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Results from the Relativistic Heavy Ion Collider Beam Energy Scan II

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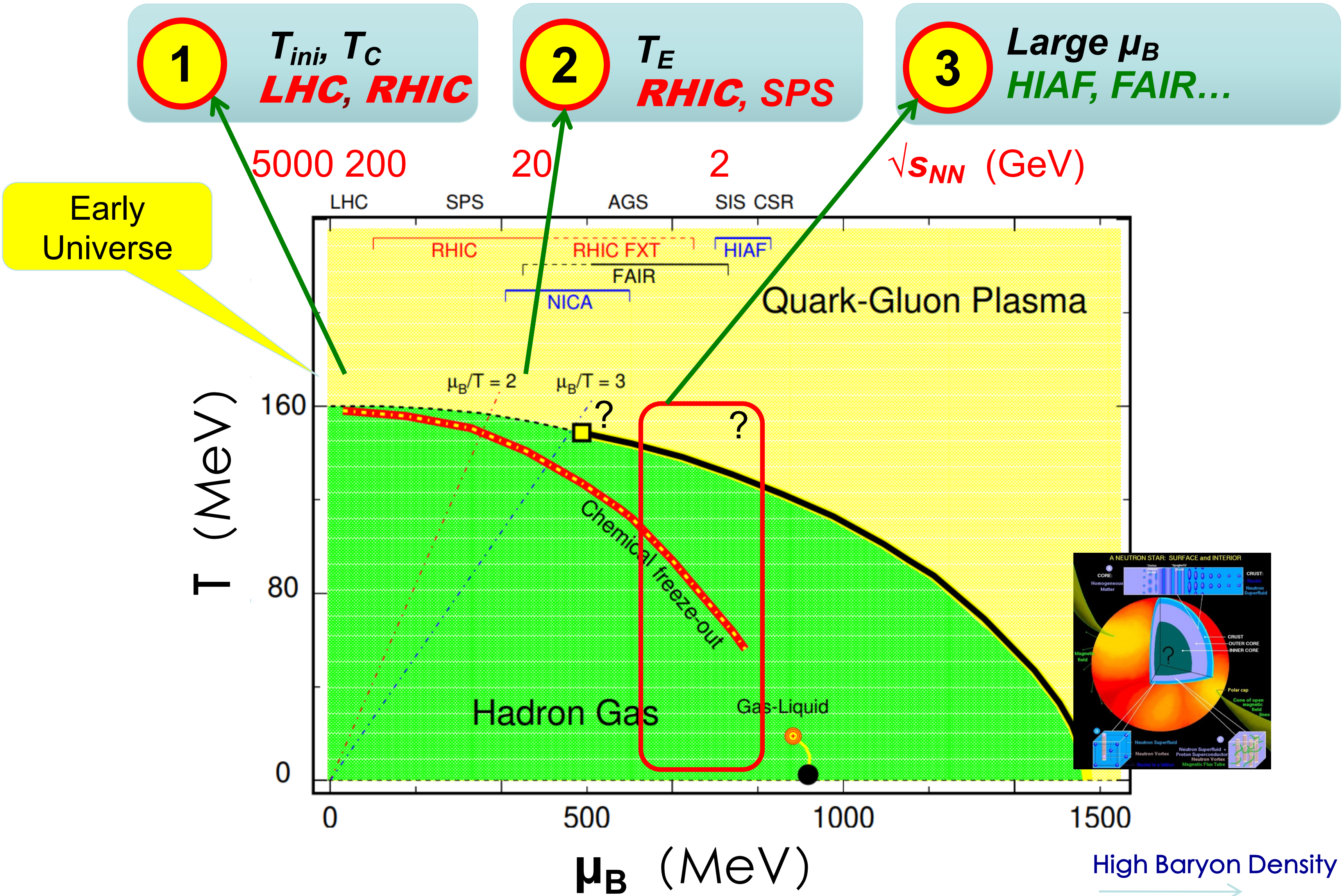
Central China Normal University

The 11th workshop of the APS Topical Group on Hadronic Physics, Mar. 14-16, 2025

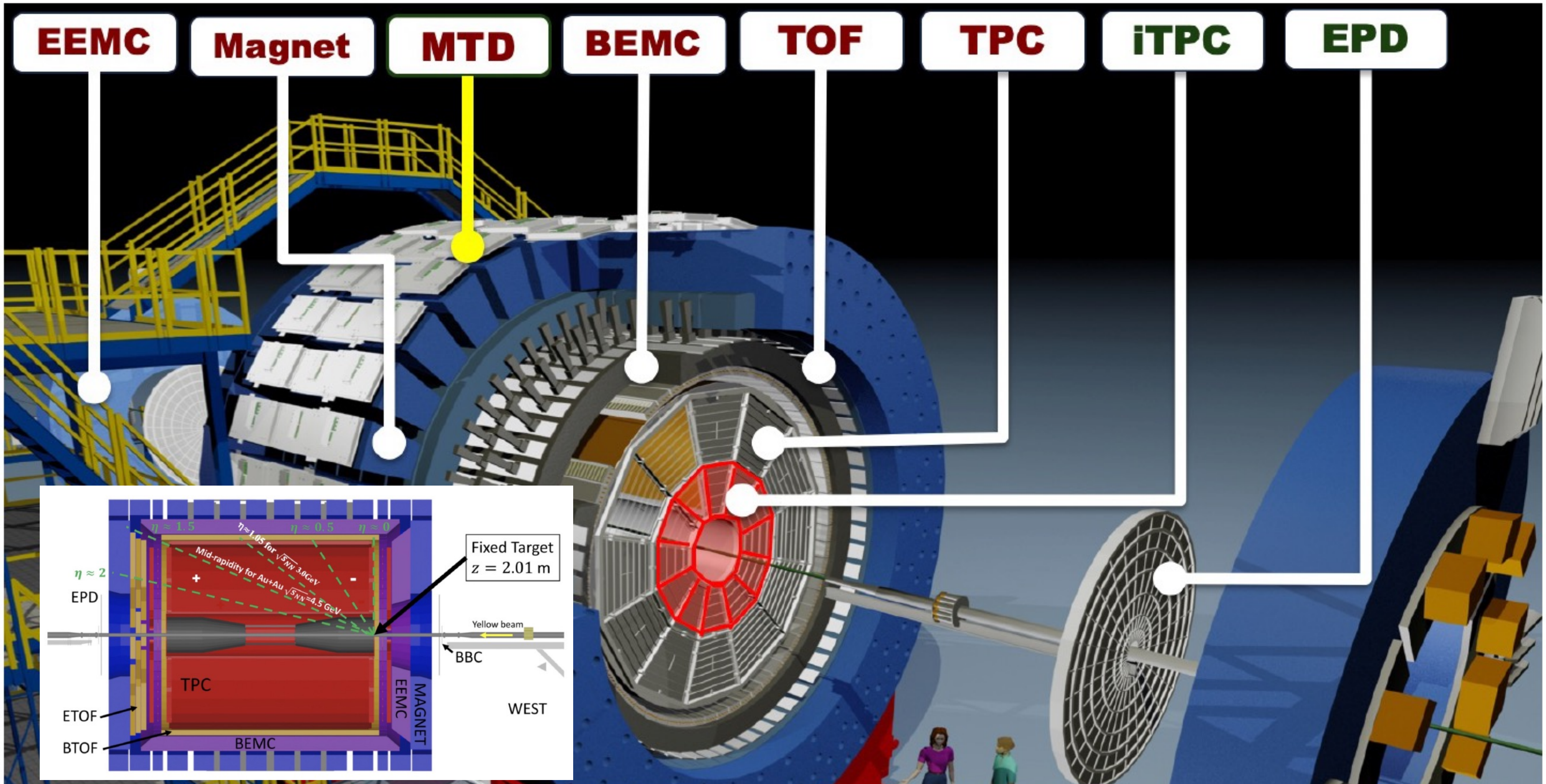
Outline

QCD Phase Diagram



A. Bzdak et al., Phys. Rept. 853, 1 (2010); X. Luo, S. Shi, Nu Xu and Y. Zhang, Particle 3, 278 (2020)

Experimental Setup



- **Larger** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

- **iTPC, EPD & eTOF** upgrades completed
- All are in data-taking for BES-II program

STAR Bean Energy Scan

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Au+Au Collisions at RHIC

Collider Runs

	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19
2	62.4	46 M	75 MeV		Run-10
3	54.4	1200 M	85 MeV		Run-17
4	39	86 M	112 MeV		Run-10
5	27	585 M	156 MeV	3.36	Run-11, 18
6	19.6	595 M	206 MeV	3.1	Run-11, 19
7	17.3	256 M	230 MeV		Run-21
8	14.6	340 M	262 MeV		Run-14, 19
9	11.5	57 M	316 MeV		Run-10, 20
10	9.2	160 M	372 MeV		Run-10, 20
11	7.7	104 M	420 MeV		Run-21

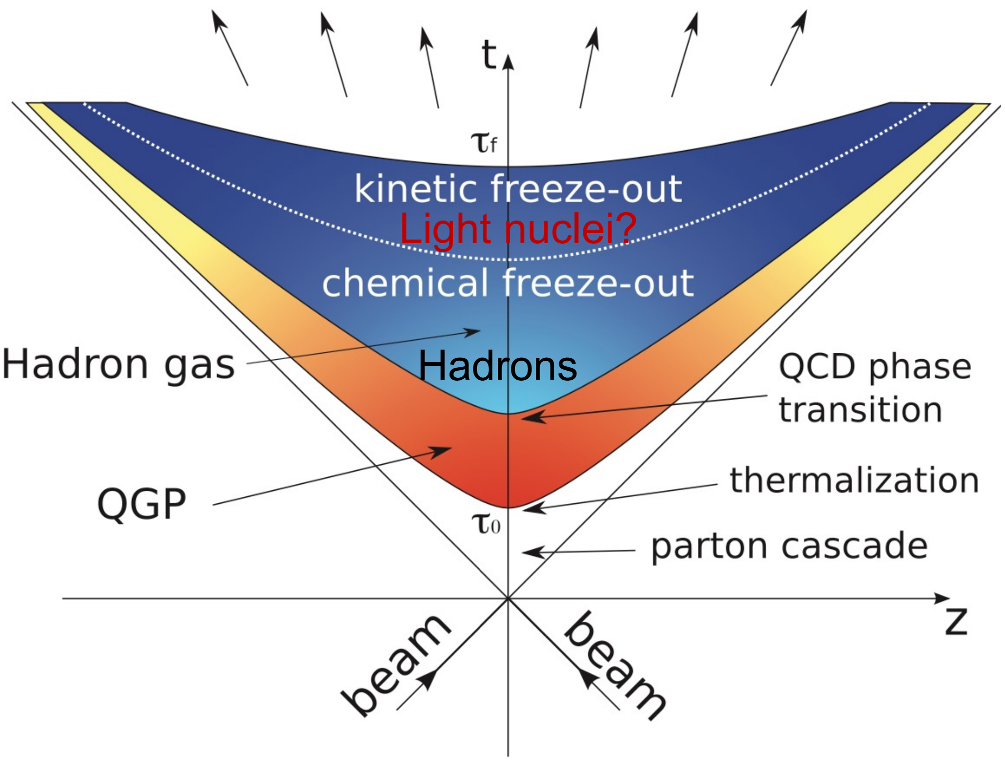
Fixed-Target Runs

	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
12	**3.0** (3.85)	**260** + 2000 M	**760** MeV	-1.05	Run-18, 21

Most precise data to map the QCD phase diagram

$3 < \sqrt{s_{NN}} < 200$ **GeV;** $760 > \mu_B > 25$ **MeV**

Motivation: Light Nuclei Production



Coalescence of nucleons

formed near kinetic freeze-out

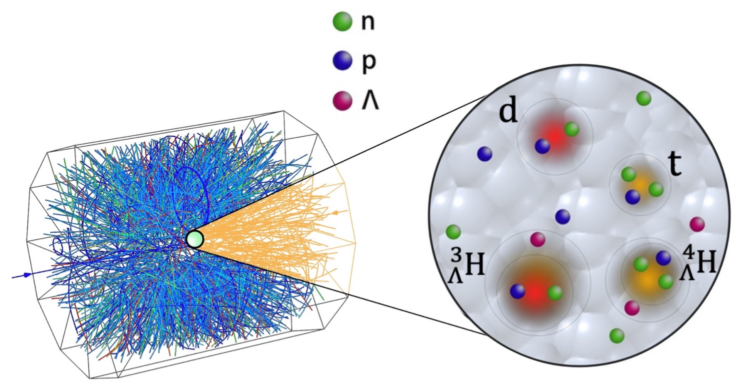


Figure courtesy of Yige Huang

$$\frac{dN_A}{d^3\mathbf{P}_A} = g_A \int \Pi_{i=1}^{A} d^3\mathbf{x}_i d^3\mathbf{p}_i\, f_N(\mathbf{x}_i, \mathbf{p}_i)$$
$$\times\, f_A(\mathbf{x}'_1, \ldots, \mathbf{x}'_A; \mathbf{p}'_1, \ldots, \mathbf{p}'_A)\delta^{(3)}\left(\mathbf{P}_A - \sum_{i=1}^{A} \mathbf{p}_i\right)$$

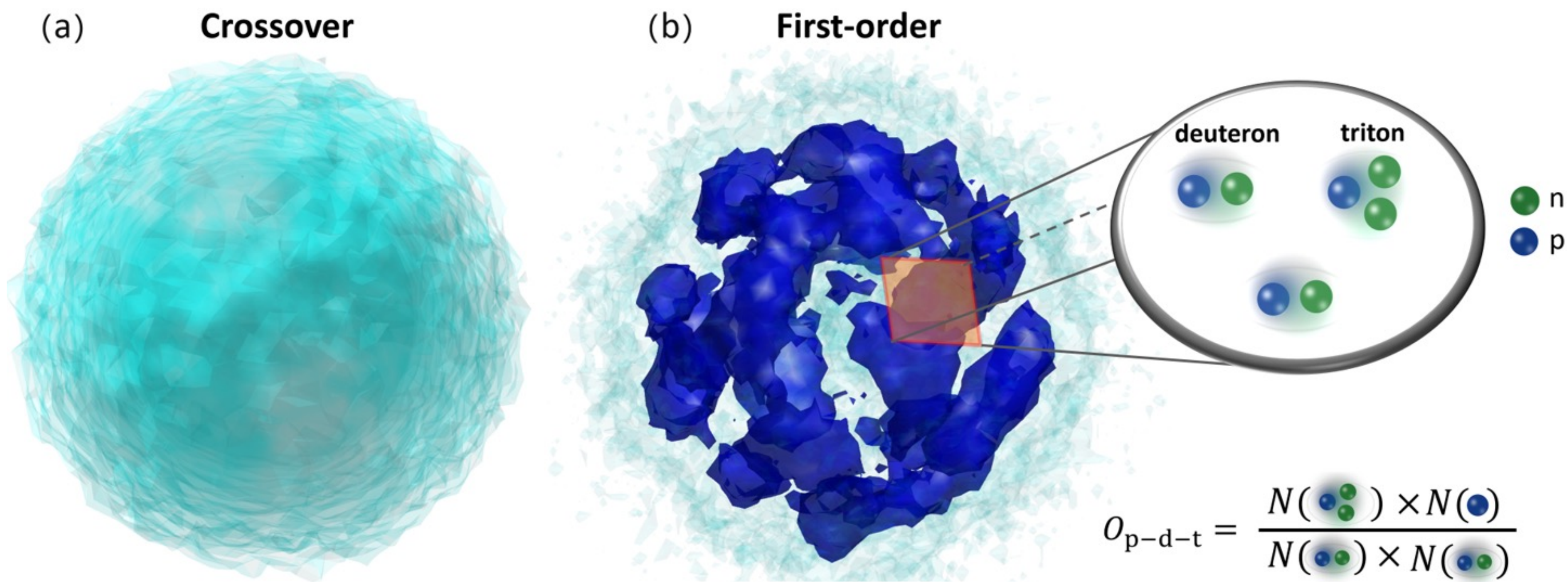
L. P. Csernai and J. I. Kapusta, Phys. Rept. 131, 223 (1986); A. Andronic et al, Nature 561, 321 (2018); J. Chen et al., Phys. Rept. 760, 1 (2018); K.-J. Sun et al., arXiv:2207.12532

Thermal emission; Nucleon coalescence; Hadronic re-scattering ($\pi NN \leftrightarrows \pi d$ …)

➢ **Abundant in the high baryon density, unclear production mechanisms**

Neutron Density Fluctuation

Figure courtesy of Kai-Jia Sun



Che Ming Ko, NST 34, 80 (2023)

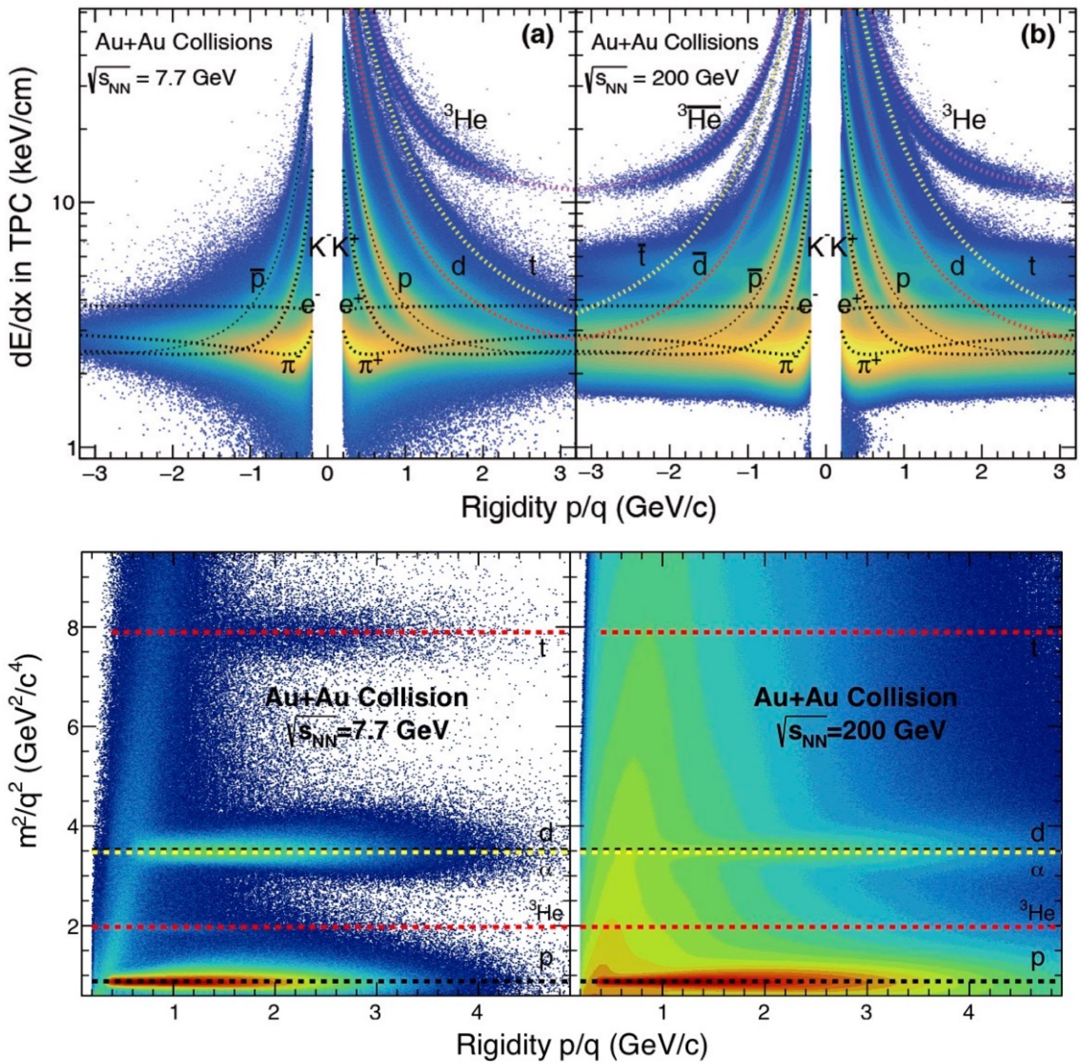
$$N_t \times N_p / N_d^2 = g(1 + \Delta n)$$

Neutron Density Fluctuations

- Nucleon coalescence: nuclear compound yield ratio is sensitive to the baryon density fluctuations and can be used to probe phase transition signal in HIC

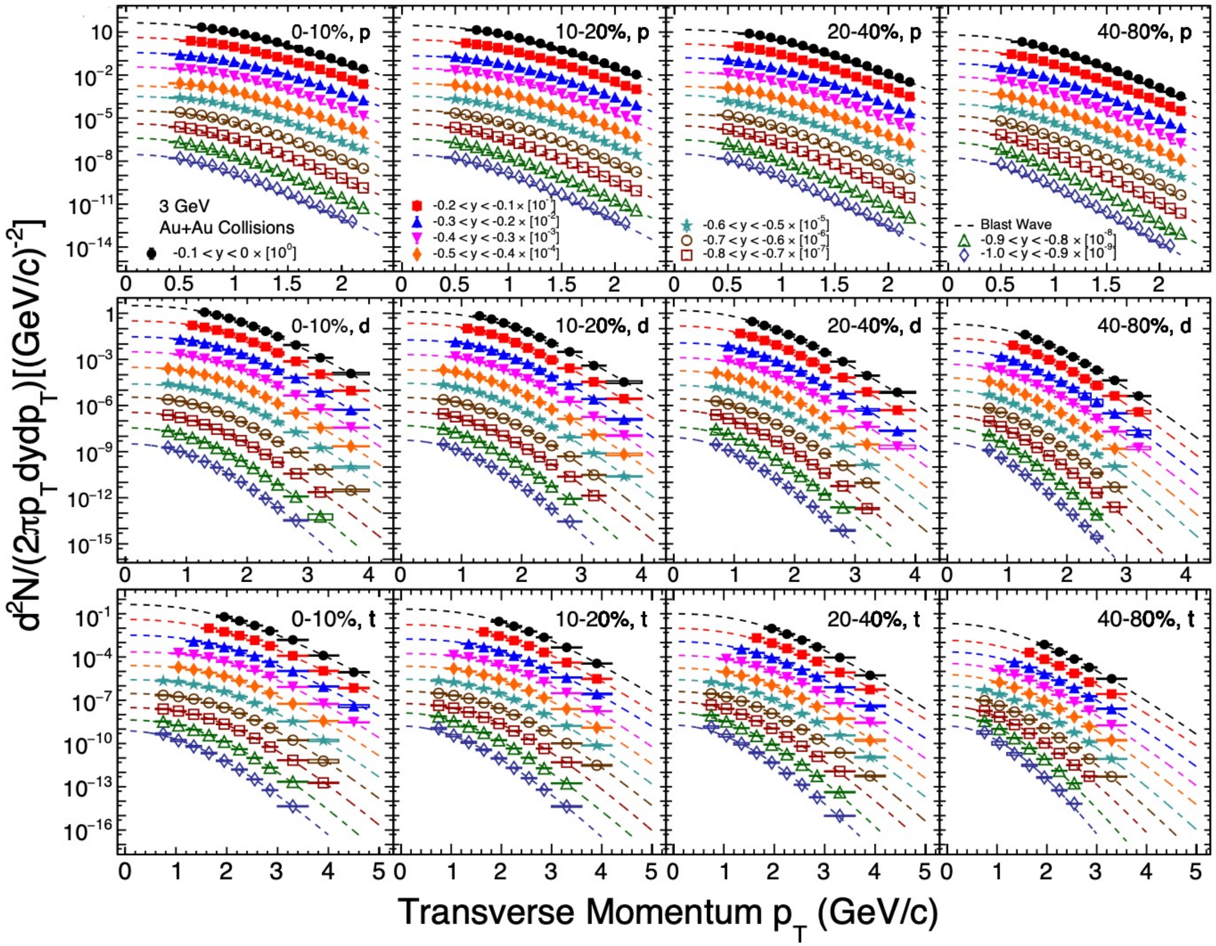
K.-J. Sun et al., PLB 781, 499 (2018); E. Shuryak and J. M. Torres-Rincon, PRC 101, 034914 (2020); K.-J. Sun et al., arXiv:2207.12532

Particle Identification



Good particle identification capability based on TPC dE/dx and TOF m^2

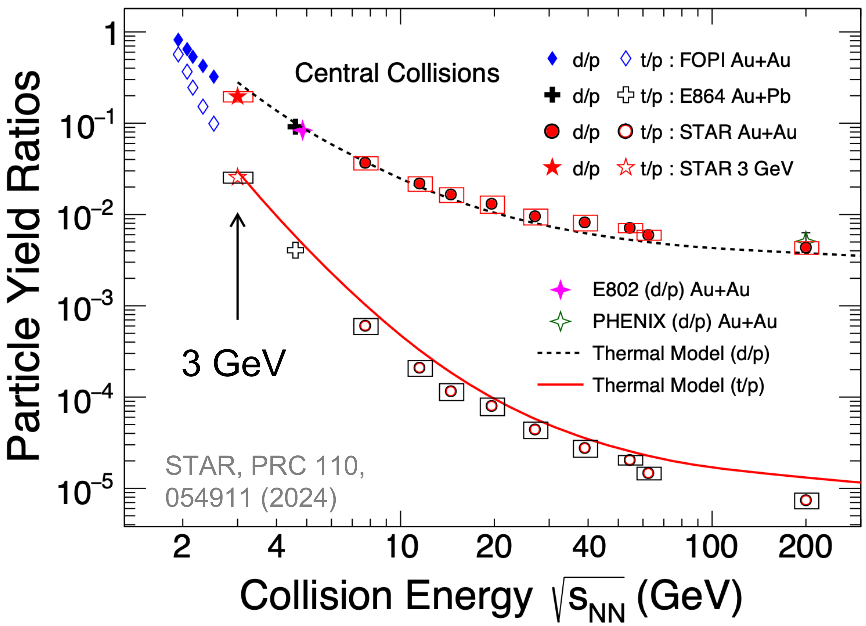
p_T Spectra of Light Nuclei

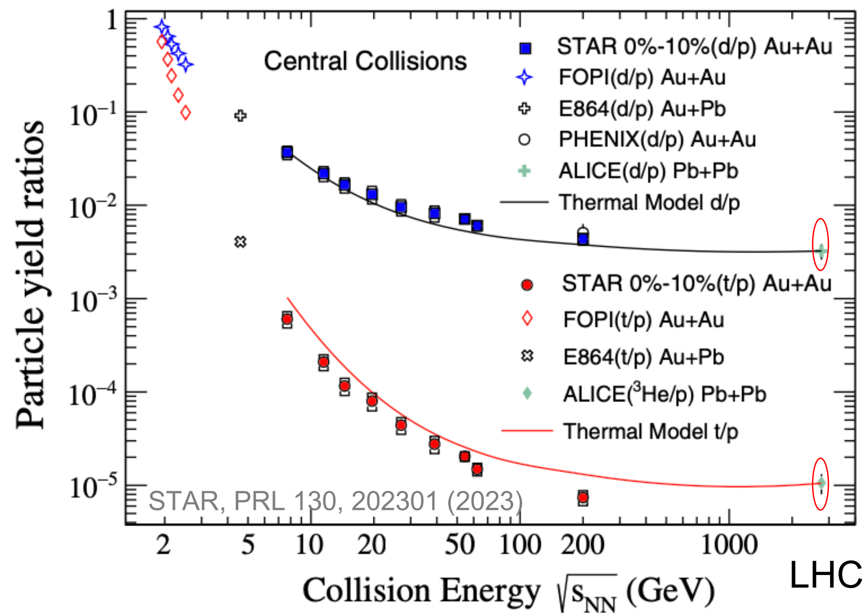


STAR, PRC 110, 054911 (2024)

➢ **Mid-rapidity transverse momentum spectra for light nuclei in 3 GeV collisions**

Particle Yield Ratios

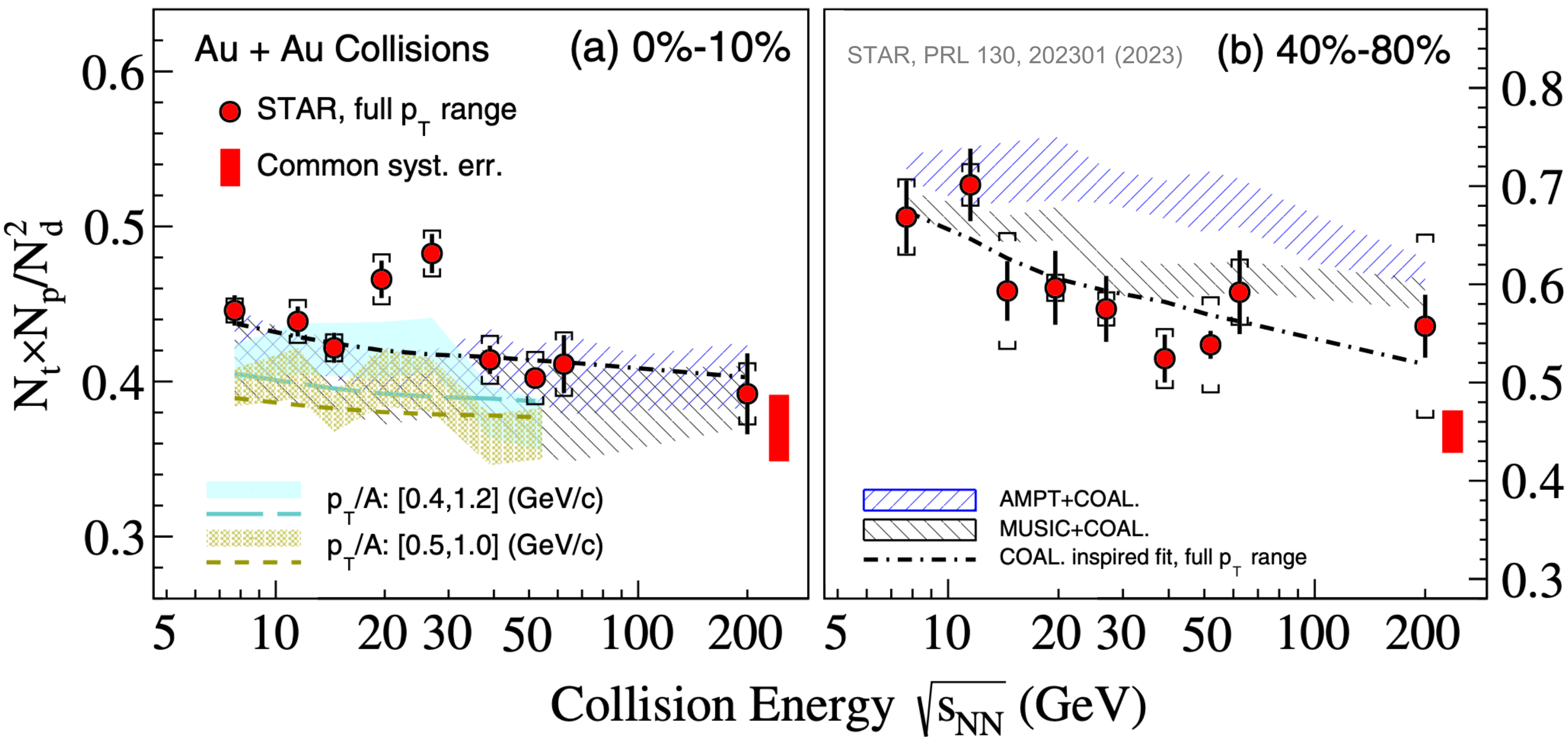




- **Thermal model well describes ALICE data, overestimates N_t/N_p below LHC energy**
- **The effects of hadronic re-scatterings during hadronic expansion may play an important role**

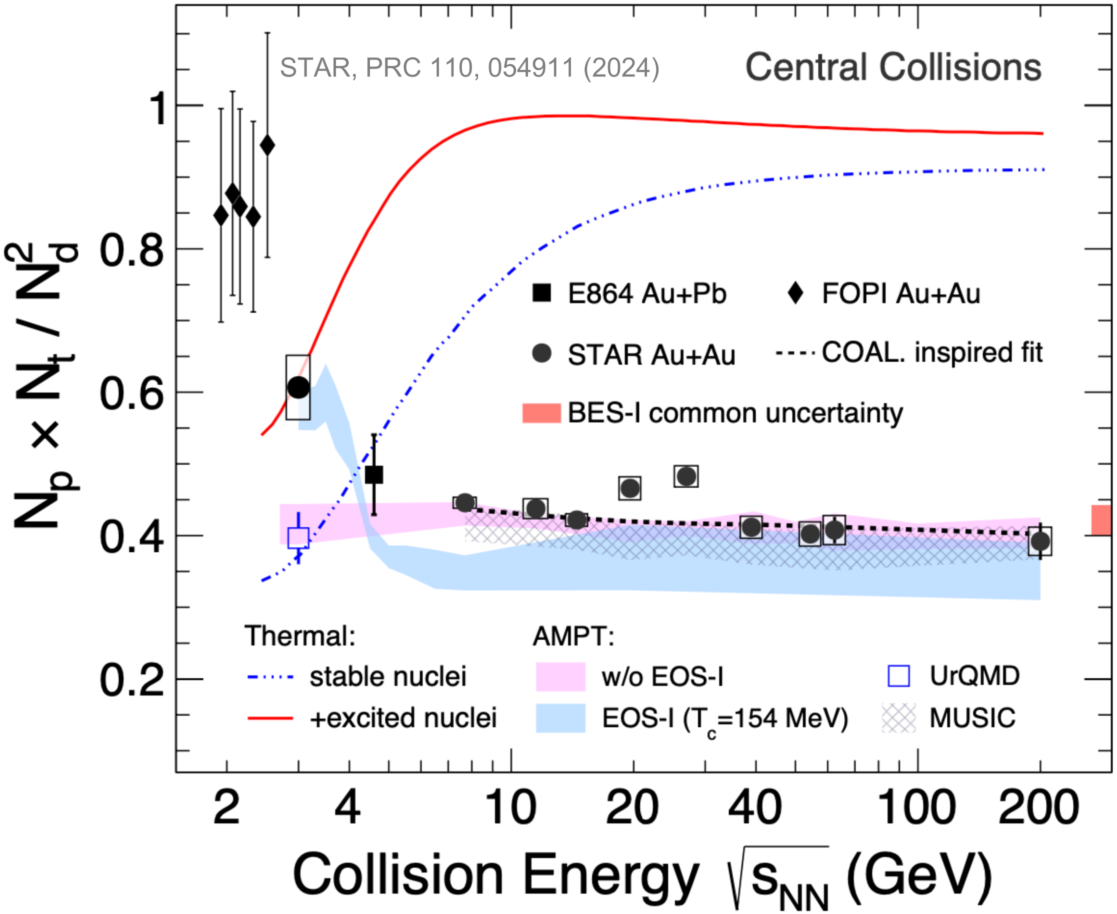
K.-J. Sun et al., Nature Commun.15,1074(2024);
FOPI, NPA 781, 459 (2007); E864, PRC 61, 064908 (2000); ALICE, PRC 93, 024917 (2016);
PHENIX, PRL 94, 122302 (2005), PRC 69, 034909 (2004)

$N_t \times N_p / N_d^2$



- **Non-monotonic behavior observed from 0%-10% central Au+Au collisions around 19.6 and 27 GeV**
- **The yield ratio in peripheral collisions exhibits a monotonic trend and can be well described by coalescence models within uncertainties**

Comparison to Models

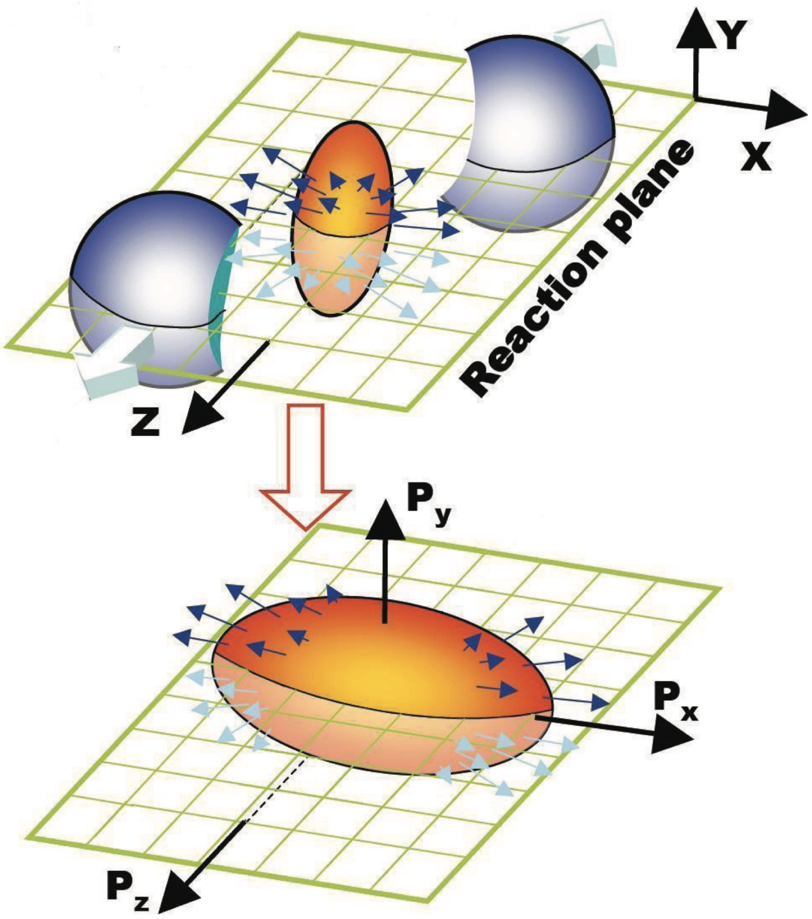


STAR, PRL 130, 202301 (2023);
E864, PRC 61, 064908 (2000);
FOPI, NPA 848, 366 (2010)
K.-J. Sun et al., arXiv:2207.12532;
W. Zhao et al., PLB 820, 136571 (2021)

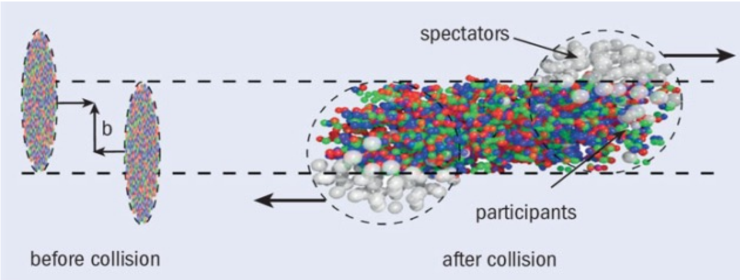
Production mechanism of light nuclei

- **7.7 – 200 GeV: well described by nucleon coalescence model**
- **3 GeV: consistent with thermal model, coincidence?**
- **The increasing trend of the yield ratio below 4 GeV, cannot be explained by models**

Anisotropic Flow

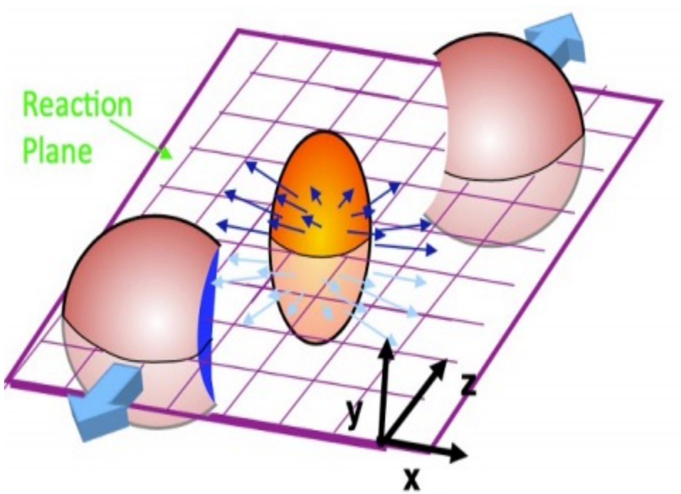


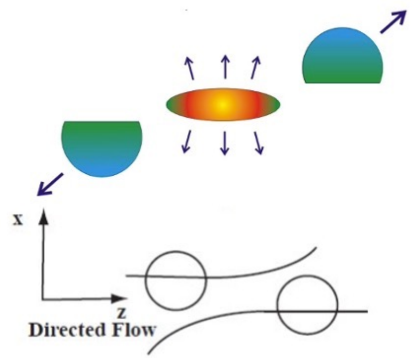
Motivation: Anisotropic Flow

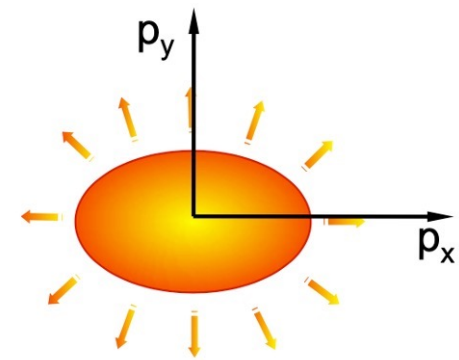


$$\frac{dN}{d(\phi-\Psi)} \sim 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi-\Psi))$$

- Directed flow:
  $v_1 = \langle \cos(\phi-\Psi) \rangle$
- Elliptic flow:
  $v_2 = \langle \cos 2(\phi-\Psi) \rangle$





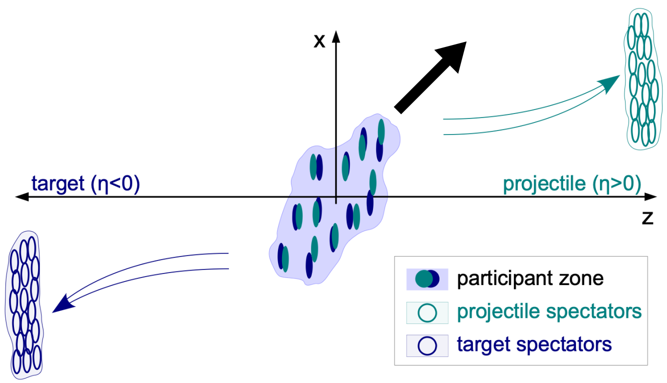


- v_1 is sensitive to the Equation-of-State (EoS)
- v_2 is sensitive the degree of freedom: partonic vs. hadronic

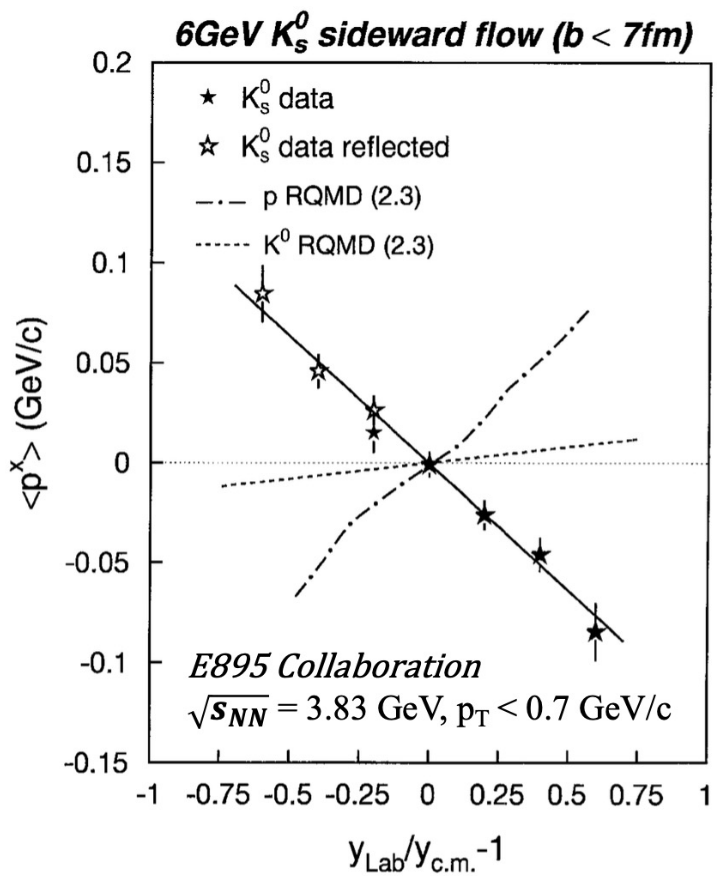
S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998)

Anti-flow of Meson v_1

Figure: Phys. Rev. Lett. 111, 232302 (2013)



E895, Phys. Rev. Lett. 85, 940 (2000)



- Bounce-off: Positive flow in positive rapidity
- Au+Au 3.83 GeV: Anti-flow of kaon at low p_T (< 0.7 GeV/c) → Kaon potential?

Elliptic Flow

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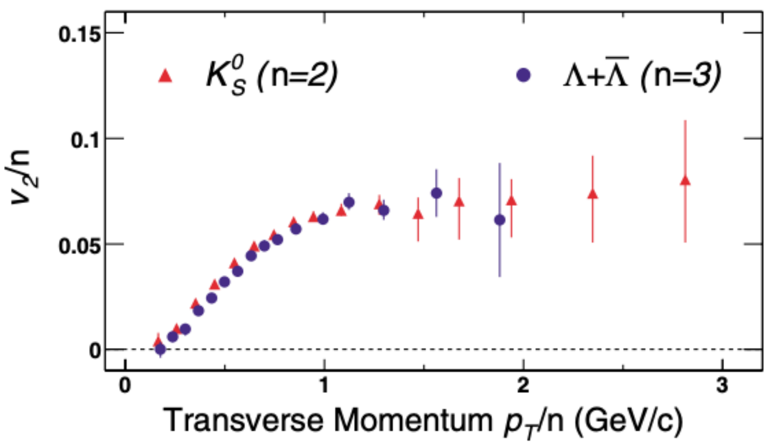
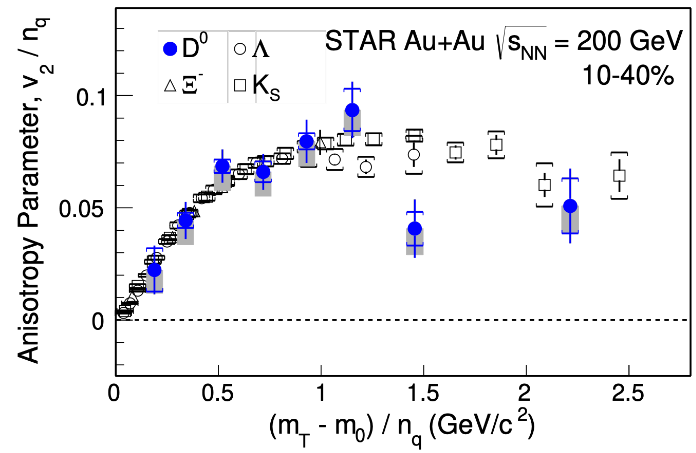
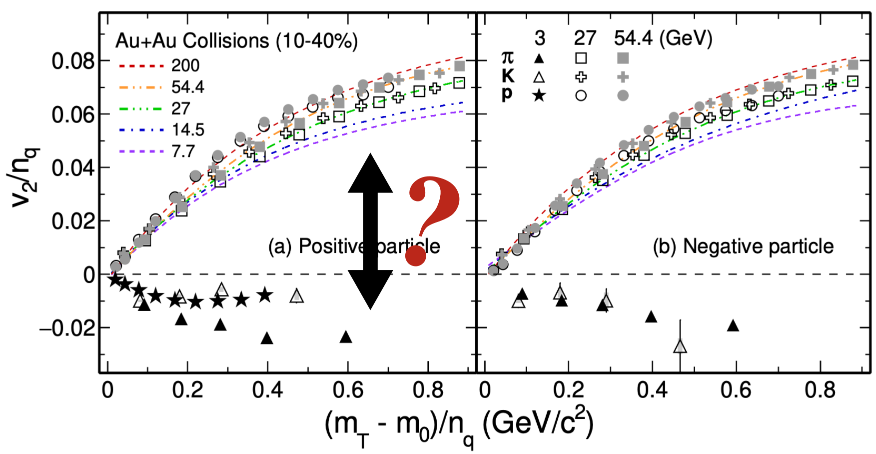
STAR, Phys. Rev. Lett. 92, 052302 (2004)



STAR, Phys. Rev. Lett. 118, 212301 (2017)





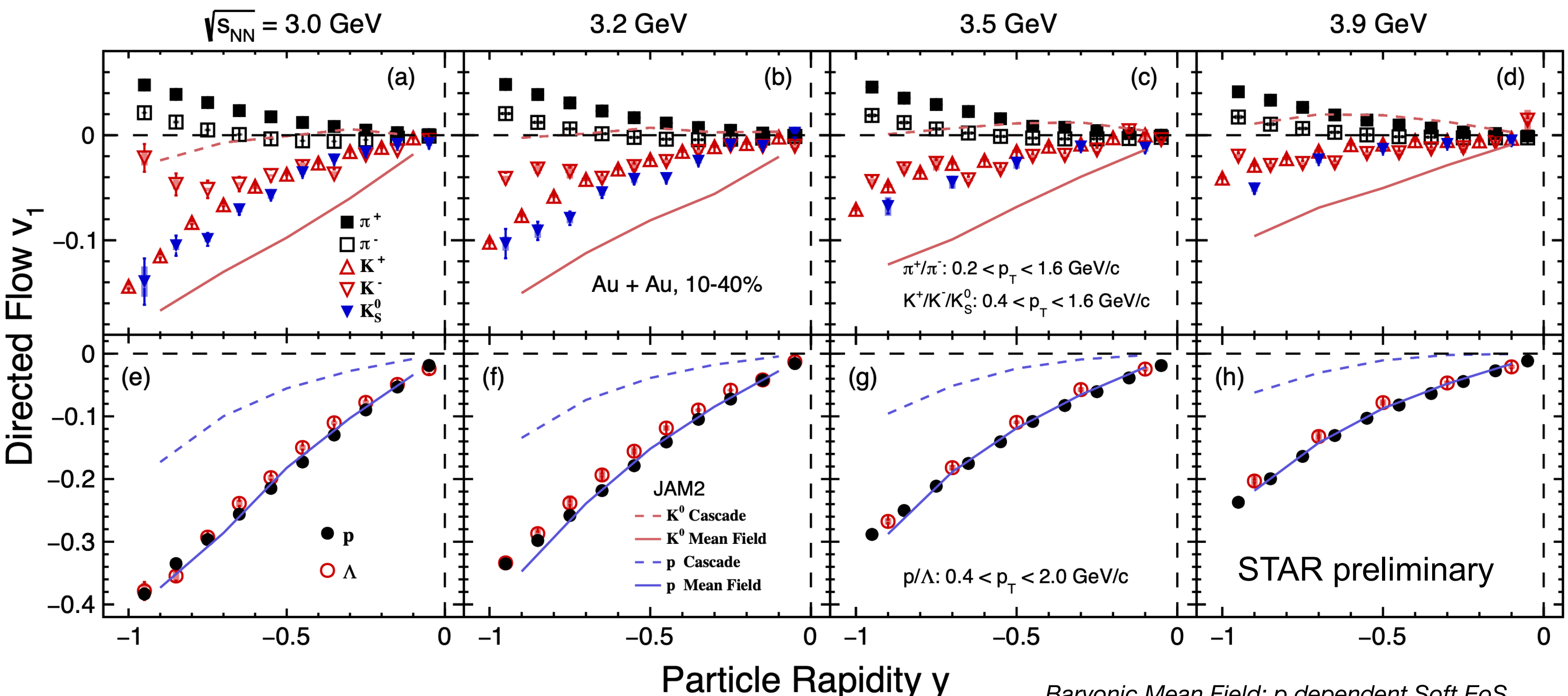
STAR, Phys. Rev. Lett. 110, 142301 (2013)
Phys. Rev. C 93, 14907 (2016), Phys. Lett. B 827, 137003 (2022)

- **200 GeV: Partonic collectivity**
- **3.0 GeV: Hadronic interaction dominates**
- **Transition in degree of freedom:**

3.0 → 7.7 GeV?

Rapidity Dependence of v_1

STAR: CPOD2024, SQM2024

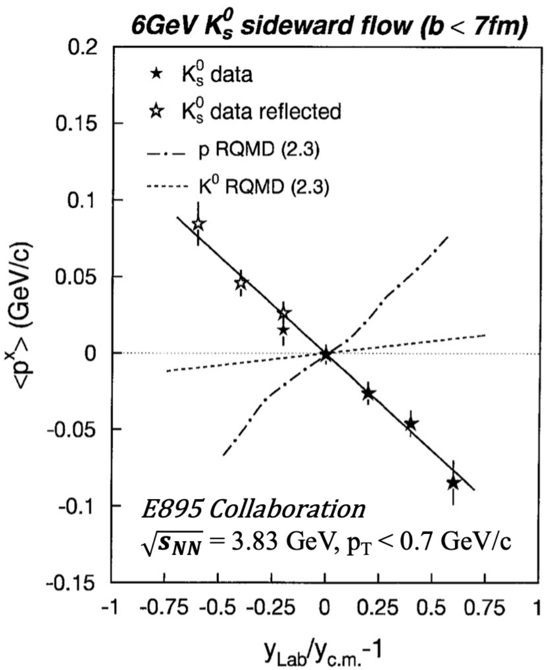


Baryonic Mean Field: p dependent Soft EoS
the nuclear incompressibility K = 210 MeV

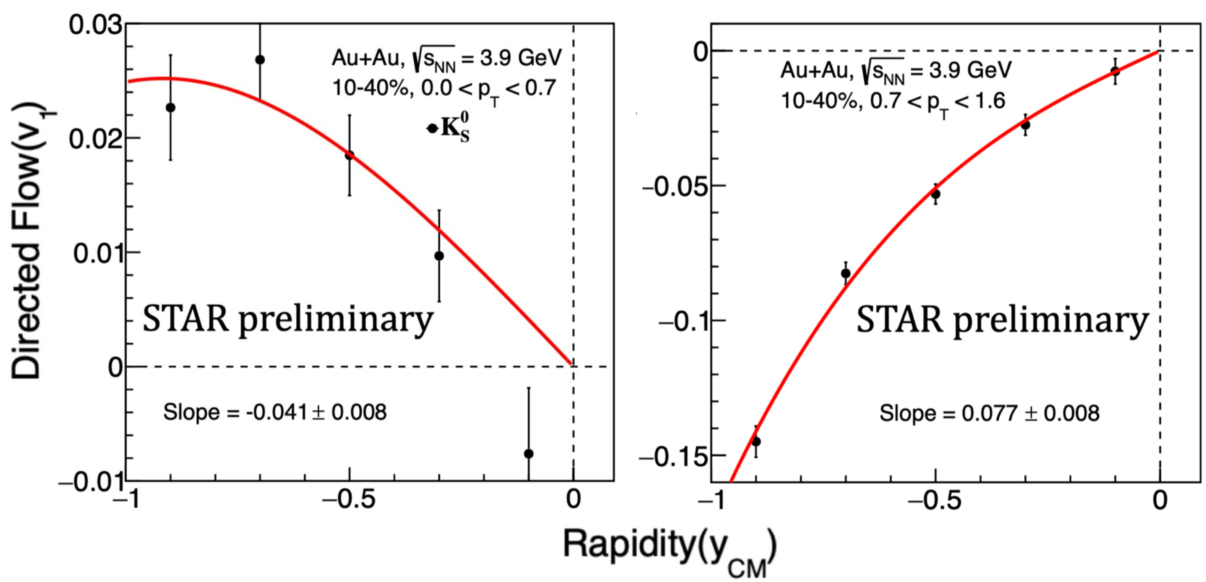
Measurements of v1 vs. rapidity for $\pi^{\pm}, K^{\pm}, K_S^0, p, \Lambda$ at 3.0, 3.2, 3.5, and 3.9 GeV

Anti-flow of Kaons

E895, Phys. Rev. Lett. 85, 940 (2000)



STAR: CPOD2024, SQM2024

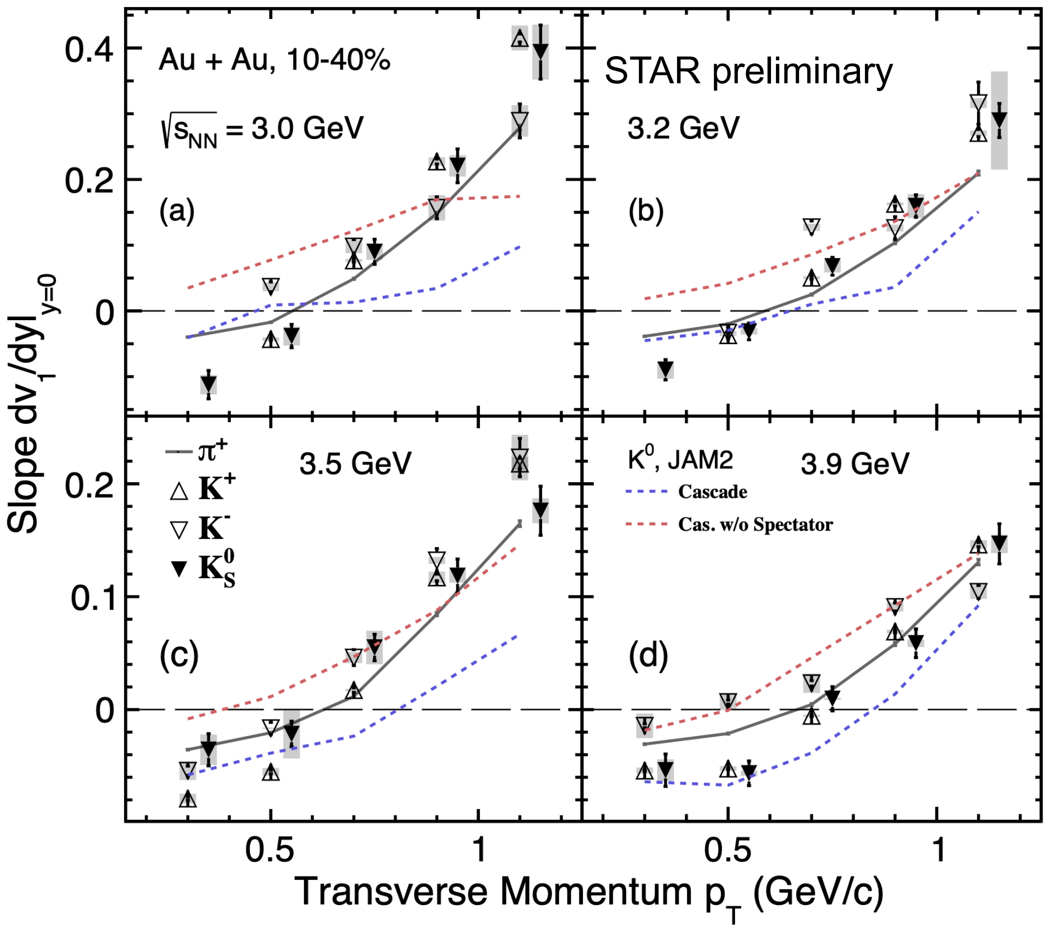


- 3.9 GeV: anti-flow observed for K_S^0 at pT < 0.7 GeV/c
- Positive directed flow slope of K_S^0 at pT > 0.7 GeV/c

Strong p_T dependence of K_S^0 v_1 slope

p_T Dependence of v_1 Slope

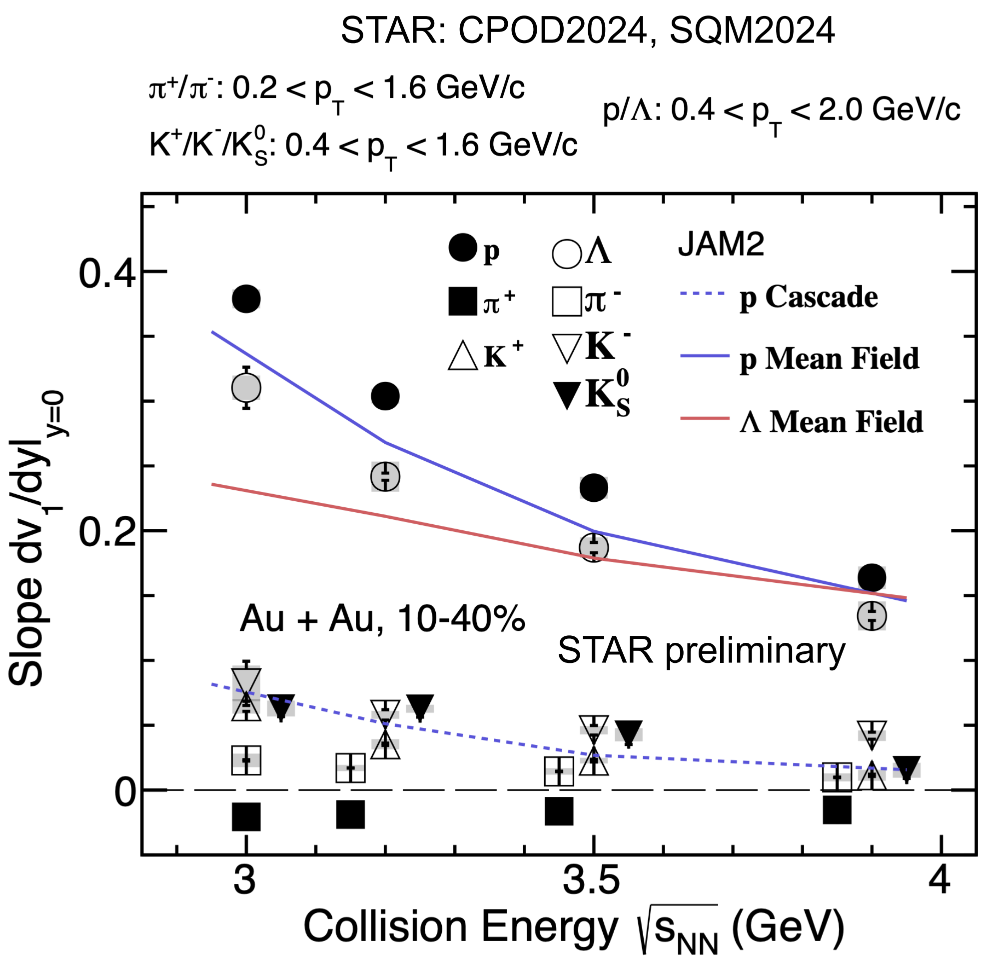
STAR: CPOD2024, SQM2024



- Anti-flow of π^+ and $K_S^0, K^\pm$ at low pT
- Anti-flow could be explained by shadowing effect from spectators

Model study:
Z. Liu and S. Shi, Phys. Rev. C 110, 034903 (2024)

Energy Dependence of v_1 Slope



- v_1 slope of baryons drops as collision energy increases
- JAM with baryonic Mean Field better describes data

  Mean field potential plays important role

p_T Dependence of v_2 at 3 - 4.5 GeV

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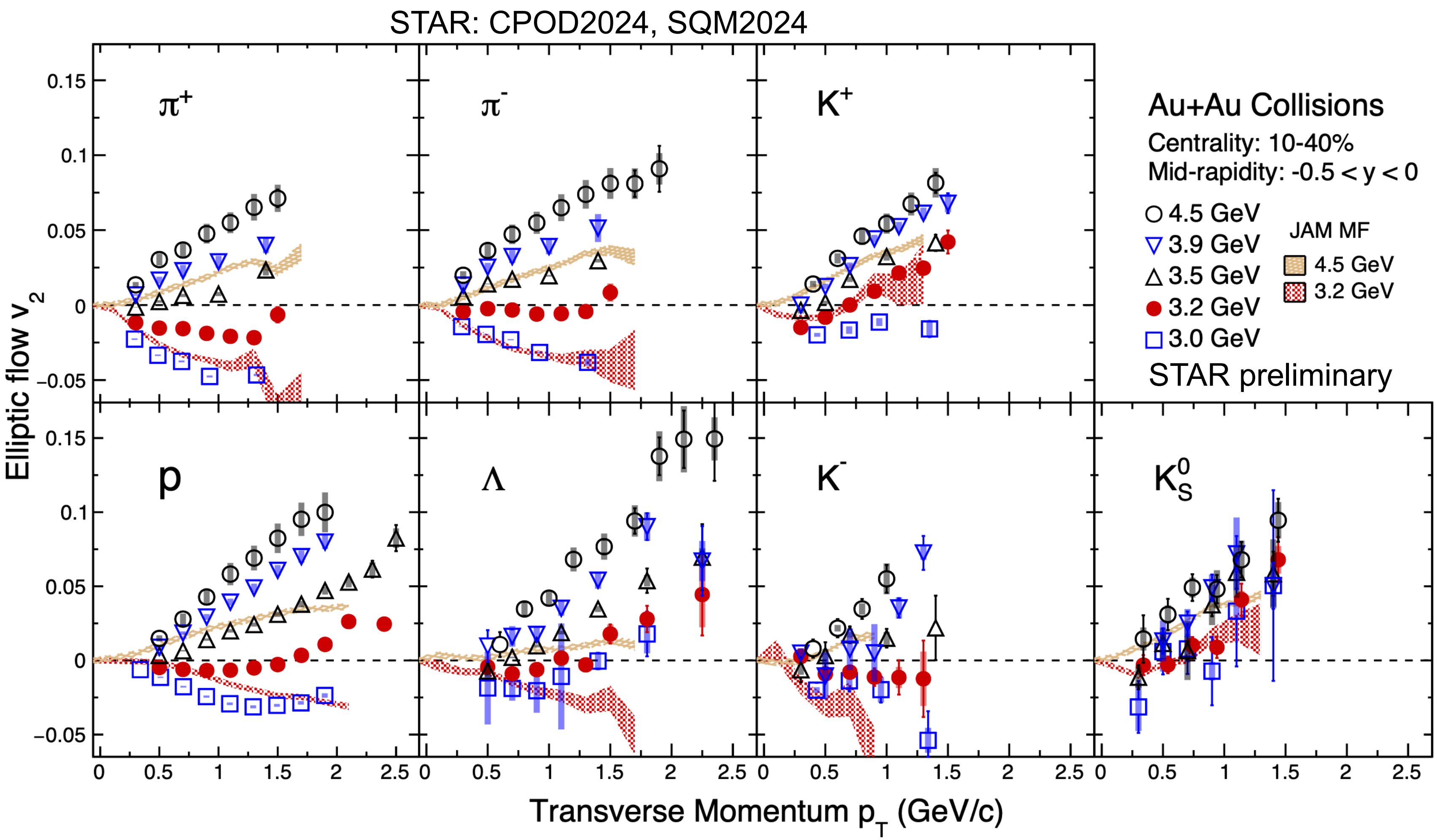
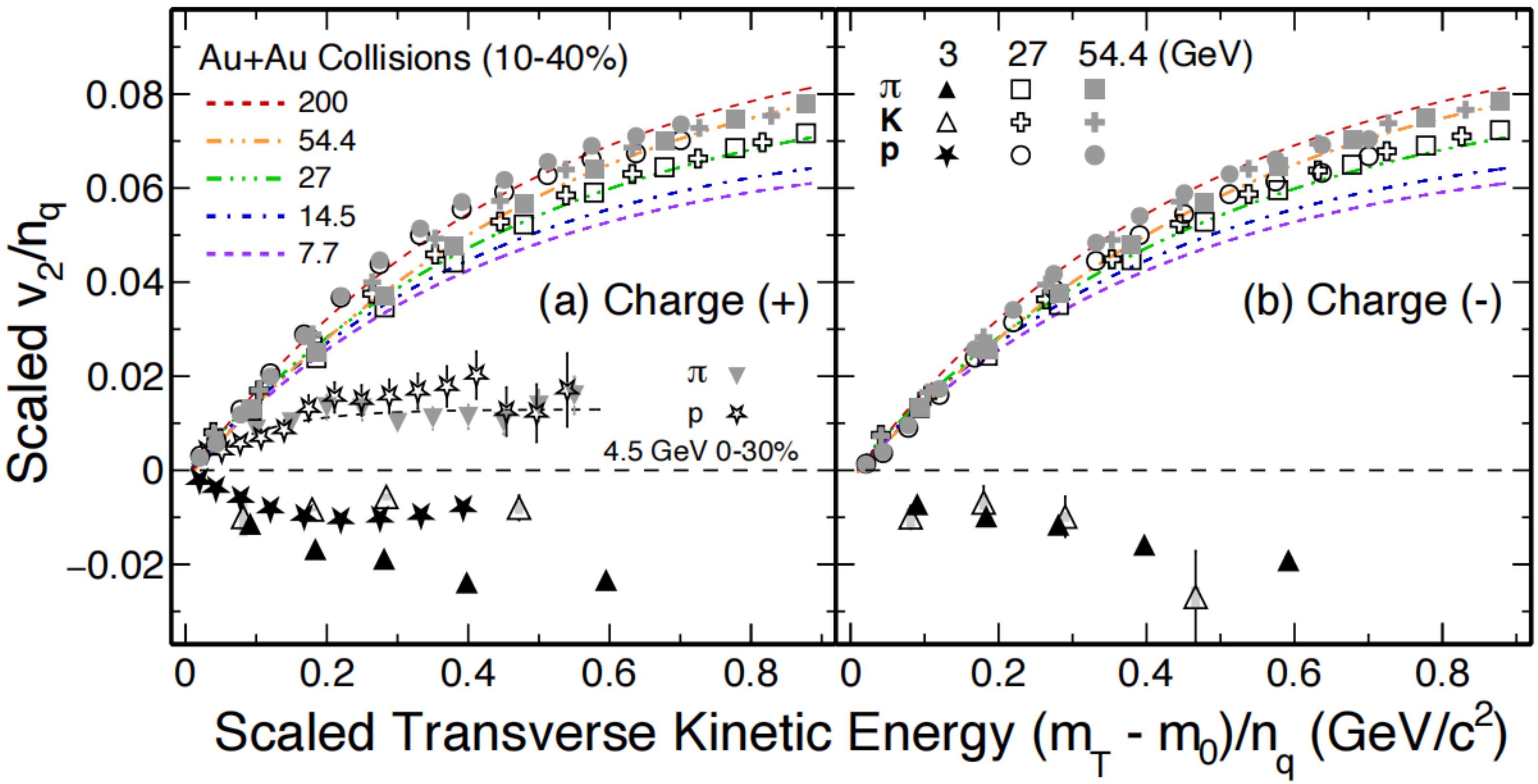


- Clear energy dependence for $v_2(p_T)$ from negative to positive: **Shadowing effect**
- JAM + baryonic Mean Field better describe the 3.2 GeV while underestimate 4.5 GeV data

Baryonic Mean Field: p dependent Soft EoS, the nuclear incompressibility K = 210 MeV

NCQ scaling at 3 GeV



STAR, Phys. Lett. B 827 (2022) 137003; Phys. Rev. C.107 (2023) 024912

- At 3 GeV, the measured midrapidity v_2 for all particles are negative and NCQ scaling is absent
- Equation-of-State dominated by baryonic interactions

→ The hadronic degree of freedom dominates

NCQ scaling of v_2 at 3 - 4.5 GeV

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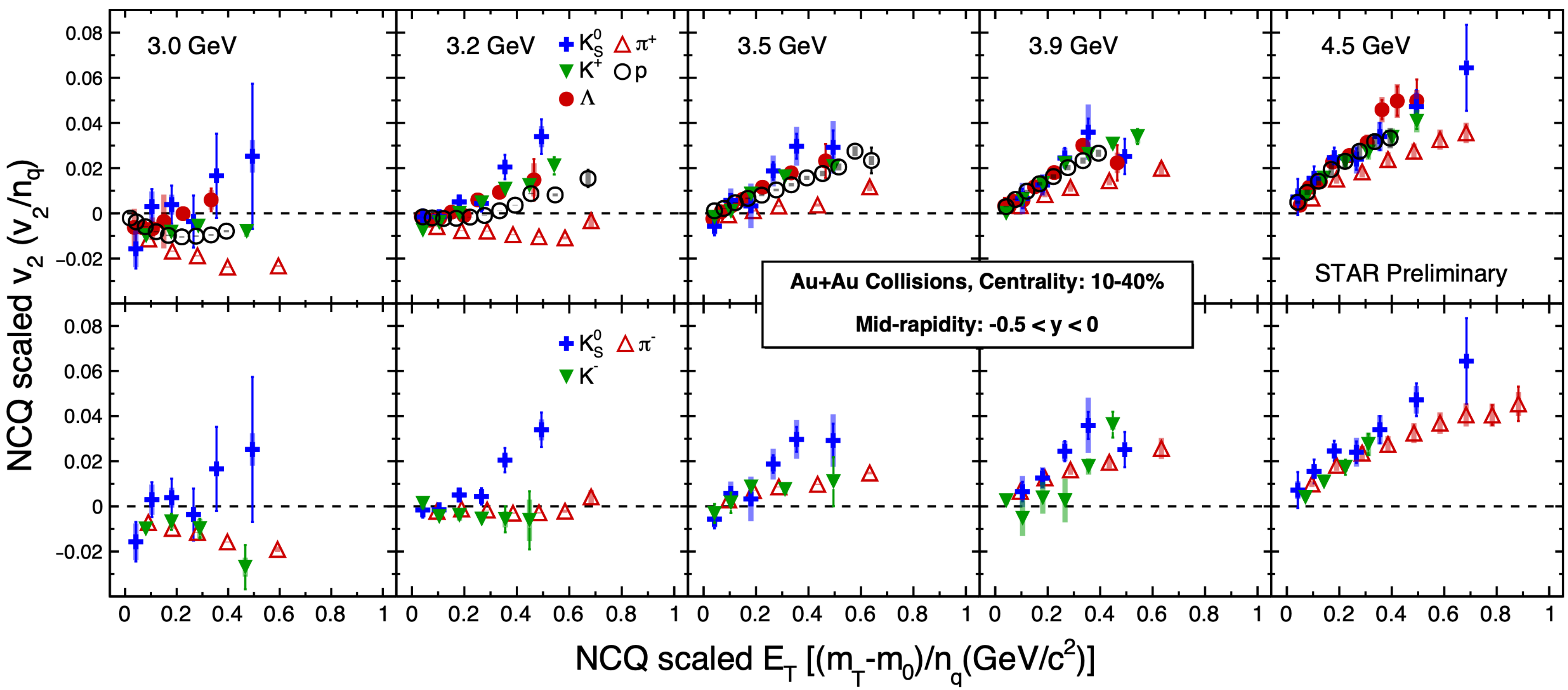
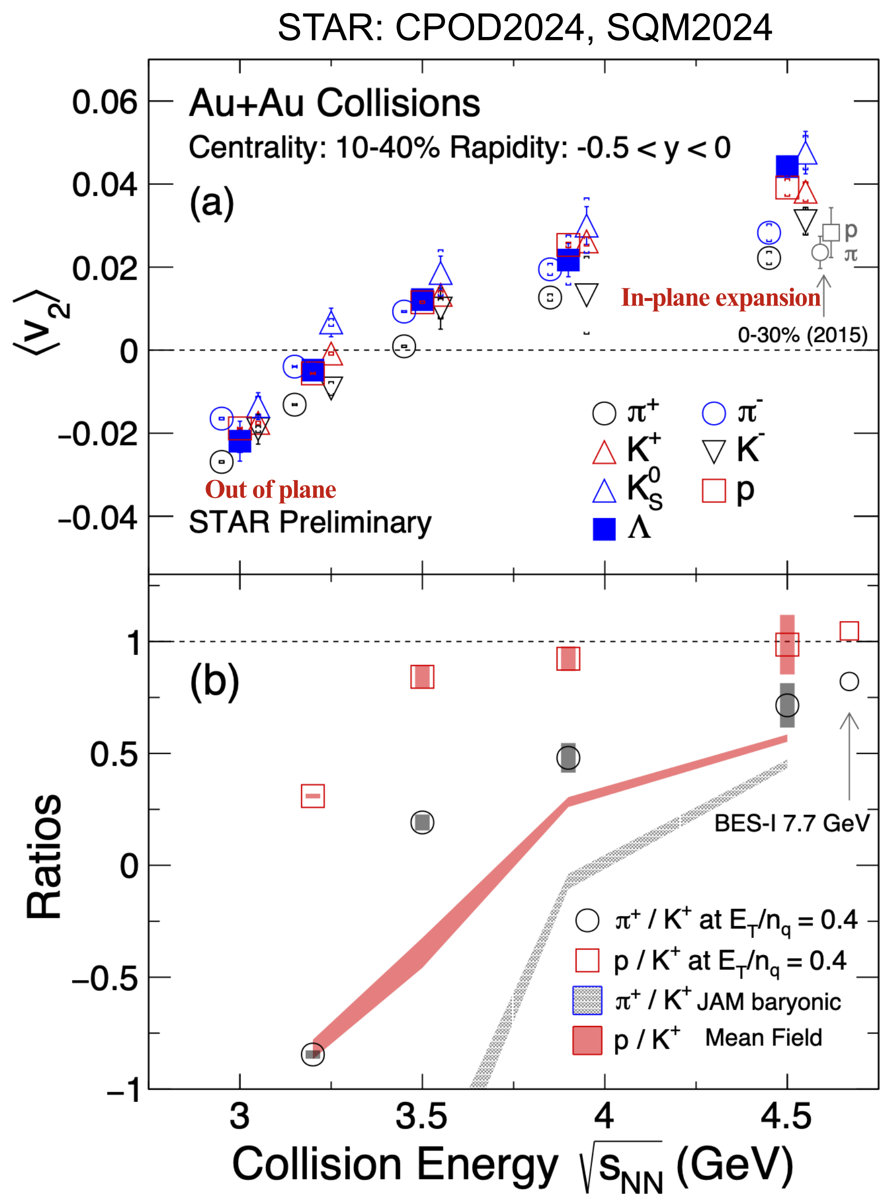
Hadronic interaction STAR: CPOD2024, SQM2024 **Partonic collectivity**



- NCQ scaling completely breaks below 3.2 GeV
- NCQ scaling becomes better gradually from 3 .2 to 4.5 GeV

Energy dependence of $\langle v_2 \rangle$



- Negative to positive flow: $3 \rightarrow 4.5$ GeV
- The NCQ-scaled v_2 ratio of p/K^+ is close to 1 at 3.9 and 4.5 GeV, while it deviates largely from 1 at 3.2 GeV

High Moments

Conserved Charges: Net Baryon, Net Charge, Net Strangeness

Measured multiplicity N, $\langle \delta N \rangle = \mathbf{N} - \langle N \rangle$

mean: $M = \langle N \rangle = C_1$

variance: $\sigma^2 = \langle (\delta N)^2 \rangle = C_2$

skewness: $S = \langle (\delta N)^3 \rangle / \sigma^3 = C_3/C_2^{3/2}$

kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^4 - 3 = C_4/C_2^2$

Moments, cumulants and susceptibilities:

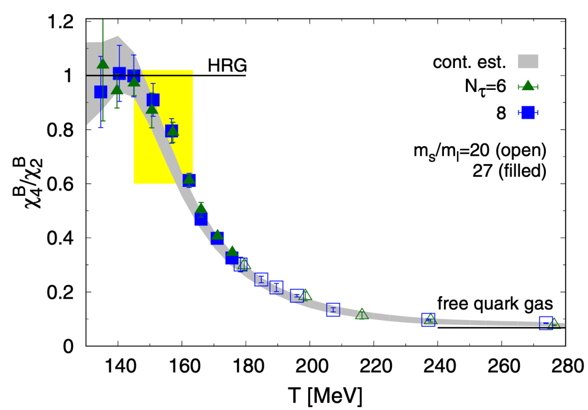
2nd order: $\sigma^2/M \equiv C_2/C_1 = \chi_2/\chi_1$

3rd order: $S\sigma \equiv C_3/C_2 = \chi_3/\chi_2$

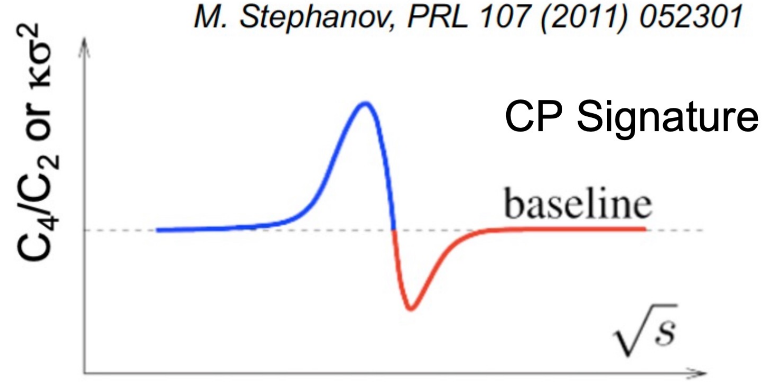
4th order: $\kappa\sigma^2 \equiv C_4/C_2 = \chi_4/\chi_2$

Sensitive to **correlation length**

Related to system **susceptibility**



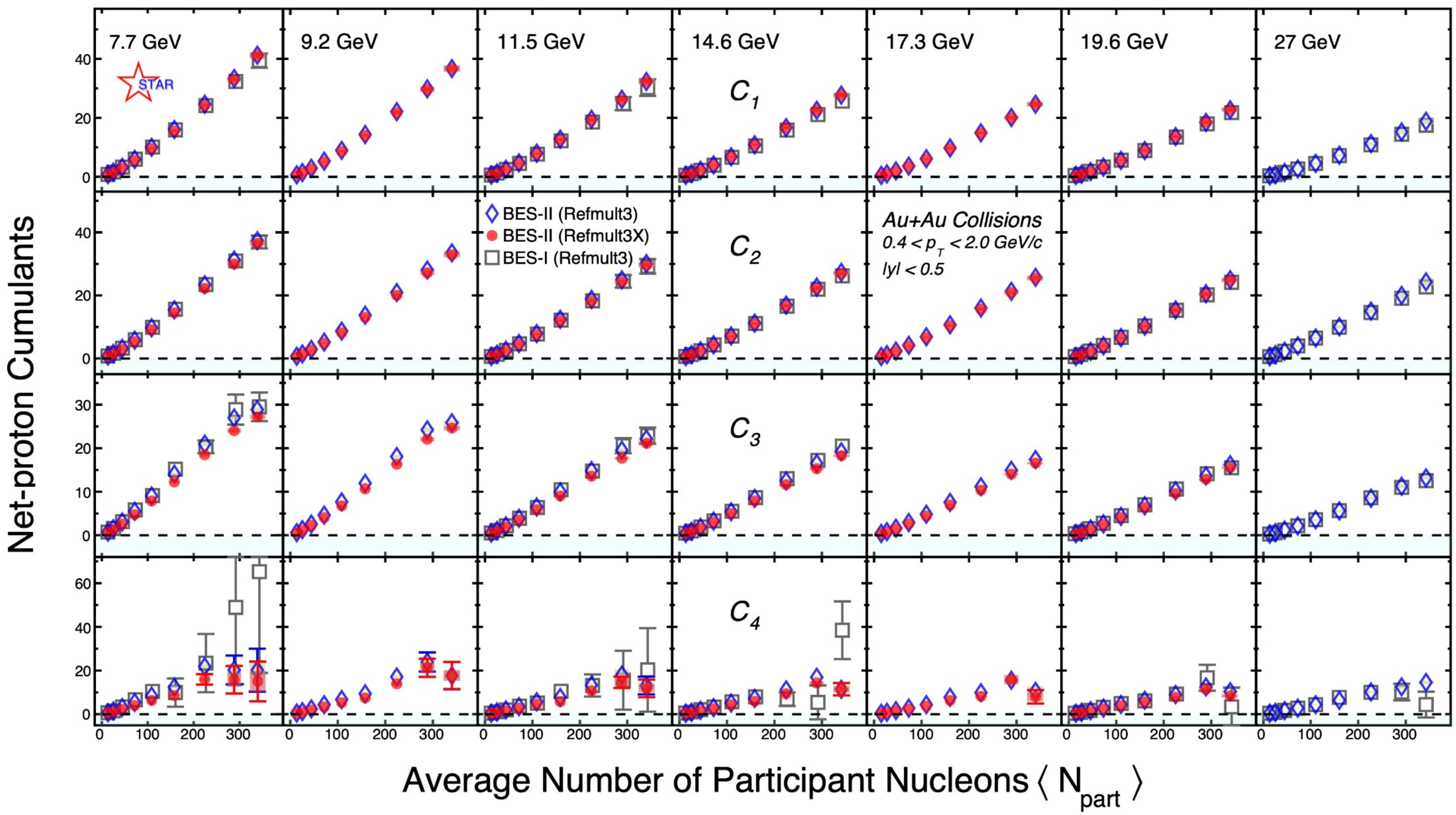
M. Stephanov, PRL 107 (2011) 052301



S. Ejiri et al,Phys.Lett. B 633, 275 (2006). Cheng et al, PRD 074505 (2009). B. Friman et al., EPJC 71, 1694 (2011). F. Karsch and K. Redlich , PLB 695, 136 (2011). S. Gupta, et al., Science, 332, 1525 (2012). A. Bazavov et al., PRL109, 192302 (2012); PRD95, 054504 (2017). S. Borsanyi et al., PRL111, 062005 (2013)

Net-proton Cumulants

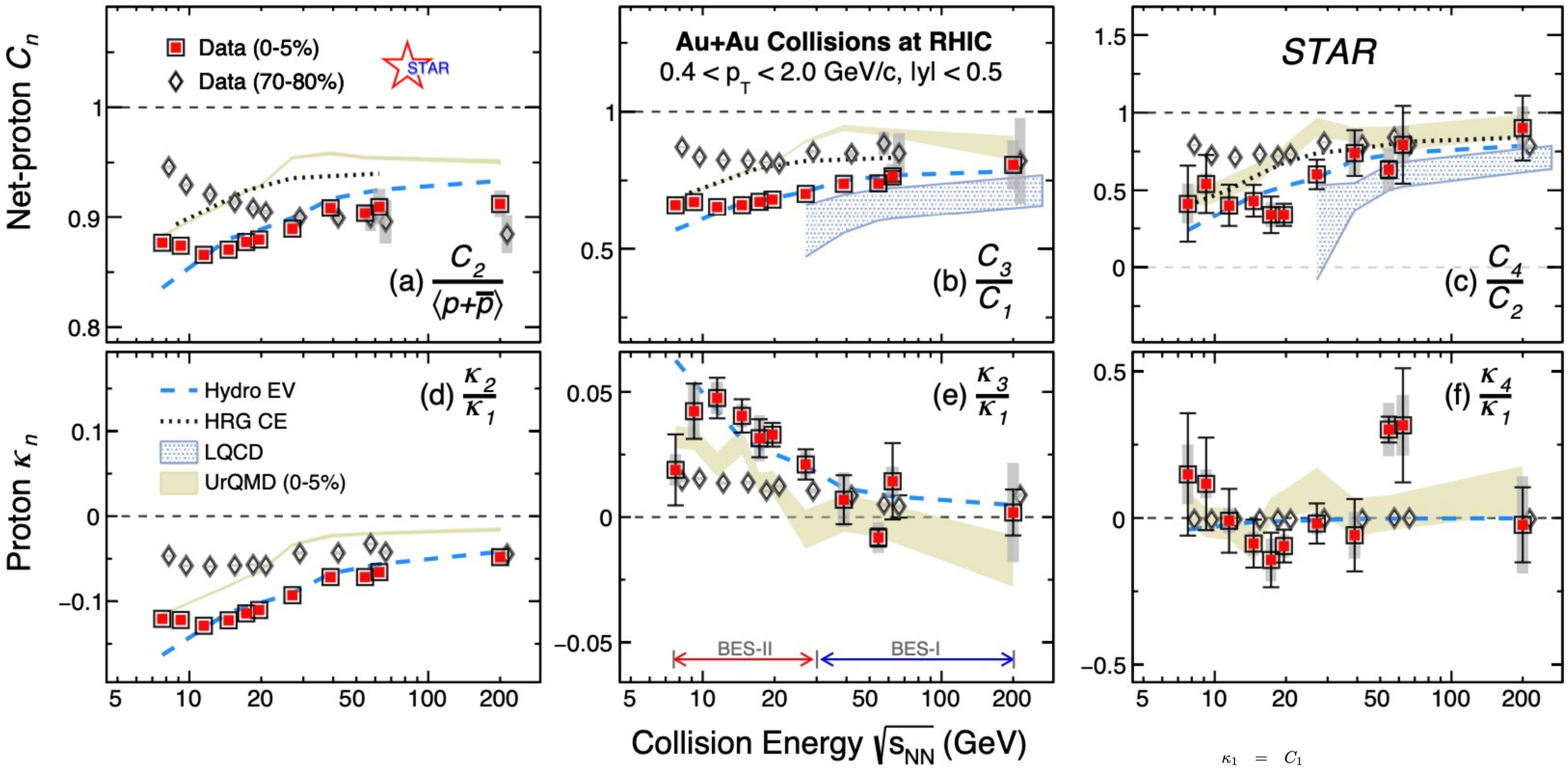
STAR: CPOD2024, SQM2024



RefMult3: ($|\eta|<1.0$) RefMult3X: ($|\eta|<1.6$)

- Higher precision than BES-I

Energy Dependence



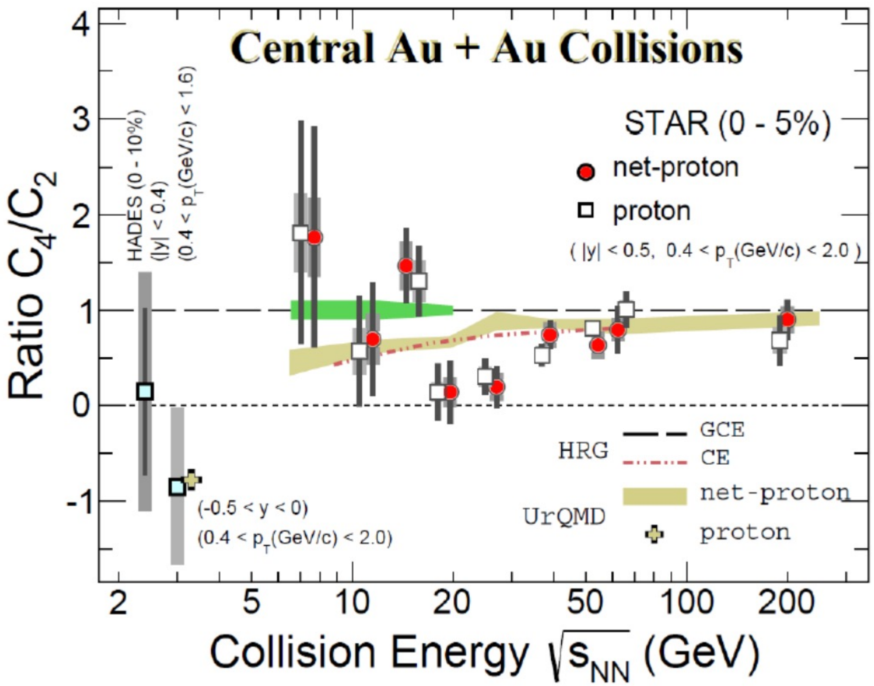
$$\begin{aligned}
\kappa_1 &= C_1 \\
\kappa_2 &= -C_1 + C_2 \\
\kappa_3 &= 2C_1 - 3C_2 + C_3 \\
\kappa_4 &= -6C_1 + 11C_2 - 6C_3 + C_4
\end{aligned}$$

- All proton factorial cumulant ratios show non-monotonic dependence
- Lattice QCD describe the data up to 27 GeV.

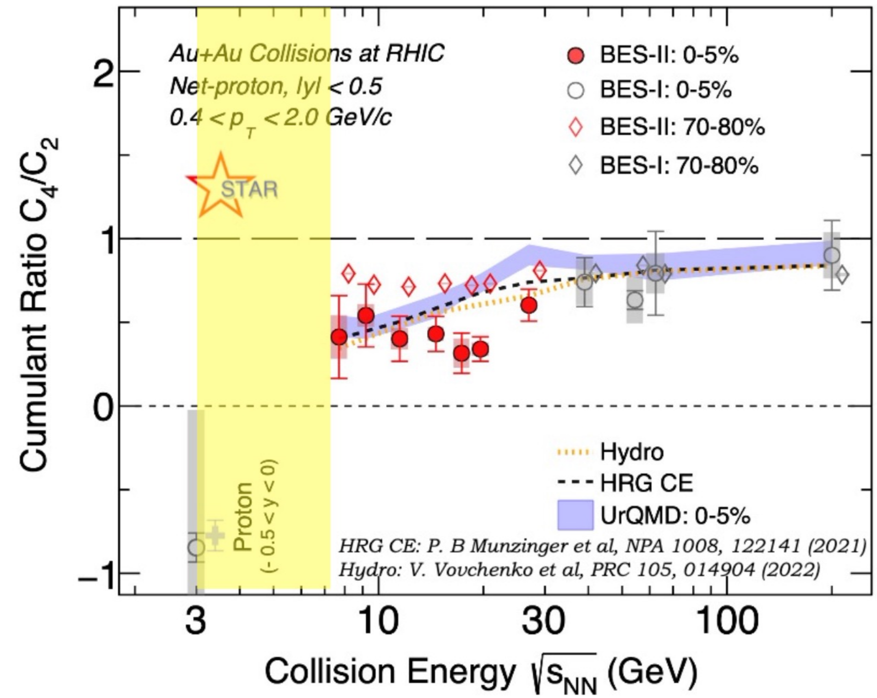
HRG CE: P .B. Munzinger et al. Nucl. Phys. A1008, 122141(2021); Hydro: HRG CE + EV, V. Vovchenko et al., Phys. Rev. C105, 014904 (2022). LQCD: A. Bazavov et al., Phys. Rev. D101, 074502 (2020). arXiv : 2407.09335

CP Search

BES-I



BES-II



- Energy gap between 3 and 7.7 GeV : important for Critical Point search
- Dynamical modelling is needed to fully understand the data

STAR: PRL126, 92301(2021); PRC104, 024902 (2021); PRL128, 202303(2022); PRC107, 024908 (2023)
HADES: PRC102, 024914(2020)

Summary

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➢ Light nuclei production

- ➢ $N_t \times N_p / N_d^2$ at 19.6 and 27 GeV from 0-10% central collisions show 4.1 σ enhancement to the coalescence baseline
- ➢ The yield ratio can serve as a tool for investigating the production mechanism.

➢ Collective flow

- ➢ Anti-flow for $K_S^0, K^{\pm}$ and π^+ observed at low pT ($\lesssim$ 0.6 GeV/c)

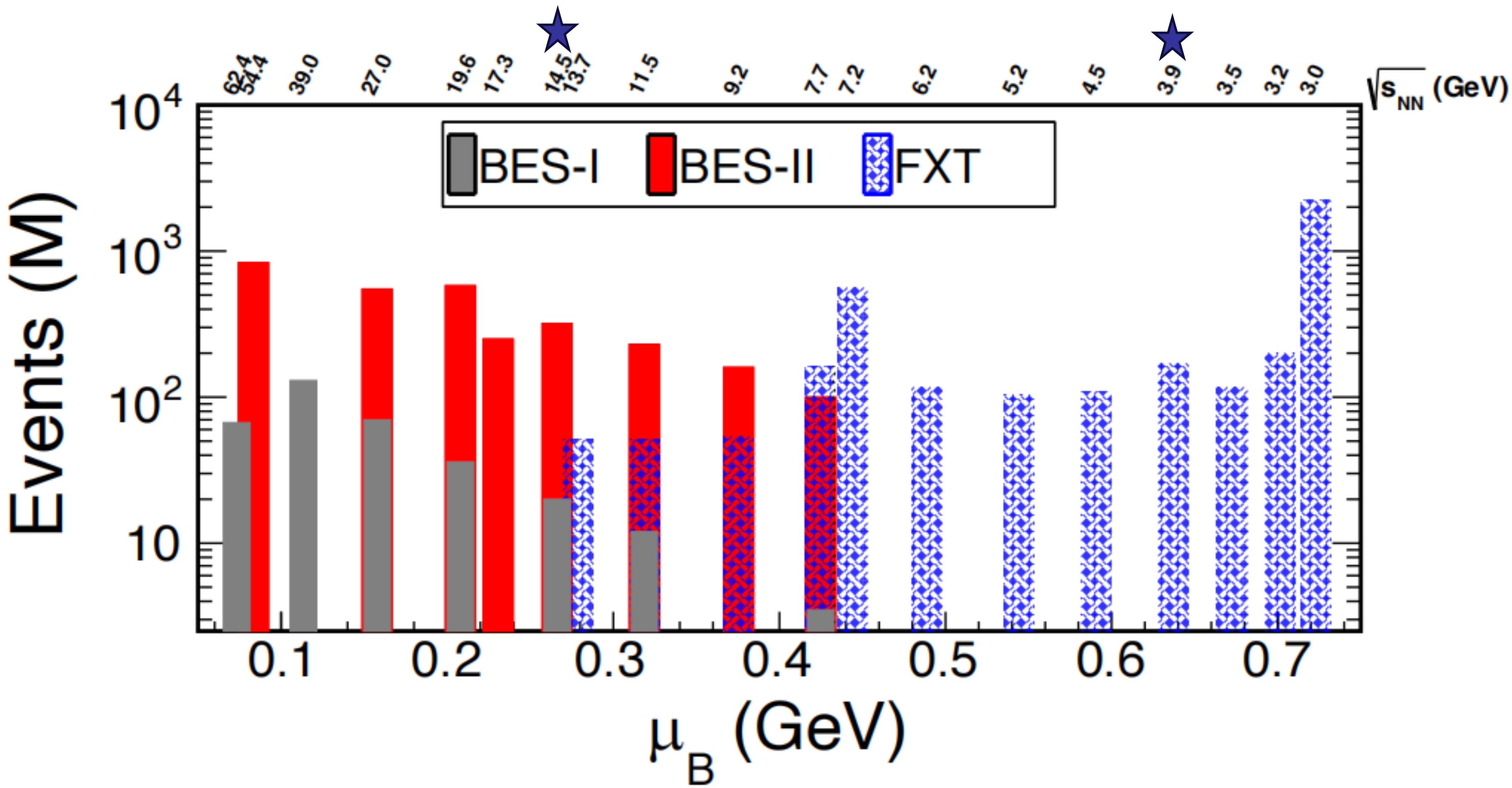
  Spectator shadowing effect is important at high baryon density region
- ➢ NCQ scaling breaks at 3.0 and 3.2 GeV, and gradually restores from 3.0 to 4.5 GeV

  Dominance of partonic interactions at 4.5 GeV

➢ High moments

- ➢ Need to understand the reason lead to the deviations around 20 GeV
- ➢ Need reliable dynamical modeling and non-CP baselines

Outlook



- Higher statistics, better detector performance and more energy points in BES-II
- Explore the QCD phase diagram

Stay tuned for more new results!

Thank you!