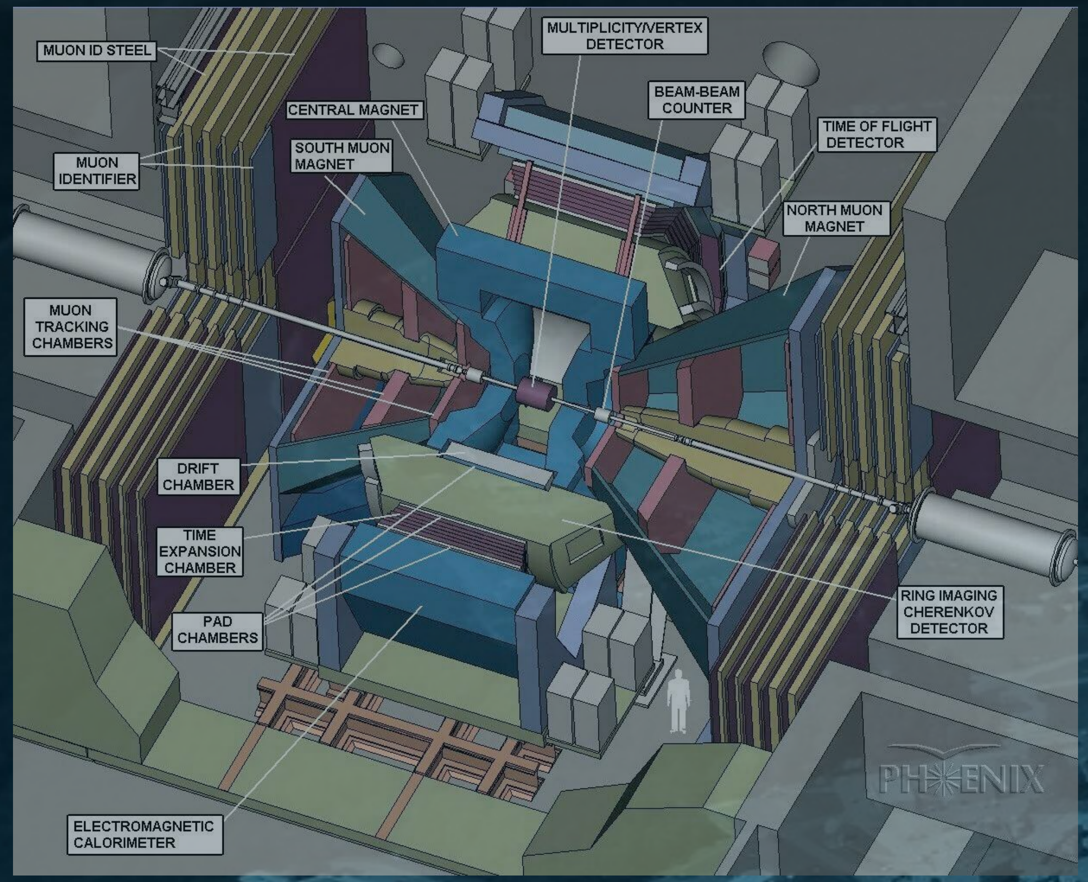
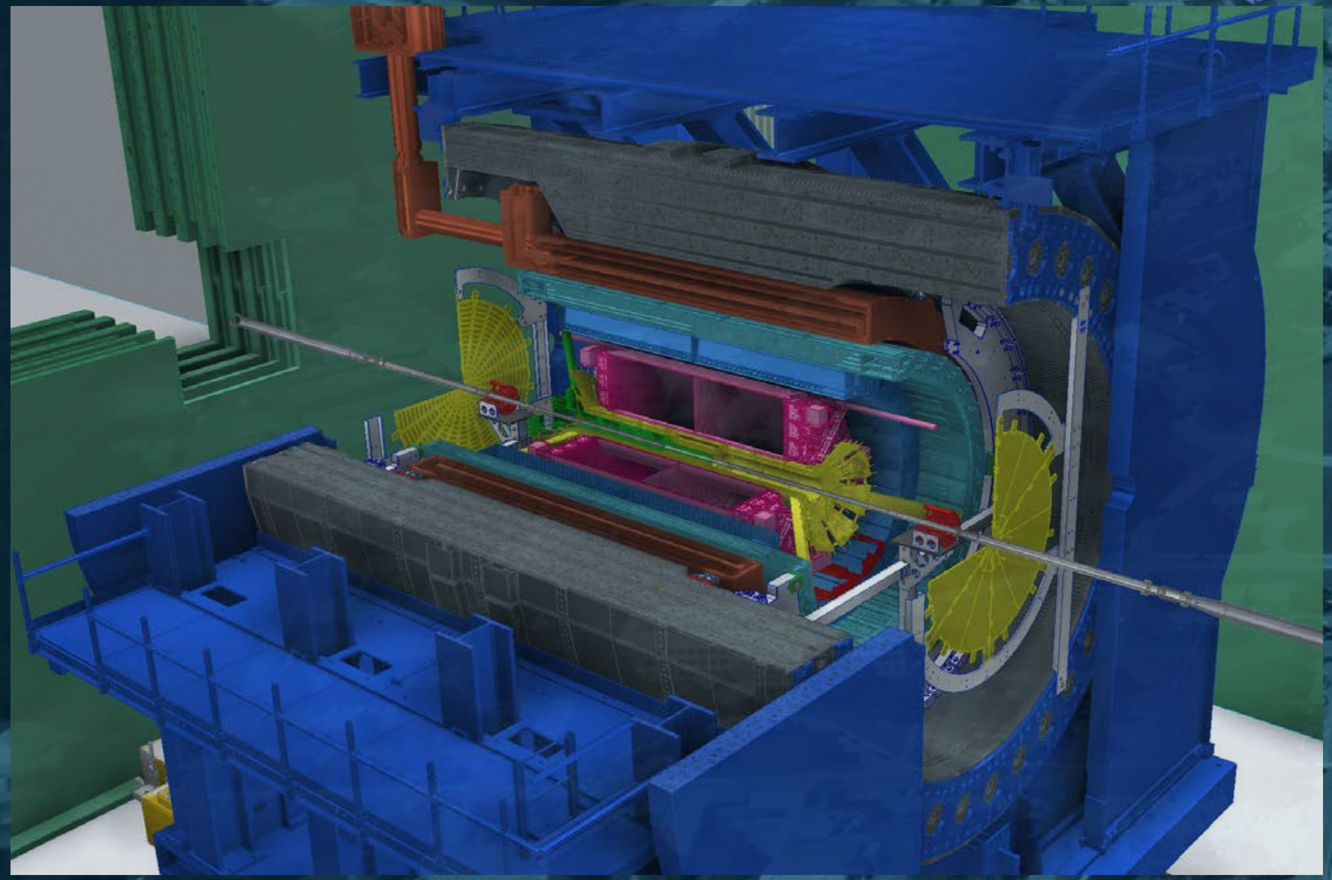
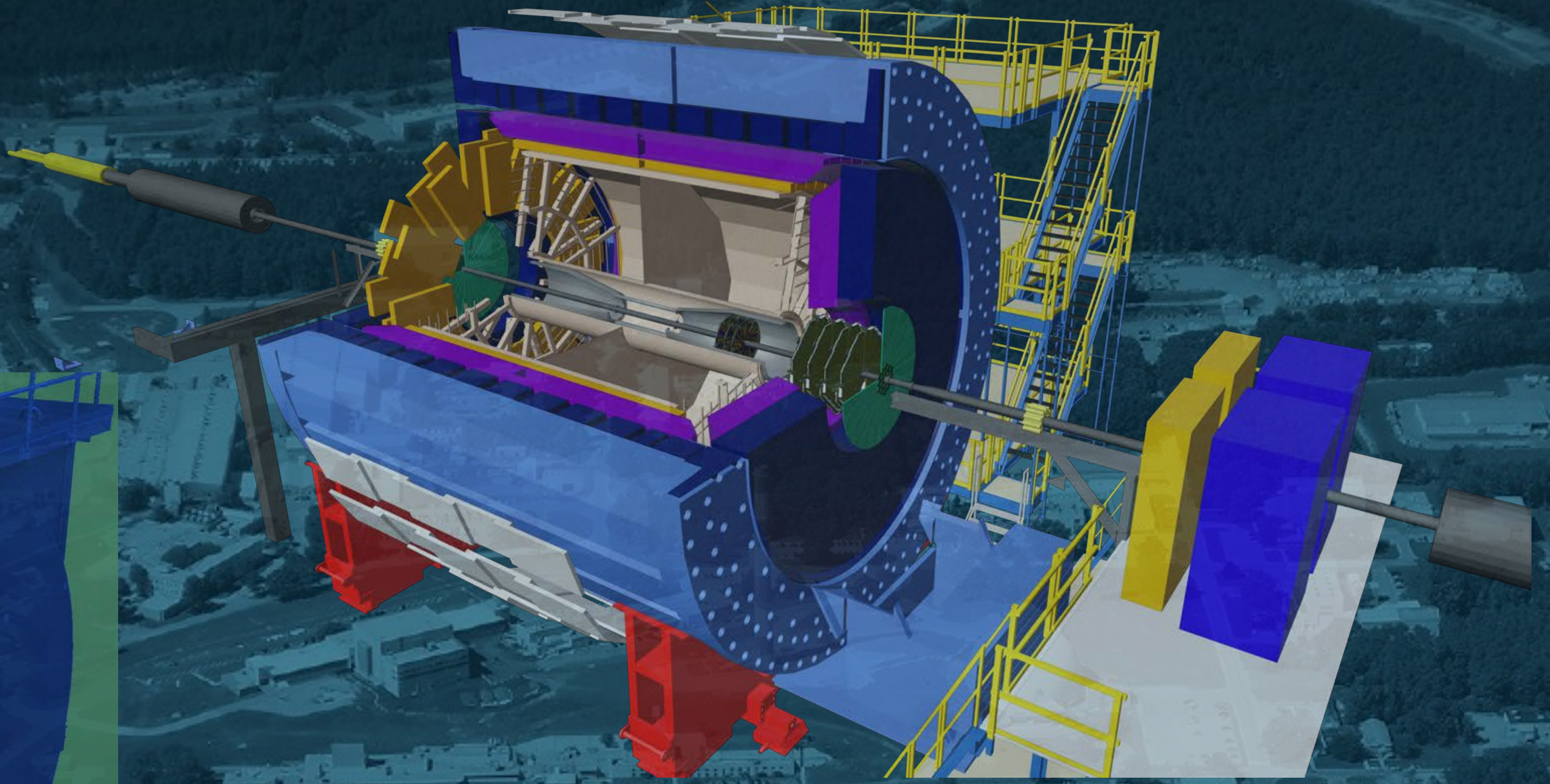






Brookhaven National Laboratory

Supported in part by the U.S. DEPARTMENT OF ENERGY | Office of Science

RHIC Highlights and Future II

Prithwish Tribedy

Brookhaven National Laboratory

ptribedy@bnl.gov

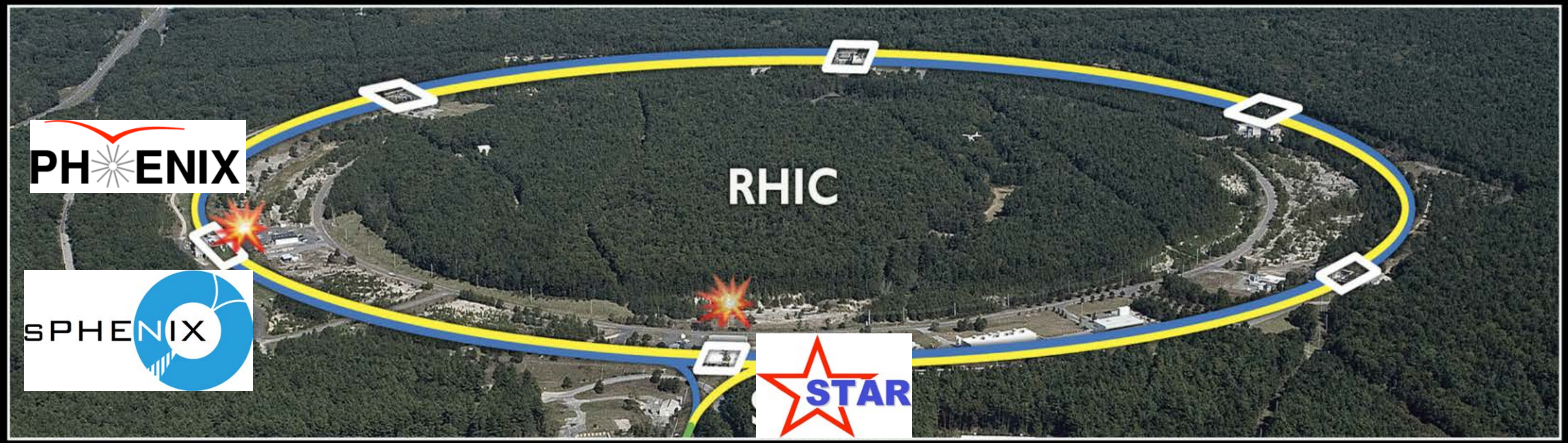
NSAC Long-Range Plan Town Hall Meeting on Hot and Cold QCD, Sep 23-25, 2022, MIT

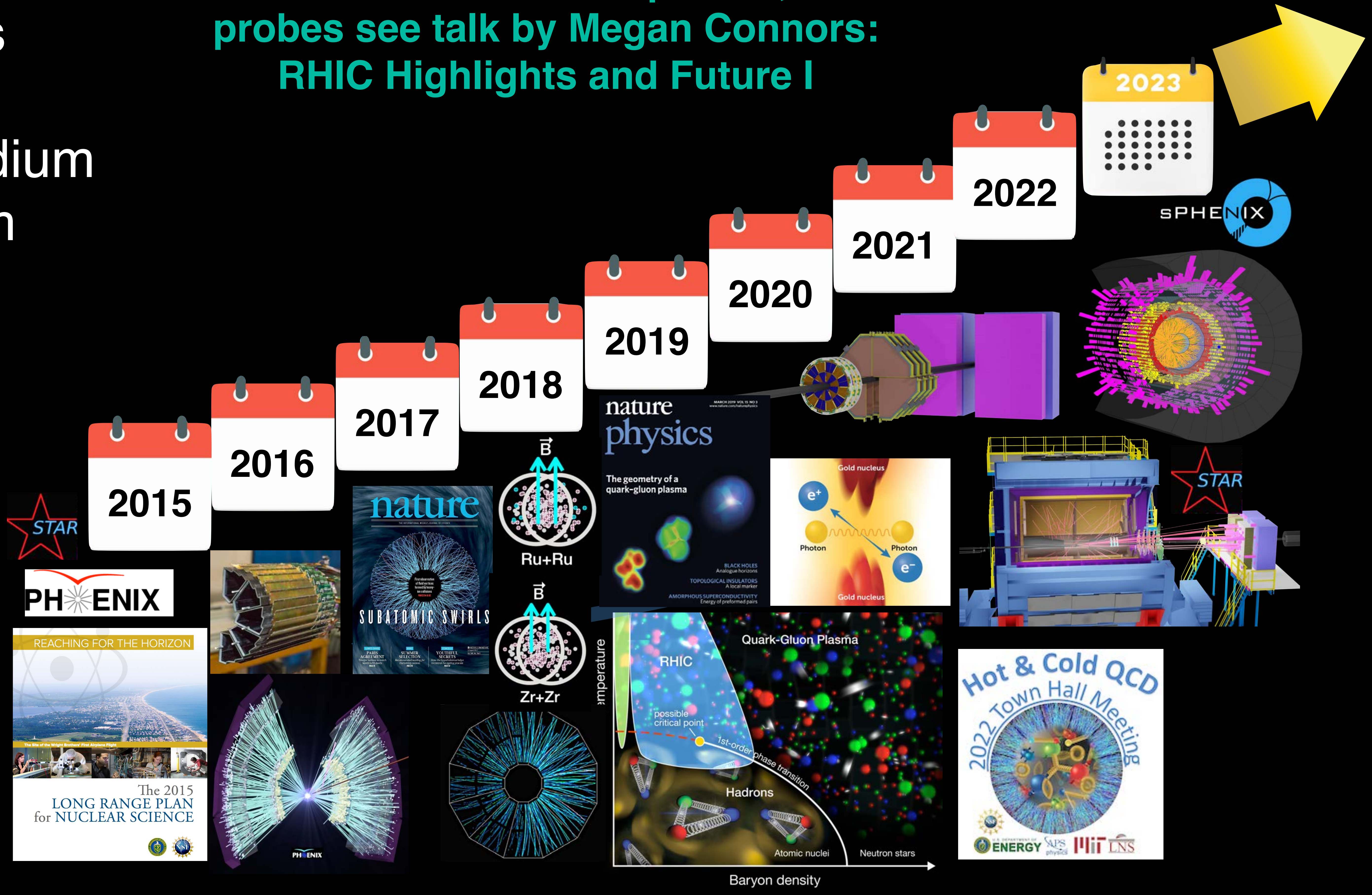
RHIC highlights & Future

NSAC 2015 LRP:
https://science.osti.gov/-/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

- Unique hot QCD topics to be done at RHIC
  1. Inner working of the QGP with hard probes
  2. Mapping the QCD phase diagrams
  3. Search for the Chiral properties of the medium
  4. Vortical fluid & new probes hydro paradigm
- Topics that bridge RHIC & EIC science
  5. Origin of small system collectivity
  6. Imaging nuclei in the pre-EIC era
  7. Microscopic structure of a baryon

This talk will focus on soft probes, for hard probes see talk by Megan Connors: RHIC Highlights and Future I





DATA ON TAPE

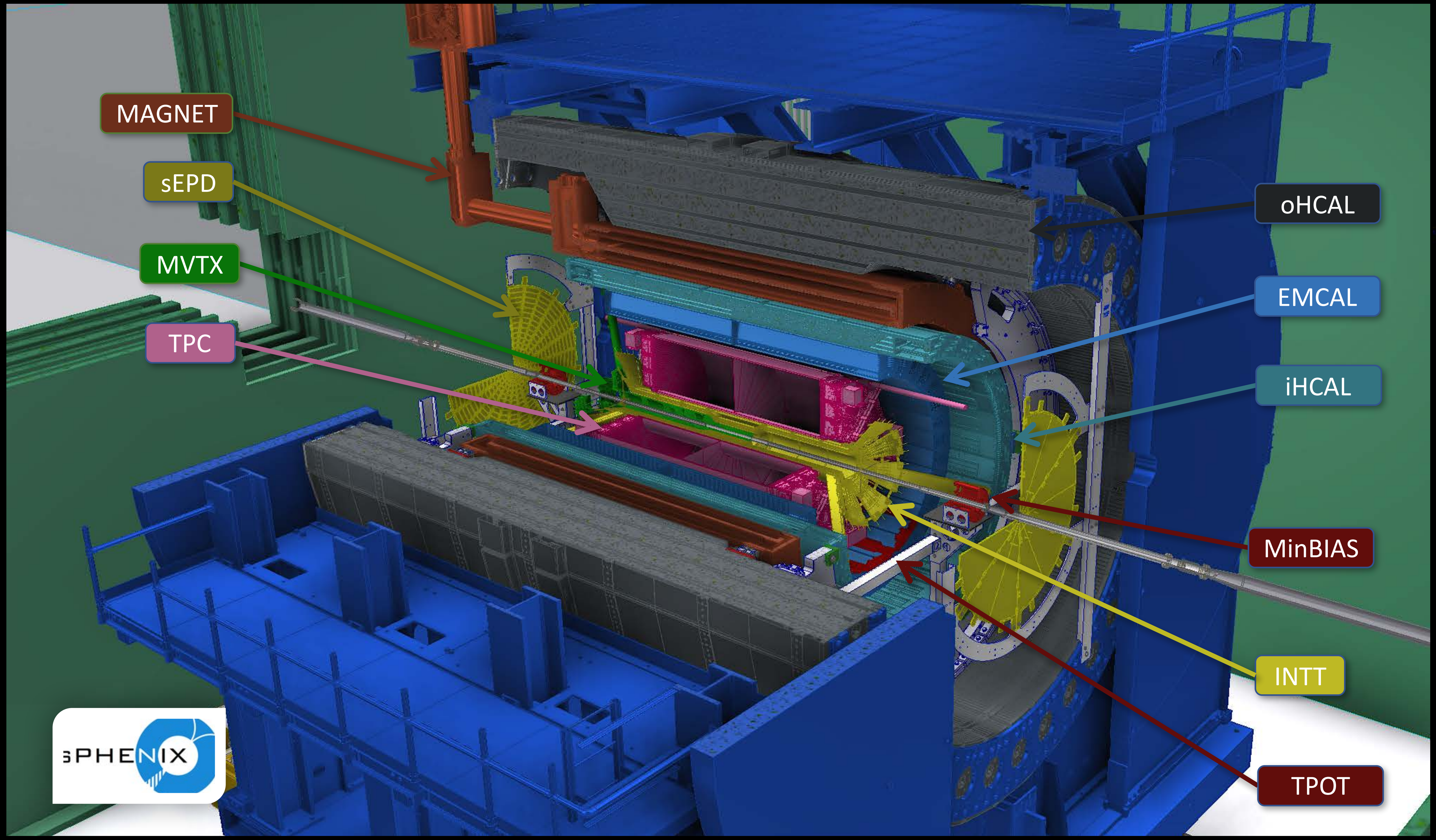
Topics that need analysis of already collected data

NEED MORE DATA

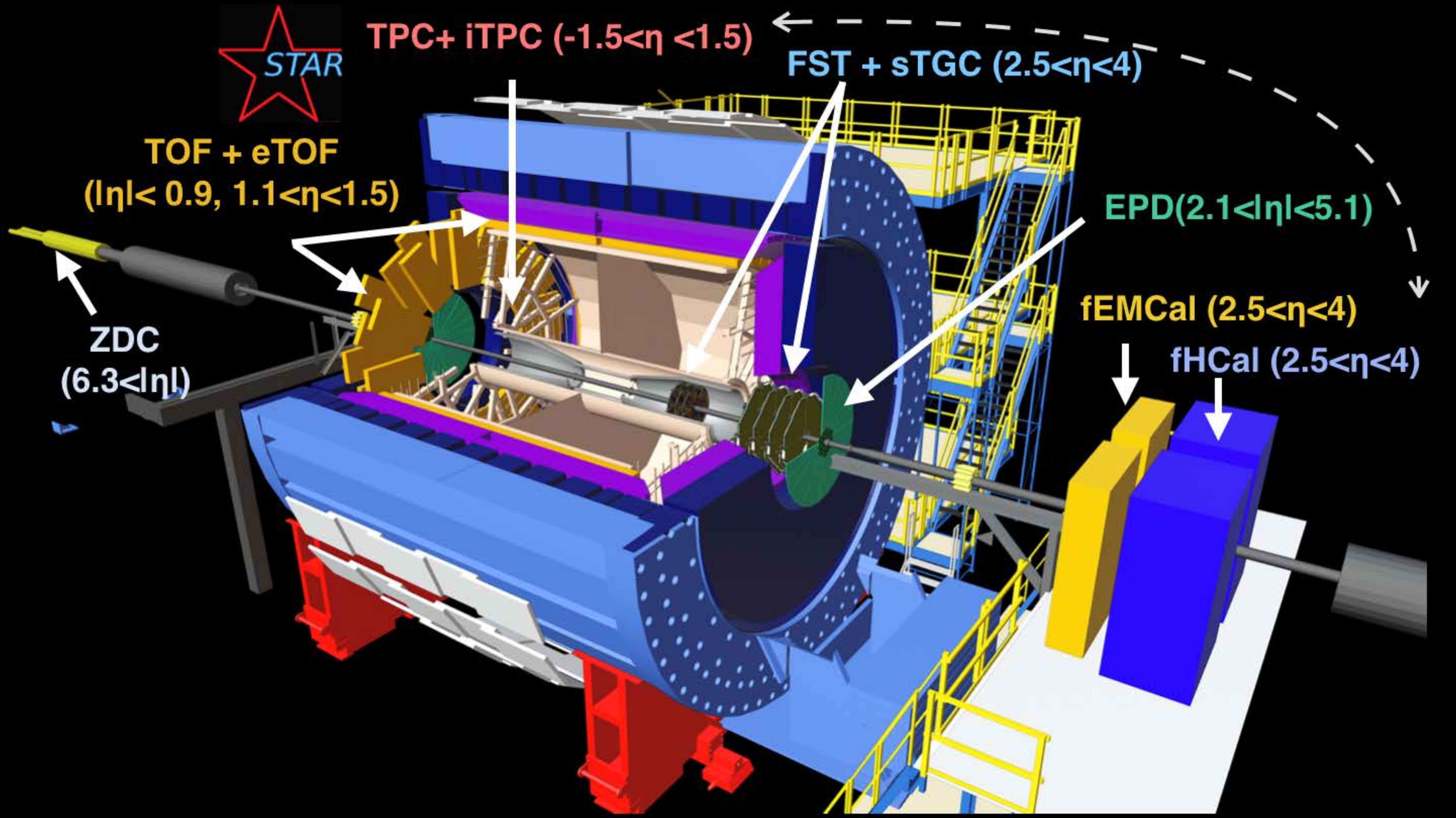
Outstanding questions that can be answered only with more data from future runs

Remaining years of RHIC running with sPHENIX & STAR

Unique, purpose-built sPHENIX detector for precision on hard probes



Significant new forward and mid-rapidity capabilities of the upgraded STAR detector



Complete the planned RHIC operations by collecting p+p, p+A & A+A data to achieve required precision
Fully exploit the unique detector capabilities, kinematics & polarization of proton beams
Compliment LHC program with probe different kinematics

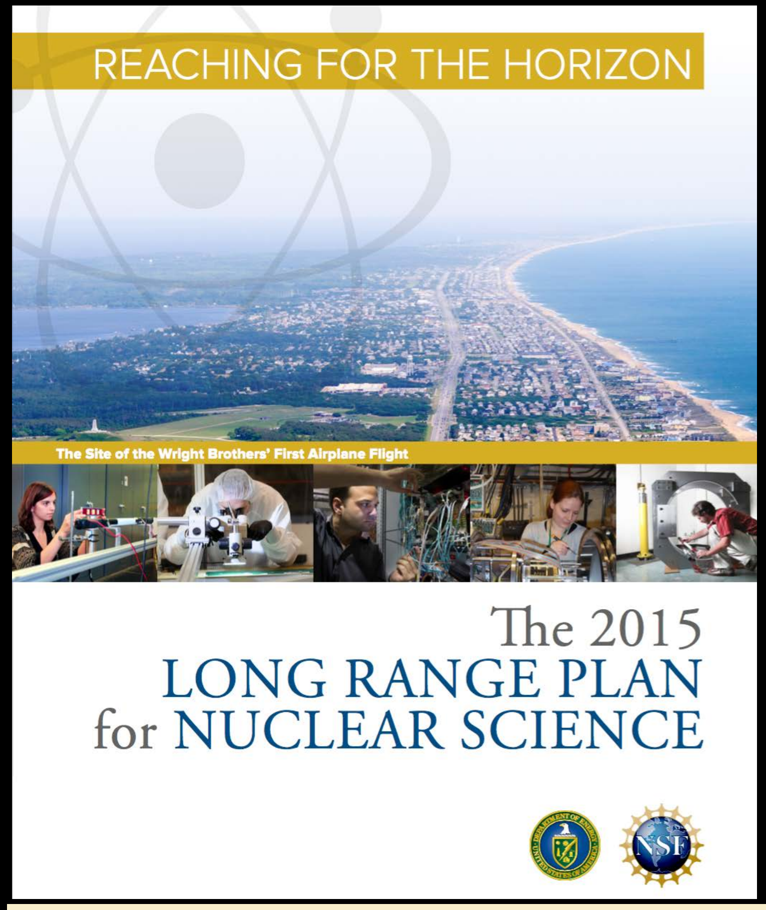
Goal is to complete the RHIC Hot and Cold QCD missions with sPHENIX and upgraded STAR detector

Unique hot QCD topics at RHIC

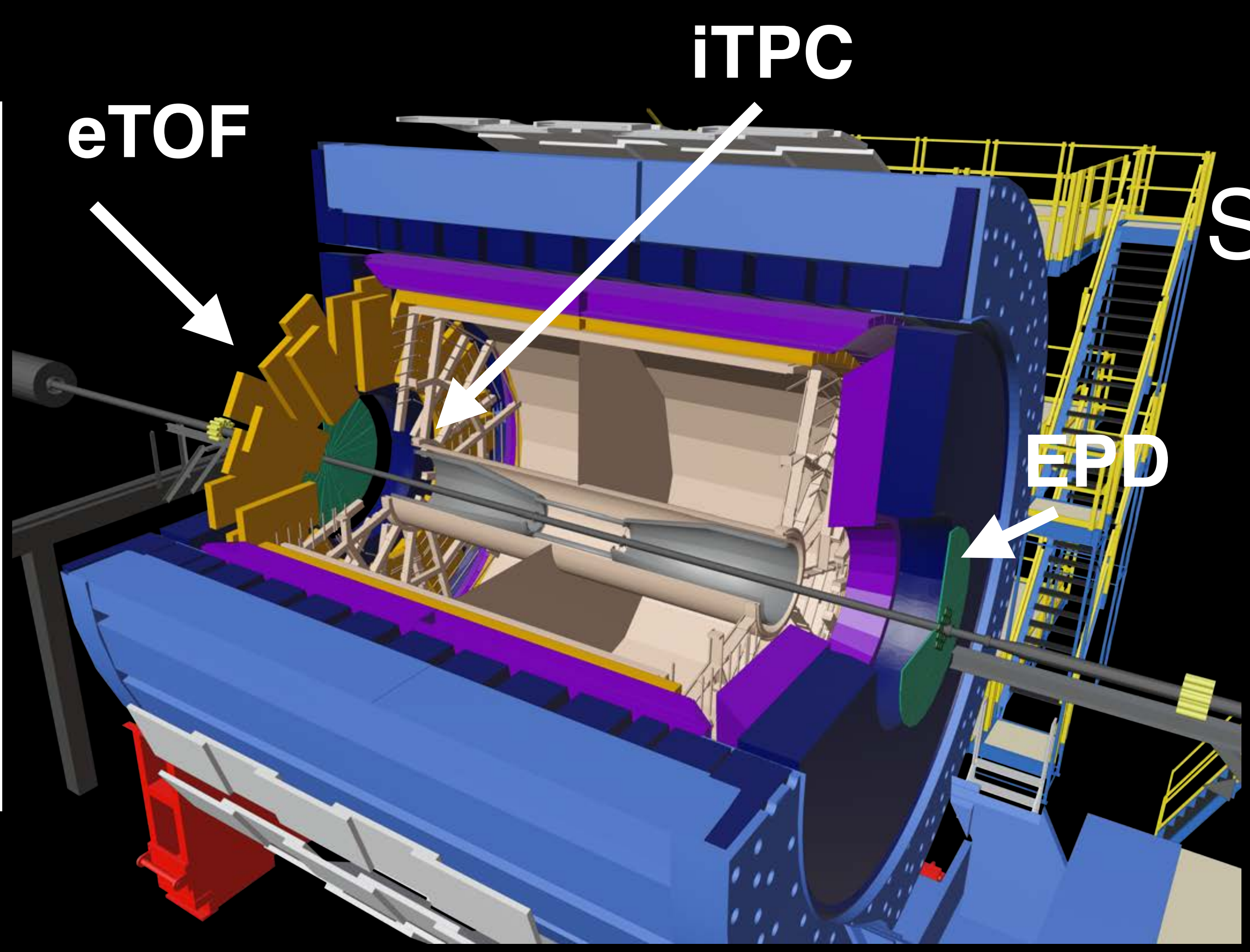
1. Mapping the QCD phase diagrams
2. Search for the Chiral properties of the medium
3. Vortical fluid & new probes of the hydrodynamic paradigm

Mapping the QCD phase diagram

Talk by Xin Dong (Sat)

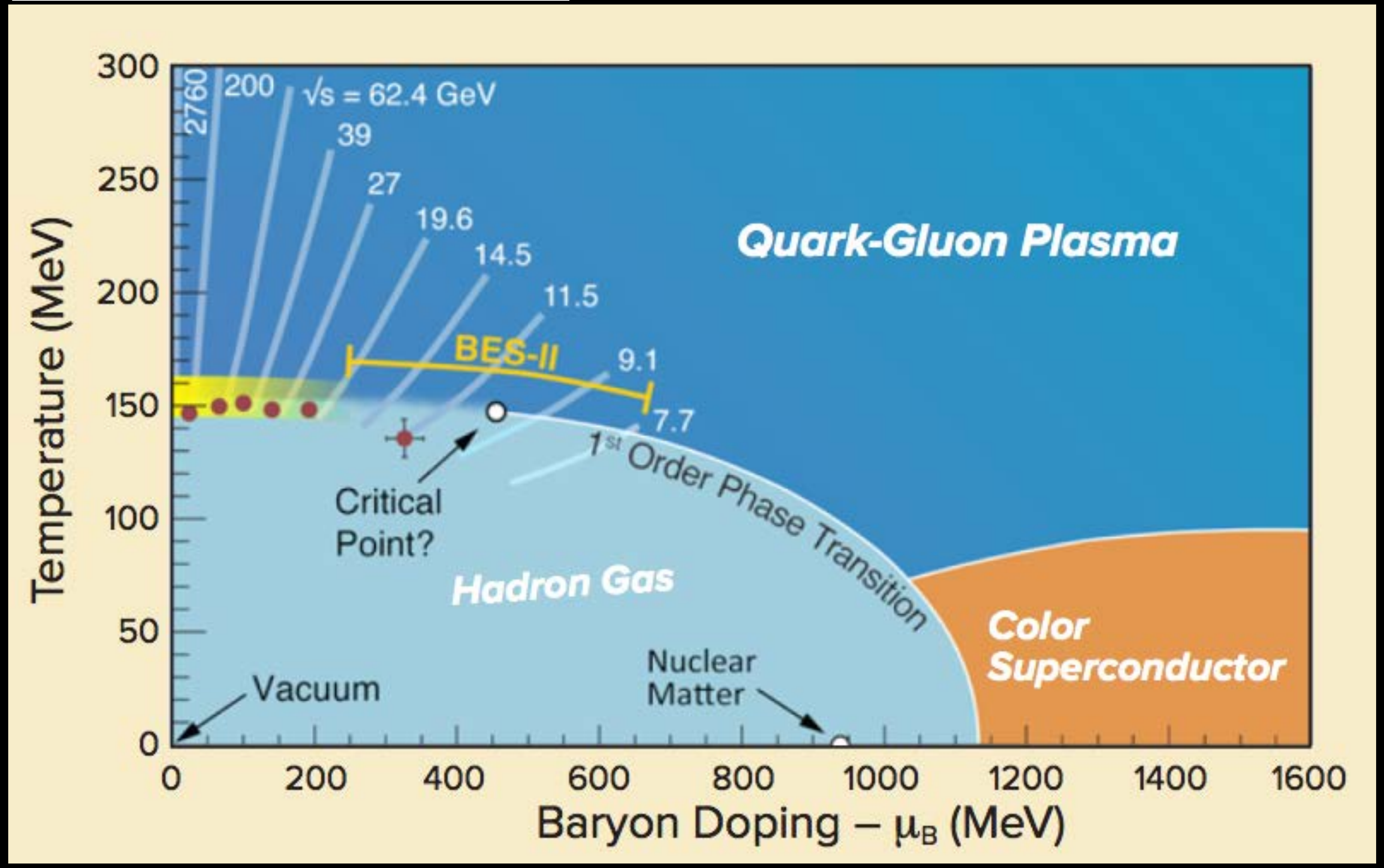


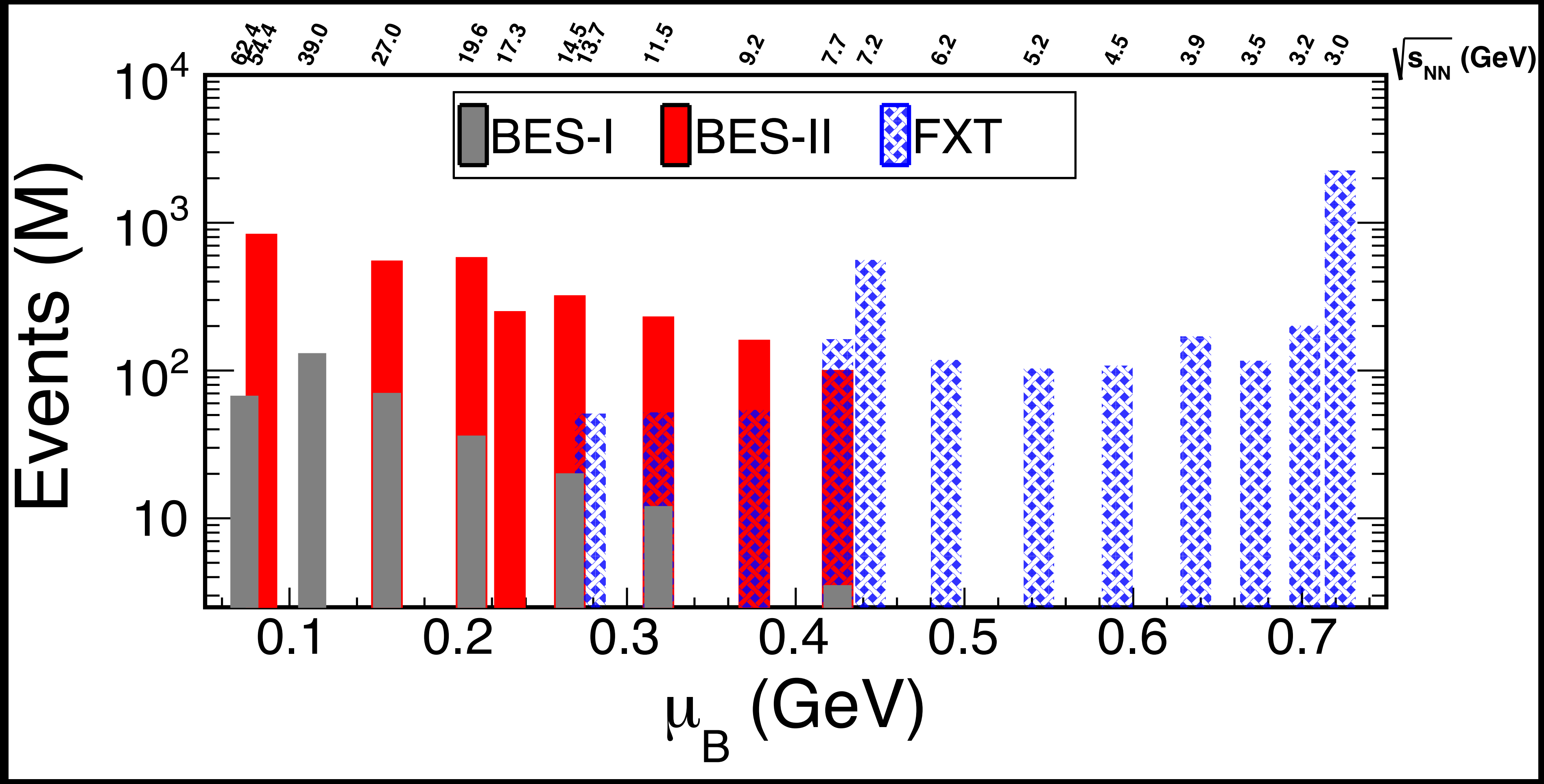
There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art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



STAR BES-II upgrade:

improved tracking, PID & event plane determination capabilities (completed in 2019)





Doping the QGP with baryons & map the region of phase diagram inaccessible to other facilities

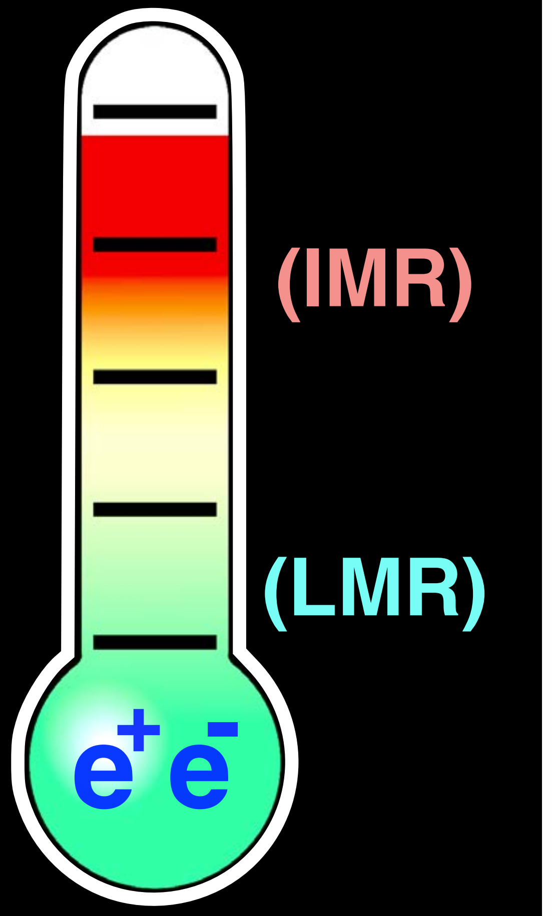
8 collider energies 7.7 - 54 GeV, 12 FXT energies 3.0 - 13.7 GeV (finished in 2021, analysis ongoing)

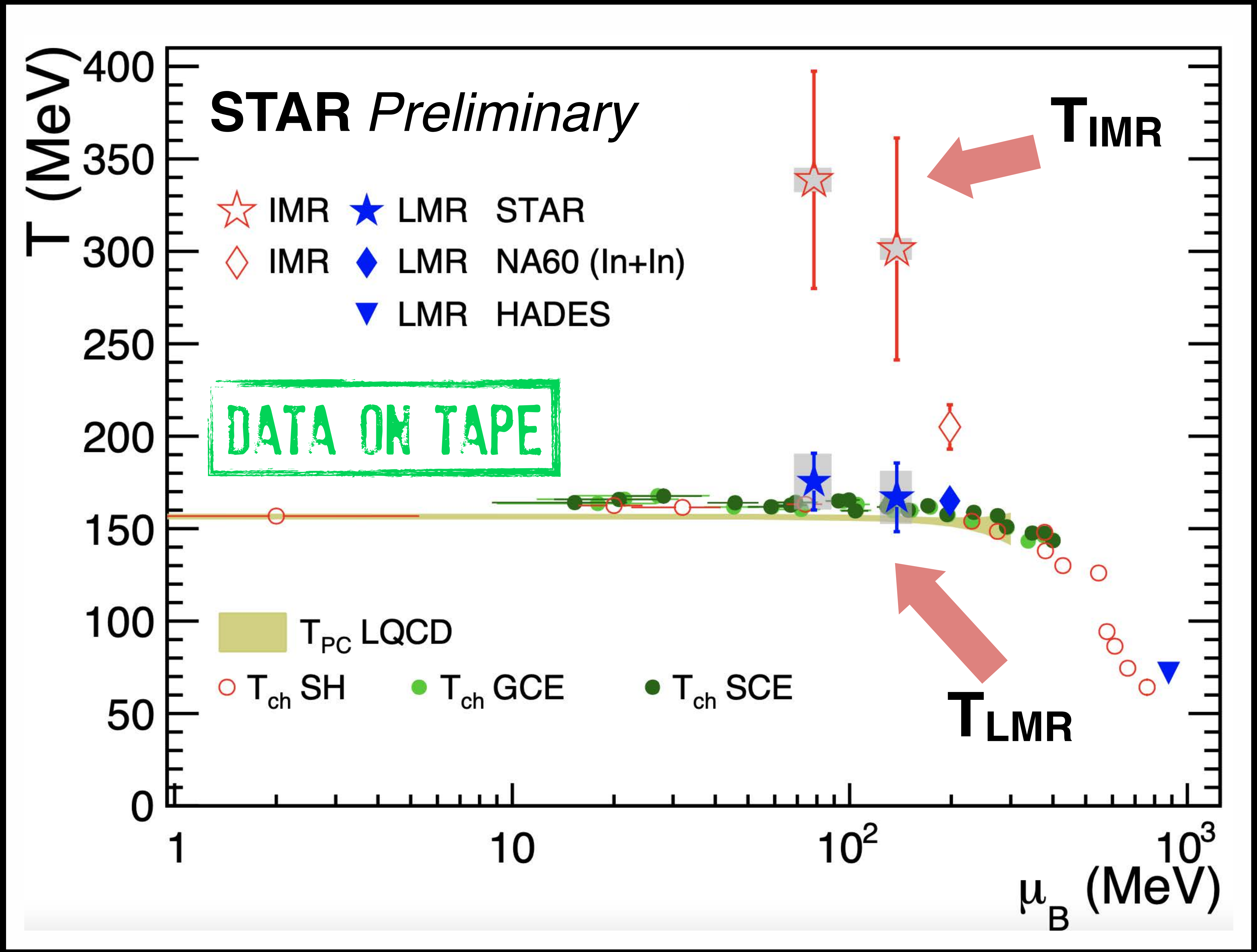
Continued support necessary to complete of the goal envisioned in 2015 NSAC LRP

Medium temperature with di-leptons

Zaochen Ye (STAR Collb.), QM 2022

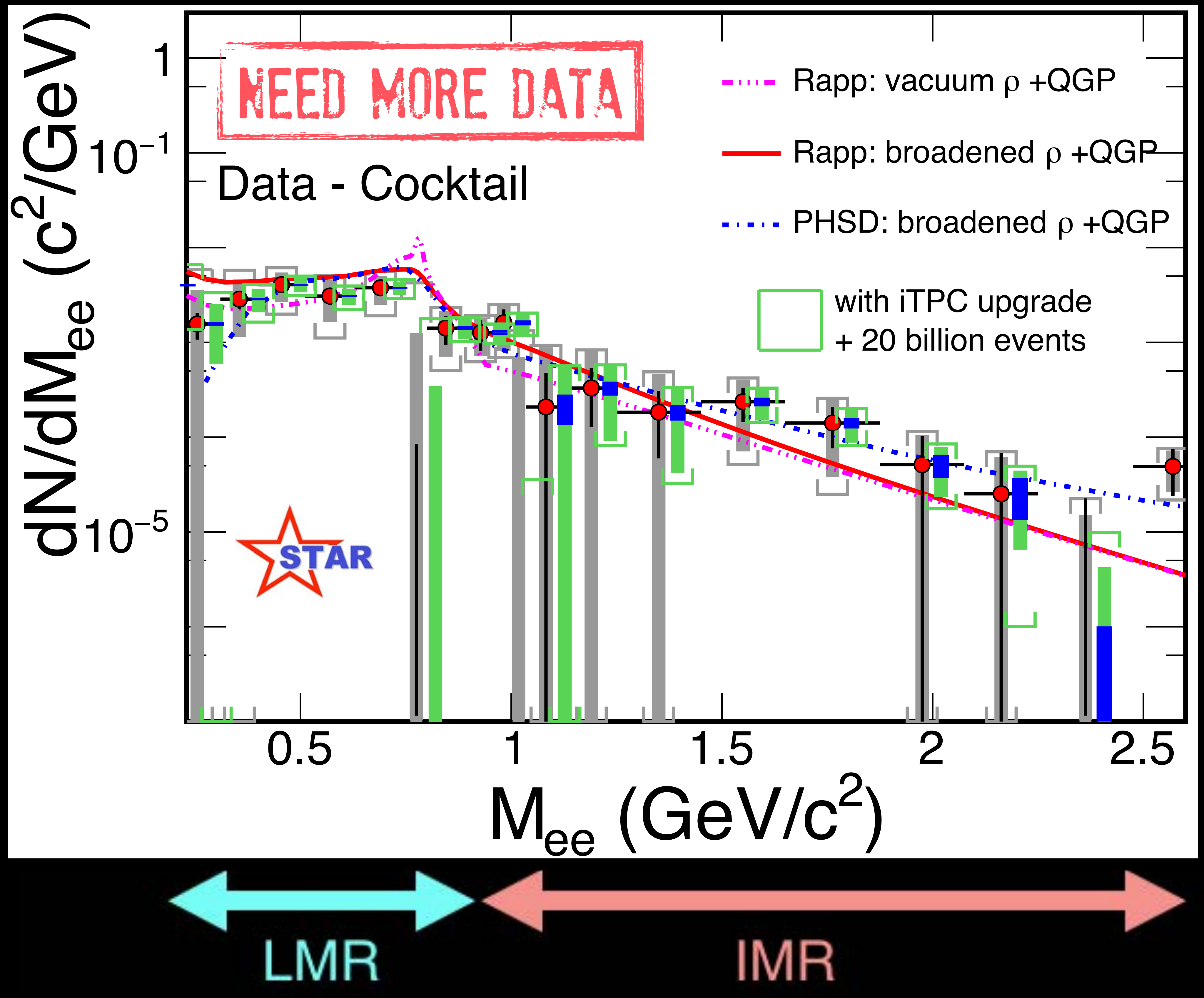
LMR measures temperature near chiral crossover
IMR measures QGP temperature





$T_{LMR} \sim T_{PC,LQCD}$ $T_{IMR} > T_{LMR}$

Di-leptons provide extraction of blue-shift free average temperature of the medium

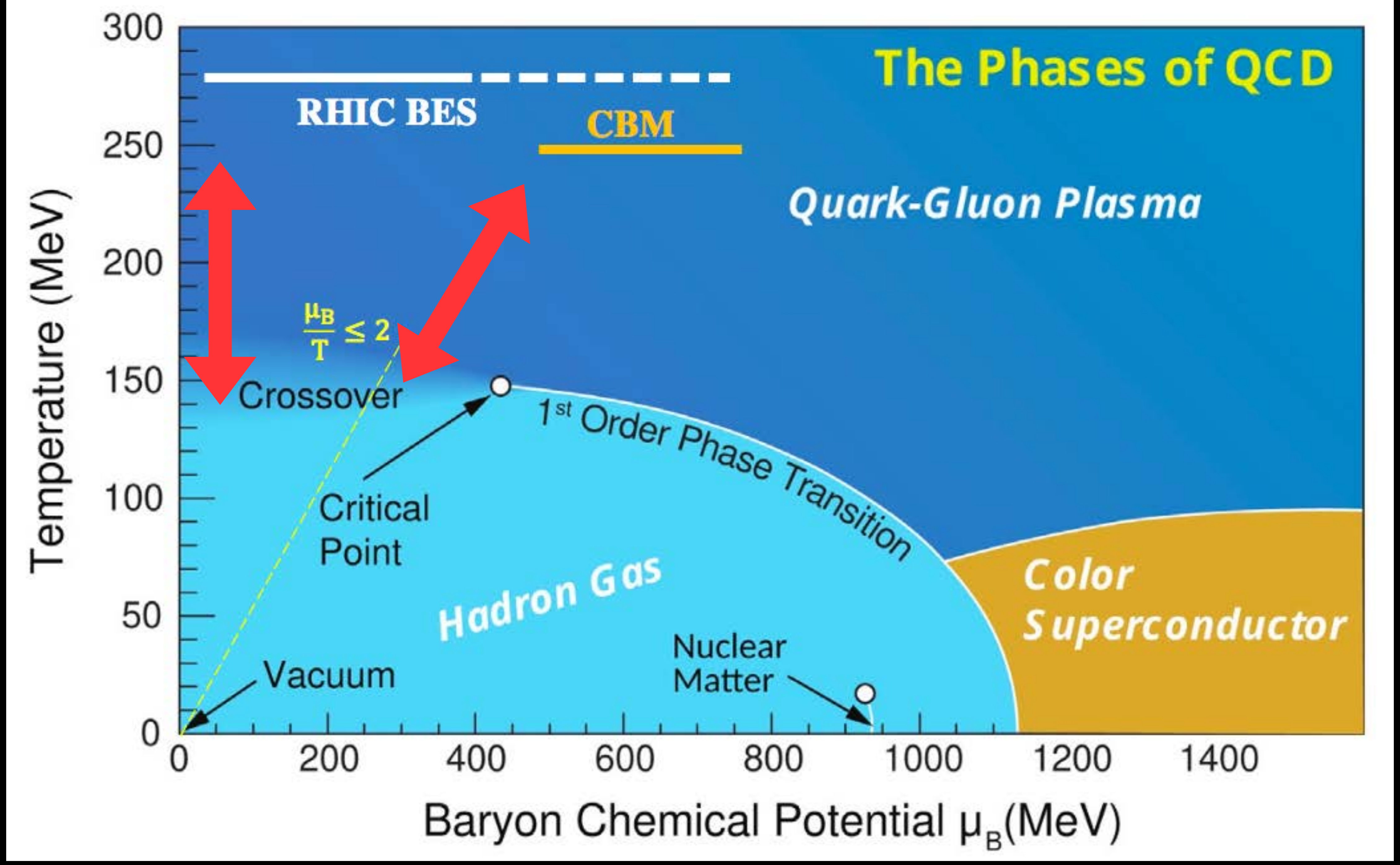


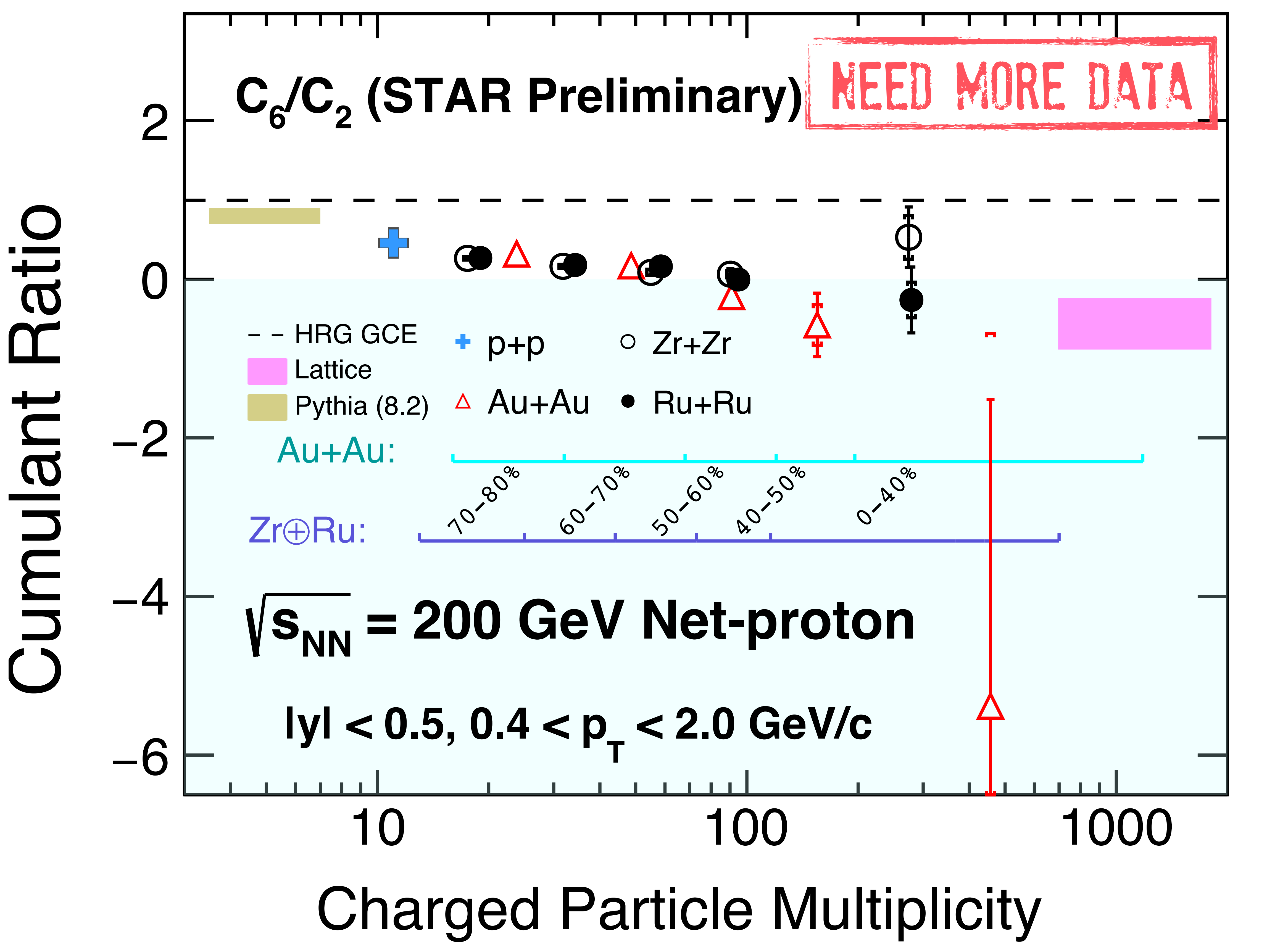
QGP temperature of ~300 MeV at 27 & 54.4 GeV, analysis of more BES-II data is anticipated

Search for the chiral crossover

Ho-San Ko QM 2022
M. Abdallah et al. (STAR Collaboration) Phys. Rev. Lett. 127, 262301 (2021)

Top RHIC energy measurements of the highest order cumulants C_6/C_2, C_5/C_1 provide opportunity for direct comparison with LQCD that predicts a chiral crossover at $\mu_B/T \leq 2$



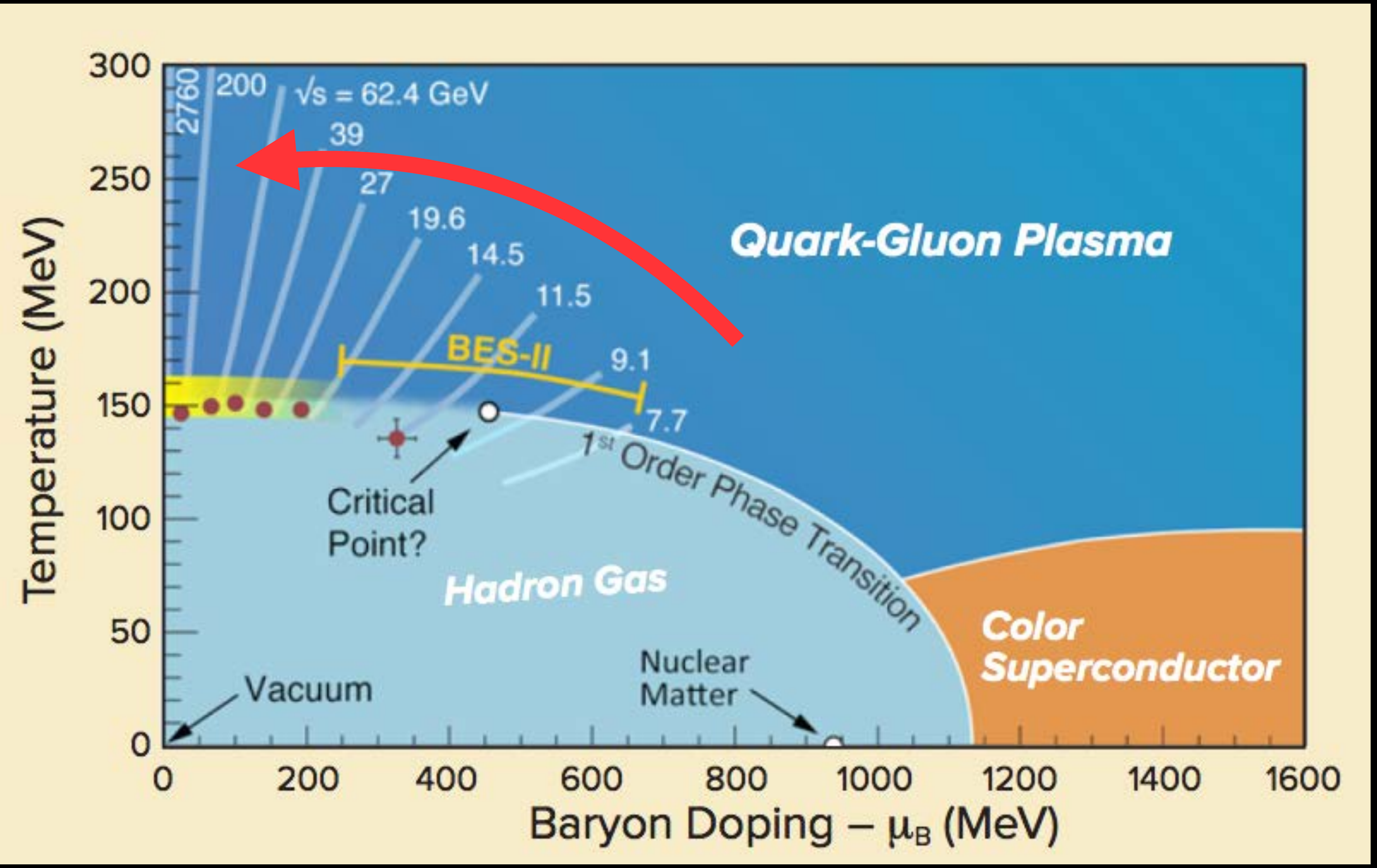


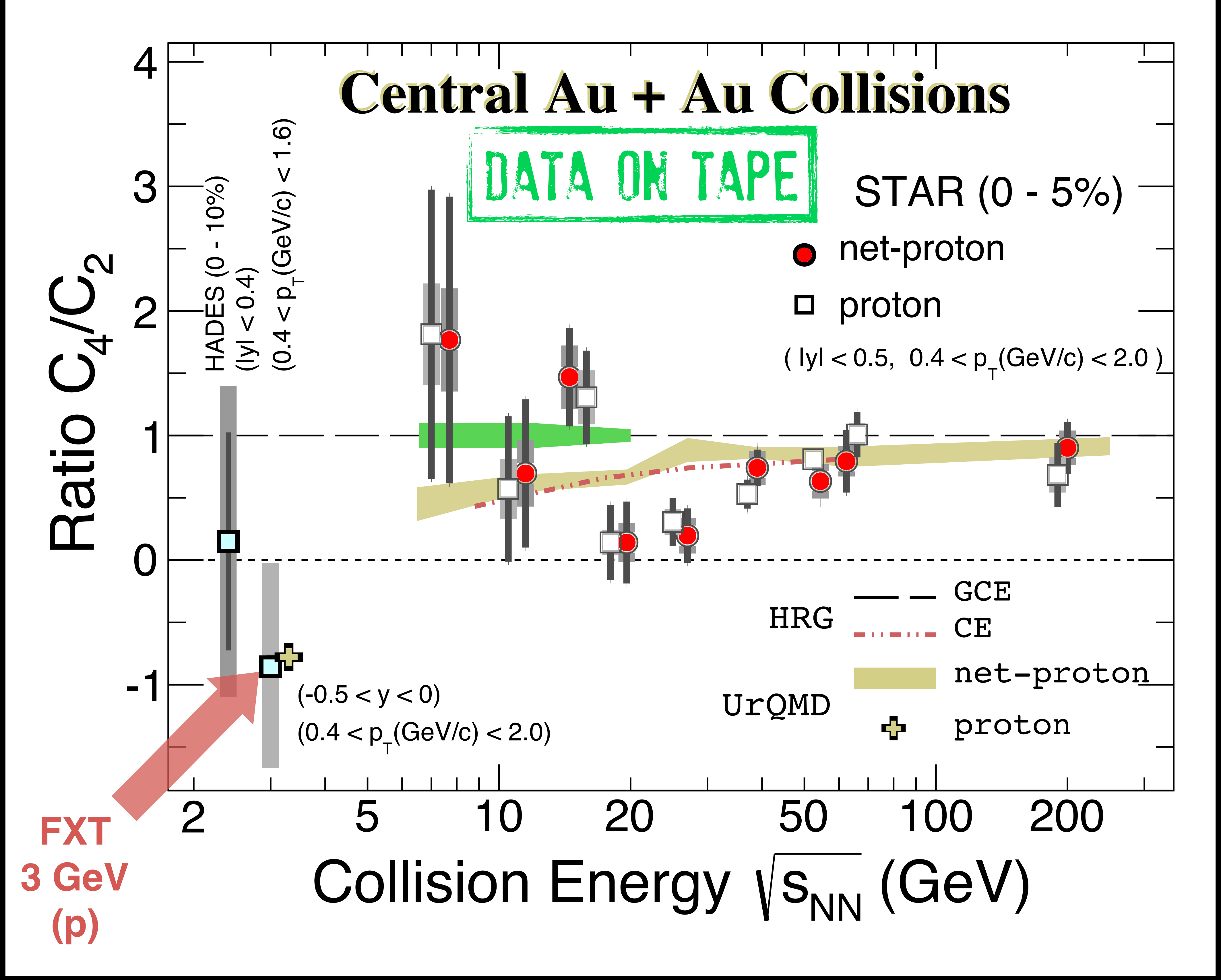
Measurements with p+p, isobar & Au+Au with multiplicity approach LQCD predictions, high statistics Run 2023 + 25 data will provide much improved precision

Search for the QCD critical point

J. Adams et al. (STAR collab.) Phys. Rev. Lett. 126 (2021) 092301
M. Abdallah et al. (STAR collab.) Phys. Rev. Lett. 128, 202303 (2022)

Proton fluctuations ($k\sigma^2 = C_4/C_2$) measured with RHIC BES-I program and Au+Au $\sqrt{s_{NN}}$ = 3 GeV FXT data





Looking for Non-monotonic trend of baryon number fluctuations with energy

Non-monotonic trend with collision energy observed with 3.1σ significance, BES-II data will improve measurement precision

Chiral Properties of the medium

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LONG RANGE PLAN
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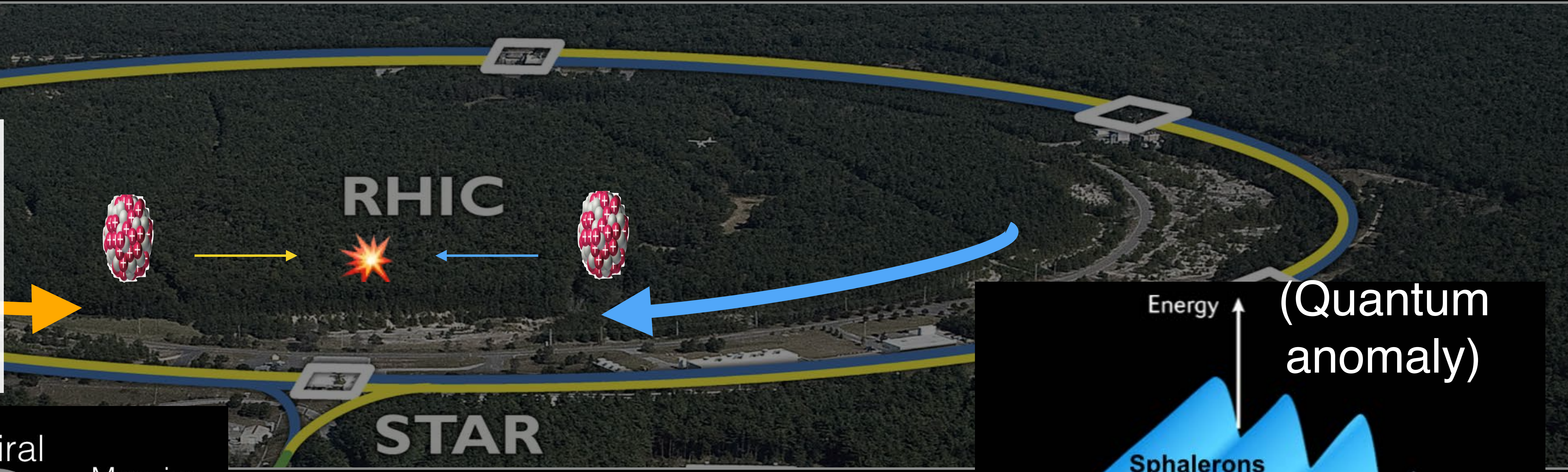
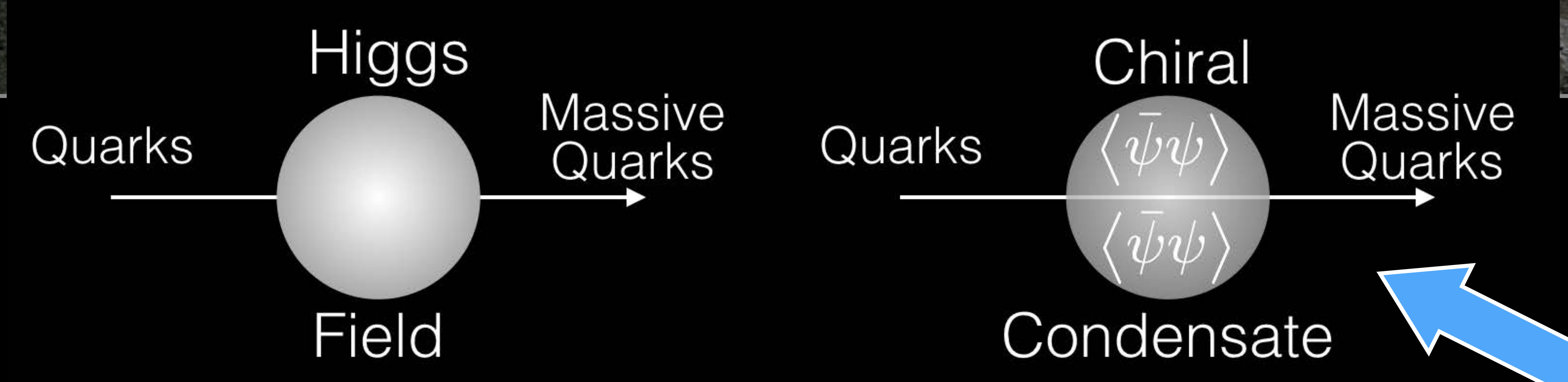
Nuclear physicists have also played a pioneering role in elucidating the anomalous properties of chiral quantum systems. The chiral magnetic effect and the chiral vortical effect, which were first identified as dynamical properties of quark-gluon plasma, are particularly interesting because they can be understood as local violations of fundamental symmetries of space-time.

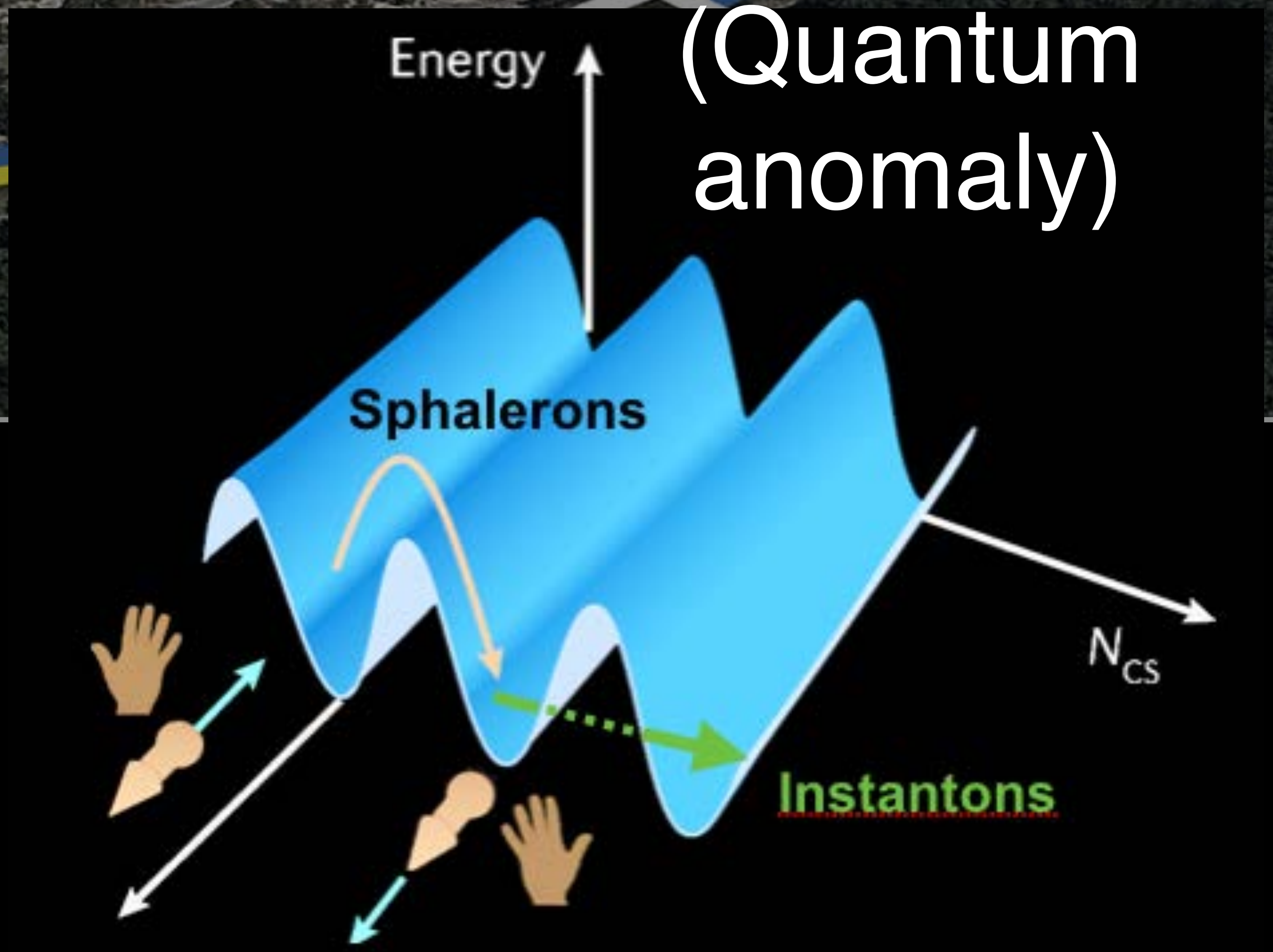




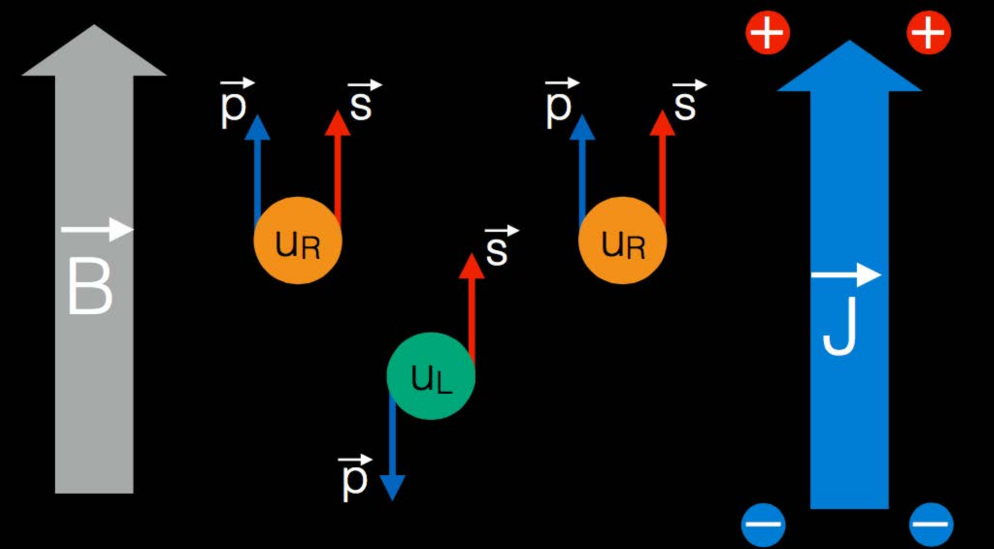
OFF

Turn this OFF

(Quantum anomaly)



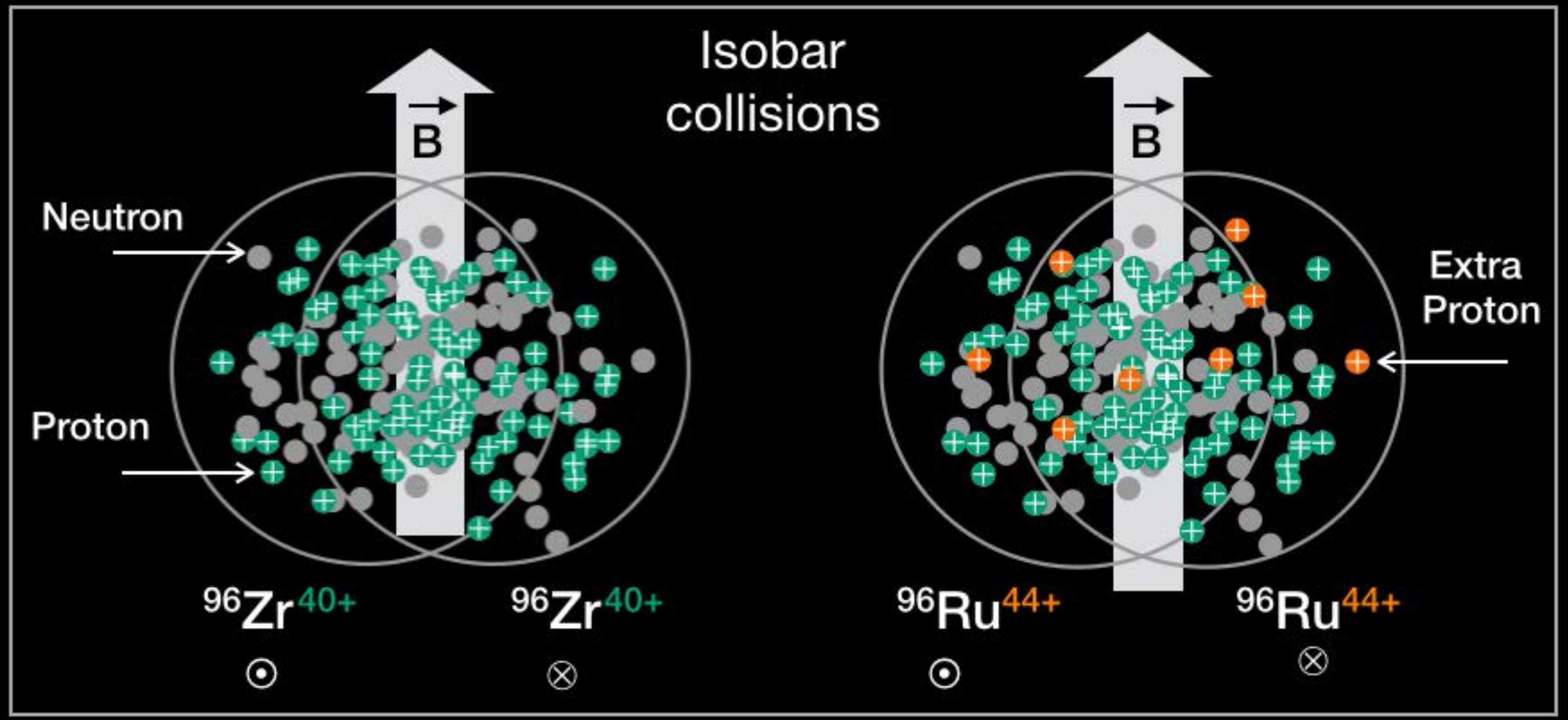
$$\mathcal{L}_{QCD} = \bar{\psi}_a \left(i(\gamma^\mu D_\mu)_{ab}\right) \psi_b - \cancel{m\delta_{ab}\bar{\psi}_a\psi_b} - \frac{1}{4} G^c_{\mu\nu} G^{\mu\nu}_c \boxed{- \frac{\theta}{32\pi^2} g^2 F^{\mu\nu}_\alpha \tilde{F}_{\alpha\mu\nu} = -\frac{\theta}{8\pi^2} g^2 \vec{E}_\alpha . \vec{B}_\alpha}$$



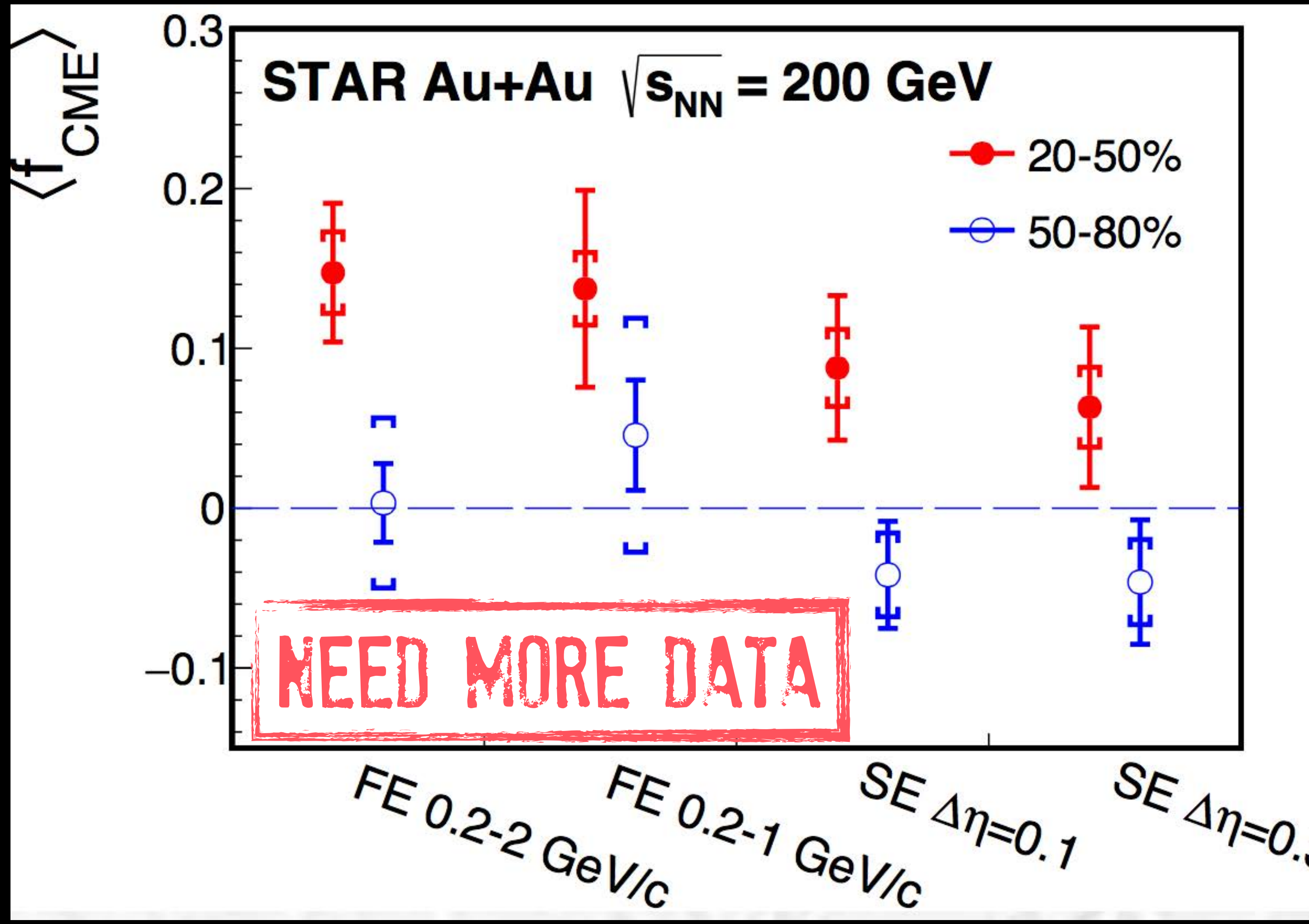
Chiral symmetry restoration ⟶ Chiral fermions
$U_A(1)$ symmetry breaking ⟶ Chirality imbalance
Strong B-field + Chirality imbalance ⟶ Chiral Magnetic Effect

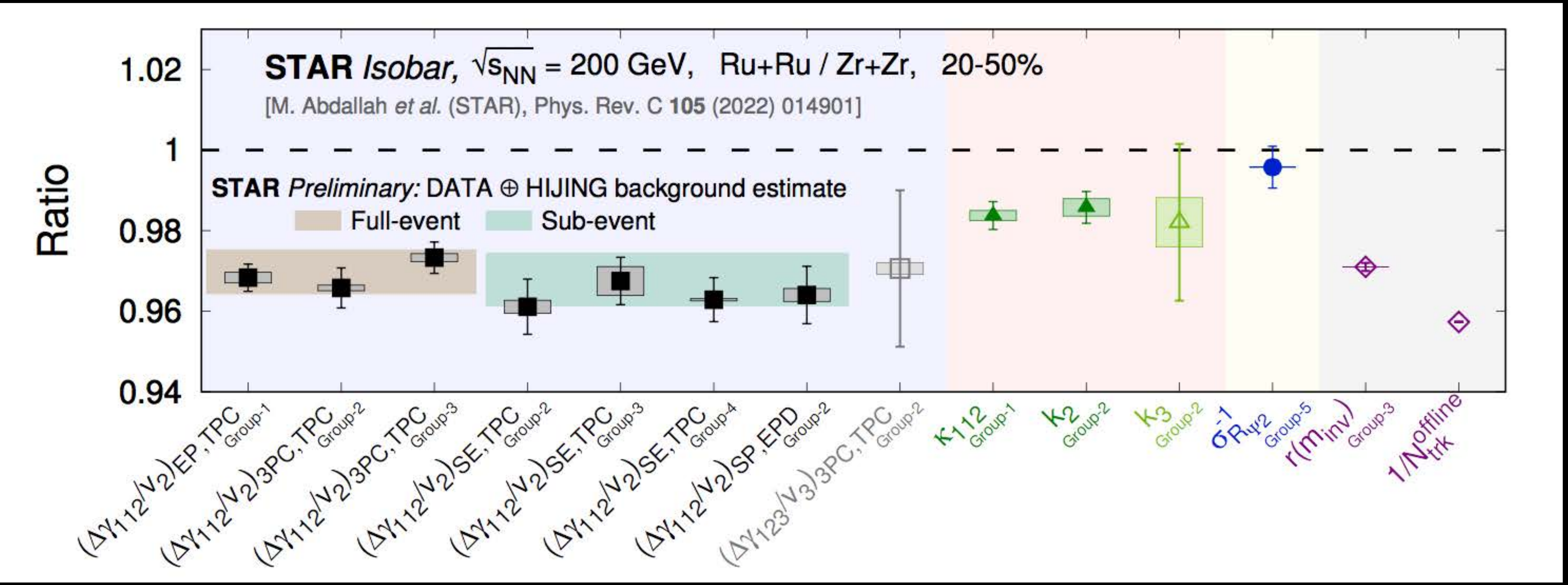
Search for the Chiral Magnetic Effect

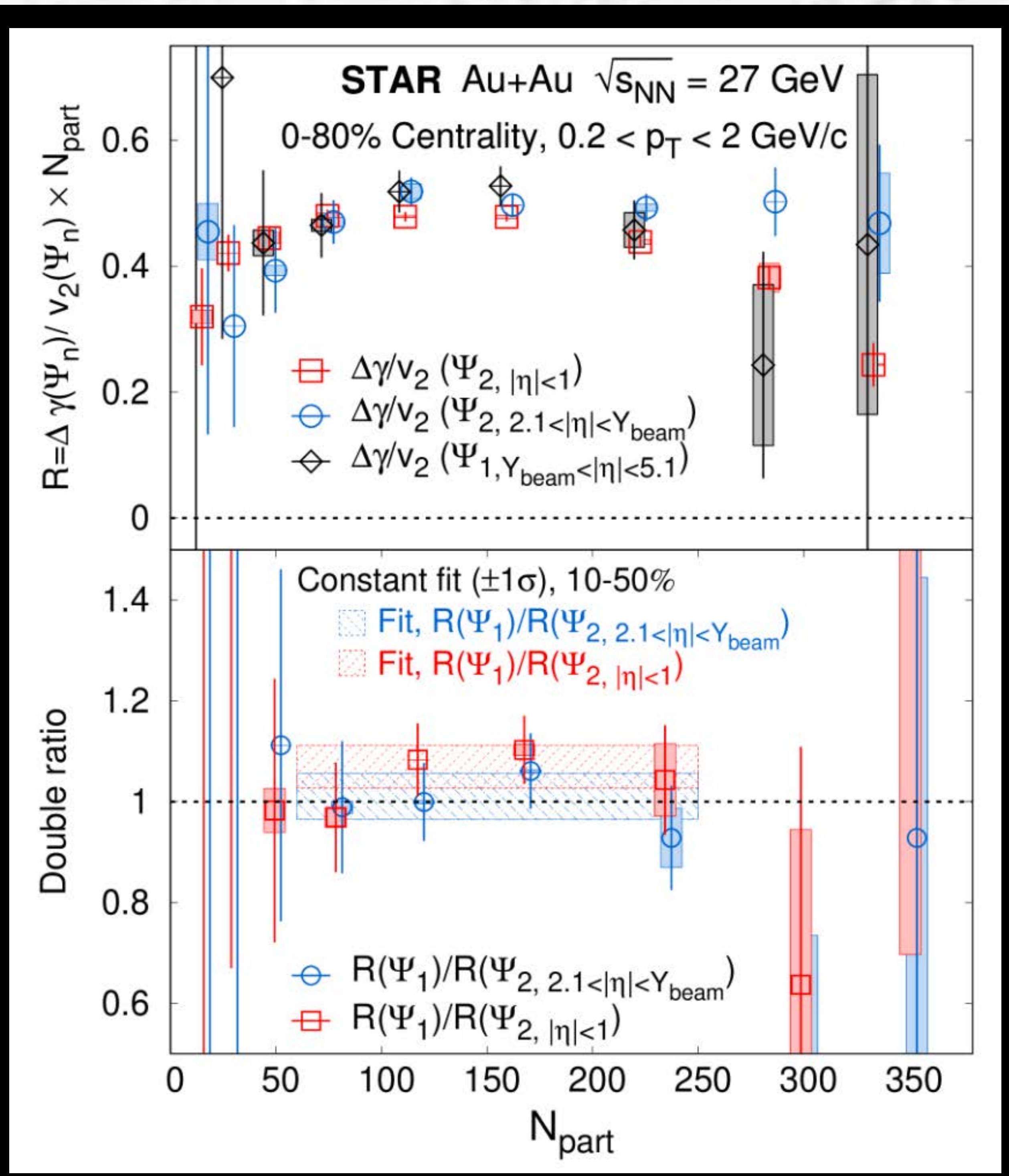
M. Abdallah et al. (STAR Collab), Phys. Rev. C 105 (2022) 1, 014901, Phys.Rev.Lett. 128 (2022) 9, 092301, STAR Collab. arXiv:2209.03467



No pre-defined signatures observed in isobar blind analysis. Unique opportunities with Run 23+25 & BES-II data







CME search has been narrowed down with precision measurements and novel techniques

Vortical fluid & new probes of hydro paradigm

Joey Adams, Kosuke Okubo QM 2022
STAR Collab. Phys. Rev. Lett. 123, 132301 (2019)
Phys. Rev. Lett. 126, 162301 (2021)

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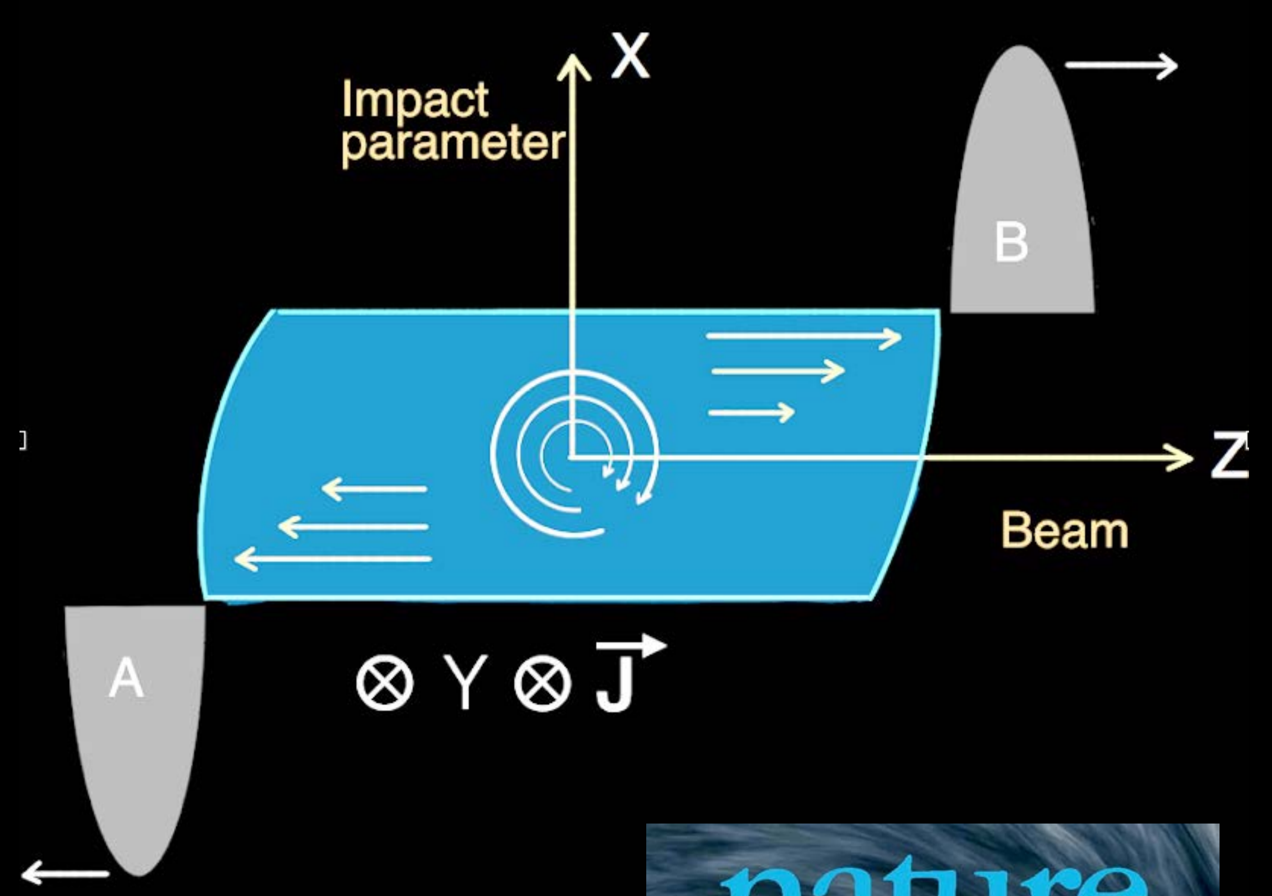
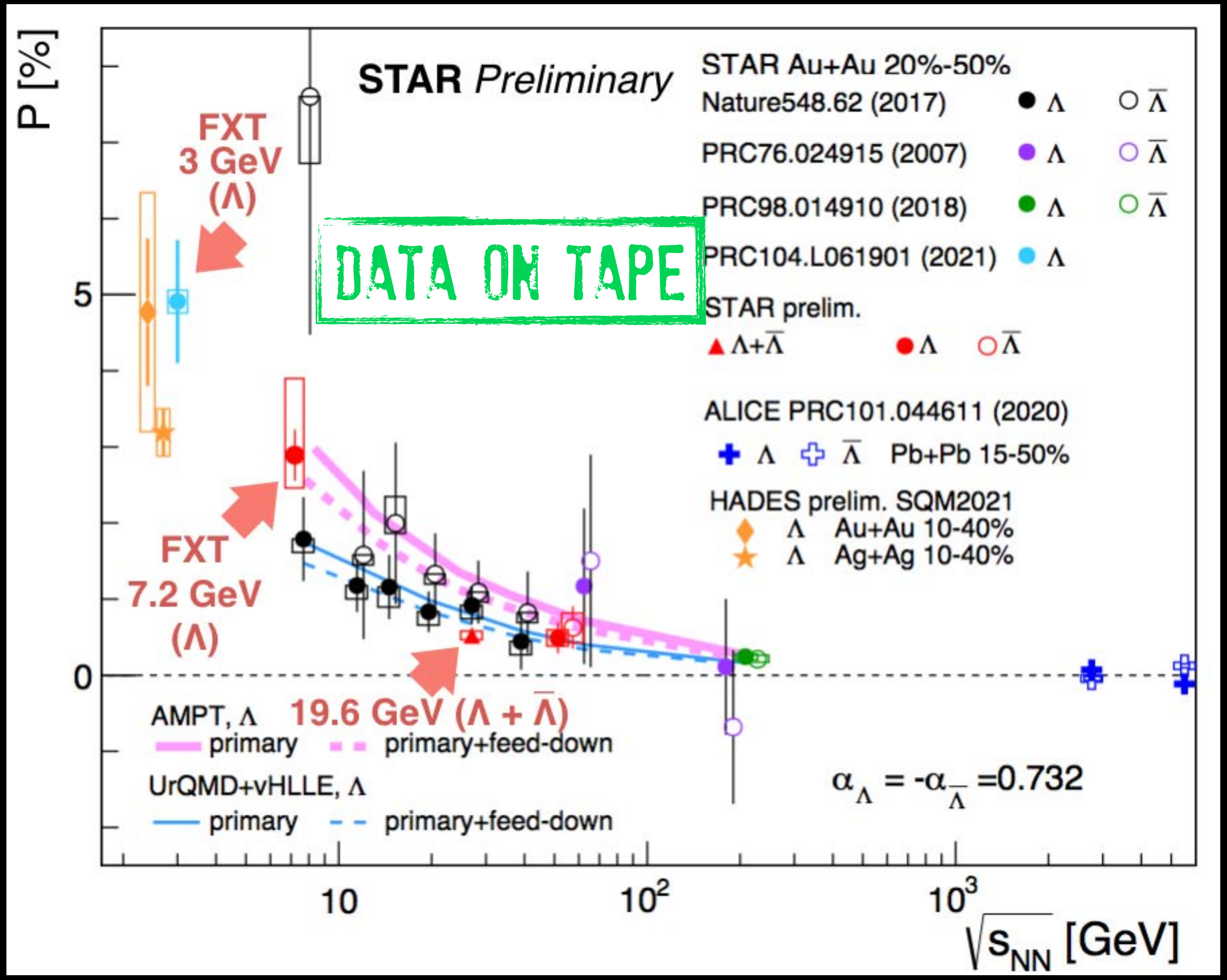
From Characterization to Understanding
The field has made substantial strides in the experimental characterization of liquid QGP, and new measurements and new discoveries are anticipated in the coming few years. Pursuing these directions will

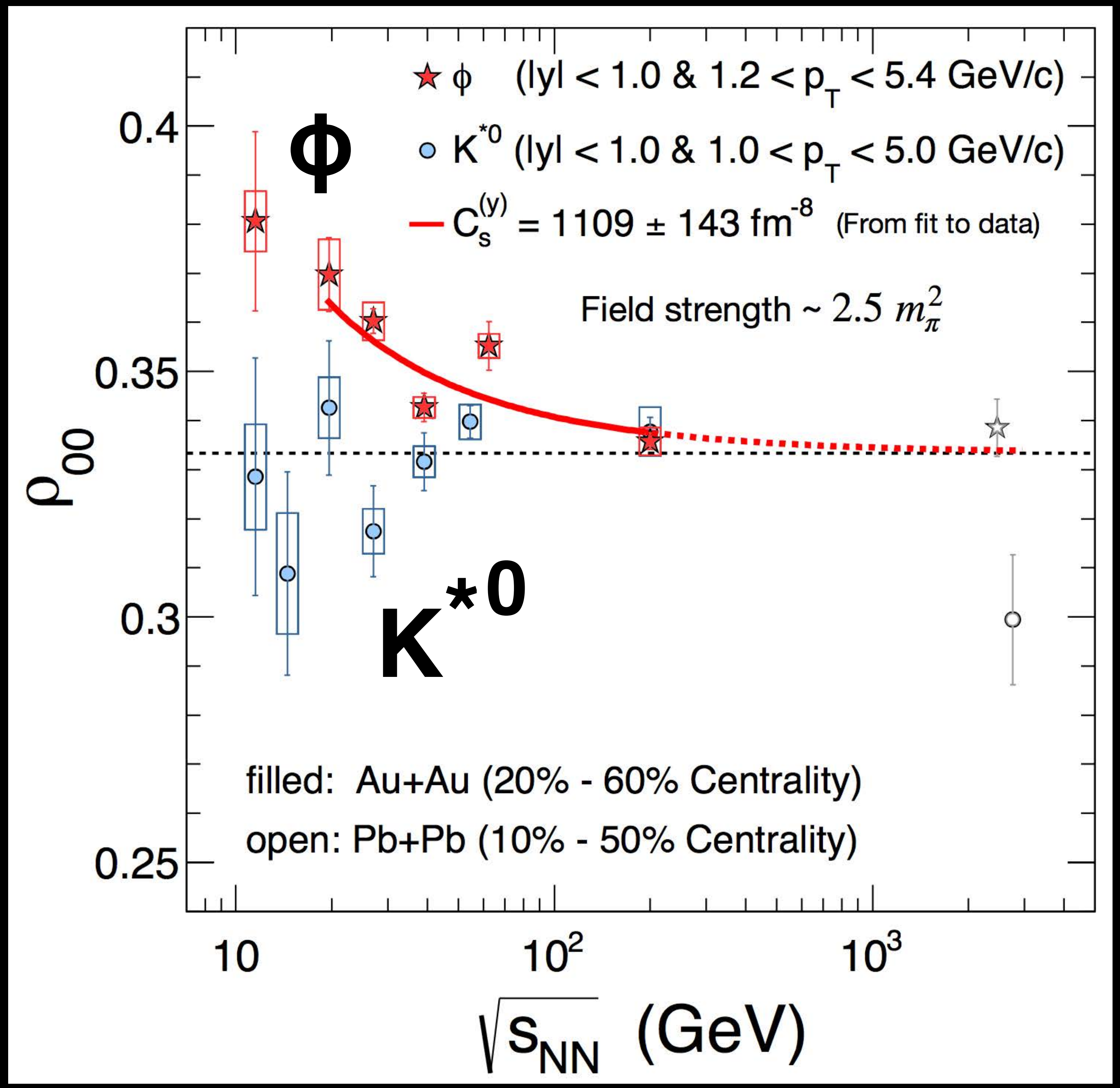
Global & local polarization of hyperons
⟶ access to gradient of fluid velocity

STAR Collab., Nature 548 (2017) 62-65
STAR Collab, Phys. Rev. C 104 (2021) L061901

M. Abdallah et al (STAR Collaboration), arXiv: 2204.02302







Observation hyperons polarization led to the discovery of vorticity in QGP opened up a new field

3D initial state with STAR forward upgrade

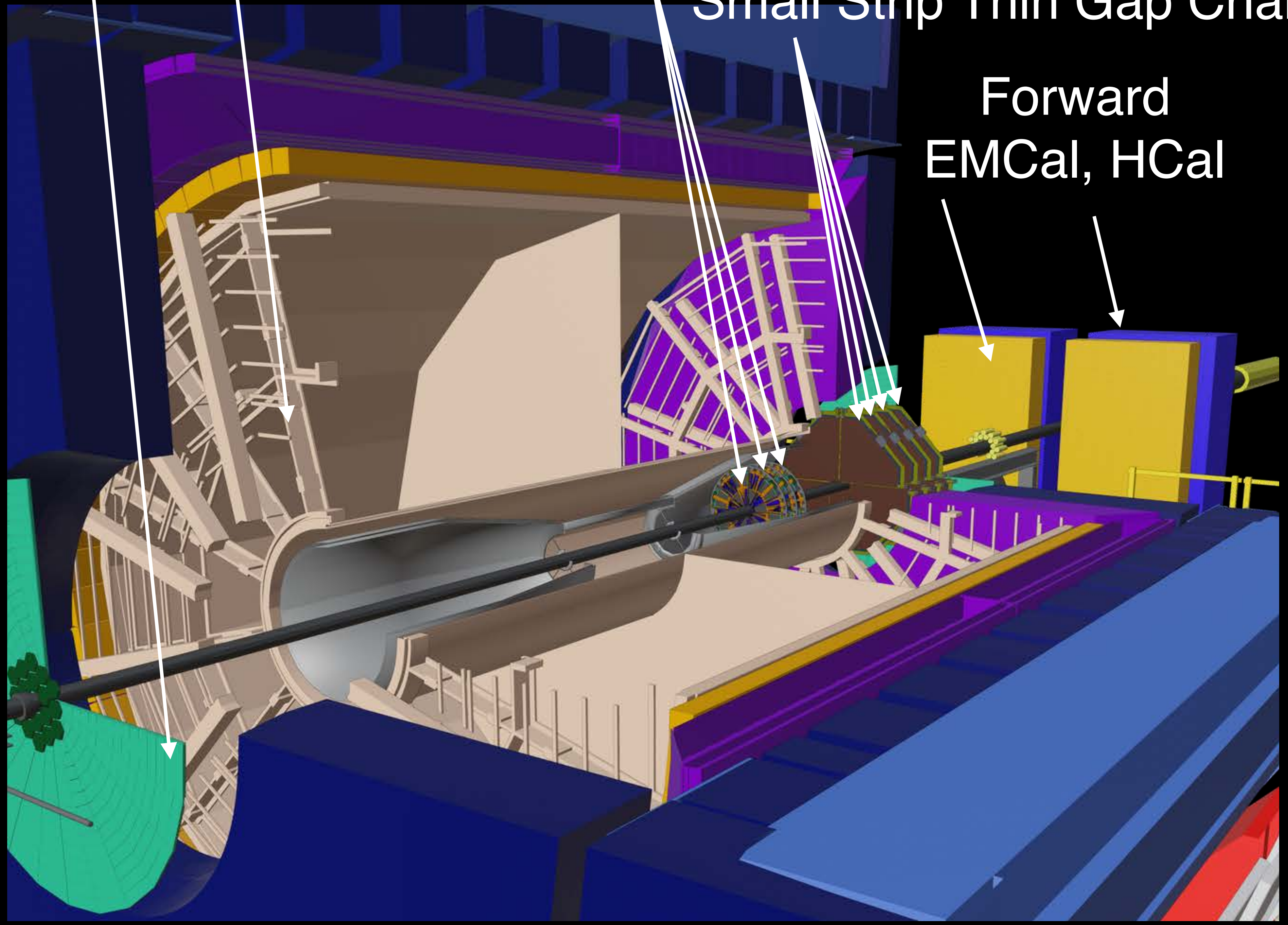
Event Plane Detectors

Inner Time Projection Chamber

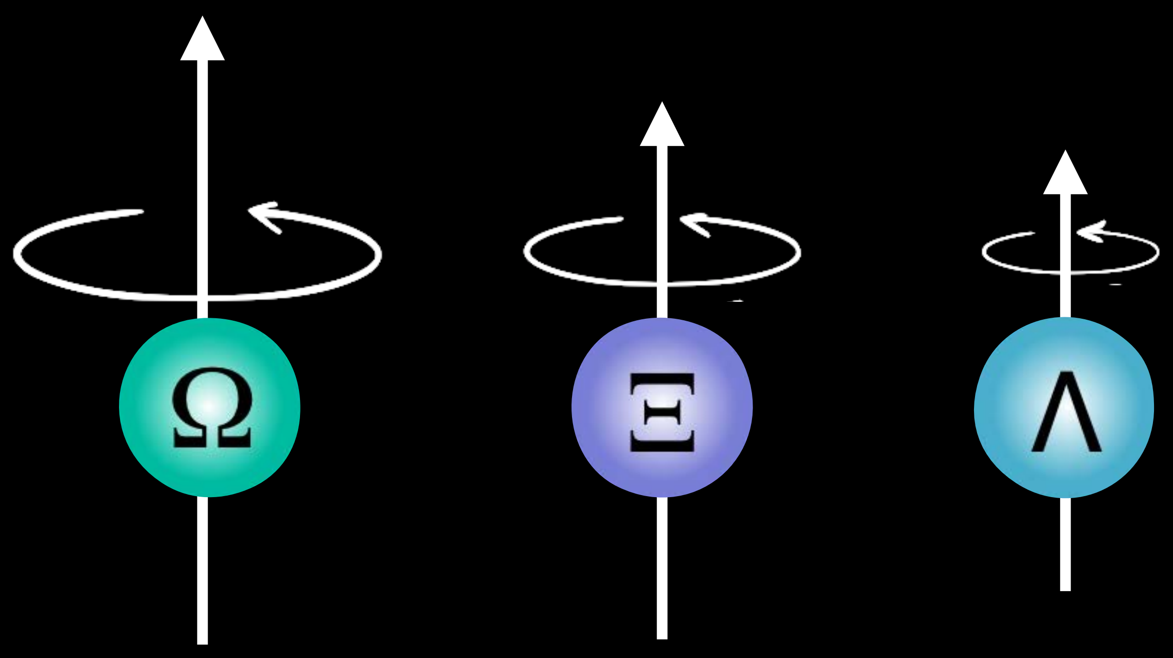
Forward Silicon Tracker

Small Strip Thin Gap Chamber

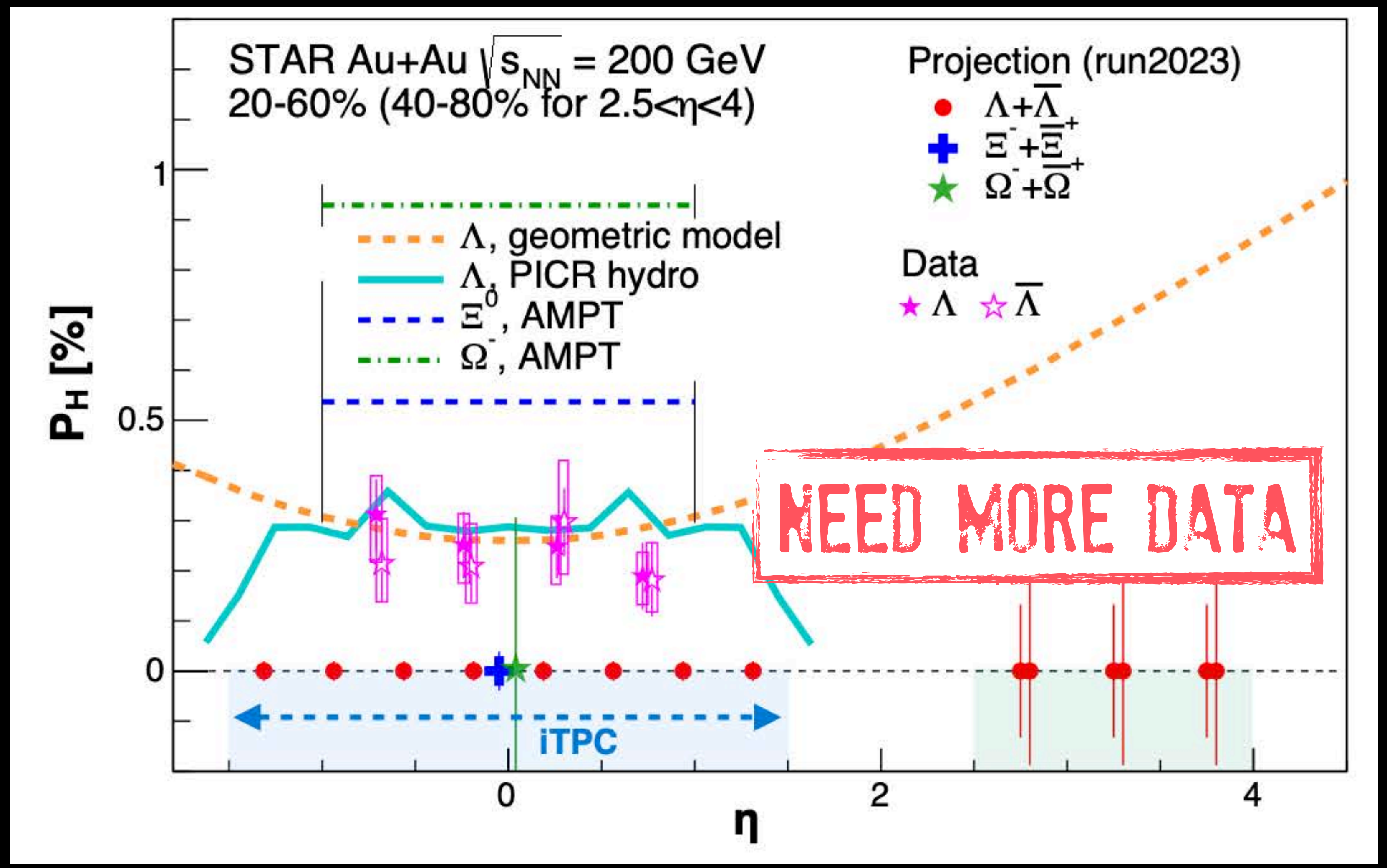
Forward
EMCal, HCal

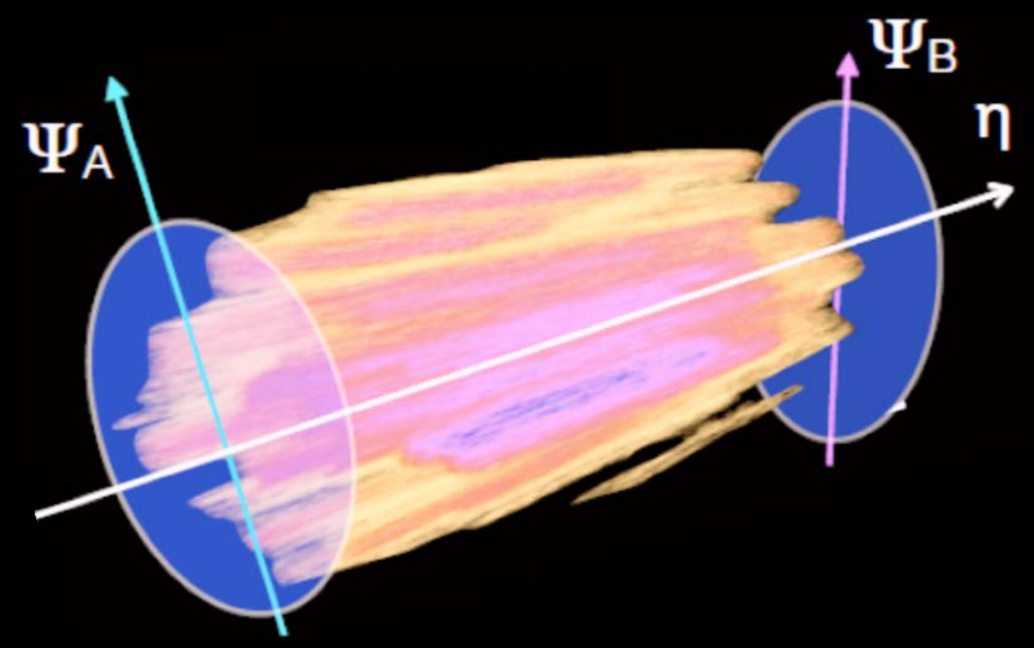


(Spacetime profile of vorticity)
Global polarization of
hyperons with rapidity

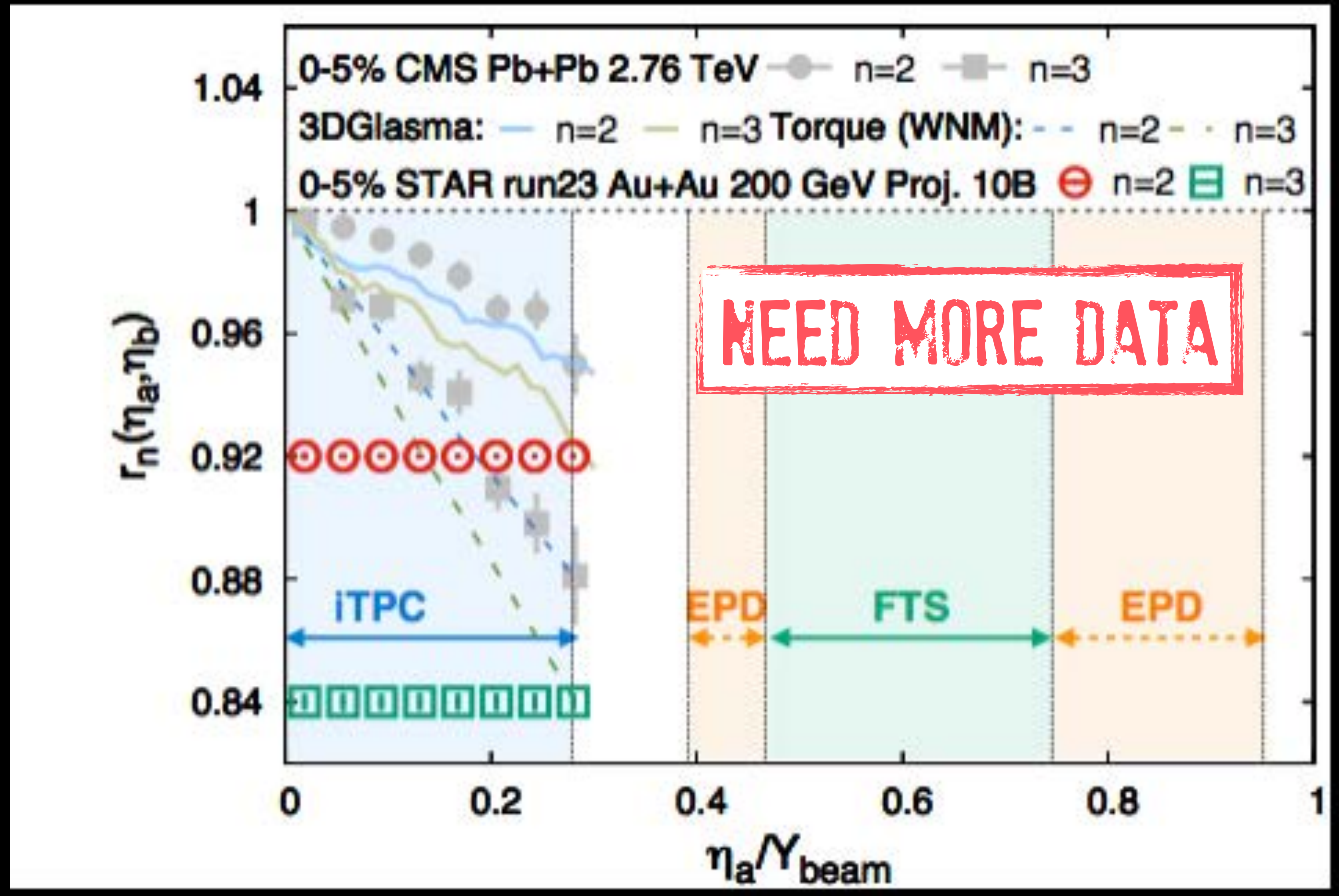


Chronometers





Longitudinal de-correlation
(3D initial state)



Unique opportunity to study initial state with extended pseudorapidity & improved PID capabilities

Topics that bridge RHIC and EIC science

- Collectivity in small system
- Imaging nuclei in the pre-EIC era
- Microscopic structure of the baryons

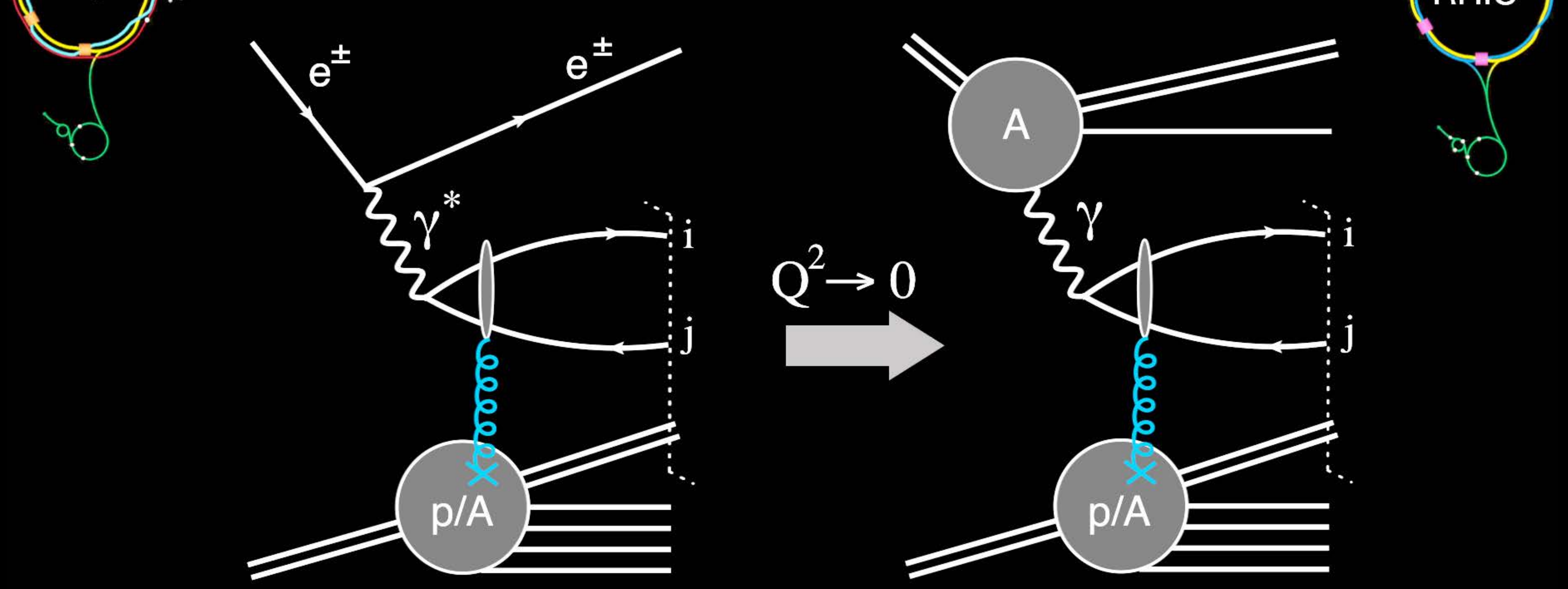
Physics topics that bridge RHIC and EIC science

STAR Collab., Phys.Rev.Lett. 129 (2022) 092501
The STAR BUR for Run 23-25

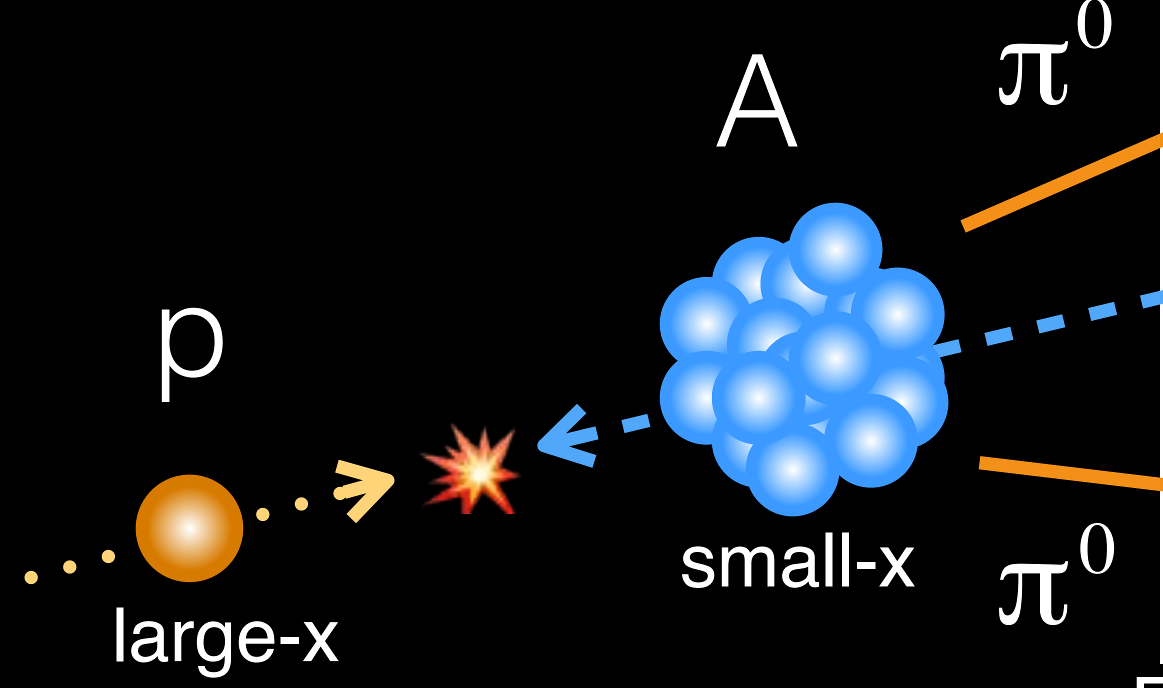
Talk by Xiaoxuan Chu (Fri), Kong Tu (Sat), Spencer Klein (Sat)

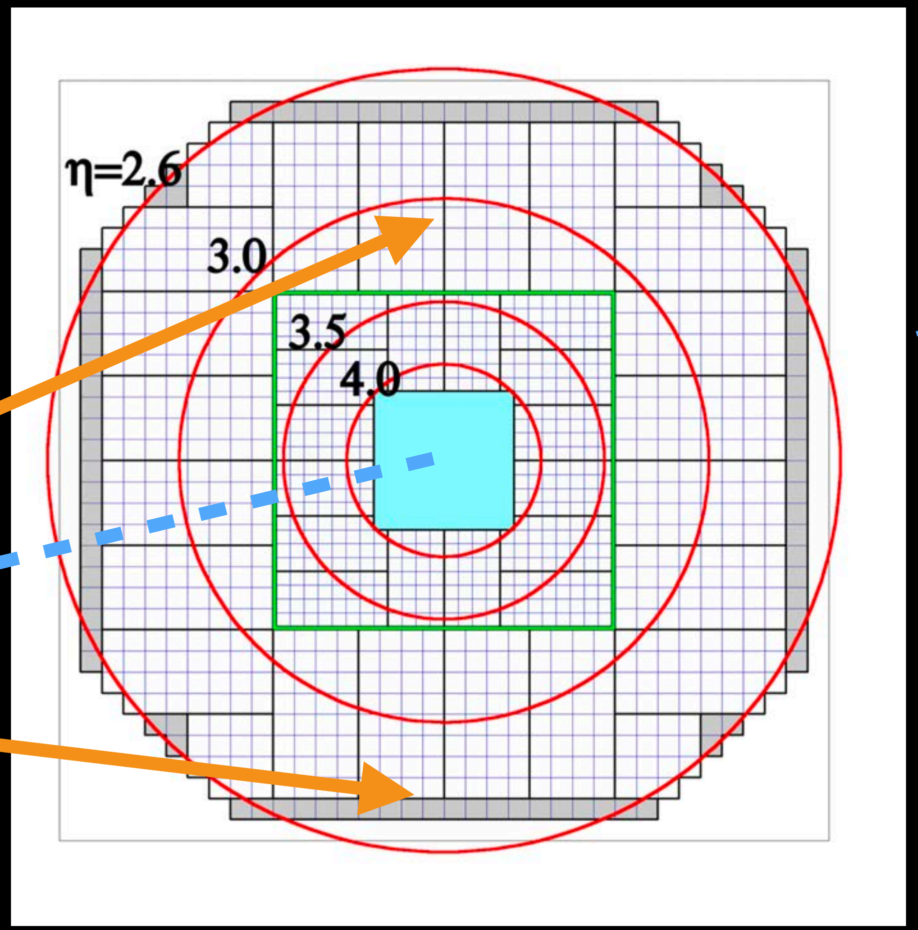
Inclusive DIS at HERA/EIC

Inclusive UPC at the LHC/RHIC

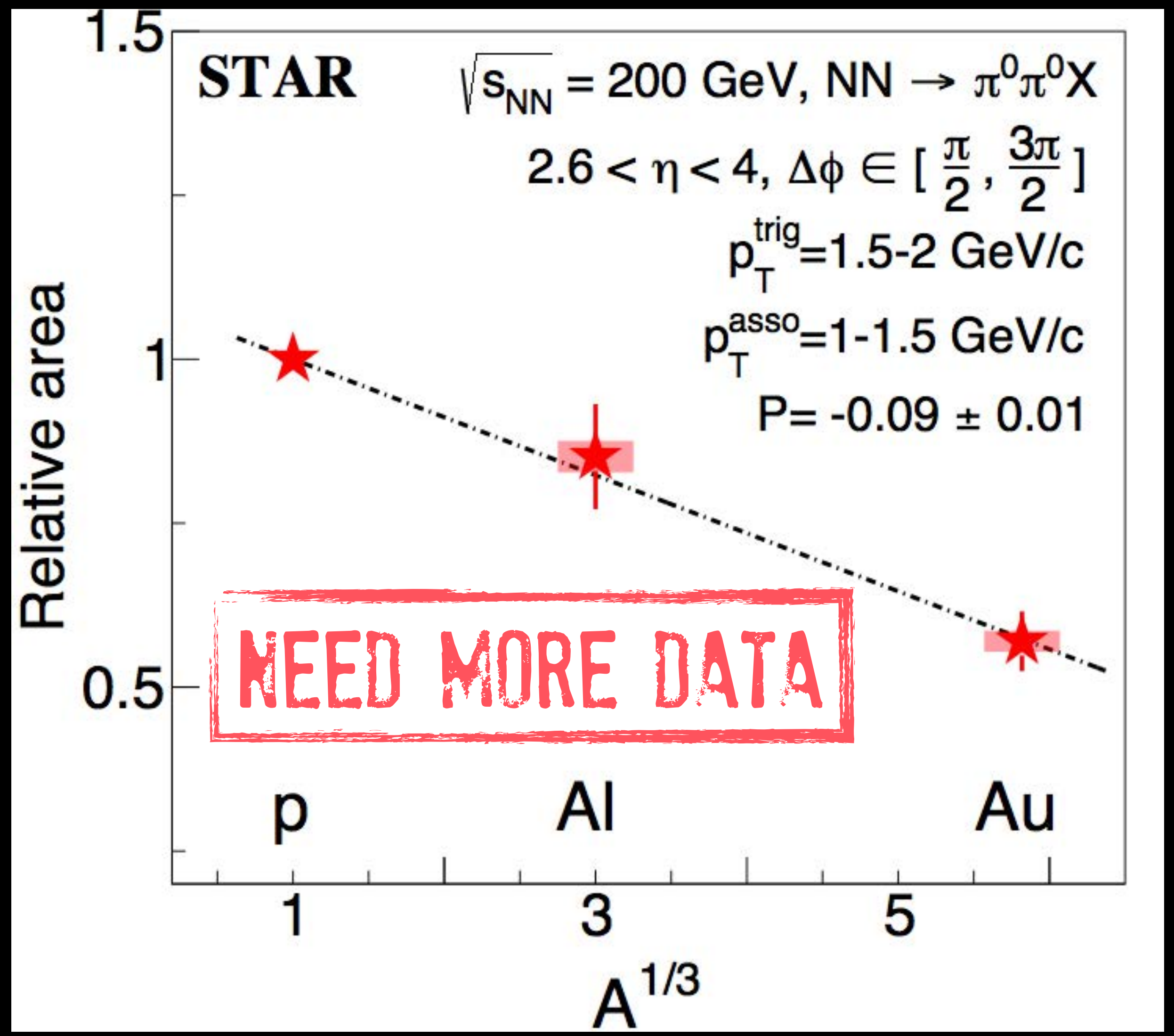


Search for gluon saturation





Forward Meson Spectrometer



$$C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \Delta\phi}$$

Area of C(Δφ) :
p+p > p+Al > p+Au

Until the EIC is built, ultra-peripheral p/A+A collisions
→ opportunity to study photoproduction (γ+p/A)

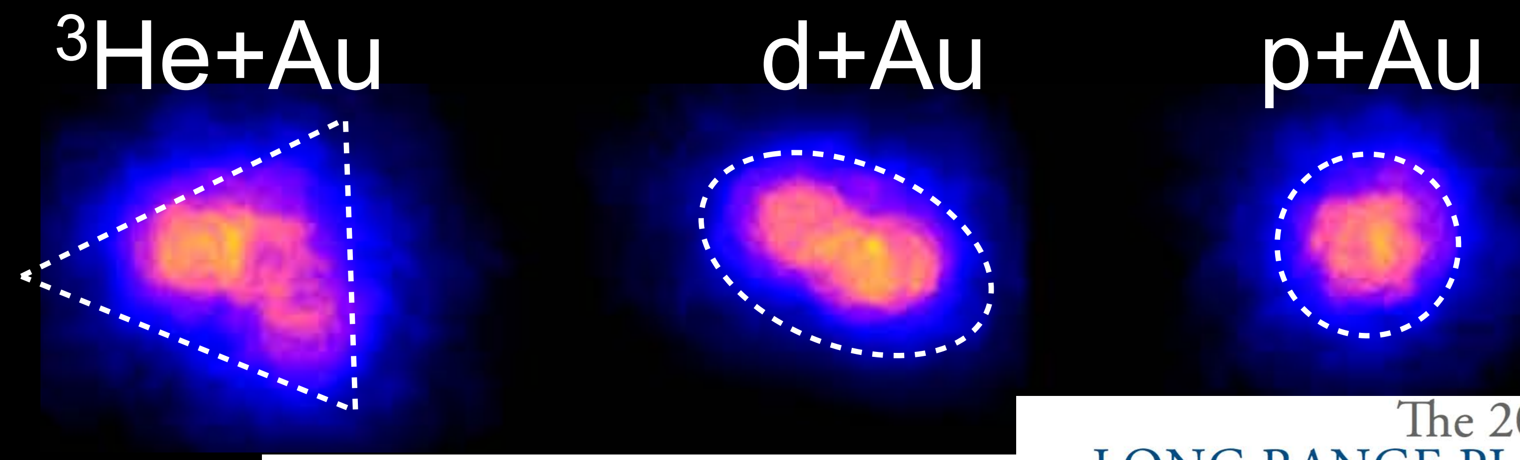
Similar target ion energy as EIC, flexibility of ions species, a natural continuation of RHIC system scan

Opportunity with p+Au Run 24 & STAR forward upgrade

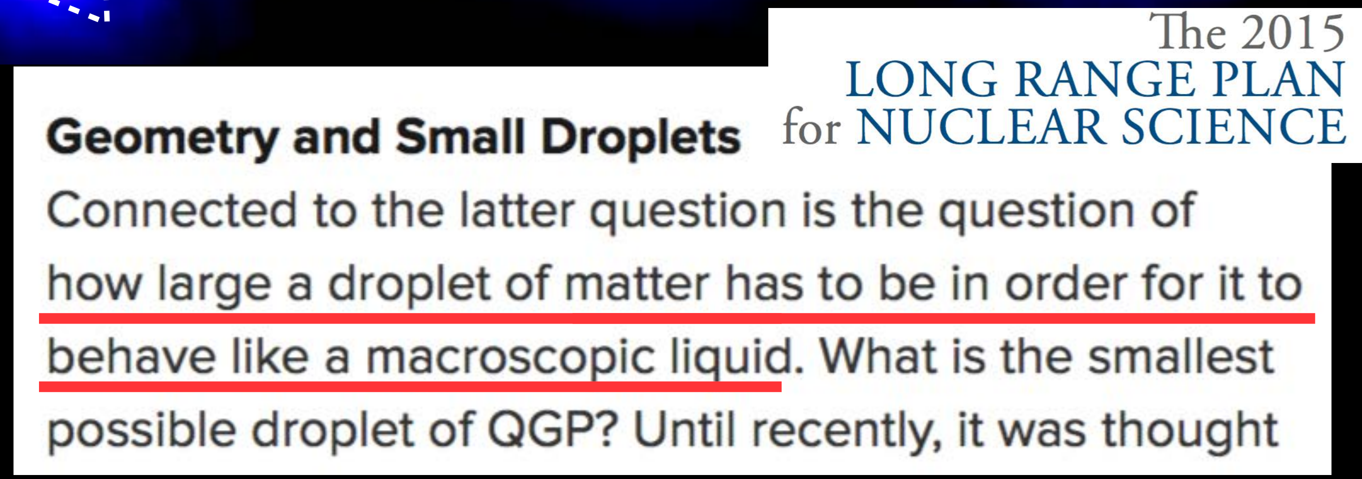
Support beyond RHIC operation to train a generation of experimentalists in preparation for the EIC

Origin of collectivity in small systems

Nagle et. al., Phys. Rev. Lett. 113, 112301



Crucial insight from RHIC measurements nearly a decade after the discovery in LHC p+p collisions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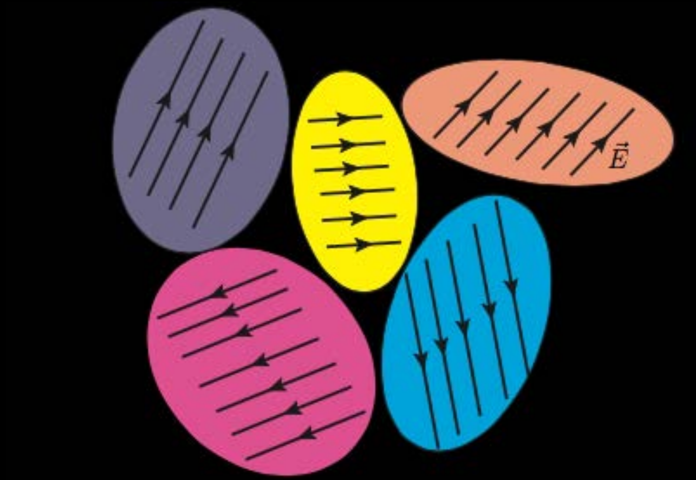
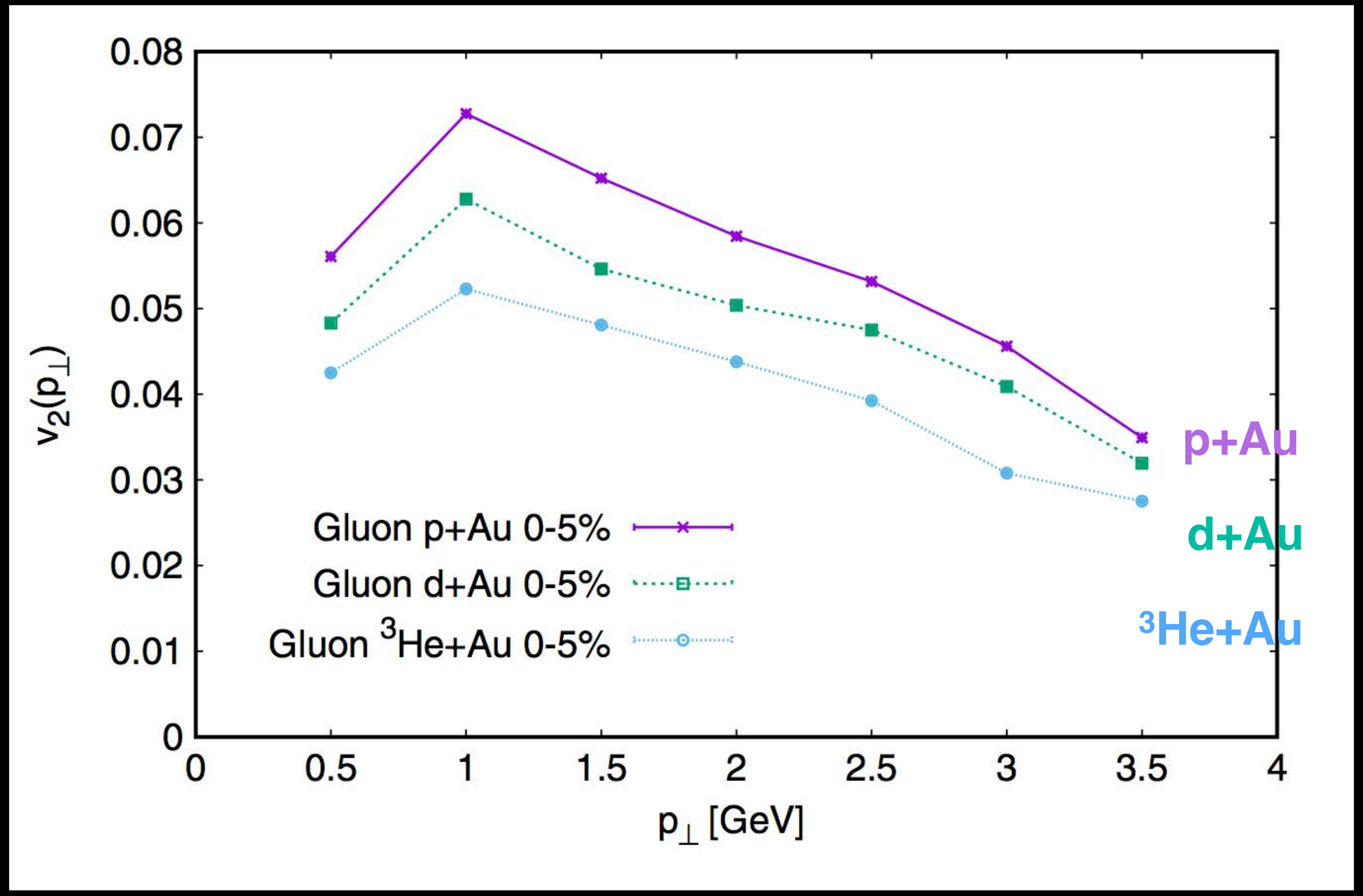
Geometry and Small Droplets

Connected to the latter question is the question of how large a droplet of matter has to be in order for it to behave like a macroscopic liquid. What is the smallest possible droplet of QGP? Until recently, it was thought

CGC (initial momentum anisotropy)

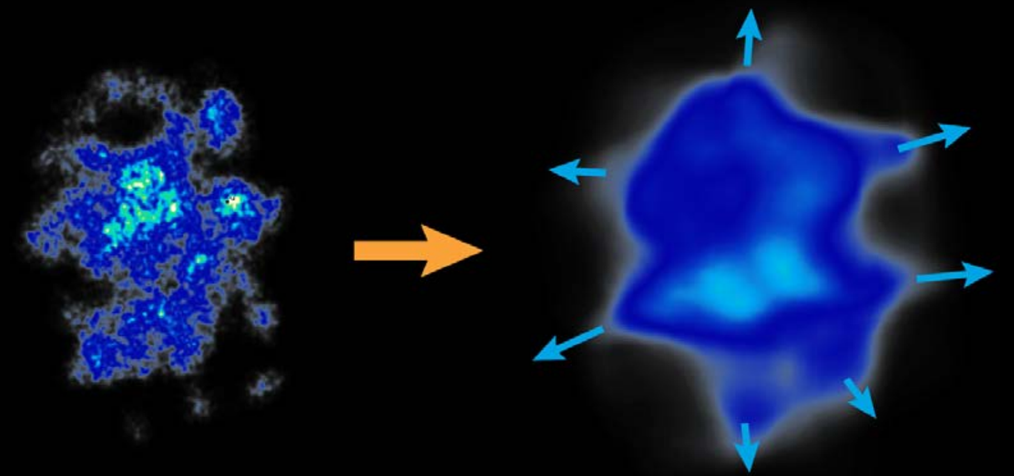


$v_2(^{3}He+Au) < v_2(d+Au) < v_2(p+Au)$

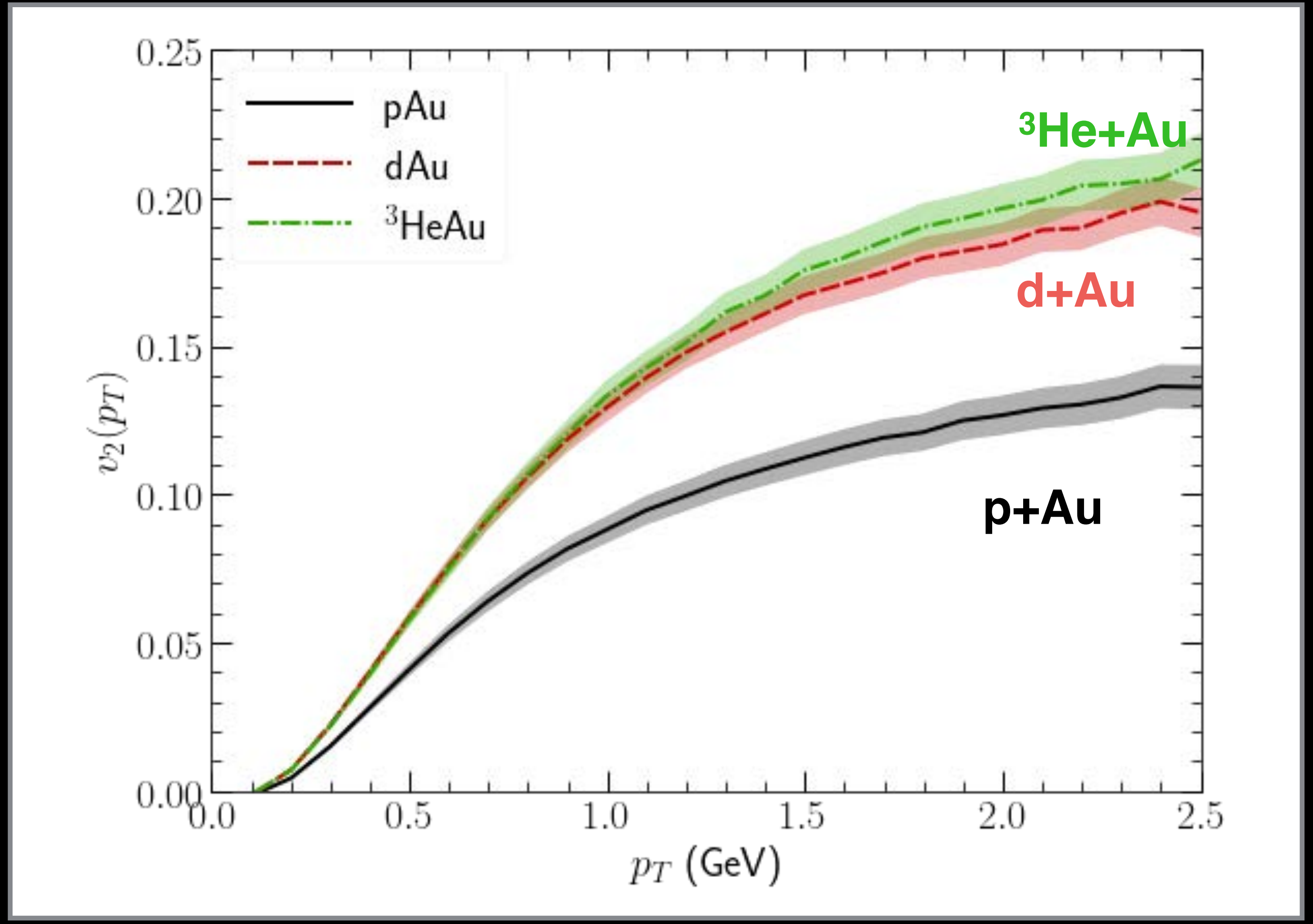


Mace et al, Phys. Rev. Lett. Erratum 123, 039901(E) (2019)

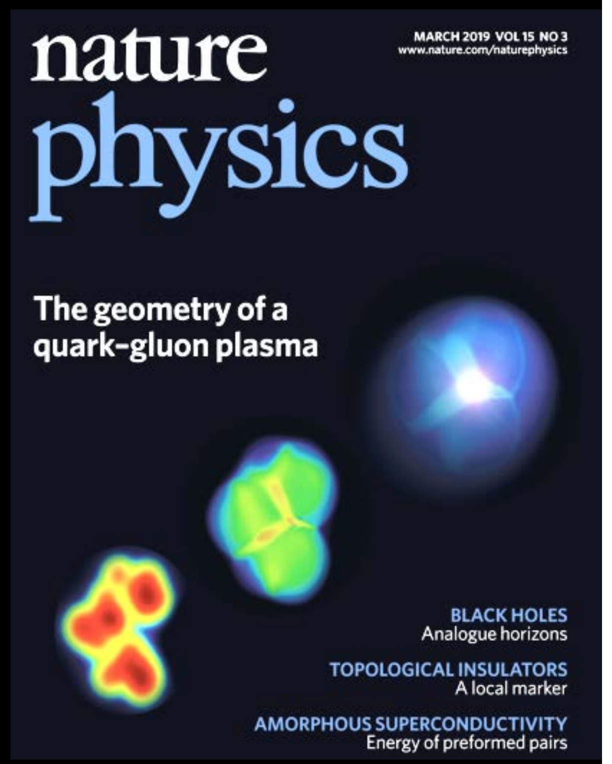
Hydrodynamics (final state)



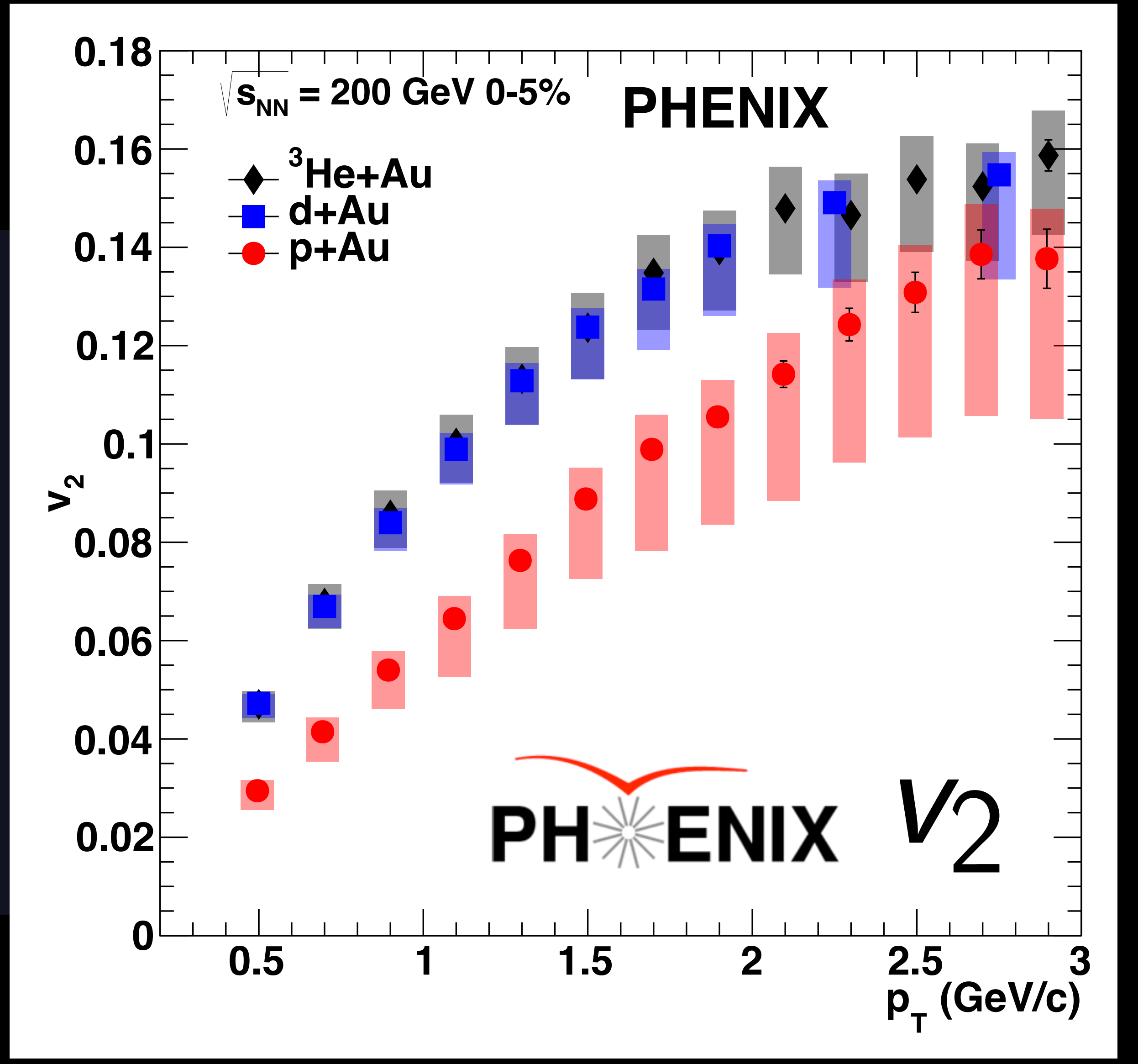
$v_2(^{3}He+Au) \sim v_2(d+Au) > v_2(p+Au)$



Schenke et al., Phys. Rev. C 102, 044905 (2020)



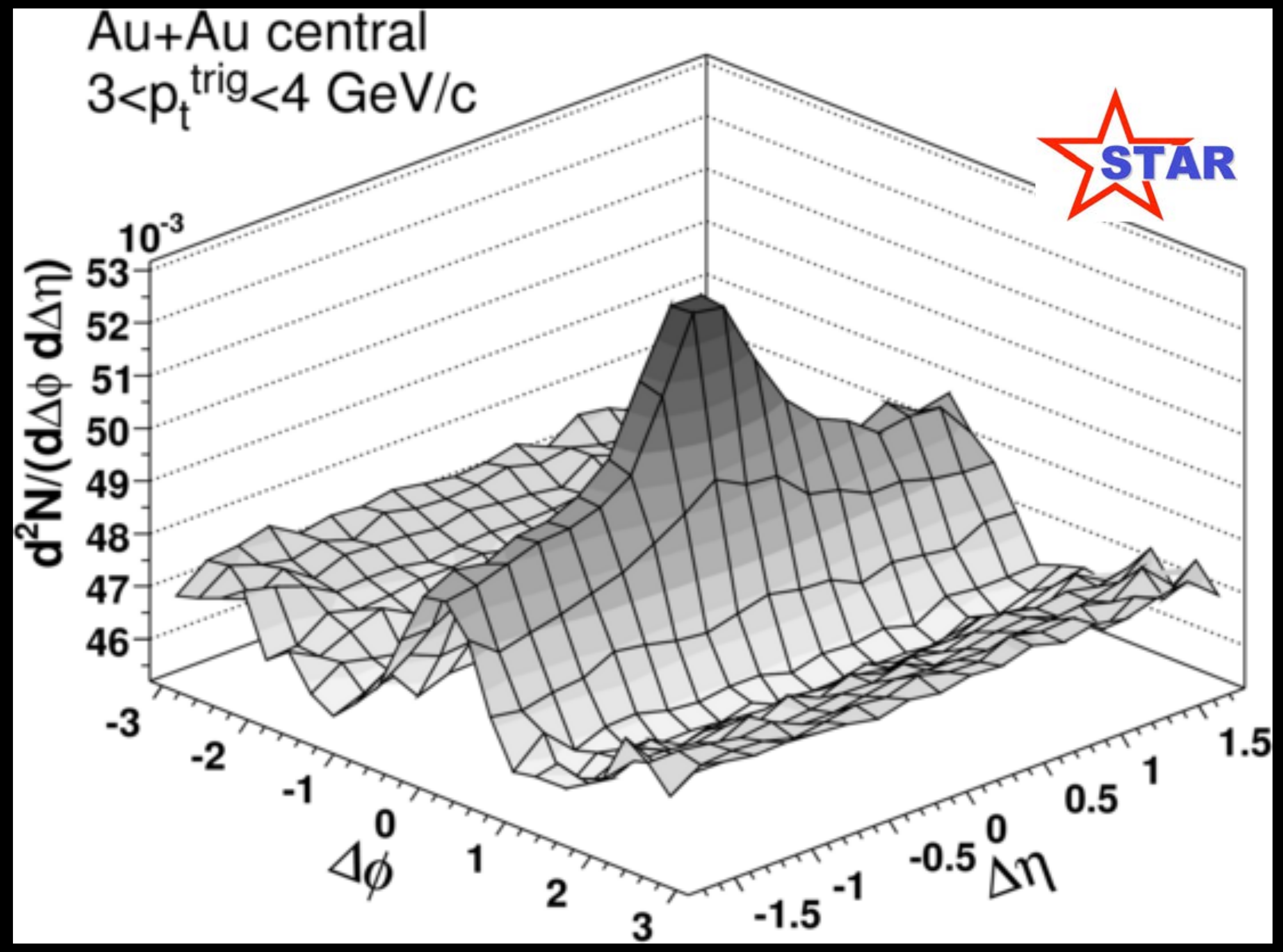
$v_2(^{3}He+Au) \sim v_2(d+Au) > v_2(p+Au)$



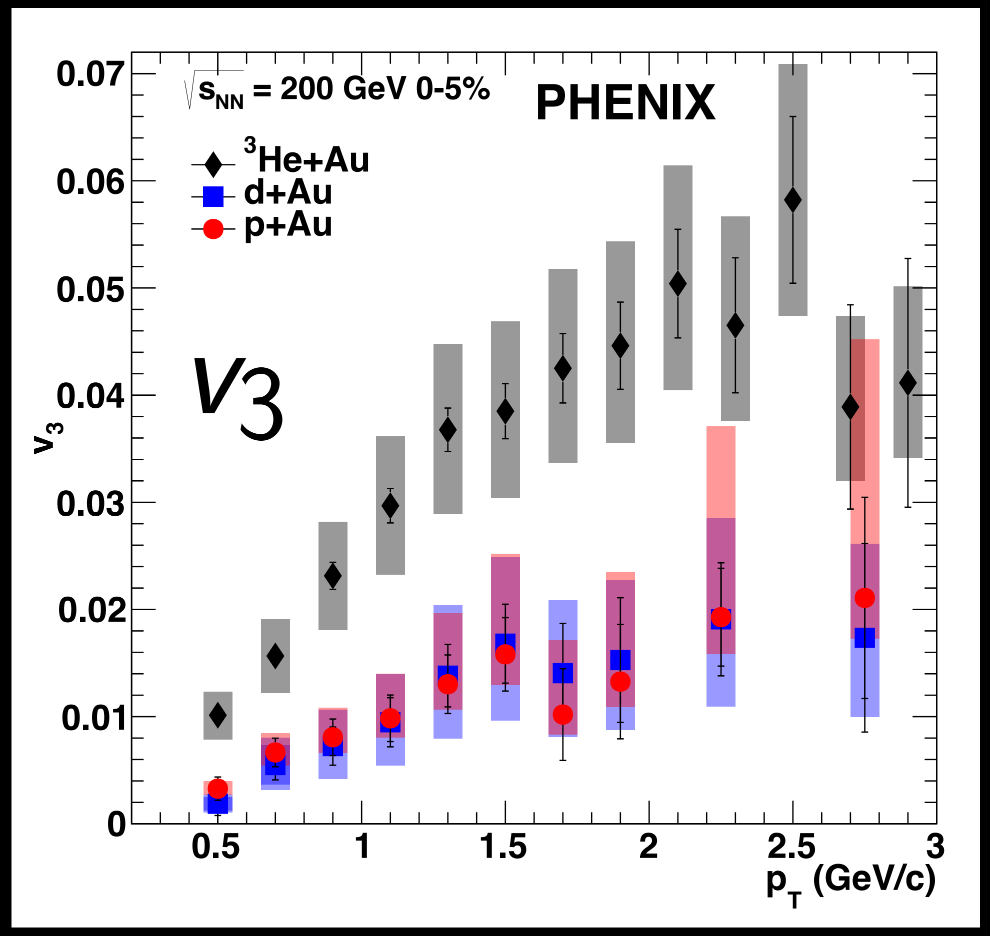
PHENIX collab, Nature Physics 15, 214–220 (2019), Phys. Rev. C 105, 024901 (2022)

PHENIX results decisively establishes role of final state, opportunities to pin down the acceptance dependence with RHIC d+Au, O+O with STAR & future p+Au run with sPHENIX + STAR

Collectivity across systems: from RHIC to EIC

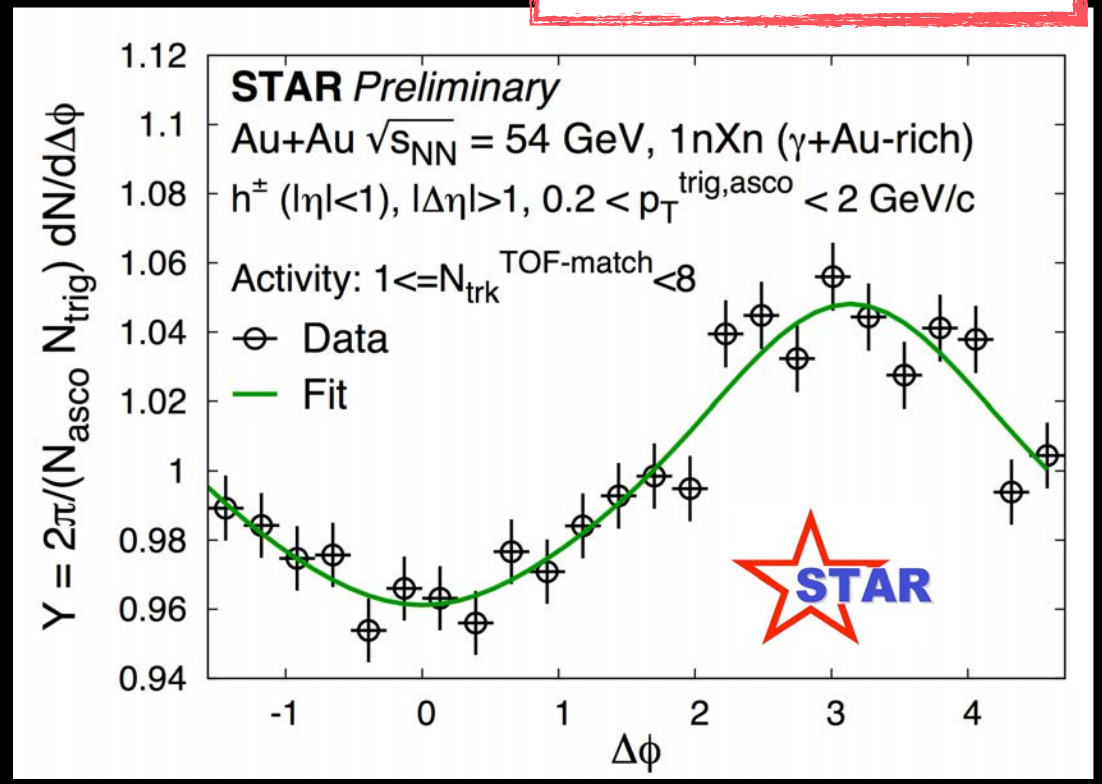


STAR collaboration, Phys. Rev. Lett. 95, 152301
Phys. Rev. C 80 (2009) 64912



PHENIX collab, Nature Physics 15, 214–220 (2019)

NEED MORE DATA



STAR Collab. QM 2022

Will γ*+A be the next small system ?

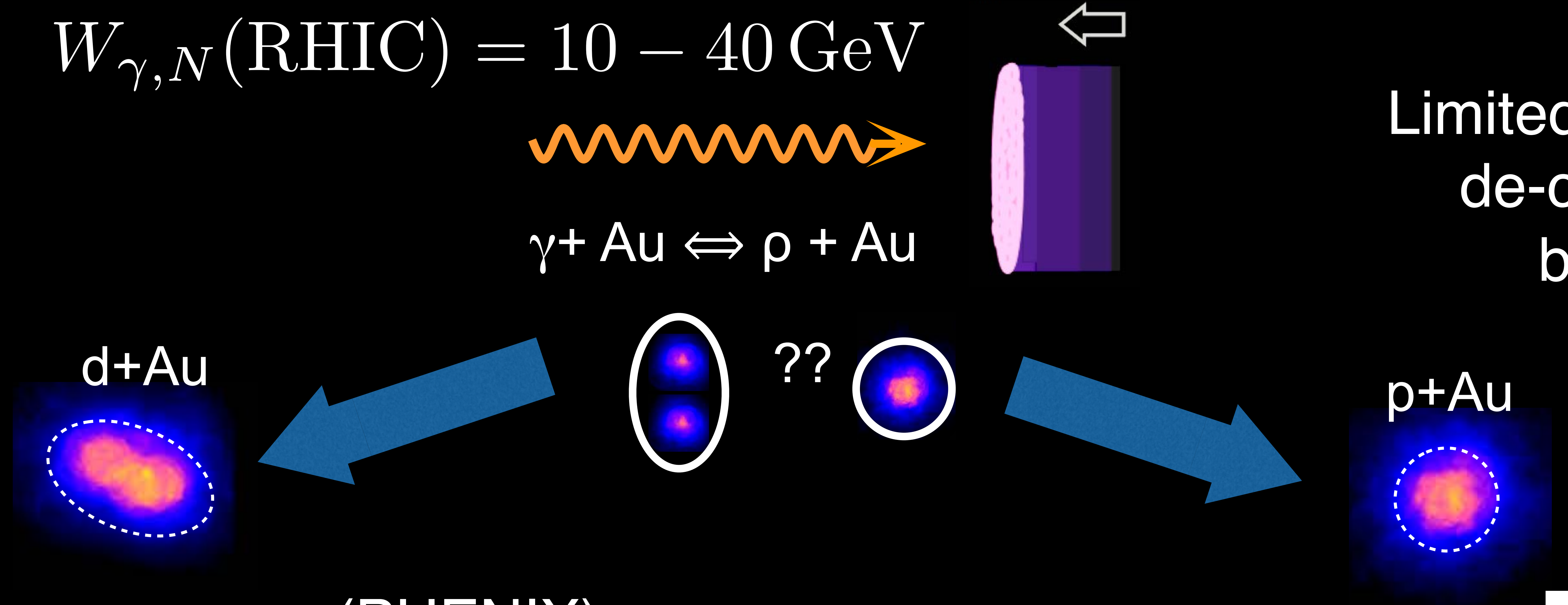
EPIC collaboration, 2030+

Push the limits of RHIC system scan, sets the stage for collectivity search at EIC

Small system collectivity: future measurements

STAR BUR for Run 23-25
sPHENIX BUP 2022 (sPH-TRG-2022-001)
ATLAS Collab,Phys. Rev. C 104, 014903 (2021)

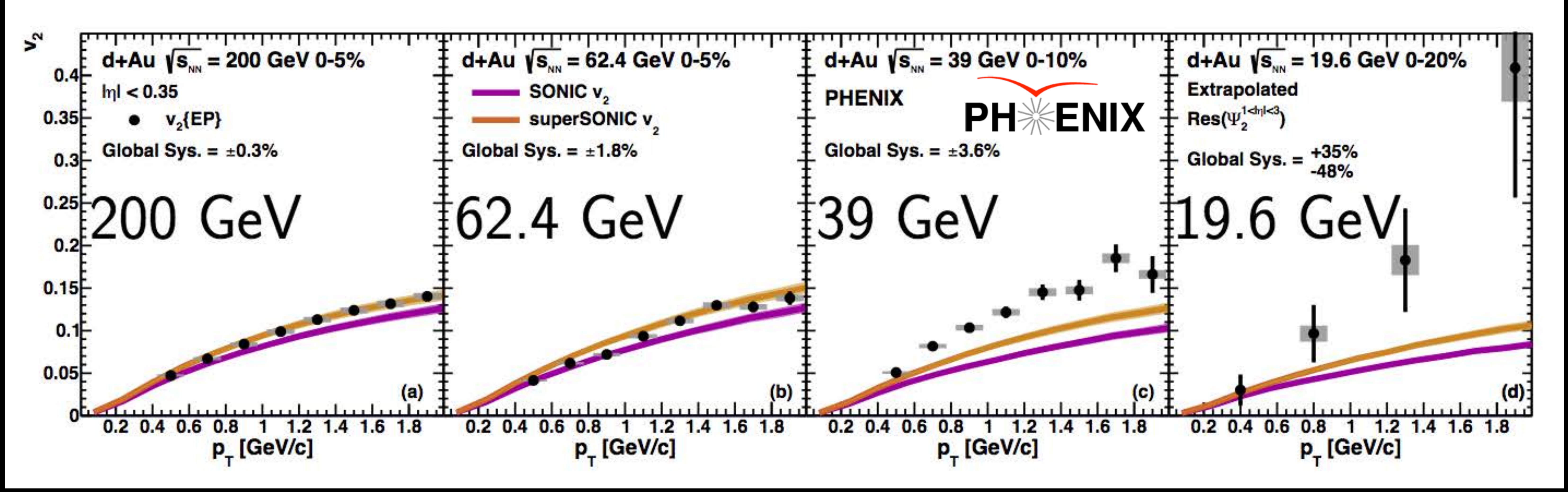
$$W_{\gamma,N}(\mathrm{RHIC}) = 10 - 40\,\mathrm{GeV}$$



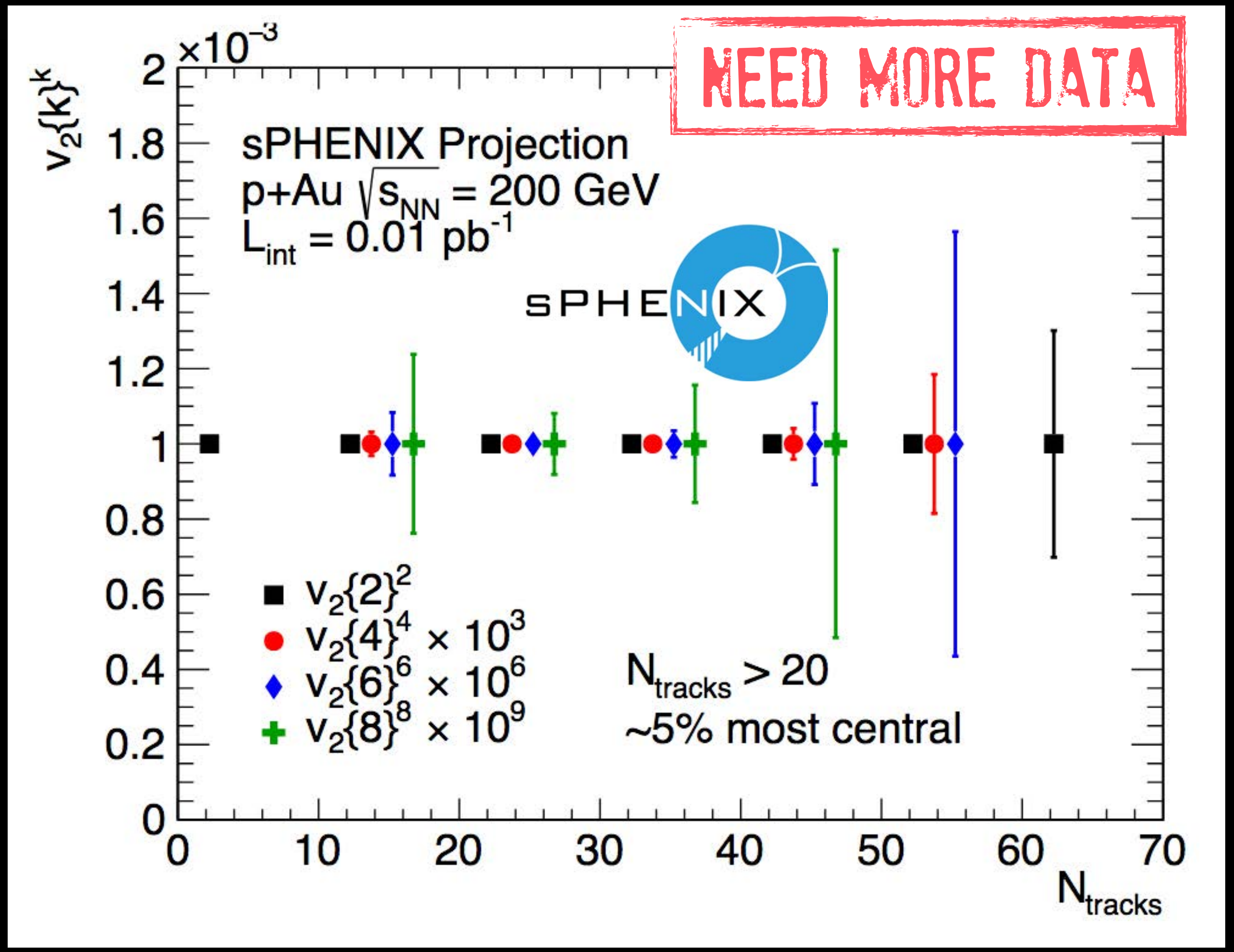
Limited kinematic control, large rapidity de-correlation in γ+Au but various baselines available at RHIC

p+Au rapidity scan (sPHENIX + STAR 2024)

d+Au beam energy scan (PHENIX)



C. Aidala et al. (PHENIX Collab), Phys. Rev. C 96, 064905



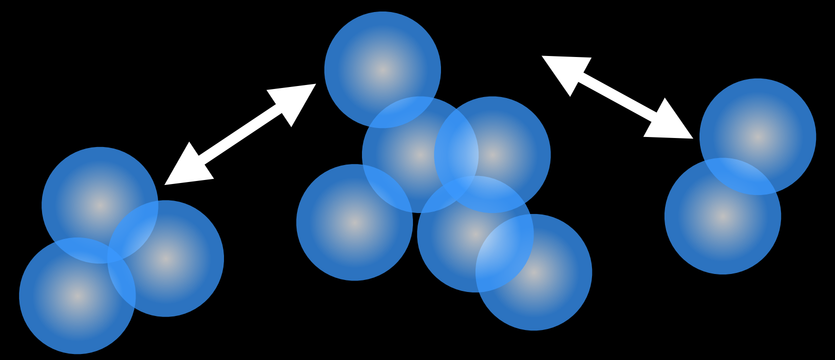
Opportunity to explore if many-body system exhibit fluid behavior in photon-induced processes

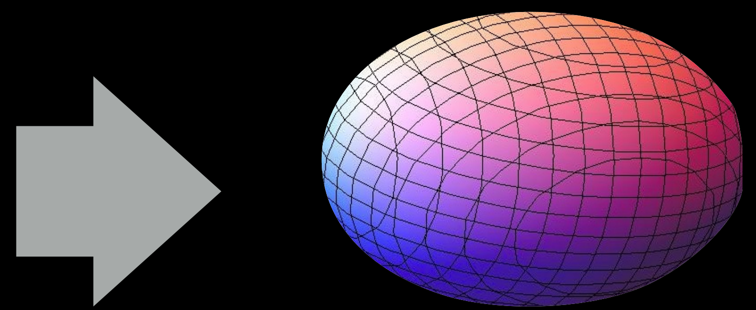
Imaging nuclei in the pre-EIC era: Approach-I

Talk by Jiangyong Jie (Sat)

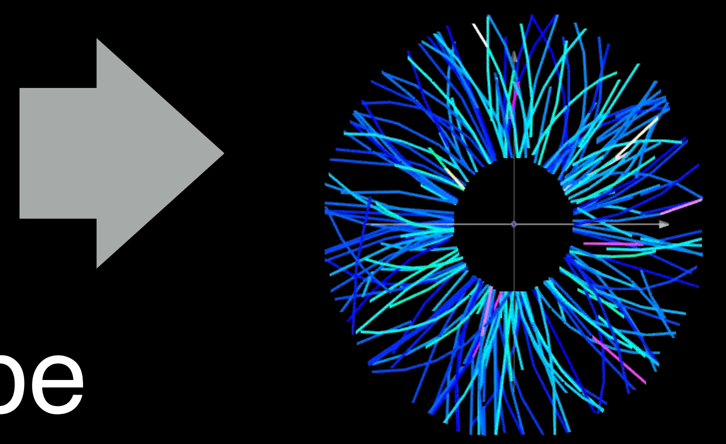
L. Adamczyk et al. (STAR Collab.), Phys. Rev. Lett 115, 222301 (2015)
M. Abdallah et al. (STAR Collab.), Phys. Rev. C 105 (2022) 1, 014901
Haojie Xu, Chunjian Zhang QM 2022

Many-body nucleon correlation

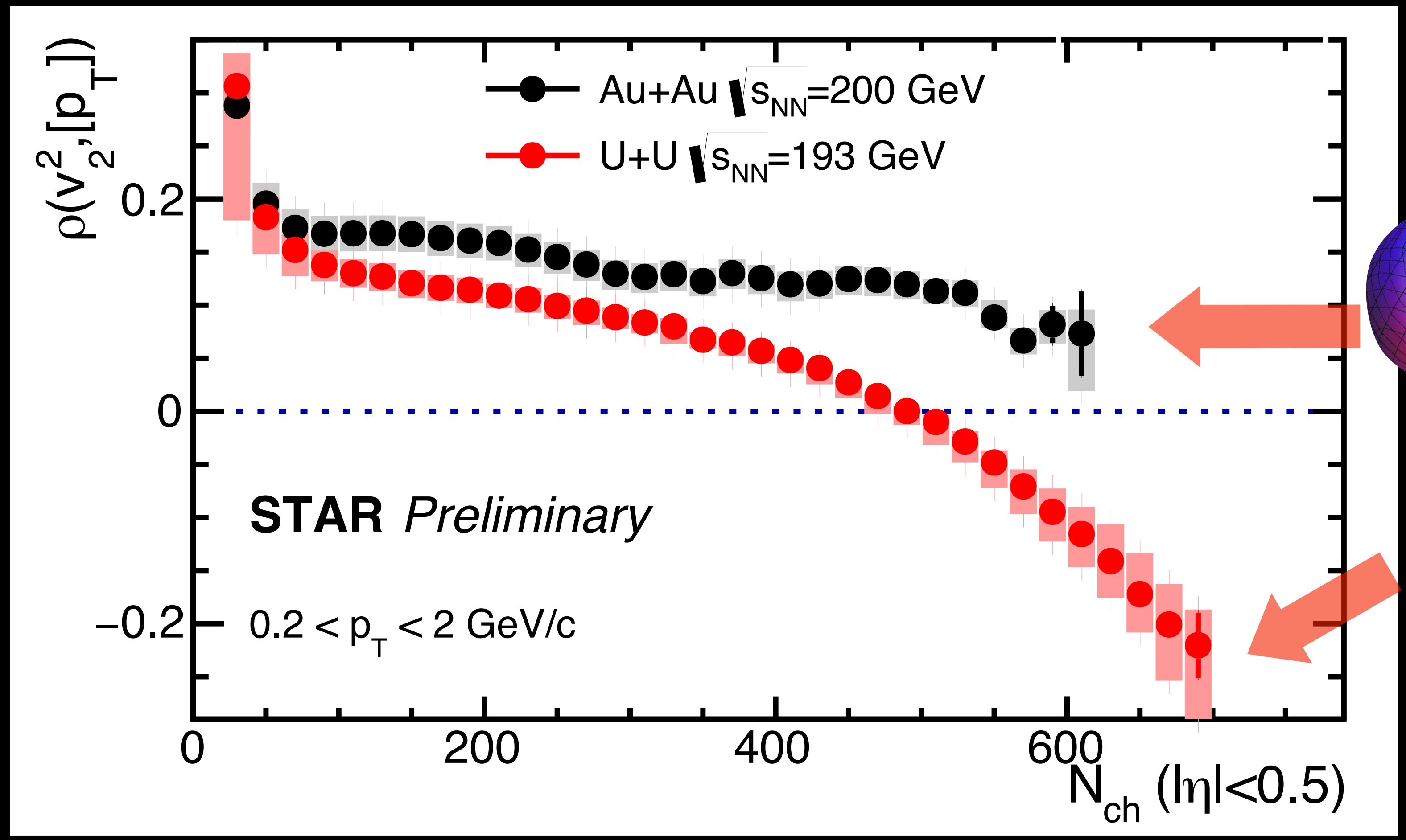




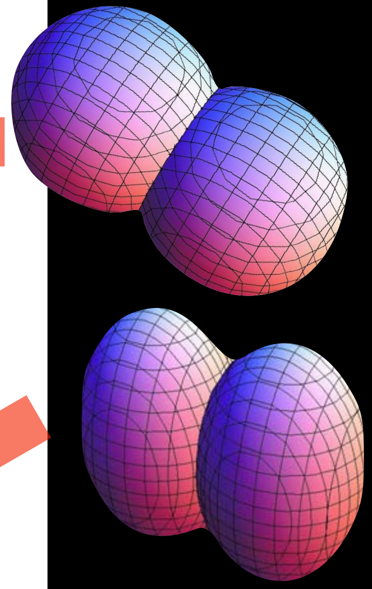
Imprints in observables



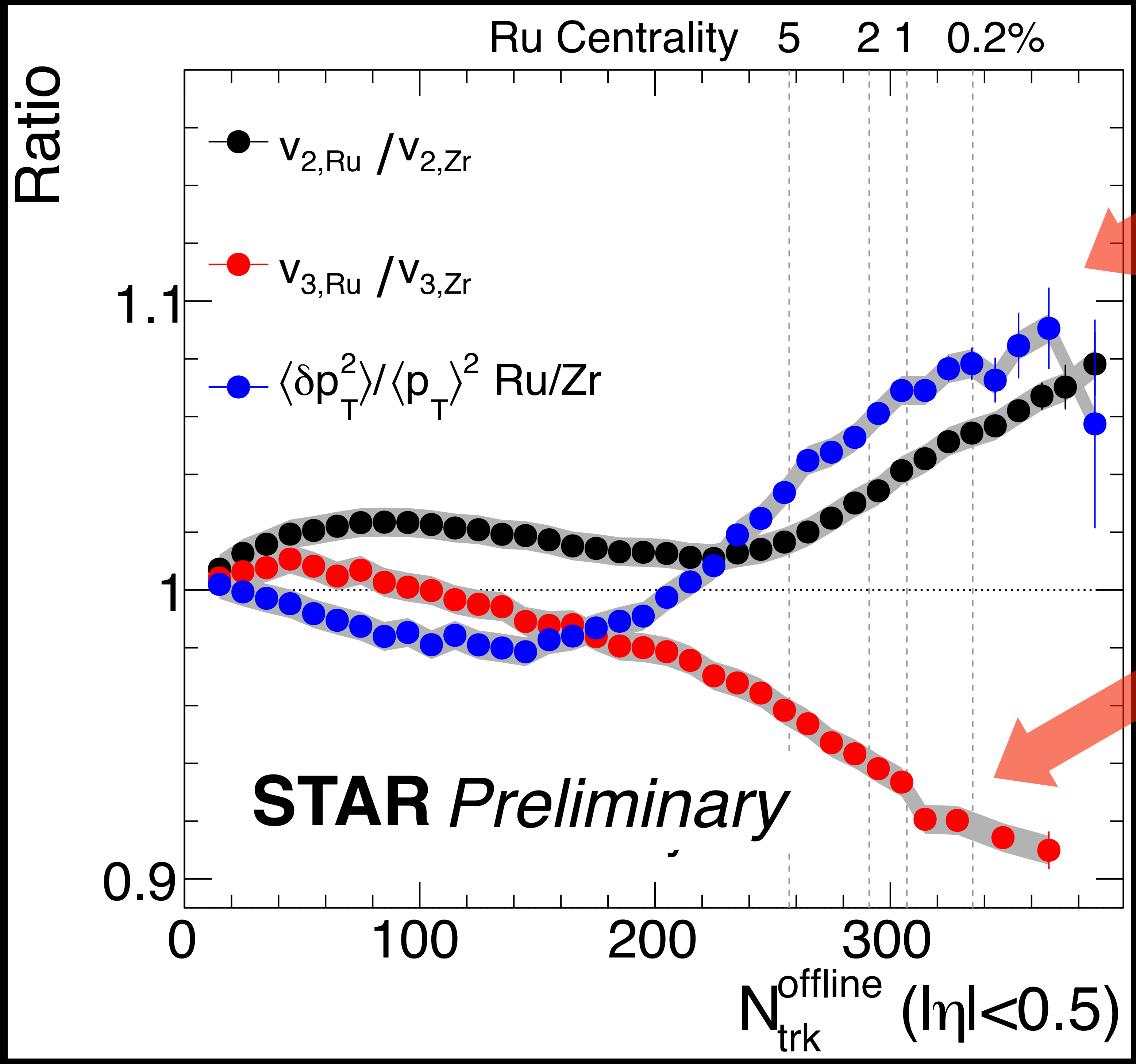
Nuclear shape



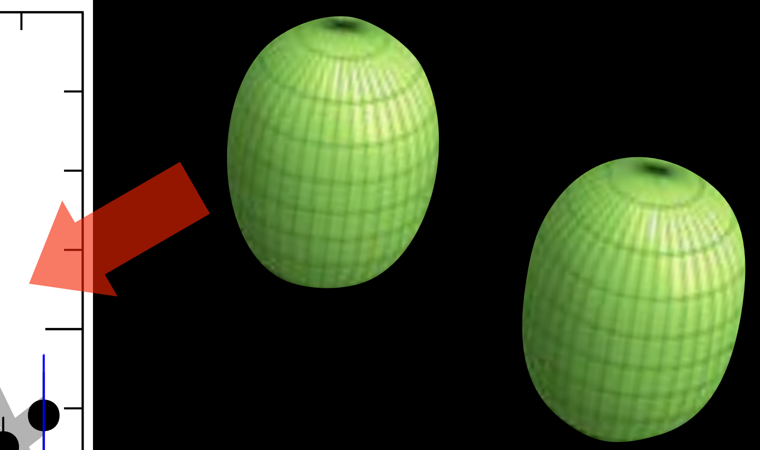
Au+Au



U+U

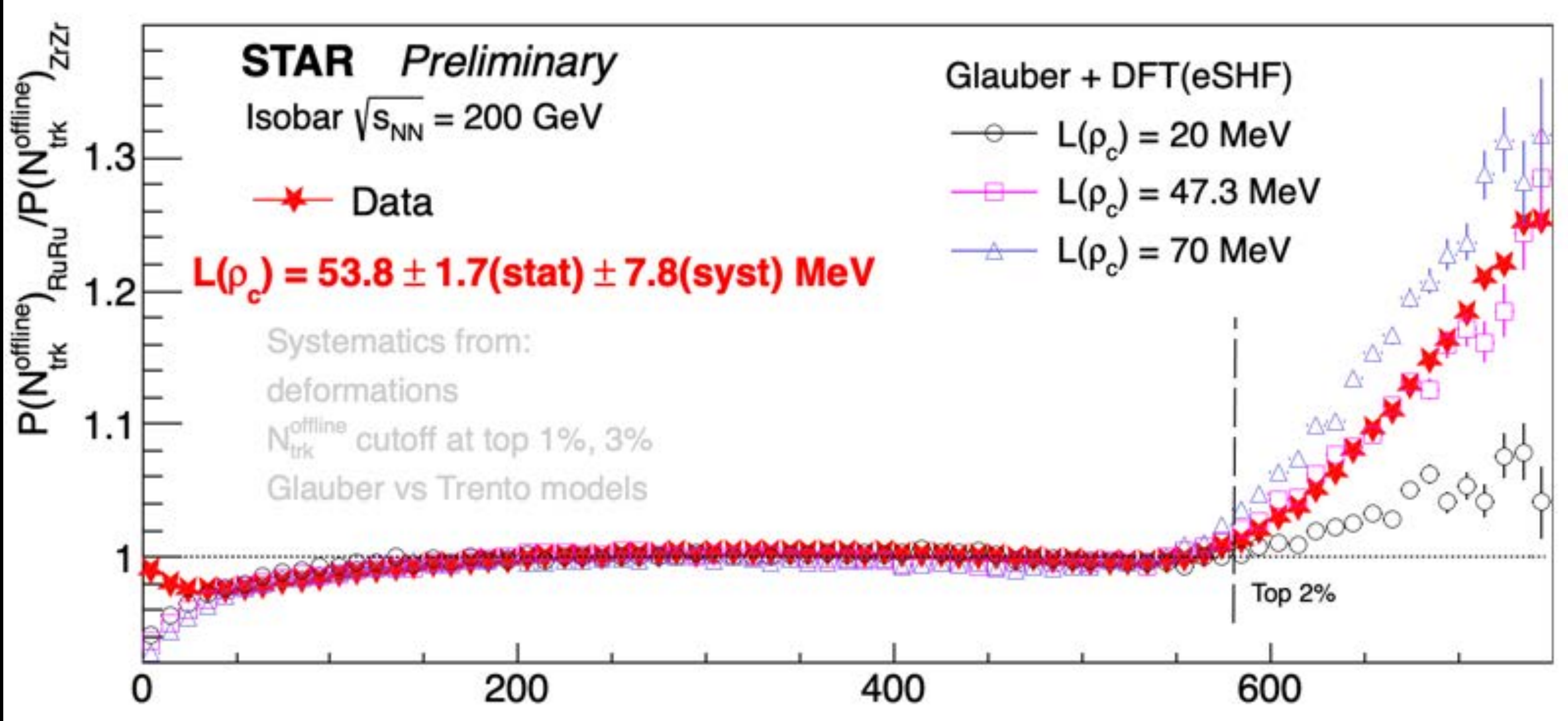


Ru+Ru

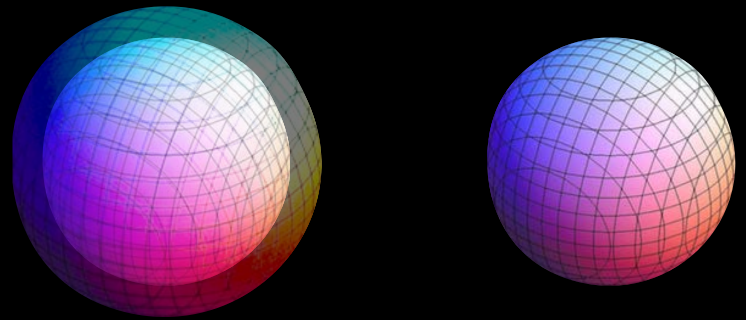


Zr+Zr

β_2(Ru) > β_2(Zr)
β_3(Zr) > β_3(Ru)



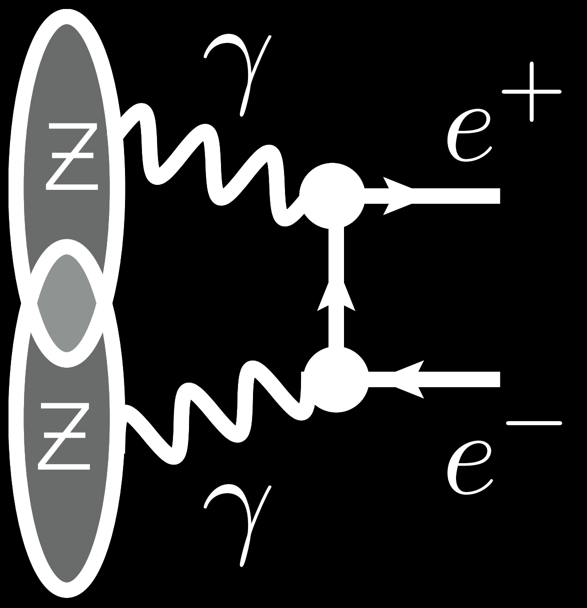
Neutron skin:
Δr_{np}(Zr) > Δr_{np}(Ru)



We have pioneered a way to constrain nuclear structure with heavy ion collisions

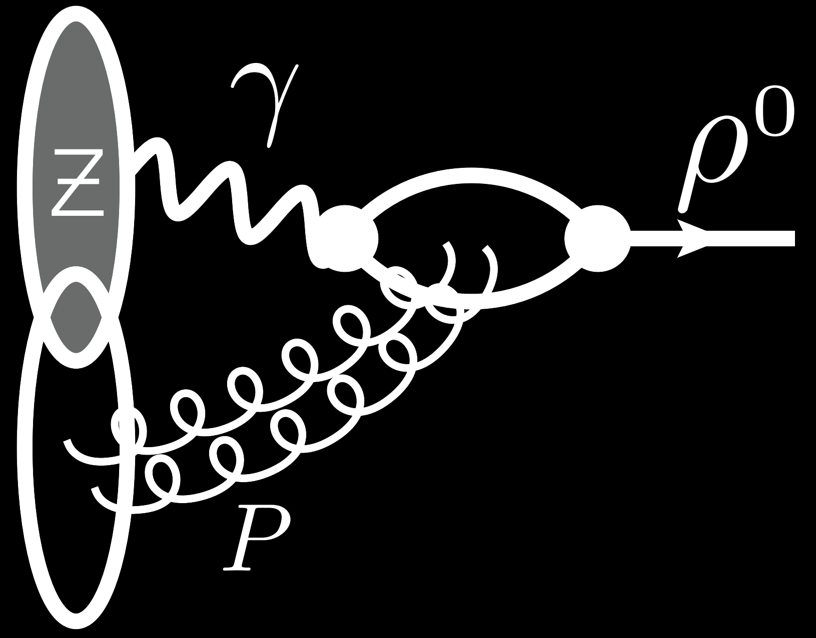
Imaging nuclei in the pre-EIC era: Approach-II

J. Adam et al. (STAR Collab.), Phys. Rev. Lett. 127, 052302
M. Abdallah et al. (STAR Collab.), arXiv:2204.01625
Xiaofeng Wang QM2022

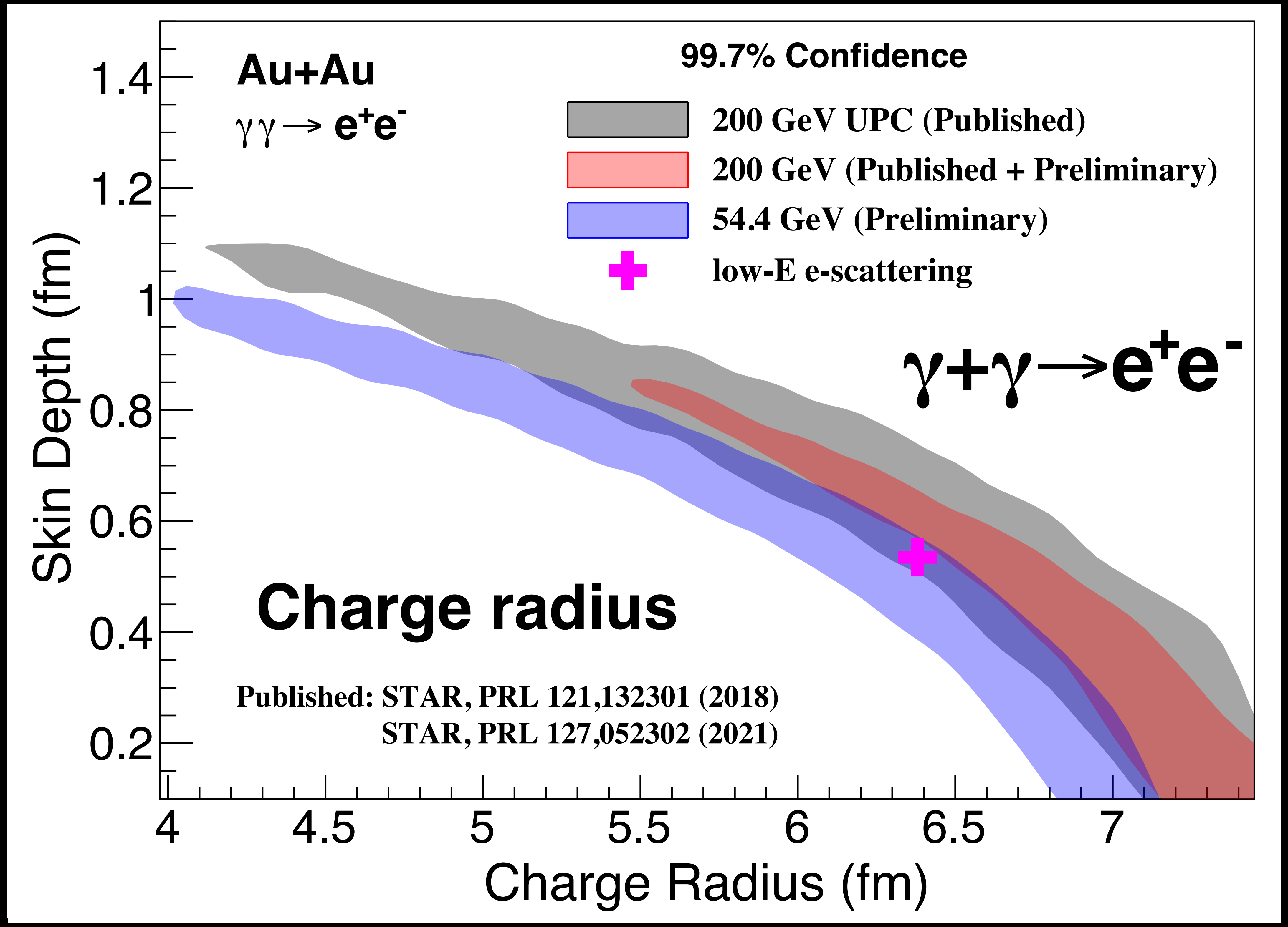


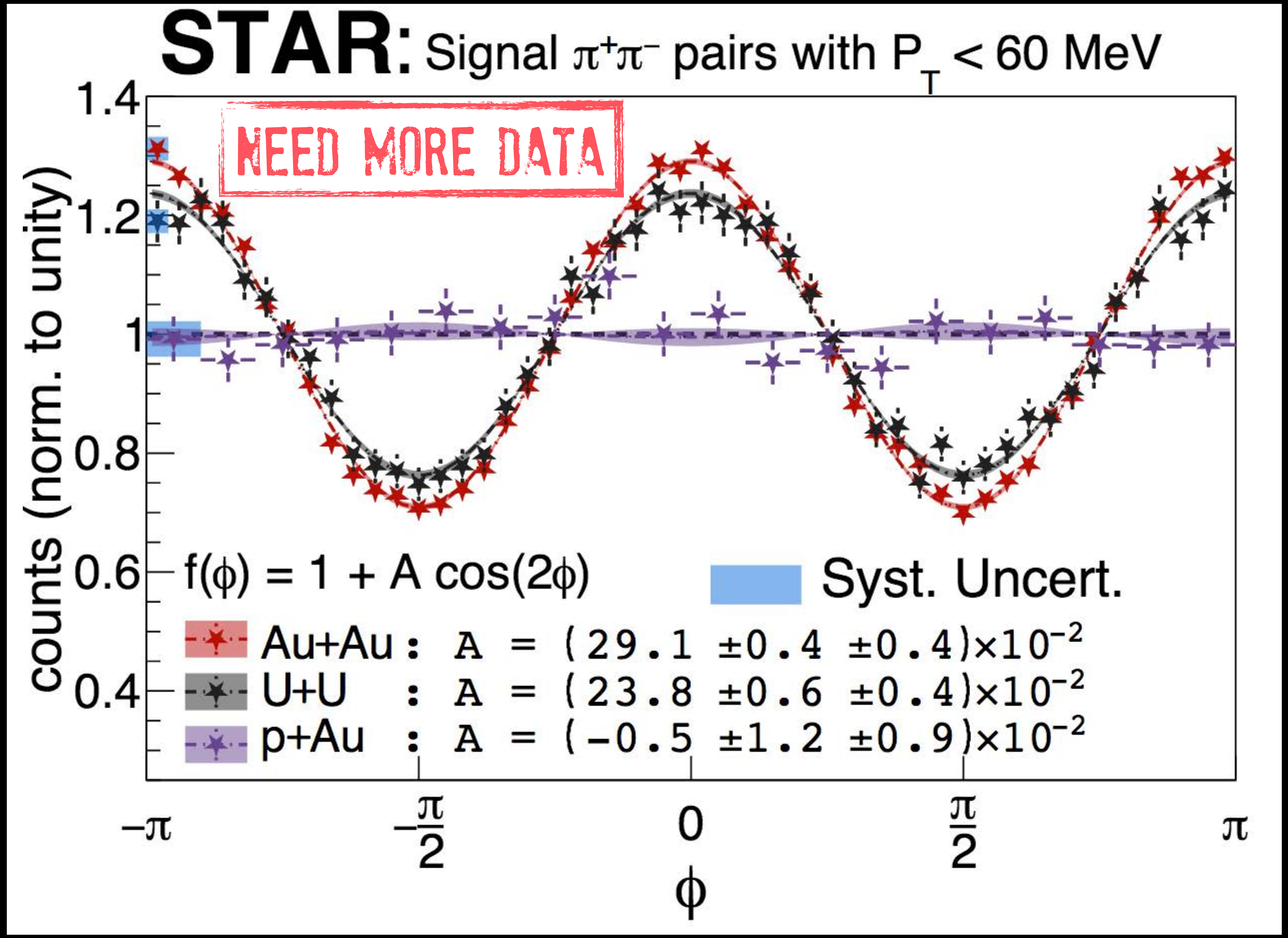
Charge radius R & skin depth a through $\gamma\gamma \rightarrow e^+e^-$ (Breit Wheeler process)

$$\rho = \frac{\rho_0}{1 + \exp\left[(r - R)/a\right]}$$



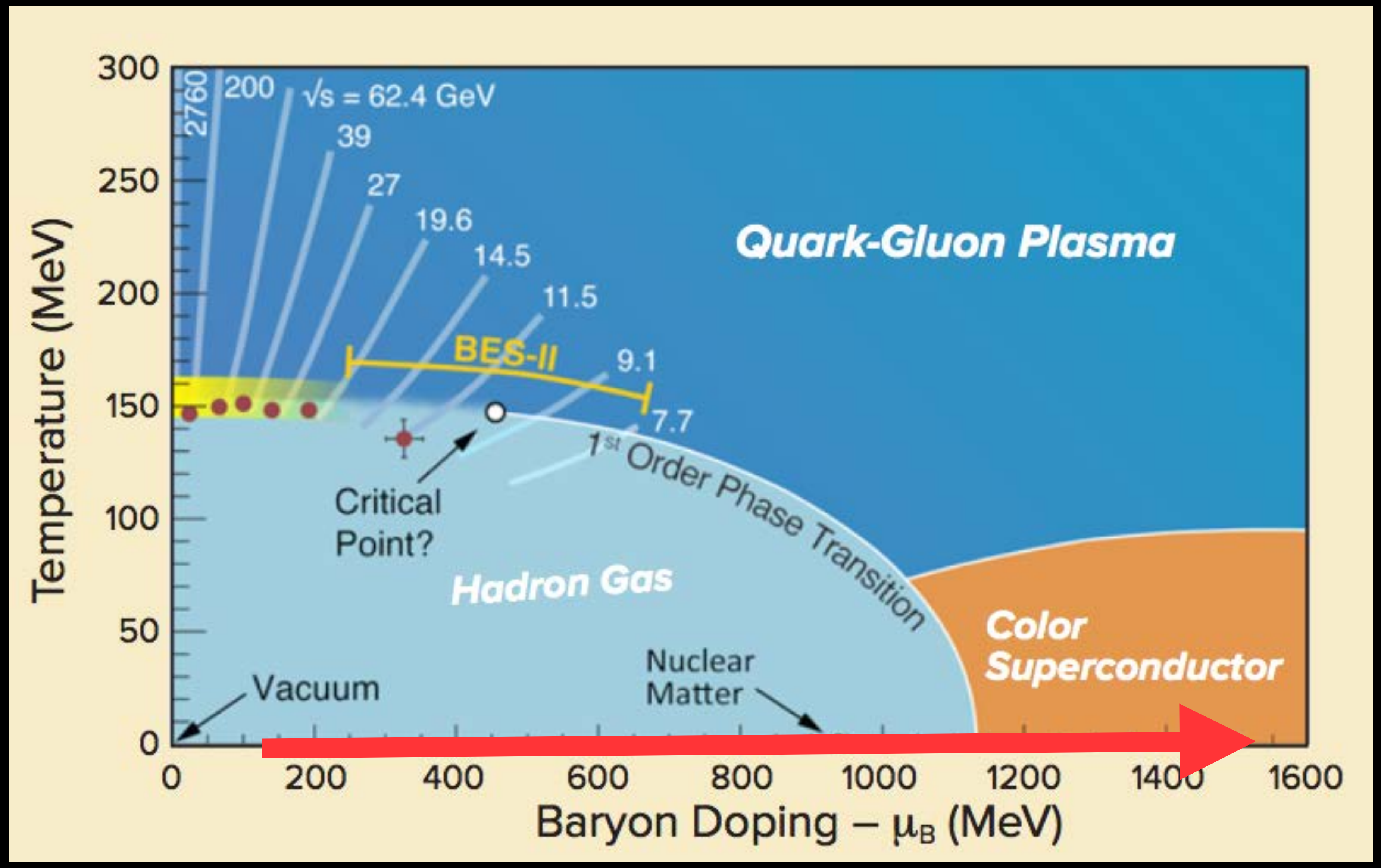
Mass radius, neutron skin through photonuclear $\gamma A \rightarrow \rho^0$ process





Novel ways of extracting nuclear charge radius, and strong-interaction (gluon) radius at RHIC energies

What makes is possible to scan along the μ_B axis ?



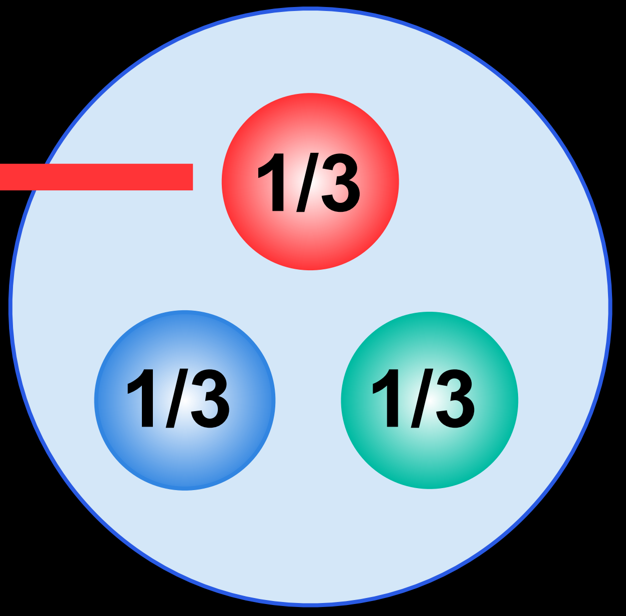
Doping the QGP with baryons is essential to map the phase diagram of the QCD

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

DOPING QGP WITH QUARKS TO MAP ITS PHASE DIAGRAM

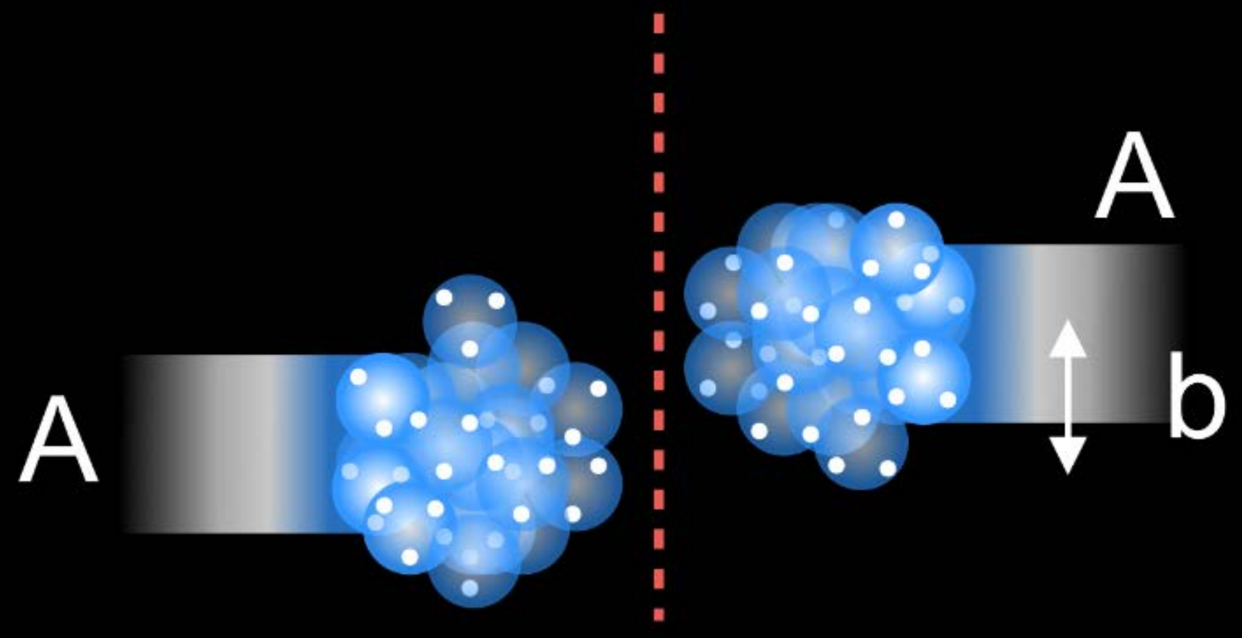
In the highest energy RHIC and LHC collisions and in the early universe, liquid QGP contains almost as many antiquarks as quarks. In the language of condensed matter physics, this is undoped QGP. It would be impossible to understand strongly correlated electron systems in condensed matter physics if all we knew were their properties in the absence of doping, with equal numbers of electrons and holes. Here too, if our goal is understanding, we must map the phase diagram of QCD as a function of both temperature and doping, in this case doping QGP with an excess of quarks over antiquarks.

Baryon number flows with the valence quarks

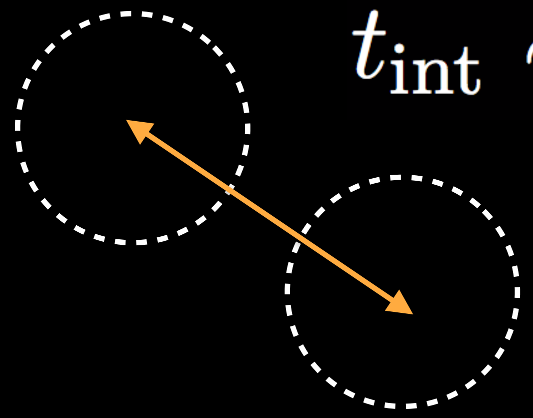


But pulling a quark stops a meson not a baryon

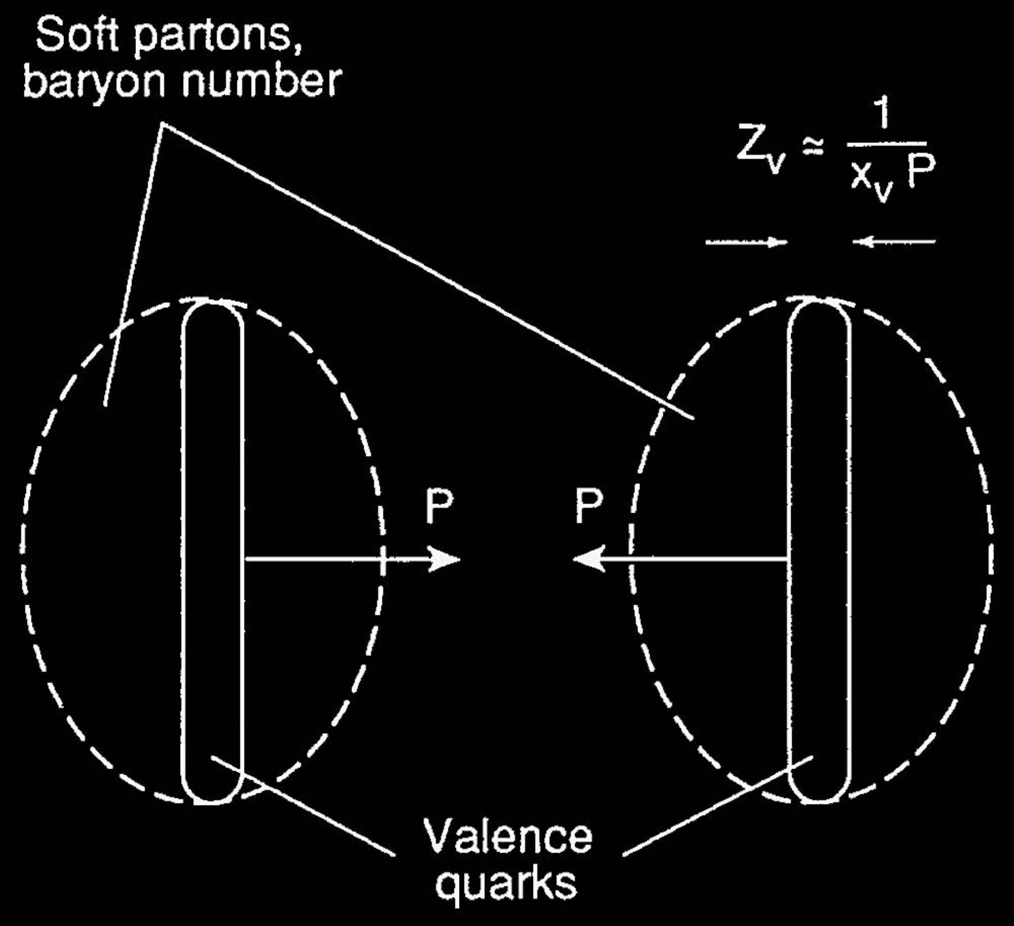
G.C. Rossi and G. Veneziano, Nucl. Phys.B123(1977) 507; Phys. Rep. 63(1980) 149, Kharzeev, Phys. Lett. B, 378 (1996) 238-246



y=0



$t_{\rm int} \sim \mathcal{O}(1)$ fm



Available time for valence quark stopping is too short

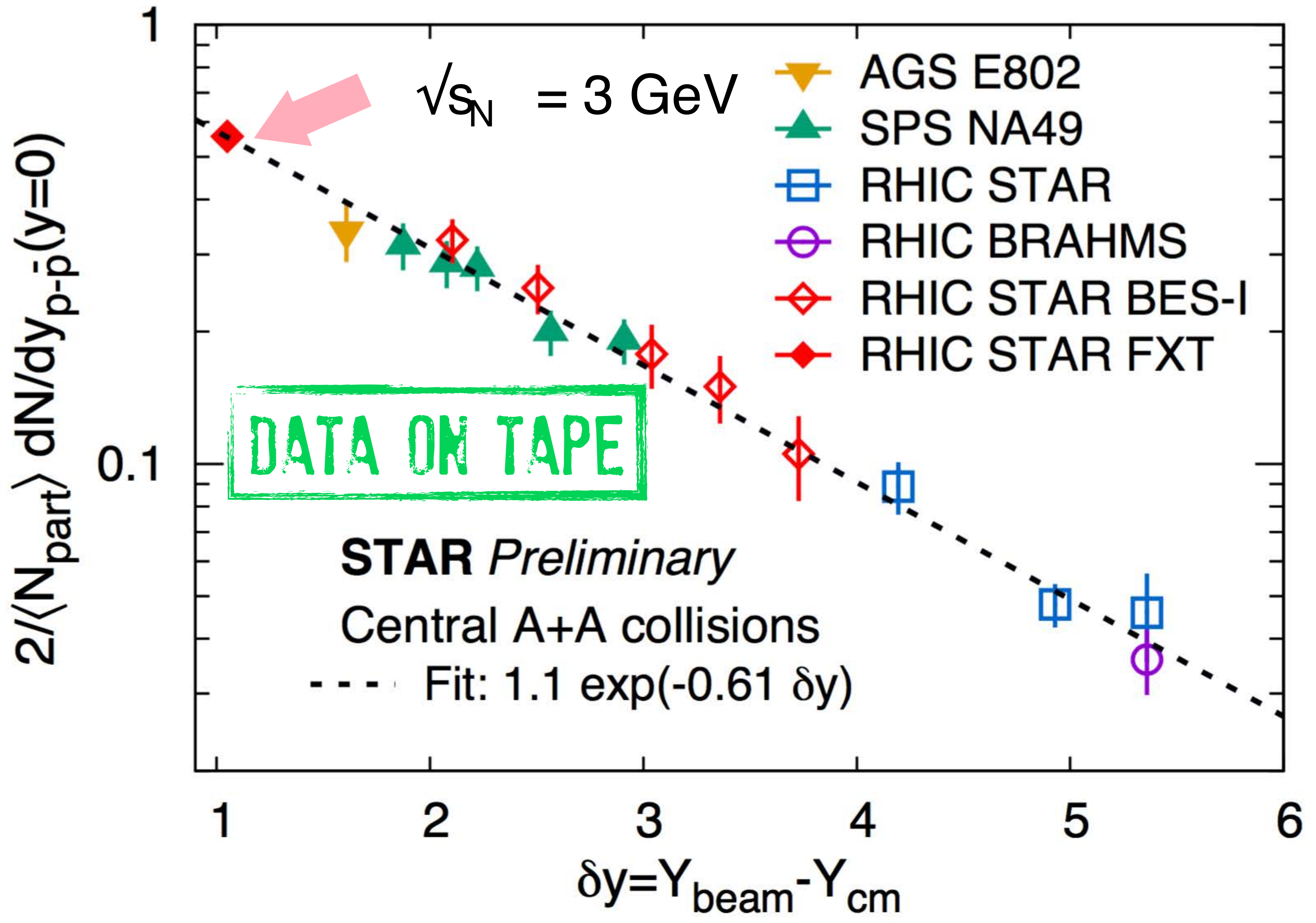
$$t_{\rm coll} \sim (x_V P)^{-1}$$

$$= (1/3 \times 100)^{-1}\ \mathrm{GeV}^{-1} = 0.006\ \mathrm{fm}$$

If baryon flows with valence quarks, then they should end up near $Y_{\rm beam}$ and not near y=0

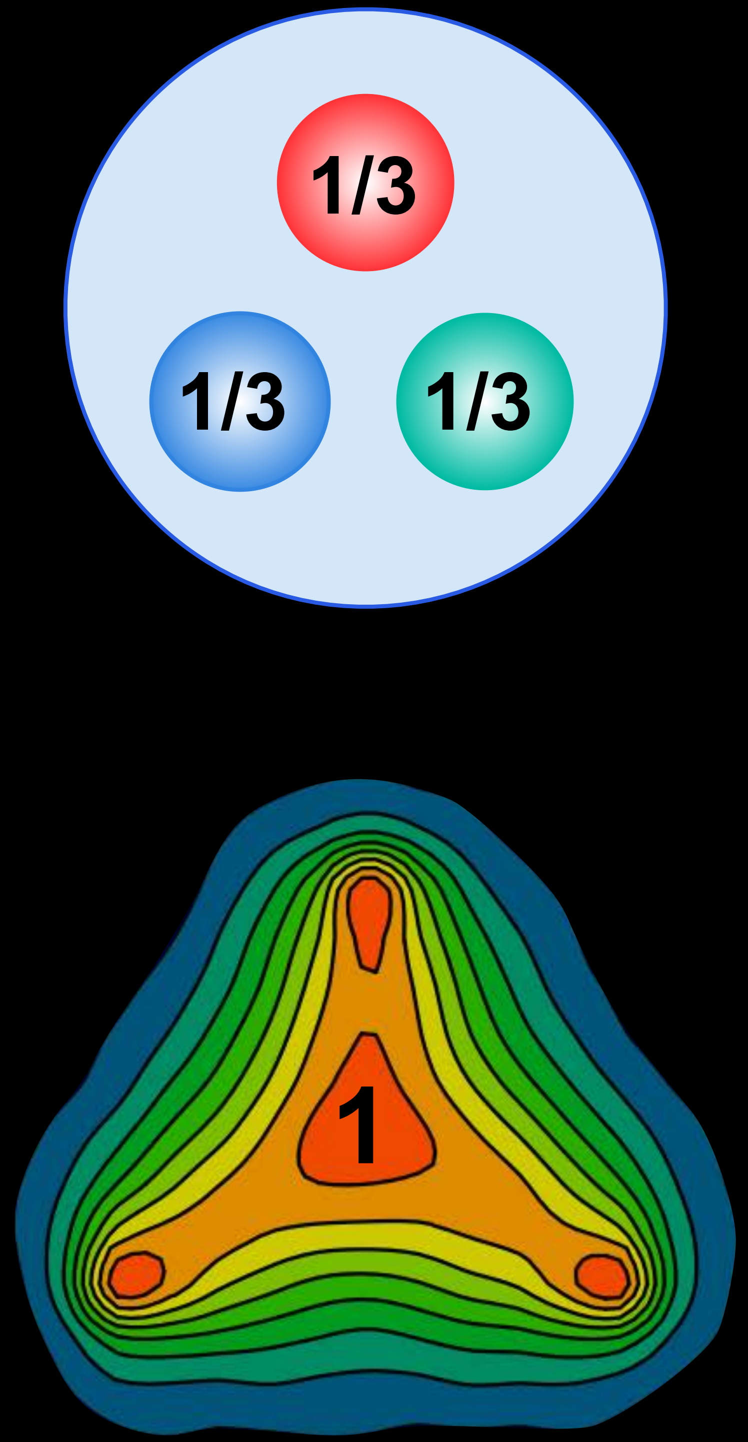
Microscopic structure of a baryon: what carries the baryon number?

Benjamin Kimelman, Nicole Lewis QM2022
B. Abelev et al. (STAR Collaboration)
Phys. Rev. C 79 (2009) 034909



Global data show exponential dependence of baryon density with rapidity shift

Baryon number flows with the valence quarks



Baryon number flows with the flow of junction

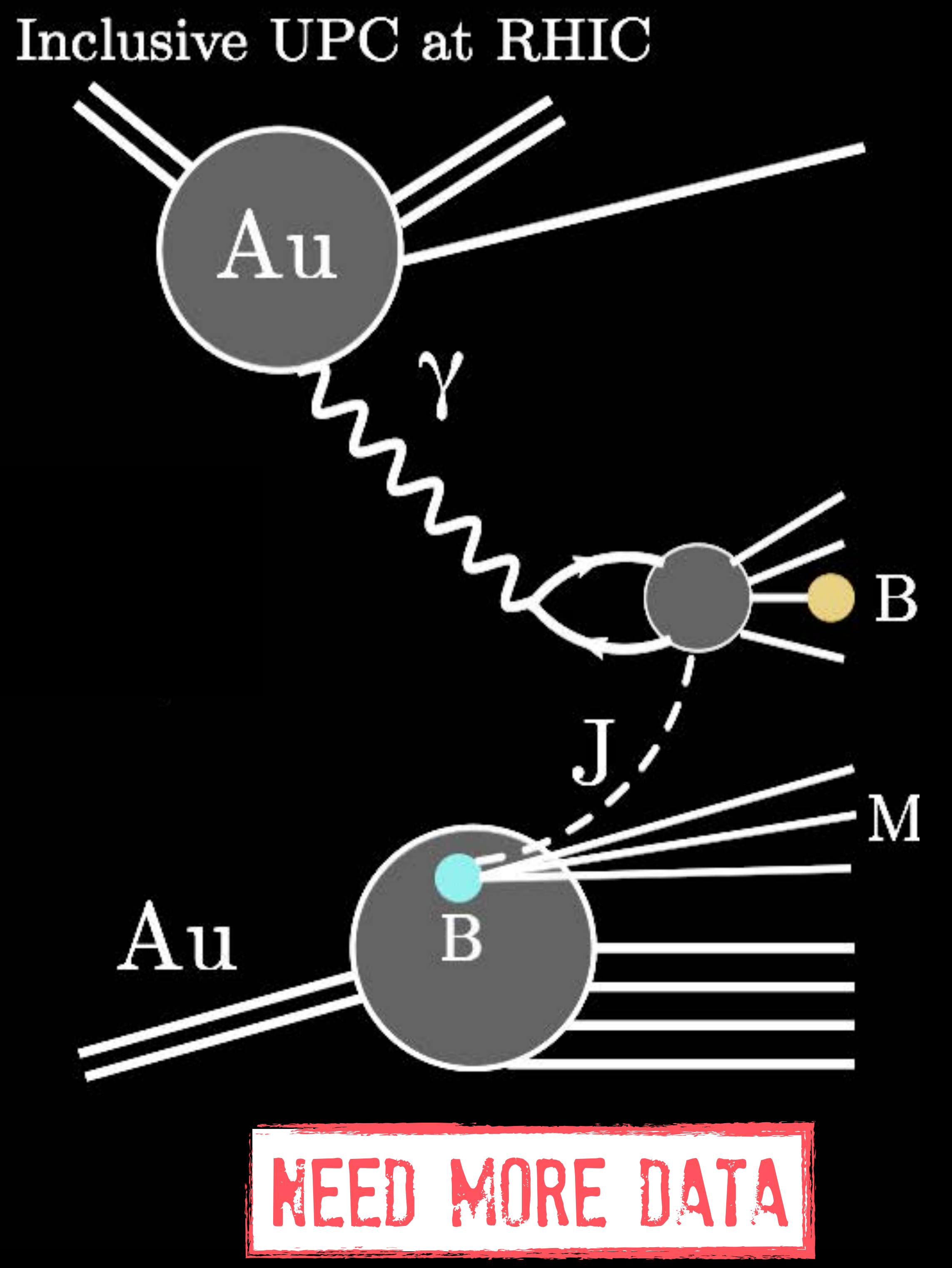
fig: Suganuma et al. AIP Conf.Proc. 756 (2005) 1, 123

$$Q \Leftrightarrow \frac{Z}{A} \times B$$

Charge vs. baryon stopping

Brandenburg, Lewis, Tribedy, Xu, arXiv:2205.05685

Rapidity dependent baryon stopping in $\gamma^{(*)}$+Au with RHIC UPC & EIC



A path towards microscopic understanding of the flow of baryon number & its stopping is possible through RHIC & future EIC measurements

Summary

Goal:

- Utilize the remaining years of RHIC run & analysis of existing data to characterize the unique plasma created in RHIC collisions & map the region of QCD phase diagram inaccessible to other facilities
- Coming decade provides opportunity to identify & perform measurements, informative towards EIC science

Measurements:

- Improved precision of the net-proton fluctuations, di-lepton spectra with BES-II data, novel observables sensitive to chiral & vortical effects
- Probes of gluon saturation, small system collectivity, nuclei imaging, 3D-initial state, bulk observables in UPCs

Needs:

- Complete the planned RHIC operations by collecting p+p, p+A & A+A data to achieve the required precision
- Continued support necessary for timely completion of the analysis & publications
- Support beyond RHIC operation to train a generation of experimentalists in preparation for the EIC