Chirality and Vorticity

Experimental perspective from nuclear collisions

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Rice University

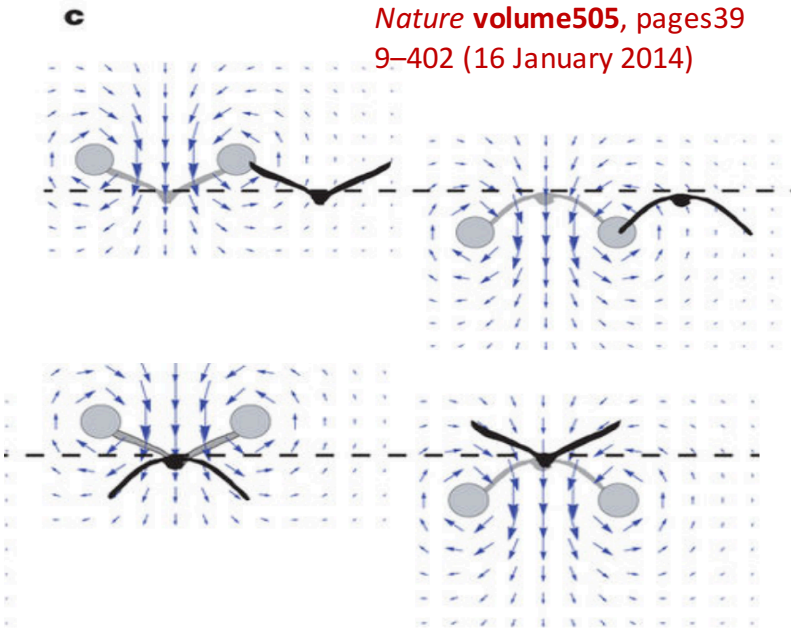
Quark Matter 2018

Why study *Chirality and Vorticity* ?

Why study *Chirality and Vorticity* ?

- Birds like **vortices**. Help flying

Nature **volume505**, pages399–402 (16 January 2014)



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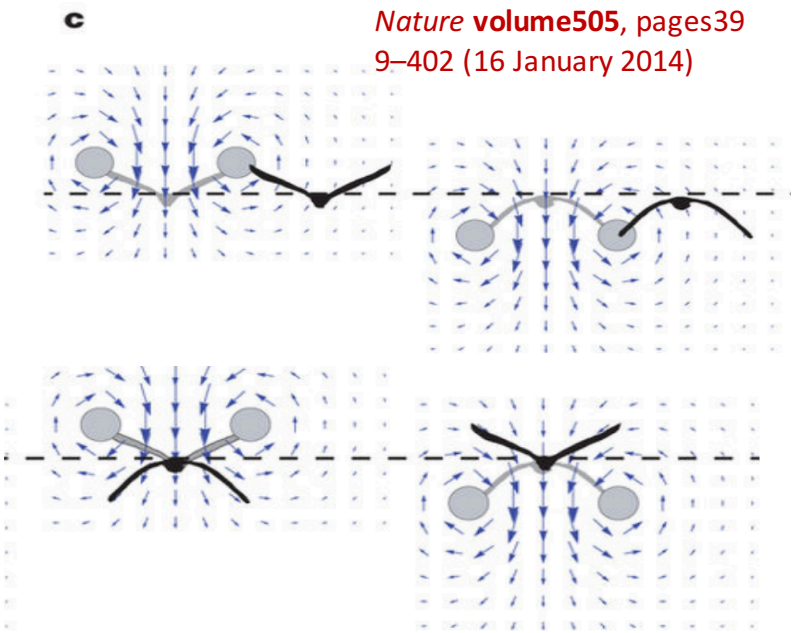

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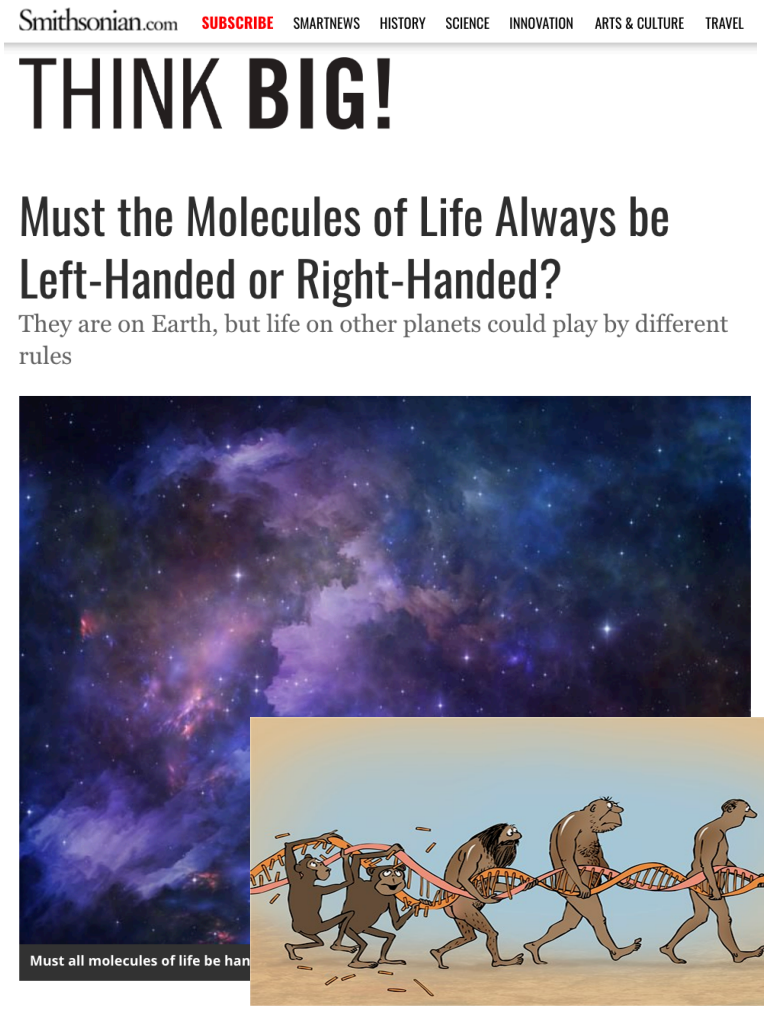

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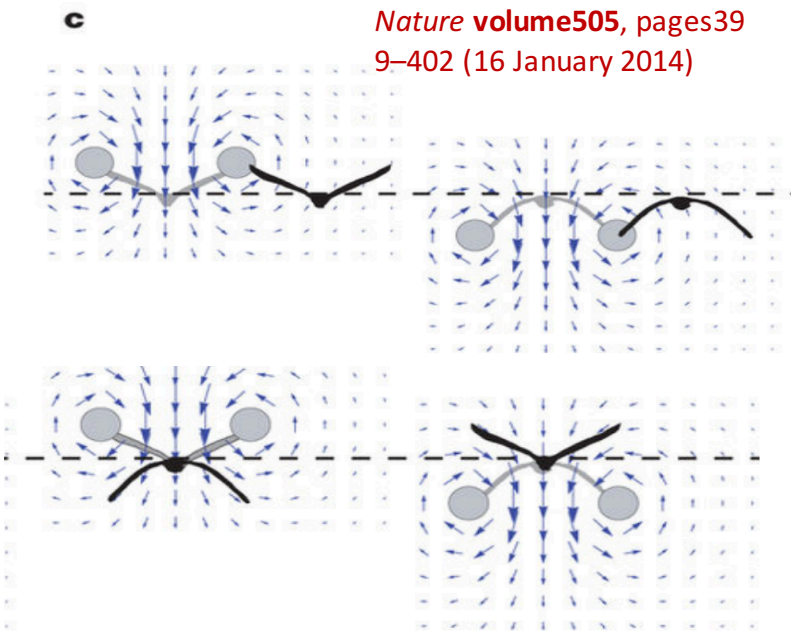


Vorticity and Chirality helps understand nature

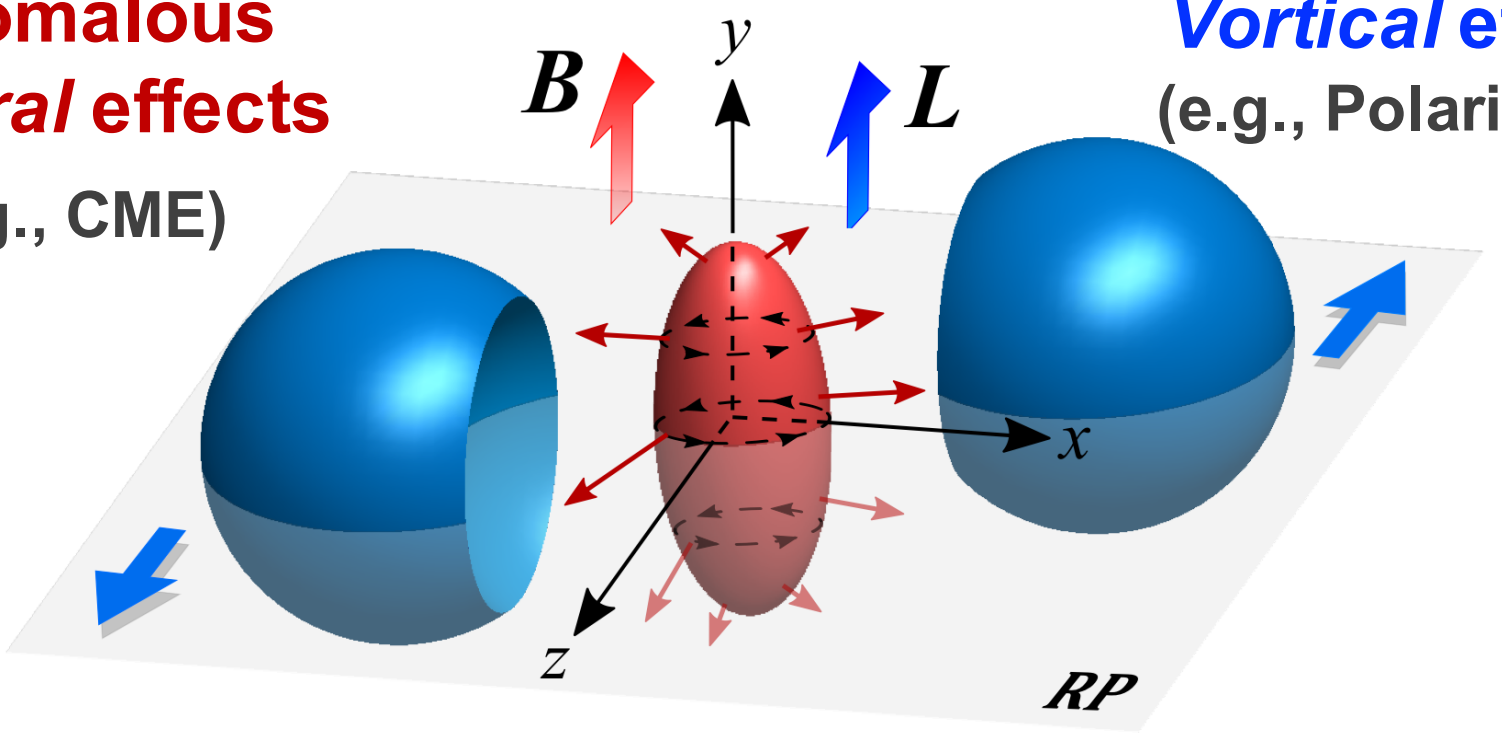
Heavy ion collisions

Anomalous *chiral* effects

(e.g., CME)

***Vortical* effects**

(e.g., Polarization)



Heavy ion collisions

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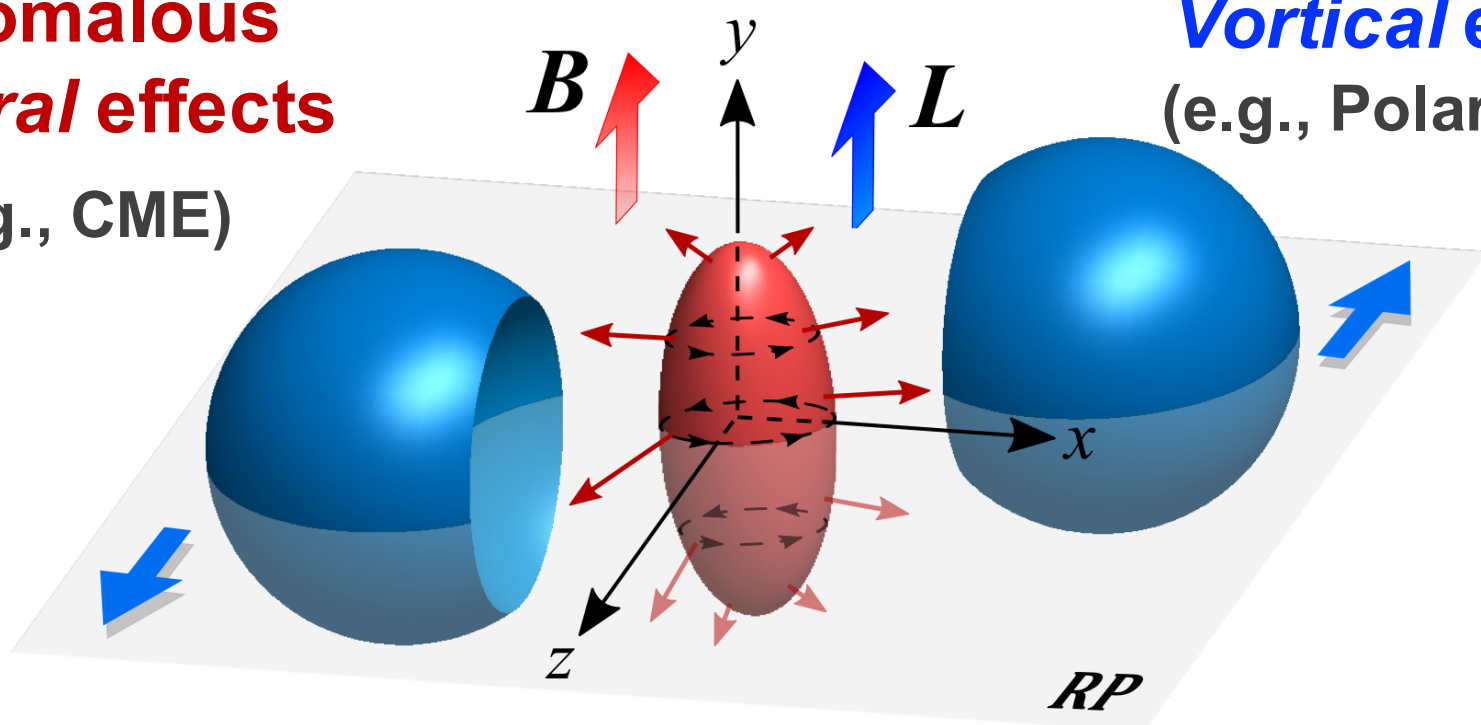
(e.g., Polarization)



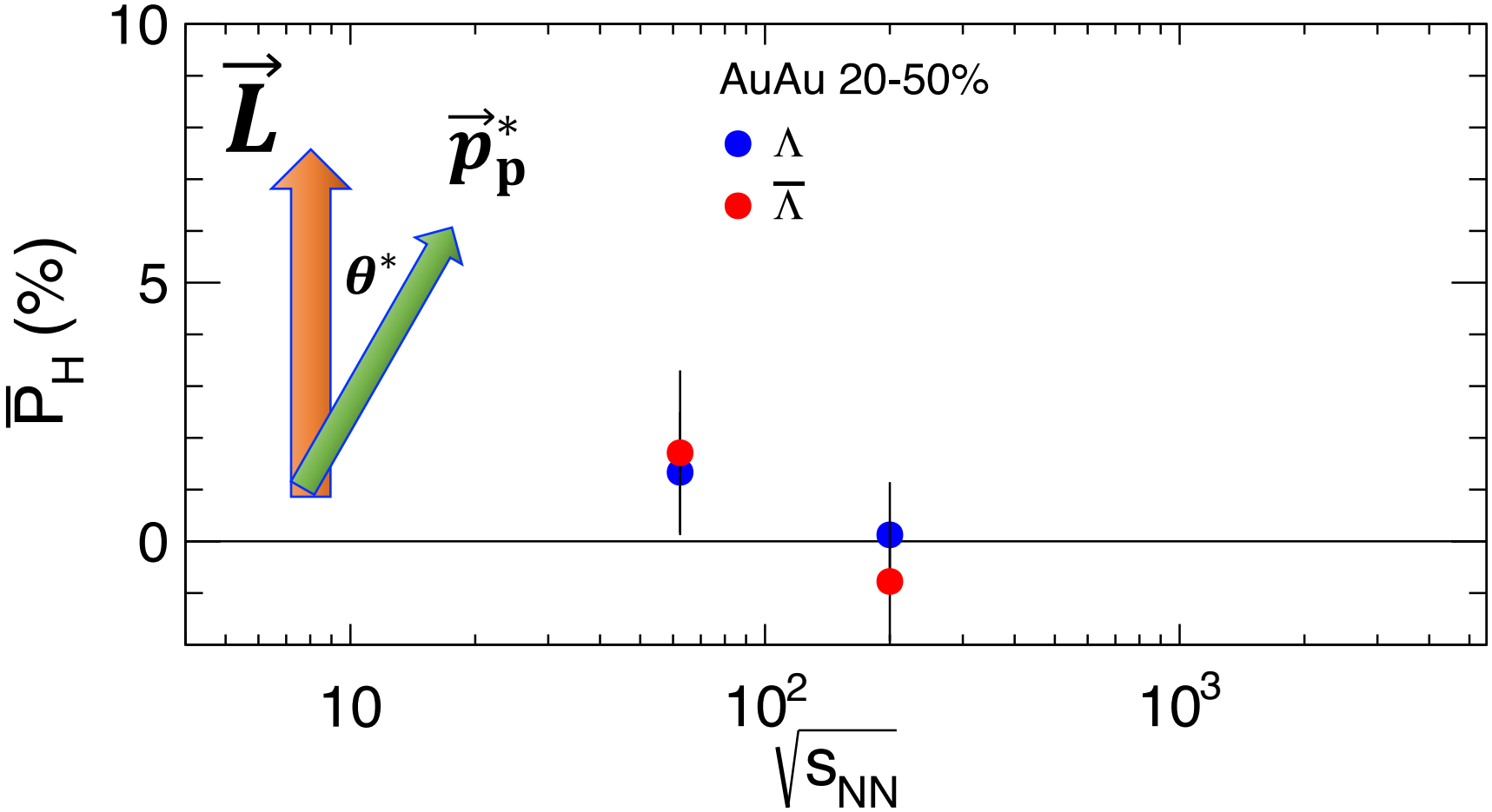
Big questions:

- Detail properties of **emergent QCD** system?
- **Chiral symmetry restored** ?

Global Λ Polarization

PRC 76 024915 (2007)

$P_H \sim \langle \cos(\theta^*) \rangle$



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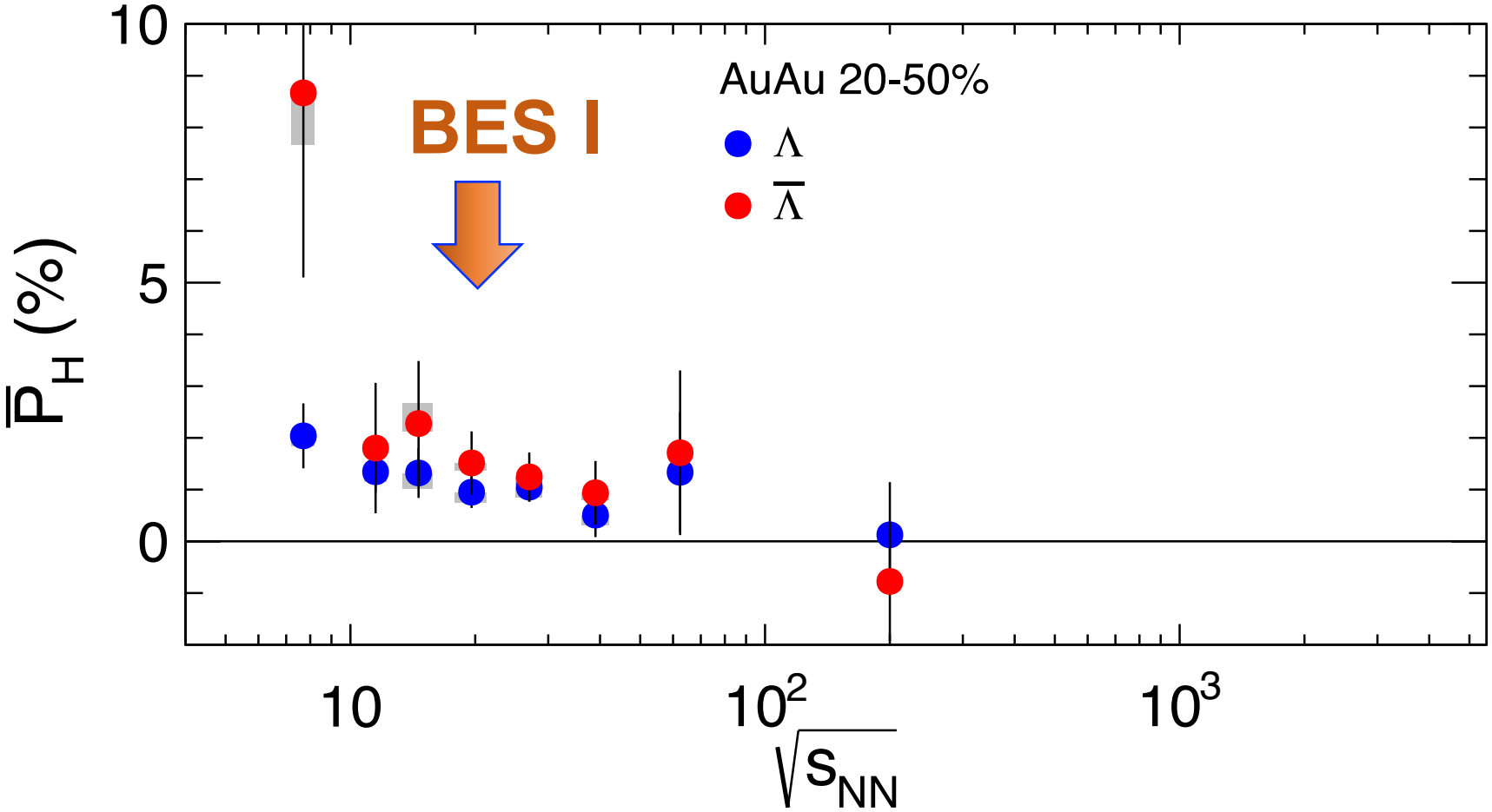

(See T. Niida's talk)

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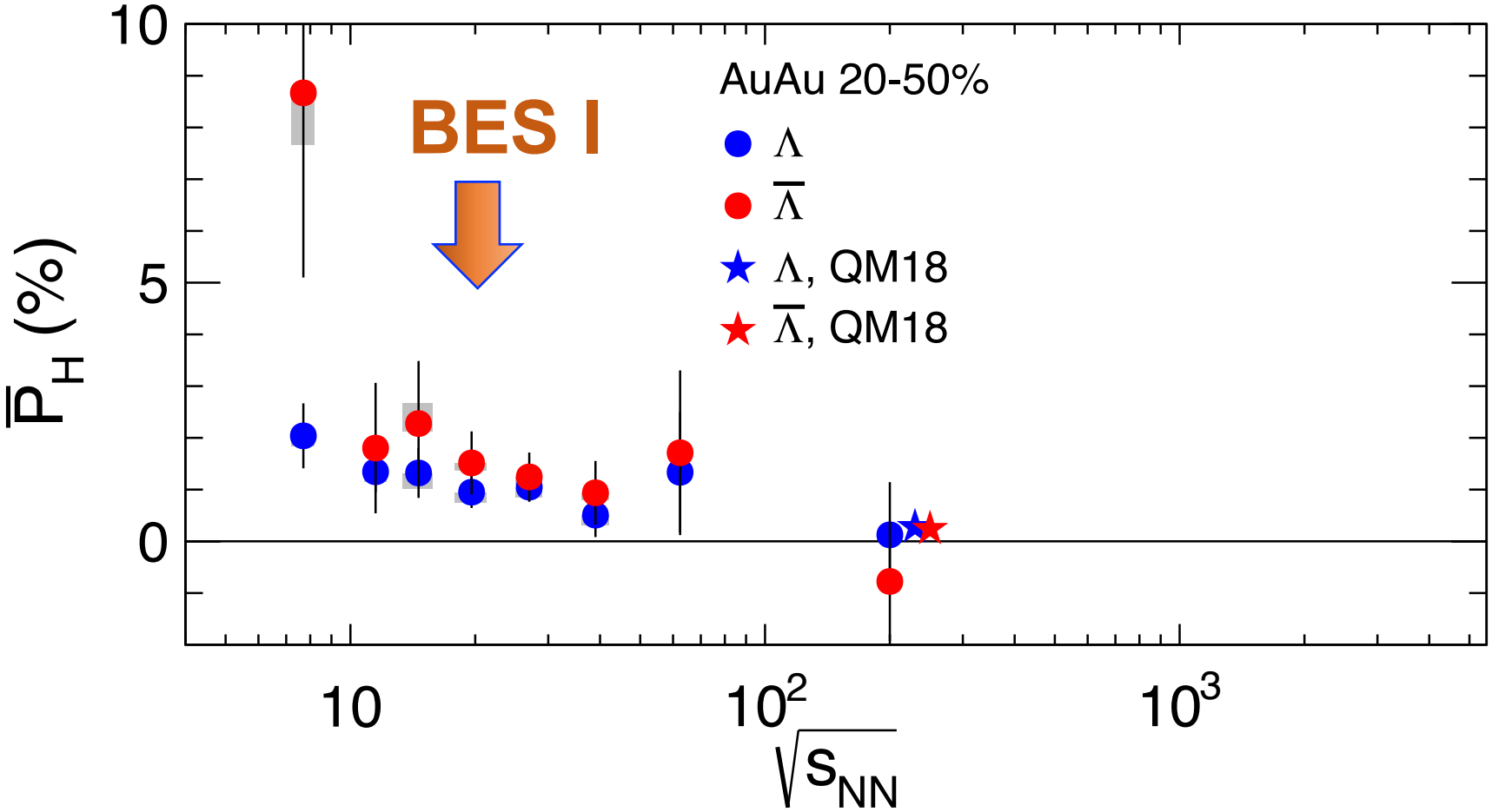

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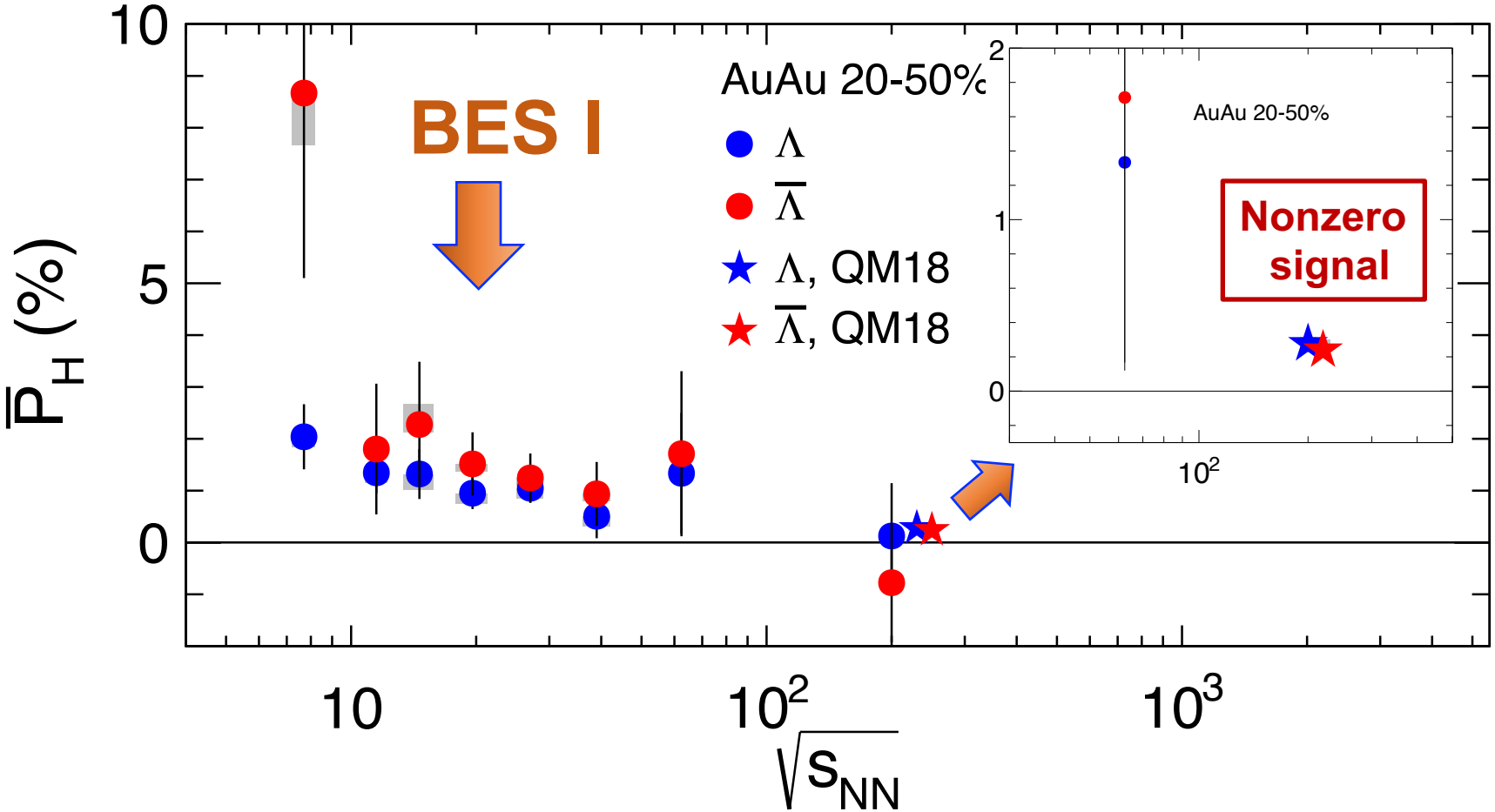

(See T. Niida's talk)

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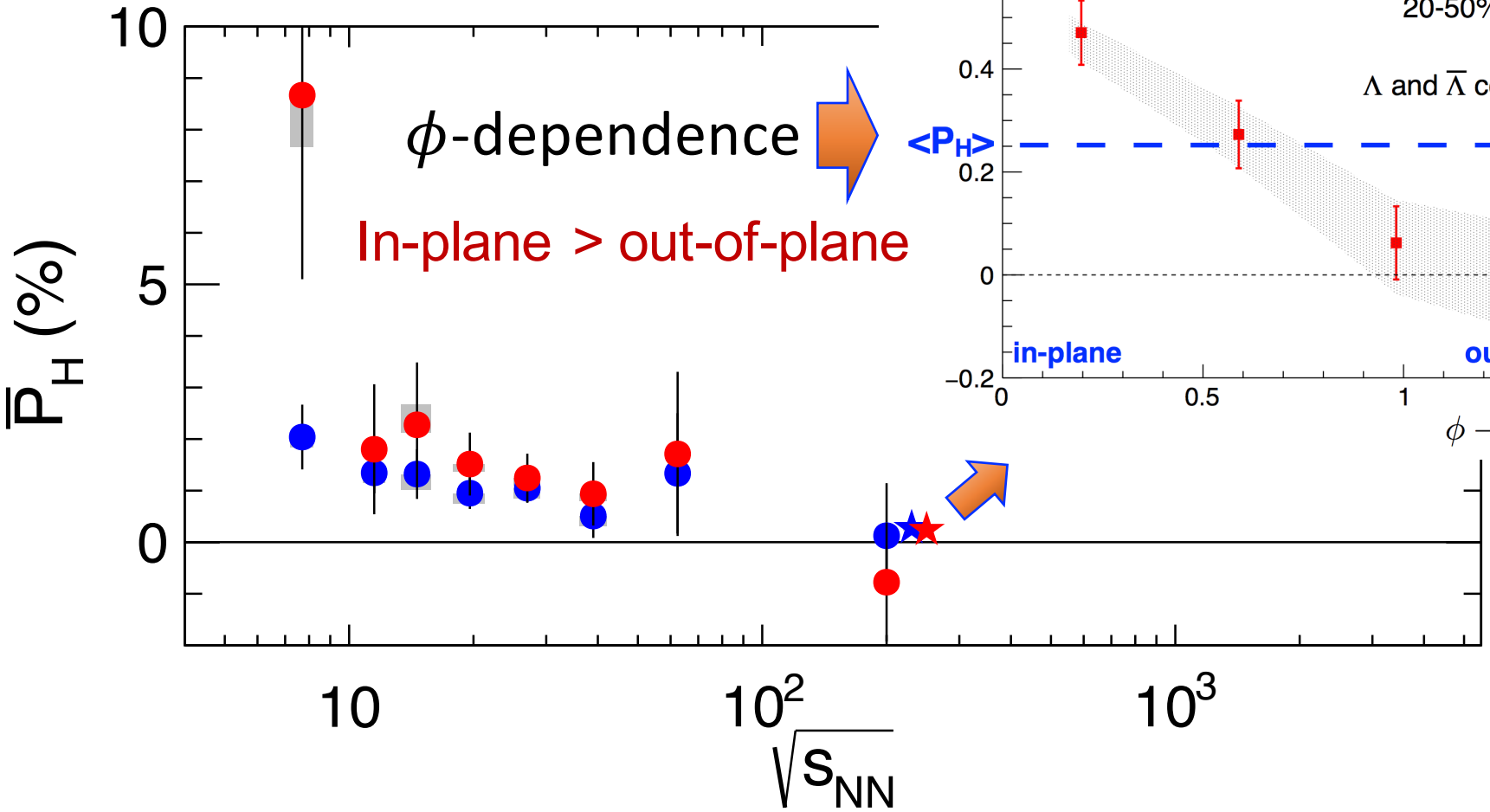
ϕ-dependence

In-plane > out-of-plane



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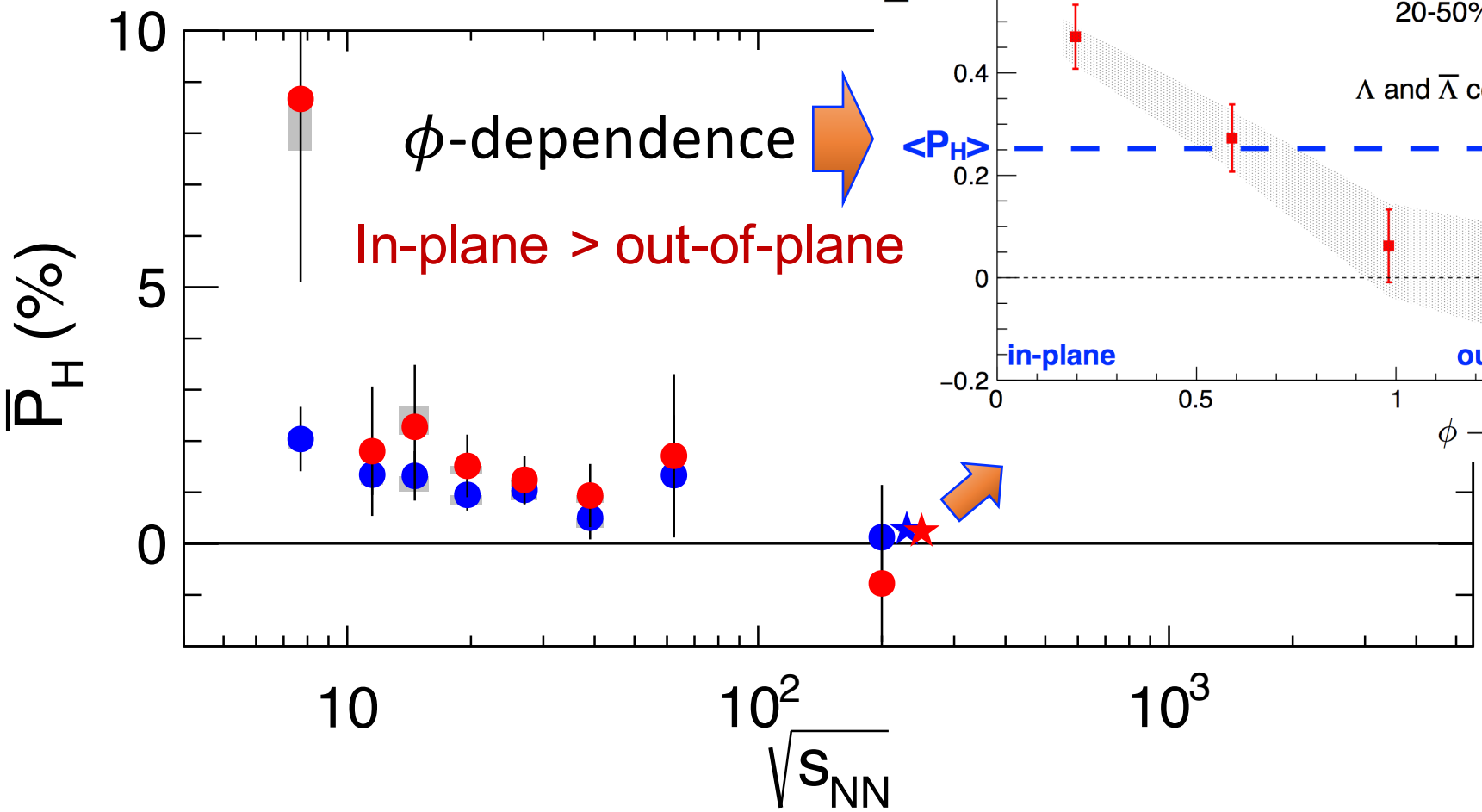

Hydrodynamics predicts azimuthal modulation

Global Λ Polarization

PRC 76 024915 (2007)
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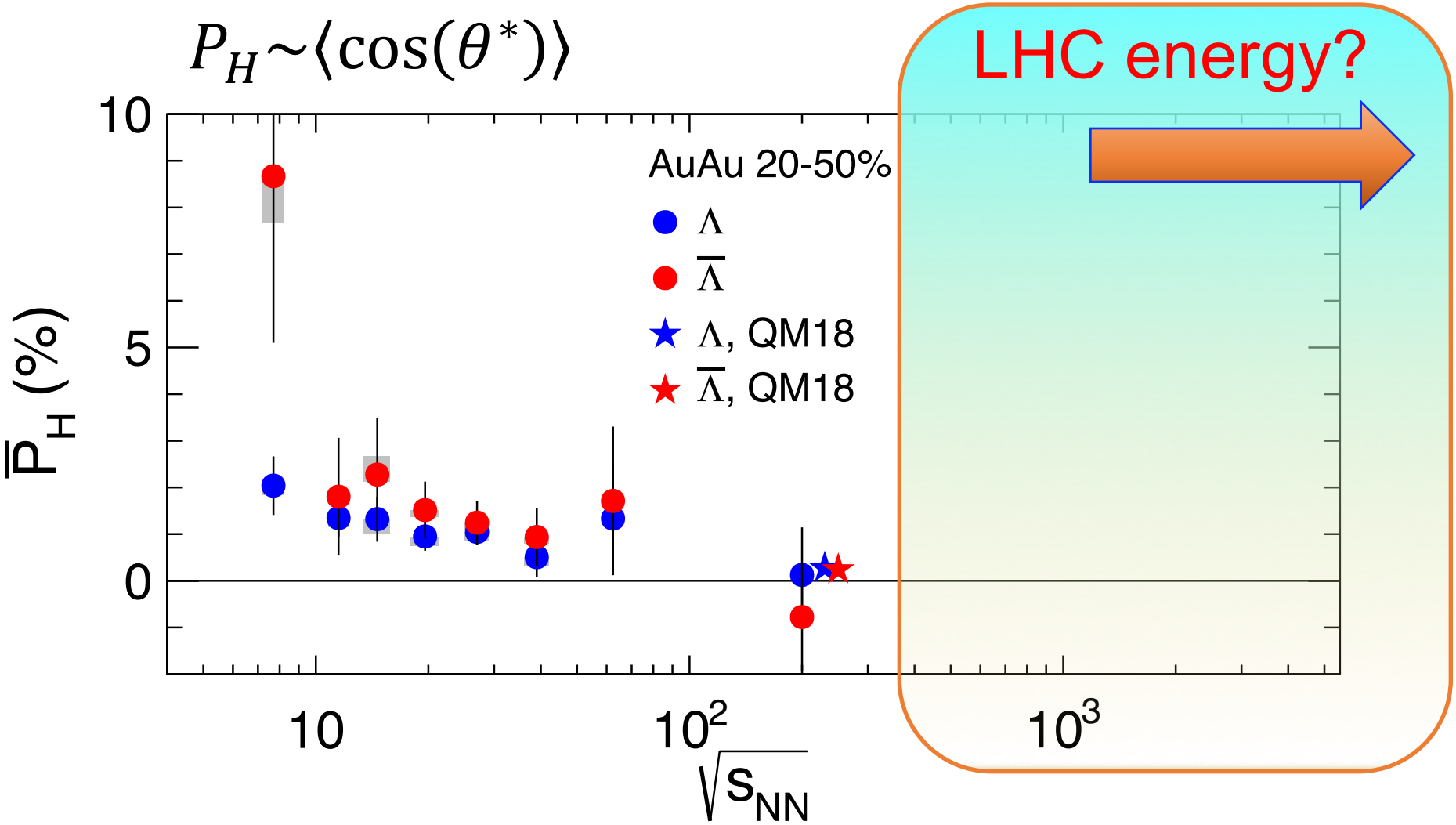

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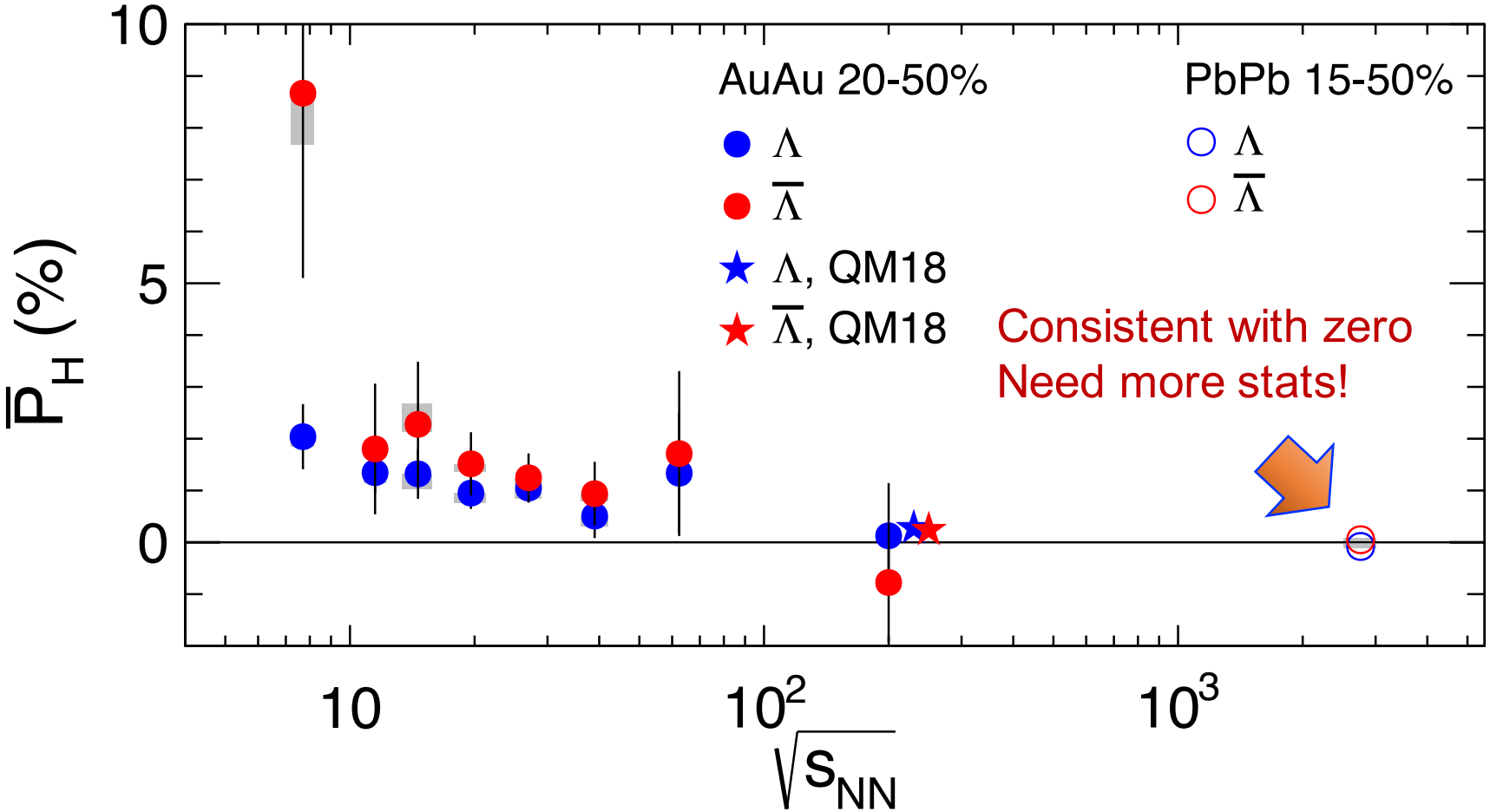

$$P_\Lambda(\%) = -0.08 \pm 0.10(\text{stat}) \pm 0.04(\text{syst})$$
$$P_{\bar{\Lambda}}(\%) = 0.05 \pm 0.10(\text{stat}) \pm 0.03(\text{syst})$$

Global Λ Polarization

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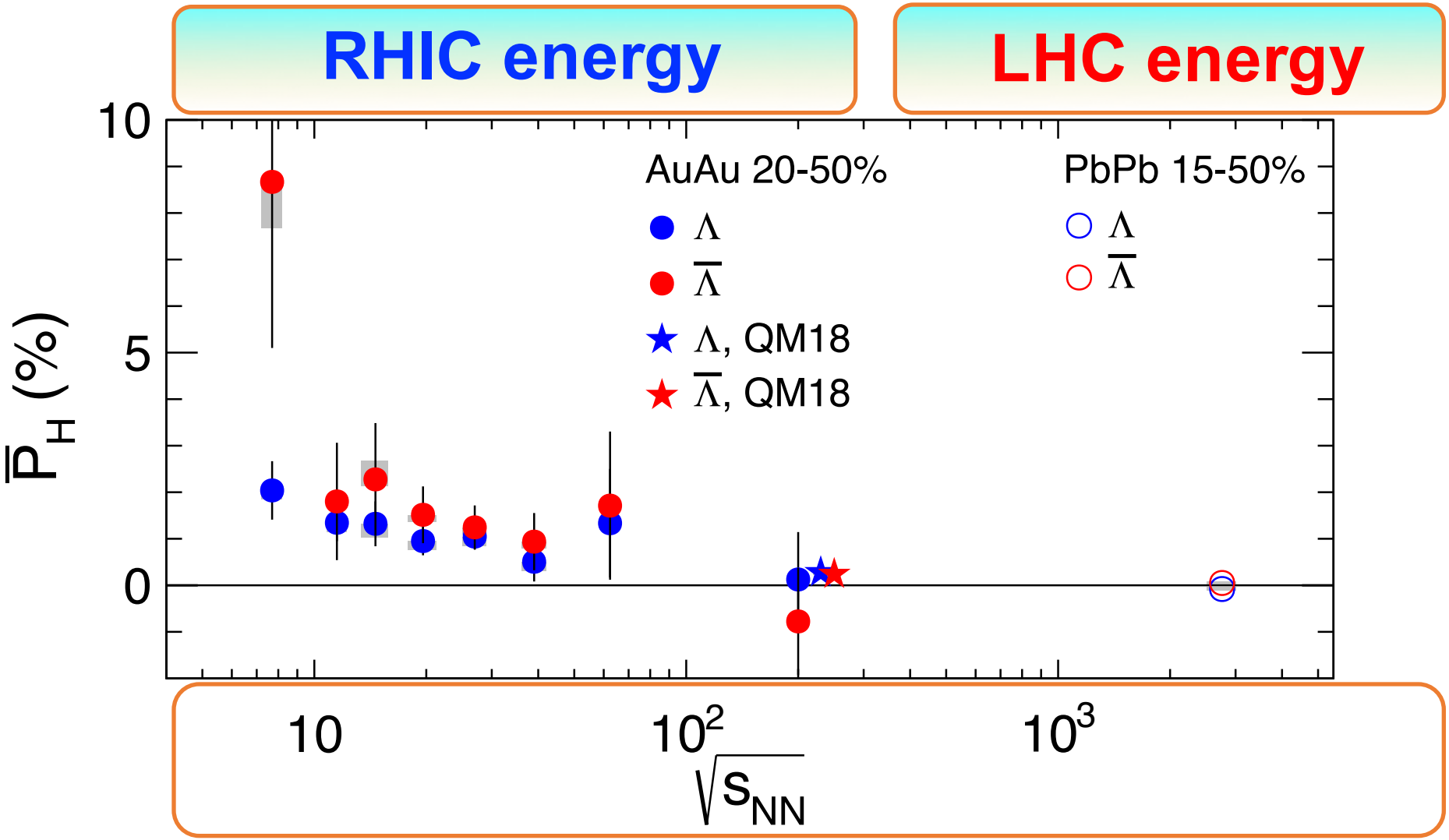
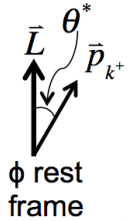


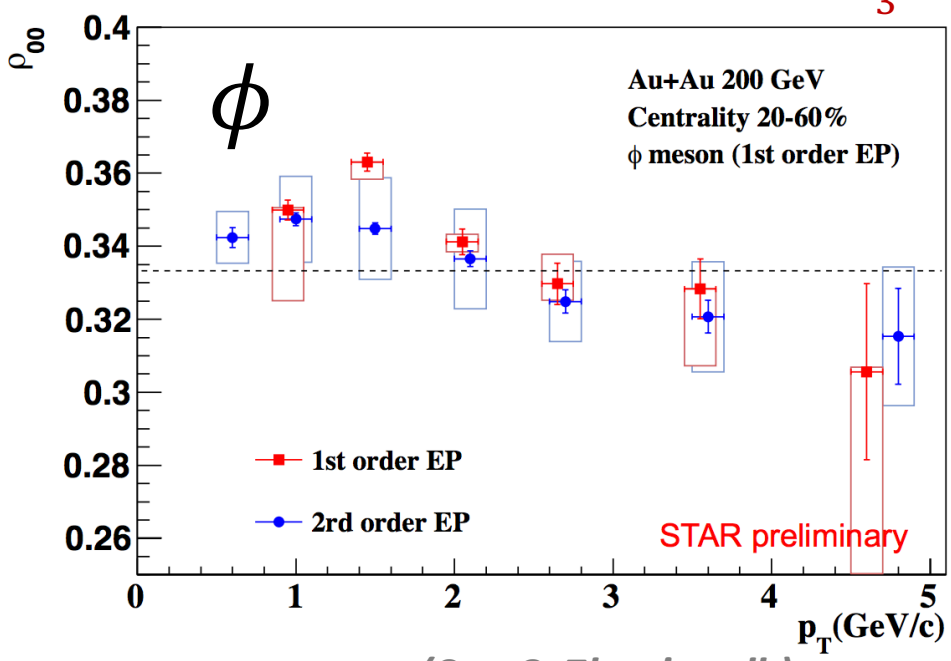
Full energy range ➡ **Full picture**

Global polarization via spin alignment



$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \{(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\}$$

STAR AuAu. First time $\rho_{00} > \frac{1}{3}$.



(See C. Zhou's talk)

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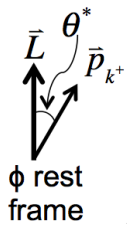

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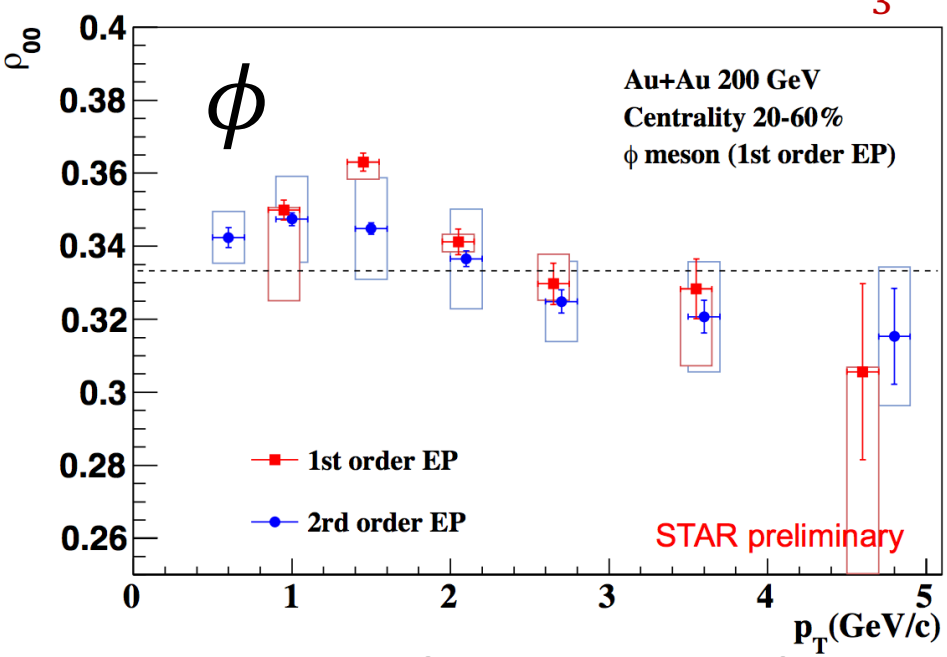
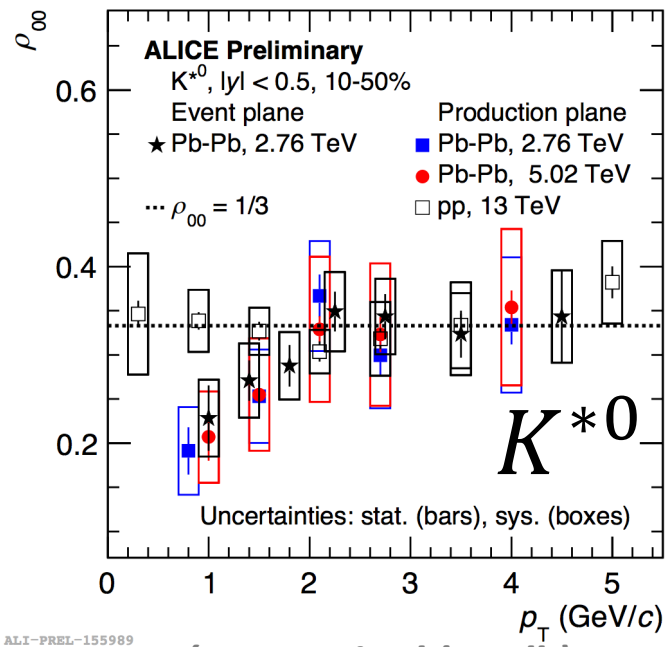


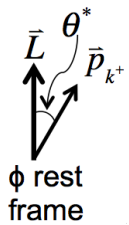
(See C. Zhou's talk)

ALICE PbPb. First time $\rho_{00} < \frac{1}{3}$?



(See R. Singh's talk)

Global polarization via spin alignment



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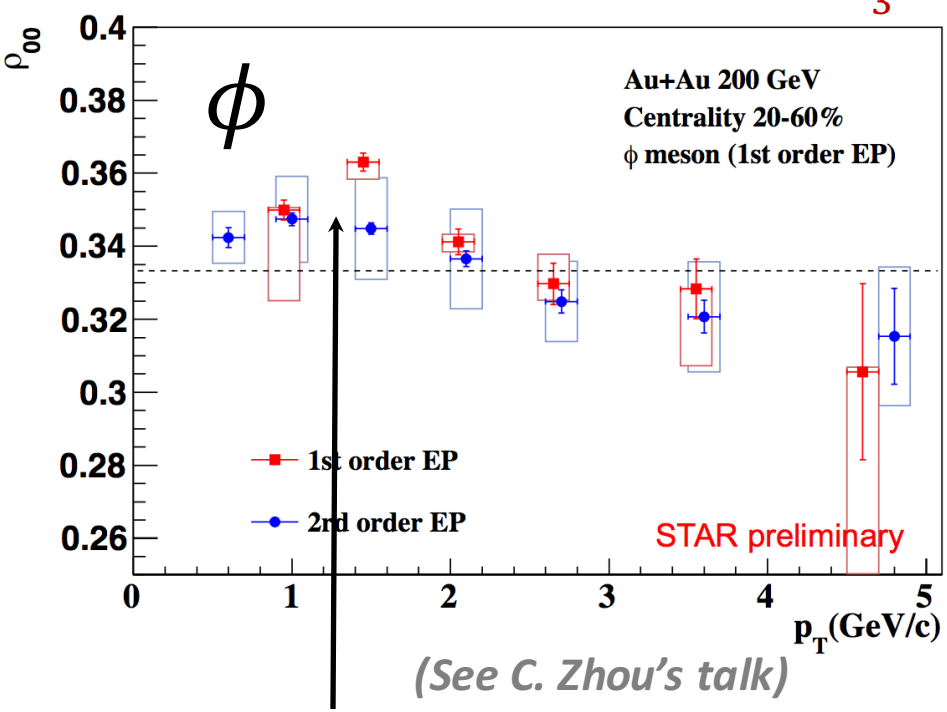

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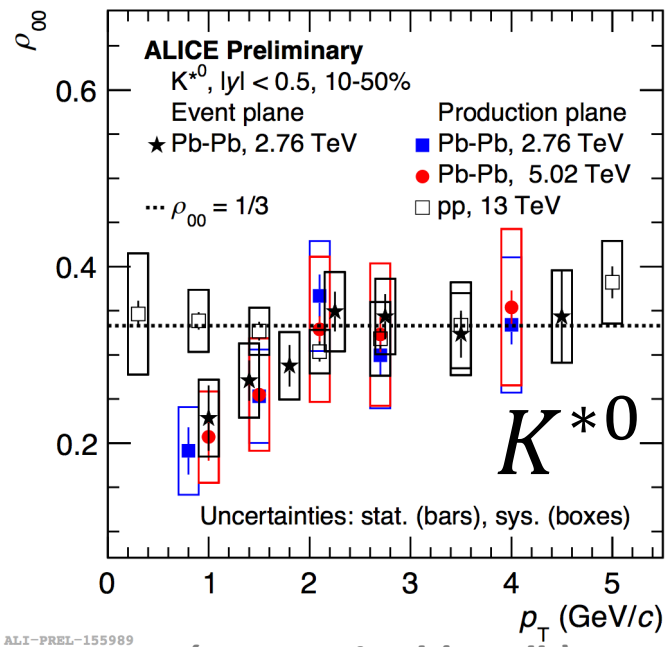
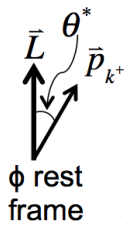


(See R. Singh's talk)

- Nontrivial dependence from STAR
- **Acceptance could play a role for ϕ?** *(See S. Shi's poster)*

Global polarization via spin alignment



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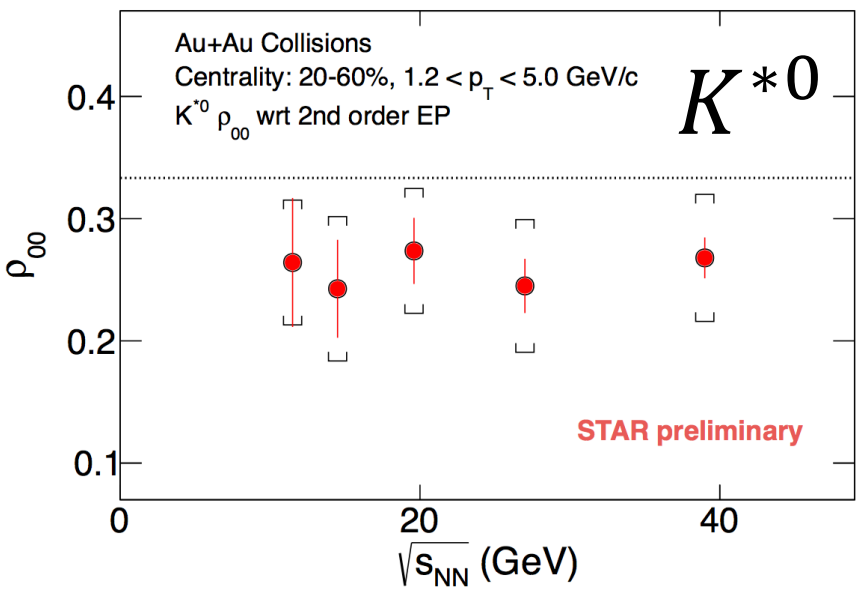

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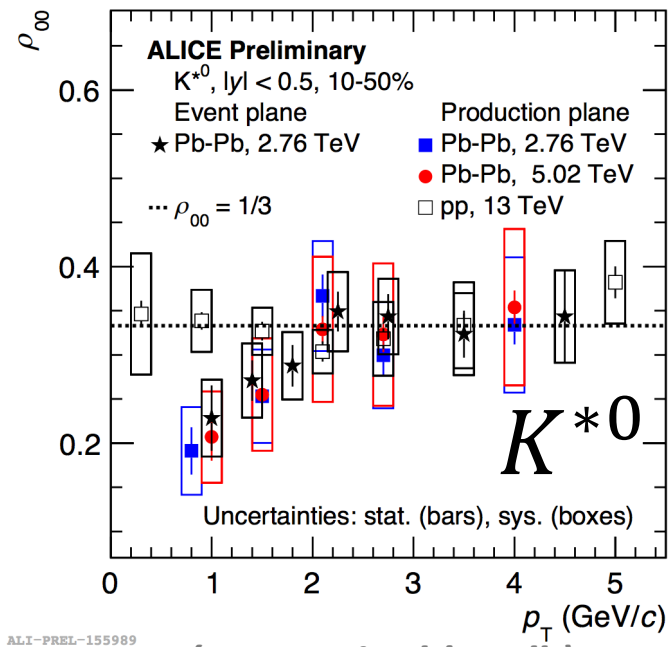


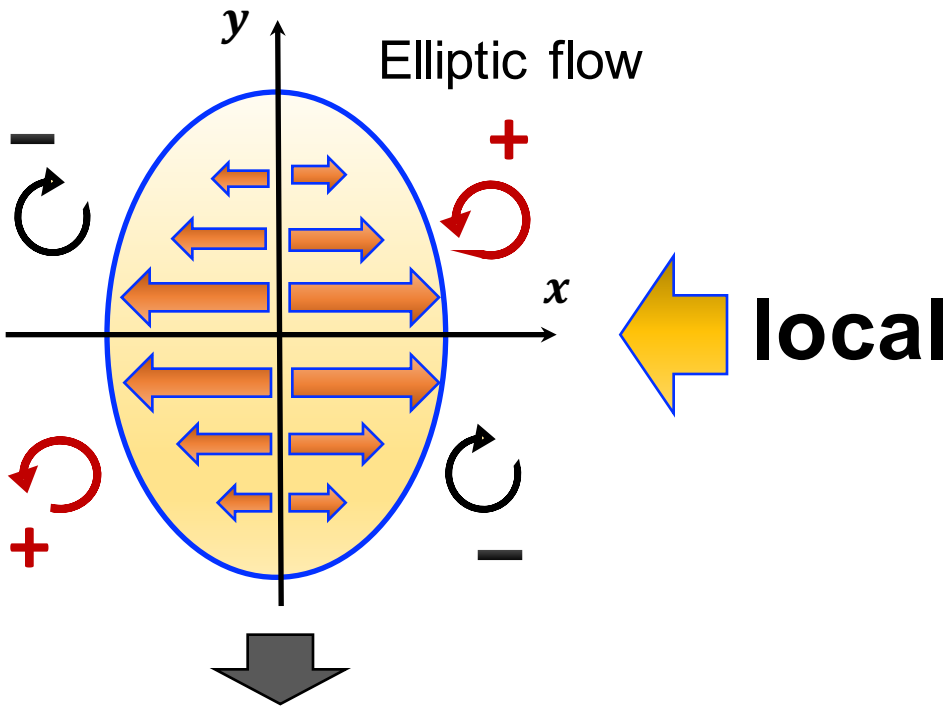
(See R. Singh's talk)

- Nontrivial dependence from STAR. **Species dependence?**
- **Polarization at LHC energy?**

Local polarization

Local polarization

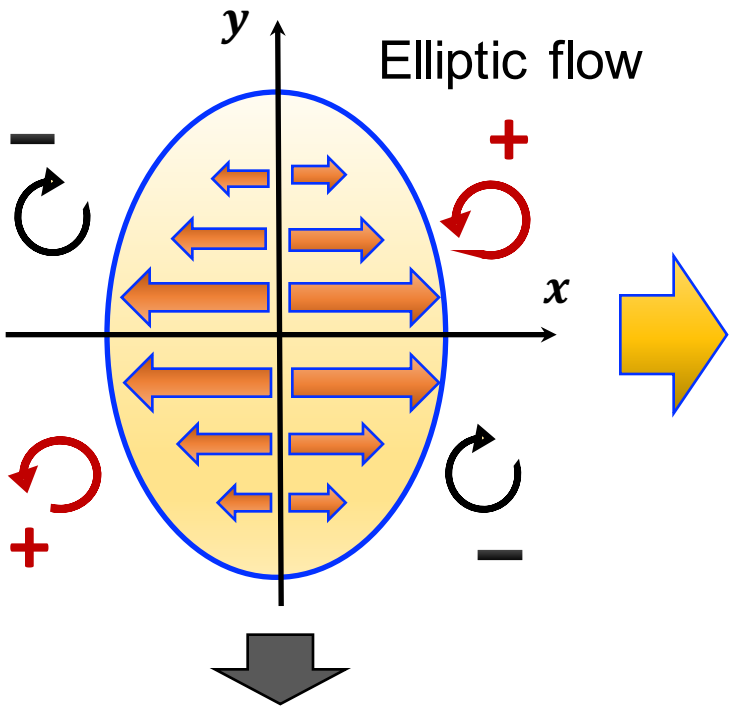
PRL 120, 012302 (2018)



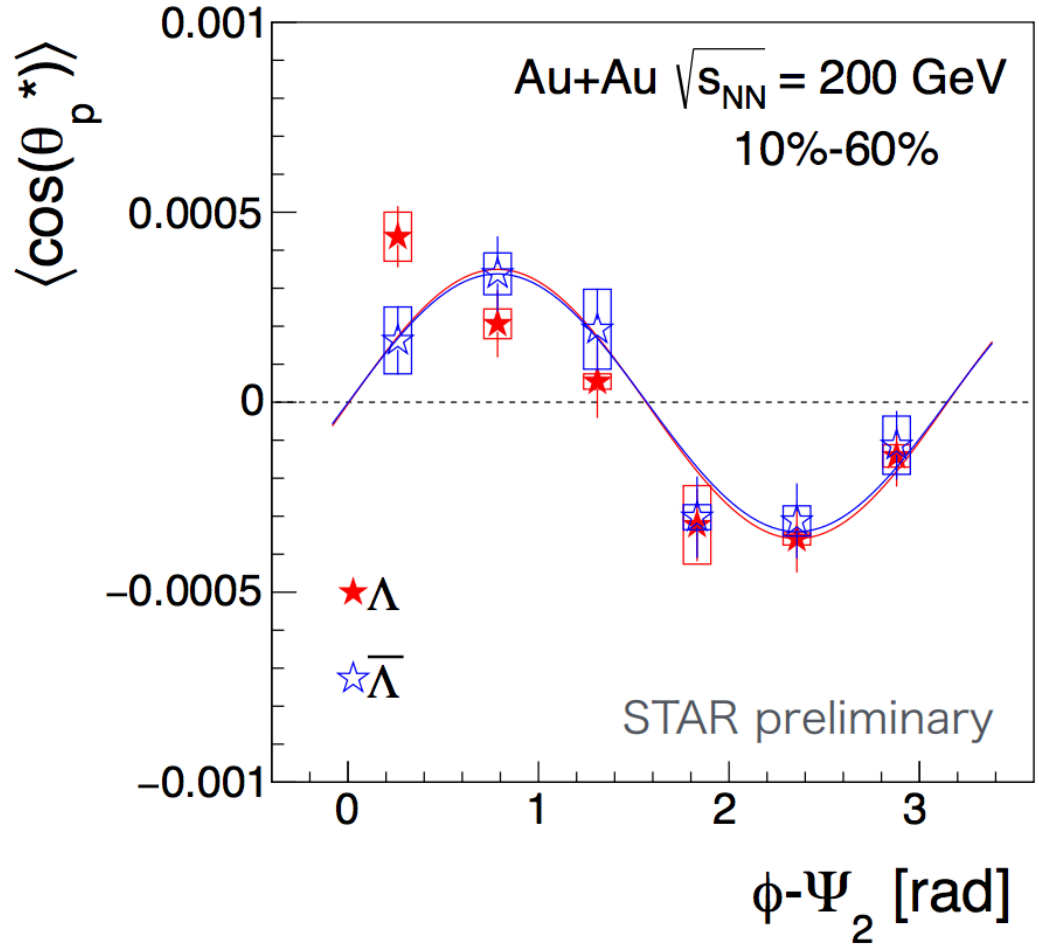
longitudinal polarization
(z-direction)
(ϕ-dependence)

Local polarization

PRL 120, 012302 (2018)



(See T. Niida's talk)



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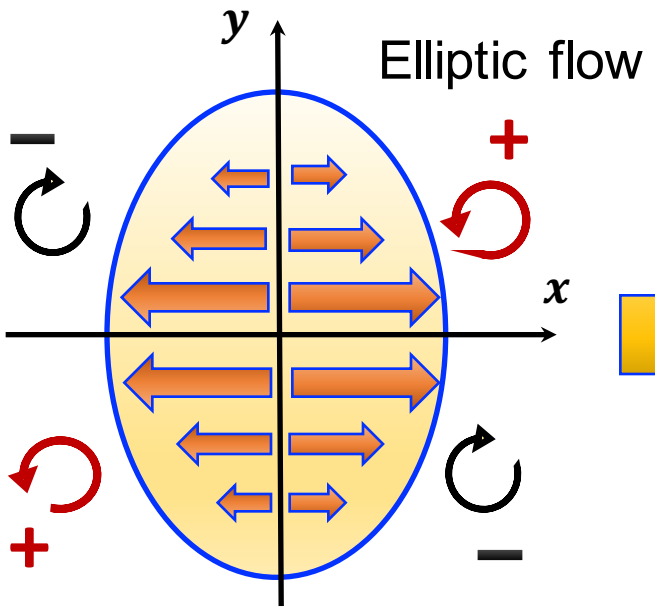
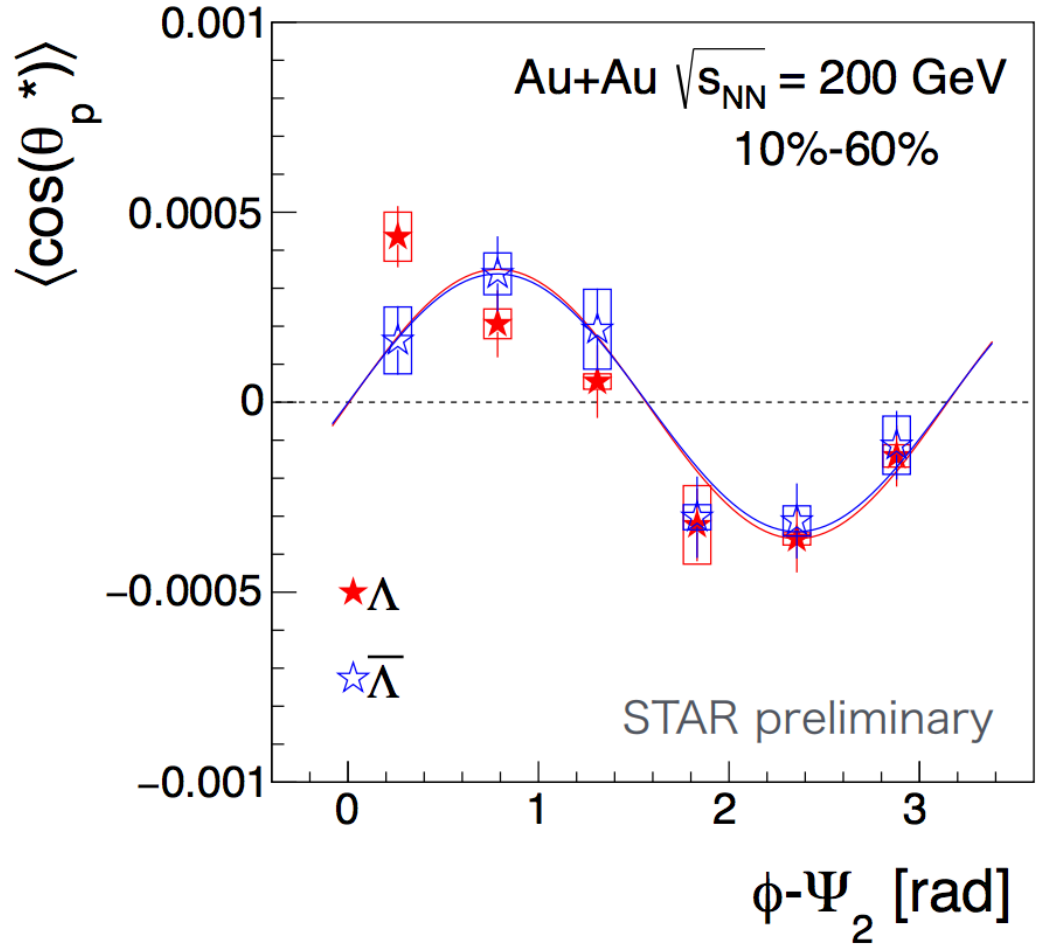
Local polarization

PRL 120, 012302 (2018)



(See T. Niida's talk)

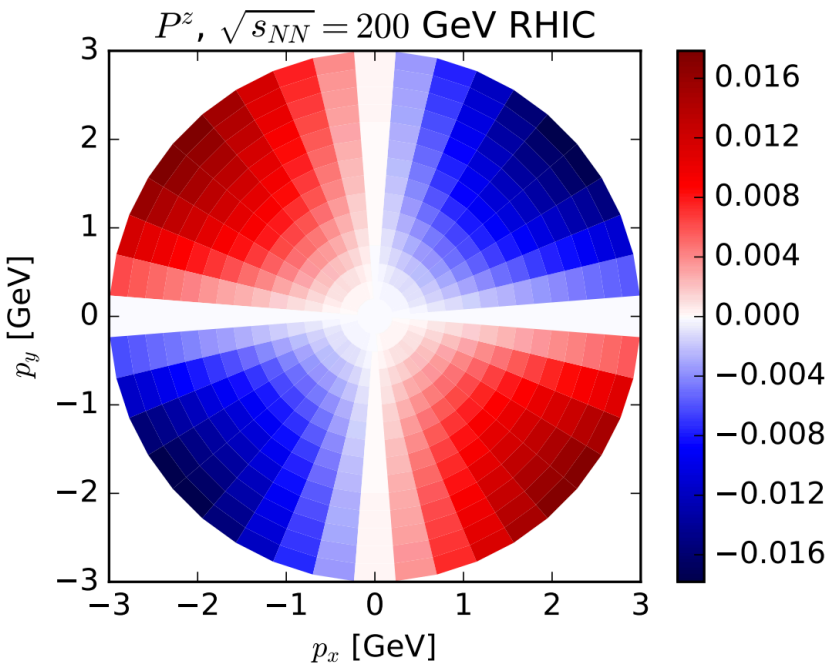


longitudinal polarization
(z-direction)
(ϕ-dependence)

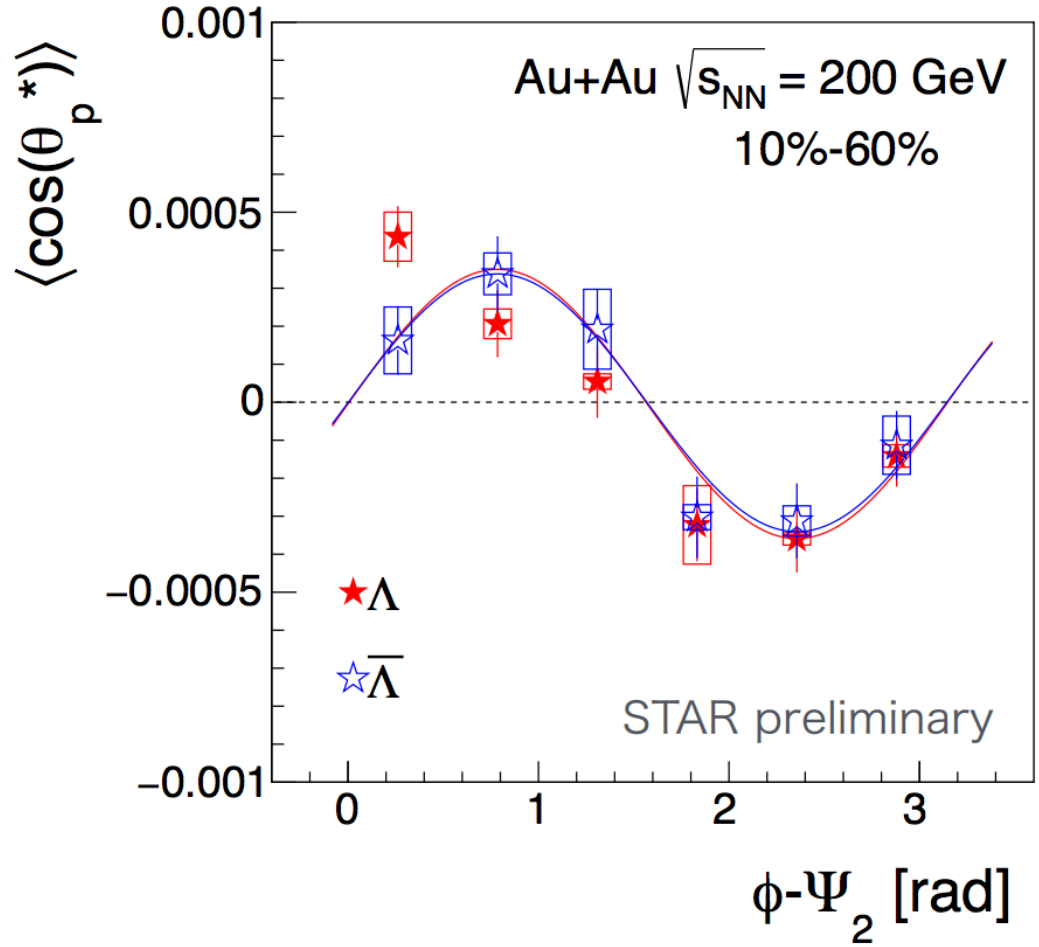
Qualitatively consistent with naïve expectation

Local polarization

(See I. Karpenko's talk)



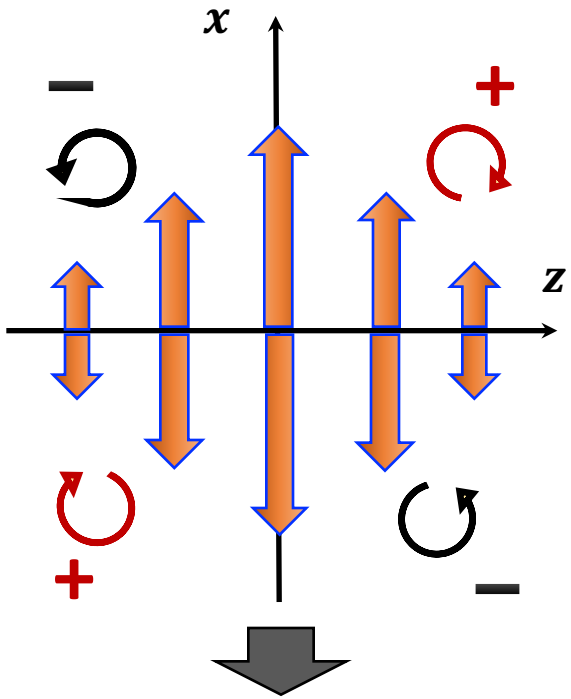
(See T. Niida's talk)



But opposite trend with full Hydro calculation

Local polarization

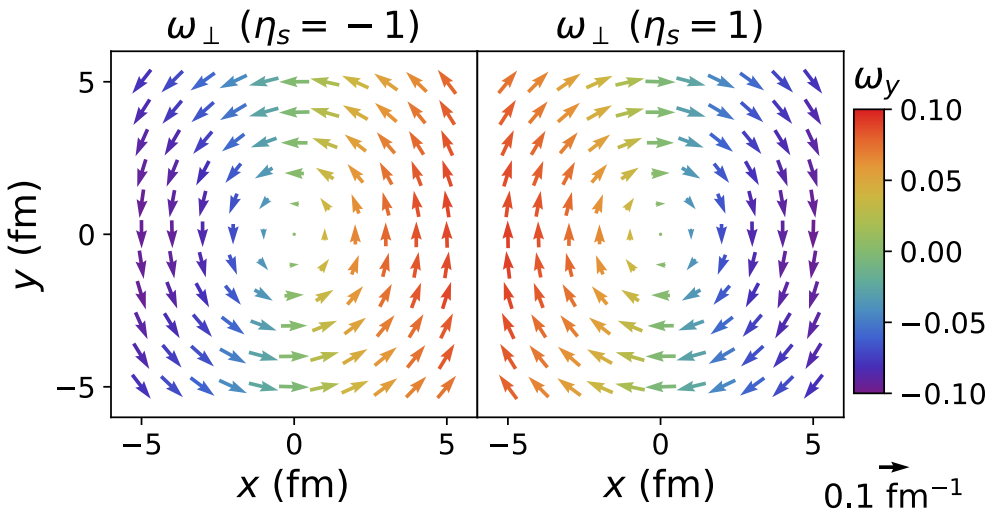
arXiv:1803.00867v1



circular polarization
(ϕ-direction)
(xz-dependence)

Local polarization

Symmetric collisions → Zero average



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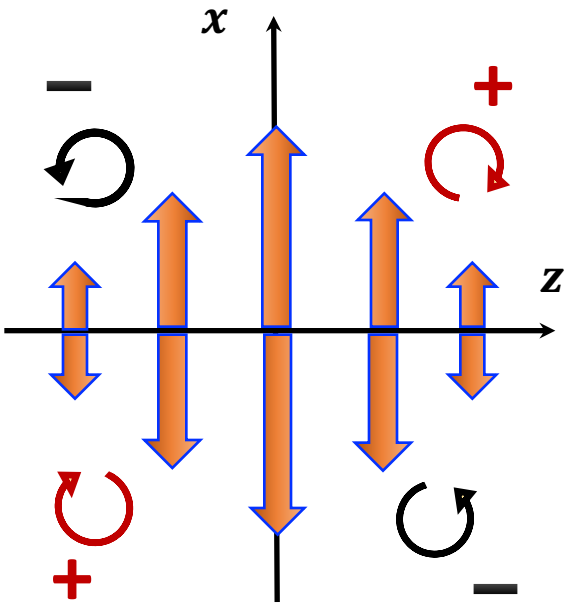

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(ϕ-direction)
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Local polarization

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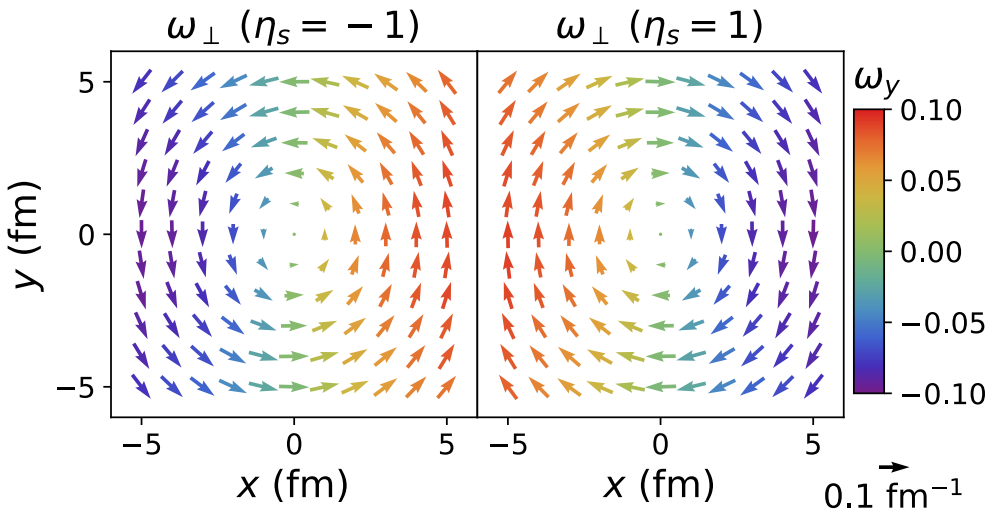

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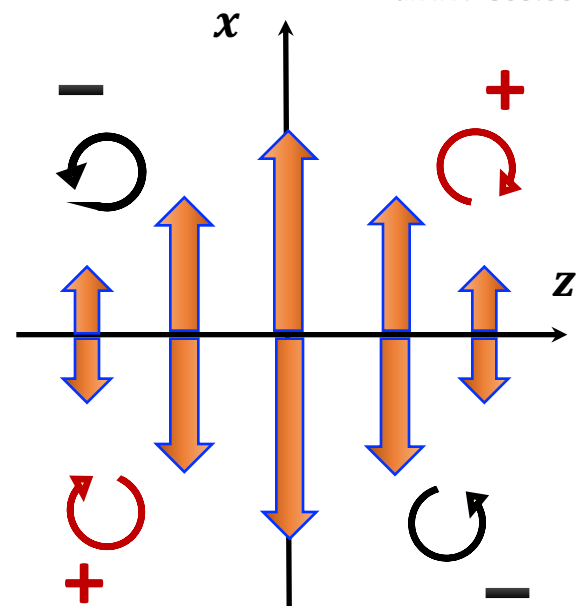


arXiv:1803.00867v1

circular polarization
(ϕ-direction)
(xz-dependence)

In asymmetric collisions:

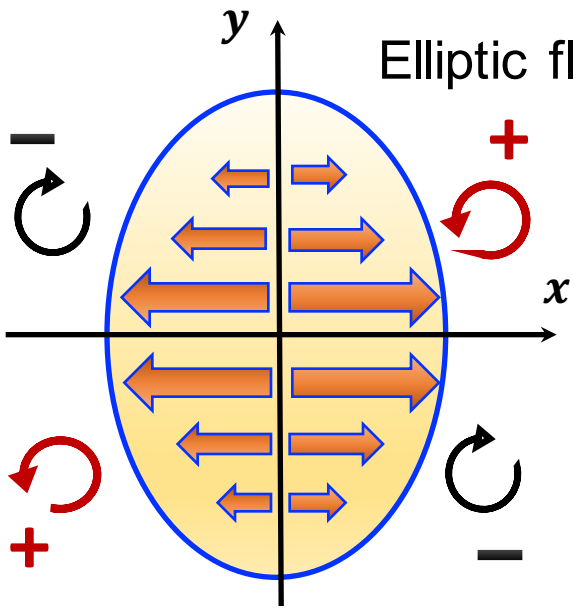
- nonzero on average
- e.g., Cu+Au?
- p+A, d+Au collisions?

Polarization in small systems?

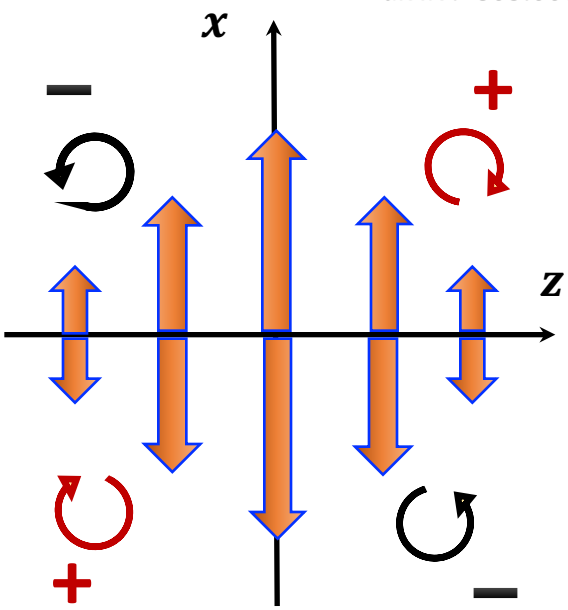
Local polarization

PRL 120, 012302 (2018)

arXiv:1803.00867v1



local



longitudinal polarization
(z-direction)
(ϕ-dependence)

circular polarization
(ϕ-direction)
(xz-dependence)

Local polarization

PRL 120, 012302 (2018)

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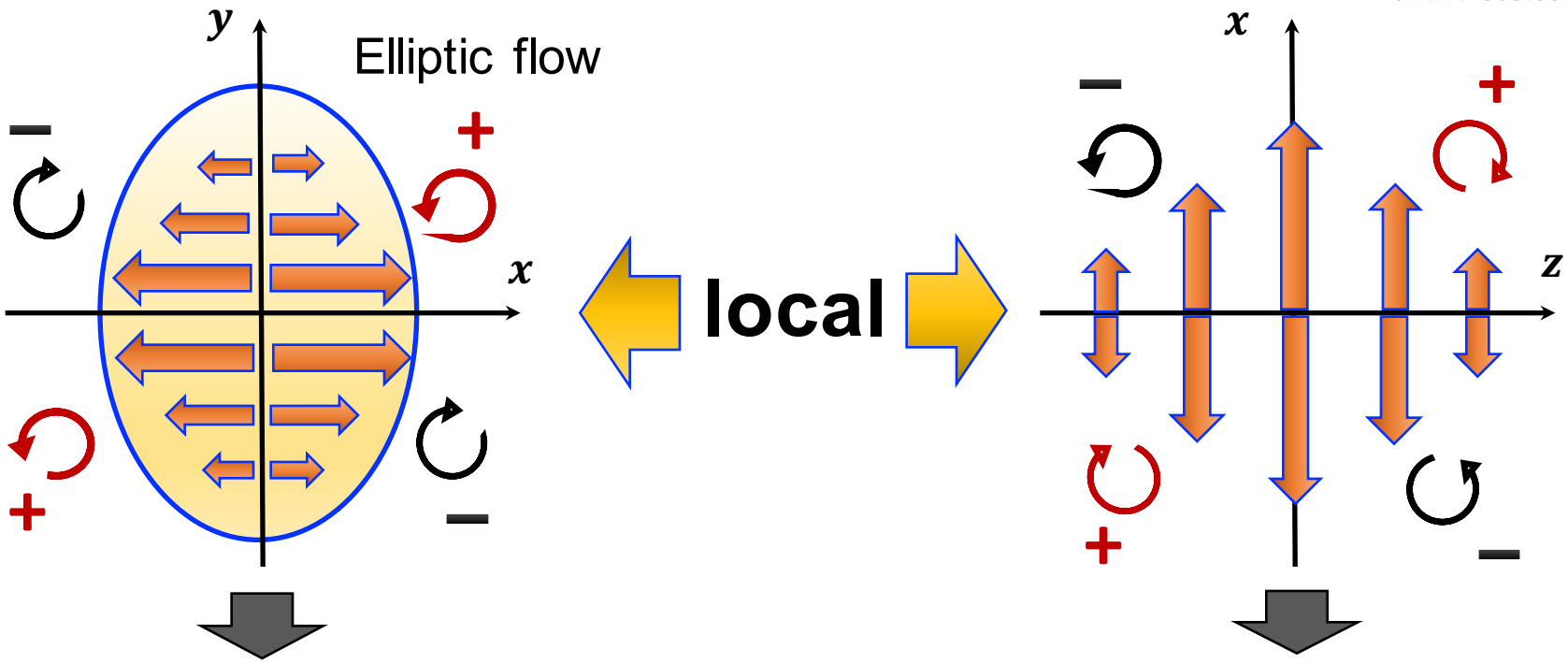

longitudinal polarization
(z-direction)
(ϕ-dependence)

circular polarization
(ϕ-direction)
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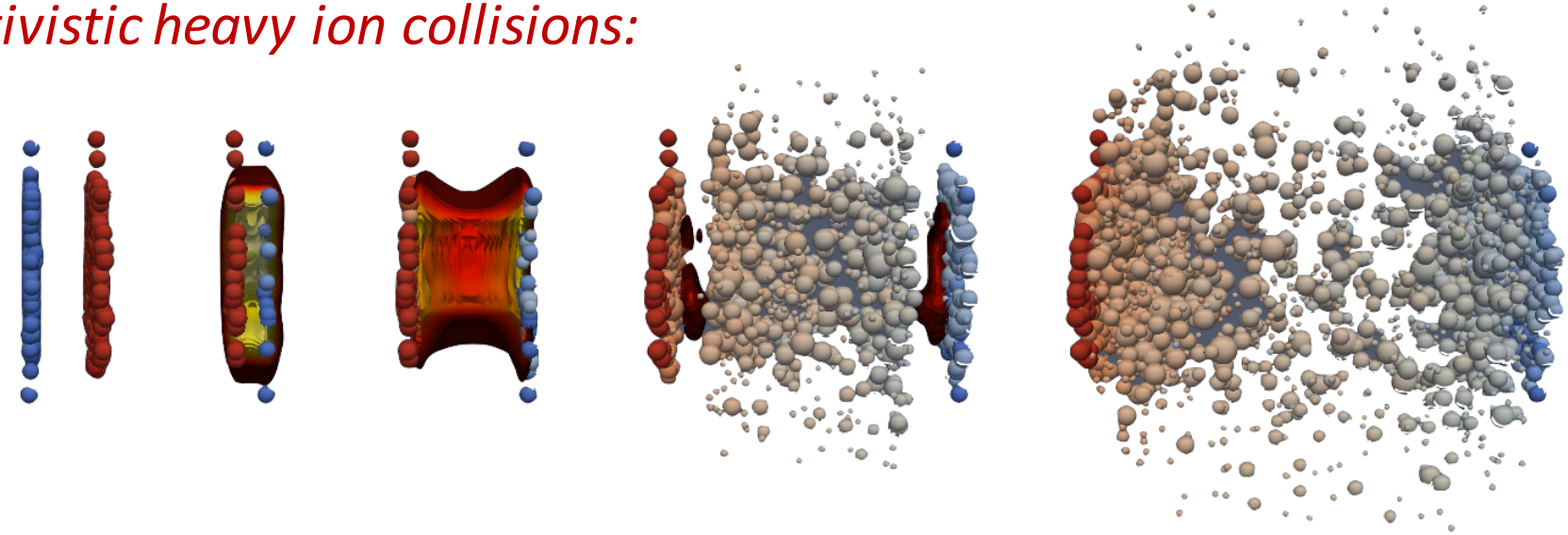
Large *local* polarization predicted at the LHC energy

(See predictions from Becattini's talk)

Chiral Magnetic Effect

Relativistic heavy ion collisions:



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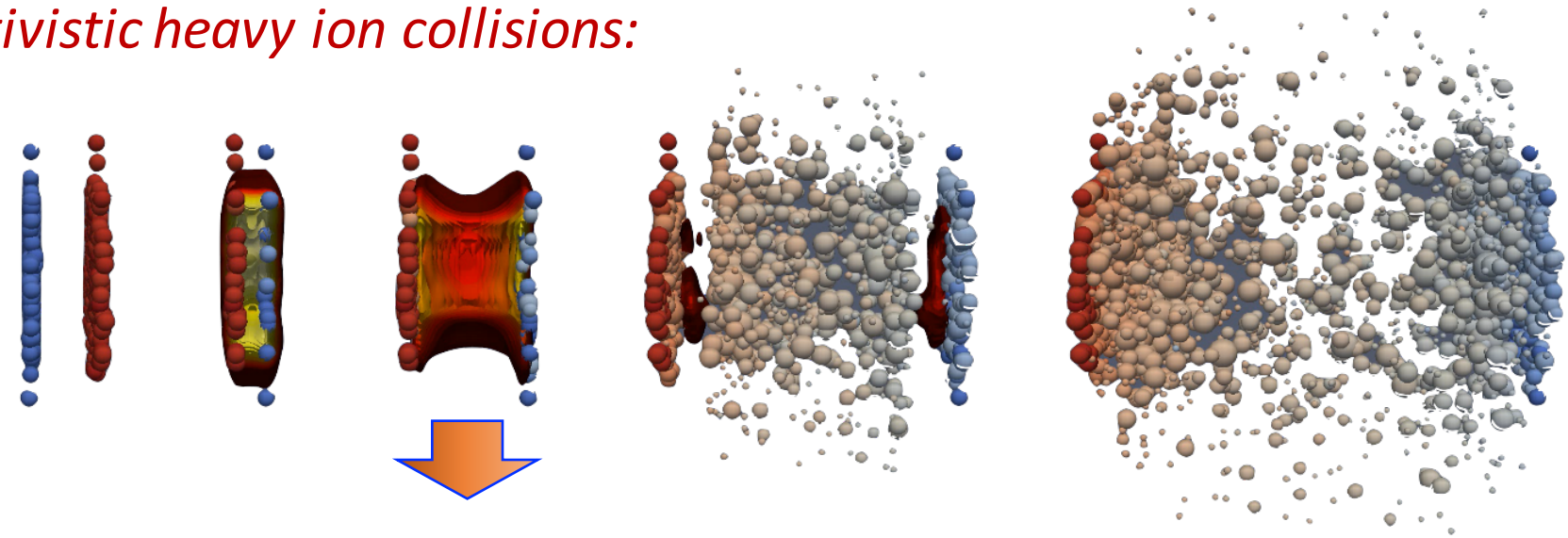

- Local strong P and CP violation
- Deconfinement, chiral symmetry restoration
- Initial strong magnetic field

Chiral Magnetic Effect

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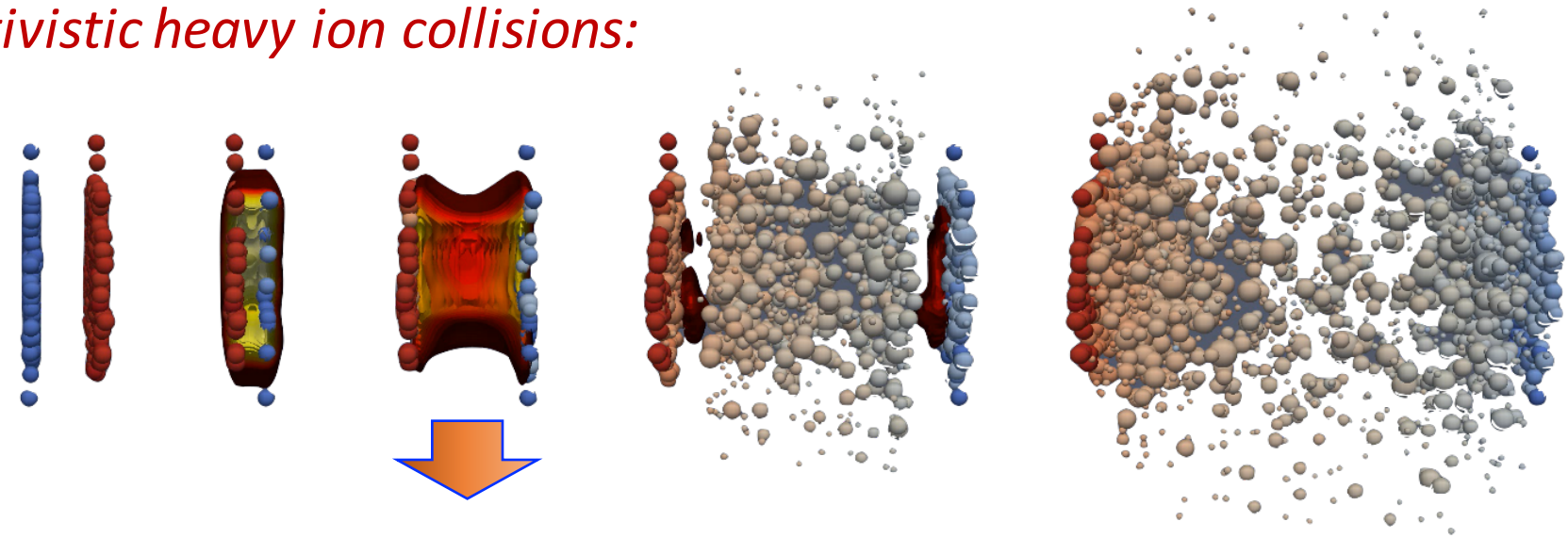

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Charge separation relative to reaction plane

Chiral Magnetic Effect

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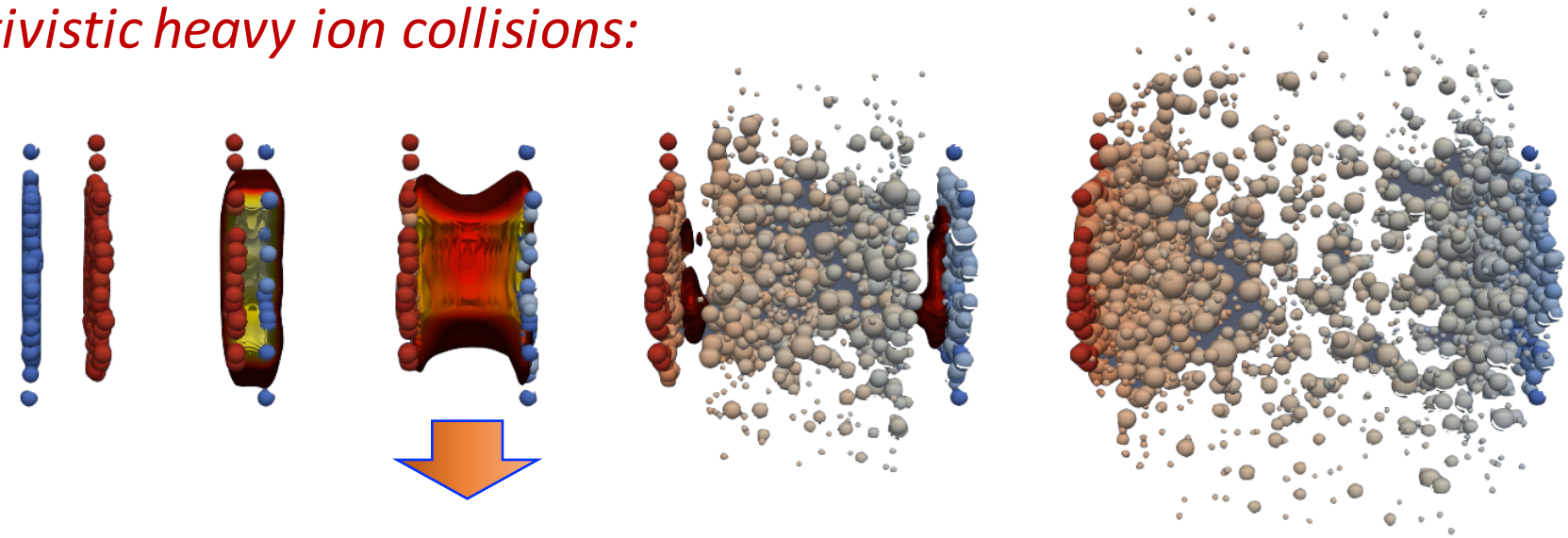

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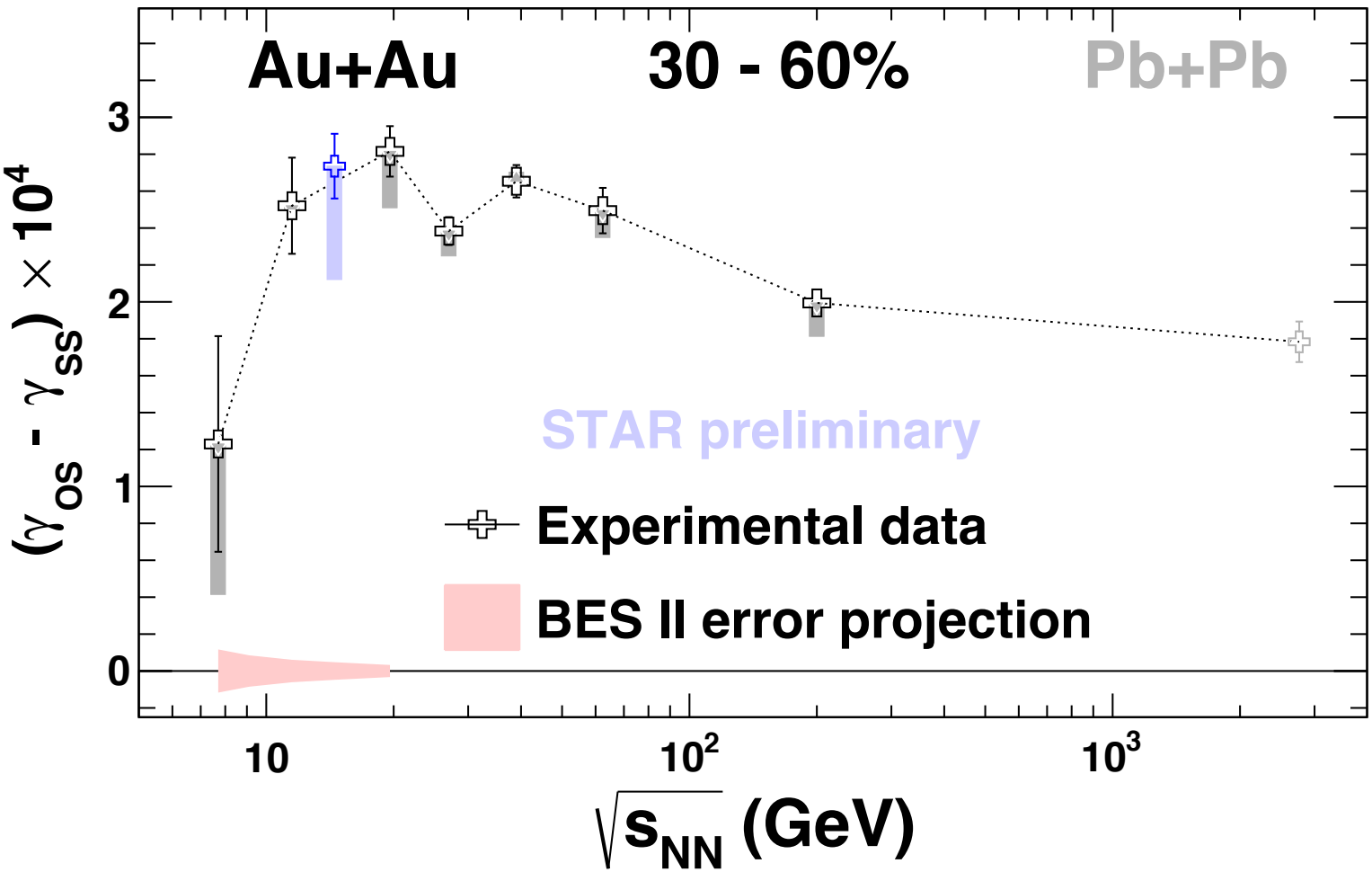
Charge separation relative to reaction plane

Three birds with one stone!

Where should we look for CME?



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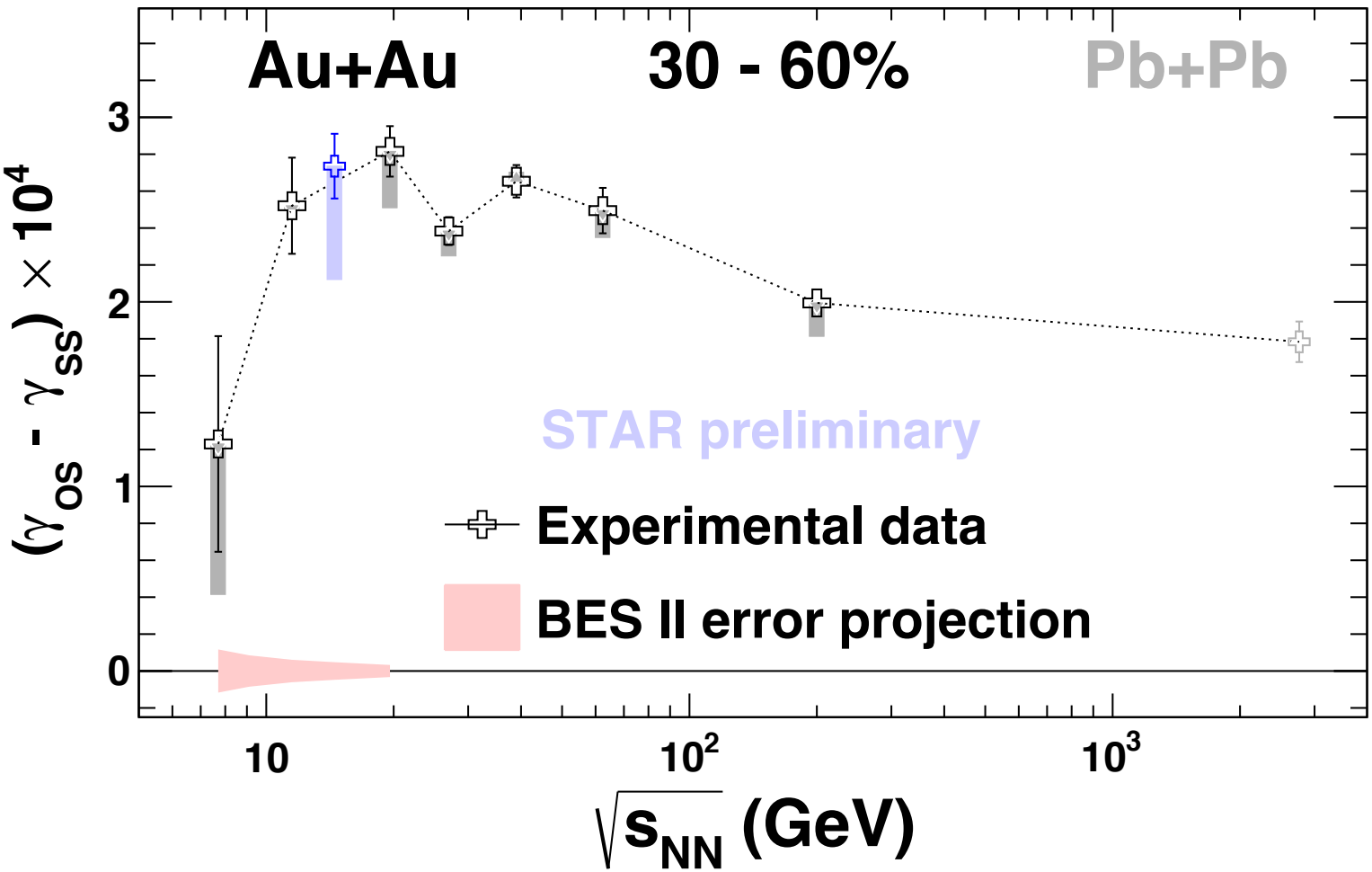
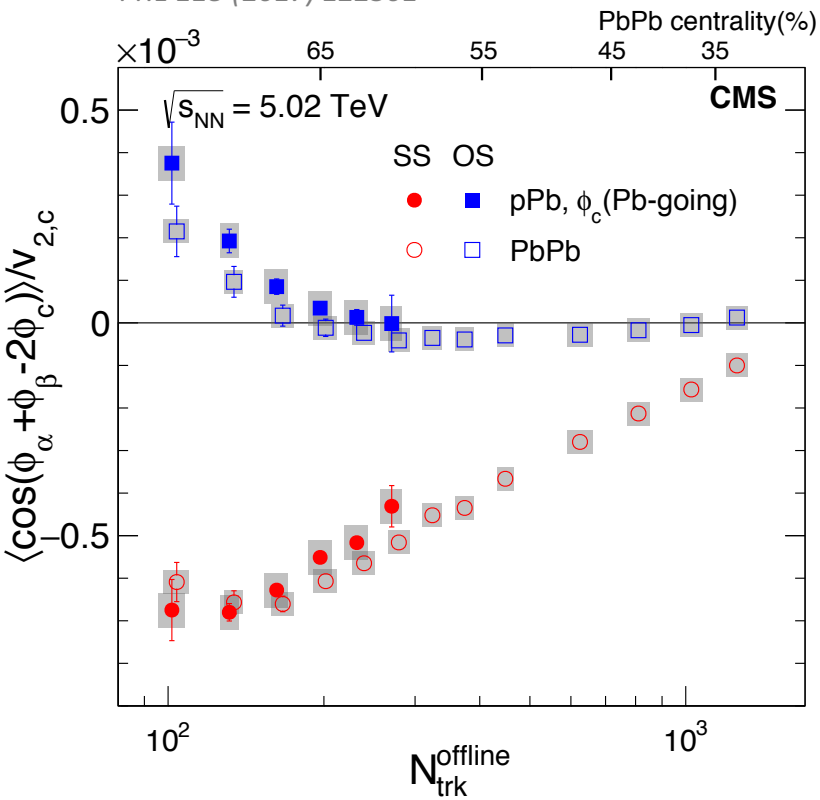


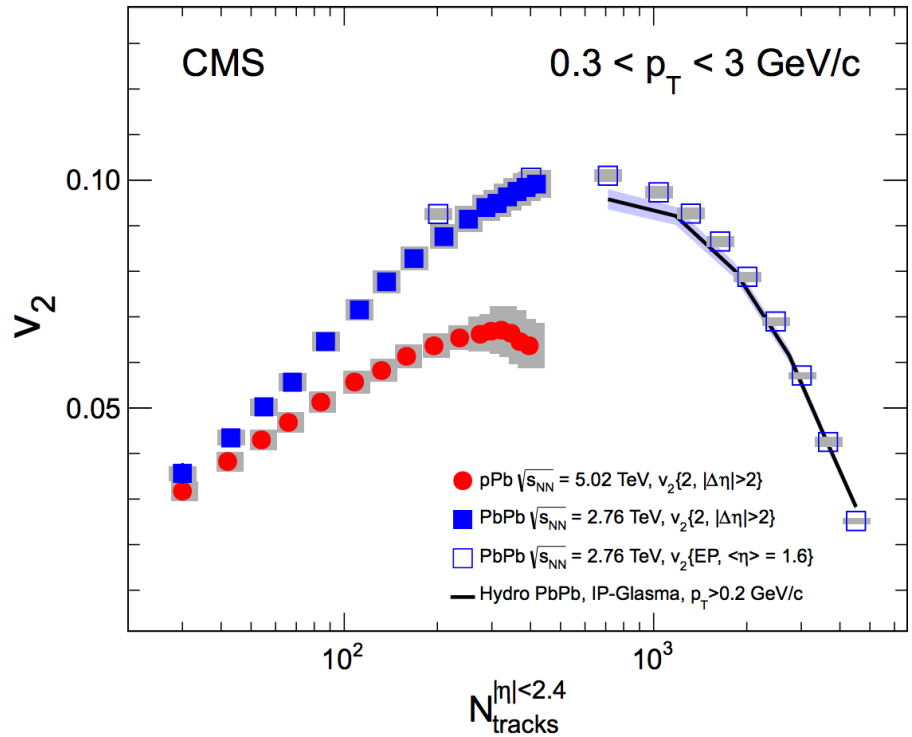
Energy dependence?

From QM 2017

PRL 118 (2017) 122301



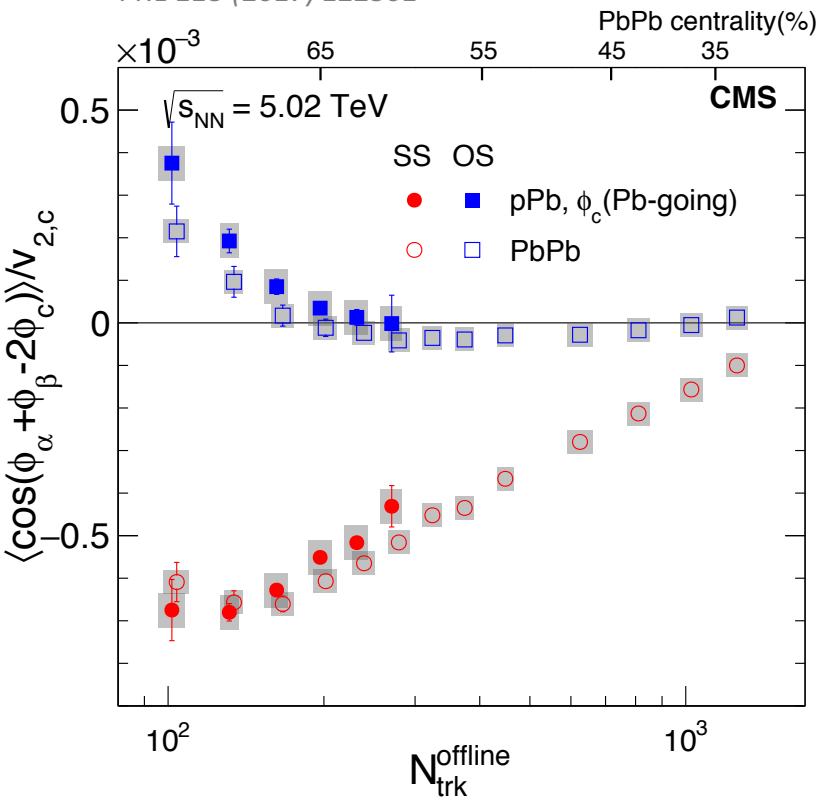
Int.J.Mod.Phys. E25 (2016) no.01, 1630002



Background is indeed present. But what is it?

From QM 2017

PRL 118 (2017) 122301



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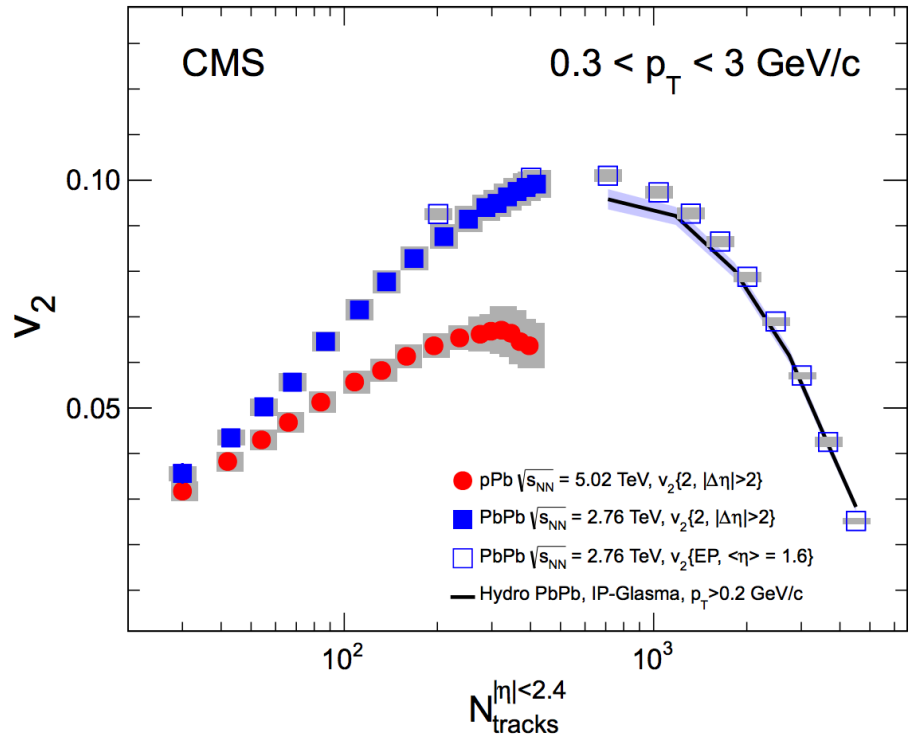

Background is indeed present. But what is it?

$$\gamma \equiv \gamma_{112} = \kappa \cdot v_2 \cdot \delta + \gamma_{cme} \ ?$$

$$\langle cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3)\rangle \equiv \gamma_{123} = \kappa \cdot v_3 \cdot \delta \ ?$$

Lect.Notes Phys. 871 (2013) 503-536 *Phys.Rev. C97 (2018), 044912*

Test the background

Ψ_2

Correlate with B

CME

$$\frac{\Delta\gamma_{112}}{v_2 \cdot \Delta\delta} = \kappa_2$$

$$\kappa_3 = \frac{\Delta\gamma_{123}}{v_3 \cdot \Delta\delta}$$

Ψ_3

Decorrelate with B

Background

Test the background

Ψ_2

Correlate with B

CME

$$\frac{\Delta\gamma_{112}}{v_2 \cdot \Delta\delta} = \kappa_2 \approx \kappa_3 = \frac{\Delta\gamma_{123}}{v_3 \cdot \Delta\delta}$$

Background scenario

Ψ_3

Decorrelate with B

Background

Test the background

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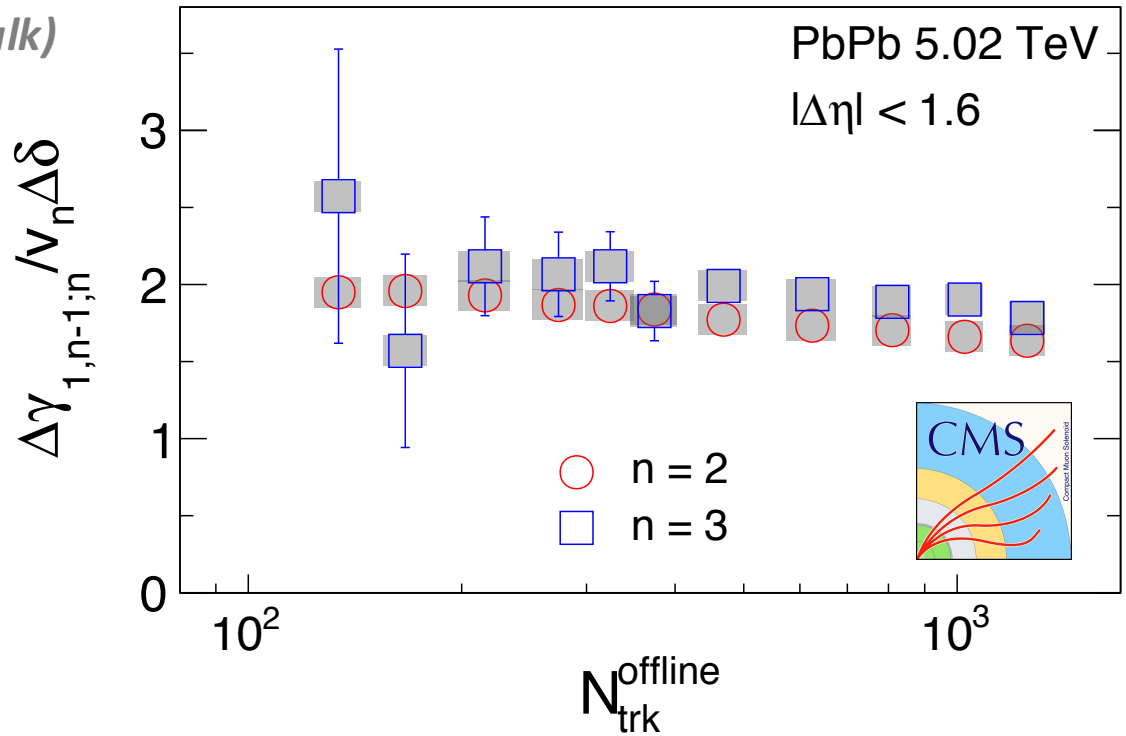
Ψ_3

Decorrelate with B

Background

Background scenario

(See Z. Tu's talk)



Test the background

Ψ_2

Correlate with B

CME

$$\frac{\Delta\gamma_{112}}{v_2 \cdot \Delta\delta} = \kappa_2 \approx \kappa_3 = \frac{\Delta\gamma_{123}}{v_3 \cdot \Delta\delta}$$

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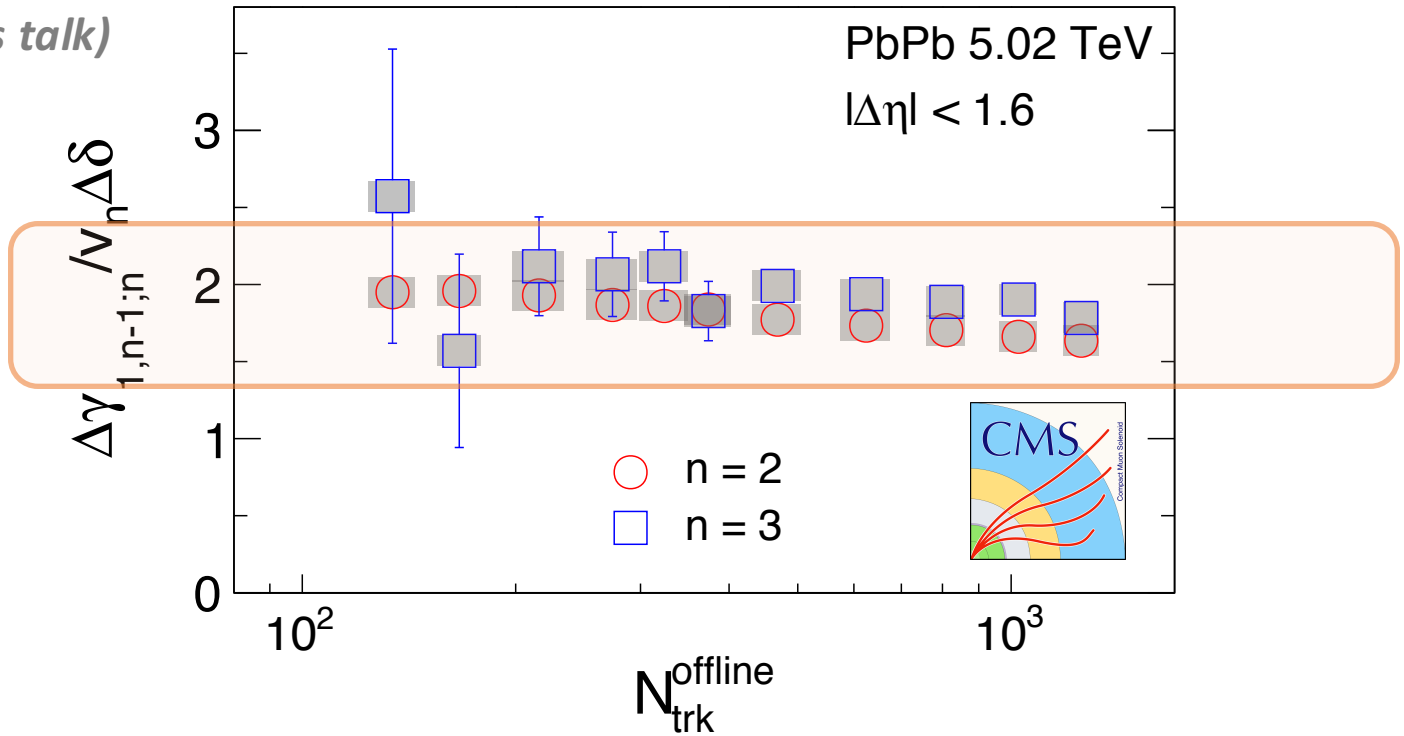
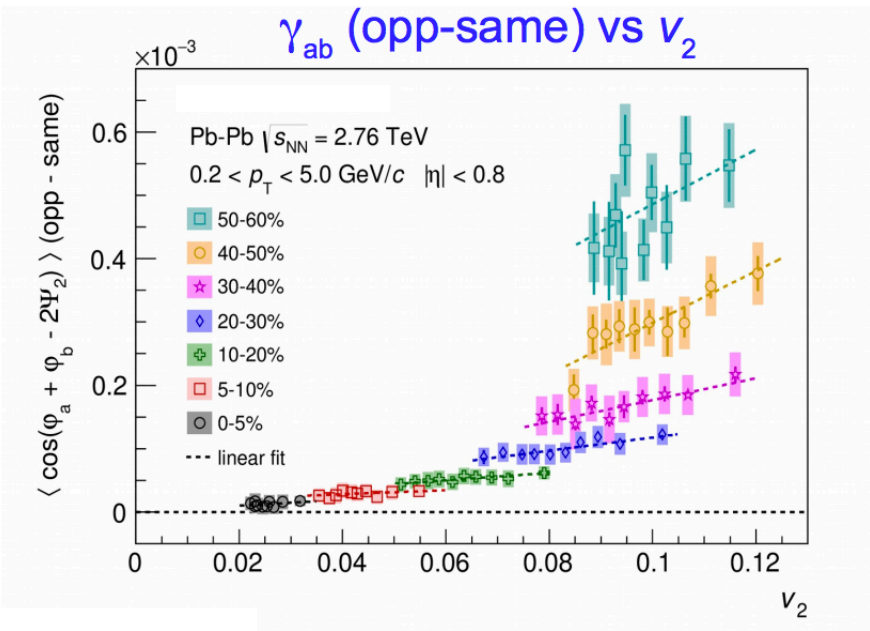


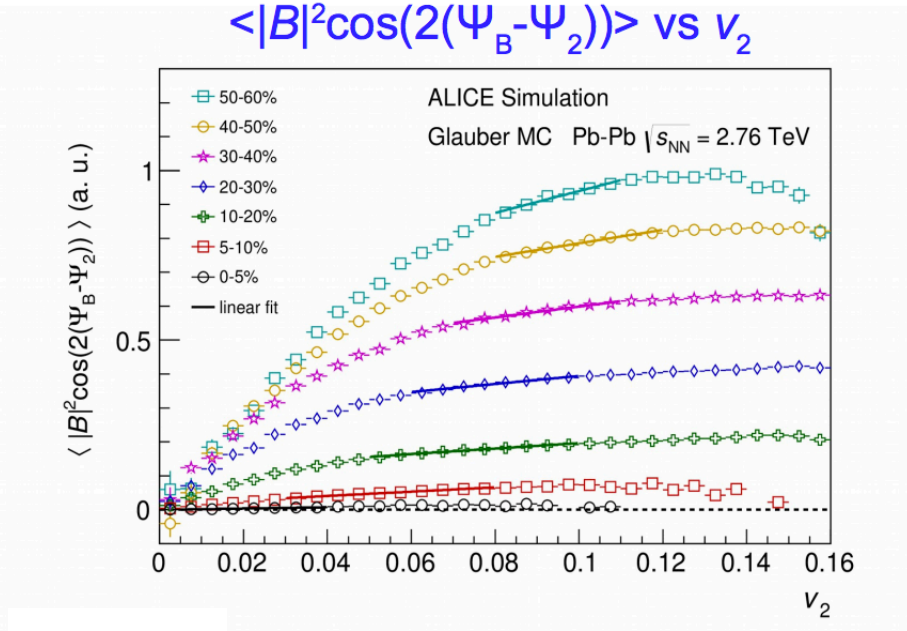
Consistent with 100% background at the LHC

Extracting CME signal at the LHC

- Event Shape Engineering (v_2)

QM 2017 ALICE





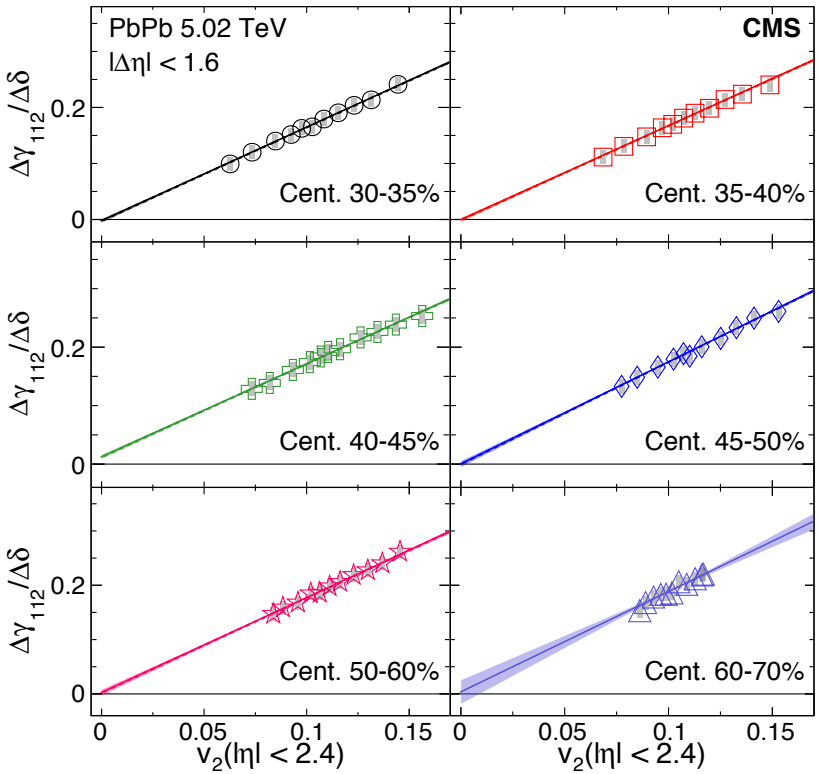
$$\gamma_{ab} = \langle \cos(\varphi_a + \varphi_b - 2\Psi_2) \rangle$$

Glauber: M. Miller et al, ARNPS 57, 205 (2007)

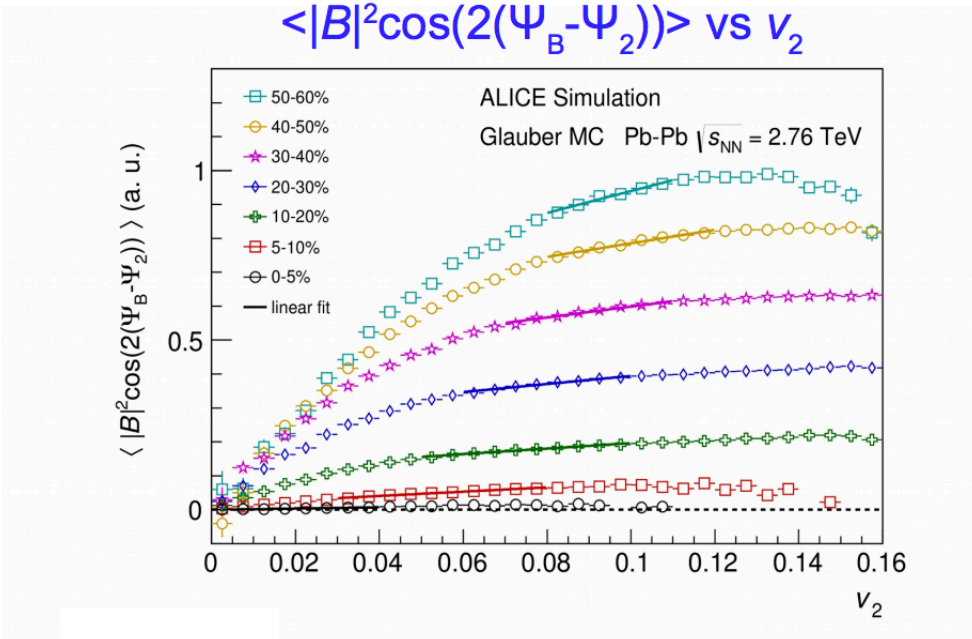
Extracting CME signal at the LHC

- Event Shape Engineering (v_2)

(See Z. Tu's talk)



QM 2017 ALICE



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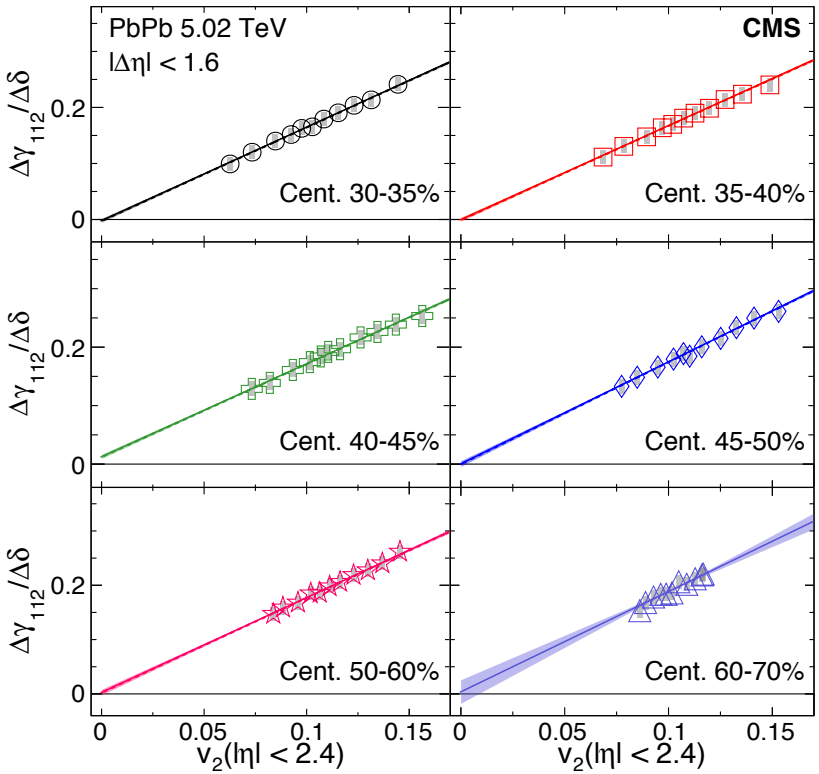

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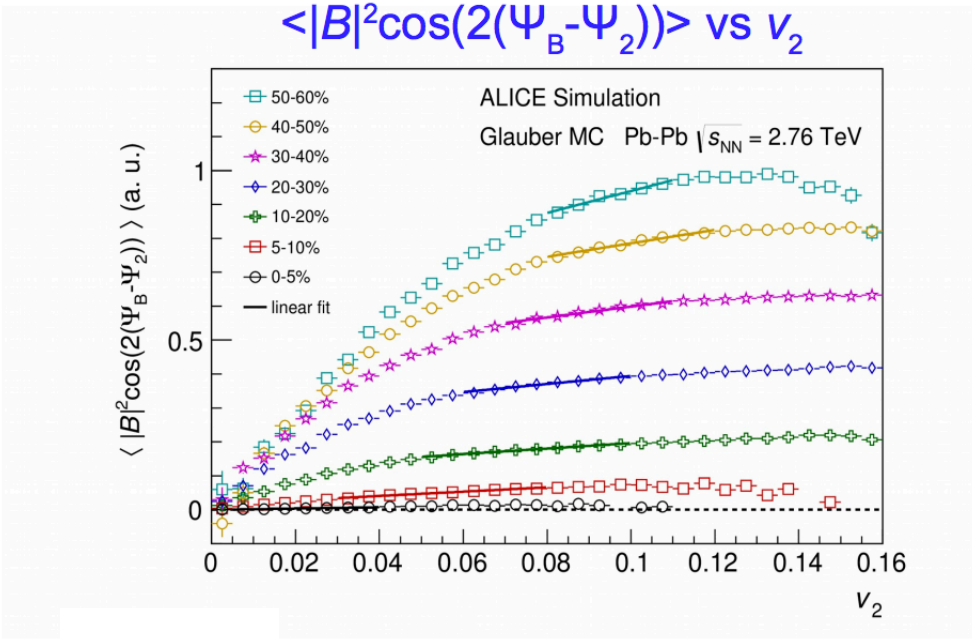


Glauber: M. Miller et al, ARNPS 57, 205 (2007)

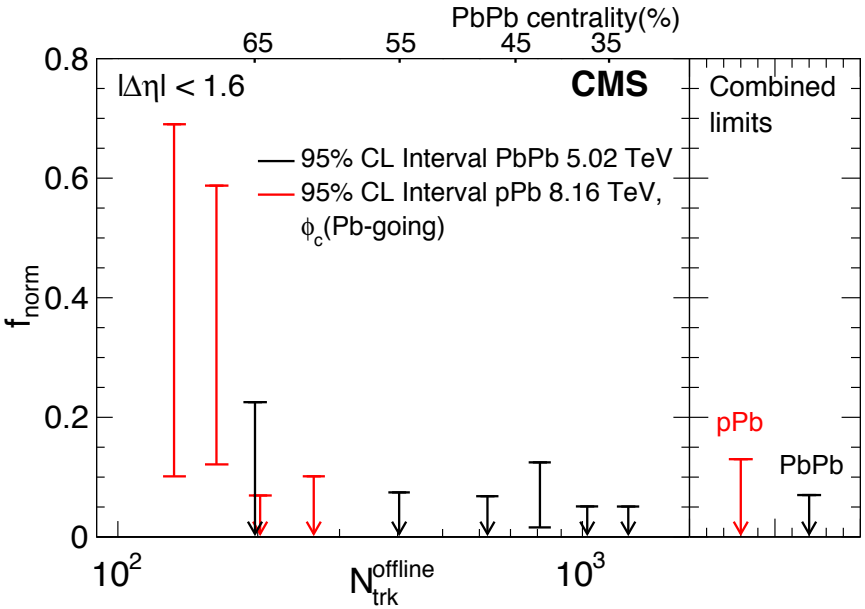
Reach the same conclusion?

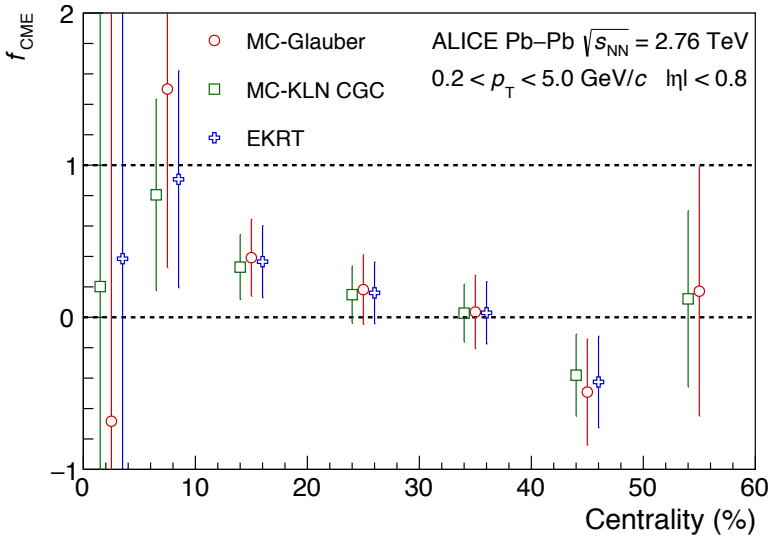
Extracting CME signal at the LHC

- Event Shape Engineering (v_2)

(See Z. Tu's talk)

QM 2017 ALICE



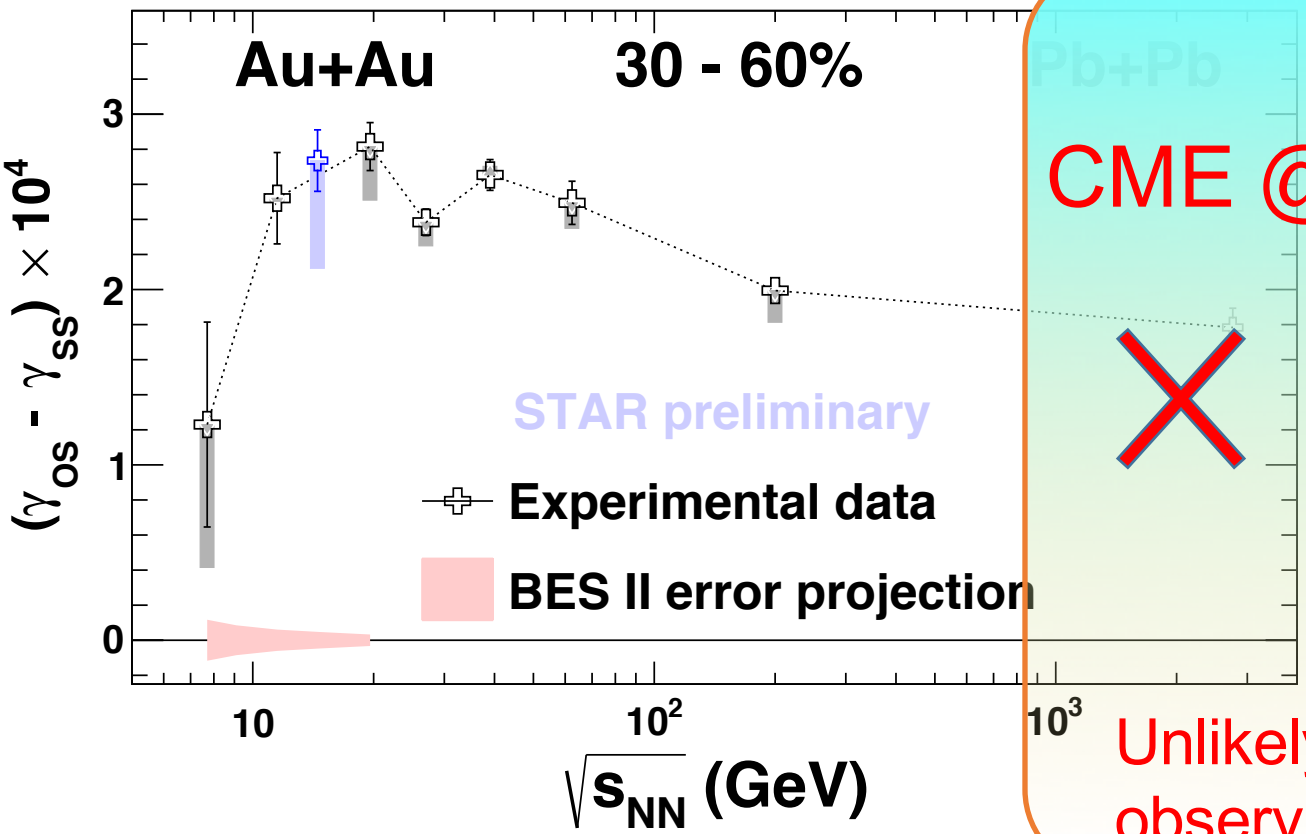


~7% in AA
(95% C.L)

f_{sig}

~30% in AA
(95% C.L)

How about RHIC energy?

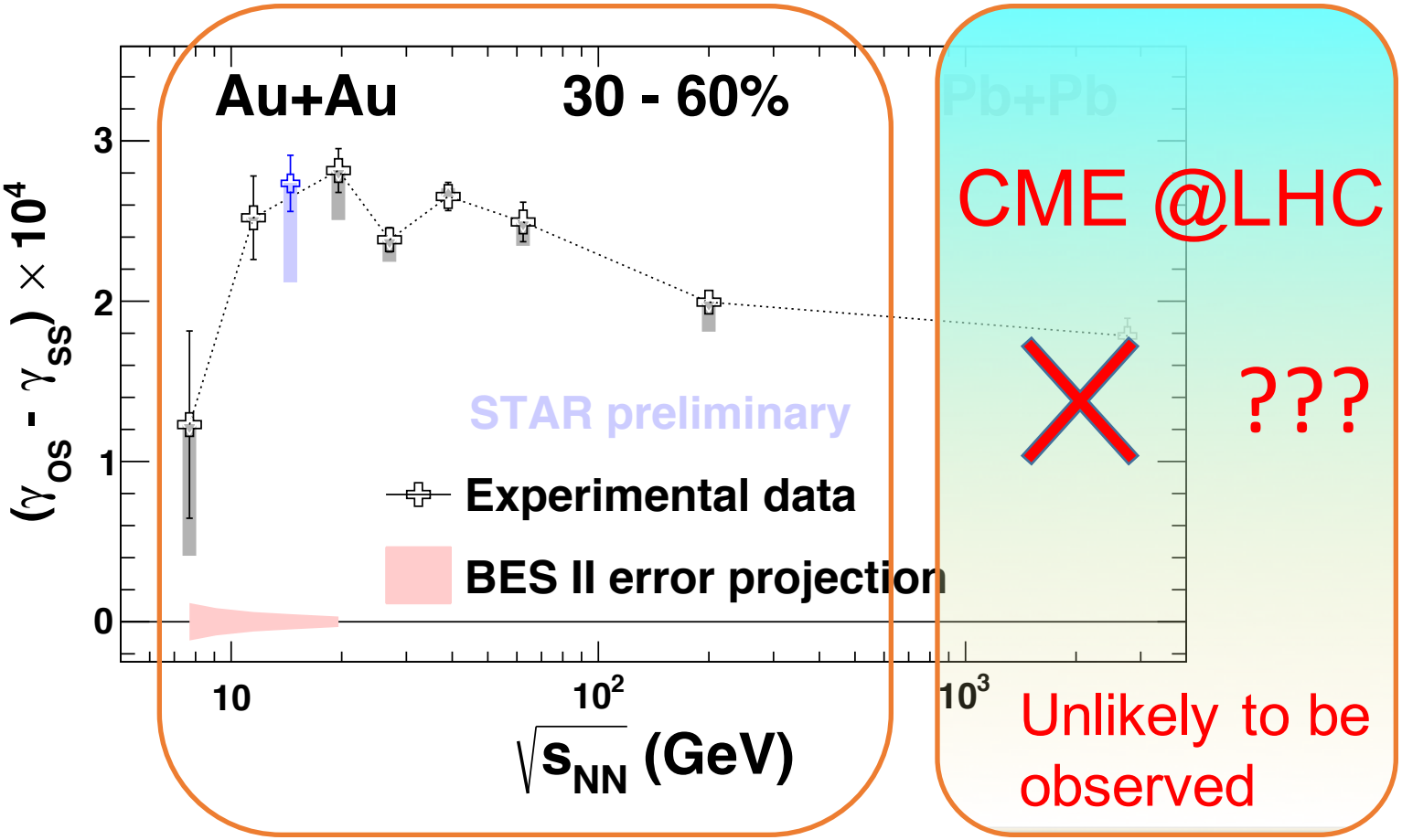


CME @LHC

???

Unlikely to be observed

How about RHIC energy?



Magnetic field last longer at RHIC energy?

Test the background @ RHIC

Test the background @ RHIC

Ψ_2

Correlate with B

CME

$$\frac{\Delta\gamma_{112}}{v_2 \cdot \Delta\delta} = \kappa_2 \approx \kappa_3 = \frac{\Delta\gamma_{123}}{v_3 \cdot \Delta\delta}$$

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Decorrelate with B

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Test the background @ RHIC

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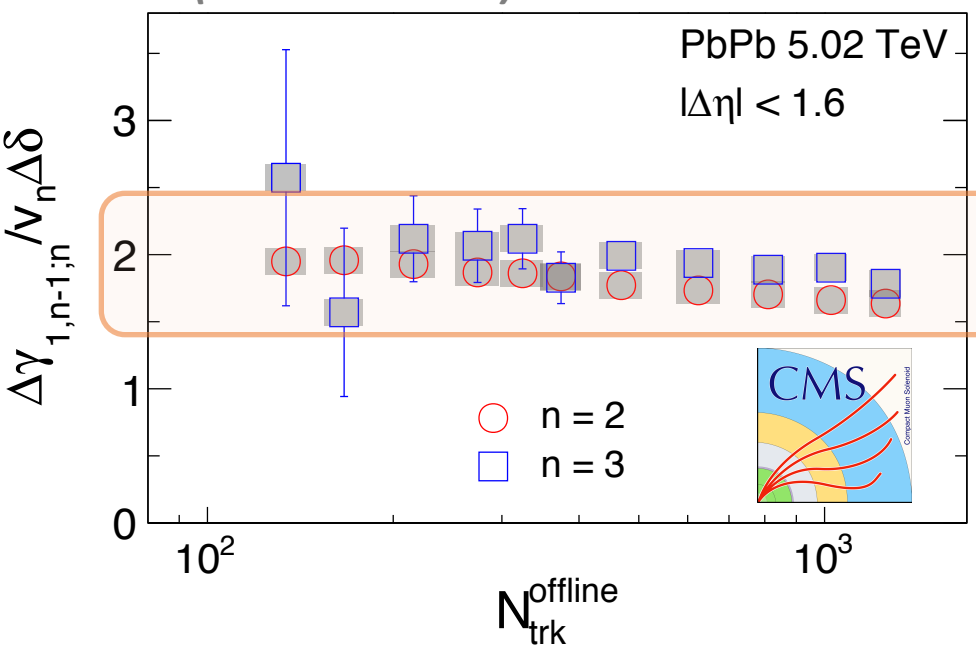
Decorrelate with B

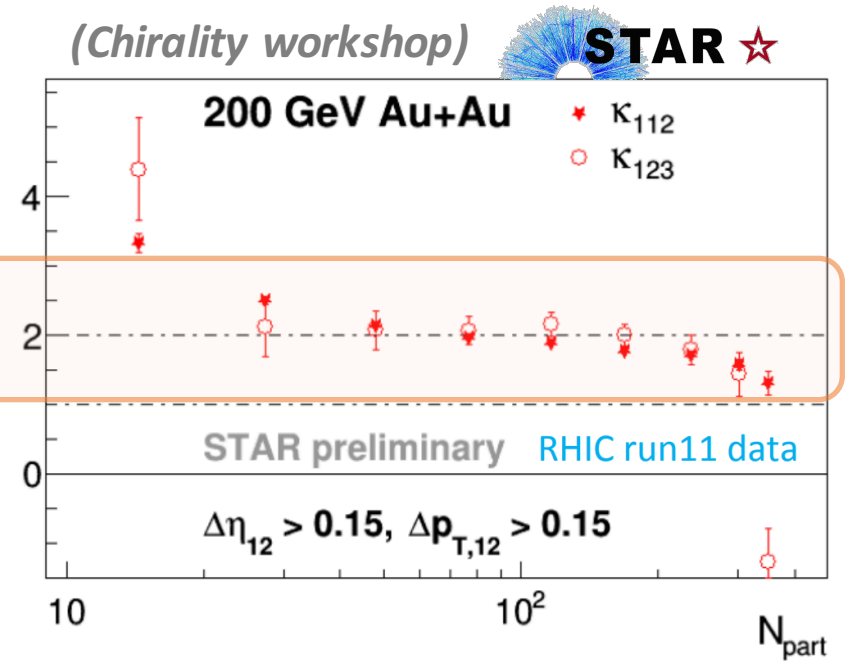
Background

Background scenario

(See Z. Tu's talk)



(Chirality workshop)



Background dominated at 200 GeV?

Extracting CME signal at RHIC

- i.e., $\Delta\gamma$ correlator vs inv mass (**and *there are more***)
- Same source of background, different technique

Extracting CME signal at RHIC

- i.e., $\Delta\gamma$ correlator vs inv mass (**and *there are more***)
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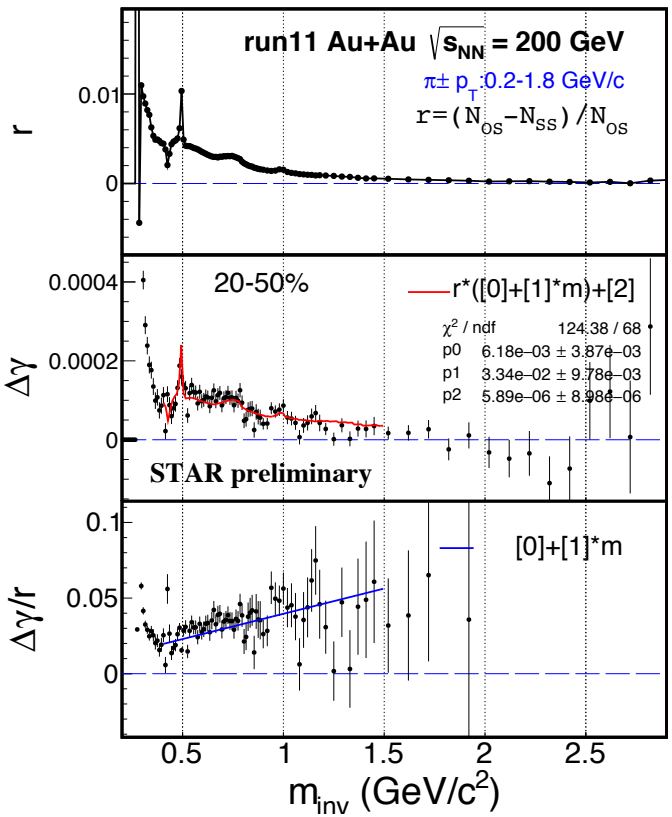
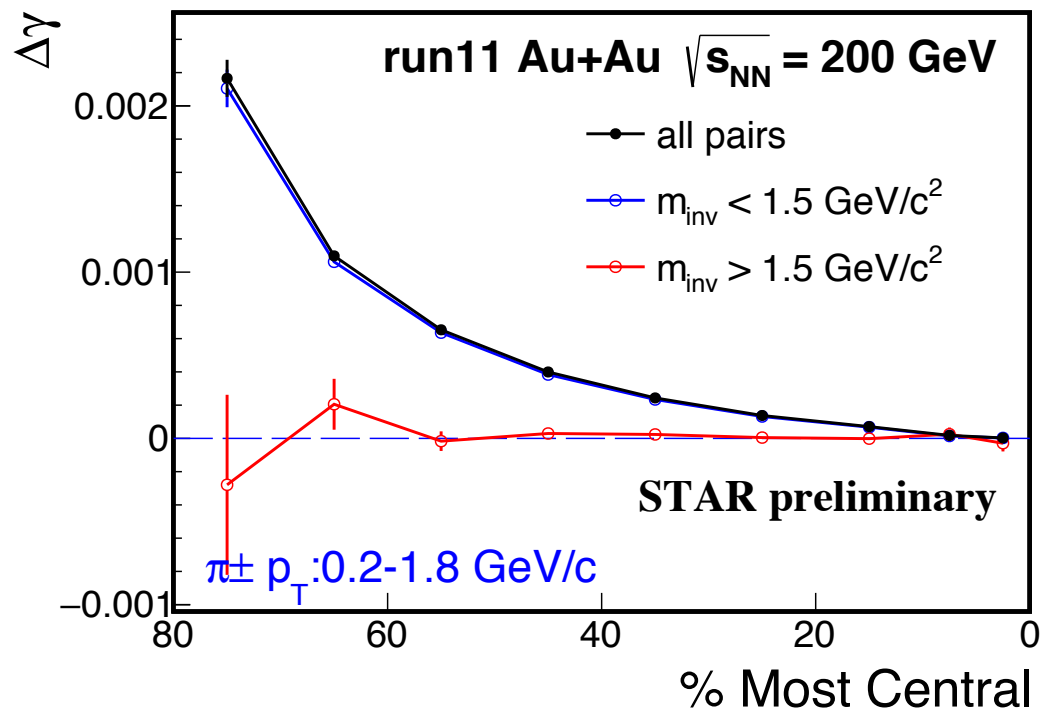


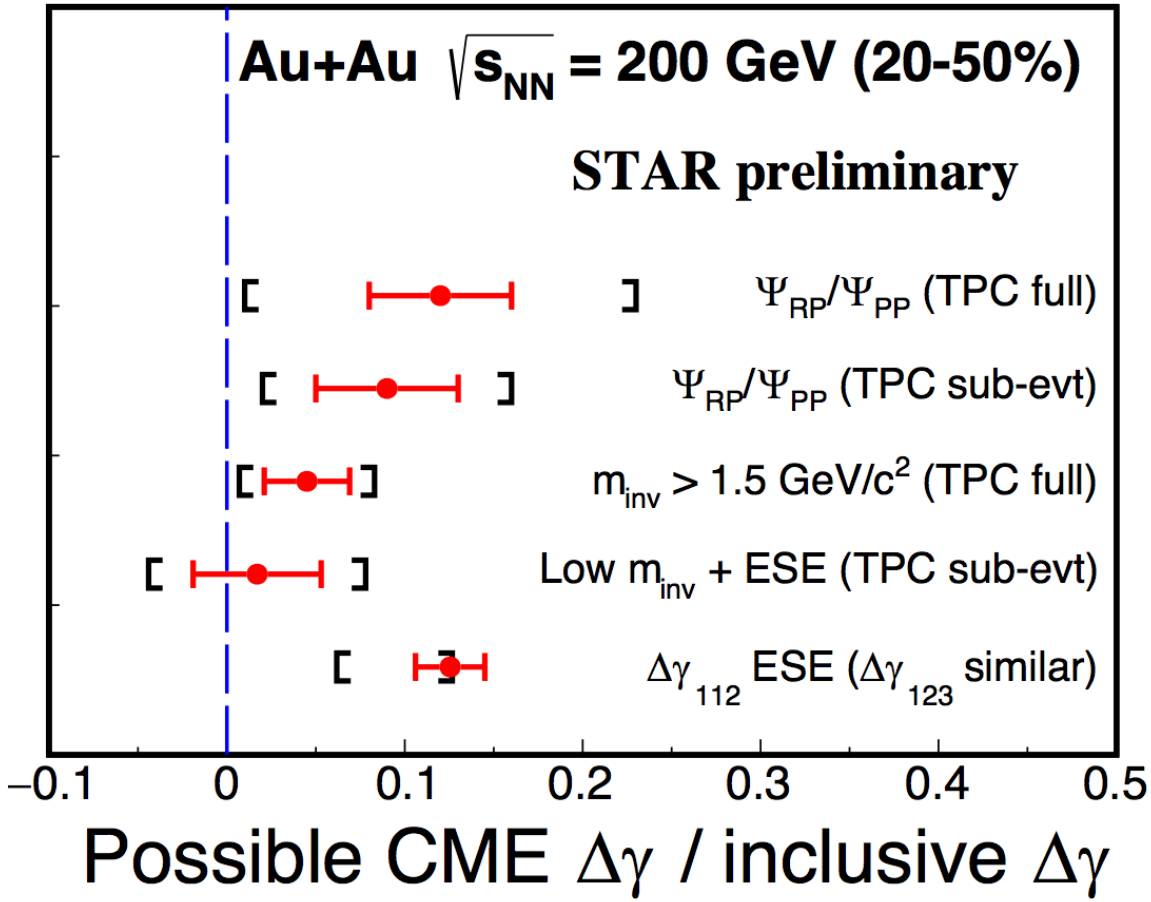
(See J. Zhao's talk)



AuAu 20-50%: CME fraction is small

Extracting CME signal at RHIC

(See Z. Ye's STAR overview talk)



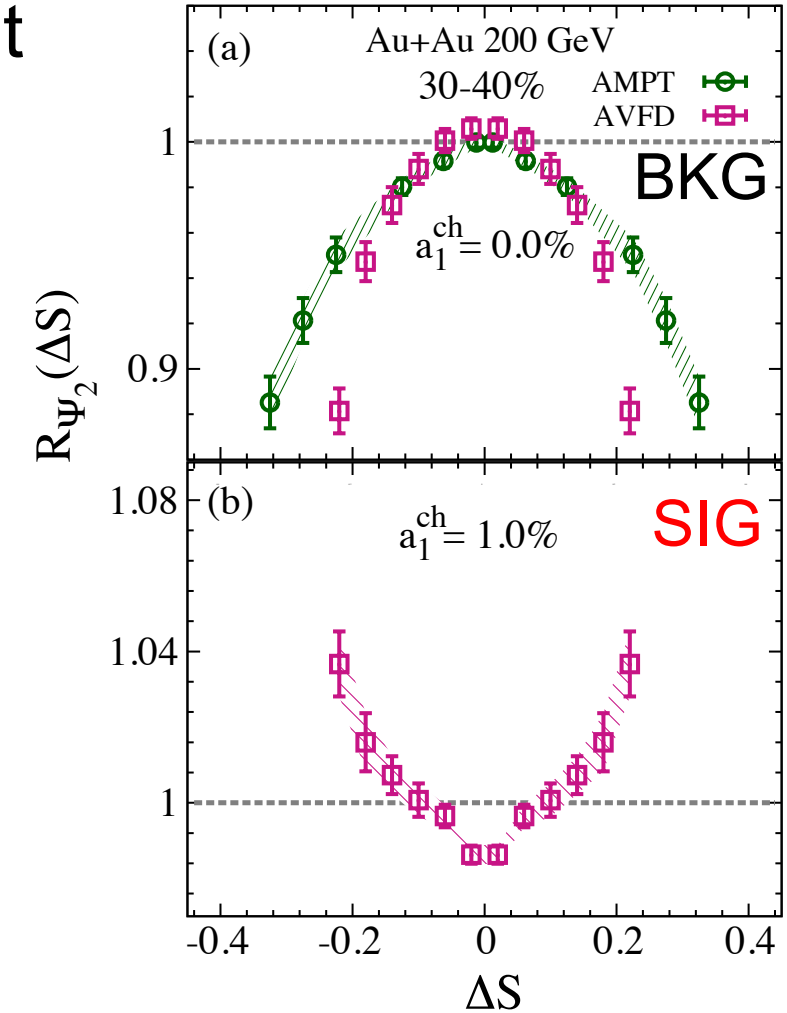
AuAu 20-50%: CME fraction: $< 5\sim20\%$

Consistent with LHC energy

A different approach: R-correlator

(See N. Abdelrahman's poster)

- A new correlator, different **"shape"** to signal and background



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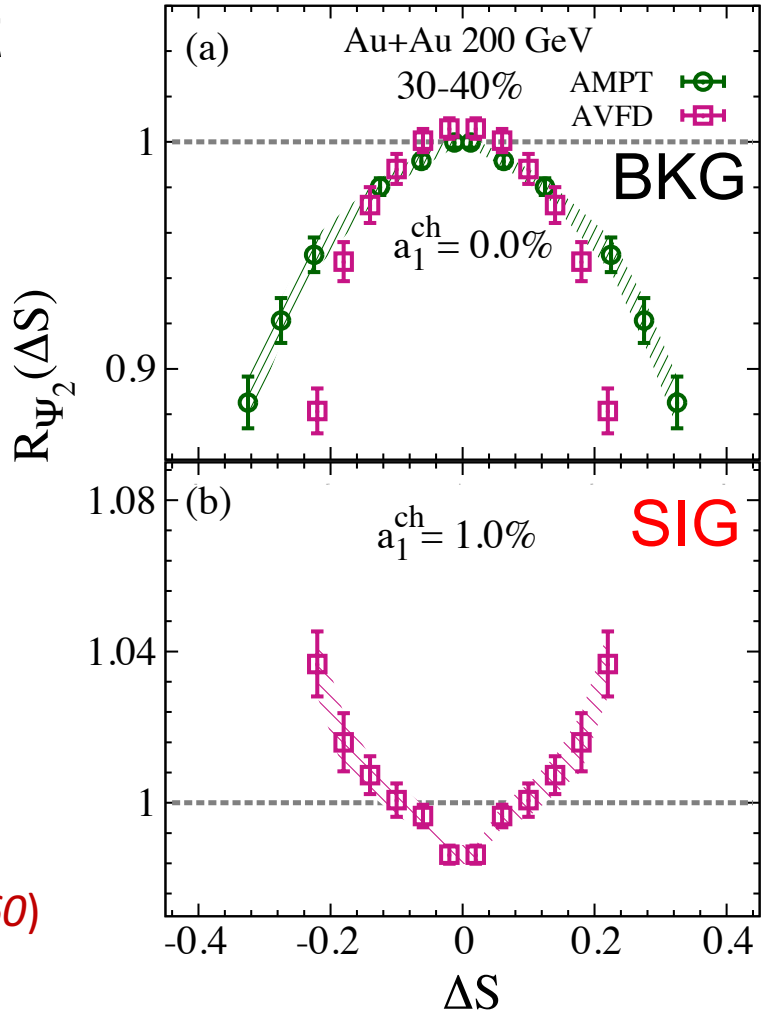

- Known backgrounds are convex?
  - e.g., flow v_2 + LCC?
- *Alternatives are available*

(*Phys. Rev. C 97, 034907 (2018), arXiv:1803.02860*)

A different approach: R-correlator

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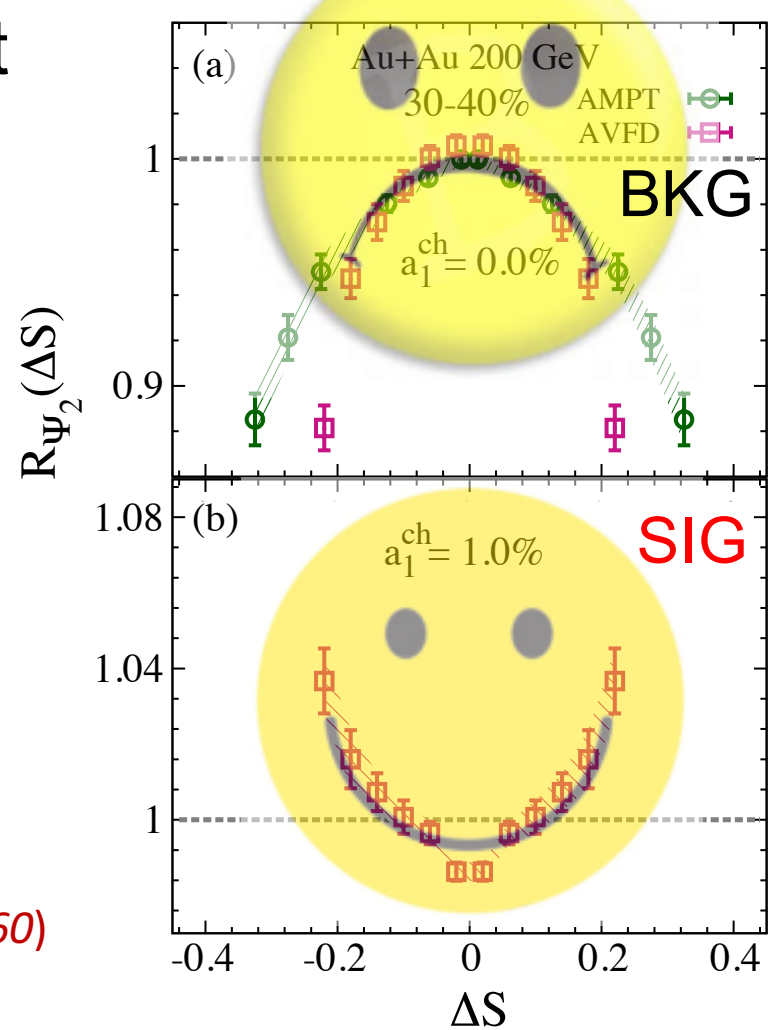


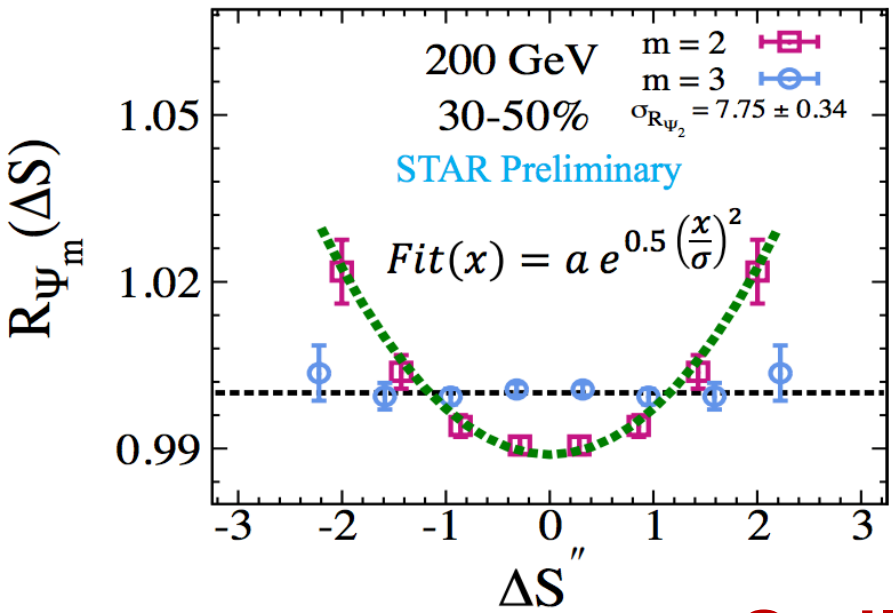
- Known backgrounds are convex?
  - e.g., flow v_2 + LCC?
- *Alternatives are available*

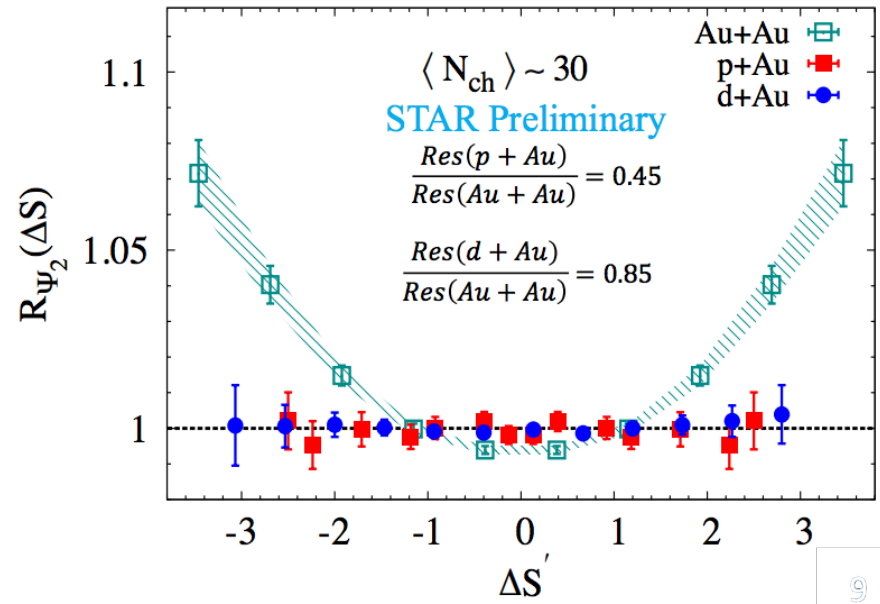
(*Phys. Rev. C 97, 034907 (2018), arXiv:1803.02860*)

Nature knows how to make us happy?

A different approach: R-correlator

(See N. Abdelrahman's poster)



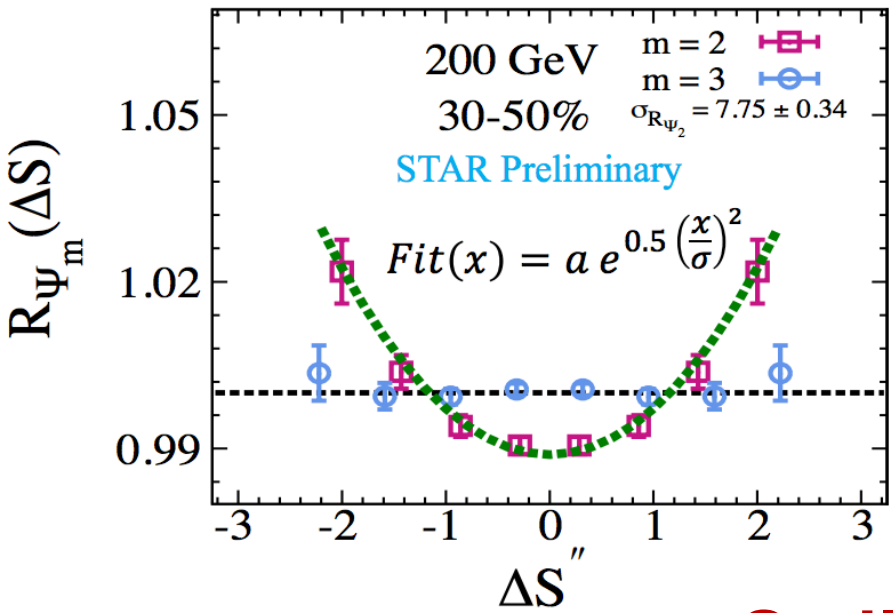


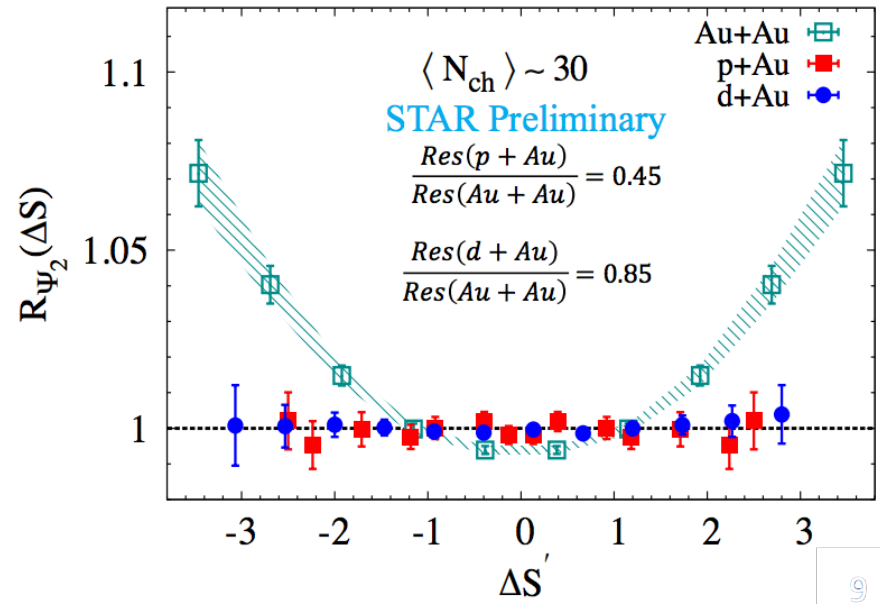
Smiley face:

- Harmonic order on 2 but not 3
- **AA** but not small systems (p+Au, d+Au)

A different approach: R-correlator

(See N. Abdelrahman's poster)





Smiley face:

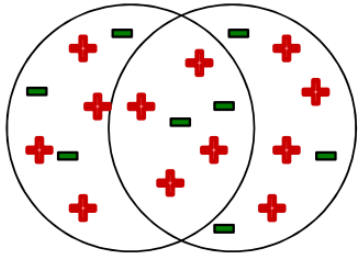
- Harmonic order on 2 but not 3
- **AA** but not small systems (p+Au, d+Au)

Where is the background?

If $a_1 \sim 1\%$ from $R_{\Psi_2}(\Delta S)$, incompatible to $\gamma_{1,n-1,n}$?

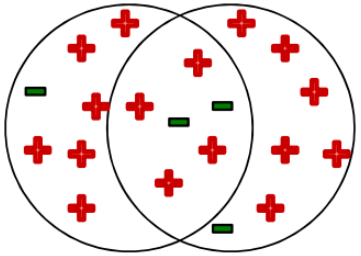
Isobaric collisions

10% difference expected in magnetic field



$_{40}Zr^{96} + {}_{40}Zr^{96}$

Vs

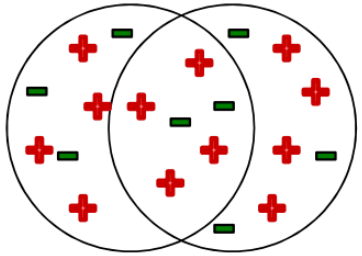


$_{44}Ru^{96} + {}_{44}Ru^{96}$

What shall we look at?

Isobaric collisions

10% difference expected in magnetic field



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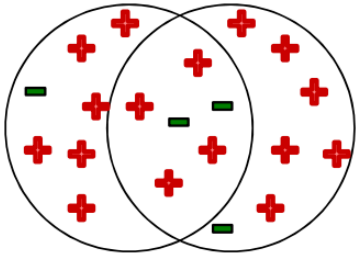
Vs



$_{44}Ru^{96} + {}_{44}Ru^{96}$

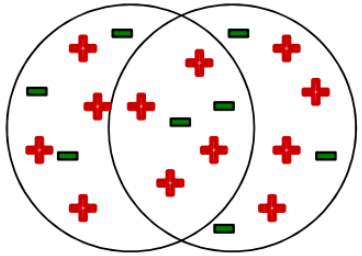
What shall we look at?

CME

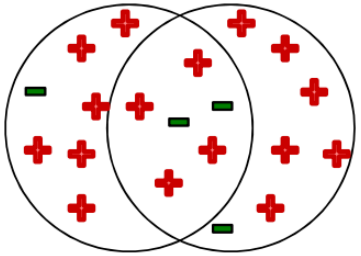
- $\kappa_{2,RuRu} > \kappa_{2,ZrZr}$?
- $\kappa_{3,RuRu} \approx \kappa_{3,ZrZr}$?
- R_{Ψ} correlator, another smiley face?

Isobaric collisions

10% difference expected in magnetic field



Vs



$_{40}Zr^{96} + {}_{40}Zr^{96}$ $\qquad$ $_{44}Ru^{96} + {}_{44}Ru^{96}$

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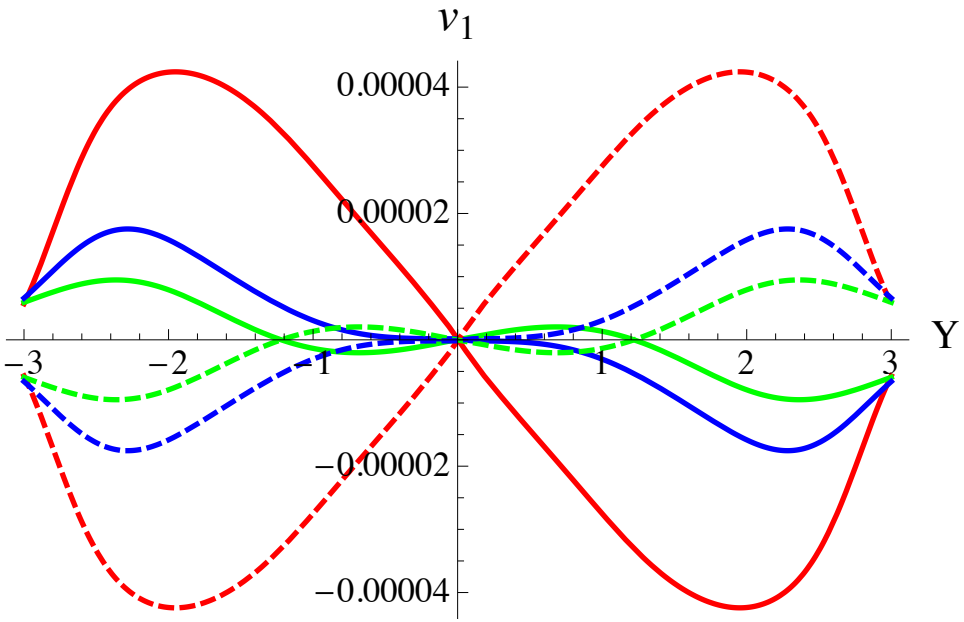
B-field

- Charge-dependent directed flow?
- **$\Lambda, \bar{\Lambda}$ Polarization?**

Charge-Dependent Directed Flow

LHC energy charged pion
theoretical prediction



Phys. Rev. C 89, 054905 (2014)

Charge-Dependent Directed Flow

LHC energy charged pion
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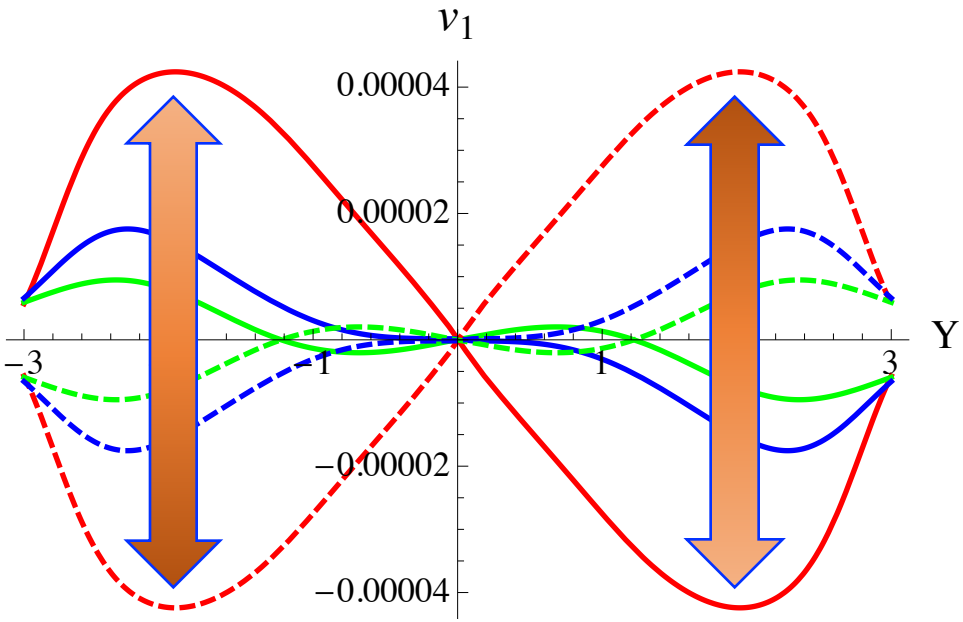
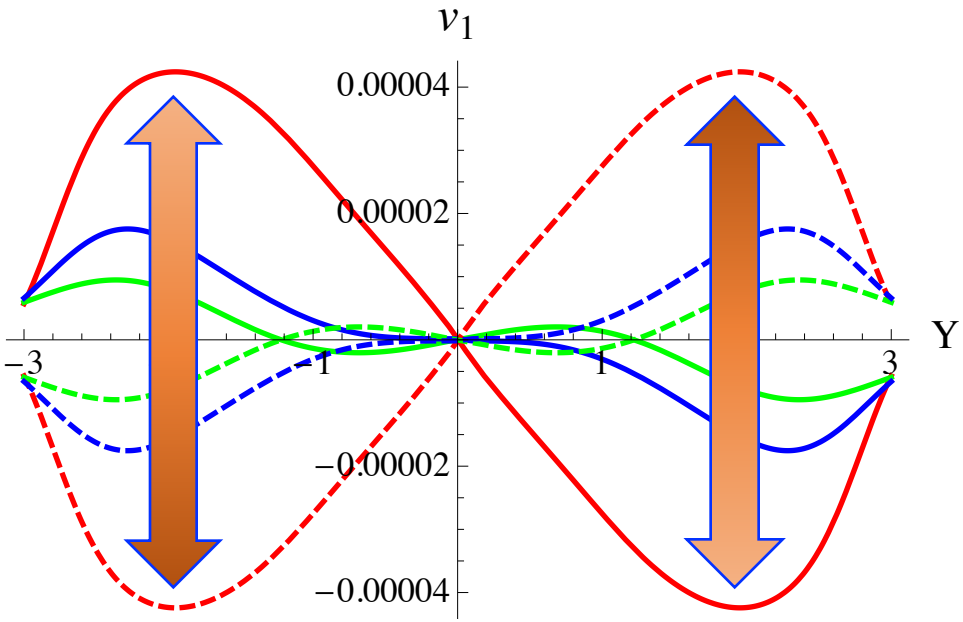


Phys. Rev. C 89, 054905 (2014)

B-field can separate v_1 with different charge sign

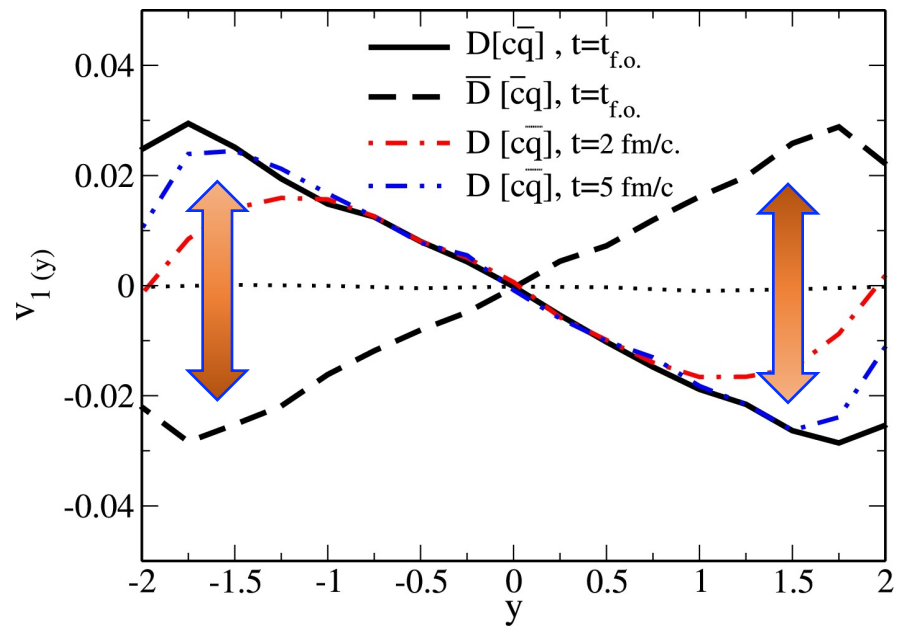
Charge-Dependent Directed Flow

LHC energy charged pion theoretical prediction



Phys. Rev. C 89, 054905 (2014)

LHC energy $D, \bar{D}$ meson theoretical prediction



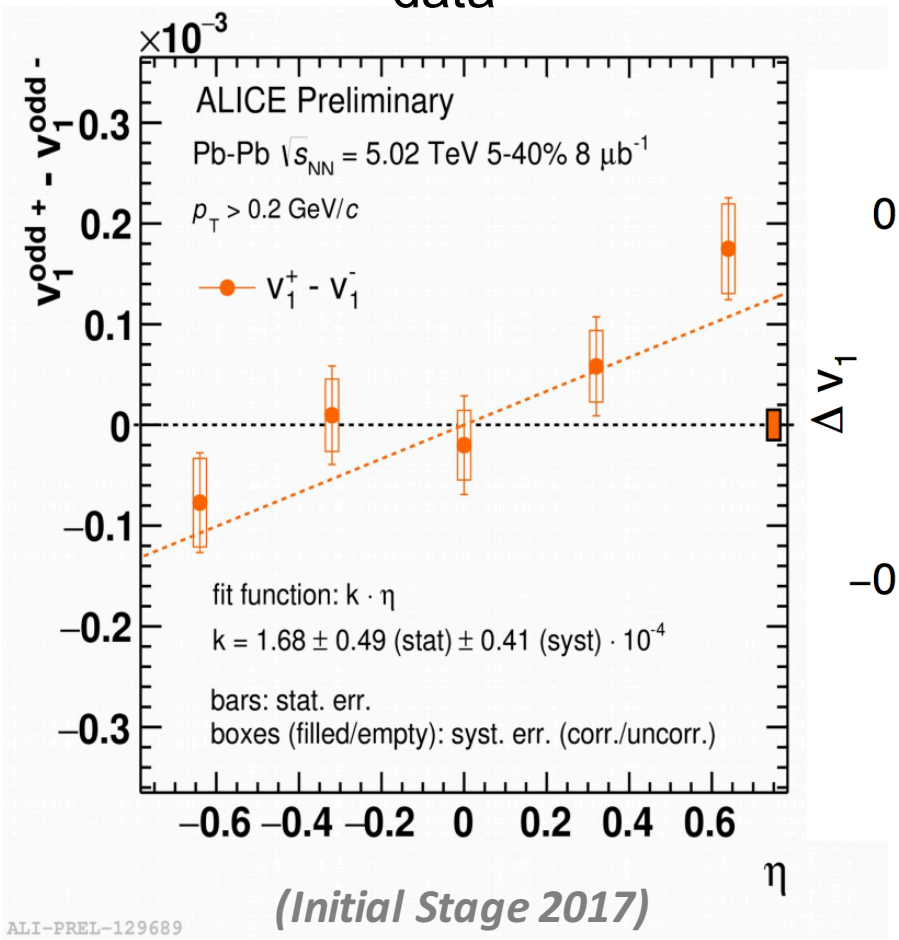
Phys.Lett. B768 (2017) 260

B-field can separate v_1 with different charge sign

- Heavy quarks probe early time, e.g., *charm*
- Constrain lifetime of B-field?

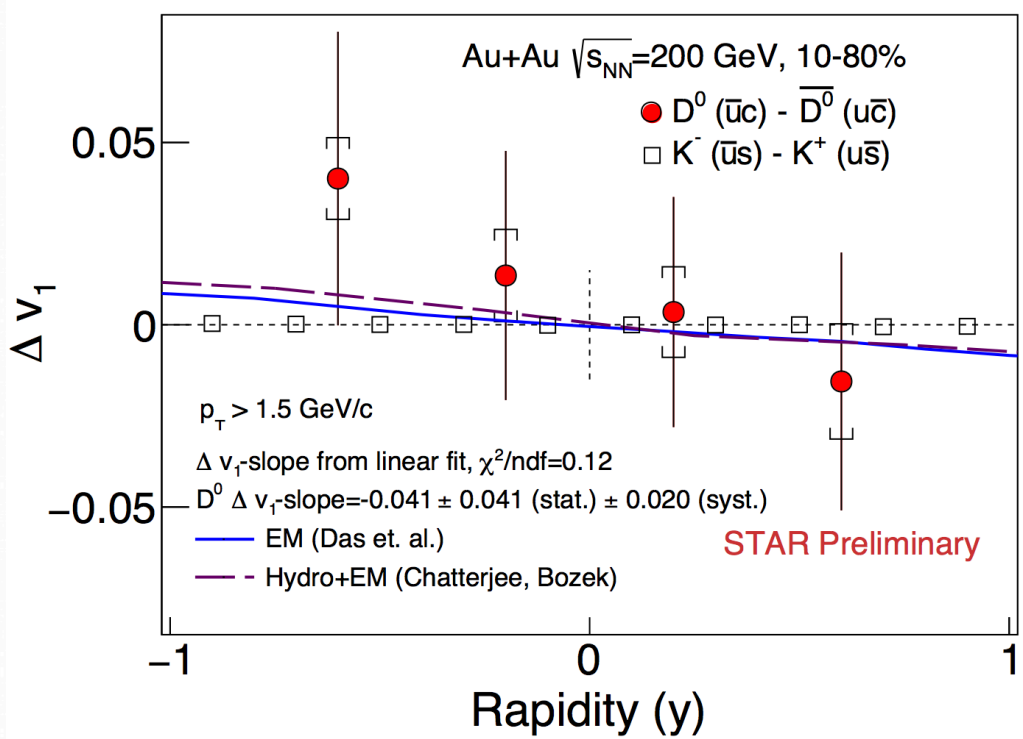
Charge-Dependent Directed Flow

LHC energy charged particle data



(Initial Stage 2017)

RHIC energy $D, \bar{D}$ meson data

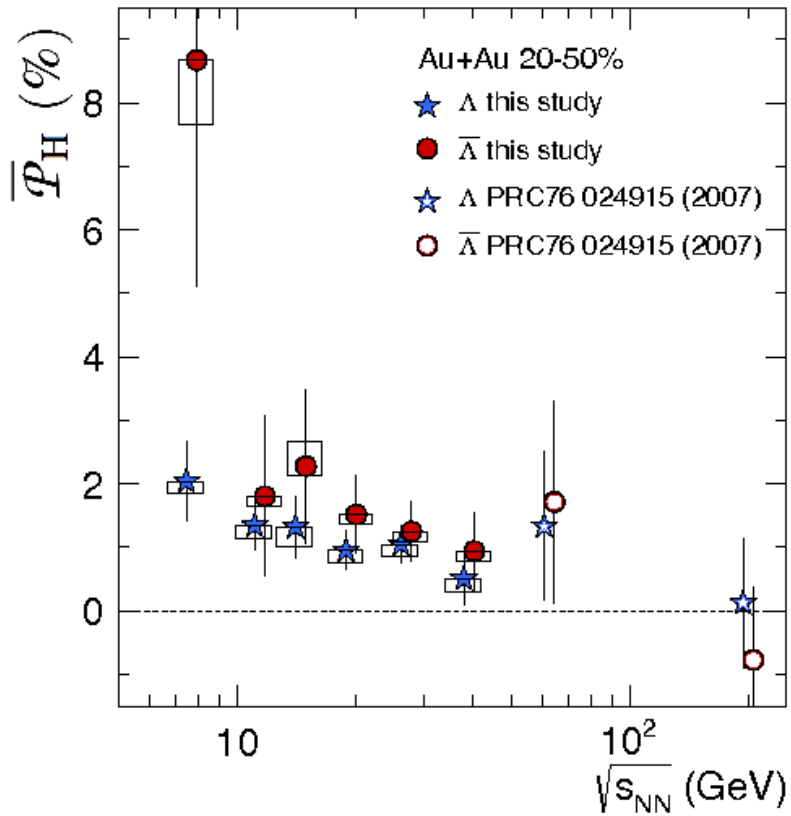


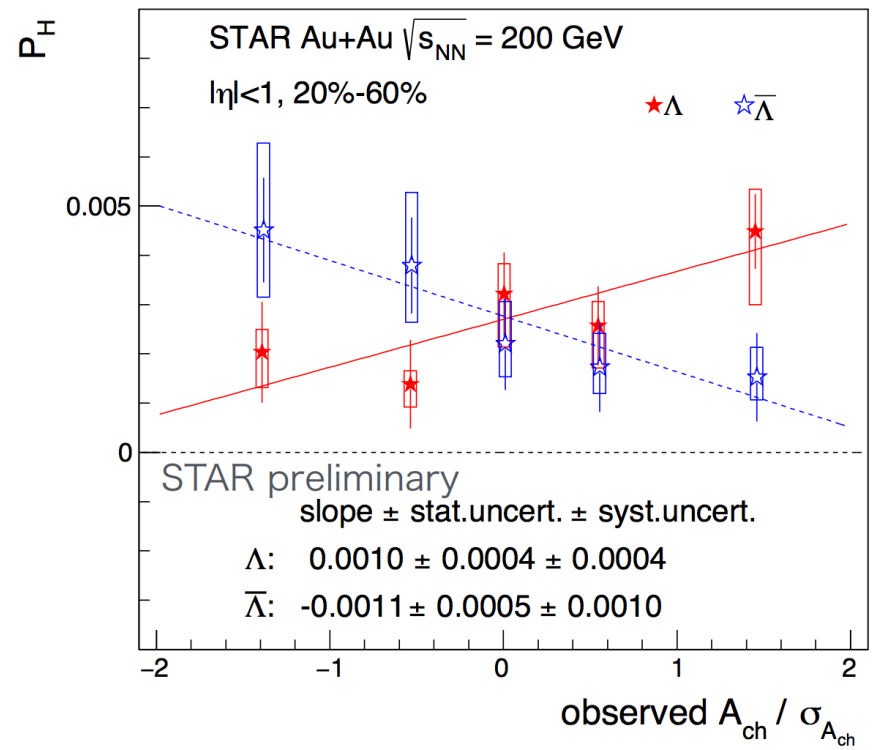
(See S. Singha's talk)

Hint of B-field? At both LHC and RHIC energy?

$\Lambda, \bar{\Lambda}$ Global Polarization

(See T. Niida's Talk)





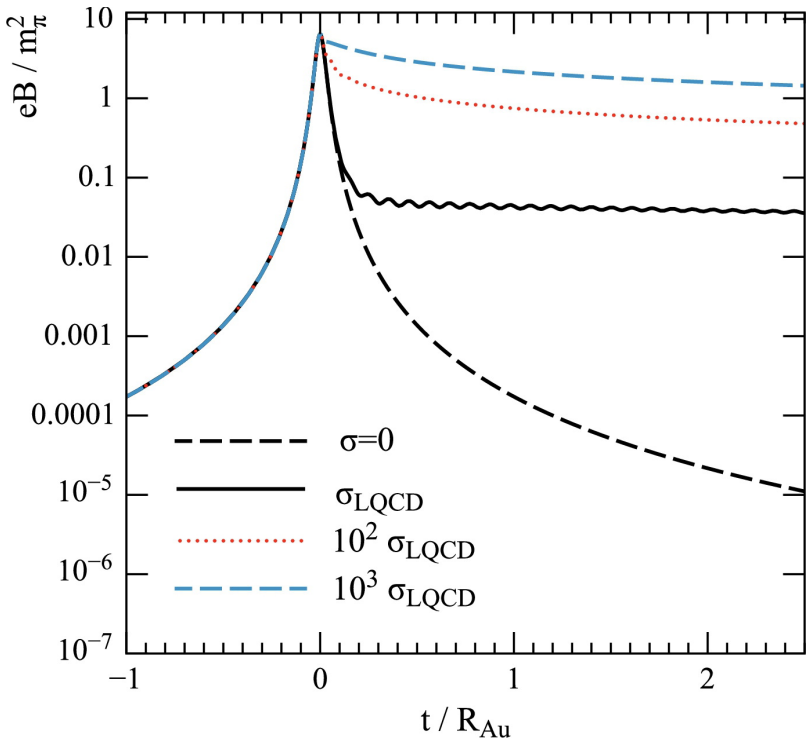
$\bar{\Lambda}$ aligns with B
Λ anti-aligns with B

$\vec{B}$

$\vec{J}_5$ current from CSE
A_{ch} dependence?

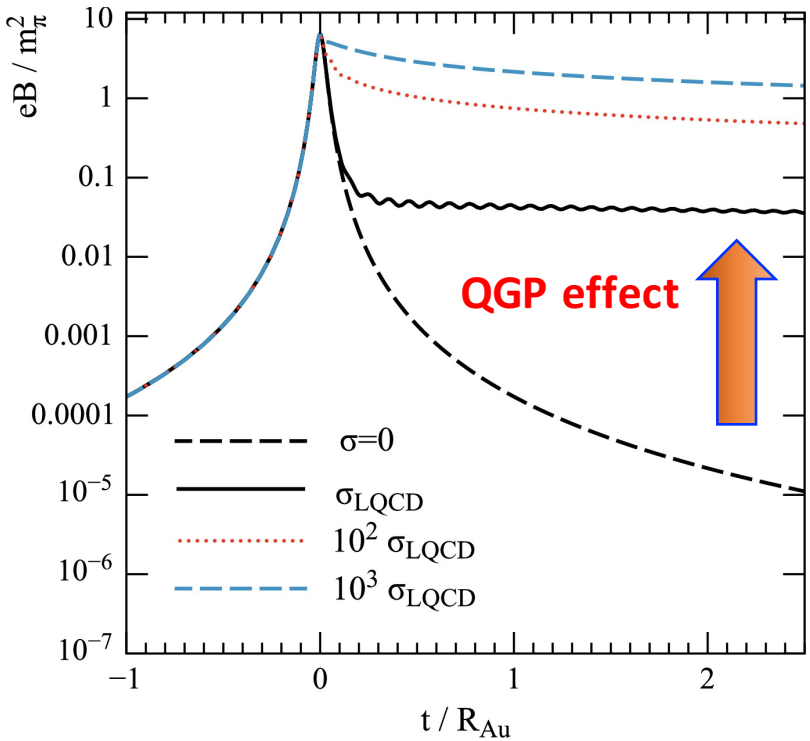
Magnetic field

Nucl. Phys. A 929 (2014) 184



Magnetic field

Nucl. Phys. A 929 (2014) 184

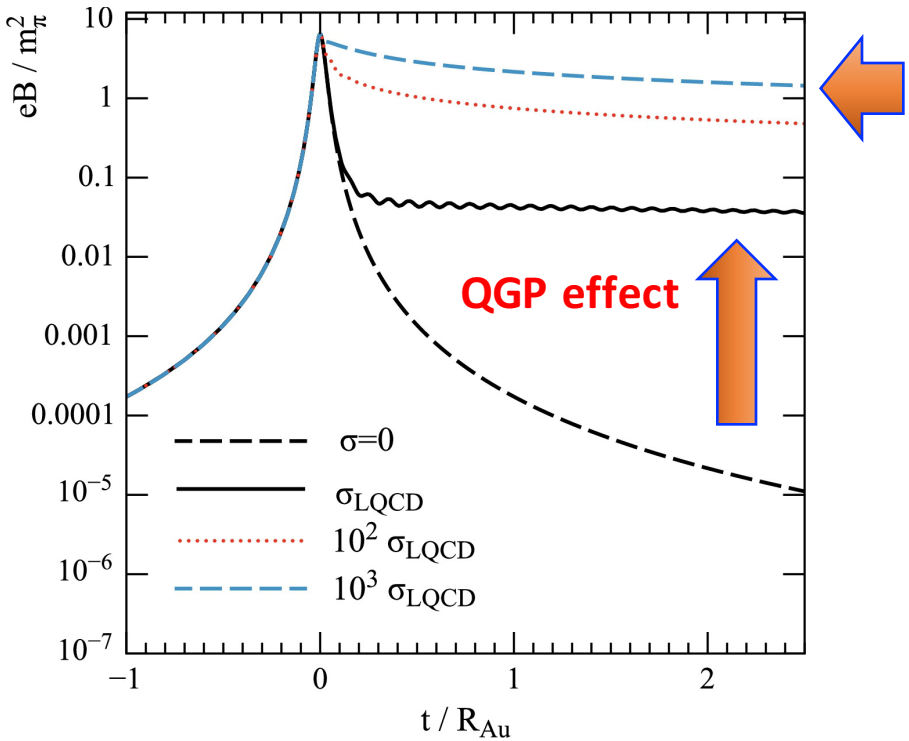


Independent observables sensitive to B-field constrains

- CME?
- Polarization?
- **Electrical conductivity of the QGP medium?**

Magnetic field

Nucl. Phys. A 929 (2014) 184



Independent observables sensitive to B-field constrains

- CME?
- Polarization?
- **Electrical conductivity of the QGP medium?**

@ RHIC

1. **Isobar data**
2. **27 GeV**
3. **BES 2**

+ Detector upgrade

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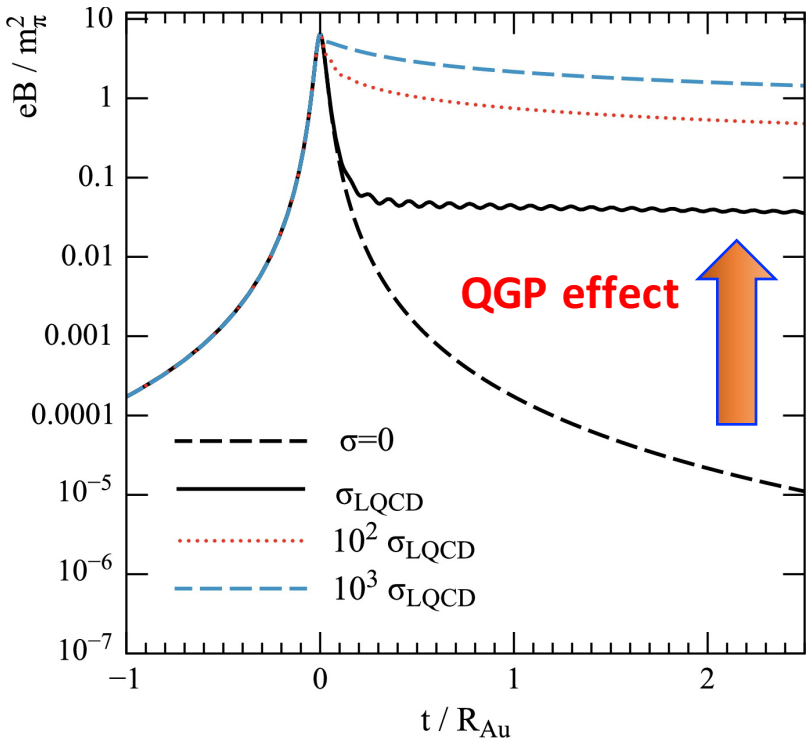

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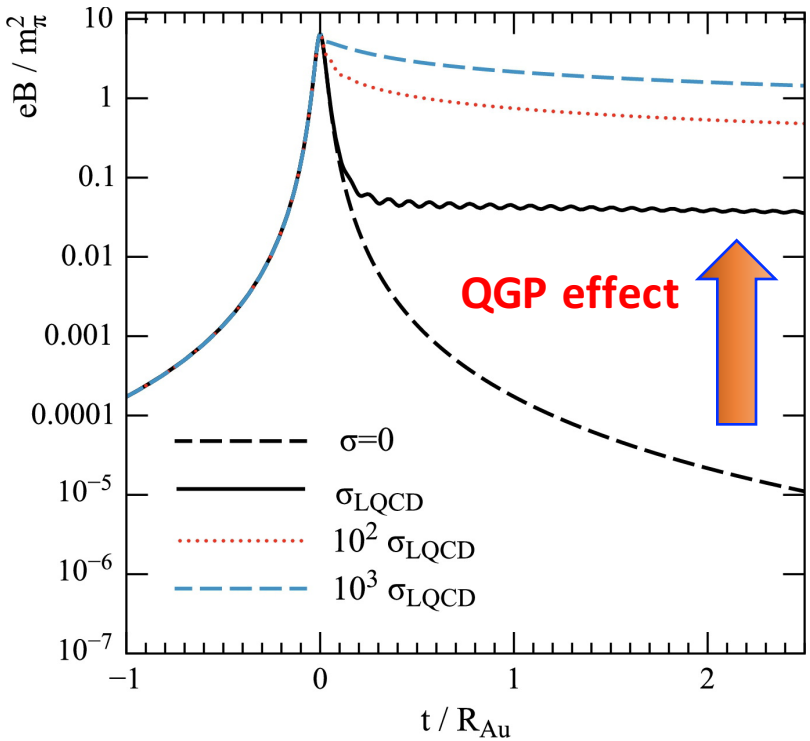

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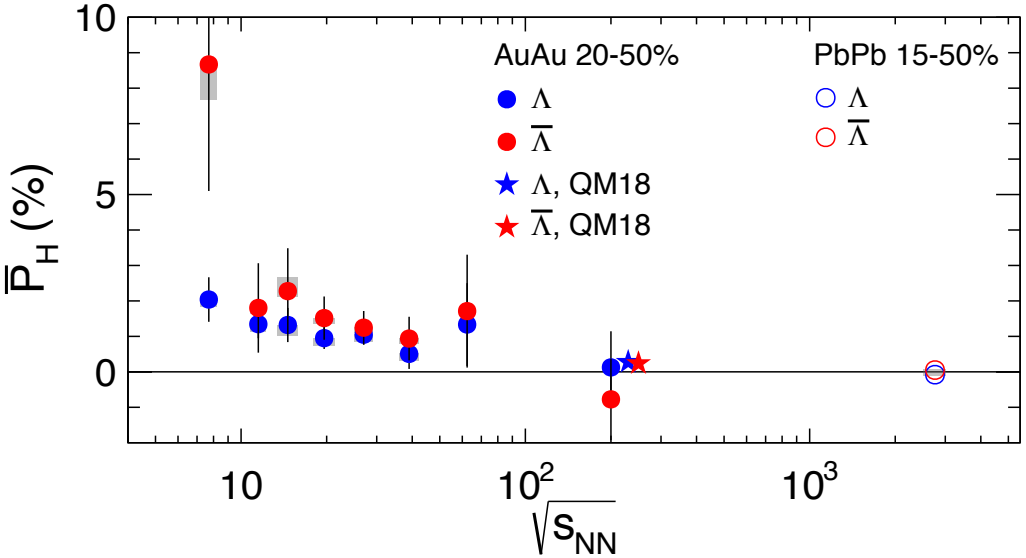
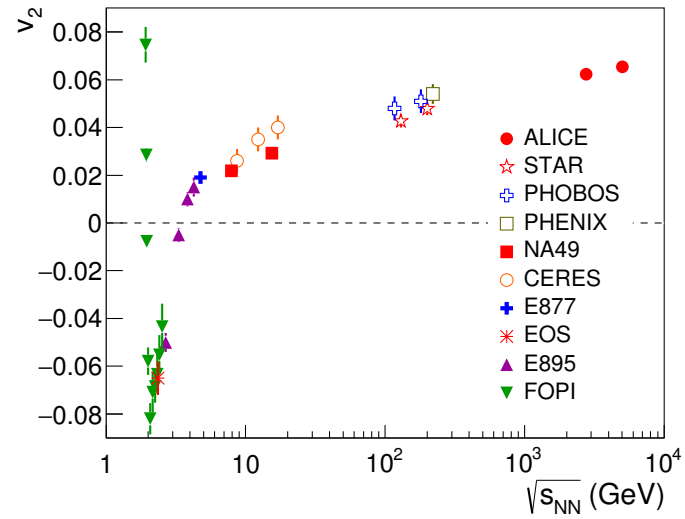
Rich insights into B-field in *energy* and *time* dependence

Summary

- From the discovery of $\Lambda, \bar{\Lambda}$ **Global Polarization at RHIC, it's just the beginning!**
- **Can hydrodynamics describe both polarization and v_n?**





- More Global/Local polarization to come:
  - **Measurements across a wide range of energy**
  - **Precise** and **differential** measurements
  - LHC experiments

Summary

- CME implies rich physics in QCD and QGP :

- Backgrounds are more understood. Similar between RHIC and LHC!
- Unlikely to see a signal @ LHC, upper limits are derived and systematics dominated.
- *Methods are gradually converging, but not yet conclusive.*

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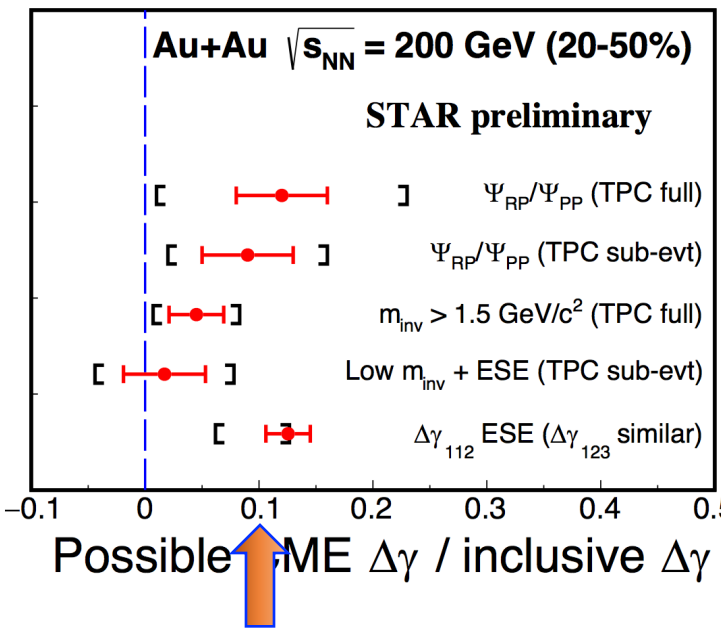

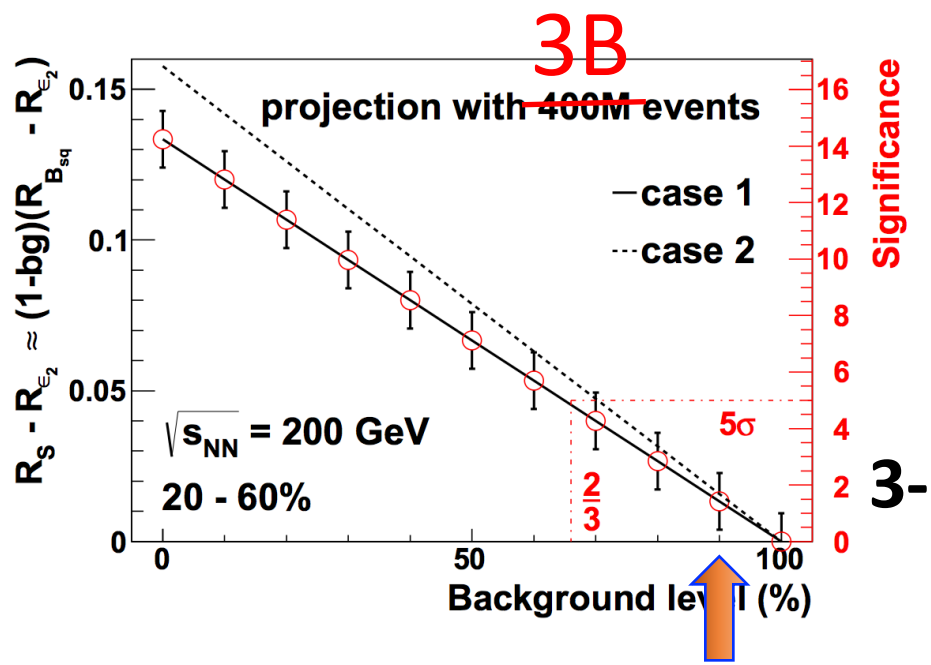

3-4σ?

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- **New Insights into B-field with independent observables are essential to the search for the CME.**

- **Isobar has a potential of discovery of CME, but…**

Extraordinary discovery requires extraordinary evidence

"… Every genuine test of a theory is an attempt to falsify it, or refute it. "

- Karl Popper

Thank you!