



Collectivity in heavy ion collisions at RHIC-STAR

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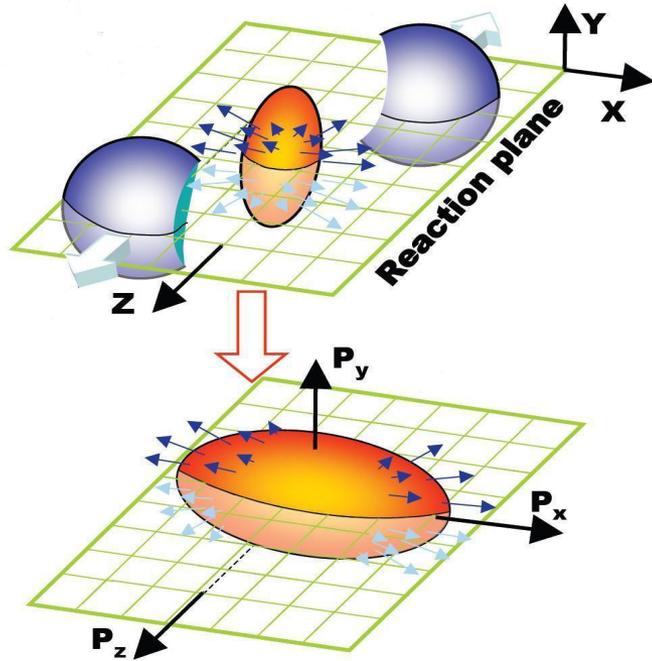
Oct. 8 - 12, 2019



Outline

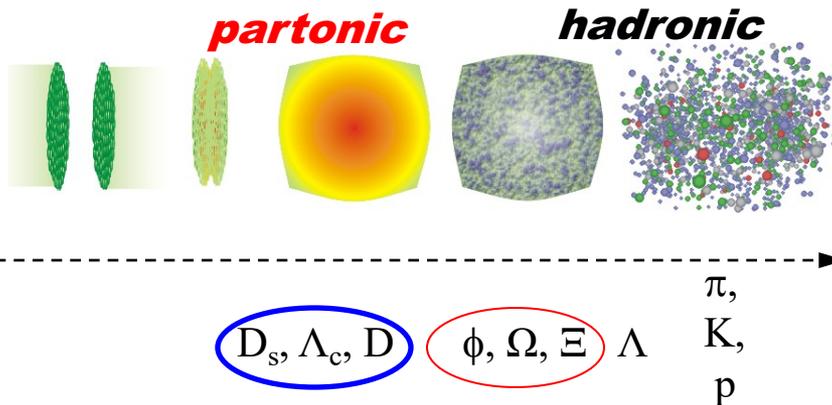
- **Introduction**
- **Heavy Ion Collisions**
- **Results and Discussions**
- **Summary and Outlook**

Anisotropic Flow



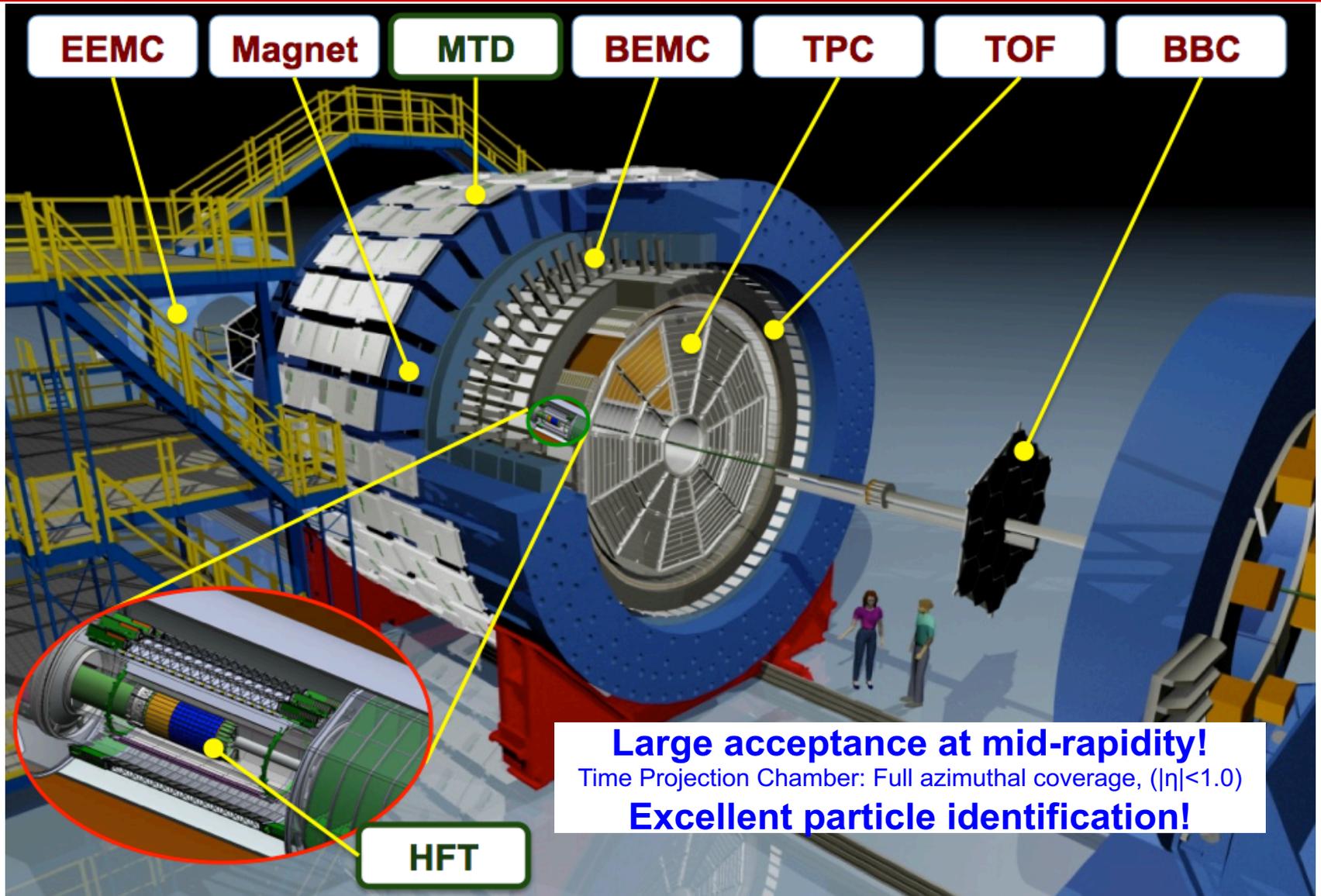
$$\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1} v_n \cos [n(\phi - \Psi_n)]$$

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

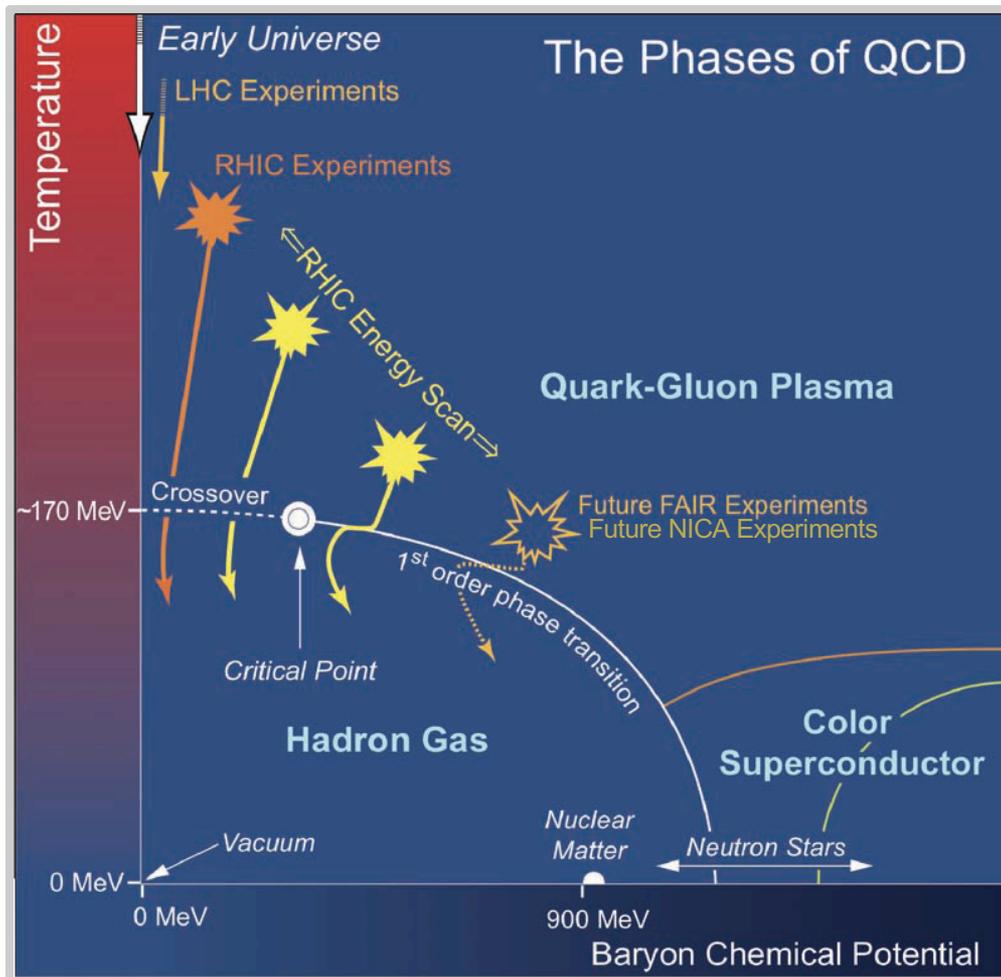


- **Anisotropic flow:**
Sensitive to the early stage of the collision
- **Heavy flavor flow**
Study medium properties from motion of heavy quarks in medium
- **Multi-strange hadrons and ϕ meson:**
Less sensitive to late hadronic rescatterings

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

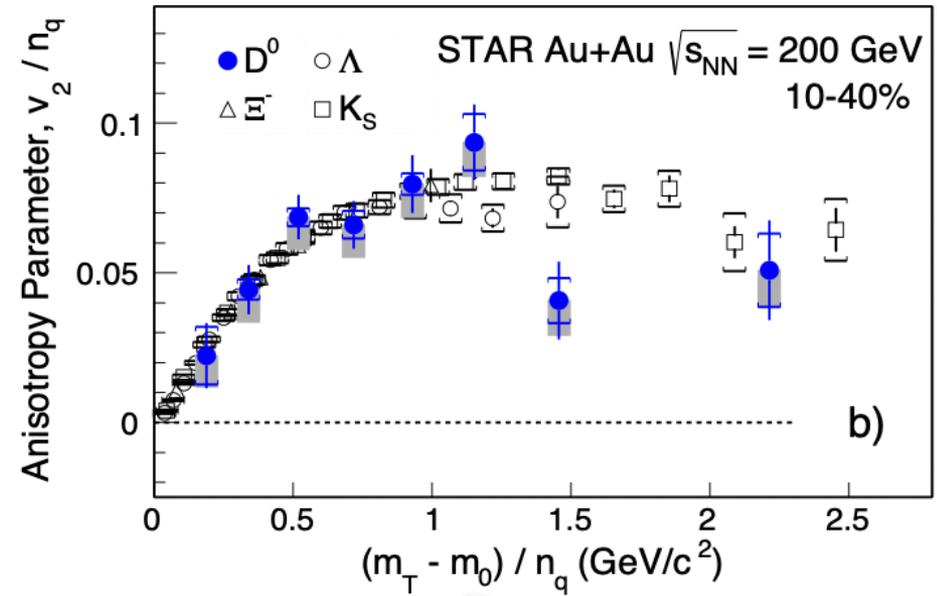
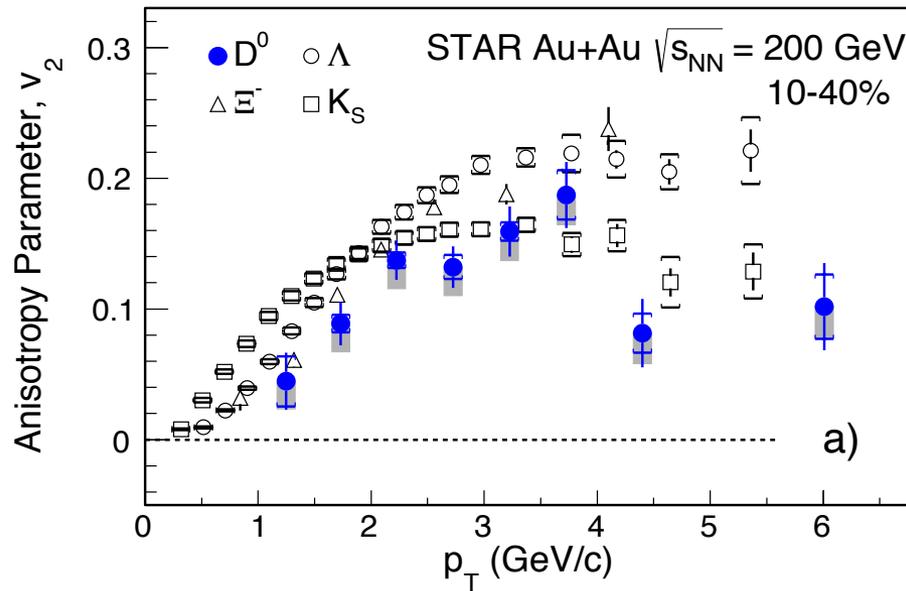
Explore the QCD phase structure!

Beam Energy Scan

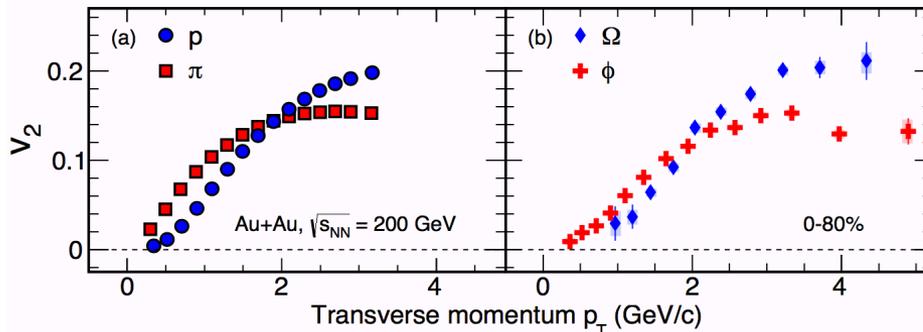


$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	BES II / BES I	Weeks	μ_B (MeV)	T_{CH} (MeV)
200	350	2010		25	166
62.4	67	2010		73	165
54.4	1000	2017			165
39	130	2010		112	164
27	70 (1000)	2011(2018)		156	162
19.6	400 / 36	2019 / 2011	3	206	160
14.5	300 / 20	2019 / 2014	2.5	264	156
11.5	230 / 12	2020 / 2010	5	315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



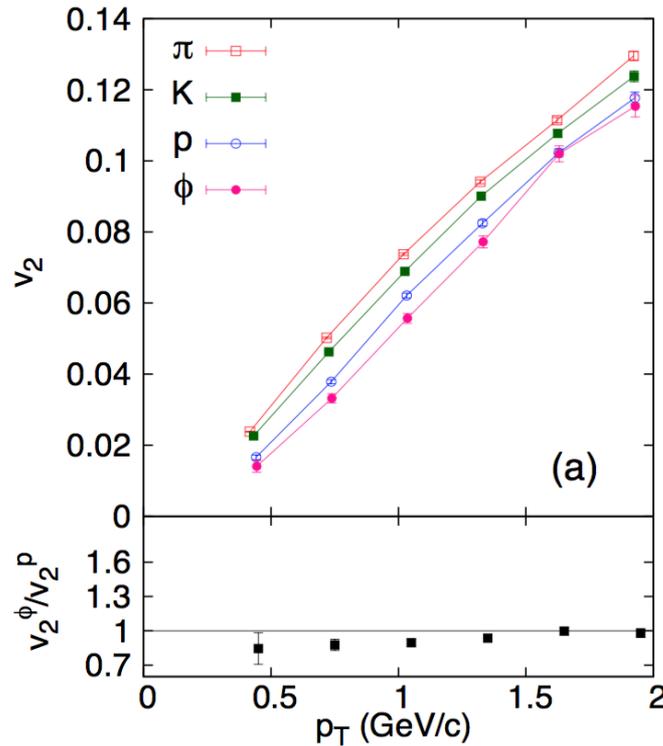
STAR: Phys. Rev. Lett.118, 212301 (2017)
 STAR: Phys. Rev. Lett.116, 062301 (2016)



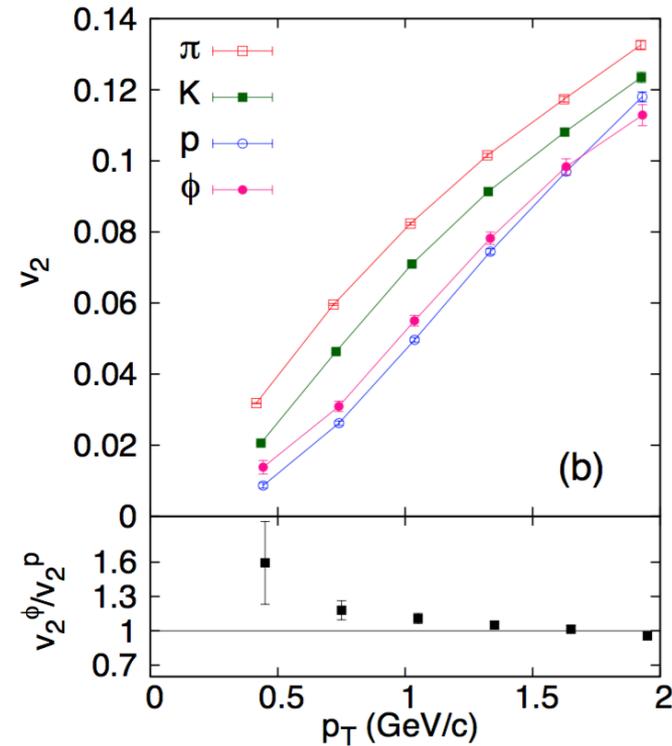
Partonic collectivity
 light (u, d and s) quarks to
 charm quarks

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

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



Before hadronic re-scattering



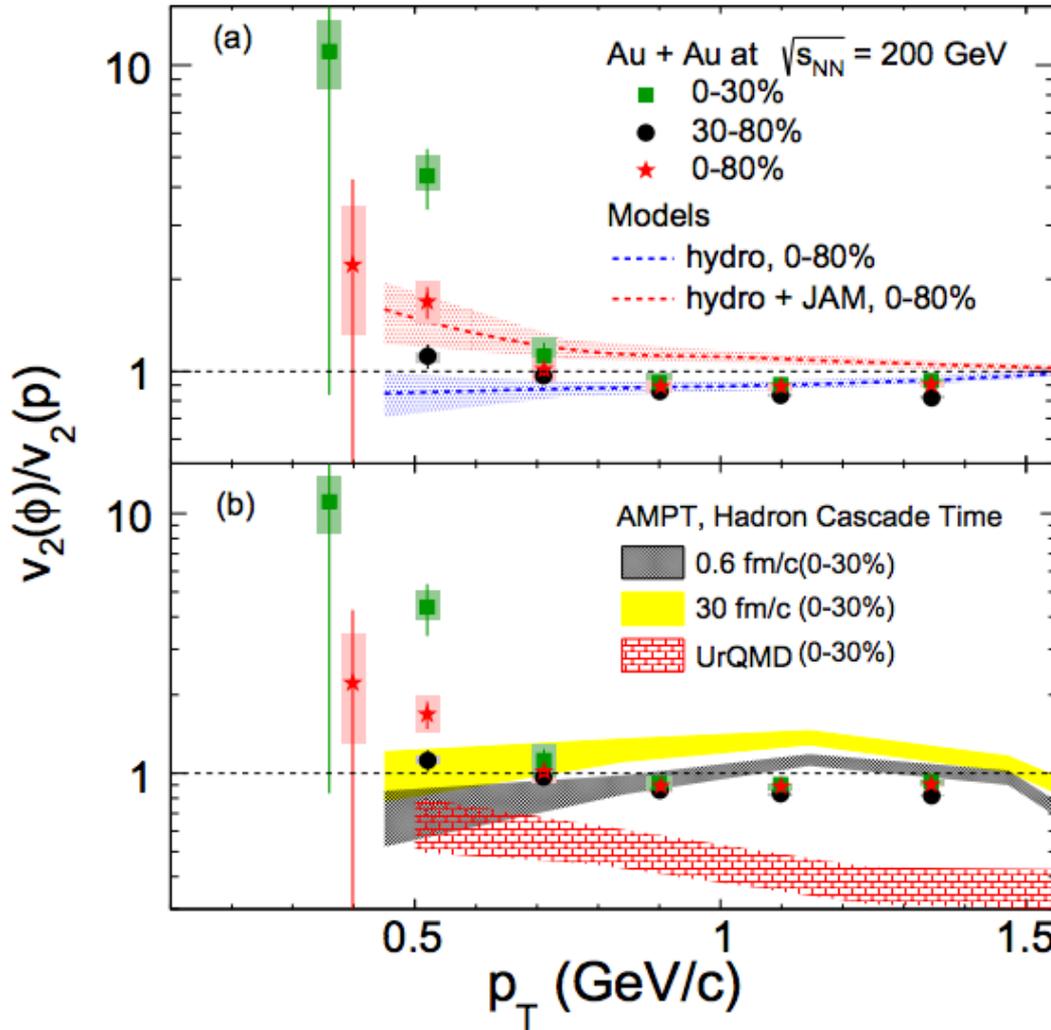
After hadronic re-scattering

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

Mass $\phi >$ mass $p \rightarrow v_2(\phi) > v_2(p)$

➔ *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 $4.35 \pm 0.98 \pm_{0.45}^{0.66}$ at $p_T = 0.52$ GeV/c in 0-30% ->

The effect of late hadronic interactions on the proton v_2

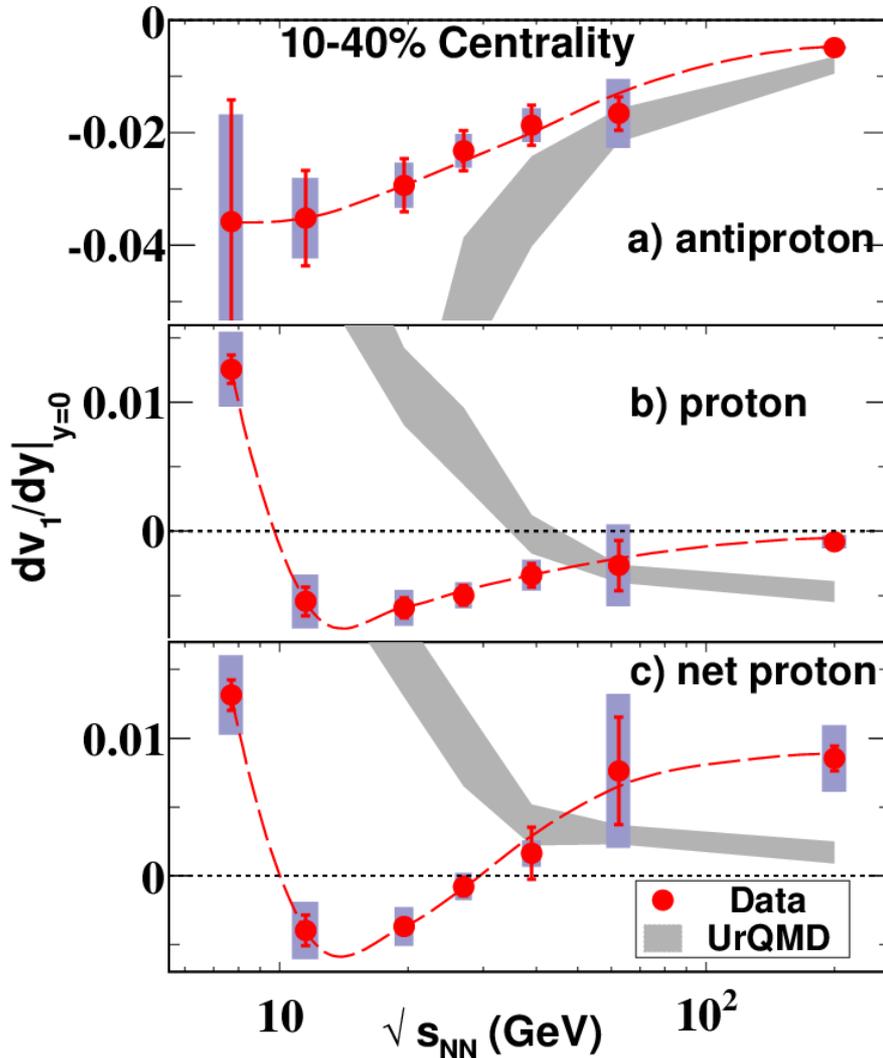
➤ Energy dependence (200, 54.4 and 27 GeV): hadronic contribution on the partonic flow

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 v_1 for all protons as:

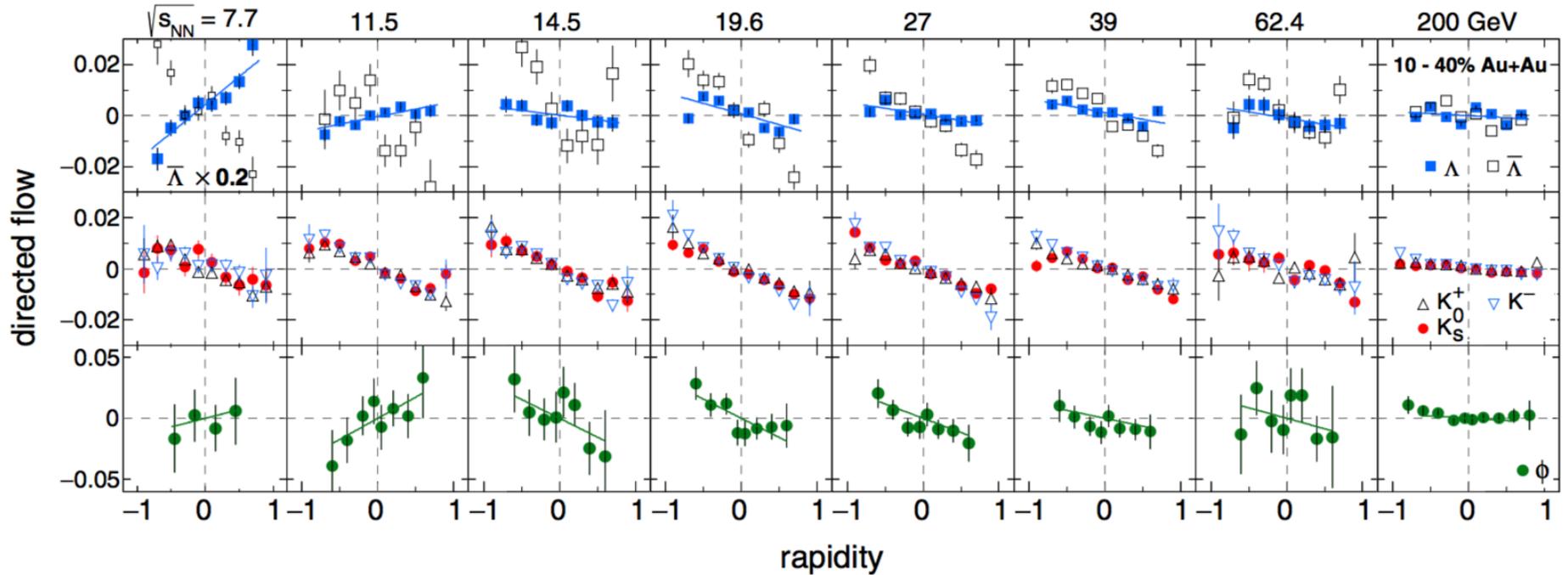
$$[v_1(y)]_p = r(y)[v_1(y)]_{\bar{p}} + [1 - r(y)][v_1(y)]_{\text{net-p}}$$

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

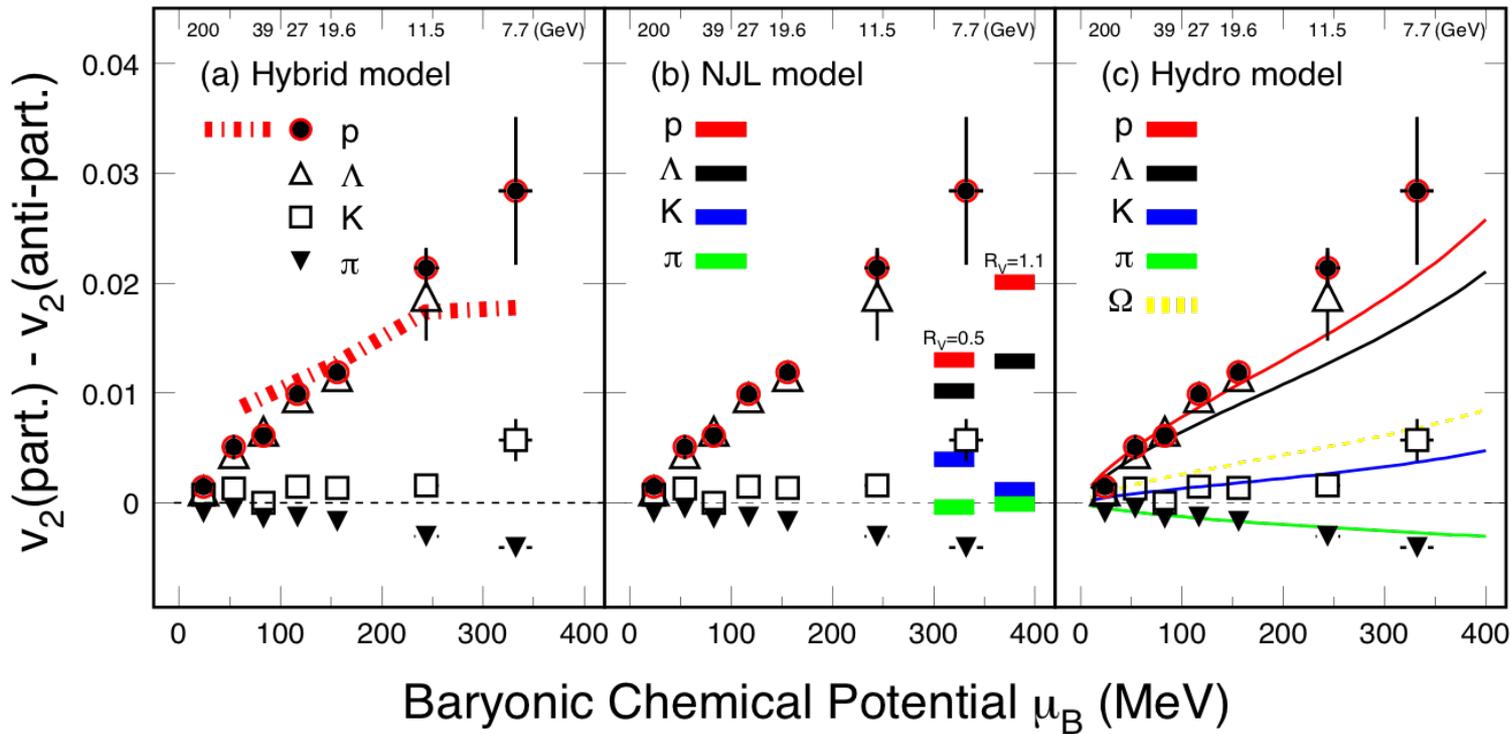


➤ Mesons and all produced baryons show negative slope except ϕ mesons when collisions energy < 14.5 GeV

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**

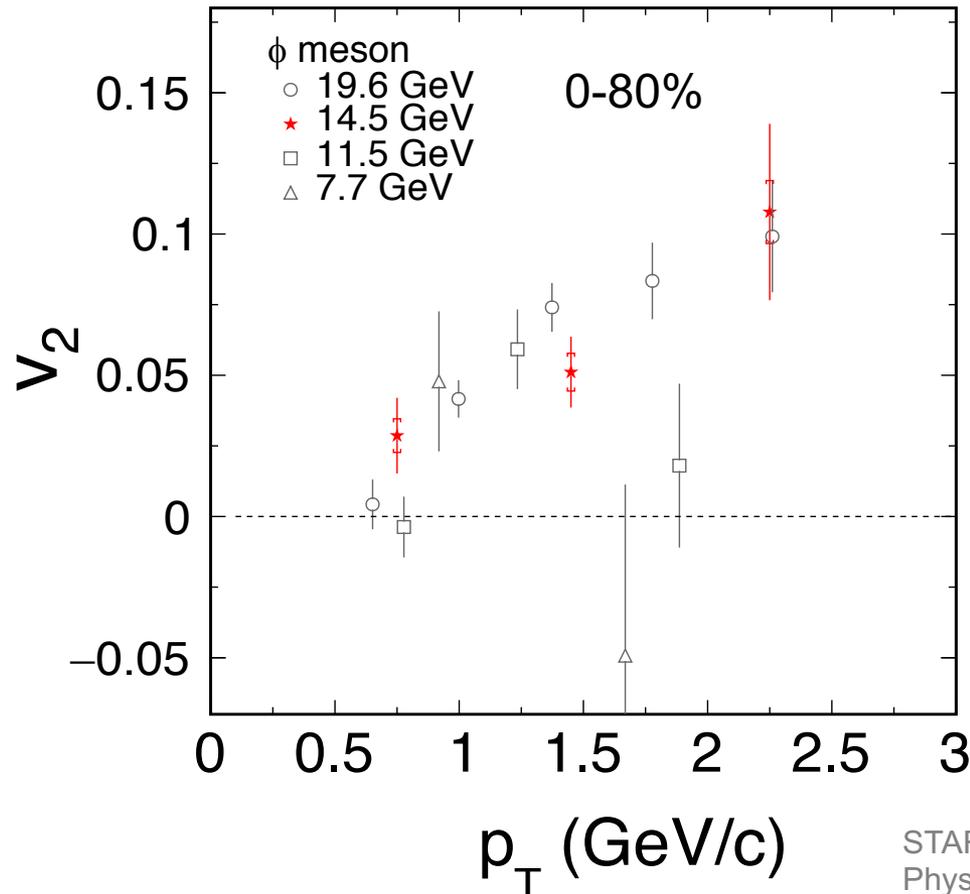
➤ **Model comparison**

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: $\Delta v_2^p > \Delta v_2^\Lambda > \Delta v_2^{\Xi} > \Delta v_2^\Omega$

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

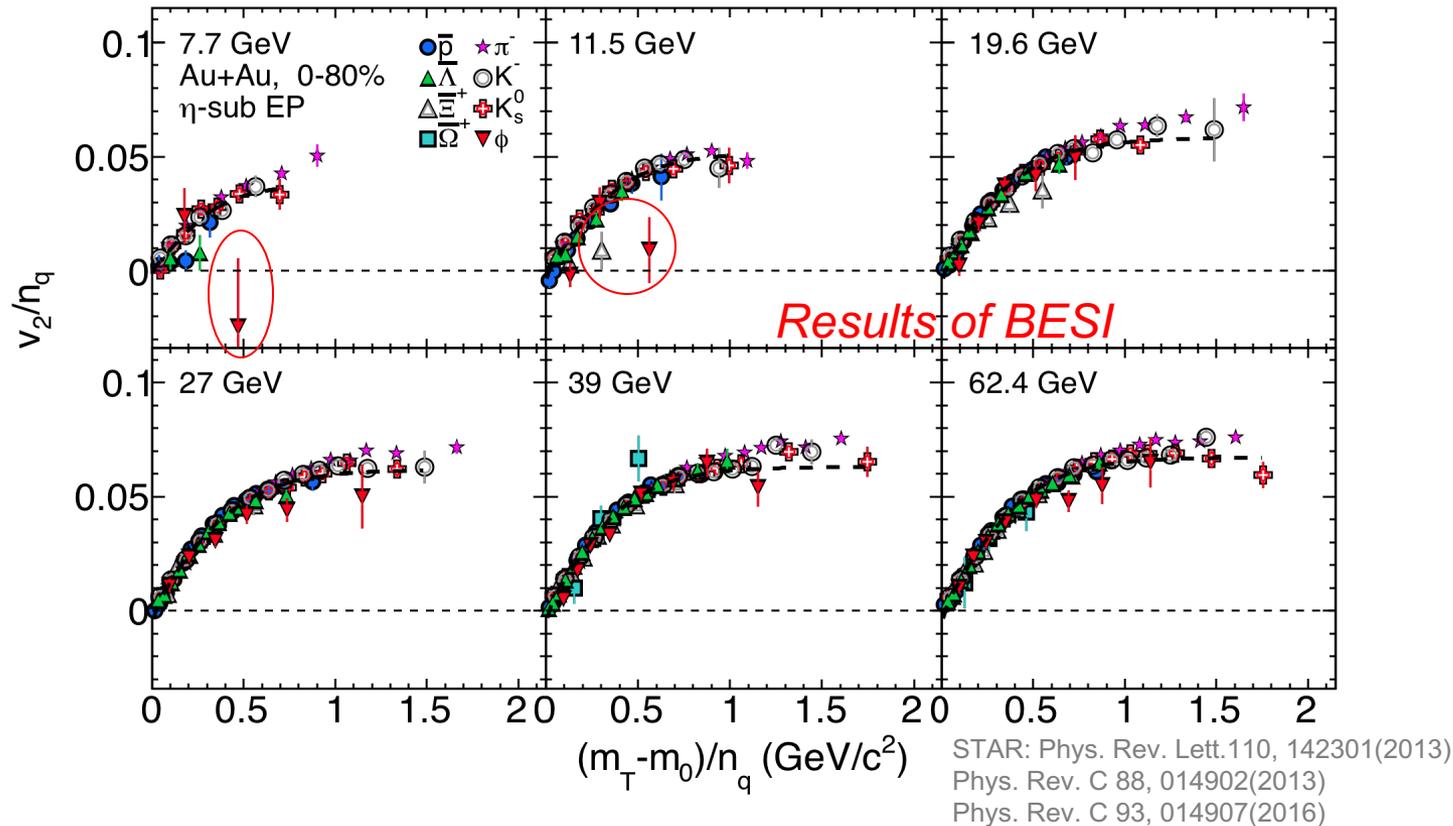
High statistics and more energies below 20 GeV needed!

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



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

BES II : multi-strange hadrons and ϕ meson



Summary

➤ Top Energy Collisions

➤ Partonic collectivity: *light flavor to charm*

➤ $v_2(\phi)/v_2(p)$: *hadronic contribution on partonic flow*

➤ 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 $1.1 < |\eta| < 1.6$

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

