STAR

RHIC & AGS
Annual Users' Meeting
Hosted By Brookhaven National Laboratory

Directed flow of particles and quarks from RHIC Beam Energy Scan measured by the STAR Experiment

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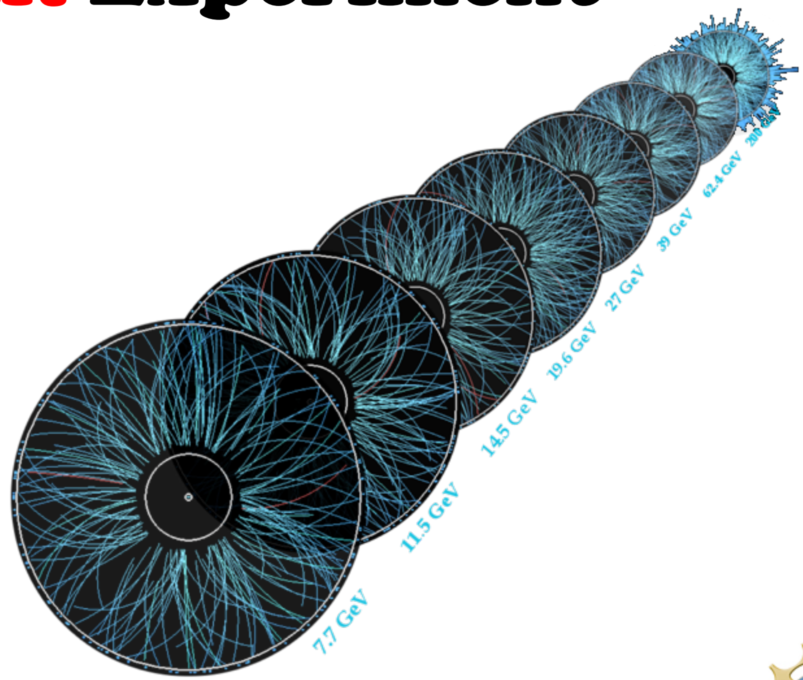
Lehigh University



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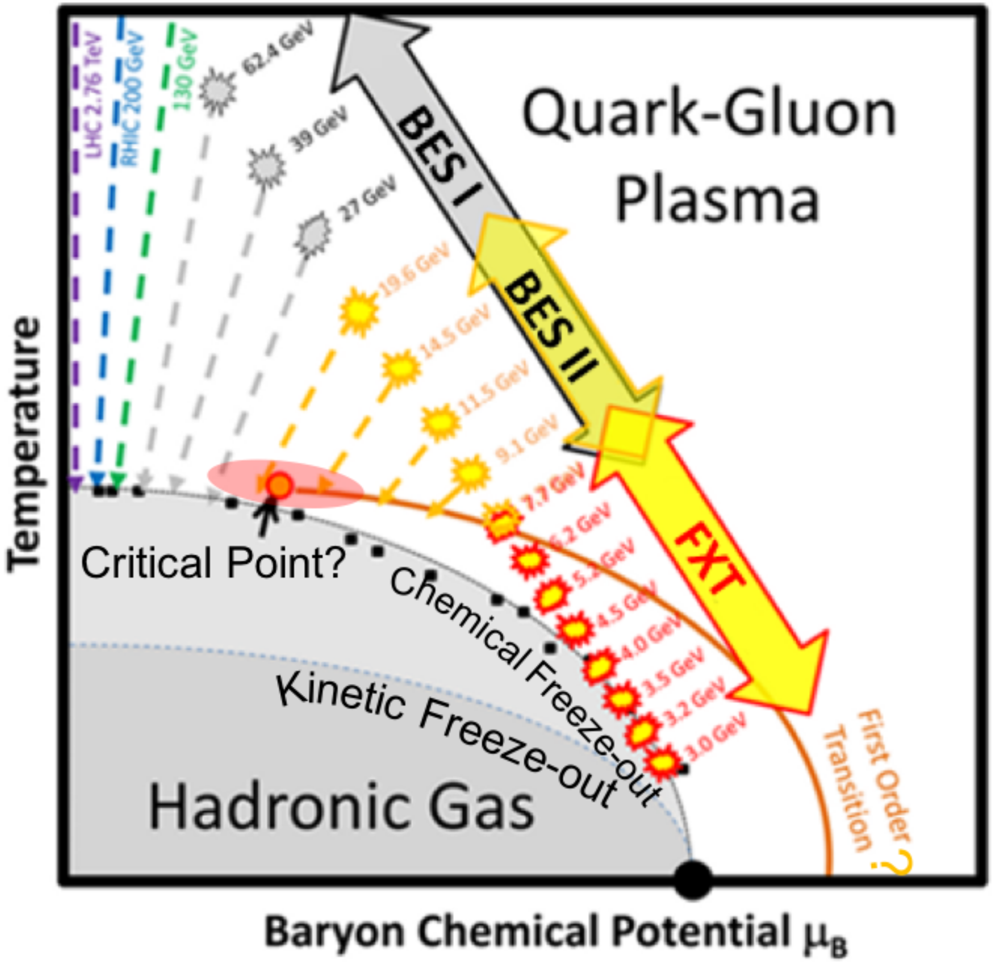
NSF

The BES program at RHIC



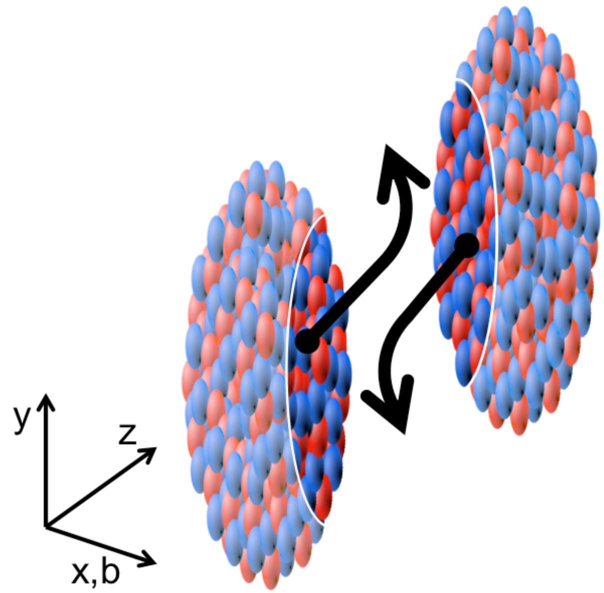
Goals of BES :

Explore QCD phase diagram

- Map turn-off of QGP signatures
- Search for the Critical Point
- Search for the First-Order Phase Transition

- **Phase diagram can be mapped** (μ_B,T) **by changing collision energy**
- **RHIC's energies are in the predicted critical point and first-order phase transition region**

Directed flow (v_1)

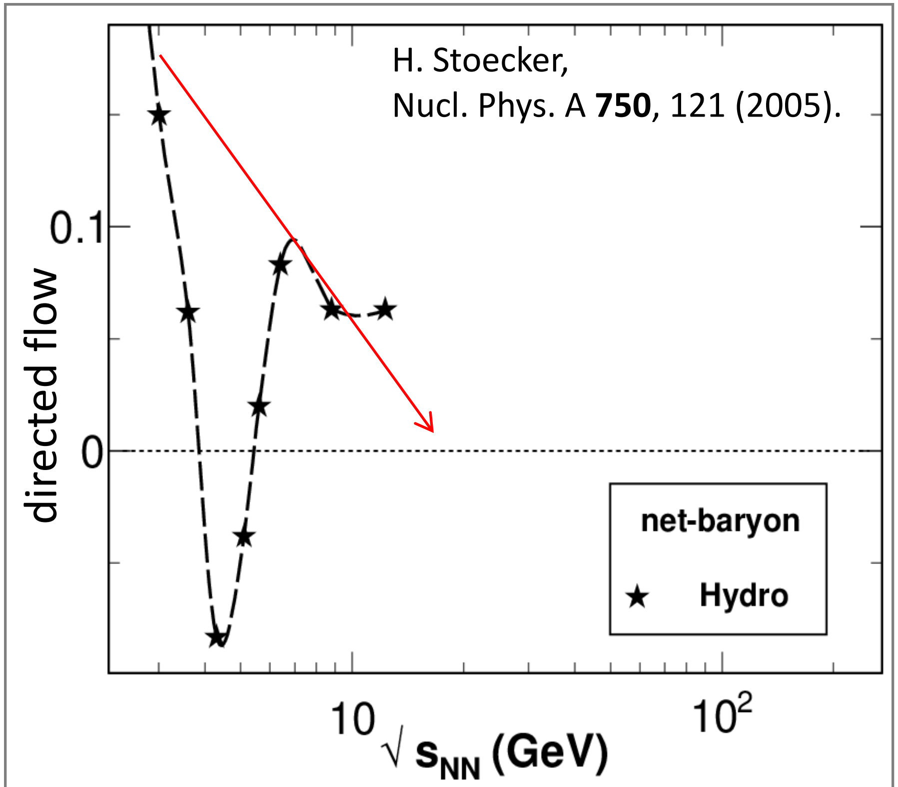


$$v_1 = \left\langle \cos\left(\phi - \Psi_{RP}\right)\right\rangle$$

- Directed flow describes the sideward collective motion of the particles within the reaction plane
- Generated during the nuclear passage time (2R/γ ≈ 0.1 fm/*c*)
- Therefore probes the very earliest stage of the collision dynamics

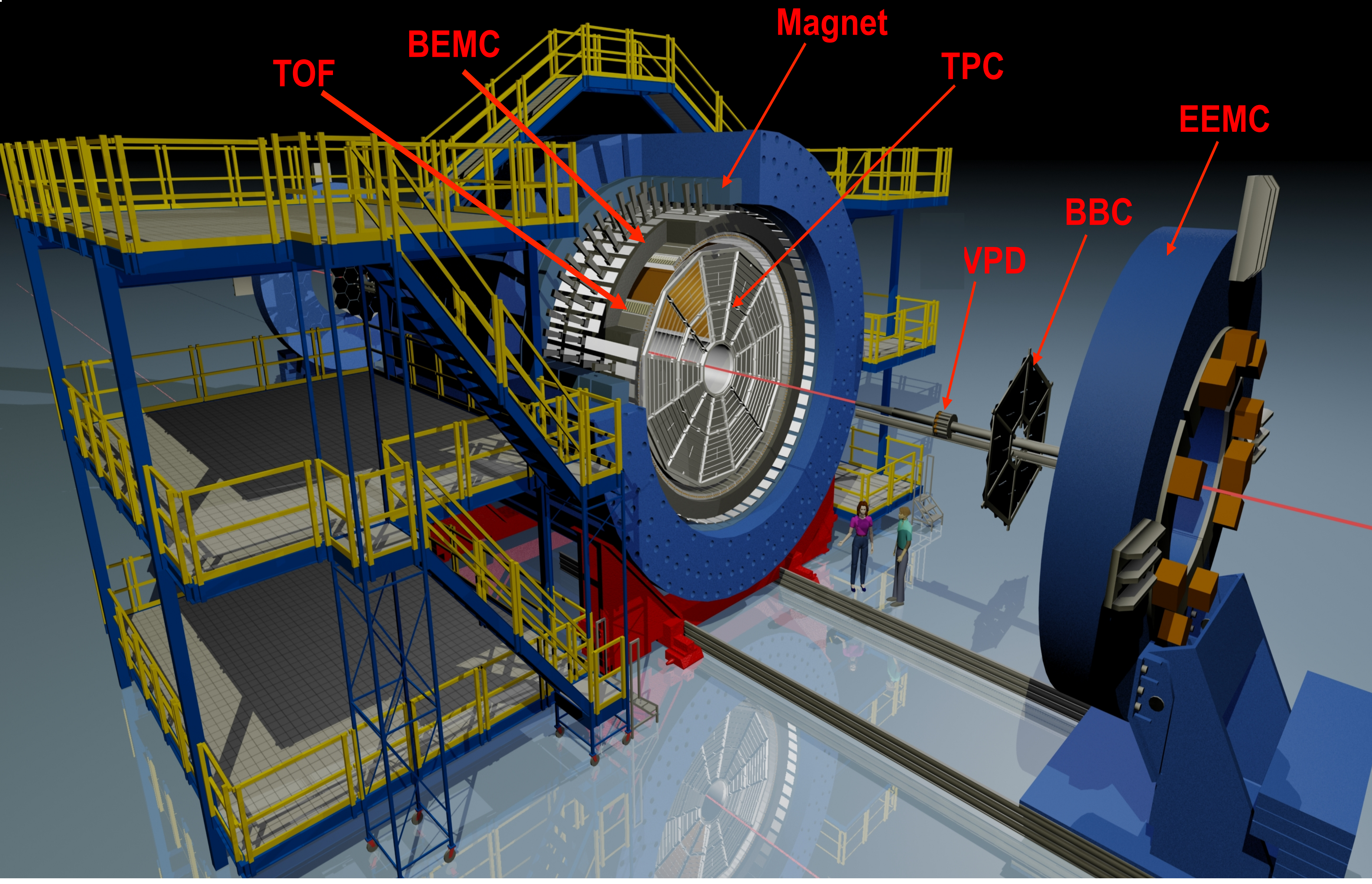
v_1 and search for the 1st -order phase transition

- "Softest Point" => EOS has a point where ratio of pressure to energy density is a minimal
- Strong softening consistent with the 1st-order Phase Transition
- Weaker softening could have other interpretations, such as shadowing effect, geometric effect or crossover EOS

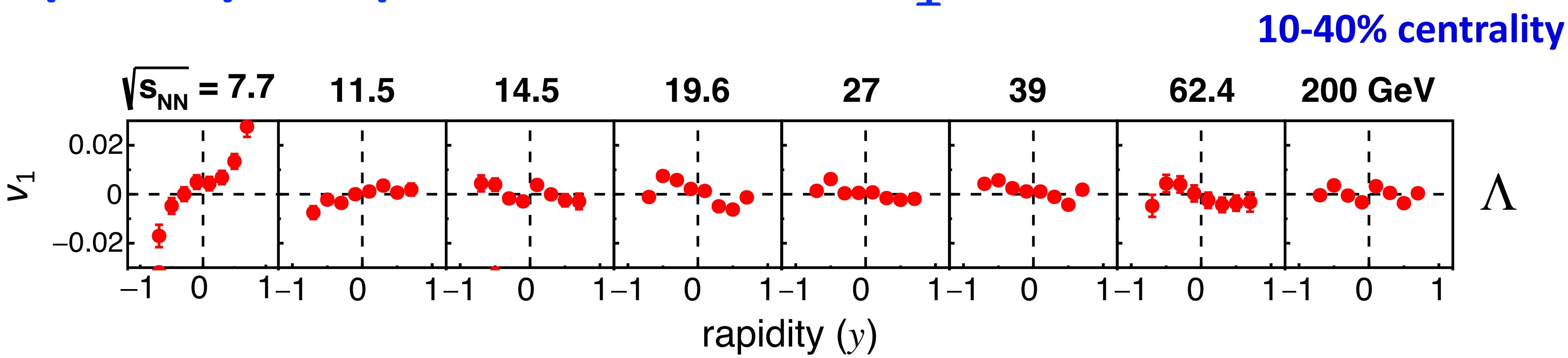


- Star markers: EOS with the assumption of the 1st -order phase transition
- Red line: EOS without phase transition

The Solenoid Tracker At RHIC (STAR)



Rapidity dependence of v_1



STAR collaboration PRL.120.062301 (2018)

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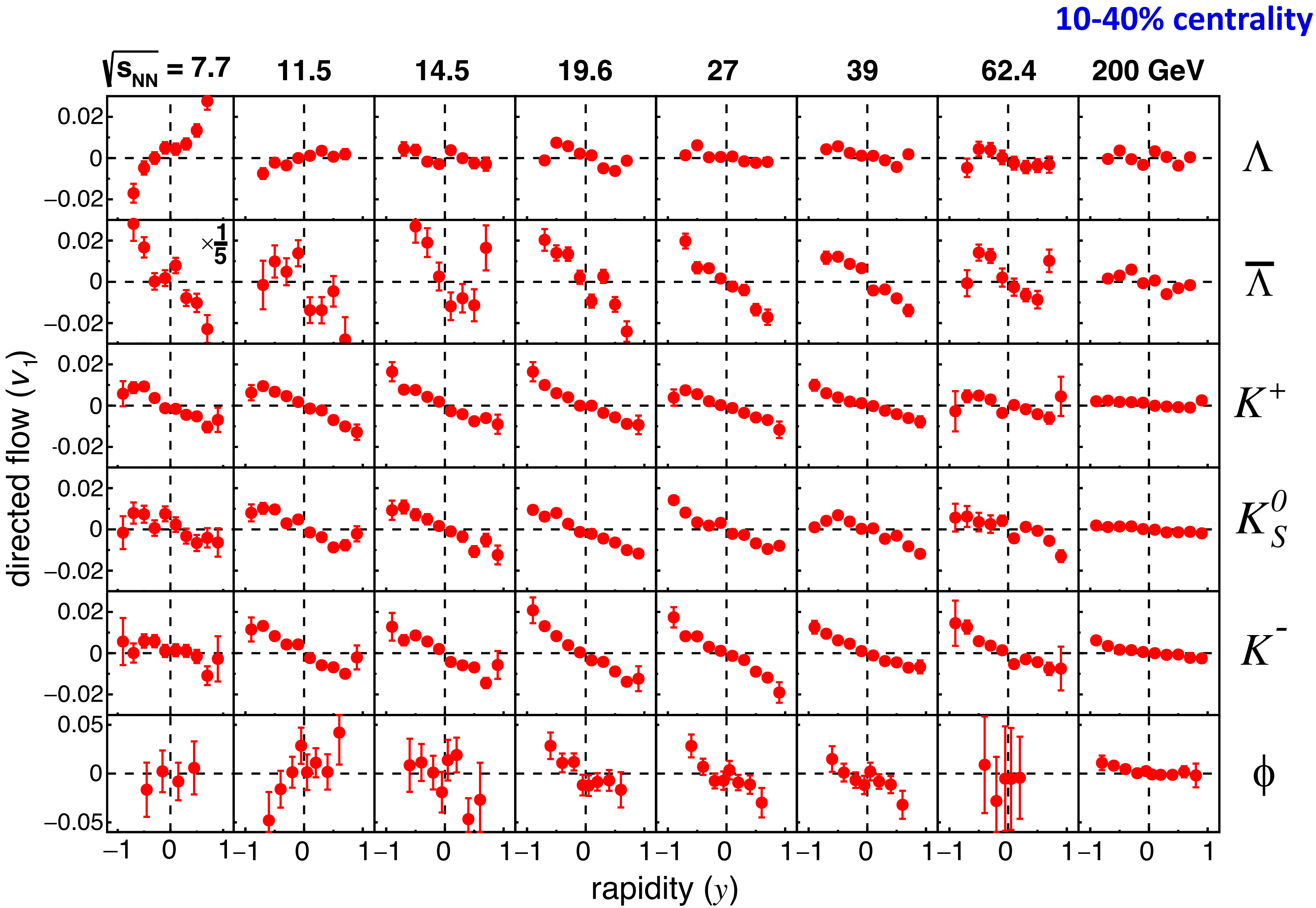

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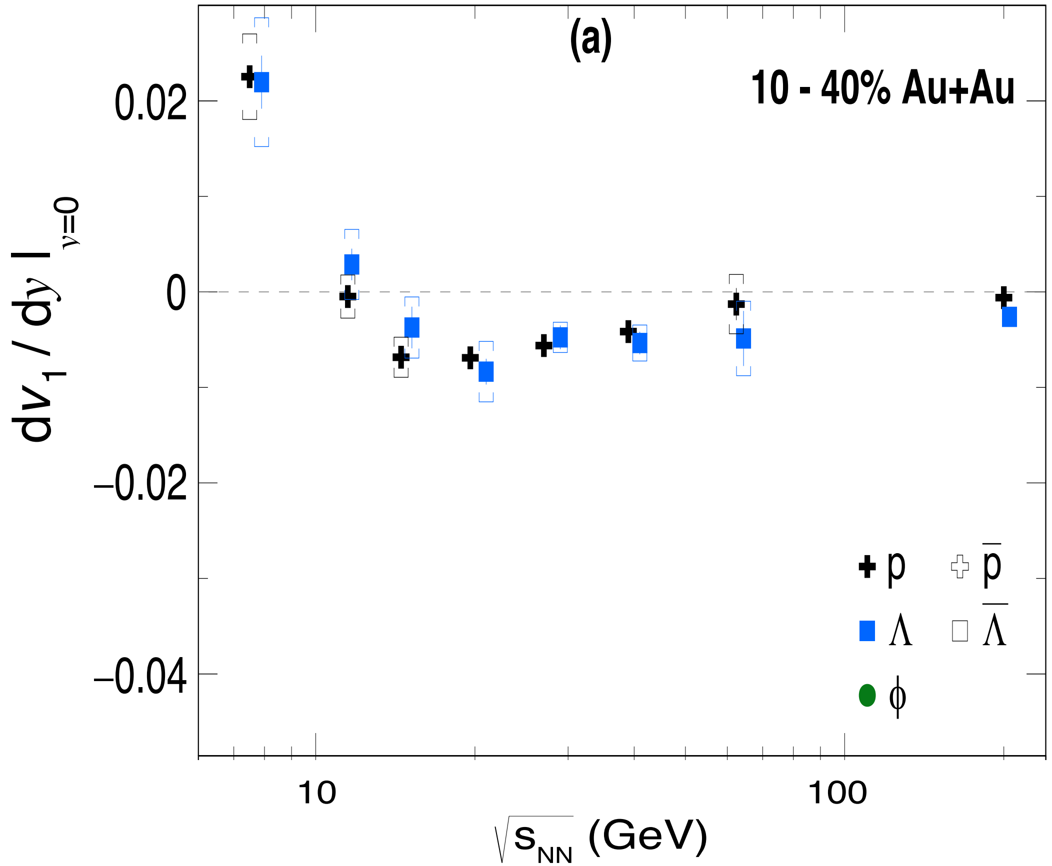
Beam energy dependence of directed flow



	quark content
anti-Λ	$\overline{uds}$
anti-p	$\overline{uud}$
ϕ	$s\bar{s}$

- A linear fit used to find dv_1/dy for all species & energies
- dv_1/dy for Λ and *p* agree within uncertainties, and the Λ slope changes sign in the same region $\sqrt{s_{NN}} < 14.5$ GeV

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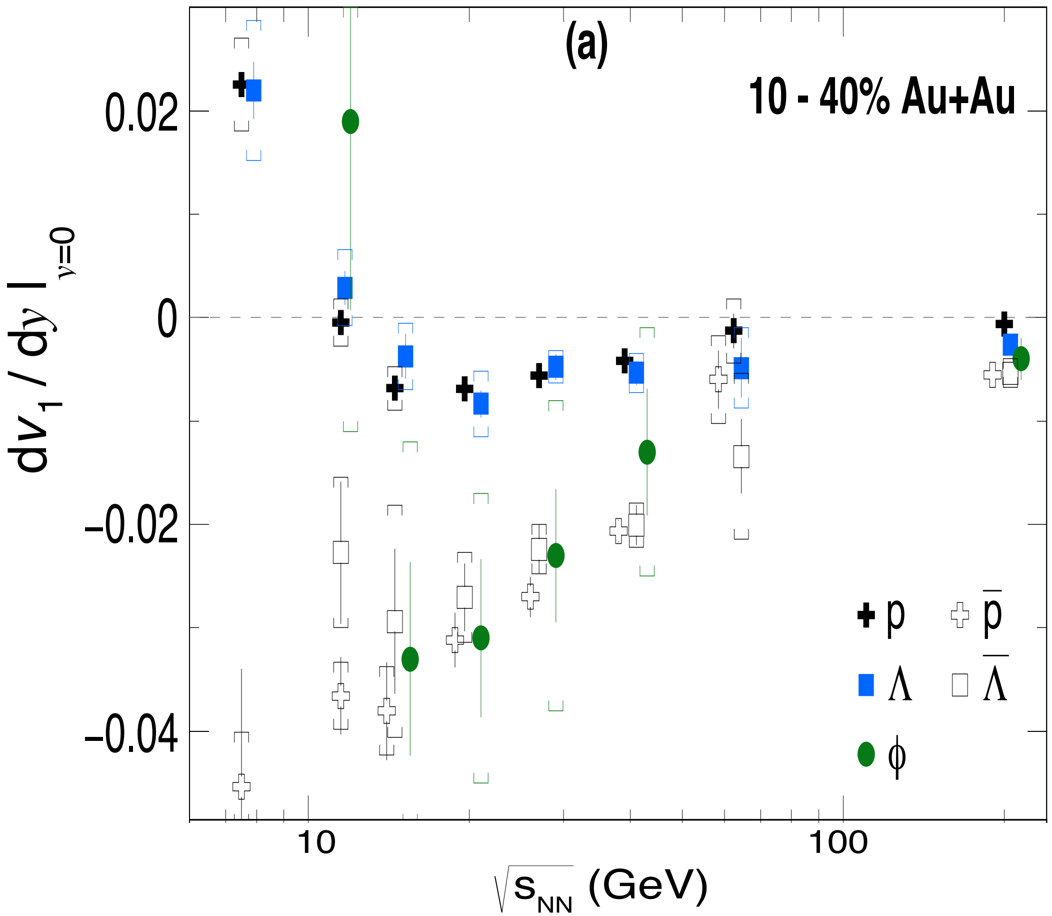

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- Particles (anti-p, anti-Λ, ϕ) with enriched produced quarks show similar behavior for $\sqrt{s_{NN}} > 14.5$ GeV

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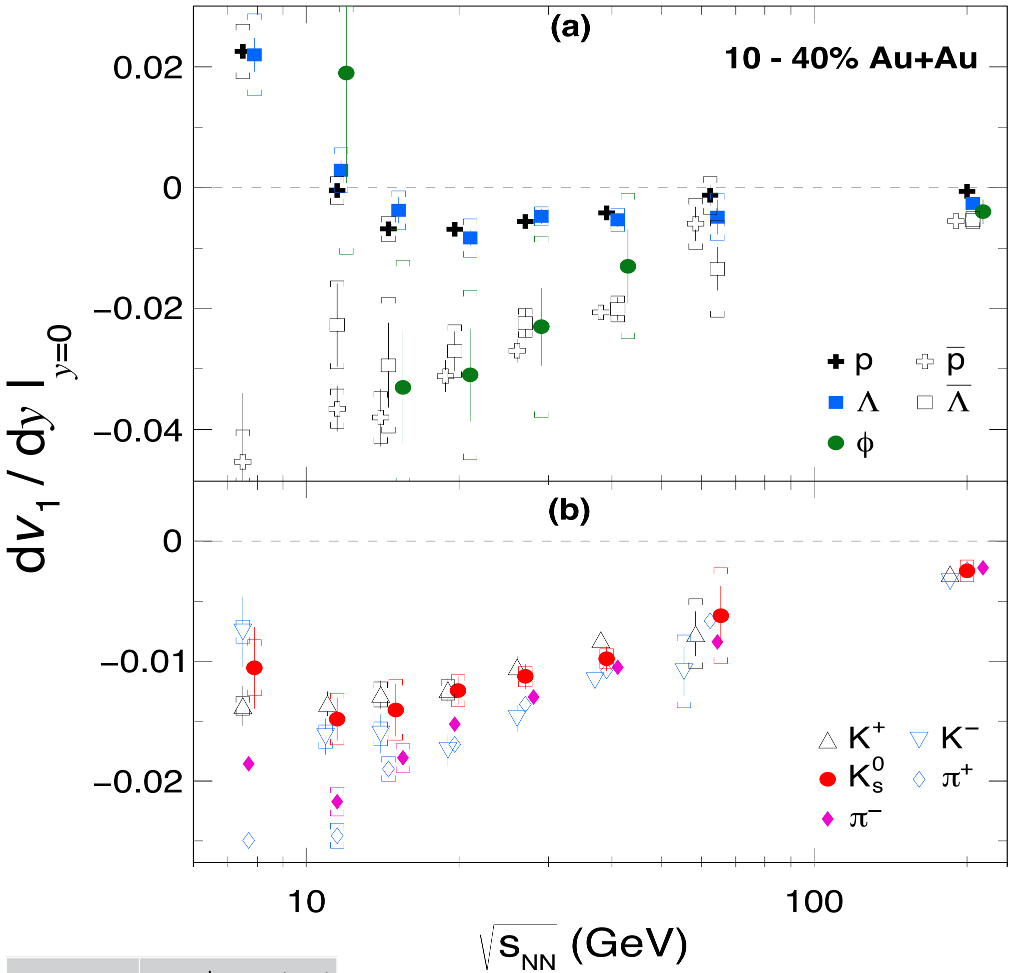
Beam energy dependence of directed flow



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- Particles (anti-p, anti-Λ, ϕ) with enriched produced quarks show similar behavior for $\sqrt{s_{NN}}$ > 14.5 GeV
- Mesons show negative dv_1/dy

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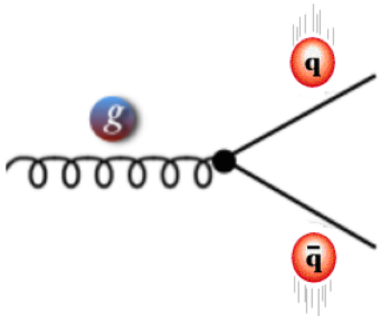
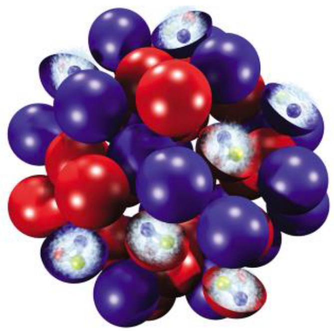
Produced vs. Transported Quarks





- u ū, d, đ, s and s̄
- pair production
- total number not conserved
- different waves of production
- may or may not be sensitive to the softening of EOS
- dominant at high collision energies
- can be studied via “produced” particles, such as anti-p, anti-Λ, K^- and ϕ whose constituent quarks are all produced

- u and d only
- from projectile nucleons
- total number conserved
- go through the whole evolution
- should be sensitive to the softening of EOS, if any
- dominant at low collision energies
- can be studied via net particles, such as
- net p, net Λ and net K

v_1 of produced quarks

Assumptions:

- v_1 is imposed at pre-hadronic stage
- Specific types of quarks have the same v_1
- Hadrons are formed via coalescence

$$(v_n)_{hadron} = \Sigma(v_n)_{\text{constituent quarks}}$$

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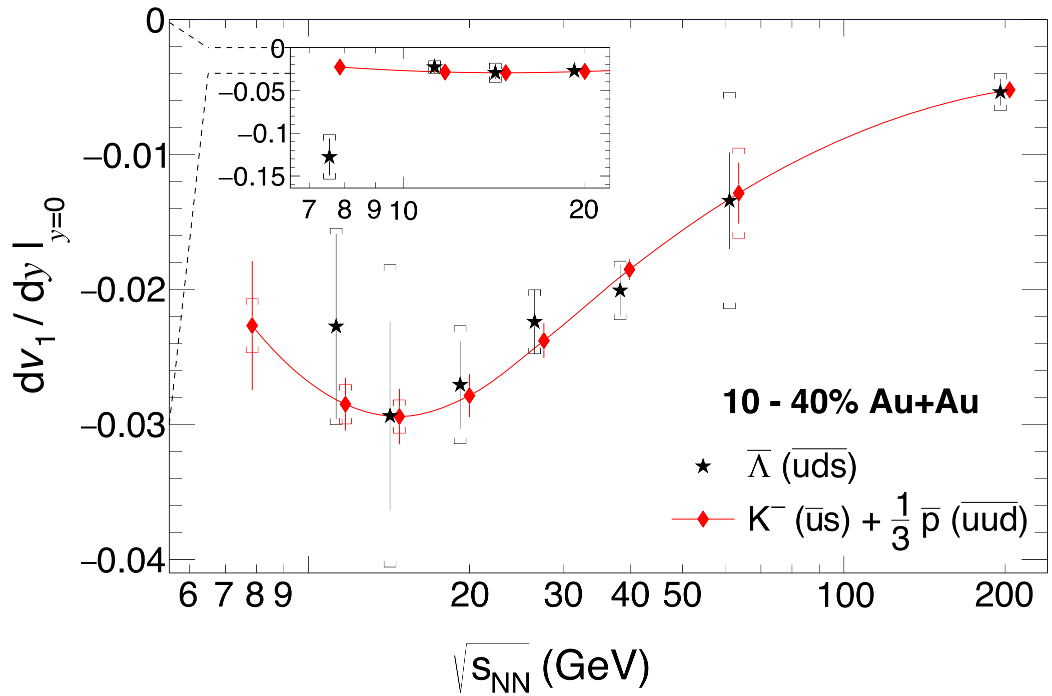

- Anti-*p* & anti-Λ show similar v_1 above $\sqrt{s_{NN}}$ > 14.5 GeV ; constituent quarks of these particles are all produced in the collision
- For anti-Λs, predicted v_1 using coalescence sum rule agrees with measured v_1 above $\sqrt{s_{NN}}$ > 11.5 GeV
- Disagreement at 7.7 GeV implies that one or more of the assumptions no longer holds below 11.5 GeV

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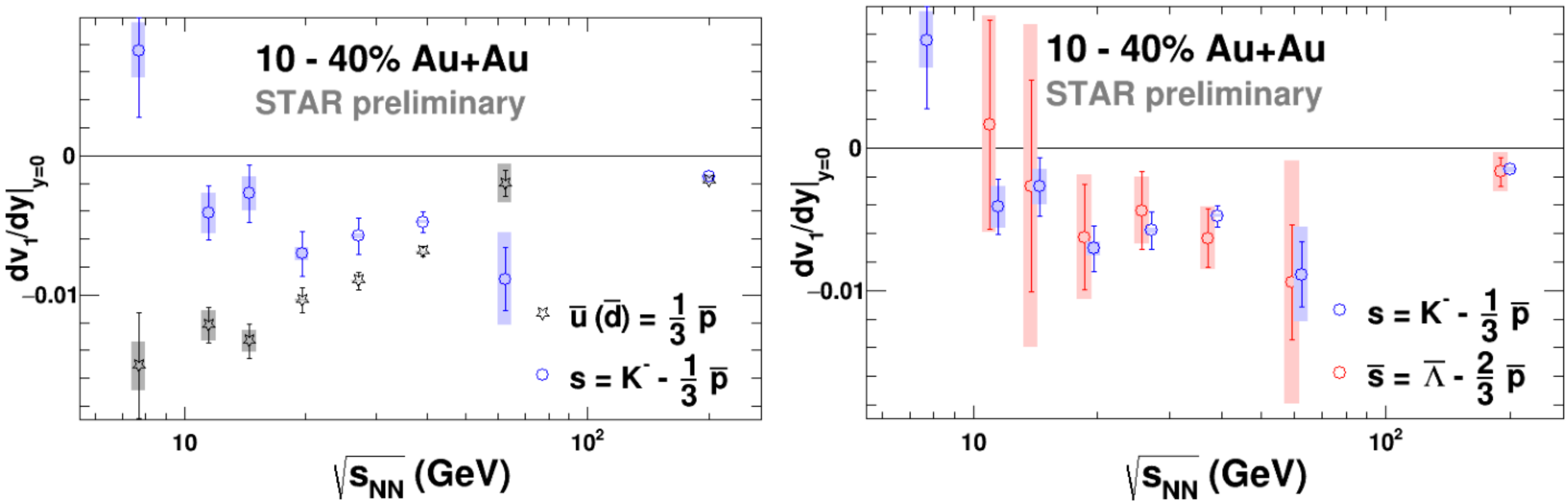
v_1 of produced quarks: u(ū, d, đ), s & $\bar{s}$

If the coalescence picture works, then...



- ū(đ) and s quarks have similar dv_1/dy at 200 GeV, and deviate at lower energies.
- s and $\bar{s}$ quarks are consistent with each other, except at the lowest energy.
- At 7.7 GeV, v1 slope of $\bar{s}$ is -0.097 ± 0.023(stat.) ± 0.026(syst.) (far off the scale).

‘Enriched’ transported quark v_1

Assume final-state particles have two quark components, one from produced q-qbar pairs, another from initial-state transported quarks

We try to disentangle the two contributions to the slope of directed flow, *F*, via net-*p*, *net*-Λ and net-*K*:

$$F_p = r_1 F_{anti\text{-}p} + (1 - r_1) F_{net\text{-}p}$$

where $r_1(y)$ =observed anti-*p* over *p* yield

Likewise for *net*-Λ and net-*K*

**In the limit of low $\sqrt{s_{NN}}$ most of u and d quarks are transported while in the limit of high $\sqrt{s_{NN}}$ most of u and d are produced

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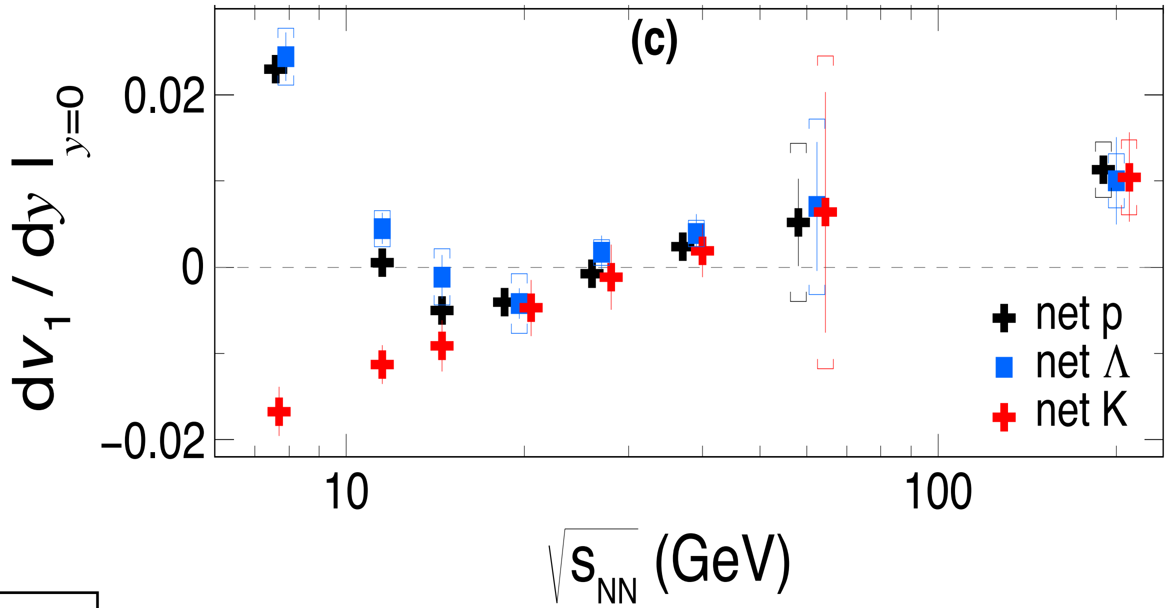

→ $(dv_1/dy)_{net\text{-}p}$ ~ $(dv_1/dy)_{net\text{-}\Lambda}$

→ $(dv_1/dy)_{net\text{-}p}$ ~ $(dv_1/dy)_{net\text{-}K}$ for $\sqrt{s_{NN}}$ > 14.5 GeV

Minimum in slope of directed flow as a function of beam energy for baryons and double sign-change for net-baryons indicate softening of EOS

**In the limit of low $\sqrt{s_{NN}}$ most of u and d quarks are transported while in the limit of high $\sqrt{s_{NN}}$ most of u and d are produced

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Summary

- Measurement of v_1 for 10 particle species allows a detailed study of constituent-quark v_1
- $dv_1/dy|_{y=0}$ for both p, Λ shows sign change and strongly depends on beam energy
- There are distinct qualitative features in 10-40% centrality dv_1/dy for baryons (sign change & minimum), antibaryons (always negative), mesons (negative & smaller magnitude)
- Many (but not all) of the measurements are consistent with the observed particles having formed via coalescence of constituent quarks
- Observed scaling behavior for produced quarks at and above 11.5 GeV, with a breakdown at 7.7 GeV, requires further study

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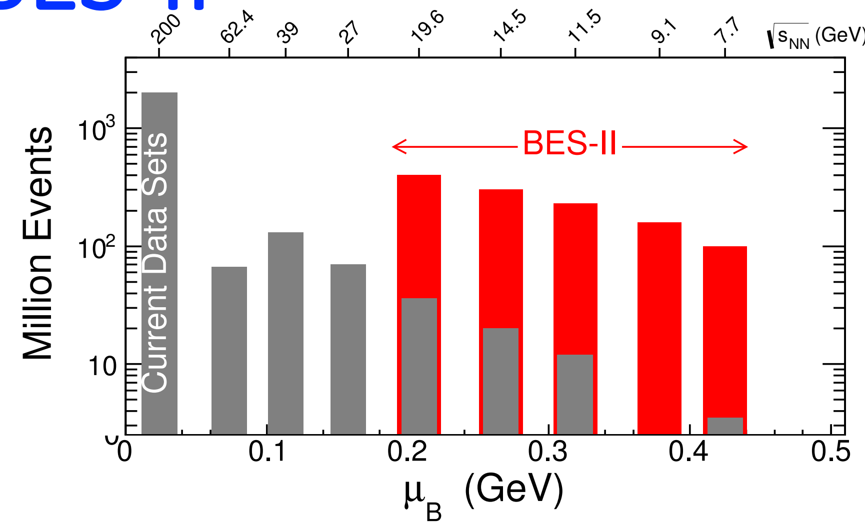
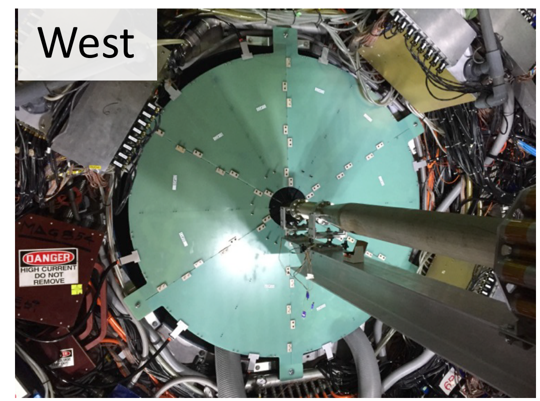
- Observed scaling behavior for produced quarks at and above 11.5 GeV, with a breakdown at 7.7 GeV, requires further study
- **These measurements will benefit from larger event statistics and forward upgrades of STAR in the phase II of the RHIC beam energy scan**

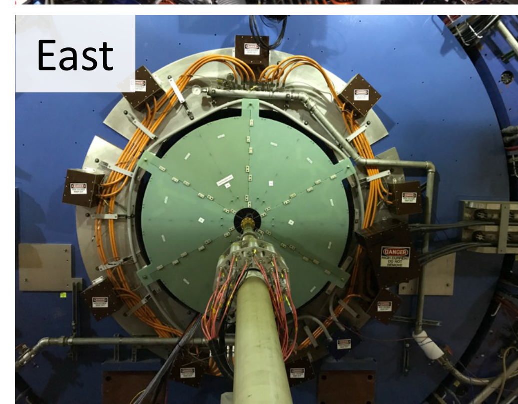
Detector upgrades for BES-II

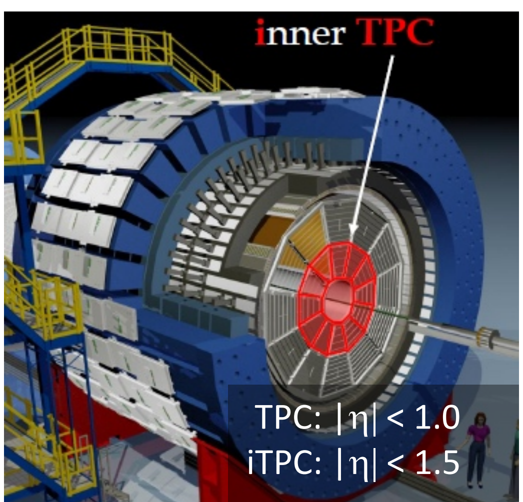
- eTOF | EPD | iTPC • **Larger acceptance**
- EPD • **Independent centrality definition & better event plane resolution**
- iTPC | eTOF • **Improved PID capabilities**
- EPD | LEReC • **Higher statistics (CAD) & improved trigger**

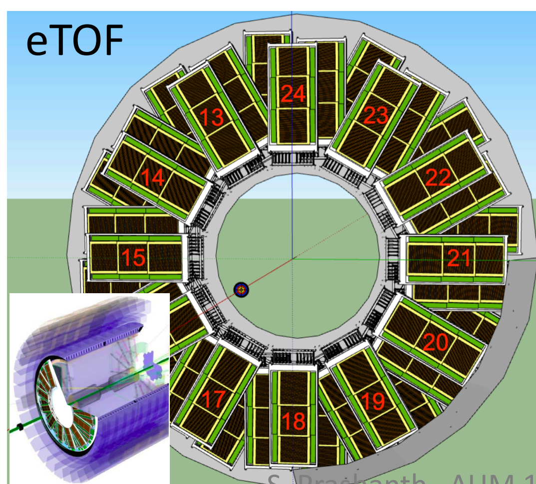


EPD









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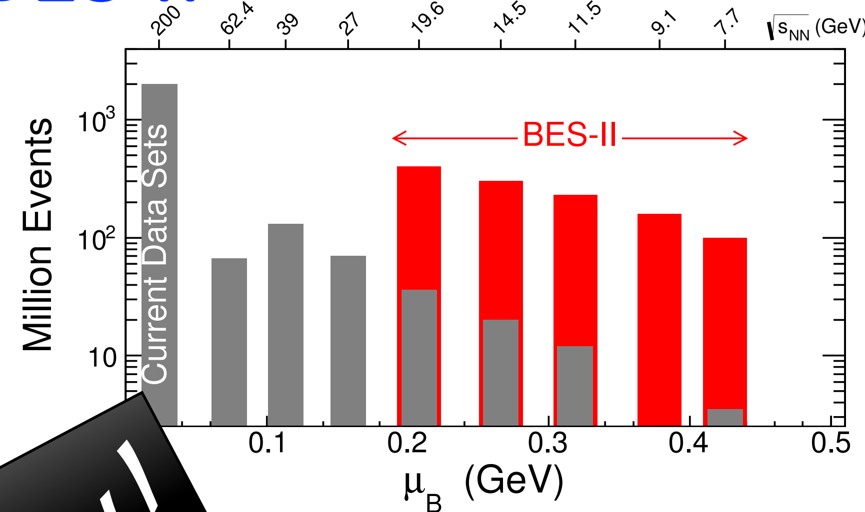
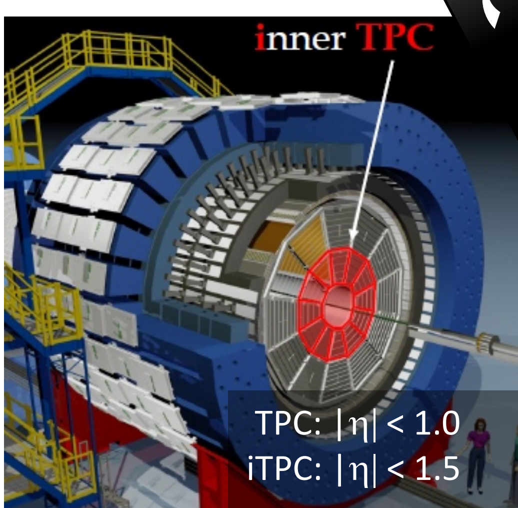
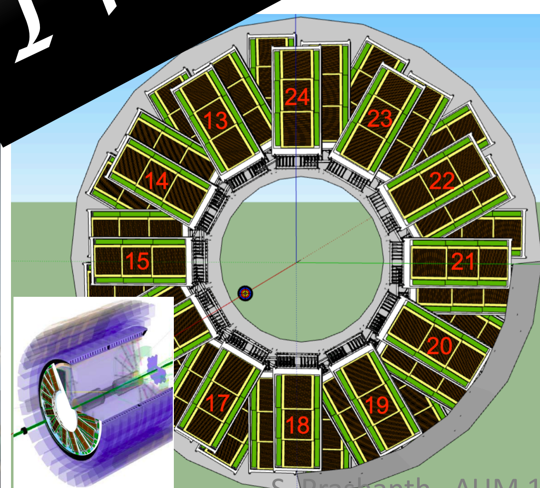
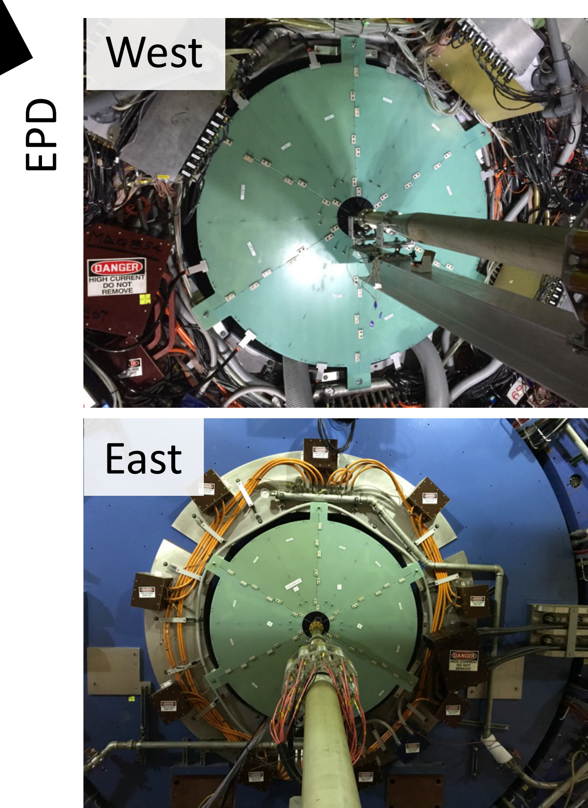
- iTPC eTOF • **Improved PID capabiliti**
- EPD LEReC • **Higher statistic**
  improved t

Thank you!









Backups

v_1 of quarks

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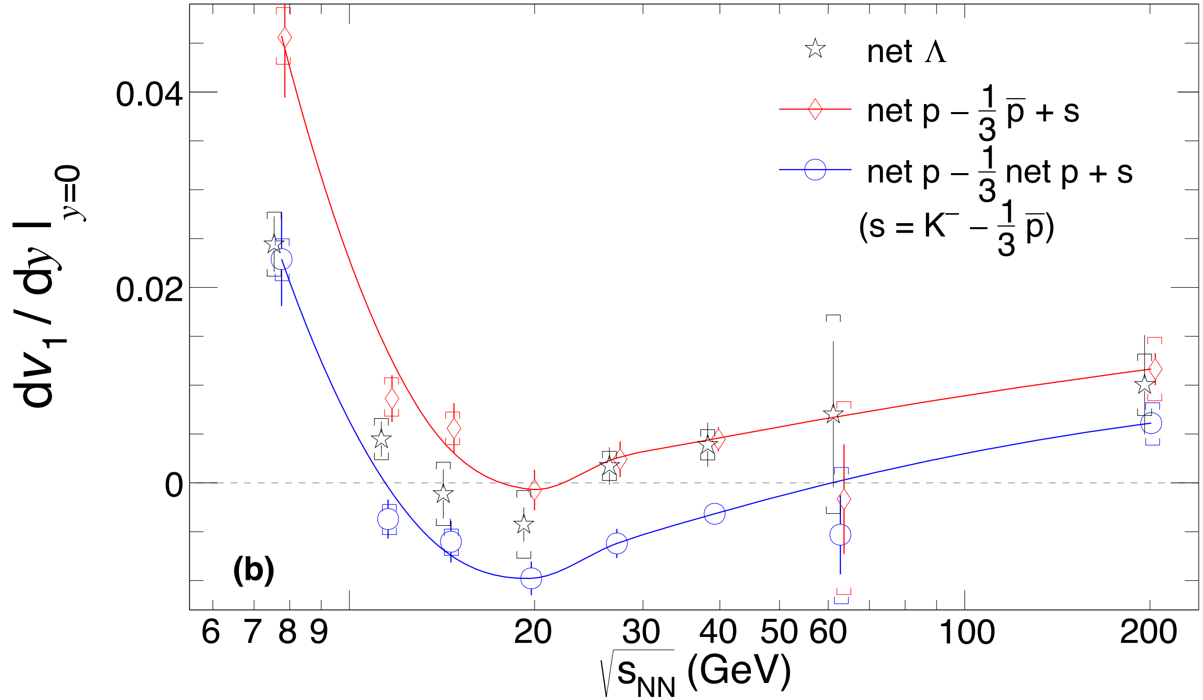


net Λ

$$\text{net p} - \frac{1}{3}\bar{\text{p}} + \text{s}$$

Assumed constituent quarks of net protons are dominated by produced quarks in the limit of high beam energy

=> Good agreement at $\sqrt{s_{NN}}$ >14.5 GeV

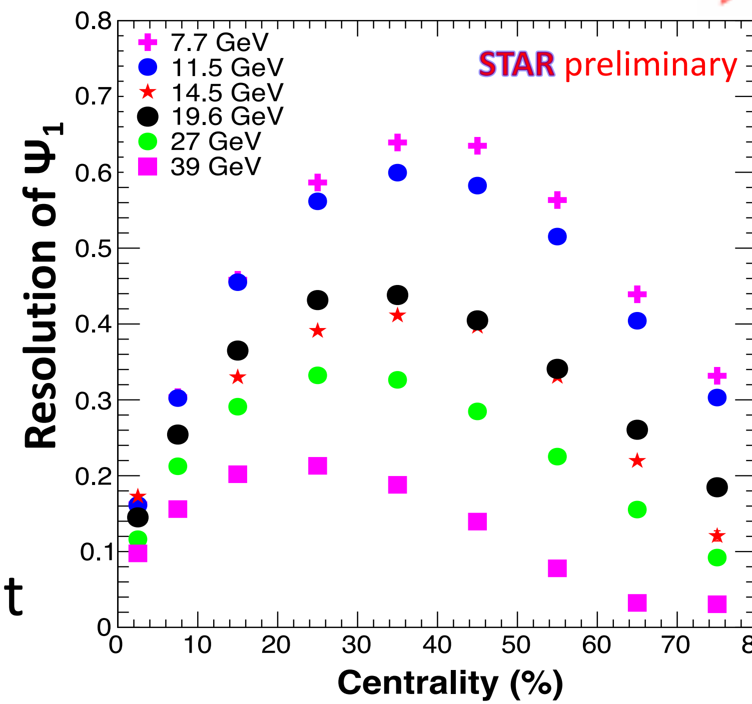
$$\text{net p} - \frac{1}{3}\text{net p} + \text{s}$$

Assumed constituent quarks of net protons are dominated by transported quarks in the limit of low beam energy

=> Good agreement at $\sqrt{s_{NN}}$ = 7.7 GeV

Event plane estimation

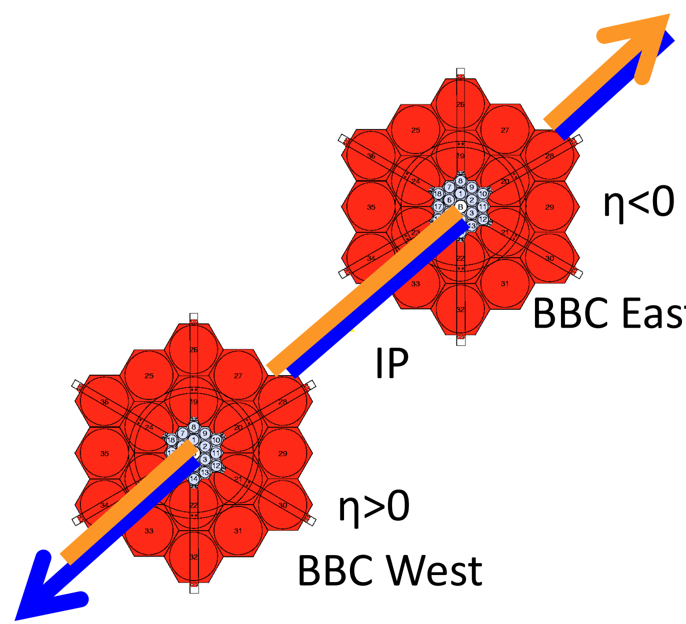
- The 1st-order reaction plane estimated using East & West BBC detectors
  - Coverage: $3.3 < |\eta| < 5.0$
  - η gap between TPC and BBC reduces non-flow contribution



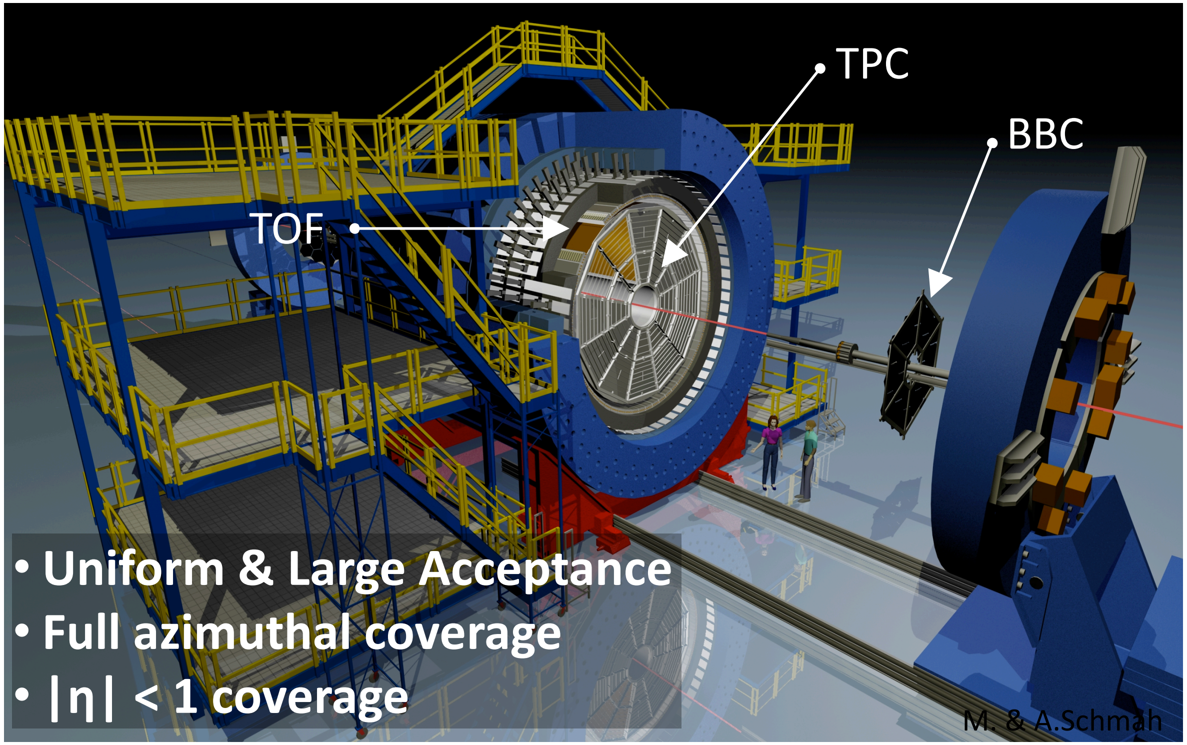
- BBC event plane resolution improves at lower energies due to strong v_1 signal near beam rapidities aligning with BBC acceptance

- Non-flat BBC Ψ_1 distribution corrected by shifting method

(Voloshin, Poskanzer, Snellings, arXiv:0809.2949)



Particle identification in STAR

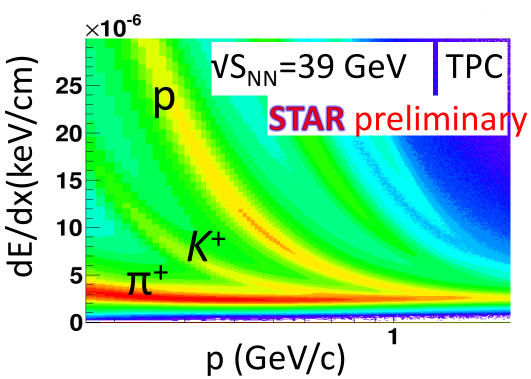


Long lived: *p, K, π*

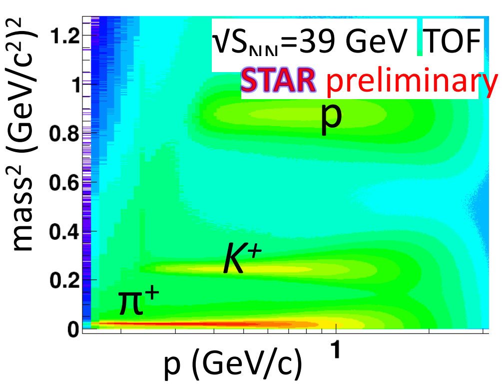
- Requires TPC & TOF hits
- *dE/dx* cut of $|n\sigma| \leq 2$
- p : $0.4 < p_T < 2.0$ GeV/c
- $K^{\pm}$ & $\pi^{\pm}$: $p_T > 0.2$ GeV/c
- $p < 1.6$ GeV/c

Short lived : Λ , K^0_S

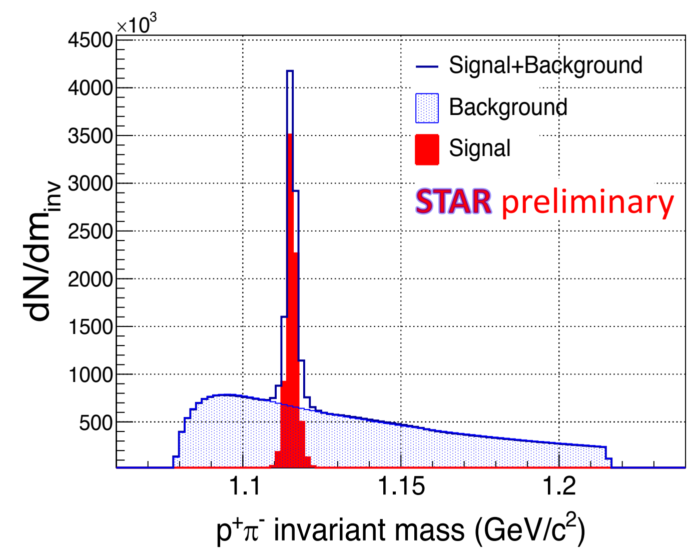
- Invariant mass technique
- Mixed-event background
- V^0 topological cuts
- TPC and/or ToF hits for daughters
- $0.2 < p_T < 5.0$ GeV/c



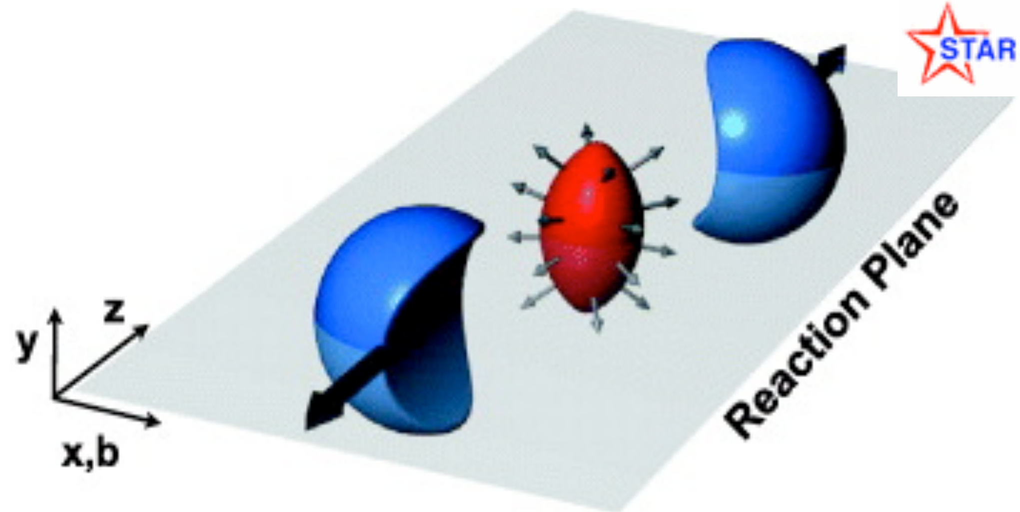
- PID using energy loss in TPC d*E*/dx



- PID using time of flight and momentum from TPC



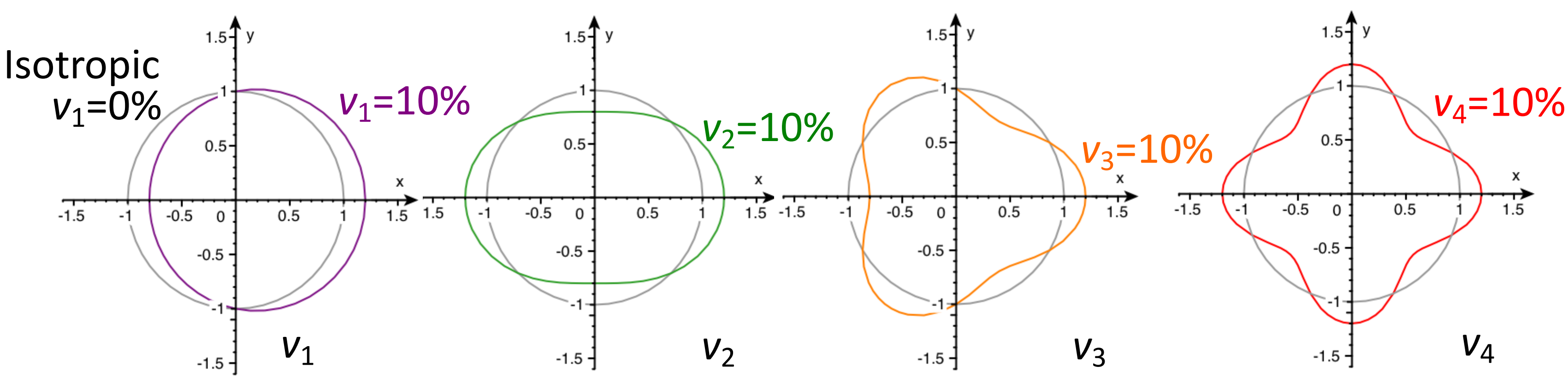
Anisotropic flow



- **Anisotropy of the azimuthal distribution of particles with respect to reaction plane (Ψ_{RP})**

$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Psi_{RP})\right) \quad \phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

- **v_1-Directed flow, v_2-Eliptic flow, v_3-Triangular flow**



Models with relevance to directed flow

UltraRelativistic Quantum Molecular Dynamics (UrQMD)

- Hadronic Boltzmann transport
- No phase transition or QGP
- Very widely used and tested; code is available to everyone

Frankfurt Hybrid Model

- Early and late stages similar to UrQMD (Boltzmann transport)
- Hydro used for intermediate stage of high energy density
- Hydro has QGP phase, with crossover & the 1st-order phase transition

Parton-Hadron String Dynamics (PHSD)

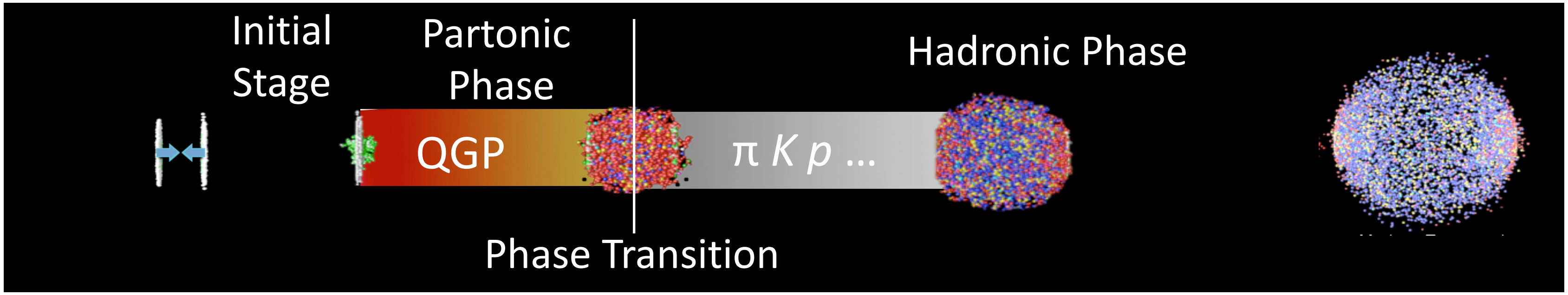
- Partonic and hadronic degrees of freedom
- QGP phase is assumed
- Crossover phase transition between QGP and hadron gas

Jet AA Microscopic (JAM) Model

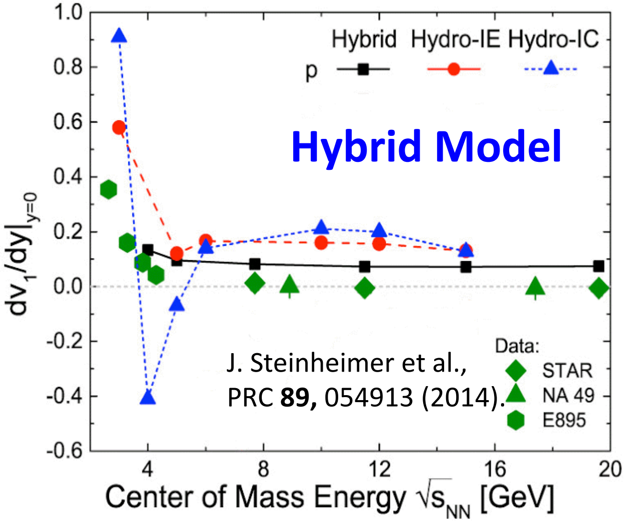
- Hadronic degrees of freedom
- No QGP
- The 1st-order phase transition is mimicked by attractive scattering, generating a 'softening' near phase boundary

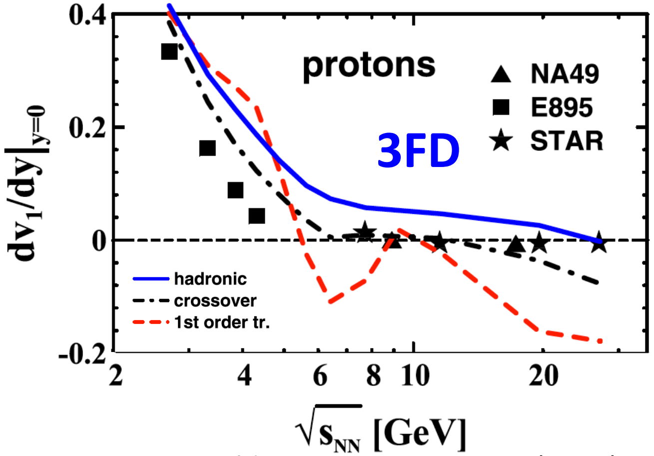
Three Fluid hydro model (3FD)

- Partonic and hadronic degrees of freedom
- Crossover & the1st-order phase transition



Selected literature - Theory

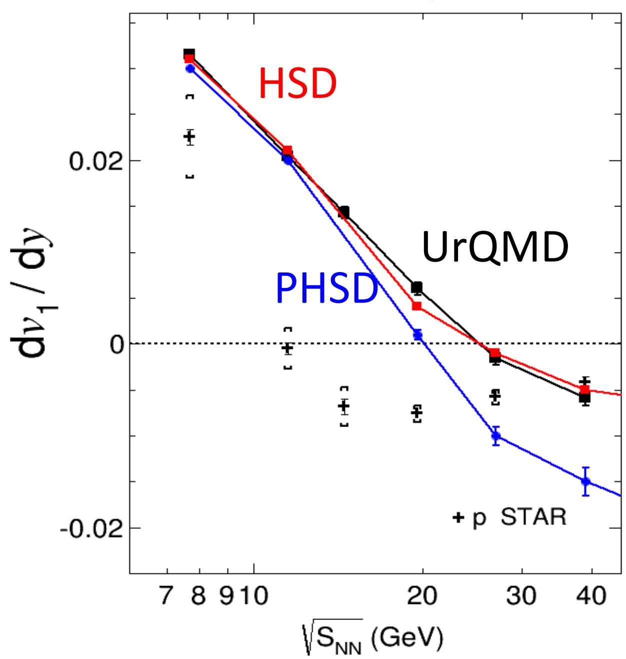




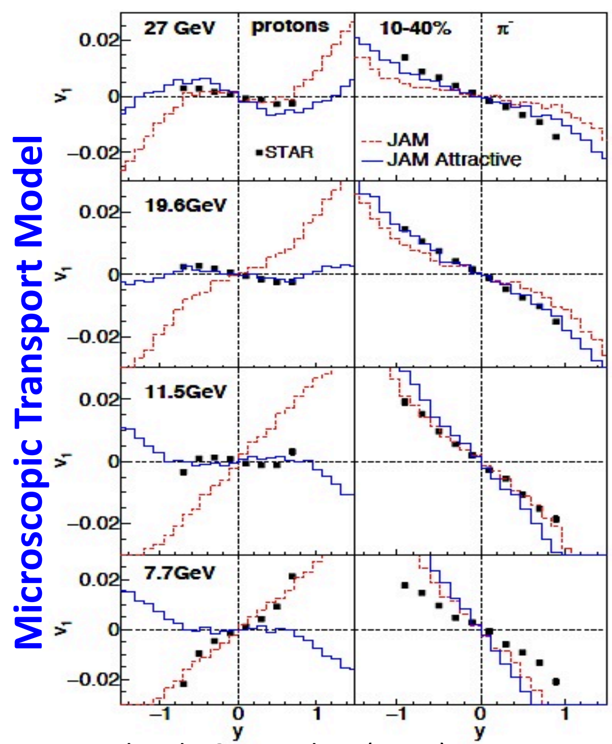
Ivanov & Soldatov PRC 91, 024915 (2015)

- Hadronic transport, Hydrodynamic, Hybrid, microscopic off-shell transport approach, 3FD – all show poor agreement with key feature of data.
- JAM model with attractive potential shows reasonable qualitative agreement above 10 GeV; authors argue it favors the 1st-order PT

Parton-Hadron-String Dynamics

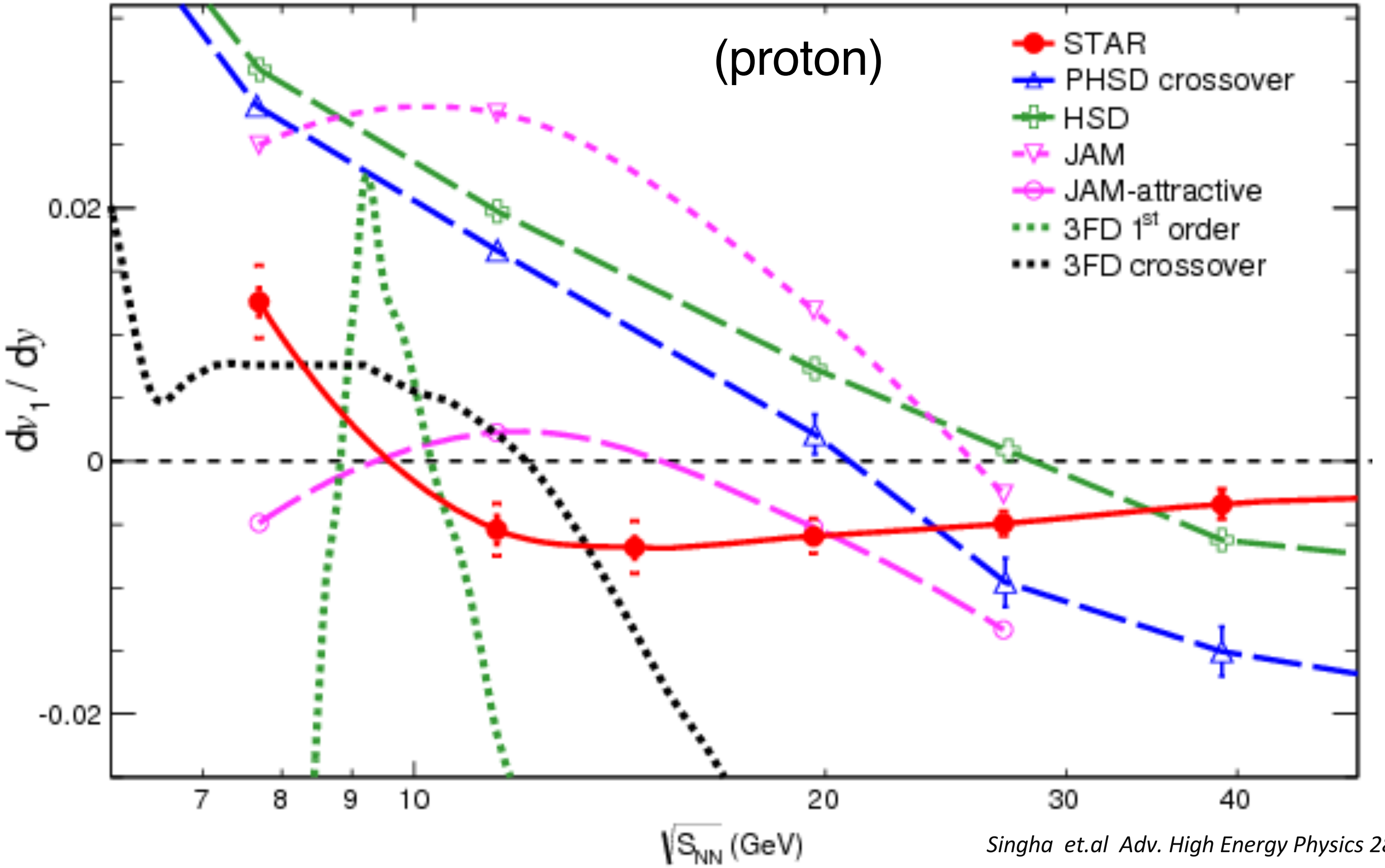


V. P. Konchakovski *et al.* PRC **90,** 014903 (2014)



Nara, Ohnishi & Stoecker, (2016) arXiv:1601.07692

Energy dependence dv_1/dy with models - Protons



Singha et.al Adv. High Energy Physics 2836989 (2016)
Frankfurt hybrid: J. Steinheimer et al., PRC 89, 054913 (2014)
3 FD: Y. Ivanov et al., PRC 91, 024915 (2015)
PHSD: V. Konchakovski et al., PRC 90, 014903 (2014)
HSD: W. Cassing et al, arXiv: 1408.4313
UrQMD: S. Bass et al, Prog. Part. Nucl. Phys 41, 255, (1998)
JAM: Y. Nara et al., arxiv: 1601.07692

→ **Present models can not reproduce the trend observed in data**
→ **More theoretical progress is needed in this direction**