Vorticity and polarization in heavy-ion collisions

(重イオン衝突における渦と偏極)

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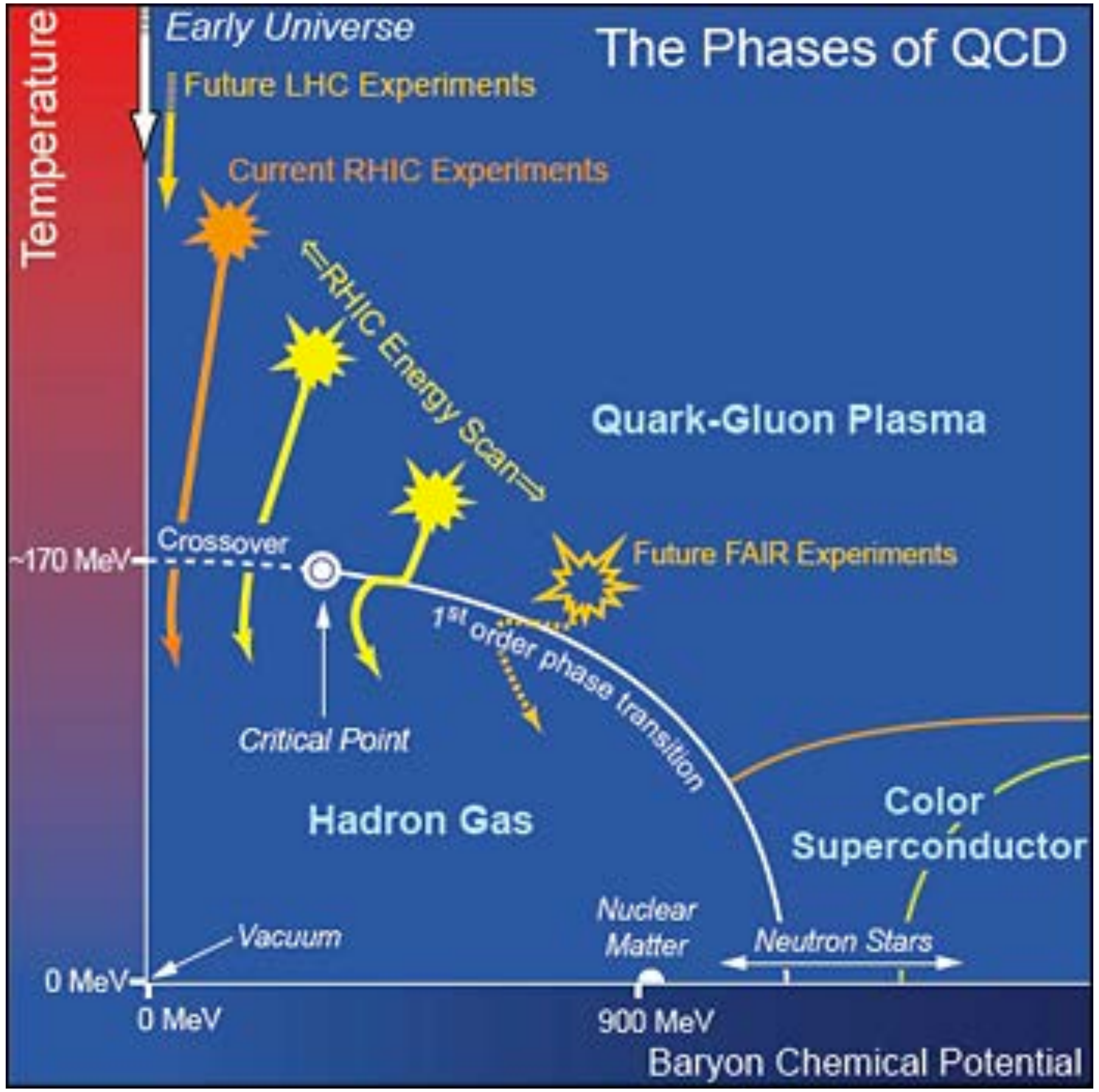
Nov. 30, 2020

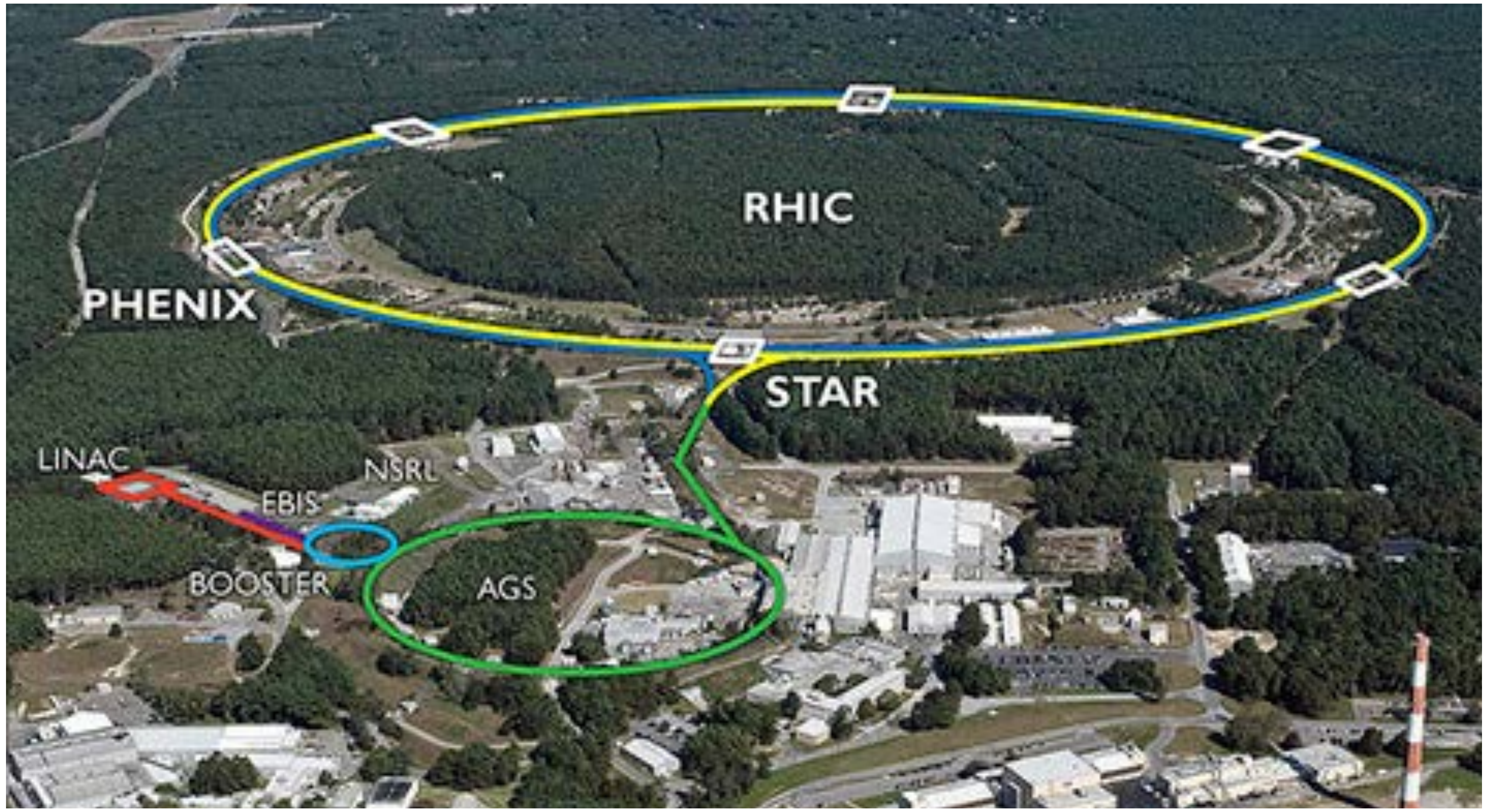
Heavy-ion collisions experiments



Main goals of heavy-ion collision experiments

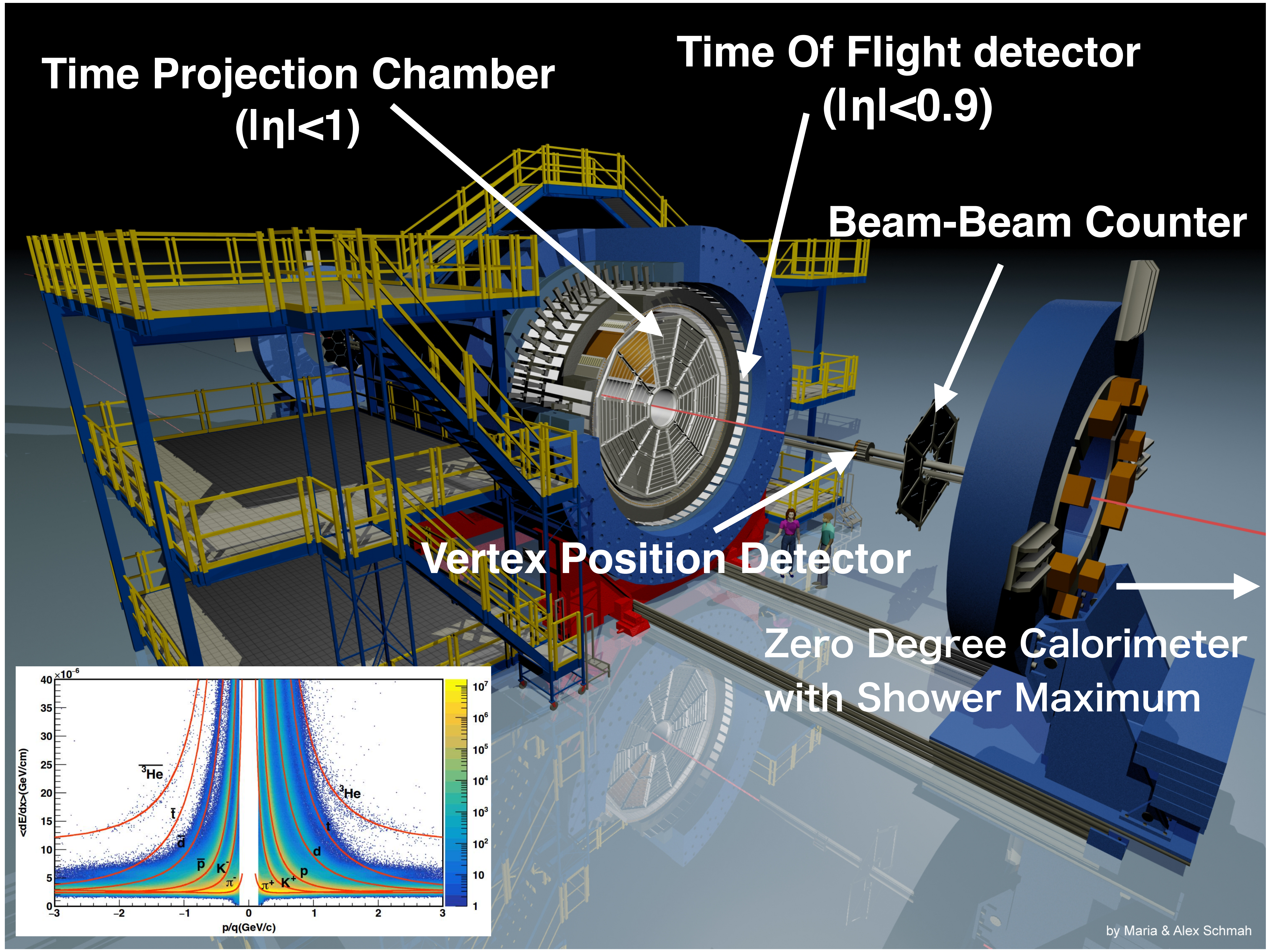
- to understand and quantify the properties of quark-gluon plasma (QGP)
- to map out QCD phase diagram
  - Critical Point search
  - Signatures of 1st-order phase transition

RHIC-STAR experiment



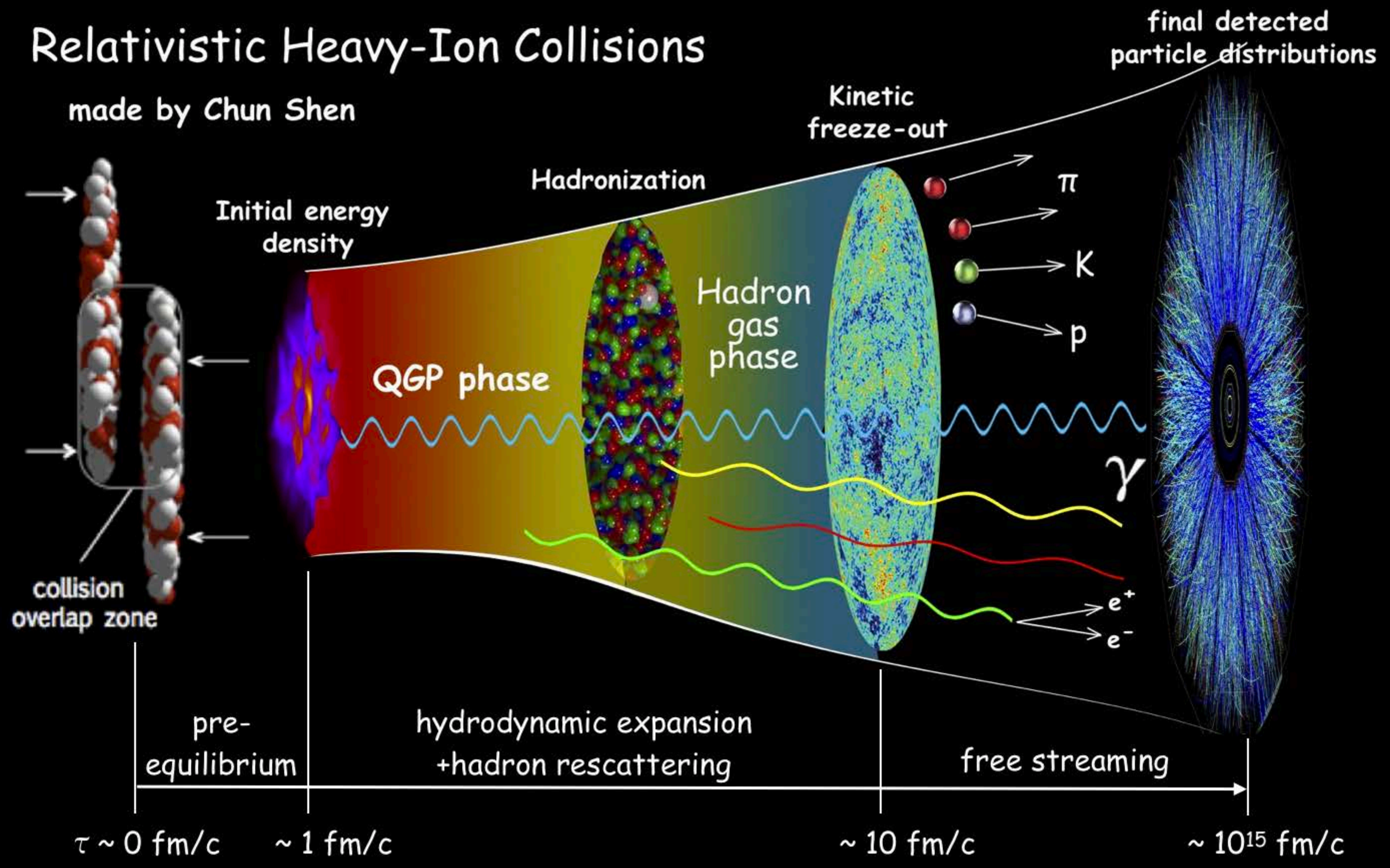
Relativistic Heavy Ion Collider (RHIC)

- in Brookhaven National Lab. (NY, USA)
- 3.8 km in circumference
- $\sqrt{s_{NN}}$ = 7.7-200 GeV for A+A
  species: p+p, p(d)+Au, He+Au, Cu+Cu, Cu+Au, A+Au…



Solenoidal Tracker At RHIC (STAR)

- Full azimuth and wide rapidity coverage
- Excellent particle identification



Challenge here:
Extract the medium properties, determining unknown dynamics, by measuring finally produced particles

Important features in non-central heavy-ion collisions

Strong magnetic field

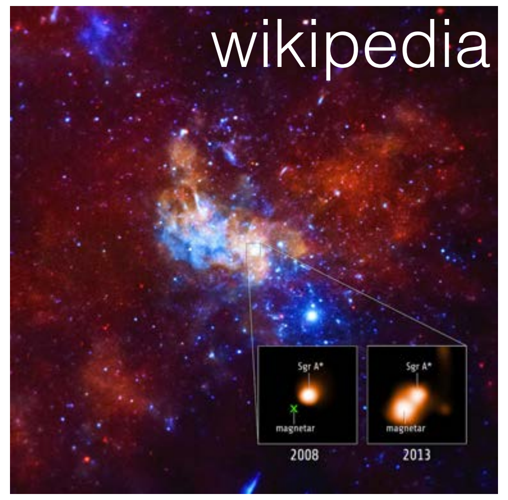
$$B \sim 10^{13}\ \mathrm{T}$$

$$(eB \sim m_\pi^2\ (\tau \sim 0.2\ \mathrm{fm}))$$

D. Kharzeev, L. McLerran, and H. Warringa, Nucl.Phys.A803, 227 (2008)
McLerran and Skokov, Nucl. Phys. A929, 184 (2014)

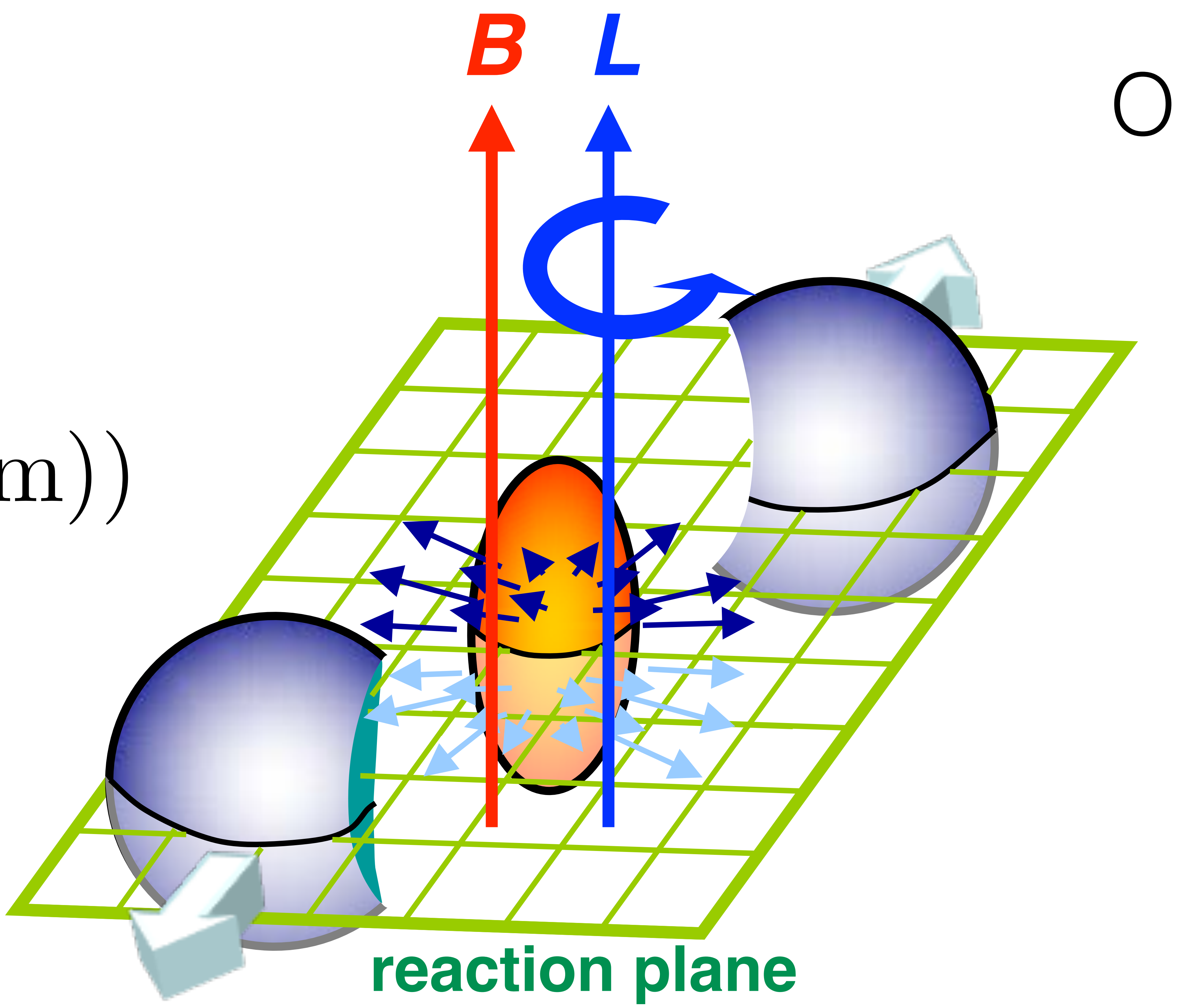
typical magnet

$B \sim 0.1 - 0.5\ \mathrm{T}$



magnetar

$B \sim 10^{11}\ \mathrm{T}$



Orbital angular momentum

$$\mathbf{L} = \mathbf{r} \times \mathbf{p}$$

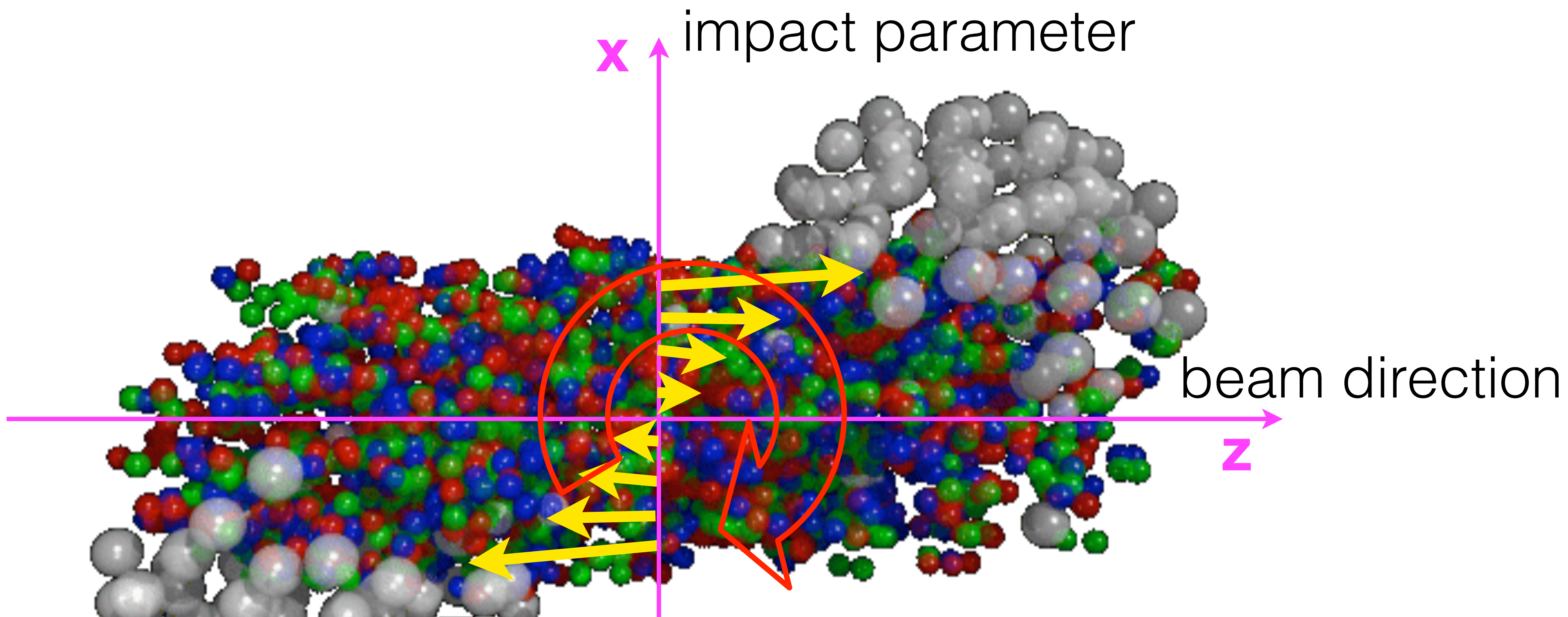
$$\sim bA\sqrt{s_{NN}} \sim 10^6 \hbar$$

Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)

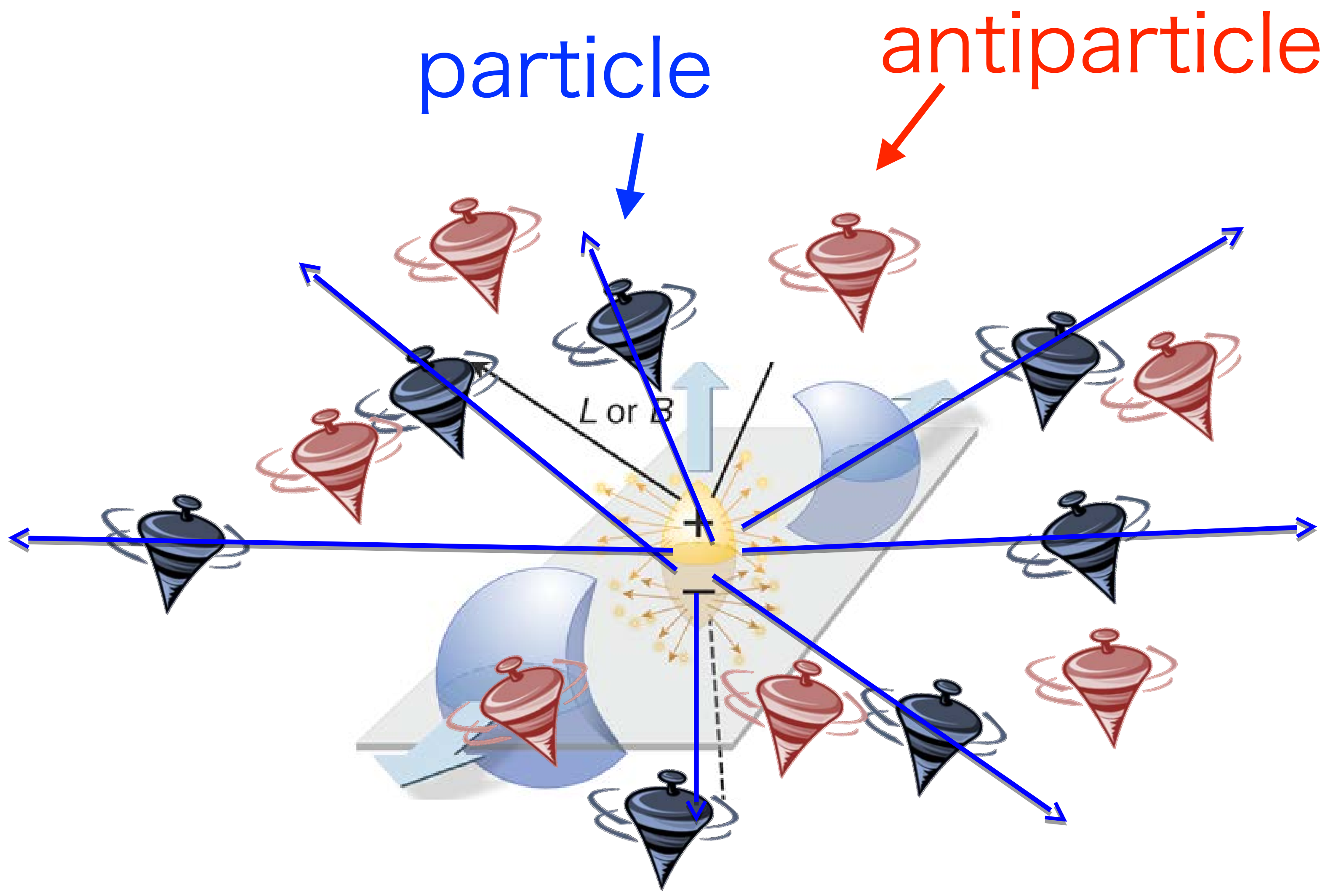
→Chiral magnetic/vortical effects

→**Particle polarization**

Global polarization



$$\omega_y = \frac{1}{2}(\nabla \times v)_y \approx -\frac{1}{2}\frac{\partial v_z}{\partial x}$$



Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)
S. Voloshin, nucl-th/0410089 (2004)

- Orbital angular momentum is transferred to particle spin
  - Particles' and anti-particles' spins are aligned along angular momentum, ***L***
- Magnetic field align particle's spin
  - Particles' and antiparticles' spins are aligned in opposite direction along ***B*** due to the opposite sign of magnetic moment

Produced particles will be "globally" polarized along ***L*** or ***B***.
B might be studied by particle-antiparticle difference.

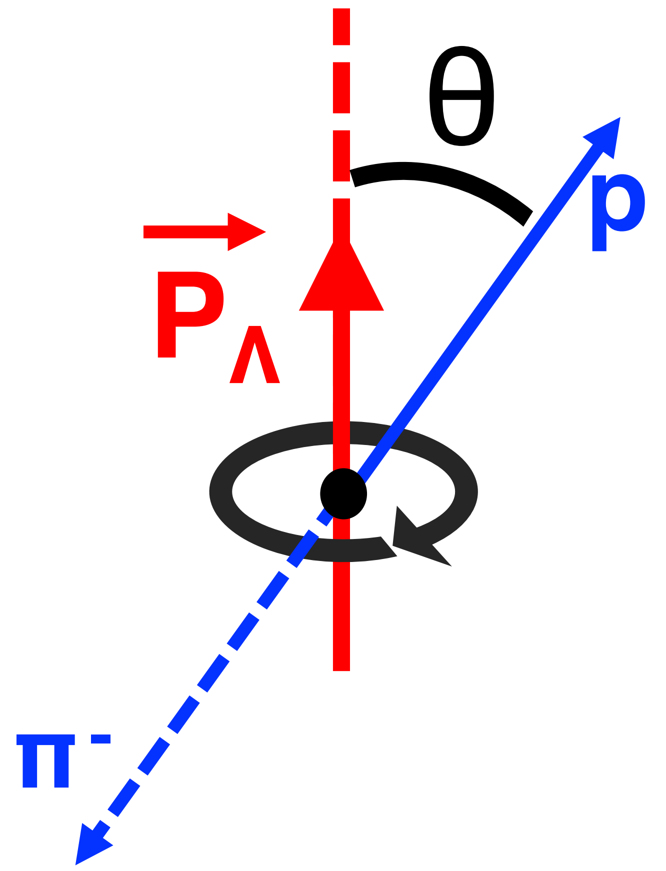
How to measure the polarization?

Parity-violating weak decay of hyperons ("self-analyzing")

$\Lambda \rightarrow p + \pi^-$

(BR: 63.9%, $c\tau$ ~7.9 cm)

Daughter baryon is preferentially emitted in the direction of hyperon's spin (opposite for anti-particle)

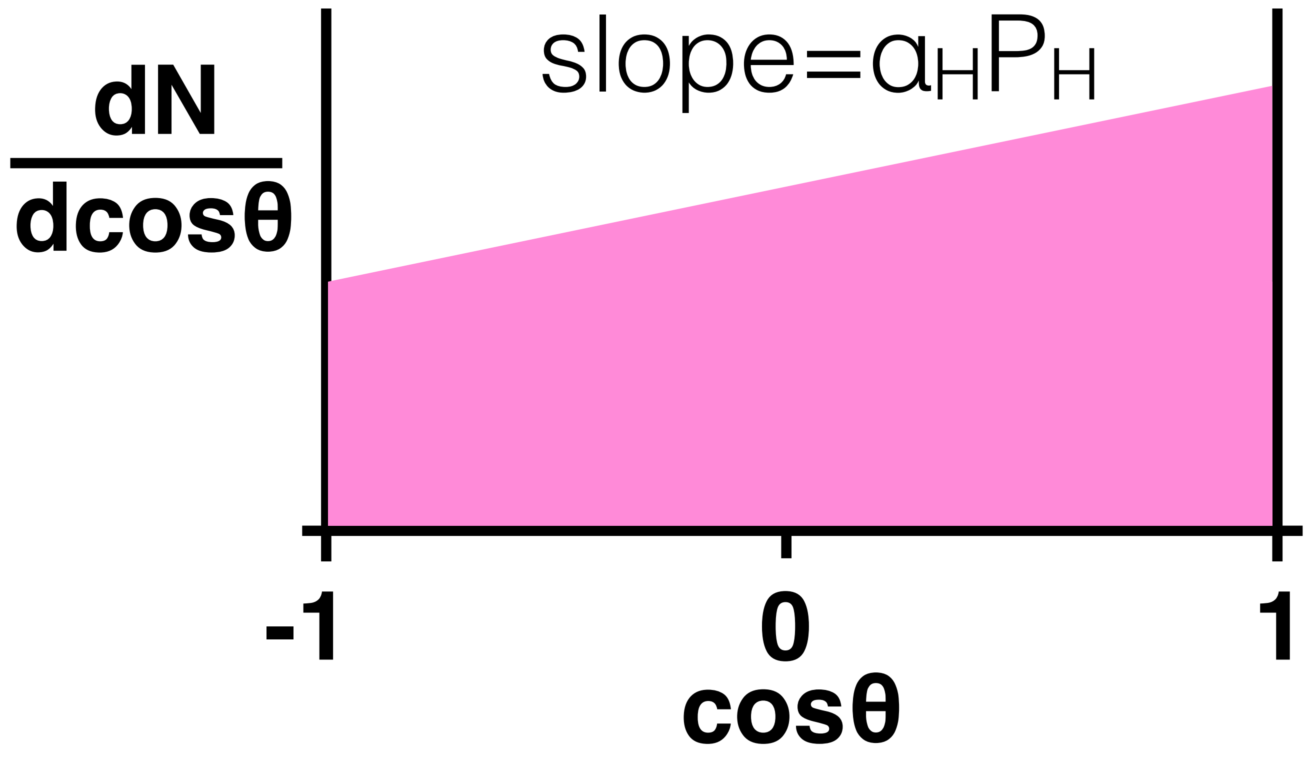


$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_H \mathrm{P_H} \cos\theta^*$$

$\mathrm{P_H}$: hyperon polarization

θ^*: polar angle of daughter relative to the polarization direction in hyperon rest frame

α_H: hyperon decay parameter



Note: α_H for Λ recently updated (BESIII and CLAS)

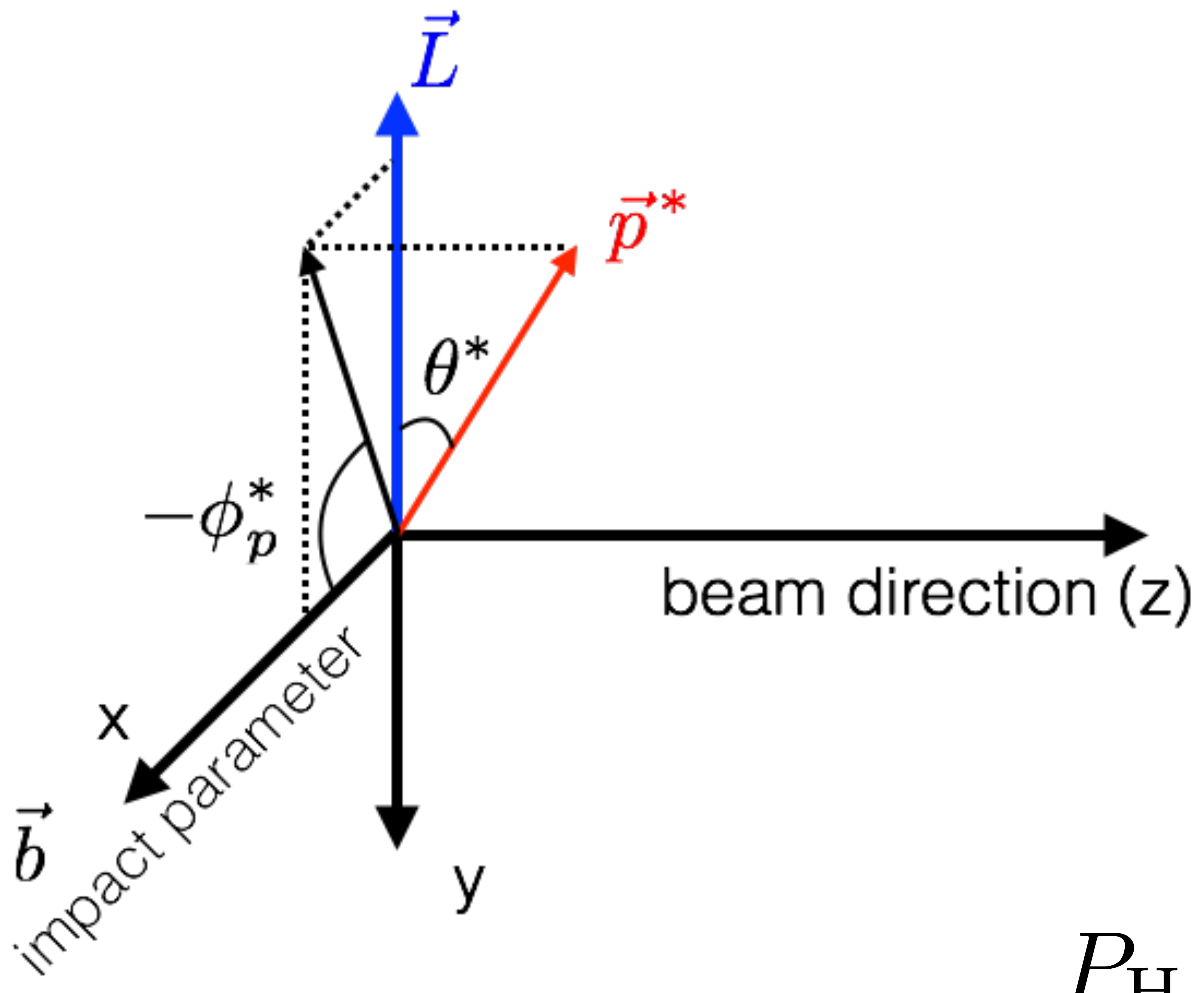
α_Λ=0.732±0.014, $\alpha_{\bar{\Lambda}}$=-0.758±0.012 P.A. Zyla et al. (PDG), PTEP2020.083C01

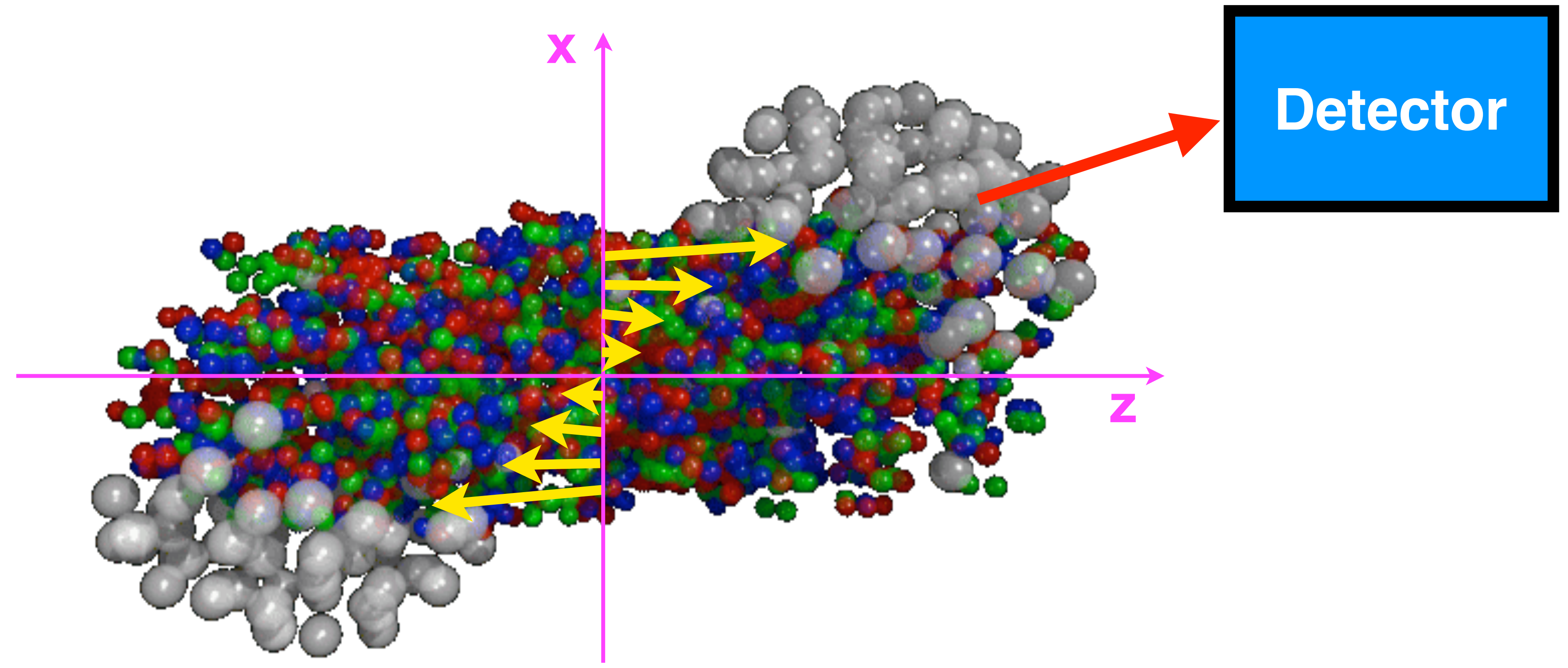
* Published results are based on $\alpha_\Lambda=-\alpha_{\bar{\Lambda}}$=0.64±0.013, but they are scaled by $\alpha_{old}/\alpha_{new}$ when comparing to new results.

How to measure the "global" polarization?

"global" polarization : spin alignment along the initial angular momentum

Projection onto the transverse plane





Angular momentum direction can be determined by spectator deflection (spectators deflect outwards)

S. Voloshin and TN, PRC94.021901(R)(2016)

$$P_{\rm H} = \frac{8}{\pi \alpha_{\rm H}} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{{\rm Res}(\Psi_1)}$$

Ψ_1: azimuthal angle of b

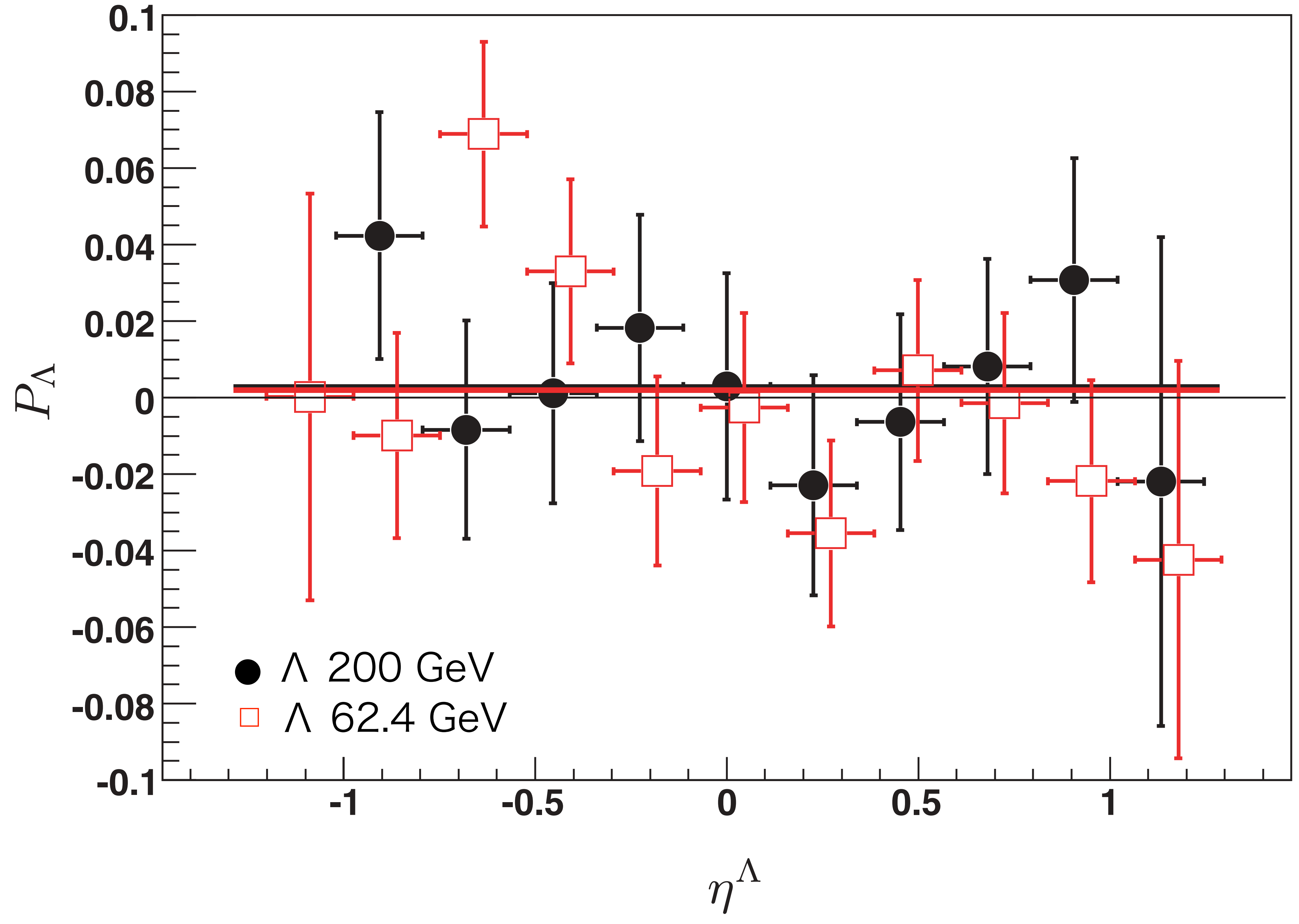
ϕ_p^*: angle of daughter proton in Λ rest frame

STAR, PRC76, 024915 (2007)

First paper from STAR in 2007

PHYSICAL REVIEW C **76**, 024915 (2007)

Global polarization measurement in Au+Au collisions



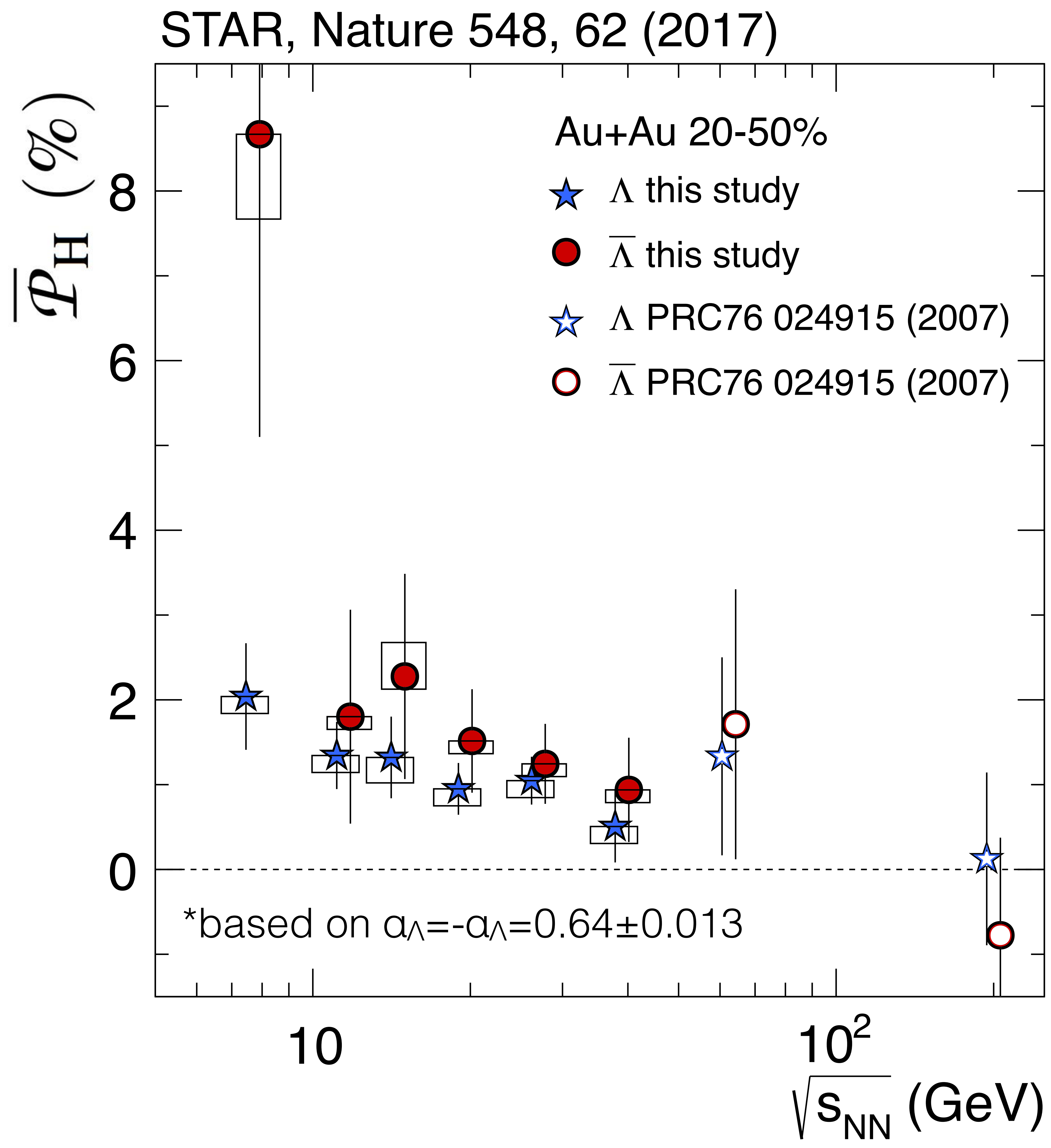
Au+Au collisions at $\sqrt{s_{NN}}$ = 62.4 and 200 GeV in 2004 with very limited statistics (~9M events)

III. CONCLUSION

The Λ and $\bar{\Lambda}$ hyperon global polarization has been measured in Au+Au collisions at center-of-mass energies $\sqrt{s_{NN}} = 62.4$ and 200 GeV with the STAR detector at RHIC. An upper limit of $|P_{\Lambda,\bar{\Lambda}}| \leqslant 0.02$ for the global polarization of Λ and $\bar{\Lambda}$ hyperons within the STAR detector acceptance is

Results were consistent with zero…, giving an upper limit of P_H<2%

First observation in lower energies (2017)



Positive polarization signal at lower energies!

- P_H looks to increase in lower energies

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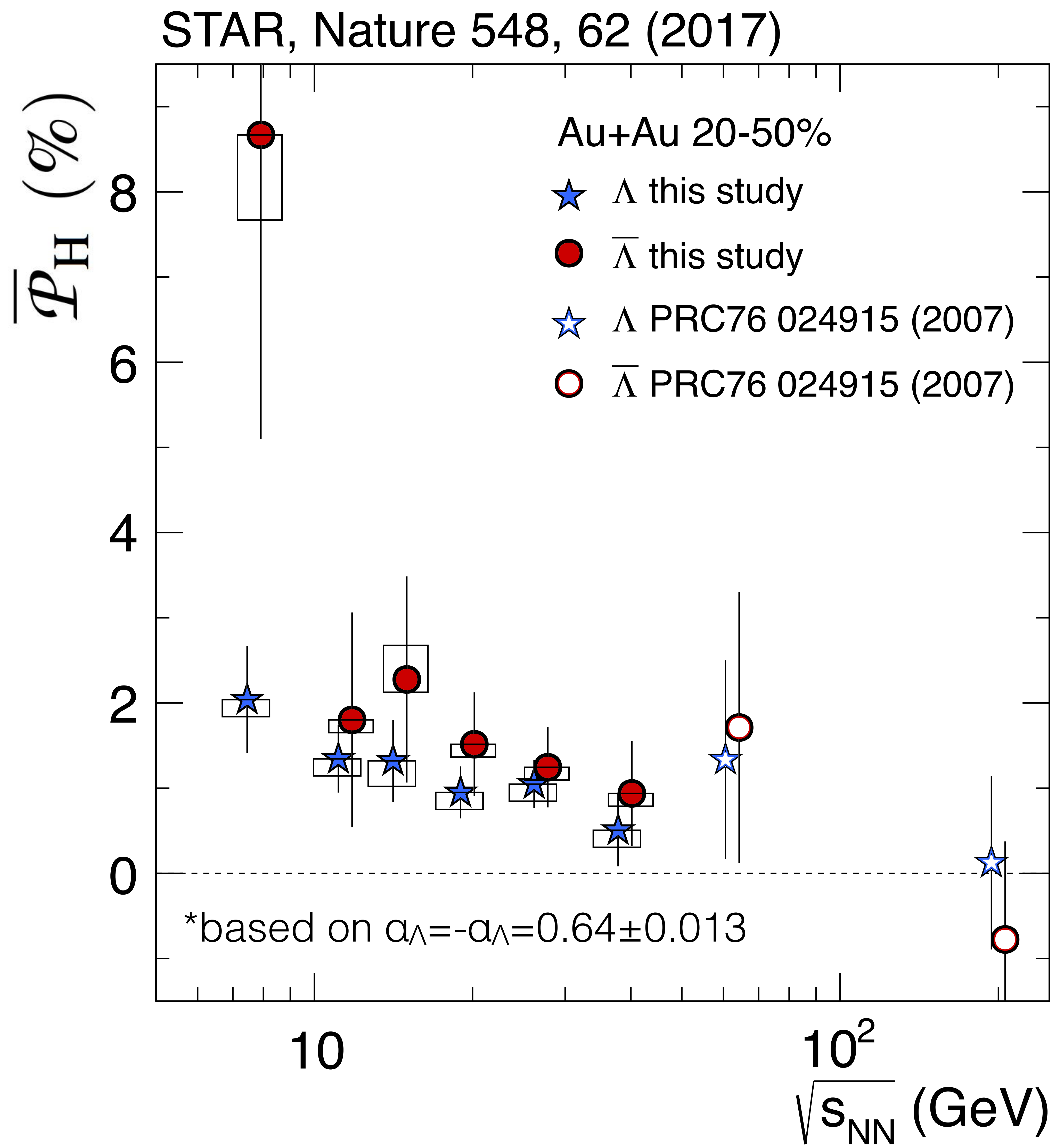
First observation in lower energies (2017)



Positive polarization signal at lower energies!

- P_H looks to increase in lower energies

Becattini, Karpenko, Lisa, Upsal, and Voloshin, PRC95.054902 (2017)

$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

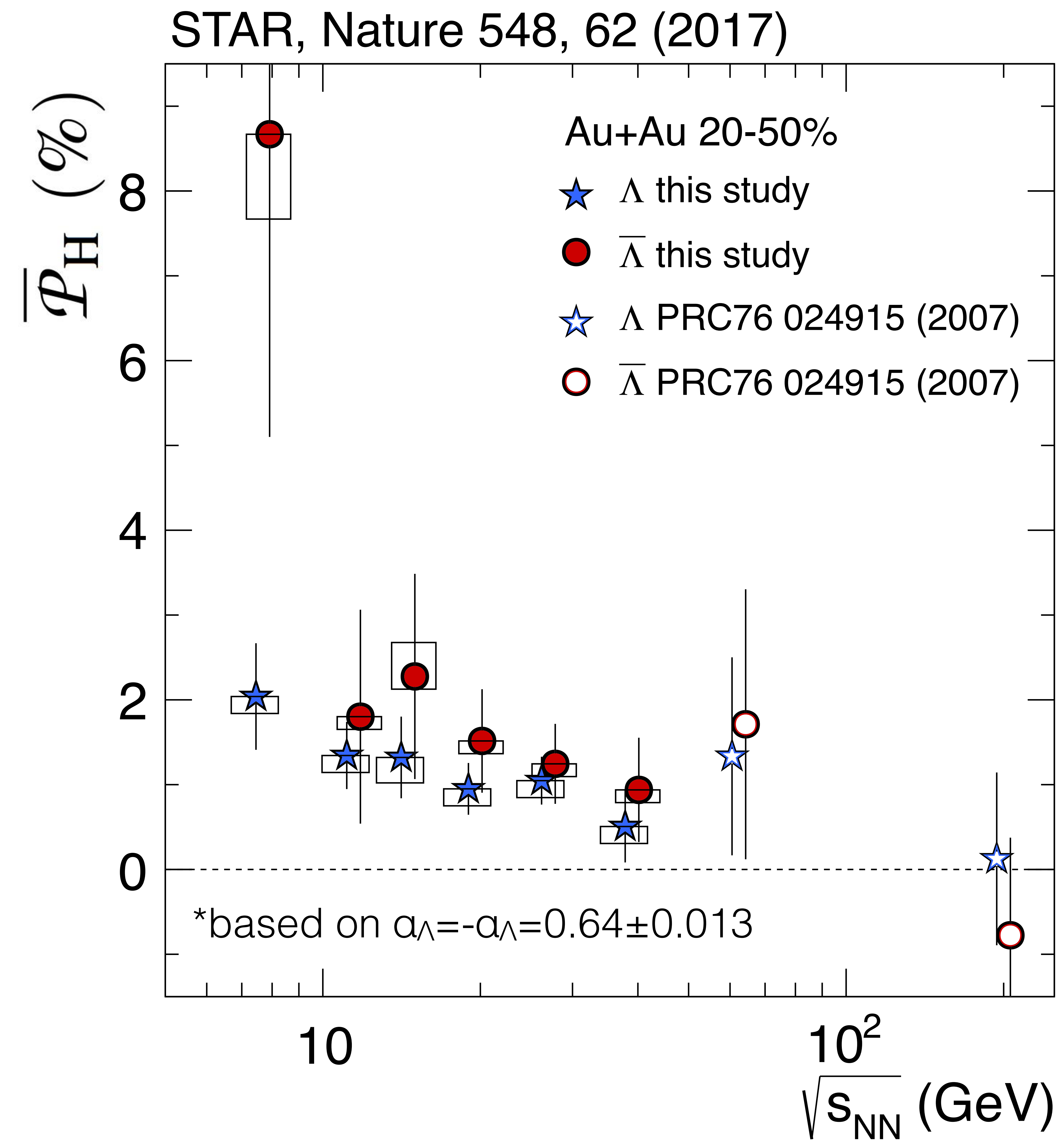
$$P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

$$\omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar$$
$$\sim 0.02\text{-}0.09\ \text{fm}^{-1}$$
$$\sim 0.6\text{-}2.7 \times 10^{22}\text{s}^{-1}$$

μ_Λ: Λ magnetic moment
T: temperature at thermal equilibrium
(T=160 MeV)

- The most vortical fluid!

First observation in lower energies (2017)



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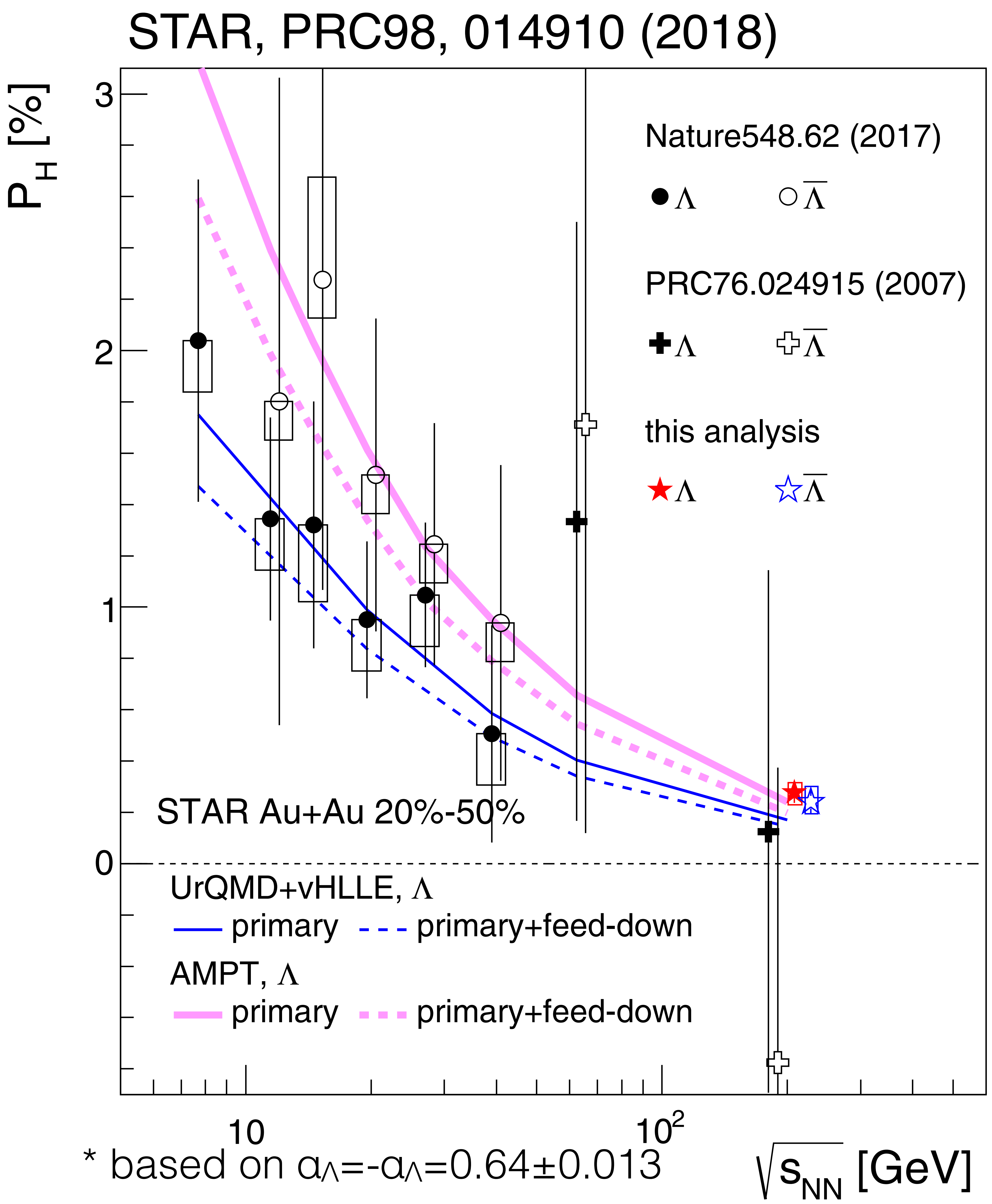
Hint of the difference between Λ and anti-Λ P_H
- Effect of the initial magnetic field? (discussed later)

Precise measurements at $\sqrt{s_{NN}}$ = 200 GeV



* based on α_Λ=-$\alpha_{\bar{\Lambda}}$=0.64±0.013

Confirmed energy dependence with new results at 200 GeV

- >5σ significance utilizing 1.5B events
- partly due to stronger shear flow structure at lower $\sqrt{s_{NN}}$ because of baryon stopping

$$P_H(\Lambda)\ [\%] = 0.277 \pm 0.040(\text{stat}) \pm^{0.039}_{0.049}\ (\text{sys})$$
$$P_H(\bar{\Lambda})\ [\%] = 0.240 \pm 0.045(\text{stat}) \pm^{0.061}_{0.045}\ (\text{sys})$$

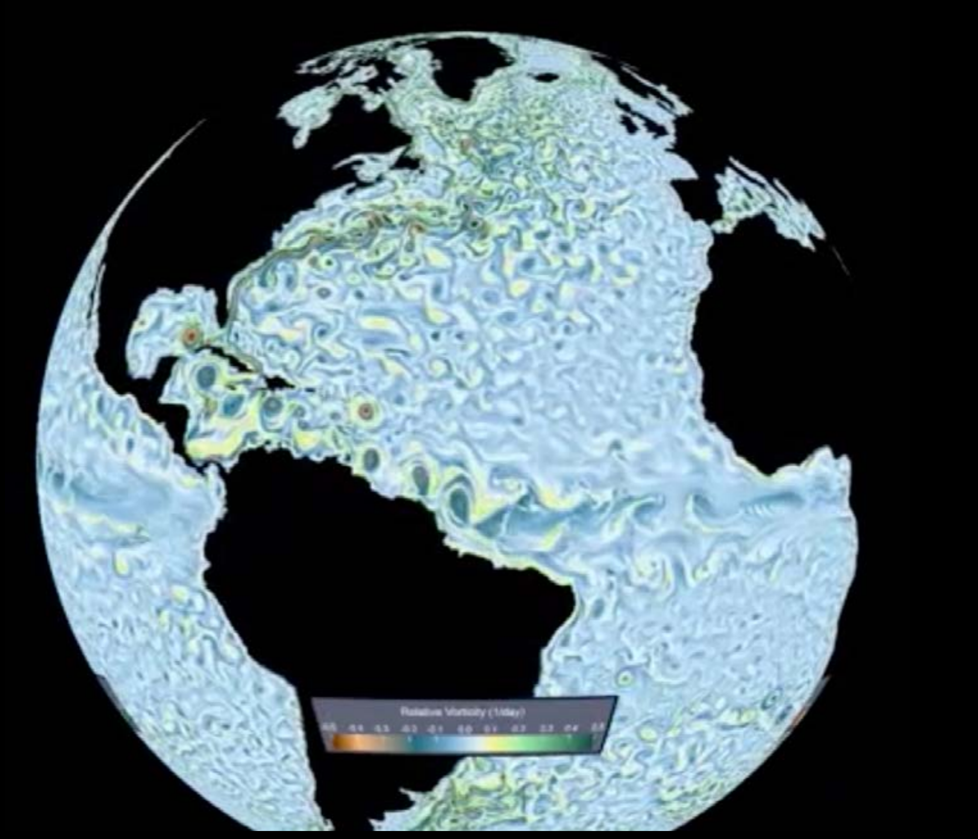
Theoretical models can describe the data well

I. Karpenko and F. Becattini, EPJC(2017)77:213, UrQMD+vHLLE
H. Li et al., PRC96, 054908 (2017), AMPT
Y. Sun and C.-M. Ko, PRC96, 024906 (2017), CKE
Y. Xie et al., PRC95, 031901(R) (2017), PICR
D.-X. Wei et al., PRC99, 014905 (2019), AMPT

Fastest vorticity

Ocean surface vorticity ~10^{-5} s^{-1}
Jupiter's great red spot ~10^{-4} s^{-1}
Core of supercell tornado ~10^{-1} s^{-1}
Rotating, heated soap bubbles ~10^{2} s^{-1}
Superfluid helium nano droplet ~10^{6} s^{-1}
Matter in heavy ion collisions **~10^{22} s^{-1}**

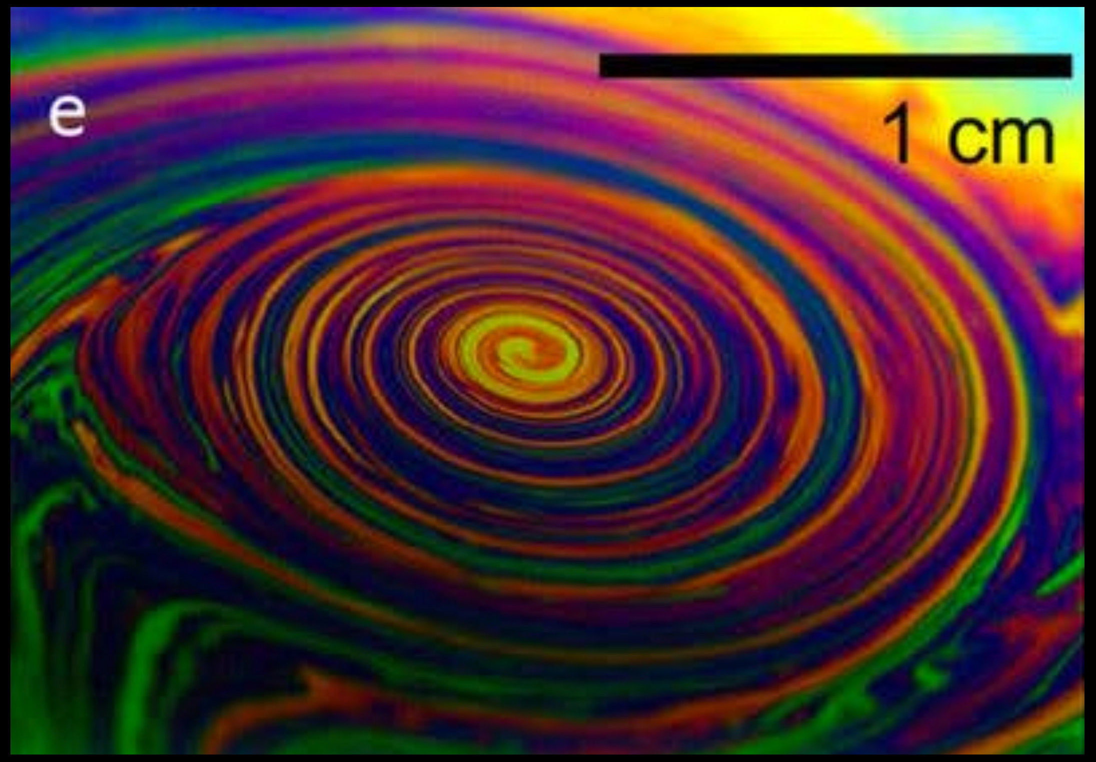
Great red spot of Jupiter (picture: NASA)
6/27, 2019 by Hubble Space Telescope

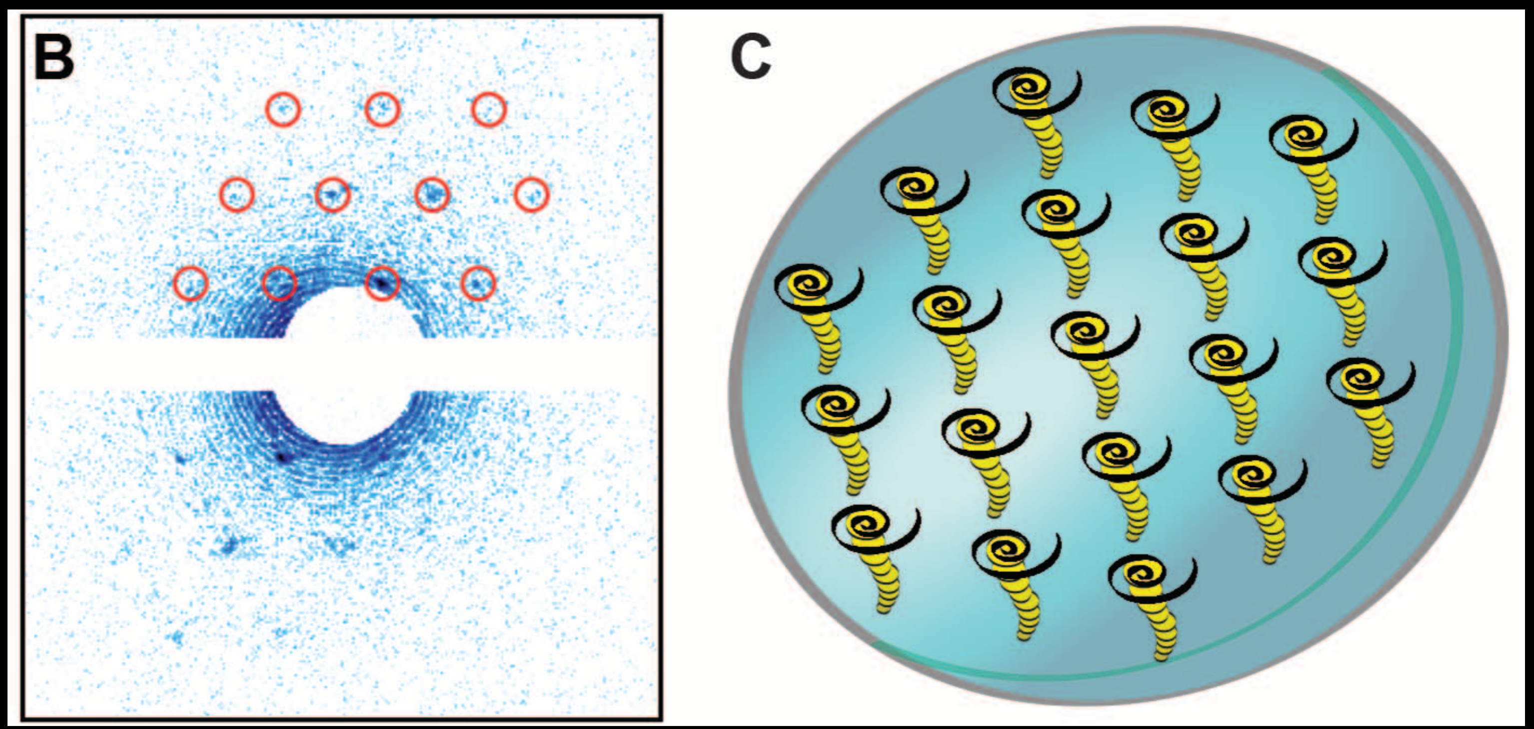


Ocean surface vorticity
https://sos.noaa.gov/datasets/ocean-surface-vorticity/

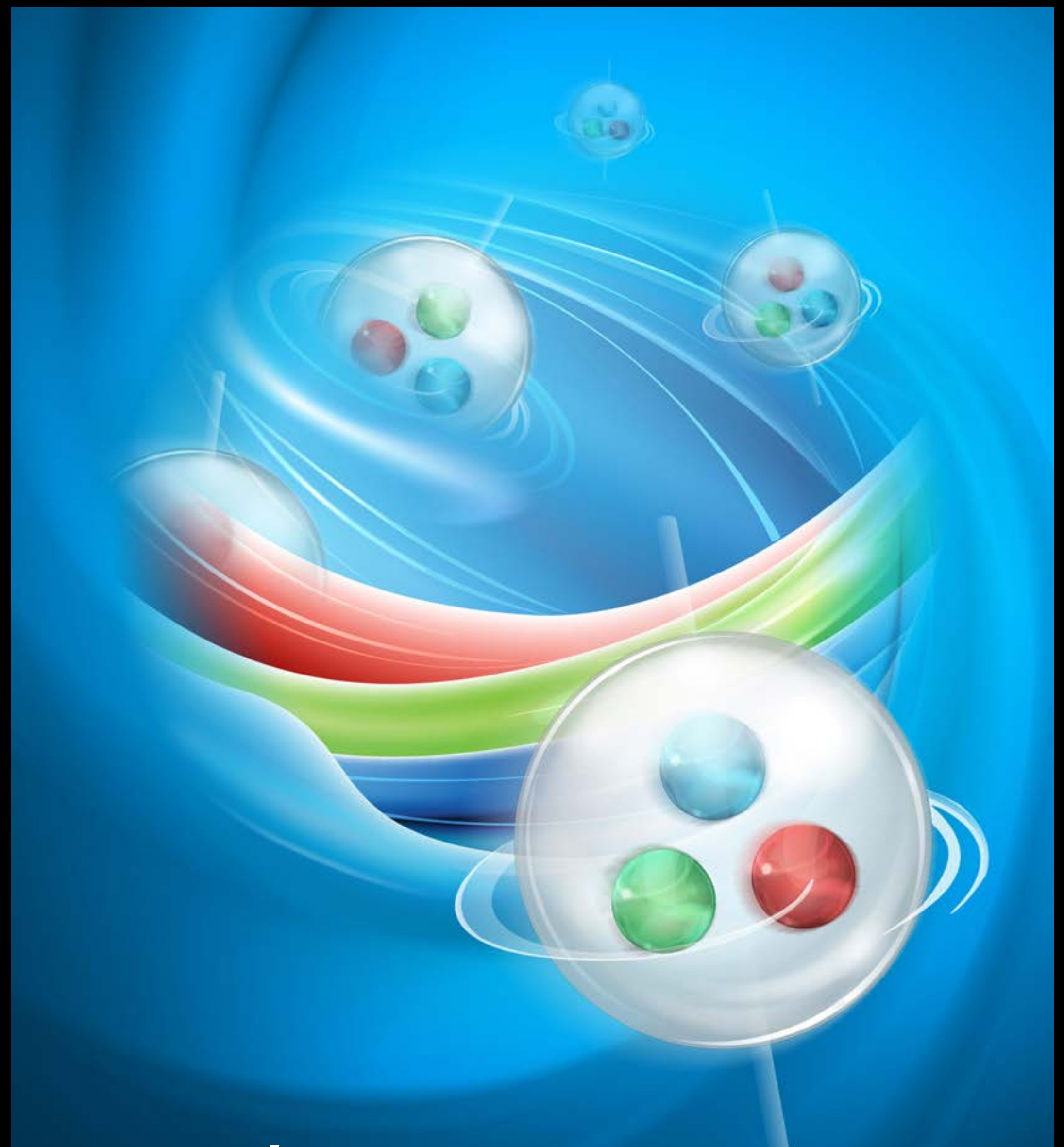
Supercell in Oklahoma (2016)
http://www.silverliningtours.com/tag/tornado/page/3/

vortex of soap bubble
T. Muel et al., Scientific Report 3, 3455 (2013)





vortex aligned to x-ray beam in He droplets
T. Muel et al., Scientific Report 3, 3455 (2013)



bnl.gov/newsroom
Perfect liquid is the most vortical fluid

Differential studies for better understanding

- Effect of initial magnetic field
  - Any particle-antiparticle difference?
- Energy dependence in lower energy
- Discrepancy between data and models ("*sign issues*")
  - Azimuthal dependence of PH
  - Local polarization along the beam direction
- Particle species dependence
  - Different mass and spin

A possible probe of B-field

Becattini, Karpenko, Lisa, Upsal, and Voloshin, PRC95.054902 (2017)

$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

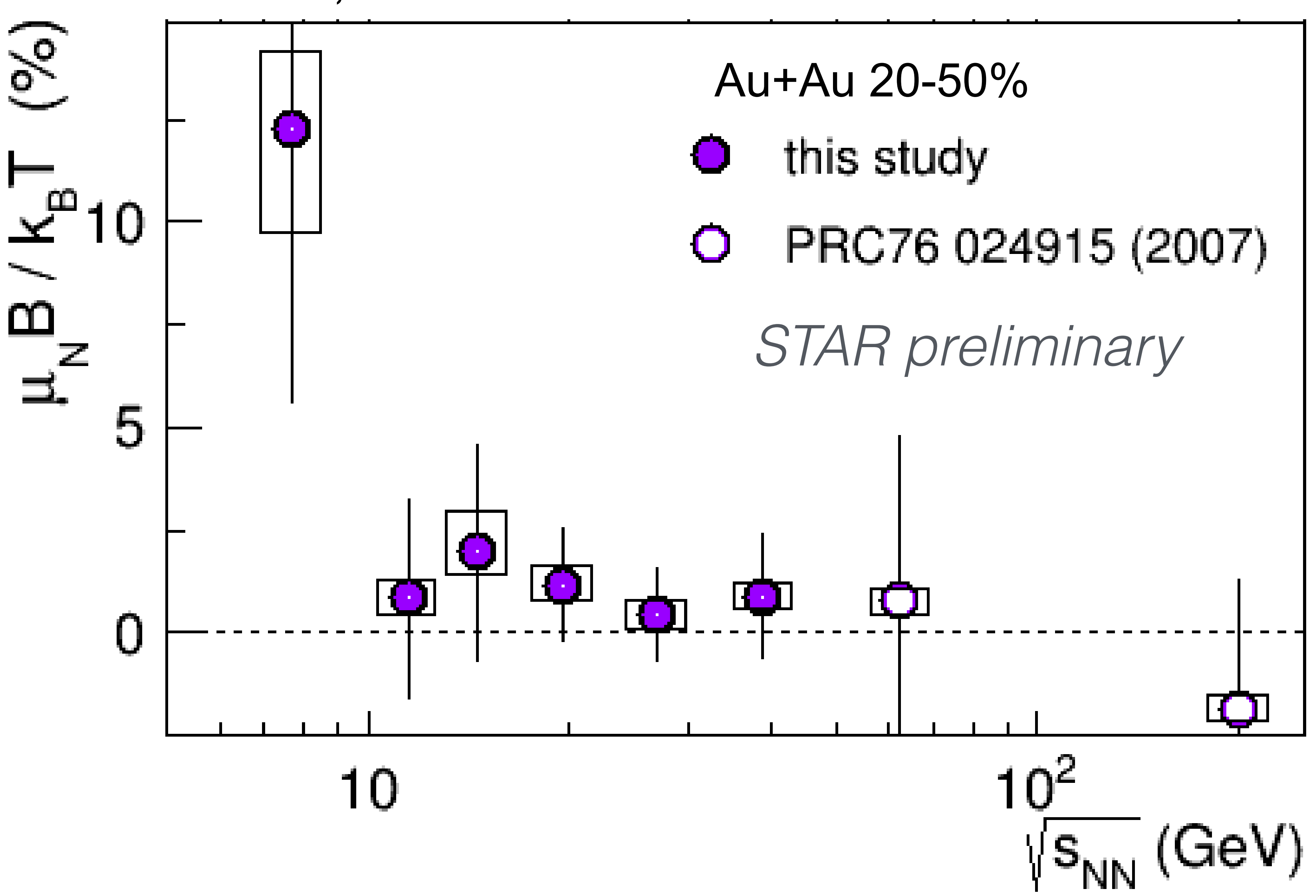
$$P_{\bar{\Lambda}} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

μ_Λ: Λ magnetic moment

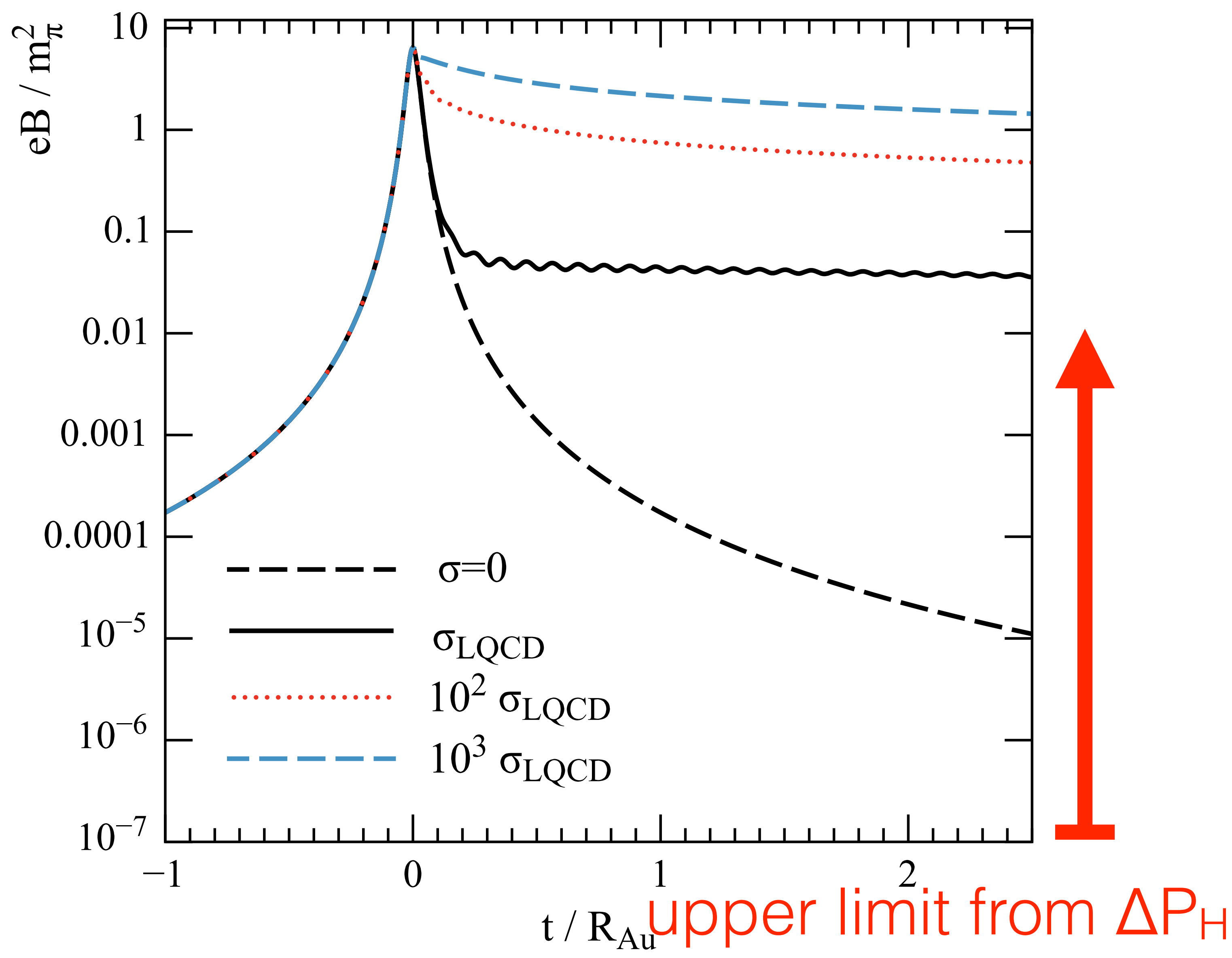
$$B = (P_\Lambda - P_{\bar{\Lambda}})T/(2\mu_\Lambda)$$
$$\sim 2 \times 10^{11} \ [\mathrm{T}]$$
$$eB \sim 10^{-2} \mathrm{m}_\pi^2$$

ΔP_Λ~0.5%, T=160MeV

STAR, QM17



McLerran and Skokov, Nucl. Phys. A929, 184 (2014)

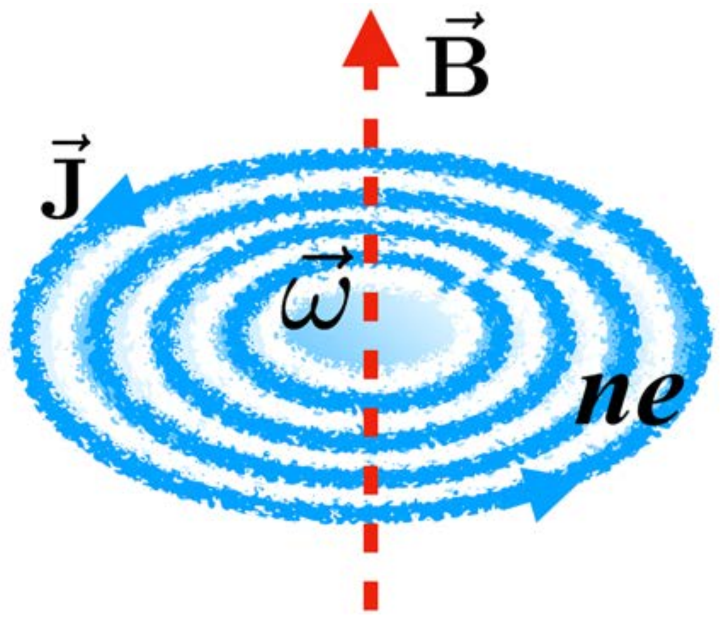


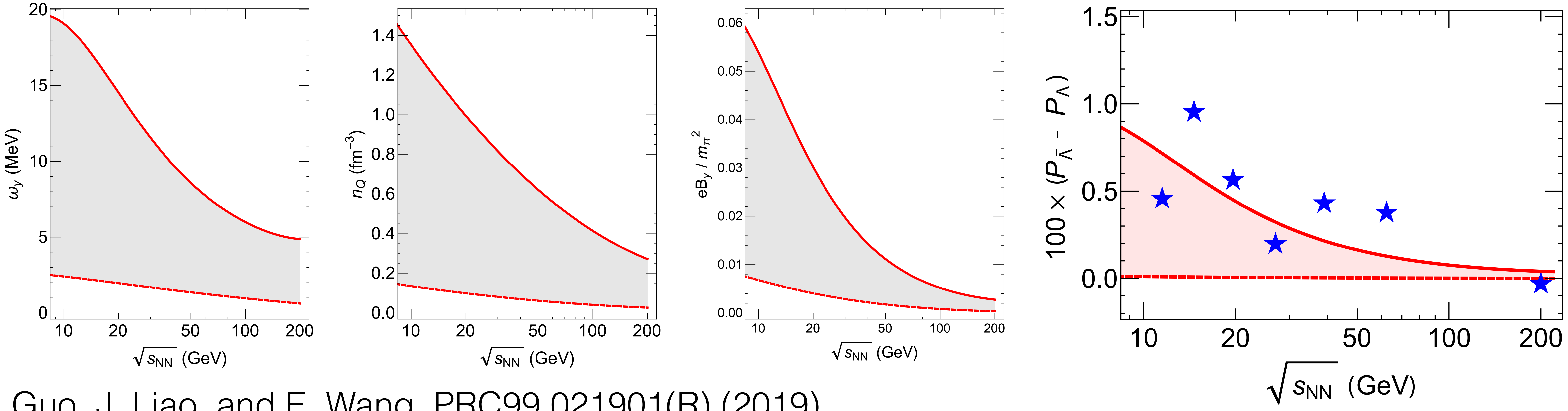
Conductivity increases lifetime.

- Based on thermal model, B-field at kinetic freeze-out could be probed by Λ-antiΛ splitting
  - Current results are consistent with zero (except 7.7 GeV)
- But the splitting could be also due to other effects…

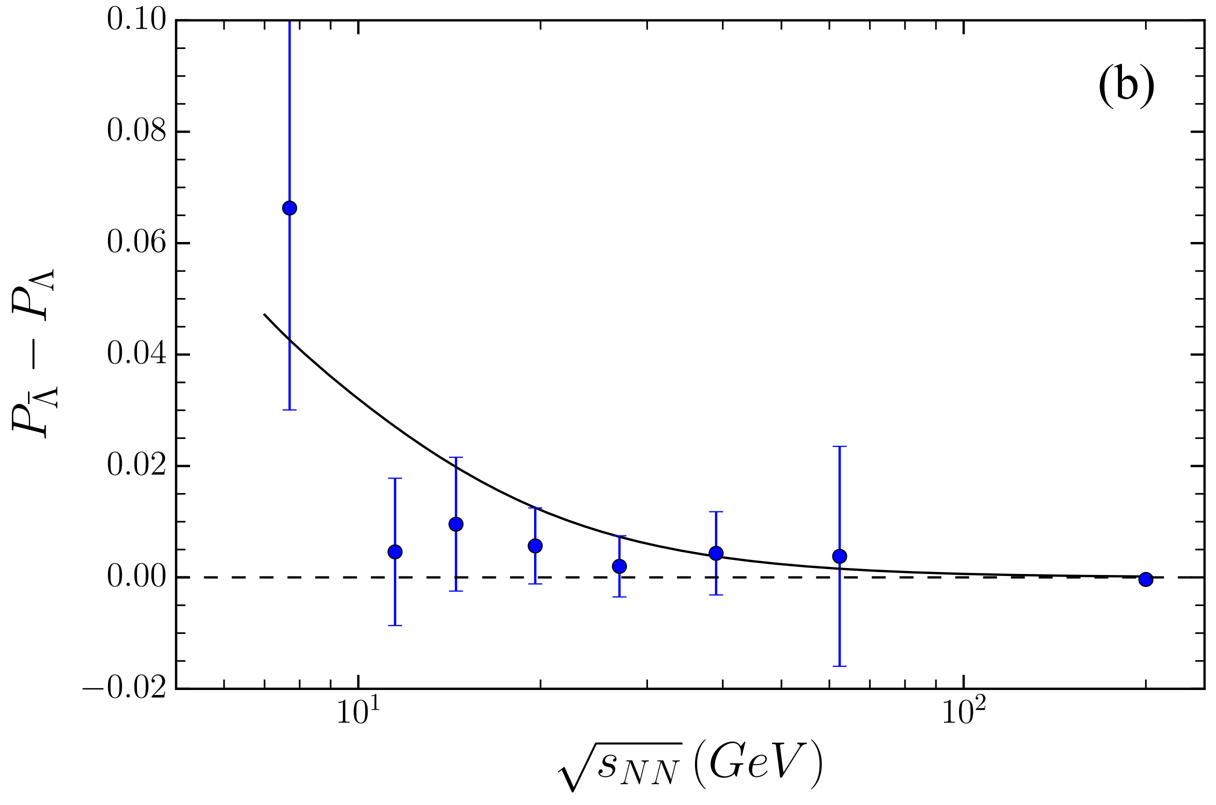
Need caution for the interpretation

- Initial magnetic field
- Effect of chemical potential (expected to be small)
  R. Fang et al.,, PRC94, 024904 (2016)
- Rotating charged fluid produces B-field with longer lifetime
  X. Guo, J. Liao, and E. Wang, PRC99.021901(R) (2019)
- Spin interaction with the meson field generated by the baryon current
  L. Csernai, J. Kapusta, and T. Welle, PRC99.021901(R) (2019)
- Different space time distributions and freeze-out of Λ and antiΛ
  O. Vitiuk, L.Bravina, E. Zabrodin, PLB803(2020)135298





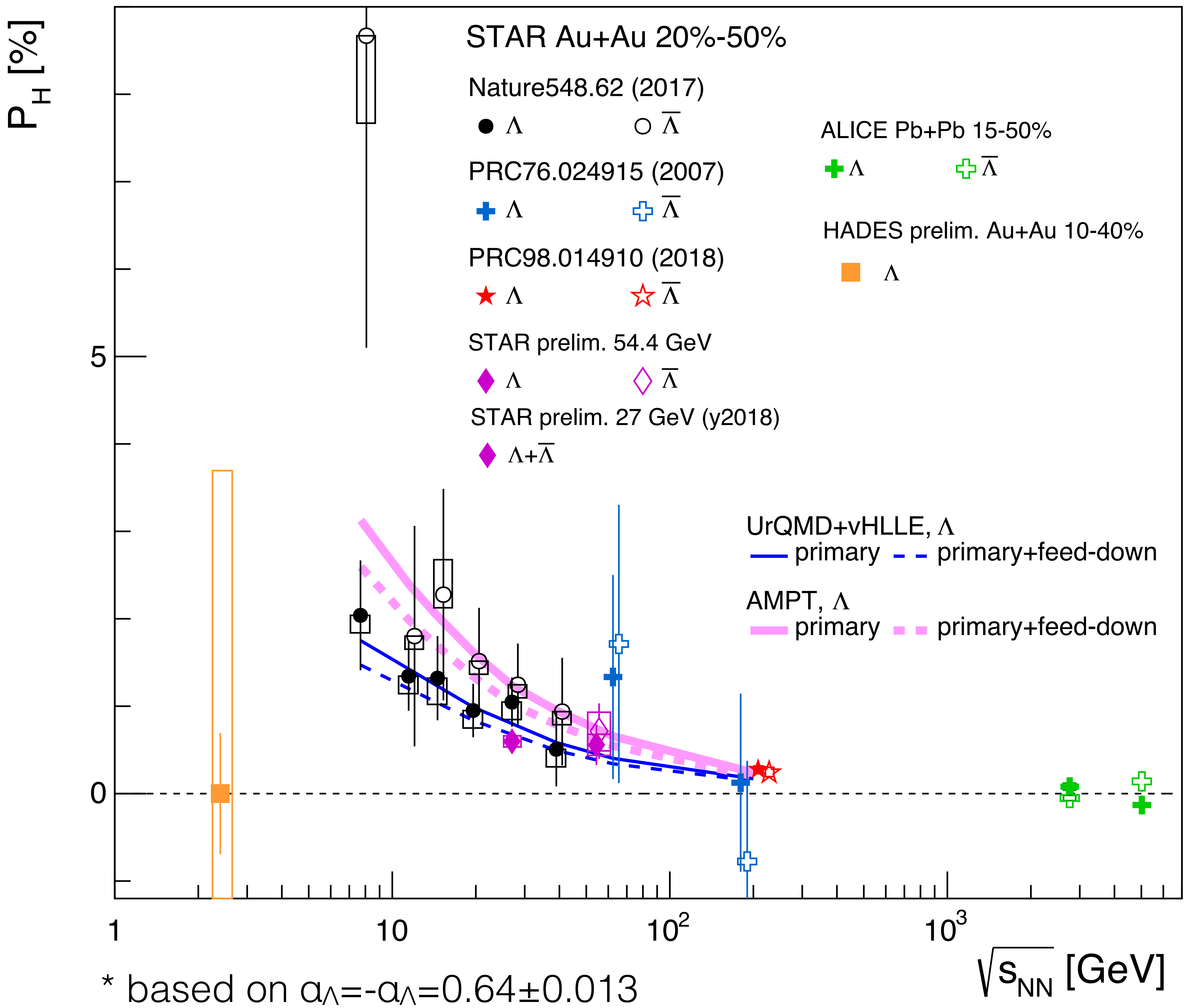
X. Guo, J. Liao, and E. Wang, PRC99.021901(R) (2019)



L. Csernai et al., PRC99.021901(R) (2019)

Complete the energy dependence

ALICE, PRC101.044611 (2020)
F. Kornas (HADES), SQM2019
J. Adams, K. Okubo (STAR), QM2019

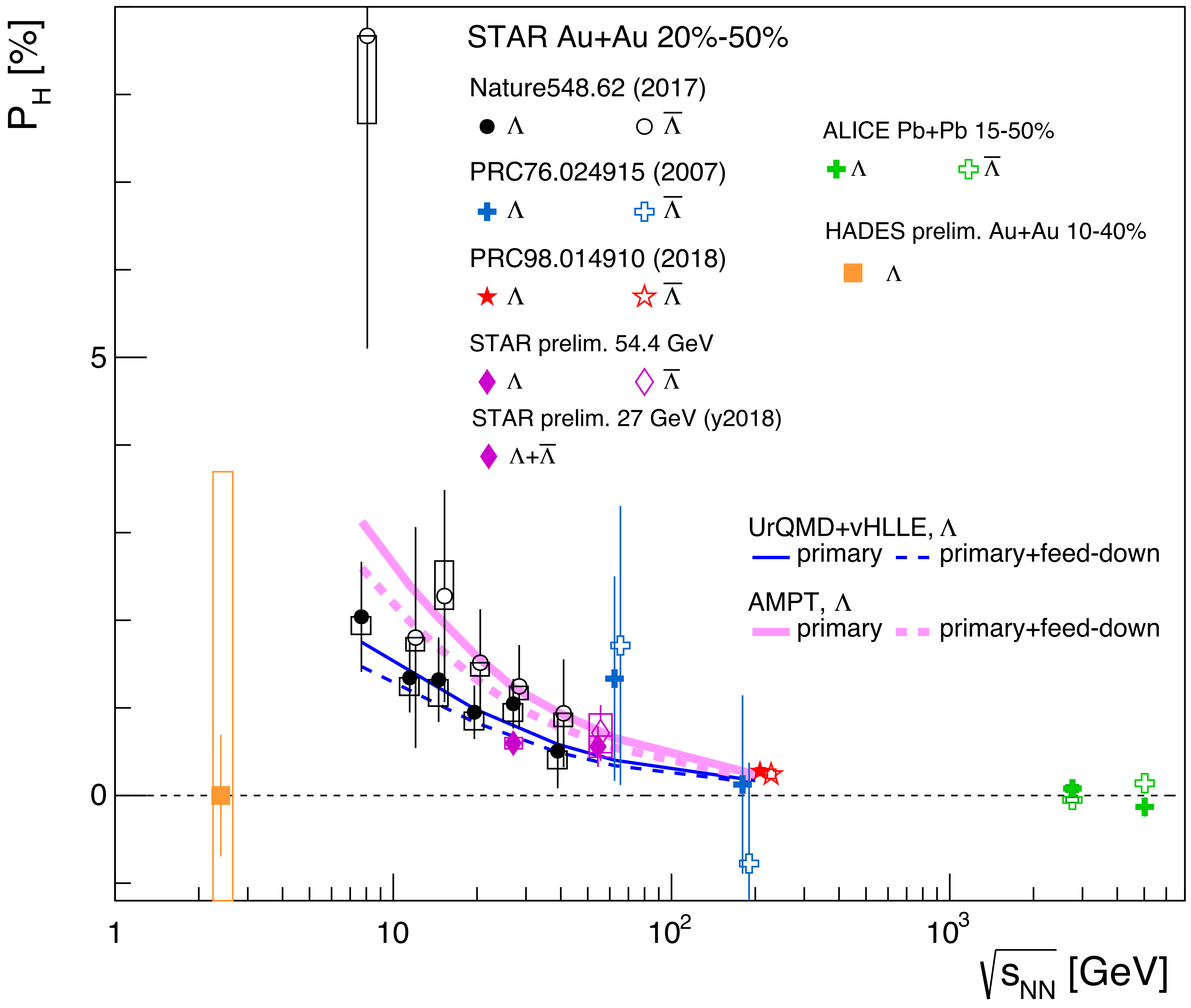


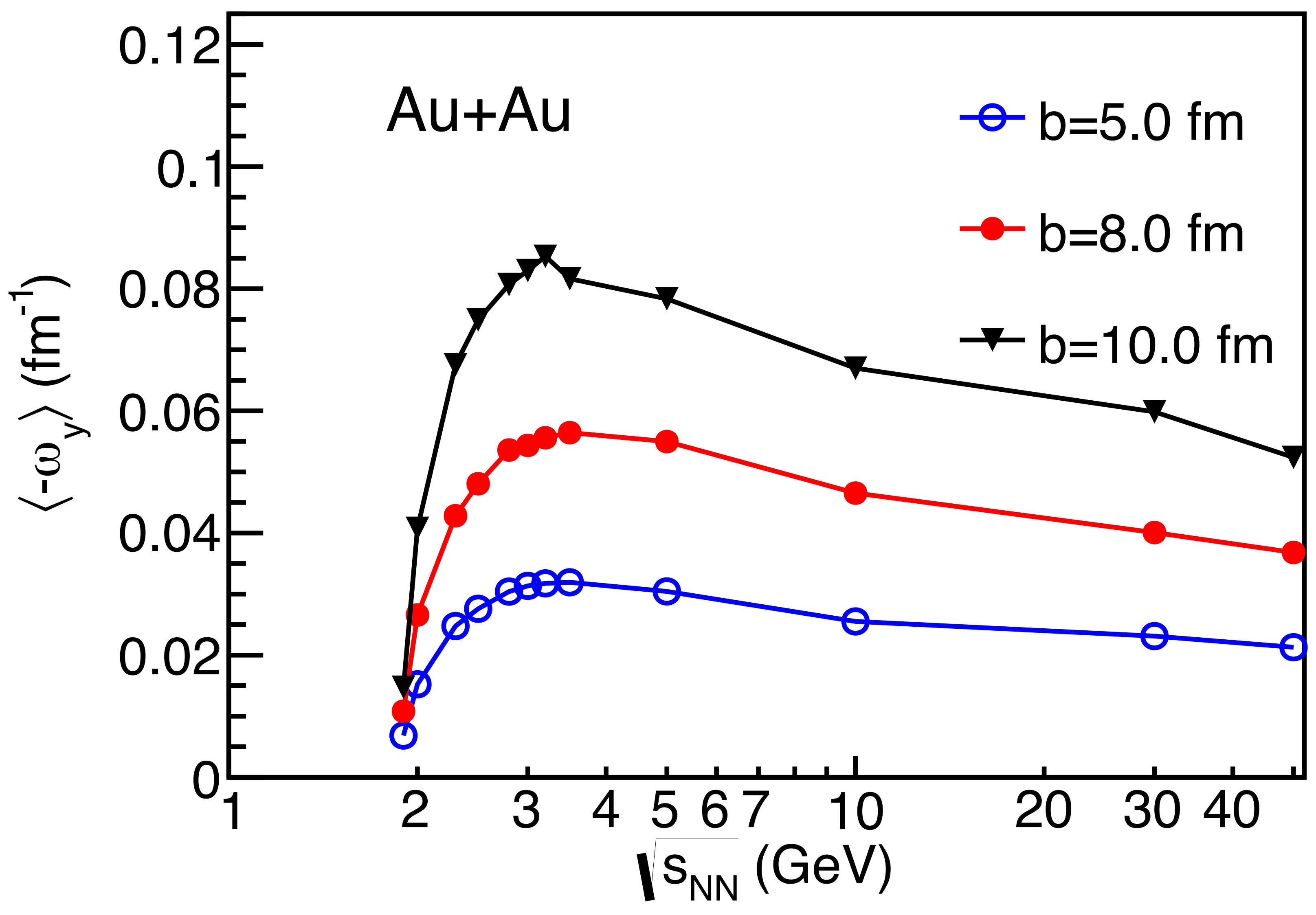
* based on α_Λ=-$\alpha_{\bar{\Lambda}}$=0.64±0.013

- STAR preliminary at 27 and 54 GeV
  ***result (54 GeV) from K. Okubo (M2) in our group**
- ALICE at 2.76 and 5.02 TeV
  - Expected signal is of the order of current statistical uncertainty
- HADES at 2.4 GeV
  - Large uncertainty but still preliminary
  - Hopefully reduce systematic uncertainty

Complete the energy dependence

ALICE, PRC101.044611 (2020)
F. Kornas (HADES), SQM2019
J. Adams, K. Okubo (STAR), QM2019





Interesting energy dependence of kinematic vorticity predicted by a transport model (UrQMD)
X.-G. Deng et al., PRC101.064908 (2020)

Complete the energy dependence

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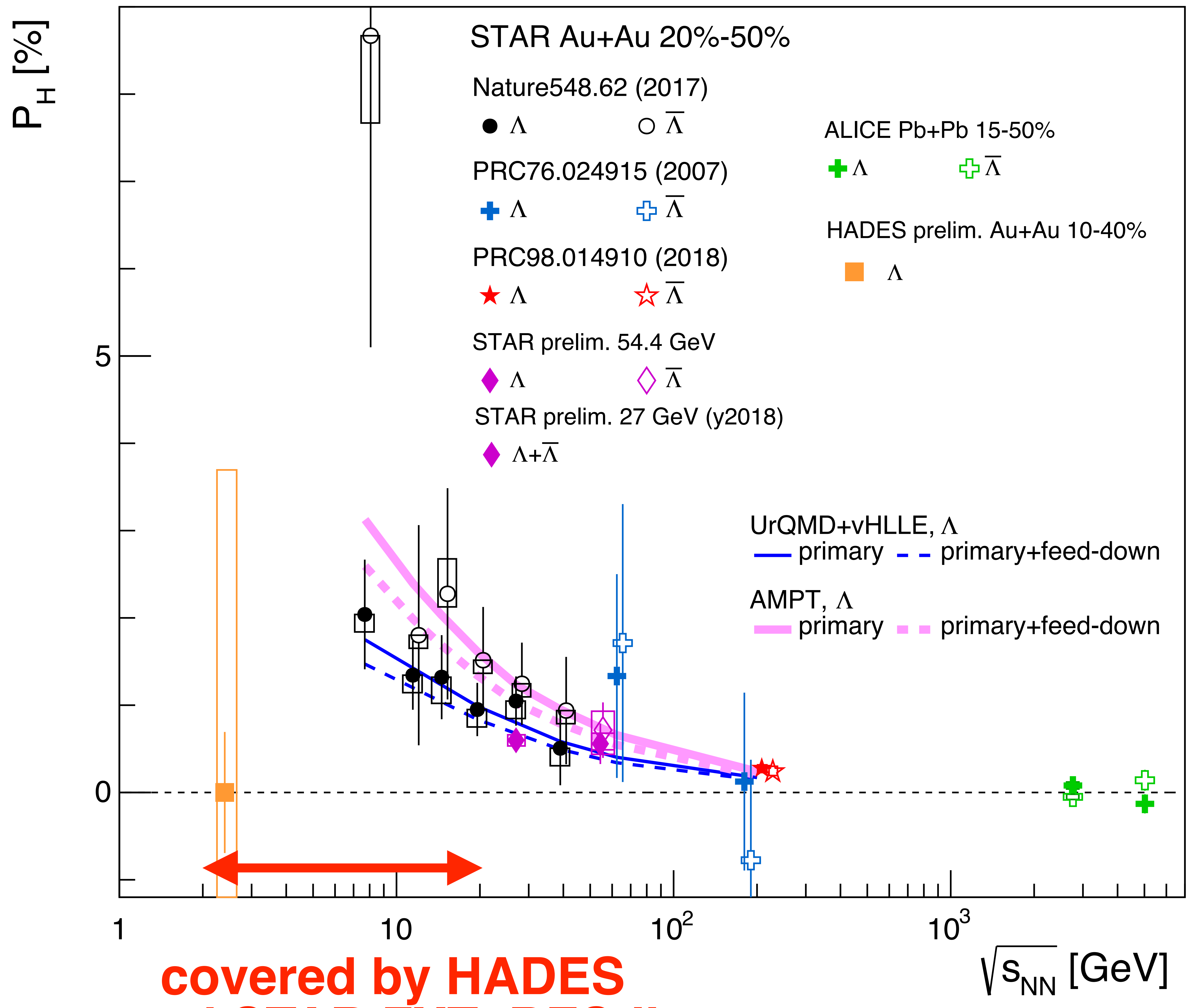
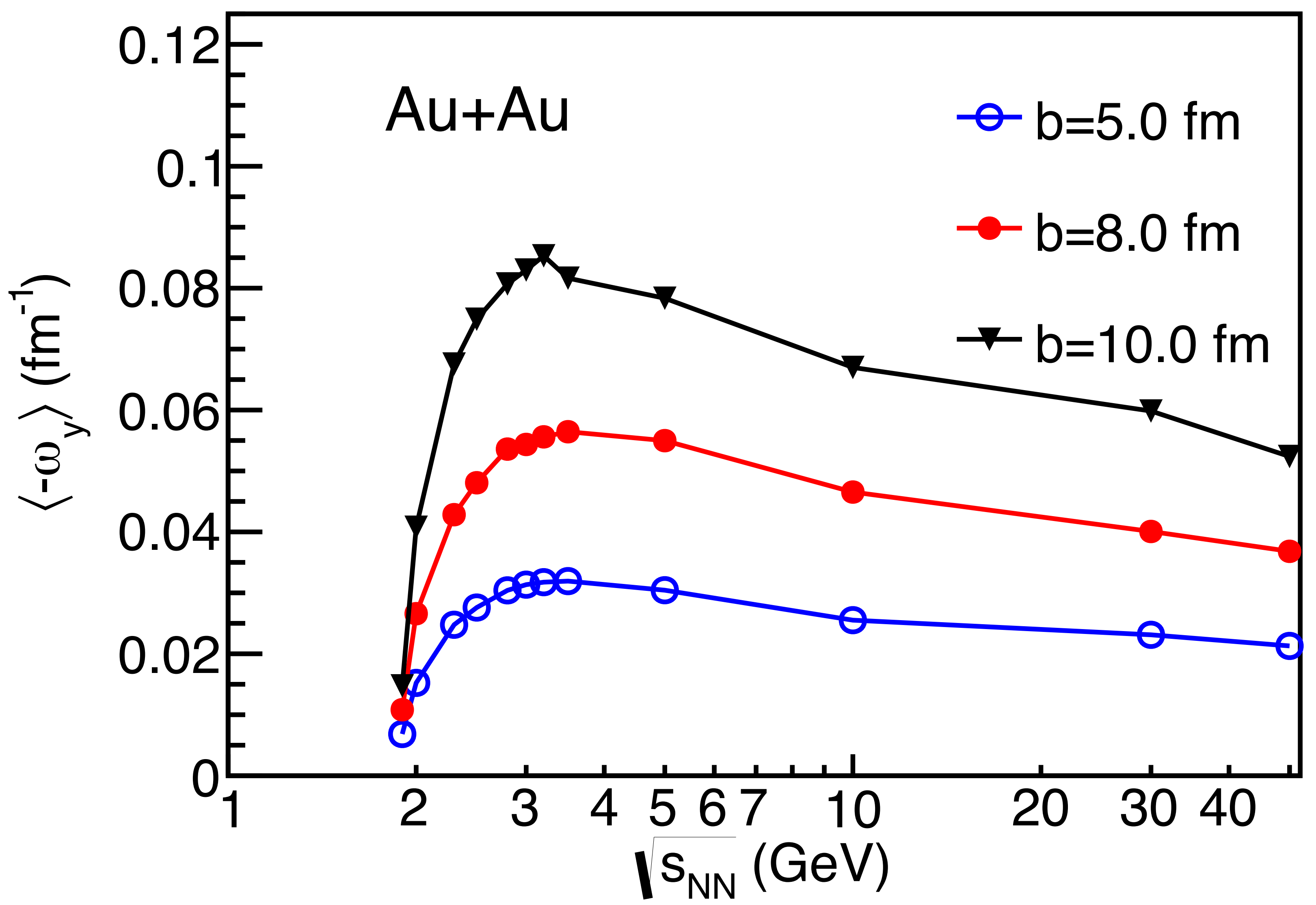


covered by HADES and STAR FXT+BES-II

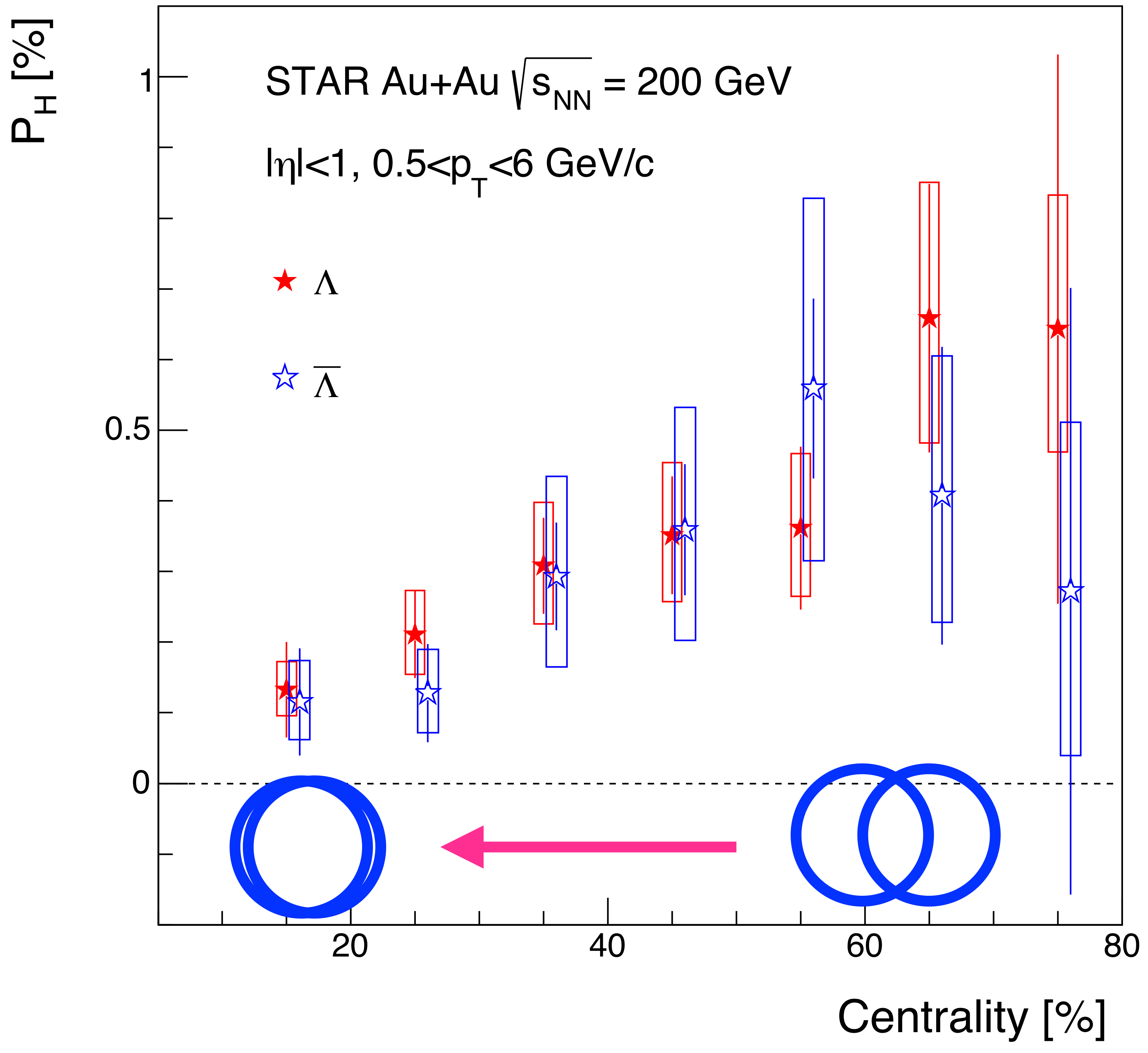


Interesting energy dependence of kinematic vorticity predicted by a transport model (UrQMD)
X.-G. Deng et al., PRC101.064908 (2020)

HADES: 2-3 GeV
STAR FXT: 3-7.7 GeV
STAR BES-II: 7.7-19 GeV

Differential measurements: centrality

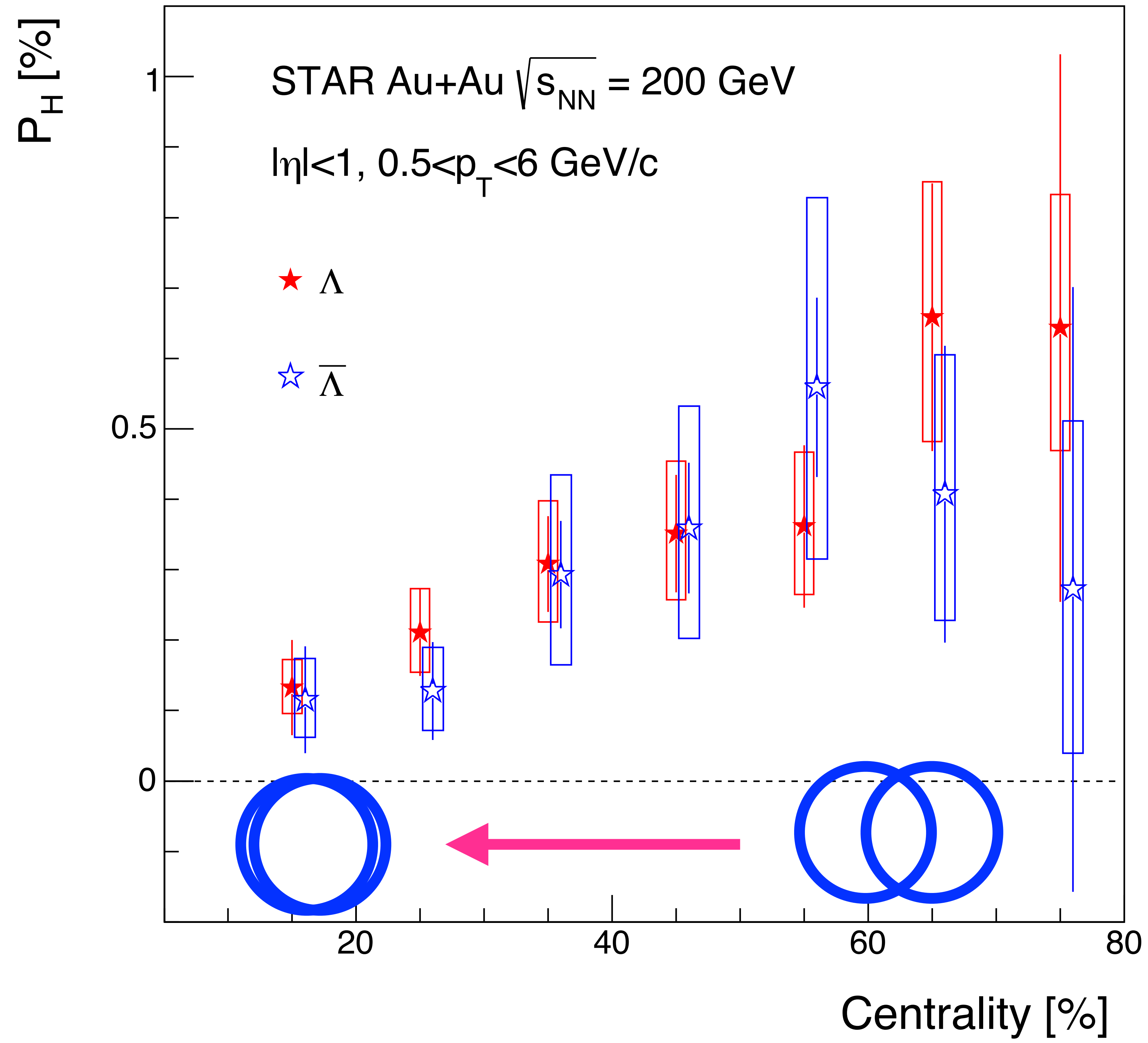
STAR, PRC98, 014910 (2018)



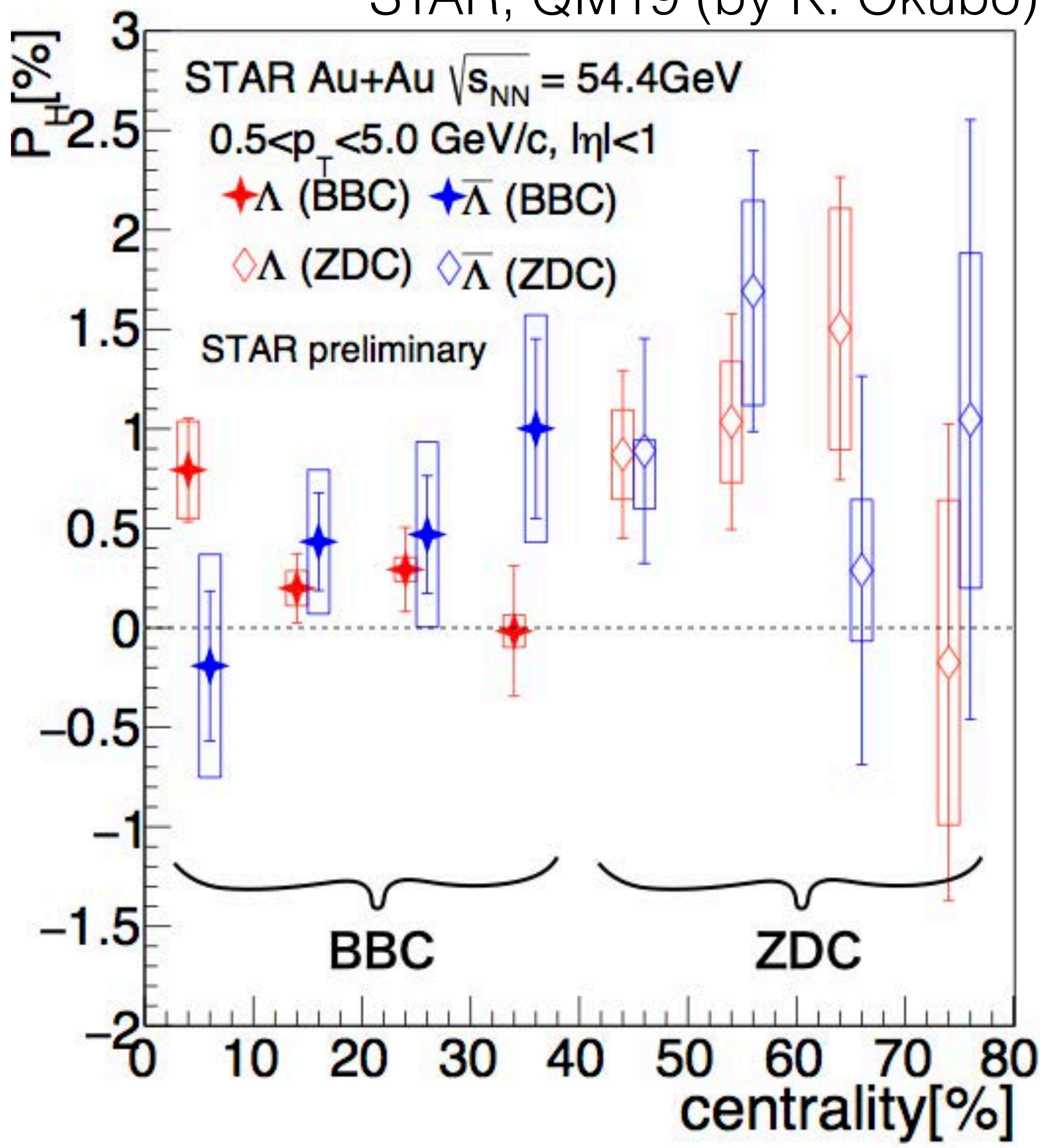
In most central collision → no initial angular momentum
The polarization decreases in more central collisions.

Differential measurements: centrality

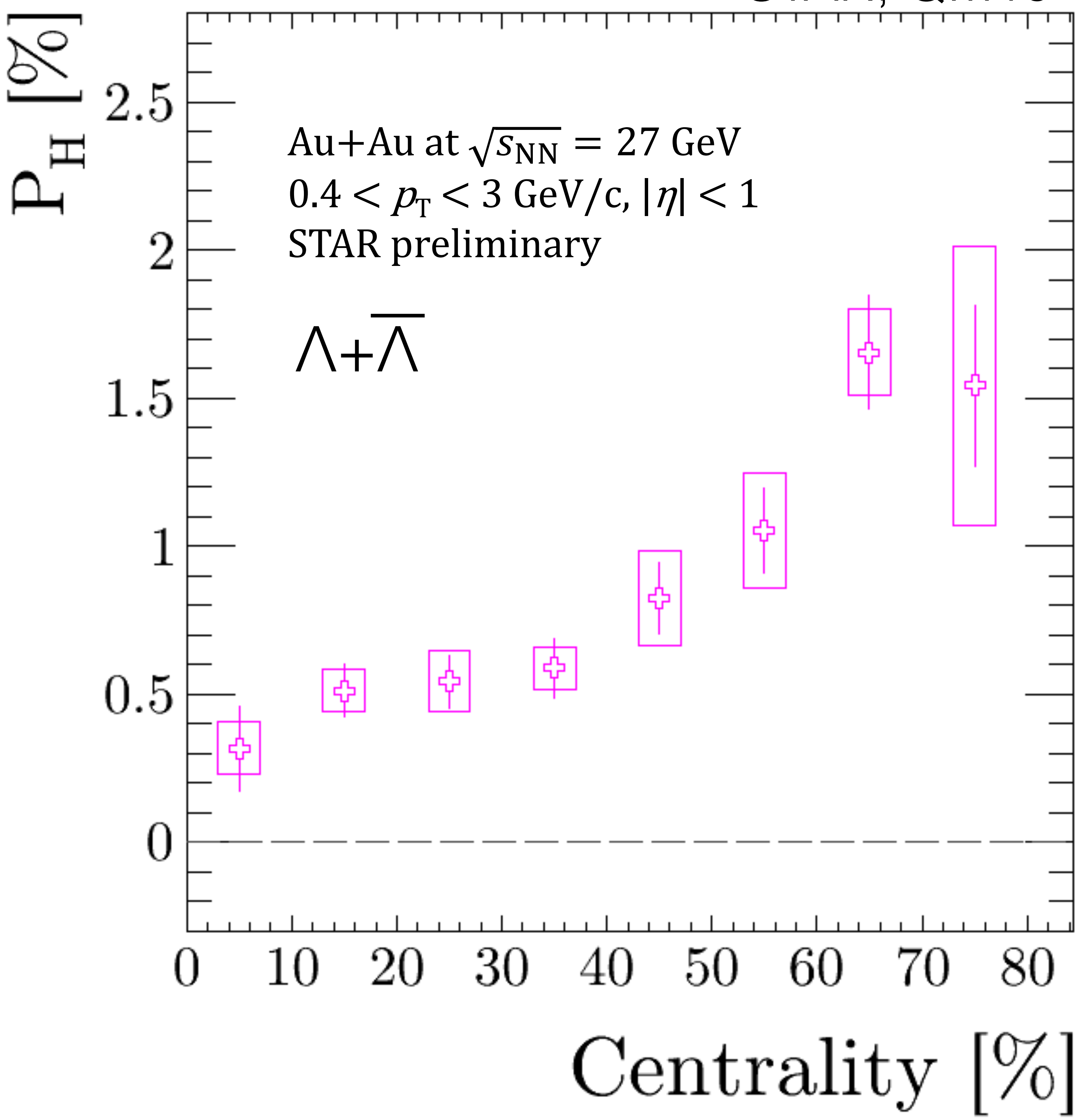
STAR, PRC98, 014910 (2018)



STAR, QM19 (by K. Okubo)



STAR, QM19



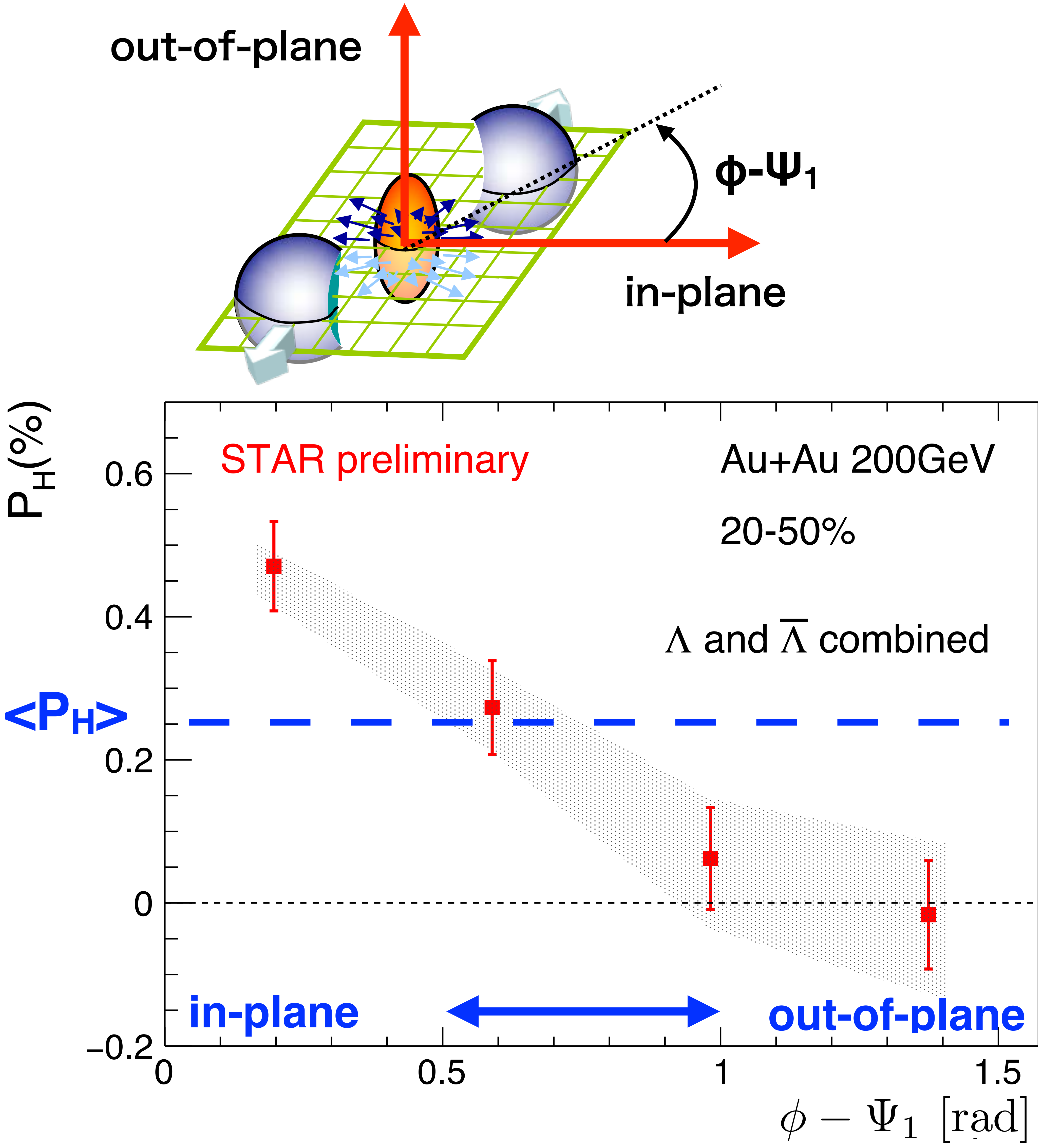
$\sqrt{s_{NN}}$ 200 GeV — 54 GeV — 27 GeV

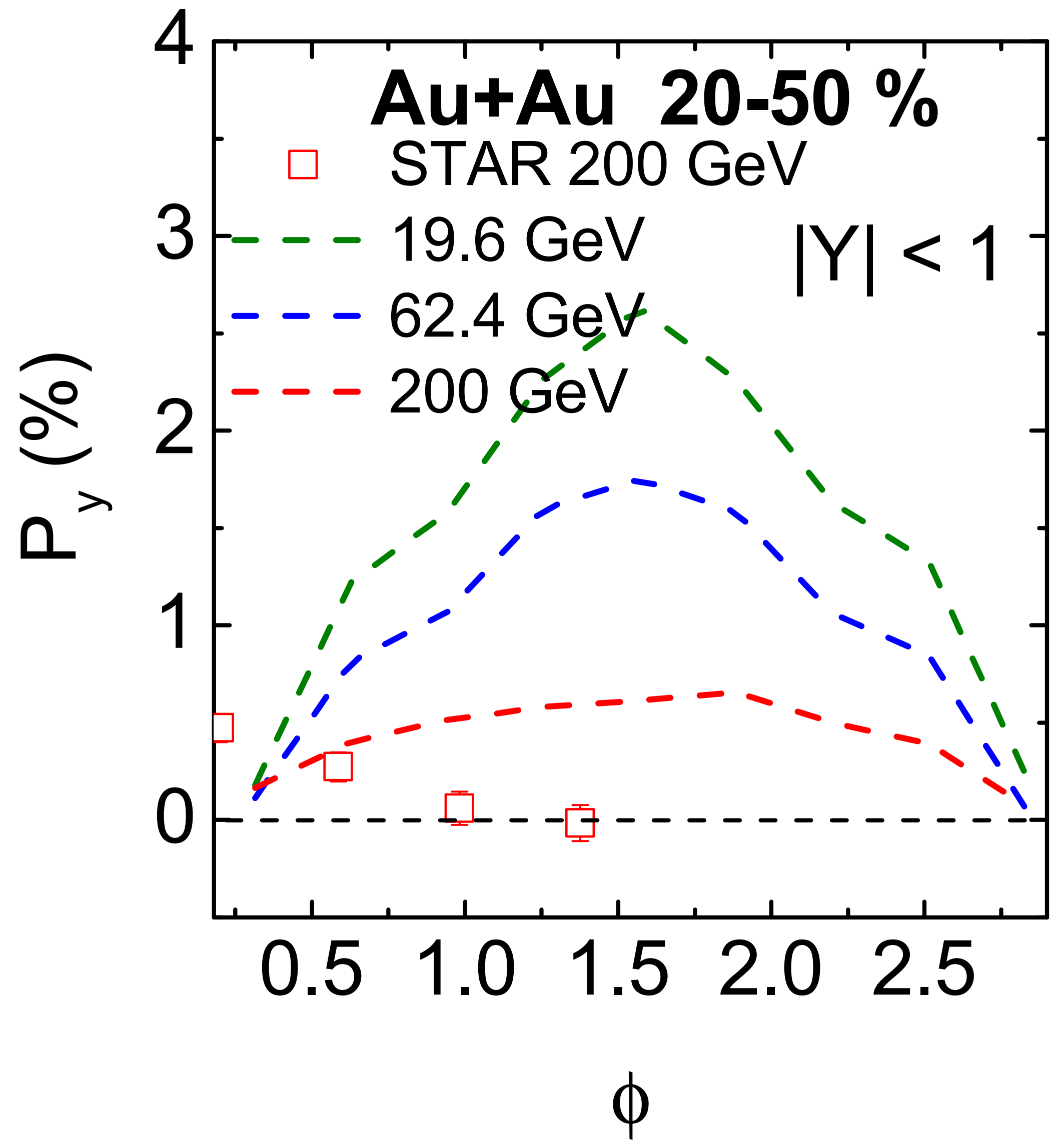
In most central collision → no initial angular momentum

The polarization decreases in more central collisions.

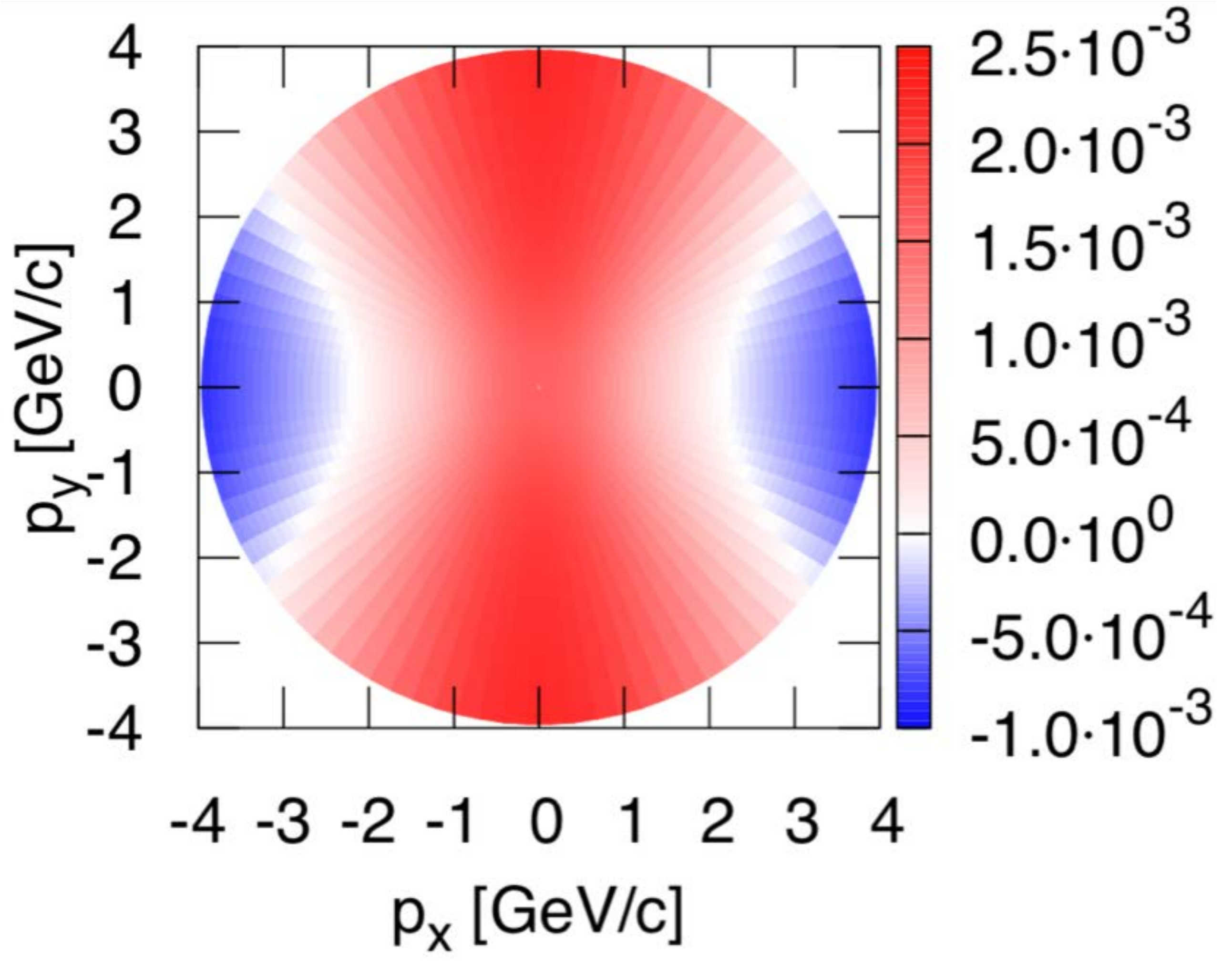
Similar trend was confirmed at lower energies.

Differential measurements: azimuthal angle





F. Becattini and M. Lisa, arXiv:2003.03640

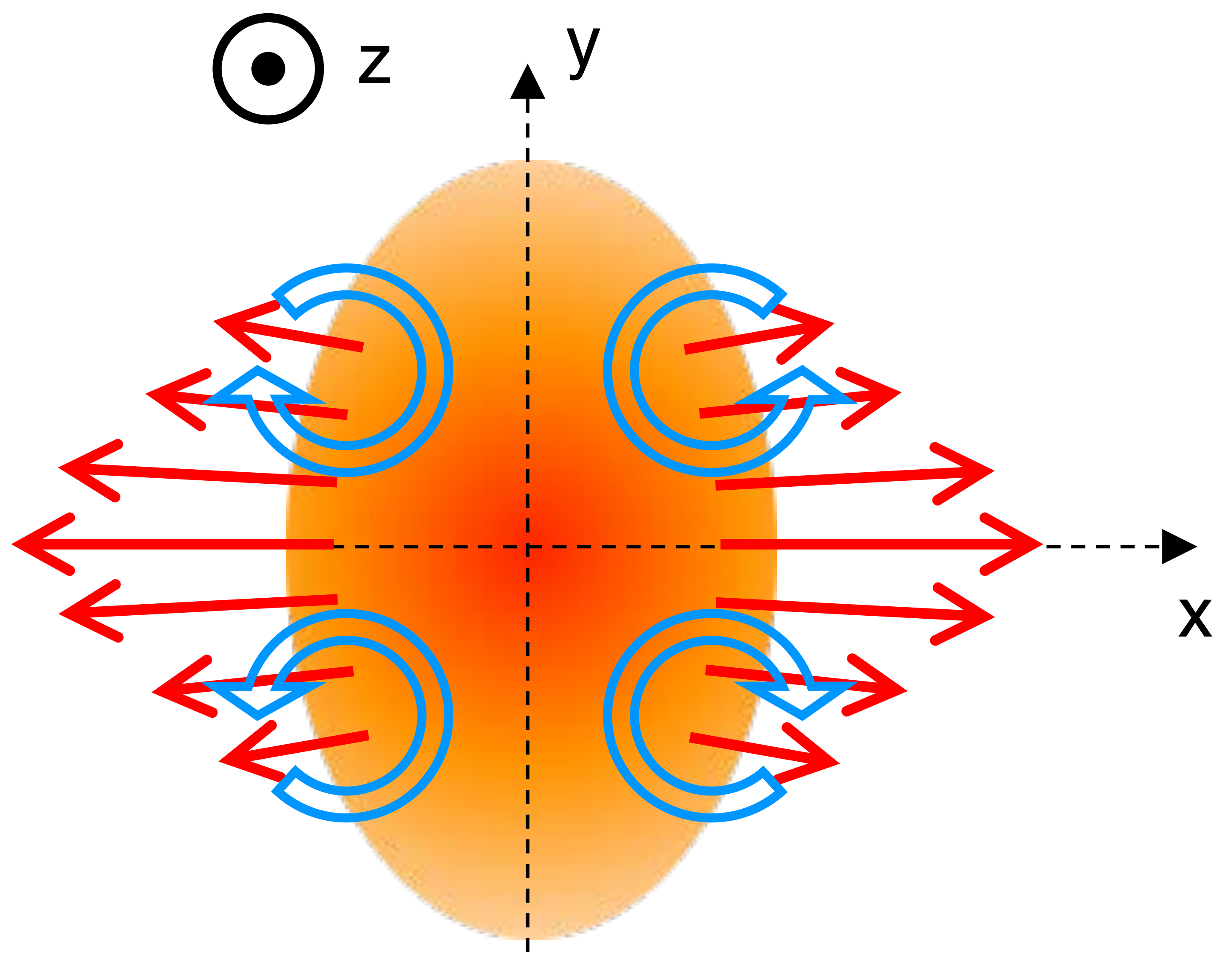


I. Karpenko and F. Becattini, EPJC(2017)77.213
D. Wei, W. Deng, and X. Huang, PRC99.014905 (2019)

- The data shows larger polarization for in-plane, while many models predict the opposite, i.e. larger for out-of-plane
- **Not fully understood yet**

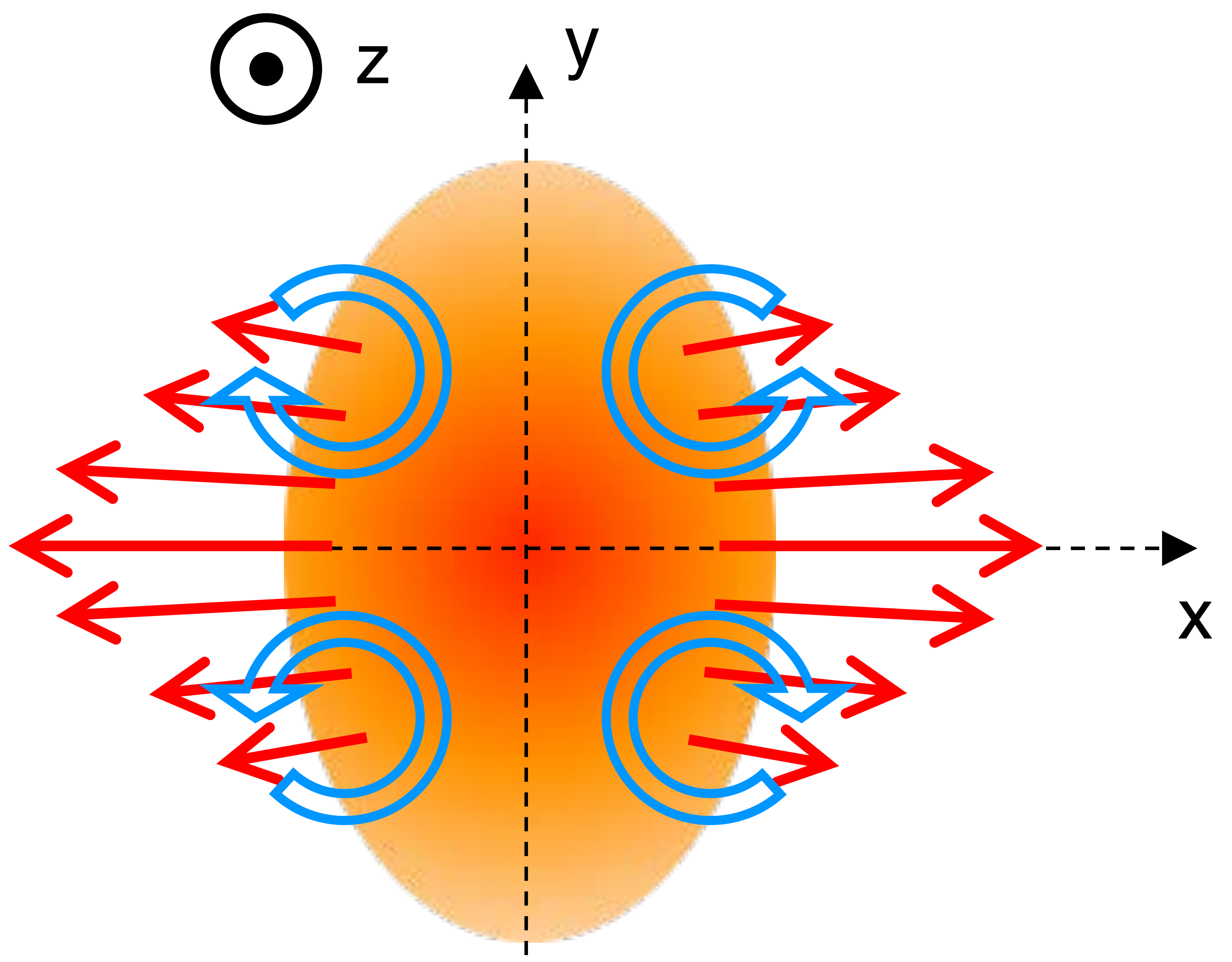
"T-vorticity" may explain the data?
H. Wu et al., PR.Research1.033058 (2019)

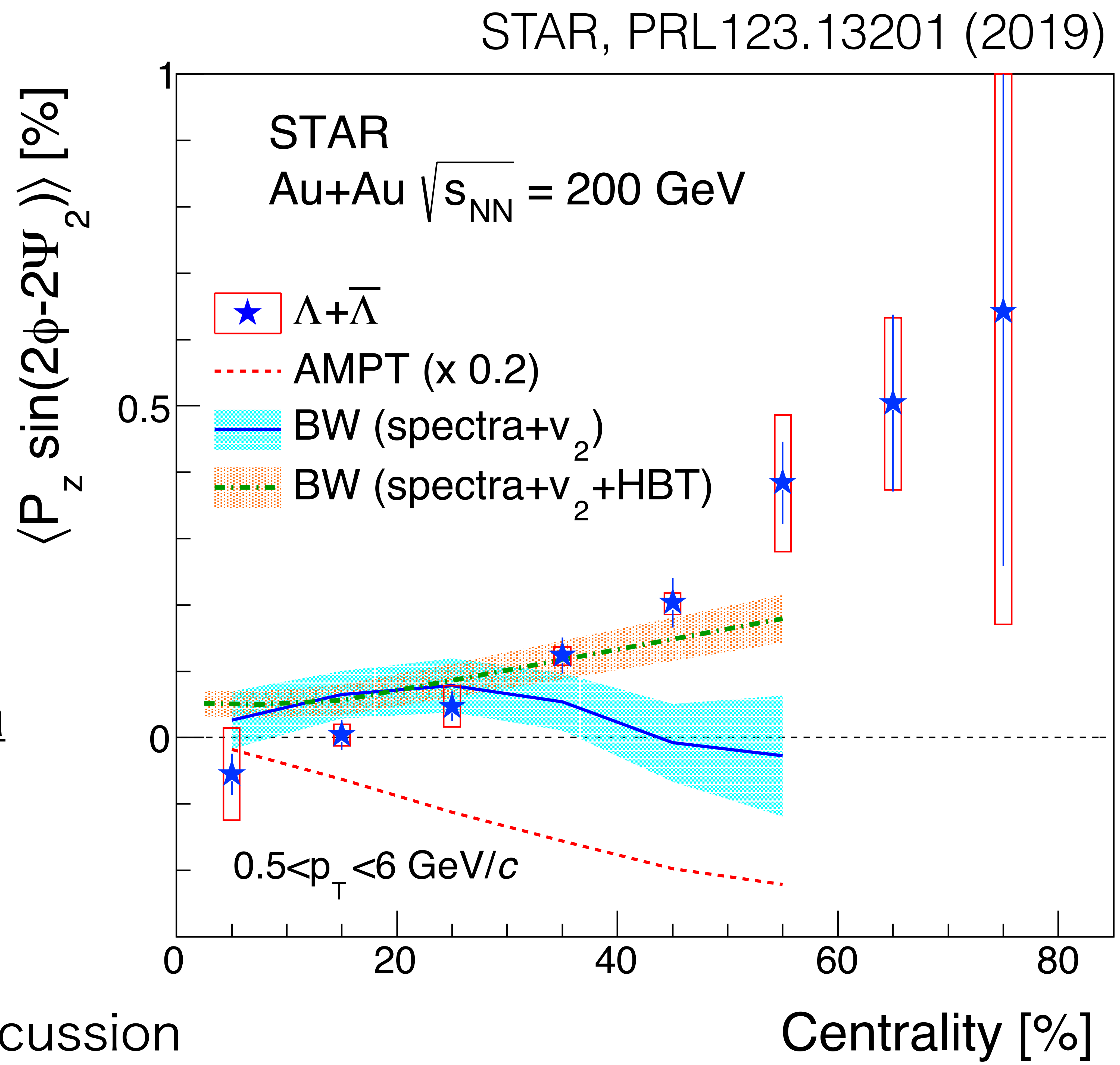
"Local" polarization due to collective expansion



- Vorticity (thus polarization) <u>along the beam direction</u> is expected from the "elliptic flow"

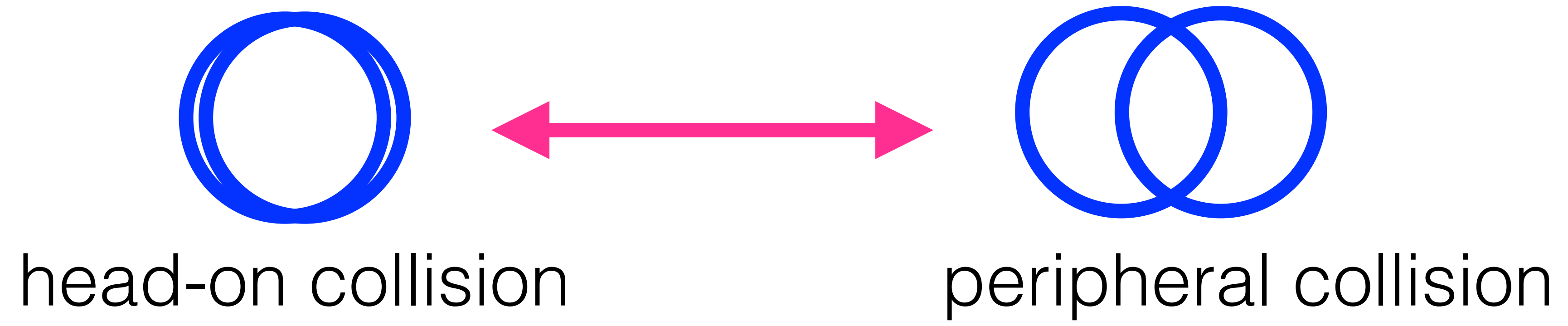
"Local" polarization due to collective expansion





- Vorticity (thus polarization) along the beam direction is expected from the "elliptic flow"
- Data indeed show such a longitudinal polarization P_z
  - Sign problem among data and theoretical models (hydro, kinetic theory, transport models) is under the discussion

Becattini and Karpenko, PRL.120.012302 (2018)
Xia et al, PRC98.024905 (2018)
Voloshin, EPJ Web Conf.171, 07002 (2018)
Sun and Ko, PRC99, 011903(R) (2019)
…more

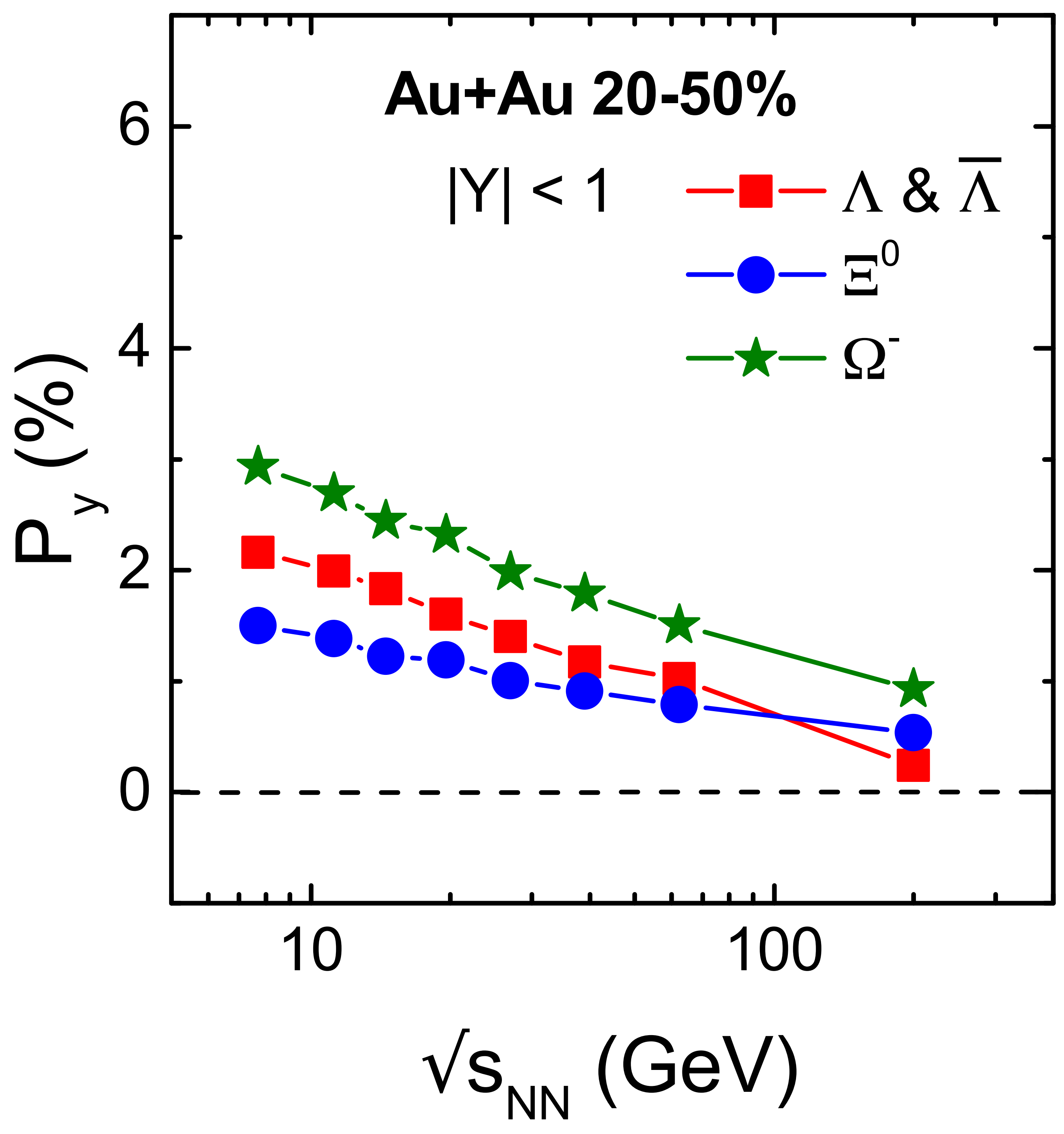


Other particles to measure polarization?

P. A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

	Mass (GeV/c^2)	cτ (cm)	decay mode	decay parameter	magnetic moment (μ_N)	spin
Λ (uds)	1.115683	7.89	Λ->πp (63.9%)	0.732±0.014	−0.613	1/2
Ξ^- (dss)	1.32171	4.91	Ξ^-->$\Lambda\pi^-$ (99.887%)	−0.401±0.010	−0.6507	1/2
Ω^- (sss)	1.67245	2.46	Ω^-->ΛK^- (67.8%)	0.0157±0.002	-2.02	3/2

W.-T. Deng and X.-G. Huang, PRC93.064907 (2016)



Natural candidates would be Ξ and Ω hyperons.

- Different spin and magnetic moments
- Less feed-down in Ξ and Ω compared to Λ
- Could be different freeze-out
- Different valence s-quarks

Based on thermal model:

$P(s=1/2) \sim \omega/(2T)$, $P(s=3/2) \sim 4\,\omega/(5T)$

F.Becattini et al., PRC95.054902 (2017)

Ξ and Ω polarization measurements

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha_H \mathbf{P}_H^* \cdot \hat{\boldsymbol{p}}_B^*\right)$$

Getting difficult due to smaller decay parameter for Ξ and Ω…

$$\alpha_\Lambda = 0.732,\ \ \alpha_{\Xi^-} = -0.401,\ \ \alpha_{\Omega^-} = 0.0157$$

spin 1/2

Polarization of daughter Λ in a weak decay of Ξ:
(based on Lee-Yang formula)

T.D. Lee and C.N. Yang, Phys. Rev.108.1645 (1957)

$$\mathbf{P}_\Lambda^* = \frac{(\alpha_\Xi + \mathbf{P}_\Xi^* \cdot \hat{\boldsymbol{p}}_\Lambda^*)\hat{\boldsymbol{p}}_\Lambda^* + \beta_\Xi \mathbf{P}_\Xi^* \times \hat{\boldsymbol{p}}_\Lambda^* + \gamma_\Xi \hat{\boldsymbol{p}}_\Lambda^* \times (\mathbf{P}_\Xi^* \times \hat{\boldsymbol{p}}_\Lambda^*)}{1 + \alpha_\Xi \mathbf{P}_\Xi^* \cdot \hat{\boldsymbol{p}}_\Lambda^*}$$

$$\mathbf{P}_\Lambda^* = C_{\Xi^-\Lambda} \mathbf{P}_\Xi^* = \tfrac{1}{3}\left(1 + 2\gamma_\Xi\right) \mathbf{P}_\Xi^*.$$

$$C_{\Xi^-\Lambda} = +0.927,\ \ \alpha^2 + \beta^2 + \gamma^2 = 1$$

spin 3/2

Similarly, daughter Λ polarization from Ω:

$$\mathbf{P}_\Lambda^* = C_{\Omega^-\Lambda} \mathbf{P}_\Omega^* = \tfrac{1}{5}\left(1 + 4\gamma_\Omega\right) \mathbf{P}_\Omega^*.$$

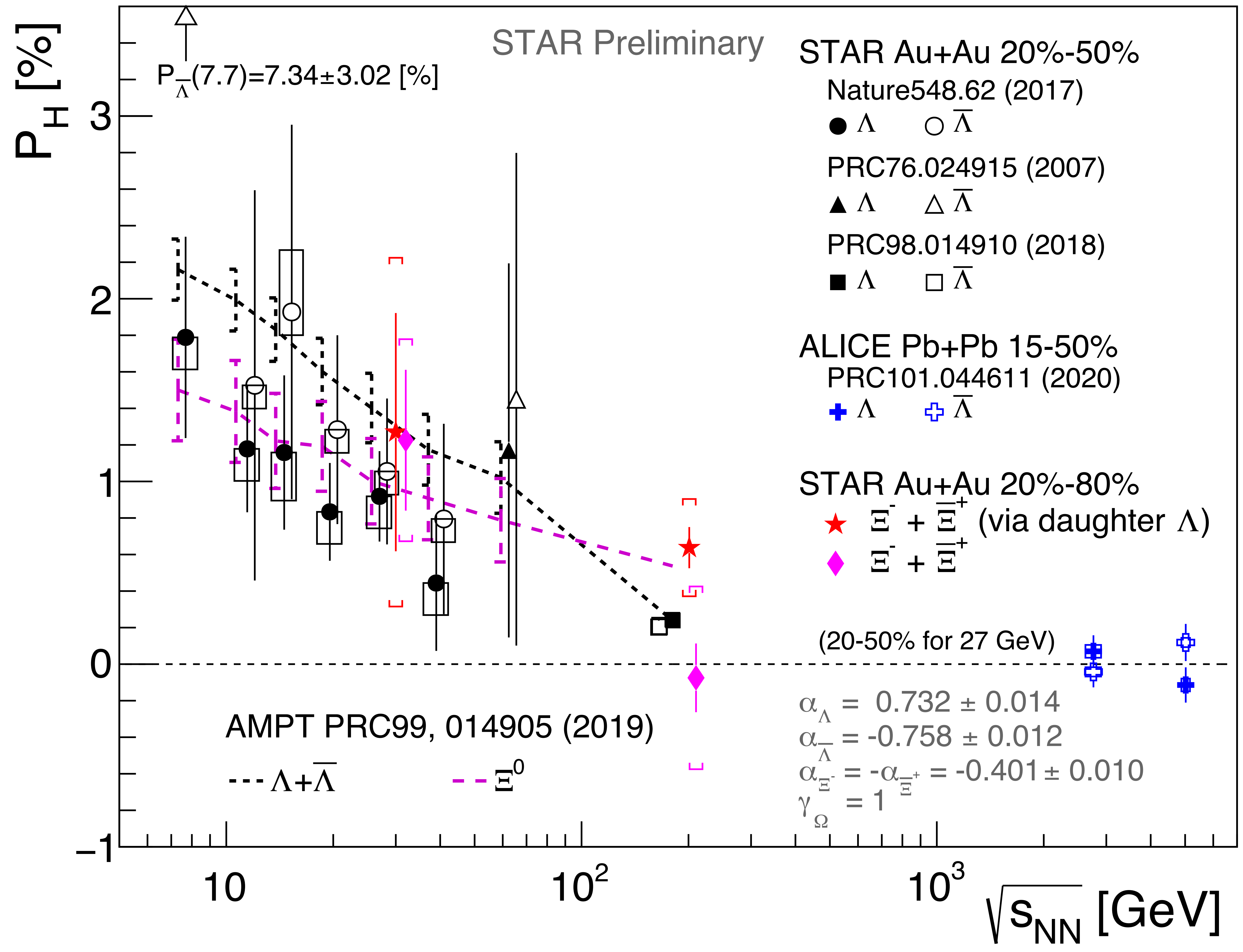
Here **γ_Ω is unknown**.
Time-reversal violation parameter β would be small, then the polarization transfer $C_{\Omega\Lambda}$ leads to:

$$C_{\Omega\Lambda} \approx +1 \text{ or } -0.6$$

Parent particle polarization can be studied by measuring daughter particle polarization!

Ξ global polarizations at $\sqrt{s_{NN}}$ = 200 GeV and 27 GeV

TN (STAR), RHIC&AGS AUM2020



* published results are rescaled by $\alpha_{old}/\alpha_{new}$~0.87

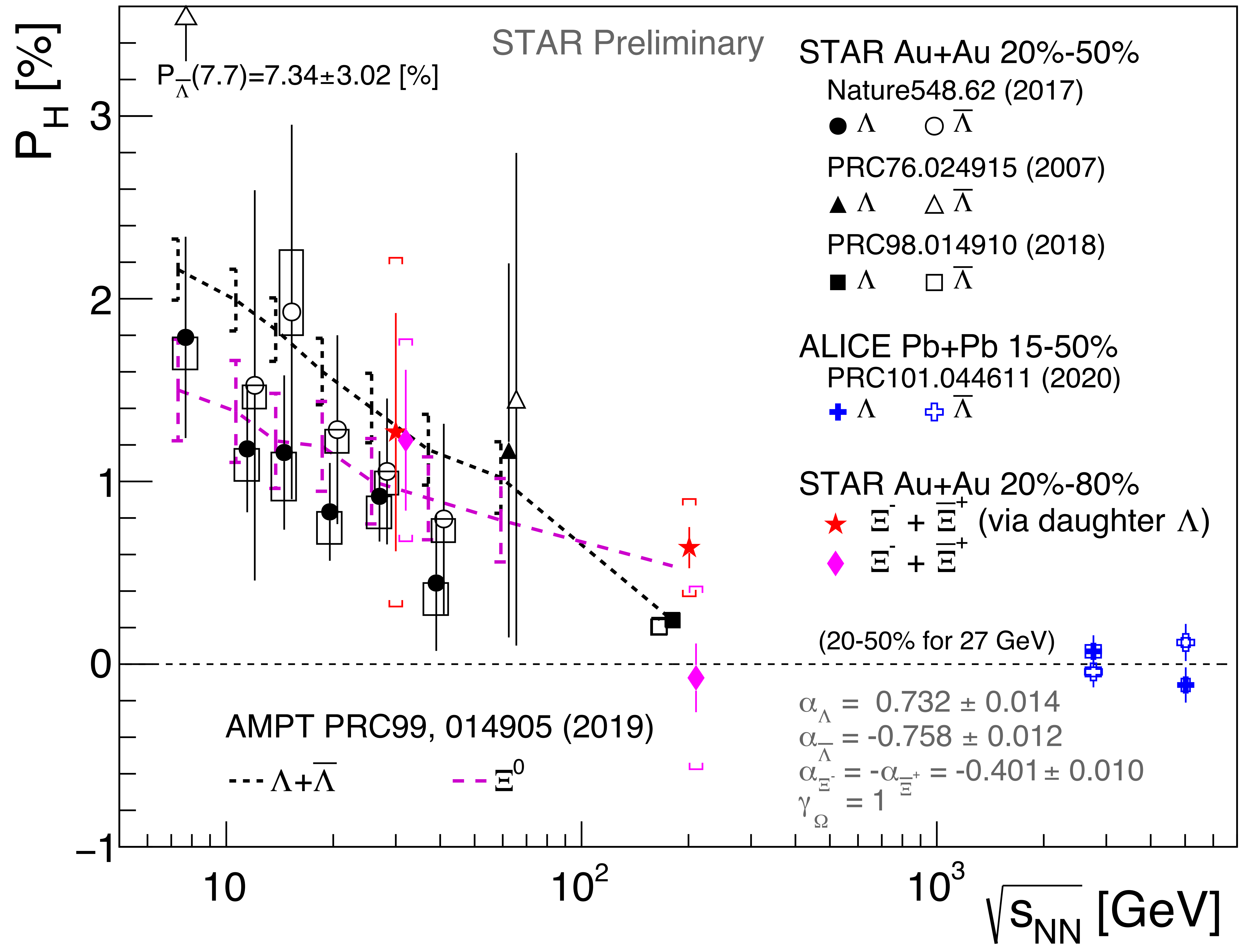
Ξ P_H by analyzing daughter Λ distributions
- less sensitive due to smaller α_Ξ=-0.4 than α_Λ=0.732

Ξ P_H via daughter Λ P_H (by granddaughter proton) with the polarization transfer $C_{\Xi\Lambda}$=+0.927
- positive polarization with 2.2σ level
- slightly larger than inclusive Λ P_H
- close to AMPT prediction

W.-T. Deng and X.-G. Huang, PRC93.064907 (2016)

Ξ global polarizations at $\sqrt{s_{NN}}$ = 200 GeV and 27 GeV

TN (STAR), RHIC&AGS AUM2020



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W.-T. Deng and X.-G. Huang, PRC93.064907 (2016)

Naive expectations in Ξ vs. Λ P_H

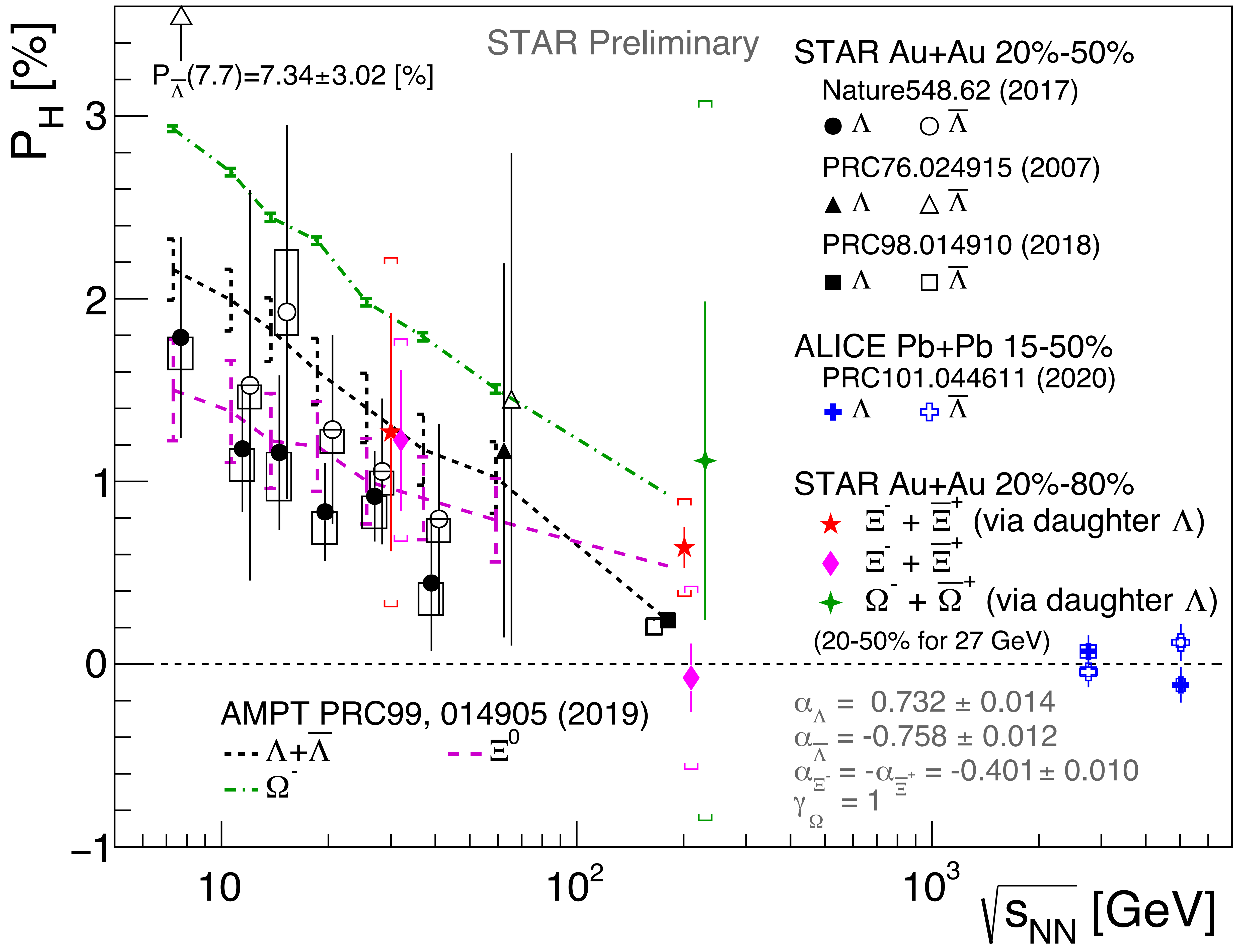
- Lighter particles could be more polarized (**Ξ<Λ**)
- Earlier freeze-out (of multi-strangeness) leads to larger P_H (**Ξ>Λ**)

O.Vitiuk, L.V.Bravina, and E.E.Zabrodin, PLB803(2020)135298

- Feed-down: ~15-20% reduction for primary Λ P_H

Ω global polarizations at $\sqrt{s_{NN}}$ = 200 GeV

TN (STAR), RHIC&AGS AUM2020



* published results are rescaled by $\alpha_{old}/\alpha_{new}$~0.87

Ω P_H via daughter Λ P_H assuming the polarization transfer $C_{\Omega\Lambda}$=+1

- Large uncertainty, to be improved in future analysis

- Based on the vorticity picture, the data seems to favor $C_{\Omega\Lambda}$=+1 (γ_Ω=+1) rather than $C_{\Omega\Lambda}$=-0.6 (γ_Ω=-1)
  ** In other words, γ_Ω can be measured in HIC assuming the global polarization*

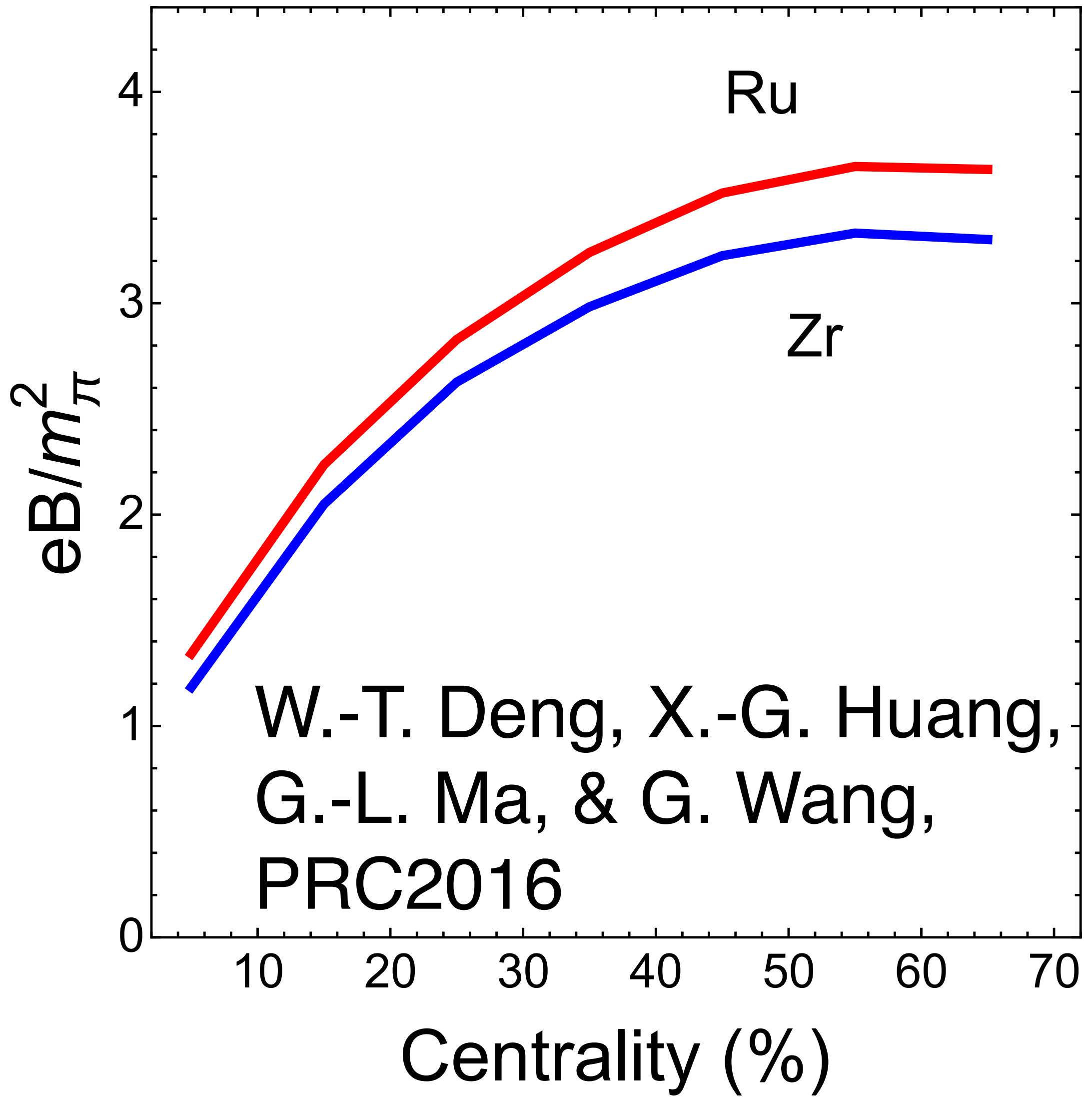
- Also close to AMPT expectation

Outlook

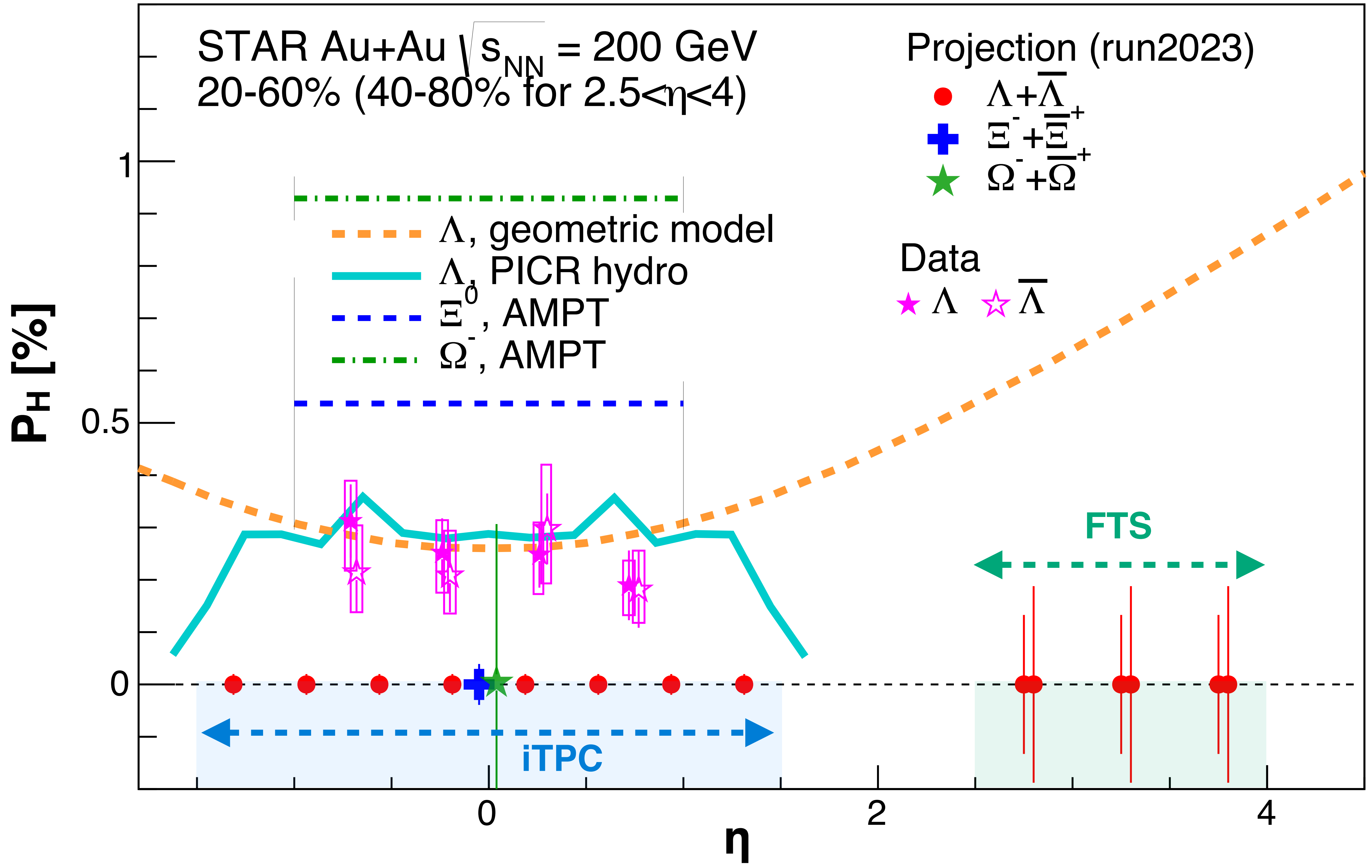
- More precise/differential measurements will be done in the following years
  - High statistics data of BES-II 7.7-19.6 GeV and FXT 3-7.7 GeV
  - Isobaric collision data (Ru+Ru, Zr+Zr), ~10% difference in B-field
  - Forward detectors in Run-2023 Au+Au 200 GeV

$^{96}_{44}$Ruthenium

$^{96}_{40}$Zirconium



BUR2020, STAR Note SN0755

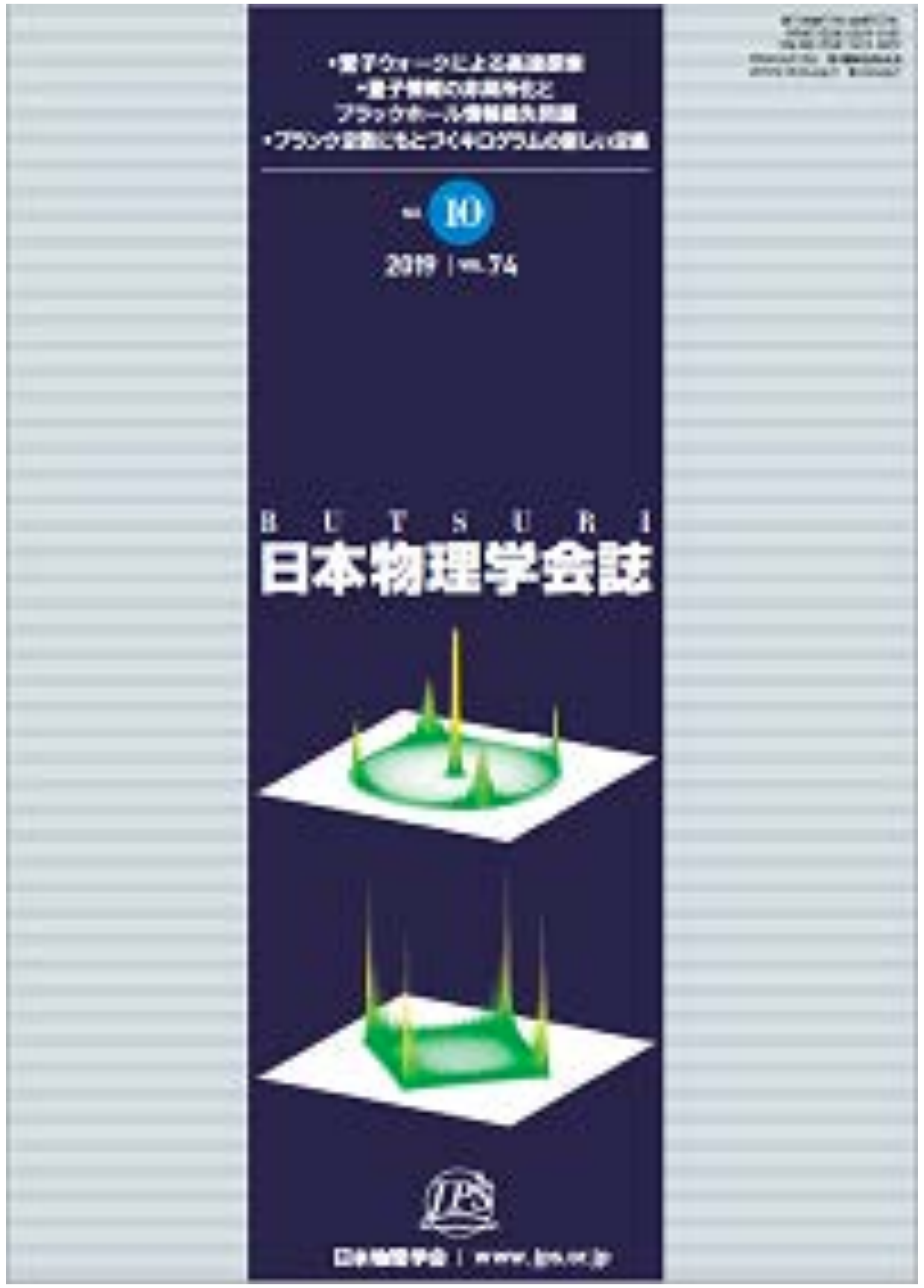


Summary

- Global and local polarization of hyperons has been observed in heavy-ion collisions
  - Most vortical fluid (ω~10^{21} s^{-1}) created in heavy-ion collisions
  - Energy dependence of global polarization, increasing in lower $\sqrt{s_{NN}}$, is captured well by theoretical models, but there are sign problems to be understood
  - Toward more differential/precise measurements, e.g. first measurements of Ξ and Ω

There are still many open questions and more precise measurements are needed for better understanding the nature of vorticity and polarization in HIC.

ご興味があれば...



最近の研究から

高速回転する流体
――クォーク・グルーオン・プラズマの渦度

新井田貴文 〈Department of Physics and Astronomy, Wayne State University niida@bnl.gov〉
江 角 晋 一 〈筑波大学数理物質系，宇宙史研究センター esumi.shinichi.gn@u.tsukuba.ac.jp〉

ビッグバン数マイクロ秒後，宇宙はクォーク・グルーオン・プラズマ（QGP）と呼ばれる物質で満たされていたと考えられる．物質の基本構成要素であるクォークは通常核子などのハドロンに閉じ込められているが，量子色力学（QCD）によると，高温または高密度下ではその閉じ込めから解放され，クォークとグルーオンのプラズマ状態になる．QGP の性質やハドロンからの相転移機構は十分には理解されておらず，これらを解明するためのアプローチが高エネルギー原子核衝突実験である．

現在，米国 BNL 国立研究所やスイスとフランス国境にある欧州原子核研究機構において，巨大加速器を用いて光速近くまで加速した原子核同士を衝突させる実験が行われている．衝突により作り出される物質の温度は数兆度（太陽中心温度の数十万倍高い）に達し，エネルギー密度は QGP 生成に必要な密度の 5 倍以上であることが測定からわかっている．これまでの実験結果と理論計算との比較により，QGP の粘性（正確にはエントロピー密度で割った粘性比）は非常に小さく，気体というより完全流体に近いことが判明している．

原子核衝突により生成される QGP は回転していると理論的に予測されてきたが，実験的証拠はこれまでにない．QGP が回転している場合，これまでの実験結果の解釈に影響を及ぼす可能性もあり，また原子核衝突のモデル，特に初期条件を決める上でも重要な要素となる．QGP が回転しているという描像は，衝突する 2 つの原子核が反対方向へ移動するために，衝突関与部が角運動量保存のために回転を続けようとすることからくる．この軌道角運動量は，反応平面に垂直な方向を指す．衝突で作り出される物質が軌道角運動量を持つと，スピン－軌道相互作用によって生成粒子のスピンが偏極すると予測される．また，回転による効果とは別に，衝突する原子核内に含まれる陽子の電荷の移動により，反応平面に垂直な方向に強磁場が発生する可能性が指摘されている．磁場によるスピン偏極の場合，磁気モーメントの符号の違いにより，単純な軌道角運動量の効果とは違い，粒子と反粒子間では偏極方向は反対になる．強磁場が存在すると，QCD の非自明な真空構造から，強い相互作用の持つ基本的な対称性の一つであるカイラル対称性に関する様々な新しい現象が誘起されると予測されており，興味深い研究対象である．

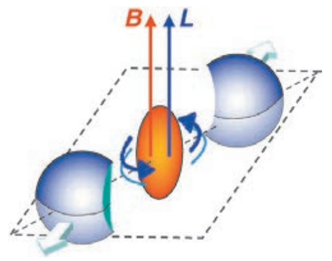
粒子のスピン測定は，ハイペロン（s クォークを含むバリオン）の崩壊を利用することで可能である．ハイペロンはバリオンと中間子等へ崩壊するが，弱い相互作用による崩壊ではパリティが保存せず，崩壊バリオンの運動量ベクトルとハイペロンのスピンに相関があることが知られている．

BNL-STAR 実験では，金原子核衝突データを用いて，ラムダ粒子のスピン偏極測定を行った．核子対あたりの衝突エネルギー $\sqrt{s_{NN}}$ ＝7.7–200 GeV においてラムダ粒子のスピン偏極が初めて測定された．この結果は衝突で作られた物質が回転していることを実験的に示す証拠である．局所的熱平衡の仮定のもとで，スピン偏極から渦度を計算すると $\omega \sim 10^{22}\ \mathrm{s}^{-1}$ となった．この値は大きさのスケールは違うものの，これまでに観測されたどの渦度よりも速いことが判明した．また，ラムダ粒子と反ラムダ粒子は，実験誤差の範囲で有意な差は無いが，系統的に反ラムダ粒子のシグナルが大きいように見える．これは初期の磁場による偏極の可能性を示している．STAR 実験は，今年からビーム走査実験 II を開始しており，アップグレードされた検出器で高統計データを収集し，スピン偏極の詳細測定および磁場効果の検証を行う予定である．

—Keywords—

中心衝突度：
原子核衝突を特徴づける量．2 つの原子核が正面衝突する場合を中心衝突，2 つの原子核中心がずれて衝突する場合を非中心衝突と呼ぶ．

反応平面：
原子核進行方向と 2 つの原子核中心を結ぶベクトルで成す平面．下図における破線で表される面．



2 つの原子核が非中心衝突したときに作られる磁場 B と軌道角運動量 L の向きを示す図．

日本物理学会誌 2019 10月号

高速回転する流体

- クォーク・グルーオン・プラズマの渦度 -

Back up

Feed-down effect

- ~60% of measured Λ are feed-down from $\Sigma^* \to \Lambda\pi$, $\Sigma^0 \to \Lambda\gamma$, $\Xi \to \Lambda\pi$
- Polarization of parent particle R is transferred to its daughter Λ
  (Polarization transfer could be negative!)

$C_{\Lambda R}$: coefficient of spin transfer from parent R to Λ
S_R : parent particle's spin
$f_{\Lambda R}$: fraction of Λ originating from parent R
μ_R : magnetic moment of particle R

$$\mathbf{S}^*_\Lambda = C\mathbf{S}^*_R \qquad \langle S_y \rangle \propto \frac{S(S+1)}{3}\left(\omega + \frac{\mu}{S}B\right)$$

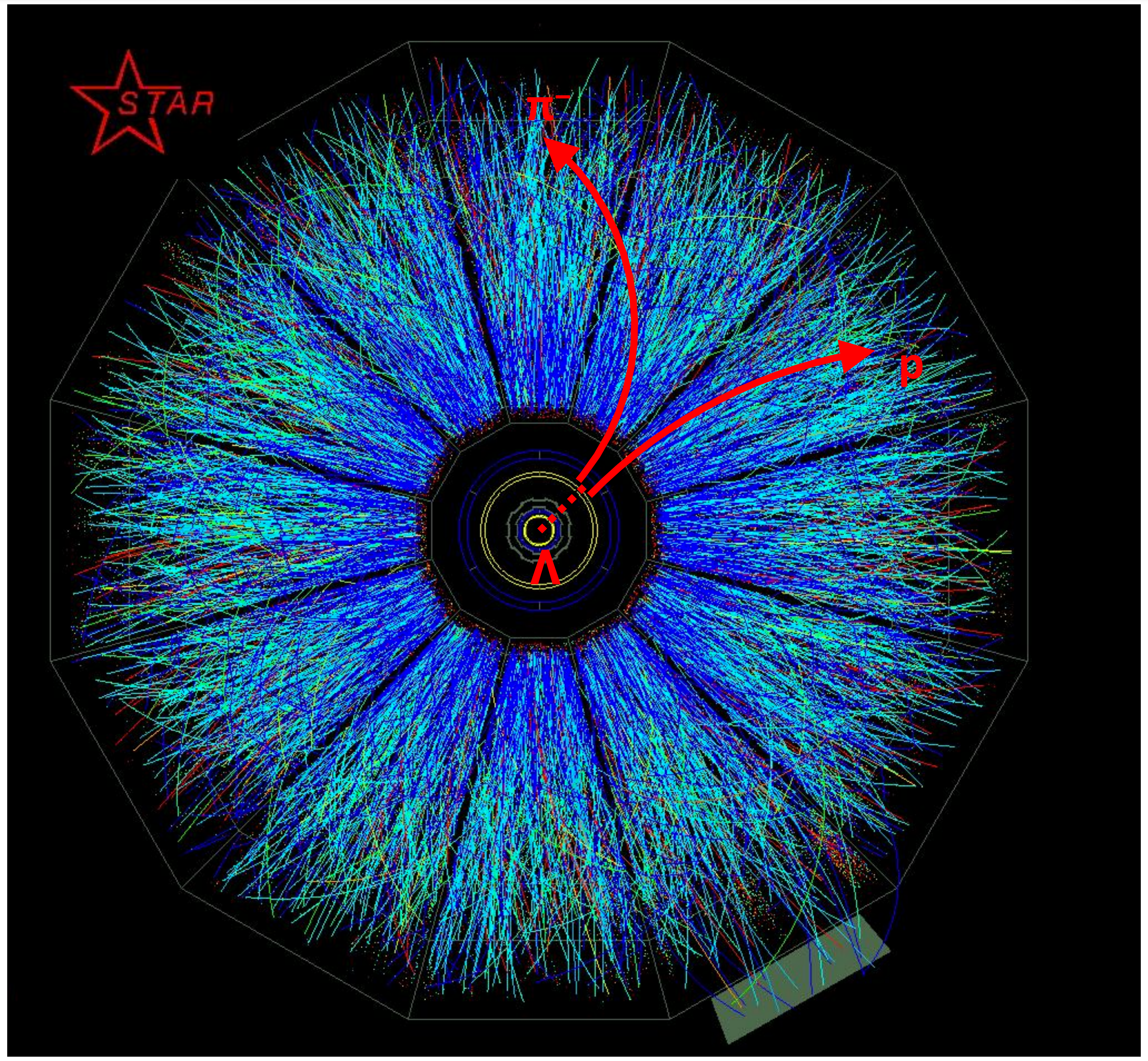
$$\begin{pmatrix} \varpi_c \\ B_c/T \end{pmatrix} = \begin{bmatrix} \frac{2}{3}\sum_R \left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3}f_{\Sigma^0 R}C_{\Sigma^0 R}\right) S_R(S_R+1) & \frac{2}{3}\sum_R \left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3}f_{\Sigma^0 R}C_{\Sigma^0 R}\right)(S_R+1)\mu_R \\ \frac{2}{3}\sum_{\overline{R}} \left(f_{\overline{\Lambda R}}C_{\overline{\Lambda R}} - \frac{1}{3}f_{\overline{\Sigma^0}\overline{R}}C_{\overline{\Sigma^0}\overline{R}}\right) S_{\overline{R}}(S_{\overline{R}}+1) & \frac{2}{3}\sum_{\overline{R}} \left(f_{\overline{\Lambda R}}C_{\overline{\Lambda R}} - \frac{1}{3}f_{\overline{\Sigma^0}\overline{R}}C_{\overline{\Sigma^0}\overline{R}}\right)(S_{\overline{R}}+1)\mu_{\overline{R}} \end{bmatrix}^{-1} \begin{pmatrix} P_\Lambda^{\mathrm{meas}} \\ P_{\overline{\Lambda}}^{\mathrm{meas}} \end{pmatrix}$$

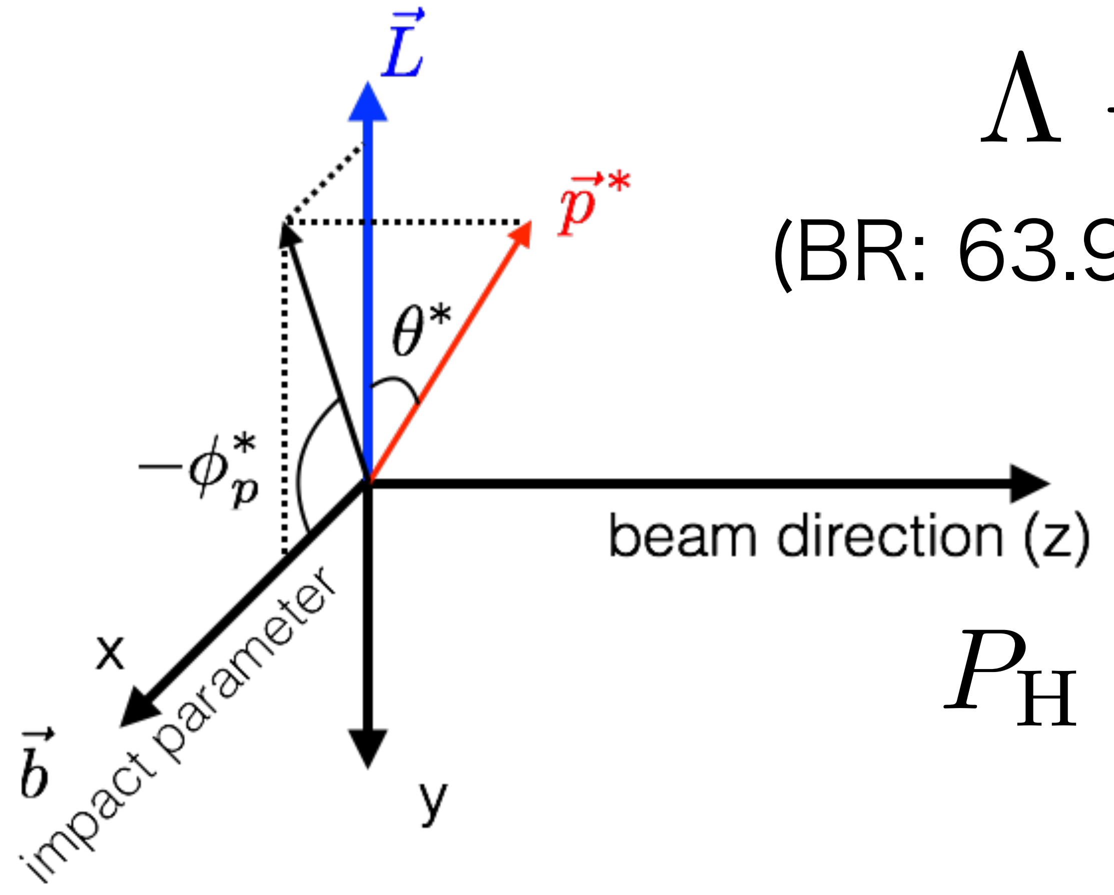
Becattini, Karpenko, Lisa, Upsal, and Voloshin, PRC95.054902 (2017)

Decay	C
Parity conserving: $1/2^+ \to 1/2^+\ 0^-$	−1/3
Parity conserving: $1/2^- \to 1/2^+\ 0^-$	1
Parity conserving: $3/2^+ \to 1/2^+\ 0^-$	1/3
Parity-conserving: $3/2^- \to 1/2^+\ 0^-$	−1/5
$\Xi^0 \to \Lambda + \pi^0$	+0.900
$\Xi^- \to \Lambda + \pi^-$	+0.927
$\Sigma^0 \to \Lambda + \gamma$	−1/3

Primary Λ polarization will be diluted by 15%-20% (model-dependent)
This also suggests that **the polarization of daughter particles can be used to measure the polarization of its parent!** e.g. Ξ, Ω

Signal extraction with Λ hyperons



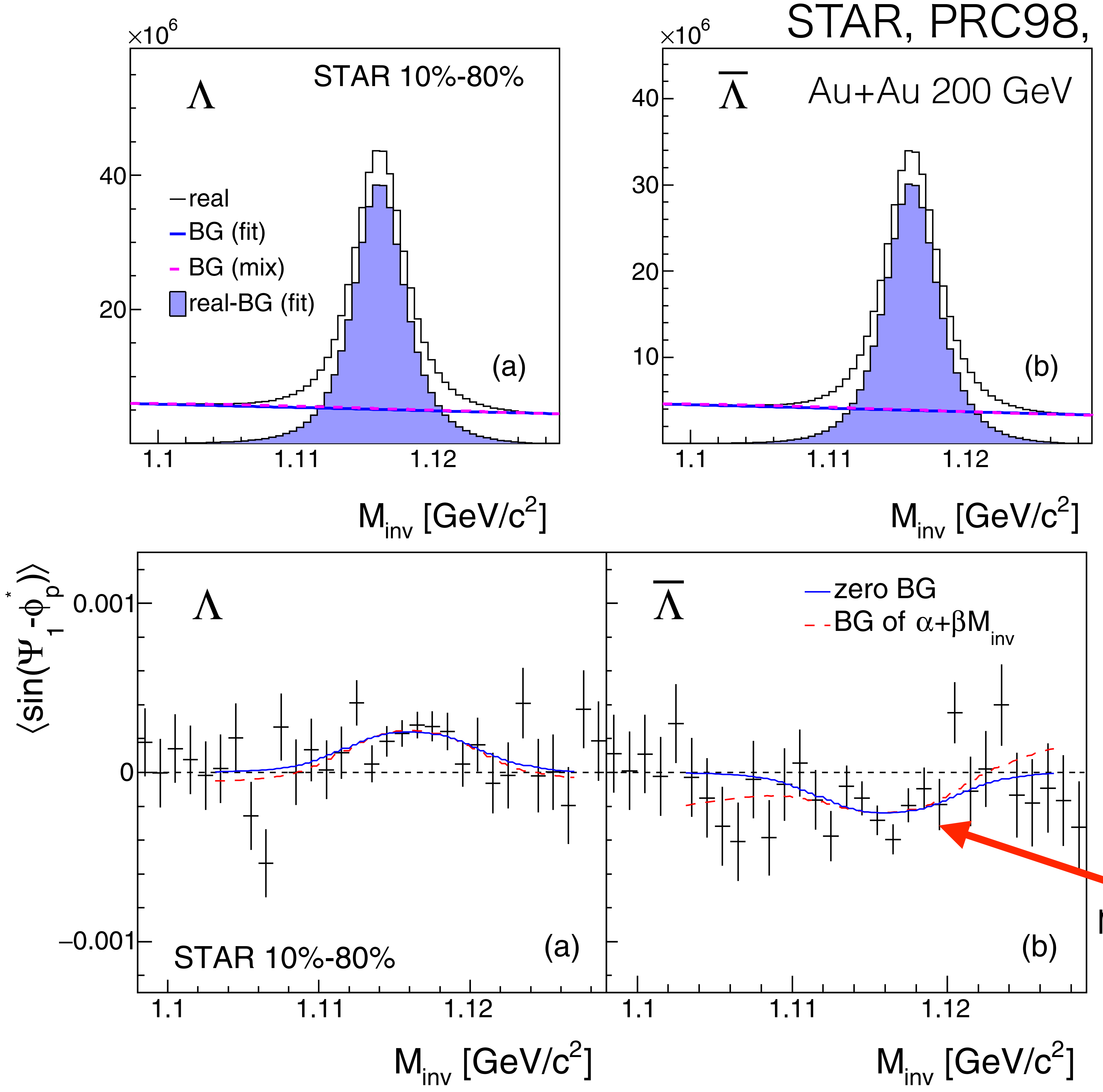


$$\Lambda \rightarrow p + \pi^-$$

(BR: 63.9%, cτ ~7.9 cm)

$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{\mathrm{Res}(\Psi_1)}$$

STAR, PRC98, 014910 (2018)



negative for anti-Λ

$$\alpha_H = -\alpha_{\bar{H}}$$

$$\langle \sin(\Psi_1 - \phi_p^*) \rangle^{\mathrm{obs}} = (1 - f^{\mathrm{Bg}}(M_{\mathrm{inv}})) \langle \sin(\Psi_1 - \phi_p^*) \rangle^{\mathrm{Sg}} + f^{\mathrm{Bg}}(M_{\mathrm{inv}}) \langle \sin(\Psi_1 - \phi_p^*) \rangle^{\mathrm{Bg}},$$