Electric charge and strangeness dependent splitting of the rapidity-odd directed flow in Au+Au collisions

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Directed flow ($\nu_1$) and splitting ($\Delta \nu_1$)

- First harmonic coefficient of Fourier decomposition of particle azimuthal distribution, $\nu_1$ - Directed Flow

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

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

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

- What drives the splitting - Initial EM-Field or QCD-driven effect?

- Measure splitting with charge ($\Delta q$) and strangeness ($\Delta S$)
EM-Field driven splitting ($\Delta v_1$) - Faraday and Hall effect?

- Beam direction: $\hat{z}$ and Impact parameter: $\hat{x}$ => Reaction Plane: $xz$
- Colliding nuclei produce B-field, $\perp$ to RP (approx) => B along $\hat{y}$
- Time varying $\vec{B}$ induces $\vec{E}$ field => Faraday effect
- Medium expands longitudinally ($\vec{u} \perp \vec{B}$) - Lorentz force pushes +ve and -ve charged particles in opposite directions => Hall effect
EM-Field driven splitting ($\Delta v_1$)?

- Faraday and Hall are competing effects - Net effect affects $v_1$
- $v_1$ for +ve particles shown (when Faraday > Hall)

**Multi-strange and the splitting ($\Delta v_1$)**

- Enhanced strange quarks production and identity retains during hadronization $\Rightarrow$ multiply multi-strange baryons ($\Xi$ and $\Omega$)
- Low scattering cross section and early thermal freeze-out - good probe of early stage of the collisions
- Multi-strange $v_1$ might be important for strangeness related splitting
Towards measurements: STAR detector at BES-II

- TPC+TOF for PID: TPC measures $-\frac{dE}{dx}$ 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 ($\Delta v_1$): Choice of particles?

1. Measurements with heavy flavors?
   - Measurements of HFs are challenging
   - Less abundantly produced - suffer large uncertainties
   - Absence of HFT in STAR BES-II and low production rate - HF measurements are difficult

2. Measurements with light hadrons?
   - Light hadrons produced in abundance - precise measurements
   - $\Delta v_1$ 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 $\Rightarrow$ $\Delta v_1$ becomes difficult to interpret
   - Avoiding transported quarks $\Rightarrow$ Splitting can be measured with light hadrons
Splitting ($\Delta v_1$): Our Approach

- Use only produced particles, $K^-$, $\bar{p}$, $\bar{\Lambda}$, $\phi$, $\Xi^+$, $\Omega^-$, and $\bar{\Omega}^+$
- 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):
  
  \[ v_1[K^-(\bar{u}s)] + v_1[\bar{\Lambda}(\bar{u}s\bar{d})] = v_1[\bar{p}(\bar{u}\bar{u}\bar{d})] + v_1[\phi(s\bar{s})] \]  
  \[ v_1[\bar{K}^-(\bar{u}s)] + v_1[\bar{\Xi}^+(\bar{d}s\bar{s})] = v_1[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] + v_1[\phi(s\bar{s})] \]  


\[ \Omega^- (sss) \quad \bar{\Omega}^+ (\bar{s}\bar{s}\bar{s}) \]
Splitting ($\Delta v_1$): Our Approach

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

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

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

- With produced particles, $K^-$, $\bar{p}$, $\bar{\Lambda}$, $\phi$, $\bar{\Xi}^+$, $\Omega^-$ and $\bar{\Omega}^+$ and make combinations - having same quark mass but different $\Delta q$ and $\Delta S$
Rearranging the $\Delta \nu_1$ in $\Delta q$ and $\Delta S$

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

<table>
<thead>
<tr>
<th>Index</th>
<th>Quark Mass</th>
<th>Charge</th>
<th>Strangeness</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\Delta m = 0$</td>
<td>$\Delta q = 0$</td>
<td>$\Delta S = 0$</td>
<td>$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^-(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$</td>
</tr>
<tr>
<td>2</td>
<td>$\Delta m \approx 0$</td>
<td>$\Delta q = \frac{2}{3}$</td>
<td>$\Delta S = 1$</td>
<td>$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{2}\phi(s\bar{s}) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$</td>
</tr>
<tr>
<td>3</td>
<td>$\Delta m \approx 0$</td>
<td>$\Delta q = 1$</td>
<td>$\Delta S = 2$</td>
<td>$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^-(ss\bar{s}) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$</td>
</tr>
<tr>
<td>4</td>
<td>$\Delta m \approx 0$</td>
<td>$\Delta q = \frac{4}{3}$</td>
<td>$\Delta S = 2$</td>
<td>$[\bar{\Xi}(\bar{d}\bar{s}\bar{s})] - [\phi(s\bar{s}) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$</td>
</tr>
<tr>
<td>5</td>
<td>$\Delta m \approx 0$</td>
<td>$\Delta q = \frac{4}{3}$</td>
<td>$\Delta S = 2$</td>
<td>$[\Xi^+ (\bar{d}\bar{s}\bar{s})] - [\phi(s\bar{s}) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$</td>
</tr>
<tr>
<td>6</td>
<td>$\Delta m = 0$</td>
<td>$\Delta q = 2$</td>
<td>$\Delta S = 6$</td>
<td>$[\bar{\Omega}^+(\bar{s}s\bar{s})] - [\Omega^- (ss\bar{s})]$</td>
</tr>
<tr>
<td>7</td>
<td>$\Delta m \approx 0$</td>
<td>$\Delta q = \frac{7}{3}$</td>
<td>$\Delta S = 4$</td>
<td>$[\Xi^+ (\bar{d}\bar{s}\bar{s})] - [K^- (\bar{u}s) + \frac{1}{3}\Omega^- (ss\bar{s})]$</td>
</tr>
</tbody>
</table>

- Combinations have same $\Delta m(\approx 0)$ different $\Delta q$ and $\Delta S$ - 7 combinations
- Degenerate combinations (Indices 4 and 5) - Good cross check
- Measure splitting with $\Delta q$ and $\Delta S$
$v_1$ vs $y$: $\Xi$ and $\Omega$ Baryons

- $\Xi(\Lambda \pi)$ and $\Omega(\Lambda K)$ baryons reconstructed by KF-Particle
- $v_1(y)$ for multi-strange hadrons - First measurement!
- Large $v_1$ for $\Omega$ baryons - the statistical uncertainties are large

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Splitting ($\Delta v_1$) at 3 different $\Delta q$ and $\Delta S$ (27 GeV)

- $\Delta v_1$ for same mass, different charge and strangeness
- $\Delta v_1$ increases at larger $y$ for $\Delta q \neq 0$
- $\Delta v_1$ 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
△ν₁-slope - splitting: hints of QED and/or QCD effect

▶ △ν₁-slope \( (d\Delta ν₁/dy) \) increases with increasing Δq and ΔS at 27 GeV

▶ Δq and ΔS are correlated (see Table at page-9)

▶ For 27 GeV, slope = 0.002905 ± 0.000481 (with Δq); > 5σ effect

▶ For 200 GeV, slope = 0.001159 ± 0.00038 (with Δq); > 2.5σ effect

▶ \( d\Delta ν₁/dy \)-slope is less for 200 GeV than 27 GeV

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**Δν₁-slope - splitting: Model comparison**

- **Data (27 GeV)**
- **Fit: C × Δq, C × ΔS ±1σ**
- **Data (200 GeV)**
- **Fit: C × Δq, C × ΔS ±1σ**

- **Models (27 GeV)**
- **AMPT × 0.3**
- **PHSD Fit (with EMF)**

- **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 - $\Xi$ and $\Omega$
- Measured charge ($\Delta q$) and strangeness ($\Delta S$) dependent splitting, $\Delta v_1$, at BES-II
- $\Delta v_1$-slope ($d\Delta v_1/dy$) increases as $\Delta q$ and $\Delta S$ 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 $\Delta v_1$-slope

THANK YOU