An Experimental Overview on

Energy Dependence of Strangeness Production

Md Nasim

Department of Physics

Indian Institute of Science Education and Research, Berhampur

The 19th International Conference on Strangeness in Quark Matter

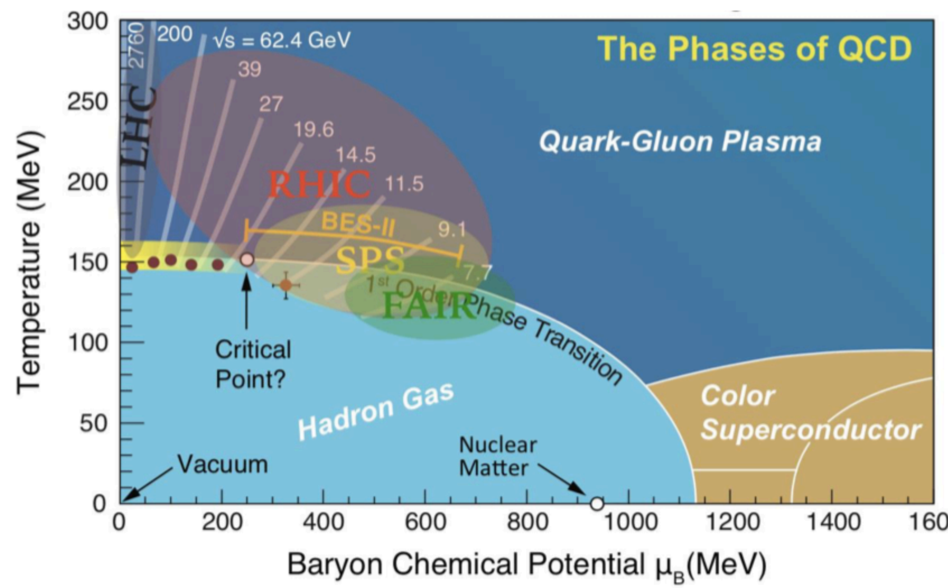
May 17-21, 2021, Brookhaven National Laboratory (Remote), Upton, New York

SQM2021

IISER BERHAMPUR

Outline

Credit: S. Mukherjee/BNL



Low Baryon Density

LHC and top RHIC energies

Goal: Study the properties of QGP

Observables: Strange Hadrons (Yield, Flow)

High and Intermediate Baryon Density

RHIC BES, SPS energies

Goal: Look for onset of de-confinement, phase boundary, Critical point

Observables: Strange Hadrons (Yield, Flow, fluctuations)

Plenty of Data

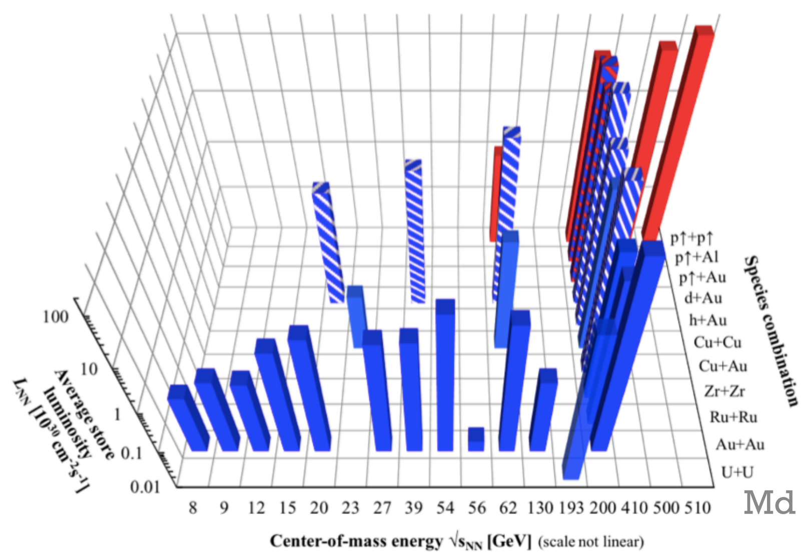
LHC:

Colliding system	$\sqrt{s_{NN}}$ (TeV)
Pb-Pb	2.76 -5.44
p-Pb	5.02-8.16
p-p	0.9-13
Xe-Xe	5.44

RHIC :

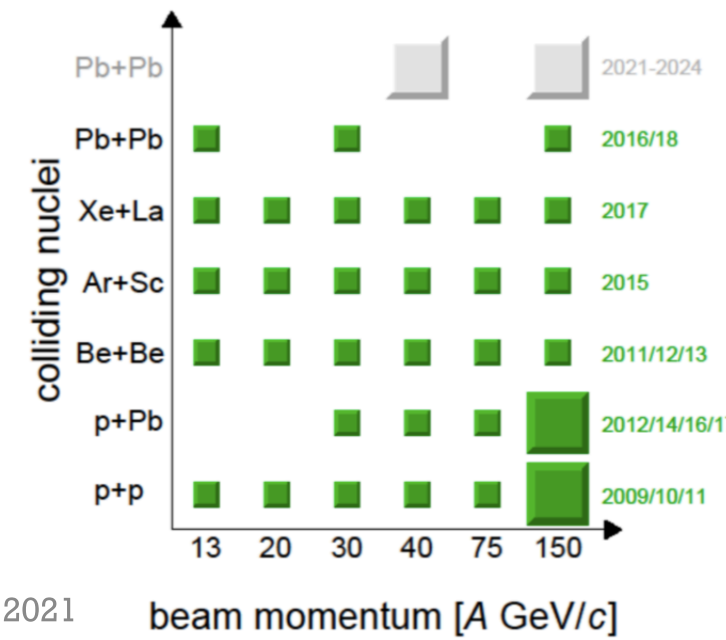
Colliding Mode ($\sqrt{s_{NN}}$)= 7.7-200 GeV

Fixed Target ($\sqrt{s_{NN}}$): 3-7 GeV



SPS:

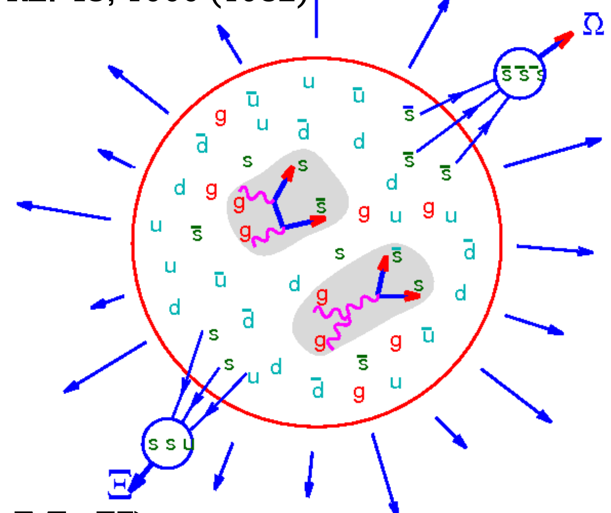
Fixed Target ($\sqrt{s_{NN}}$): 5.1-16.8 GeV



Strangeness as a probe

- Larger production cross-section in QGP compared to hadronic medium.
  - an enhancement is expected

J. Rafelski and B. Muller, PRL. **48**, 1066 (1982)



- Flow of strange vs non-strange hadrons
  - Probe to the partonic collectivity

STAR: PRL 99 (2007) 112301

B. Mohanty and N. Xu, J. Phys. G **36**, 064022 (2009).

- s-quark mass ~ 100-150 MeV
  - can be thermalized in QGP medium (T~200-300 MeV)

- Strangeness is conserved in strong interaction.
  - probe for the QCD critical point

M. A. Stephanov, PRL **102**, 032301 (2009)

p_T integrated particle ratios

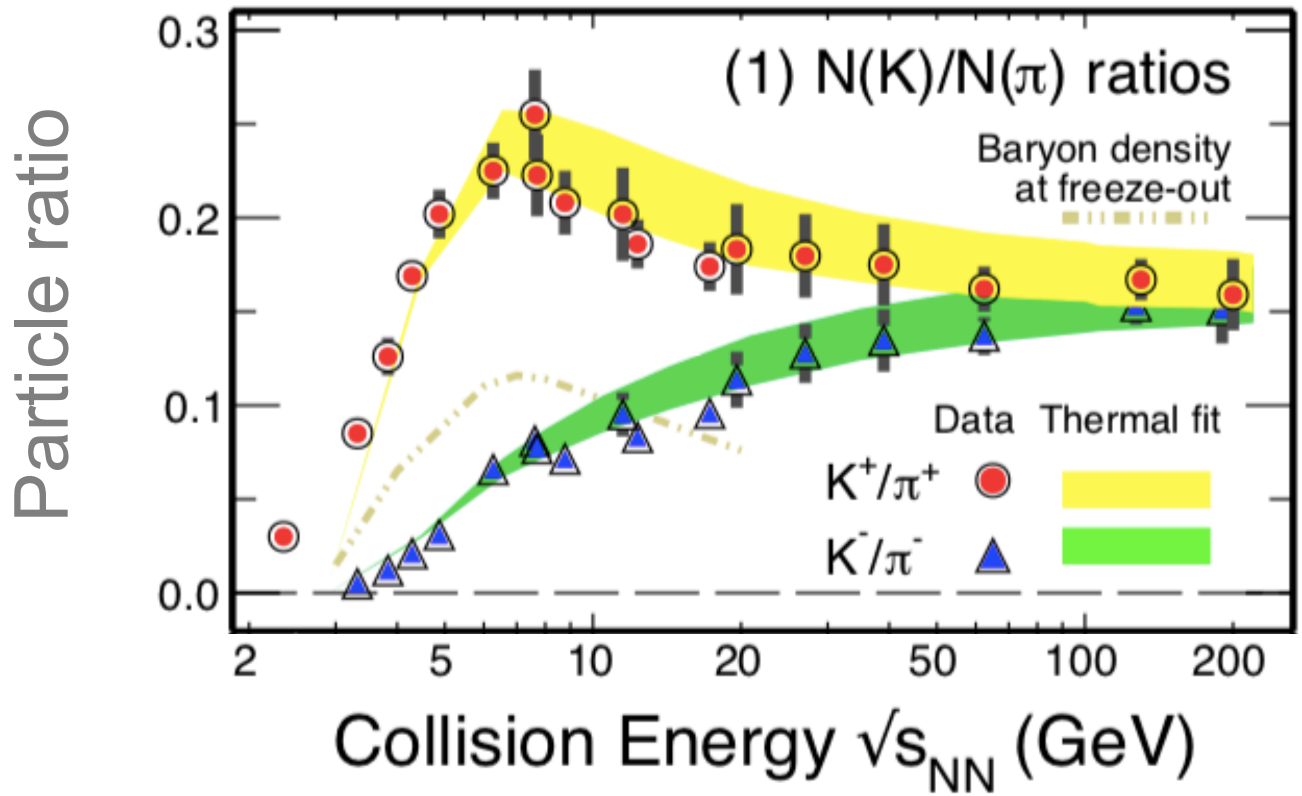
Test of Thermal Model,
Re-scattering Effect & Strangeness Enhancement

References:

E-802, E-866: PRC 60, 044904 (1999)
E866, E917: PLB 476, 1 (2000)
E866, E917: PLB 490, 53 (2000)
NA49: PRC 66, 054902 (2002)
NA49: PRC 77, 024903 (2008)
STAR: PRC 96, 044904 (2017)
J. Cleymans et. al, PLB 615, 50 (2005)
J. Randrup et. al, PRC 74, 047901 (2006)
K. Fukushima, et. al, AAPPS Bull. 31 (2021) 1
M. Gaździcki et al, Act. Phys Polon. B 30, 2705 (1999)
HADES: PL B 778, 2018.403-407, PRC. 80.025209. (2009)
E917: PRC. 69.054901 (2004)
P. Braun-Munzinger: NPA 772, 167 (2006), K. Redlich: PLB 603, 146 (2004)

Talks:
S. Pulawski Tue, 10.10
F. Ercolessi, Tue, 10.30
S. Harabasz, Tue, 12.10
G. Xie Tue, 12.30
A. Caliva, Tue, 13.35
V. Sumberia, Wed, 09.30
D. Oliinychenko, Wed, 10.10

K/π Ratios: Energy dependence

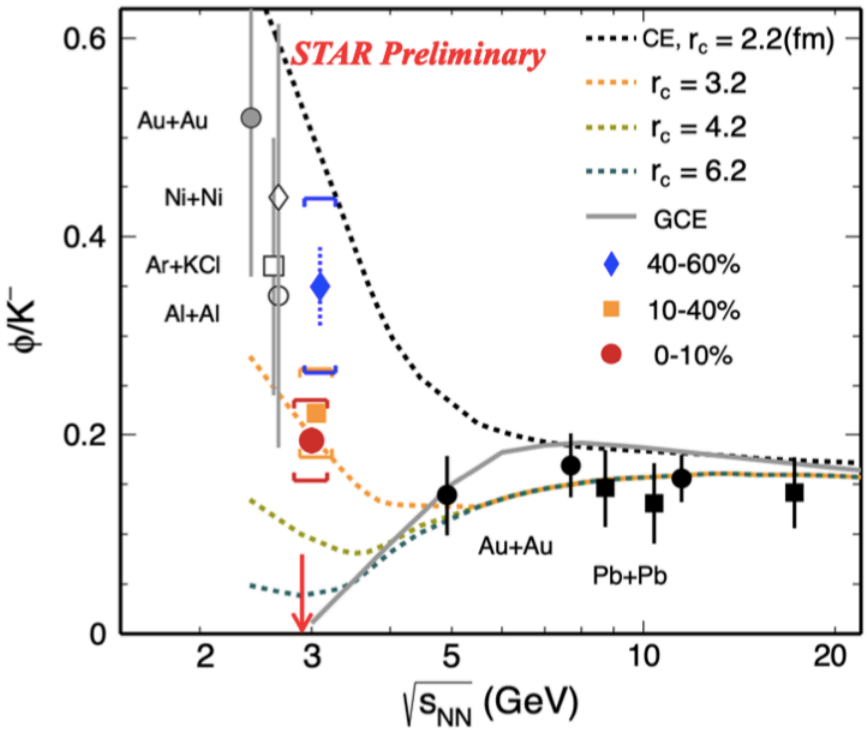


- K/π ratios and its energy dependence is **fairly well described by a thermal model calculations.**

- Horn in K^+/π^+ → signature of a change in degrees of freedom (baryon to meson or hadrons to QGP)

Φ/K ratio: Energy dependence

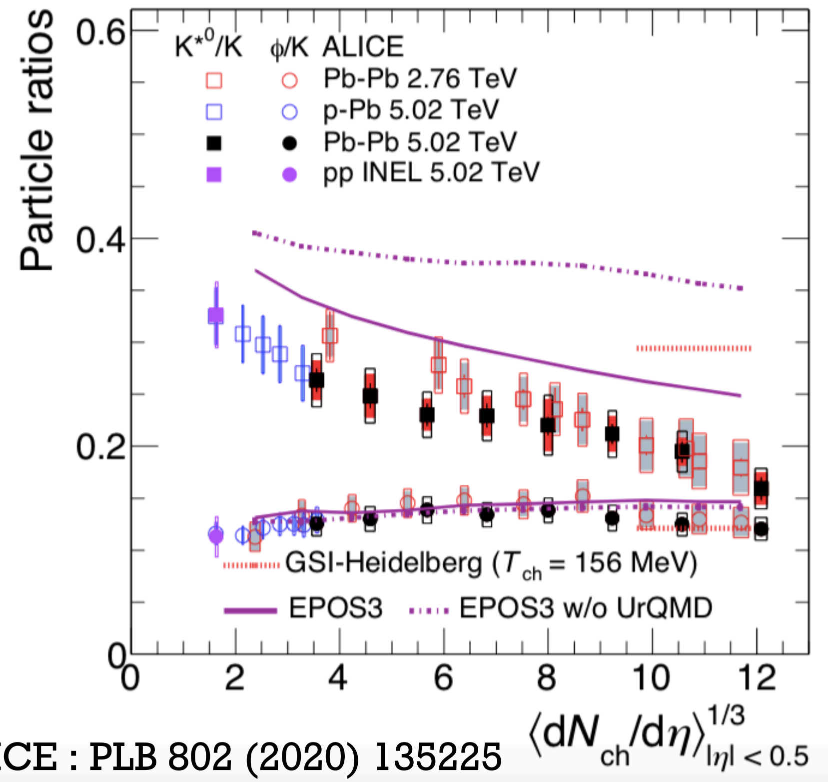
High Baryon Density Matter : GCE vs CE



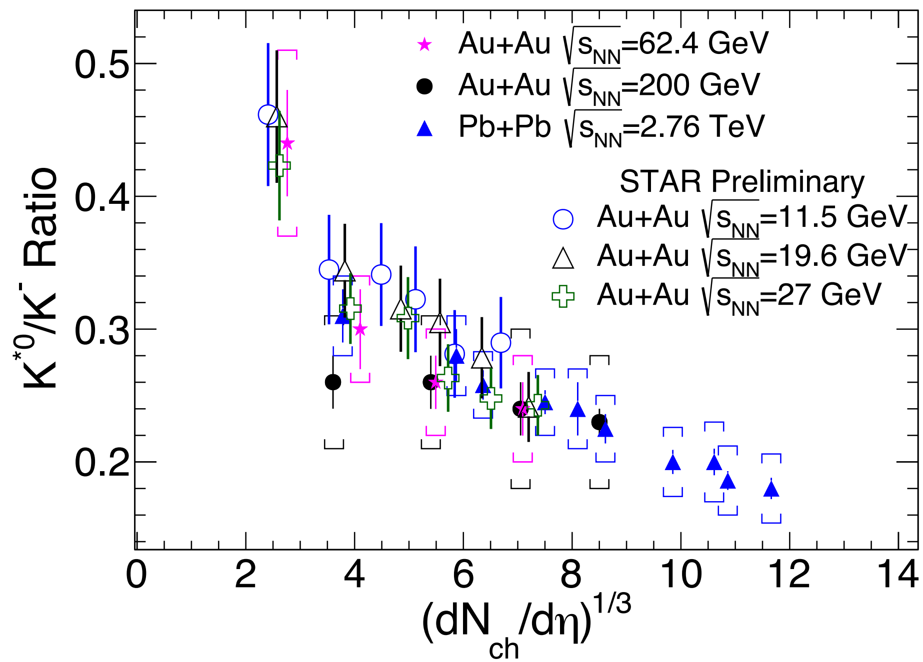
- The strange hadron yield and ratios may be sensitive to the strangeness production mechanism.
- Grand canonical ensemble (GCE) and canonical ensemble (CE) calculations predicts different values of Φ/k ratio at very low energies.

→ Data favors the Canonical Ensemble at high baryon density

K^{*0}/K ratio: Evidence of re-scattering effect



ALICE : PLB 802 (2020) 135225



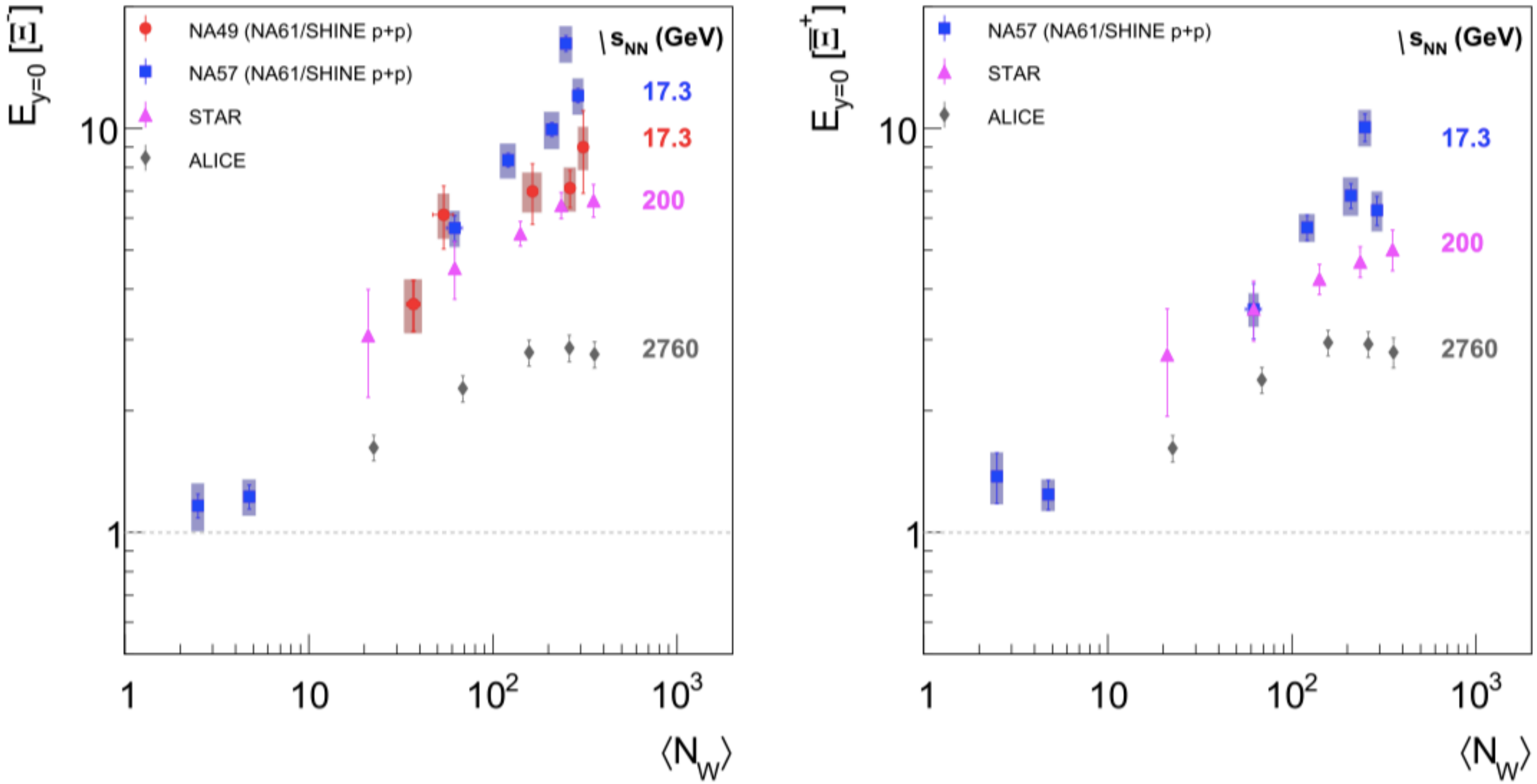
STAR: PRC **71**, 064902 (2005)

K^{*0}/K : (i) Ratio decreases with increasing multiplicity
(ii) Thermal model over-predicts data

Φ/K : (i) Nearly independent of multiplicity
(ii) Thermal model reproduces the data

Evidence of re-scattering in central A+A collisions

Strangeness enhancement in A+A



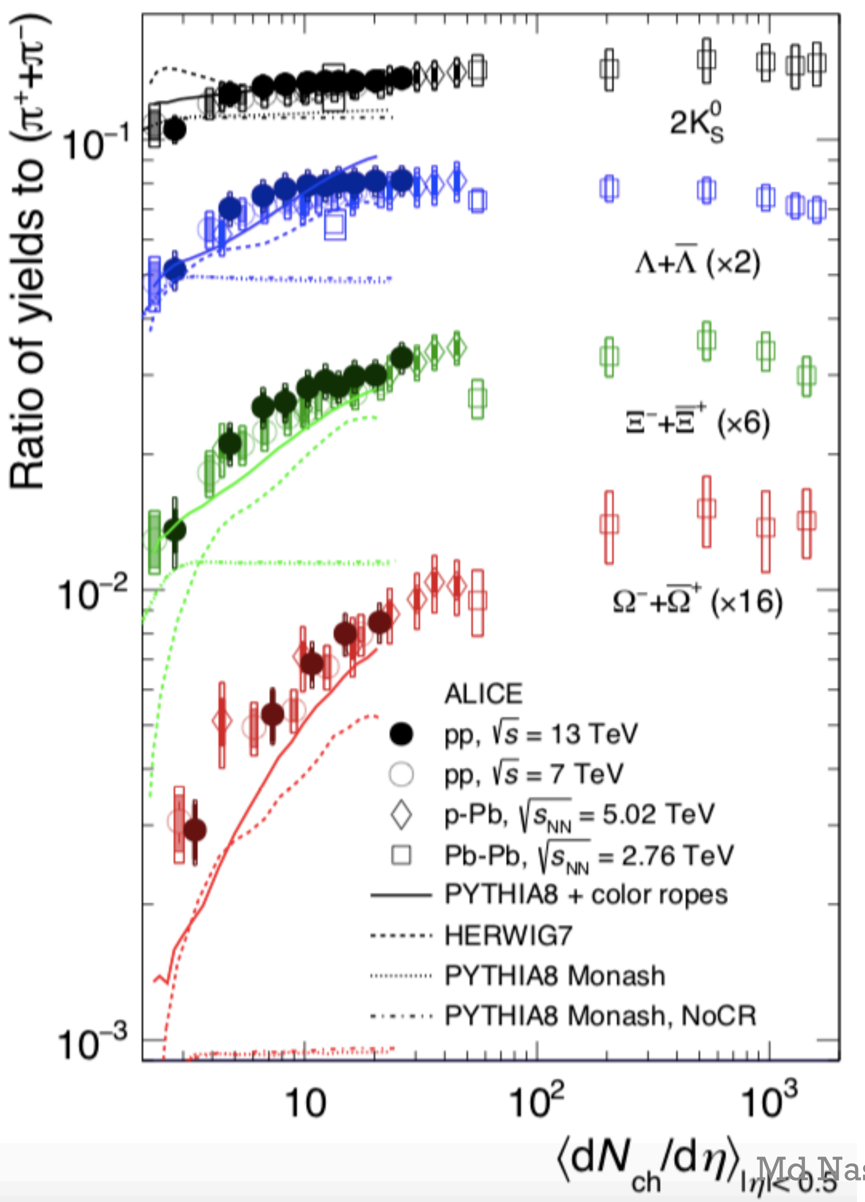
- Enhancement increases with collisions centrality

  →Signature of Quark-Gluon Plasma

- Ey (SPS) > Ey (RHIC) > Ey (LHC)

NA61/SHINE :EPJC (2020) 80:833

Strangeness enhancement in small system



- Ratios increases with multiplicity

→ Strangeness enhancement

- Ratios depend on multiplicity, irrespective of system size

High multiplicity p+p collisions show similar behavior as A+A collisions

ALICE: EPJC 80 (2020) 693

ALICE: Nature Physics 13 (2017) 535

Particle ratios as function of p_T

Test of hydrodynamics, coalescence and hybrid models

References:

H. Song et al, PRC 83, 054912 (2011)

H. Song et al, PLB 658, 279 (2008)

K. Warner, PRL 109, 102301 (2012)

V. Minissale, et. al. PRC 92,5 (2015)

ALICE: PRC **91**, 024609, (2015)

ALICE: PRL **111**, 222301, (2013)

ALICE: arXiv:2105.04890

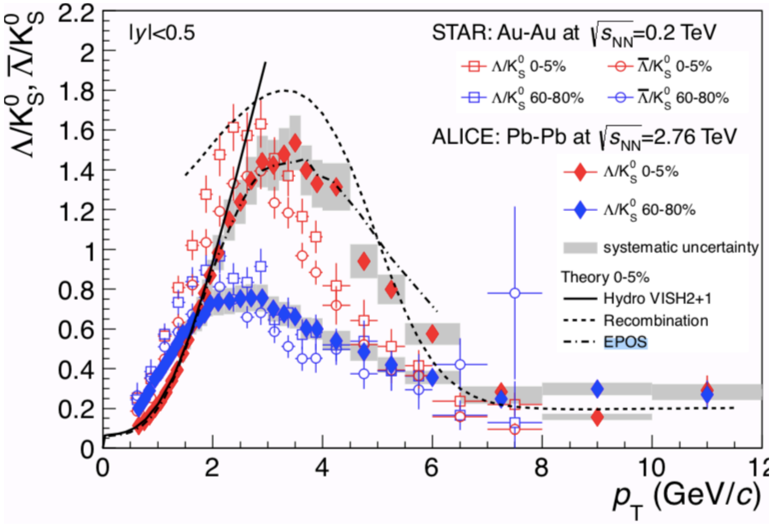
ALICE: EPJC 81 (2021) 256

STAR: PRC 102, 34909 (2020)

STAR: PRC 93, 021903 (2016)

Talk:
Y. Huang, Tue, 9.30
A. Caliva, Tue, 13.35

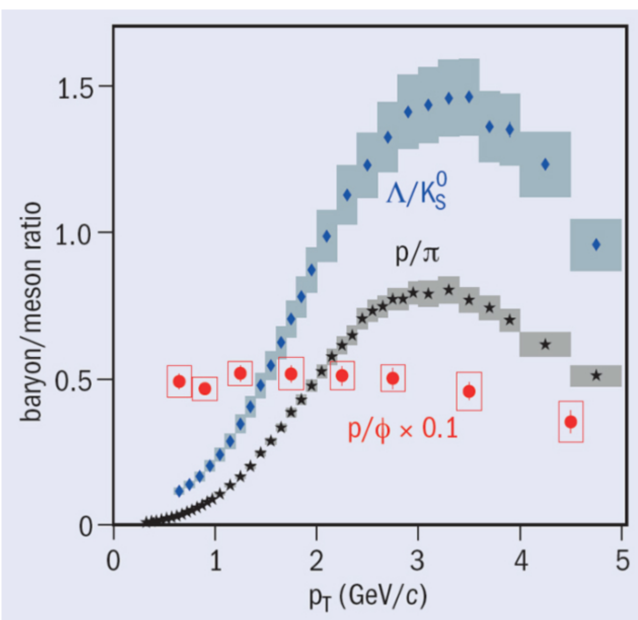
Baryon-to-meson ratio at LHC (and top RHIC energy)



Recombination : describes the shapes

Hydrodynamics: only explains the low p_T

EPOS (with flow): gives good description



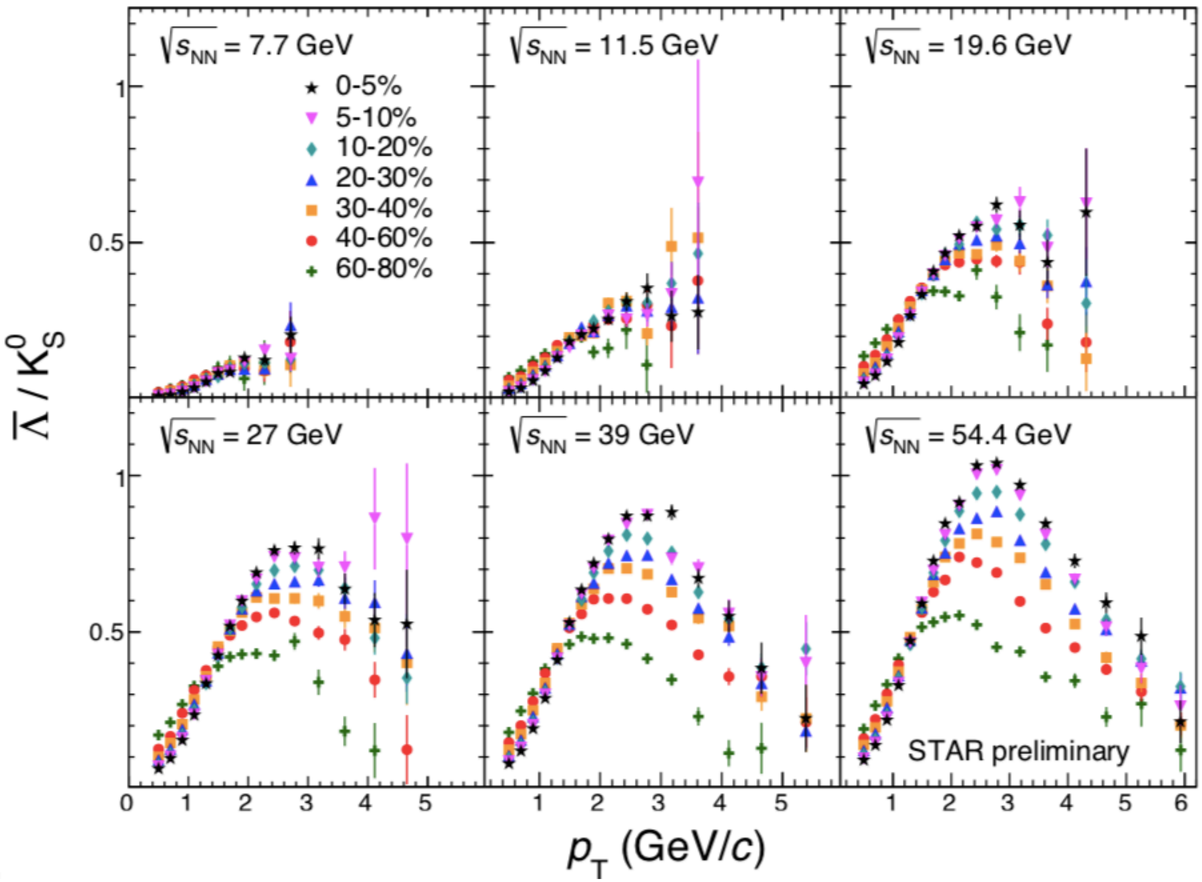
CERN COURIER: 23 February 2015

- p/ϕ ratio that is constant with p_T.

→ **Consistent with Hydrodynamic prediction**

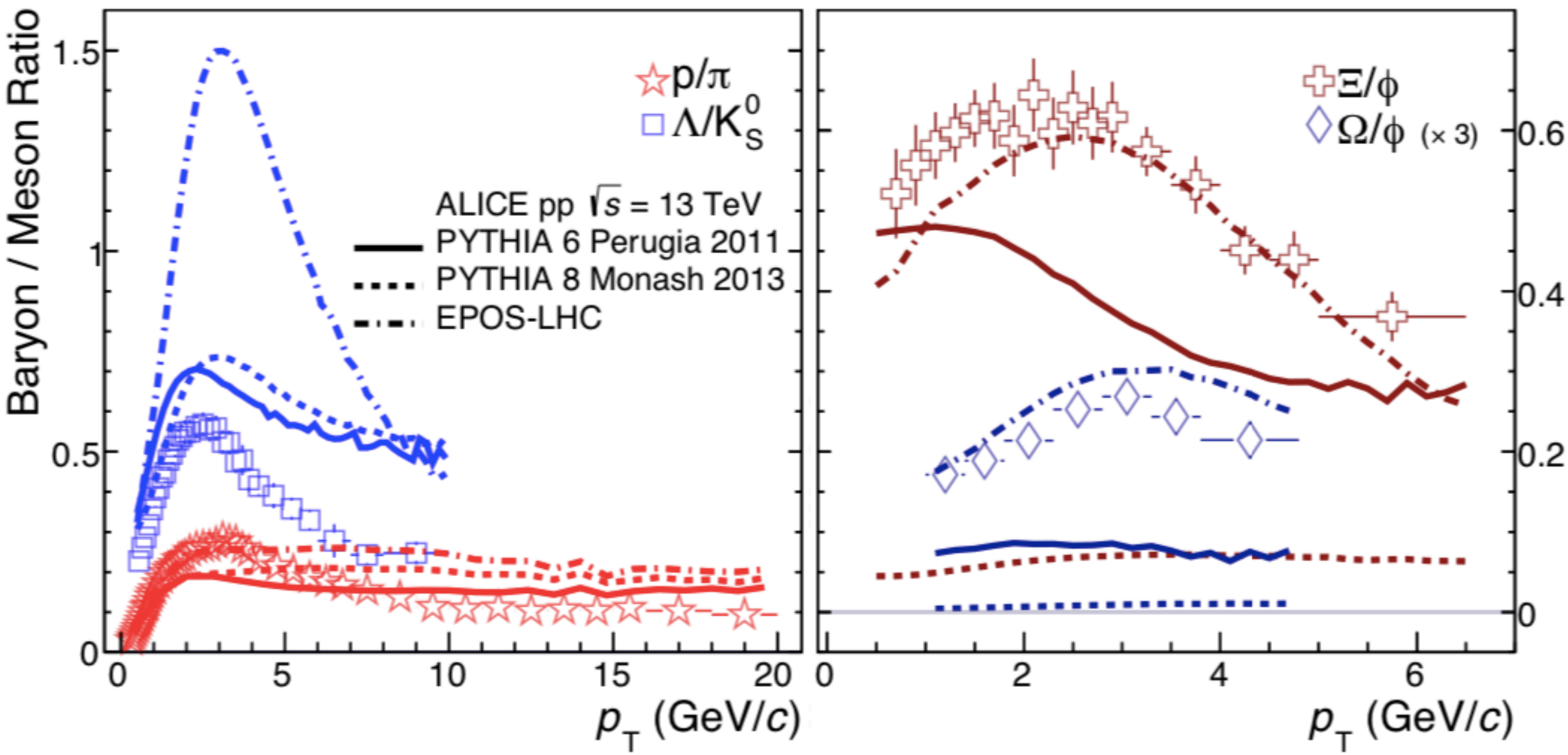
- Coalescence + fragmentation approach one can also explain flat p/ϕ ratio .

Baryon-to-meson ratio at RHIC BES



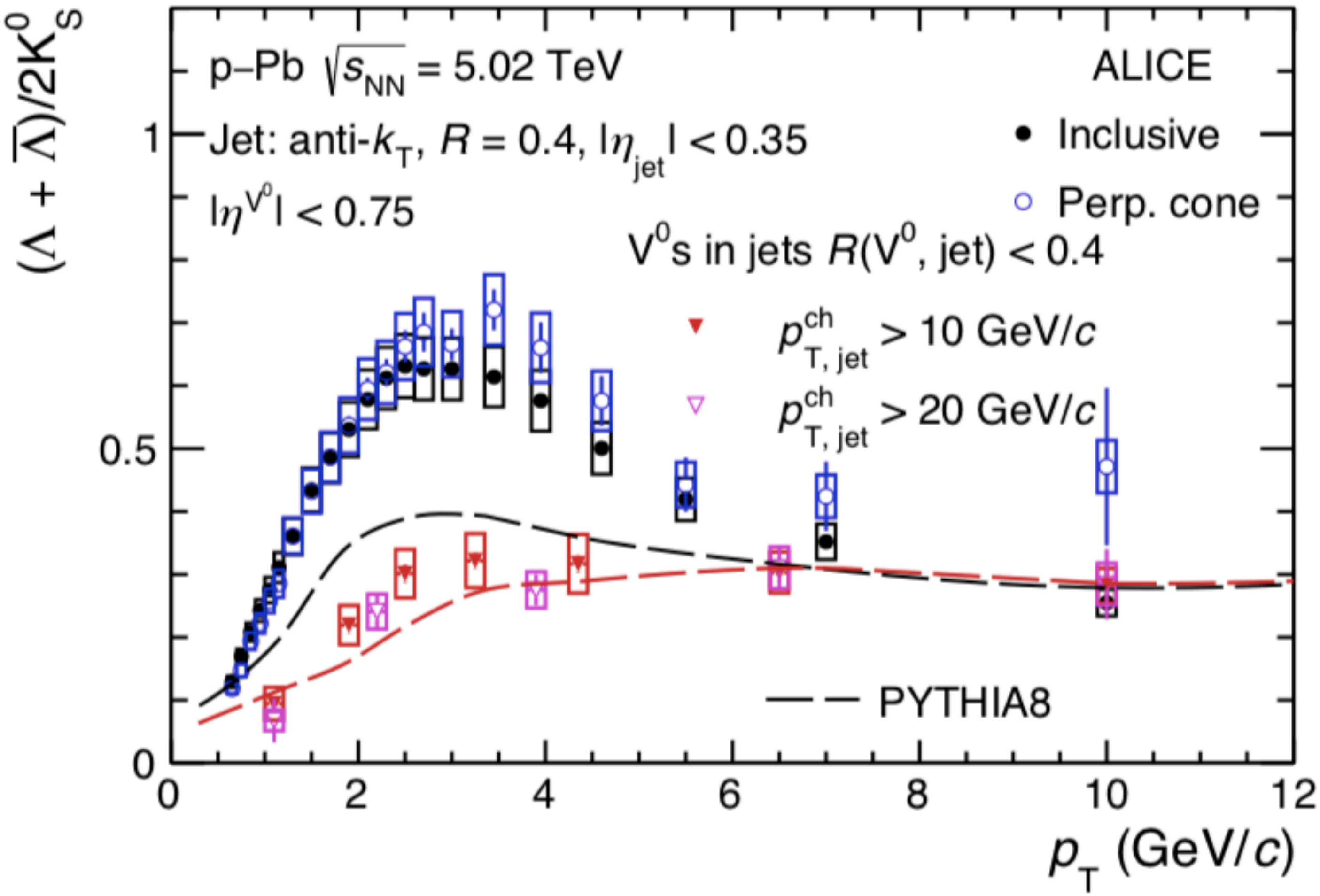
- Baryon enhancement at intermediate p_T in central collisions for $\sqrt{s_{NN}} \geq 19$ GeV
- Within the uncertainties no difference between central and peripheral collisions for $\sqrt{s_{NN}} < 19.6$ GeV

Baryon-to-meson ratio in p+p (p+Pb)



p+p collisions show similar p_T dependence of baryon/meson ratios as in A+A collisions

Baryon-to-meson ratio in p+p (p+Pb)

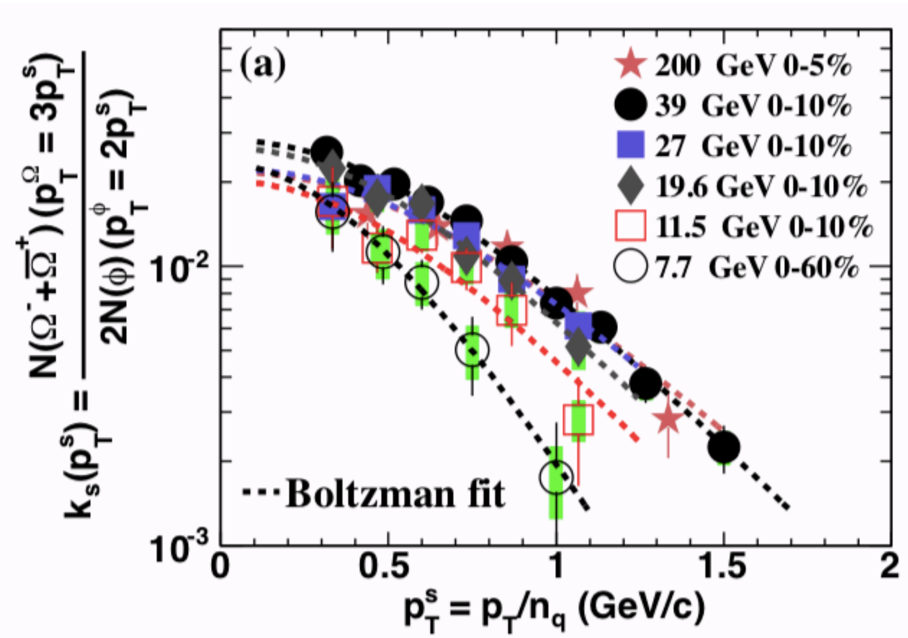


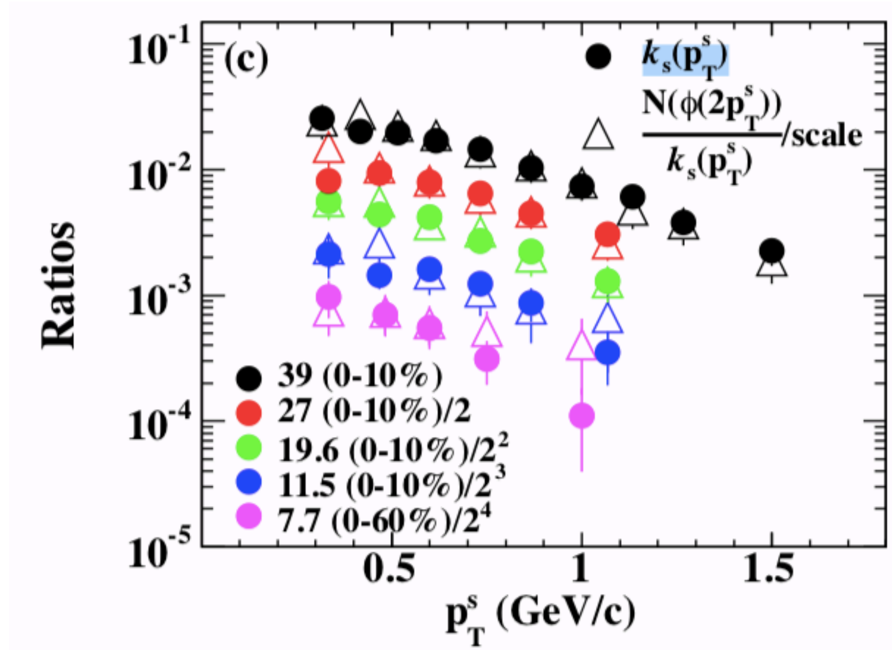
Strange Hadrons In Jets

Observed enhancement in baryon-to-meson ratio could be due to interplay of radial flow and parton recombination at intermediate p_T

Number of constituent quark scaled Ω/Φ:

Strange-quark p_T distribution





- Strange p_T quark distribution obtained from Ω/Φ ratios
- One single strange quark distribution describes both Ω and ϕ spectra. (Need more statistics at low beam energies to conclude)

→ Evidence for quark coalescence at RHIC

Nuclear Modification Factor
&
Collective flow

Parton energy loss, Partonic Collectivity and Equation of States

References:

STAR: PRC 102,034909 (2020)

STAR: PRL 120, 62301 (2018)

STAR: PRL 112, 162301 (2014)

ALICE: JHEP 09 (2018) 006

STAR: PRL 116 (2016) 6, 062301

STAR: arXiv:2103.09451

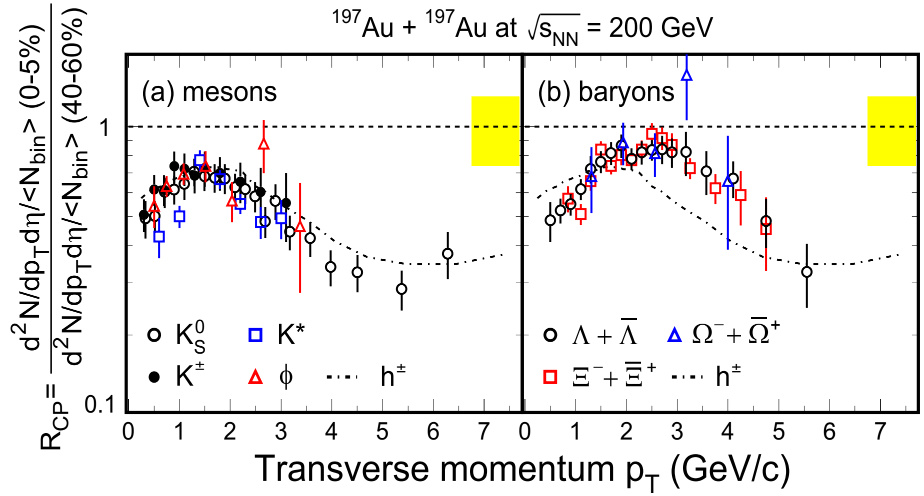
STAR: PRL 110, 142301 (2013)

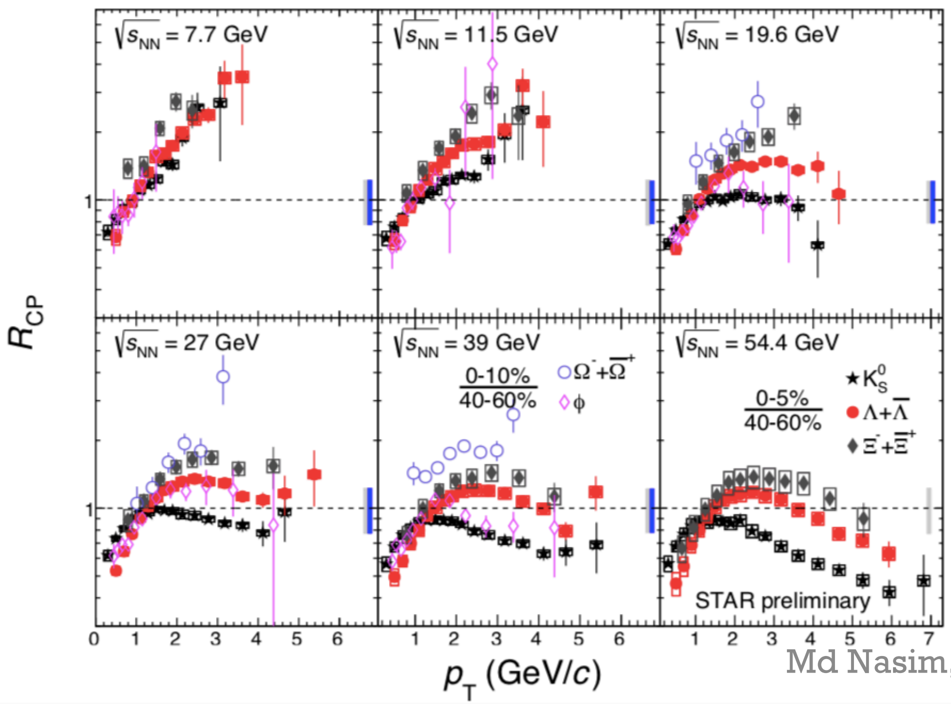
A.M. Poskanzer et al PRC 58, 1671 (1998)

P. Kolb, et al NPA 715, 653c (2003)

Talks:
G. Xie, Tue, 12.30
Y. Huang Tue, 9.30
Q. Wang, Tue, 9.30
P. Dixit, Tue, 10.10
L. Mitrankov, Tue, 11.10

Nuclear Modification Factor





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

$\sqrt{s_{NN}}$ ≥19.6 GeV

- Suppression at high p_T

→ energy loss of partons in QGP

- Baryon vs meson at intermediate p_T

→ parton recombination

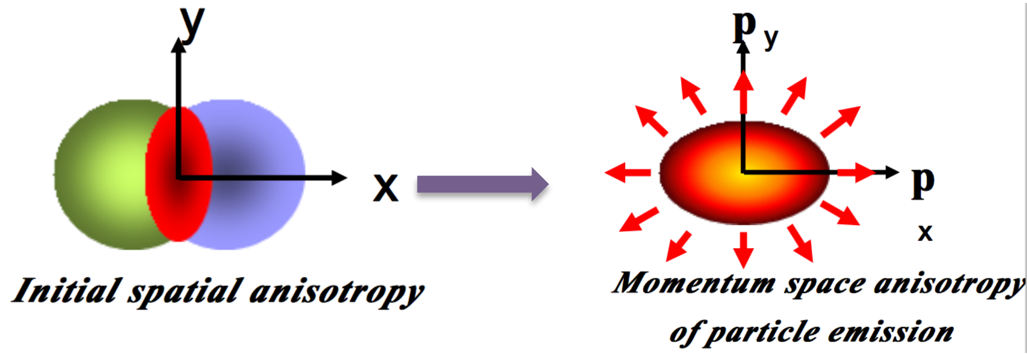
$\sqrt{s_{NN}}$ ≤ 11.5 GeV

- No suppression for the highest measured p_T
- Disappearance of baryon –meson separation

→ parton energy loss less important

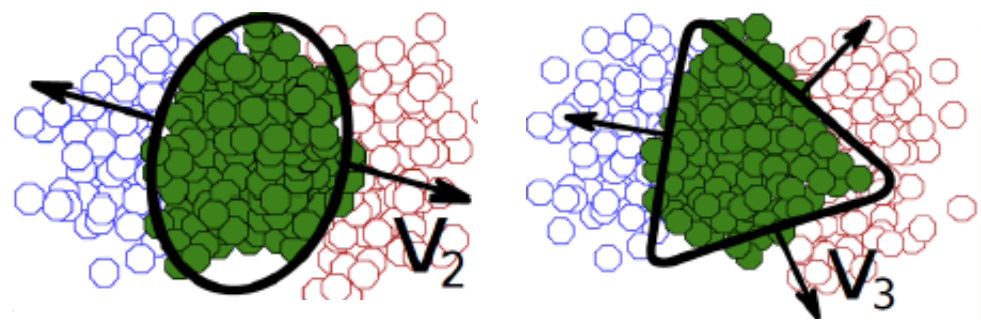
Azimuthal Anisotropy

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



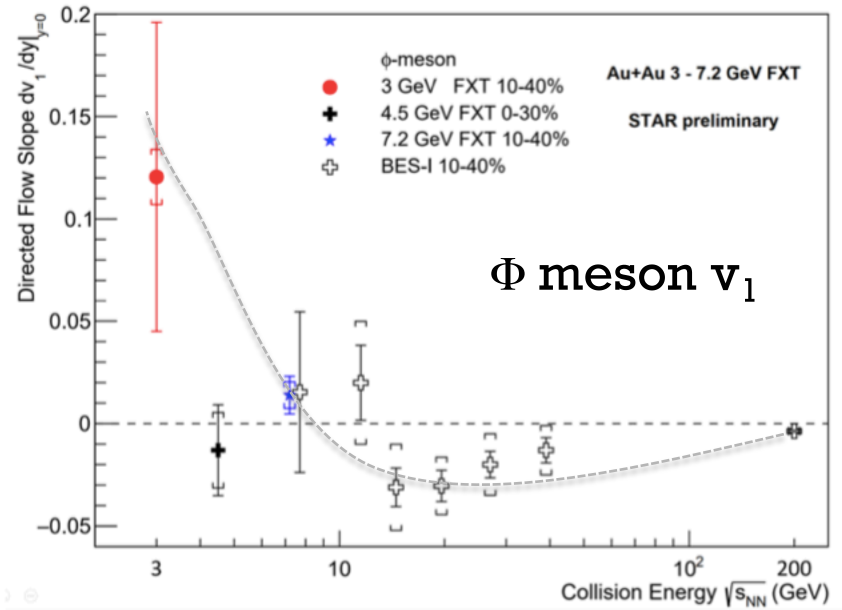
$$\frac{dN}{d\phi} = 1 + 2\sum_{n=1}^{\infty} v_n \cos\{n(\phi - \psi_n)\}$$

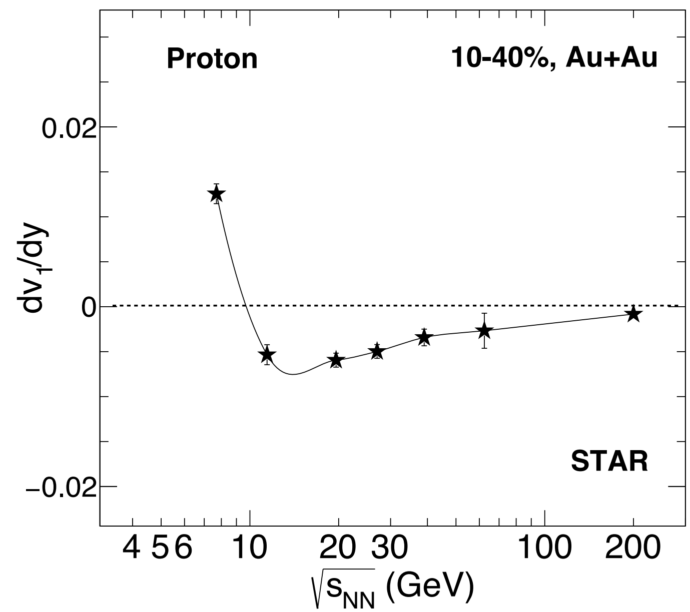
$$v_n = \langle \cos\{n(\phi - \psi_n)\} \rangle$$



- sensitive to early times in the evolution of the system
- sensitive to the equation of state

Directed flow (v_1)

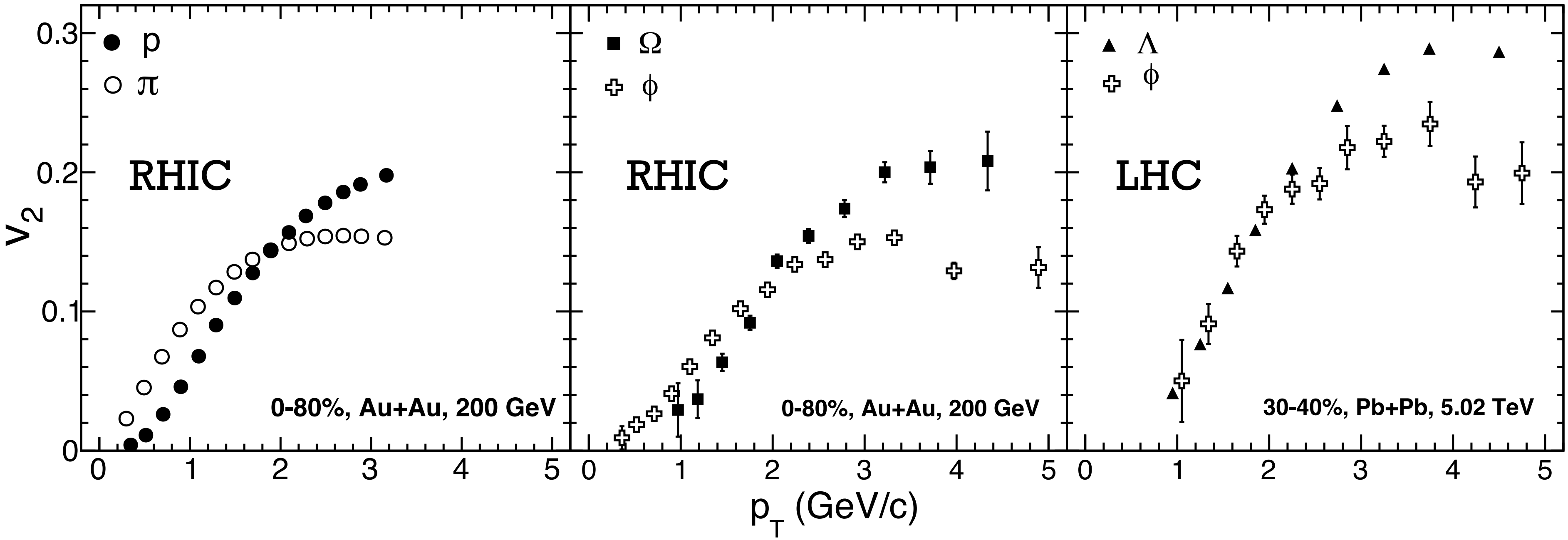




Slope of ϕ meson and proton v_1 changes sign at low energy

→ Could be related to the change of equation of states

Elliptic flow of strange hadrons

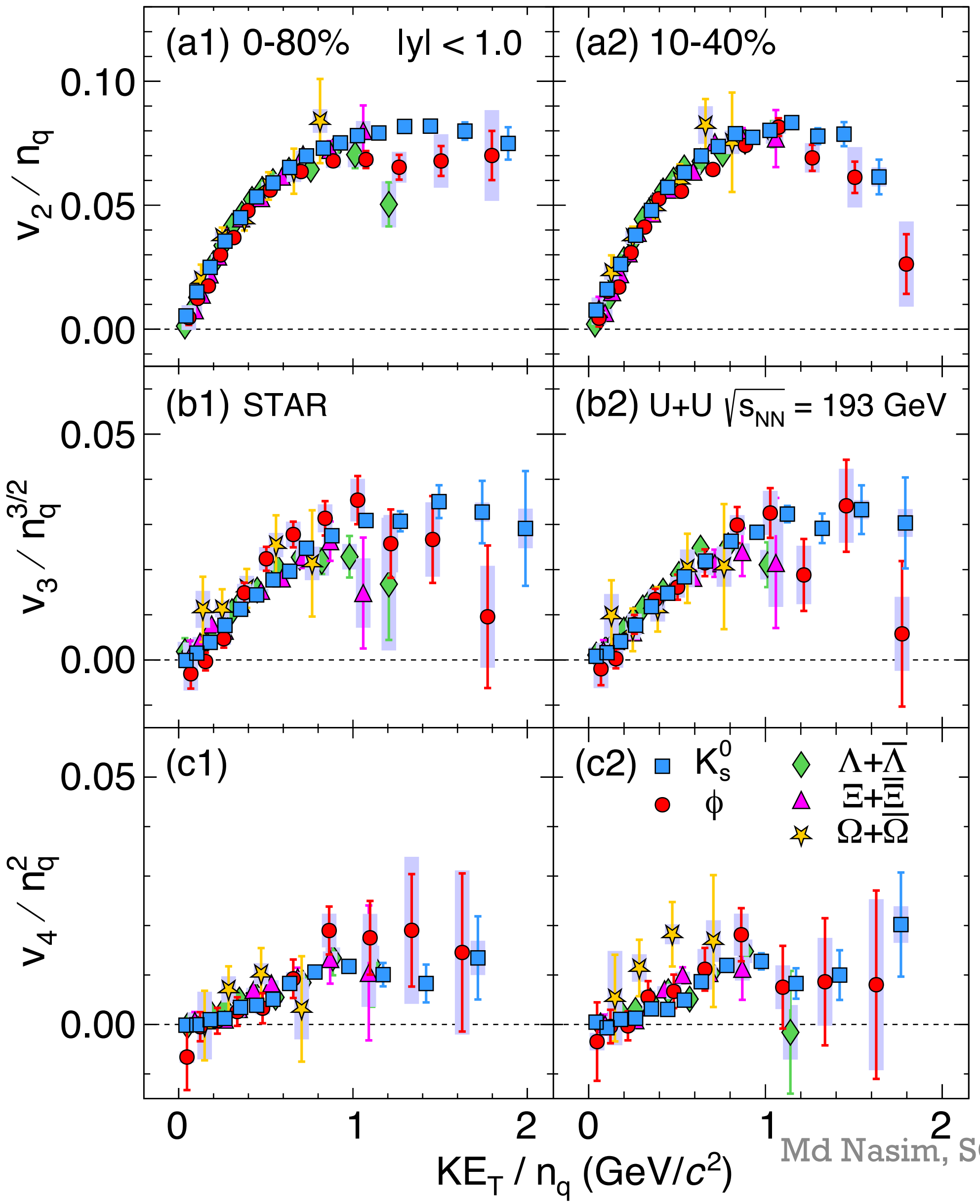


- $v_2(p_T)$ follows a mass ordering at low p_T – **Hydrodynamics**

- Intermediate p_T:
  (i) baryons vs Mesons – **Recombination**

  (ii) $v_2(\phi) \sim v_2(\pi)$
  $v_2(\Omega) \sim v_2(p)$ } Partonic Collectivity

Quarks scaling of strange hadrons v_n

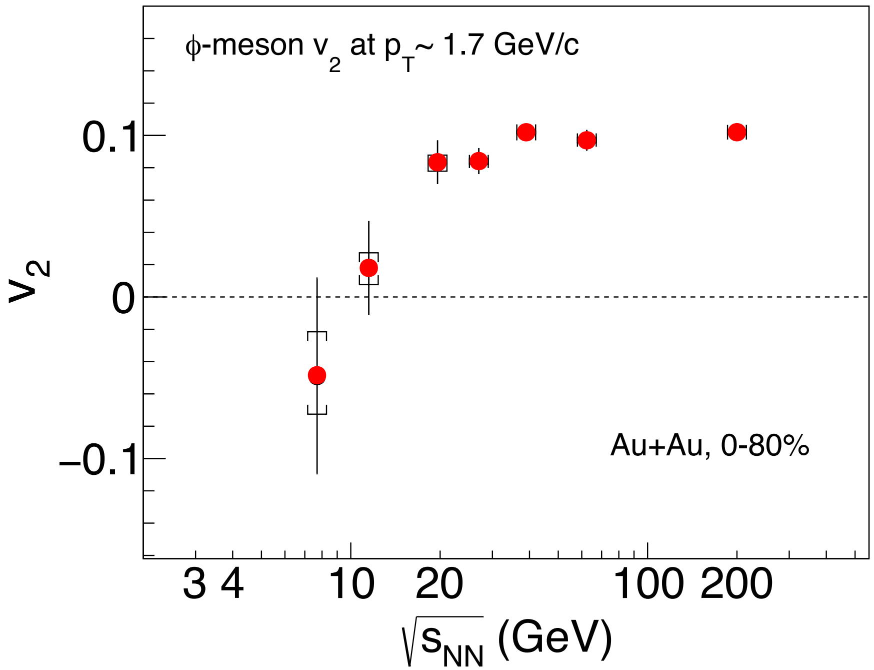


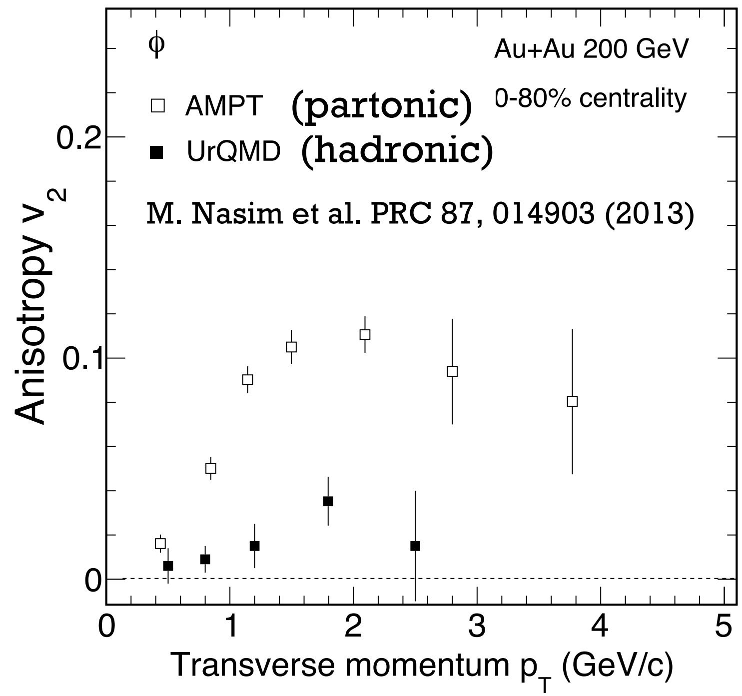
U+U @ 193 GeV

NCQ scaling works at top RHIC energies for v_2 and higher harmonics of strange hadrons

→ Partonic Collectivity

Energy dependence of ϕ meson v_2 (at intermediate p_T)

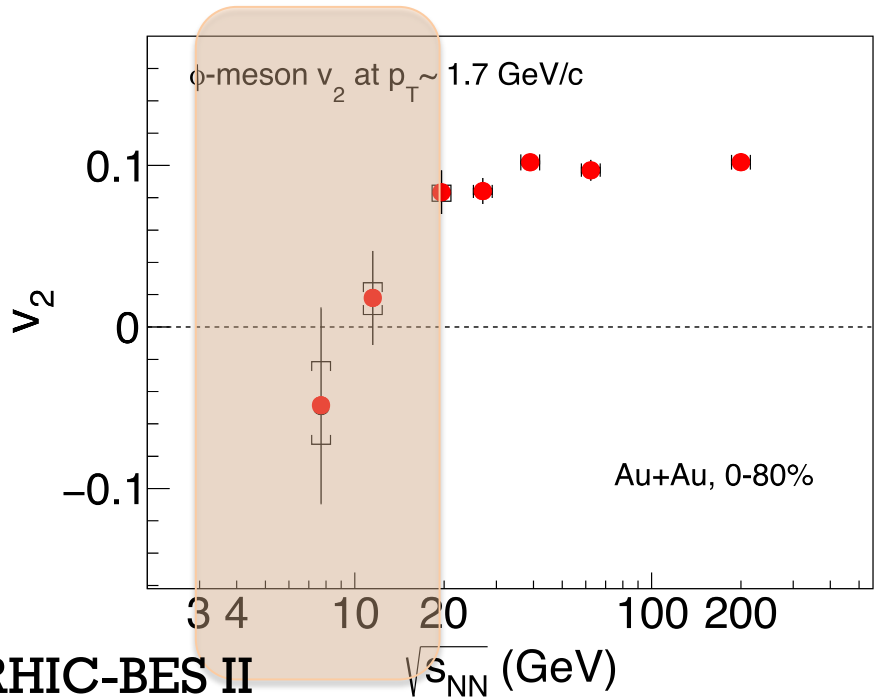




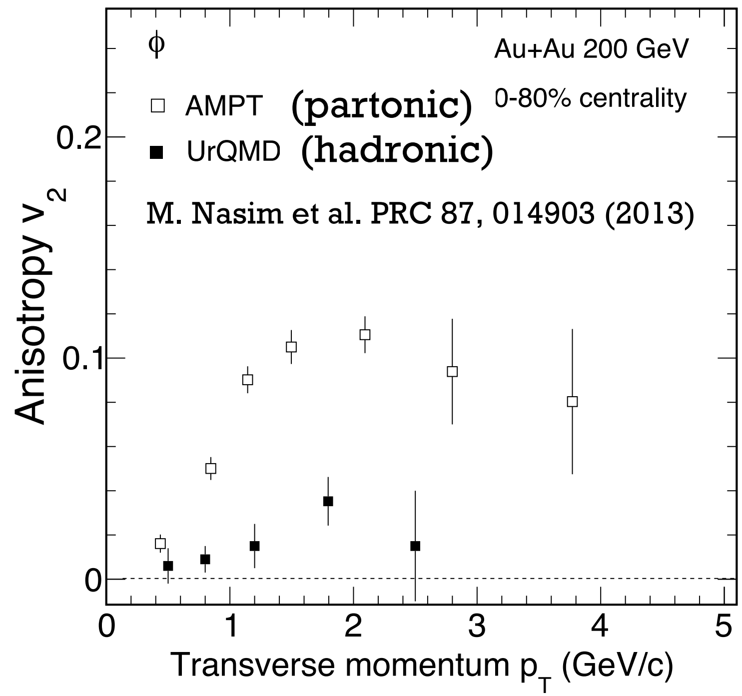
- ϕ meson v_2 at intermediate p_T is close to zero at 11.5 and 7.7 GeV

  → Less partonic contribution at low beam energy.

Energy dependence of ϕ meson v_2 (at intermediate p_T)



RHIC-BES II
+ FXT Program



- ϕ meson v_2 at intermediate p_T is close to zero at 11.5 and 7.7 GeV
  → Less partonic contribution at low beam energy.

Lifetime and yield and flow of Hypernuclei

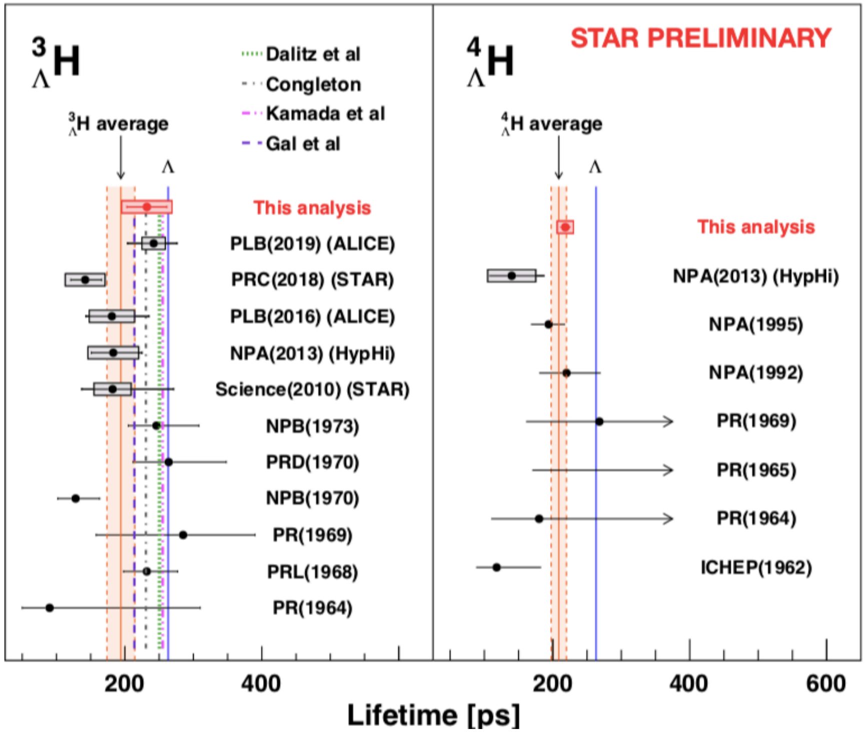
probe to study the hyperon- nucleon (Y-N) interaction.

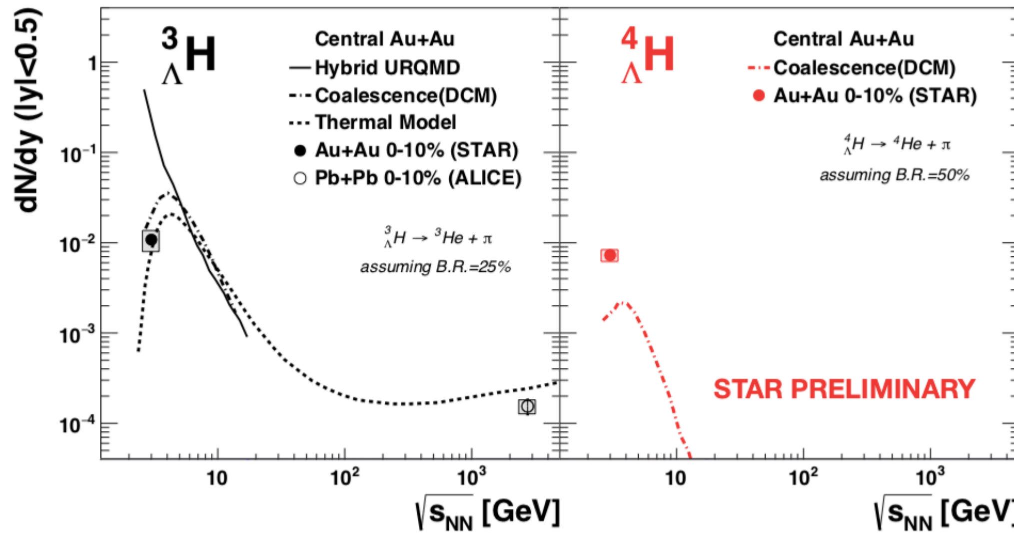
References:

NC46(1966)786 (Dalitz et al)
JPG NPP 18(1992)339 (Congleton)
PRC57(1998)1595 (Kamada et al)
PLB791(2019)48 (Gal et al)
ALICE: PLB 754 (2016) 360
PLB714(2012),85 (Hybrid URQMD,Coalescence(DCM))
PLB 697 (2011)203 (Thermal Model)

Talks:
P. Fecchio, Fri, 9.50
C. Hu, Fri, 10.30
Y.-H. Leung, Fri, 14.05

Lifetime & yield of hypernuclei

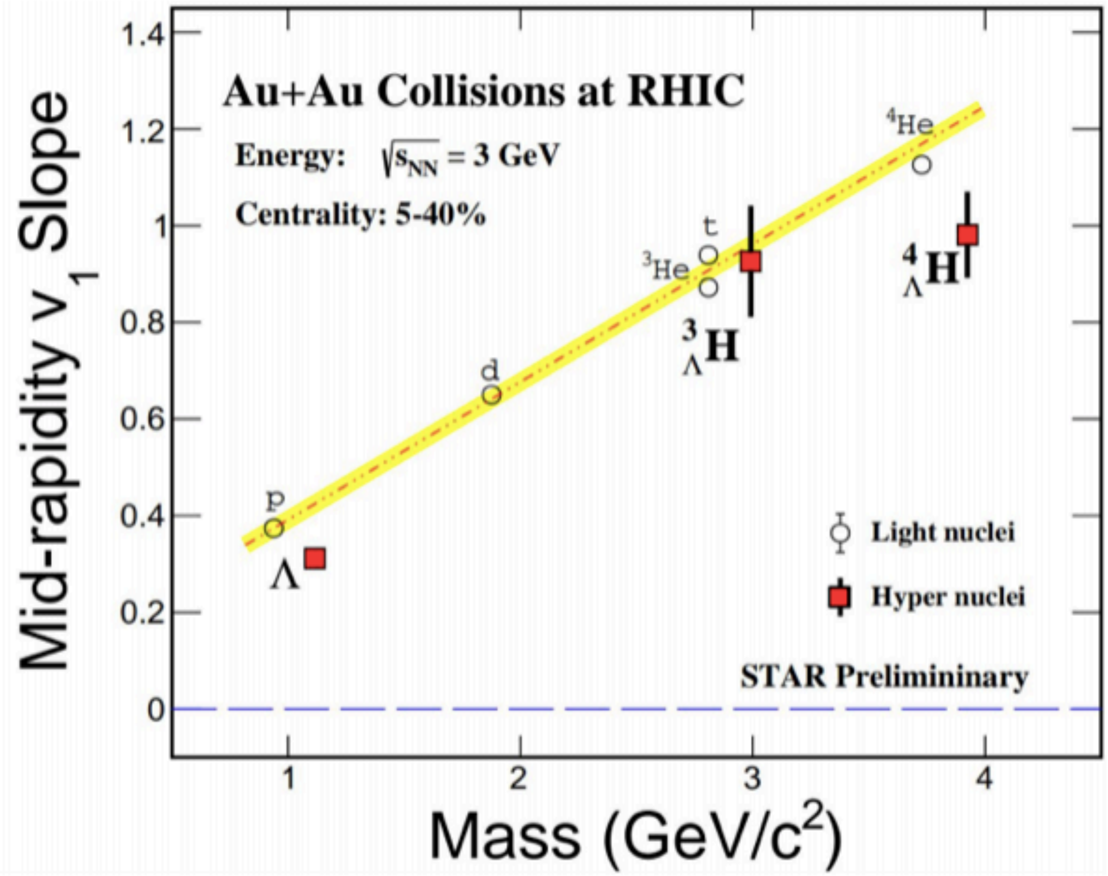




→ Data suggests hyper-nuclei is a loosely bound states

- Thermal model which adopts the canonical ensemble describes $^{3}_{\Lambda}H$

Directed flow of hypernuclei



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

Summary

- **p_T integrated particle ratio:**
  (i) *Thermal model describes data fairly well*
  (ii) *There are evidences of hadronic re-scattering effect in A+A*
  (iii) QGP-like signature in small system

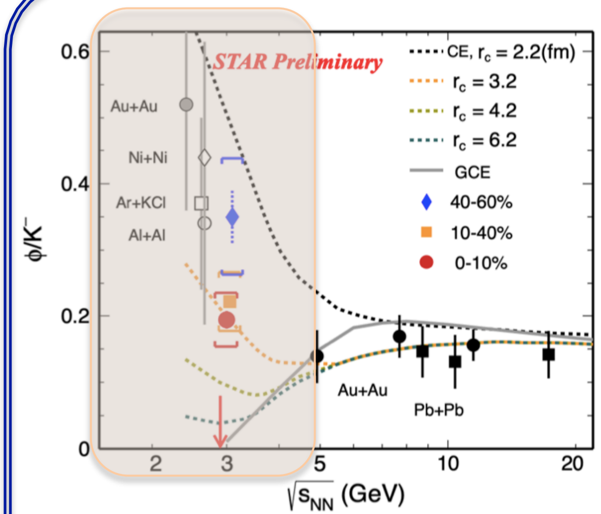
- **Baryon-to-Meson ratio vs p_T:**
  (i) Enhancement at intermediate p_T
  (ii) Flat p/Φ ratio in Pb+Pb at 2.76 TeV

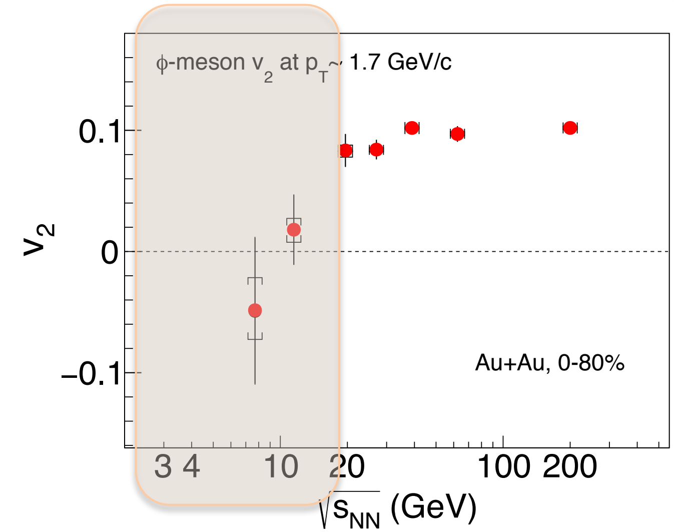
  } - Interplay of radial flow & coalescence

- **Nuclear Modification Factor and Collective flow:**
  $\sqrt{s_{NN}} > 11.5$ GeV : Partonic interaction dominated matter

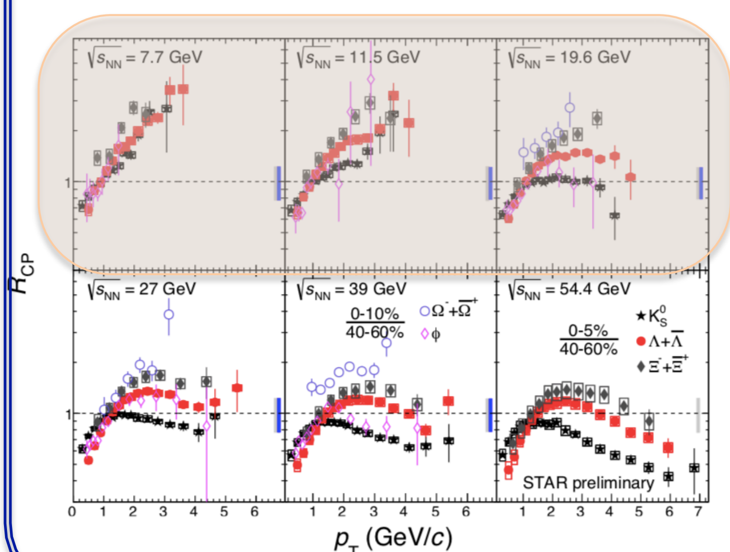
  $\sqrt{s_{NN}} \leq 11.5$ GeV : Hadronic interaction dominated matter

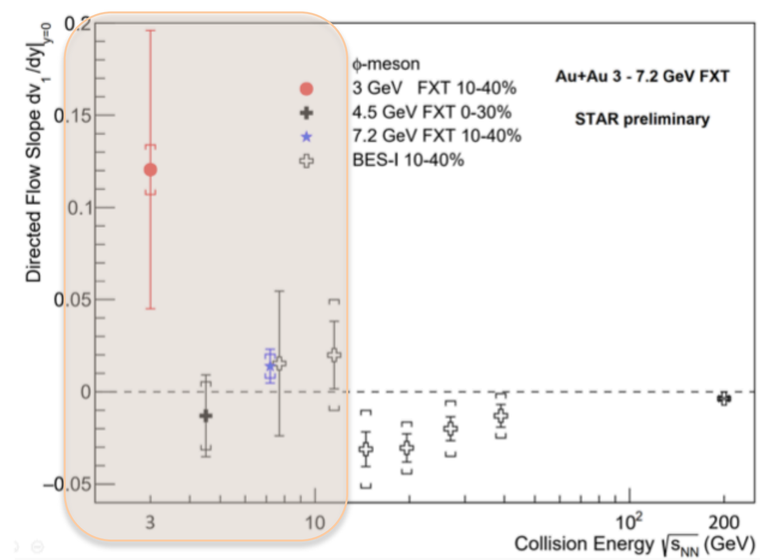
- **Hupernuclei:** Precise measurement of lifetime using HI experiments
  - data suggests hypernuclei production from coalescence of hyperons and nucleons


STAR Preliminary
CE, r_c = 2.2(fm)
r_c = 3.2
r_c = 4.2
r_c = 6.2
GCE
40-60%
10-40%
0-10%
Au+Au
Ni+Ni
Ar+KCl
Al+Al
Au+Au
Pb+Pb
ϕ/K^-
$\sqrt{s_{NN}}$ (GeV)


ϕ-meson v_2 at p_T~ 1.7 GeV/c
Au+Au, 0-80%
v_2
$\sqrt{s_{NN}}$ (GeV)

Thank You


$\sqrt{s_{NN}}$ = 7.7 GeV
$\sqrt{s_{NN}}$ = 11.5 GeV
$\sqrt{s_{NN}}$ = 19.6 GeV
$\sqrt{s_{NN}}$ = 27 GeV
$\sqrt{s_{NN}}$ = 39 GeV
$\sqrt{s_{NN}}$ = 54.4 GeV
0-10% / 40-60%
$\Omega^- + \overline{\Omega}^+$
ϕ
0-5% / 40-60%
K^0_S
$\Lambda+\overline{\Lambda}$
$\Xi^- + \overline{\Xi}^+$
STAR preliminary
R_{CP}
p_T (GeV/c)


ϕ-meson
3 GeV FXT 10-40%
4.5 GeV FXT 0-30%
7.2 GeV FXT 10-40%
BES-I 10-40%
Au+Au 3 - 7.2 GeV FXT
STAR preliminary
Directed Flow Slope $dv_1/dy|_{y=0}$
Collision Energy $\sqrt{s_{NN}}$ (GeV)