
Beam Energy Scan at STAR

Yield and Flow Measurements

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Indian Institute of Science Education and Research, Berhampur

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Motivation

Goal:

Mapping the **QCD** phase-structure

- 1) Phase-boundary
- 2) Onset of de-confinement
- 3) QCD critical point

RHIC BES:

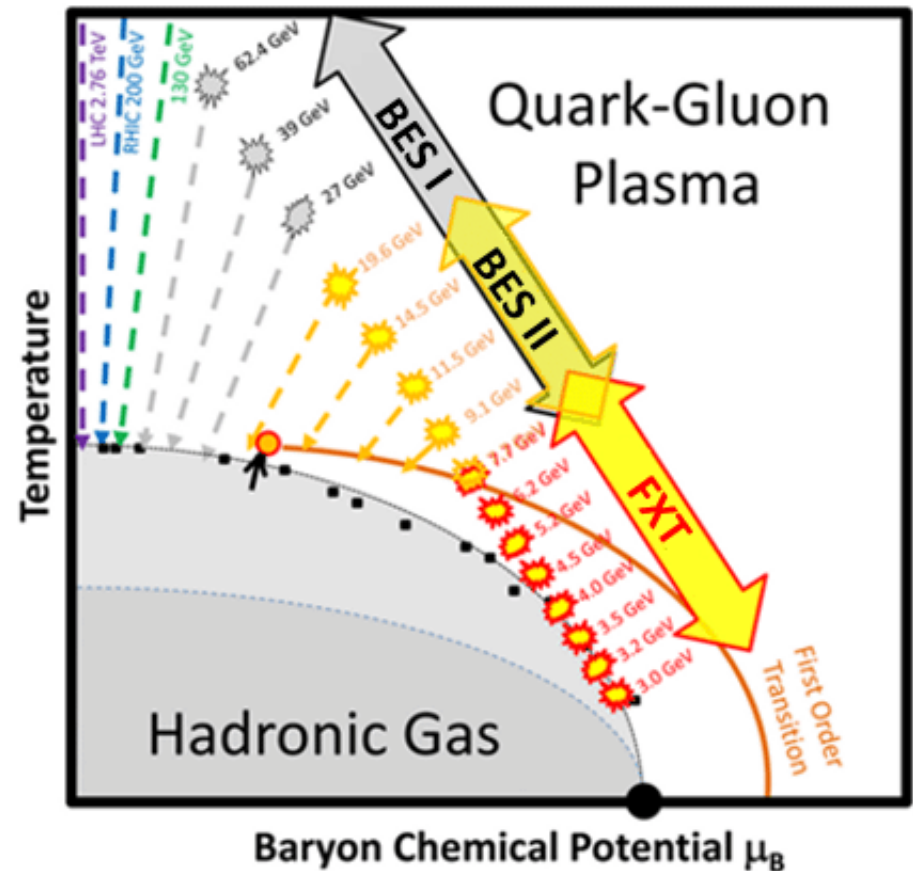
Collisions: Au+Au

Collider Mode:

$$\sqrt{s_{NN}} = 7.7 - 62.4 \text{ GeV}$$

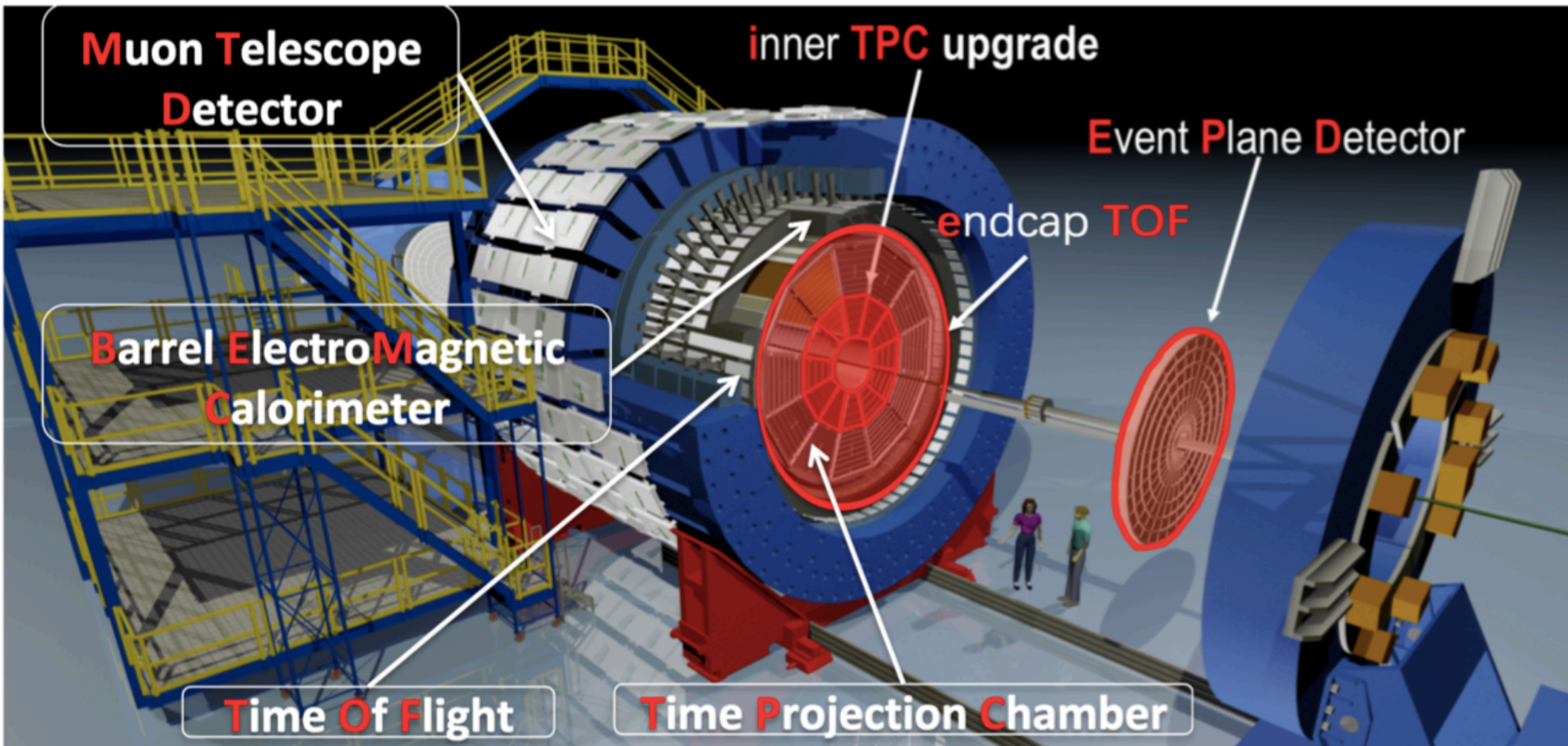
Fixed Target Mode:

$$\sqrt{s_{NN}} = 3 - 13.7 \text{ GeV}$$



Data taking for phase -II of BES is completed in 2021.

The STAR Experiment



Selected Physics Results From BES

- Light and Strange Hadrons

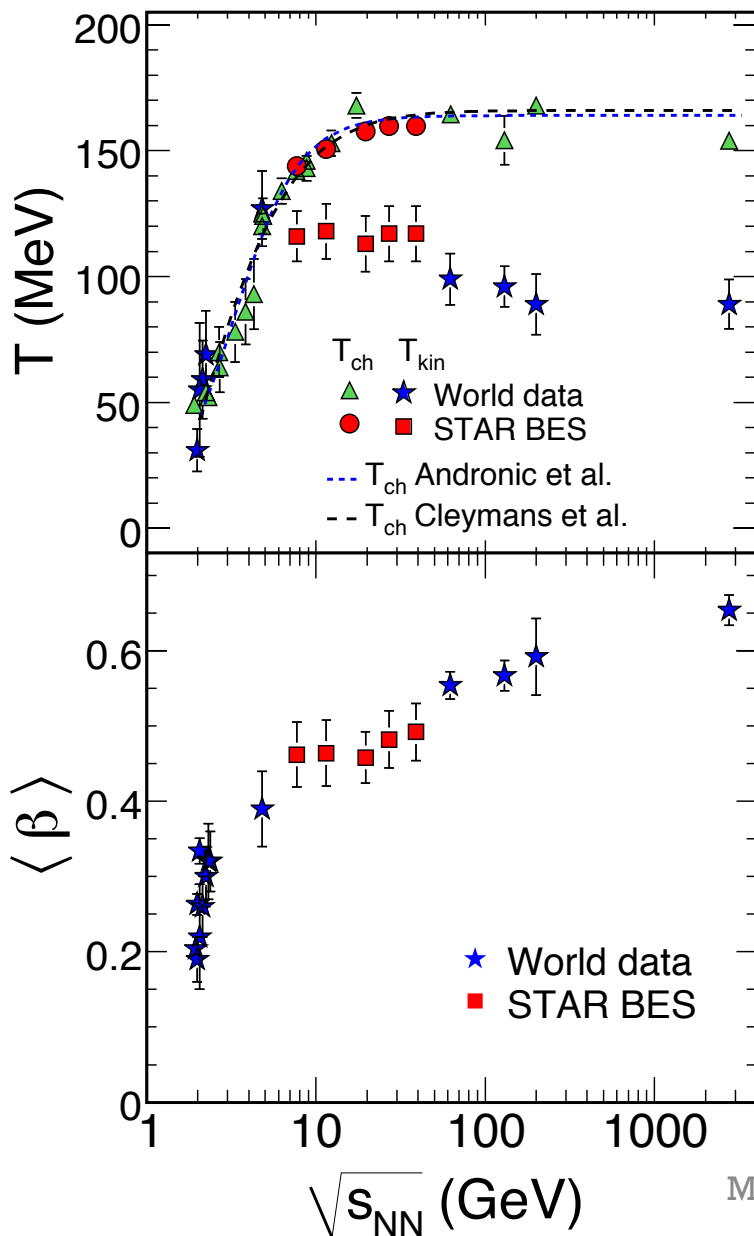
- ① Freeze-out Parameters
- ② Particle Ratios
- ③ Nuclear Modification Factor
- ④ Collective Flow

New results from Au+Au collisions at $\sqrt{s_{NN}} = 3 \text{ GeV}$ and 54.4 GeV

- Nuclei and Hyper-nuclei

- ① Particle Yields
- ② Collective Flow

Freeze-out Parameters



Chemical freeze-out:
Particle ratios get fixed

Kinetic freeze-out :
Momentum distributions get fixed

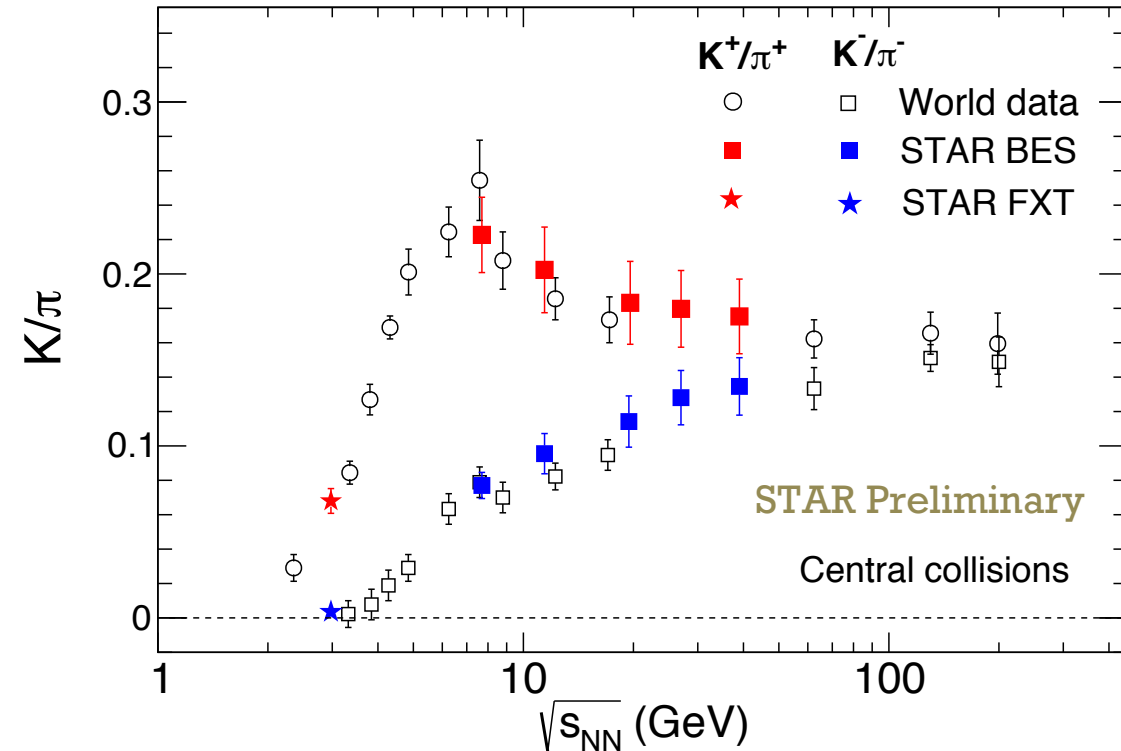
- The difference between chemical and kinetic freeze-out temperatures increases with increasing energy

→ *Increasing hadronic interactions after chemical freeze-out at higher energies*
- Radial flow velocity increases with increasing energy

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

Particle Ratios (K/π)

(Strange over non-strange)



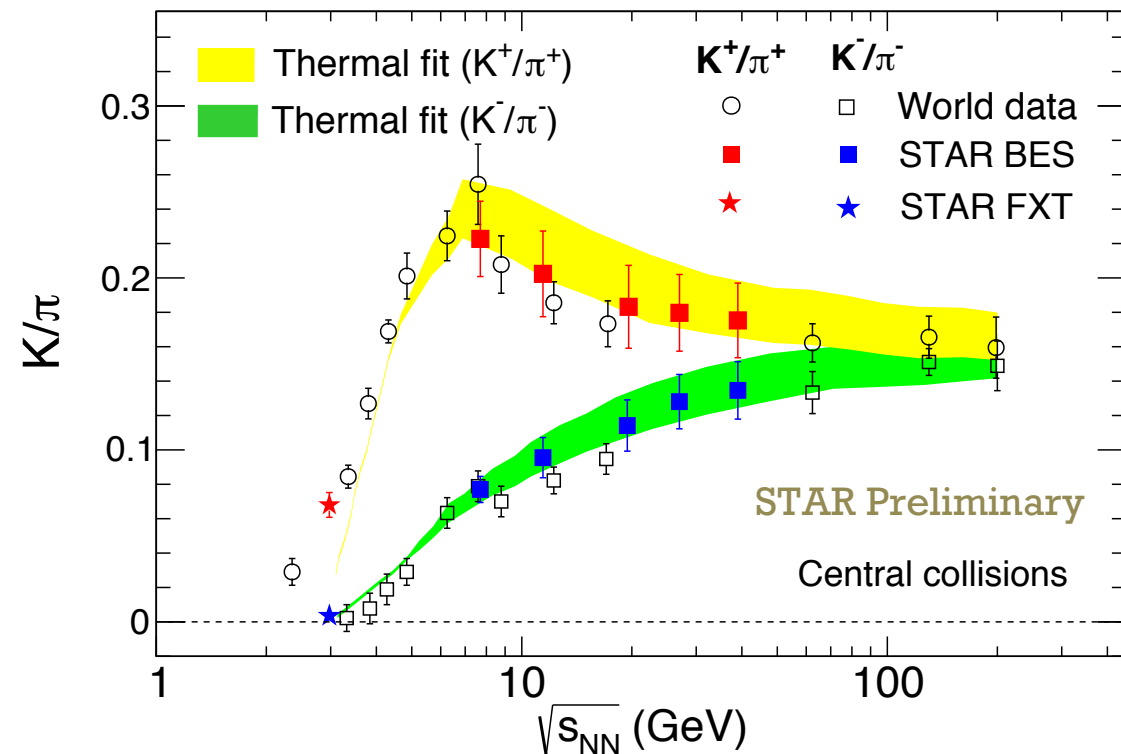
New data :
3 GeV

KaoS, J. Phys. G 28, 2011 (2002)
E866/E917, Phys. Lett. B490, 53 (2000)
NA49, Phys. Rev. C 77, 024903 (2008)
NA49, Phys. Rev. C 66, 054902 (2002)
STAR, Phys. Rev. C 96, 044904 (2017)
E866/E917, Phys. Lett. B476, 1 (2000)
Thermal, Phys. Lett. B, 673, 142 (2009)
J. Cleymans et al., Phys. Lett. B, 615, 150 (2005)
M. Gazdzicki et.al, Acta Phys Polon. B30,2705 (1999)

- Results from BES energies follow world data trend
- Smooth K^+/π^+ ratio vs. $\sqrt{s_{NN}}$ including STAR data

Particle Ratios (K/π)

(Strange over non-strange)



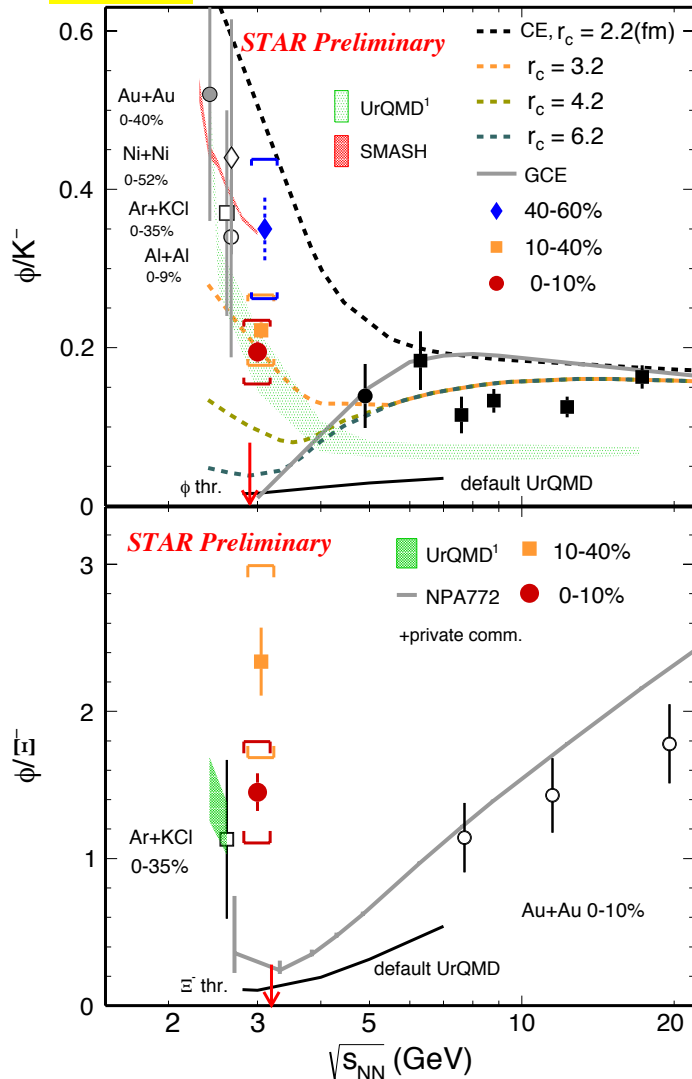
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- Results from BES energies follow world data trend
- Smooth K^+/π^+ ratio vs. $\sqrt{s_{NN}}$ including STAR data
- **Thermal model describes data**

Particle Ratios (ϕ/K and ϕ/Ξ)

New



High baryon density matter : GCE vs CE

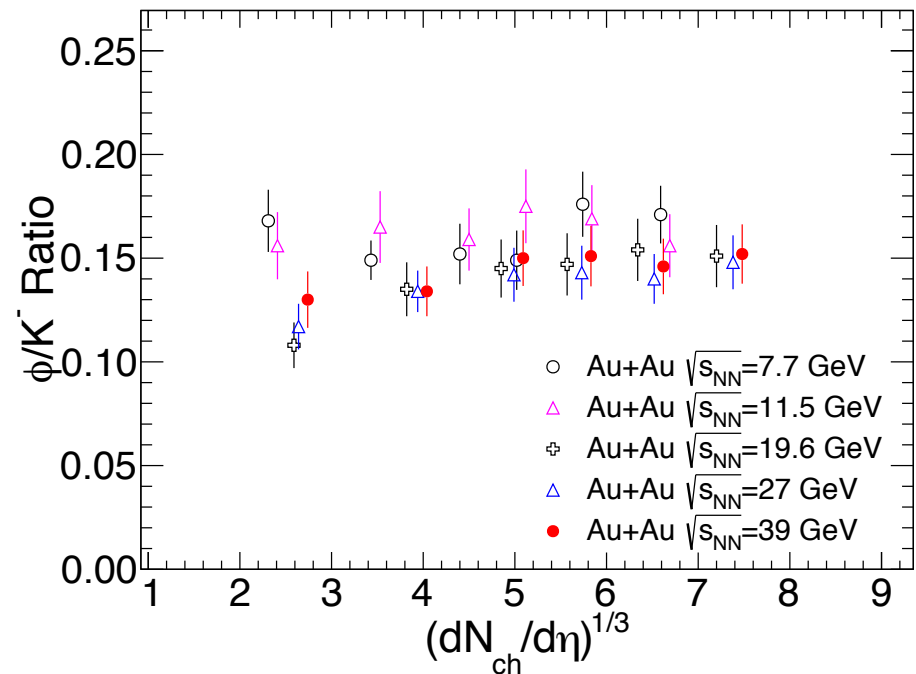
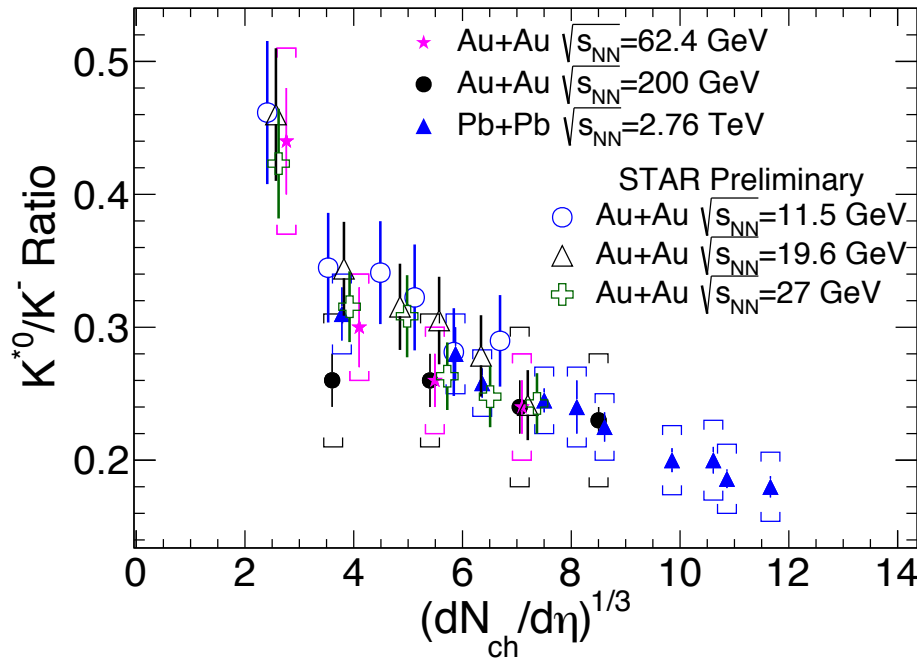
→ Data favor the Canonical Ensemble at high baryon density

→ Canonical suppression of strange hadrons at high baryon density

HADES: Phys. Lett. B 778, 2018.403-407, Phys.Rev. C. 80.025209. (2009);
 E917: Phys. Rev. C. 69.054901 (2004);
 NA49 : Phys. Rev. C 78, 044907 (2008), Phys. Rev. C 77, 024903 (2008),
 Phys. Rev. C 66, 054902 (2002)
 CE,GCE, K. Redlich: Phys. Lett. B 603, 146 (2004); Private Communication;
 SMASH : Phys. Rev. C 99, 064908 (2019)

HADES: Eur. Phys. J. A (2016) 52: 178
 STAR: Phys. Rev. C 102 (2020) 34909
 NPA772: A. Andronic et al. Nucl. Phys. A 772, 167 (2006);
 +private communication
 UrQMD1: J. Phys. G: Nucl. Part. Phys. 43 (2016) 015104 (14pp);
 UrQMD (public version): Prog. Part. Nucl. Phys. 41 (1998)
 225-370

Particle Ratios (K^{*0}/K and ϕ/K)



Lifetime : ~ 4 fm (K^{*0}) and ~ 42 fm (ϕ)

K^{*0}/K : Ratio decreases with increasing multiplicity

ϕ/K : Nearly independent of multiplicity

*Evidence of re-scattering on daughters of K^{*0} in central A+A collisions*

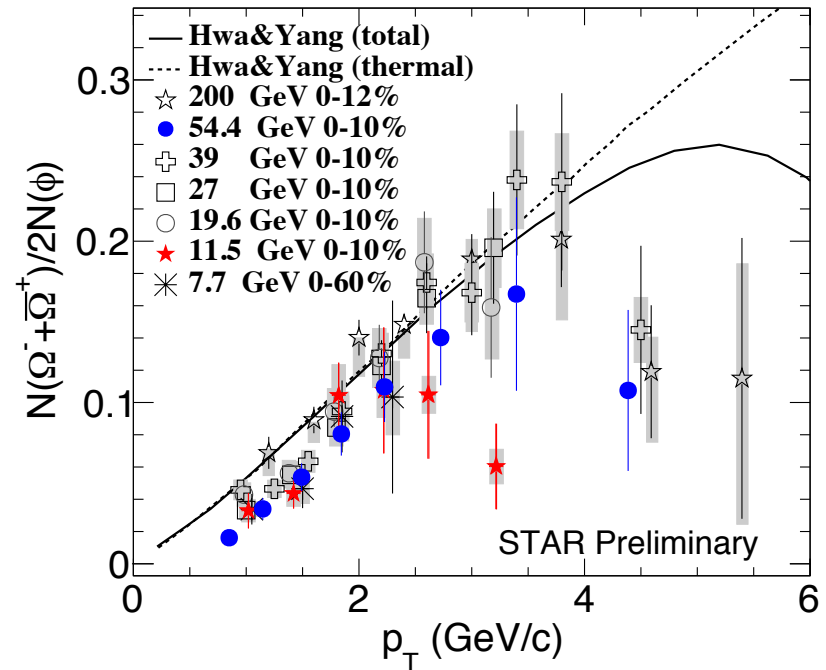
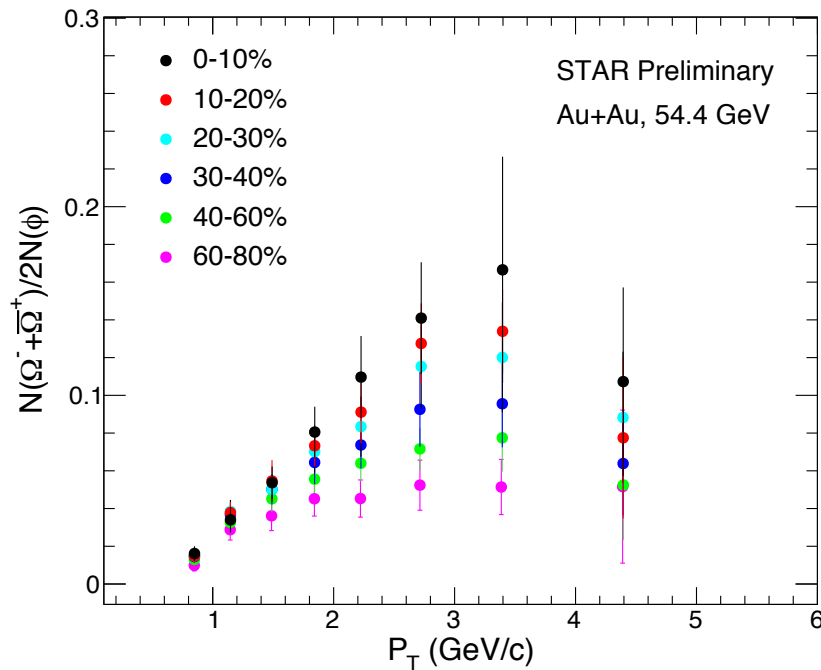
STAR: PRC **71**, 064902 (2005)

STAR: PRC 93 (2016) (R) 21903

ALICE: PRC 91 (2015) 024609

Baryon-to-Meson Ratio

New



- Baryon enhancement at intermediate p_T in central collisions
 → **Parton recombination model can explain the observed shape for $\sqrt{s_{NN}} \geq 19.6$ GeV**

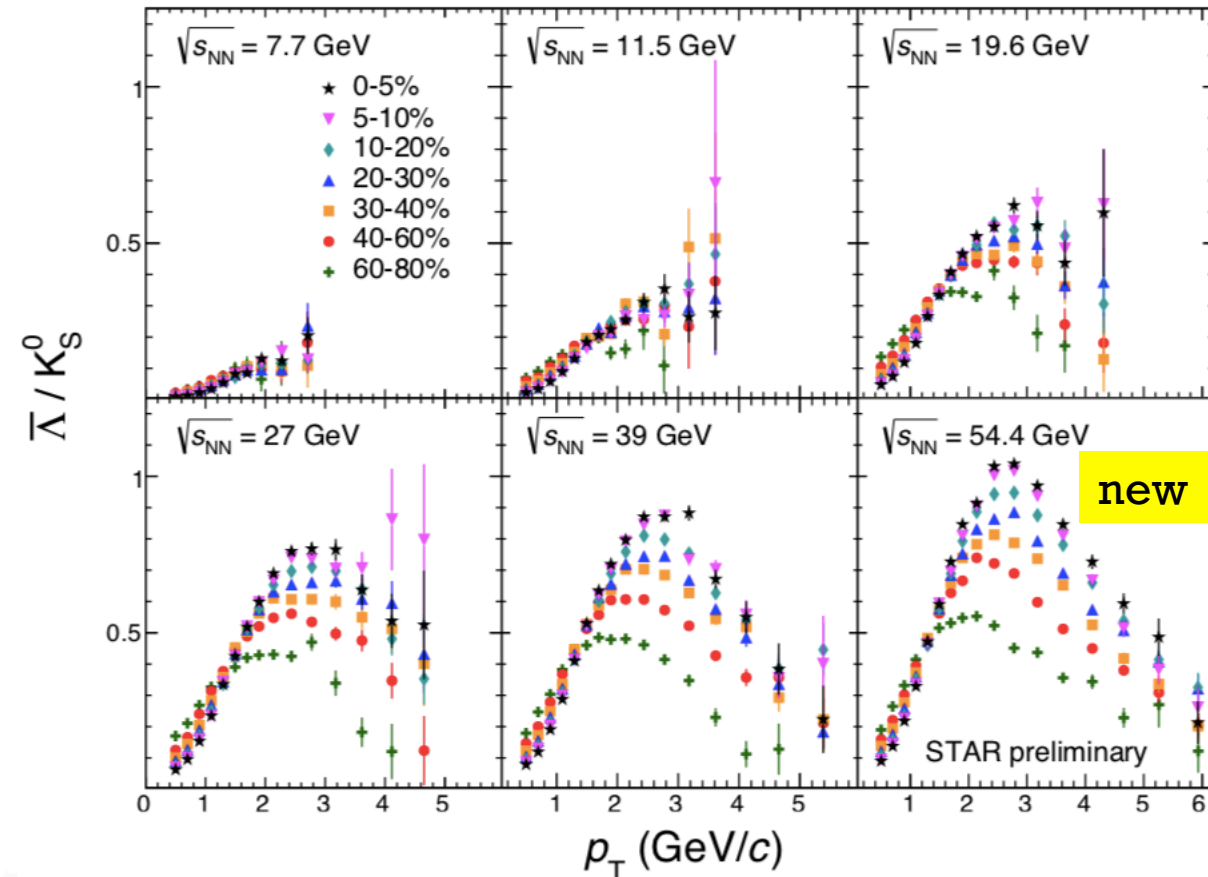
R. C. Hwa and C. B. Yang, PRC 75, 054904 (2007)

STAR: PRC 79, 64903 (2009)

STAR: PRC 93, 021903 (2016)

Need more statistics for
 $\sqrt{s_{NN}} < 19$ GeV (BES-II)

Baryon-to-Meson Ratio



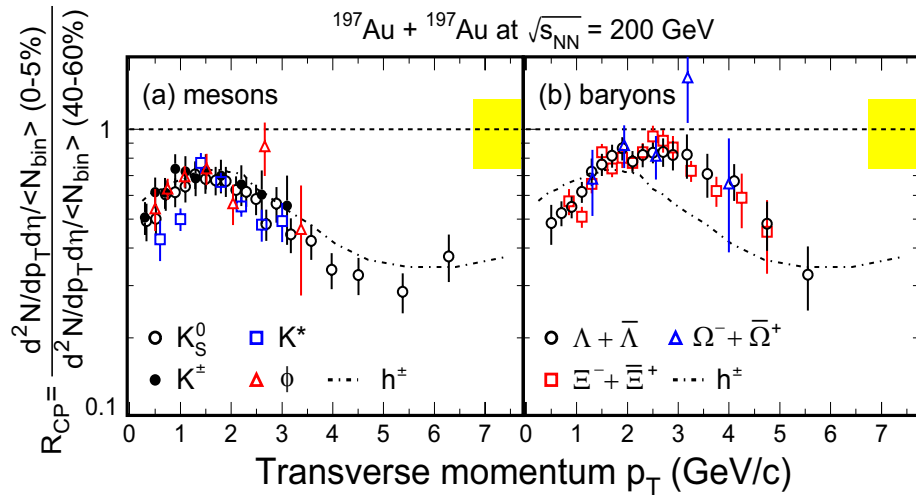
- Baryon enhancement at intermediate p_T in central collisions for $\sqrt{s_{NN}} \geq 19.6$ GeV

→ Parton recombination model can explain the observed shape

- Within the uncertainties no difference between central and peripheral collisions for $\sqrt{s_{NN}} \leq 11.5$ GeV

STAR: PRC 102, 34909 (2020)

Nuclear Modification Factor



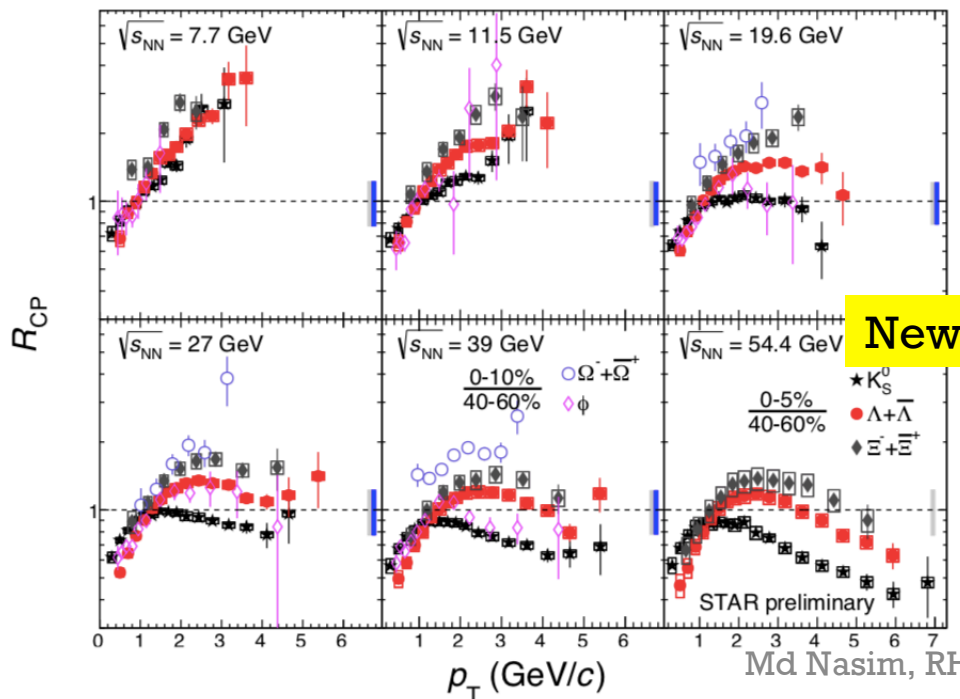
$$R_{CP} = \left[\frac{d^2 N^{\text{central}} / dp_T dy}{d^2 N^{\text{peripheral}} / dp_T dy} \right] \cdot \left[\frac{N_{\text{bin}}^{\text{peripheral}}}{N_{\text{bin}}^{\text{central}}} \right]$$

$\sqrt{s_{\text{NN}}} \geq 27$ GeV

- Suppression at high p_T
→ Energy loss of partons in QGP
- Baryon vs meson at intermediate p_T
→ Parton recombination

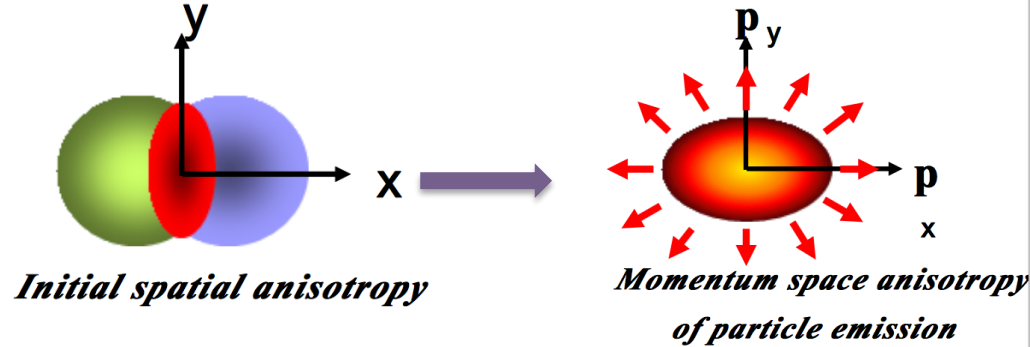
$\sqrt{s_{\text{NN}}} \leq 11.5$ GeV

- No suppression for the highest measured p_T
→ Parton energy loss, if any, is subdominant
- Baryon - meson separation is not significant



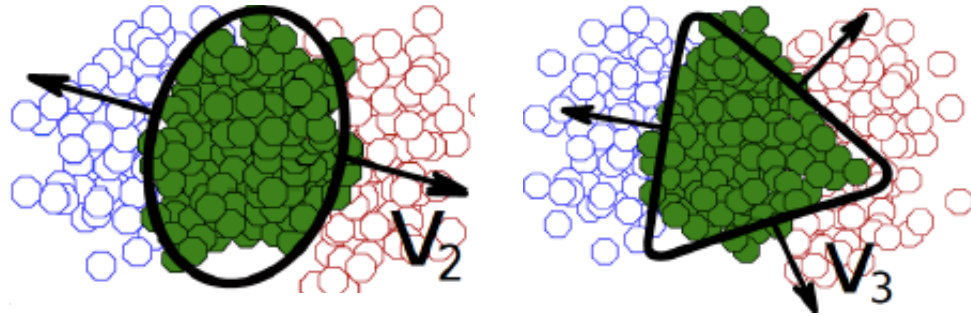
Azimuthal Anisotropy

Pressure gradient transfers initial spatial anisotropy to final state momentum space anisotropy



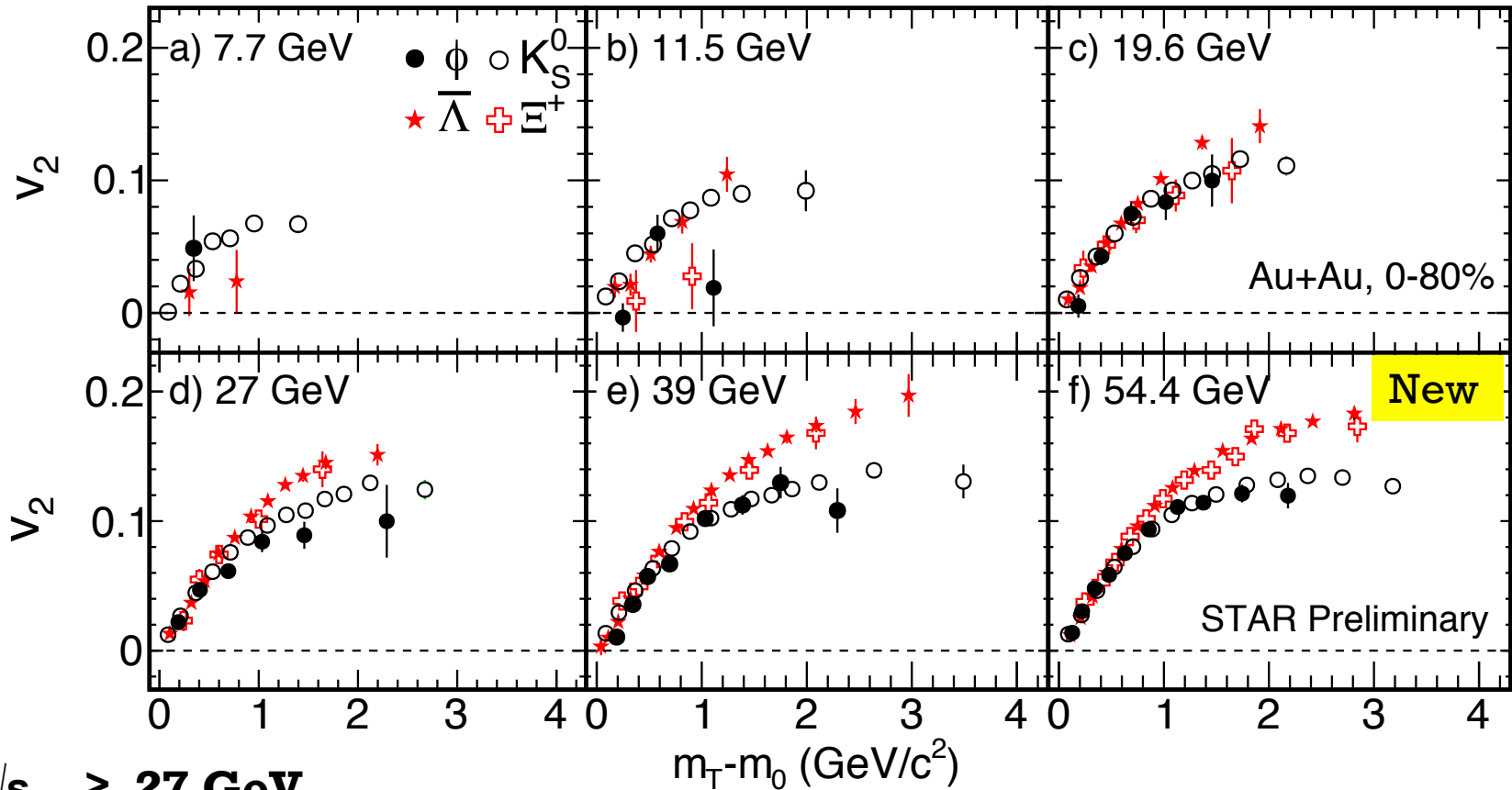
$$\frac{dN}{d\phi} = 1 + 2 \sum_{n=1}^{\infty} v_n \cos\{n(\phi - \psi_n)\}$$

$$v_n = \langle \cos\{n(\phi - \psi_n)\} \rangle$$



The azimuthal anisotropy parameters (v_n) are sensitive probe to the matter created in heavy-ion collisions.

Elliptic Flow of Strange Hadrons



STAR: PRL 110, 142301 (2013)

$\sqrt{s_{NN}} \geq 27 \text{ GeV}$

- Baryon-meson separation at intermediate $m_T - m_0$

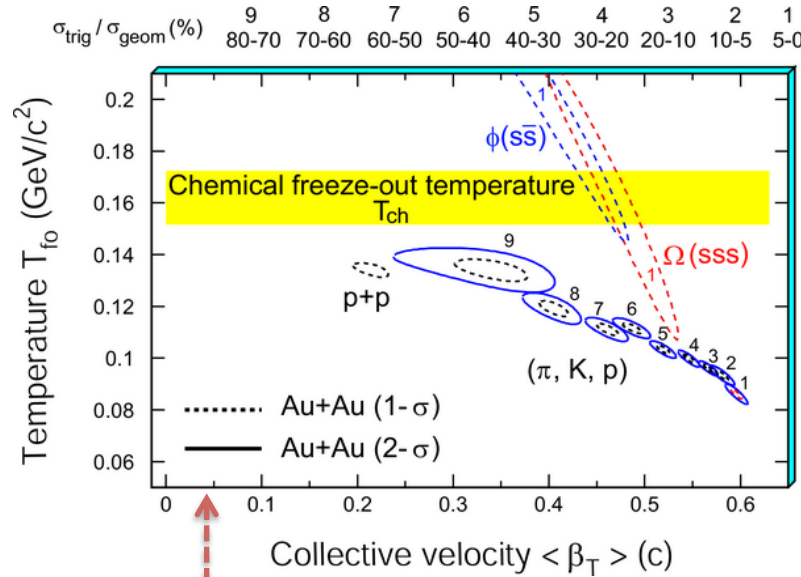
→ Parton recombination

$\sqrt{s_{NN}} \leq 19.6 \text{ GeV}$

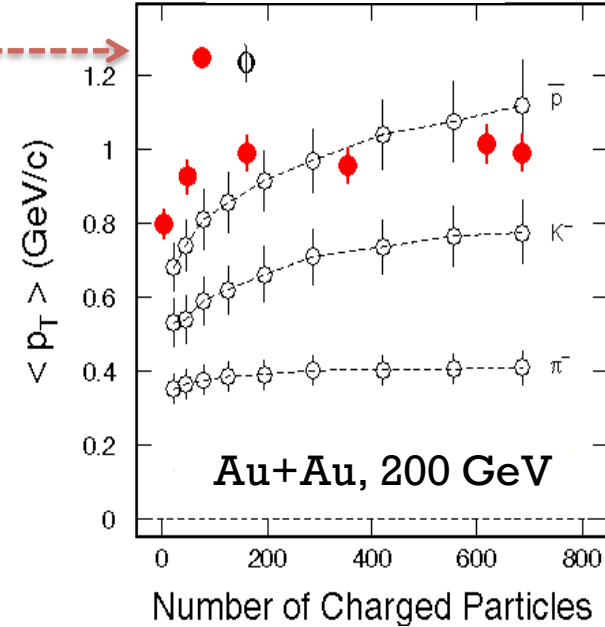
- No significant baryon - meson separation for the highest measured $m_T - m_0$

→ Probably dominated by hadronic interaction

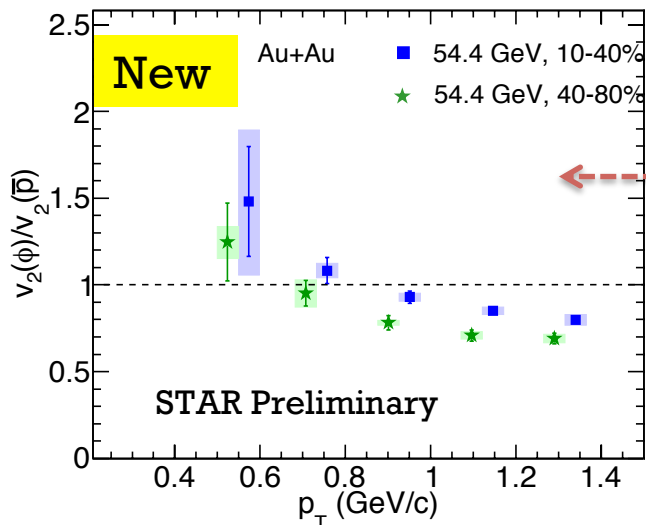
ϕ mesons v_2 : Probe to Partonic Collectivity



$\langle p_T \rangle$ of ϕ is almost independent of centrality unlike anti-protons



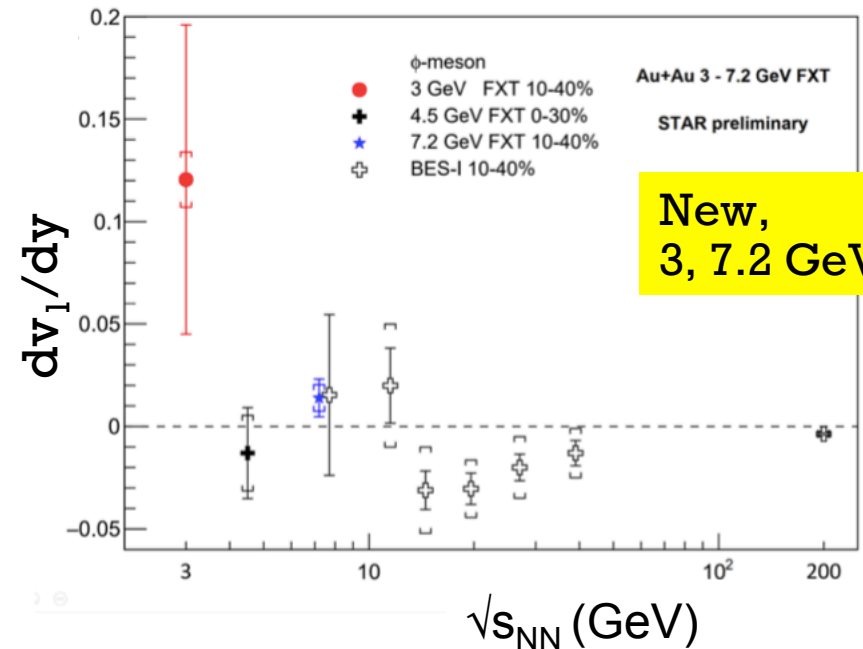
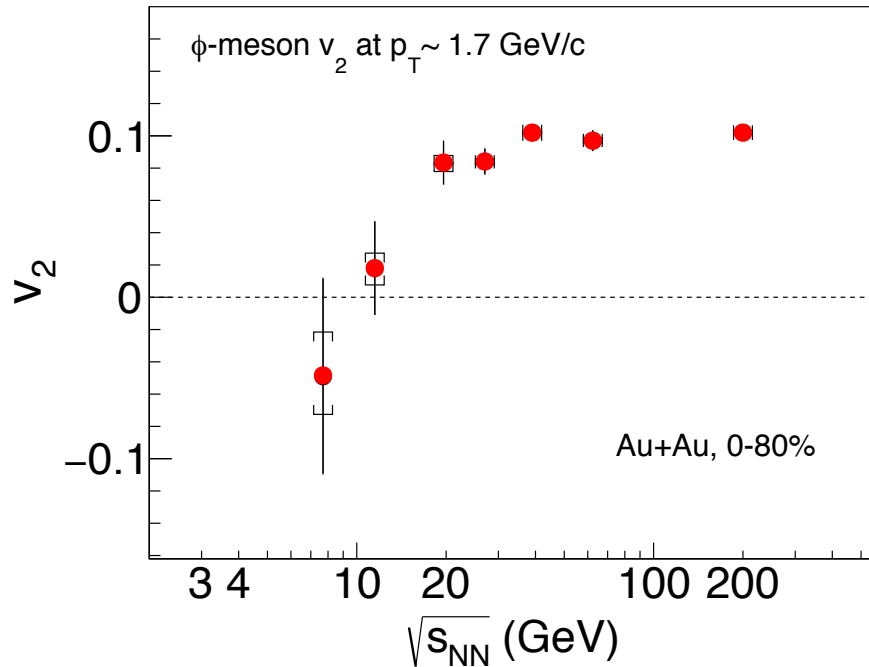
STAR : Phys. Lett. B 612 (2005) 181



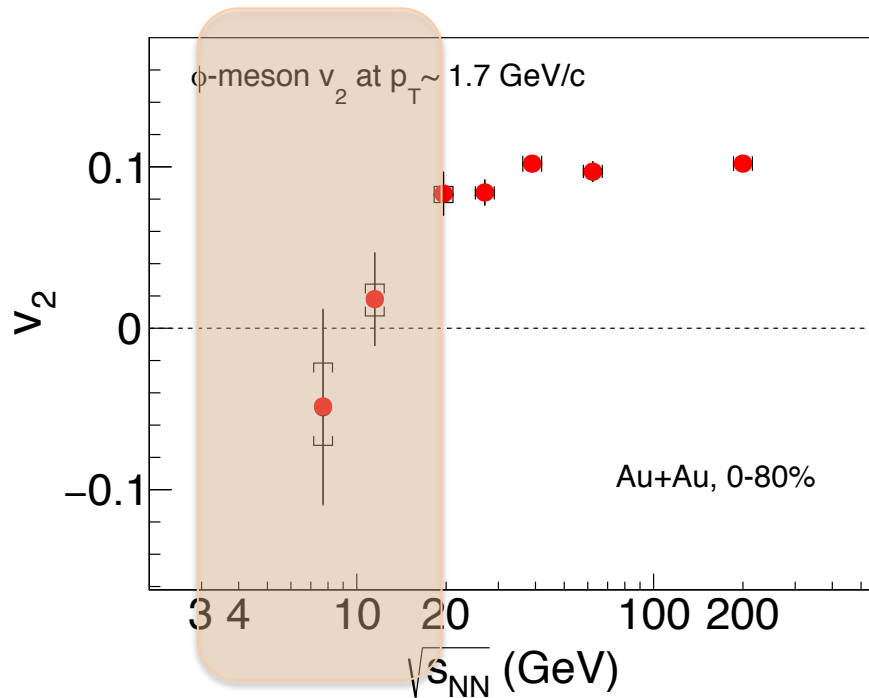
ϕ v_2 less affected by hadronic interaction compared to anti-proton

- Indicates possibly ϕ decouples early in the interaction
- Clean probe to partonic collectivity

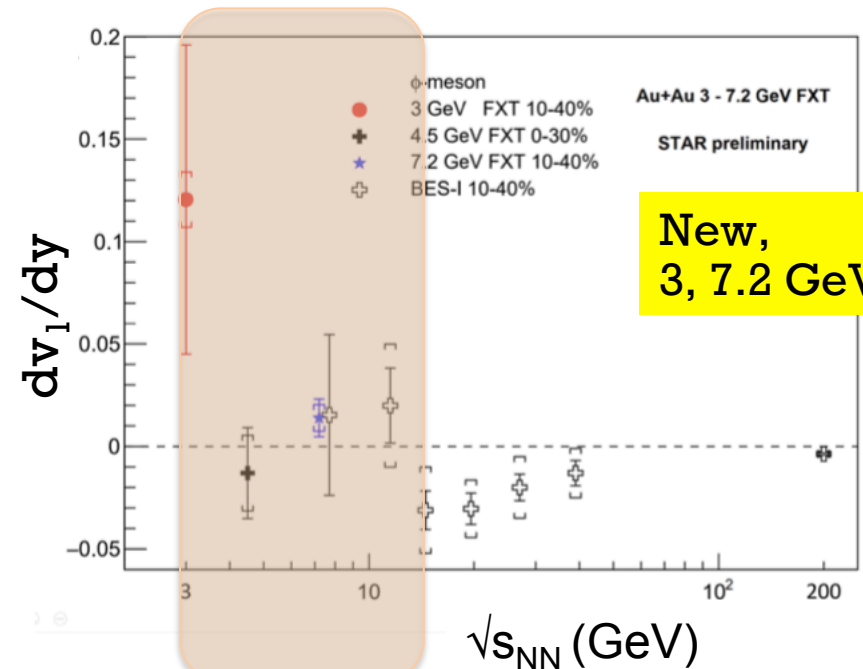
Energy Dependence of ϕ meson v_n (Partonic vs Hadronic)



Energy Dependence of ϕ meson v_n (Partonic vs Hadronic)



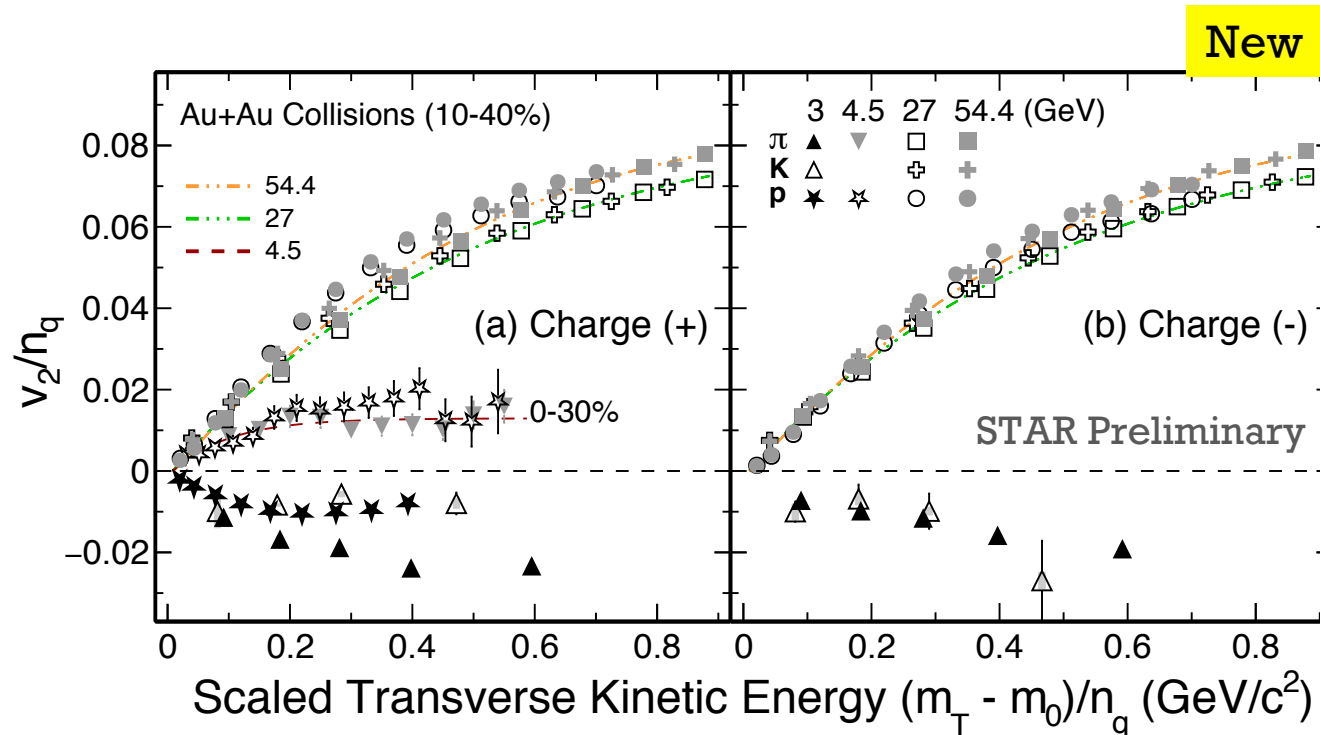
Less partonic contribution at low beam energy.



New,
3, 7.2 GeV

Could be related to the change of equation of states

Collectivity at 3 GeV (Au+Au, FXT data)



- The measured v_2 for all particles are negative at 3 GeV
- The NCQ scaling breaks, especially for positively charged particles

→ Hadronic interaction dominated matter

Selected Physics Results From BES

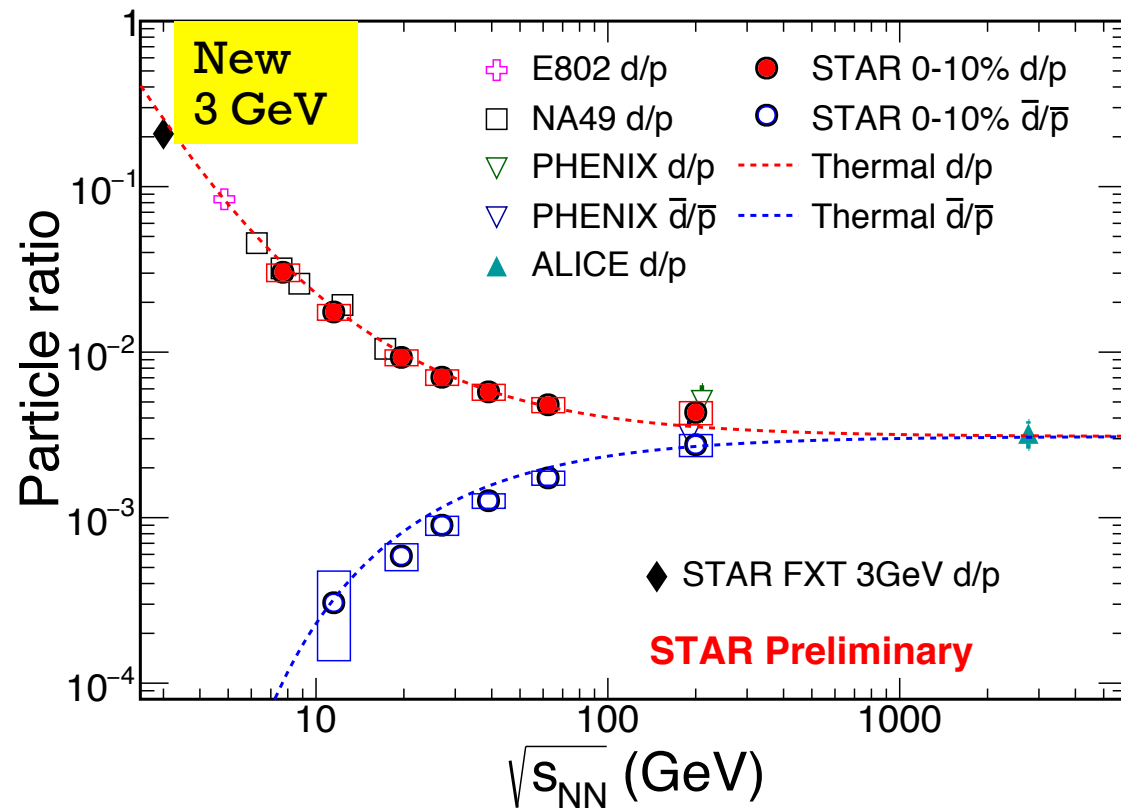
- Light and Strange Hadrons

- ① Freeze-out Conditions
- ② Particle Ratios
- ③ Nuclear Modification Factor
- ④ Collective Flow

- Nuclei and Hyper-nuclei

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Light Nuclei Production: d/p Ratios



Binding energies : ~ 2.2 MeV
for (anti-)deuteron

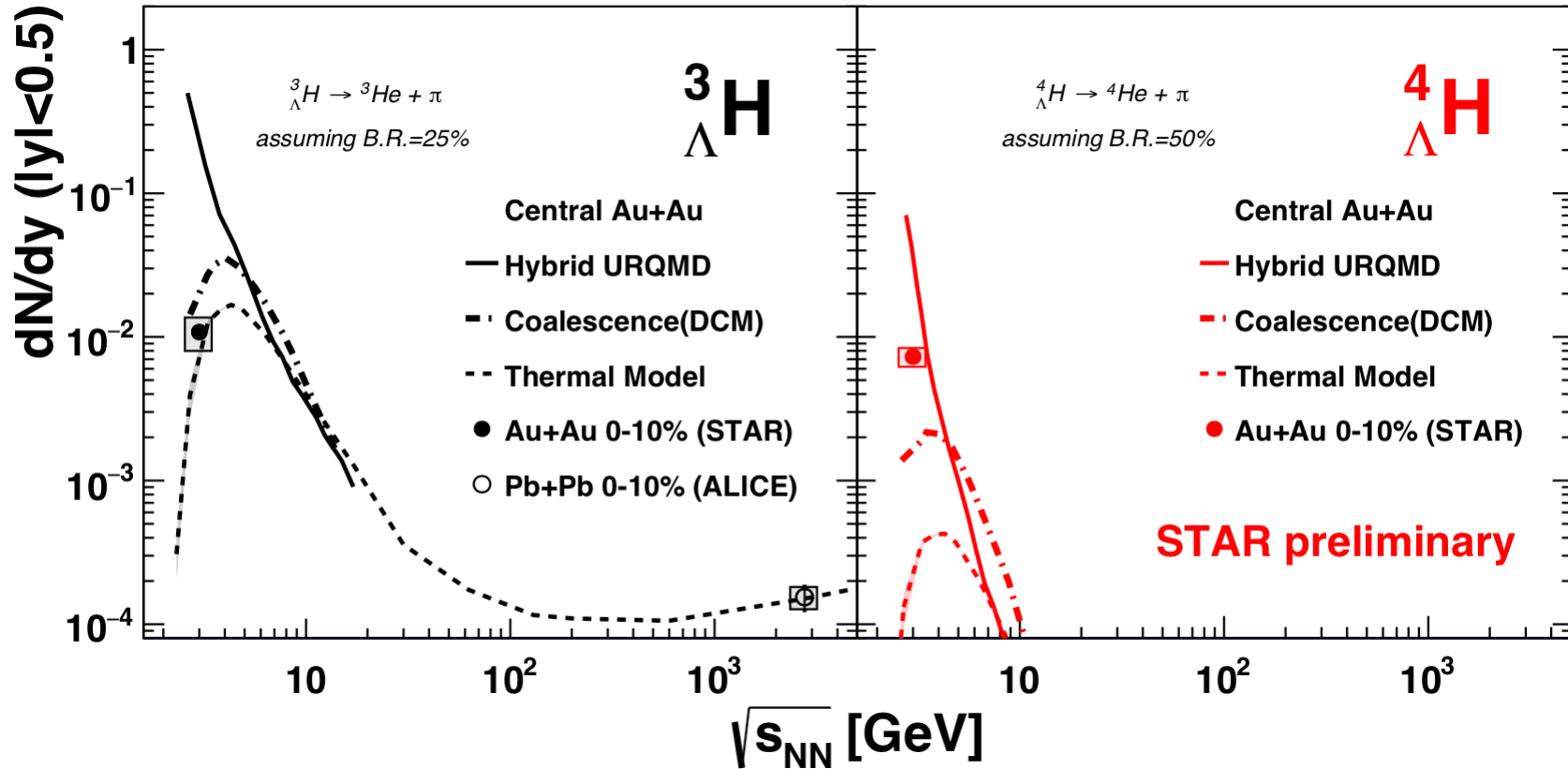
Freeze-out
temperature: ~ 100 MeV

Production mechanism of
light nuclei is important to
understand

Statistical thermal model describes the data.

Hyper-Nuclei Production

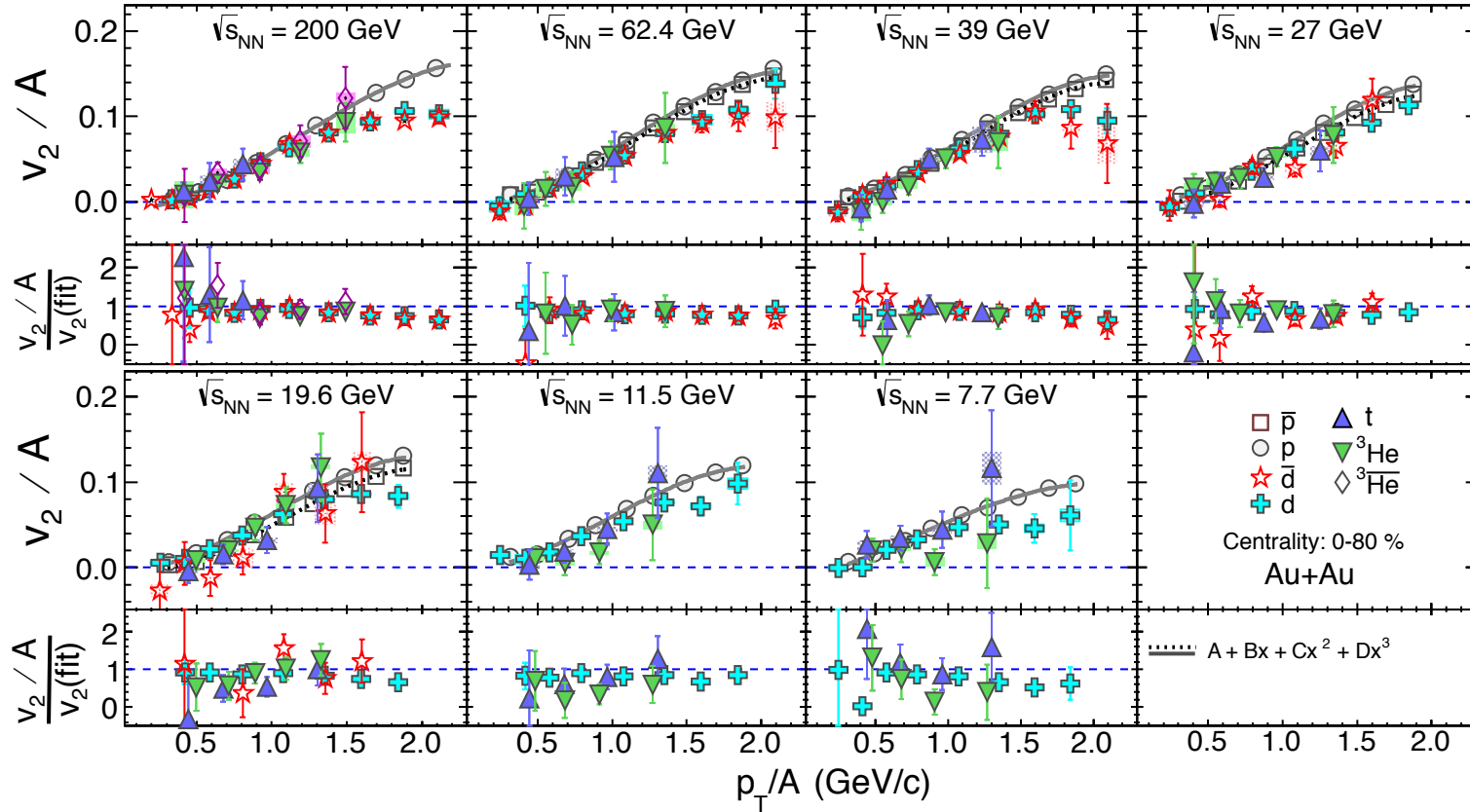
Important probe to Y-N interactions and hyperon contribution to nuclear EoS



New

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

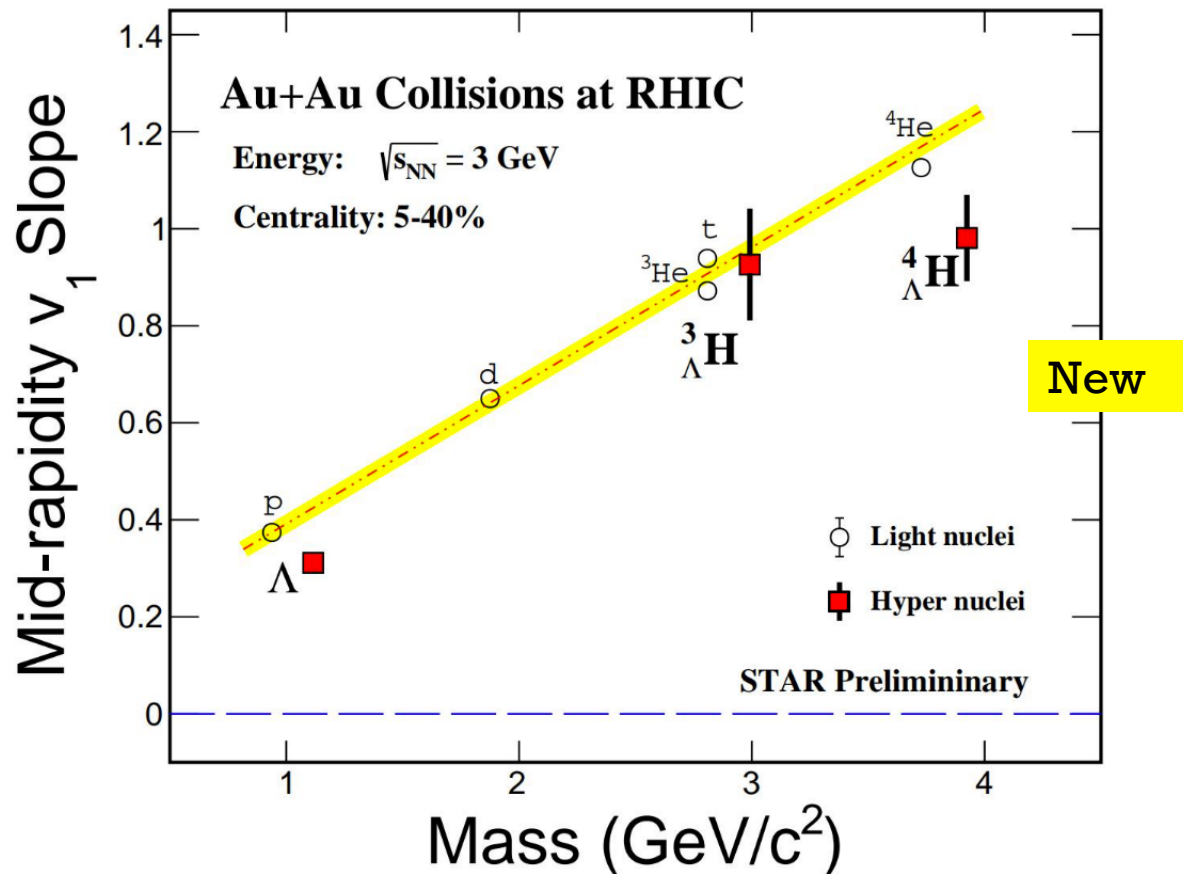
Elliptic Flow of Nuclei



- Nuclei v_2 show atomic number scaling

Nuclei production mainly through coalescence of nucleons

Directed Flow of Nuclei and Hyper-Nuclei



- First observation of hypernuclei collective flow (v_1) in heavy-ion collisions
- v_1 slope seems to follow atomic number scaling
- **Hypernuclei production mainly from coalescence of hyperons and nucleons**

Summary

Mapping the QCD phase-diagram

$\sqrt{s_{NN}} \geq 27 \text{ GeV} :$

- There are clear evidence for QGP formation
- Hadronization at intermediate p_T is dominated by quark coalescence

$\sqrt{s_{NN}} \leq 11.5 \text{ GeV} :$

- Medium created is likely hadronic interaction dominated
- Lack of evidence for the quark coalescence at intermediate p_T

High precision measurements are needed for $\sqrt{s_{NN}} < 20 \text{ GeV}$ (BES-II)

Understanding nuclei and hyper-nuclei production

- Thermal model describes yields (except $_{\Lambda}^4\text{H}$)
- Flow measurement indicates (hyper)nuclei production through coalescence

STAR BES-II

New measurements using high statistics data and with improved detector condition will be available soon.

Collider Mode:

Collision Energy (GeV)	7.7	9.2	11.5	14.6	17.3	19.6	27
Performance in BES-I	2010	NA	2010	2014	NA	2011	2011
Good Events (M)	4.3	NA	11.7	12.6	NA	36	70
Days running	19	NA	10	21	NA	9	8
Data Hours per day	11	NA	12	10	NA	9	10
Fill Length (min)	10	NA	20	60	NA	30	60
Good Event Rate (Hz)	7	NA	30	23	NA	100	190
Max DAQ Rate (Hz)	80	NA	140	1000	NA	500	1200
Performance in BES-II							
(achieved)	2021	2020	2020	2019	2021	2019	2018
Required Number of Events	100	160	230	300	250	400	NA
Achieved Number of Events	101	162	235	324	TBD	582	560
fill length (min)	30	45	25	45	50	60	120
Good Event Rate (Hz)	22	33	80	170	265	400	620
Max DAQ rate (Hz)	600	700	550	800	1300	1800	2200
Data Hours per day	13	13	13	9	15	10	9
Projected number of weeks	11-20	8.5-14	7.6-10	5.5	2.5	4.5	NA
weeks to reach goals	12.8	14.6	8.9	8.6	TBD	5.1	4.0

STAR BES-II

New measurements using high statistics data and with improved detector condition will be available soon.

Fixed Target Mode:

Beam Energy	$\sqrt{s_{NN}}$ (GeV)	Expected Duration	Actual Duration	Proposed Events	Recorded Events	Year
3.85	3.0	4 days	3.5 days	100 M	258 M	2018
3.85	3.0	3 days	3.3 days	300 M	307 M	2021
3.85	3.0	3 weeks	TBD	2 B	TBD	2021
4.59	3.2	2 days	46 hours	200 M	200.6 M	2019
5.75	3.5	1 day	23 hours	100 M	115.6 M	2020
7.3	3.9	0.5 days	12 hours	50 M	52.7 M	2019
7.3	3.9	1 day	29 hours	100 M	117 M	2020
9.8	4.5	1 day	31 hours	100 M	108 M	2020
13.5	5.2	1 days	21 hours	100 M	103 M	2020
19.5	6.2	1 days	22 hours	100 M	118 M	2020
26.5	7.2	parasitic	2 days	none	155 M	2018
26.5	7.2	parasitic	3.5 days	none	317 M	2020
26.5	7.2	parasitic	TBD	none	TBD	2021
31.2	7.7	0.5 days	11.5 hours	50 M	50.6 M	2019
31.2	7.7	1 day	26 hours	100 M	112 M	2020
44.5	9.1	0.5 days	12 hours	50 M	53.9 M	2021
70	11.5	0.5 days	12 hours	50 M	51.7 M	2021
100	13.7	0.5 days	10 hours	50 M	50.7 M	2021

Thank You