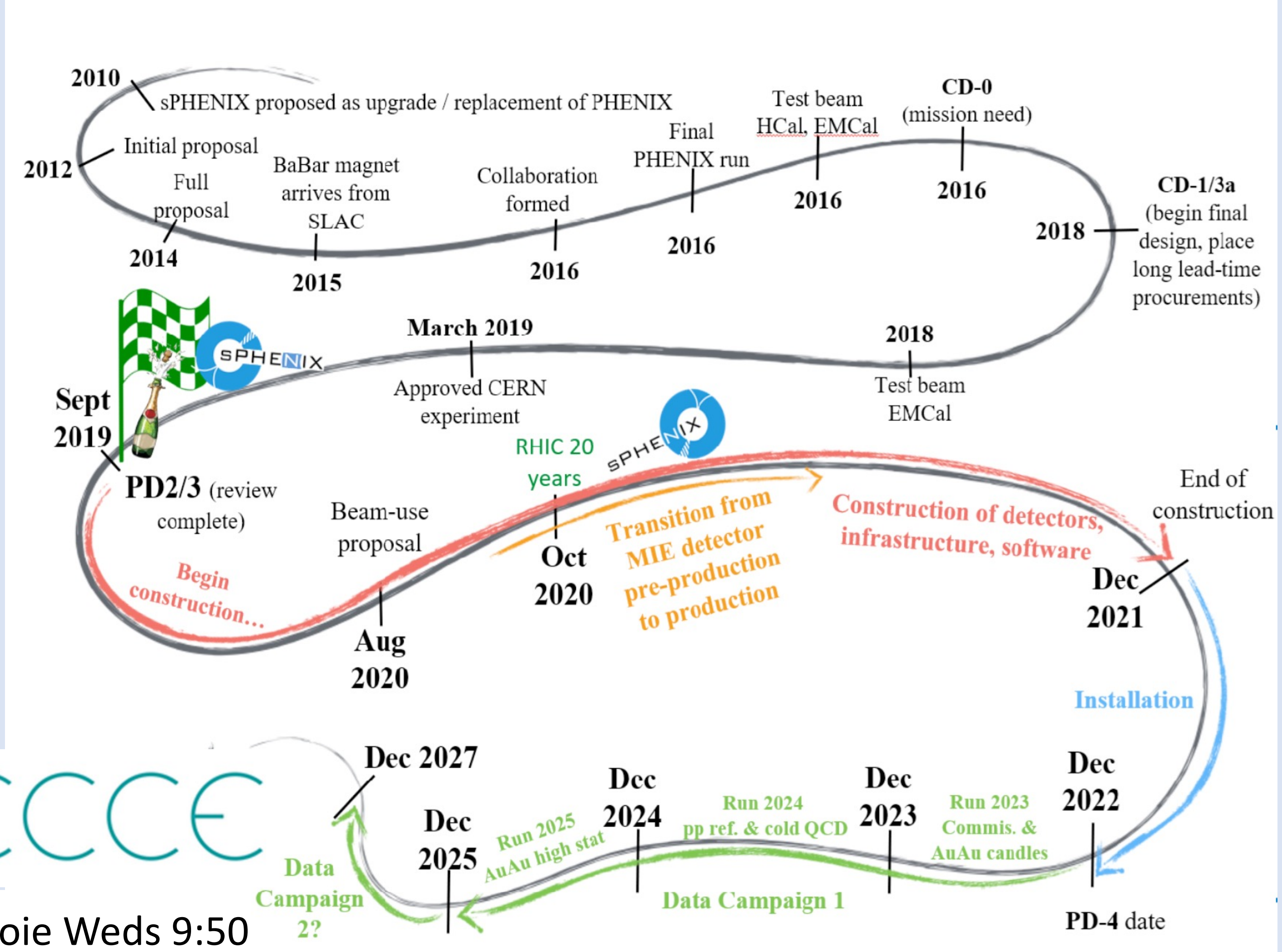


Parton energy loss
vary mass/momentum of probe



Cold QCD
vary temperature of QCD Matter

sPHENIX Timeline

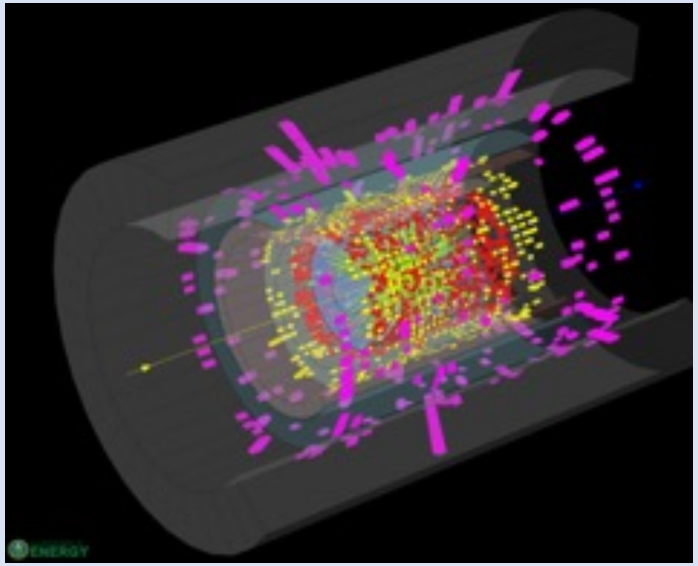


ECCE

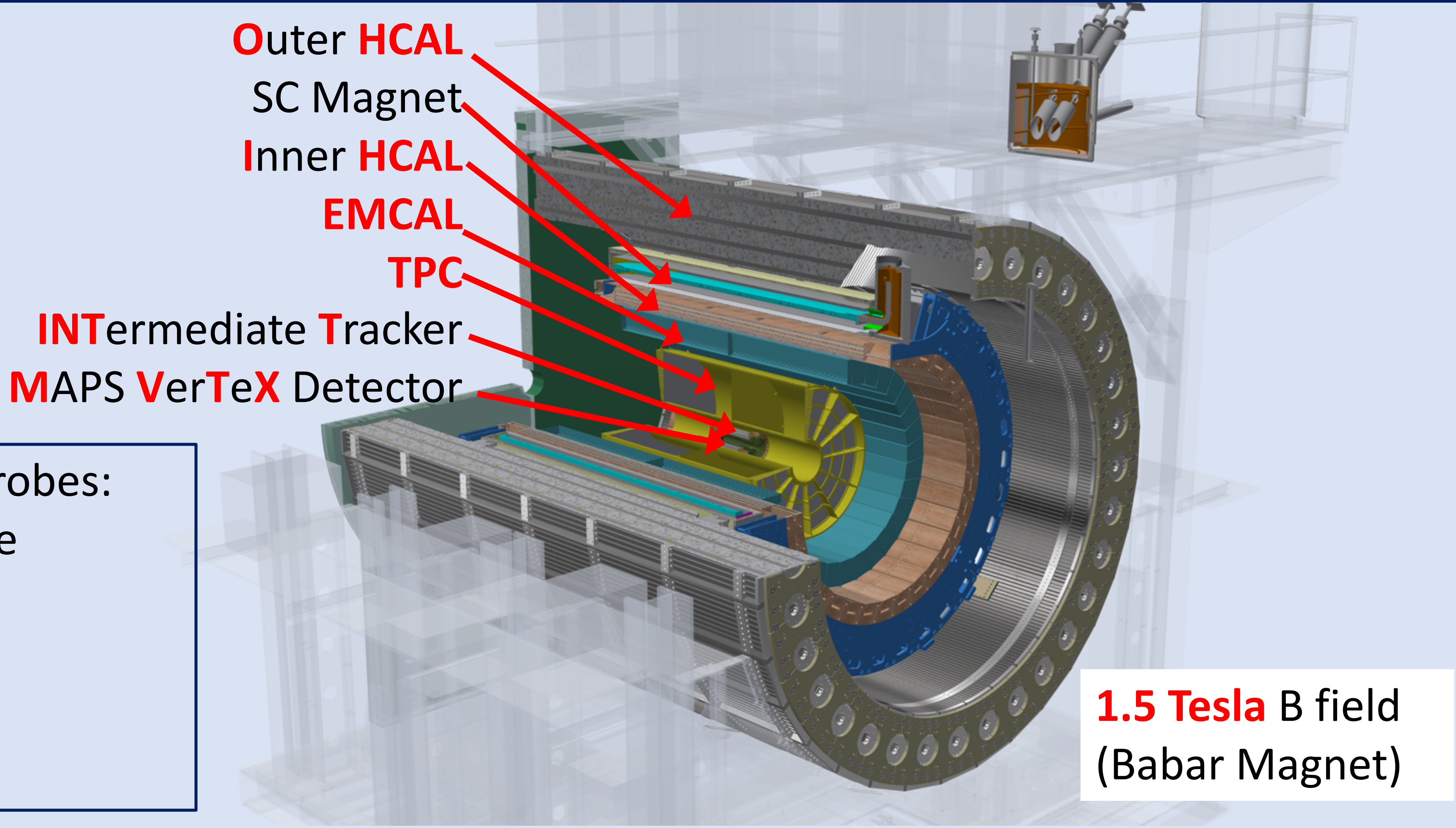
J.Lajoie Weds 9:50

Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.
Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}
Year-2	p+p	200	11.5	—	48 pb^{-1}
Year-2	p+Au	200	11.5	—	0.33 pb^{-1}
Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}

sPHENIX → data taking in early 2023



sPHENIX Design



Advantages for hard probes:

- Hermetic acceptance
- Large data rate
- Hcal
- Precision tracking
- Unbiased triggering

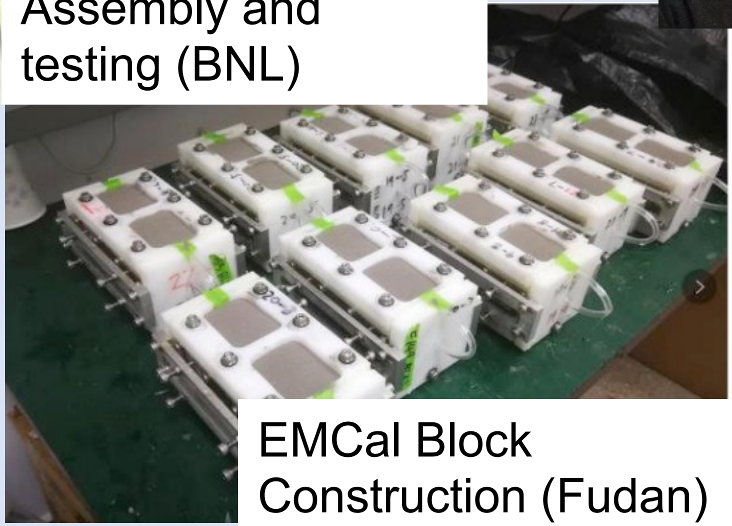
1.5 Tesla B field
(Babar Magnet)

sPHENIX Construction Proceeding!

Inner Field Cage Test

EMCal Sector Assembly and testing (BNL)

>50% of Calo blocks completed!



EMCal Block Construction (Fudan)

OHCal construction is complete!

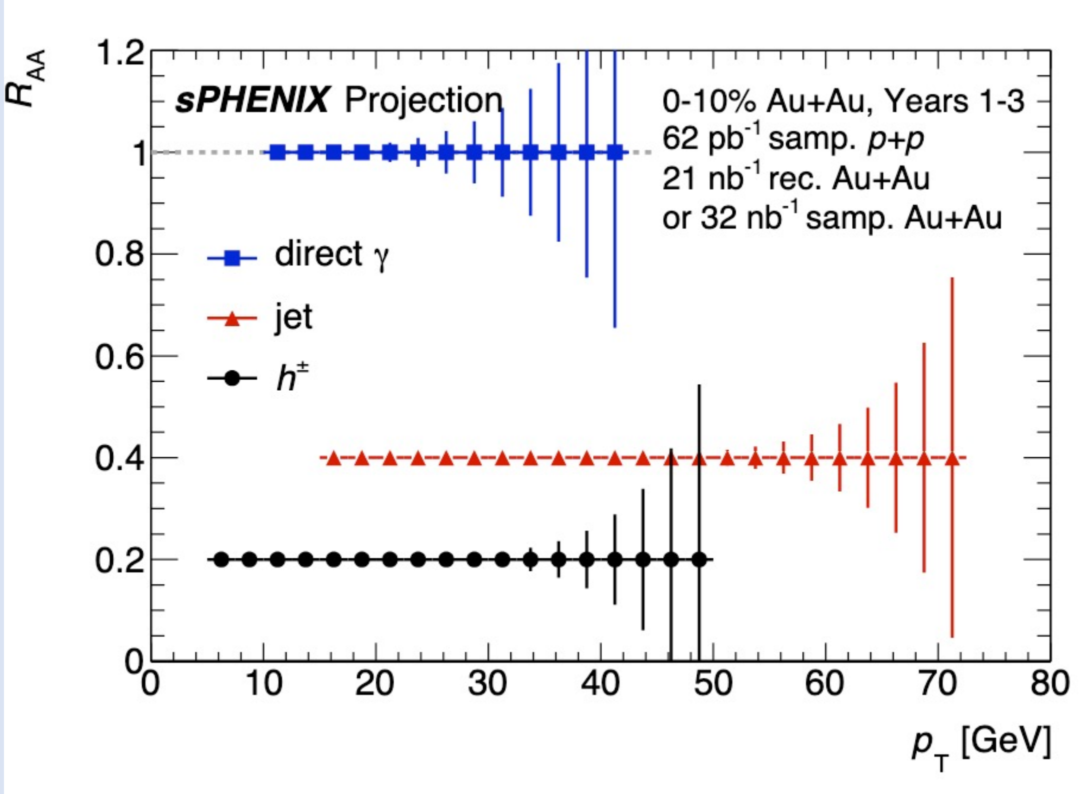
1st sPHENIX Component Installed in Hall

sPHENIX Physics Capabilities

New detector developments brings new physics capabilities to RHIC

- 3rd generation, 3 layer, large acceptance MAPS micro vertex detector
  - Precision HF and Jet Structure Measurements
- First mid-rapidity hadronic calorimeter + new EMCal Design
  - Allows Calorimeter only/Particle Flow Jets for improved JES and JER
- Readout at (nearly) the full Au+Au luminosity
  - High statistics jet measurements open a wealth of differential measurements
- Streaming readout for pp/pA collisions
  - Allows similar p+p and Au+Au HF statistics at RHIC

sPHENIX γ/Jet reach 2023-2025

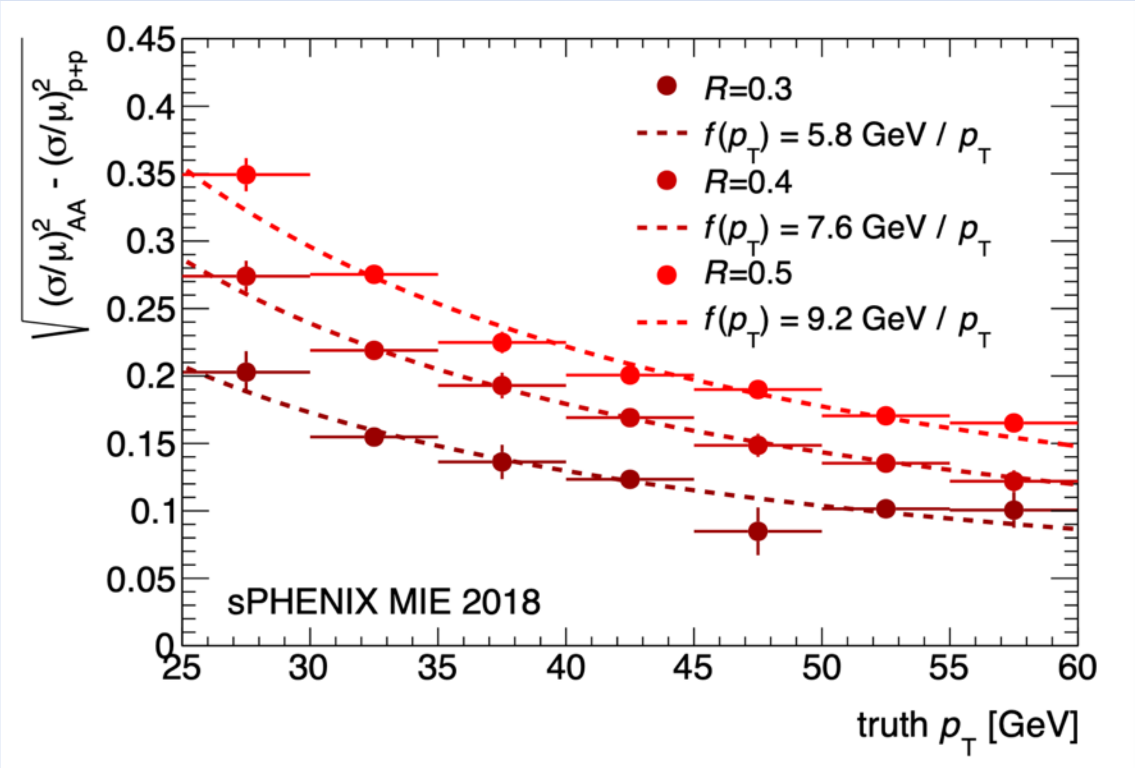


Signal	Au+Au 0–10% Counts	p+p Counts
Jets $p_T > 20$ GeV	22 000 000	11 000 000
Jets $p_T > 40$ GeV	65 000	31 000
Direct Photons $p_T > 20$ GeV	47 000	5 800
Direct Photons $p_T > 30$ GeV	2 400	290
Charged Hadrons $p_T > 25$ GeV	4 300	4 100

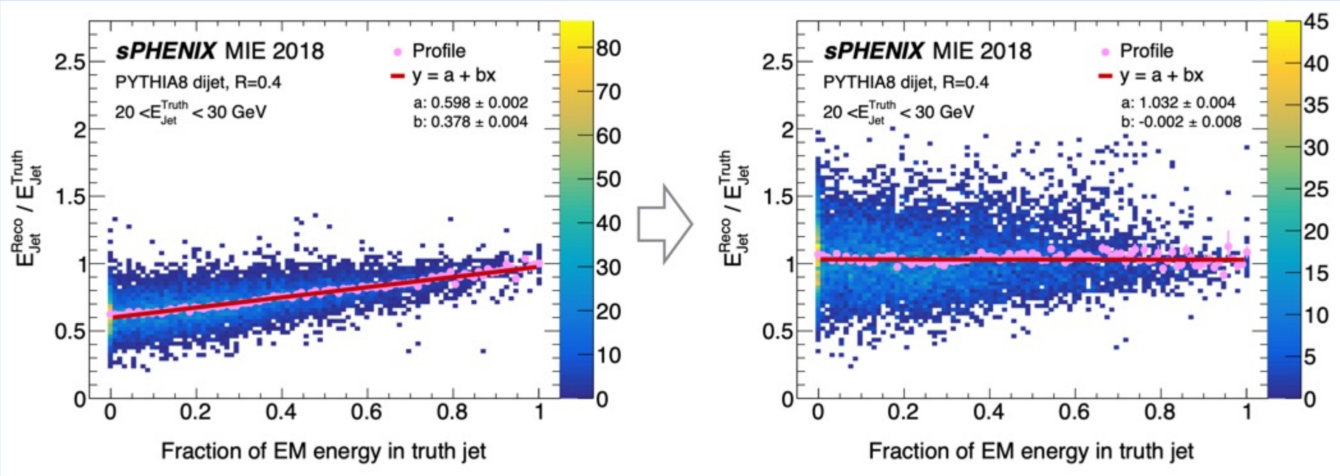
Projected counts from proposed 2023–2025 data taking

Large data rate + hermetic EMCal/HCal detectors allow jet reconstruction the kinematic region accessible by the LHC! **Complementarity** is key.

sPHENIX Calorimeter Jet performance



Calibration of Jet Energy Scale



Au+Au response as pp response ⊗ UE

- Identical sensitivity to fragmentation in both systems

Can the resolution be further improved?

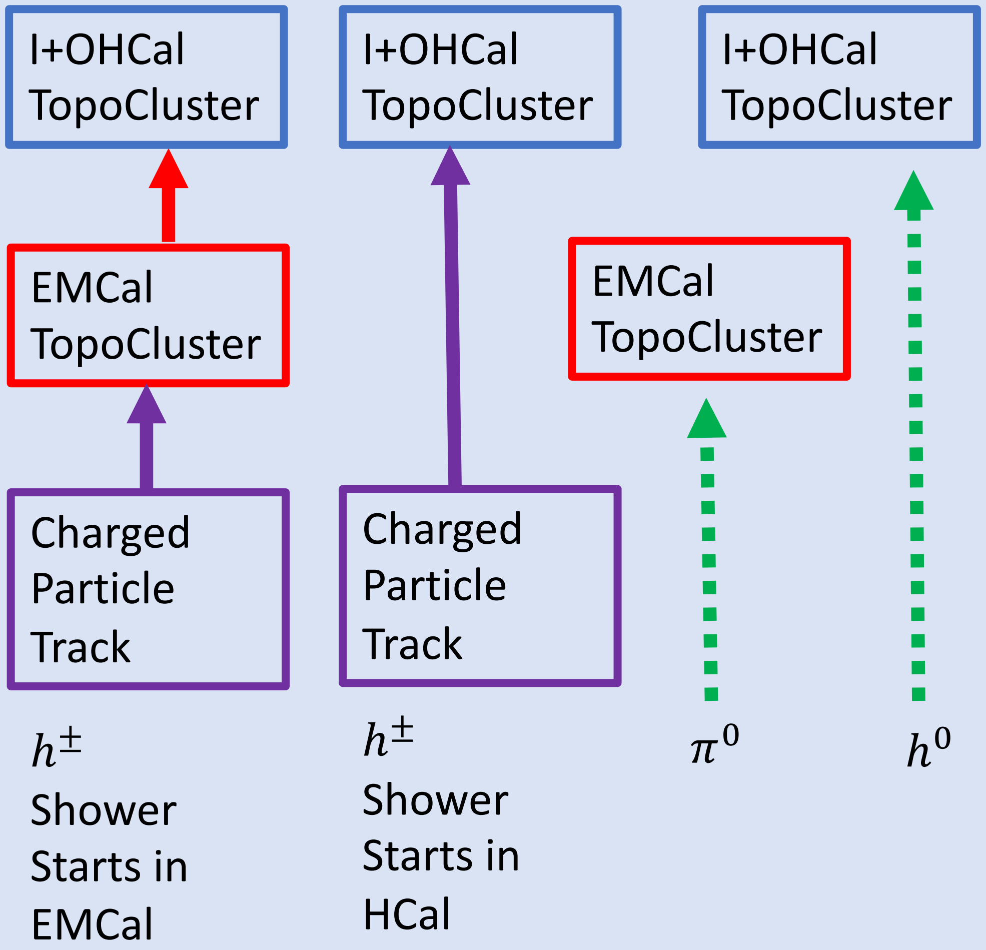
Particle Flow

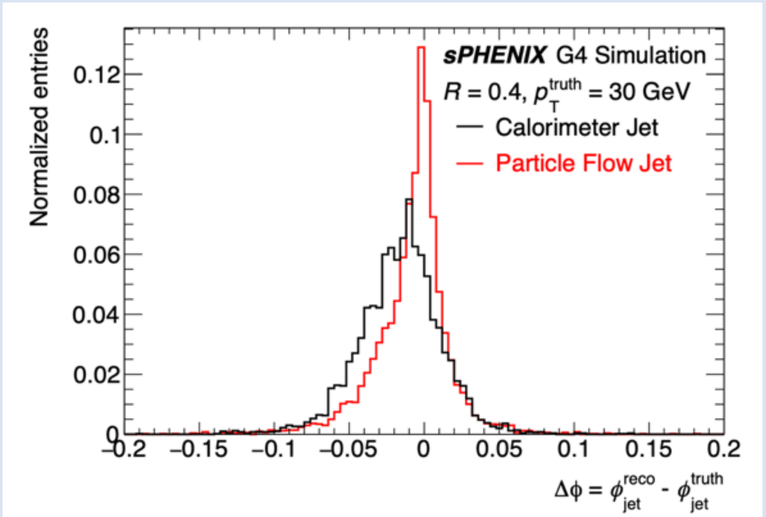
Deconvolution of Underlying Event (UE) term in Au+Au response

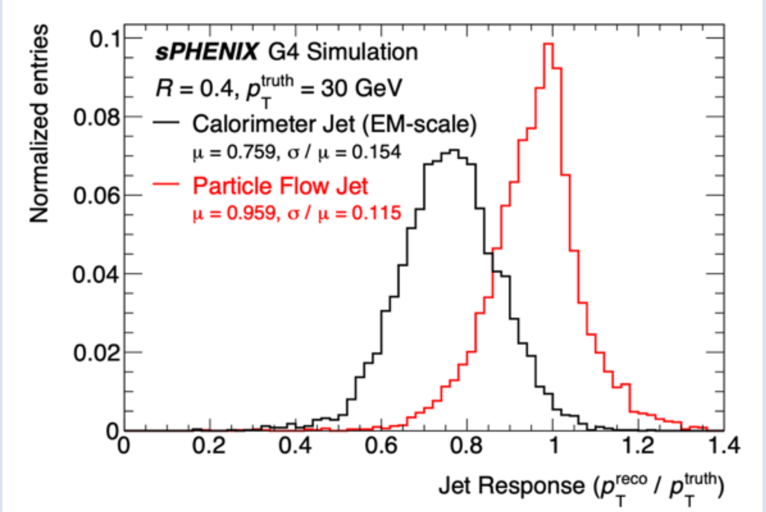
$$\frac{\sigma_{p_T}}{p_T} = \underbrace{\frac{n}{p_T}}_{\text{Noise}} \oplus \underbrace{\frac{s}{\sqrt{p_T}}}_{\text{Stochastic}} \oplus \underbrace{c}_{\text{Constant}}$$

sPHENIX Particle Flow

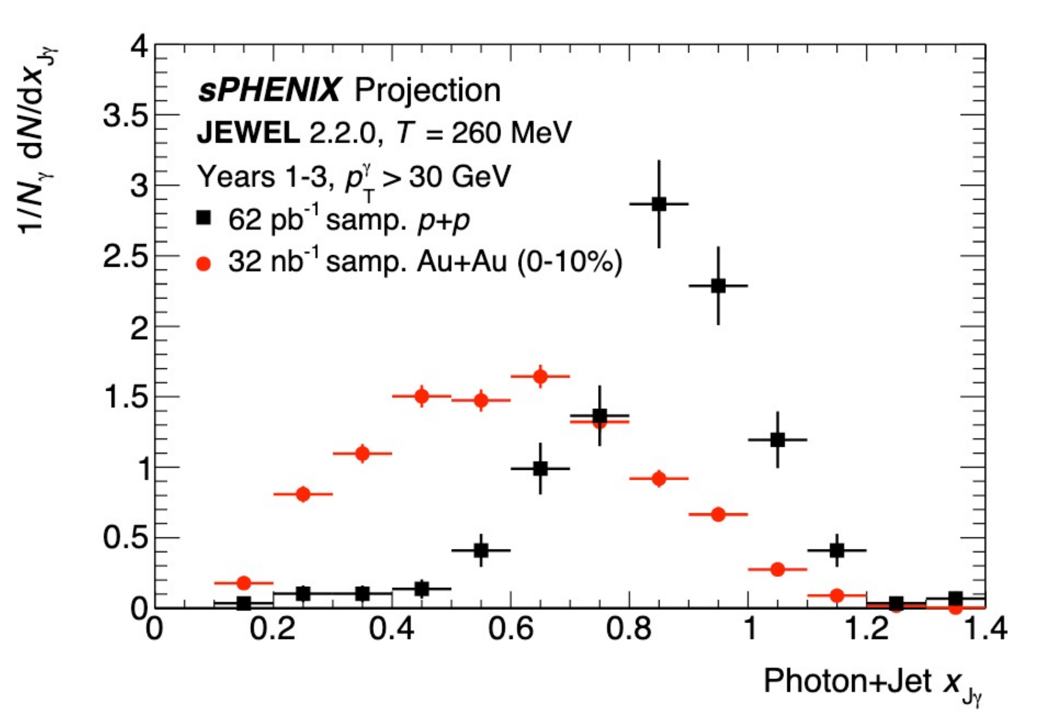
- Implementation of **particle-flow** jet reconstruction using "best of" techniques from ATLAS/CMS
  - Charged particle tracking important for jet physics
  - Significant improvement in angular resolution and p_T response possible
- Particle-flow jets will enable the measurement of **jet sub-structure observables**

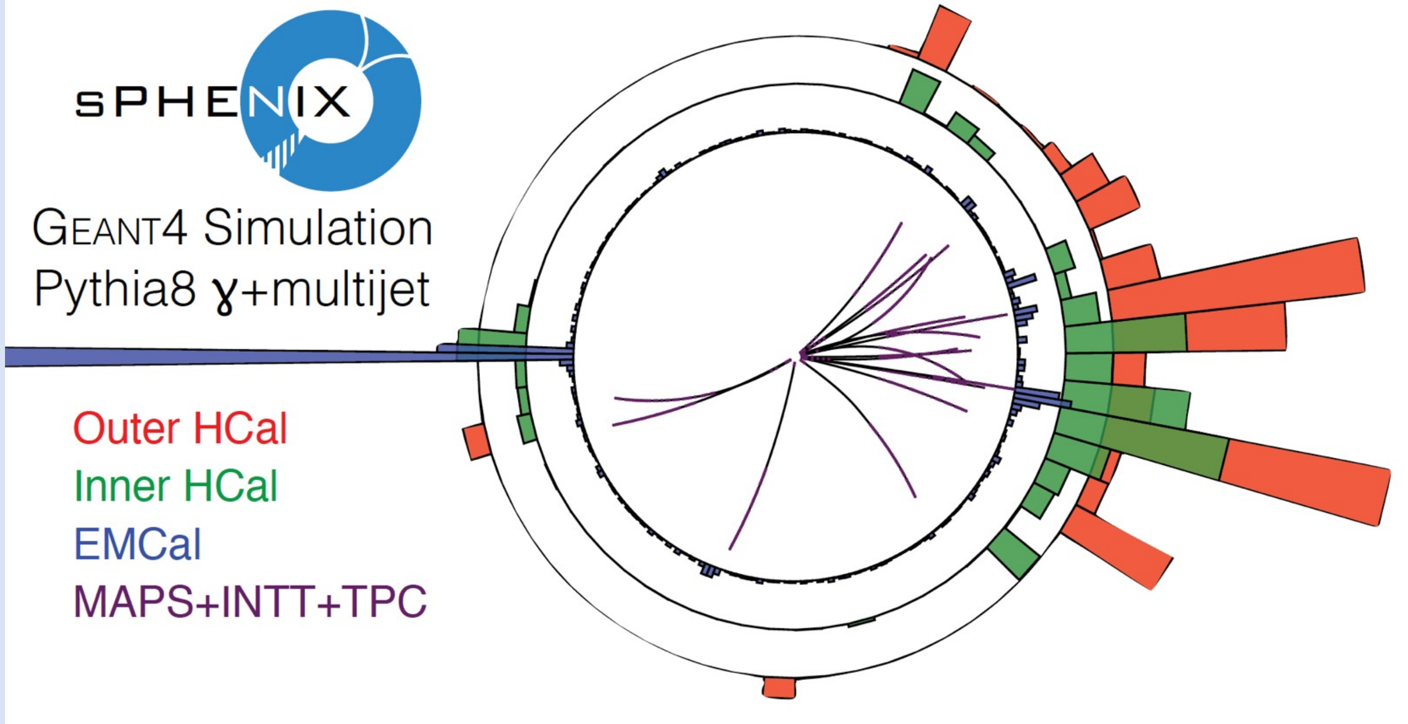






sPHENIX $X_{J\gamma}$



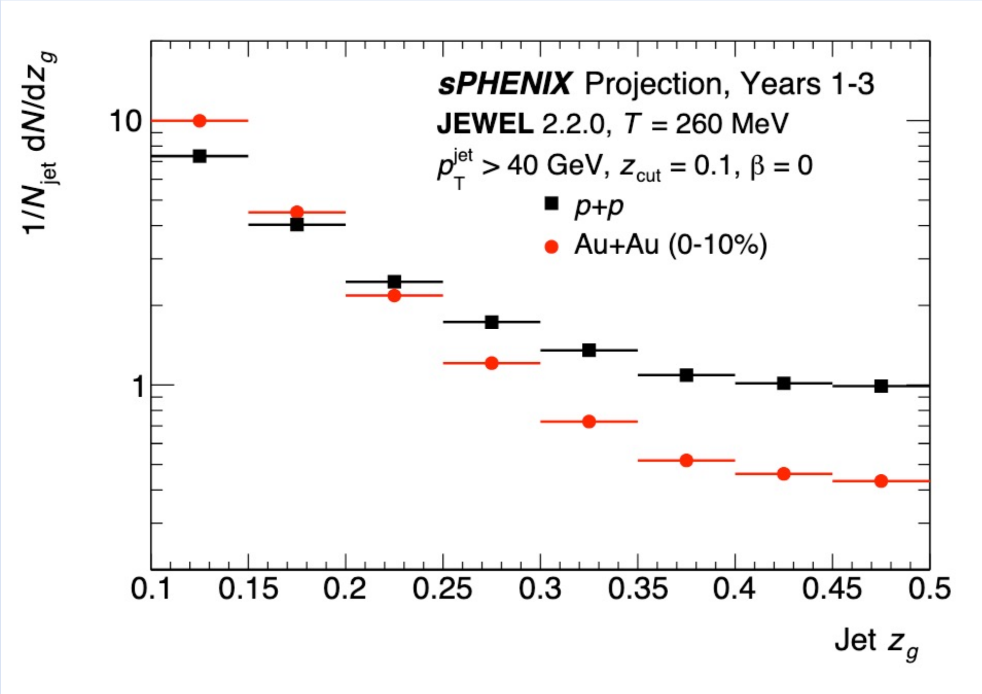


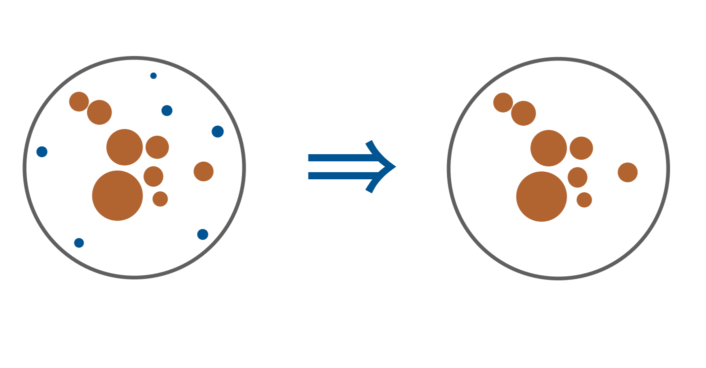
$$X_{J\gamma} = \frac{p_T^{Jet}}{E_T^{\gamma}}$$

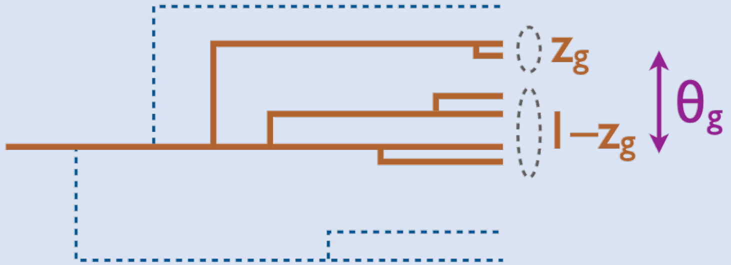
Dramatic difference between vacuum and in-medium photon jet imbalance

- Distinguish different models
  - For example W. Dai, I. Vitev, B. Zhang -Phys. Rev. Lett. 110, 142001 also predicts a dramatic difference at RHIC vs LHC
- Day 1 Measurement

Groomed Momentum Sharing Z_g







Based on declustering an angular-ordered tree

Soft Drop Condition:

$$z > z_{\text{cut}}\ \theta^{\beta}$$

energy threshold

angular exponent

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

J. Thaler ALICE Jet Workshop (2015)

Larkoski et al., PRD 91, 111501 (2015)

Jet structure observables using particles → sensitive to ill constrained hadronization dynamics

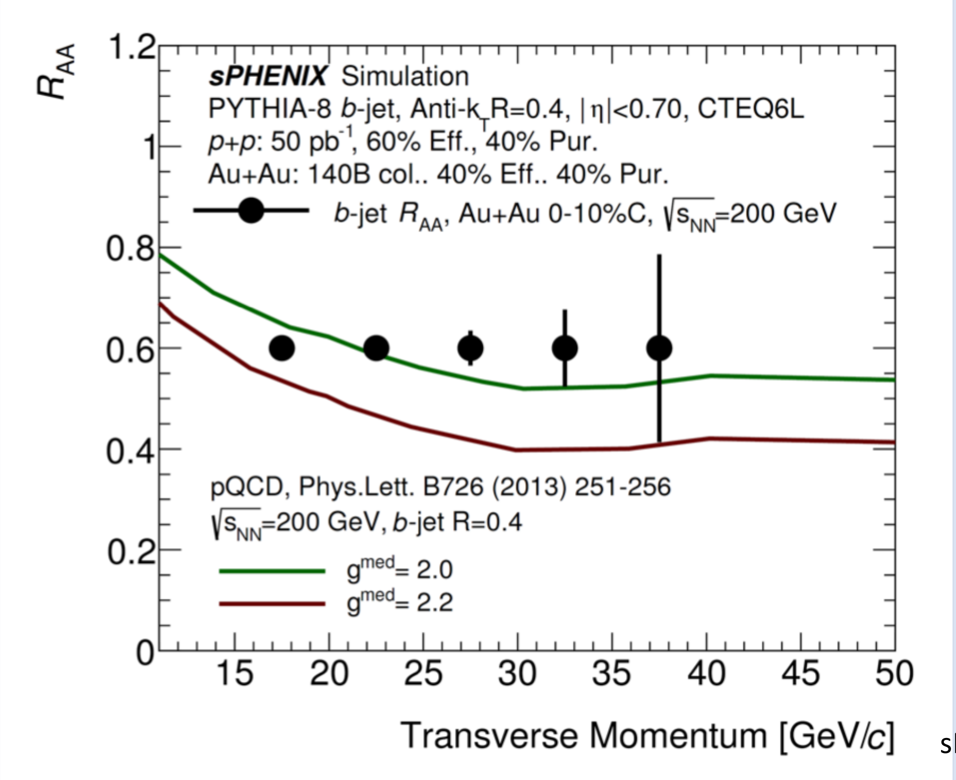
- This plays a role for the small jets favored in HI analyses as well!
- Observables built from jet-like structures may be more robust → **Connection to fundamental QCD**

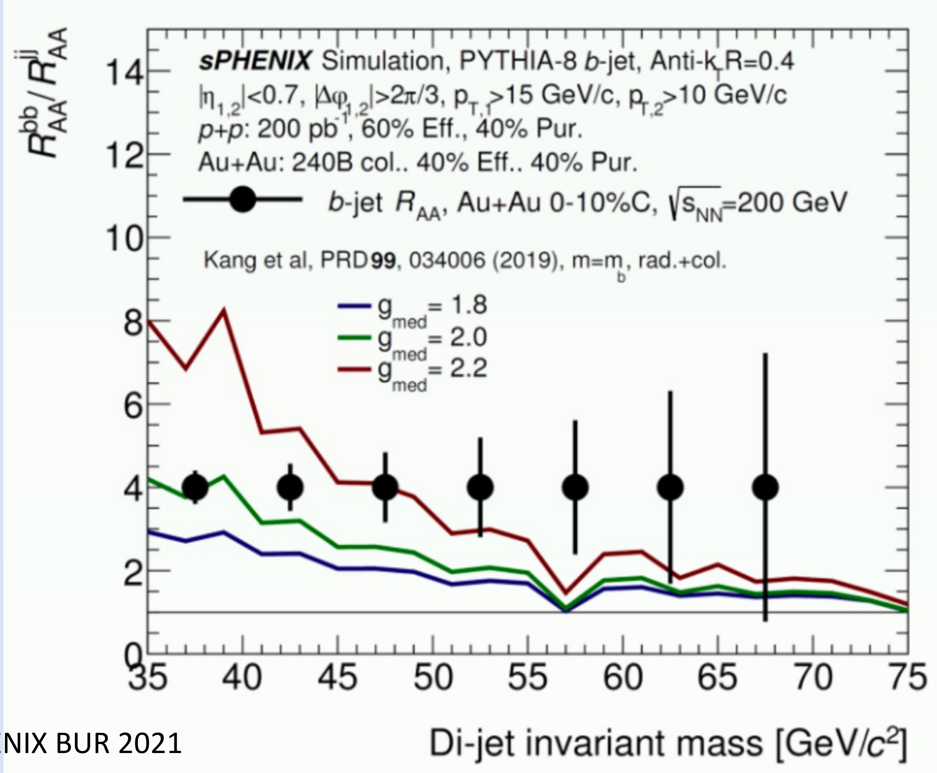
Default values for q, b make observables comparable to theoretical calculations → converge to DGLAP splitting functions in infinite momentum limit

Heavy Flavor at sPHENIX

b-tagged jet R_{AA}

HF Jets Require Precision Tracking!





sPHENIX BUR 2021

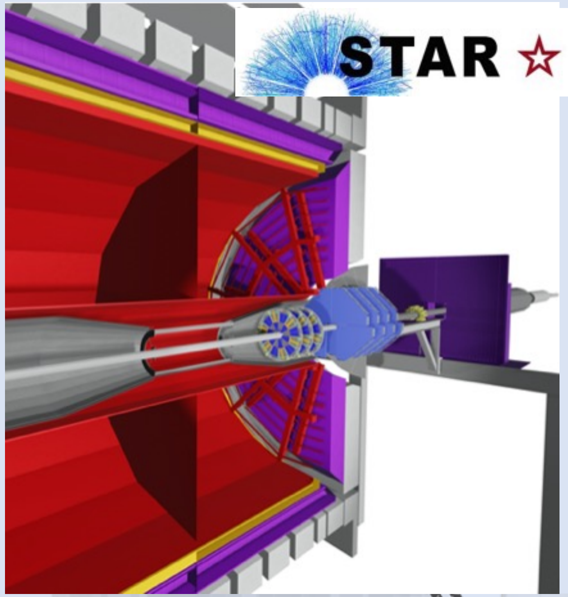
2 b-jet finding methodologies:

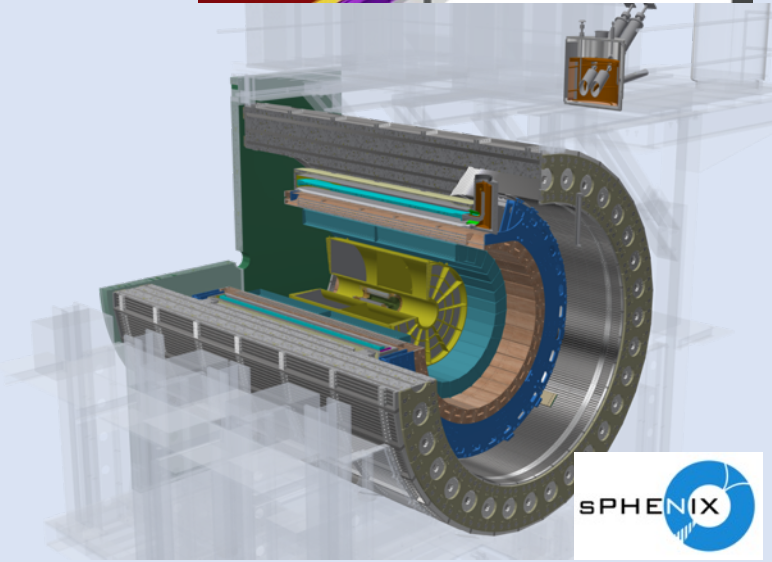
- High-DCA track tagger
- Secondary vertices tagger

Invariant mass of back-to-back HF jet pairs allows for studying the propagation of quarks in the QGP

Conclusions

- Upgrades are on schedule despite COVID restrictions and shutdowns!
- This is the result of the hard work by many people who put in innumerable extra hours at their labs/BNL! (Includes driving halfway across the country to work!)





Conclusions

- RHIC is carrying out the priorities of the LRP
  - Precisely how does QCD lead to the emergent phenomena we observe?
  - **sPHENIX** is essential to the goal of probing the QGP to resolve its properties
  - Absolutely vital the entire program be carried out
    - The **sPHENIX** and **STAR** physics goals will have **serious negative impacts** if the runs are reduced to only **20 cryo-weeks** in 2023-25
- The new **sPHENIX** detector (and **STAR** with improved capabilities) will result in an exciting post-BESII Era!
- How do quarks and gluons form a strongly coupled, nearly perfect liquid? What are its properties?
- How do the proton constituents lead to its spin?