Recent Results and Future Prospects from the STAR Beam Energy Scan Program

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University of California, Davis
For the STAR Collaboration

57th Rencontres de Moriond
QCD and High Energy Interactions
La Thuile, Italy
31.03.2023

Supported in part by

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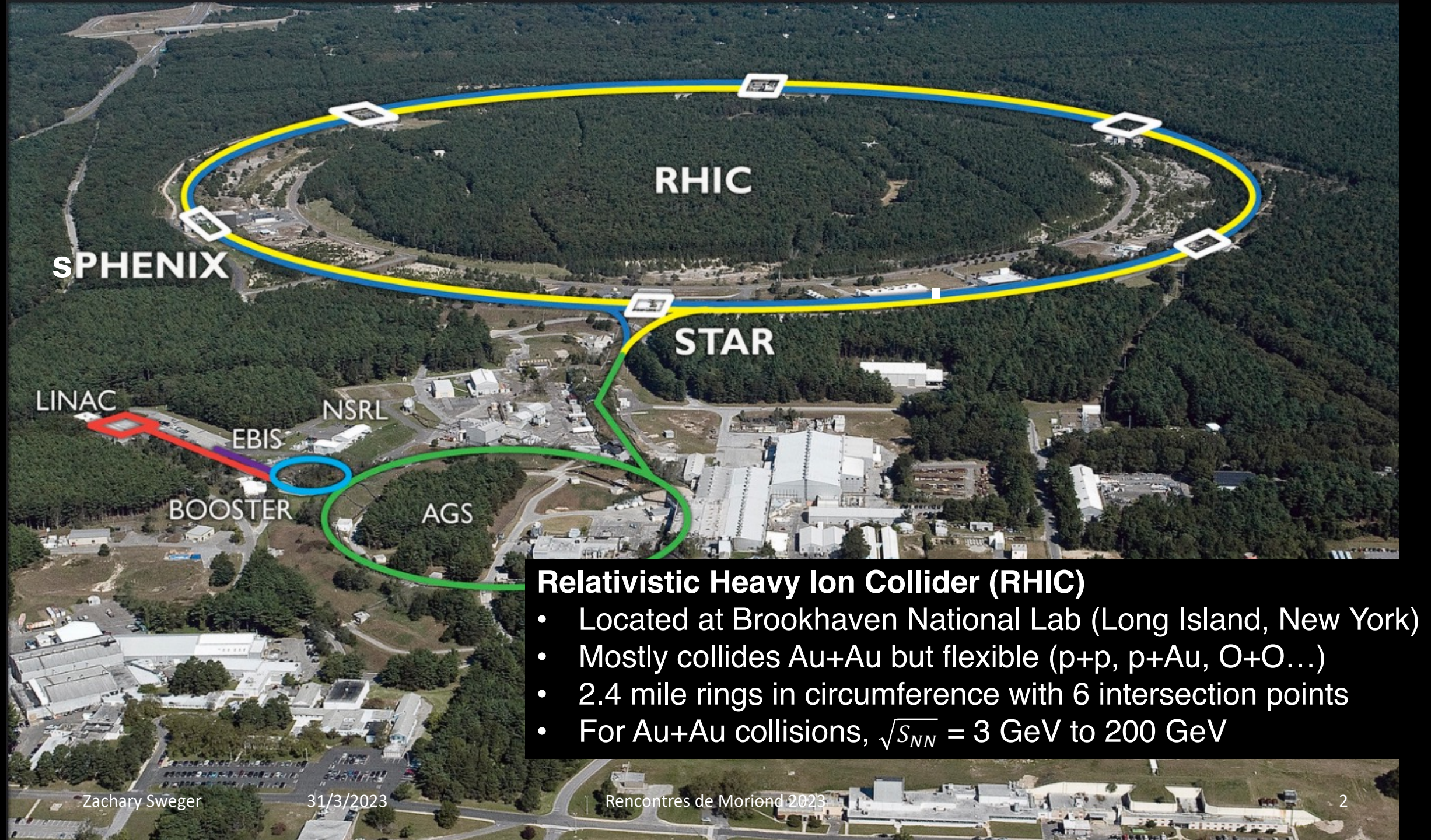
STAR

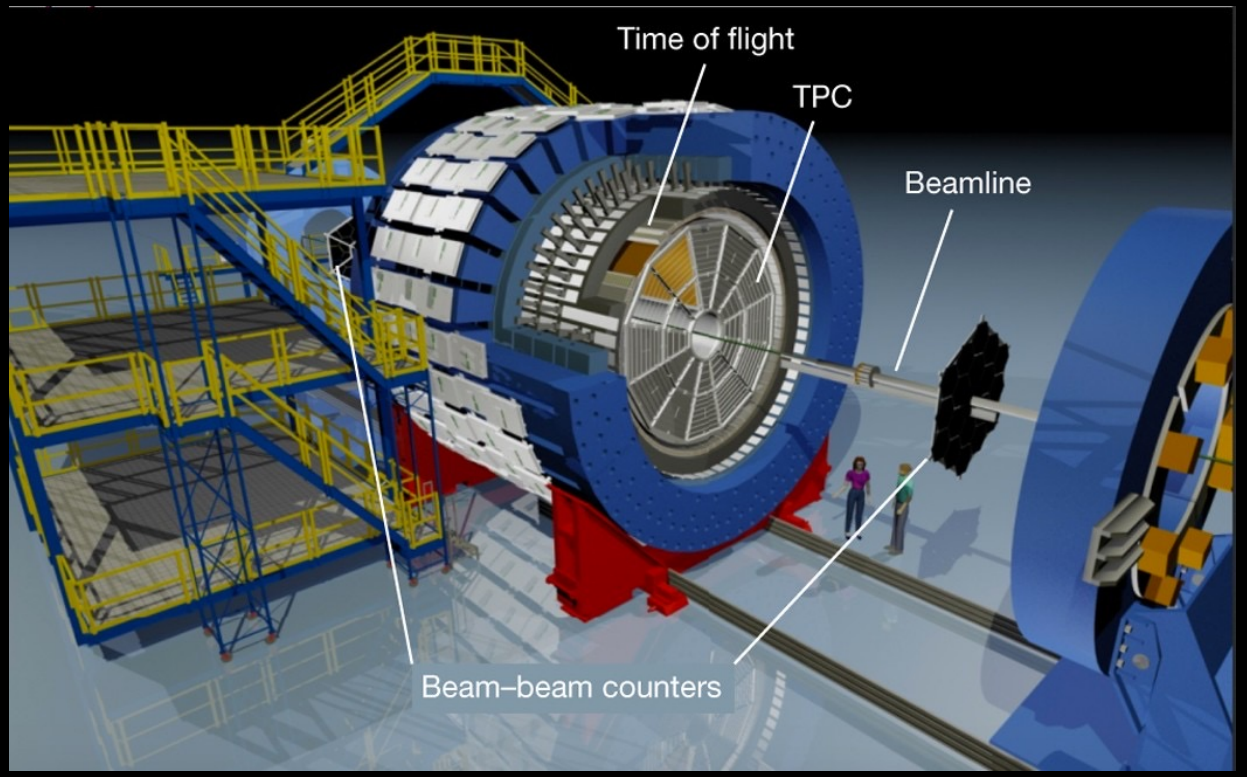


Relativistic Heavy Ion Collider (RHIC)

- Located at Brookhaven National Lab (Long Island, New York)
- Mostly collides Au+Au but flexible (p+p, p+Au, O+O…)
- 2.4 mile rings in circumference with 6 intersection points
- For Au+Au collisions, $\sqrt{s_{NN}}$ = 3 GeV to 200 GeV

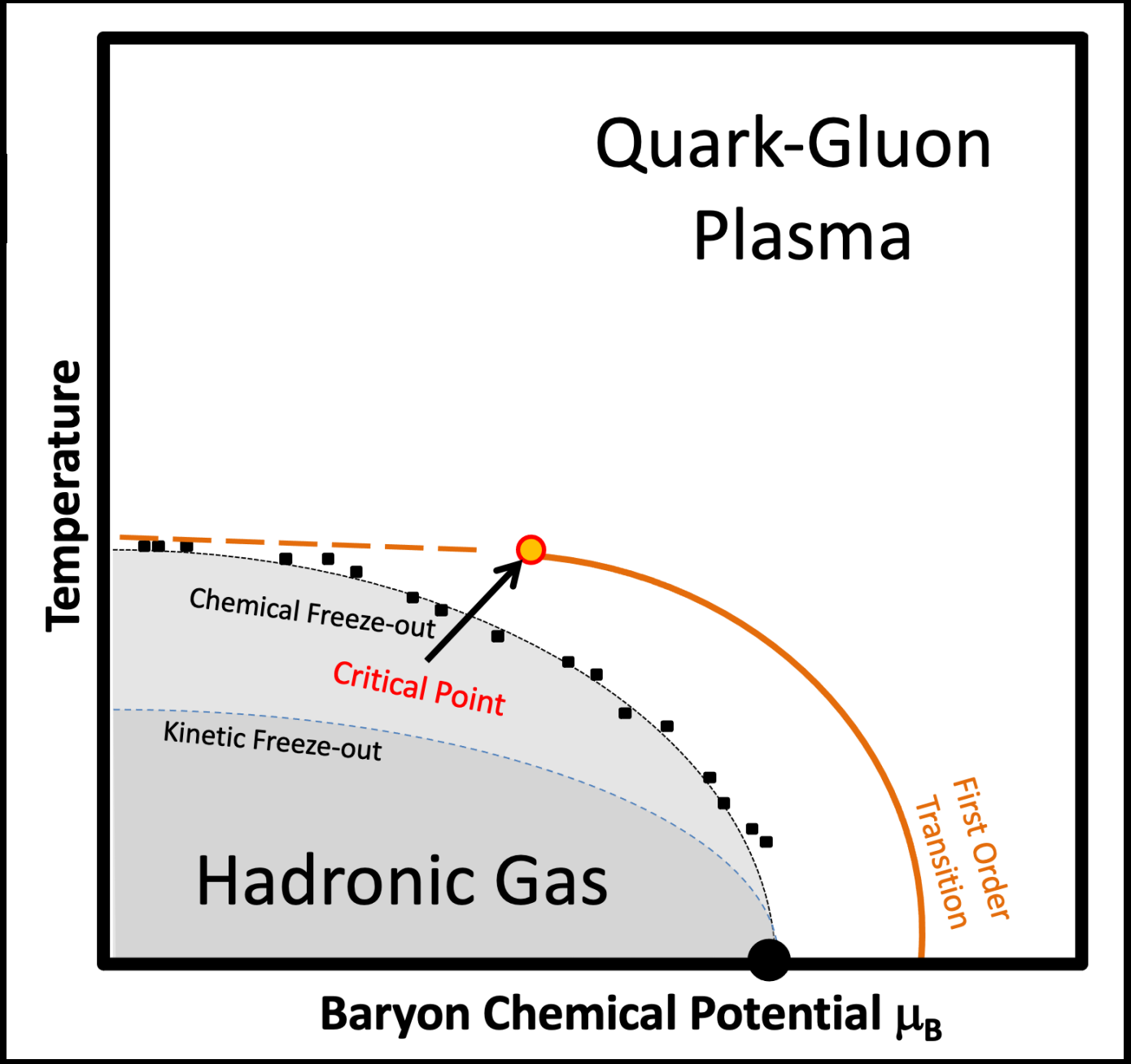
The STAR Detector

- Solenoidal magnet with 0.5T uniform field
- Time projection chamber (TPC)
- Time-of-flight (TOF) detector for precision particle identification at high momentum
- Electromagnetic calorimeters for jets, leptons, and photons



Phases of QCD Matter

QCD Phase Diagram



G. Odyniec, J. Phys.: Conf. Ser. 455 012037 (2013)
B. Kimelman, Quark Matter (2022)

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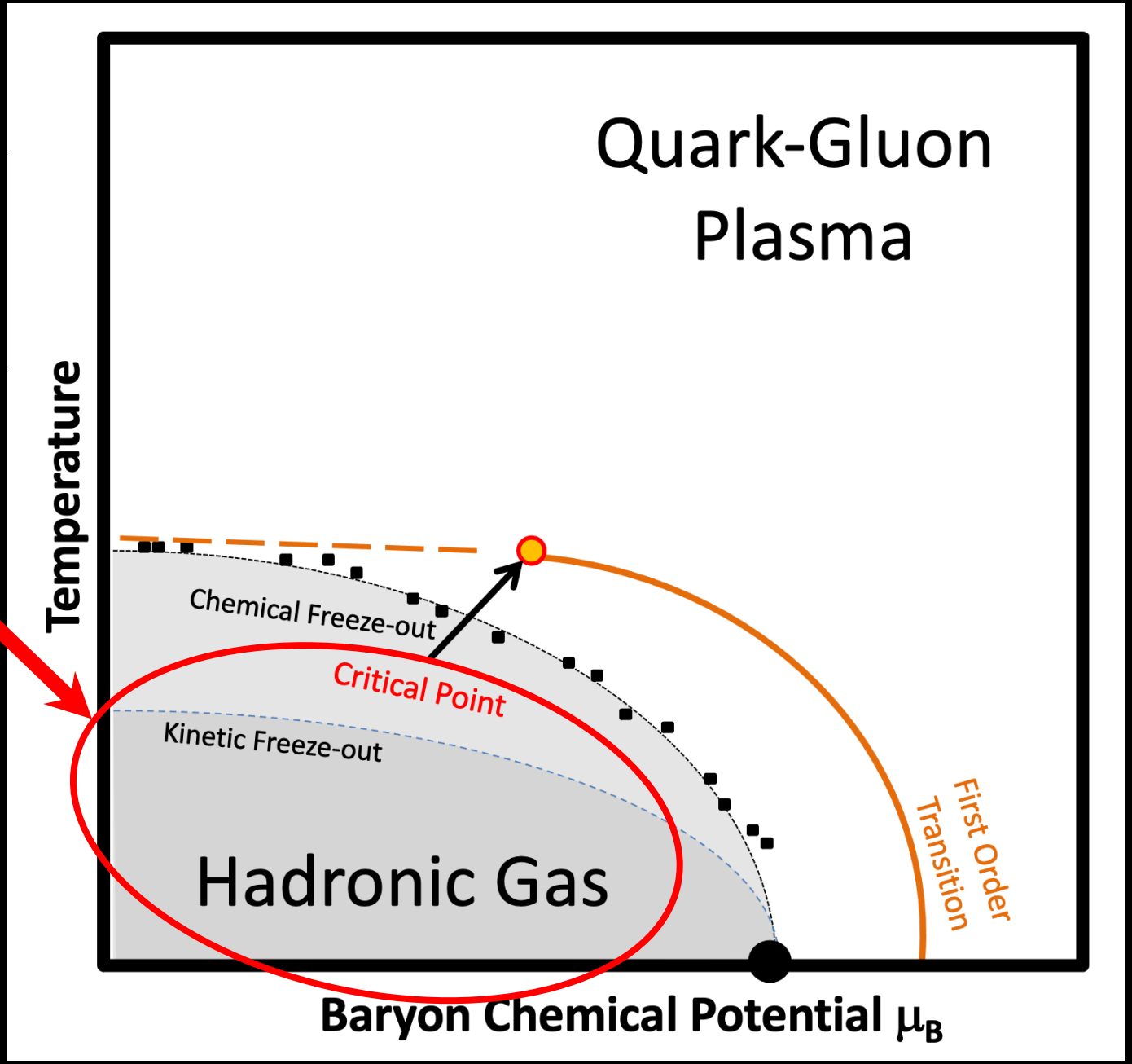

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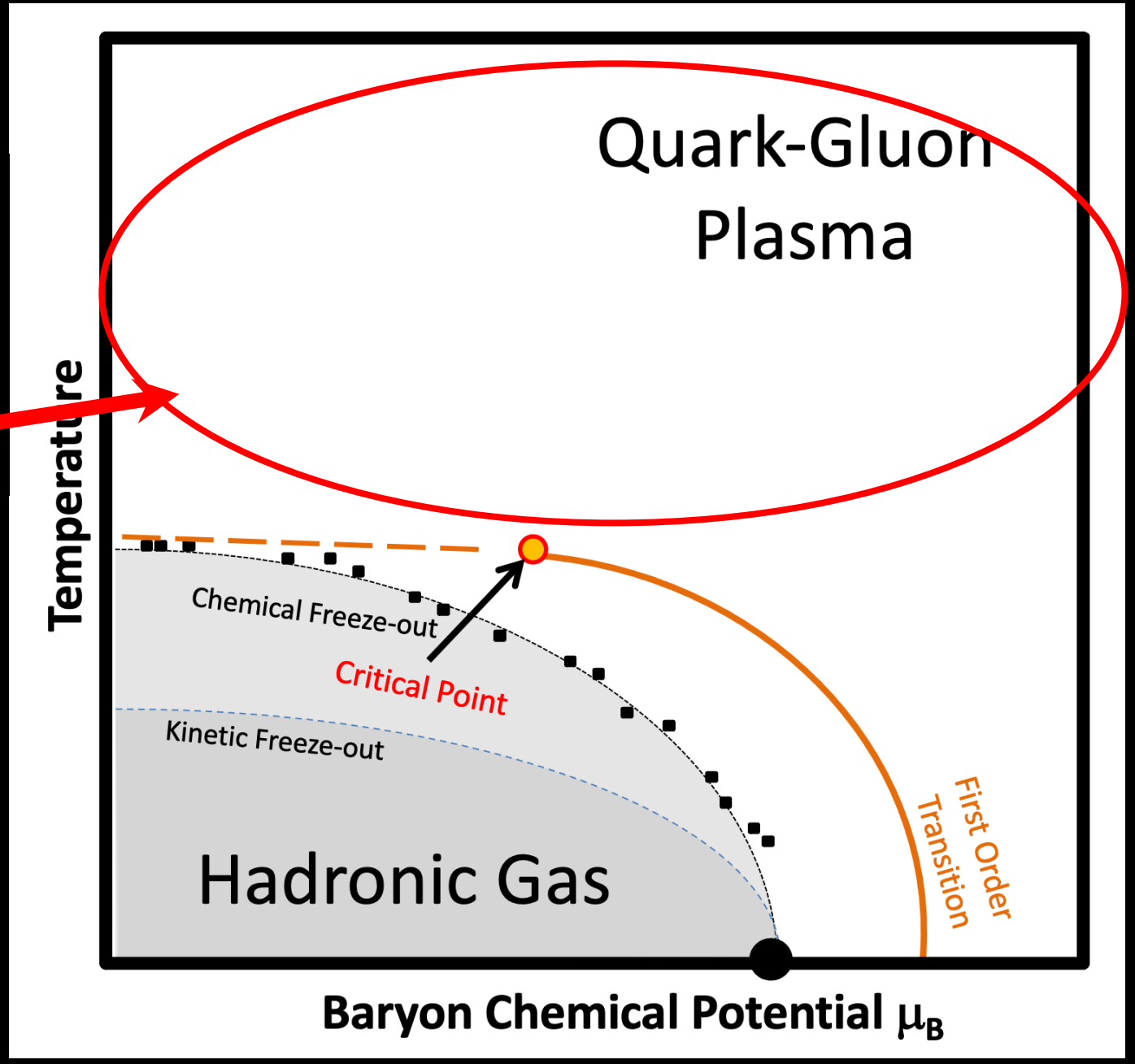

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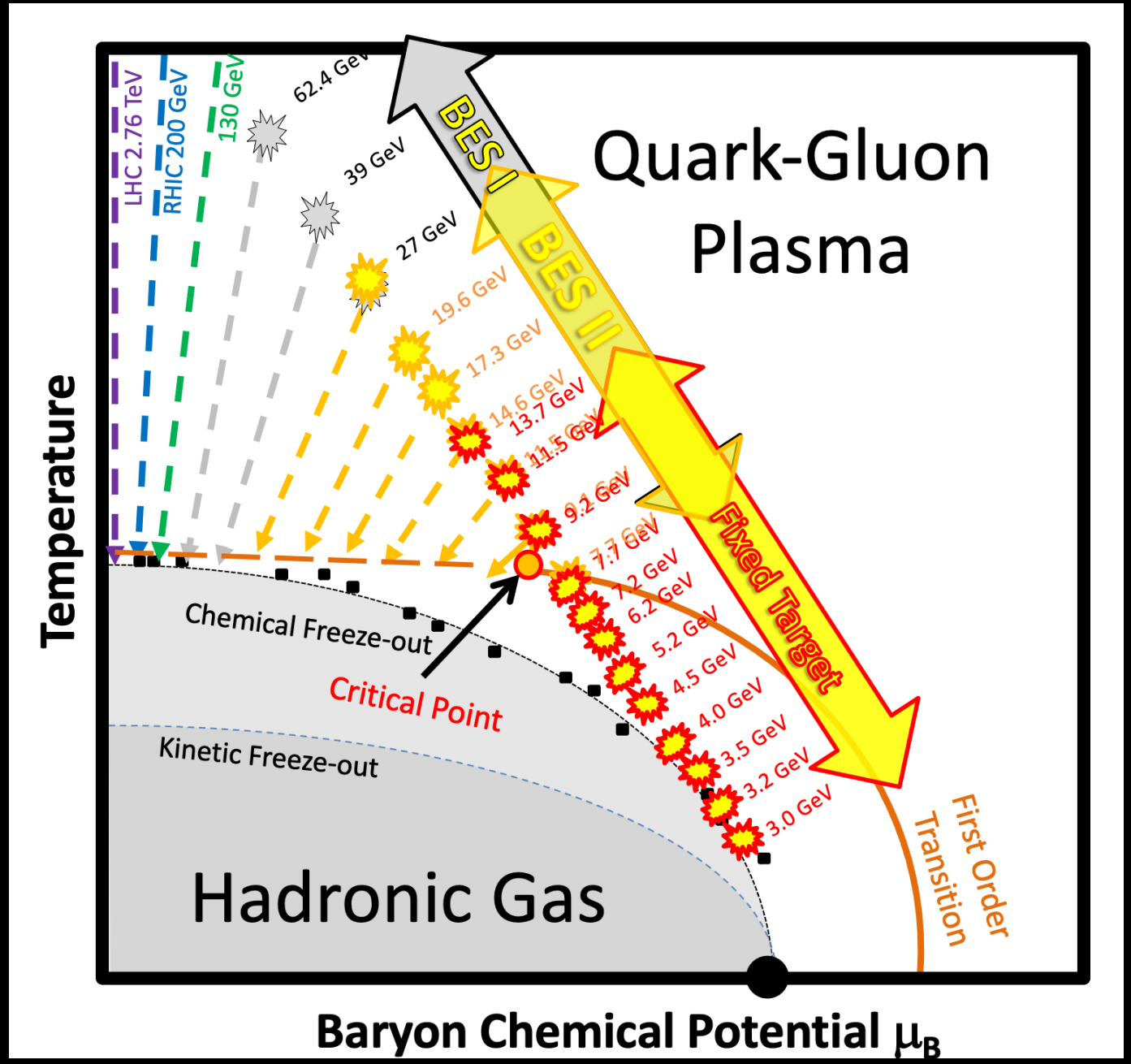
Beam Energy Scan and Fixed-Target Programs (BES-I, BES-II, FXT)

- Scanning phase of QCD matter in Au+Au collisions
- Searching for critical point, 1st-order phase transition, confinement onset…



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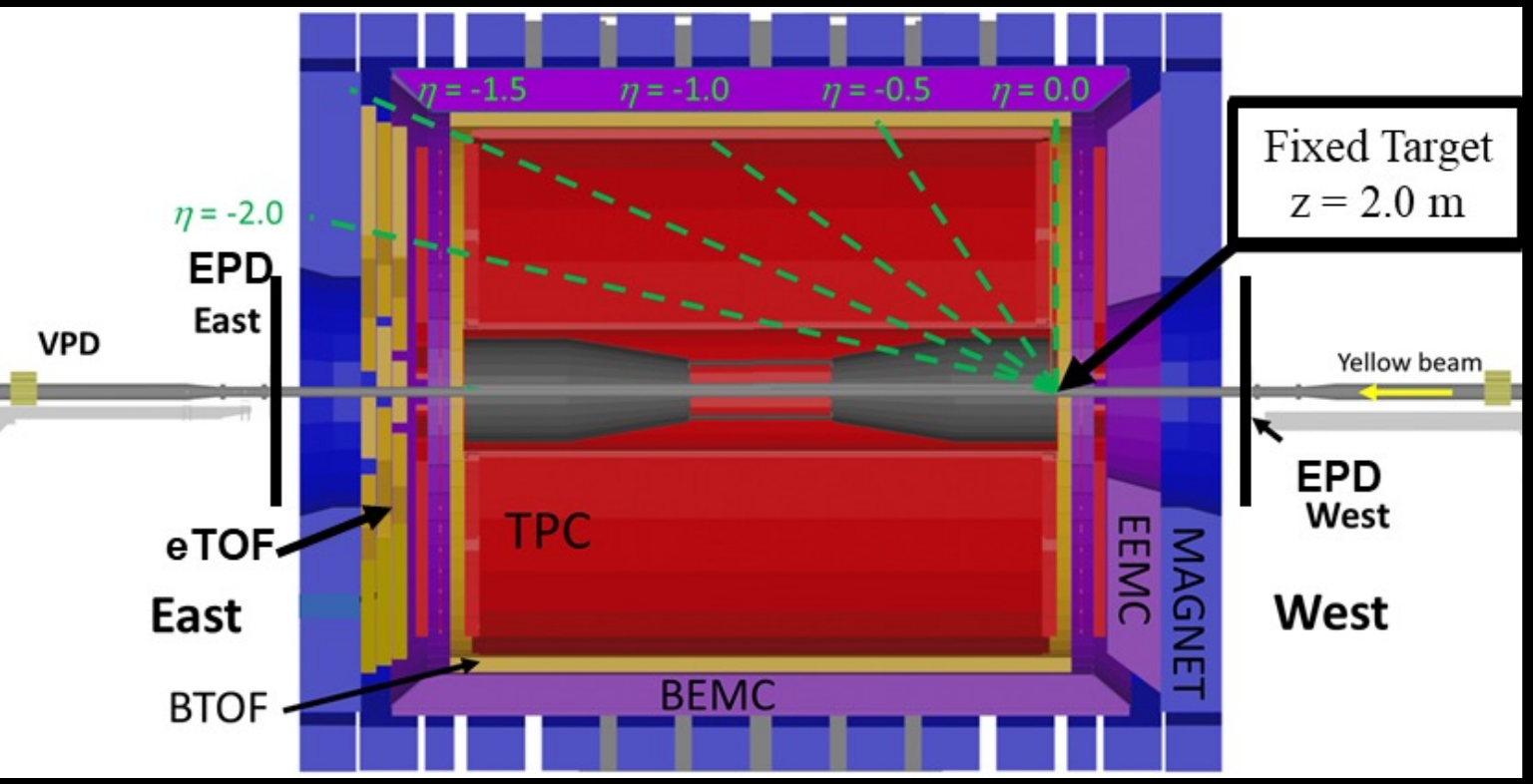
Fixed-Target Program

- 250 μm gold foil inserted into beam pipe, 2 cm below beam axis
- First physics runs at $\sqrt{s_{NN}}$ = 3.0 GeV and 7.2 GeV in 2018
- Now have data at 9 energies from $\sqrt{s_{NN}}$ of 3.0 - 7.7 GeV
- Acceptance shifts with respect to midrapidity (midrapidity outside acceptance at high end)



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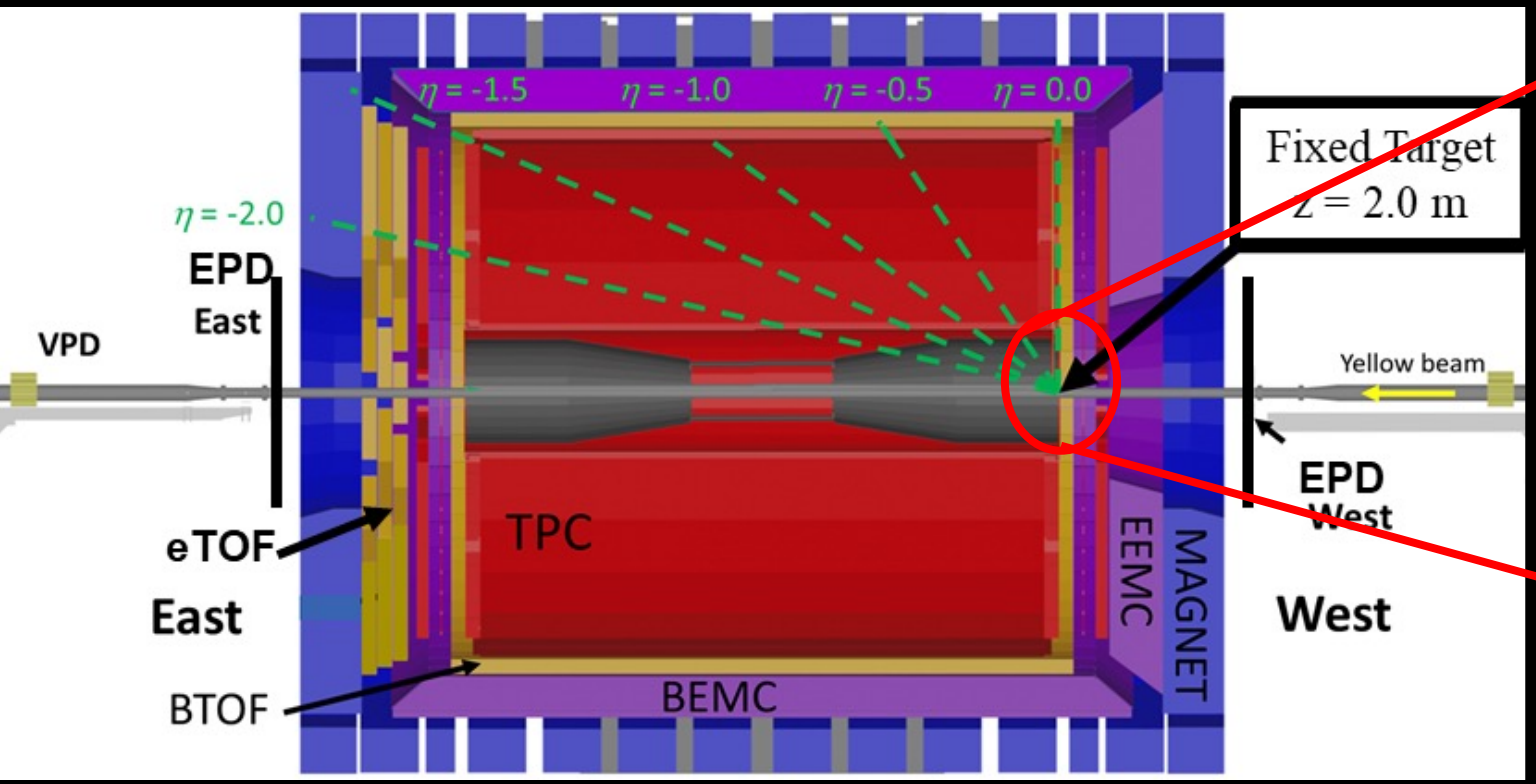
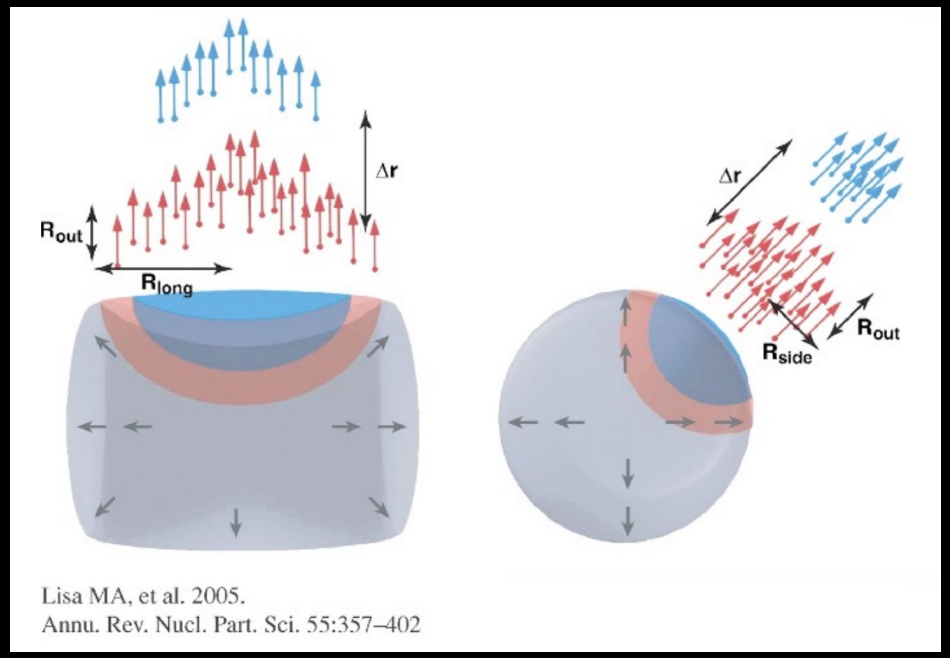


Femtoscopy → Size/Shape of Hot Nuclear Source

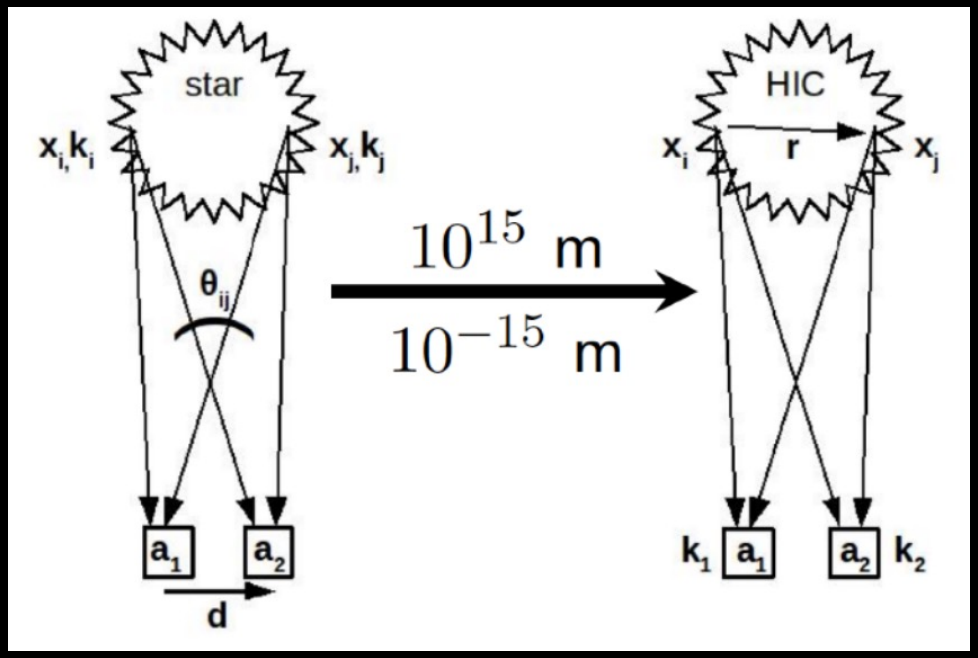
- Interference of produced particles encodes shape of source in 3D ($R_{out}/R_{side}/R_{long}$)
- Inspired by Hanbury Brown Twiss (HBT) interferometry for measuring the size of stars in astronomy

R. Hanbury Brown, R.Q. Twiss,
DOI: 10.1080/14786440708520475 (1954)

Heavy-Ion Collision Interaction Region



HBT Interferometry



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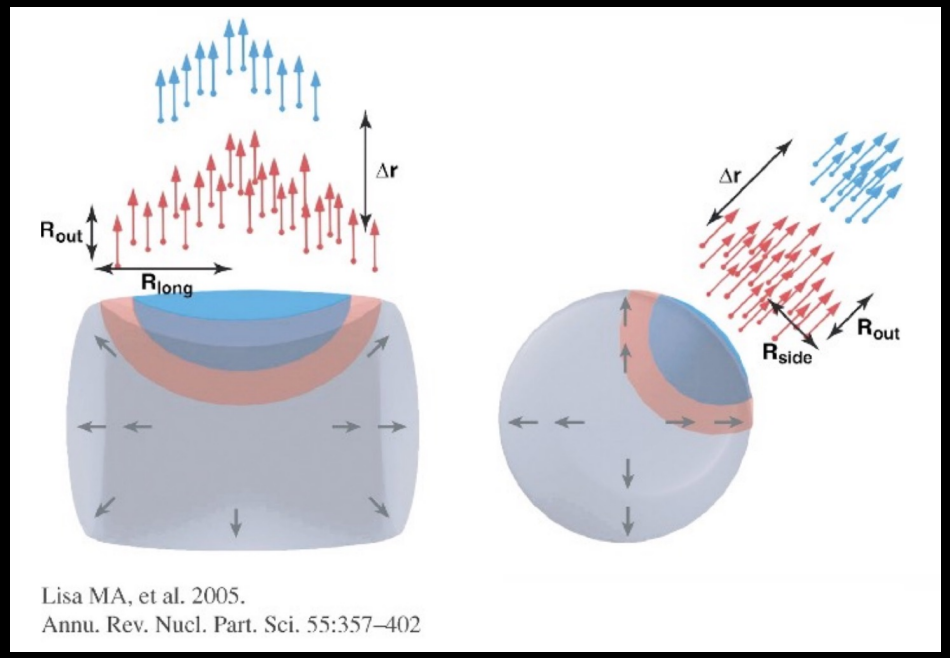
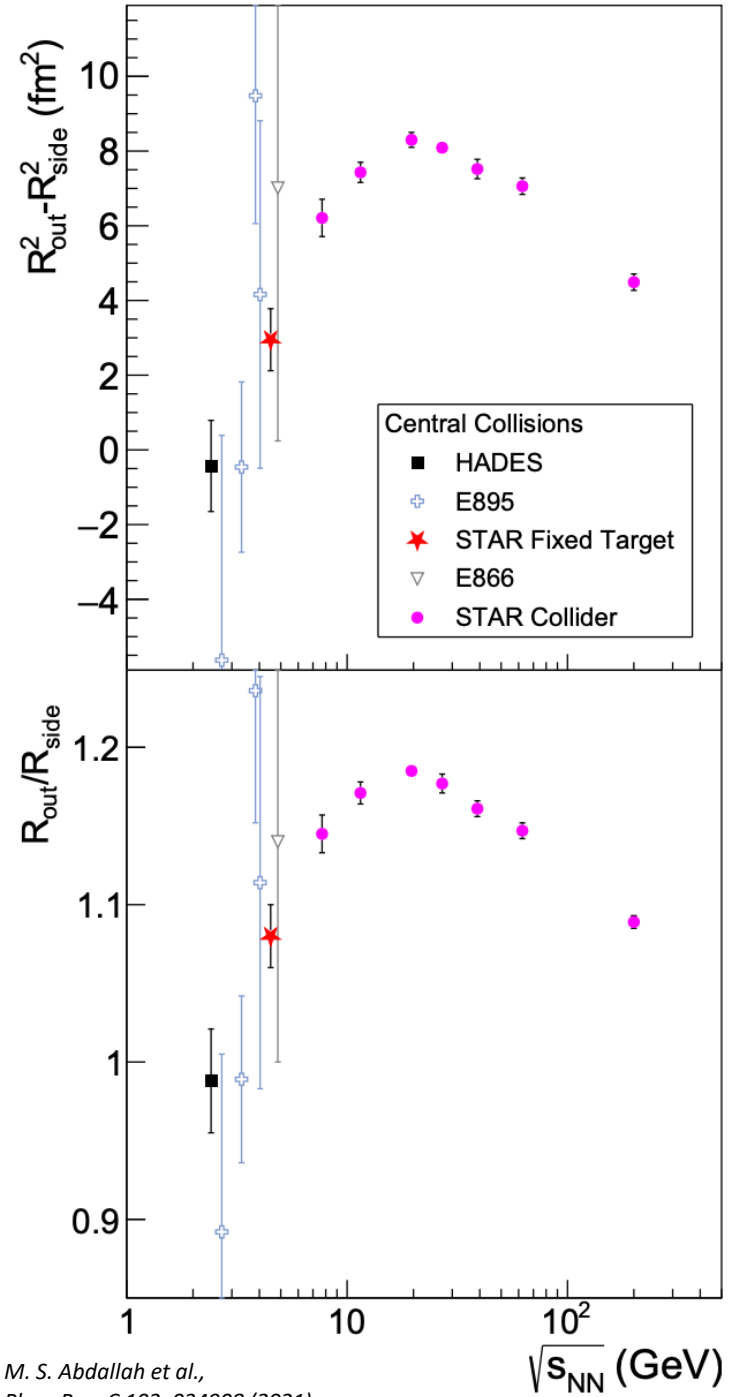
- Peak in R_{out}/R_{side} might probe first-order phase transition!

Heavy-Ion Collision Interaction Region



Lisa MA, et al. 2005.
Annu. Rev. Nucl. Part. Sci. 55:357–402



M. S. Abdallah et al., Phys. Rev. C 103, 034908 (2021)

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- Leptons can probe temperature deep within fireball
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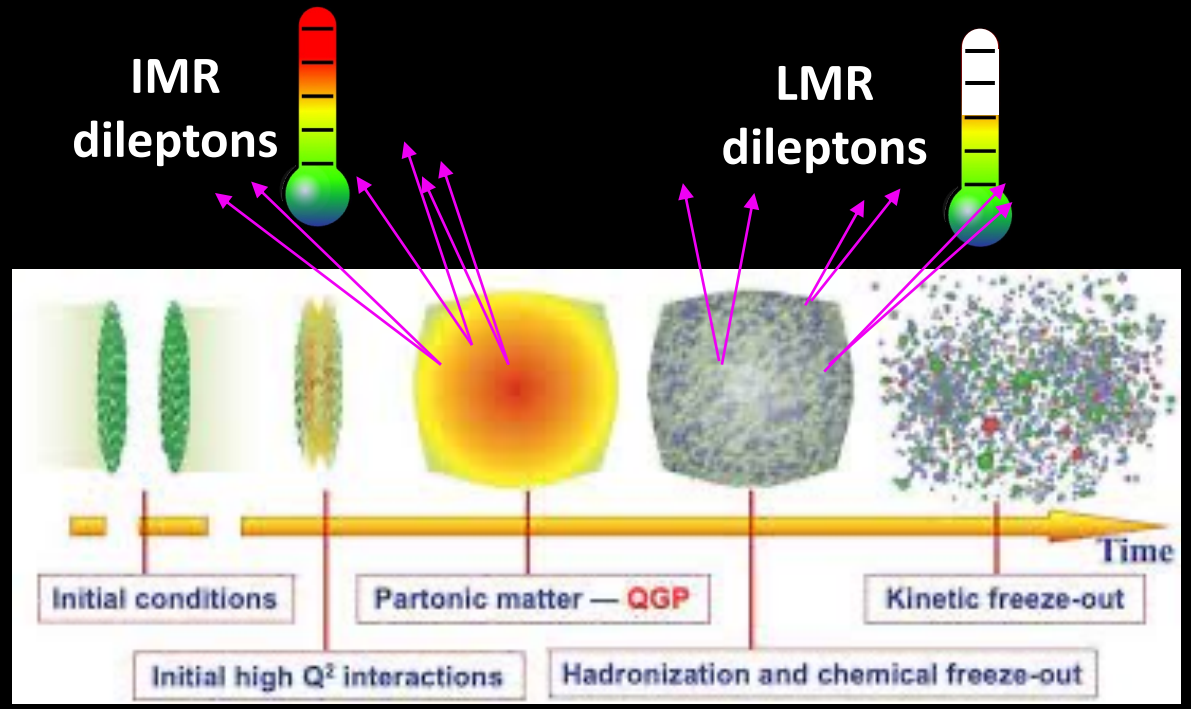

Z. Liang, M. Lisa & X. Wang, Nuclear Physics News, 30:2, 10-16 (2020)

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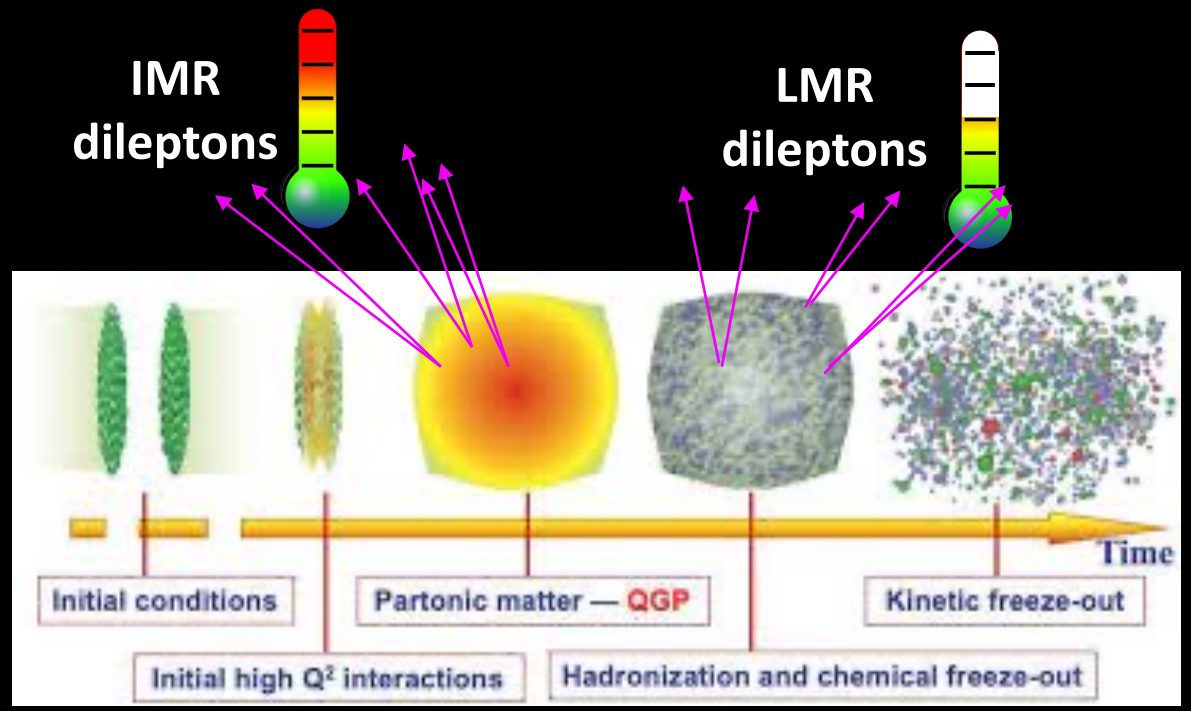

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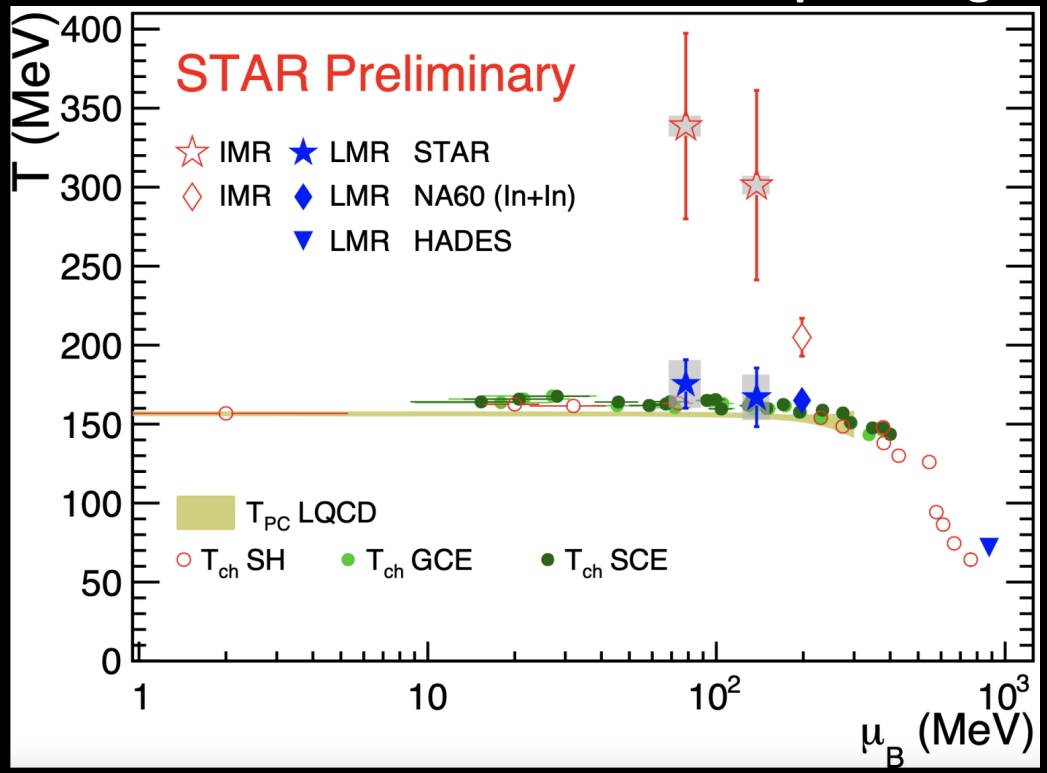
Fireball and chemical freezeout temps diverge!

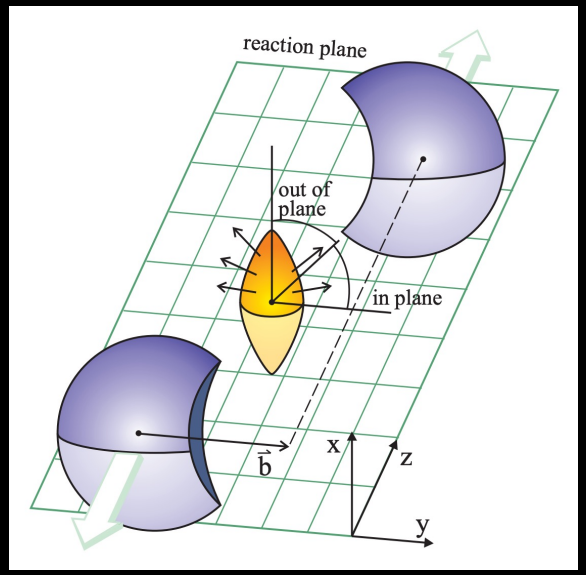


Nihar Sahoo, ICPAQGP (2023)

Flow → Fireball Constituents

- Elliptic flow (v_2): anisotropy of collision geometry → particles emitted asymmetrically

Elliptic Flow



B. Betz, arXiv:0910.4114 (2009)

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- Motivation: we infer flow of fireball constituents from detected particles
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- NCQ scaling: **N**umber of **C**onstituent **Q**uark scaling → elliptic flow of hadrons scales with their number of valence quarks.

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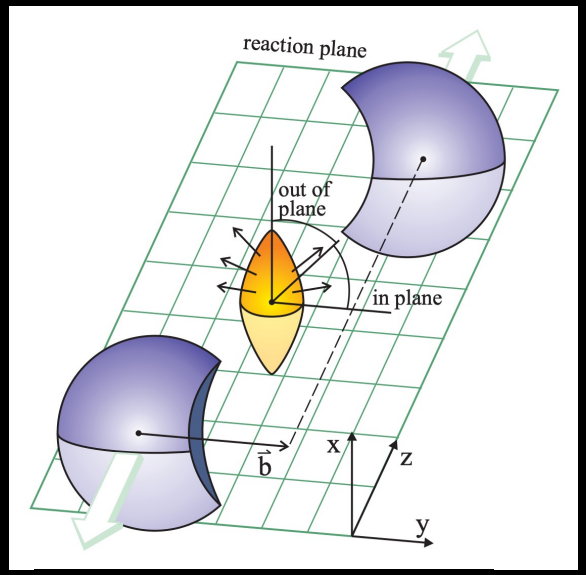

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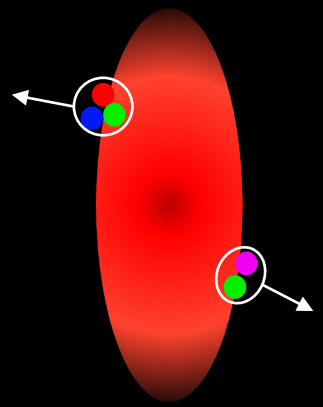
Hadrons Freezing Out



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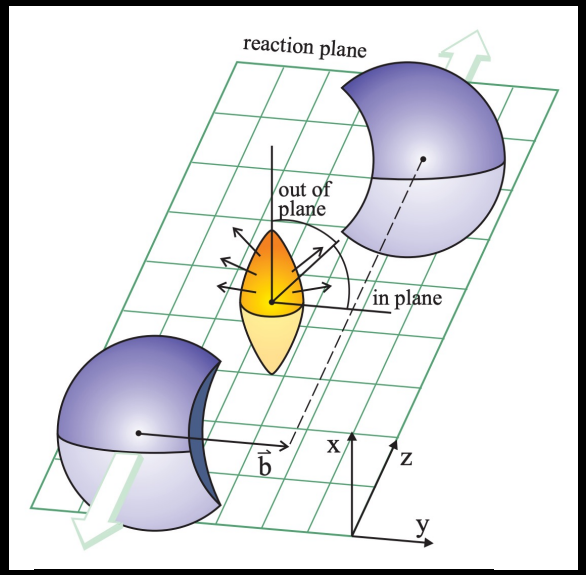
Elliptic Flow



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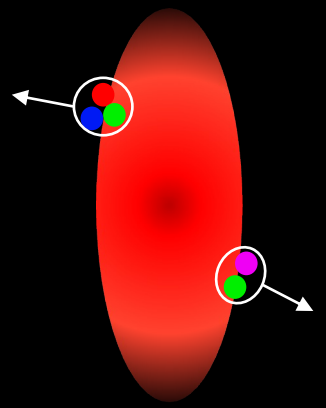
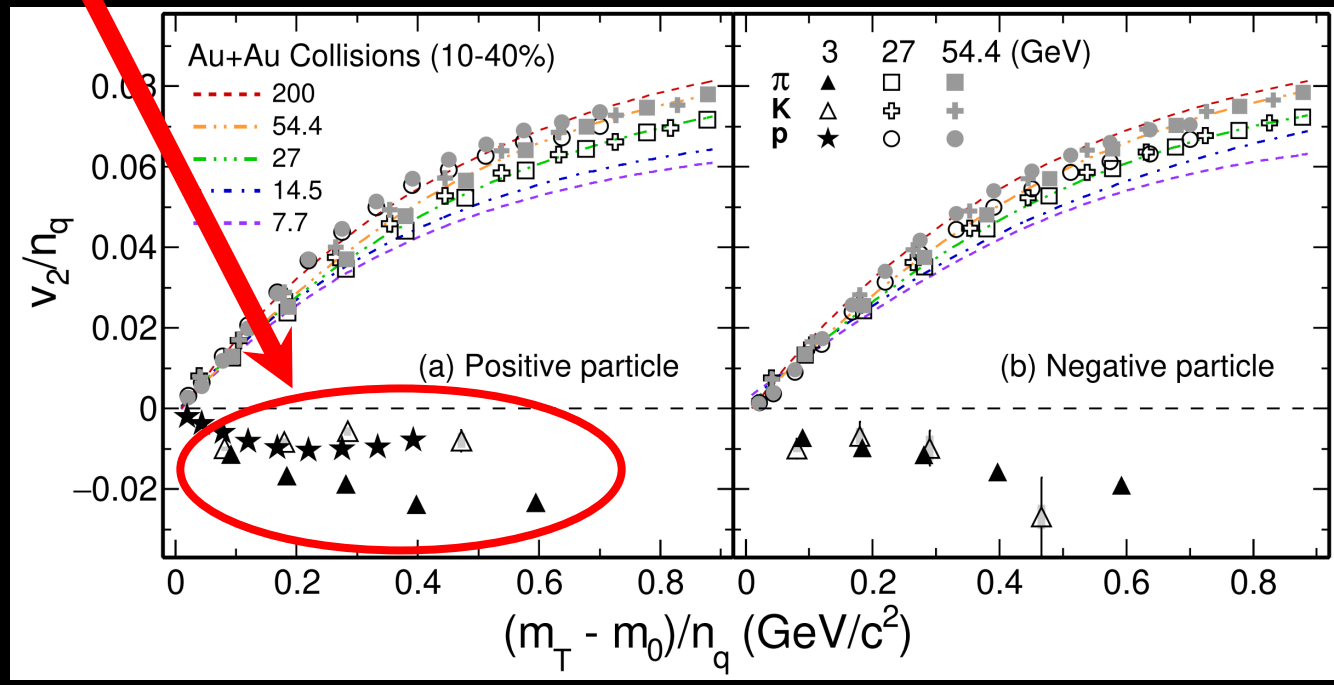


Disappearance of NCQ Scaling at 3 GeV!

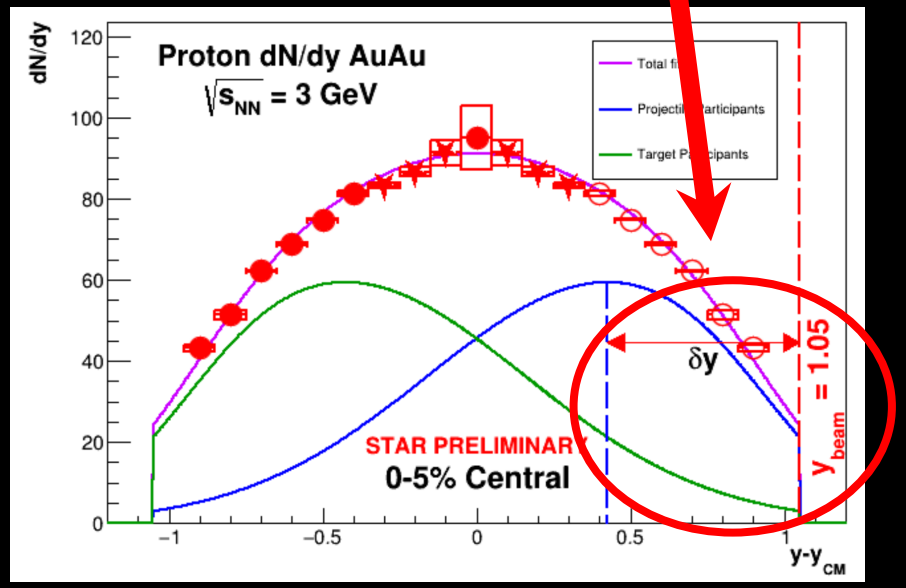


Phys. Lett. B 827.137003 (2022)

Particle Spectra → Stopping and the Equation of State

- Protons shifted from beam rapidity (stopping)

Proton Number by Rapidity



Particle Spectra → Stopping and the Equation of State

- Protons shifted from beam rapidity (stopping)
- Less stopping → softer equation of state

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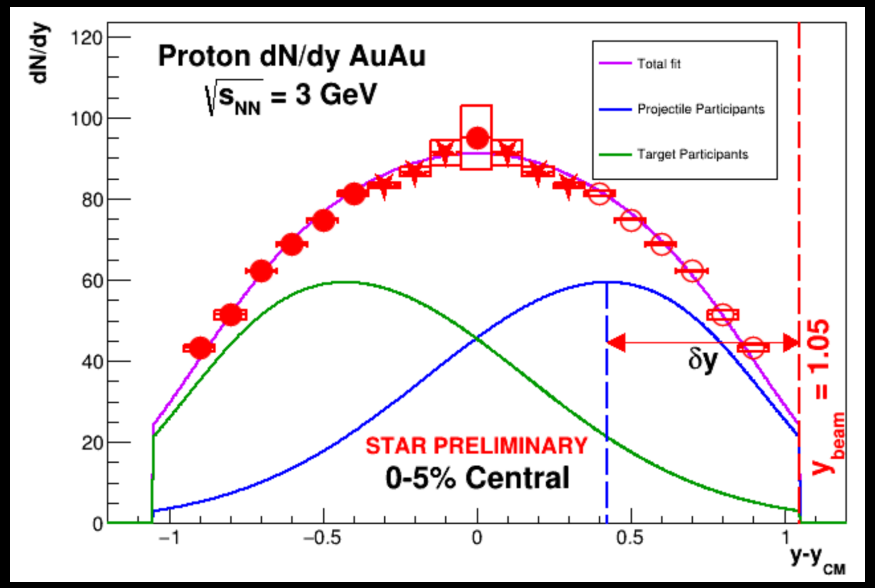
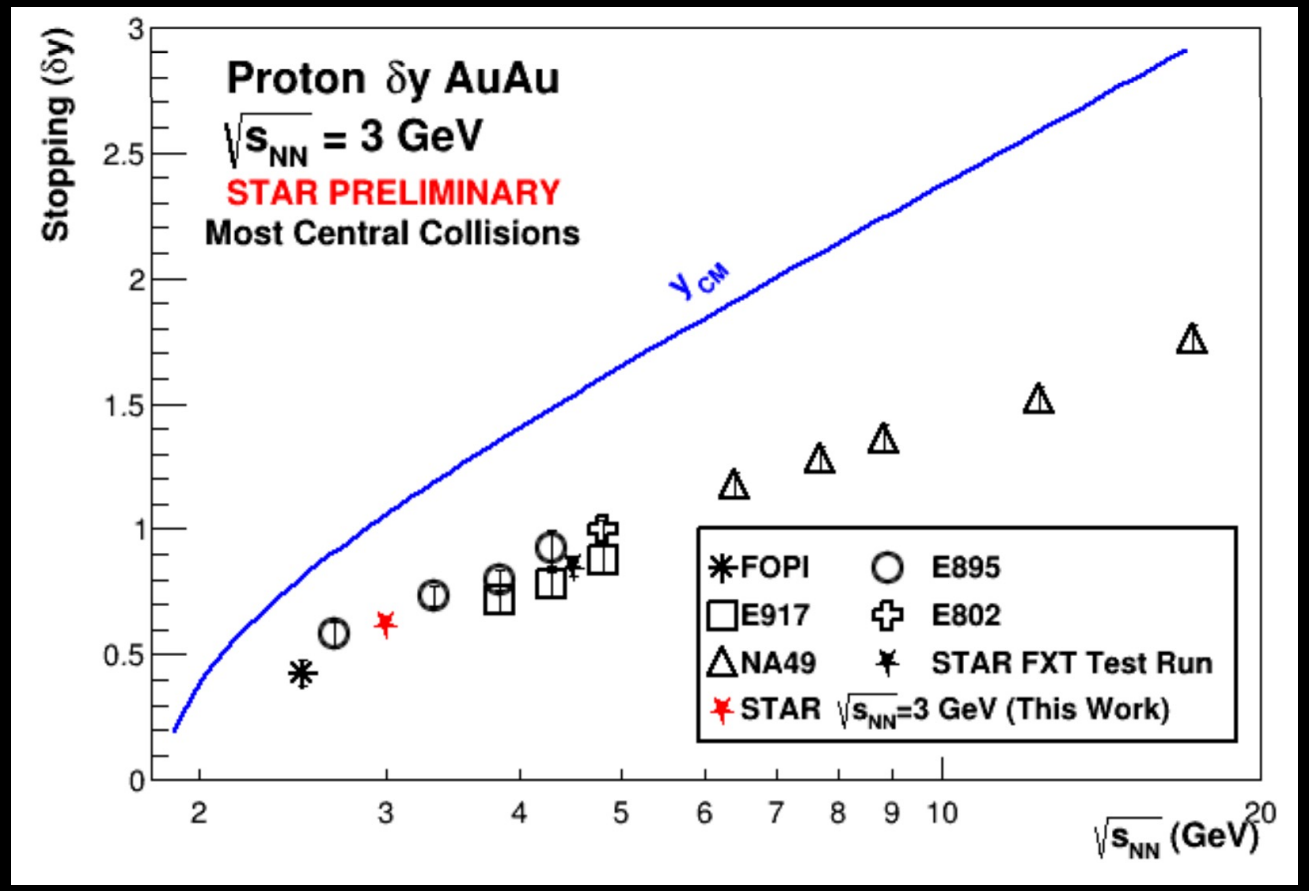


Proton Stopping in Au+Au Collisions



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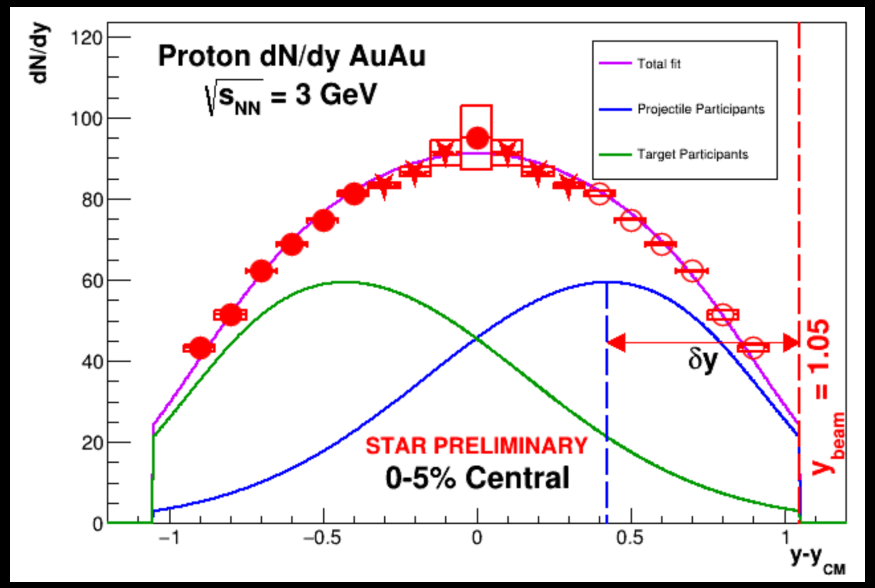

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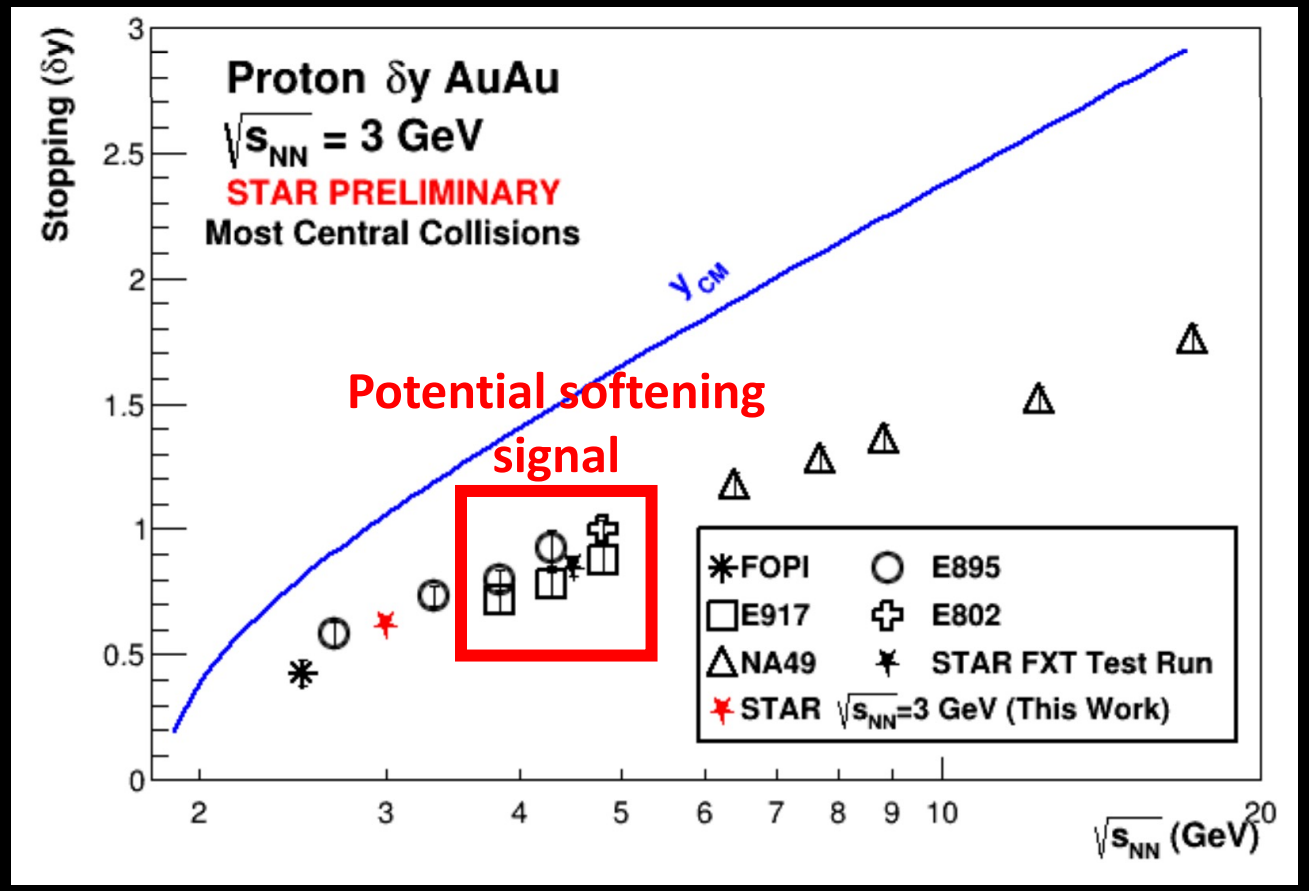

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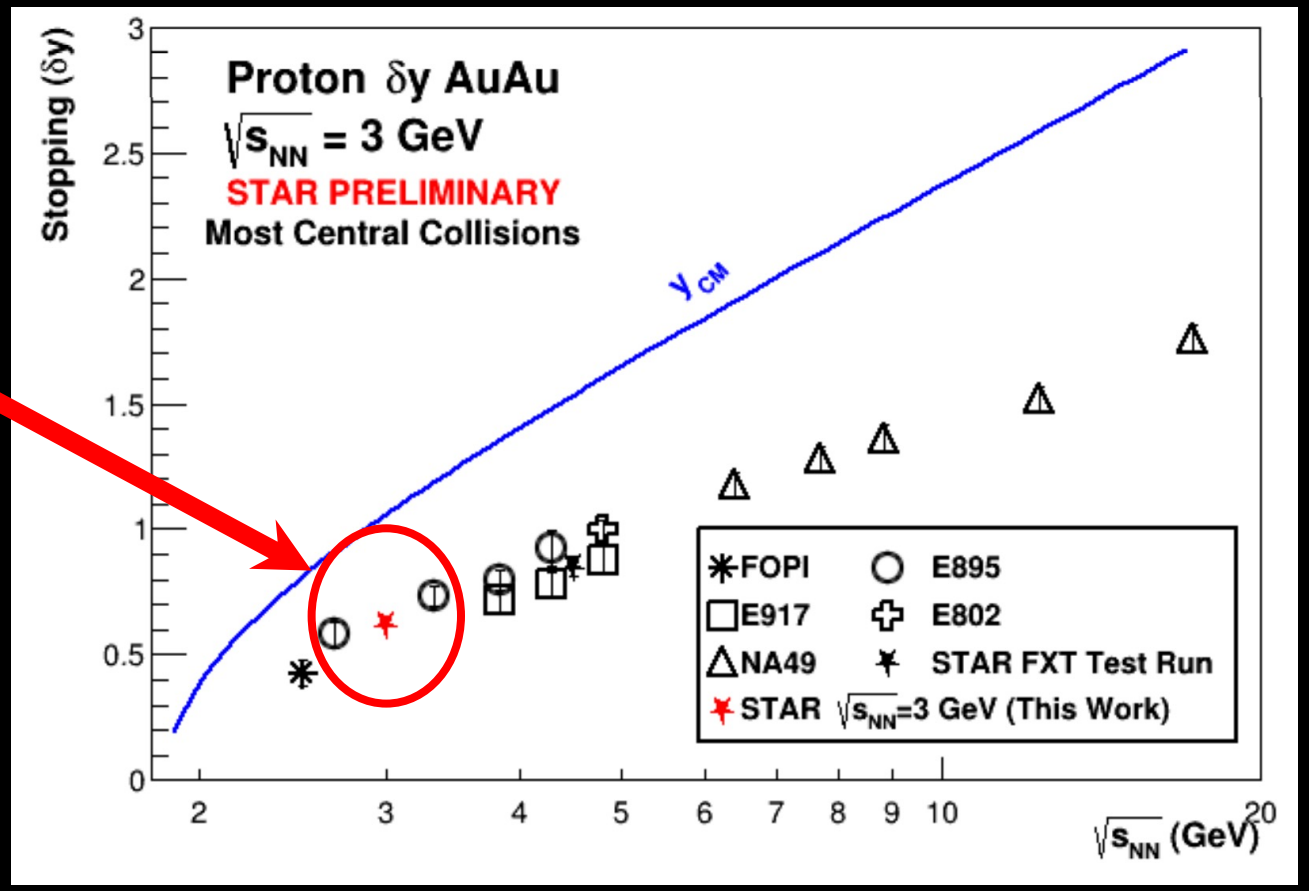

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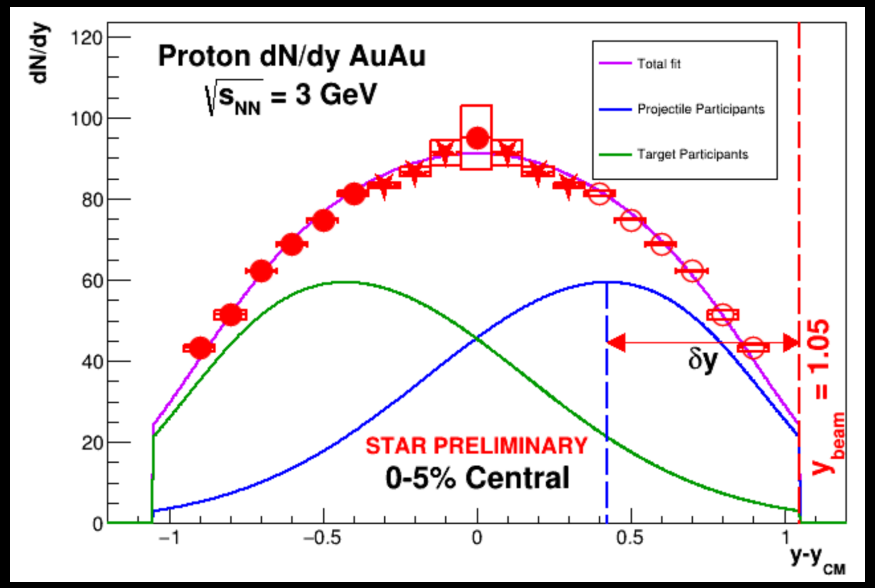

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- New 3 GeV measurement
- Keep an eye out for remaining fixed-target measurements from STAR!

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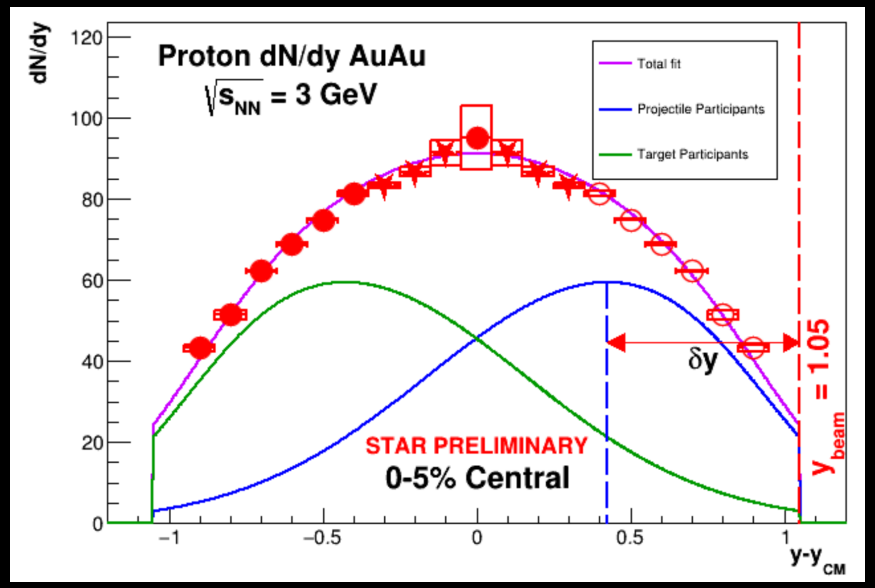

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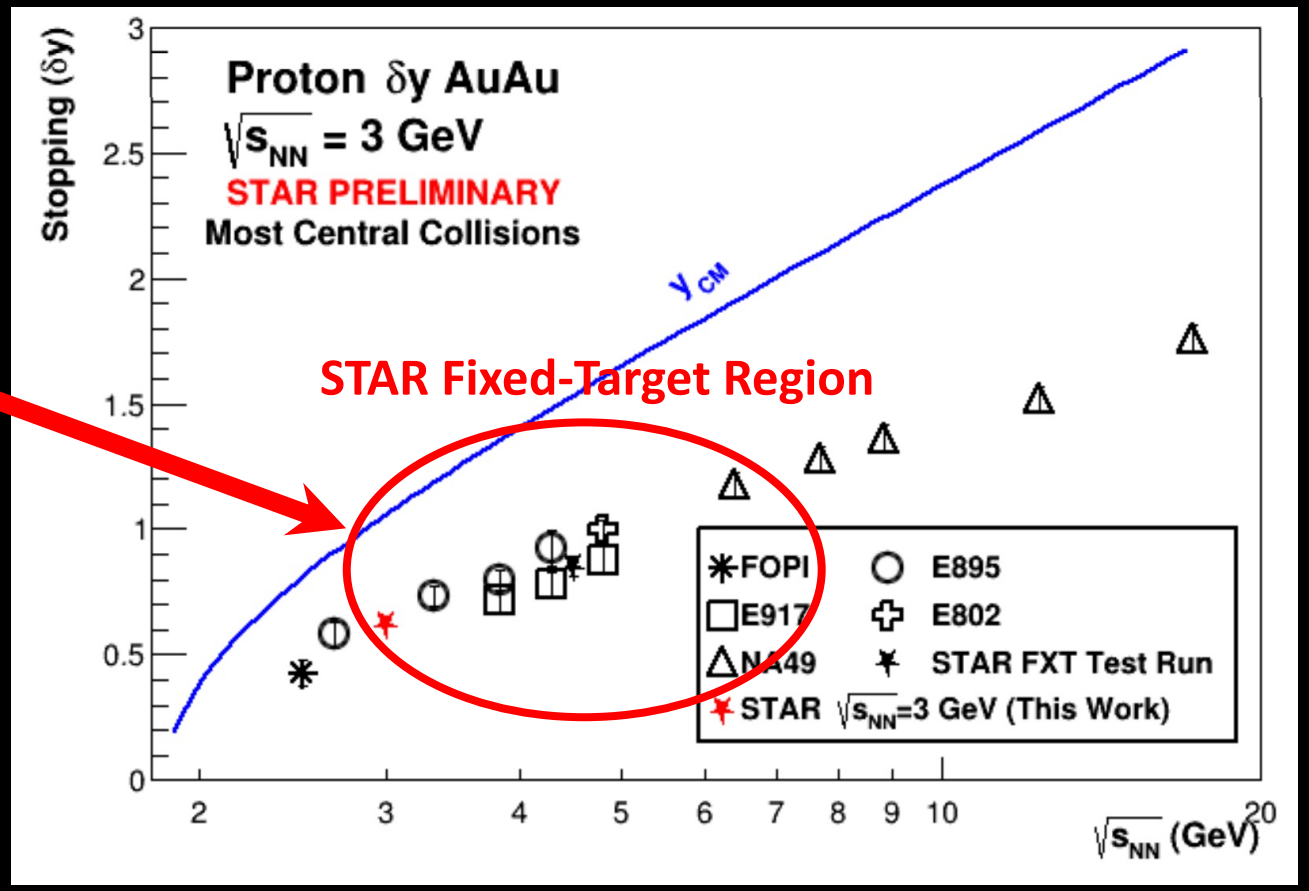
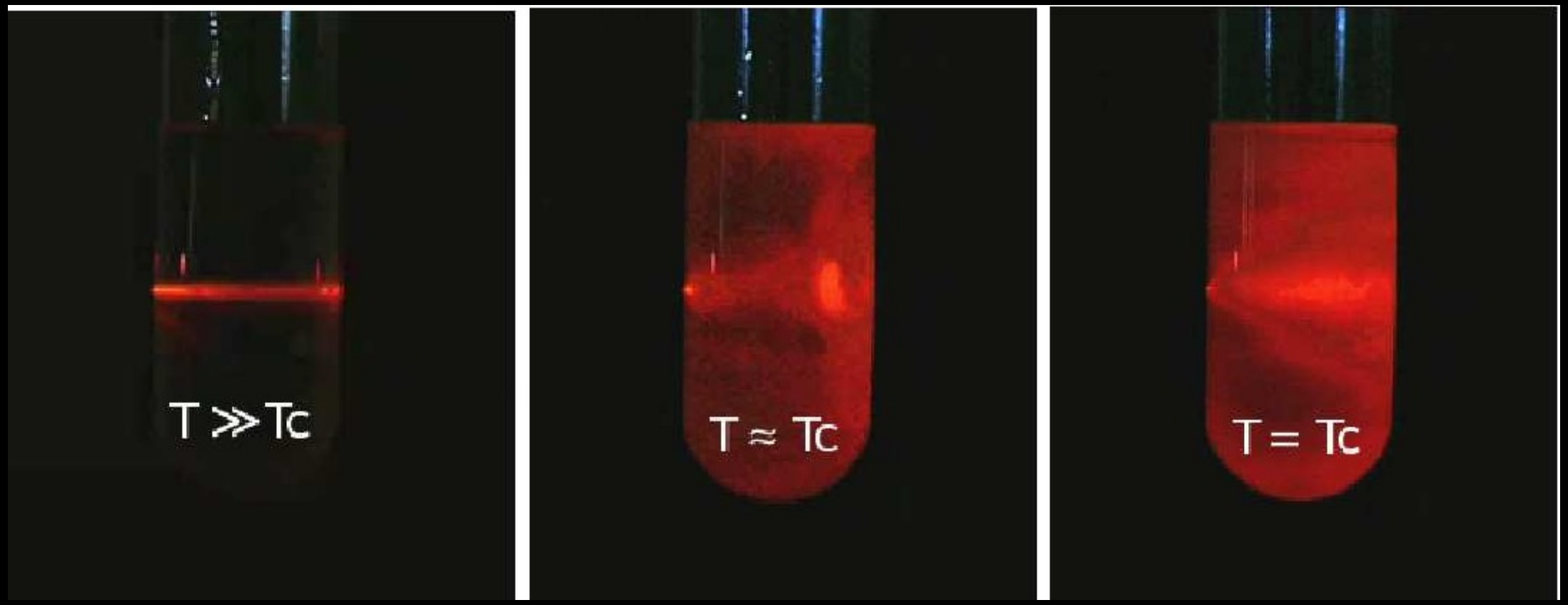


Critical Fluctuations



T. Csorgo, arXiv:0903.0669 (2009)

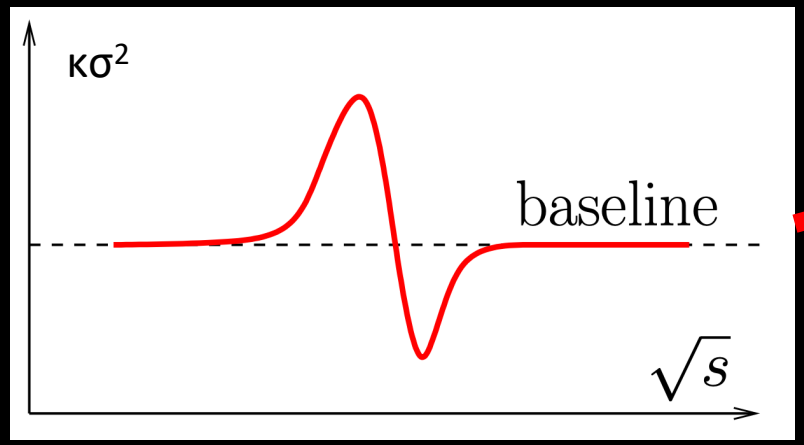
High Moments Analyses → Proton Kurtosis and Critical Point!

- Non-monotonic collision-energy dependence of baryon-number kurtosis predicted near critical point
- Counting (anti)protons in each event (N)
- Measuring mean, variance, skewness, and kurtosis

$$\kappa = \left[\left\langle (\delta N)^4 \right\rangle / \sigma^4\right] - 3 \quad (\delta N = N - \langle N \rangle)$$

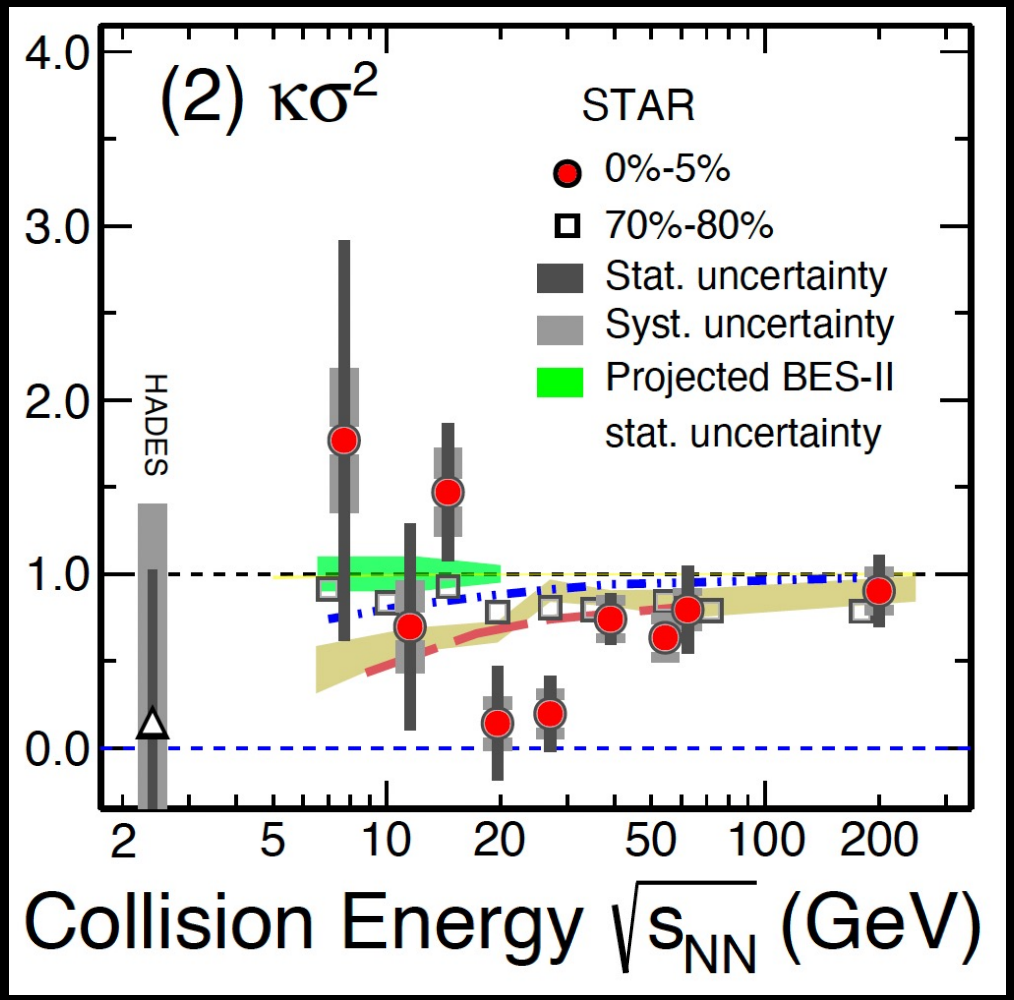
- BES-I observed non-monotonicity with 3.1σ significance

Predicted Fluctuation in Kurtosis Near Critical Point



M. Stephanov. J. Physics G.: Nucl. Part. Phys. 38 (2011) 124147

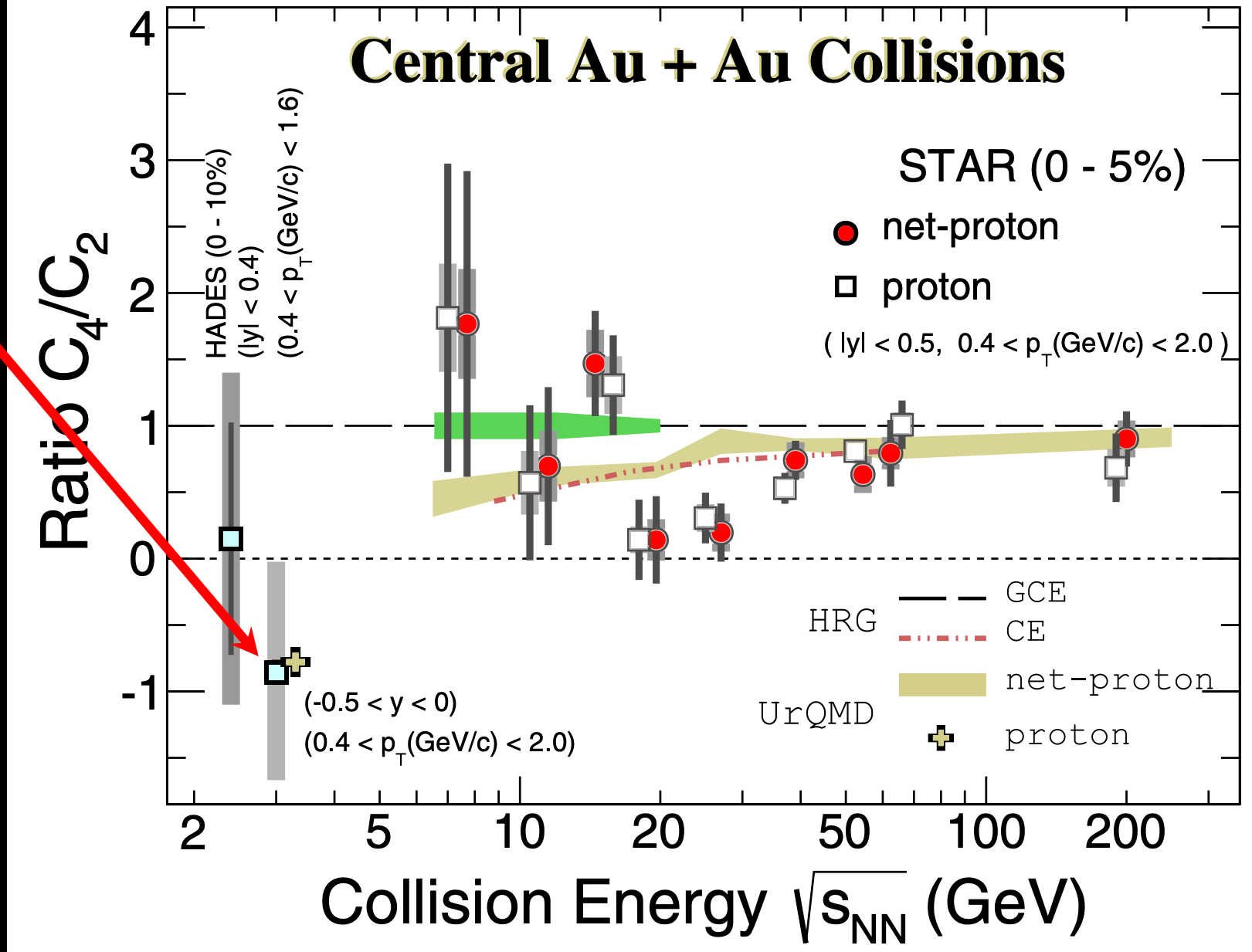
BES-I Kurtosis Results



J. Adam et al. (STAR Collaboration), Phys. Rev. Lett. 126, 092301

Proton Kurtosis

- New 3 GeV data point



STAR, Phys. Rev. Lett. 128, 202303 (2022); Phys.Rev.C 107.024908 (2023).
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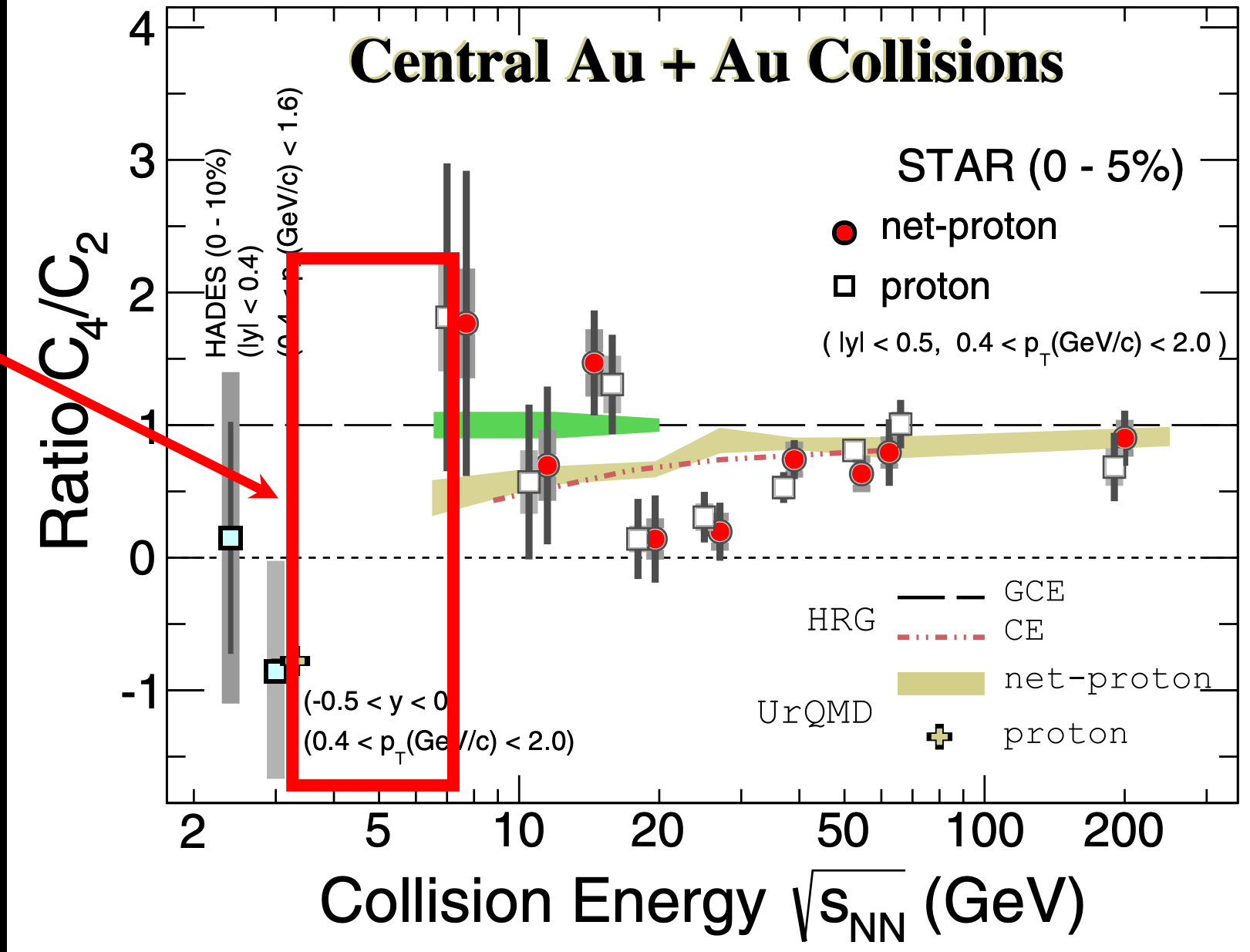
- FXT Program will cover gap (my analysis!)



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Proton Kurtosis

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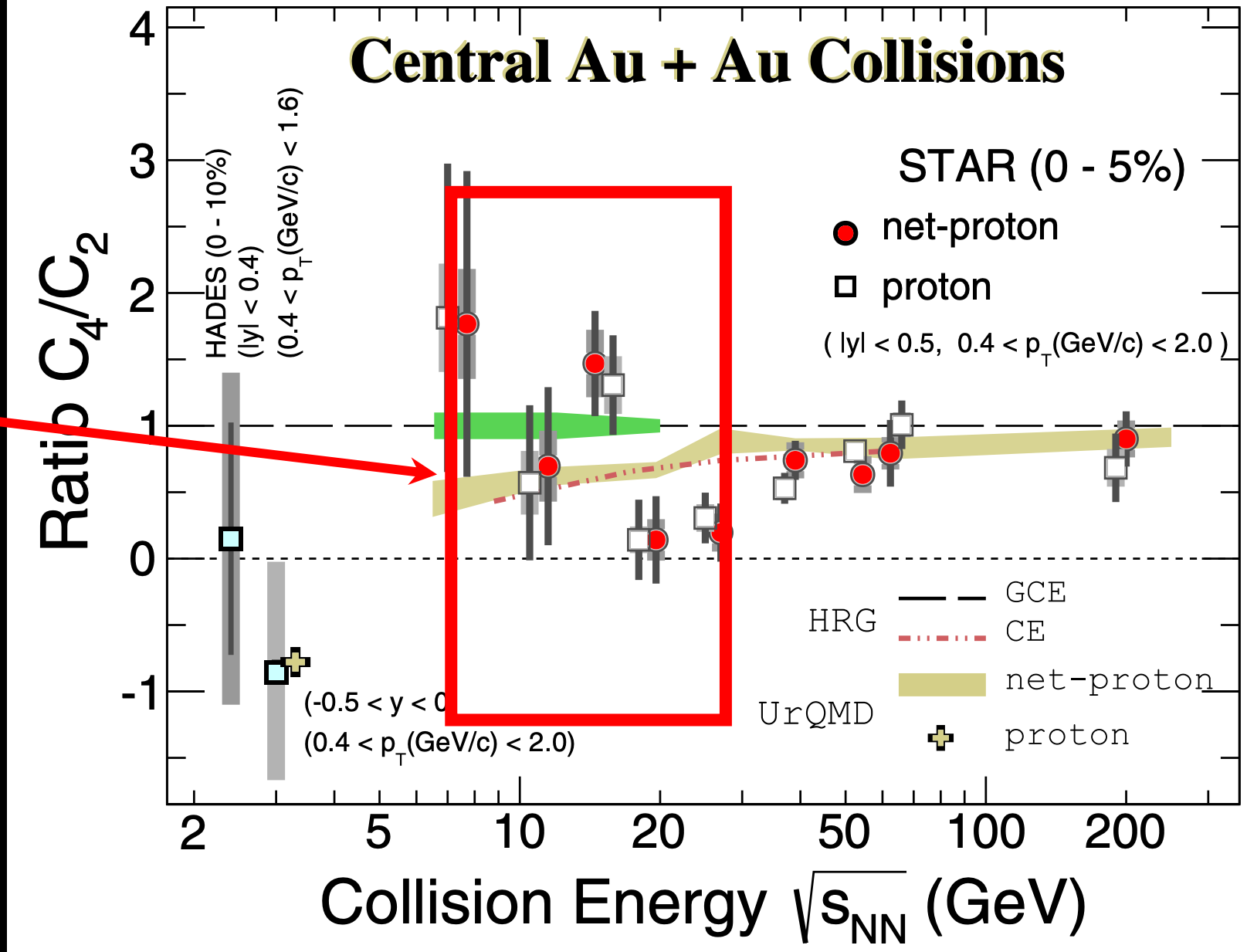
- High-statistics data re-collected at BES-I energies below 27 GeV (BES-II)



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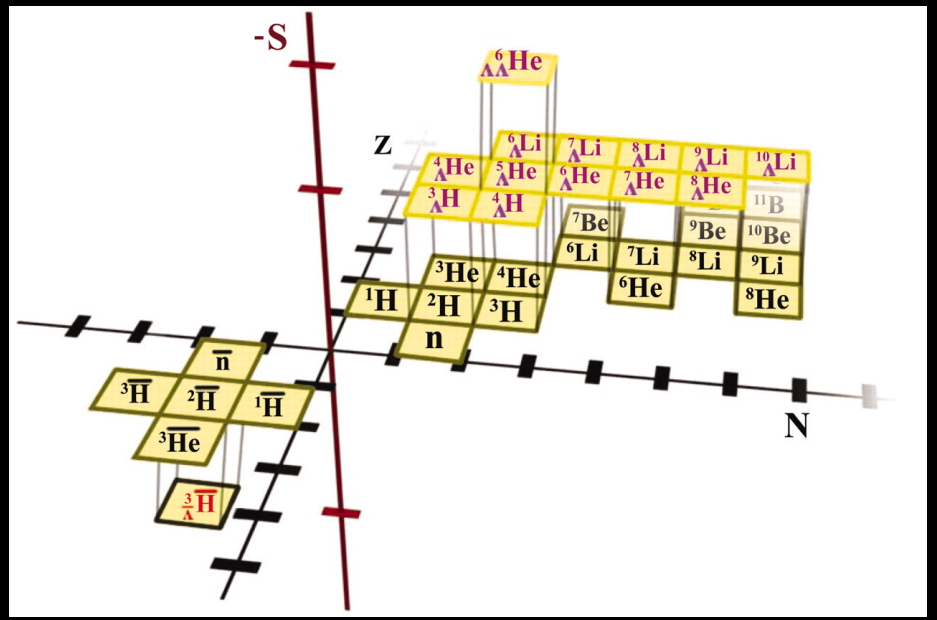
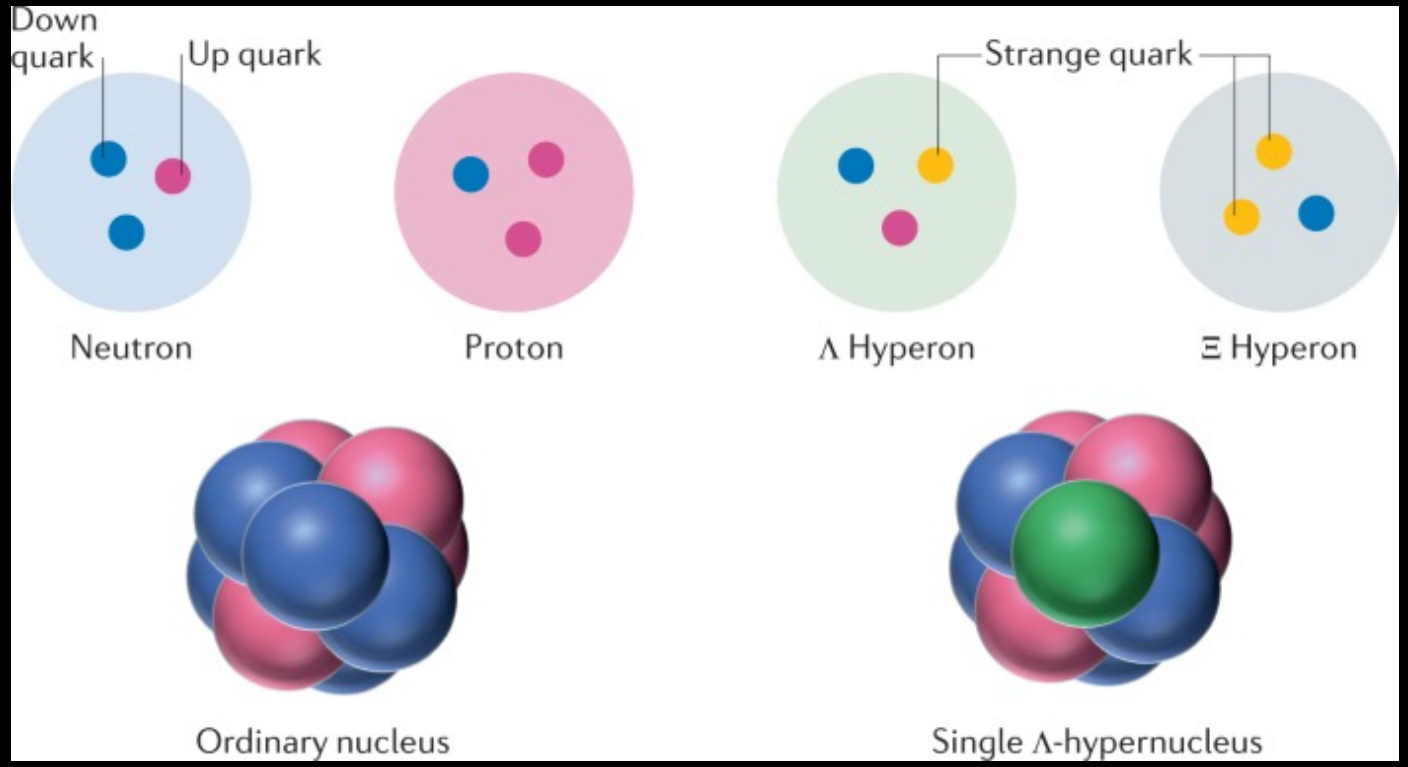
Hypernuclei → An Interesting Aside to the Phase Diagram

- Replace one nucleon by a nucleon with strangeness (**Λ** or Ξ)

Nuclei in 3 Dimensions



STAR, Science 328, 58-62(2010)



Saito, T.R., Dou, W., Drozd, V. et al., Nat Rev Phys 3, 803–813 (2021)

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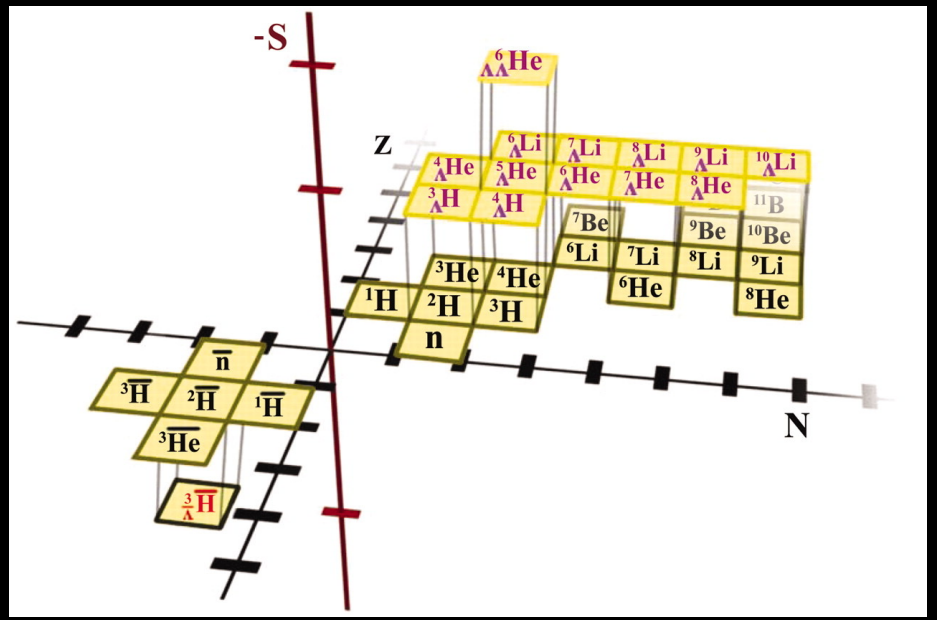

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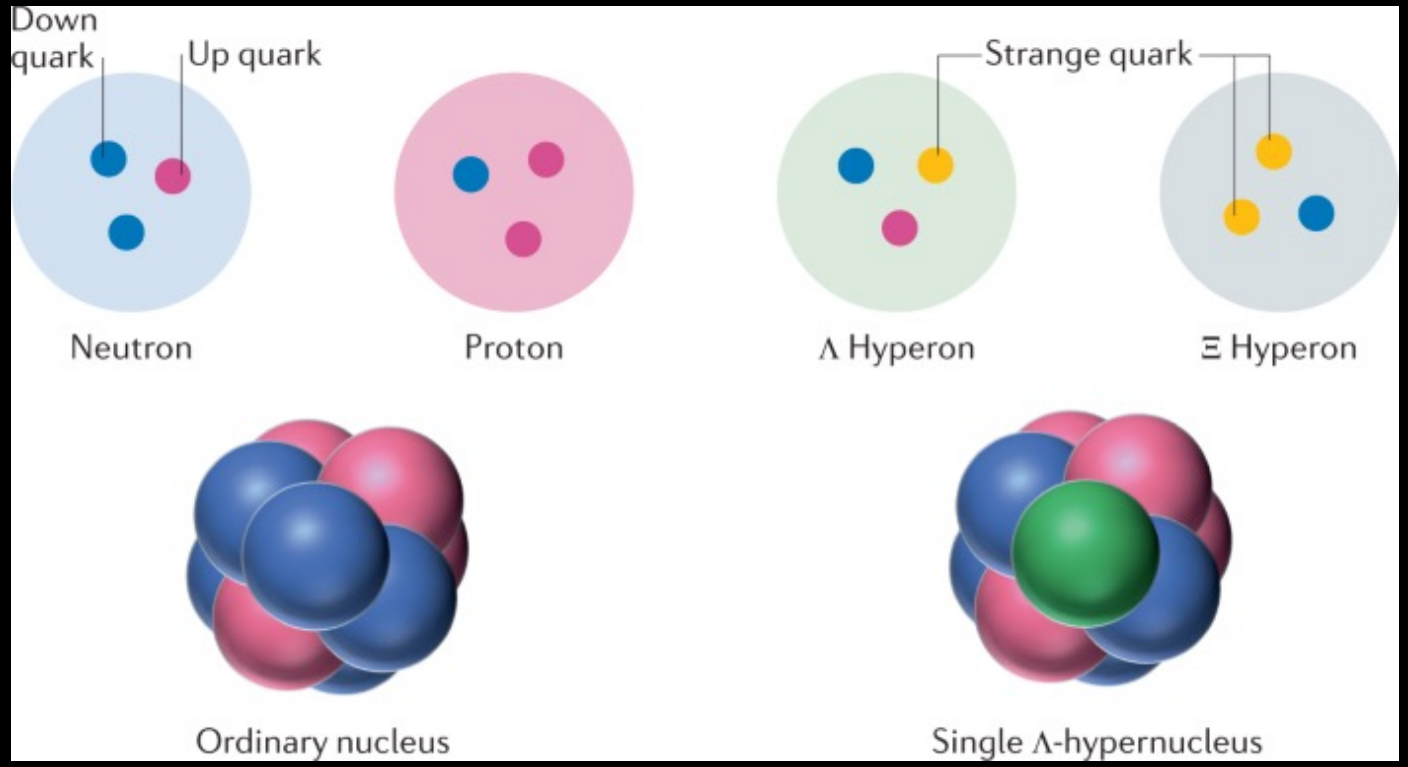

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- STAR observed anti-hyper-hydrogen-4 for the first time!

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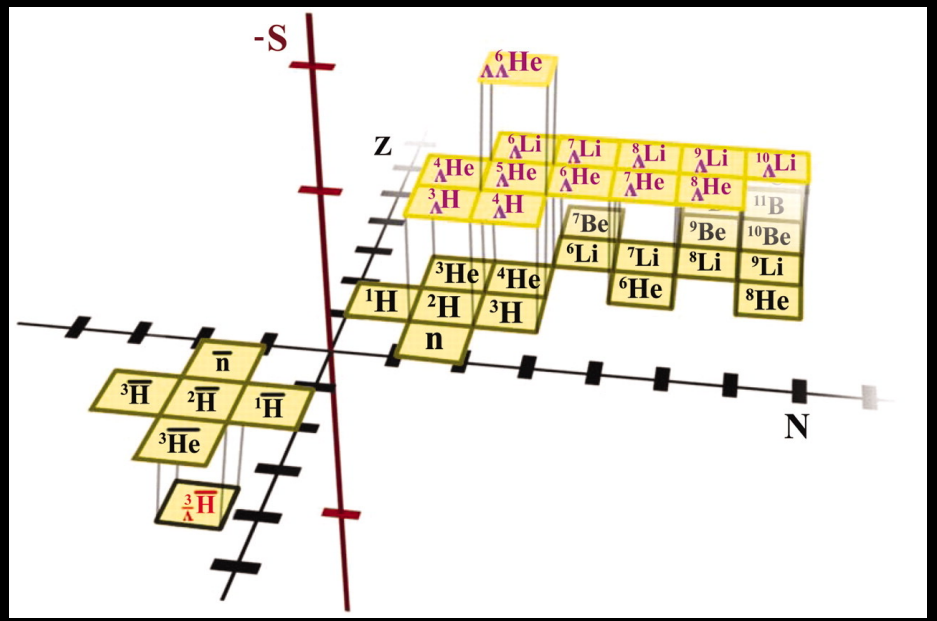
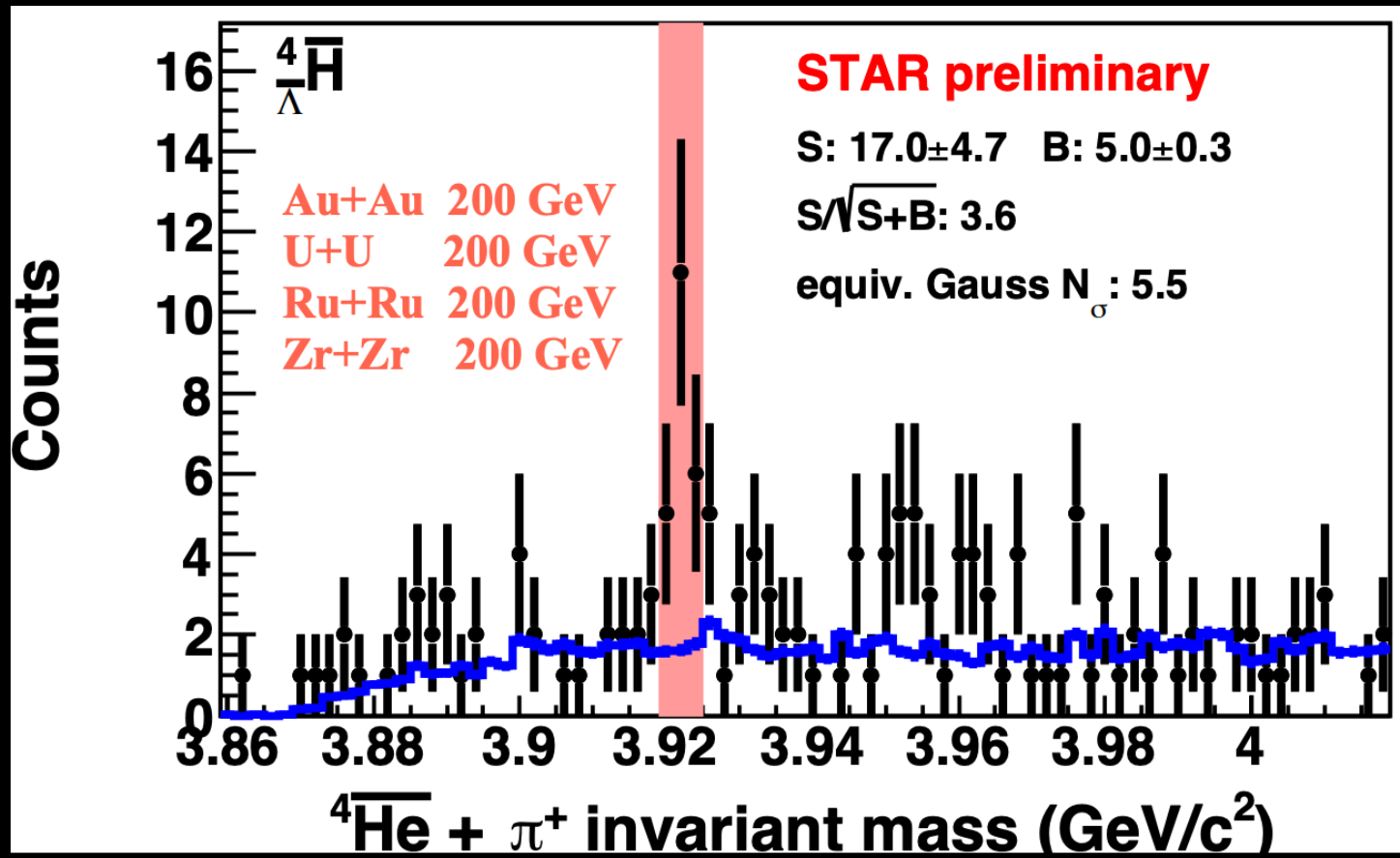


STAR, Science 328, 58-62(2010)



Looking Forward

- STAR recently finished our BES-II/FXT data-taking
- In the coming months to years, we expect to publish high-precision results on Au+Au collisions from 3.0 to 27 GeV
- Keep an eye out for new results on
  - Hypernuclei searches
  - Femtoscopy and 1st-order phase transition
  - Dileptons mapping fireball temperature
  - Flow mapping onset of NCQ scaling
  - Proton stopping and a softening of the equation of state
  - Proton high-moments searching for signatures of QCD critical point