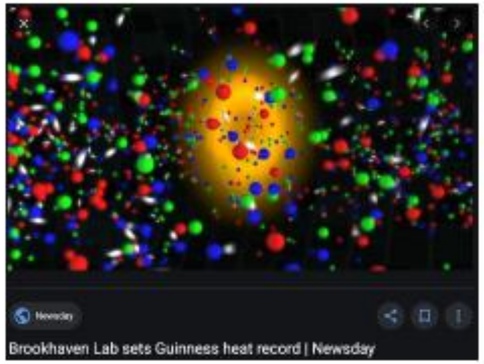
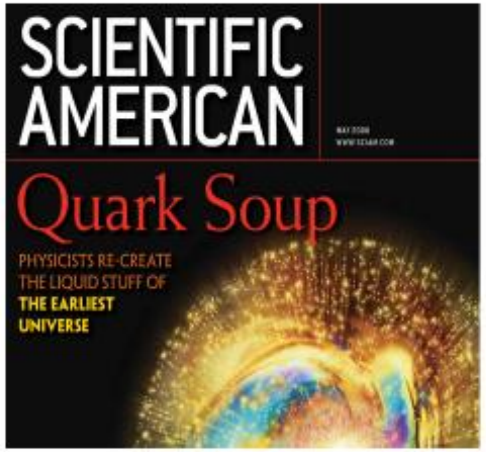
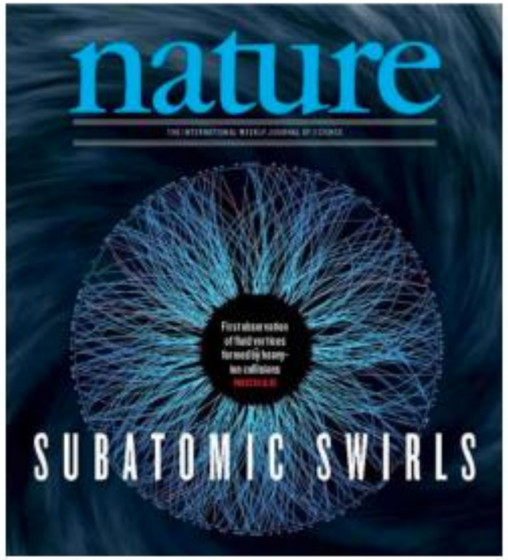


Hottest



Least viscous



Most vortical

???

Supported in part by

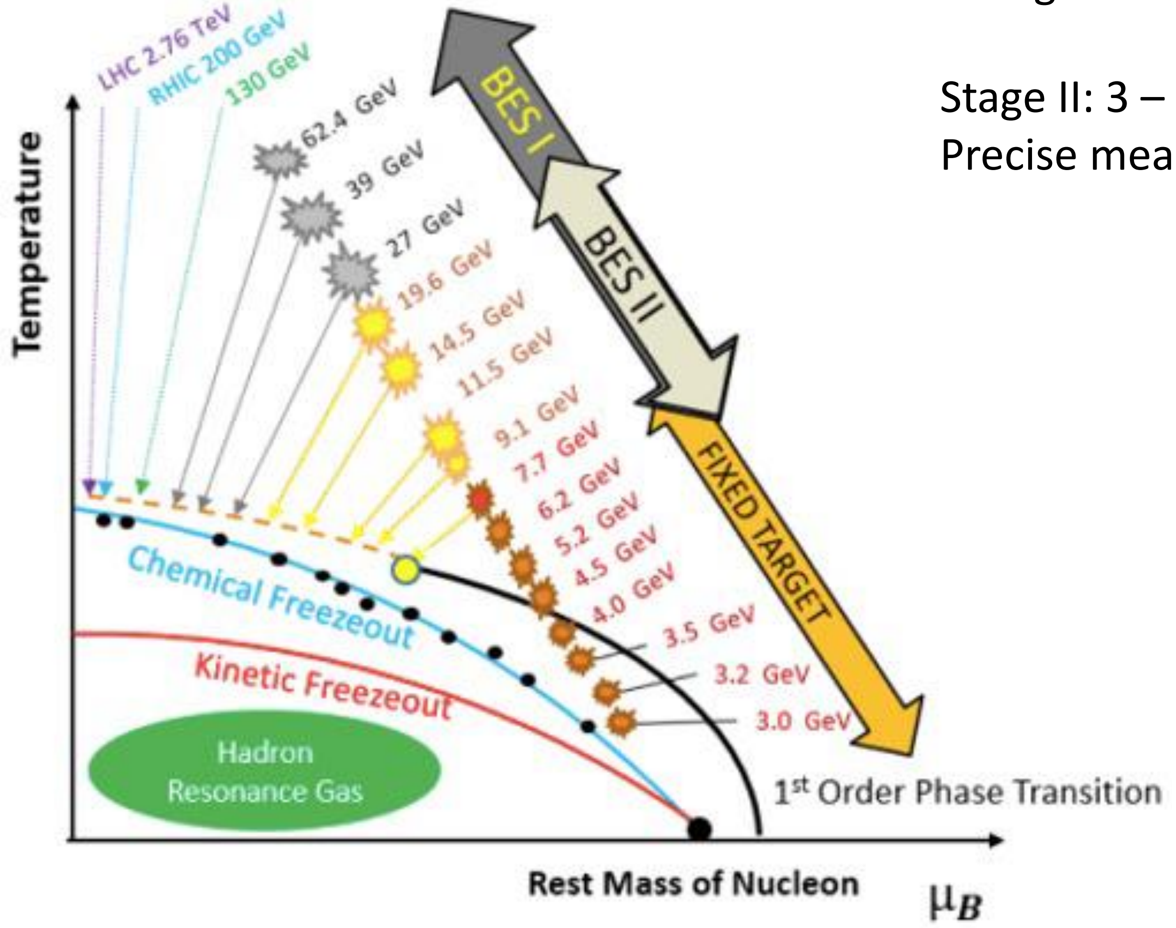
U.S. DEPARTMENT OF ENERGY

STAR experiment results from Beam Energy Scan program

Alexey Aparin for the STAR collaboration
Joint Institute for Nuclear Research

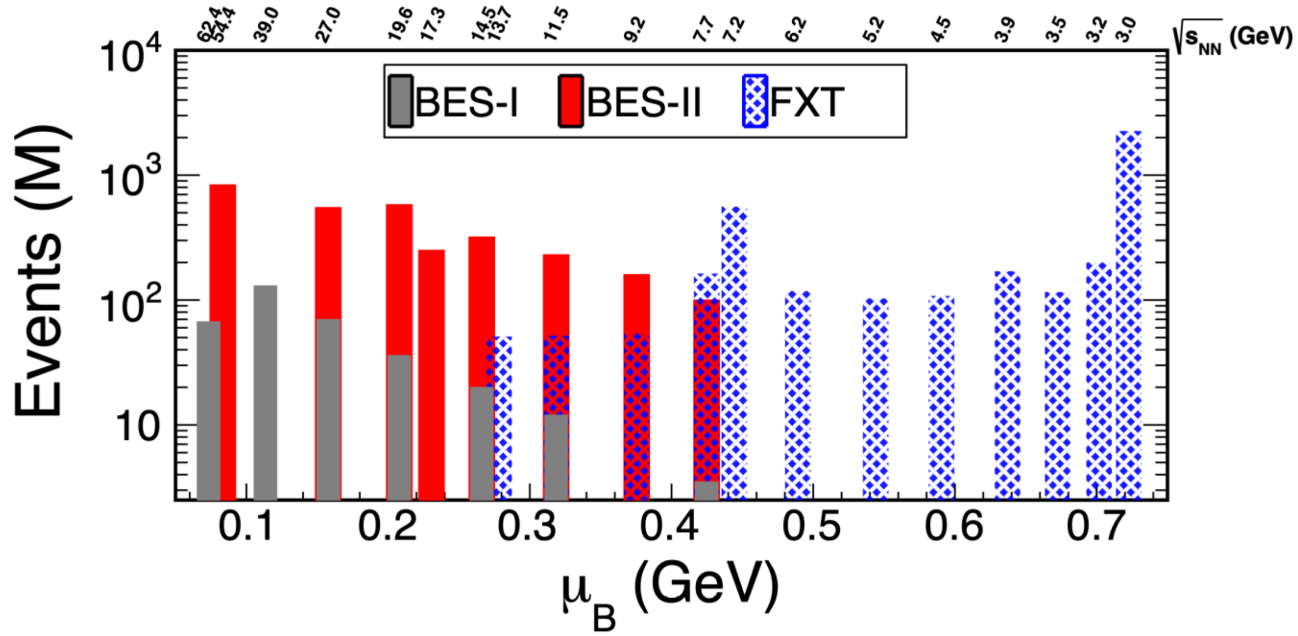
Part of this work has been supported by Russian Science Foundation under grant № 22-72-10028

Beam Energy Scan to map the QCD phase diagram

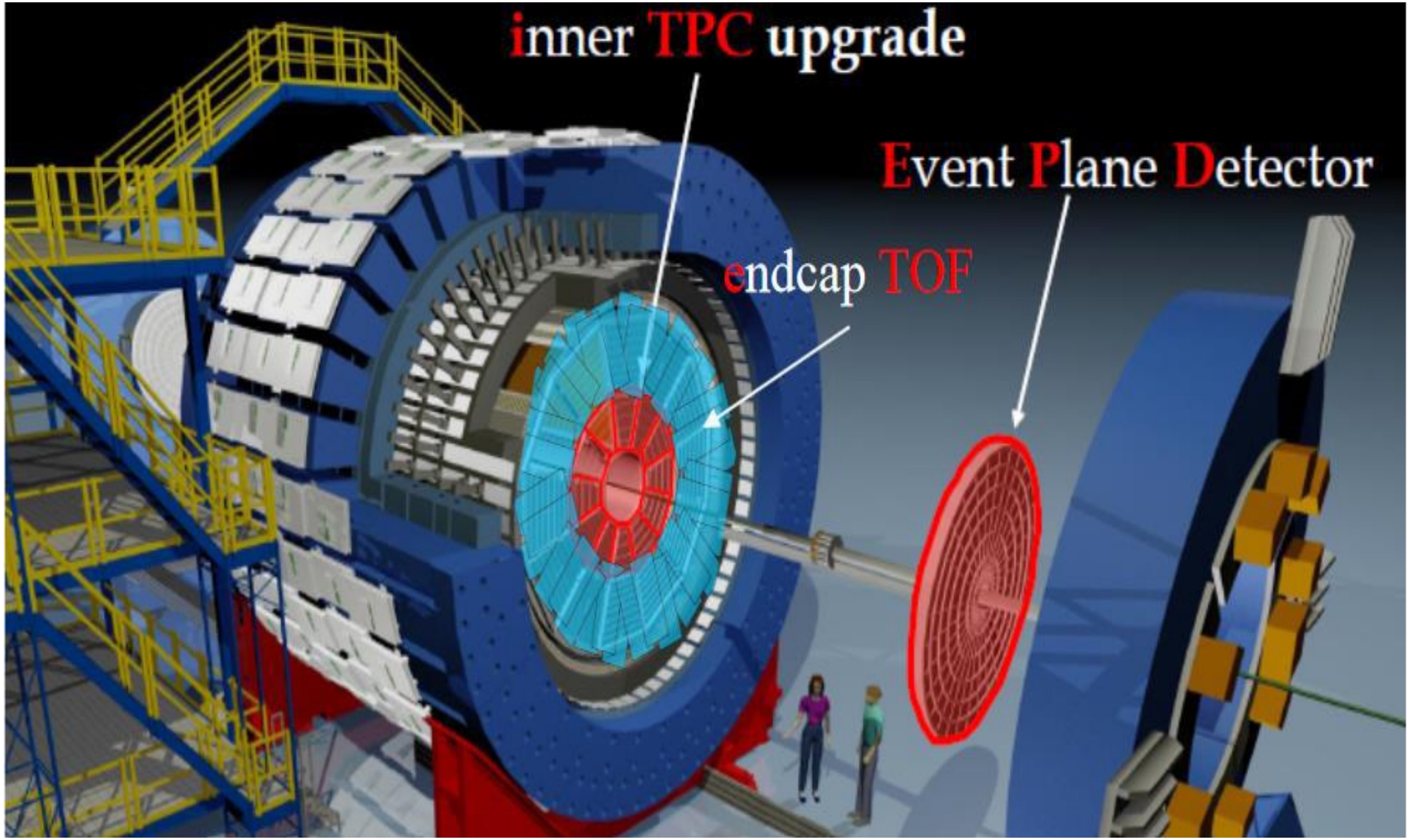


Two stages of Beam Energy Scan:
Stage I: 7.7 – 39 GeV 2010 – 2014
First glance at low energy region, rather low statistics

Stage II: 3 – 54.4 GeV 2017 – 2021
Precise measurements at low energies, large statistics



STAR detector upgrades

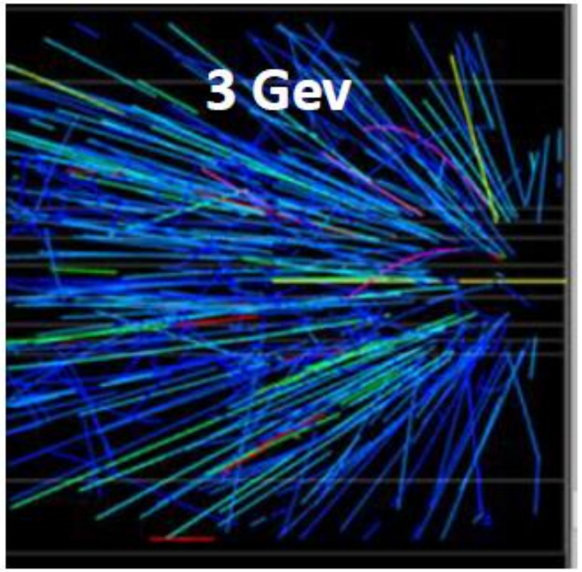


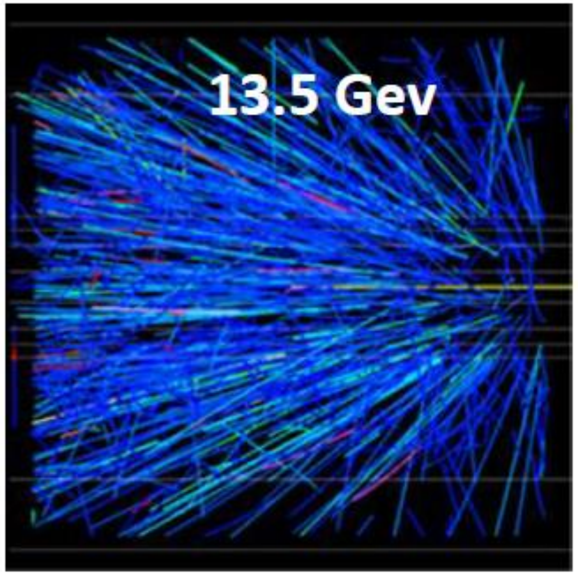
- **Tracking and PID (full 2π)**
  TPC: |η| < 1
  iTPC (2019+): |η| < 1.5
  TOF: |η| < 1
  eTOF (2019+): -1.6 < η < -1
  BEMC: |η| < 1
  EEMC: 1 < η < 2
  HFT (2014-2016): |η| < 1
  MTD (2014+): |η| < 0.5 (partial azimuthal coverage)

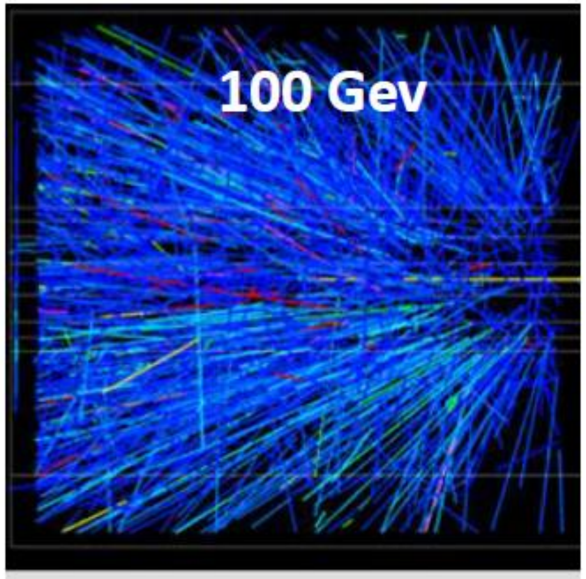
- **MB trigger and event plane reconstruction**
  BBC (before 2018): 3.3 < |η| < 5
  EPD (2018+): 2.1 < |η| < 5.1
  VPD: 4.2 < |η| < 5
  ZDC: 6.5 < |η| < 7.5

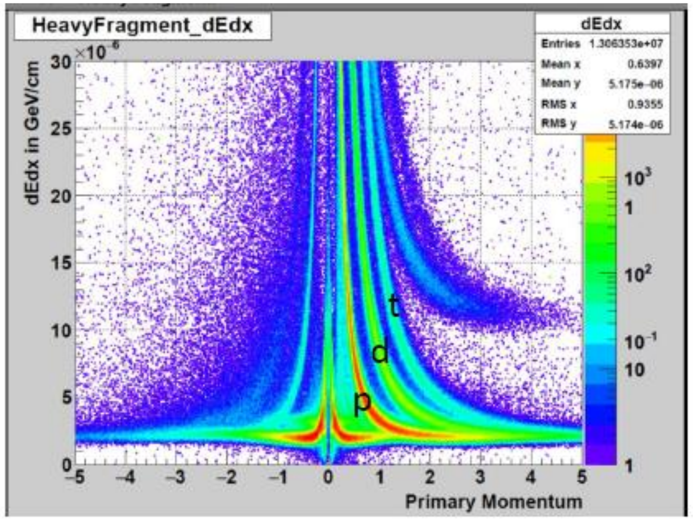
- **Recent upgrades 2022**
  FCS: 2.5 < |η| < 4
  FTS: 2.5 < |η| < 4
  ECAL & HCAL: 2.5 < |η| < 4

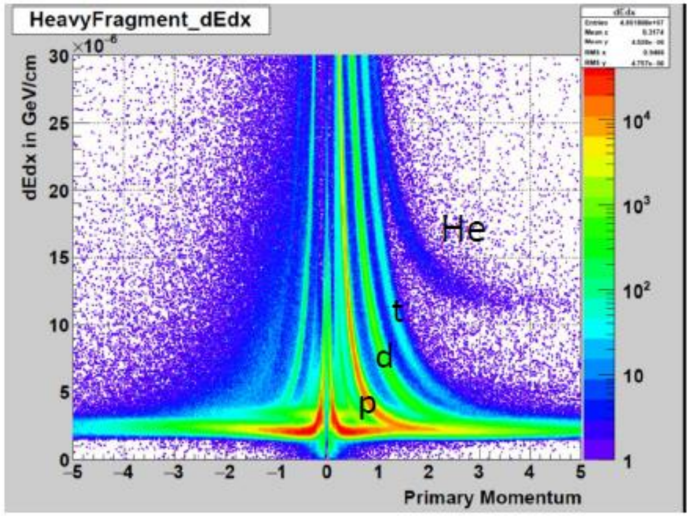
TPC coverage at FXT energies

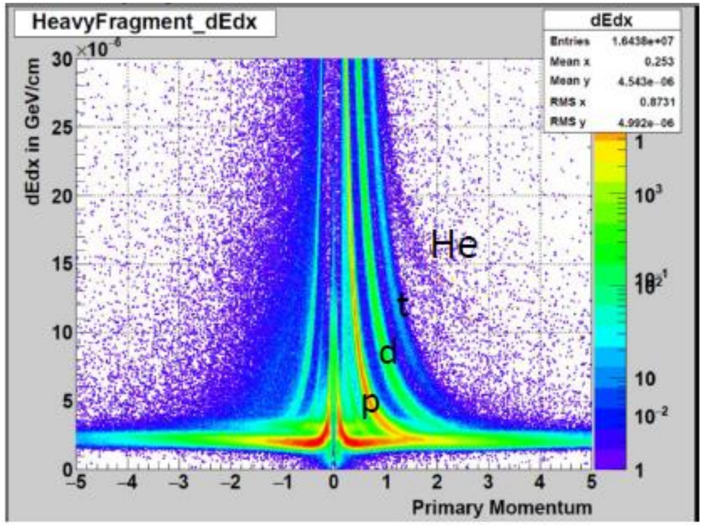




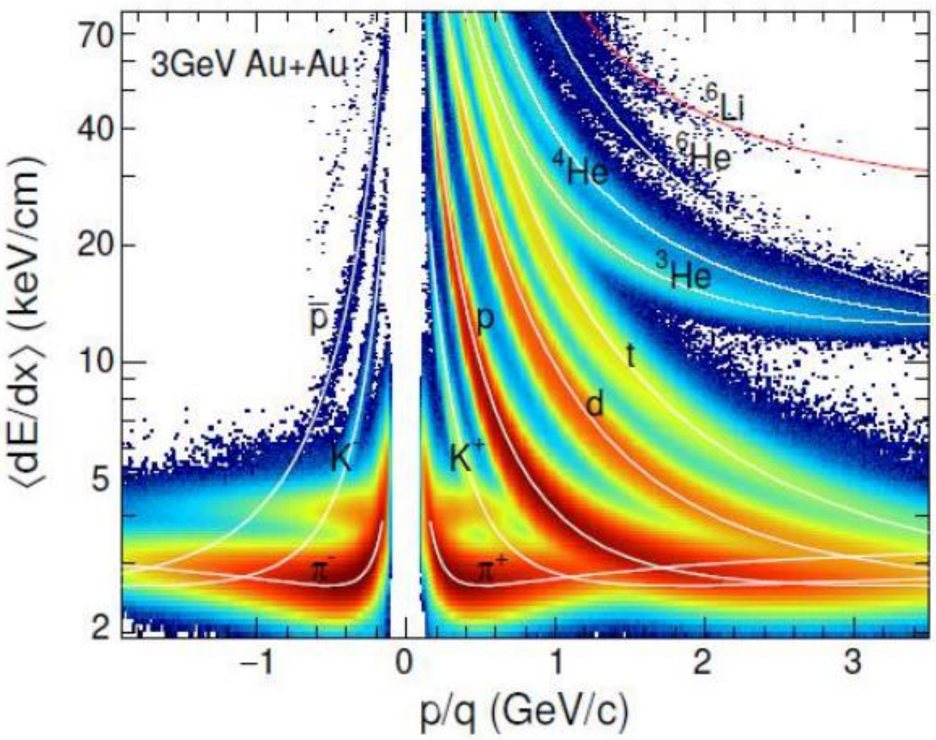


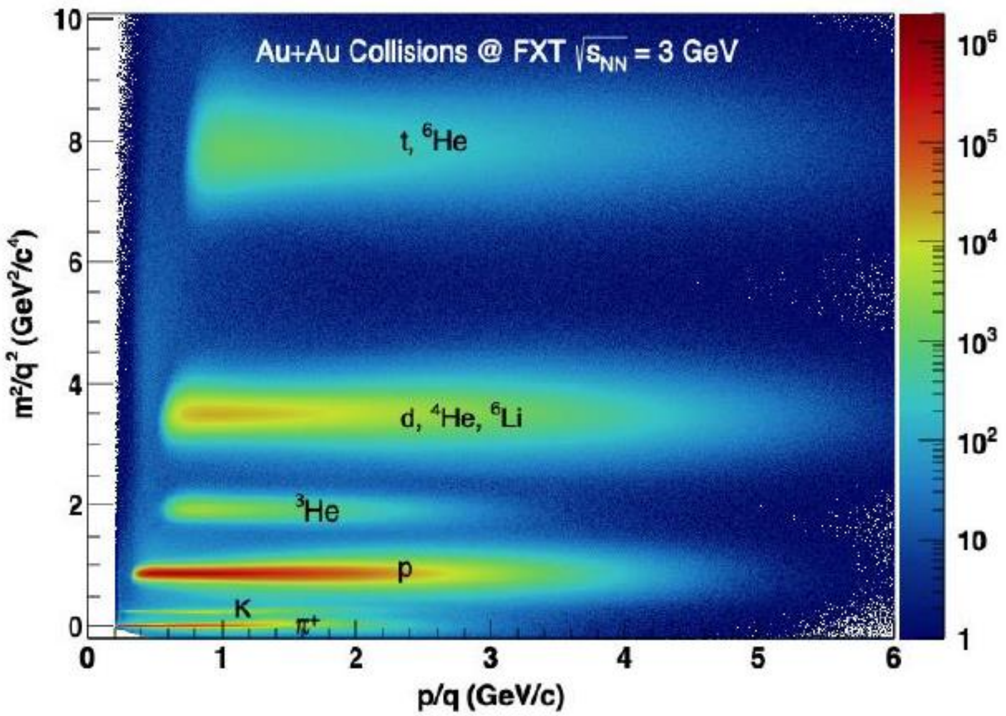






Particle identification at 3 GeV

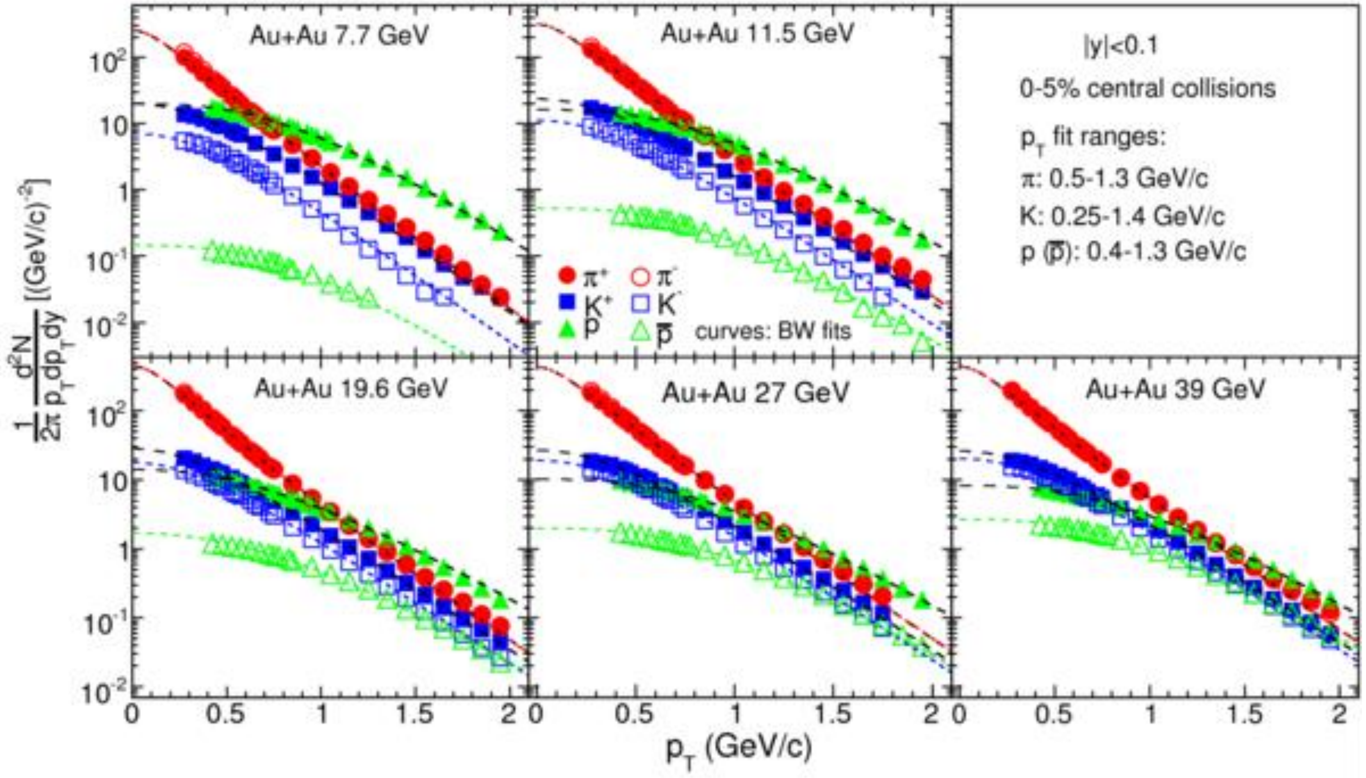


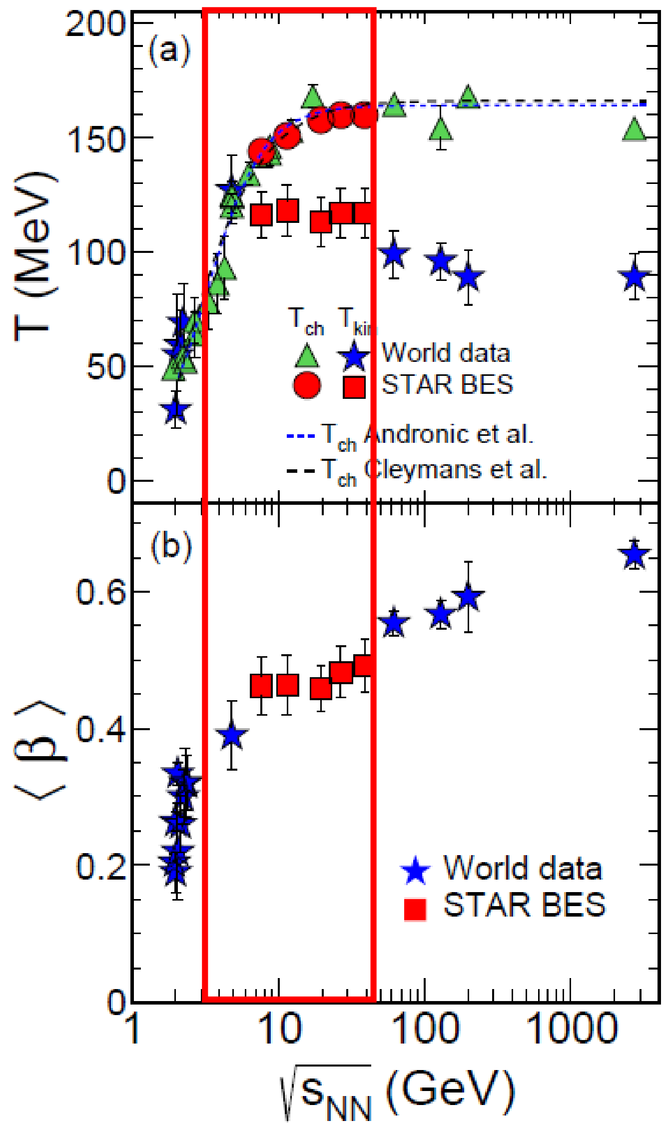


Detects particles in the $0 < \eta < 2$ range
π, K, p, d, t, h, α through dE/dx and ToF
K^0_s, Λ, Ξ, Ω, φ, $^3_\Lambda H$, $^4_\Lambda H$ trough invariant mass

About 300M events analyzed from 2018,
2B more recorded in 2021

Collectivity and temperature of the medium



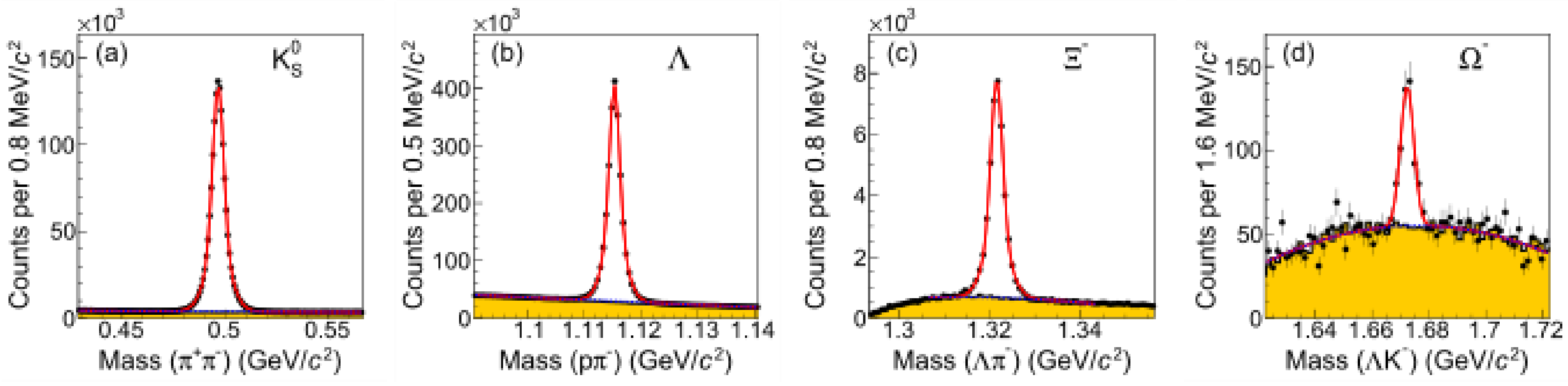


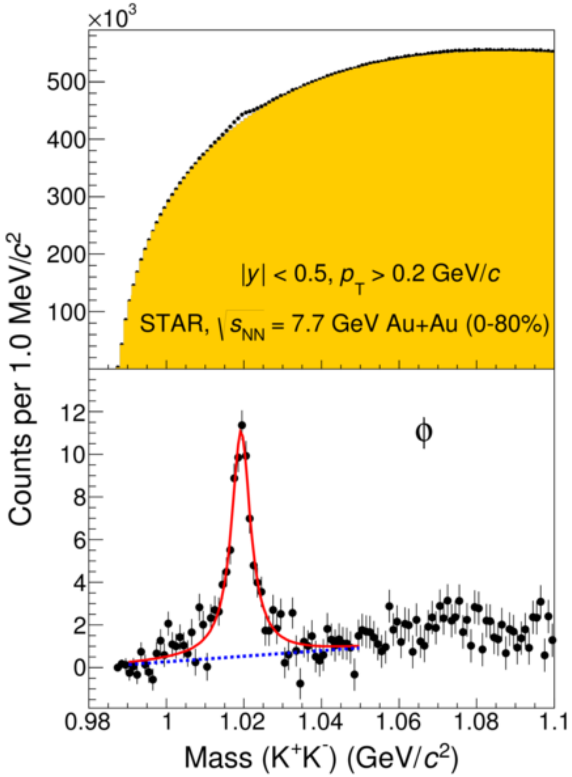
Parameters: Temperature (T_{kin}) and transverse radial velocity (β) obtained by fitting the momentum distribution of particles.

Phys. Rev. C **96** (2017) 44904

Strange particle production at BES-I

STAR, $\sqrt{s_{NN}}$ = 7.7 GeV Au+Au (0-80%), |y|<0.5



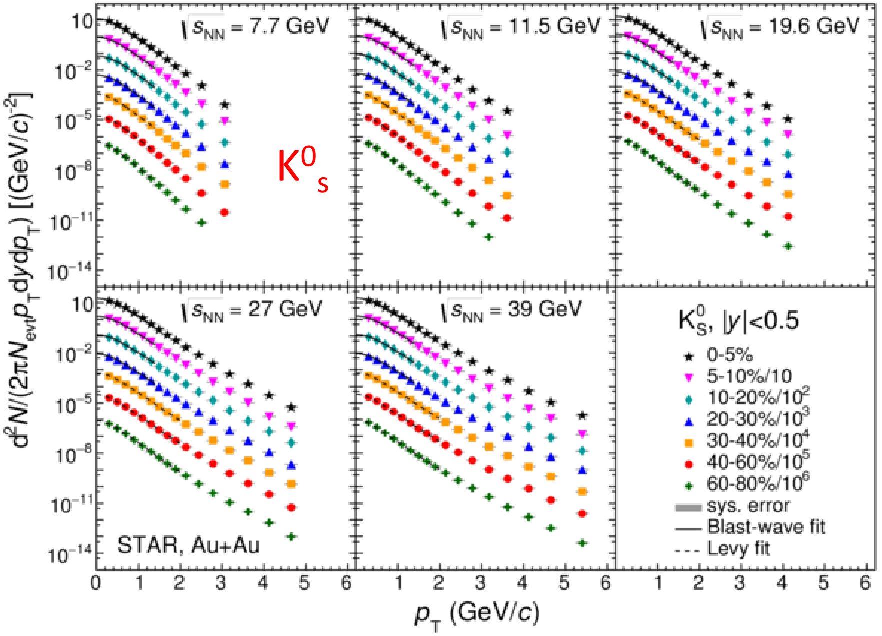


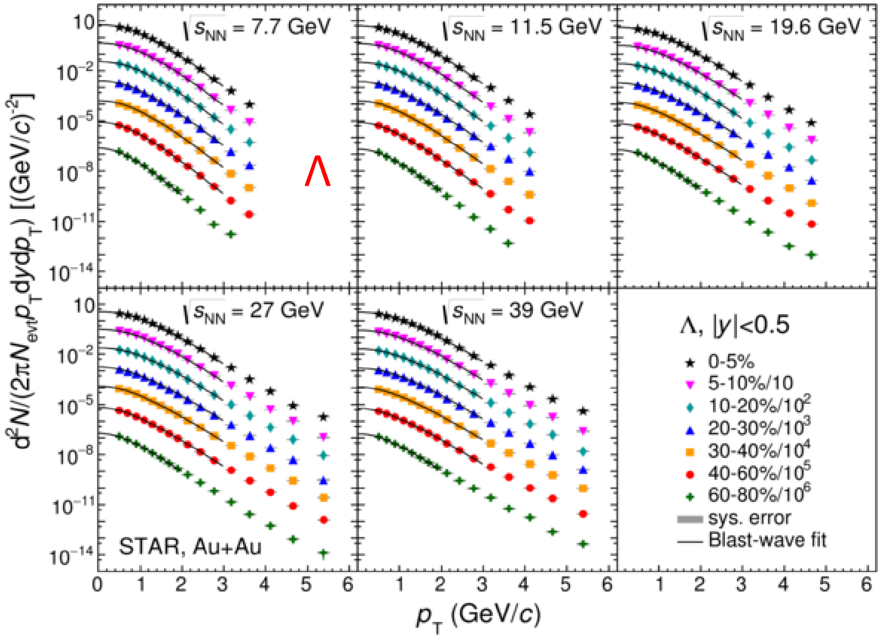
$\sqrt{s_{NN}}$ (GeV)	z-vertex range (cm)	MB events (10^6)
7.7	[-70, 70]	4.4
11.5	[-50, 50]	12.0
19.6	[-70, 70]	36.3
27	[-70, 70]	72.8
39	[-40, 40]	134.3

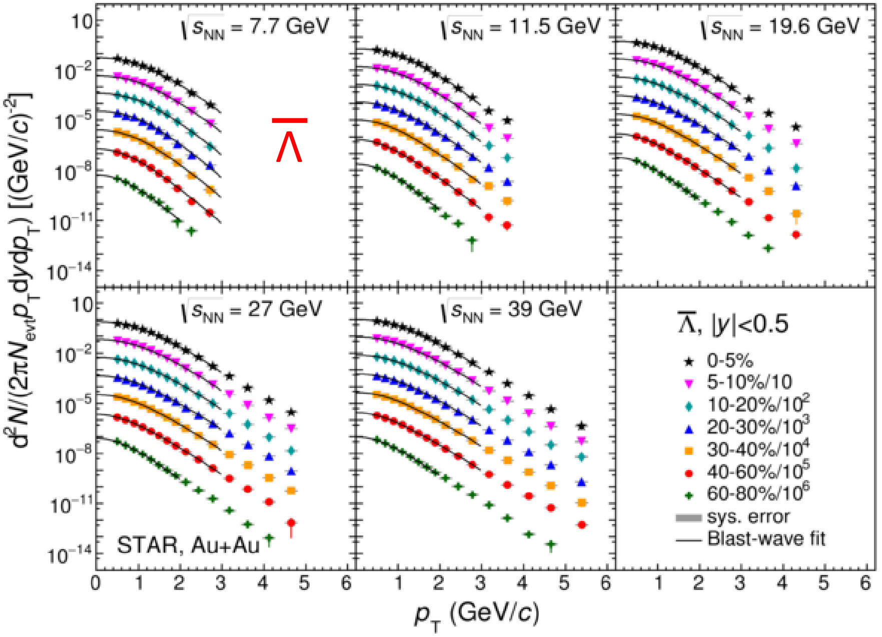
$$
\begin{aligned}
&K^0_S \to \pi^+ + \pi^-, && 69.20\%;\\
&\Lambda(\overline{\Lambda}) \to p(\overline{p}) + \pi^-(\pi^+), && 63.9\%;\\
&\Xi^-(\overline{\Xi}^+) \to \Lambda(\overline{\Lambda}) + \pi^-(\pi^+), && 99.887\%;\\
&\Omega^-(\overline{\Omega}^+) \to \Lambda(\overline{\Lambda}) + K^-(K^+), && 67.8\%;\\
&\phi \to K^+ + K^-, && 49.1\%.
\end{aligned}
$$

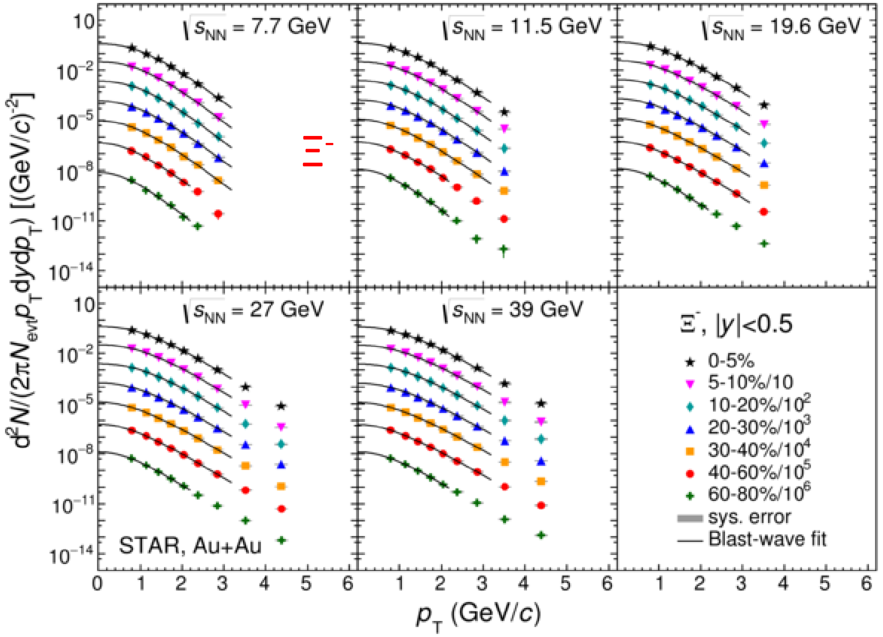
Phys. Rev. C **102** (2020) 34909

Strange particle production at BES-I









K^0_s, Λ, anti-Λ, Ξ^- transverse momentum spectra at midrapidity |y| < 0.5

Levy fit

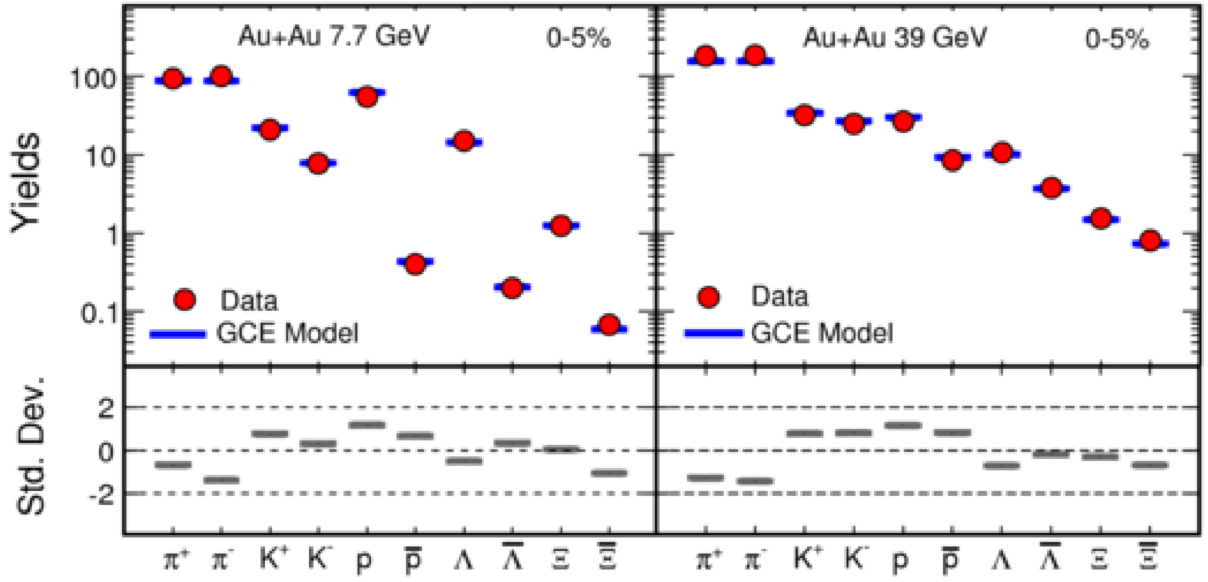
$$\frac{d^2N}{2\pi p_T dp_T dy} \propto \left(1+\frac{m_T-m_0}{nT}\right)^{-n}$$

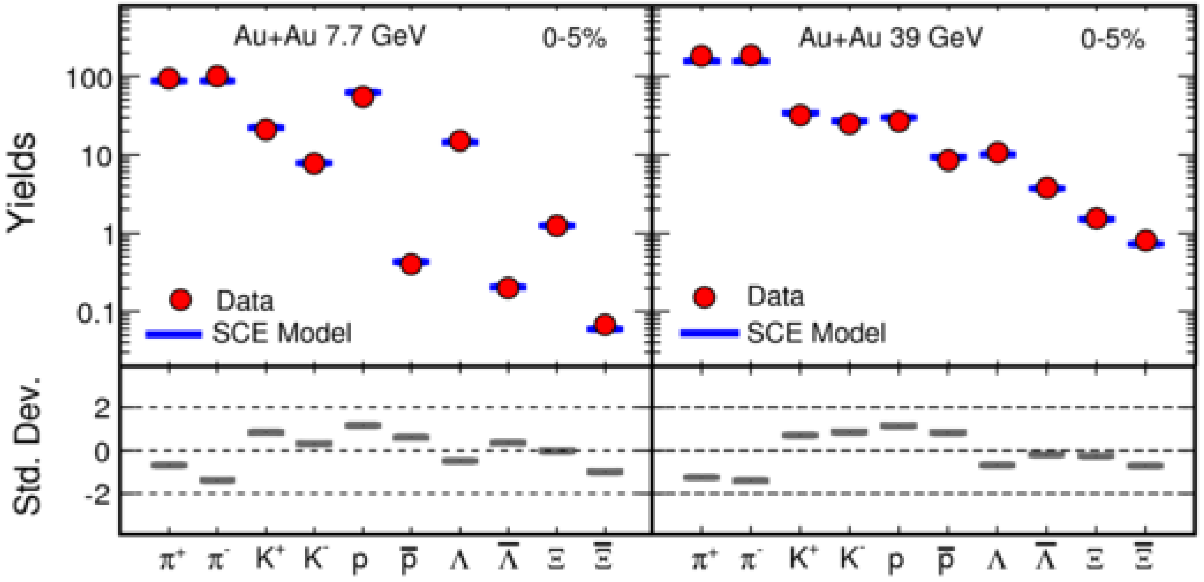
Blast-wave fit

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

Phys. Rev. C **102** (2020) 34909

Comparison to thermal model predictions





Blast-wave fits for particle spectra

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

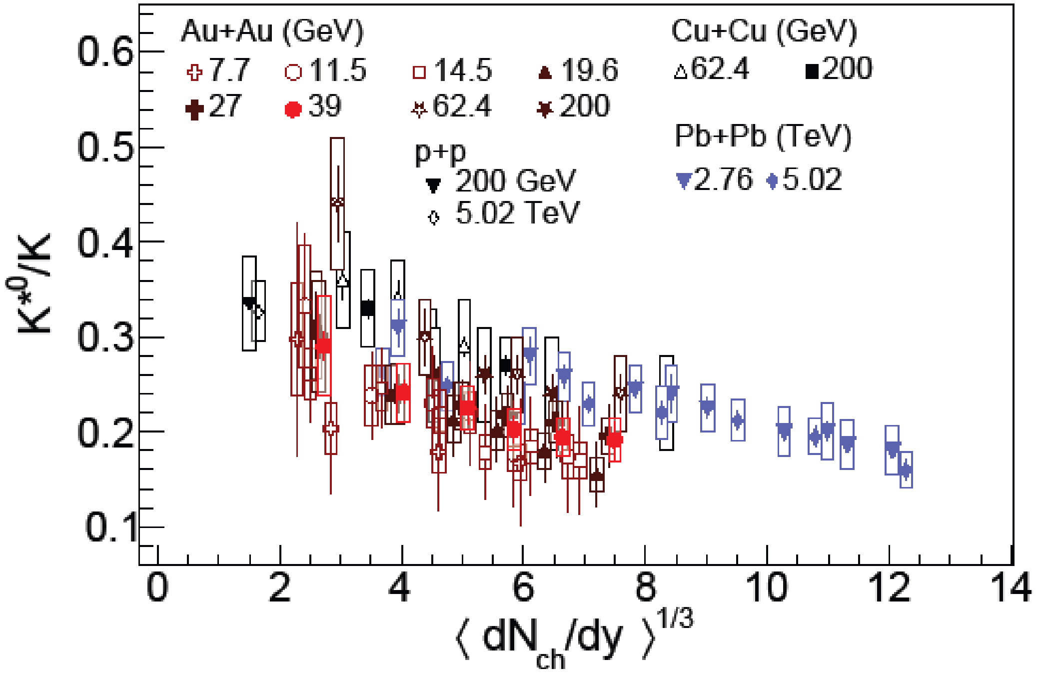
Grand Canonical Ensemble – B, Q and S are conserved on average
Canonical Ensemble – exact conservation of B, Q and S
Strangeness Canonical Ensemble – exact conservation of S

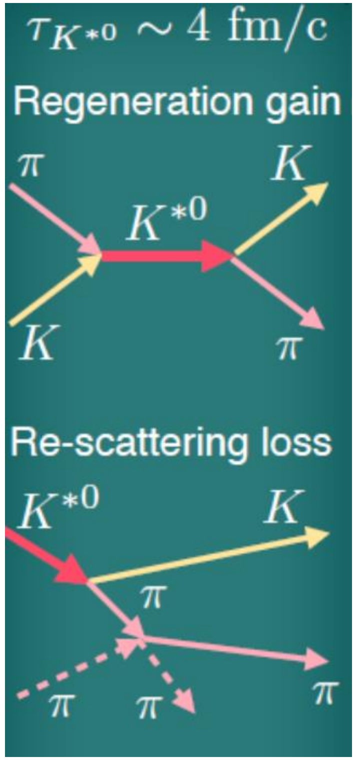
Phys. Rev. C **96** (2017) 44904

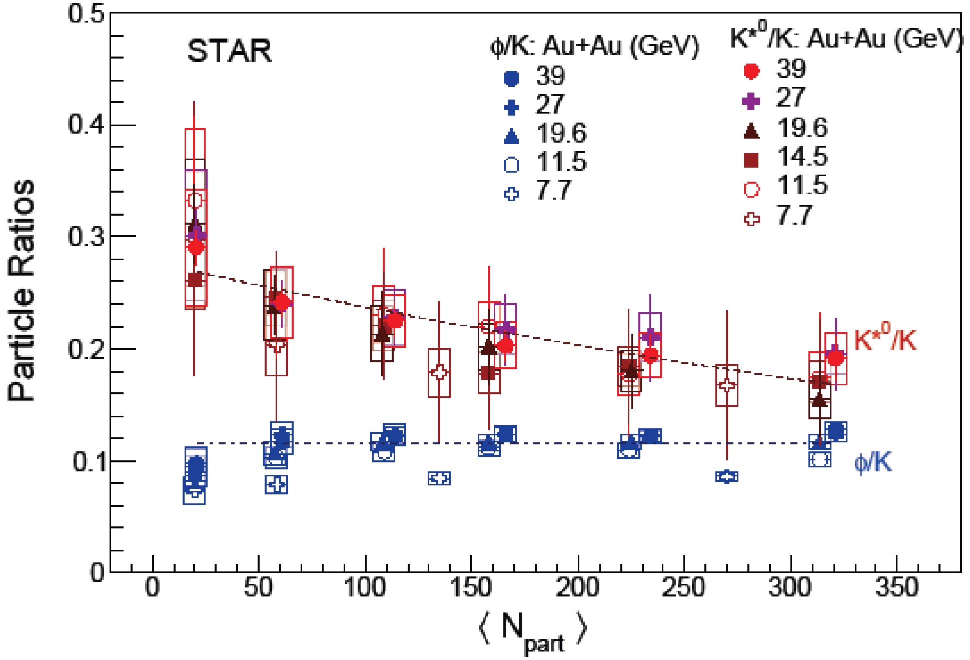
Hidden vs. open strangeness production

Ratio K^{*0} to K from BES data suggests re-scattering loss in medium due to shorter lifetime of K^{*0}

The K^{*0}/K ratio shows a centrality dependence and follows the same trend among different collision energies. On the contrary, the ϕ/K ratio is mostly independent of centrality.

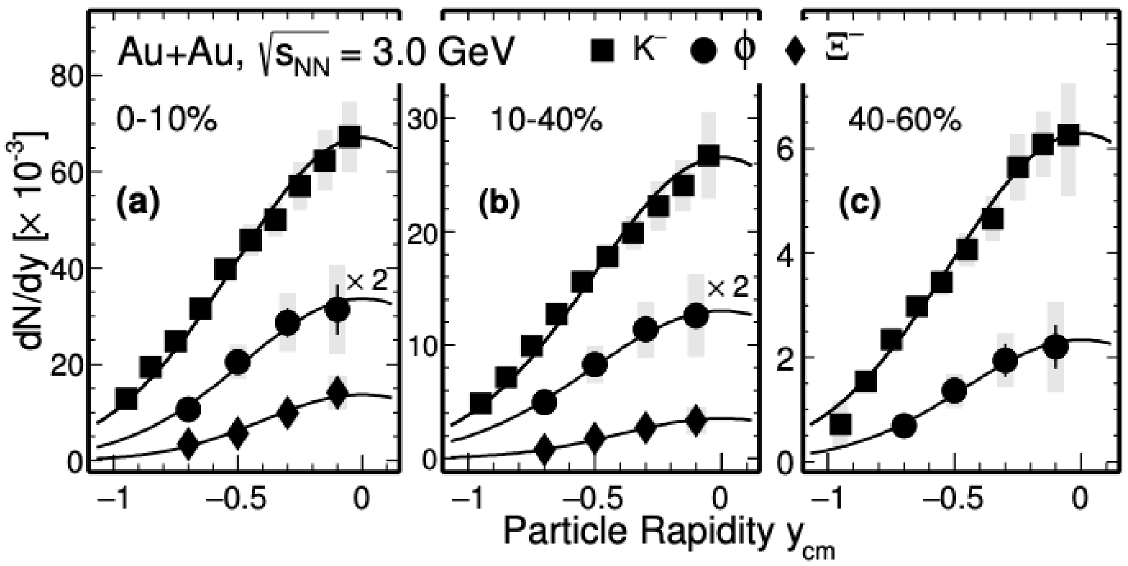


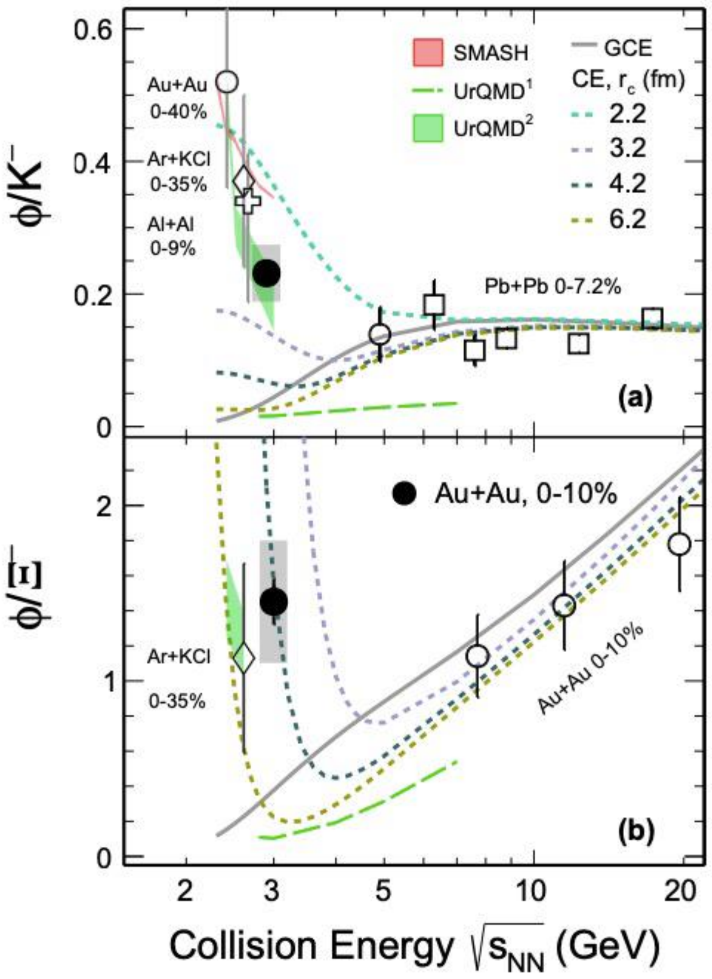




e-Print: 2210.02909 [nucl-ex]

Hidden vs. open strangeness production





The thermal model with grand canonical ensemble (GCE) under-predicts the ratios

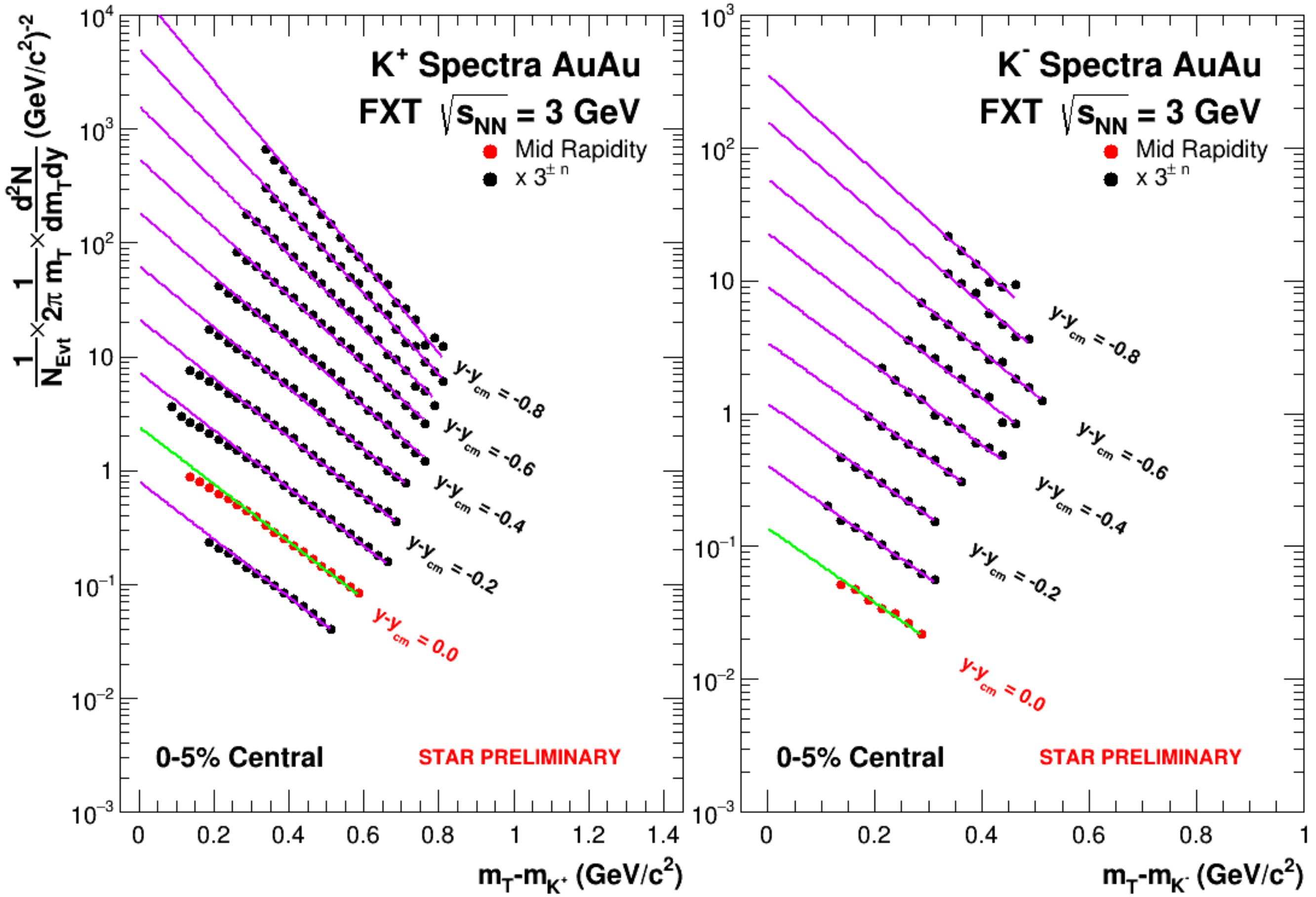
The canonical ensemble (CE) calculations reproduce the ratios with a correlation length of 3-4 fm

These observations imply that strange particles are produced in a system of high baryon density causing the small correlation length

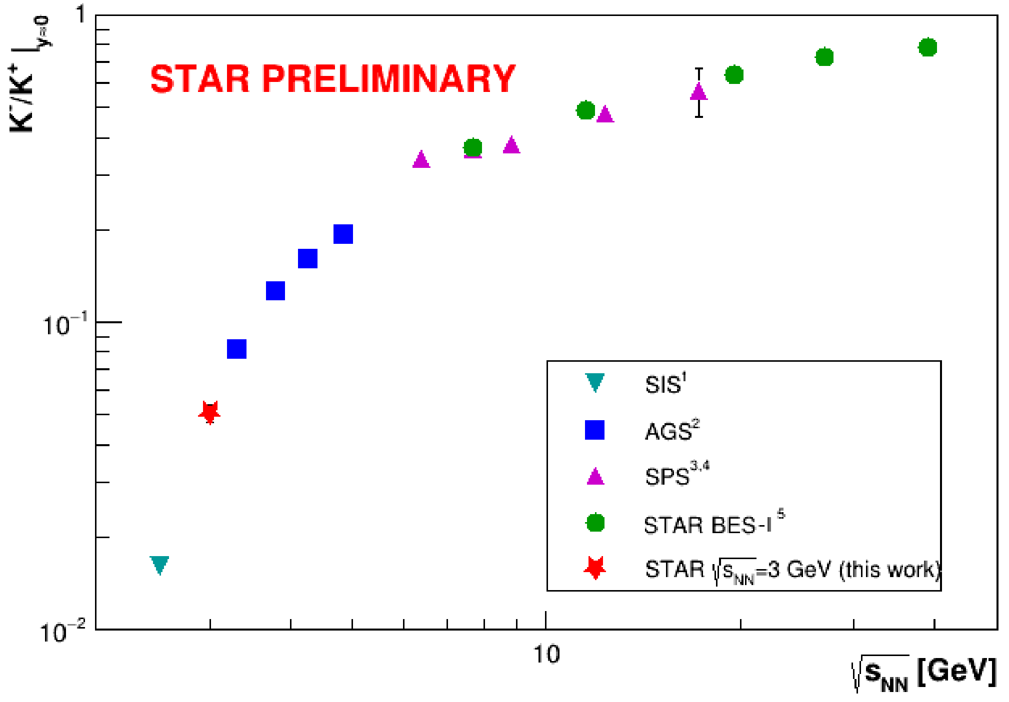
Phys. Lett. B **831**(2022) 137152

Charged kaon production at 3 GeV

Kaon spectra near midrapidity described well with m_T exponential function since Bose-Einstein enhancement and radial flow effects mostly cancel



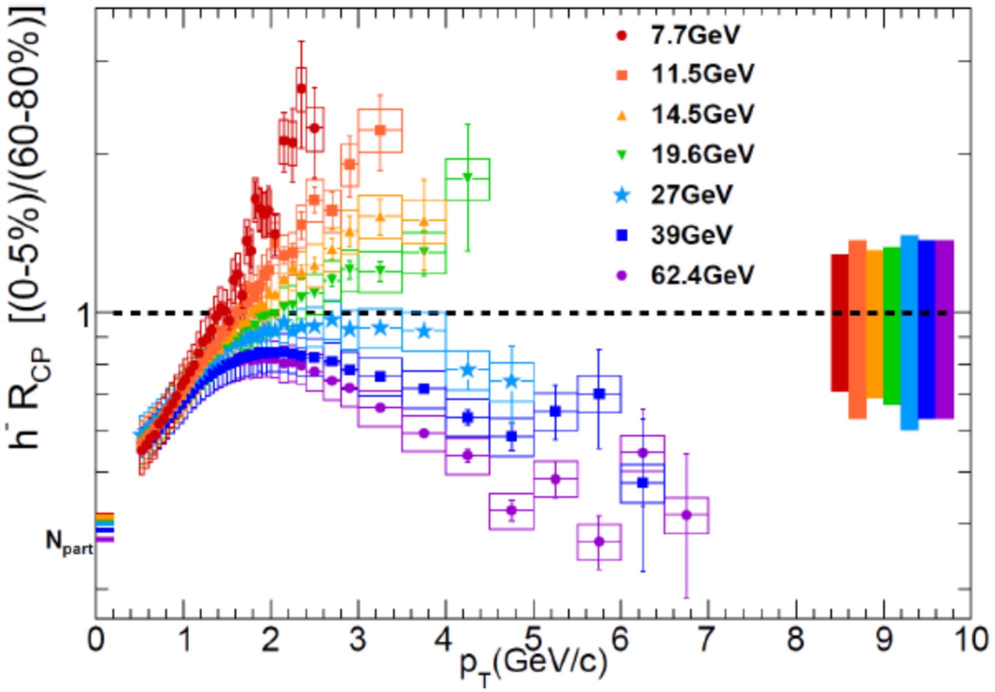
K^-/K^+ ratio at midrapidity is affected by baryon stopping



1 A. Forster et al. (KaoS Collaboration), J. Phys. G **28**, 2011 (2002)
2 L. Ahle et al. (E866 and E917 Collaborations), Phys. Lett. B**490**, 53 (2000)
3 C. Alt et al. (NA49 Collaboration), Phys. Rev. C **77**, 024903 (2008)
4 S. Afanasiev et al. (NA49 Collaboration), Phys. Rev. C **66**, 054902 (2002)
5 L. Adamczyk et al. (STAR Collaboration), Phys. Rev. C **96**, 044904 (2017)

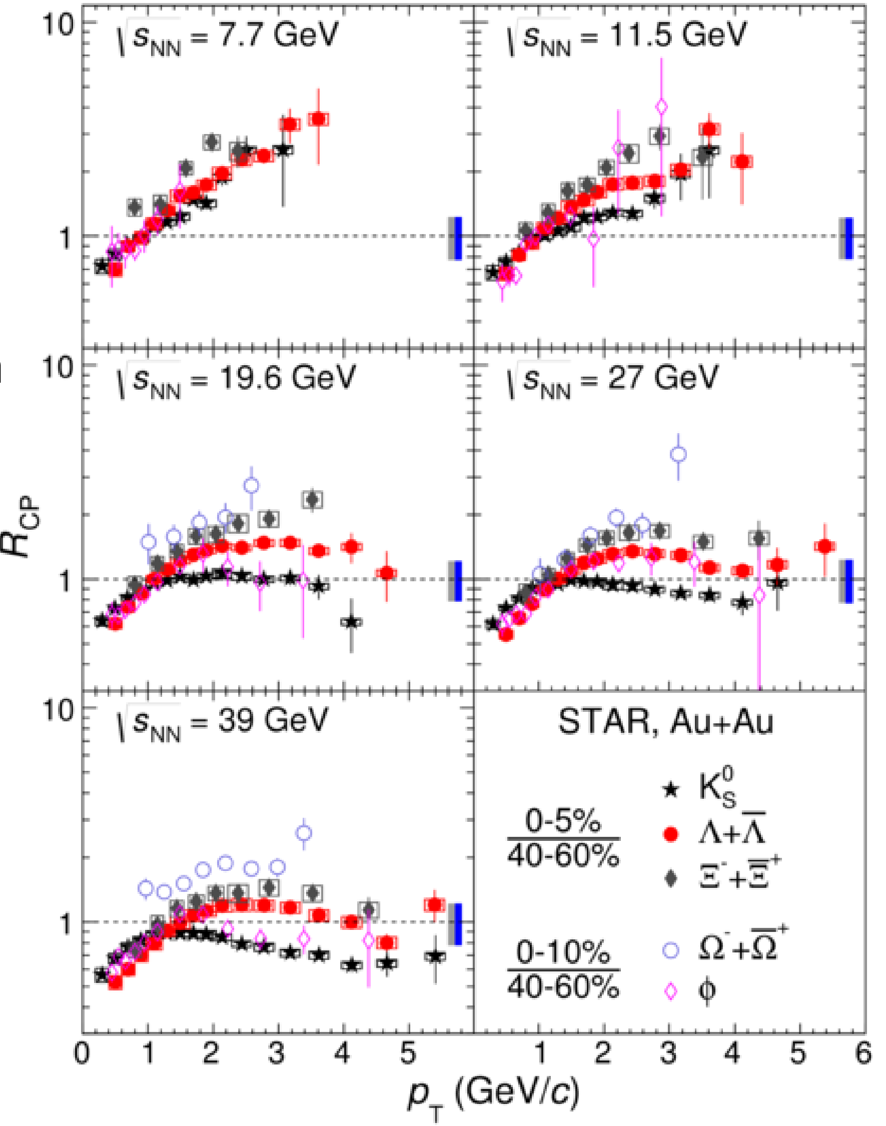
Nuclear modification in the medium

$$R_{cp} = \frac{d^2 N dp_t d\eta / < N_{coll} > (central)}{d^2 N dp_t d\eta / < N_{coll} > (peripheral)}$$



R_{cp} has two regimes in the behavior depending on the collision energy:
decrease of particle production with high p_T in central collisions at high energies
smooth growth of particle production in central collisions at low collision energies.

High statistics of BES-II will allow to measure R_{cp} in high p_T region at low collision energies

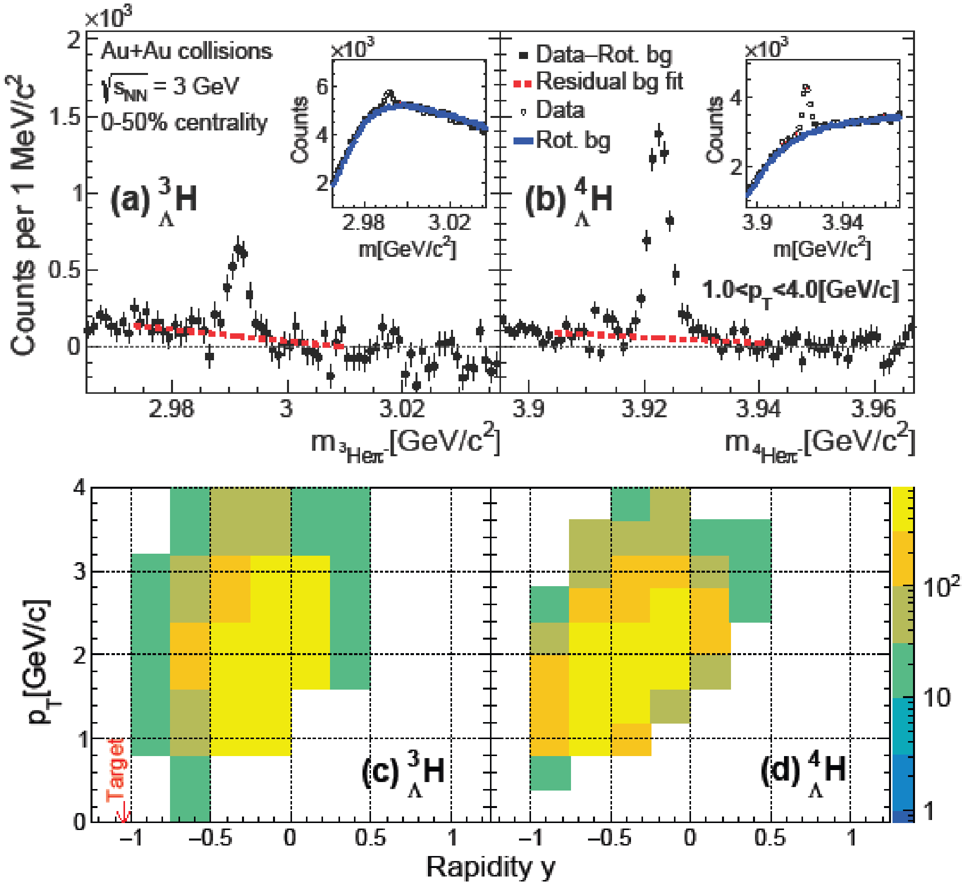


Phys. Rev. C **102** (2020) 34909
Phys. Rev. Lett. **121** (2018) 32301

Hypernuclei production

300M Au+Au data without iTPC and eTOF

Candidate reconstruction via invariant mass in two body decay



$$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$$

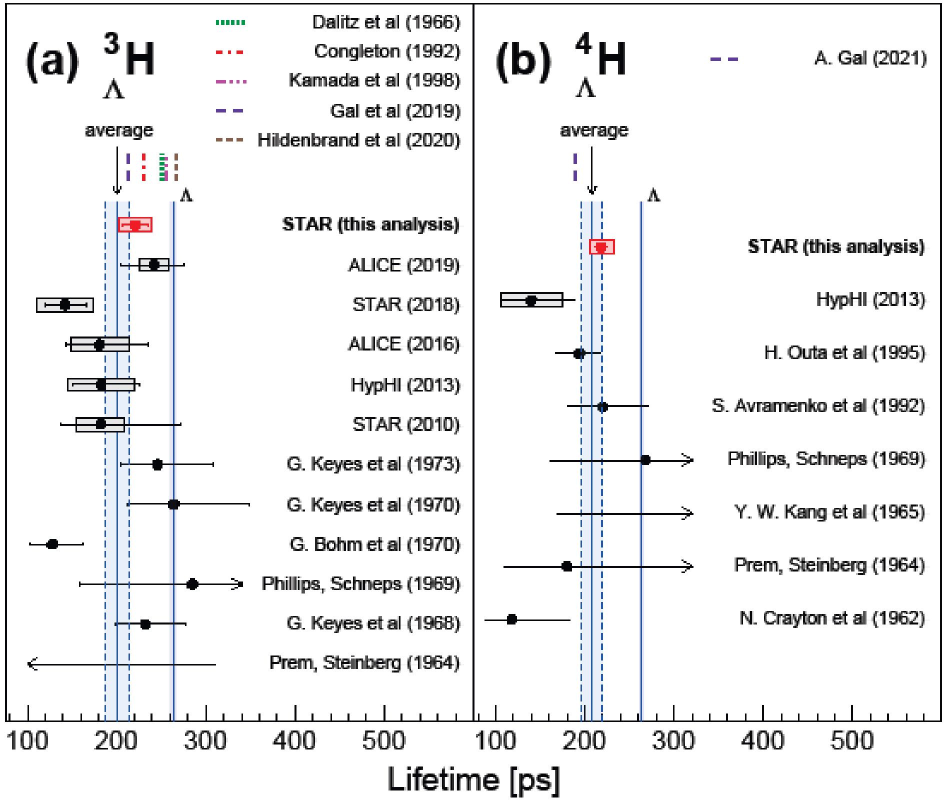
$$^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$$

Measured lifetime results at $\sqrt{s_{NN}}$ = 3.0 and 7.2 GeV are in a good agreement with each other

The combined results are

$$\tau({}^{3}_{\Lambda}H) = 221 \pm 15(\text{stat.}) \pm 19(\text{syst.})\ \text{ps.}$$

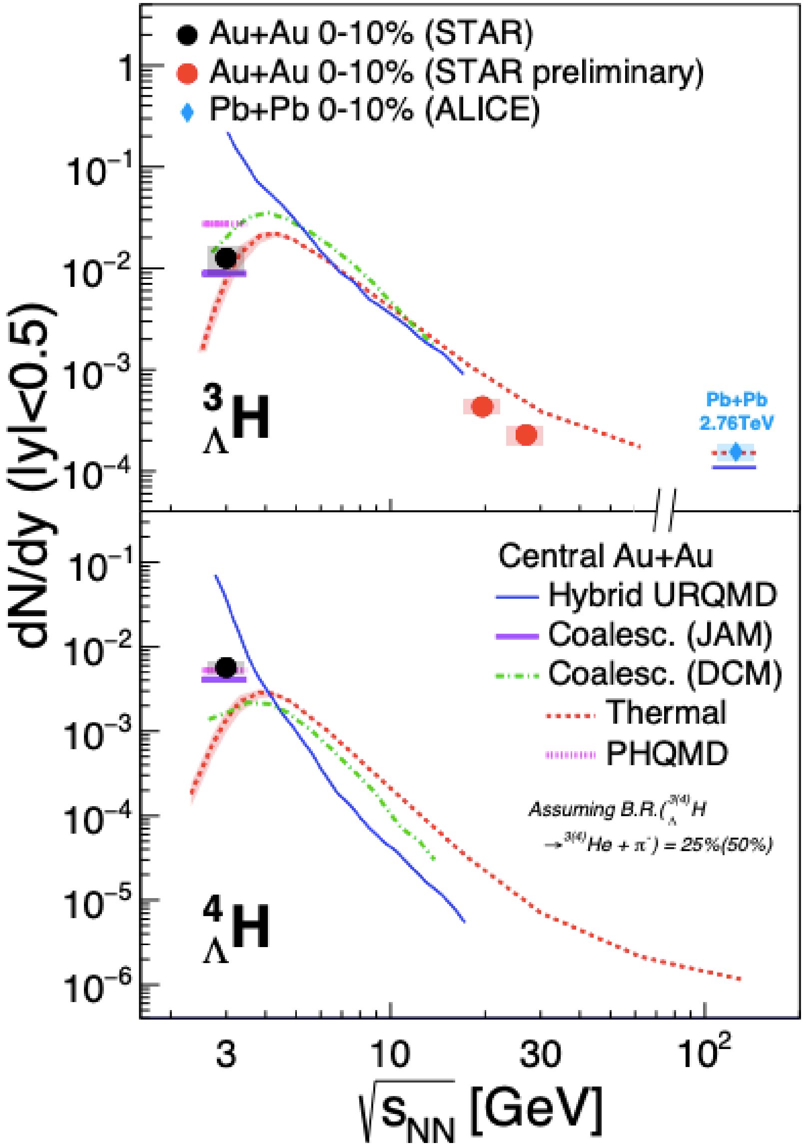
$$\tau({}^{4}_{\Lambda}H) = 218 \pm 6(\text{stat.}) \pm 13(\text{syst.})\ \text{ps.}$$



Lifetime measurements are consistent with previous measurements and have higher precision

PRL **128** (2022) 202301

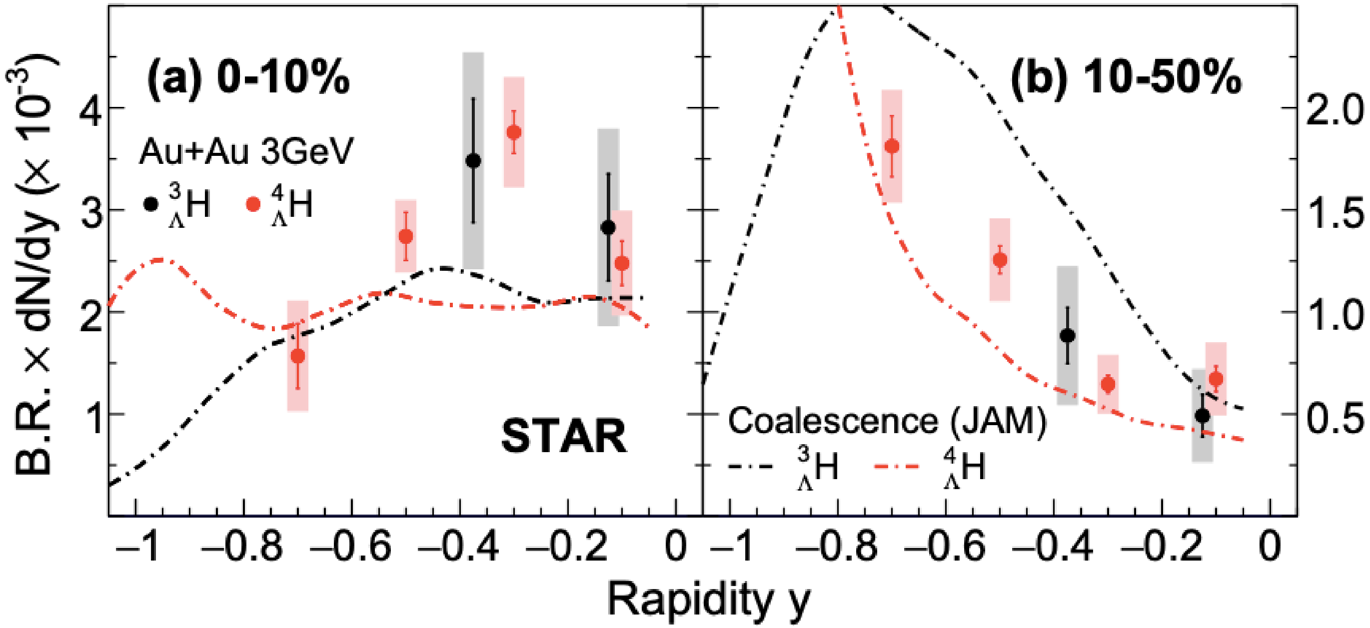
Hypernuclei production



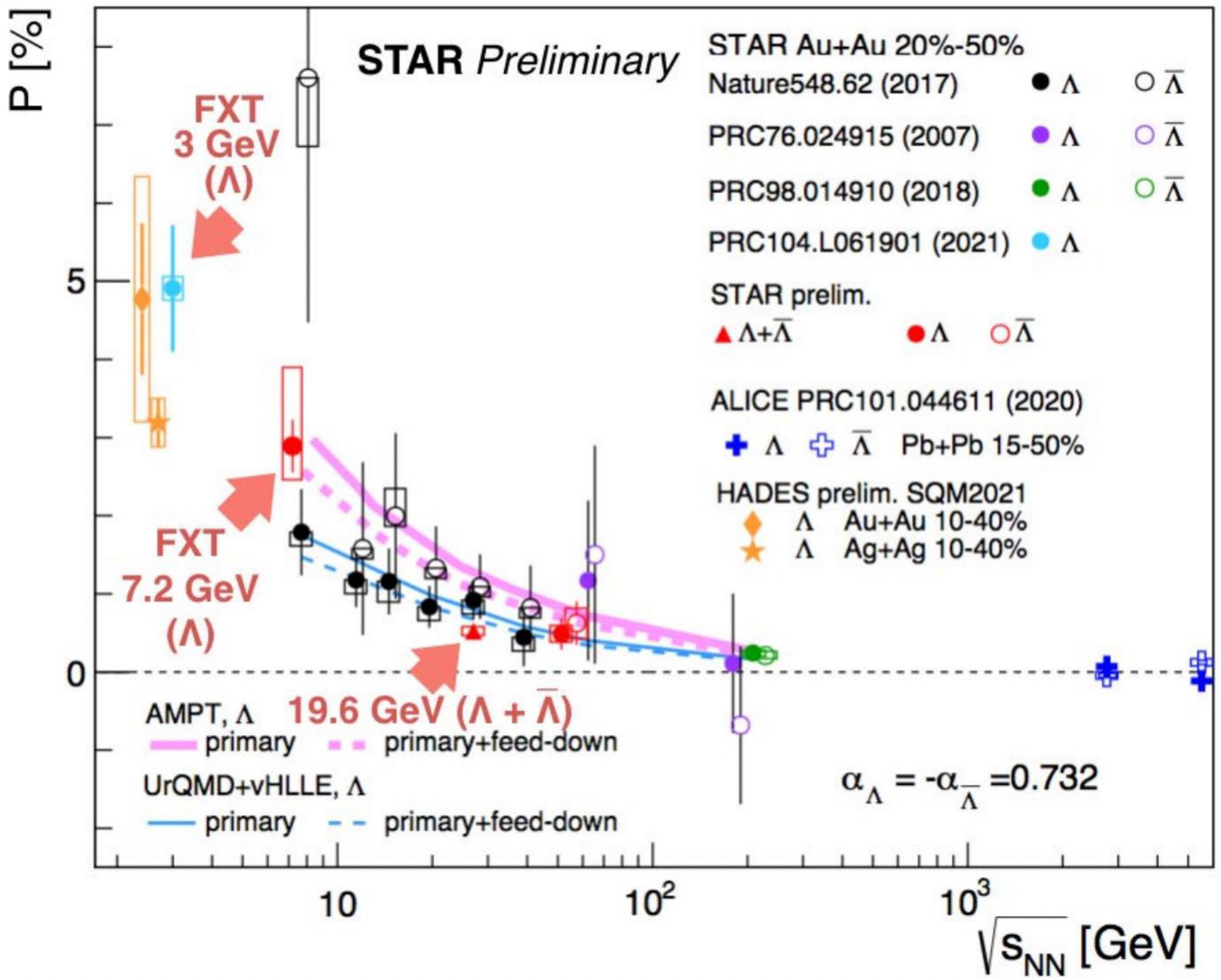
PRL **128** (2022) 202301

Hypertriton yields follow the thermal model prediction

Hyper-H4 yields are under predicted by the thermal model



Global hyperon polarization measurements



Global hyperon polarization over a large range of collision energy is measured and can be described by hydrodynamic and transport models with intense fluid vorticity of the QGP

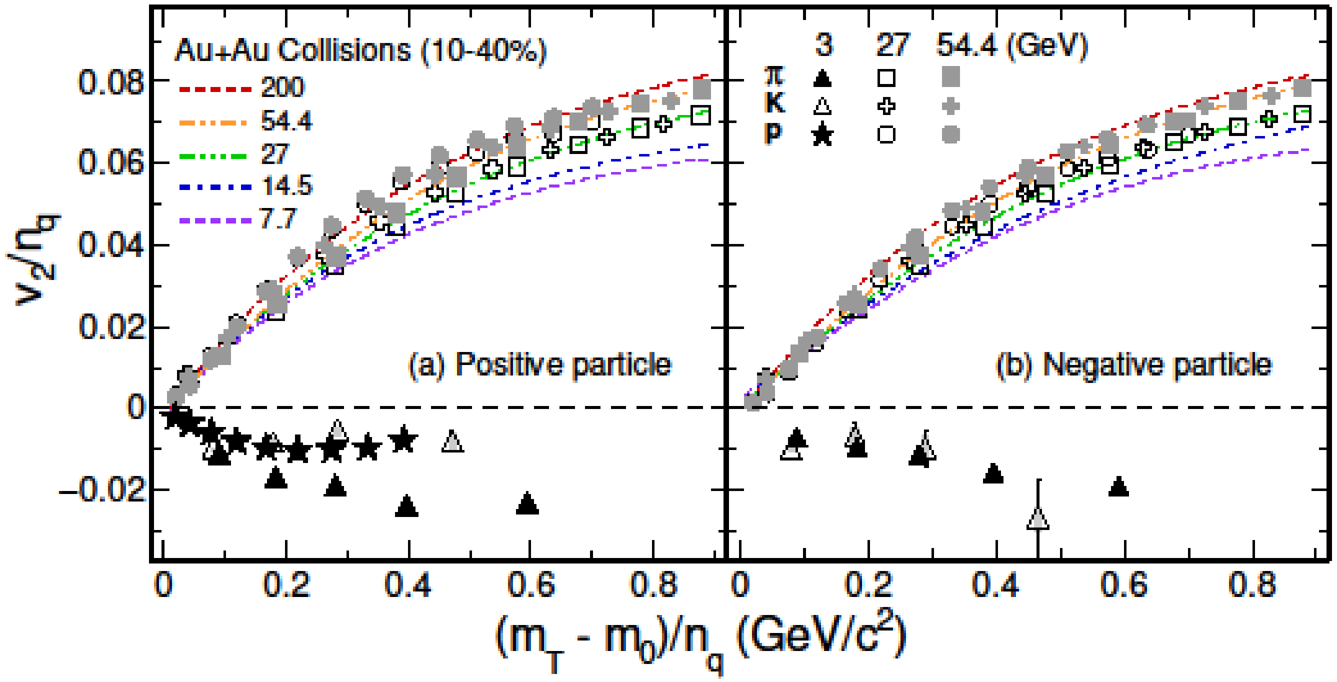
The observation of substantial polarization in these collisions may require a reexamination of the viscosity of any fluid created in the collision, of the thermalization timescale of rotational modes, and of hadronic mechanisms to produce global polarization.

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1+\alpha_H|\vec{\mathcal{P}}_H|\cos\theta^*\right)$$

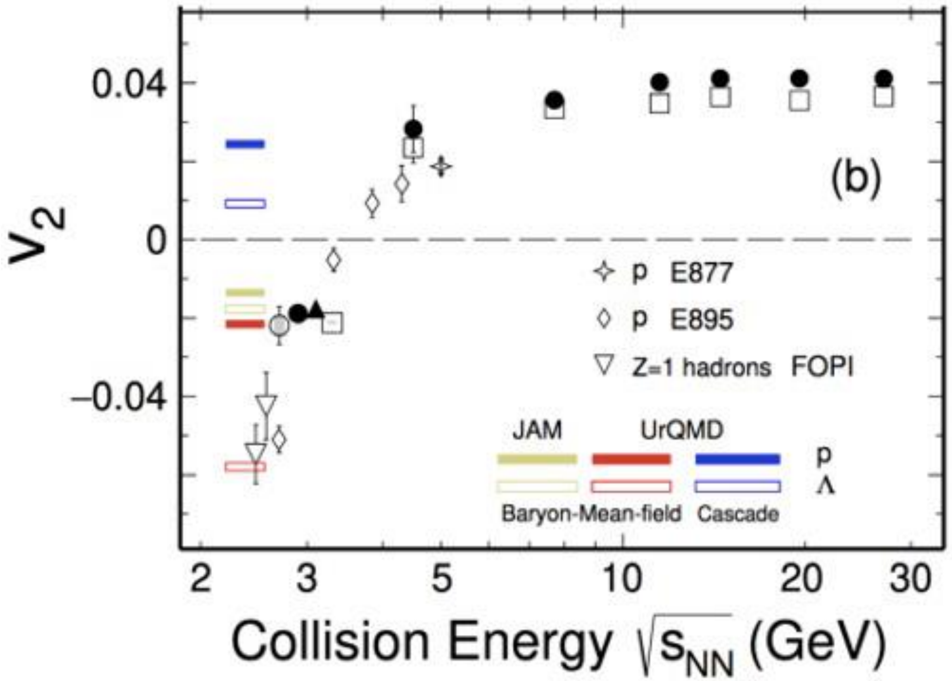
Nature 548 (2017) 62,
PRC **104** (2021) 061901,
arXiv: 2204.02302

Elliptic flow at 3 GeV

Elliptic flow is negative (squeeze-out) at 3 GeV, as expected from the previous AGS data



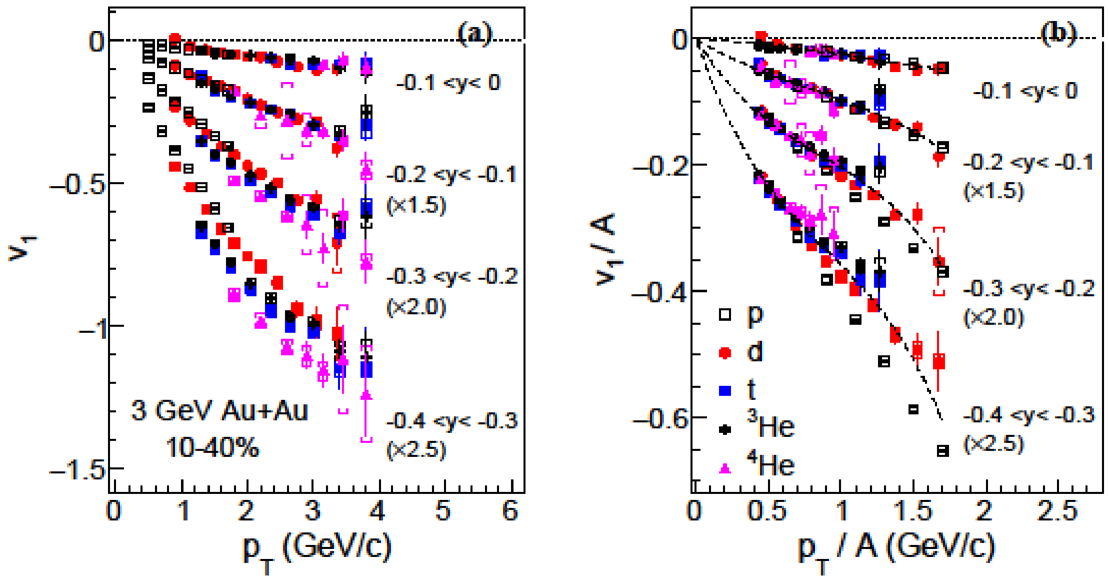
The quark number scaling has been used at higher energies as a signature of the QGP. At 3 GeV, the scaling is broken down e.g. hadronic gas (not QGP).



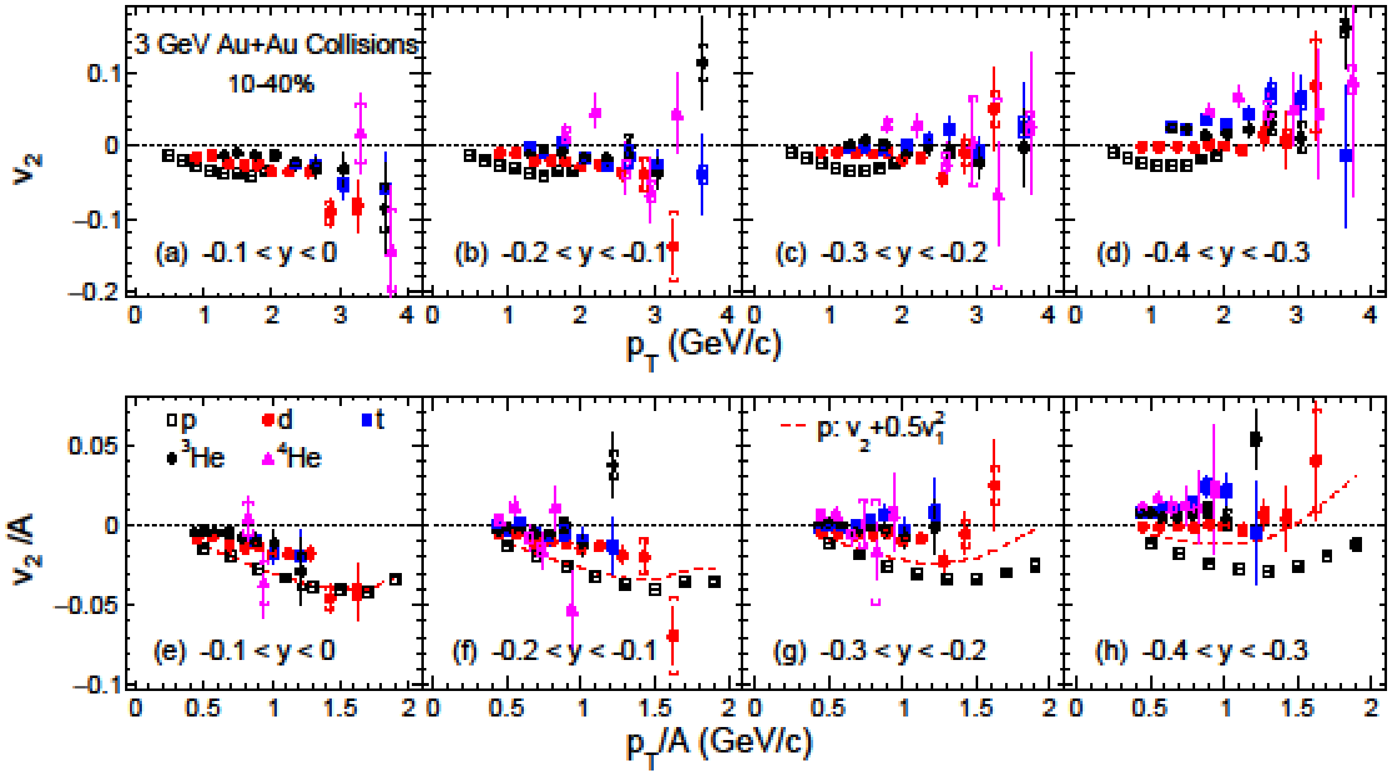
Phys. Lett. B **827** (2022) 137003

Collective flow of light nuclei

v_1 and v_2 values are negative for all measured light nucleus species except for v_2 within $-0.4 < y < -0.3$



This indicates that no A scaling is observed in these data for light nucleus v_2 at 3 GeV. The A scaling has been observed for $p_T/A < 1.5$ GeV/c in higher energy Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 200$ GeV



The v_1 scaling behavior suggests the light nuclei are formed via nucleon coalescence

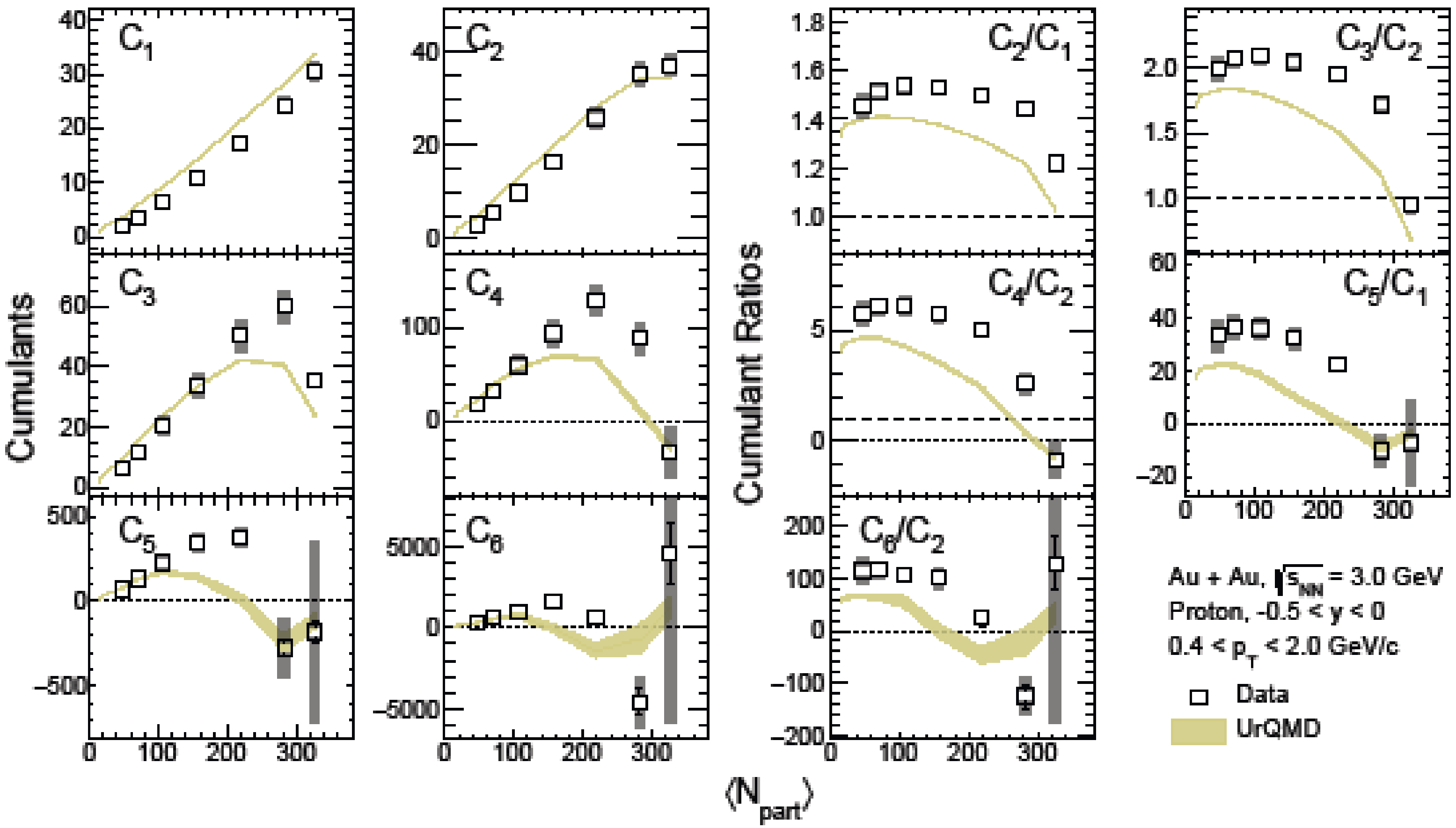
The scaling worsens for $p_T/A > 1$ GeV/c in the range $-0.4 < y < -0.3$, where simple coalescence may not apply

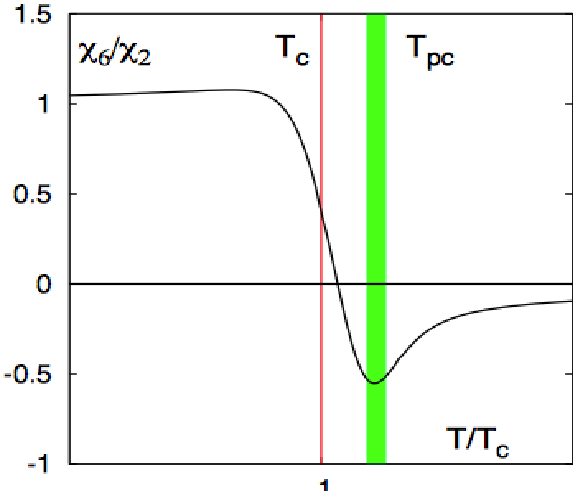
Increasing contamination of target-rapidity ($y = -1.045$) fragments may also play a role

Phys. Lett. B **827** (2022) 136941

Higher-order cumulants at 3 GeV

Cumulants of proton and its ratios at 3 GeV





Susceptibility ratios fluctuate near the CP. It can be measured via cumulants of net-protons

$$C_1 = \langle N \rangle$$

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

$$C_3 = \langle (\delta N)^3 \rangle$$

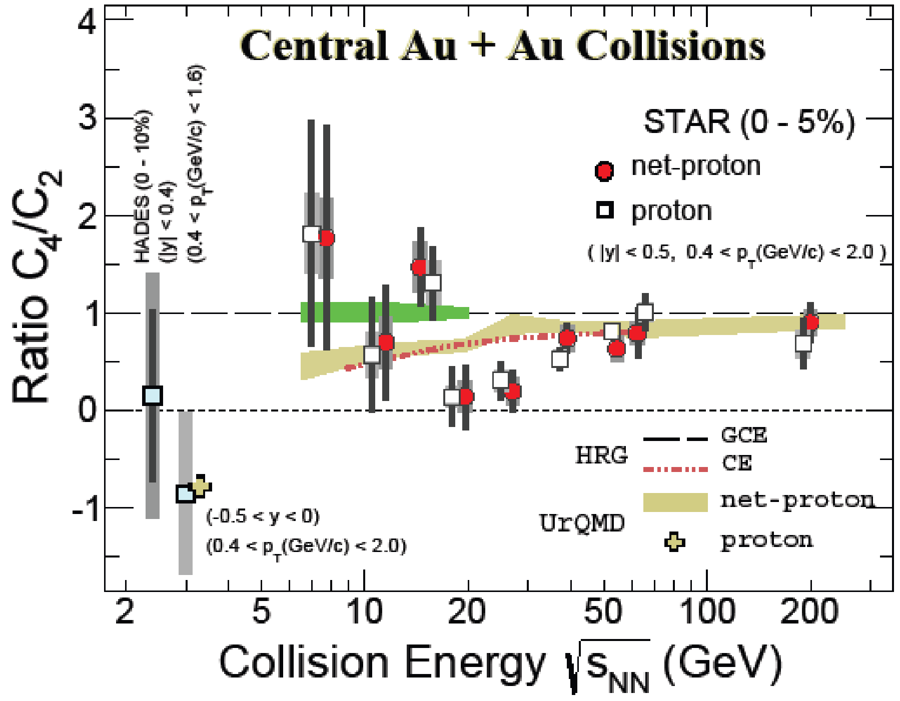
$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$$

Higher-order cumulant ratios C4/C2, C5/C1, and C6/C2 in most central events appear least affected by volume fluctuations in the 3 GeV Au+Au collisions

e-Print: 2209.11940 [nucl-ex]

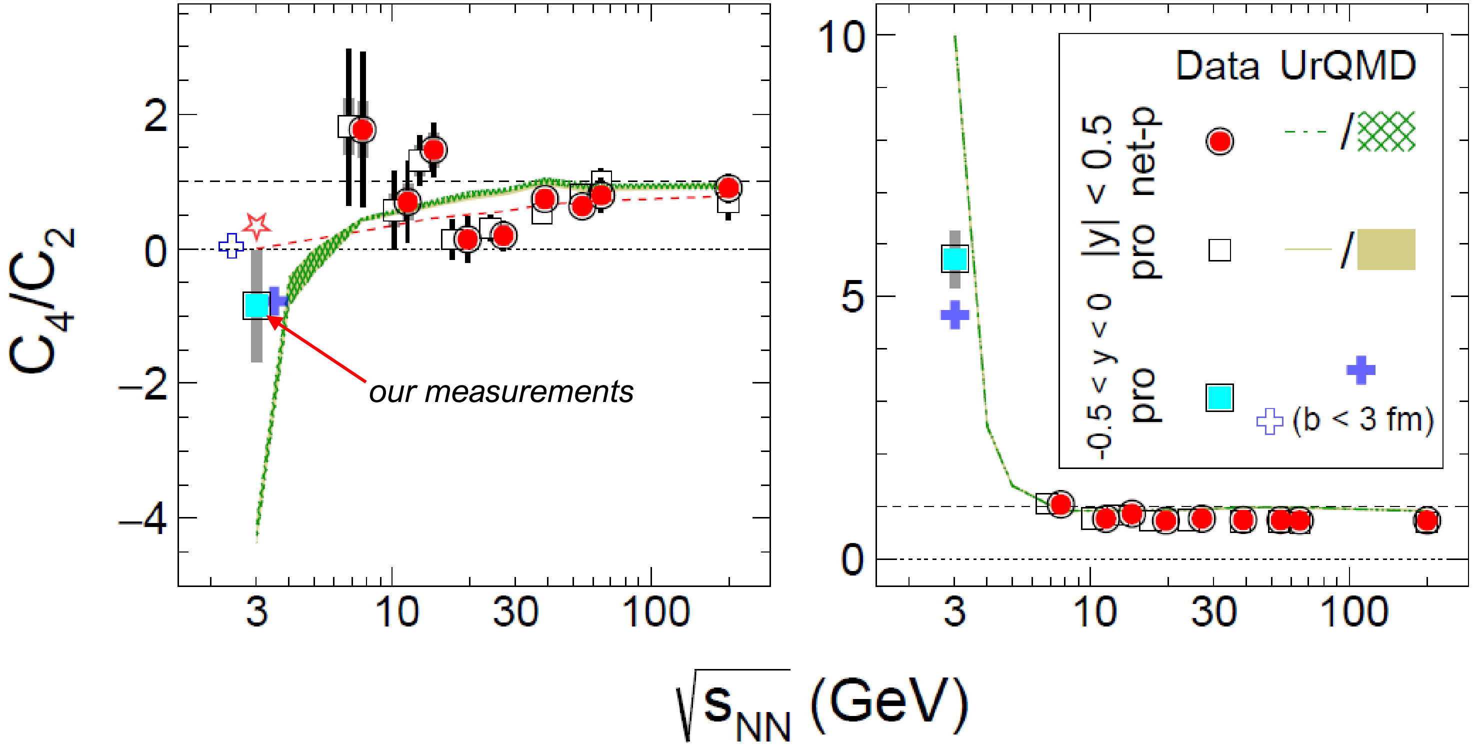
Energy dependence of net-proton cumulant ratio

Previous measurements of net-protons by STAR and HADES suggested the sign change at energies of BES-II



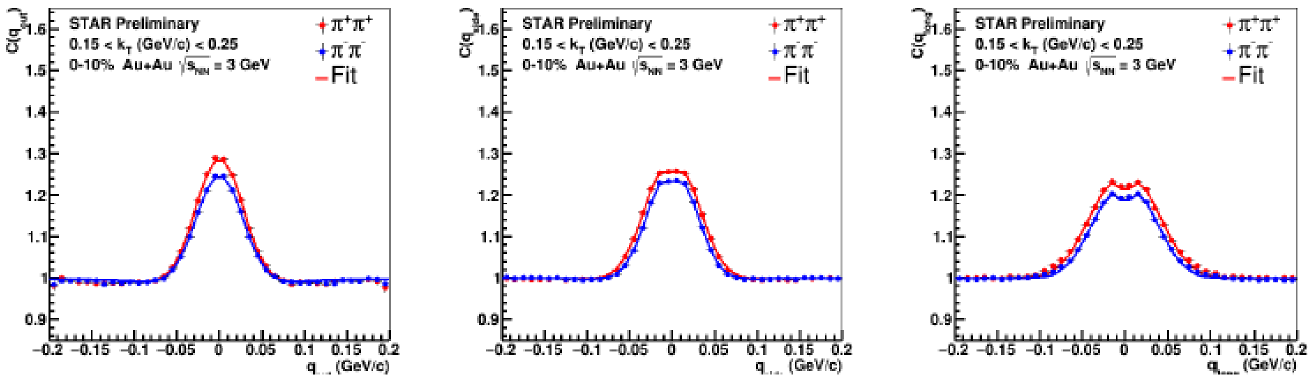
0-5% centrality

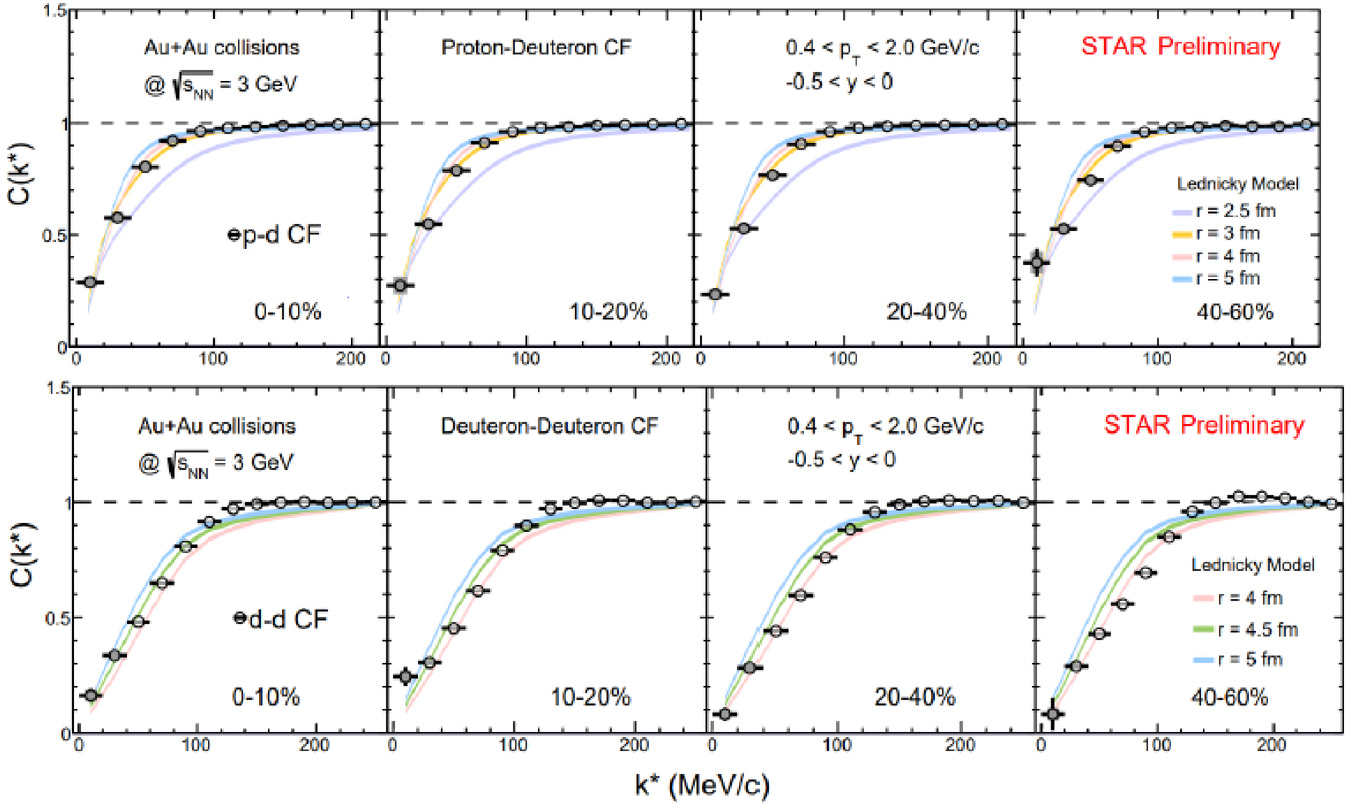
50-60% centrality



The data and results of both UrQMD and hydrodynamic models of C4/C2 in the most central collisions at 3 GeV are consistent, which signals the effects of baryon number conservation and an energy regime dominated by hadronic interactions

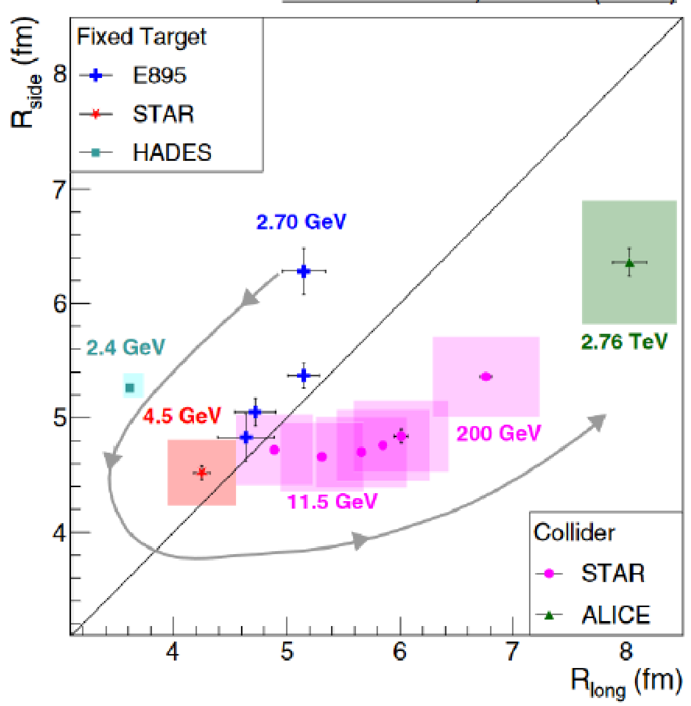
Femtoscopy results from FXT program





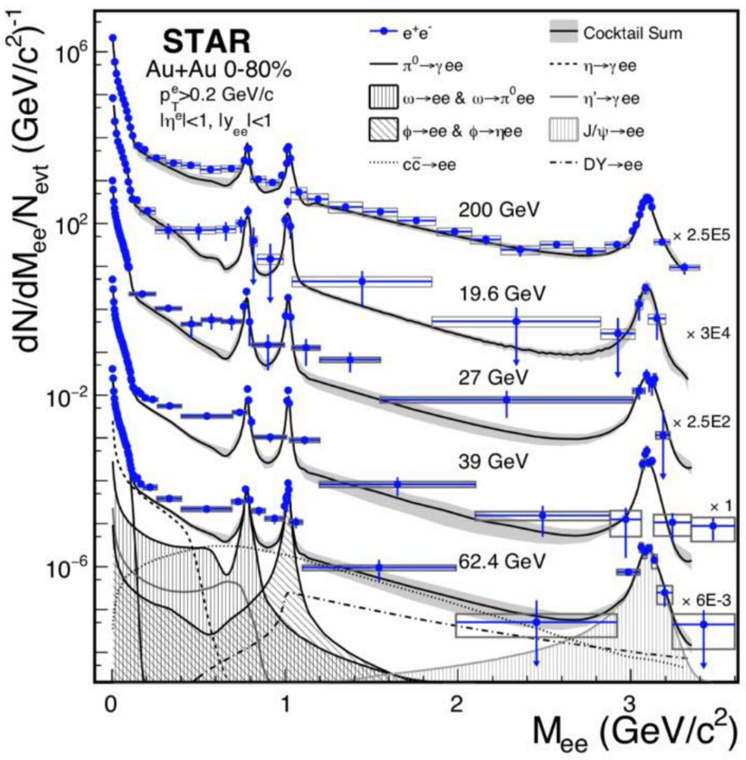
Many interesting results from low energy nuclear collisions: ππ, pp, pd, dd, and others provide information about particle interactions

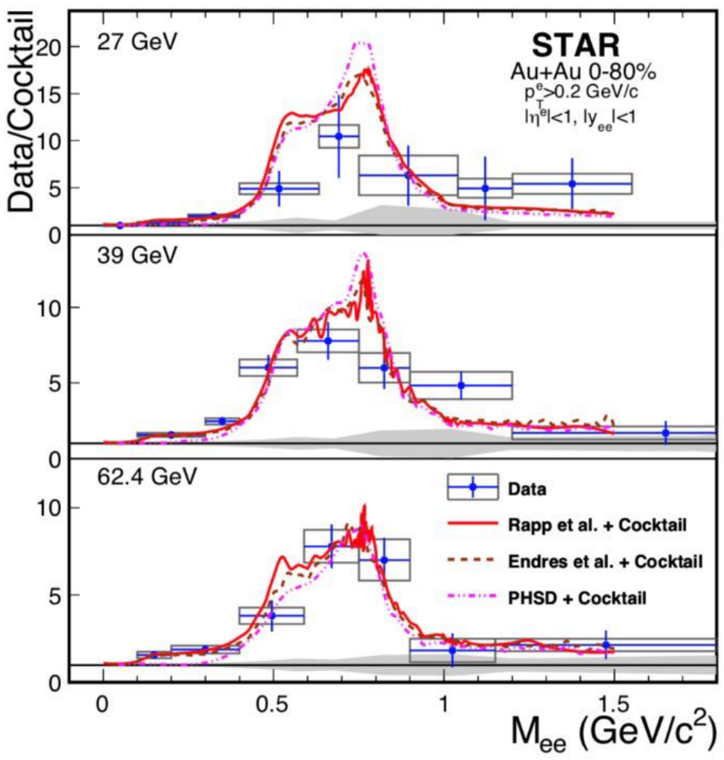
STAR. PRC 103, 034908(2021)

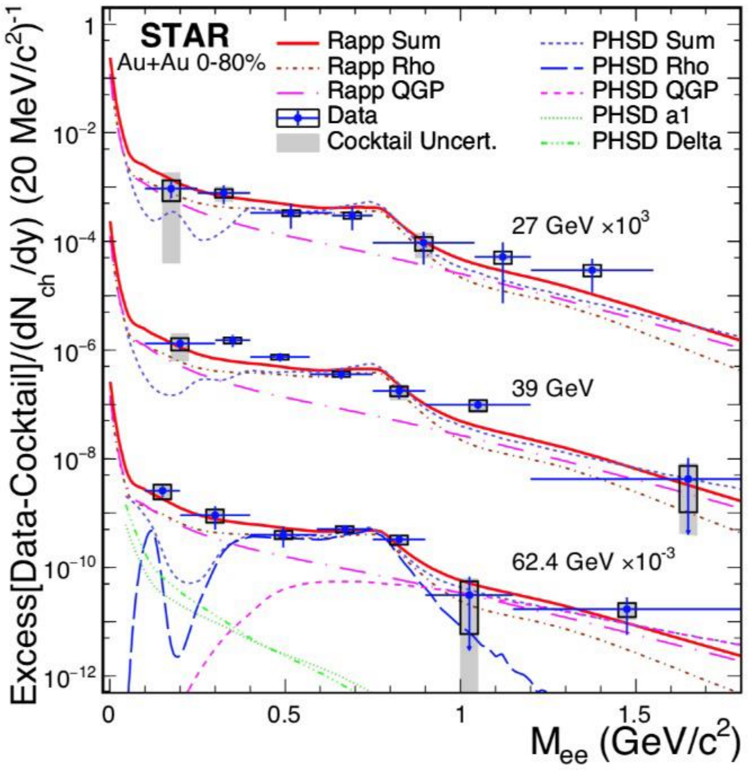


The source shape evolves from oblate to prolate, as energy increases

Dielectron production in BES-I



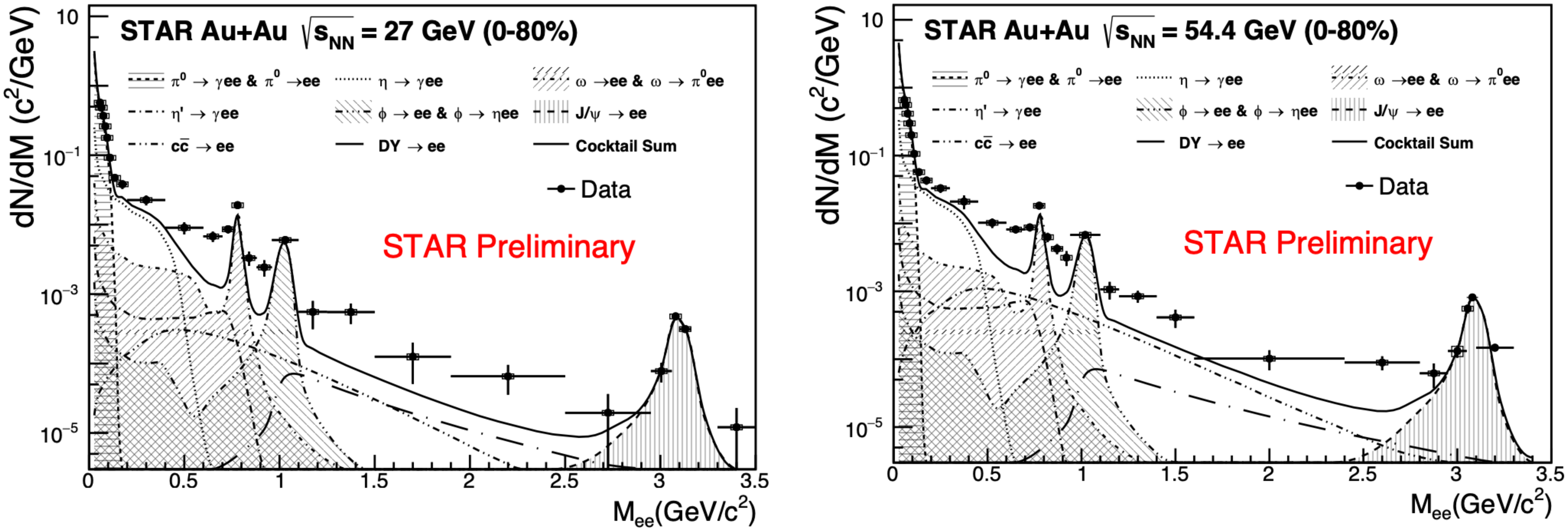




200 GeV: high yield of heavy flavor quark semi-leptonic decay
19.6–62.4 GeV: lack of statistics

arXiv:1810.10159
Phys. Lett. B 750,64-71(2015)
Phys. Rev. Lett. 113,022301 (2014)

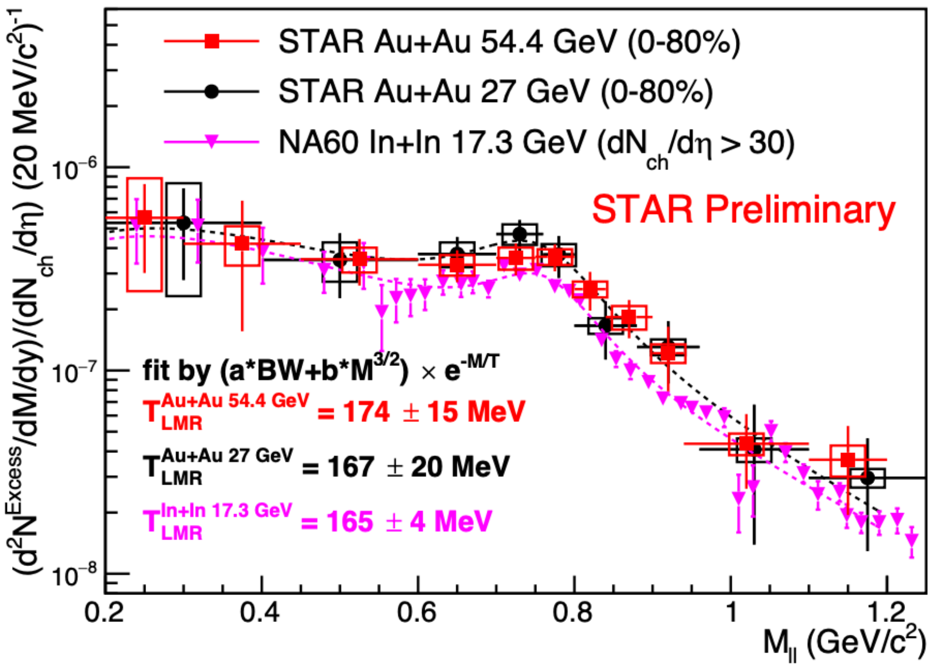
Dielectron production at 27 and 54.4 GeV Au+Au collisions



Clear enhancement compared to ρ excluded cocktail simulation in LMR and IMR

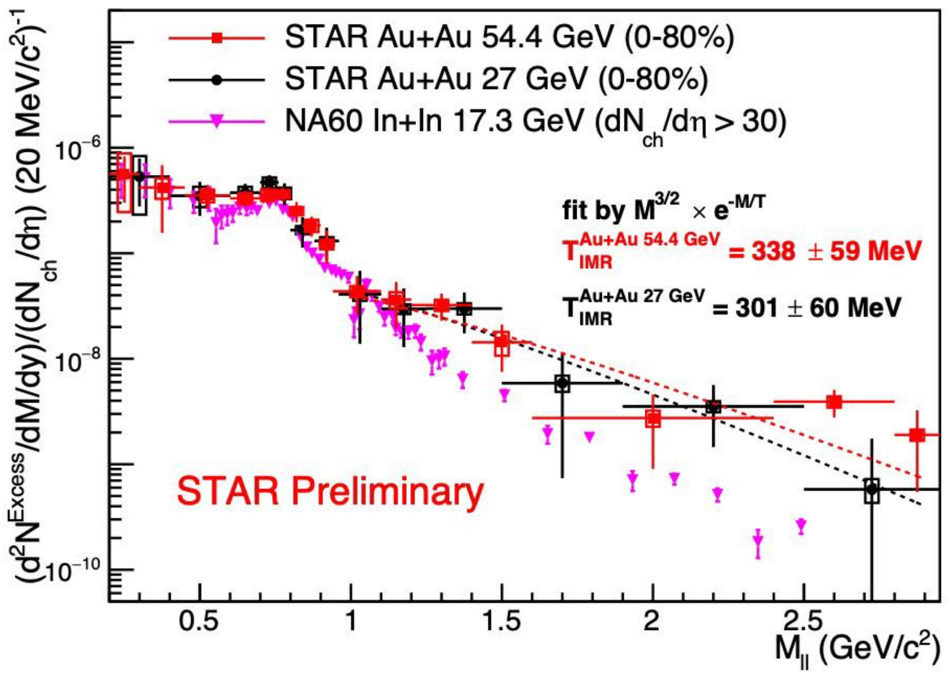
Thermal dileptons

Excess dielectron spectra in 27 and 54.4 GeV Au+Au collisions and NA60 In+In collisions are similar



T extracted from low mass region around the pseudo critical temperature T_{pc} (156 MeV)

Thermal dielectrons is the major source in IMR

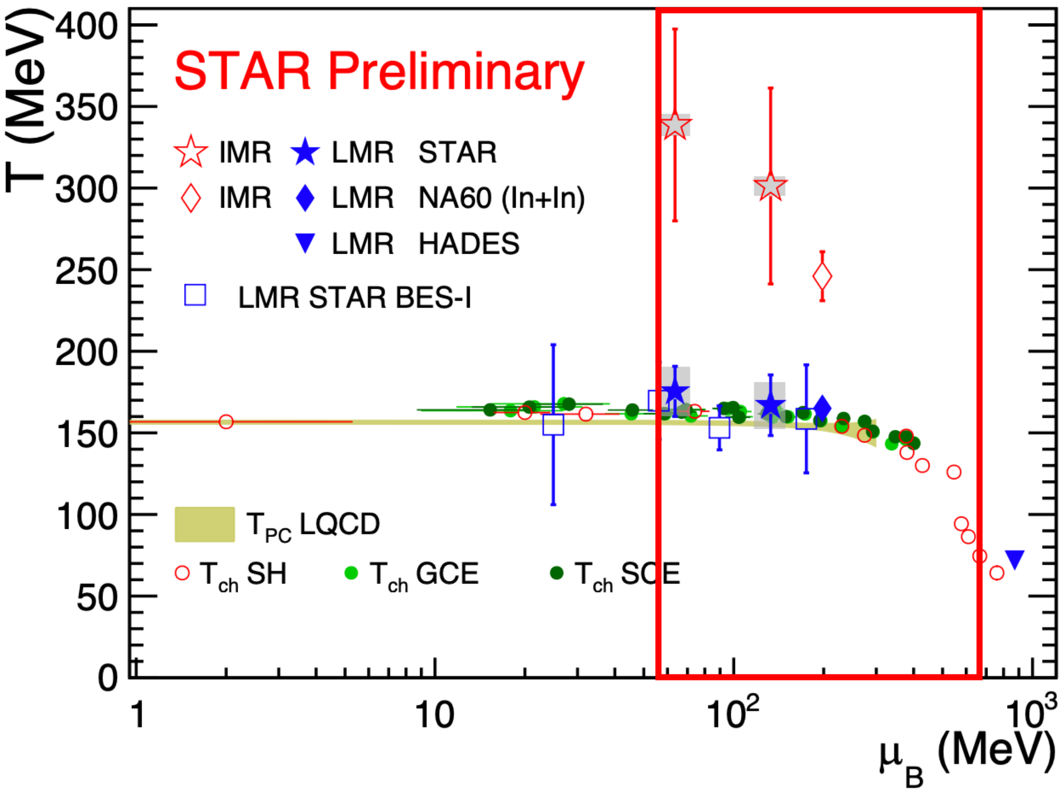


T in 27 and 54.4 GeV are consistent with each other

T > T_{pc} (156 MeV): emission dominantly from QGP

NA60: EPJC (2009) 59: 607–623
HotQCD: PLB **795** (2019) 15-21

Phase diagram mapping with dielectrons



T_{LMR} close to T_{ch} and T_{pc}
ρ meson dominantly emitted around phase transition

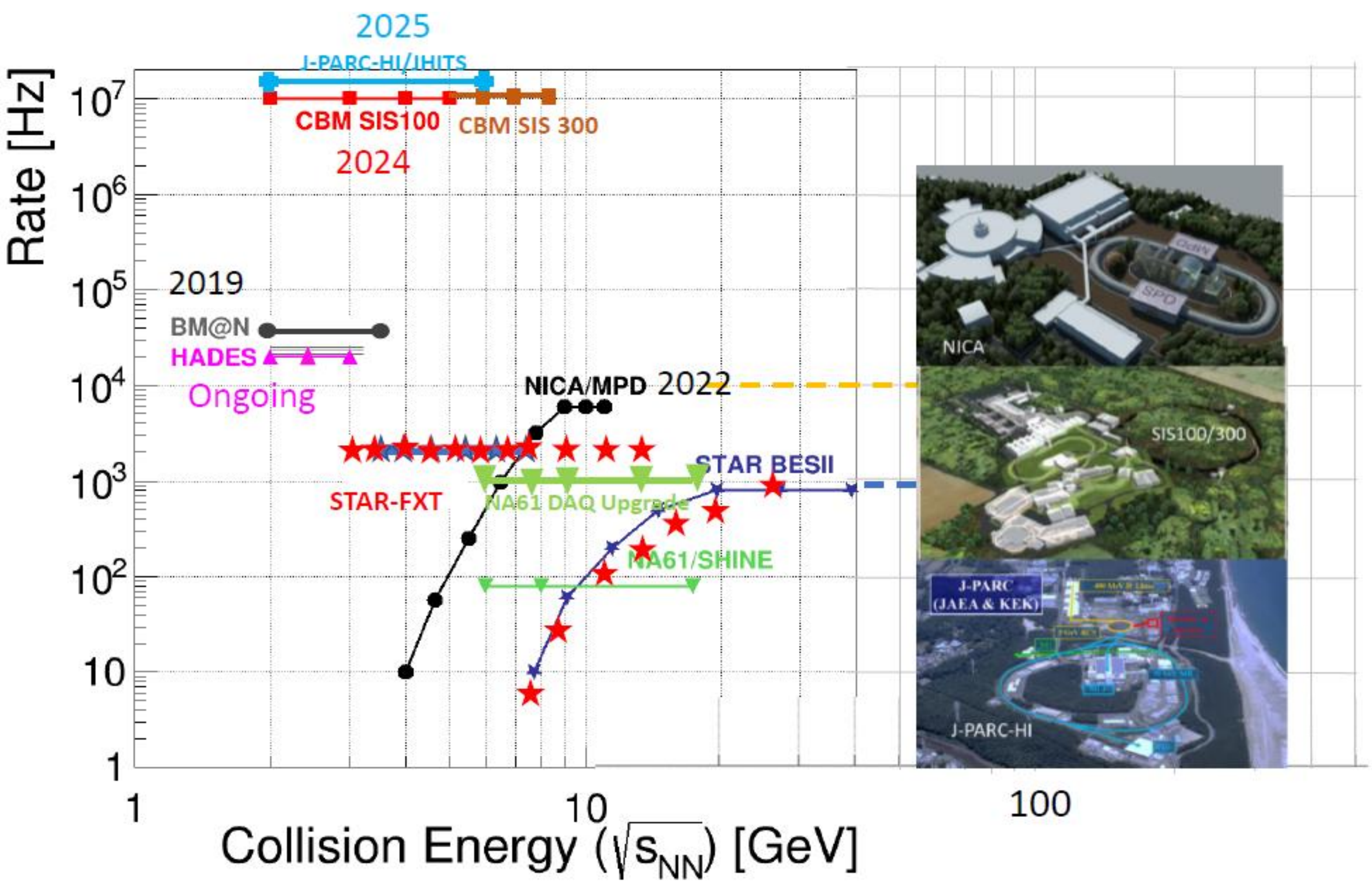
T_{IMR} higher than T_{LMR}, T_{ch} and T_{pc}
dielectron dominantly emitted from QGP phase

High statistics data sample between 7.7 GeV and 19.6 GeV in STAR BES-II will help map the kink region

Enhanced tracking and particle identification capabilities with iTPC and eTOF upgrades

NA60: EPJC (2009) 59 607–623
HADES: Nature Physics 15, 1040-1045 (2019)
Tch SH: P. Braun-Munzinger et al. Nature 561, 321-330 (2018)
Tch GCE/SCE: STAR PRC **96**, 044904 (2017)

HIC facilities and experiments



SPS up to 160 GeV

NICA/MPD is a Collider exp.
NICA single beam of about 10 GeV

Nuclotron reaches up to 3.5 GeV

JPARC up to about 18 GeV

Summary

- ✓ BES-I was performed between 2010 – 2014 and demonstrated the capability of RHIC to operate at low energies
- ✓ BES-II has increased statistics by a factor of 10 for most of the energies and provided additional data with FXT mode of STAR detector
- ✓ BES-II data were taken after several detector upgrades
- ✓ Previous energy scans had demonstrated that at low energies many signatures of sQGP are turned off
- ✓ The first results are from the lowest energy FXT system and these demonstrate that the system is clearly in the hadronic gas phase (as expected)
- ✓ Data taking has been very successfully completed and new results are on the way

Thank you for the attention!

Part of this work has been supported by Russian Science Foundation under grant № 22-72-10028

Backup slides

Statistics and run time at BES in 2010-2017

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year	μ_B (MeV)	T_{CH} (MeV)
200	350	2010	25	166
62.4	67	2010	73	165
54.4	1200	2017	90	
39	39	2010	112	164
27	70	2011	156	162
19.6	36	2011	206	160
14.5	20	2014	264	156
11.5	12	2010	315	152
9.2	0.3	2008	355	140
7.7	4	2010	420	140

BES-II statistics and run time

Recent BES-II, FXT and 200 GeV datasets (years 2018-2021)

$\sqrt{s_{NN}}$ (GeV)	Beam Energy (GeV/nucleon)	Collider or Fixed Target	$y_{center\ of\ mass}$	μ_B (MeV)	Run Time (days)	No. Events Collected (Request)	Date Collected
200	100	C	0	25	2.0	138 M (140 M)	Run-19
27	13.5	C	0	156	24	555 M (700 M)	Run-18
19.6	9.8	C	0	206	36	582 M (400 M)	Run-19
17.3	8.65	C	0	230	14	256 M (250 M)	Run-21
14.6	7.3	C	0	262	60	324 M (310 M)	Run-19
13.7	100	FXT	2.69	276	0.5	52 M (50 M)	Run-21
11.5	5.75	C	0	316	54	235 M (230 M)	Run-20
11.5	70	FXT	2.51	316	0.5	50 M (50 M)	Run-21
9.2	4.59	C	0	372	102	162 M (160 M)	Run-20+20b
9.2	44.5	FXT	2.28	372	0.5	50 M (50 M)	Run-21
7.7	3.85	C	0	420	90	100 M (100 M)	Run-21
7.7	31.2	FXT	2.10	420	0.5+1.0+ scattered	50 M + 112 M + 100 M (100 M)	Run-19+20+21
7.2	26.5	FXT	2.02	443	2+Parasitic with CEC	155 M + 317 M	Run-18+20
6.2	19.5	FXT	1.87	487	1.4	118 M (100 M)	Run-20
5.2	13.5	FXT	1.68	541	1.0	103 M (100 M)	Run-20
4.5	9.8	FXT	1.52	589	0.9	108 M (100 M)	Run-20
3.9	7.3	FXT	1.37	633	1.1	117 M (100 M)	Run-20
3.5	5.75	FXT	1.25	666	0.9	116 M (100 M)	Run-20
3.2	4.59	FXT	1.13	699	2.0	200 M (200 M)	Run-19
3.0	3.85	FXT	1.05	721	4.6	259 M -> 2B(100 M -> 2B)	Run-18+21

BES-I (years 2010, 2011, 2014)

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

STAR event with new sub-detectors

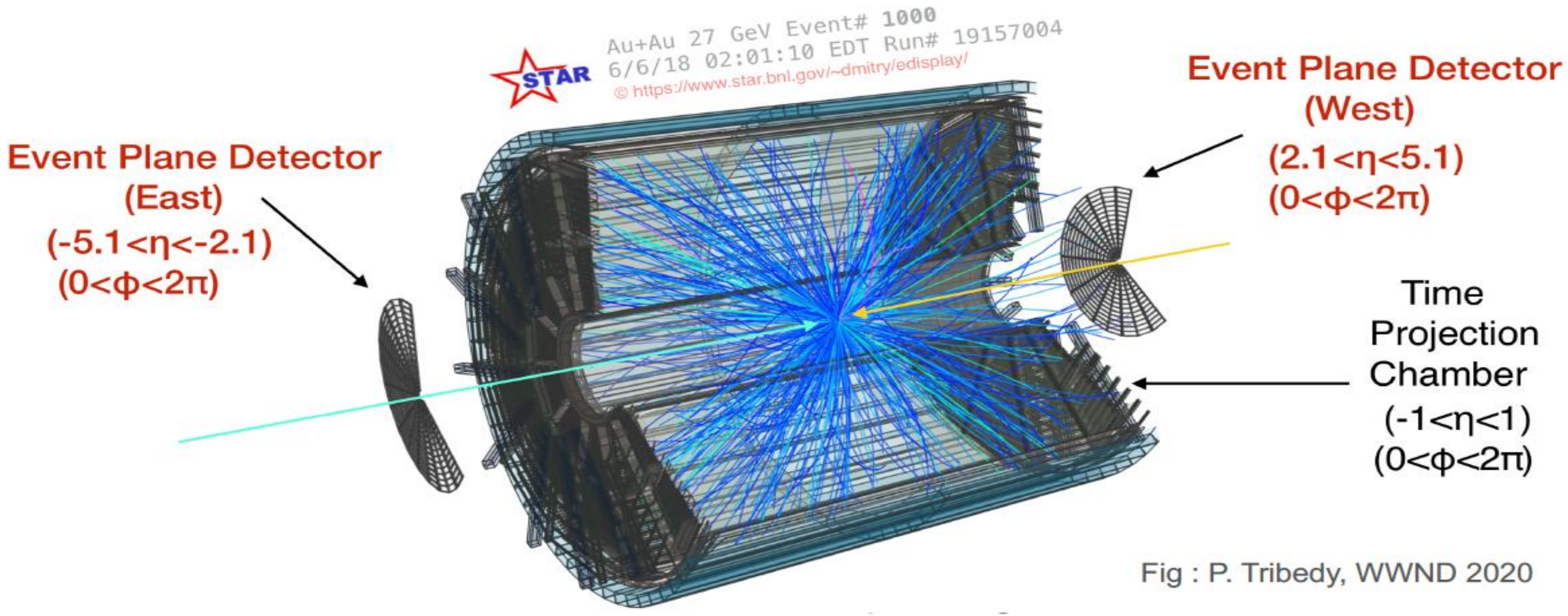
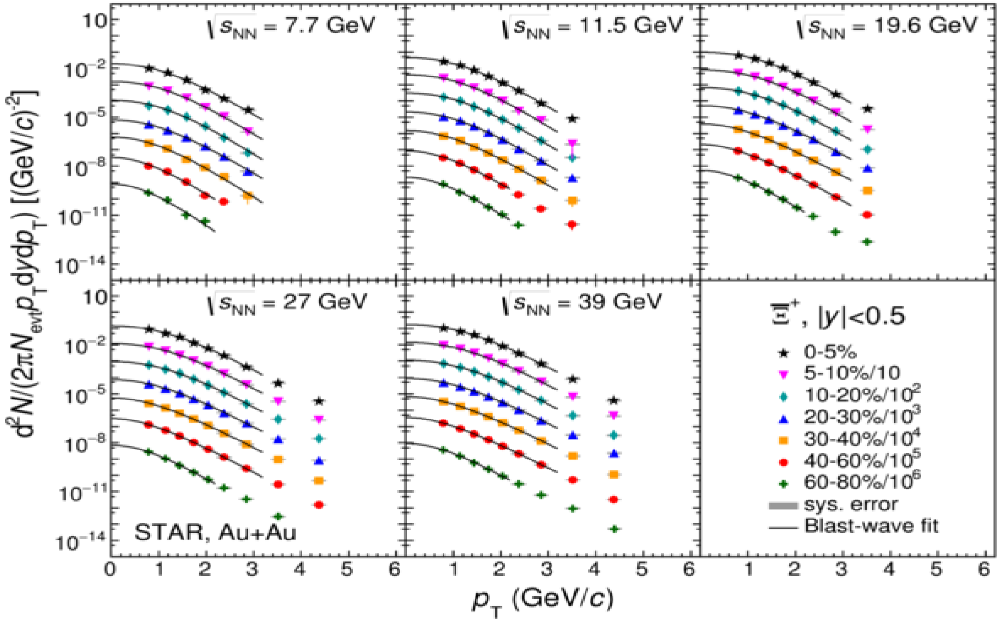


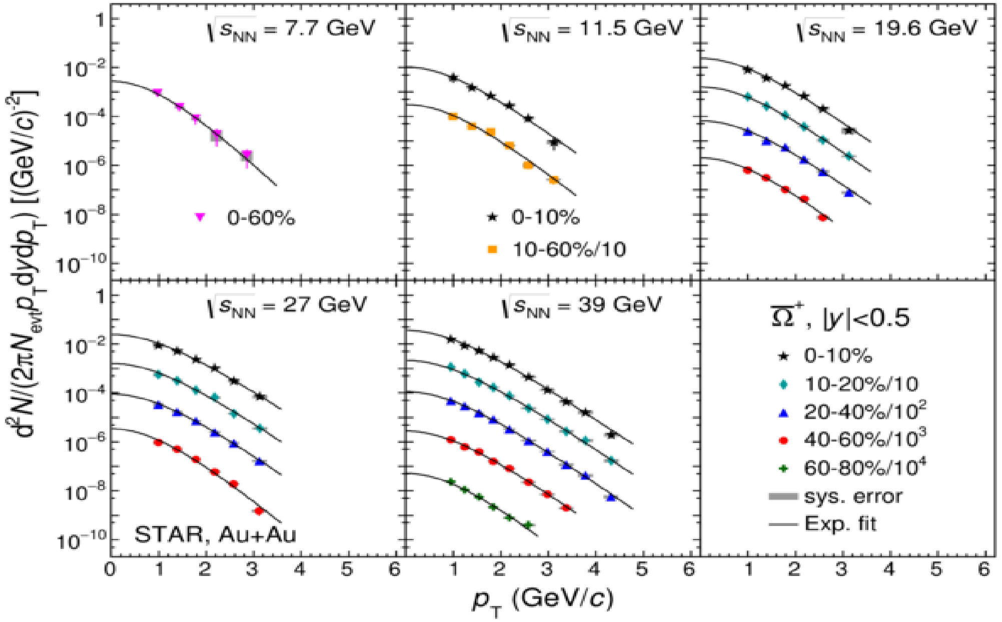
Fig : P. Tribedy, WWND 2020

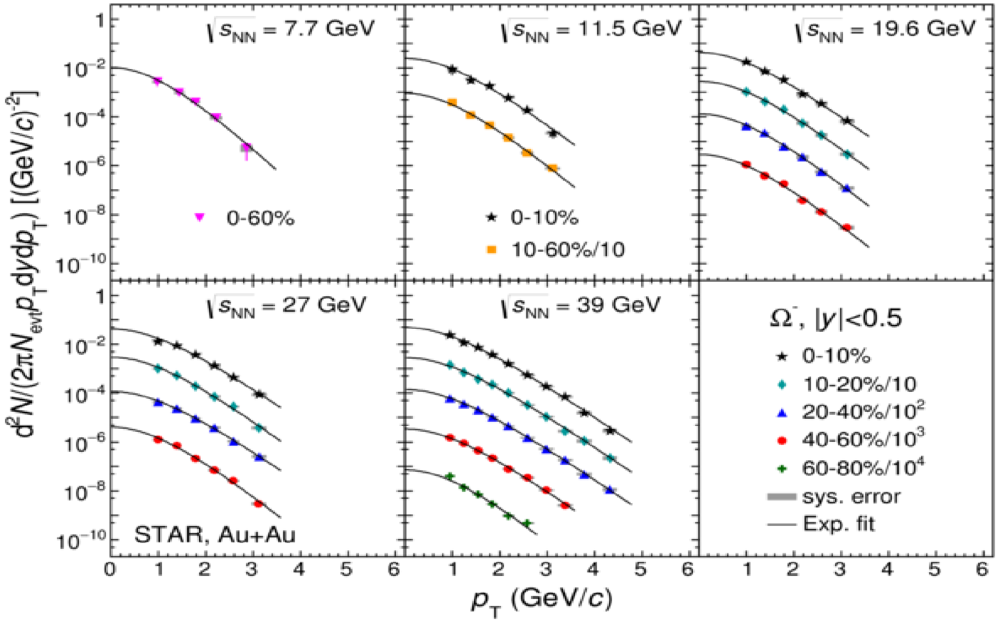
Full azimuthal coverage
Large separation in η between TPC and EPD

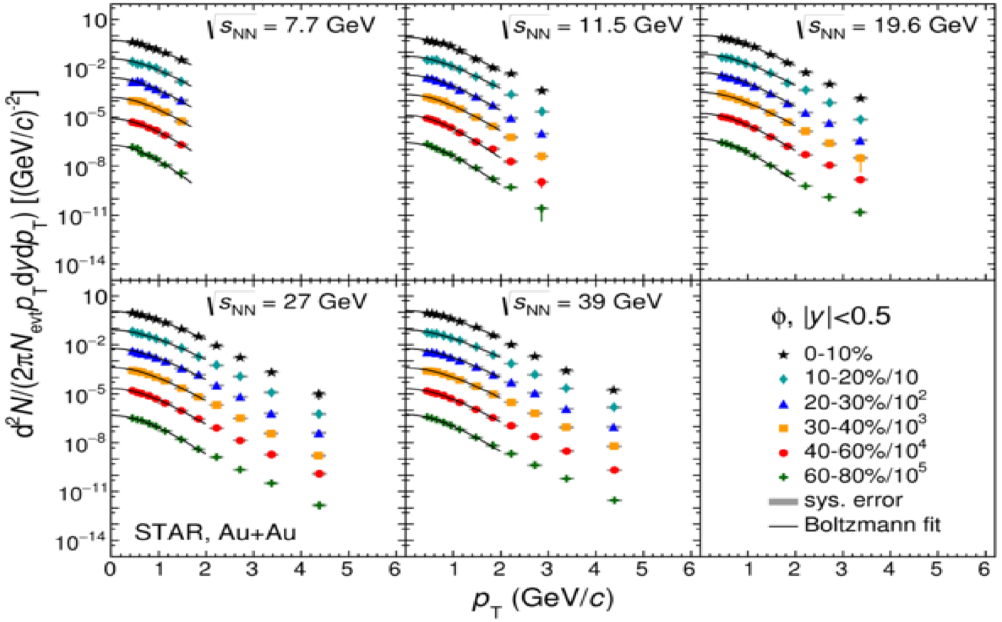
J. Adams et al. Nucl. Instrum. Meth. A 968 (2020)

Strange particle production at BES-I

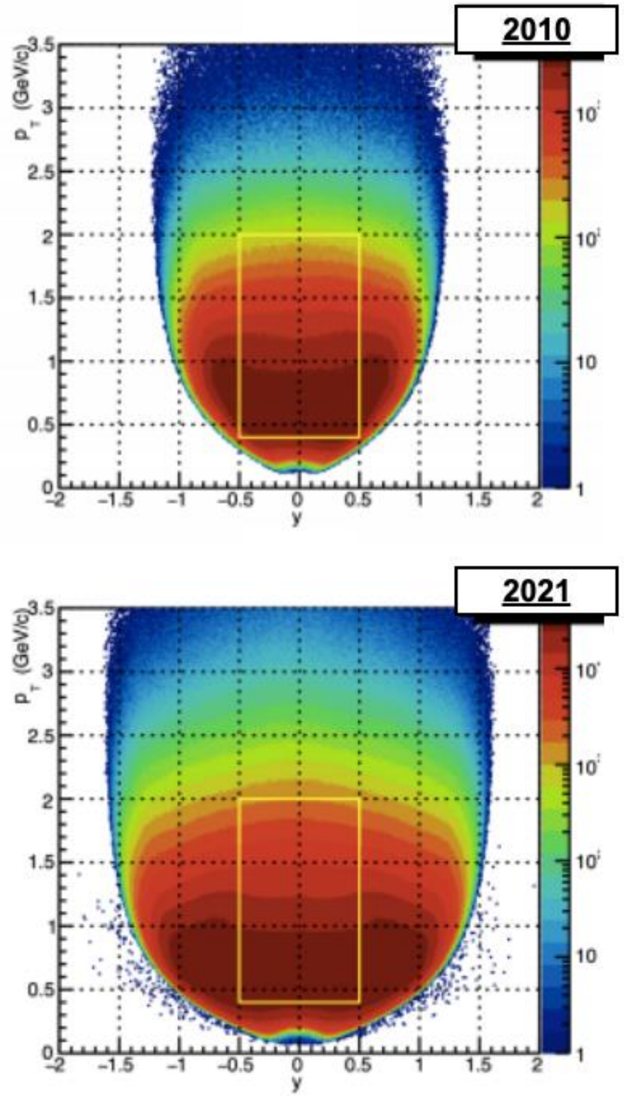


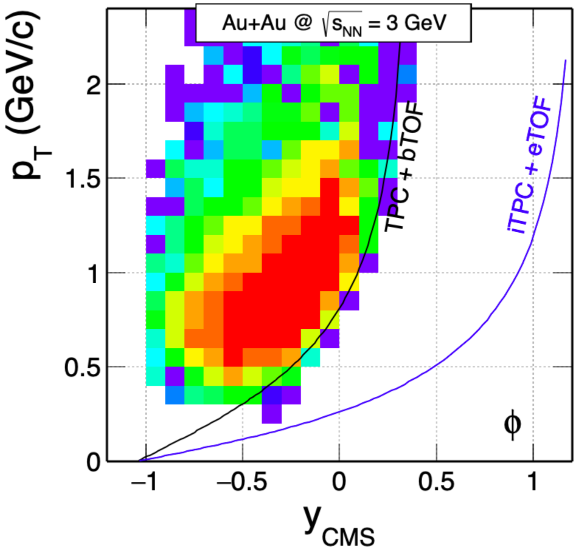


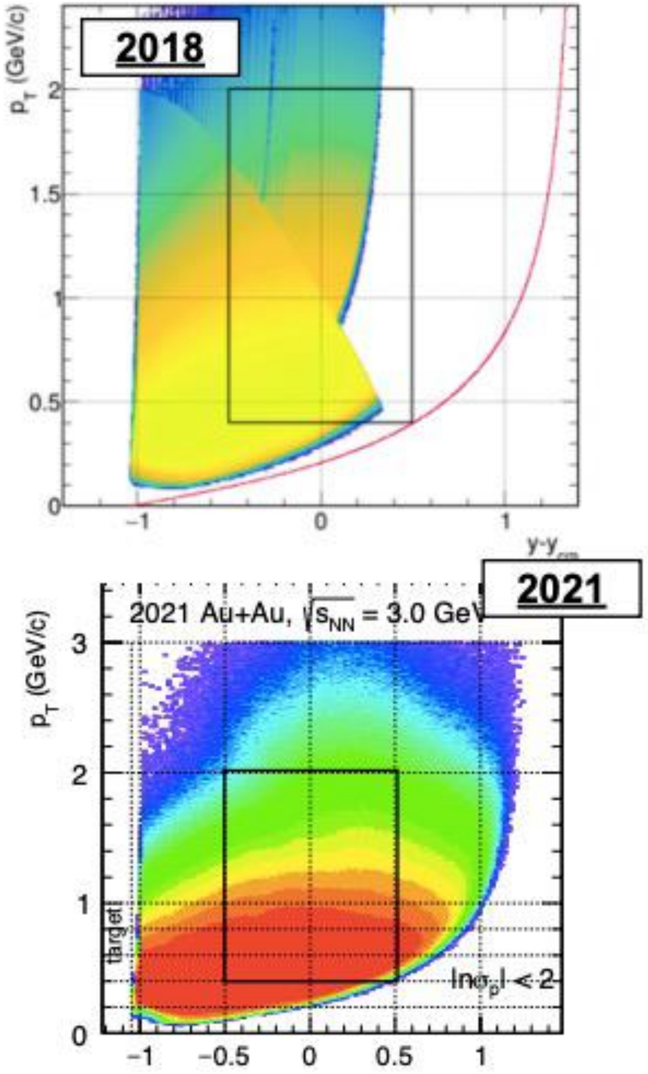




New acceptance







Light nuclei acceptance