Overview of recent STAR results

Nihar Ranjan Sahoo
(For the STAR collaboration)
Shandong University, Qingdao, China

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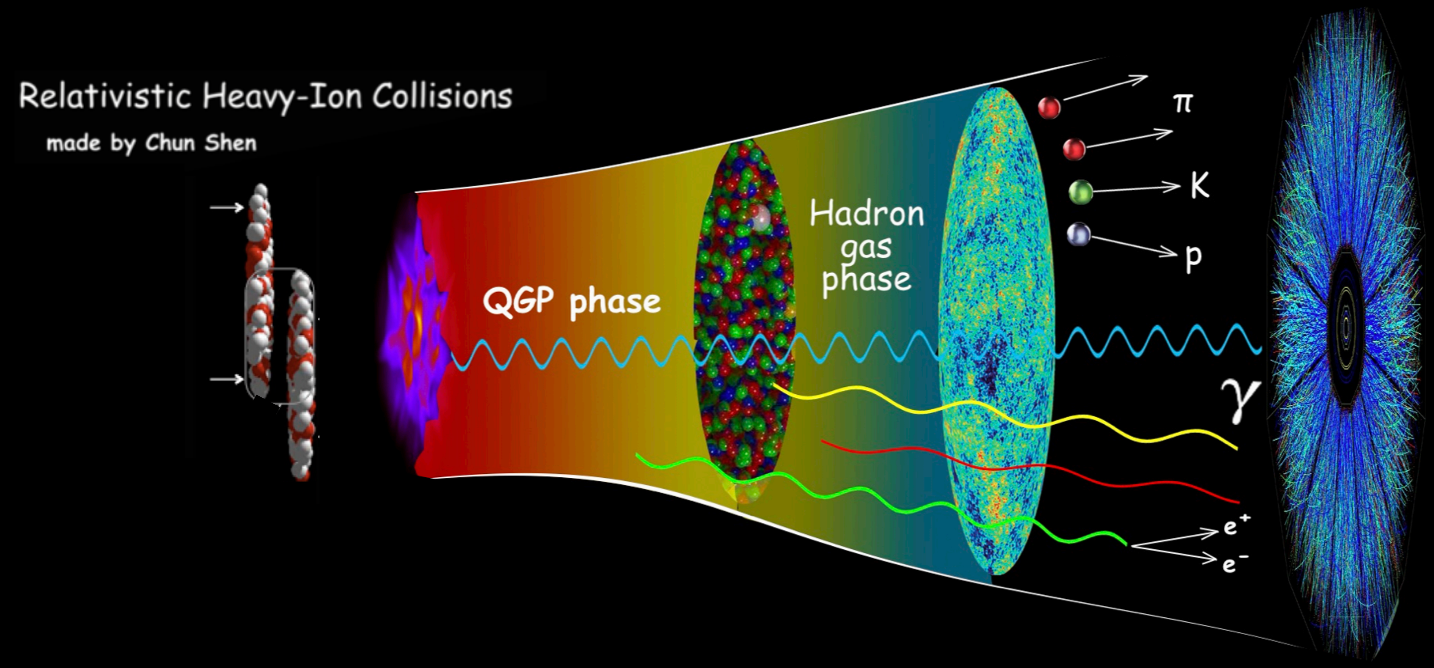
Hot QCD physics in heavy-ion collisions at RHIC



- Suppression of heavy quark and their flow
- Sequential suppression of heavy quarkonia
- Jet quenching and its manifestations

Inner workings of QGP
Hard Probes program

- QCD phase diagram and QCD critical point
- Collectivity and signature of partonic phase
- Medium as most vortical fluid
- Hypernuclei production at high baryon density

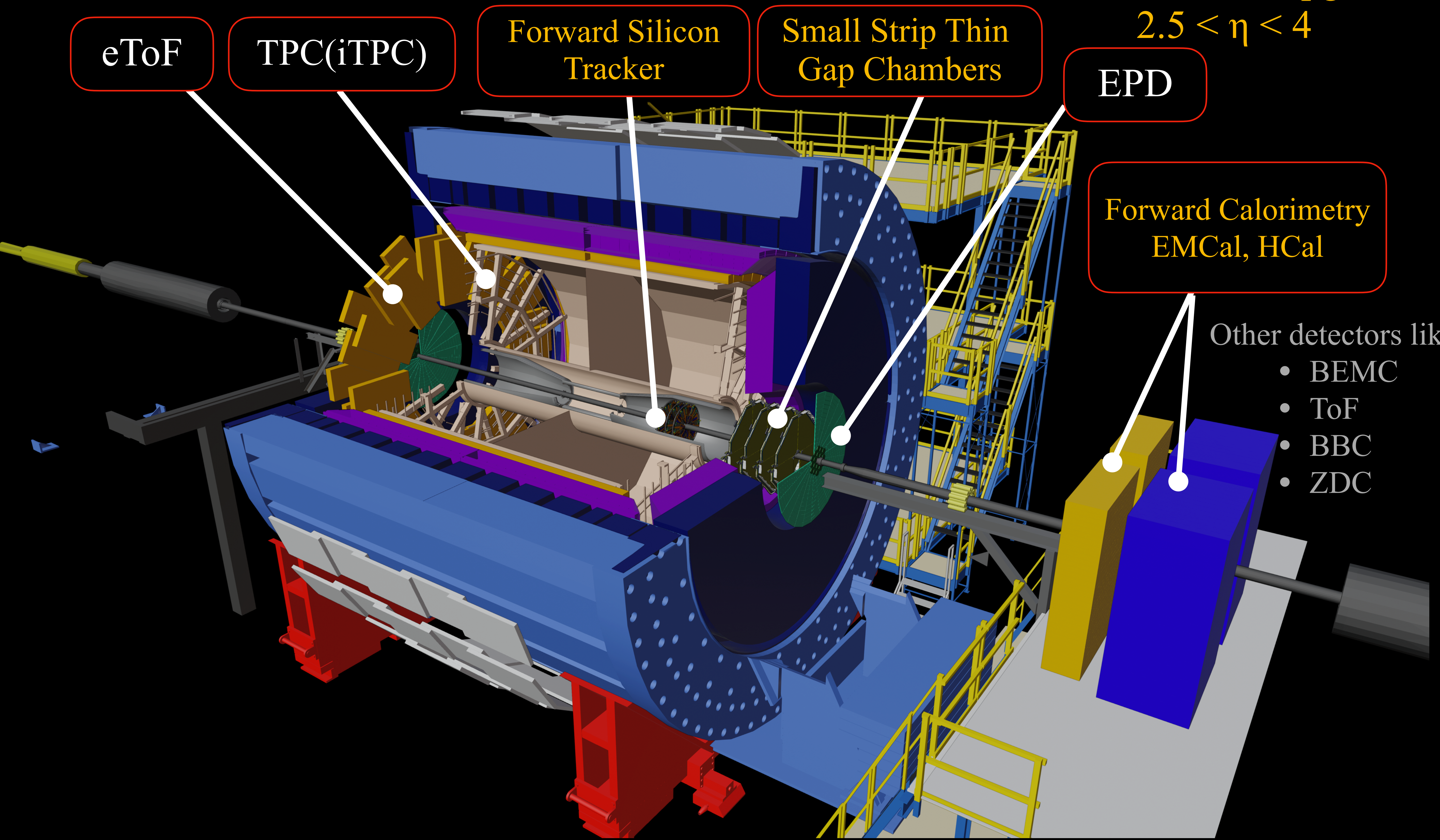
Bulk properties of QGP
Beam Energy Scan program

Emergent QED/QCD phenomena: Ultra-Peripheral Collisions (UPCs)

STAR detector

BES-II upgrade

Forward upgrade:
$2.5 < \eta < 4$

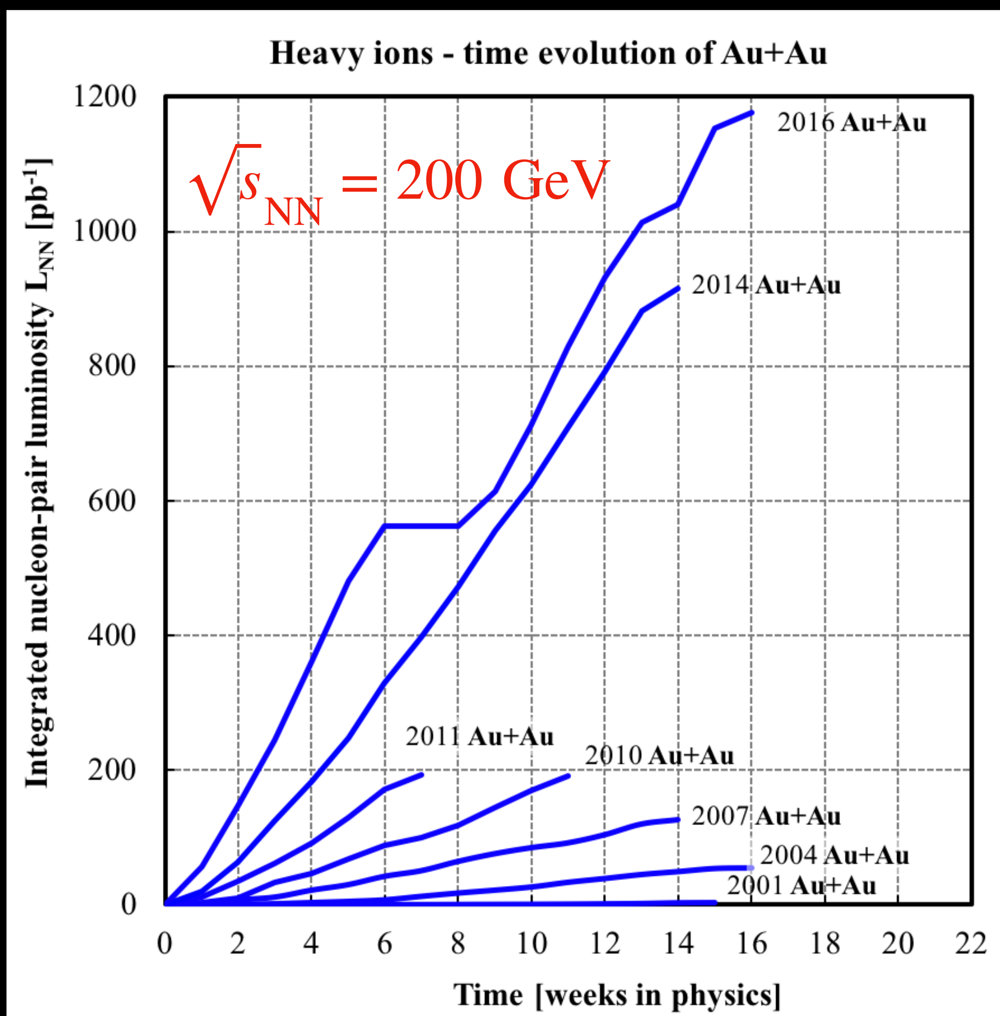


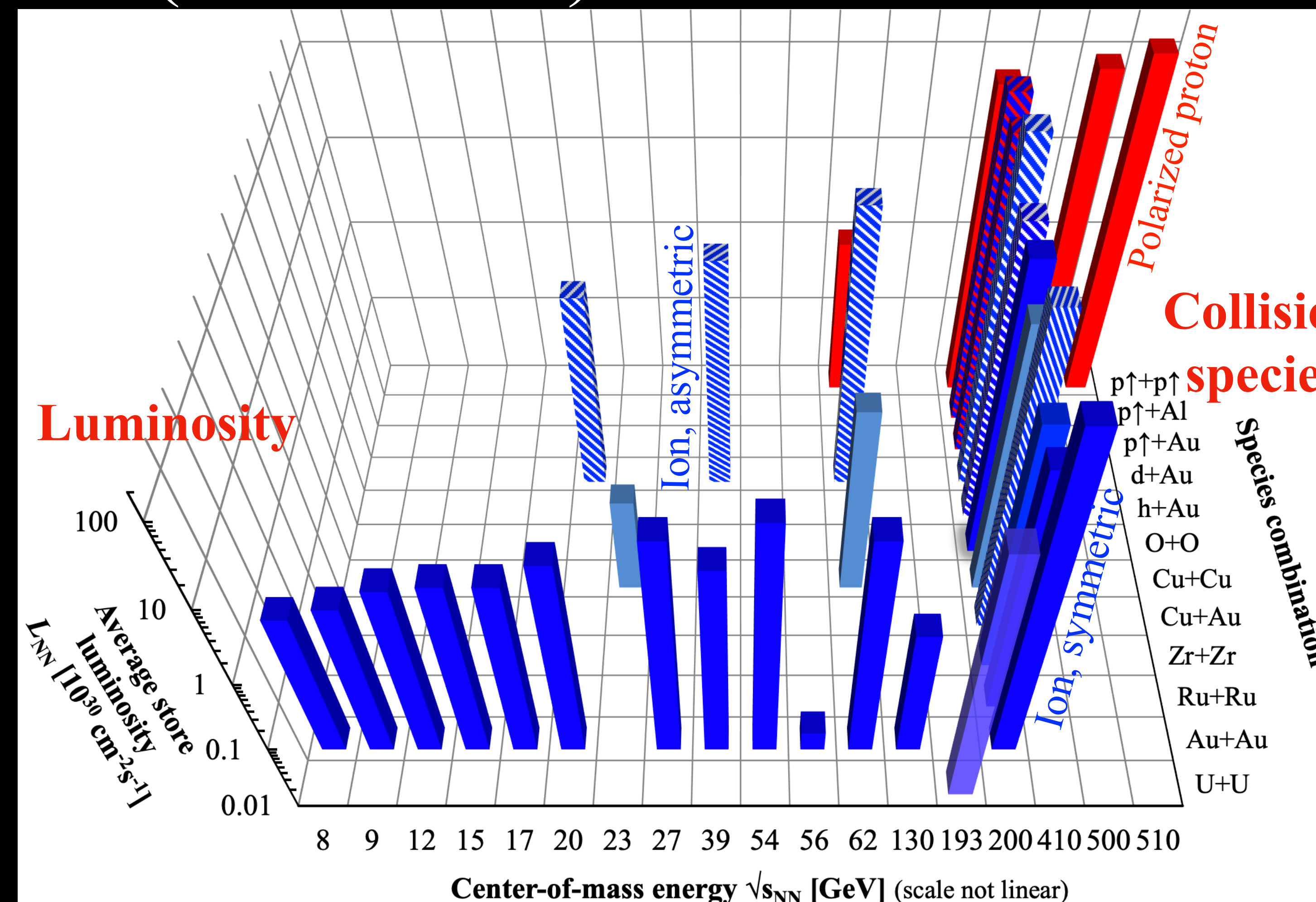
Other detectors like
- BEMC
- ToF
- BBC
- ZDC

RHIC energies, collision species, and luminosity

(2000-2022)

https://www.agsrhichome.bnl.gov/RHIC/Runs/



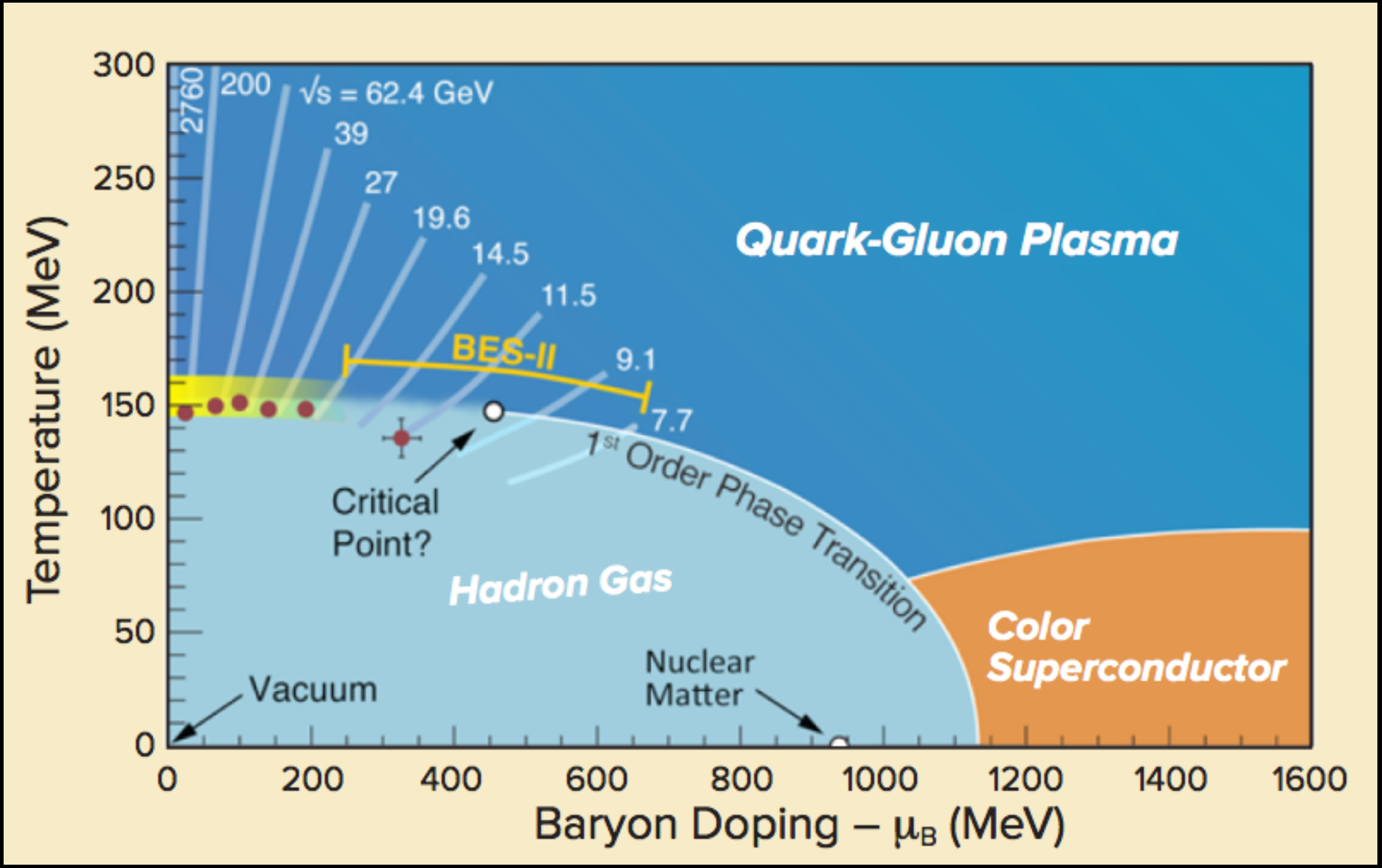


Collision energies

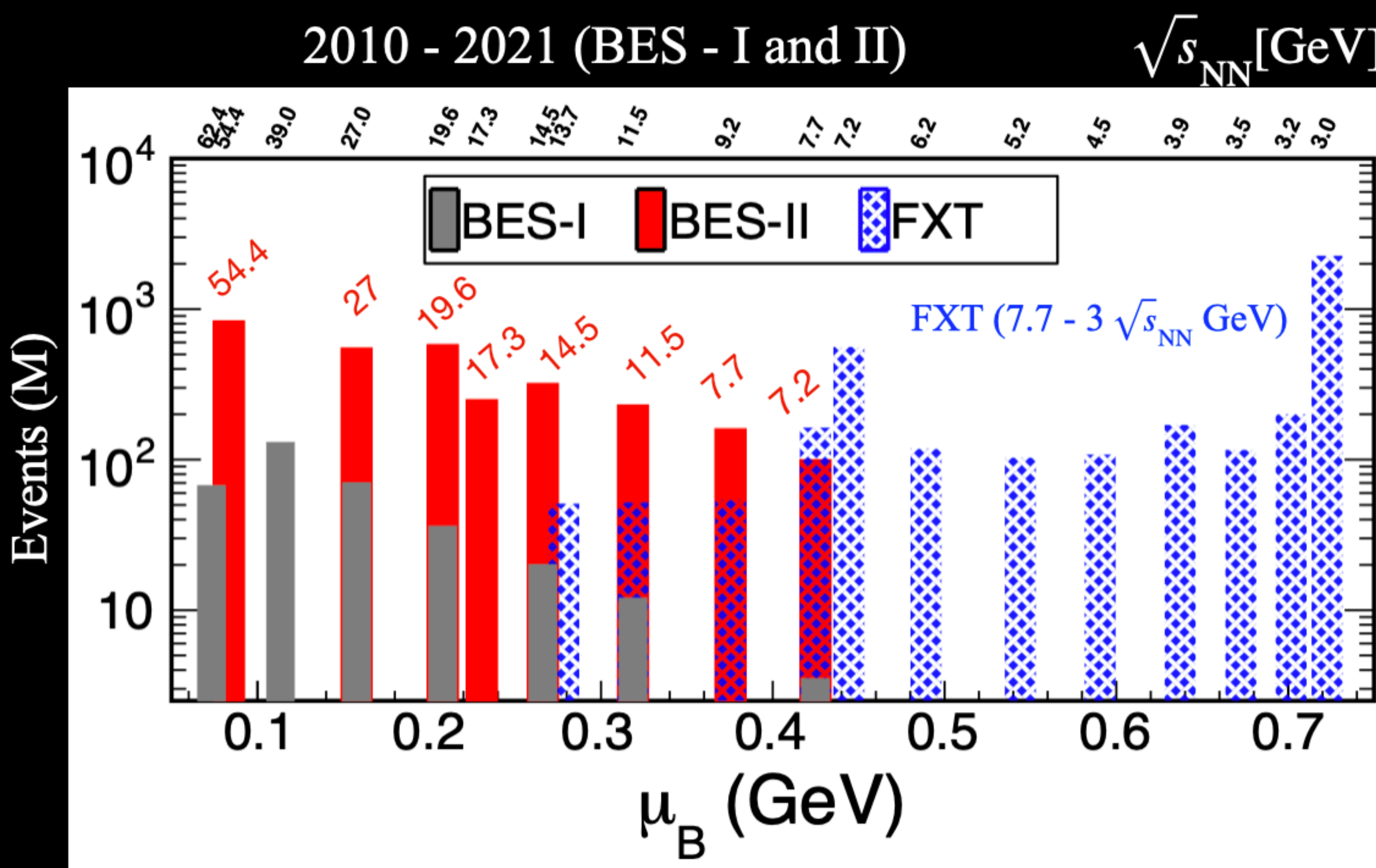
$L_{NN} = A_1 A_2 L$

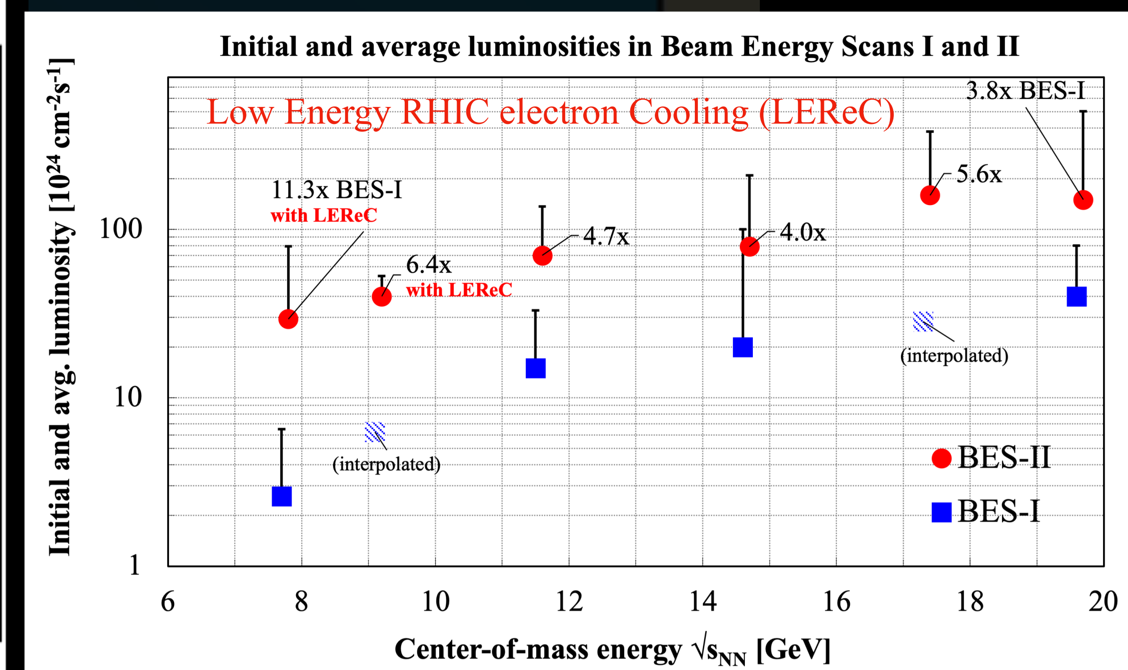
- Increase in statistics over the years for precision measurement
- Different collision species to study the QCD medium

STAR Beam Energy Scan program



STAR Beam Energy Scan program





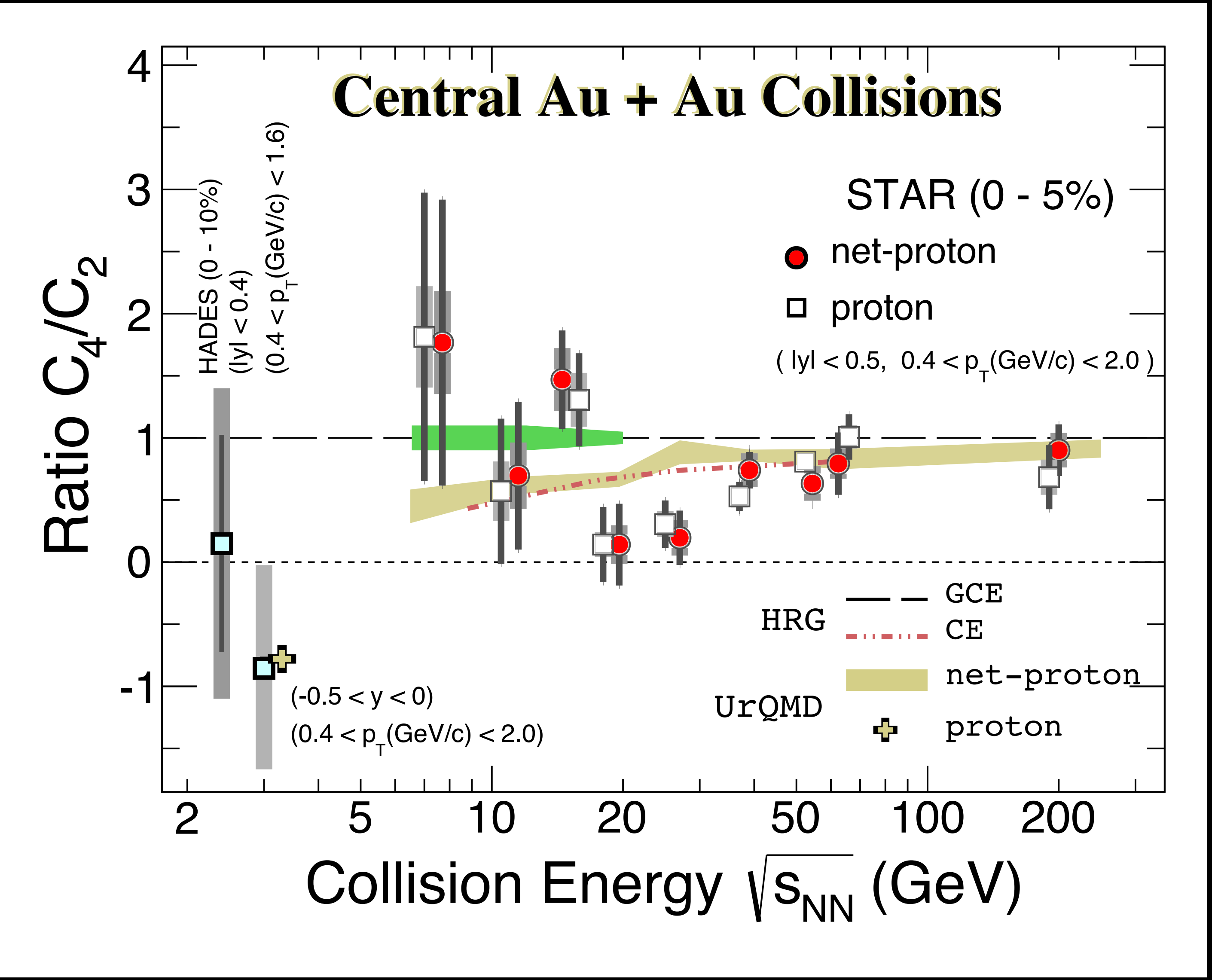
https://www.agsrhichome.bnl.gov/RHIC/Runs/

- Some preliminary BES-II results will be presented at this conference
- BES-II data production of full statistics and analyses ongoing

Search for QCD critical point

Net-proton fluctuations

STAR: PRL 128, 202303 (2022)



Susceptibility Cumulants

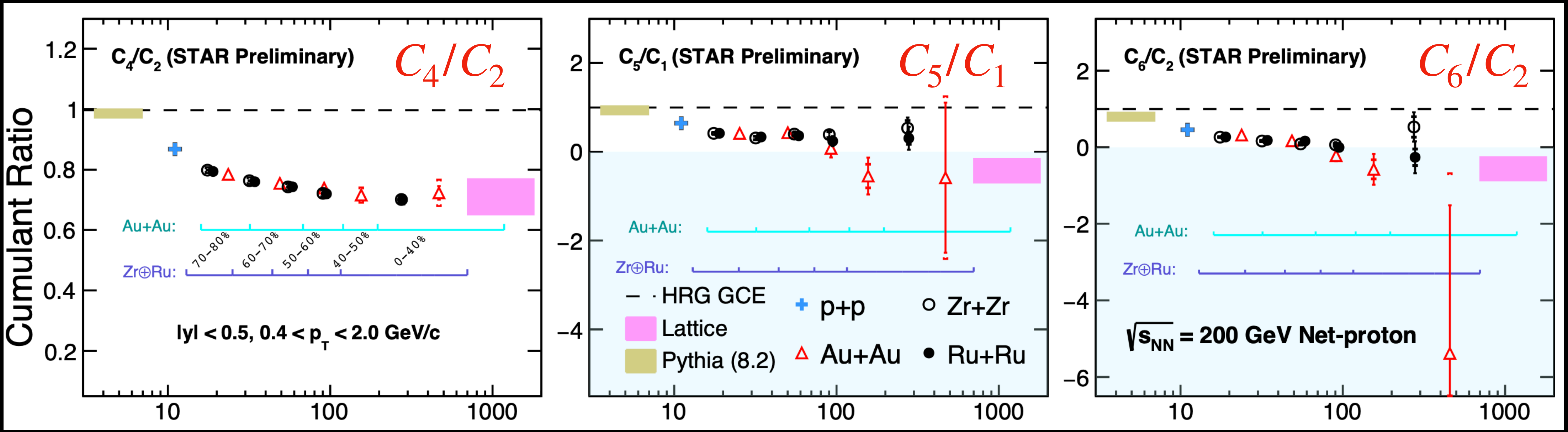
$$\chi_4/\chi_2 \longrightarrow C_4/C_2$$

- Non-monotonic behavior as a function of $\sqrt{s}_{NN}$
  Significance of 3.1σ relative to Skellam expectation

- At $\sqrt{s}_{NN}$ = 3 GeV, fluctuations driven by baryon number conservation
  Hadronic interaction dominates

Mapping QCD phase diagram

Multiplicity dependence of fluctuations

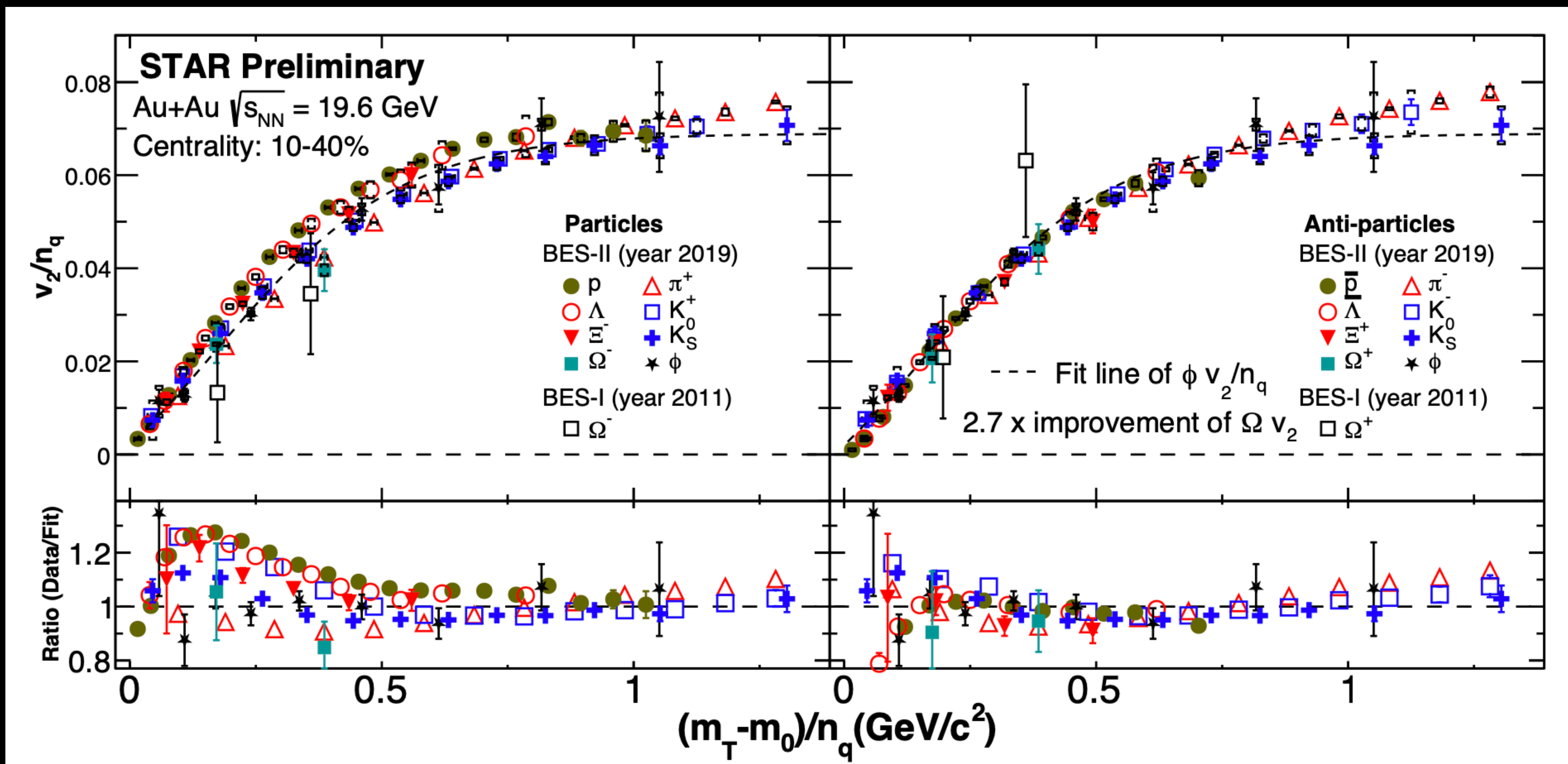


- C_4/C_2, C_5/C_1, and C_6/C_2 decrease with increasing multiplicity
- At high-multiplicity, cumulant ratios approach toward lattice prediction for the thermalized QCD matter and smooth crossover (μ_B~0)

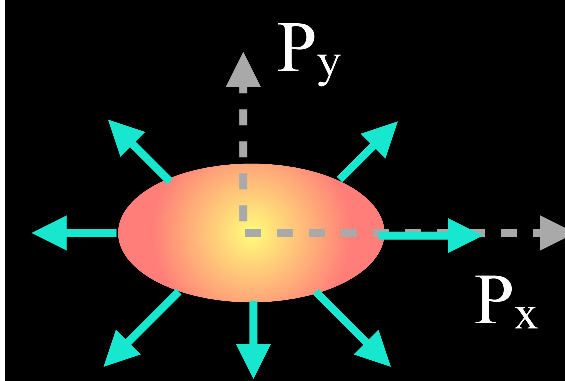
STAR: arXiv: 2207.09837
Lattice: PRD 101 (2020) 7, 074502

Partonic collectivity in QGP

See Subhash Singha's talk



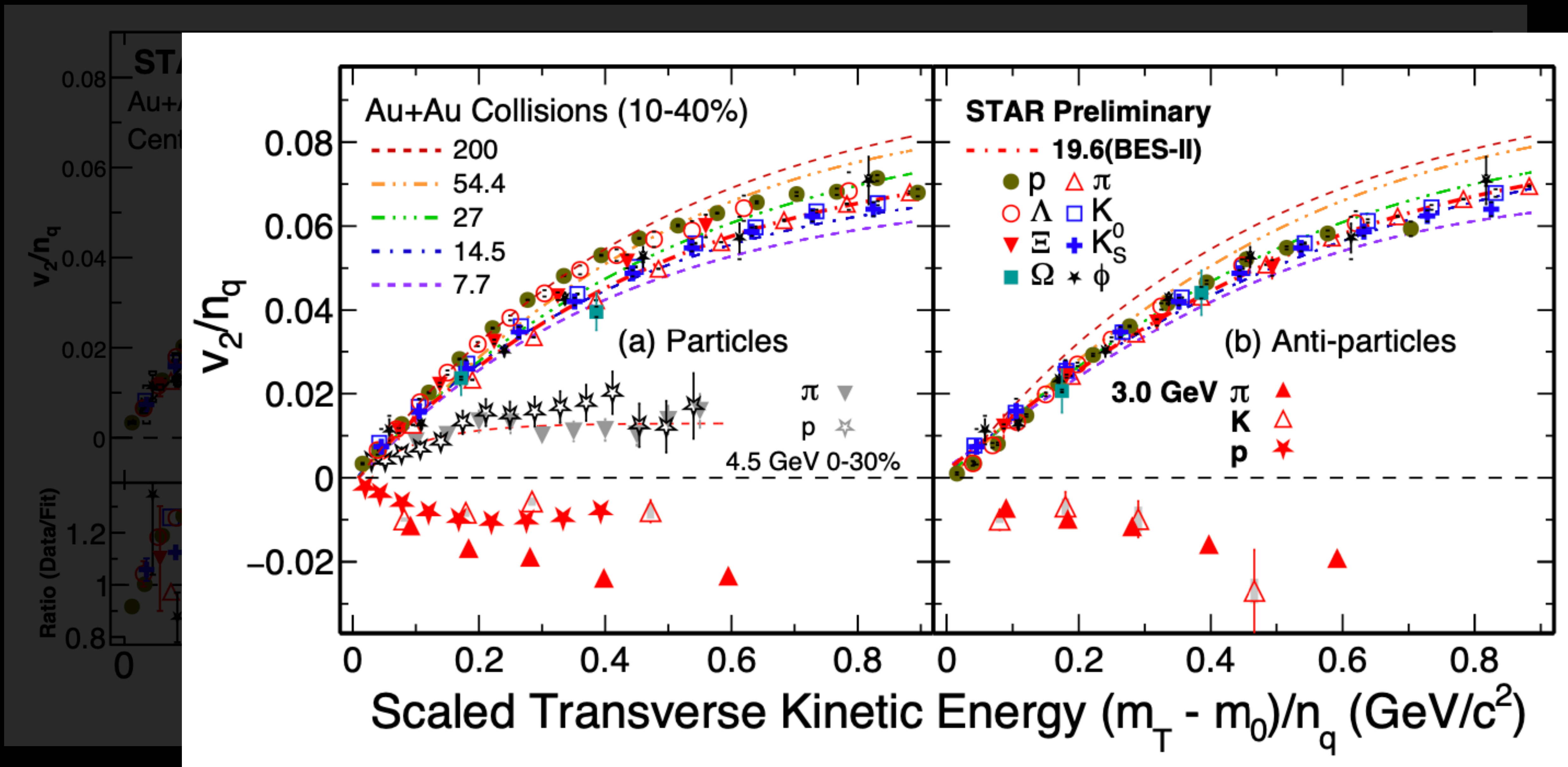
$$v_2 = \langle \cos(2\phi) \rangle$$



Number of constituent quark (NCQ) scaling of anti-particles holds better than particles

Indicating the contribution of transported quarks in particles

Partonic collectivity in QGP

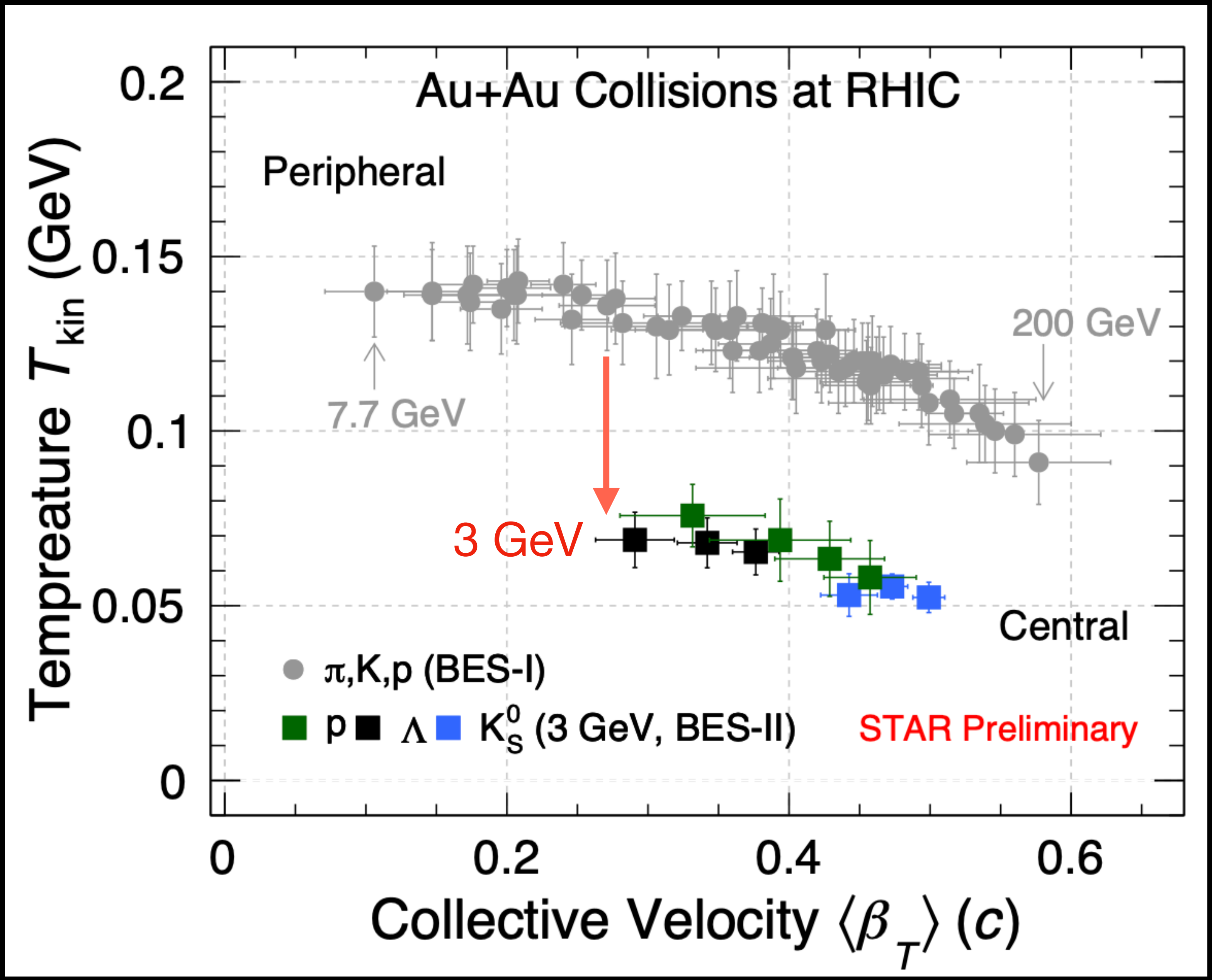


At $\sqrt{s_{NN}}$ = 3 GeV: v_2 for all particles are negative, and the NCQ scaling is absent

Disappearance of partonic collectivity and likely dominated by baryonic interactions

STAR: PLB 827 (2022) 137003

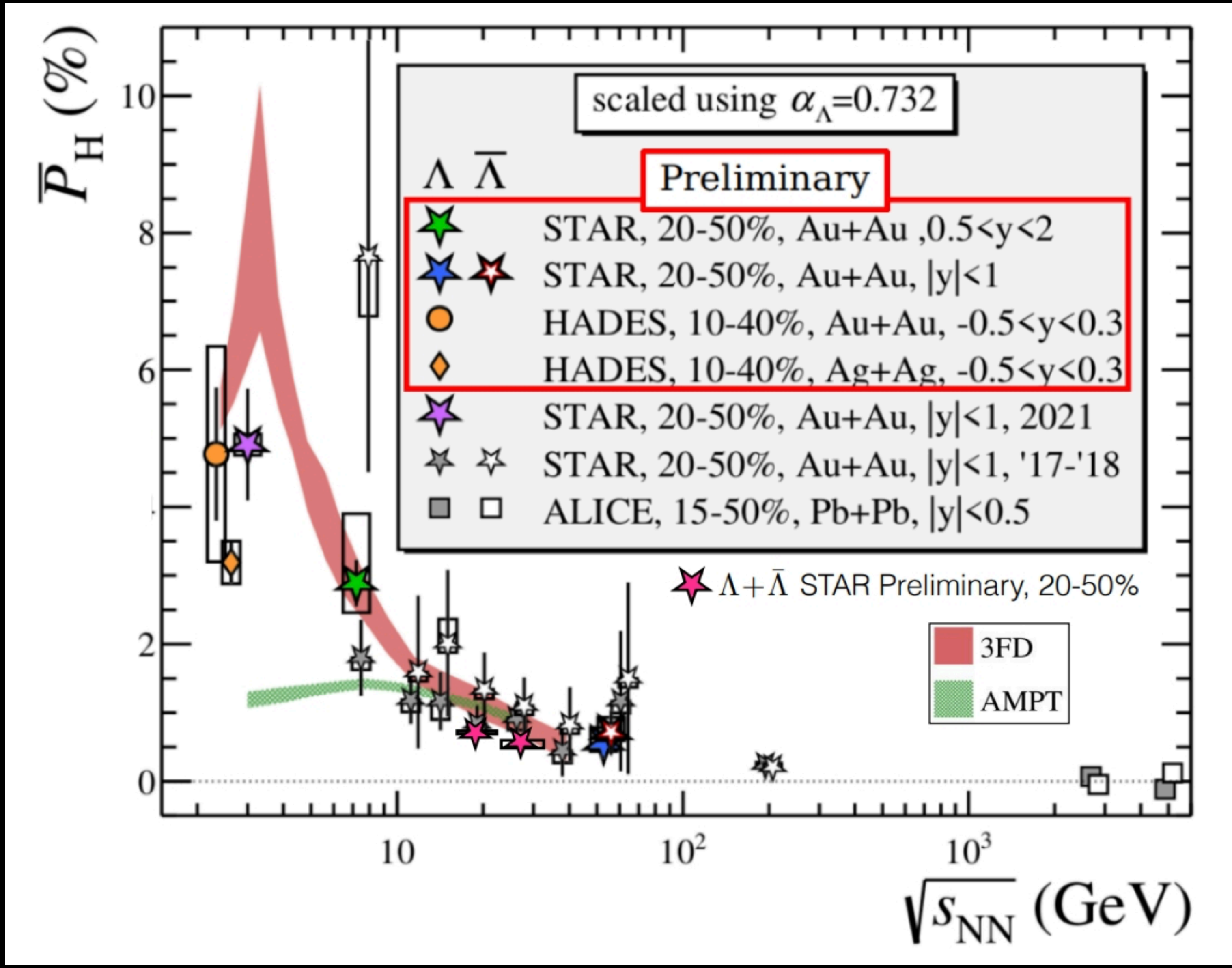
Kinetic freeze-out properties

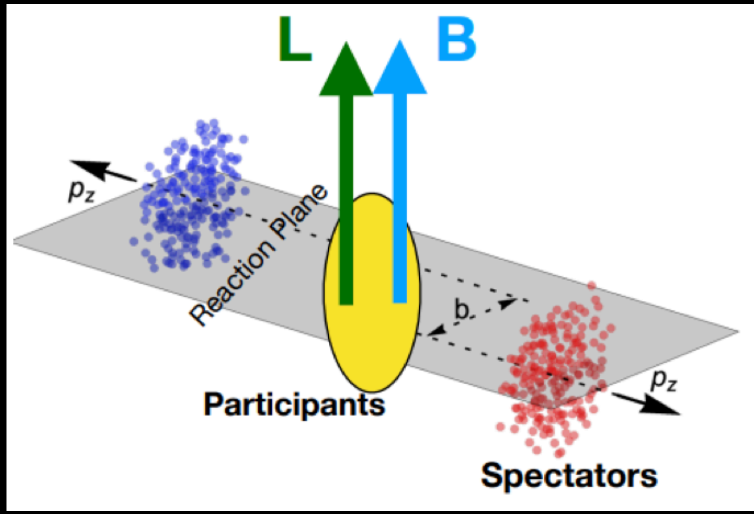


At $\sqrt{s_{NN}}$ = 3 GeV,
Implying different EOS at freeze-out

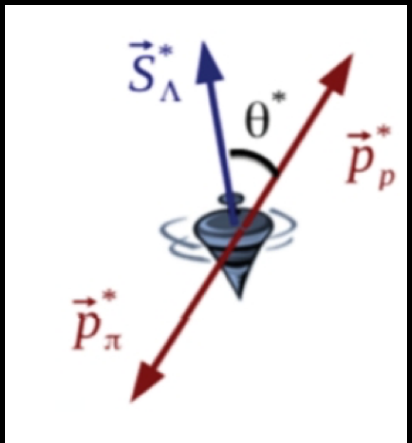
Most vortical fluid created in heavy-ion collisions

Spin polarization of hyperons along the orbital angular momentum





$$\bar{P}_{\rm H} \equiv \langle P_{\rm H} \cdot \hat{J}_{\rm sys} \rangle$$



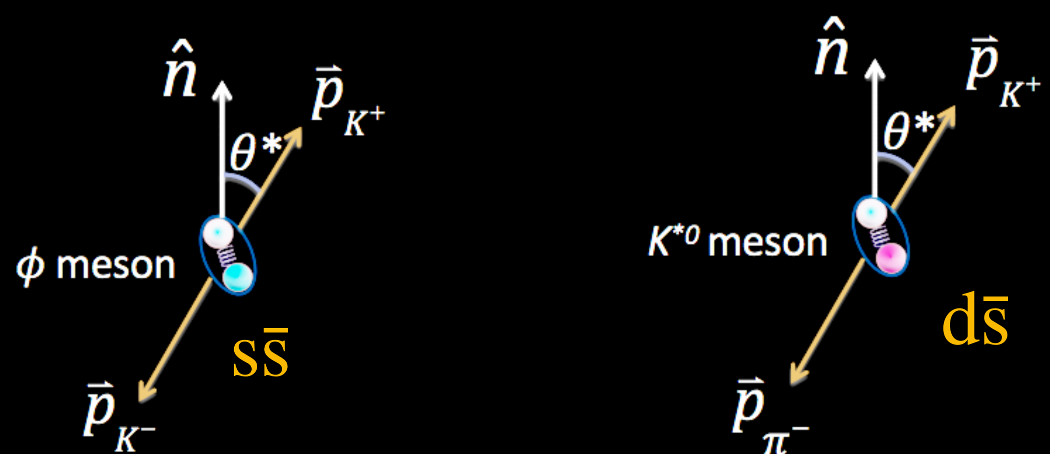
- Large polarization → Effect of system's angular momentum
- Precision new FXT (3 GeV) and BES-II (19.6 GeV) results follow the global trend
- Separation between Λ and $\bar{\Lambda}$ → Effect of magnetic field (Spin-magnetohydrodynamics, *PRL* 129 (2022) 19, 192301)

Global spin alignment of vector-mesons in heavy-ion collisions

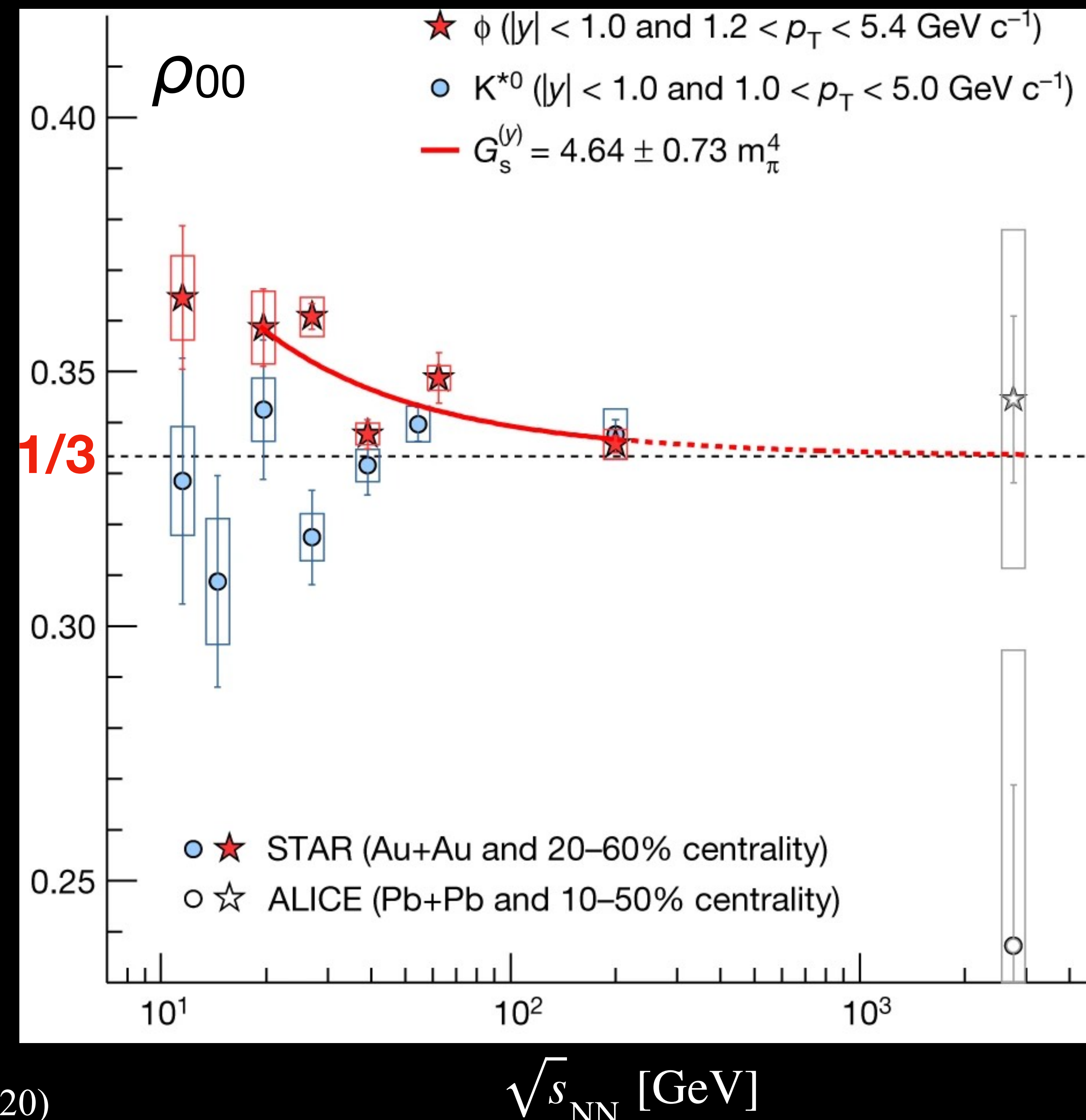
See Subhash Singha's talk

STAR: Nature
https://www.nature.com/articles/s41586-022-05557-5

Vector meson



$$\frac{dN}{d(\cos\theta^*)} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$



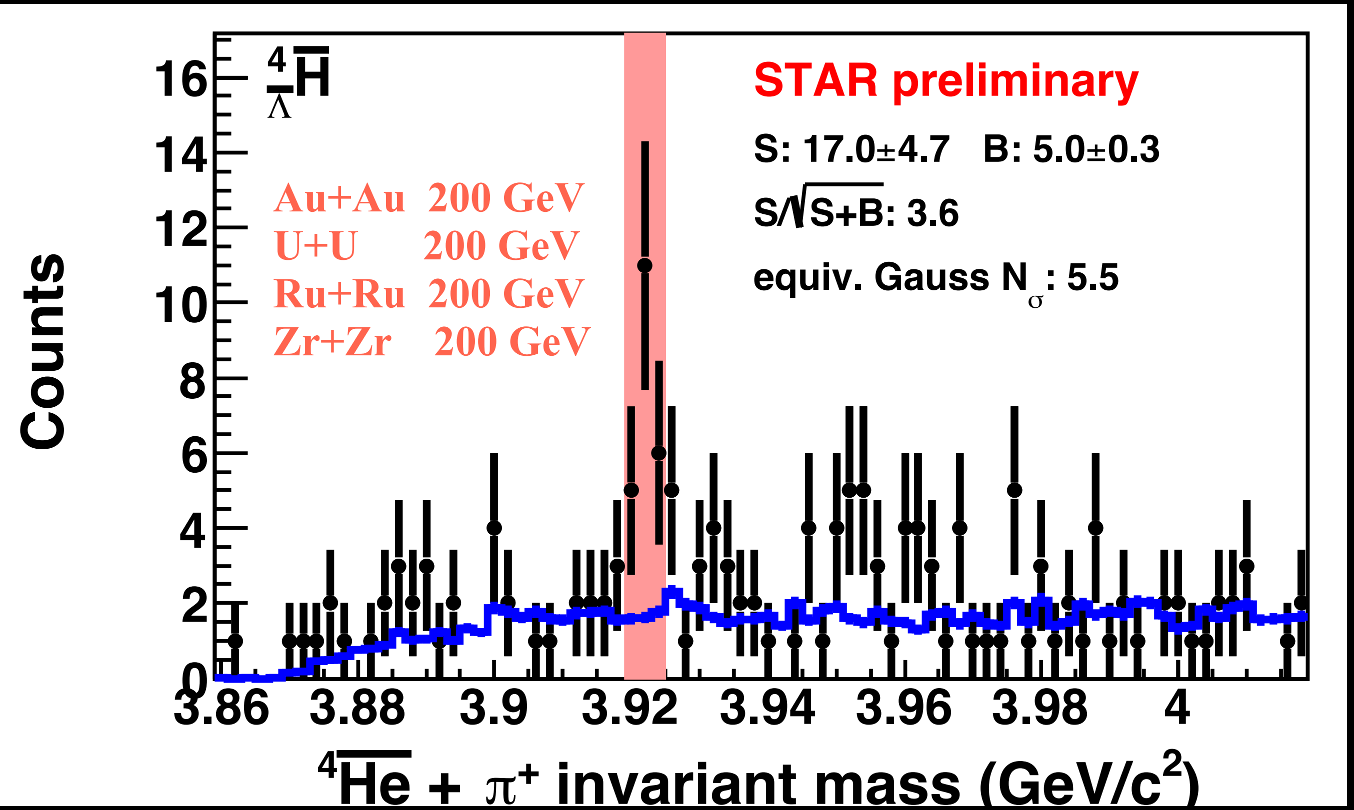
Possible explanation of this deviation for φ-spin alignment from 1/3 → vector meson field

Phys. Rev. D 101 096005 (2020); Phys. Rev. D 102, 056013 (2020)

Production of hypernuclei in heavy-ion collisions

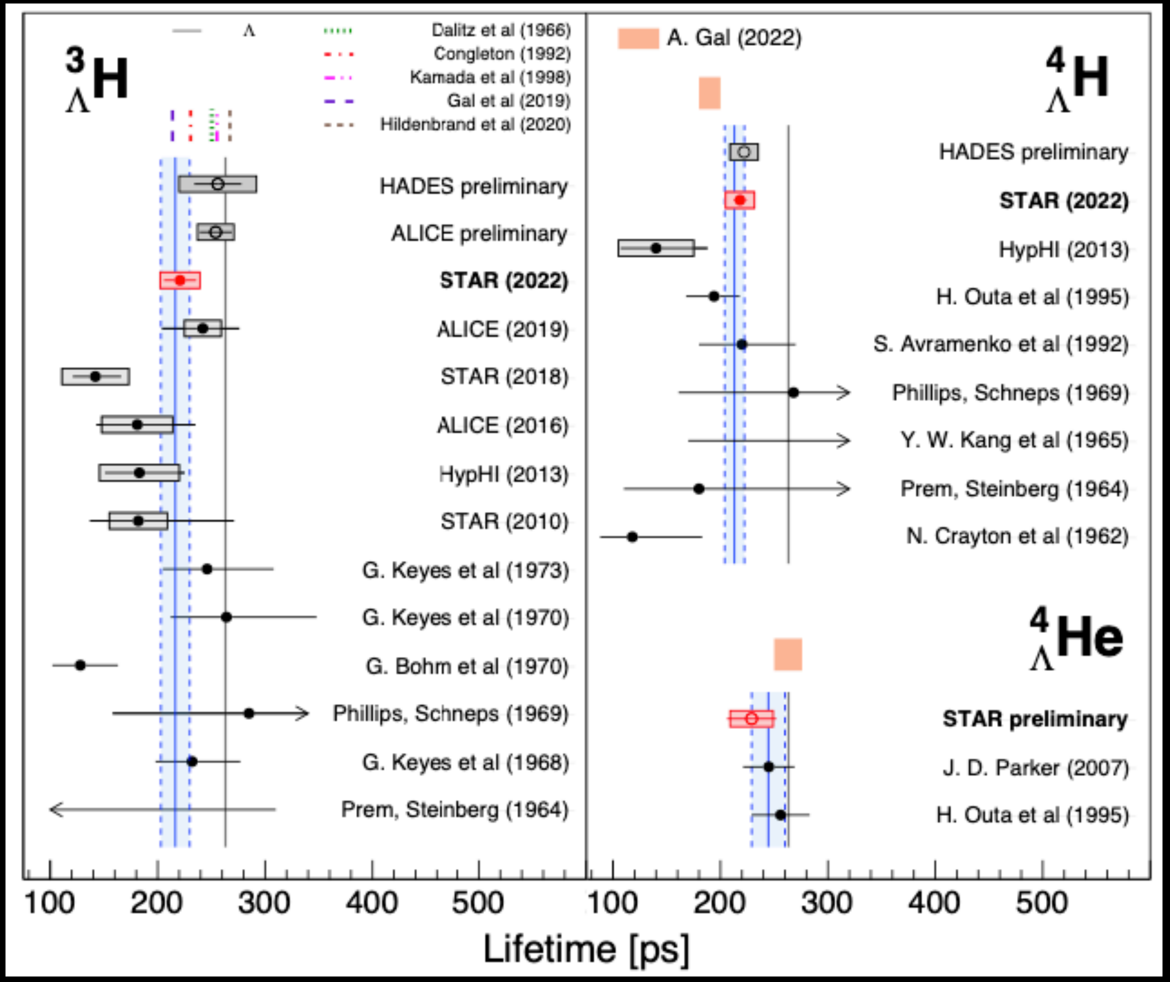
STAR: PRL 128, 202301 (2022)

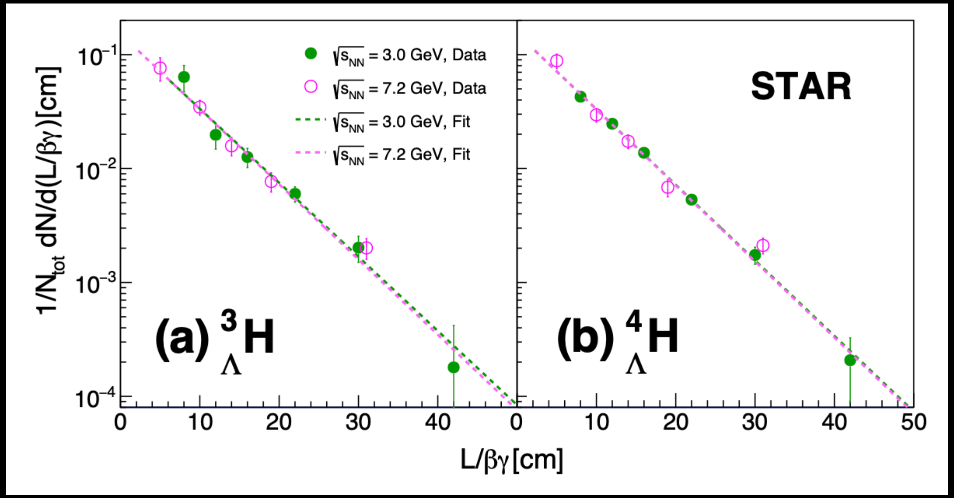
First observation of anti-Hyper-Hydrogen-4



$^{4}_{\bar{\Lambda}}\overline{H} \longrightarrow {}^{4}\overline{He} + \pi^{+}$

Lifetime measurement of Hypernuclei

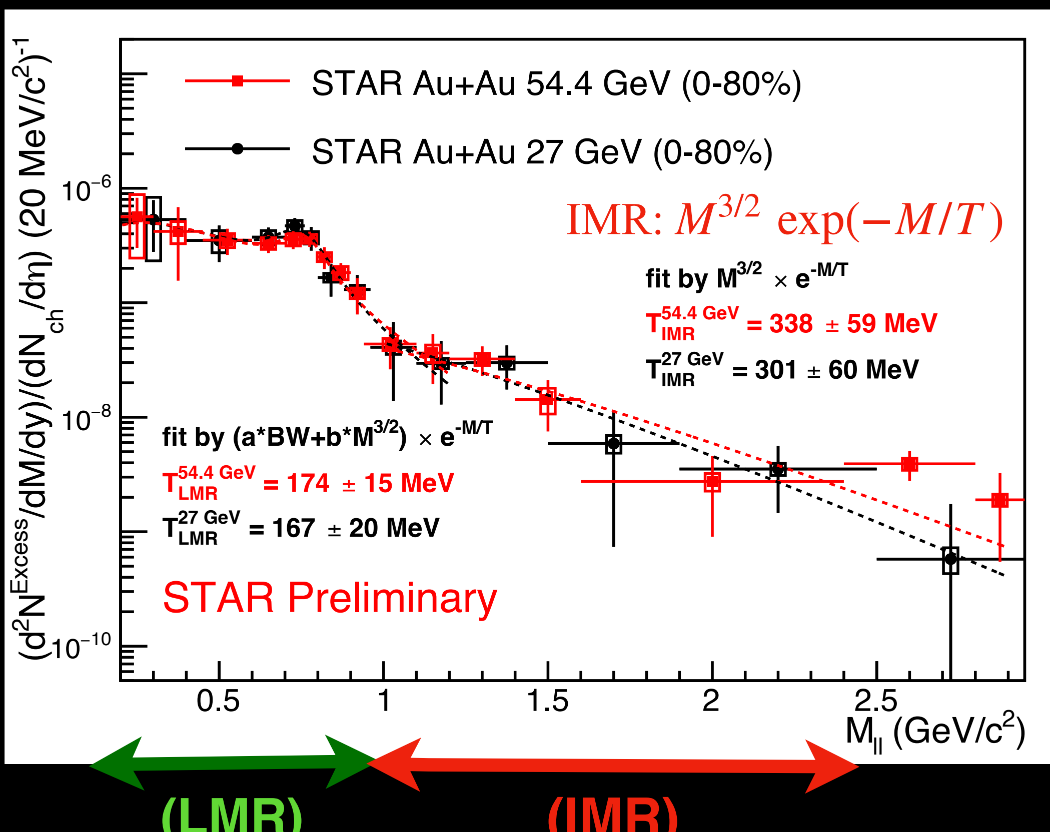


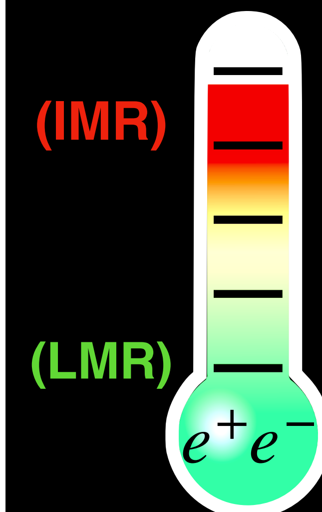


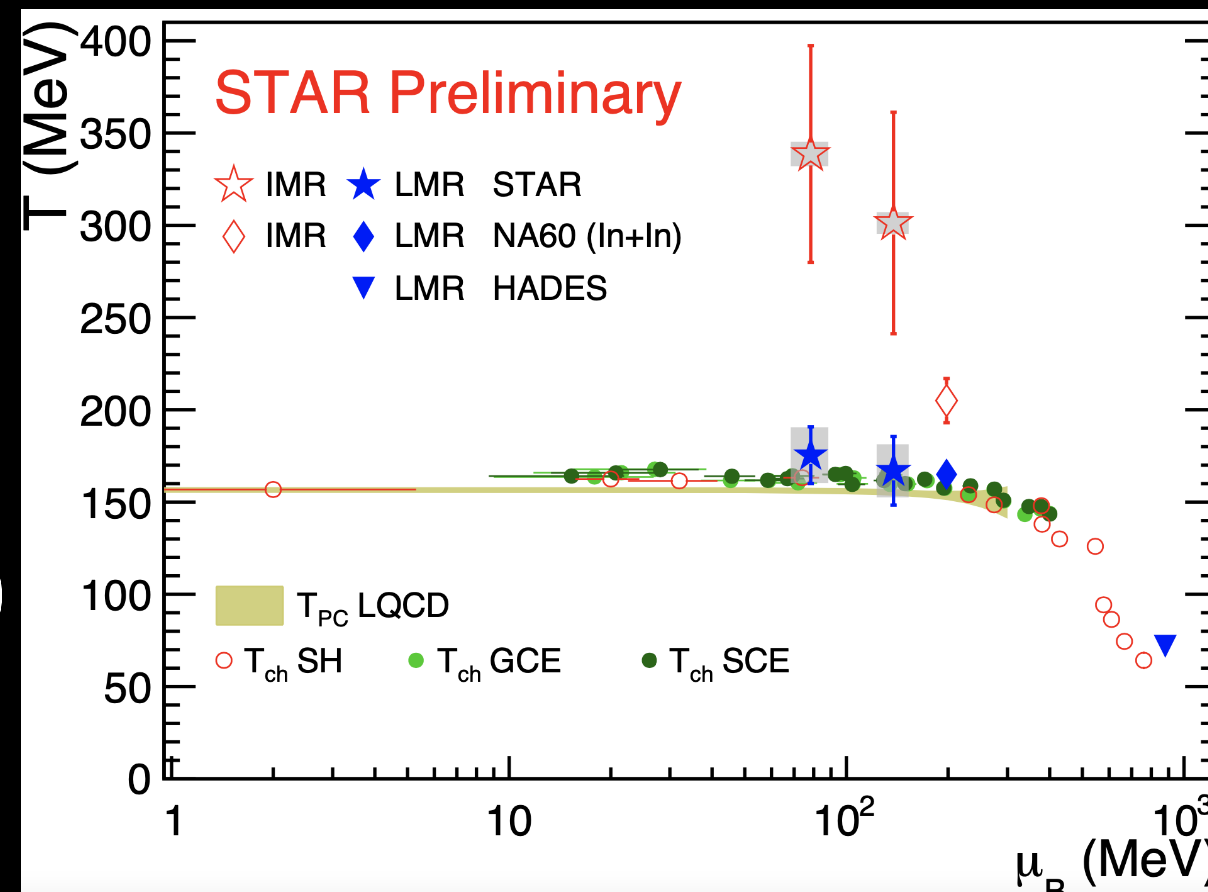
More results coming with STAR FXT data…

QGP medium temperature with dileptons

Dileptons as EM probes:
i) Emitted throughout the evolution, ii) Temperature without blueshift effect (unlike direct photon), and iii) accessible through in-medium spectral function







IMR thermal dielectron: T_{IMR} ~ 320 MeV

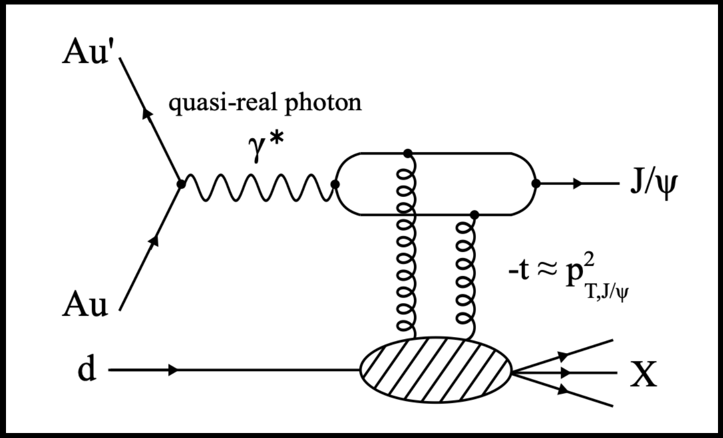
First direct measurement of QGP temperature at RHIC

Physics in ultra-peripheral collisions (UPC)

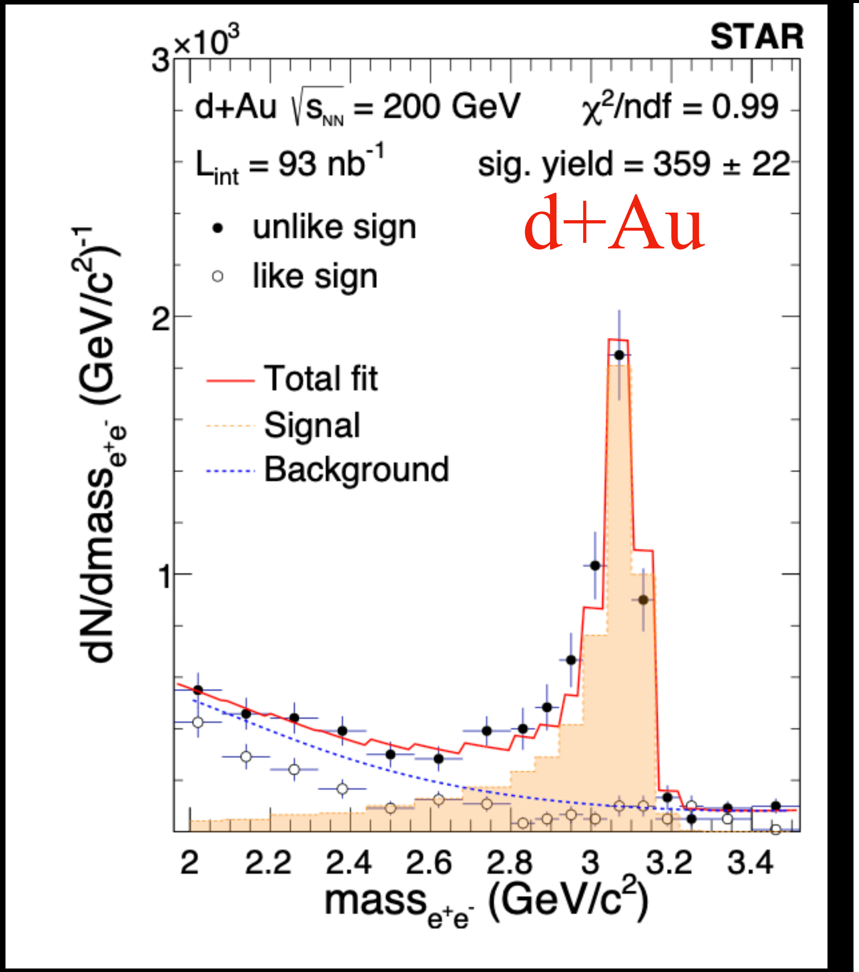
Coherent photoproduction of vector meson in UPC

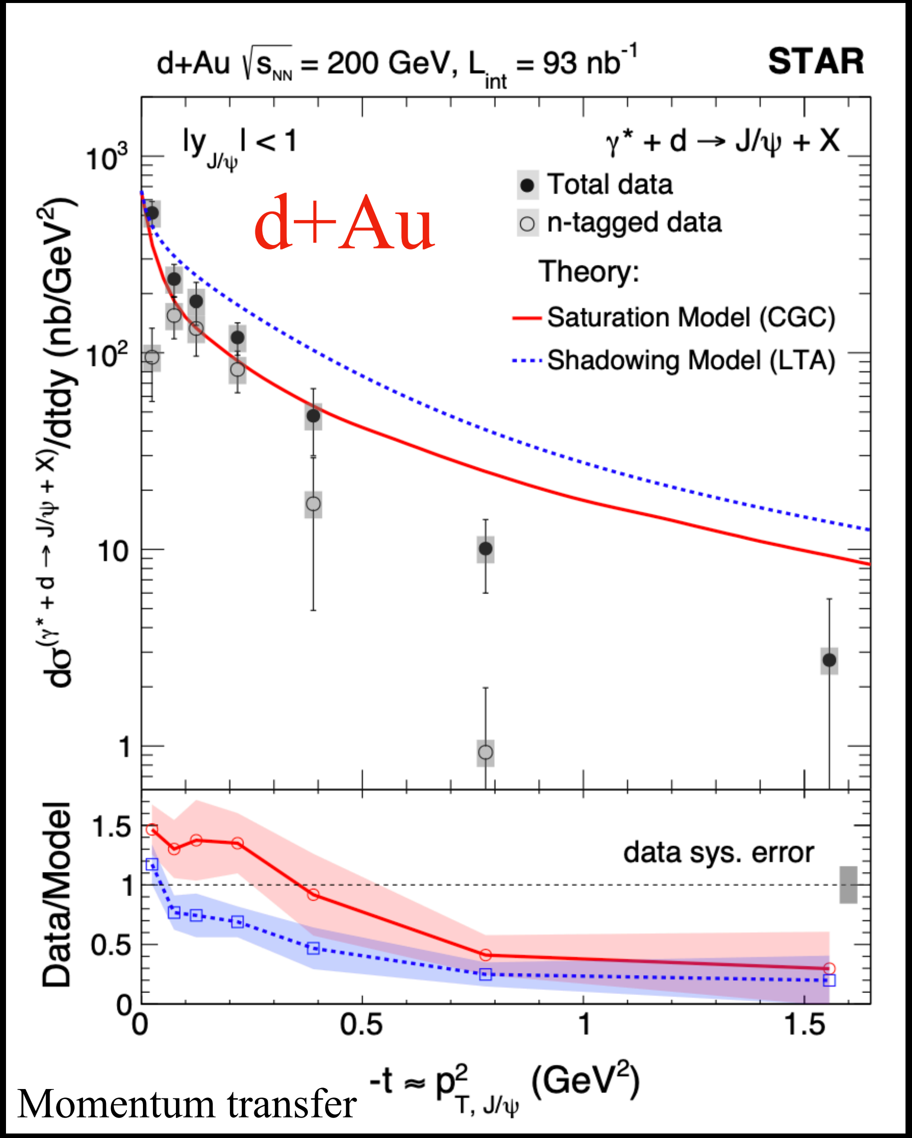
Sensitive to gluon density and its spatial distribution in the target nucleus

STAR: PRL 128 (2022) 12, 122303



$J/\psi \rightarrow e^{+}e^{-}$



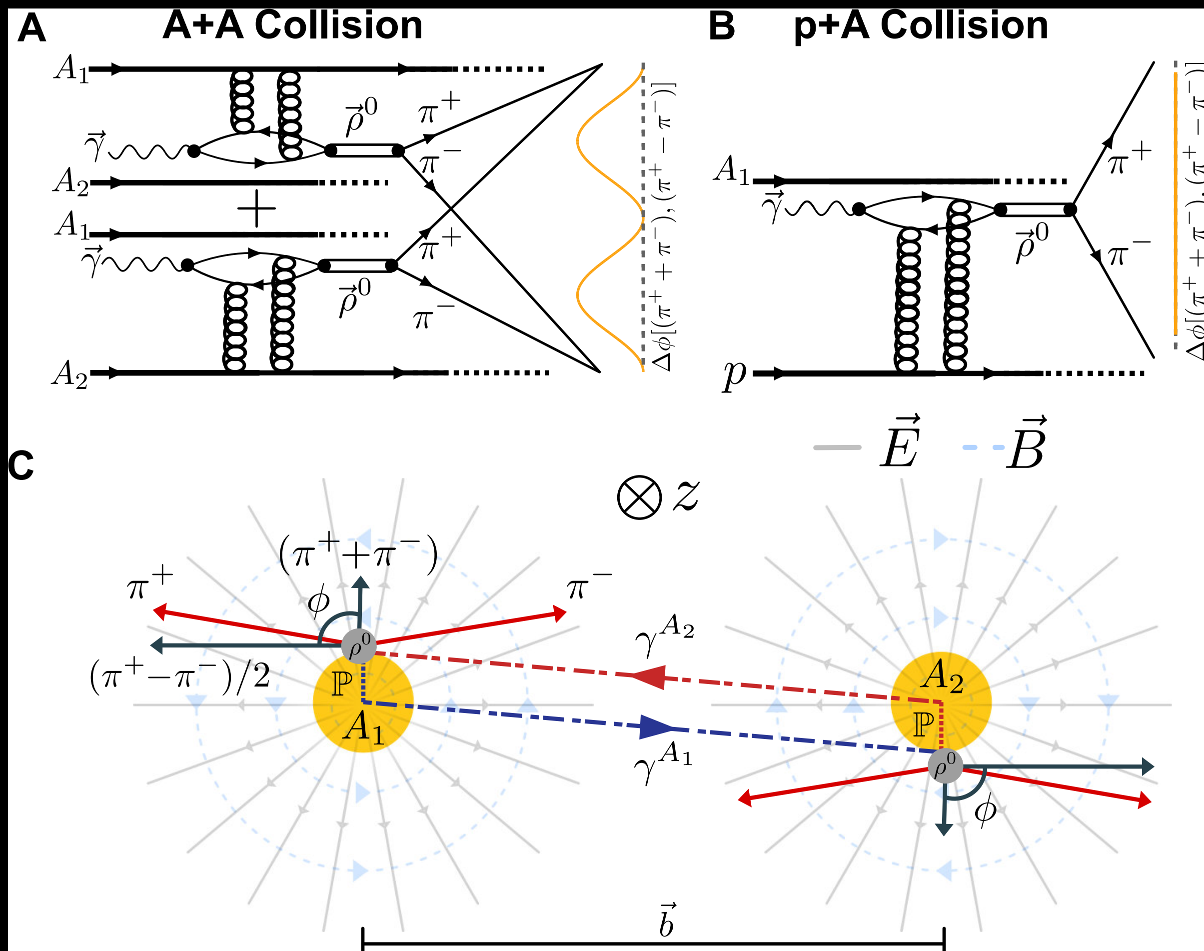


Au+Au analysis underway

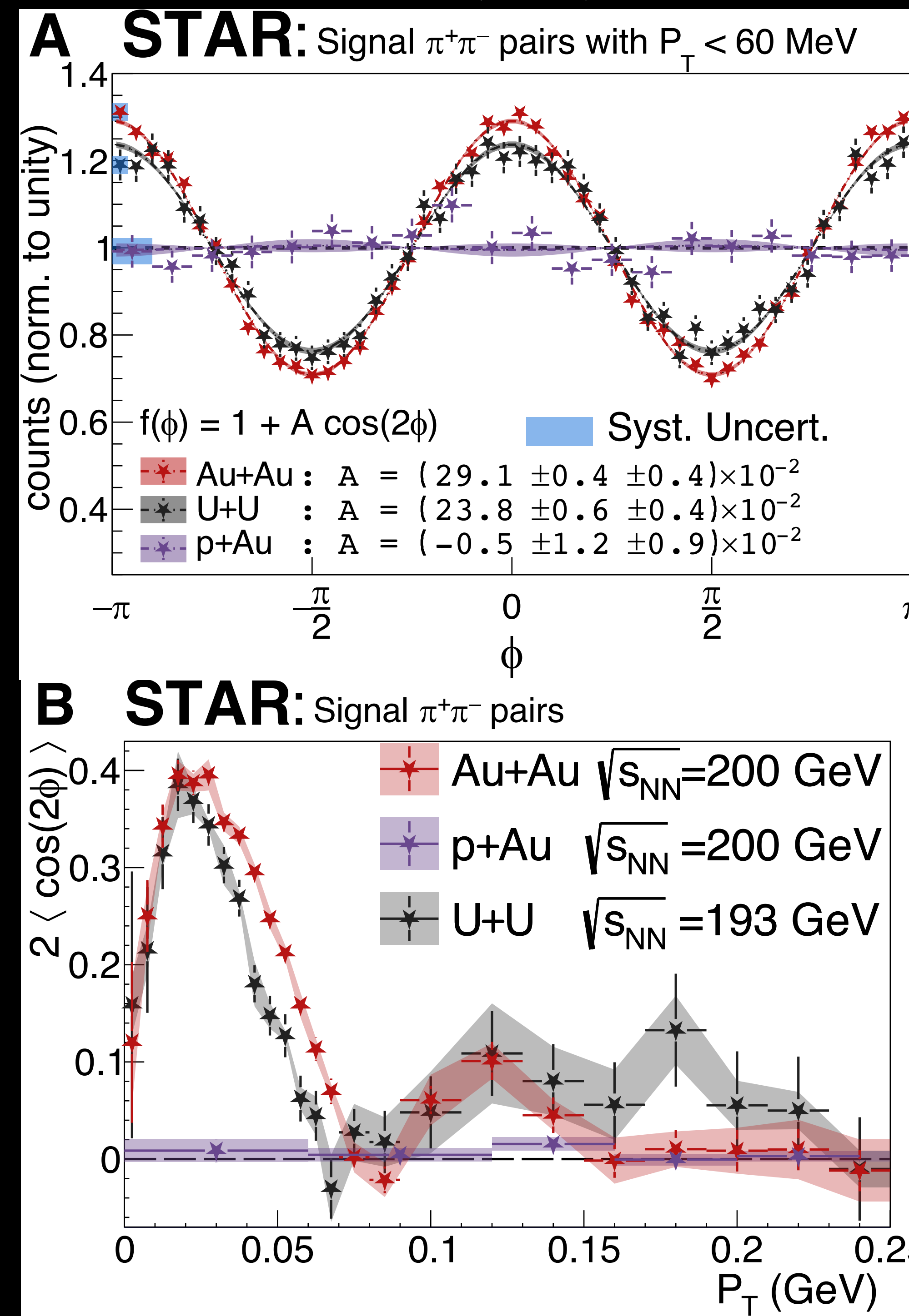
See Ashik Iqbal Sheikh's talk

A neutron tagged d-going ZDC: first measurement of incoherent diffractive J/ψ cross-section at low momentum transfer in UPC events

Spin-interference pattern in ρ^0 decays (UPC events)



STAR: Sci. Adv. 9 (2023) 3903



cos(2φ) modulation observed in A+A UPC

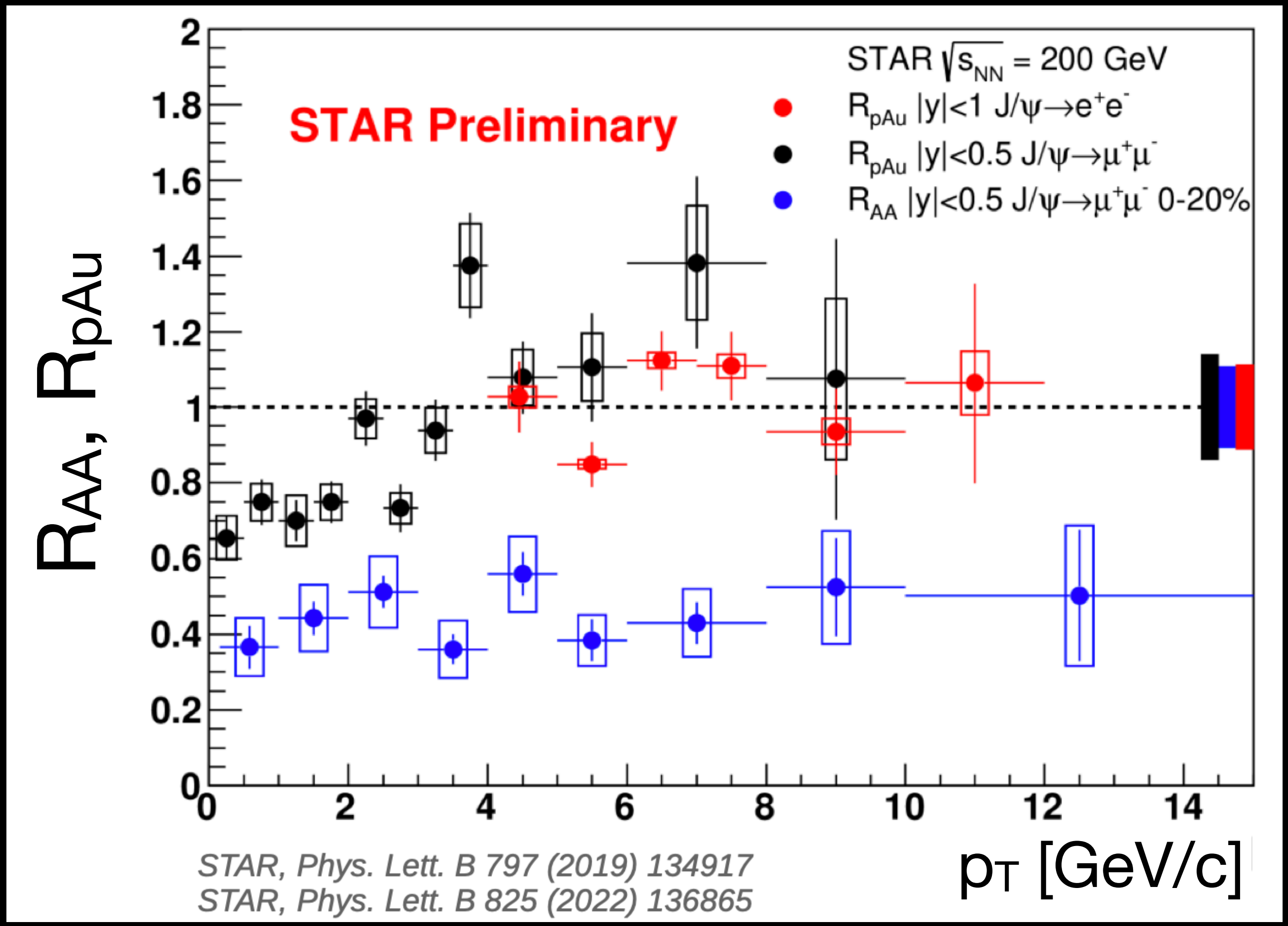
- Sensitive to form factor
- Not observed in p+A collisions due to lack of interference

Au+Au analysis underway
See Ashik Iqbal Sheikh's talk

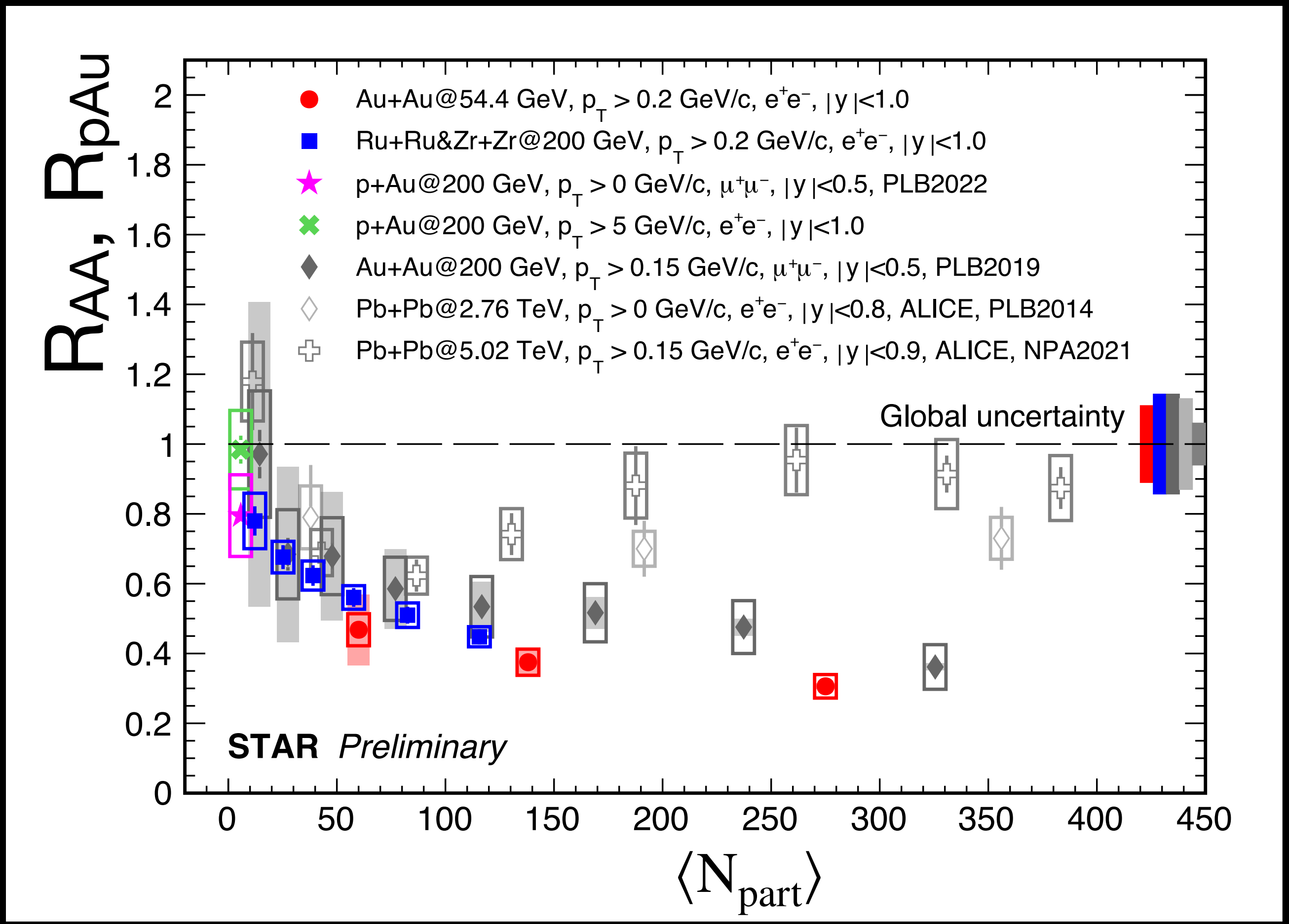
Hard probes to study inner-workings of QGP

J/ψ production in heavy-ion collisions

Hot vs. cold QCD medium: Au+Au vs. p+Au



Suppression vs. regeneration



Low p_T < 2 GeV: Cold nuclear matter effect

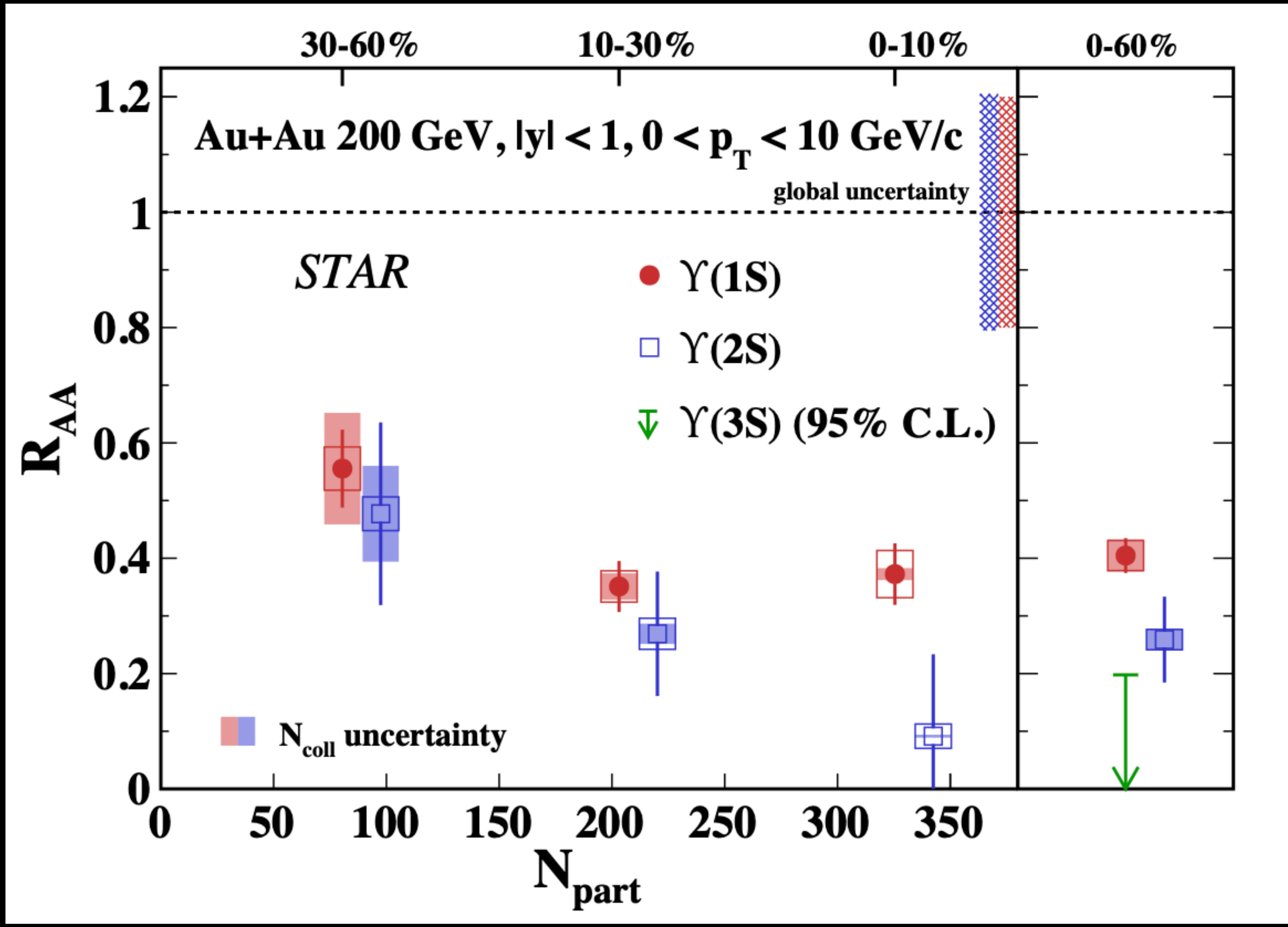
High p_T: suppression in Au+Au due to QGP

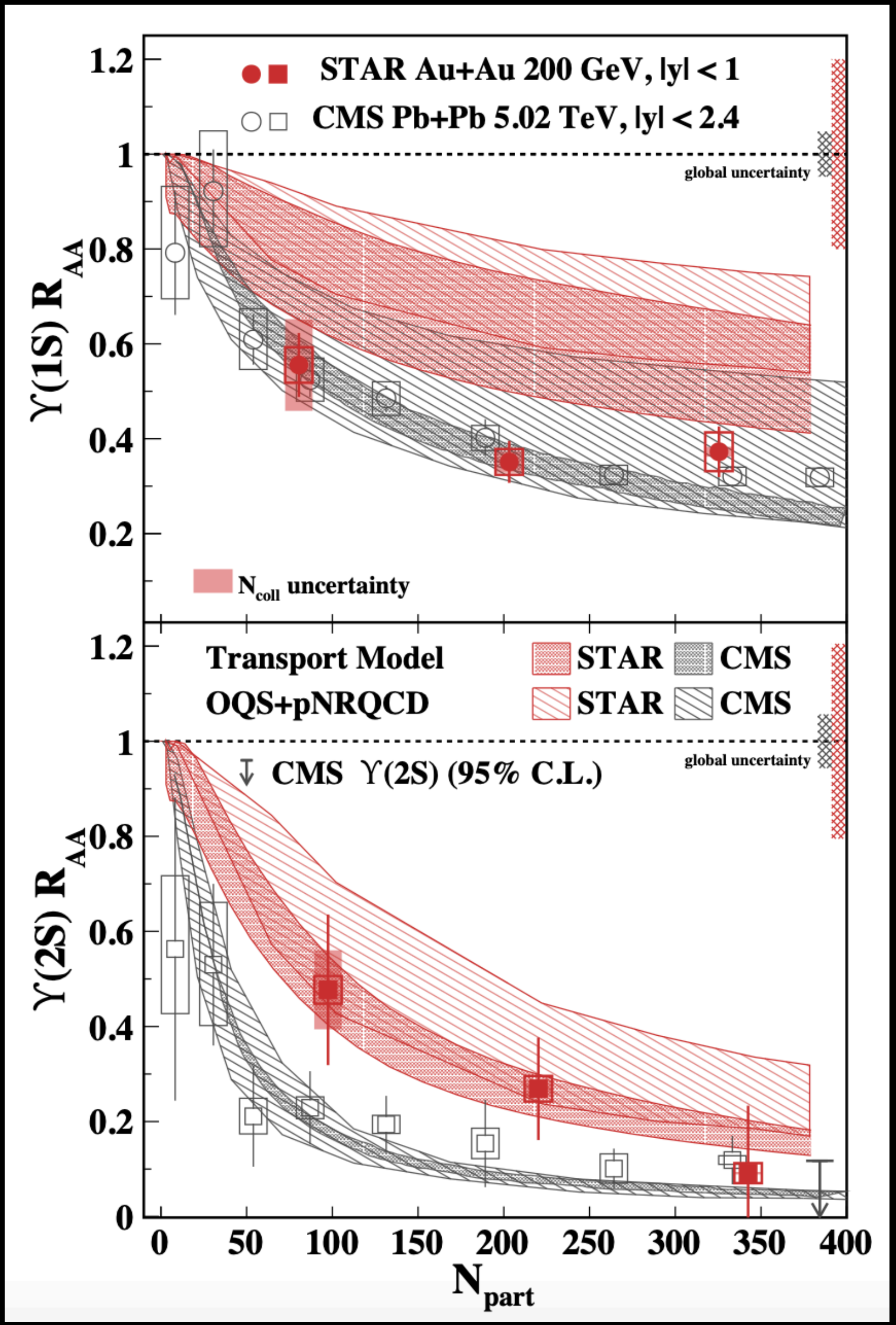
At high p_T: Strong suppression at RHIC and regeneration at LHC

ϒ(nS) suppression in heavy-ion collisions

Studying different states of bottomonia provides information of thermal and dynamical properties of QGP

STAR: arXiv:2207.06568



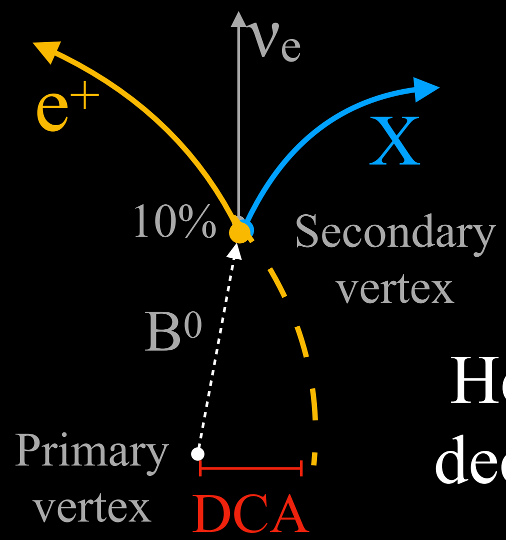


Observed sequential suppression of different ϒ(nS) states
[ϒ(1S) > ϒ(2S) > ϒ(3S)]

ϒ(1S): Similar suppression at RHIC and LHC

ϒ(2S): Less suppression in peripheral collisions at RHIC

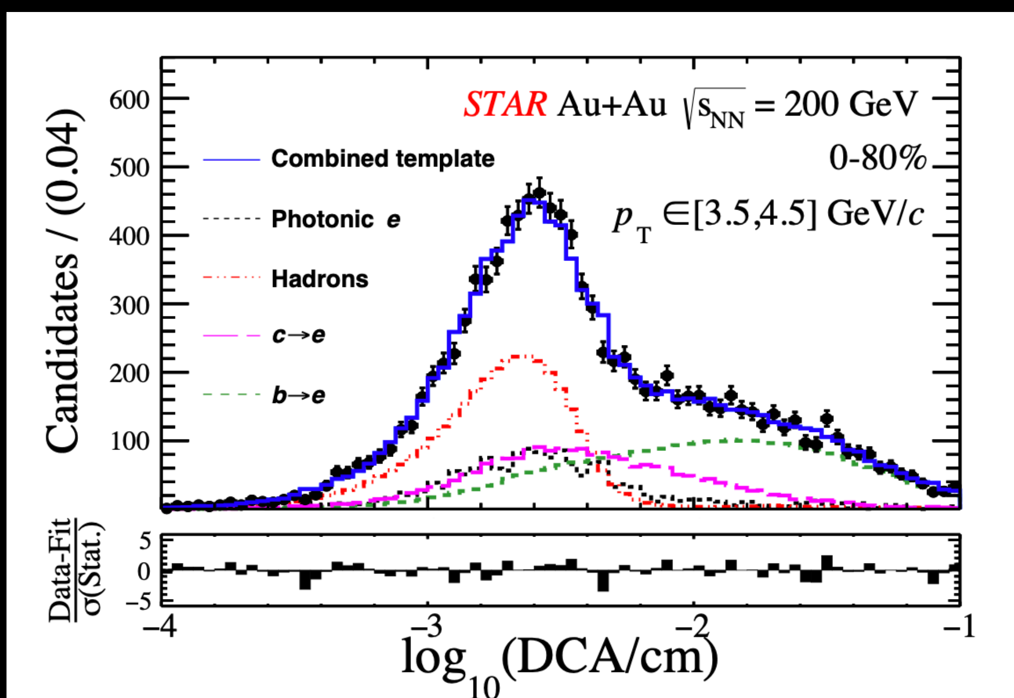
Mass ordering of parton energy loss

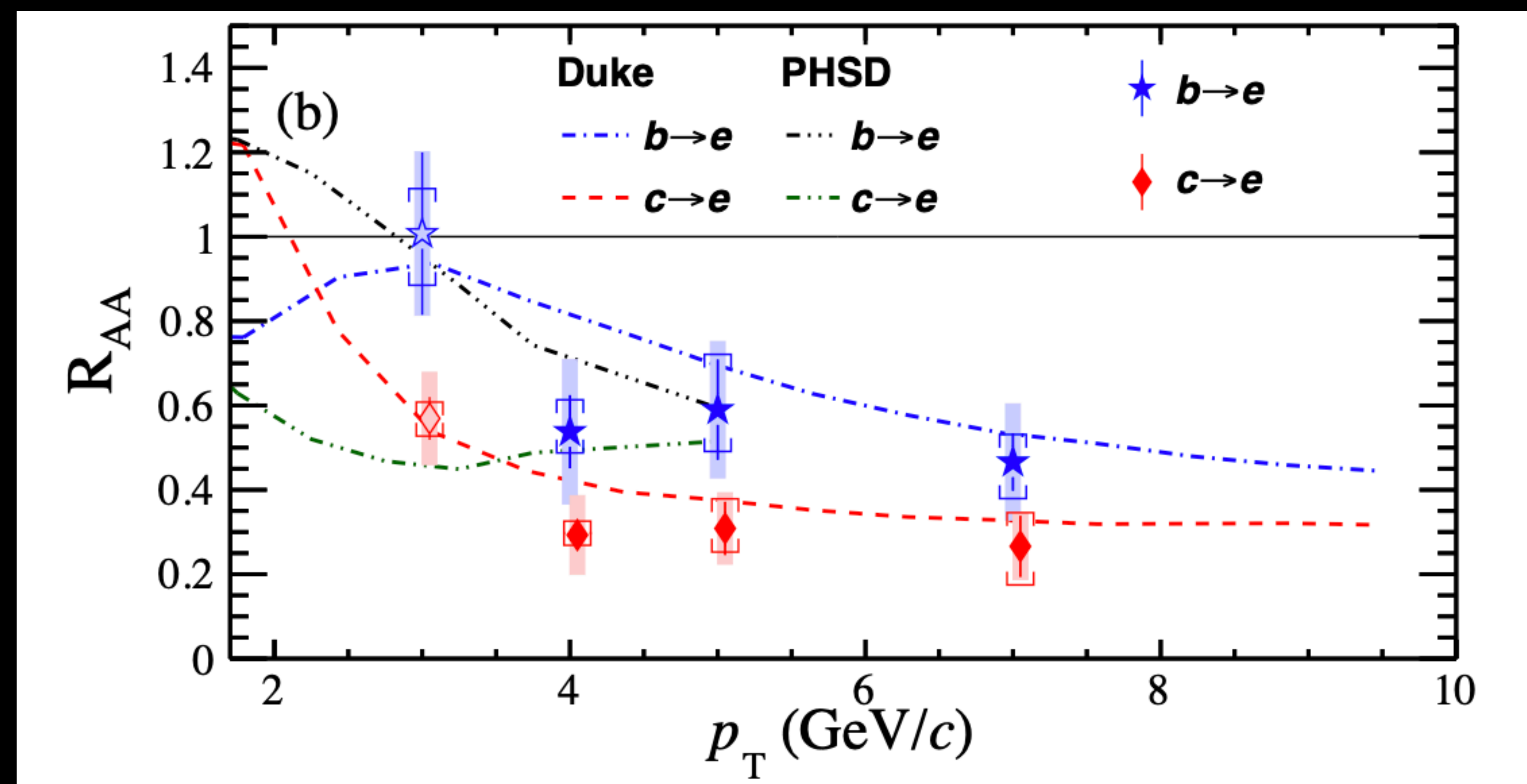


Heavy-flavor decay electron

STAR, Eur. Phys. J. C (2022) 82:1150

Parton energy loss: Hierarchy ordered by parton color charge and mass



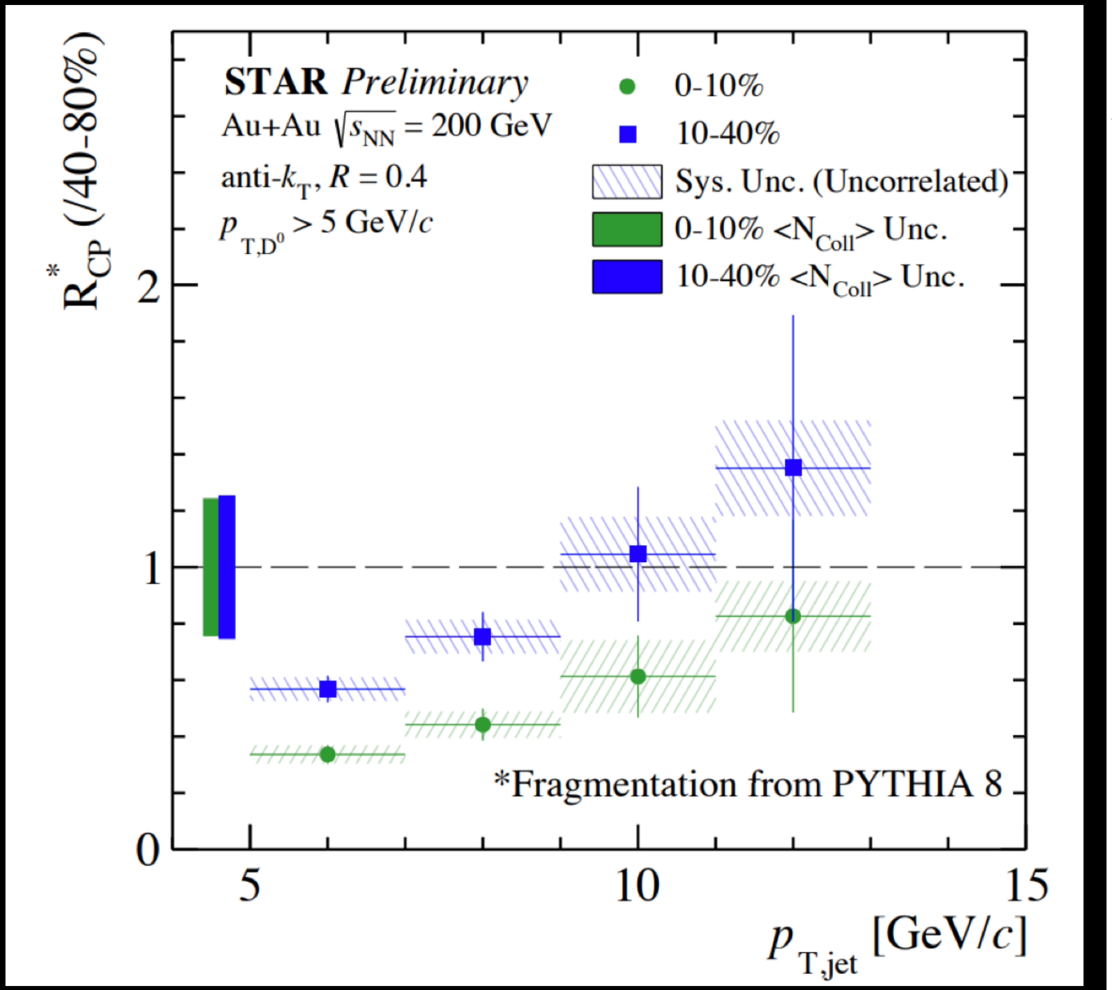


R_{AA} of bottom-decay electron less than that of charm-decay

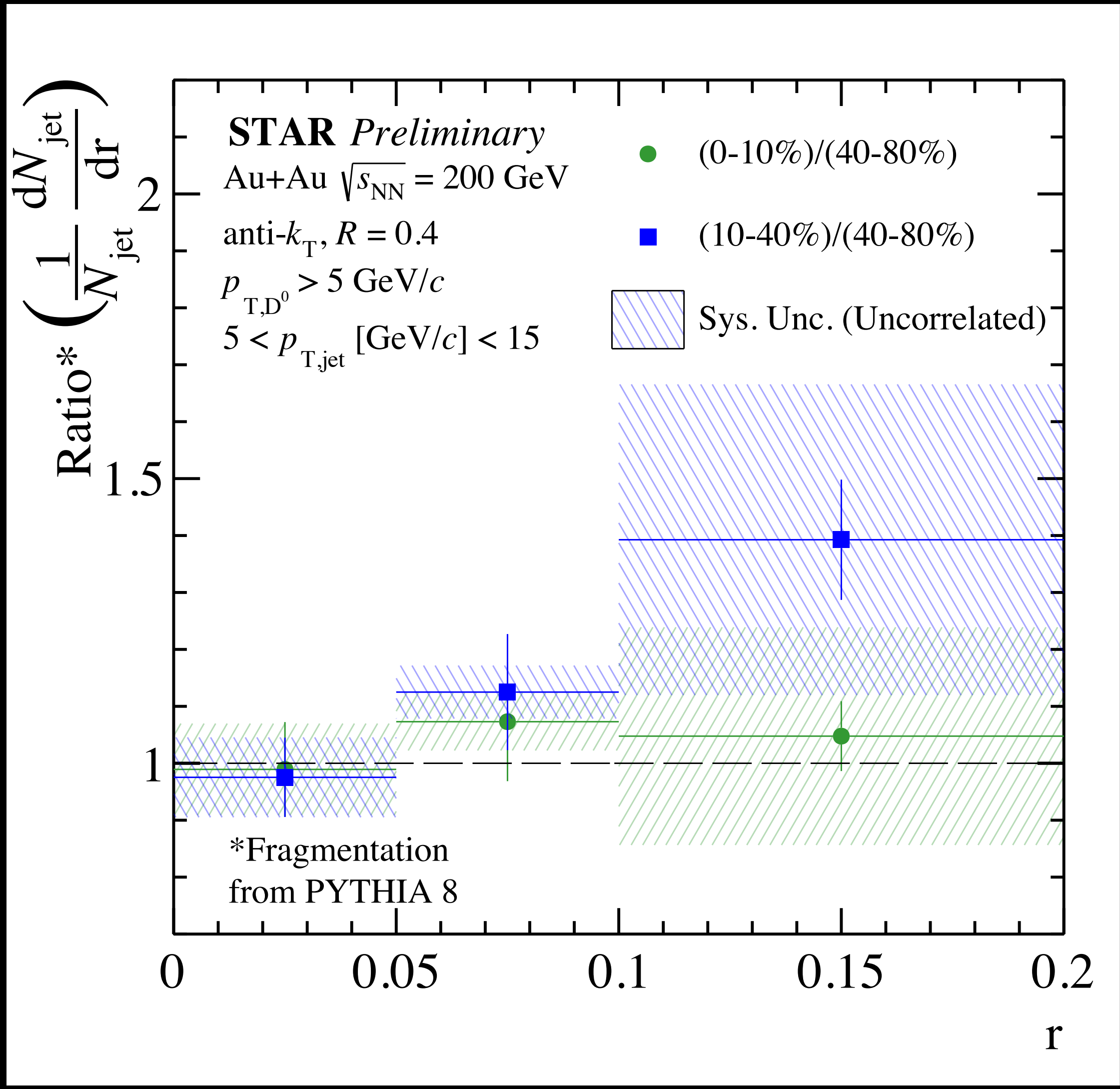
$\Delta E(c) > \Delta E(b)$

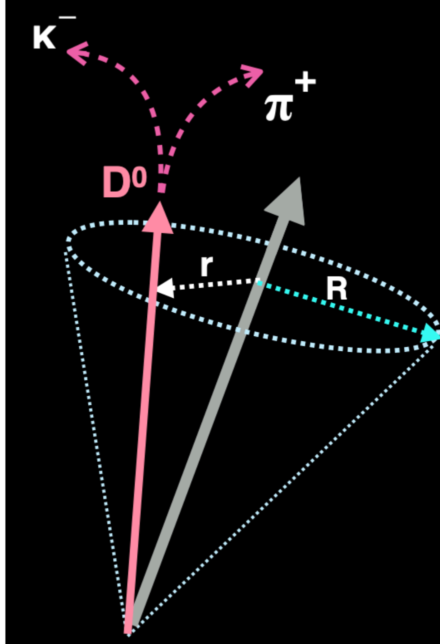
D^0-tagged jet measurement in heavy-ion collisions at RHIC

D^0-tagged jet suppression



D^0-tagged jet shape modification





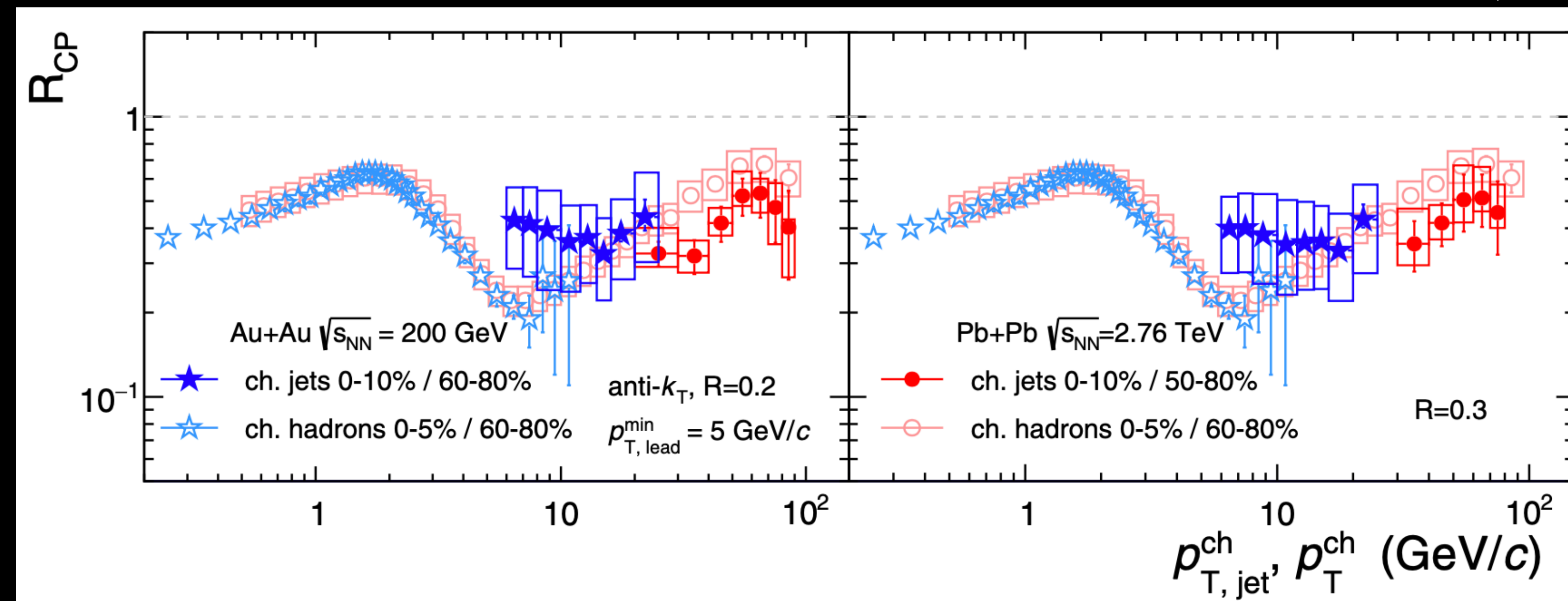
- R_{CP}: strong suppression at low jet p_T
- Ratio of radial distributions is consistent with unity within uncertainties (Unlike at LHC)

Jet quenching at RHIC and its manifestations

STAR: PRC **102**, 054913 (2020)

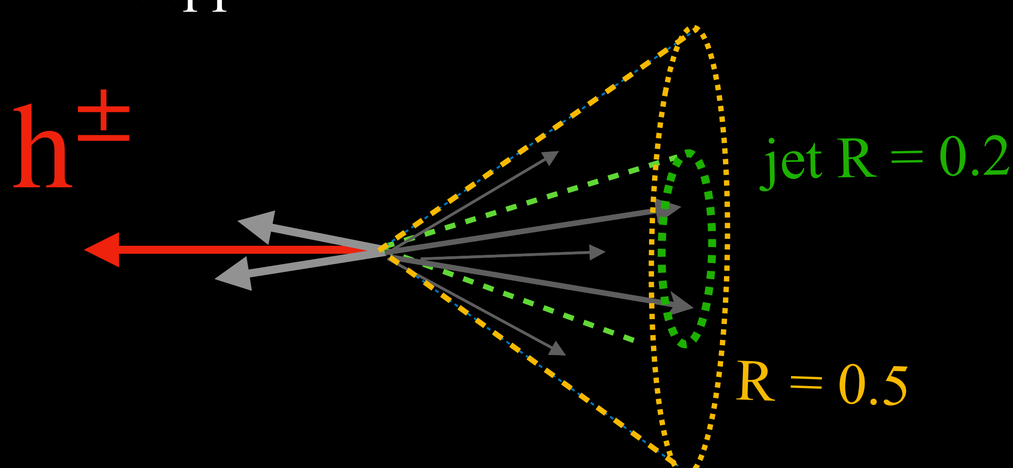
Inclusive jet suppression R_{CP}

RHIC and LHC comparable

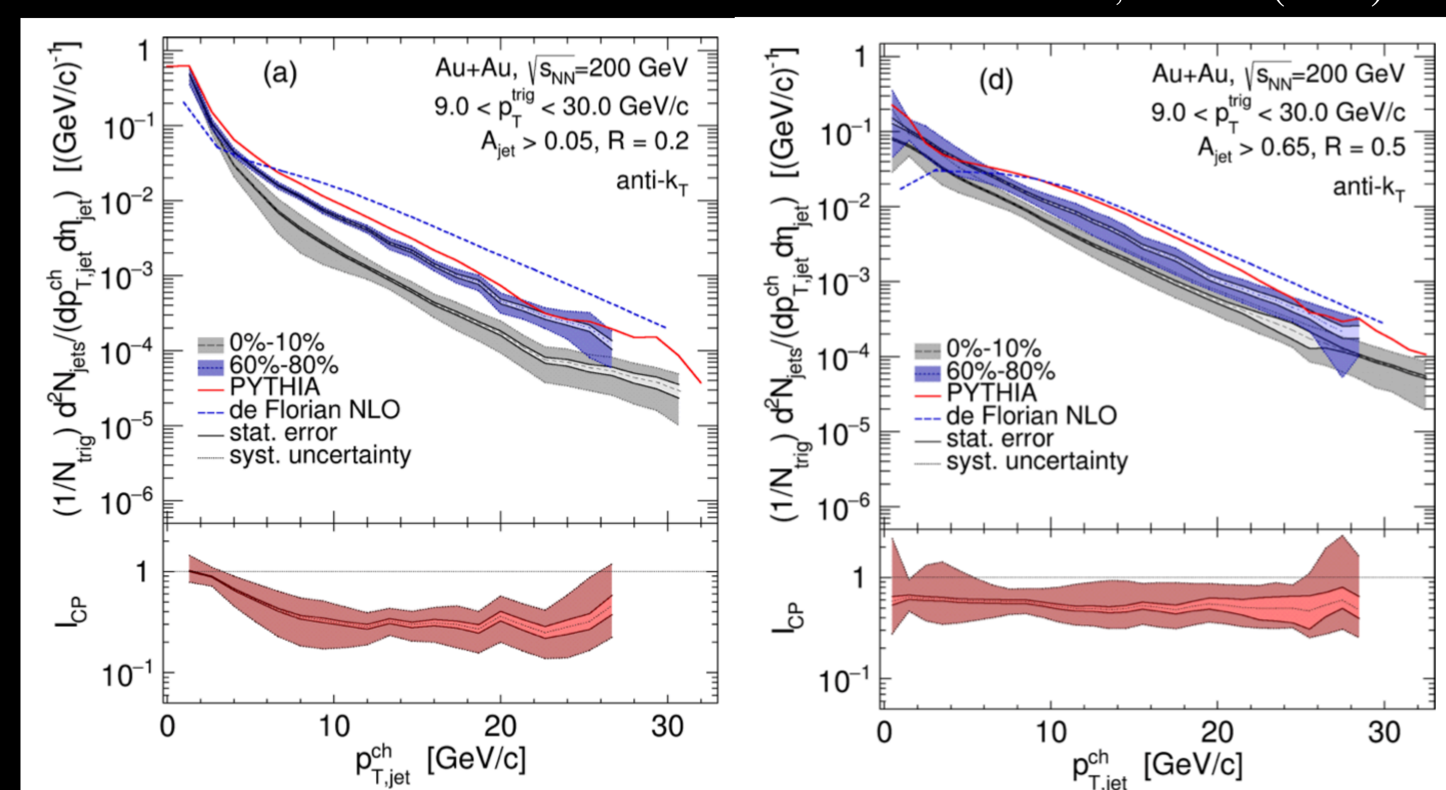


Semi-inclusive h+jet suppression I_{CP}

- Mixed event techniques to subtract uncorrelated background
- A hint of jet-R dependence of suppression

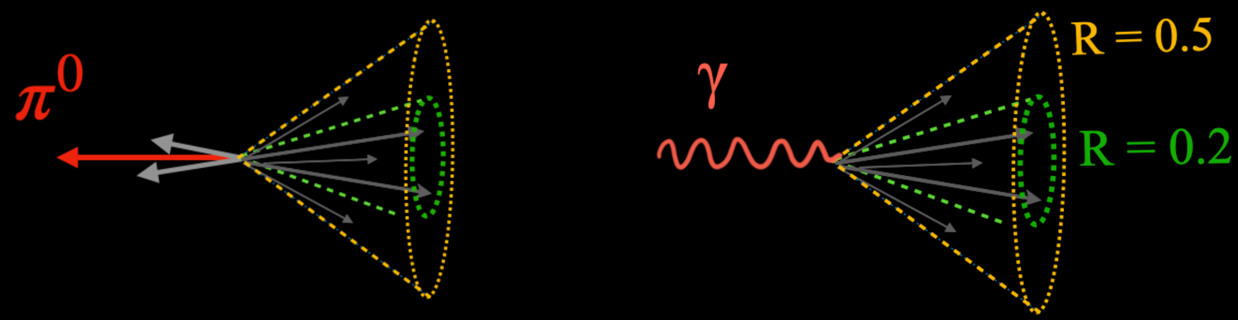


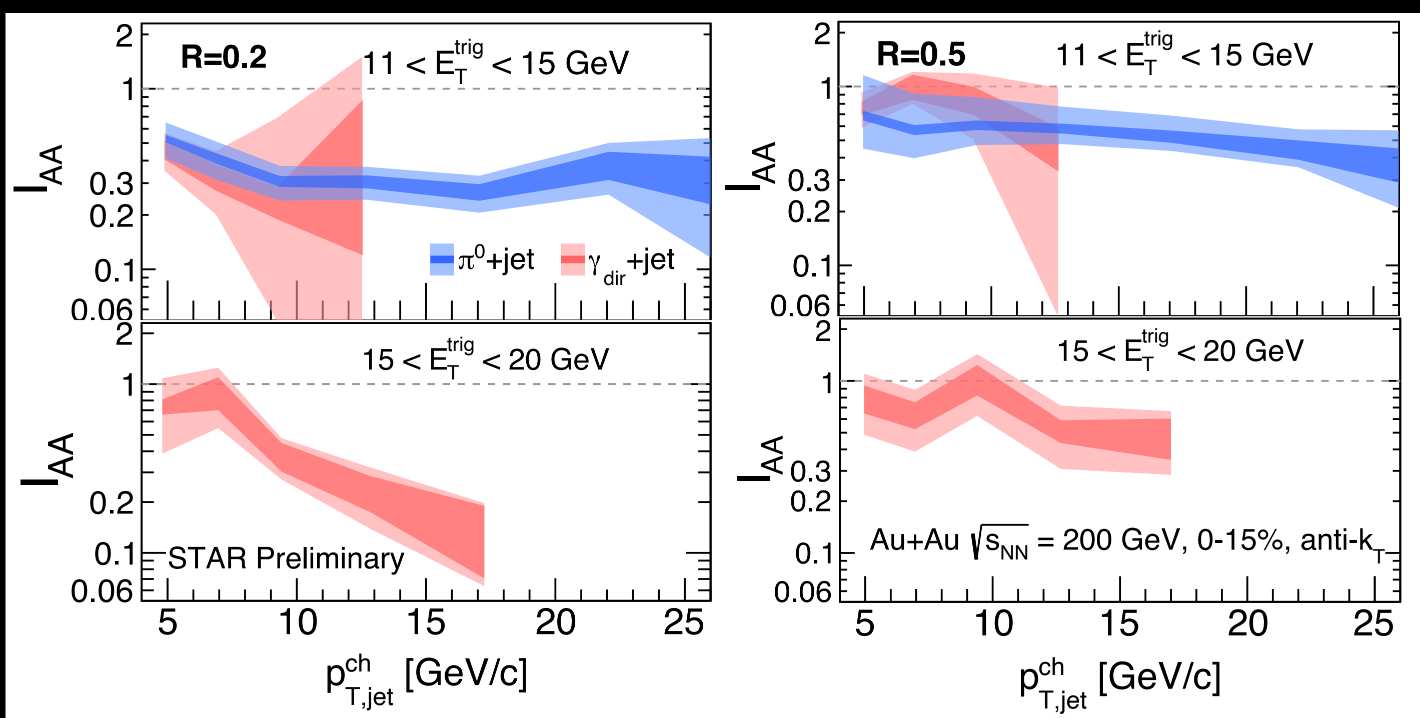
STAR: PRC **96**, 024905 (2017)



Jet quenching: R-dependence of jet yield suppression

Semi-inclusive π^0+jet and γ+jet suppression I_{AA}

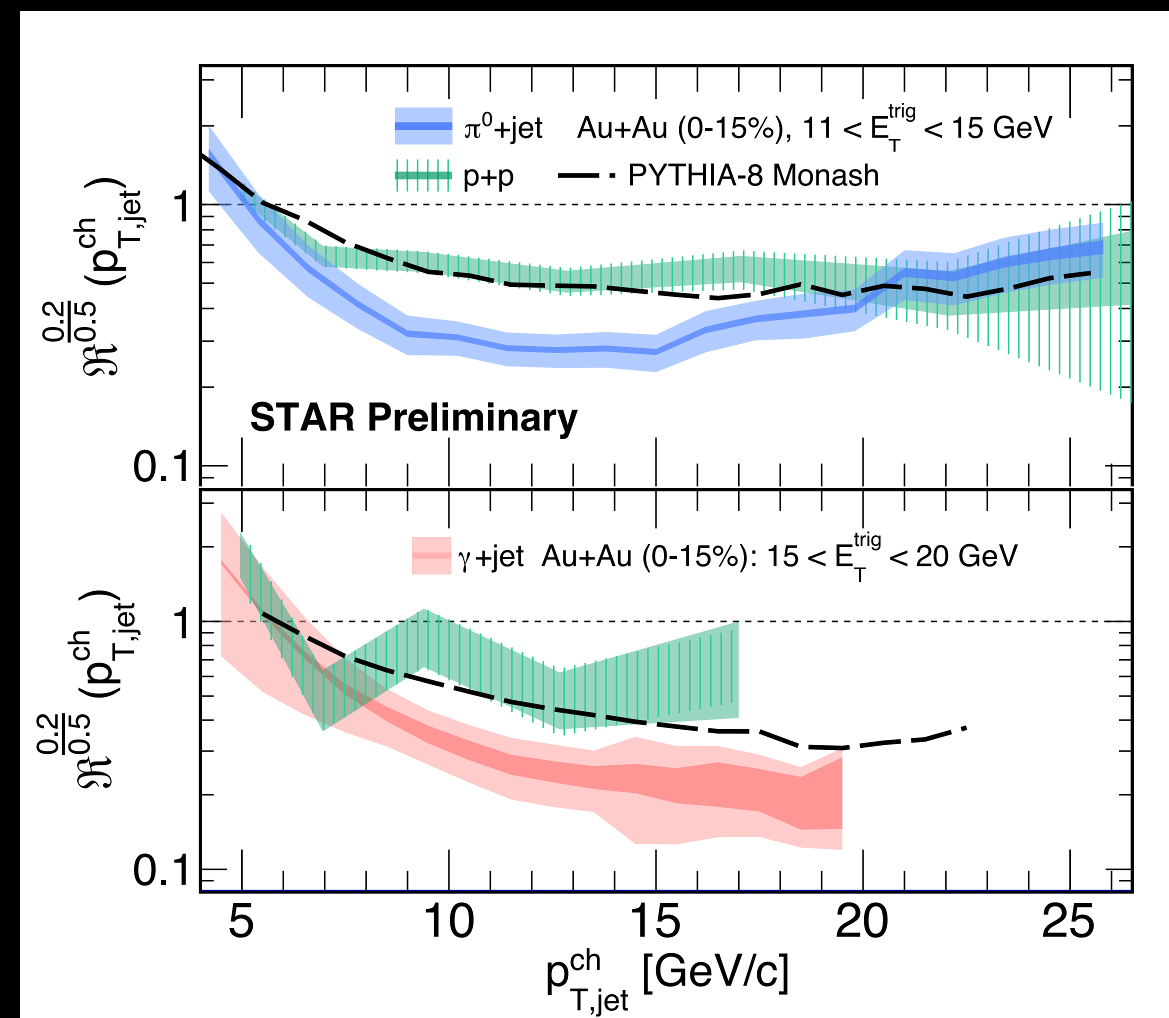




- R dependence of jet yield suppression
- No clear difference between π^0+jet and γ+jet suppression within uncertainty

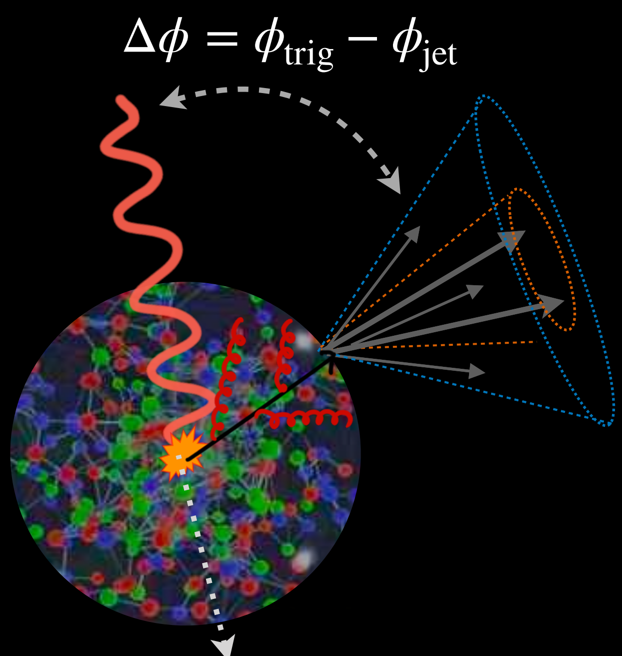
Jet shape modification in QGP

$$\mathfrak{R}^{\frac{\text{small}-R}{\text{large}-R}} = \frac{Y(p_T^{\text{jet,ch}})^{\text{small}-\text{R}}}{Y(p_T^{\text{jet,ch}})^{\text{large}-\text{R}}}$$



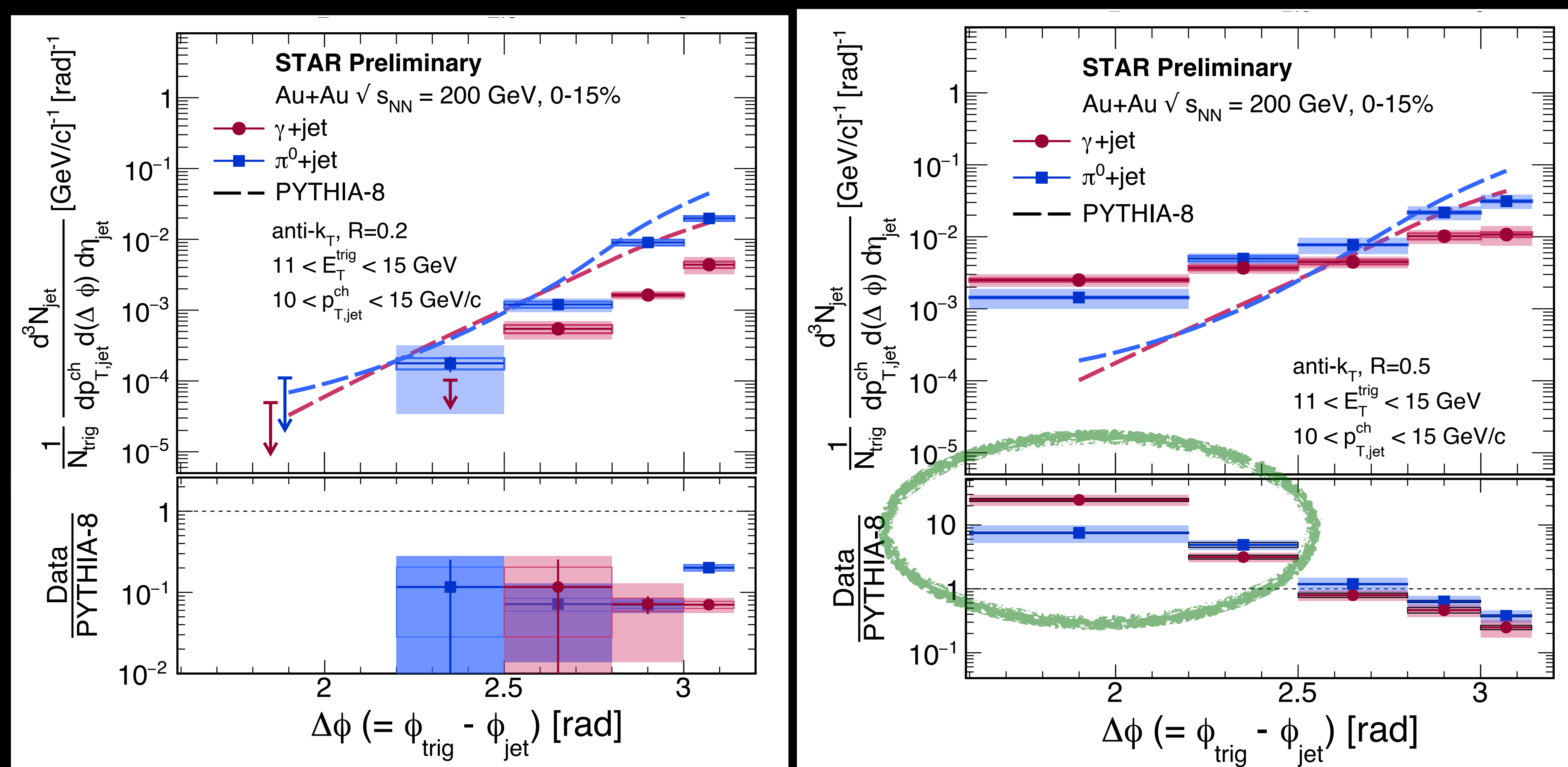
Intra-jet broadening in heavy-ion collisions

Jet acoplanarity in heavy-ion collisions



γ+jet and π⁰+jet azimuthal correlations in Au+Au collisions

***R*=0.2** **11 < E_T^{trig} < 15 GeV** ***R*=0.5**



- Rutherford scattering: Energetic parton resolves microstructure of QGP
- Vacuum shower and medium effect

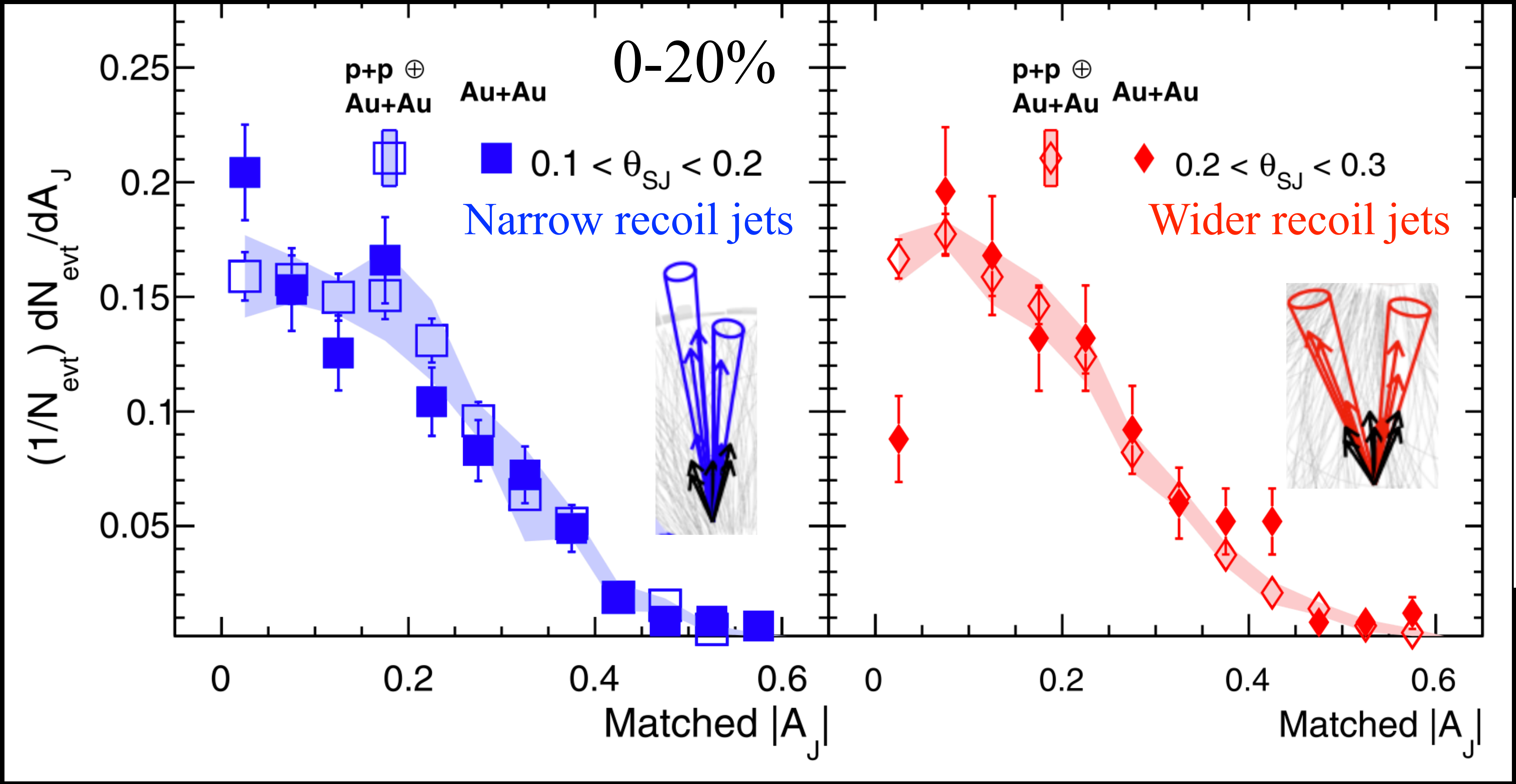
(Same observation is reported at ALICE)

First evidence of significant medium-induced jet acoplanarity in QGP for jets with R=0.5

Jet energy loss dependence on its substructure

STAR: PRC 105 (2022) 4, 044906

Jet with hardcore selection



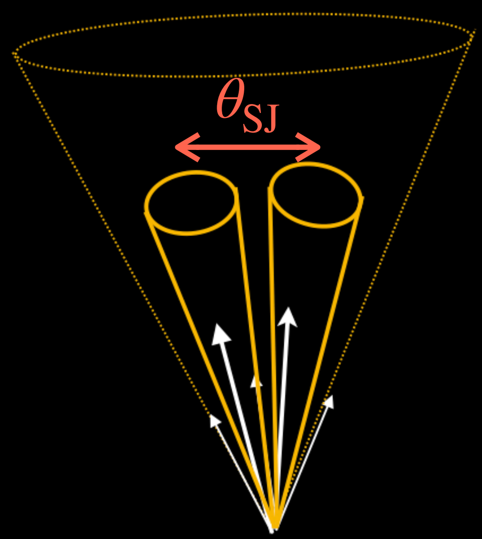
$$A_J = \frac{p_{\mathrm{T,jet}}^{trig} - p_{\mathrm{T,jet}}^{\mathrm{recoil}}}{p_{\mathrm{T,jet}}^{trig} + p_{\mathrm{T,jet}}^{\mathrm{recoil}}}$$

Satisfying SoftDrop grooming condition

Au+Au, p+p $\sqrt{s_{NN}}$ = 200 GeV
Anti-k_T R_{jet} = 0.4, Anti-k_T R_{SJ} = 0.1
$|\eta_{jet}|+R_{jet} < 1.0$

HardCore Di-jets
Trigger $p_{T,jet}$ > 16 GeV/c
Recoil $p_{T,jet}$ > 8 GeV/c

Recoil Matched Jet θ_{SJ} Selection
$\Delta\phi$ (jet, HT) > $2\pi/3$



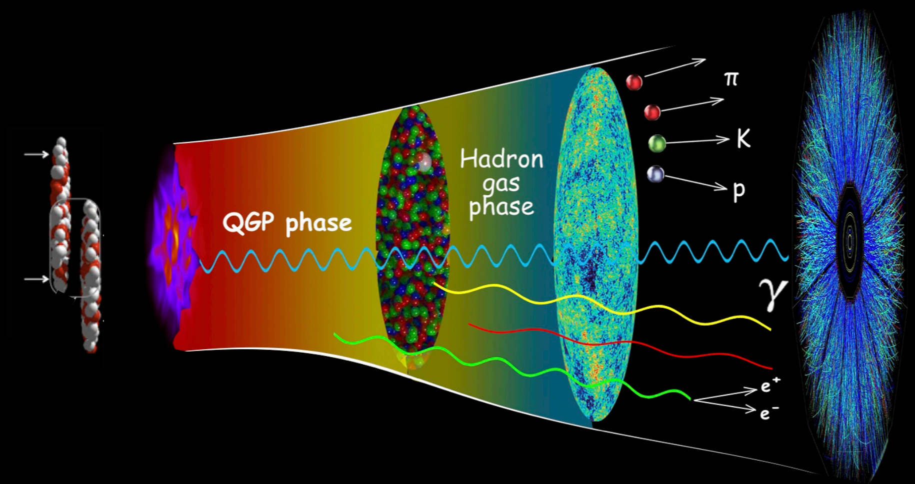
First evidence for energy loss being independent on its opening angle (with hardcore jet selection)

What we have learned so far?

Bulk properties of QGP

Beam Energy Scan program:

- Non-monotonic behavior in higher order susceptibilities ratios (Possible QCD CP signature?)
- Possible different EOS at 3 GeV (FXT)
- Disappearance of partonic collectivity and absence of NCQ scaling at 3 GeV
- Most vortical fluid (angular momentum, B-field?)
- Hypernuclei production at high baryon density



Inner workings of QGP

Hard Probes program

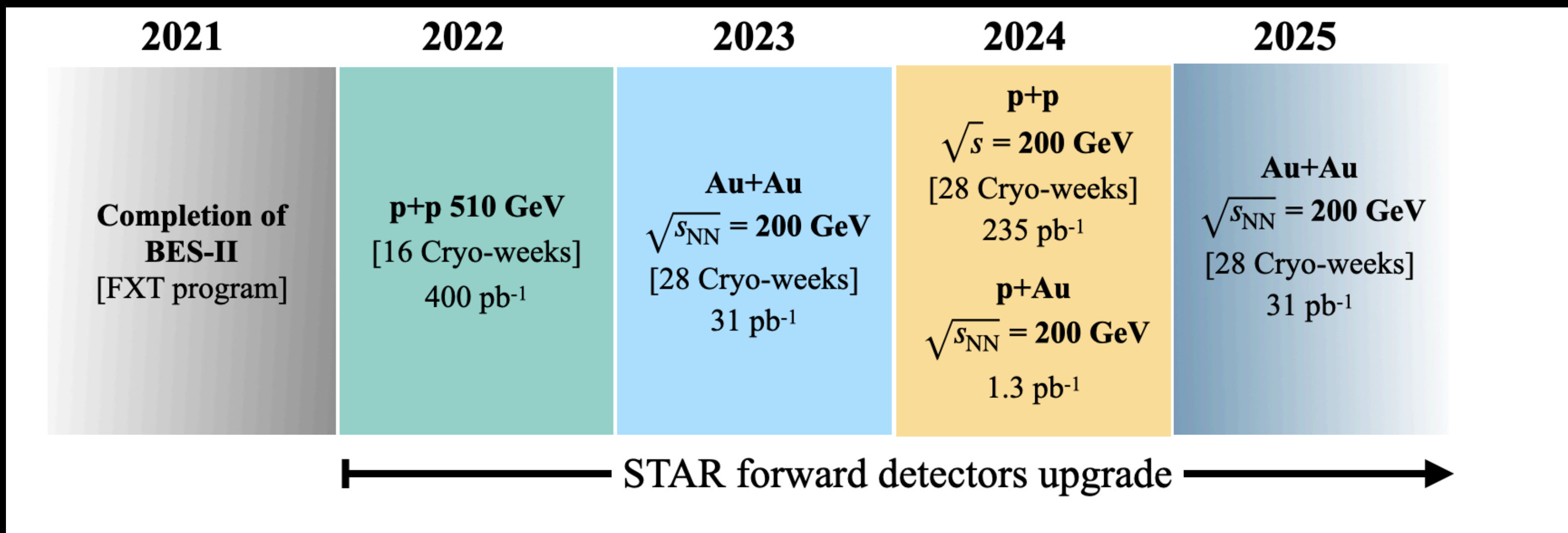
- Suppression of open heavy flavor and quarkonia
- Mass dependent parton energy loss
- Jet suppression and accoplanarity (different manifestation of jet-medium interactions)

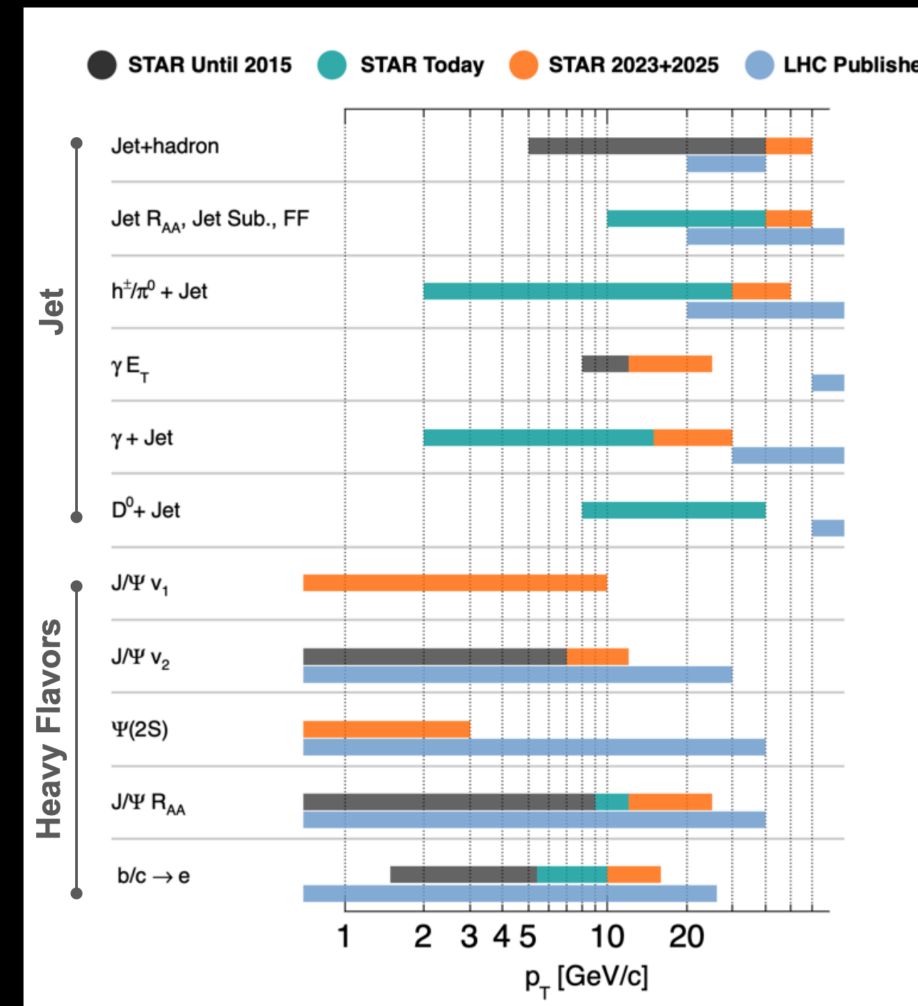
Many important results not covered due to limited time
BES-II data analyses ongoing

STAR enters to a precision era …

Future of STAR data taking plan

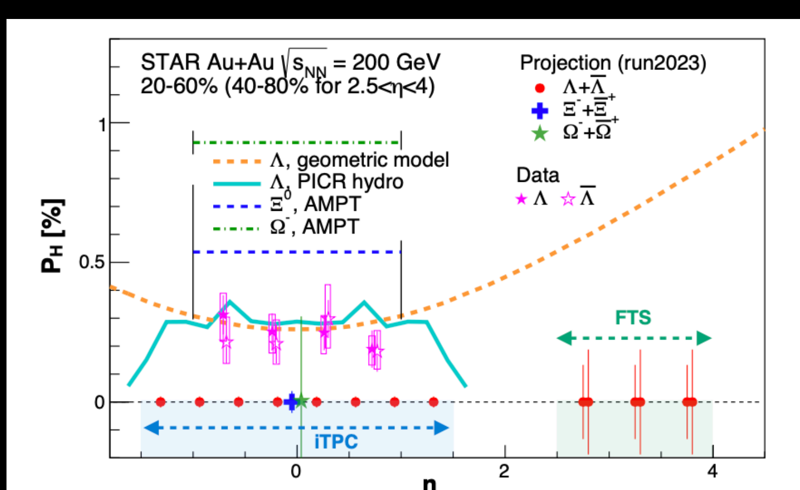
STAR physics program for Run23+25

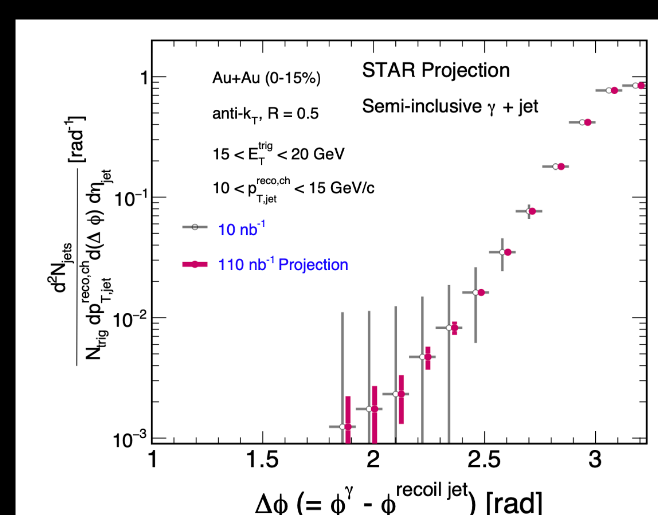


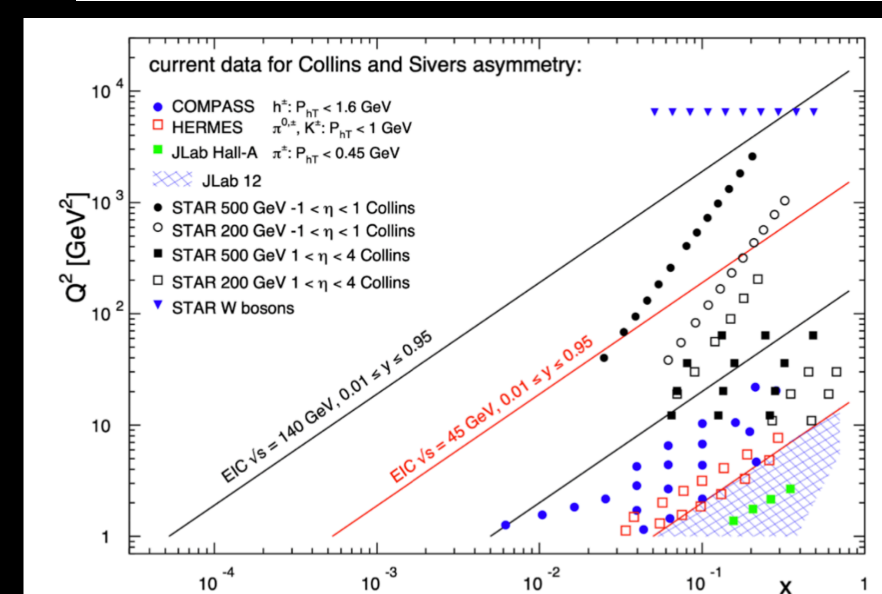


It includes Hot-QCD and Cold-QCD programs

- Hot-QCD program: Study the microstructure of the QGP (Precision jet and heavy-flavor measurements)
- Cold-QCD program will provide inputs for future EIC program







Variety of physics topics ongoing in STAR from hot QCD to cold QCD sides

Upcoming data taking in 2023-2025 will be crucial for the completion of RHIC scientific mission
(Particularly high precision measurement)

Stay tuned for exciting physics at STAR…

Thank you

Chilika Lake nearby (a brackish water lagoon)