Selected Results from STAR Beam Energy Scan

CERN EP Seminar

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Outline

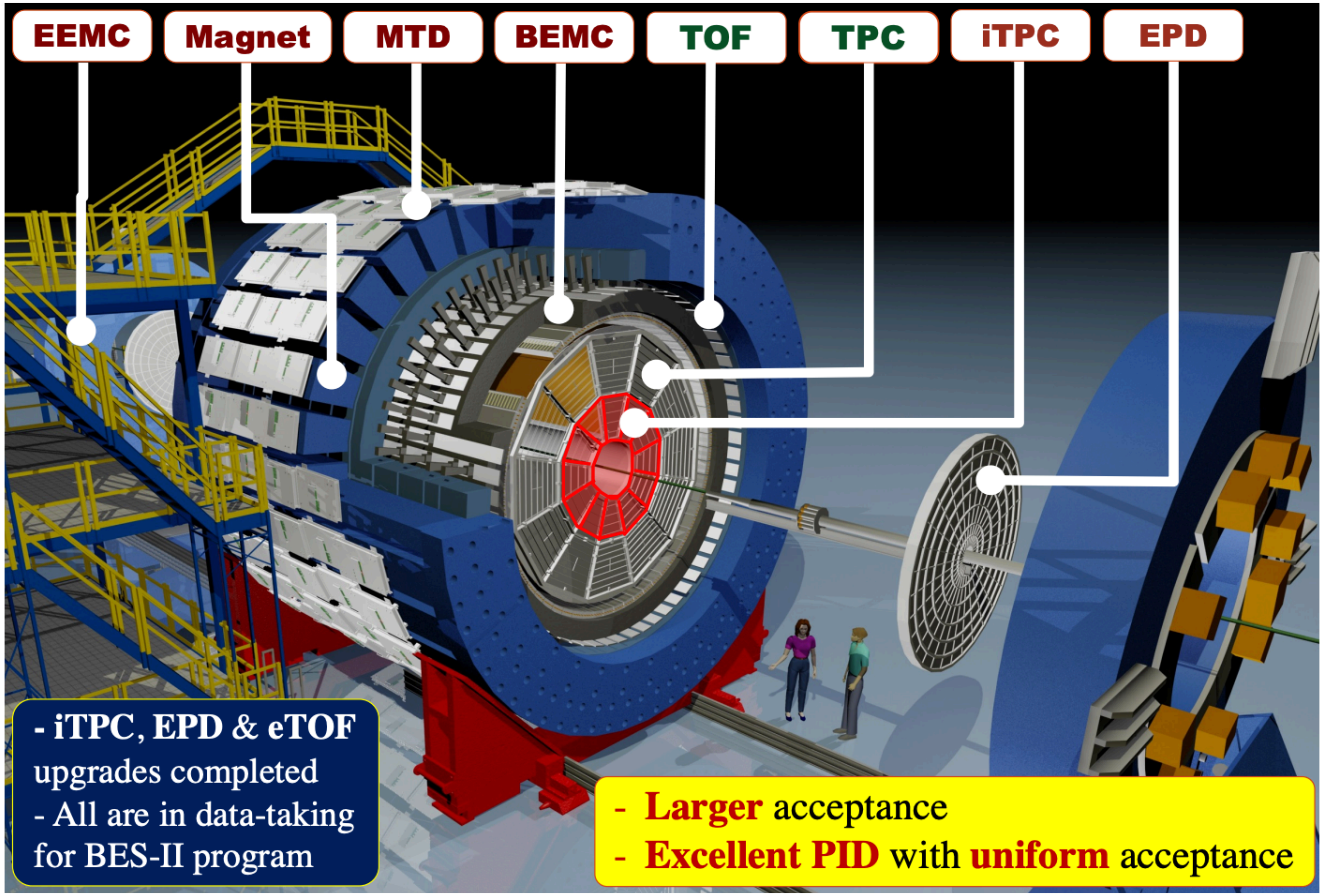
- **Introduction**
- **STAR BES-II**
  - Particle Production
  - Collective Flow
  - Higher Order Cumulants
  - Thermal Dileptons
  - Light Nuclei and Hypernuclei
  - Global Polarization and Spin Alignment
- **Summary**

Relativistic Heavy Ion Collider (RHIC)

- Located at Brookhaven National Laboratory
- STAR+sPHENIX (currently running)
- Collision species (p+p, p+Au, Au+Au, ...)
- Collision energies ($\sqrt{s_{NN}}$=3-200 GeV for Au+Au)

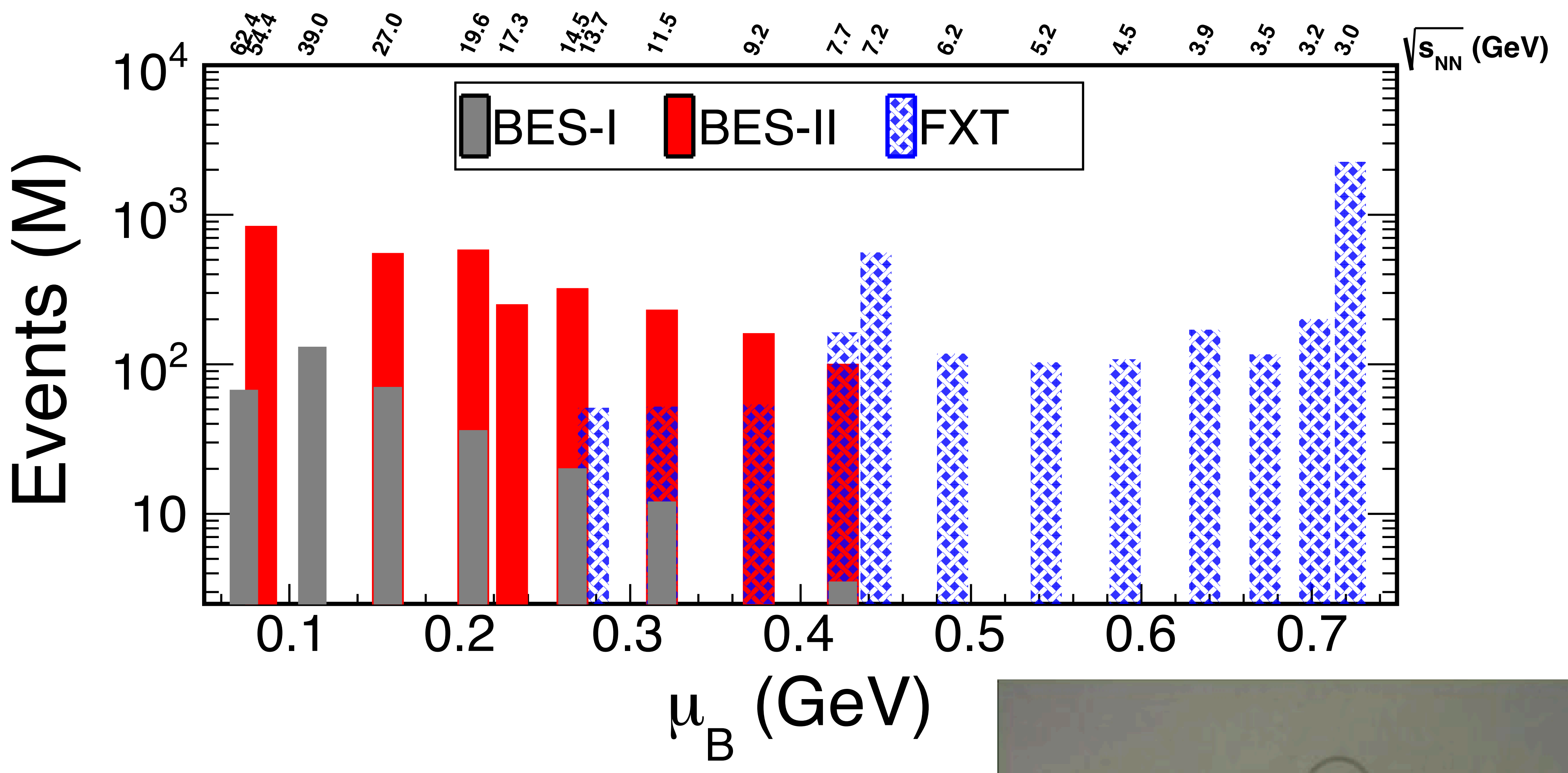
The STAR (Solenoidal Tracker At RHIC) Detector

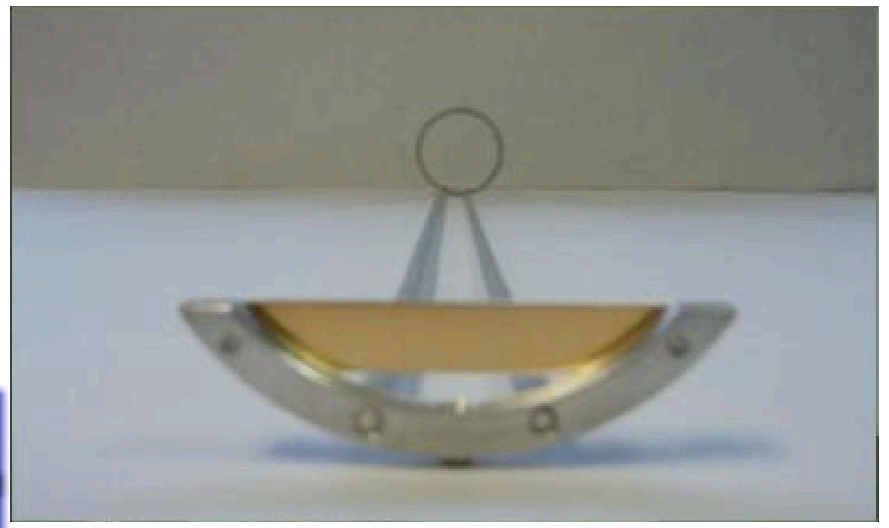
- Solenoidal magnet with 0.5T uniform field
- Time projection chamber (TPC)
- Time-of-flight (TOF) detector
- Electromagnetic calorimeters

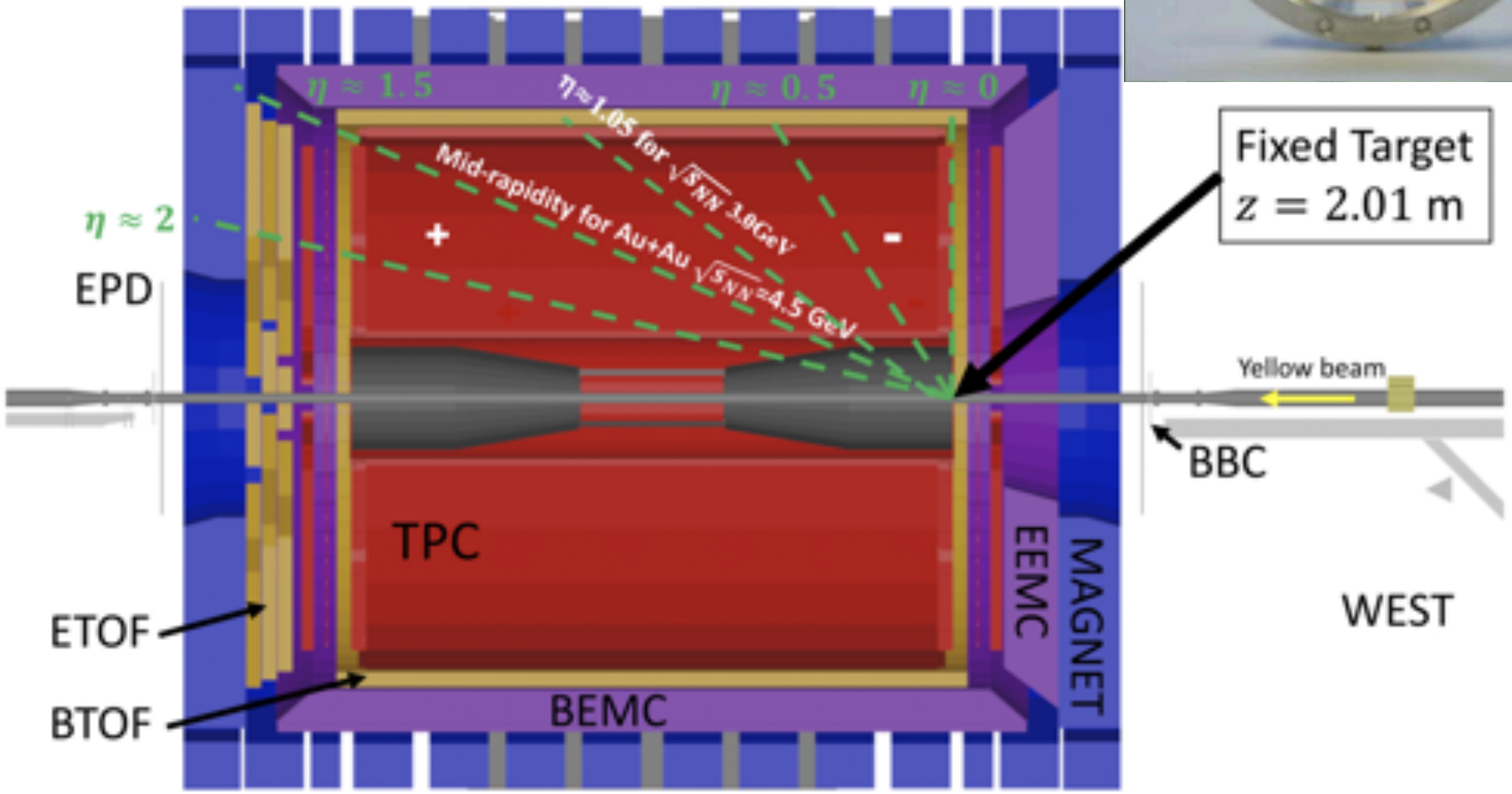


Beam Energy Scan (BES)

- BES-I (2009-2011)
  - Au+Au collisions $\sqrt{s_{NN}}$ = 7.7-62 GeV
  - Main objectives:
    - Search for onset of deconfinement
    - Search for critical end point
- BES-II (2018-2021)
  - High statistics Au+Au collisions $\sqrt{s_{NN}}$ =3-54.4 GeV
  - Fixed target (FXT) collisions extend energy reach down to $\sqrt{s_{NN}}$ =3 GeV
    - Search for possible formation and investigate properties of dense baryonic matter

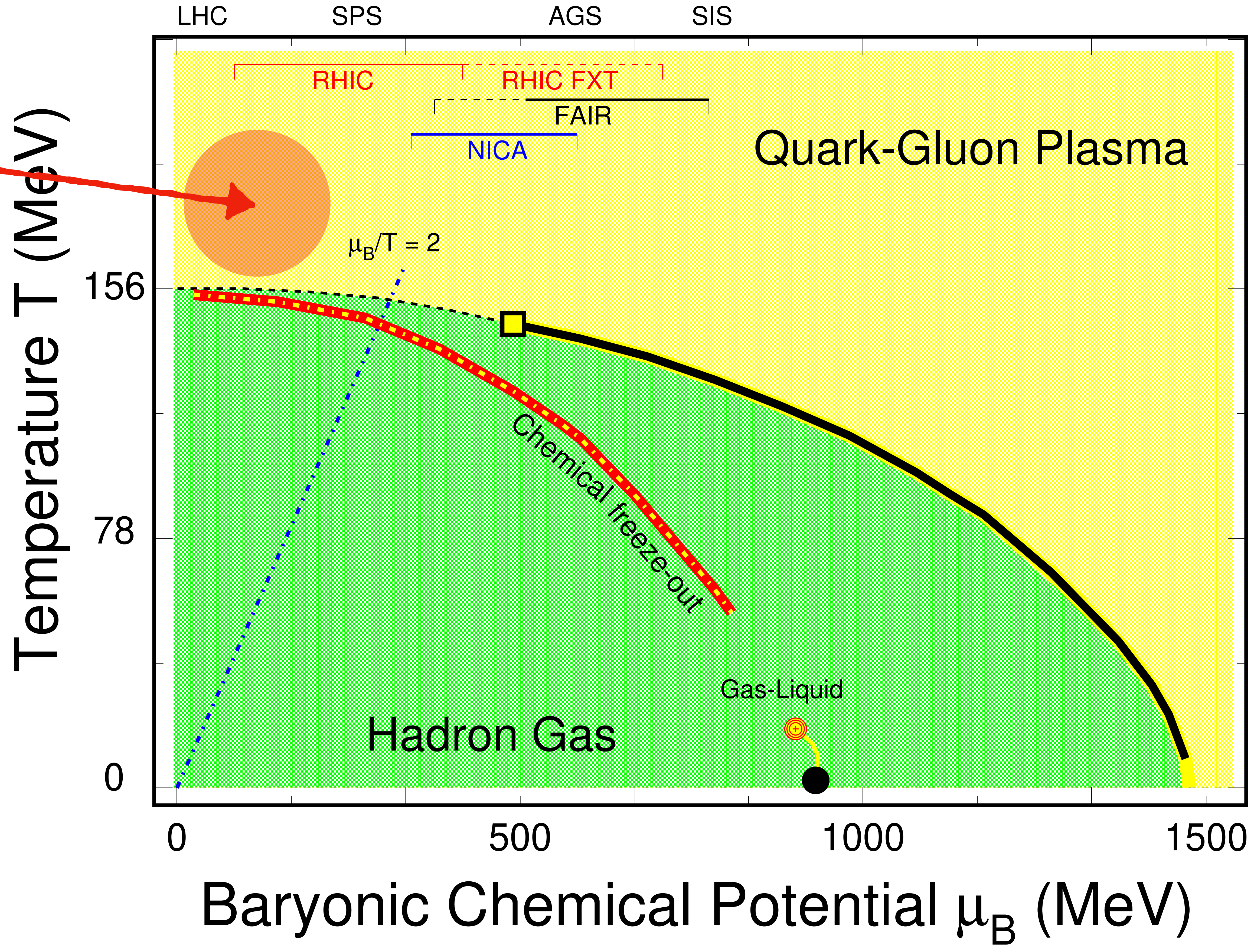






Probing the QCD Phase Diagram

- **QGP formation at top RHIC energies**
  $\sqrt{s_{NN}}$ = 200 GeV, μ_B = 20 MeV
  - Probe characteristics with heavy flavor, strangeness, jets etc.



STAR, PRL126,9,092301(2021)

Probing the QCD Phase Diagram

- **QGP formation at top RHIC energies**

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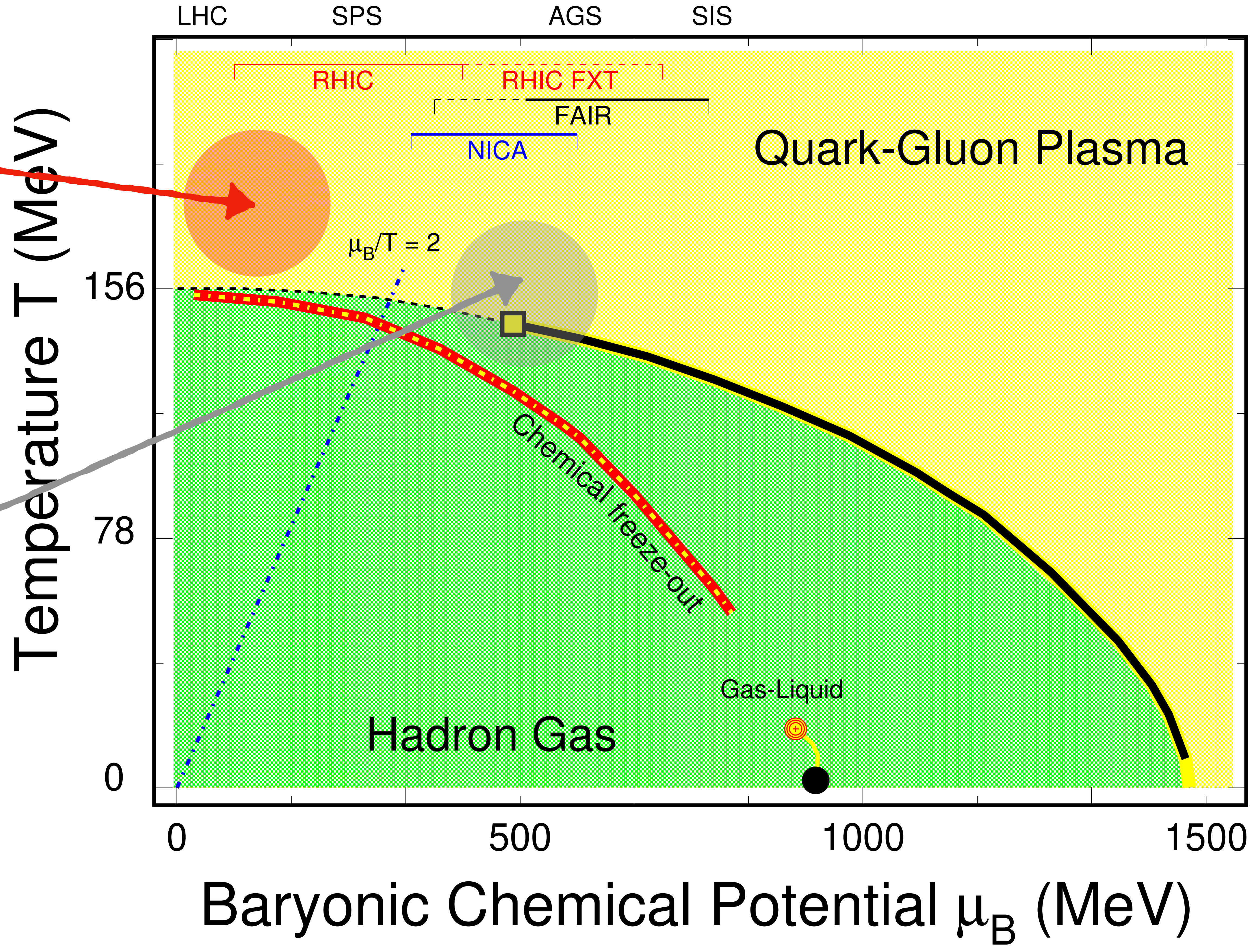
- **Intermediate μ_B region: STAR collider mode**

  $\sqrt{s_{NN}}$ = 7.7-27 GeV, μ_B = 420 - 200 MeV

  - Probe onset of deconfinement
  - Search for critical phenomena



STAR, PRL126,9,092301(2021)

Probing the QCD Phase Diagram

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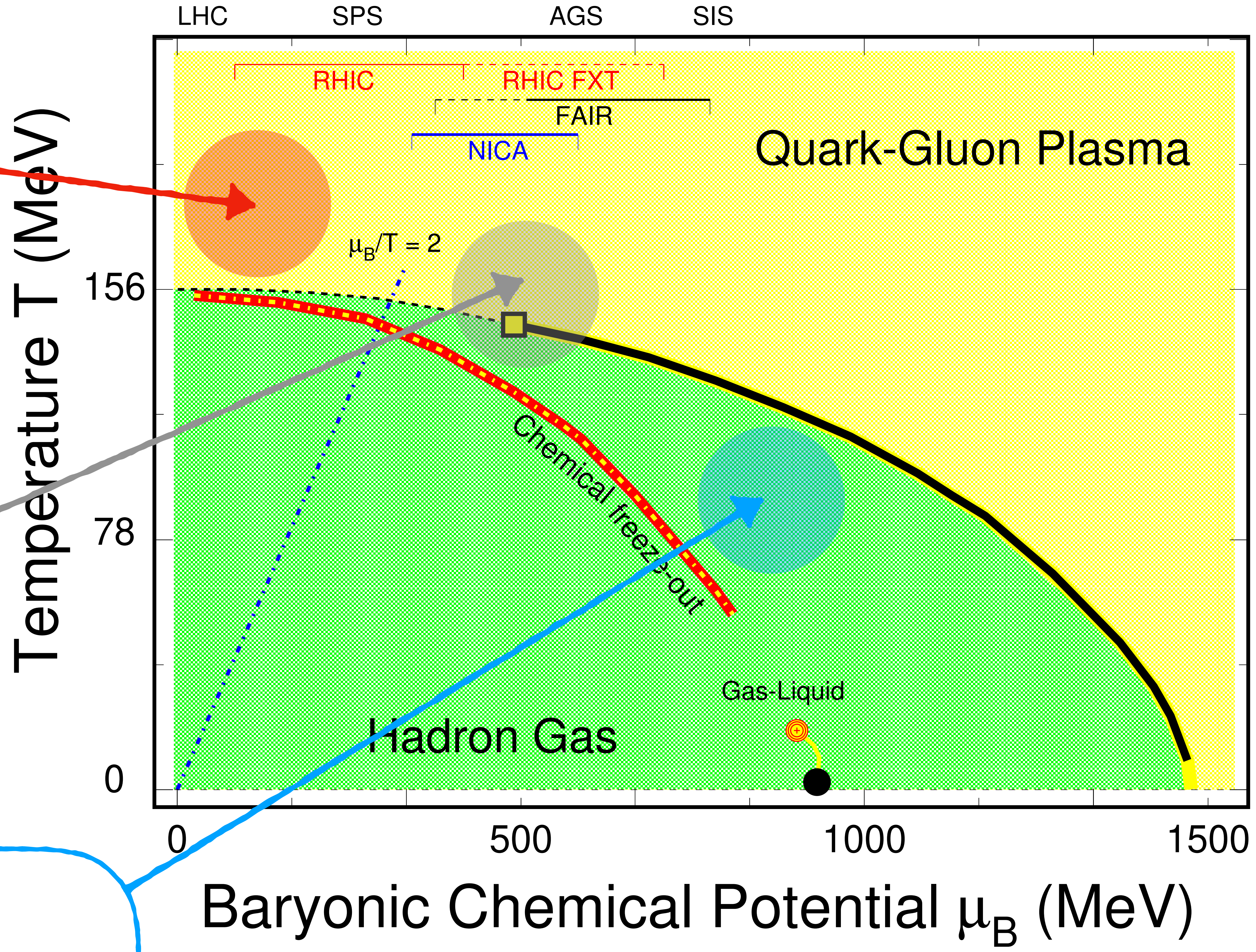
  - Probe onset of deconfinement
  - Search for critical phenomena

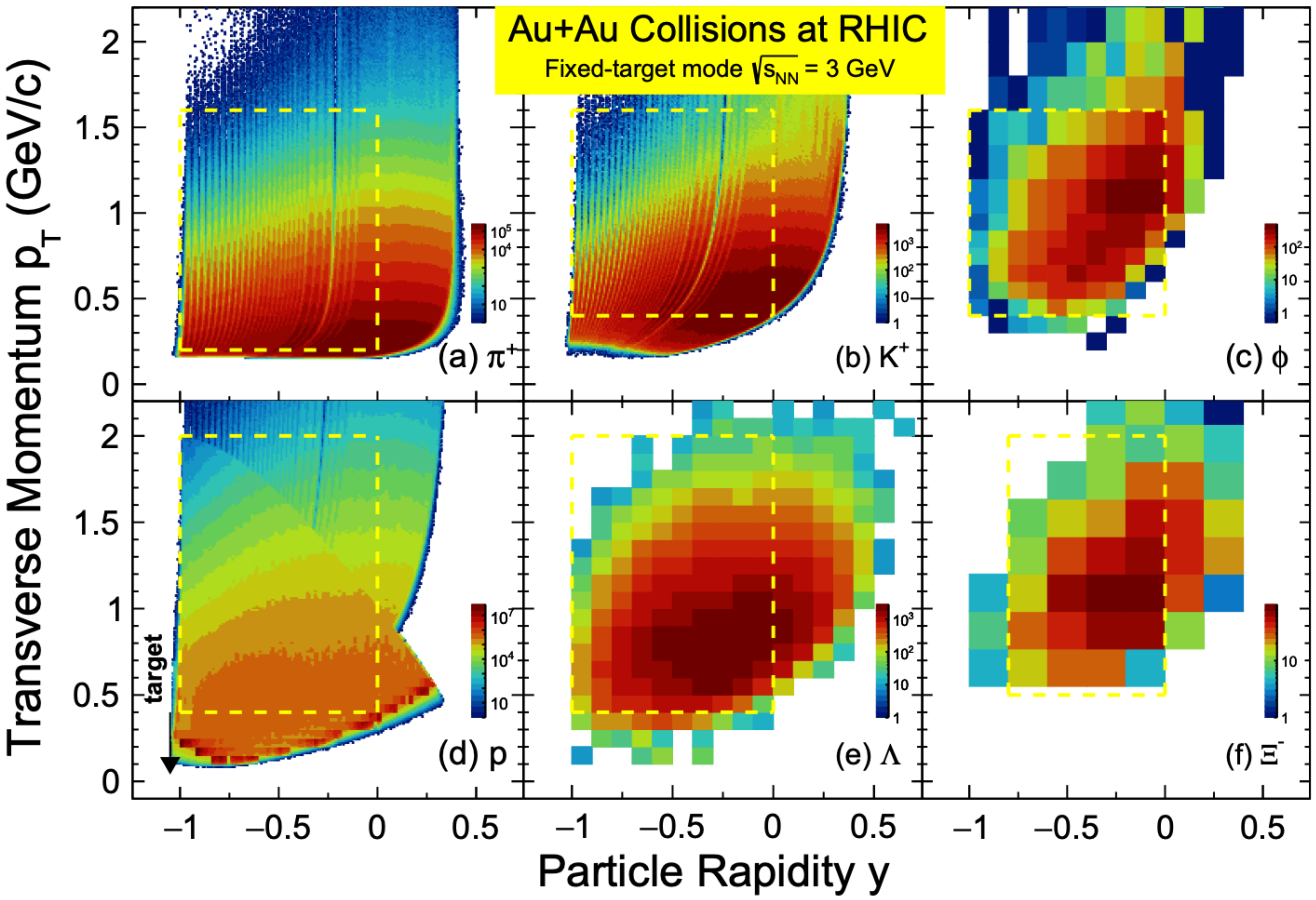
- **High μ_B region: STAR fixed-target (FXT)**
  $\sqrt{s_{NN}}$ = 3.0-13.7 GeV, μ_B = 750 - 280 MeV
  - Nature of produced medium (hadronic vs partonic?)
  - Investigate properties of dense baryonic matter

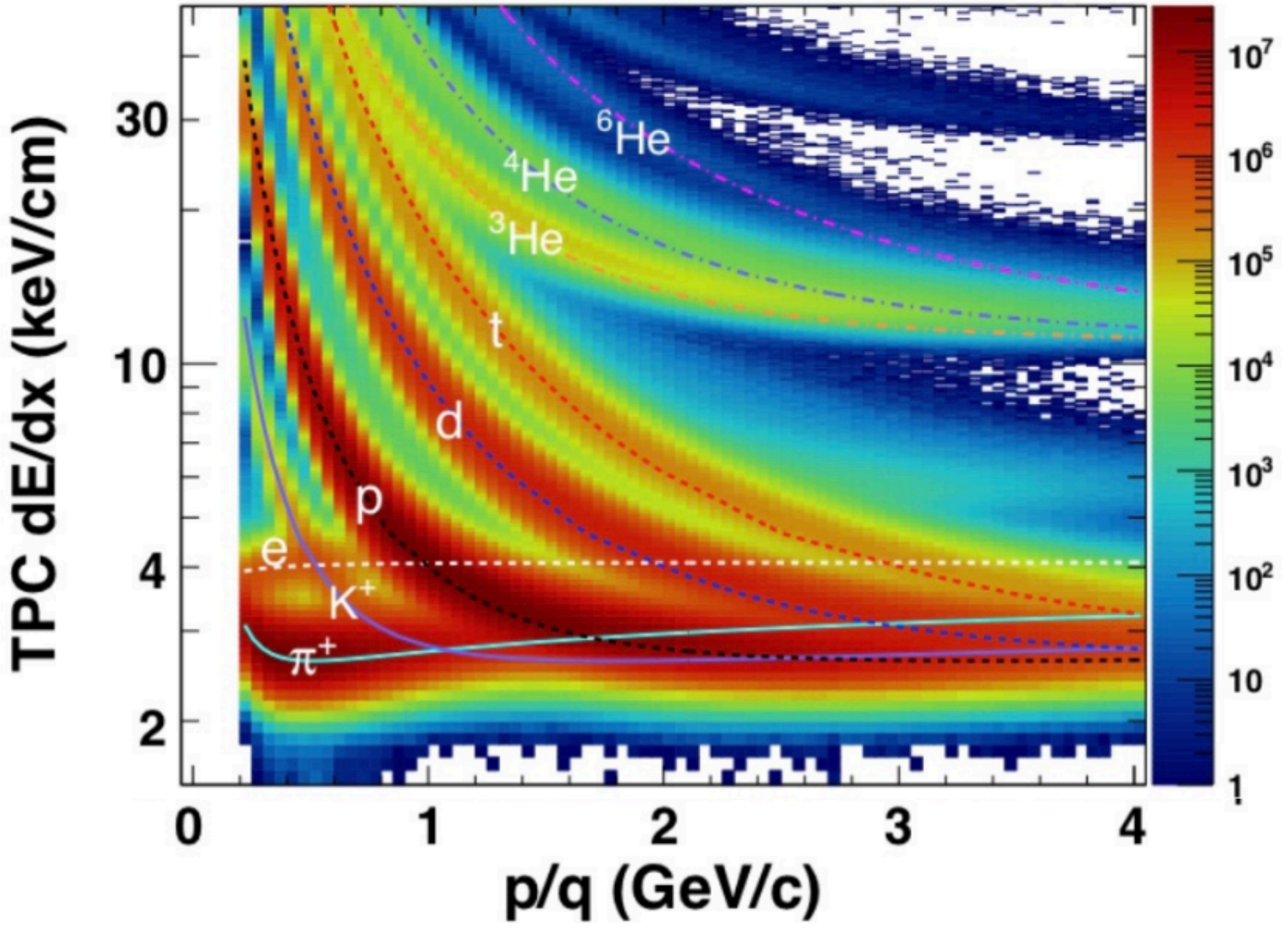


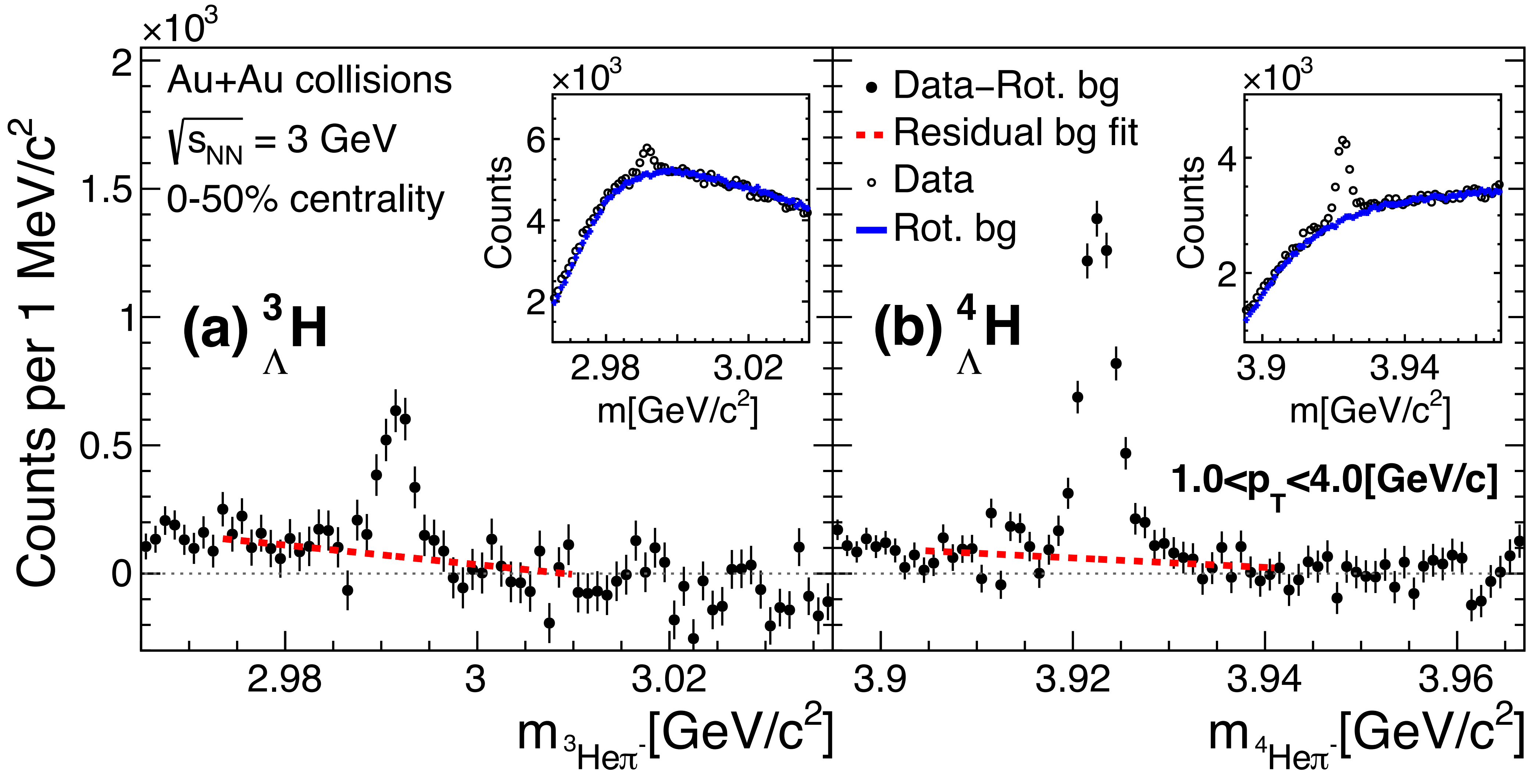
STAR, PRL126,9,092301(2021)

Probing the QCD Phase Diagram

Fixed Target Au+Au Collisions at 3 GeV

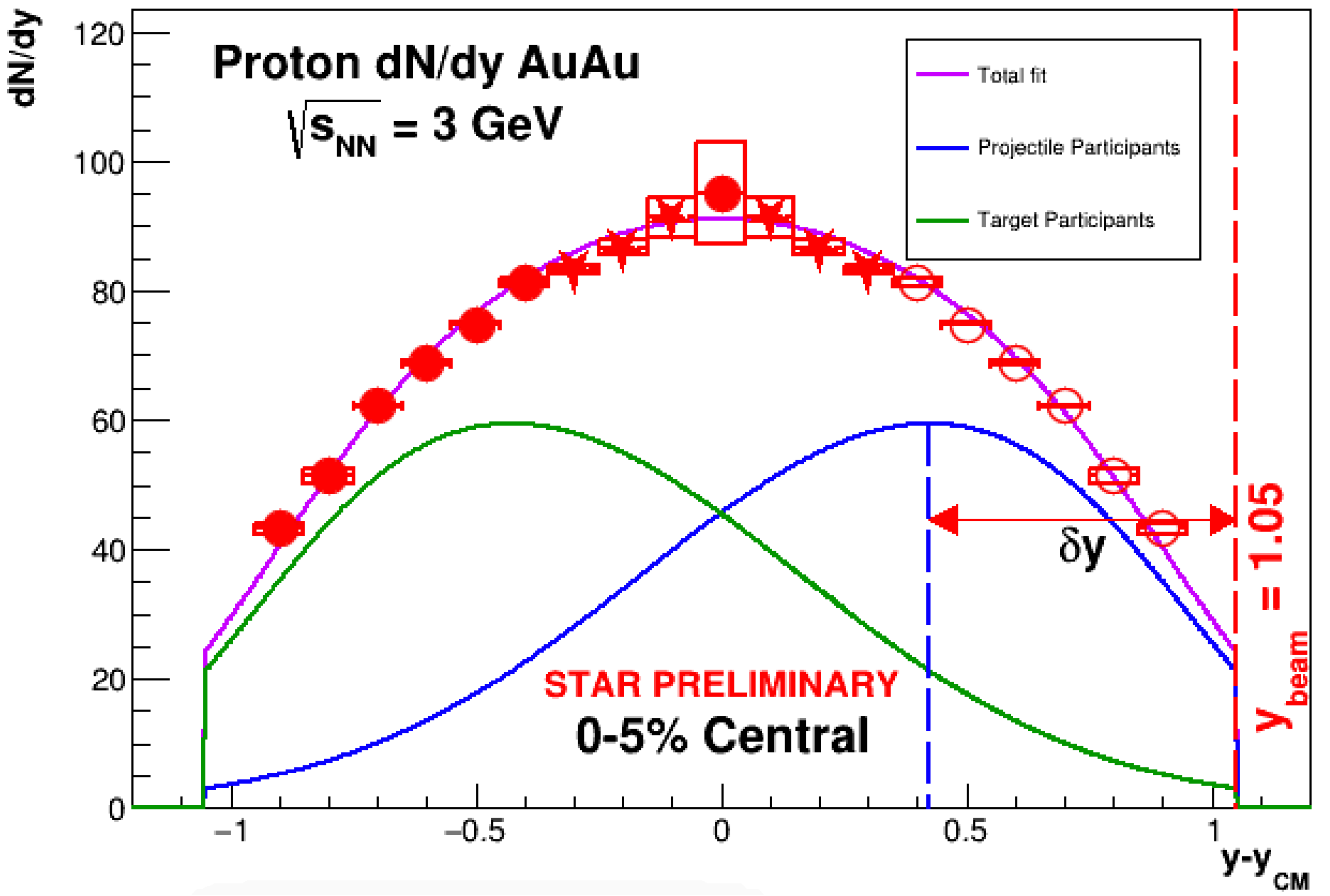


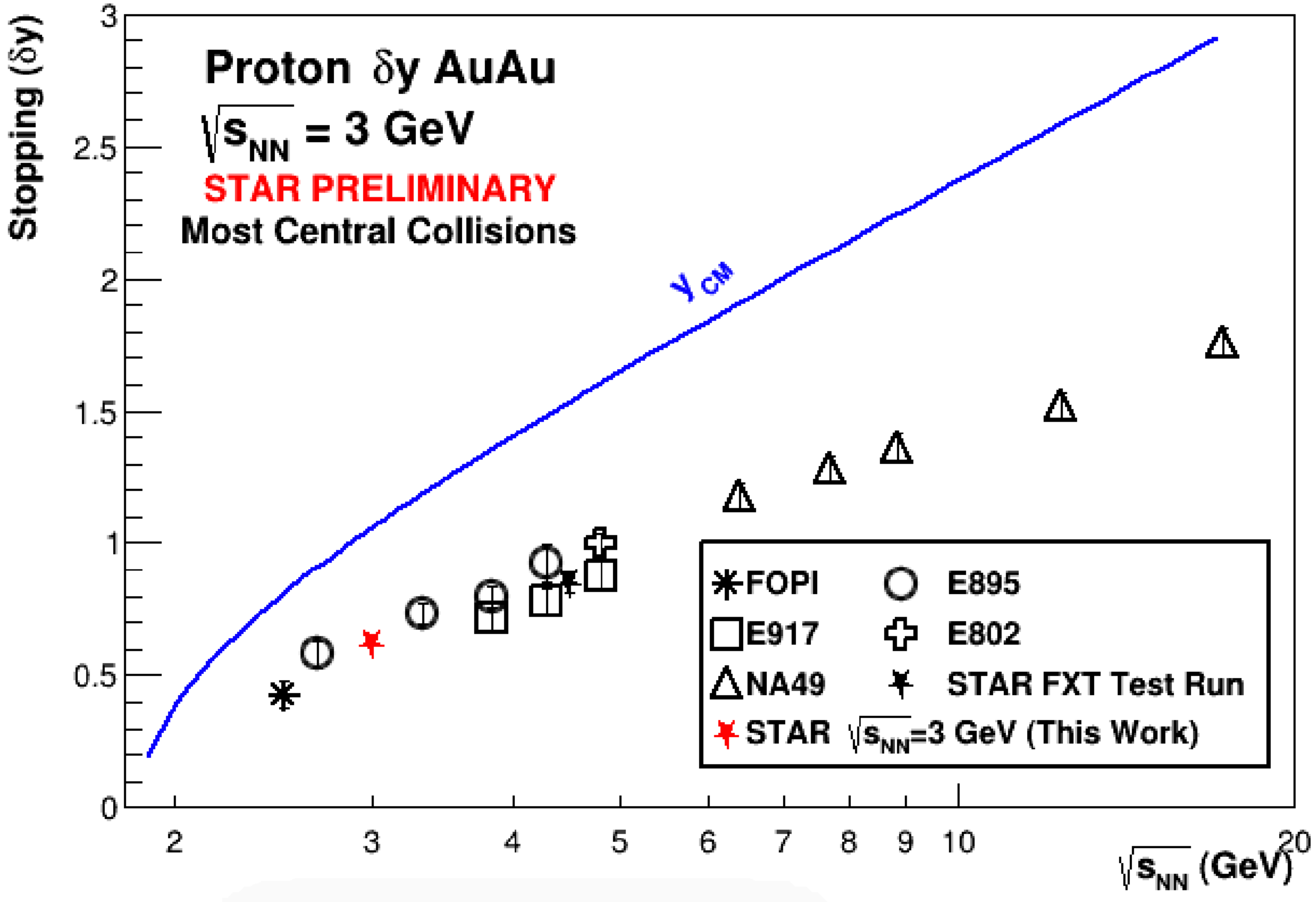




- 260M events collected in 2018
- Good mid-rapidity coverage for most particles
- Nuclei up to A=6, hypernuclei up to A=4

Baryon Stopping at 3 GeV

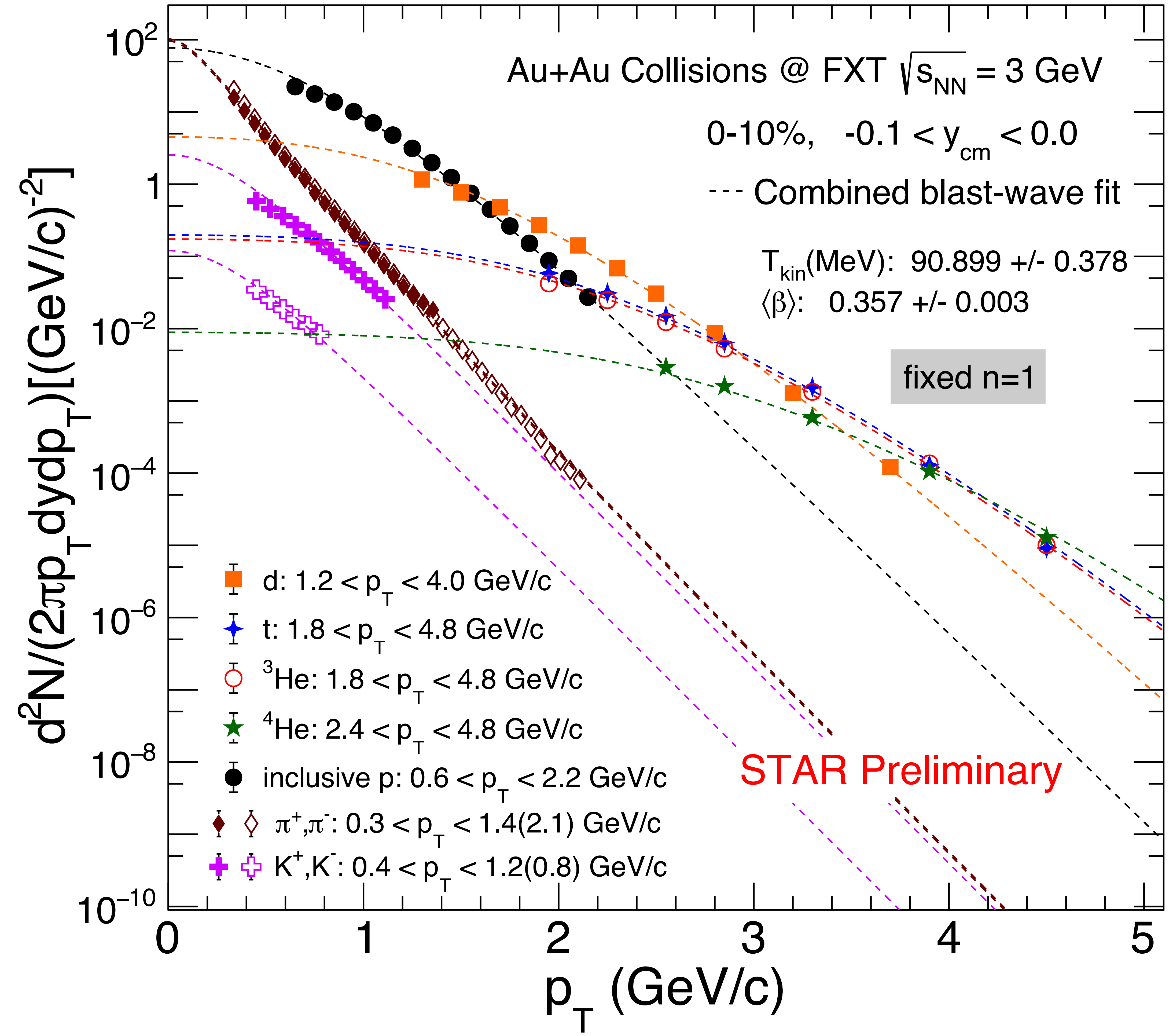


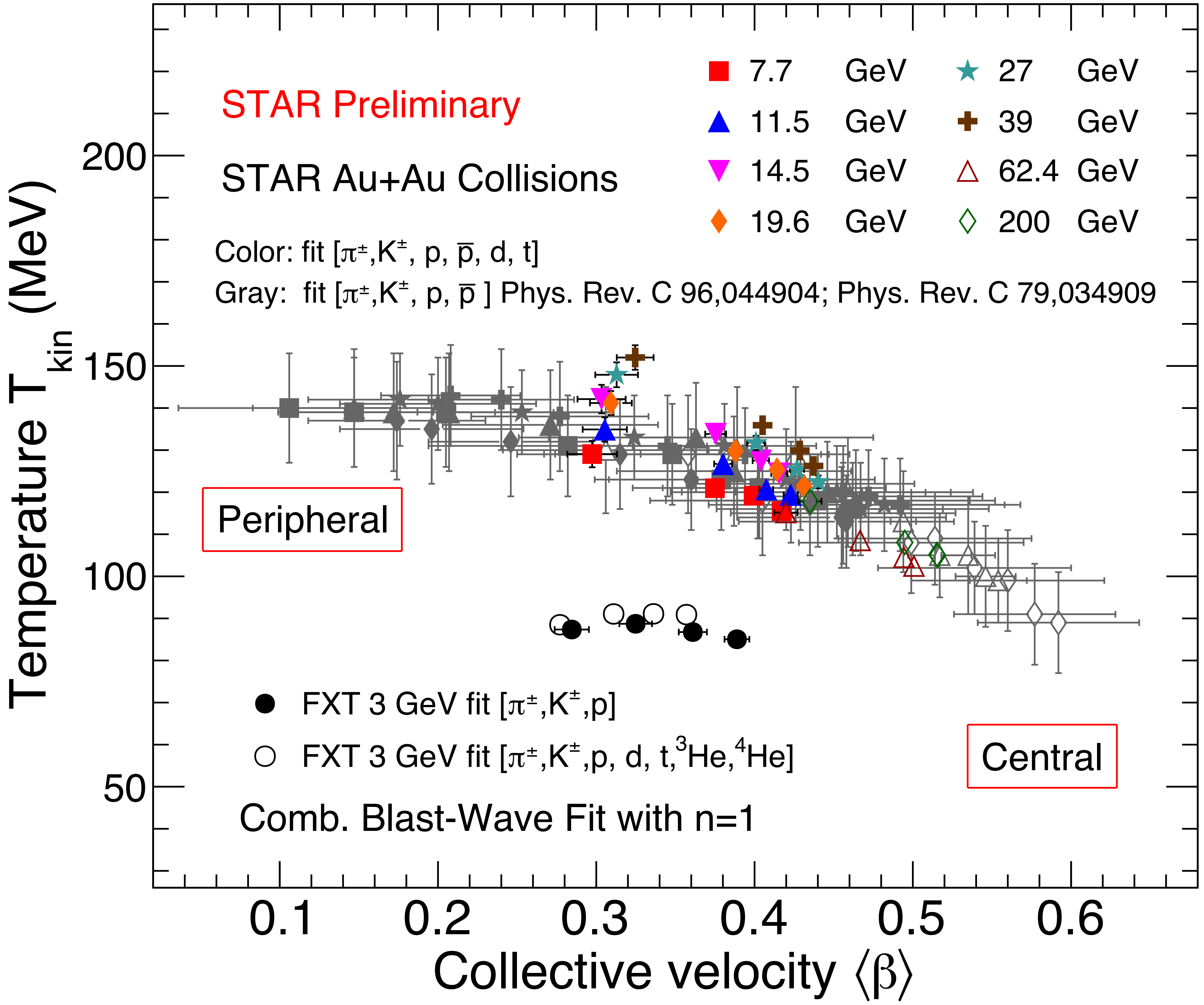


- The stopping, δy, is defined as the shift of the participant proton peak from beam rapidity

Baryon stopping ⟶ High baryon density

Kinematic Freezeout Properties at 3 GeV





- Extract common kinetic freeze-out temperature T_{kin} and average transverse radial flow velocity β through combined Blast Wave fit

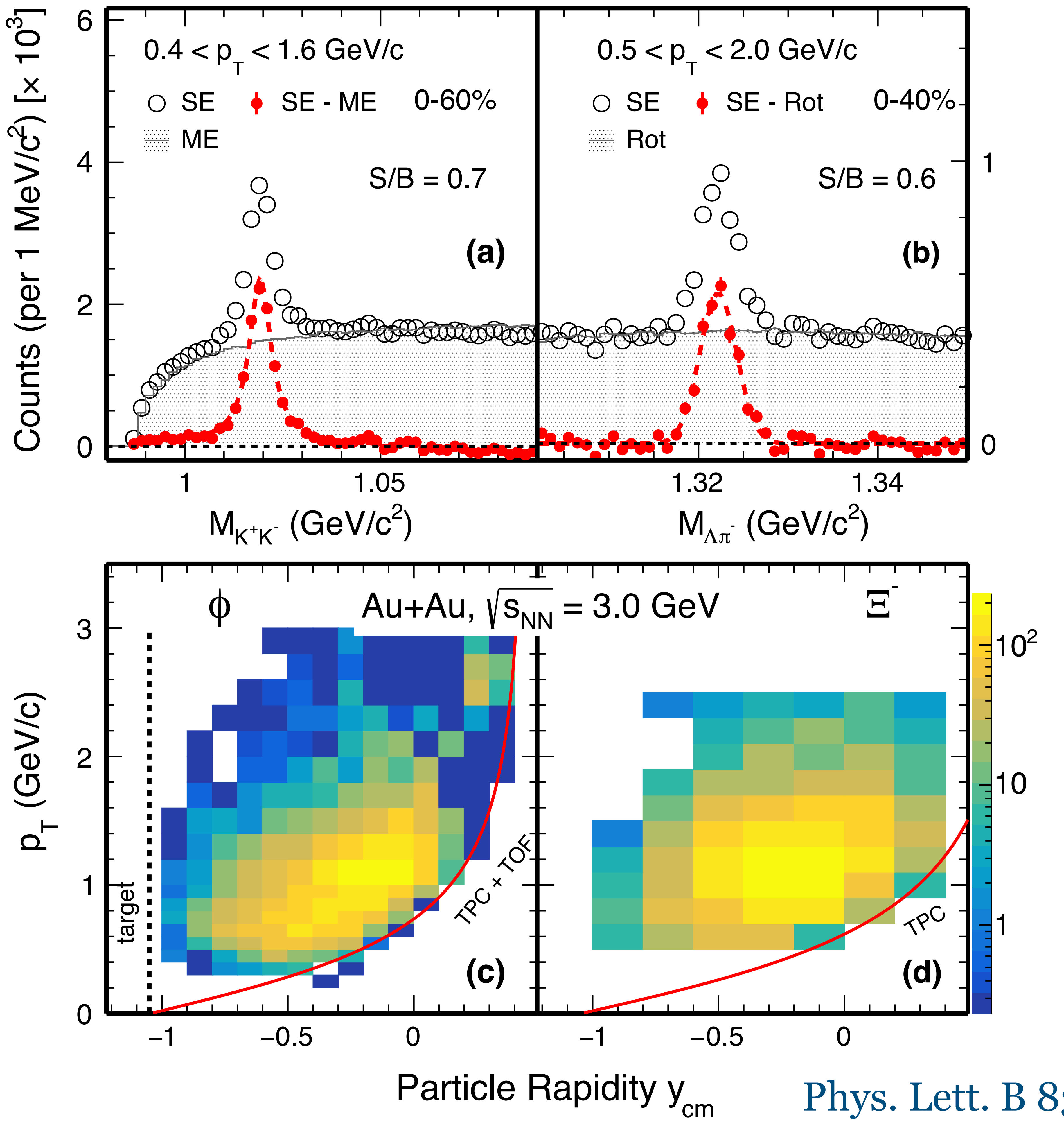
$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

- At 3 GeV, T_{ch} ~ 80MeV, similar with T_{kin}

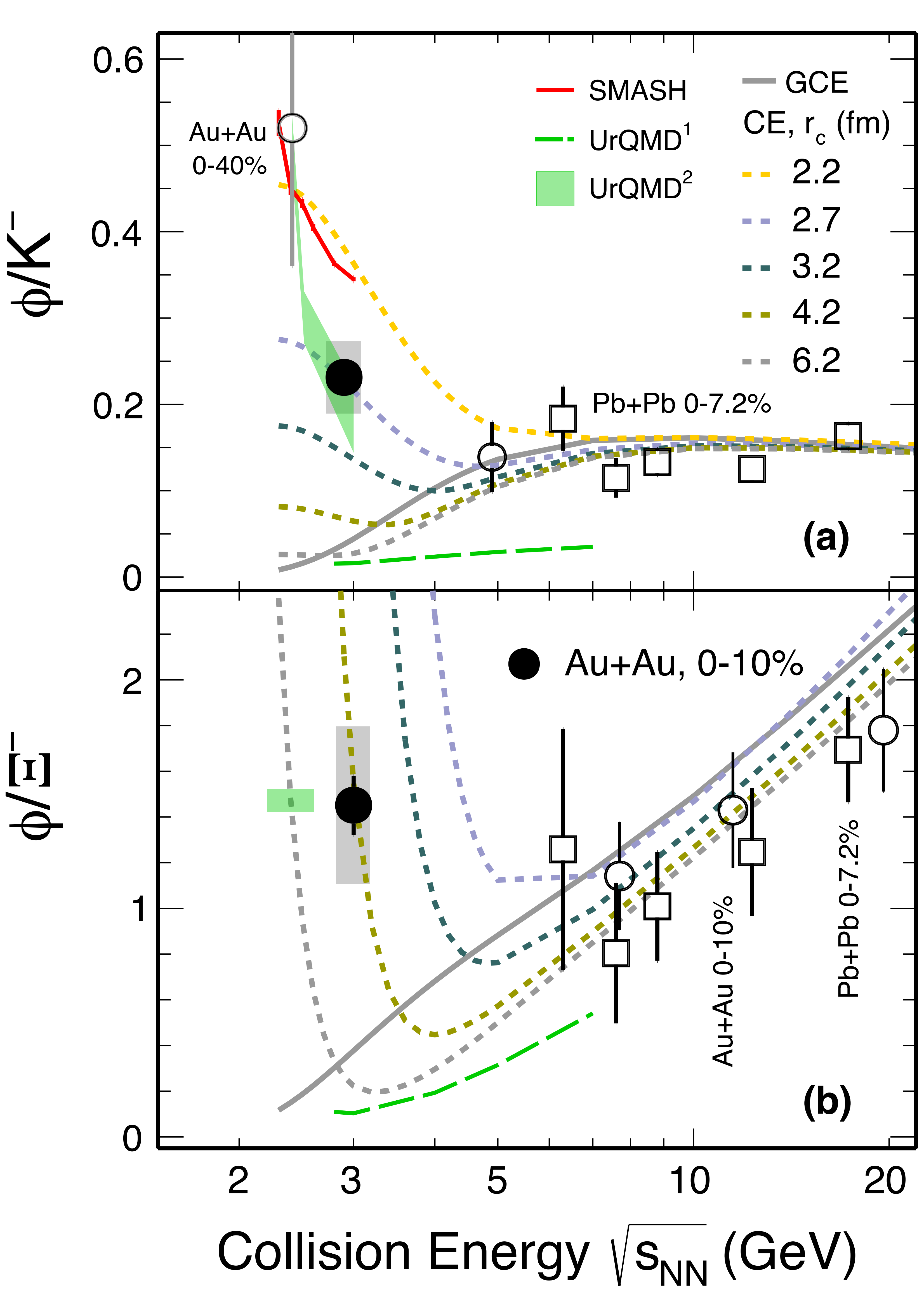
A. Andronic et al., Phys. A 834, 237c (2010)

Few hadronic interactions b/w chemical and kinetic freeze-out at 3 GeV

Strangeness Production at 3 GeV



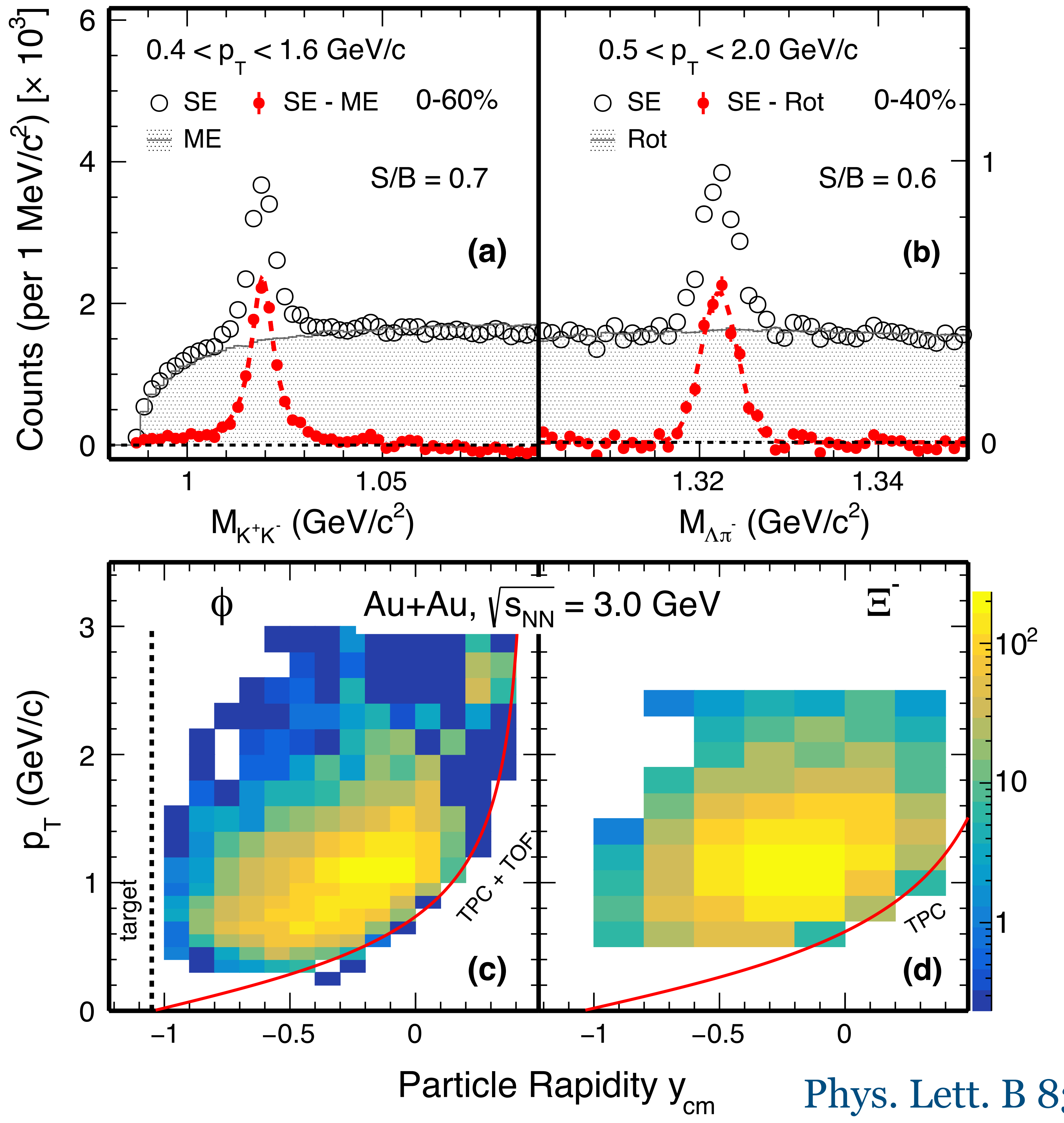
Phys. Lett. B 831 (2022) 137152



- Strange hadrons (Λ, K_S, ϕ, Ξ^-) reconstructed via hadronic decay channels
- CE is mandatory to describe ϕ/K^- and ϕ/Ξ^- at 3 GeV

Strong effect from canonical suppression

Strangeness Production at 3 GeV

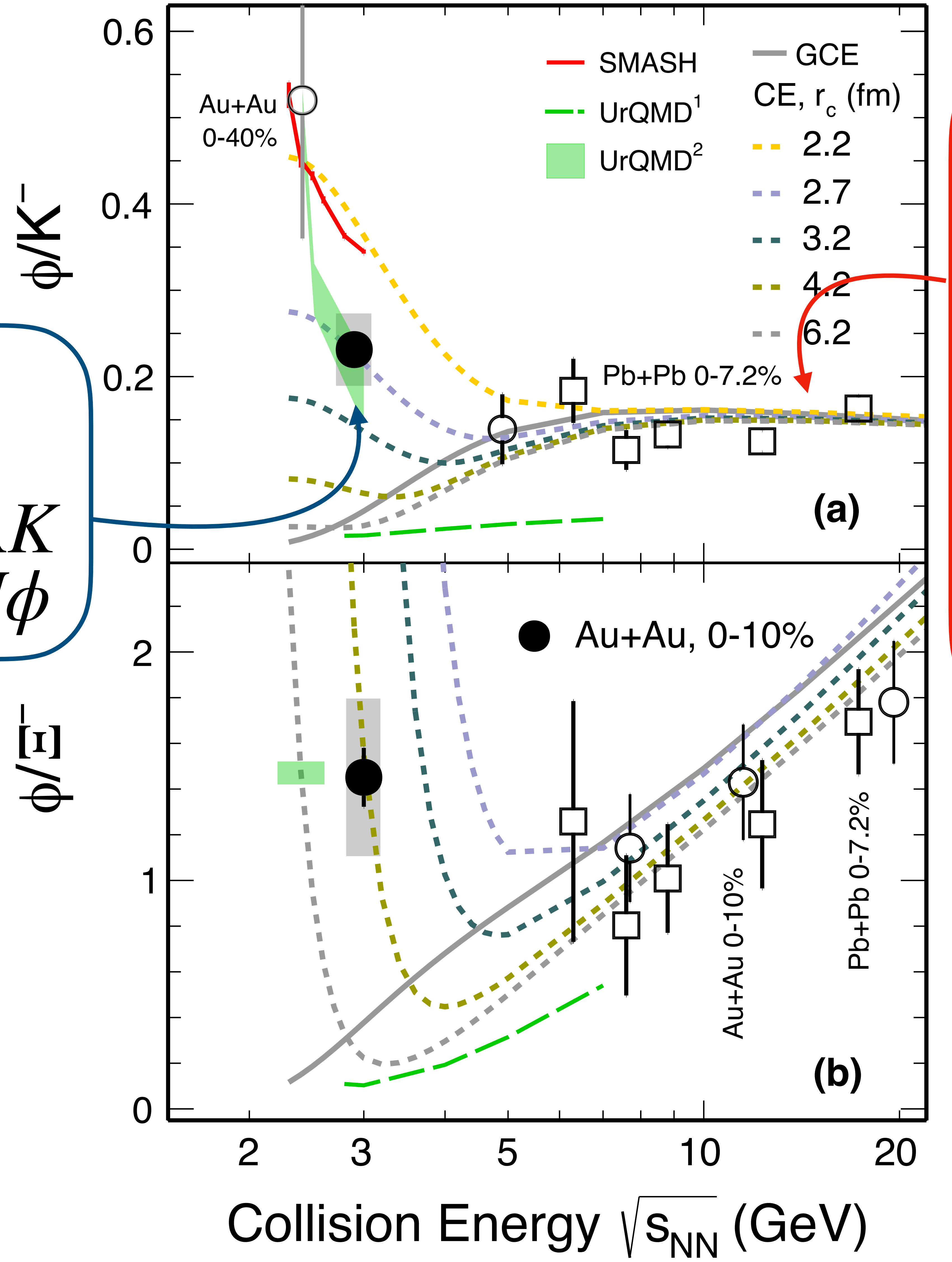


Phys. Lett. B 831 (2022) 137152

In hadronic matter:

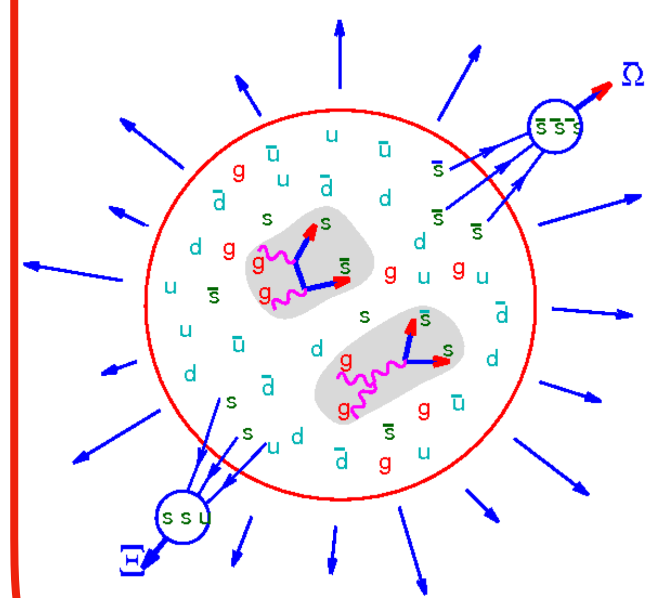
$NN \rightarrow N\Lambda K$

$NN \rightarrow NN\phi$



In QGP:

$gg \rightarrow s\bar{s}$



Wikipedia

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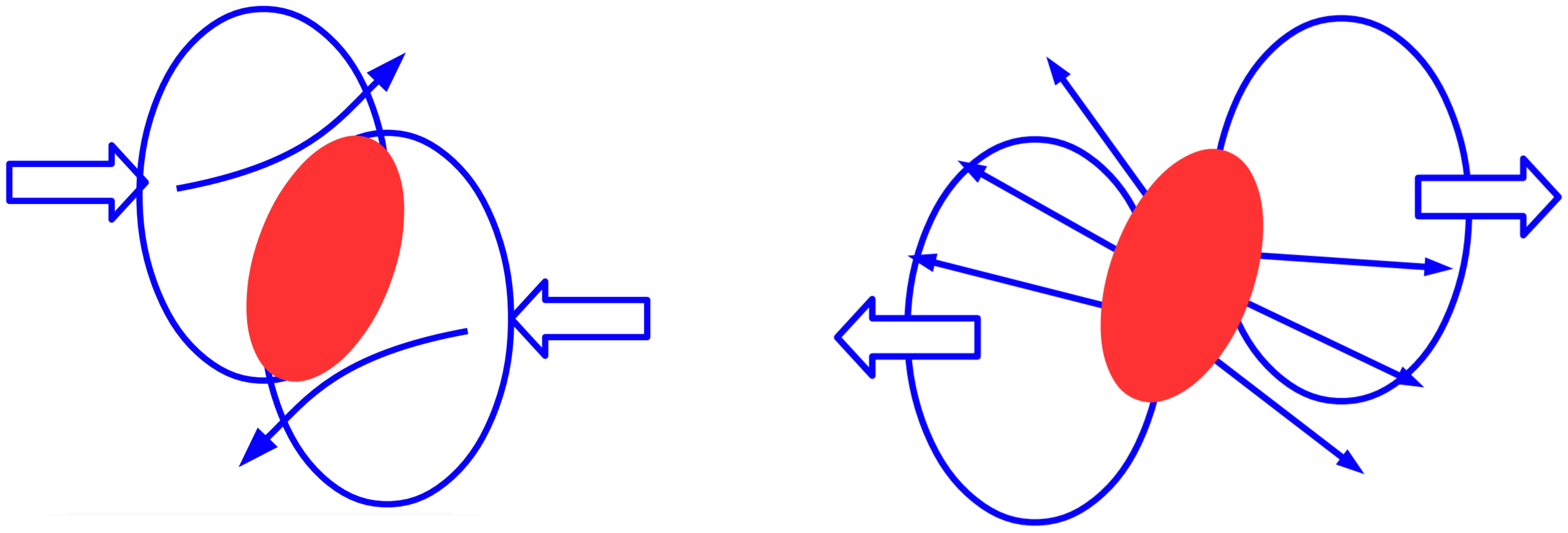
- CE is mandatory to describe ϕ/K^- and ϕ/Ξ^- at 3 GeV

Strong effect from canonical suppression

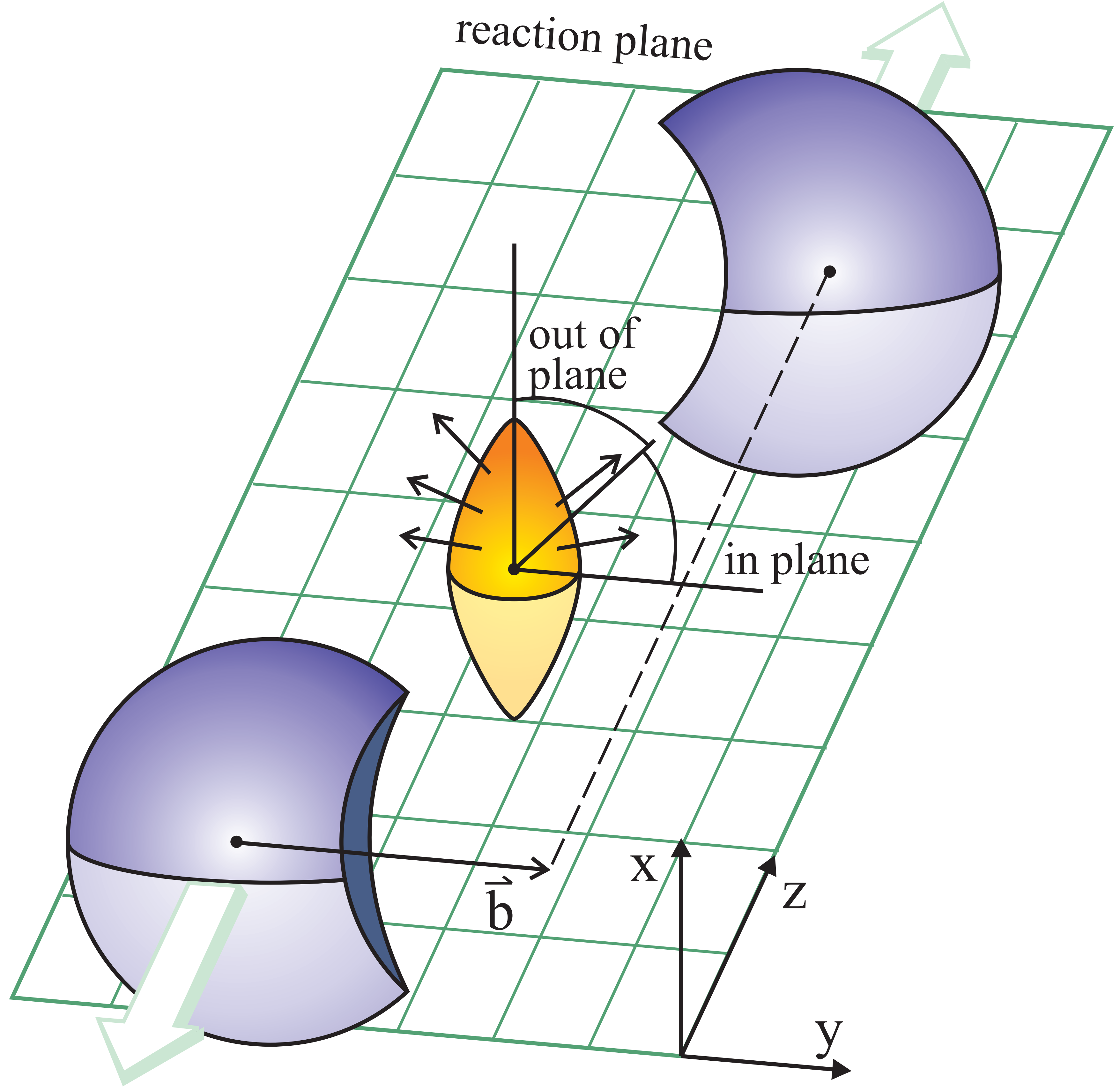
Directed and Elliptic Flow

- v_1 "directed flow" characterizes sideward flow of particles

Compression stage → +ve v_1 Expansion stage → -ve v_1



A. Ohnishi, HYP2022



Event plane angle ↓

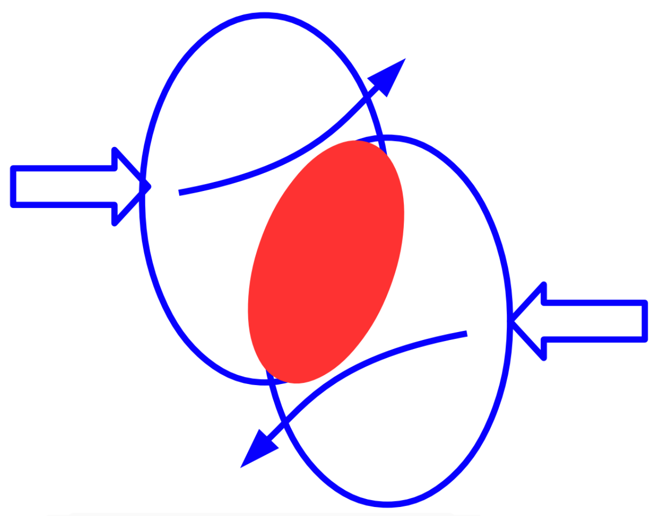
$$\frac{dN}{d\phi} \sim 1 + \sum_{n=1}^{\infty} 2v_n cos(n(\phi - \Psi))$$

- v_2 "elliptic flow" caused by pressure gradients from almond shaped interaction region

v_1 and v_2 are very sensitive to the stiffness of nuclear EoS in the high baryon density region

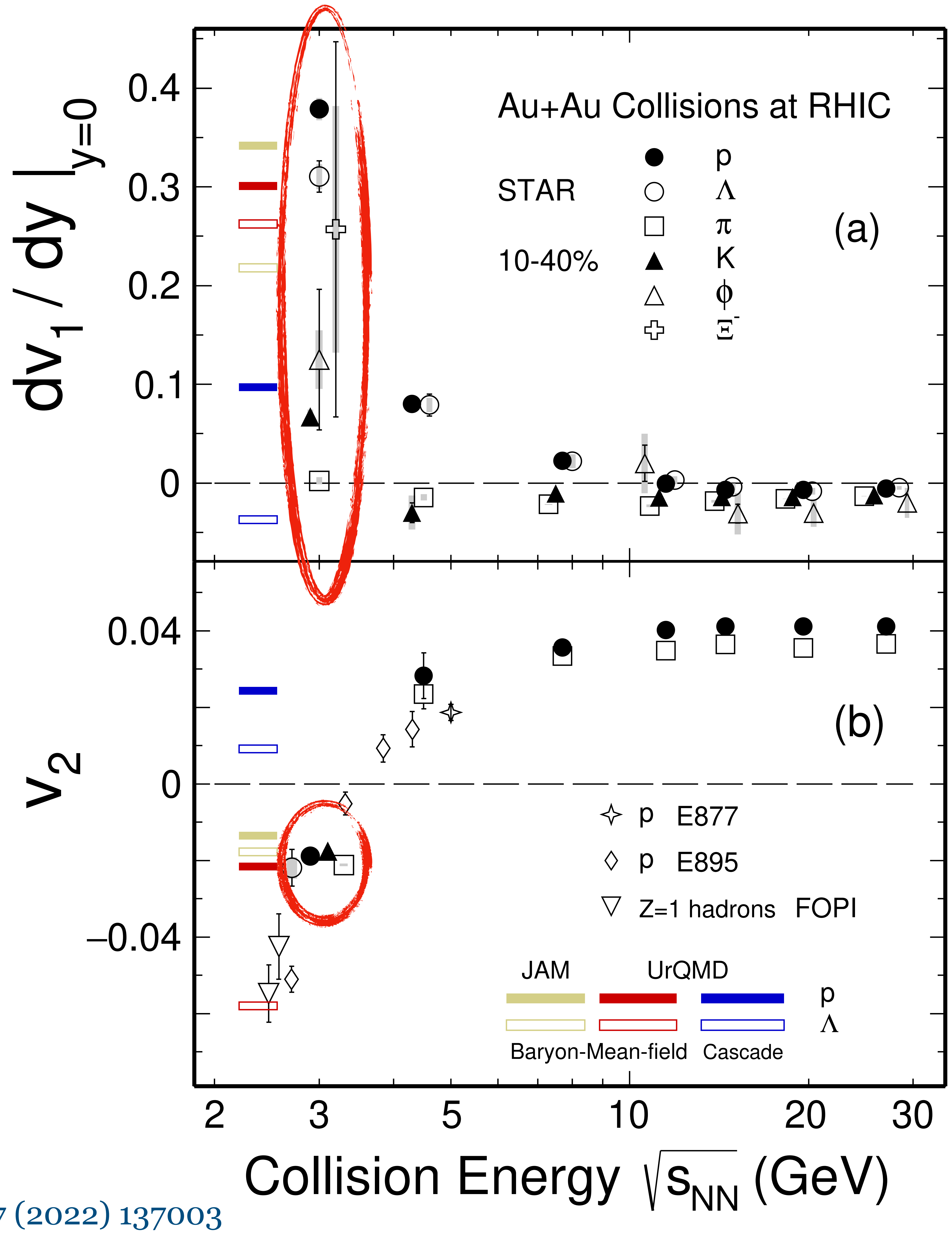
Energy Dependence of Collective Flow

- Significant +ve dv_1/dy observed at 3 GeV



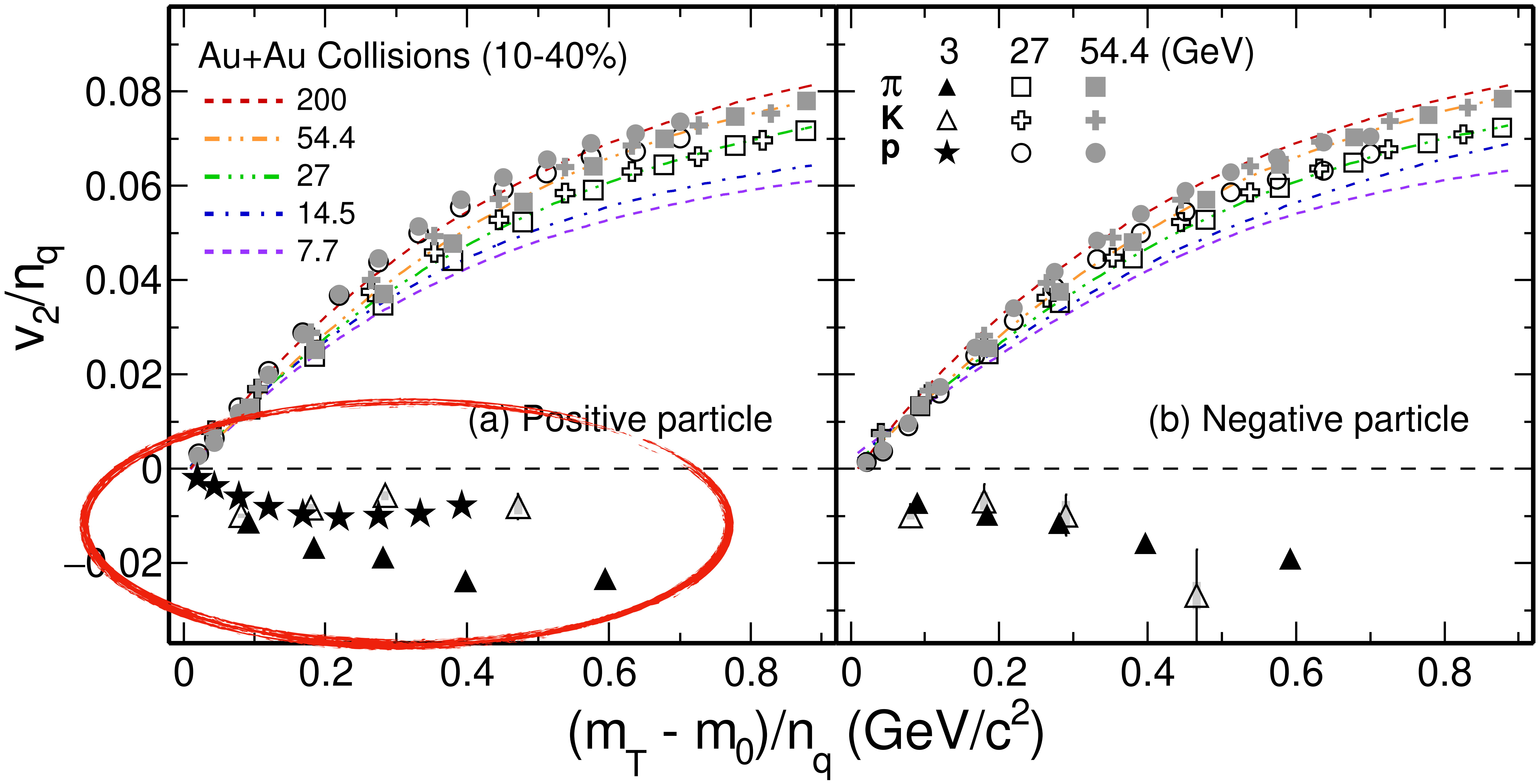
- -ve v_2 observed at 3 GeV
    - Similar to expectations from hadronic transport models with baryon-mean-field

Suggests that the dominant degrees of freedom at 3 GeV are the interacting baryons



Phys.Lett.B 827 (2022) 137003

Disappearance of NCQ scaling at 3 GeV

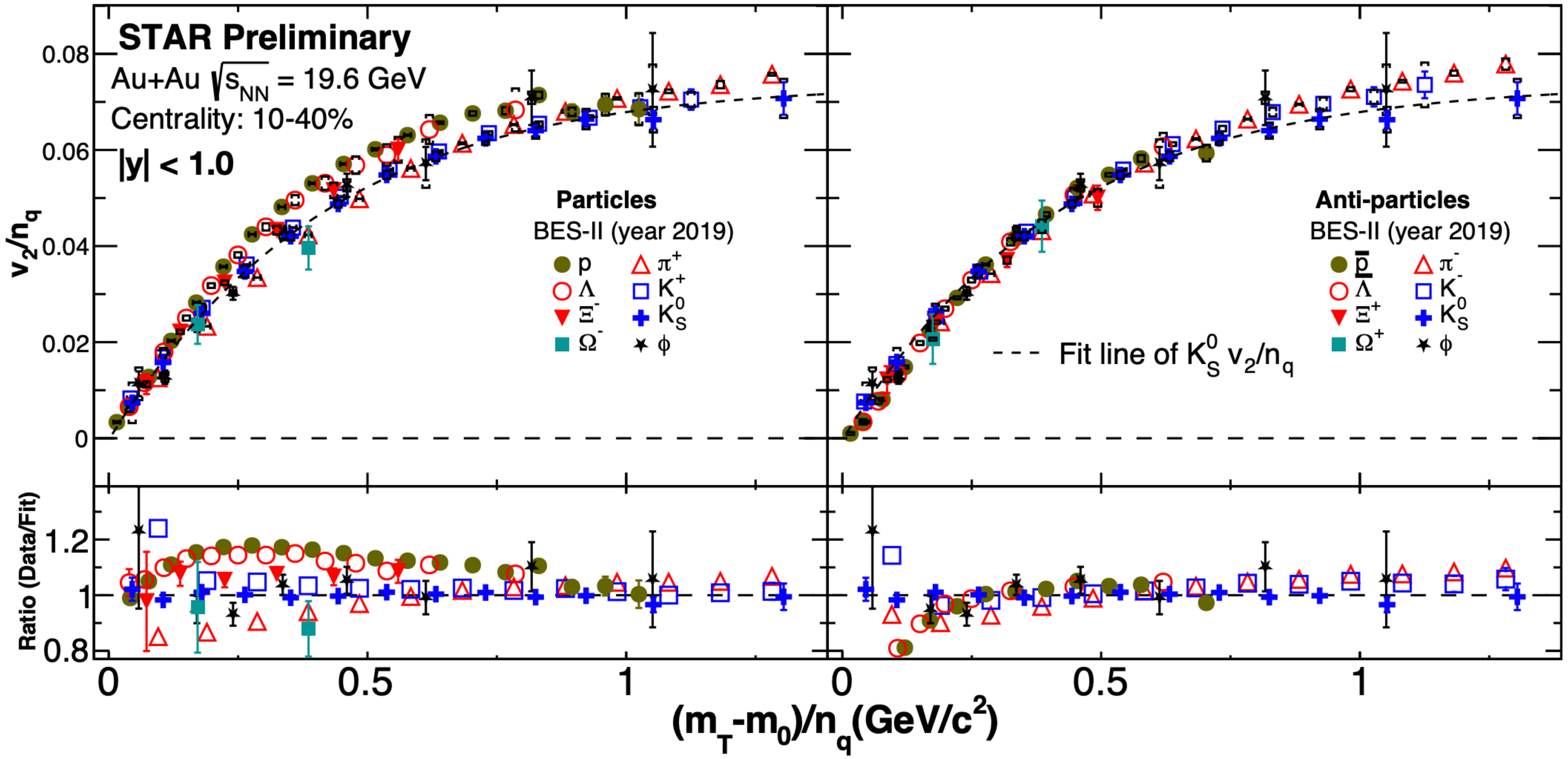


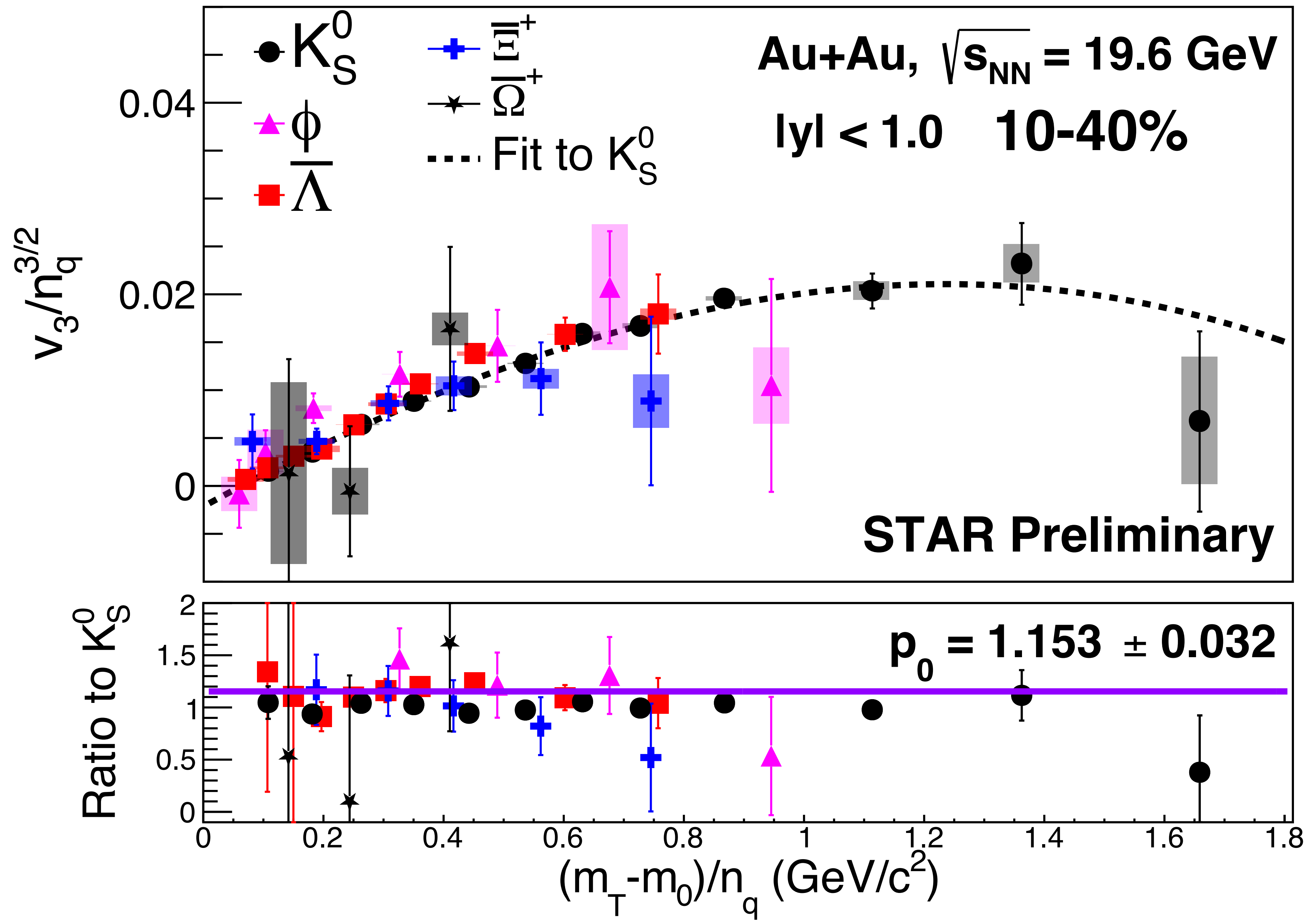
Phys.Lett.B 827 (2022) 137003

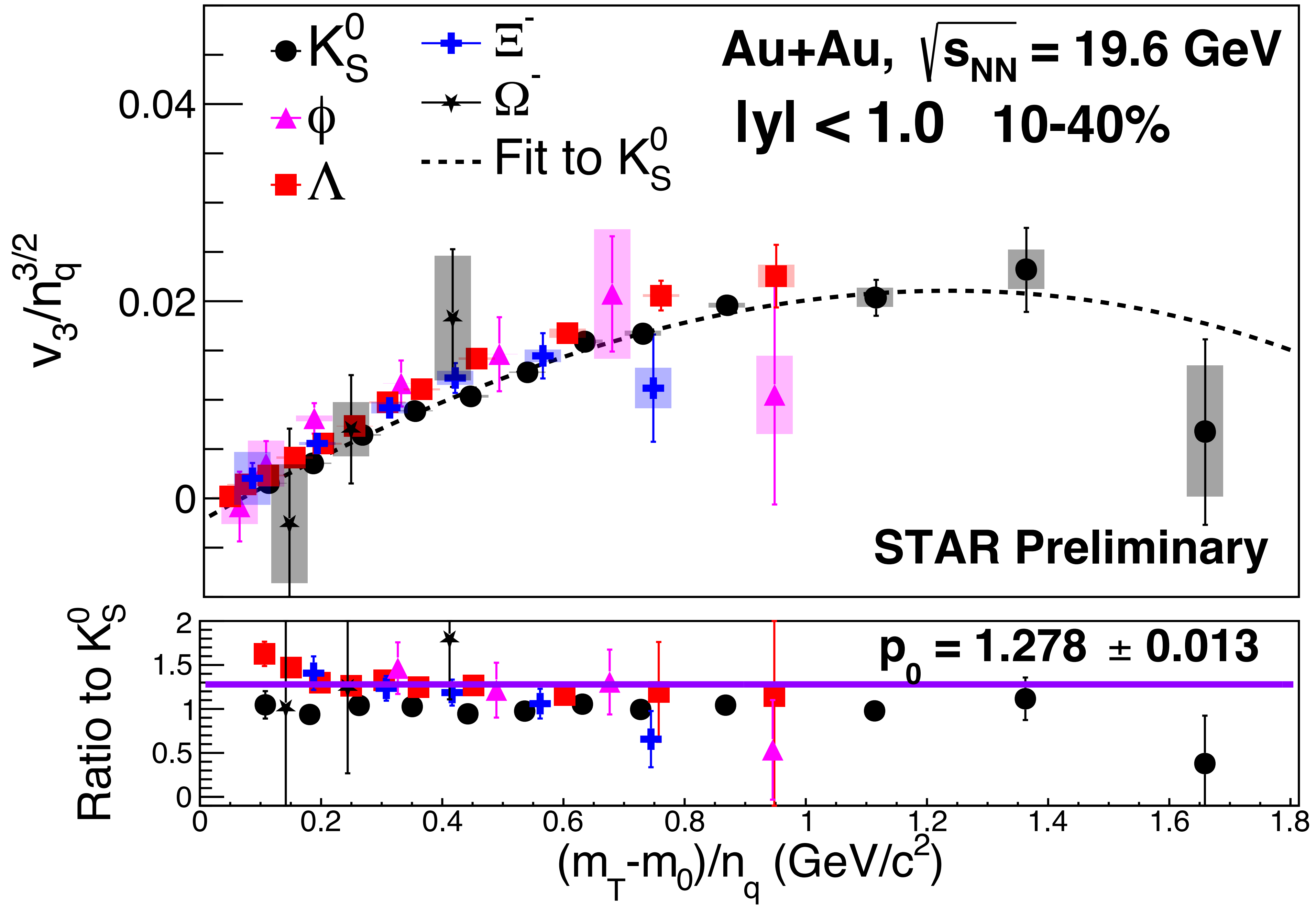
- The number of constituent quark (NCQ) scaling for v_2 holds at high energies, consistent with partonic collectivity
  - Scaling deteriorates as energy decreases
- Disappearance of NCQ scaling at 3 GeV

Suggests that hadronic matter is predominantly produced in 3 GeV Au+Au collisions

NCQ scaling of v_2 and v_3 at 19.6 GeV







- Scaling of v_2 within (10%)20% for (anti-)particles
- Scaling of v_3 within (15%)30% for (anti-)particles

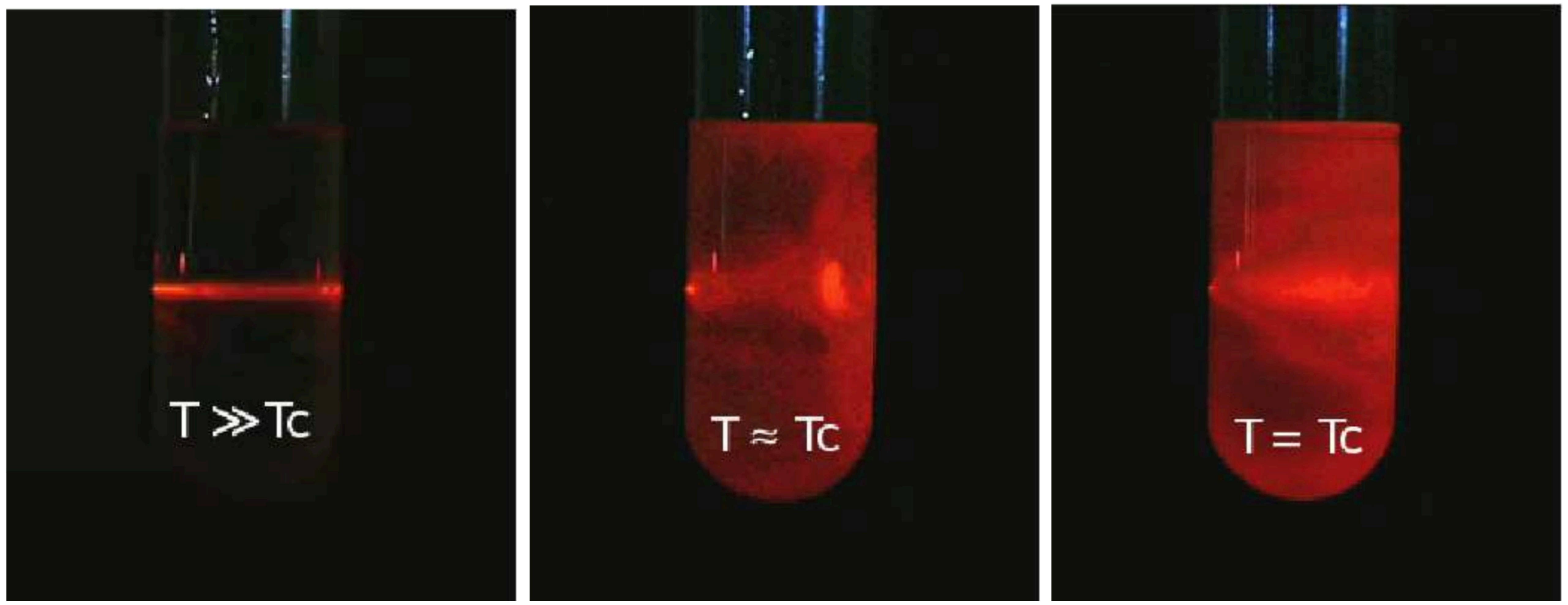
(except at low p_T for $\overline{\Lambda}$ and $\overline{p}$)

Disappearance of partonic collectivity: a gradual process?

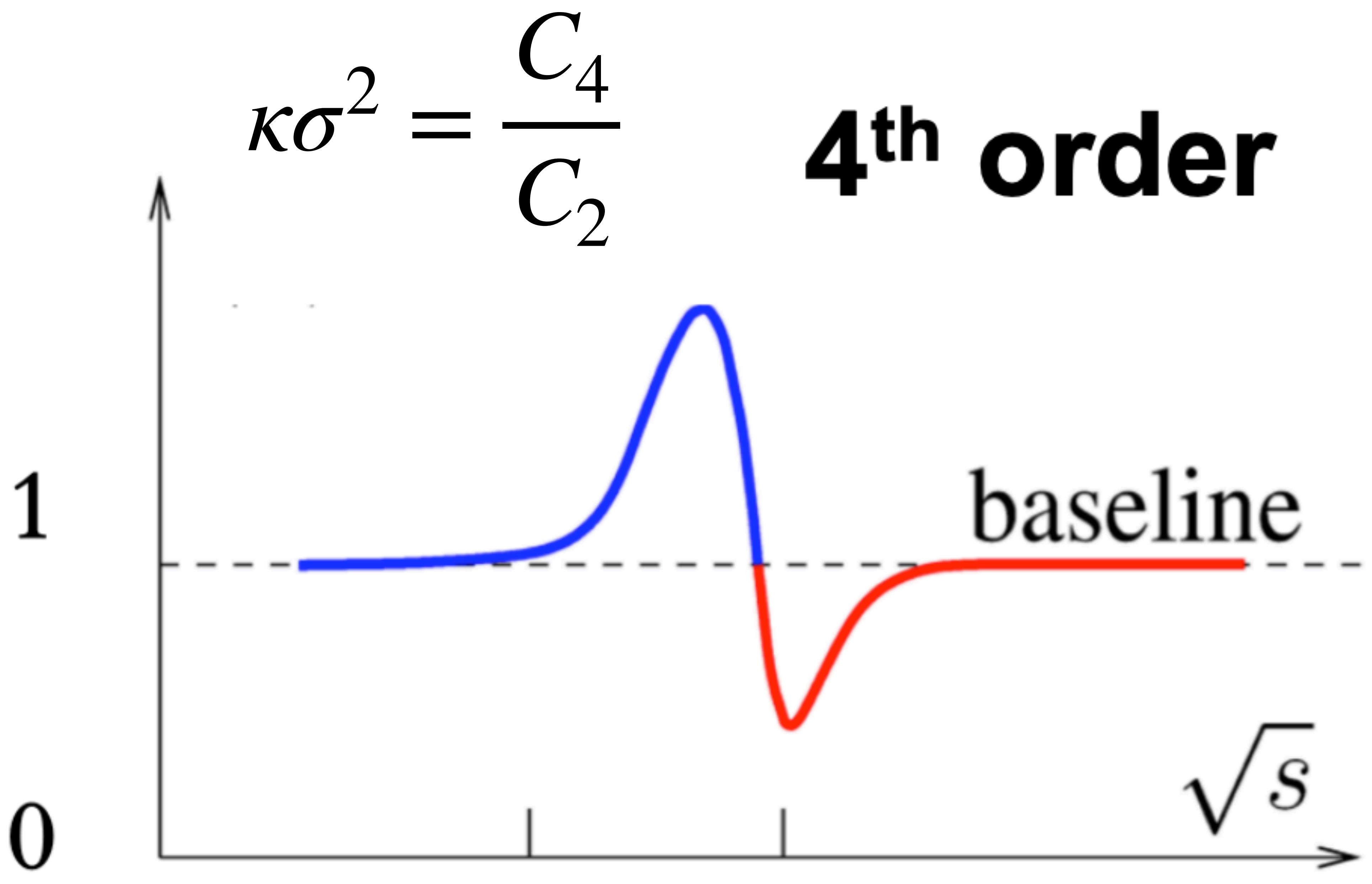
Higher Order Cumulants

$$C_1 = < N > \qquad \delta N = N - < N >$$
$$C_2 = < (\delta N)^2 >$$
$$C_3 = < (\delta N)^3 >$$
$$C_4 = < (\delta N)^4 > - 3 < (\delta N)^2 >^2$$
$$C_5 = < (\delta N)^5 > - 5 < (\delta N)^3 > < (\delta N)^2 >$$
$$C_6 = < (\delta N)^6 > - 15 < (\delta N)^4 > < (\delta N)^2 > - 10 < (\delta N)^3 >^2 + 30 < (\delta N)^2 >^3$$

- Cumulants of conserved quantities (Q, B, S) characterize event-by-event fluctuations
    - Sensitive to the correlation length, which diverges at CP
- Non-monotonic behavior of $\kappa\sigma^2$ of net protons proposed as signature of CP



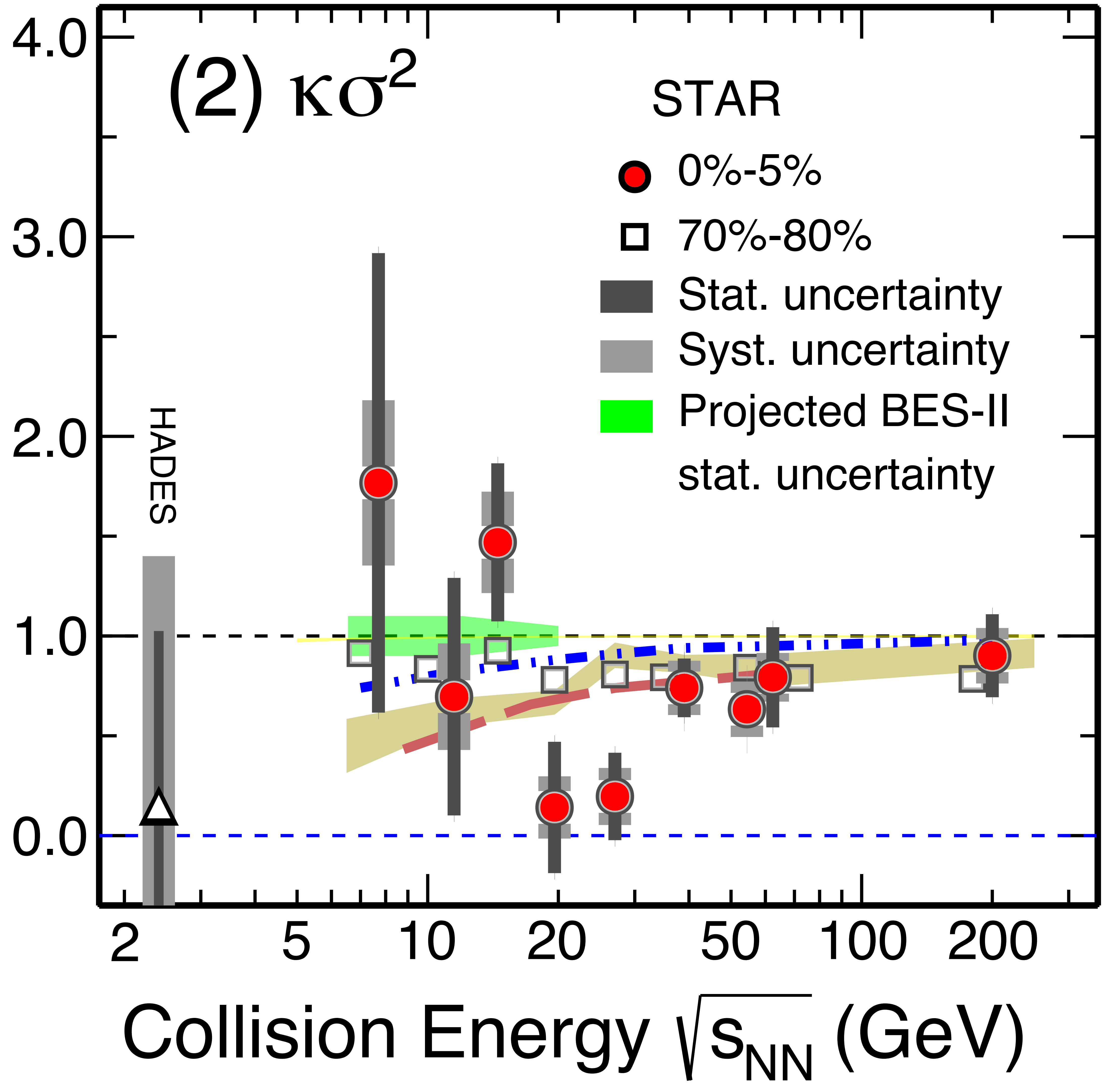
http://www.msm.cam.ac.uk



M. A. Stephanov, PRL 107,052301(2011)

Net Proton Kurtosis from BES-I

Non-monotonicity observed with 3.1σ significance from BES-I data

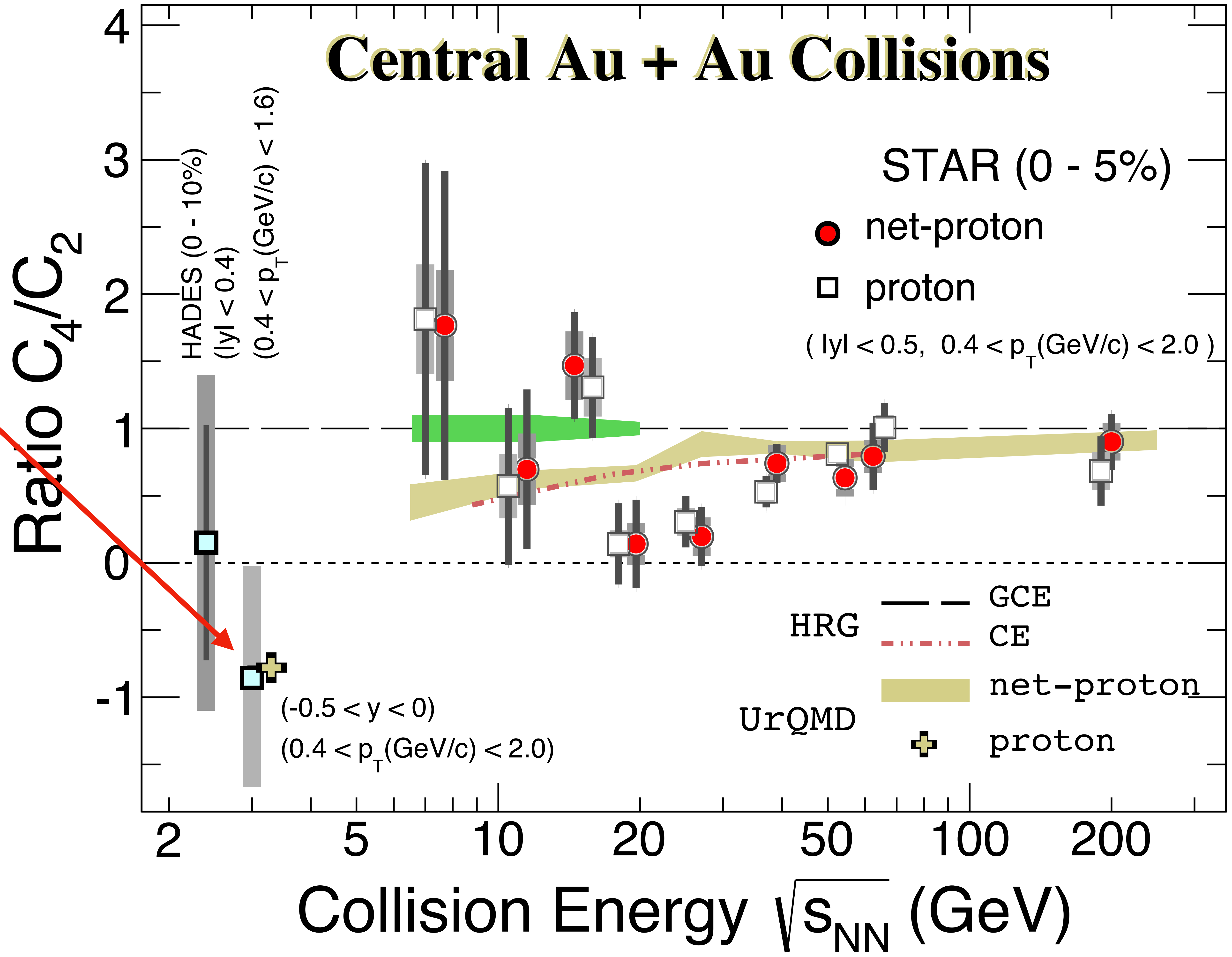


Phys.Rev.Lett. 126 (2021) 9, 092301

Net Proton Kurtosis from BES-II

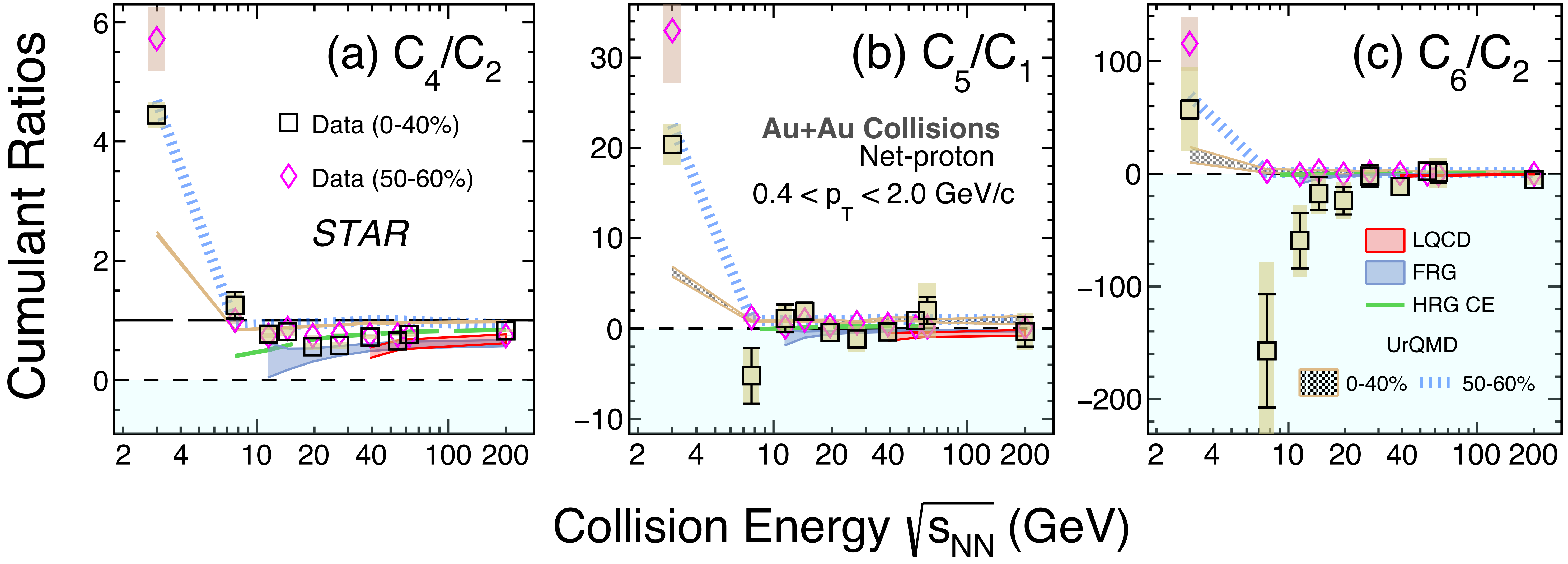
- New 3 GeV measurement consistent with hadronic transport model UrQMD
- Suppression of C_4/C_2 is consistent with fluctuations driven by baryon number conservation

Hadronic interaction dominated region in central Au+Au collisions at 3 GeV

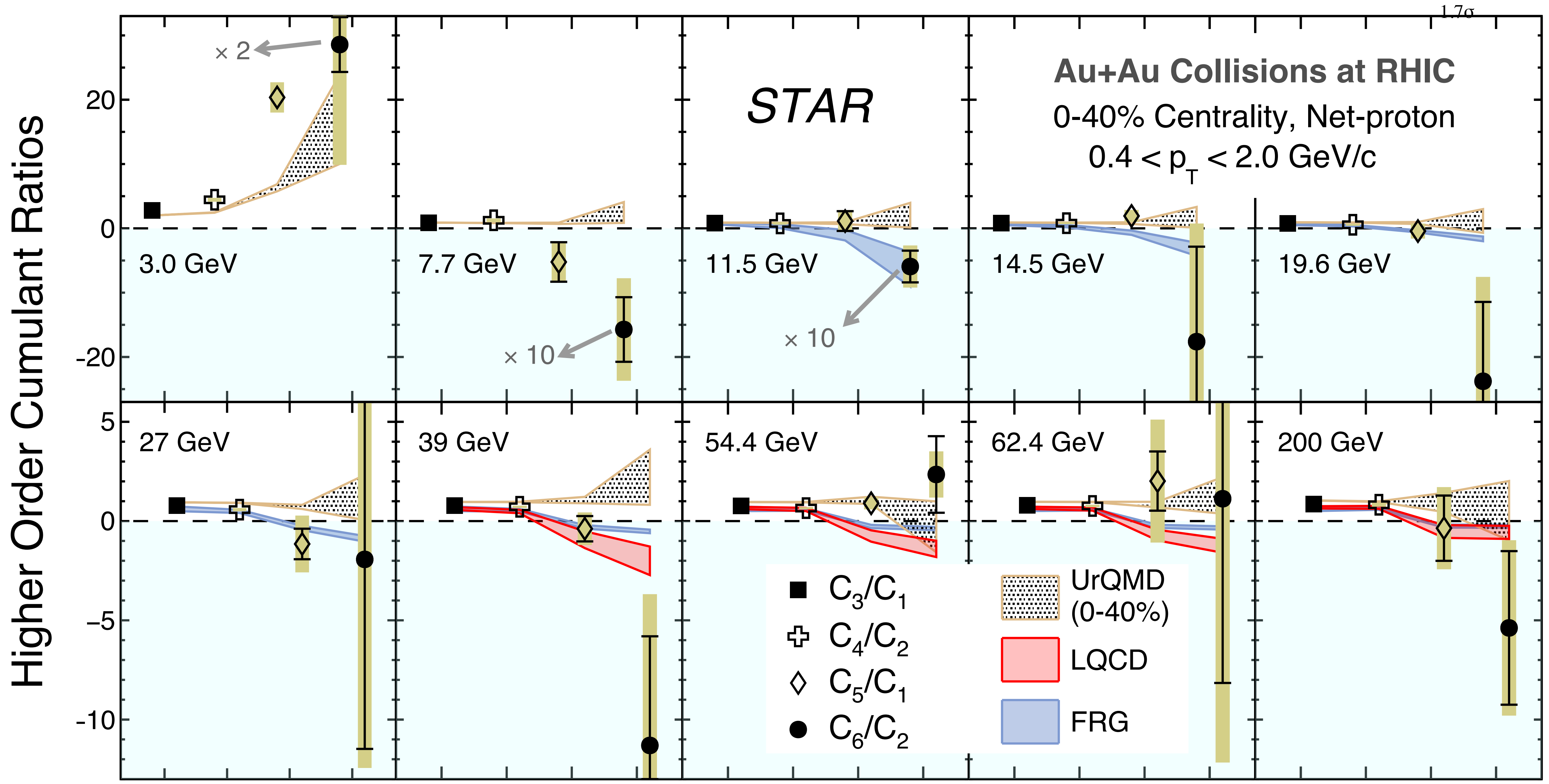


Phys.Rev.Lett. 128 (2022) 20, 202303

5th and 6th Order Cumulants



- C_6/C_2 at 0-40% seems to be increasingly -ve from 200 to 7.7 GeV
  - -ve C_6/C_2 predicted by LQCD which includes crossover quark-hadron transition
  - +ve C_6/C_2 at 50-60% 3 GeV, similar with UrQMD



- LQCD predicts the ordering

$$C_3/C_1 > C_4/C_2 > C_5/C_1 > C_6/C_2$$

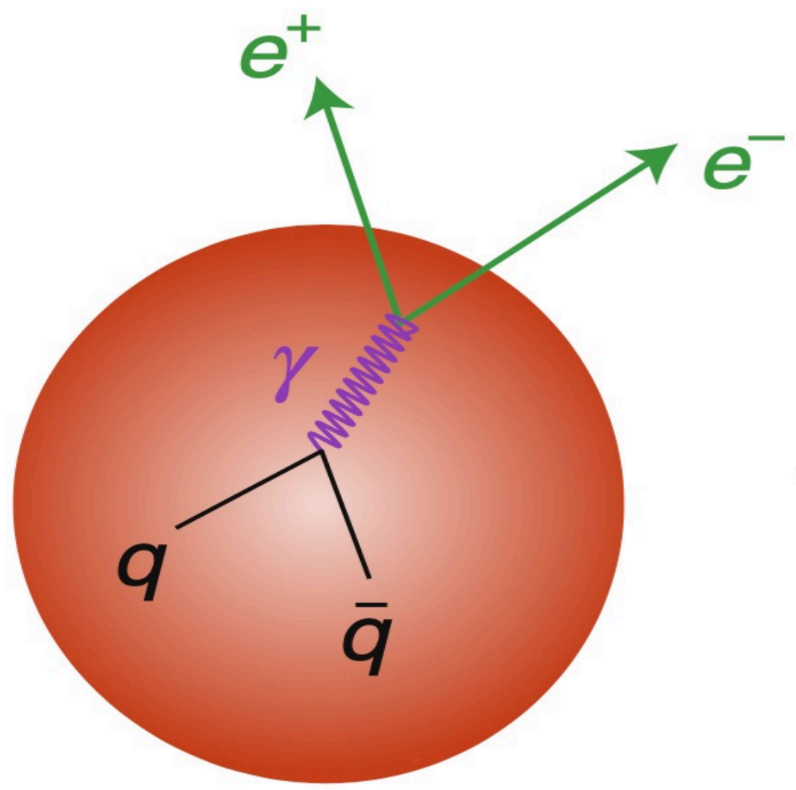
- A reverse ordering seen at 3 GeV
  - Same trend from UrQMD

Suggests matter is predominantly hadronic at 3 GeV

Phys.Rev.Lett. 130 (2023) 8, 082301

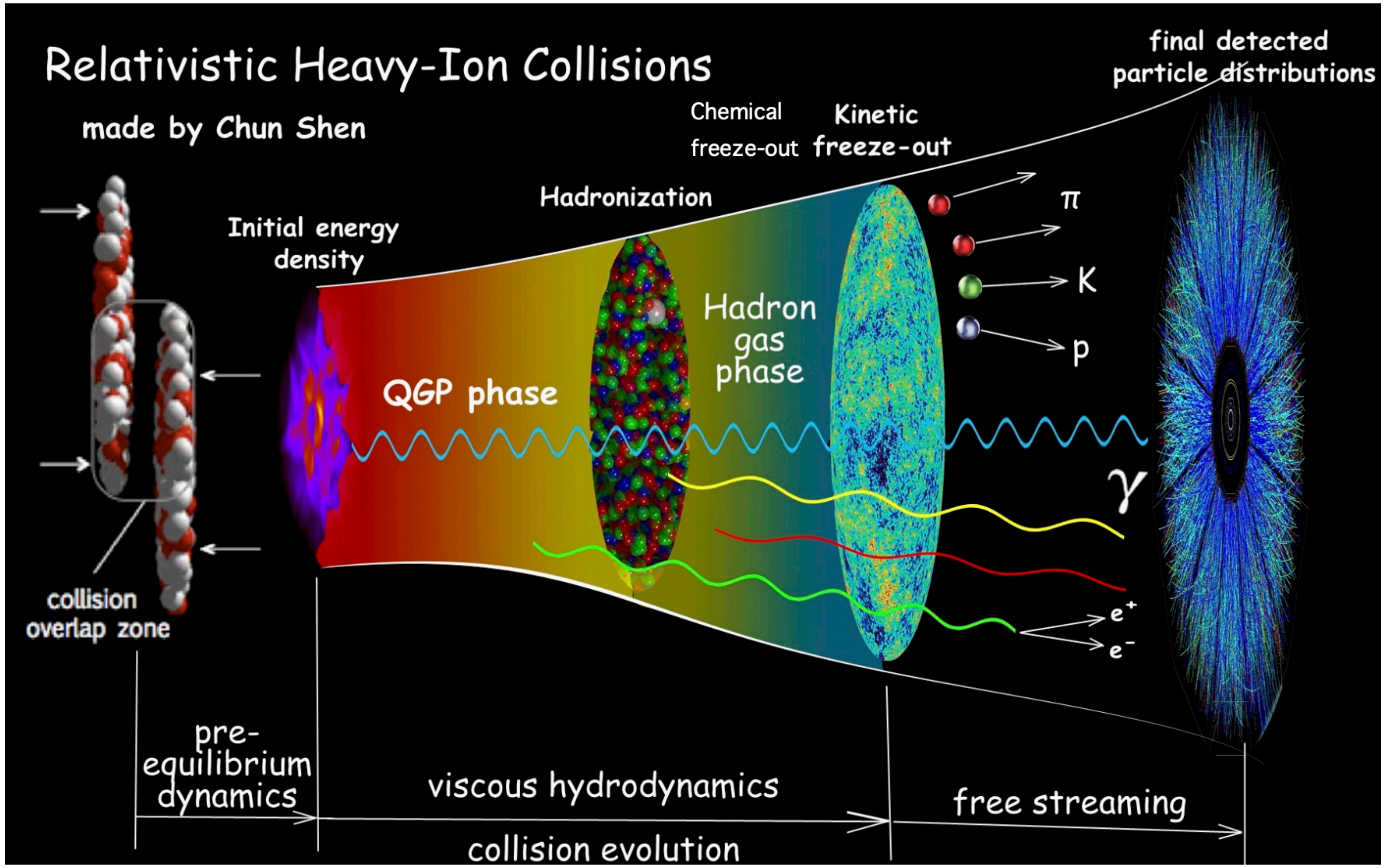
Measuring the Temperature with Thermal Dileptons

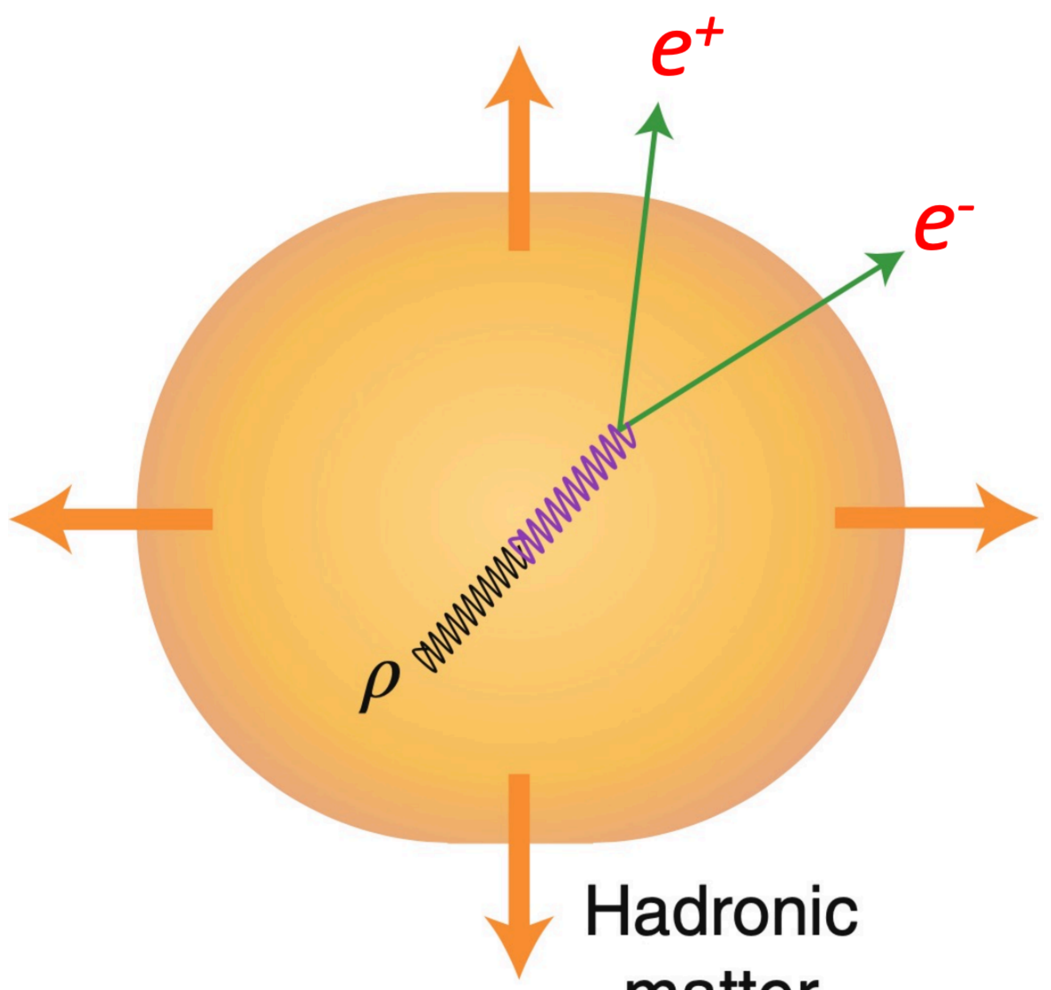
Courtesy of Ralf Rapp



Quark–gluon plasma

$$q + \bar{q} \rightarrow \gamma^* \rightarrow e^+ + e^-$$



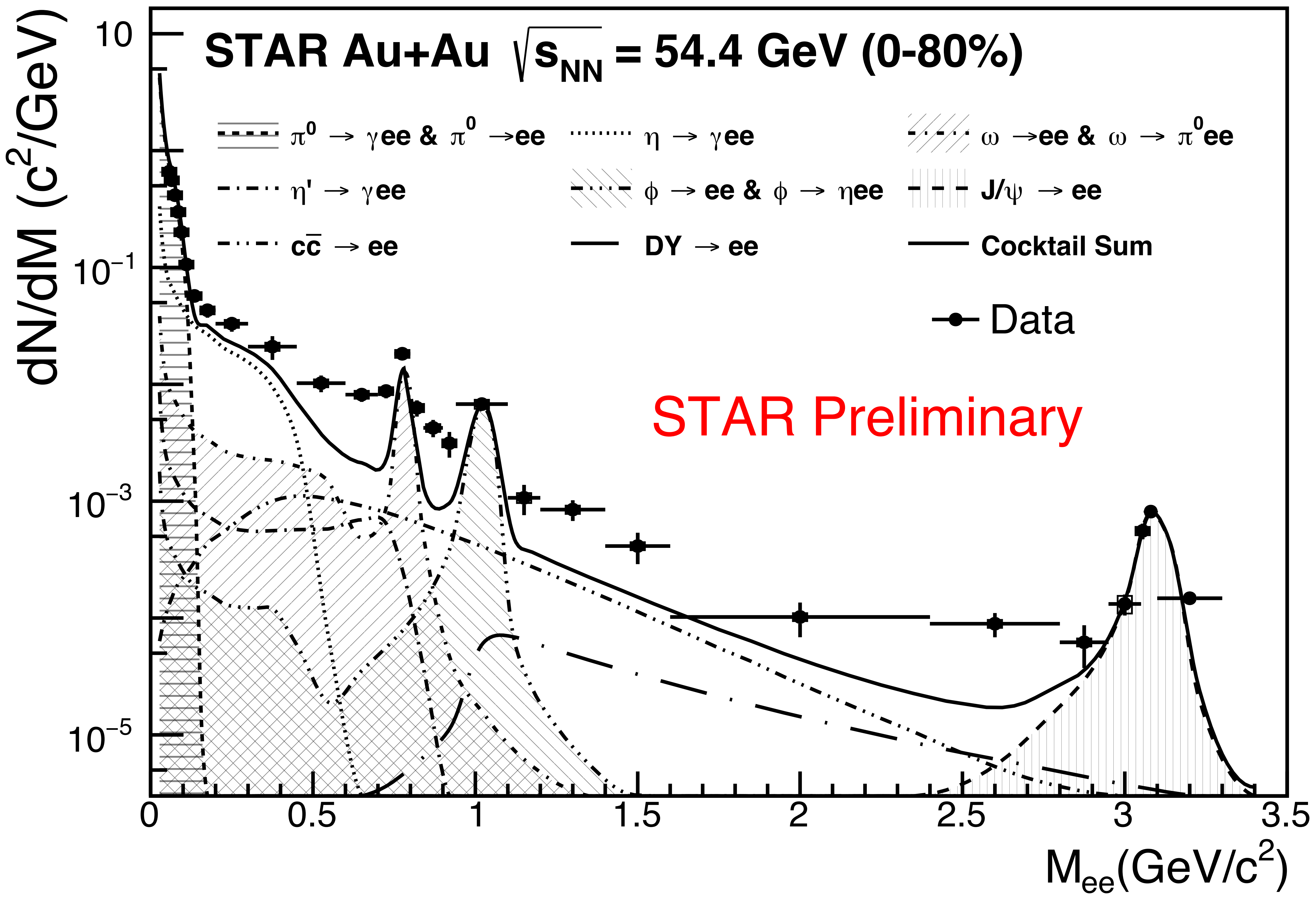


Hadronic matter

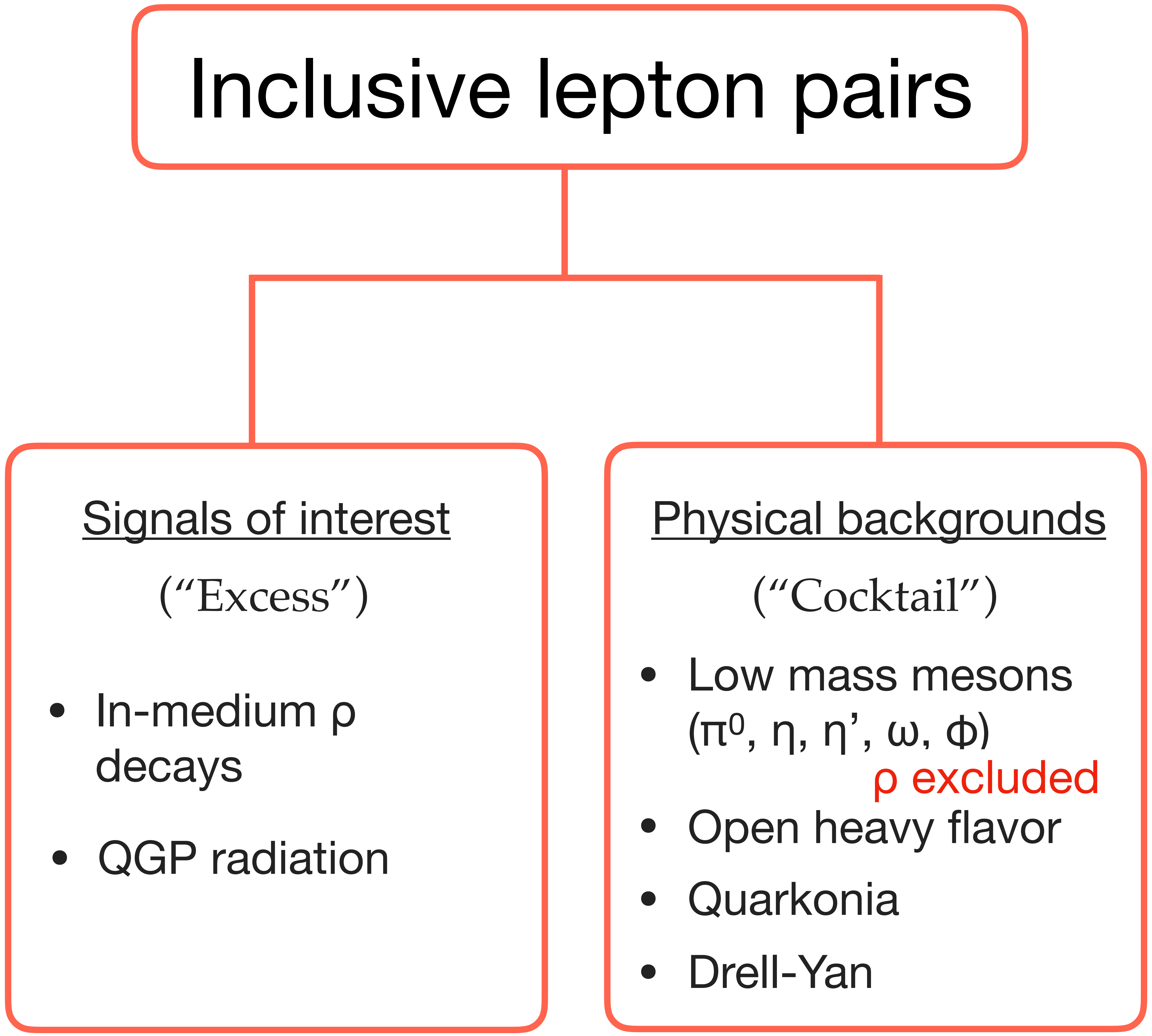
$$\pi^+ + \pi^- \rightarrow \rho \rightarrow e^+ + e^-$$

Thermal dileptons can access the hot QCD medium at both QGP phase and hadronic phase

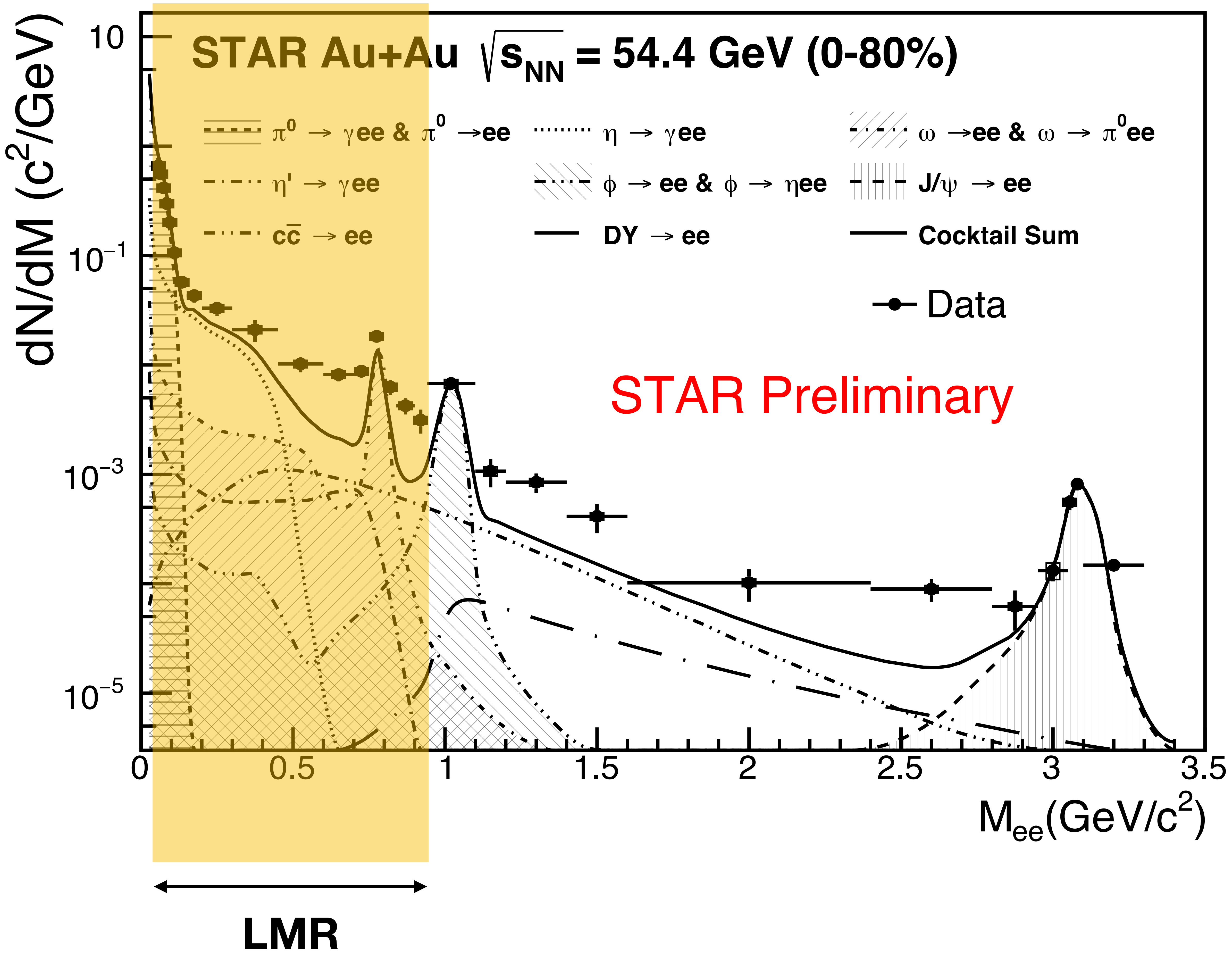
Cocktail Method

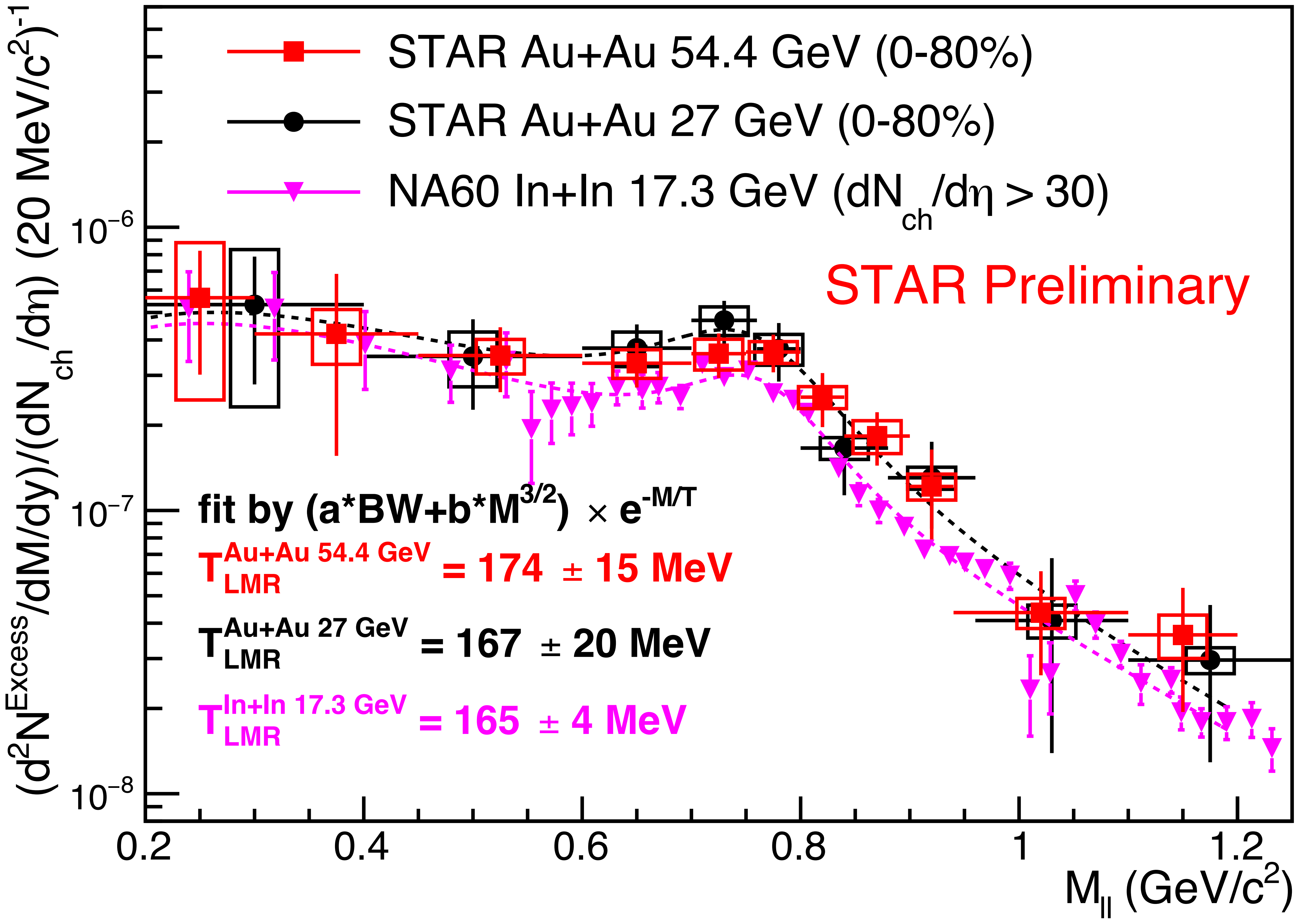


- "Excess" = "Inclusive" - "Cocktail Sum"



The Low Mass Region



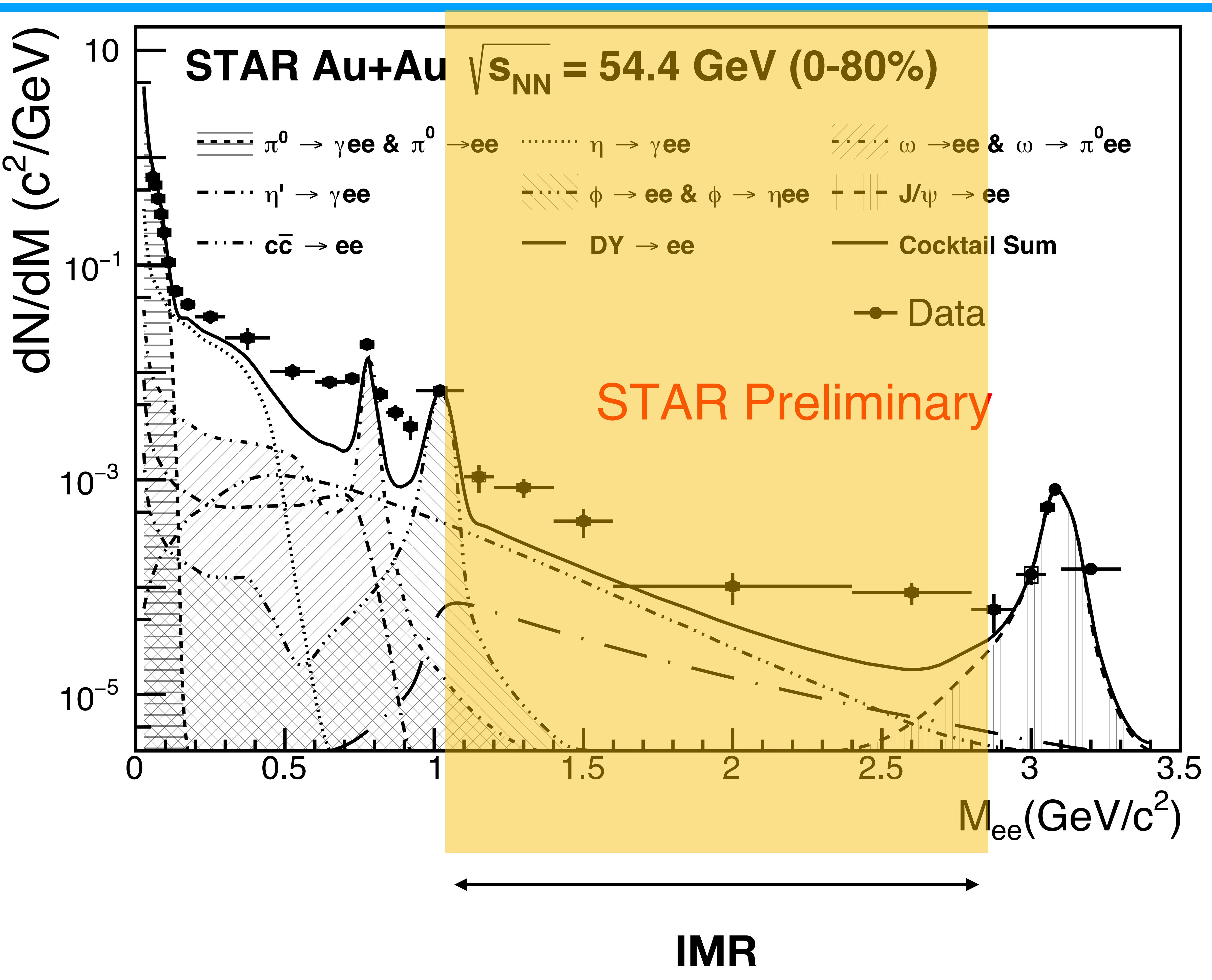


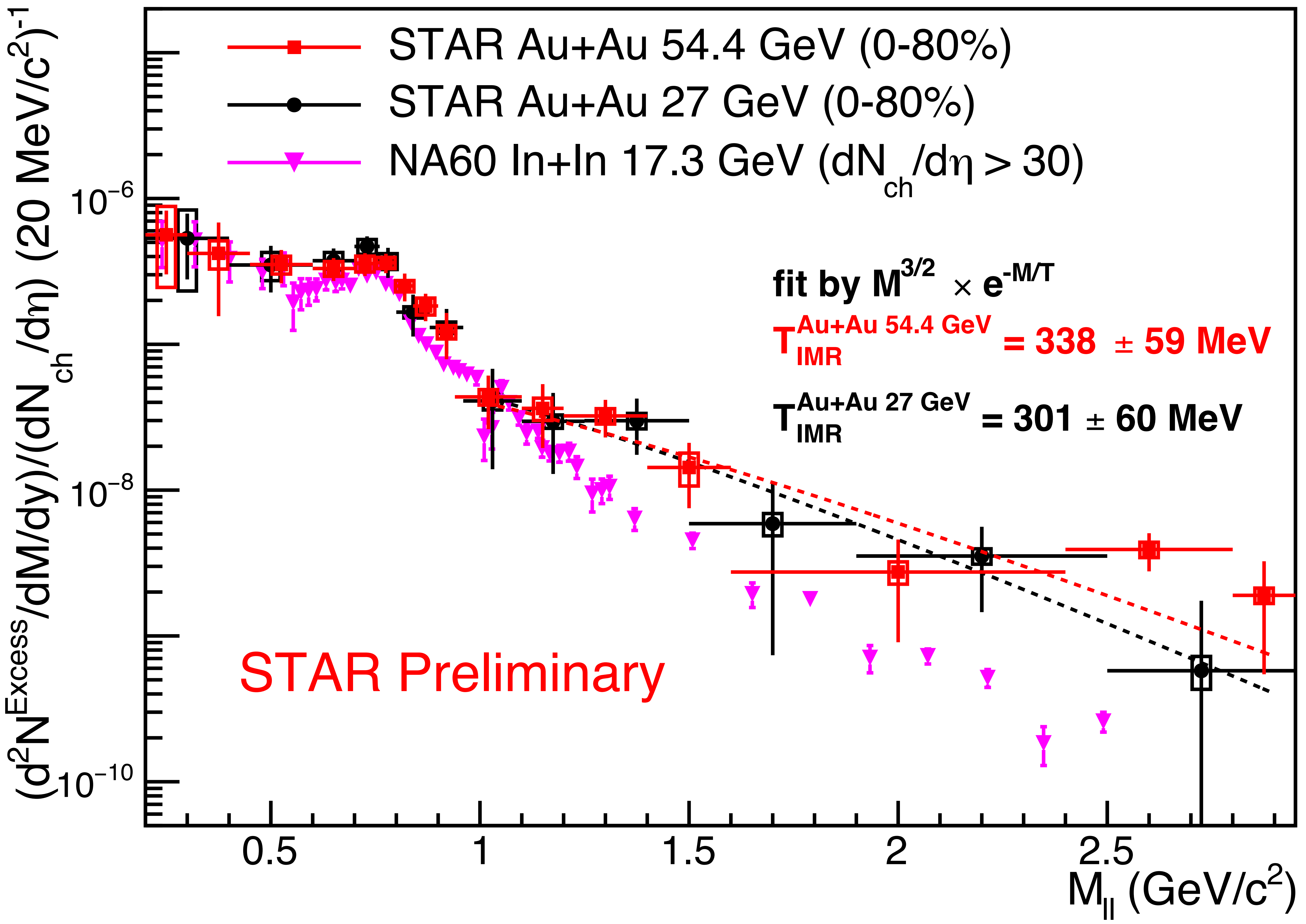
- "Excess" = "Inclusive" - "Cocktail Sum"

- In-medium ρ dominated

In-medium ρ dominated produced from a "similar hot bath" in 27/54.4 GeV Au+Au and 17.3 GeV In+In

The Intermediate Mass Region



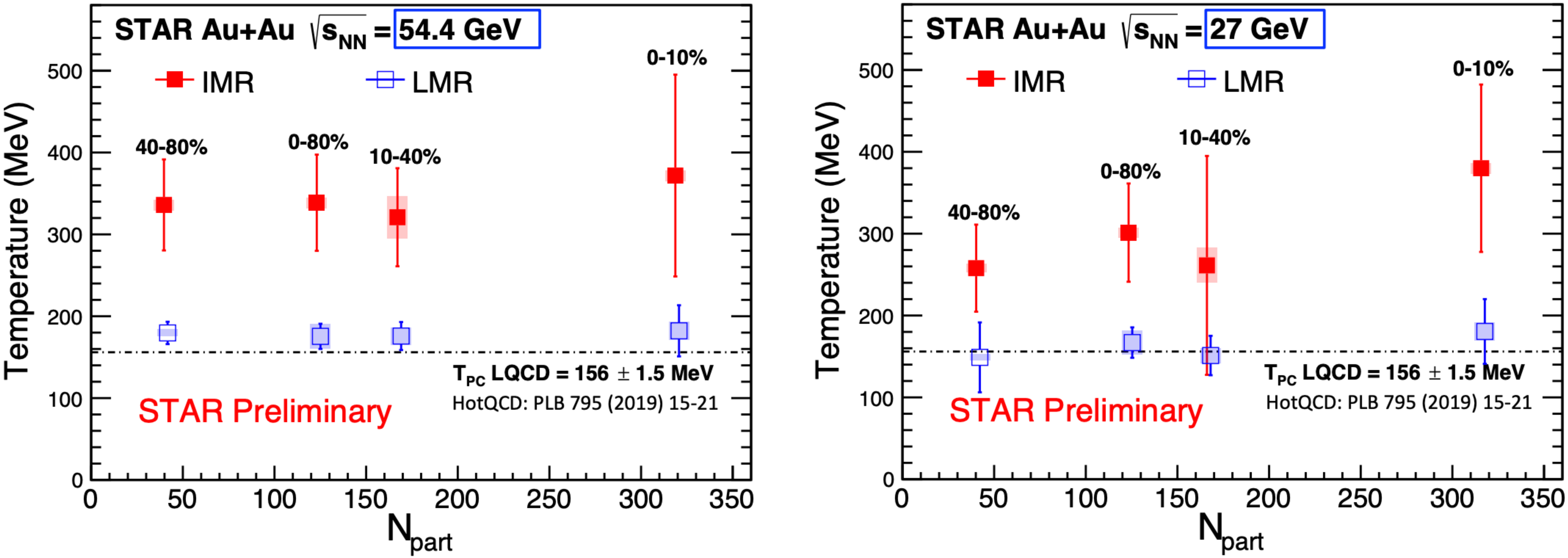


- T_{IMR} from STAR data: ~320 MeV

- "Excess" = "Inclusive" - "Cocktail Sum"

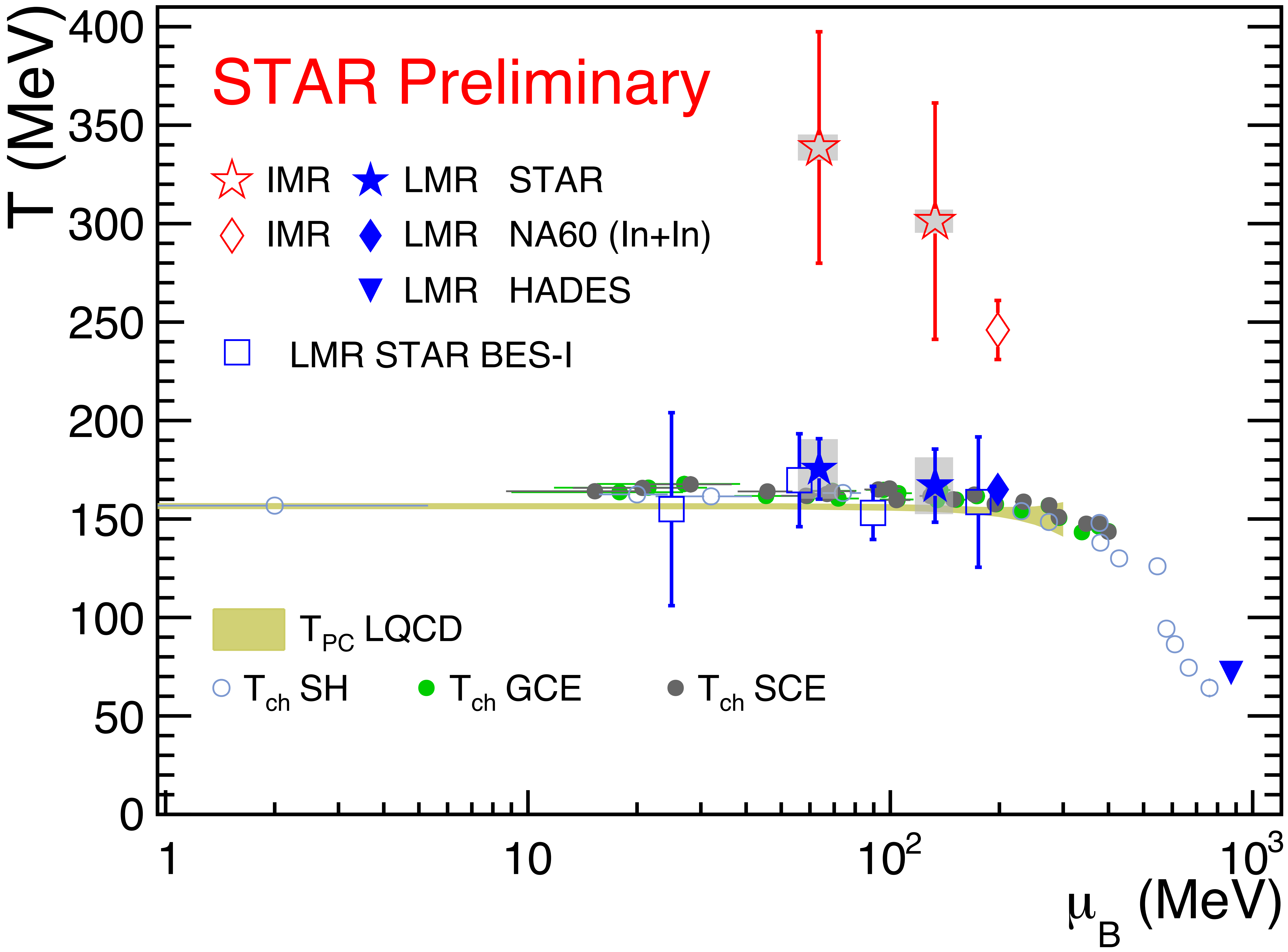
$T_{IMR} > T_{PC}$ (156 MeV): consistent with the emission source dominantly from QGP

Centrality Dependence of Thermal Dielectrons



No clear centrality dependence of the temperatures at IMR and LMR

Temperature Measurement of the QGP



$T_{LMR} \approx T_{PC} \approx T_{ch}$

LMR dileptons emitted from hadronic phase around phase transition

$T_{IMR} > T_{PC}$

IMR dileptons emitted from QGP phase

Nuclei and Hypernuclei

- Nuclei and hypernuclei yields have been suggested to be sensitive to critical fluctuations and the onset of deconfinement

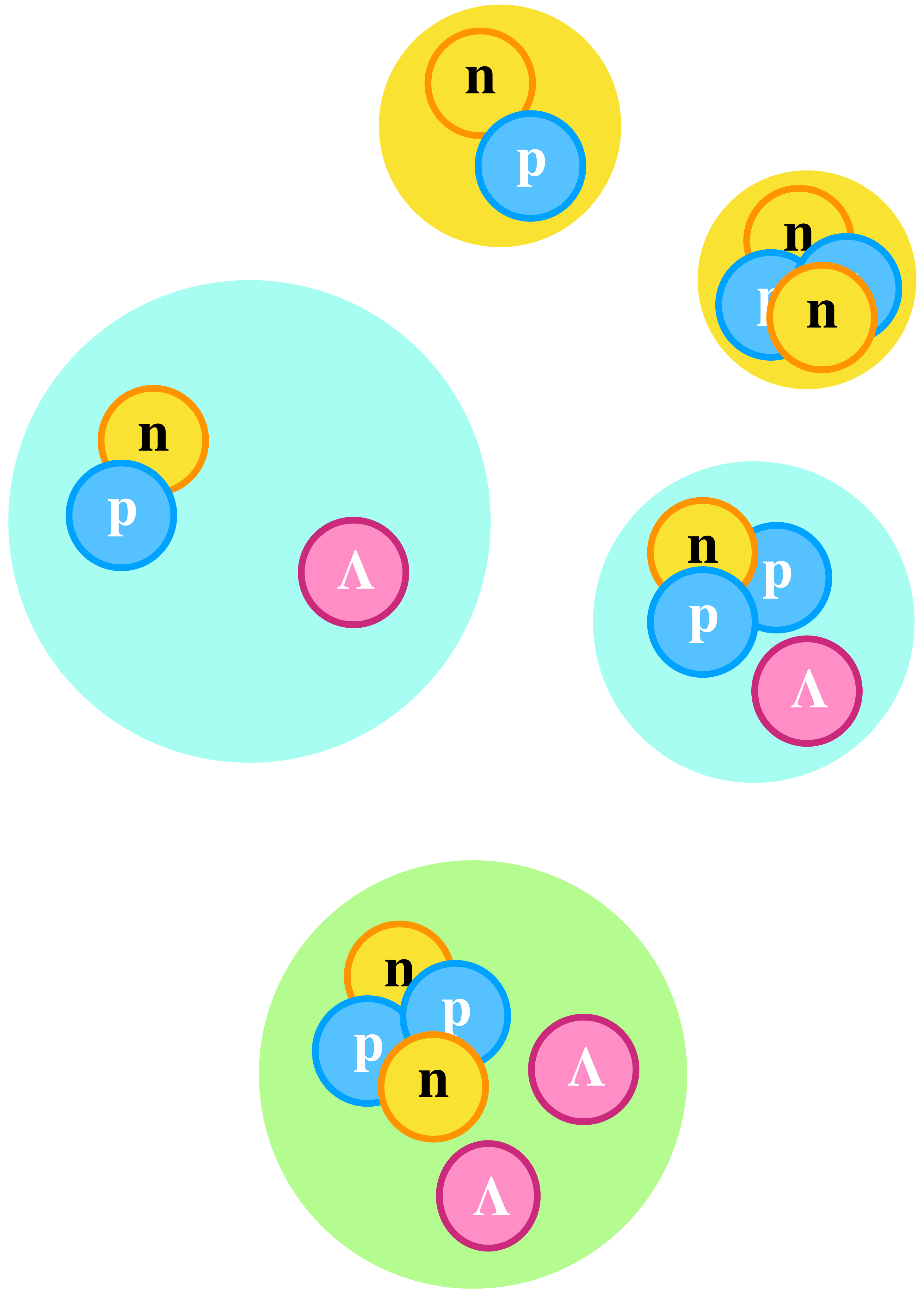
  - *Assume coalescence formation of nuclei*

$$\frac{t \times p}{d^2}$$

Sensitive to neutron density fluctuations

$$\frac{{}^{3}_{\Lambda}\mathrm{H}}{{}^{3}\mathrm{He} \times \frac{\Lambda}{\mathrm{p}}}$$

Sensitive to baryon-strangeness correlations



Need to first understand light nuclei production mechanisms

Phys. Lett. B 684 (2010) 224
Phys. Lett. B 781 (2018) 499

Light Nuclei Production Models

Thermal models

- Nuclei are formed earlier at the hadronic chemical freeze-out
- Thermal and chemical equilibrium (T, μ_B)

Coalescence models

- Nuclei are formed at late stages of collision
- Nucleons bind into nuclei if they are close in phase space

Dynamical models

$$\pi d \leftrightarrow \pi np$$
$$\pi t \leftrightarrow \pi nnp$$
$$\pi {}^3\text{He} \leftrightarrow \pi npp$$
$$\ldots$$

- Disintegration cross-sections are large

Nucl. Phys. A 1005 (2021) 121754

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$$\ldots$$

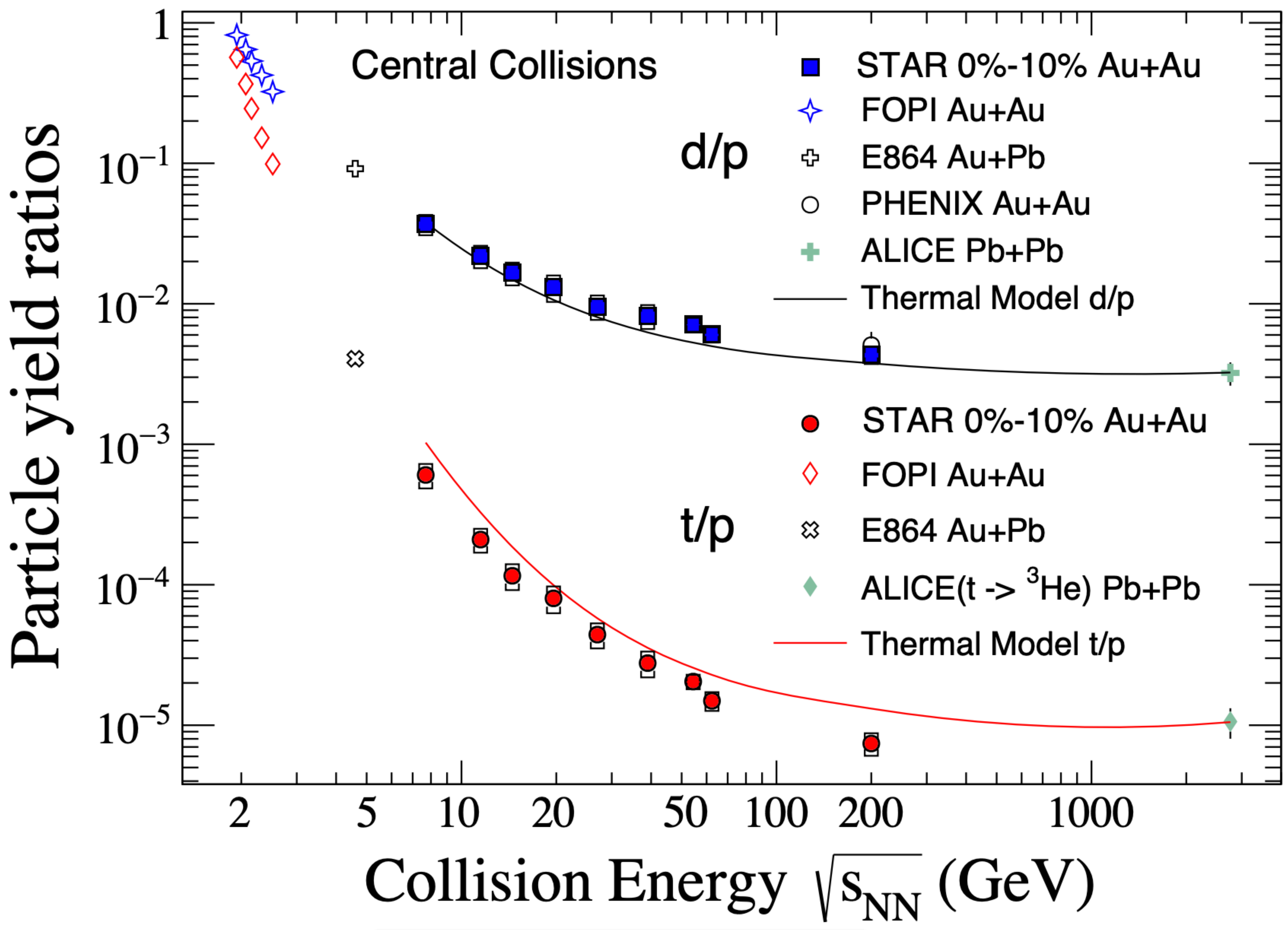
- Disintegration cross-sections are large

Nucl. Phys. A 1005 (2021) 121754

Nuclei are formed FIRST
then resonances decay into nucleons

Resonances decay into nucleons FIRST
then nucleons coalescence into nuclei

Light Nuclei Ratios in Central Collisions

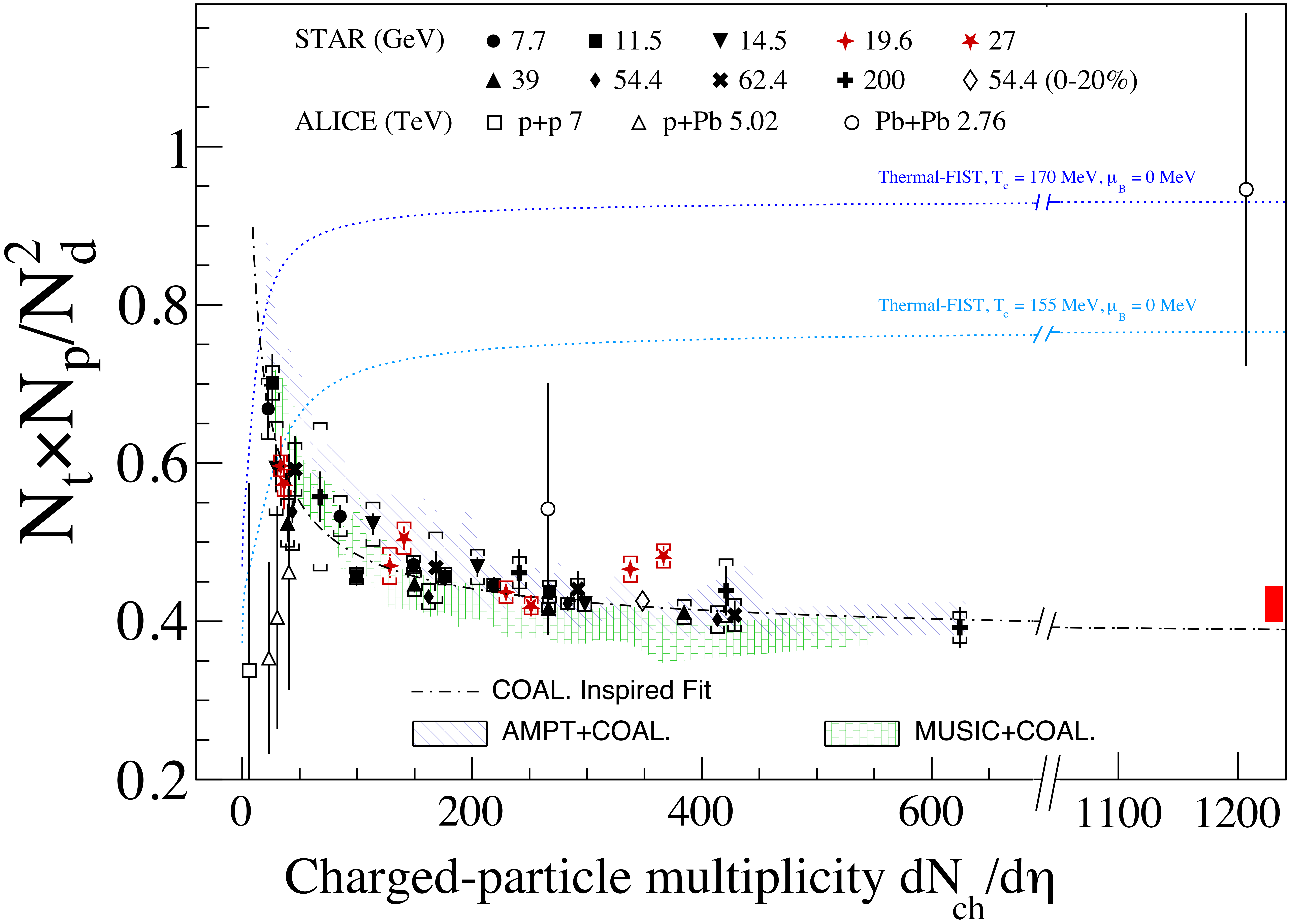


arXiv:2209.08058 (accepted by PRL)

- d/p fairly well described by thermal model, but t/p is overestimated
- Effects from hadronic re-scattering?

arXiv:2207.12532

Nuclear Compound Yield Ratio



arXiv:2209.08058 (accepted by PRL)

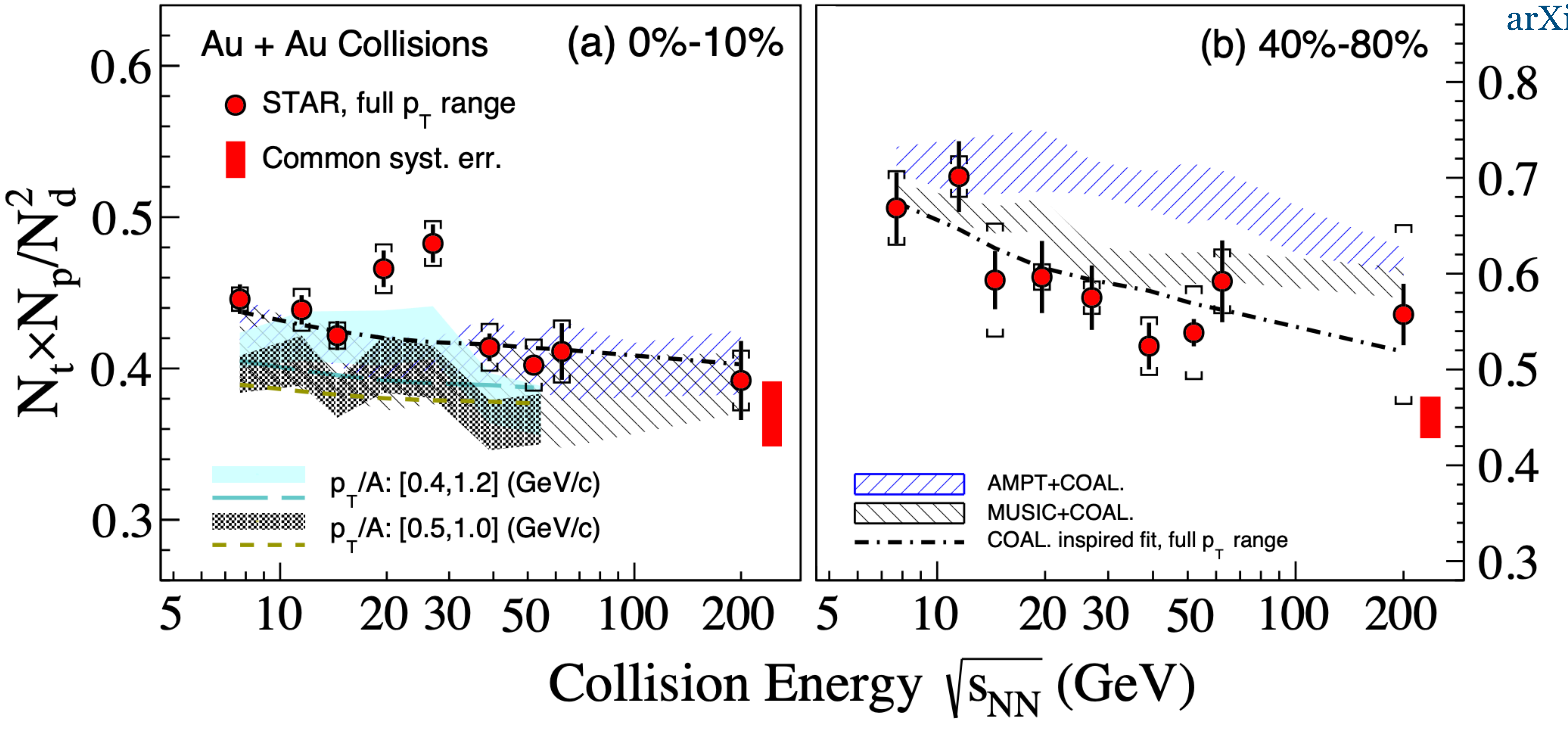
- Light nuclei yield ratio deviates strongly from thermal model from $\sqrt{s_{NN}}$ = 7.7-200 GeV

Yield ratio exhibits approx. scaling behavior with $dN_{ch}/d\eta$;

Described by coalescence

Energy Dependence of Nuclear Compound Yield Ratio

arXiv:2209.08058 (accepted by PRL)



$$\frac{t \times p}{d^2} = g(1 + \Delta n)$$

- In a coalescence picture, compound yield ratio is sensitive to baryon density fluctuations
  - In the vicinity of the critical point, density fluctuations become larger
- In central collisions, non-monotonic behavior around 19.6 and 27 GeV observed with a combined significance of 4.1σ
  - Enhancements decreases with decreasing p_T acceptance

Hypernuclei

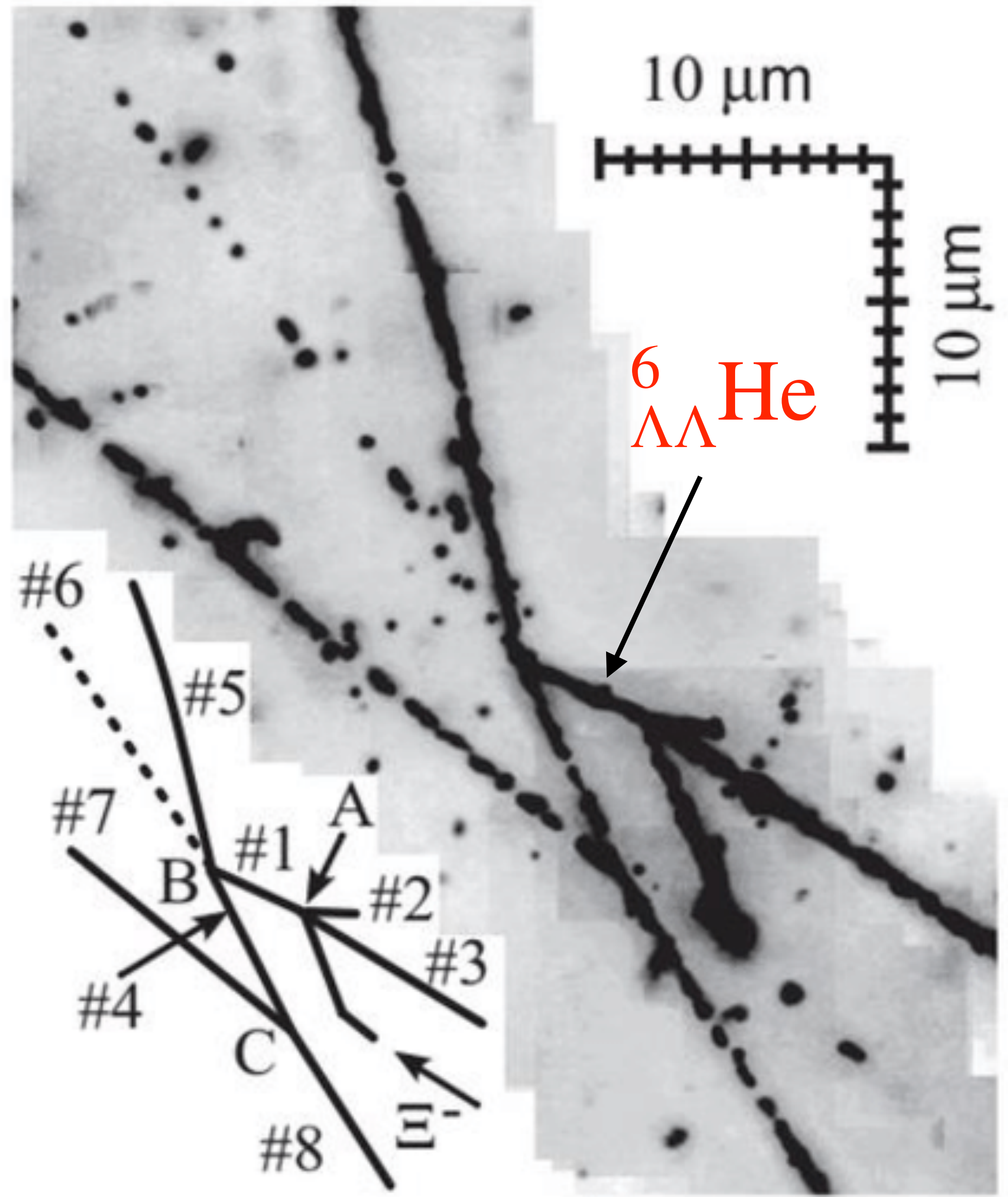
- Strangeness carrying nuclei which decays weakly
- Production yields / flow:

  Provides another deg. of freedom to study production mechanisms

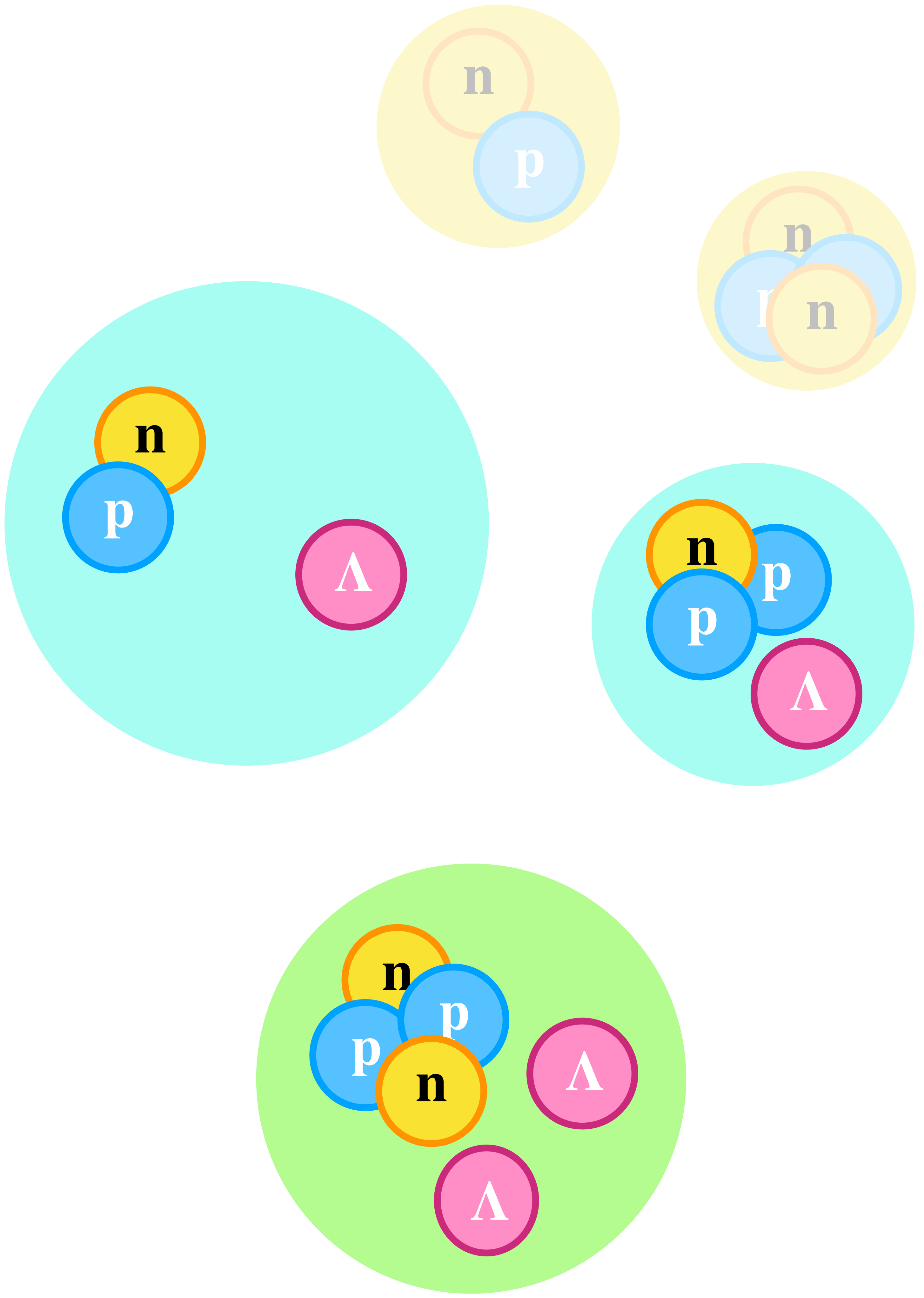
- Intrinsic properties (e.g.: τ, B_Λ)

  Constrain the ΛN interaction ⟶ *EoS neutron stars*

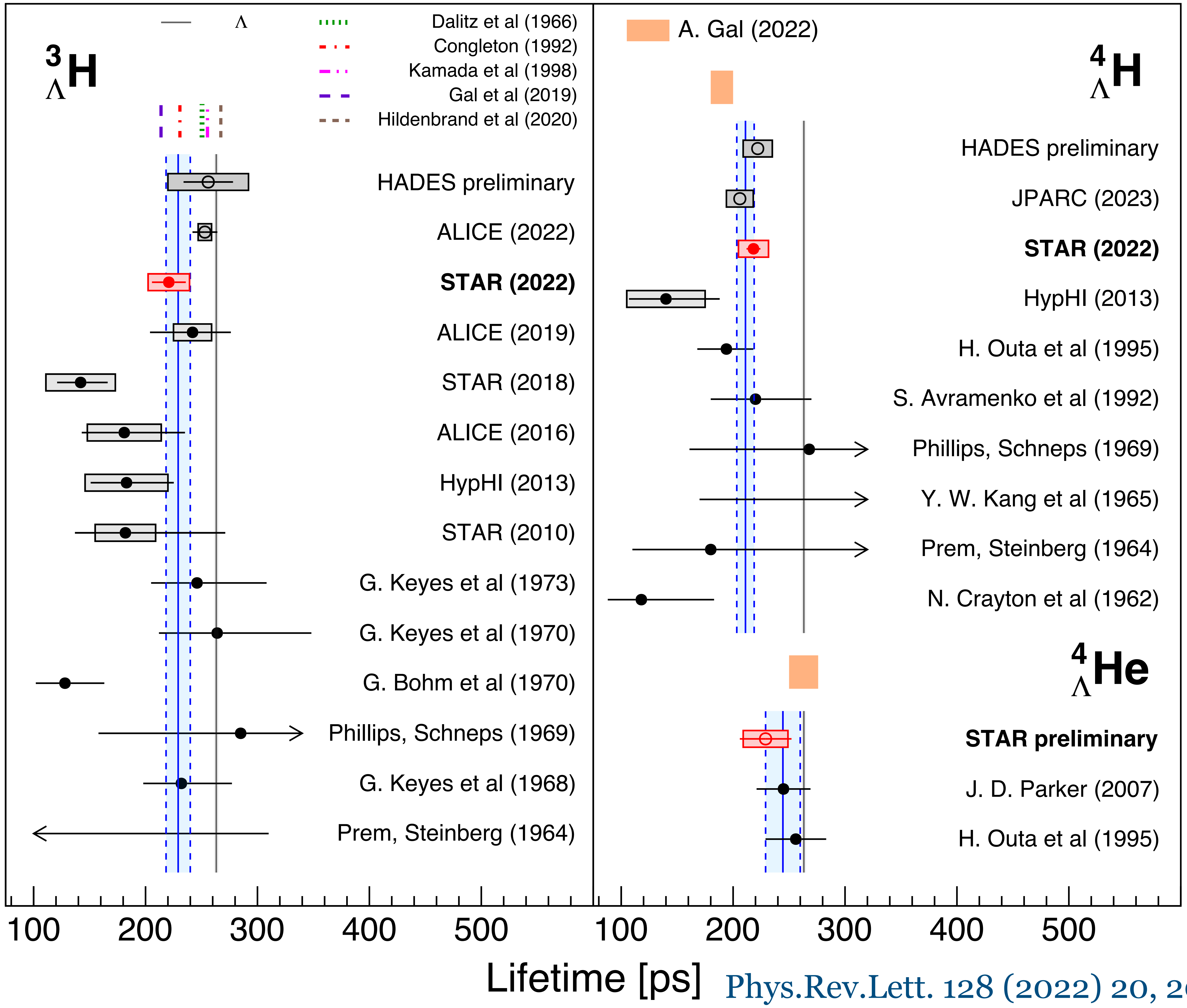
- Search for exotic states



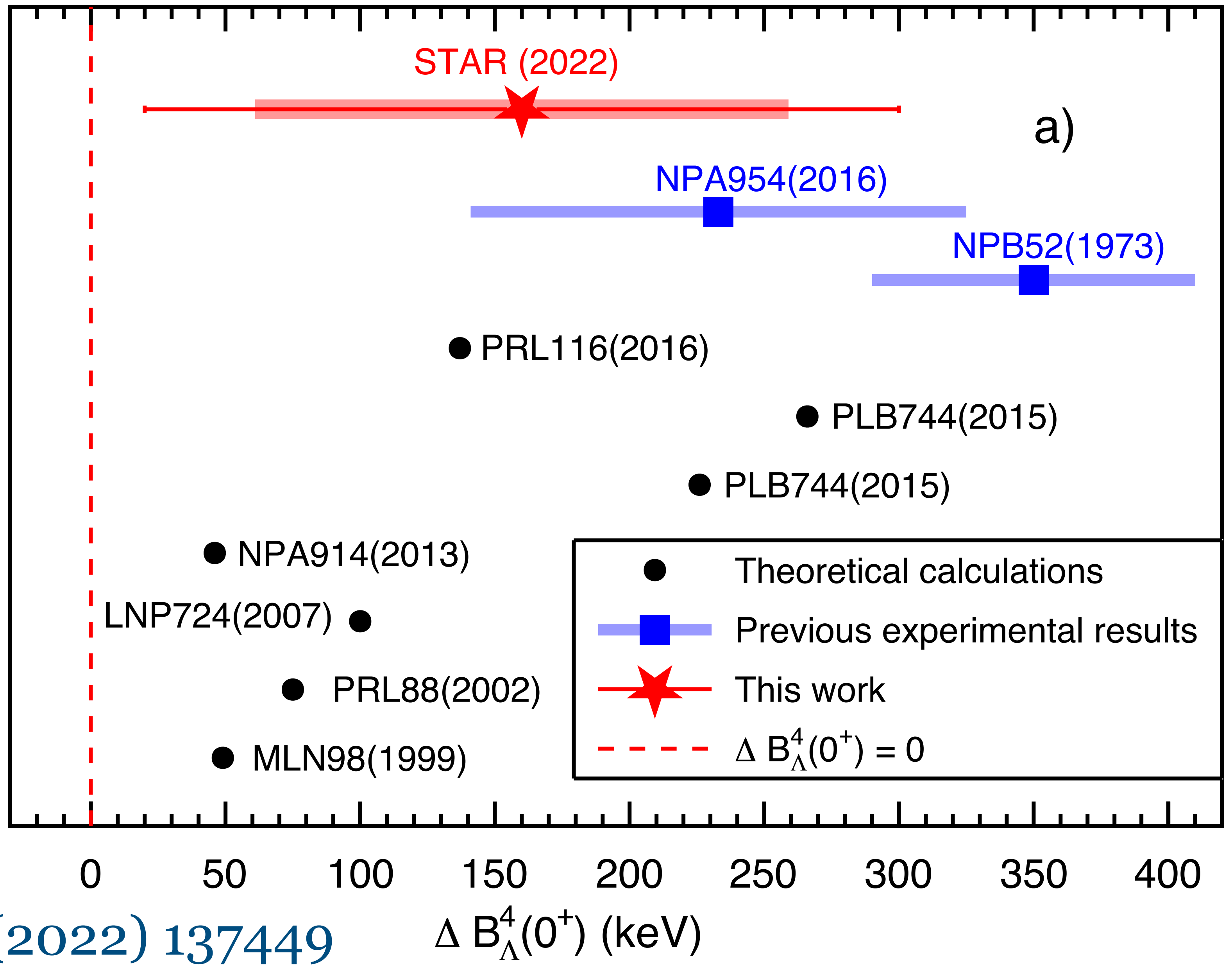
Phys. Rev. Lett. 87, 212502 (2001)
Phys. Rev. C 88, 014003 (2013)



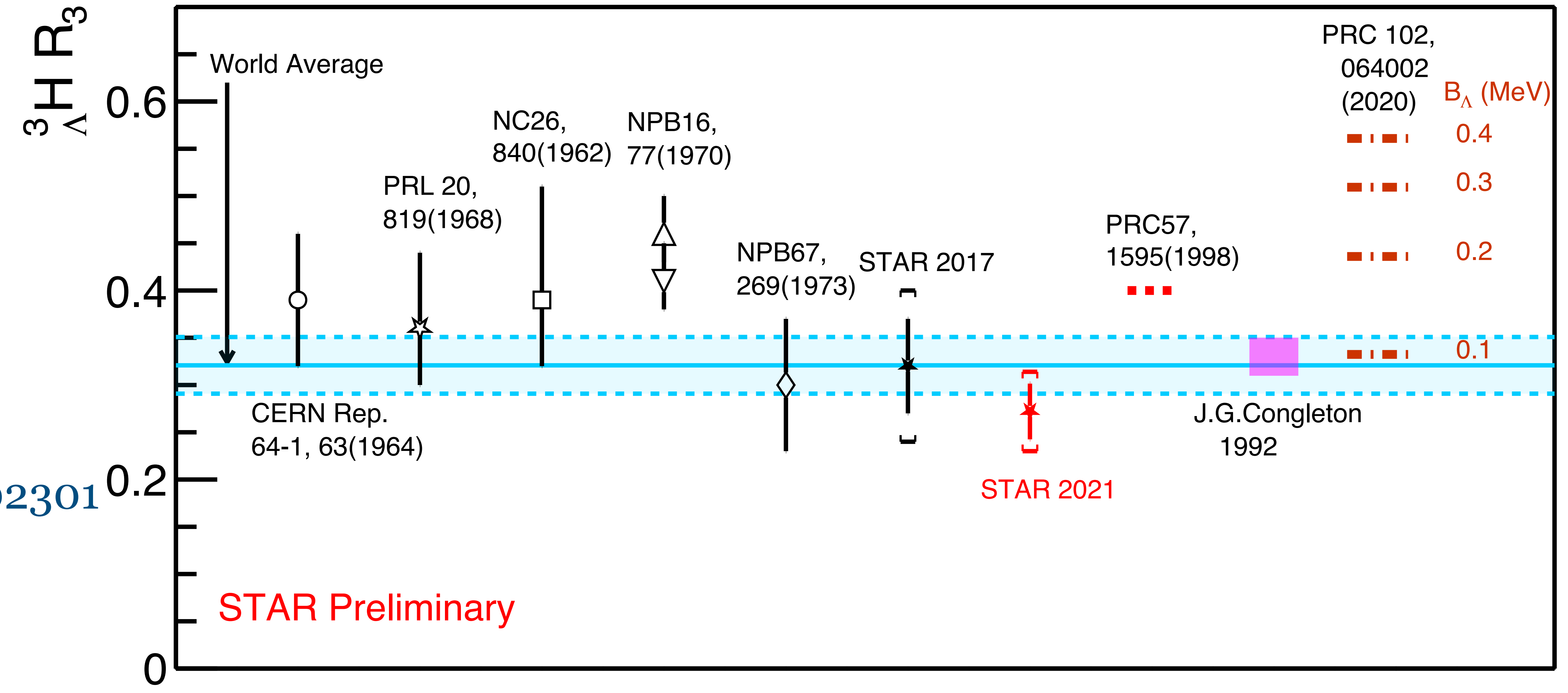
Hypernuclei Lifetime, Branching Ratio and Binding Energy



Phys.Rev.Lett. 128 (2022) 20, 202301

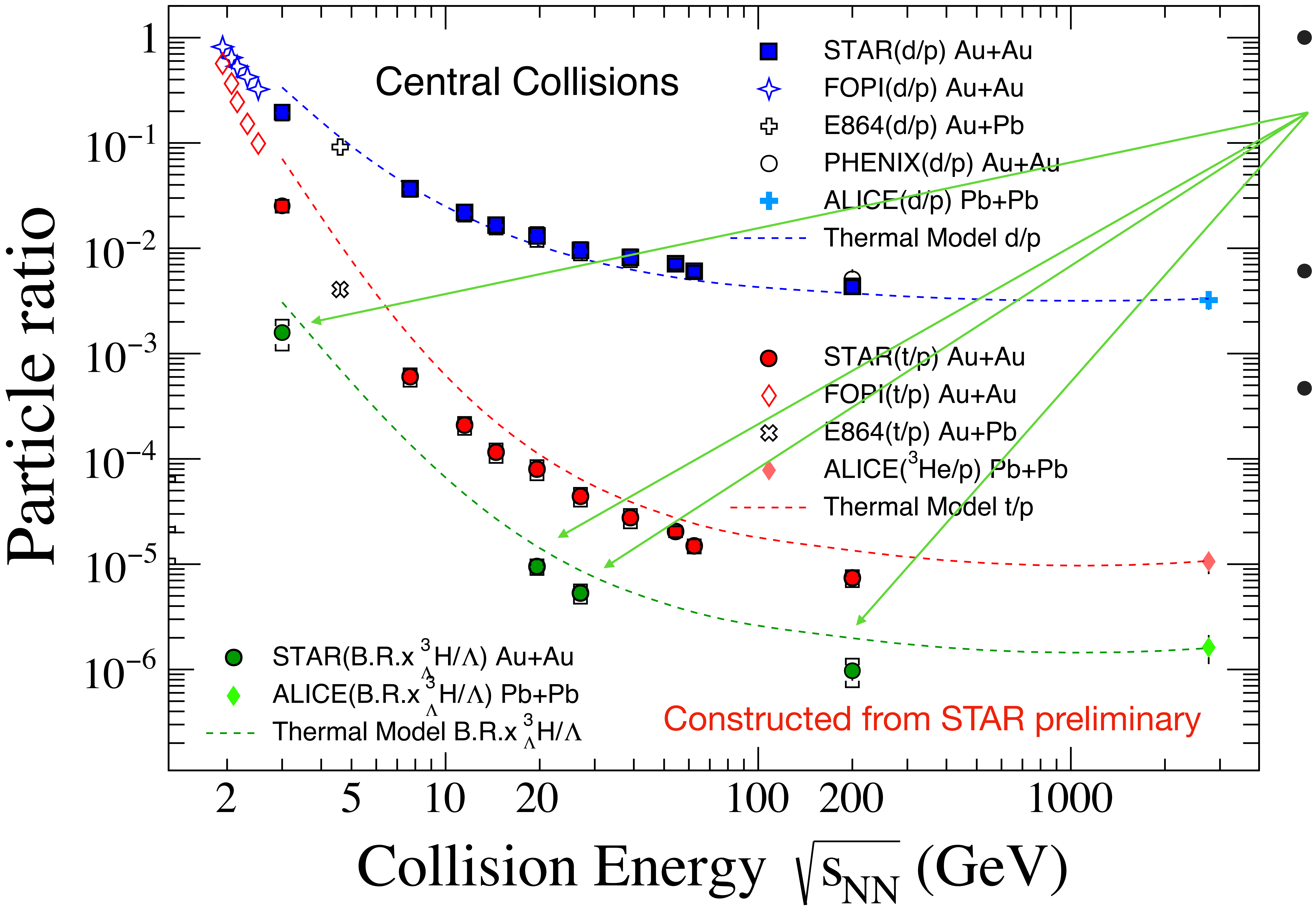


Phys. Lett. B 834 (2022) 137449



BES-II data improves our understanding of hyperrnuclei structure

Thermal model comparisons



- Similar to tritons, hypertritons are overestimated by the thermal model
- Effects from hadronic re-scattering?

arXiv:2207.12532

- Suppression due to large size?

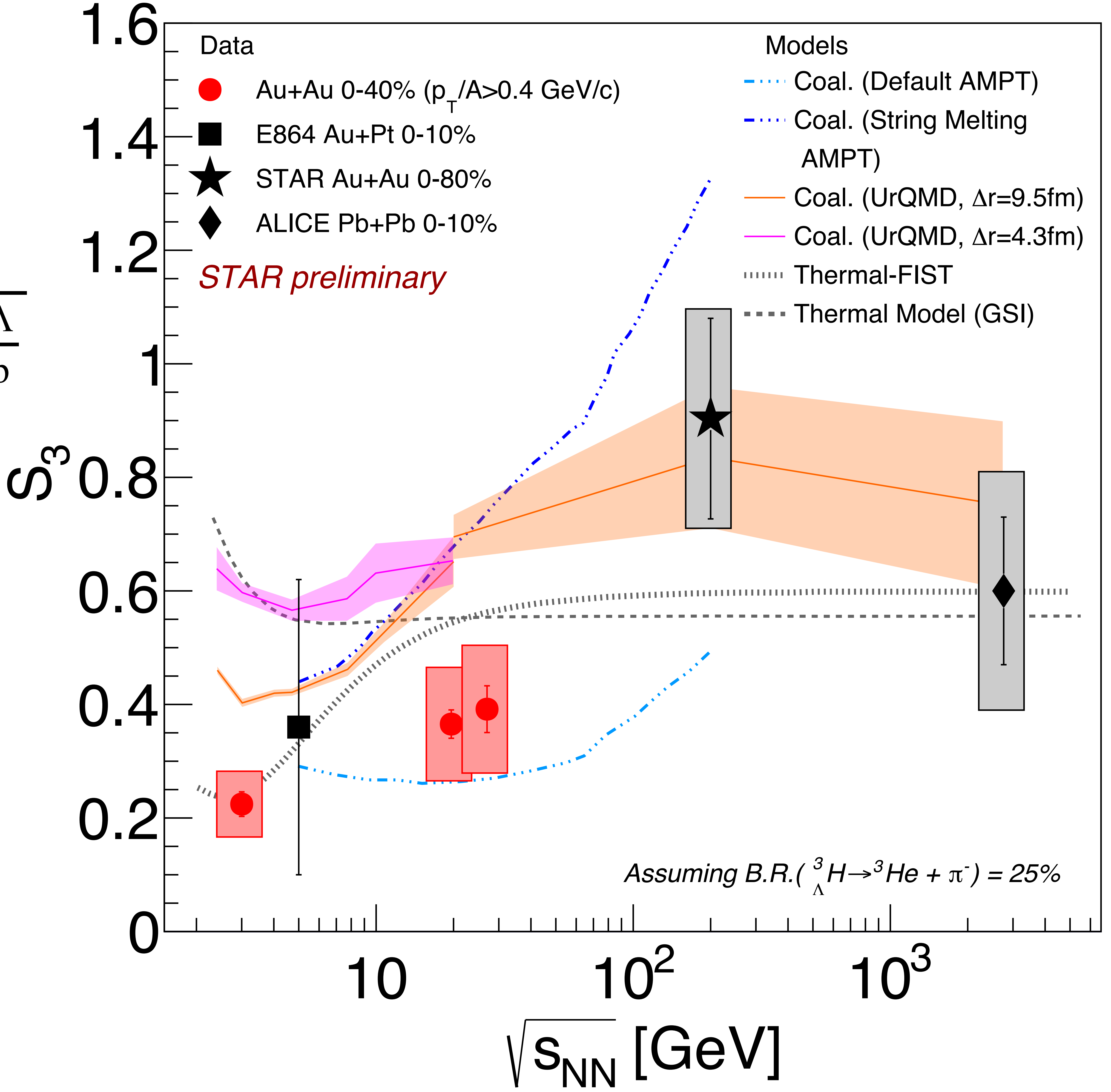
Phys.Rev.C 107 (2023)

Strangeness population factor S_3 as a Probe for Medium Properties?

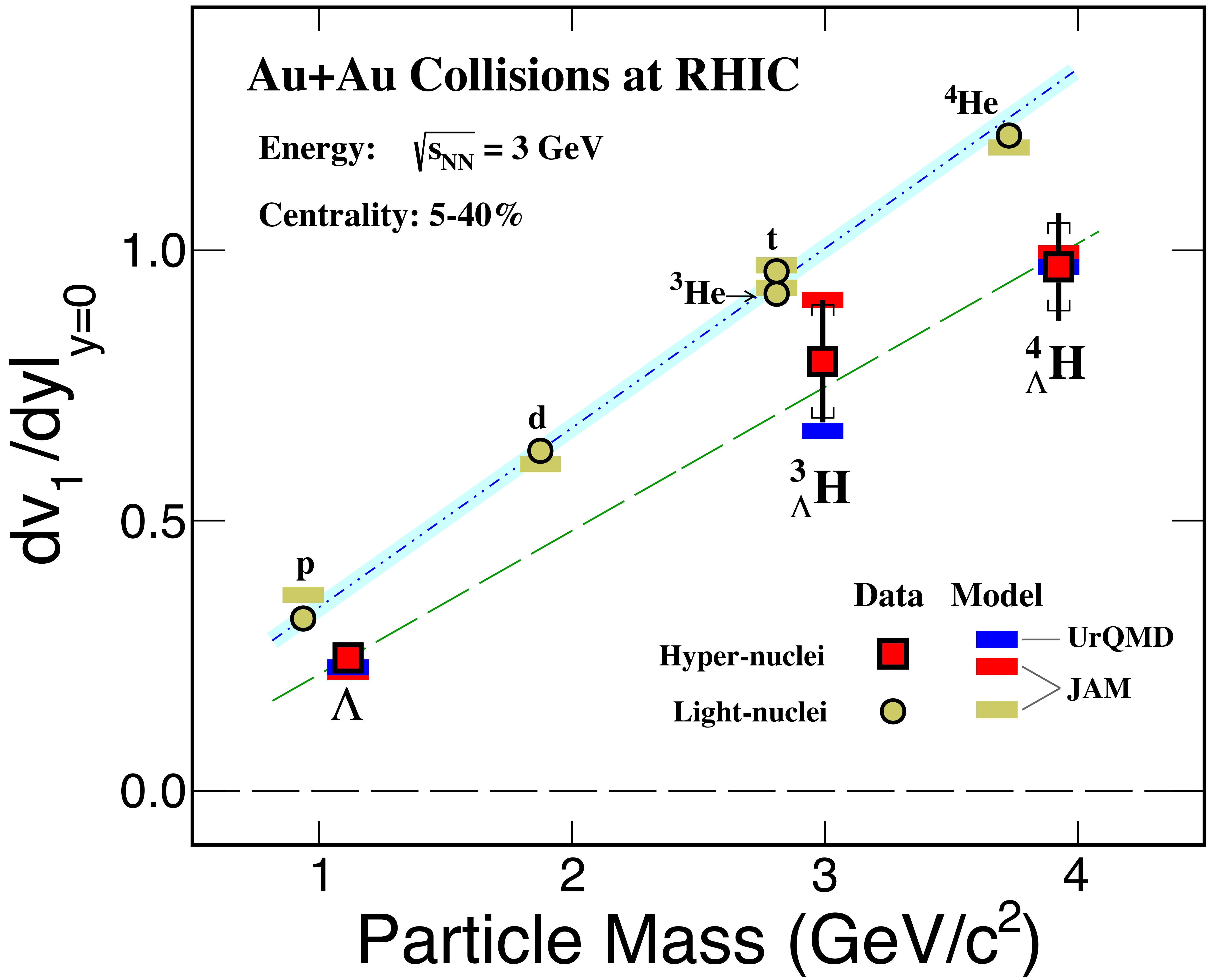
- Increasing trend of S_3 originally proposed as a signature of onset of deconfinement
    - Model is not quantitatively compatible with data

$$S_3 = \frac{^3_\Lambda H}{^3He \times \frac{\Lambda}{p}}$$

- Thermal-FIST also suggest increasing trend
    - Unstable nuclei breakup enhance ^3He yields?
- Coalescence+transport also suggest increasing trend
    - Suppression of $^3_\Lambda H$ due to large size



Nuclei and Hypernuclei Directed Flow



arXiv:2211.16981 (accepted by PRL)

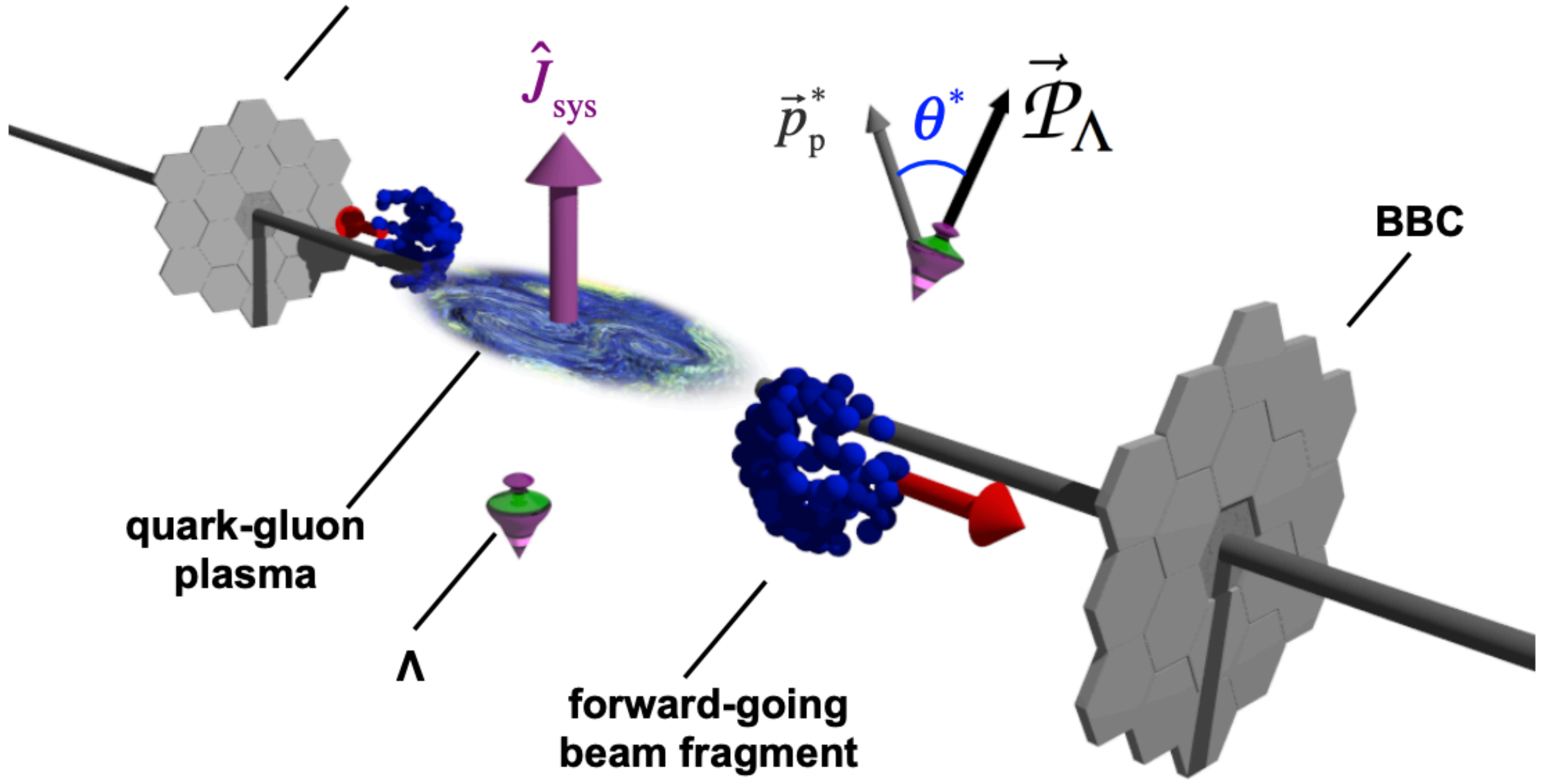
- v_1 slope of light nuclei follow mass number scaling at 3 GeV
- First observation of hypernuclei collectivity v_1 in HI collisions
- Hypernuclei v_1 slope also follows mass number scaling, consistent with coalescence models

Results qualitatively consistent with (hyper)nuclei production from coalescence

Global Hadron Polarization

- Λ global polarization: evidence for the most vortical fluid

STAR, Nature 548, 62 (2017)



- Global polarization is the alignment between:

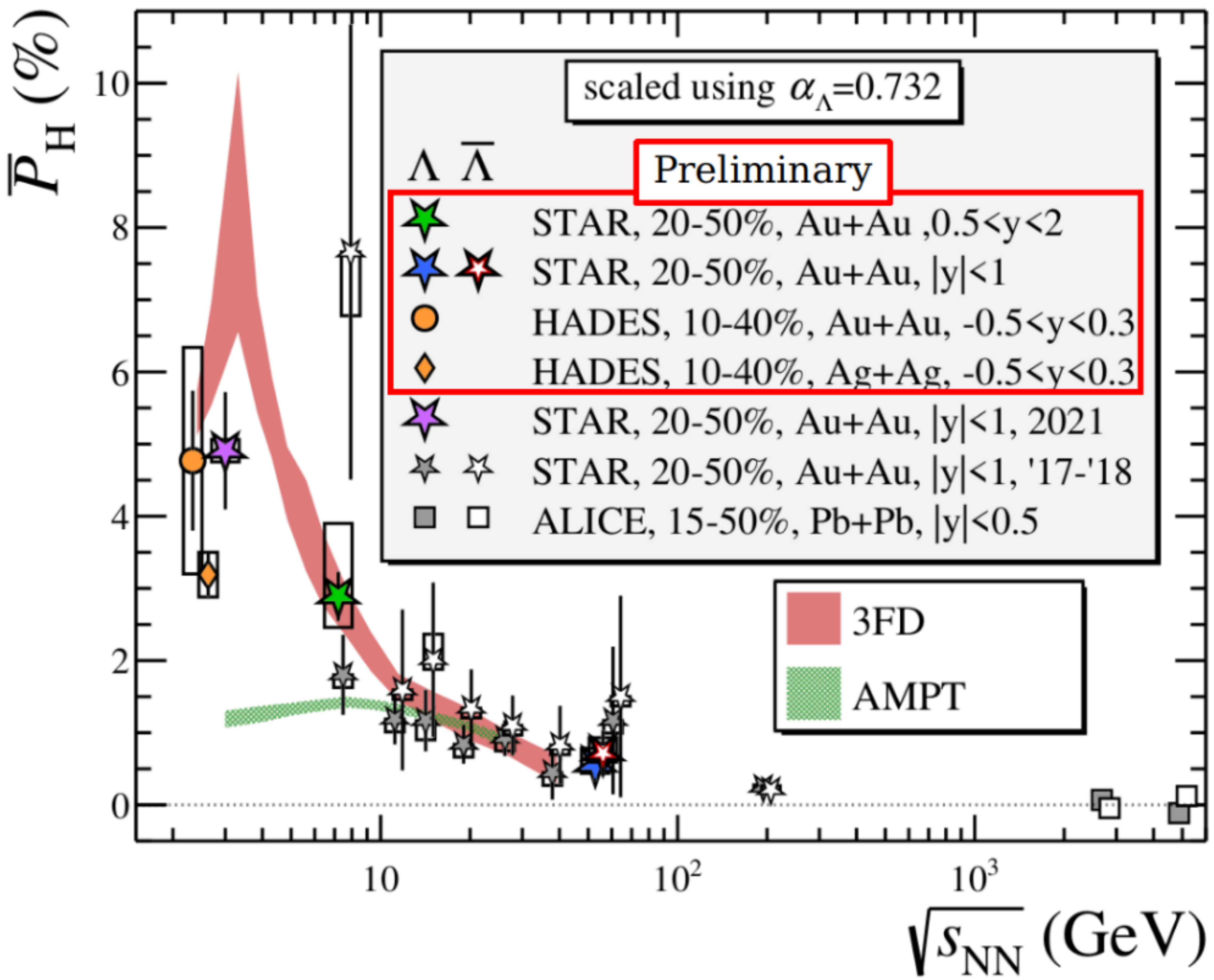
spin of emitted particles

Orbital angular momentum (OAM) of a non-central collision

Decay proton tends to be emitted along the spin direction of the parent Λ

$$\overline{\mathcal{P}}_{\mathrm{H}} \equiv \langle \vec{\mathcal{P}}_{\mathrm{H}} \cdot \hat{J}_{\mathrm{sys}} \rangle = \frac{8}{\pi \alpha_{\mathrm{H}}} \frac{\left\langle \cos\left(\phi_p^* - \phi_{\hat{J}_{\mathrm{sys}}}\right)\right\rangle}{R_{\mathrm{EP}}^{(1)}}$$

Phys. Rev. C 104 (2021) 61901

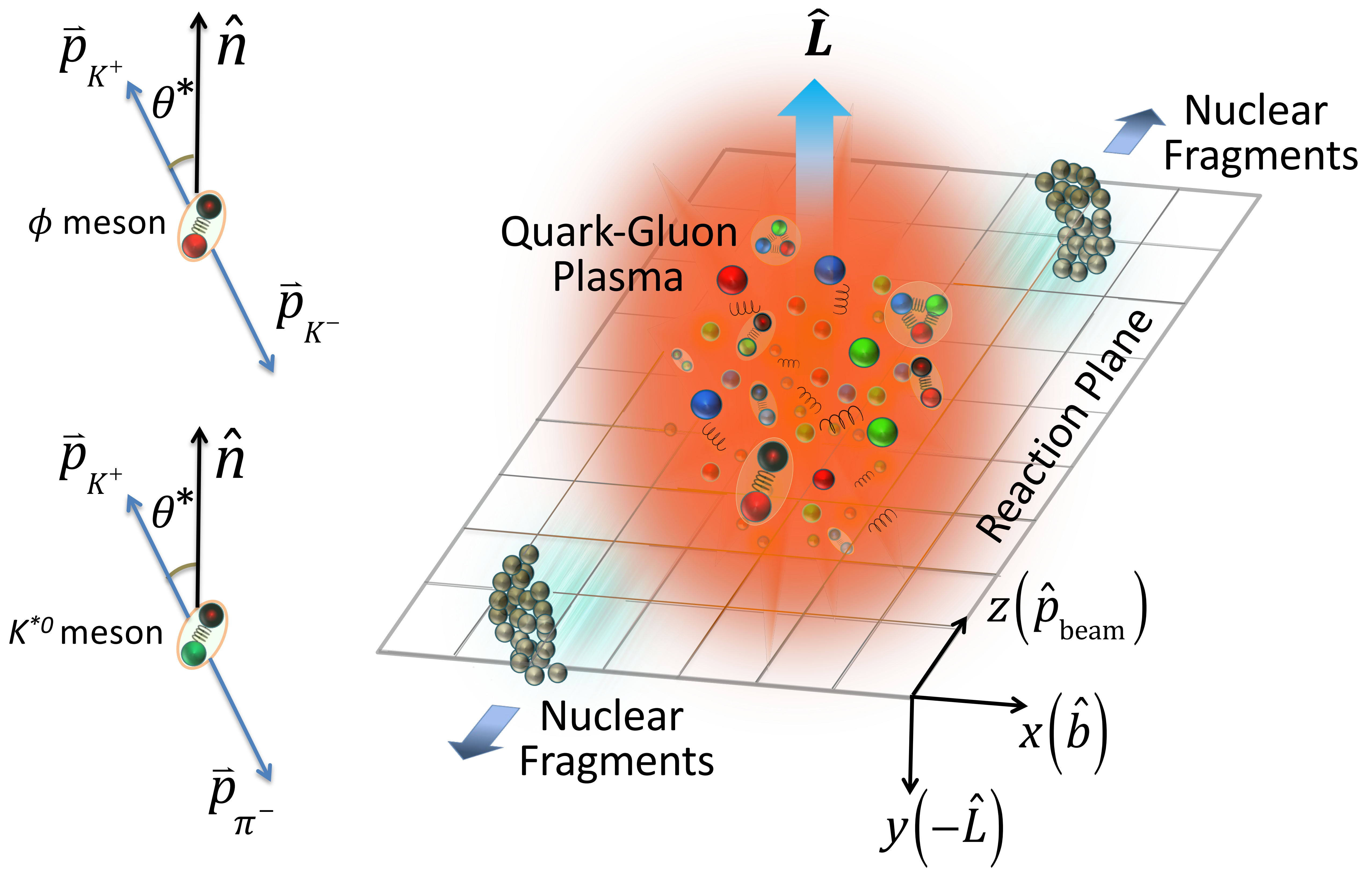


- Increasing trend of $\overline{\mathrm{P}}_{\mathrm{H}}$ persists at 3 GeV

May imply that hadronic system evolves hydrodynamically

Global Spin Alignment

Nature 614 (2023) 7947, 244-248



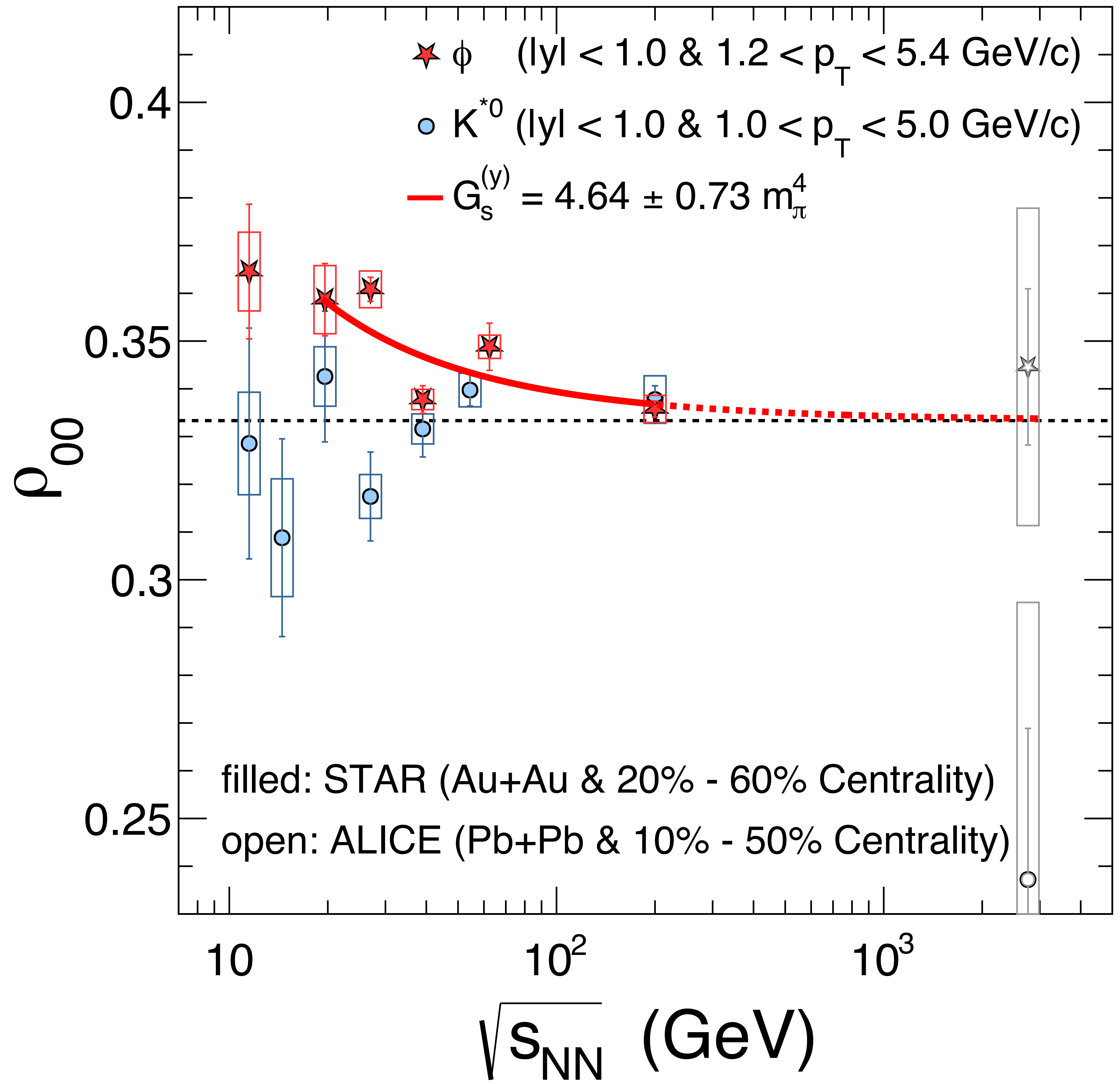
$$\frac{dN}{d(\cos\theta^*)} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$

- $\rho_{00} = 1/3$ -> 3 spin states have equal probability to be occupied
- $\rho_{00} \neq 1/3$ -> spin alignment

- OAM also influences production of vector mesons such as $\phi(1020)$ and K^{*0} (892)

Energy Dependence of Global Spin Alignment

Nature 614 (2023) 7947, 244-248



Observed spin-alignment for ϕ cannot be explained by conventional mechanisms

- Model with a connection to strong force fields accommodates the data

  Phys. Rev. D, 101(9):096005, 2020

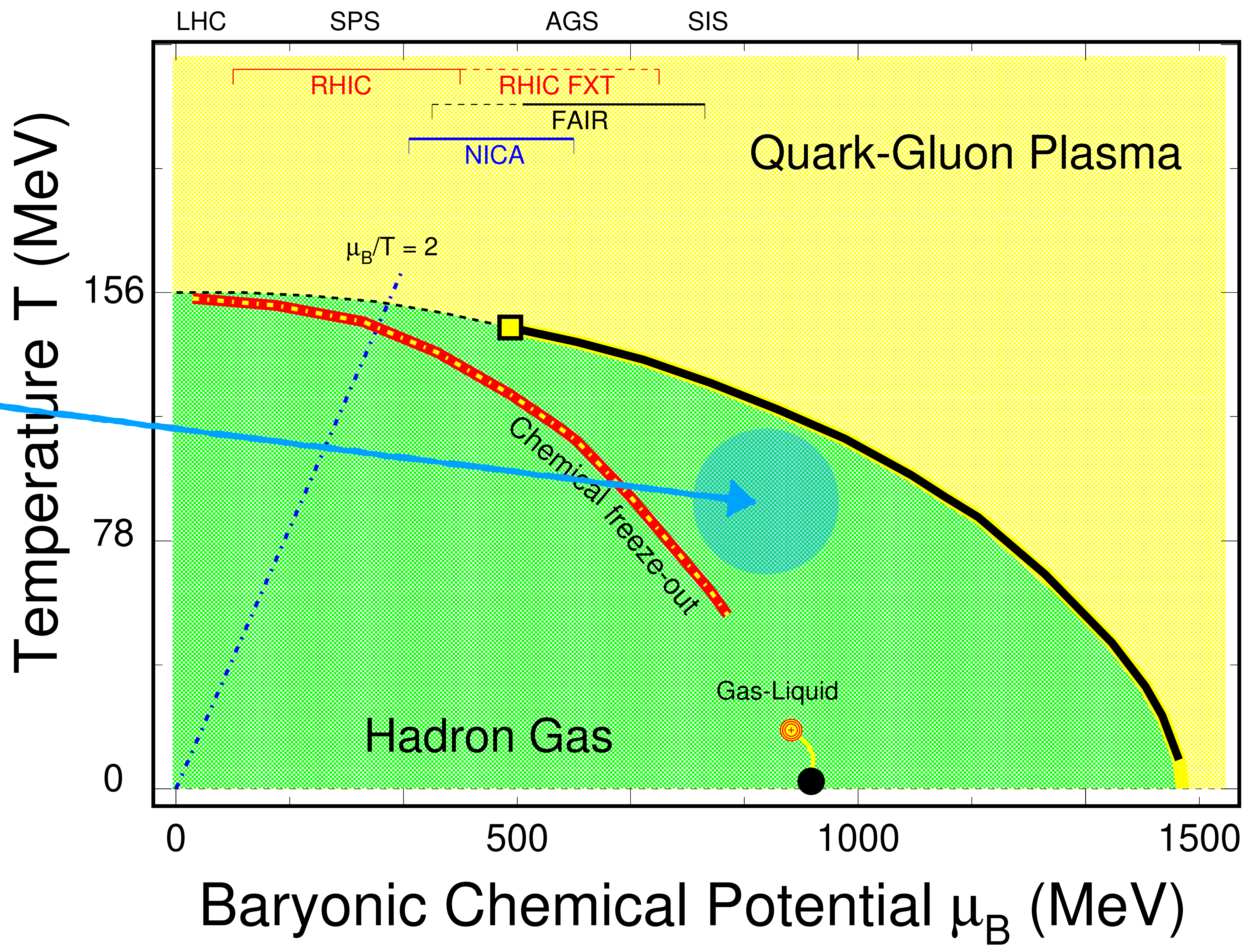
  - ϕ-meson fields ⟷ ϕ-meson analogous to EM fields ⟷ photon

- Decreasing trend is explained by $1/T^2_{eff}$ dependence originating from the polarization of quarks in the ϕ-meson field

- Absence of spin-alignment for K^{*0} could be due to in-medium effects/different quark content

Summary

- Results on strangeness production, collective flow, global polarization, net-proton cumulants are compatible with <u>a predominantly hadronic medium formed in $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions</u>



Summary

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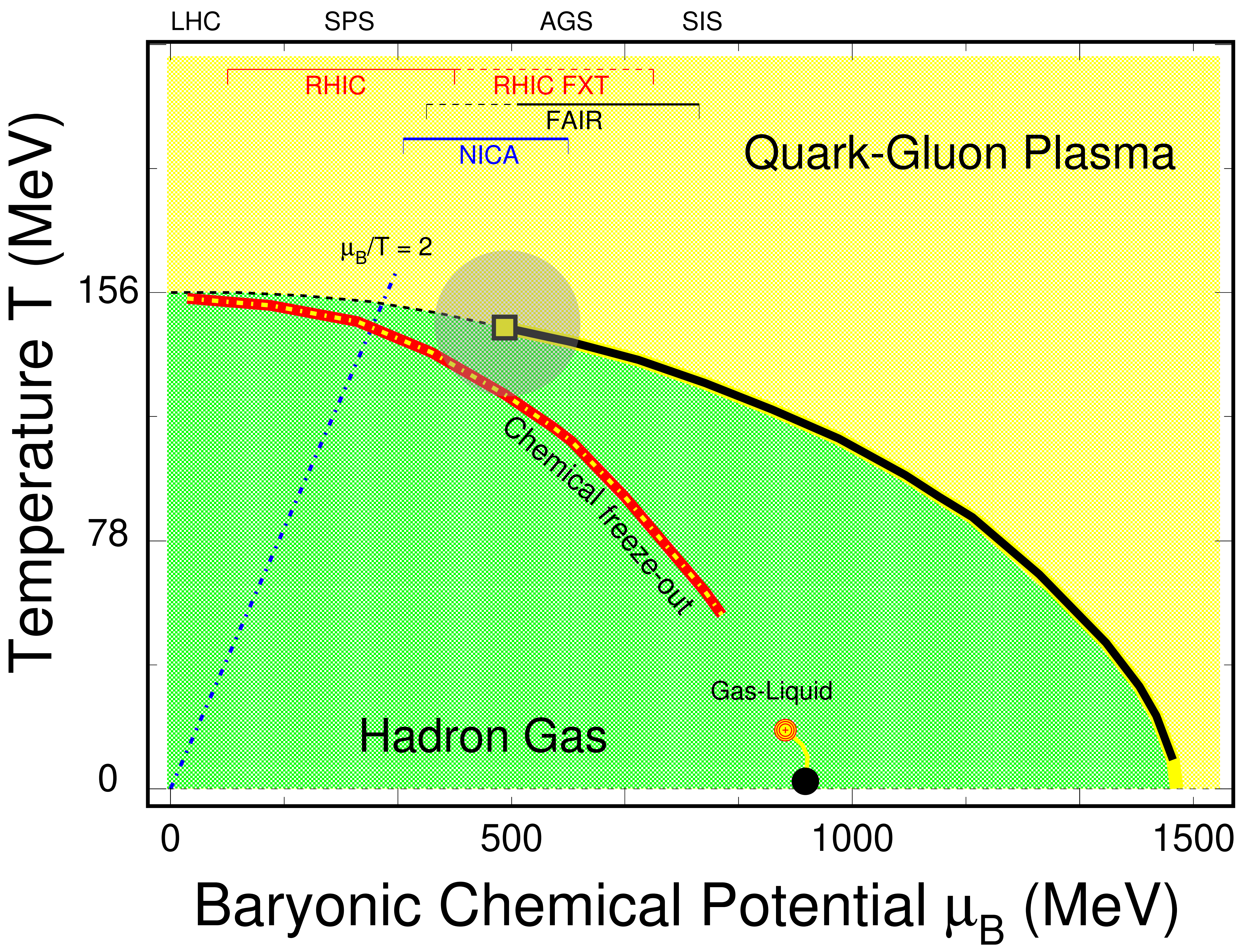
- No concrete conclusions on search for critical point
  - If exist, it should lie b/w 3 and 27 GeV

    FXT (3-7.7 GeV) and high statistics COL(7.7-27 GeV) data are crucial for further investigations



Summary

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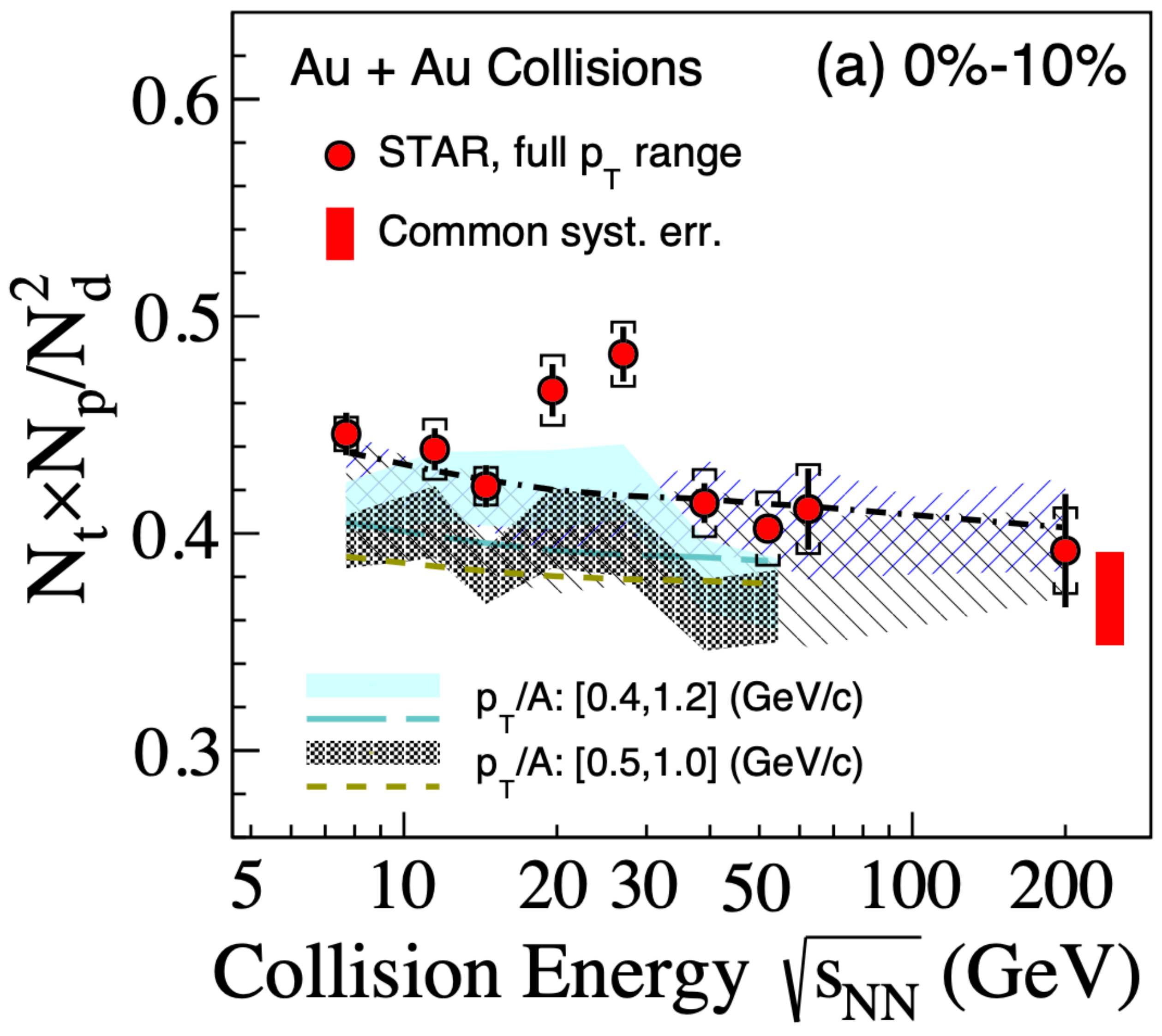
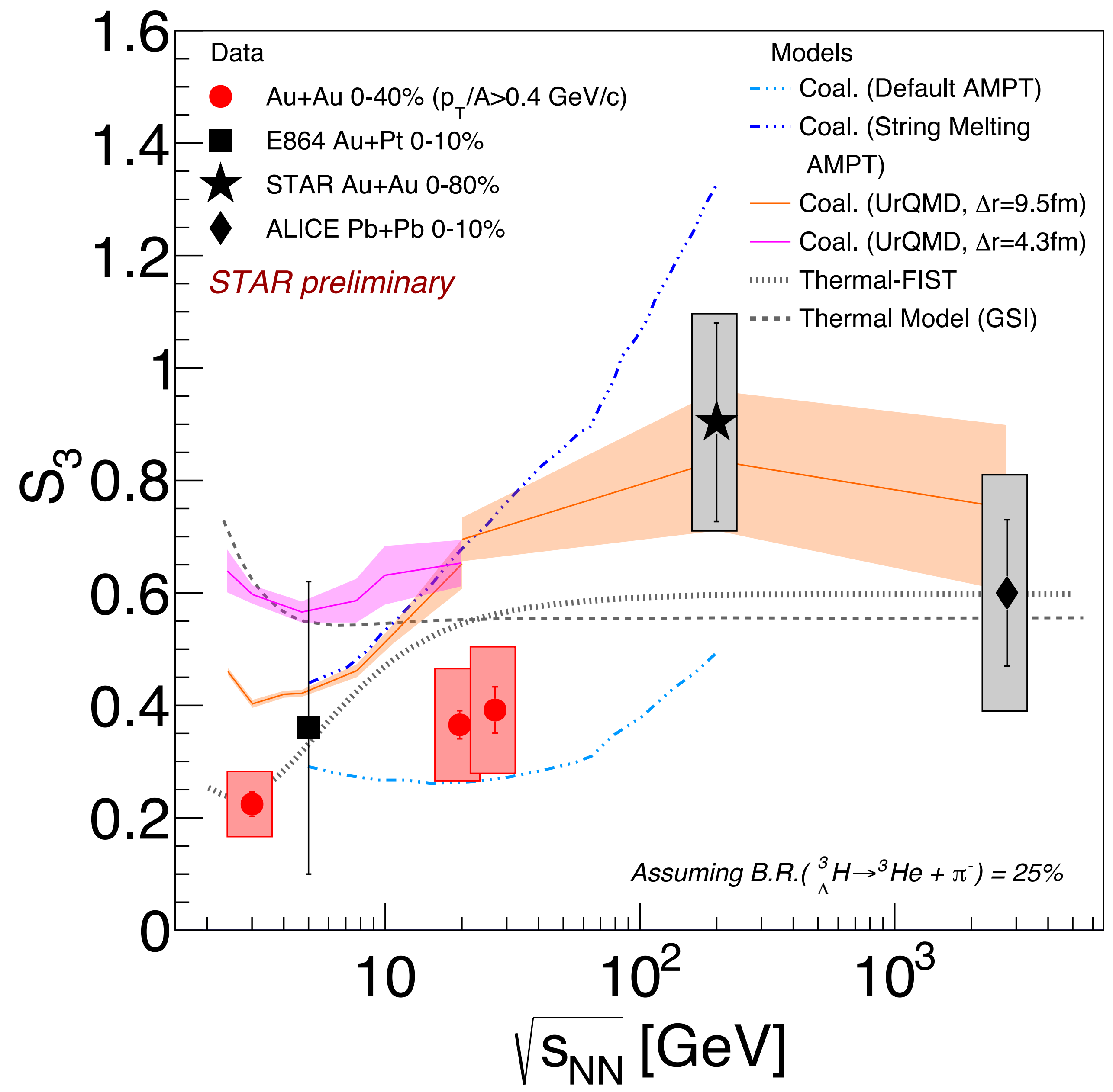
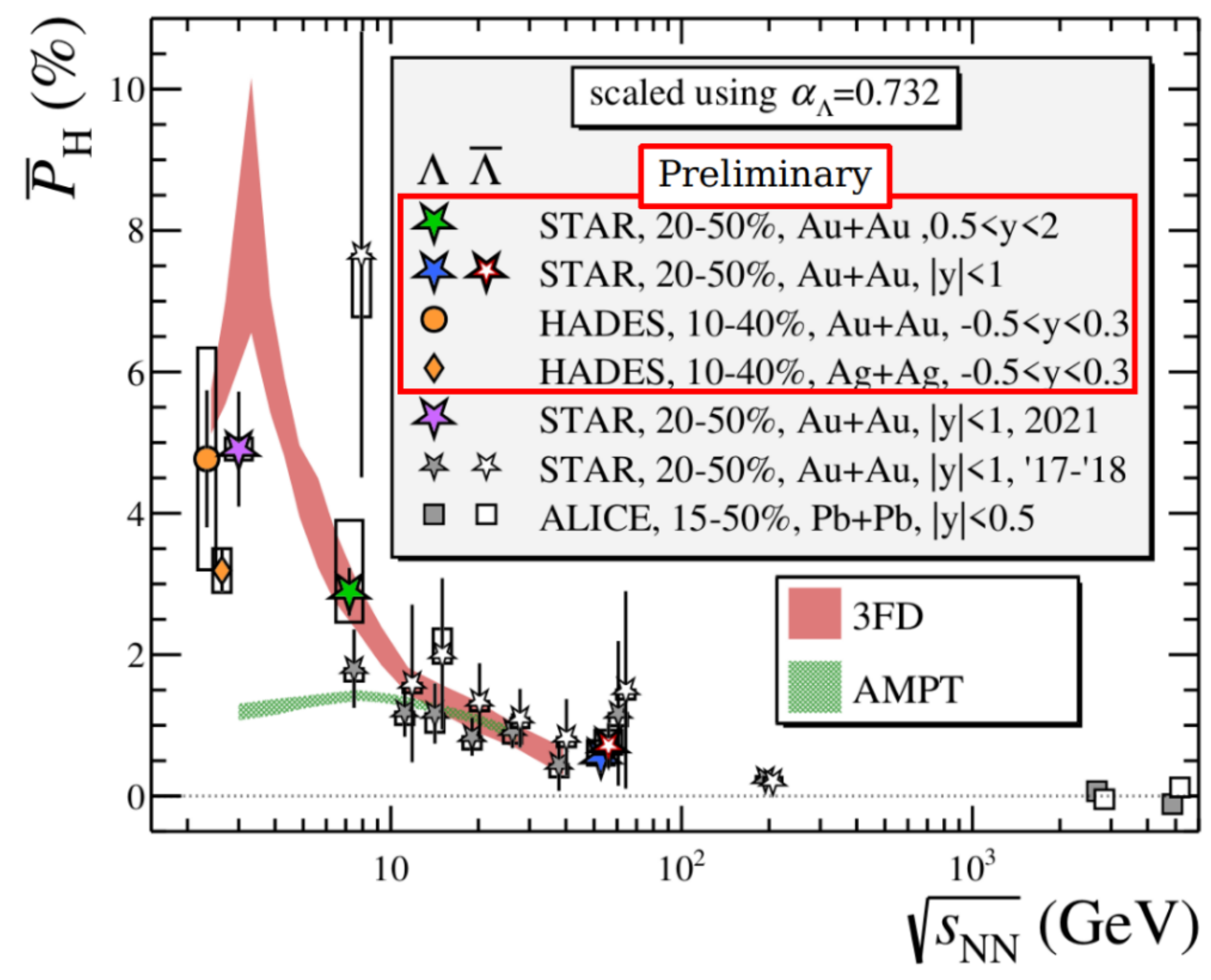
  FXT (3-7.7 GeV) and high statistics COL(7.7-27 GeV) data are crucial for further investigations

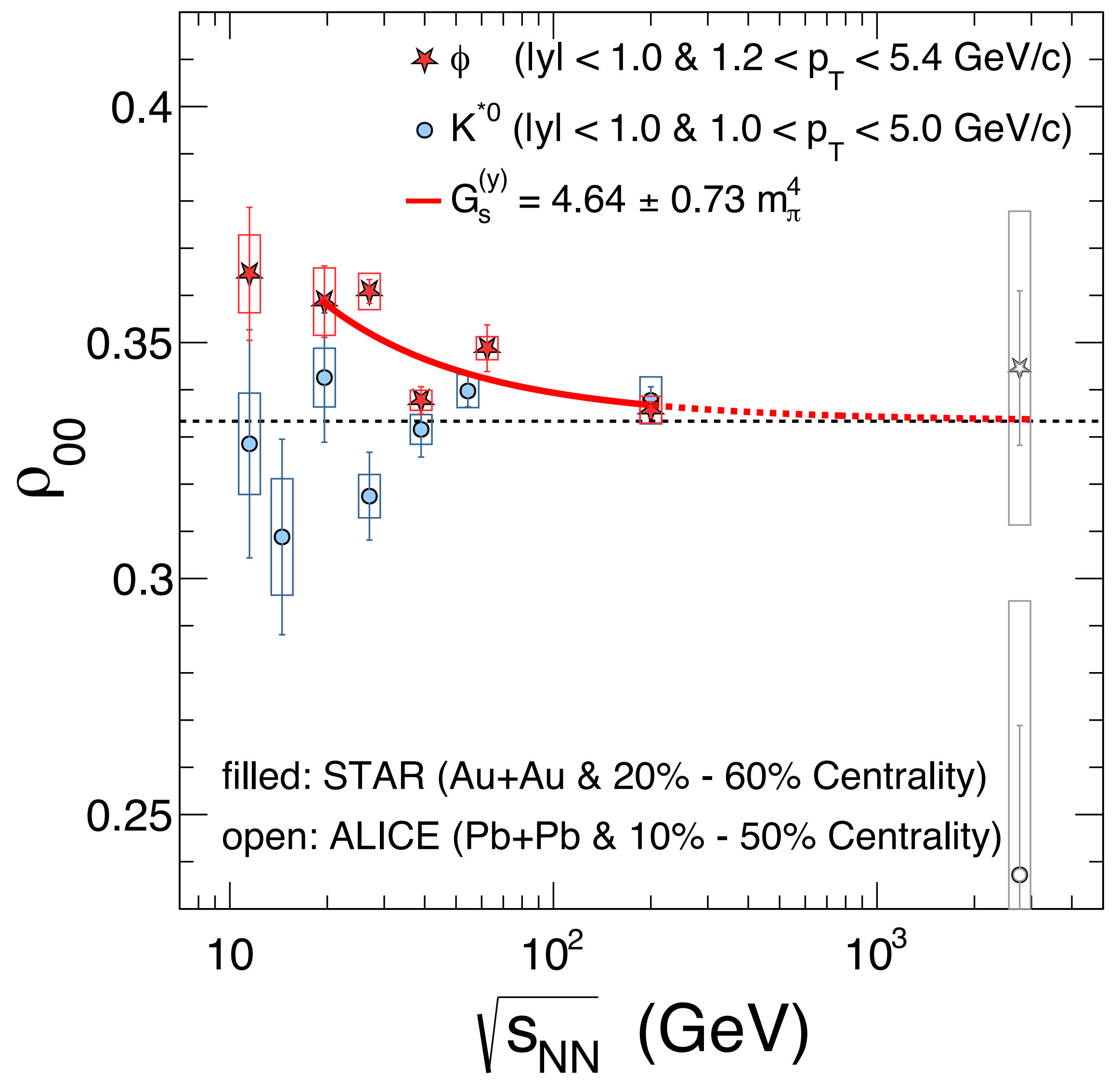
- New probes to diagnose the QCD medium: (hyper)nuclei, spin alignment, etc.

  Theoretical developments and experimental efforts necessary to understand such probes









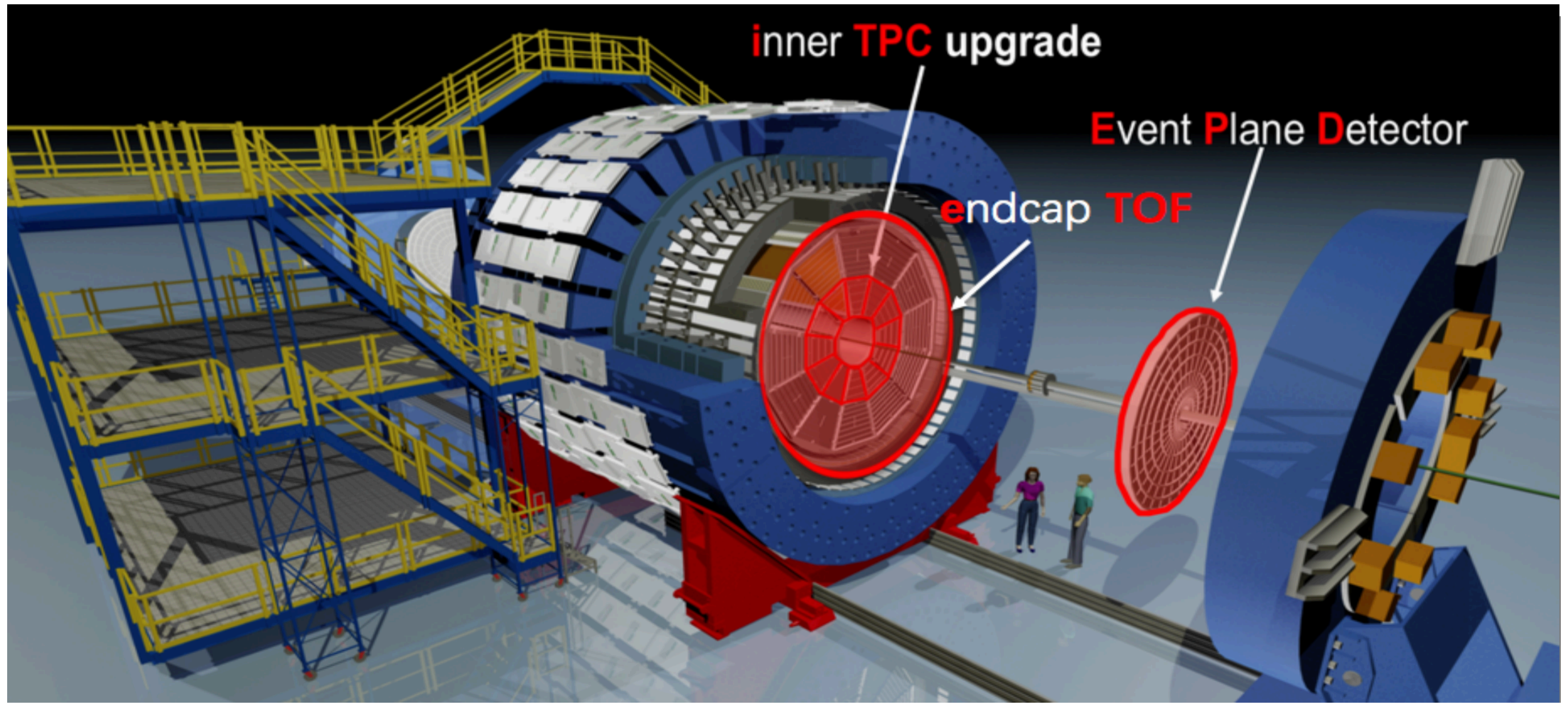
Outlook

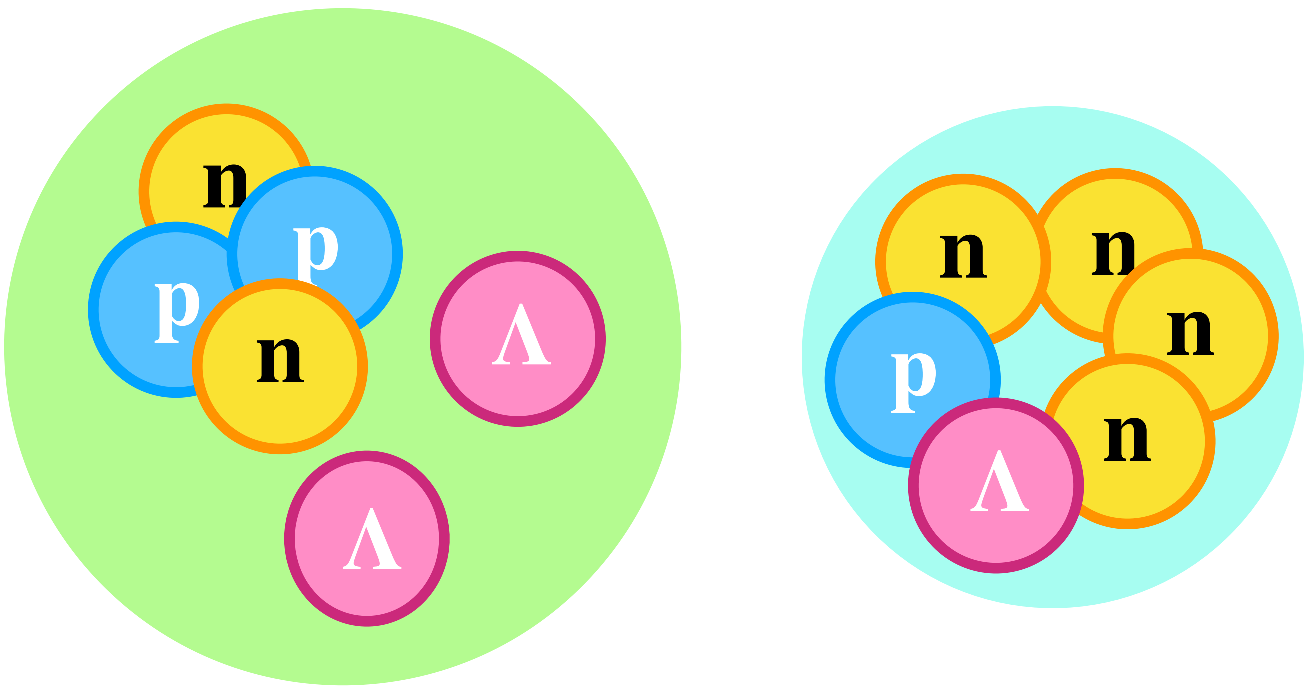
- iTPC and eTOF upgrades in 2019

  Crucial to maintain mid-rapidity coverage b/w 3.2-4.5 GeV

- High statistics data from 3-27 GeV

  Including 2B events at 3 GeV taken in 2021

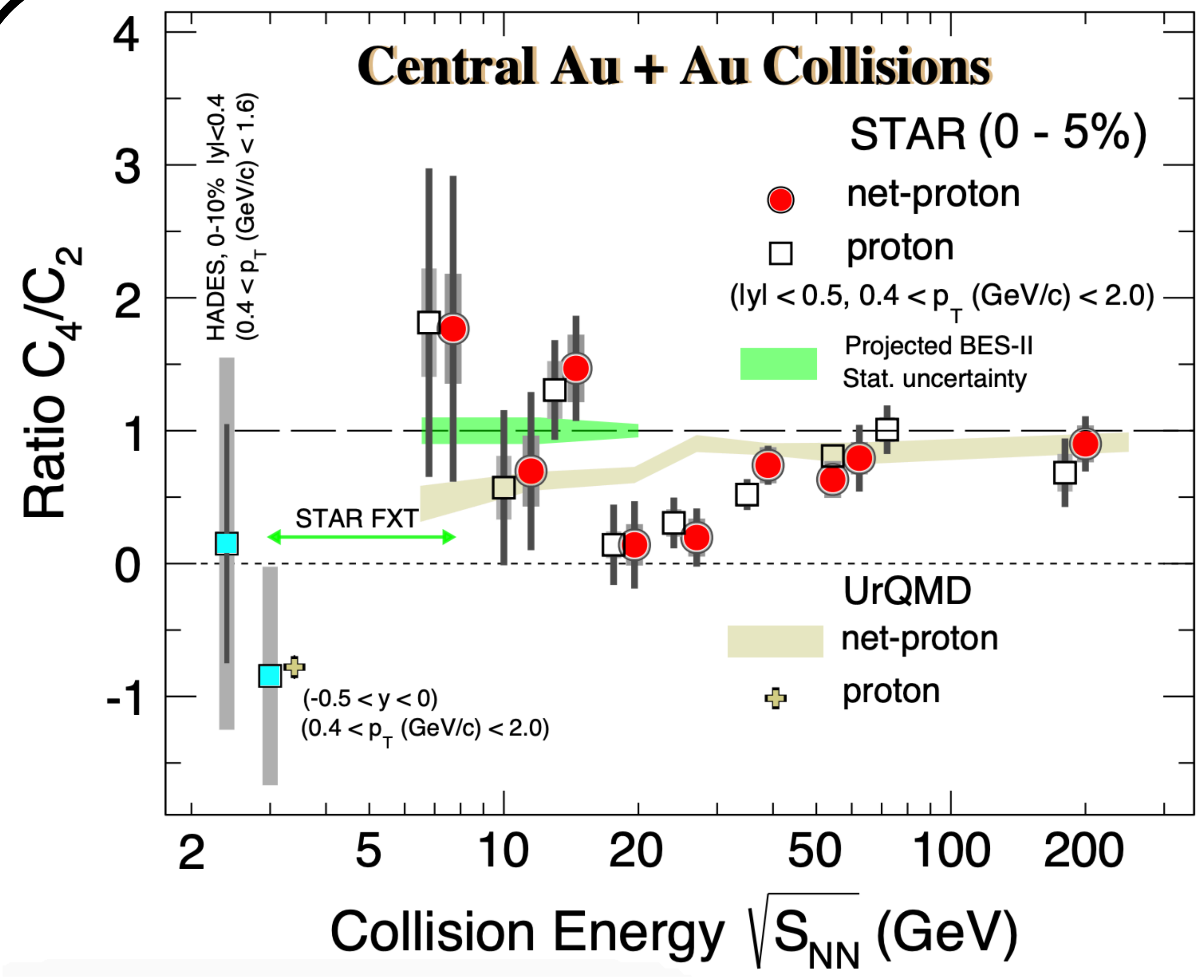




Double-Λ hypernuclei: ${}^{4}_{\Lambda\Lambda}H$

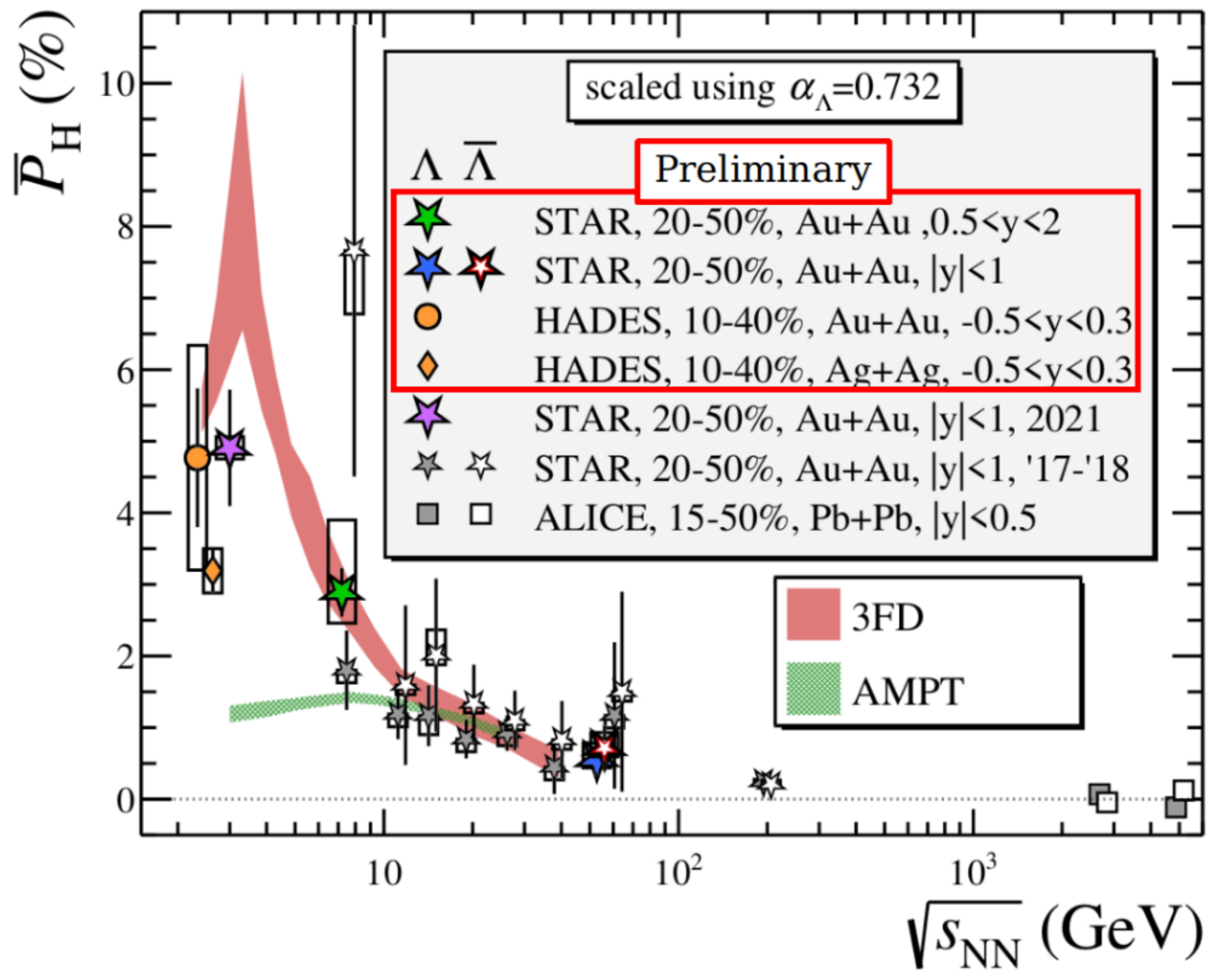
Neutron-rich hypernuclei: ${}^{6}_{\Lambda}H$

Unstable nuclei: ${}^{4}Li \rightarrow {}^{3}He + p$



BES-II FXT data: fill the gap b/w 3-7.7 GeV

BES-II COL data: with 10-20X statistics to confirm the non-monotonicity



Measure the magnetic field from $P_{\Lambda} - P_{\bar{\Lambda}}$ splitting?

Many more BES results to come!

Stay tuned, and

Thank you for listening!

Backup slides follow

S_3 and S_4 at 3 GeV

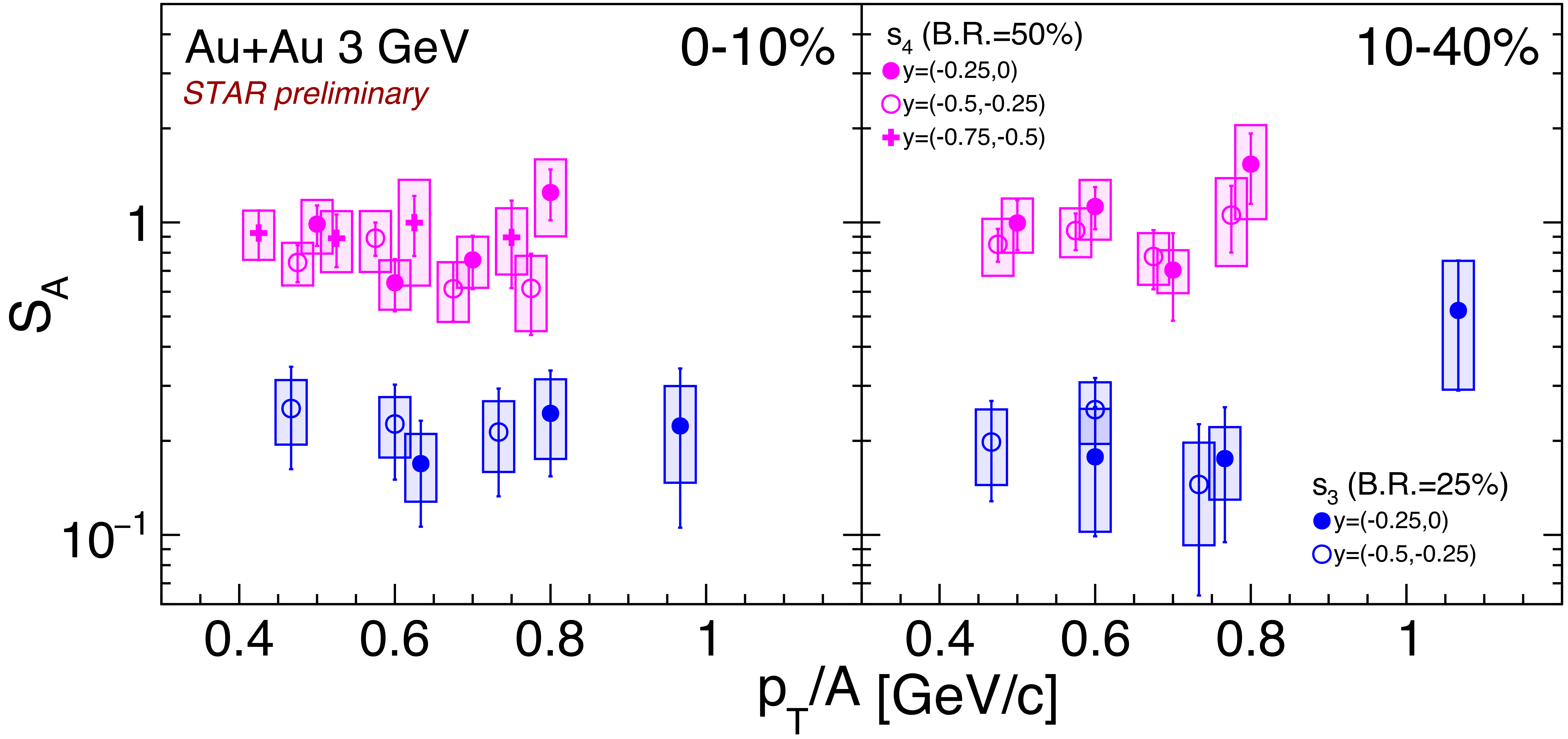
S. Zhang et al, PLB 684(2010)224

- Strangeness population factor:

$$S_A = \frac{{}^{A}_{\Lambda}\mathrm{H}}{{}^{A}\mathrm{He} \times \frac{\Lambda}{\mathrm{p}}}$$

- Differential analogue = ratio of coalescence parameters for hypernuclei and nuclei

$$\frac{{}^{A}_{\Lambda}\mathrm{H}(A \times p_T)}{{}^{A}\mathrm{He}(A \times p_T) \times \frac{\Lambda}{\mathrm{p}}(p_T)} = \frac{B_A({}^{A}_{\Lambda}\mathrm{H})(p_T)}{B_A({}^{A}\mathrm{He})(p_T)}$$



- B_A of light nuclei follows similar trends in p_T, rapidity, centrality

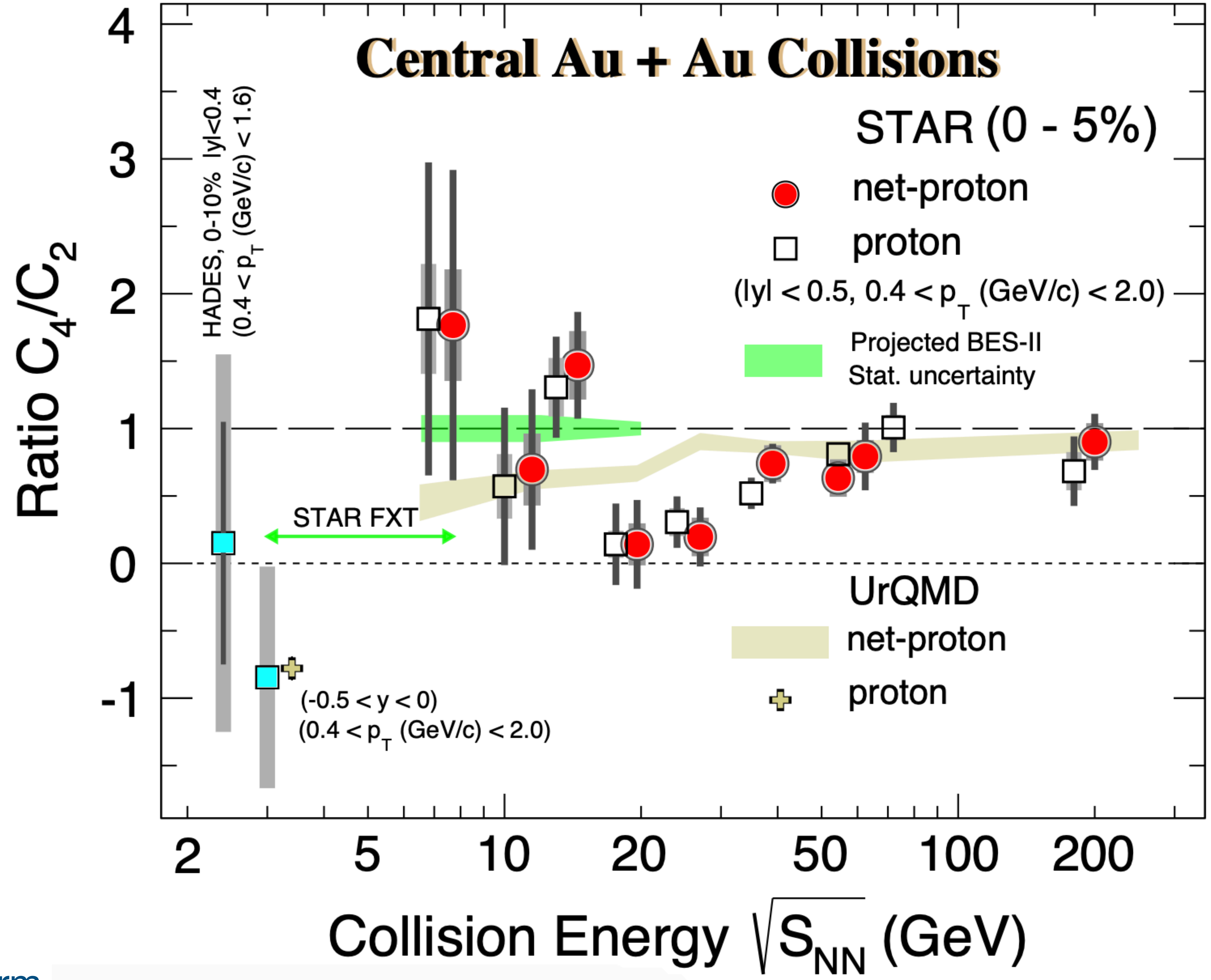
Mechanics behind formation for hypernuclei and nuclei are similar

Net Proton Kurtosis from BES-II

- New 3 GeV measurement consistent with hadronic transport model UrQMD

- Suppression of C_4/C_2 is consistent with fluctuations driven by baryon number conservation

Hadronic interaction dominated region in the top 5% central Au+Au collisions at 3 GeV



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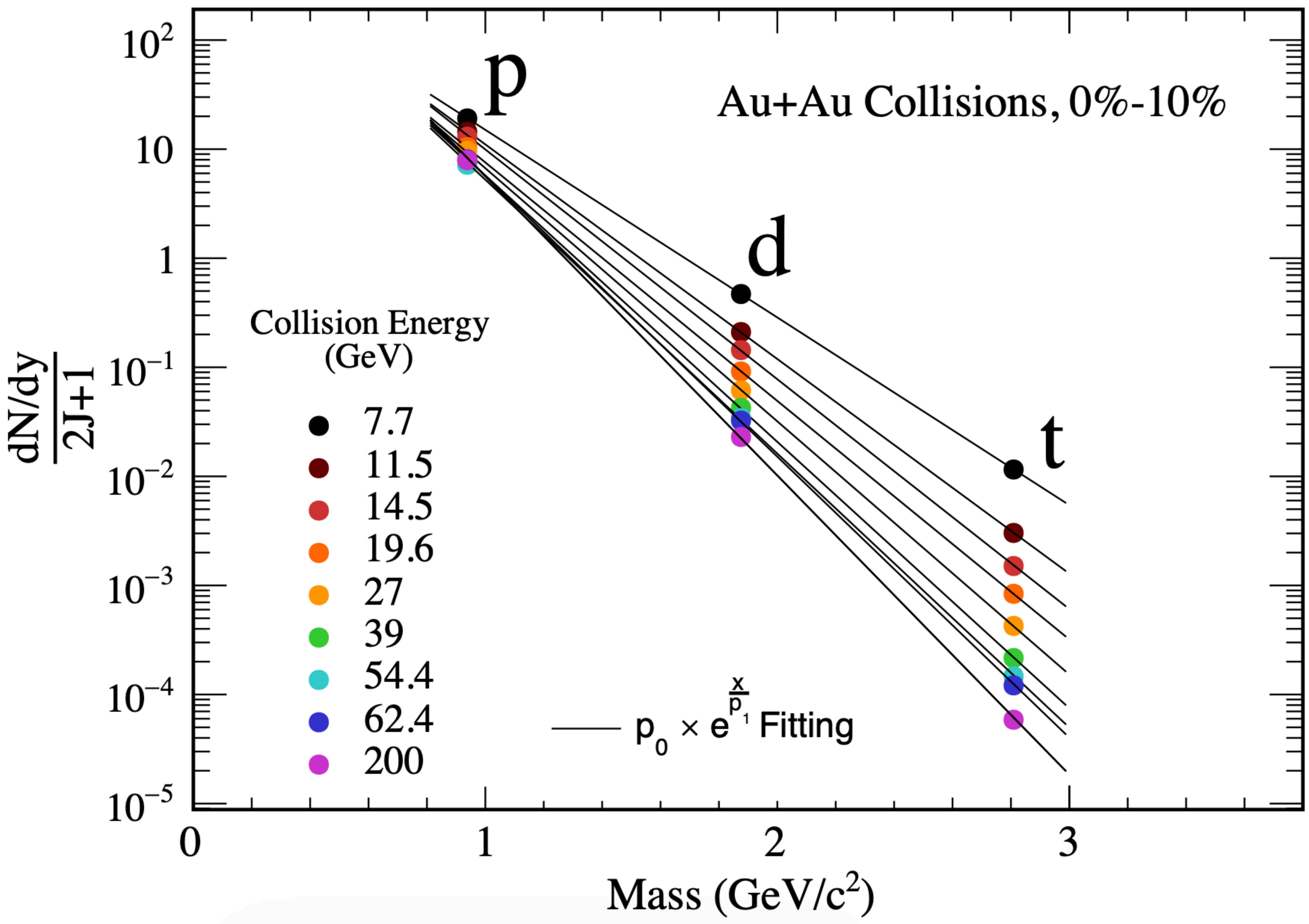
Phys.Rev.Lett. 128 (2022) 20, 202303

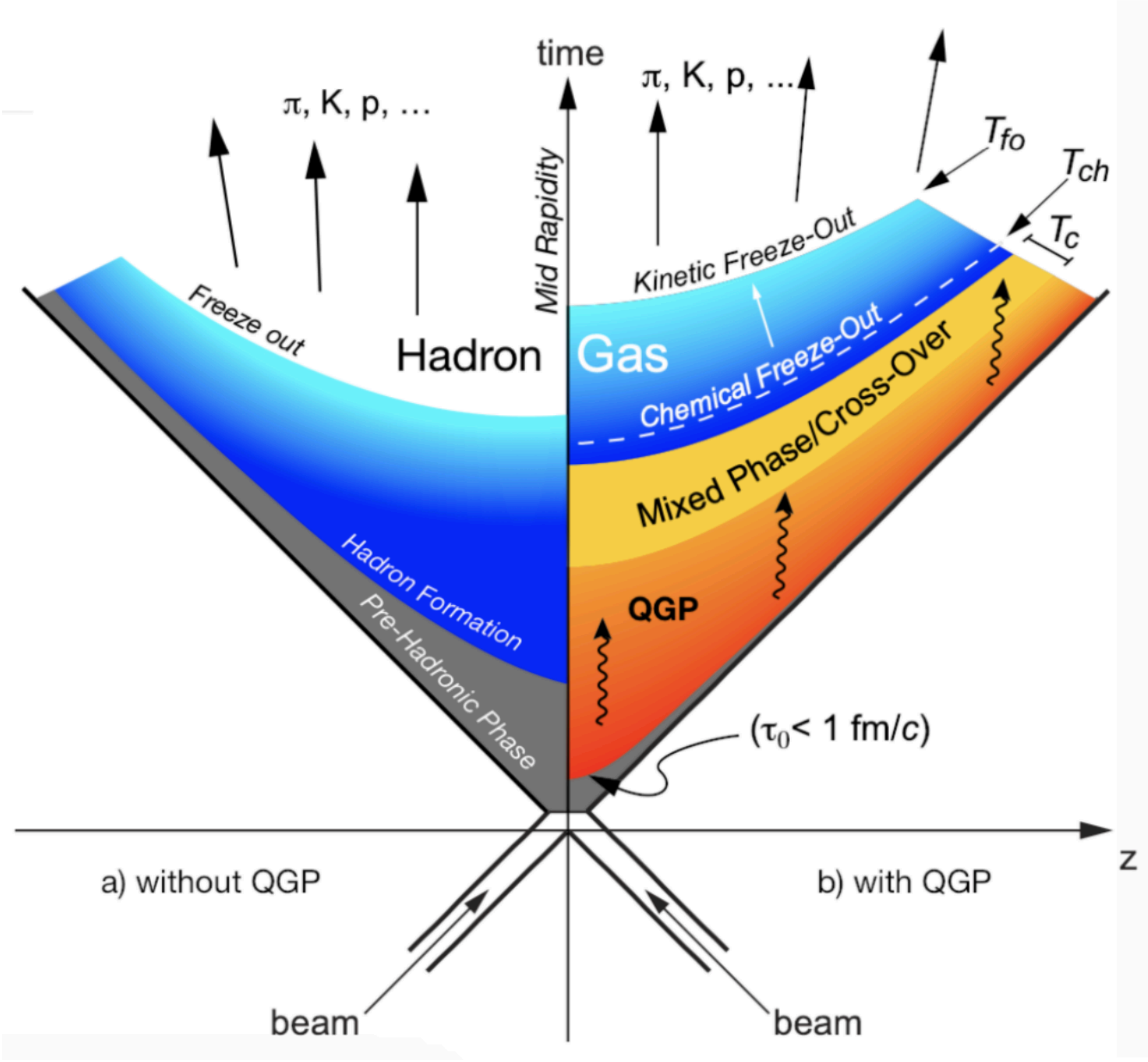
Light Nuclei Ratios in Central Collisions

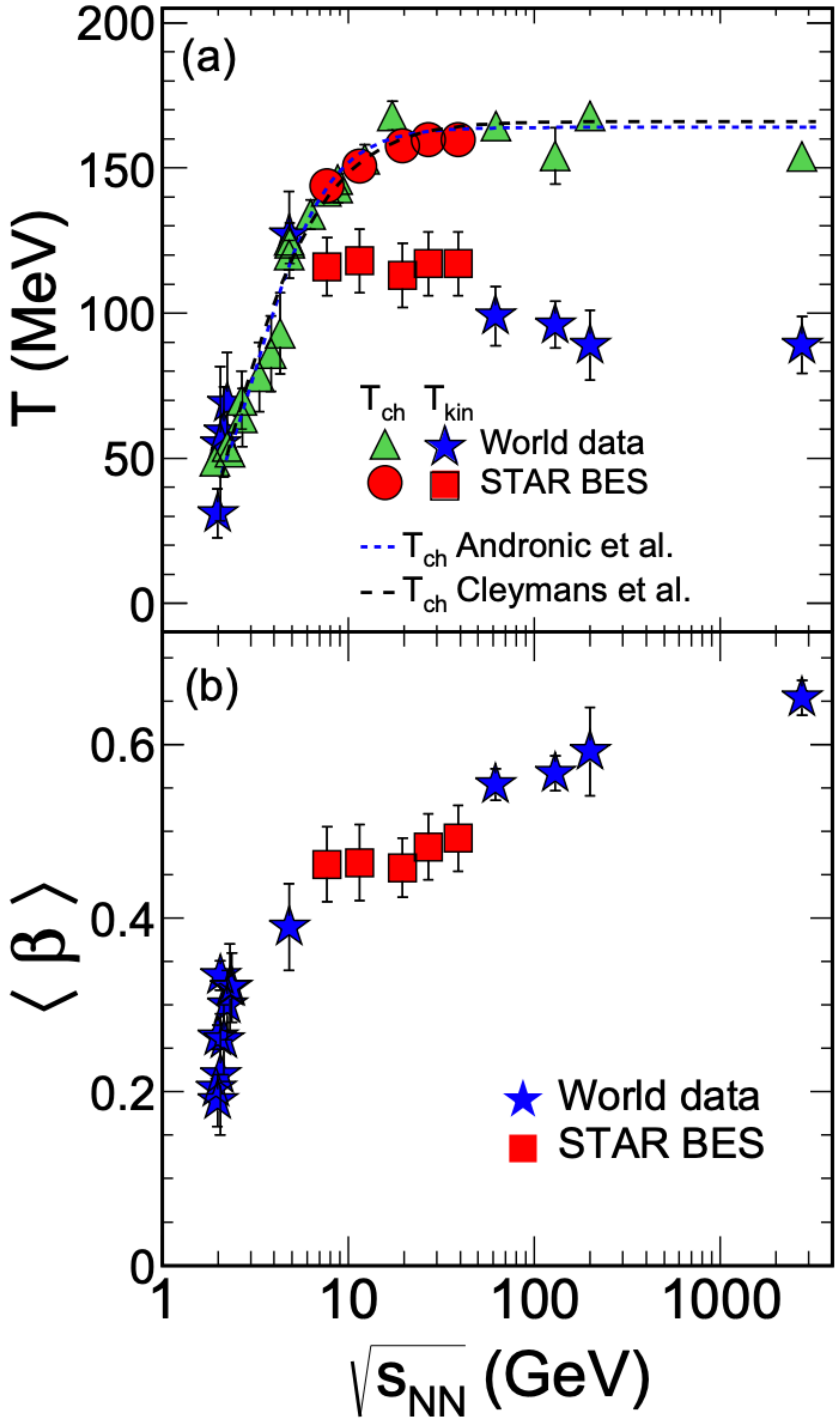


- Light nuclei yields, when scaled by spin degeneracy, follows exponential scaling very well

Trend is not expected for thermal models (due to feed-down contributions to proton from baryonic resonances)

Energy Dependence of Kinetic and Chemical Freeze-out





Probing the Magnetic-Field

- Vorticity gives +ve contribution to P_Λ and $P_{\bar{\Lambda}}$

  Quarks and anti-quarks' spins are aligned with the angular momentum.

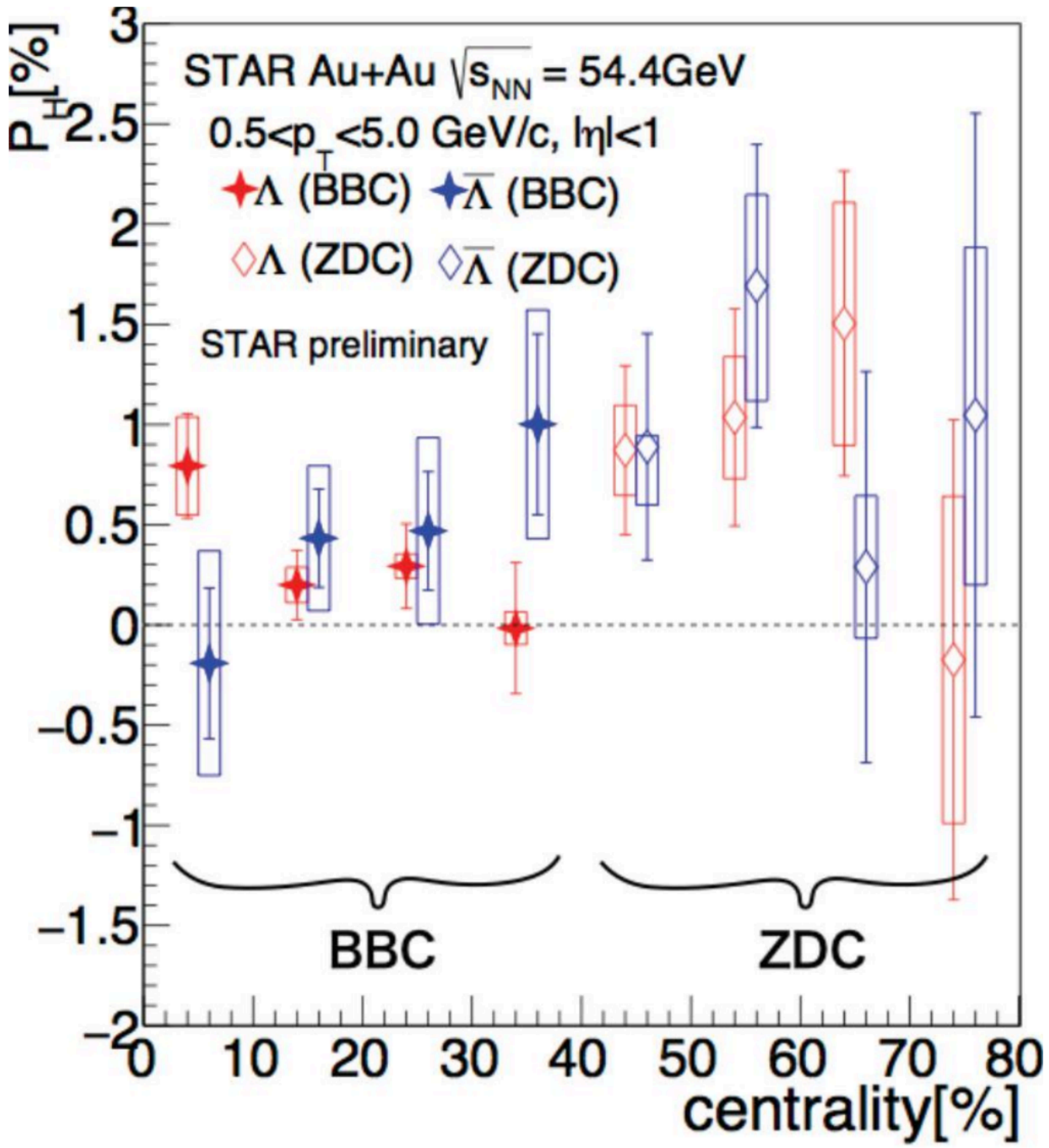
- Magnetic field enhances $P_{\bar{\Lambda}}$ but suppresses P_Λ

  Quarks and anti-quarks get aligned in the opposite direction due to opposite signs of their magnetic moments

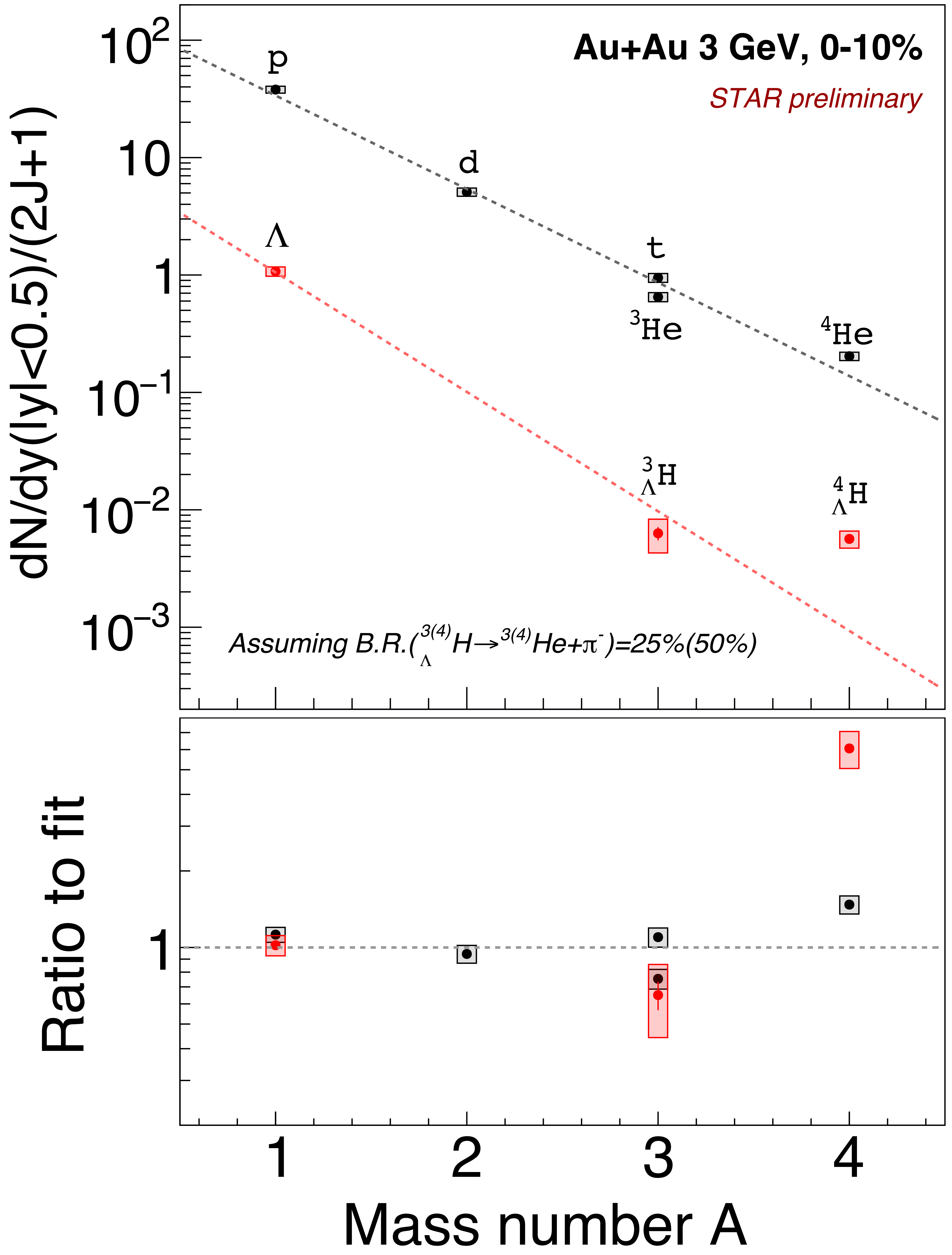
- Magnetic field in QGP can be probed by $P_{\bar{\Lambda}}$ - P_Λ

No splitting observed at 54.5 GeV

Await results from high statistics data at 19.6 and 27 GeV from BES-II

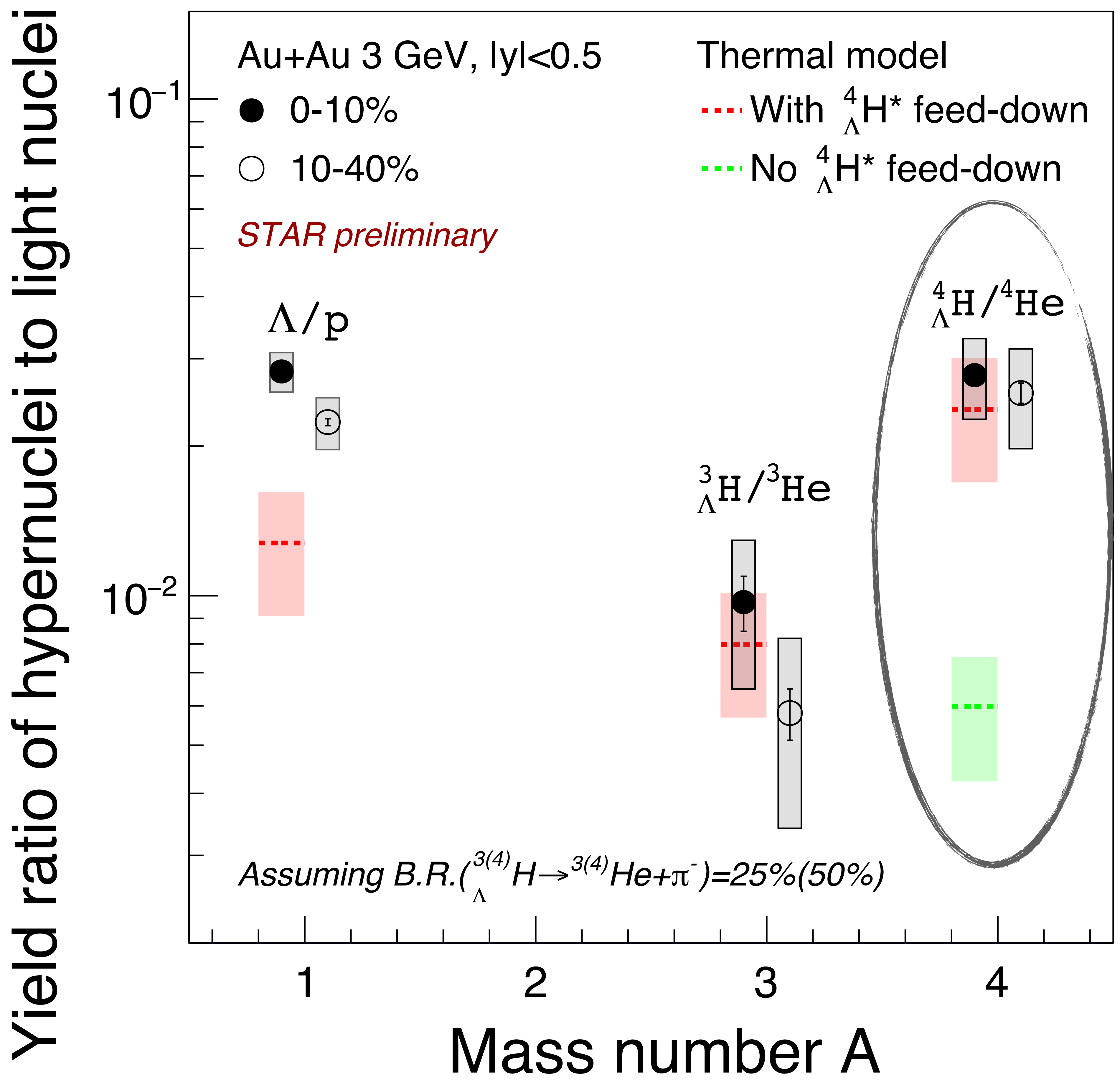


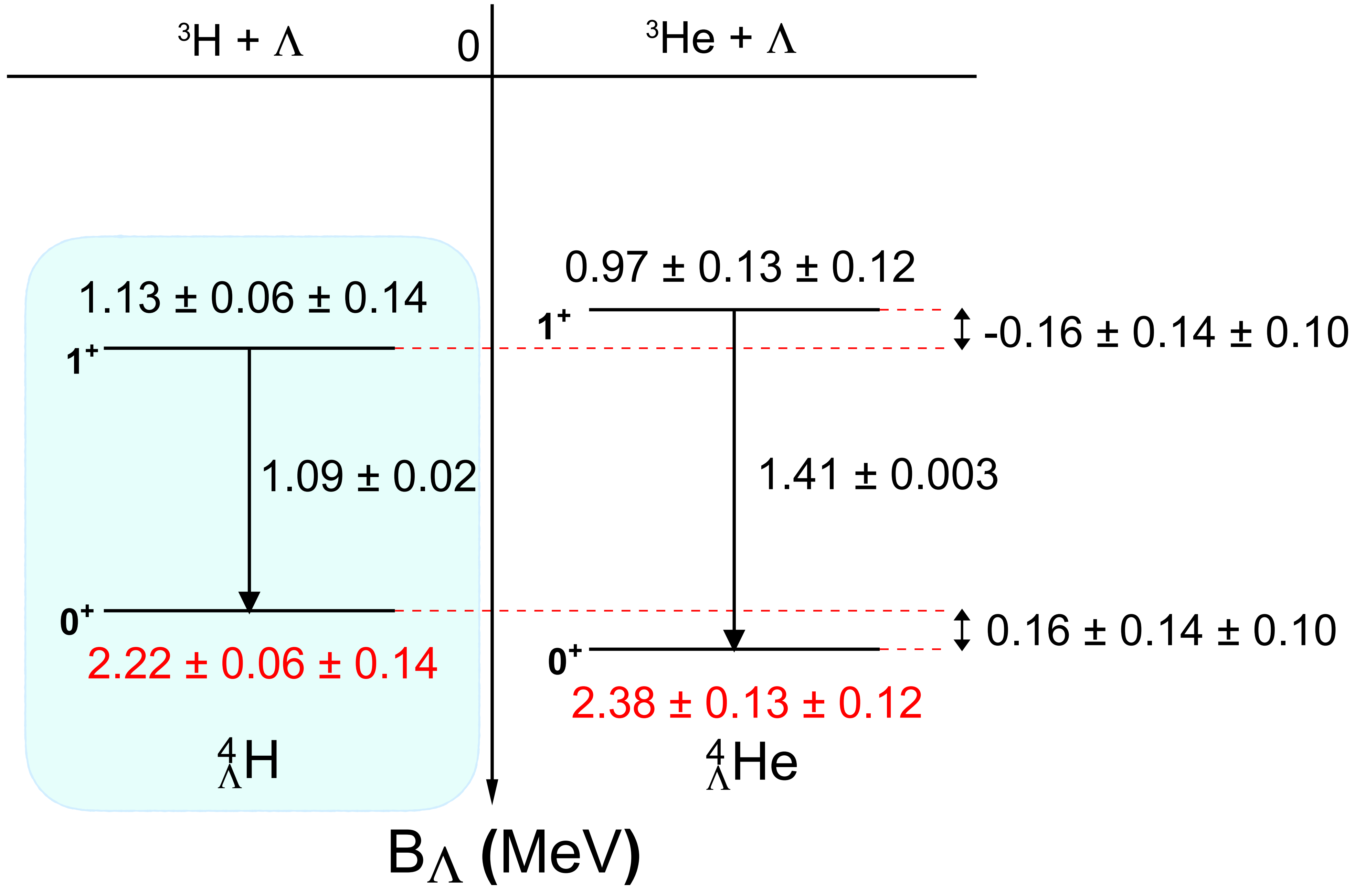
Hypernuclei and light nuclei ratio at 3 GeV



- Thermal / coalescence models predict approx. exponential dependence of yields / (2J+1) vs A
- $^{4}_{\Lambda}$H lies a factor of 6 above exponential fit to $(\Lambda, {}^{3}_{\Lambda}\mathrm{H}, {}^{4}_{\Lambda}\mathrm{H})$

Excited Hypernuclei States?





STAR, Phys. Lett. B 834 (2022) 137449

$^4_\Lambda H^*(J^+ = 1)$
$\rightarrow {}^4_\Lambda H(J^+ = 0) + \gamma$

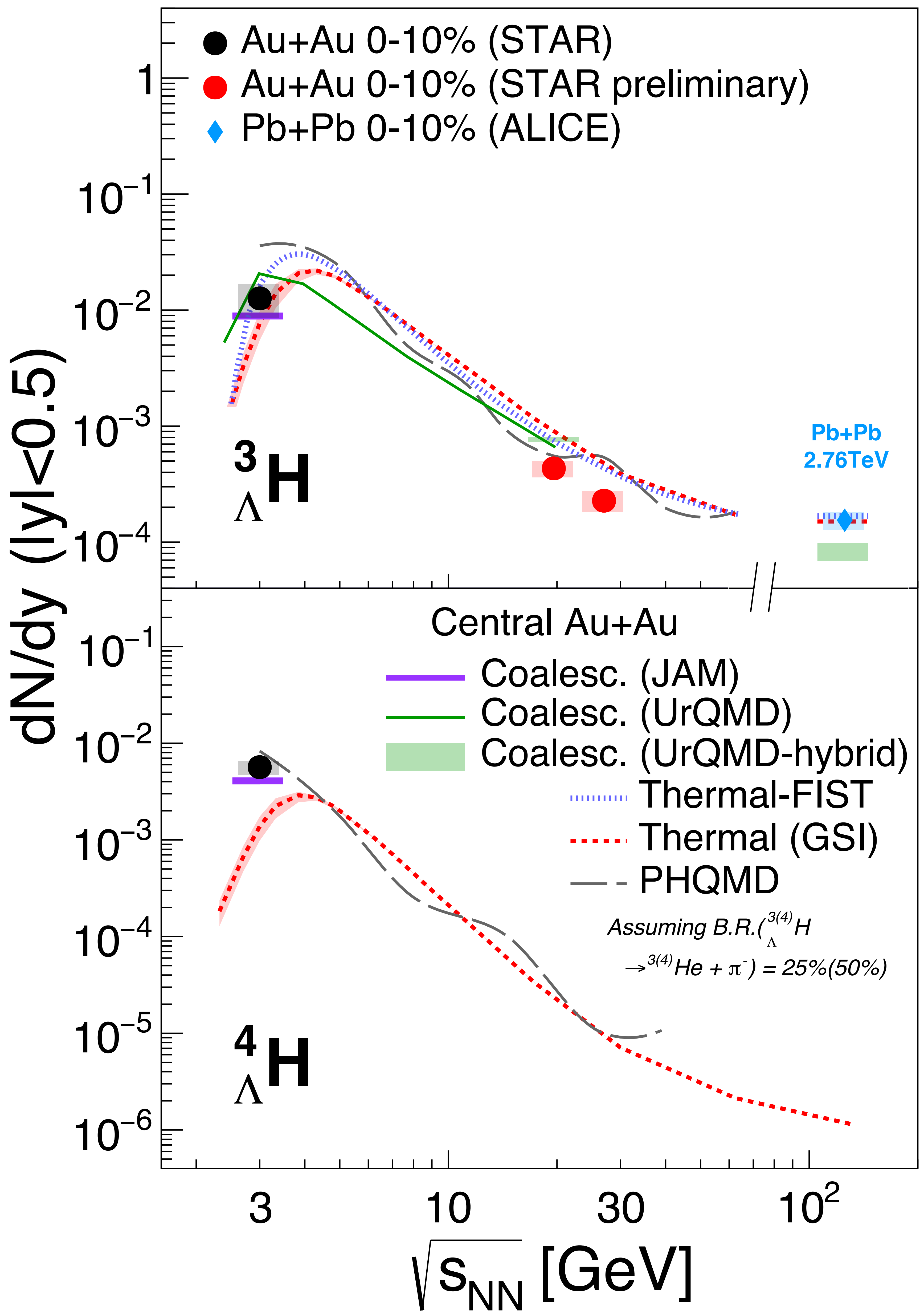
- Non-monotonic behavior in light-to hyper-nuclei ratio vs A observed

- Thermal model calculations including excited $^4_\Lambda H^*$ feed-down show a similar trend

Data support creation of excited hypernuclei from heavy-ion collisions

A. Andronic et al, PLB 697 (2011)203 (updated, preliminary) (Thermal Model)

Energy Dependence of Hypernuclei Yields



- $^{3}_{\Lambda}H$ yield at mid-rapidity increases from 2.76 TeV to 3 GeV
  - Driven by **increase in baryon stopping** at low energies

Light Nuclei Production Models

Nucl. Phys. A 1005 (2021) 121754

Thermal models

- Nuclei are formed earlier at the hadronic chemical freeze-out
- Thermal and chemical equilibrium (T, μ_B)

Coalescence models

- Nuclei are formed at late stages of collision
- Nucleons bind into nuclei if they are close in phase space

Dynamical models

$\pi d \leftrightarrow \pi np$

$\pi t \leftrightarrow \pi nnp$

$\pi ^3\text{He} \leftrightarrow \pi npp$

$\ldots$

- Disintegration cross-sections are large

Prob. of formation may depend on wave-function

Probe structure of (hyper)nuclei with production yields?

Anti-nuclei yield detected in space

Implications for dark matter searches?

Phys. Rev. D 99, 023016