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Optimal Observables for the Chiral Magnetic Effect from Machine Learning

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Phys. Rev. C *letter* in press

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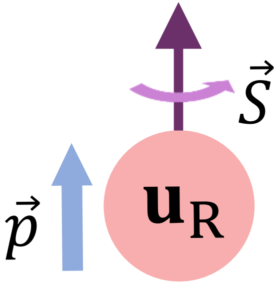
The Chiral Magnetic Effect

For right-handed particles positive charge:

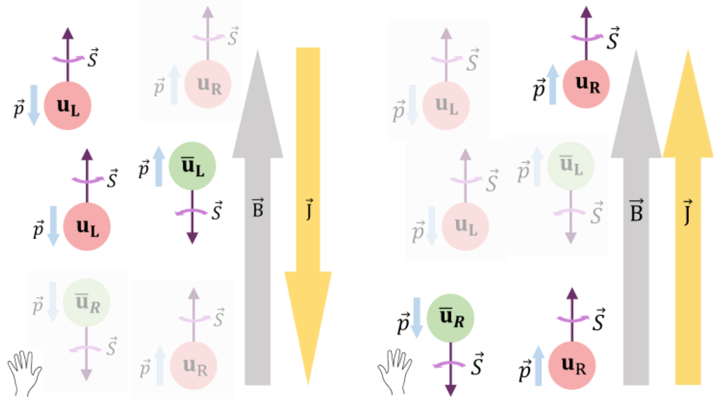
- $\vec{p}\,||\,\vec{S}\,||\,\vec{\mu}$
- $\text{Energy} = -\vec{\mu}\cdot\vec{B} \propto -\vec{p}\cdot\vec{B}$



lower energy if moving along B field direction

$$\vec{J} = \sigma_A \mu_5 \vec{B}$$

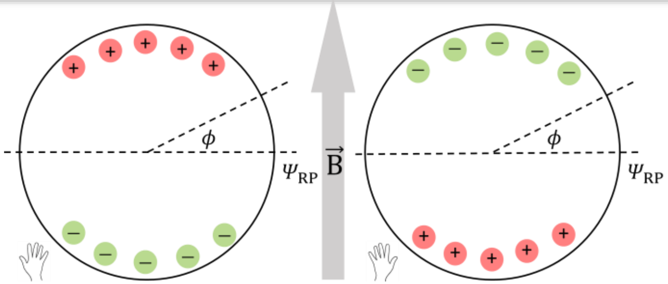
$$\mu_5 \sim \mu_R - \mu_L$$



[1] K. Fukushima, *et al.* Phys. Rev. D 78, 074033 (2008)
[2] D. E. Kharzeev, *et al.* Nucl. Phys. A 803, 227 (2008)

Conventional Observables

$$a_1 = \langle \sin(\phi^\alpha - \Psi_{RP}) \rangle$$



Case 1 $\boldsymbol{\mu_5 > 0}$
$a_1^+ \approx 1, a_1^- \approx -1$

Case 2 $\boldsymbol{\mu_5 < 0}$
$a_1^+ \approx -1, a_1^- \approx +1$

[3] S. A. Voloshin, Phys. Rev. C 70, 057901 (2004)

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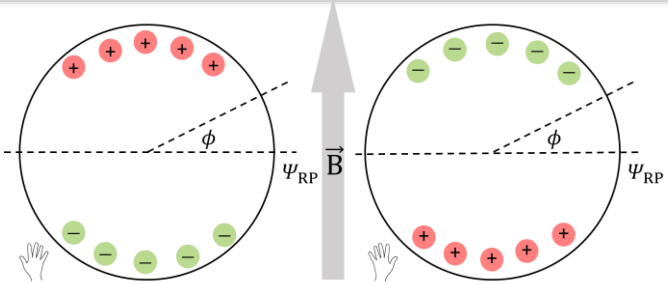
$$\langle a_1^+ \rangle = \langle a_1^- \rangle = 0$$



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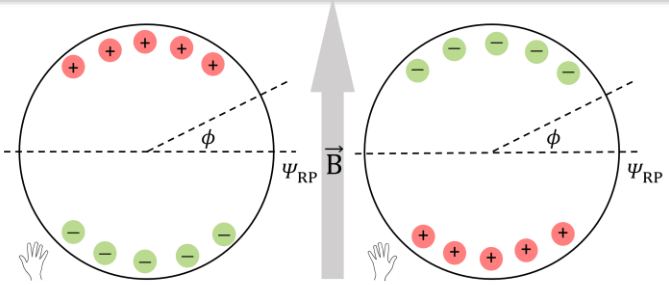
Conventional Observables

$$a_1 = \langle \sin(\phi^\alpha - \Psi_{RP}) \rangle$$

$$\langle a_1^+ \rangle = \langle a_1^- \rangle = 0$$

$$\gamma_\perp^{\alpha,\beta} = \langle \sin(\phi^\alpha - \Psi_{RP}) \sin(\phi^\beta - \Psi_{RP}) \rangle$$

$$\boldsymbol{\gamma_\perp^{os-ss}} \begin{cases} \gamma_\perp^{os} = \frac{1}{2}(\gamma_\perp^{+,-} + \gamma_\perp^{-,+}) \approx -1 \\ \gamma_\perp^{ss} = \frac{1}{2}(\gamma_\perp^{+,-} + \gamma_\perp^{-,+}) \approx +1 \end{cases}$$



Case 1 $\boldsymbol{\mu_5 > 0}$ | Case 2 $\boldsymbol{\mu_5 < 0}$

$a_1^+ \approx 1, a_1^- \approx -1$ | $a_1^+ \approx -1, a_1^- \approx +1$

$$\gamma_\perp^{+,-} = \gamma_\perp^{-,+} \approx -1$$

$$\gamma_\perp^{+,+} = \gamma_\perp^{-,-} \approx 1$$

[3] S. A. Voloshin, Phys. Rev. C 70, 057901 (2004)

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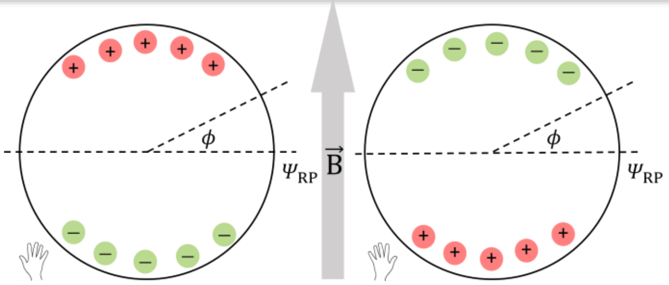

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$$\gamma_\perp^{+,-} = \gamma_\perp^{-,+} \approx -1$$

$$\gamma_\perp^{+,+} = \gamma_\perp^{-,-} \approx 1$$

Background: $\gamma_{||}^{\alpha,\beta} = \langle \cos(\phi^\alpha - \Psi_{RP}) \cos(\phi^\beta - \Psi_{RP}) \rangle$

$$\boldsymbol{\gamma = \gamma_{||} - \gamma_\perp = \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle}$$

$$\boldsymbol{\delta = \gamma_{||} + \gamma_\perp = \langle \cos(\phi_\alpha - \phi_\beta) \rangle}$$

$$\boldsymbol{\gamma^{os-ss}, \qquad \delta^{os-ss}}$$

[3] S. A. Voloshin, Phys. Rev. C 70, 057901 (2004)

The Core Challenge: Background Contamination

Substantial Background Effect

- Local charge conservation (**LCC**)
- Resonance decay
- Transverse momentum conservation
- ……
- Simulate the charge separation signal of CME[4,5]

Traditional Methods Failed

- Conventional observables: **cannot effectively disentangle** CME-induced charge separation from background[6].

[4] J. Zhao and F. Wang, Prog. Part. Nucl. Phys. 107, 200 (2019)
[5] D. E. Kharzeev, *et al*, Int. J. Mod. Phys. E 33, 2430007 (2024)
[6] S. Choudhury, *et al*. Chin. Phys. C 46, 014101 (2022)

Contents

Define Physical Parameters

- Harmonic coefficients

$$v_n^{(m)} \equiv \frac{\langle p_T^m \cos(n\,\varphi_n)\rangle}{\langle p_T^m\rangle}, \quad a_n^{(m)} \equiv \frac{\langle p_T^m \sin(n\,\varphi_n)\rangle}{\langle p_T^m\rangle}$$

- Separate them into P-odd and P-even observables

$$\{o\} \equiv \left\{\left(a_{2j-1,c}^{(m)}, v_{2j-1,c}^{(m)}\right)\right\}_{\substack{j\in\mathbb{N},\ 0<j\leq N/2,\\ m\in\{0,\ldots,M\},\\ c\in\{\pi^+,\pi^-\}}}$$

$$\{e\} \equiv \left\{\frac{1}{N_{\mathrm{ch}}}\right\} \bigcup \left\{\left(a_{2j,c}^{(m)}, v_{2j,c}^{(m)}\right)\right\}_{\substack{j\in\mathbb{N},\ 0<j\leq N/2,\\ m\in\{0,\ldots,M\},\\ c\in\{\pi^+,\pi^-\}}}$$

Construct & Optimize Observables

- Potential CME observable

$$O = \sum_{j} X_j^{(\mathrm{L})}\, e_j + \sum_{j,j'} X_{j,j'}^{(\mathrm{E})}\, e_j\, e_{j'} + \sum_{j,j'} X_{j,j'}^{(\mathrm{O})}\, o_j\, o_{j'}$$

- **Anomalous Viscous Fluid Dynamics**(AVFD)[7,8] , generate data:

$$O_{\mathrm{C,L}}\; O_{\mathrm{C},\cancel{\mathrm{L}}},\; O_{\cancel{\mathrm{C}},\mathrm{L}},\; O_{\cancel{\mathrm{C}},\cancel{\mathrm{L}}}$$

- Loss function

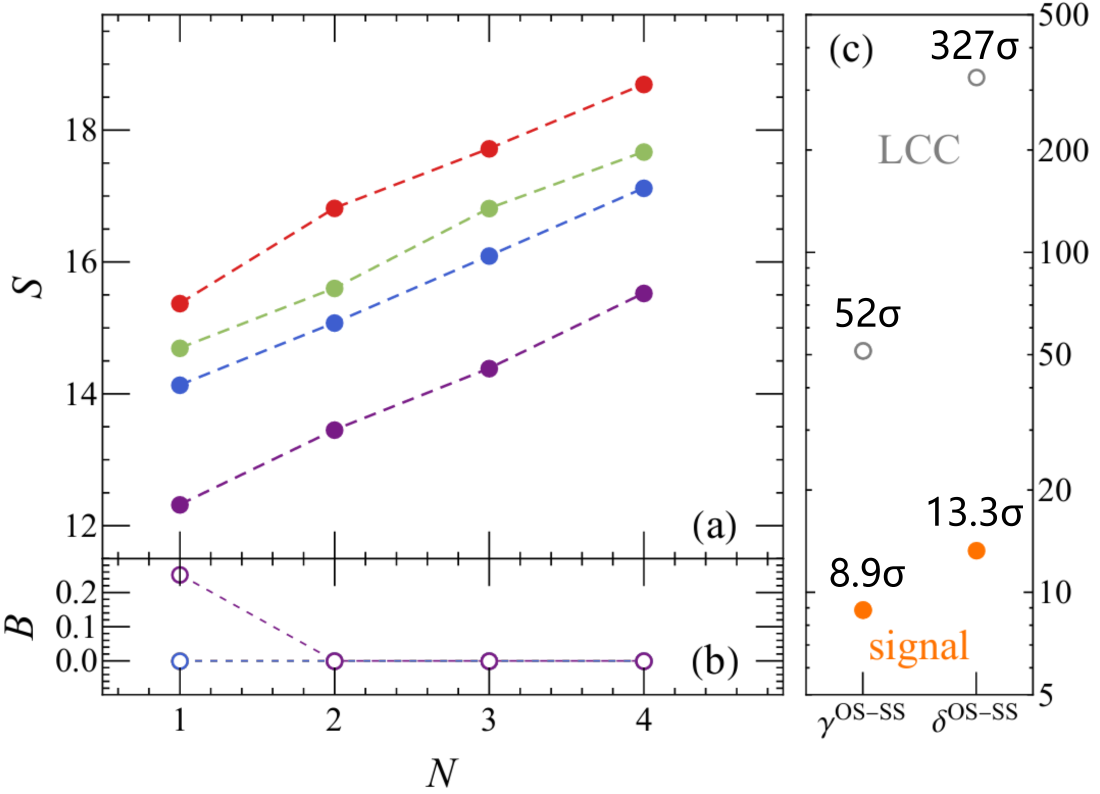
$$\mathcal{L} = \lambda \underbrace{\left(\frac{(O_{\mathrm{C,L}} - O_{\mathrm{C},\cancel{\mathrm{L}}})^2}{\Delta^2_{\mathrm{C,L}} + \Delta^2_{\mathrm{C},\cancel{\mathrm{L}}}} + \frac{(O_{\cancel{\mathrm{C}},\mathrm{L}} - O_{\cancel{\mathrm{C}},\cancel{\mathrm{L}}})^2}{\Delta^2_{\cancel{\mathrm{C}},\mathrm{L}} + \Delta^2_{\cancel{\mathrm{C}},\cancel{\mathrm{L}}}} \right)}_{\text{Minimize the background}} - \underbrace{\left(\frac{(O_{\mathrm{C,L}} - O_{\cancel{\mathrm{C}},\mathrm{L}})^2}{\Delta^2_{\mathrm{C,L}} + \Delta^2_{\cancel{\mathrm{C}},\mathrm{L}}} + \frac{(O_{\mathrm{C},\cancel{\mathrm{L}}} - O_{\cancel{\mathrm{C}},\cancel{\mathrm{L}}})^2}{\Delta^2_{\mathrm{C},\cancel{\mathrm{L}}} + \Delta^2_{\cancel{\mathrm{C}},\cancel{\mathrm{L}}}} \right)}_{\text{Maximize the CME signal.}}$$

- Iterate the parameters $\left\{X_j^{(\mathrm{L})}, X_{j,j'}^{(\mathrm{E})}, X_{j,j'}^{(\mathrm{O})}\right\}$, using the **gradient descent** method and minimize loss function

[7] S. Shi, Y. Jiang, E. Lilleskov, and J. Liao, Annals Phys. 394, 50 (2018)
[8] Y. Jiang, S. Shi, Y. Yin, and J. Liao, Chin. Phys. C 42, 011001 (2018)

Contents

Background Suppression & Sensitivity



- sig./bkg. to statistics ratio

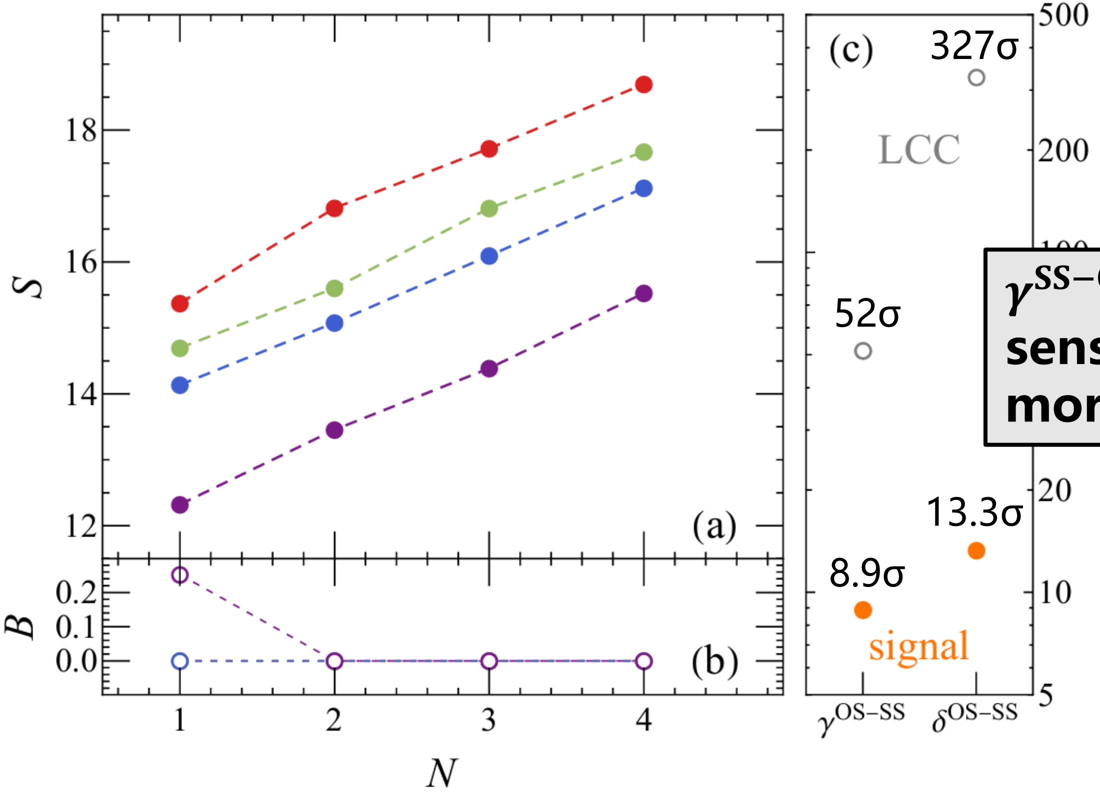
$$S = \frac{1}{2}\left(\frac{O_{\mathrm{C,L}} - O_{\not{\mathrm{C}},\mathrm{L}}}{\sqrt{\frac{\Delta^2_{\mathrm{C,L}}+\Delta^2_{\not{\mathrm{C}},\mathrm{L}}}{N_{\mathrm{ev}}}}} + \frac{O_{\mathrm{C},\not{\mathrm{L}}} - O_{\not{\mathrm{C}},\not{\mathrm{L}}}}{\sqrt{\frac{\Delta^2_{\mathrm{C},\not{\mathrm{L}}}+\Delta^2_{\not{\mathrm{C}},\not{\mathrm{L}}}}{N_{\mathrm{ev}}}}}\right)$$

$$B = \frac{1}{2}\left(\frac{O_{\mathrm{C,L}} - O_{\mathrm{C},\not{\mathrm{L}}}}{\sqrt{\frac{(\Delta^2_{\mathrm{C,L}}+\Delta^2_{\mathrm{C},\not{\mathrm{L}}})}{N_{\mathrm{ev}}}}} + \frac{O_{\not{\mathrm{C}},\mathrm{L}} - O_{\not{\mathrm{C}},\not{\mathrm{L}}}}{\sqrt{\frac{(\Delta^2_{\not{\mathrm{C}},\mathrm{L}}+\Delta^2_{\not{\mathrm{C}},\not{\mathrm{L}}})}{N_{\mathrm{ev}}}}}\right)$$

harmonic order N=1-4,

p_T weight M=0-3

Background Suppression & Sensitivity



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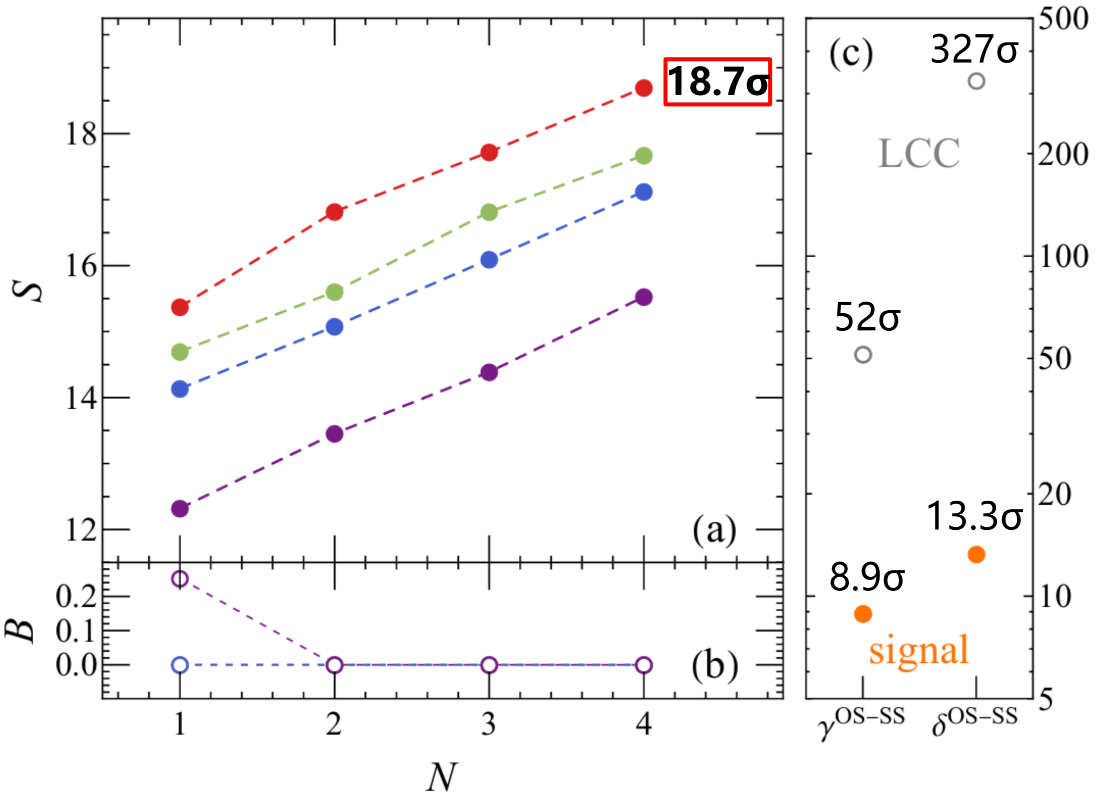
$$S = \frac{1}{2}\left(\frac{O_{\mathrm{C,L}} - O_{\bar{\mathrm{C}},\mathrm{L}}}{\sqrt{\frac{\Delta^2_{\mathrm{C,L}}+\Delta^2_{\bar{\mathrm{C}},\mathrm{L}}}{N_{\mathrm{ev}}}}} + \frac{O_{\mathrm{C},\bar{\mathrm{L}}} - O_{\bar{\mathrm{C}},\bar{\mathrm{L}}}}{\sqrt{\frac{\Delta^2_{\mathrm{C},\bar{\mathrm{L}}}+\Delta^2_{\bar{\mathrm{C}},\bar{\mathrm{L}}}}{N_{\mathrm{ev}}}}}\right)$$

γ^{SS-OS} and δ^{SS-OS} :
sensitive to CME signal, but more sensitive to LCC background.

harmonic order N=1-4,

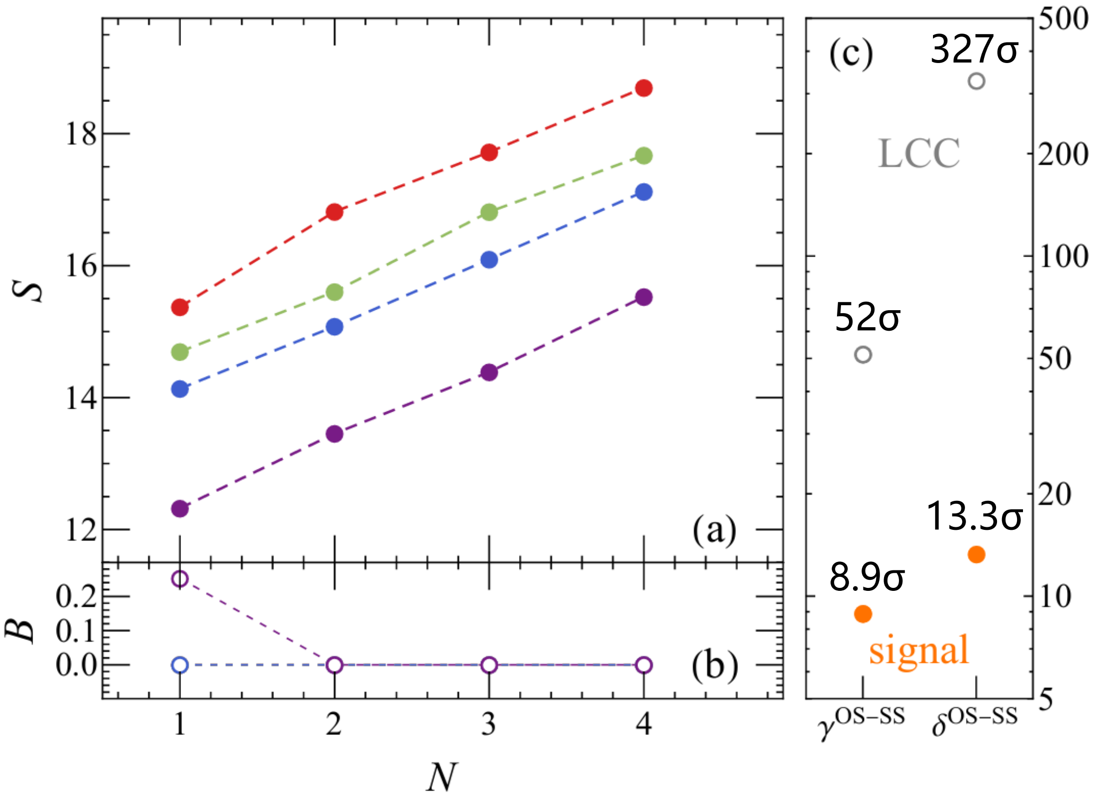
p_T weight M=0-3

Background Suppression & Sensitivity



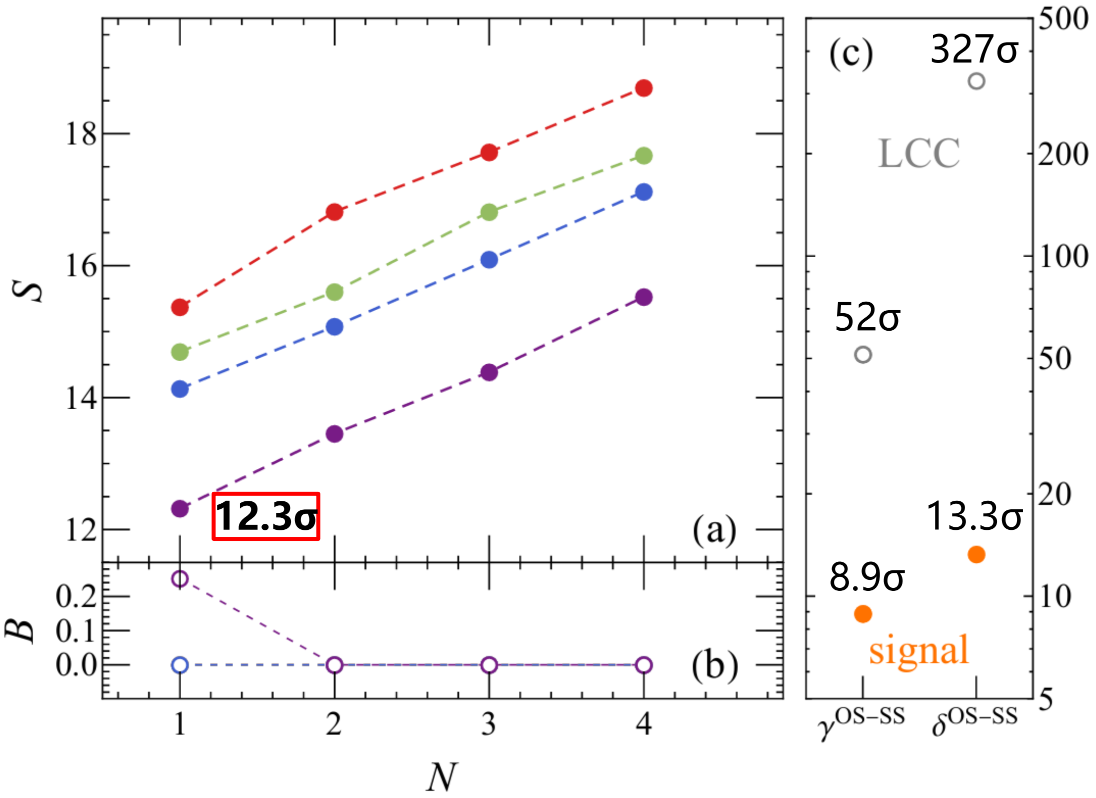
- ➢ **Dramatically Improved Sensitivity.**

Background Suppression & Sensitivity



- ➢ **Dramatically Improved Sensitivity.**
- ➢ **Complete Background Suppression.**

Background Suppression & Sensitivity



- ➢ **Dramatically Improved Sensitivity.**
- ➢ **Complete Background Suppression.**
- ➢ **Effective Even at Low Complexity.**

Contents

Summary

- **Novel machine learning method, construct optimized observables for detecting the CME**
  - higher sensitivity
  - near-zero background
  - systematic framework for enhanced signal

Outlook

- Further Improve Performance: incorporate additional parameters
  - Rapidity, particle species, centrality ……

- Directly applicable to RHIC/LHC experiments.
  - Validate "Ideal O_{CME}" : use "ultra-high-energy collisions (CME negligible) + Ru+Ru vs. Zr+Zr comparisons"
  - Standard:

$$O_{CME}^{Ru+Ru} \approx 1.2 O_{CME}^{Zr+Zr}$$

Thank you !

AVFD parameters

Framework	Anomalous Viscous Fluid Dynamics (AVFD)	CME Parameter	0.05
Collision System	Au+Au Collisions	LCC Parameter	0.33
Center-of-Mass Energy	$\sqrt{s_{NN}} = 200GeV$	Magnetic Field Lifetime	0.6 fm
Centrality Range	30–40%	Scanned Parameters	Harmonic order N=1–4; p_T weight M=0–3
Number of Simulated Events	~3×10⁶		

$$O_{\mathrm{C,L}} = \langle O \rangle^{\mathrm{CME-on}}_{\mathrm{LCC-on}}, \quad \Delta_{\mathrm{C,L}} = \left(\langle O^2 \rangle^{\mathrm{CME-on}}_{\mathrm{LCC-on}} - O^2_{\mathrm{C,L}} \right)^{\frac{1}{2}}$$