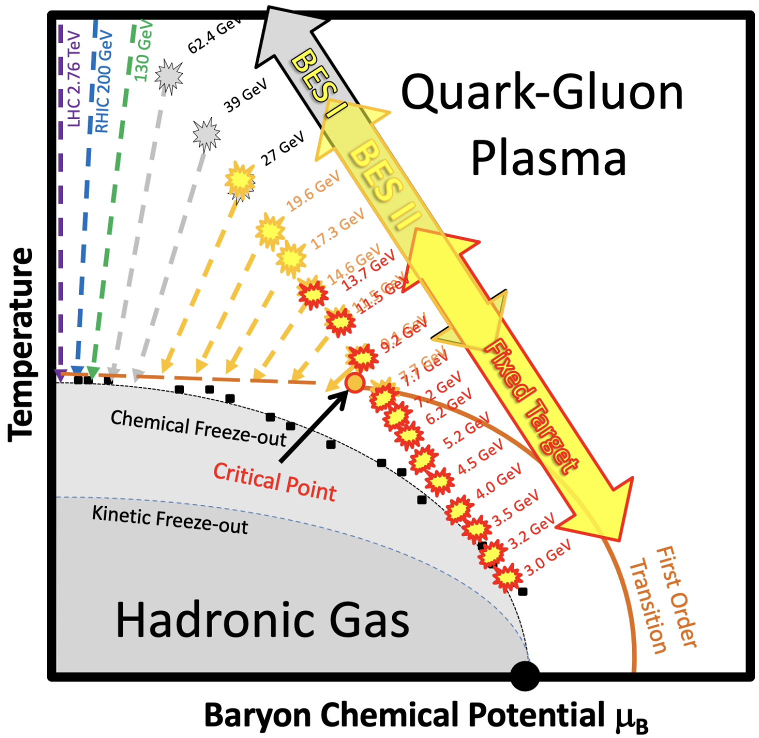
Latest Results from the STAR BES

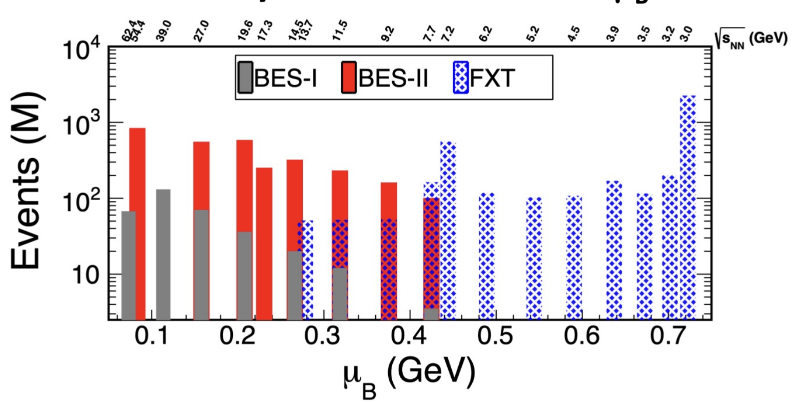
Zebo Tang

University of Science and Technology of China

XI MPD Collaboration Meeting
JINR, April 18–20, 2023

RHIC Beam Energy Scan program





BESI: 2010, 2011 and 2014

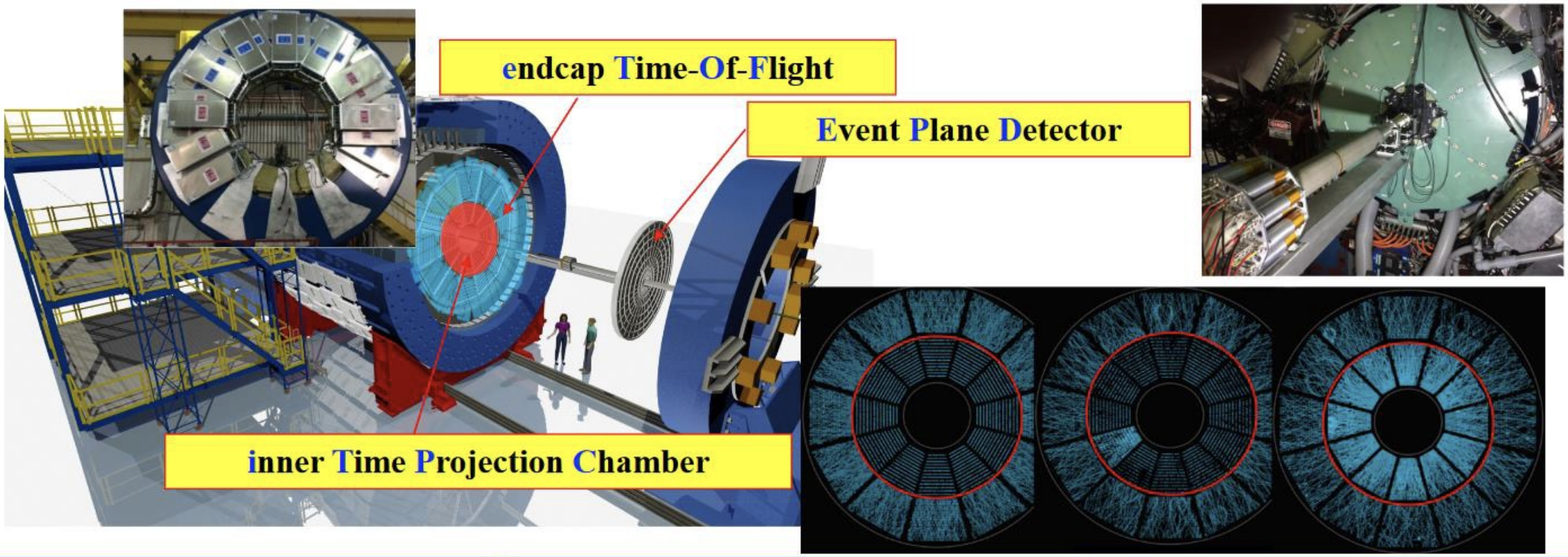
- 7.7–62.4 GeV
- First glance with low statistics
- Nonmonotonic behaviors observed

$\sqrt{s_{NN}}$ (GeV)	No. of events (million)
7.7	4
11.5	8
19.6	17.3
27	33
39	111

BESII: 2017–2021

- 3.0–54.4 GeV
- High statistics
- Upgraded detectors

Upgrades for BESII



iTPC upgrade	EPD upgrade	eTOF upgrade
|η|<1.5	**2.1<|η|<5.1**	**-1.6<η<-1.1**
p_T >60 MeV/c	Better trigger & b/g reduction	Extend forward PID capability
Better dE/dx resolution Better momentum resolution	Greatly improved Event Plane info (esp. 1st-order EP)	Allows higher energy range of Fixed Target program
Fully operational in 2019	**Fully operational in 2018**	**Fully operational in 2019**

BES–II datasets

Collider mode

$\sqrt{s_{NN}}$	Year	Events
54.4	17	1200 M
27	18	550 M
19.6	19	580 M
17.3	21	250 M
14.5	19	320 M
11.5	20	230 M
9.2	20	160 M
7.7	21	100 M

TPC+TOF acceptance:
$-1<\eta<1$ for Collider mode
$0<\eta<1.5$ for Fixed–target

Fixed–target mode

$\sqrt{s_{NN}}$	$-y_{cms}$	Year	Events
13.7	2.69	21	50 M
11.5	2.51	21	50 M
9.2	2.28	21	50 M
7.7	2.10	19+20	160 M
7.2	2.02	20	310 M
6.2	1.87	20	120 M
5.2	1.68	20	100 M
4.5	1.52	20	110 M
3.9	1.37	19+20	160 M
3.5	1.25	20	110 M
3.2	1.13	19	200 M
3.0	1.05	18 21	259 M 2000 M

Recent presentations on STAR BES

- Electromagnetic Probes
  - “The Electromagnetic Probes at RHIC-STAR”
  - Chi Yang, XI MPD Collaboration Meeting, Nov. 10, 2022
- Directed and elliptic flow
  - “Results from the RHIC Beam Energy Scan Program”
  - Shusu Shi, Workshop on physics performance studies at NICA, Dec. 13, 2022
- Net-proton fluctuations/light nuclei production
  - “Study of the QCD Phase Diagram via Beam Energy Scan at RHIC”
  - Xiaofeng Luo, VBLHEP Seminar, Mar. 17, 2023

- Review
  - “Results from the Beam Energy Scan program at STAR”
  - Grigory Nigmatkulov, Forum “Nucl. Sci. and Tech.”, Sept. 26, 2022
- Review
  - “STAR experiment results from Beam Energy Scan Program”
  - Alexey Aparin, ICPPA 2022, Dec. 2, 2022

# of strangeness
Latest Results from the STAR ~~BES~~
3 GeV Au+Au Data

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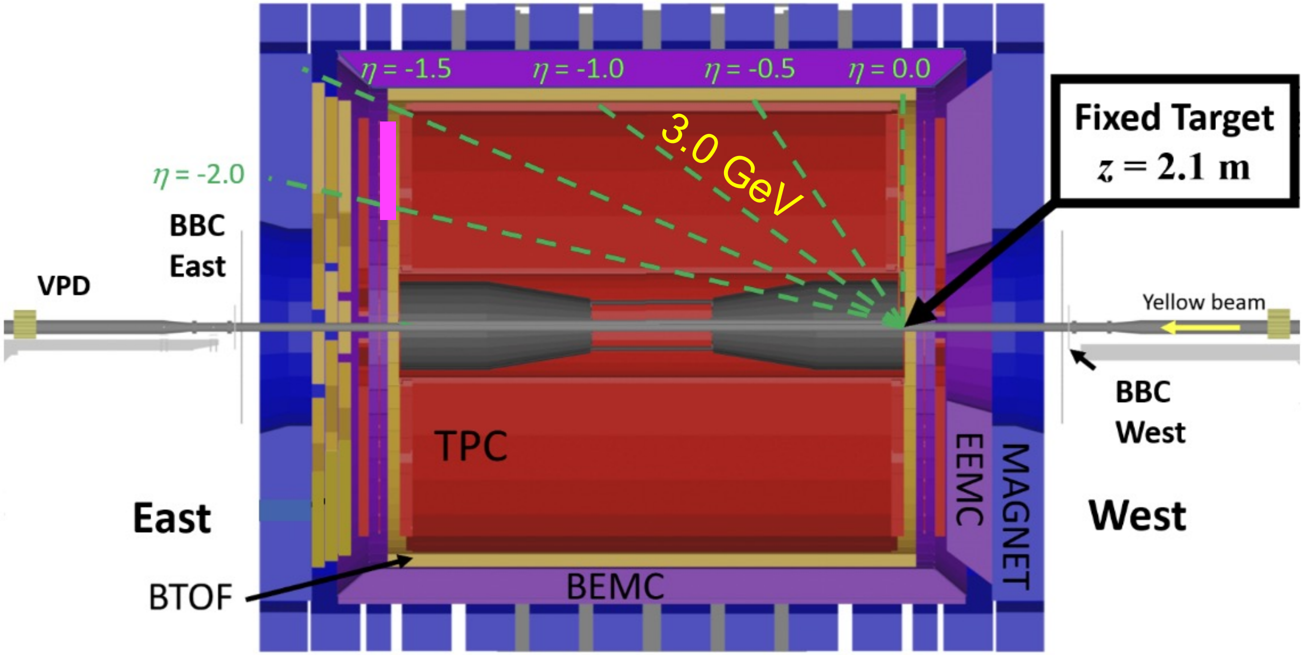
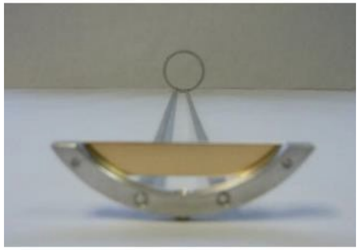
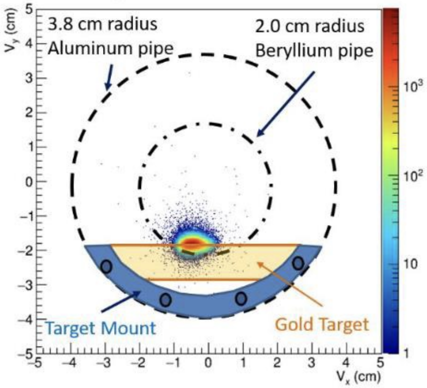
Outline

- Strangeness production
- Strangeness collectivity
- Hyperon global polarization
- Hypernuclei
- Summary
- Proposal of fixed-target at MPD

3 GeV FXT data at STAR



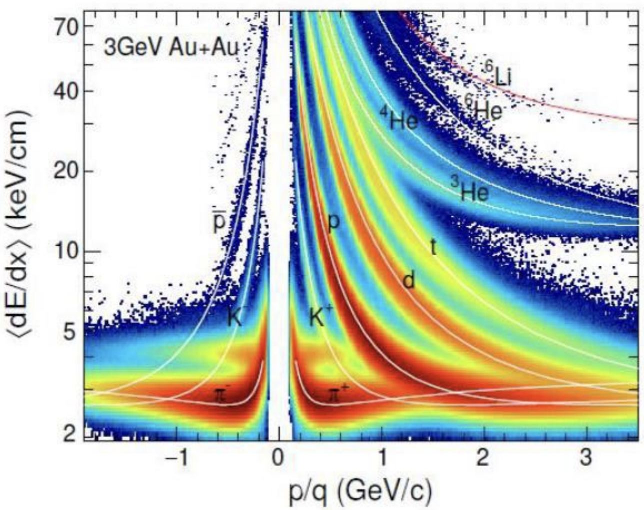




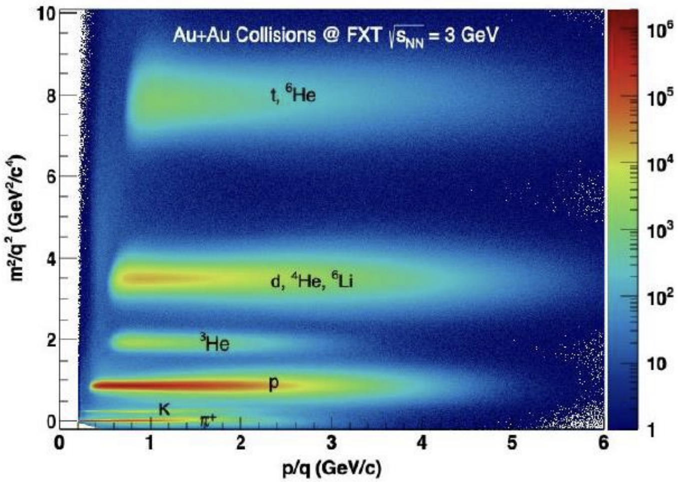
4.6–days data taking
259 M good MB events

Particle identification

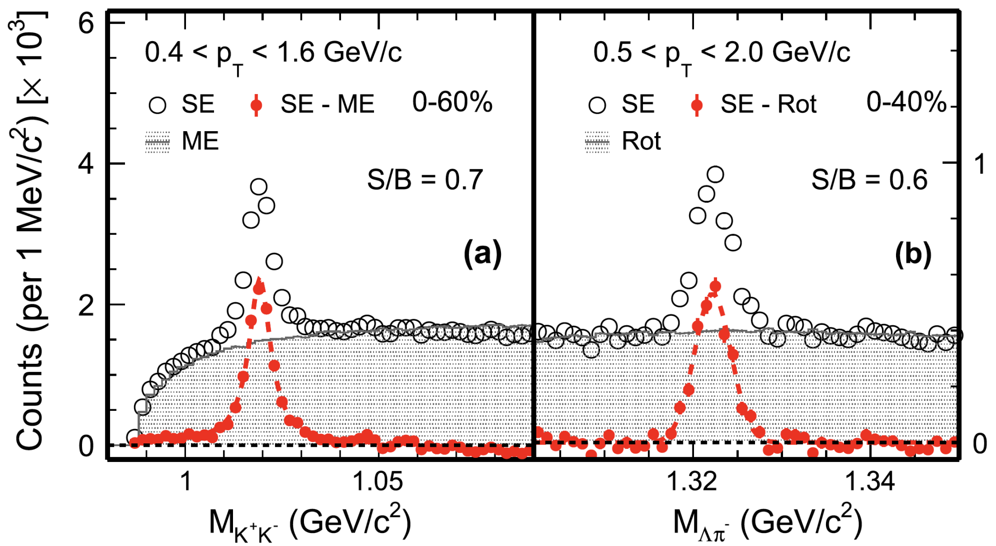
TPC



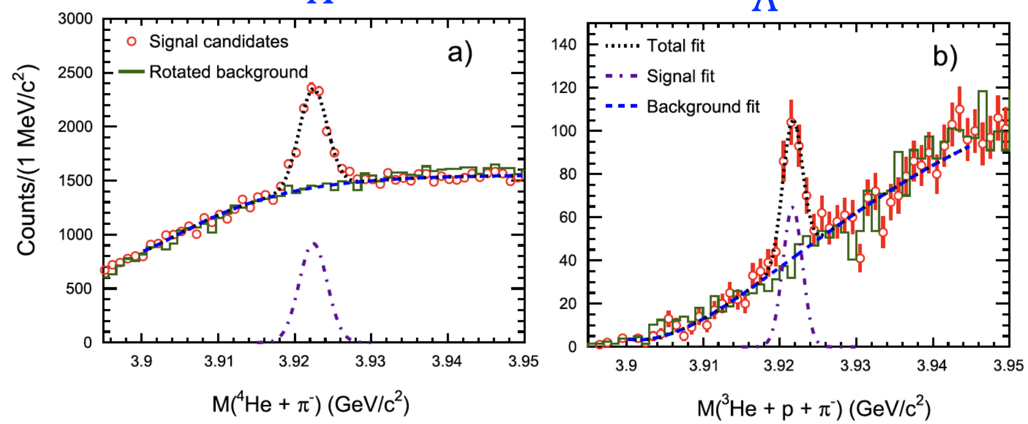
TOF



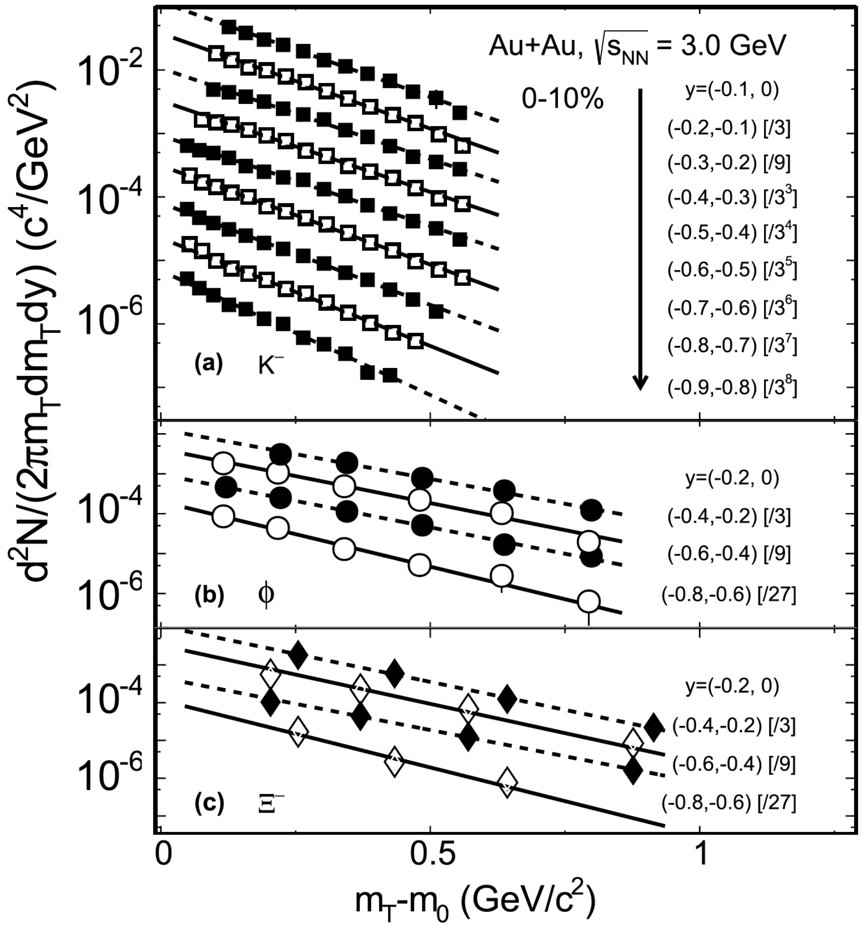
ϕ Ξ^-



${}^{4}_{\Lambda}H$ ${}^{4}_{\Lambda}He$



Strangeness transverse mass spectra

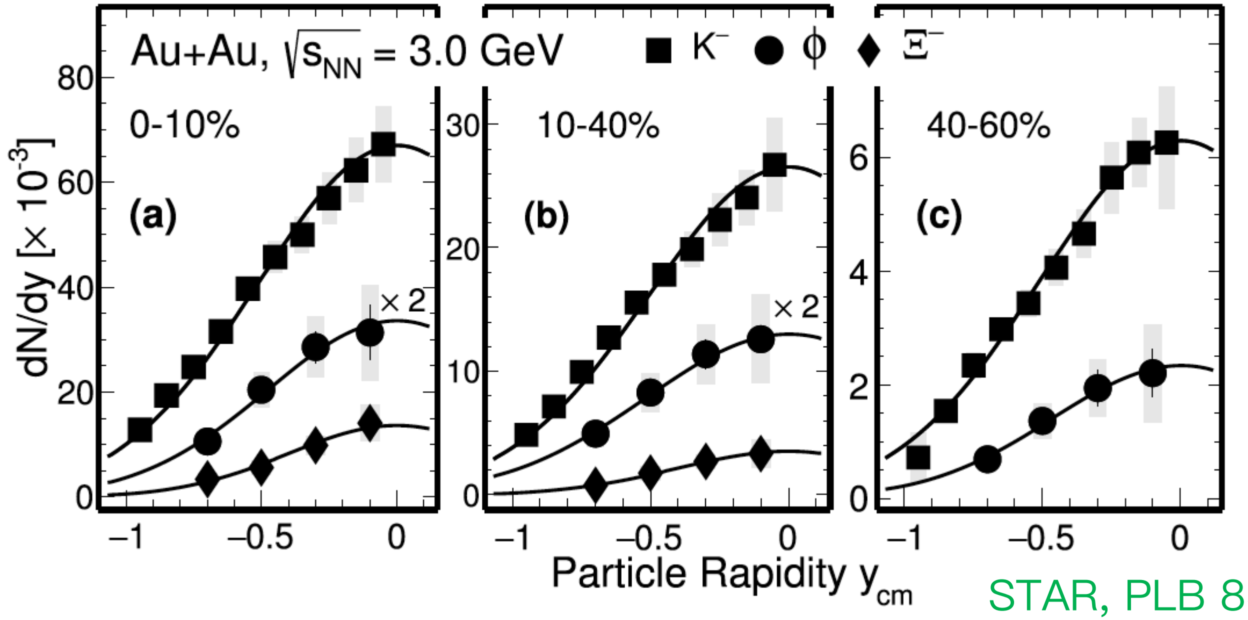


STAR, PLB 831, 137152 (2022)

- 2D differential spectra measured for K^-, ϕ and Ξ^-
- Fit to m_T–exponential function to extracted dN/dy and $T_{\rm eff}$
- $T_{\rm eff}$ is higher for ϕ than $K^-$and Ξ^-

Centrality	ϕ $T_{\rm eff}$ (MeV)	K^- $T_{\rm eff}$ (MeV)	Ξ^- $T_{\rm eff}$ (MeV)
0–10%	$177 \pm 5 \pm 8$	$158 \pm 3 \pm 3$	$156 \pm 3 \pm 24$
10–40%	$159 \pm 4 \pm 5$	$142 \pm 3 \pm 3$	$146 \pm 4 \pm 17$
40–60%	$151 \pm 5 \pm 11$	$115 \pm 4 \pm 4$	–

Total yield extraction

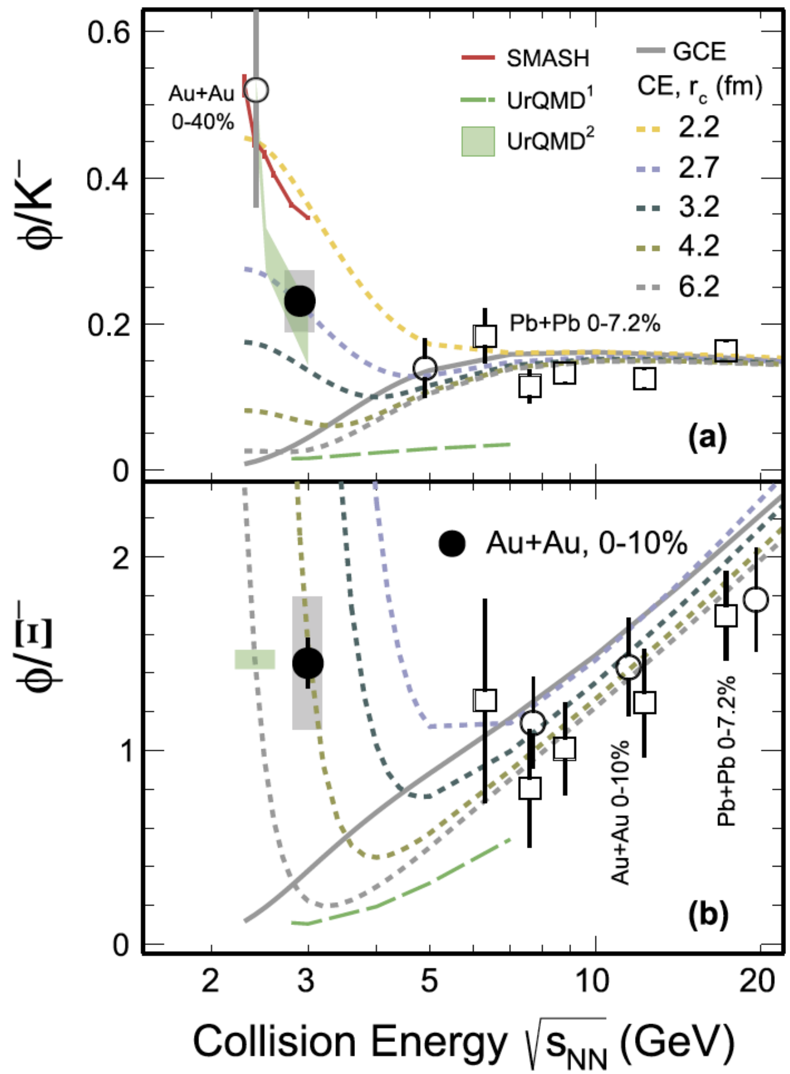


STAR, PLB 831, 137152 (2022)

- Rapidity distributions are fit to Gaussian distribution to extrapolate to the unmeasured rapidity region
- Only small fraction of the yield is outside of the rapidity acceptance

	K^-	ϕ	Ξ^-
Fraction	~5%	~9%	~6%

Particle ratios

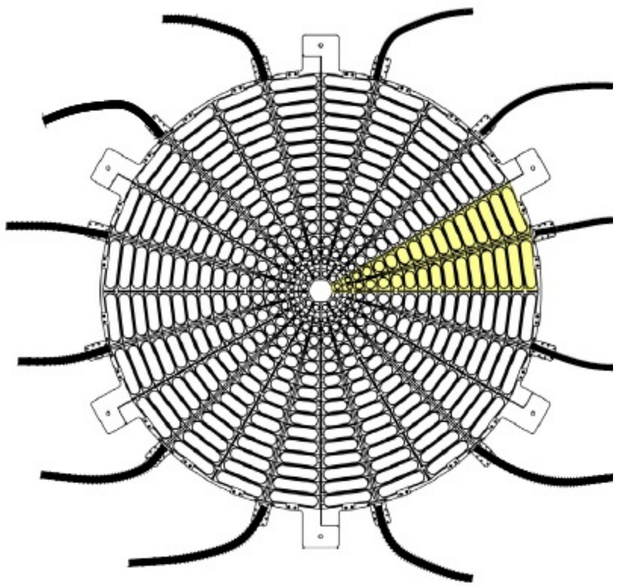


STAR, PLB 831, 137152 (2022)

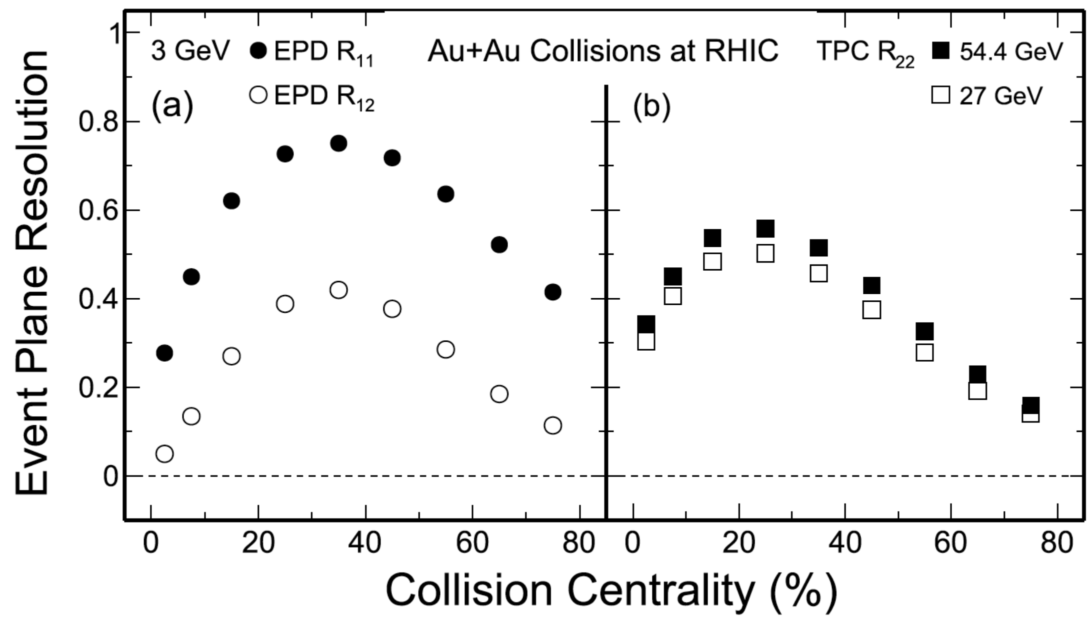
- Both ϕ/K^- and ϕ/Ξ^- are significantly higher than Grand Canonical Ensemble calculations
- Favors Canonical Ensemble with small correlation length
  - $r_c \sim 2.7\ fm$ for ϕ/K^-
  - $r_c \sim 4.2\ fm$ for ϕ/Ξ^-

  Local strangeness conservation plays an important role
- Hadronic transport models with high mass resonance describe data
- Change of medium properties at low energy
- Precise data between 3 and ~10 GeV are needed

Collectivity with STAR–EPD



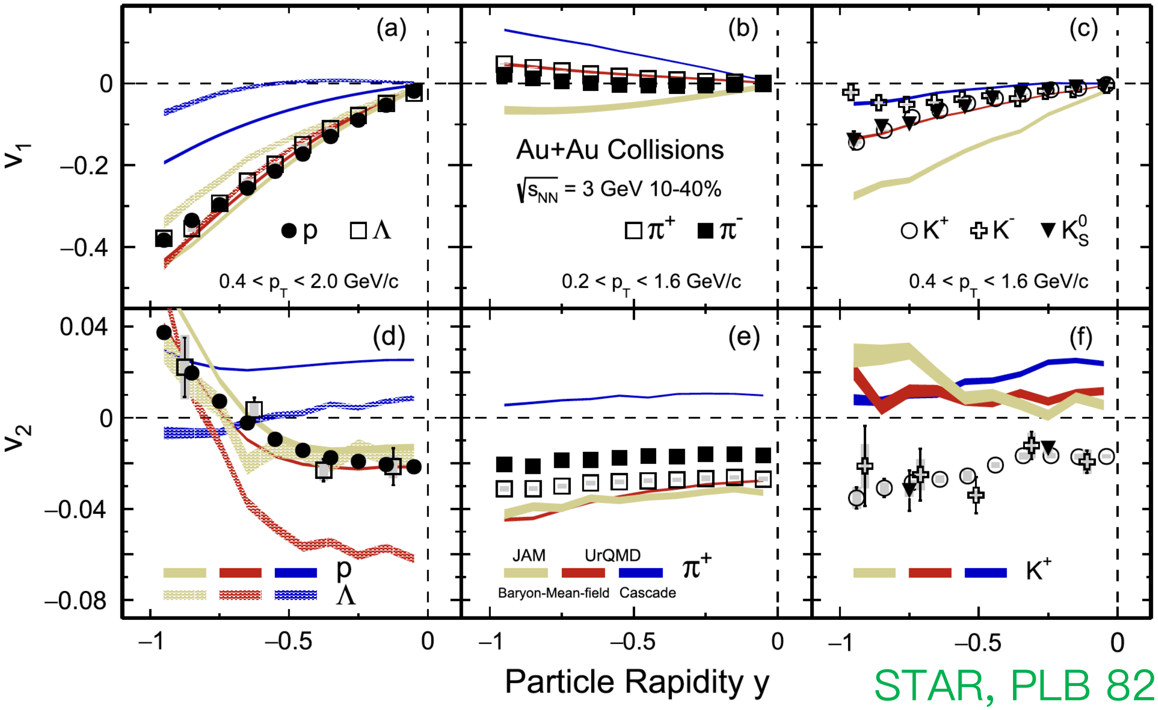
$-5.3 < \eta < -2.6$



STAR, PLB 827, 137003 (2022)

- Excellent resolution of Ψ_1 can be determined from EPD thanks to the large v_1 signal at forward rapidity and low energy
- v_1 and v_2 are measured with respect to Ψ_1 for various particles in Au+Au collisions at 3 GeV by STAR

Rapidity dependence of collectivity



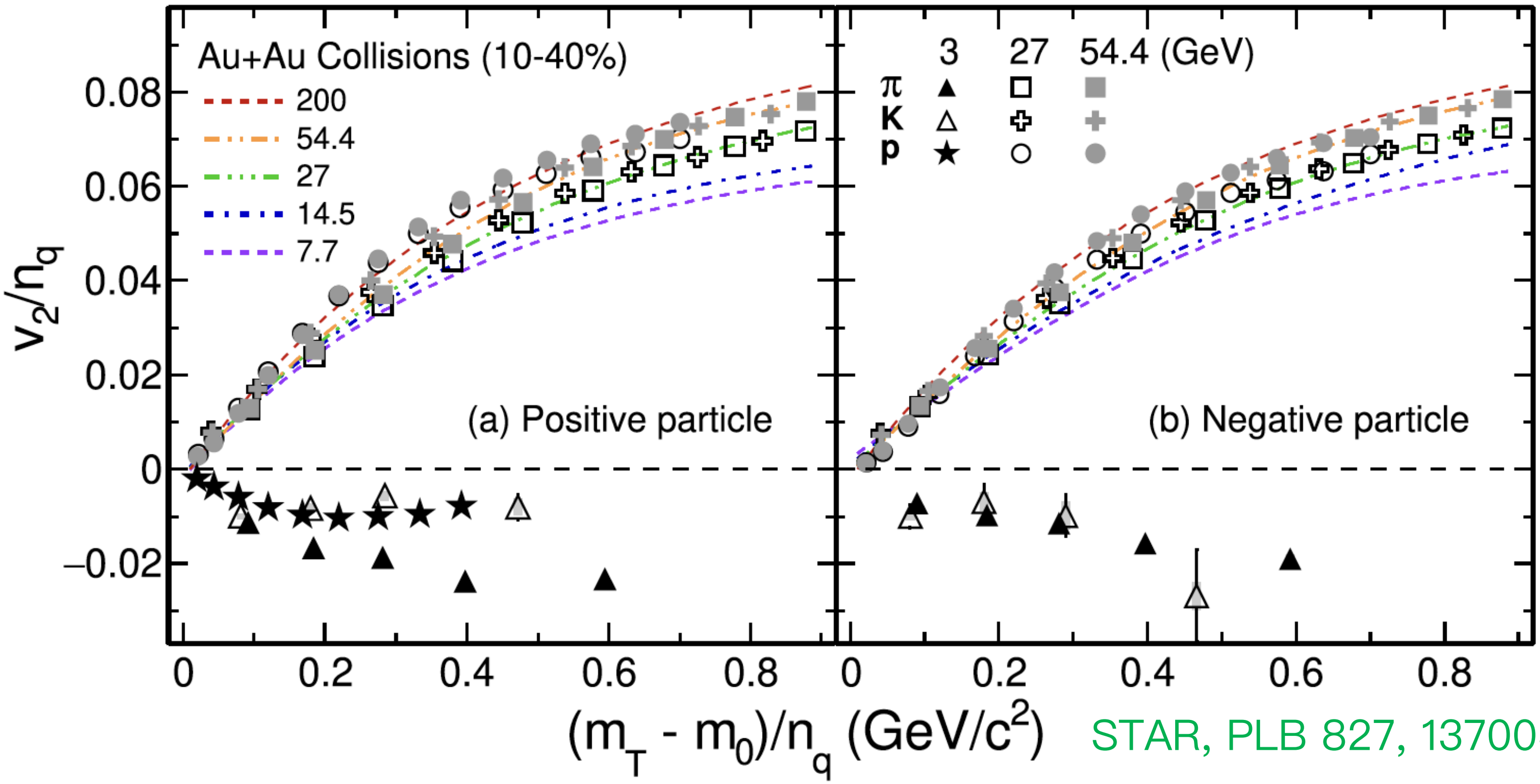
STAR, PLB 827, 137003 (2022)

dv_1/dy:
- Largest and positive for p and Λ and nearly zero for pion
- Positive and small change dependence for kaon ($K^+ > K^-$)

v_2: Negative for all particle species at mid–rapidity

UrQMD with baryonic mean–field describes data except for K and Λ v_2
➔ Baryonic scattering dominate

NCQ scaling of elliptic flow

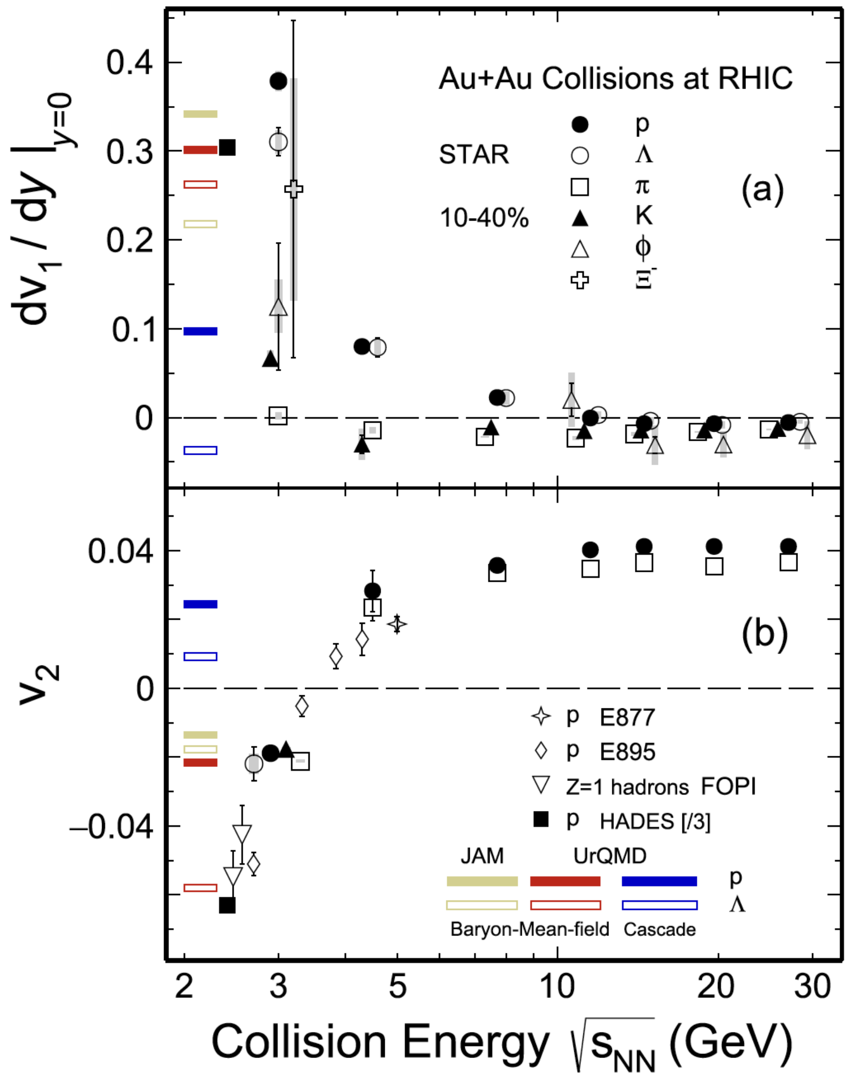


STAR, PLB 827, 137003 (2022)

- At high energy, v_2 is positive and follows NCQ scaling
- At 3 GeV, v_2 is negative and NCQ scaling breaks

Disappearance of partonic flow at 3 GeV

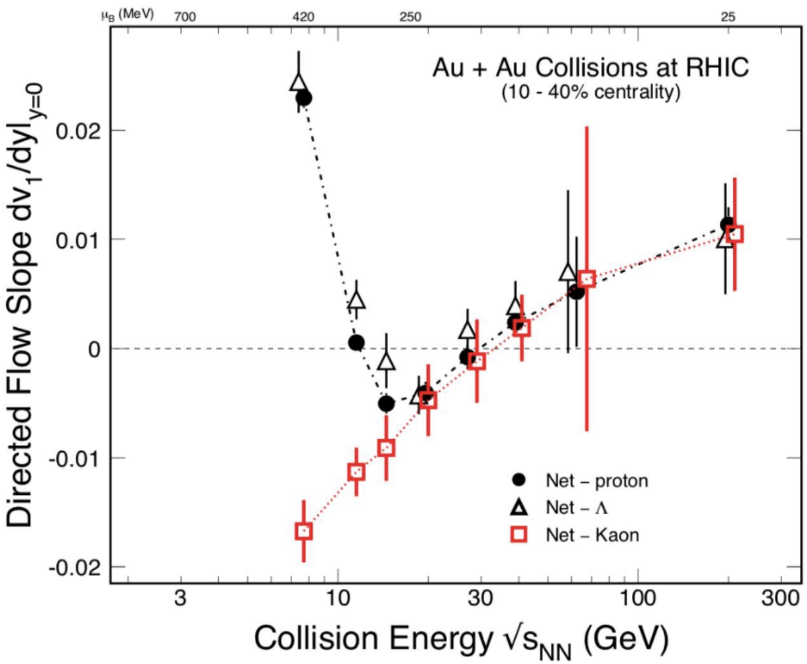
Energy dependence of collectivities



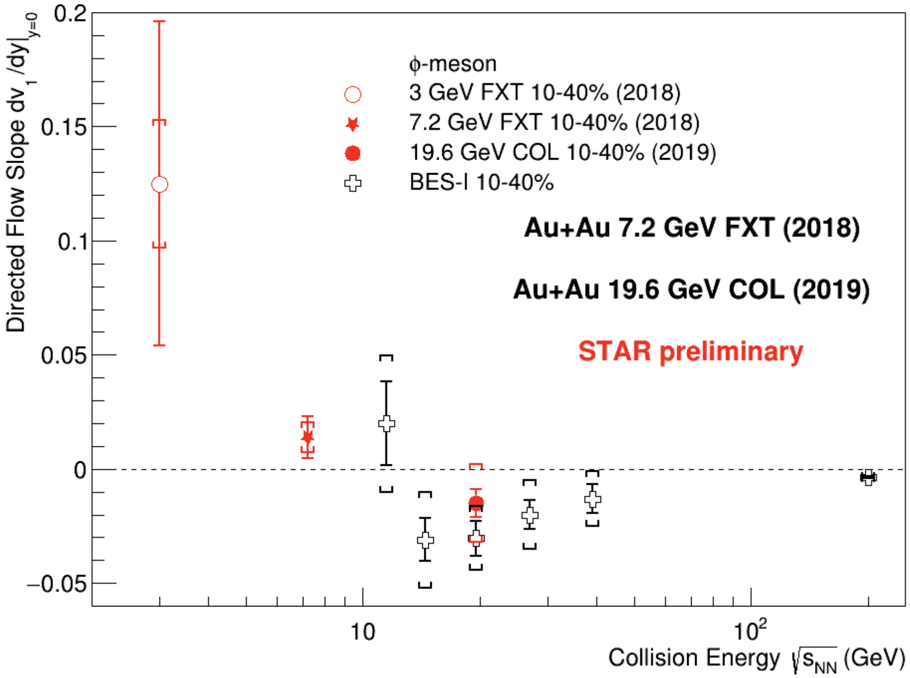
STAR, PLB 827, 137003 (2022)

- v_1 slope and v_2 for all particles are opposite to that at high energy
- Clear mass and flavor dependence for v_1 slope, not the case for v_2
- JAM and UrQMD with baryonic mean–field qualitatively describe data
- Baryonic interactions dictate the collision dynamics at 3 GeV

Where is the softest point?

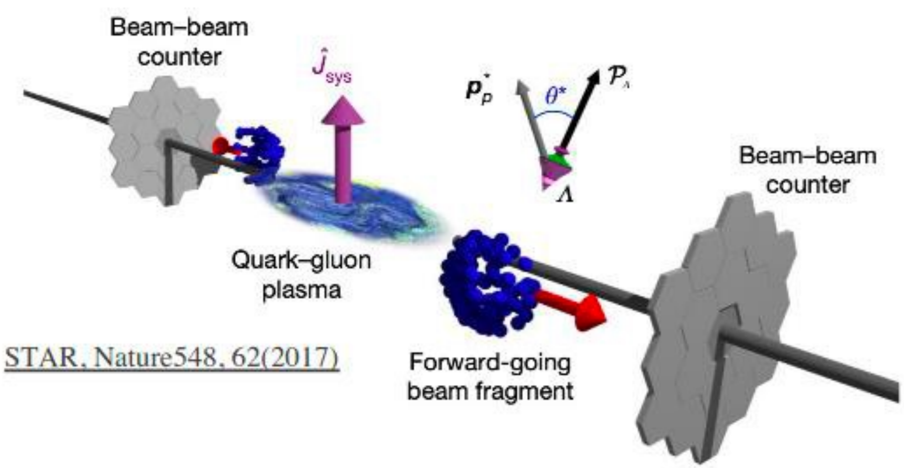


STAR, PRL 120, 062301 (2018)

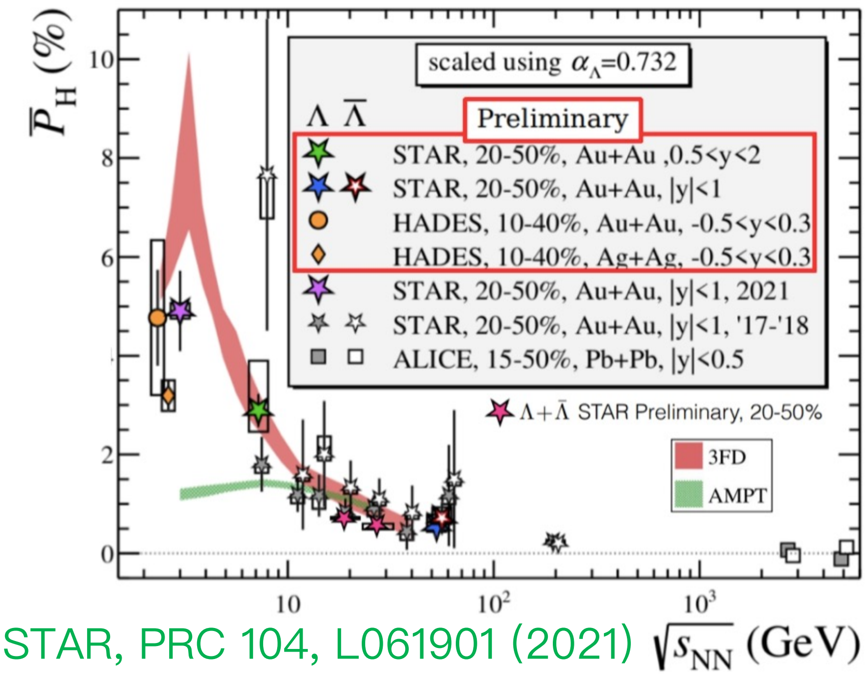


- Net–Λ and ϕ show nonmonatomic trend with minimum at 10–20 GeV
- Net–Kaon seems change sign between 7.7 and 3 GeV
- More and precise data in the gap is interesting and important

Hyperon global polarization



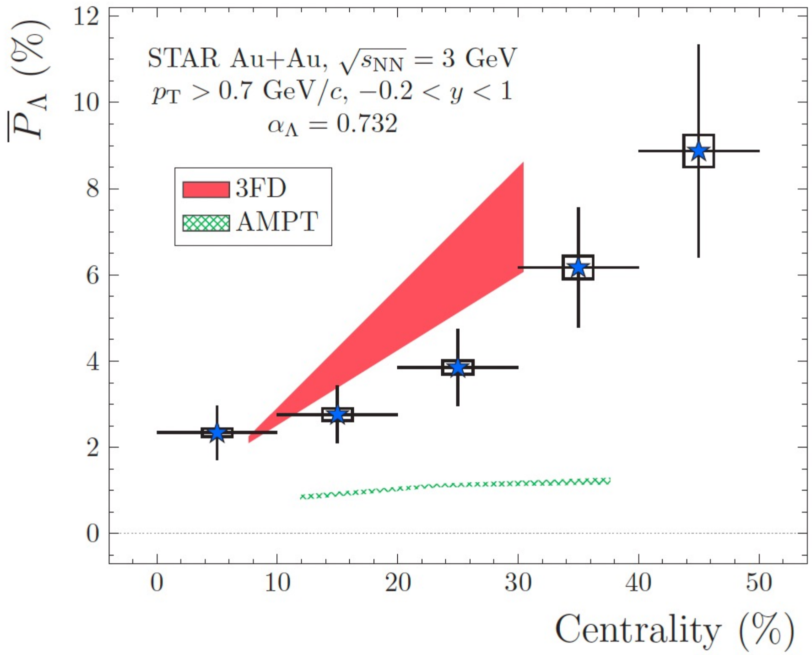
STAR, Nature548, 62(2017)

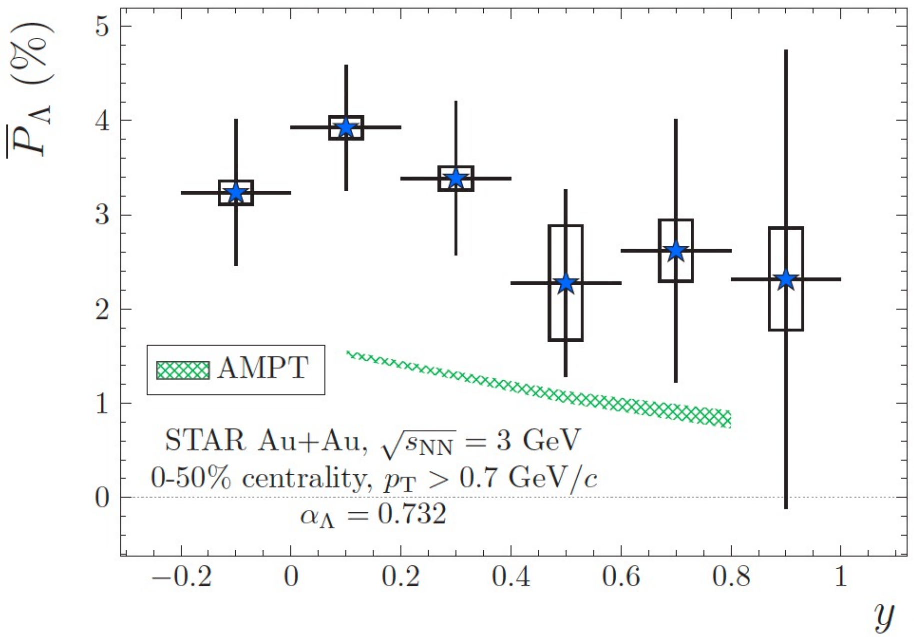


STAR, PRC 104, L061901 (2021)

- Global polarization proposed in 2004 and discovered with BES–I data in 2017
- Polarization observed at 3 GeV is so far the largest
- Described by 3FD but higher than partonic–transport AMPT

Hyperon global polarization

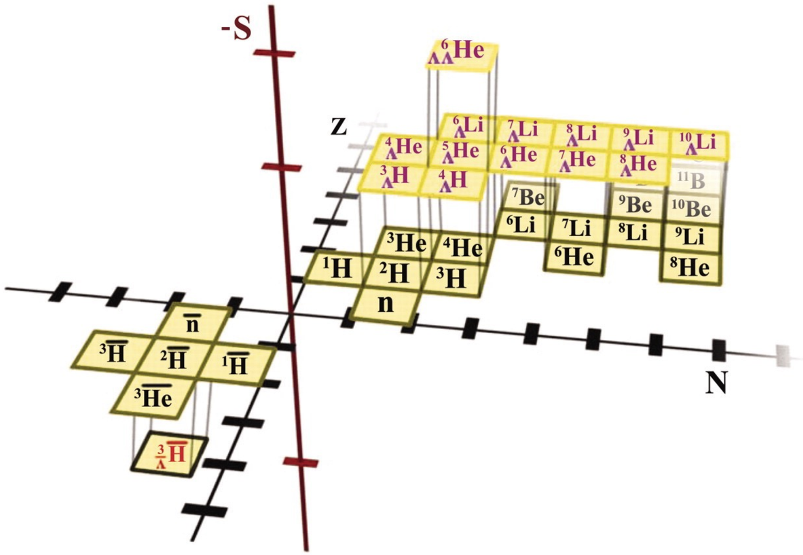




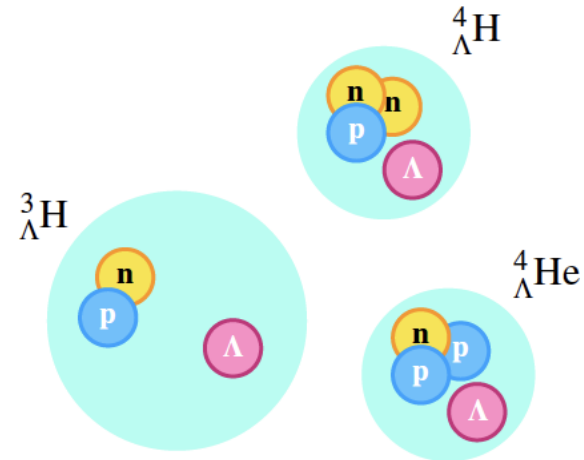
STAR, PRC 104, L061901 (2021)

- Significant dependence on centrality is observed, consistent with increasing initial global angular momentum in peripheral collisions
- Predicted strong rapidity dependence yet be confirmed with better statistics

Hypernuclei



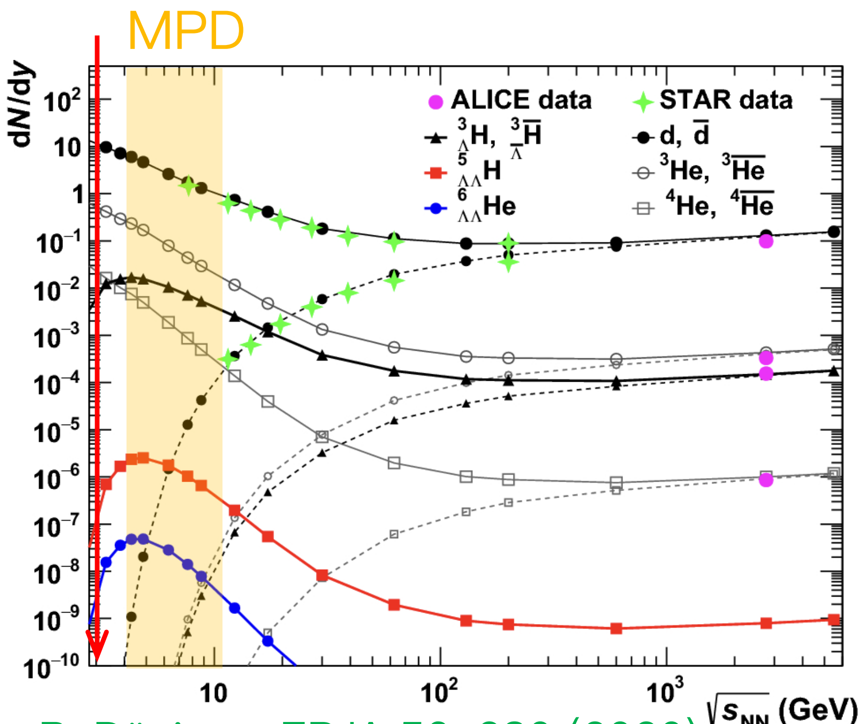
STAR, Science 328, 58 (2010)



Y. Leung

- Hypernuclei can be used to probe the hyperon–nucleon (Y–N) interaction
- Crucial for the understanding of the Equation–of–State of high baryon density objects such as neutron stars

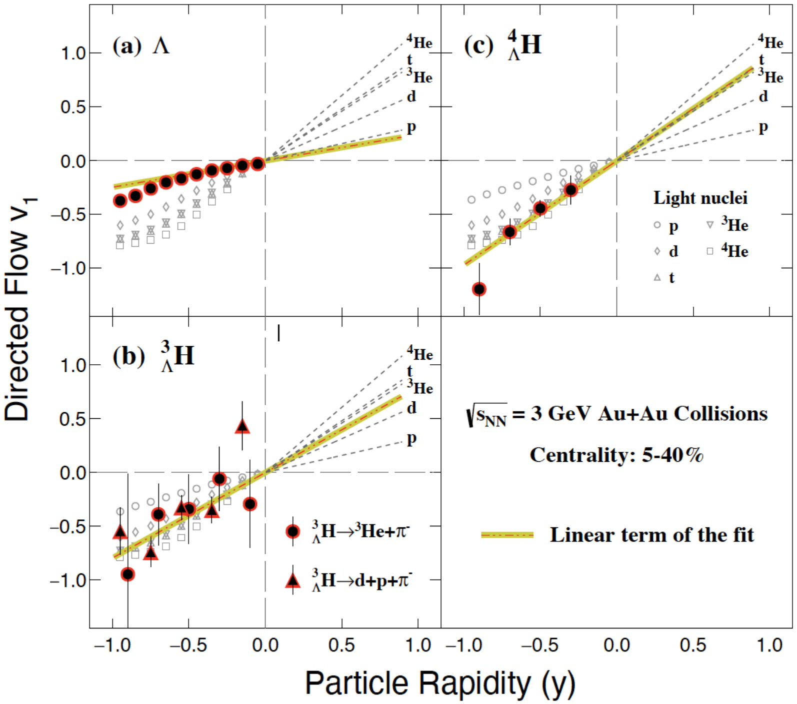
Hypernuclei production

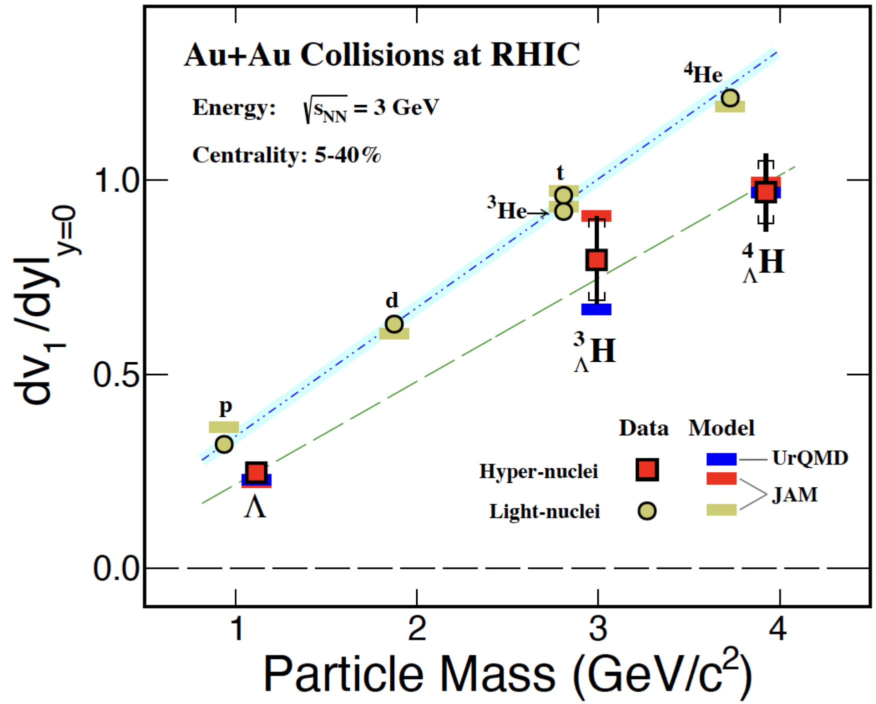


B. Dönigus, EPJA 56, 280 (2020)

- Low-energy heavy ion collision provides unique laboratory
- Maximum yield at STAR BESII-FXT and MPD energies
- 3 GeV is not a optimal energy but demonstrates fantastic capability

Hypernuclei directed flow



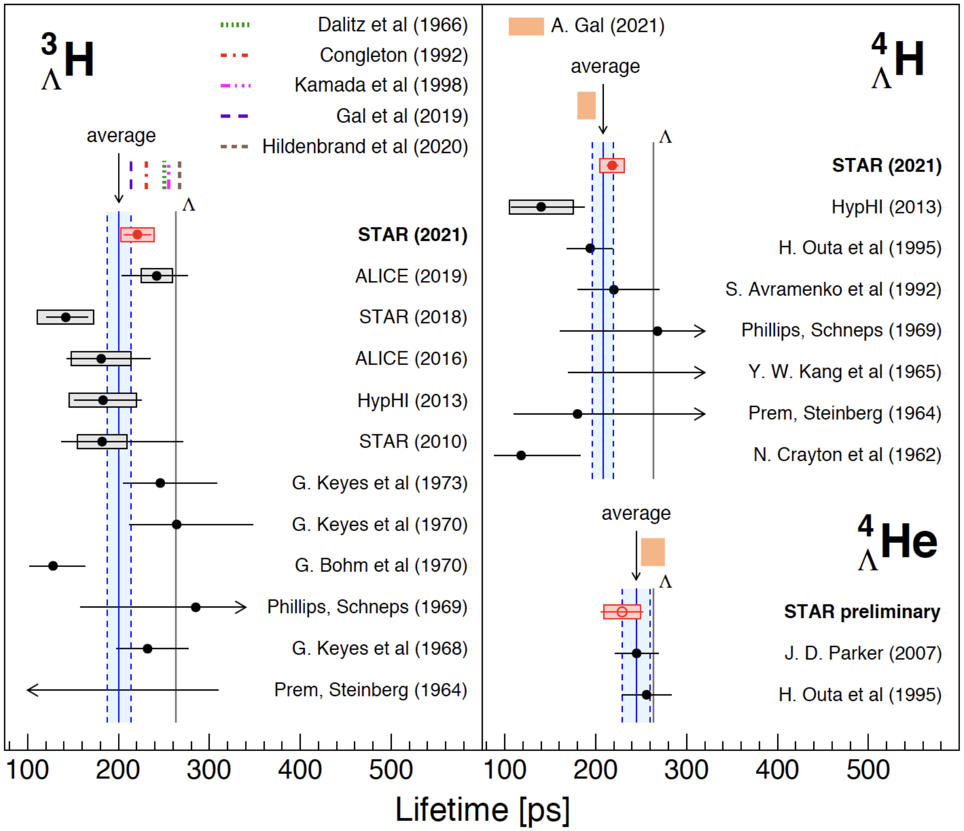


STAR, arXiv:2211.16981,
accepted by PRL

- First observation of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ directed flow
- dv_1/dy of hypernuclei are similar but syst. lower than light nuclei
- Transport models with coalescence afterburner describe data

Coalescence could be the dominant mechanism

Hypernuclei lifetime



STAR, PRL 128, 202301 (2022)

A. Gal and H. Garcilazo, PLB 791, 48 (2019)
J.G. Congleton, J. Phys. G 18, 339 (1992)

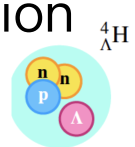
- Hypernuclei lifetime is sensitive to its binding energy
- Control measurement:
  $\tau(\Lambda) = 267 \pm 4\, ps$ compared to
  $\tau(\Lambda) = 263 \pm 2\, ps$ from PDG
- New $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$ and $^{4}_{\Lambda}He$ results with improved precision
- Global average of $^{3}_{\Lambda}H$
  - $\tau(^{3}_{\Lambda}H) = (76 \pm 5)\%\ \tau(\Lambda)$
  - consistent with theoretical calculations including π FSI and Λd 2–body picture
- Ratio of $\tau(^{4}_{\Lambda}H)$ and $\tau(^{4}_{\Lambda}He)$ consistent with isospin rule

$$\frac{\Gamma(^{4}_{\Lambda}\mathrm{He} \to {}^{4}\mathrm{He} + \pi^{0})}{\Gamma(^{4}_{\Lambda}\mathrm{H} \to {}^{4}\mathrm{He} + \pi^{-})} \approx \frac{1}{2}$$

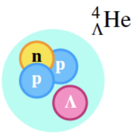
A. Gal, EPJ Web Conf 259, 08002 (2022)

Charge symmetry breaking

- Charge symmetry of strong interaction predicts identical interaction of Λp and Λn

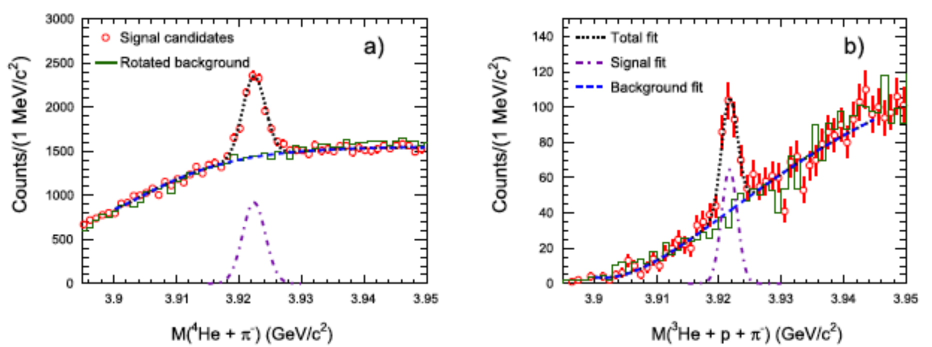


- The Λ binding energy of ${}^4_\Lambda H$ and ${}^4_\Lambda He$ should be equal according to charge symmetry $B_\Lambda = M_\Lambda + M_{core} - M_{hypernucleus}$

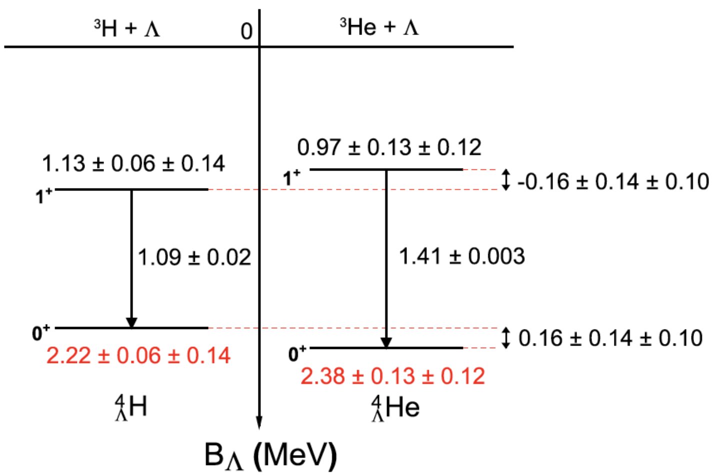


- Previous measurements reported large binding energy difference
  - $\Delta B^4_\Lambda(0^+) = 350 \pm 60\ keV$
  - Long–standing puzzle

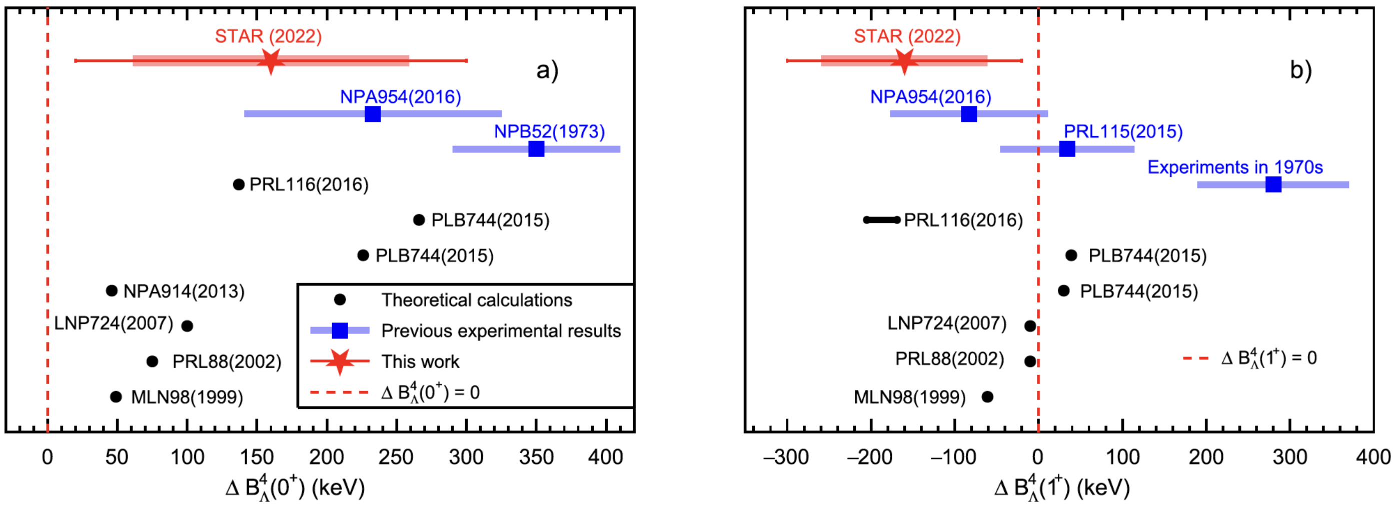
- The binding energy of ground state of ${}^4_\Lambda H$ and ${}^4_\Lambda He$ is updated with the 3 GeV Au+Au data



STAR, PLB 834, 137449 (2022)



Charge symmetry breaking



STAR, PLB 834, 137449 (2022)

- $\Delta B^4_\Lambda(0^+) = 160 \pm 140(stat.) \pm 100\ (syst.)\ keV$
- Combining with γ–transition energy measurements gives

  $\Delta B^4_\Lambda(1^+) = -160 \pm 140(stat.) \pm 100\ (syst.)\ keV$

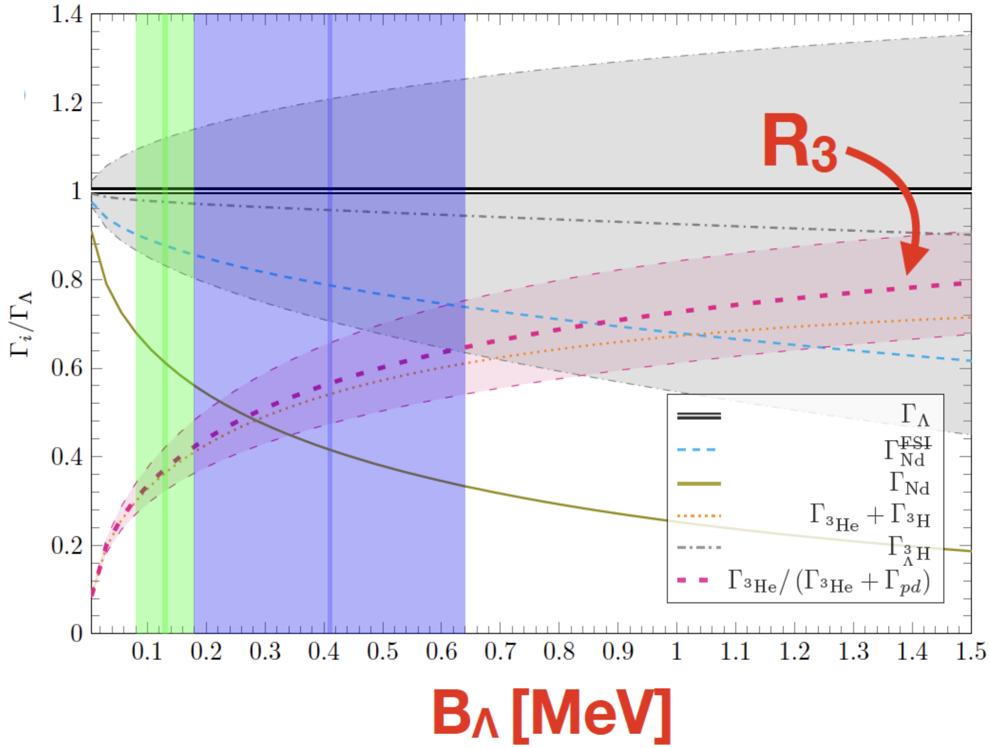
- Both are consistent with theoretical calculations within uncertainties

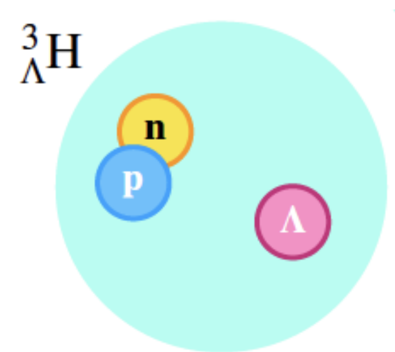
  Better precision is still needed

Hypertriton relative branching ratio

The ratio of ${}^3_\Lambda H$ 2–body and 3–body decay branching ratio is predicted to strongly depend on the binding energy

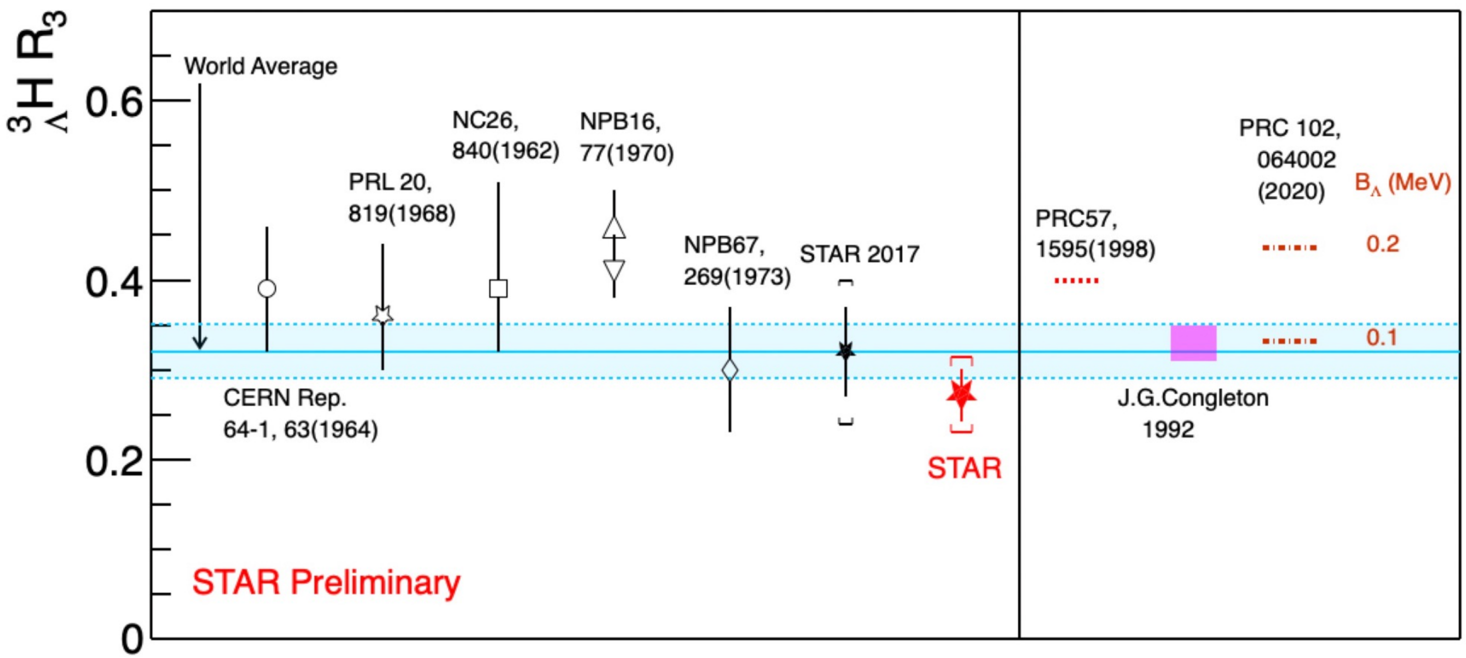
$$R_3 = \frac{B.R.({}^3_\Lambda H \to {}^3He\pi^-)}{B.R.\left({}^3_\Lambda H \to {}^3He\pi^-\right) + B.R.({}^3_\Lambda H \to dp\pi^-)}$$





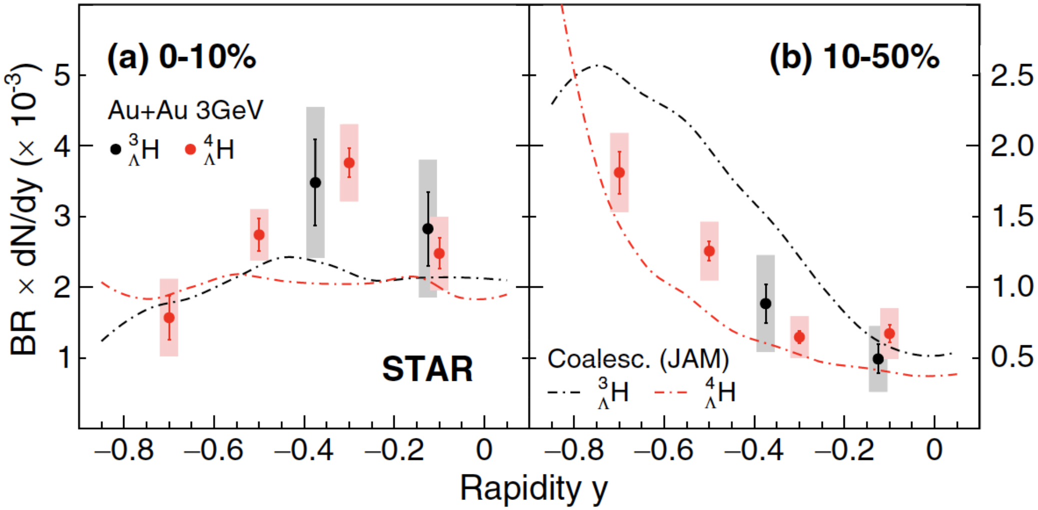
Hildenbrand et al, PRC 102, 064002 (2020)

Hypertriton relative branching ratio



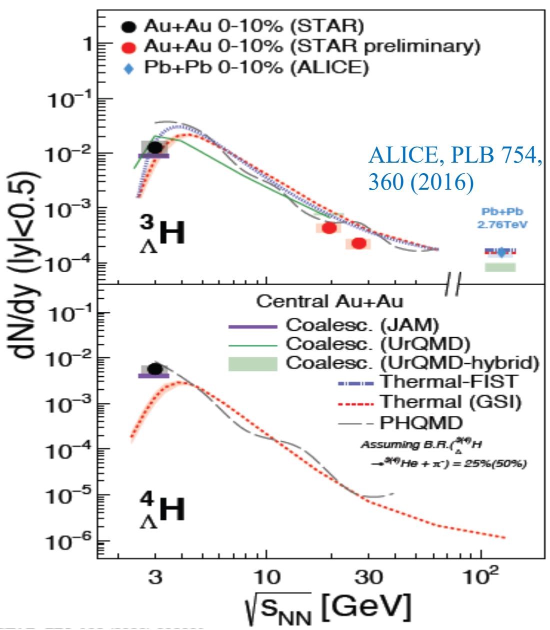
- $R_3 = 0.272 \pm 0.030(stat.) \pm 0.042(syst.)$ from 3 GeV Au+Au
- Updated global average $R_3 = 0.32 \pm 0.03$
  - Consistent with theoretical models assuming $B(\Lambda) \sim 0.1$ MeV

Hypernuclei production



- Different rapidity distribution in central and semi-central collisions
- JAM roughly describes data

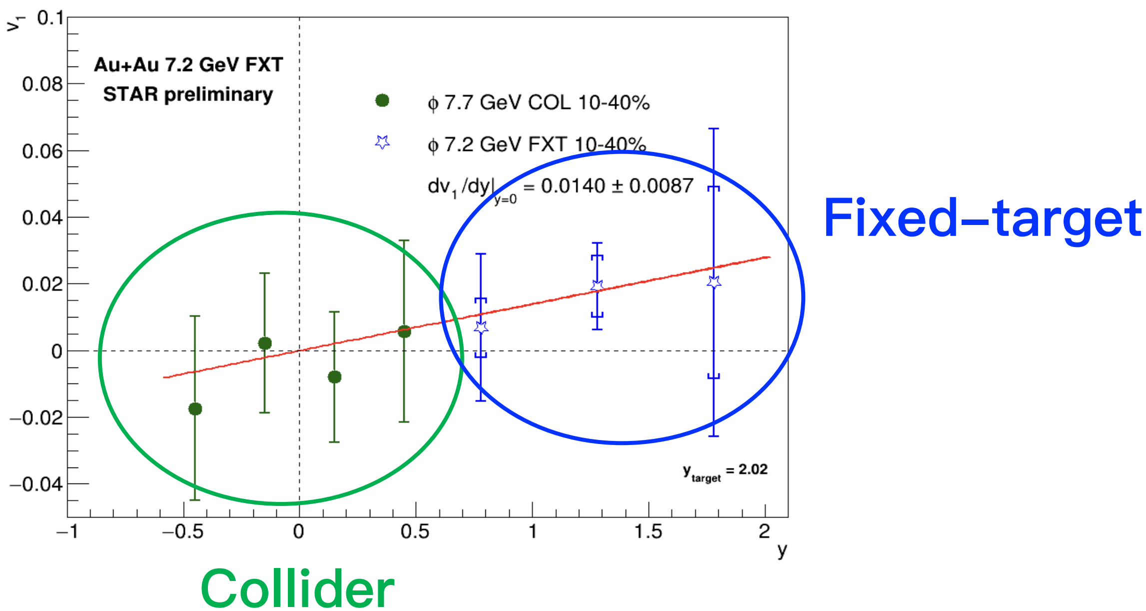
STAR, PRL 128, 202301 (2022)



- Strong energy dependence predicted by various models
- 3 GeV data provide first constraints for models in high baryon density region
- Looking forward
  - Precision
  - More energy points

Summary and Outlook

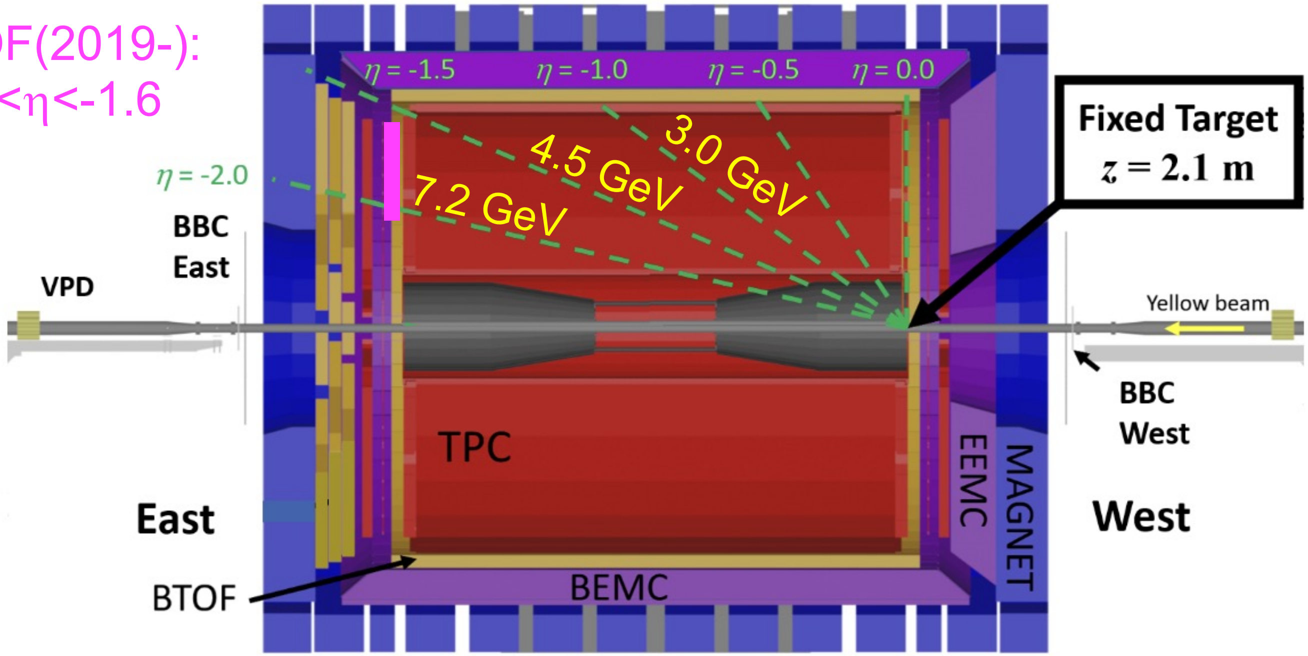
- STAR 259 M Au+Au collision at 3 GeV showed great physics capability
- MPD is complementary to STAR BESII in many aspects
  A simple example :

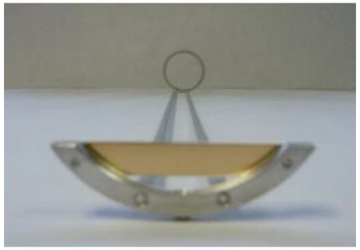


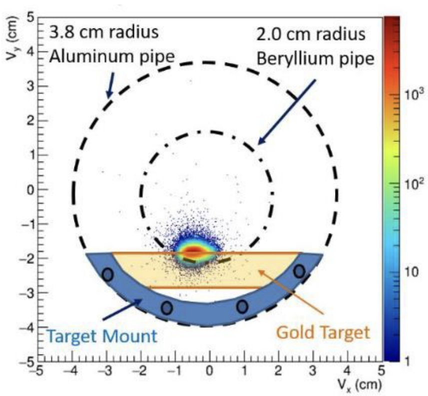
- Looking forward to exciting MPD physics program
- How about placing fixed–targets at the **MPD**

FXT at STAR

eTOF(2019-):
-2.1<η<-1.6







$\sqrt{s_{NN}}$	$-y_{cms}$
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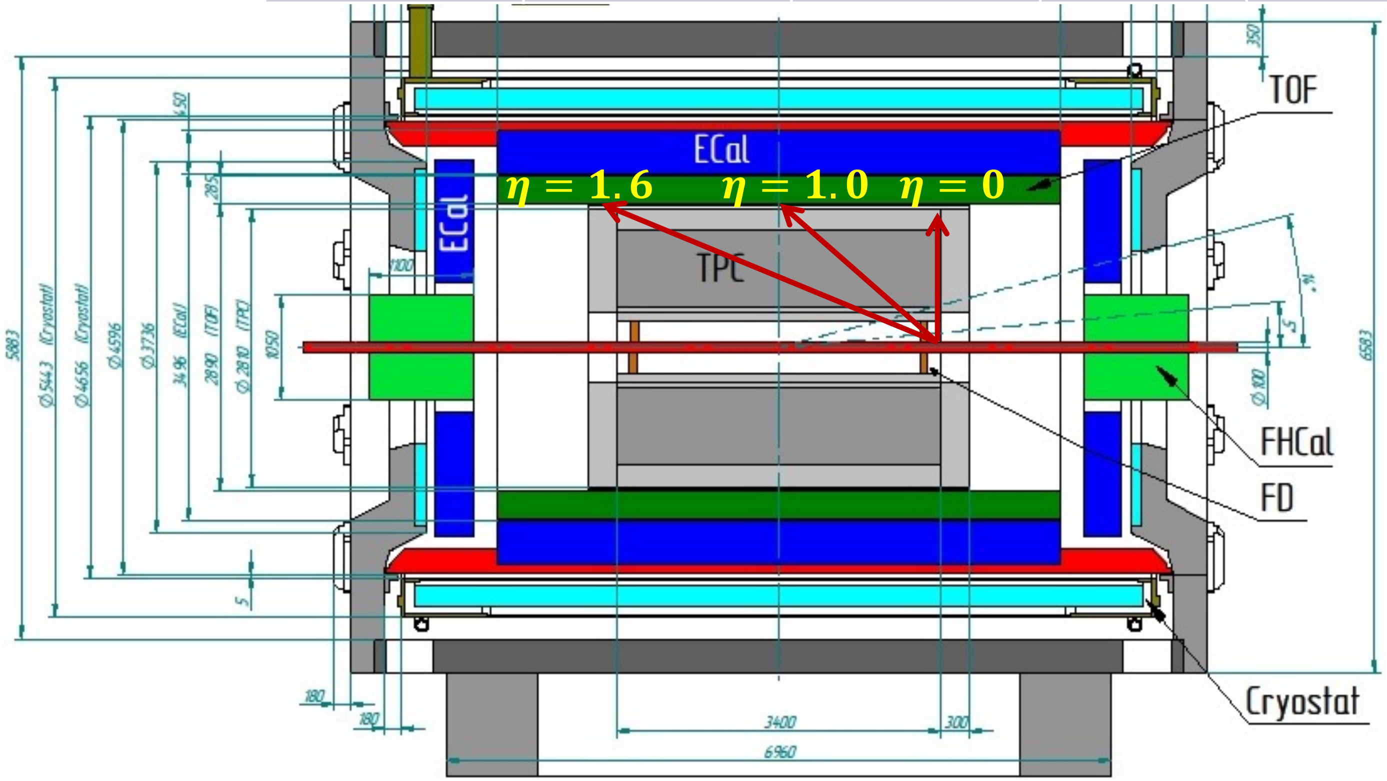
11.5	2.51
9.2	2.28
7.7	2.10
7.2	2.02
6.2	1.87
5.2	1.68
4.5	1.52
3.9	1.37
3.5	1.25
3.2	1.13
3.0	1.05

Rapidity acceptance for FXT at MPD

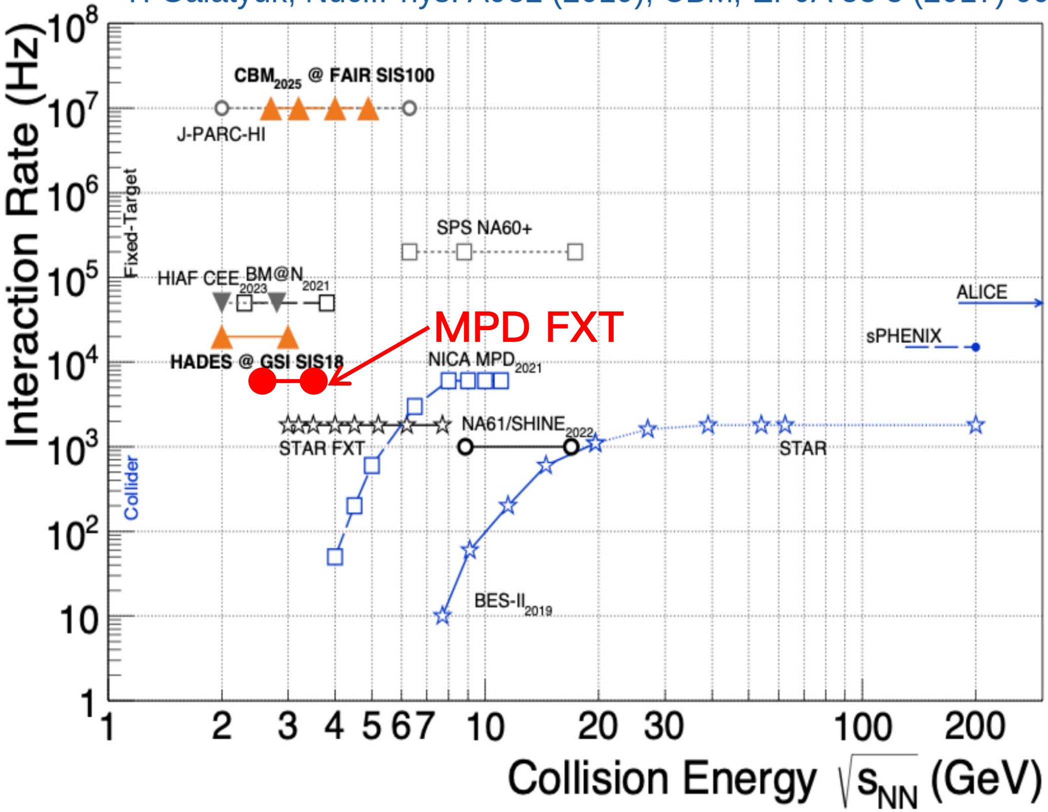
E_{beam}	$\sqrt{s_{NN}}$ at Collider	$\sqrt{s_{NN}}$ at FXT	$-y_{cms}$	TPC+TOF+ECal coverage
5.5	11	3.5	1.23	(−1.23, 0.37)
4.6	9.2	3.2	1.14	(−1.14, 0.47)
2	4	2.5	0.70	(−0.70, 0.90)



Large rapidity acceptance at mid-rapidity w/ central detectors

Why not fixed–target at MPD?

T. Galatyuk, Nucl.Phys. A982 (2019); CBM, EPJA 53 3 (2017) 60



Thanks!

- DAQ rate not limited by beam intensity
- Loose requirement on beam quality $(\sigma_{x,y}, \sigma_z)$
- Enough mid–rapidity acceptance of central detectors
- Same detector setup and similar analysis framework as collision mode
- Essential to get large data sample
  - at low energy
  - at day1
- Extend to lower energy