# Collectivity and CBM

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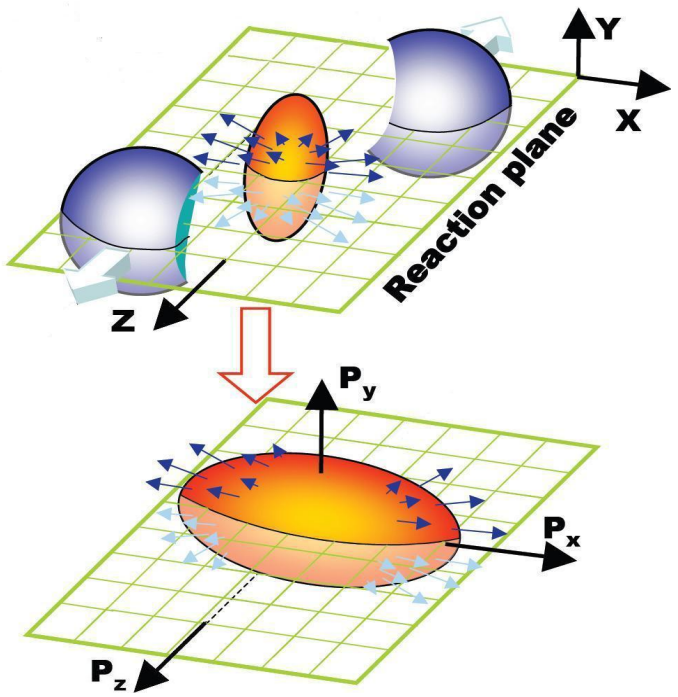
# Outline

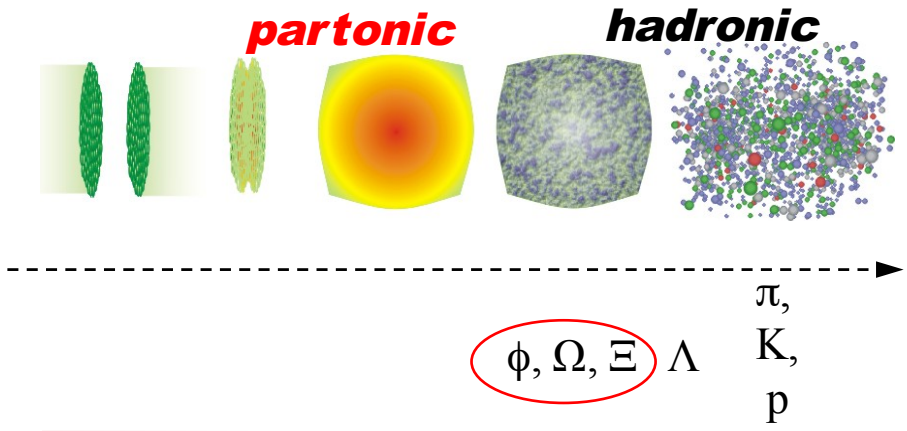
- **Introduction**
- **Beam Energy Scan**
- **Results and Discussions**
- **Summary and Outlook**

# Anisotropic Flow



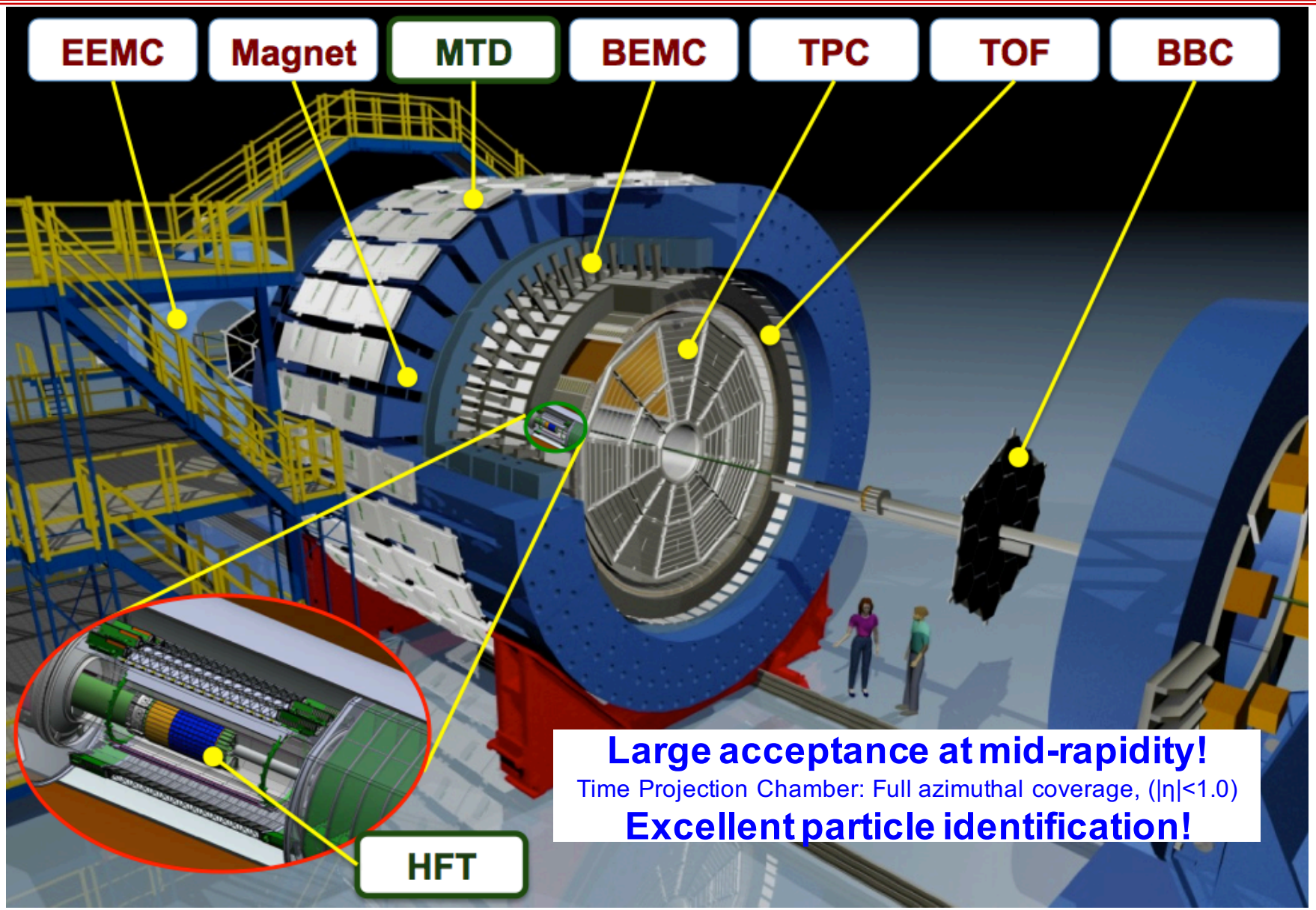

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} v_n \cos\left[n(\phi - \Psi_n)\right]$$

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

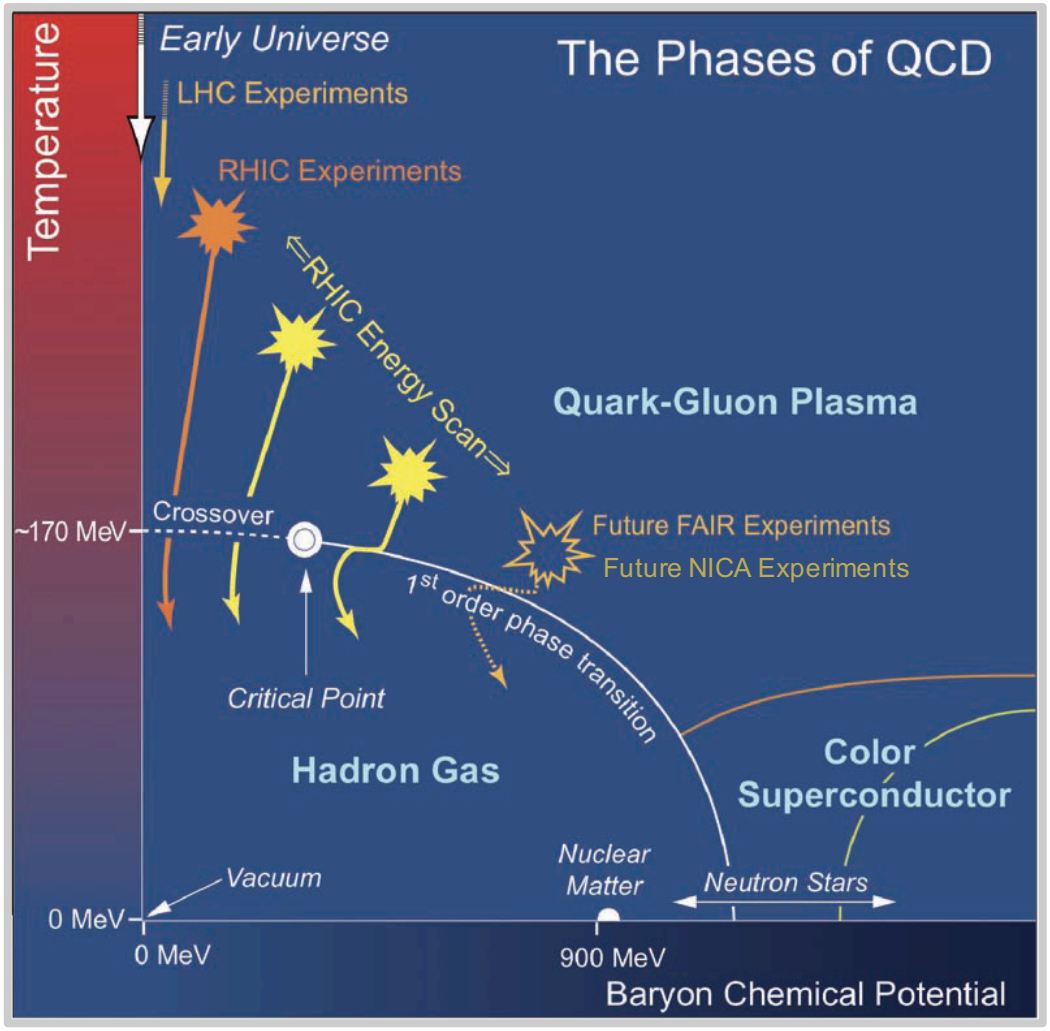



- **Anisotropic flow**:
  *Sensitive to the early stage of the collision*
- **Multi-strange hadrons and ϕ meson**:
  *Less sensitive to late hadronic rescatterings*

# 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

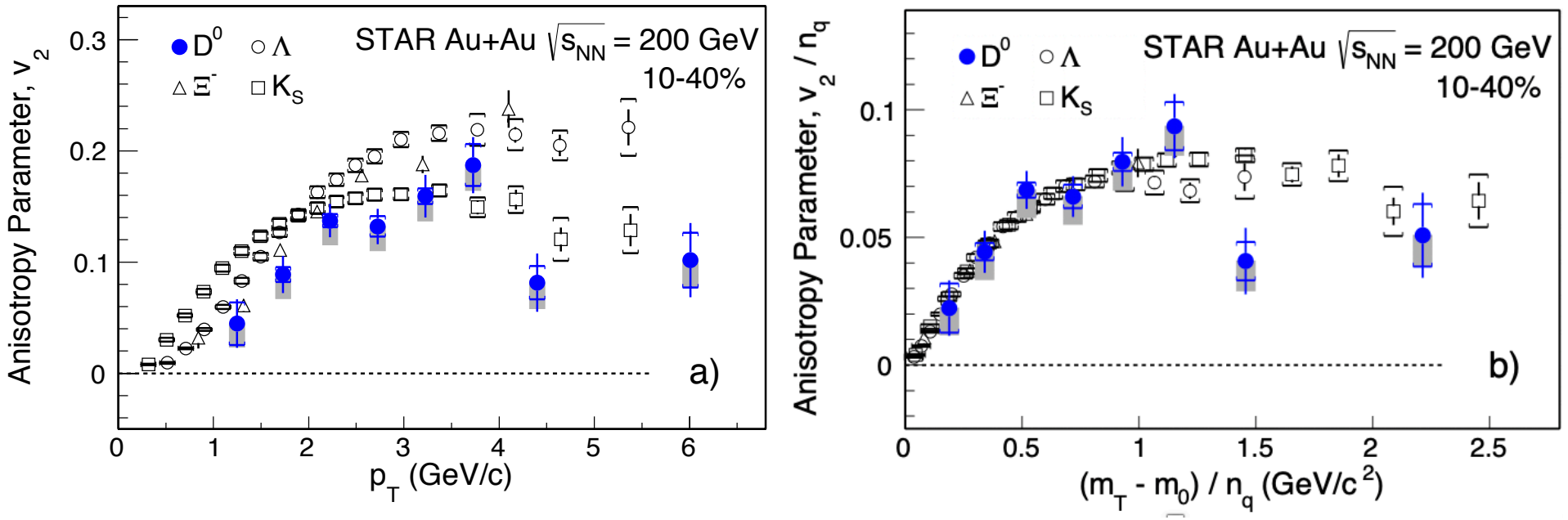
**2022 – :** RHIC+FAIR NICA
BES-III
Fixed-target programs

*Explore the QCD phase structure!*

# Beam Energy Scan I

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

# Partonic Collectivity



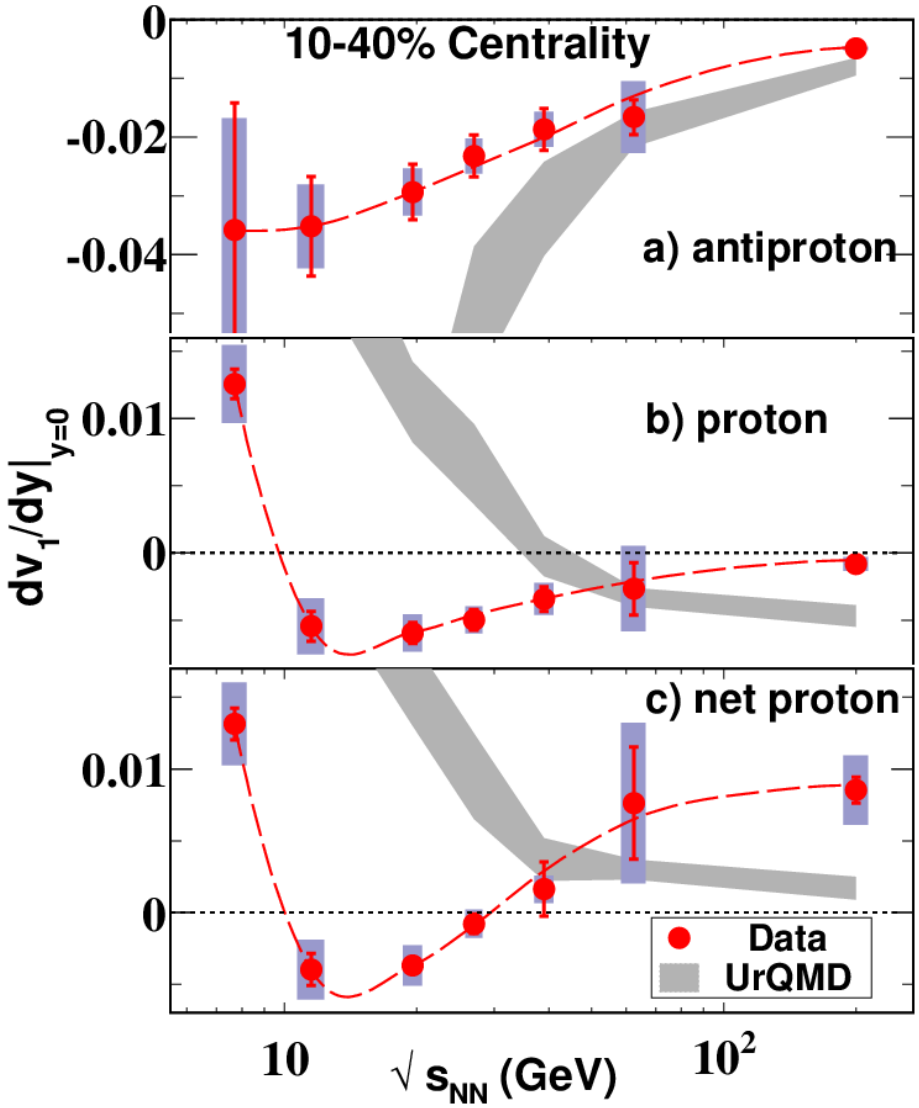

STAR: Phys. Rev. Lett.118, 212301 (2017)

***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

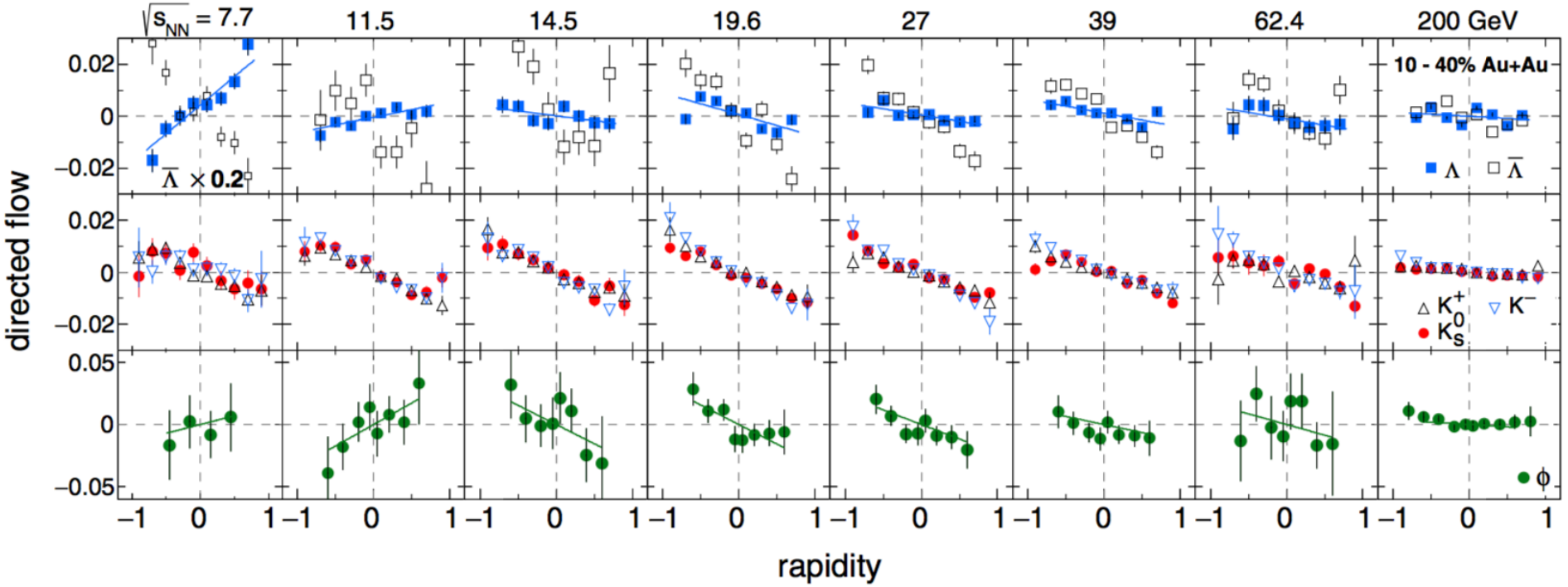
The slope of net-p is based on expressing the y dependence of v1 for all protons as:

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

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 $v_1$: $\phi$ Mesons

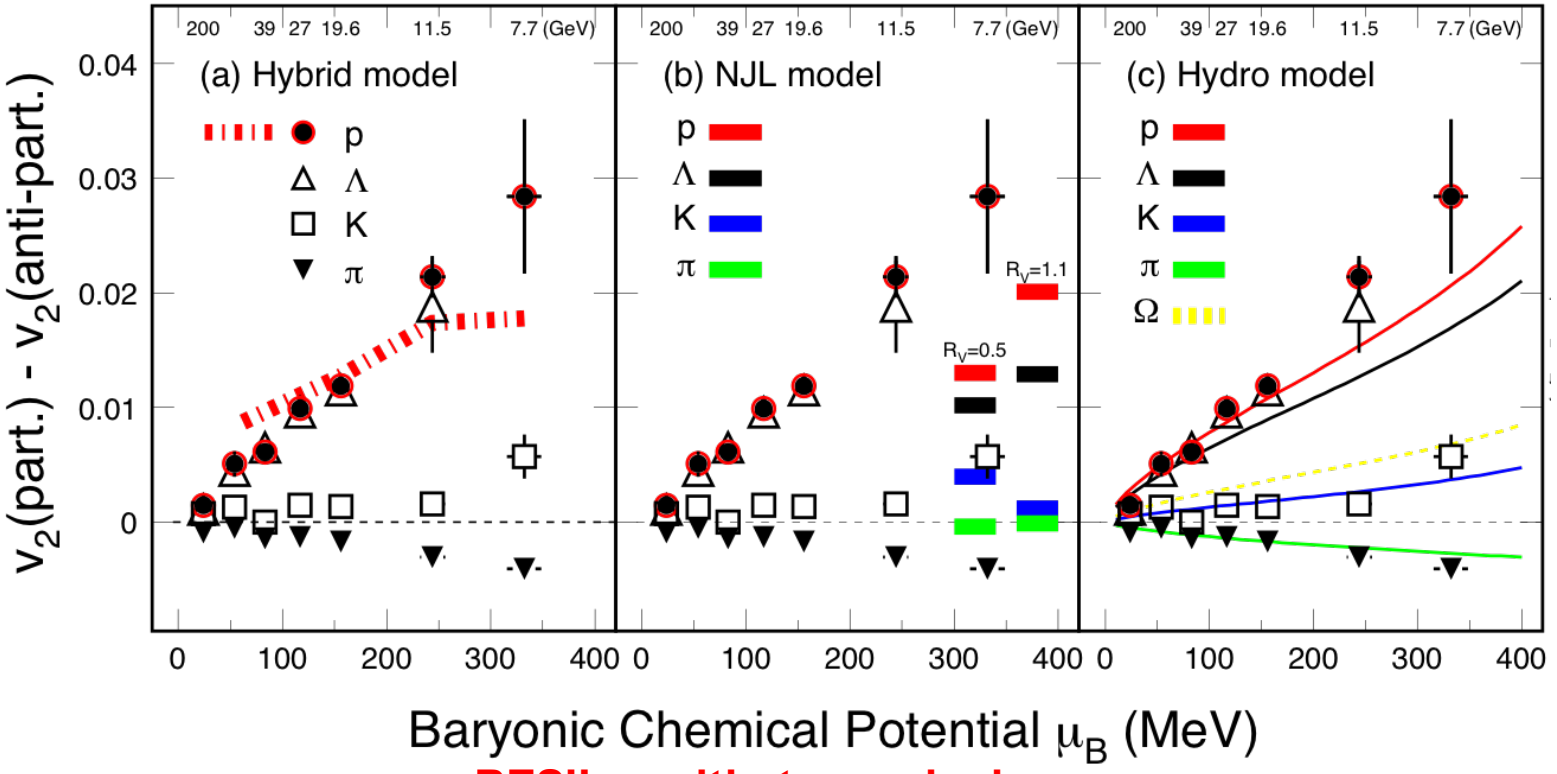



- Mesons and all produced baryons show negative slope except $\phi$ mesons when collisions energy < 14.5 GeV

***Change of medium property? High precision data needed: BESII***

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

# Particle vs. Anti-particle $v_2$

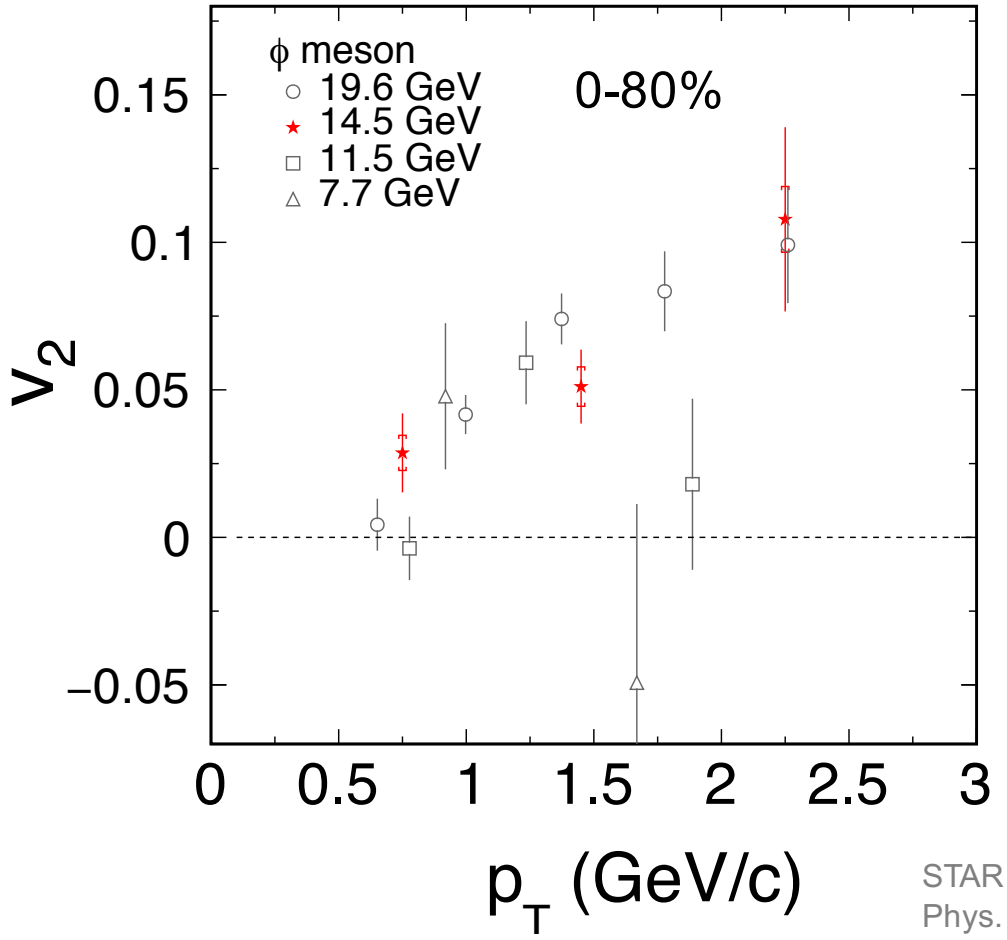



**BESII : multi-strange hadrons**

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

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

# $\phi$ Meson $v_2$



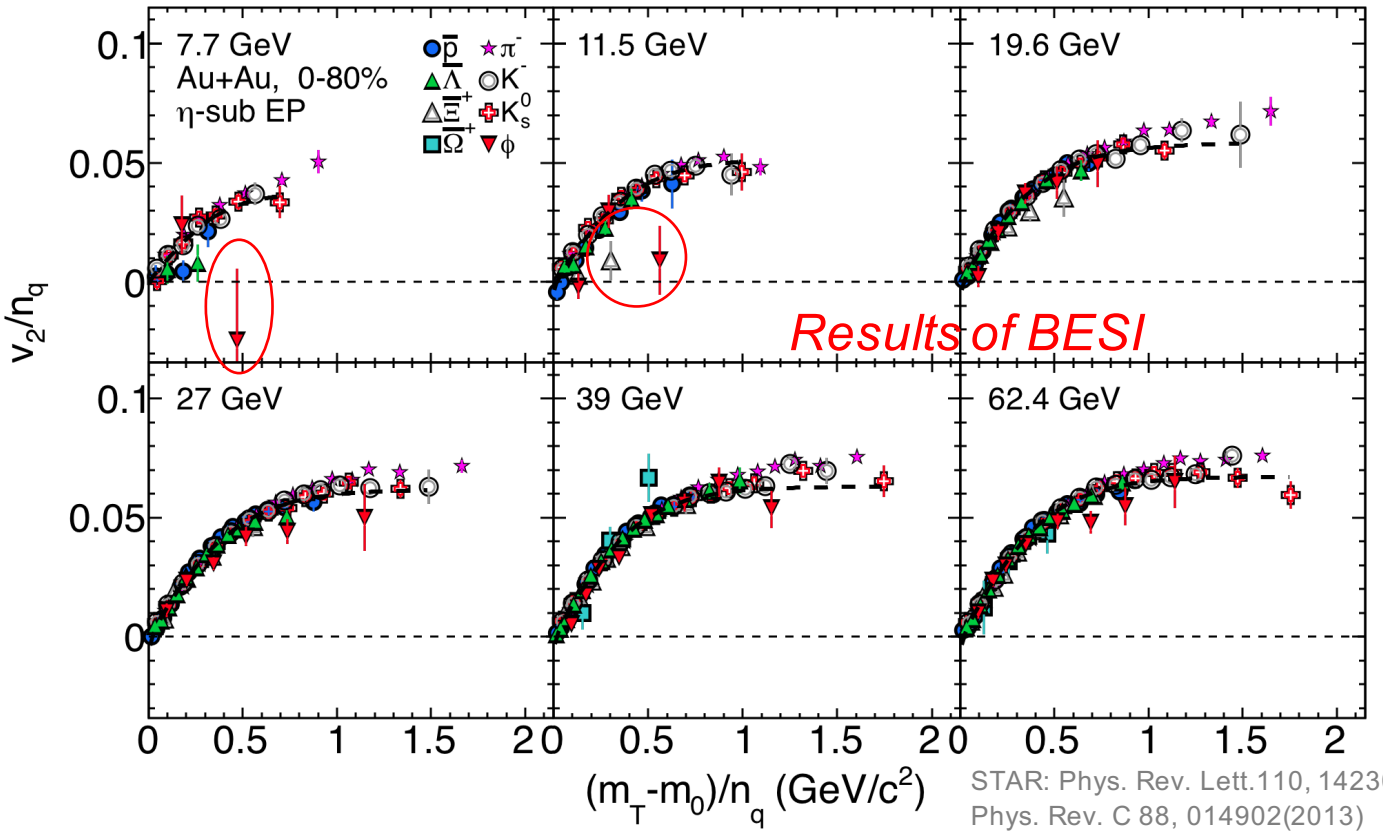

**$\phi$ meson is less sensitive to late hadronic interactions**[1]

**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

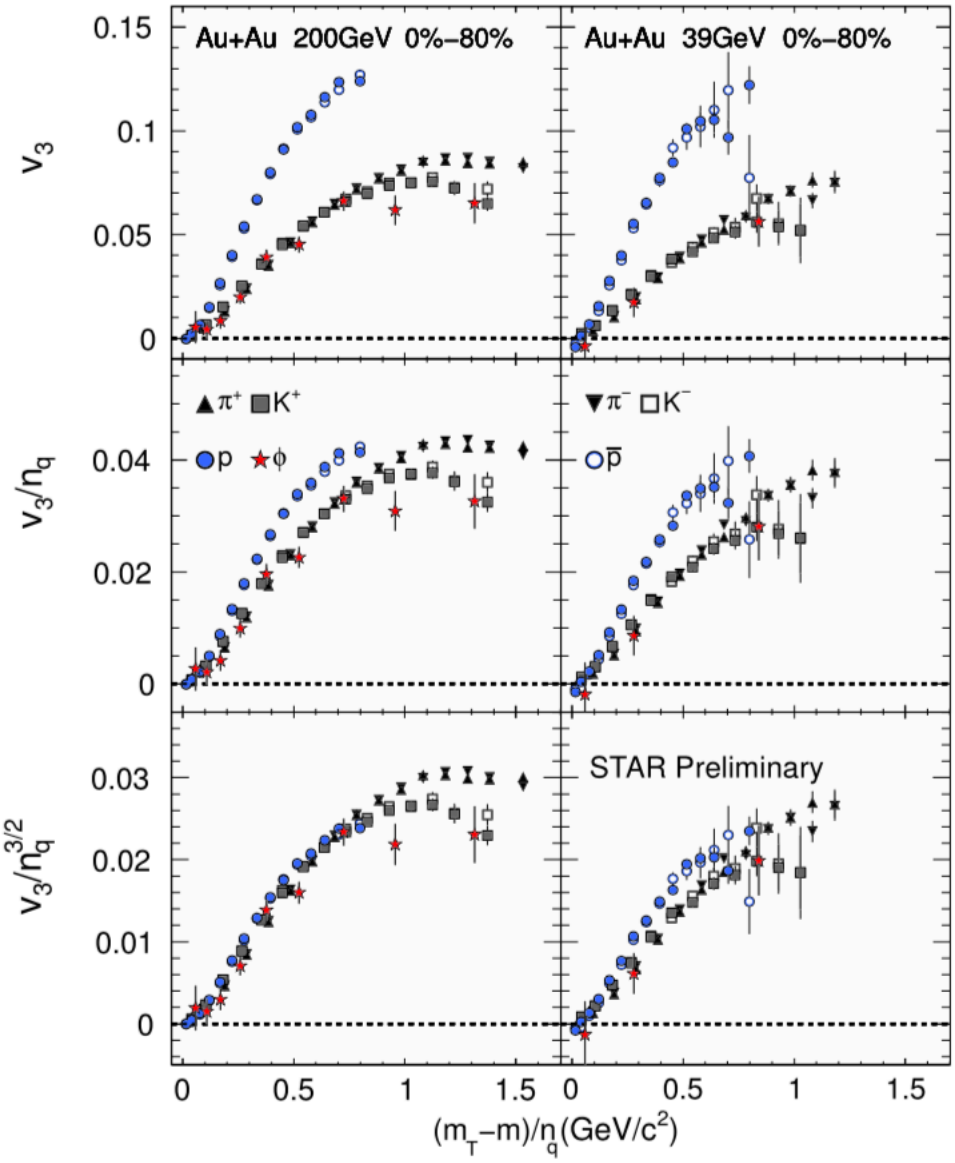



STAR: Phys. Rev. Lett.110, 142301(2013)
Phys. Rev. C 88, 014902(2013)
Phys. Rev. C 93, 014907(2016)

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

# Triangular Flow




**Better NCQ scaling achieved at 39 GeV (up to 0.8 GeV/$c^2$) and 200 GeV (up to 0.8 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 | **400** / 36 | **2019**/2011 | **3** | 206 | 160 |
| 14.5 | **300** / 20 | **2019**/2014 | **2.5** | 264 | 156 |
| 11.5 | **230** / 12 | **2019**/2010 | **5** | 315 | 152 |
| 9.2 | **160** / 0.3 | **2020** / 2008 | **9.5** | 355 | 140 |
| 7.7 | **100** / 4 | **2020** / 2010 | **14** | 420 | 140 |

Precision measurements, map the QCD phase diagram

***200 < $\mu_B$ < 420MeV***

# Summary

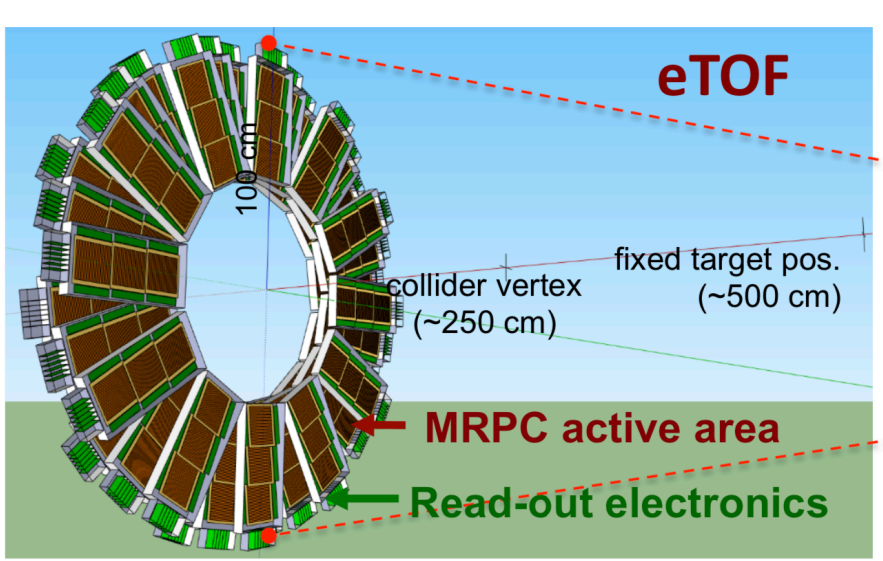
- **Beam Energy Scan II**
  - **$v_1$ slope of net-proton:**

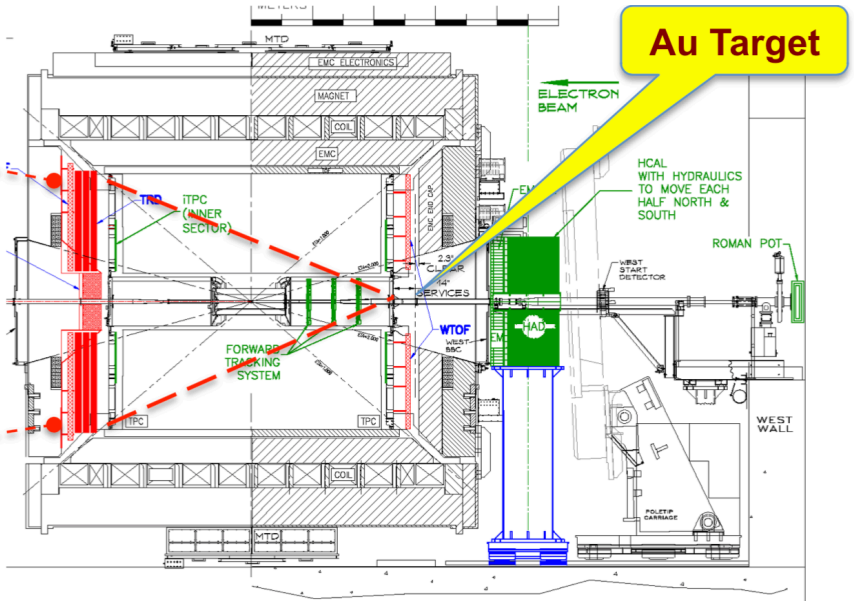
    *Centrality dependence*
  - **$\phi$ meson $v_1$**

    *Slope change: sensitive to properties of the medium?*
  - **$\phi$ meson and multi-strange $v_2$**

    *Partonic vs. hadronic*

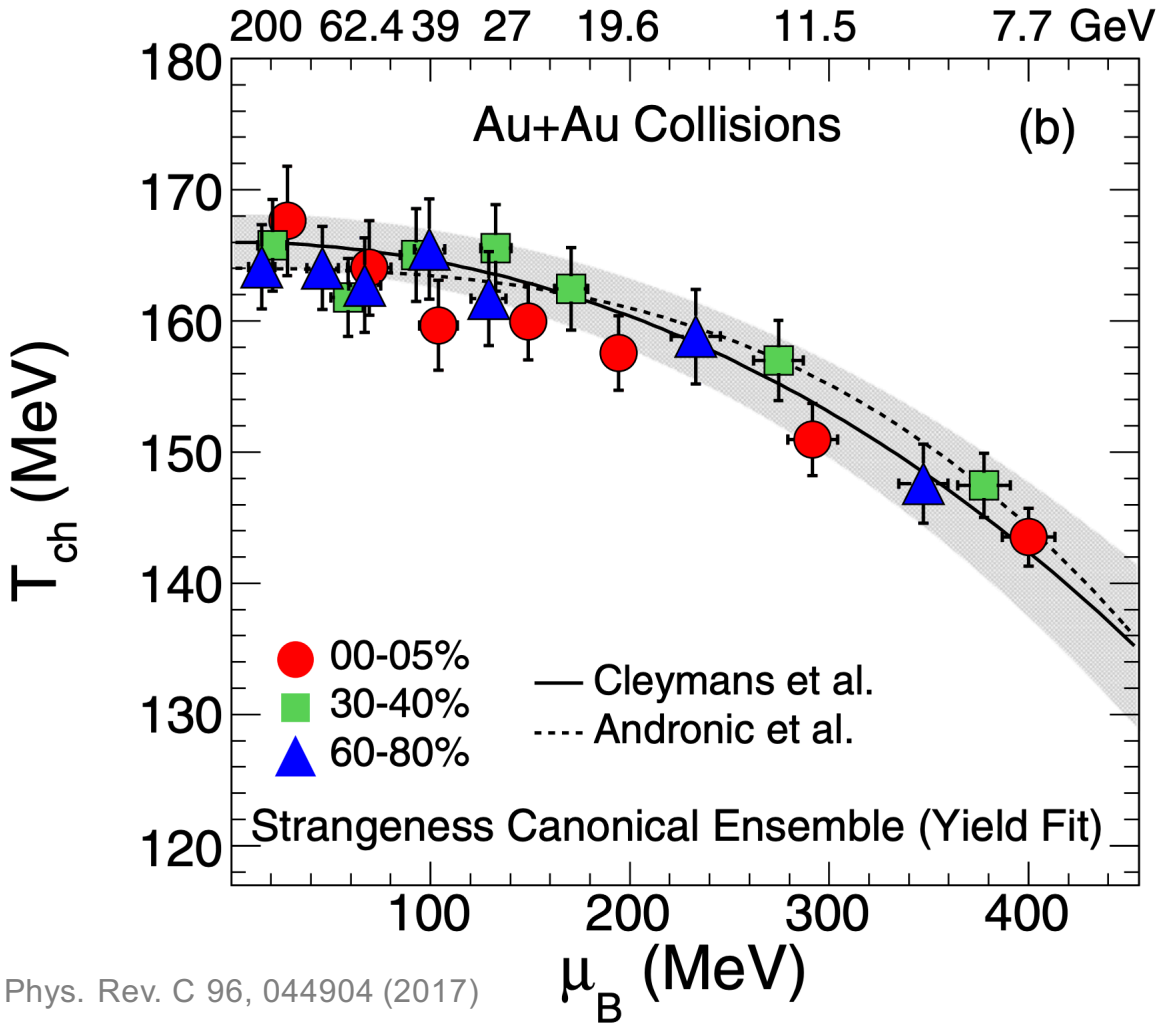
# CBM Phase-0 Exp: eTOF at STAR




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 GeV (750 ≥ $\mu_B$ ≥ 420 MeV)
*$v_n$ and strangeness production*

# Strangeness Production




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

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