Splitting of directed flow for identified light hadrons (π, K, p) and strange baryons (Ξ, Ω) in Au+Au and isobar collisions at STAR

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STAR

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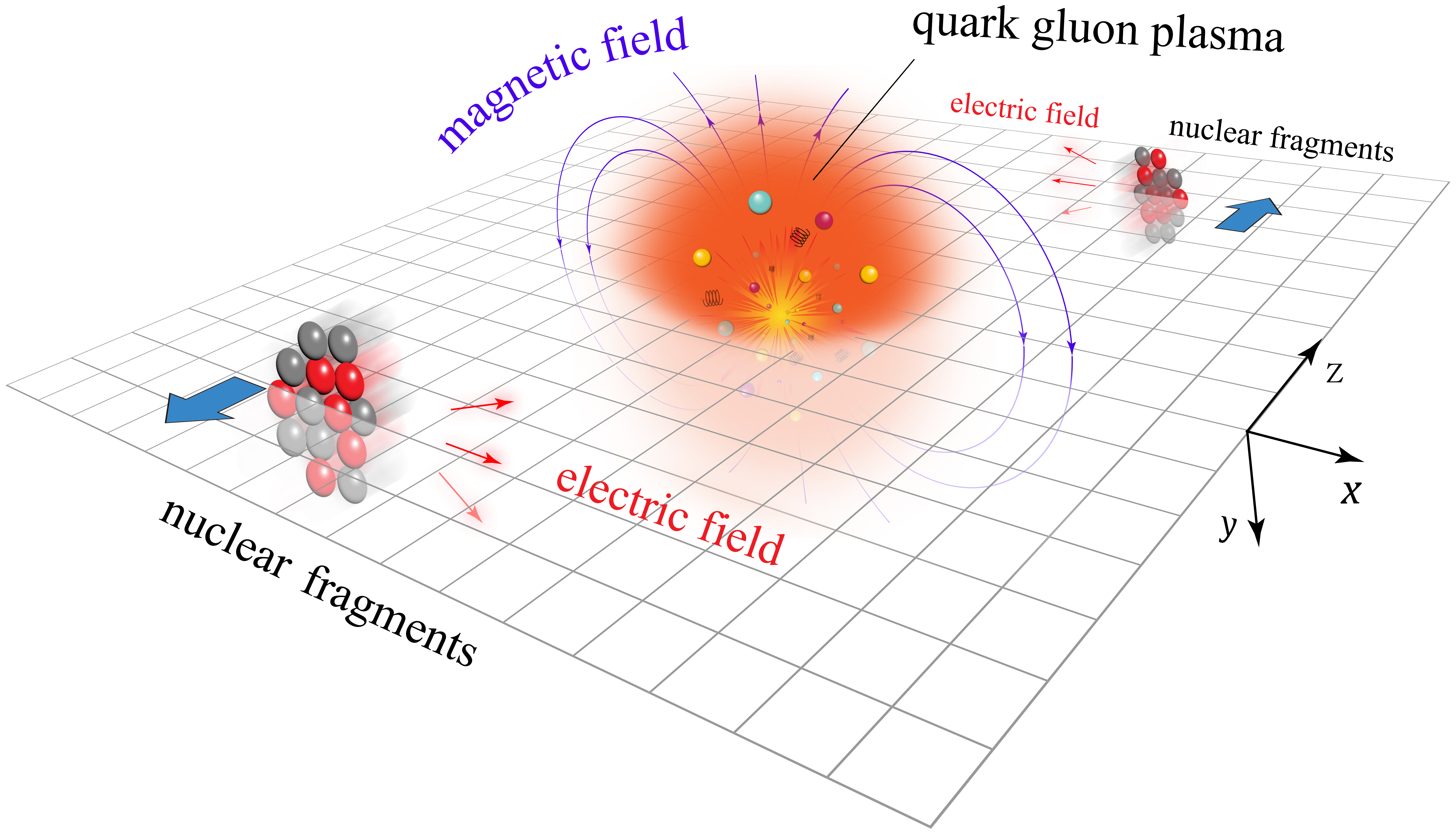
Directed flow (v_1) and splitting (Δv_1)

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

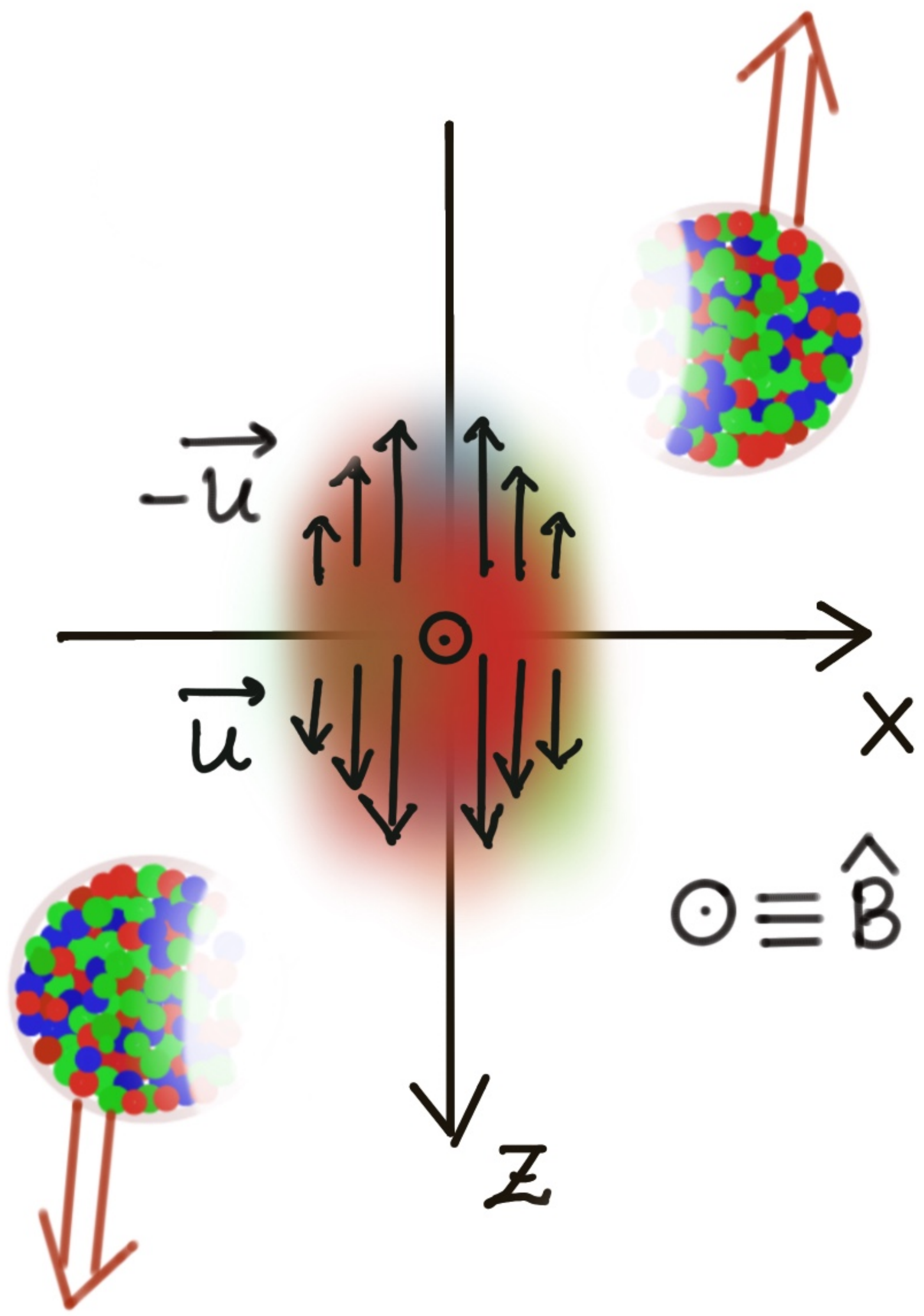
$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T dy}\left(1 + 2\sum_{n=1}^{+\infty} v_n \cos n(\phi - \Psi_{RP})\right)$$

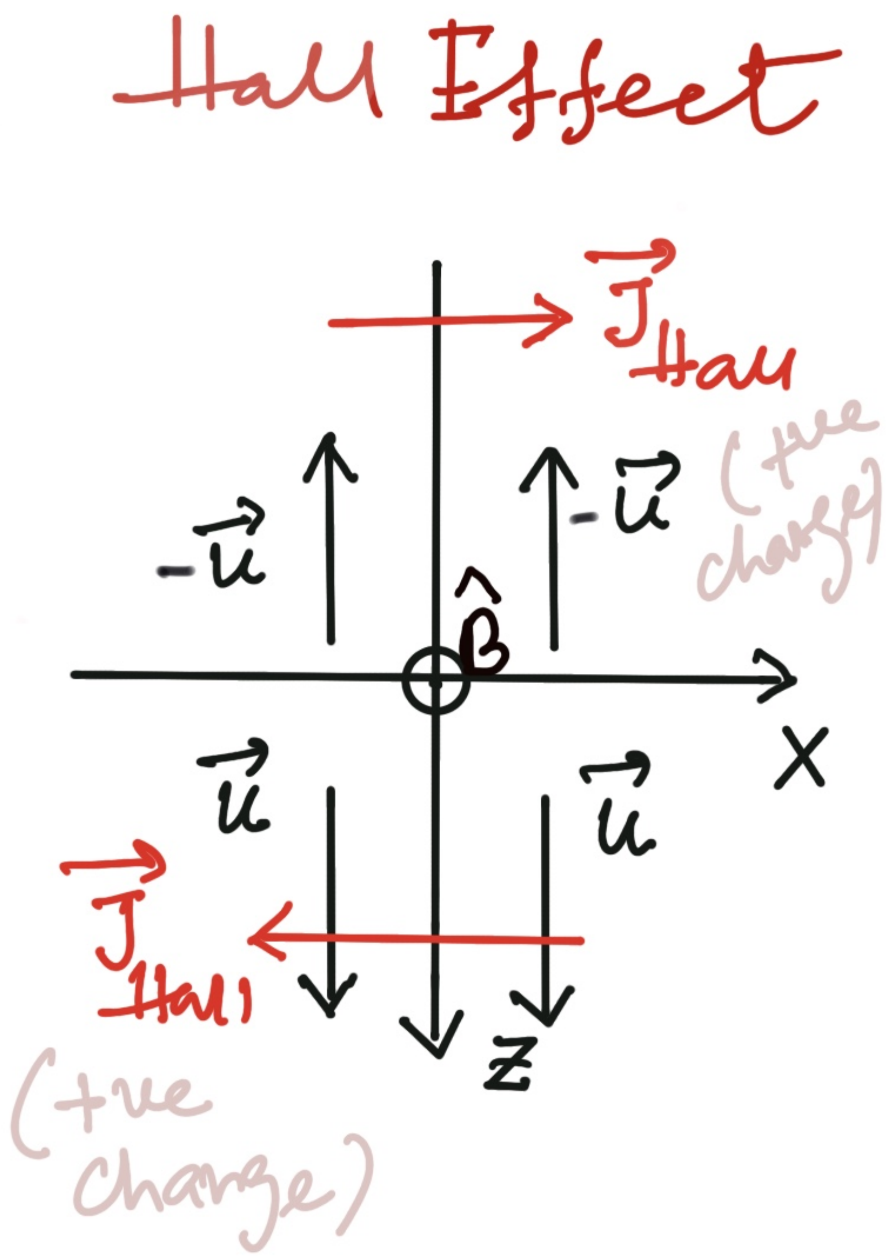
where $v_n = \langle \cos n(\phi - \Psi_{RP}) \rangle$

- Probe early stage of the collisions - strong electromagnetic (EM) field
- EM field has observable consequences on v_1 splitting with charge

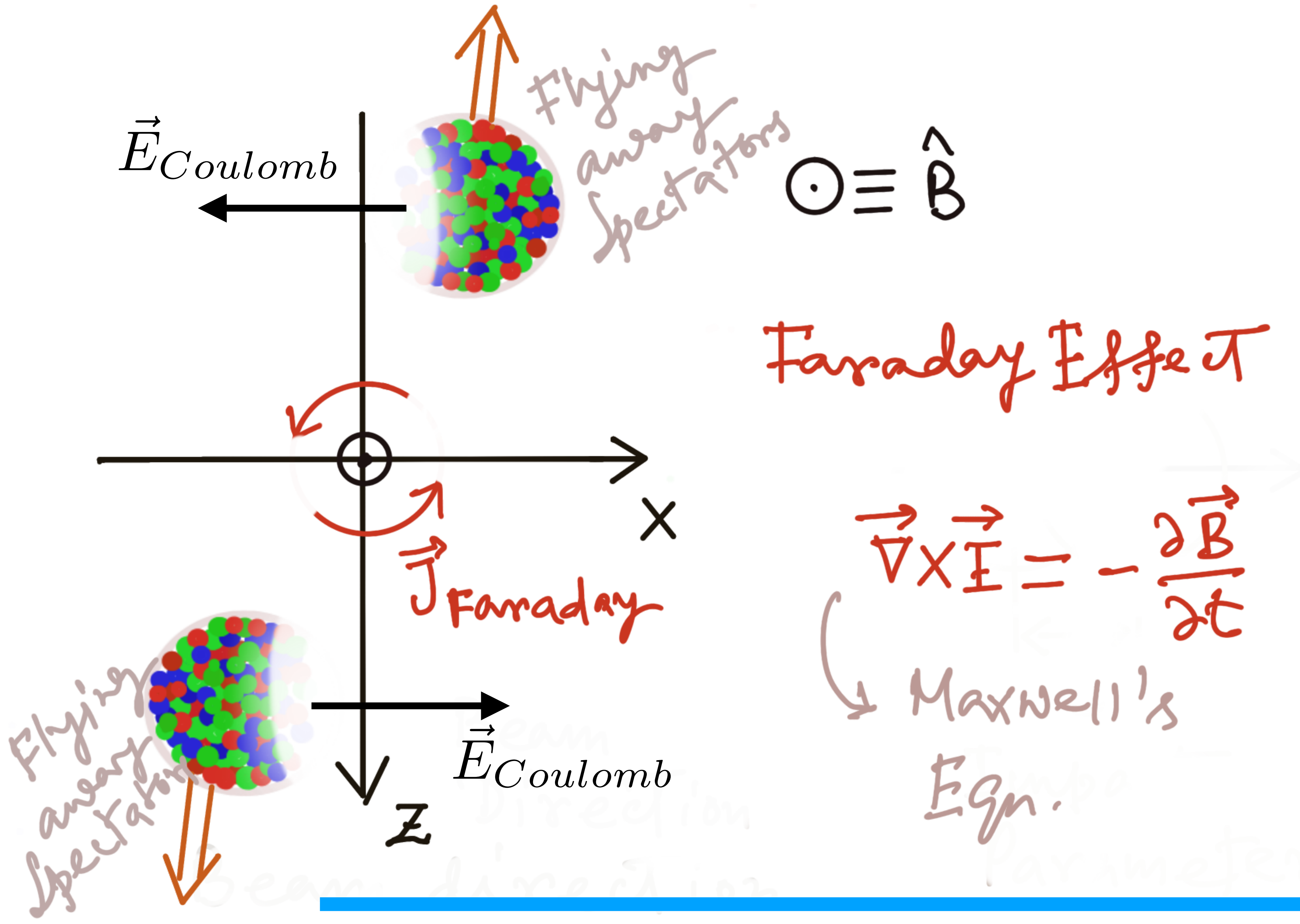


EM field drives splitting - Hall and Faraday effect



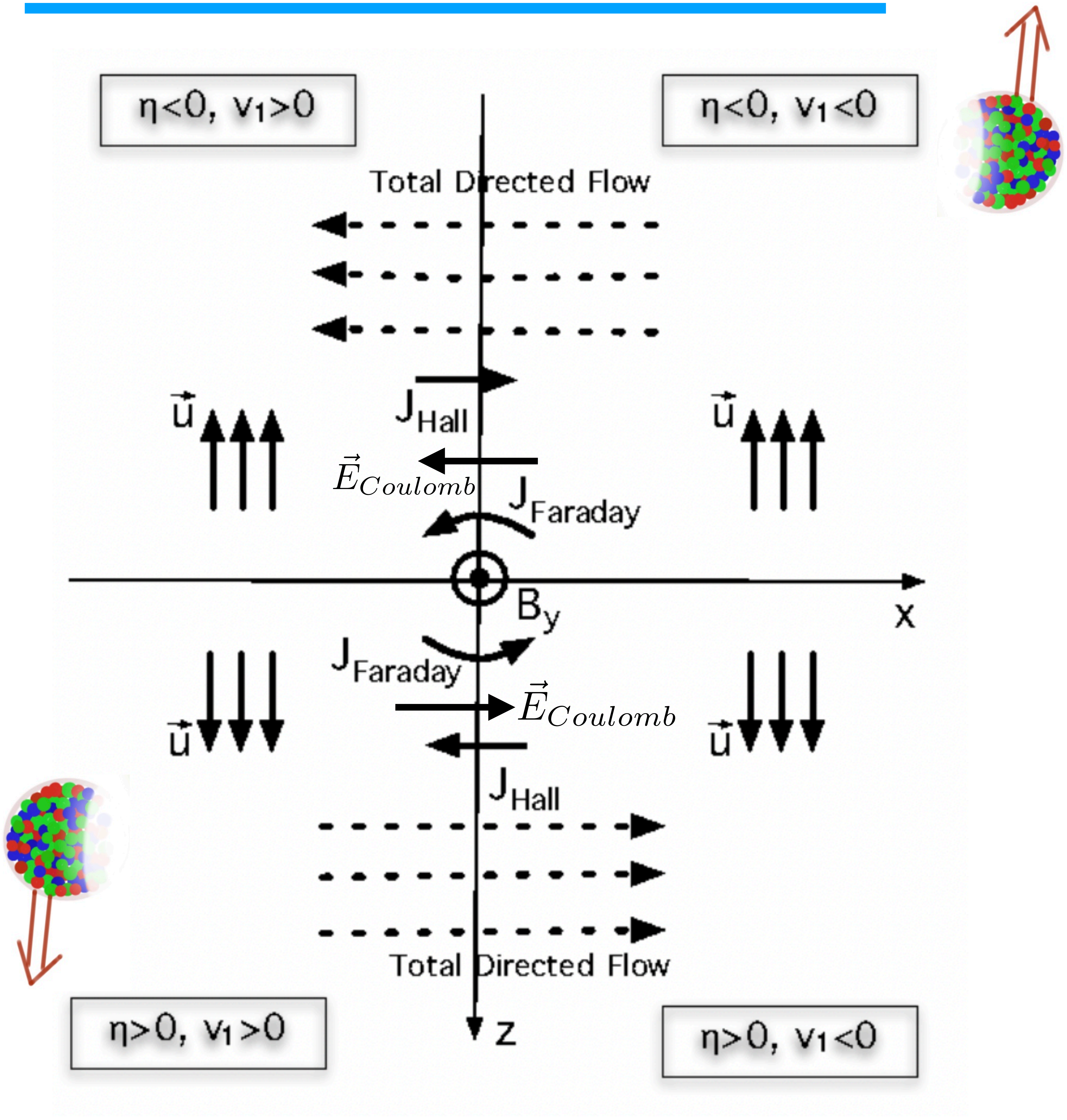


- Beam direction: $\hat{z}$ and impact parameter: $\hat{x}$ => reaction plane: xz
- Medium expands longitudinally ($\vec{u} || \hat{z}$, $\vec{u} \perp \vec{B}$)
- Lorentz force pushes positively and negatively charged particles in opposite directions => Hall effect



- 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



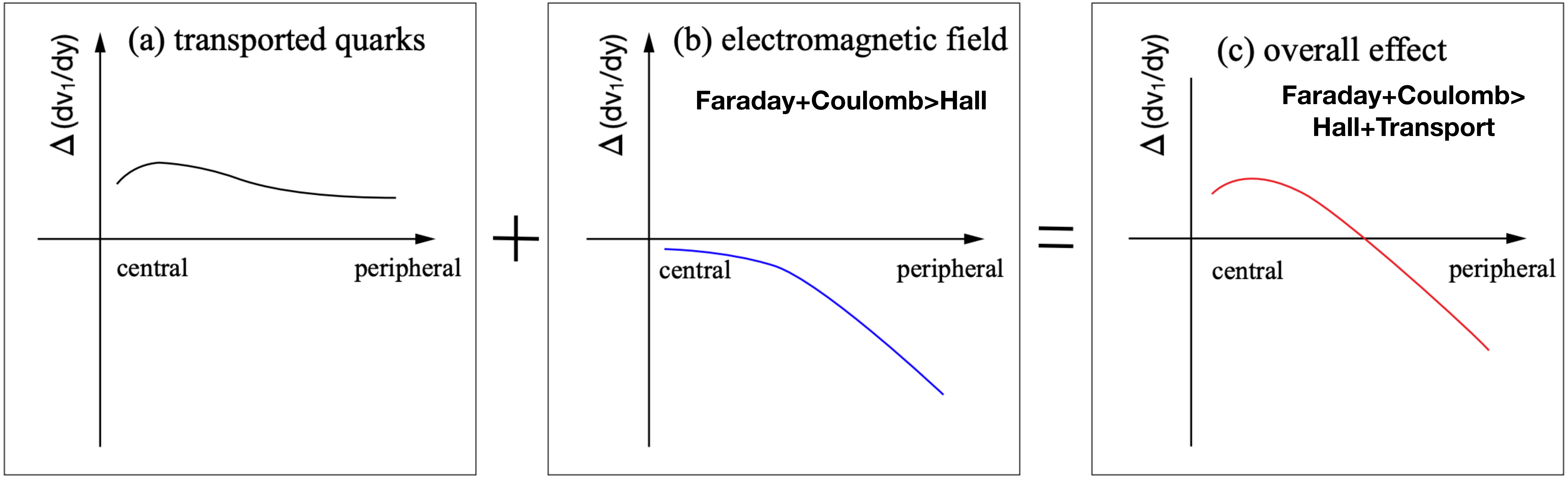
Gursoy et al., Phys. Rev. C 89, 054905 (2014)
Gursoy et al., Phys. Rev. C 98, 055201 (2018)

- Faraday, Coulomb and Hall are competing effects
- 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
- Net effect of Faraday, Hall and Coulomb affects v_1 and splitting between particles and antiparticles
- Can we measure this splitting in experiment?

Splitting: Interplay between transported quarks and EM field

- 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



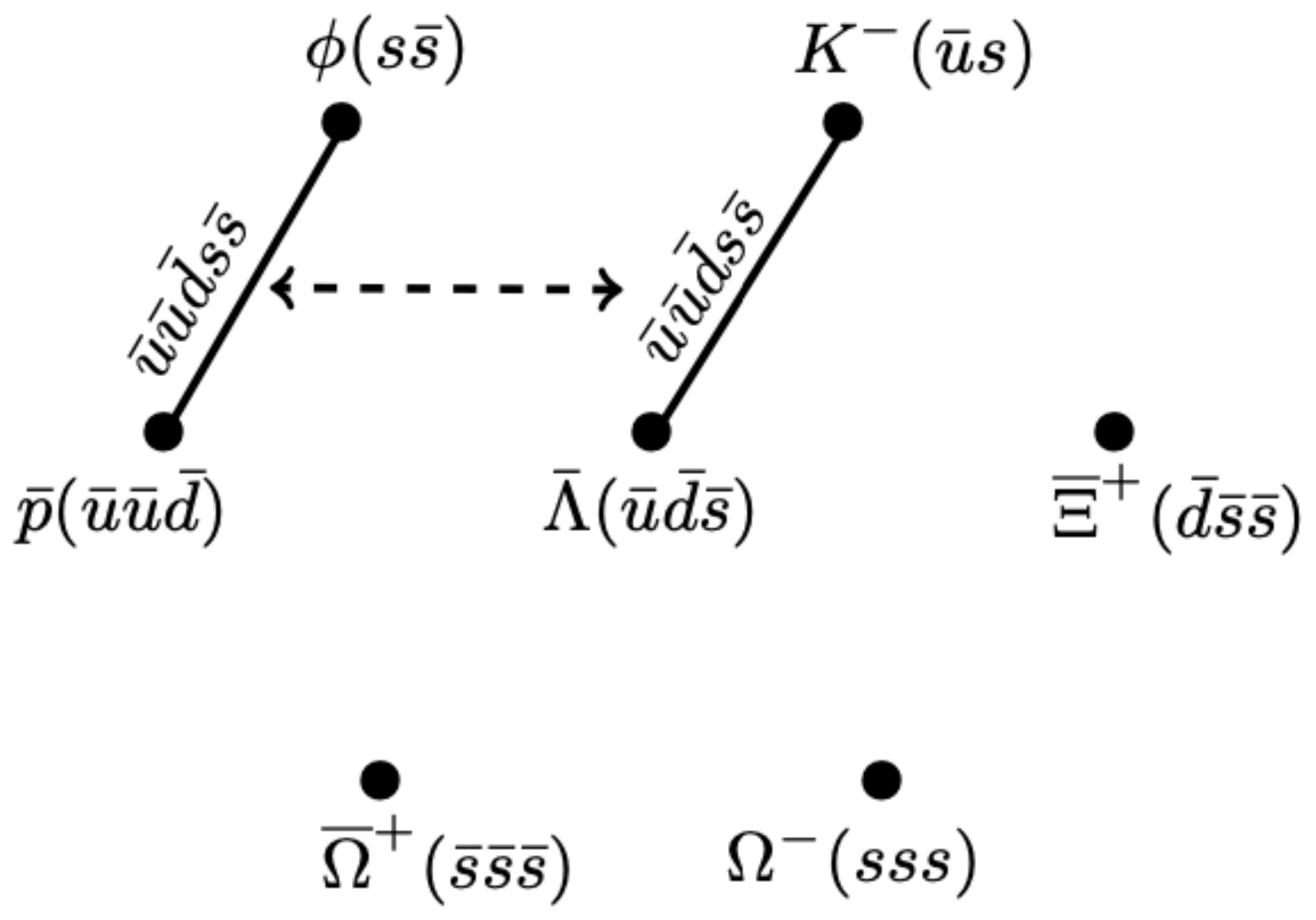
- Measure splitting between particle and anti-particle ($\Delta dv_1/dy = dv_1^{'}/dy - dv_1/dy$) with centrality

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

Splitting: An approach to avoid transported quark effect

- Use only produced particles: K^-, $\bar{p}$, $\bar{\Lambda}$, ϕ, $\overline{\Xi}^+$, Ω^- and $\overline{\Omega}^+$
- Coalescence-inspired sum rule: $v_1(hadron) = \sum v_1^i(q_i)$, with $q_i \rightarrow$ constituent quarks
- Test sum rule (same $y - p_T/n_q$ space, with $n_q \rightarrow$ no. of constituent quarks)

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



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

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

Combining different produced particles

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

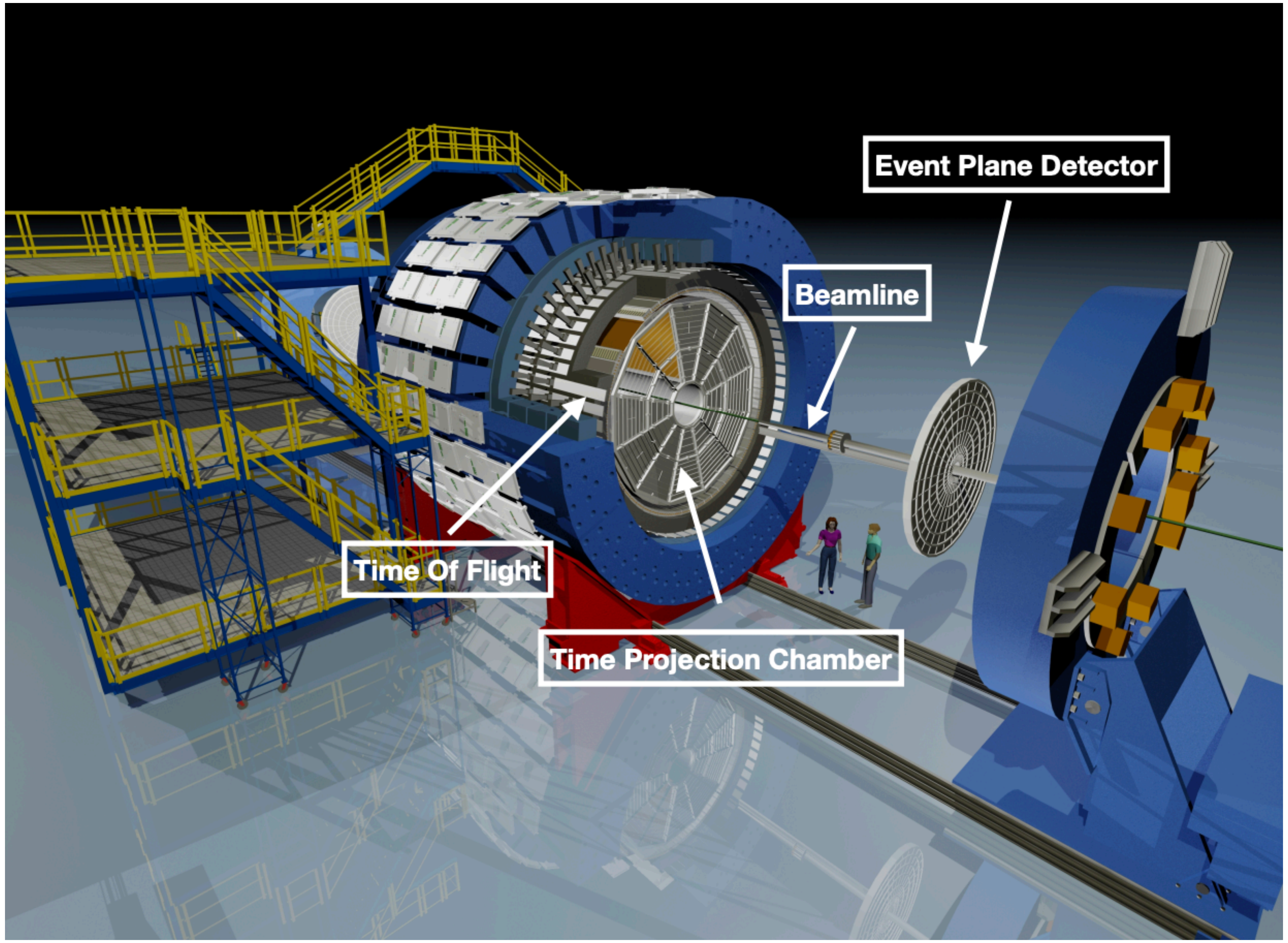
Index	Quark Mass	Charge	Strangeness	Expression
1	$\Delta m = 0$	$\Delta q = 0$	$\Delta S = 0$	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^-(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$
2	$\Delta m \approx 0$	$\Delta q = 1$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^-(sss)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

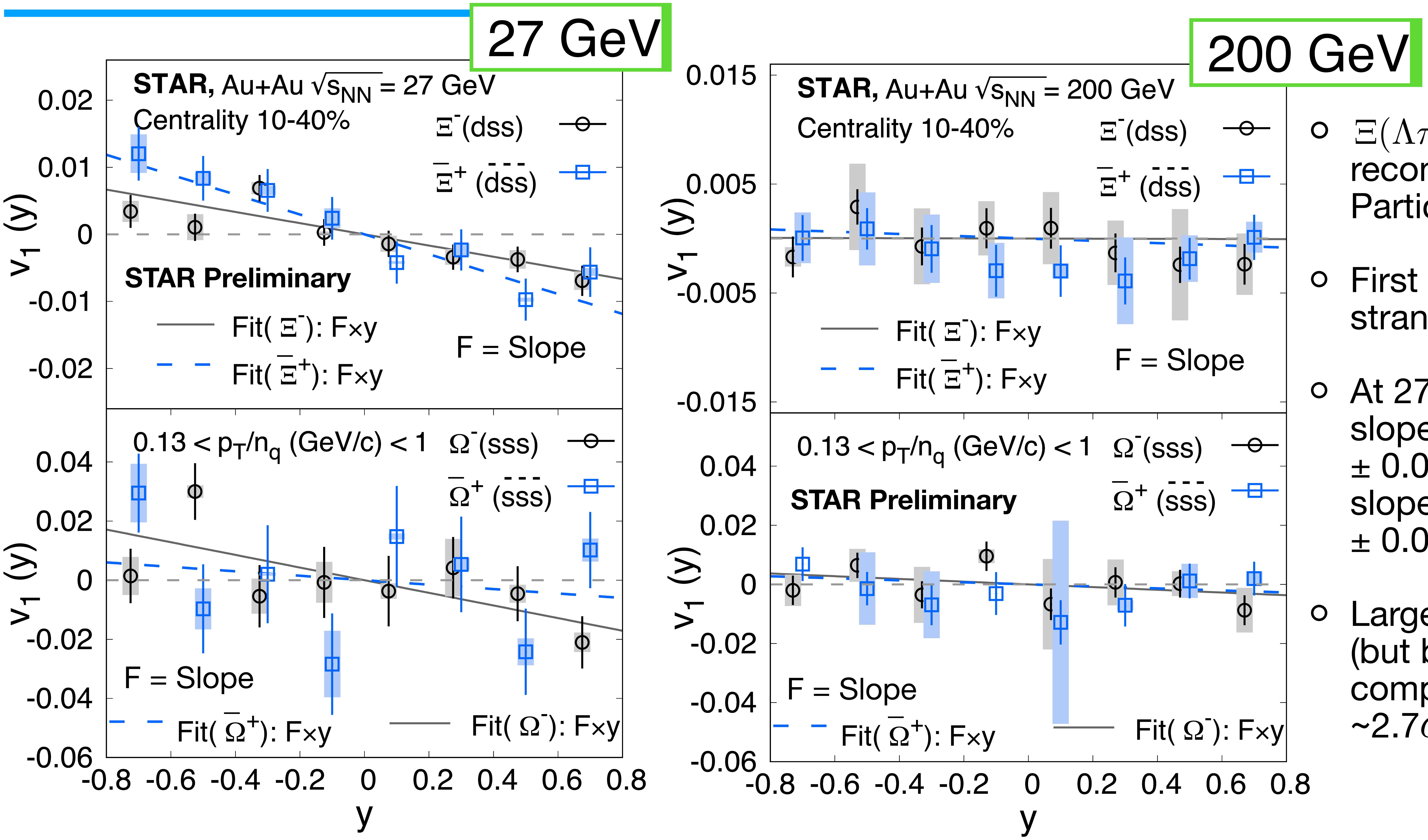
- TPC+TOF for PID: TPC measures dE/dx of tracks ($|\eta| < 1$, $0 < \phi < 2\pi$) and TOF measures time of flight ($|\eta| < 0.9$)
- EPD ($2.1 < |\eta| < 5.1$) or ZDC ($|\eta| > 6.3$) for event plane reconstruction



Datasets analyzed:

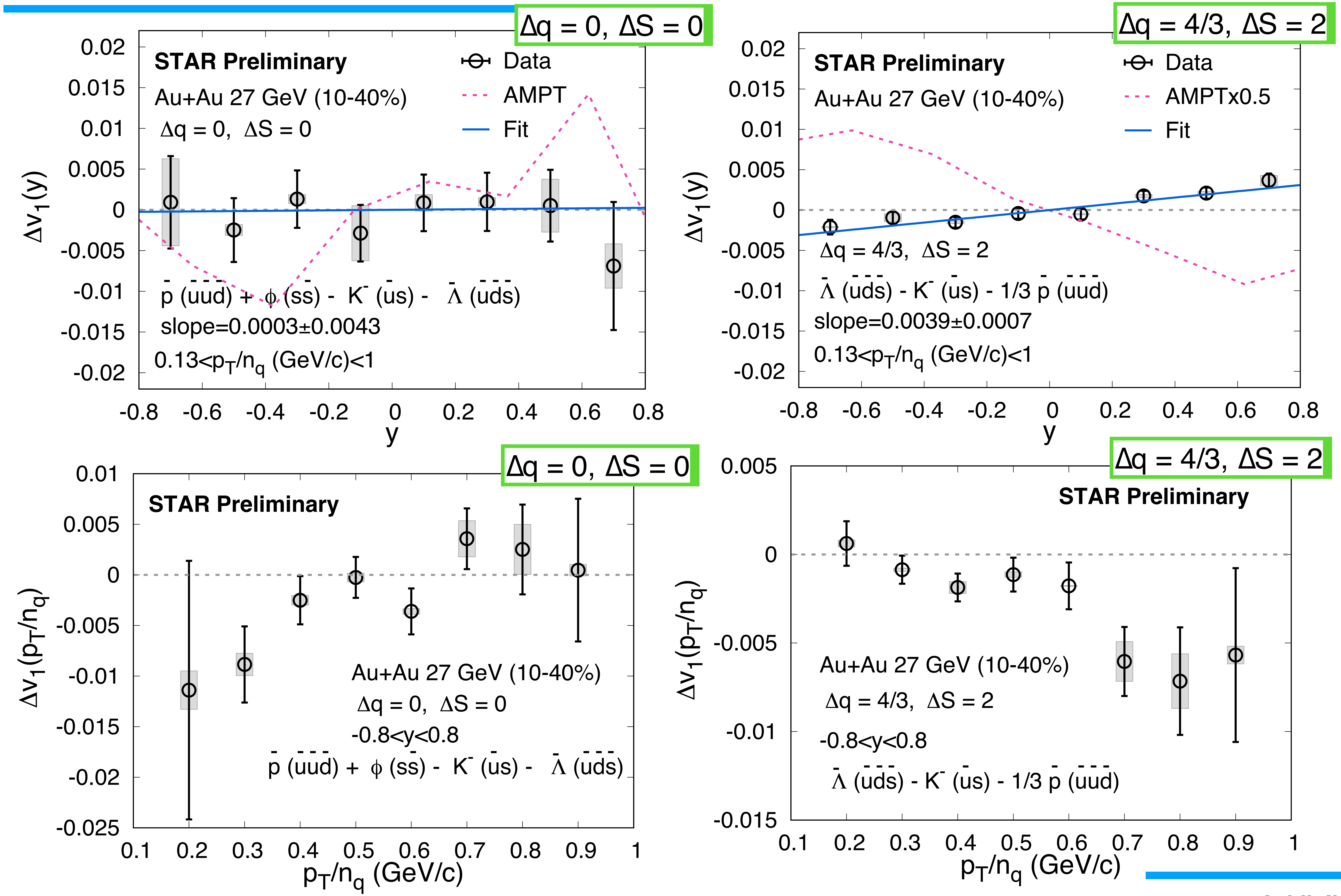
- At $\sqrt{s_{NN}} = 27$ GeV Au+Au at BES-II, and $\sqrt{s_{NN}} = 200$ GeV Au+Au, and isobaric (Ru+Ru and Zr+Zr) collisions

v_1 vs y : Ξ and Ω Baryons



- $\Xi(\Lambda\pi)$ and $\Omega(\Lambda K)$ reconstructed by KF-Particle
- First $v_1(y)$ for multi-strangeness
- At 27 GeV, slope (Ω^-) = −0.0214 ± 0.008, slope (Ξ^-) = −0.0083 ± 0.002
- Large v_1 slope for Ω^- (but big errors) compared to Ξ^- ~2.7σ significance

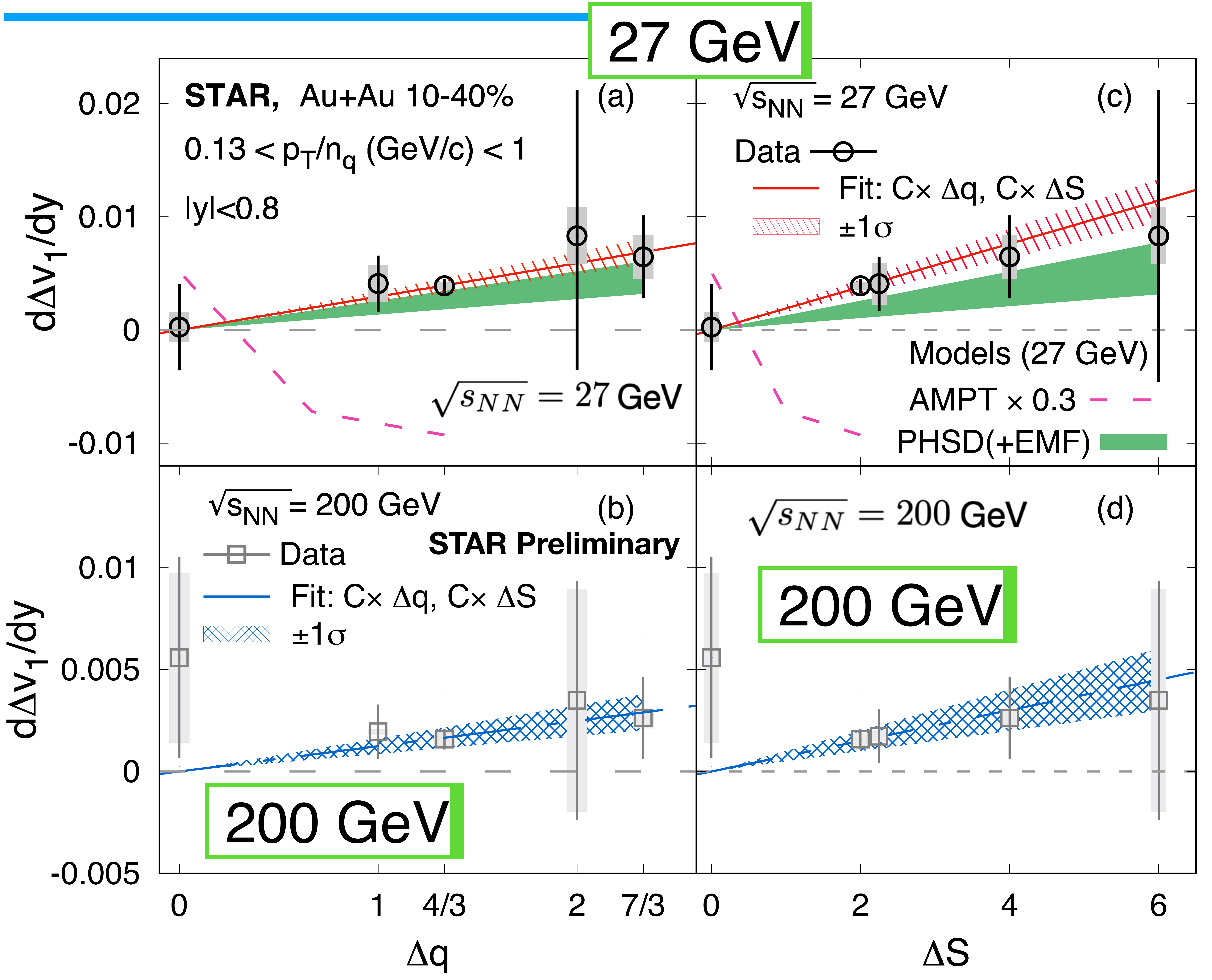
Splitting at 2 different Δq and ΔS (27 GeV)



- Δv_1 slope ~0 for $\Delta q = 0,\ \Delta S = 0$
- $|\Delta v_1|$ increases at larger y and p_T/n_q for $\Delta q \neq 0, \Delta S \neq 0$
- AMPT has the opposite trend for $\Delta q \neq 0,\ \Delta S \neq 0$
- No EM field in AMPT

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

Splitting with charge and strangeness

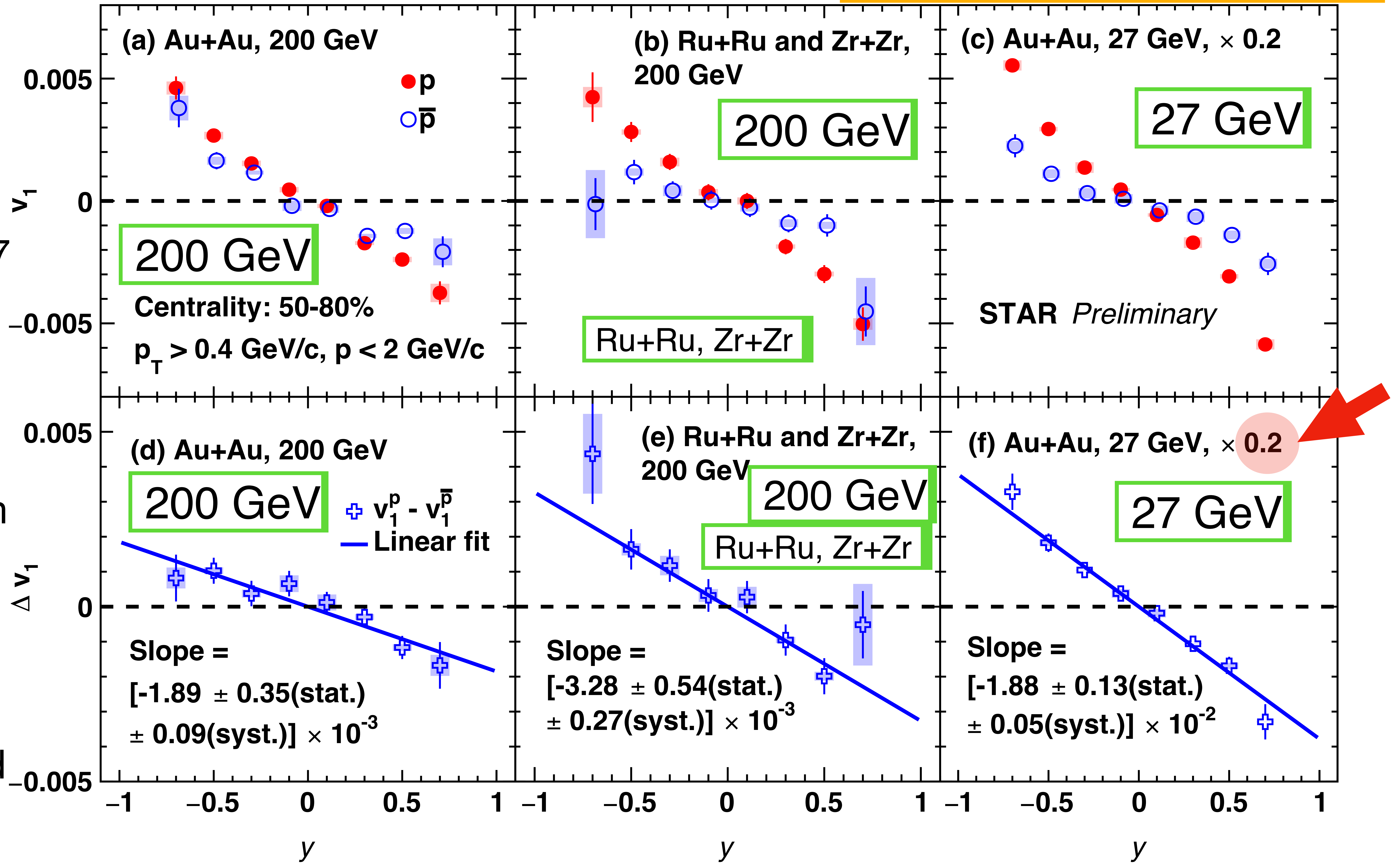


- Δv_1 slope (fit constrained to origin) increases with Δq and ΔS
- Splitting increases going from $\sqrt{s_{NN}} =$ 200 to 27 GeV
- AMPT can not explain the data
  (Nayak et al., Phys. Rev. C 100, 054903 (2019))
- PHSD(+EMF) can describe the data within errors, but EMF is not the sole difference between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

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

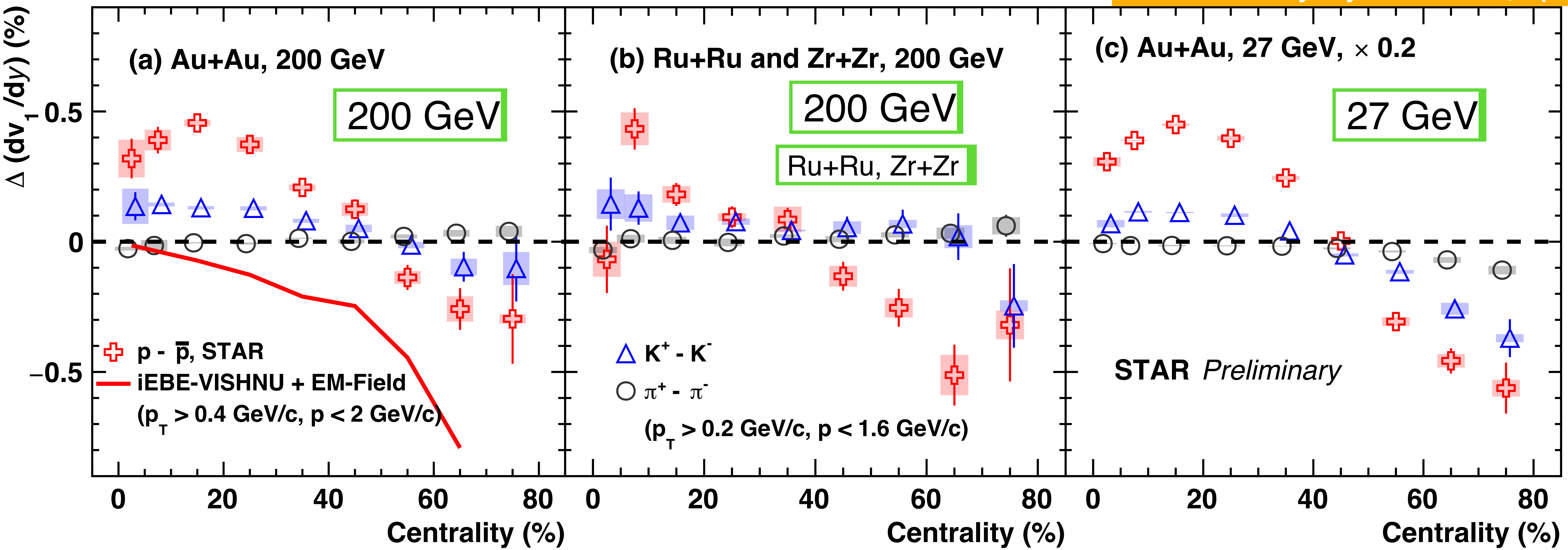
STAR Poster by Diyu Shen: T01, Apr7

- 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 - Longer persistence of EM field at lower energy?



Splitting between particle and anti-particle with centrality

STAR Poster by Diyu Shen: T01, Apr7



- $\Delta dv_1/dy$ 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)

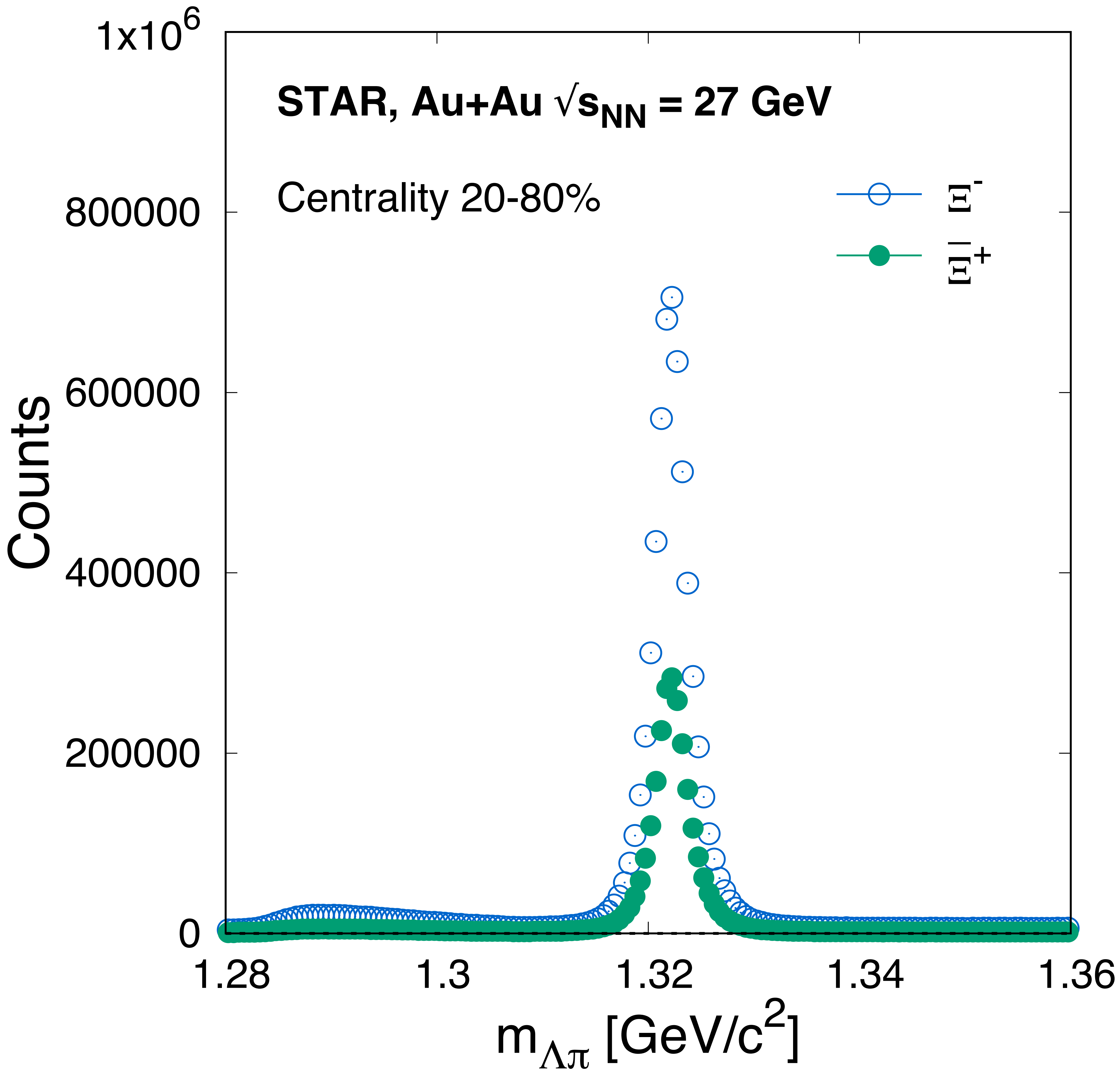
Summary

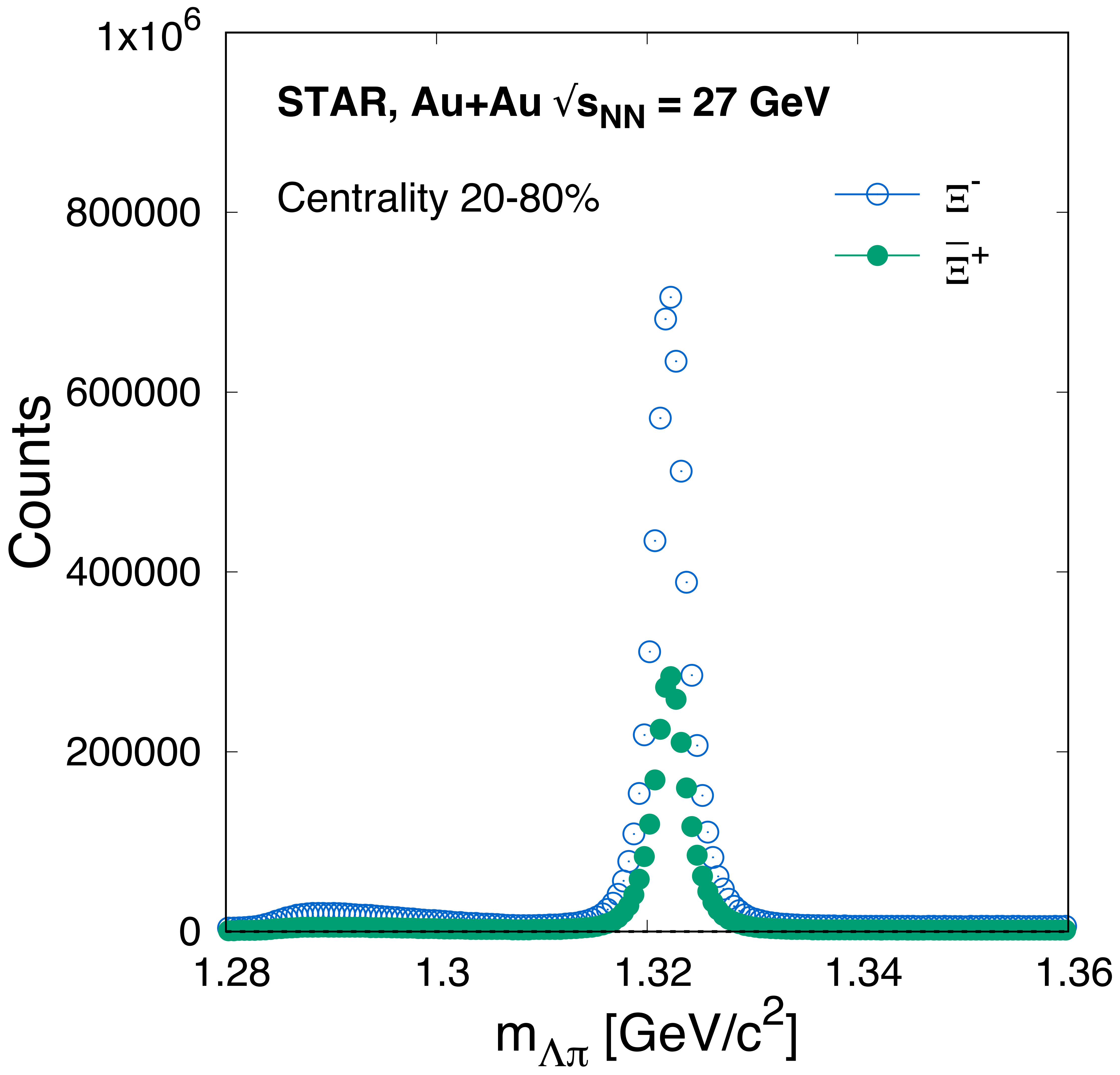
- First measurements of v_1 of multi-strange baryons - Large v_1-slope (with large errors) for Ω^- compared to Ξ
- Measured charge (Δq) and strangeness (ΔS) dependent splitting - free from the transported quark effect
- Splitting increases with Δq and ΔS, stronger in lower collision energy
- PHSD+EM 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

Backup

Invariant mass : Ξ and Ω Baryons





- $\Xi(\Lambda\pi)$ and $\Omega(\Lambda K)$ reconstructed by KF-Particle (I. Kisel (CBM), J. Phys. Conf. Ser. 1070, 012015 (2018))