Probing electromagnetic field with charge dependence of directed flow in STAR experiment at RHIC

Ashik Ikbal Sheikh (for the STAR Collaboration)

Kent State University

ICTP SAIFR

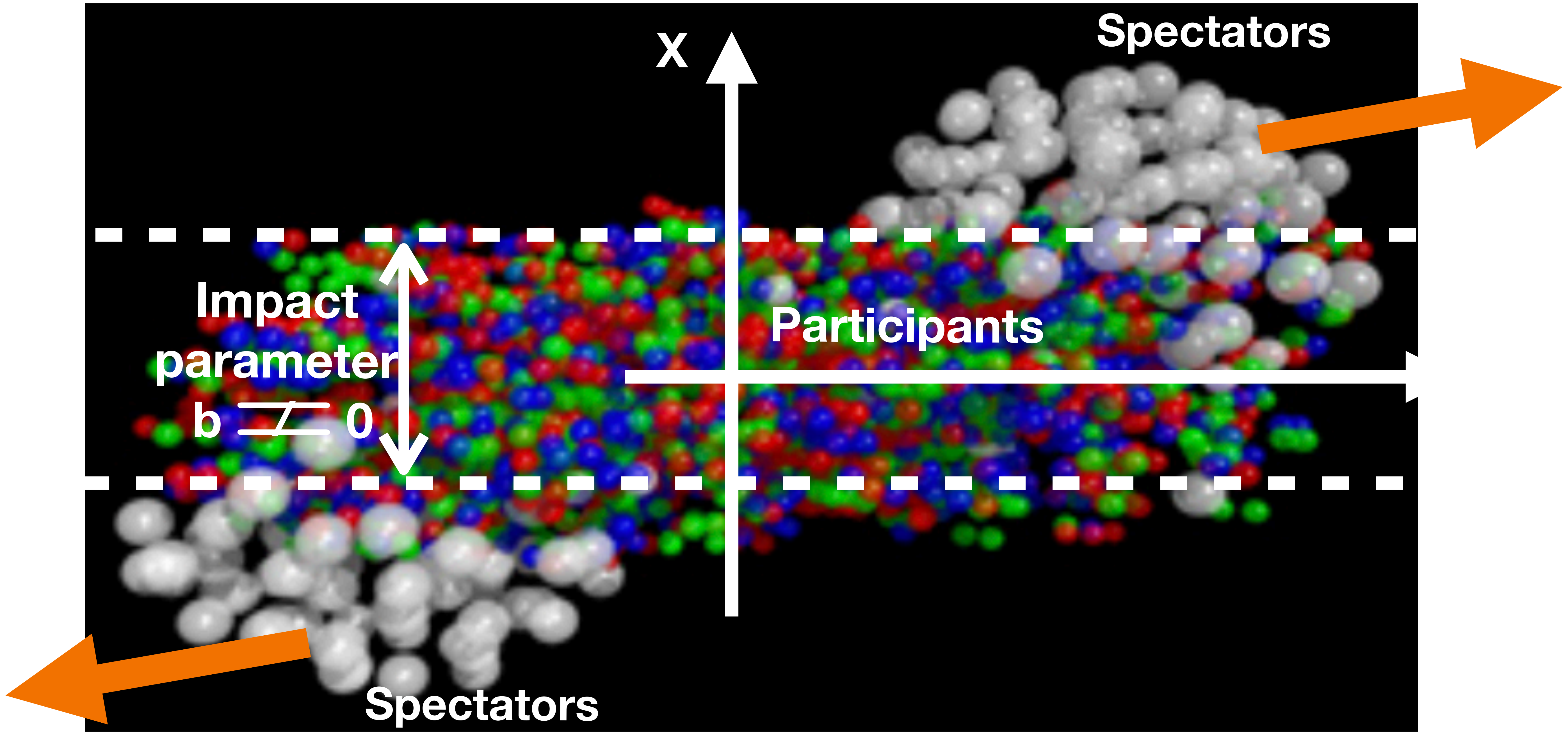
STAR

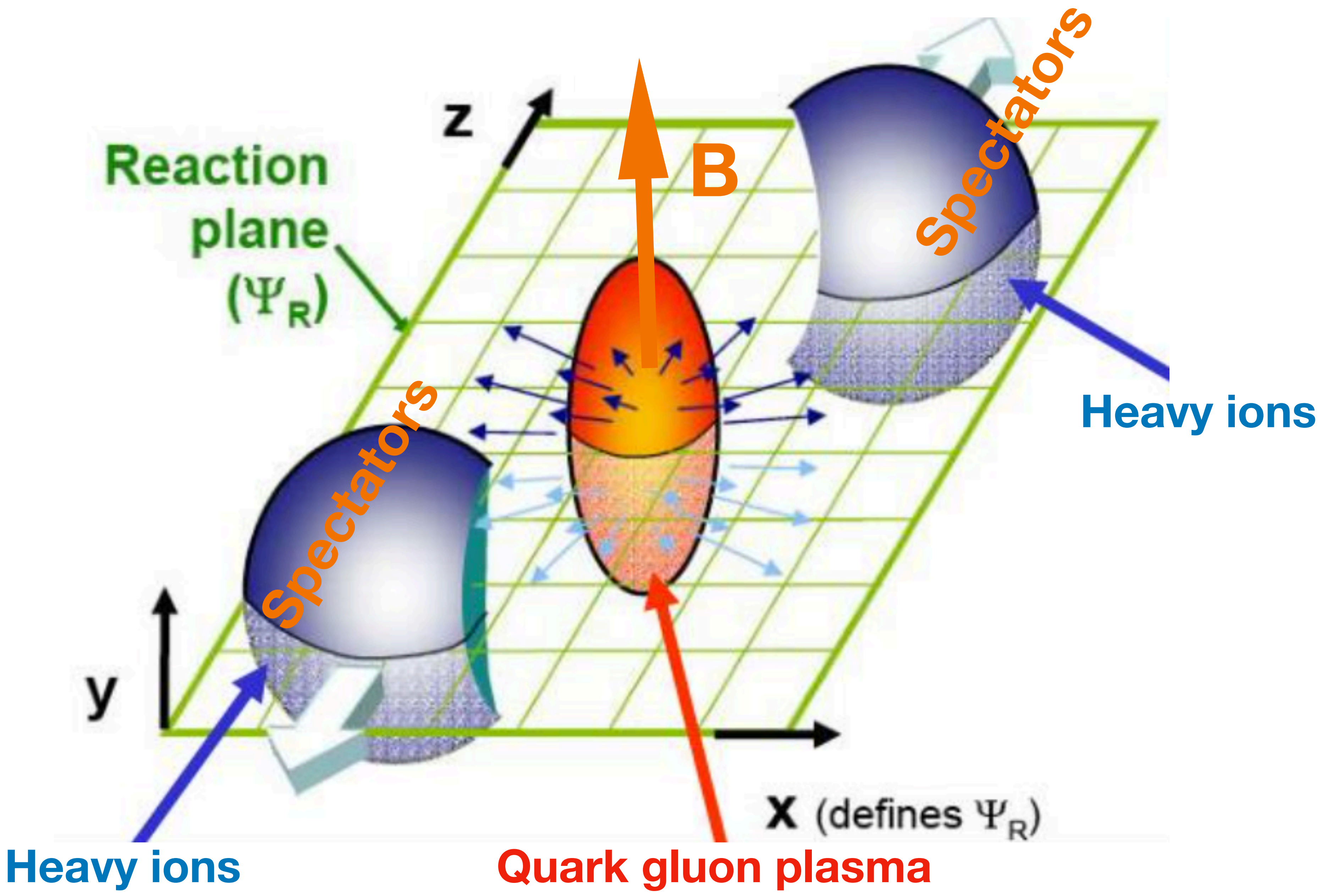
Workshop on Electromagnetic Effects in Strongly Interacting Matter
ICTP SAIFR, São Paulo, Brazil, Oct 25 - 28, 2022

KENT STATE UNIVERSITY

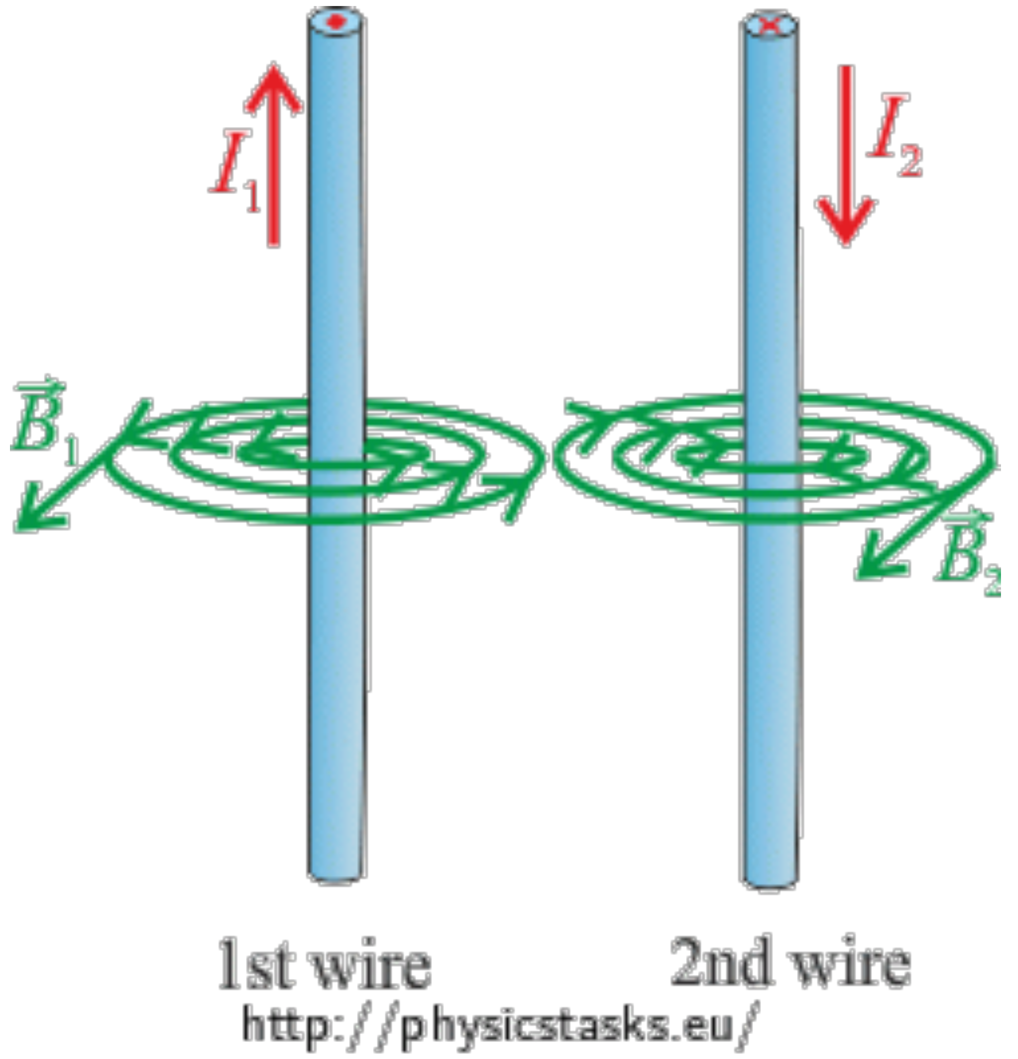
Supported in part by
U.S. DEPARTMENT OF ENERGY | Office of Science

Magnetic field in heavy ion collisions





- Non-central HICs (non-zero impact parameter)
- Charged spectator nuclei produce electric currents (like two parallel current carrying wires in opposite directions)
- The currents can produce magnetic fields
- Magnetic fields due to these two sources add up



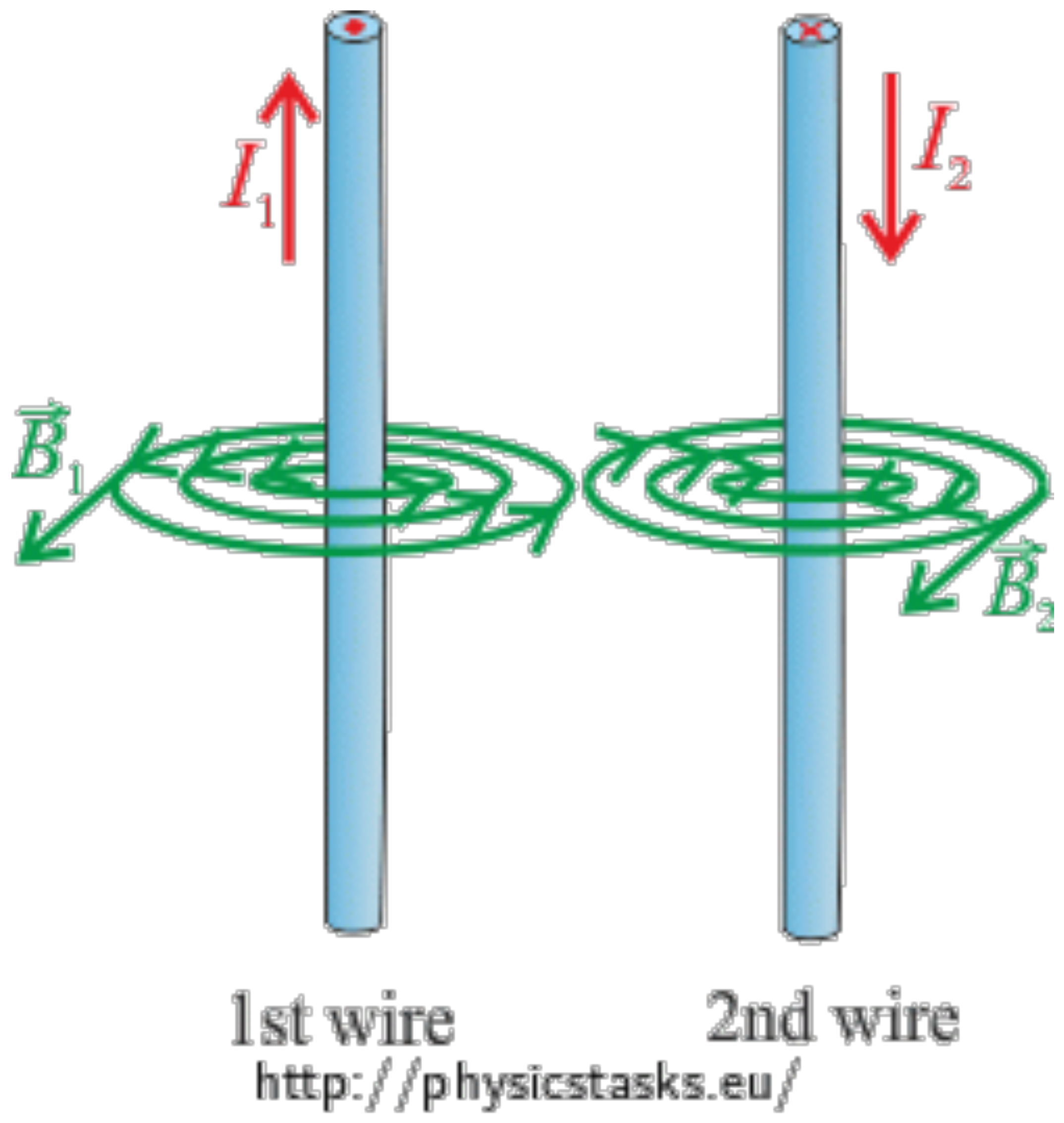
Estimates of the produced magnetic field

- A crude estimate of the magnetic field (using Biot-Savart Law):

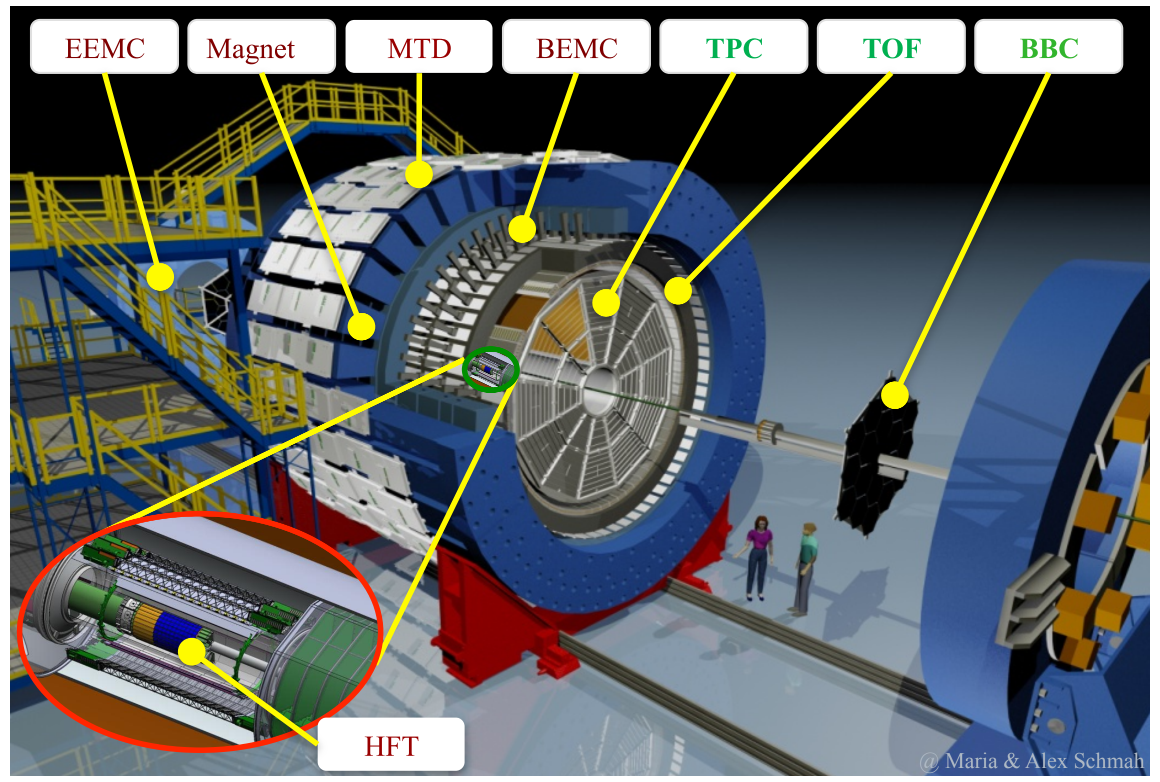
$-eB_y \sim 40m_\pi^2 \sim 10^{18}$Gauss (At RHIC Au+Au collisions, $\sqrt{s_{NN}} = 200$ GeV, b = 5 fm, t = 0)

- Strongest magnetic field ever produced in laboratory

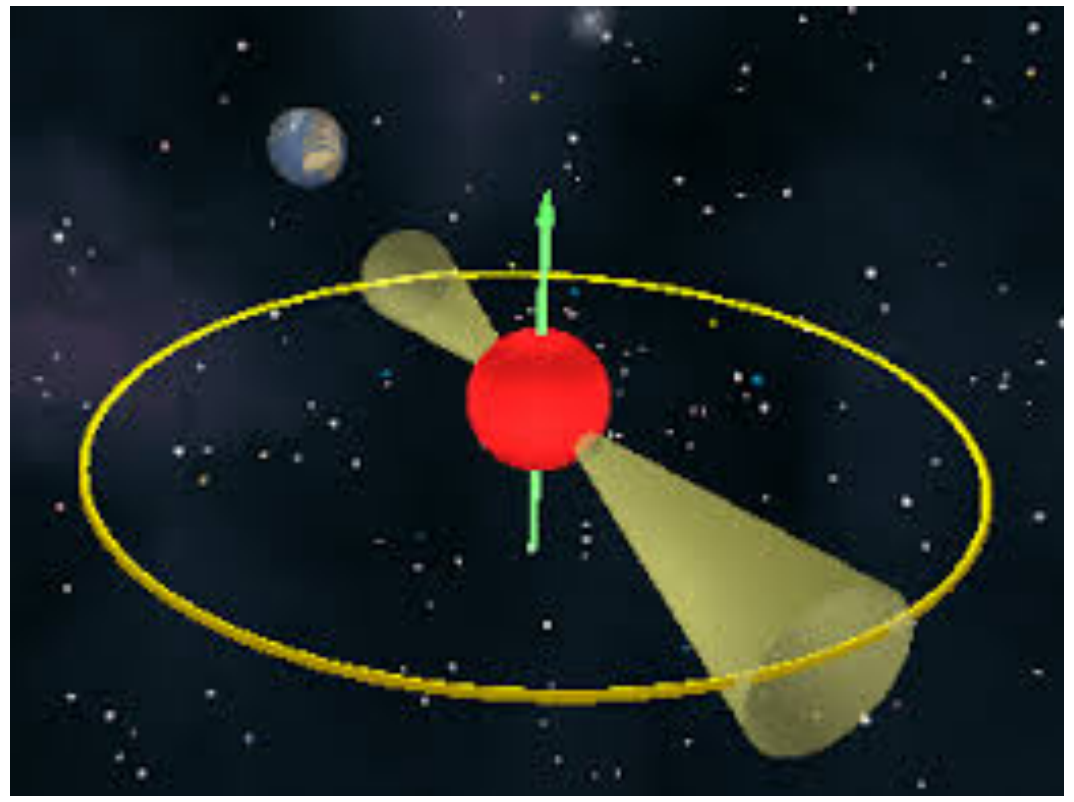
- B-field has observable effects on properties of produced particles, such as anisotropic flow



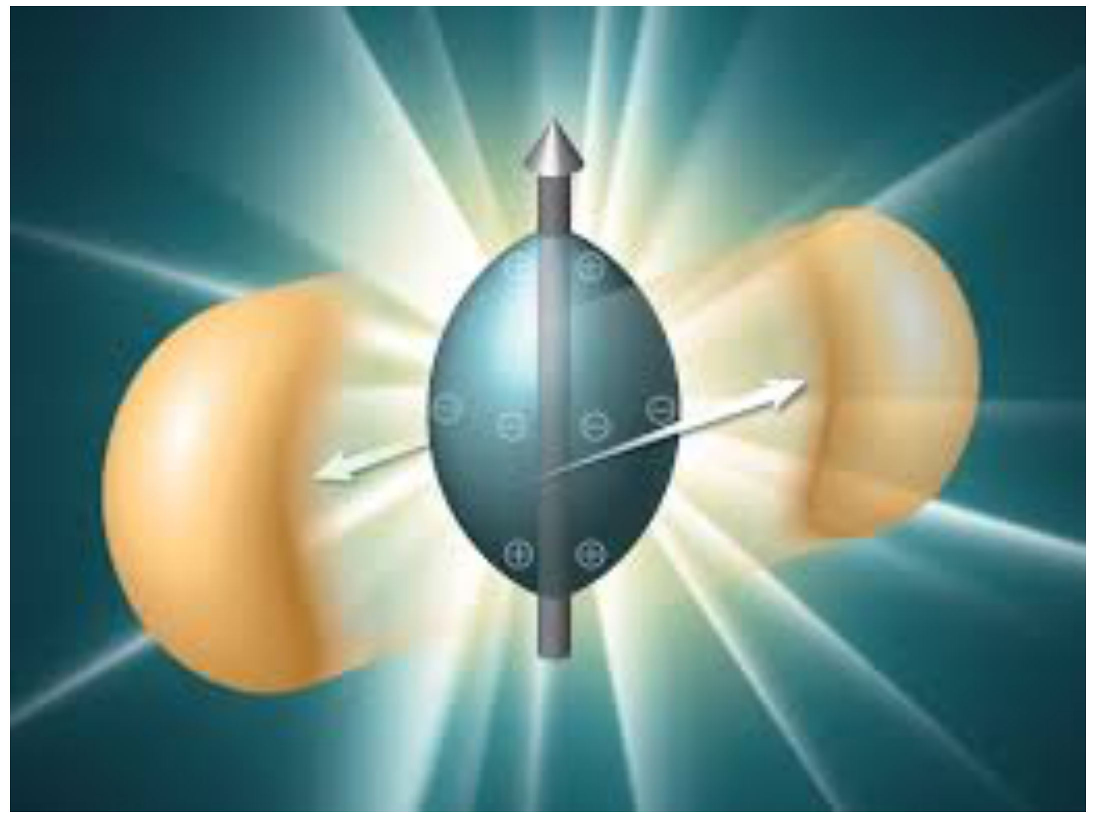
Earth
~0.5 Gauss



STAR magnet
~5000 Gauss



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



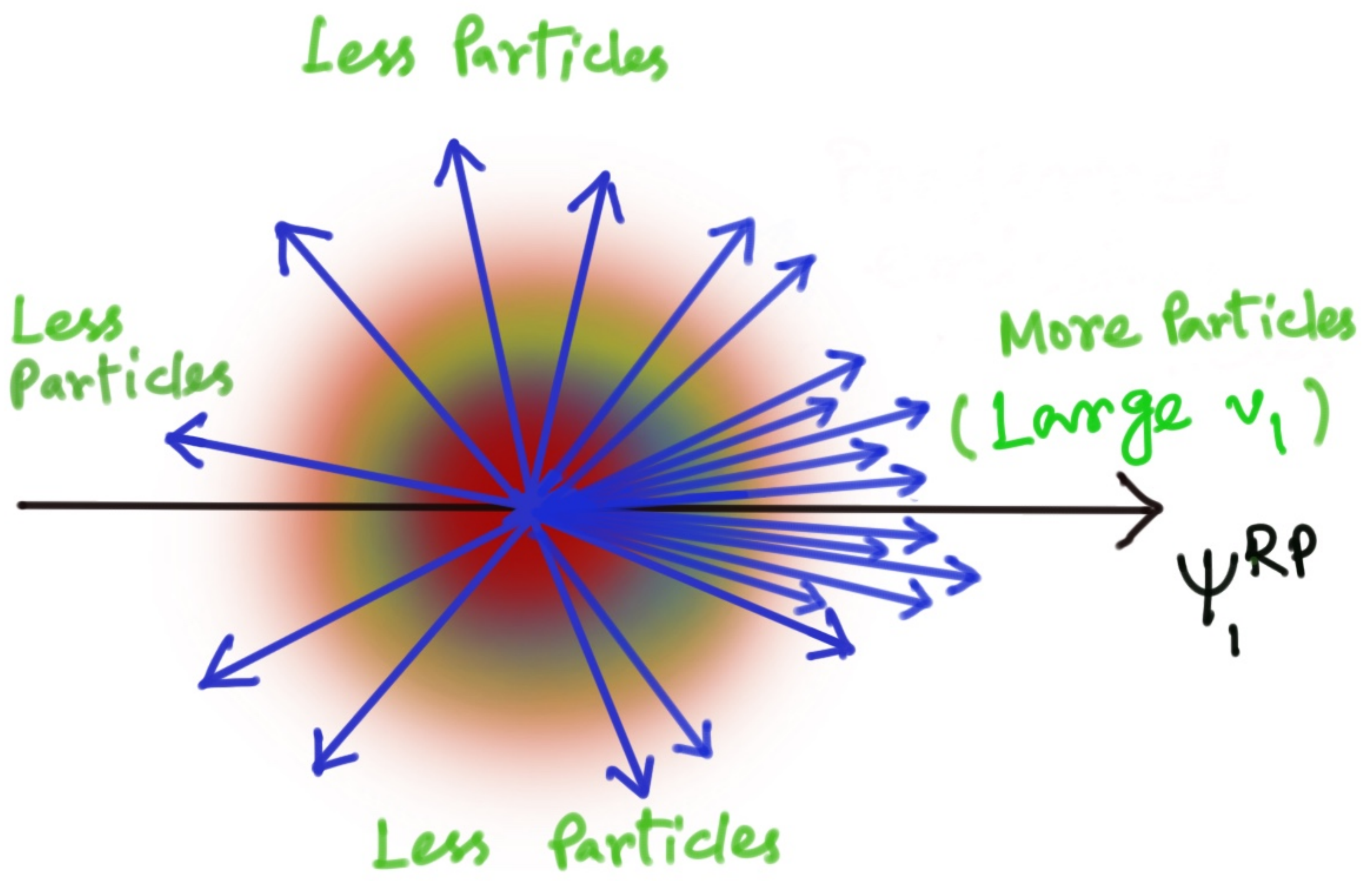
Heavy ion collisions
~ 10^{18} Gauss

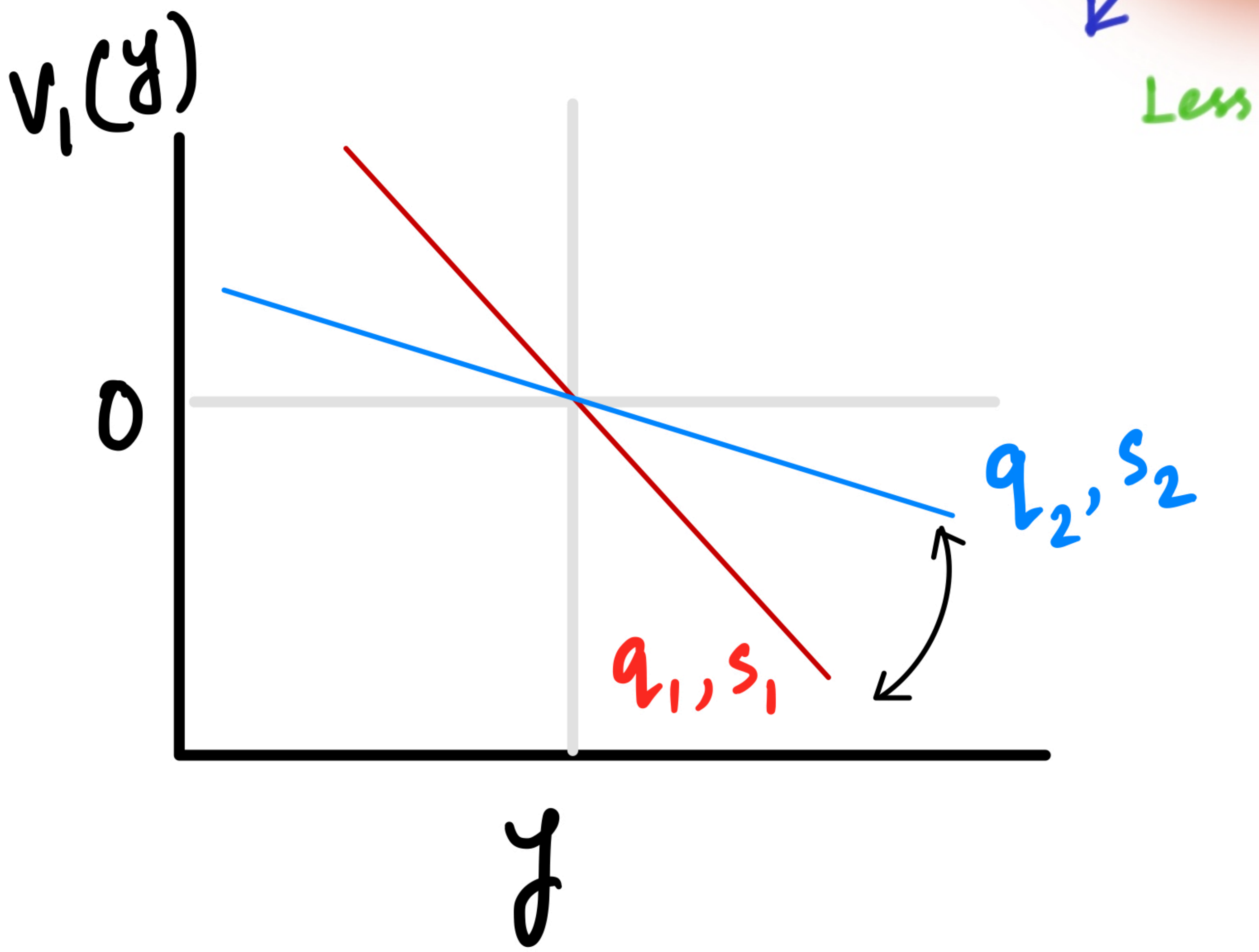
Directed flow (v_1) and charge splitting (Δv_1)

- First harmonic coefficient of Fourier decomposition of particle azimuthal distribution - directed flow (v_1)

$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T dy}\left(1 + 2\sum_{n=1}^{+\infty} v_n \cos n(\phi - \Psi_{RP})\right)$$

where $v_n = \langle \cos n(\phi - \Psi_{RP}) \rangle$

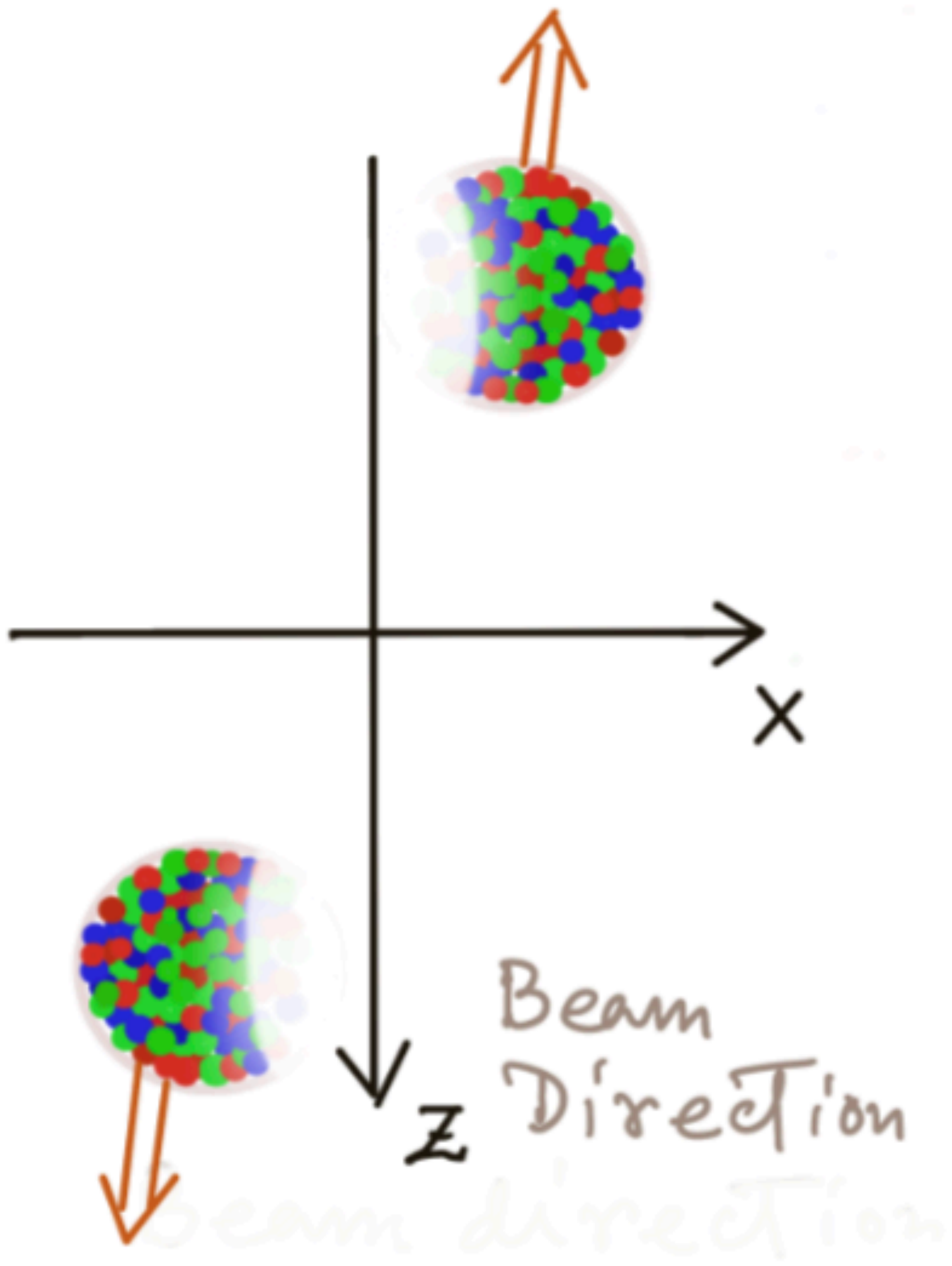


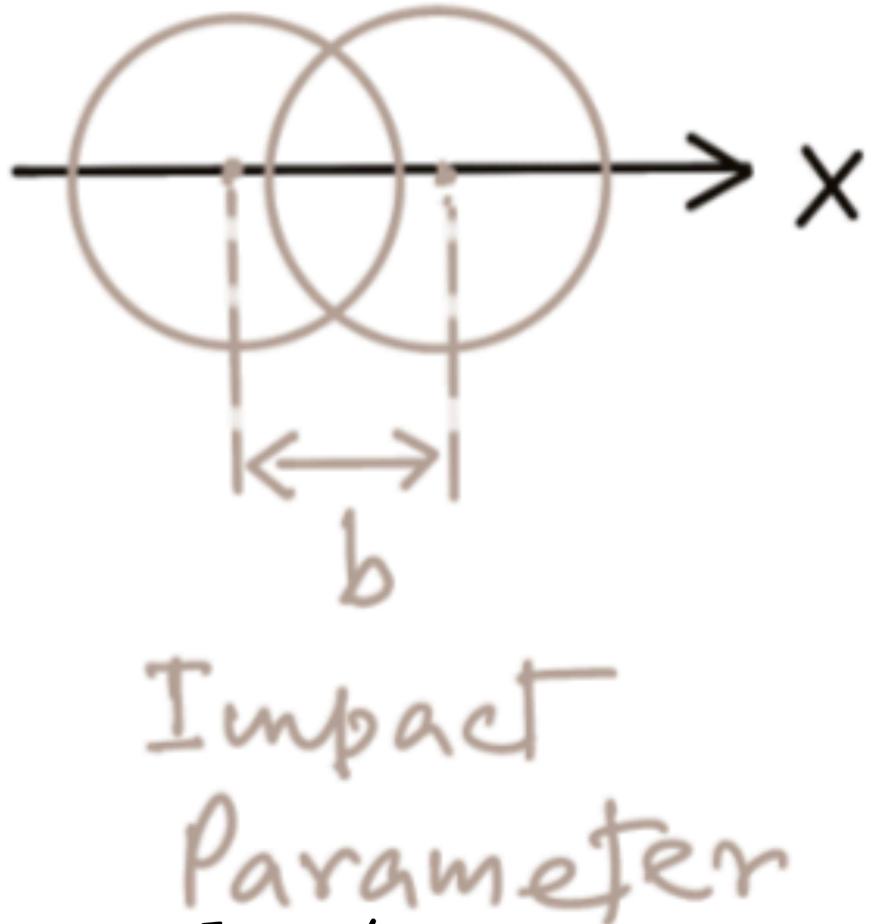


- Probe early stage of the collisions - strong electromagnetic (EM) field

- EM field has observable consequences on charge driven v_1 splitting (Δv_1)

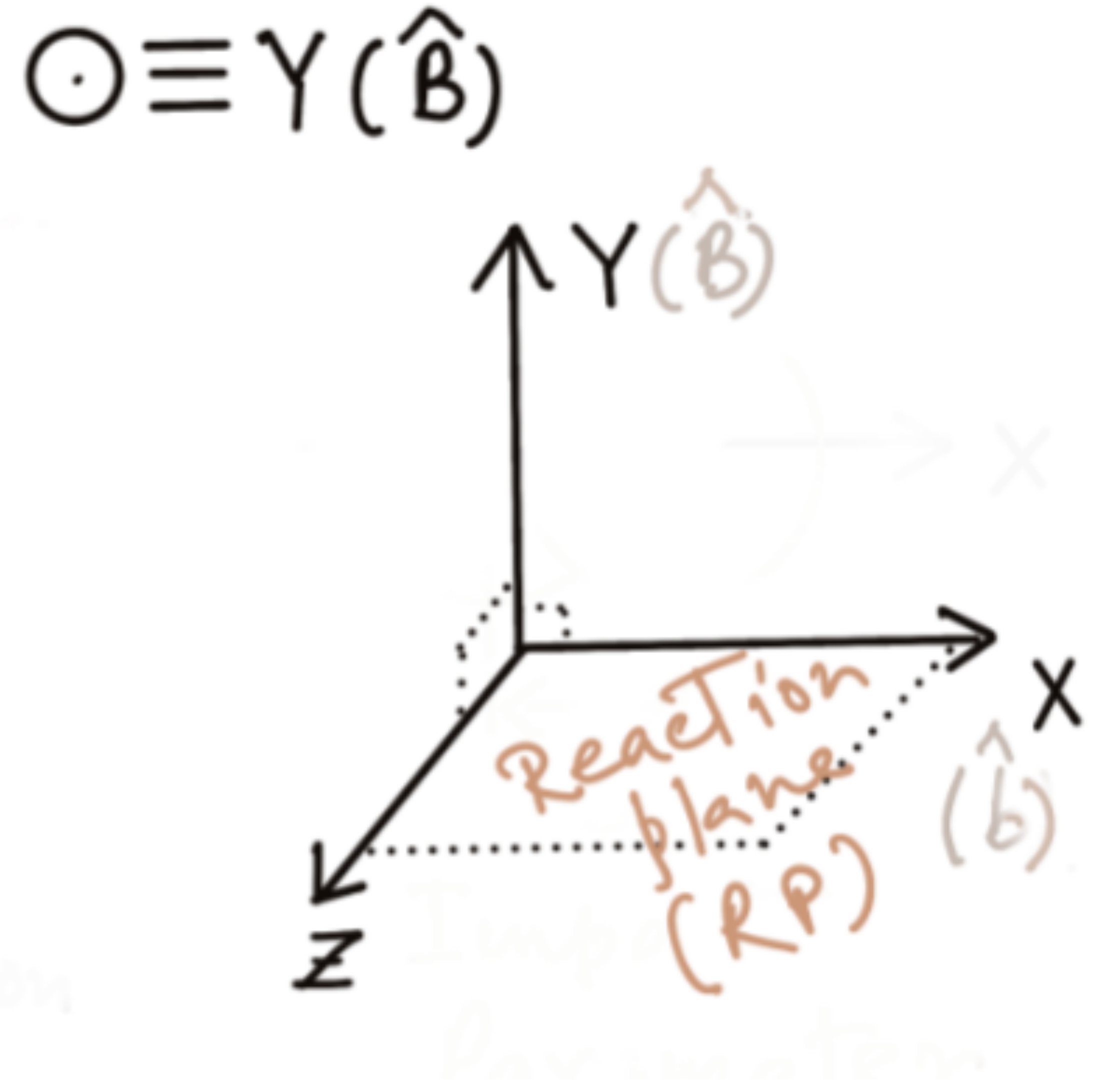
EM field drives splitting



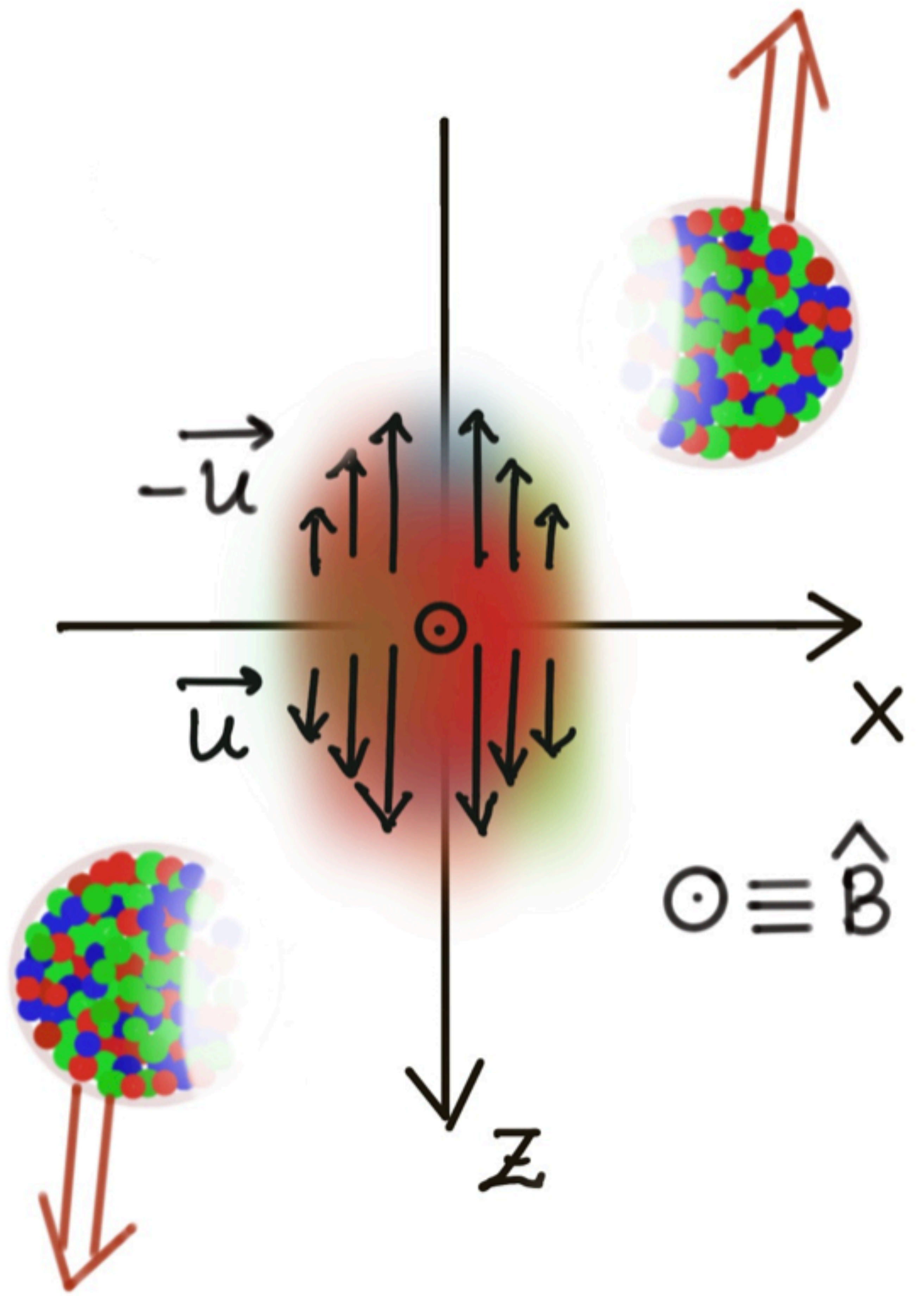


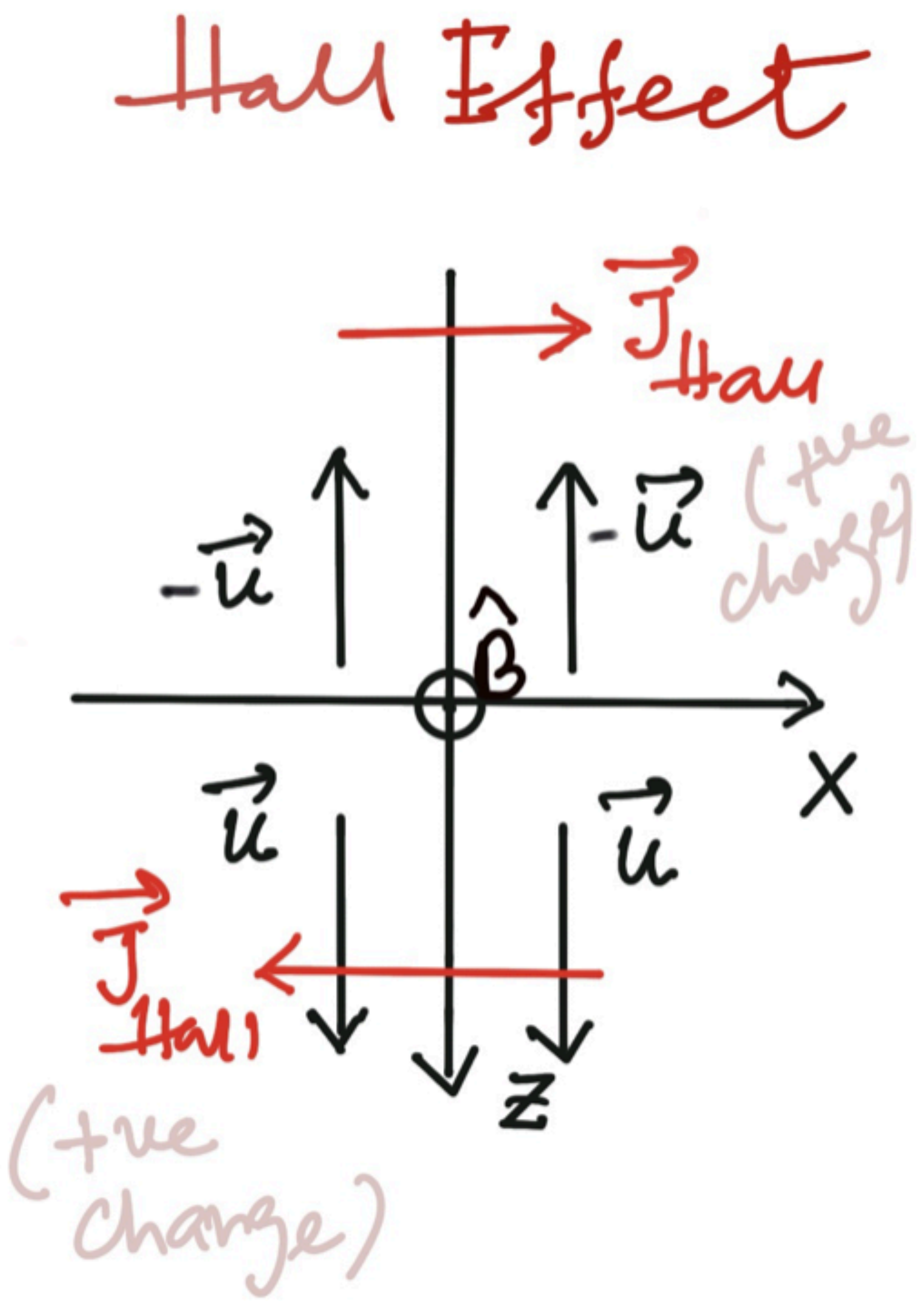
$b \neq 0$

- Assume a non-central HIC $(b \neq 0)$
- Beam direction: $\hat{z}$, Impact parameter: $\hat{x}$
- Reaction plane (RP): xz
- Charged spectators produce magnetic field - $\vec{B} \perp RP$



EM field drives splitting - Hall effect

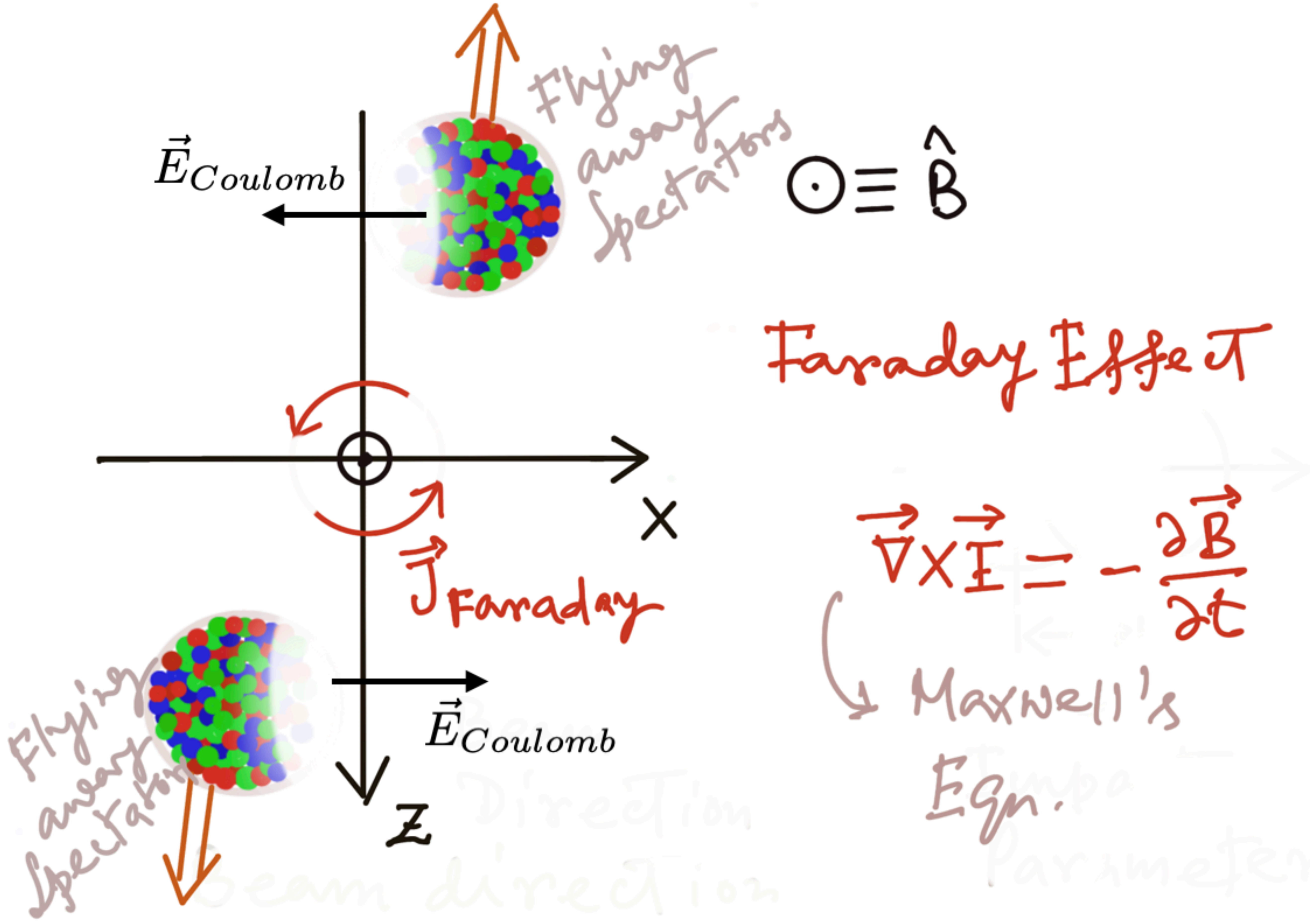




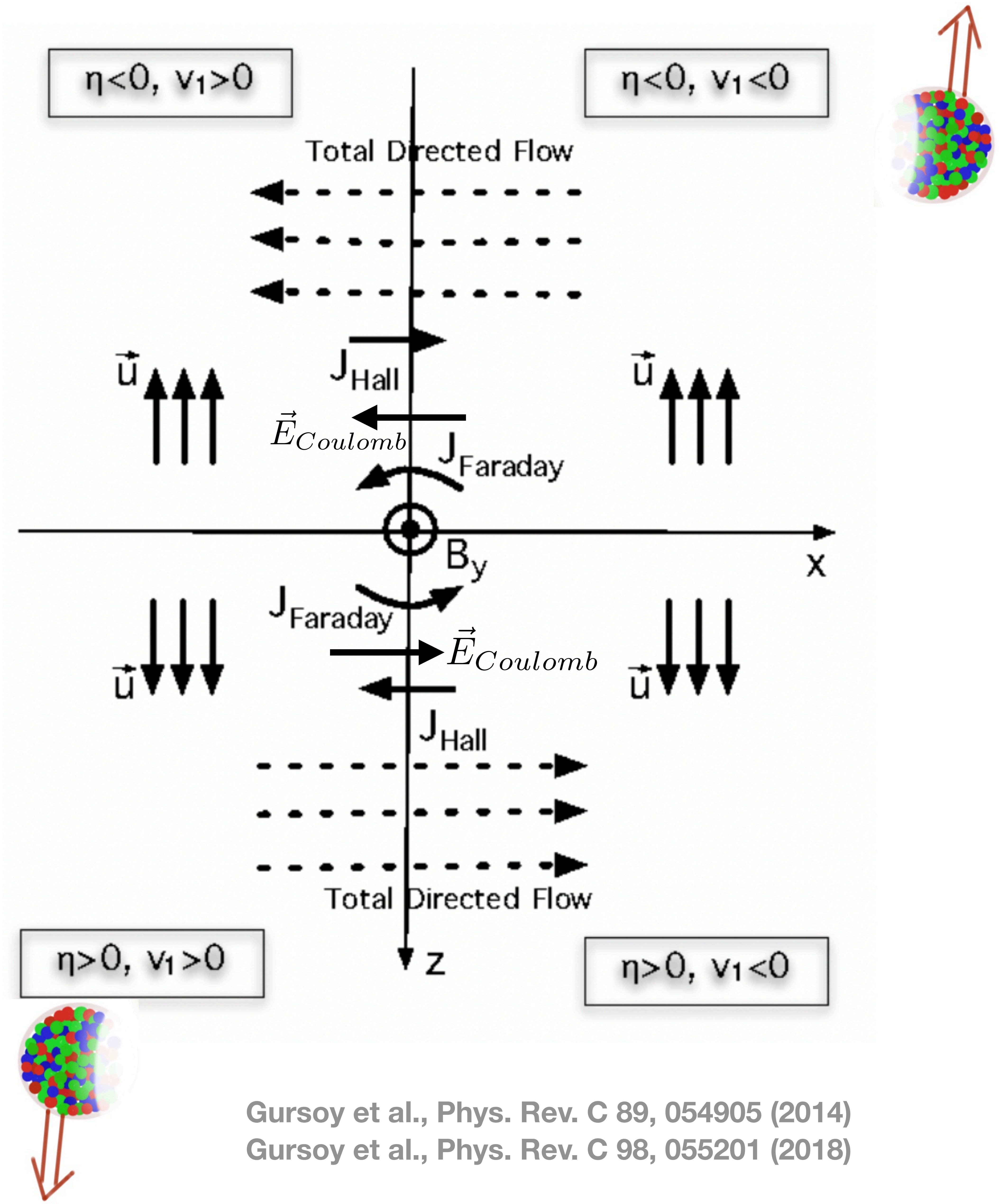
- Produced medium expands longitudinally ($\vec{u}||\hat{z}$, $\vec{u} \perp \vec{B}$)
- Lorentz force pushes positively and negatively charged particles in opposite directions
- Generated current $\perp \vec{B}, \vec{u}$ => Hall effect

EM field drives splitting - Faraday and Coulomb effect

- Spectators fly away, $\vec{B}$ decays down fast
- Time varying $\vec{B}$ induces $\vec{E}$ field => Faraday effect
- Charged spectators also generate Coulomb field



EM field drives splitting - Hall, Faraday and Coulomb effect

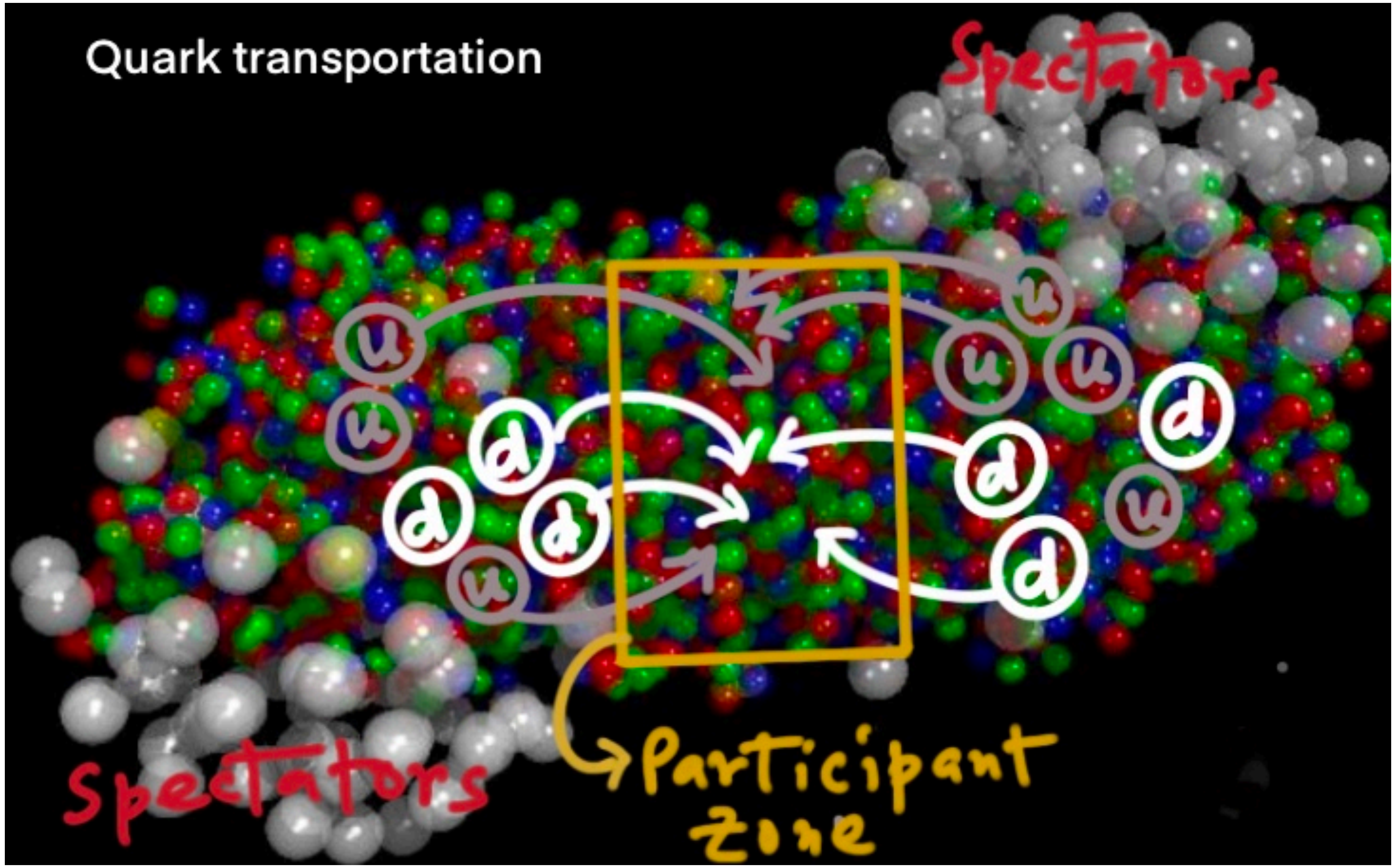


Gursoy et al., Phys. Rev. C 89, 054905 (2014)
Gursoy et al., Phys. Rev. C 98, 055201 (2018)

- Faraday, Coulomb and Hall are competing effects
- Net effect of Faraday, Hall and Coulomb affects v_1 and splitting between particles and antiparticles
- Direction of v_1 for positive particles shown by dashed arrows (when Faraday+Coulomb > Hall)
- Direction of v_1 for negative particles - the other way around
- EM field drives v_1 splitting (Δv_1) between particles and anti-particles
- Can we measure this splitting?

Splitting (Δv_1): Challenge in measurements (Transport)

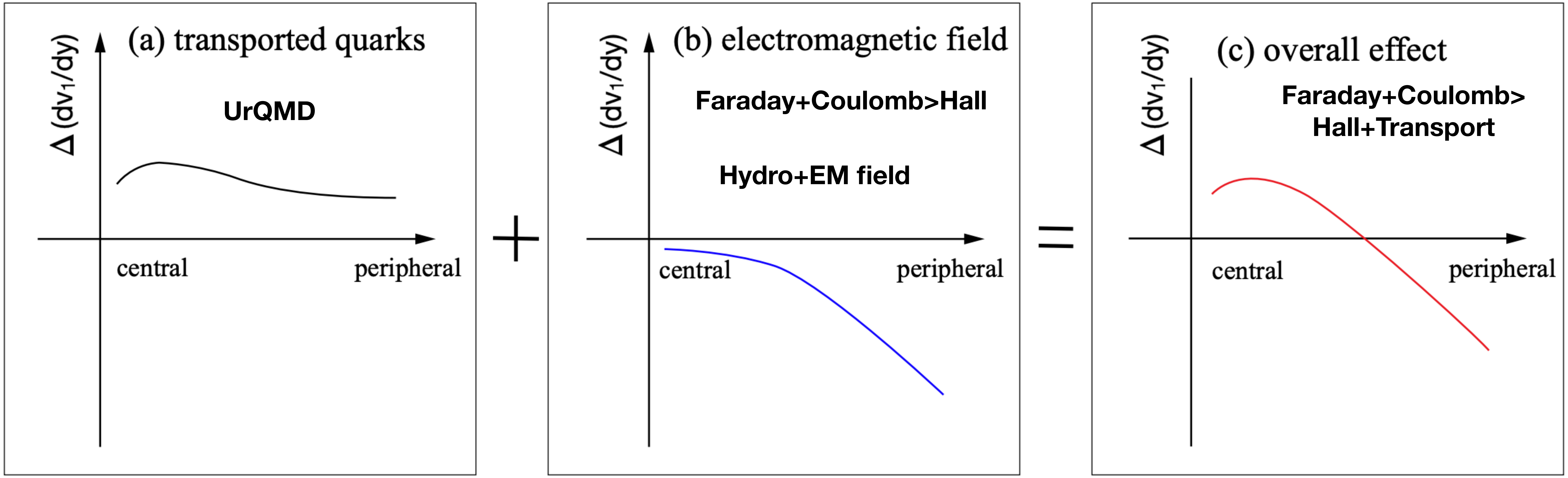
- The u, d quarks can be transported from beam rapidity
- Since transported quarks travel from beams, they suffer a lot more interactions than produced quarks
- Transported quarks have different v_1 than produced quarks
- There is already a v_1 splitting between quarks (transported) and anti-quarks (produced)
- This splitting interferes with the EM field driven splitting, becoming difficult to isolate



Interplay between transported quarks and EM field (a qualitative picture)

- Quarks transported from beam rapidity (u, d) have different v_1 than produced quarks ($\bar{u}$, $\bar{d}$, s, $\bar{s}$) => a splitting between quarks (transported) and anti-quarks (produced)

- This splitting acts as a background effect for EM-field-driven splitting and should be avoided



- Splitting between particle and anti-particle ($\Delta dv_1/dy = dv_1^+/dy - dv_1^-/dy$) with centrality

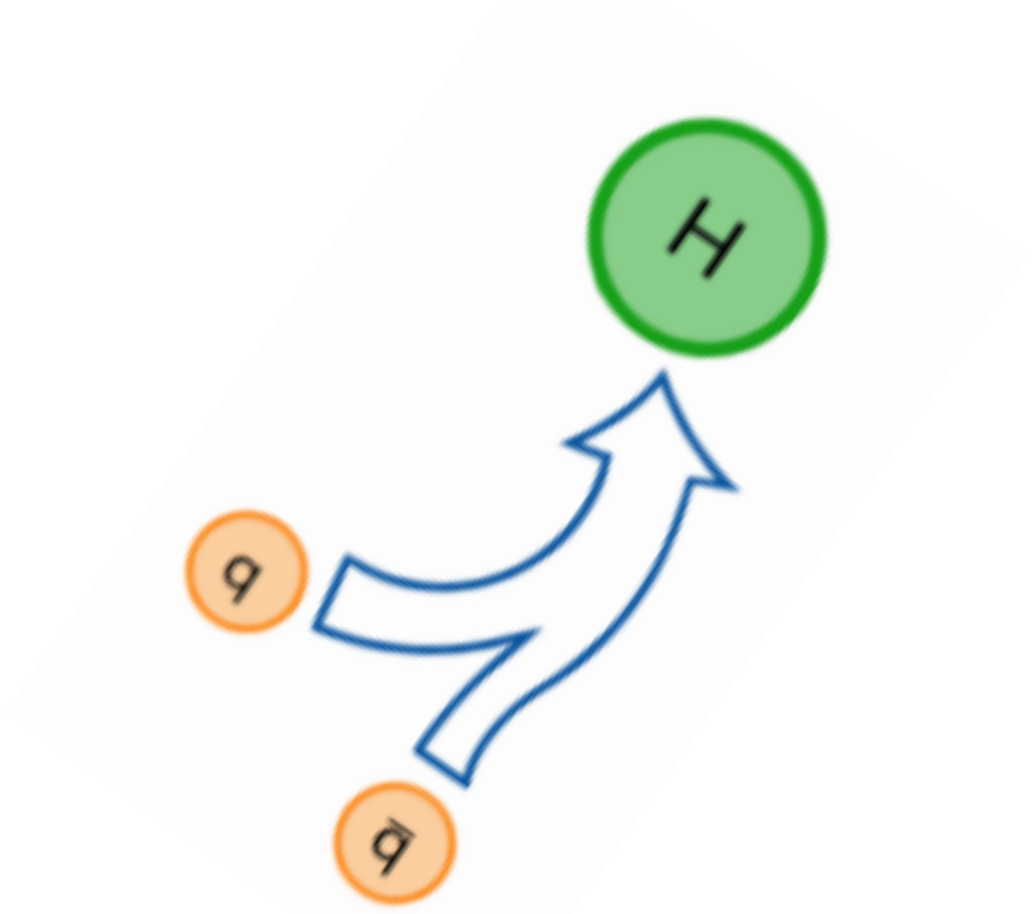
- $\Delta dv_1/dy < 0$ could be a signature of EM field (Faraday+Coulomb > Hall+Transport)

Splitting (Δv_1): An approach to subtract transported quark effect

A. Ikbal, D. Keane, P. Tribedy, Phys. Rev. C 105, 014912 (2022)
STAR Collaboration, Phys. Rev. Lett. 120, 062301 (2018)

- In experiment, it is impossible to distinguish between produced and transported u and d quarks
- Avoid particles containing u, d quarks
- Use only produced particles (only produced constituent quarks – $\bar{u}, \bar{d}, s, \bar{s}$): K^-, $\bar{p}$, $\bar{\Lambda}$, ϕ, $\overline{\Xi}^+$, Ω^- and $\overline{\Omega}^+$
- With these particles, make a clean case to measure EM field-driven-splitting
- Combine different particles and compare the combinations with same mass at the constituent level
- Apply and test coalescence-inspired sum rule: $v_1(hadron) = \sum v_1^i(q_i)$, (same $y - p_T/n_q$ space, with $n_q \rightarrow$ constituent quarks)

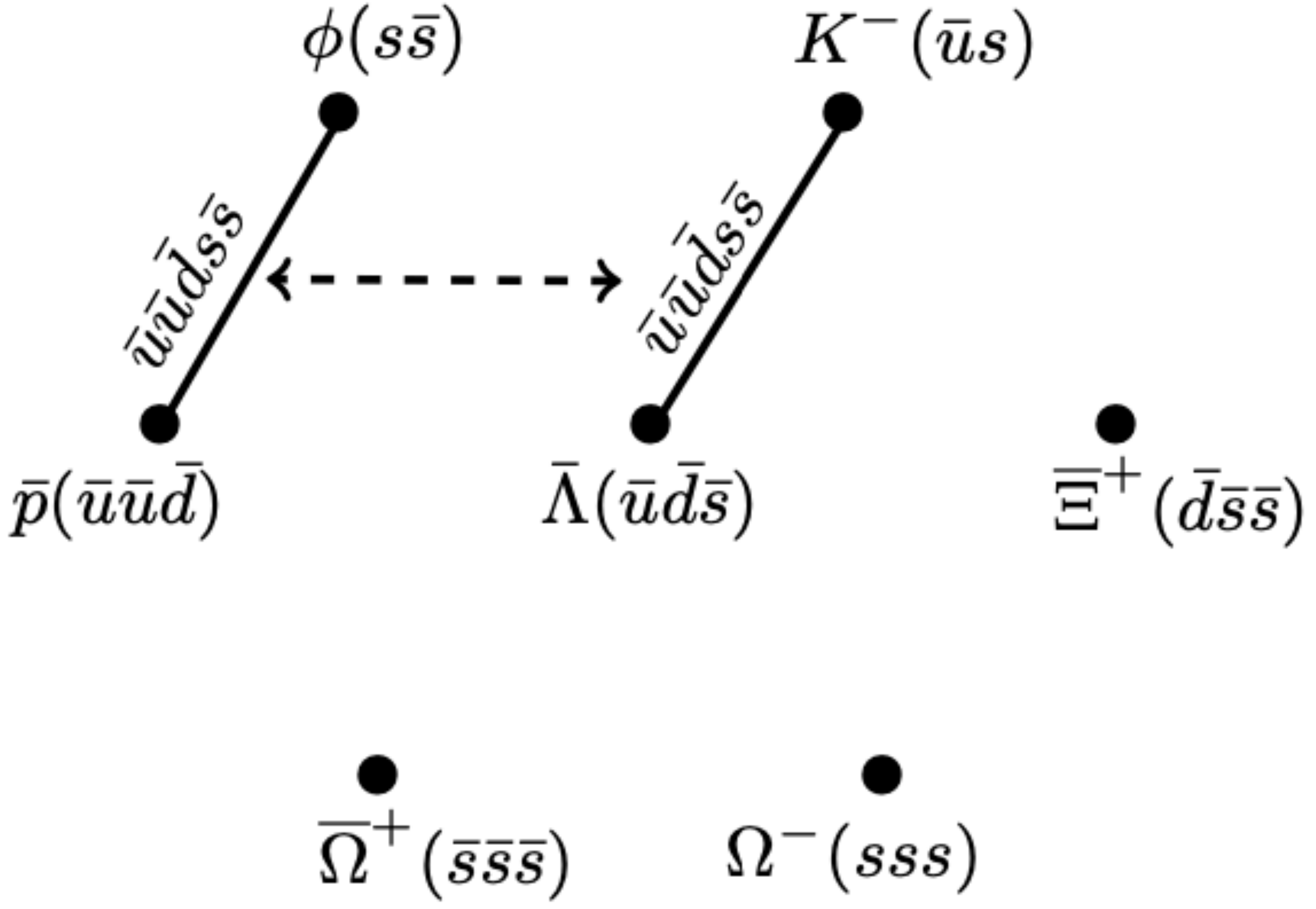
  $q_i \rightarrow$ Constituent quarks



Splitting (Δv_1): Testing Coalescence sum rule

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

- Combine particles and make identical constituent quark combinations

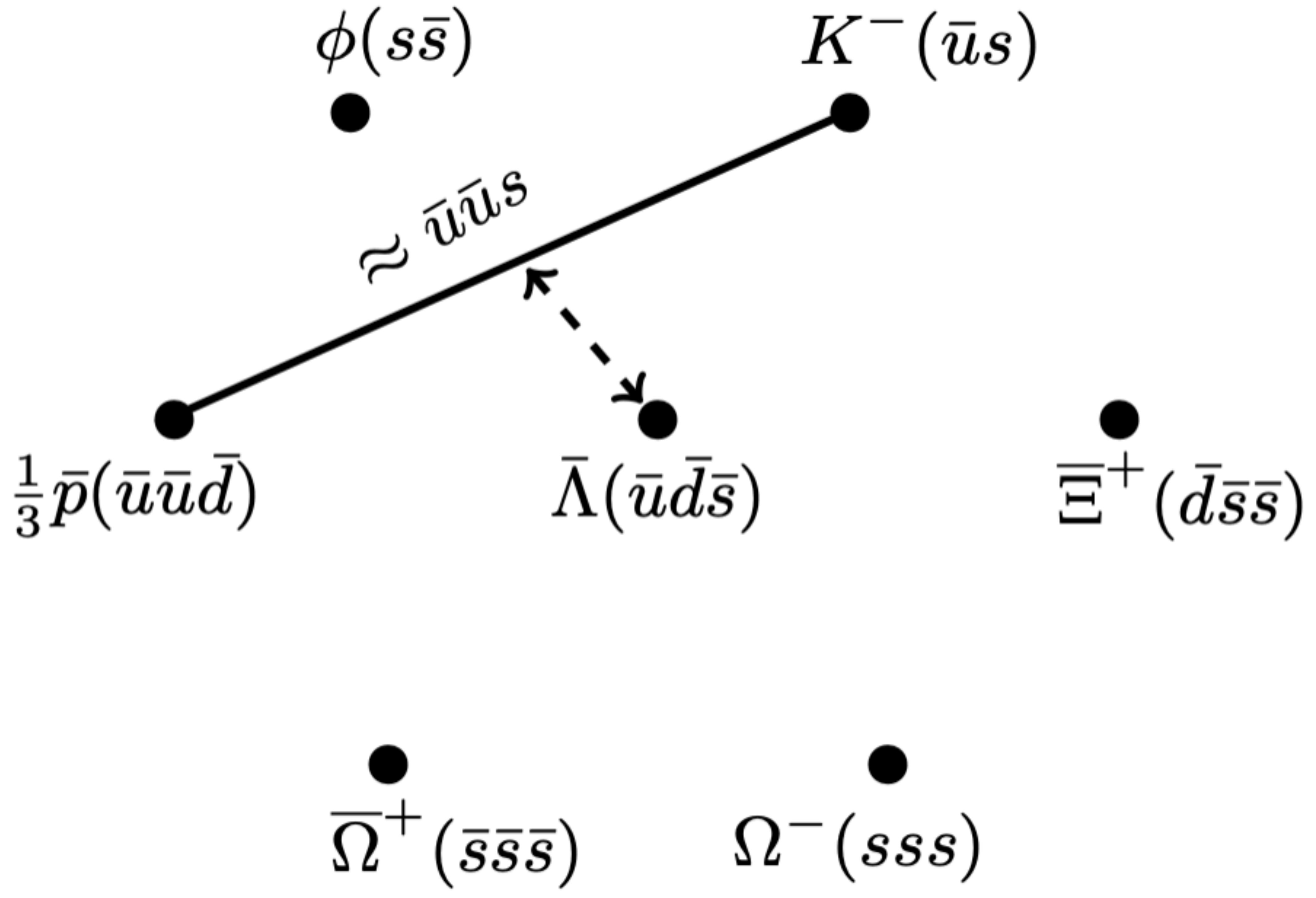


$$v_1[K^-(\bar{u}s)] + v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})] = v_1[\bar{p}(\bar{u}\bar{u}\bar{d})] + v_1[\phi(s\bar{s})]$$

- Charge difference, $\Delta q = 0$ and strangeness difference, $\Delta S = 0$

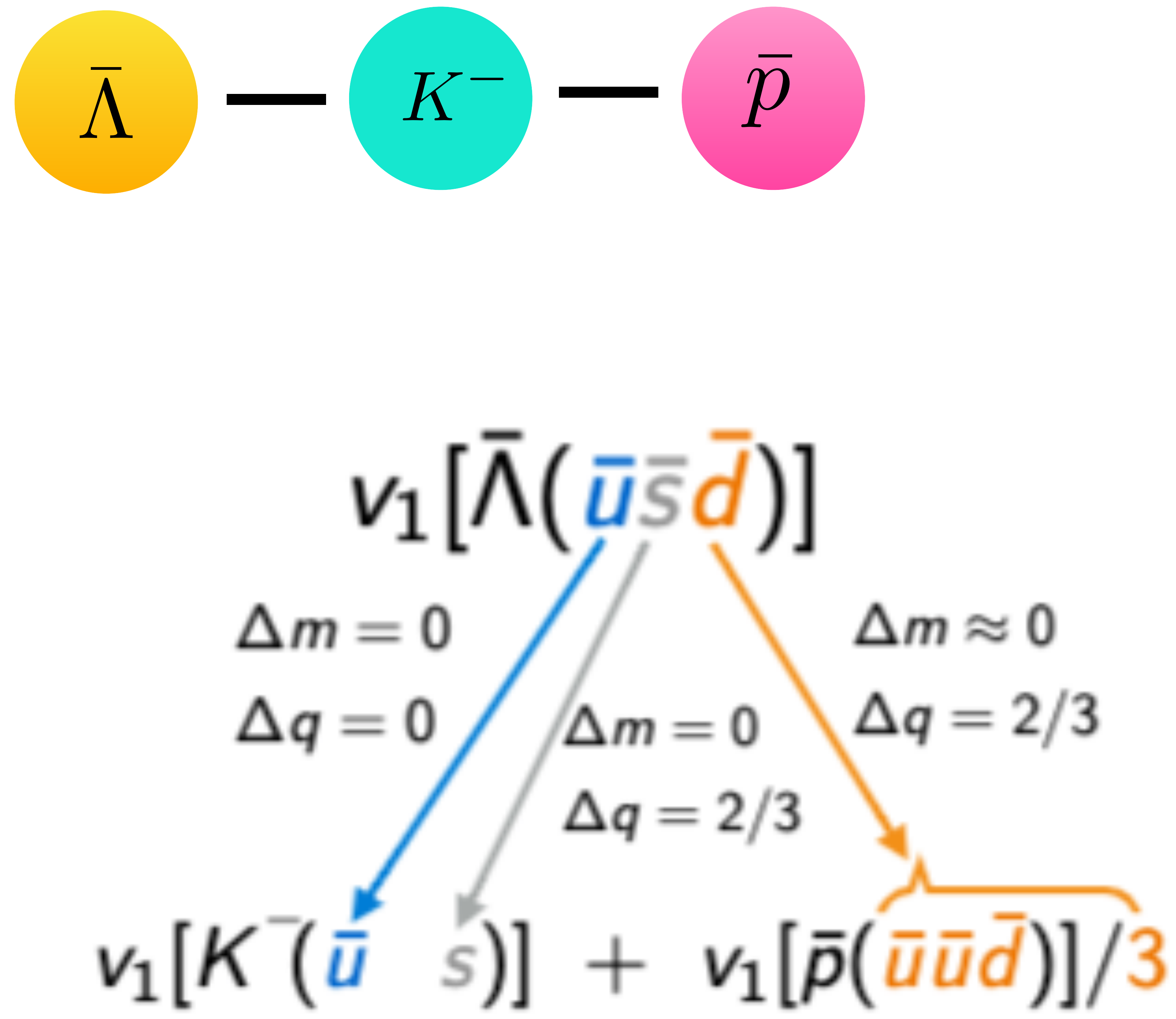
Splitting: Combination with non-zero Δq and ΔS

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



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

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



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

Combining different produced particles

- Combinations having same or nearly same quark mass but different Δq and ΔS
  => No contribution from transported quark

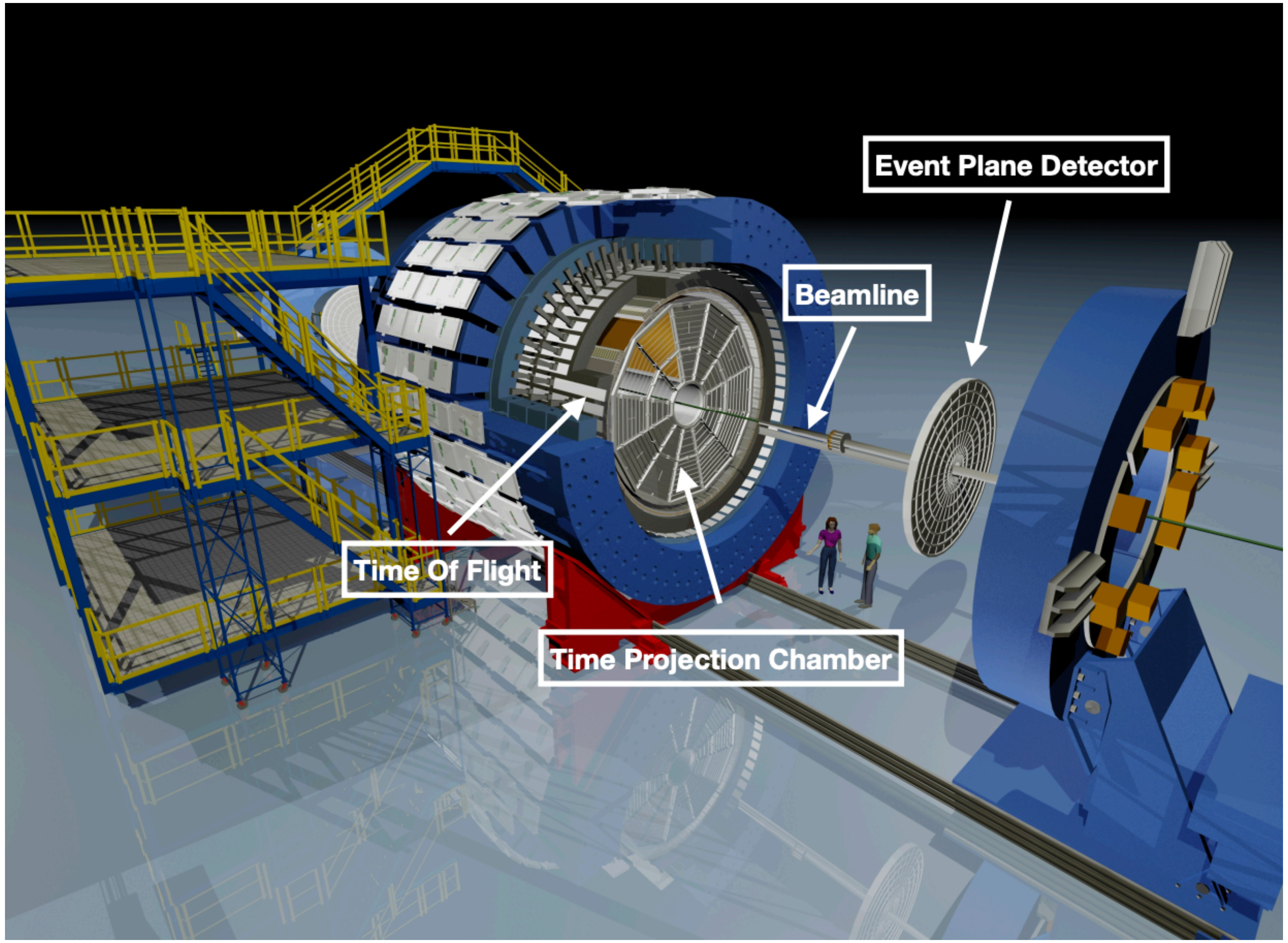
Index	Quark Mass	Charge	Strangeness	Expression
1	$\Delta m = 0$	$\Delta q = 0$	$\Delta S = 0$	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^{-}(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$
2	$\Delta m \approx 0$	$\Delta q = 1$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^{-}(sss)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

- Only 5 combination differences among many are independent
- Two degenerate combinations in $\Delta S = 2$ - Good cross check
- Measure splitting with Δq and ΔS, though they are correlated

Towards measurements: STAR detector and datasets

- TPC+TOF for PID: TPC measures dE/dx of tracks ($|\eta| < 1$, $0 < \phi < 2\pi$) and TOF measures time of flight ($|\eta| < 0.9$)
- EPD ($2.1 < |\eta| < 5.1$) or ZDC ($|\eta| > 6.3$) for event plane reconstruction

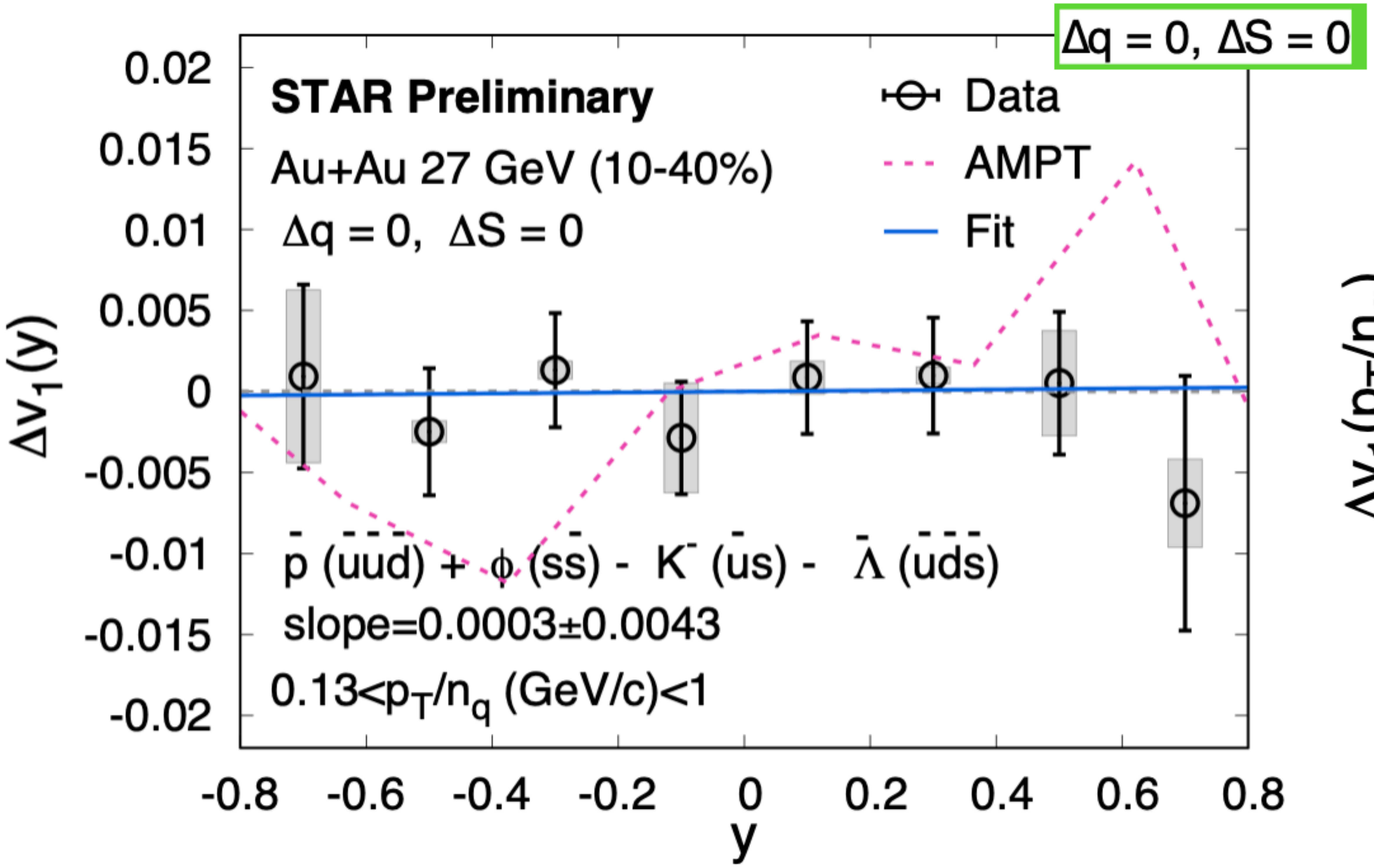


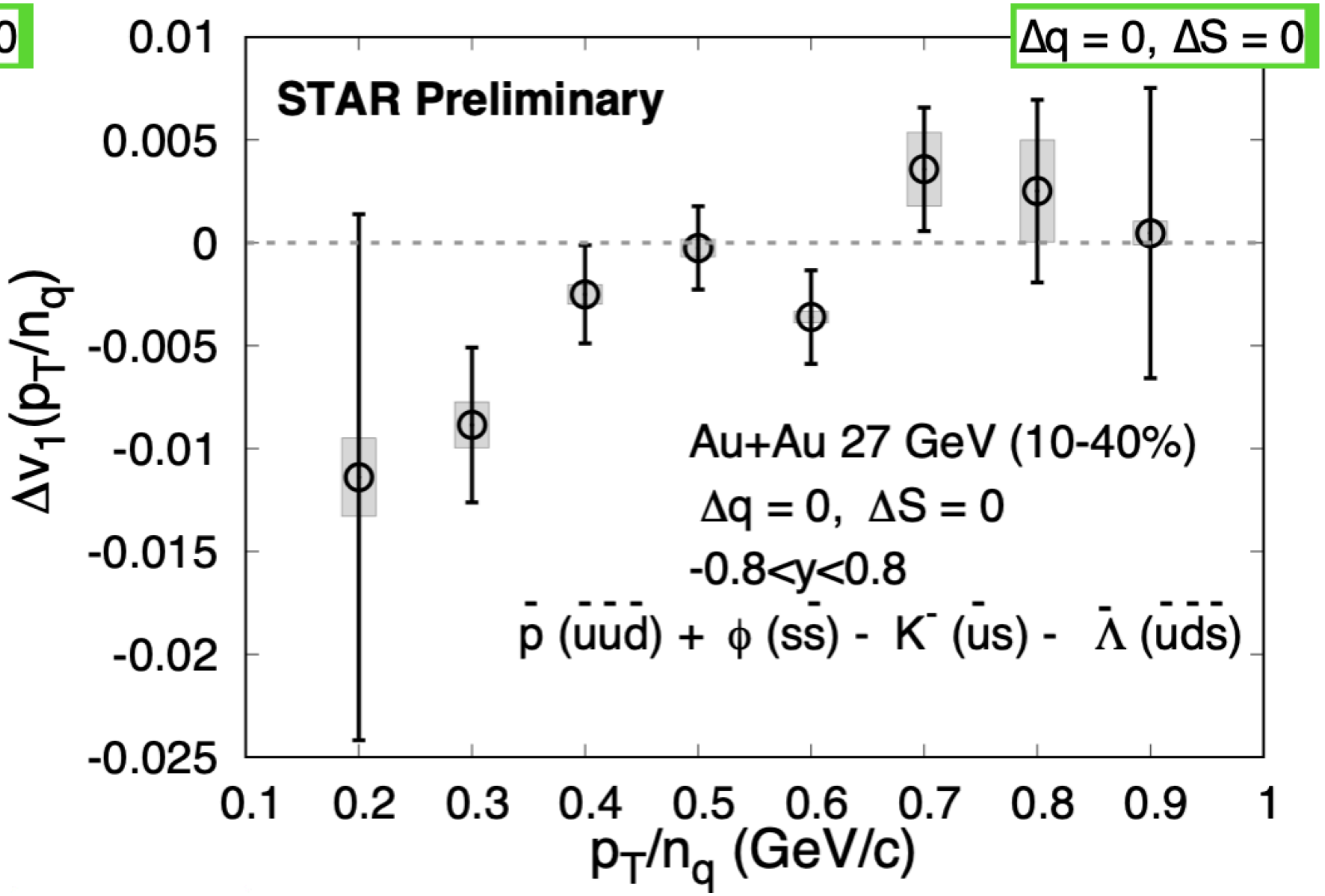
Datasets analyzed:

- At $\sqrt{s_{NN}} = 27$ GeV Au+Au at BES-II, and $\sqrt{s_{NN}} = 200$ GeV Au+Au and isobaric collisions (Ru+Ru and Zr+Zr)

Coalescence sum rule at Au+Au @ 27 GeV

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

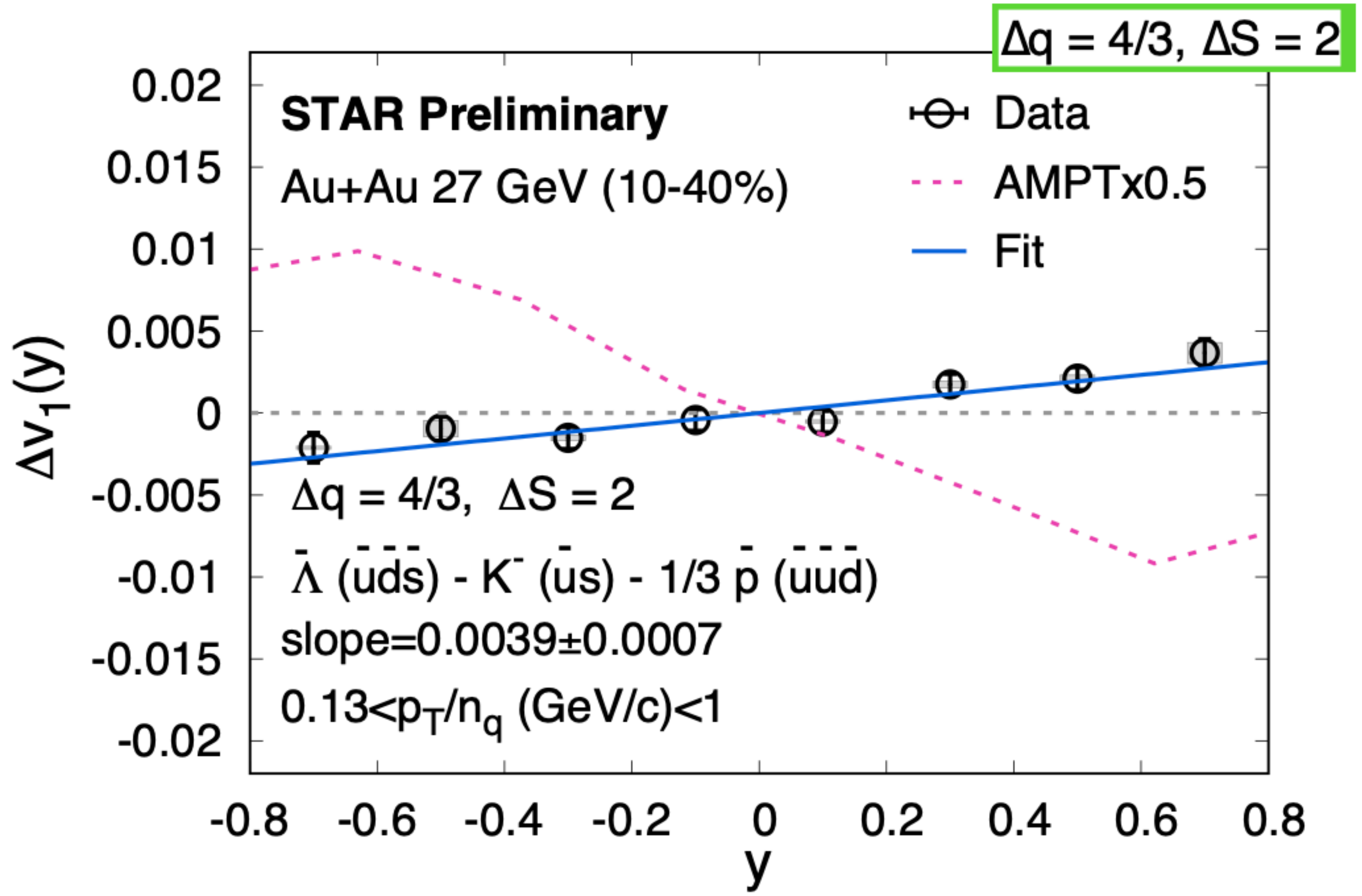


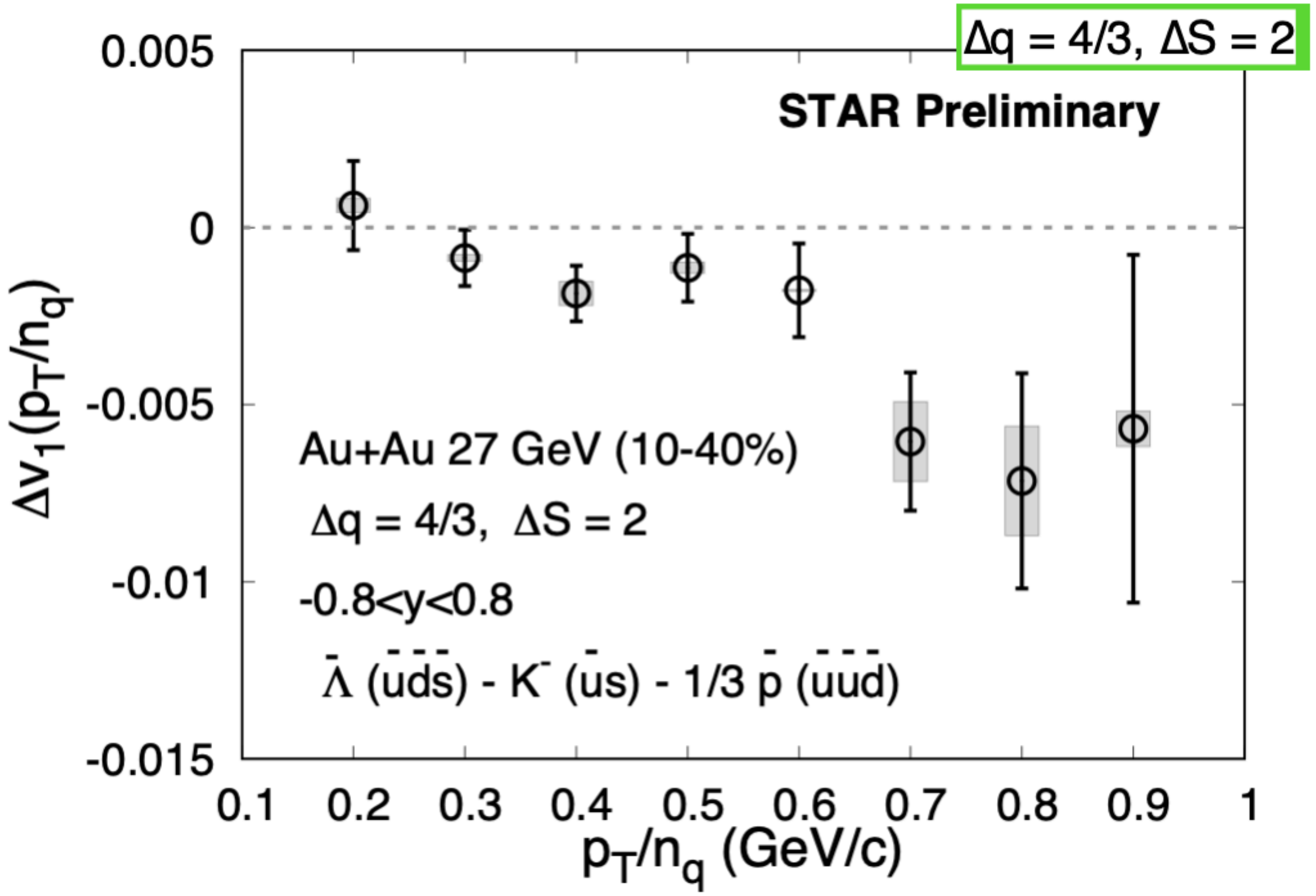


- Test of sum rule with identical quark combinations
- Δv_1 slope (with y) ~ 10^{-4}
- Sum rule holds within measured uncertainties

Splitting at non-zero Δq and ΔS (27 GeV)

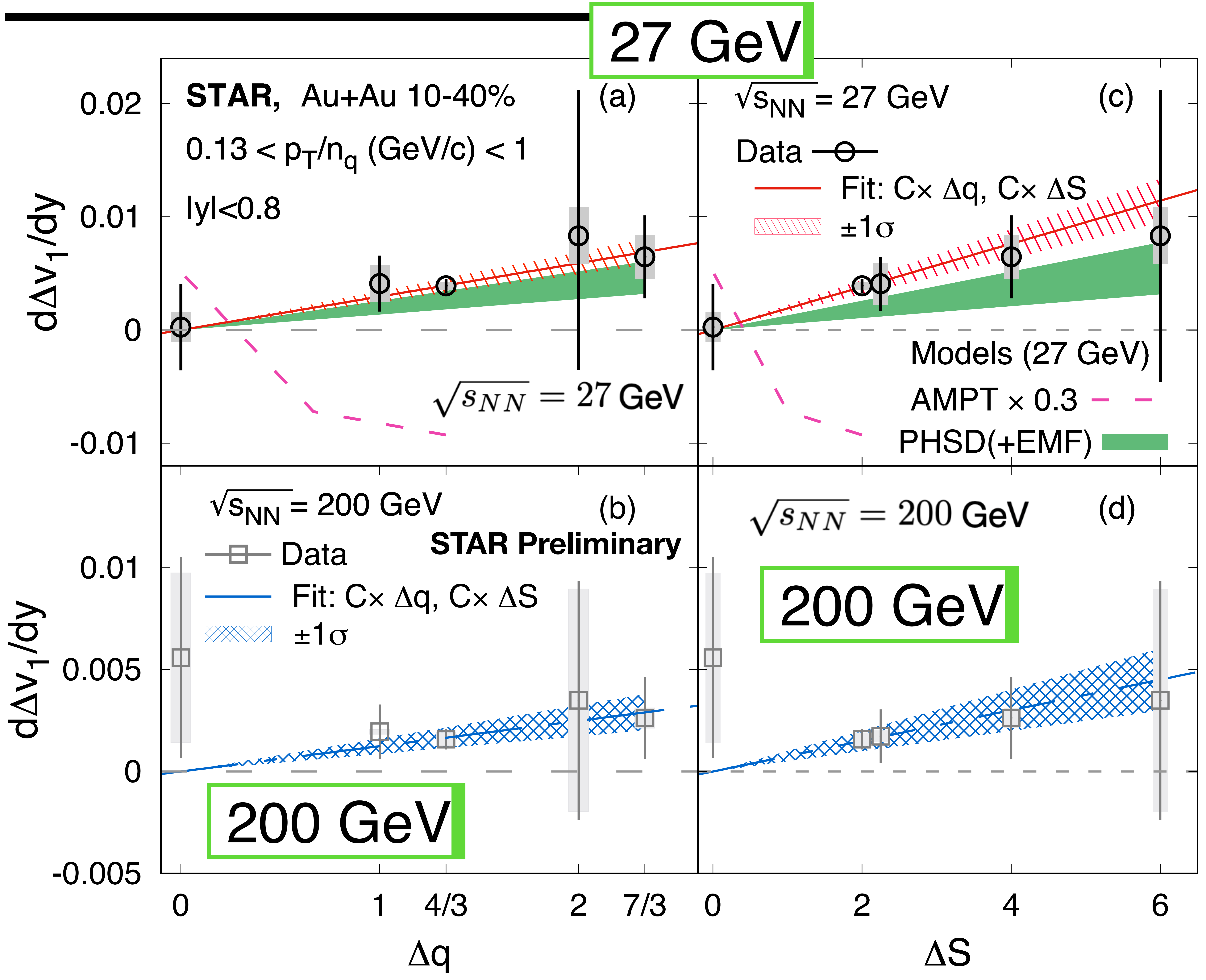
$$v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})] \quad \text{vs} \quad v_1[K^-(\bar{u}s)] + \frac{1}{3} v_1[\bar{p}(\bar{u}\bar{u}\bar{d})]$$





- $|\Delta v_1|$ increases at larger y and p_T/n_q
- Significant non-zero slope (with y) for $\Delta q = 4/3$, $\Delta S = 2$
- AMPT has the opposite trend - No EM field in AMPT

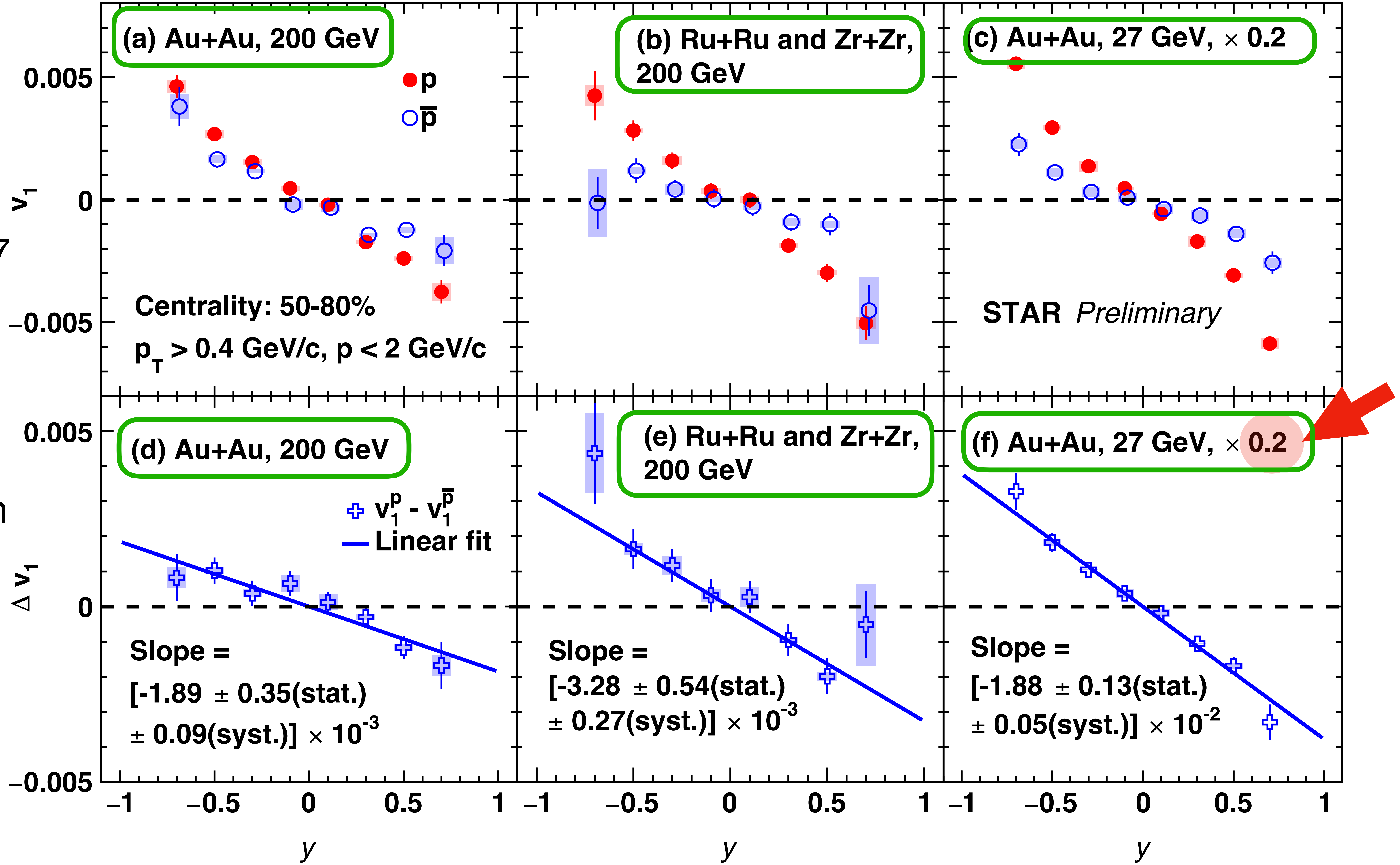
Splitting with charge and strangeness



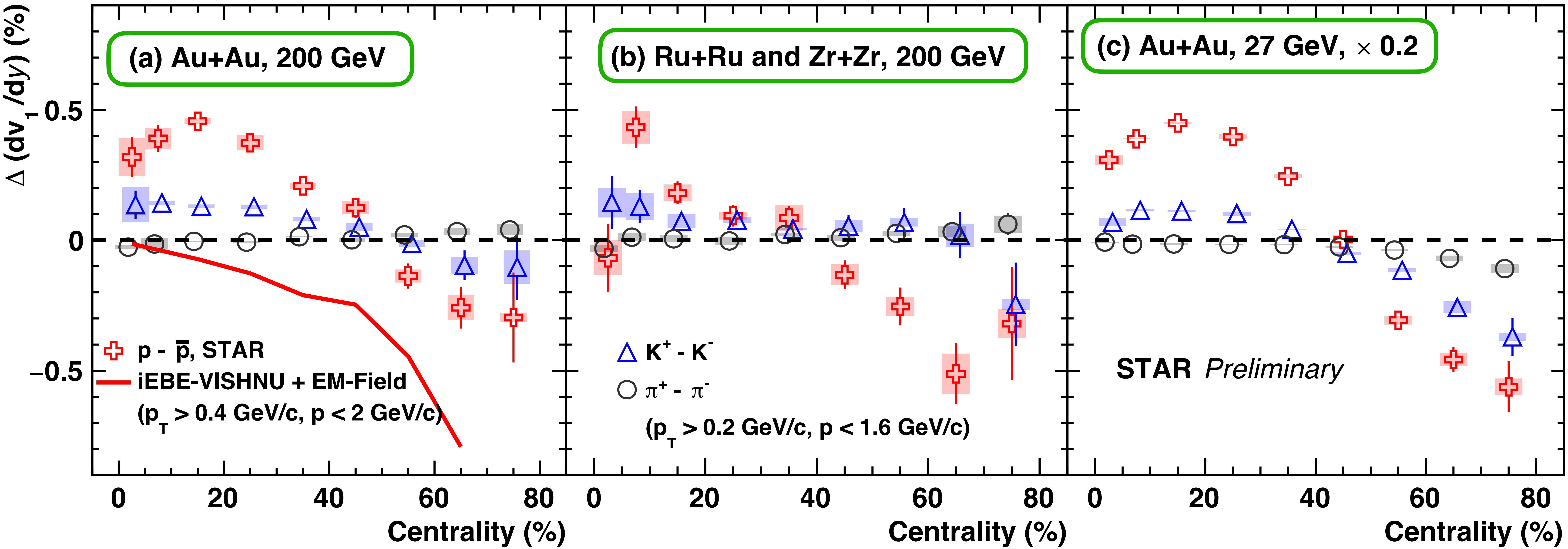
- Δv_1 slope (fit constrained to origin) increases with Δq and ΔS
- Splitting increases going from $\sqrt{s_{NN}}$ = 200 to 27 GeV (longer persistence of EM field at lower energy!)
- AMPT can not explain the data
  (Nayak et al., Phys. Rev. C 100, 054903 (2019))
- PHSD(+EMF) can describe the data within errors, but EMF is not the sole difference between these two models

Splitting between proton and anti-proton in 50-80% centrality

- Splitting shown so far based on species with produced quarks only
- v_1 and Δv_1 for p and $\bar{p}$ are shown in Au+Au 27 GeV, 200 GeV and Ru+Ru, Zr+Zr at 200 GeV collisions
- $\Delta dv_1/dy$ between p and $\bar{p}$ is negative, with >5σ significance
- $\Delta dv_1/dy$ is much (~factor 5) stronger at 27 GeV



Splitting between particle and anti-particle with centrality



- $\Delta dv_1/dy$ for $\pi^+ - \pi^-$, $K^+ - K^-$ and p-$\bar{p}$ are shown in Au+Au 27 GeV, 200 GeV and Ru+Ru, Zr+Zr at 200 GeV collisions
- $\Delta dv_1/dy$ decreases from central to peripheral collisions, with more than 5σ significance
- $\Delta dv_1/dy < 0$ in peripheral collisions => qualitatively agrees with expectation of EM field effect (Faraday+Coulomb > Hall+Transport)

Summary

- Measured charge (Δq) and strangeness (ΔS) dependent splitting - free from the transported quark effect
- Splitting increases with Δq and ΔS, stronger in lower collision energy
- PHSD+EM field calculations can describe the charge-dependent splitting within uncertainties
- Negative value of slope of splitting between particles and anti-particles in peripheral collisions => qualitatively agrees with expectation of EM field effect (Faraday+Coulomb > Hall+Transport)

Thank You