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# Collectivity and Beam Energy Scan Program

**Shusu Shi 施梳苏**

**Central China Normal University**  
华中师范大学

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Workshop on STAR Forward Tracking Detector Upgrade and Related Physics

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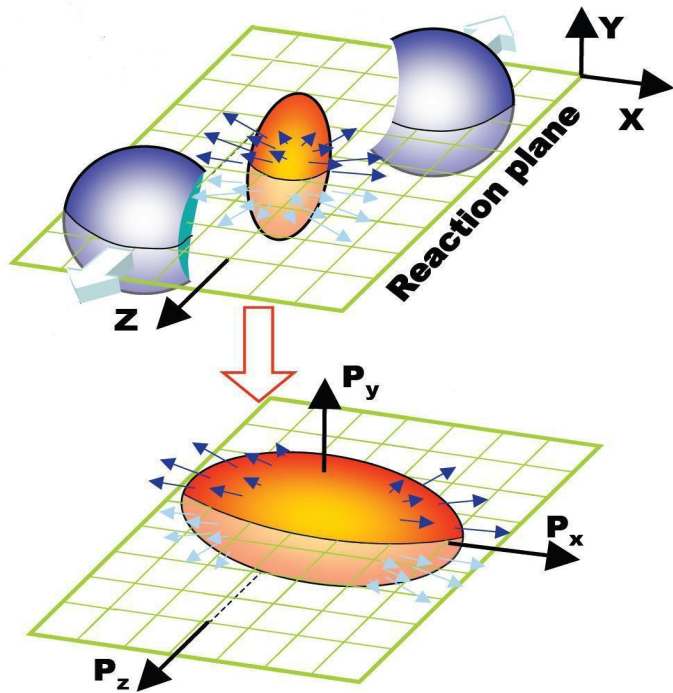
# Outline

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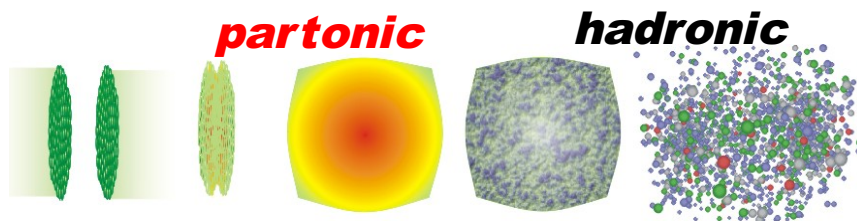
- **Introduction**
- **Beam Energy Scan**
- **Results and Discussions**
- **Summary and Outlook**

# Anisotropic Flow



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

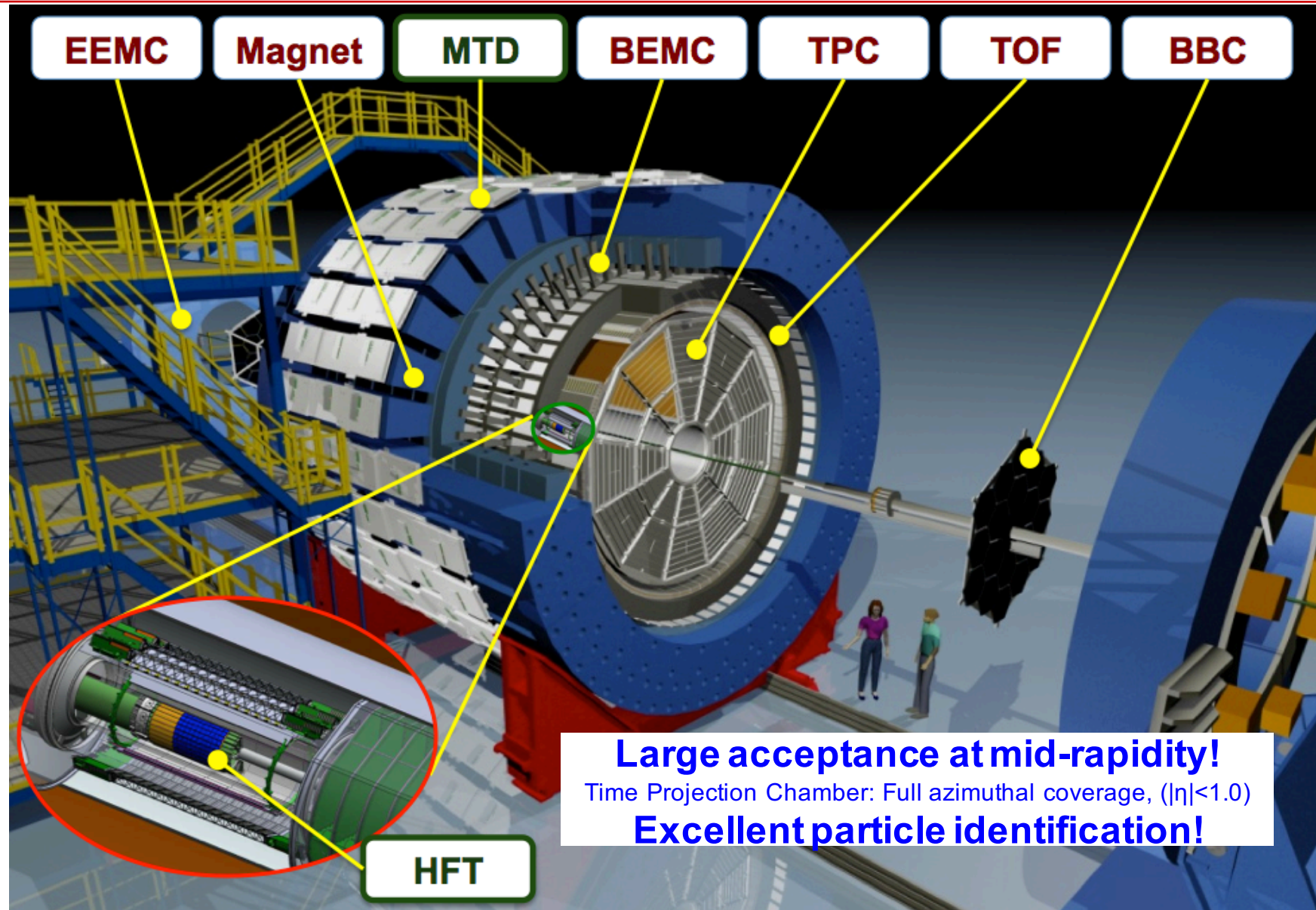
$v_1$ : directed flow;  $v_2$ : elliptic flow;  
 $v_3$ : triangular flow



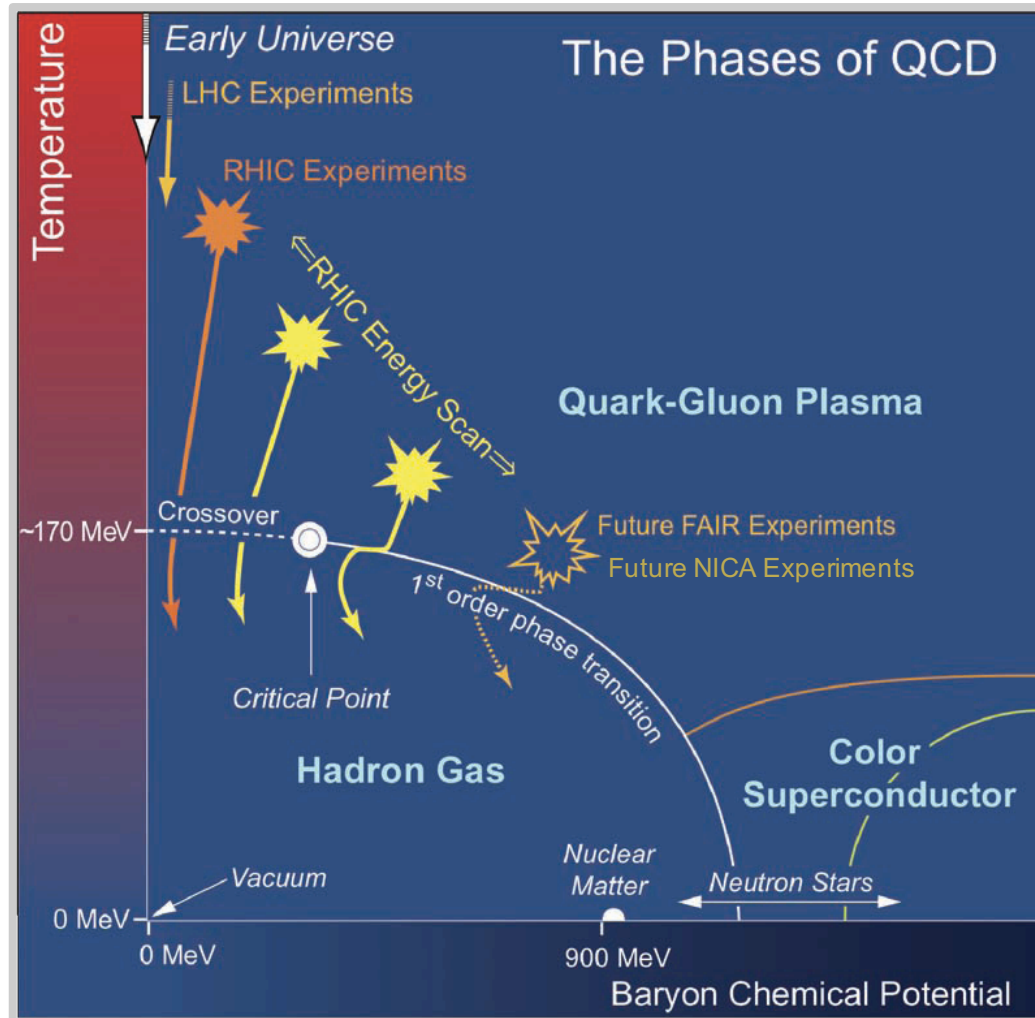
- **Anisotropic flow:**  
*Sensitive to the early stage of the collision*
- **Multi-strange hadrons and  $\phi$  meson:**  
*Less sensitive to late hadronic rescatterings*

$\phi, \Omega, \Xi, \Lambda$   $\pi, K, p$

# STAR Detectors



# Beam Energy Scan



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

**2019 – 2020: RHIC BES-II**  
7.7, 9.2, 11.5, 14.5, 19.6 GeV  
FXT: 7.7, 4.5, 3.9, 3.6, 3.0 GeV

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

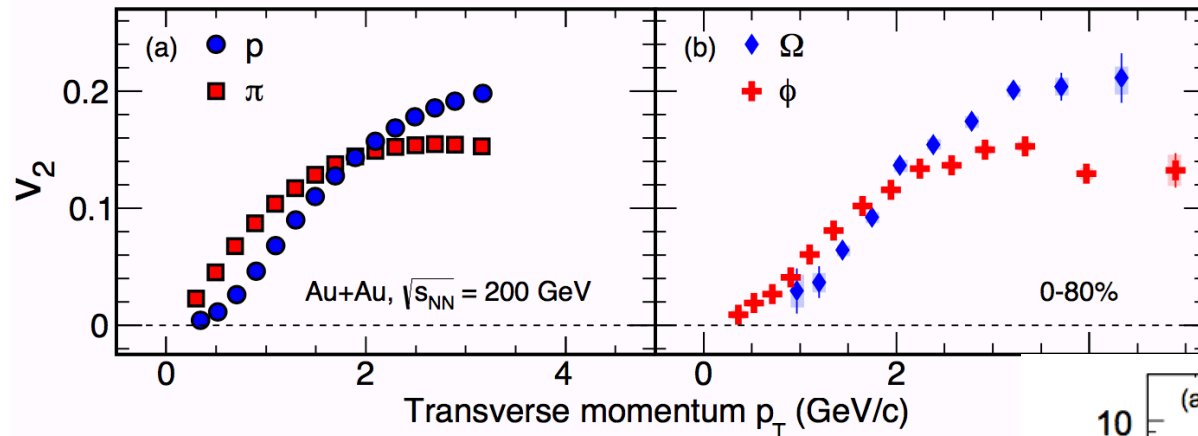
*Explore the QCD phase structure!*

# Beam Energy Scan I



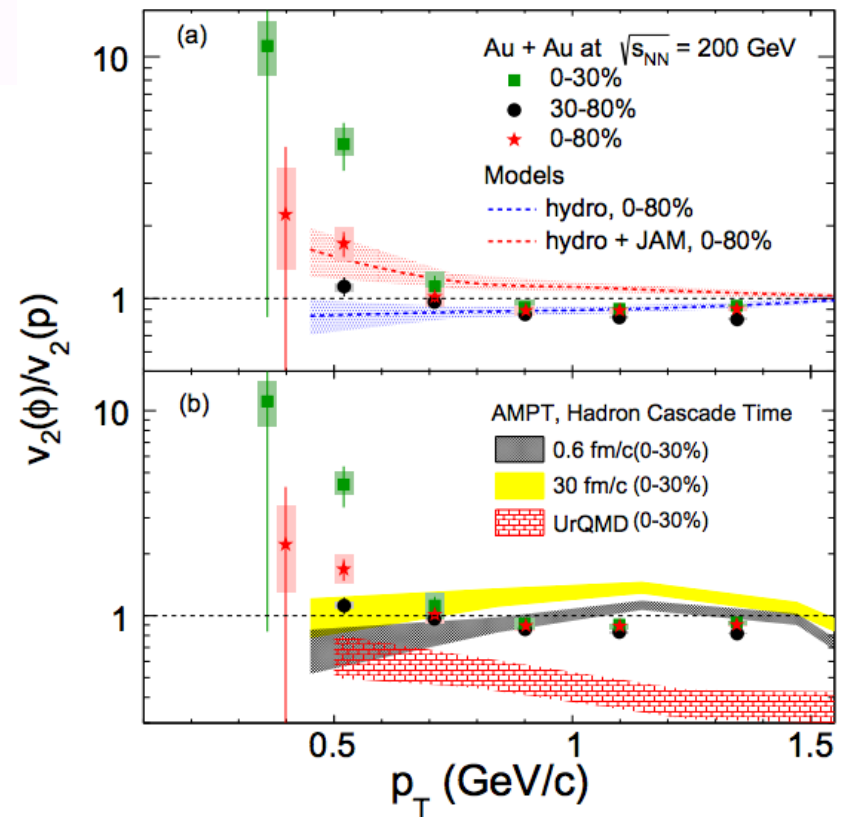
$\sqrt{s_{NN}}$ (GeV)	Events ( $10^6$ )	Year
200	350	2010
62.4	67	2010
<b>54.4</b>	<b>1000</b>	<b>2017</b>
39	39	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	4	2010

# Partonic Collectivity

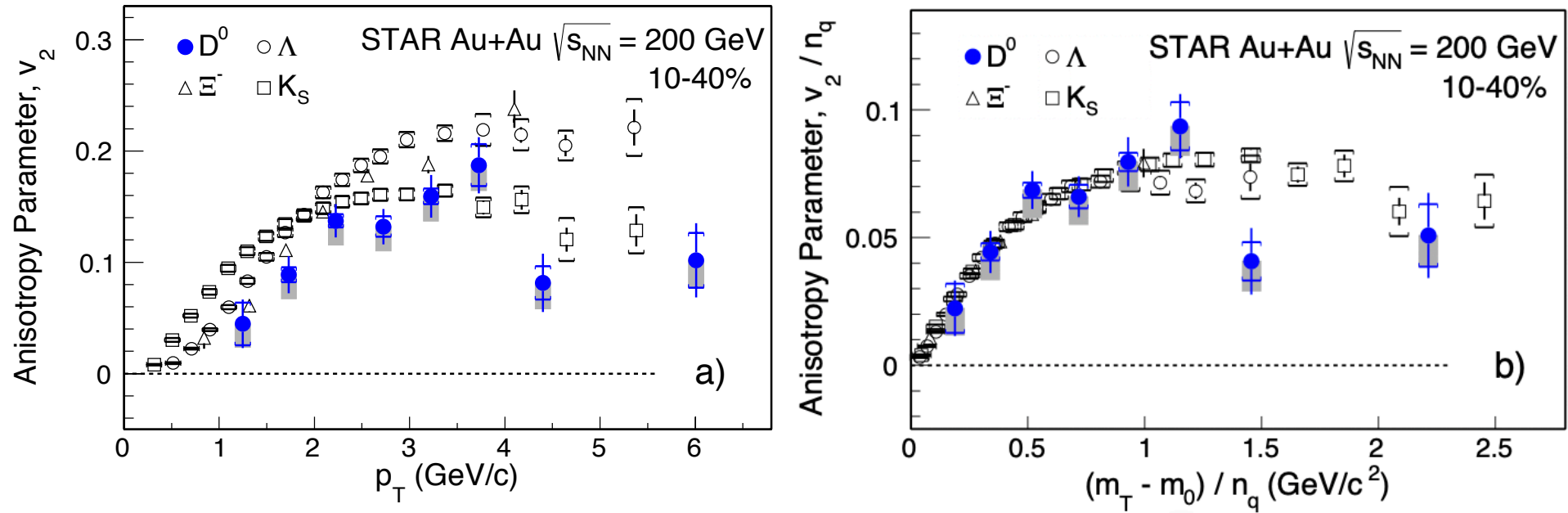


STAR: Phys. Rev. Lett.116, 062301(2016)

- The baryon-meson  $v_2$  splitting and the similar magnitude of  $v_2$  between  $\Omega$  and proton: **partonic collectivity**
- The broken mass ordering for  $\phi$  mesons and protons:  **$\phi$  mesons insensitive to hadronic interactions**



# Charm Quark Collectivity



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

## *Partonic collectivity*

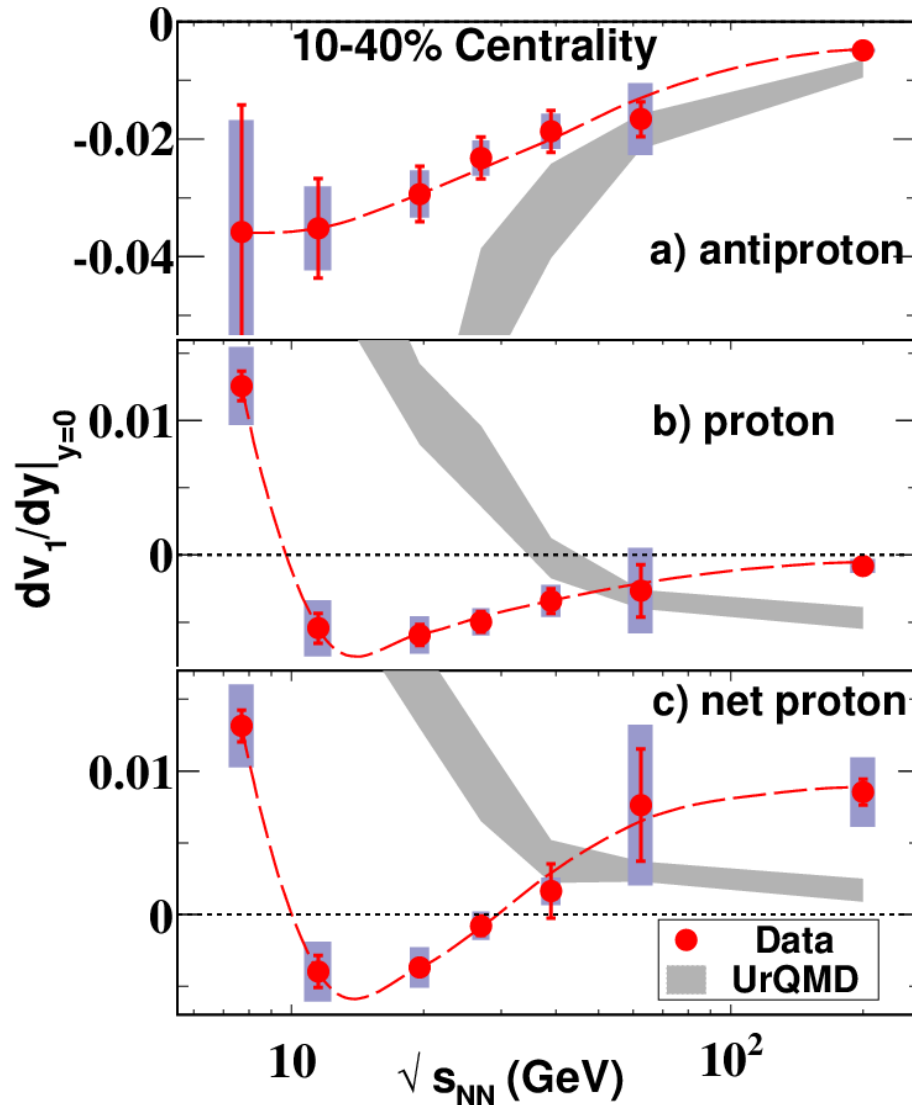
light (u, d and s) quarks to charm quarks



# 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:

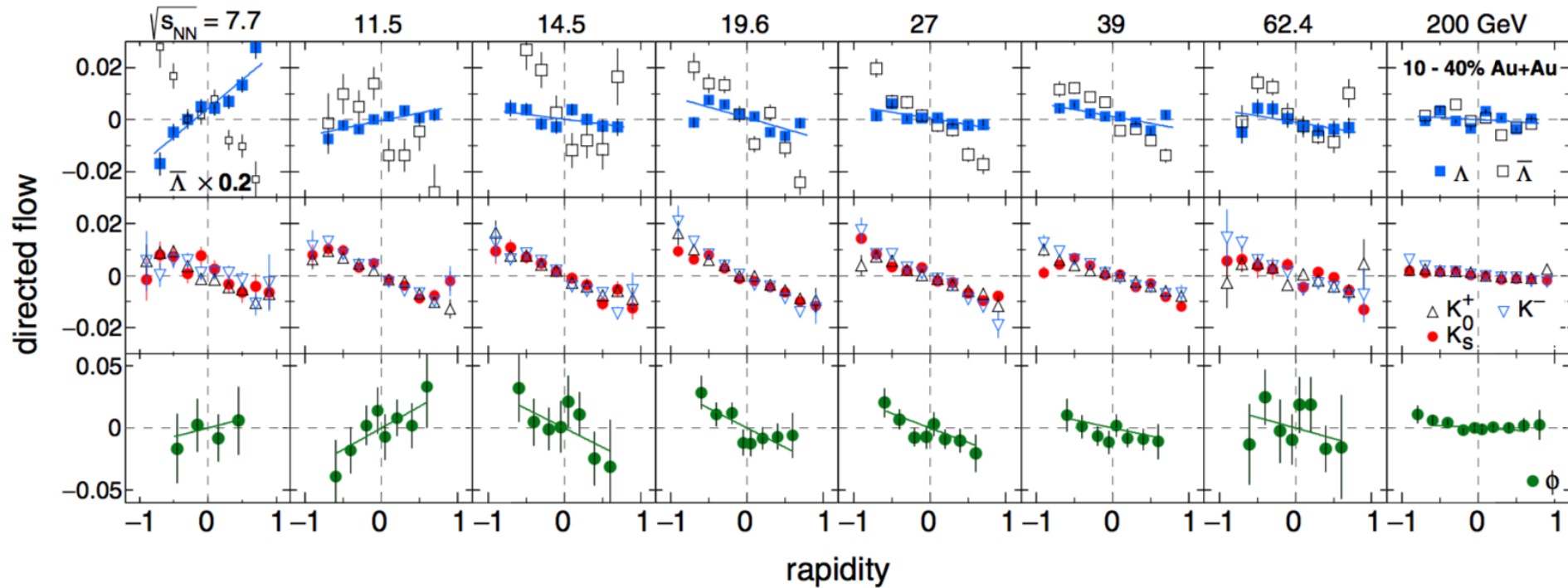
$$[v_1(y)]_p = r(y)[v_1(y)]_{\bar{p}} + [1 - r(y)][v_1(y)]_{\text{net-p}}$$

$r$ : the ratio of anti-p to p.

STAR: Phys. Rev. Lett. 112, 162301(2014)

H. Stoecker, Nucl. Phys. A 750, 121(2005)

# Directed Flow $v_1$ : $\phi$ Mesons

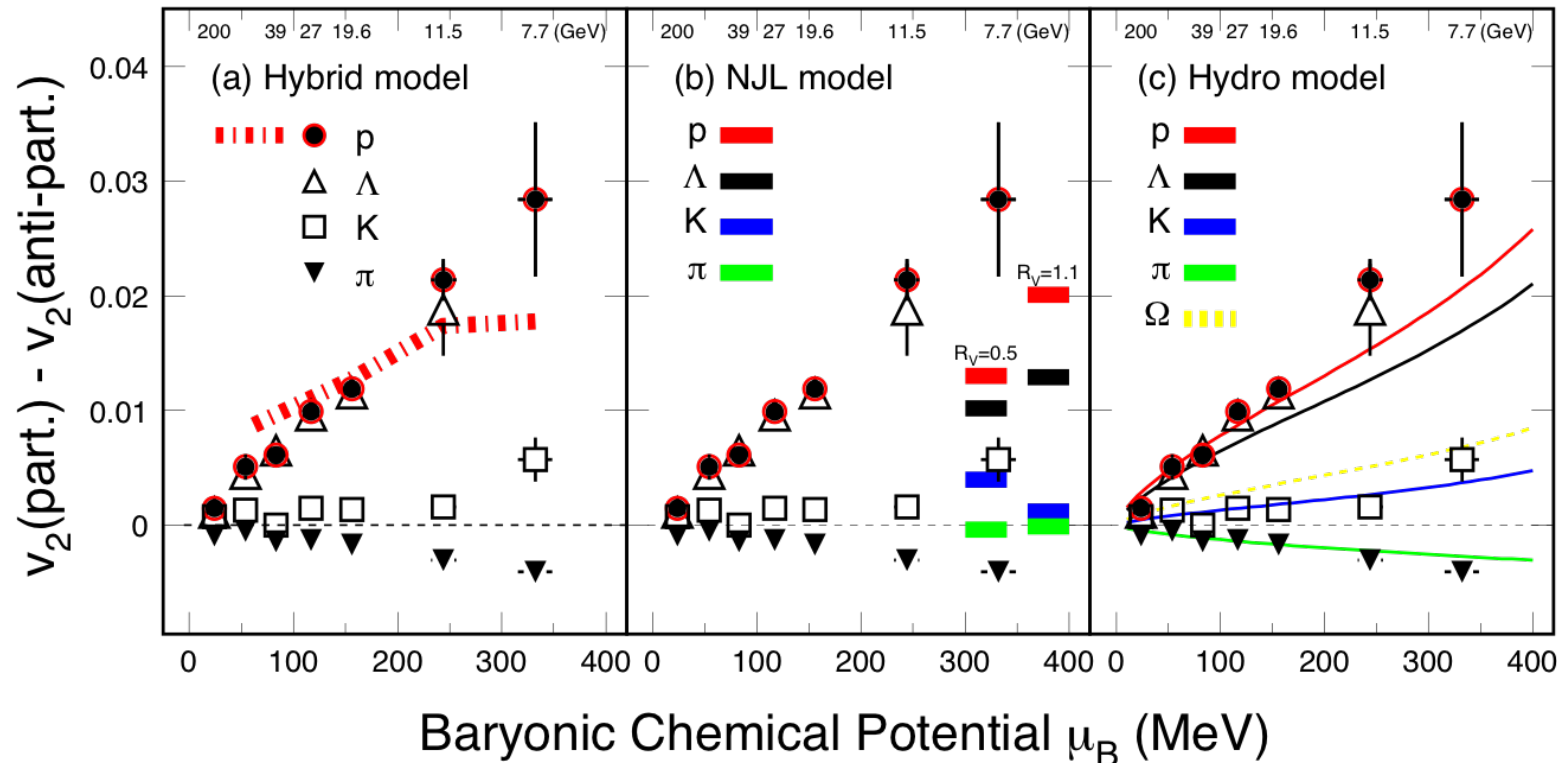


- Mesons and all produced baryons show negative slope except  $\phi$  mesons when collisions energy  $< 14.5$  GeV

**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**

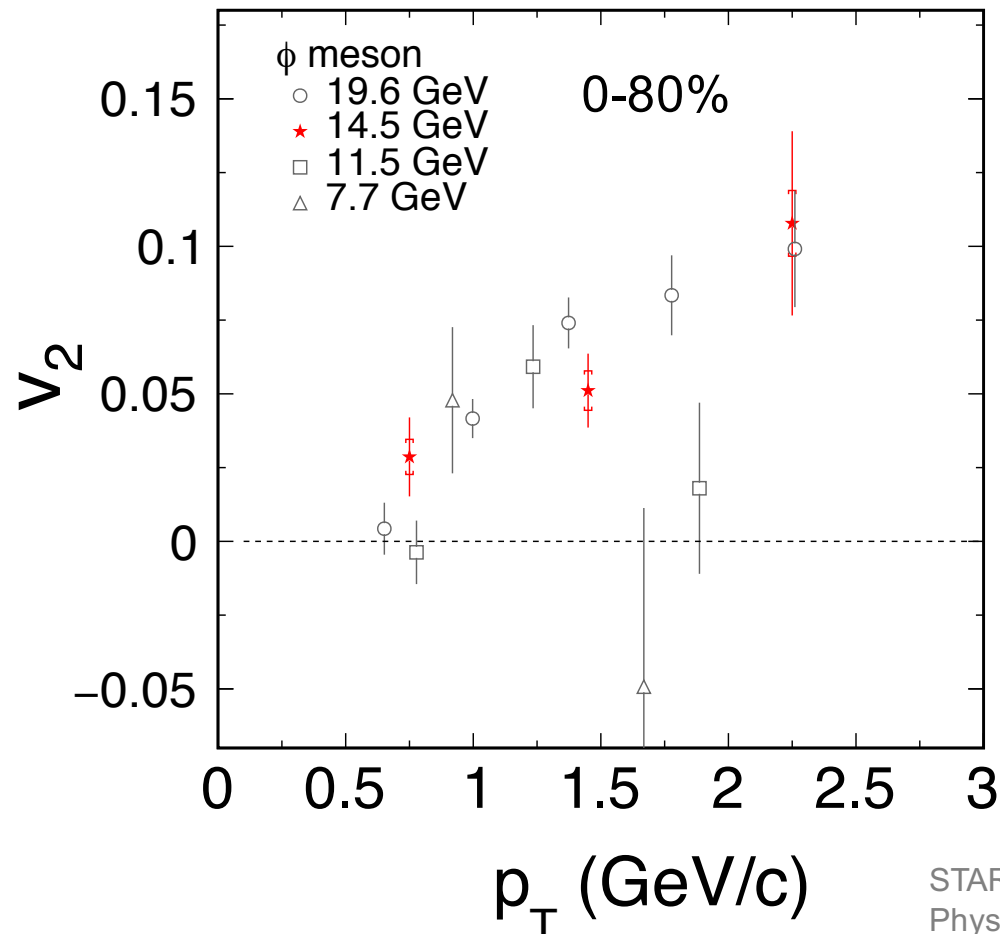
## ➤ Model comparison

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)

# $\phi$ Meson $v_2$



**$\phi$  meson is less sensitive to late hadronic interactions<sup>[1]</sup>**

**Sizable  $\phi$  meson  $v_2$ : comparable to 19.6 GeV**

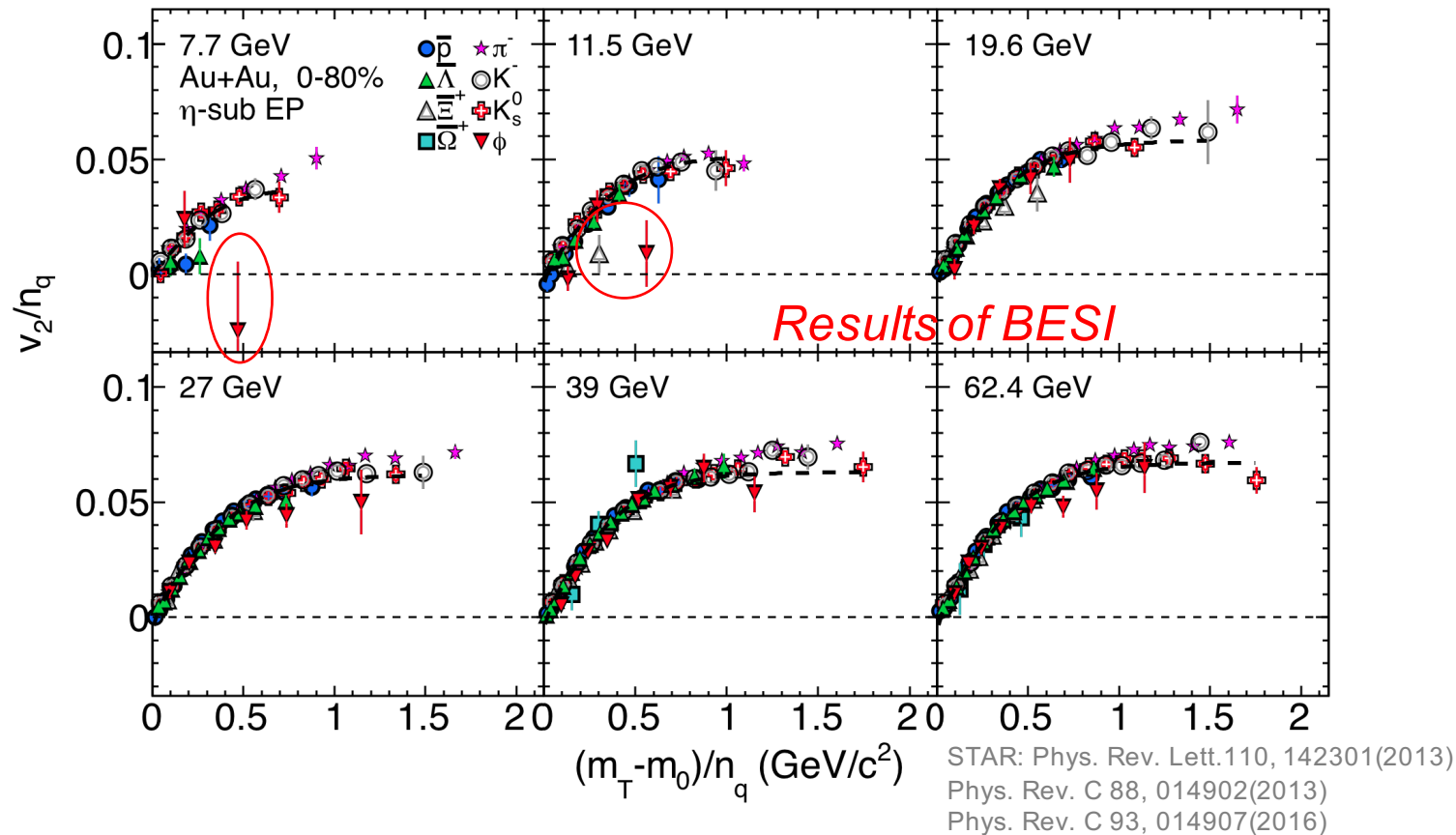
**High statistics and more energies below 20 GeV needed!**

STAR: Phys. Rev. C 88, 014902(2013)

Phys. Rev. C 93, 014907(2016)

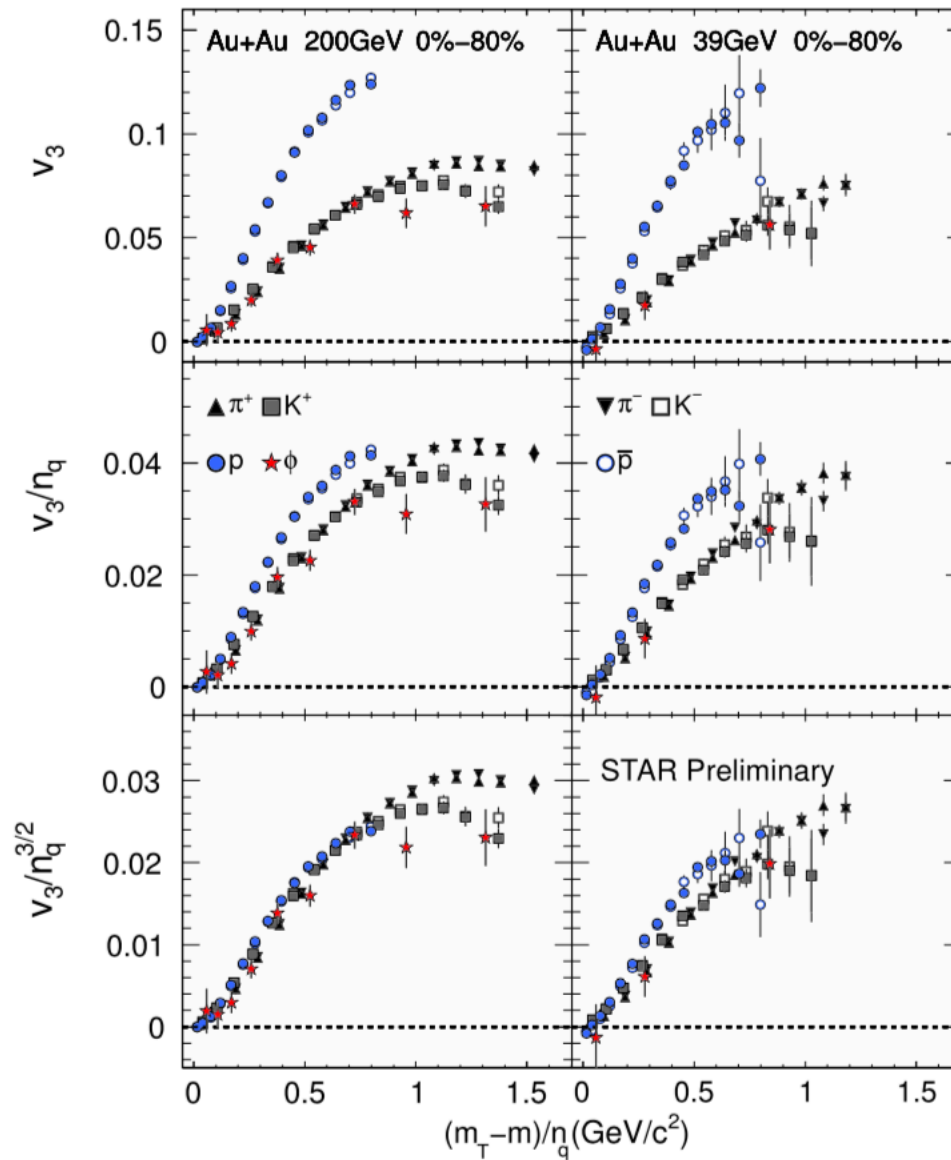
[1] STAR: Phys. Rev. Lett. 116, 062301(2016)

# Multi-strange Hadron $v_2$ in BESII



- **BES I:  $v_2$  of multi-strange hadrons and  $\phi$  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  $\phi$  meson**

# Triangular Flow



**Better NCQ scaling  
achieved at 39 GeV  
(up to 0.8  $\text{GeV}/c^2$ ) and  
200 GeV (up to 0.8  
 $\text{GeV}/c^2$ ) by using  
scaling factor  $n_q^{3/2}$**

STAR: QM2014  
R. Lacey, J. Phys. G 38 (2011) 124048

# 2019-2020: BES II at RHIC



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

Precision measurements, map the QCD phase diagram

$$200 < \mu_B < 420 \text{ MeV}$$

# 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  $\sim 1.7$  in  $\eta$ ; improves  $dE/dx$  resolution*
- **ETOF upgrade**  
*New charged hadron PID capabilities for  $1.1 < |\eta| < 1.6$*

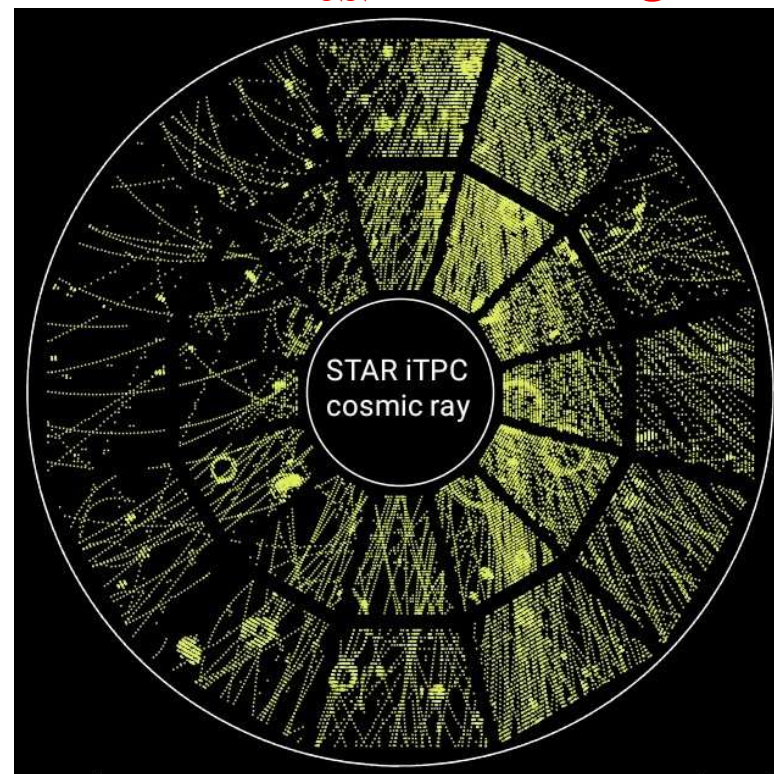
## Fixed target program

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

## RHIC BES-II: 2019-2010

**19.6, 14.5, 11.5, 9.2 and 7.7 GeV**

**Focus on  $\sqrt{s_{NN}} \leq 20$  GeV region**





# Summary

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## ➤ Top Energy

*Partonic collectivity*

## ➤ Beam Energy Scan II

### ➤ $v_1$ slope of net-proton:

*Centrality dependence*

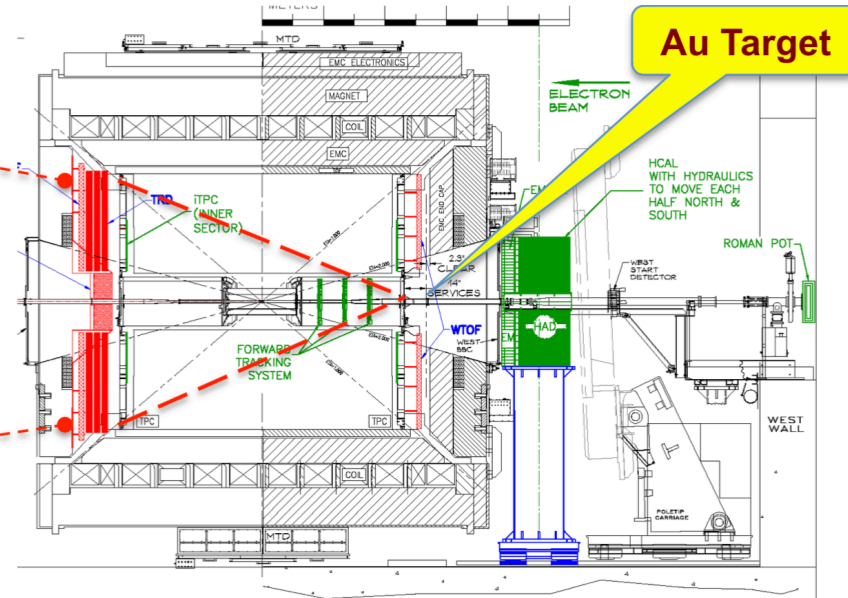
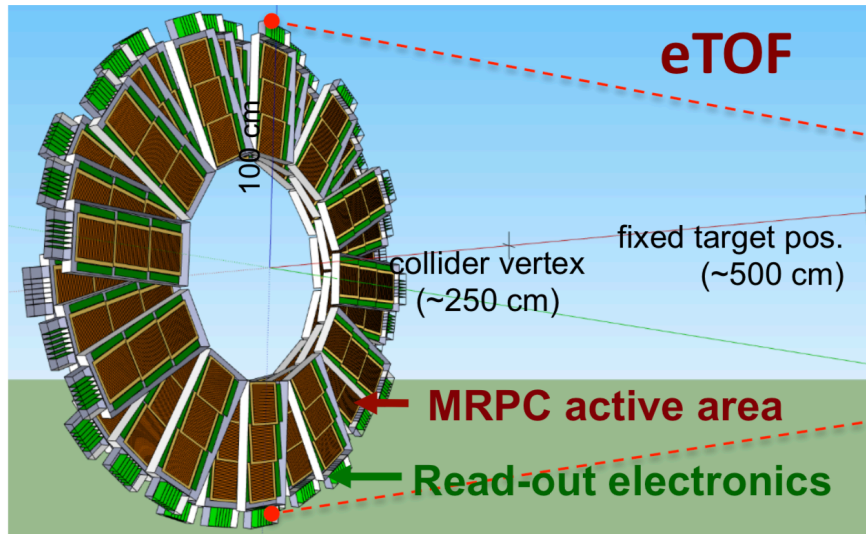
### ➤ $\phi$ meson $v_1$

*Slope change: sensitive to properties of the medium?*

### ➤ $\phi$ meson and multi-strange $v_2$

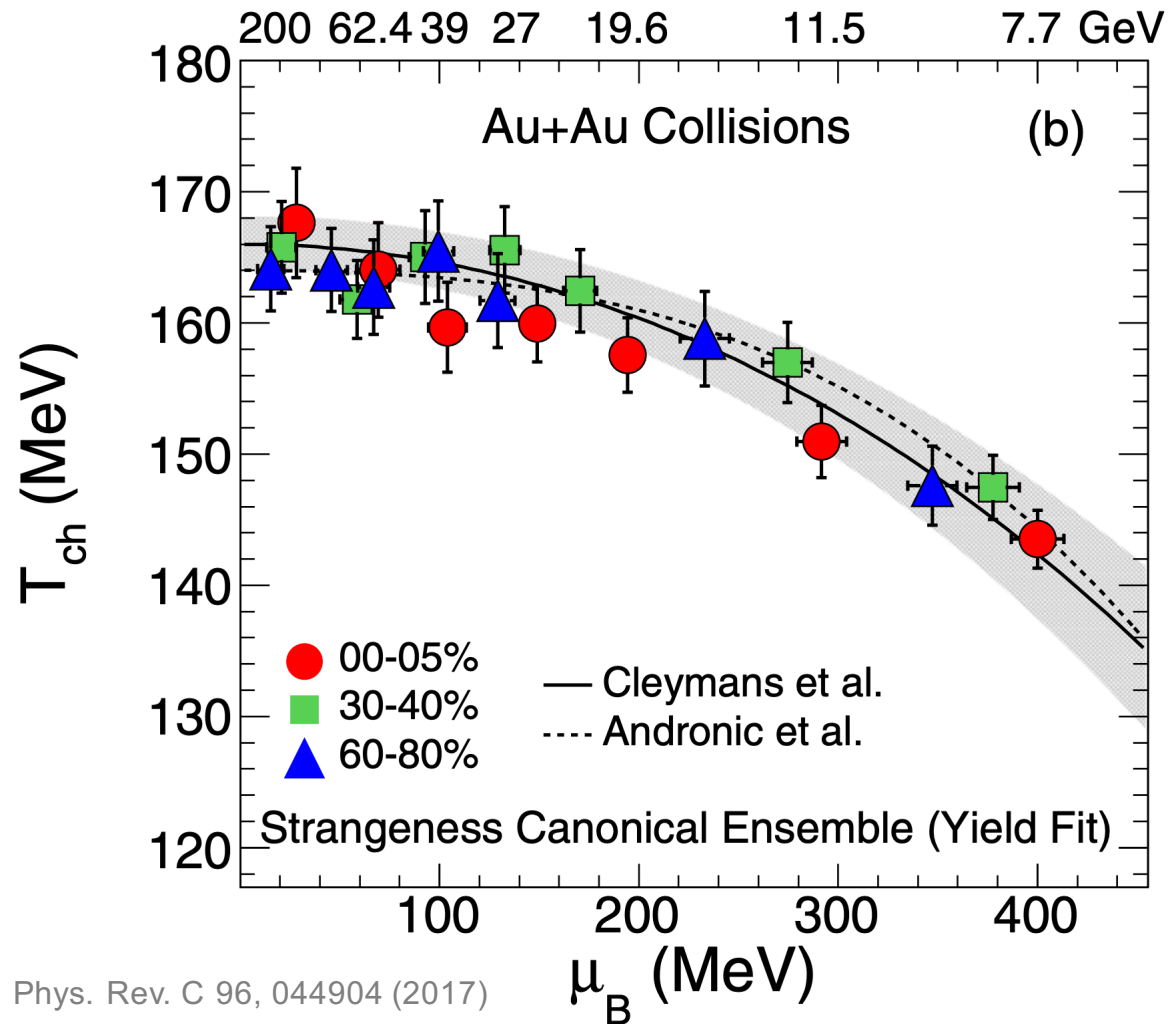
*Partonic vs. hadronic*

# CBM Phase-0 Exp: eTOF at STAR



RHIC Beam Energy Scan II Fixed-target programs:  
Complementary to part of CBM's physics program  
 $\sqrt{s_{NN}} = 3, 3.6, 3.9, 4.5, 7.7 \text{ GeV}$  ( $750 \geq \mu_B \geq 420 \text{ MeV}$ )  
 *$v_n$  and strangeness production*

# Strangeness Production



STAR: Phys. Rev. C 96, 044904 (2017)

Chemical freeze-out parameters:  $T_{ch}$ ,  $\mu_B$ ,  $\gamma_s$