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

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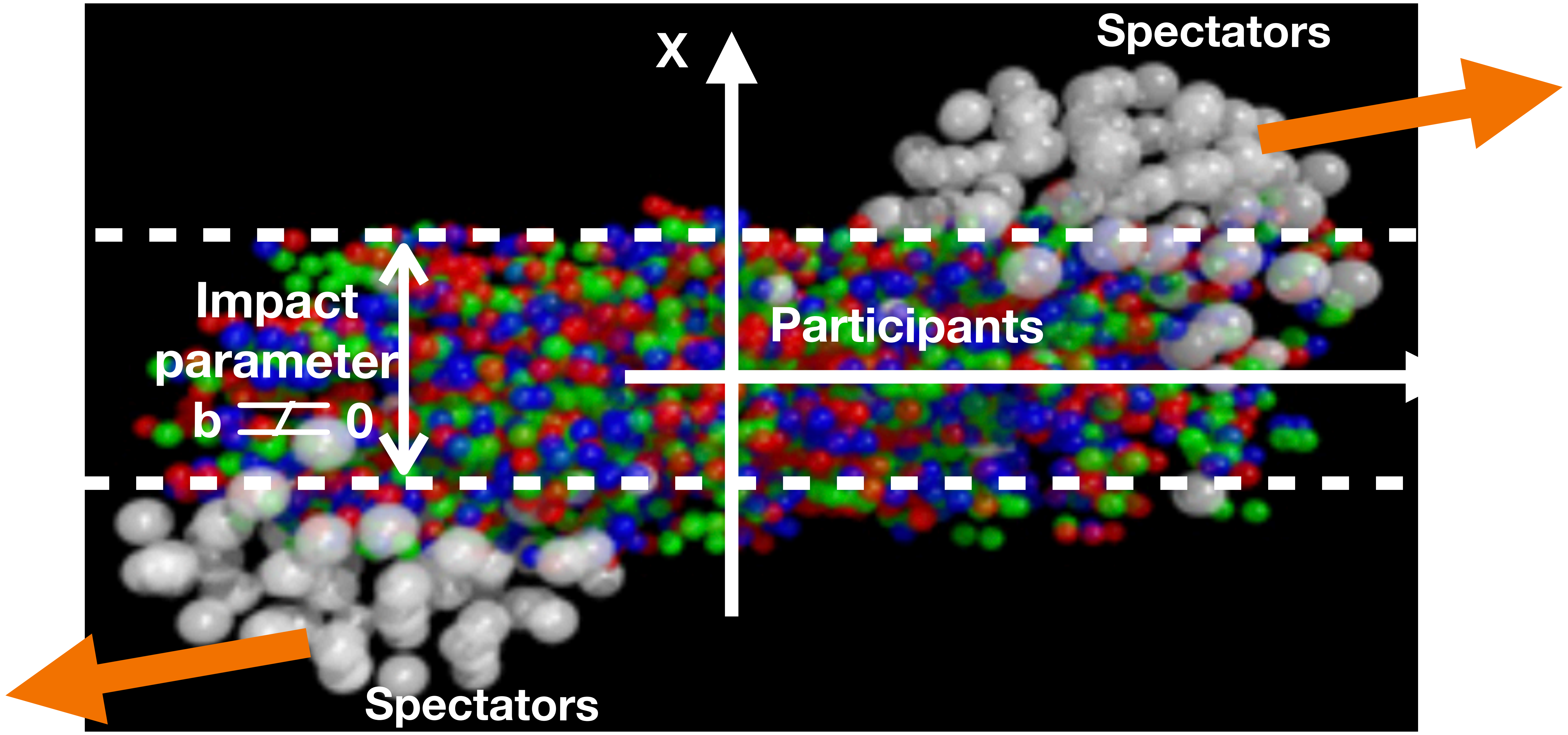
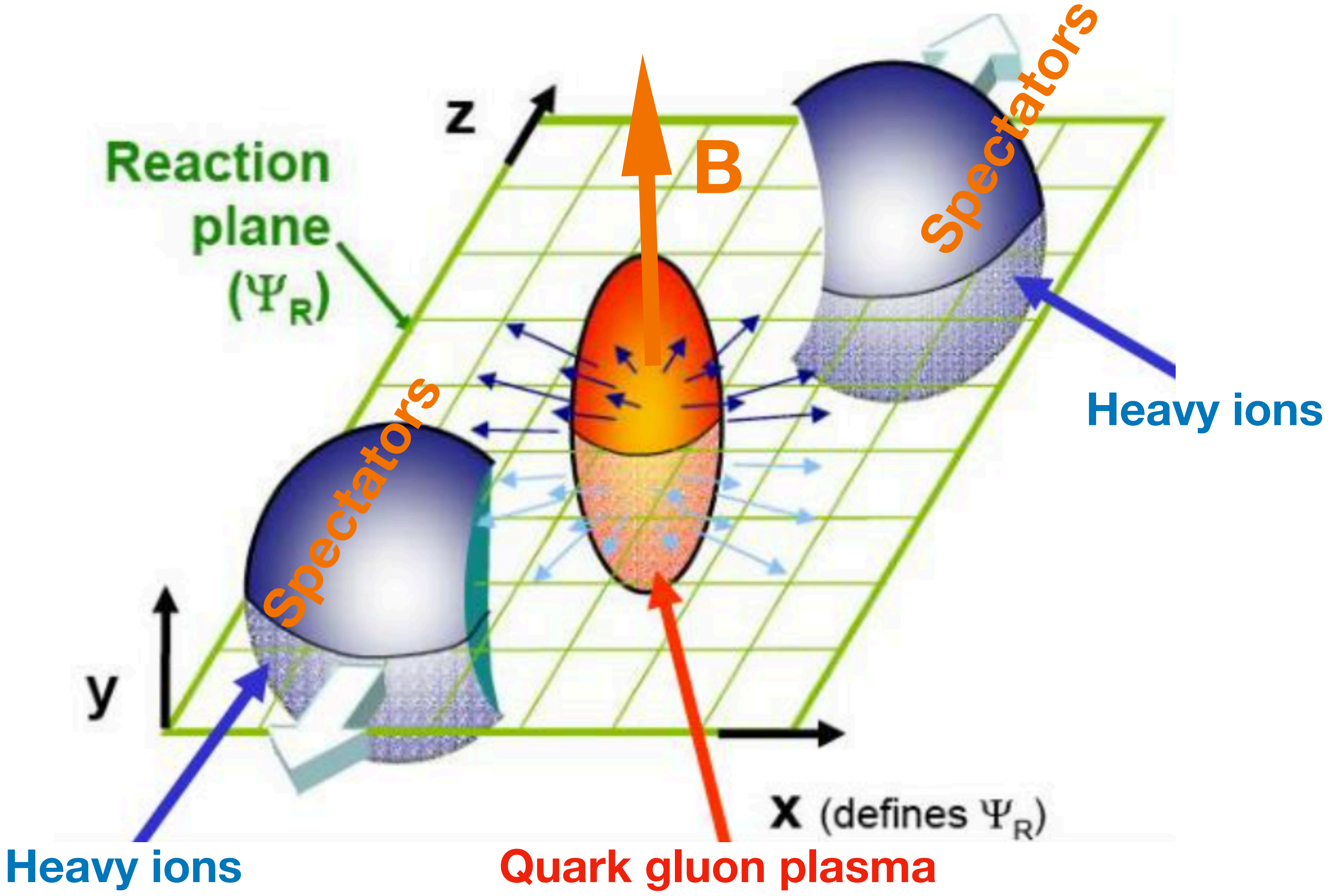
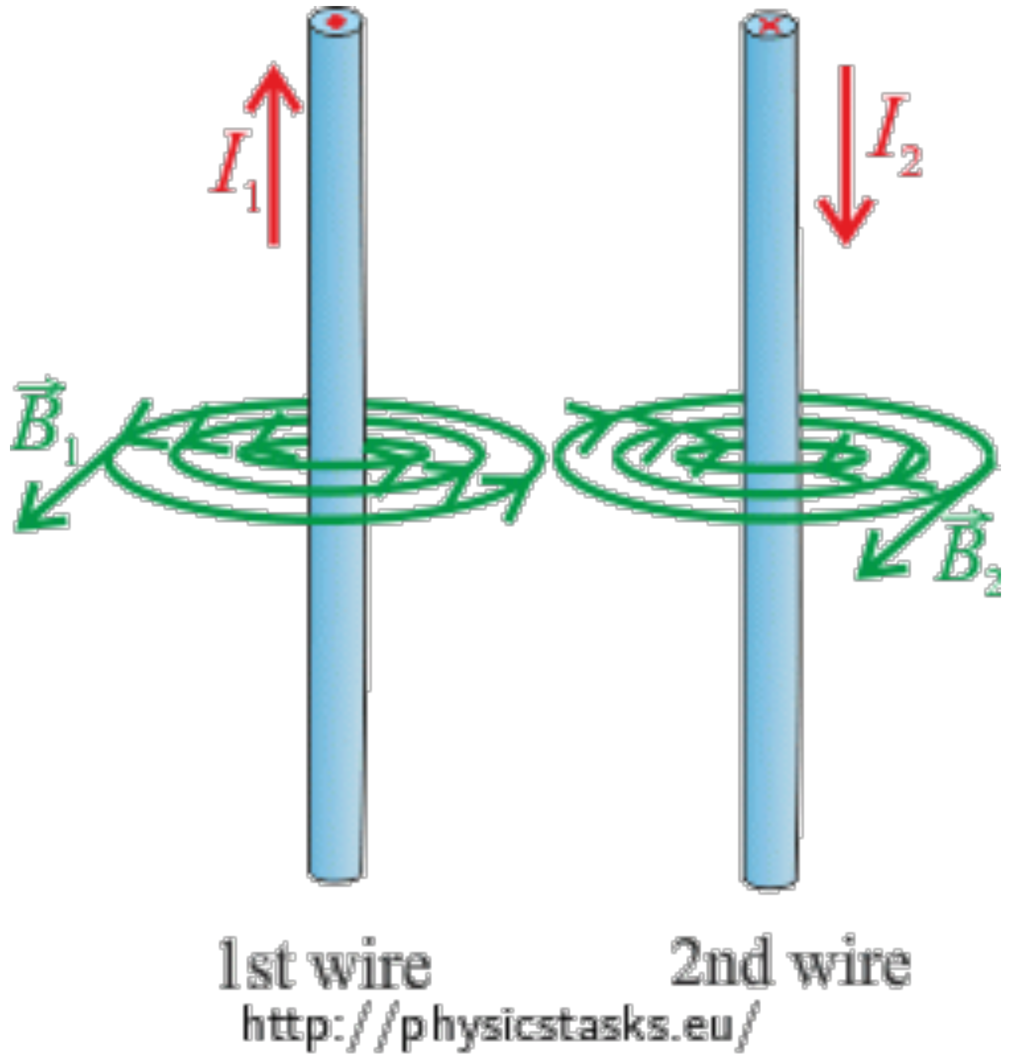
Magnetic field in heavy ion collisions





- ◉ 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



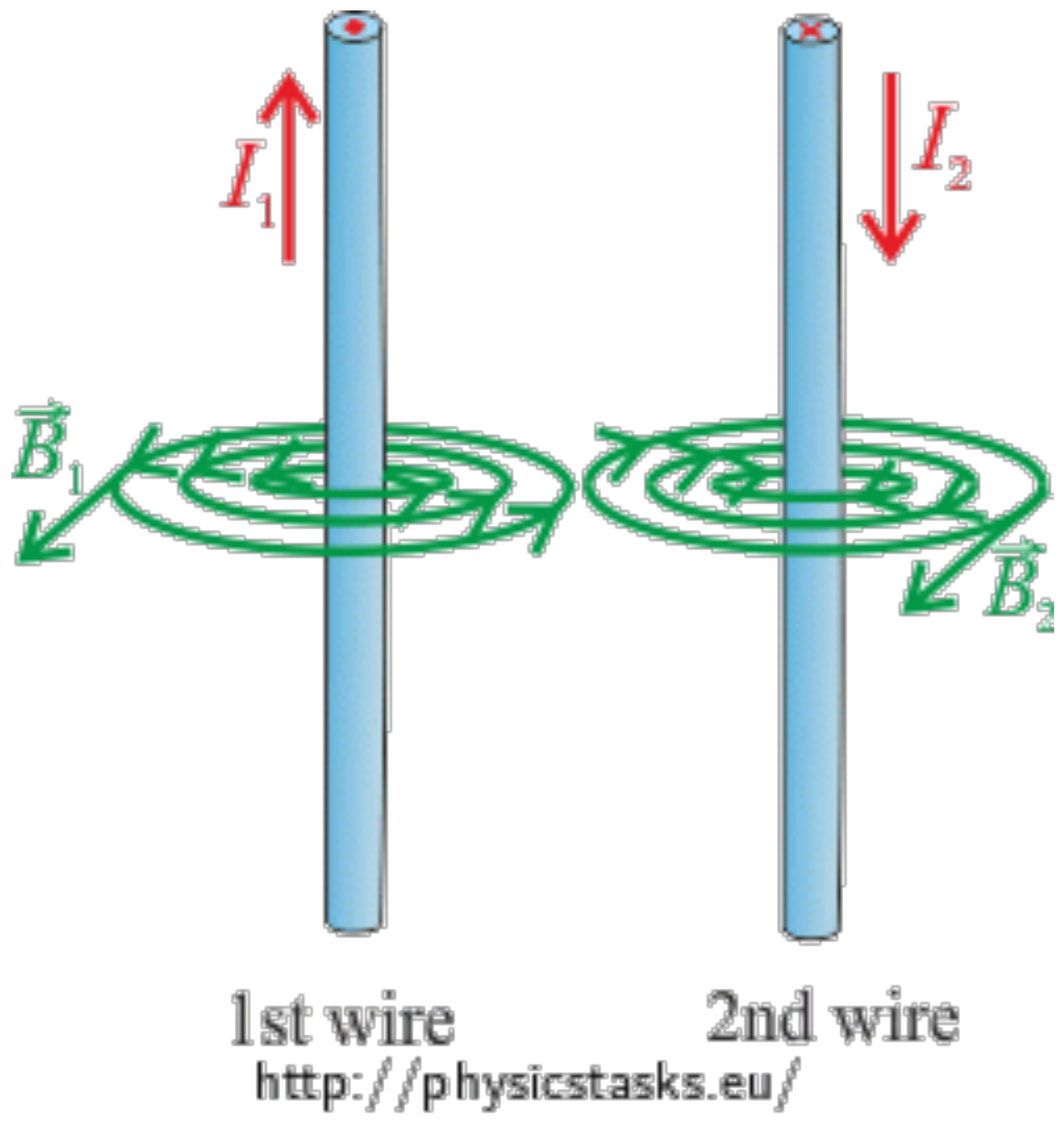
Estimates of the produced magnetic field

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

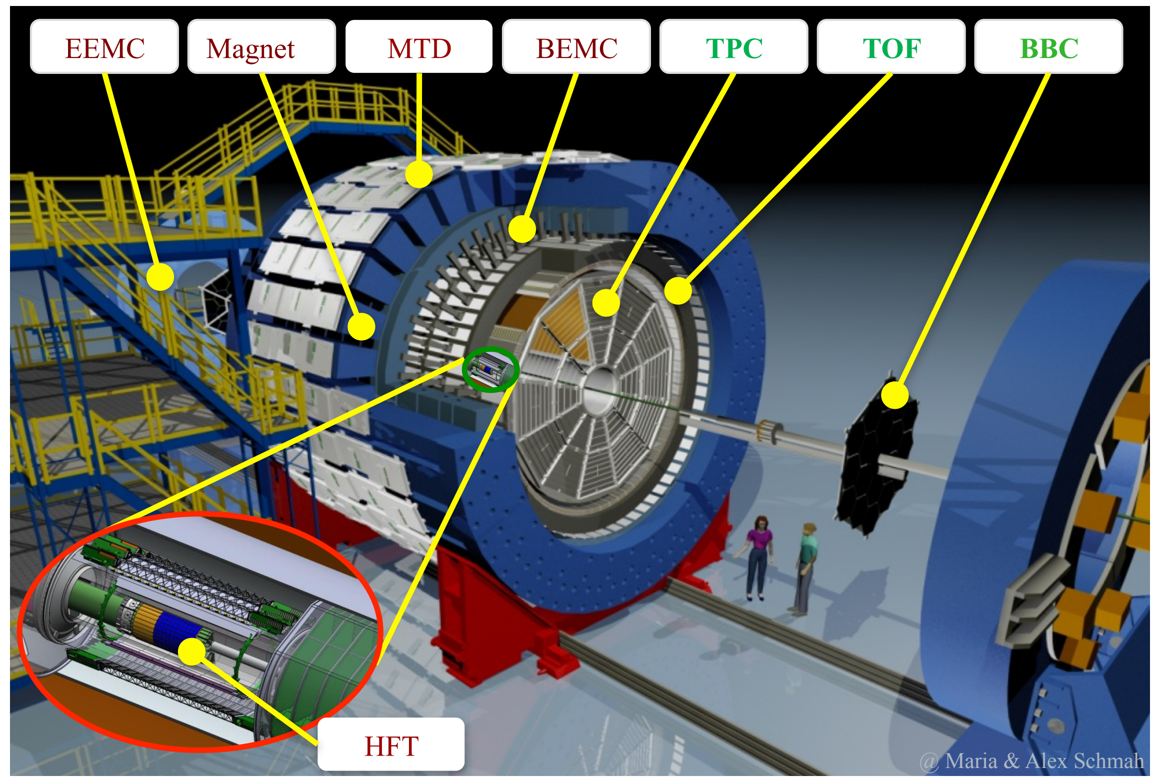
$-eB_y \sim 40m_\pi^2 \sim 10^{18}$ Gauss (At RHIC Au+Au collisions, $\sqrt{s_{NN}} = 200$ GeV, b = 5 fm, t = 0)

- Strongest magnetic field ever produced in laboratory

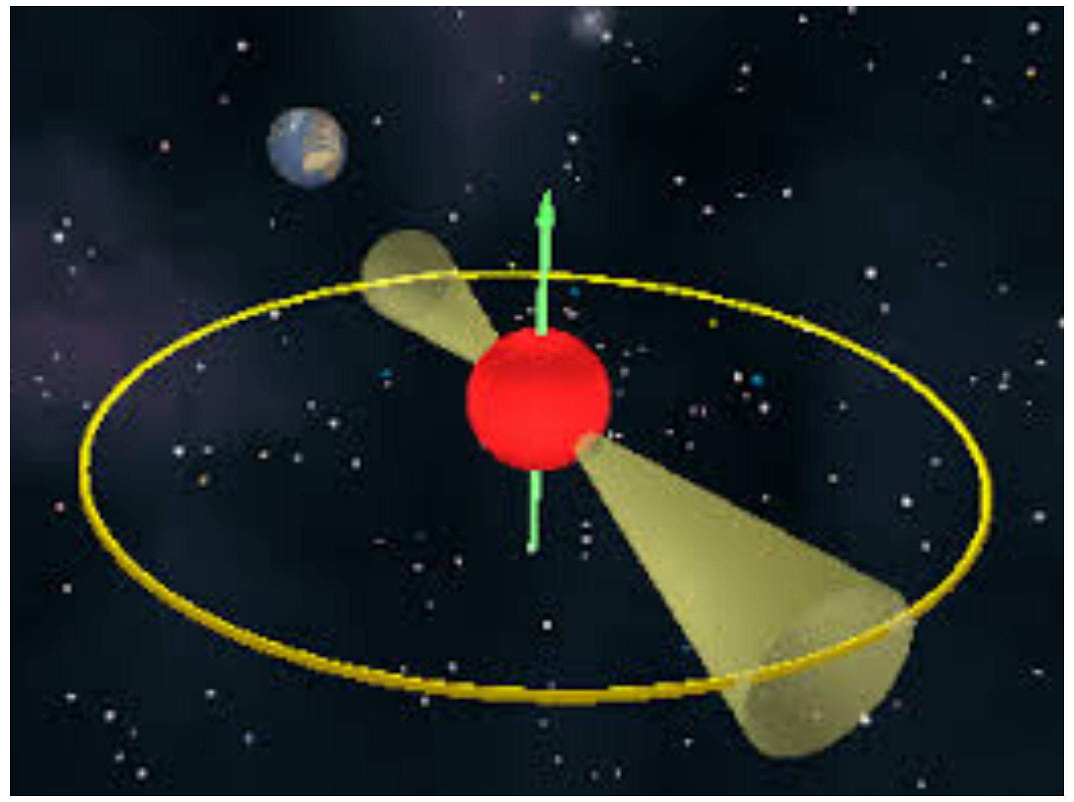
- B-field has observable effects on properties of produced particles, such as anisotropic flow



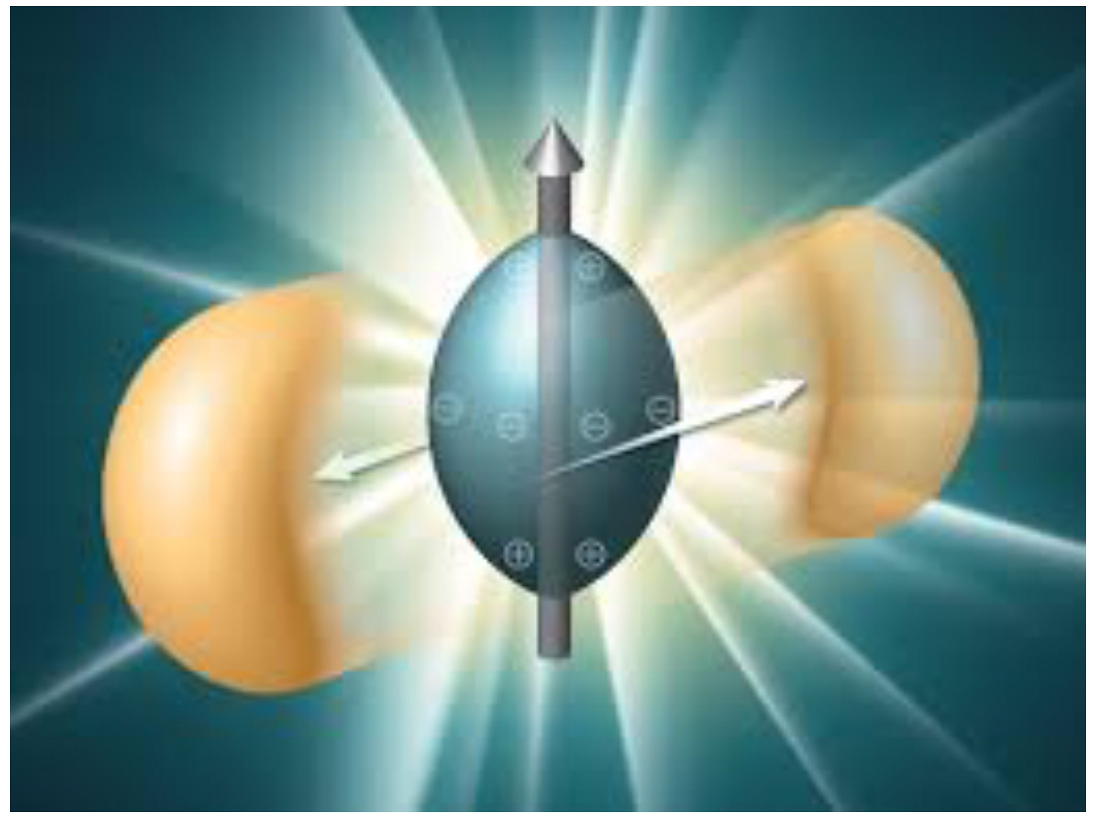
Earth
~0.5 Gauss



STAR magnet
~5000 Gauss



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



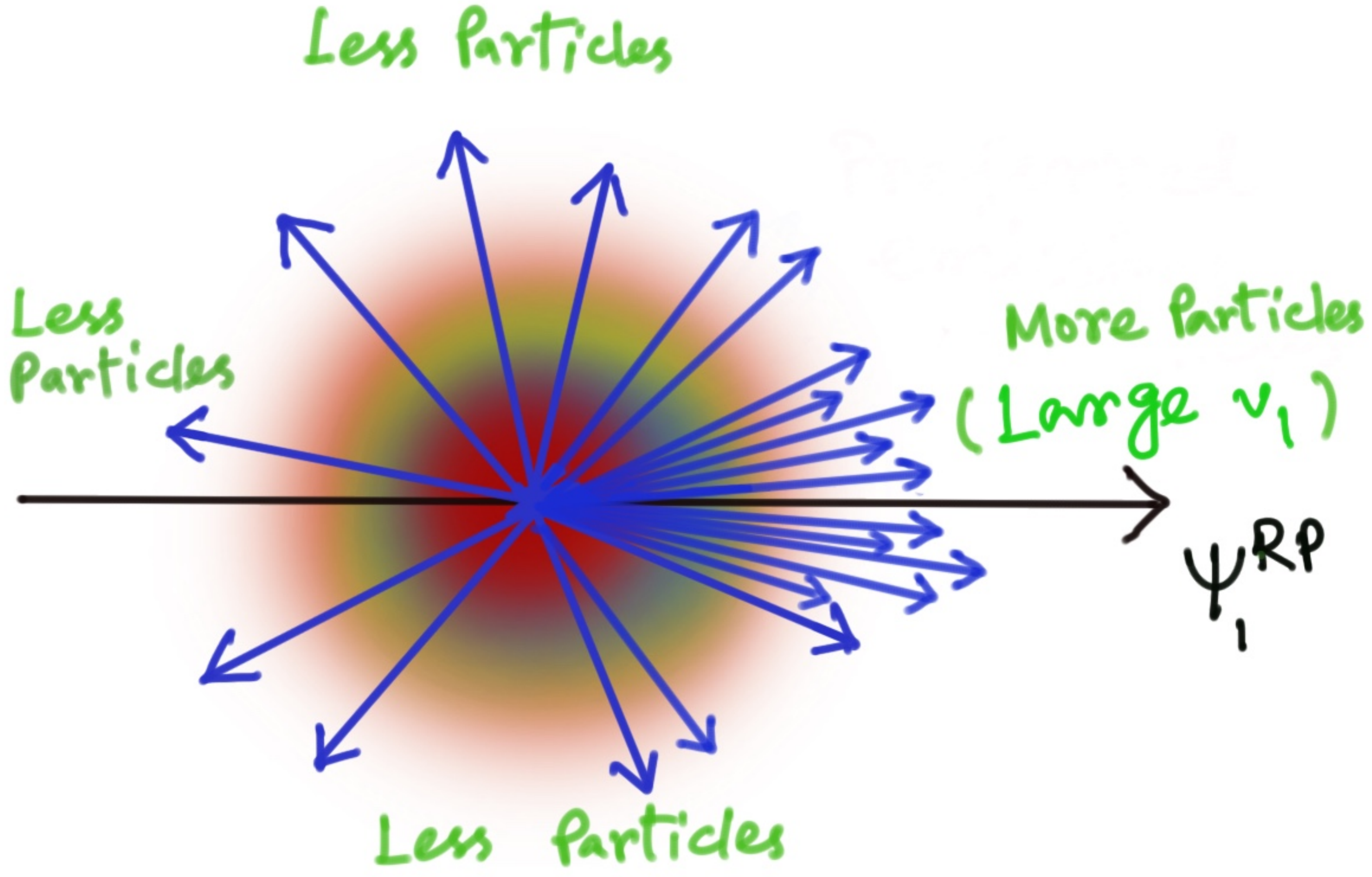
Heavy ion collisions
~ 10^{18} Gauss

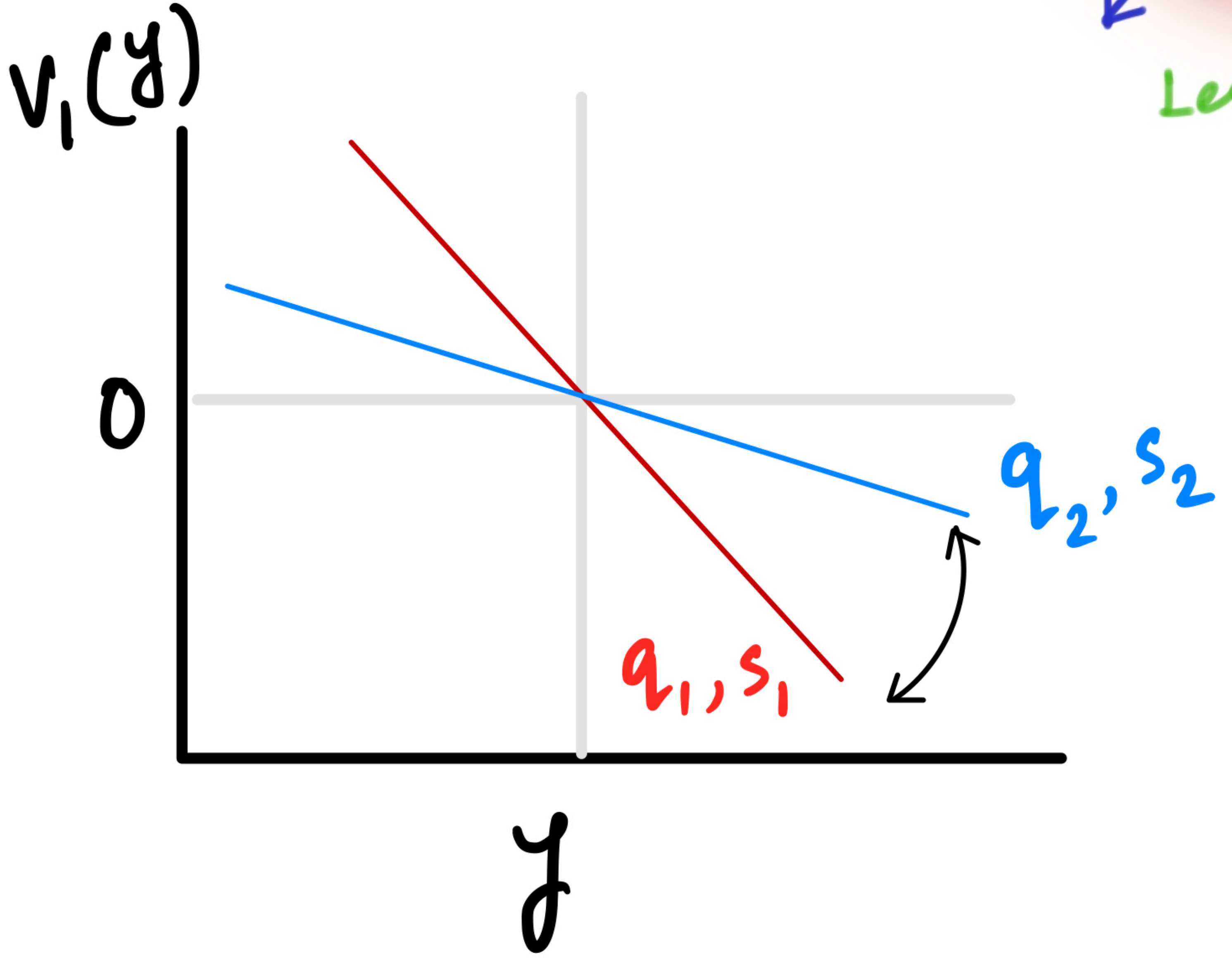
Directed flow (v_1) and charge splitting (Δv_1)

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

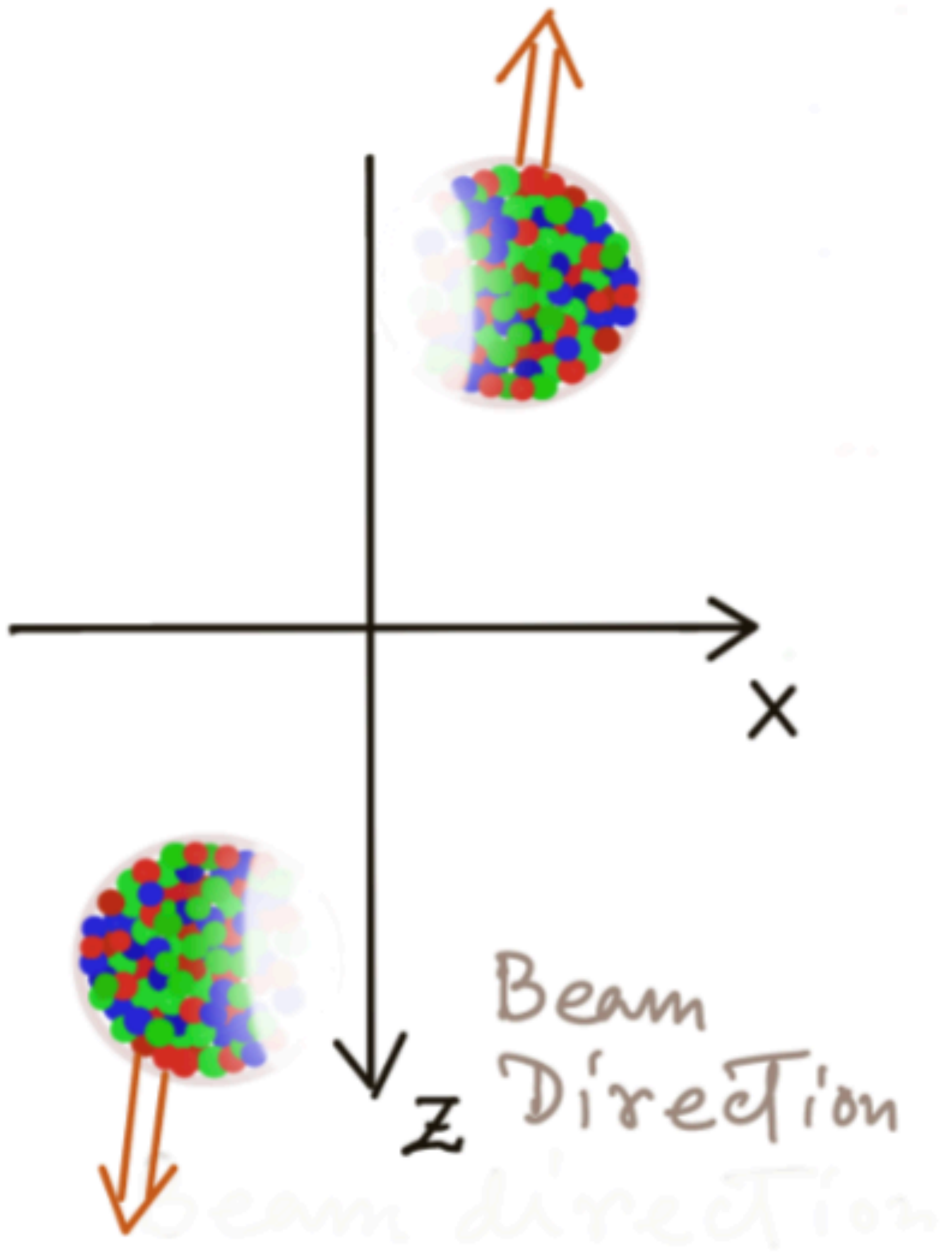


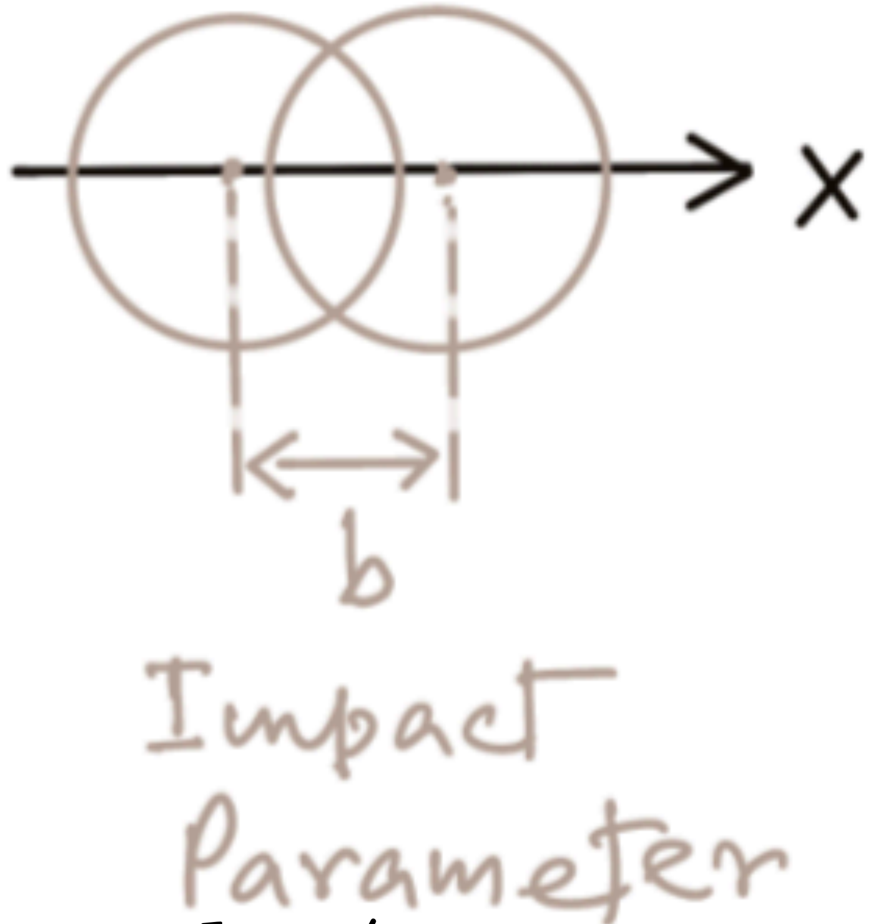


- Probe early stage of the collisions - strong electromagnetic (EM) field

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

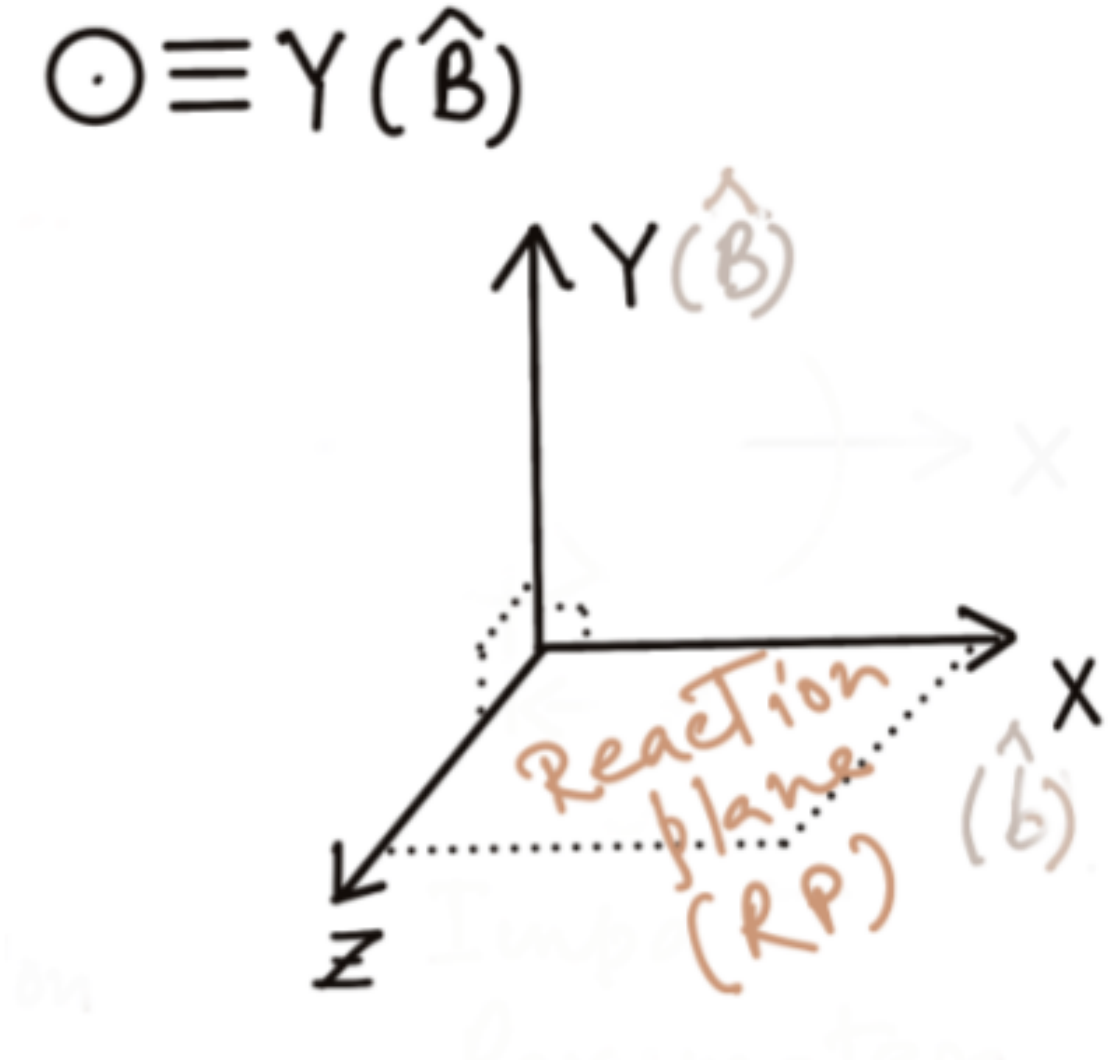
EM field drives splitting



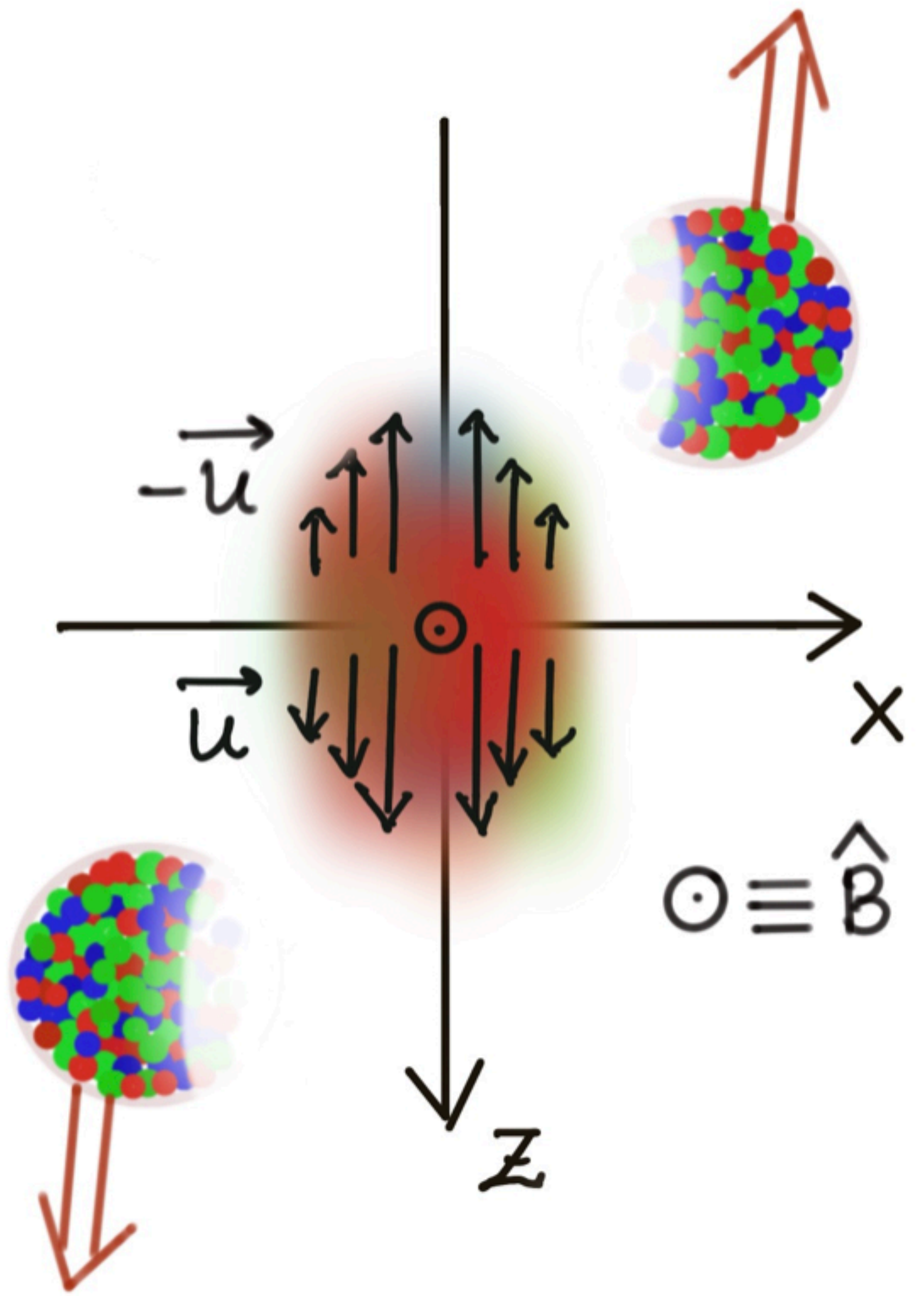


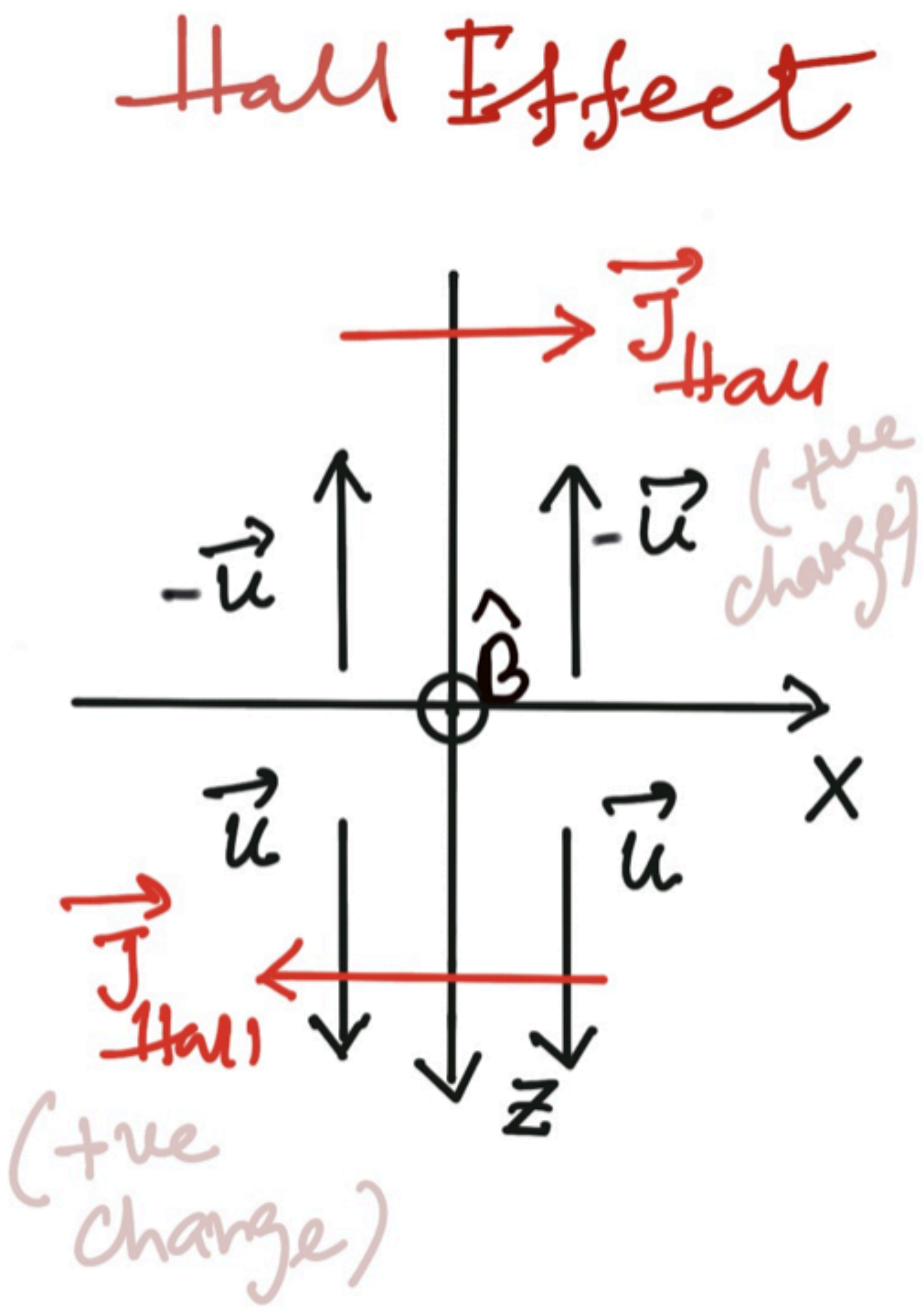
$b \neq 0$

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



EM field drives splitting - Hall effect

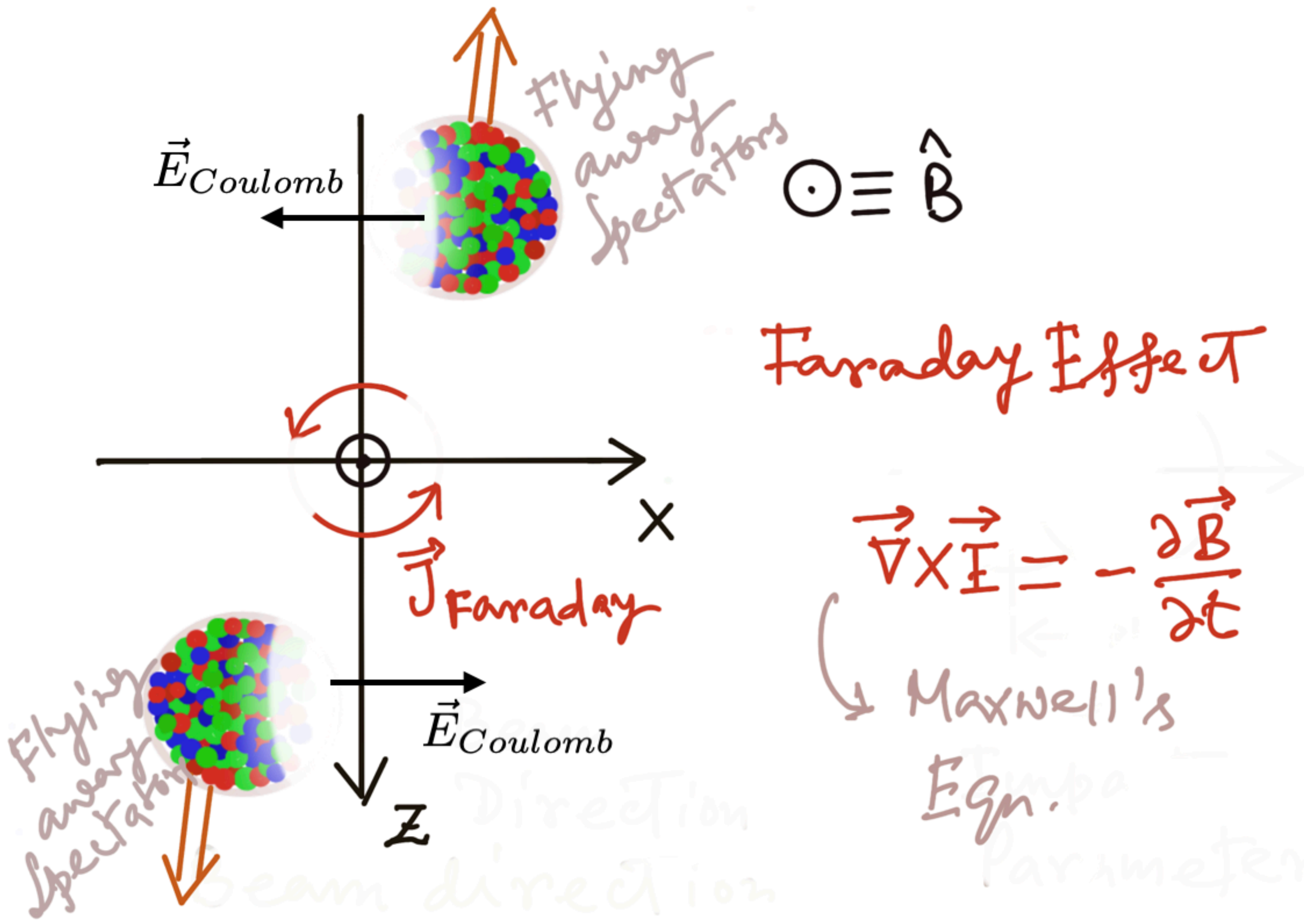




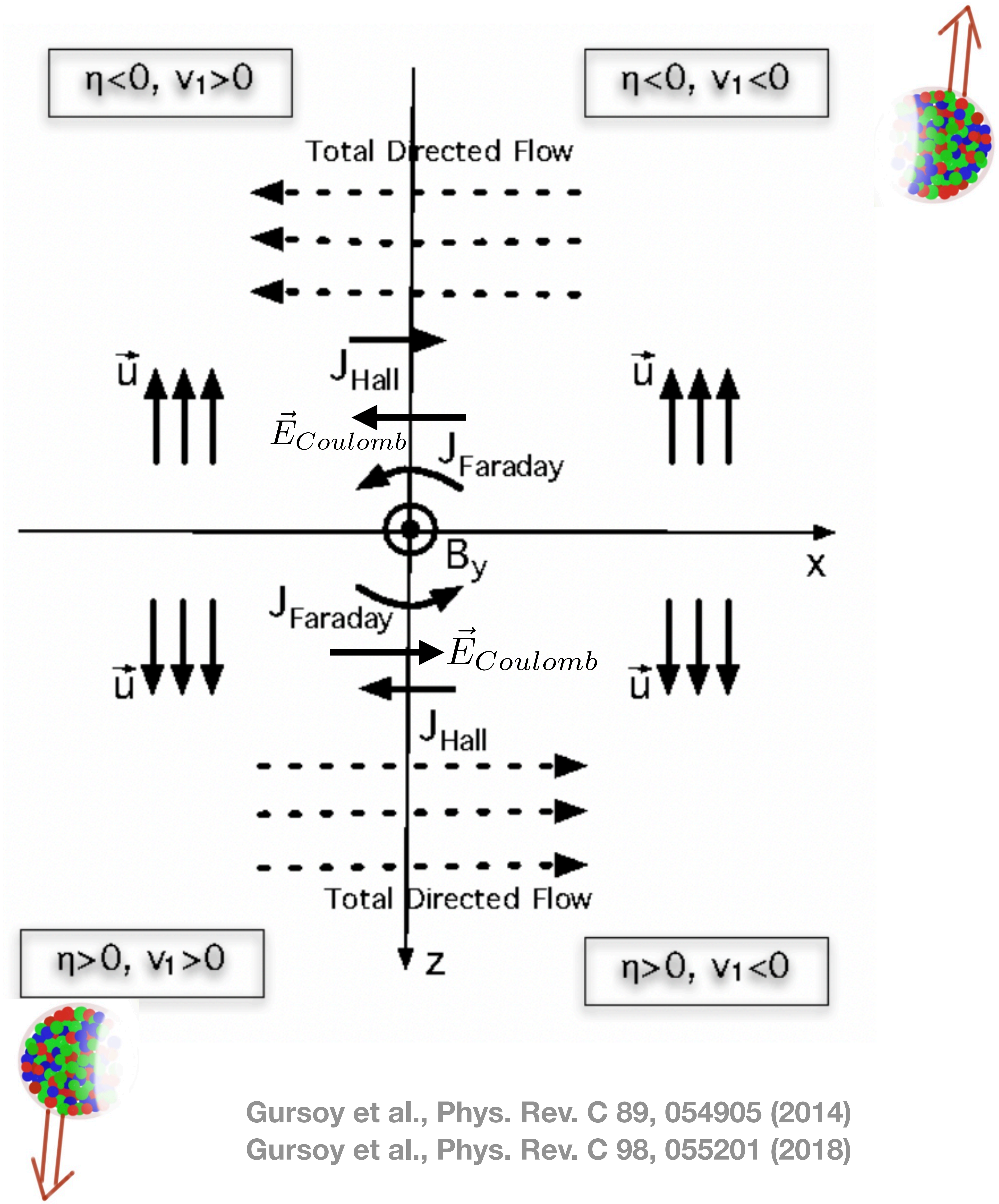
- Produced medium expands longitudinally ($\vec{u}||\hat{z}$, $\vec{u} \perp \vec{B}$)
- Lorentz force pushes positively and negatively charged particles in opposite directions
- Generated current $\perp \vec{B}, \vec{u}$
  => Hall effect

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

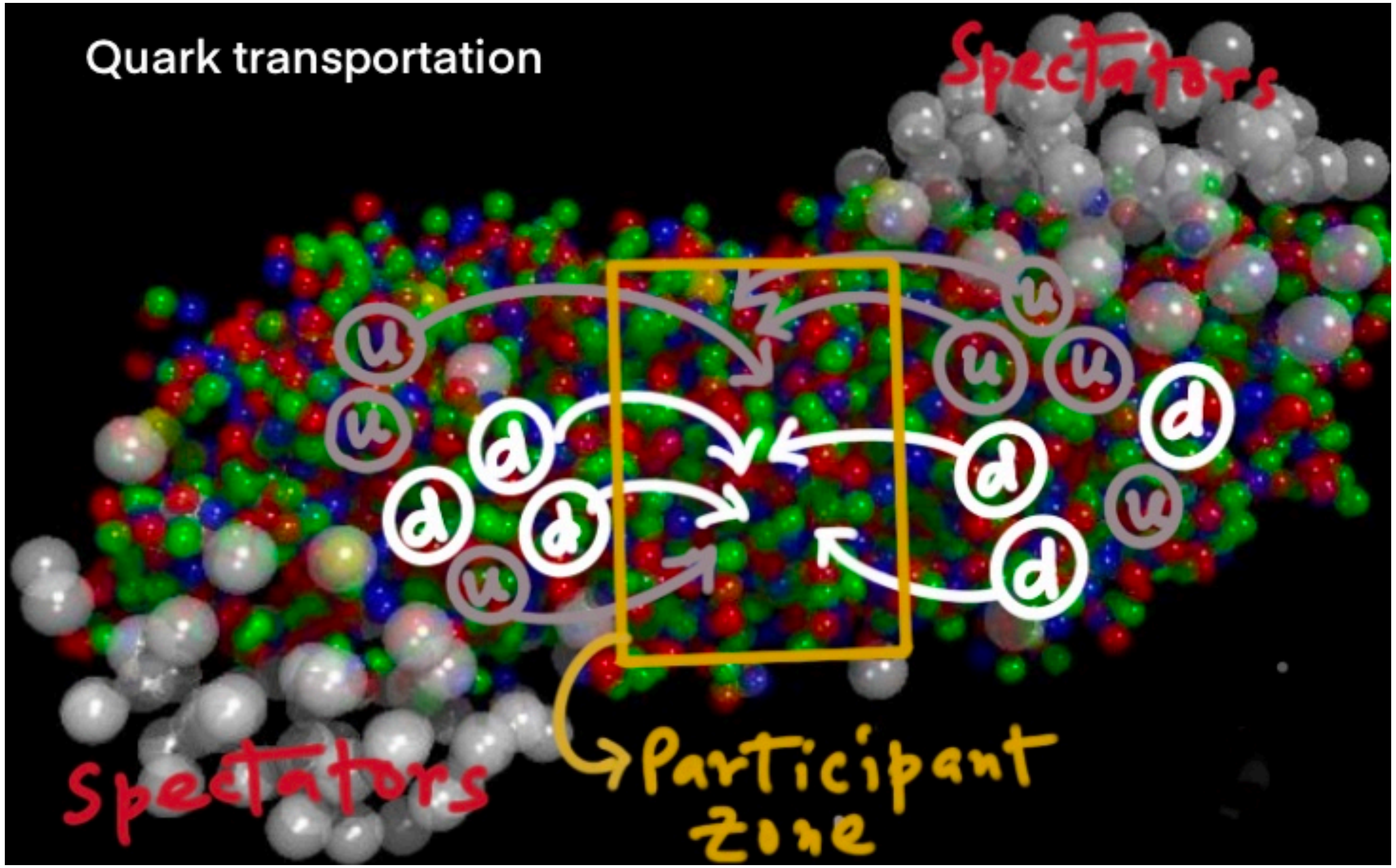


- Faraday, Coulomb and Hall are competing effects
- Net effect of Faraday, Hall and Coulomb affects v_1
- Direction of v_1 for positive particles shown by dashed arrows (when Faraday+Coulomb > Hall)
- Direction of v_1 for negative particles - the other way around
- EM field drives v_1 splitting (Δv_1)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

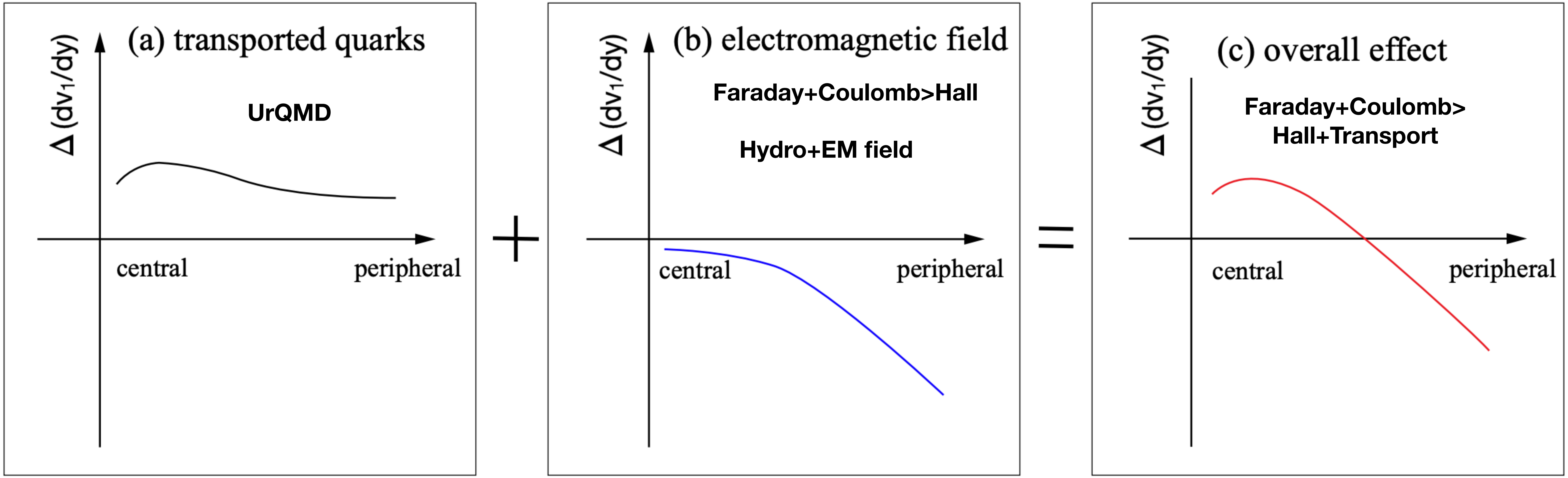
Gursoy et al., Phys. Rev. C 89, 054905 (2014)
Gursoy et al., Phys. Rev. C 98, 055201 (2018)

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 ($\bar{u},\ \bar{d},\ s,\ \bar{s}$)
- 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)

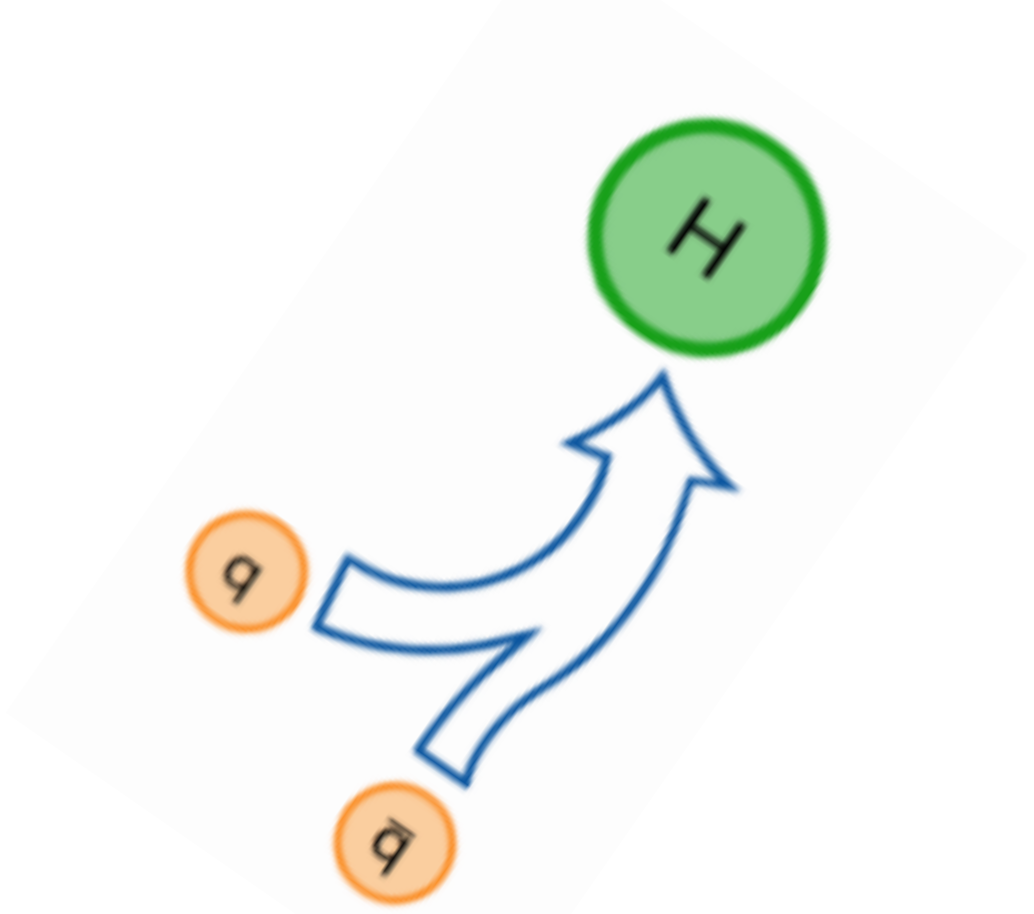


- Splitting between particle and anti-particle ($\Delta dv_1/dy = dv_1^+/dy - dv_1^-/dy$) with centrality
- $\Delta dv_1/dy < 0$ could be a signature of EM field (Faraday+Coulomb > Hall+Transport)

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)

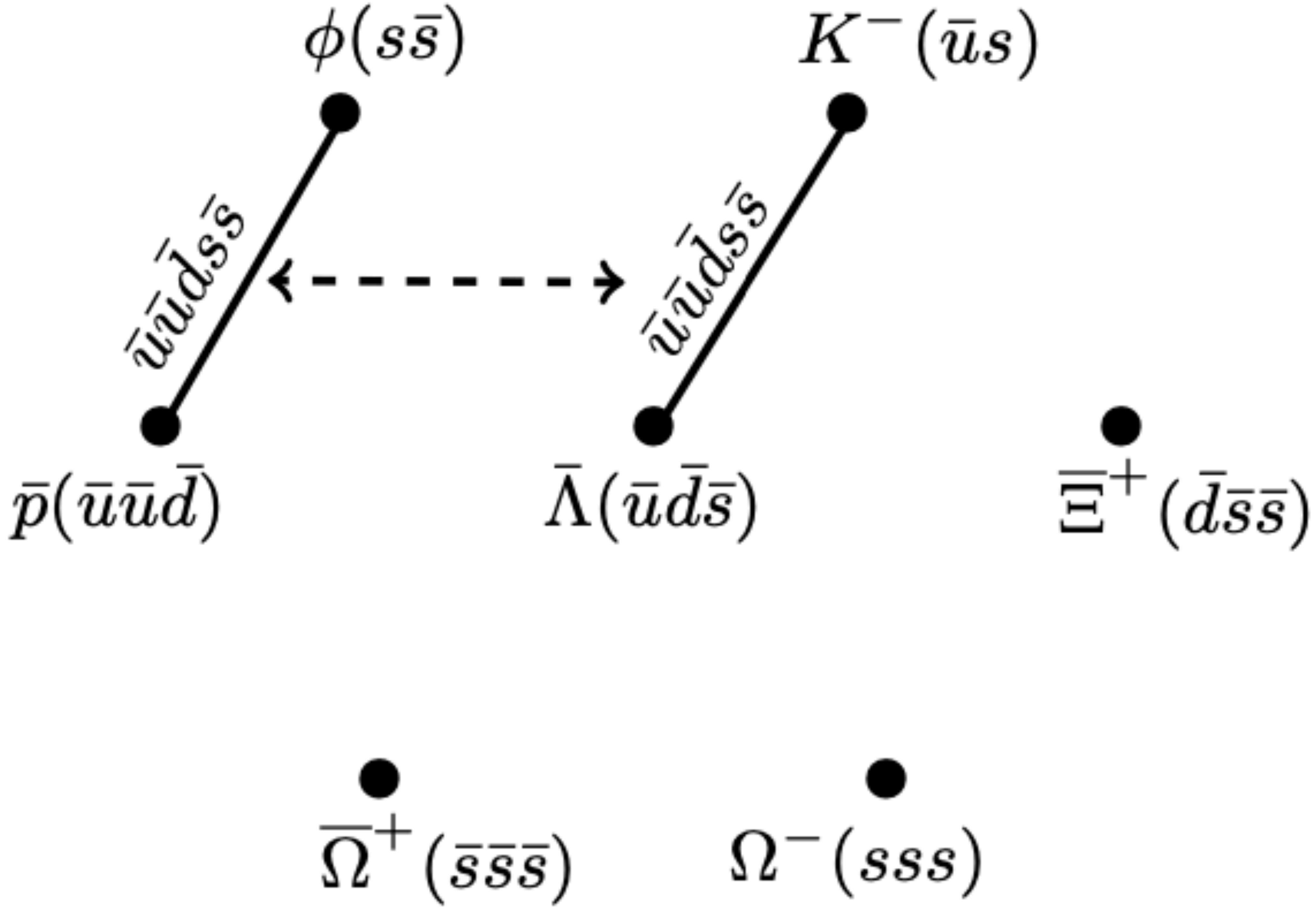
- In experiment, it is impossible to distinguish between produced and transported u and d quarks
- Avoid particles containing u, d quarks
- Use only produced particles (only produced constituent quarks — $\bar{u}, \bar{d}, s, \bar{s}$): K^-, $\bar{p}$, $\bar{\Lambda}$, ϕ, $\overline{\Xi}^+$, Ω^- and $\overline{\Omega}^+$
- 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

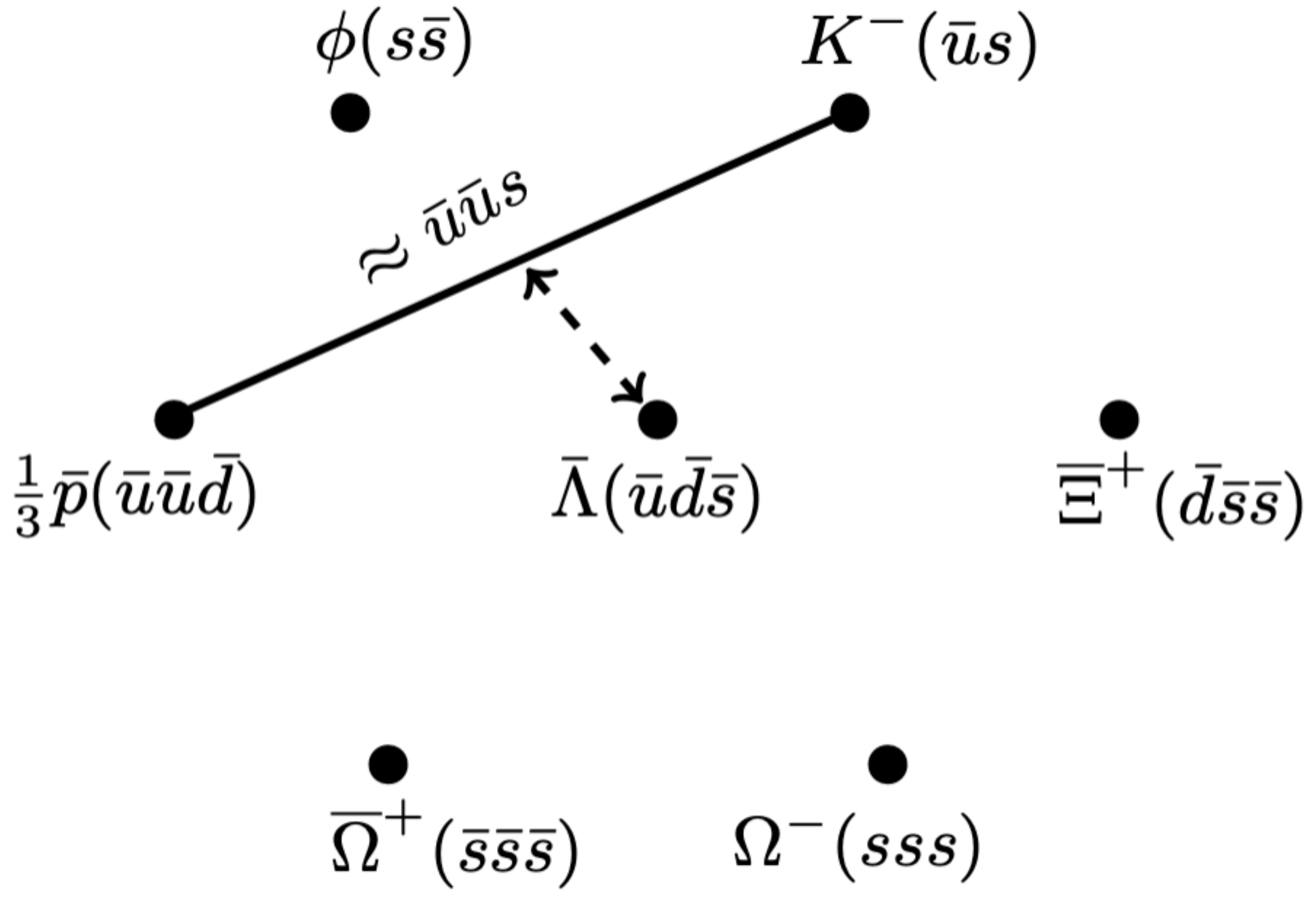


$$v_1[K^-(\bar{u}s)] + v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})] = v_1[\bar{p}(\bar{u}\bar{u}\bar{d})] + v_1[\phi(s\bar{s})]$$

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

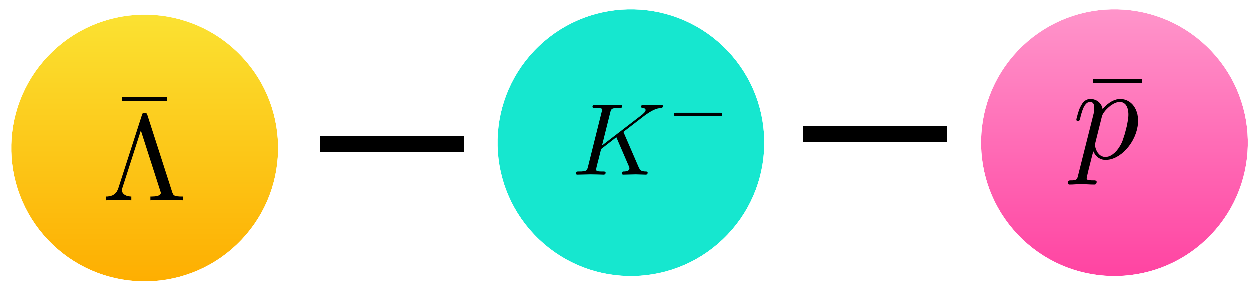
Splitting: Combination with non-zero Δq and ΔS

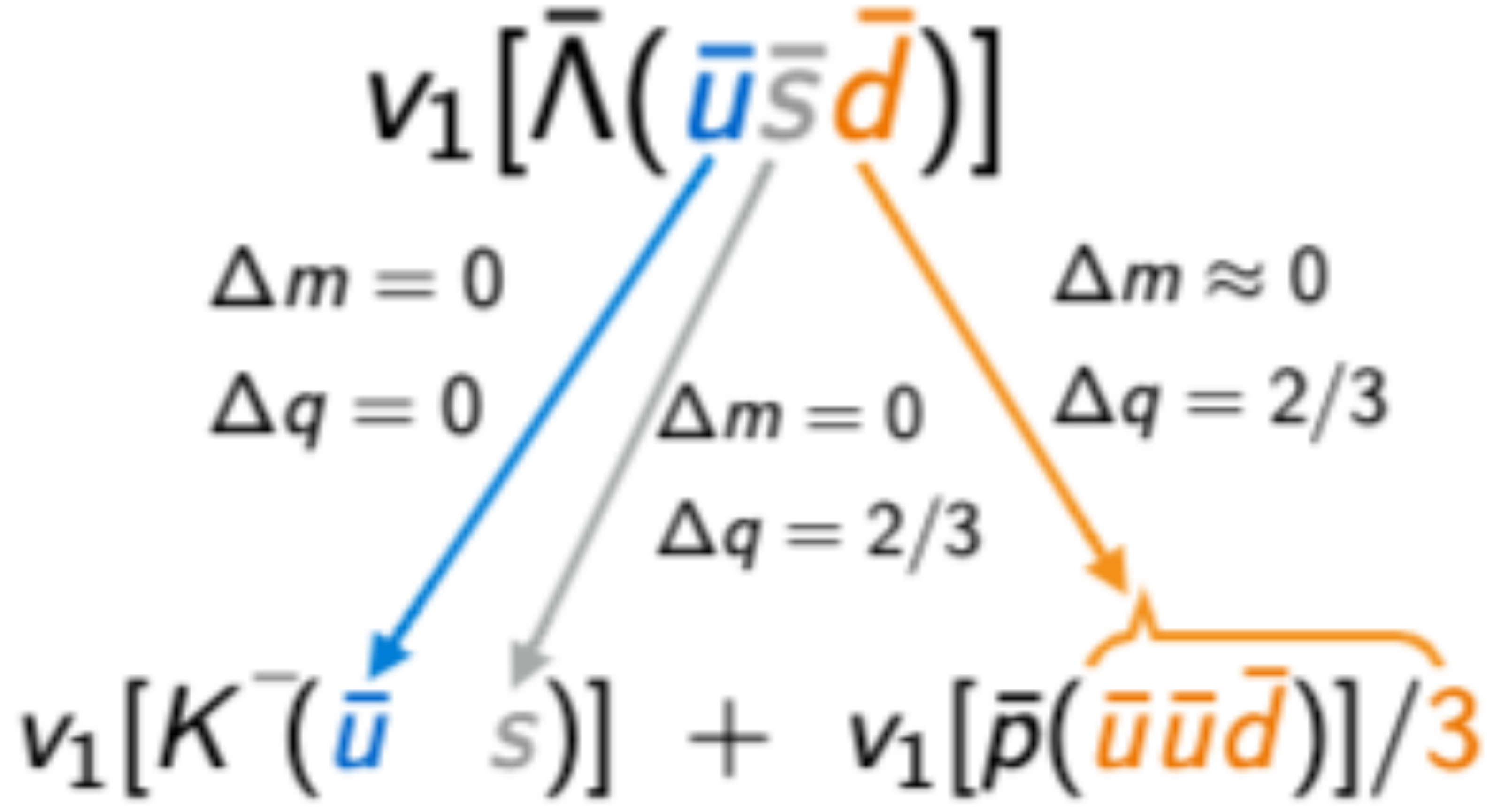
- Combine particles and make non-identical quark combinations, same mass at the constituent level



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

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





- Charge difference, Δq = 4/3 and strangeness difference, ΔS = 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	$\Delta m \approx 0$	$\Delta q = \frac{7}{3}$	$\Delta S = 4$	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\Omega^-(sss)]$

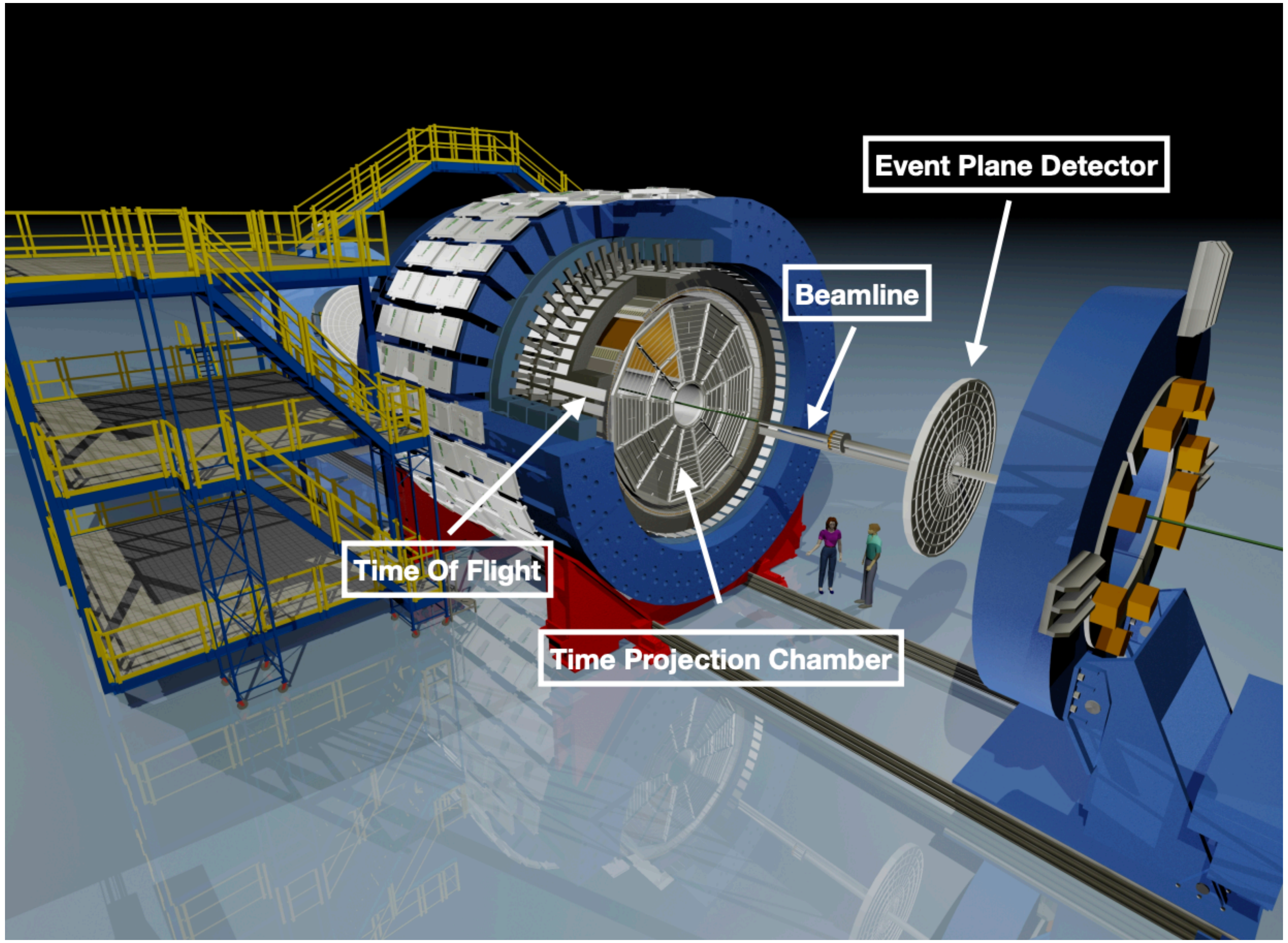
A. Ikbal, D. Keane, P. Tribedy, Phys. Rev. C 105, 014912 (2022)

- 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

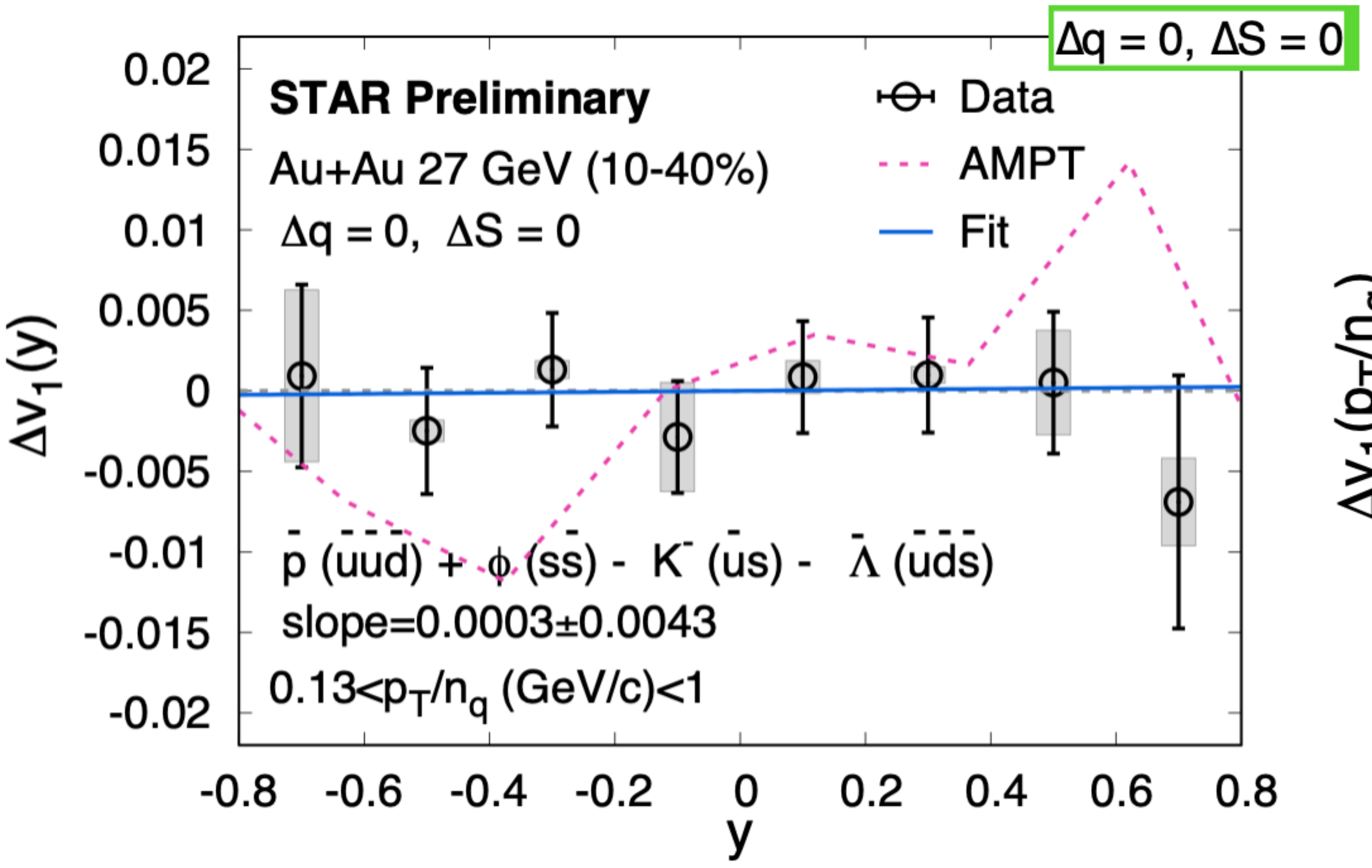


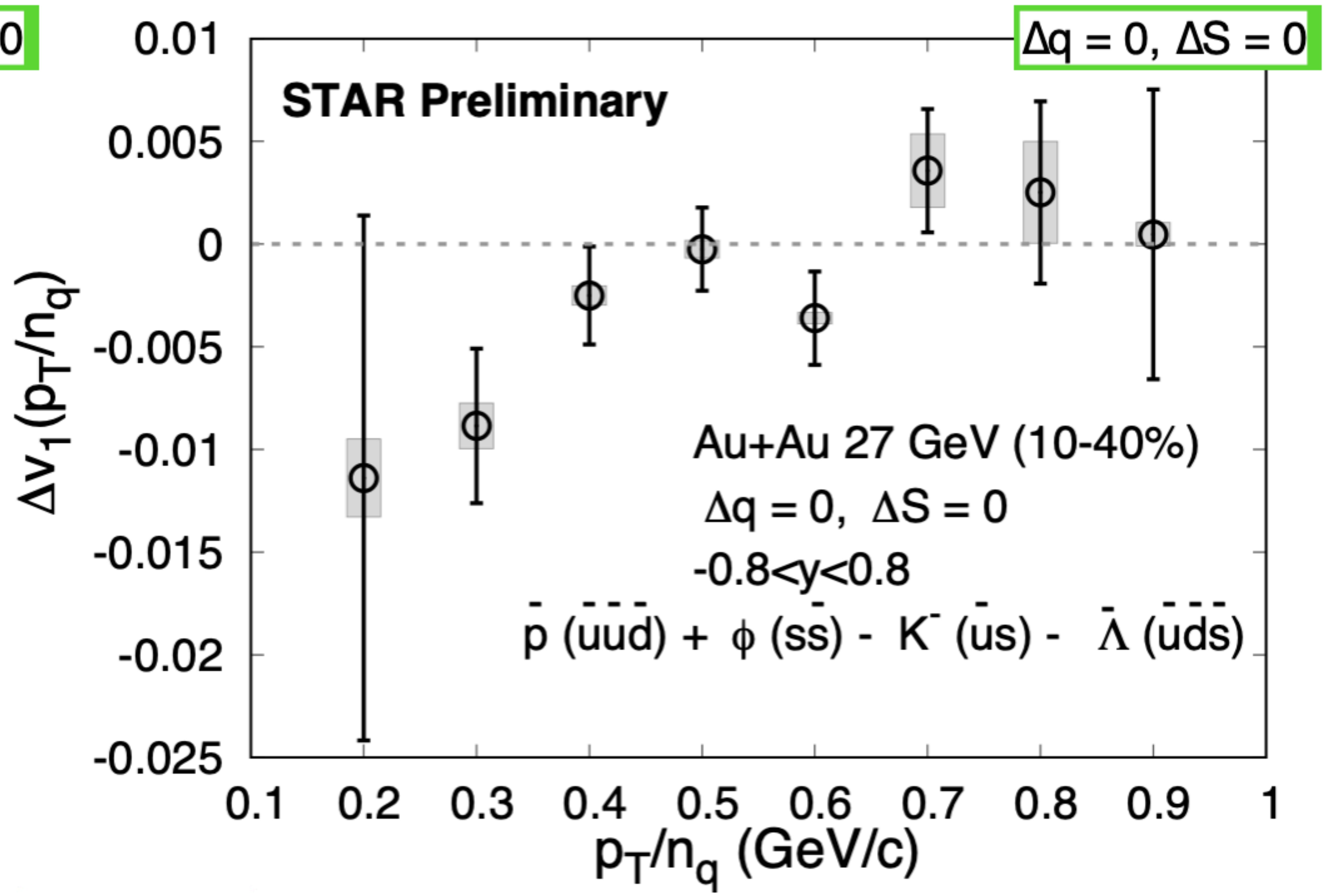
Datasets analyzed:

- 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

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

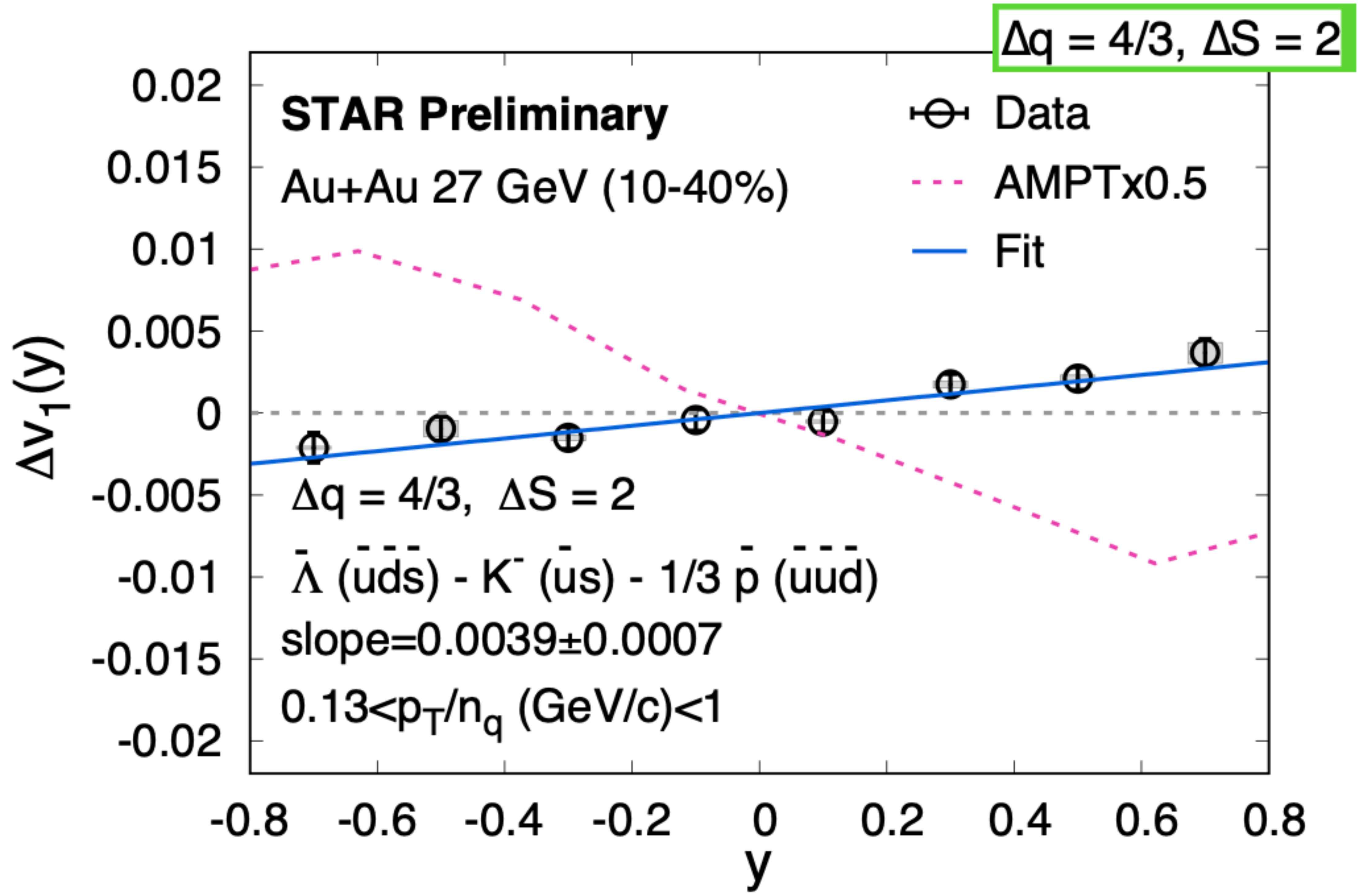


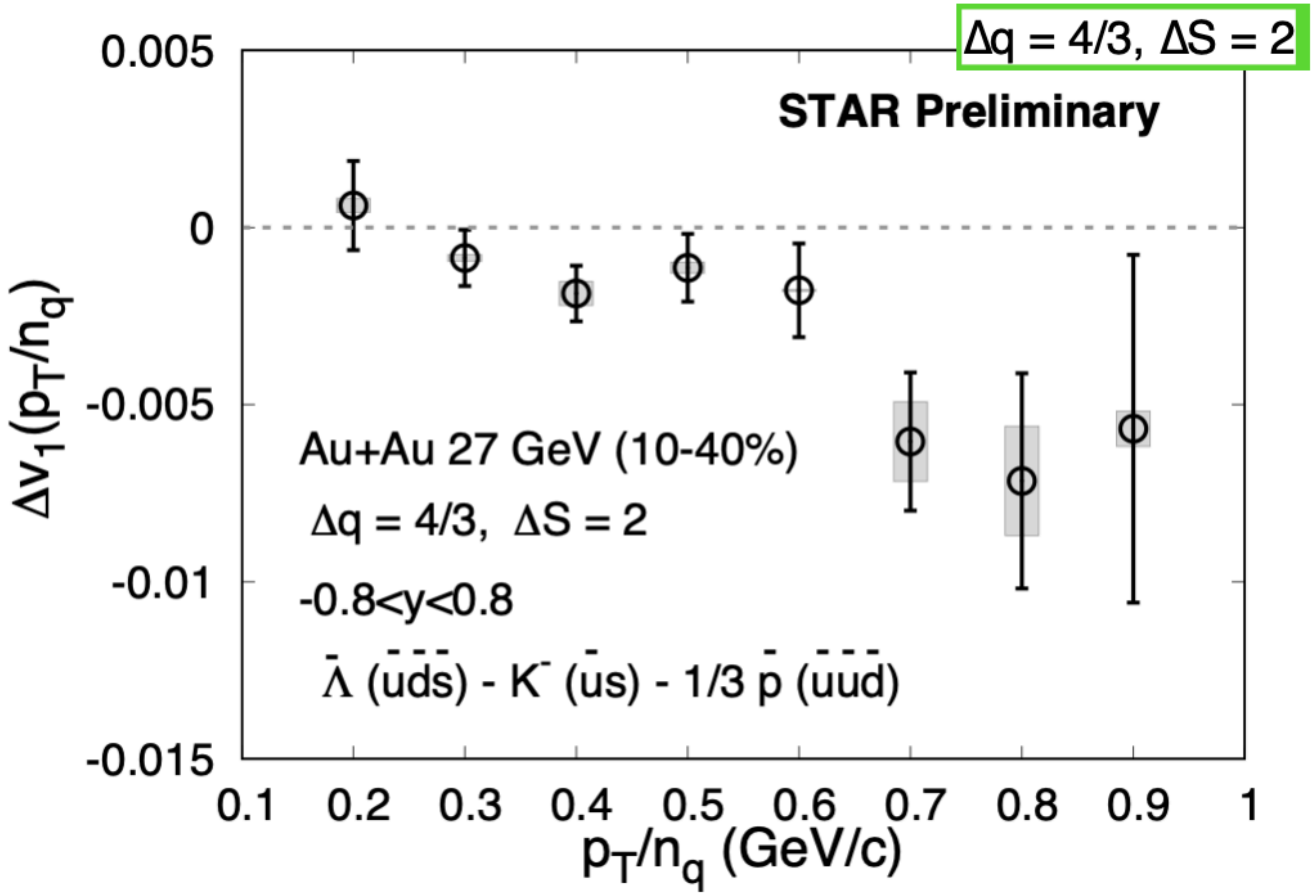


- Test of sum rule with identical quark combinations
- Δv_1 slope (with y) ~ 10^{-4}
- Sum rule holds within measured uncertainties

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

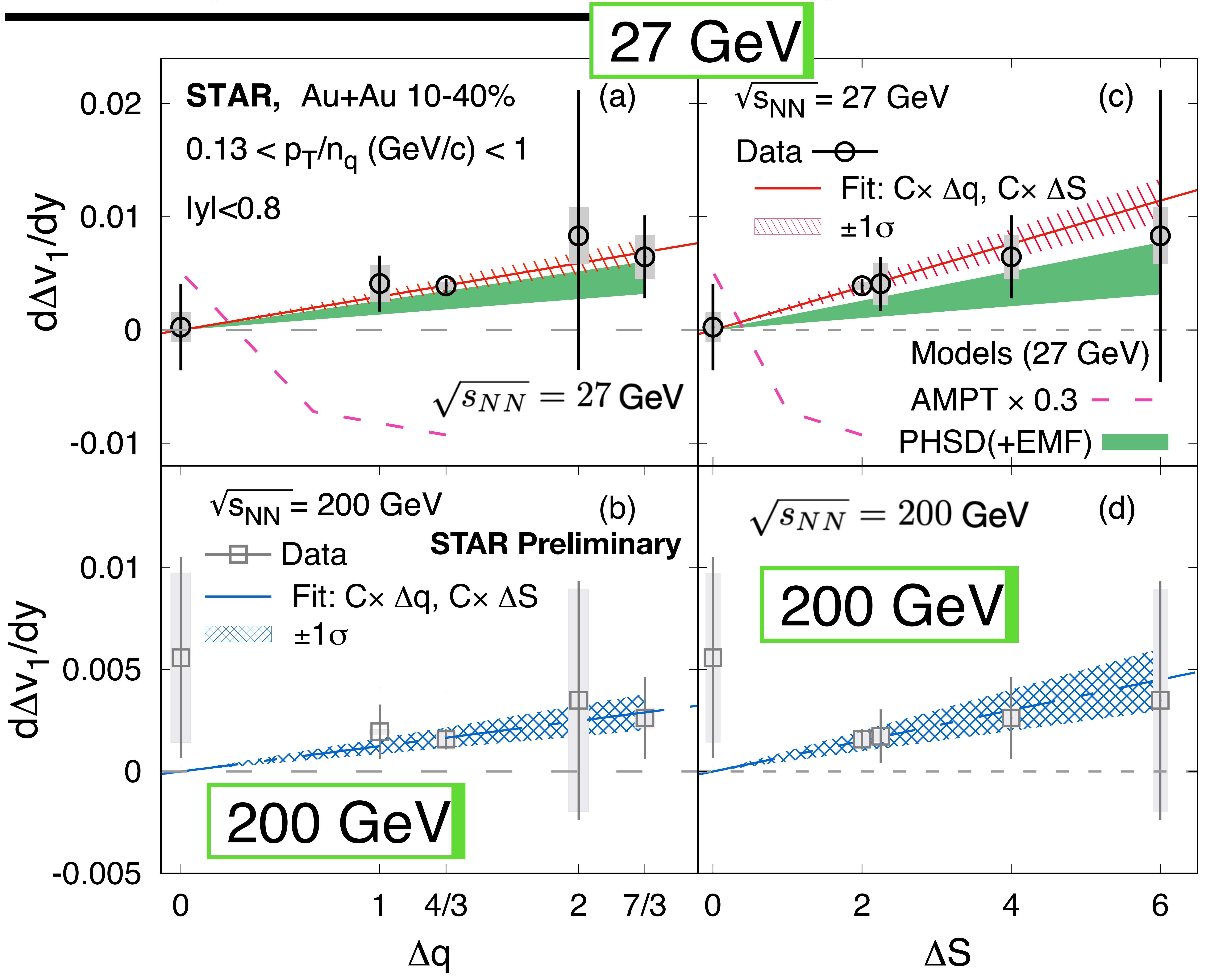
$$v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})] \quad \text{vs} \quad v_1[K^-(\bar{u}s)] + \frac{1}{3} v_1[\bar{p}(\bar{u}\bar{u}\bar{d})]$$





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

Splitting with charge and strangeness

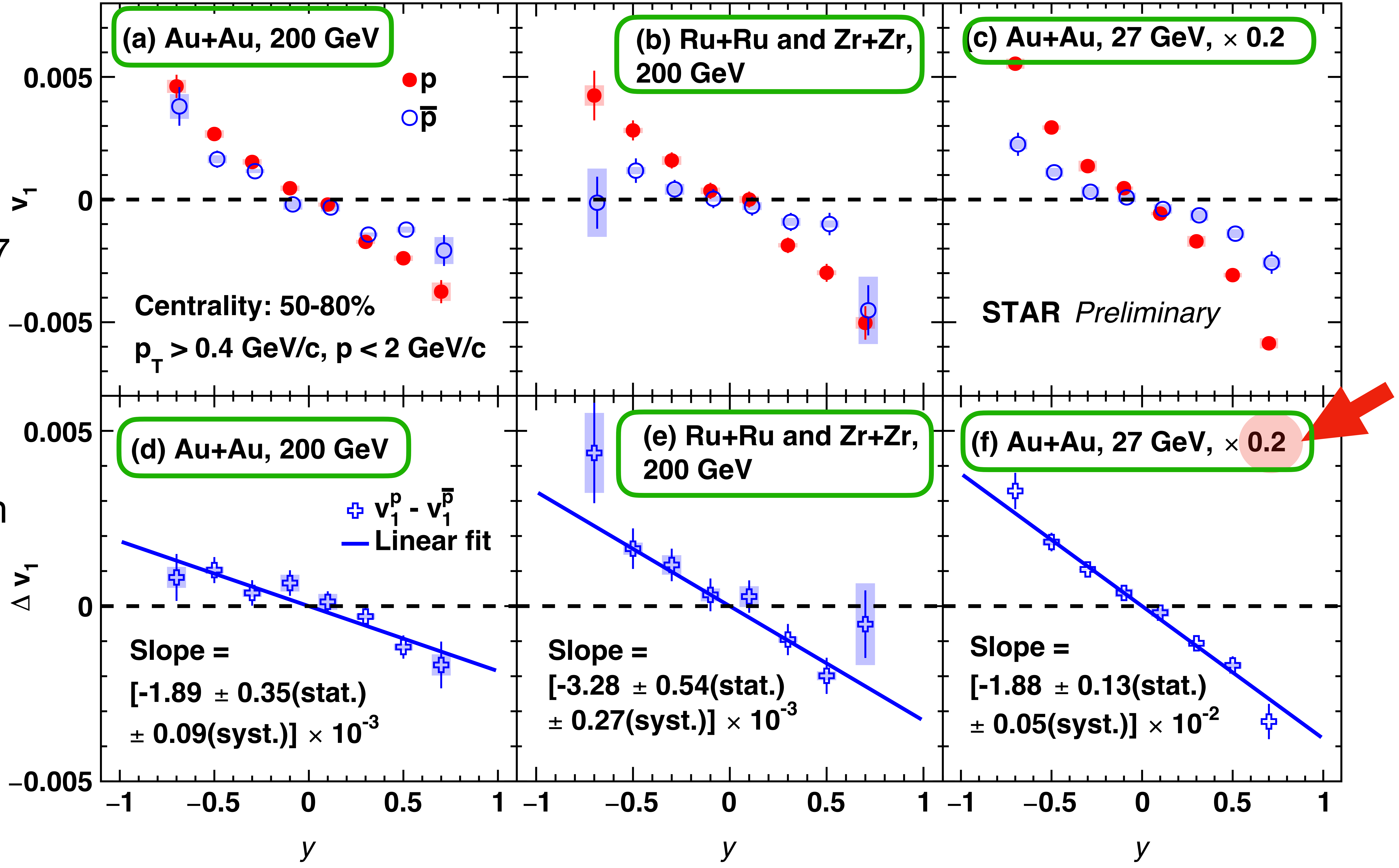


- Δv_1 slope (fit constrained to origin) increases with Δq and ΔS
- Splitting increases going from $\sqrt{s_{NN}}$ = 200 to 27 GeV (longer persistence of EM field at lower energy!)
- AMPT can not explain the data

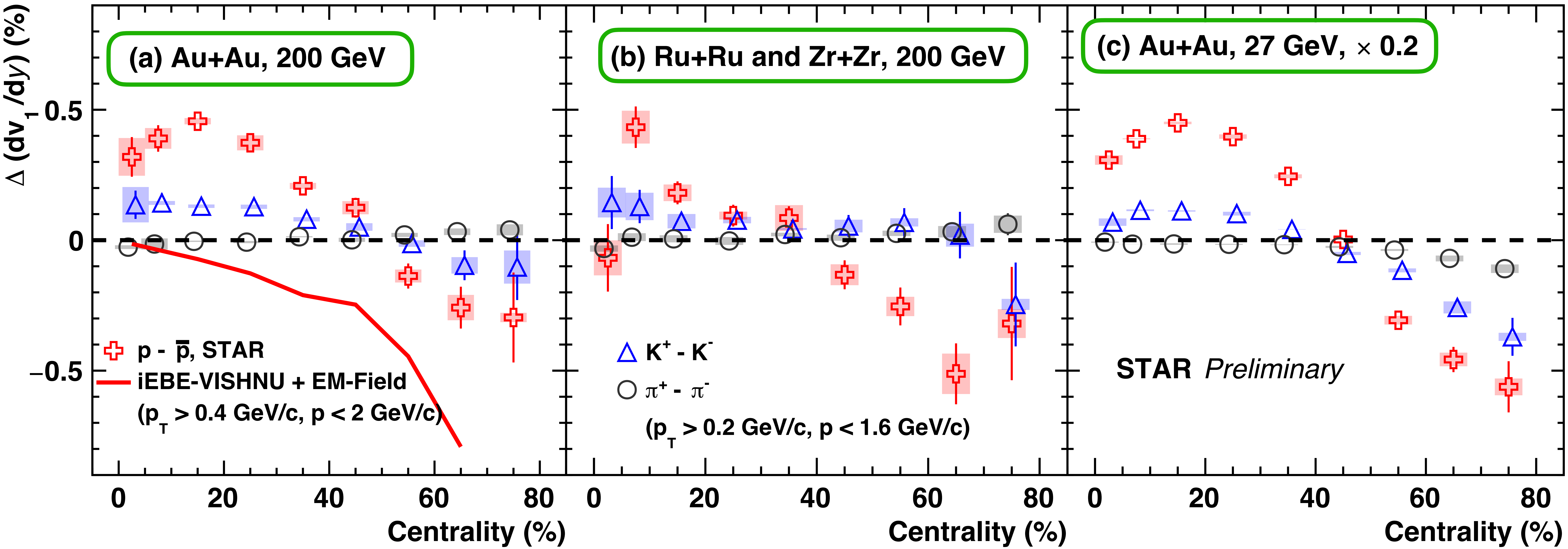
  (Nayak et al., Phys. Rev. C 100, 054903 (2019))
- PHSD(+EMF) can describe the data within errors, but EMF is not the sole difference between these two models

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 $\bar{\mathrm{p}}$ 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 $>5\sigma$ 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