v_1 Splitting and EM Field Effects

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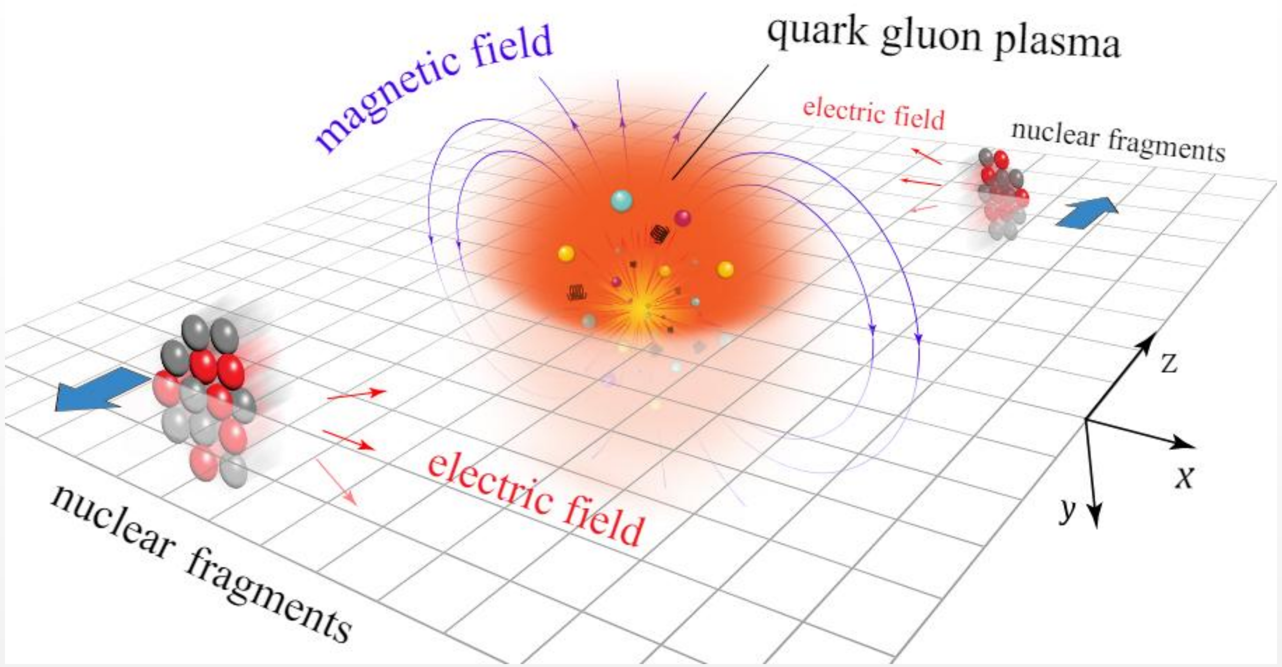
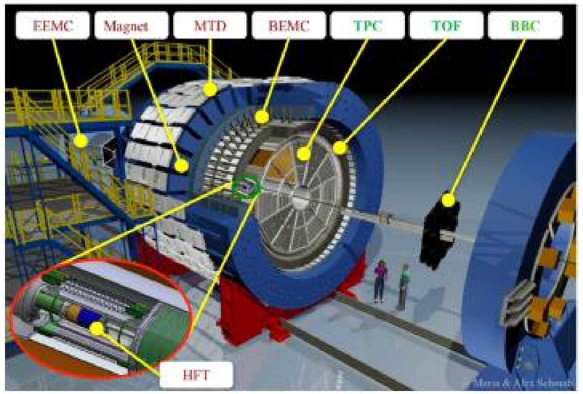
EM field in heavy-ion collisions

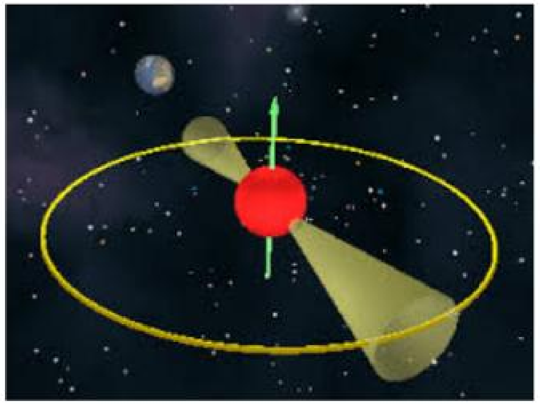


- Strongest man-made magnetic field: $-eB_y \sim 10^{18}$ Gauss (rough estimate for 200 GeV Au+Au at b = 5 fm, t = 0)
- Driving force of the CME
- Any experimental evidence?

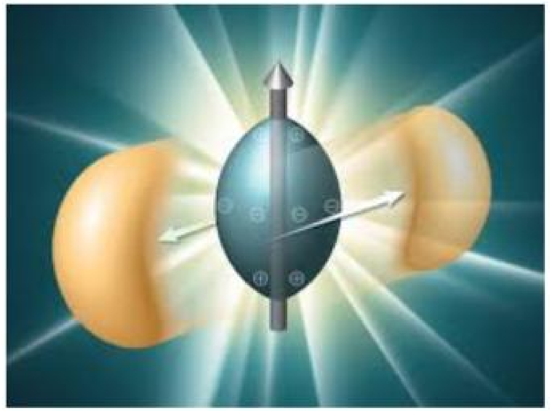
Earth
~0.5 Gauss



STAR magnet
~5000 Gauss



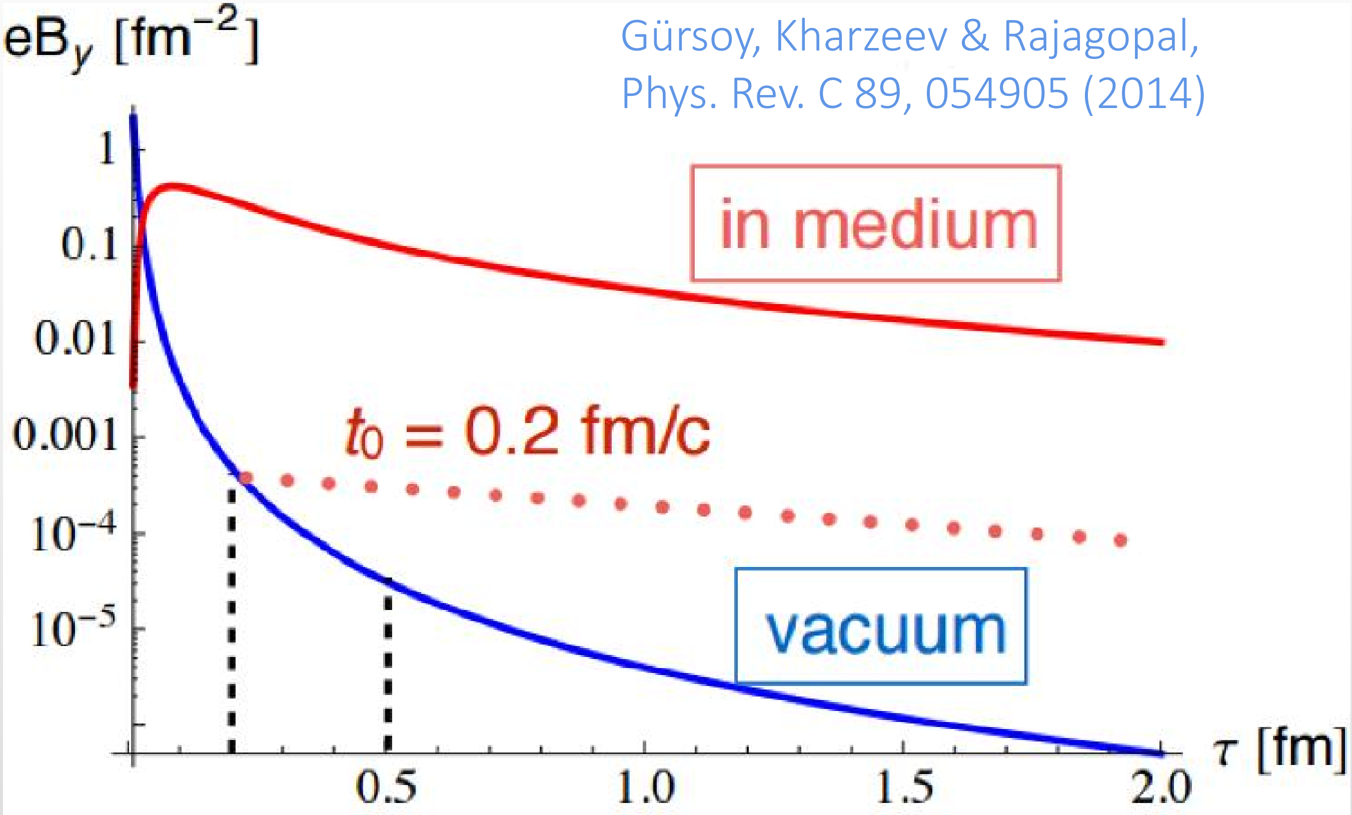
Neutron Star (Magentar)
~ 10^{14} Gauss

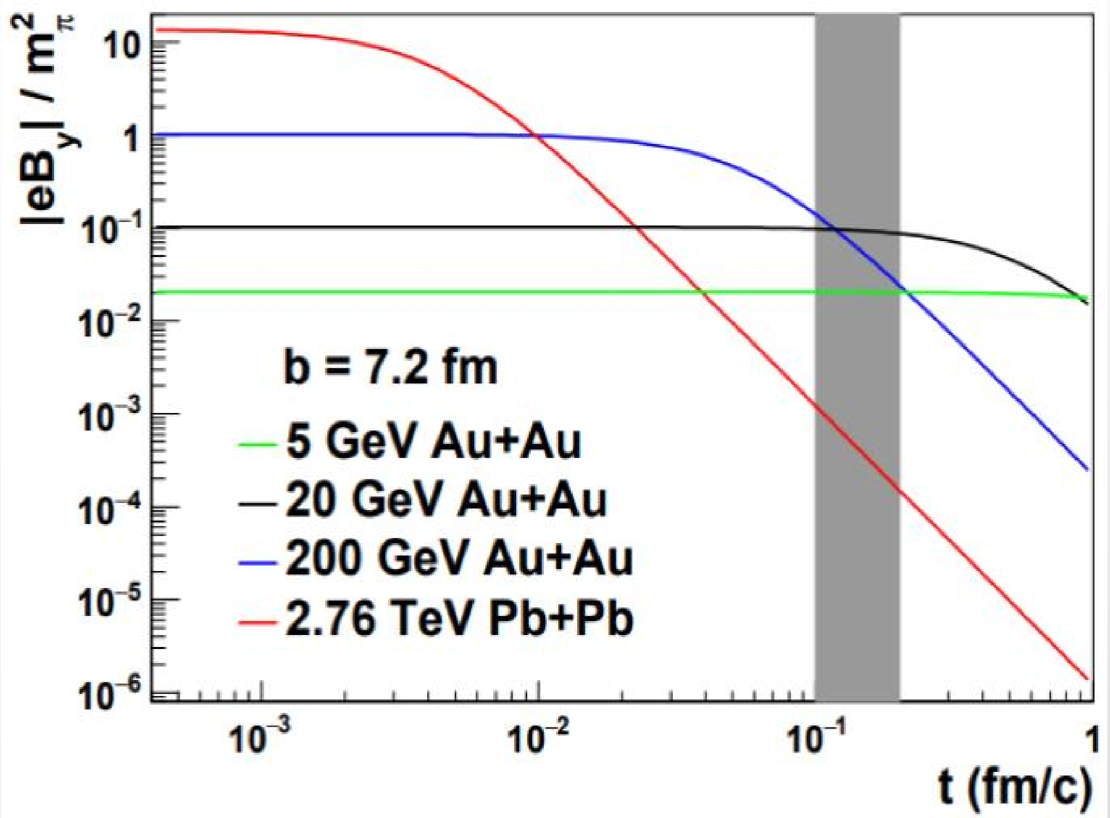


Heavy ion collisions
~ 10^{18} Gauss

Time evolution

- In vacuum, the *B* field drops like a rock.
- A conducting medium is needed to save the day (t = 0.1 ~ 0.2 fm/c).
- A higher collision energy doesn't mean a stronger *B* field in the medium.





Evidence of the Coulomb field

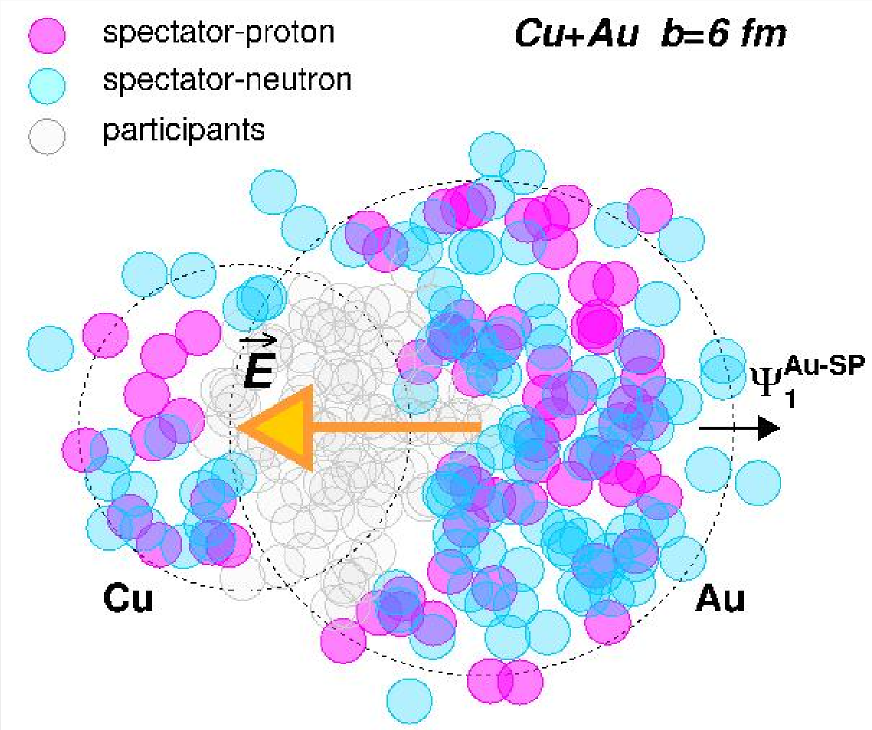
- Asymmetric collisions (Cu+Au) create in-plane electric fields.
- Similar to the *B* field, and easier to observe:
  - h^+ goes along *E*, and h^- to the opposite
  - charge-dependence of v_1

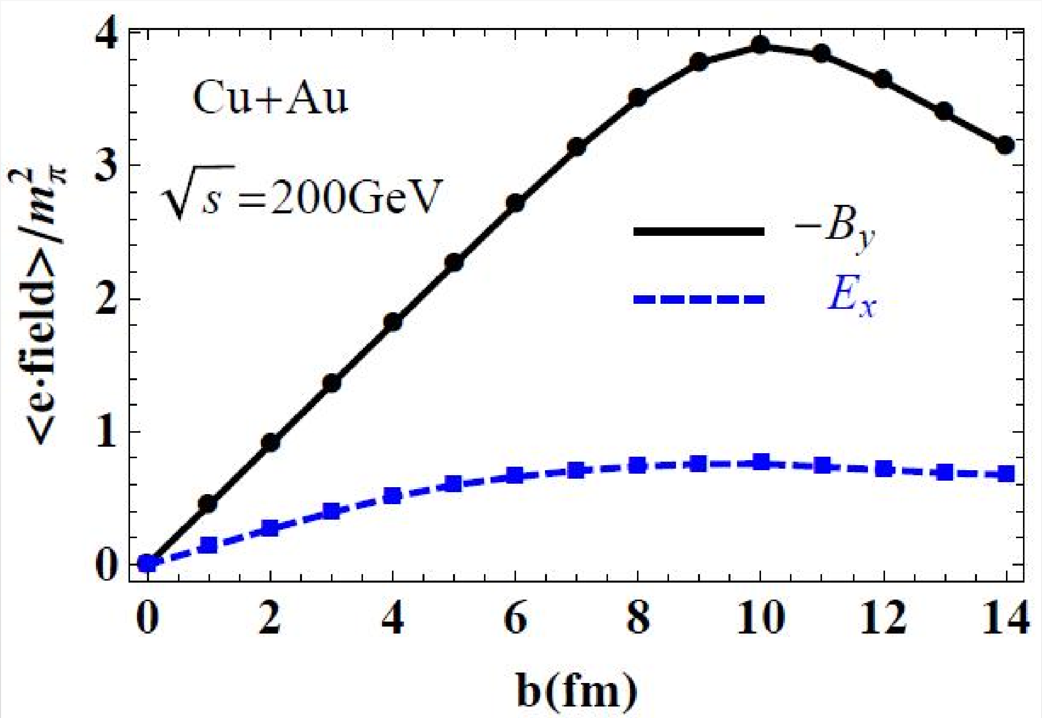
Y. Hirono et al., PC 90 (2014) no.2, 021903

$$v_1^{\pm} = v_1 \pm d_E \langle \cos(\Psi_1 - \psi_E) \rangle$$

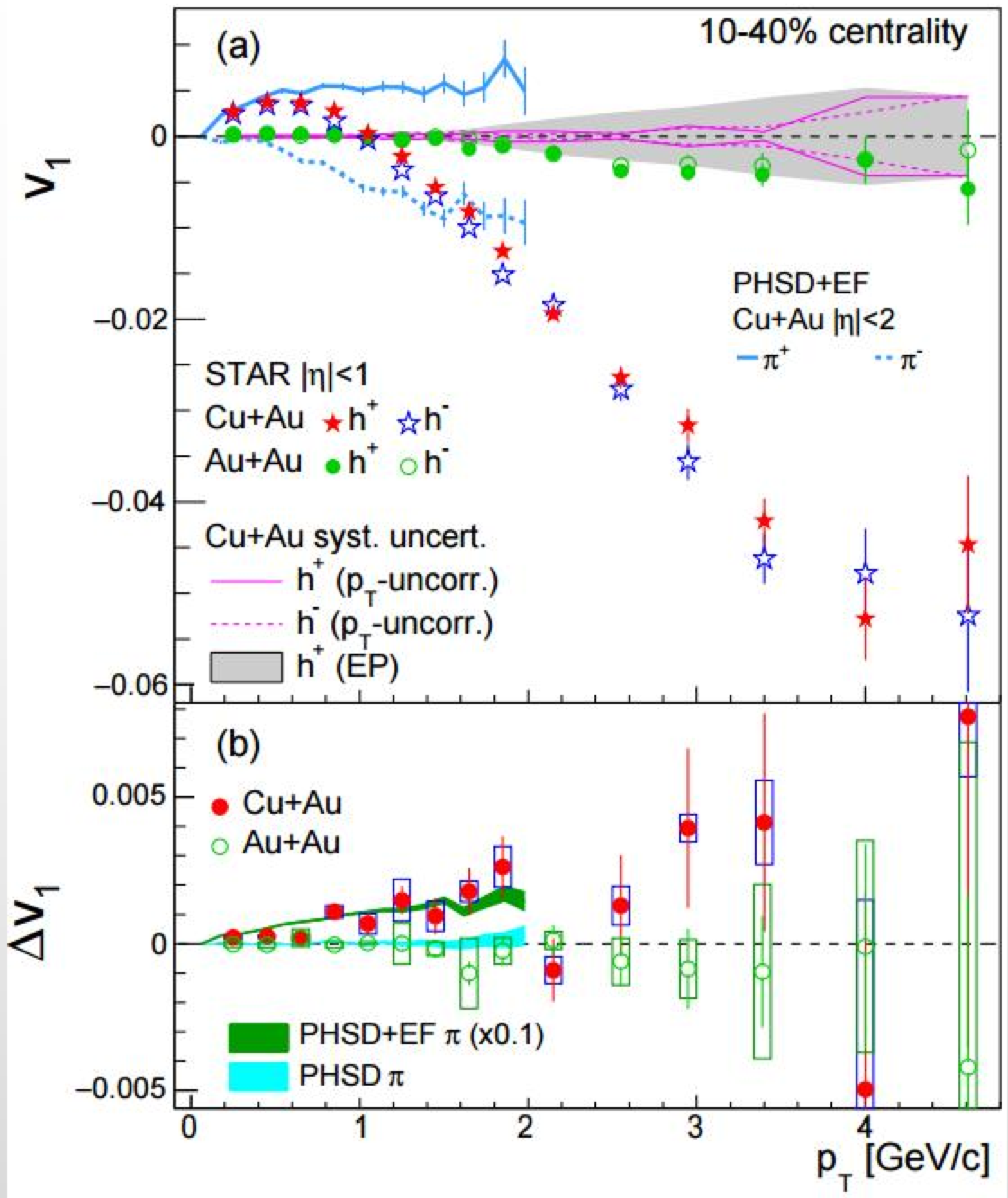
$$\frac{dN^{\pm}}{d\phi} \propto 1 + 2v_1 \cos(\phi - \Psi_1) \pm 2d_E \cos(\phi - \psi_E) \cdots$$

ψ_E: electric field direction
d_E: electric dipole





v_1 in Cu+Au@200 GeV



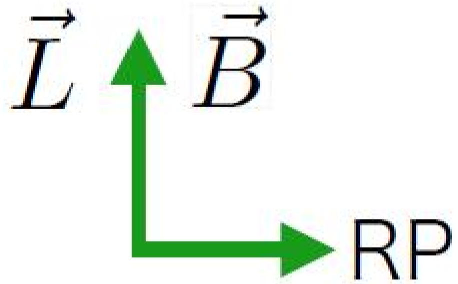
$$v_1^{\pm} = v_1 \pm d_E \langle \cos(\Psi_1 - \psi_E) \rangle$$

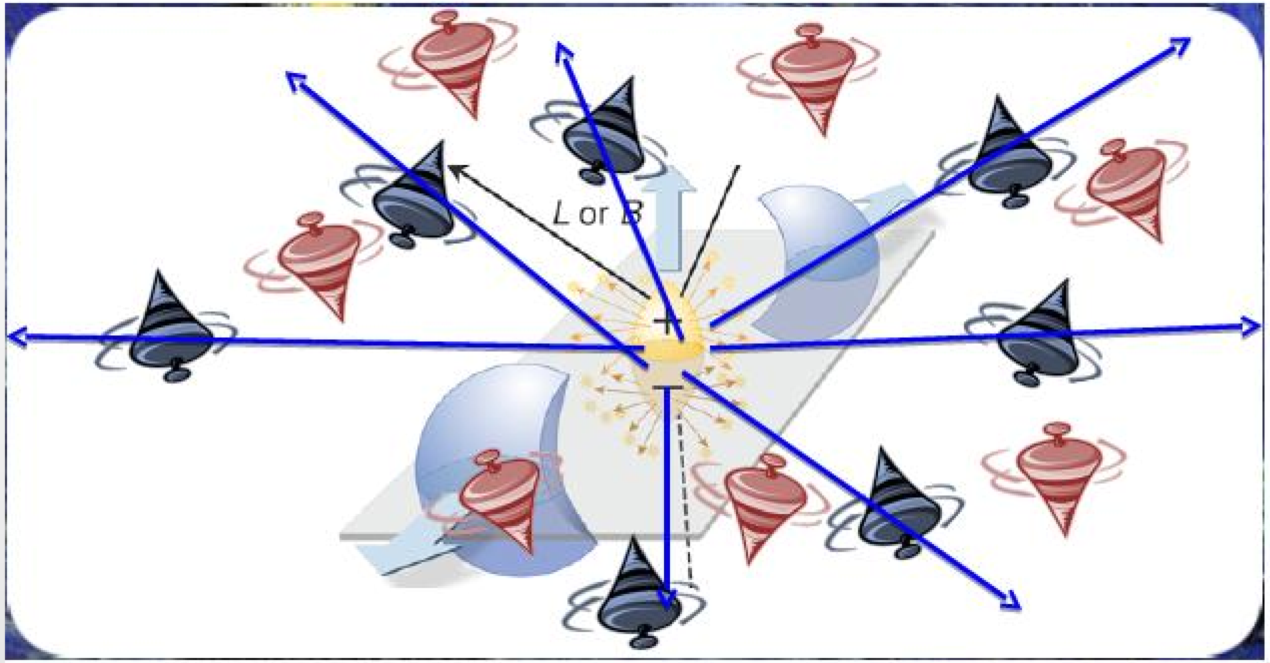
- On average, ψ_E is along the ψ_{RP} direction.
- $v_1(p_T)$ splits between h^+ and h^-.
- The sign is right.
- The magnitude is 10% of what was expected.
- The initial electric field does leave an imprint on final-stage particles!
- Not all quarks are created in early times.

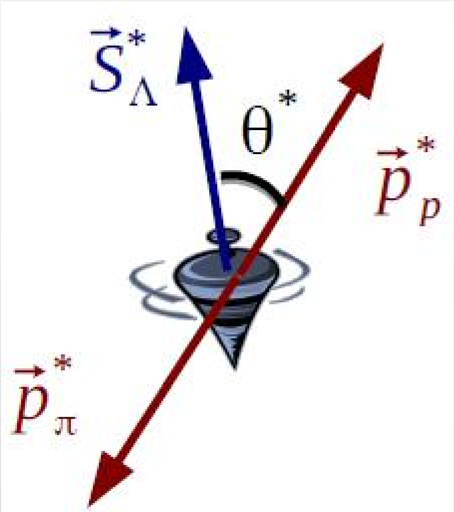
STAR, Phys. Rev. Lett. 118 (2017) 12301

Evidence of the magnetic field

- spin-orbit coupling
  - spins of Λ and anti-Λ are both polarized with angular momentum L
- spin polarized by the *B* field
  - Λ spin anti-aligned with *B*
  - anti-Λ spin aligned with *B*







daughter protons prefer to go along Λ spin (opposite for anti-Λ)

$$P_H = \frac{8}{\pi\alpha}\frac{\langle\sin(\Psi_1 - \phi_p^*)\rangle}{\mathrm{Res}(\Psi_1)}\mathrm{sgn}_\Lambda$$

ϕ_p^*: ϕ of daughter proton in Λ rest frame

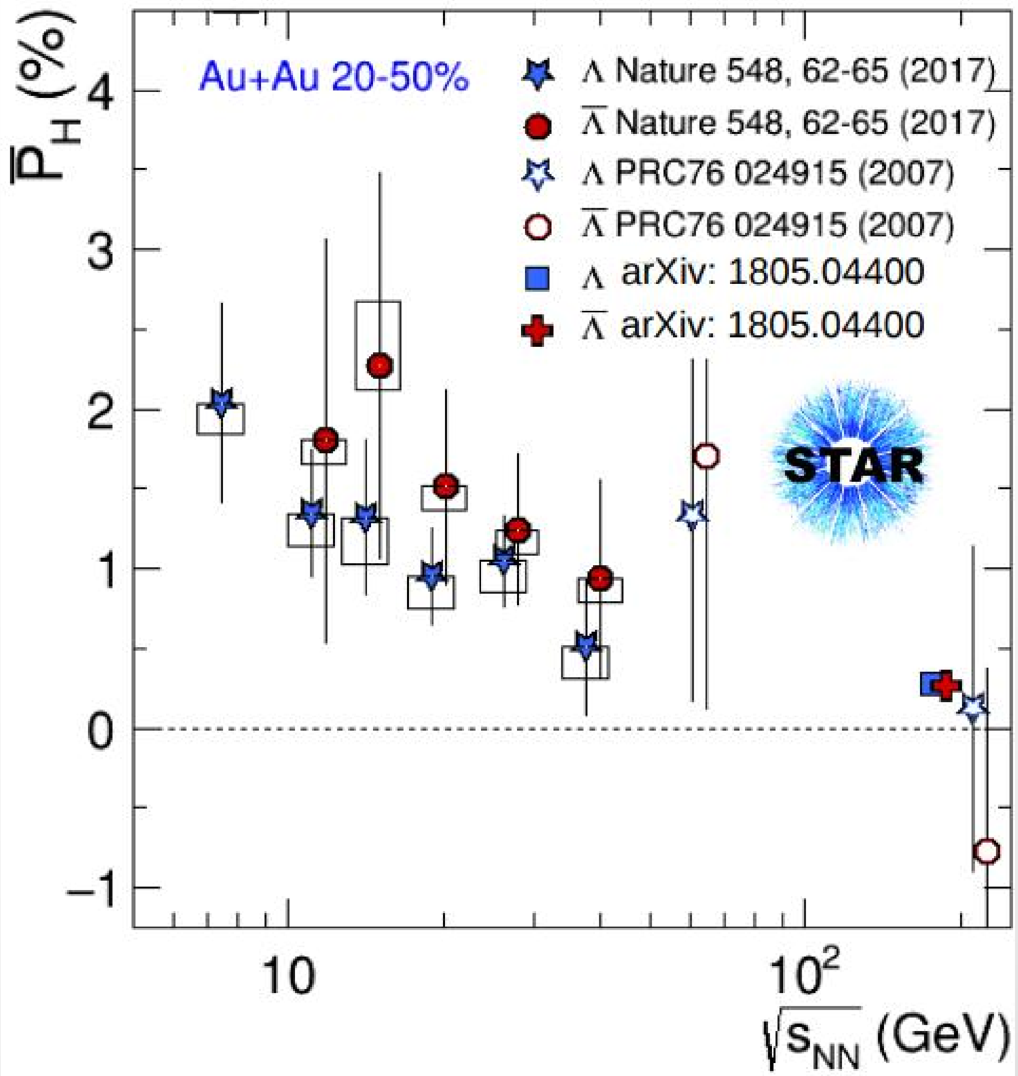
Ψ_1: 1st-order event plane

sgn_Λ: 1 for Λ, -1 for anti-Λ

α: Λ decay parameter (=0.642±0.013)

STAR, PRC 76 024915 (2007)

Λ polarization

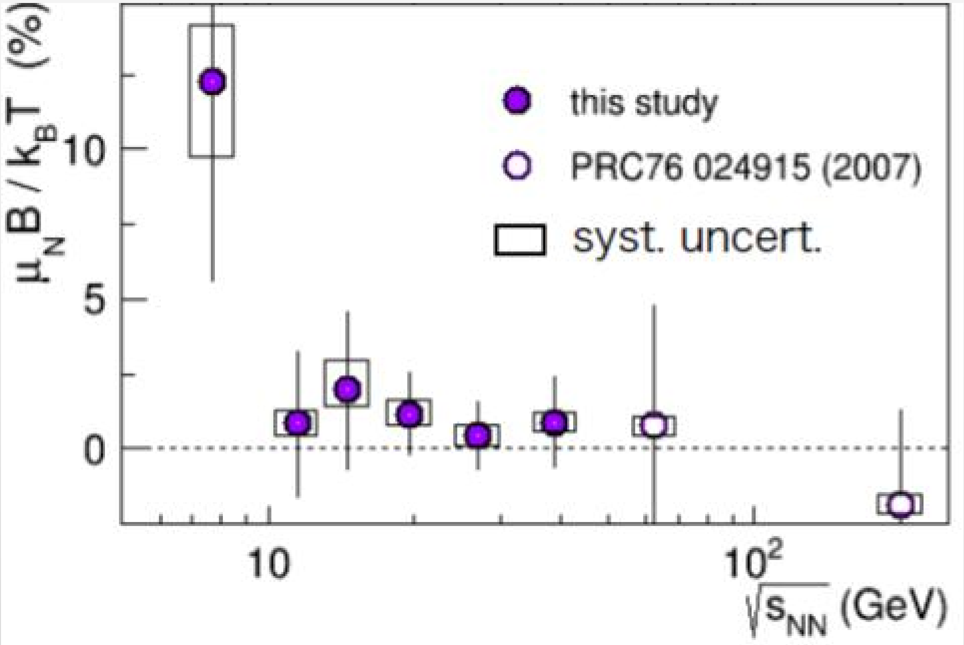


STAR, Nature 548 (2017) 62

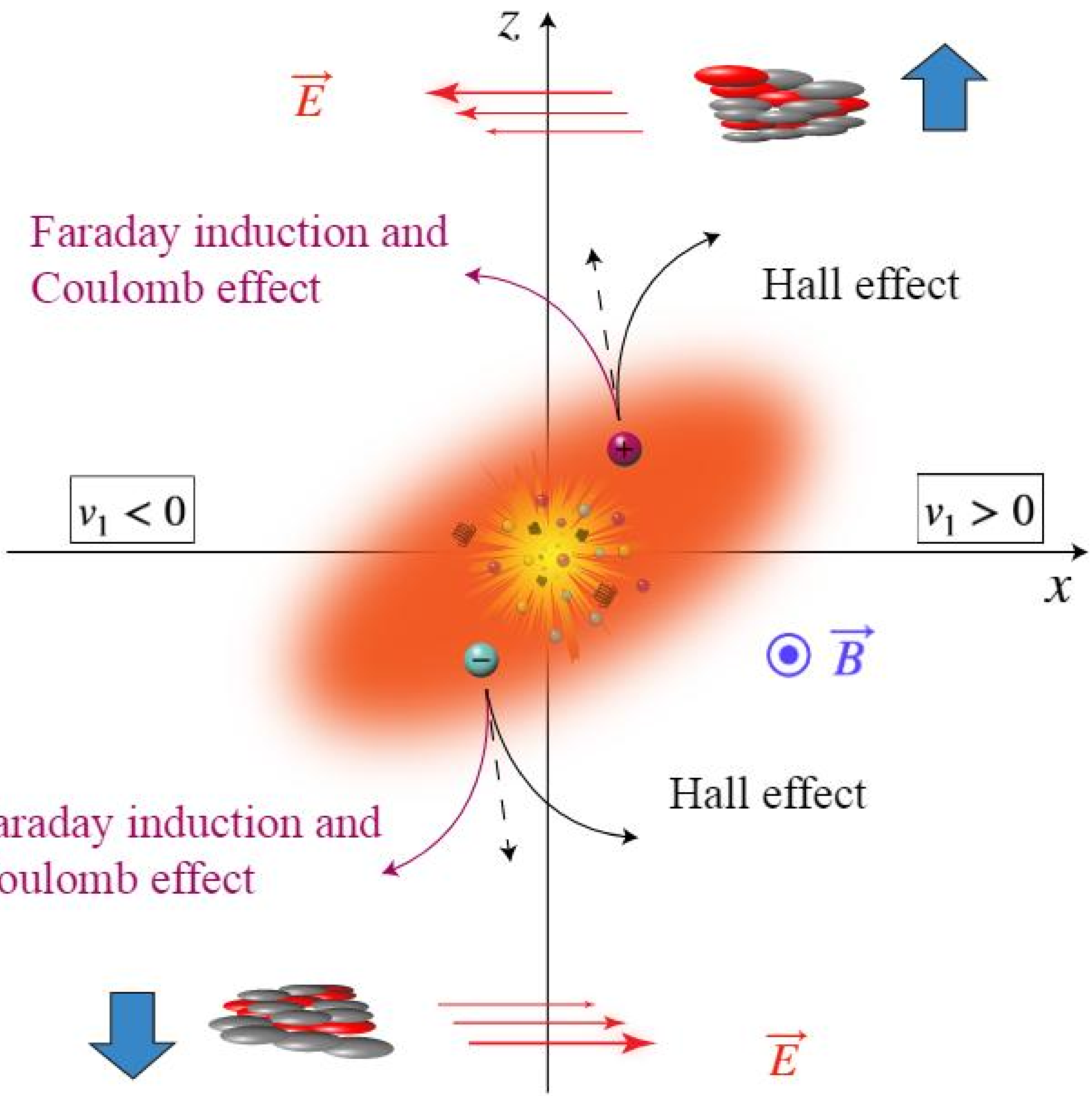
- Systematically, $P_H(\Lambda) < P_H(\text{anti-}\Lambda)$ implying a magnetic field
- For small polarization

$$P_\Lambda \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

$$P_{\bar{\Lambda}} \approx \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$



v_1 in symmetric collisions



The baseline $v_1(y)$ at midrapidity has a negative slope, due to the tilted fireball.

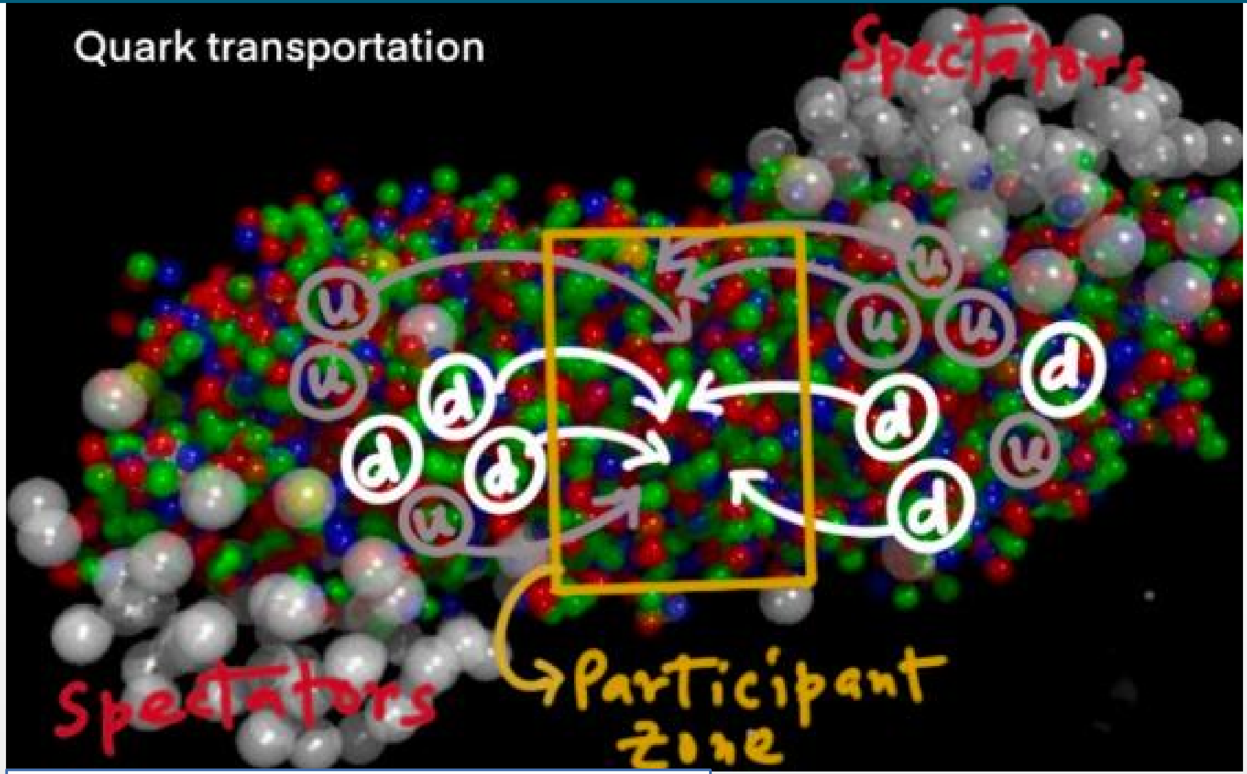
Three EM field effects:

- Hall effect (Lorentz force)
- Faraday induction (fast decay of *B* field)
- Coulomb effect

The Hall effect and the Faraday+Coulomb effect are competing each other, and the net effect can split dv_1/dy between particles and antiparticles.

Transported quarks

- *u* and *d* quarks can be transported from incident nucleons to midrapidity.
- They suffer more interactions than quarks later produced in pair.
- Transported quarks and produced quarks have different v_1 (or v_2).
- Previously the idea of transported quarks was used to explain all the v_2 ordering.
- dv_1/dy should follow the same ordering if transported quarks play a dominant role.



$$
\begin{aligned}
&v_2[\pi^- = d\bar{u}] > v_2[\pi^+ = u\bar{d}],\\
&v_2[\mathrm{K}^+ = u\bar{s}] > v_2[\mathrm{K}^- = \bar{u}s],\\
&v_2[p = uud] > v_2[\bar{p} = \bar{u}\bar{u}\bar{d}],\\
&v_2[\Lambda = uds] > v_2[\bar{\Lambda} = \bar{u}\bar{d}\bar{s}],\\
&v_2[p = uud] > v_2[\Lambda = uds],\\
&(v_2[p = uud] - v_2[\bar{p} = \bar{u}\bar{u}\bar{d}])\\
&> (v_2[\Lambda = uds] - v_2[\bar{\Lambda} = \bar{u}\bar{d}\bar{s}]).
\end{aligned}
$$

Au nuclei are neutron(ddu) rich.

J. C. Dunlop, M. A. Lisa and P. Sorensen, PRC84 044914 (2011)

Interplay between all known effects

An illustrative picture for the v_1 slope difference between protons and antiprotons.

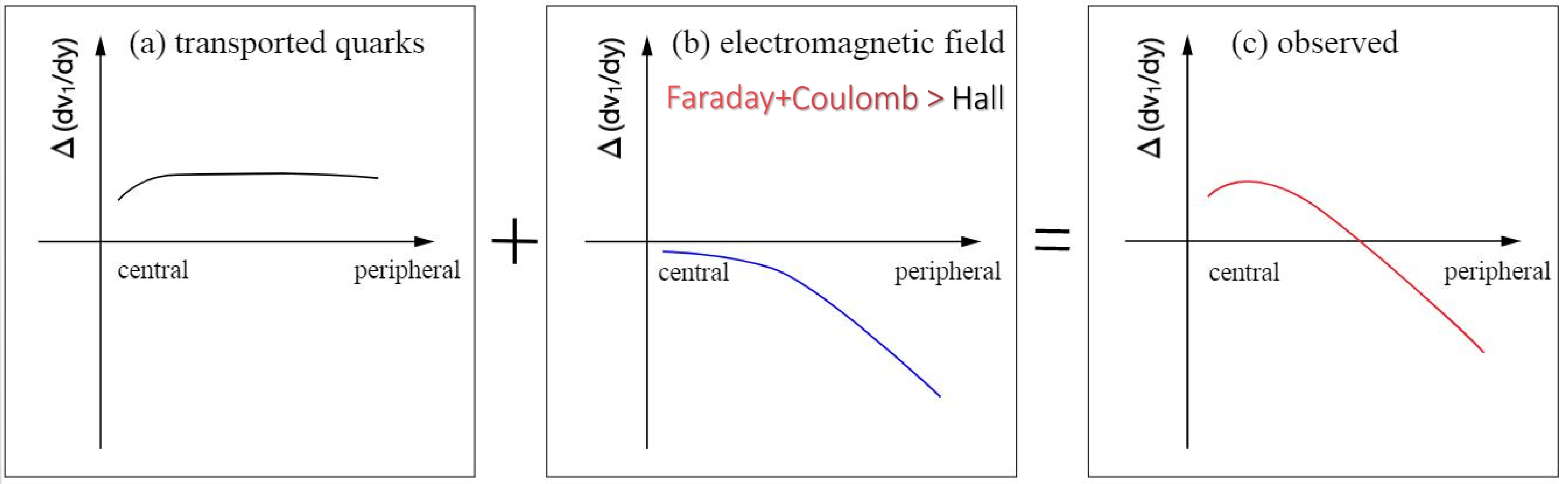
- For the beam energies under study, transported quarks always give a positive value.

AMPT, UrQMD…

- Theory predicts Faraday+Coulomb > Hall, and the net EM effect is negative.

U. Gursoy et al, Phys. Rev. C 98, 055201 (2018).

- The sign change from positive (central collisions) to negative (peripheral) will be the signature of Faraday+Coulomb effect in symmetric collisions.



Interplay between all known effects

An illustrative picture for the v_1 slope difference between protons and antiprotons.

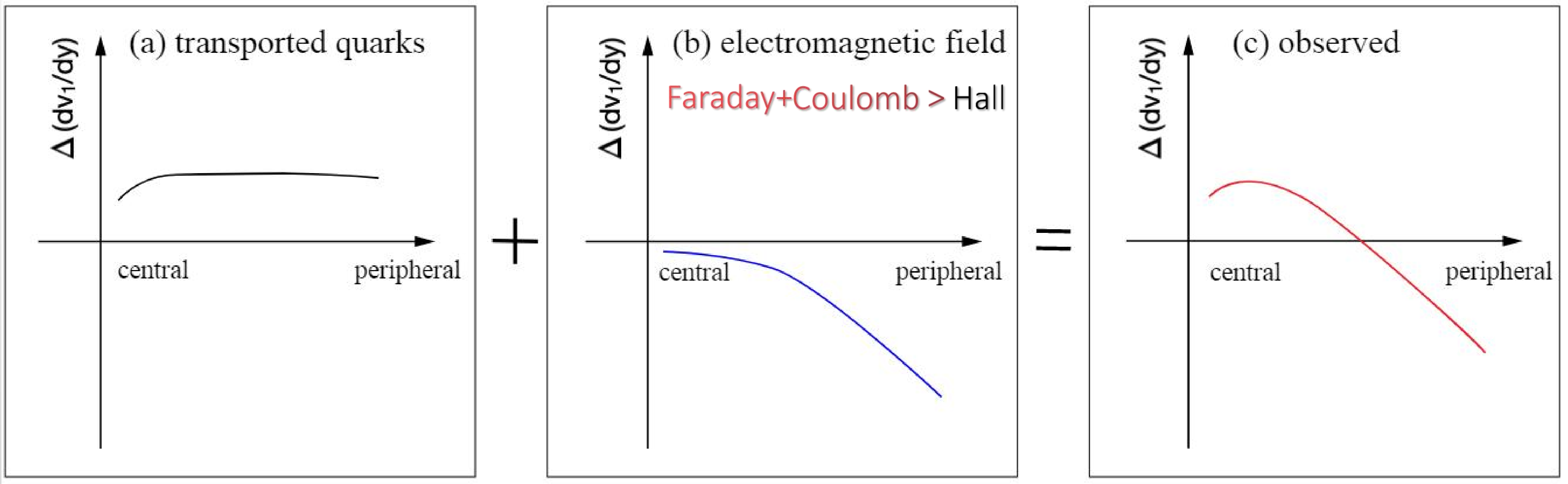
- The v_1 slope difference between K^+ and K^- should follow the same pattern.

Smaller magnitudes, due to lower $\langle p_T \rangle$ and later formation time than protons.

- The one between π^+ and π^- will be different.
  - transported quarks will give a negative contribution.
  - the net EM field effect is also negative.
  - no sign change, always negative or very close to zero.

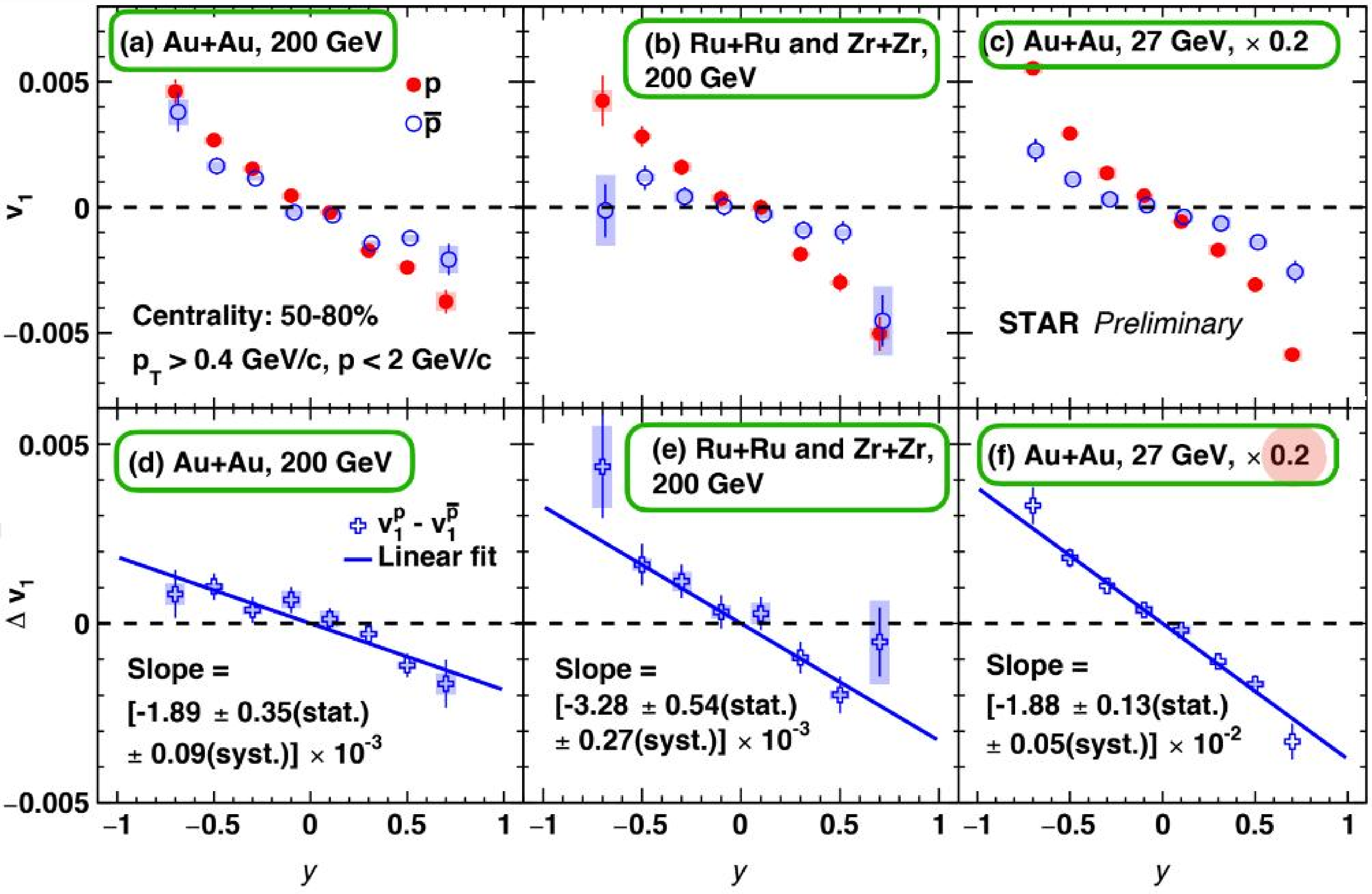
ρ decay may dilute pion splitting; Δ++ enhances proton splitting.

U. Gursoy et al, PRC 98, 055201 (2018).

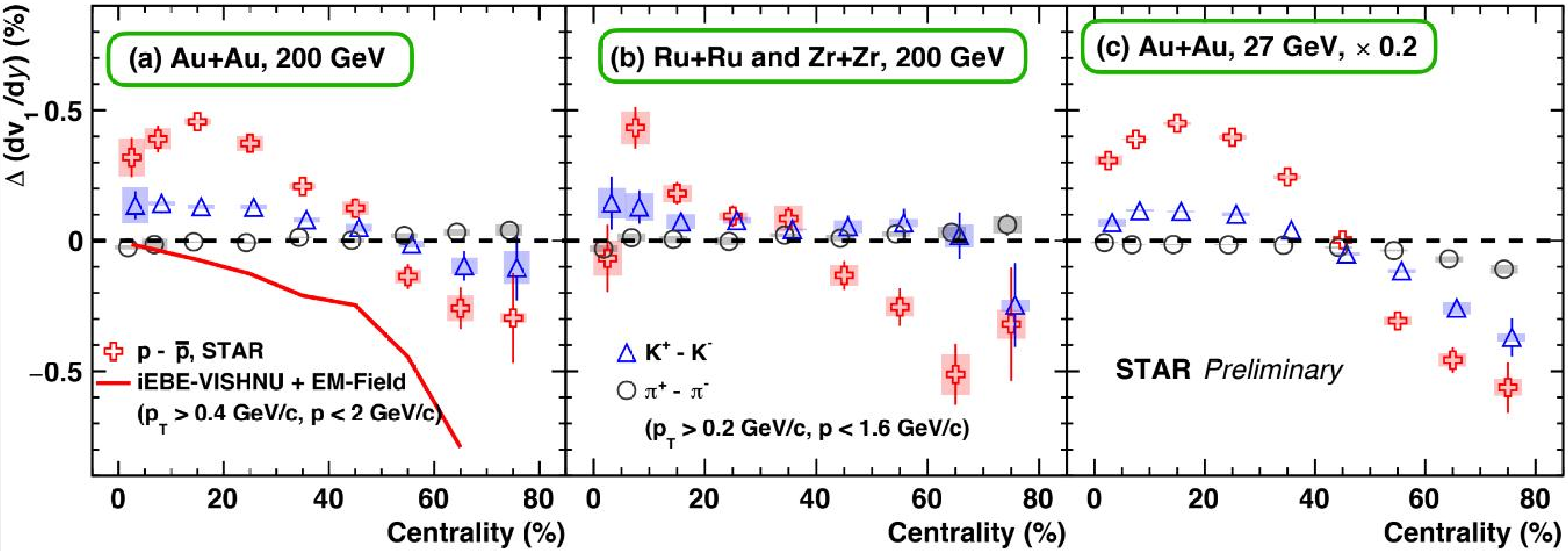


Proton splitting in 50-80% centrality

- v_1 splitting between protons and antiprotons in peripheral collisions of 200 GeV Au+Au and isobar, and 27 GeV Au+Au.
- v_1 slope difference is negative, with > 5σ significance.
- Stronger effect at 27 GeV.
- This cannot be explained by transported quarks or Hall effect alone. Faraday+Coulomb is needed.

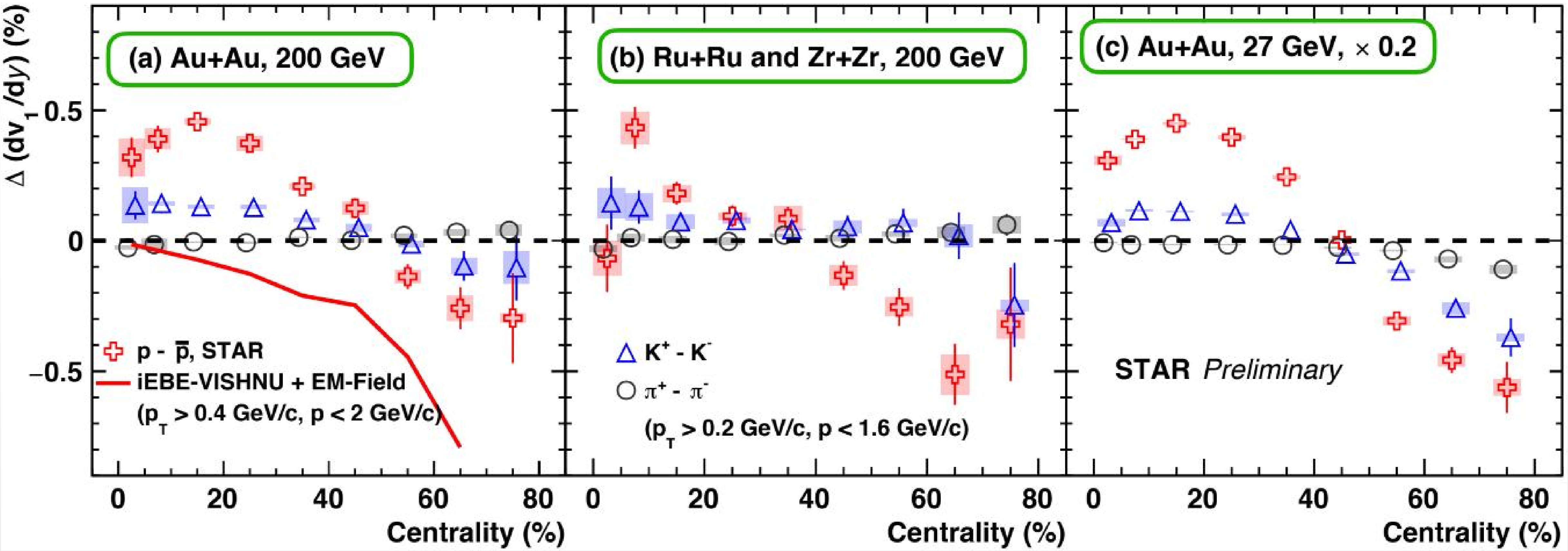


dv_1/dy splitting vs centrality



- Sign change in $\Delta(dv_1/dy)$ occurs for both protons and kaons.
- The magnitudes follow the expected ordering between protons and kaons.
- Pion results are either consistent with zero or negative, as expected.

dv_1/dy splitting vs centrality



Is it possible that there is no Faraday+Coulomb, and transported quark v_1 goes negative? (1st-order phase transition at 27 GeV?)

- In that case, the pion results will be positive at 27 GeV.

- That scenario is contracted by data.

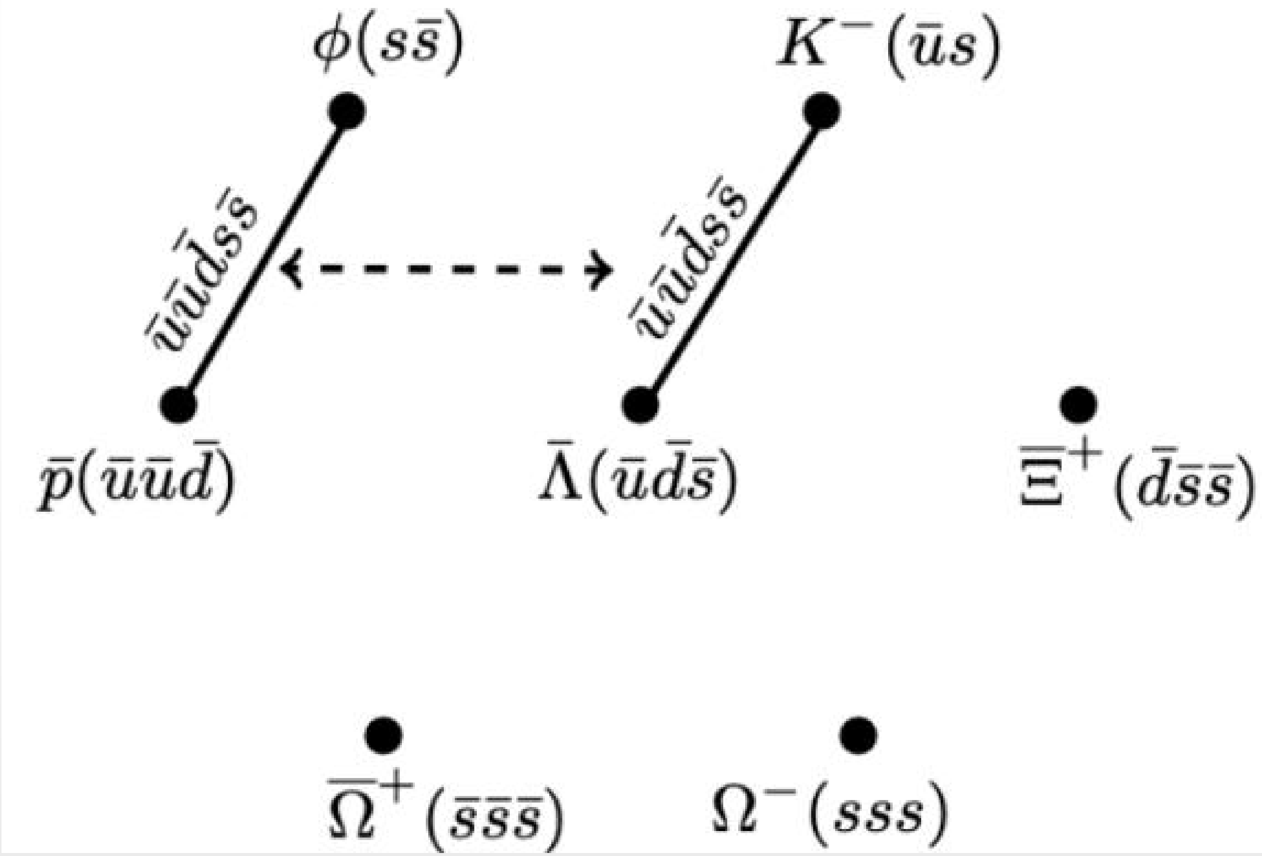
Alternative approach: assuming coalescence

Assumptions:
- v_1 is developed in prehadronic stage.
- coalescence sum rule,

  v_1(hadron) = Σv_1(constituent quarks)

Only use prdouced particles to avoid transported quark effect.

Combine particles and make identical constituent quark combinations.



A. Ikbal, D. Keane, P. Tribedy, Phys. Rev. C 105, 014912 (2022)

$$v_1[K^-(\bar{u}s)] + v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})] = v_1[\bar{p}(\bar{u}\bar{u}\bar{d})] + v_1[\phi(s\bar{s})]$$

This is a baseline test.

charge difference $\Delta q = 0$, and strangeness difference $\Delta S = 0$

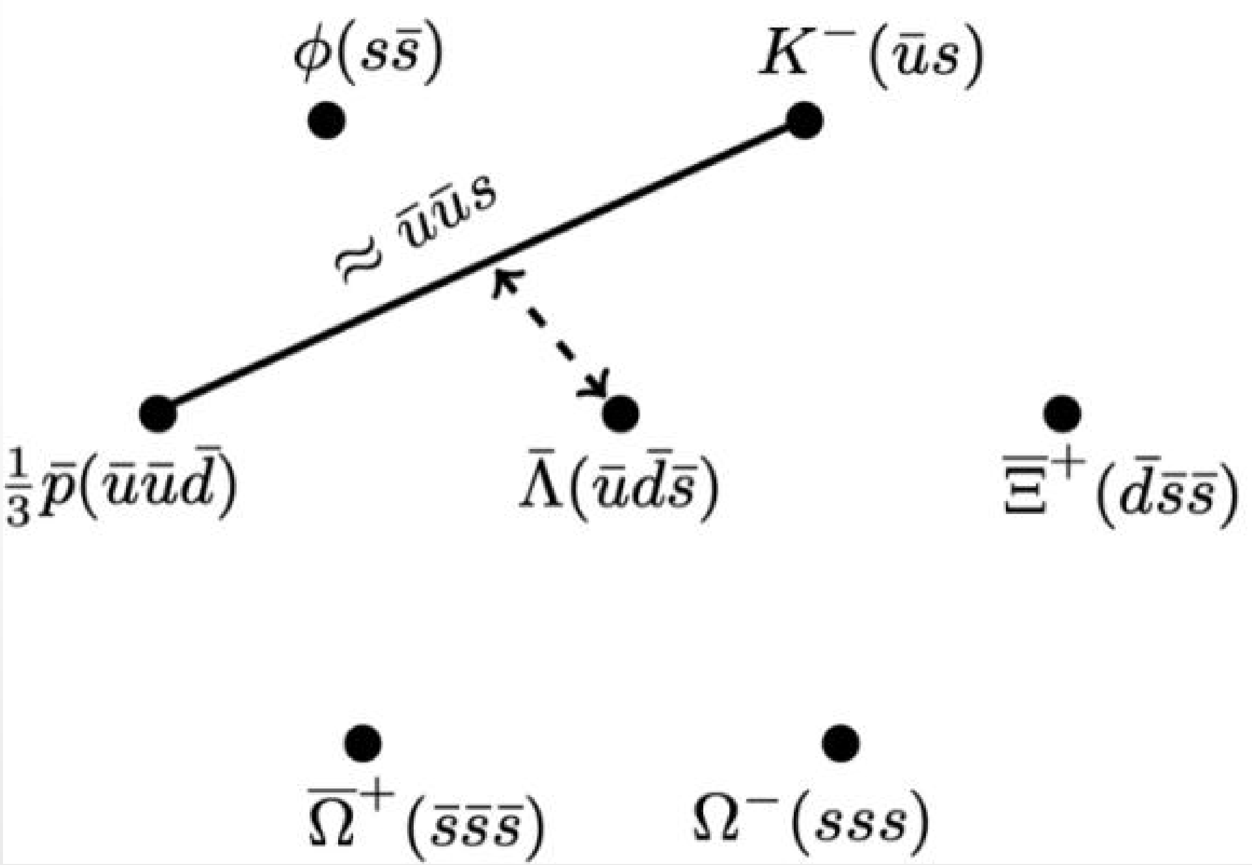
Alternative approach: assuming coalescence

Assumptions:
- v_1 is developed in prehadronic stage.
- coalescence sum rule,

  v_1(hadron) = Σv_1(constituent quarks)

Only use prdouced particles to avoid transported quark effect.

Combine particles and make non-identical quark combinations, same mass at the constituent level.



A. Ikbal, D. Keane, P. Tribedy, Phys. Rev. C 105, 014912 (2022)

$$v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})] \quad \text{vs} \quad v_1[K^-(\bar{u}s)] + \frac{1}{3}v_1[\bar{p}(\bar{u}\bar{u}\bar{d})]$$

This may reflect an effect on charge, like the EM field effect.

charge difference $\Delta q = 4/3$, and strangeness difference $\Delta S = 2$

5 independent combinations

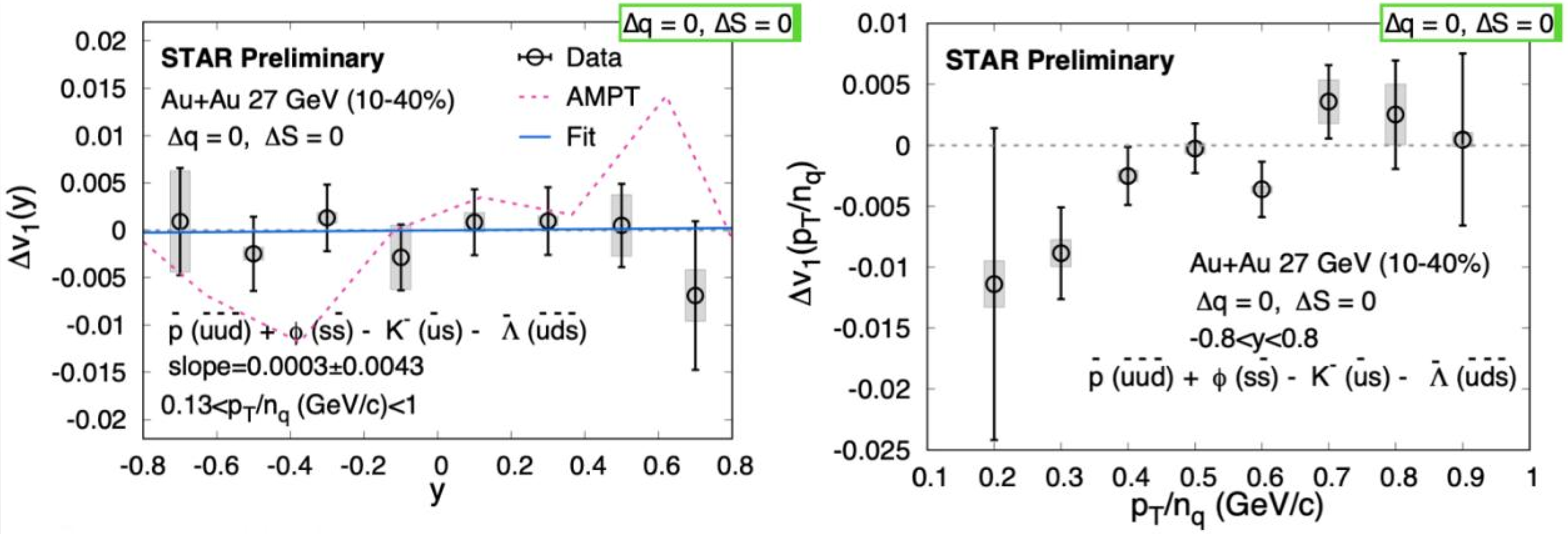
Index	Quark Mass	Charge	Strangeness	Expression
1	$\Delta m = 0$	$\Delta q = 0$	$\Delta S = 0$	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^-(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$
2	$\Delta m \approx 0$	$\Delta q = 1$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^-(sss) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
3	$\Delta m \approx 0$	$\Delta q = \frac{4}{3}$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
4	$\Delta m = 0$	$\Delta q = 2$	$\Delta S = 6$	$[\overline{\Omega}^+(\bar{s}\bar{s}\bar{s})] - [\Omega^-(sss)]$
5	$\Delta m \approx 0$	$\Delta q = \frac{7}{3}$	$\Delta S = 4$	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\Omega^-(sss)]$

A. Ikbal, D. Keane, P. Tribedy, Phys. Rev. C 105, 014912 (2022)

- Δq = 0 and ΔS = 0 (case 1): check the baseline.
- Δq and ΔS are correlated, except in cases 4 and 5: check which is the dominant factor.
- Two degenerate combinations in ΔS = 2 (cases 2 and 3): check Δq effect alone.

Case 1

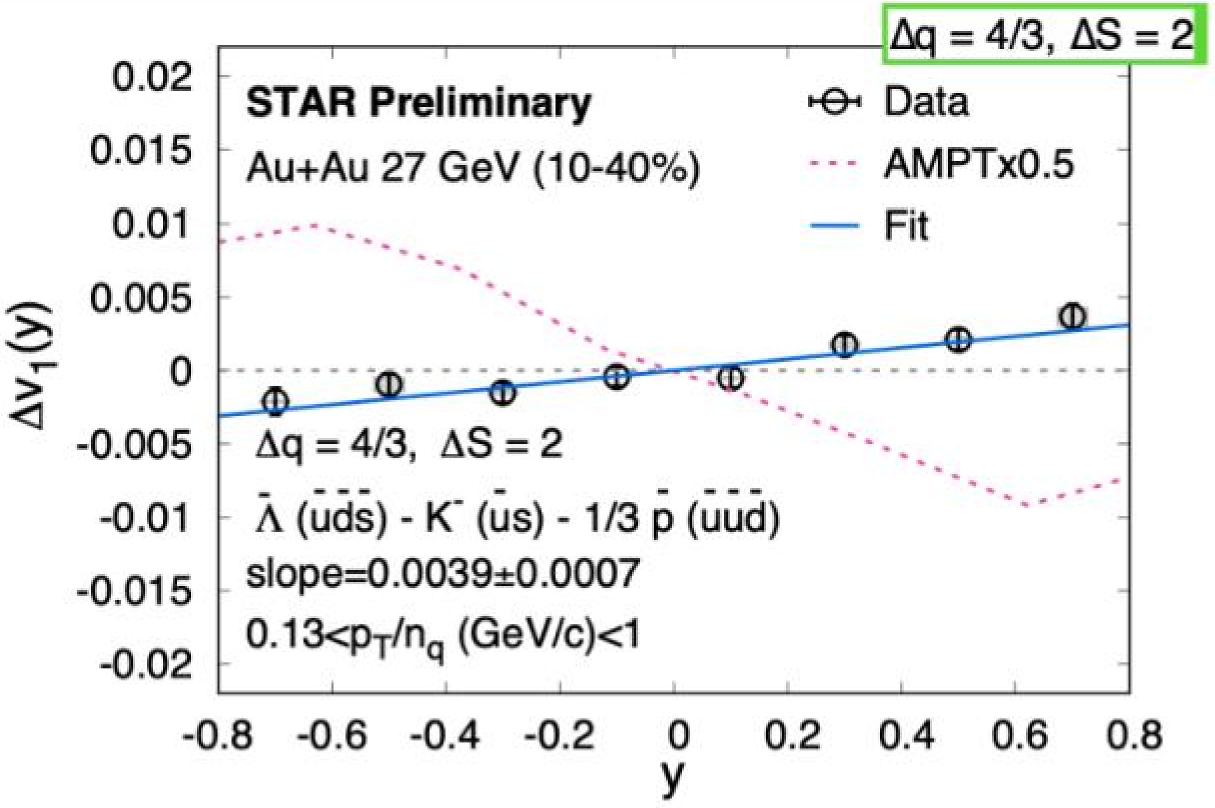
$$v_1[K^-(\bar{u}s)] + v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})] \overset{?}{=} v_1[\bar{p}(\bar{u}\bar{u}\bar{d})] + v_1[\phi(s\bar{s})]$$

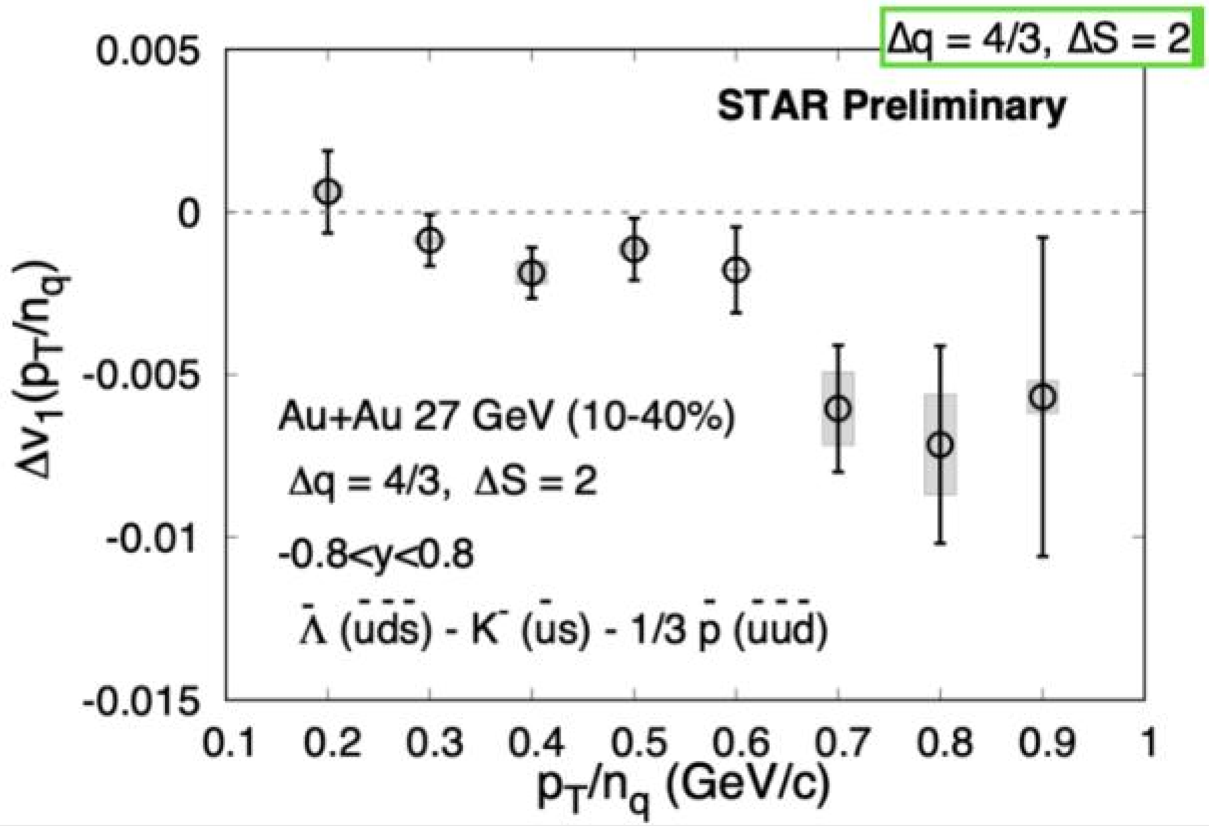


- $\Delta v_1(y)$ slope consistent with zero ($\sim 10^{-4}$) for 10-40% Au+Au at 27 GeV.
- Coalesence sum rule holds within the uncertainties.

Case 3

$v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})]$ vs $v_1[K^-(\bar{u}s)] + \frac{1}{3}v_1[\bar{p}(\bar{u}\bar{u}\bar{d})]$

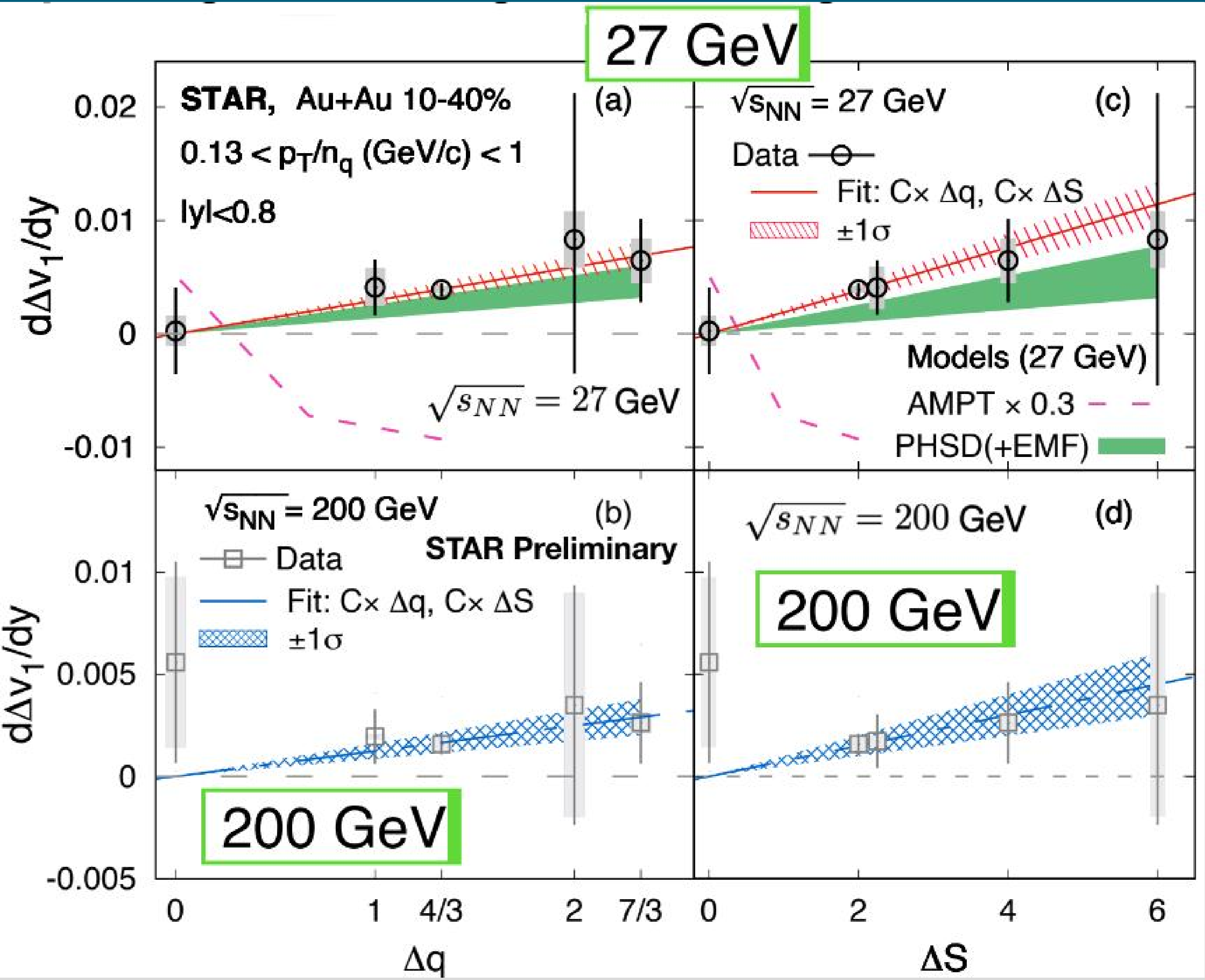




- Significantly positive $\Delta v_1(y)$ slope for $\Delta q = 4/3$ and $\Delta S = 2$.
- AMPT (no EM field) has the opposite trend.

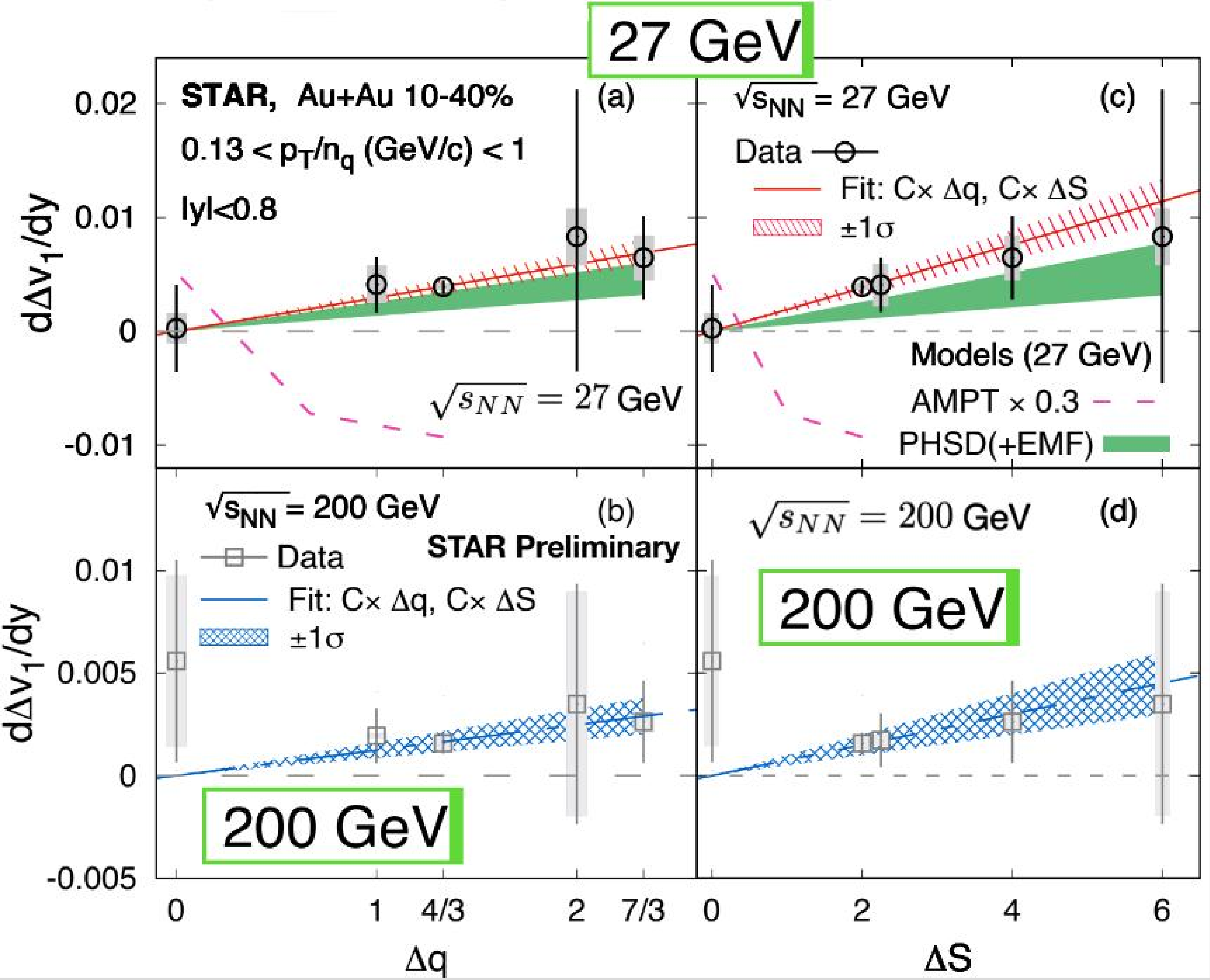
Nayak et al., Phys. Rev. C 100, 054903 (2019)

All the cases



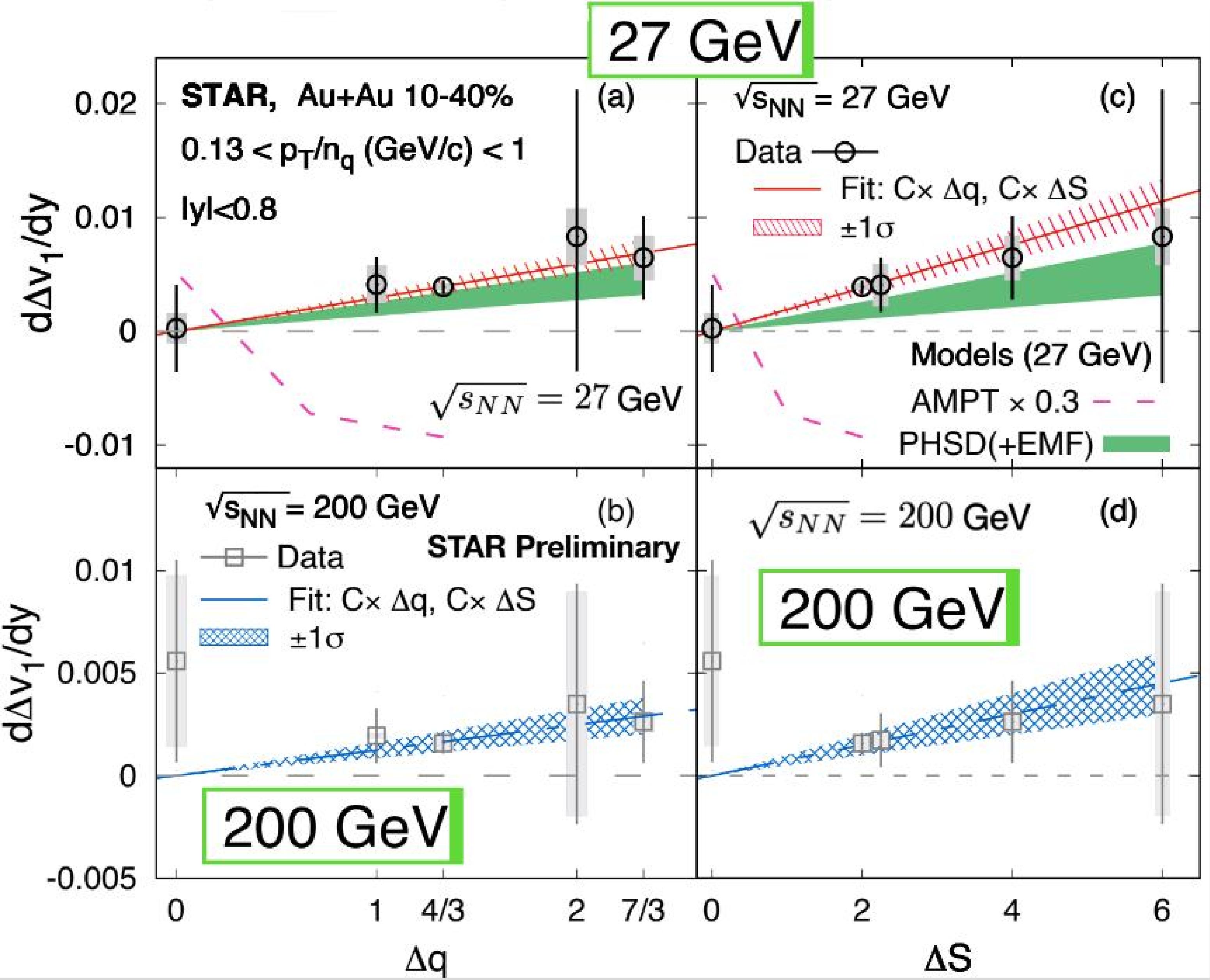
- $\Delta v_1(y)$ slope increases with Δq and ΔS, with fit forced to (0,0) .
- Stronger splitting at 27 GeV than 200 GeV (stronger EM field at lower energies?)
- AMPT can not explain the data
- PHSD(+EMF) can describe the data within errors, but EMF is not the sole difference between these two models.

All the cases



- $\Delta v_1(y)$ slope increases with Δq and ΔS, with fit forced to (0,0) .
- The "extra" point at (0,0) reduces the fit error and increases the significance.
- But it relies on the assumption that coalescence strictly holds.
- Letting go (0,0), the 5 points can be well fit with a constant. Then it could be just a slight break-down of coalescence, with no EMF effects.

All the cases



Which is the dominant factor, Δq or ΔS?

- Cases 4 and 5 support ΔS, if we ignore the errors.
- It could be that the seemingly increasing trend on the left is caused by ΔS, not Δq.

  p -> Λ + K⁺ (**uud -> uds + u $\bar{s}$**)
- Cases 2 and 3 appear to be a constant to my eyes: Δq alone shows no effect.

The current precision is not enough to test this good idea.

Summary

- The initial EM field is very intense in HIC, but decaying fast.

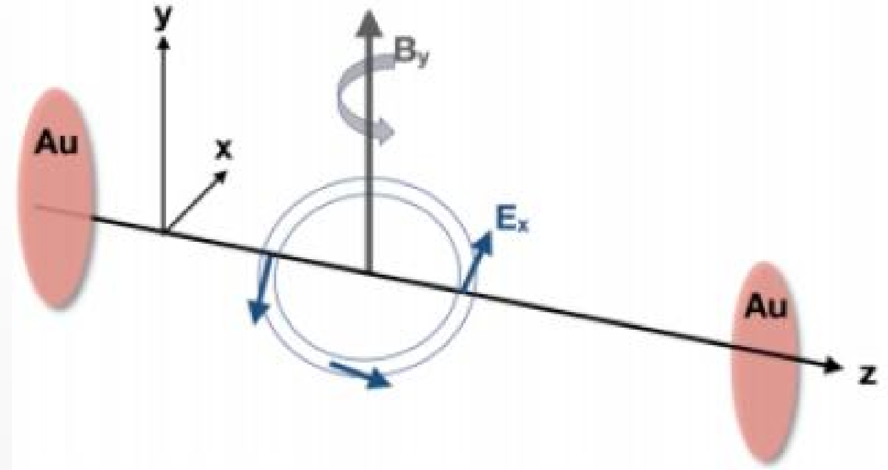
- Evidence of Coulomb effect via v_1 in asymmetric collisions.
  - $v_1(p_T)$ splits between h^+ and h^-

- Evidence of Faraday+Coulomb via v_1 in symmetric collisions.
  - sign change in $\Delta(dv_1/dy)$ for p and K
  - cannot be explained by Hall+transported quark

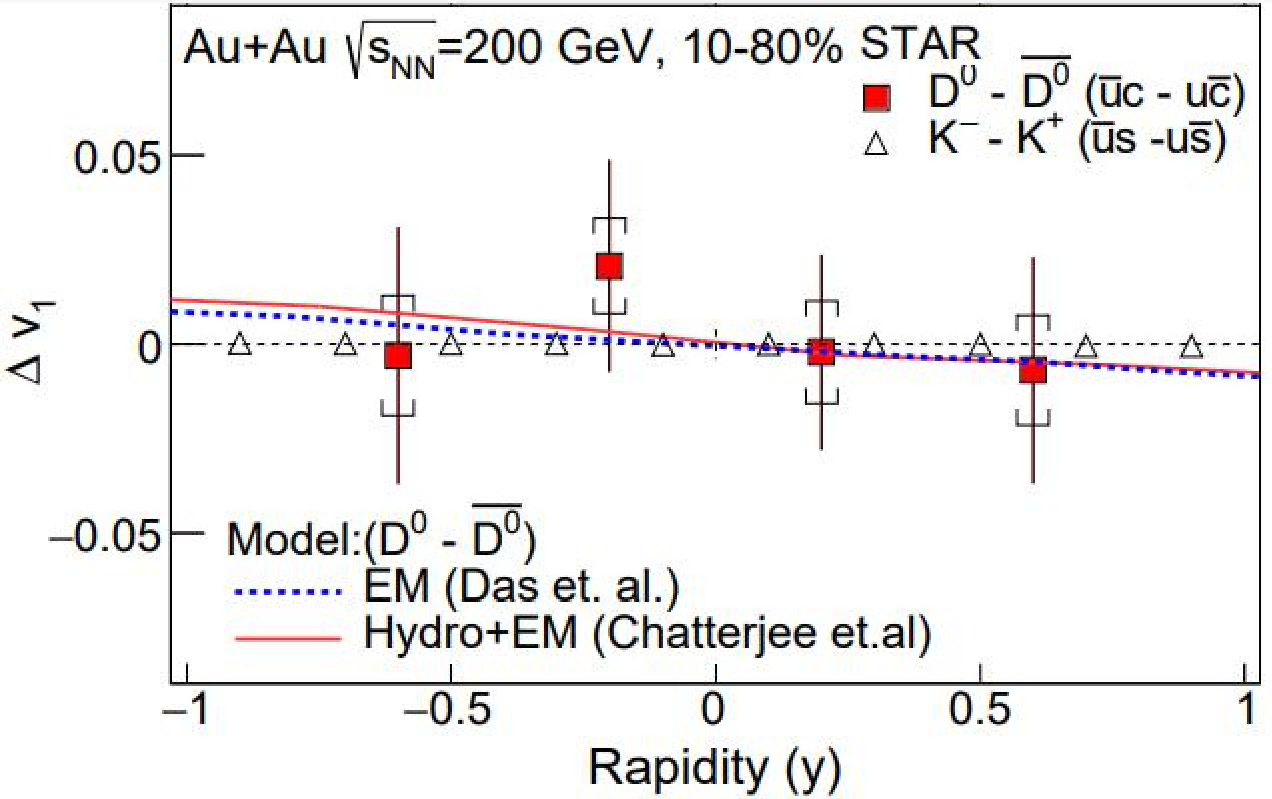
- Evidence of Hall effect via v_1 in symmetric collisions.
  - $\Delta(dv_1/dy)$ increases with both Δq and ΔS for 5 cases.
  - many caveats in the interpretation.
  - needs better precision.

Backup slides

v_1 of charm quarks



c and c-bar quarks are deflected differently by the EM force, after their early production (τ_{CQ} ~ 0.1 fm/c).



- Δv_1 slope between D^0 and D^0-bar: −0.011 ± 0.034 (stat.) ± 0.020 (syst.)
- Too large uncertainties.
- Prediction from -0.008 to -0.004.
- Transported *u* could contribute to Δv_1 roughly -0.015*10% (10% more D^0-bar)

STAR, Phys. Rev. Lett. 123 (2019) 162301;
EM: Das et. al., Phys Lett B 768, 260 (2017);
Hydro+EM: Chatterjee, Bojek, PRL120(2018)192301