In part supported by

System size dependence of high-p_T hadron yield modification in the QGP with $\sqrt{s_{NN}}$=200 GeV isobar collisions at STAR

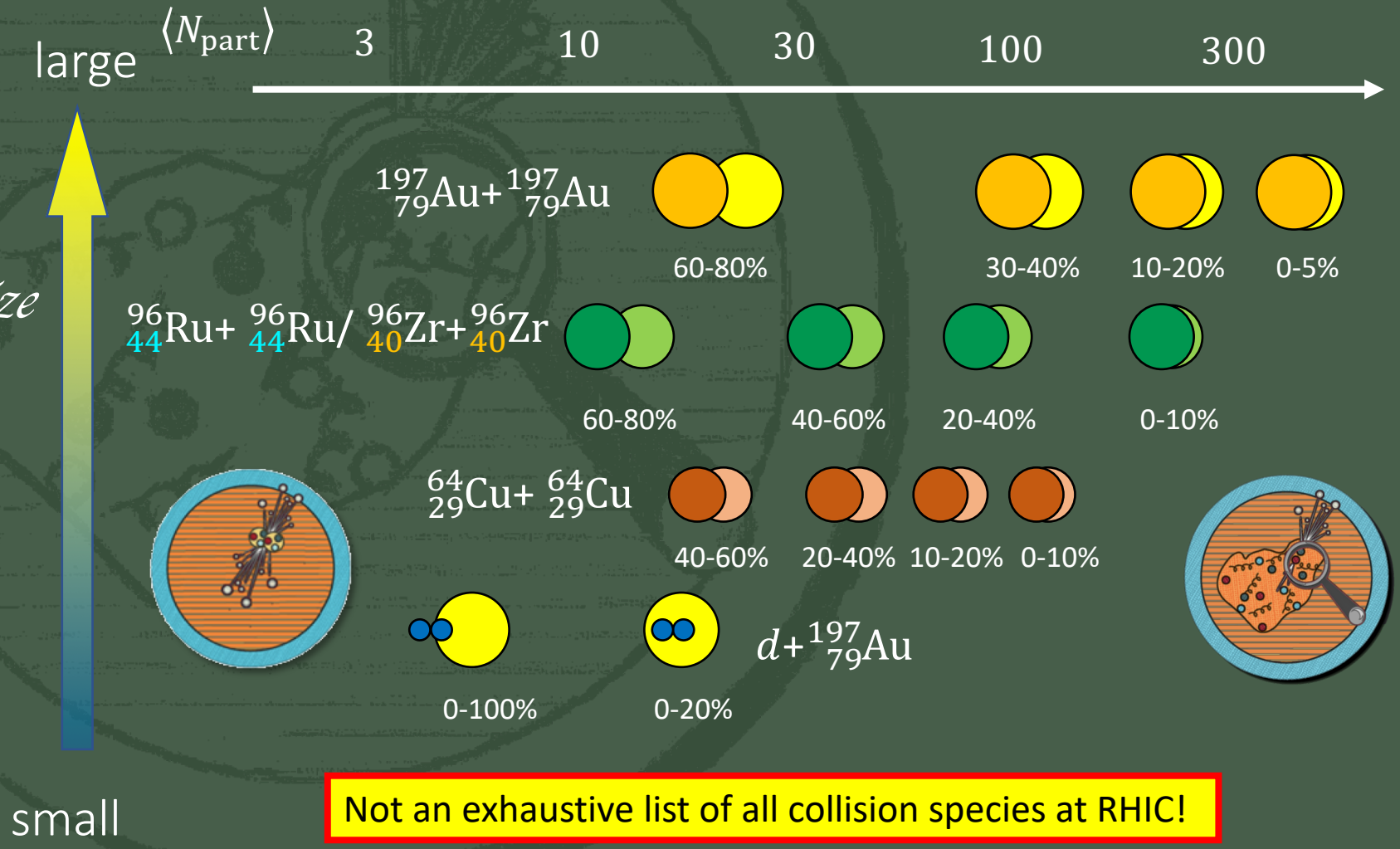
Tong Liu (Yale University) for the STAR collaboration

tong.liu@yale.edu

Hot Quarks 2022, Estes Park, CO

System Size Dependence of QGP Properties

- RHIC has provided us with a variety of collision systems
- For different collision systems, same N_{part} leads to different initial geometries
- What are the decisive factors of medium properties?

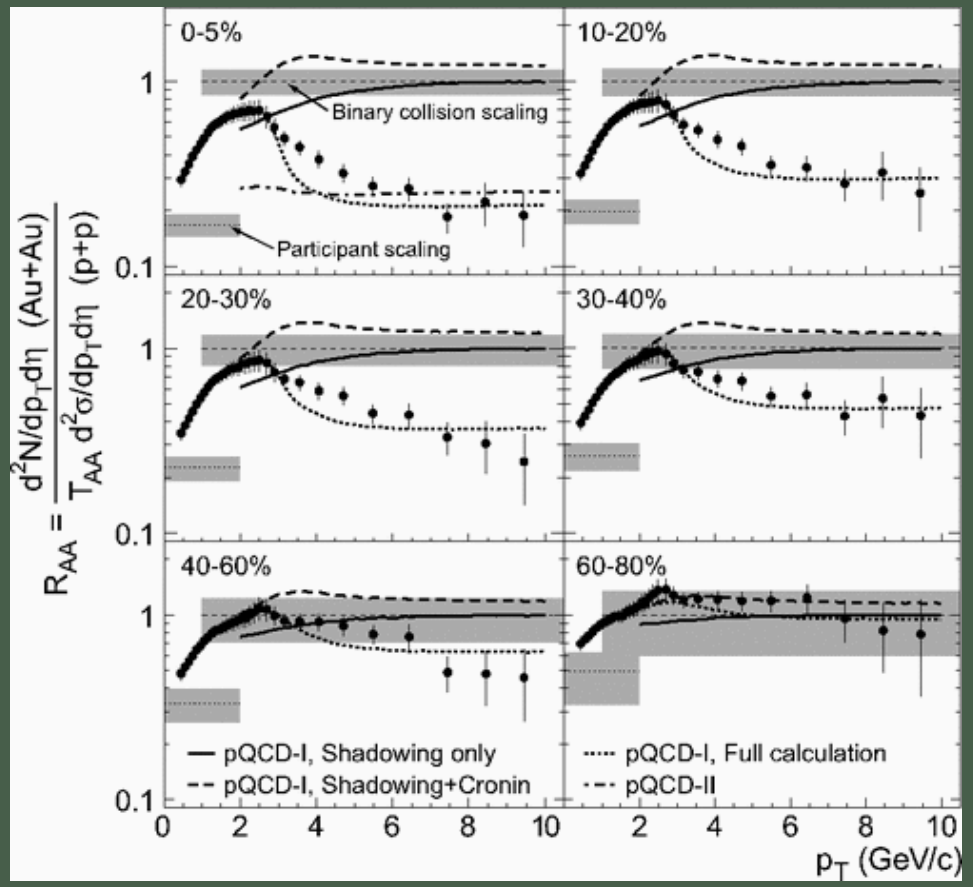


High p_{T} Hadron as QGP Probe

- Hard partons lose energy in QGP: Jet quenching
- High p_{T} hadrons: proxy to hard partons
- Nuclear modification factor

$$R_{\mathrm{AA}} = \frac{1}{N_{\mathrm{ev}}^{\mathrm{AA}}} \frac{d^2N^{\mathrm{AA}}/d\eta dp_{\mathrm{T}}}{T_{\mathrm{AA}} d^2\sigma^{\mathrm{NN}}/d\eta dp_{\mathrm{T}}}, T_{\mathrm{AA}} = \langle N_{\mathrm{coll}} \rangle / \sigma_{\mathrm{inel.}}^{\mathrm{NN}}$$

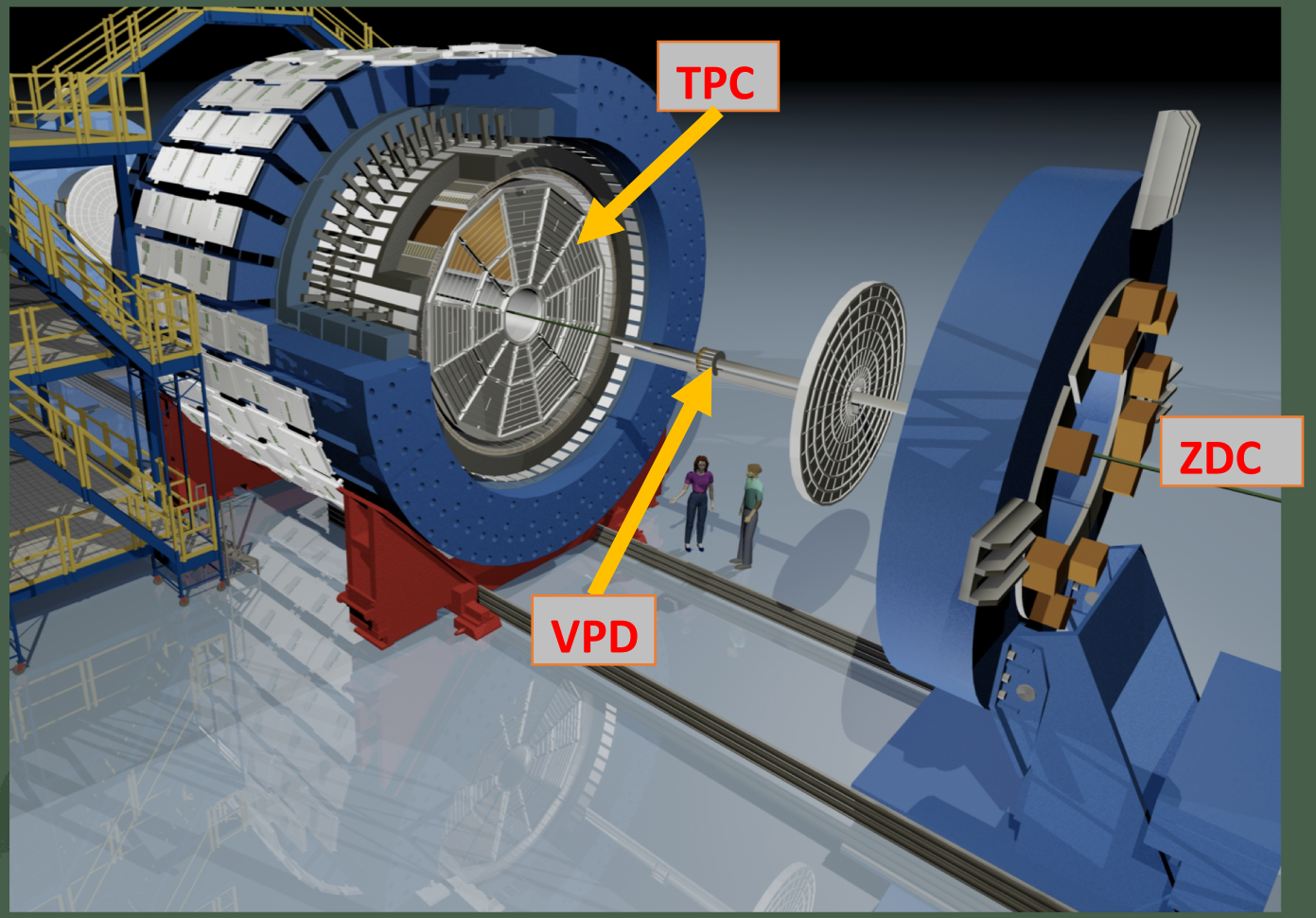
- Glauber model:
  - $\langle N_{\mathrm{part}} \rangle$ scaling for low- p_{T}
  - $\langle N_{\mathrm{coll}} \rangle$ scaling for high- p_{T}
- Combine with existing Au+Au, Cu+Cu & d+Au data
  - Continuous evolution with system size



STAR, Phys.Rev.Lett. 91 (2003) 172302, 2003

The STAR Detector

- **Time Projection Chamber (TPC)**
  - Momentum reconstruction for charged tracks
  - $|\eta| < 1$, full azimuthal coverage
- **Vertex Position Detector(VPD)**
  - Triggering & vertex reconstruction
- **Zero Degree Calorimeter (ZDC)**
  - Triggering & luminosity monitoring



Isobar Collisions

- Run 18 Zr+Zr & Ru+Ru Collisions
  - Size between large (Au+Au) and small (p/d+Au) systems
  - Subtle difference in nuclear structure & size between Ru+Ru and Zr+Zr
  - Large statistics:2B Zr+Zr & 1.8B Ru+Ru minimum-bias events
  - Controlled run conditions, resulting in minimized systematics
  - High precision & multi-differential studies on QGP Properties

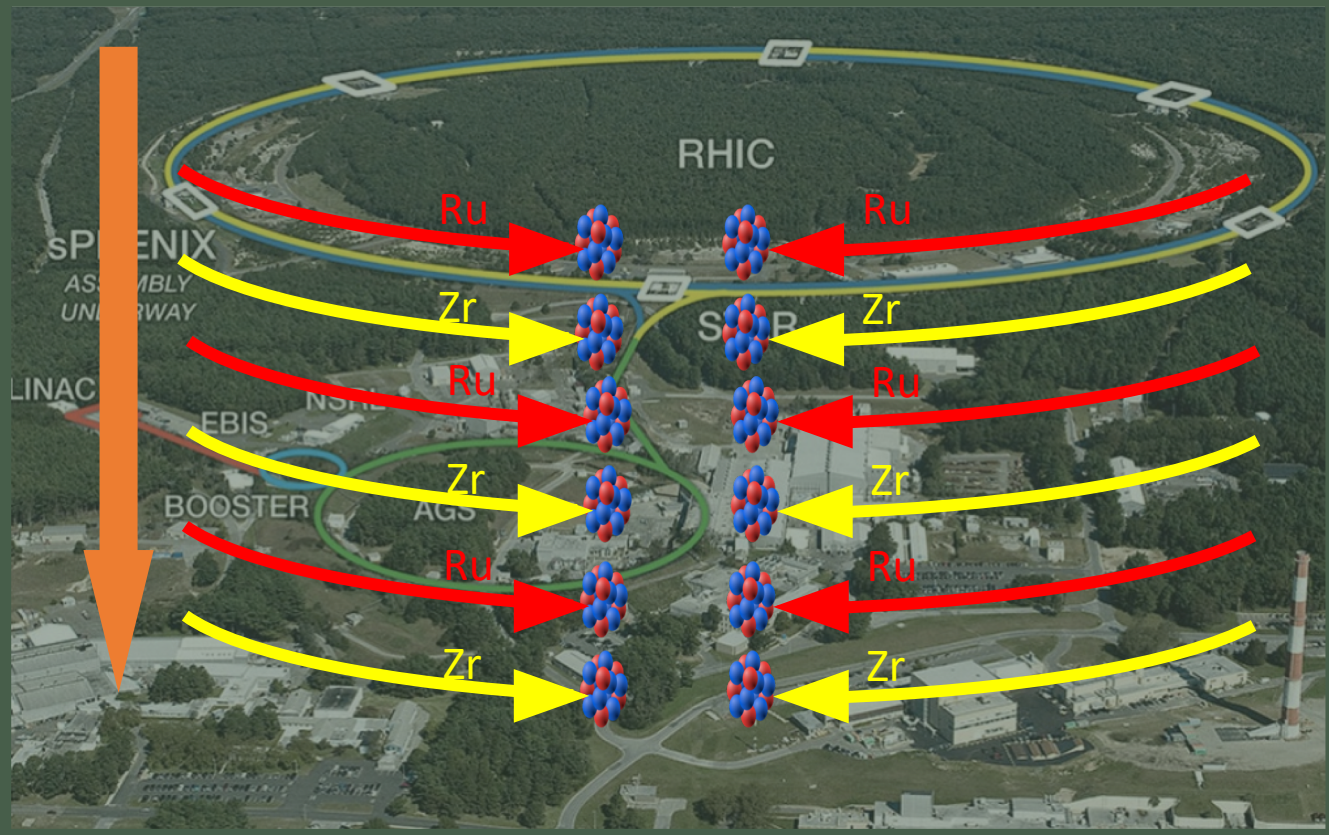
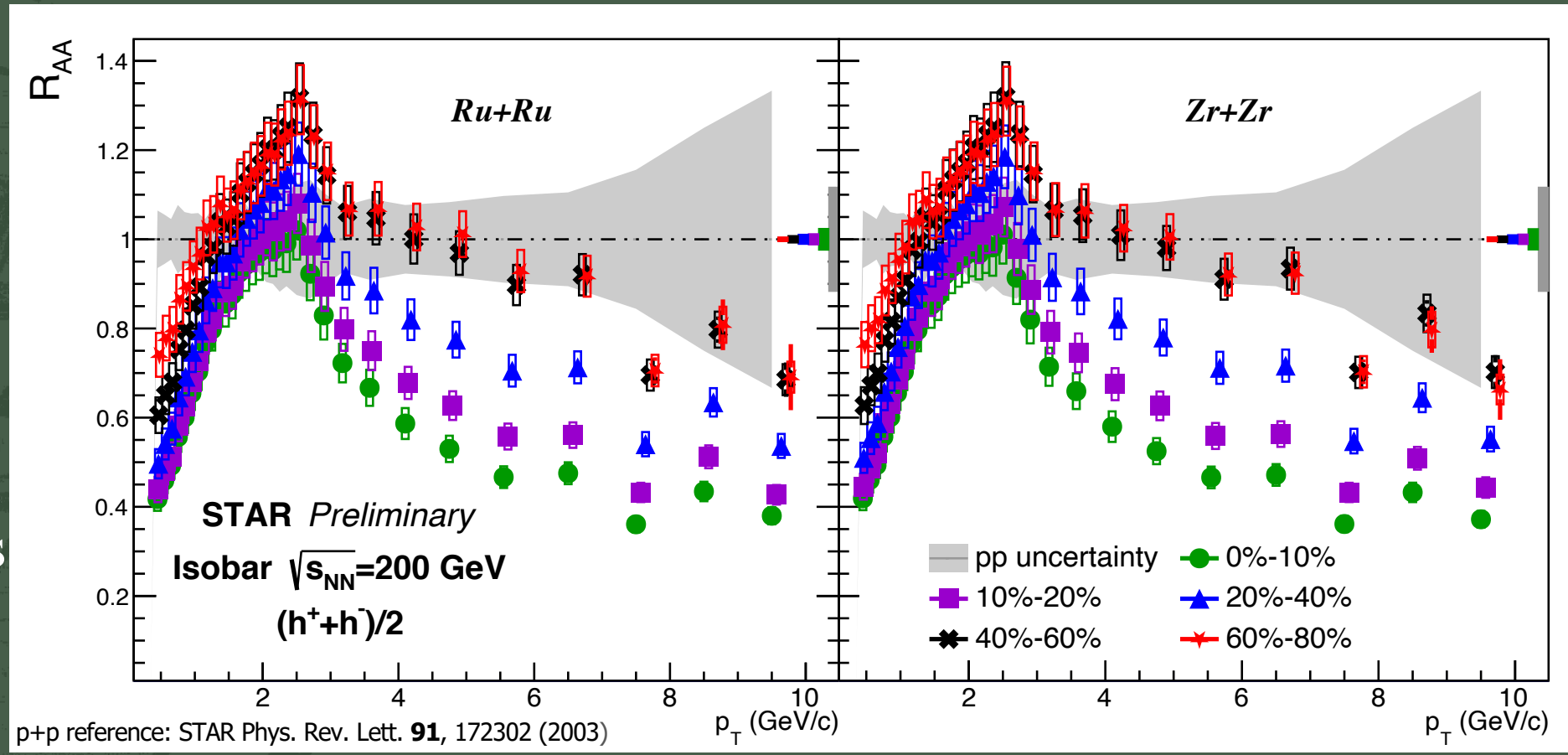


Photo Credit: https://en.wikipedia.org/wiki/Nucleon
https://www.interactions.org/press-release/start-22nd-run-relativistic-heavy-ion-collider-rhic

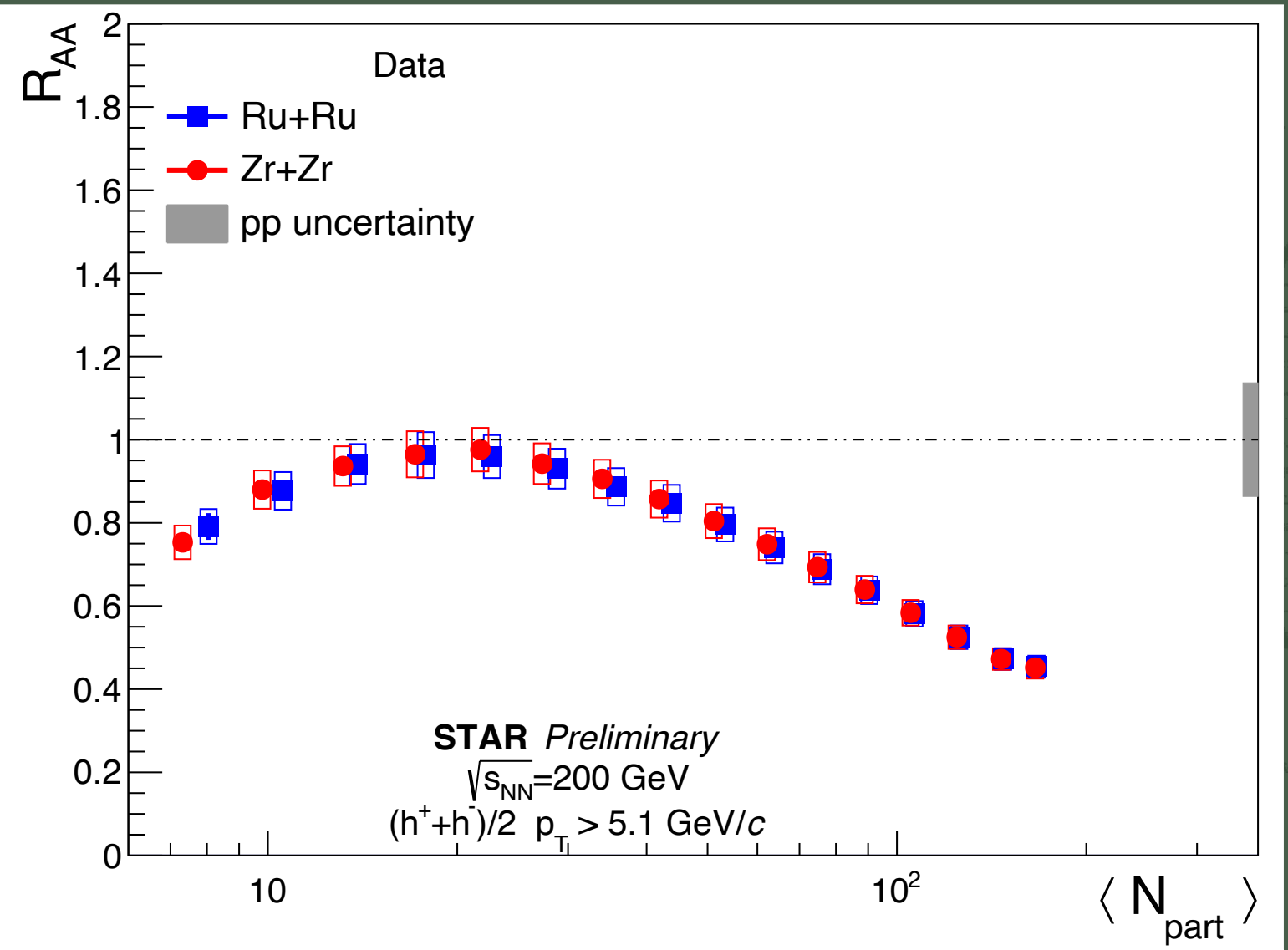
Inclusive Hadron R_{AA} in Isobar Collisions

- Ru+Ru & Zr+Zr show similar level of suppression
- Significant high-p_T suppression for central events
- Suppression decreases with centrality
  - 40-60% looks similar to 60-80%

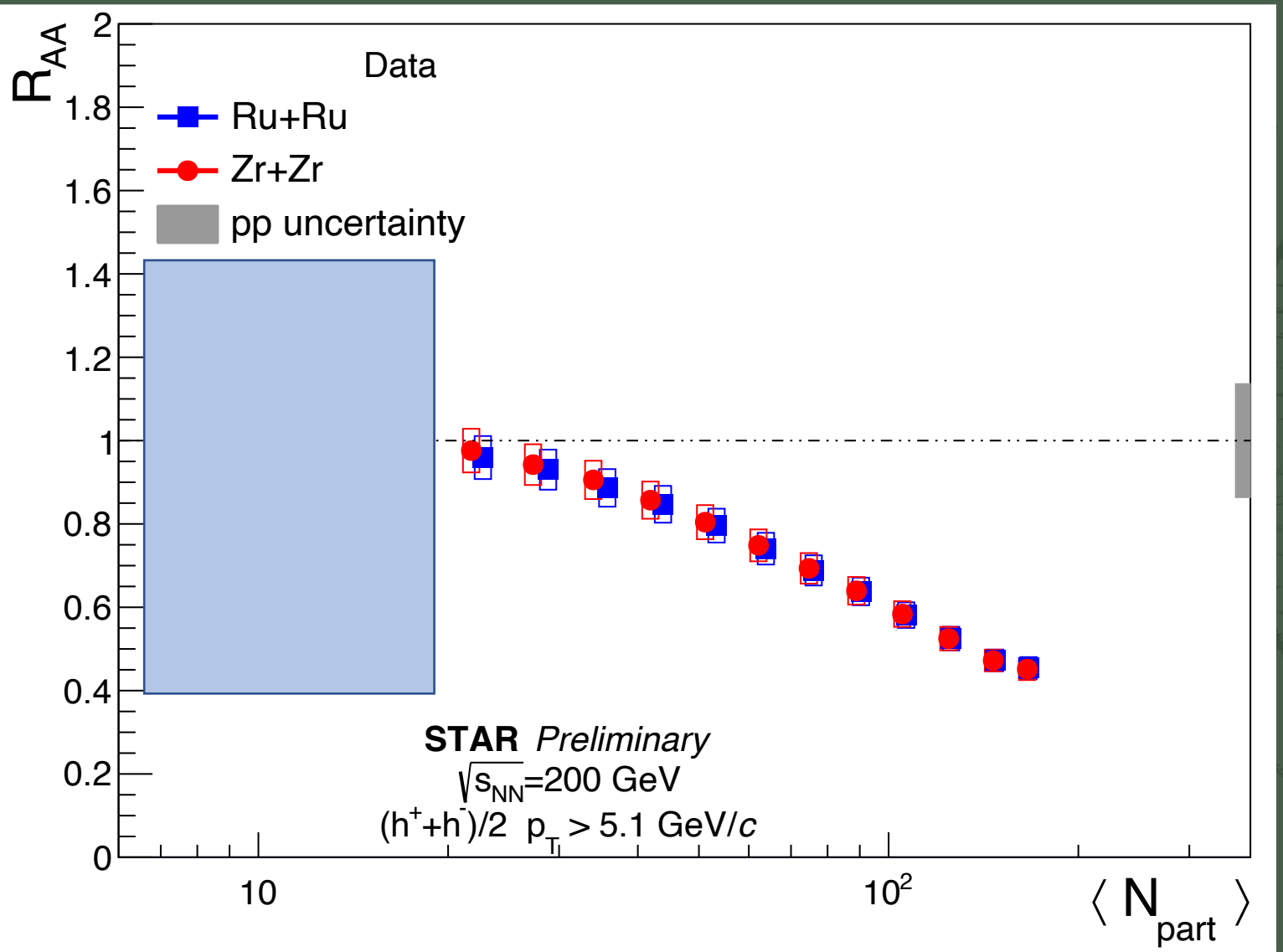


$$R_{\mathrm{AA}} = \frac{1}{N_{\mathrm{ev}}^{\mathrm{AA}}} \frac{d^2N^{\mathrm{AA}}/d\eta dp_{\mathrm{T}}}{T_{\mathrm{AA}} d^2\sigma^{\mathrm{NN}}/d\eta dp_{\mathrm{T}}}, T_{\mathrm{AA}} = \langle N_{\mathrm{coll}} \rangle / \sigma_{\mathrm{inel.}}^{\mathrm{NN}}$$

R_{AA} as a Function of N_{part}

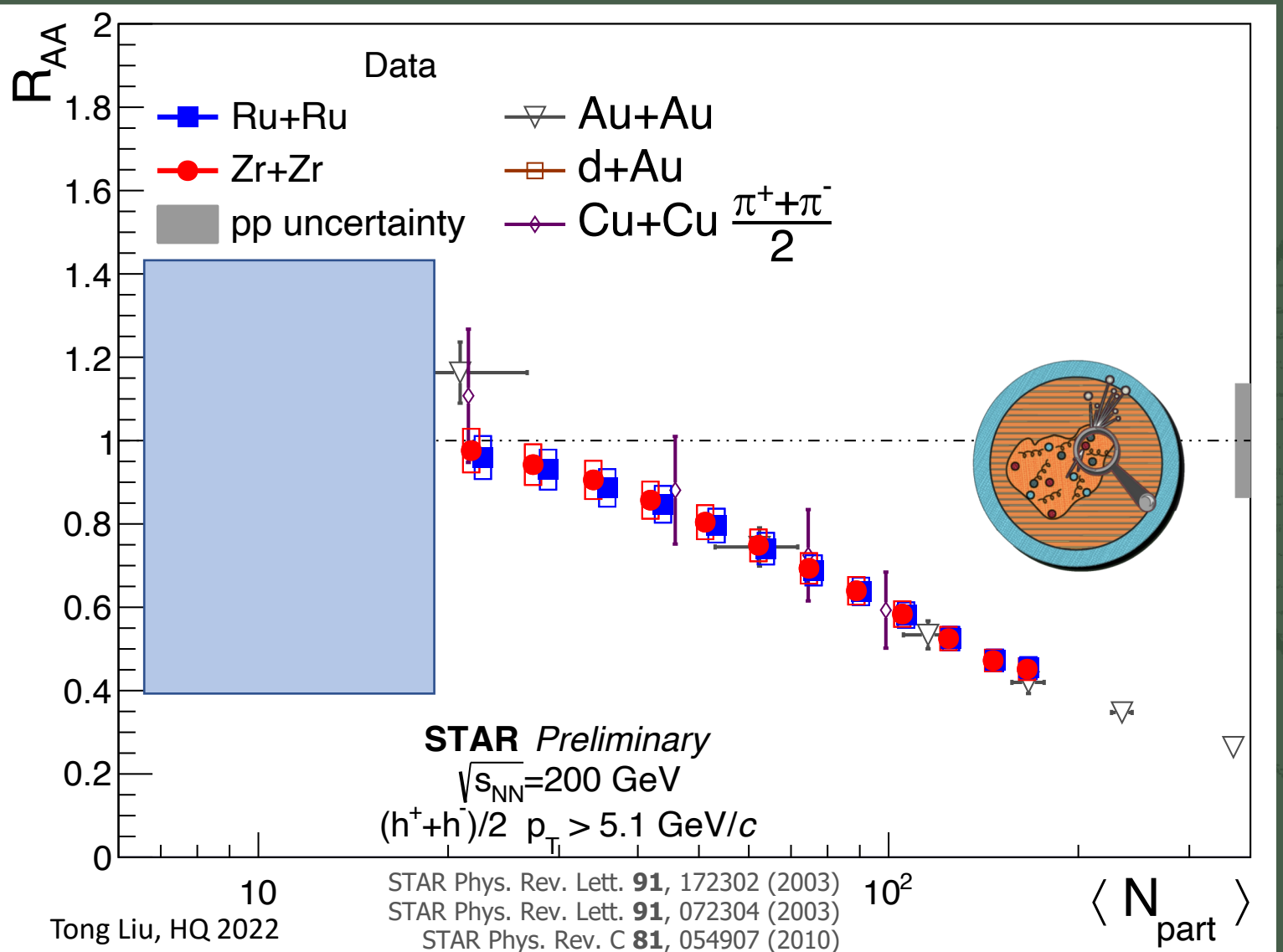


R_{AA} as a Function of N_{part}



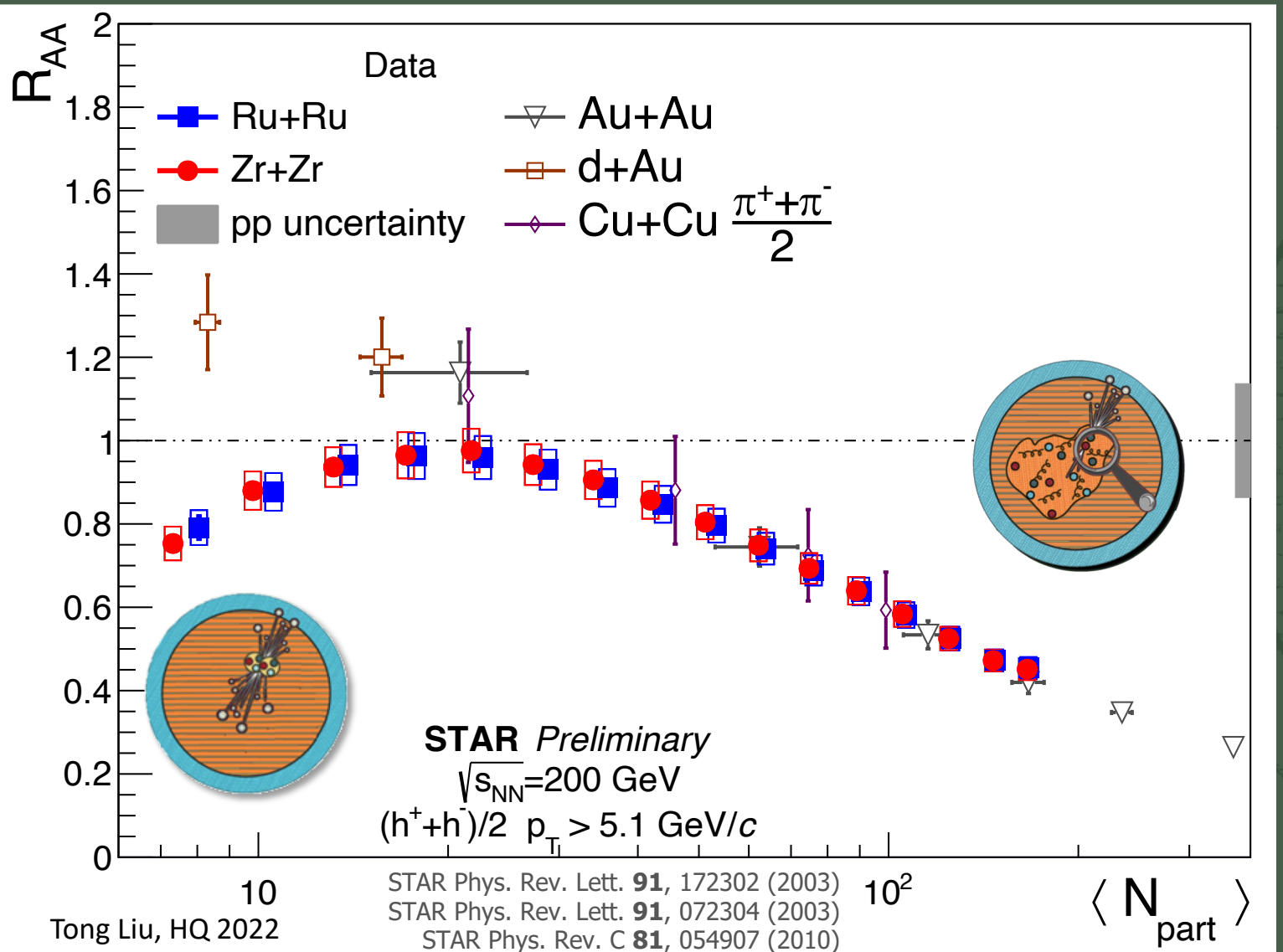
- R_{AA} in 0-60% central events ($\langle N_{part} \rangle$ >20) decreases with $\langle N_{part} \rangle$

R_{AA} as a Function of N_{part}



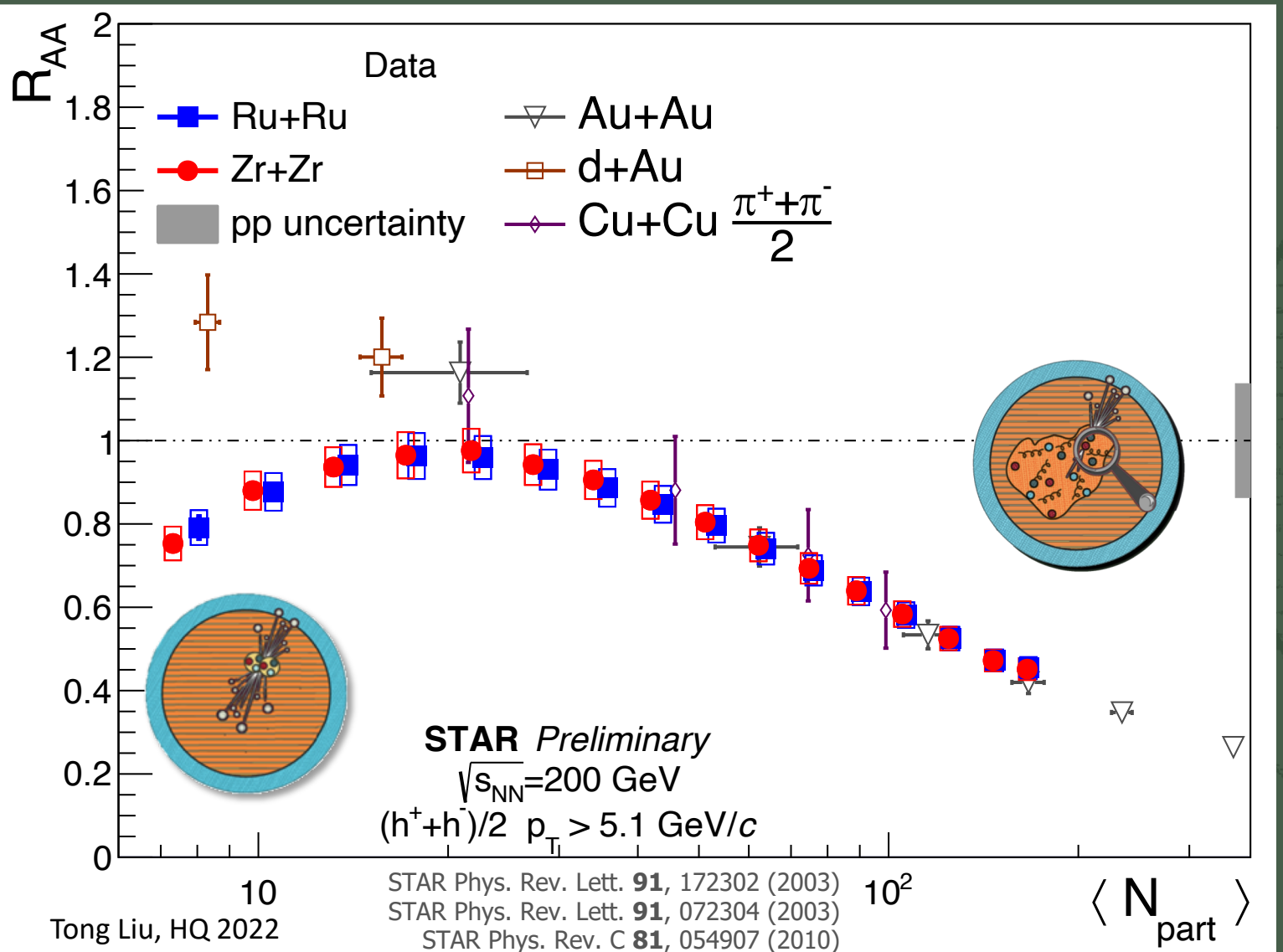
- R_{AA} in 0-60% central events ($\langle N_{part} \rangle$ >20) decreases with $\langle N_{part} \rangle$
- **Same R_{AA} at same $\langle N_{part} \rangle$ regardless of collision system**

R_{AA} as a Function of N_{part}



- R_{AA} in 0-60% central events ($\langle N_{part} \rangle$ >20) decreases with $\langle N_{part} \rangle$
- **Same R_{AA} at same $\langle N_{part} \rangle$ regardless of collision system**
- Deviation from trend starting at $\langle N_{part} \rangle \lesssim 20$

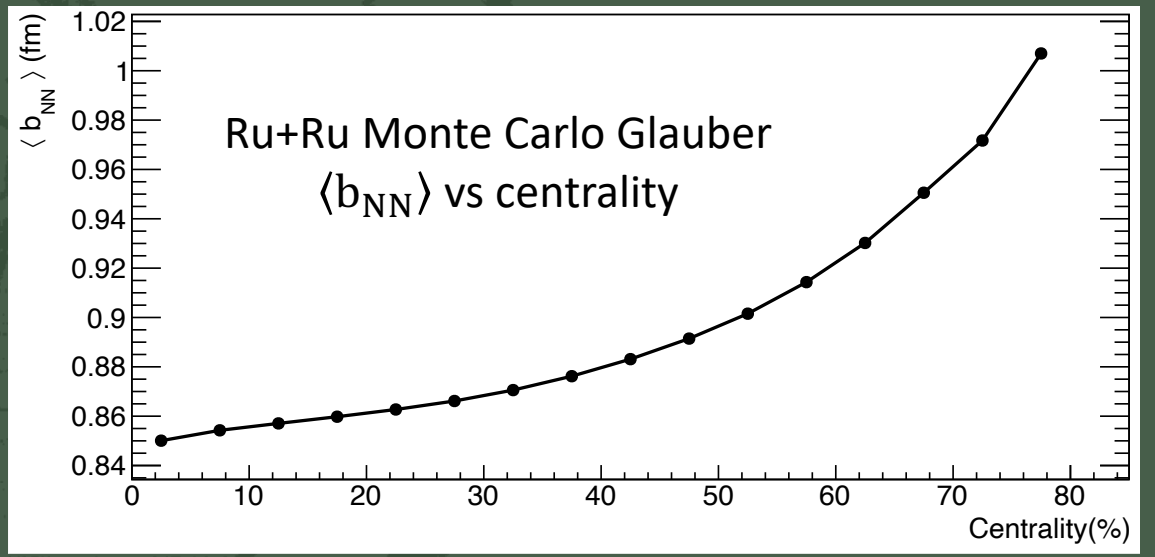
R_{AA} as a Function of N_{part}

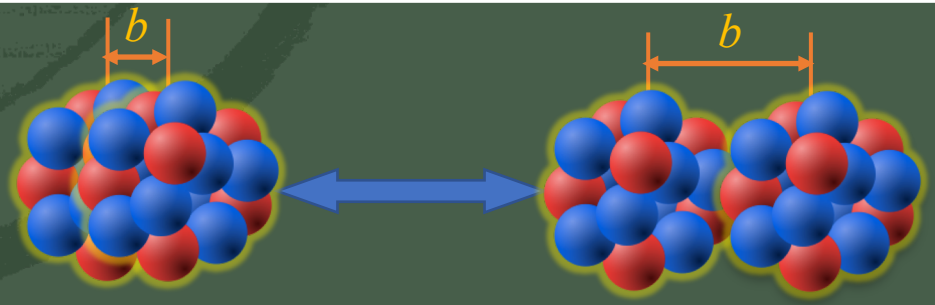


- R_{AA} in 0-60% central events ($\langle N_{part} \rangle$ >20) decreases with $\langle N_{part} \rangle$
- **Same R_{AA} at same $\langle N_{part} \rangle$ regardless of collision system**
- Deviation from trend starting at $\langle N_{part} \rangle \lesssim 20$
- $R_{AA} = \frac{1}{N_{ev}^{AA}} \frac{d^2N^{AA}/d\eta dp_T}{T_{AA} d^2\sigma^{NN}/d\eta dp_T}$,
  $T_{AA} = \langle N_{coll} \rangle / \sigma_{inel.}^{NN}$

Caveat in MC Glauber Model

- Glauber model claims that hard probe production scales with N_{coll}
  - Comes with a hard ball potential cutoff
- All Nucleon-Nucleon (NN) collisions are **NOT** created equal
  - Those with smaller impact parameter (b_{NN}) have larger hard-scattering probability
- $\langle b_{NN} \rangle$ increases with centrality
  - **Peripheral AA** collisions also have **more "peripheral" NN** collisions





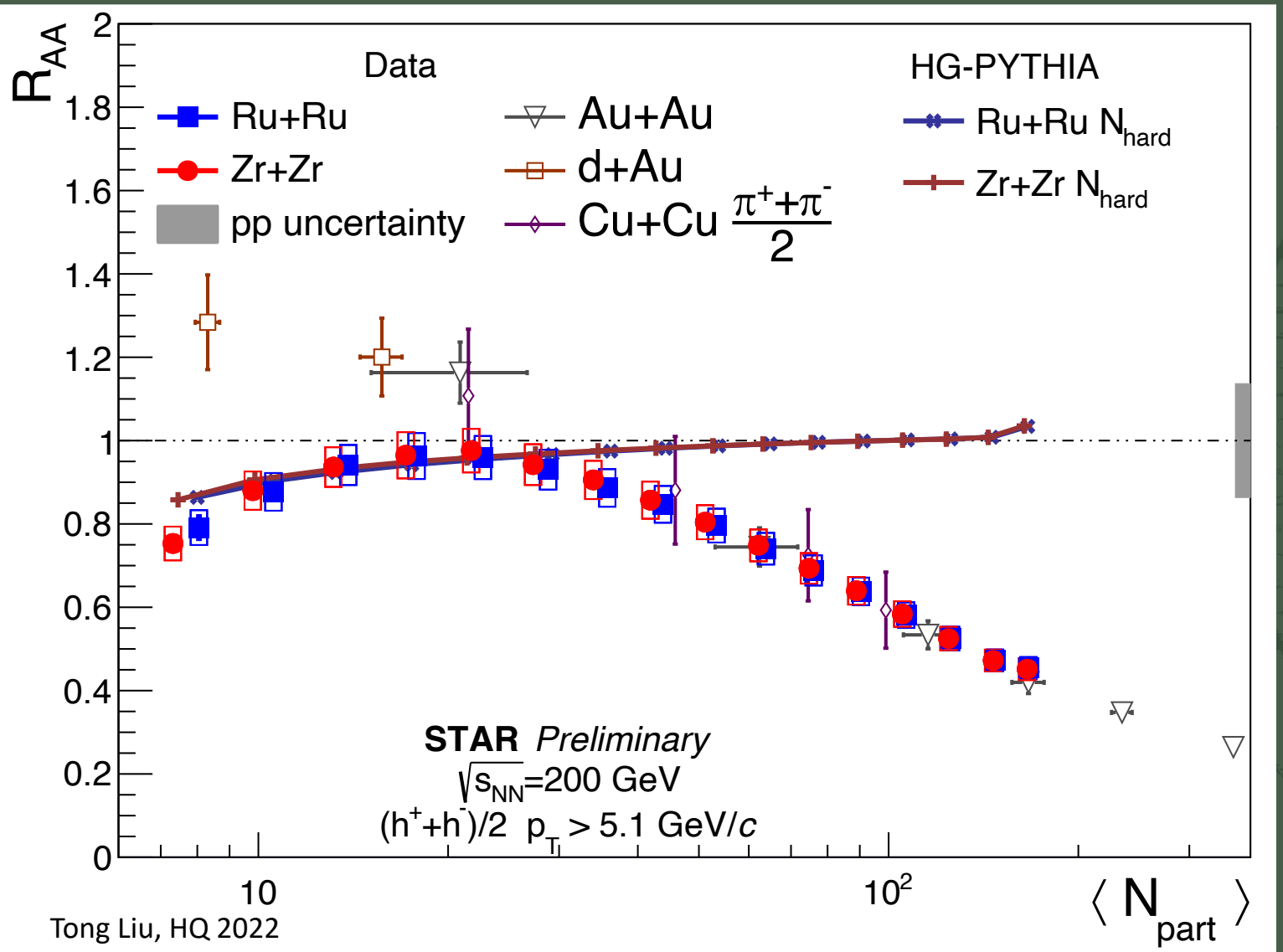
Caveat in MC Glauber Model

- Glauber model claims that hard probe production scales with N_{coll}
  - Comes with a hard ball potential cutoff
- All Nucleon-Nucleon (NN) collisions are **NOT** created equal
  - Those with smaller impact parameter (b_{NN}) have larger hard-scattering probability
- $\langle b_{NN} \rangle$ increases with centrality
  - **Peripheral AA** collisions also have **more "peripheral" NN** collisions

- HG-PYTHIA[1] : benchmarking on **number of hard scatterings** (N_{hard}) instead of N_{coll}
  - $N_{hard} = \sum_{i=1}^{N_{coll}} N_{hard}^{i}\,(b_{NN}^{i})$
  - Ask for N_{coll} PYTHIA events with number of Multi-Parton Interactions**(MPI)**= $\boldsymbol{N_{hard}^{i}}$
  - Create synthetic event by stacking tracks from all PYTHIA events together
  - Classify centrality based on synthetic event multiplicity
  - Try $\langle N_{hard} \rangle$ and hadron yield in R_{AA} calculation

[1] Loizides & Morsch, Phys.Lett. B773 (2017) 408-411

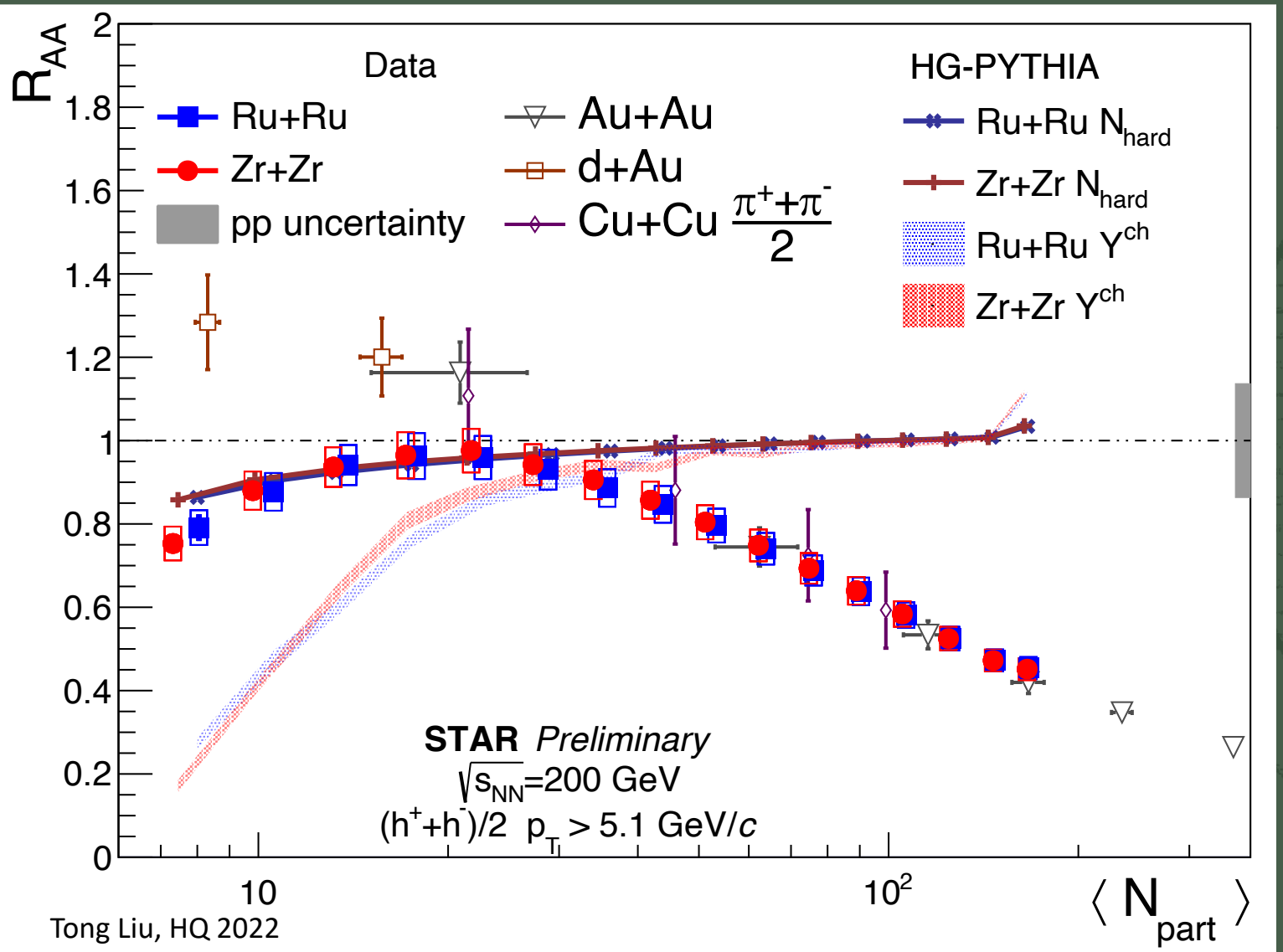
R_{AA} as a Function of N_{part}



- Calculation based on $\langle N_{hard} \rangle$ qualitatively describes the drop in R_{AA} in peripheral collisions
  - Slightly above data in the most peripheral bin

[1] Loizides & Morsch, Phys.Lett. B773 (2017) 408-411

R_{AA} as a Function of N_{part}

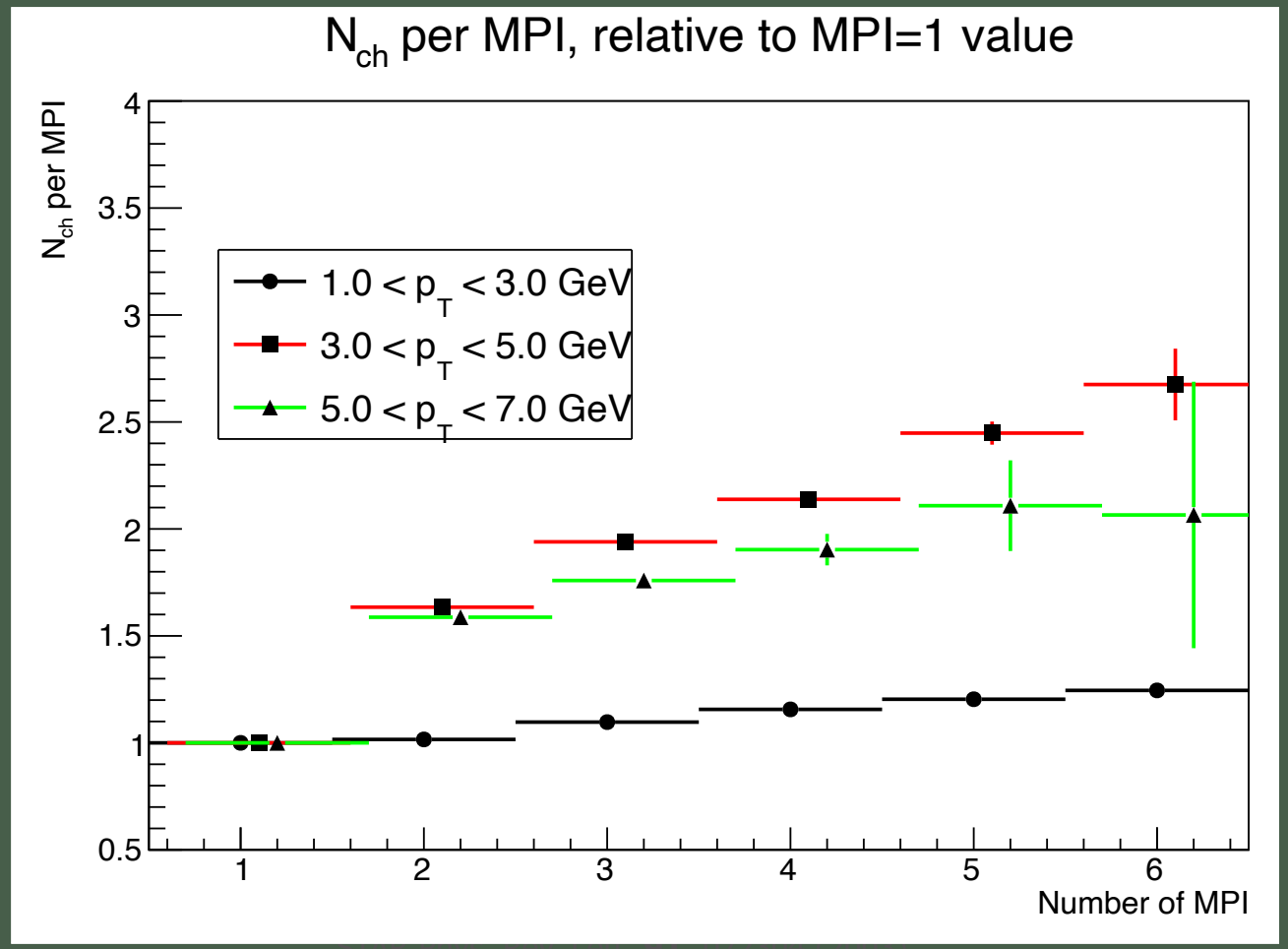


- Calculation based on $\langle N_{hard} \rangle$ qualitatively describes the drop in R_{AA} in peripheral collisions
  - Slightly above data in the most peripheral bin
- One step further: treat synthetic PYTHIA events as real data
  - Predicted R_{AA} significantly lower than data

[1] Loizides & Morsch, Phys.Lett. B773 (2017) 408-411

PYTHIA Multi-Parton Interaction (MPI) model

[1] Loizides & Morsch, Phys.Lett. B773 (2017) 408-411



- HG-PYTHIA model presumes the number of hard scatterings is proportional to number of MPI
- High p_T charged hadron yield doesn't follow this assumption
  - Deviates from scaling with MPI
  - Deviation is small for low p_T, and the biggest at ~ 3 GeV/c
- More detailed study on PYTHIA high p_T production mechanism needed

Conclusions

- Medium suppression of high-p_T hadrons mainly determined by $\langle N_{\mathrm{part}} \rangle$
- Selection bias observed in peripheral events
- Effect qualitatively described by HG-PYTHIA
  - N_{hard} based R_{AA} slightly higher than data in the most peripheral bin
  - Synthetic PYTHIA event yield prediction significantly lower than data

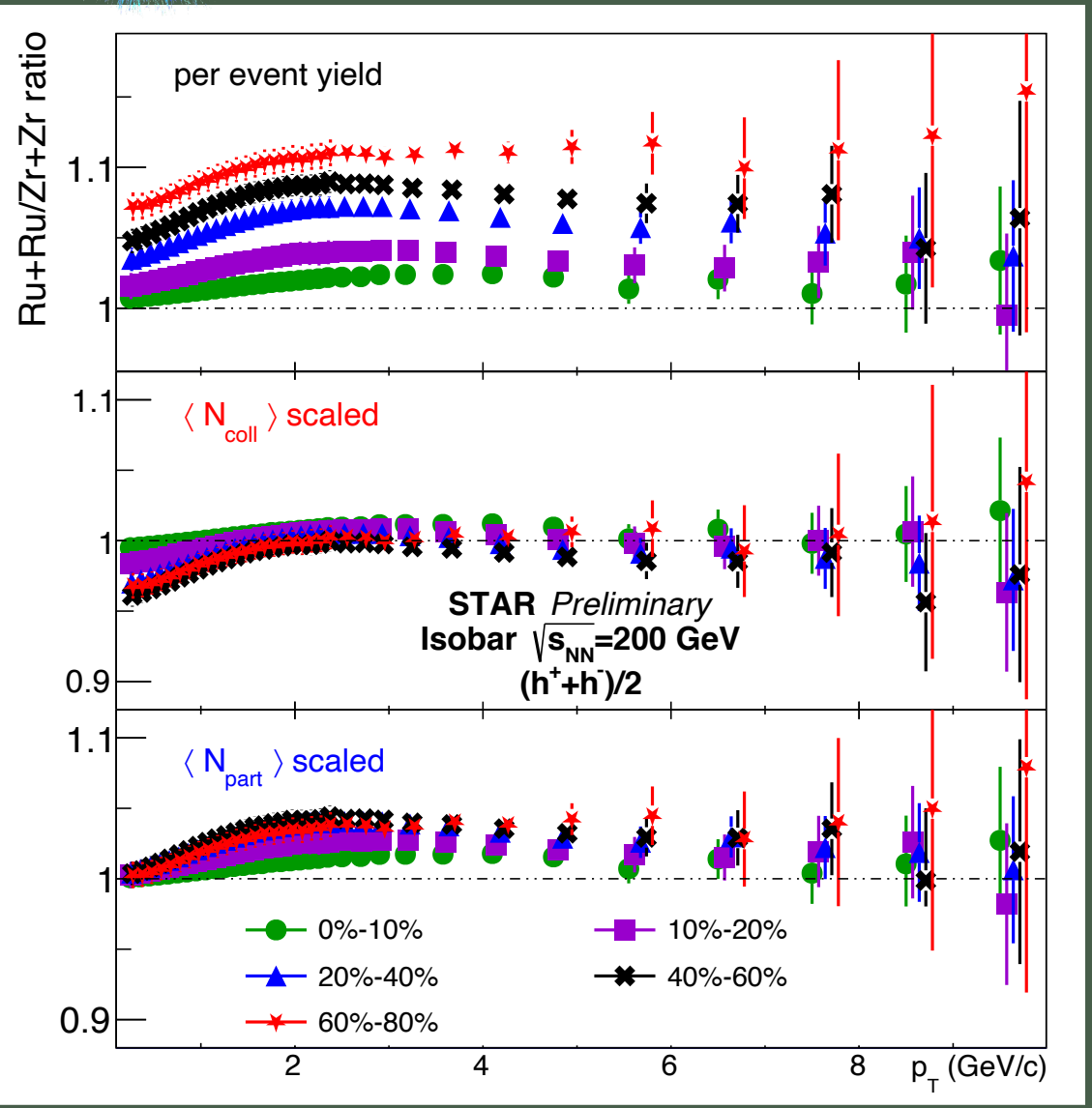
Outlook

- Detailed study of selection bias in high-p_T particle yield
  - Better understanding of PYTHIA MPI model
- More differential study on dependence of quenching: volume, path-length, etc.
- Finer binning on centrality, compare Ru vs Zr result at same $\langle N_{\mathrm{part}} \rangle$


Thank you!

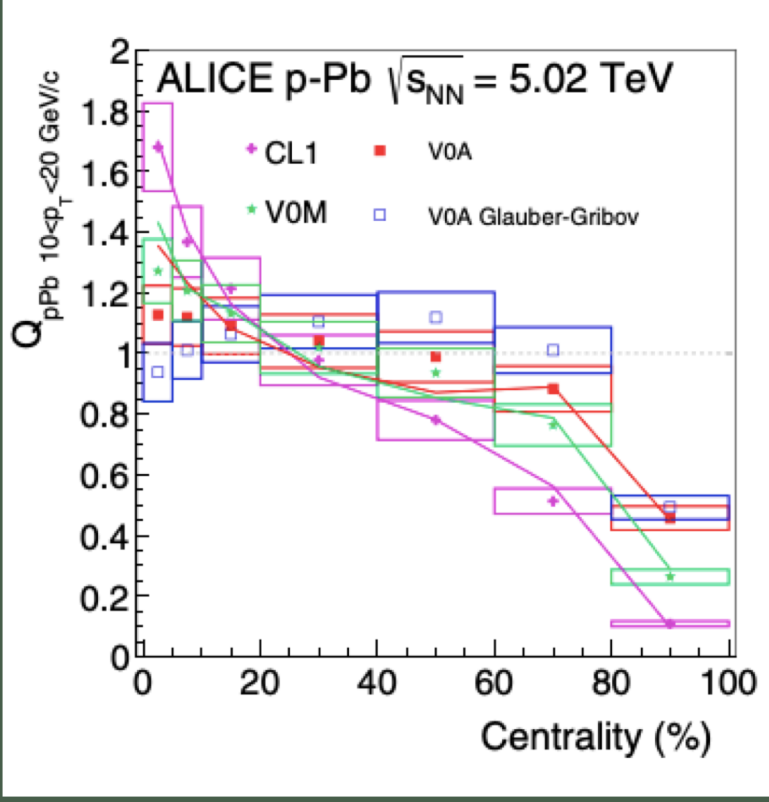
BACKUP

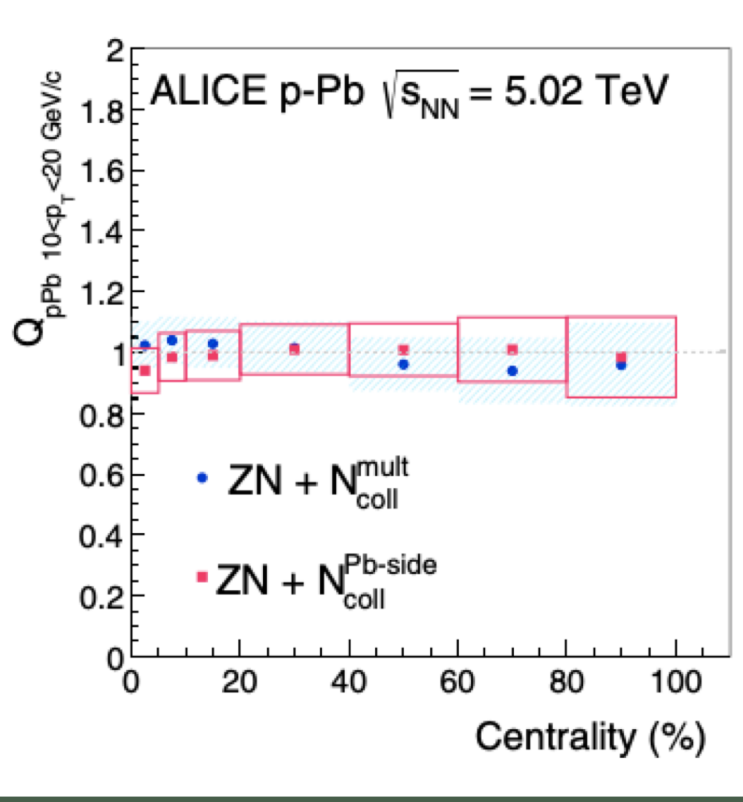
Ru+Ru/Zr+Zr Yield Ratio

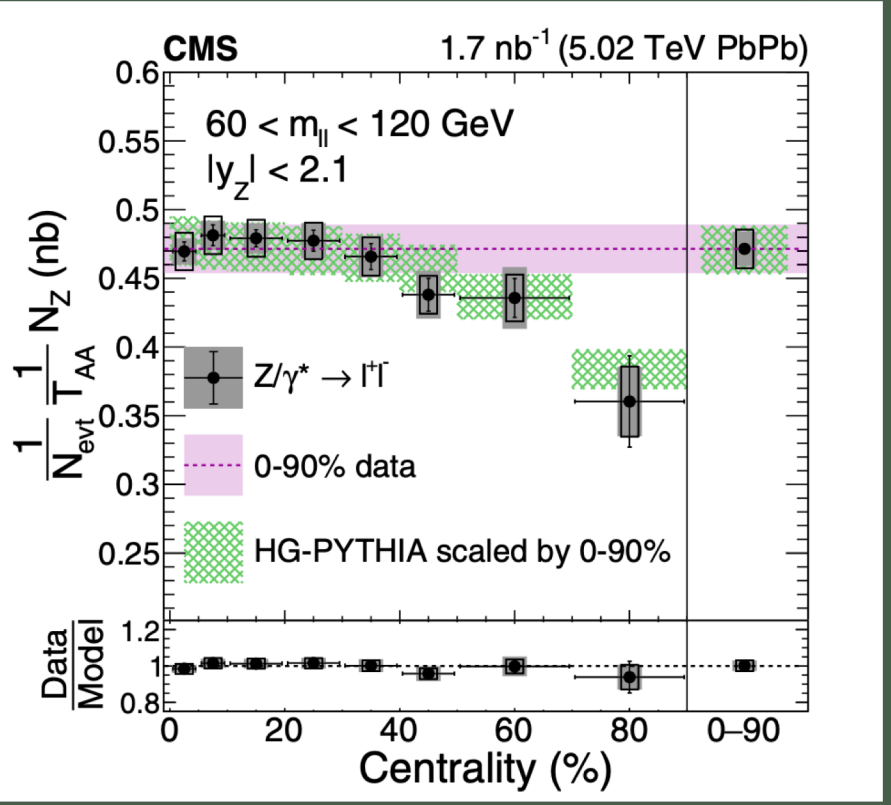


- For the same centrality class, Ru+Ru collisions have bigger N_{coll}
- Ru+Ru/Zr+Zr per-event yield ratio >1
  - Strong resolution on system size difference
- N_{coll}- scaled ratio consistent with unity at high p_T
  - No significant difference on quenching
- N_{part}-scaled ratio
  - Consistent with unity at the lowest p_T
  - Rising with p_T: flow effect?

Selection Bias on High-p_T Probes in Peripheral Events



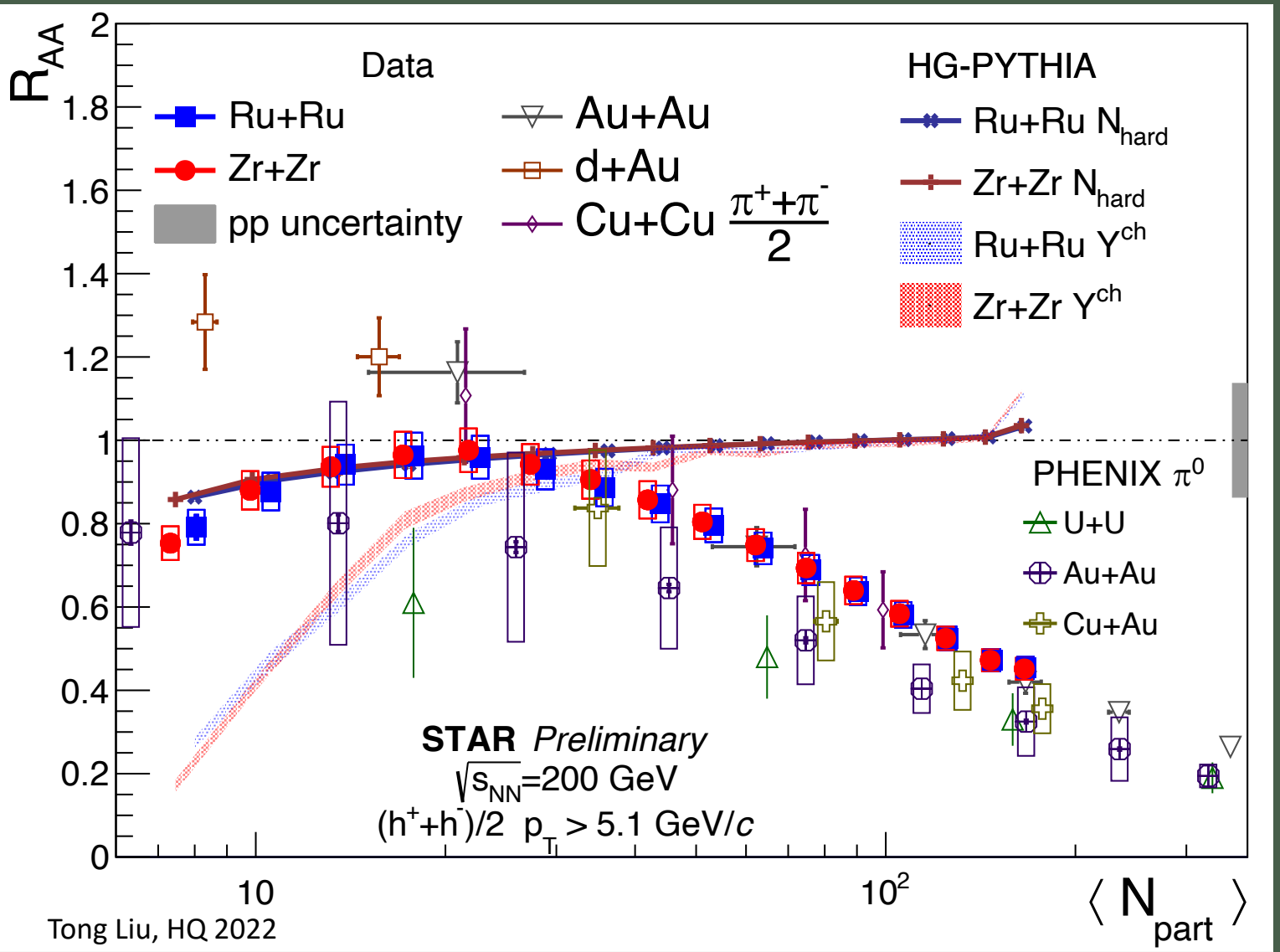




- ALICE show different selection biases on different centrality definitions
- CMS observed suppression in peripheral events for Z-boson yield

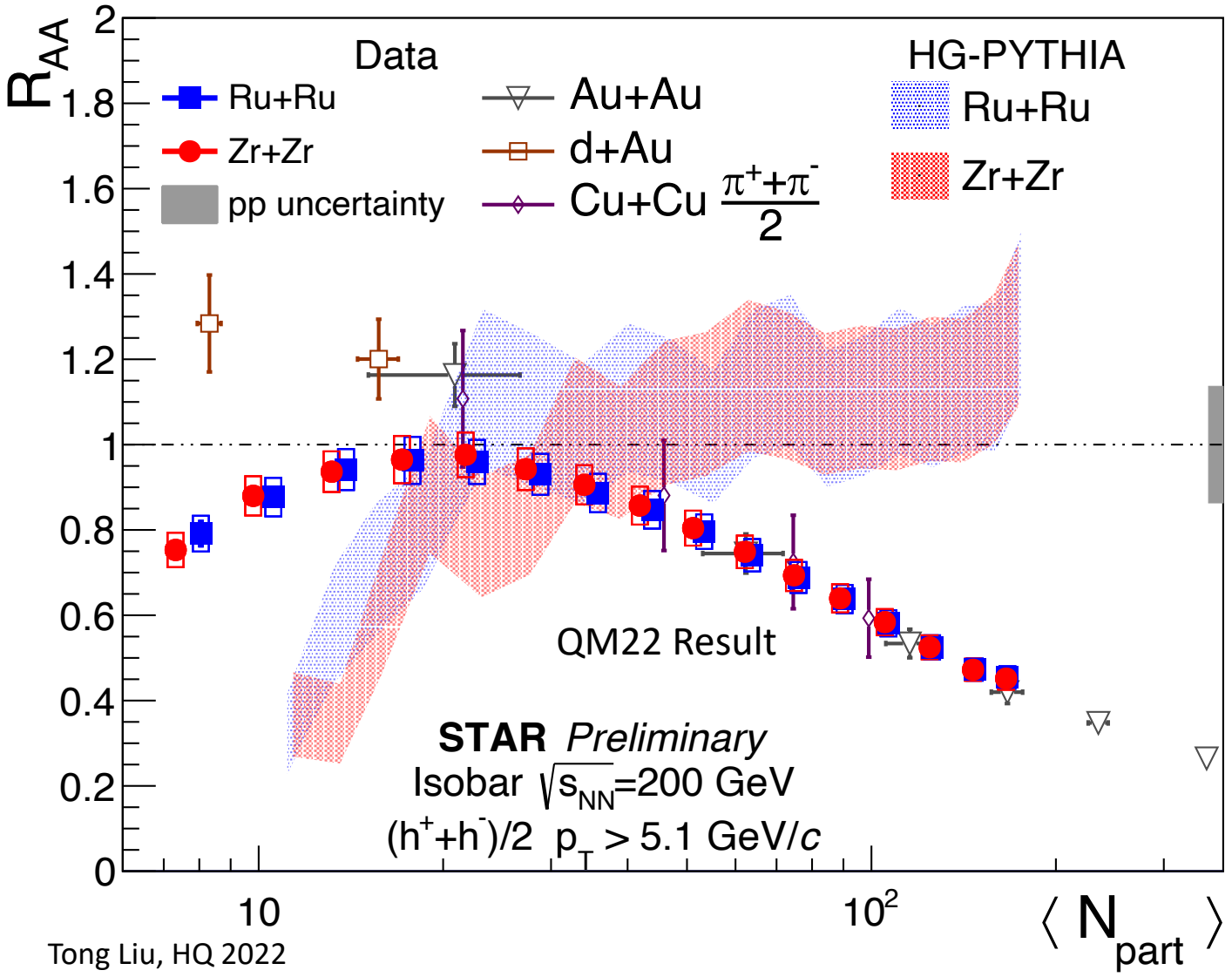
ALICE, Phys. Rev. C 91, 064905 (2015)
CMS, Phys. Rev. Lett. 127, 102002 (2021)

R_{AA} with PHENIX results



STAR Phys. Rev. Lett. **91**, 172302 (2003)
STAR Phys. Rev. Lett. **91**, 072304 (2003
STAR Phys. Rev. C **81**, 054907 (2010)
PHENIX Phys. Rev. C **102**, 064905 (2020)
PHENIX Phys. Rev. C **98**, 054903 (2018)
PHENIX Phys. Rev. Lett. **101**, 232301(2008)

HG-PYTHIA: Change from QM22



- The NN cross section used in this plot was 64mb (which is the default in the code for LHC), we changed it to 42 mb to fit RHIC energy
- We ran much more statistics for p+p collision