STAR results on strangeness and electric charge dependent splitting of the rapidity-odd directed flow

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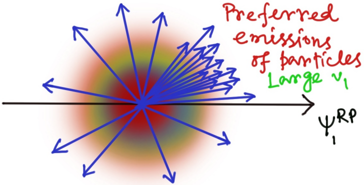
Directed flow (v_1) and splitting (Δv_1)

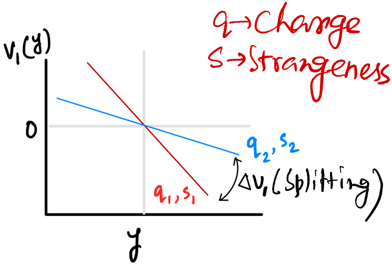
- First harmonic coefficient of Fourier decomposition of particle azimuthal distribution, v_1 - Directed Flow

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

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

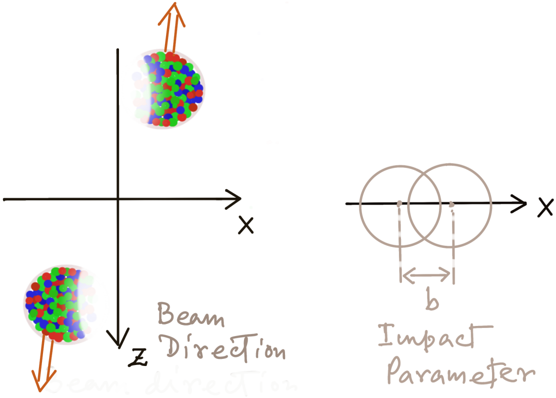
- Probe early stage of the collisions - strong EM-Field





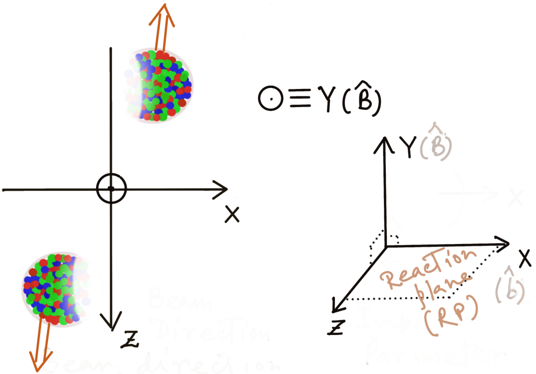
- What drives the splitting - Initial EM-Field or QCD-driven effect?
- Measure splitting with charge (Δq) and strangeness (ΔS)

EM-Field driven splitting (Δv_1)?



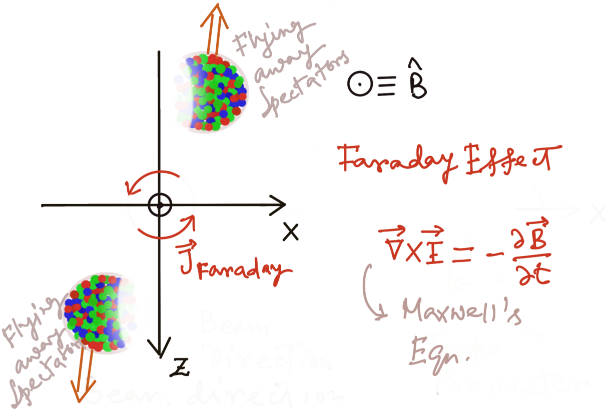
- Collisions along z-axis (Beam direction is $\hat{z}$)
- Impact parameter (b) is in $\hat{x}$

EM-Field driven splitting (Δv_1)?



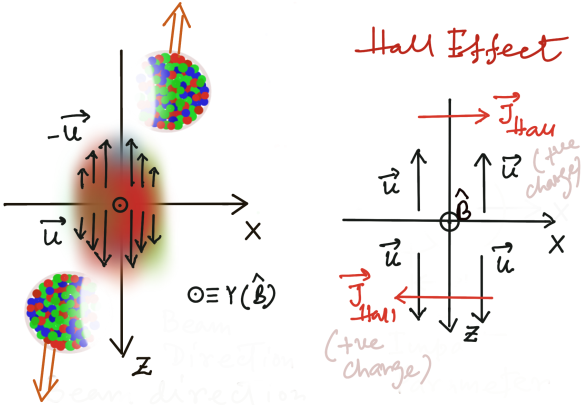
- Colliding nuclei produce strong EM-Field
- A crude estimate:
  At RHIC collisions (Au+Au@$\sqrt{s_{NN}} = 200$ GeV, $b = 5$ fm, $t = 0$),
  $-eB_y \sim 40 m_\pi^2 \sim 10^{18}$ Gauss (Rep. Prog. Phys. 79, 076302 (2016))
- xz-plane defines Reaction Plane (RP)
- Magnetic field (B) $\perp$ to RP (approx) - B along Y-axis

EM-Field driven splitting (Δv_1) - Faraday effect ?



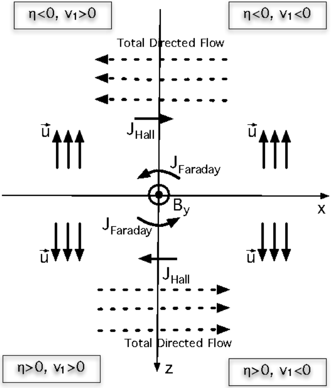
- As spectators fly away, $\vec{B}$ falls rapidly with time
- Time varying $\vec{B}$ induces $\vec{E}$ field => Faraday effect
- Charged particles get pushed - produces an electric current

EM-Field driven splitting (Δv_1) - Hall effect?



- Medium has initial longitudinal expansion velocity, $\vec{u} \parallel \hat{z} => \vec{u} \perp \vec{B}$
- Lorentz force results in electric current (along x(-x) direction) depending upon electric charge
- Current $\perp \vec{B}, \vec{u} =>$ Hall effect

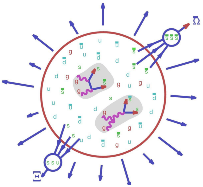
EM-Field driven splitting (Δv_1)?



U. Gursoy et al., Phys. Rev. C 89, 054905 (2014)

- Faraday and Hall are competing effects
- Net current is sum of them - affects v_1
- v_1 for +ve particles shown (when Faraday > Hall)

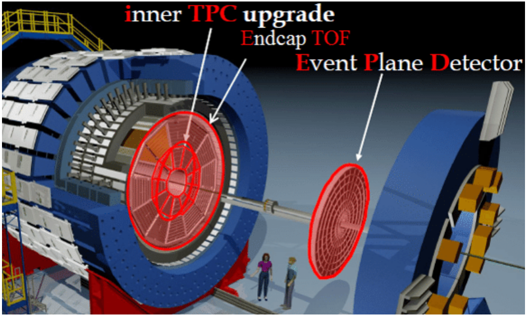
Multi-strange and the splitting (Δv_1)



Cartoon: Eur. Phys. J. A 51, 114 (2015)

- Strange quarks (s and $\bar{s}$) are produced in an enhanced manner in the plasma
- They retain their identity during the hadronization => multiply multi-strange baryons (Ξ and Ω)
- Low scattering cross section and thermal freeze-out occurs much earlier than for non- or single-strange particles
- Multi-strange baryons might be a good probe of the early stage of the collisions
- v_1 is sensitive to the early stage too
- Multi-strange v_1 might be used to search for strangeness dependent splitting (if there is any)

Towards measurements: STAR detector at BES-II



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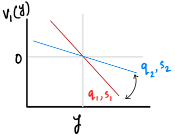
- TPC+TOF for PID: TPC measures -dE/dx of tracks ($|\eta| < 1$, $0 < \phi < 2\pi$) and TOF measures time of flight ($|\eta| < 0.9$)
- EPD ($2.1 < |\eta| < 5.1$) or ZDC ($|\eta| > 6.3$) for event plane reconstruction
- Data sets (analyzed):
  Au+Au at $\sqrt{s_{NN}} = 27$ GeV (year-2018) and $\sqrt{s_{NN}} = 200$ GeV (year-2016)

Splitting (Δv_1): Choice of particles?



(1) Measurements with heavy flavors?

- Measurements of HFs are challenging
- Less abundantly produced - suffer large uncertainties
- Absence of HFT in BES-II and low production rate - HF measurements are difficult

(2) Measurements with light hadrons?

- Light hadrons produced in abundance - precise measurements
- Δv_1 measurements come with drawbacks:
  (a) Most of the (anti)-particles contain transported quarks (u and d)
  (b) Transported quarks have different v_1 than the produced => Δv_1 becomes difficult to interpret
- Avoiding transported quarks => Splitting can be measured with light hadrons

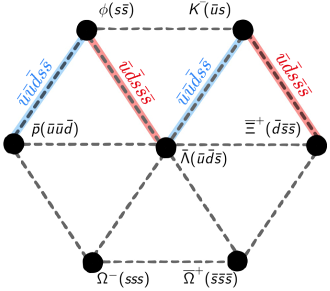
Splitting (Δv_1): Our Approach

- Use only produced particles, K^-, $\bar{p}$, $\bar{\Lambda}$, ϕ, $\overline{\Xi}^+$, Ω^- and $\overline{\Omega}^+$
- Based on Quark coalescence
- Coalescence-inspired sum rule: v_1 (Hadron) $= \sum v_1^i(q_i)$
- A new way to test coalescence sum rule (same $y - p_T/n_q$ phase space, with $n_q \rightarrow$ no. of constituent quarks):

$$v_1[K^-(\bar{u}s)] + v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})] = v_1[\bar{p}(\bar{u}\bar{u}\bar{d})] + v_1[\phi(s\bar{s})] \quad (1)$$

$$v_1[K^-(\bar{u}s)] + v_1[\bar{\Xi}^+(\bar{d}\bar{s}\bar{s})] = v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})] + v_1[\phi(s\bar{s})] \quad (2)$$

- In the hexagon: blue lines (Eqn.1) and red lines (Eqn.2)



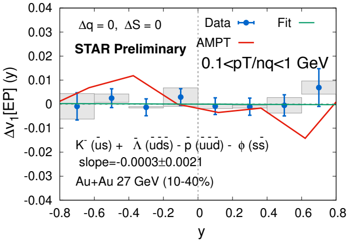
Splitting (Δv_1): Our Approach

- New idea to show the coalescence sum rule holds (with identical quarks):

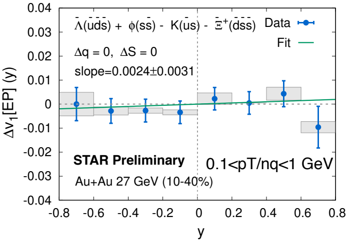
$$v_1[K^-(\bar{u}s)] + v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})] = v_1[\bar{p}(\bar{u}\bar{u}\bar{d})] + v_1[\phi(s\bar{s})] \qquad (1)$$

$$v_1[K^-(\bar{u}s)] + v_1[\bar{\Xi}^+(\bar{d}\bar{s}\bar{s})] = v_1[\bar{\Lambda}(\bar{u}\bar{s}\bar{d})] + v_1[\phi(s\bar{s})] \qquad (2)$$

(1)



(2)



- With produced particles, K^-, $\bar{p}$, $\bar{\Lambda}$, ϕ, $\bar{\Xi}^+$, Ω^- and $\overline{\Omega}^+$ and make combinations - having same quark mass but different Δq and ΔS

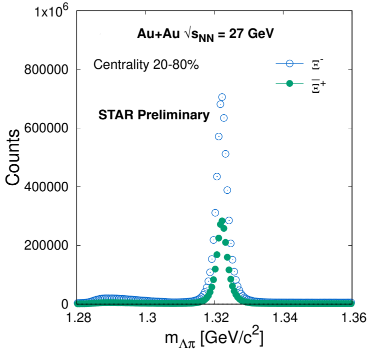
Rearranging the Δv_1 in Δq and ΔS

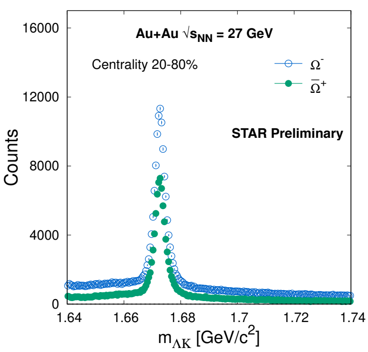
Particles: $K^{-}(\bar{u}s)$, $\bar{p}(\bar{u}\bar{u}\bar{d})$, $\bar{\Lambda}(\bar{u}\bar{d}\bar{s})$, $\phi(s\bar{s})$, $\overline{\Xi}^{+}(\bar{d}\bar{s}\bar{s})$, $\Omega^{-}(sss)$, $\overline{\Omega}^{+}(\bar{s}\bar{s}\bar{s})$

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

- Combinations have same $\Delta m(\approx 0)$ different Δq and ΔS - 7 independent combinations
- Degenerate combinations (Indices 4 and 5) - Good cross check
- Measure splitting with Δq and ΔS

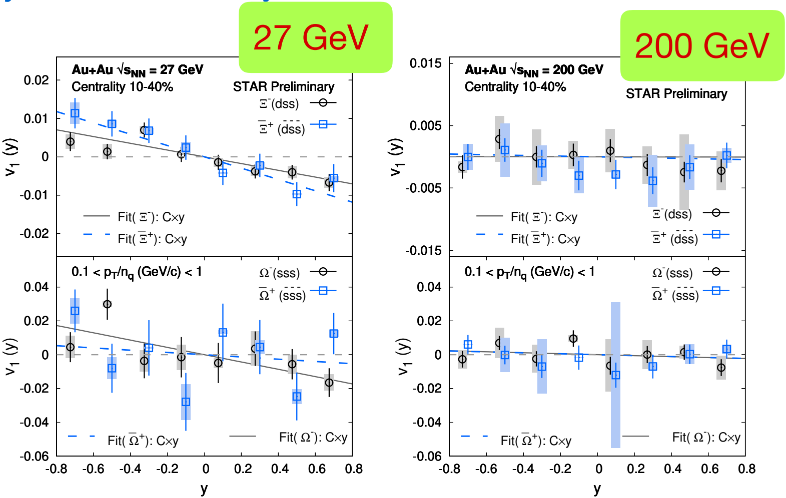
Ξ and Ω Baryon reconstruction: Invariant Mass with KFP





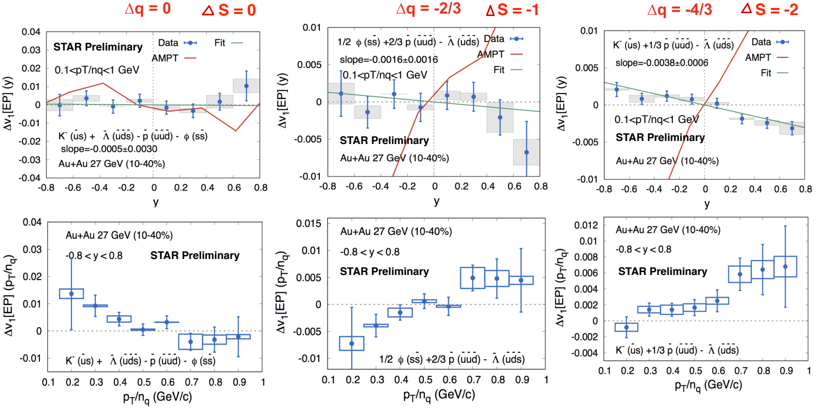
- Ξ and Ω baryons are reconstructed in $\Lambda\pi$ and ΛK channel respectively using KF-Particle (J. Phys. Conf. Ser. 1070, 012015 (2018))
- Good purity is achieved with KF-Particle

v_1 vs y : Ξ and Ω Baryons



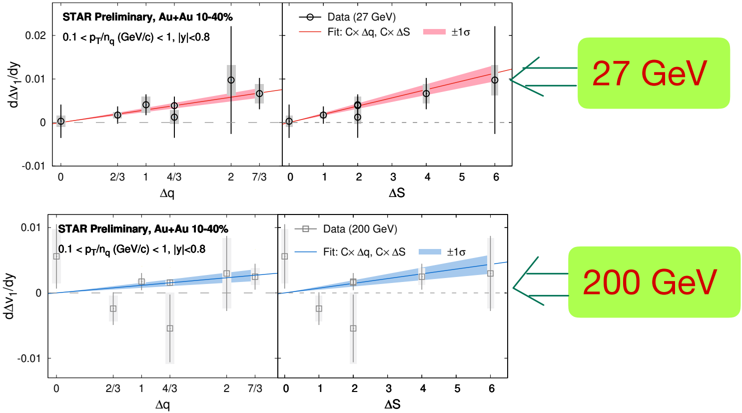
- v_1 (y) for multi-strange hadrons - First measurement!
- Large v_1 for Ω baryons - the statistical uncertainties are large

Splitting (Δv_1) at 3 different Δq and ΔS (27 GeV)



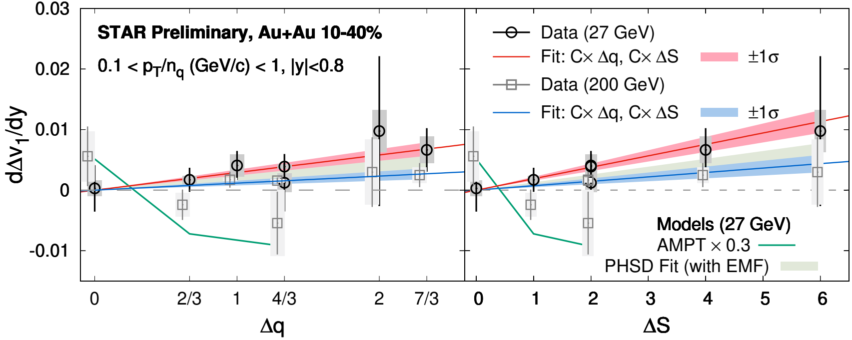
- Δv_1 for same mass, different charge and strangeness
- Δv_1 increases at larger y for $\Delta q \neq 0$
- Δv_1 also increases with p_T/n_q when $\Delta q \neq 0$
- AMPT (Phys. Rev. C 100, 054903 (2019)) has opposite trend for $\Delta q \neq 0$ - No EM-Field is implemented in AMPT

Δv_1-slope - splitting: hints of QED and/or QCD effect



- $d\Delta v_1/dy$ increases with increasing Δq and ΔS at 27 GeV
- Δq and ΔS are correlated (see Table at page-13)
- For 27 GeV, slope $= 0.002905 \pm 0.000481$ (with Δq) and 0.0018844 ± 0.000308 (with ΔS); $> 5\sigma$ effect
- For 200 GeV, slope $= 0.001159 \pm 0.00038$ (with Δq) and 0.00072 ± 0.000241 (with ΔS); $> 2.5\sigma$ effect
- $d\Delta v_1/dy$-slope is less for 200 GeV than 27 GeV

Δv_1-slope - splitting: Model comparison



- AMPT can not explain the data (Phys. Rev. C 100, 054903 (2019))
- PHSD(+EM-Field) can describe the data within the uncertainties

Summary

- First measurements of v_1 of multi-strange baryons - Ξ and Ω
- Measured charge (Δq) and strangeness (ΔS) dependent splitting, Δv_1, at BES-II
- Δv_1-slope ($d\Delta v_1/dy$) increases as Δq and ΔS increase at 27 GeV
- PHSD+EM-Field calculations can describe data within uncertainties
  - Hints of EM-Field effect in the splitting
- Net strangeness is also an important key factor for Δv_1-slope

THANK YOU