相对论重离子碰撞中的手征磁效应回顾

清华大学 施舒哲

清華大學
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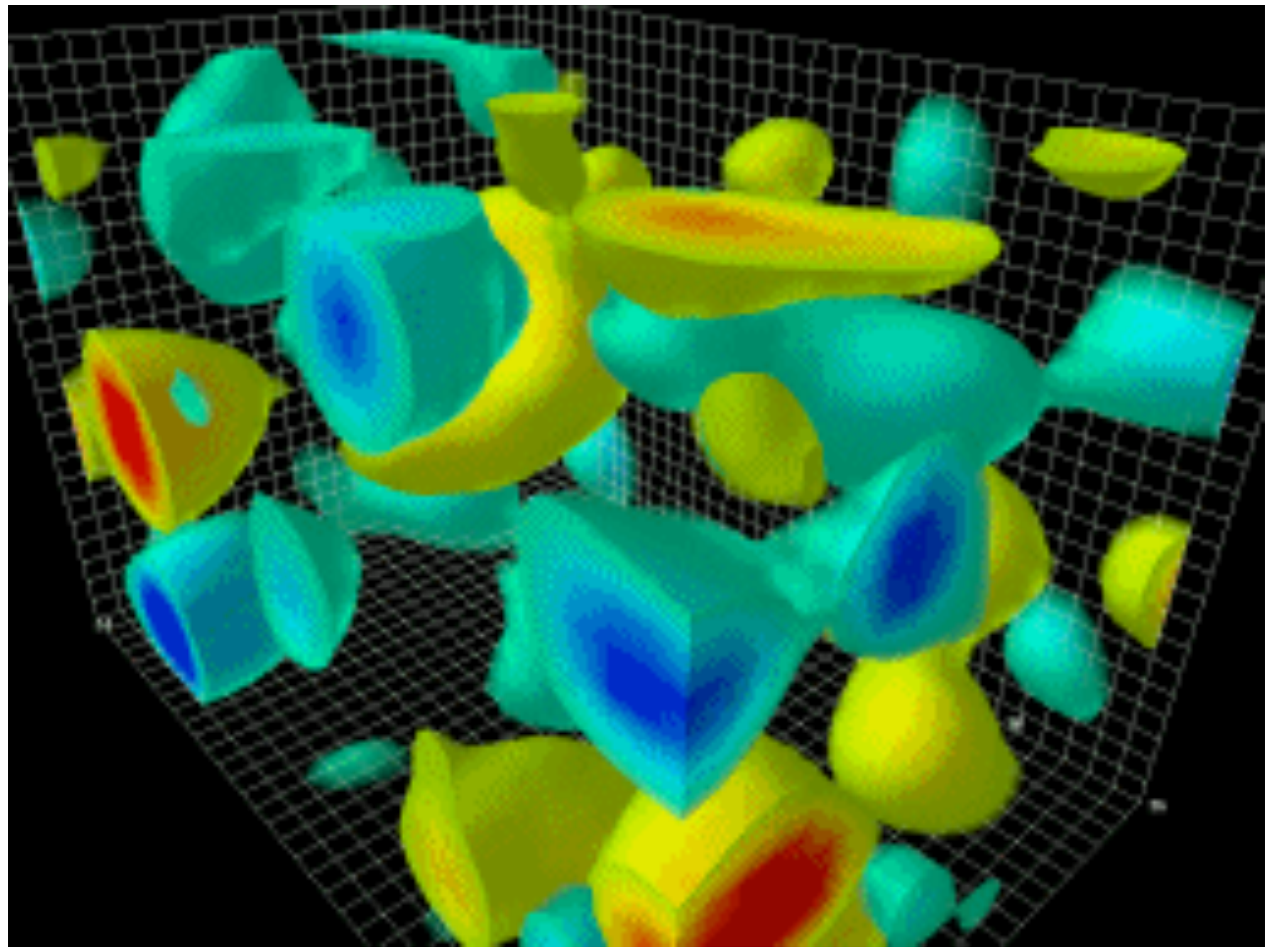
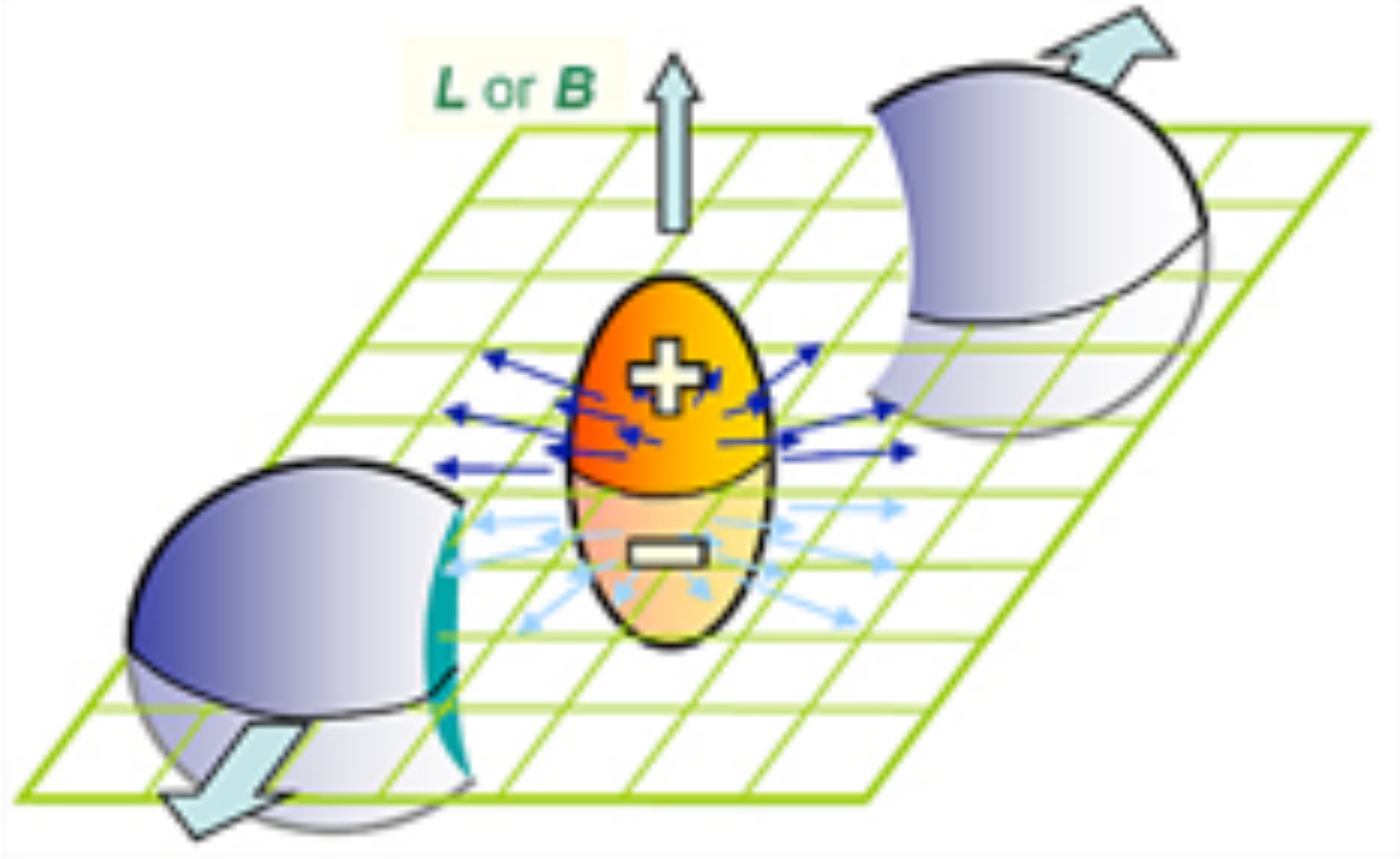
Chirality in QCD

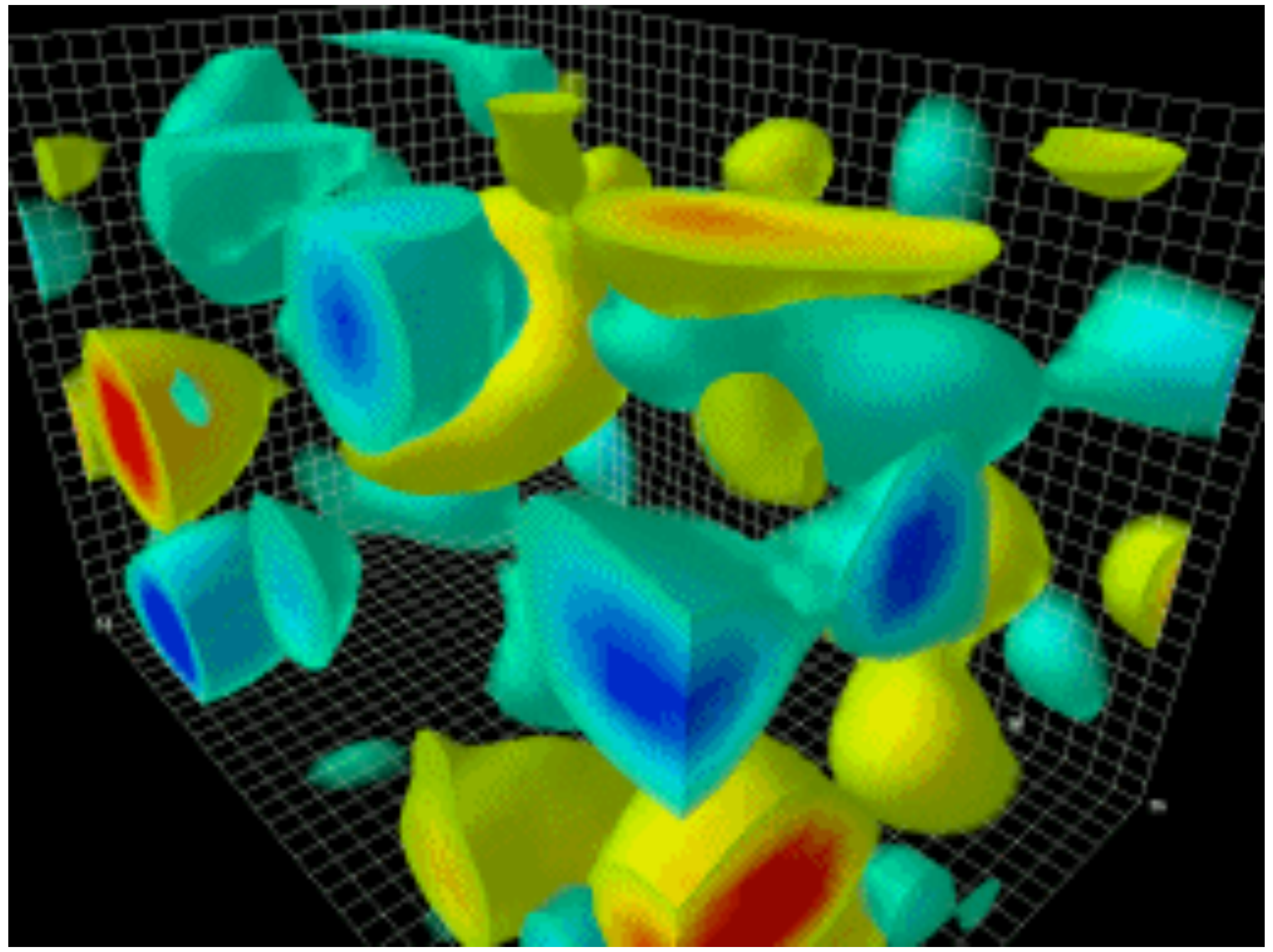


Topology
⊗ Chiral
⊗ Anomaly

$$Q_W = \frac{g^2}{32\pi^2} \int d^4x \, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

Chiral Magnetic Effect





Magnetic Field

B ~ γ Z Q b / R^3

(10^{15} T @ 200 GeV Au-Au)

$\otimes$

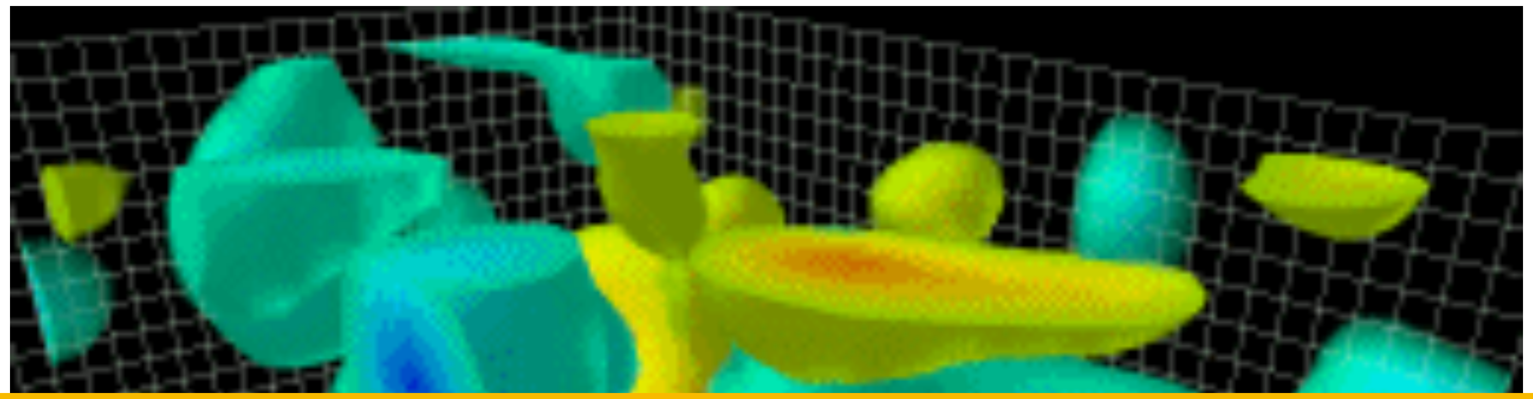
Topology

$\otimes$ Chiral

$\otimes$ Anomaly

$$Q_w = \frac{g^2}{32\pi^2} \int d^4x \, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

Chiral Magnetic Effect



The Chiral Magnetic Effect

Kenji Fukushima, Dmitri Kharzeev, H.Warringa, PhysRevD.78.074033

recent reviews:

Chiral magnetic effect reveals the topology of gauge fields in heavy-ion collisions

Dmitri Kharzeev, Jinfeng Liao, Nature Review Physics 3 (2021) 1, 55-63

Chapter in QGP6

Dmitri Kharzeev, Jinfeng Liao, Prithwish Tribedy, 2405.05427

B ~ γ Z Q b / R^3

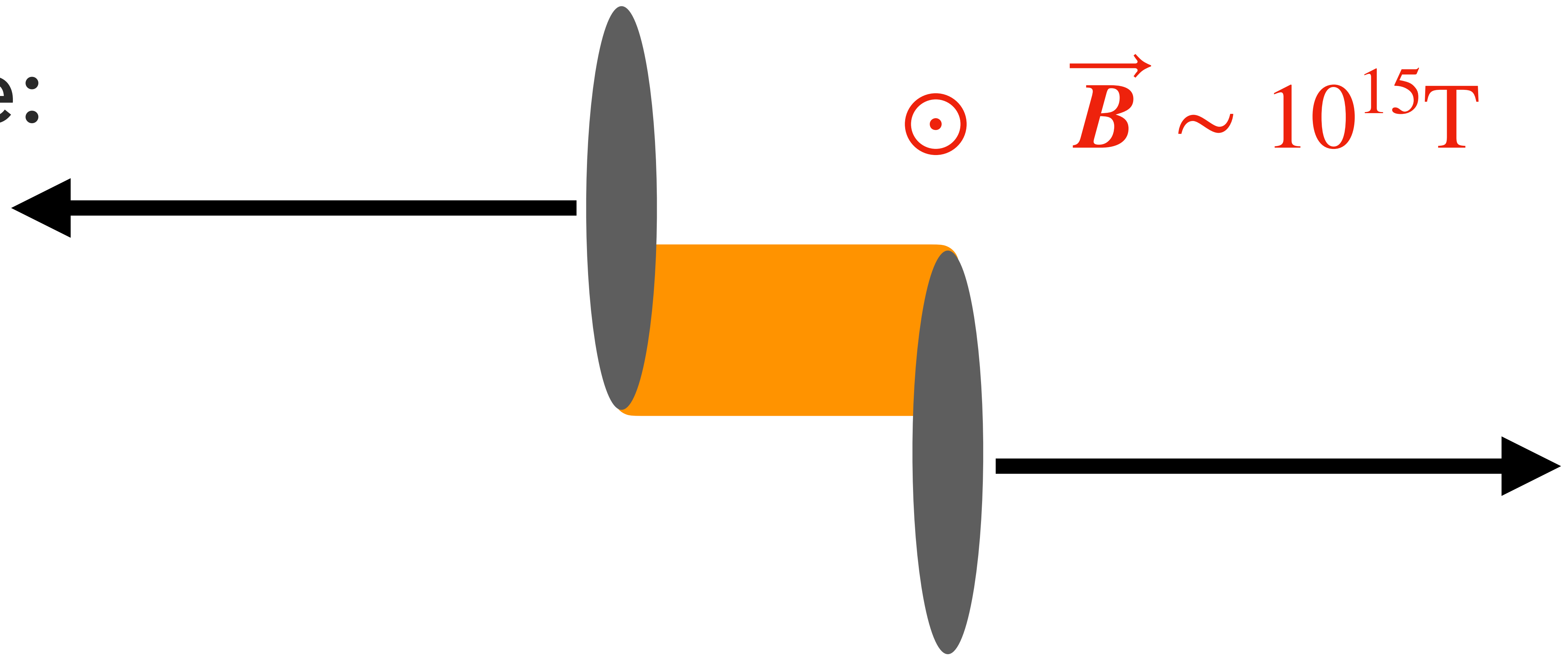
(10^{15} T @ 200 GeV Au-Au)

⊗ Anomaly

$$Q_w = \frac{g^2}{32\pi^2}\int d^4x\, F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$

Chiral Magnetic Effect

For right-handed particles w/ positive charge:



1. $\vec{p} \parallel \vec{S} \parallel \vec{\mu}$
2. $\mathrm{Energy} = -\vec{\mu} \cdot \vec{B} \propto -\vec{p} \cdot \vec{B}$

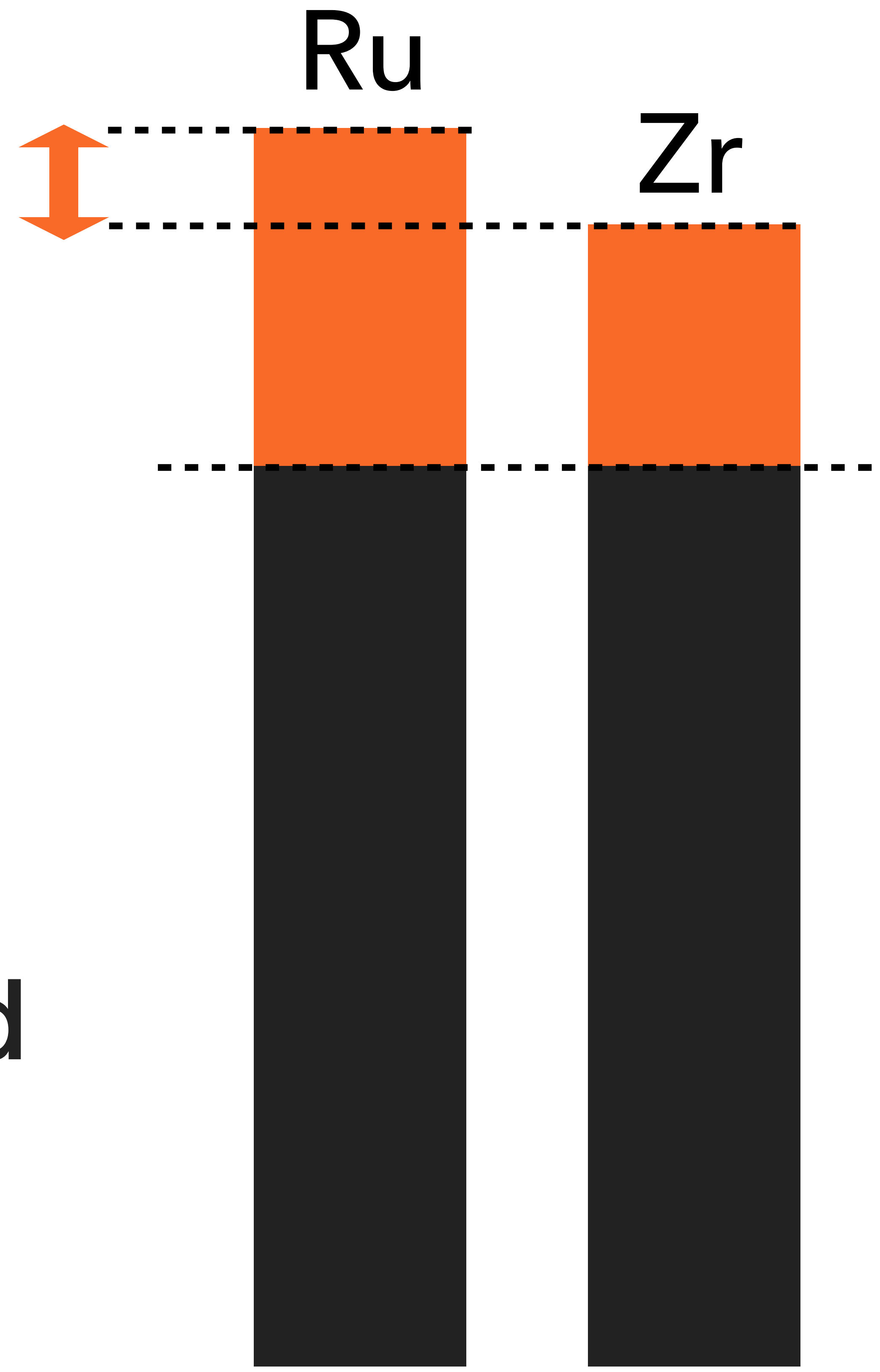
$\Rightarrow$ lower energy if moving along B field direction

$$\boxed{\vec{J} = \sigma_A \mu_A \vec{B}}$$

expectation before the isobar collisions:

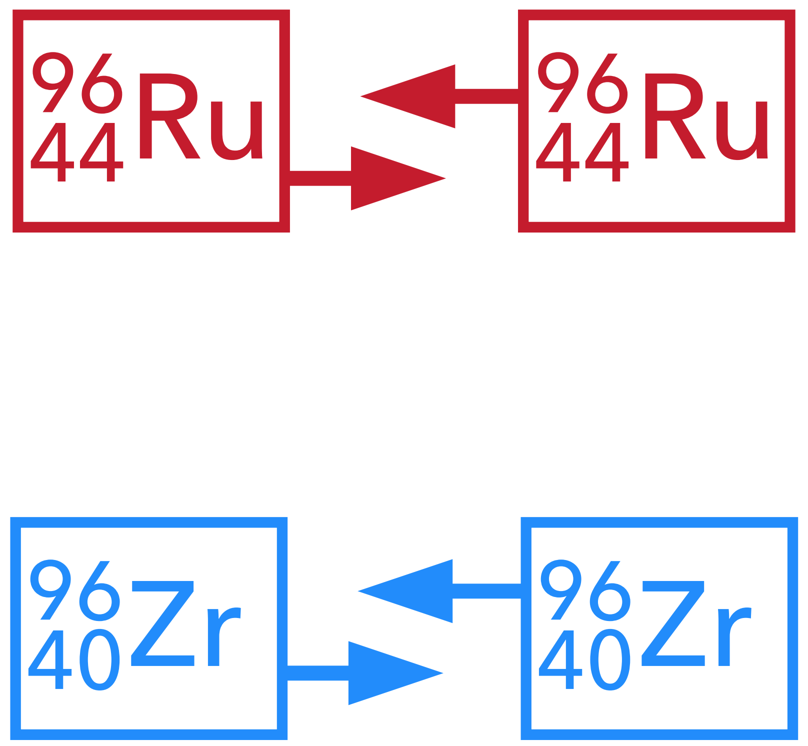
Correlator[Ru] > *Correlator*[Zr] → **CME**

Correlator[Ru] = *Correlator*[Zr] → **no CME**



Different Proton # → Different CME Signal

Same Baryon # → Same Background

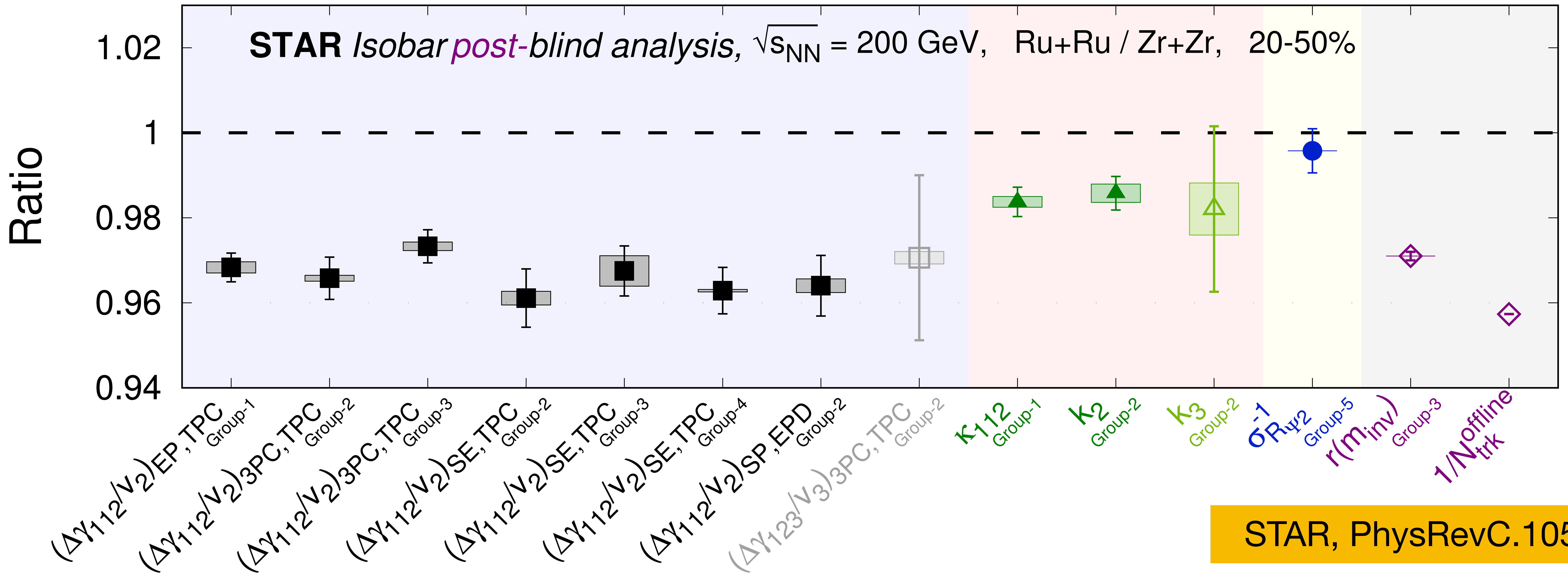


expectation before the isobar collisions:

Correlator[Ru] > *Correlator*[Zr] → **CME**

Correlator[Ru] = *Correlator*[Zr] → **no CME**

measurement: *Correlator*[Ru] < *Correlator*[Zr]



STAR, PhysRevC.105.014901

expectation before the isobar collisions:

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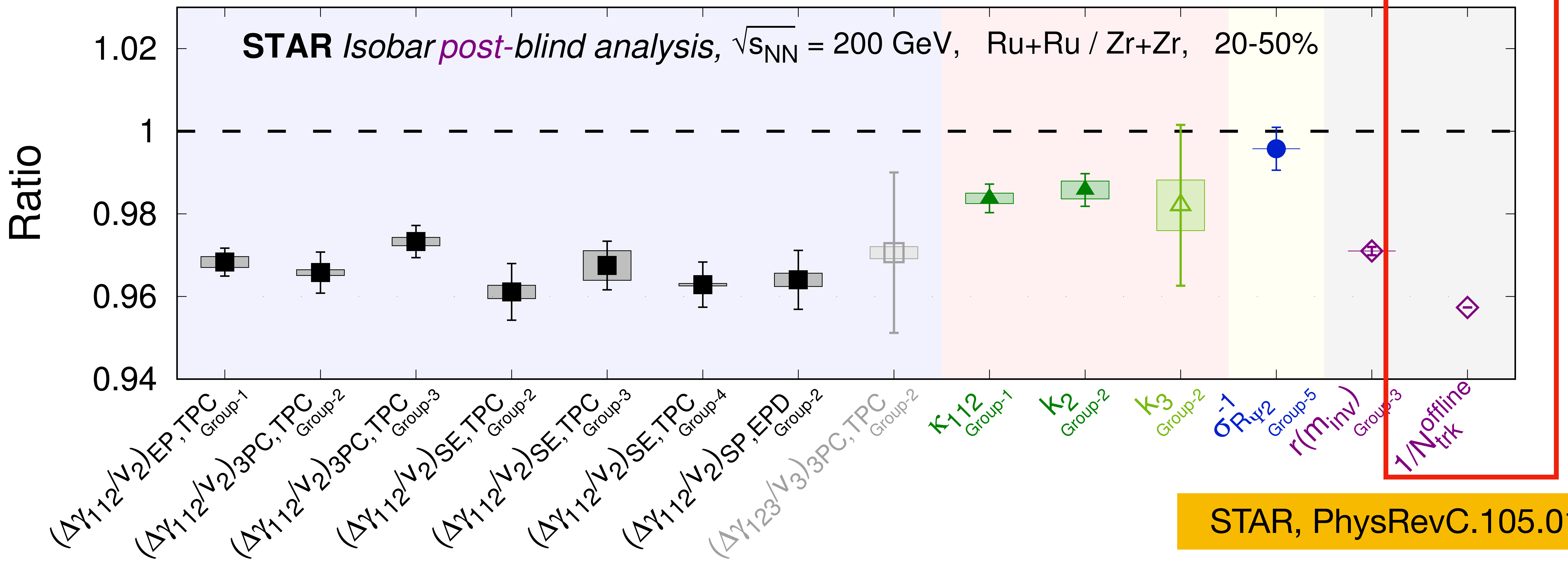

STAR, PhysRevC.105.014901

measuring CME in isobar

expectation before the isobar collisions:

Correlator[Ru] > *Correlator*[Zr] → **CME**

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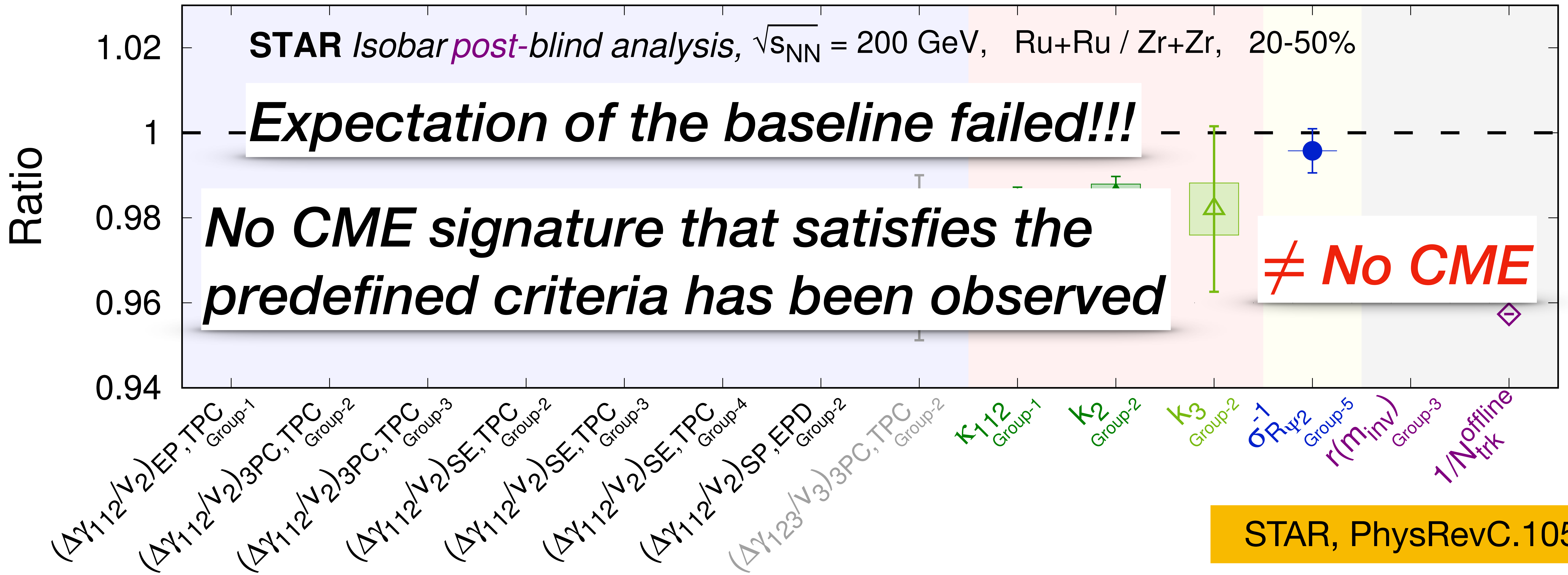
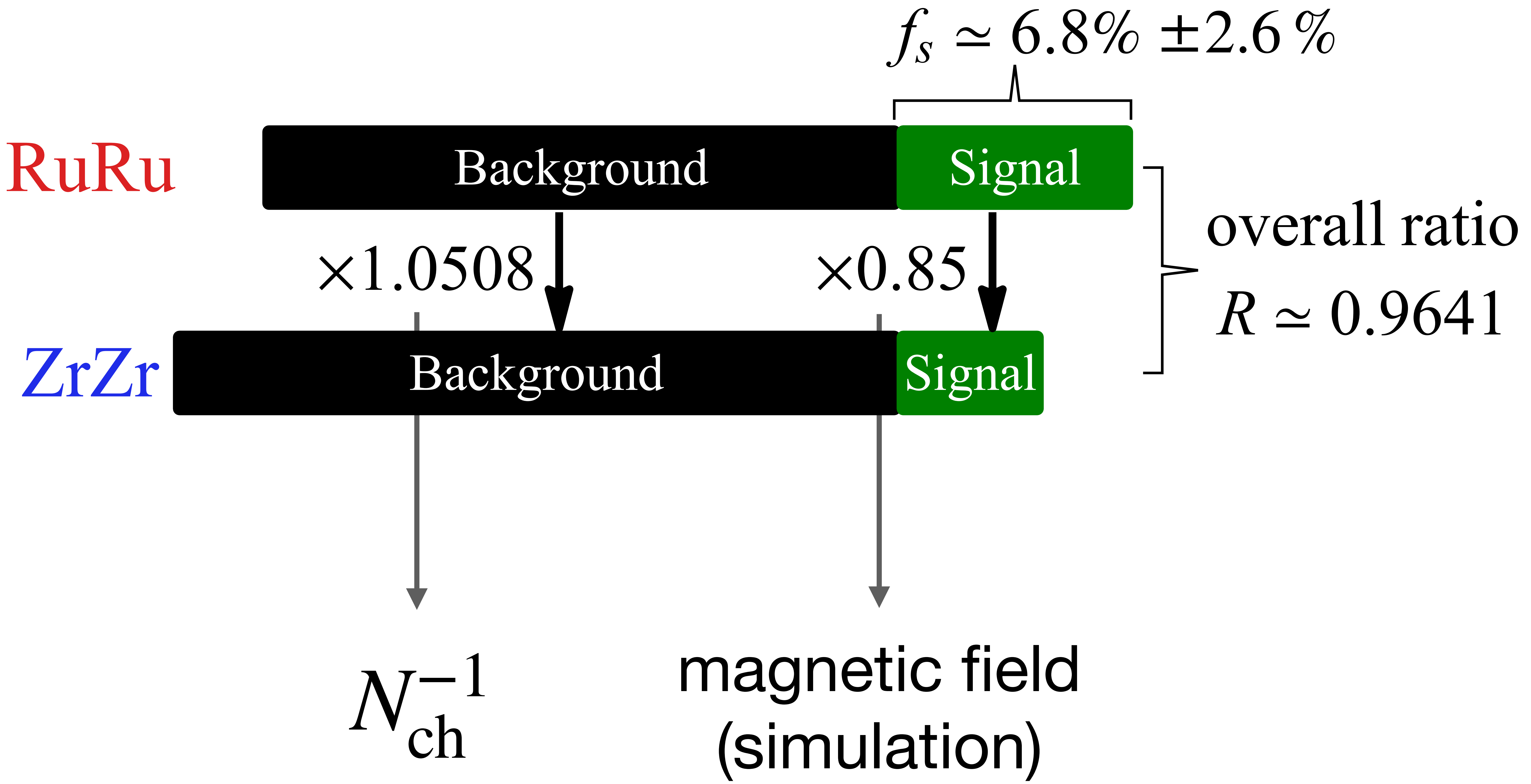


STAR, PhysRevC.105.014901

possible CME signal in isobar?



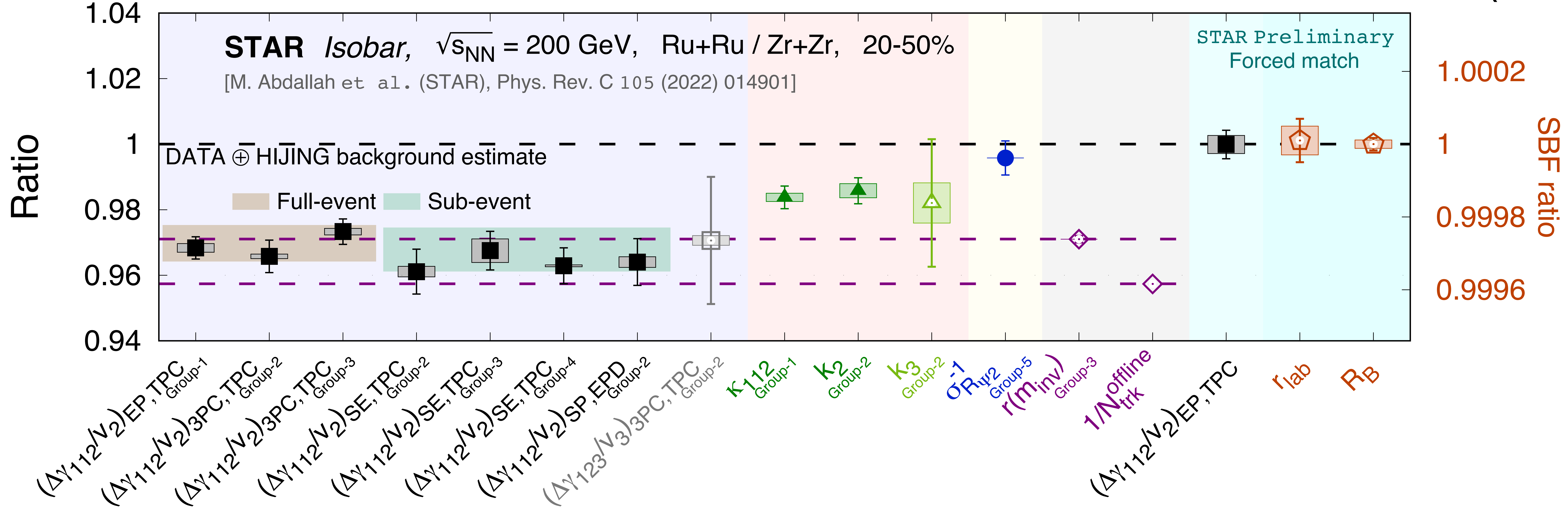
Dmitri Kharzeev, Jinfeng Liao, SS, PhyRevC.106.L051903

possible CME signal in isobar?

updates in experiment: controlling background

Tang, QM2023

EPJ Web of Conferences 296, 01024 (2024)



N_{ch}^{-1}

magnetic field (simulation)

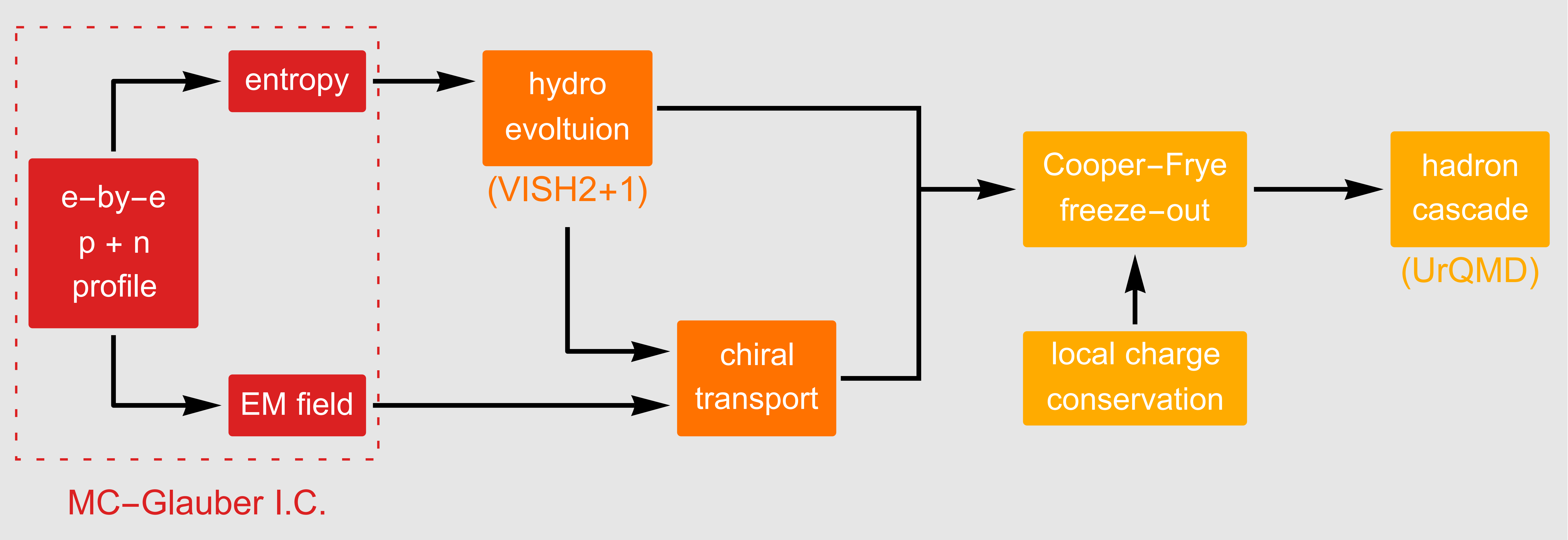
Dmitri Kharzeev, Jinfeng Liao, SS, PhyRevC.106.L051903

challenges in accurate, first-principle calculation

$$\vec{J} = \sigma_A \, \mu_A \, \vec{B}$$

μ_A → axial charge

$\vec{B}$ → magnetic field: life time $\sim R/\gamma_{\text{beam}}$ + medium feedback



AVFD model: Jinfeng Liao, SS + Hou, Jiang, Lilleskov, Yin, Zhang, ChinPhysC.42.011001, Annals Phys.394.50, PhysRevLett.125.242301

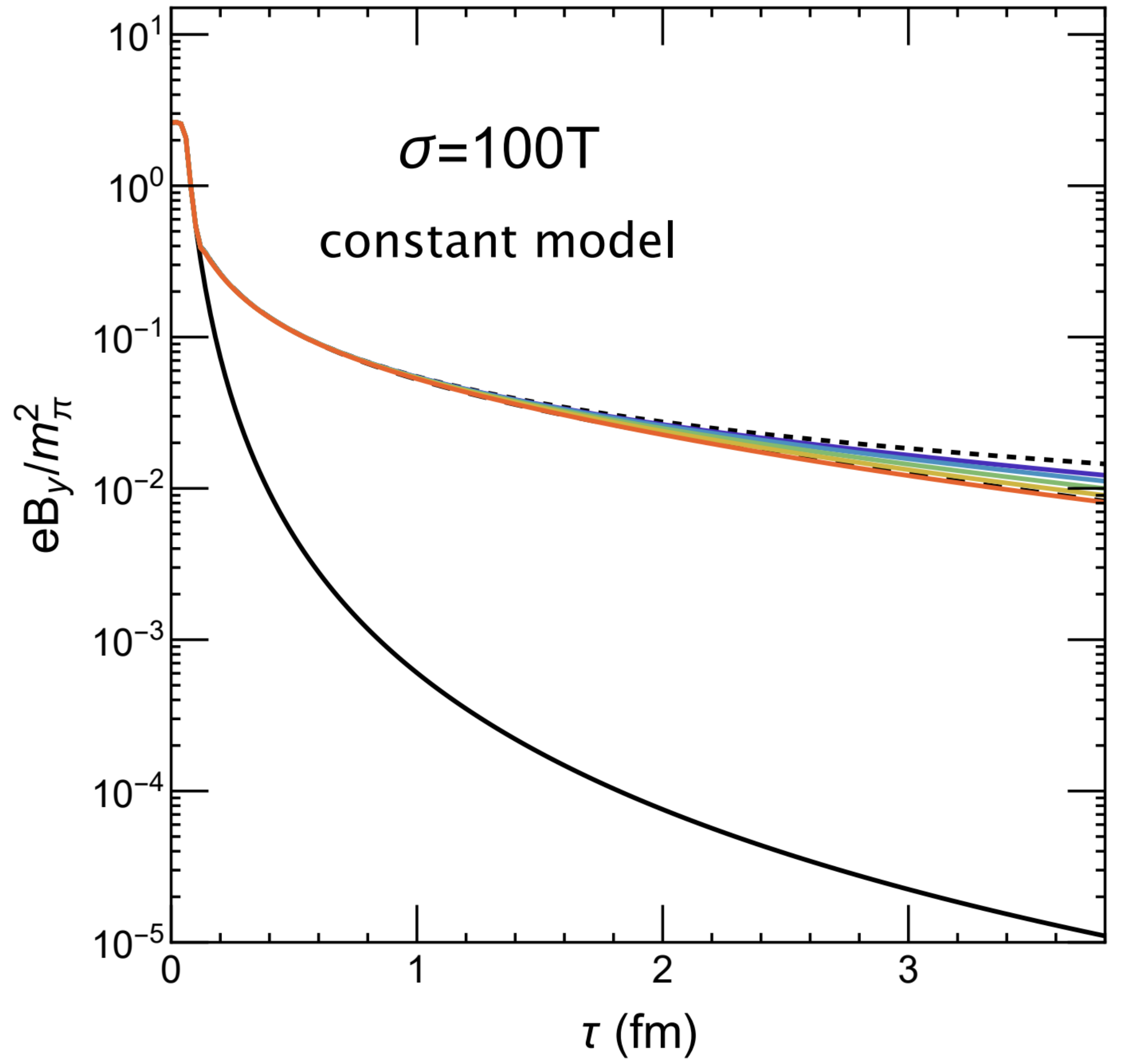
challenges in accurate, first-principle calculation

$$\vec{J} = \sigma_A \, \mu_A \, \vec{B}$$

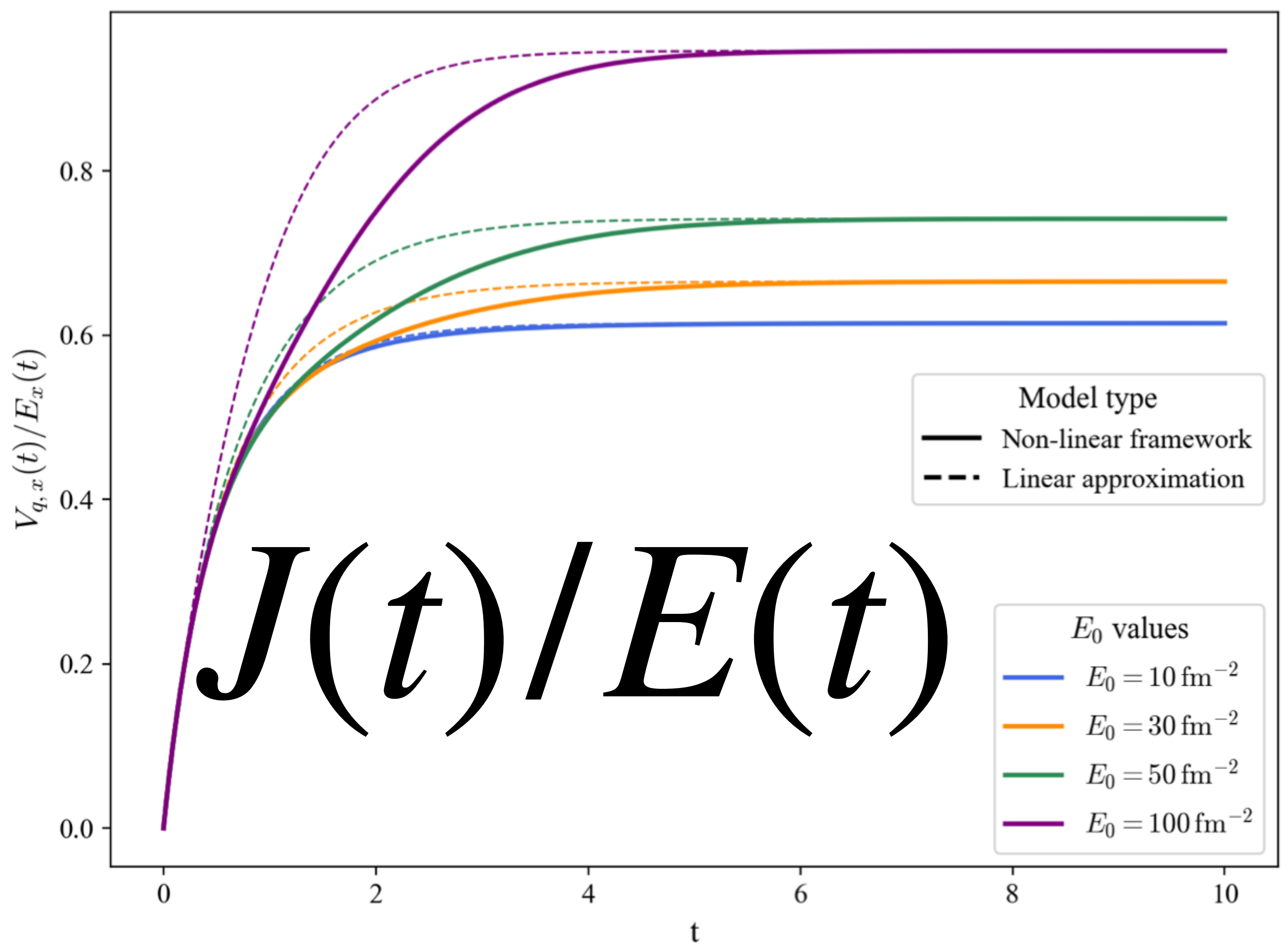
axial charge

magnetic field: life time $\sim R/\gamma_{\text{beam}}$ + medium feedback

Maxwell equation / Magnetohydrodynamics

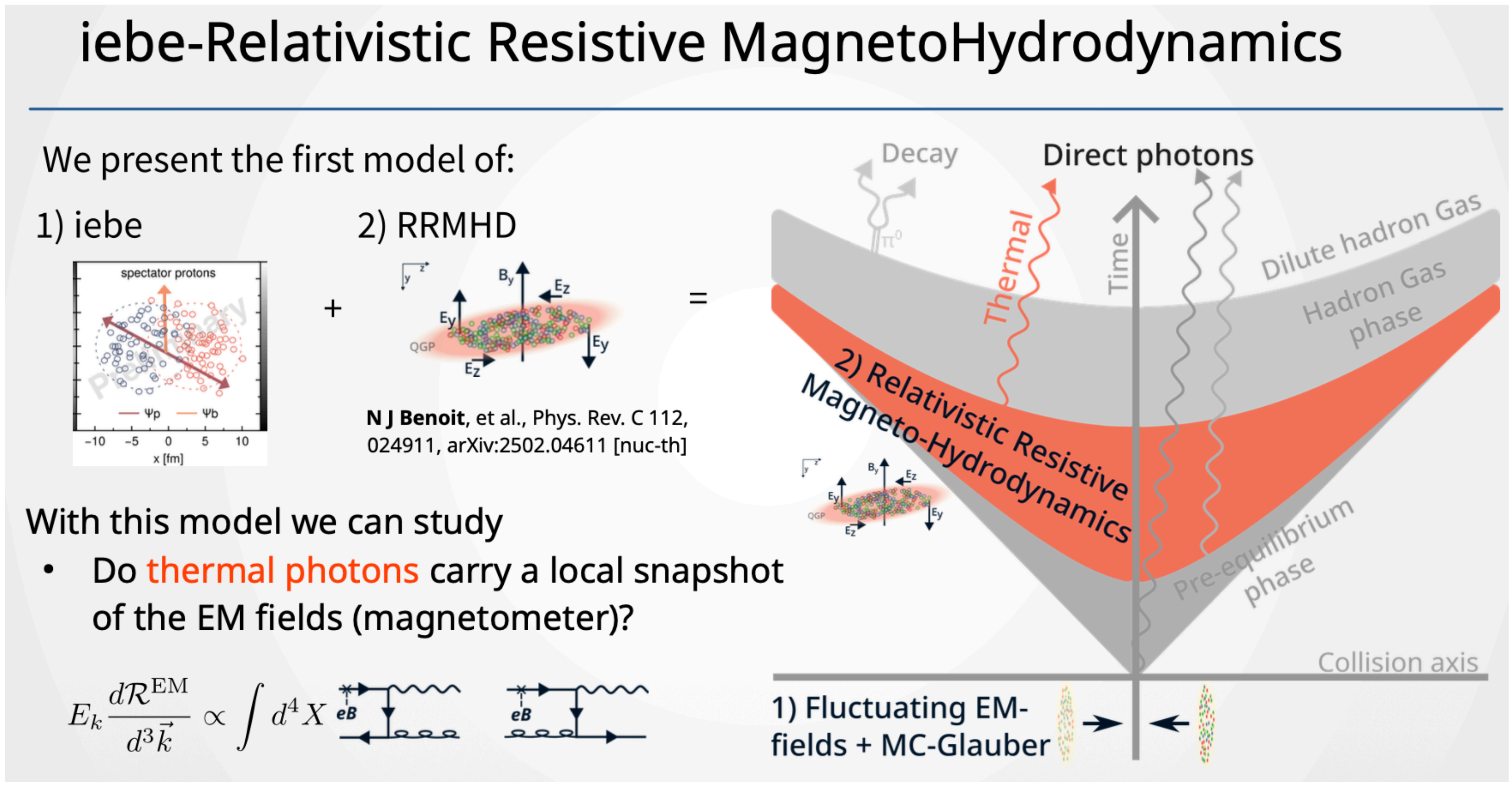


Huang, She, SS, Huang, Liao, PhysRevC.107.034901



Kushwah et al, PhysRevD.113.036021

Benoit et al, PhysRevC.112.024911



challenges in accurate, first-principle calculation

axial charge

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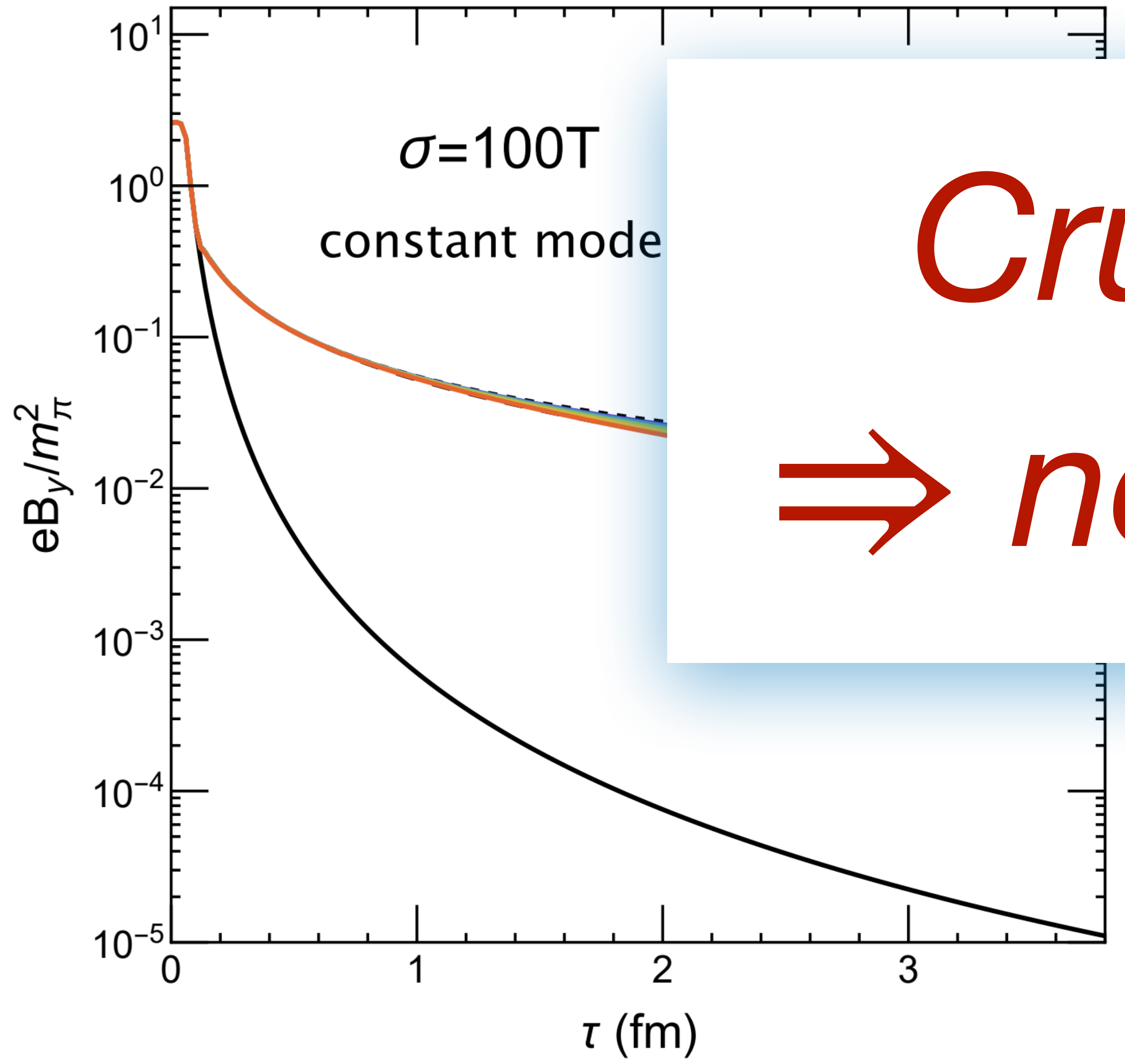
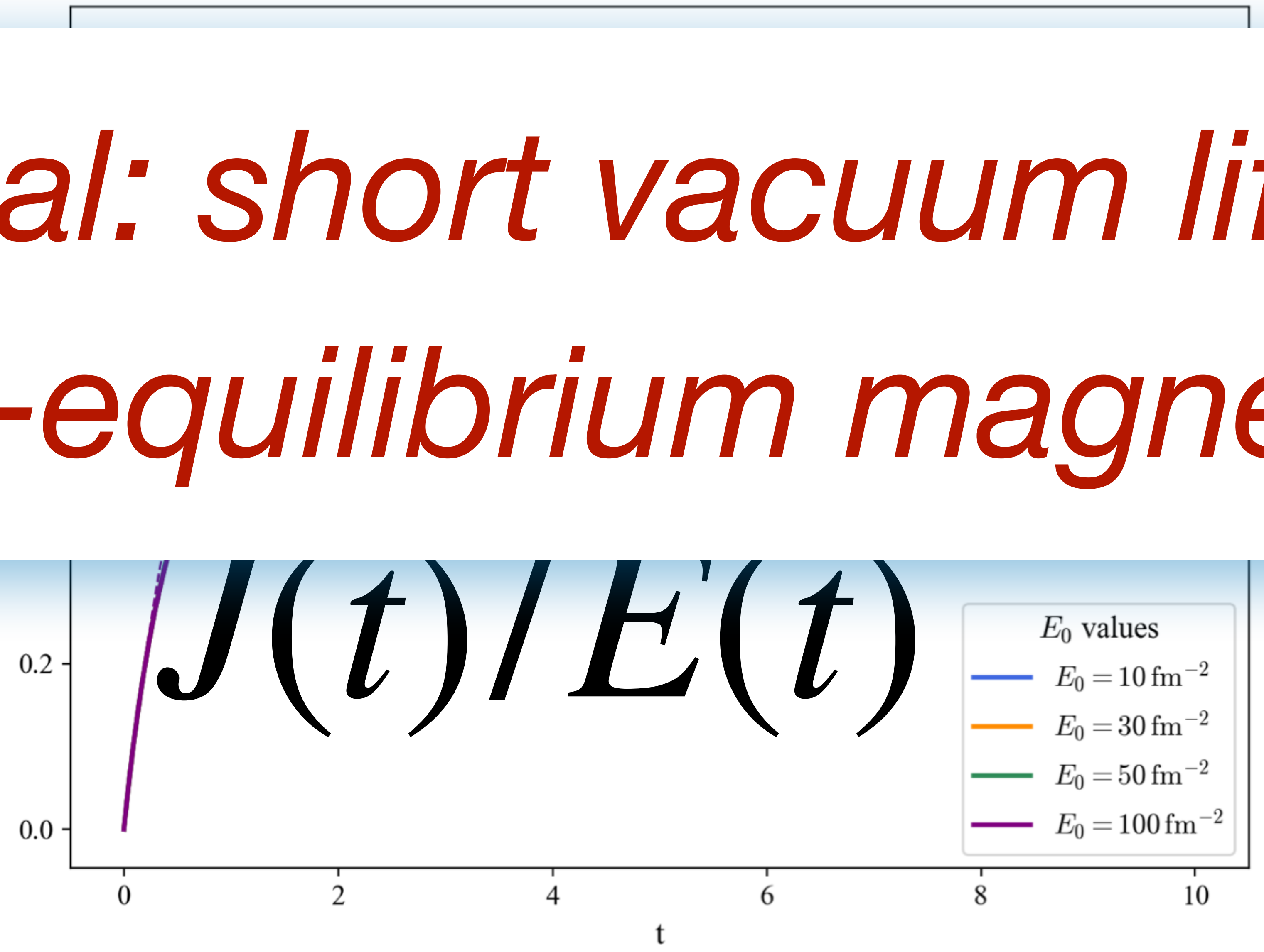
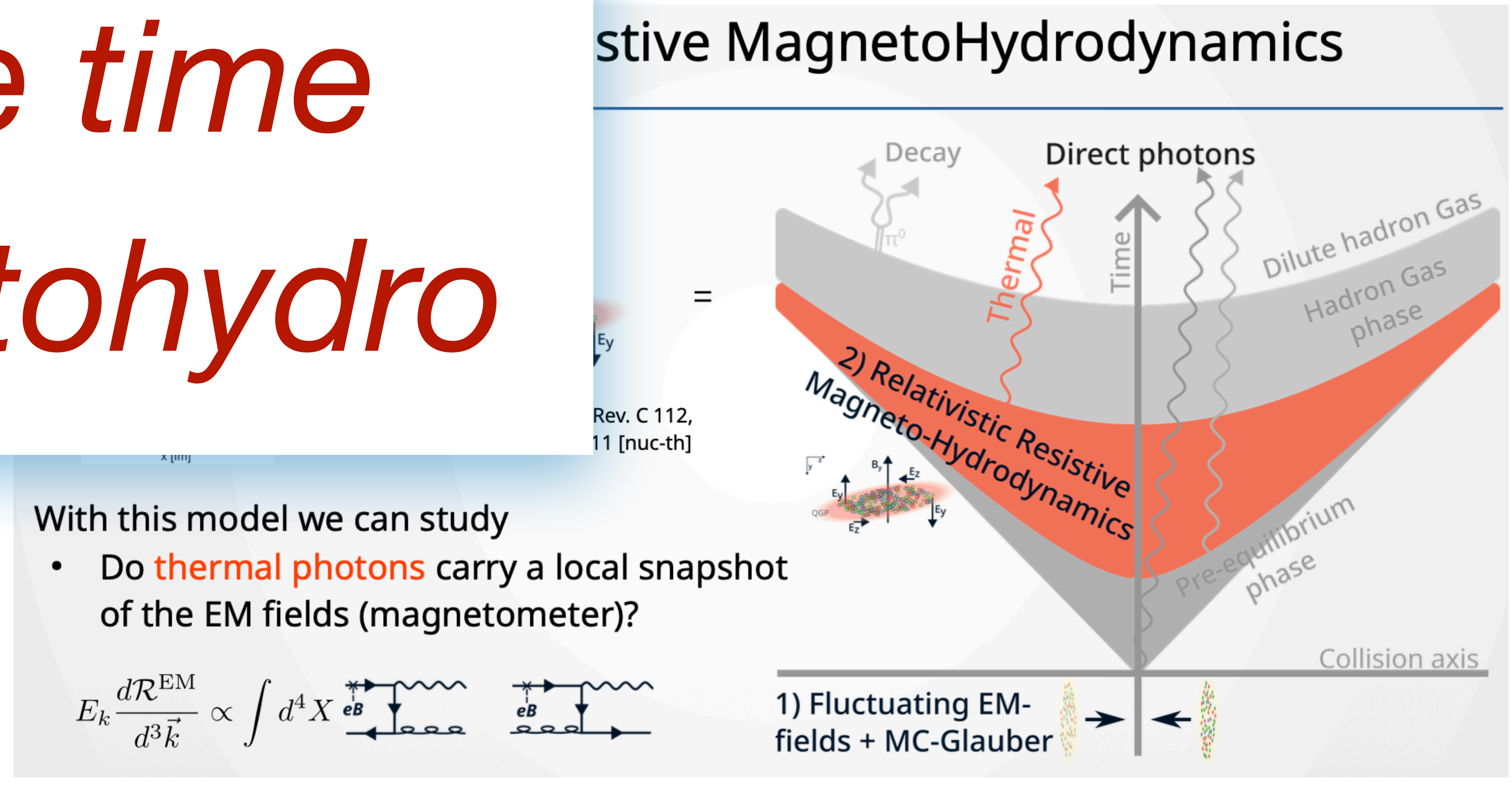
magnetic field: life time $\sim R/\gamma_{\mathrm{beam}}$ + medium feedback

Maxwell equation / Magnetohydrodynamics

Benoit et al, PhysRevC.112.024911







Crucial: short vacuum life time

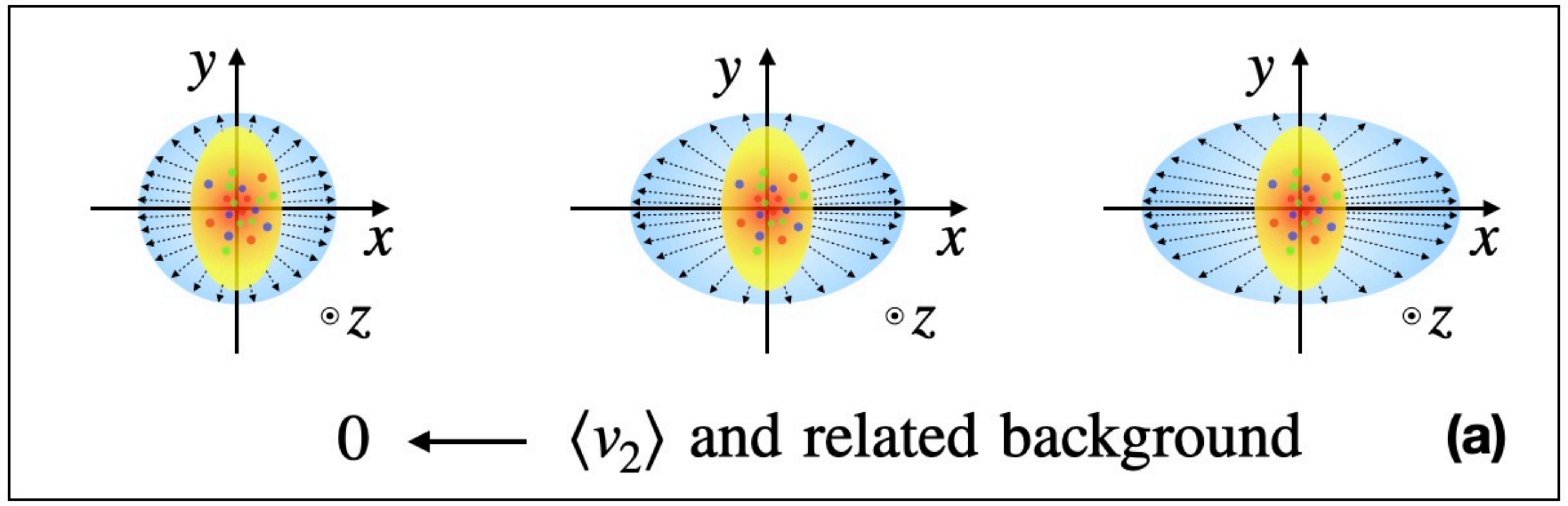
⇒ non-equilibrium magnetohydro

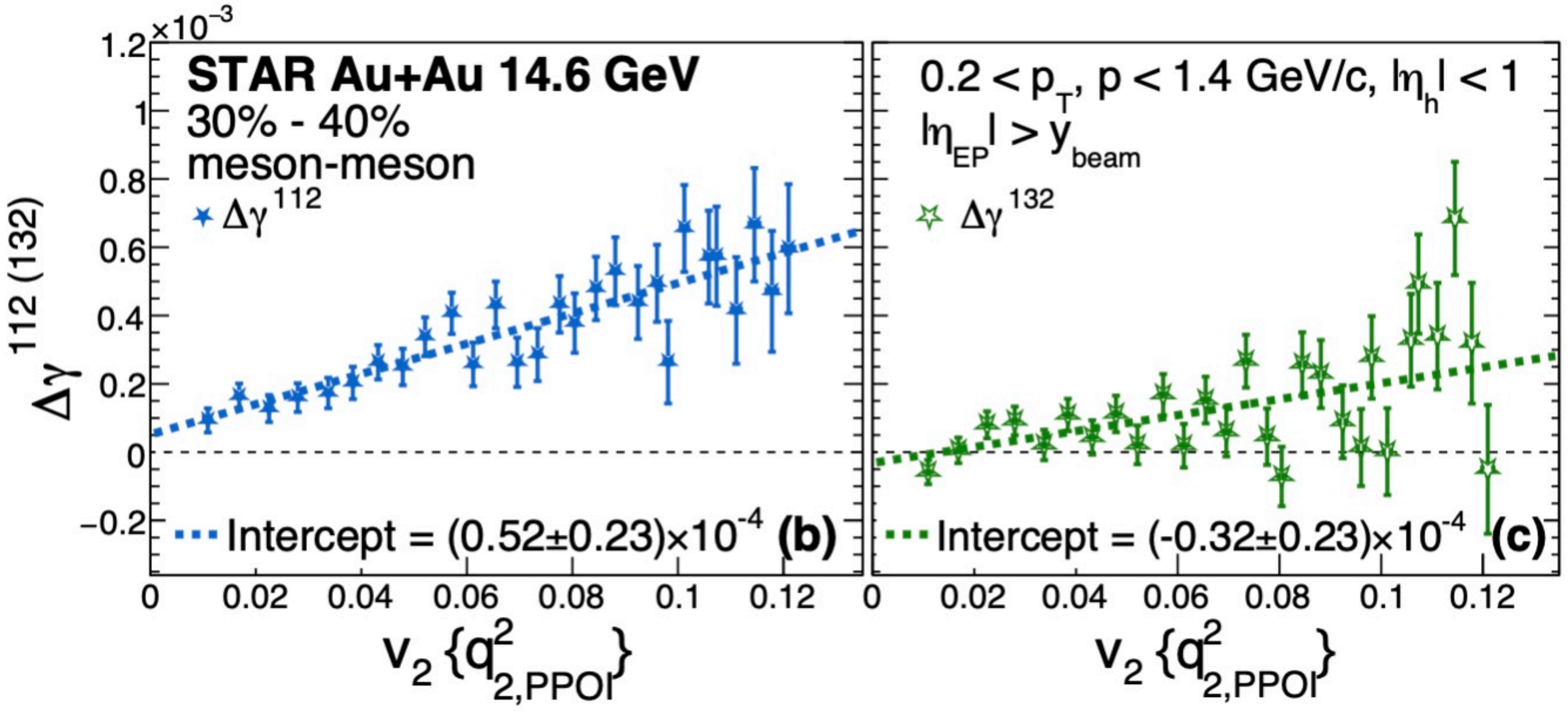
Huang, She, SS, Huang, Liao, PhysRevC.107.034901

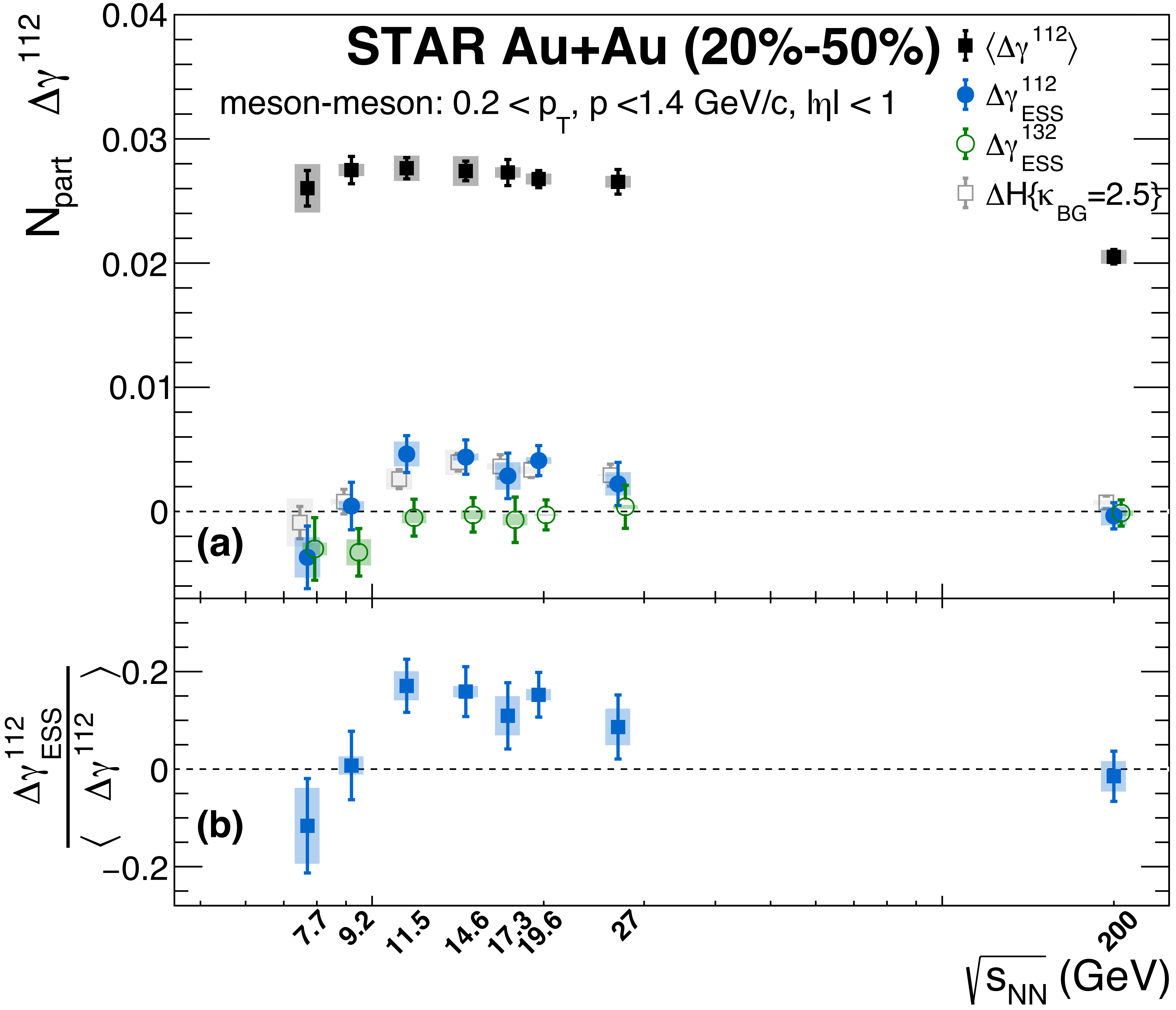
Kushwah et al, PhysRevD.113.036021

lower beam energy — long lifetime

STAR, 2506.00265+PhysRevC.113.014912







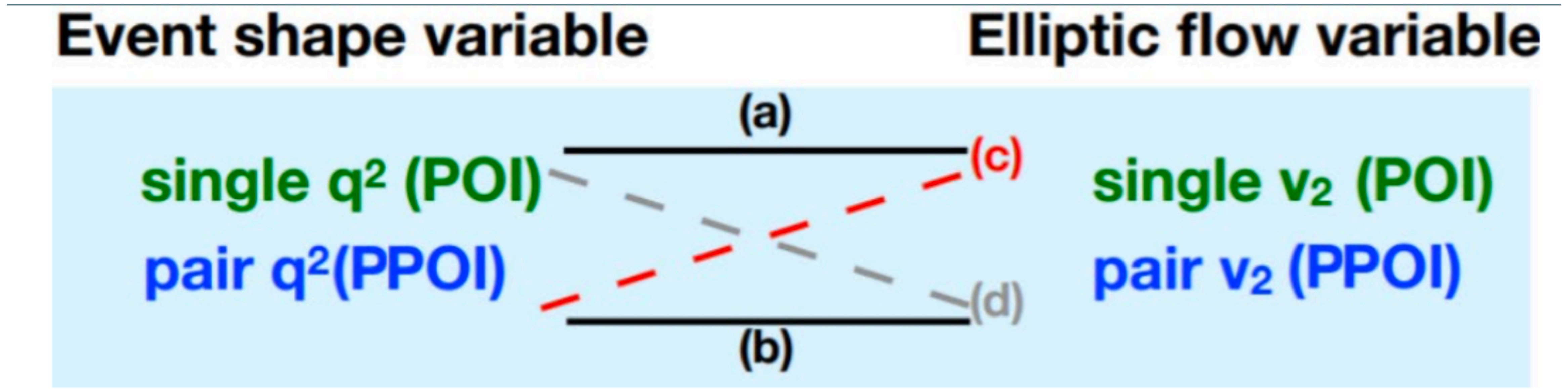
STAR: $\sim 3\sigma$ significance @ 11.5-19.6 GeV

lower beam energy — long lifetime

STAR, 2506.00265+PhysRevC.113.014912

background subtraction methods in experiment: shape engineering

(I)



(II) Event Plane vs Spectator Plane comparison

Test background in no-CME experiments? e.g. 5.02 TeV PbPb

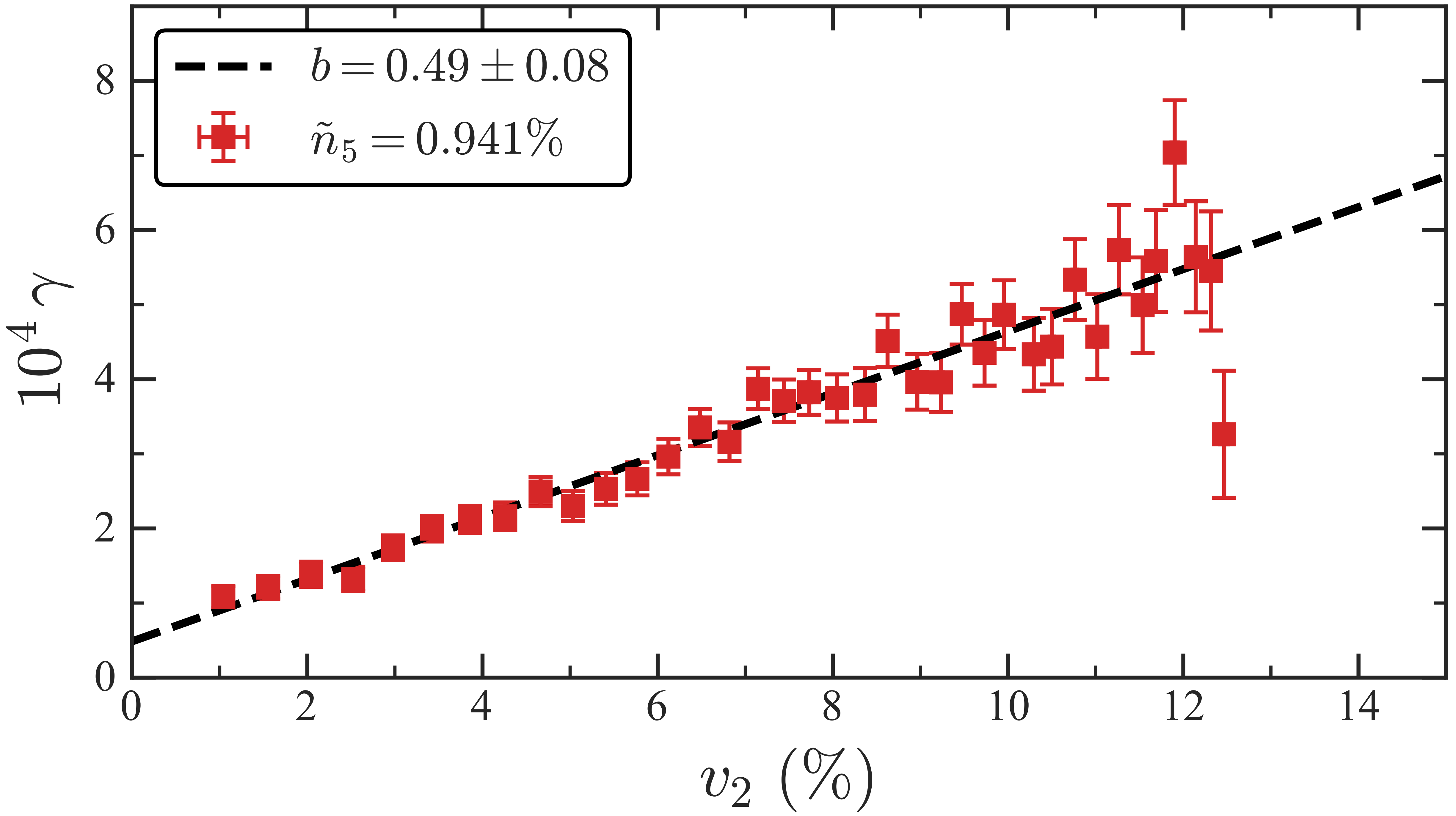
STAR: $\sim 3\sigma$ significance @ 11.5-19.6 GeV

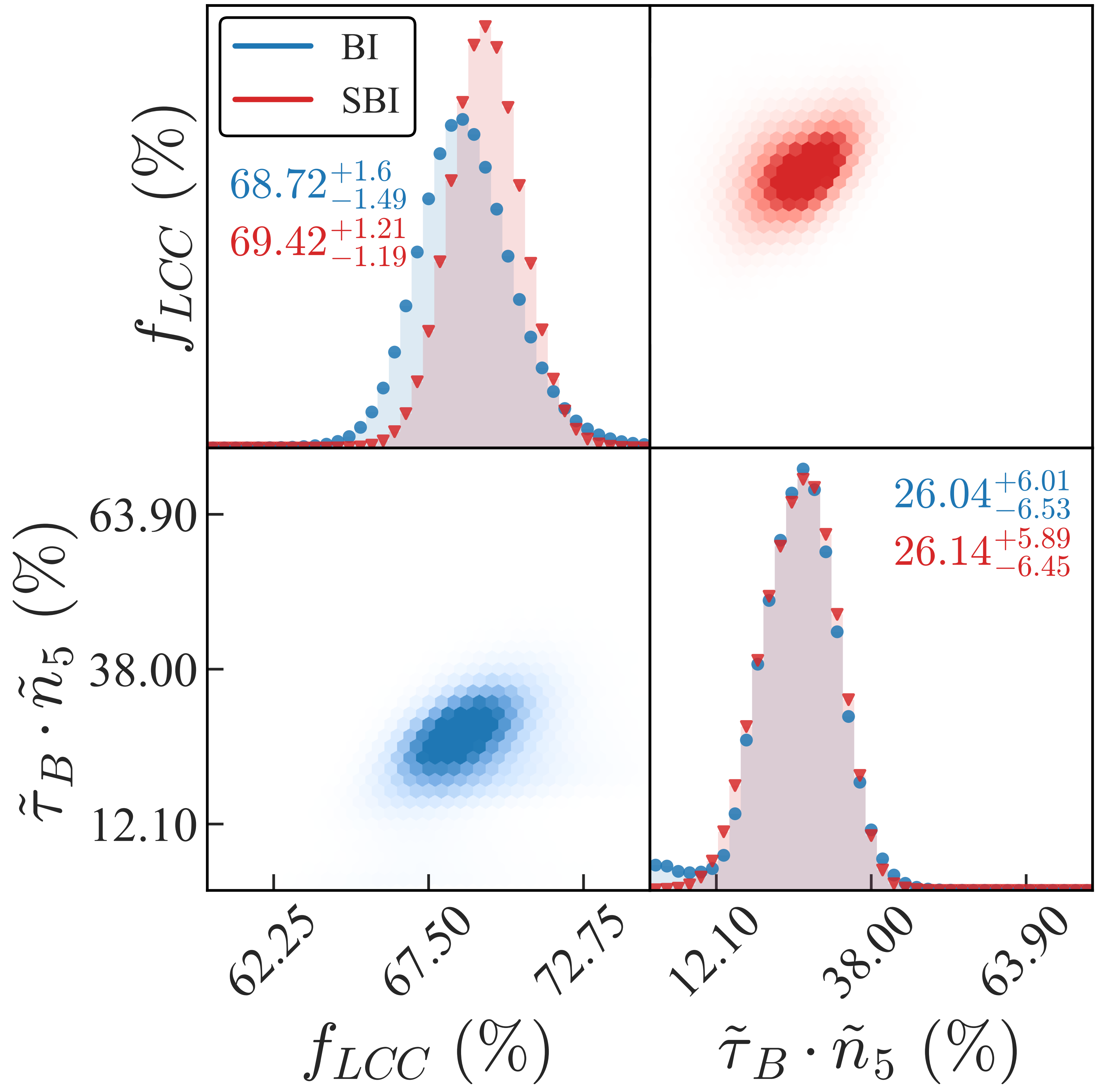
lower beam energy — long lifetime

STAR, 2506.00265+PhysRevC.113.014912

A machine-learning extraction

$$\Delta\gamma, \Delta\delta \rightarrow f_{\mathrm{LCC}}, \tau_B, n_5$$





Alex Akridge, Yu Guo, J. Liao, SS, Hongxi Xing, Hui Zhang, in prep.

STAR: $\sim 3\sigma$ significance @ 11.5-19.6 GeV

STAR, 2506.00265+PhysRevC.113.014912

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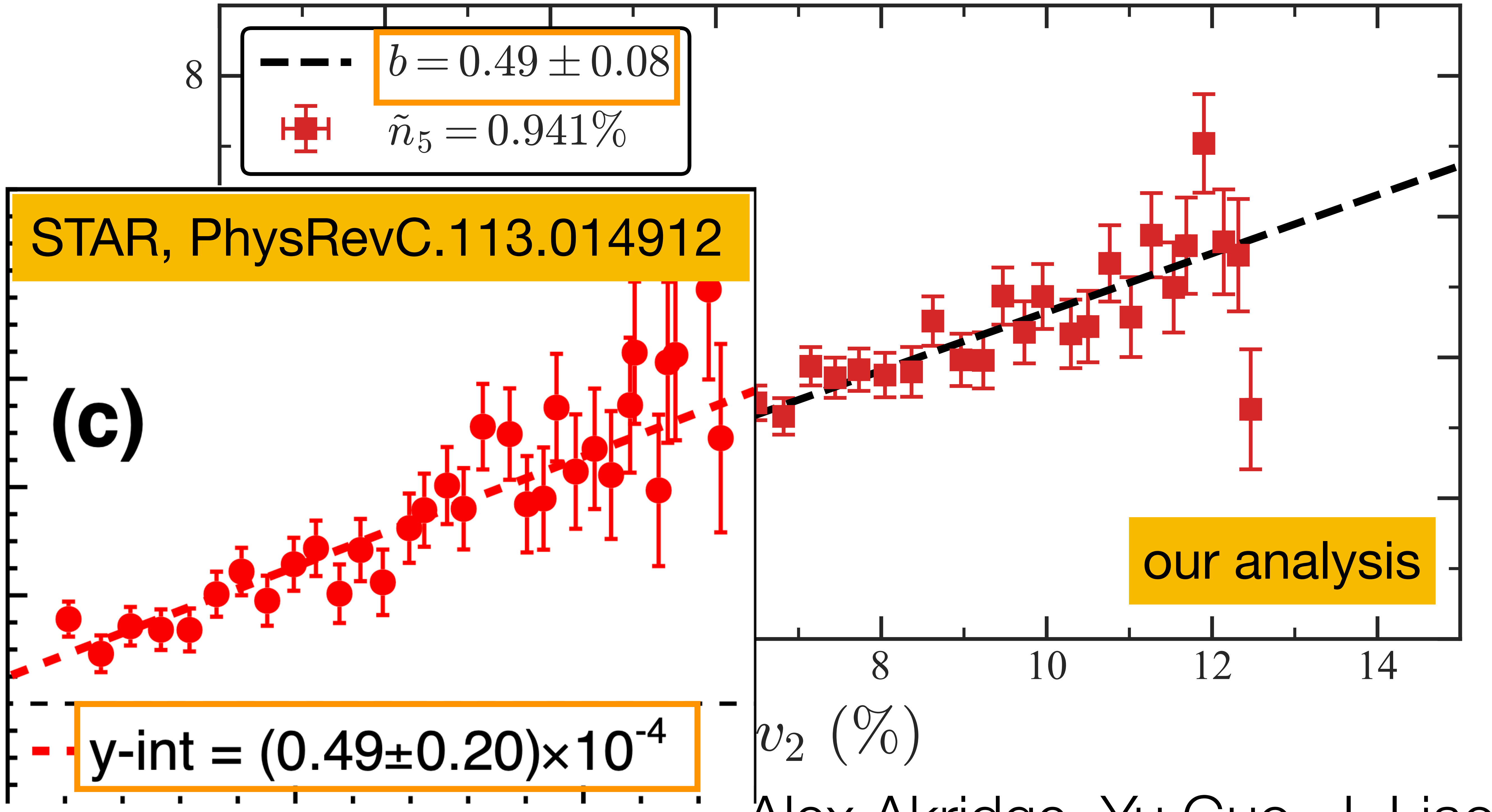
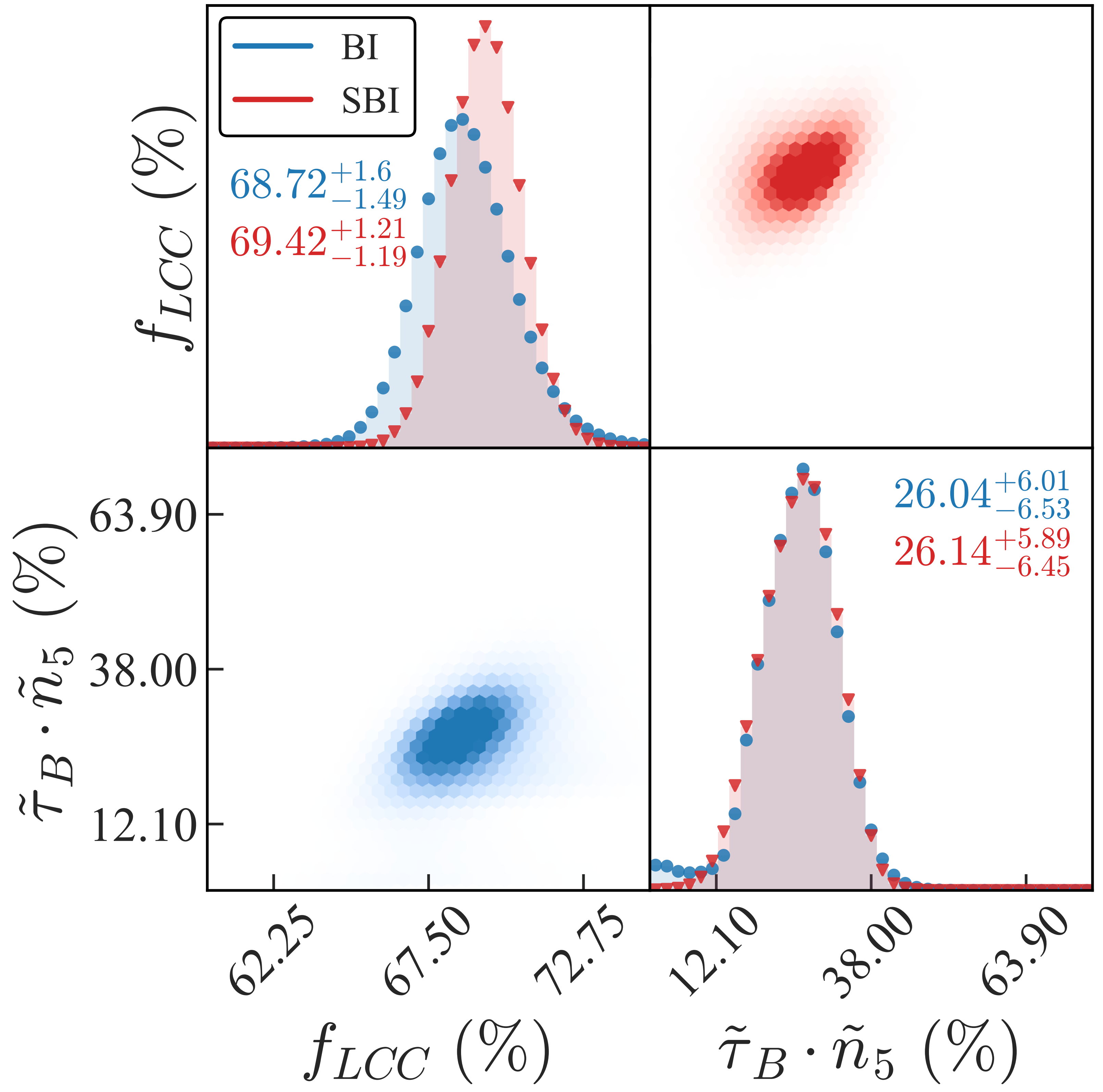


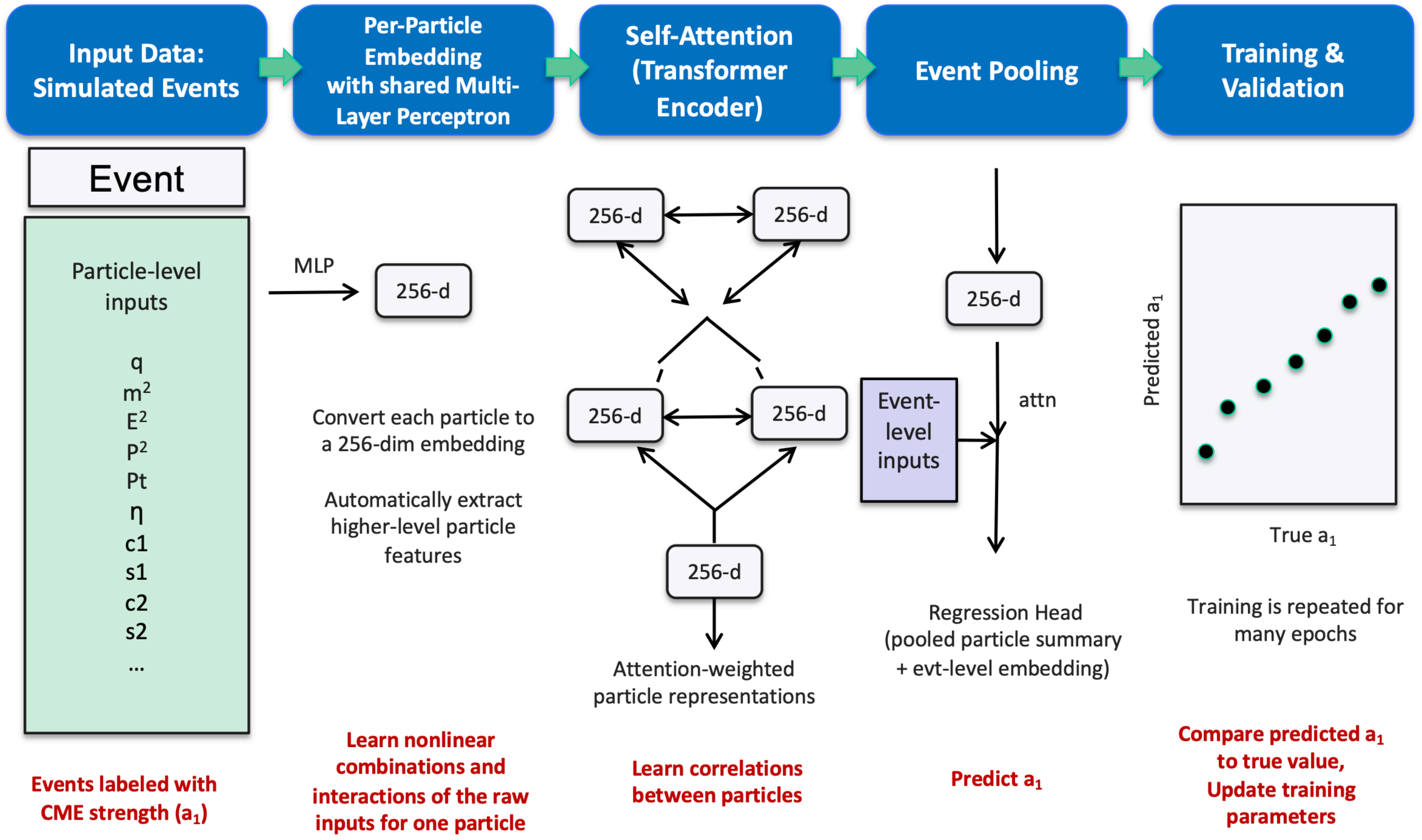


Alex Akridge, Yu Guo, J. Liao, SS, Hongxi Xing, Hui Zhang, in prep.

STAR: $\sim 3\sigma$ significance @ 11.5-19.6 GeV

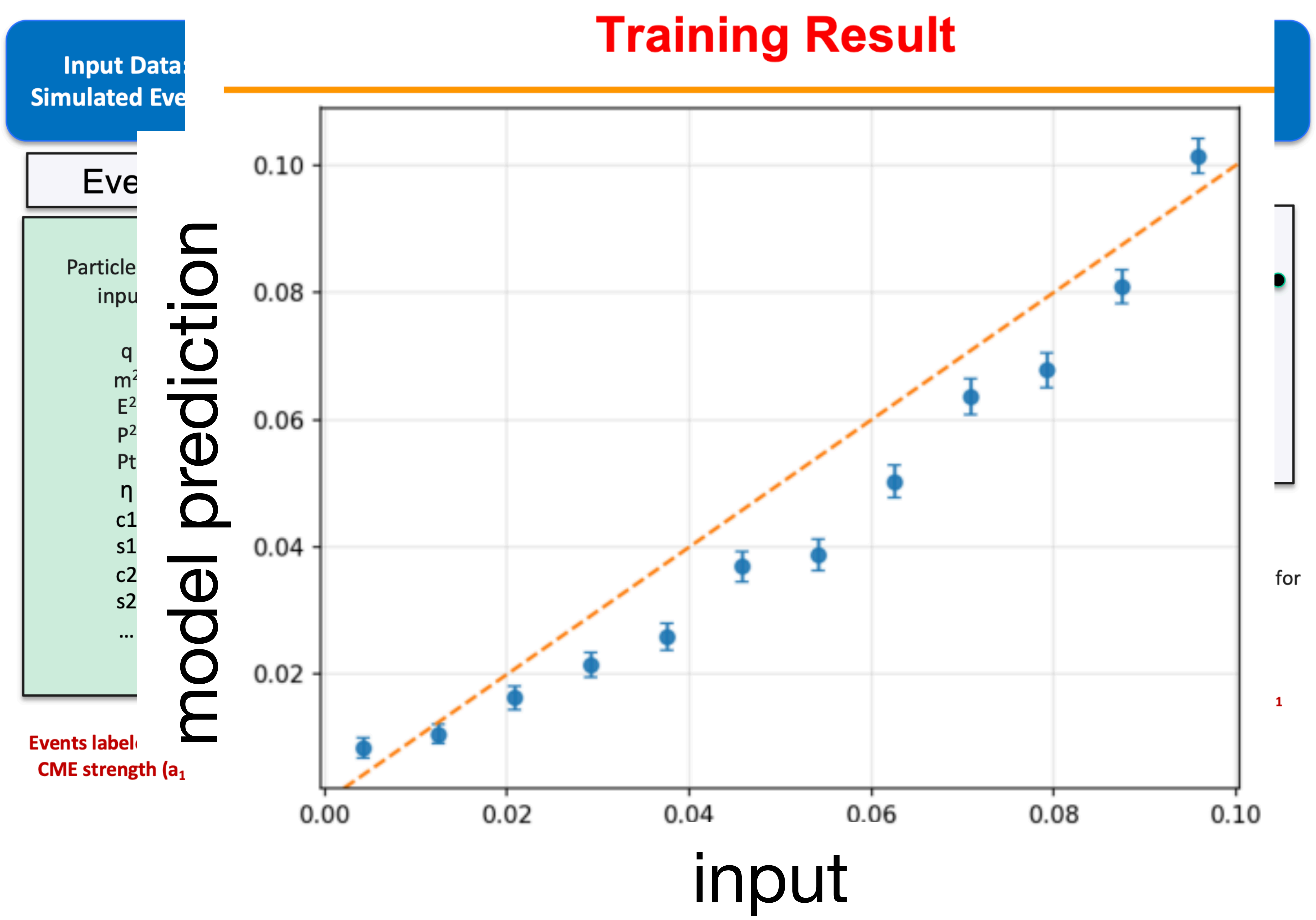
more opportunities from machine learning

signal extraction w/ Transformer



more opportunities from machine learning

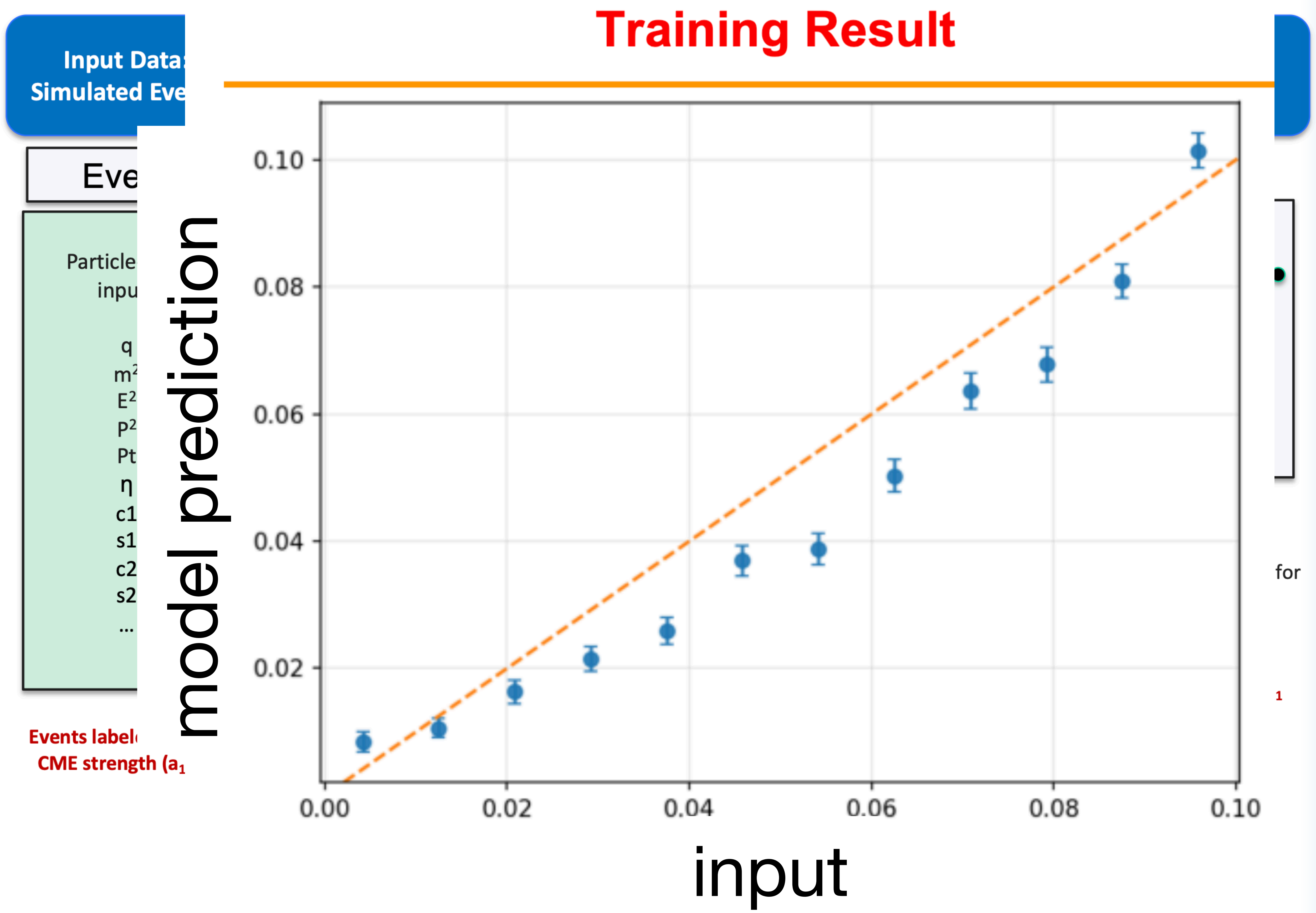
signal extraction w/ Transformer



Aihong Tang @ SQM2026

more opportunities from machine learning

signal extraction w/ Transformer



Aihong Tang @ SQM2026

“optimal” obs. trained w/ exp.

harmonic coefficients

$$O = L_{2i}\, c_{2i} + B_{i,j}\, c_i\, c_j$$

param. to be trained

$$O_{\mathrm{Pb+Pb@5.02TeV}} \to 0$$

maximize $O_{\mathrm{RuRu}} - O_{\mathrm{ZrZr}}$

check: $O_{\mathrm{RuRu}} \approx 1.2\, O_{\mathrm{ZrZr}}$?

Hirono, Ikeda, Kharzeev, Ziyi Liu, SS,
PhyRevC.112.L051904+in progress

outlooks

- non-equilibrium magnetohydrodynamics

- background models of CME can/shall be tested

- correlation between and helicity? $(a_1^+ \propto \mu_5)$