Recent heavy-ion results from STAR

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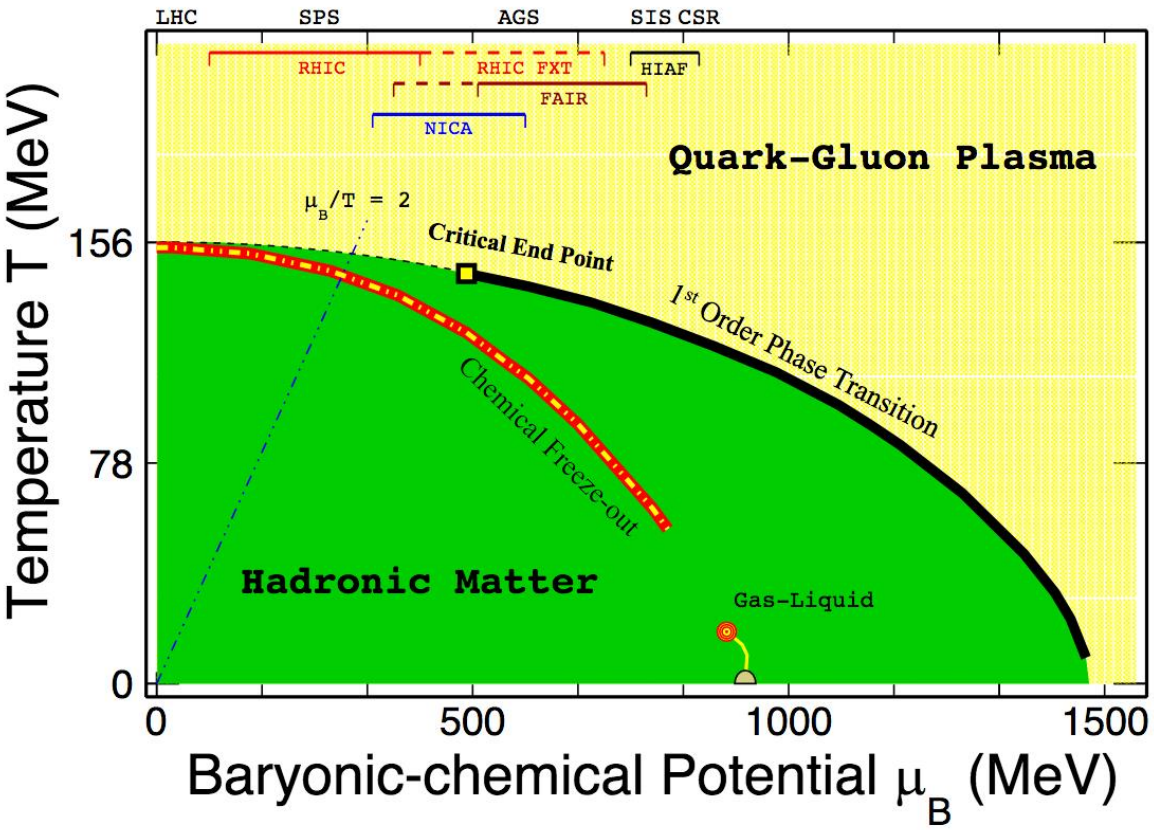
HIGH ENERGY PHYSICS BRANCH OF CPS
山东大学
SHANDONG UNIVERSITY
第十三届全国粒子物理学术会议
（2021）

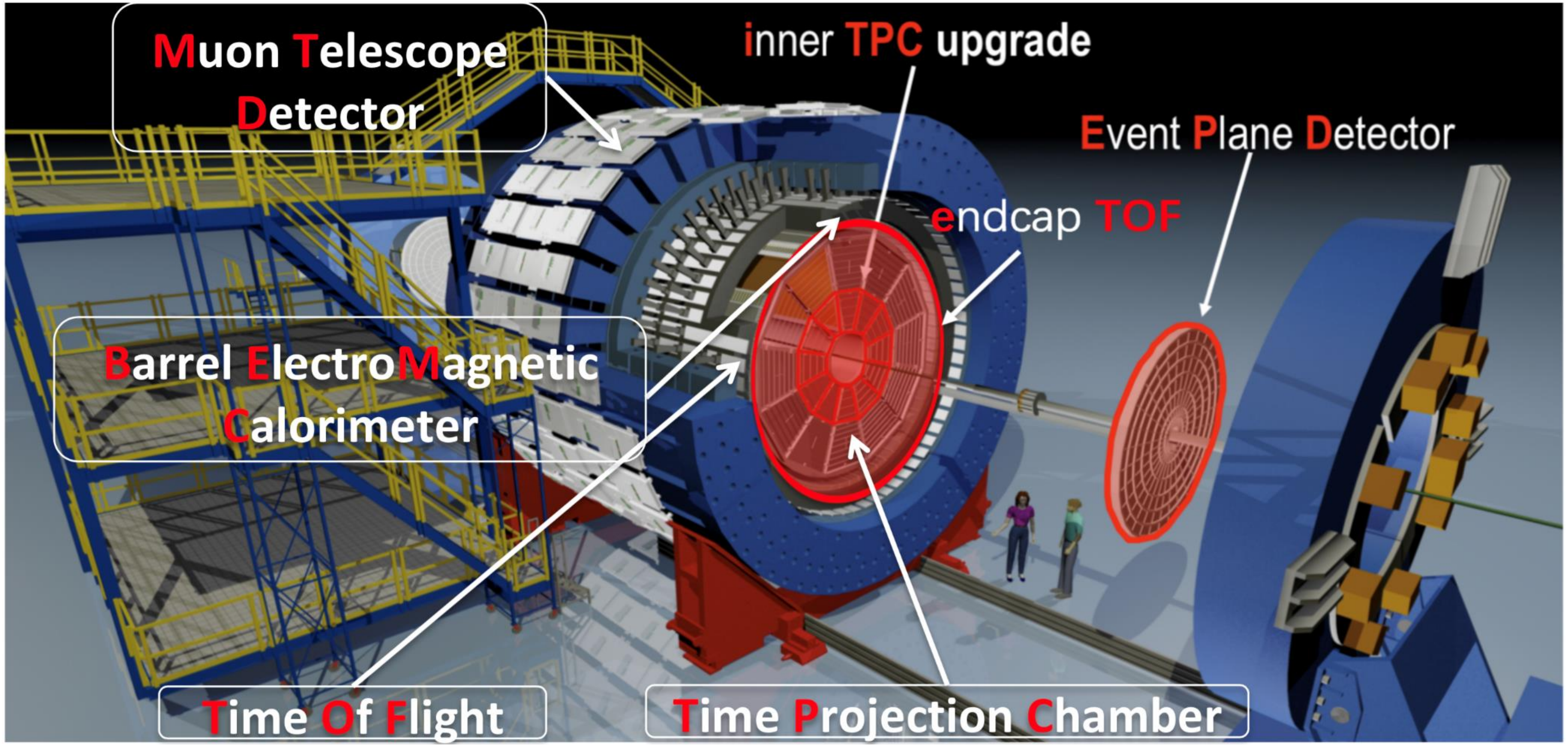
Outline



STAR, Phys. Rev. Lett. ***126*** *(2021) 092301*

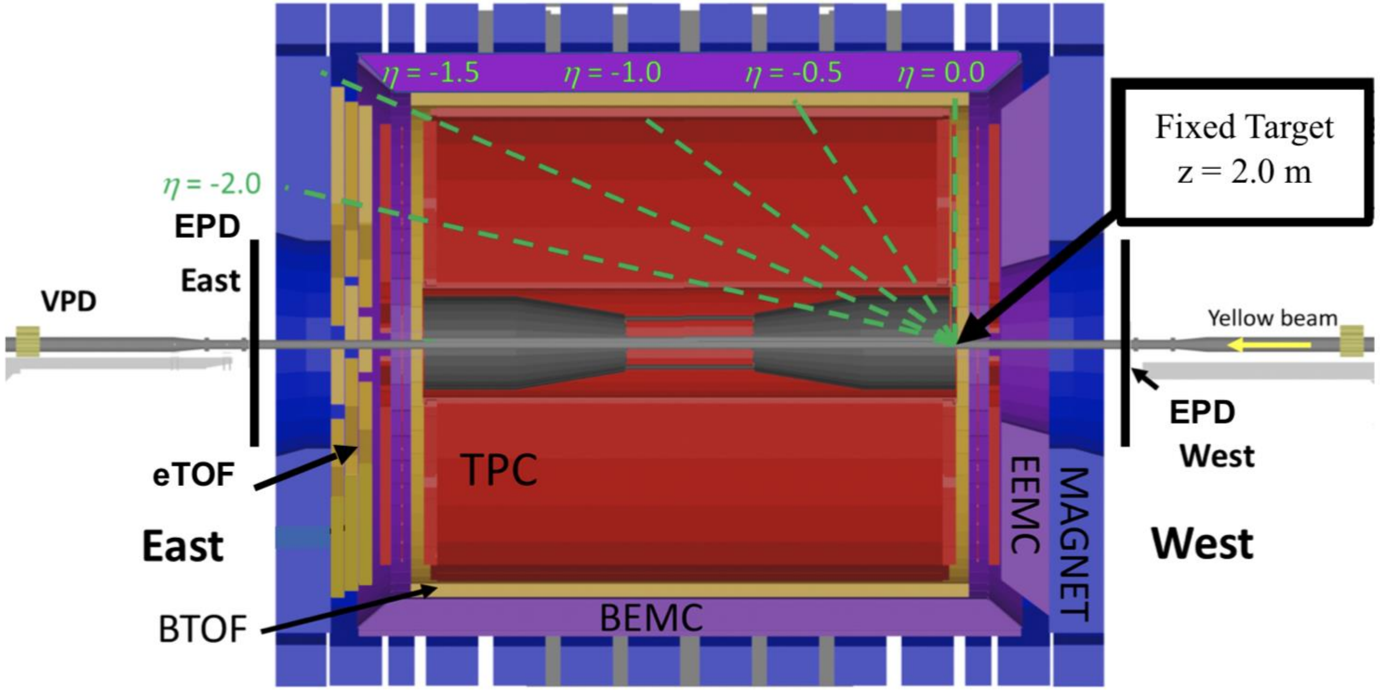
- Heavy flavor
  - Quark-gluon plasma properties
- Light flavor
  - QCD medium properties, phase transition
- Hypernuclei and two-particle correlations
  - Y-Y/Y-N interactions, EOS at high density
- Global polarization
  - Vorticity
- STAR beyond 2022+

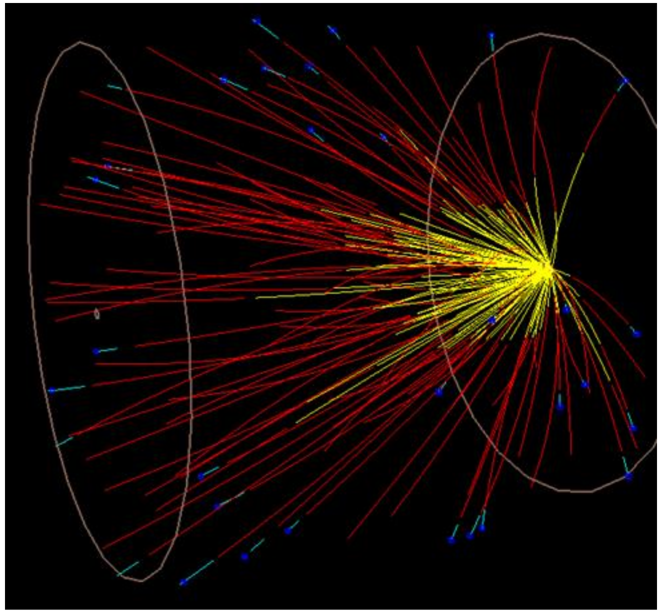
STAR detector at RHIC



- Event Plane Detector for reaction plane and centrality determination and triggering
- End-cap Time-of-Flight for forward PID
- Inner TPC for increasing TPC acceptance ~1.5 in η and improving dE/dx resolution

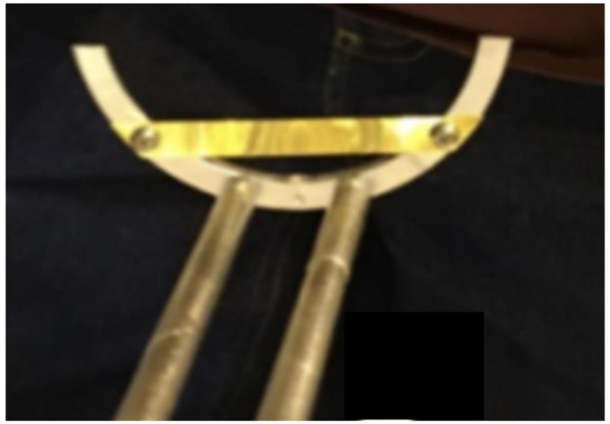
The STAR fixed-target (FXT) setup

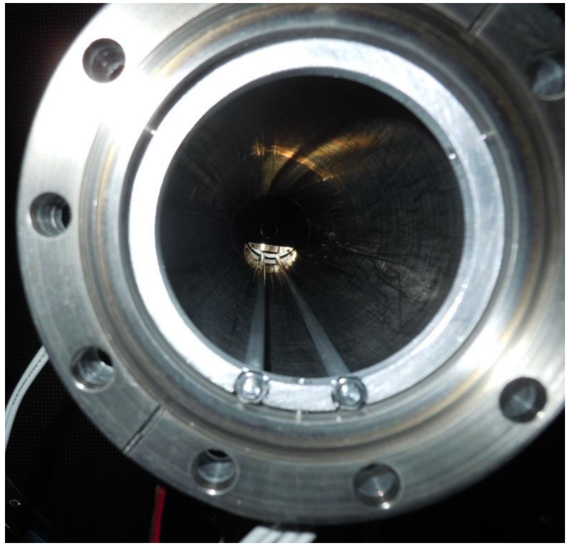




Gold Target:

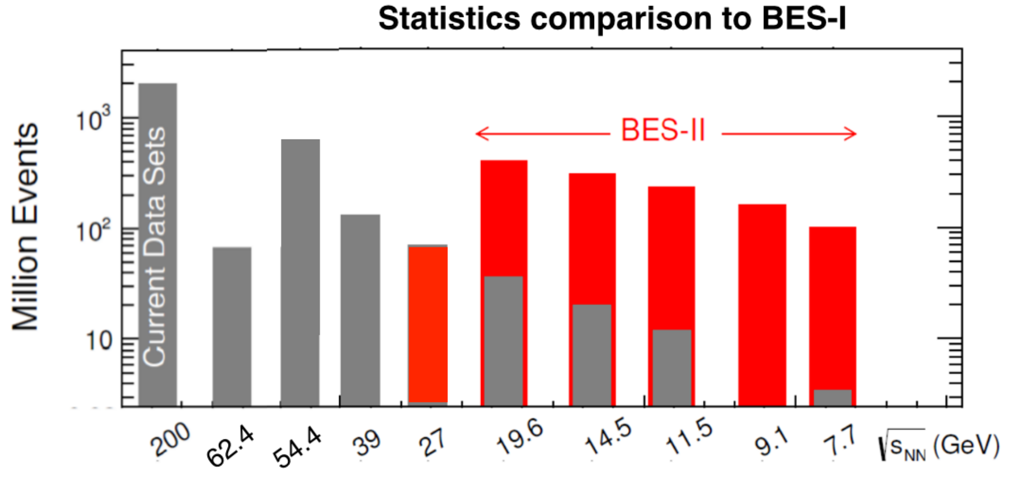
- 250 μm foil
- 2 cm below nominal beam axis
- 2 m from center of STAR





Datasets and STAR BES-II

- Collision energies: 200 — 7.7 GeV, μ_B: 20 — 420 MeV
- Access with FXT to high baryon density regions with μ_B up to 720 MeV



STAR BES-II, FXT data taking

Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events Requested (Recorded)	Date Collected
31.2	7.7 (FXT)	420	0.5+1.1 days	100 M (50 M+112 M)	Run-19+20
19.5	6.2 (FXT)	487	1.4 days	100 M (118 M)	Run-20
13.5	5.2 (FXT)	541	1.0 day	100 M (103 M)	Run-20
9.8	4.5 (FXT)	589	0.9 days	100 M (108 M)	Run-20
7.3	3.9 (FXT)	633	1.1 days	100 M (117 M)	Run-20
5.75	3.5 (FXT)	666	0.9 days	100 M (116 M)	Run-20
4.59	3.2 (FXT)	699	2.0 days	100 M (200 M)	Run-19
3.85	3.0 (FXT)	721	4.6 days	100 M (259 M)	Run-18
26.5	**7.2 (FXT)**	**443**	**2 day**	**155 + 317 M**	**Run-18/20**
3.85	**3.0(FXT)**	**721**	**3.5 weeks**	**2.3 B (2.3 B)**	**Run-21**
44.5	**9.2(FXT)**	**373**	**0.5 days**	**50 M (50 M)**	**Run-21**
70	**11.5(FXT)**	**316**	**0.5 days**	**50 M (50 M)**	**Run-21**
100	**13.7(FXT)**	**276**	**0.5 days**	**50 M (50 M)**	**Run-21**

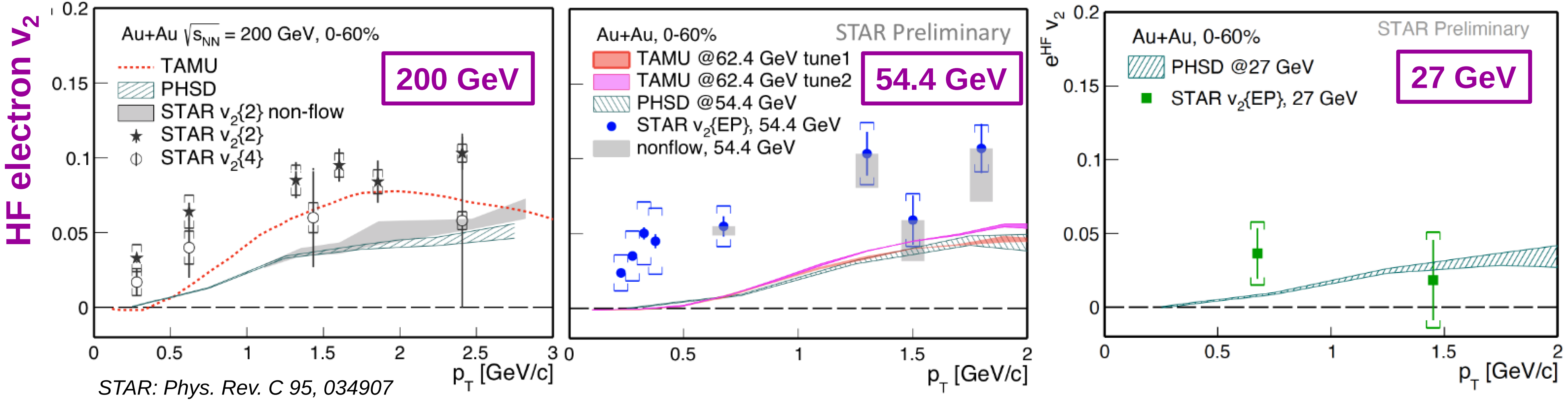
STAR BES-II, Collider mode data taking

Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Number Events Requested (Recorded)	Date Collected
13.5	27	156	(560 M)	Run-18
9.8	19.6	206	400 M (582 M)	Run-19
7.3	14.6	262	300 M (324 M)	Run-19
5.75	11.5	316	230 M (235 M)	Run-20
4.59	9.2	373	160 M (162 M)[1]	Run-20+20b
3.85	**7.7**	**420**	**100M (100M)**	**Run-21**
8.65	**17.3**	**230**	**250M (250M)**	**Run-21**

Successful completion of BES-II and FXT data taking, thanks to excellent RHIC performance!

Energy dependence of HF electron v_2

- HF flow at lower energies?
- High statistics data at 54.4 and 27 GeV, taken in 2017 and 2018 respectively

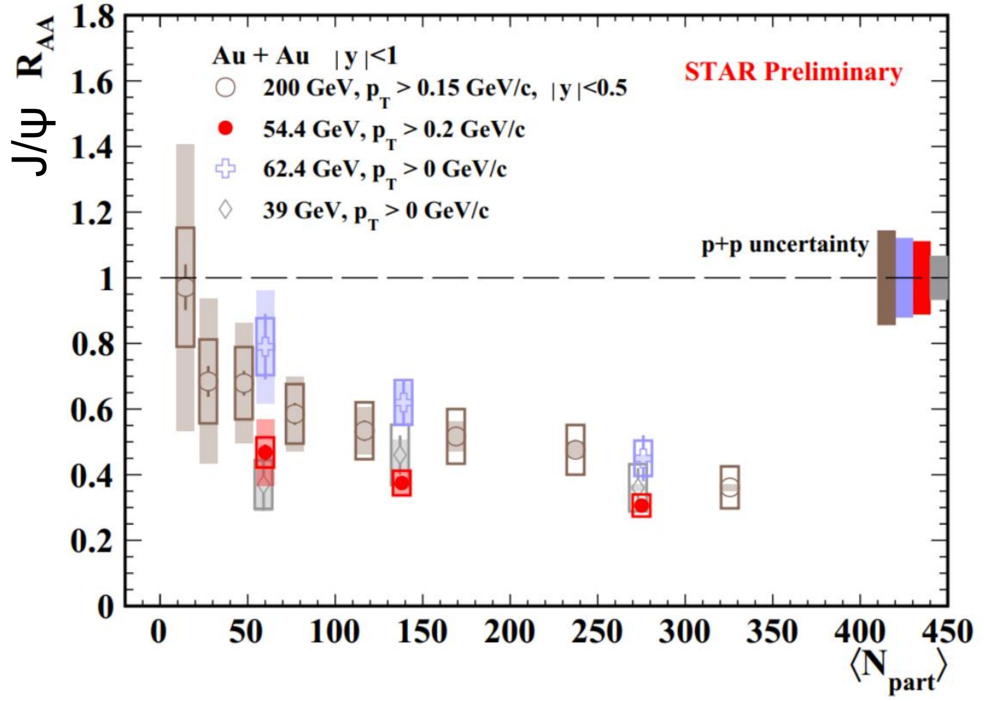


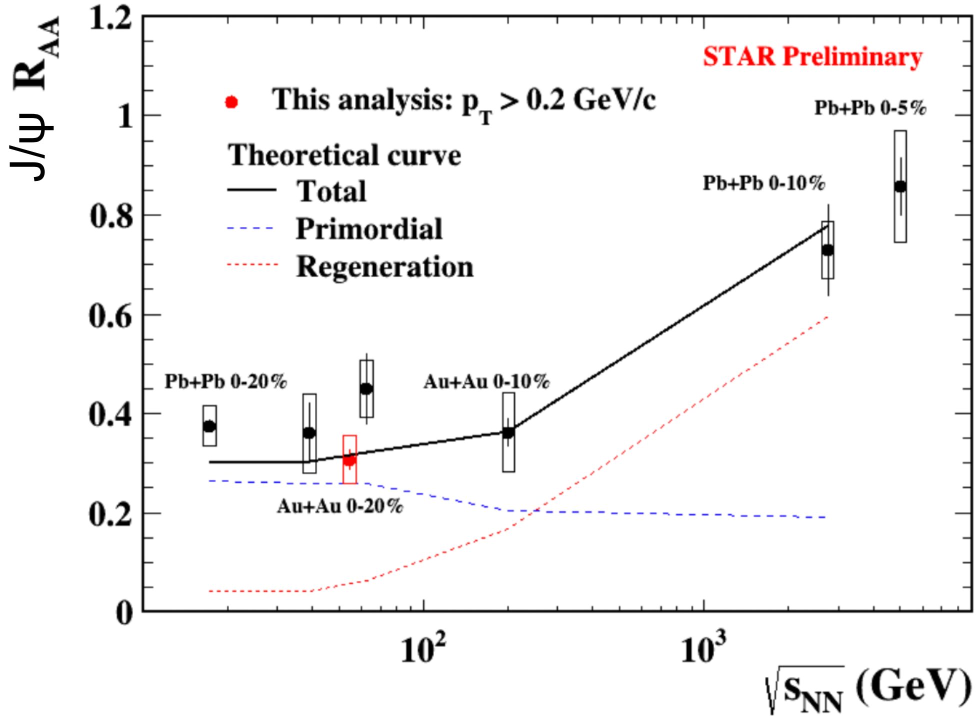
- Similar v_2 for HF electrons at 200 and 54.4 GeV, hint of smaller v_2 at 27 GeV
- Models fail describing data at low p_T (< 1.4 GeV/c) for 54.4 GeV

S. Zhang, SQM2021; Y. Ji, HP2020

Energy dependence of J/ψ suppression

- J/ψ suppression: interplay of color screening and regeneration
- 10x more data at 54.4 GeV than for previous measurements at 62.4 and 39 GeV





Theoretical curve:

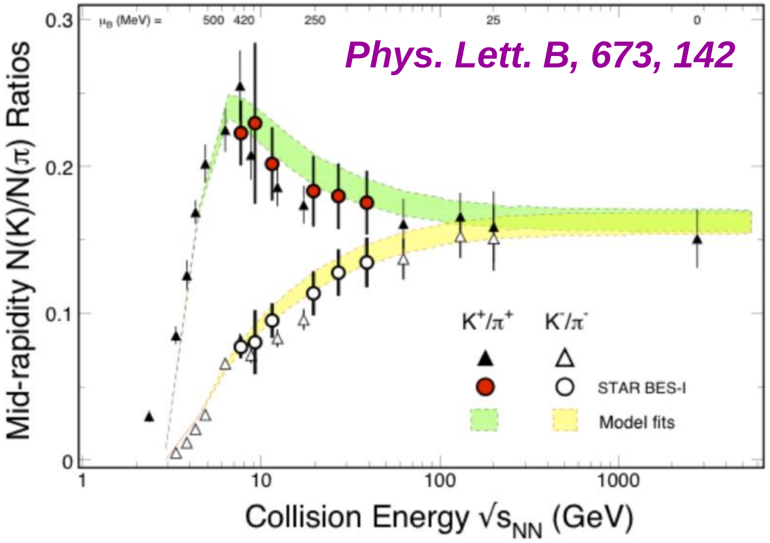
R.Rapp et al Phys. Rev. C 82 (2010) 064905 (private communications)

- Similar J/ψ R_{AA} values between 54.4 and 200 GeV

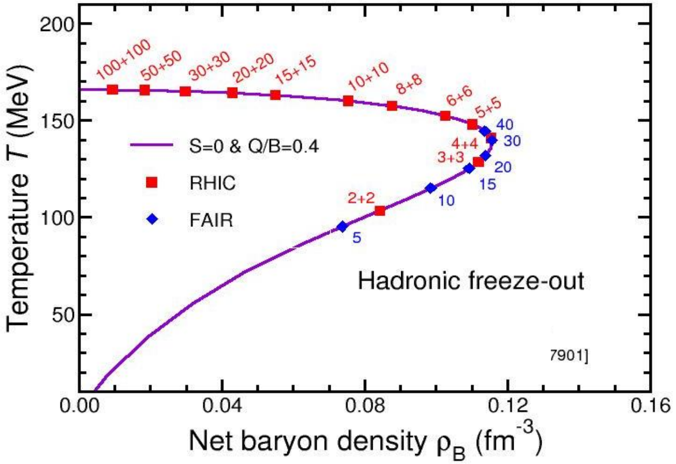
K. Shen, SQM2021 & poster session

- Will help constrain the contributions from color screening and regeneration

Strangeness production in BES-I

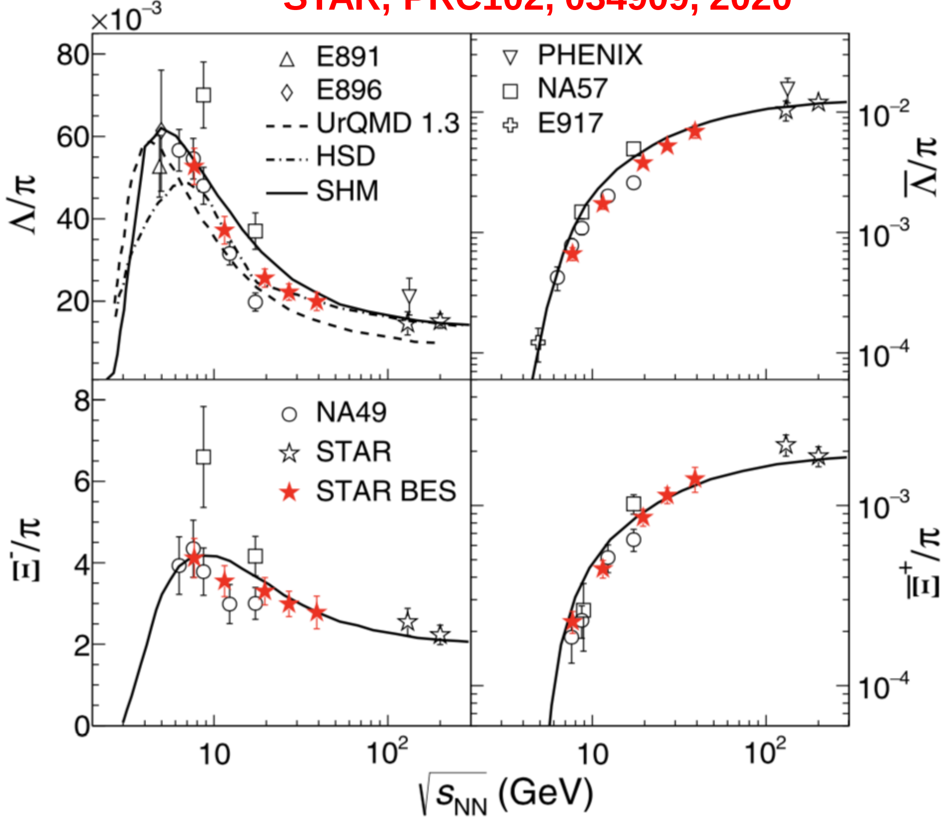


RHIC BES

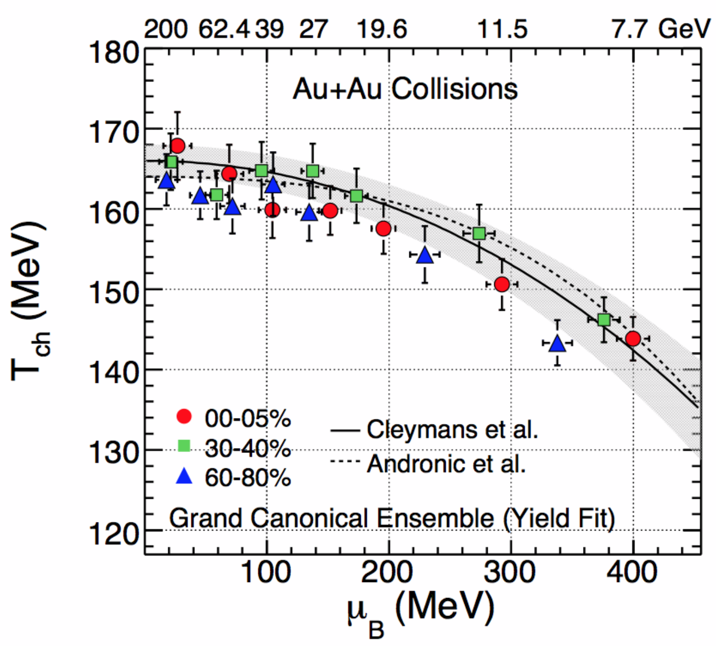


J. Randrup et al., PRC 74, 047901 (2006)

STAR, PRC102, 034909, 2020

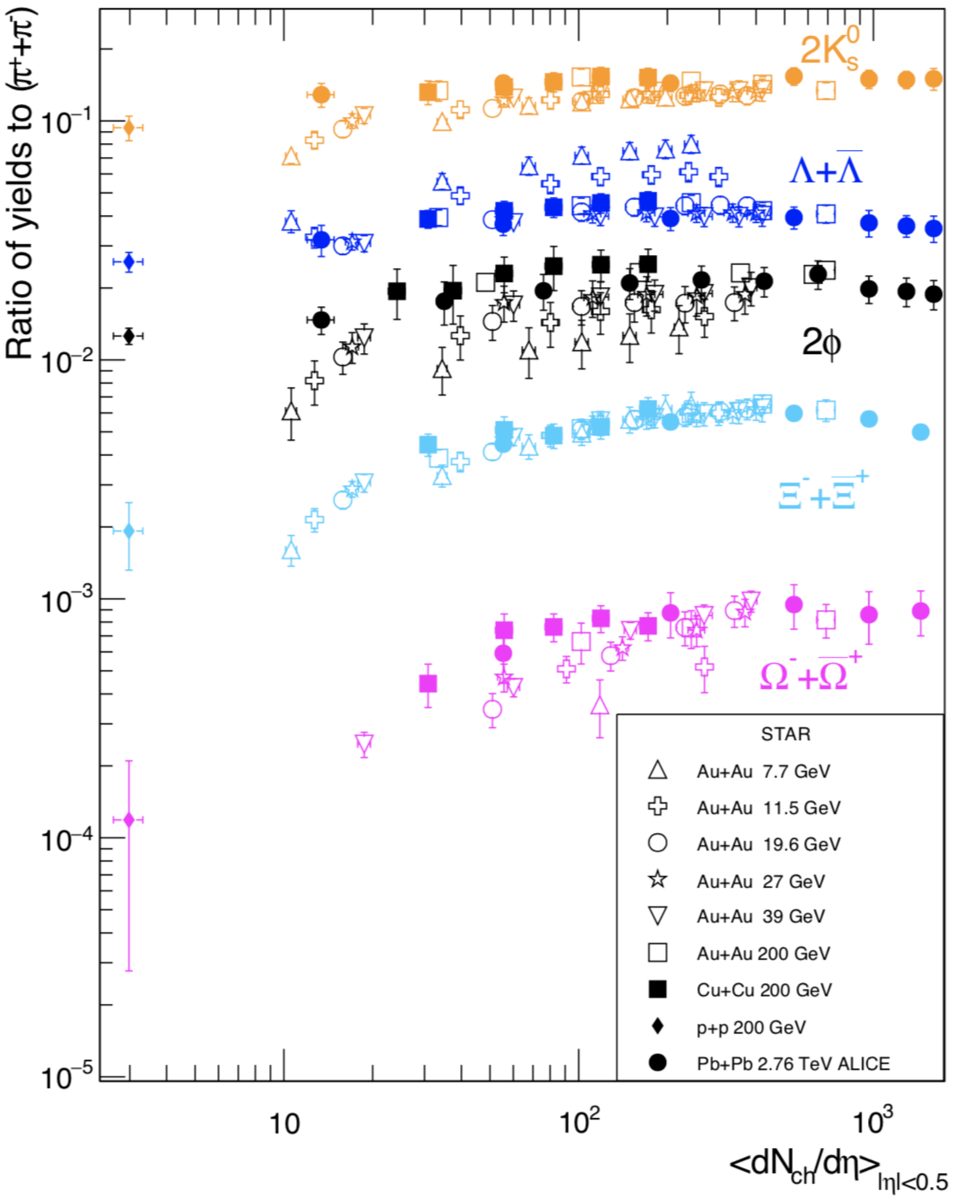


STAR，PRC 96, 044904, 2017



- Particle ratios consistent with the picture of a **maximum net-baryon density around $\sqrt{s_{NN}}$ ~ 8 GeV at freeze-out**

BES-I strange hadron to pion ratios vs $dN_{ch}/d\eta$



STAR, PRC96, 044904, 2017
STAR, PRC102, 034909, 2020
ALICE, PRC88, 044910, 2013

Y. Huang, SQM2021

$$\frac{dn}{dy} = \frac{\sqrt{M(1+\sinh^2 y)}}{\sqrt{1+M\sinh^2 y}}\frac{dn}{d\eta},$$

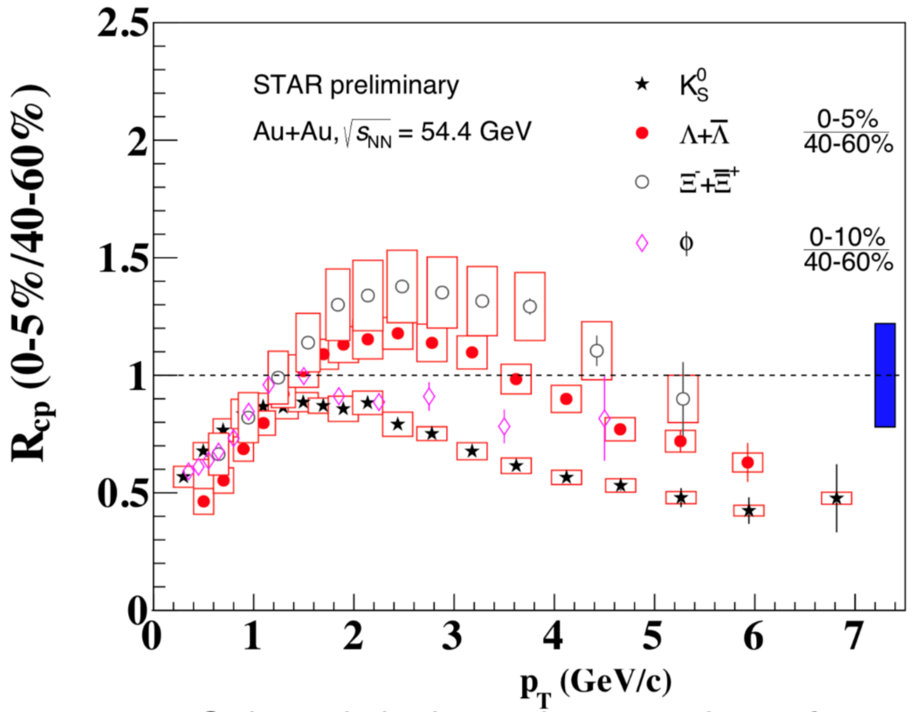
where $M = 1 + m^2/p_t^2$

$$dN_{ch}/d\eta = \sum dN_{ch}/d\eta\,(k^{\pm},\pi^{\pm},p,\bar{p})$$

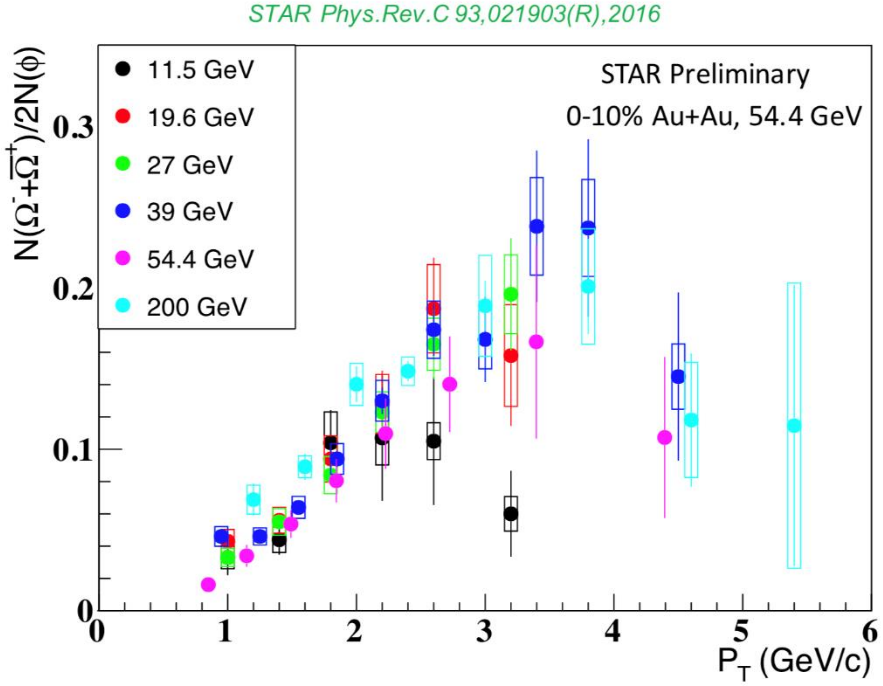
$$dN_{ch}/d\eta(\eta=0) \sim dN_{ch}/d\eta(|\eta|<0.5)$$

- The ratios at different energies, centralities, and systems mainly depend on charged hadrons multiplicity, except for Λ and ϕ
- The ratios saturate at large charged hadrons multiplicity

Strangeness production at 54.4 GeV



Only statistical error bars are shown for ϕ

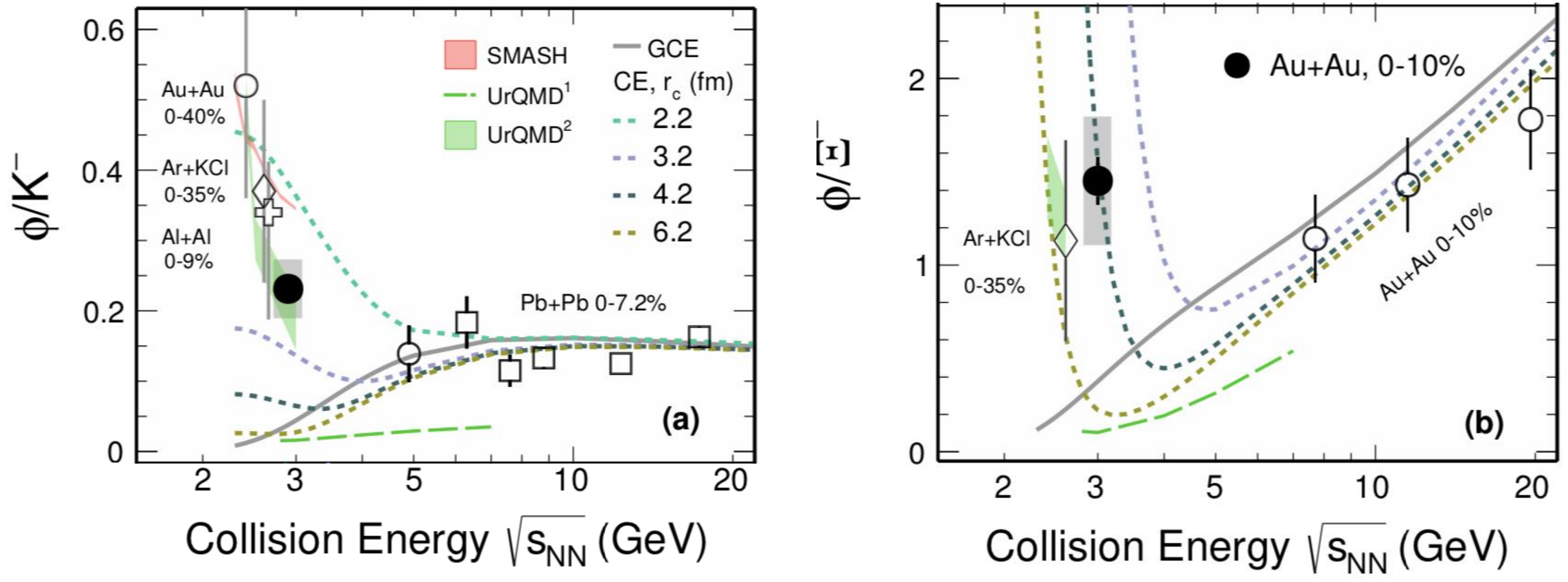


Y. Huang, SQM2021

- R_{CP} suppression at high p_T : parton energy loss
- R_{CP} separation between baryons and mesons at intermediate p_T : strange hadrons are from coalescence hadronization
- Ω/ϕ ratio enhancement at intermediate p_T : Ω, ϕ formation through strange quark recombination

ϕ and Ξ production at 3 GeV (FXT)

- Low energies and/or small systems: local strangeness conservation
- Canonical instead of grand canonical ensemble (GCE) describes statistical production



STAR, arXiv: 2108.00924

$\phi(s\bar{s}),\ S = 0$

$K^-(s\bar{u}),\ S = -1$

$\Xi^-(dss),\ S = -2$

Statistical models:
A. Andronic et al, Nucl. Phys. A 772, 167;
J. Cleymans et al, Phys. Lett. B 603, 146

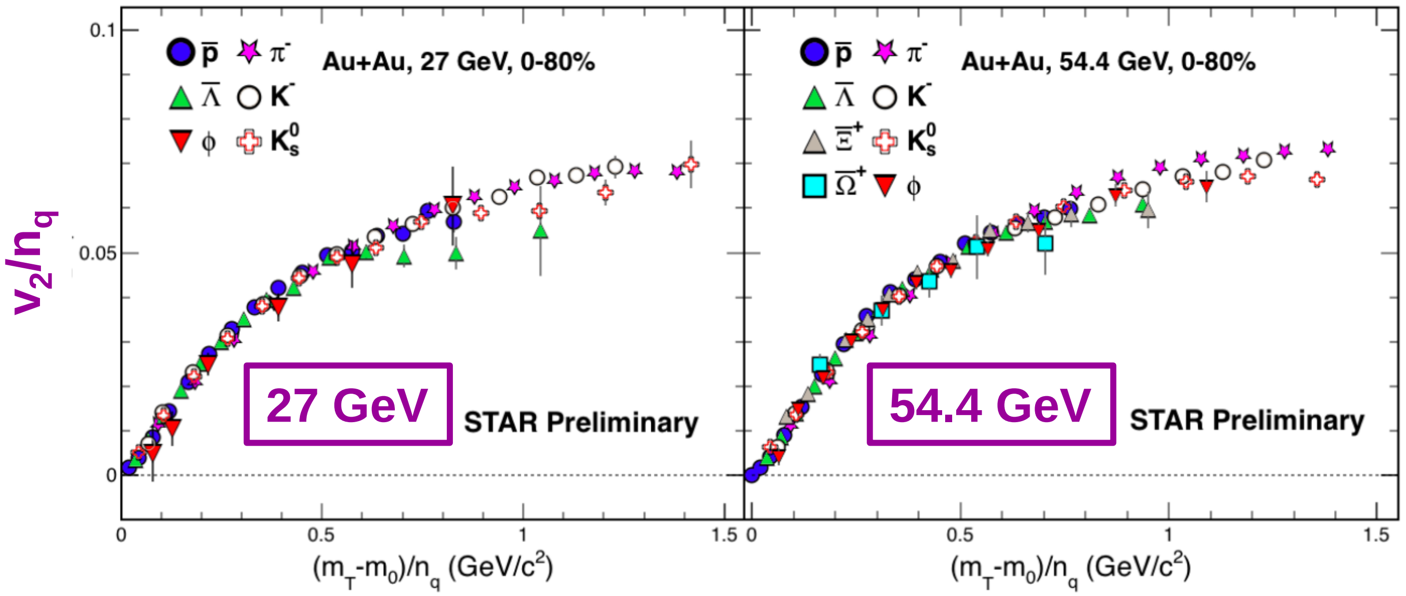
Yingjie Zhou's talk

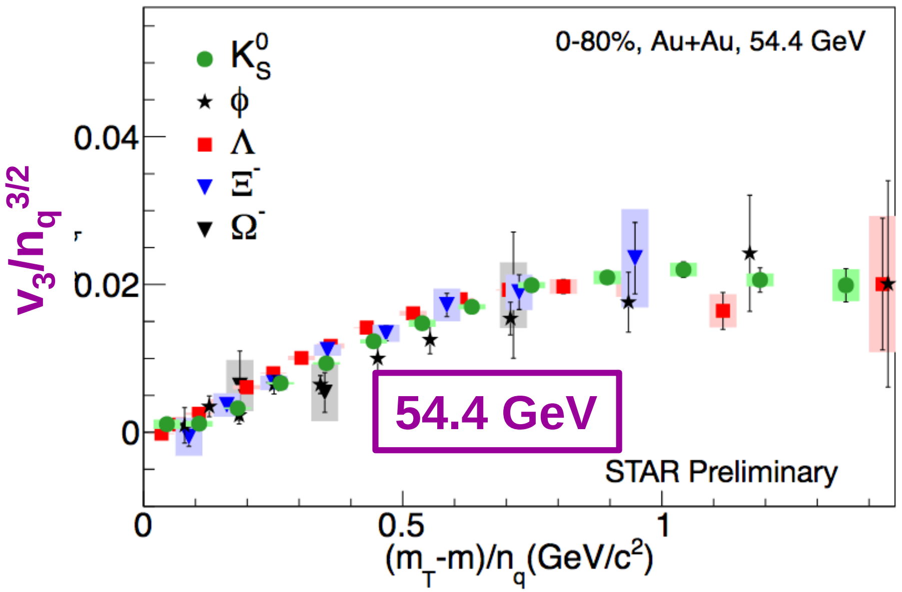
- ϕ/K^- and ϕ/Ξ^- measurements at 3 GeV strongly disfavor GCE

Strange hadron flow at 54.4 and 27 GeV

- Strange hadrons: Small hadronic cross-section. Partonic vs hadronic contribution to flow

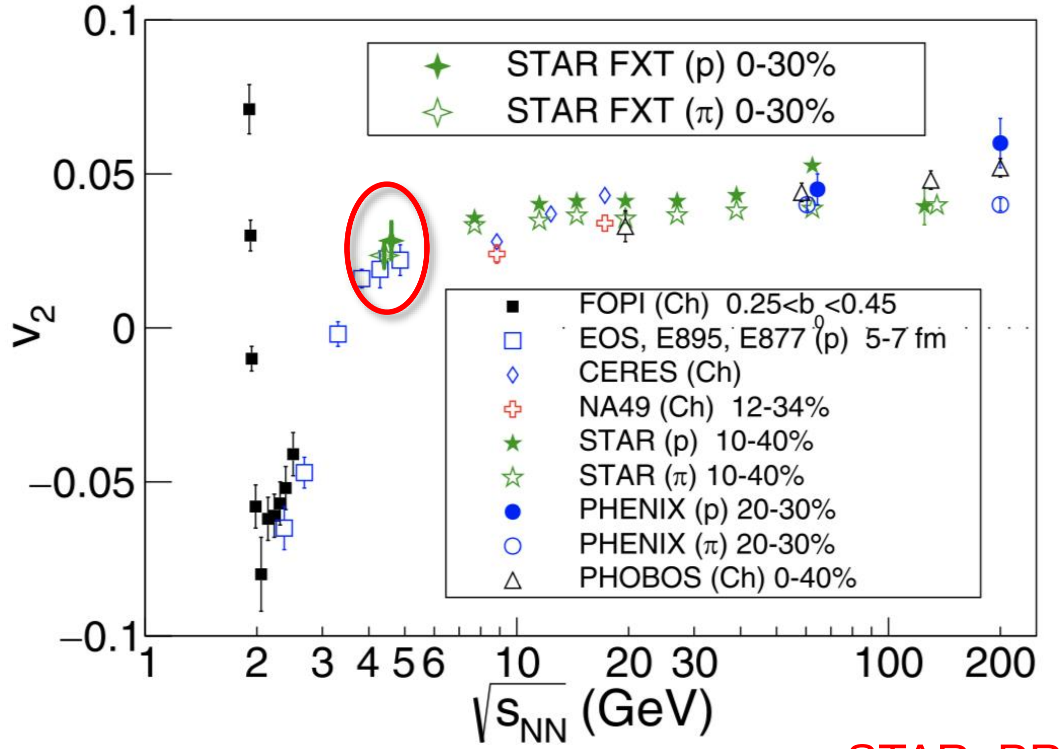
Shusu Shi's talk tomorrow morning

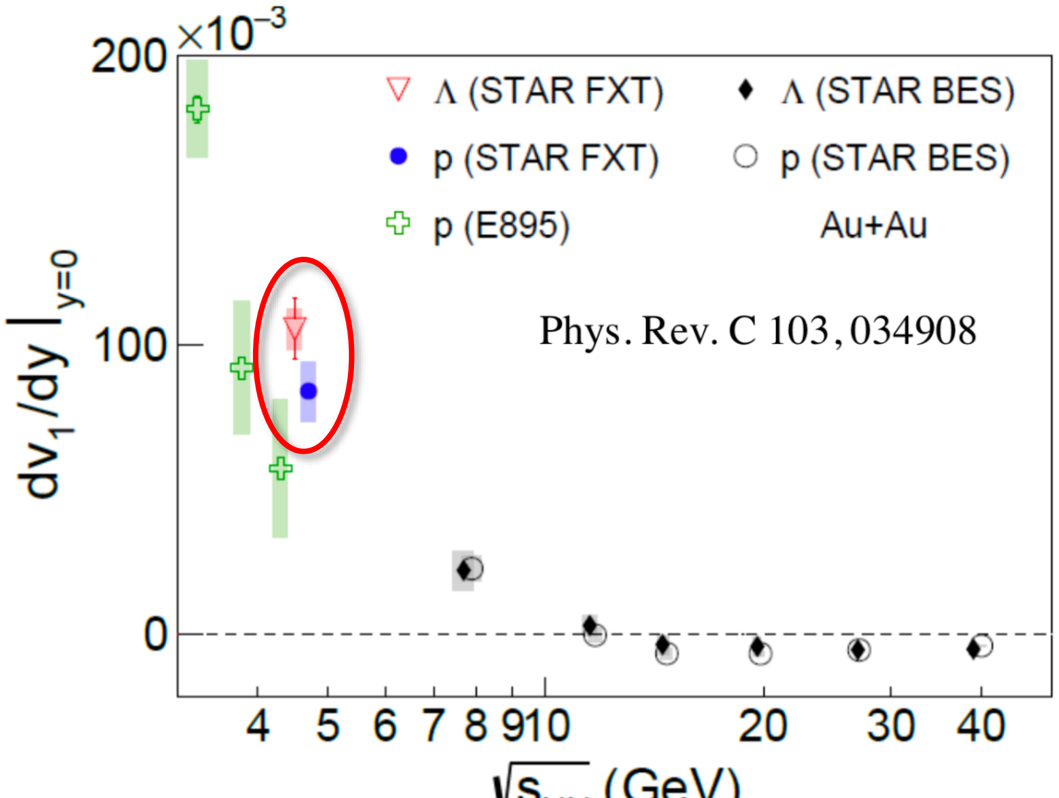




- NCQ scaling holds for strange hadrons at 54.4 and 27 GeV: dominance of partonic collectivity

Collective flow in Au+Au $\sqrt{s_{NN}}$=4.5 GeV (FXT)



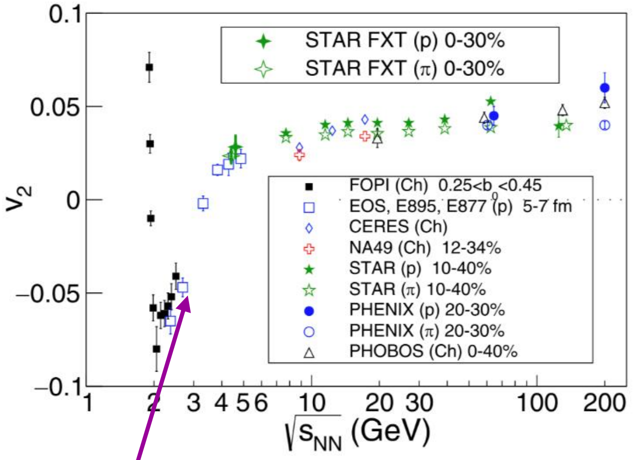


STAR, PRC103, 034908, 2021

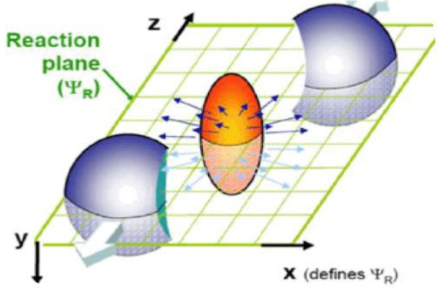
- First STAR FXT paper based on the 2015 FXT test run (1.3 M events taken within half an hour)
- Flow results consistent with world data within uncertainties

Collectivity at 3 GeV (FXT)

STAR, PRC103, 034908, 2021

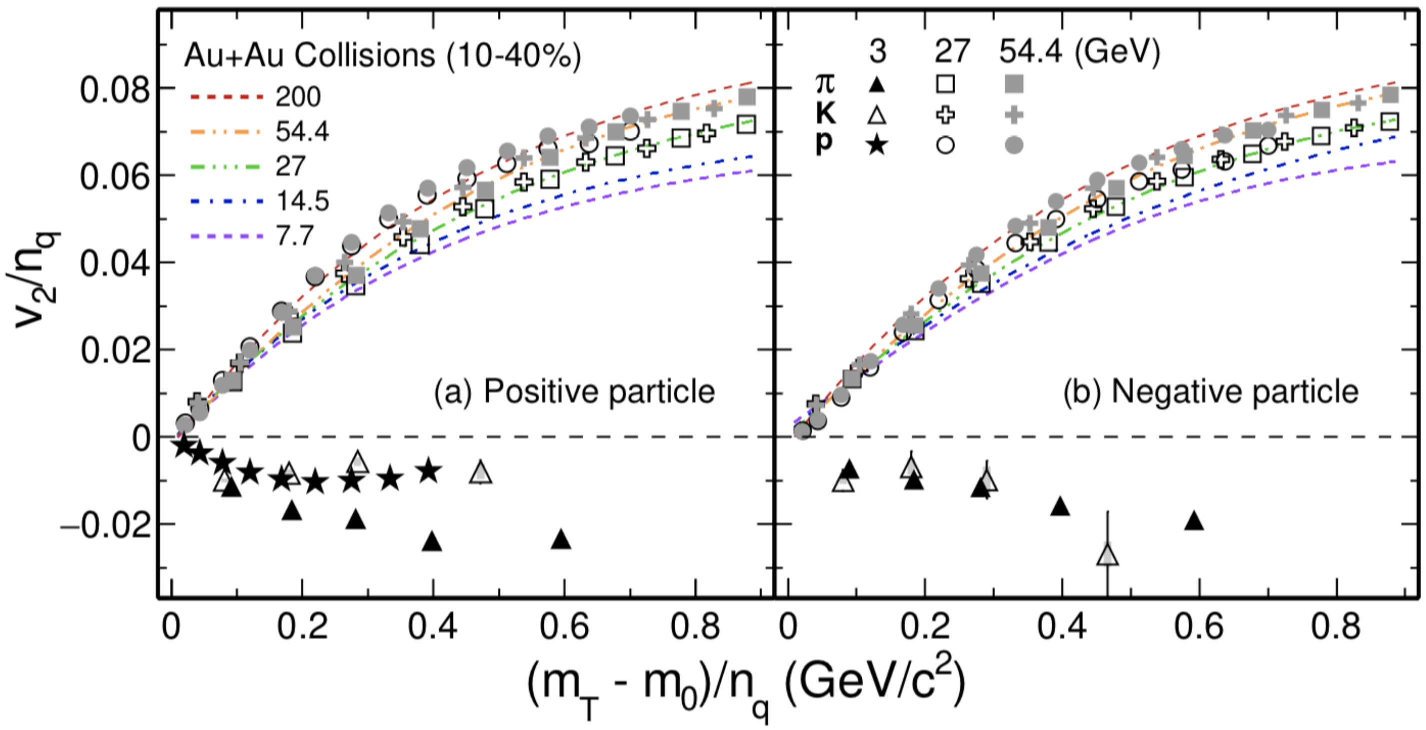


"squeeze-out" (v_2<0) at 3 GeV



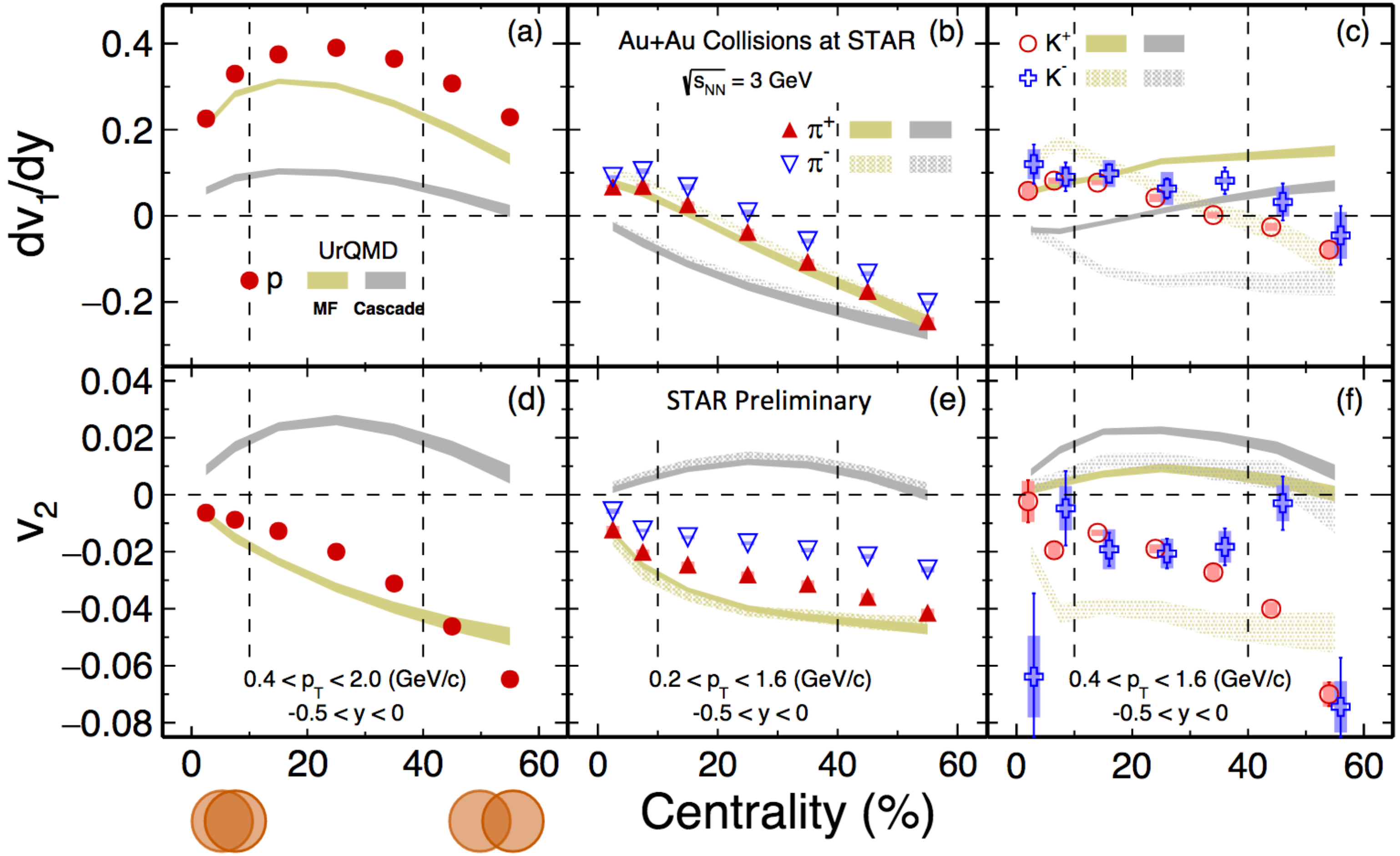
STAR, arXiv: 2108.00908

Shusu Shi's talk tomorrow morning



- NCQ scaling holds for energies from 200 down to 7.7 GeV collisions: partonic collectivity
- v_2 values are negative and NCQ scaling breaks down at 3 GeV: medium less dominated by partonic interactions

Collectivity at 3 GeV (FXT)



proton

pion

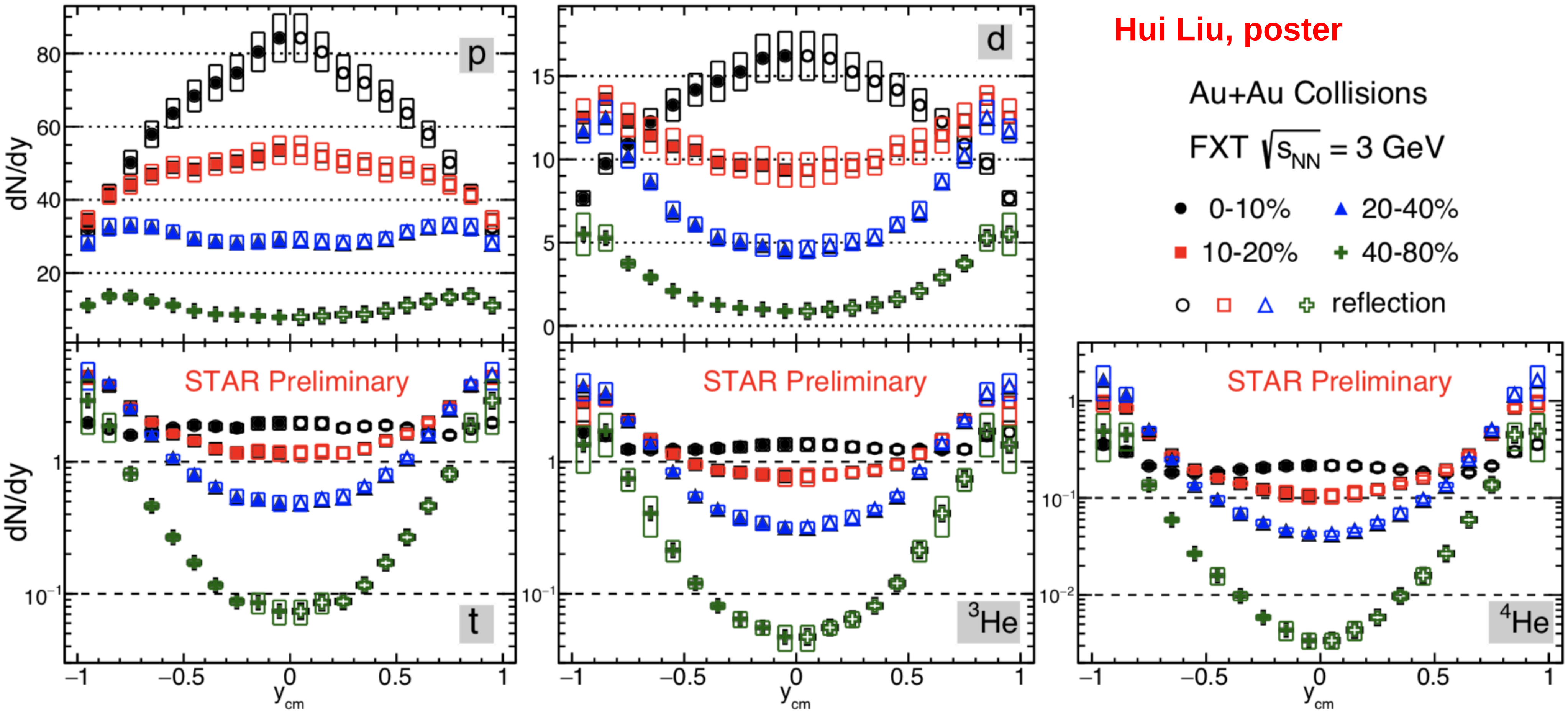
kaon

Shusu Shi's talk tomorrow morning

- UrQMD cascade mode fails to describe data
- Need baryonic mean field interactions to generate trends seen in data

Medium dominated by baryonic interactions and nuclear EoS

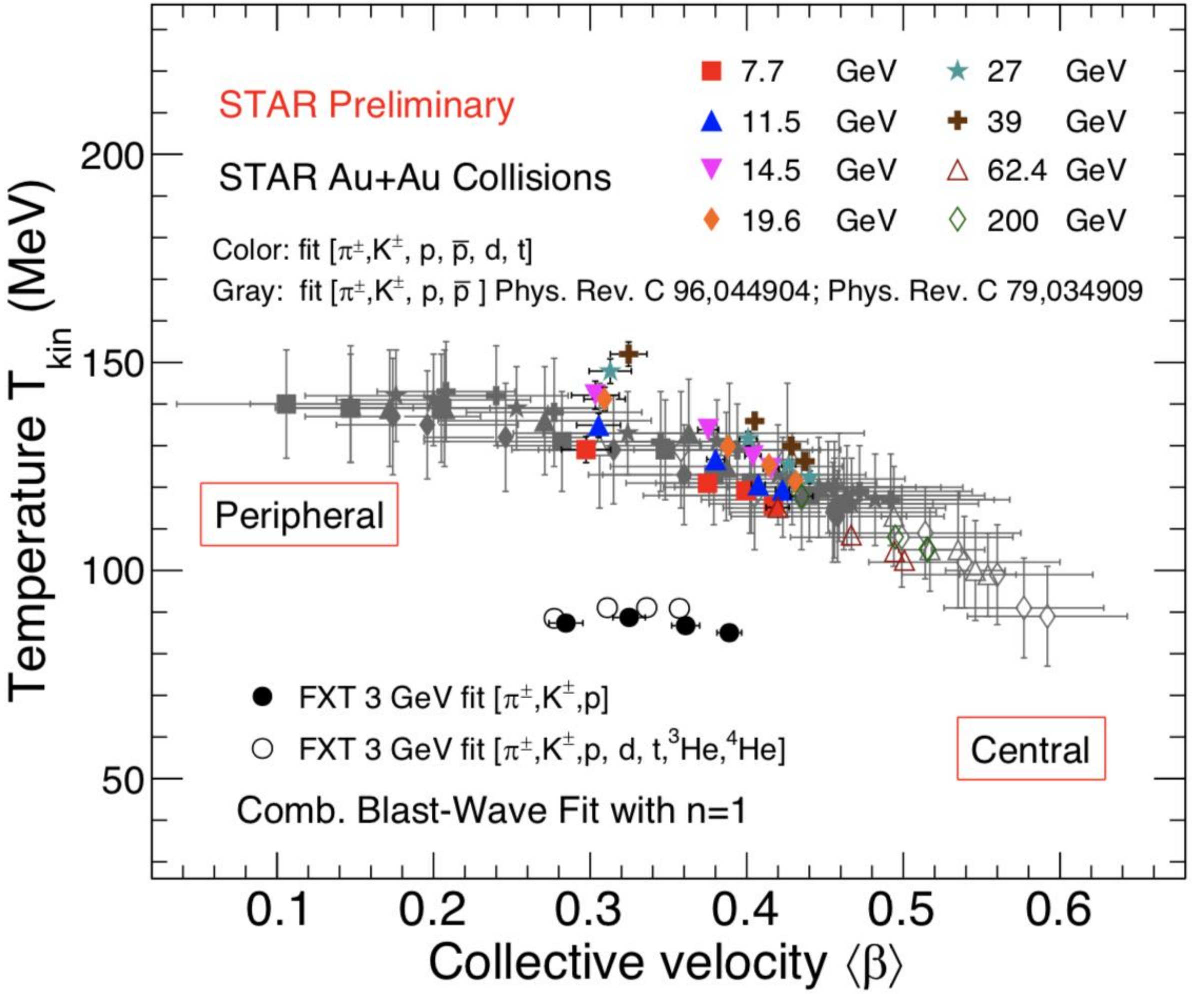
Light nuclei production at 3 GeV (FXT)



- $-1 < y_{cm} < 0$: obtained by p_T spectra; $0 < y_{cm} < 1$: reflection by measured range
- Systematic uncertainties are evaluated by various track cuts and different fit functions
- dN/dy of particles shows strong rapidity and centrality dependence

Light nuclei production at 3 GeV (FXT)

Hui Liu, poster



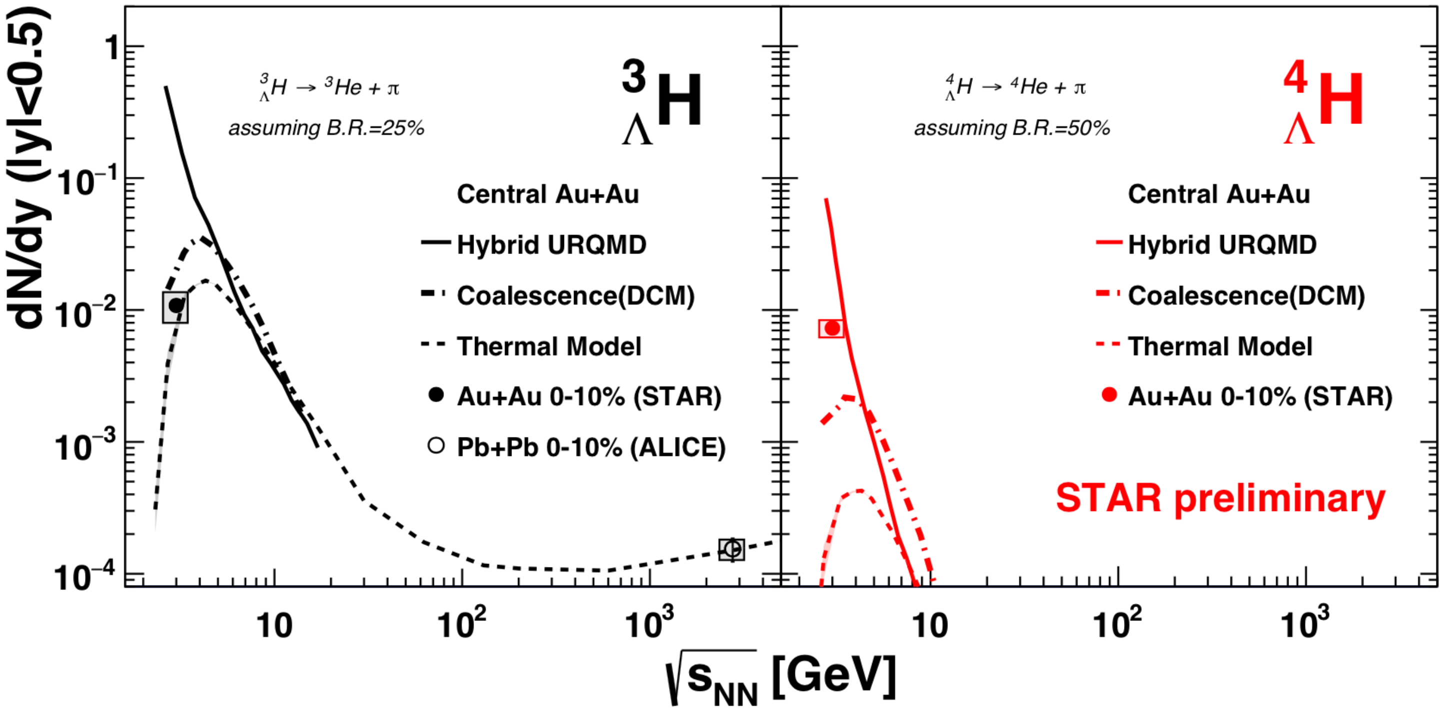
- Choose pion, kaon, inclusive proton, deuteron and triton for combined blast-wave fit at BES-I
- T_{kin} shows a stronger energy dependence from 7.7 to 39 GeV when light nuclei are considered into combined fit, especially in peripheral collisions
- FXT 3 GeV shows different trend compared to BES-I Au+Au collisions, indicate a different medium equation of state (EoS) at 3 GeV

Phys. Rev. C 96 (2017) 44904

Phys. Rev. C 79 (2009) 34909

Hypernuclei production at 3 GeV (FXT)

- Lifetime, yield, flow of hypernuclei: important to understand Y-N interactions and hyperon contribution to nuclear EoS



Models: J. Steinheimer et al, Phys. Lett. B. 714,85; A. Andronic et al, Phys. Lett. B 697, 203 (Private communincations)
ALICE: Phys. Lett. B 754, 360

$^{3}_{\Lambda}\mathrm{H}: \tau = 232.1 \pm 29.2(\mathrm{stat}) \pm 36.7(\mathrm{syst})[\mathrm{ps}]$

$^{4}_{\Lambda}\mathrm{H}: \tau = 218.3 \pm 7.5(\mathrm{stat}) \pm 11.8(\mathrm{syst})[\mathrm{ps}]$

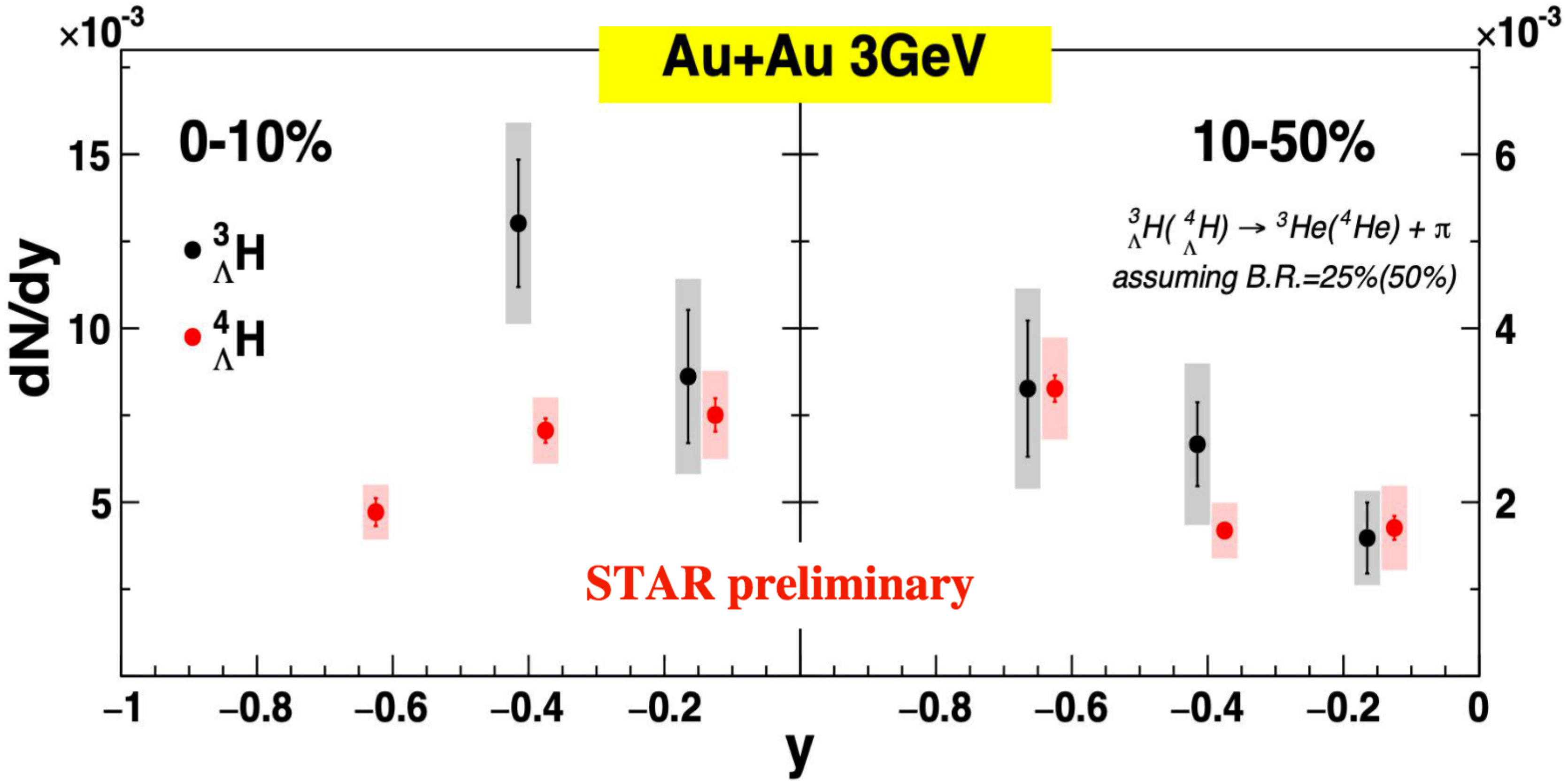
- $^{4}_{\Lambda}$H lifetime measurement most precise to date !

Xiujun Li, poster

- Thermal (with canonical ensemble) and coalescence model calculations describe $^{3}_{\Lambda}$H yields, but lower than $^{4}_{\Lambda}$H yield

C. Hu, SQM2021

Hypernuclei production: rapidity dependence

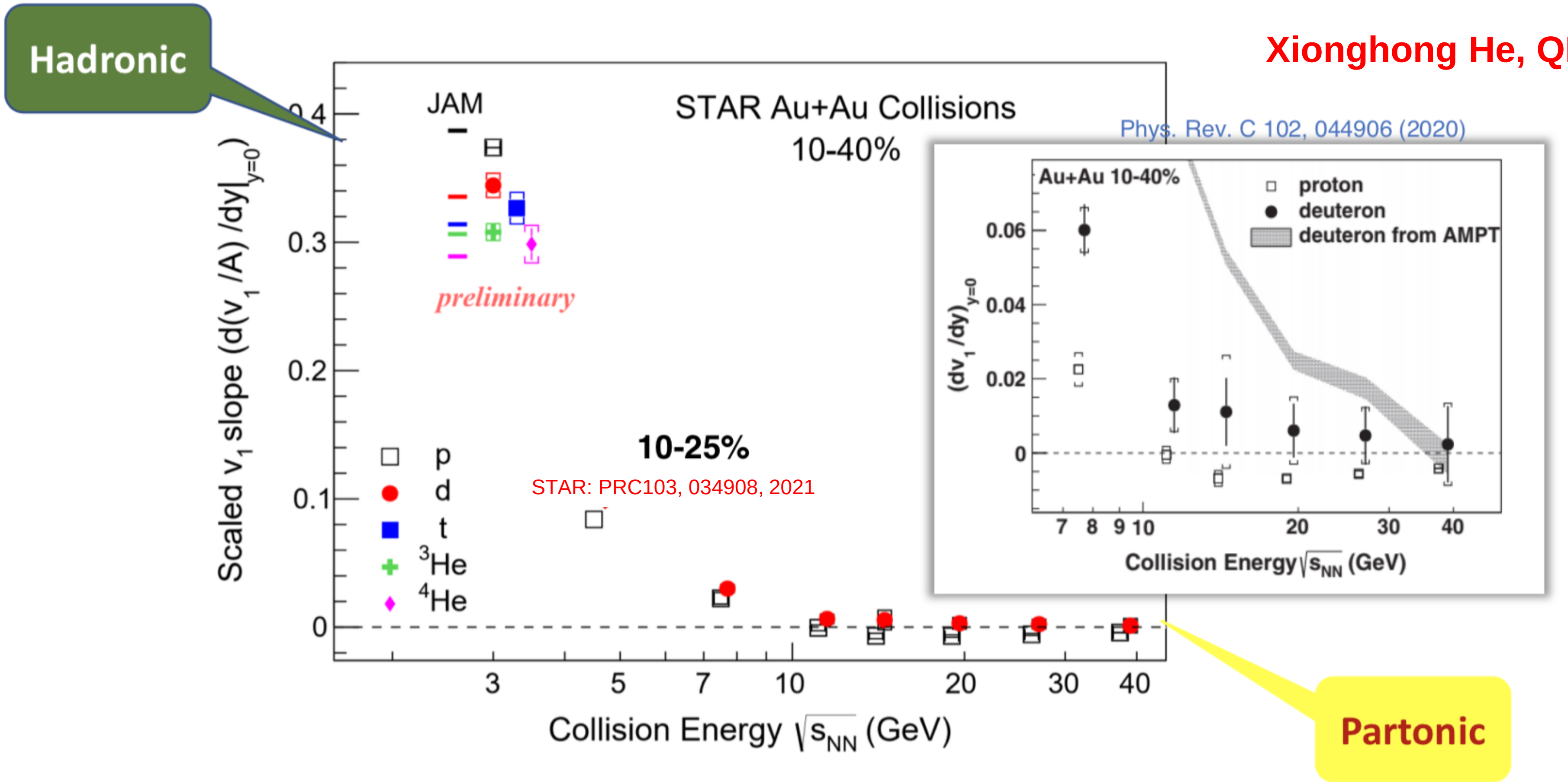


- Difference in rapidity distribution for $^4_\Lambda$H between central and mid-central collisions
- Could be contributions from spectator reactions in $^4_\Lambda$H production in non-central collisions

C. Hu, SQM2021

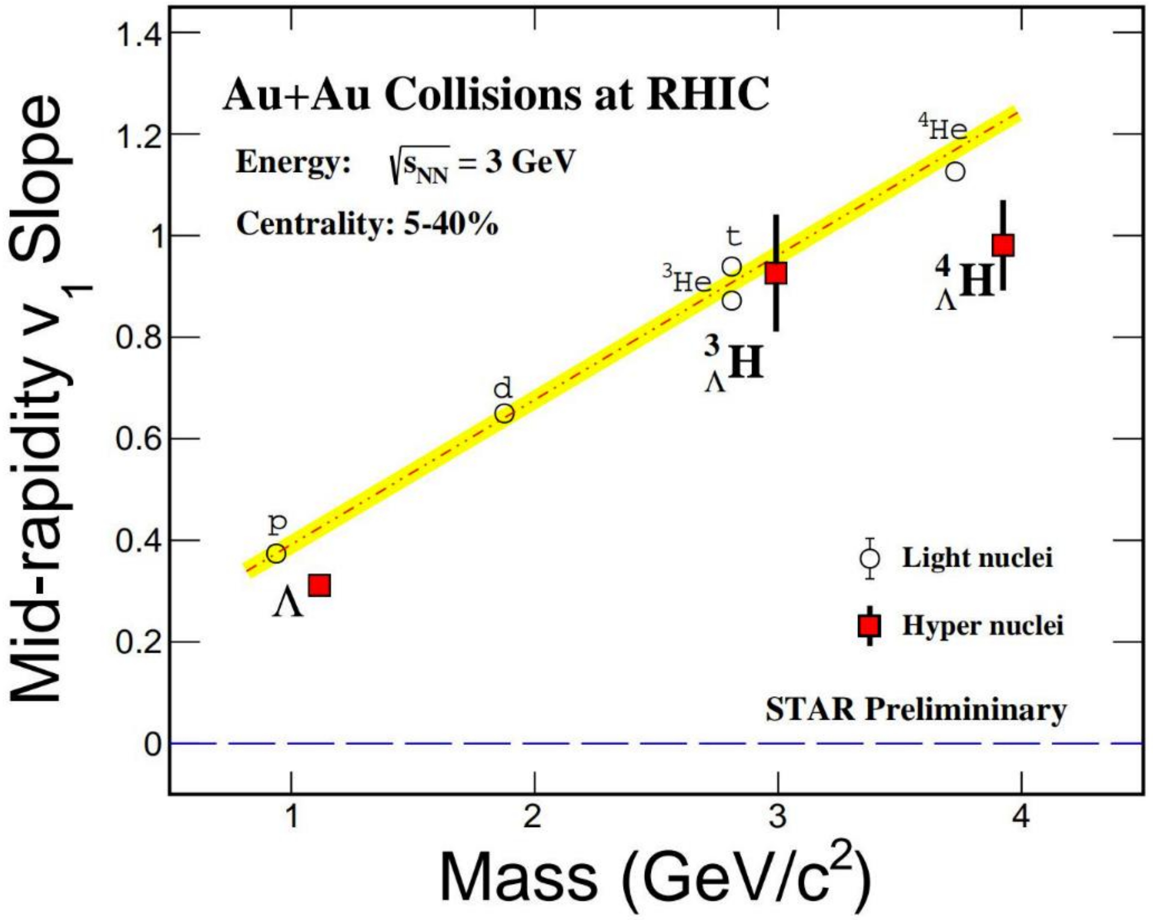
Light nuclei directed flow at 3 GeV (FXT)

Xionghong He, QPT2021



- Hadronic model JAM reproduces light nuclei v_1 at 3 GeV
- Different scaling behavior at low and high collision energies → change of dominant interactions

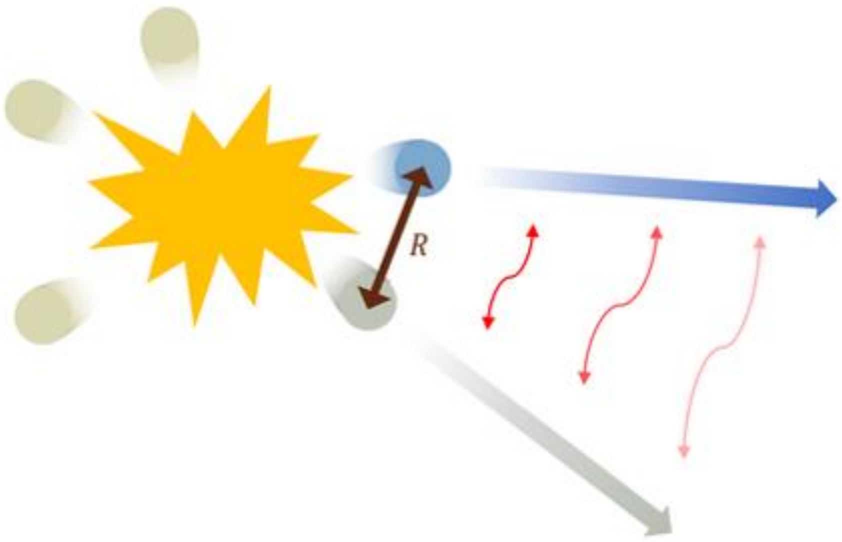
Hypernuclei directed flow at 3 GeV (FXT)



Chenlu Hu, QPT2021

- Directed flow of hypernuclei suggests mass number scaling
- Indicates a coalescence production of hypernuclei

Femtoscopy: short-range correlation



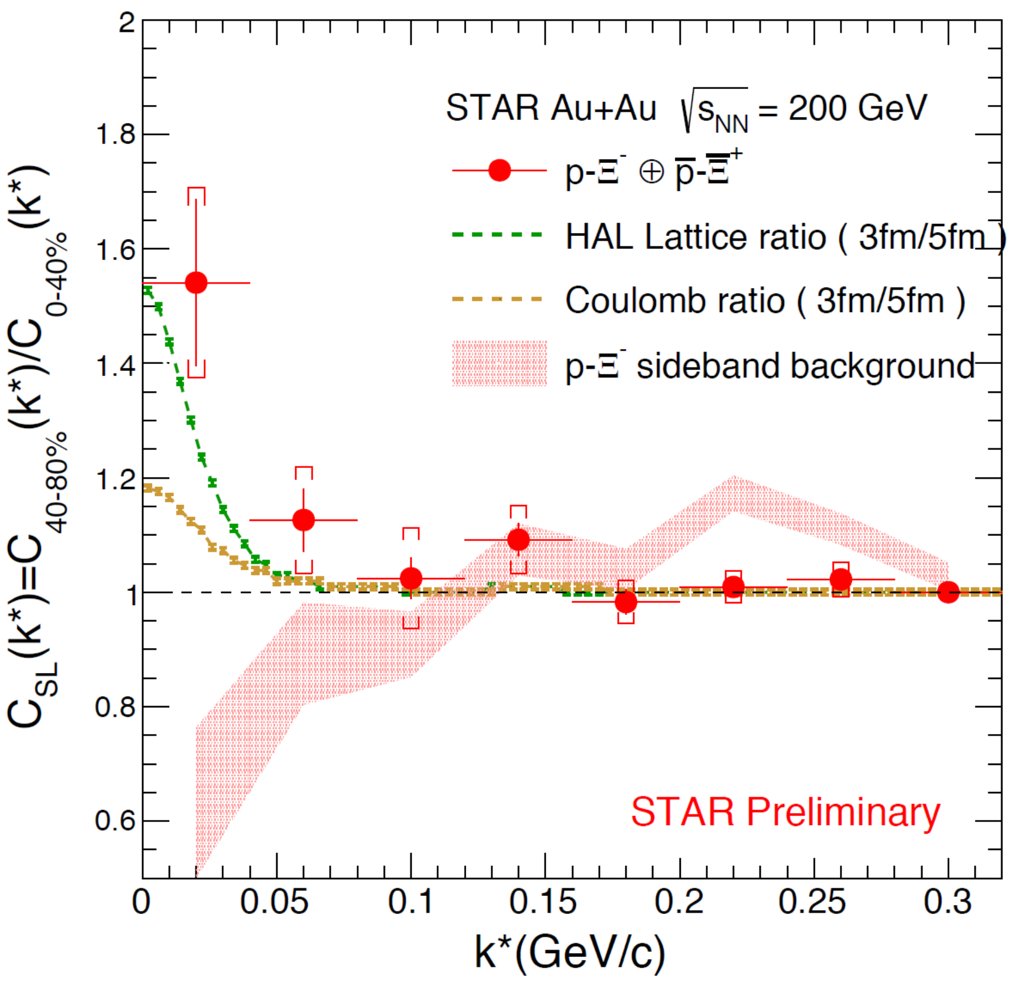
- Study the spatial and temporal extent of the emission source
  - Quantum statistics; final-state interactions
- Y-Y and Y-N interactions are essential inputs for understanding EoS of neutron stars
- Observable: two-particle correlation

$$C(q) = \frac{A(q)}{B(q)}$$

q – relative momentum between two particles
$A(q)$ – signal correlation from same events
$B(q)$ – background correlation from mixed events

200 GeV Au+Au: *p*-Ξ^- Correlation

Ke Mi's talk on Monday

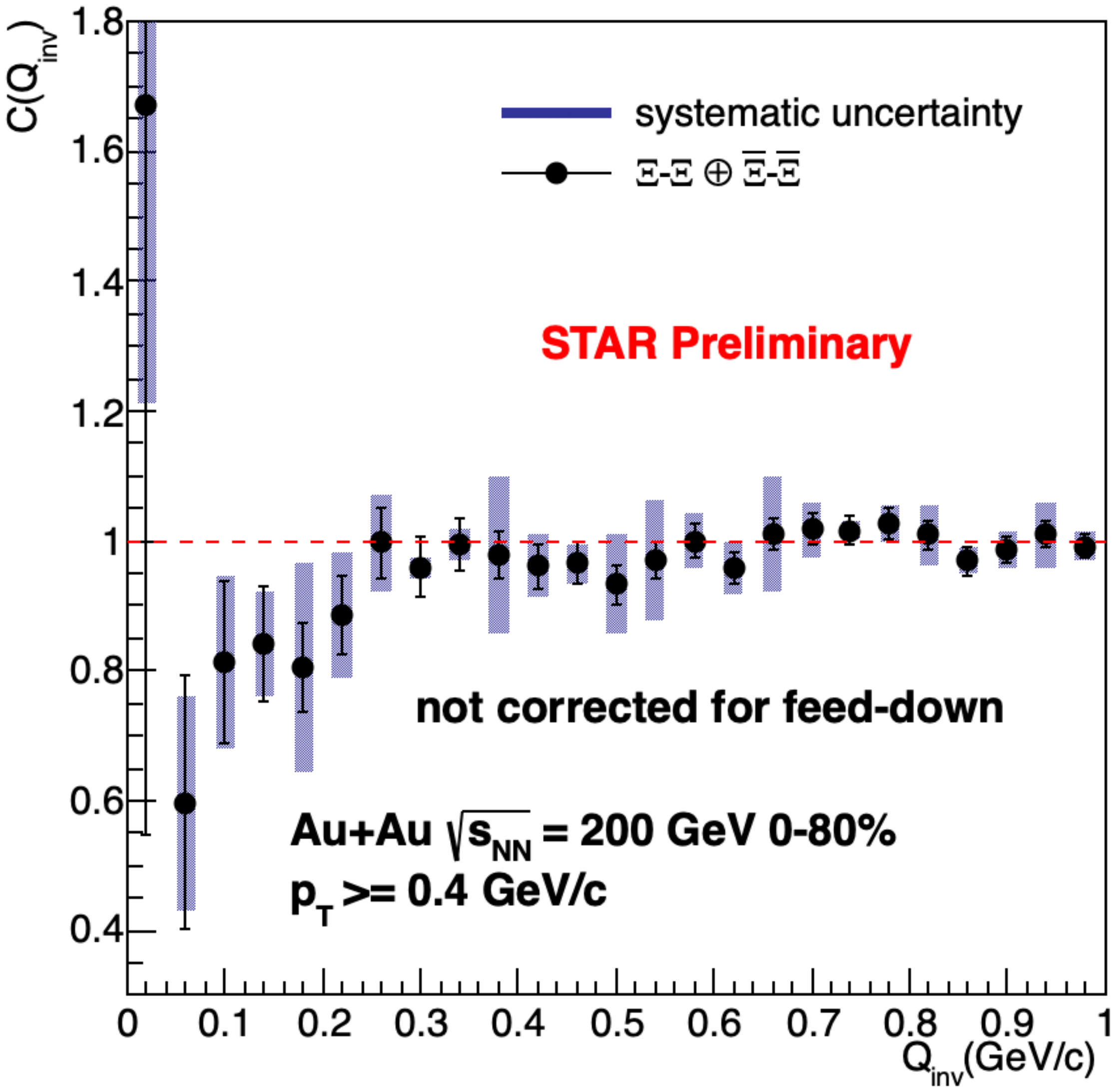


$$C_{SL}(k^*) = \frac{C(k^*)_{40-80\%}}{C(k^*)_{0-40\%}}$$

- *First measurement of p-Ξ⁻ correlation in Au+Au*
- Stronger correlation in peripheral than central collisions (system size)
- Peripheral/central: attractive strong interaction at k* < 0.1 GeV/c beyond Coulomb interaction and background
- Consistent with lattice-QCD calculation

K. Morita, et al., PRC 94 (2016) 031901
T. Hatsuda, NPA 967 (2017) 856

200 GeV Au+Au: Ξ-Ξ correlation

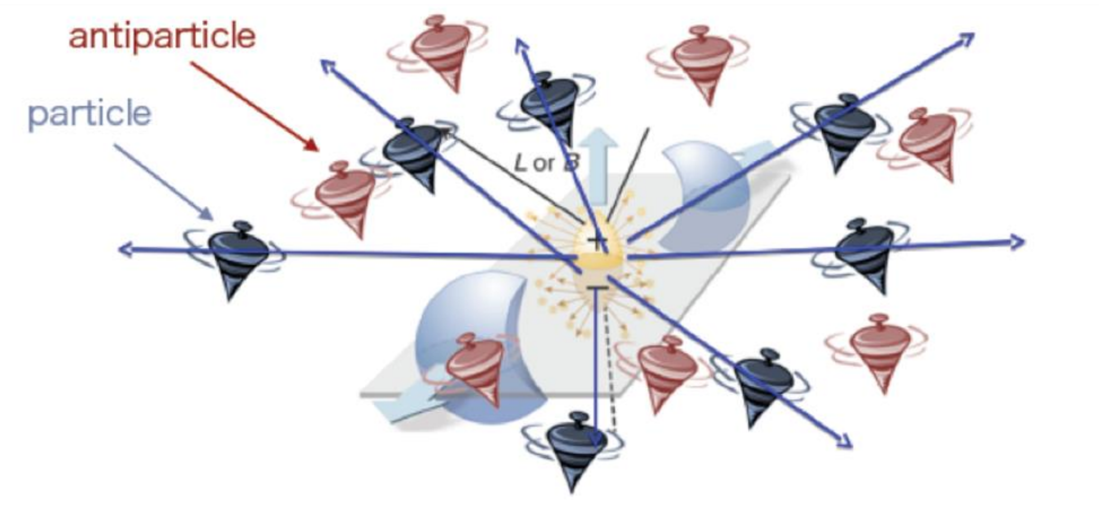


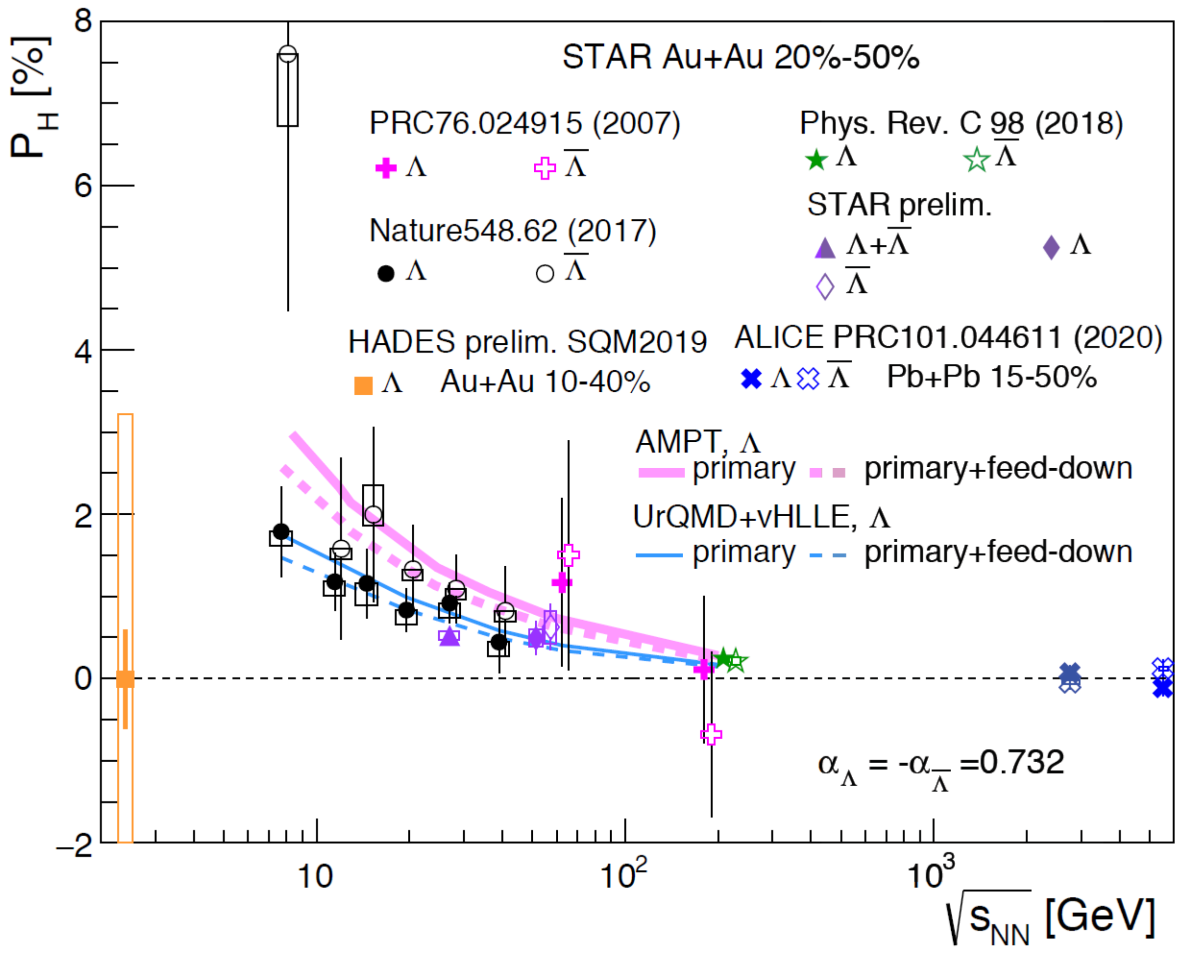
- *First measurement of Ξ-Ξ correlation in Au+Au collisions*
- Indication of negative correlation at small Q_{inv}
- Need to understand feed-down contribution and Coulomb effect

→ More statistics in 2023+25

M. Isshiki, SQM2021

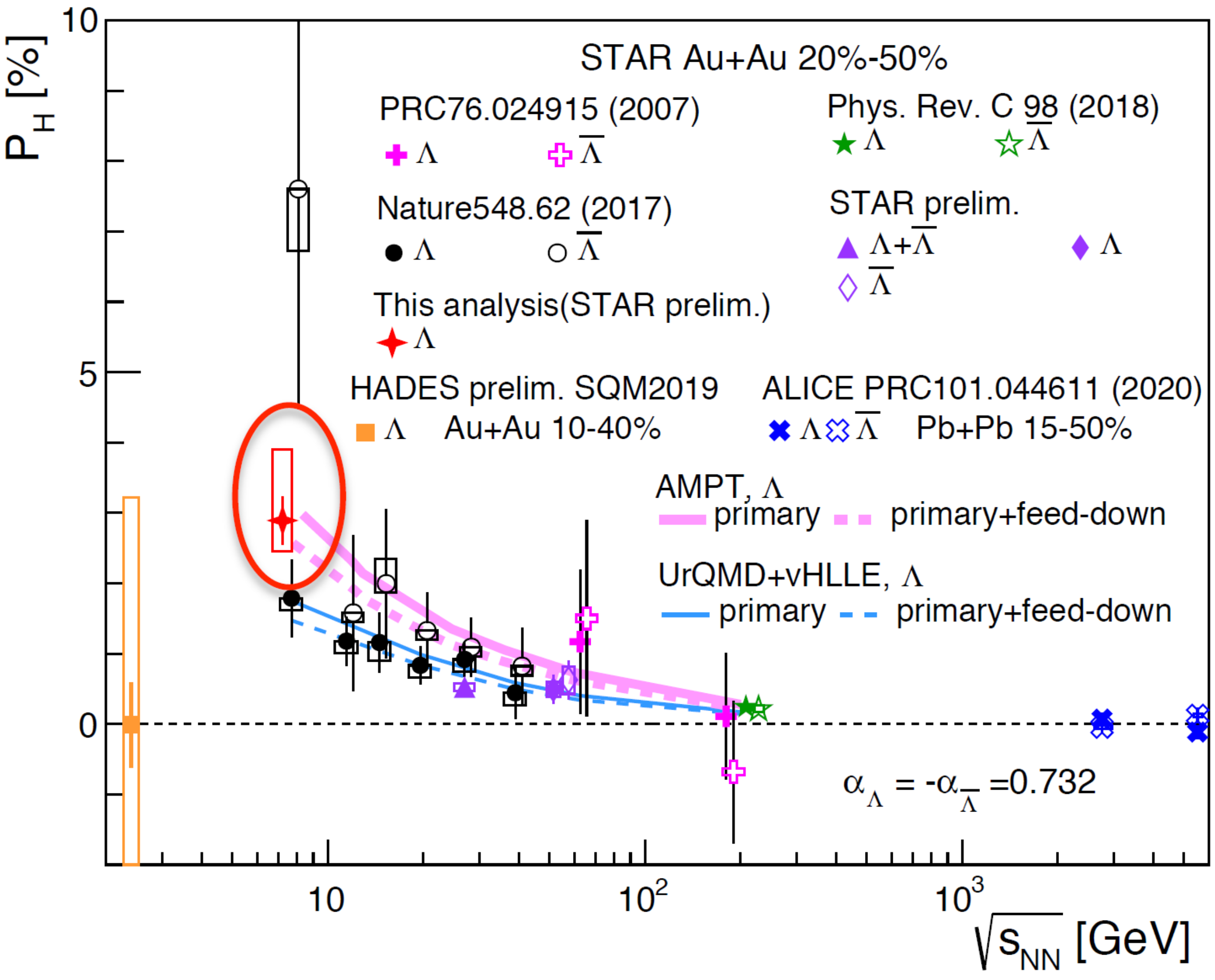
Λ global polarization





- **Magnetic field →** Λ and anti-Λ align in opposite directions
- **Fluid vorticity →** Λ and anti-Λ align in same direction

Λ P_H at 7.2 GeV Au+Au (FXT)

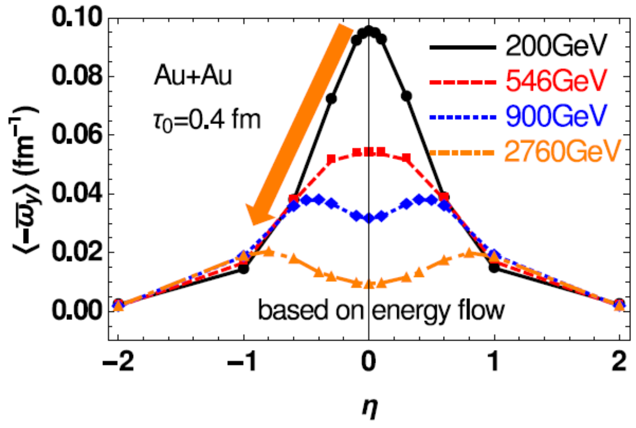


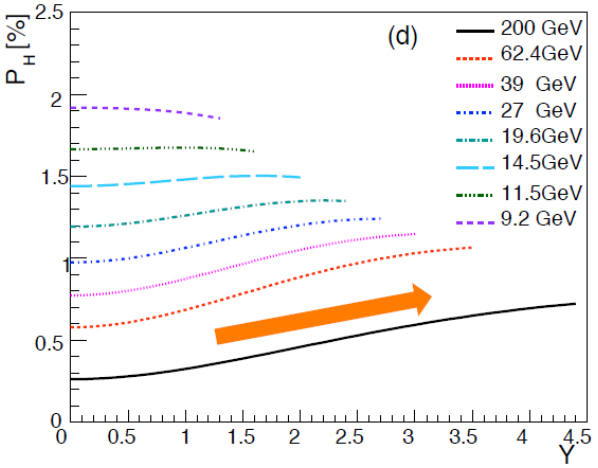
- *First measurement at $\sqrt{s_{NN}}$ = 7.2 GeV Au+Au (FXT)*
- Positive polarization for Λ
  - $0.6 < y+|y_{beam}| < 1.8$
- Follow the world data trend
  - Increasing polarization with decreasing collision energy

K. Okubo, SQM2021

Rapidity dependence of Λ P_H

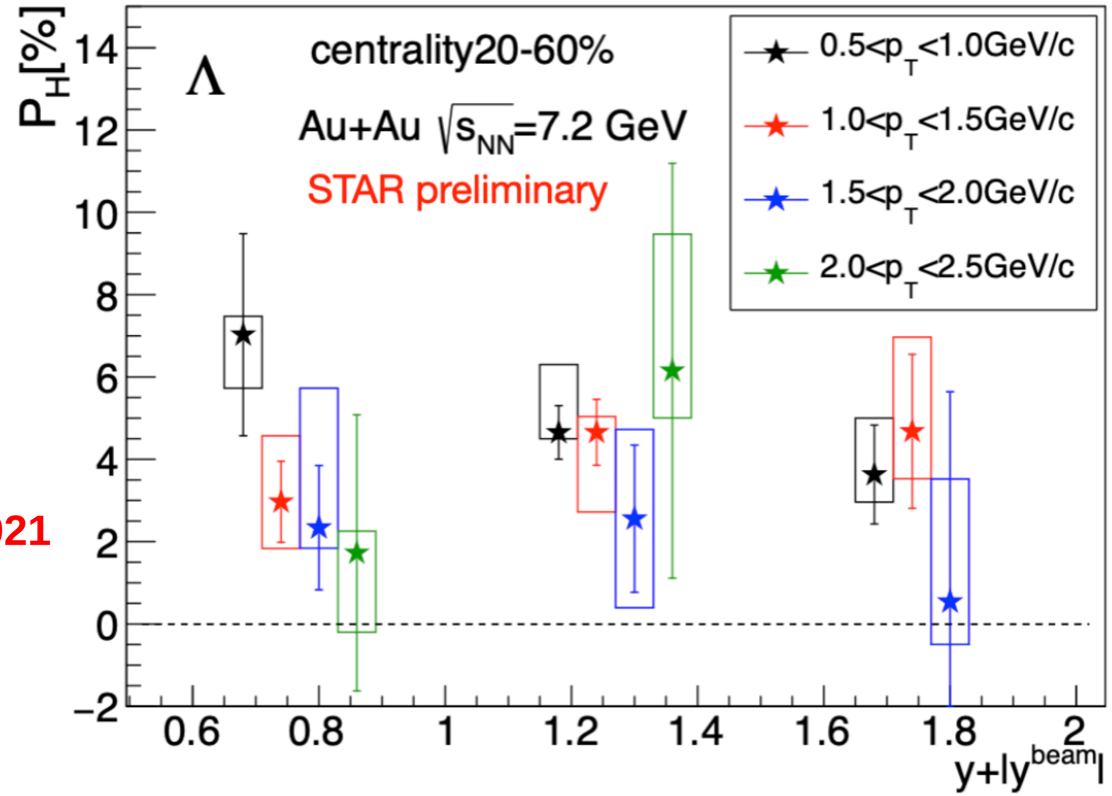
W-T Deng, X-G Huang, PRC 93 (2016) 064907





Z-T Liang, et. al, arXiv: 1912.10223

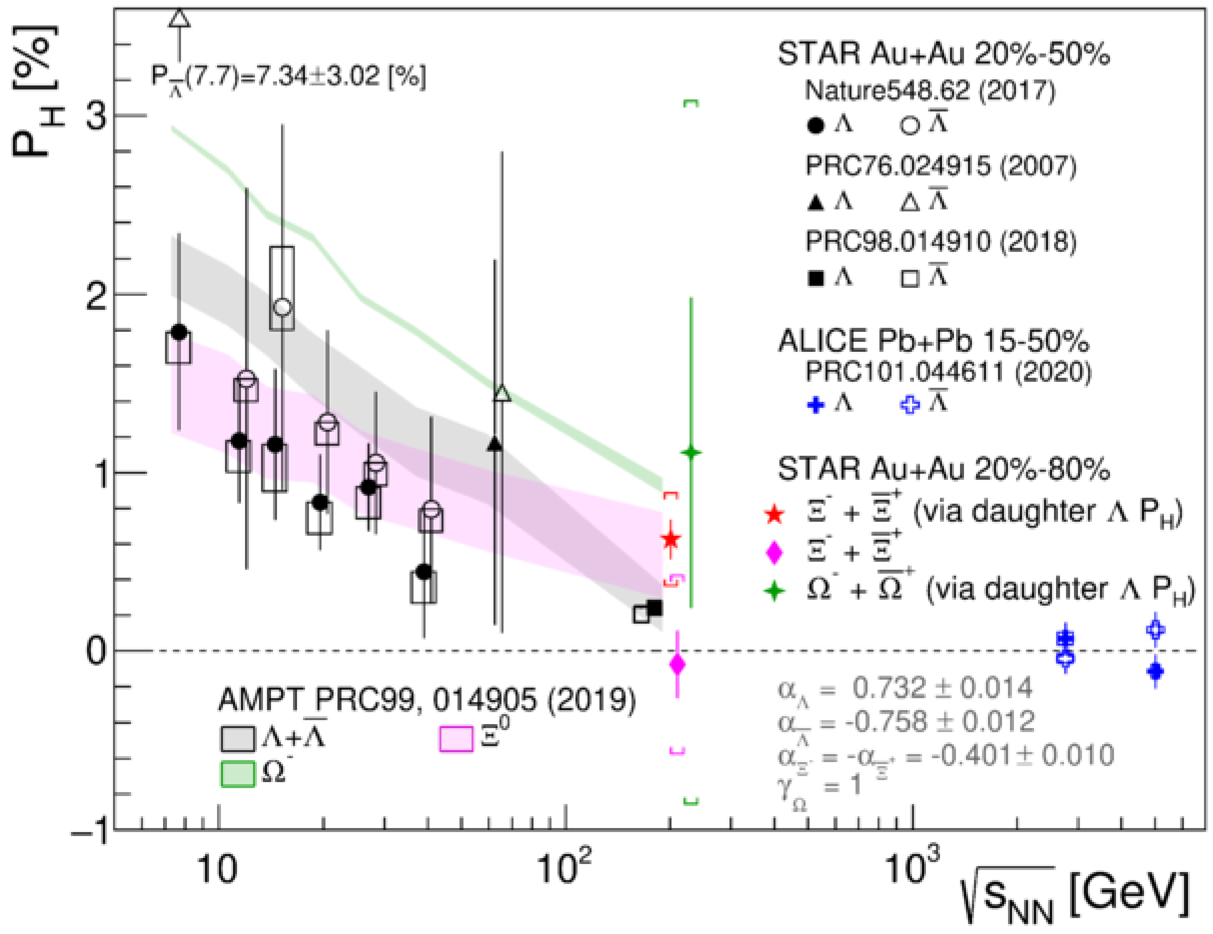
K. Okubo, SQM2021



- No significant rapidity dependence ($\Delta y \sim 1.2$) within uncertainties

→ BES-II larger rapidity coverage

Extend measurements to Ξ and Ω



STAR: PRL 126, 162301, 2021

- *First measurement of Ξ and Ω global polarization* in 200 GeV Au+Au collisions
  - ➢ Important addition to Λ results
- Within 20-80%, |y| < 1, p_T > 0.5 GeV/c
  - ➢ $\langle P_\Lambda \rangle$ (%) = 0.24 ± 0.03(stat) ± 0.03(syst)
  - ➢ $\langle P_\Xi \rangle$ (%) = 0.47 ± 0.10(stat) ± 0.23(syst)
  - ➢ $\langle P_\Omega \rangle$ (%) = 1.11 ± 0.87(stat) ± 1.97(syst)
- Consistent with picture of system fluid vorticity

More statistics in 2023+25

STAR Beyond BES-II (2022+)

- The **forward upgrade** includes **Trackers** (silicon microstrip tracker & **small-strip Thin Gap Chamber**) and **Calorimeters (ECAL & HCAL)** dedicated to study nuclear structure and QGP

Forward-rapidity 2.8<η<4.2

A+A

Beam:
Full Energy AuAu (2023/25)

Physics Topics:
- Temperature dependence of viscosity through flow harmonics up to η~4
- Longitudinal decorrelation up to η~4
- Global Lambda Polarization
  → strong rapidity dependence

p↑+p↑ & p↑+A

Beam:
500 GeV: p+p
200 GeV: p+p and p+A

Physics Topics:
pp:
- TMD measurements at high x
  - o transversity → tensor charge
  - o Sivers through DY, direct γ and tagged jets

pA:
- Gluon PDFs for nuclei
- R_{pA} for direct photons & DY, and hadrons
- Test of Saturation predictions through di-hadrons, γ-Jets, di-jets

→ all measurement are critical to the scientific success of EIC to test universality and factorization

Observables:
- ❑ inclusive and di-jets
- ❑ hadrons in jets
- ❑ Lambda's
- ❑ correlations mid-forward & forward-forward rapidity

Requirements from Physics:
- ❑ good e/h separation
- ❑ hadrons, photon, π^0 identification

Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

FY2022: 500 GeV polarized pp run

All other data taking in parallel to sPHENIX data taking campaign: AA, pA, pp

Chi Yang, QPT2021

Summary & outlook

Topics (partly) covered:

- Heavy flavor
- Light flavor
- Light nuclei and hypernuclei
- Two-particle correlations
- Vorticity

Topics not covered: CME/fluctuations/jet/EM probes/small system/spin…

Coming up soon: Isobar, BES-II, O+O, …

Look forward to more exciting results from STAR!