Flow Measurements with Beam Energy Scan

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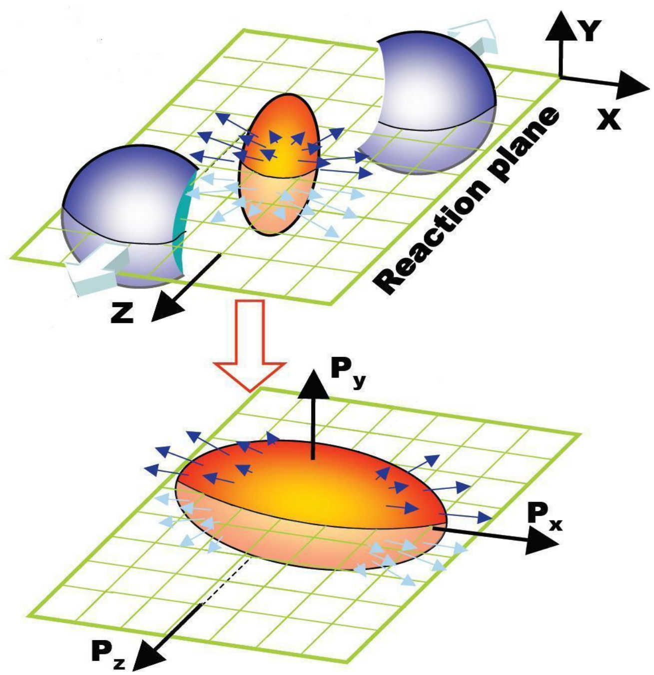
Outline

- Introduction
- STAR Detector
- Energy Dependence
- Particle vs. Anti-particle v_2
- ϕ meson v_2
- Baryon/Meson Separation
- Summary and Outlook

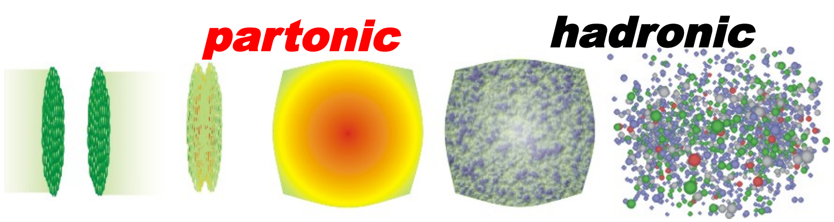
Elliptic Flow (v_2)



$$\varepsilon = \frac{< y^2 - x^2 >}{< y^2 + x^2 >}$$

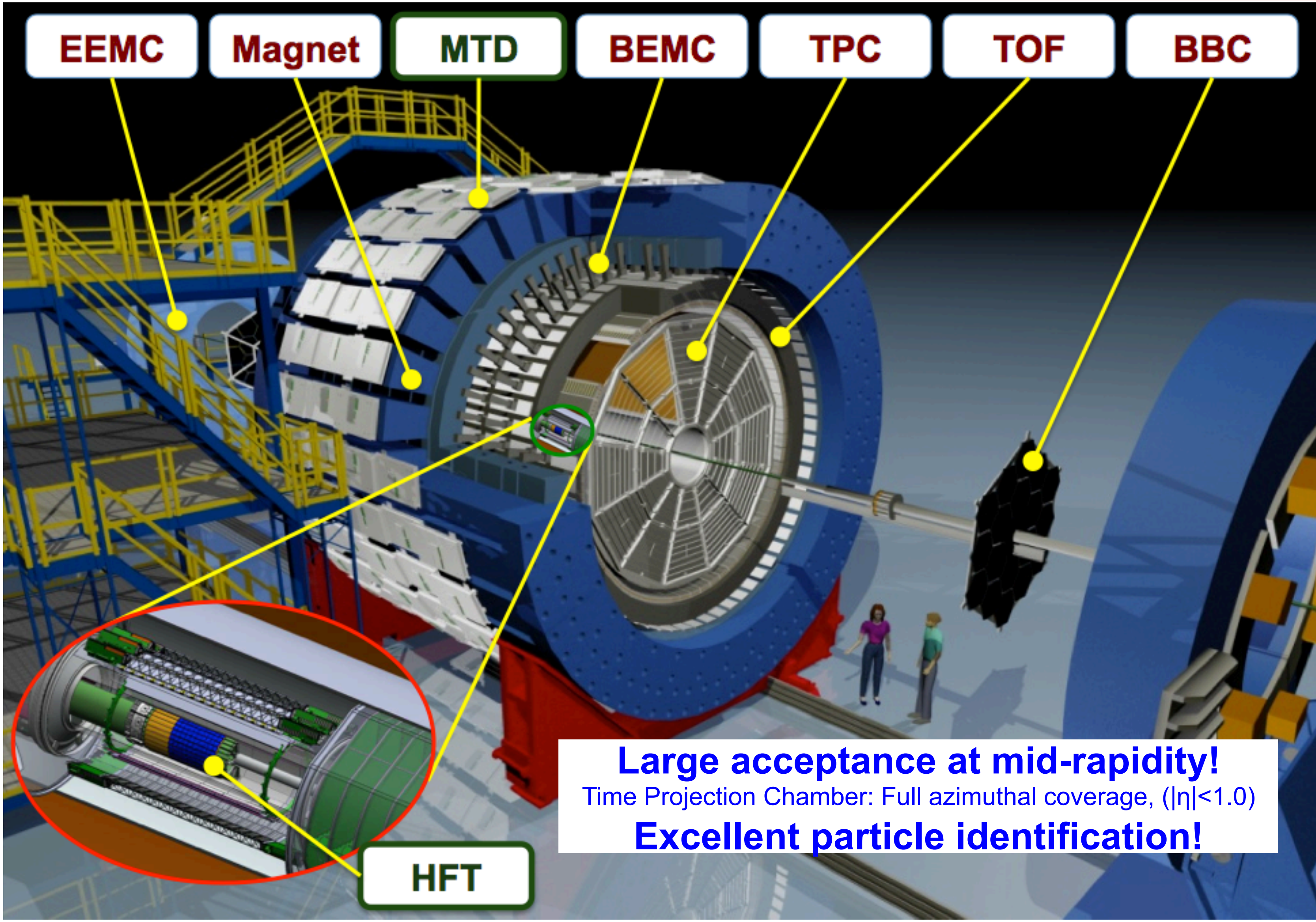
$$v_2 =< \cos 2\varphi >, \quad \varphi = \tan^{-1}(\frac{p_y}{p_x})$$

- **Elliptic flow =>**
- Initial spatial anisotropy ε->
  Final momentum anisotropy v_2
  ➔ Interactions among constituents
- Self-quenching with time
  - Sensitive to the early stage of the system evolution
- **Multi-strange hadrons and ϕ meson**
  Less sensitive to late hadronic interactions

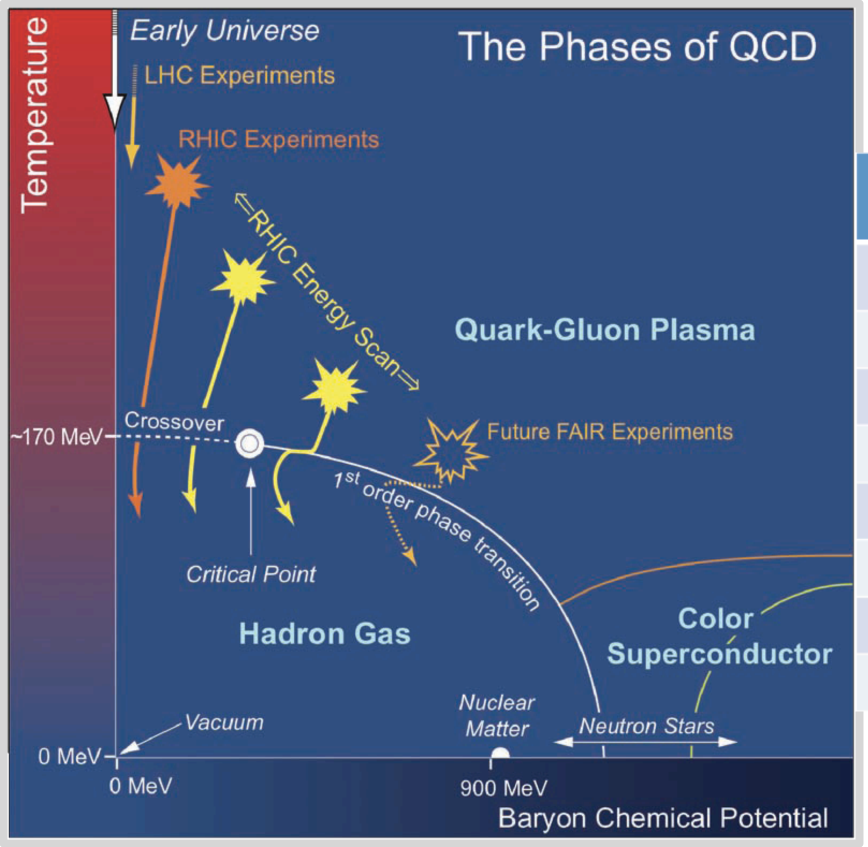


D_s, Λ_c, D   ϕ, Ω, Ξ   Λ   π, K, p

STAR Detectors



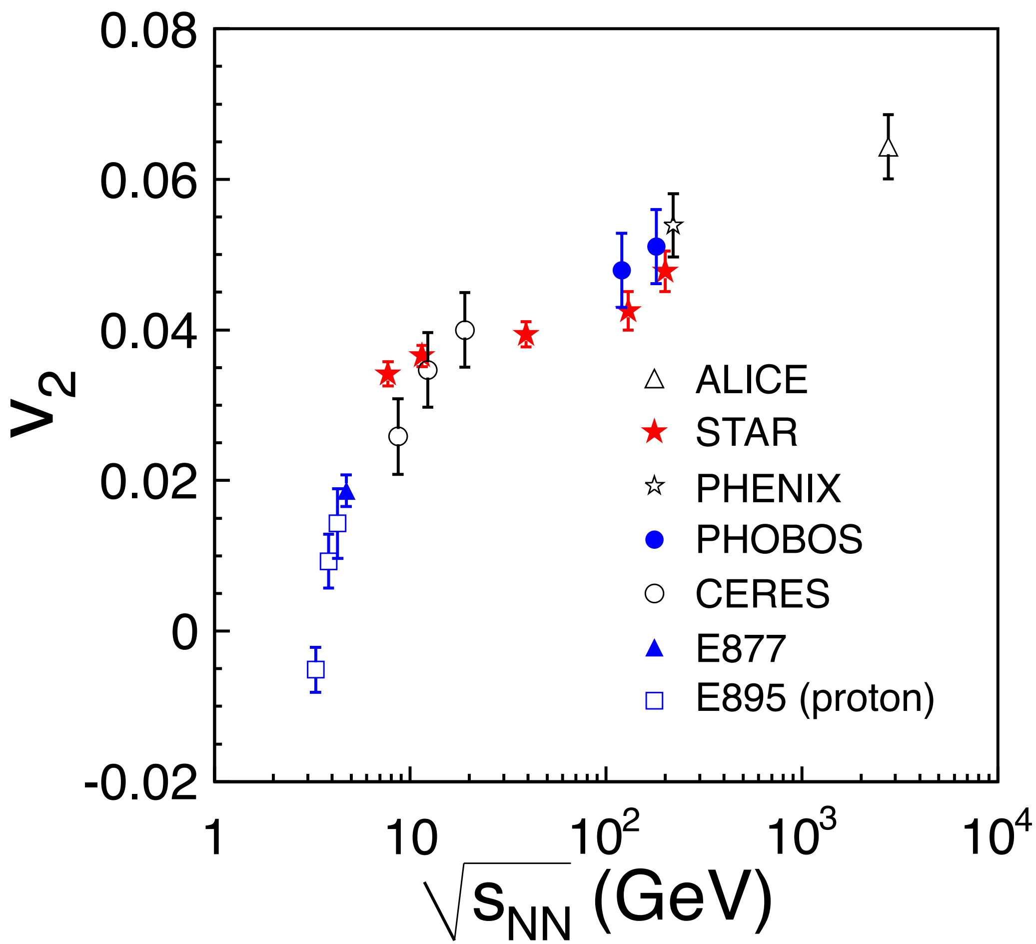
Beam Energy Scan



$\sqrt{s}$ (GeV)	Statistics (Millions)	Year	μ_B (MeV)	T (MeV)	μ_B /T
7.7	~4	2010	420	140	3.020
11.5	~12	2010	315	152	2.084
14.5	~ 20	2014	266	156	1.705
19.6	~36	2011	205	160	1.287
27	~70	2011	155	163	0.961
39	~130	2010	115	164	0.684
62.4	~67	2010	70	165	0.439
200	~350	2010	20	166	0.142

Search for the QCD critical point and phase boundary!

Energy Dependence

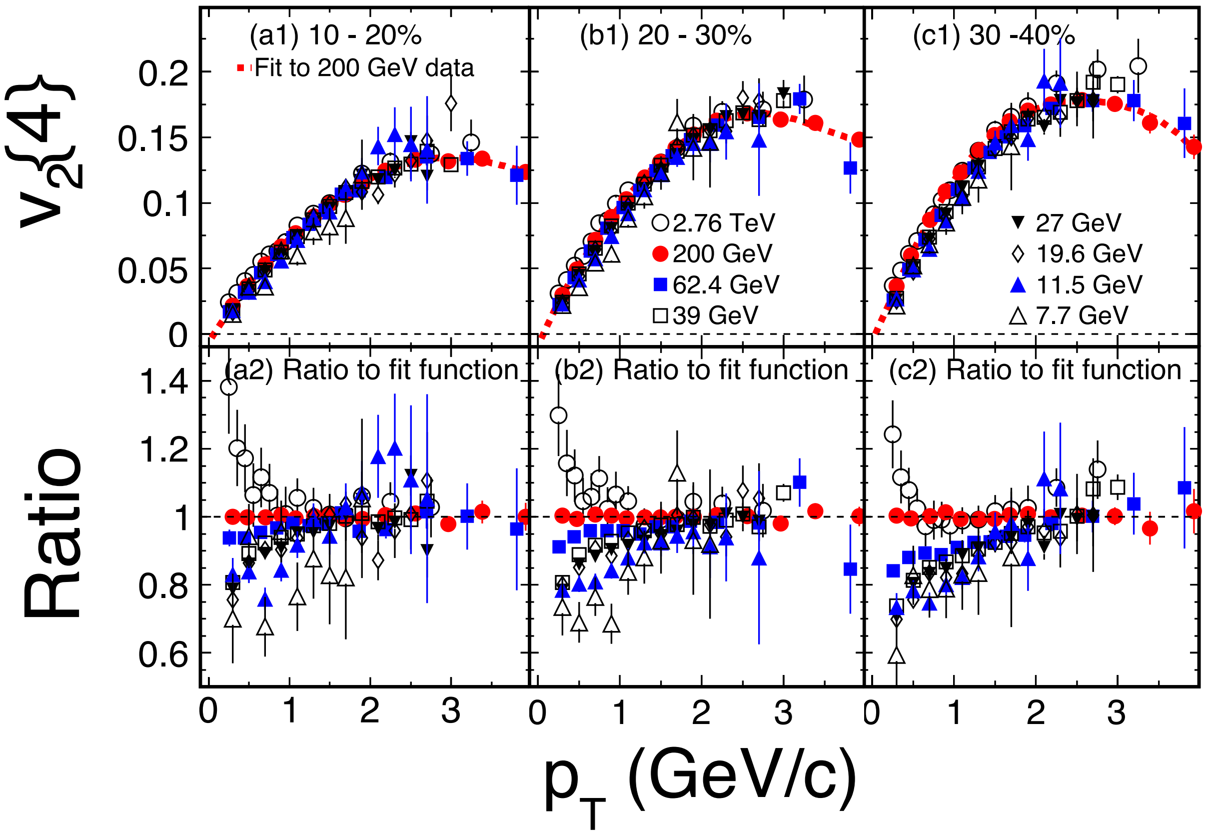


- **STAR, ALICE: $v_2\{4\}$ results**
  - Centrality: 20-30%
- **An increasing trend is observed for p_T integrated v_2 from AGS to LHC**
  - The rate of increase with collision energy is slower from 7.7 to 39 GeV compared to that between 3 to 7.7 GeV

ALICE: Phys. Rev. Lett. 105, 252302 (2010)
PHENIX: Phys. Rev.Lett. 98, 162301 (2007).
PHOBOS: Phys. Rev.Lett. 98, 242302 (2007).
CERES: Nucl. Phys. A 698, 253c (2002).
E877: Nucl. Phys. A 638, 3c(1998).
E895: Phys. Rev. Lett. 83, 1295 (1999).
STAR 130 and 200 GeV: Phys. Rev. C 66,873 034904 (2002); Phys. Rev. C 72,790 014904 (2005)

STAR: Phys. Rev. C 86, 054908(2012)

Energy Dependence

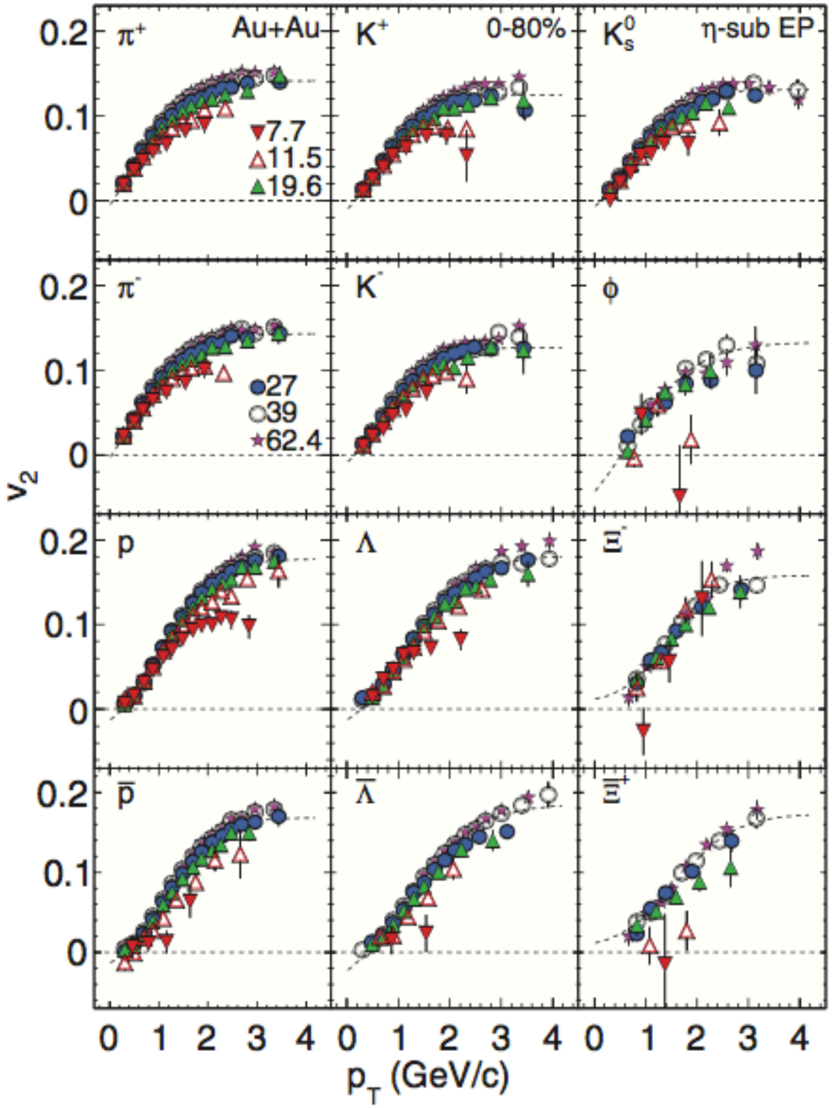


STAR: Phys. Rev. C 86, 054908(2012)

ALICE data: Phys. Rev. Lett. 105, 252302 (2010)

- **$v_2\{4\}$ results**
  - Three centrality bins
- **Consistent $v_2(p_T)$ from 7.7 GeV to 2.76 TeV for p_T > 2 GeV/c**
- **p_T< 2GeV/*c***
  - The v_2 values rise with increasing collision energy
    ->
    Large collectivity?
    Particle composition?

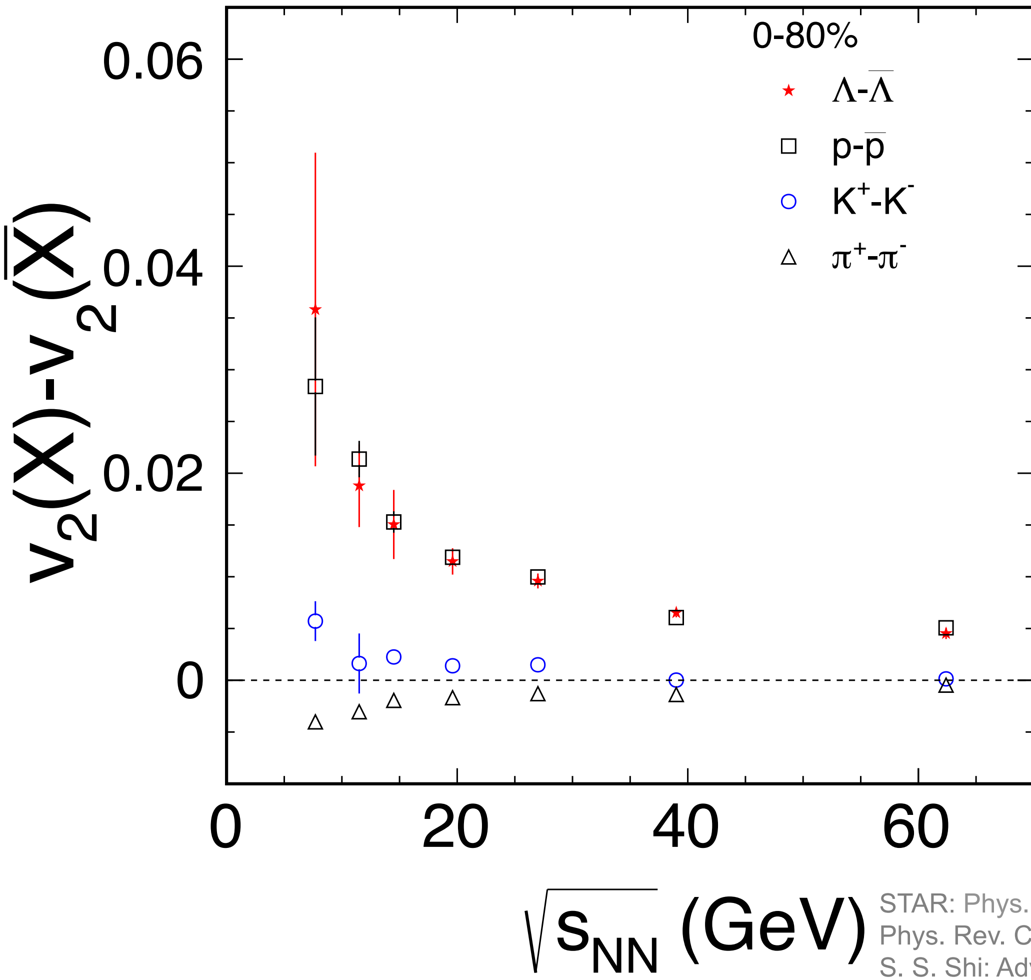
Energy Dependence



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

- **Similar $v_2(p_T)$ shape for PID**

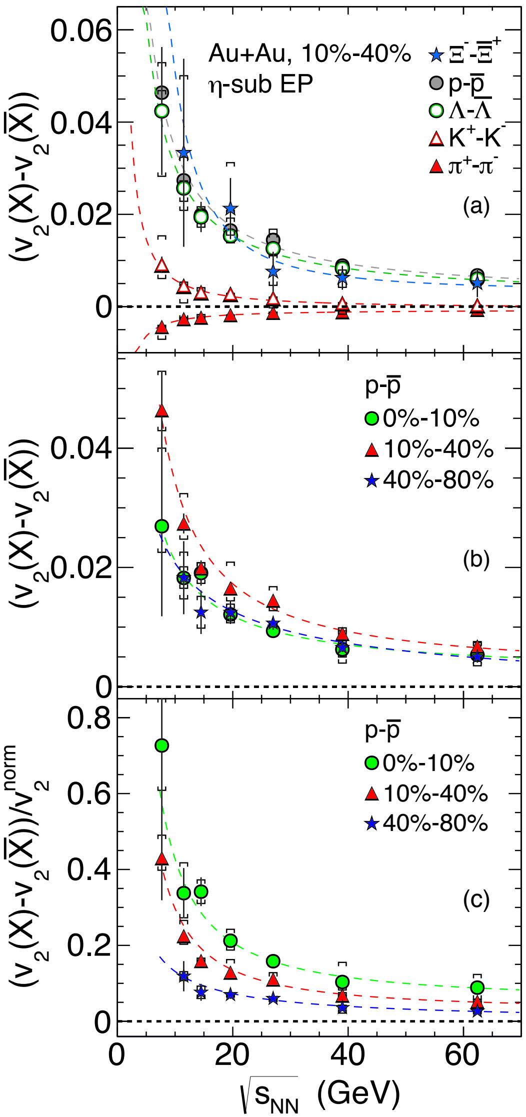
Particle vs. Anti-particle v_2



STAR: Phys. Rev. Lett. 110 (2013) 142301
Phys. Rev. C 93, 014907(2016)
S. S. Shi: Adv. High Energy Phys. 2016, 1987432 (2016)

- **Significant difference between baryon and anti-baryon v_2 is observed**

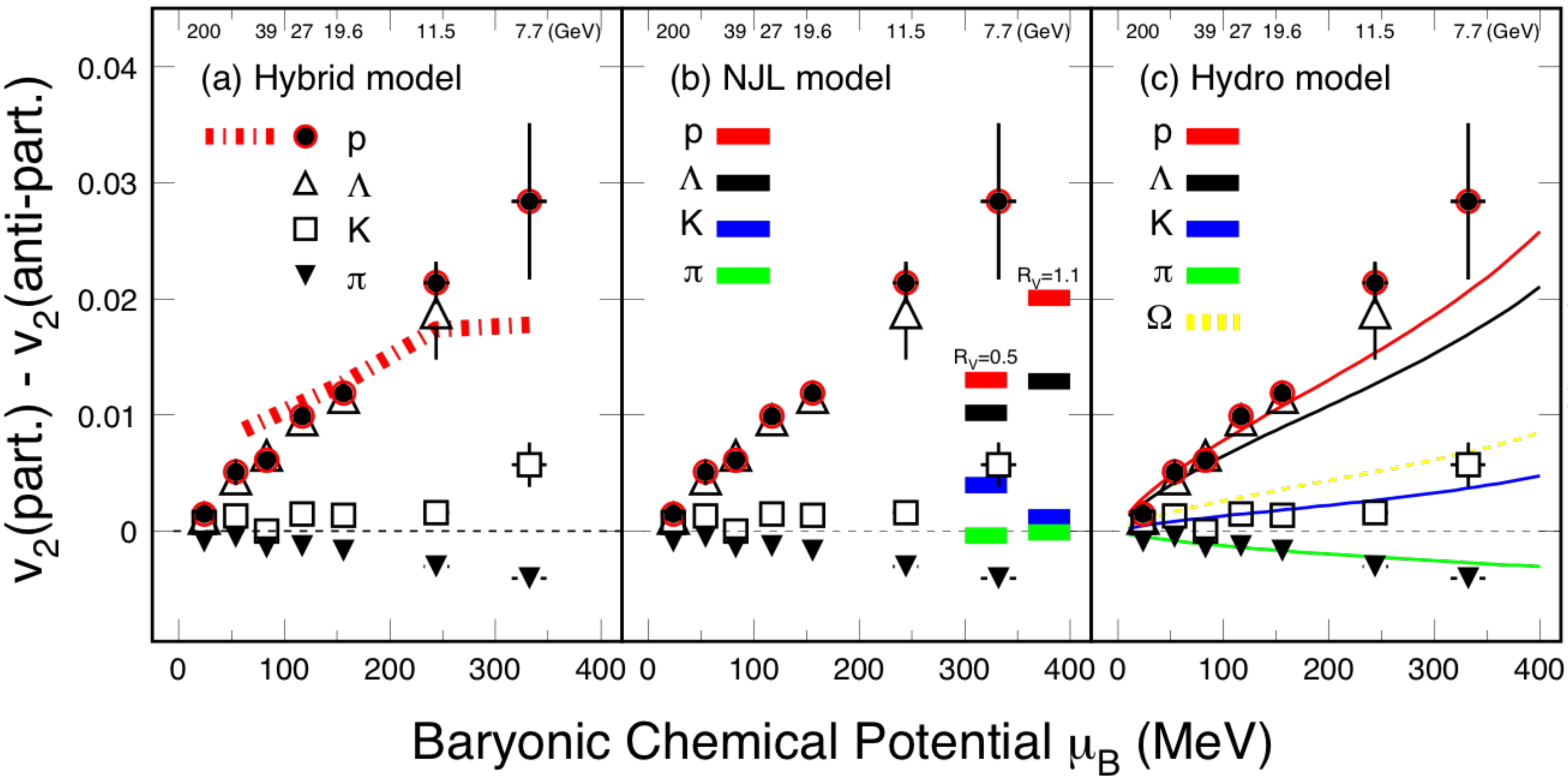
Particle vs. Anti-particle v_2



- the relative difference normalized by v_2^{norm}, the proton elliptic flow at p_T = 1.5 GeV/c, shows a clear centrality dependence with a bigger effect for the more central collisions

STAR: Phys. Rev. C 93, 014907(2016)

Particle vs. Anti-particle v_2



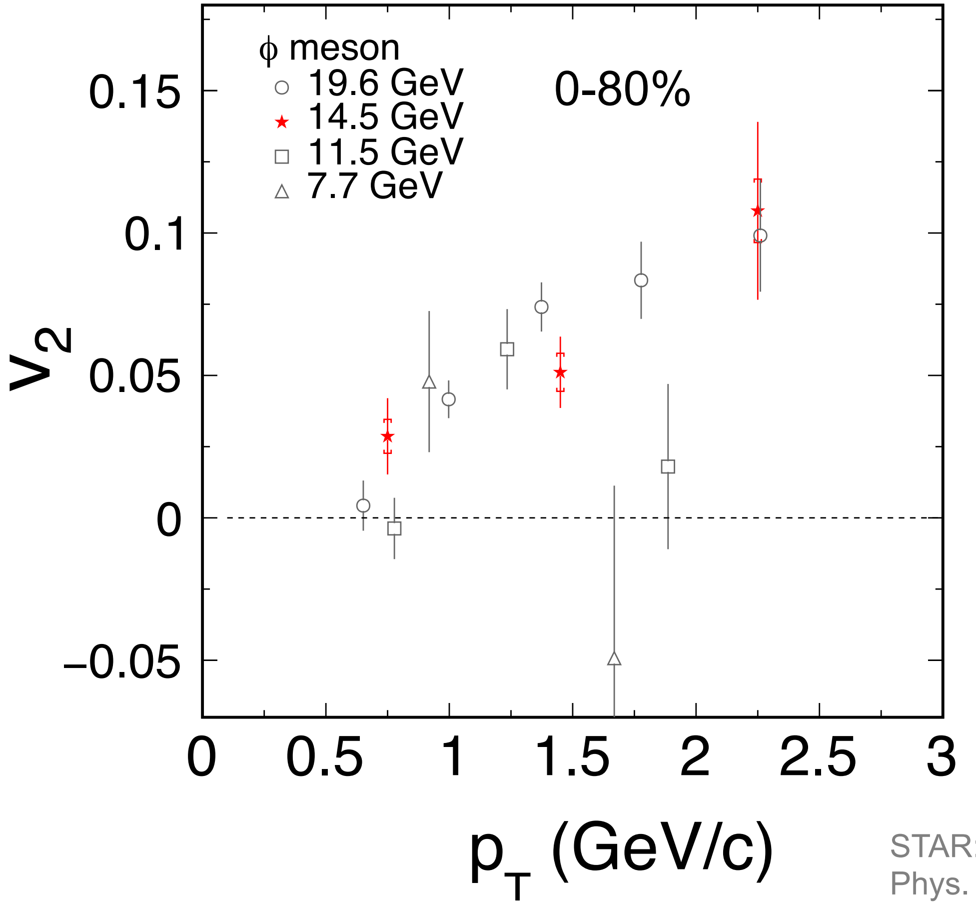
- **The difference between particles and anti-particles increases with decreasing beam energy – NCQ scaling breaks**
- **Model comparison**

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, 44902(2013); J. Xu et al., PRL112, 012301(2014); Y. Hatta et al., PRD92, 114010(2014)

ϕ Meson v_2



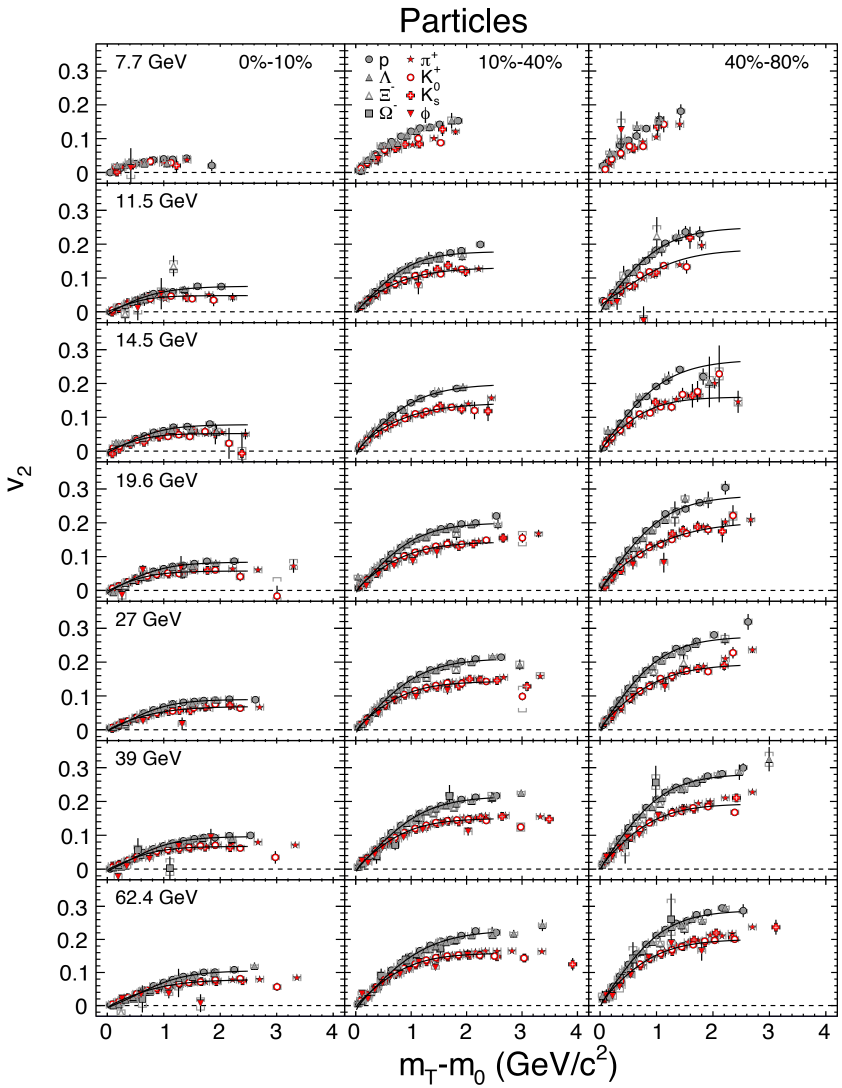
ϕ meson is less sensitive to late hadronic interactions[1]

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)

Baryon/Meson Separation

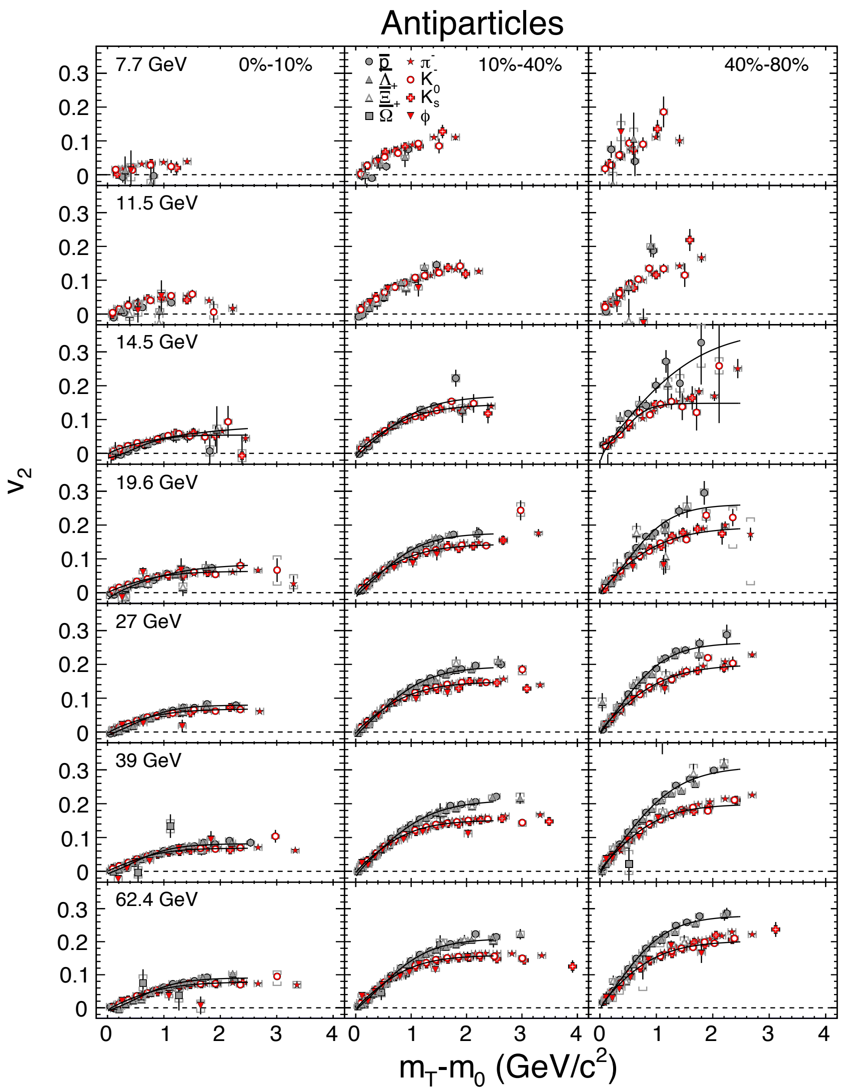


A splitting between baryons and mesons is observed at all energies except 7.7 GeV and all centralities.

At 7.7 GeV we are limited by the number of events.

STAR: Phys. Rev. C 93, 014907(2016)

Baryon/Meson Separation



The splitting between baryons and mesons is observed significant for all energies above 14.5 GeV and also at 14.5 GeV for 40%–80%.

For these energies below 11.5 GeV, we are limited by the number of events.

STAR: Phys. Rev. C 93, 014907(2016)

Summary

- **Energy Dependence**

  Similar $v_2(p_T)$ shape from 7.7 GeV to 2.76 TeV

- **Particle vs. Anti-particle v_2**

  The difference increases with decreasing beam energy

- **ϕ Meson v_2 and Baryon/Meson Separation**

  Limited by statistics when beam energy < 14.5 GeV

RHIC BES-I:

$\sqrt{s_{NN}} \geq 39$ GeV: partonic interactions dominant

$\sqrt{s_{NN}} \leq 11.5$ GeV: hadronic interactions dominant

RHIC BES-II:

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

BES II

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