Collectivity of strange and charm hadrons and $D_s^{\pm}$ production at RHIC-STAR

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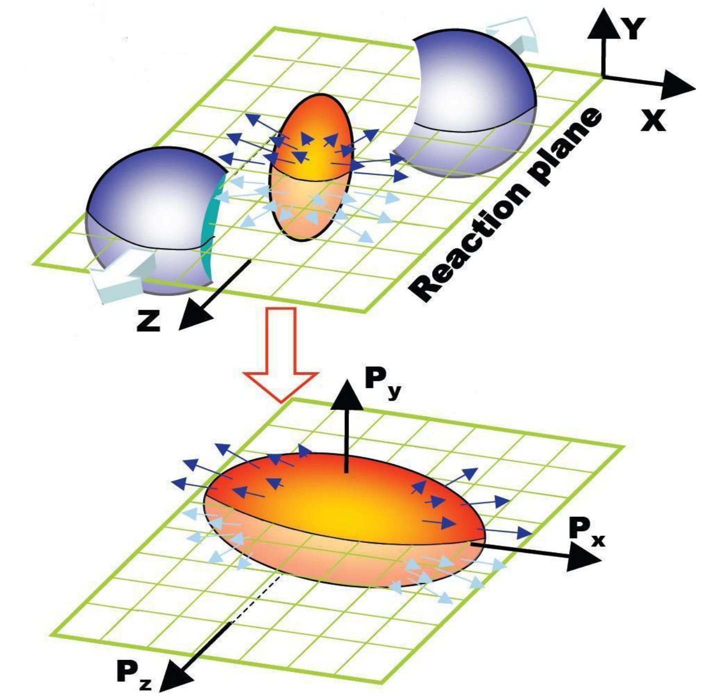
Outline

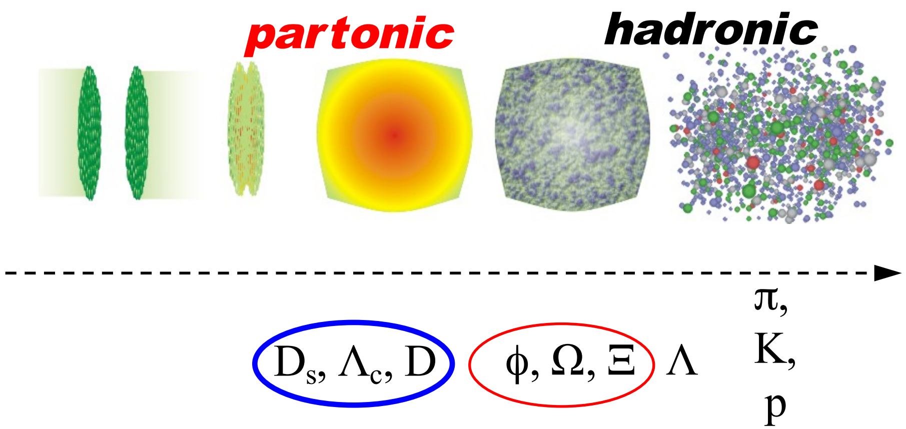
- Introduction
- Heavy Ion Collisions
- Results and Discussions
- Summary and Outlook

Anisotropic Flow



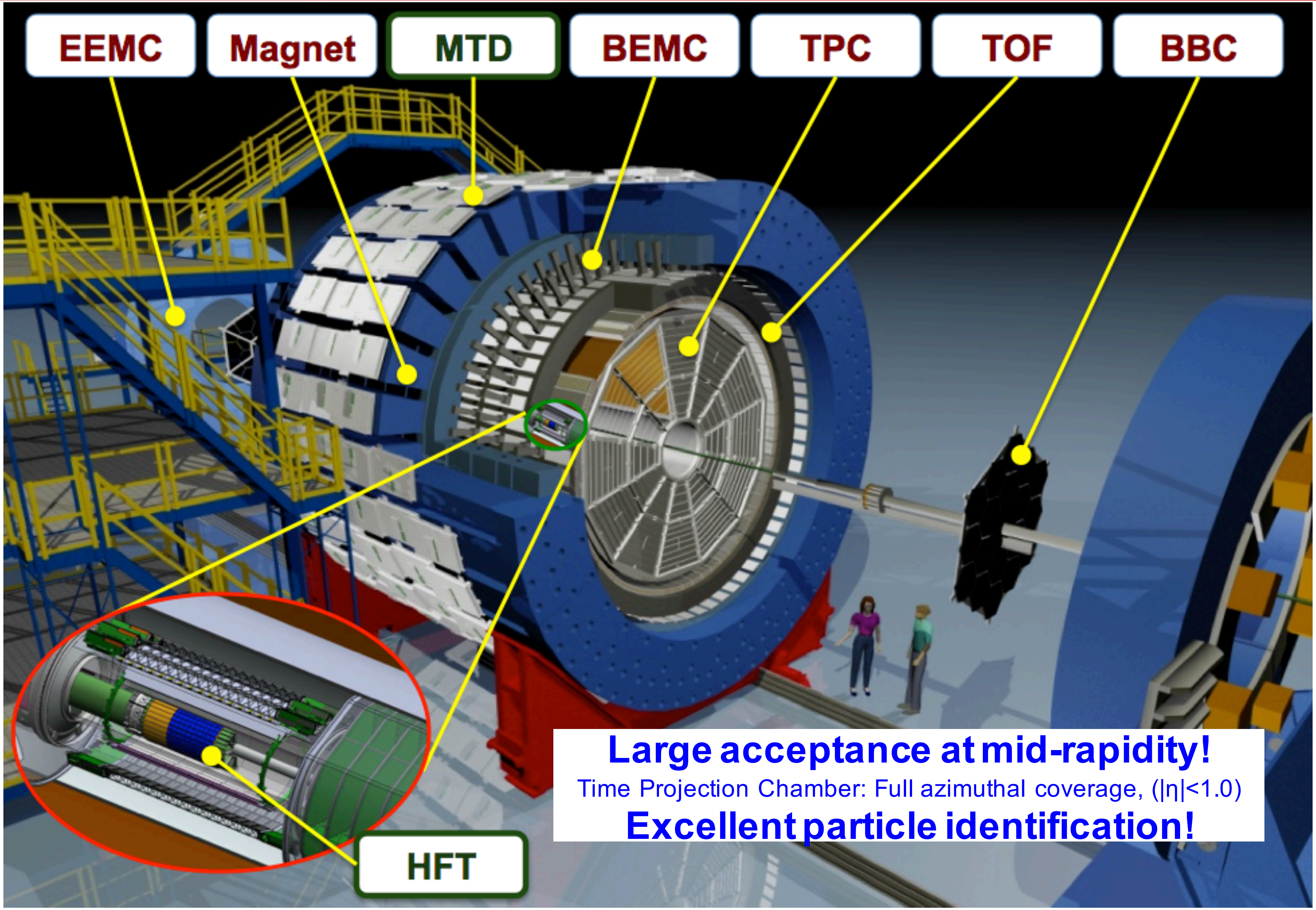
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} v_n \cos\left[n(\phi - \Psi_n)\right]$$

v_1: directed flow; v_2: elliptic flow;
v_3: triangular flow

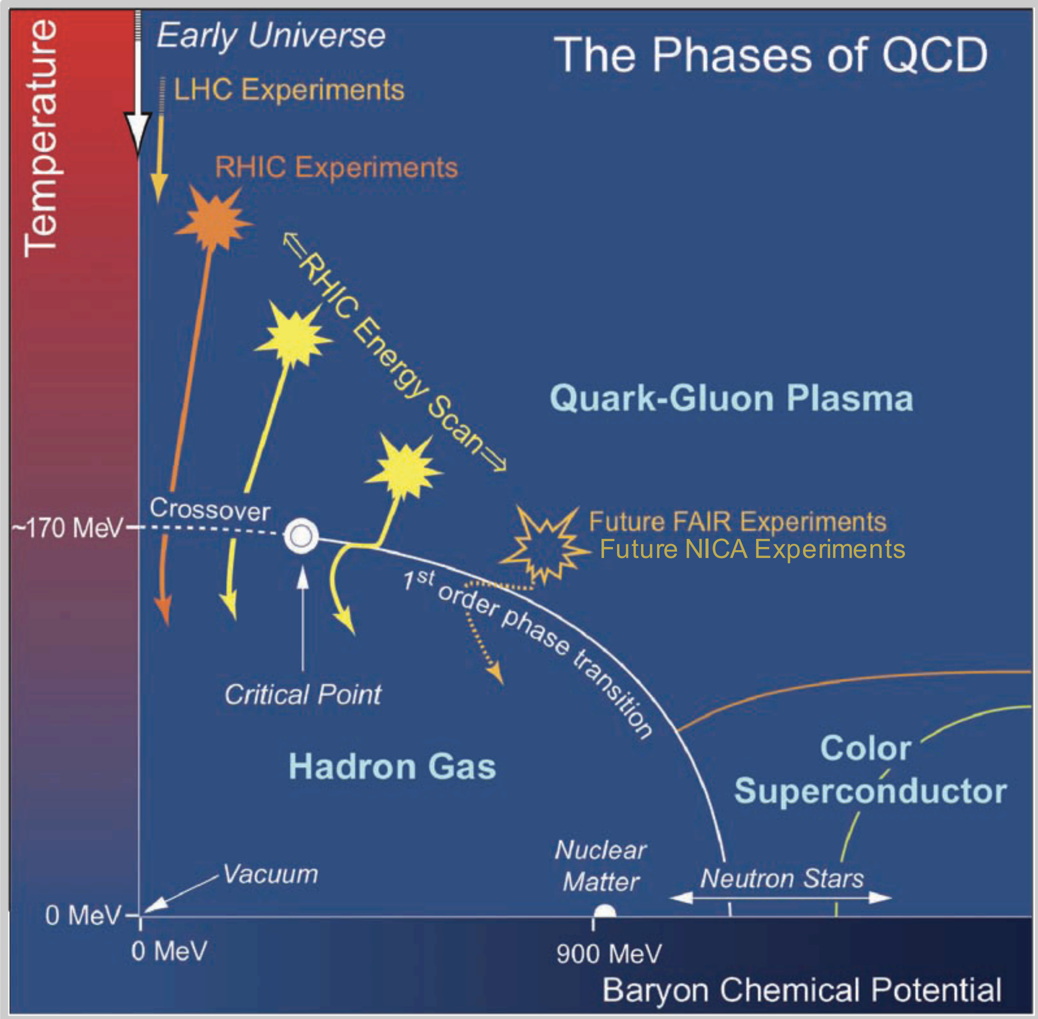


- **Anisotropic flow**:
  Sensitive to the early stage of the collision
- **Heavy flavor flow**
  Study medium properties from motion of heavy quarks in medium
- **Multi-strange hadrons and ϕ meson**:
  Less sensitive to late hadronic rescatterings

STAR Detectors



Heavy Ion Collisions



2000 – 2016 RHIC+LHC
High energy collisions
QGP properties

2010 – 2017: RHIC BES-I
7.7, 11.5, 14.5, 19.6, 27, 39, 54.4 GeV

2019 – 2021: RHIC BES-II
7.7, 9.2, 11.5, 14.5, 17.1, 19.6 GeV
FXT: 7.7, 4.5, 3.9, 3.6, 3.0 GeV

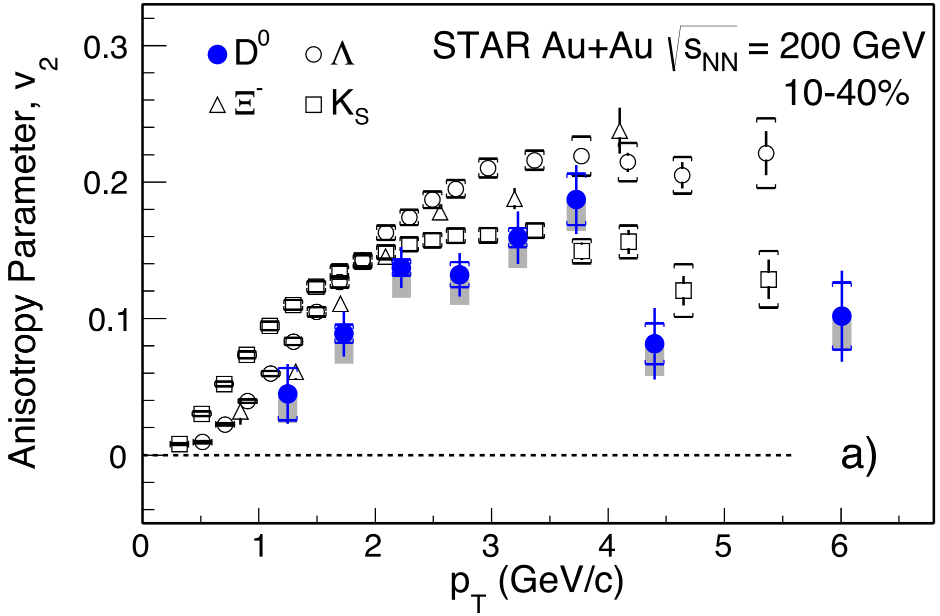
2022 – : RHIC+FAIR NICA
BES-III
Fixed-target programs

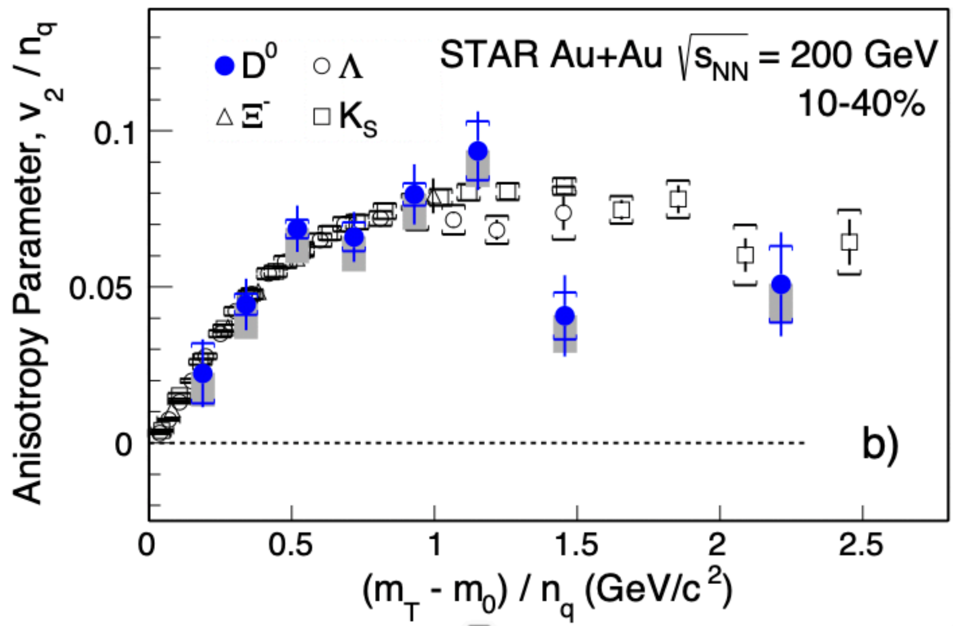
Explore the QCD phase structure!

Beam Energy Scan

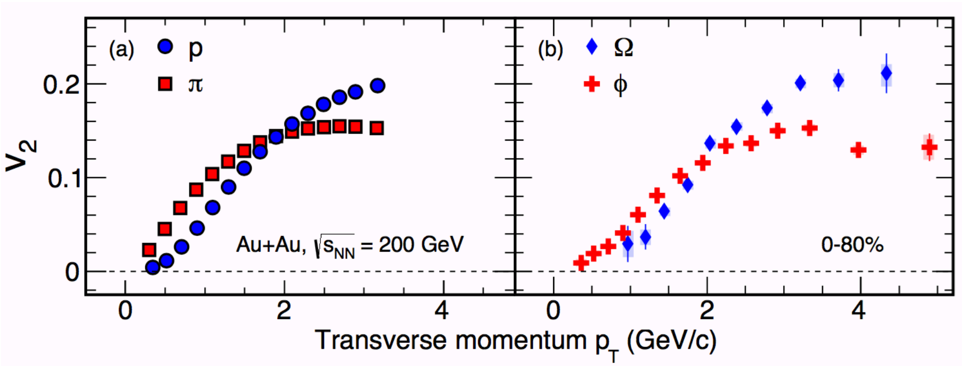
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	Weeks	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
54.4	1000	2017			165
39	130	2010		112	164
27	70 (1000)	2011(2018)		156	162
19.6	**400** / 36	**2019**/ 2011	**3**	206	160
14.5	**300** / 20	**2019**/ 2014	**2.5**	264	156
11.5	**230** / 12	**2020**/ 2010	**5**	315	152
9.2	**160** / 0.3	**2020** / 2008	**9.5**	355	140
7.7	**100** / 4	**2021** / 2010	**14**	420	140
17.1	250	2021			

Partonic Collectivity





STAR: Phys. Rev. Lett.118, 212301 (2017)
STAR: Phys. Rev. Lett.116, 062301 (2016)

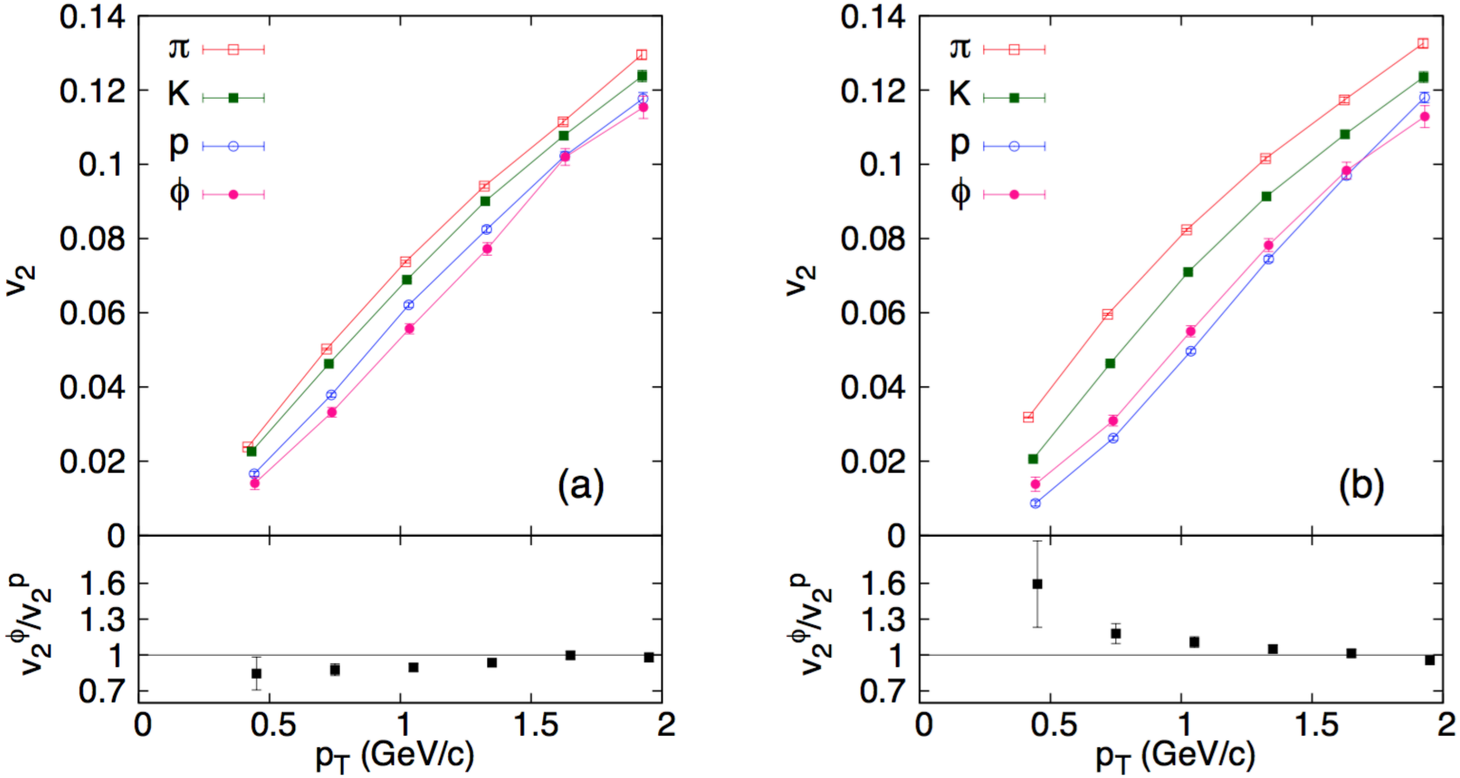


Partonic collectivity

light (u, d and s) quarks to charm quarks

$v_2(\phi)$ versus $v_2(p)$

Model calculations: T. Hirano et al., ; PRC77, 044909 (2008), PRC92, 044907 (2015)



Before hadronic re-scattering

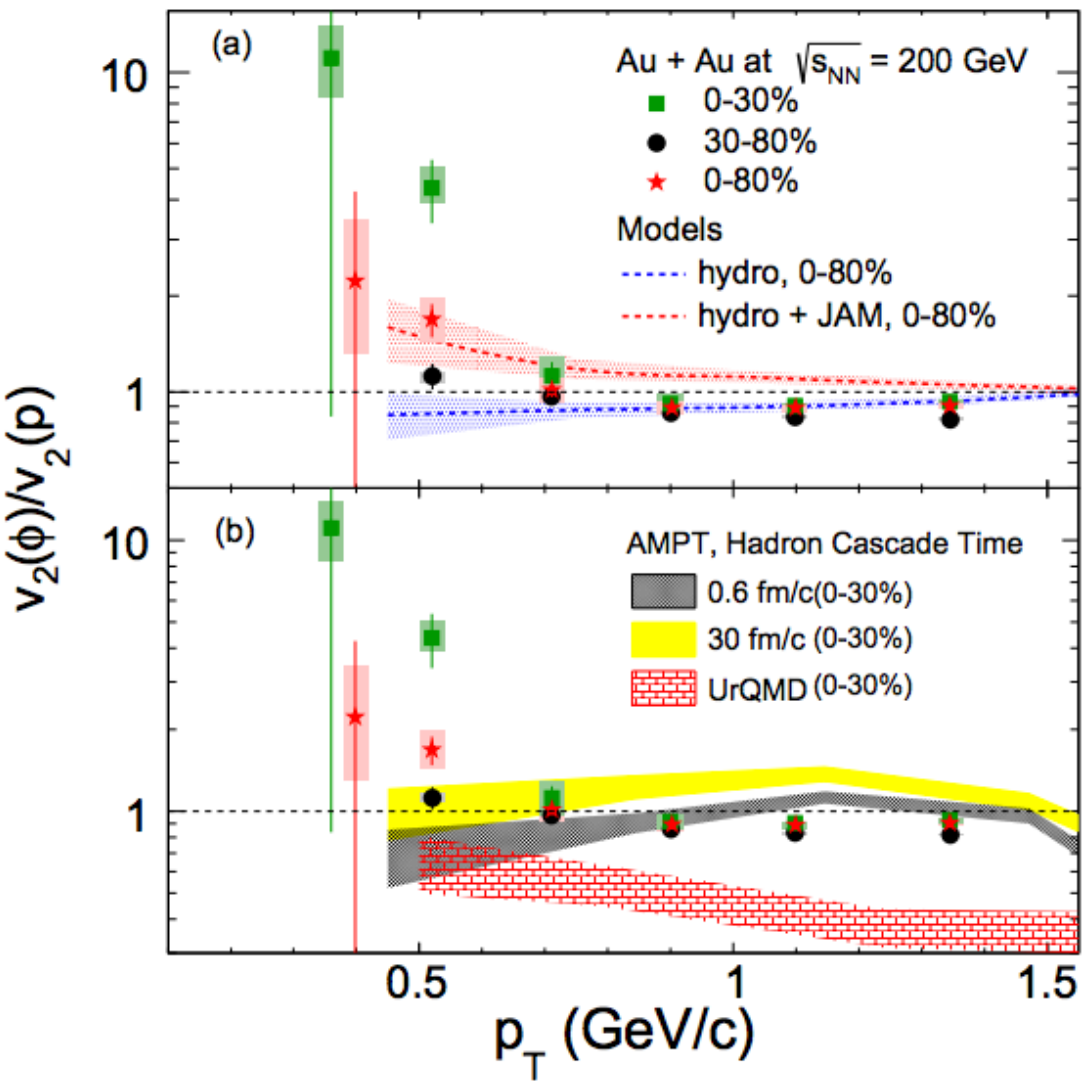
After hadronic re-scattering

- **Ideal hydro + hadron cascade (JAM)**
- **Small hadron cross section + hadronic re-scattering effect on v_2**

  Mass φ > mass p ➔ $v_2(\phi) > v_2(p)$

  ➔ ***Break mass ordering for φ mesons and protons***

$v_2(\phi)$ versus $v_2(p)$



- **Model study indicates with increasing hadronic cascade time (more hadronic re-scattering), the $v_2(\phi)/v_2(p)$ ratio increases**

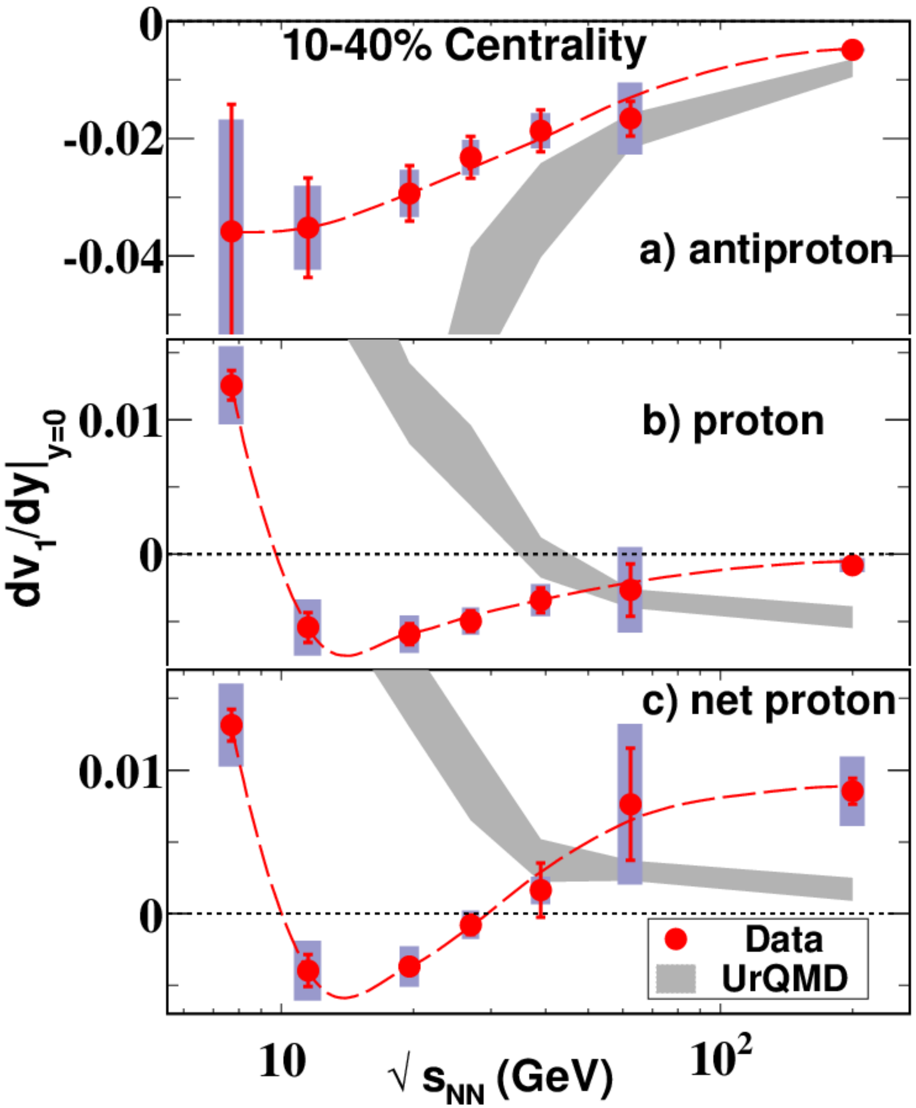
- **The ratio $v_2(\phi)/v_2(p)$ is $4.35 \pm 0.98 \pm^{0.66}_{0.45}$ at p_T = 0.52 GeV/c in 0-30% ->**
  The effect of late hadronic interactions on the proton v_2

- **Energy dependence (200, 54.4 and 27 GeV): hadronic contribution on the partonic flow**

STAR: Phys. Rev. Lett.116, 062301 (2016)
Model calculations: T. Hirano et al., ; PRC77, 044909 (2008), PRC92, 044907 (2015)

Directed Flow v_1: Softest Point

BESII : centrality dependence



dv_1/dy: the slope of directed flow versus rapidity near mid-rapidity

- Hydrodynamic calculation with the 1st-order phase transition motivates the study
- Net-proton slope changes sign twice
  EOS softest point?
- UrQMD fails to reproduce the data

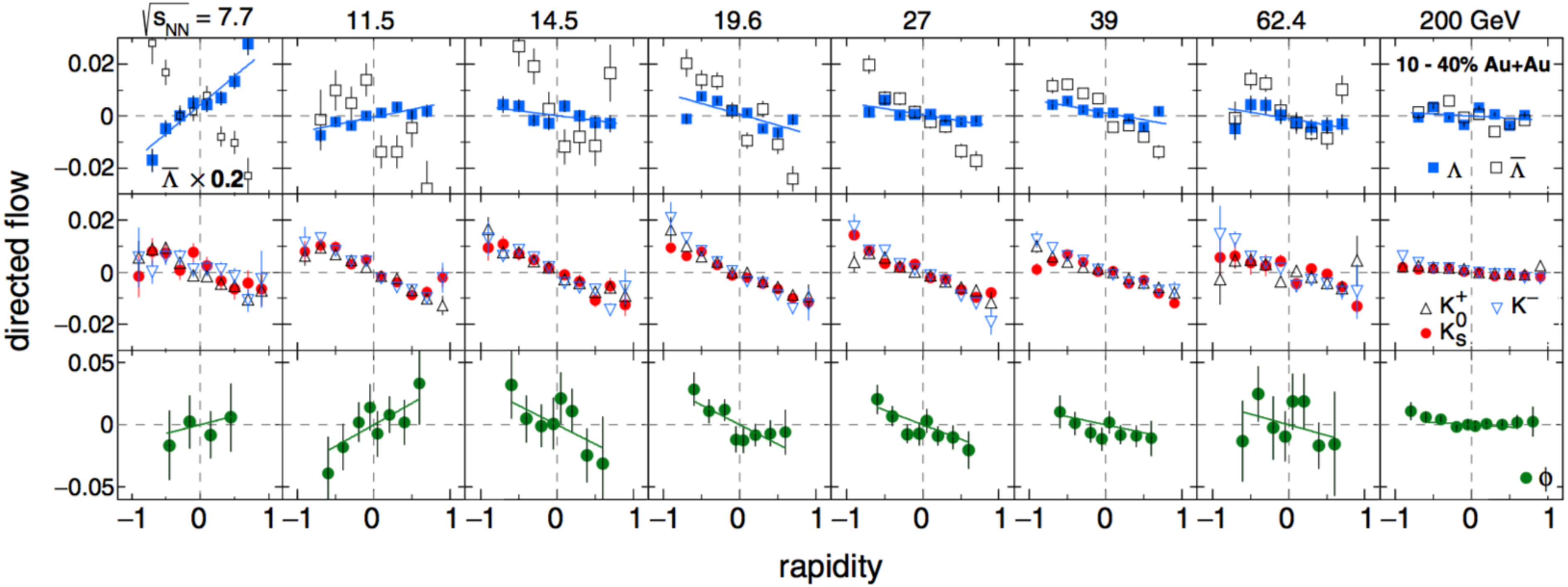
The slope of net-p is based on expressing the y dependence of v1 for all protons as:

$$[v_1(y)]_p = r(y)[v_1(y)]_{\bar{p}} + [1 - r(y)][v_1(y)]_{\text{net-}p}$$

r: the ratio of anti-p to p.

STAR: Phys. Rev. Lett. 112, 162301(2014)
H. Stoecker, Nucl. Phys. A 750, 121(2005)

Directed Flow v_1: ϕ Mesons

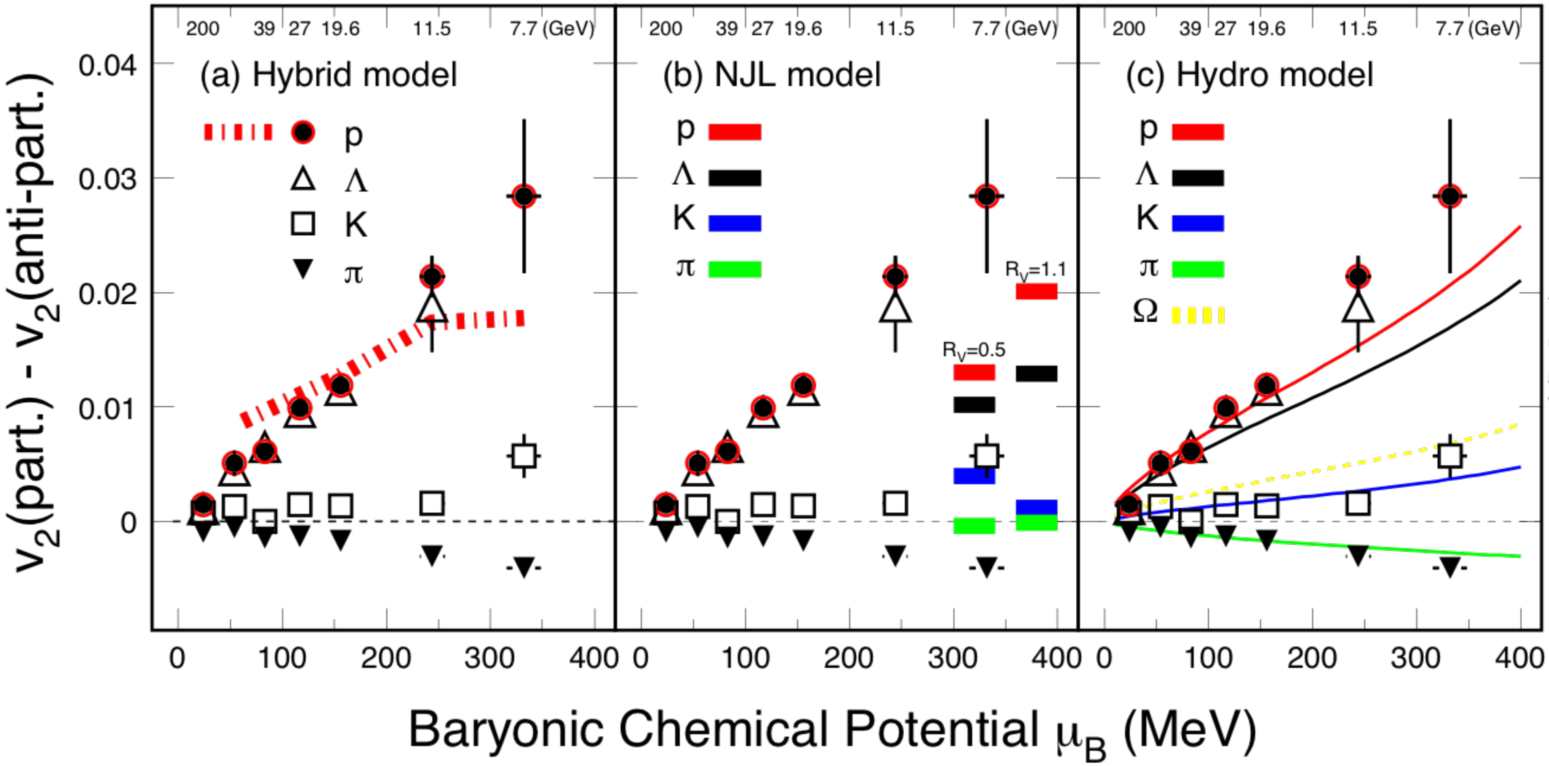


➢ Mesons and all produced baryons show negative slope except ϕ mesons when collisions energy < 14.5 GeV

Change of medium property? High precision data needed: BESII

STAR: Phys. Rev. Lett. **120**, 062301(2018)

Particle vs. Anti-particle v_2

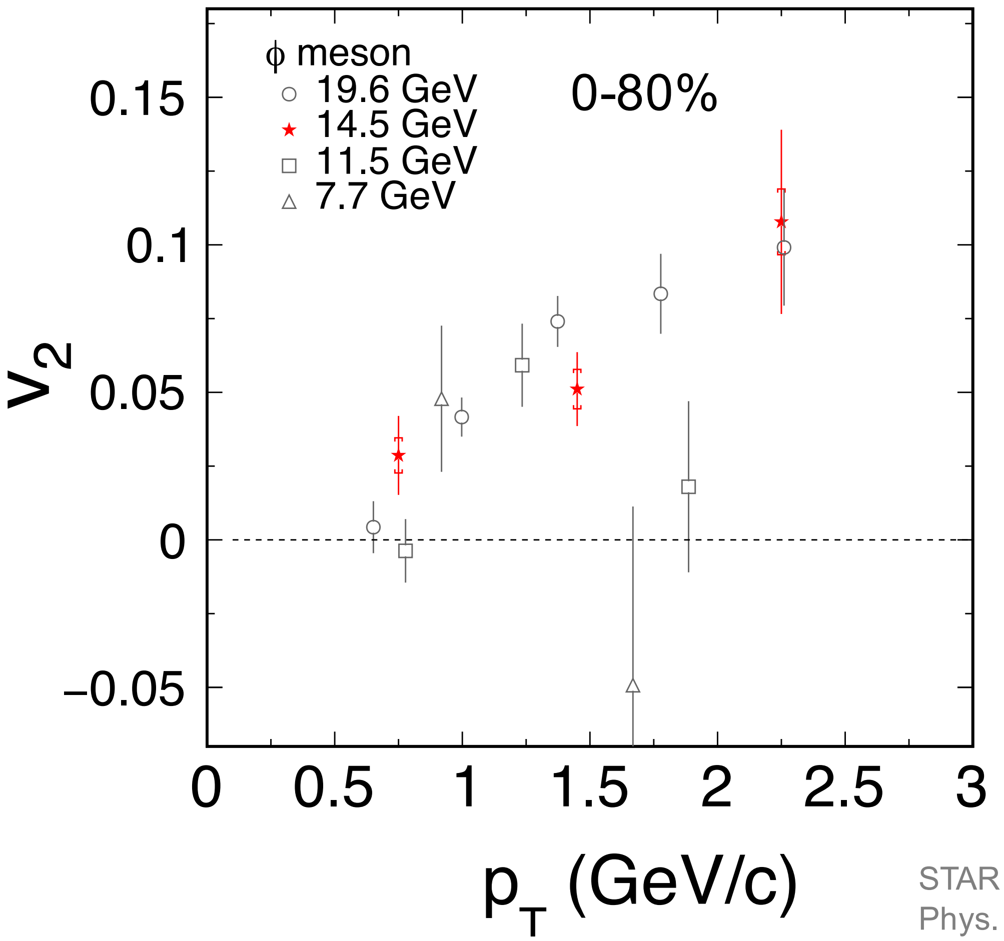


BESII : multi-strange hadrons

- **The difference between particles and anti-particles increases with decreasing beam energy – NCQ scaling breaks**
- **Model comparison** STAR: Phys. Rev. Lett. **110** (2013) 142301
  - Hydro + Transport (UrQMD): consistent with baryon data
  - Nambu-Jona-Lasino (NJL) model (partonic + hadronic potential): hadron splitting consistent
  - Analytical hydrodynamic solution: $\Delta v_2^{\bar{p}} > \Delta v_2^{\Lambda} > \Delta v_2^{\Xi} > \Delta v_2^{\Omega}$

J. Steinheimer et al., PRC86, 44903(2012); J. Xu et al., PRL112, 012301(2014); Y. Hatta et al., PRD92, 114010(2015)

ϕ Meson v_2



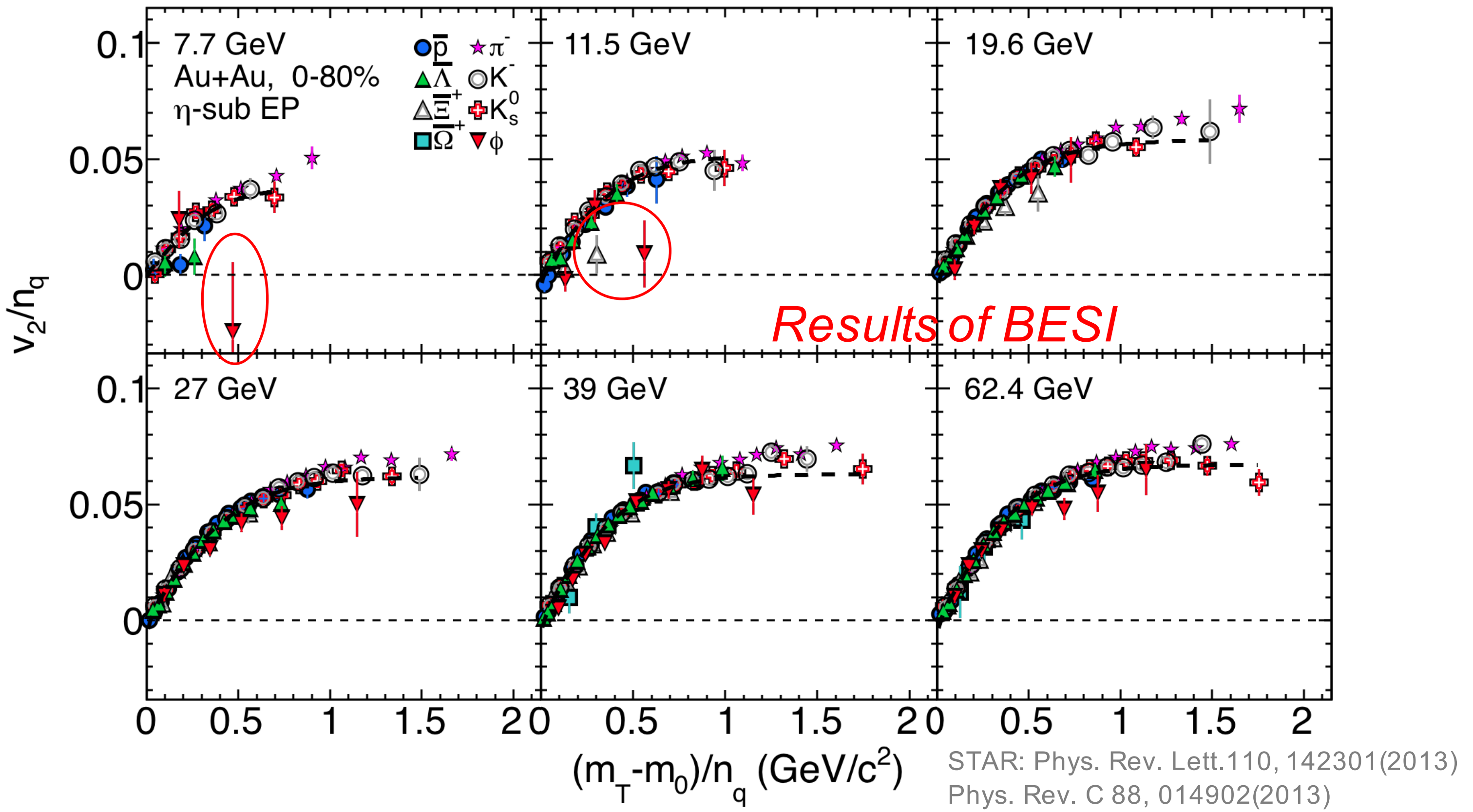
ϕ meson is less sensitive to late hadronic interactions[1]

Sizable ϕ meson v_2: comparable to 19.6 GeV

High statistics and more energies below 20 GeV needed!

STAR: Phys. Rev. C 88, 014902(2013)
Phys. Rev. C 93, 014907(2016)
[1] STAR: Phys. Rev. Lett. 116, 062301(2016)

Multi-strange Hadron v_2 in BESII

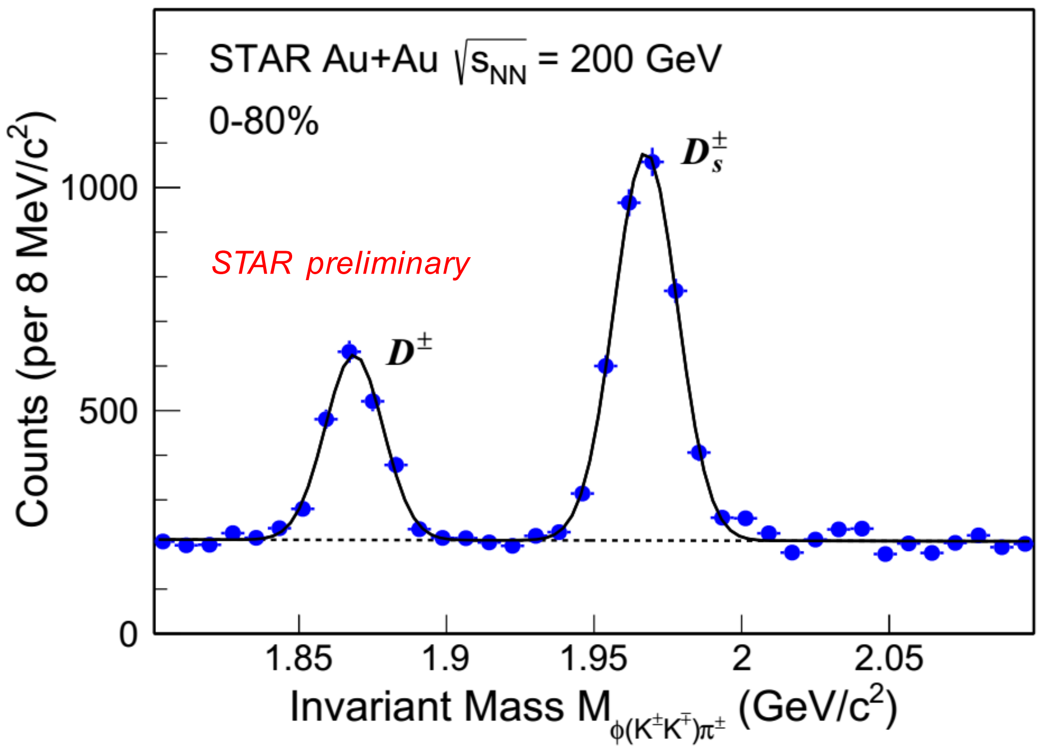


STAR: Phys. Rev. Lett.110, 142301(2013)
Phys. Rev. C 88, 014902(2013)
Phys. Rev. C 93, 014907(2016)

- **BESI: v_2 of multi-strange hadrons and ϕ mesons seems dropping when collision energy < 20 GeV**
- **BESII: precise measurements will offer information on partonic vs. hadronic degree of freedom: *QCD phase structure***

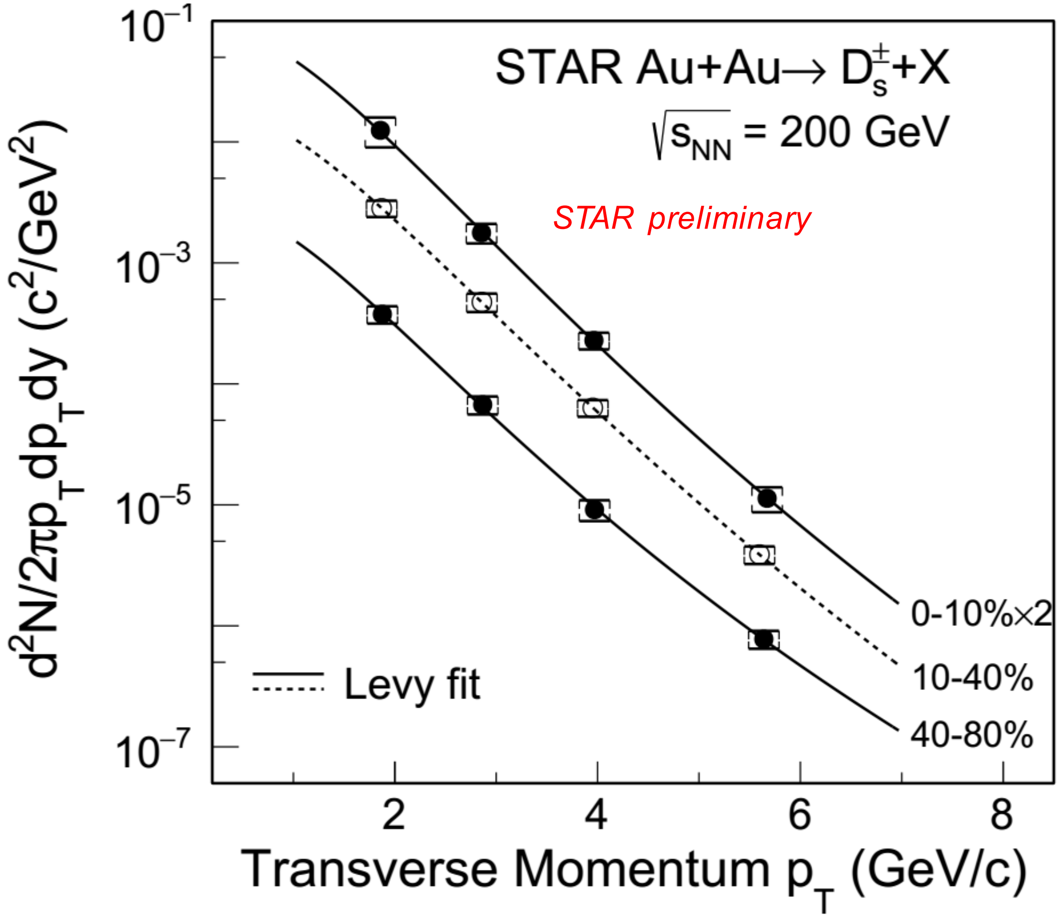
BESII : multi-strange hadrons and ϕ meson

Invariant Mass distribution



- 2014+2016 data (860 M + 1000 M events)
- Improved signal number and significance.

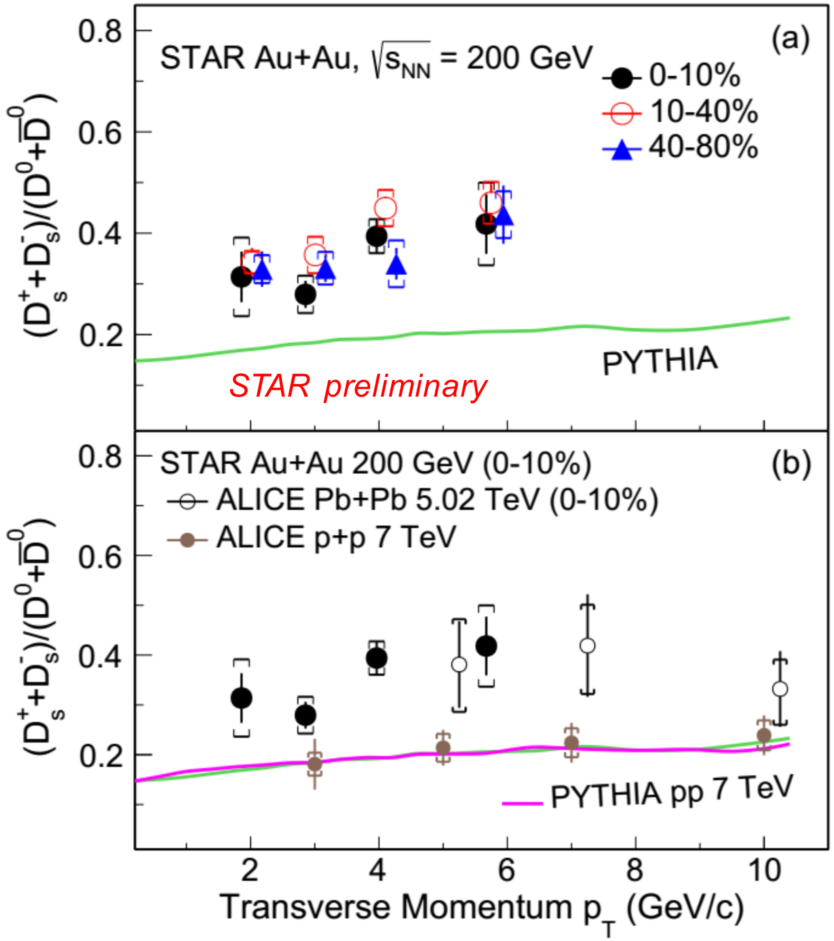
p_T Spectrum



Dataset: year 2014 + 2016

Centrality dependence of p_T spectrum

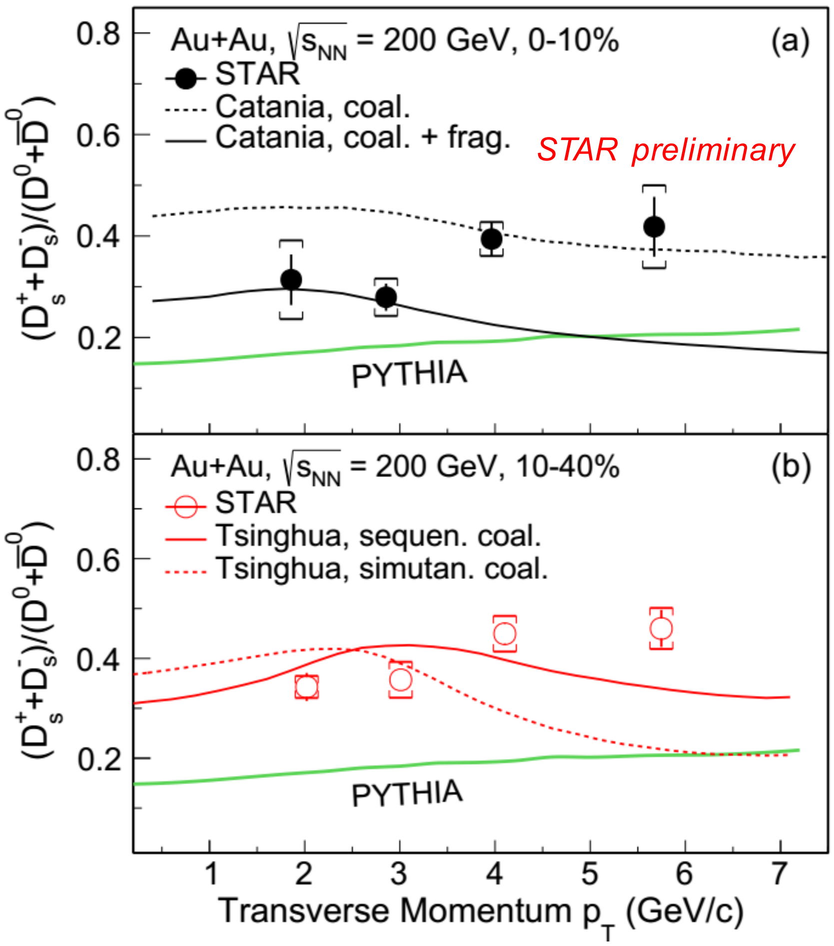
$D_s^{\pm}/D^0$ Ratio



- $D_s^{\pm}/D^0$ ratio: larger enhancement (~1.5-2 times) relative to PYTHIA, no clear centrality dependence.
- Consistent well with ALICE measurements.
- Strangeness enhancement + coalescence hadronization mechanism.

ALICE data: JHEP, 2018, 2018(10): 174
EPJC, 2017, 77: 550

$D_s^{\pm}/D^0$ Ratio



- Coal. + frag. : consistent well for 1.5 < p_T < 4 GeV/c,
  Coal. : consistent well for 4 < p_T < 8 GeV/c.
- Seq. coal. : a little higher than our measurement for 1.5 < p_T < 4 GeV/c, lower than that for 4 < p_T < 8 GeV/c.
- Strangeness enhancement + coalescence hadronization play an important role for charm quark hadronization.

Catania: EPJC 2017, 77: 348
Tsinghua: arxiv: 1805.10858v1

Summary

- **Top Energy Collisions**
  - **Partonic collectivity:** *light flavor to charm*
  - **$v_2(\phi)/v_2(p)$:** *hadronic contribution on partonic flow*
  - **$D_s^{\pm}$ production:** *charm quark hadronization mechanism*

- **Beam Energy Scan II**
  - **v_1 slope of net-proton:** *non-monotonic as energy*
  - **φ meson v_1:** *slope change, sensitive to properties of the medium?*
  - **φ meson and multi-strange v_2:** *Partonic vs. hadronic*

BES-II is Ongoing

Electron cooling + longer beam bunches for BES-II
factor 4-15 improvement in luminosity compared with BES-I

Detector upgrade

- **Event Plane Detector**
  important for flow and fluctuation analyses
- **iTPC upgrade**
  increases TPC acceptance to ~1.7 in η; improves dE/dx resolution
- **ETOF upgrade**
  New charged hadron PID capabilities for 1.1<|η|<1.6

Fixed target program

extends STAR's physics reach to region of compressed baryonic matter

RHIC BES-II：2019-2021

19.6, 17.1, 14.5, 11.5, 9.2 and 7.7 GeV
Focus on $\sqrt{s_{NN}} \leq 20$ GeV region