STAR Heavy-Ion Results

David Tlusty
For the STAR Collaboration
Creighton University, Physics Department

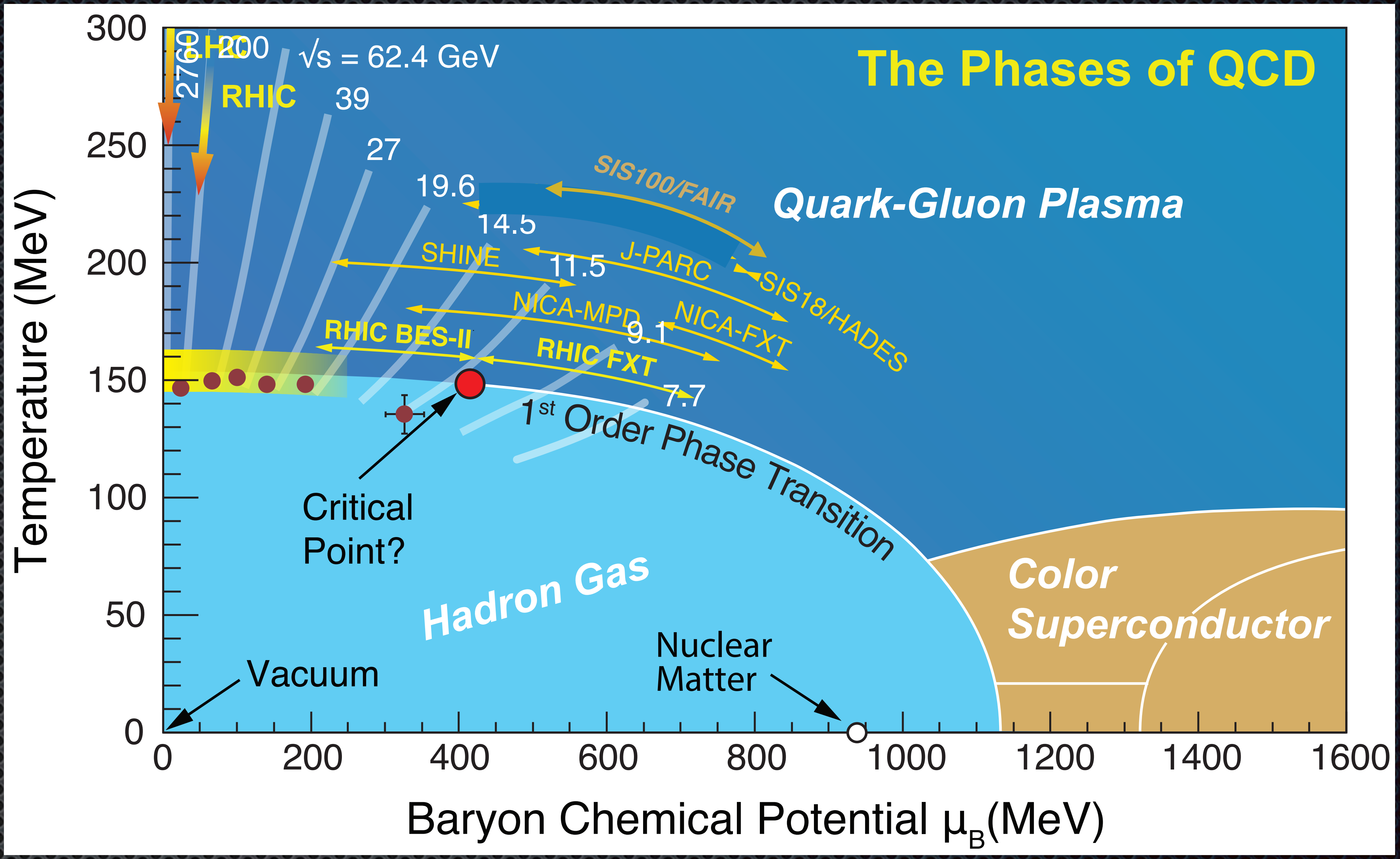
Creighton UNIVERSITY
College of Arts and Sciences

Office of Science
U.S. Department of Energy

Outline

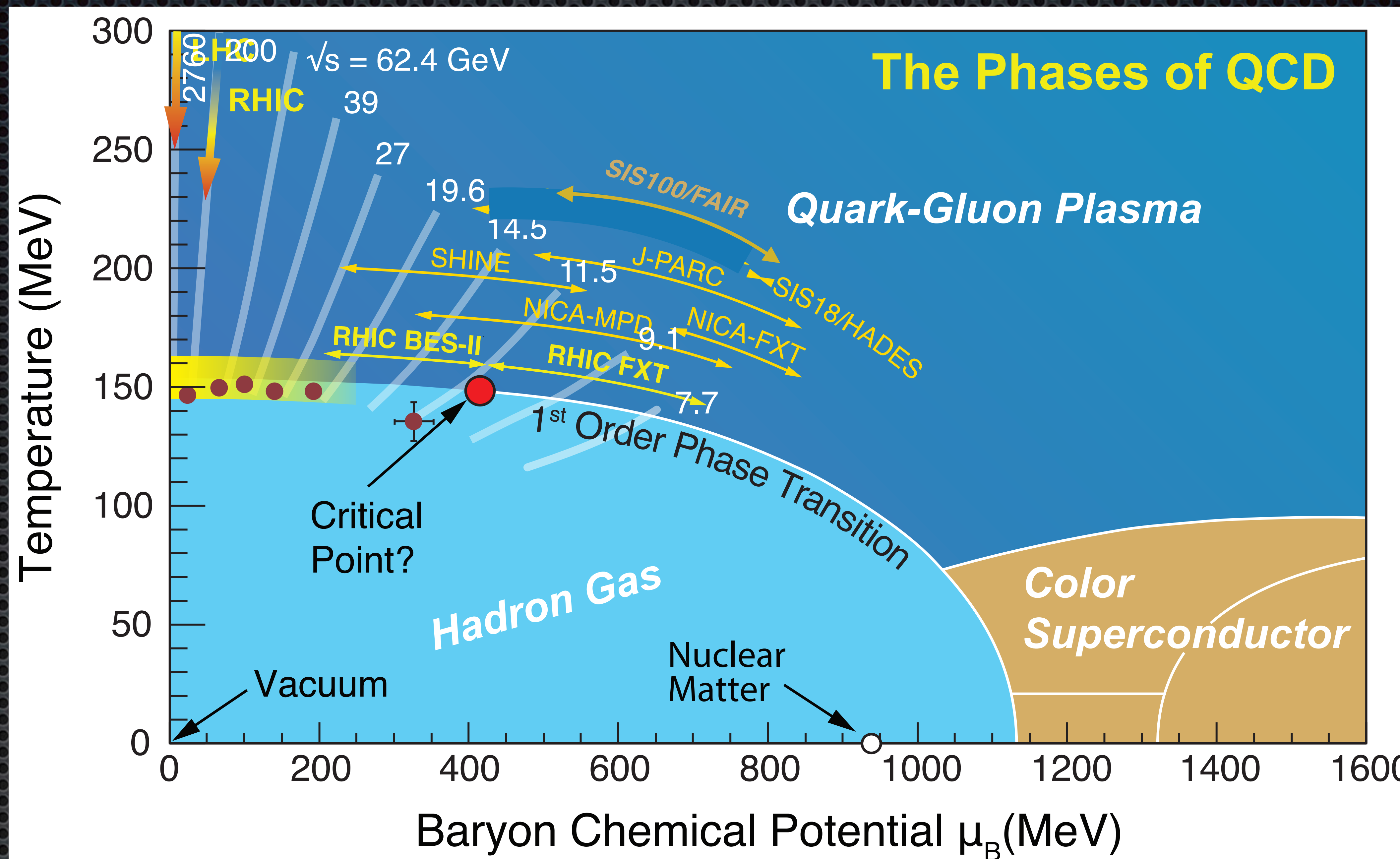
- **QCD Phase Diagram of Nuclear Matter**
  - **Heavy-Ion Collisions - main tool to explore QCD**
  - **Relativistic Heavy Ion Collider**
  - **Introduction to STAR Experiment**
- Physics Observables Measured by STAR and Highlight Results
  - Bulk Properties of "hot" Matter
  - Anisotropic Flow
  - Production Supression and Enhancement
  - Hypertriton
  - Electromagnetic Processes
  - Global Hyperon Polarization
- Detector Upgrades and Future Programs
- Summary

QCD Phase Diagram



QCD Phase Diagram

- ★ The temperature, T, measures the average excitation energy per degree of freedom
  - early universe after the Big Bang
    - (T >> 10^{10} K & negligibly small baryon surplus)
- ★ The baryon chemical potential, μ_B, is a measure of the excess of baryons over antibaryons
  - atomic nuclei and collapsed stars (μ_B > 1GeV)



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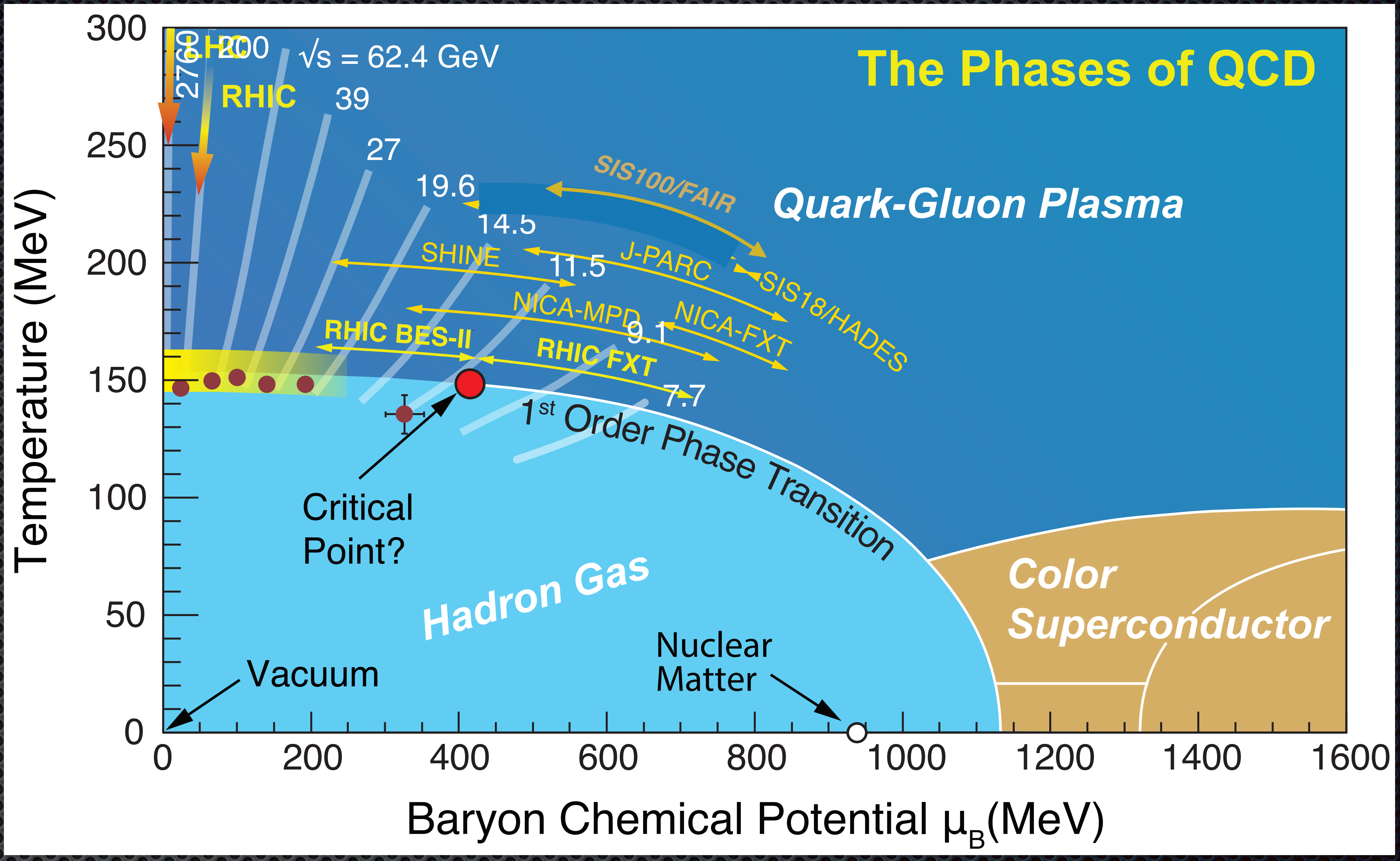
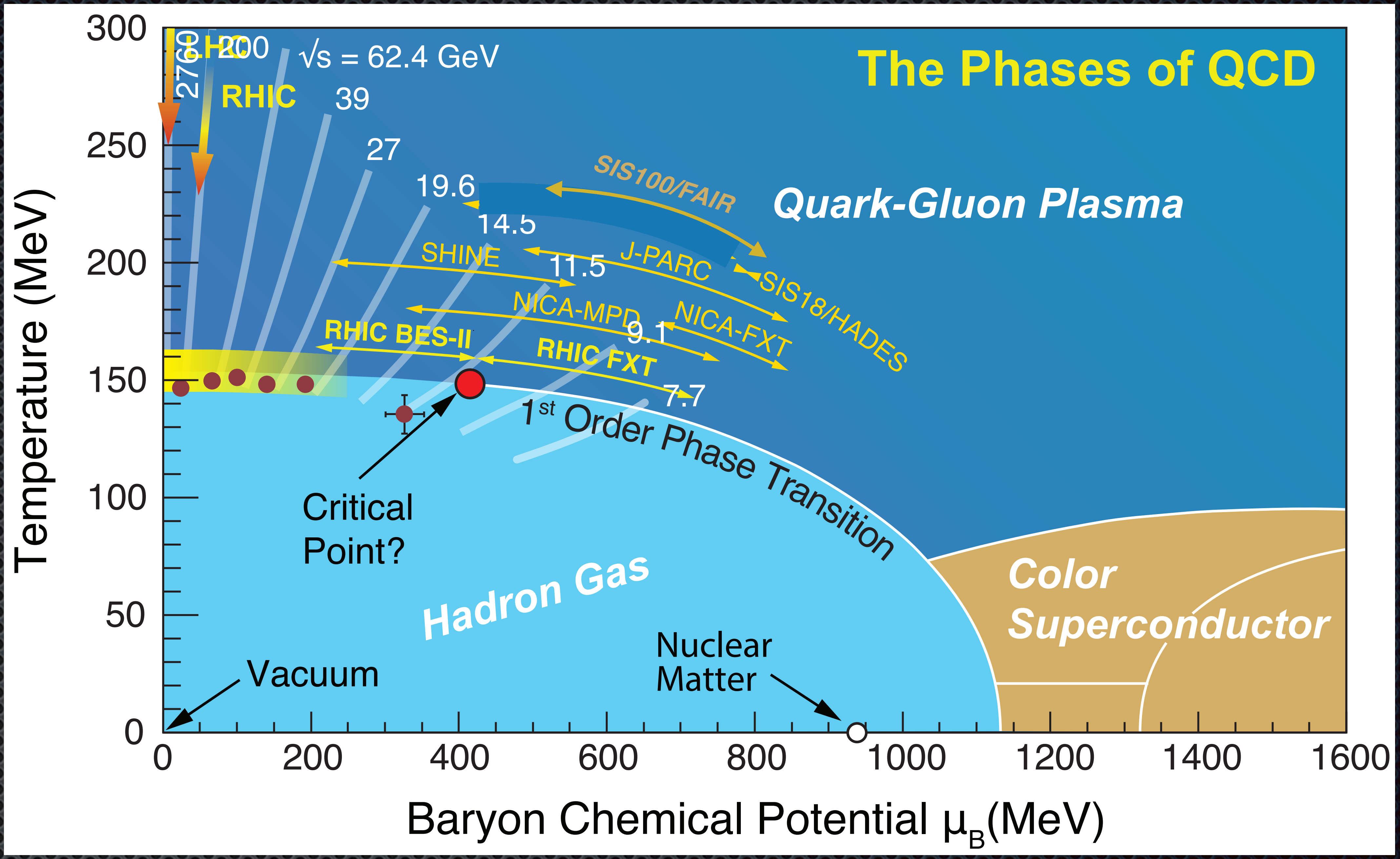


- ★ Experimentally, one can access different regions of the phase diagram by varying centre-of-mass energy $\sqrt{s_{NN}}$ of ion collisions

QCD Phase Diagram and RHIC



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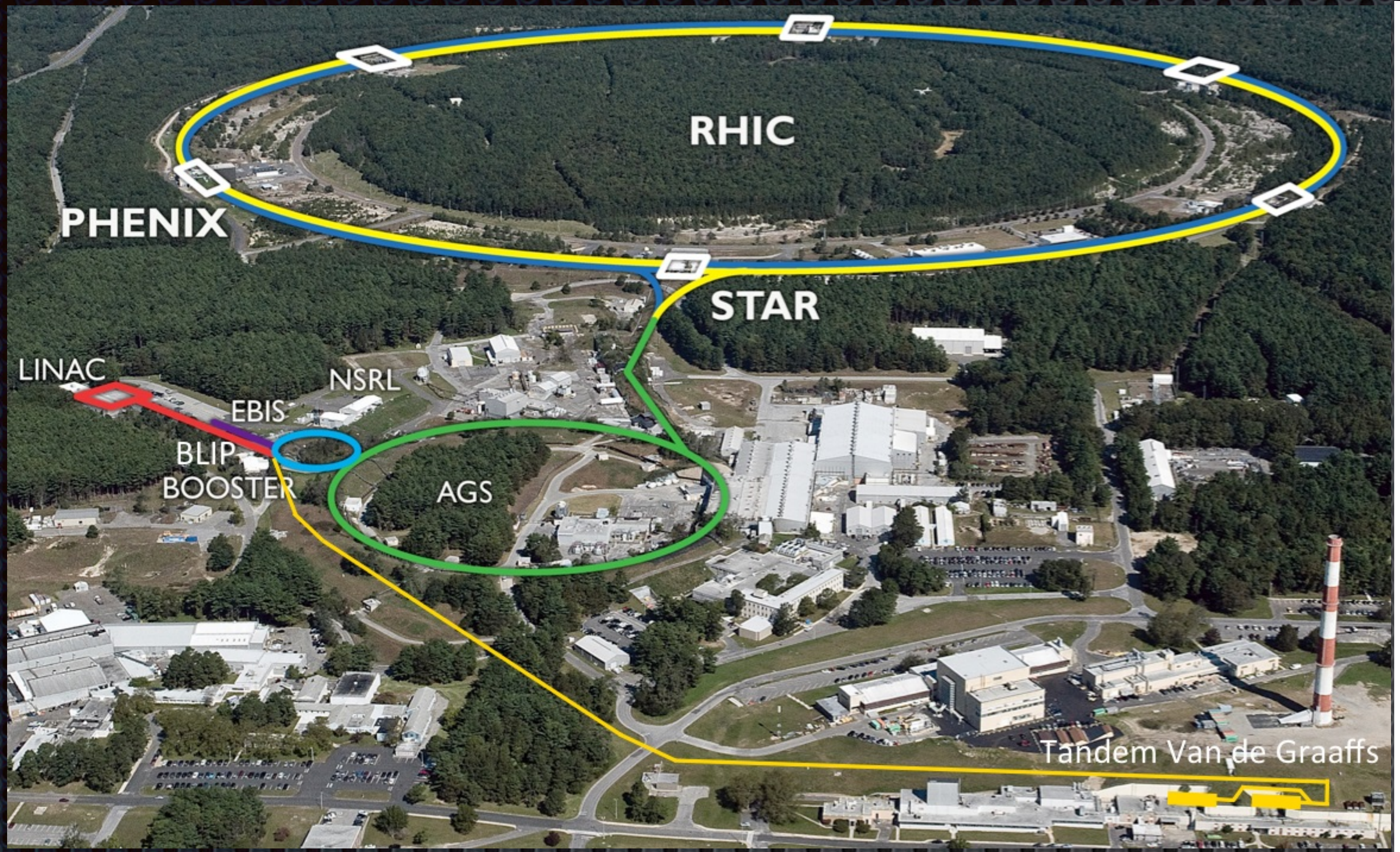

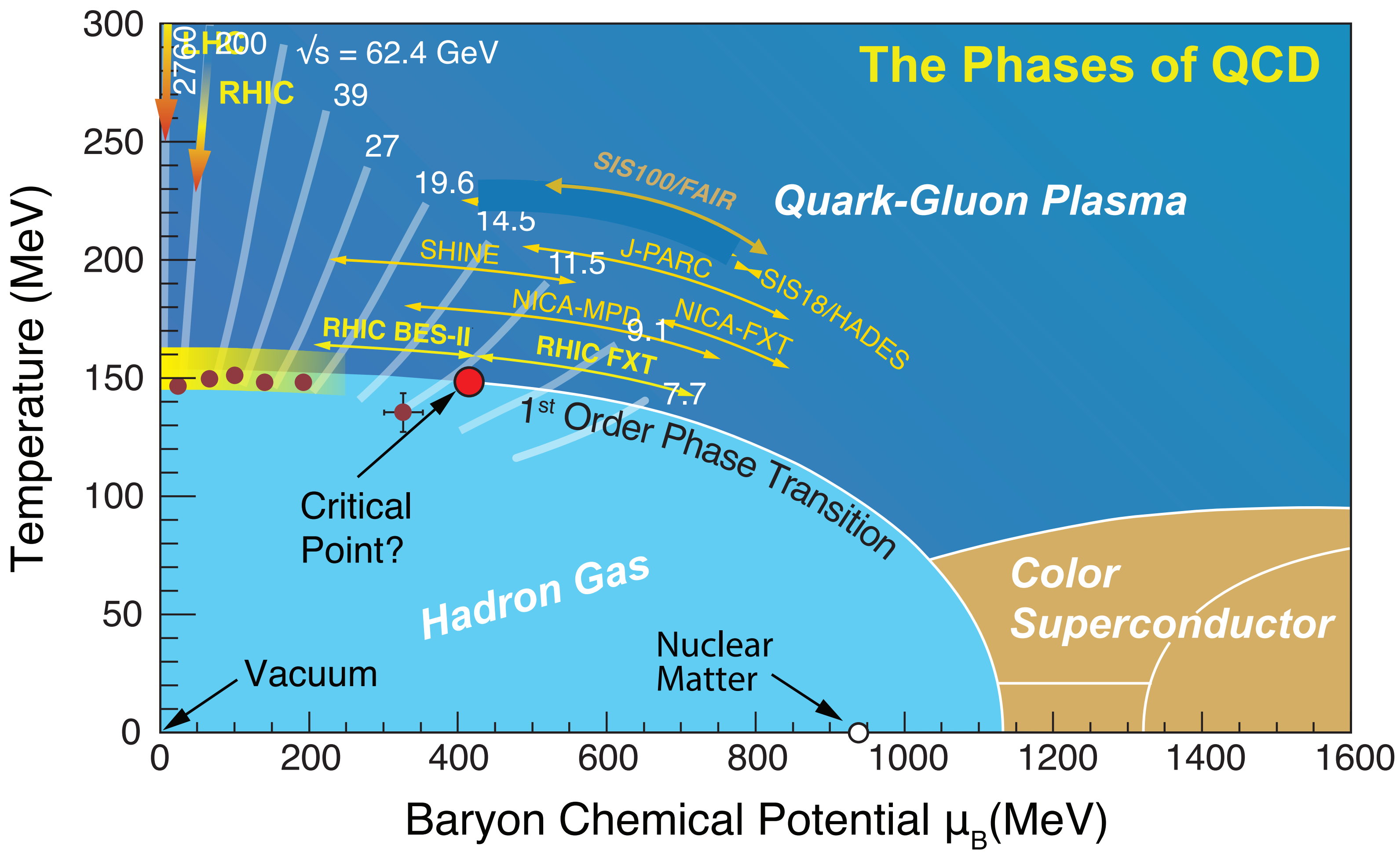

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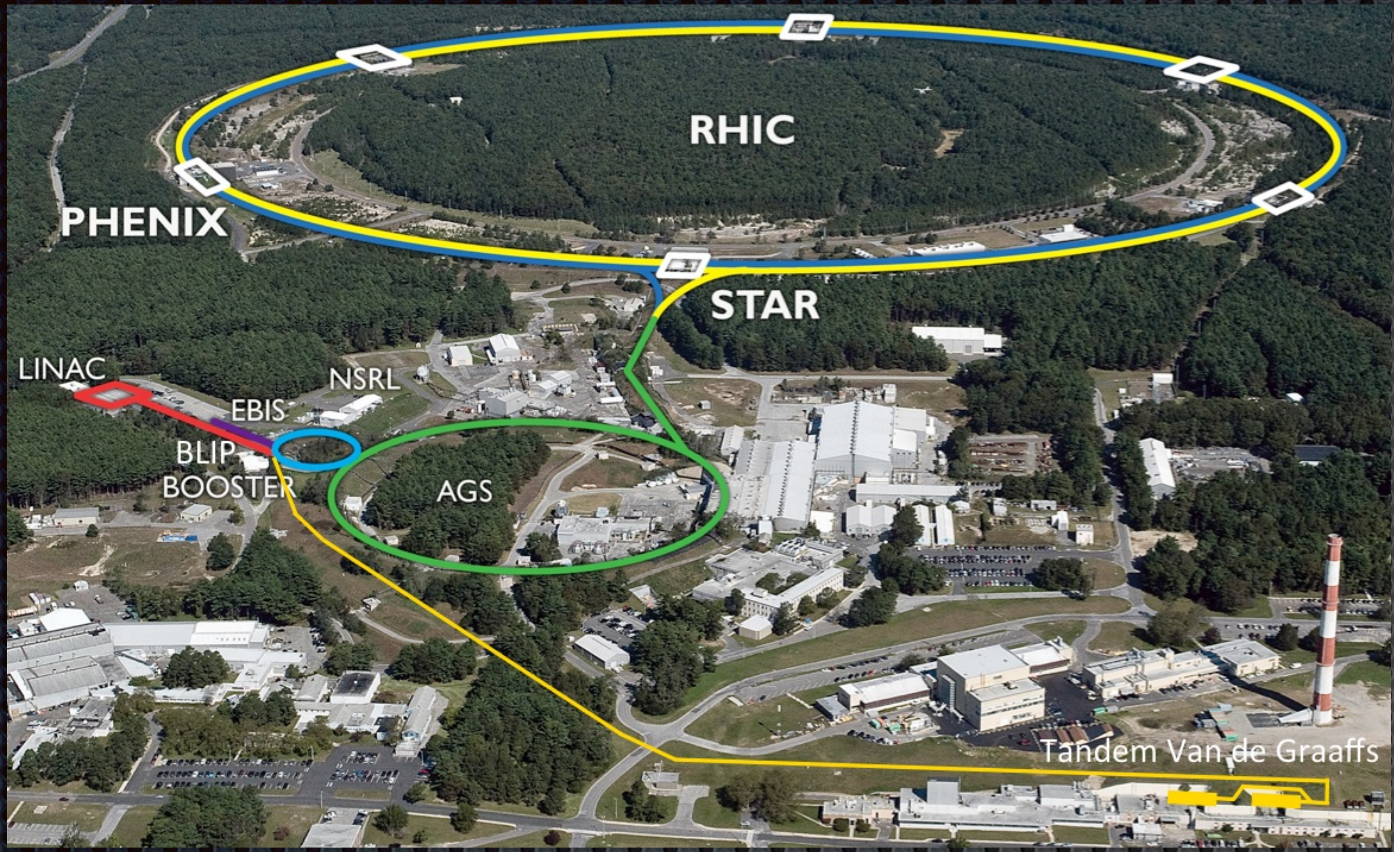

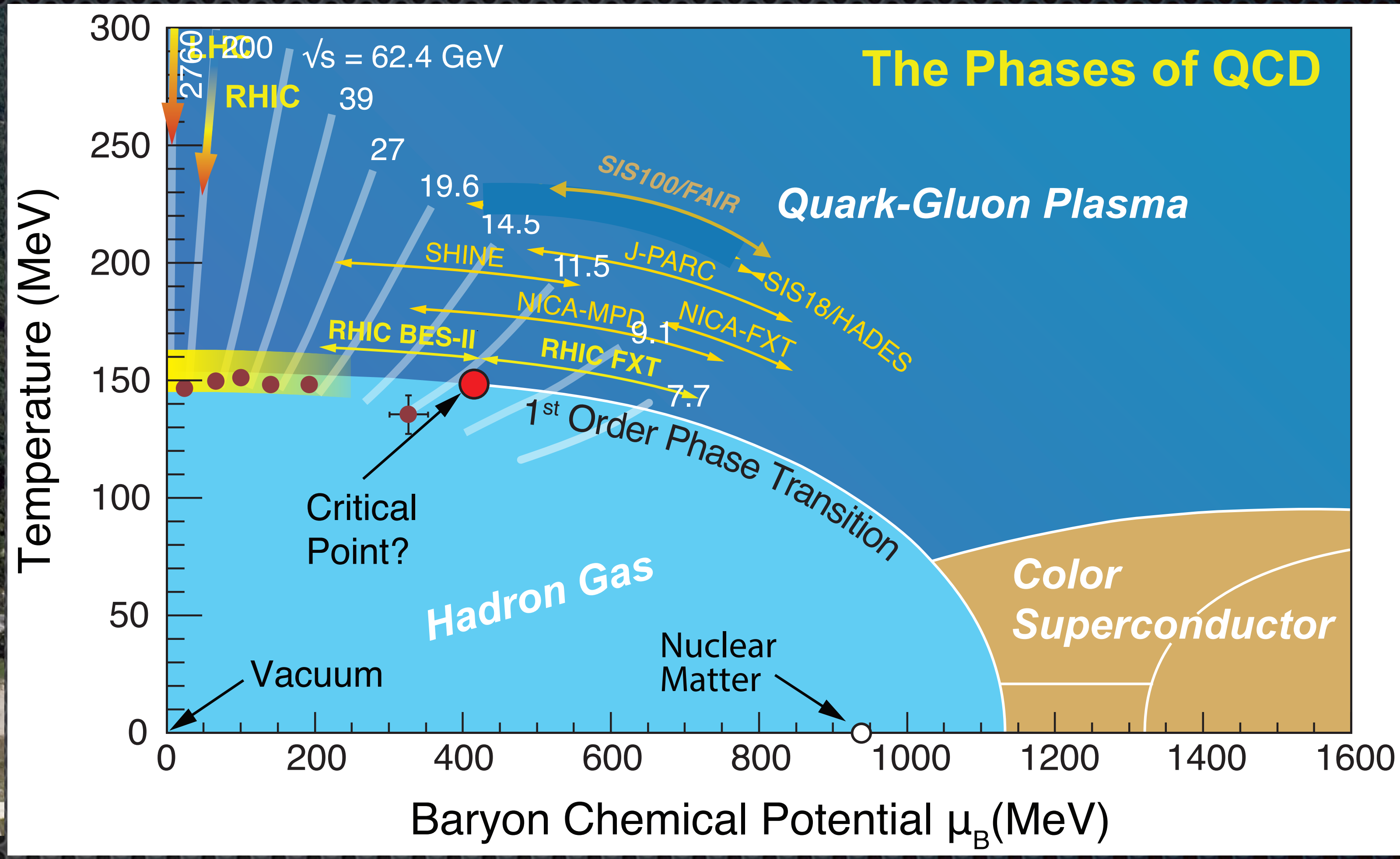

- ★ **R**elativistic **H**eavy **I**on **C**ollider
  - $\sqrt{s_{NN}}$ from 200 GeV down to 3 GeV
  - p+p, p+Al,Au, d+Au, ^{3}He+Au, Cu+Cu, Cu+Au, Au+Au, U+U

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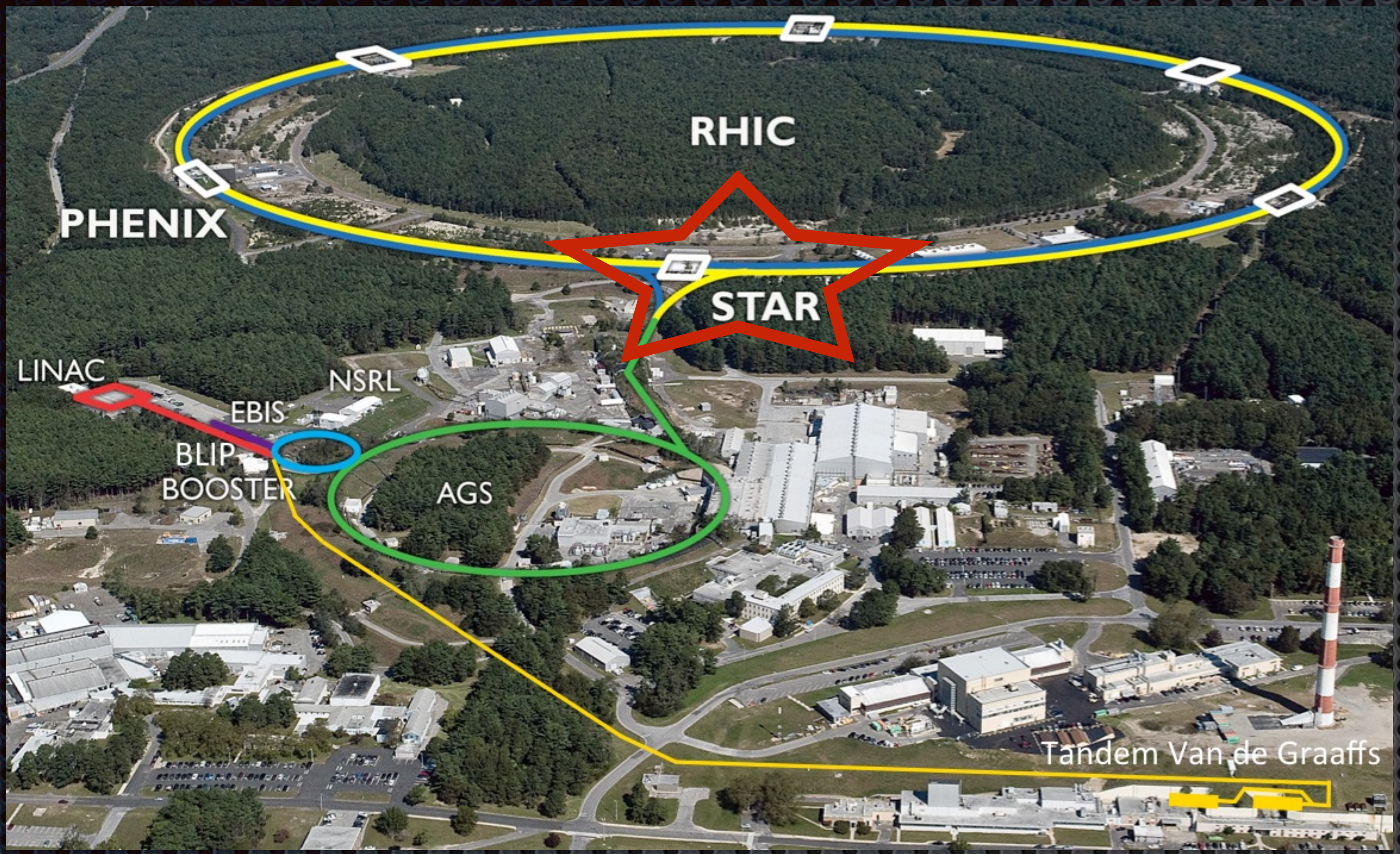
The Solenoidal Tracker At RHIC



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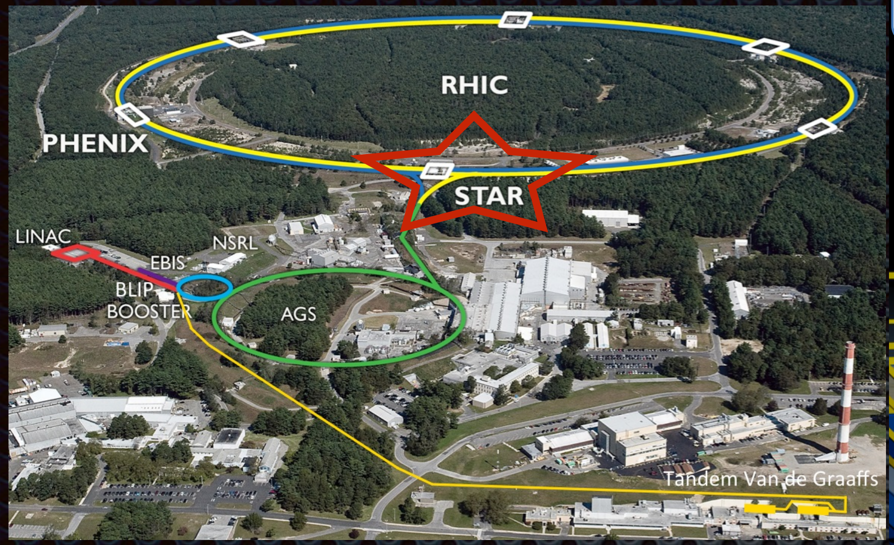

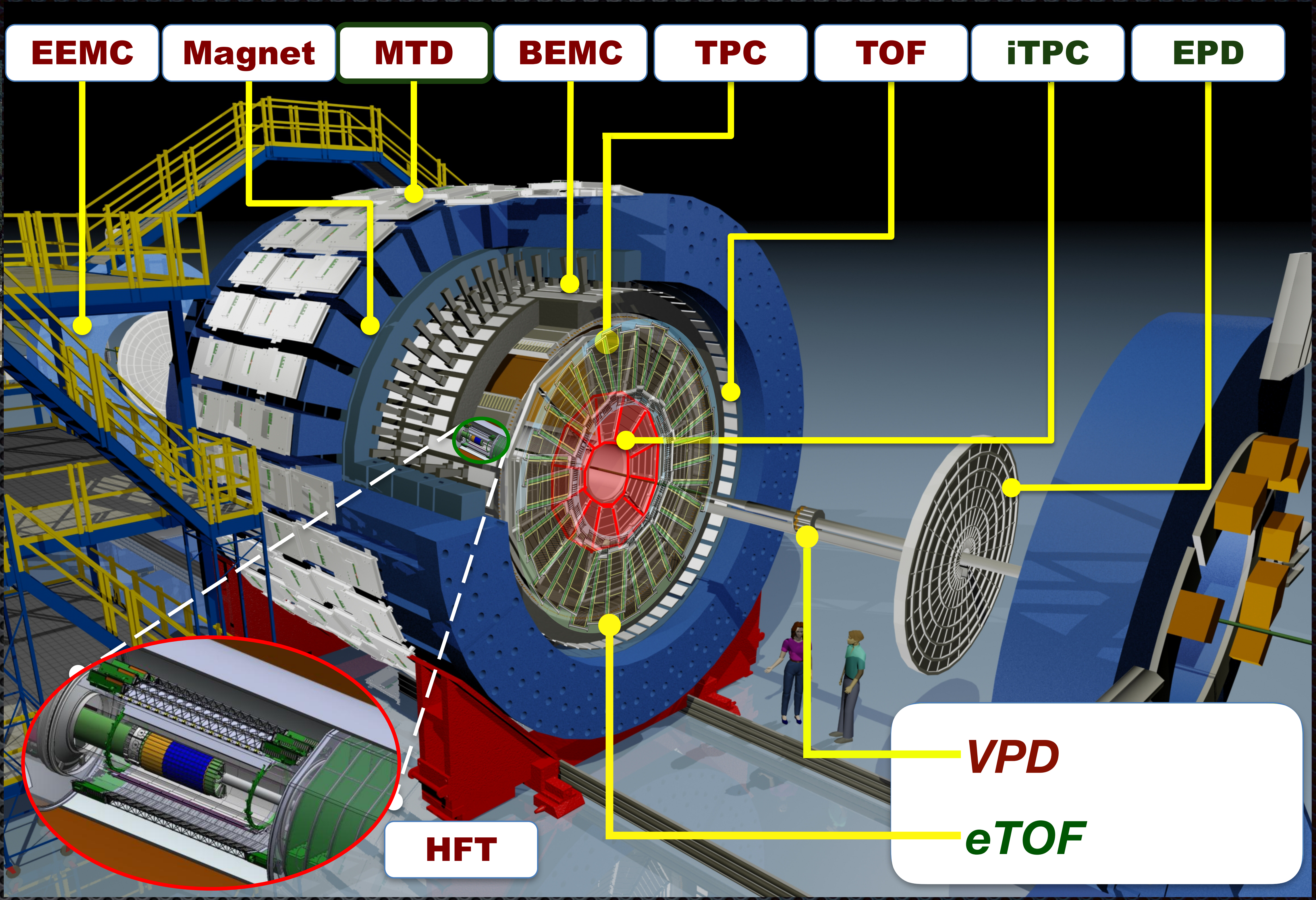

- ★ tracking of charged particles covered in full 2π azimuth
- ★ new subsystems
  - inner Time Projection Chamber (**iTPC**) upgrade
    - increased acceptance in pseudorapidty
  - Event Plane Detector (**EPD**)
  - endcap Time-Of-Flight (**eTOF**)
    - particle identification in forward direction

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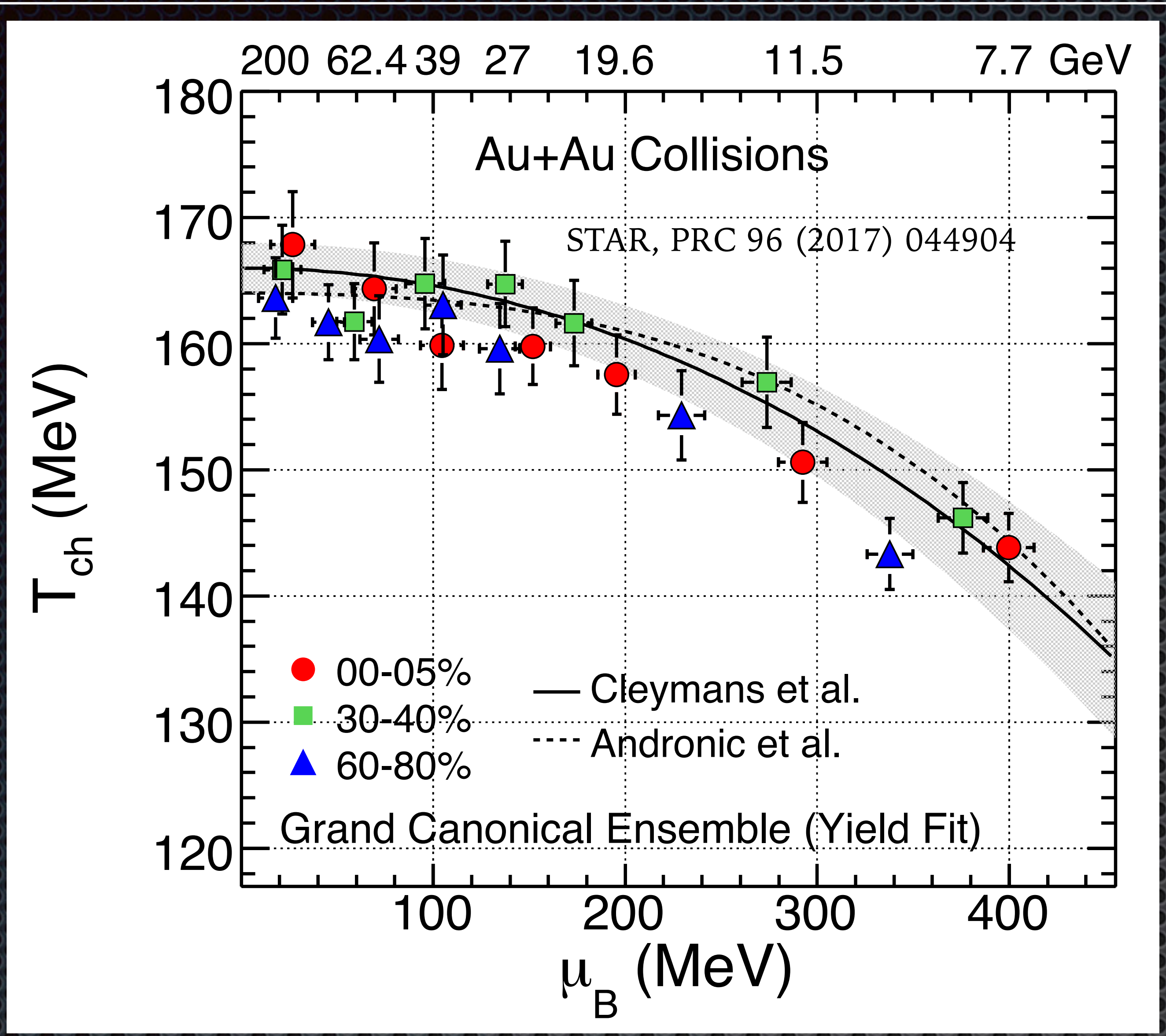

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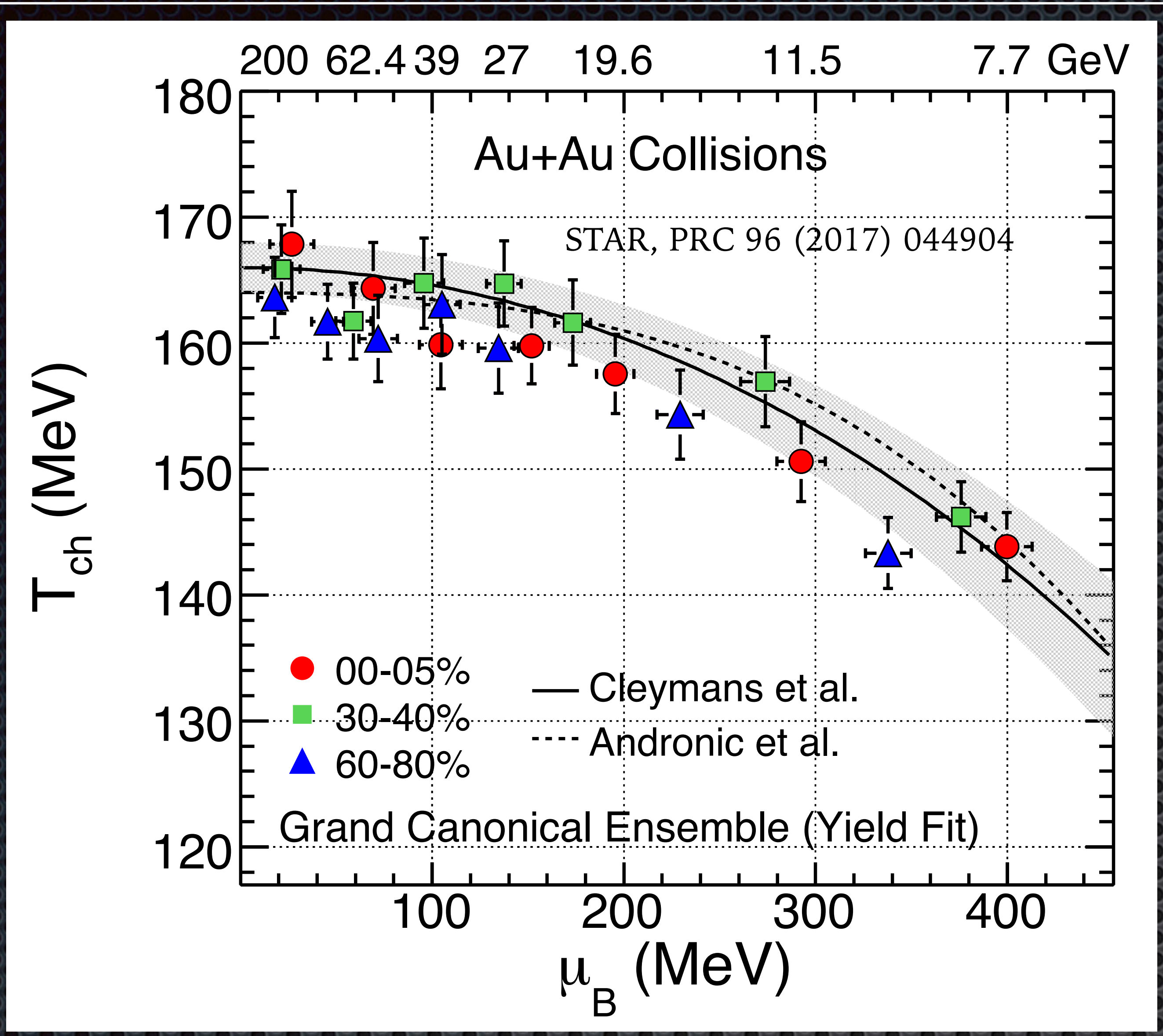

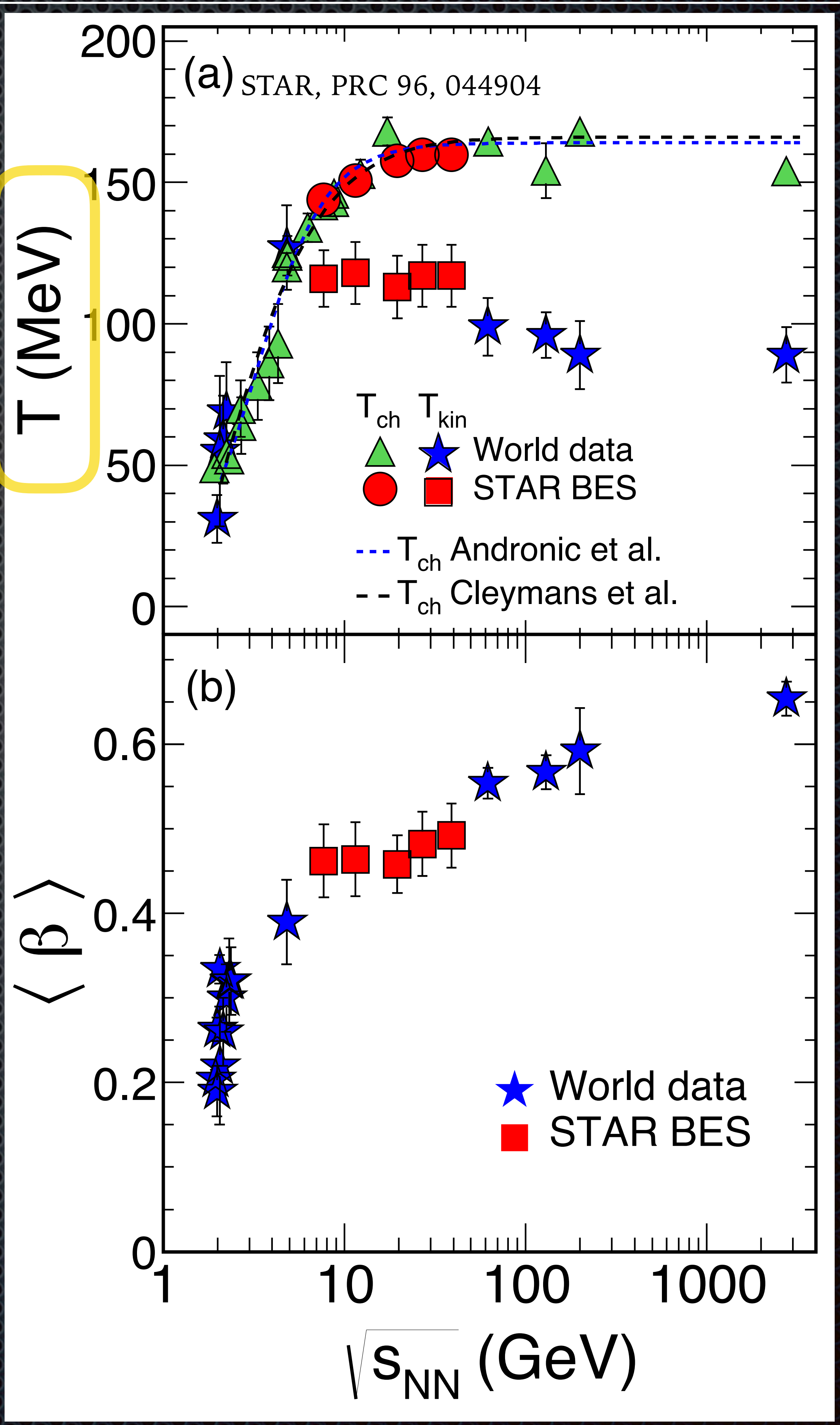

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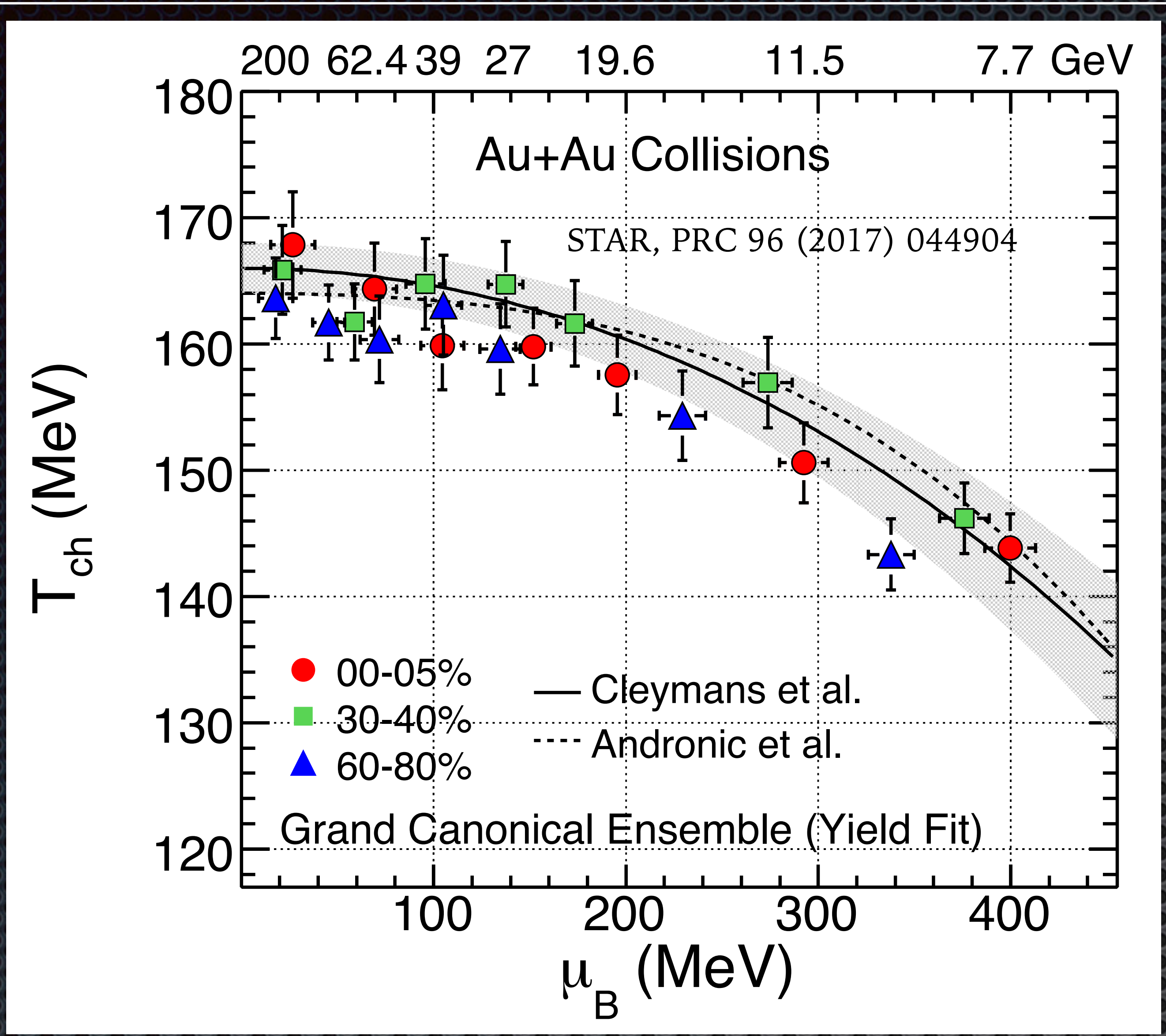

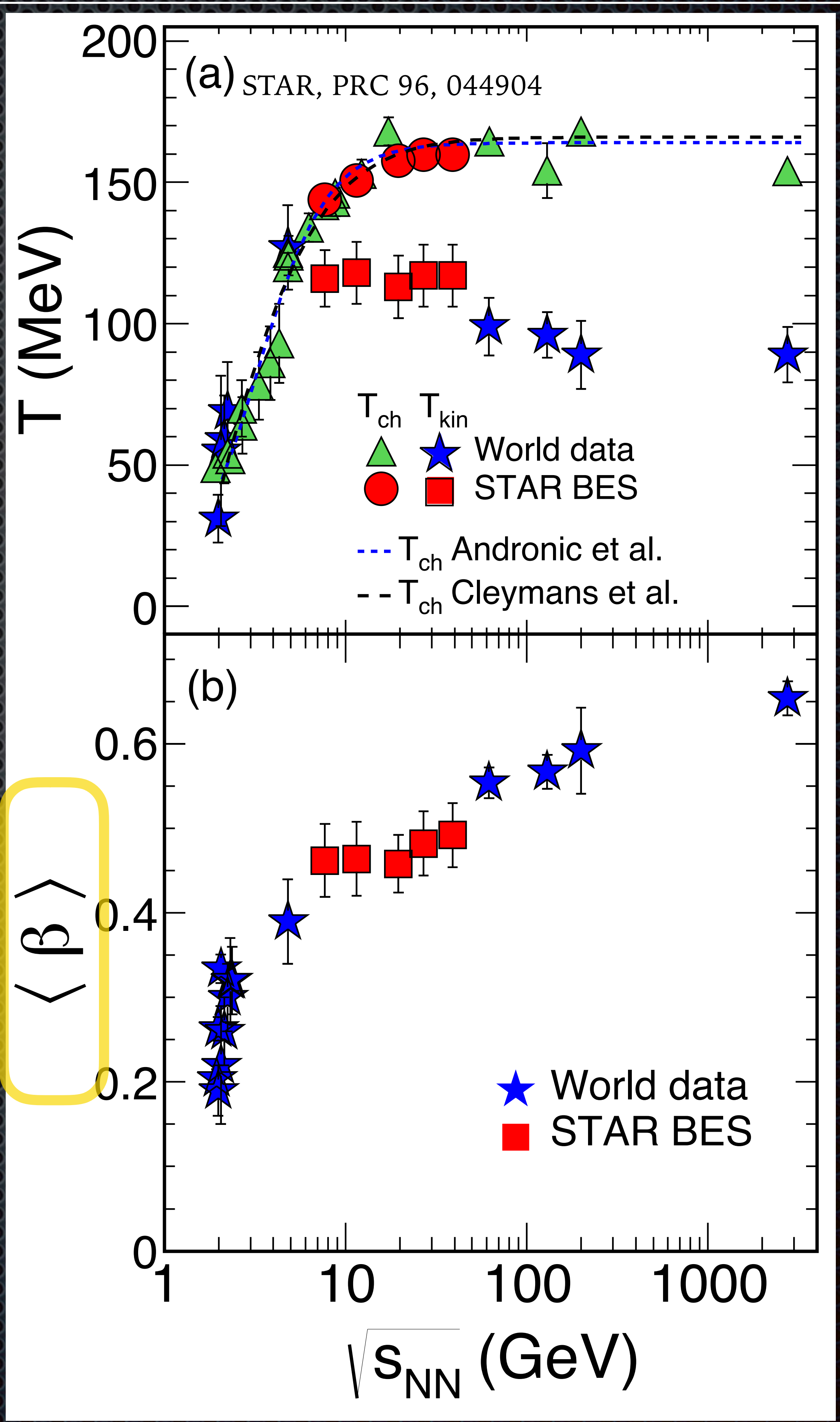

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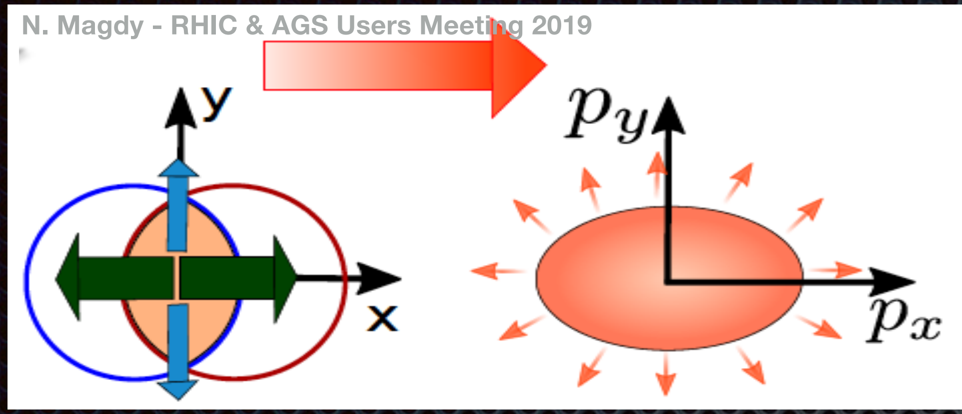
- ⟨ β ⟩ - radial flow velocity

Anisotropic Flow

Anisotropic Flow

★ Asymmetry in initial geometry ⟹ final-state momentum anisotropy



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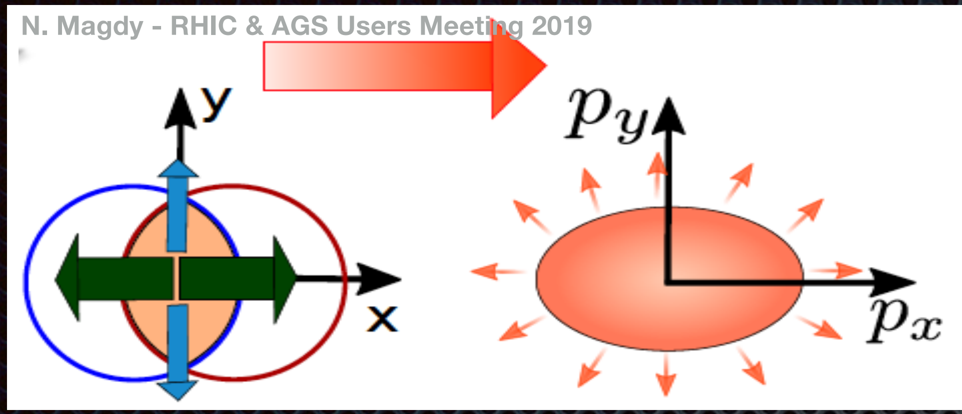

★ $dN/d\varphi \propto \left(1+2\sum_n \boldsymbol{v}_n \cos(n(\varphi-\Psi_R))\right)$

- $\boldsymbol{v}_1$≈directed (v_1); $\boldsymbol{v}_2$≈elliptical (v_2); $\boldsymbol{v}_3$≈triangular (v_3) flow
- $\boldsymbol{v}_n$ influenced by eccentricities, ε_n, fluctuations, system size, speed of sound, $c_s(\mu_B,T)$, and transport coefficient, $\eta/s(\mu_B,T)$

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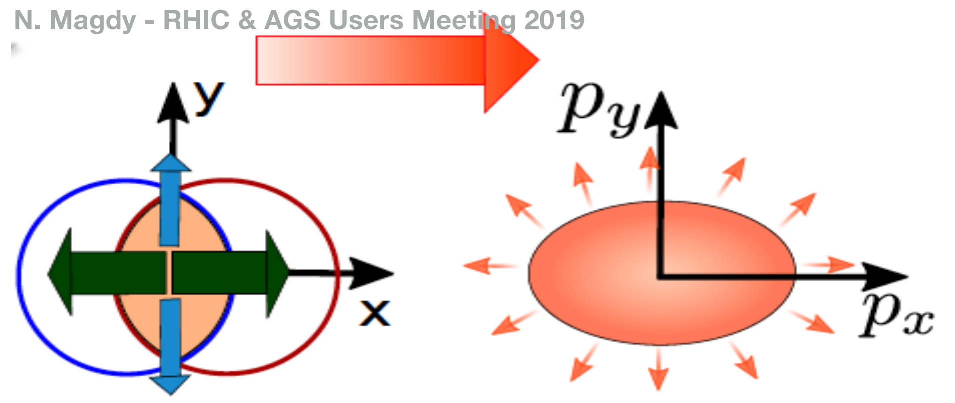

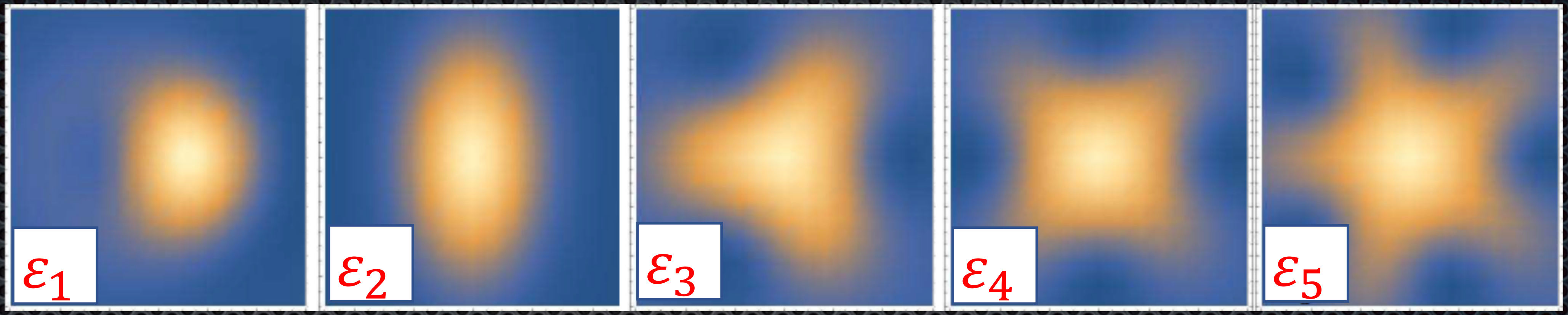

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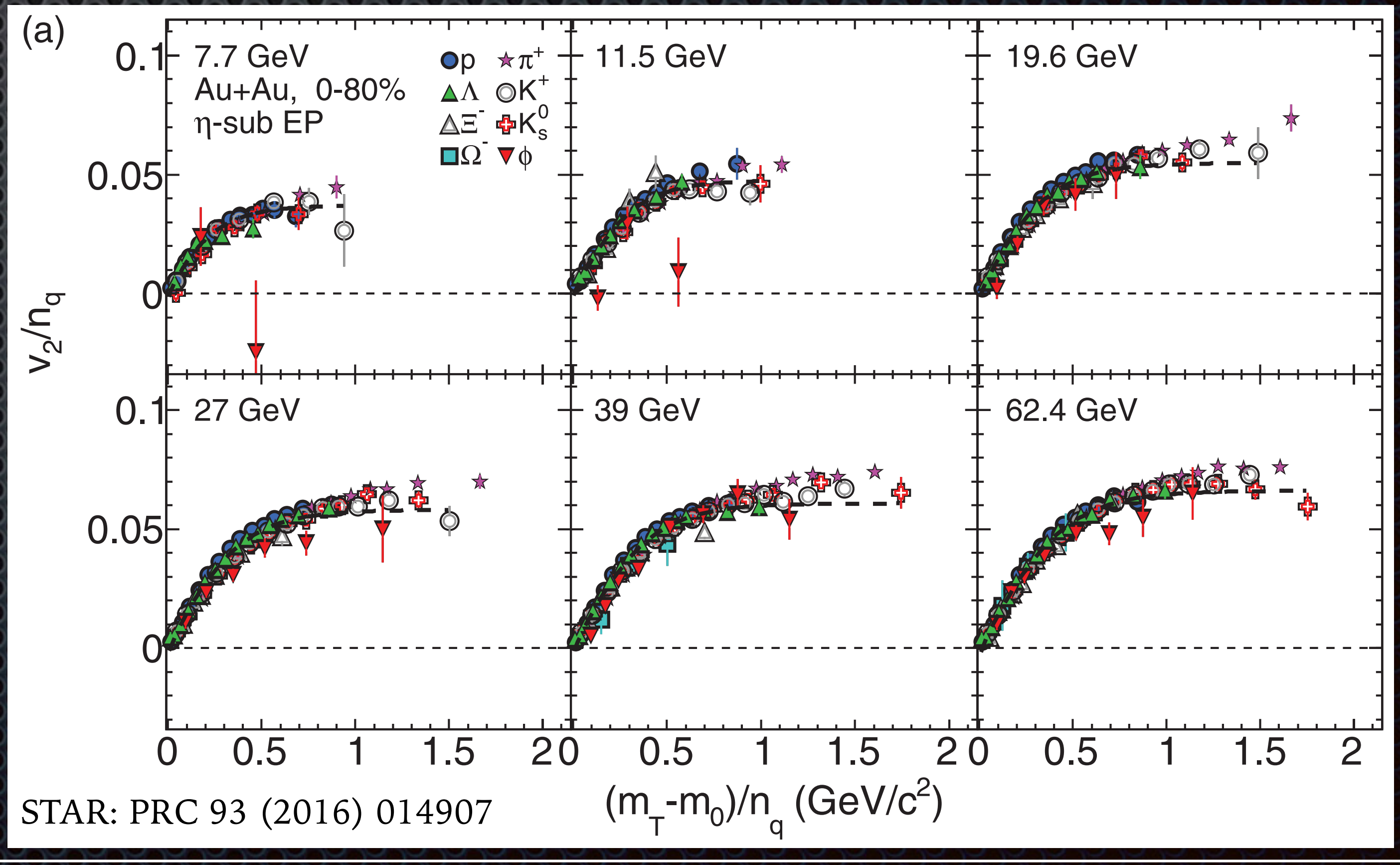
- STAR presented
  - Number of constituent quark scaling behavior of v_2
  - The scaling breakdown for ϕ meson at 11.5 and 7.7GeV
    - ϕ significantly lower collision x-section in hadron gas than other hadrons



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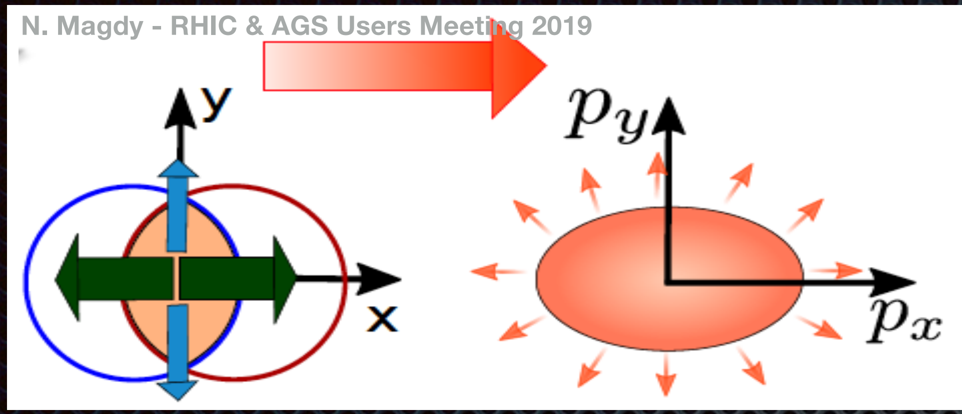

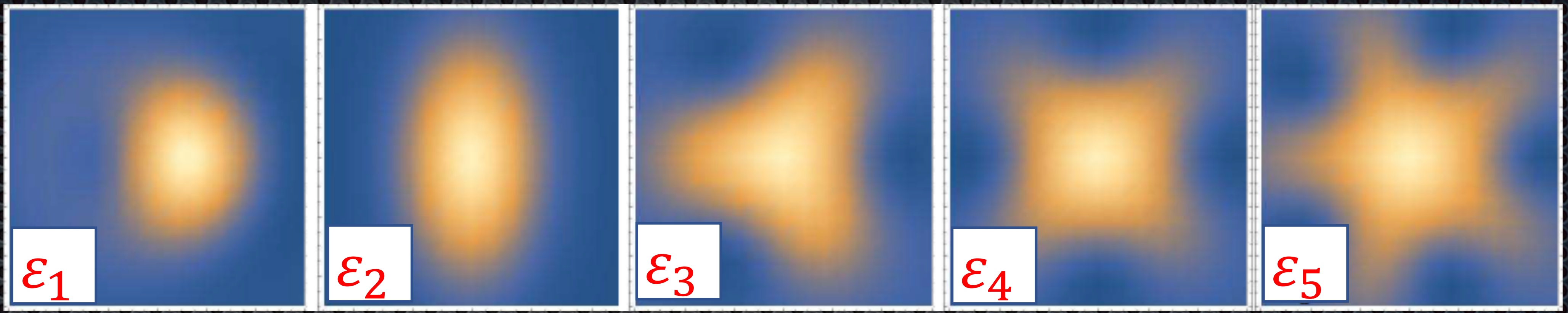

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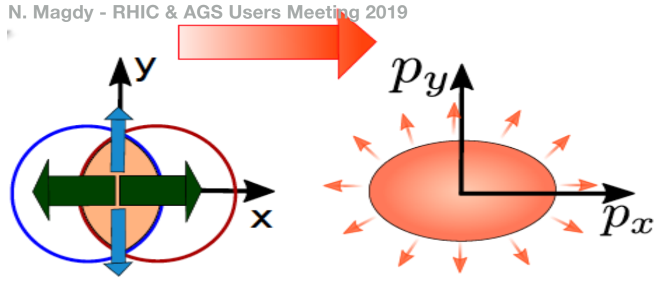

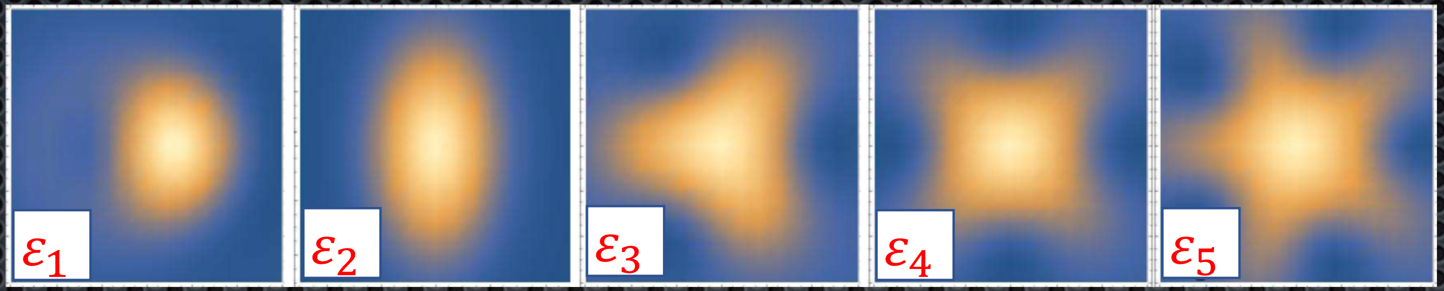

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- ★ $v_2 \propto \varepsilon_2$ & $v_3 \propto \varepsilon_3$ & $\eta/s[T]$ reduces v_n/ε_n
  - acoustic scaling [PRL 122 (2019) 172301]:

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto -n^2 \left\langle \frac{\eta}{s}(T) \right\rangle \langle N_{\mathrm{ch}} \rangle^{-1/3}$$

N_{ch} … charged particle multiplicity

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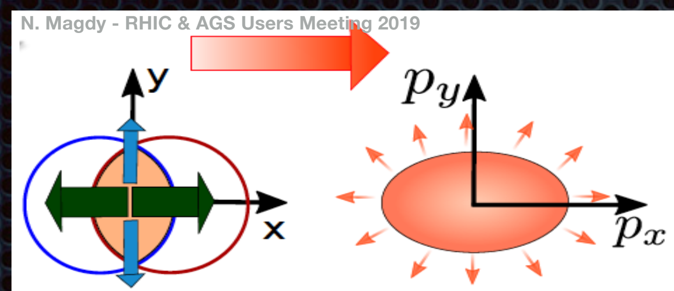

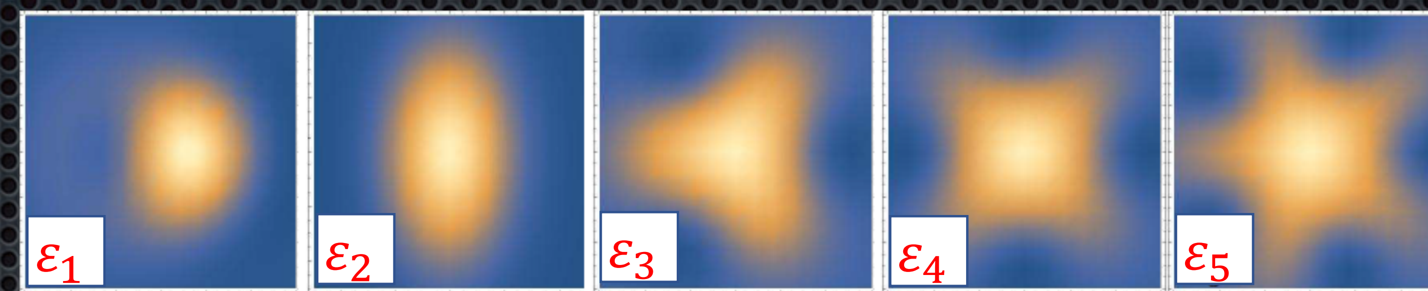

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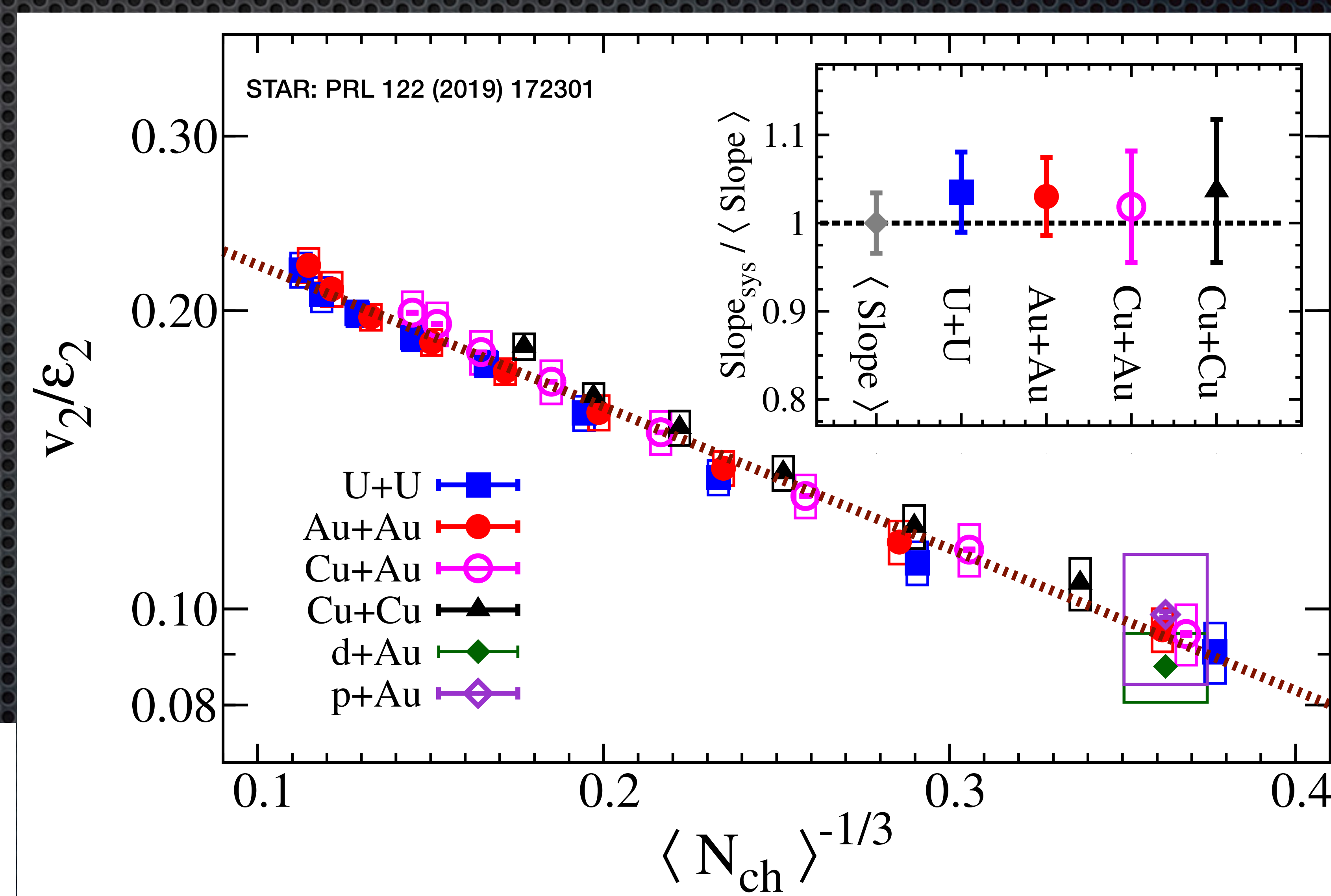
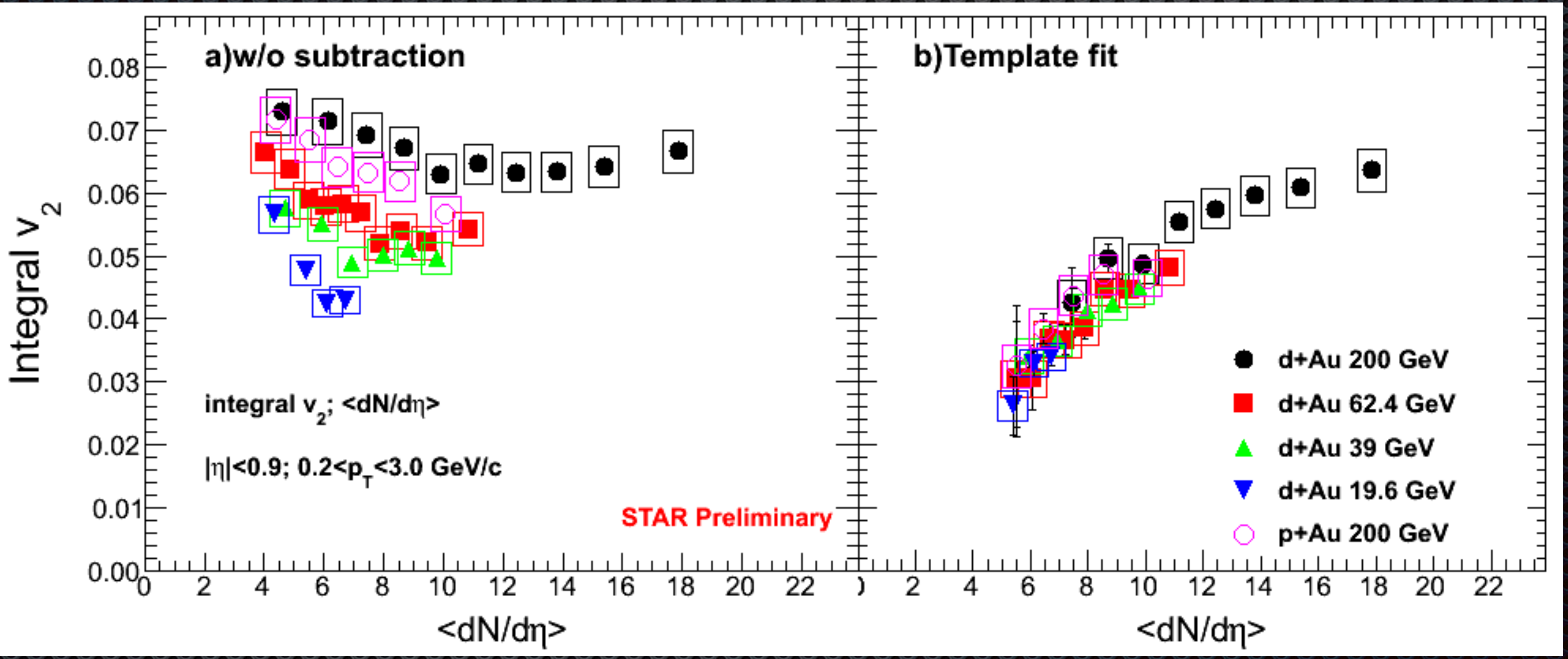
d+Au & p+Au follows the trend (N_{ch} ~ 21)



Elliptical Flow in Small Systems

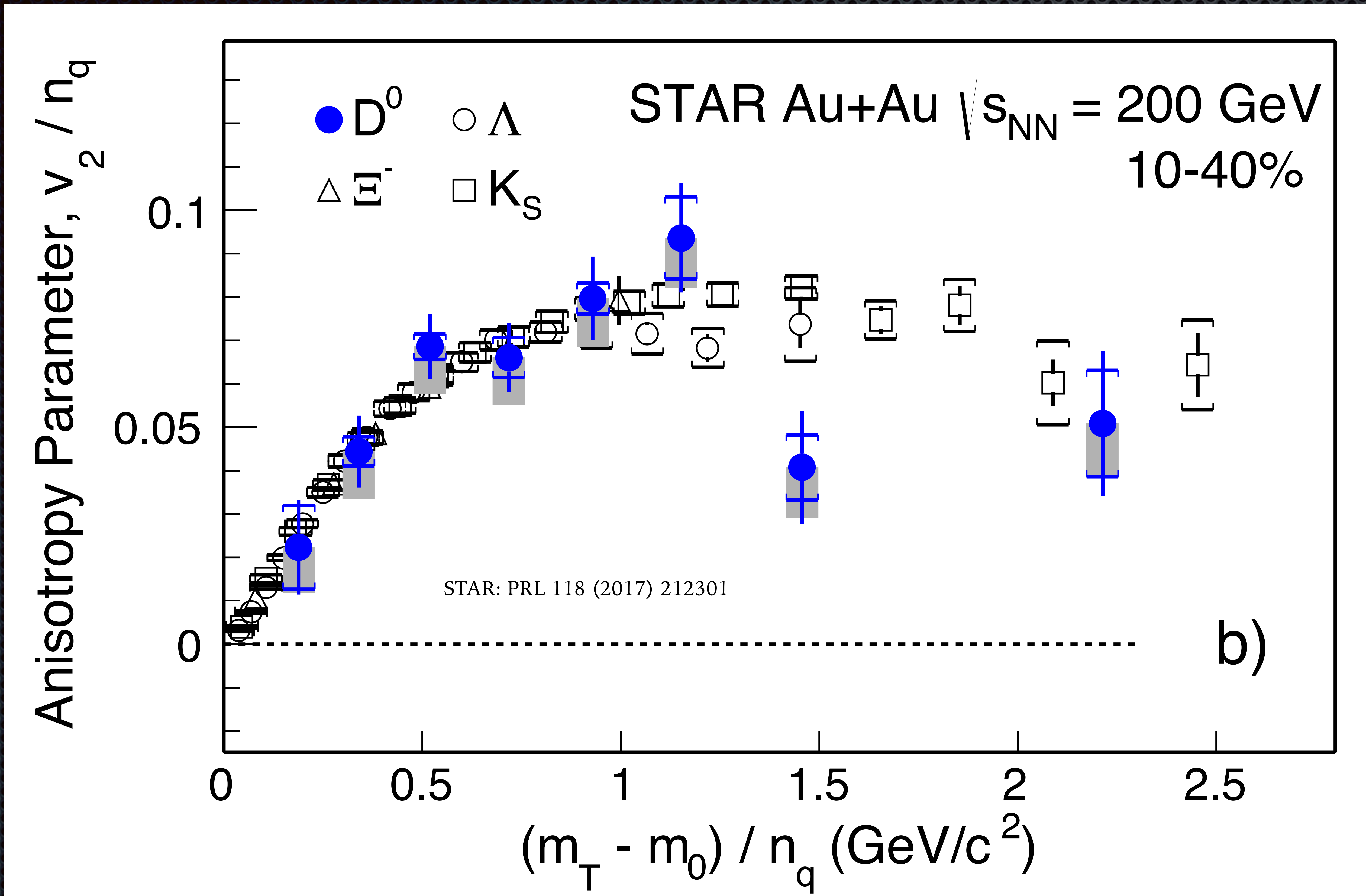
★ Small Systems - low multiplicity p+Au, d+Au

- v_2 extracted from two particle correlation
  - pseudorapidity $|\eta| < 0.9$, $|\Delta\eta| > 1.0$: reduces short range nonflow
- Long range nonflow contribution (near side ridge) significant
  - subtracted using new method developed by ATLAS [ATLAS: PRL 116 (2016) 172301]



★ Collectivity plays an important role for the flow in small systems

Elliptic Flow of D^0 Mesons



J. Bielcik, Tuesday 1pm, Room 2

L. Kramarik,

Poster #?

- Strong collective behavior of charm quarks

Directed Flow

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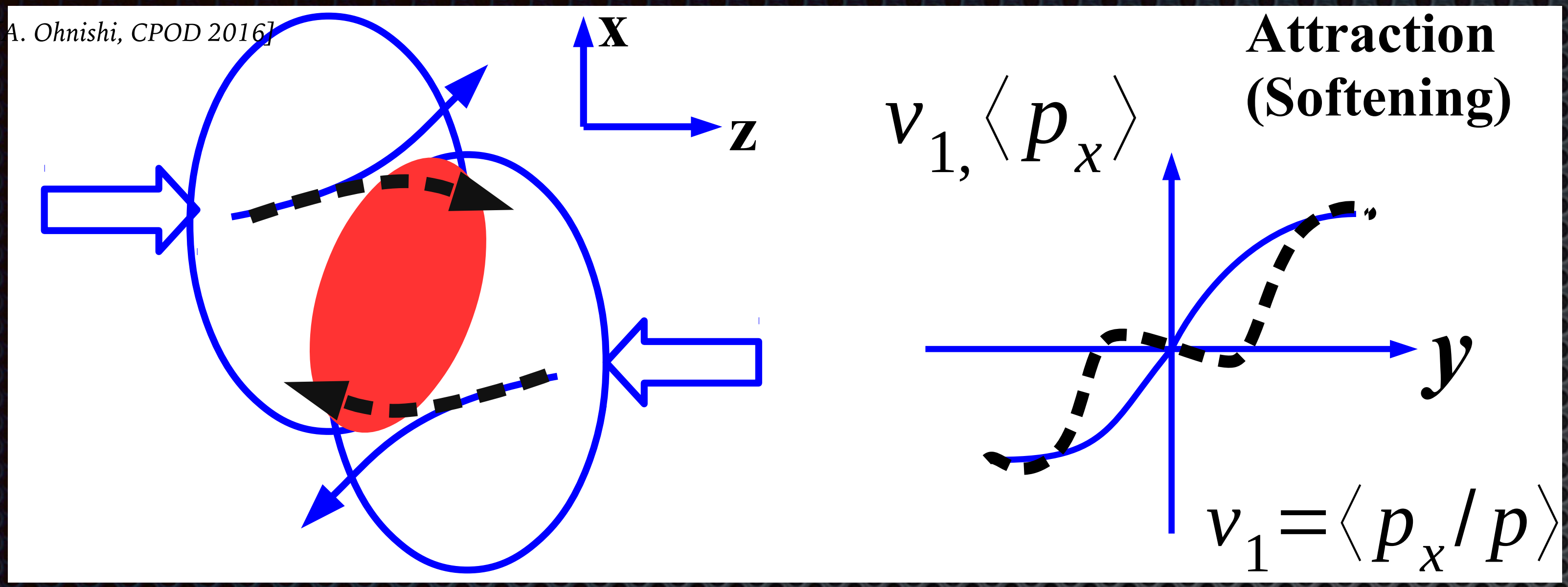

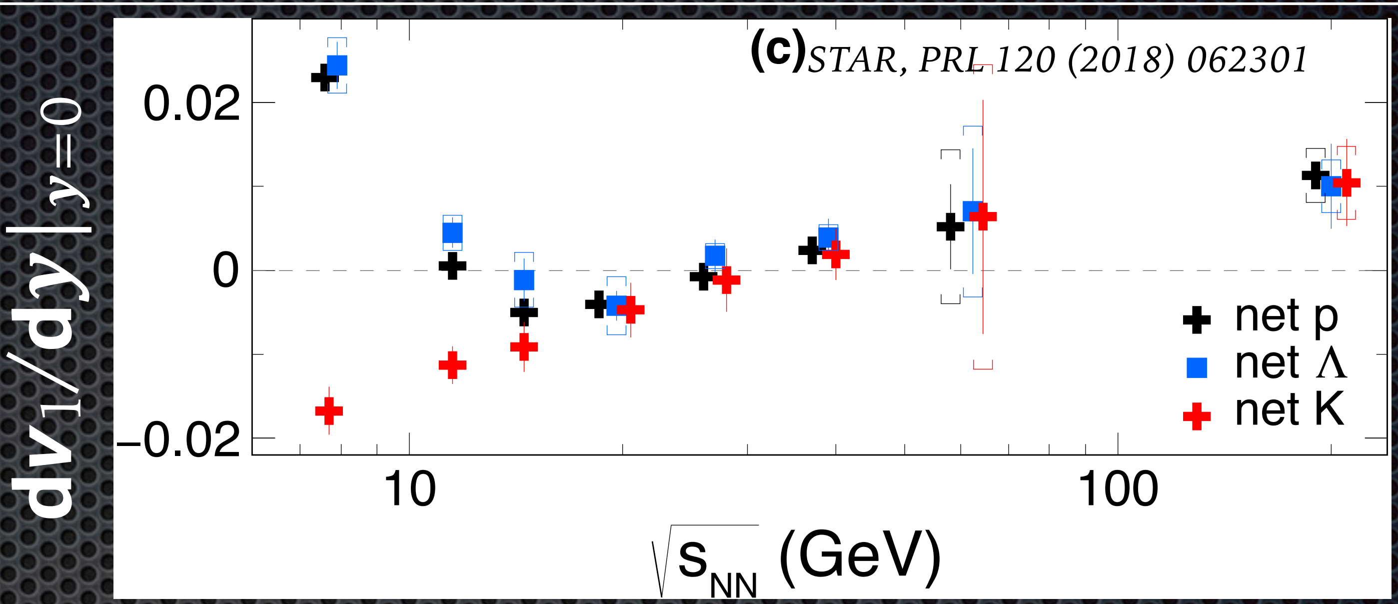

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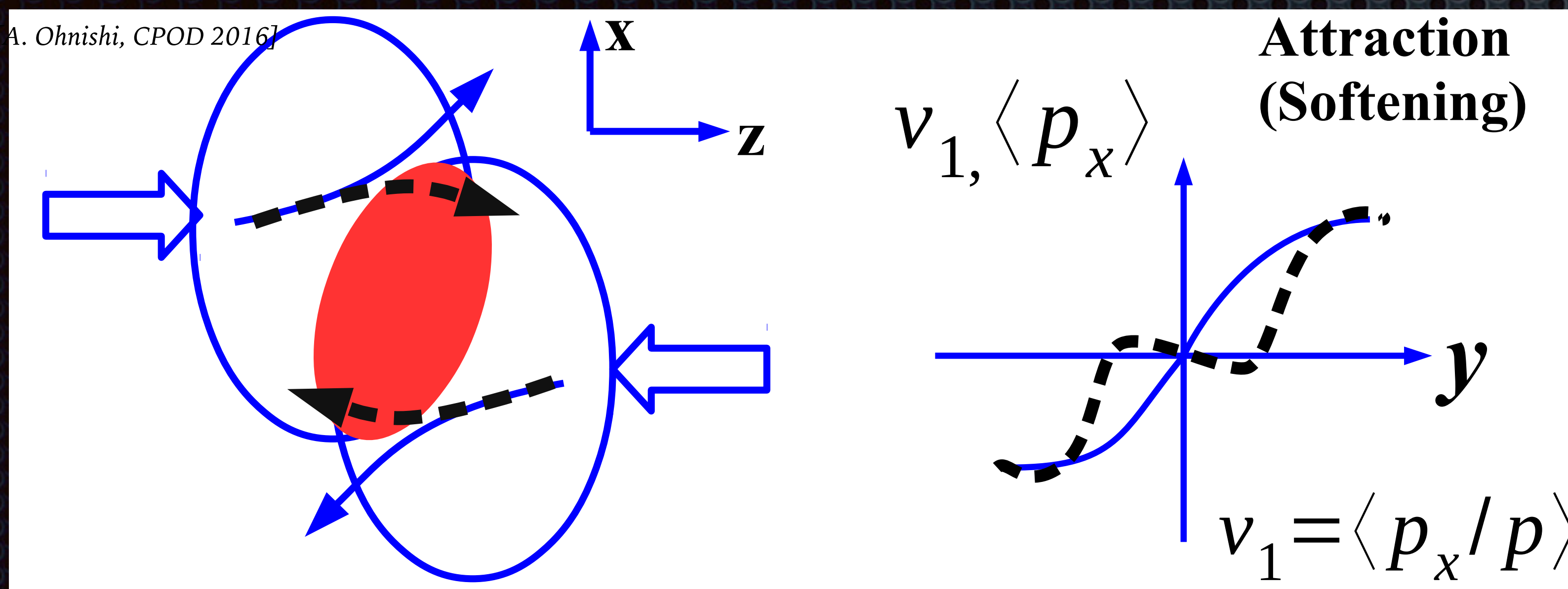

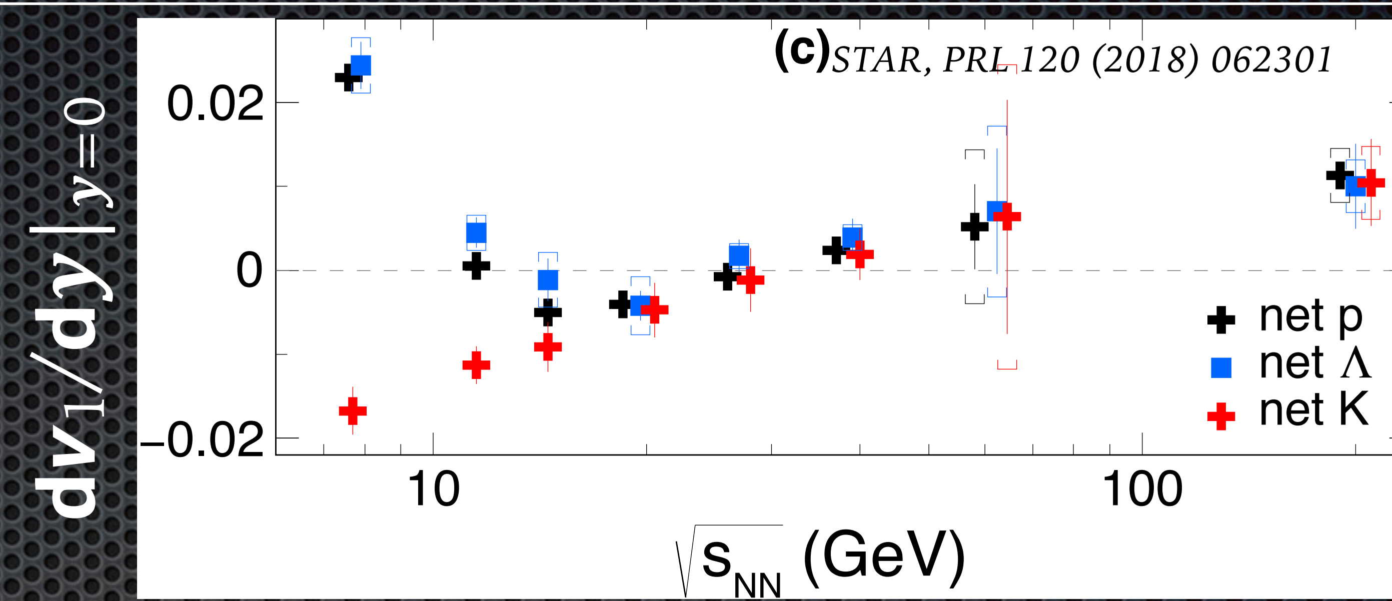

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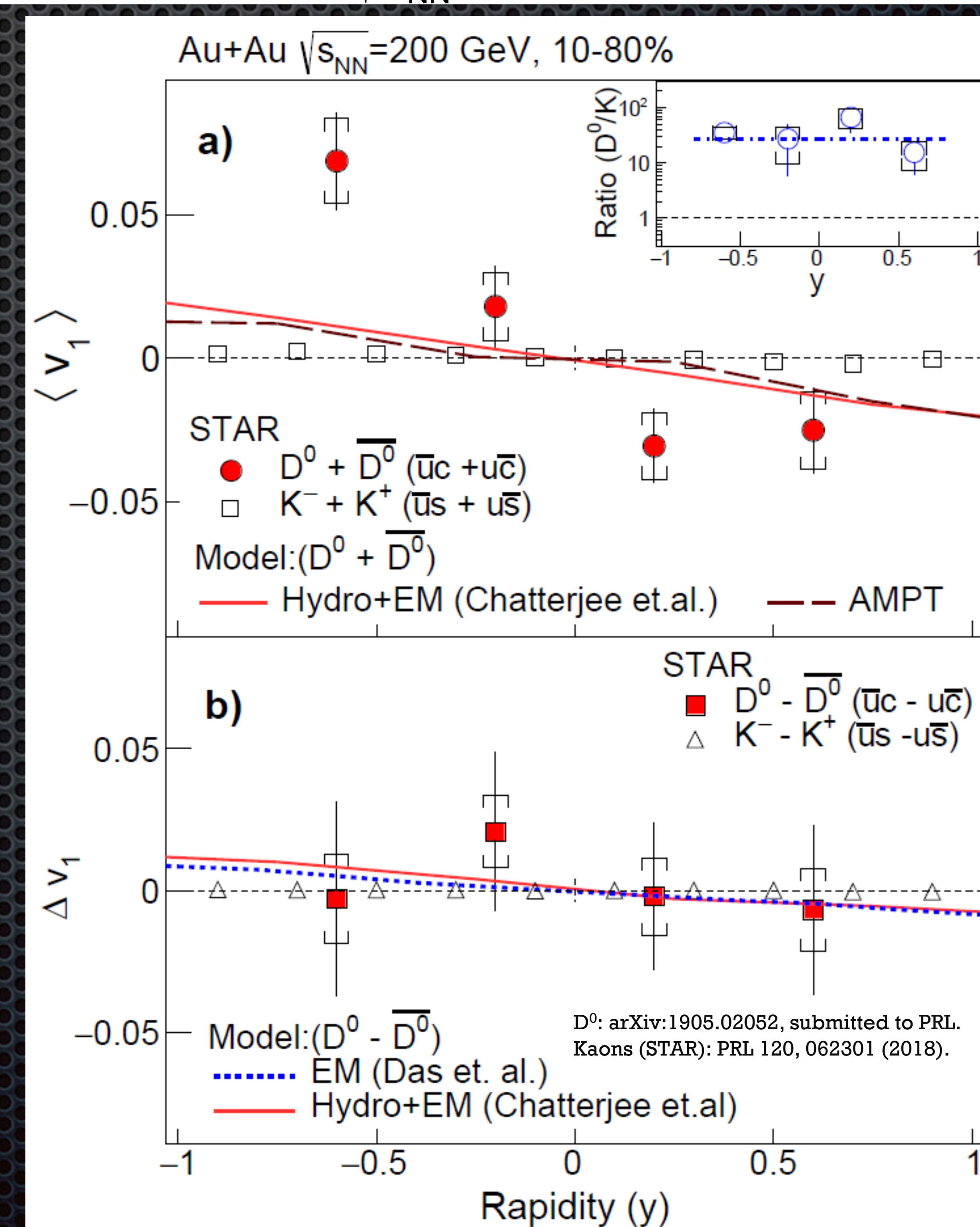
  - Net baryons show hints of a minimum and double-sign change ⟹ indicating the softening EoS
- ★ First v_1 measurement of D^0 mesons
  - The tilt of bulk x longitudinal density profile of heavy quarks
  - Rapidity dependent slope is much steeper for both $D^0 + \overline{D^0}$ than for kaons
  - More in J. Bielcik talk (Tuesday 1pm, Room 2)



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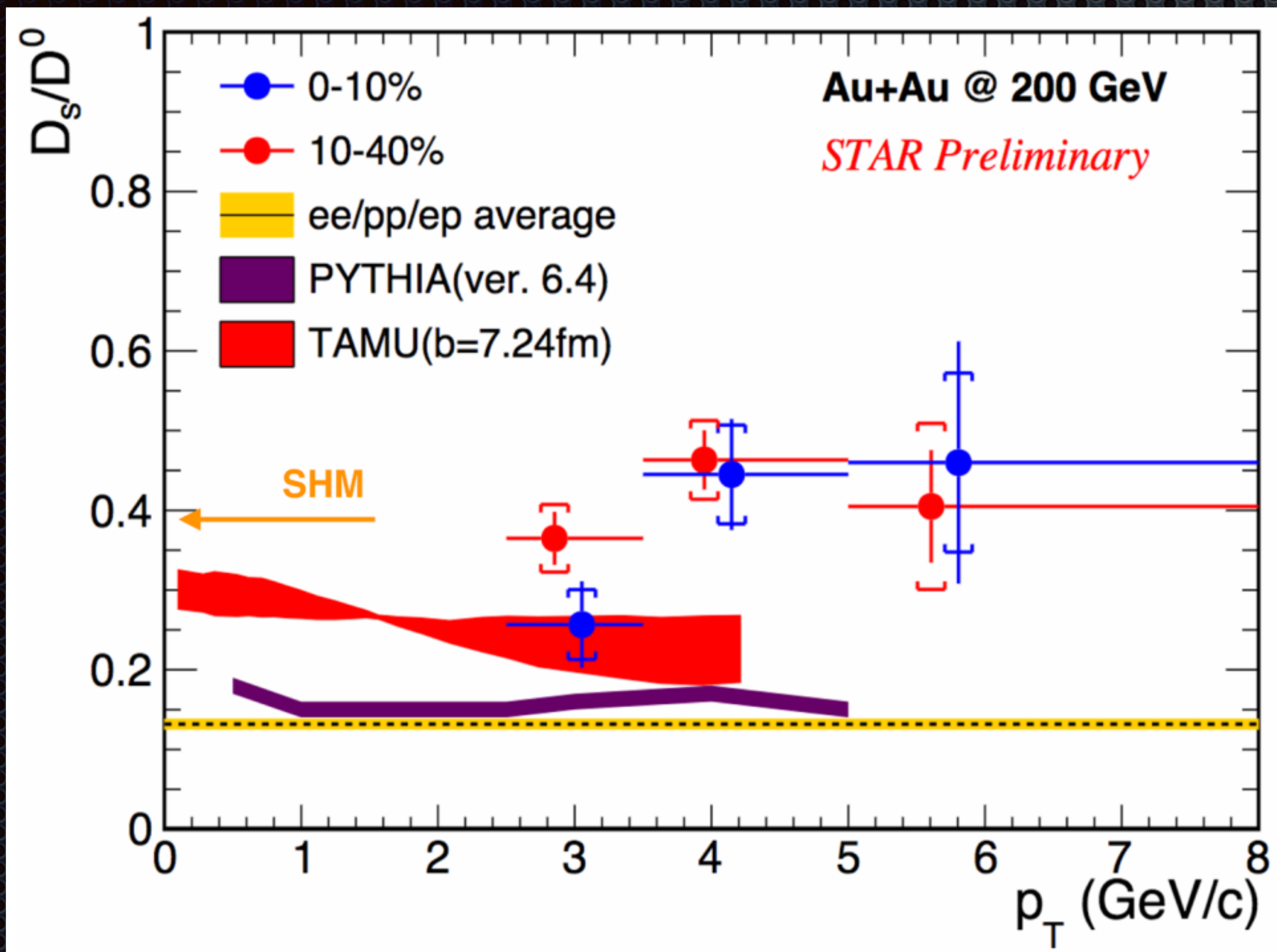
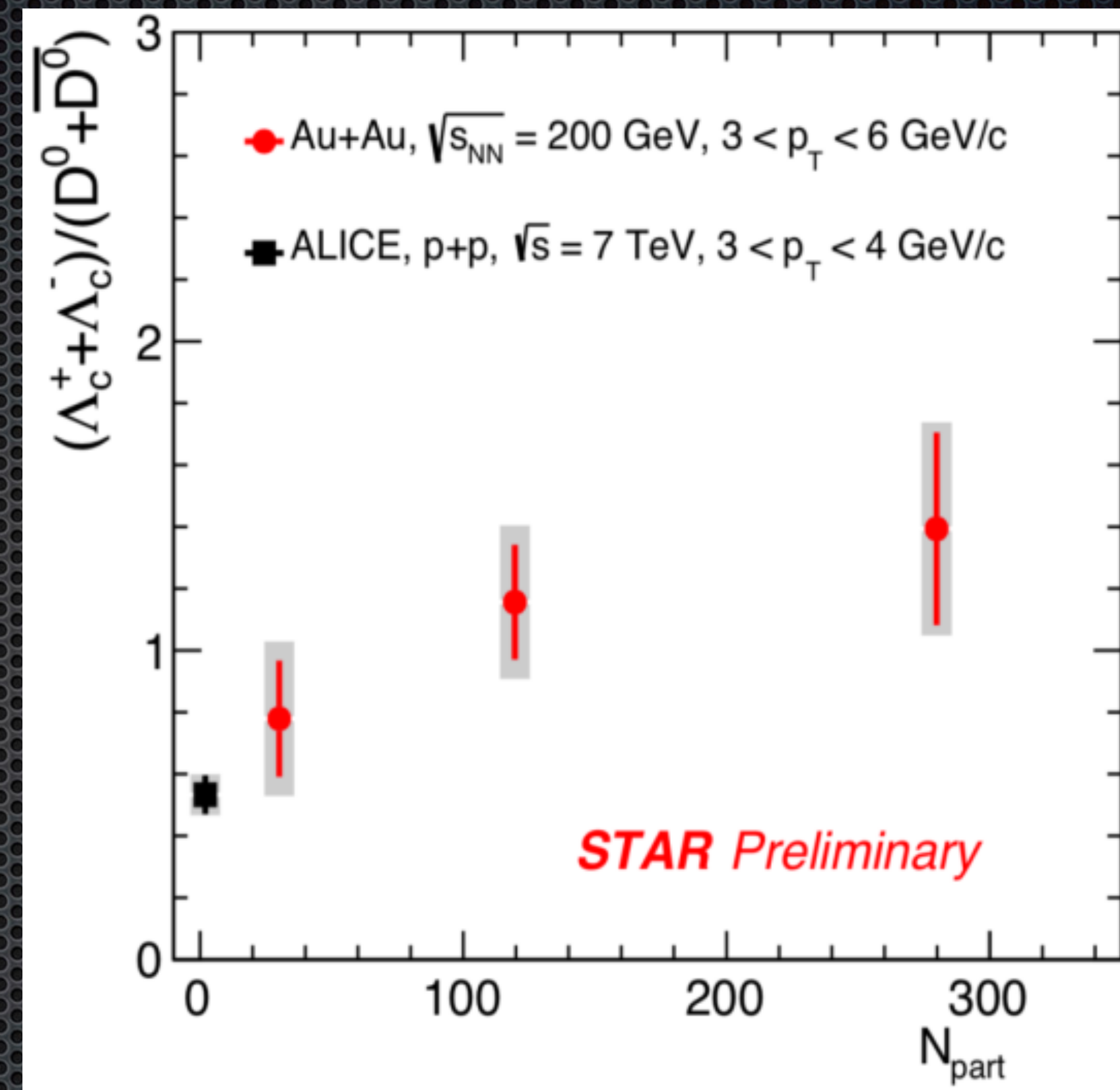
D_s/D^0 and Λ_c/D^0

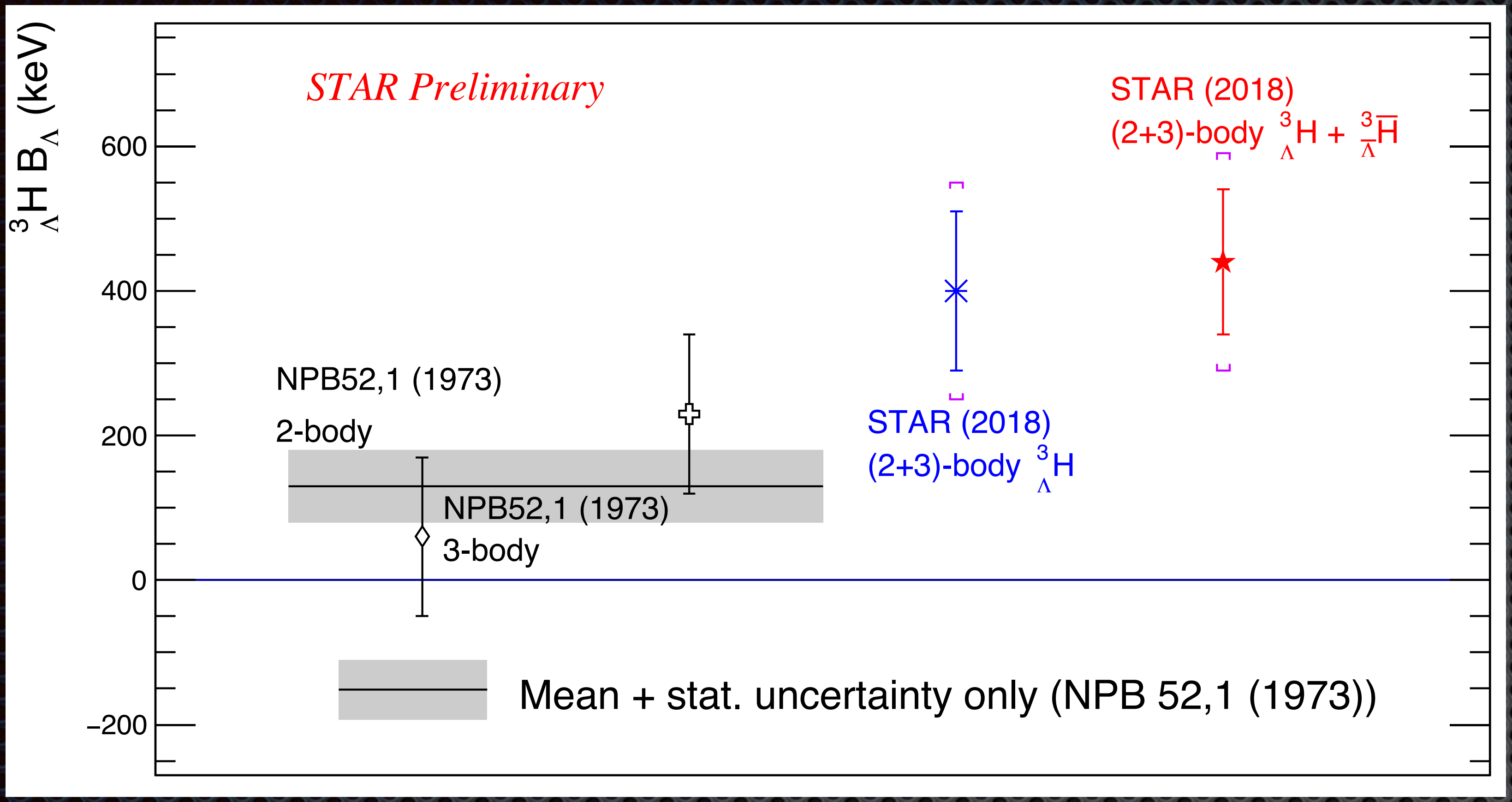


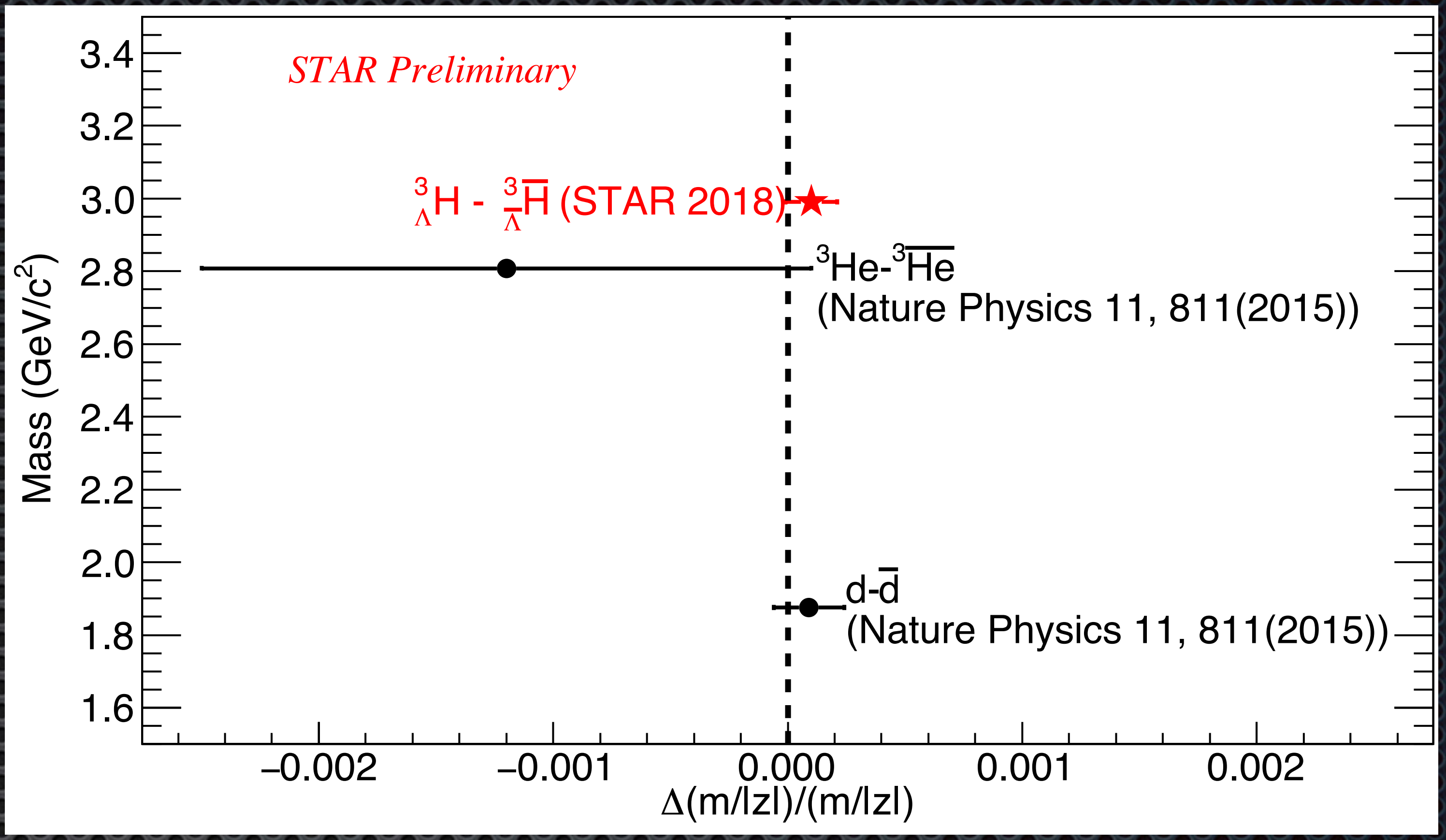


★ Strong enhancement compared to
- HERA
- Pythia

★ Comparable with baryon-to-meson ratios of light flavor hadrons

(Anti-)Hypertriton Binding Energy and Mass





- ★ Providing insight on Hyperon-Nucleon interaction - probe of a neutron star structure
- ★ Mass difference is the first test of the CPT symmetry in the light hyper-nuclei sector

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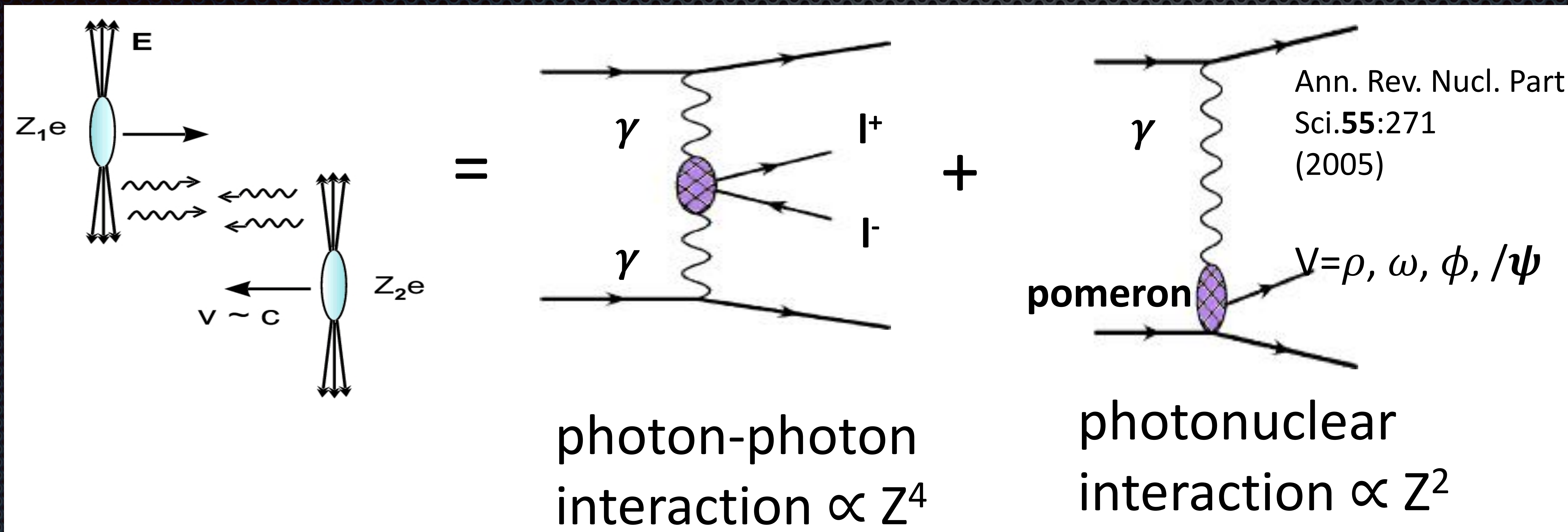
Coherent γ+γ and γ+Nuclear Processes

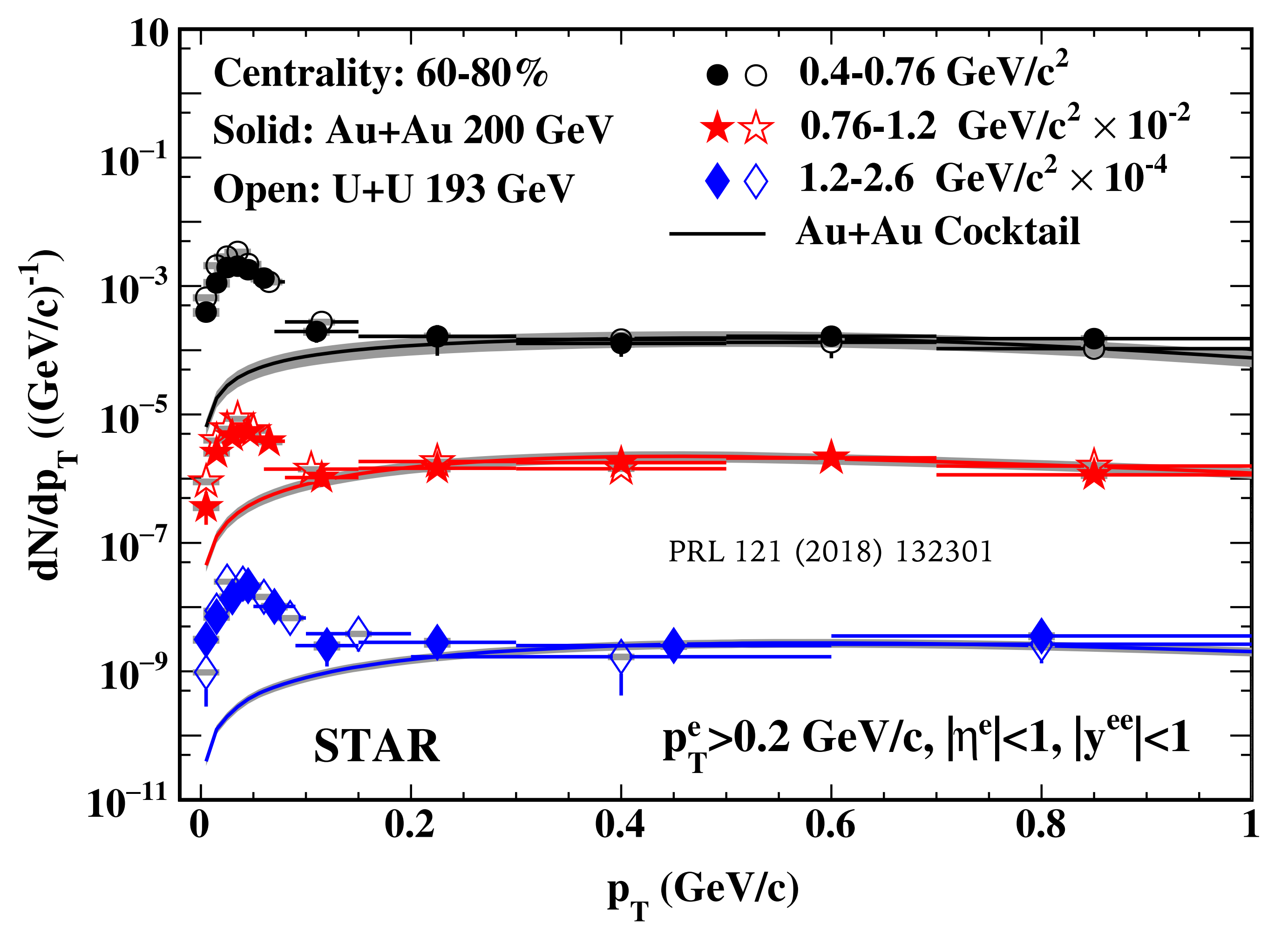


- ★ Colliding ions generate strong electromagnetic fields
- ★ Coherent interactions: γ + whole nucleus

Low-p_T J/ψ And Di-electron Enhancement

STAR:PRL 121 (2018) 132301

Low-p_T J/ψ And Di-electron Enhancement



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STAR PRL 121 (2018) 132301

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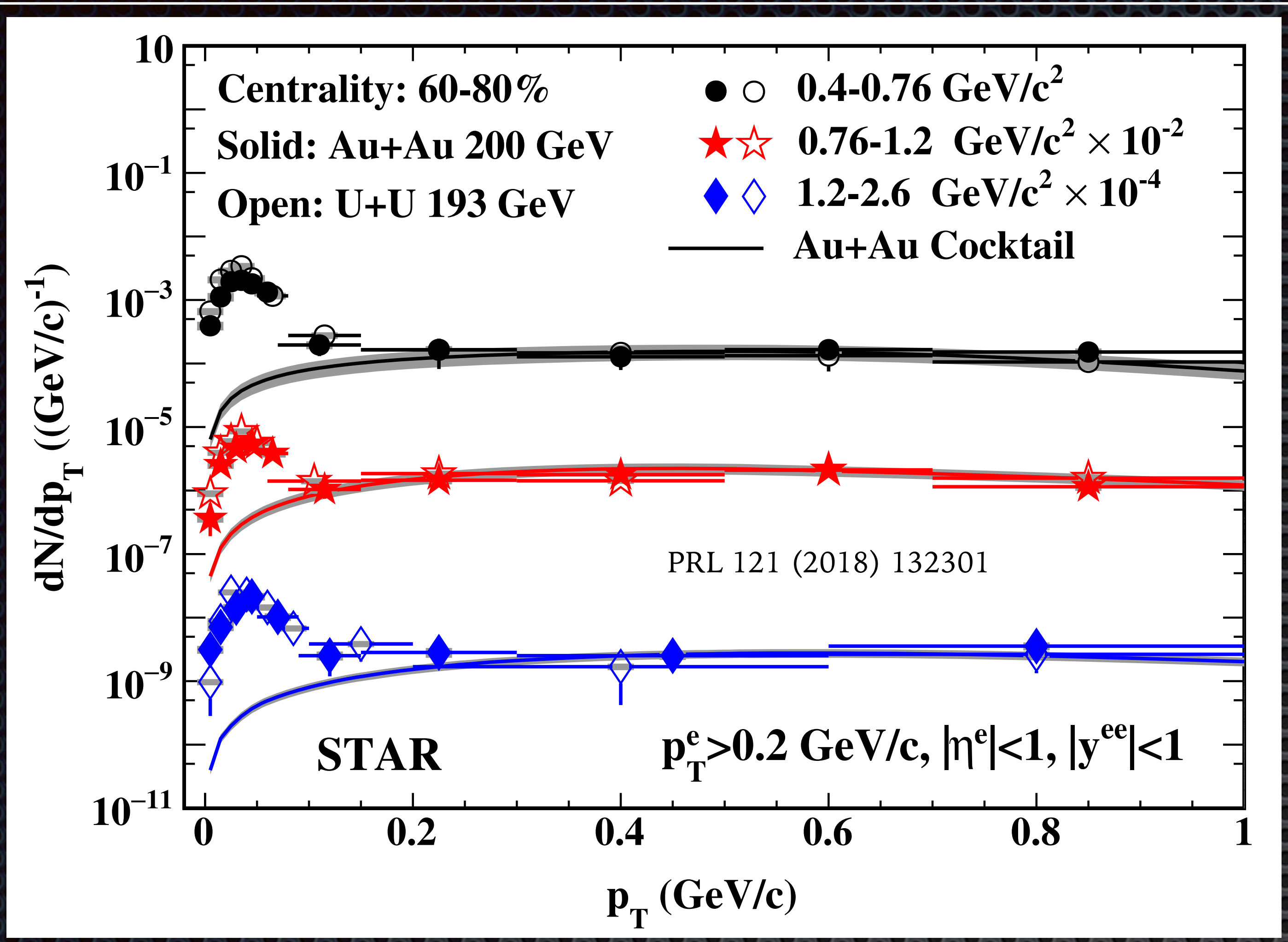
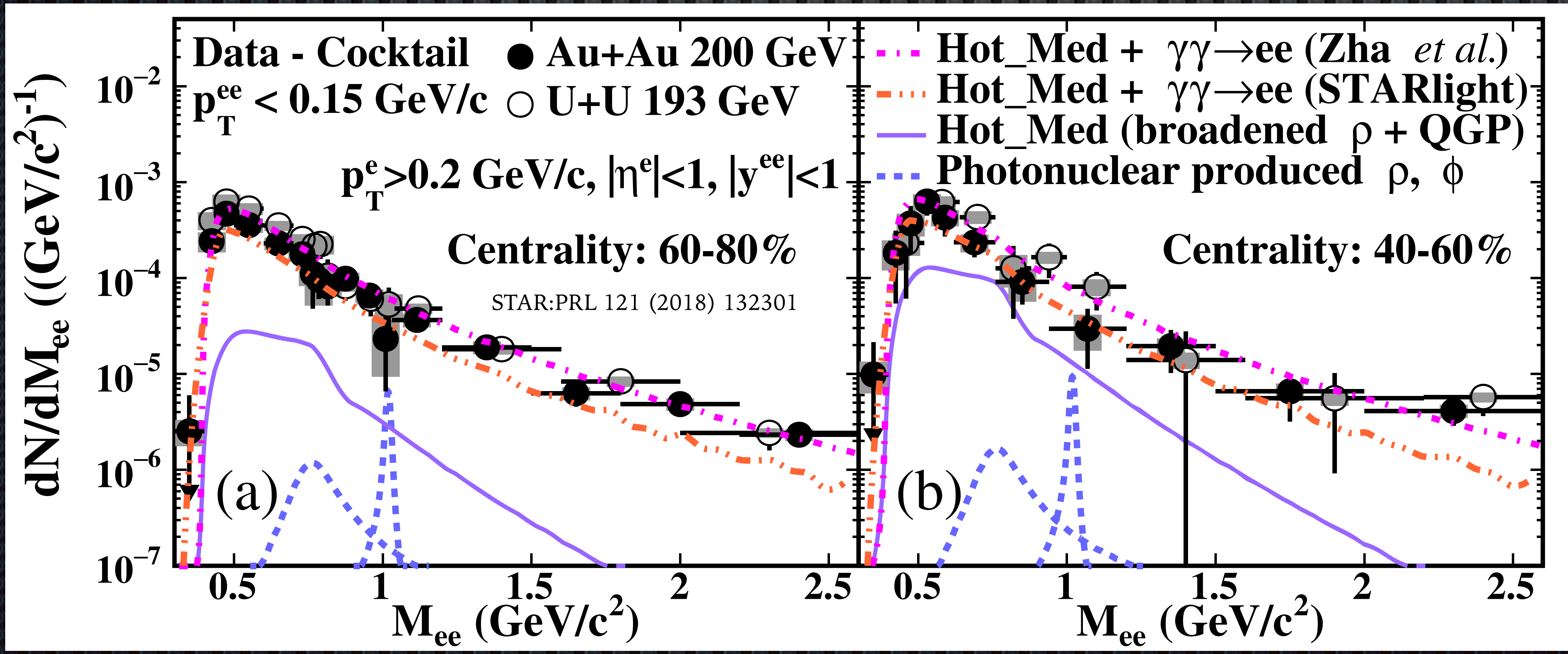
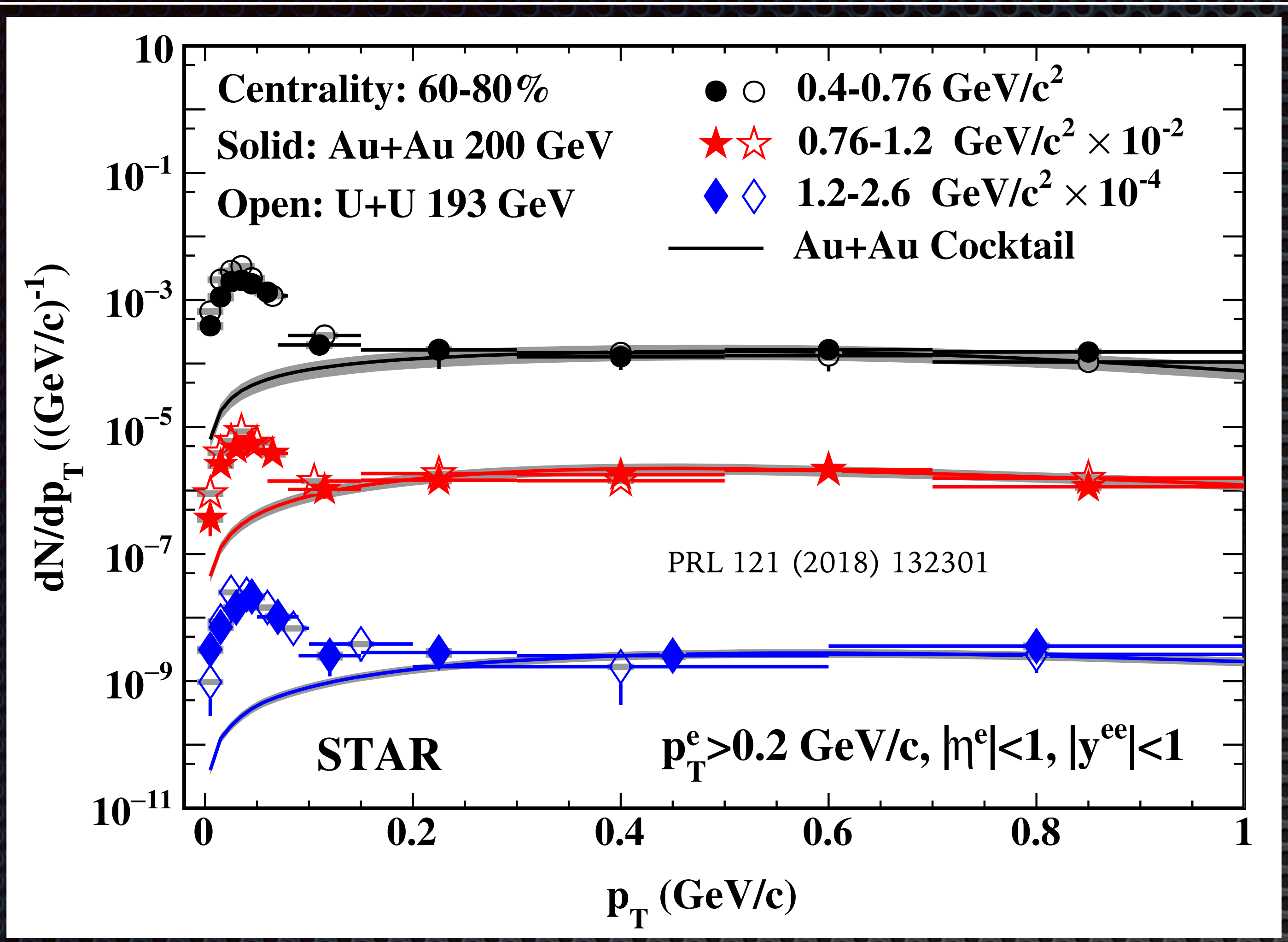


- ★ Significant di-lepton enhancement at low-p_T
- ★ The invariant mass M_{ee} shape of the low p_T region described well by two models

[Zha et al.: PLB 781 (2018) 182, STARlight: PRC 97 (2018) 054903]



Low-p_T J/ψ And Di-electron Enhancement



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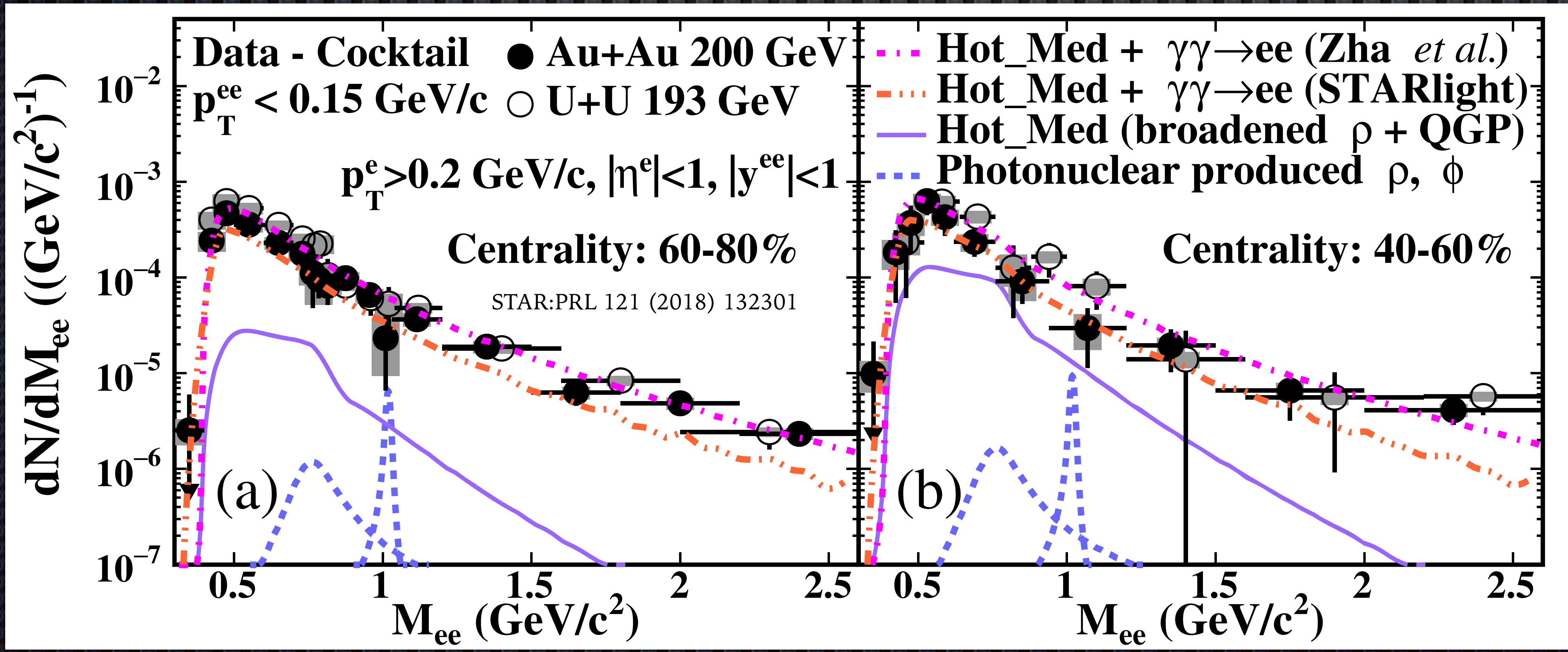
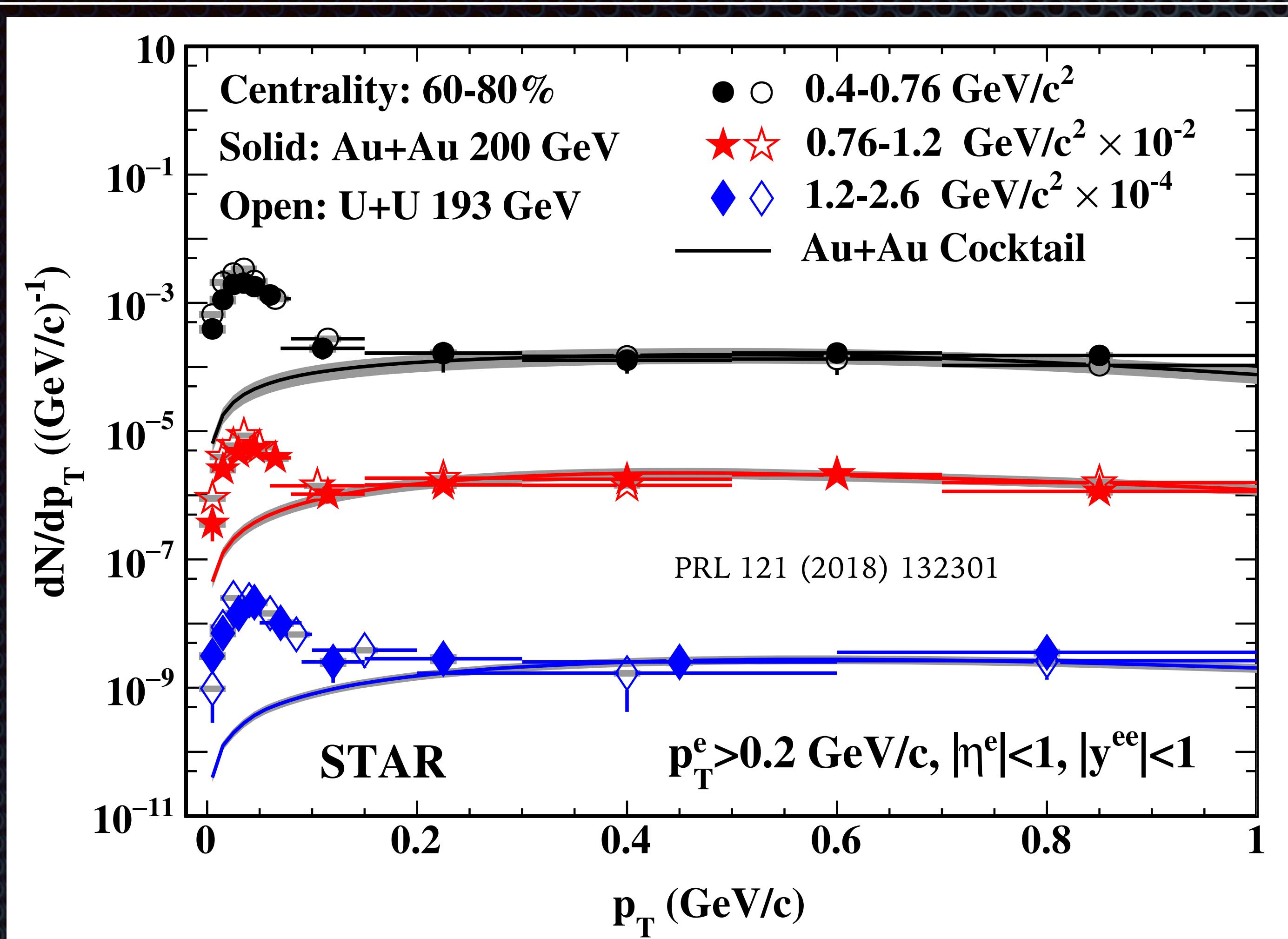
  - No effect of hadronic interactions on virtual photon production



Low-p_T J/ψ And Di-electron Enhancement



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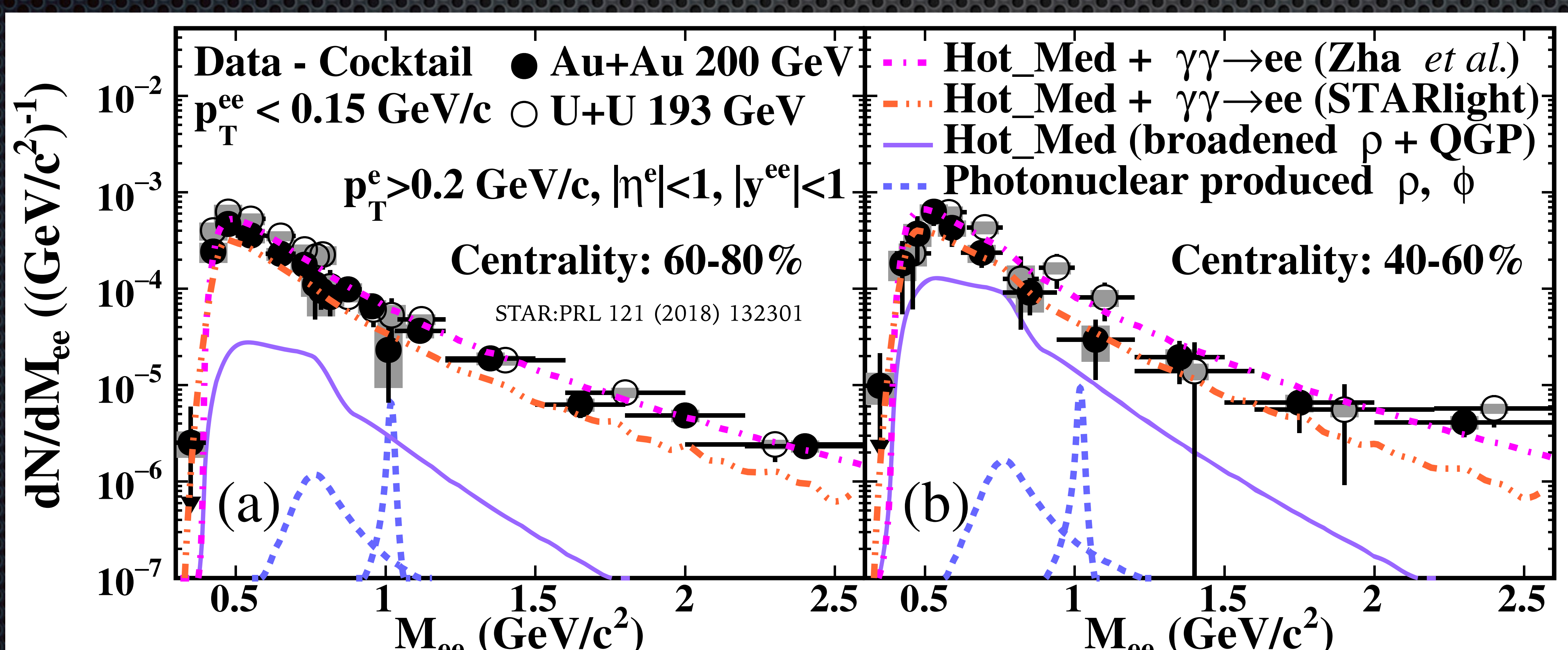

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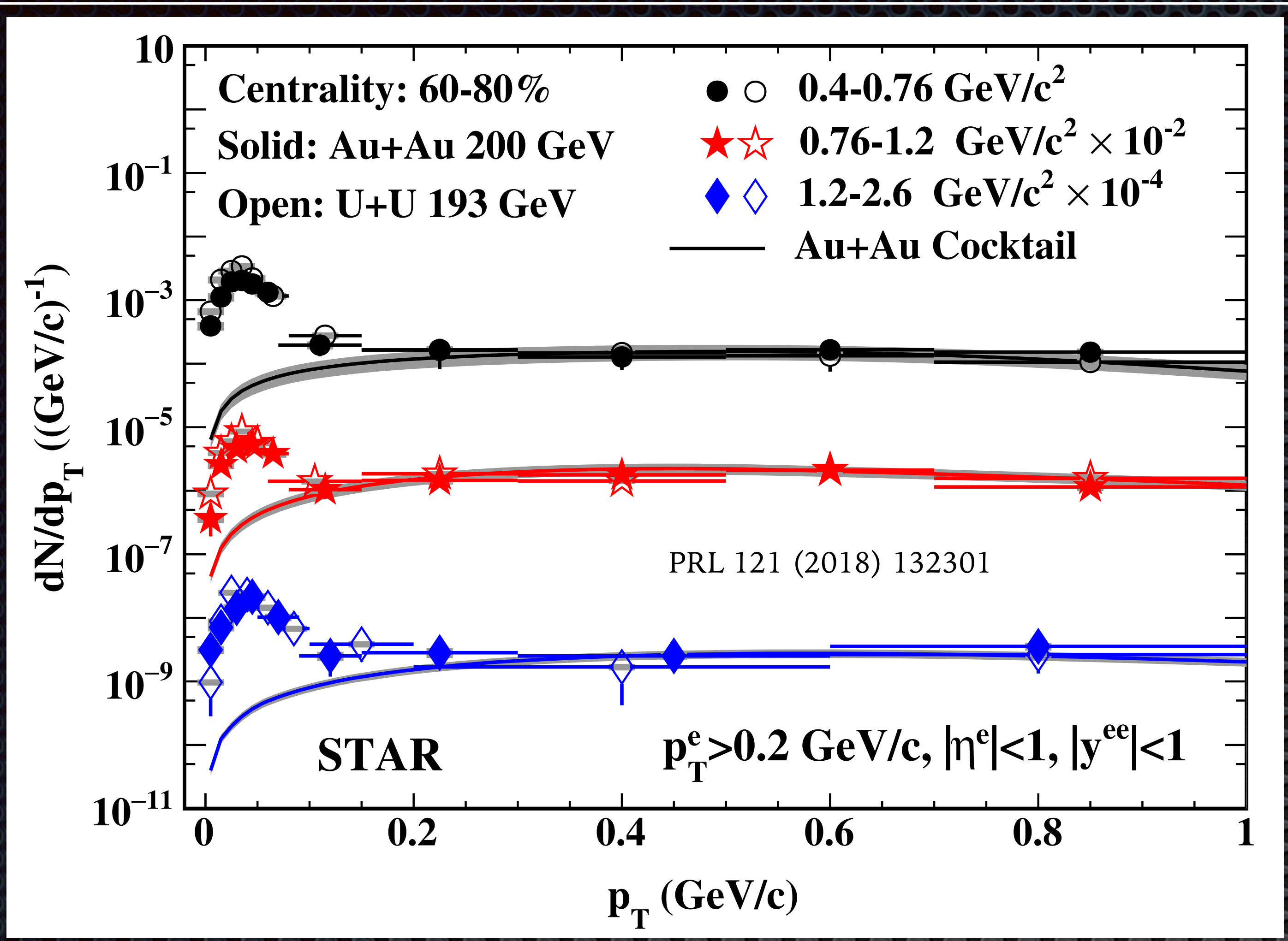

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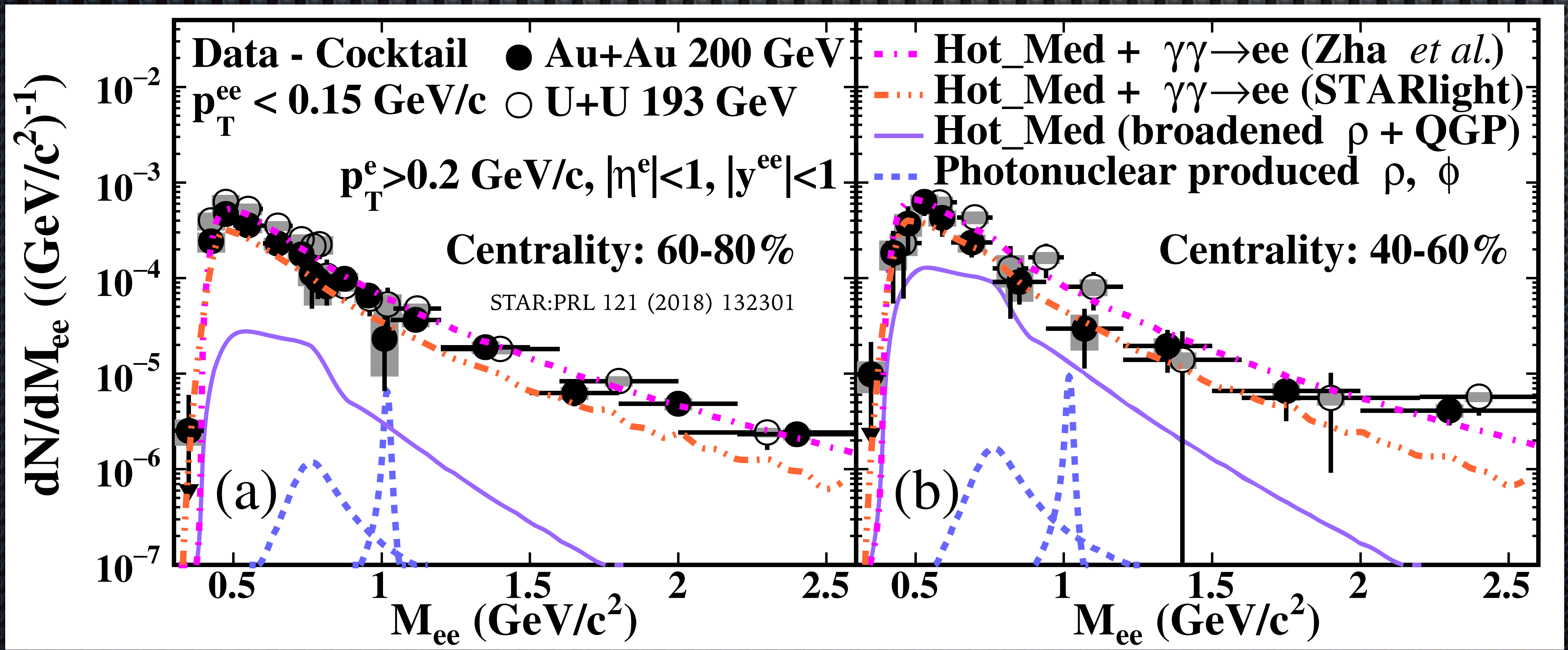

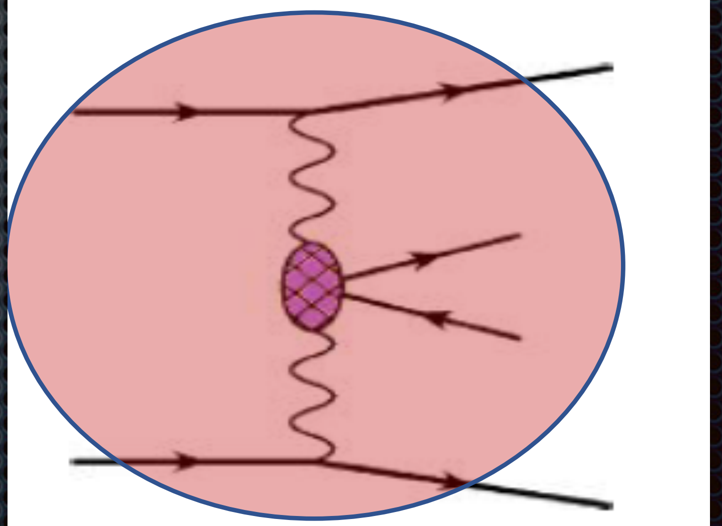

photon-photon interaction $\propto Z^4$

Low-pT J/ψ Enhancement

arXiv:1904.11658

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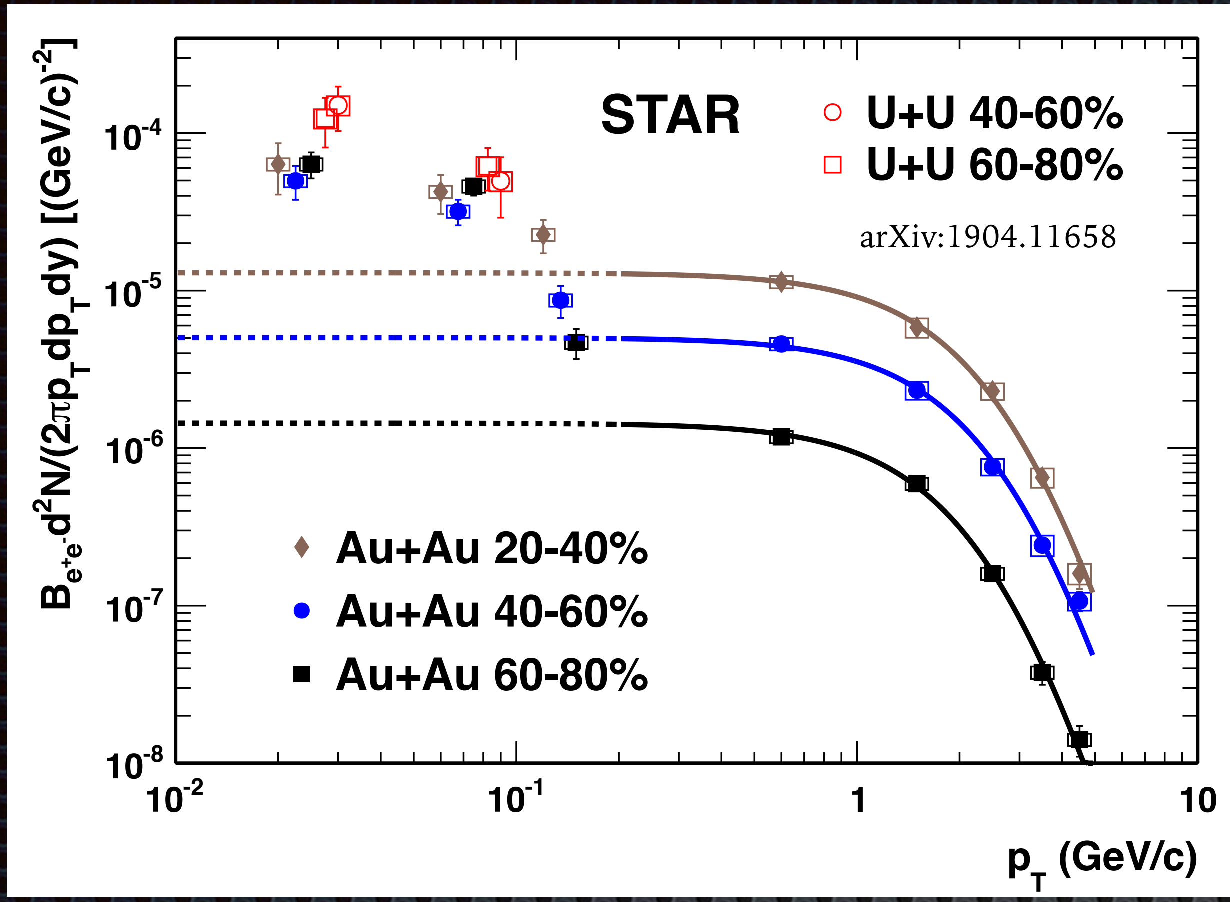
Low-pT J/ψ Enhancement



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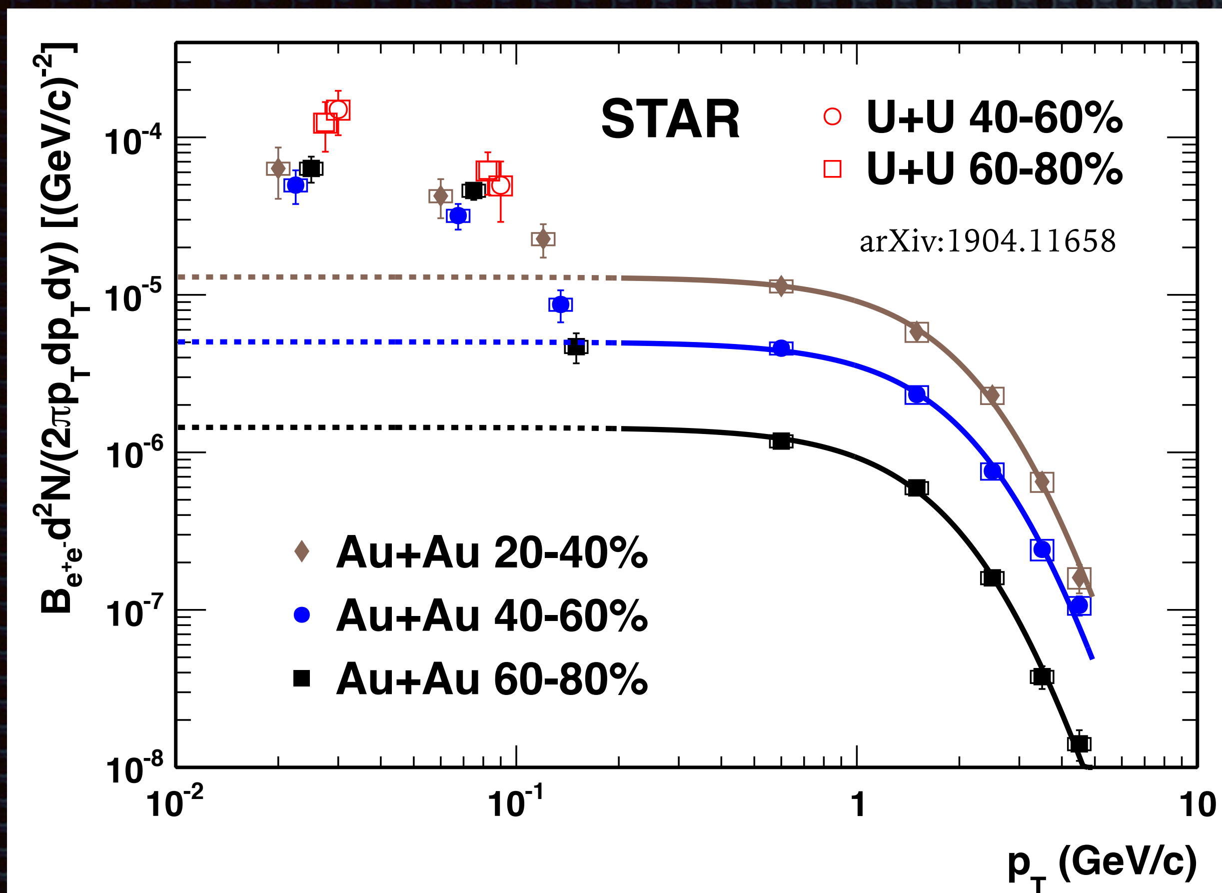
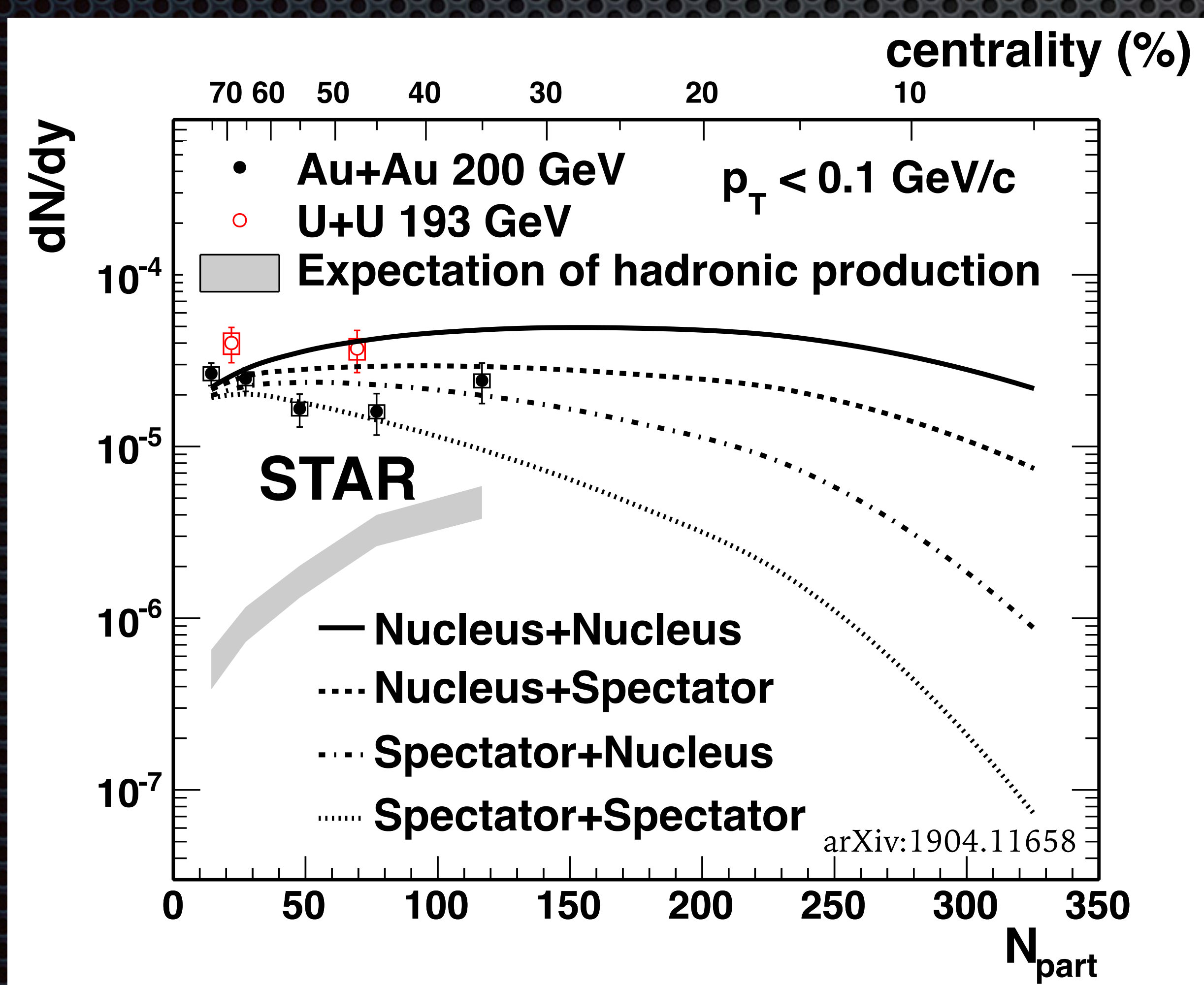
Low-pT J/ψ Enhancement

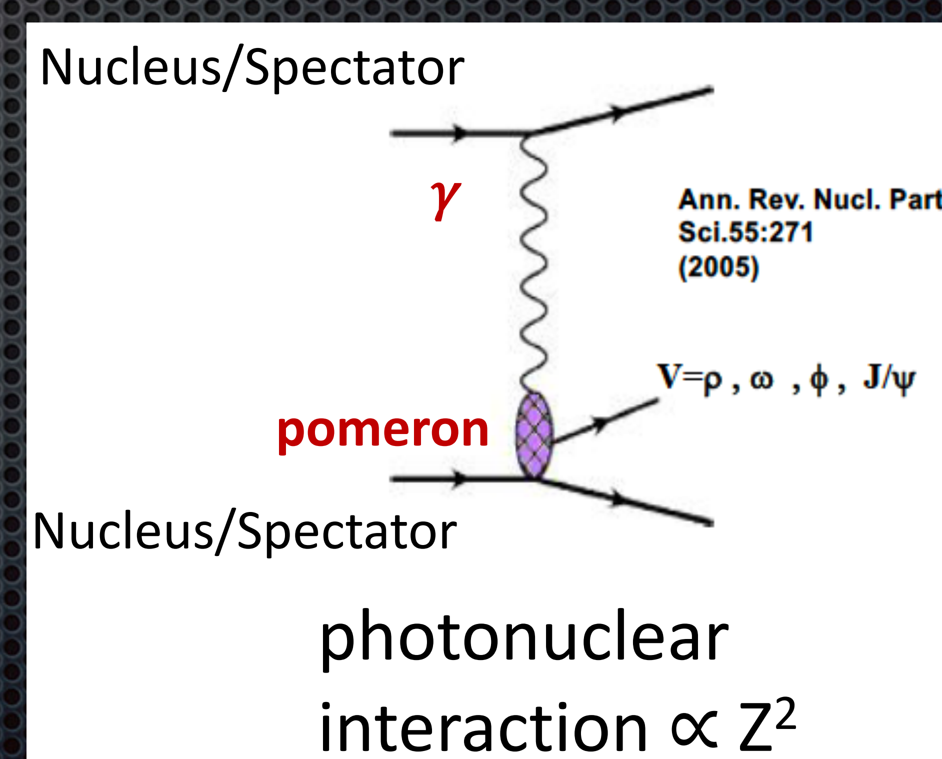


- ★ Significant J/ψ enhacement at low p_T relative to extrapolation
- ★ Low-p_T yield enhancement most consistent with the Nucleus+Spectator scenario in the coherent photoproduction model

[W. Zha et al., PRC 97 (2018) 044910]

- There may exist a partial disruption by hadronic interactions in the overlaping region



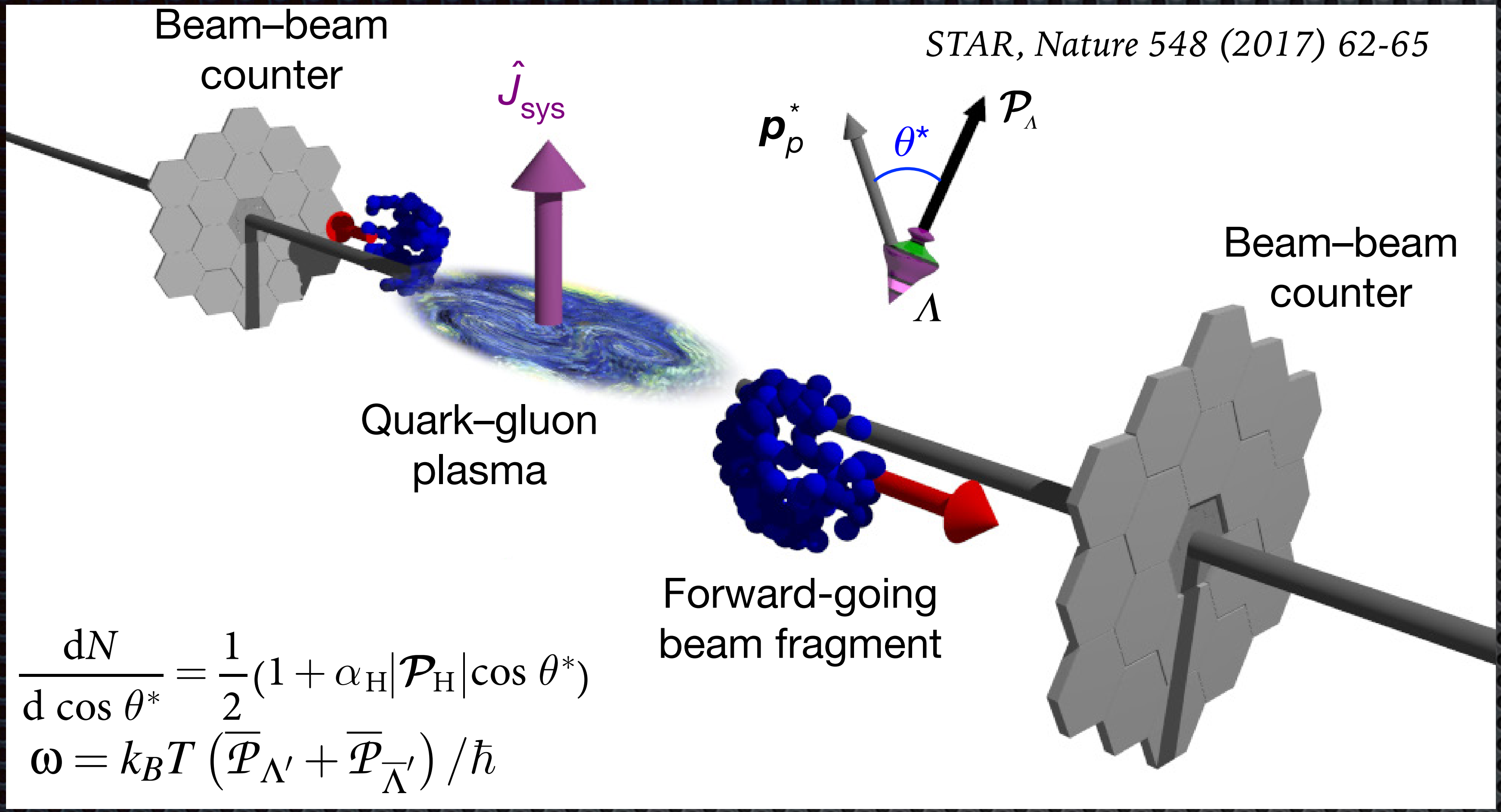


Global Hyperon Polarization

STAR, Nature 548 (2017) 62-65

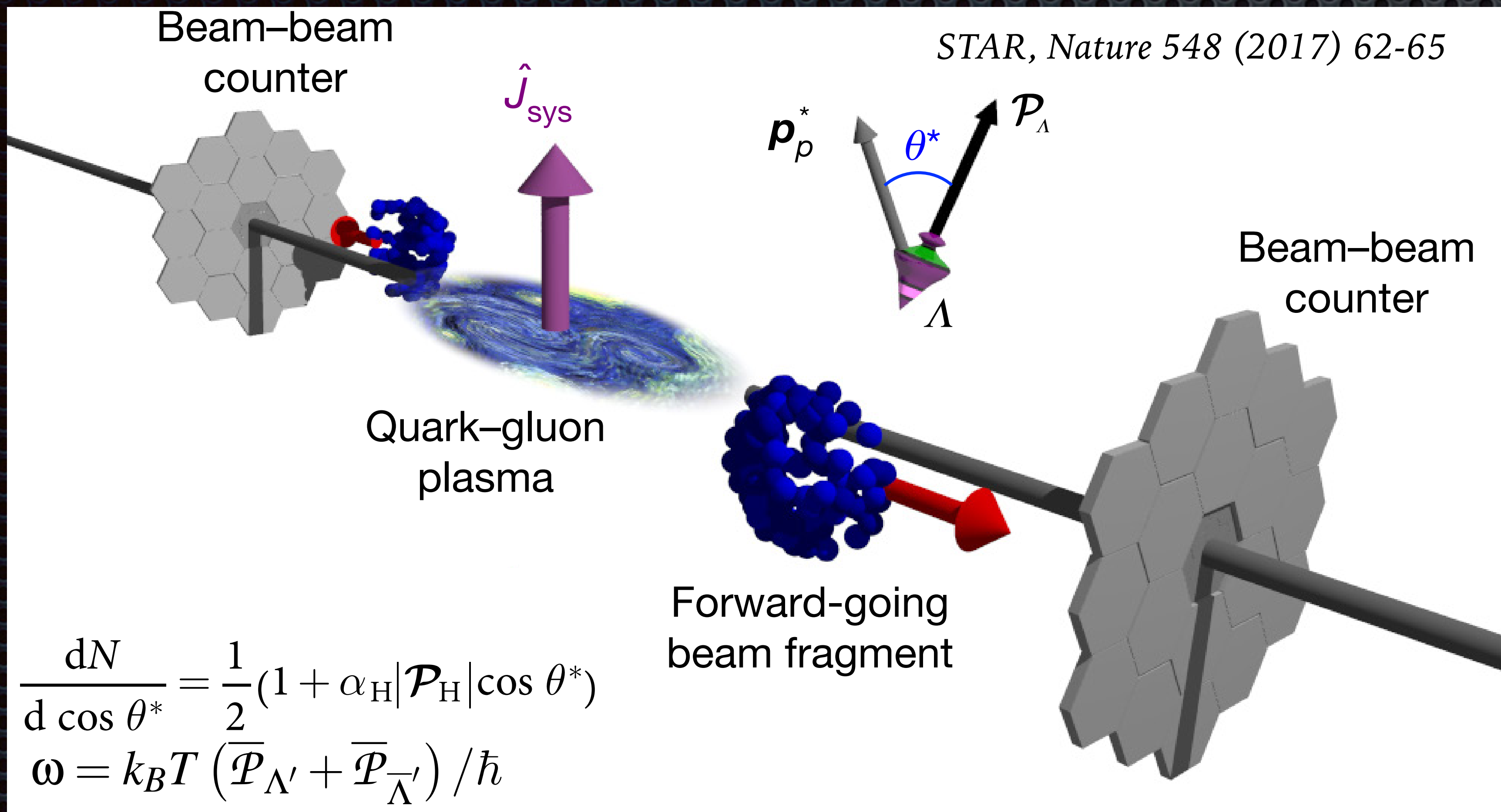
$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}(1 + \alpha_{\mathrm{H}}|\mathcal{P}_{\mathrm{H}}|\cos\theta^*)$$

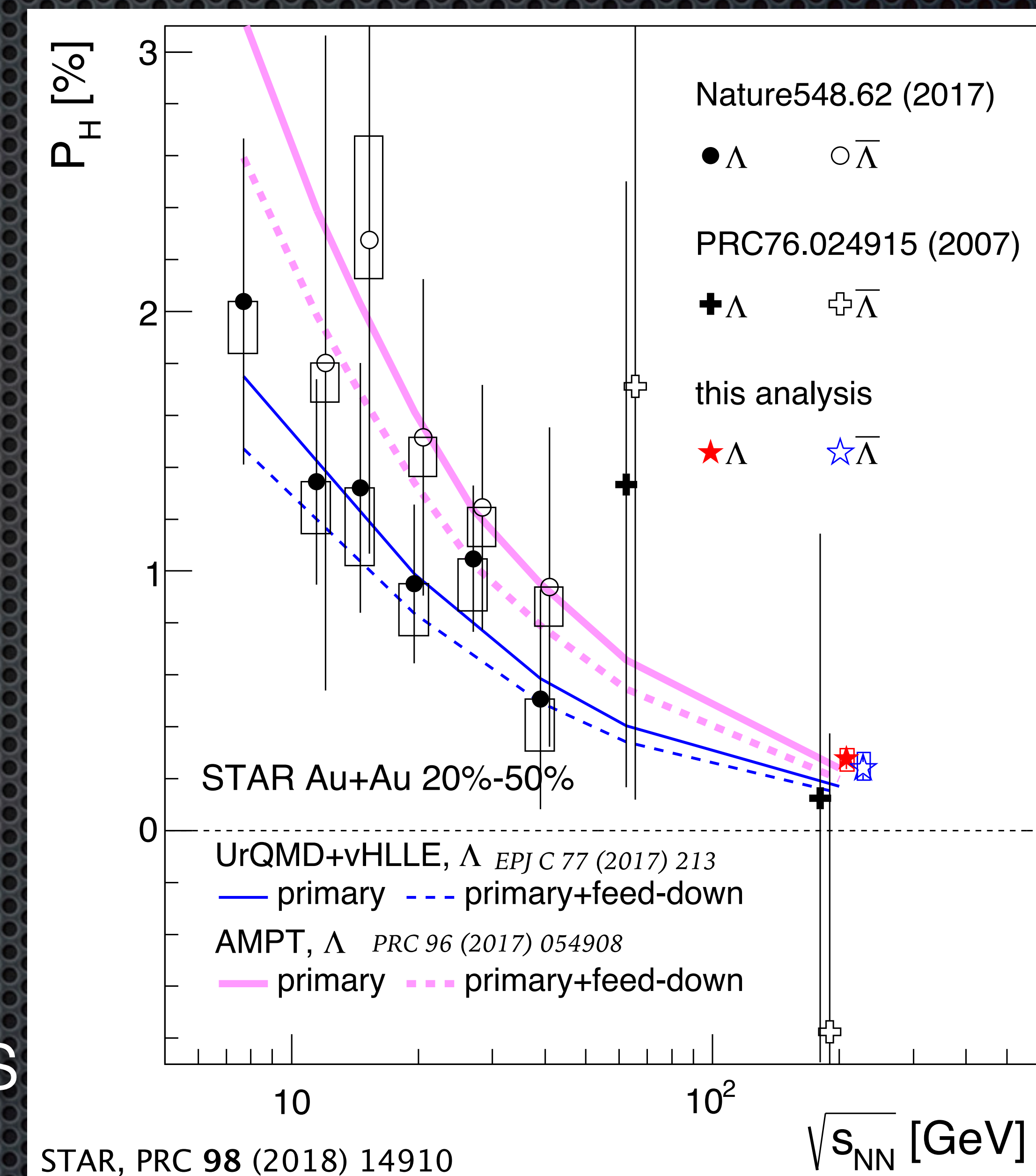
Global Hyperon Polarization



Global Hyperon Polarization

★ Measurement of vorticity ω of the QGP (perfect liquid)





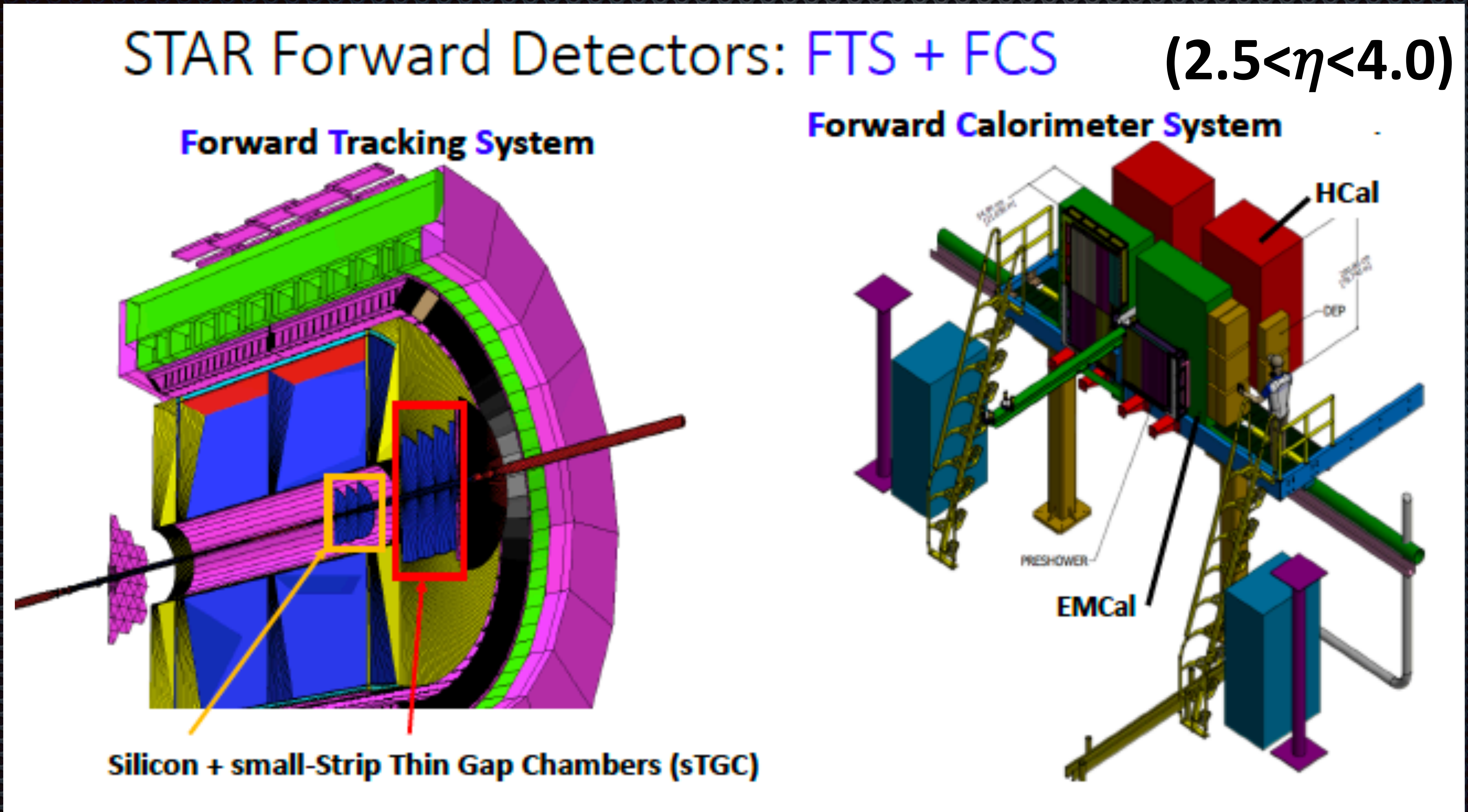
★ With the new 200 GeV results, the polarization is found to decrease at higher collision energies

★ May provide important information on the chiral dynamics of the system

- Axial charge separation due to the Chiral Vortical Effect [PRC 97 (2018) 041902]

★ Difference between P_H and $P_{\bar{H}}$ provide constraints on the magnitude and the lifetime of the magnetic field in heavy-ion collisions [PRC 95 (2017) 054902]

Outlook: Forward Upgrade



- ★ Positive internal review in November 2018 - will be ready for 2022
- ★ Cold QCD and heavy-ion physics

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- Small droplets of QGP?

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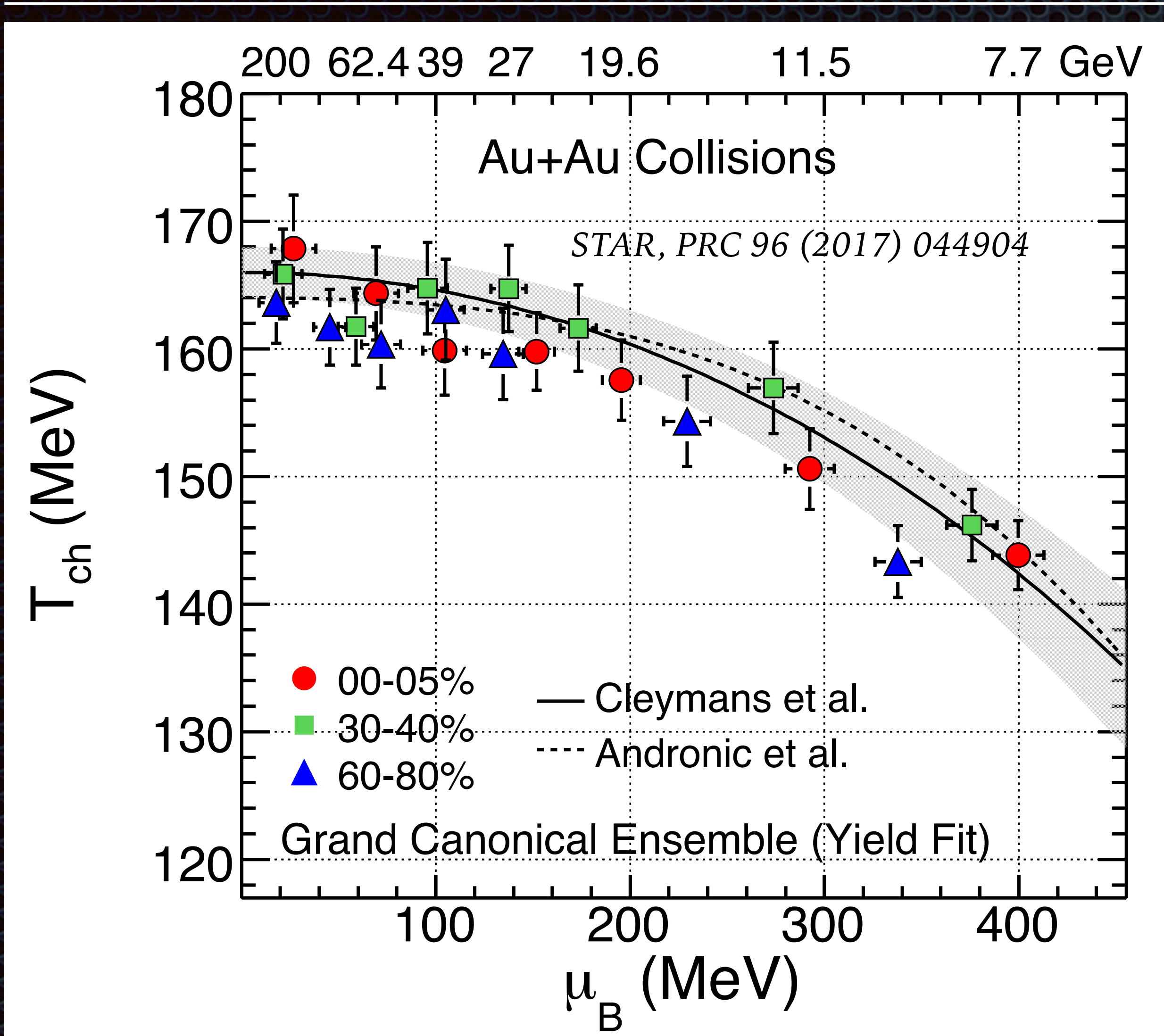
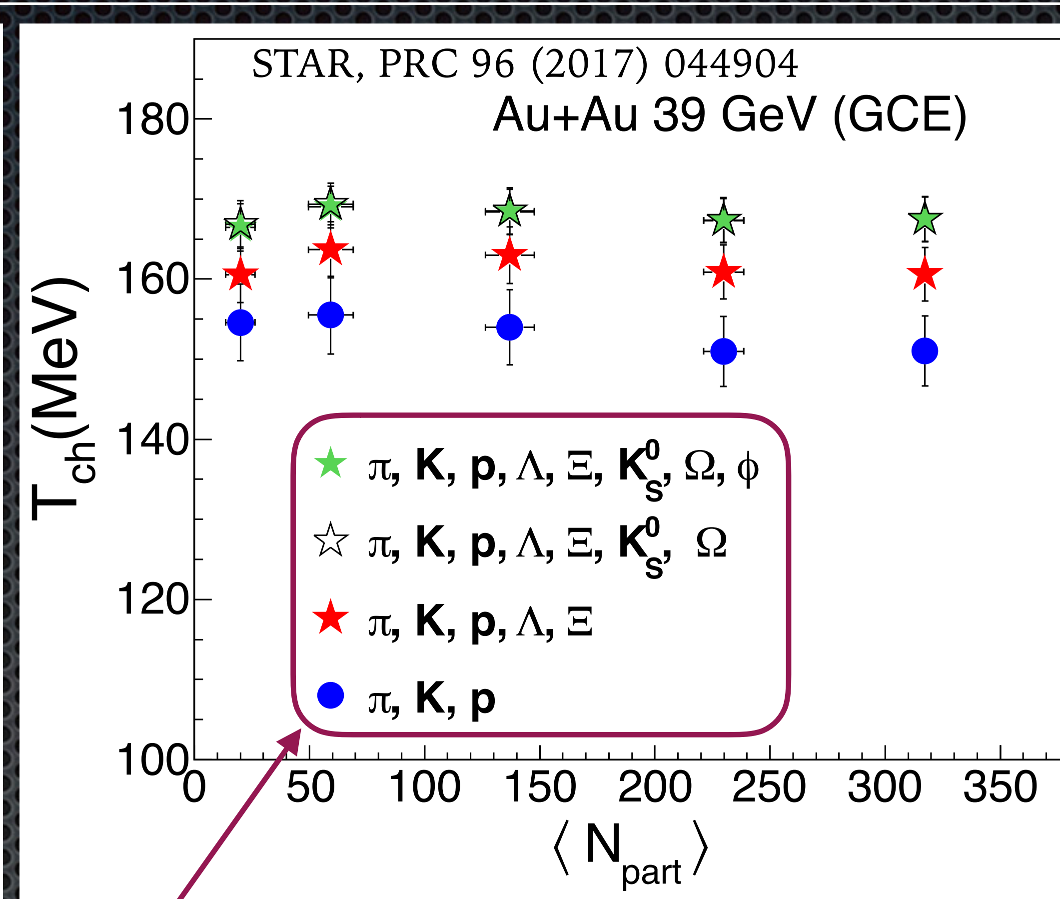
- ★ Stay tuned - many more exciting results are coming

Thank you

Backup Slides

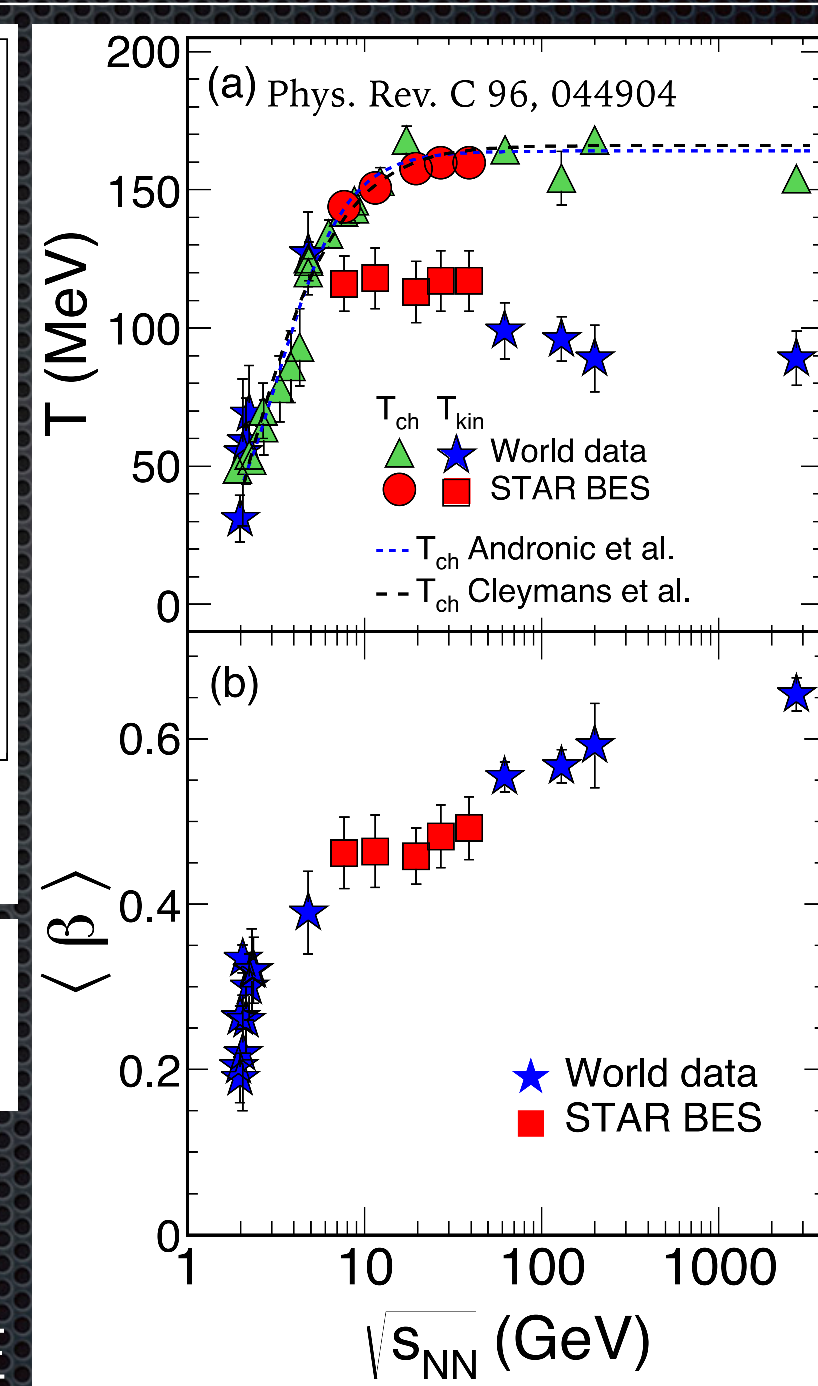
Freeze-out Temperatures from STAR BES-I





particles used for the THERMUS fit

[Wheaton et al., CPC180 (2009) 84]



- ★ Tch - chemical freeze-out temperature
  - particles included in the THERMUS model fit were π, K, p, p̄, Λ, and Ξ
  - T_{ch} appears to be lower when strange particles were excluded from the fit
- ★ T - kinetic freeze-out temperature
  - the separation between between T_{ch} and T grows with increasing energy
    - might suggest the effect of increasing hadronic interactions between chemical and kinetic freeze-out at higher energies
- ★ ⟨ β ⟩ - radial flow velocity
  - rapid **x** slow increase at lower **x** higher energies