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U.S. DEPARTMENT OF ENERGY
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Recent Highlights from STAR BES Phase II

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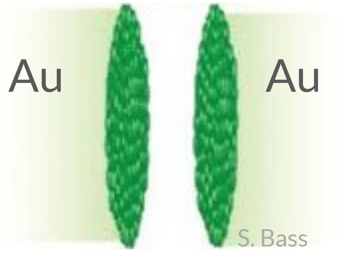
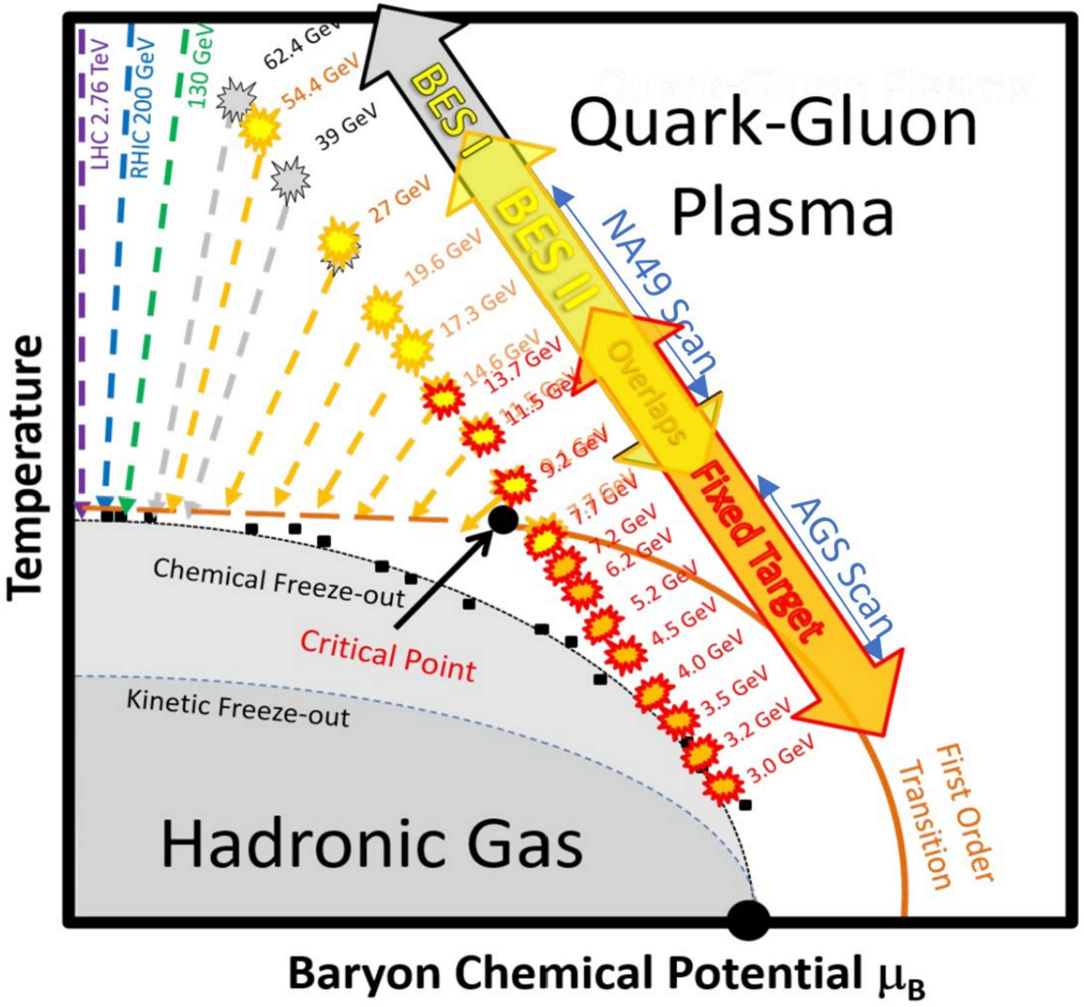
The Beam Energy Scan at RHIC

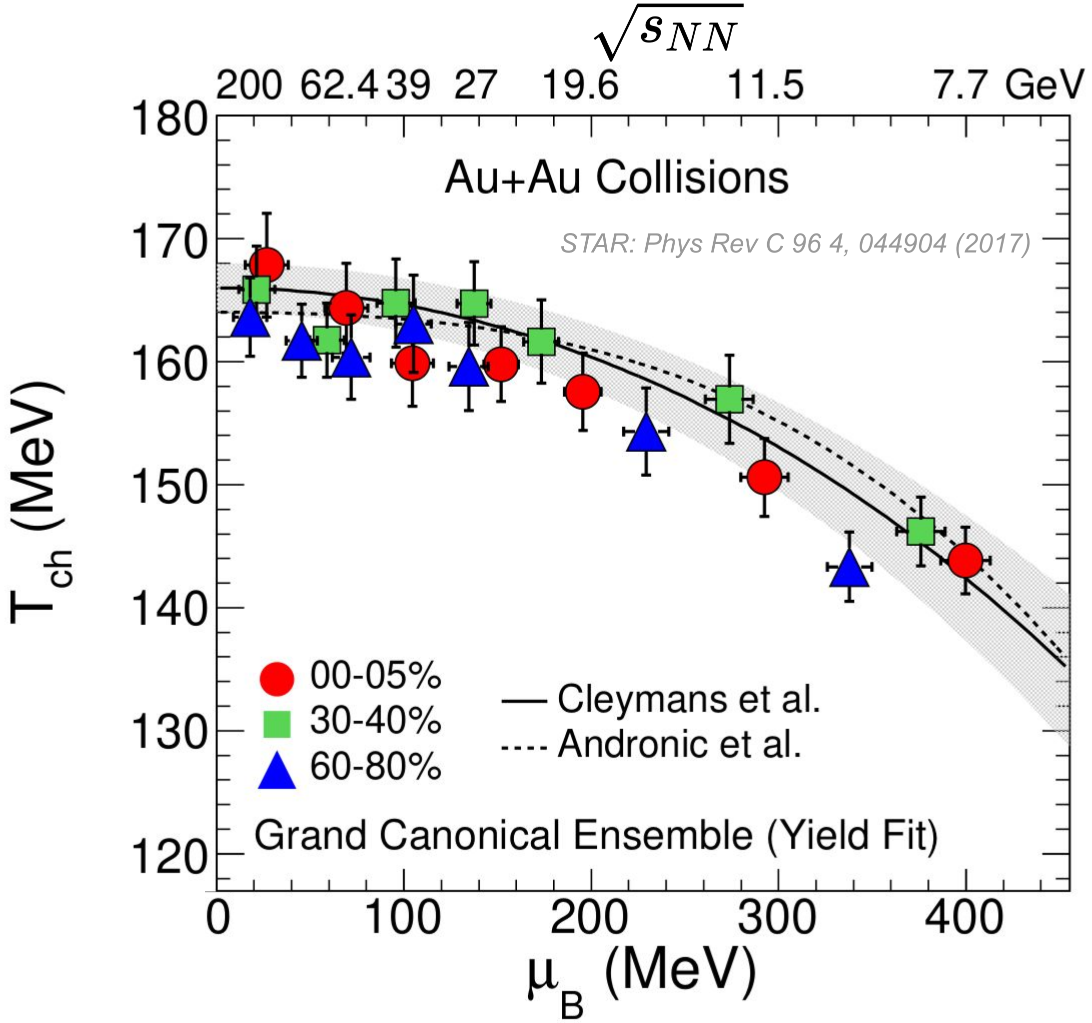


BES-I : 2010-2011
BES-II: 2019-2021

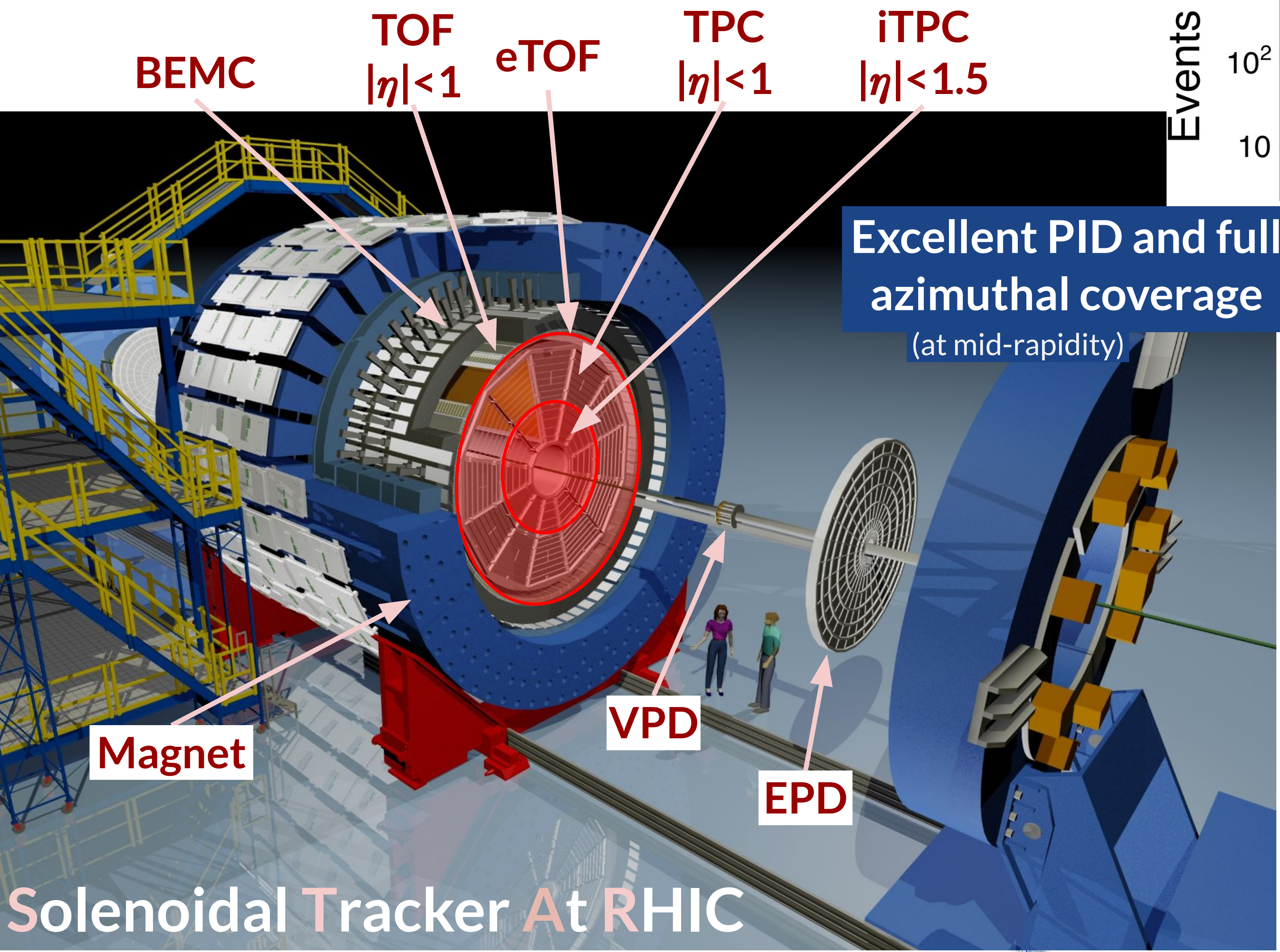
Explore the properties of QCD matter at various center of mass energies

Vary beam energy to scan QCD phase space

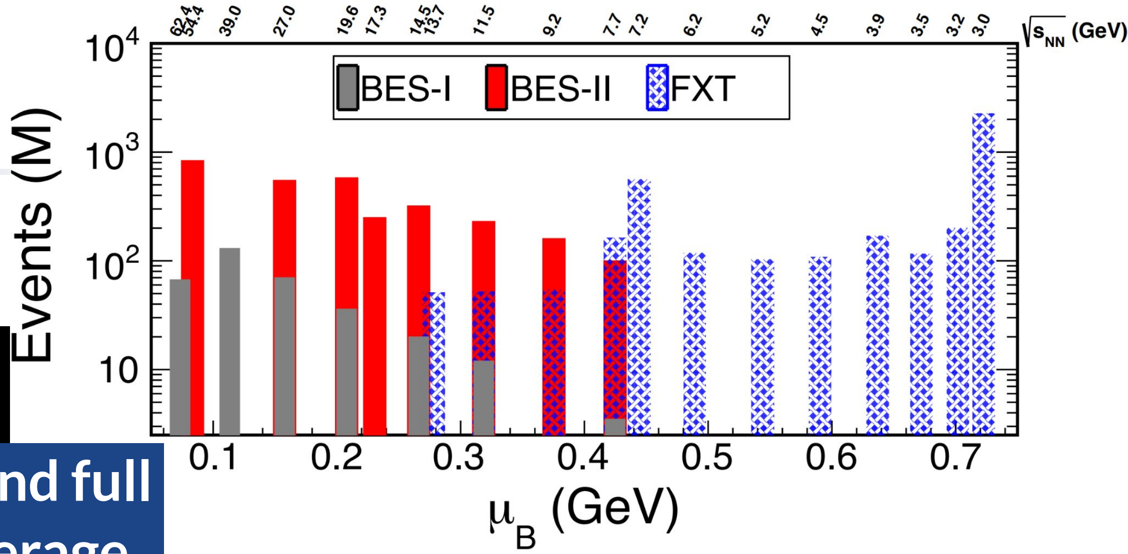




STAR BES-II Detector



Excellent PID and full azimuthal coverage
(at mid-rapidity)



BES-II

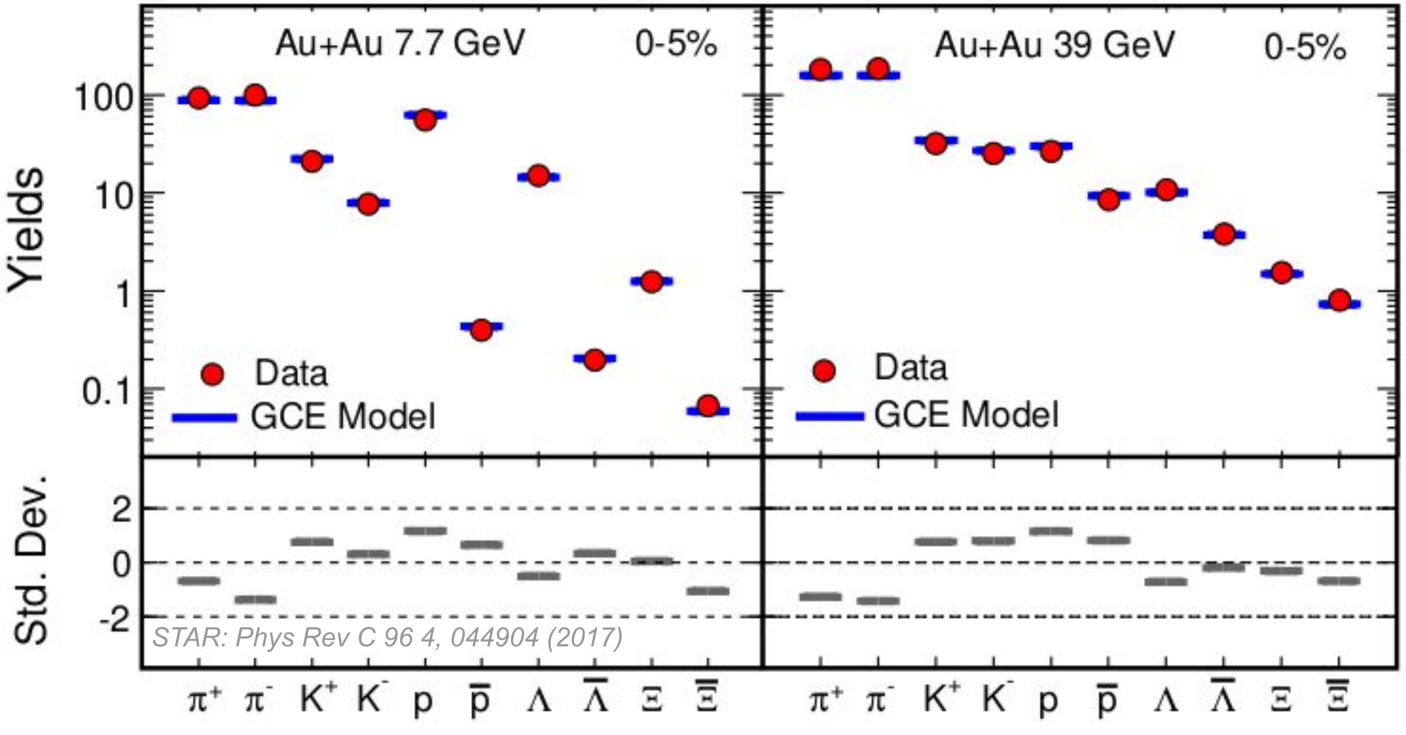
- **Higher statistics** than BES-I at low energies
- **Wider pseudo-rapidity** acceptance with iTPC
- **Fixed target** program can probe large μ_B

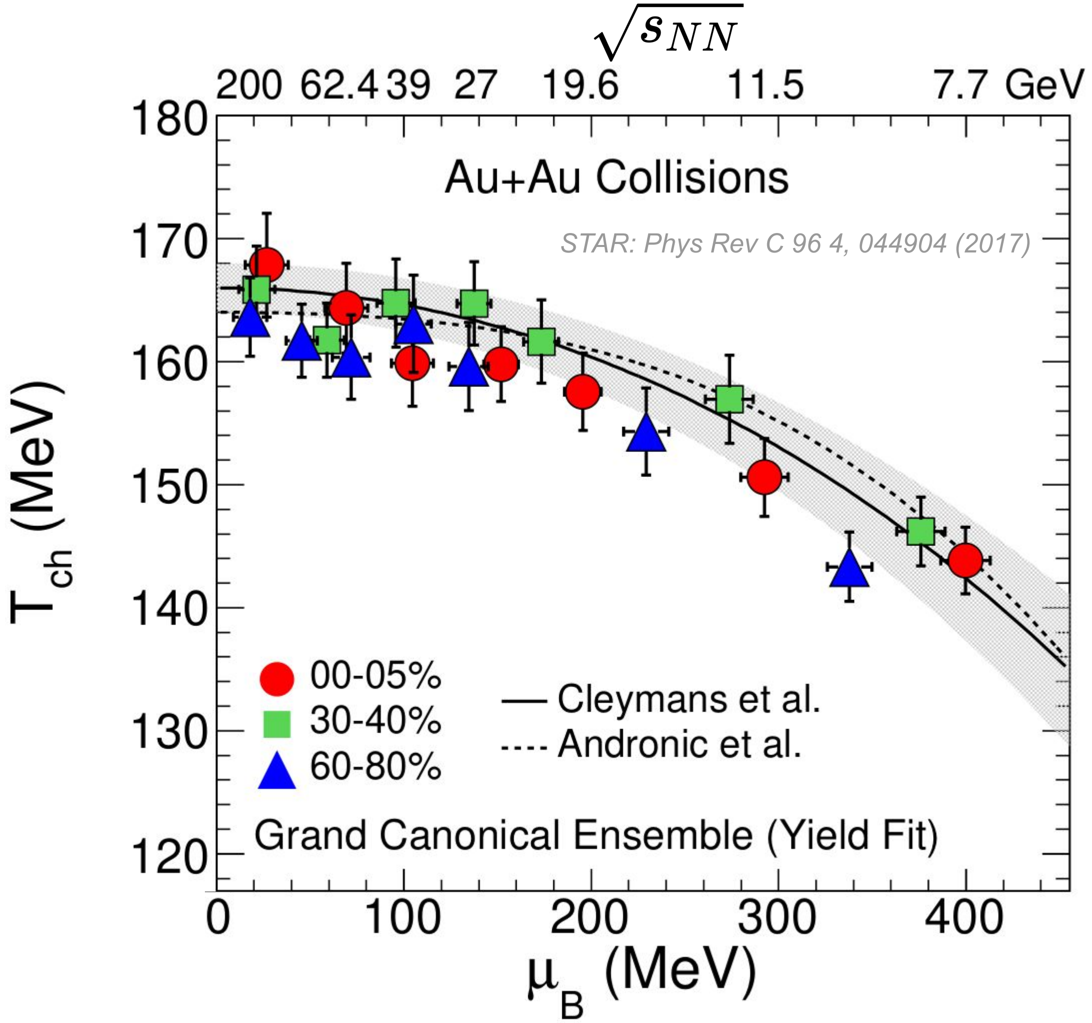
Where Are We on the QCD Phase Diagram?

$$\frac{N_{\bar{p}}}{N_p} \approx e^{-\frac{2\mu_B}{T_{ch}}}$$

Measure particle yields and compare to a statistical thermal model with parameters $T, V, \mu_B, \mu_S, \mu_Q$

Extract thermodynamic properties at chemical freeze-out for each energy and centrality

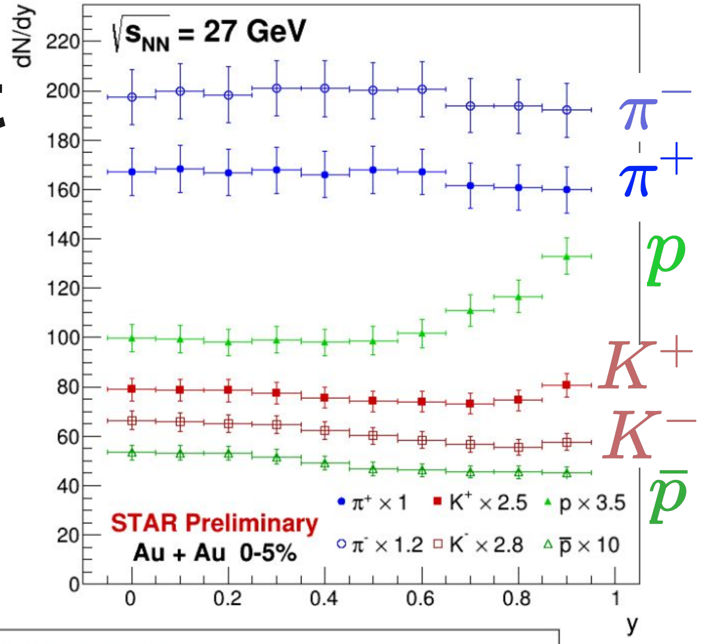


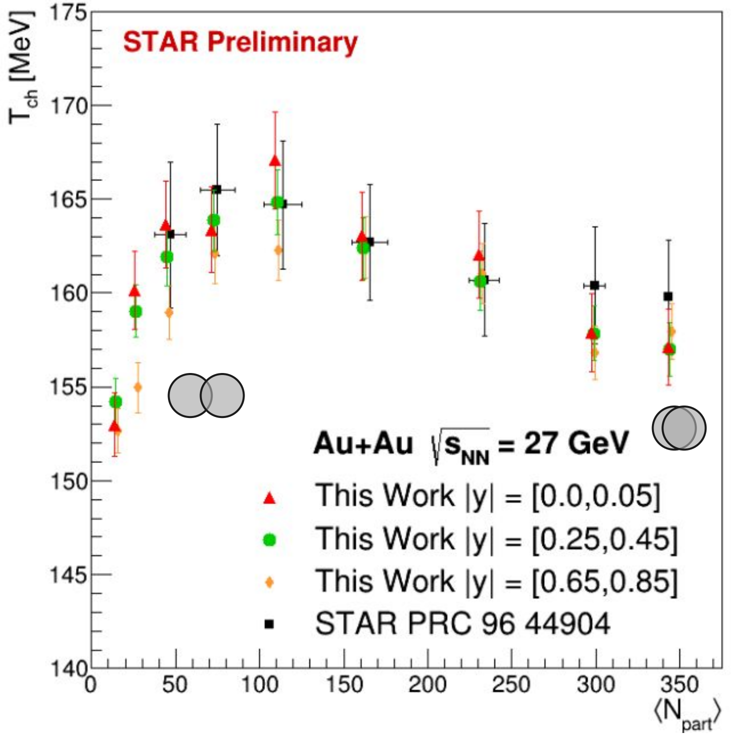


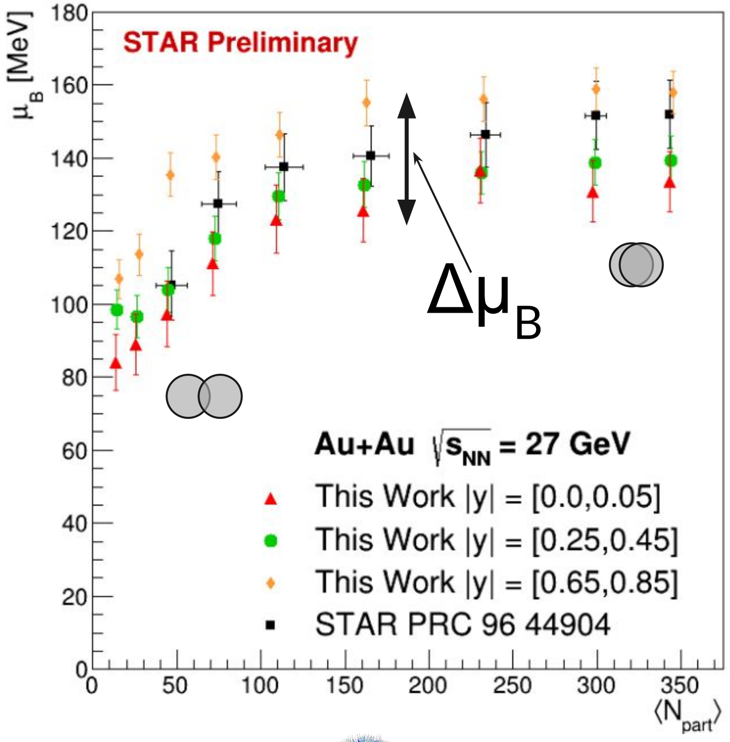
Rapidity Dependence of Chemical Freeze-Out

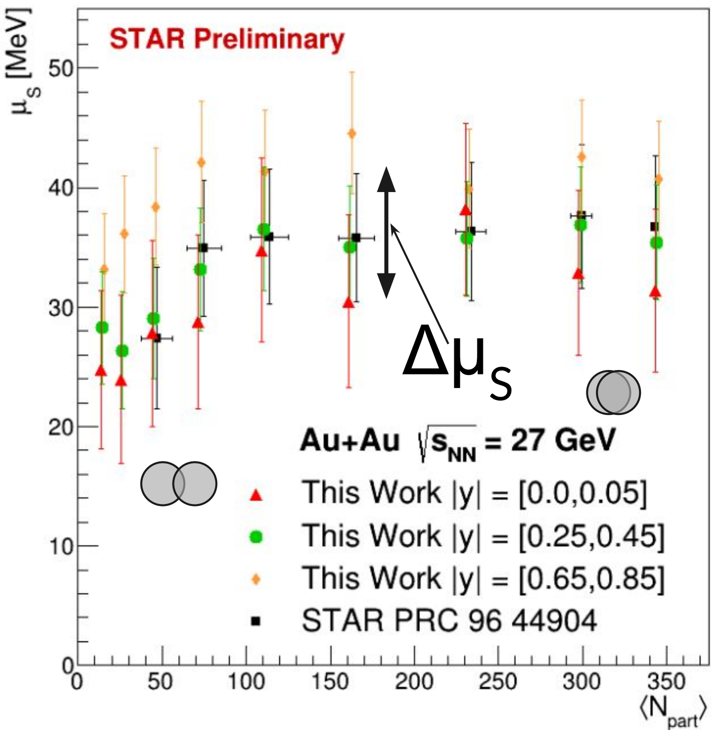
- Rapidity density of $\pi^{\pm}, K^{\pm}, p, \bar{p}$ measured at $\sqrt{s_{NN}}$ =27 GeV
- Rapidity dependence of chemical freeze-out parameters
  - $\Delta\mu_B \approx 25$ MeV for $\Delta y=1$ from baryon stopping
  - $\Delta\mu_S \approx 10$ MeV for $\Delta y=1$ from associated production

$$(p + N \rightarrow \Lambda + K^{+} + N)$$



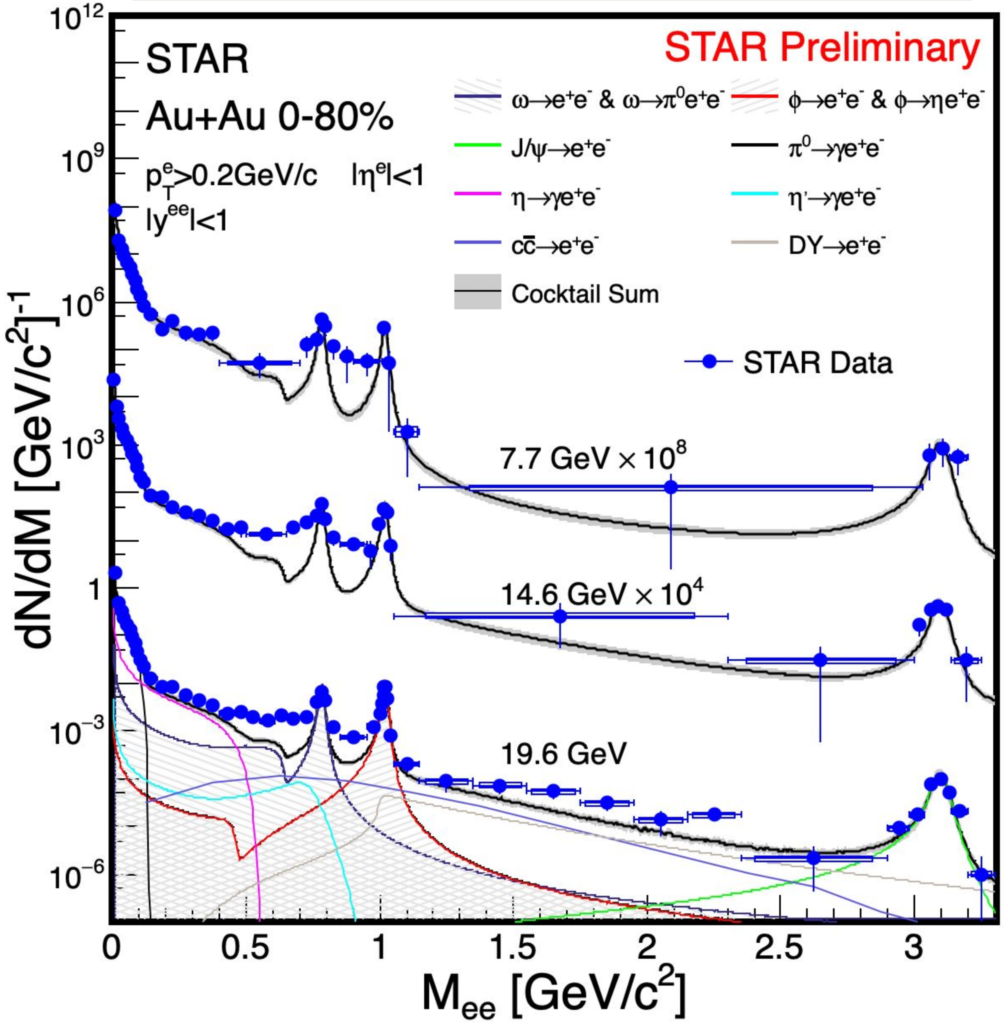




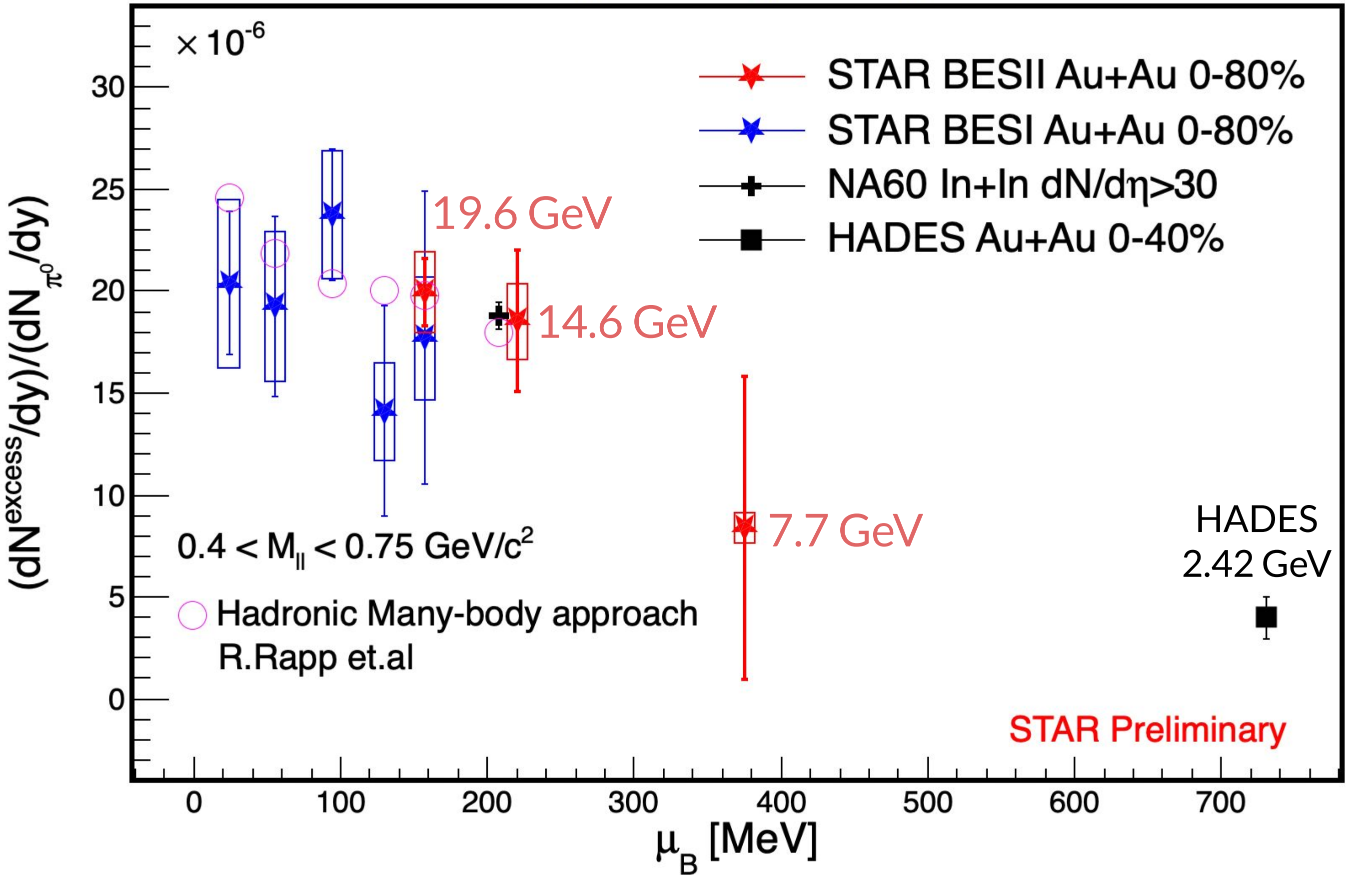


Thermal Dielectrons

Subtract known physics cocktail
➔ Left with thermal electrons



$N_{\pi^0} = (N_{\pi^+} + N_{\pi^-})/2$

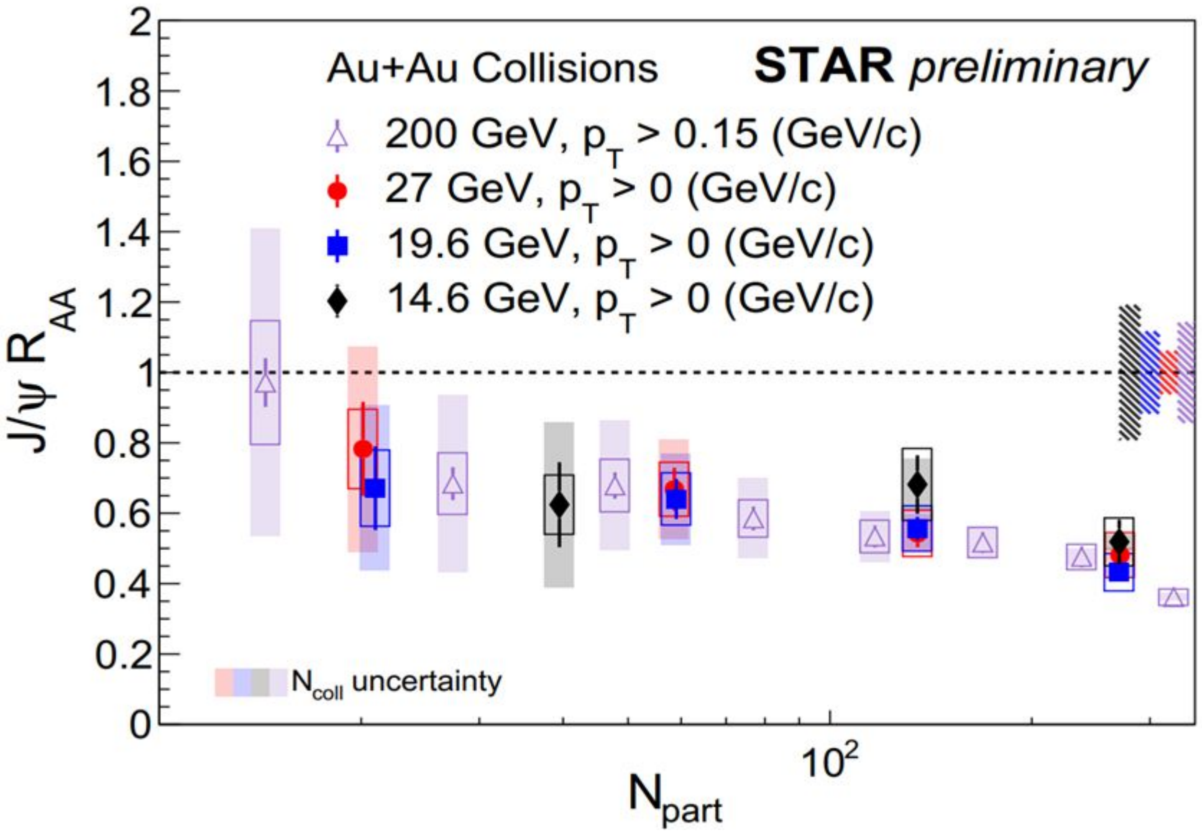


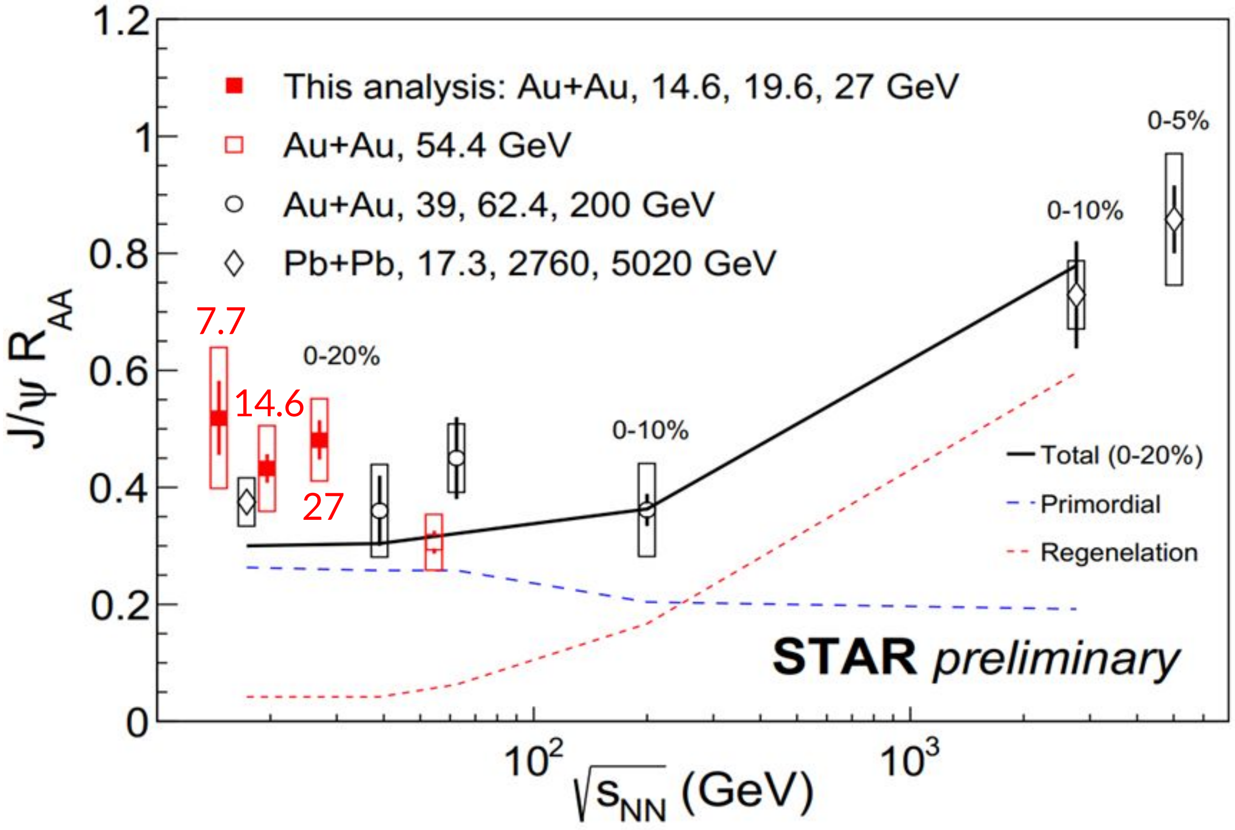
Hint of decreasing yield with increasing μ_B

(data - cocktail, normalized by $N\pi^0$)

Connects STAR BES-I and HADES data

Energy Dependence of J/ψ R_{AA}

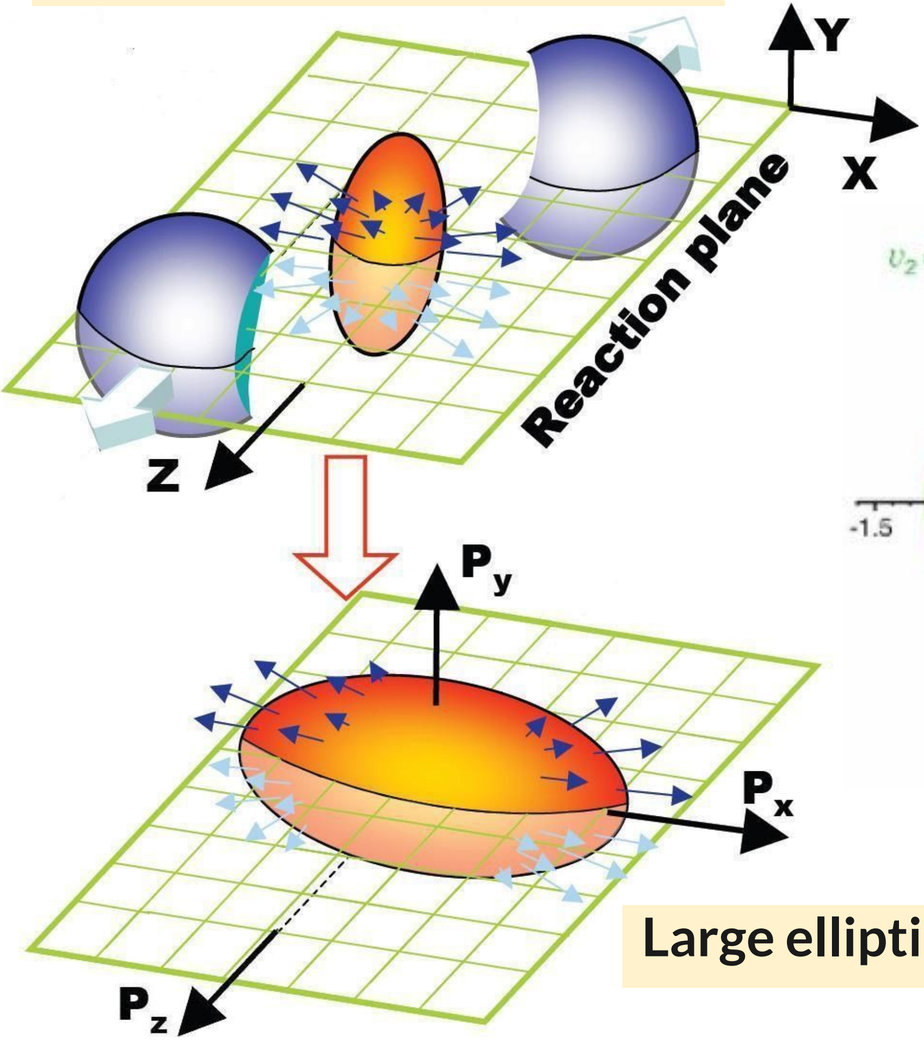




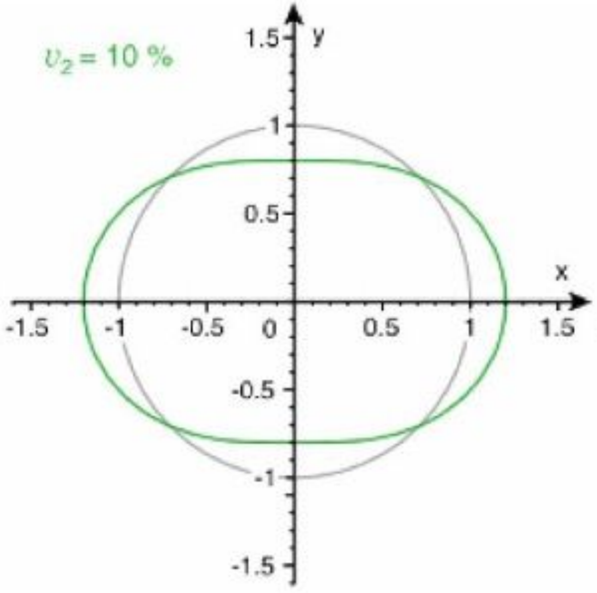
- R_{AA} shows no significant energy dependence at RHIC for similar $\langle N_{participants} \rangle$
- No significant energy dependence of J/ψ R_{AA} in central collisions is observed within uncertainties from 7.7 up to 200 GeV.
    - Interplay of dissociation and regeneration effects from RHIC to LHC energies.

Elliptic Flow and NCQ Scaling

Geometry of ion overlap produces pressure gradient



$$\frac{dN}{d(\phi-\Psi)} \sim 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi-\Psi))$$



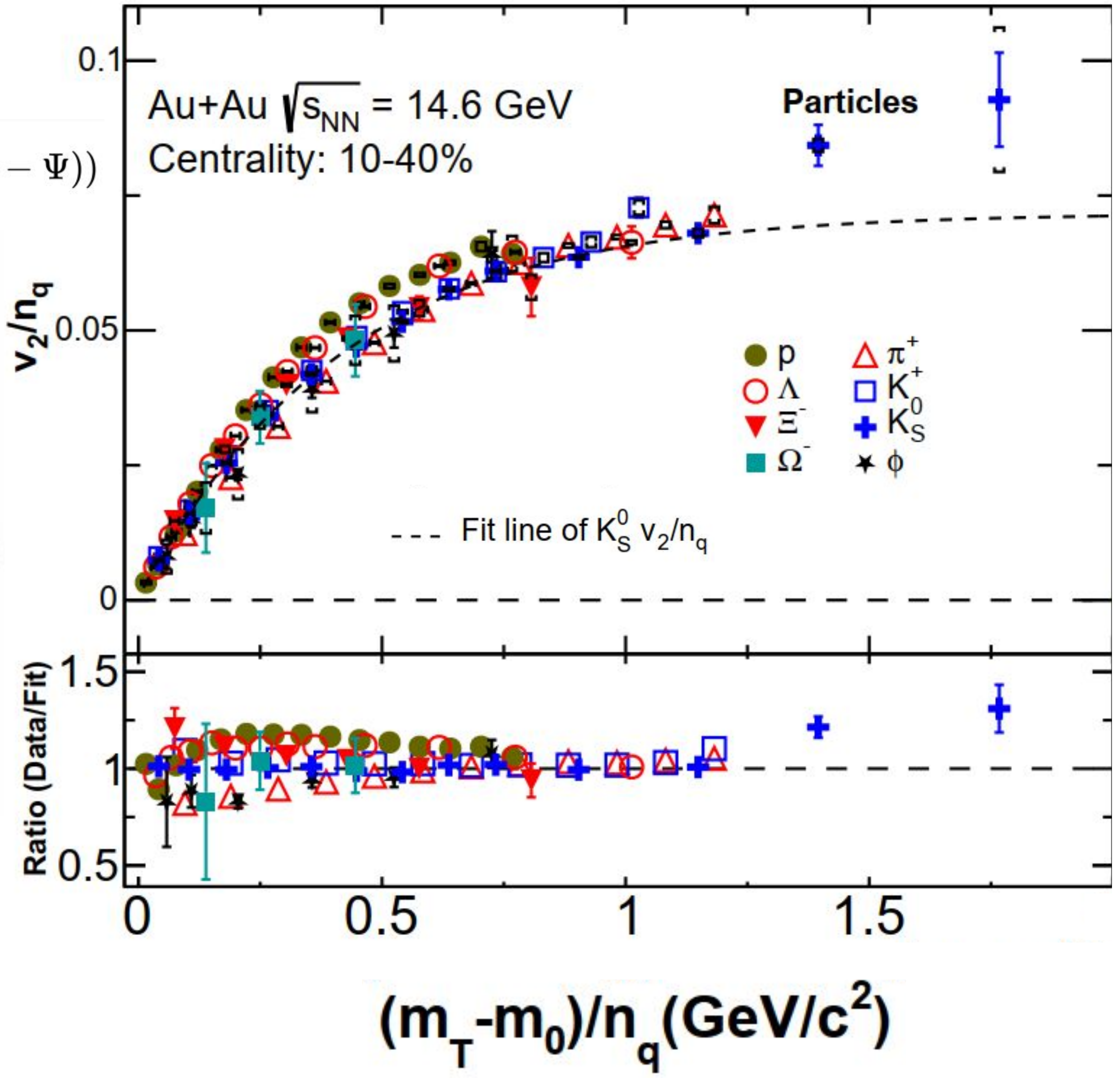
Large elliptic flow (v_2)

(NCQ)

Number of Constituent Quark Scaling

Each quark flows independently

Universal curve for v_2 per quark vs m_T per quark

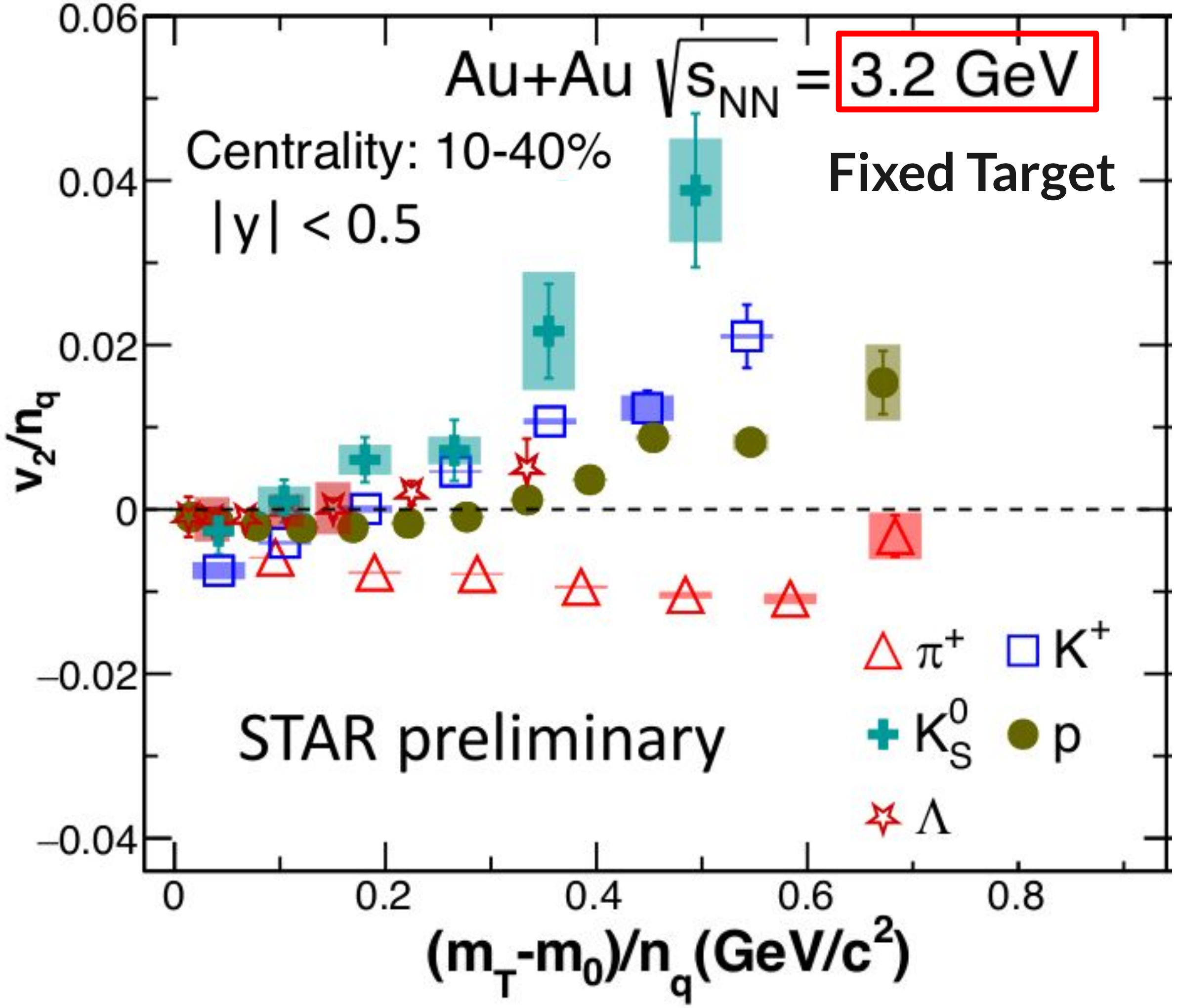


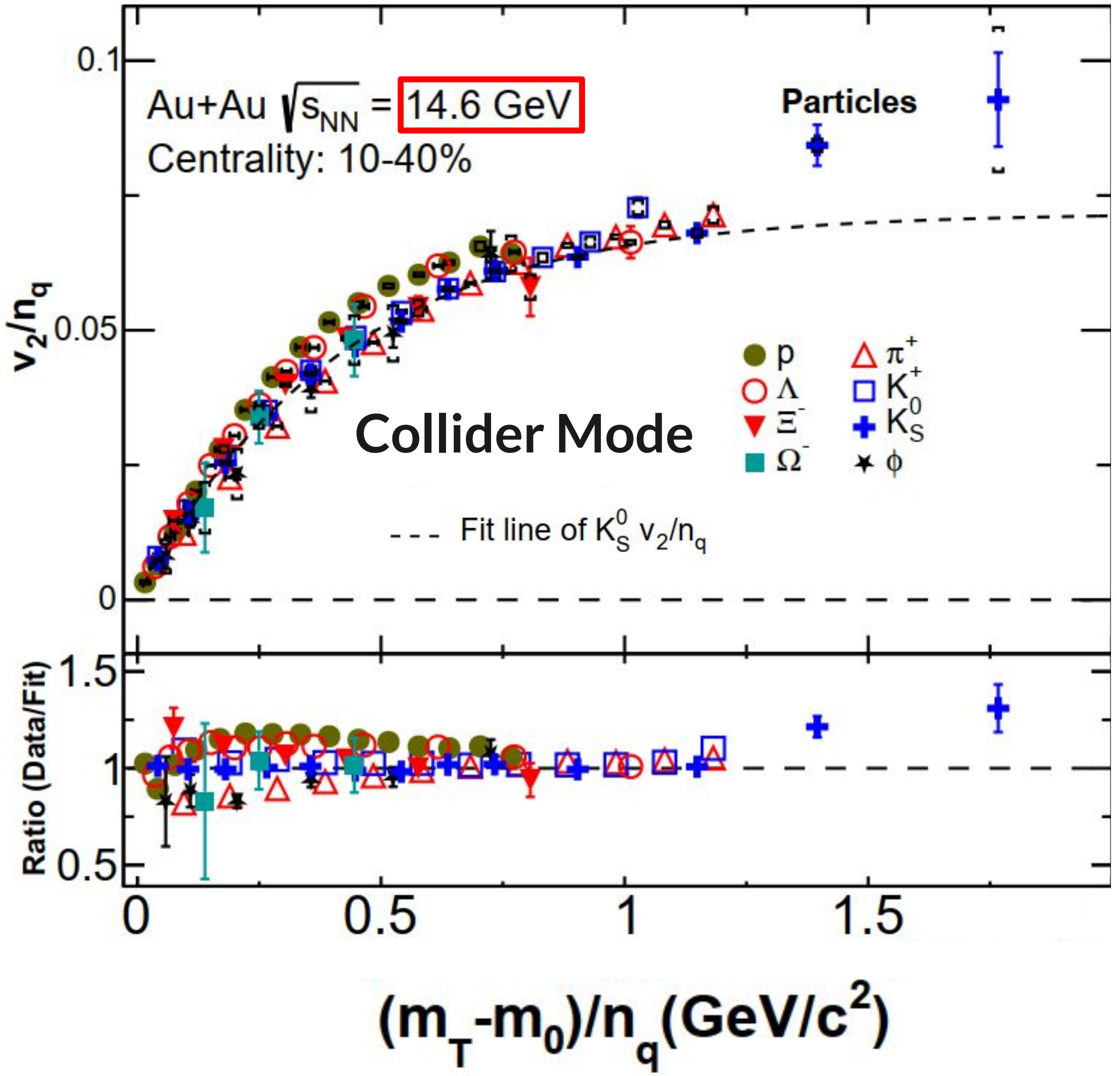
Disappearance of NCQ Scaling

NCQ Scaling seemingly broken at 3.2 GeV
Suggests dominance of hadronic matter at this energy

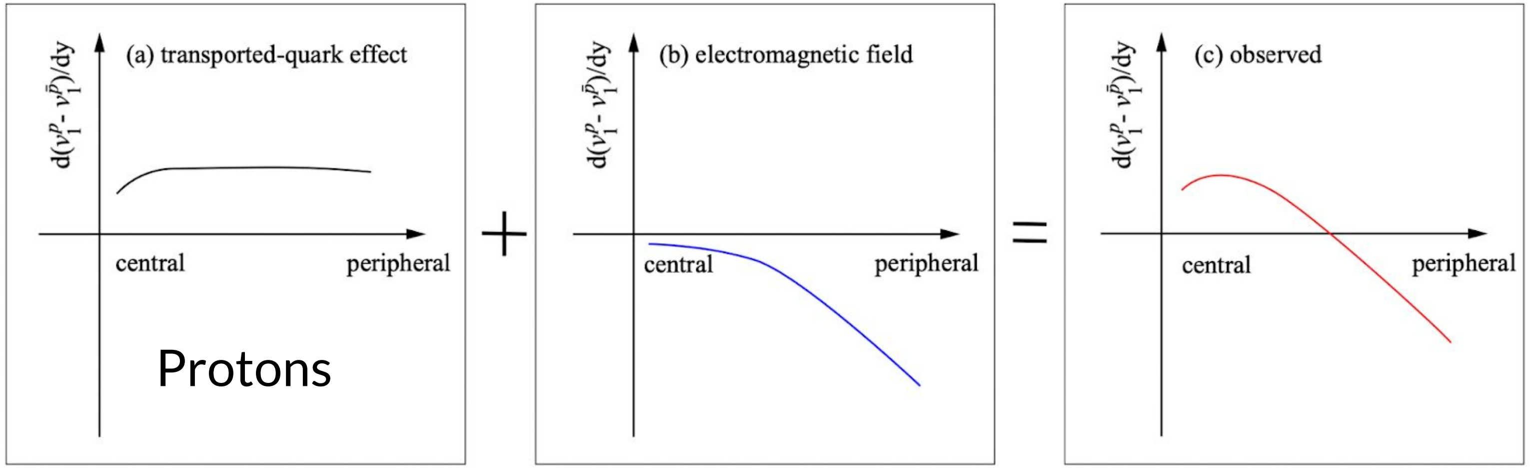
(NCQ)

Number of Constituent Quark Scaling
Each quark flows independently
Universal curve for v_2 per quark vs m_T per quark





Electromagnetic Field Effects in QGP

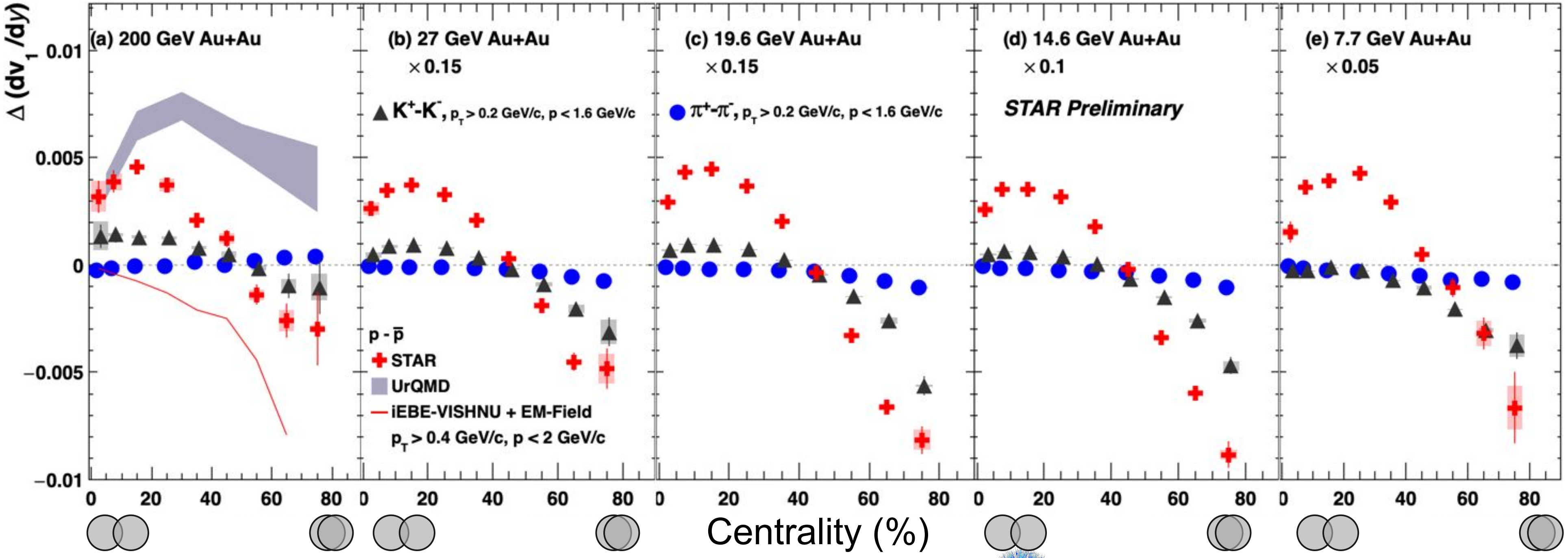


Quarks in expanding medium experience various forces:

- **Hall Effect**: **F**= q(**v**×**B**)
- **Coulomb Effect: E** generated by spectators
- **Faraday Induction**: Decreasing magnetic field as spectators fly away
- **Transported quark effect**:

Transported v_1 ≠ Produced v_1

(other mechanisms under investigation)



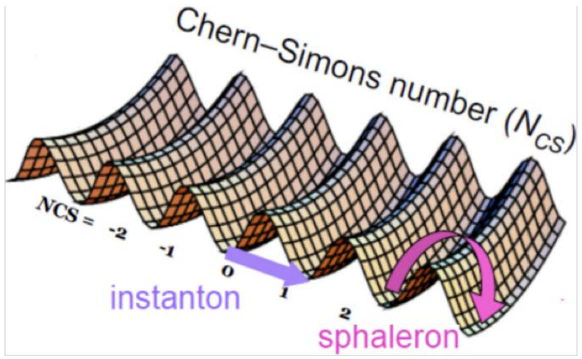
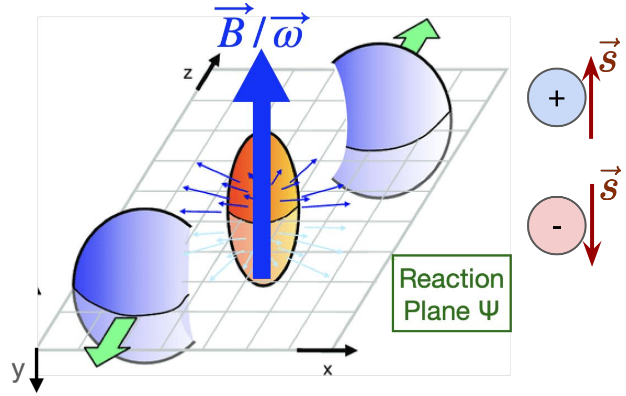
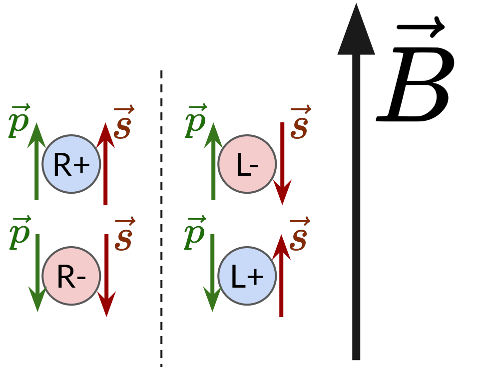
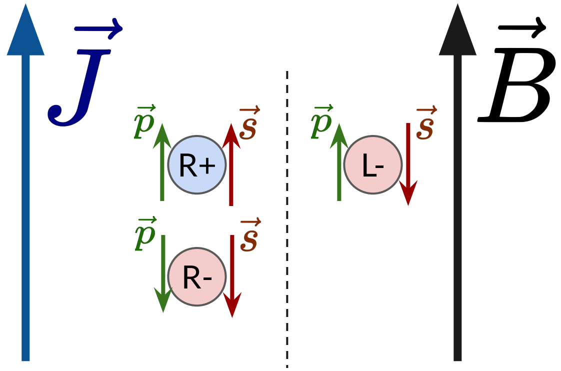
Negative $\Delta(dv_1/dy)$ consistent with Faraday+Coulomb effect in peripheral collisions

STAR: arXiv:2401.04838 (2024)

The Chiral Magnetic Effect (CME)

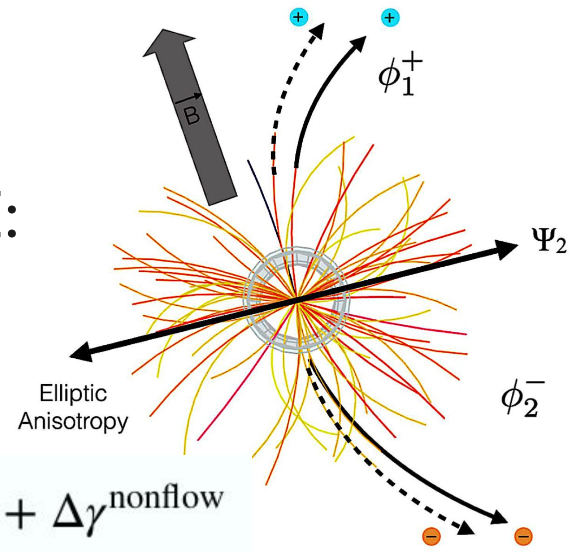
$$\vec{J} = \frac{e^2}{2\pi^2}\mu_5\vec{B}$$

odd parity ($\vec{J}$) — even parity ($\vec{B}$)

Restore chiral symmetry and create chiral imbalance	Spins align with strong magnetic field	Momenta of chiral quarks (anti-)aligned with spin	Net electrical current with chiral imbalance
			

Experimental signal of CME:

Charge separation along B field



Observable:

$$\Delta\gamma^{112} = \gamma^{OS} - \gamma^{SS} = \Delta\gamma^{\mathrm{CME/CVE}} + k\frac{v_2}{N} + \Delta\gamma^{\mathrm{nonflow}}$$

For a strong CME signal, need:

1. Strong magnetic field (many spectators ➔ Au)
2. Long lived magnetic field (low energy)

BES-II data

Search for the Chiral Magnetic Effect

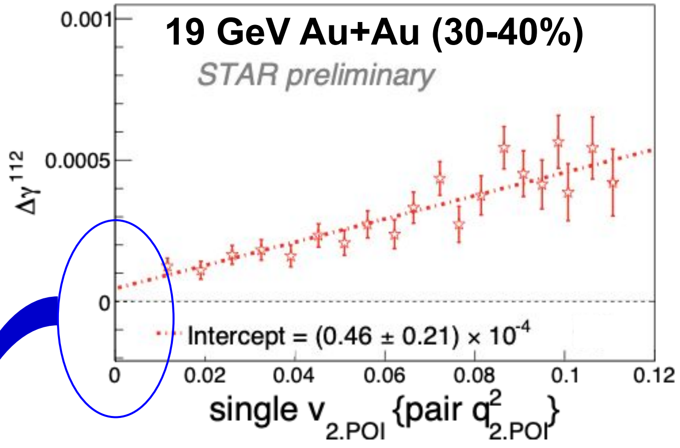
Event Shape Selection Spectator Ψ_1

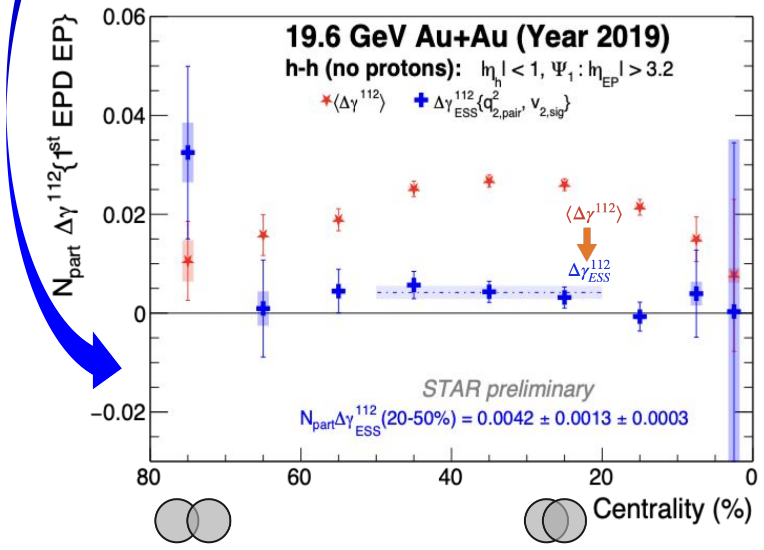
$$\Delta\gamma^{112} = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

Measured Signal Backgrounds

Event Shape Selection ➔ Extrapolate to zero flow to reduce CME background

Z. Xu et al Phys. Rev. C 107, L061902
Z. Xu et al, PLB 848(2024)138367





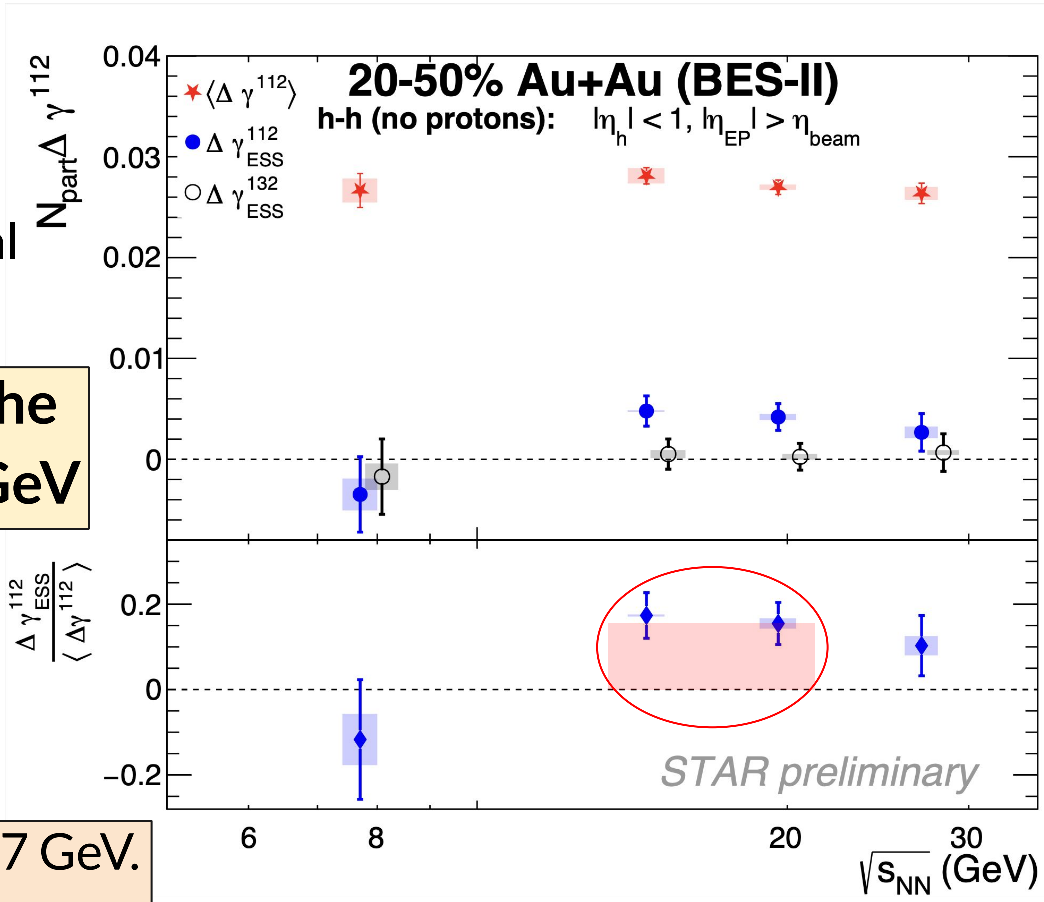
$$\Delta\gamma_{ESS}^{112} = Intercept \times (1 - v_2)^2$$

Intercept ($\Delta\gamma_{ESS}^{112}$) expected to be a sensitive observable for CME signal

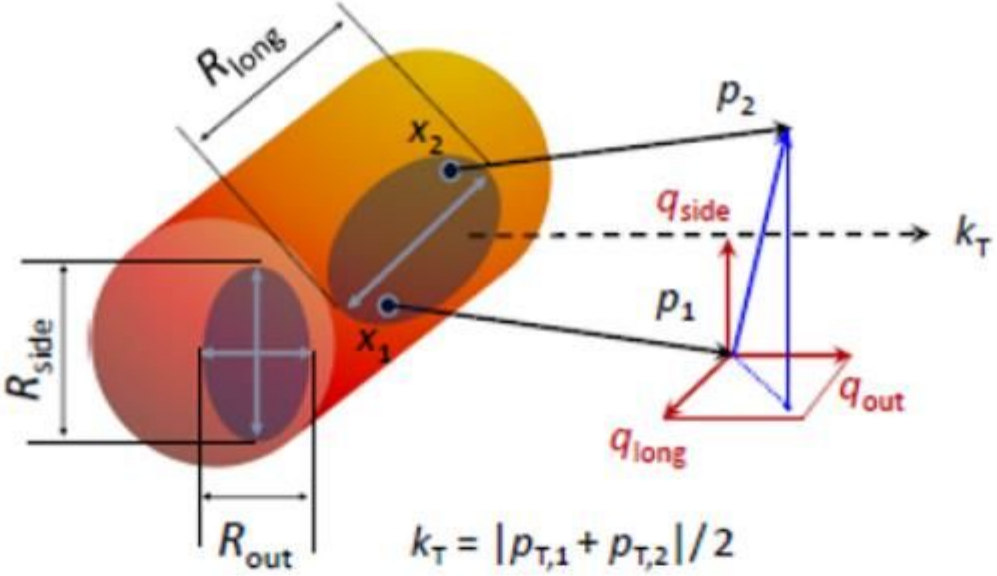
3σ significance found for the intercept at 14.6 and 19.6 GeV

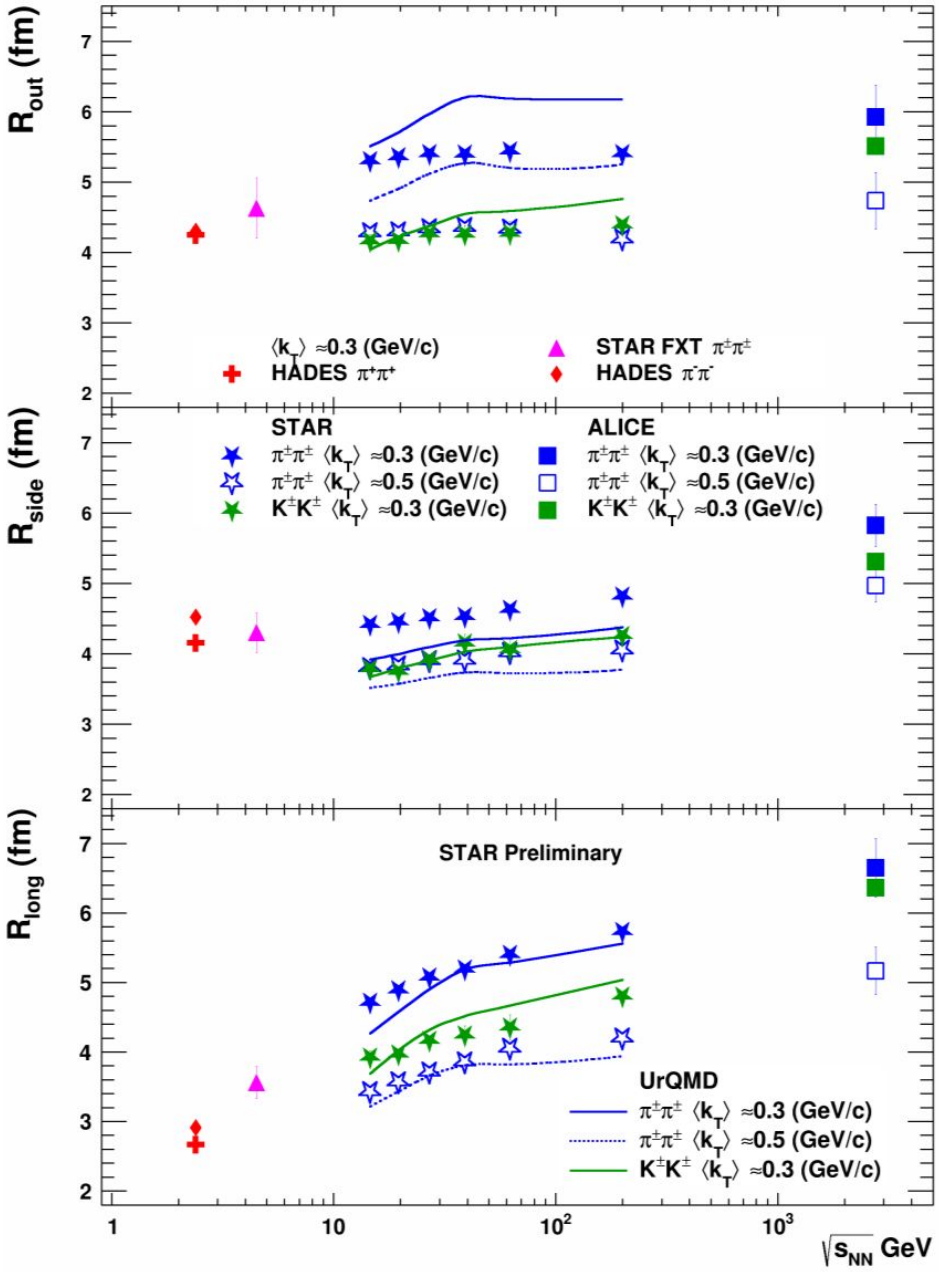
Intercept of background indicator $\Delta\gamma^{132}$ is consistent with zero

$\Delta\gamma_{ESS}^{112}$ consistent with zero at 7.7 GeV. Disappearance of chiral symmetry?



3D Pion/Kaon Femtoscopy





3D analysis finds that extracted radii
- Increase with collision energy
- Decrease with k_T
- Are larger for kaons than pions

(for comparable conditions)

UrQMD qualitatively consistent with trends in data

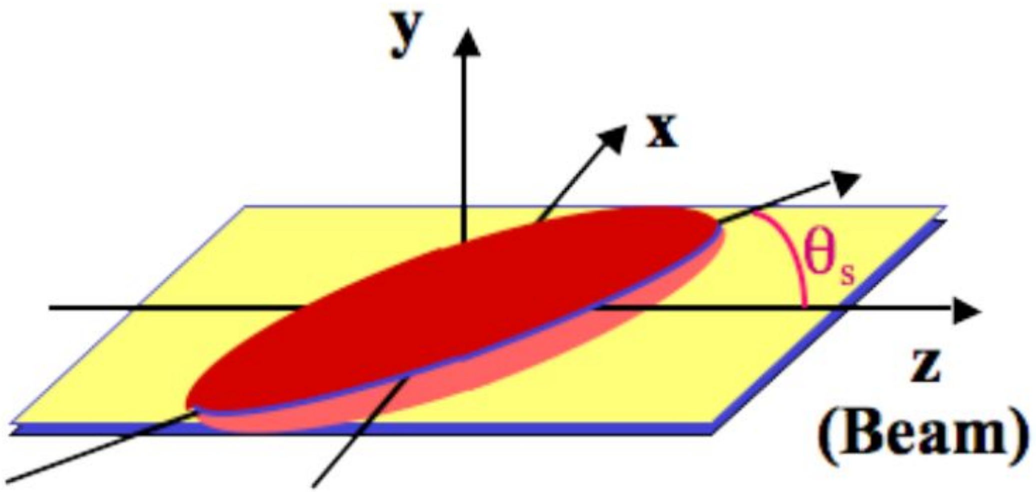
Azimuthally Sensitive Femtoscopy

OL: Out-Long
SL: Side-Long

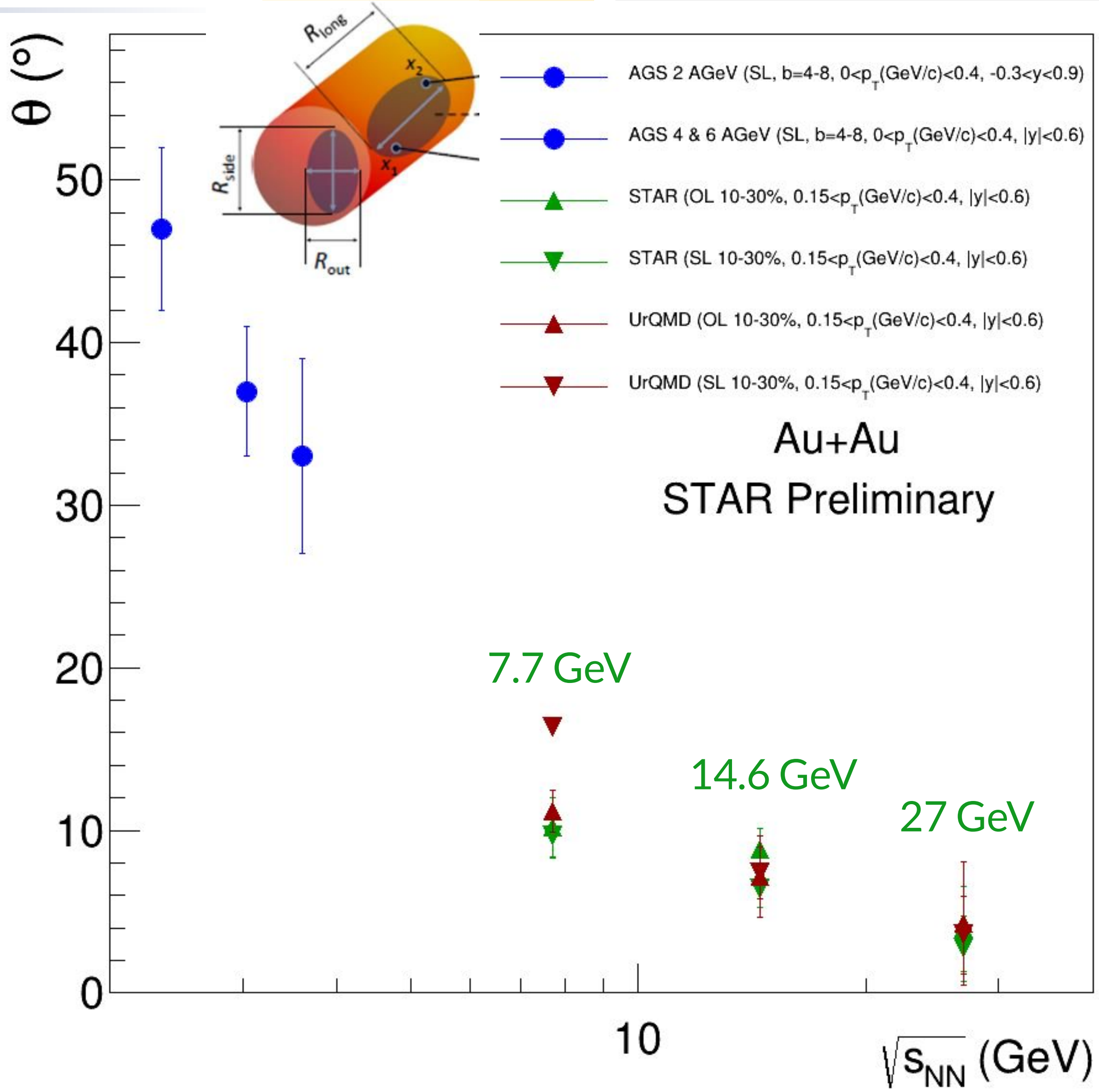
Tilt measured in both transverse directions

Fireball created in heavy-ion collisions tilted with respect to reaction plane

Measured at RHIC for the first time!



Tilt increases with decreasing collision energy



Summary

- STAR is a versatile detector!
  - Sensitivity of thermal μ_B and μ_S to rapidity measured
  - Hint of decreasing thermal dielectron yield with increasing μ_B
  - J/ψ R_{AA} shows no dependence on energy from 7.7 to 200 GeV
  - Disappearance of NCQ scaling at 3.2 GeV ➔ suggests hadronic matter
  - Charge dependent v_1 measurements consistent with dominance of Faraday+Coulomb effect in peripheral collisions
  - Possible hint of Chiral Magnetic Effect at 14.6 and 19.6 GeV
  - Fireball size and tilt measured with femtoscopic correlations

- High statistics data at low energies helps complete the QGP story
- The fixed target program extends STAR's reach into the QCD phase diagram

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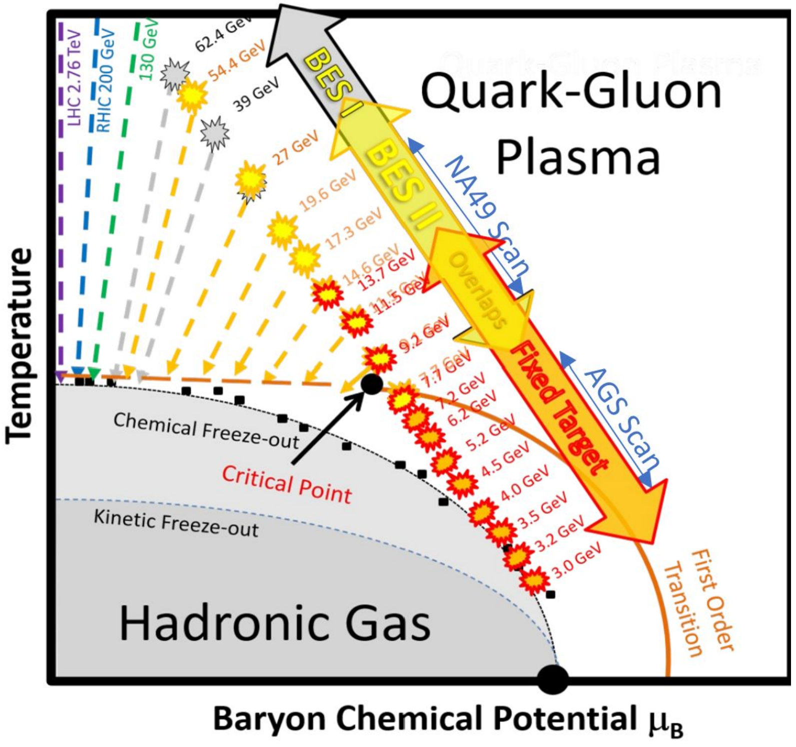
Thanks for your attention!

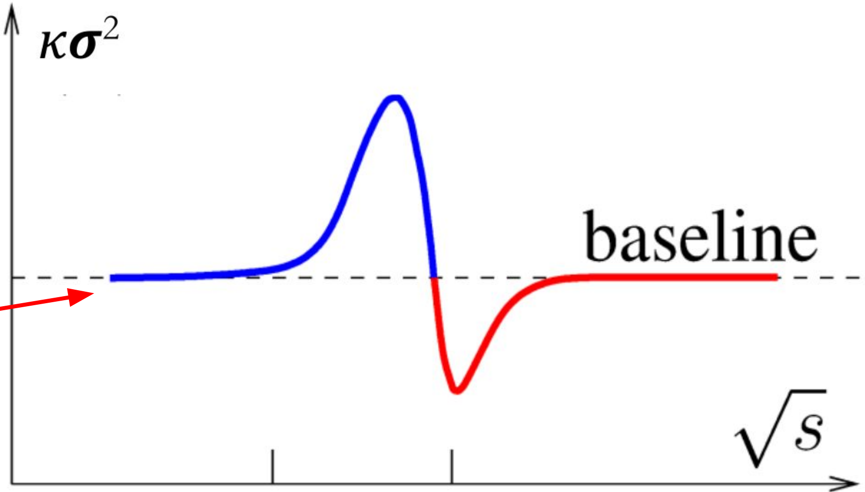
Backup

Net-Proton Fluctuations

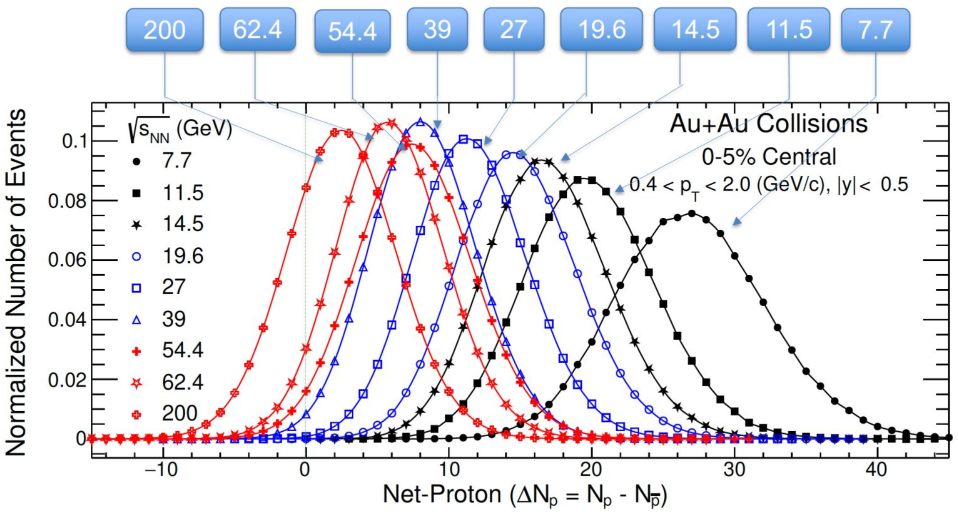


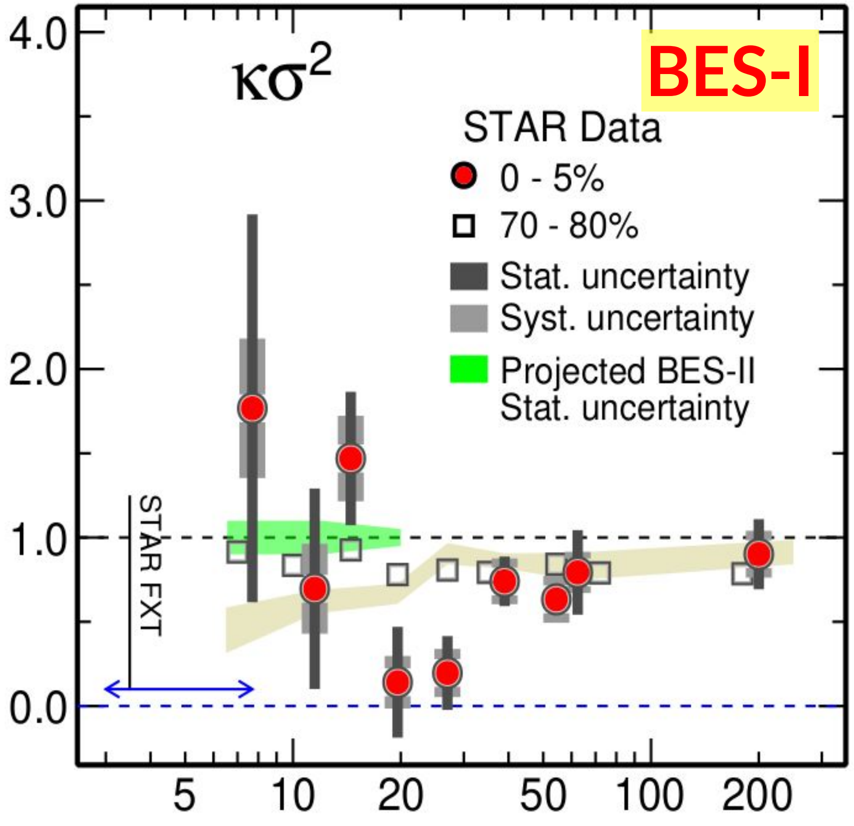
BES-II results coming soon

Possible signal when crossing critical point



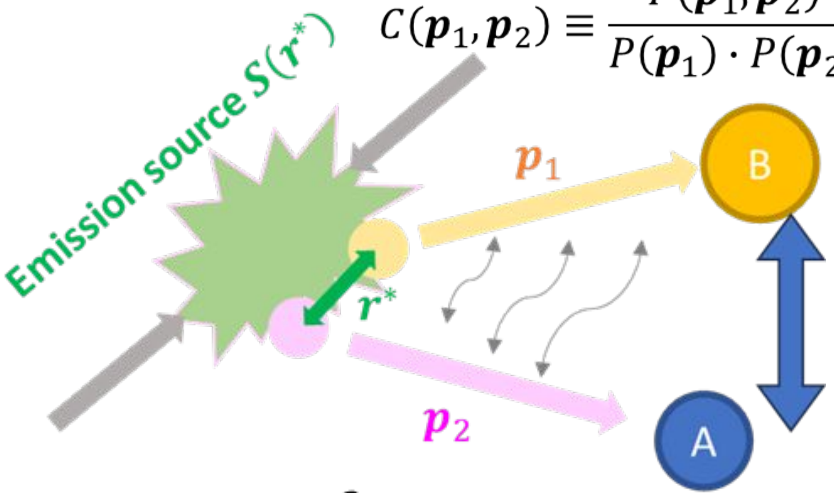
X. Luo https://indico.ihep.ac.cn/event/12478/

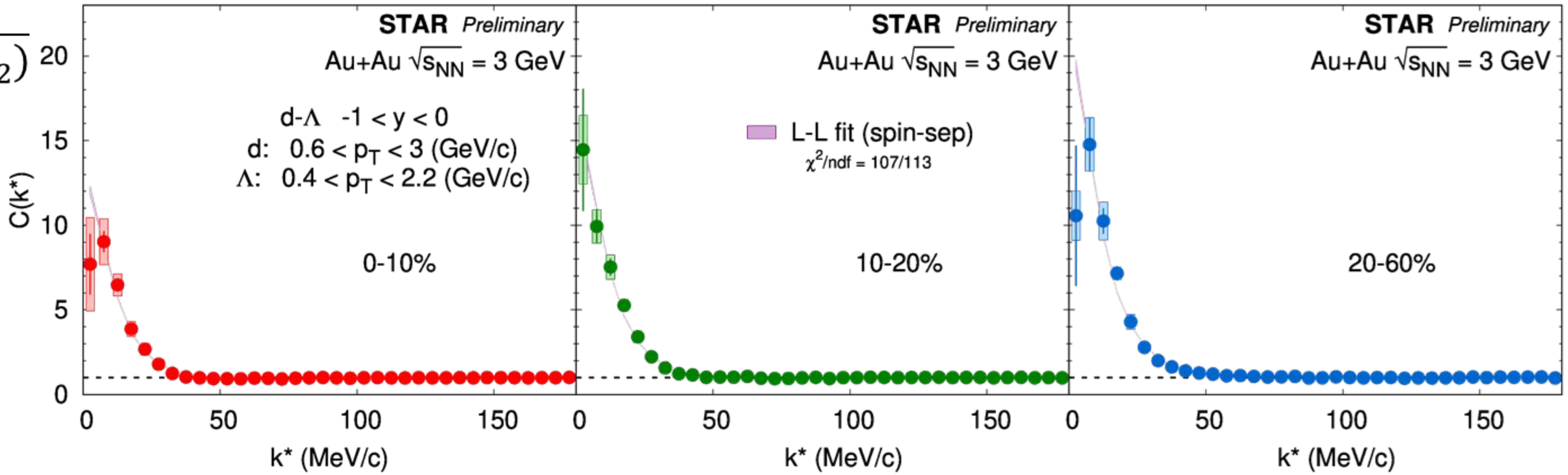




d-Λ Correlation Measurement

$$C(\boldsymbol{p}_1, \boldsymbol{p}_2) \equiv \frac{P(\boldsymbol{p}_1, \boldsymbol{p}_2)}{P(\boldsymbol{p}_1) \cdot P(\boldsymbol{p}_2)}$$

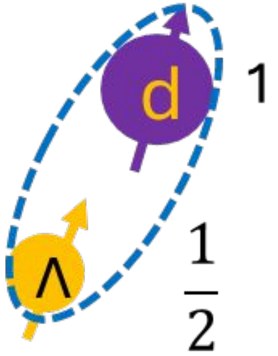




$$C(\boldsymbol{k}^*) = \int d^3r^* S(\boldsymbol{r}^*) |\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2$$

Distribution of the relative distance of particle pair

Relative wave function of the particle pair



Doublet State	$^2S_{1/2}$	(D)
Quartet State	$^4S_{3/2}$	(Q)

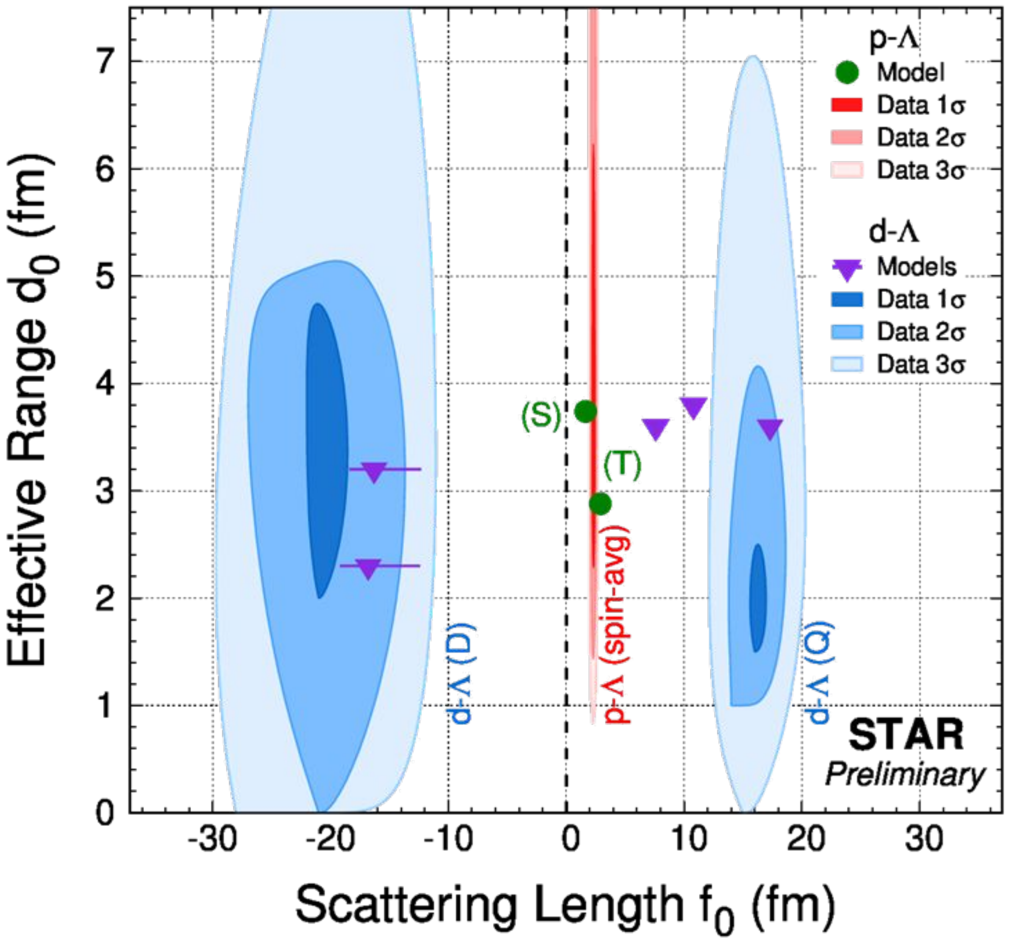
First d-Λ correlation measurement in heavy-ions!

Simultaneous fit to data in different centralities R^i_G, f_0(D), d_0(D), f_0(Q), and d_0(Q) with Lednicky-Lyuboshitz approach

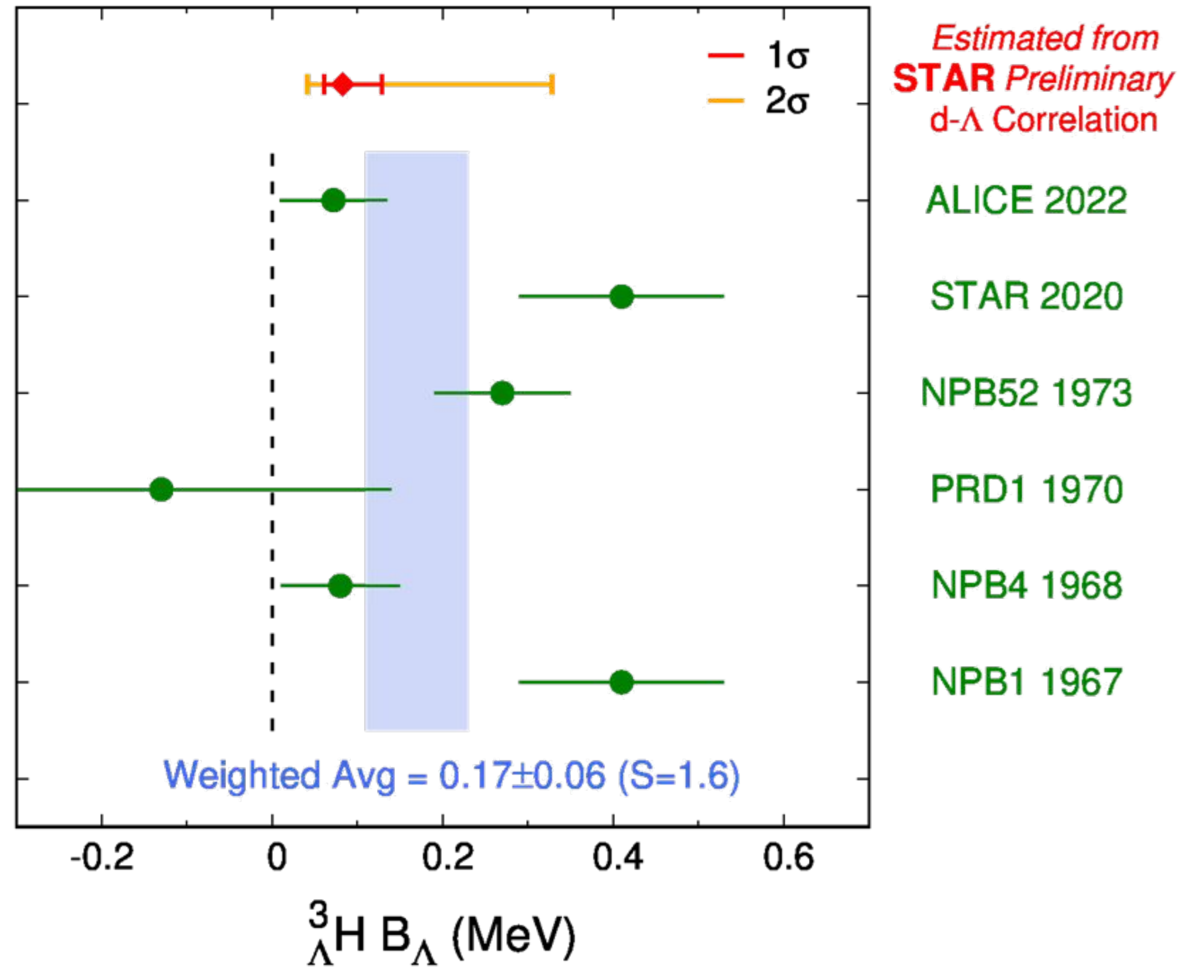
$$f_0(\mathrm{D}) = -20^{+3}_{-3}\ \mathrm{fm} \qquad d_0(\mathrm{D}) = 3^{+2}_{-1}\ \mathrm{fm}$$

$$f_0(\mathrm{Q}) = 16^{+2}_{-1}\ \mathrm{fm} \qquad d_0(\mathrm{Q}) = 2^{+1}_{-1}\ \mathrm{fm}$$

d-Λ Correlation Measurement



Constrained fit separated two spin states in d-Λ



With Bethe formula ${}^{3}_{\Lambda}H\ B_{\Lambda} = [0.04, 0.33]\ (MeV)$ @ 95% CL, consistent with the world average

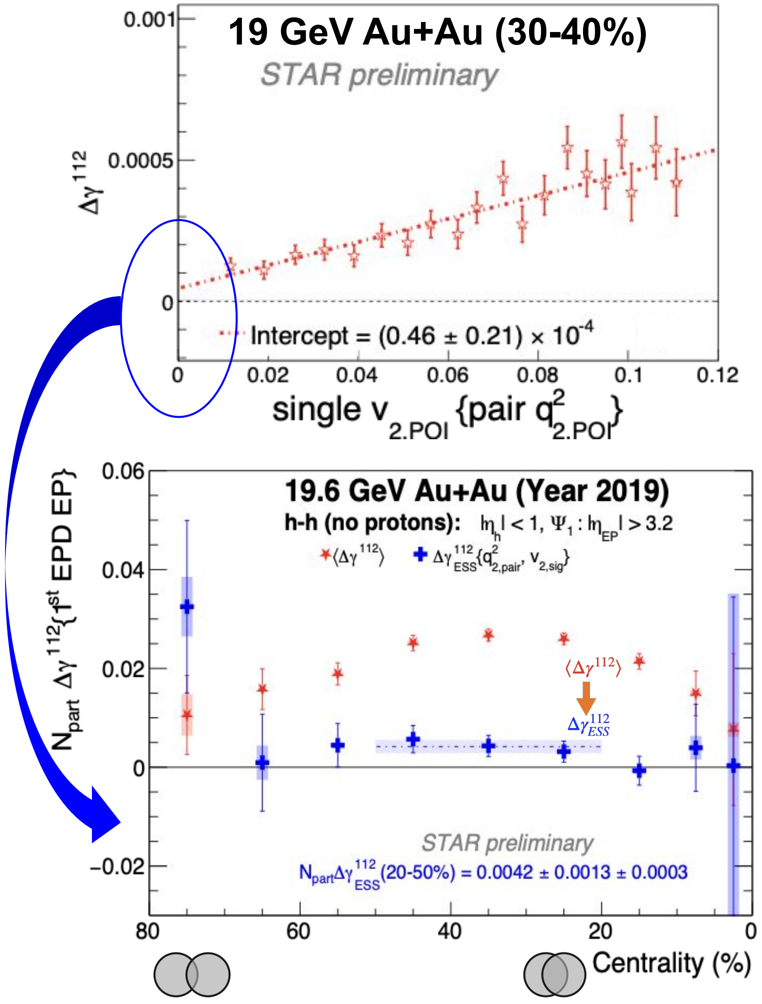
Search for the Chiral Magnetic Effect

Event Shape Selection | **Spectator Ψ_1**

$$\Delta\gamma^{112} = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

Measured ↓ Signal ↓ Backgrounds

Event Shape Selection ➔ Extrapolate to zero flow to reduce CME background



○ Use Spectator Plane Ψ_1 from EPD to mitigate nonflow.
○ Spectators are more correlated with magnetic field.

○ Restored signal:

$$\Delta\gamma_{ESS}^{112} = Intercept \times (1 - v_2)^2$$

Z. Xu et al Phys. Rev. C 107, L061902
Z. Xu et al, PLB 848(2024)138367

BES-II Result:
○ 3σ significance found for the intercept at 14.6 and 19.6 GeV.
○ Approaching 7.7 GeV, data indicate no chiral symmetry?
○ Intercept of BKG-indicator $\Delta\gamma^{132}$ is consistent with zero.