STAR OVERVIEW
RECENT RESULTS AND HIGHLIGHTS

Nicole Lewis for the Star Collaboration (BNL)

Initial Stages 2023

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Brookhaven National Laboratory

STAR

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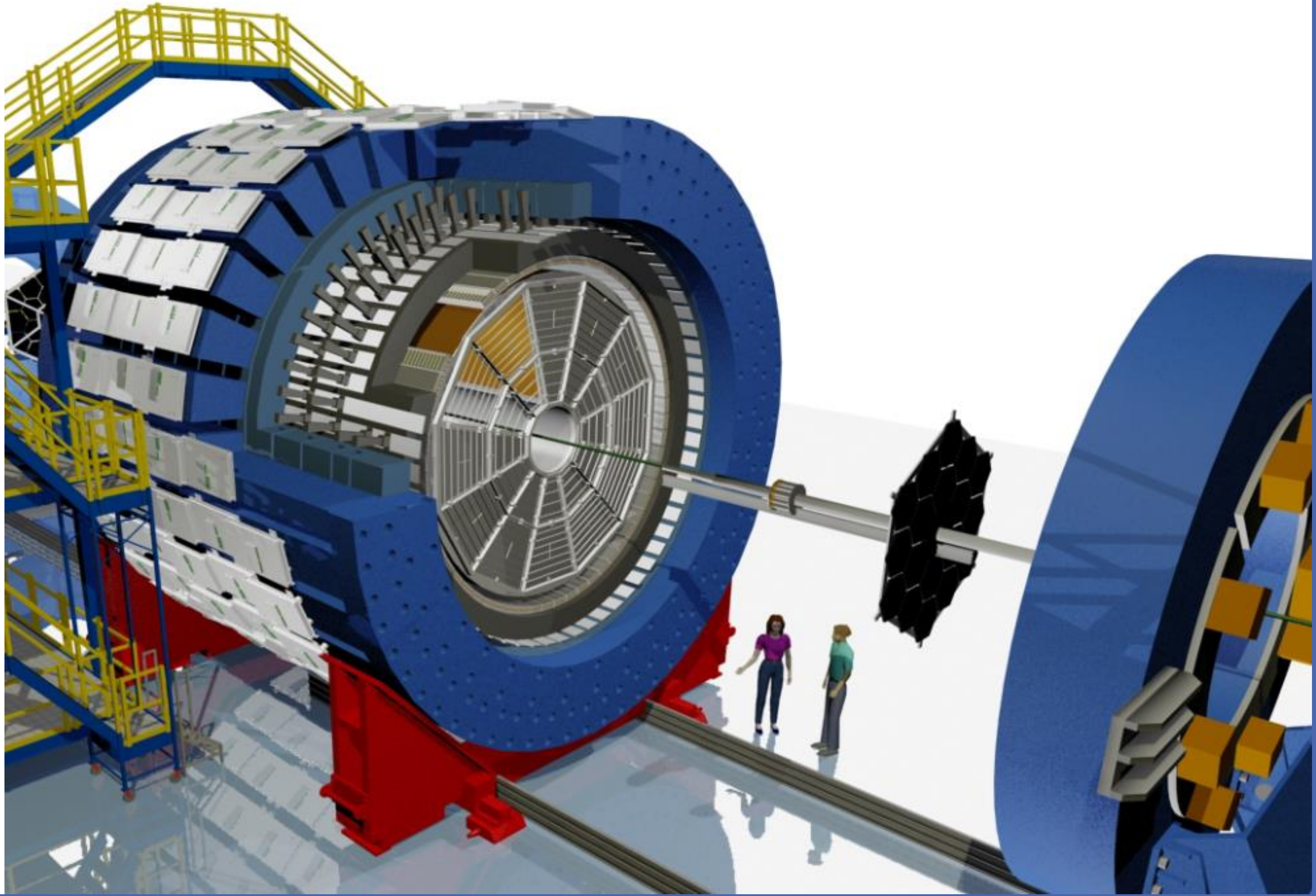
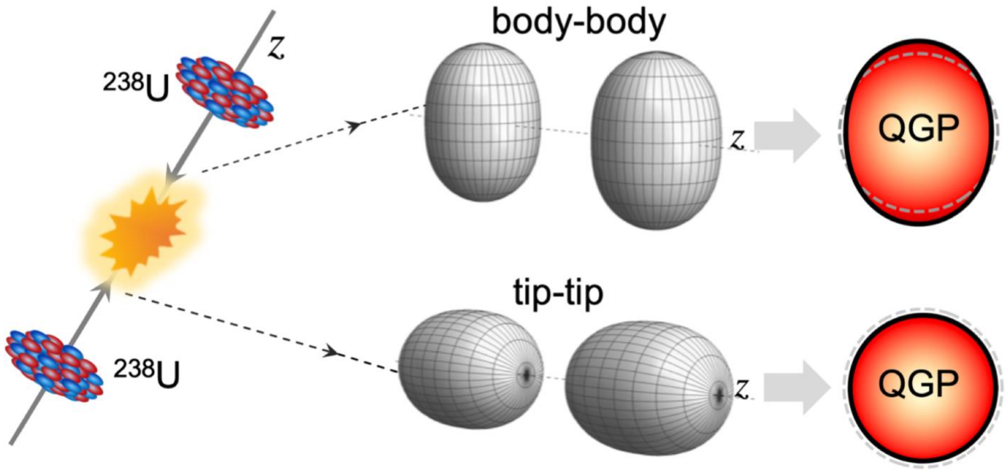
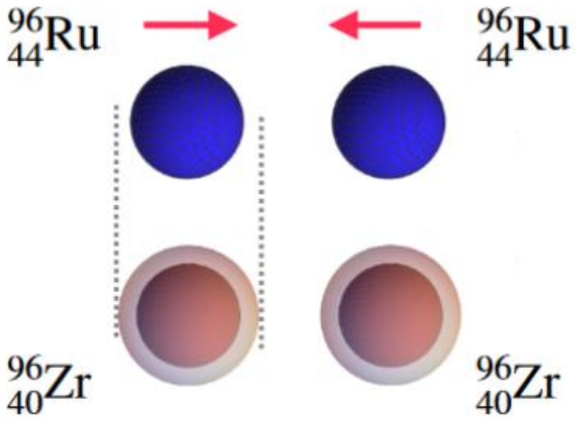
Outline

- Flow Correlations
- Hard Probes
- Polarization in Heavy Ion Collisions
- Low-x Measurements



Flow Correlations



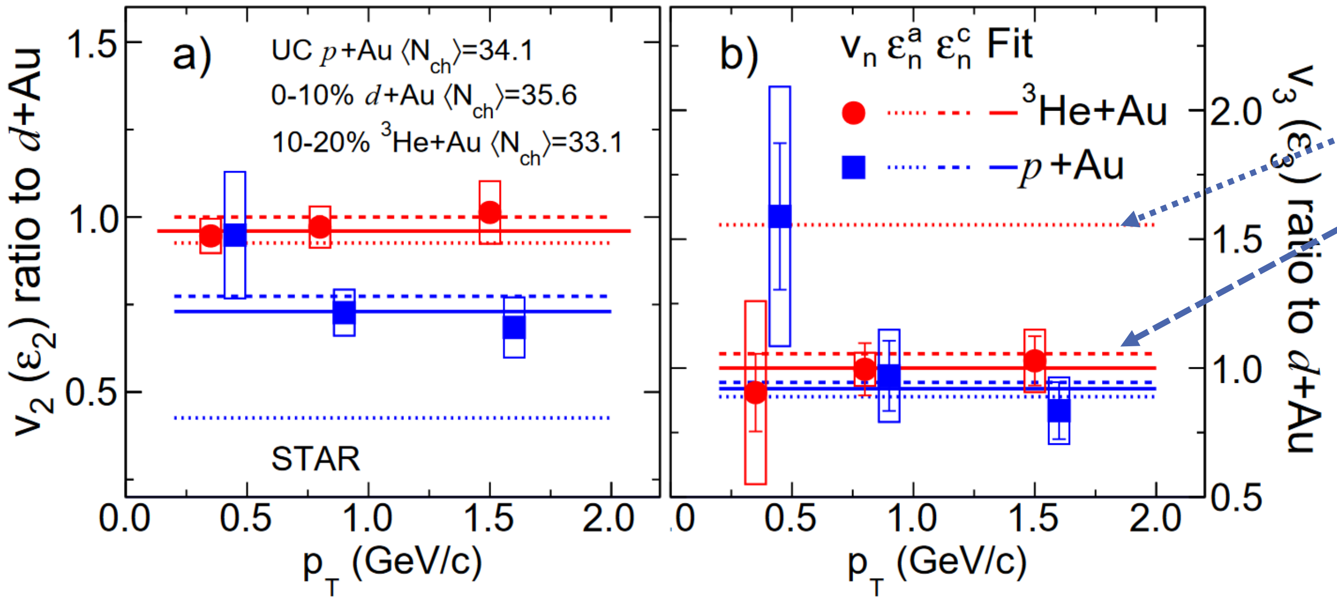


v_2 and v_3 in $p + \mathrm{Au}$, $d + \mathrm{Au}$ and $^3\mathrm{He} + \mathrm{Au}$

See Talk by Shengli Huang
Wed, Parallel Session 6

Ratio to $d + \mathrm{Au}$ for similar mean multiplicity

- Final-state effects are expected to largely cancel out
- Sensitive to effects from initial spatial geometry and contributions from initial stage pre-equilibrium flow



STAR Collaboration, PRL **130,** 242301 (2023)

- Two theory comparisons:
  - ε_n with nucleon spatial fluctuations
  - ε_n with nucleon + sub-nucleon spatial fluctuations
- Same v_3 measured in all systems, consistent with:
  - Sub-nucleon spatial geometry

    or

  - Large initial stage pre-flow contribution

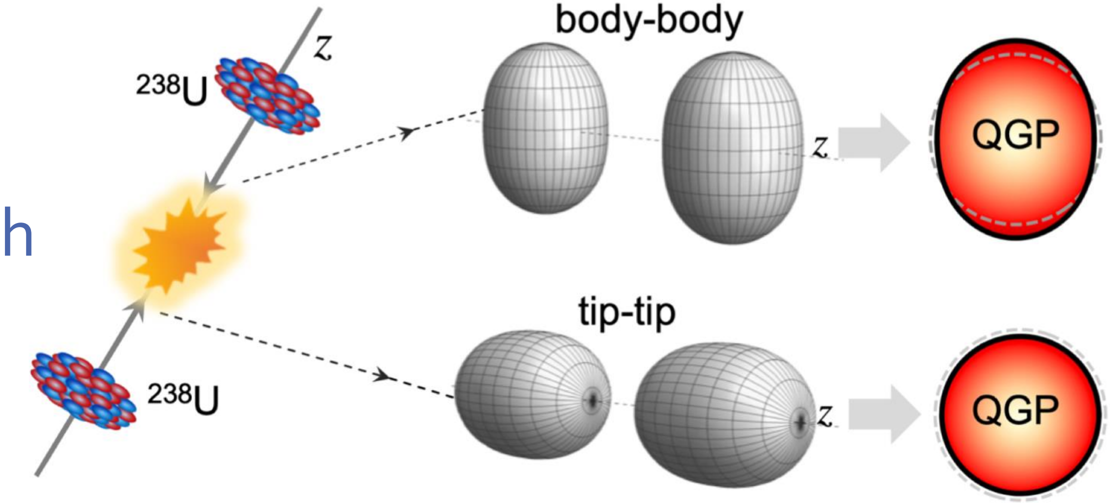
Imaging the Shape of Atomic Nuclei

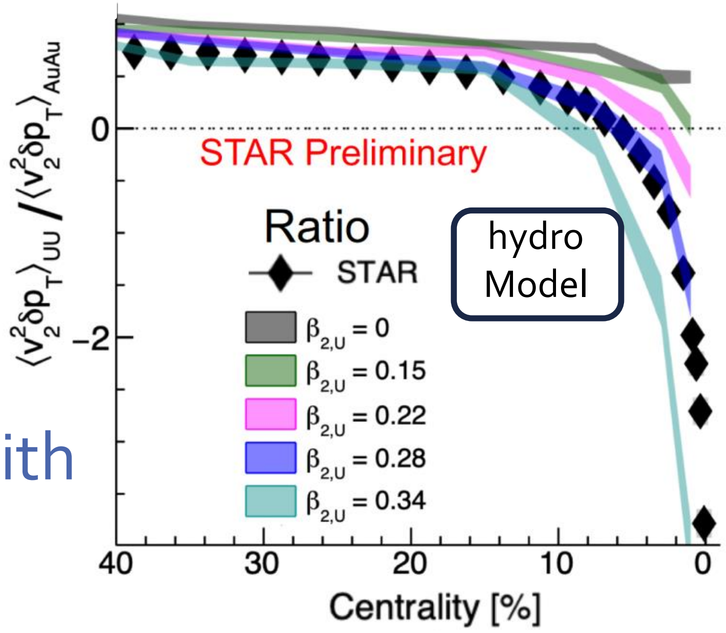
See Talk by Jiangyong Jia: Tues, Parallel Session 1

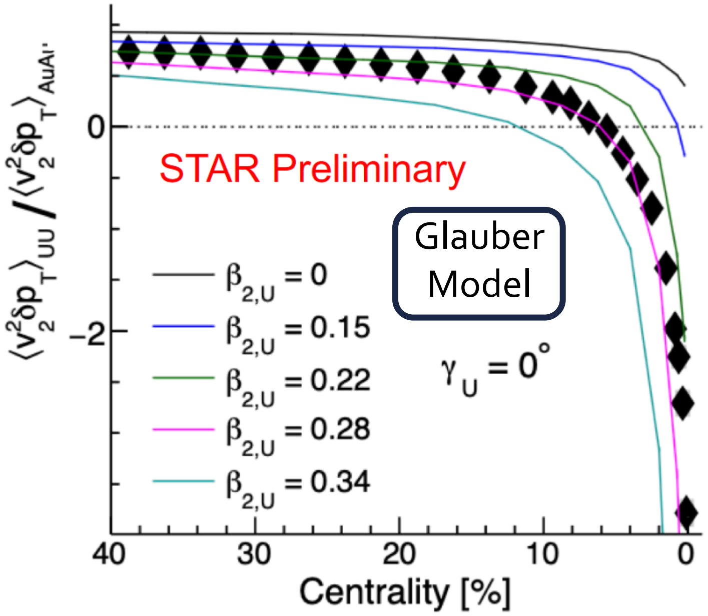
- Random orientation increases the flow fluctuation and correlations with p_T for $\mathrm{U+U}$ compared to $\mathrm{Au+Au}$
  - Take ratio of correlations to constrain nuclear shape parameters

$$\frac{\langle v_2^2\, \delta p_T\rangle_{\mathrm{UU}}}{\langle v_2^2\, \delta p_T\rangle_{\mathrm{AuAu}}}$$

- Compare with hydro and Glauber Models
- Constraints on quadrupole deformation, $\beta_{2,\mathrm{U}}$, and triaxiality, γ_{U}, consistent with low energy measurements

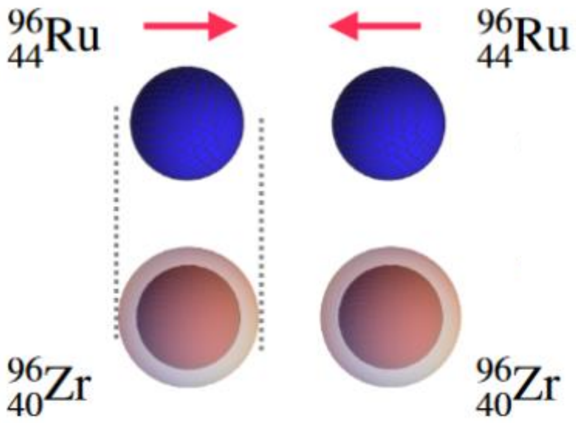




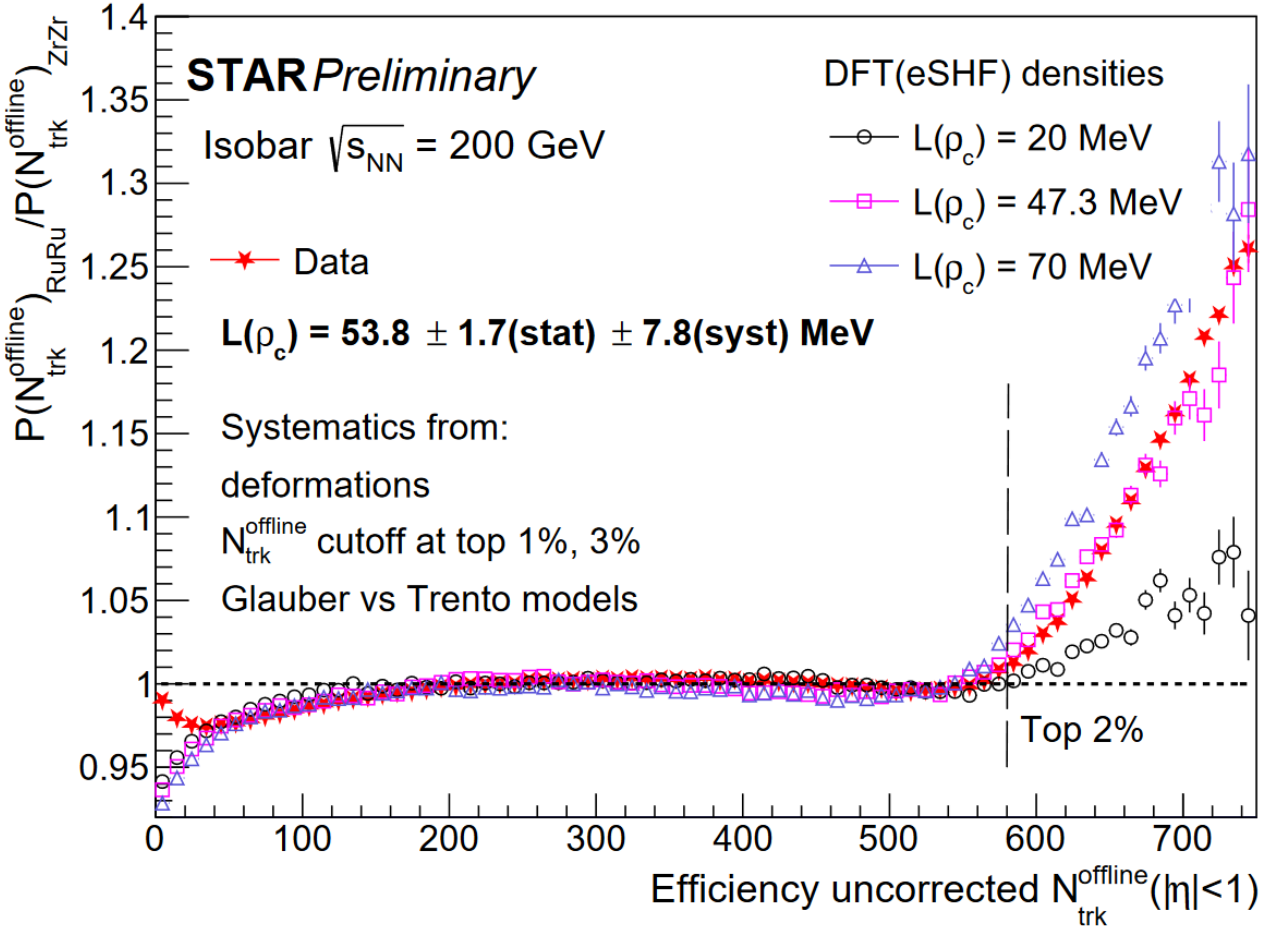


Measuring Nuclear Structure with Isobar Collisions

See Poster by Haojie Xu

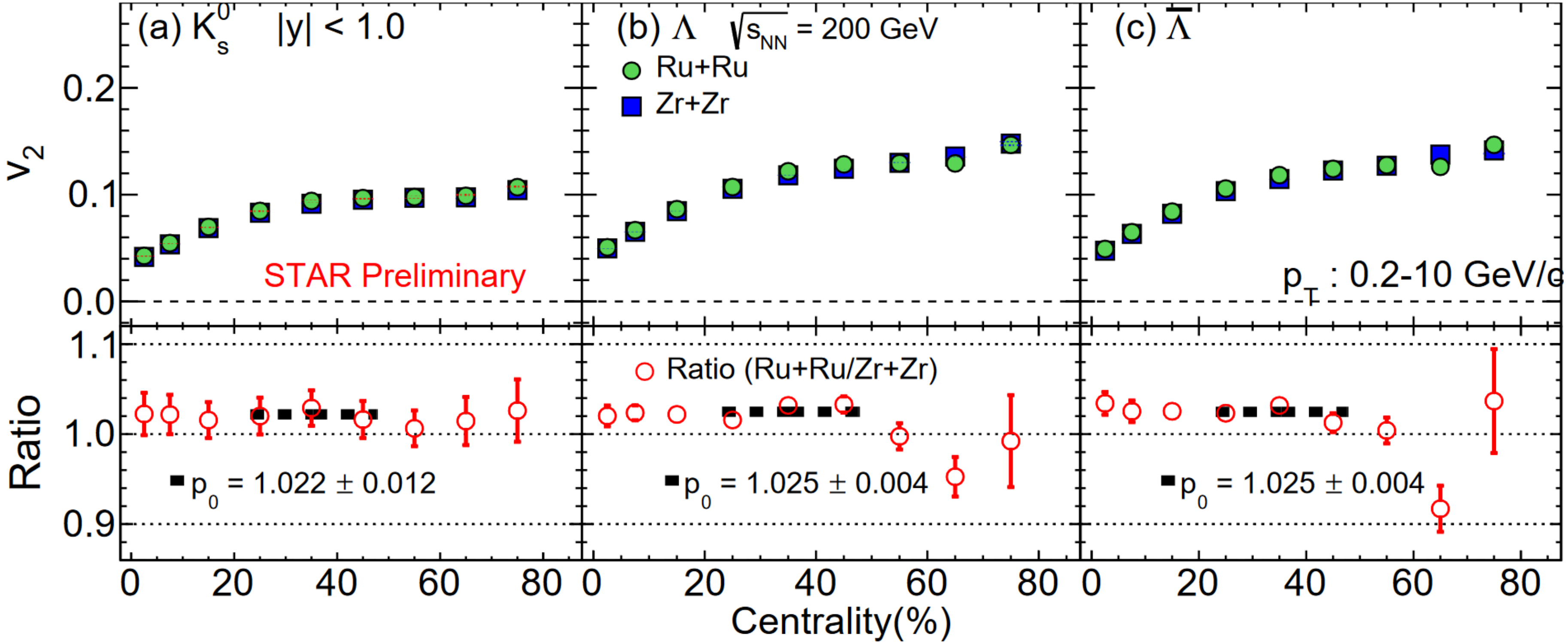


- Difference in number of neutrons affects the nucleus's size and density
- Use the multiplicity distribution to extract
  - Neutron skin thickness
  - Nuclear symmetry energy



Elliptic flow of strange and multi-strange hadrons in isobar collisions

See Poster by Priyanshi Sinha



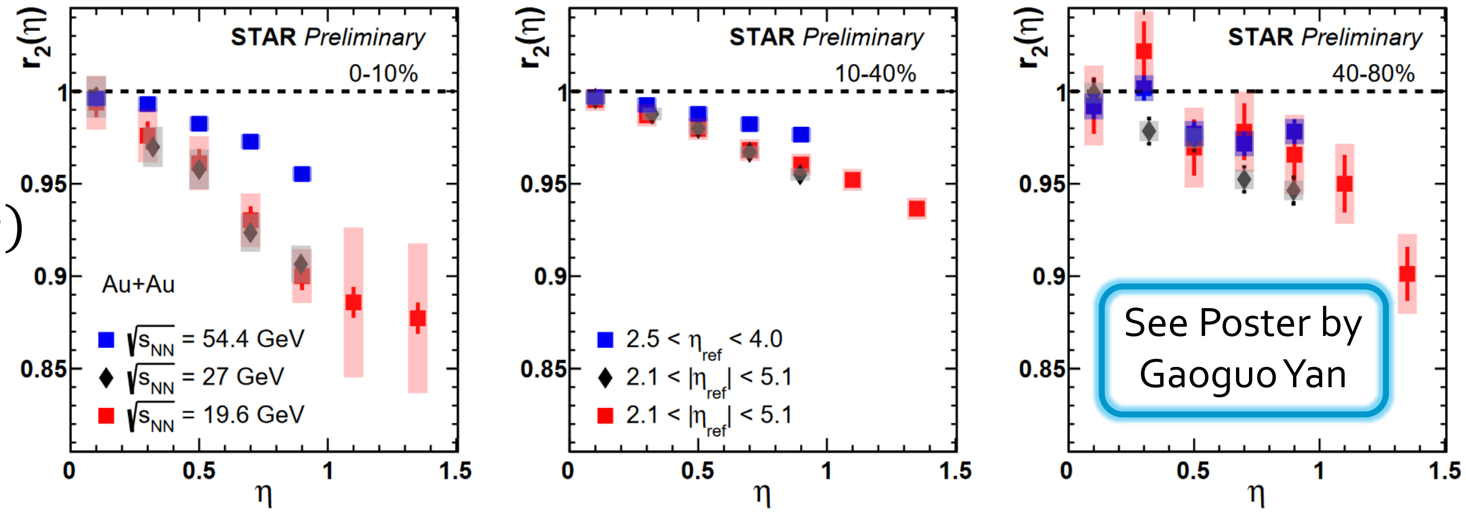
Ratio between v_2 in $\mathrm{Ru} + \mathrm{Ru}$ and $\mathrm{Zr} + \mathrm{Zr}$ is systematically greater than 1

- Caused by differences in the nuclear shape between the colliding nuclei

Longitudinal De-correlation of v_2 and v_3

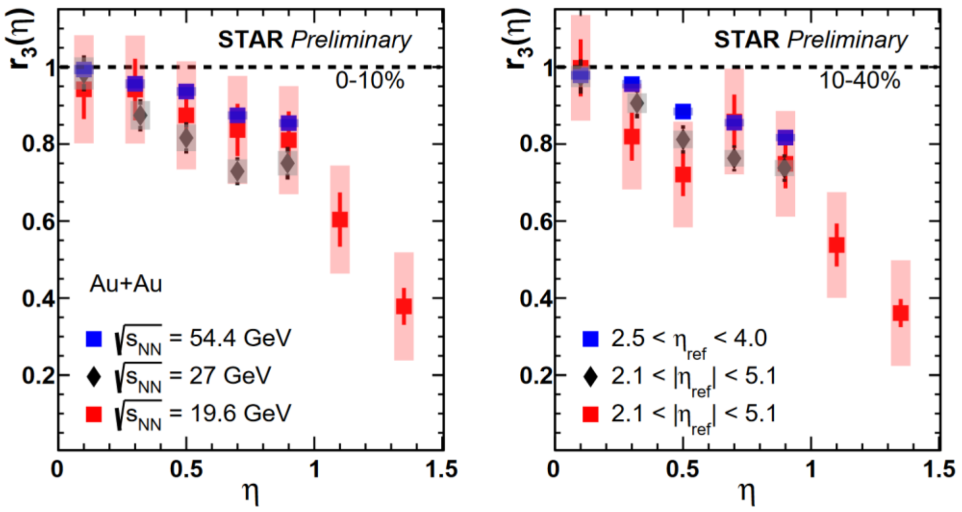
- $r_n(\eta)$: Measures how much v_n changes along the longitudinal direction
- Probing initial state dynamics in 3D and measuring the dynamical evolution of the QGP

$r_2(\eta)$

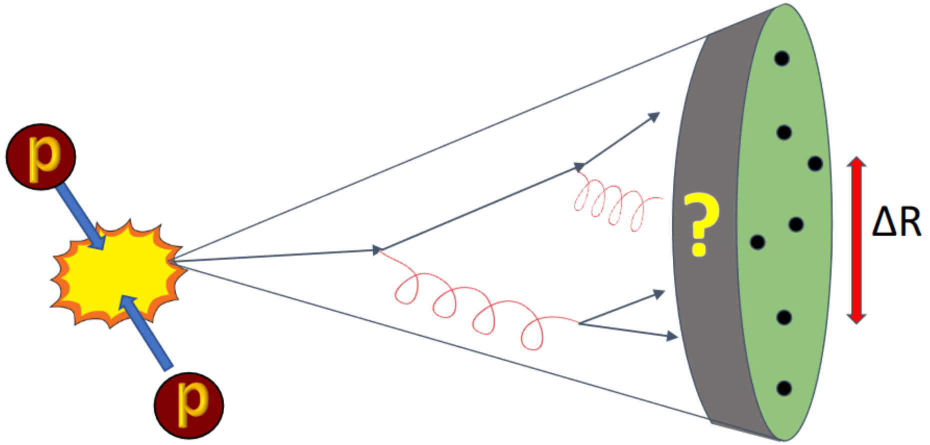


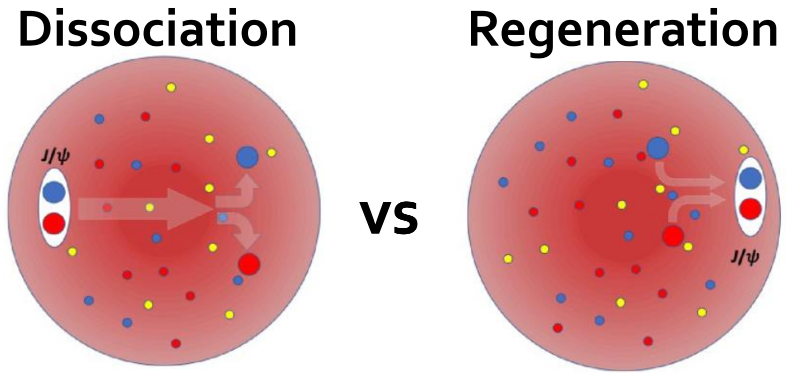
- $r_2(\eta)$ shows clear centrality dependence
- $r_3(\eta)$ shows much weaker centrality dependence
- Larger longitudinal de-correlations at lower collision energies

$r_3(\eta)$



Hard Probes





Jet Substructure in $p + p$

See Talk by David Stewart
Wed, Parallel Session 5

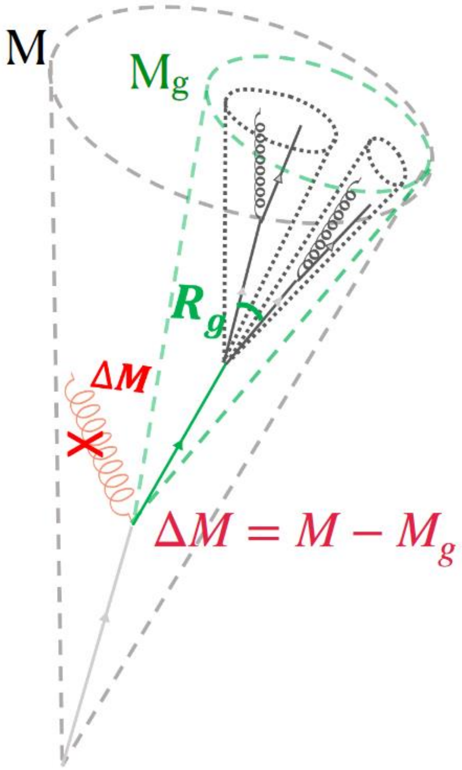
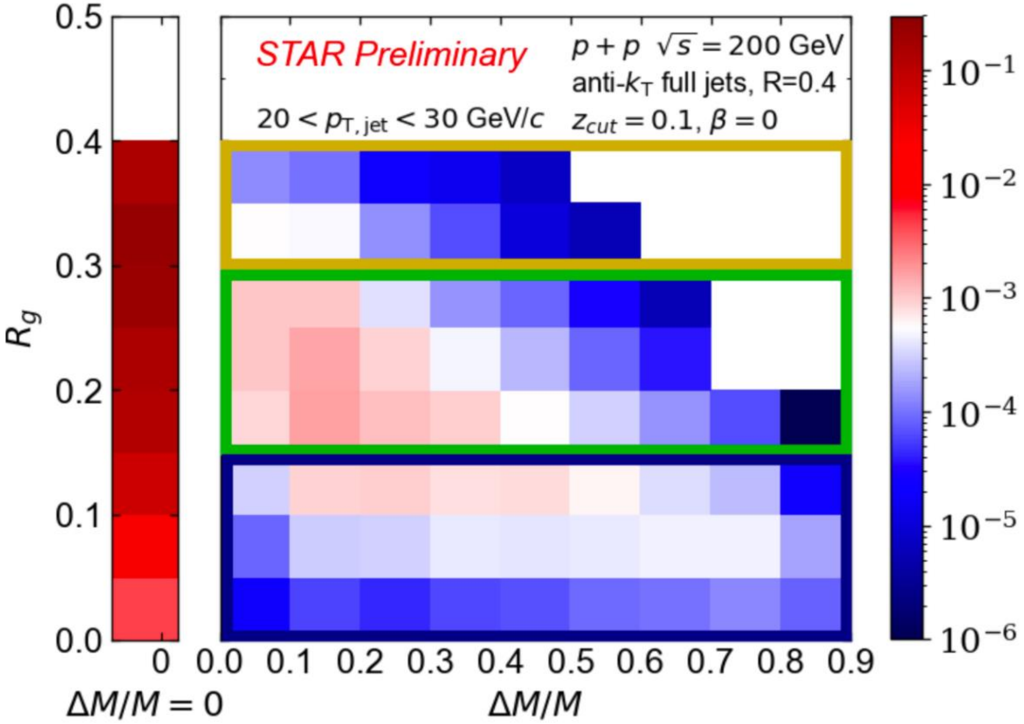
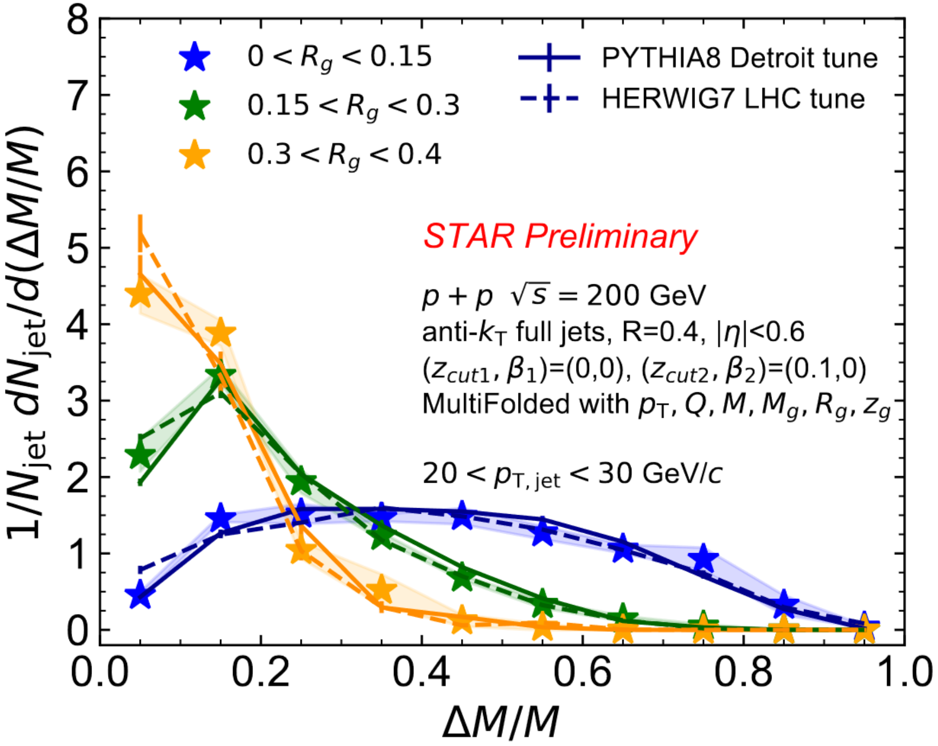


Figure from Nihar Sahoo, HP2023





- Reconstruct jet, then groom to isolate non-perturbative part of shower
- Anti-correlation between collinear dropped jet mass $\Delta M/M$ and R_g
- Consistent with angular ordering of the parton shower

Energy-Energy Correlators (EEC) for Jets in $p + p$

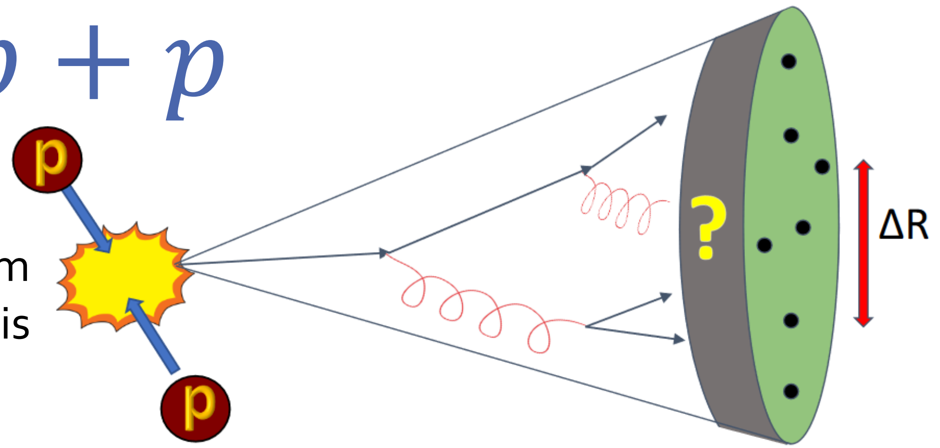
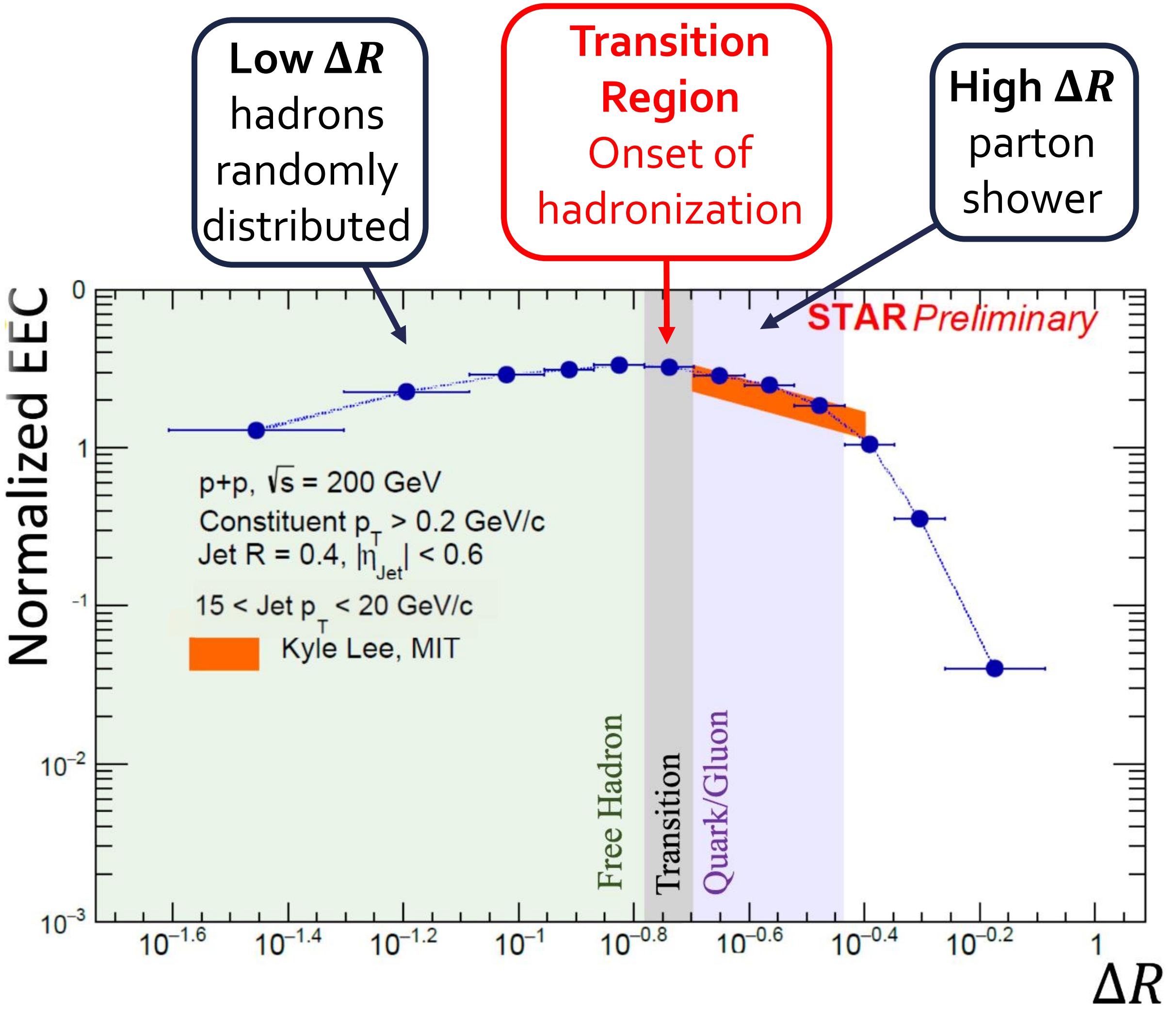


Diagram from Andrew Tamis HP 2023

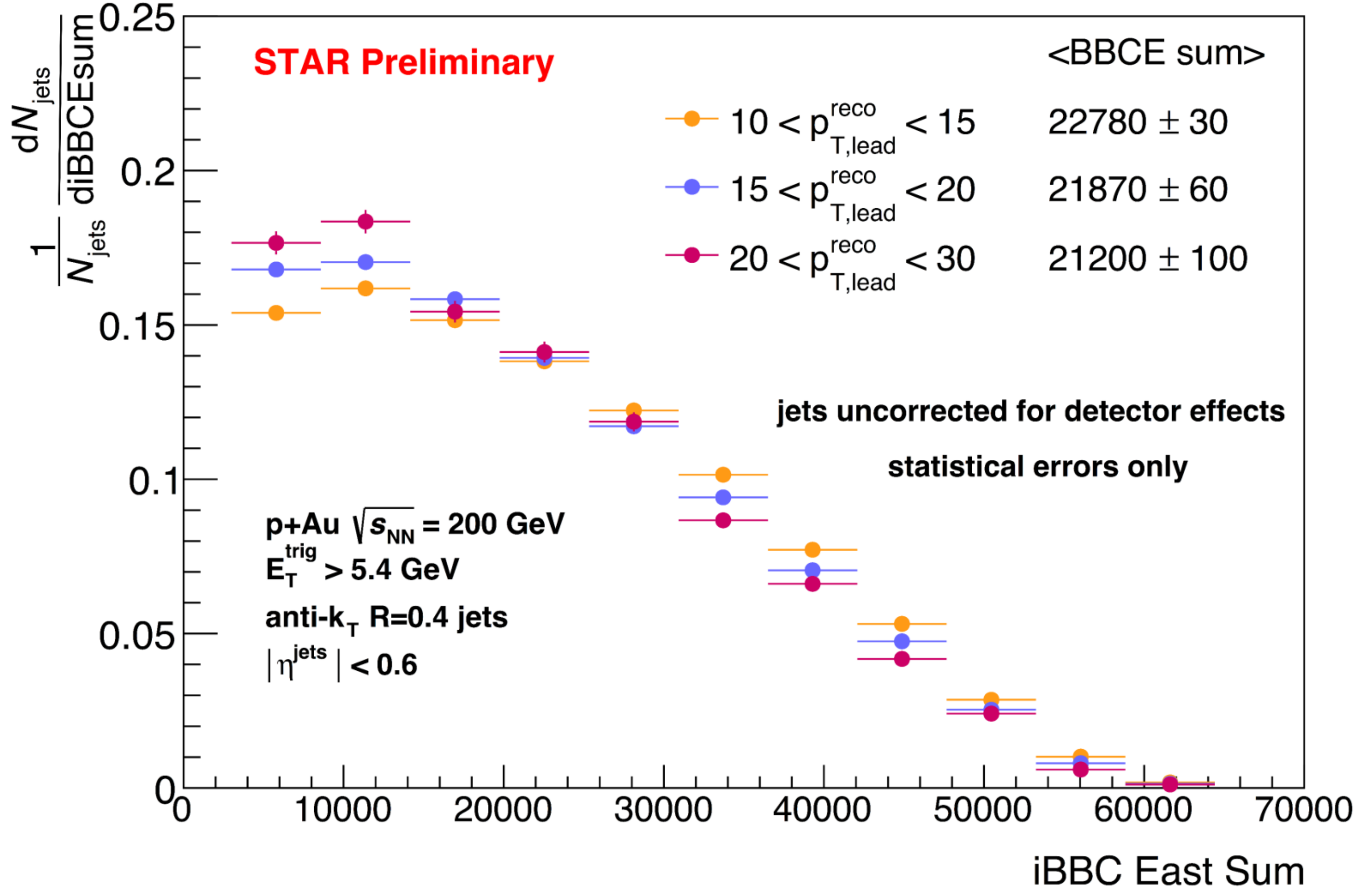
See Talk by David Stewart: Wed, Parallel Session 5

$$\text{Normalized EEC} = \frac{1}{\sum_{\text{Jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,\text{jet}}^2}} \frac{d\left(\sum_{\text{Jets}} \sum_{i \neq j} \frac{E_i E_j}{p_{T,\text{jet}}^2}\right)}{d(\Delta R)}$$

- Studying how the energy is distributed as a function of spatial separation within the jet
- Probing hadronization scale and jet evolution
  - Transition region is $\Delta R \times p_T^{\text{jet}} \sim 2 - 3\ \text{GeV}$ independent of jet p_T



Jet-Event Activity Correlations in $p + \mathrm{Au}$



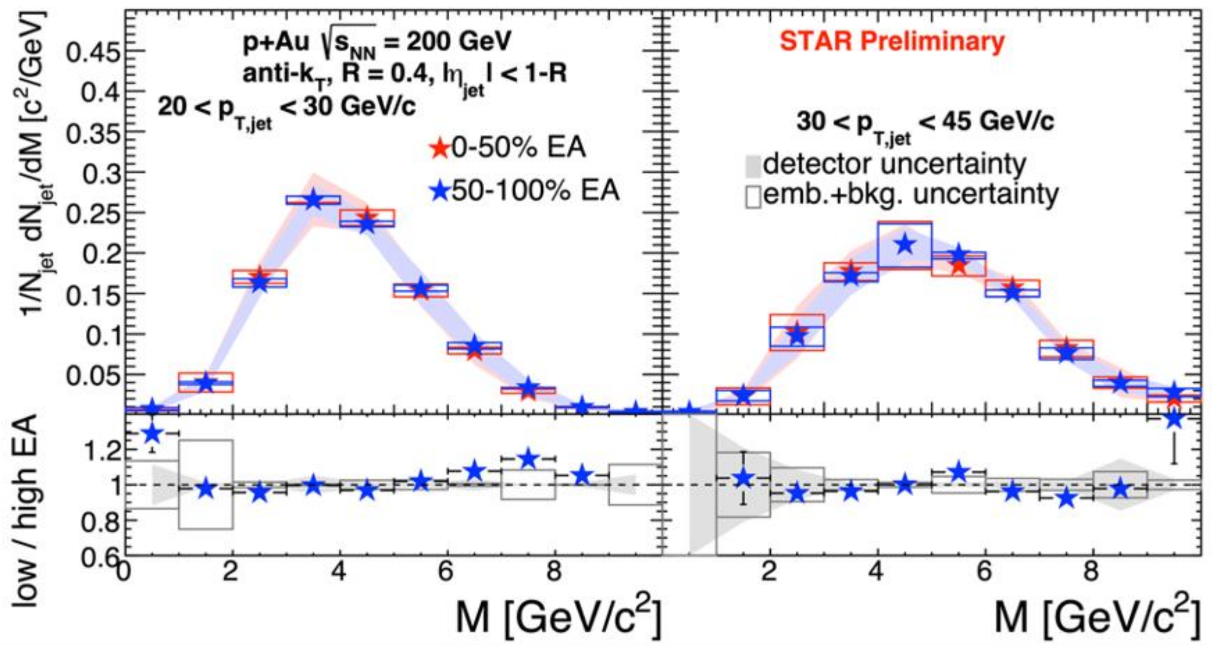
See Talk by David Stewart
Wed, Parallel Session 5

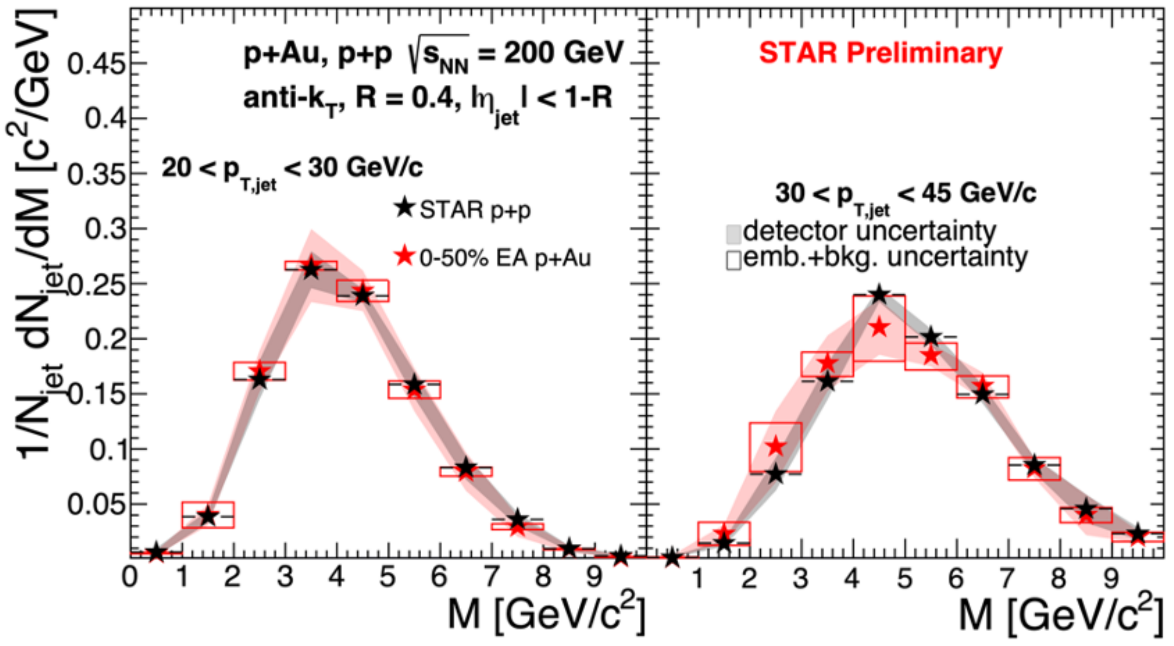
- Anti-correlation between jet p_T at mid-rapidity and Event Activity (EA) at forward-rapidity
  - i.e. lowest-p_T jets have a broader EA distributions
  - Hard and soft scale physics are correlated over broad range of rapidities

Jet Mass Distribution in $p + \mathrm{Au}$

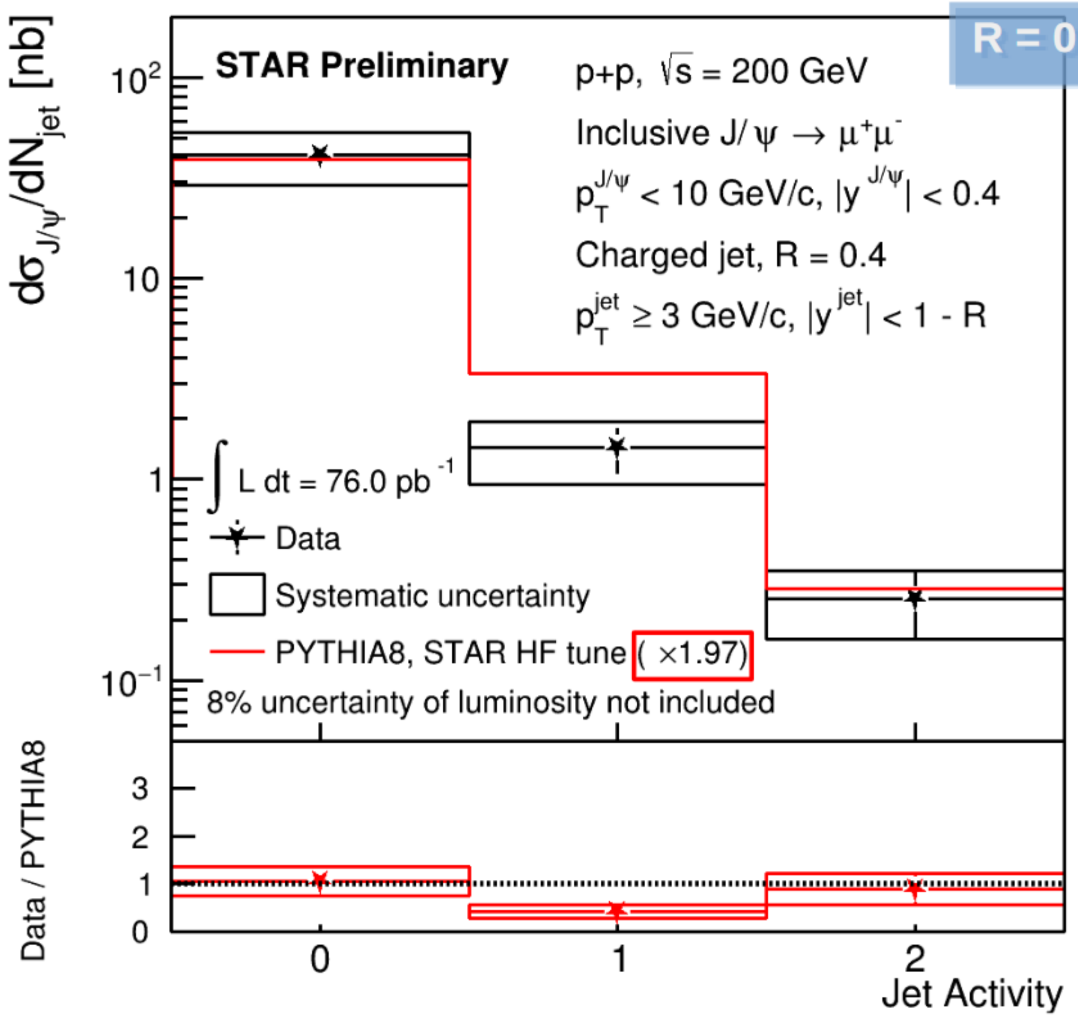
- Shape of jet mass distribution does not change with event activity (EA)
- M distribution in high-EA $p + \mathrm{Au}$ also consistent with $p + p$
- **Null result for jet quenching in $p + \mathrm{Au}$**

See Talk by David Stewart
Wed, Parallel Session 5



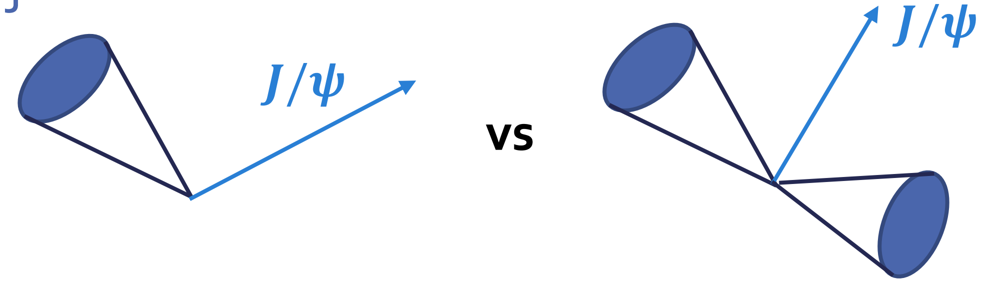


J/ψ Production with Jet Activity in $p + p$



See Talk by Barbara Trzeciak
Tues, Parallel Session 4

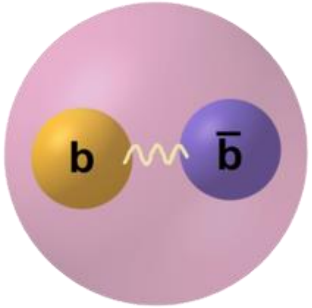
- J/ψ cross section as a function of number of jets



- Constraining J/ψ production mechanism: color singlet vs color octet
- In the measured kinematics, PYTHIA8 predicts a larger fraction of J/ψs are produced in association with jets than observed in data
- Theoretical model calculations needed

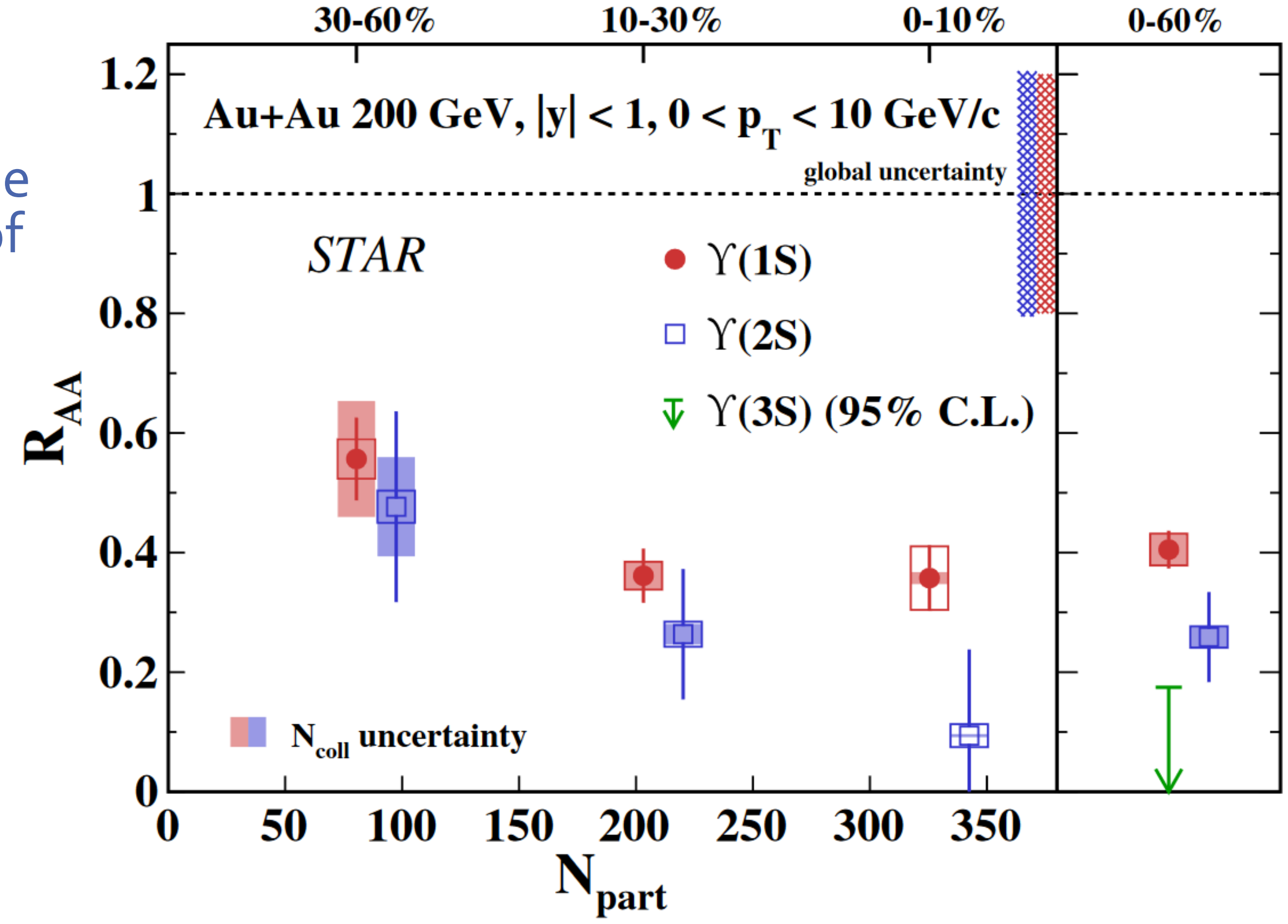
Suppression of Υ States in $Au + Au$

See Talk by Barbara Trzeciak: Tues, Parallel Session 4



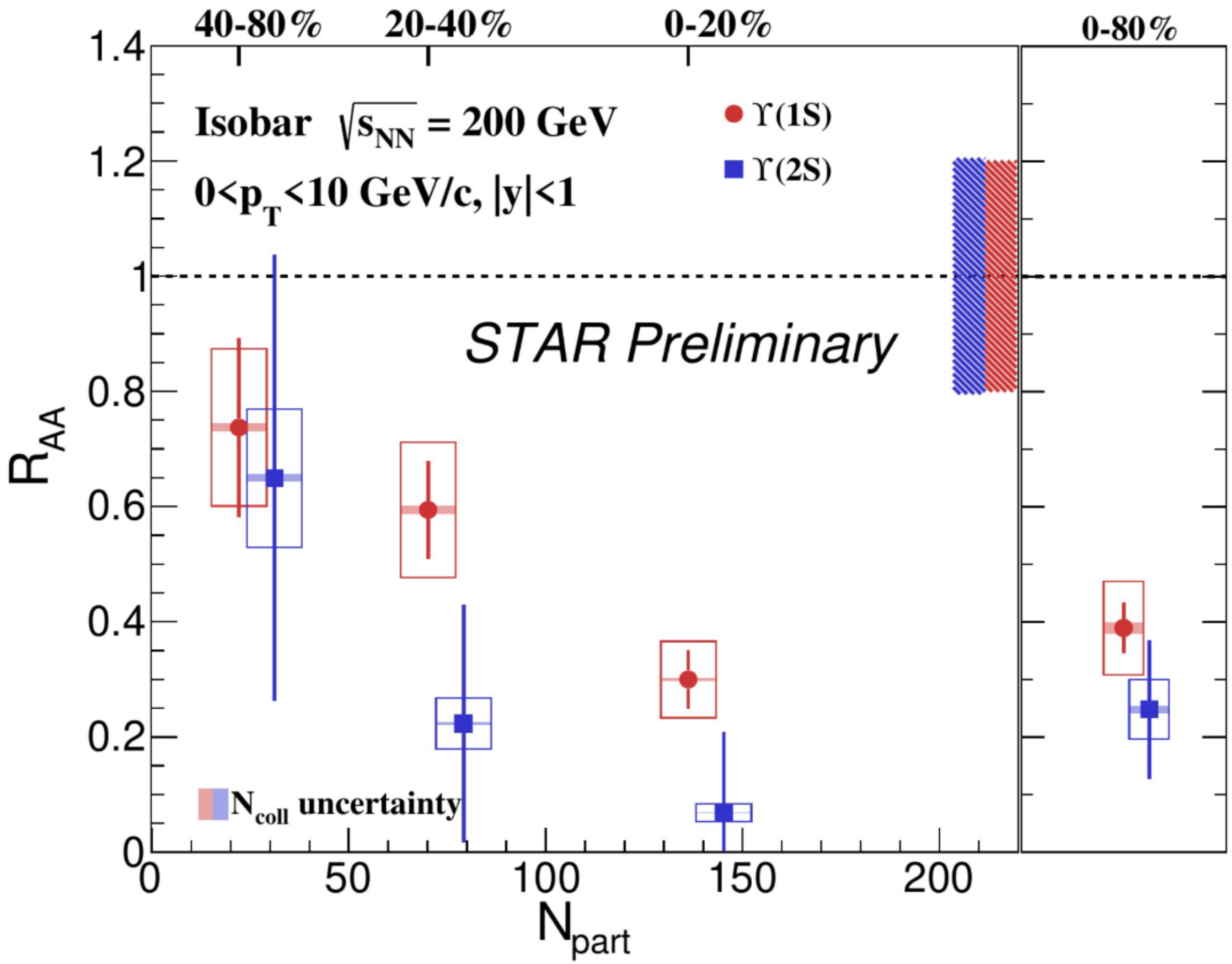
- A colored dipole
- Sensitive to the temperature of the QGP

- Significant suppression of Υ states compared to $p + p$
  - Increases with centrality
  - Sequential suppression pattern: higher excited states more suppressed due to their lower binding energies



STAR Collaboration, PRL **130,** 112301 (2023)

Suppression of ϒ States in Isobar Collisions



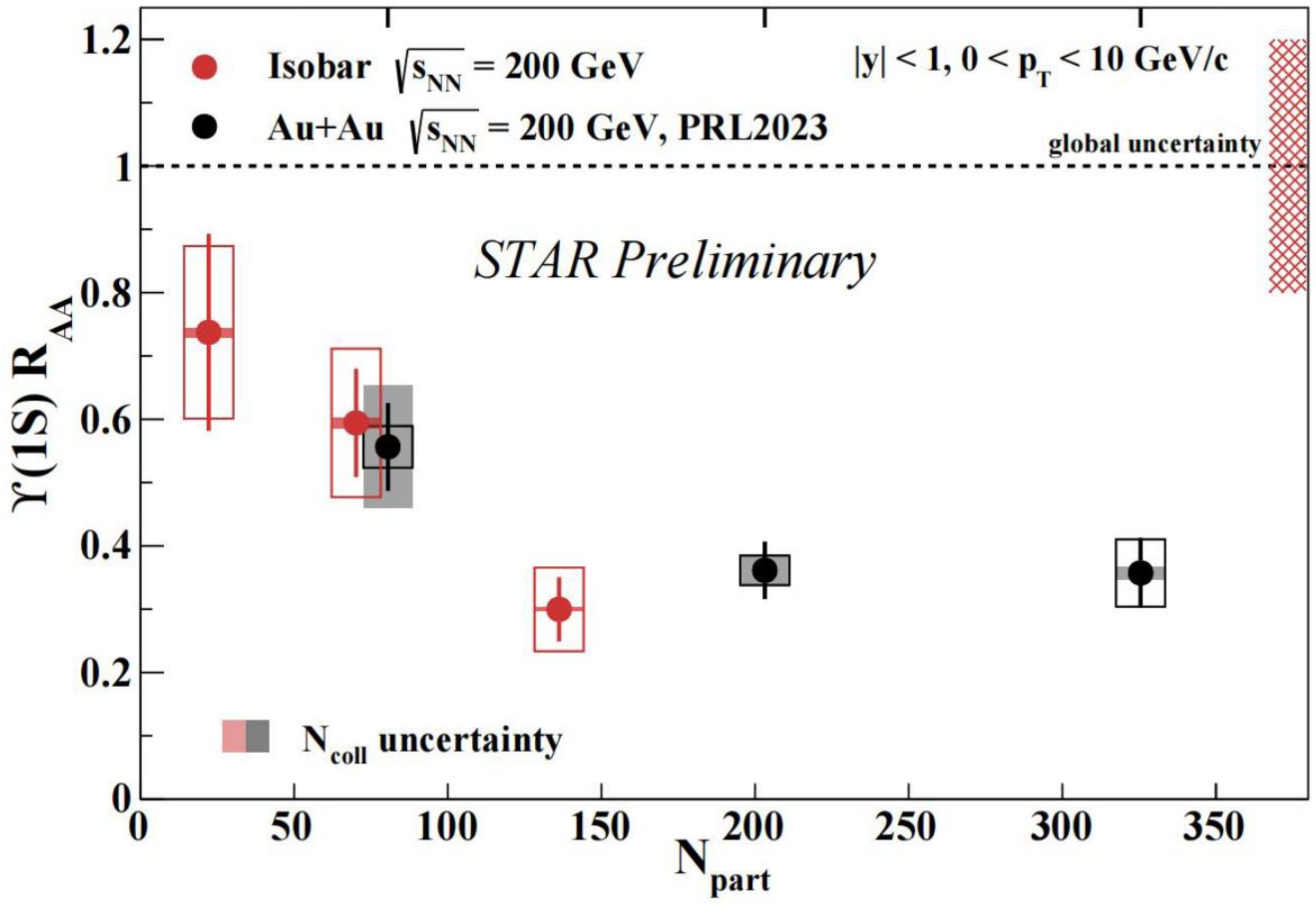
See Talk by Barbara Trzeciak
Tues, Parallel Session 4

$^{96}_{40}Zr$ $^{96}_{44}Ru$ ⟷ $^{197}_{79}Au$

Similar R_{AA} suppression of ϒ states in isobar collisions as $Au + Au$

- Increases with centrality
- Hint of sequential suppression pattern

Suppression of Υ States in Isobar Collisions



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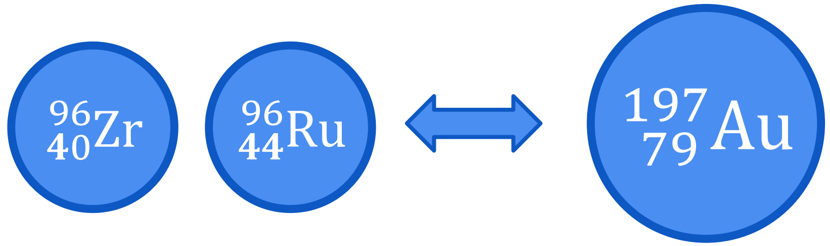
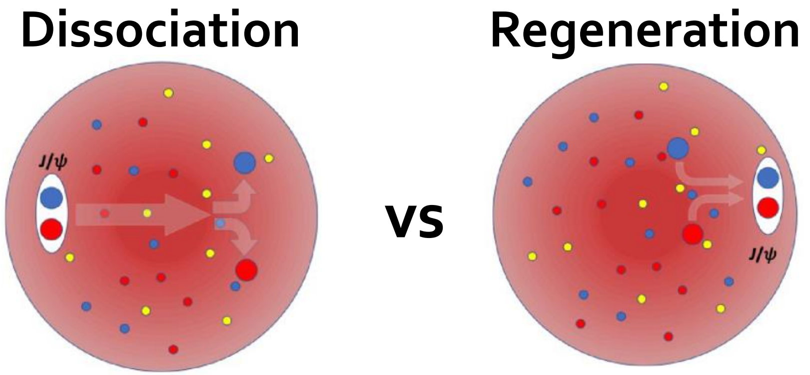


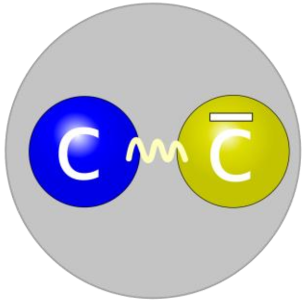
Similar R_{AA} suppression of Υ states in isobar collisions as Au + Au

- No significant dependence on collision species
- Suppression is driven by system size, $\langle N_{part} \rangle$

J/ψ Supression

See Talk by Barbara Trzeciak
Tues, Parallel Session 4

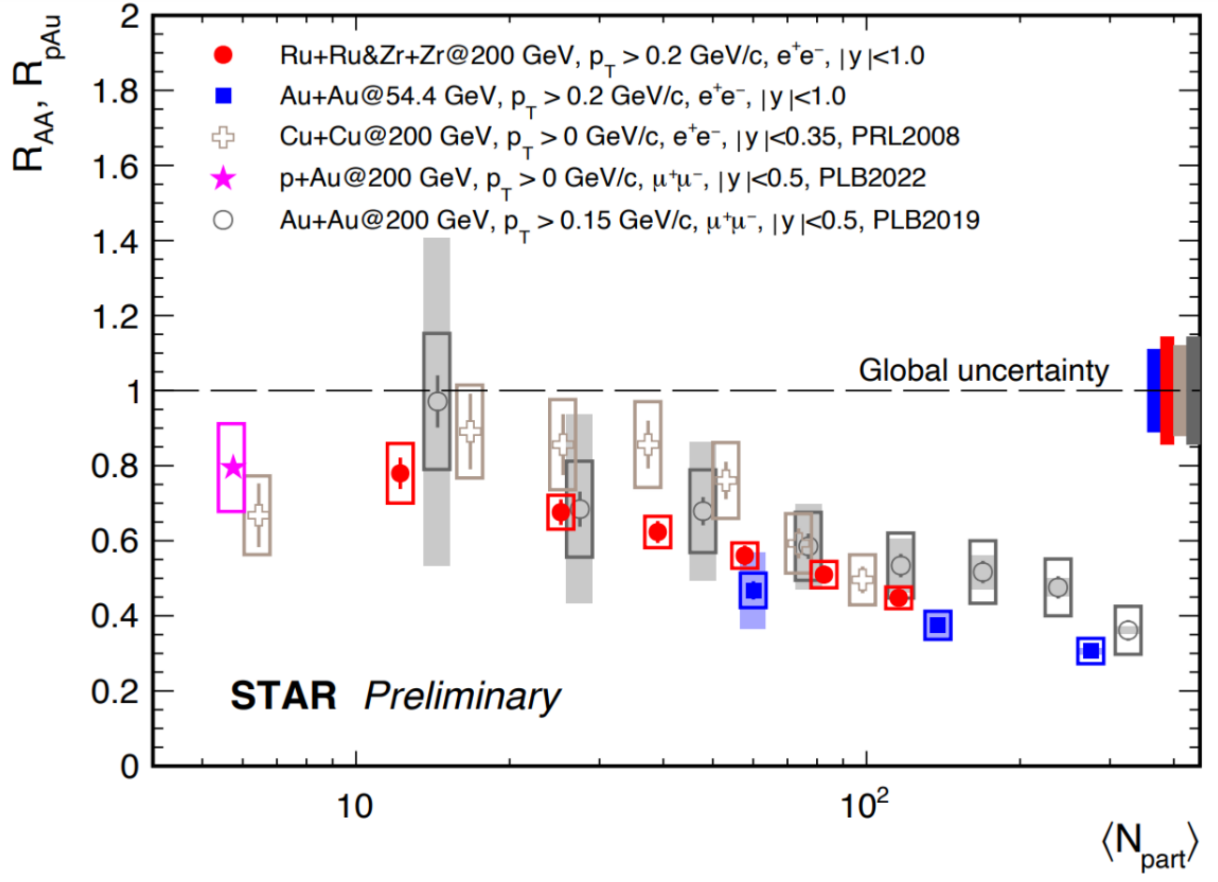




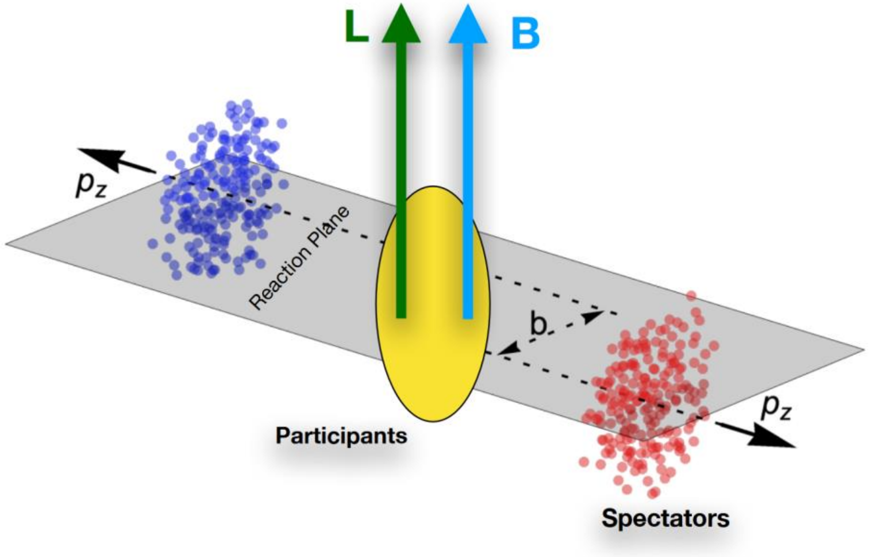
Also a colored dipole

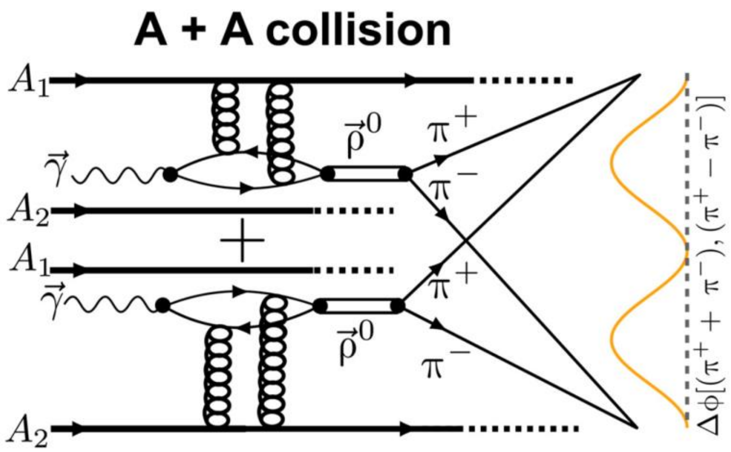
- Less massive than Υ
- Expected larger contribution from regeneration

- J/ψ R_{AA} suppression in isobar collisions is consistent with $Au + Au$ at similar $\langle N_{\text{part}}\rangle$
- Suppression is driven by system size $\langle N_{\text{part}}\rangle$, not the collisions geometry



Polarization in Heavy Ion Collisions





Global Spin Alignment of ϕ and K^{*0}

- Measuring ρ_{00}, the 00^{th} component of the spin density matrix
  - ρ_{00} deviating from $1/3$ indicates spin alignment
  - Conventional causes of polarization:

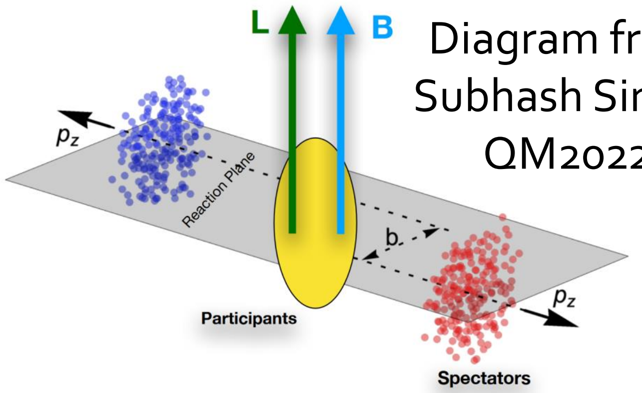
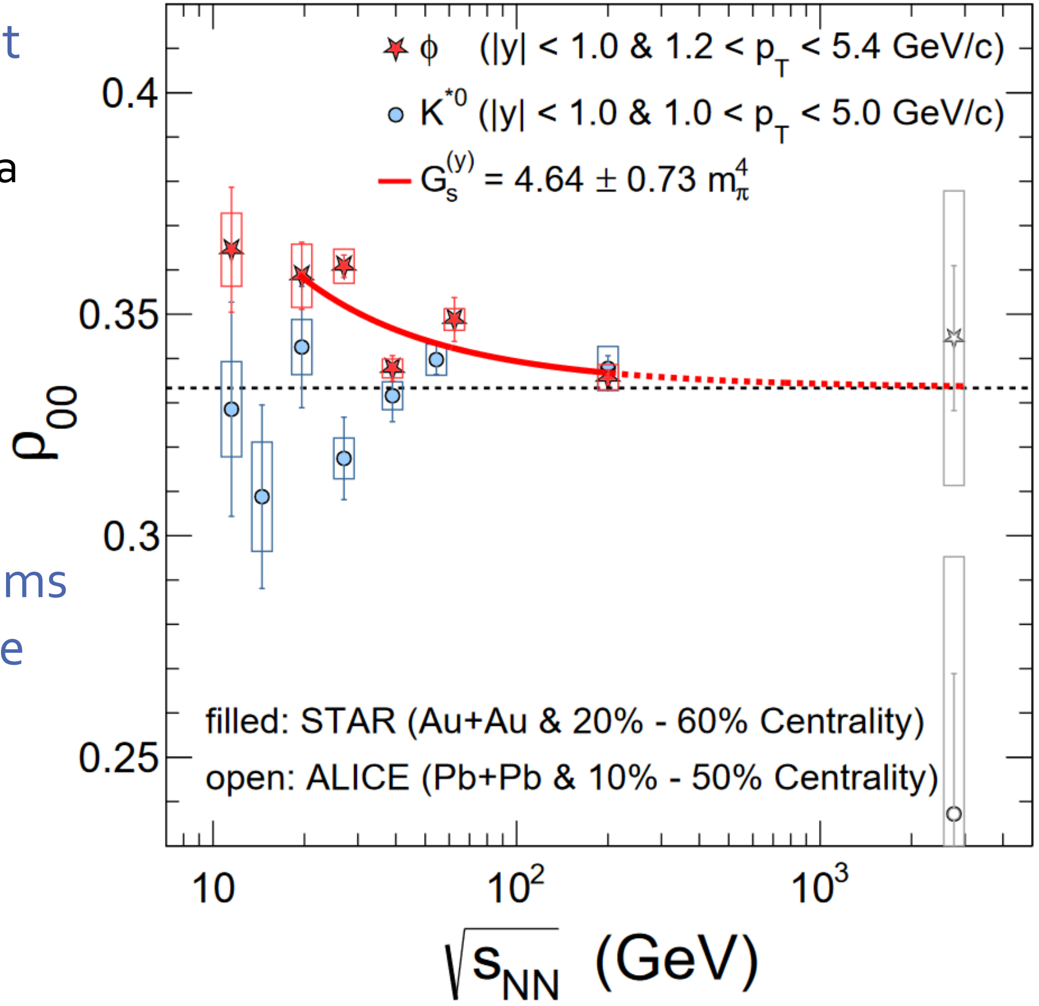


Diagram from Subhash Singha QM2022

STAR Collaboration, Nature **614**, 244 (2023)

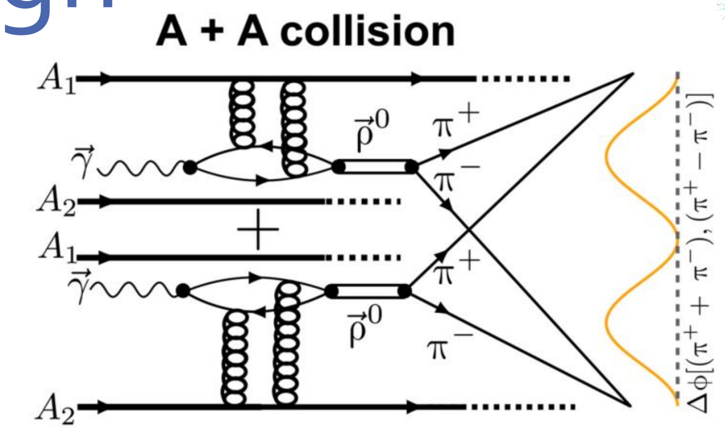


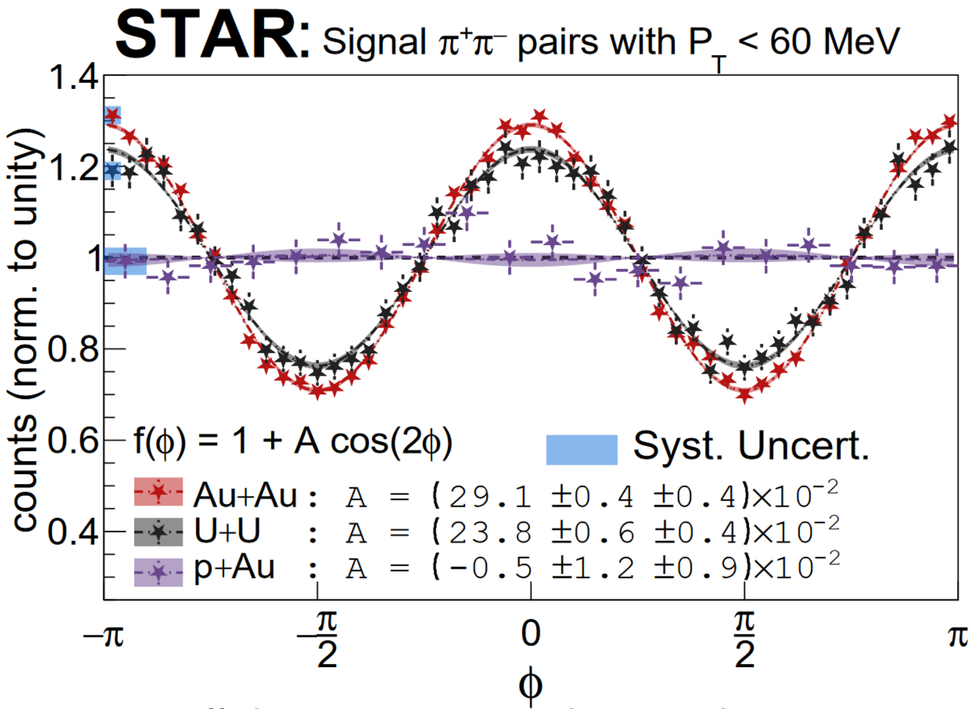
- Large excess of ϕ ρ_{00} compared to K^{*0} ρ_{00}
  - Cannot be explained by conventional mechanisms
  - Consistent with polarization due to strong force field
  - **Possible connection to effects from glasma fields**
    A. Kumar, B. Müller, and D.L. Yang, arXiv:2304.04181 (2023)

Nuclear Tomography Through Entanglement

See Poster by Sam Corey and Daniel Brandenburg

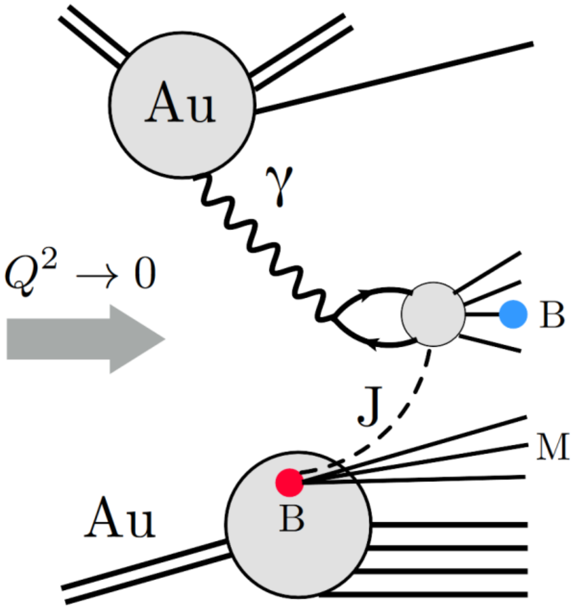
- Quantum interference between one ion emitting the ρ versus the other
  - Analogous to a double-slit pattern
- No entanglement in $p + Au$
- Strong Modulation in $A + A$ collisions
  - Difference in $Au + Au$ vs $U + U$ sinsitve to nuclear geometry
  - Used to extract nuclear mass radius

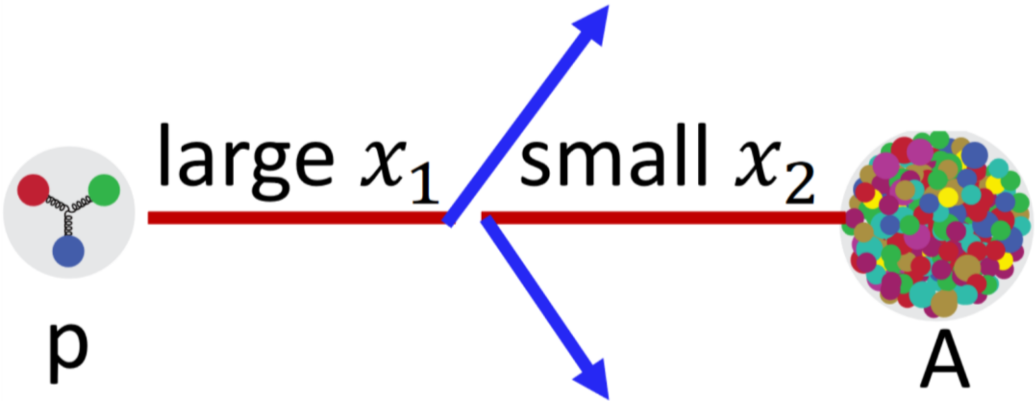




STAR Collaboration, Sci. Adv. **9,** eabq3903 (2023)

Low-x Measurements

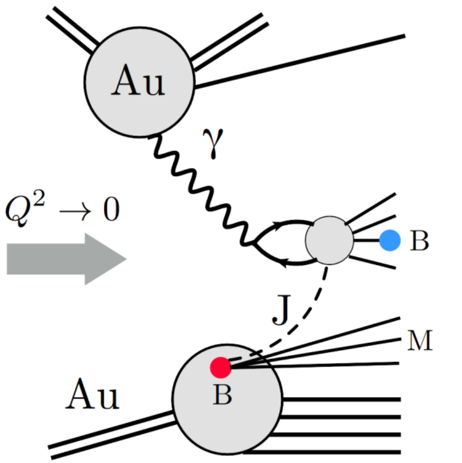




Baryon Stopping in $\gamma + \mathrm{Au}$

For more information see:
N. Lewis, DIS 2023
C.Y. Tsang, APS GHP 2023

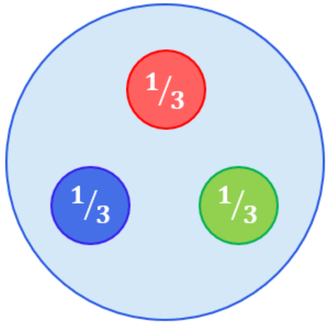
- Clear signature of baryon stopping in inclusive photonuclear collisions
  - Similar to eA except $Q^2 \to 0$



arXiv:2205.05685 (2022)

- Not consistent with the baryon number being carried by the valence quarks
  - Alternative model: baryon junction, a Y-shaped configuration of low-x gluons which carries the baryon number

    D. Kharzeev, Physics Letters B **378**, 238 (1996)



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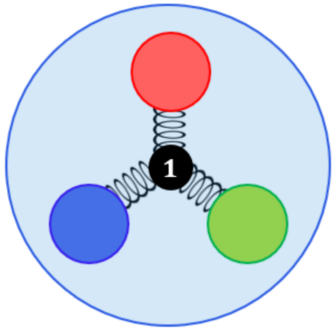
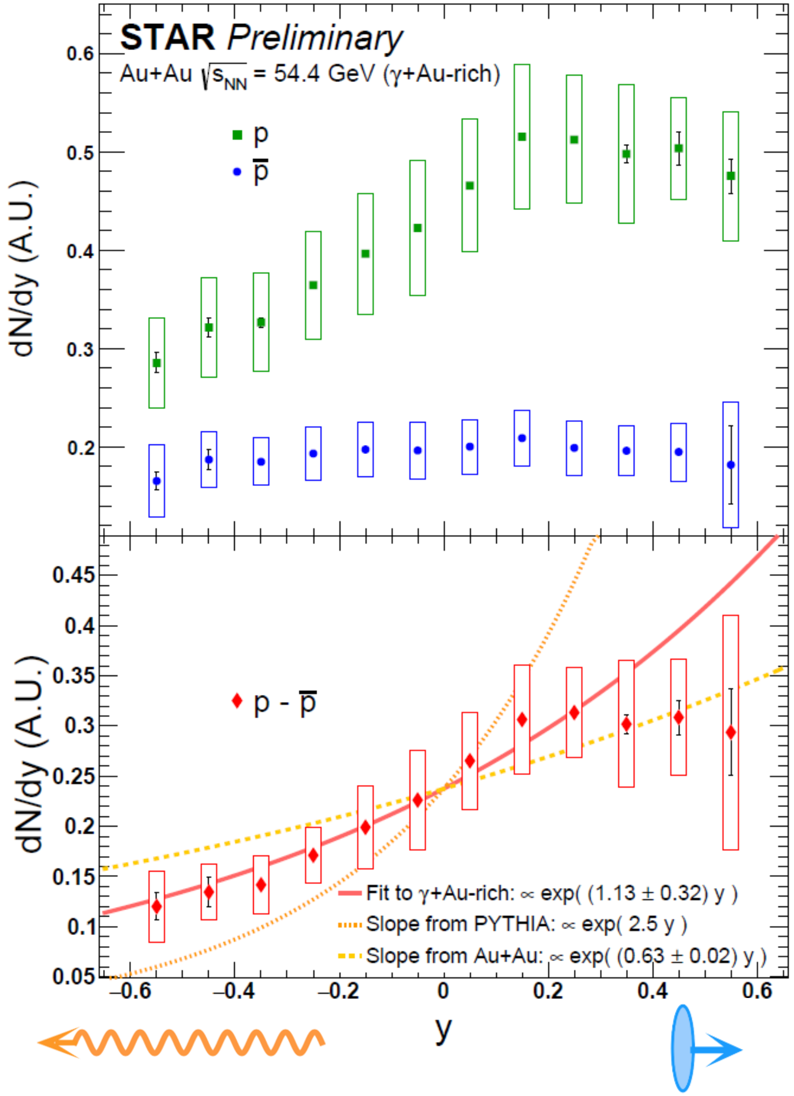


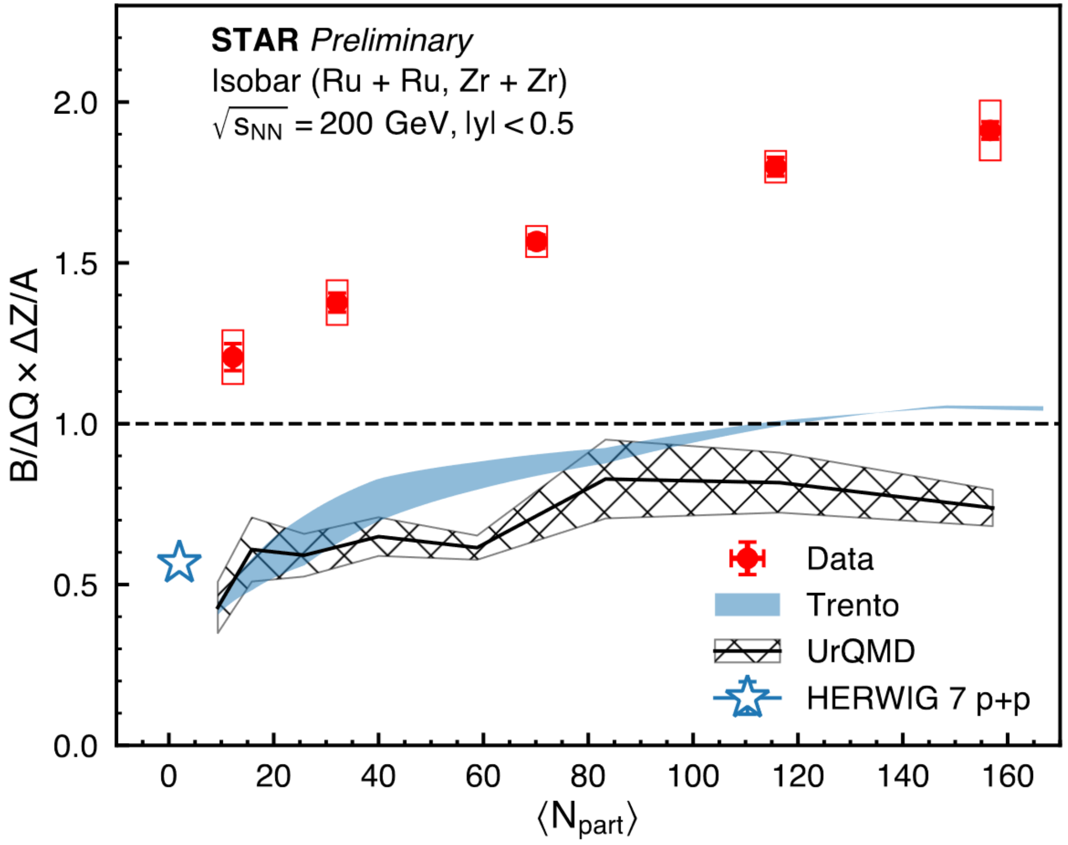


Charge Stopping vs Baryon Stopping Using Isobar Collisions

For more information see:
N. Lewis, DIS 2023
C.Y. Tsang, APS GHP 2023

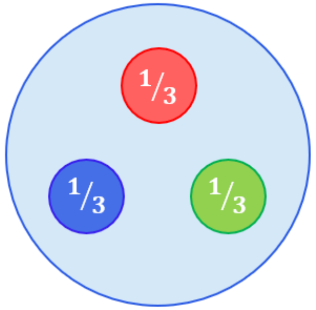
Charge stopping difficult to measure experimentally

- Measure net-charge yield difference instead: $\Delta Q = Q(\mathrm{Ru}) - Q(\mathrm{Zr})$
- Compare to net-baryon yield, B



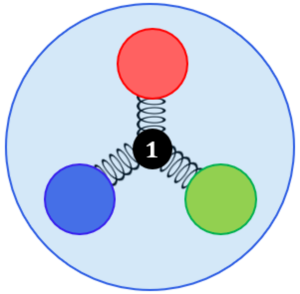
If quarks carry baryon number:

$$\frac{B}{\Delta Q} \times \frac{\Delta Z}{A} \leq 1$$



- Model calculations predict < 1

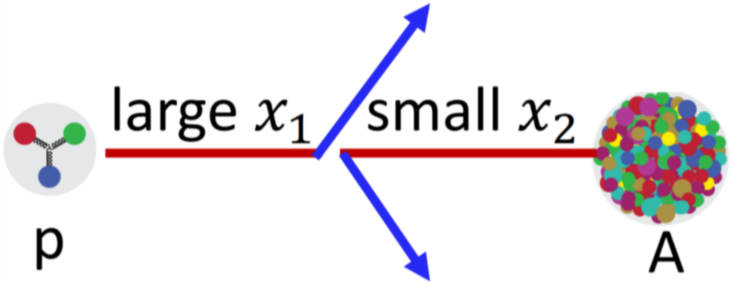
For all centralities: $\frac{B}{\Delta Q} \times \frac{\Delta Z}{A} > 1$



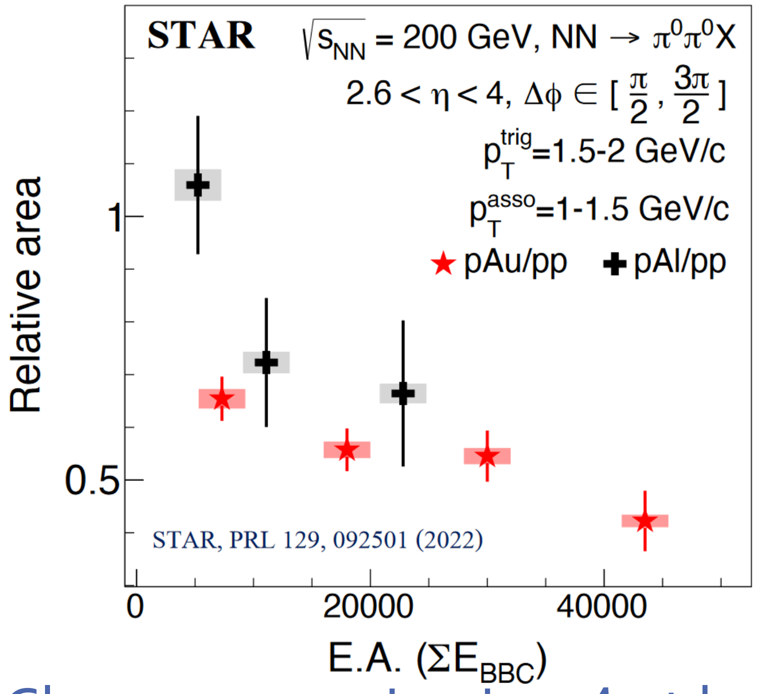
- Consistent with baryon junction prediction
- Larger reaction cross section due to junctions carrying a much smaller momentum fraction: more baryon stopping arXiv:2205.05685 (2022)
- Shape consistent with effects from the neutron skin

Di-π^0 Correlations in $p+p$, $p+\mathrm{Al}$, $p+\mathrm{Au}$, $d+\mathrm{Au}$

See Talk by Matt Posik: Tues, Parallel Session 4

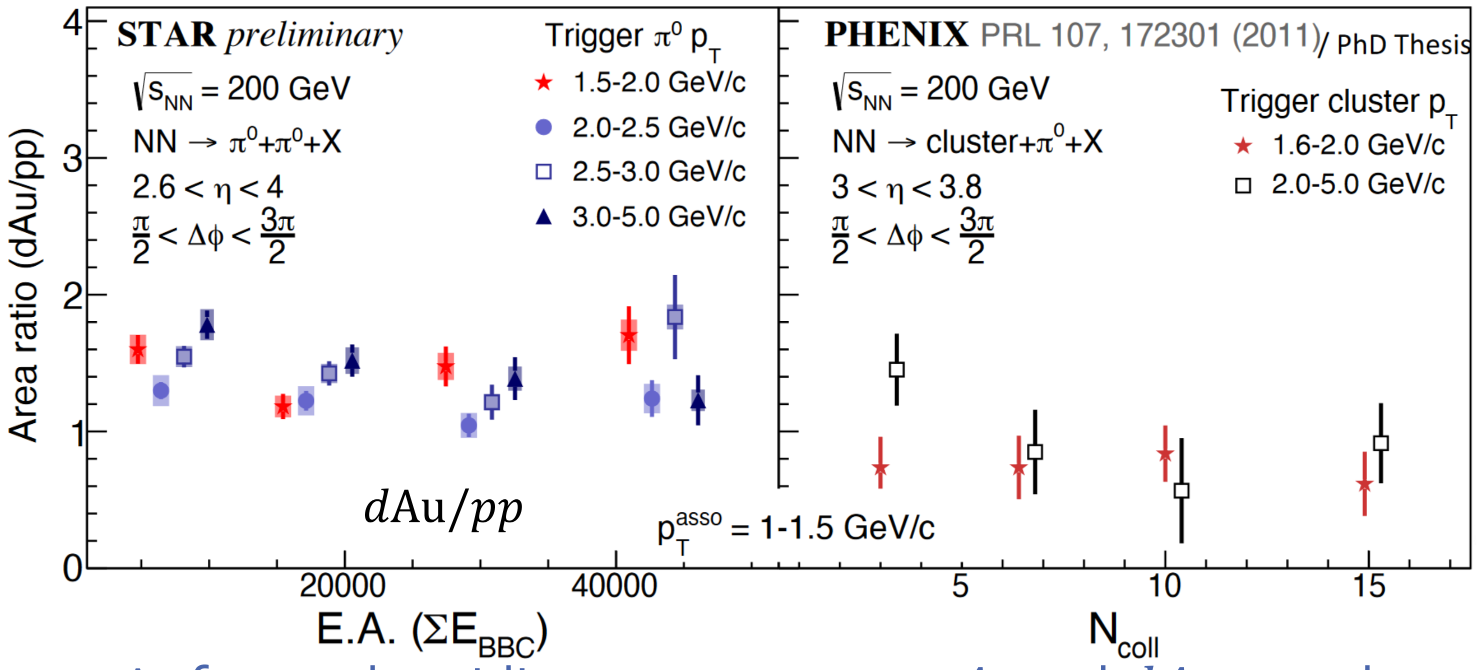


STAR, PRL **129**, 092501 (2022)



Clear suppression in pA at low p_T
- Increases with event activity (E. A.)

Probing nonlinear gluon dynamics at small-x



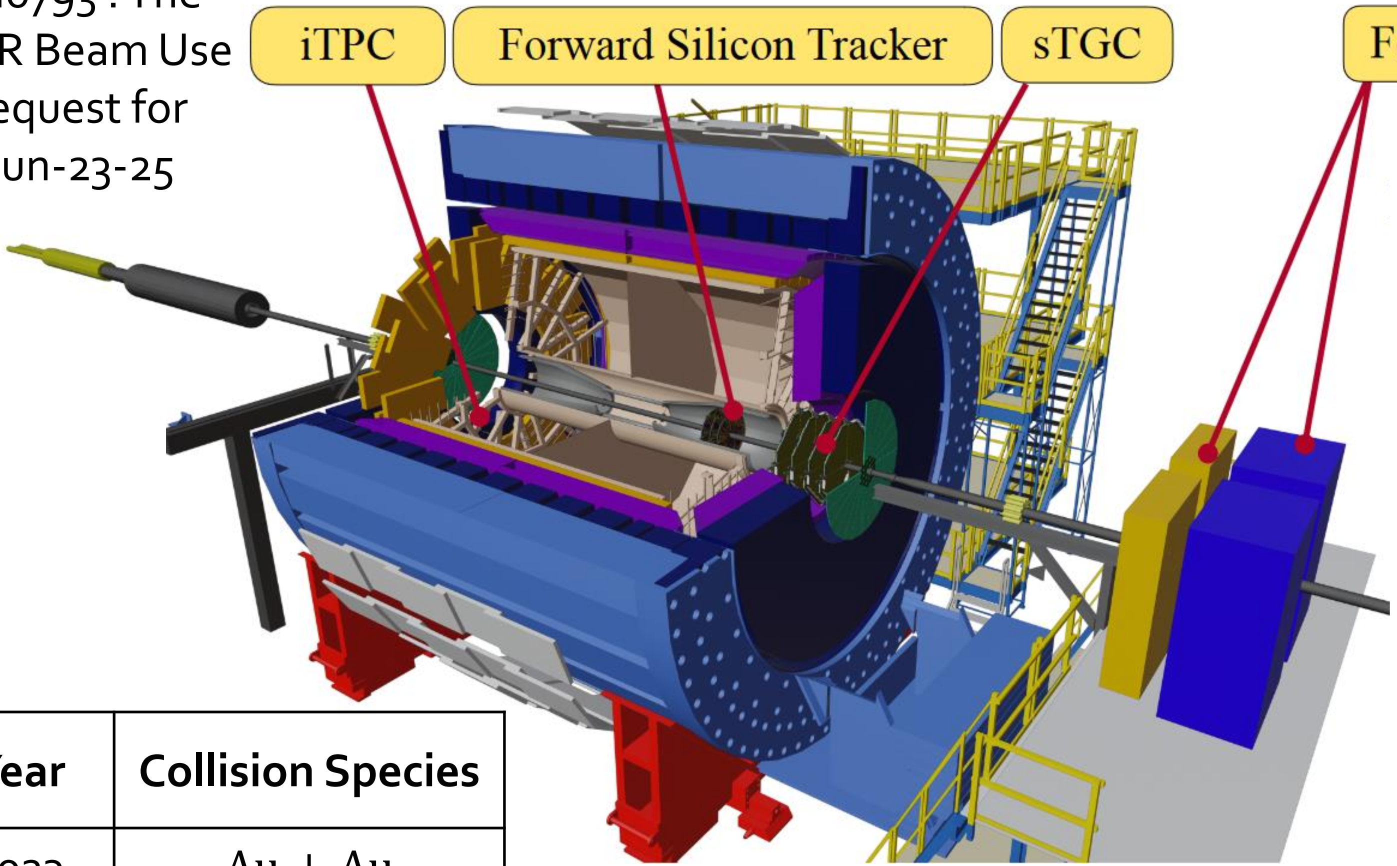
At forward rapidity, compare pp, pA, and dA to study Double Parton Scattering (DPS): two separate hard interactions in a single collision
- No suppression in overlapping RHIC kinematics in $d+\mathrm{Au}$
- Suppression only observed at very low p_T at PHENIX

Summary & Take Home

- STAR is able to probe fundamental properties of initial-state nuclear physics using a wide range of collision species and energies
- Flow Correlations
  - Collectivity in $p+\mathrm{Au}$, $d+\mathrm{Au}$ and $^{3}\mathrm{He}+\mathrm{Au}$ $\rightarrow$ consistent with large contribution from sub-nucleon flow or pre-flow
  - Probe nuclear structure and geometry
  - Larger longitudinal de-correlations at lower collision energies
- Hard Probes
  - Constraining jets in $p+p$ and $p+A$
  - Υ sequential suppression and J/ψ suppression is driven by system size
- Polarization in heavy ion collisions
  - Global Spin alignment of ϕ and K^{*0} consistent with a strong force field effect
- Low-x Measurments
  - Measurements sensitive to the carrier of the baryon number
  - Forward di-hadron correlations probe nonlinear gluon behavior

Future Data Taking with STAR

SN0793 : The STAR Beam Use Request for Run-23-25



Year	Collision Species
2023	Au + Au
2024	$p + p$, p + Au
2025	Au + Au

STAR Forward Upgrade
$2.5 < \eta < 4$

- Rapidity dependence of flow harmonics
- Longitudinal de-correlations
- Nonlinear gluon dynamics through dihadrons, γ-Jet, di-jets
- R_{pA} for direct photons, Drell Yan, hadrons

STAR Posters

- Elliptic flow of strange and multi-strange hadrons in isobar collisions at RHIC, **Priyanshi Sinha**
- Longitudinal De-correlation of Anisotropic Flow at RHIC-STAR , **Gaoguo Yan**
- Measurement of Femtoscopic correlation function between D^0 mesons and charged hadrons in $\mathrm{Au+Au}$ collisions at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$, **Priyanka Roy Chowdhury**
- Nuclear Tomography through Entanglement Enabled Spin Interference , **Sam Corey**
- Probing the neutron skin and nuclear symmetry energy with isobar collisions at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$ by STAR, **Haojie Xu**

STAR Talks

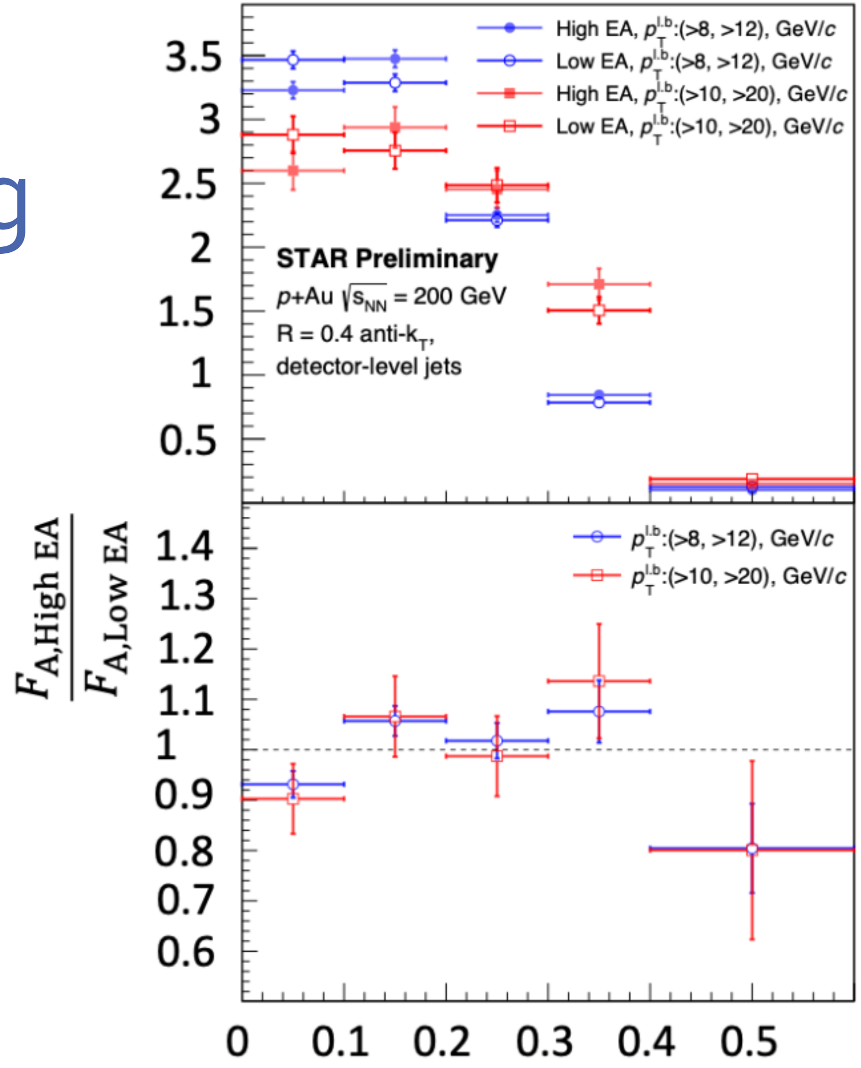
- Imaging the shape of atomic nuclei in high-energy collisions from STAR, **Jiangyong Jia, Tuesday 2:20 PM**
- Recent quarkonium results from the STAR experiment, **Barbara Trzeciak, Tuesday 5:10 PM**
- Probing gluon saturation through two-particle correlations at STAR, **Matt Posik, Tuesday 6:10 PM**
- Systematic study of flow harmonics via di-hadron correlations at mid-rapidity in $p+\mathrm{Au}$, $d+\mathrm{Au}$ and $^3\mathrm{He}+\mathrm{Au}$ collisions at $200\ \mathrm{GeV}$, **Shengli Huang, Wednesday 2:20 PM**
- Measurements of jet substructure in $p+p$ and jet-event activity correlations in $p+\mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$ at STAR, **David Stewart, Wednesday 3:00 PM**

Back Up

Dijet p_T Balance in $p + \mathrm{Au}$ Indicates No Jet Quenching

See Talk by David Stewart
Wed, Parallel Session 5

- Jet p_T is correlated with event activity $(\mathrm{E.A.})$ in a way that could indicate jet quenching
- But the dijet p_T balance does not change with event activity
  - Dijet acoplanarity also does not change with event activity



$$A_J \equiv \frac{p_{T,\mathrm{lead}} - p_{T,\mathrm{sub}}}{p_{T,\mathrm{lead}} + p_{T,\mathrm{sub}}}$$

Baryon Stopping vs Charge Stopping Using Isobar Data

- $^{96}_{44}\mathrm{Ru} + ^{96}_{44}\mathrm{Ru}$ and $^{96}_{40}\mathrm{Zr} + ^{96}_{40}\mathrm{Zr}$ at $\sqrt{s_{NN}} = 200$ GeV
- Difference in net-charge yield:

$$\Delta Q = Q(\mathrm{Ru}) - Q(\mathrm{Zr}) = \left[(N_{\pi^+} - N_{\pi^-}) + (N_{K^+} - N_{K^-}) + \left(N_p - N_{\bar{p}}\right)\right]_{\mathrm{Ru}} - [\,]_{\mathrm{Zr}}$$

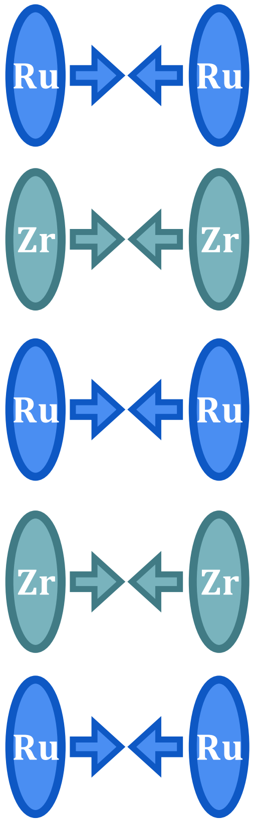
$$\approx N_\pi(R2_\pi - 1) + N_K(R2_K - 1) + N_p\left(R2_p - 1\right)$$

Double ratios: $R2_\pi = \dfrac{\left(N_{\pi^+}/N_{\pi^-}\right)_{\mathrm{Ru}}}{\left(N_{\pi^+}/N_{\pi^-}\right)_{\mathrm{Zr}}}$

- Net-baryon yield:

$$B = \left(N_p - N_{\bar{p}}\right) + (N_n - N_{\bar{n}}) \approx \left(N_p - N_{\bar{p}}\right) + \left(N_{\bar{p}}\sqrt{\frac{N_d}{N_{\bar{d}}}} - N_p\sqrt{\frac{N_{\bar{d}}}{N_d}}\right)$$

- Using inclusive particle yields, not removing contributions from weak decays



J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)

Baryon Stopping vs Charge Stopping Using Isobar Data
Derivation of the Charge Difference Formula

STAR

Double ratios:

$$R2_\pi = \frac{(N_{\pi^+}/N_{\pi^-})_{\mathrm{Ru}}}{(N_{\pi^+}/N_{\pi^-})_{\mathrm{Zr}}} \approx \frac{(1+(N_{\pi^+}-N_{\pi^-})/N_\pi)_{\mathrm{Ru}}}{(1+(N_{\pi^+}-N_{\pi^-})/N_\pi)_{\mathrm{Zr}}} = \frac{1+\Delta R^\pi_{\mathrm{Ru}}}{1+\Delta R^\pi_{\mathrm{Zr}}} \approx 1+\Delta R^\pi_{\mathrm{Ru}} - \Delta R^\pi_{\mathrm{Zr}}$$

And similarly for $R2_K$ and $R2_p$, where $N_\pi = \frac{N_{\pi^+} + N_{\pi^-}}{2}$

For the net charge difference:

$$\Delta Q = Q(\mathrm{Ru}) - Q(\mathrm{Zr}) = \left[(N_{\pi^+} - N_{\pi^-}) + (N_{K^+} - N_{K^-}) + \left(N_p - N_{\bar{p}}\right)\right]_{\mathrm{Ru}} - [\,]_{\mathrm{Zr}}$$

So

$$(N_{\pi^+} - N_{\pi^-})_{\mathrm{Ru}} - (N_{\pi^+} - N_{\pi^-})_{\mathrm{Zr}} = (\,N_\pi \times \Delta R^\pi_{\mathrm{Ru}}\,)_{\mathrm{Ru}} - (\,N_\pi \times \Delta R^\pi_{\mathrm{Zr}}\,)_{\mathrm{Zr}}$$

$$\approx N_\pi(\Delta R^\pi_{\mathrm{Ru}} - \Delta R^\pi_{\mathrm{Zr}}) \approx N_\pi(R2_\pi - 1)$$

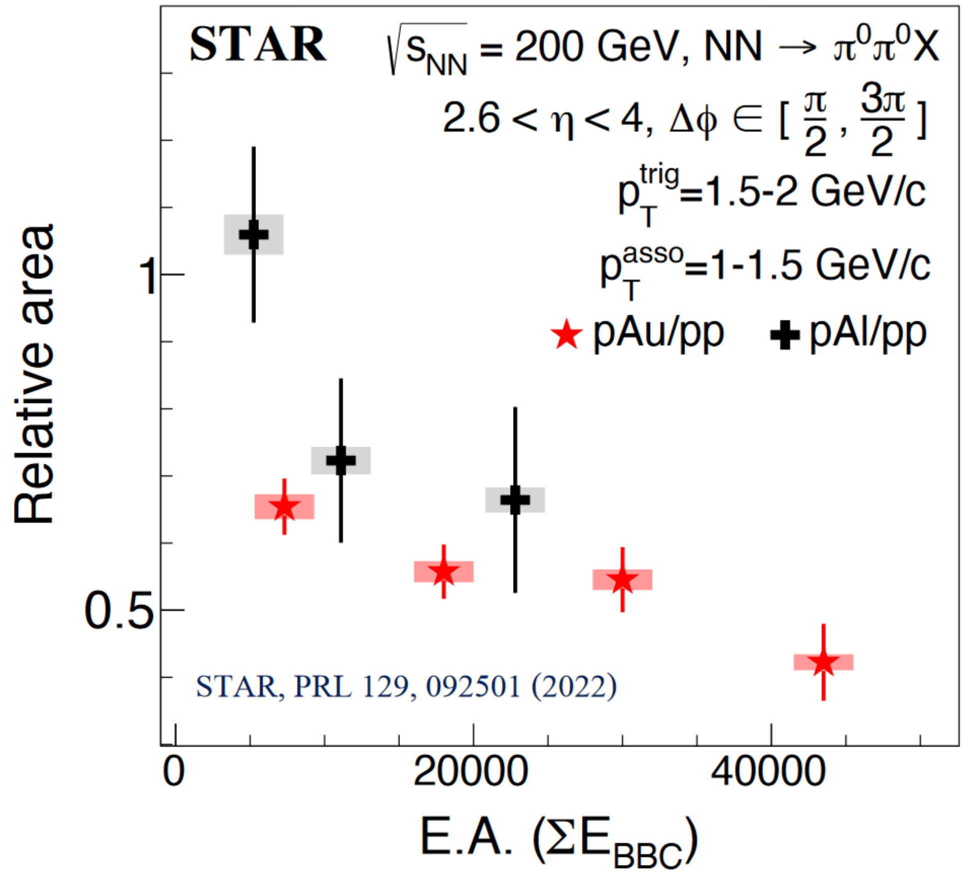
And

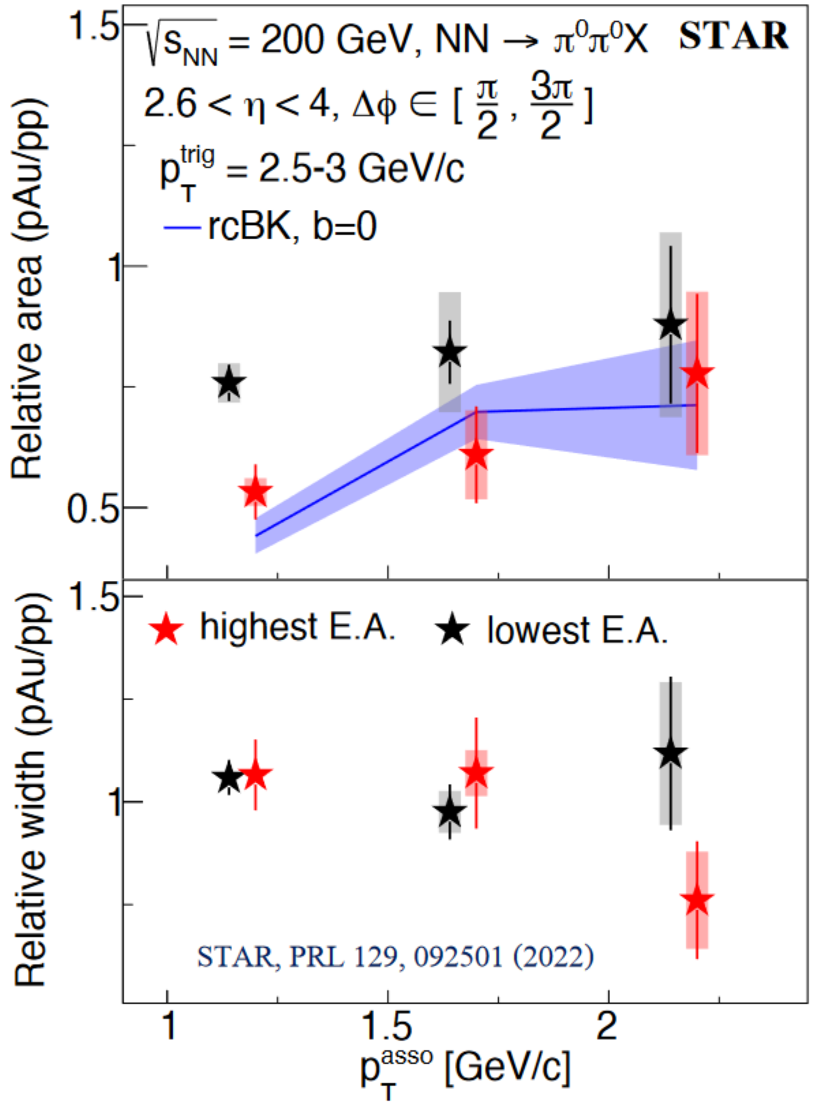
$$\Delta Q = Q(\mathrm{Ru}) - Q(\mathrm{Zr}) \approx N_\pi(R2_\pi - 1) + N_K(R2_K - 1) + N_p\left(R2_p - 1\right)$$

J. D. Brandenburg, N. Lewis, P. Tribedy, Z. Xu, arXiv:2205.05685 (2022)

Di-π^0 Correlations in $p+p$, $p+\text{Al}$, $p+\text{Au}$, $d+\text{Au}$

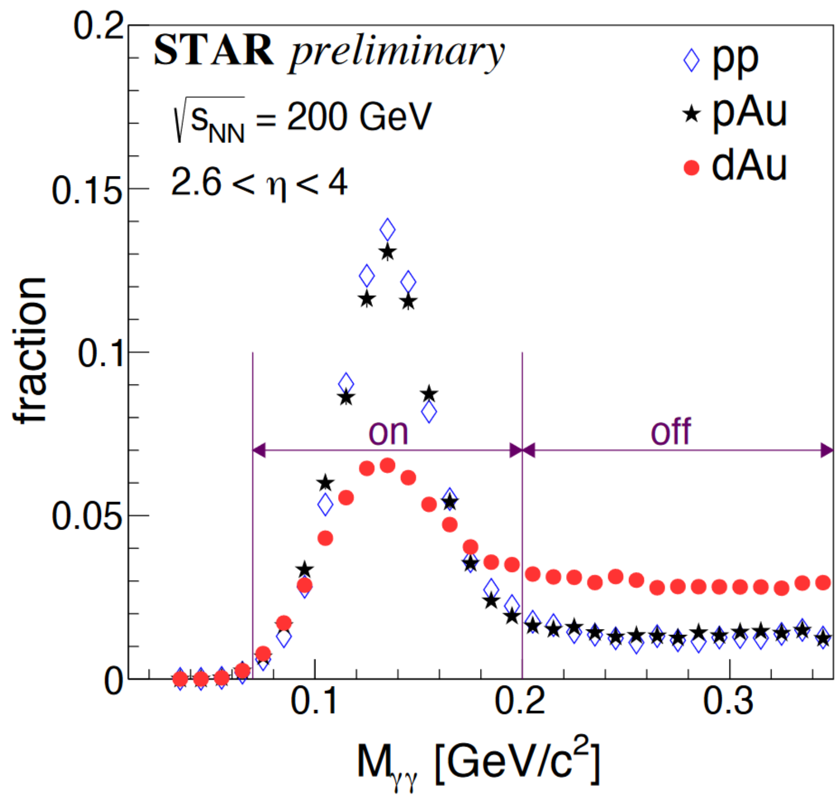
See Talk by Matt Posik
Tues, Parallel Session 4

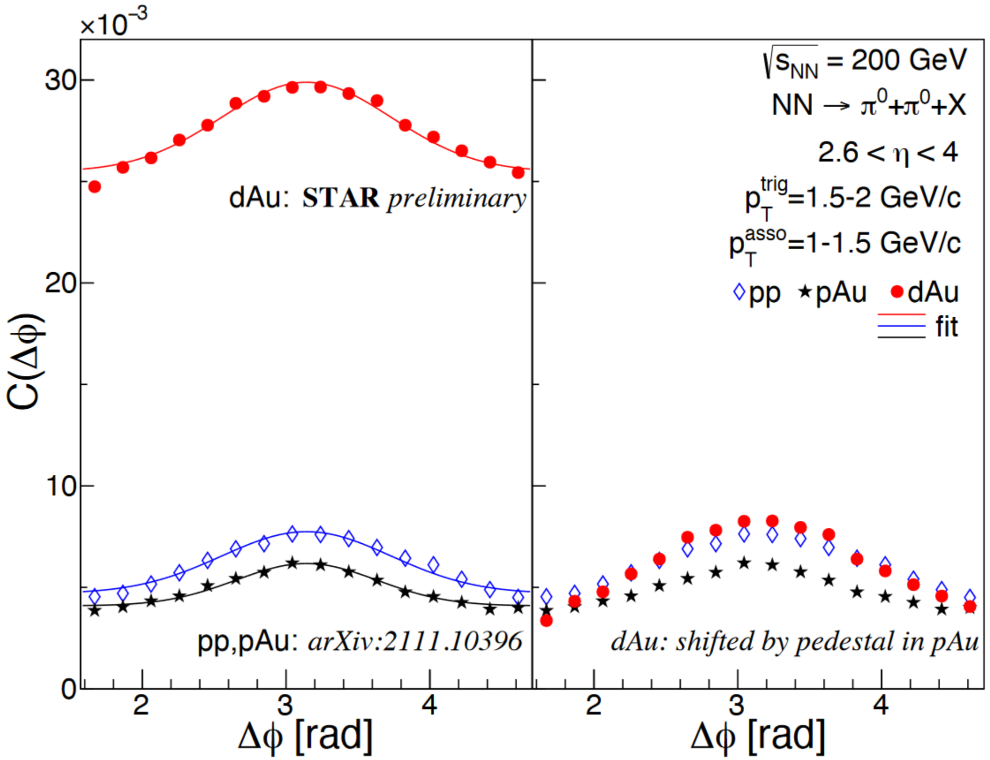




- Suppression increase with Event Activity (E.A.)
- No broadening of the correlation function observed

Di-π^0 Correlations in $p+p$, $p+\mathrm{Al}$, $p+\mathrm{Au}$, $d+\mathrm{Au}$





See Talk by Matt Posik Tues, Parallel Session 4

$d+\mathrm{Au}$ has a $\times 5$ higher pedestal compared to $p+p$ and $p+\mathrm{Au}$

- Could be explained through Double Parton Scattering (DPS): two separate hard interactions in a single collision
- π^0 PID has a much higher background in $d+\mathrm{Au}$ compared to $p+p$ and $p+\mathrm{Au}$
- Di-π^0 measurements favor cleaner pA comparted to dA collisions