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

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STAR

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Outline

❖ Motivation

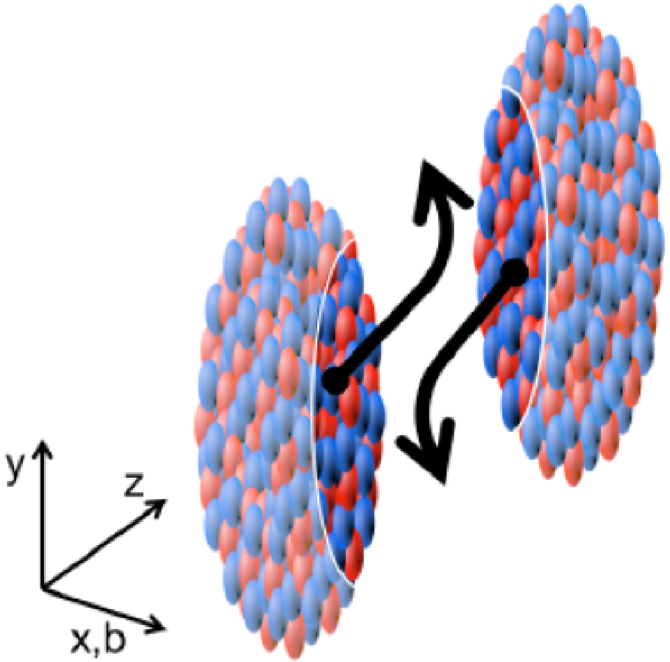
❖ v_1@BES for 10 particle species

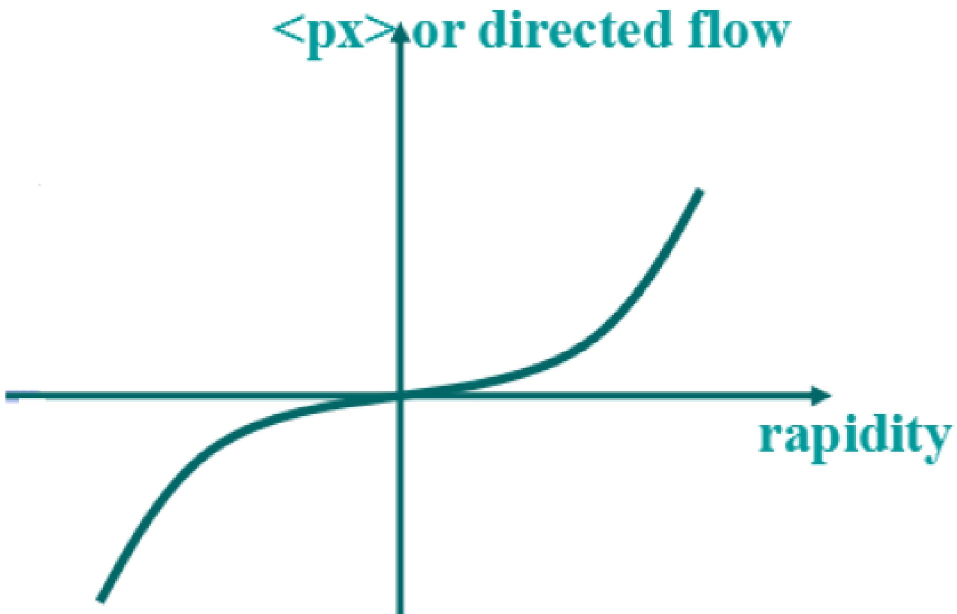
❖ Test of the coalescence picture

❖ v_1 of quarks

❖ Summary

Directed flow (v_1)



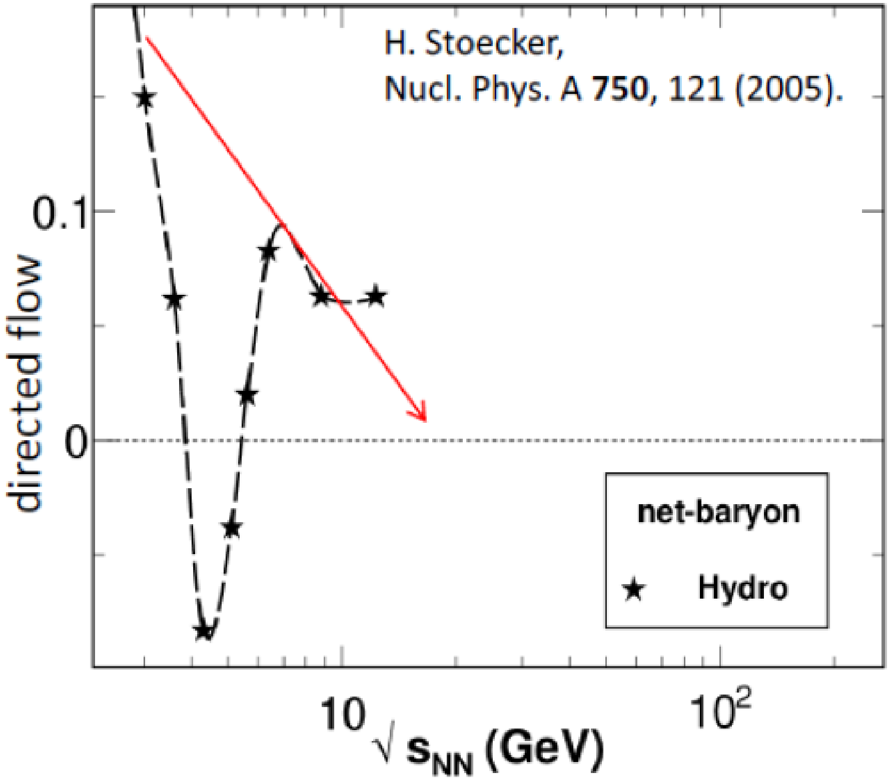


This example mostly applies to baryon transport. Other mechanisms could cause an opposite sign of v_1.

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

- Directed flow (v_1) describes the sideward collective motion of the particles within the reaction plane (x-z plane)
- Generated during the nuclear passage time ($2R/\gamma$)
- Probes the very earliest stage of the collision dynamics

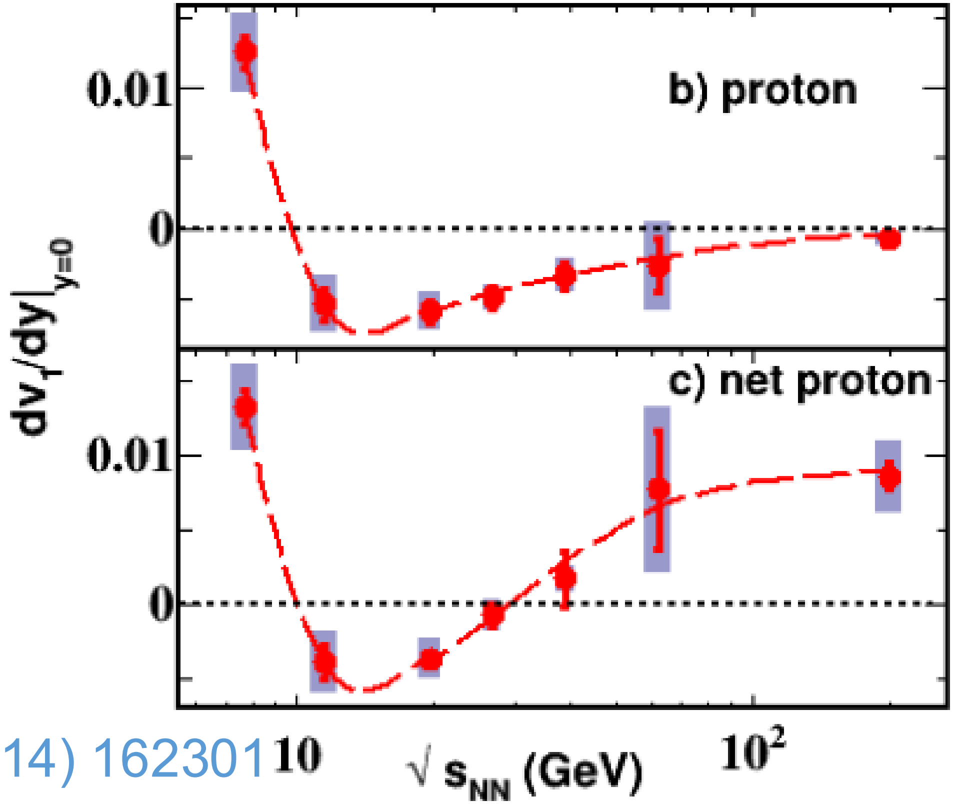
Softest point



- "Softest Point" in EOS => a minimum in the ratio of pressure to energy density
- Strong softening consistent with the 1st-order PT
- Weaker softening is more likely due to crossover

Y. Nara, H. Niemi, J. Steinheimer, and H.Stöcker, Phys. Lett. B769 (2017) 543.
Yu. B. Ivanov and A. A. Soldatov, Phys. Rev. C91 (2015) 024915.

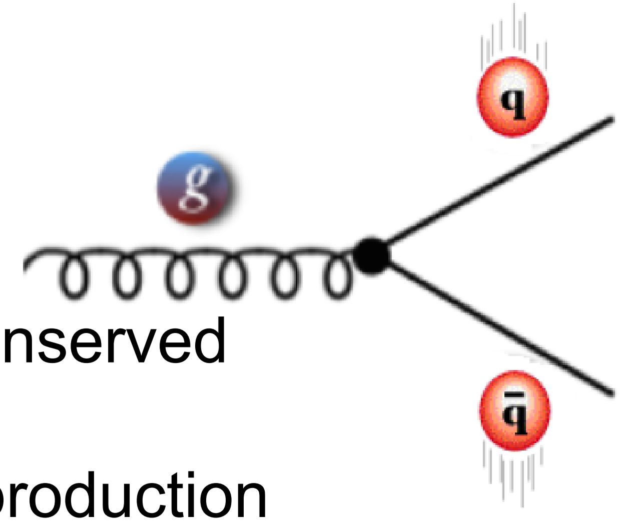
- Equation of State without phase transition (PT): a monotonic trend
- Equation of State assuming 1st-order PT: a dip in v_1 as a function of beam energy



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

produced vs transported

- **u**, **ū**, **d**, **đ**, **s** and **s̄**

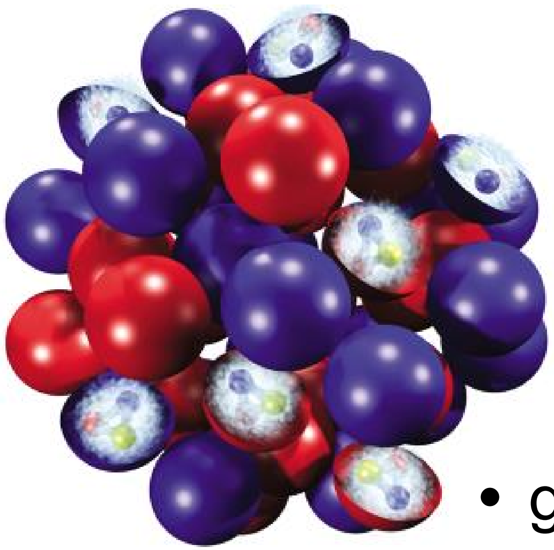


- pair production
- total number not conserved
- different waves of production

S. Pratt, PoS CPOD2013 (2013) 023

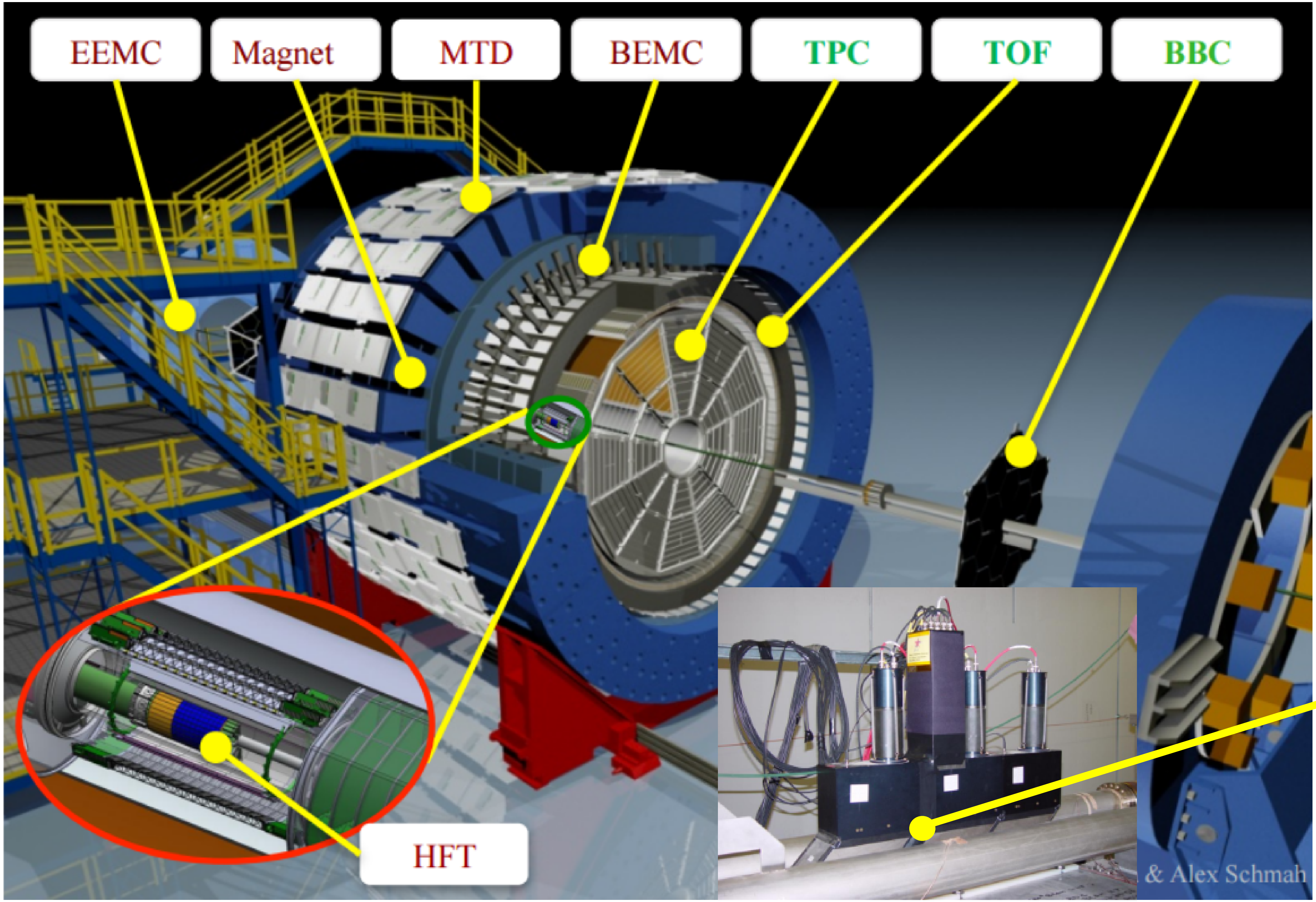
- may or may not be sensitive to the softening of EOS
- dominant at high collision energies
- can be studied via "produced" particles, such as anti-p, anti-Λ, K^- and φ

whose constituent quarks are all produced



- **u** and **d** only
- from projectile nucleons
- total number conserved
- go thru 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

STAR detectors



Detectors used here:

Time Projection Chamber
- Tracking
- Full azimuthal coverage
- $|\eta| < 1$ coverage
- PID for lower momenta

Time-Of-Flight
- PID for higher momenta

Beam-Beam Counter
- 1st-order event plane for lower beam energies

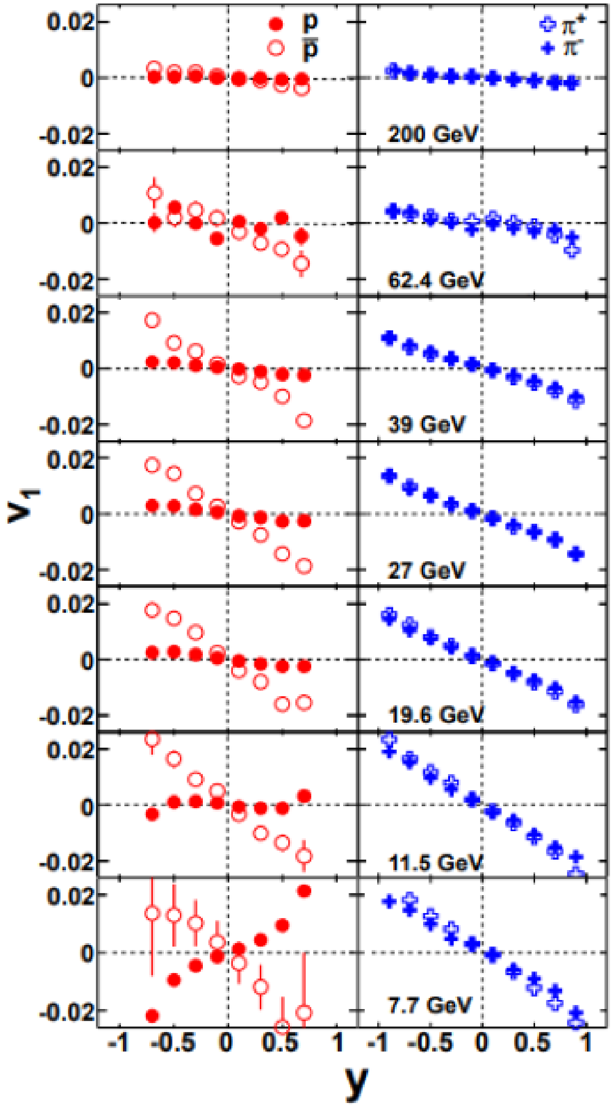
Zero Degree Calorimeter Shower Max Detector
- 1st-order event plane for 200 GeV and 62.4 GeV

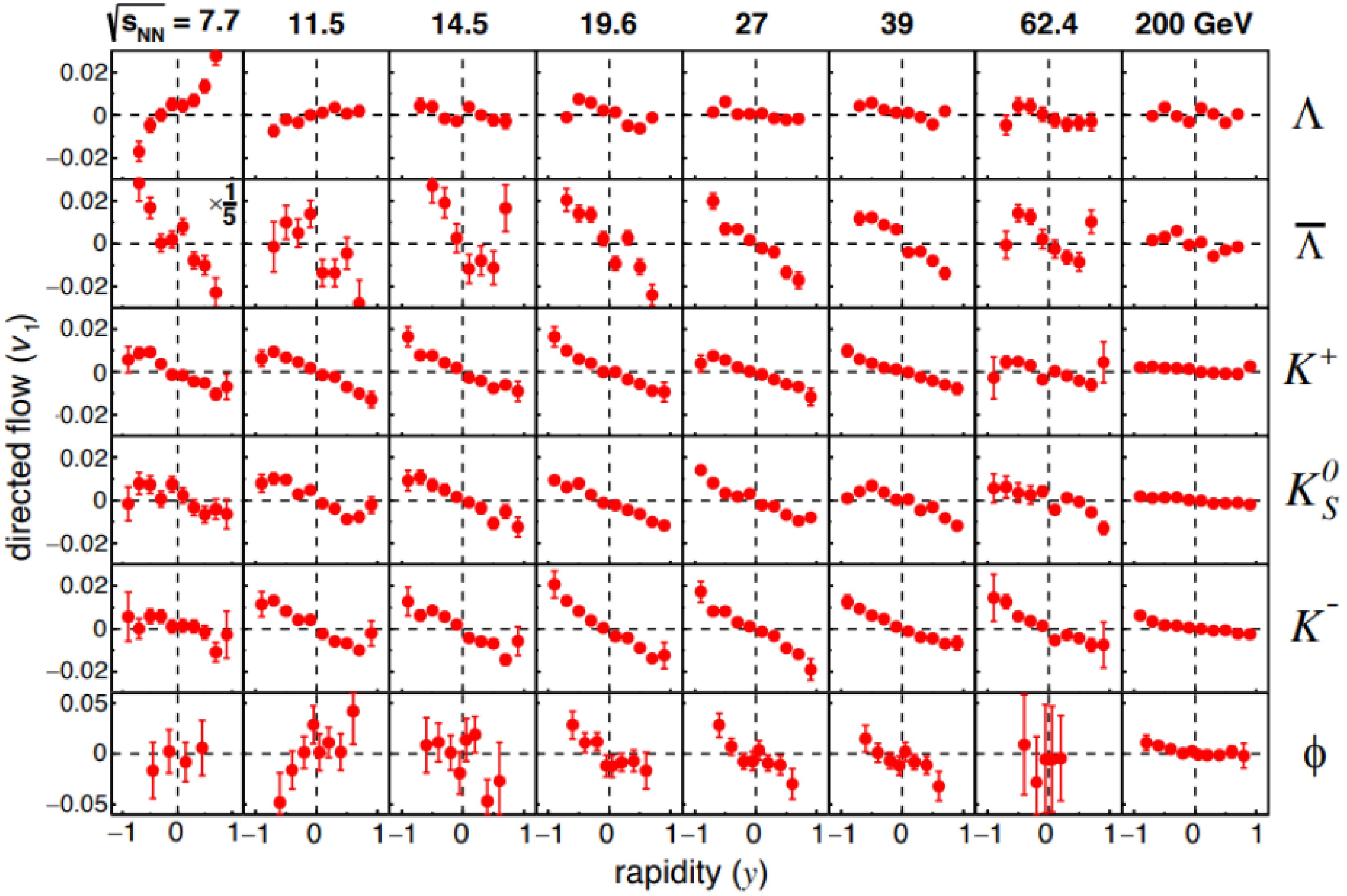
$v_1(y)$: 10 species & 8 energies

10-40% Au+Au collisions.

STAR, Phys. Rev. Lett. **112** (2014) 162301; Phys. Rev. Lett. **120** (2018) 62301

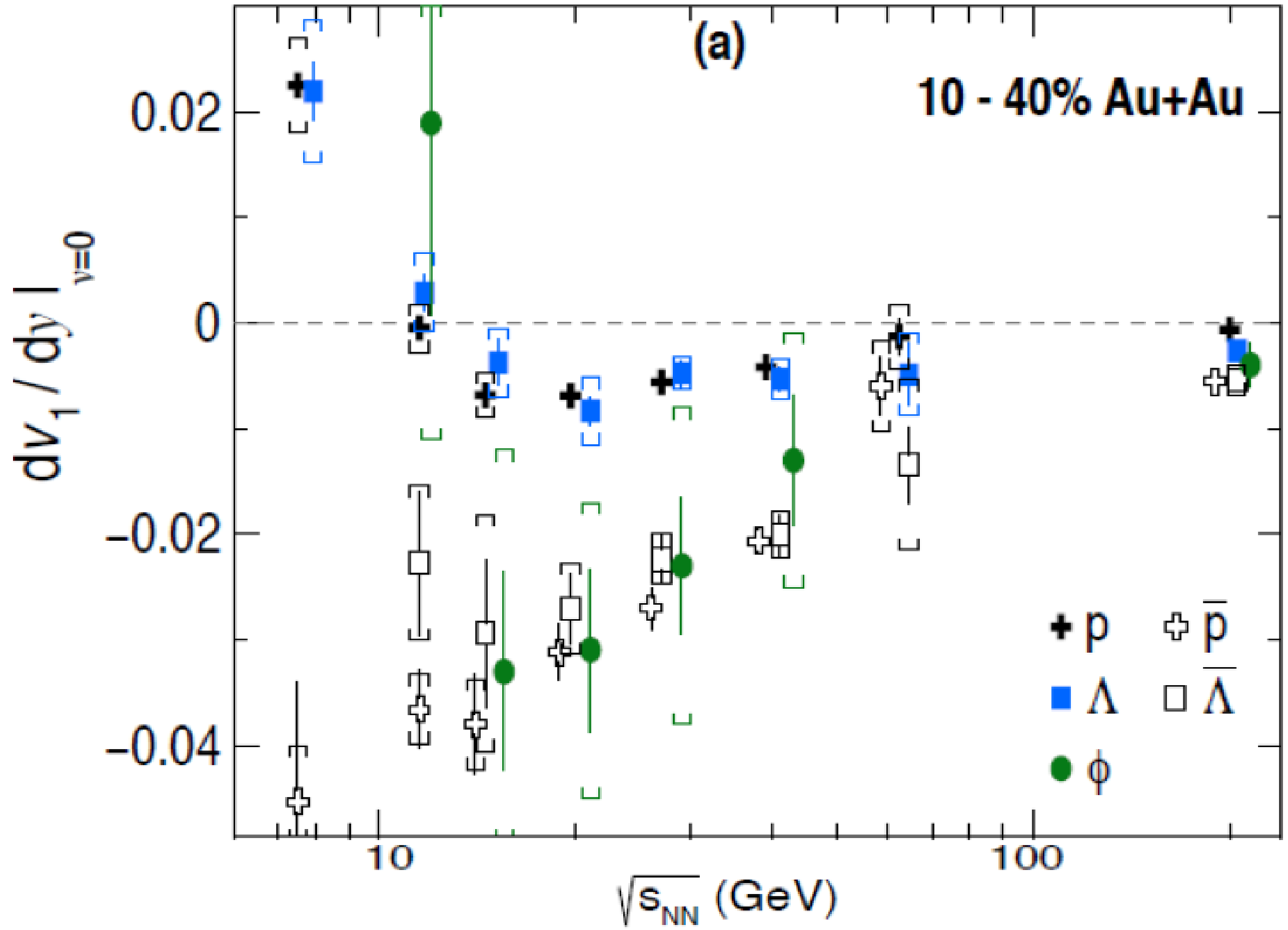
To extract v_1 slope, use linear fit over $|y| < 0.6$ for Φ and over $|y| < 0.8$ for all other species.

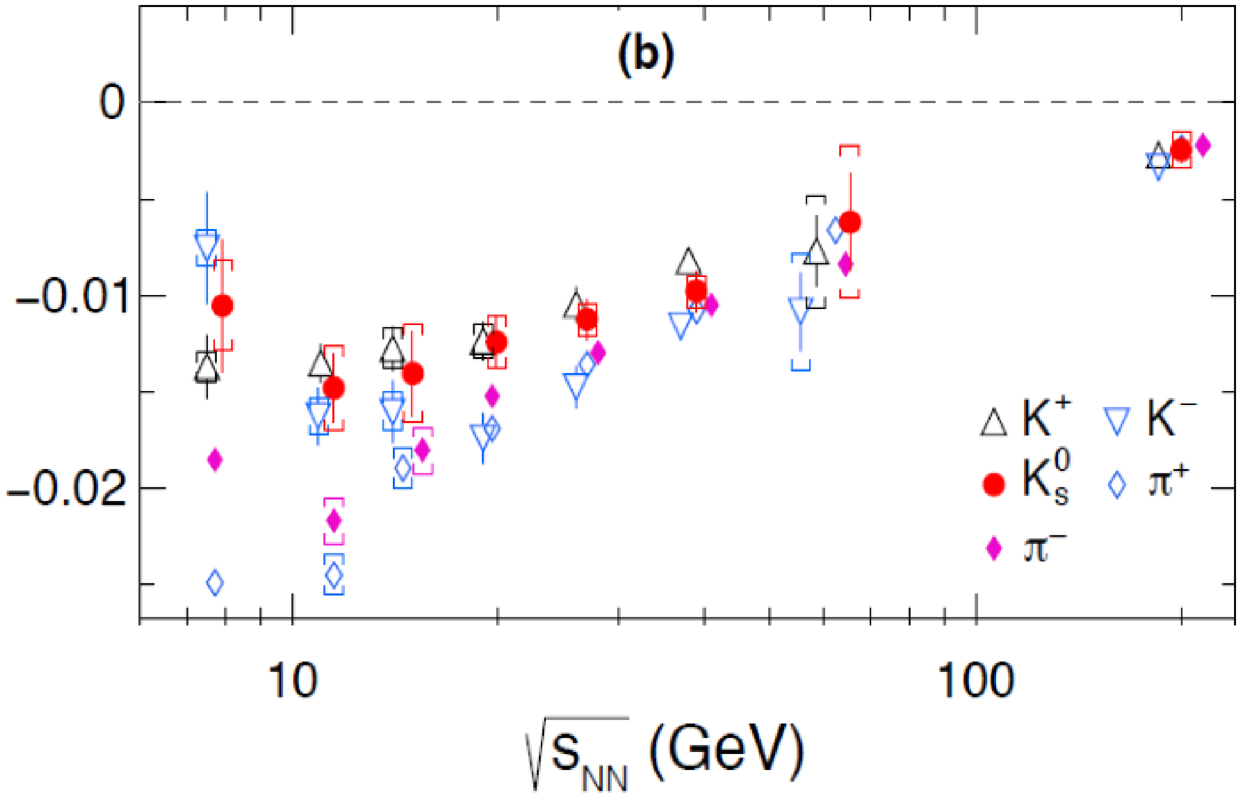




dv_1/dy vs beam energy

STAR, Phys. Rev. Lett. **120** (2018) 62301



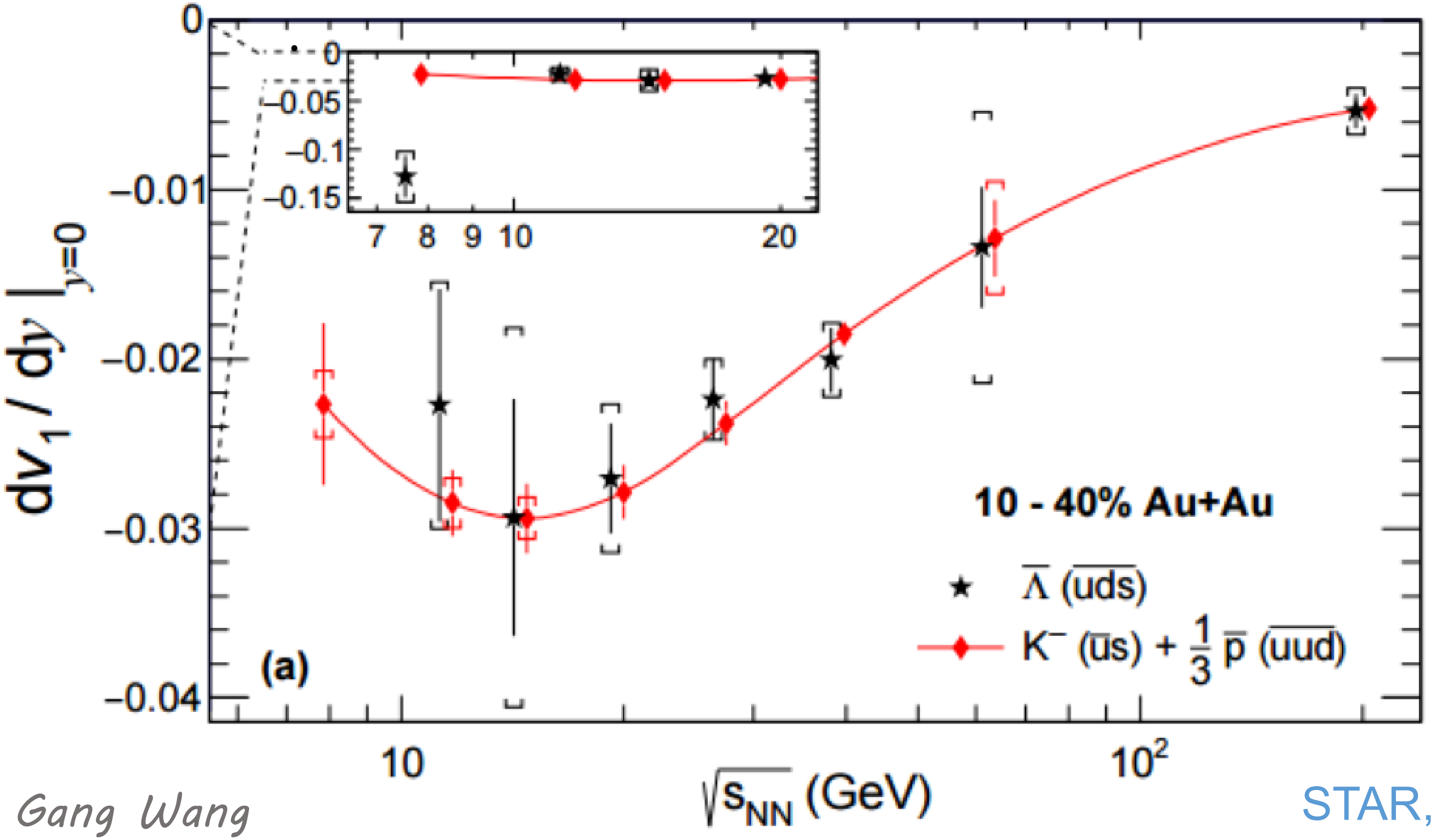


- dv_1/dy for Λ follows proton, and changes sign in the same region $\sqrt{s_{NN}}$ < 14.5 GeV
- Purely produced particles (anti-p, anti-Λ, Φ) show similar behavior above 14.5 GeV
- Mesons show negative dv_1/dy

Coalescence sum rule: "produced" particles

Assumptions:

- v_1 is developed in prehadronic stage
- Hadrons are formed via coalescence: $(v_n)_{hadron} = \Sigma(v_n)_{constituent\ quarks}$
- $(v_1)_{\bar{u}} = (v_1)_{\bar{d}}$ and $(v_1)_s = (v_1)_{\bar{s}}$

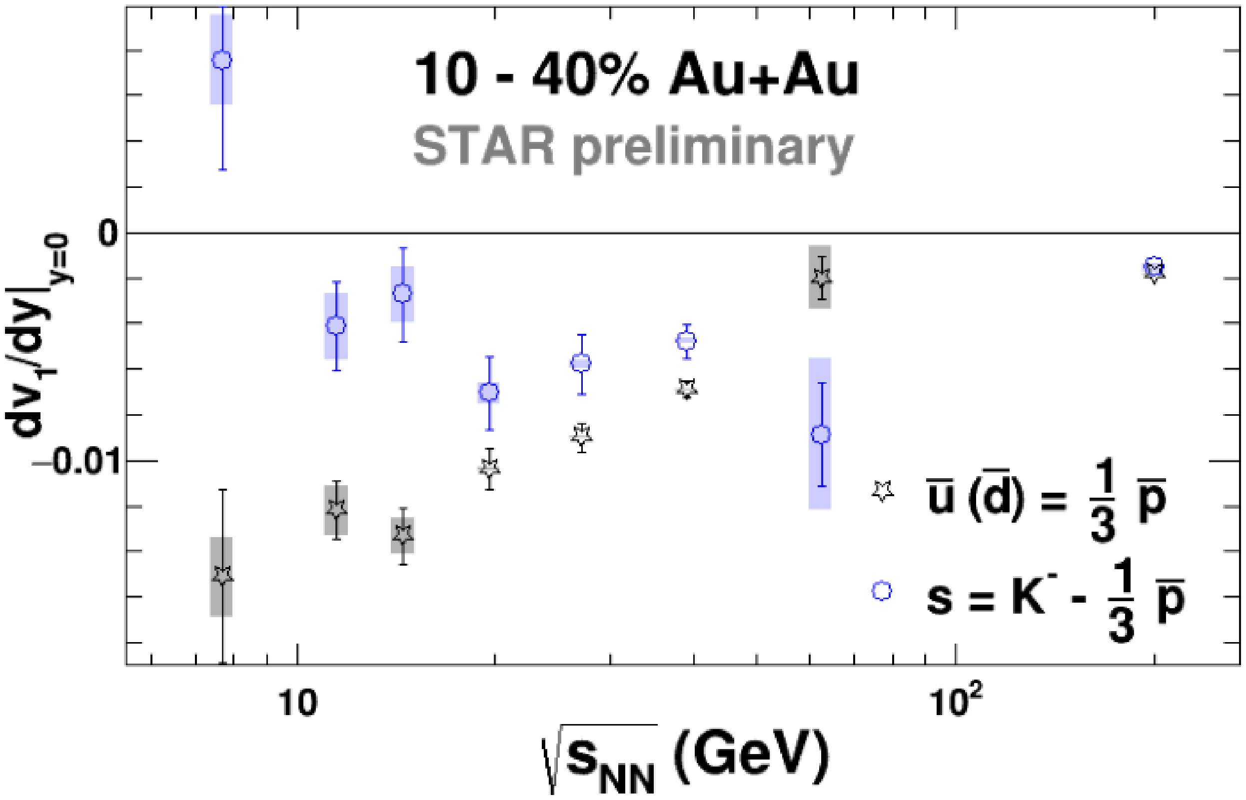


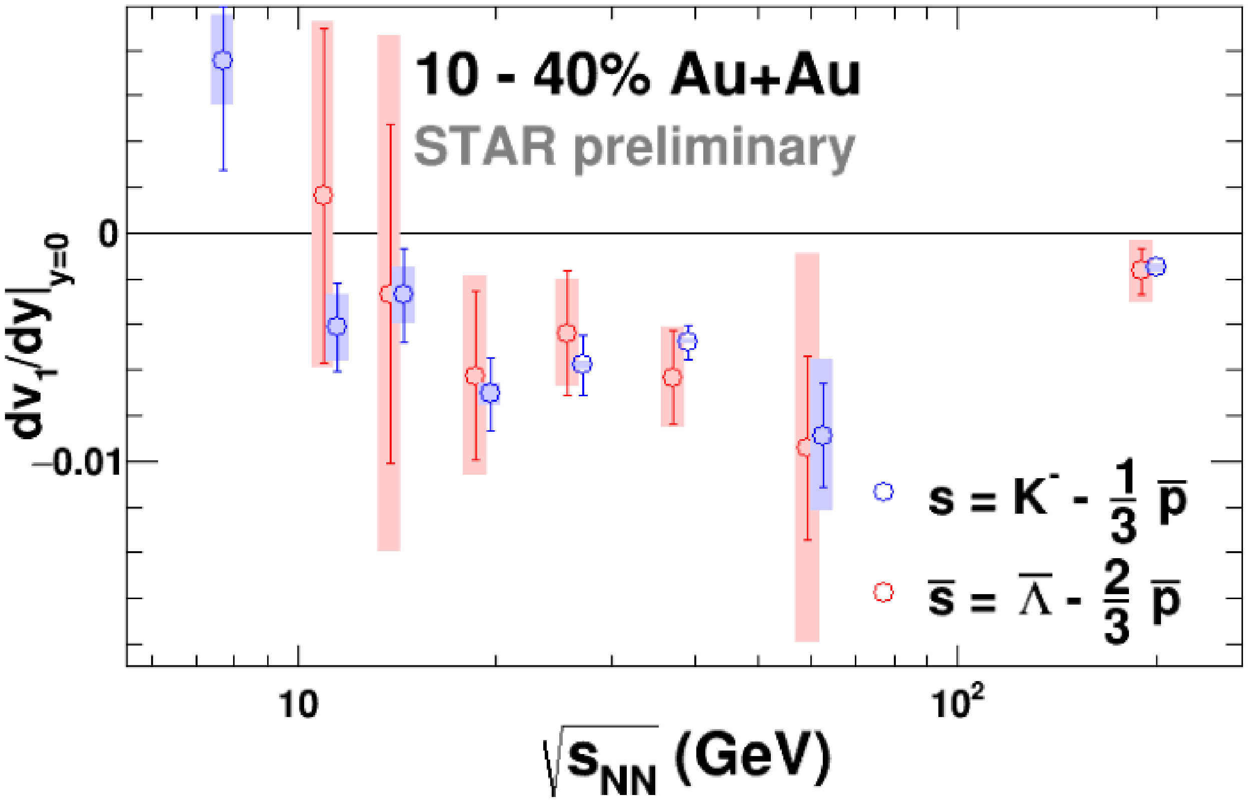
- Constituent quarks of anti-p, anti-Λ and K^- are all produced in the collision.
- For anti-Λs, prediction using coalescence sum rule agrees with measured v_1 above $\sqrt{s_{NN}}$ = 11.5 GeV.
- Disagreement at 7.7 GeV implies the failure of one or more of the assumptions below 11.5 GeV.

STAR, Phys. Rev. Lett. **120** (2018) 62301

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

If the coalescence picture works, then...



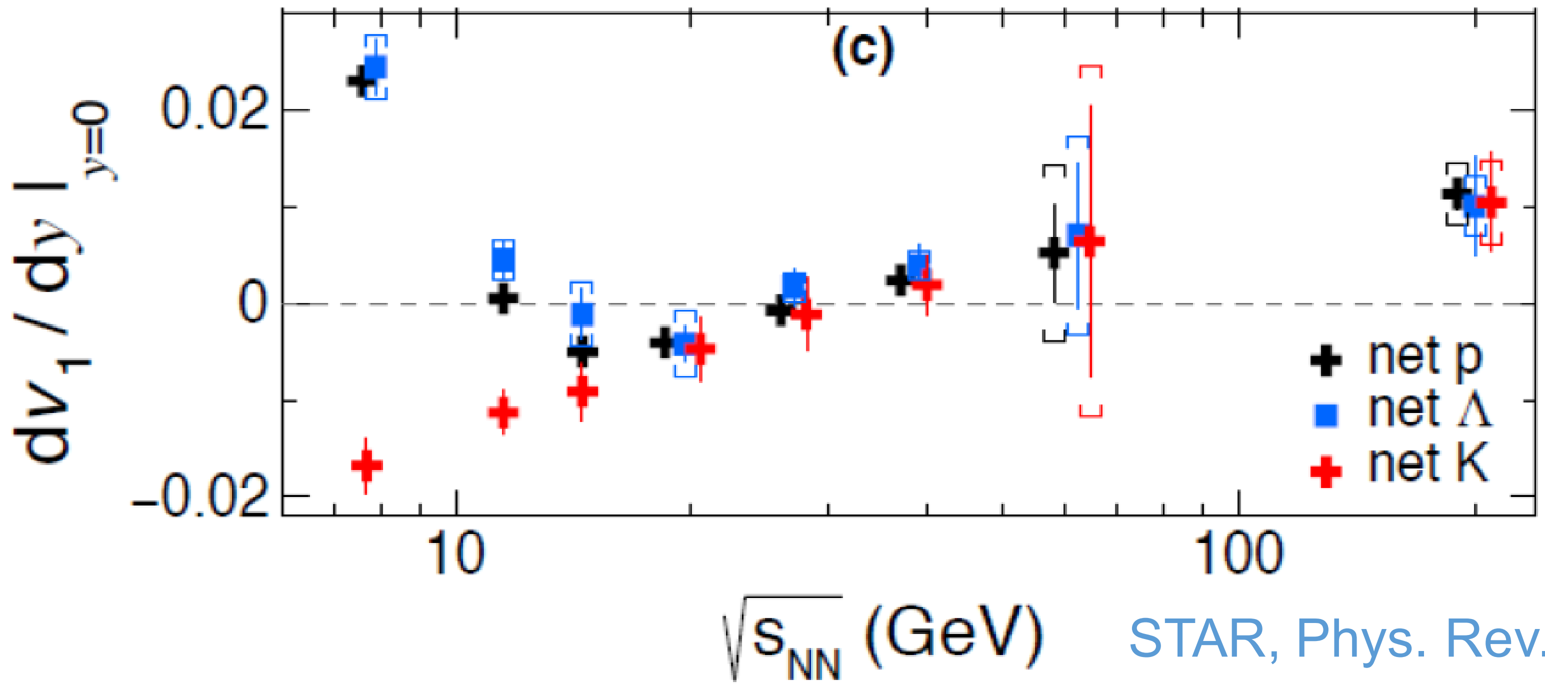


- **ū**(**đ**) and **s** quarks have similar dv_1/dy at 200 GeV, and deviate at lower energies.
- **s** and $\bar{\mathbf{s}}$ quarks are consistent with each other, except at the lowest energy.
  - At 7.7 GeV, v_1 slope of $\bar{\mathbf{s}}$ is -0.097 ± 0.023(stat.) ± 0.026(syst.) (far off the scale).

$v_1(y)$ slope: net particles

- "Net particle" represents the excess yield of a particle species over its antiparticle.
- Net particles are more directly related to the transported quark number.

transported from projectile nucleons



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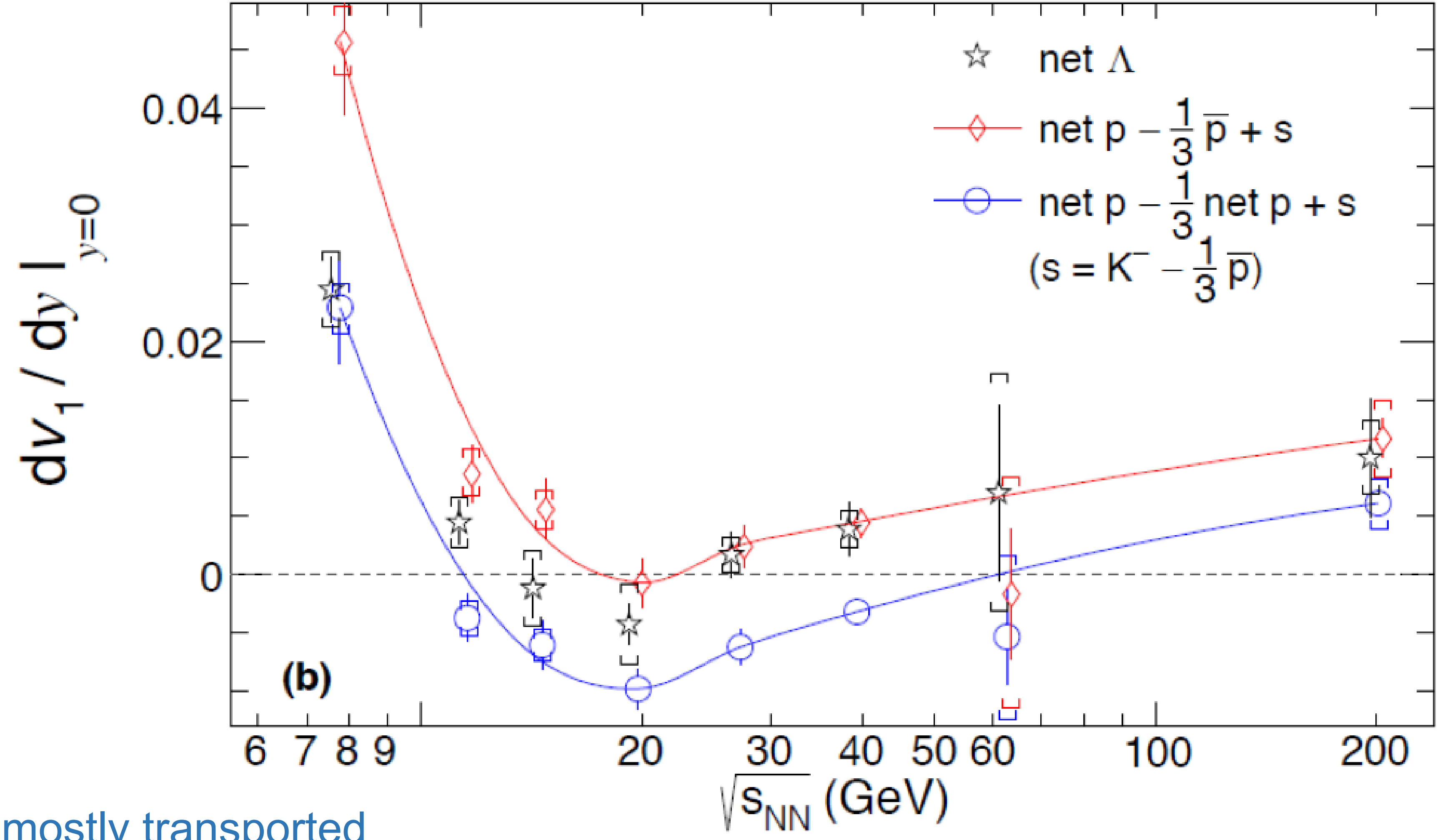
$$[v_1(y)]_{net-p} = \frac{[v_1(y)]_p - r(y)[v_1(y)]_{\bar{p}}}{1-r(y)}$$

r(y): the ratio of the observed anti-p to p yield at each collision energy.

For net Λ and net K:
p is replaced with Λ and K^+, respectively;
anti-p is replaced with anti-Λ and K^-, respectively.

Coalescence sum rule: net particles



For net particles that contain transported quarks, we replace a **u** quark in net p with an **s** quark to reproduce net-Λ in two scenarios.

1) the **u** quark (being replaced) was **produced**: works at higher energies.

2) all the quarks in net p have the same v_1 (**mostly transported**): works at the lowest energy.

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$$\underbrace{\text{net p} - \tfrac{1}{3}\,\text{net p} + \text{s} \qquad\qquad \text{net p} - \tfrac{1}{3}\,\overline{\text{p}} + \text{s}}_{\text{net }\Lambda}$$

mostly transported (low energy limit)

produced (high energy limit)

Number of transported u+d per net proton

Assume $\mu_{u(d)} = \mu_B / 3$, and then statistically in a net proton,

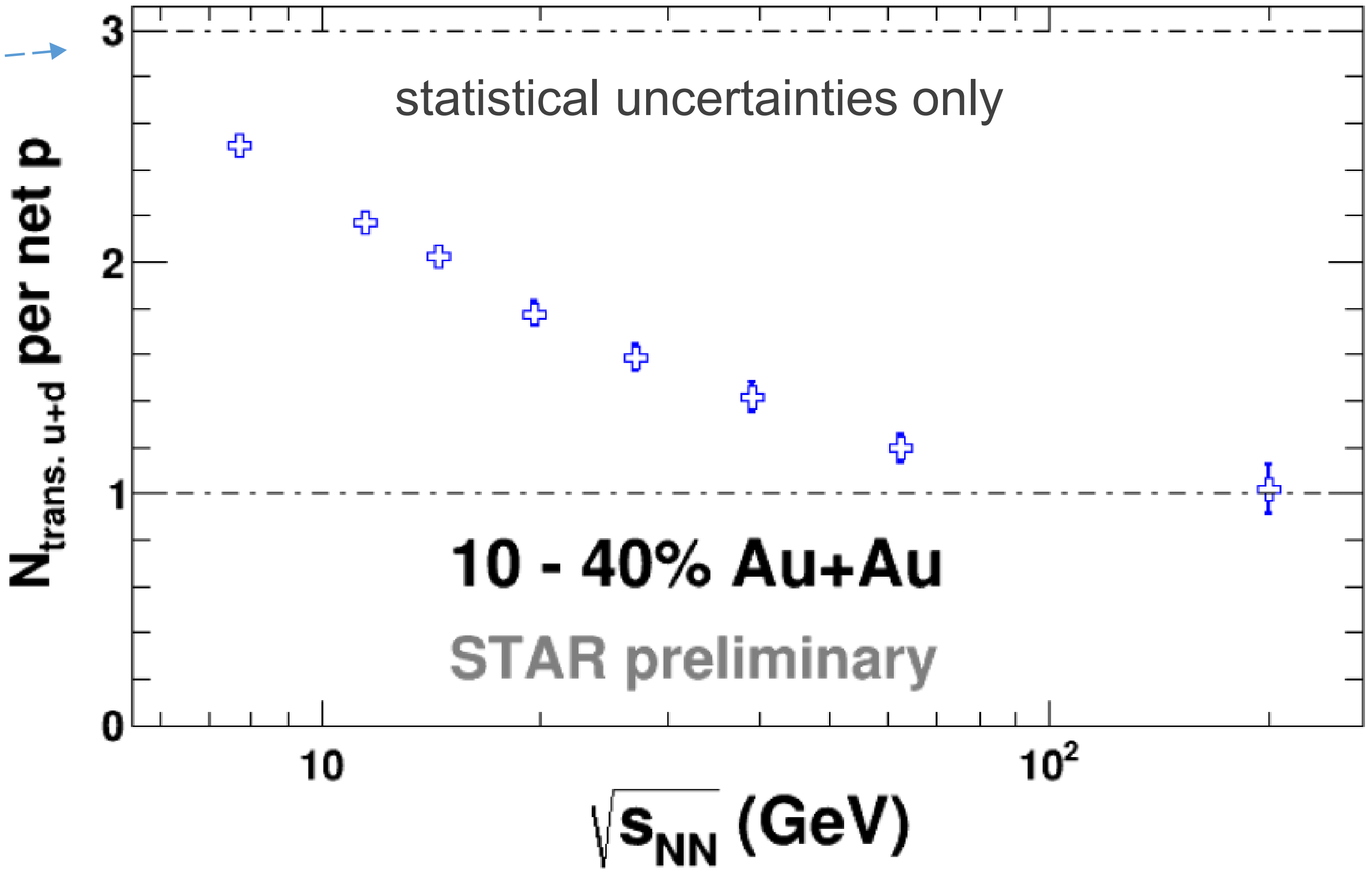
$$N_{trans.\ u+d} = 3 * [1 - \exp(-2\mu_{u(d)} / T_{ch})] / (1 - r_{anti\text{-}p/p}).$$

μ_B and T_{ch} values have been published by STAR.

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

$r_{anti\text{-}p/p}$ is the ratio of observed anti-p to proton yield at each energy.

low energy limit

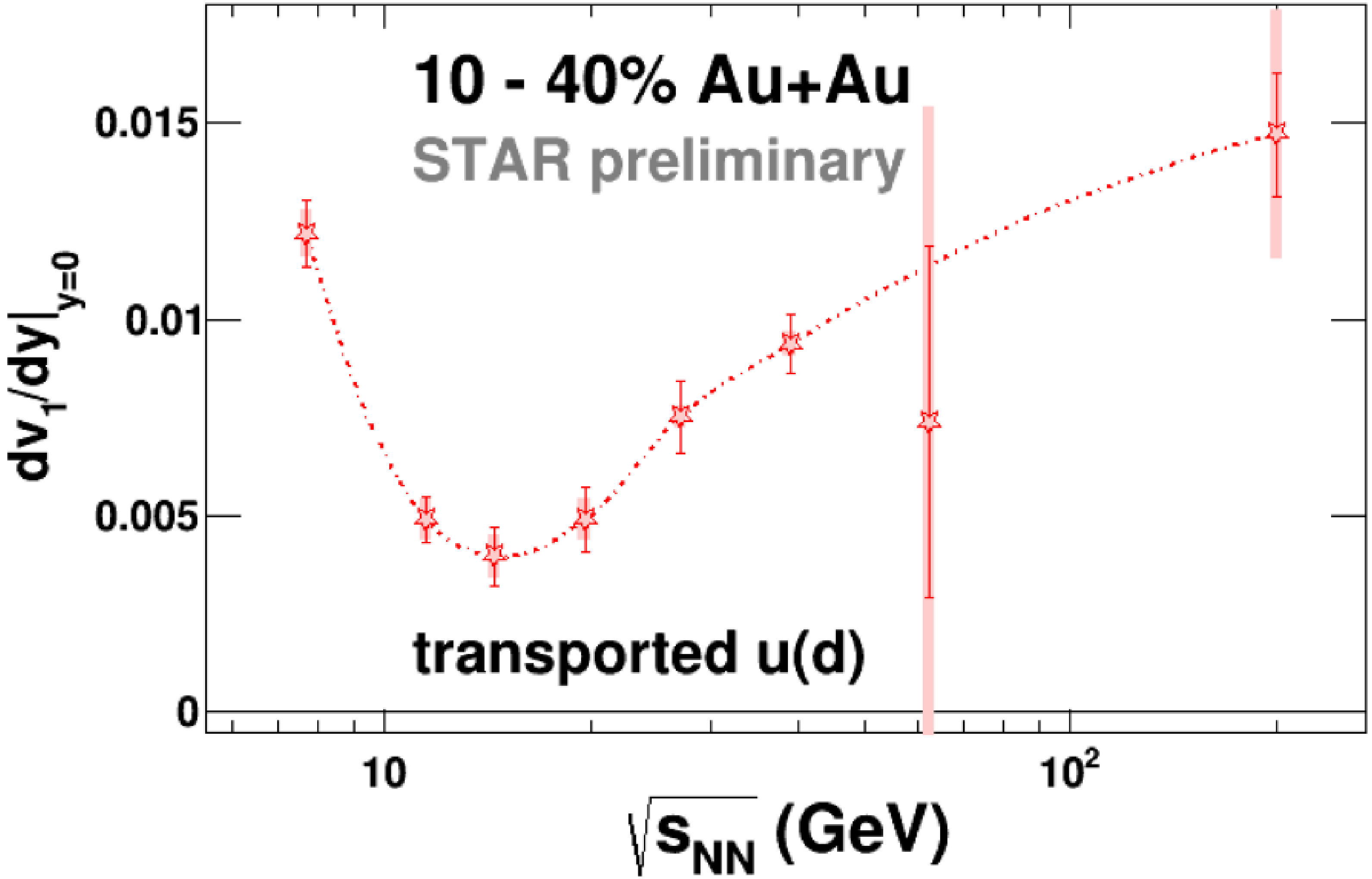


high energy limit

v_1 of transported u(d) quarks

$(v_1)_{trans.\ \mathbf{u(d)}} = [(v_1)_{net\ p} - (3 - N_{trans.\ \mathbf{u+d}}) * (v_1)_{\bar{u}(\bar{d})}] / N_{trans.\ \mathbf{u+d}}$

v_1 of transported **u**(**d**) is positive for all beam energies.



v_1 of transported u(d) quarks

$(v_1)_{\text{trans. } \mathbf{u(d)}} = [(v_1)_{\text{net p}} - (3 - N_{\text{trans. } \mathbf{u+d}}) * (v_1)_{\bar{u}(\bar{d})}] / N_{\text{trans. } \mathbf{u+d}}$

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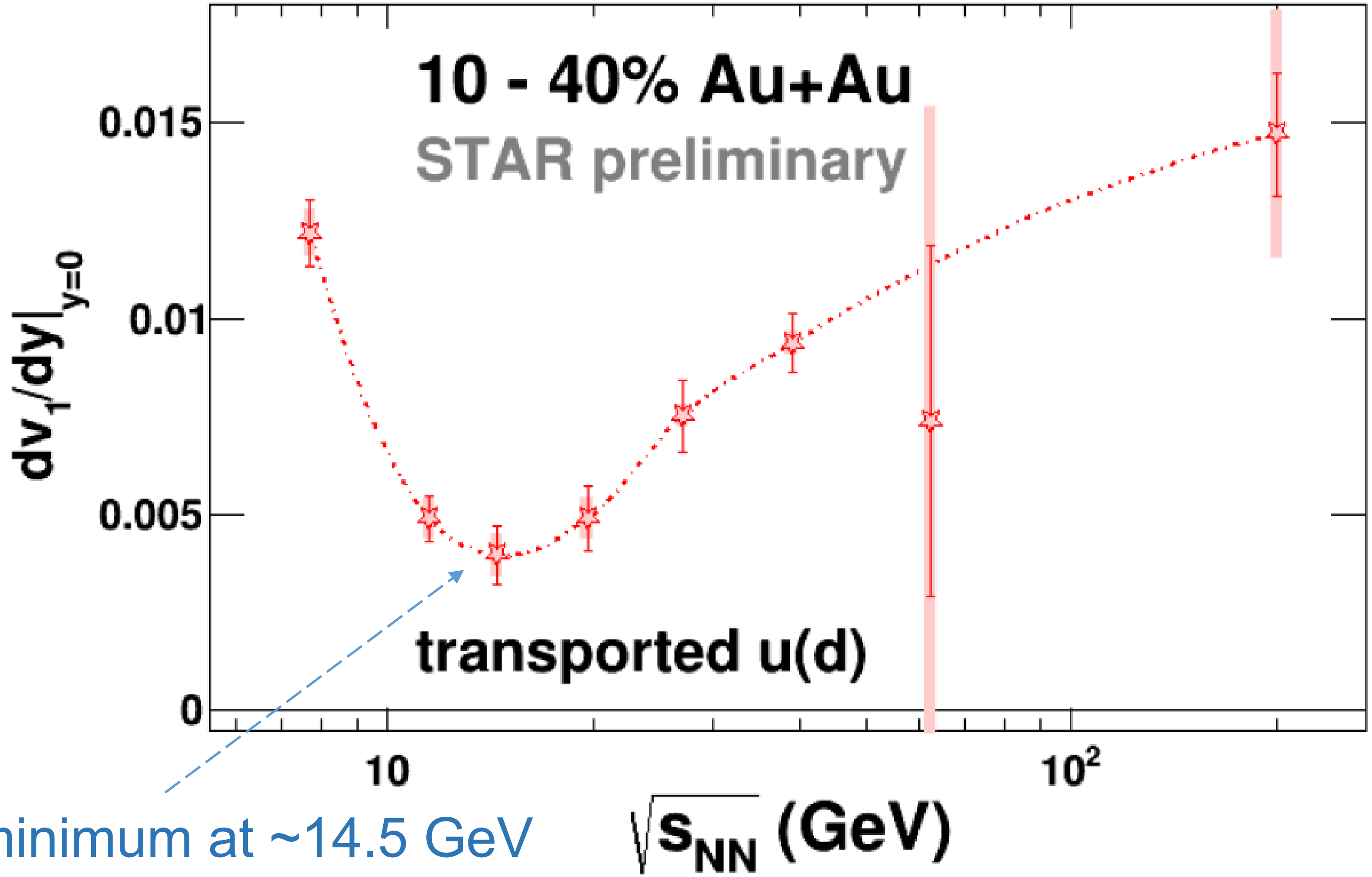


A minimum at ~14.5 GeV

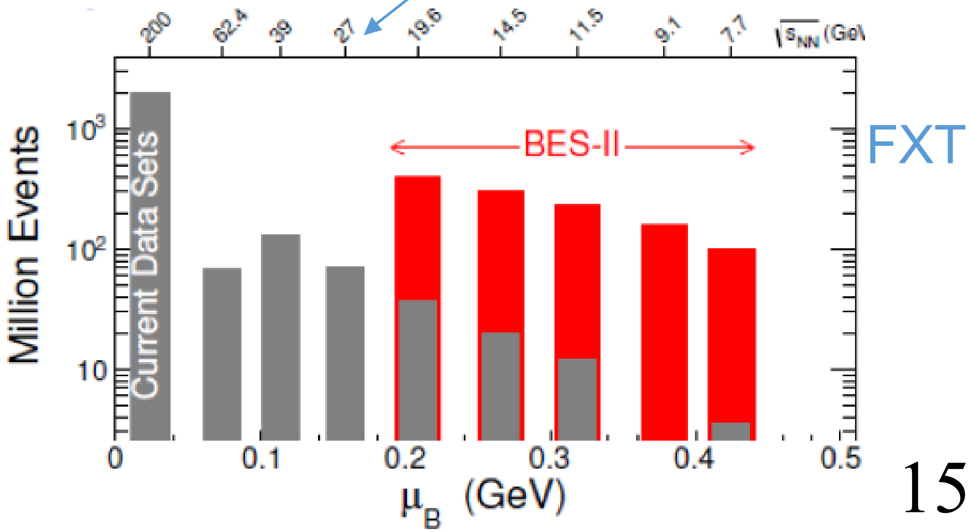
Summary

- 10 species & 8 energies allow a detailed study of constituent-quark v_1.
- In most cases, the coalescence picture works for both "produced" particles and net particles.

  whose constituent quarks are all produced

  - the scaling behavior holds for produced quarks at and above 11.5 GeV, but breaks down at 7.7 GeV.
- v_1 of produced quarks
  - $\mathbf{u/\bar{u}/d/\bar{d}}$ and **s** are close to each other at 200 GeV, and deviate at lower energies.
  - **s** and $\mathbf{\bar{s}}$ are consistent with each other, except at 7.7 GeV.

this year!



- v_1 of transported quarks
  - $N_{\mathrm{trans.}\,\mathbf{u+d}}$ per net proton is estimated.
  - a minimum at ~14.5 GeV.

  evidence of the softest point?

- BES-II & detector upgrades (EPD, eTOF, iTPC)

Backup slides

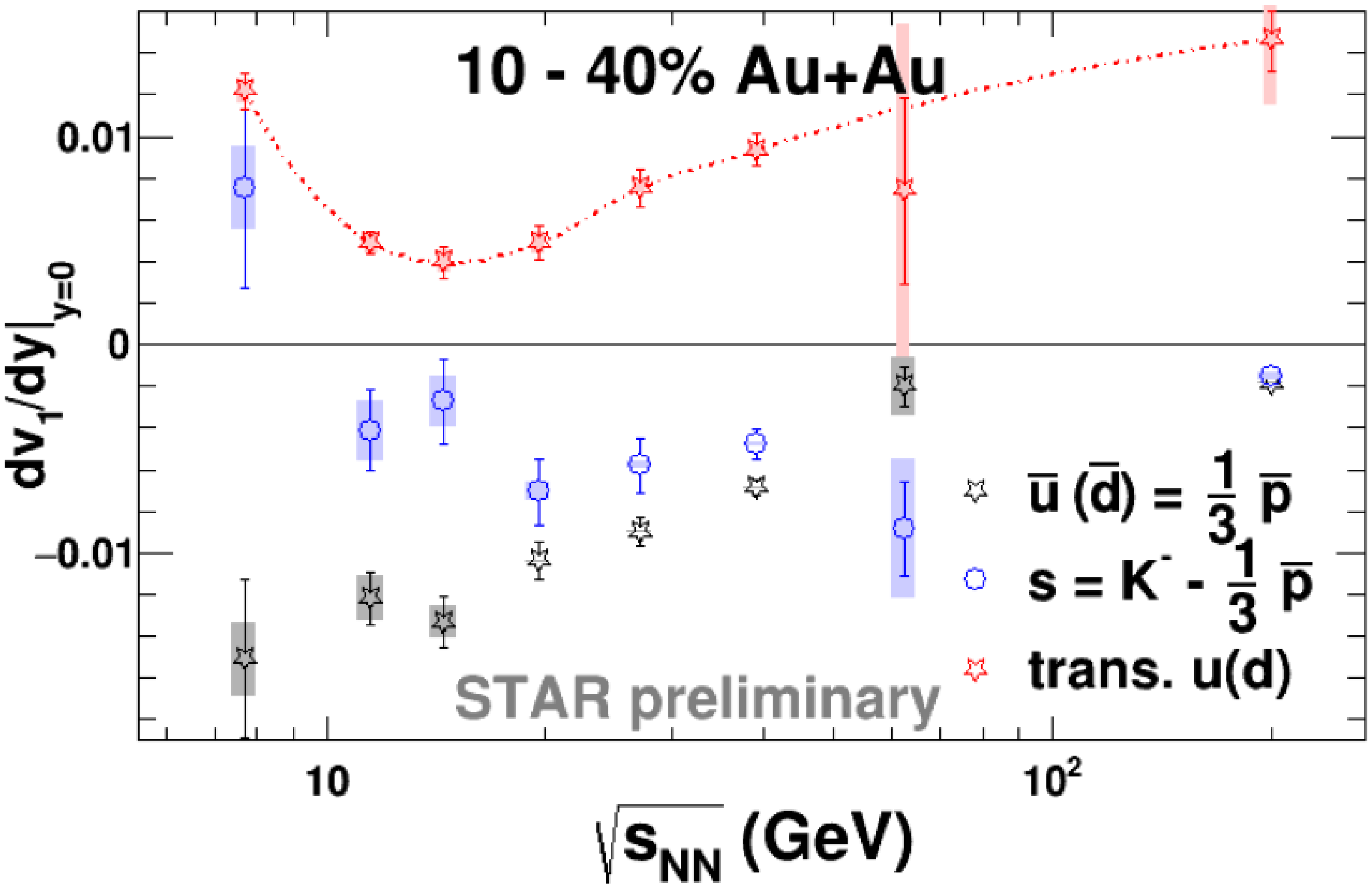
Comparison: different types of quarks

s and transported **u**(**d**) are close to each other at 7.7 GeV (the associated production?)

p -> Λ + K+ (**uud** -> **uds** + **u** $\bar{\mathbf{s}}$)

It looks like the s follows a transported **u**.

Then the **s** quark enters other strange hadrons in the medium.



Coalescence sum rule

We have a set of assumptions, namely that v_1 is imparted while quarks are deconfined, that specific types of quarks have the same v_1 in the QGP, and that the detected hadrons form via statistical coalescence.

The coalescence sum rule should apply to not only v_1, but also all other v_n: the v_n of a particle is the sum of the v_n of its constituent quarks. Take $\pi^+(u\bar{d})$ as an example, and ignore the normalization:

$$
\begin{aligned}
v_n^{\pi^+} &= \iiint \cos(n\varphi^{\pi^+})[1+2v_n^u \cos(n\varphi^u)][1+2v_n^{\bar{d}} \cos(n\varphi^{\bar{d}})]\delta(\varphi^{\pi^+}-\varphi^u)\delta(\varphi^{\pi^+}-\varphi^{\bar{d}})d\varphi^u d\varphi^{\bar{d}} d\varphi^{\pi^+} \\
&= \int \cos(n\varphi^{\pi^+})[1+2v_n^u \cos(n\varphi^{\pi^+})][1+2v_n^{\bar{d}} \cos(n\varphi^{\pi^+})]d\varphi^{\pi^+} \\
&\approx \int \cos(n\varphi^{\pi^+})[1+2(v_n^u + v_n^{\bar{d}})\cos(n\varphi^{\pi^+})]d\varphi^{\pi^+} \\
&= v_n^u + v_n^{\bar{d}}
\end{aligned}
$$

The δ-functions are due to the coalescence mechanism. The observed N_{cq} scaling for v_2 assumes all the quarks contribute the same v_2. In the v_1@BES study, we have less strict assumptions: we assume the produced u, d, ū and đ quarks all have the same v_1, and assume s and ŝ have the same v_1. However, the latter may not hold at low energies. For transported quarks, we assume the transported u and d have the same v_1.

Estimation with thermal equilibrium

With statistical thermal equilibrium, we have the chemical potentials of quarks:

$$\mu_{\mathbf{u}} = \mu_B / 3 + 2*\mu_Q / 3$$

$$\mu_{\mathbf{d}} = \mu_B / 3 - \mu_Q / 3$$

$$\mu_{\mathbf{s}} = \mu_B / 3 - \mu_Q / 3 - \mu_S$$

Courtesy of Jinfeng Liao

For each **u** quark, the fraction of the transported **u** quark is

$$f_{\mathbf{u}} = [\exp(\mu_{\mathbf{u}}/T) - \exp(-\mu_{\mathbf{u}}/T)] / \exp(\mu_{\mathbf{u}}/T) = 1 - \exp(-2*\mu_{\mathbf{u}}/T)$$

Boltzmann statistics is used here. Similar for $f_{\mathbf{d}}$ and $f_{\mathbf{s}}$.

The number of transported quarks per net proton is then

$$(2*N_p*f_{\mathbf{u}} + N_p*f_{\mathbf{d}}) / (N_p - N_{anti\text{-}p}) = (2*f_{\mathbf{u}} + f_{\mathbf{d}}) / (1 - r_{anti\text{-}p/p})$$

In our current data handling, we ignore the difference between u and d, so we take

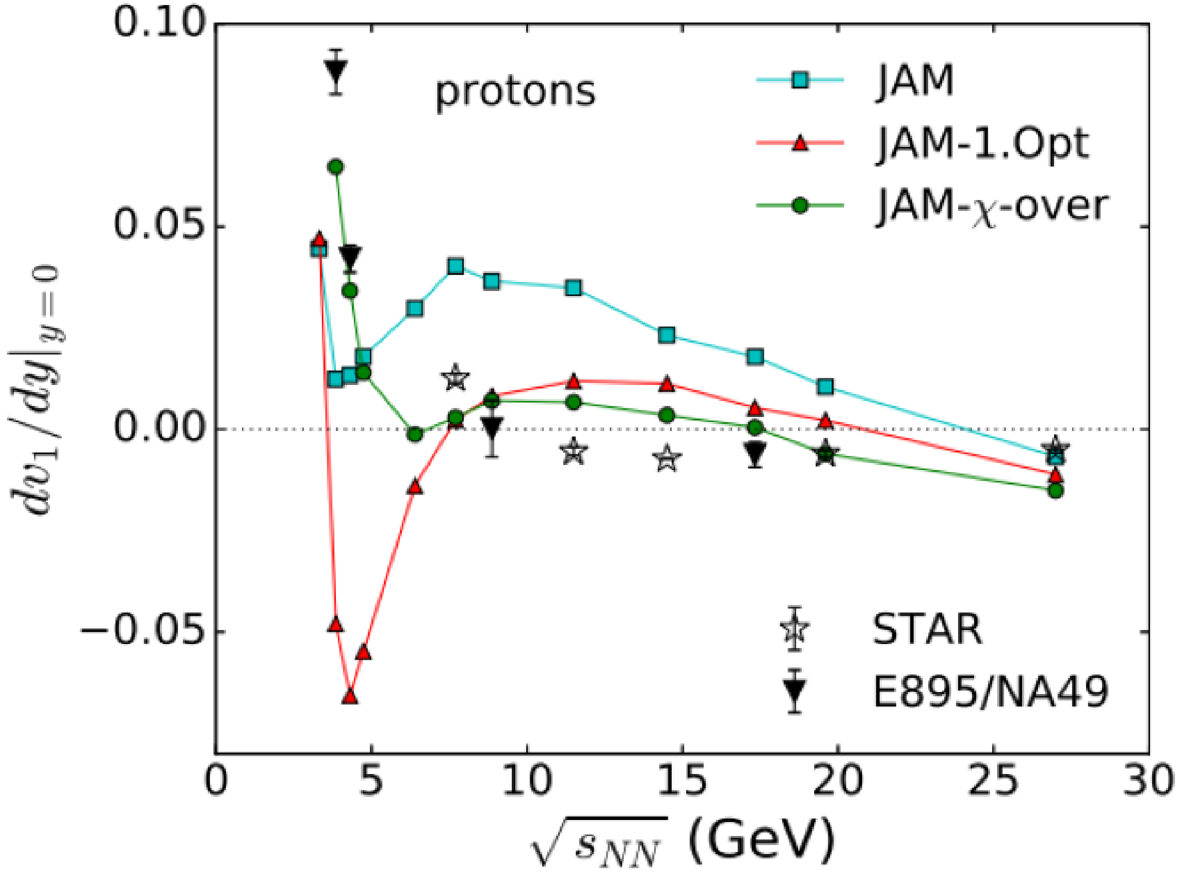
$$\mu_{\mathbf{u}(\mathbf{d})} = \mu_B / 3$$

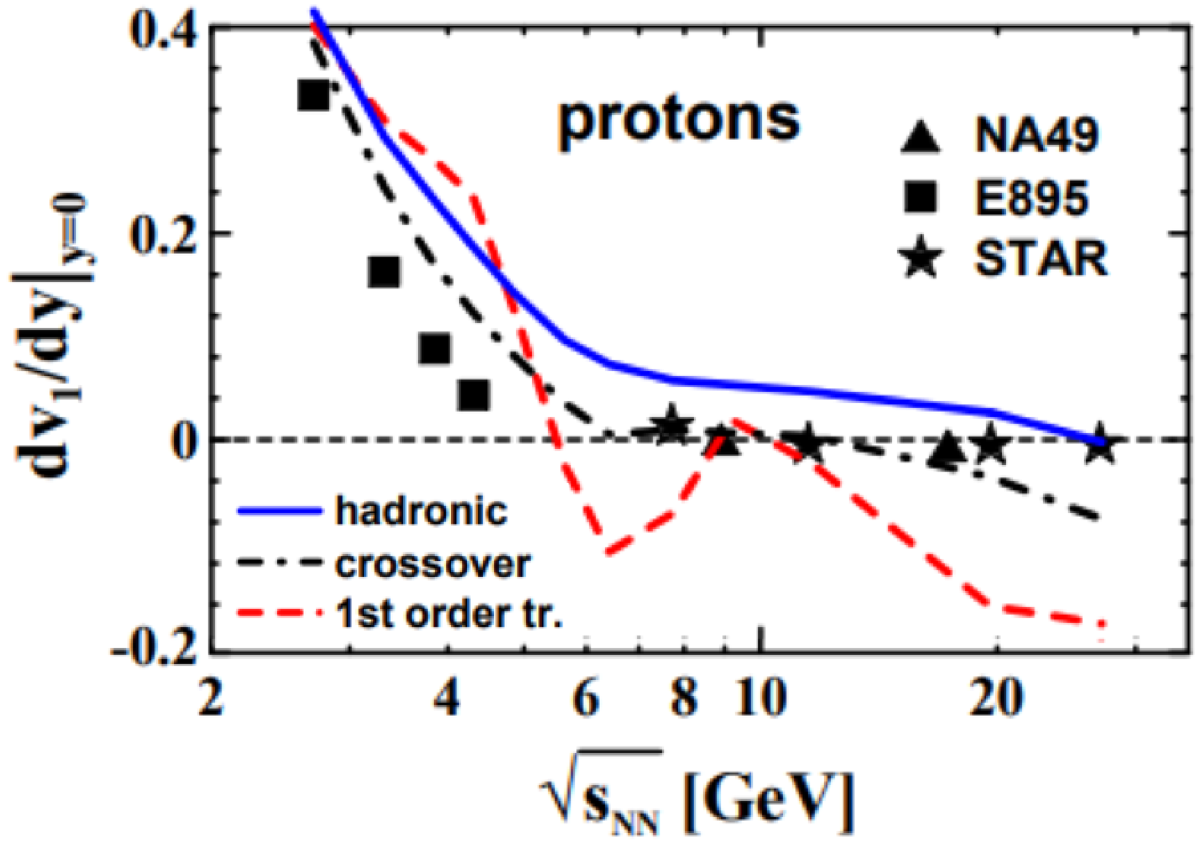
and on average in each net p,

$$N_{trans.\ \mathbf{u}(\mathbf{d})} = 3 * [1 - \exp(- 2\mu_{\mathbf{u}(\mathbf{d})} / T_{ch})] / (1 - r_{anti\text{-}p/p})$$

$r_{anti\text{-}p/p}$ is the ratio of observed anti-p to proton yield at each energy.

Models





Yasushi Nara, Harri Niemi, Jan Steinheimer, and Horst Stöcker, Phys. Lett. B769 (2017) 543. arXiv:1611.08023

3FD: Yu. B. Ivanov and A. A. Soldatov, Phys. Rev. C91 (2015) 024915; arXiv:1412.1669