Beam Energy Scan at STAR
Yield and Flow Measurements

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Indian Institute of Science Education and Research, Berhampur

RHIC & AGS Users' Meeting, 2021

Supported in part by
U.S. DEPARTMENT OF ENERGY | Office of Science

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Motivation

Goal:

Mapping the QCD phase-structure

1) Phase-boundary

2) Onset of de-confinement

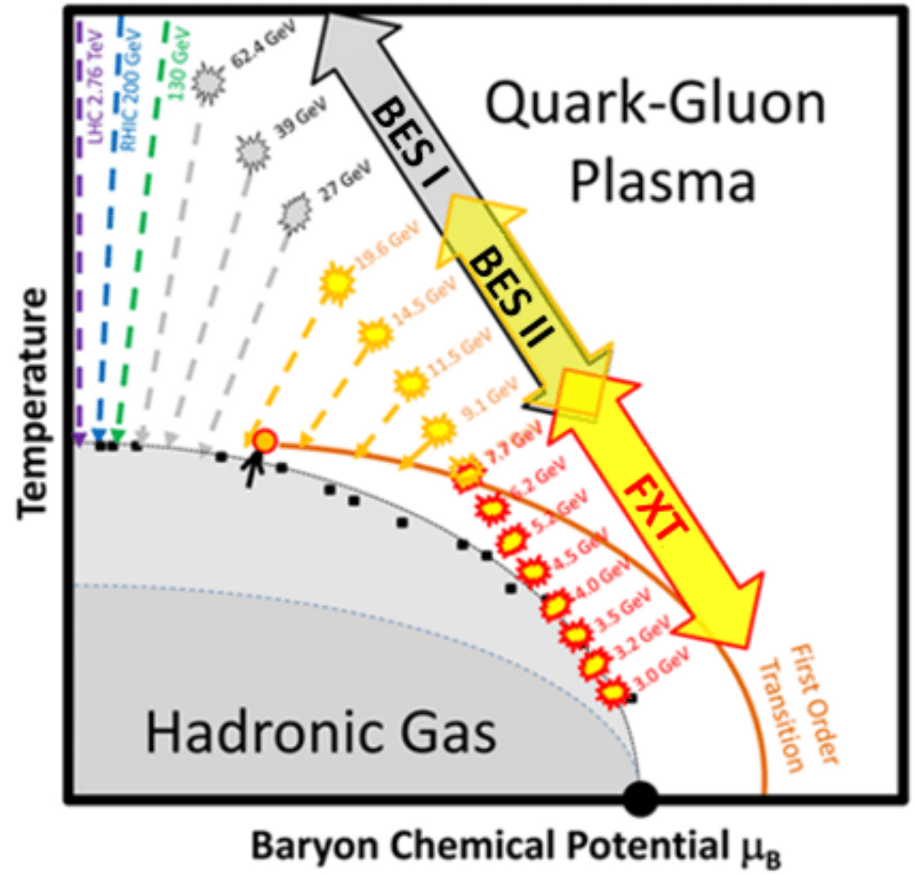
3) QCD critical point

RHIC BES:

Collisions: Au+Au

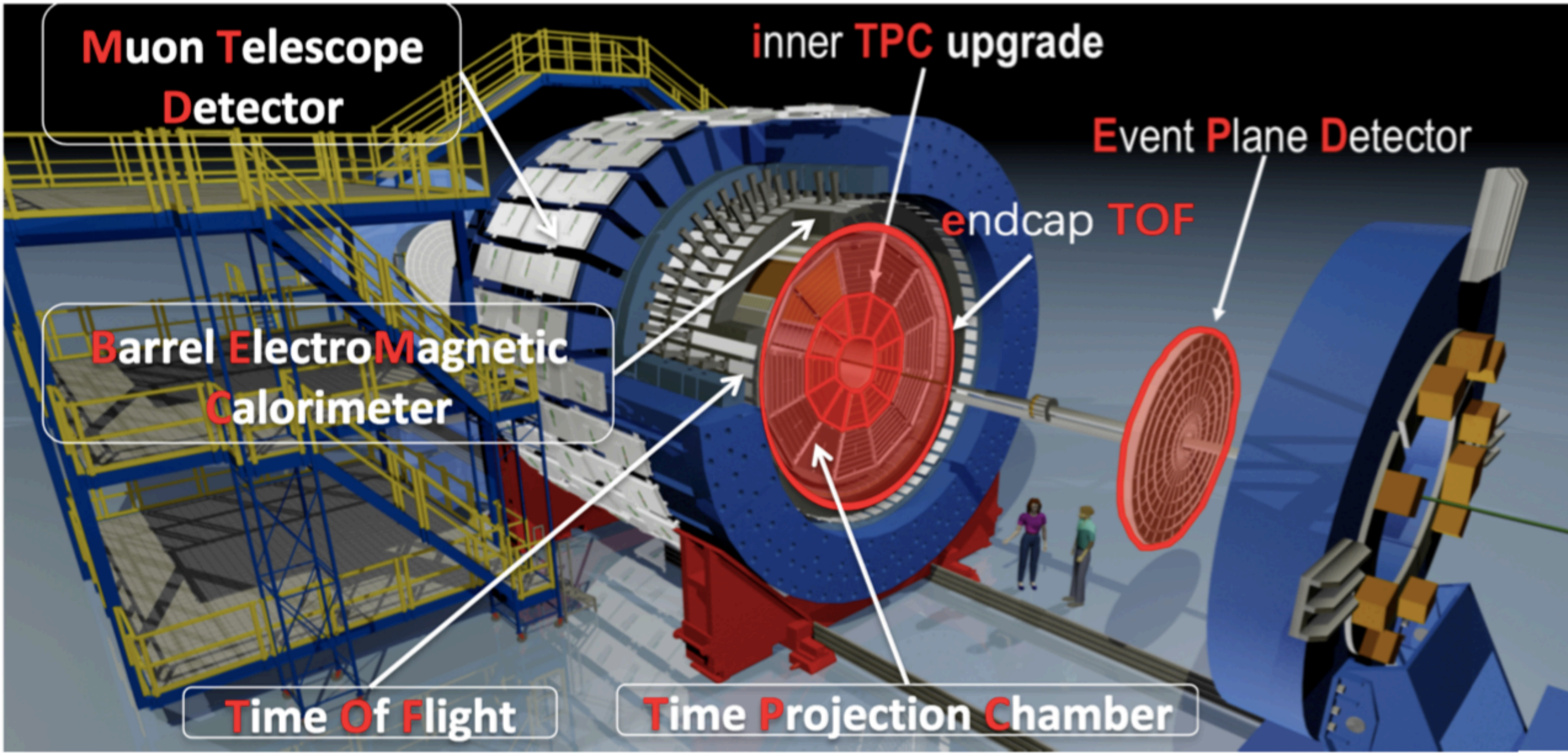
Collider Mode:
$\sqrt{s_{NN}}$ = 7.7 – 62.4 GeV

Fixed Target Mode:
$\sqrt{s_{NN}}$ = 3 – 13.7 GeV



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

The STAR Experiment



Selected Physics Results From BES

- Light and Strange Hadrons

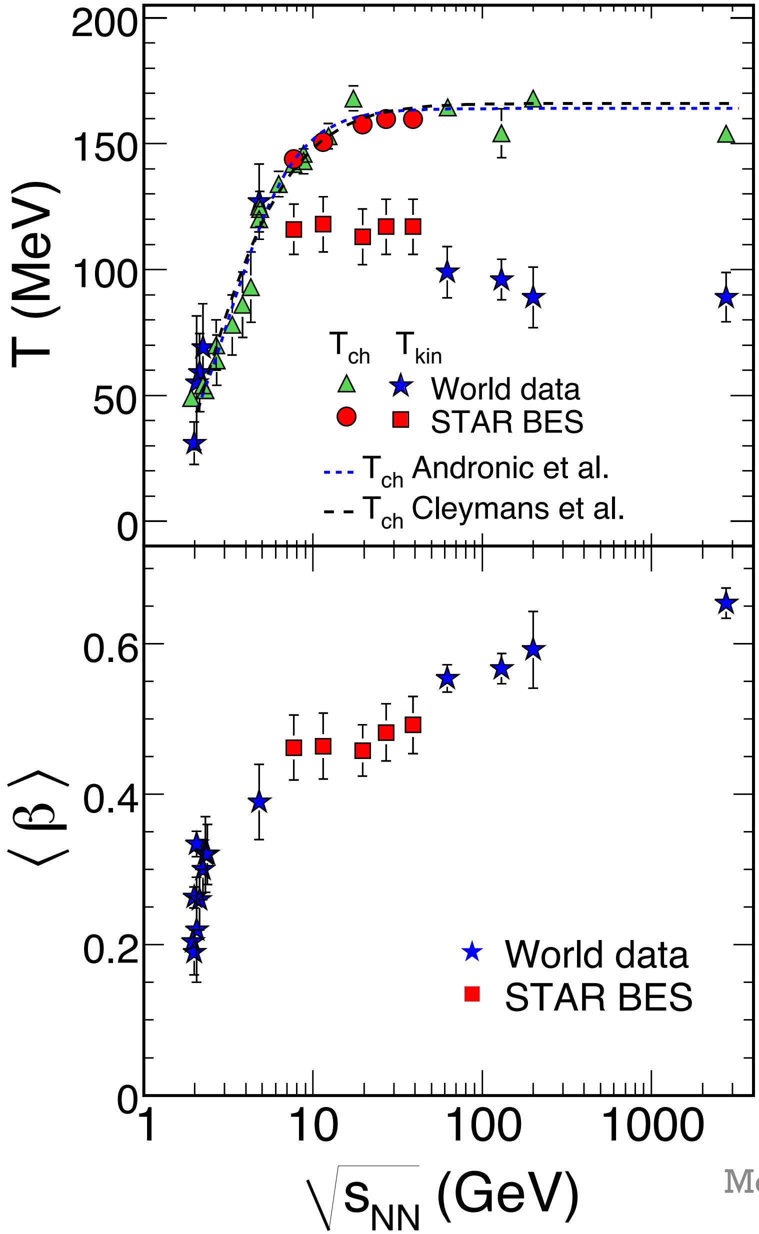
  ① Freeze-out Parameters
  ② Particle Ratios
  ③ Nuclear Modification Factor
  ④ Collective Flow

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

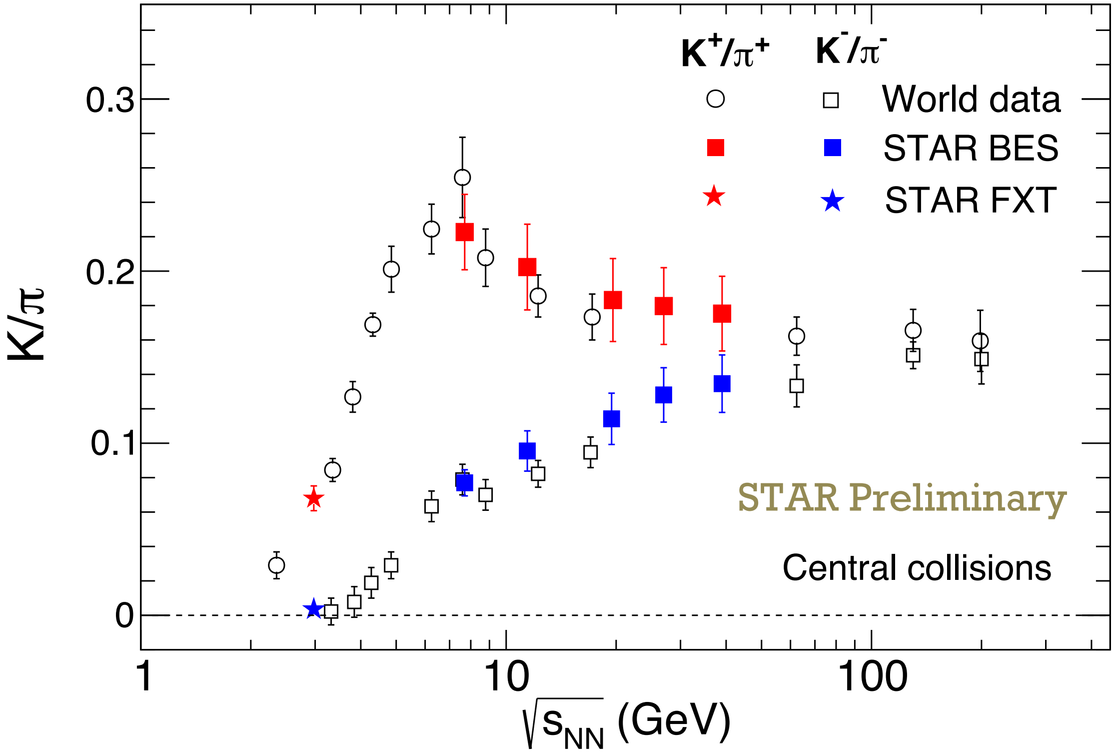
  → Increasing hadronic interactions after chemical freeze-out at higher energies

- Radial flow velocity increases with increasing energy

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

Particle Ratios (K/π)

(Strange over non-strange)



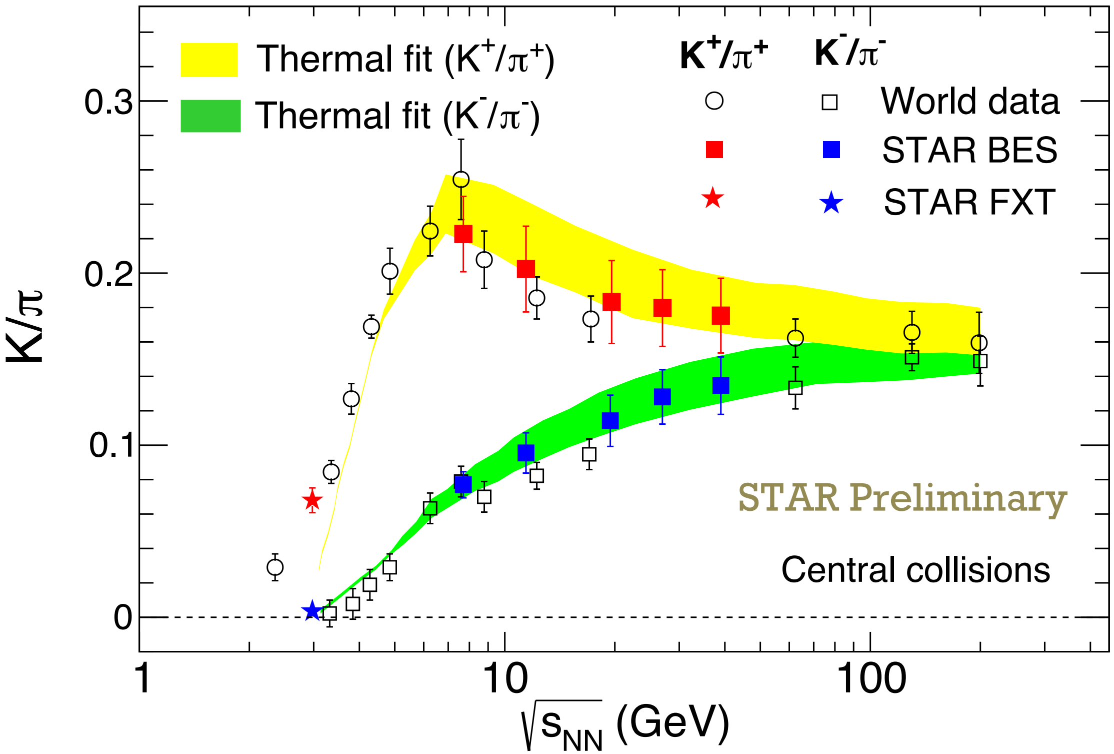
New data : 3 GeV

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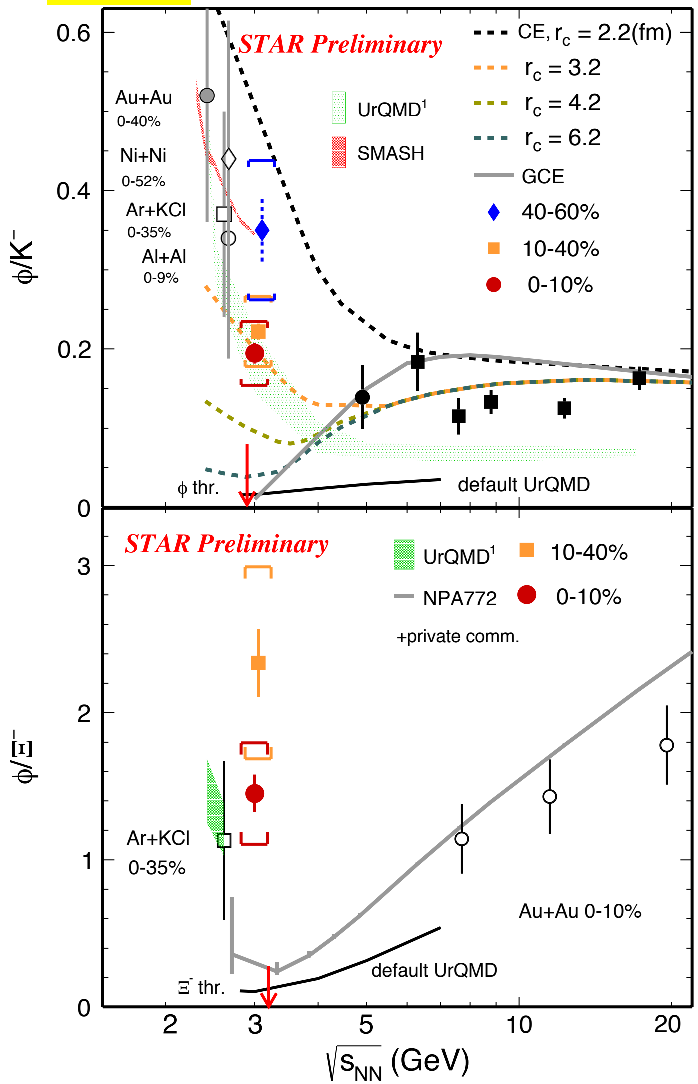
- Results from BES energies follow world data trend
- Smooth K^+/π^+ ratio vs. $\sqrt{s_{NN}}$ including STAR data
- **Thermal model describes data**

Particle Ratios (ϕ/K and ϕ/Ξ)

New



High baryon density matter : GCE vs CE

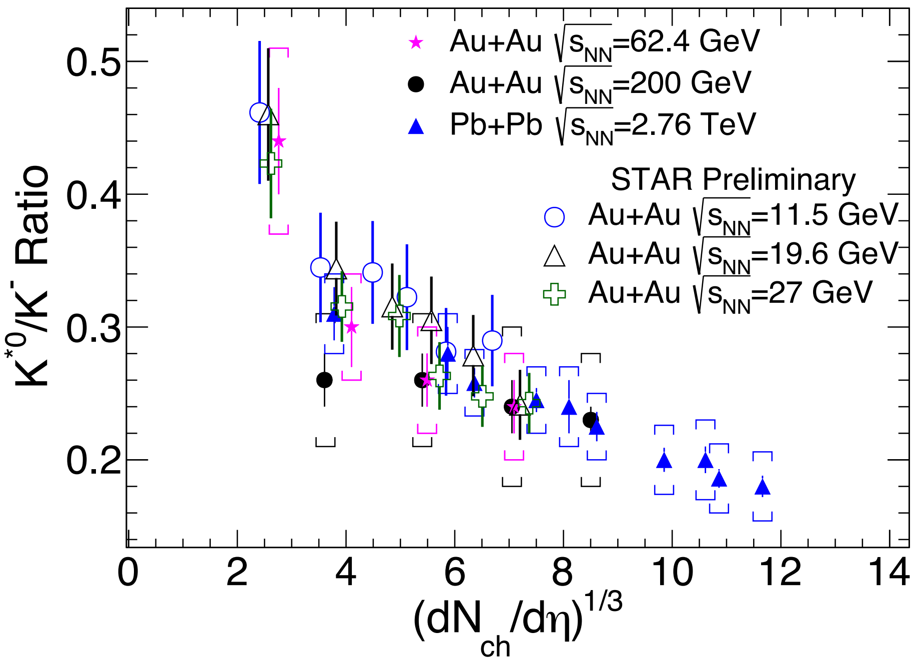
→ Data favor the Canonical Ensemble at high baryon density

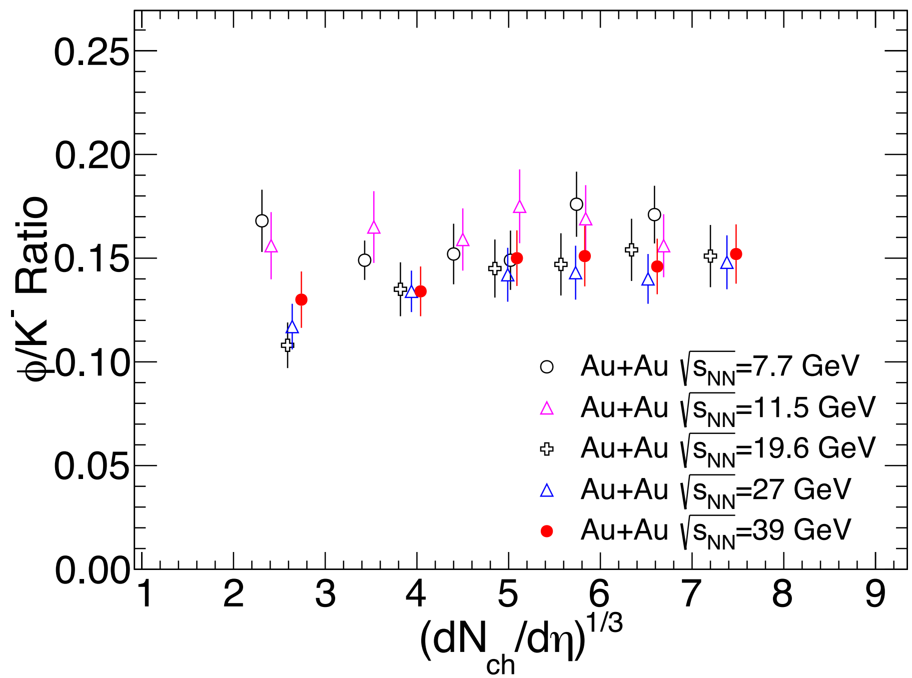
→ Canonical suppression of strange hadrons at high baryon density

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

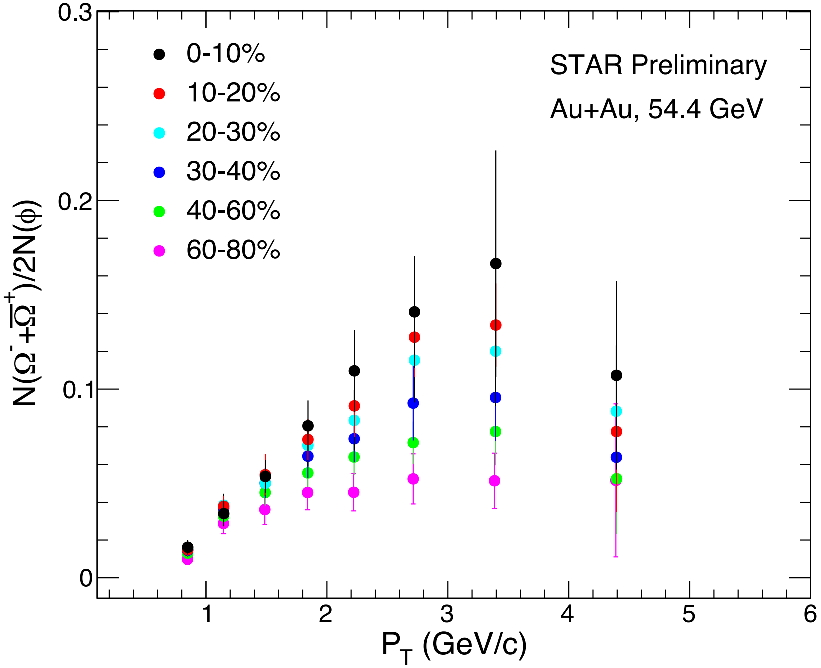
STAR: PRC **71**, 064902 (2005)

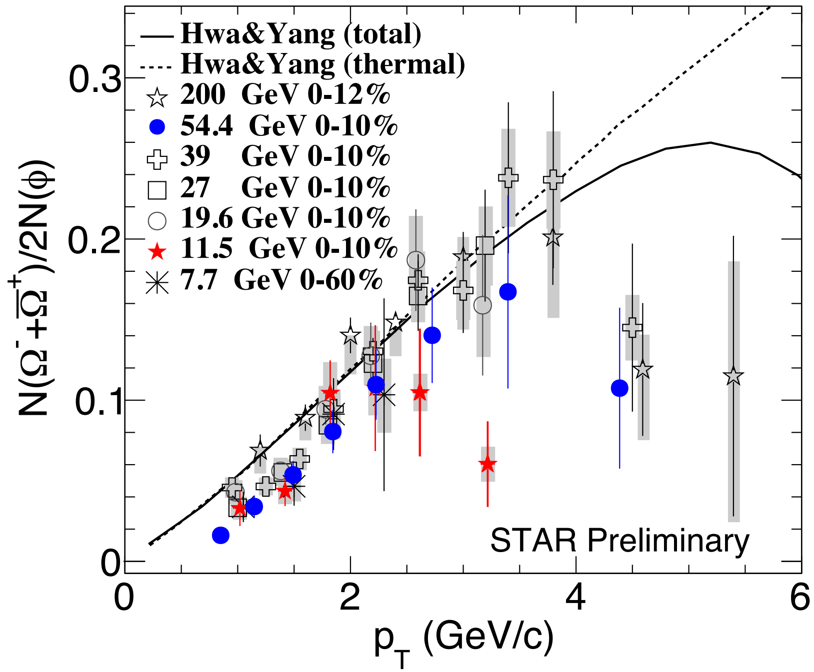
STAR: PRC 93 (2016) (R) 21903

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

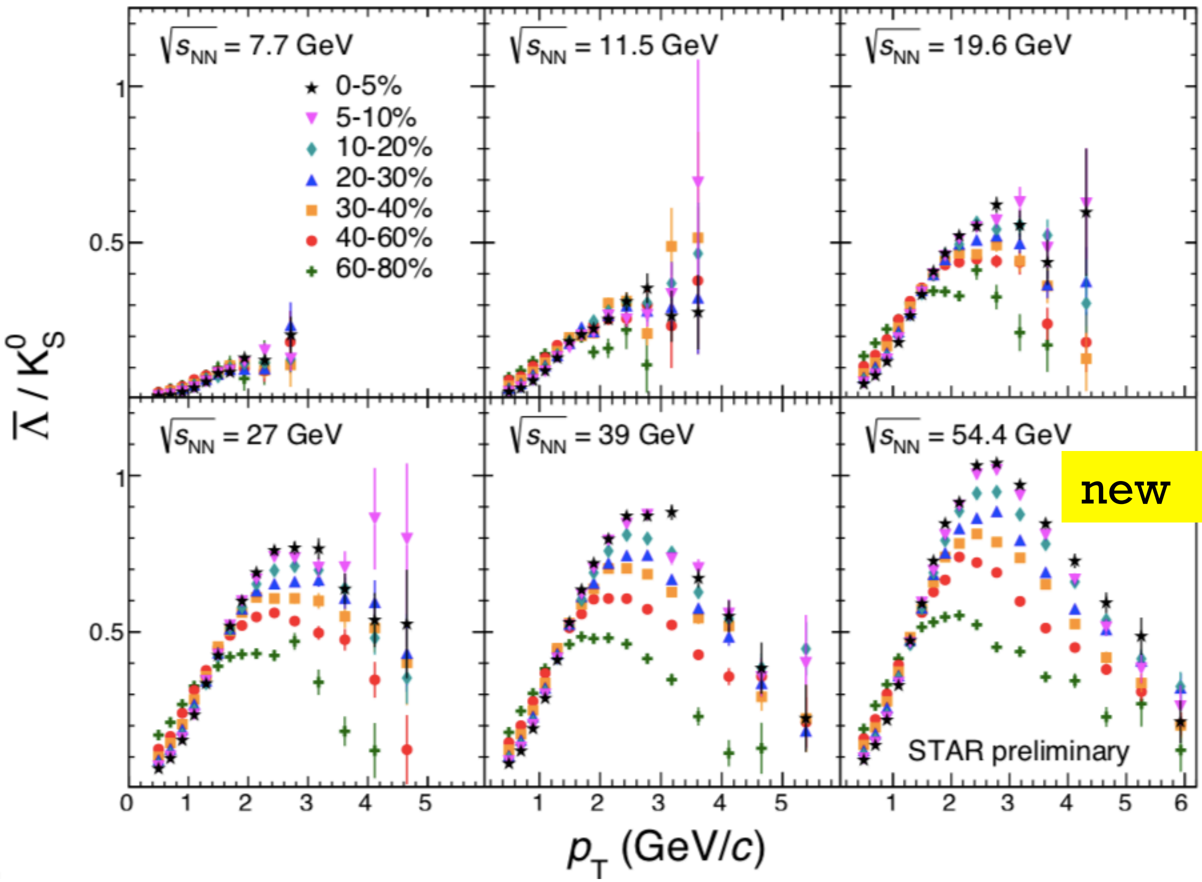
Need more statistics for $\sqrt{s_{NN}} <$ 19 GeV(BES -II)

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

STAR: PRC 79, 64903 (2009)

STAR: PRC 93, 021903 (2016)

Baryon-to-Meson Ratio



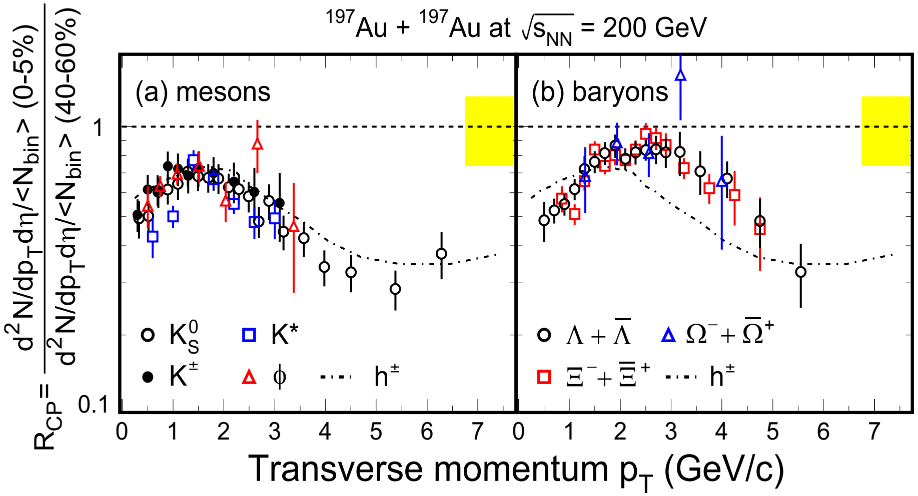
- Baryon enhancement at intermediate p_T in central collisions for $\sqrt{s_{NN}} \geq$ 19.6 GeV

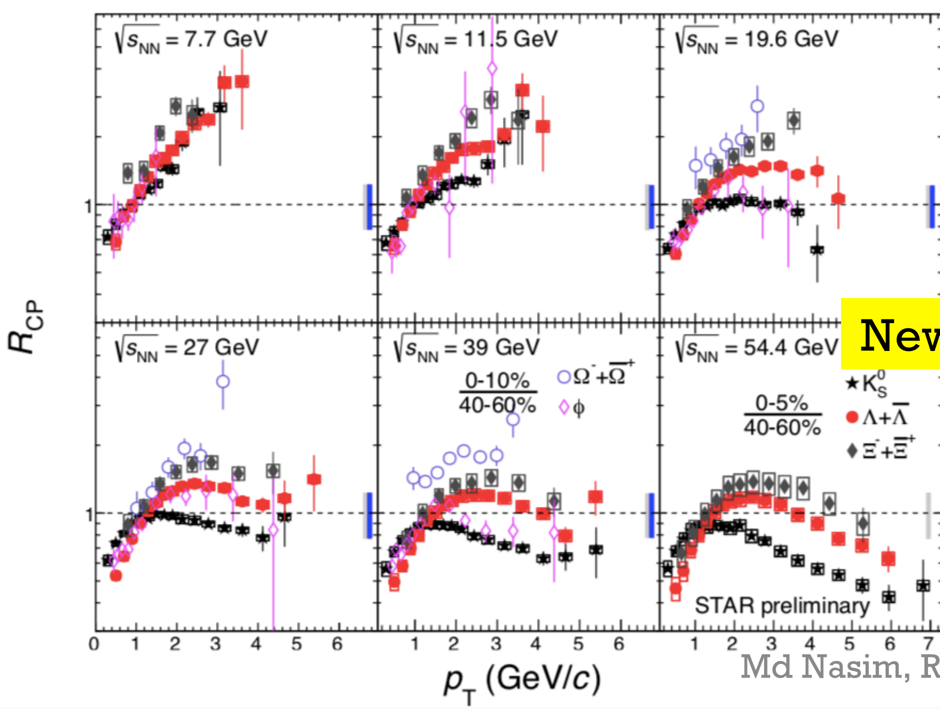
→ Parton recombination model can explain the observed shape

- 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





New

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

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

- Suppression at high p_T

→ Energy loss of partons in QGP

- Baryon vs meson at intermediate p_T

→ Parton recombination

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

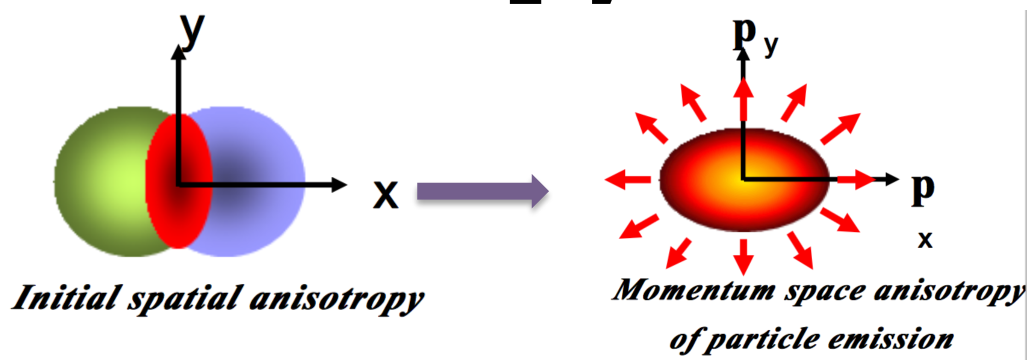
- No suppression for the highest measured p_T

→ Parton energy loss, if any, is subdominant

- Baryon –meson separation is not significant

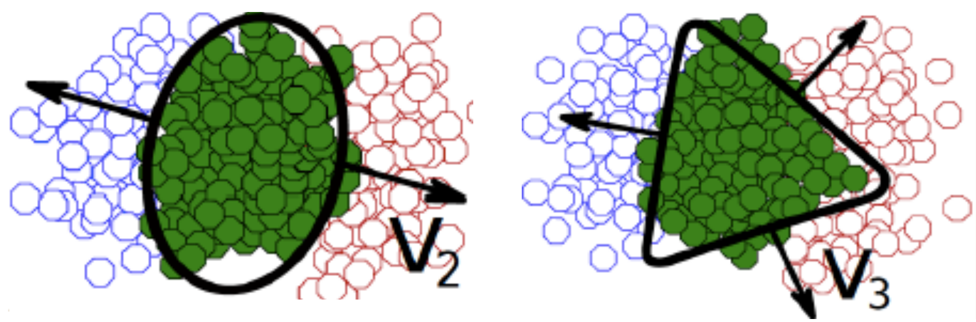
Azimuthal Anisotropy

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



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

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

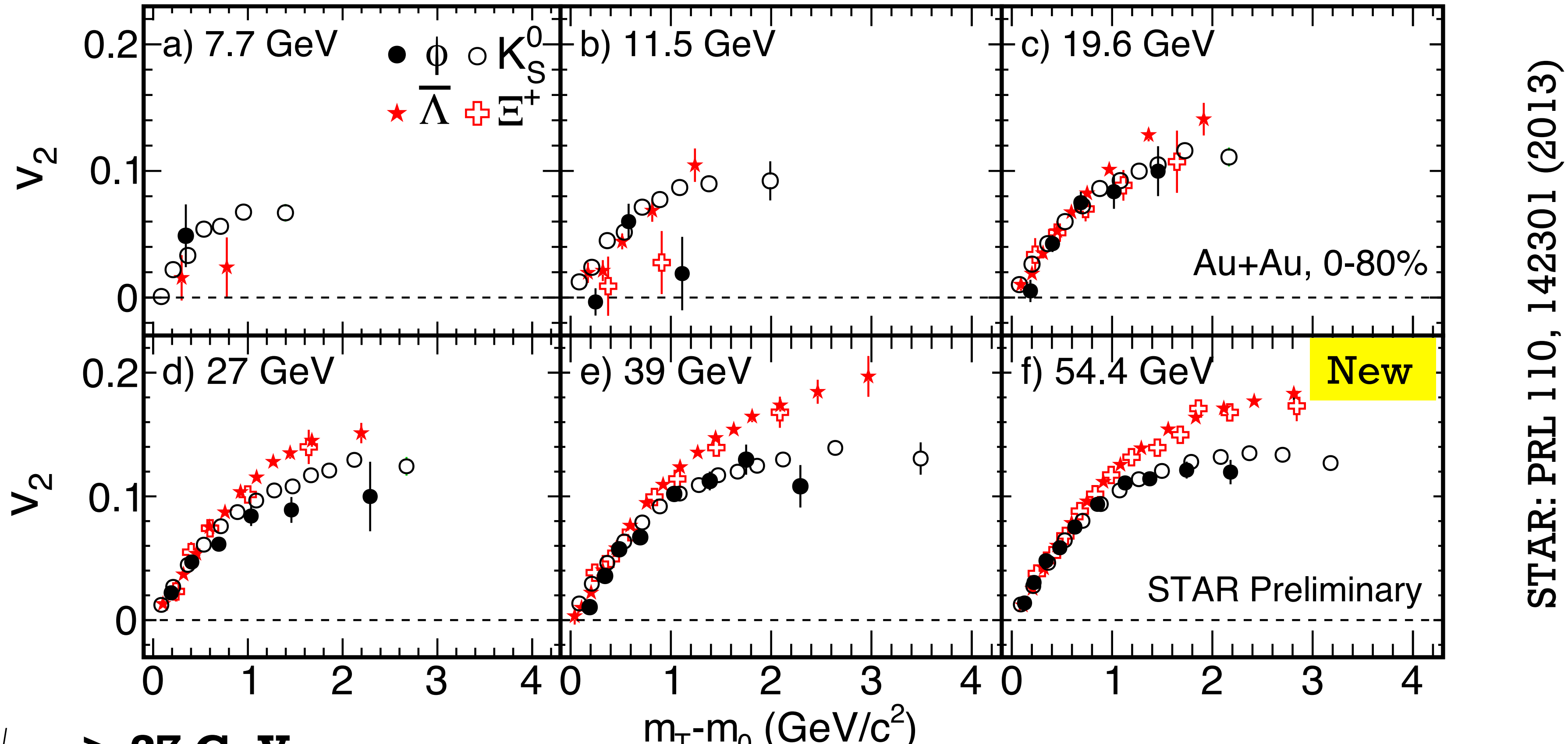


The azimuthal anisotropy parameters (v_n) are sensitive probe to the matter created in heavy-ion collisions.

A.M. Poskanzer, S.A. Voloshin, PRC 58, 1671 (1998)

P. Kolb, U. W. Heinz, NPA 715, 653c (2003)

Elliptic Flow of Strange Hadrons



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

- Baryon-meson separation at intermediate m_T-m_0

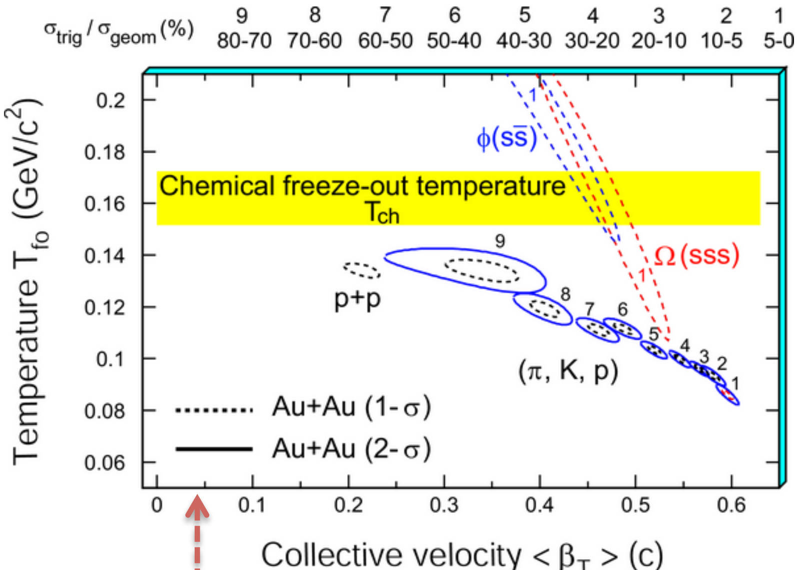
→ Parton recombination

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

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

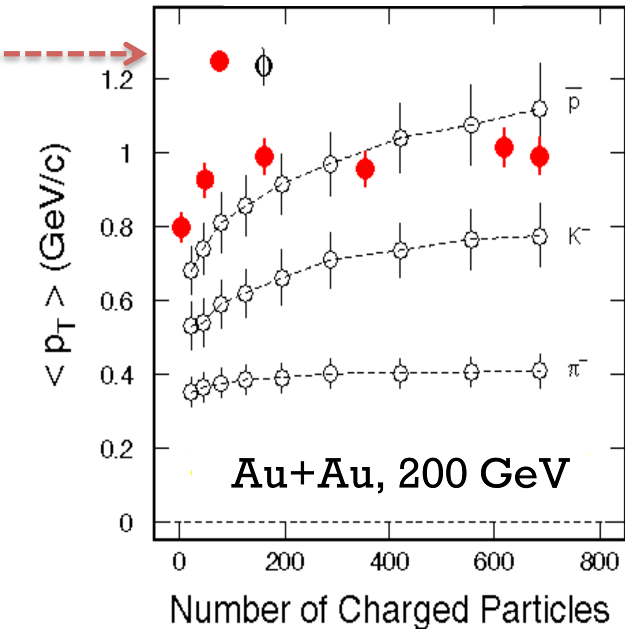
→ Probably dominated by hadronic interaction

ϕ mesons v_2: Probe to Partonic Collectivity

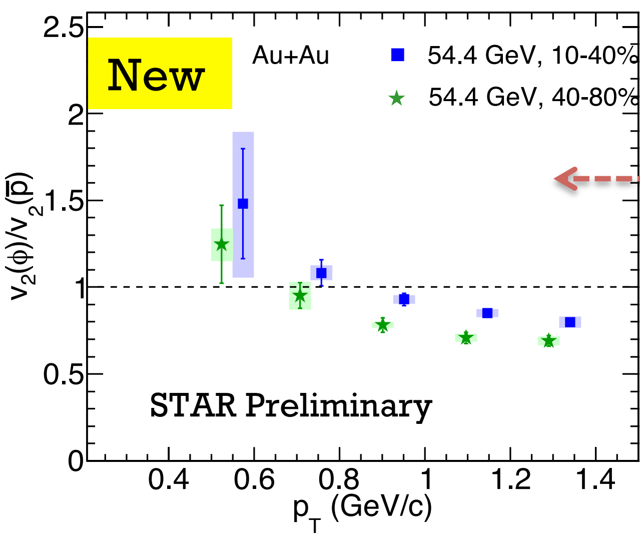


ϕ freezes out at higher temperature than π,k,p

$<p_T>$ of ϕ is almost independent of centrality unlike anti-protons



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

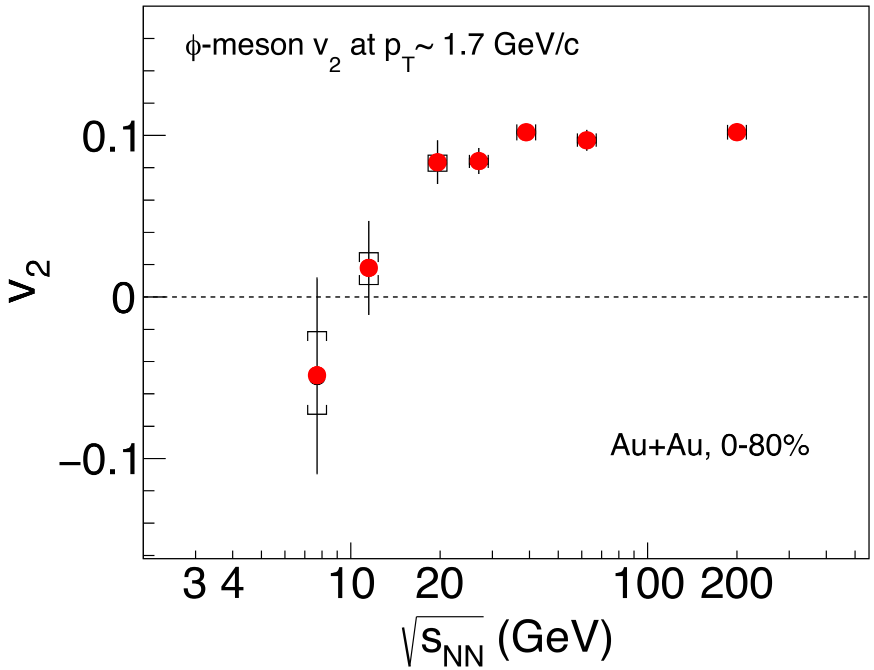


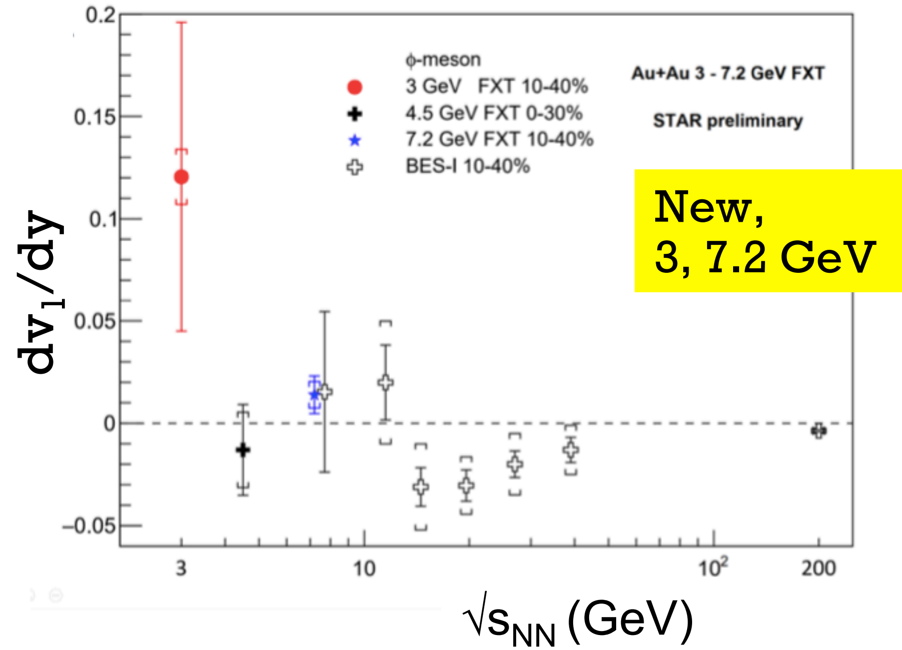
ϕ v_2 less affected by hadronic interaction compared to anti-proton

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

Energy Dependence of ϕ meson v_n

(Partonic vs Hadronic)

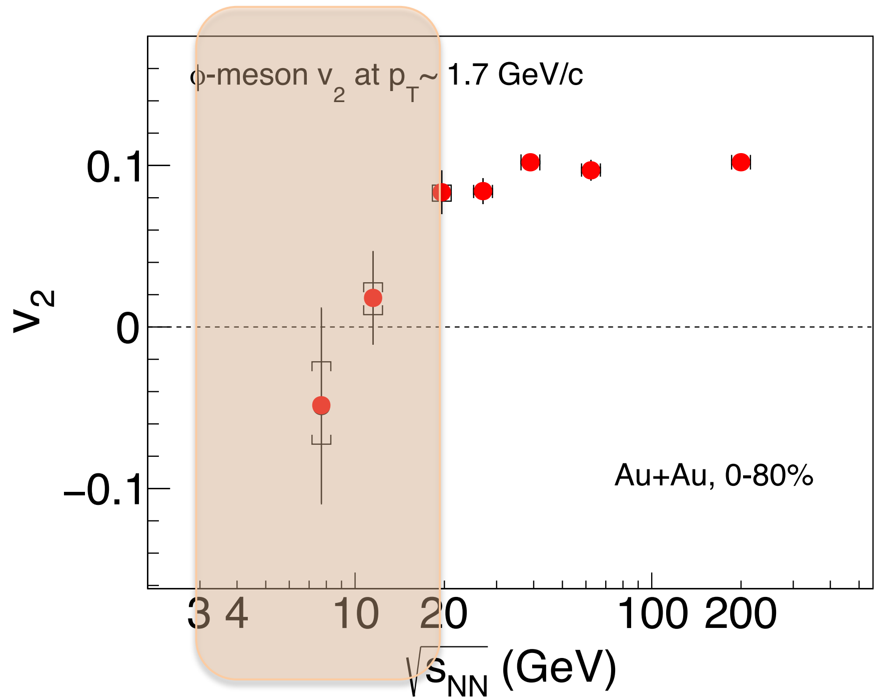


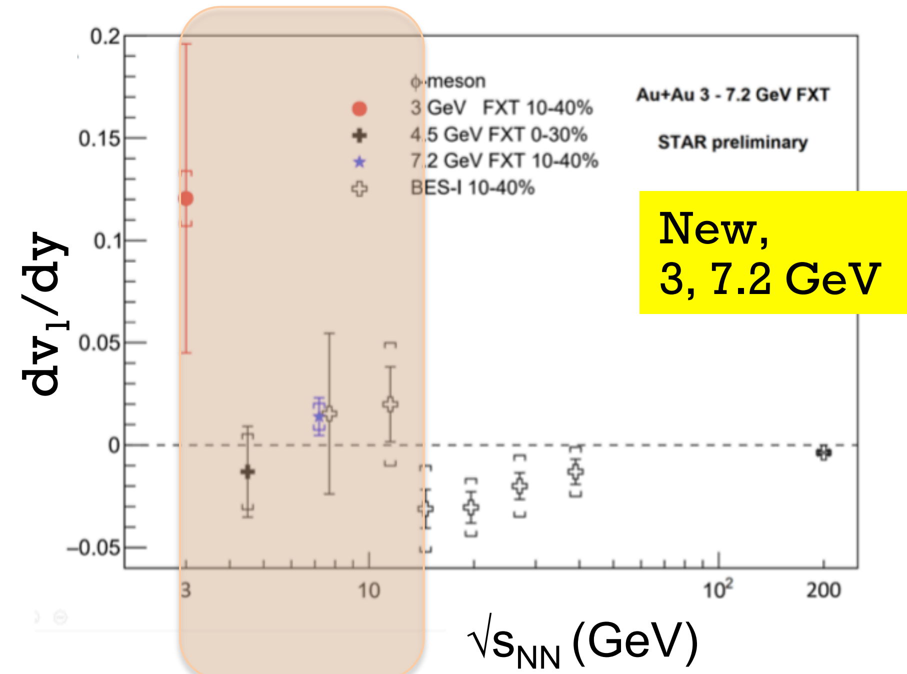


STAR: PRL 110, 142301 (2013)

Energy Dependence of ϕ meson v_n

(Partonic vs Hadronic)



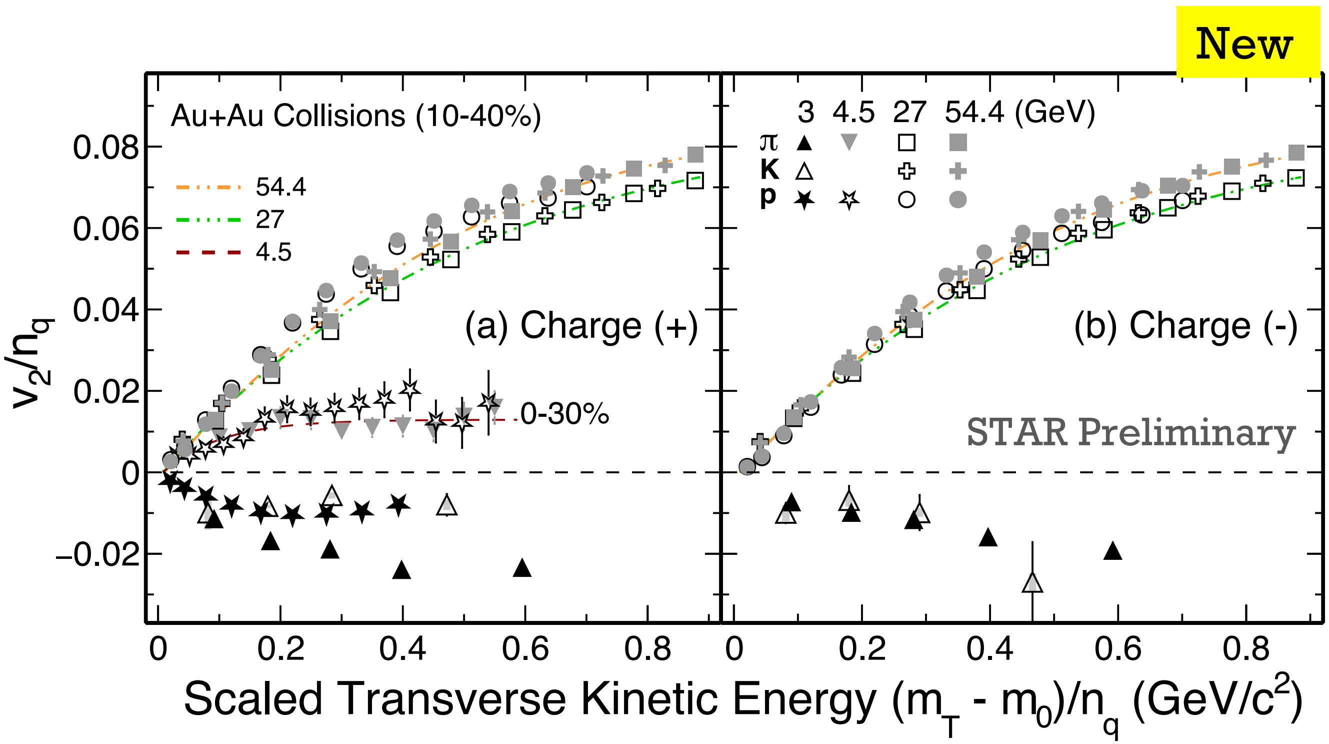


Less partonic contribution at low beam energy.

Could be related to the change of equation of states

STAR: PRL 110, 142301 (2013)

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

  ① Particle Yields
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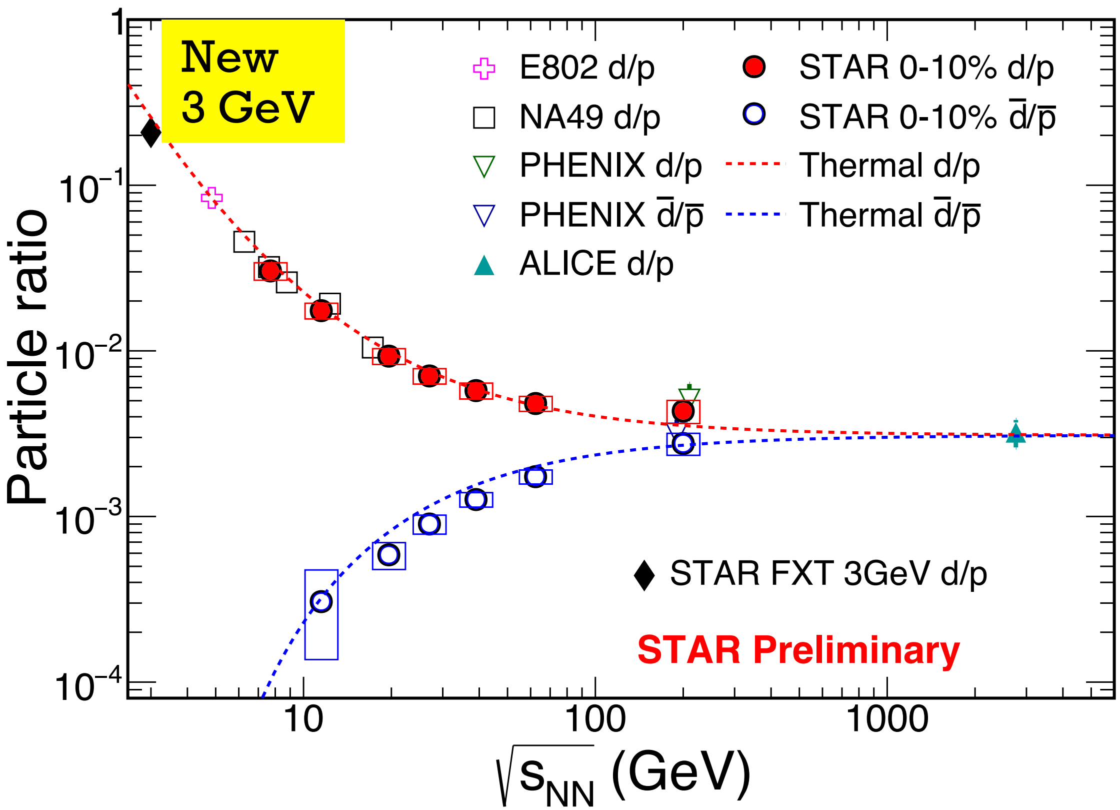
Light Nuclei Production: d/p Ratios



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

Freeze-out temperature: ~ 100 MeV

Production mechanism of light nuclei is important to understand

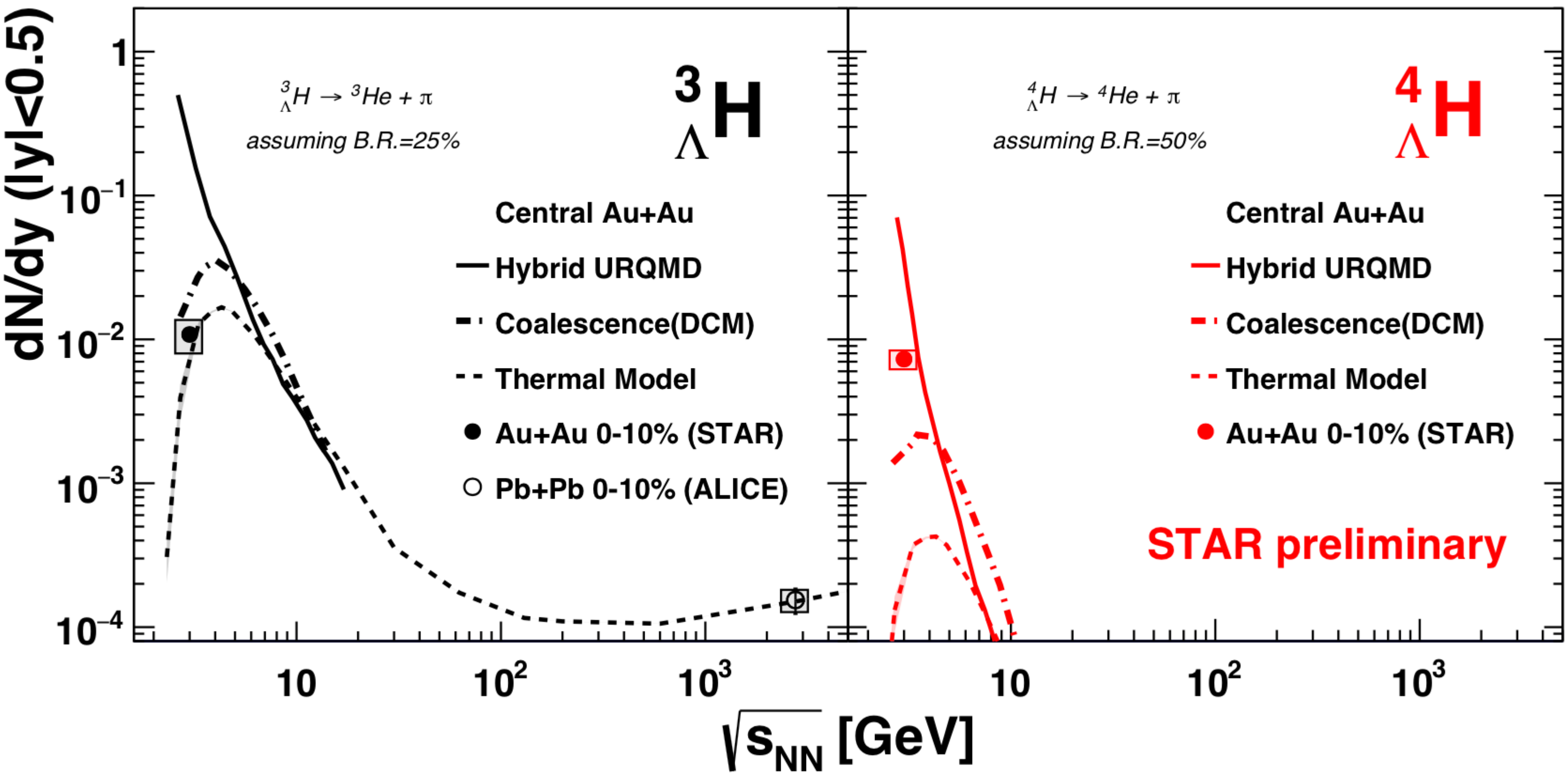
Statistical thermal model describes the data.

STAR: PRC 99, 064905 (2019)

Hyper-Nuclei Production

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

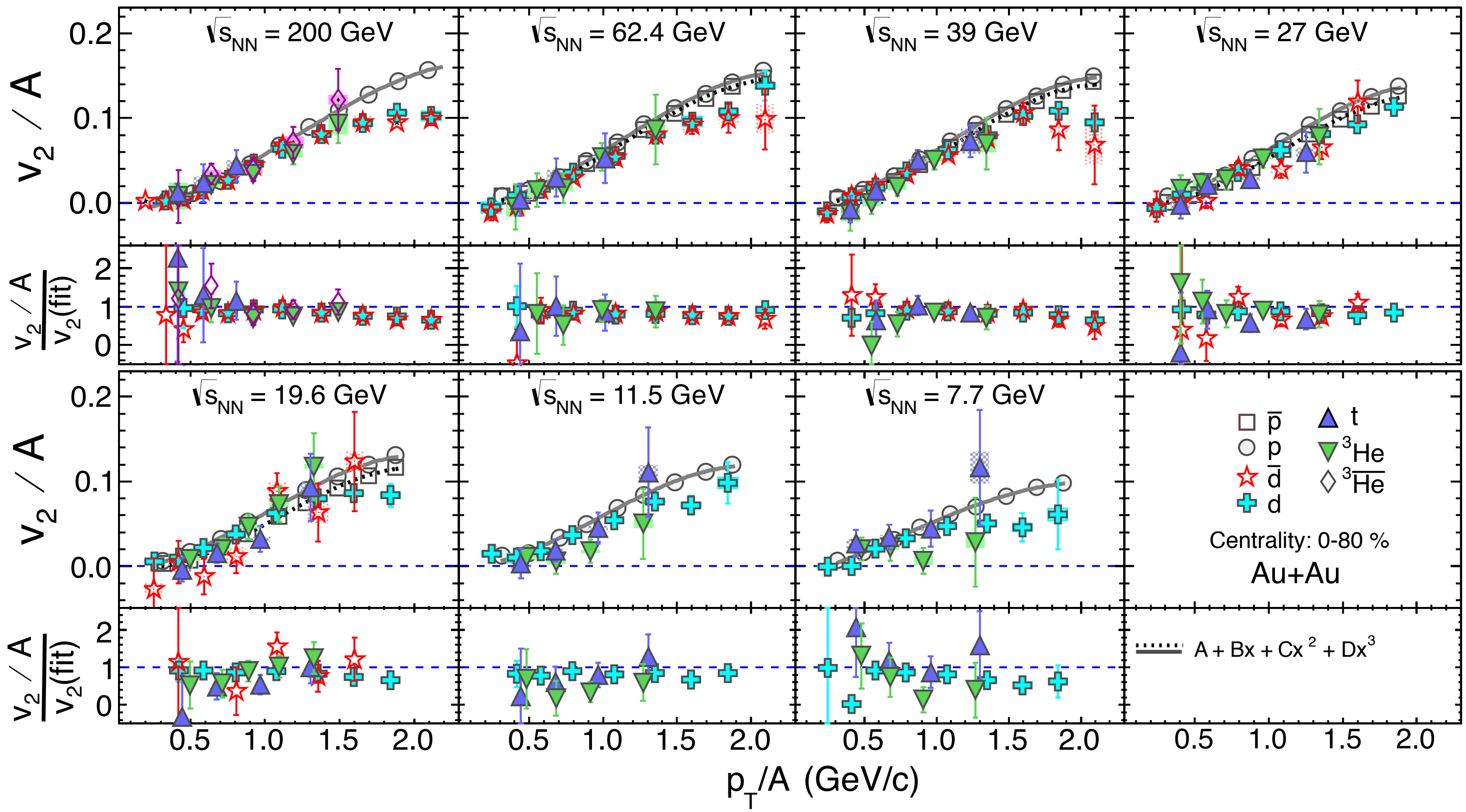
New



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

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

Elliptic Flow of Nuclei

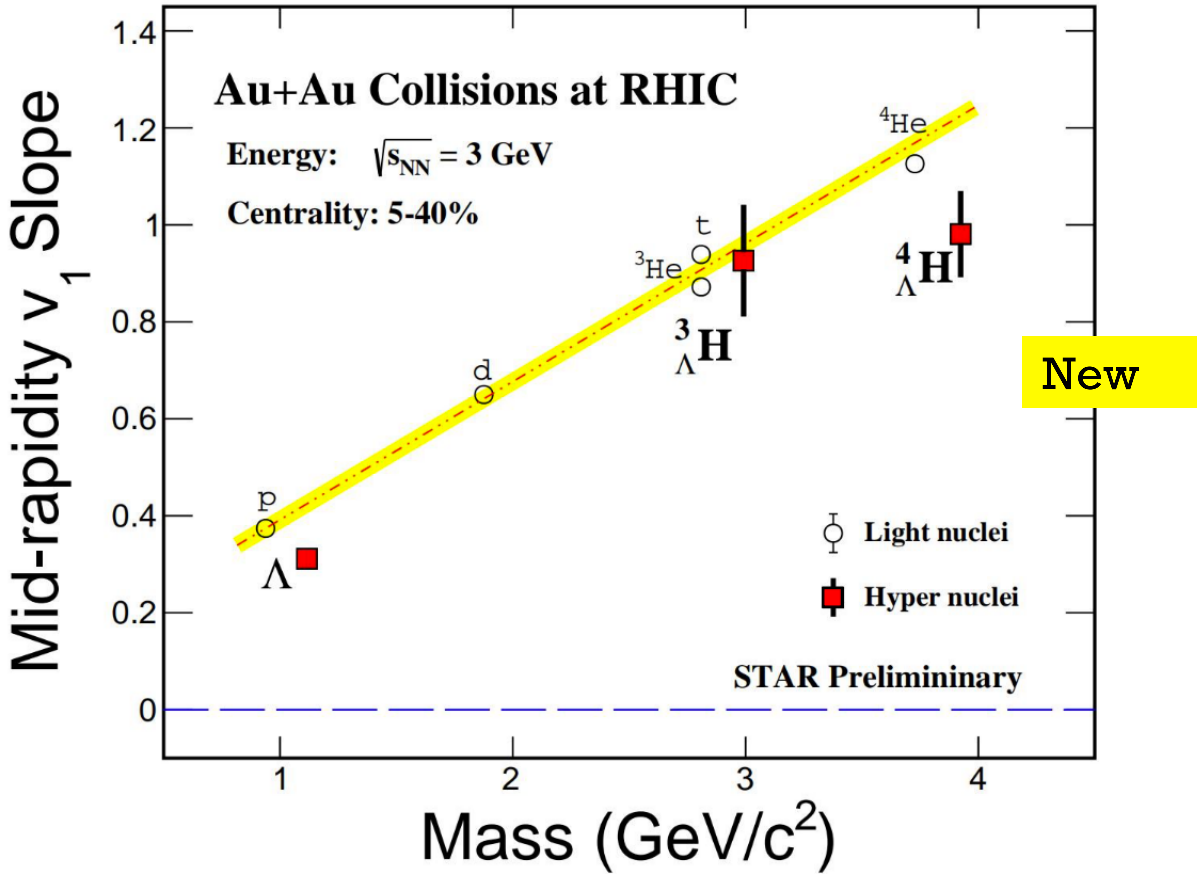


- Nuclei v_2 show atomic number scaling

Nuclei production mainly through coalescence of nucleons

STAR: PRC **94** (2016) 34908

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

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

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

$\sqrt{s_{NN}} \leq 11.5$ 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 $\sqrt{s_{NN}} < 20$ GeV (BES-II)

Understanding nuclei and hyper-nuclei production

- Thermal model describes yields (except ${}_{\Lambda}^{4}H$)
- 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