Open questions in Lambda polarization after QM18

Laszlo P. Csernai,
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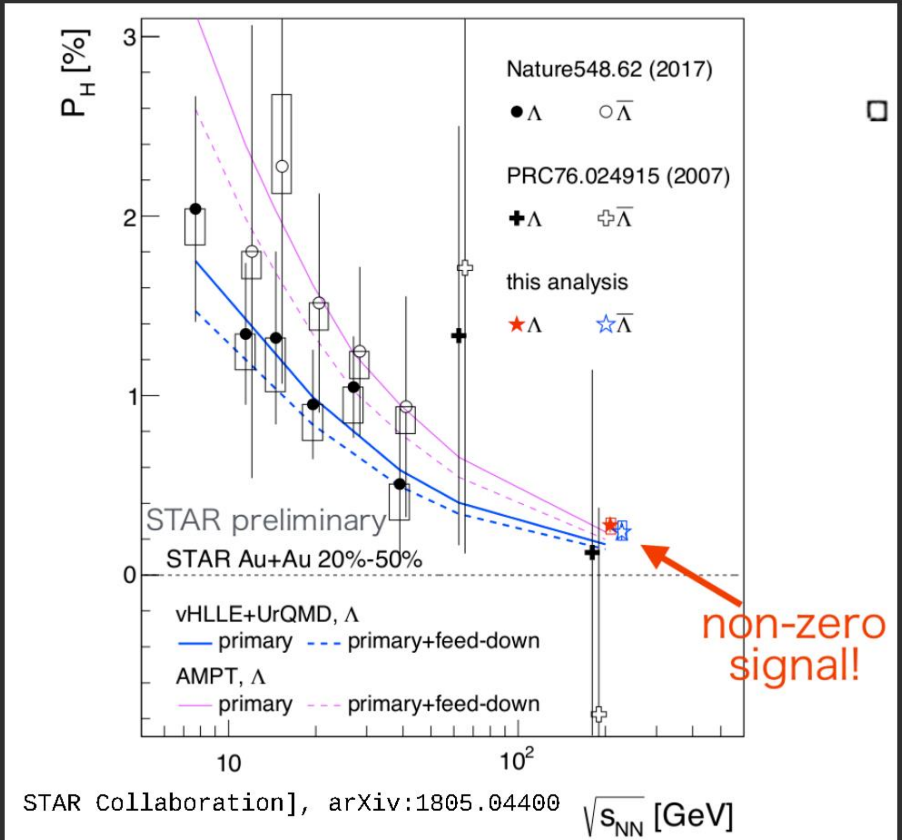
COST-THOR Working Group Meeting,
Lisboa, June 11-14, 2018

[F. Becattini, QM18]

Polarization



One of the most important new results in last year:
Global Λ hyperon polarization in nucl. coll., Nature, August 2017

Sensitive measure of angular momentum, collective shear & vorticity in peripheral heavy ion collisions!

P_H is defined positive, but points in the –y direction !

Z. Ye, T. Niida, this conference

In agreement with most calculations using the formula

$$S^\mu(p) = \frac{1}{8m}\epsilon^{\mu\nu\rho\sigma}p_\sigma \frac{\int_\Sigma d\Sigma_\tau p^\tau n_F(1-n_F)\partial_\nu\beta_\rho}{\int_\Sigma d\Sigma_\tau p^\tau \, n_F}$$

L. Csernai, L. G. Pang, X. N. Wang, C. Ko, X. G. Wang, Q. Wang, X. L. Xia, J. Liao, A. Sorin, O. Teryaev, I. Karpenko, F.B.

I. Karpenko, Y. Xie this conference

How to measure?

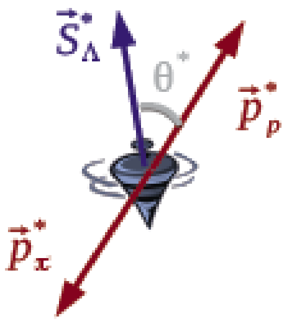
[T. Niida, QM18]

Parity-violating decay of hyperons

In case of Λ's decay, daughter proton is preferentially emitted in the direction of Λ's spin (opposite for anti-Λ)

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \mathbf{P}_H \cdot \mathbf{p}_p^*)$$

P_H: Λ polarization
p_p^*: proton momentum in Λ rest frame
α_H: Λ decay parameter
($\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$)

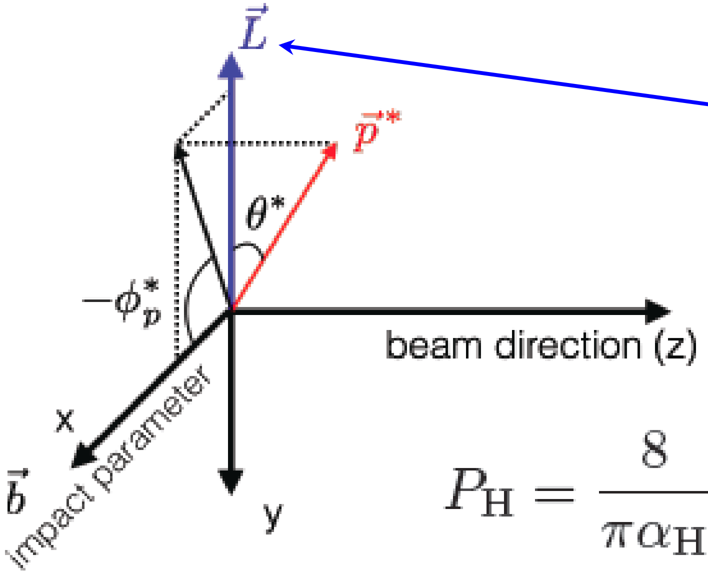


$$\Lambda \rightarrow p + \pi^-$$

(BR: 63.9%, cτ ~7.9 cm)

Projection onto the transverse plane

- ★ Direction of the angular momentum is determined by the angle of spectator plane (spectators deflect outwards)
  - S. Voloshin and TN, PRC94.021901(R)(2016)
- ★ Flow analysis technique can be used for signal extraction
  - STAR, PRC76, 024915 (2007)



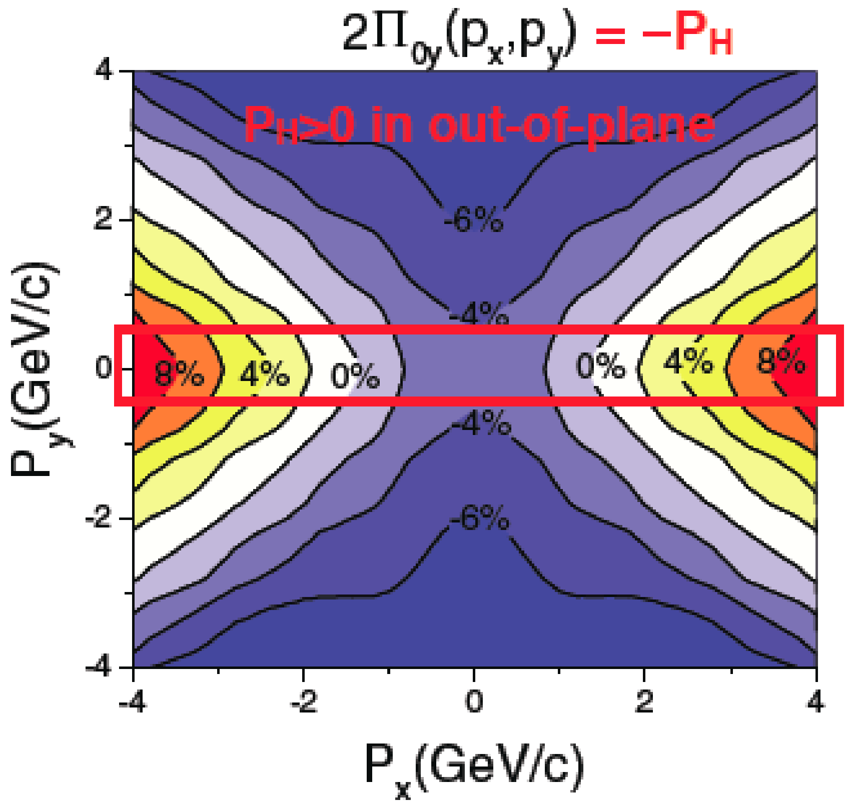
P_H is defined positive, but points in the –y direction !

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

ϕ_p^*: ϕ of daughter proton in Λ rest frame
STAR, PRC76, 024915 (2007)

F. Becattini et al.,
PRC93, 069901(E)(2016)
PRC88, 034905 (2013)

Au+Au 200 GeV



P_H<0 in in-plane

P_H is defined positive, but points in the –y direction !

P_H & Py have opposite sign !

Figure:
[Yilong Xie QM 2018]

Question # 1

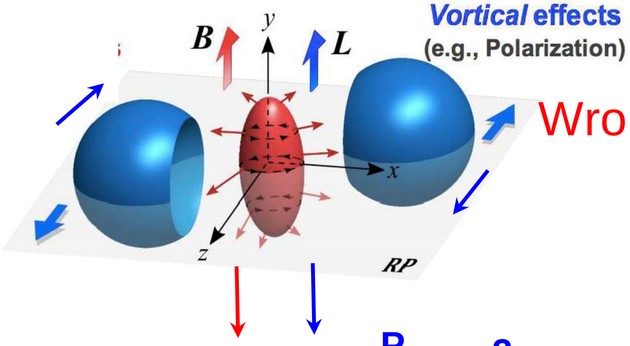
Dependence of polarization on the emission angle of the Λ

$\mathbf{P}_{\Lambda}\ (p_x, p_y)$

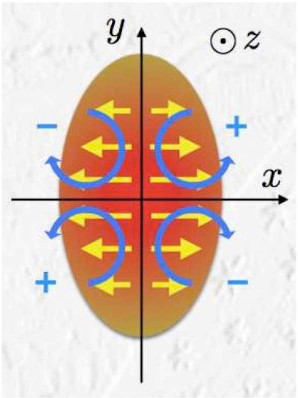
[Marco van Leeuwen, Summary QM18]

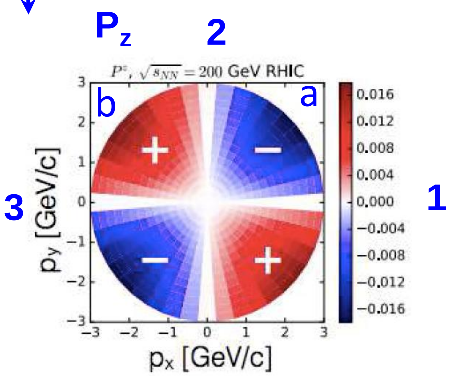
General convention:
Projectile is at + X
Projectile moves twrd + Z
Here NOT !!!

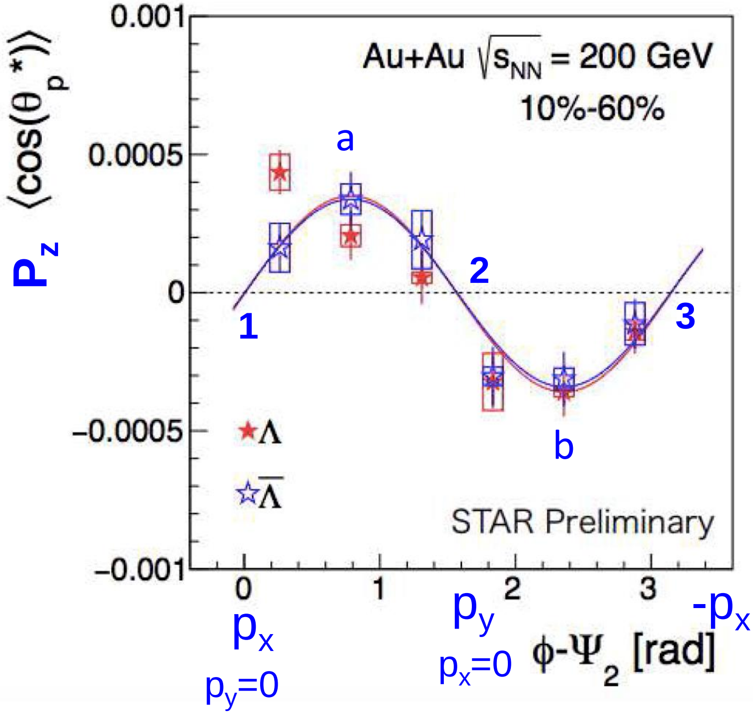
Vorticity

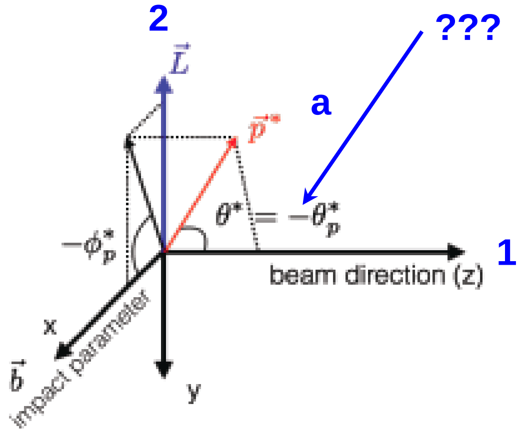


Wrong !!!









[STAR-arxiv-1805.04400 &
STAR- Zhenyu Ye, QM 18]

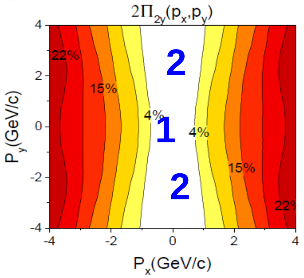
Clear effect seen: modulation of longitudinal spin alignment with angle to event plane

However: sign is opposite of expected!

$P_z(p_x,p_y)$
from elliptic
flow vorticity

$P_z(p_x,p_y)$
no shear
vorticity

$P_{2y}(p_x,p_y)$
/w shear &
no vorticity



[Yilong Xie, UoB, talk - QM18]

Introduction: Angular momentum

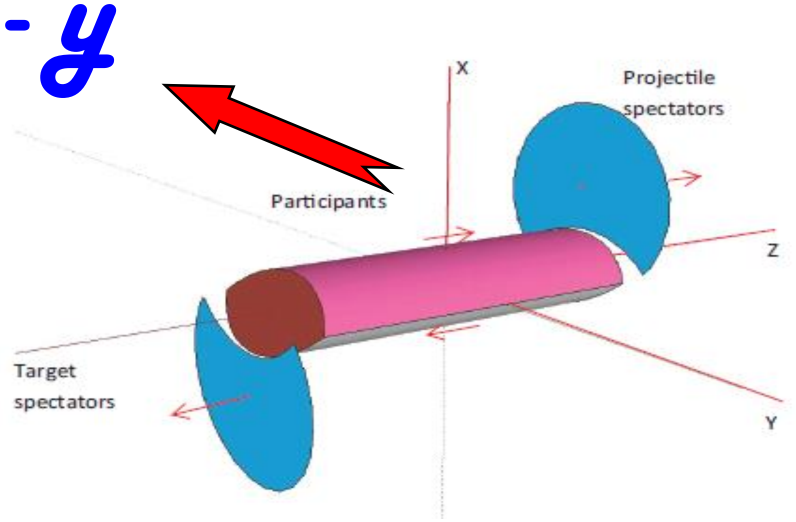


Fig.1 3D view after collisions. Tilted Initial State

[L. P. Csernai, et al. Phys. Rev. C **87**, 034906 (2013)]

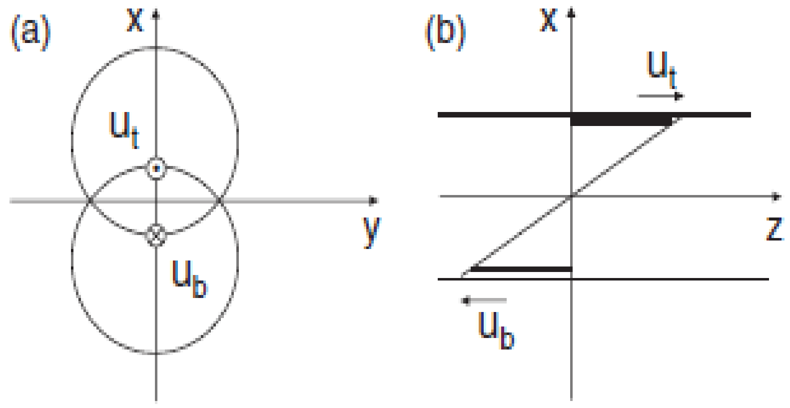
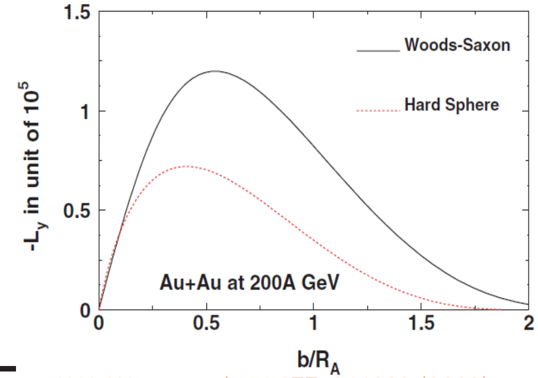
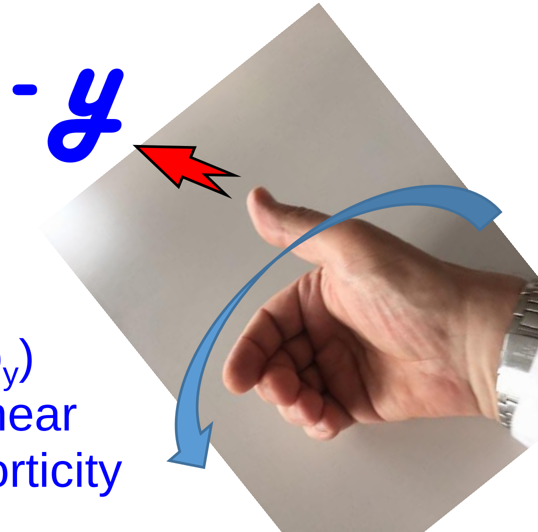


Fig.2 (a)Transverse view. (b) Shear velocity profile.



X.N. Wang, et al., PRC77, 044902 (2008)

- Tilted initial state (Fig. 1) carries the angular momentum from impact.
- The velocity shear (Fig. 2b) will further rotate this initial state, and even leads to Kelvin Helmholtz Instability(KHI).



P_y (p_x,p_y)
from shear
flow vorticity

[Yilong Xie, UoB, QM18]

Polarization vector

Refs. [Becattini, 2008, 2013] revisited the relativistic thermodynamics with spin: adding a rotation term into the density operator for a rotating gas system in local equilibrium:

$$\hat{\rho} = \frac{1}{Z} exp[-\hat{H}/T + \mu\hat{Q} + \boxed{\omega\hat{J}}]$$

→distribution function → Spin tensor → Pauli-Lubanski vector → Polarization 4-vector
→The Λ polarization (3-)vector in CM frame:

$$\Pi(p) = \frac{\hbar\epsilon}{8m}\frac{\int dV\, n_F(x,p)\boxed{(\nabla\times\beta)}}{\int dV\, n_F(x,p)} + \frac{\hbar p}{8m}\times\frac{\int dV\, n_F(x,p)\boxed{(\partial_t\beta + \nabla\beta^0)}}{\int dV\, n_F(x,p)}$$

1:Vorticity 2:Expansion

where $\beta^\mu(x) = [1/T(x)]u^\mu(x)$ e inverse temperature four-vector field. Then thermal vorticity is ω= $\nabla\times\beta$.

In experiments, the polarization is measured in particle's rest frame---- Lorentz-boosting:

$$\mathbf{\Pi}_0(p) = \mathbf{\Pi}(p) - \frac{\mathbf{p}}{p^0(p^0+m)}\mathbf{\Pi}(p)\cdot\mathbf{p} \,,$$

In experiments, the polarization is measured globally-----Integrating the y component of polarization Π_{0y}(p) over momentum space, to obtain the global polarization:

$$<\Pi_{0y}>_p = \frac{\int dpdx\Pi_{0y}(p,x)n_F(x,p)}{\int dpdx\, n_F(x,p)} = \frac{\int dp\Pi_{0y}(p)n_F(p)}{\int dp\, n_F(p)}$$

[F. Becattini, L.P. Csernai, and D.J. Wang, Phys. Rev. C **88**, 034905 (2013).]

Results: X and Z components

[Yilong Xie (U. Bergen) Quark Matter 2018 inv. talk.: *Global Λ polarization …*]

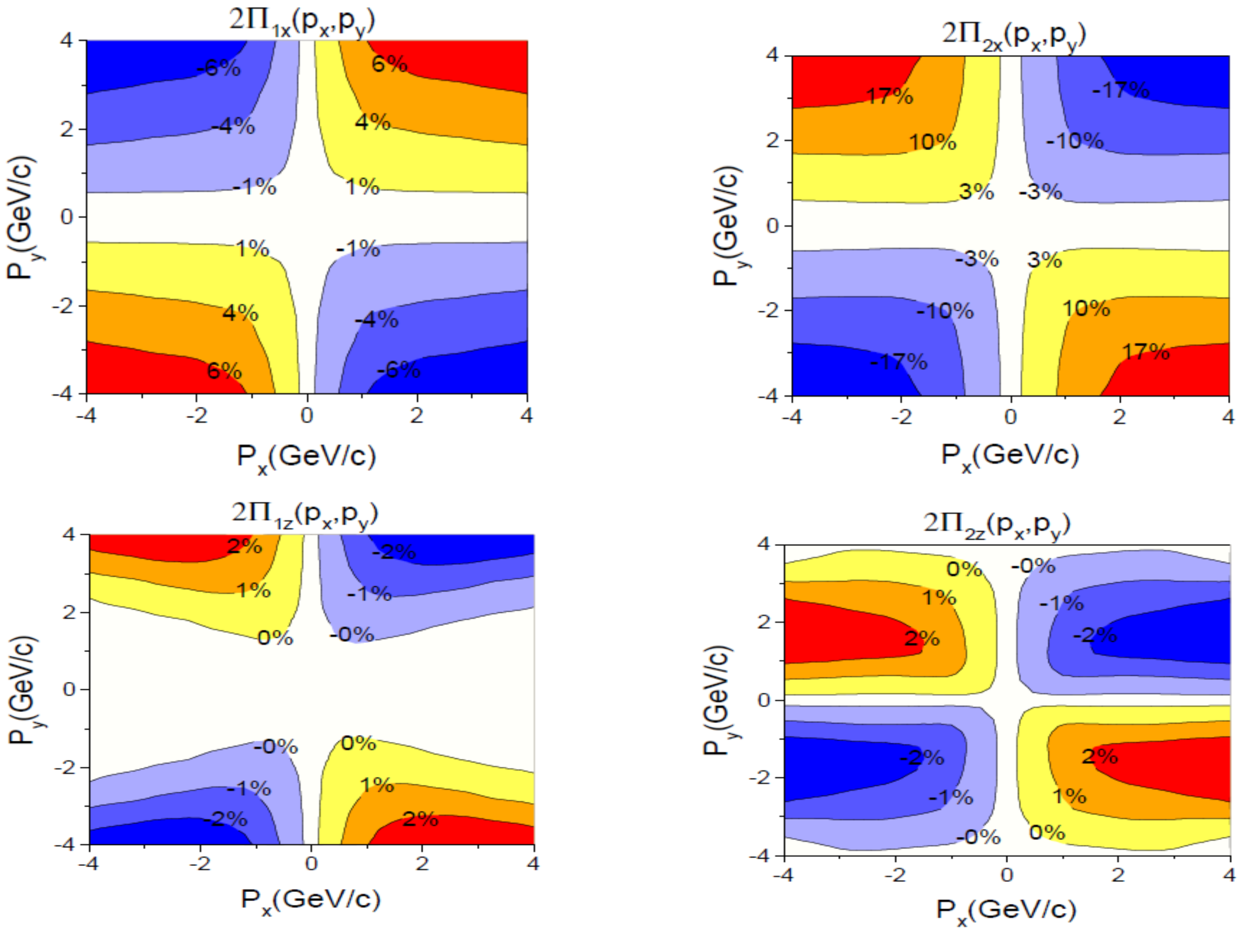
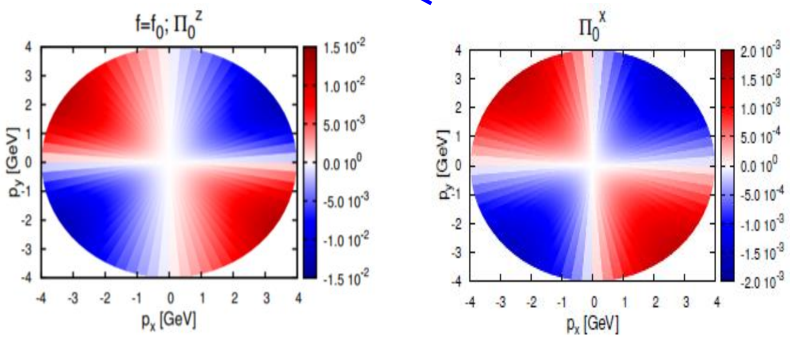


Fig. 7 The first (left) and second (right) terms of the x(up) and y(down) components of the **Λ** polarization for momentum vectors in the transverse plane at pz = 0,for the FAIR U+U reaction at 8.0 GeV

1. Small magnitude.
2. Anti-symmetric

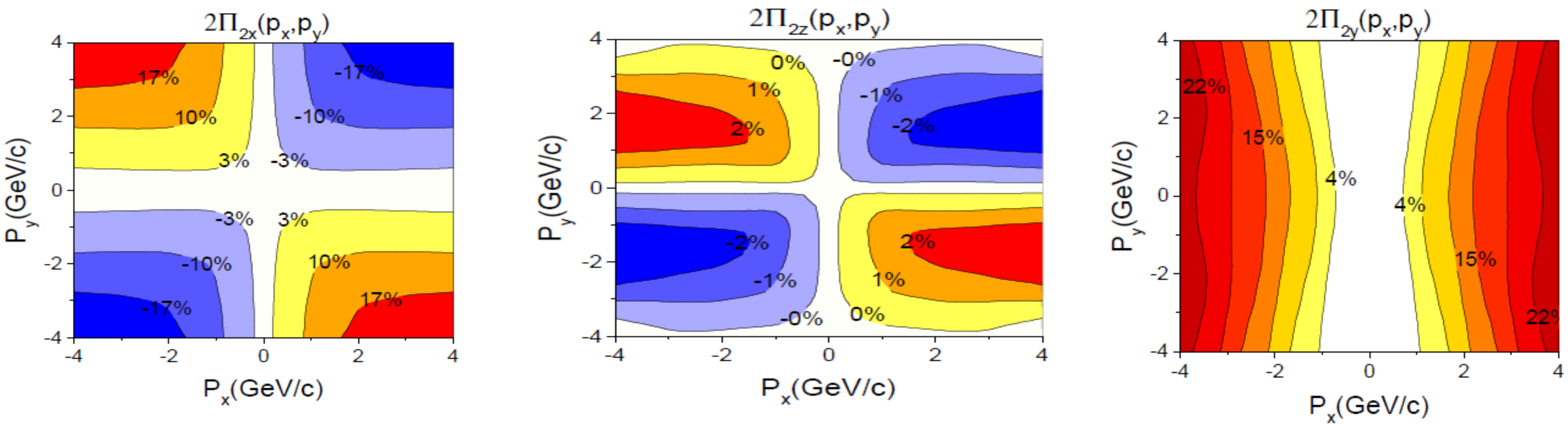
P_z & P_x : no shear flow vorticity



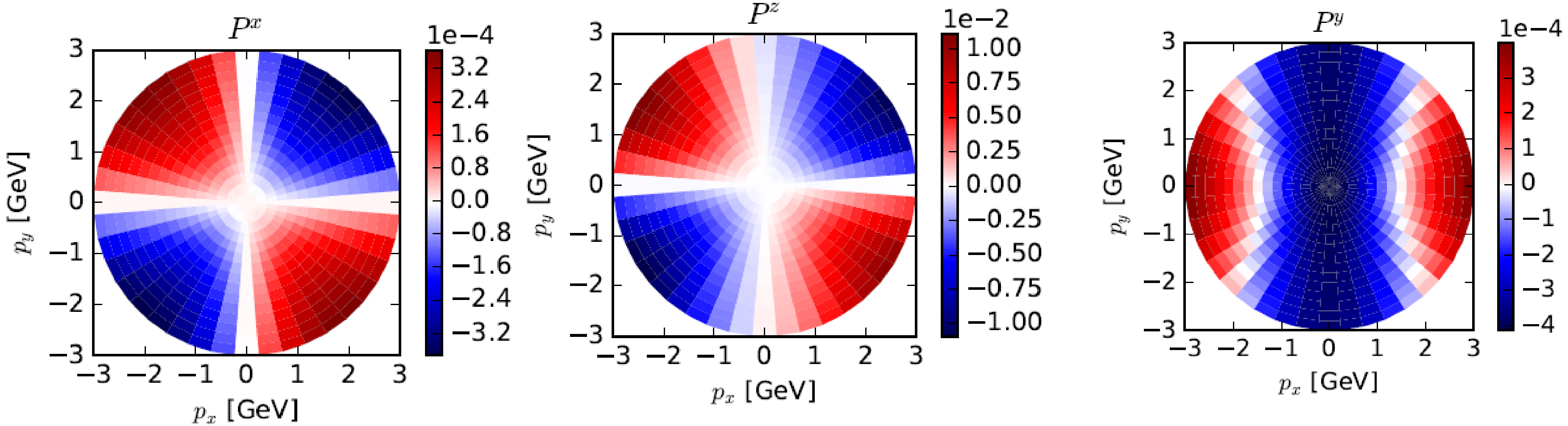
ECHO-QGP numerical code, implementing relativistic dissipative hydrodynamics in the causal Israel-Stewart framework in 3+1 dimensions with an initial Bjorken flow profile

[Becattini, et al., Eur. Phys. J. C 75, 406 (2015).]

Conclusion # 1



[Yilong Xie, talk QM18]
2: no shear vorticity

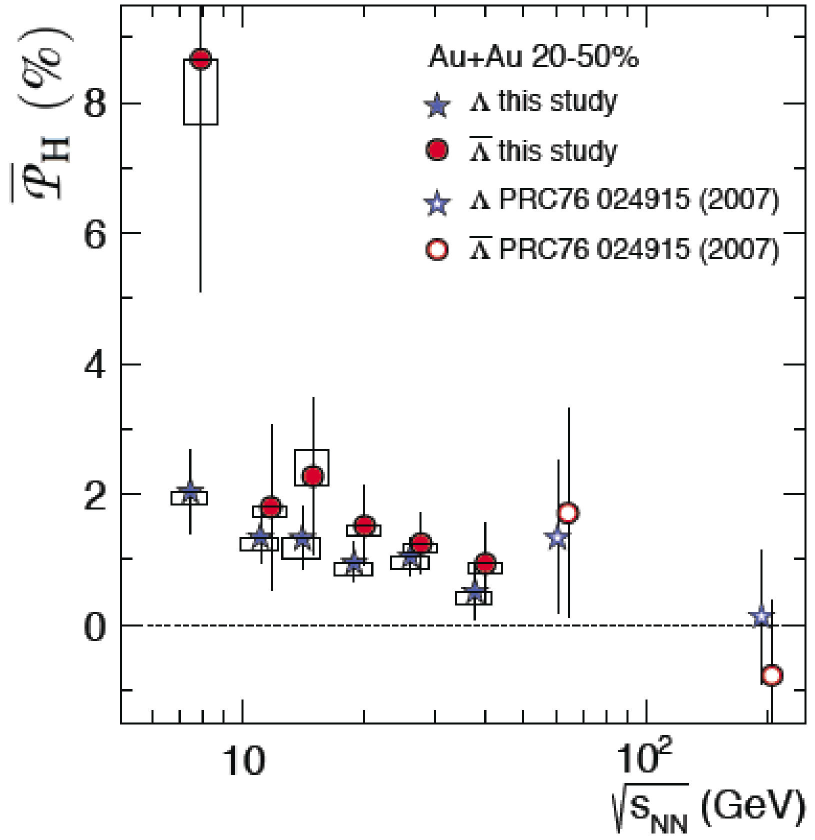


[I. Karpenko, talk QM18]
no initial shear
no NR vorticity

* Signature in theory is in agreement !!! (Magnitude is I.S. dependent)
* Exp. is a mix of P-s for X & Y and 1 & 2 components

Question # 2

What causes the difference of Λ and anti-Λ polarization ?



[STAR, Nature 548 (2017) 62.]

Λ & anti-Λ polarization measurement, BES: STAR Collaboration, Nature 548, 62 (2017)

Indication of larger polarization of anti-Λ-s (**?**)

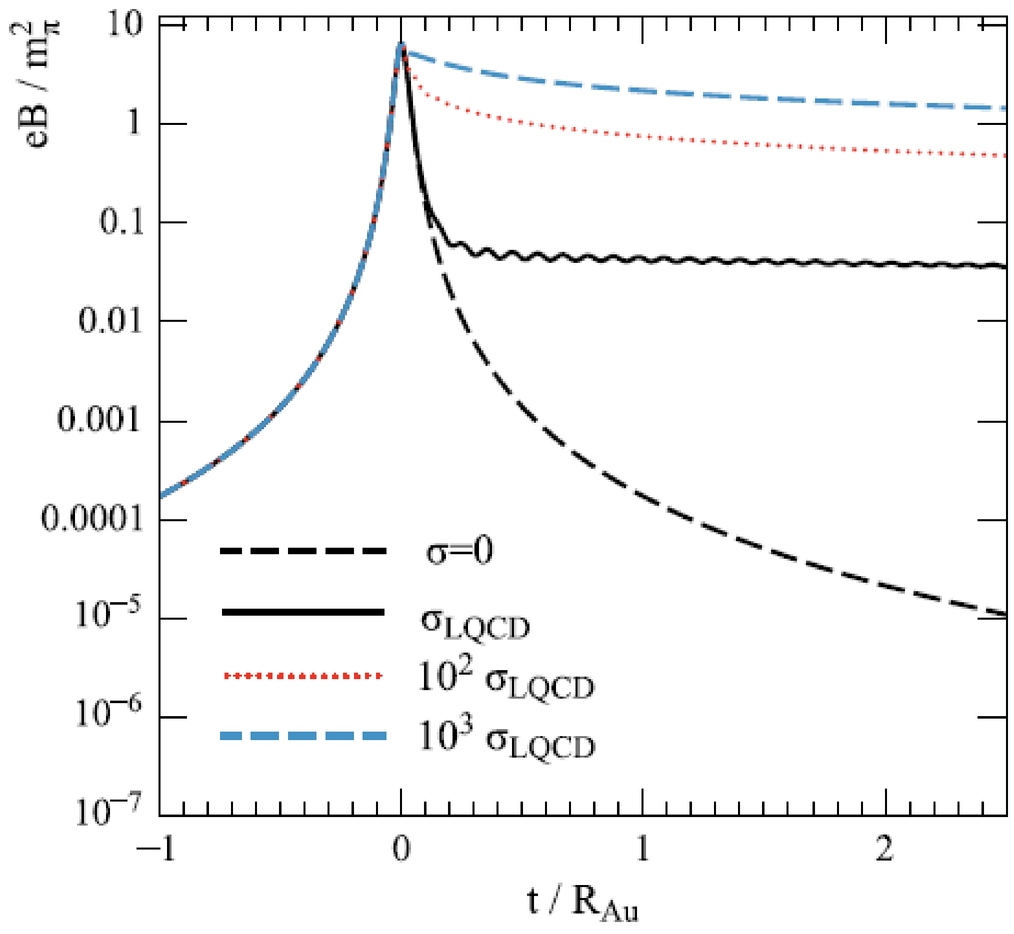
- Frequently attributed to magnetic effect caused the P & T spectators.

- Summarized by [Karpenko, talk QM18]:
  * Vorticity creates the average polarization.
  * The magnetic moment makes the Polarization splitting for Λ and anti-Λ
  * Question is there magnetic field at hadronization & freeze-out (**??**)

- Spectators are Lorentz contracted to $\Delta t = 2R_N/\gamma$

Frequently cited (!!!) :

L. McLerran, V. Skokov / Nuclear Physics A 929 (2014) 184–190



Magnetic field for **STATIC** medium with Ohmic conductivity.

The magnetic field lifetime in a collision

There is an internal current, j_{int}, generated in the medium.

"The characteristic time scale is defined by the external magnetic field and proportional to the thickness of the nucleus in the beam direction, i.e. tc~2R/ γ.For the top RHIC energy, tc ~ 0.2 fm/c."

"These subtle [expansion] effects, however, cannot be taken into account in the present studies ... "

"The conducting medium in the collision is not formed immediately, because the quarks need time to be created from the glasma field. Nonetheless, to make our estimates of the conductivity effects as optimistic as possible we will consider that the conducting medium is formed immediately after the collision and **does not alter (!)** during the evolution."

The magnetic field lifetime in a collision **2**

V. VORONYUK *et al.*
PHYSICAL REVIEW C **83**, 054911 (2011)

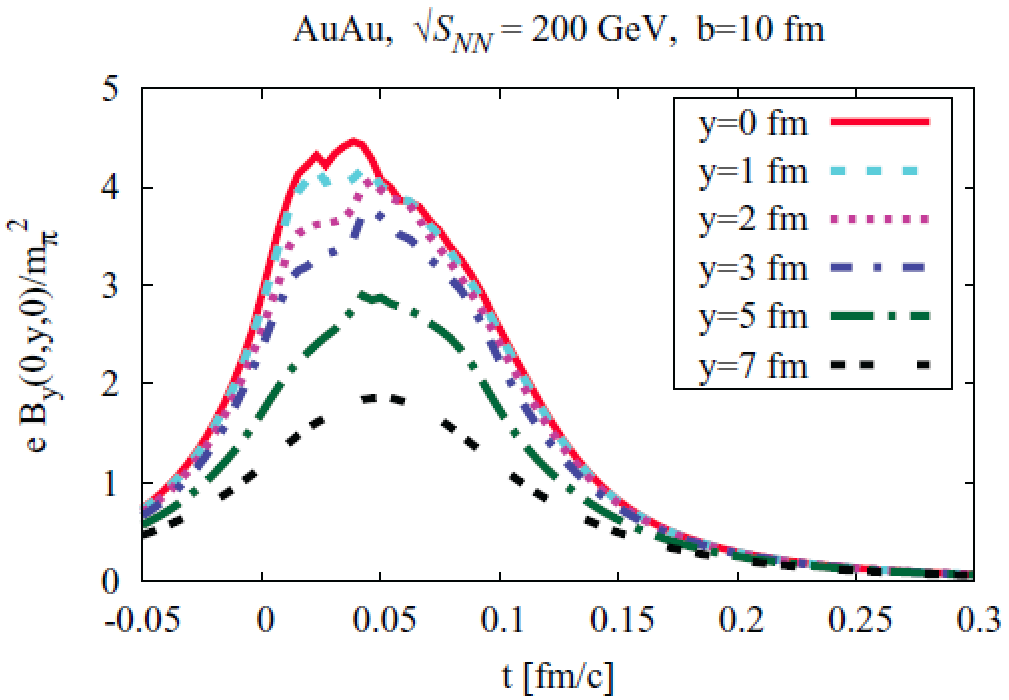


FIG. 6. (Color online) Time evolution of the magnetic field at the point y for the central overlap point $x = 0$.

[V. Voronyuk, V. D. Toneev, W. Cassing, E. L. Bratkovskaya, V. P. Konchakovski, S. A. Voloshin]

The magnetic field in the expanding medium is short lived, t ~ 0.15 fm/c at the initial moments, where quarks are not yet created.

The effect of this initial field is utterly negligible at the freeze out time of t_{FO} ~ 10 fm/c.

Dynamical hydro calculations assume that thermal, spin, and vorticity are equilibrated by the FO time. The spin-orbit interaction is assumed to be sufficiently strong (and equal) to achieve this equilibrium.

Competing strong spin-orbit interaction ↔ Hypernuclei

- In all calculations **spin-orbit equilibration** is assumed, by freeze-out
- However, from initial vorticity it takes time to build up Λ polarization
- Spin-orbit interaction for Λ and anti-Λ is not the same
- This is indicated by spin-orbit splitting of Hypernuclei !

- Presented also at **Workshop on Chirality, Vorticity** …,Firenze, 19-22 March & **QM2018,** Lido di Venezia, 14-19 May, 2018 :
  - **L.P. Csernai**, Uo Bergen: Λ polarization in peripheral heavy ion collisions
  - **I. Vassiliev** for the FAIR/CBM Collaboration: Perspectives on strangeness physics with CBM experiment
  - **Stefania Bufalino**, Politecnico and INFN Torino: Strangeness and nuclei production in nuclear collisions
  - **Tetyana Galatyuk**, TU Darmstadt / GSI: Future facilities for high μ_B physics

Λ & Anti-Λ Coupling to Nucleons

Difference based on Hypernuclei: 1.0 – 1.5 MeV i.e. ~ 20% of nuclear binding energy !!!

∃ ~ 20 Λ-hypernuclei ($T_{1/2} = 10^{-10}$s) 1953-1995

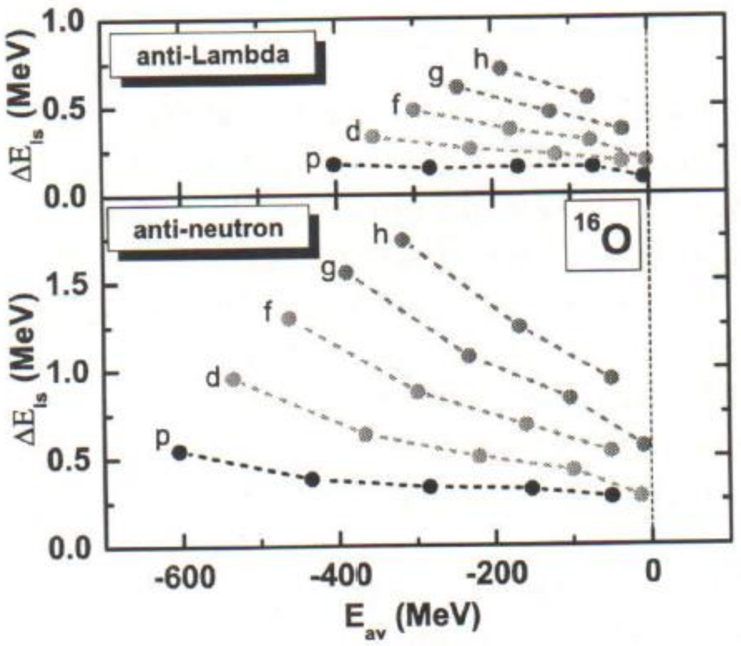


Fig. 2. Spin-orbit splitting $\epsilon_A(nl_{l-1/2}) - \epsilon_A(nl_{l+1/2})$ in the spectra of anti-Lambda and anti-neutron in ^{16}O versus the average energy of a pair of spin doublets. The vertical dashed line shows the continuum limit.

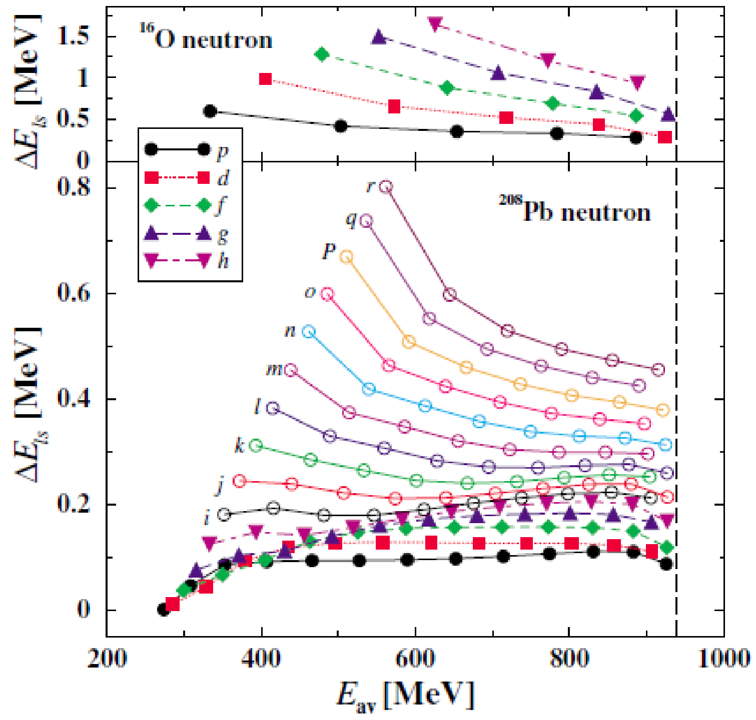


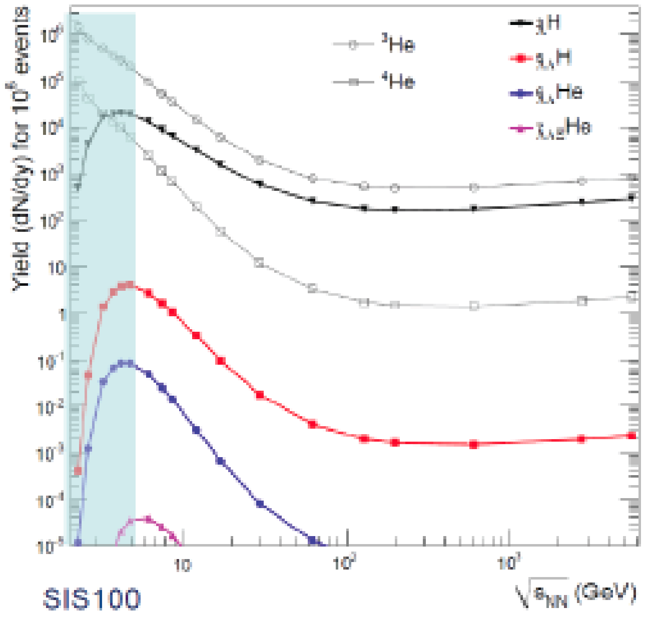
FIG. 2 (color online). Spin-orbit splitting $\epsilon_A(nl_{l-1/2}) - \epsilon_A(nl_{l+1/2})$ in antineutron spectra of ^{16}O and ^{208}Pb versus the average energy of a pair of spin doublets. The vertical dashed line shows the continuum limit.

[ZhouSG-etal-PhysRevLett.91(2003)262501]

[SongCY-etal-IJMPE19(2010)2538]

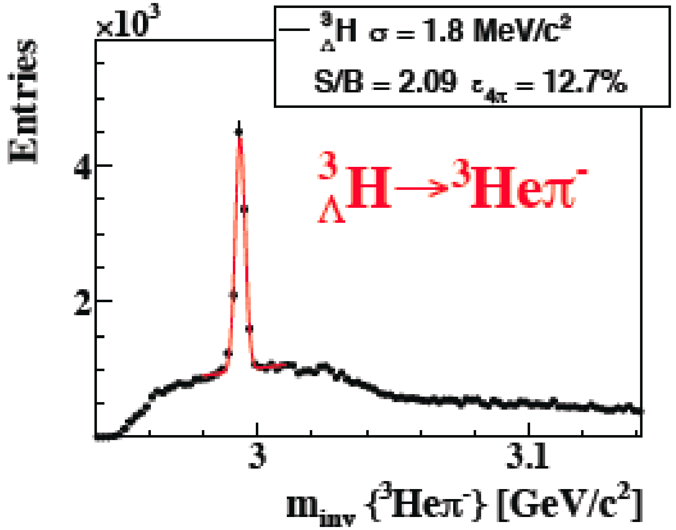
[Csernai, Chirality WS, 2018]

Hypernuclei production in A+A collisions

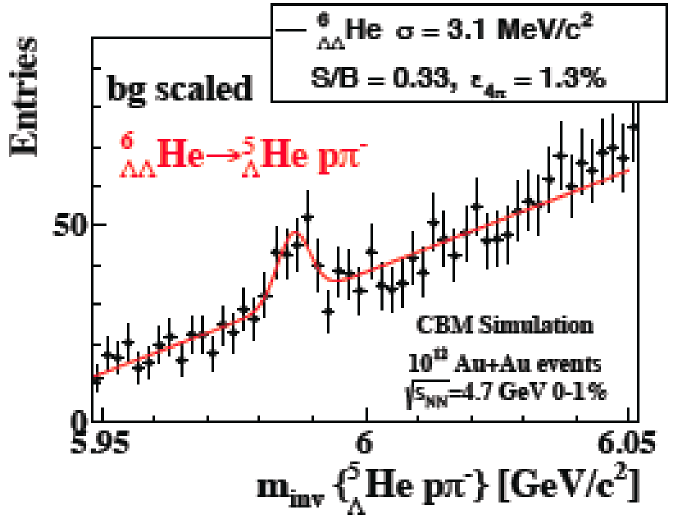


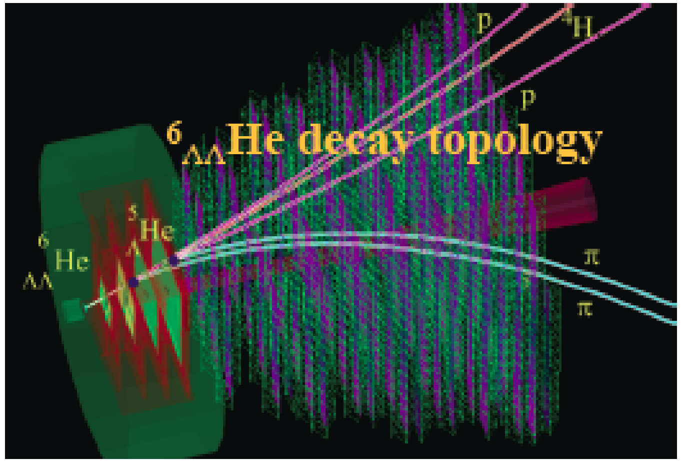
A. Andronic et al., Phys. Lett. B697 (2011) 203

5M mbias events Au+Au at 10AGeV/c
5 sec at 1MHz IR (1.8 k/sec)



Expected collection rate: ~60 $^6_{\Lambda\Lambda}$He
in 1 week at 10MHz IR

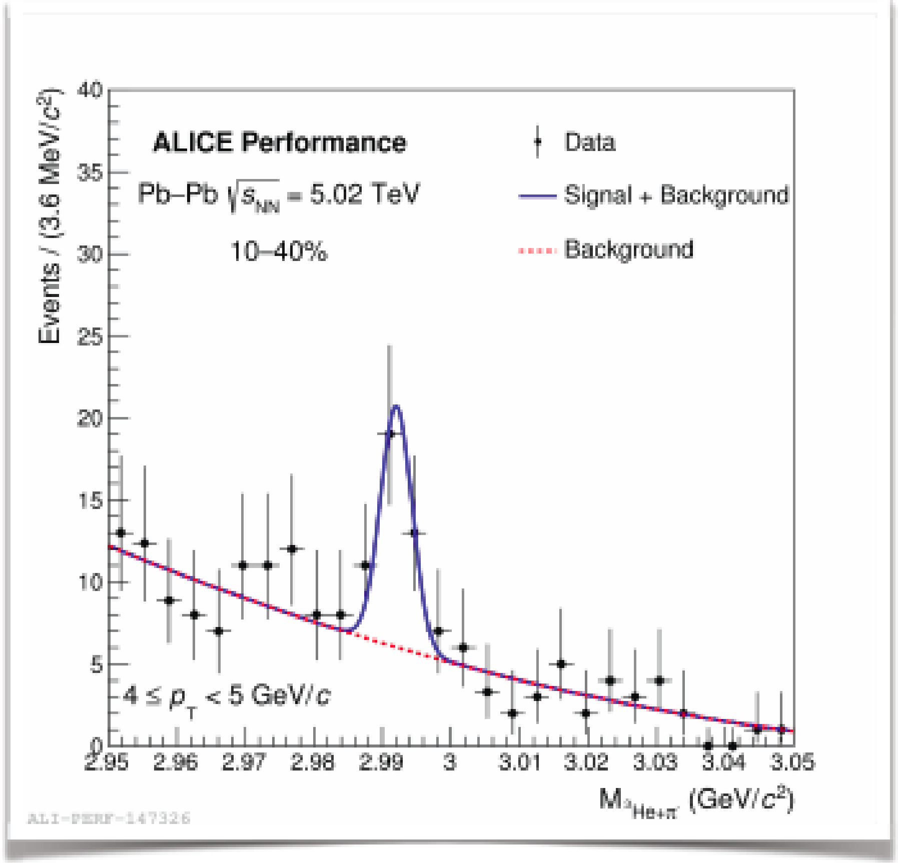


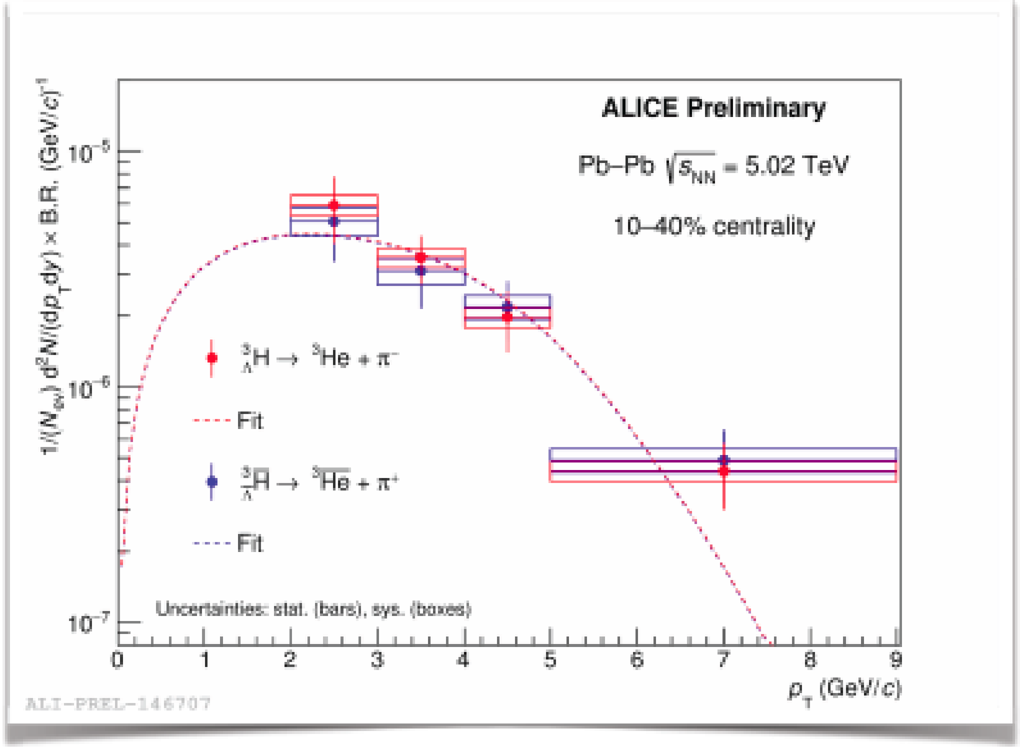


- According to the current theoretical predictions CBM will be able to perform comprehensive study of hypernuclei, including:
  - precise measurements of lifetime;
  - excitation functions;
  - flow.
- It has a huge potential to register and investigate double Λ hypernuclei.

[Vassiliev, QM 2018]

Hypertriton search with ALICE at the LHC

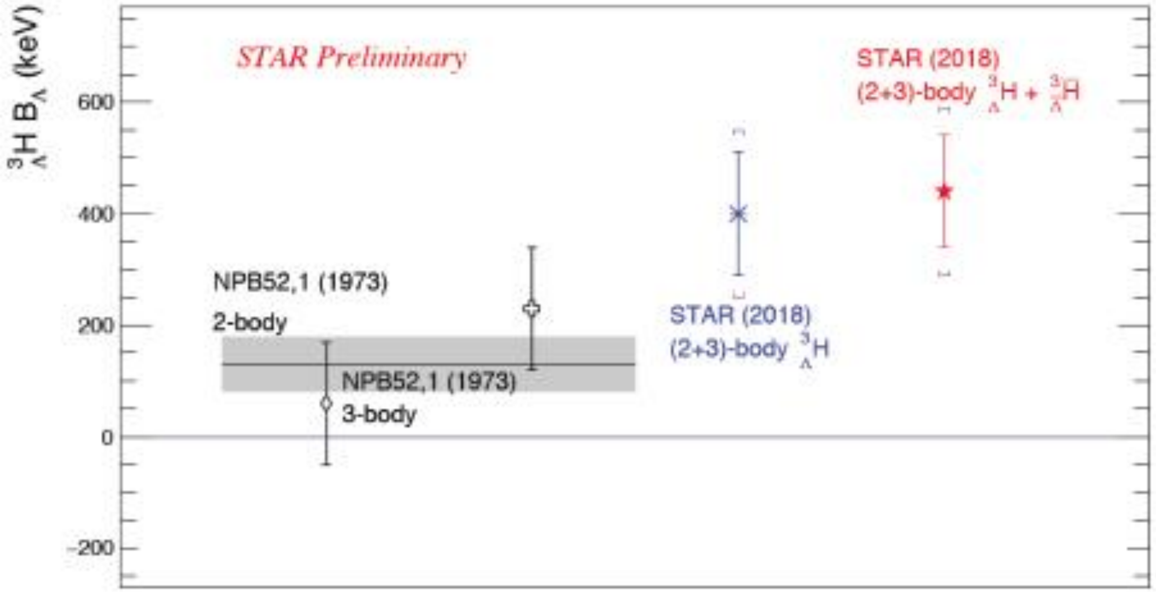




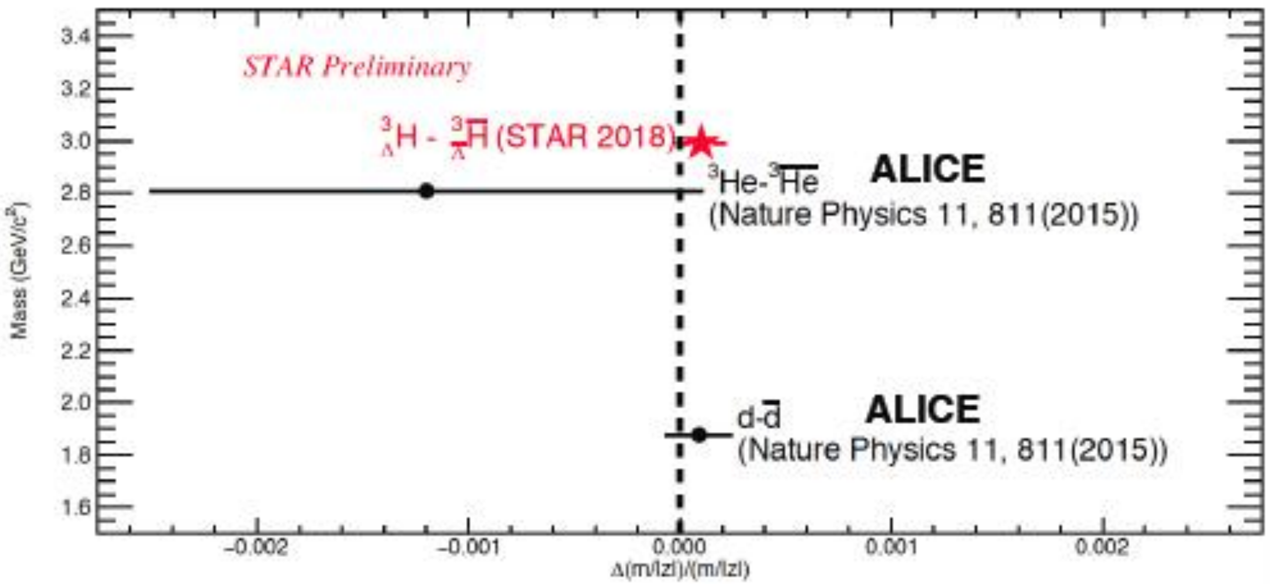
[Stefania Bufalino, QM 2018]

Hypertriton: news from STAR

Latest news

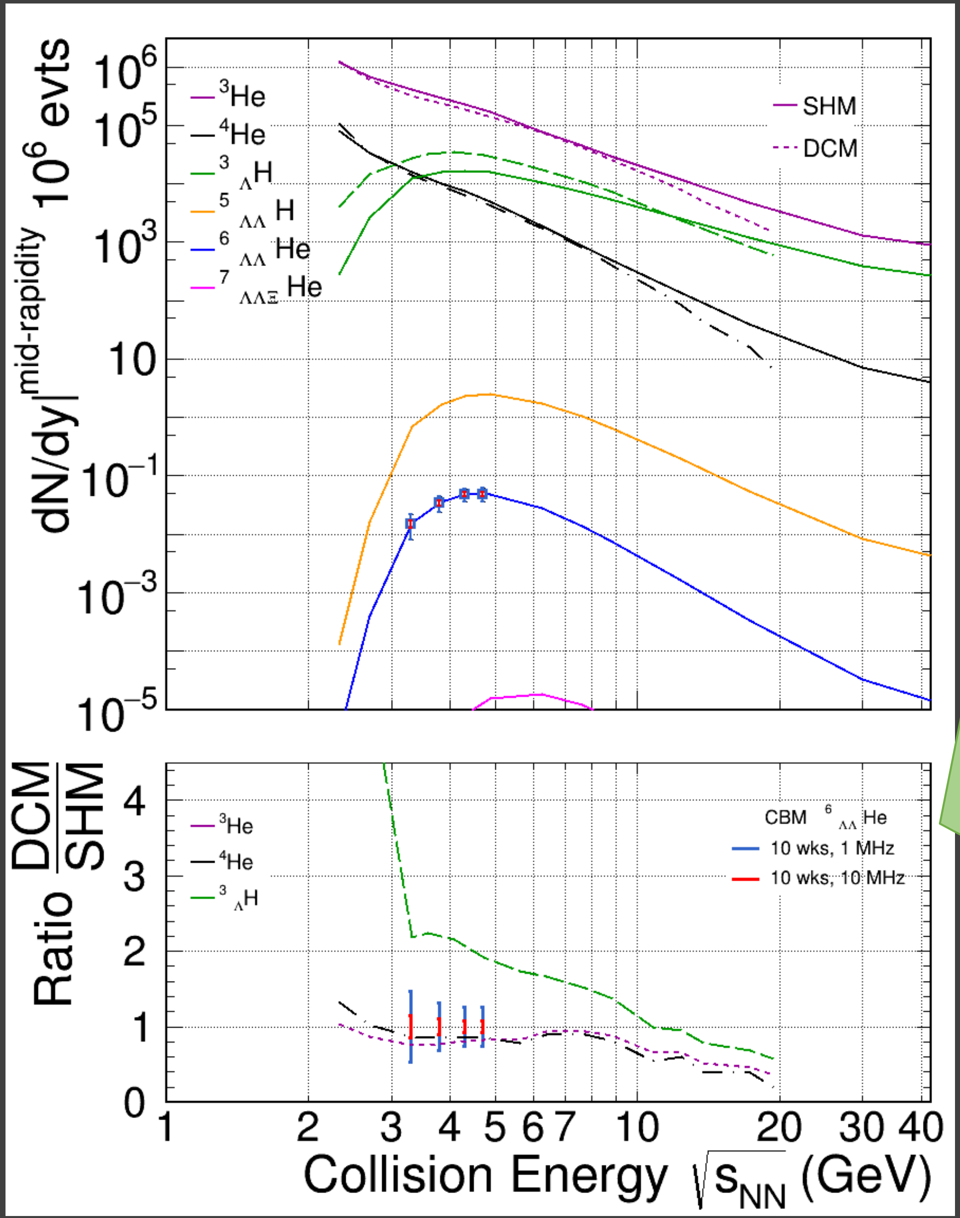


Mass difference measurement for hyper-matter confirms the result obtained with light nuclei and it is consistent with CPT prediction.



$$\Delta m = 2.8 \mathrm{Gev}/c^2 \text{ between } {}^3_\Lambda H \text{ and } {}^3_\Lambda \bar{H}.$$

[Stefania Bufalino, QM 2018]



SHM: A. Andronic et al., Phys.Lett. B697 (2011)
DCM: J. Steinheimer et al., Phys.Lett. B714 (2012)

Nuclei and hyper-nuclei production

- How do nuclei and hyper-nuclei form?
  - Compact multi-quark states at the phase boundary?
  - Coalescence?
- What are their properties?
- Do *YY* bound states exist?

ALICE Collab., Phys. Lett. B 754 (2016) 360
STAR Collab., arXiv:1710.00436 [nucl-ex]
HAL CD Coll., arXiv:1709.00654 [hep-lat]

Precision measurement of spectra, life-time and flow pattern

CBM	$\sqrt{s_{NN}}$	Run time	ε %	$R_{int,}$ MHz	*Duty F* %	Yield
$^{3}_{\Lambda}H$	4.7 GeV	1 wks	19	10	50	5.5×10^9
$^{4}_{\Lambda}He$	4.7 GeV	1 wks	15	10	50	2.7×10^8
$^{6}_{\Lambda\Lambda}He$	4.7 GeV	10 wks	1	10	50	146
MPD S2						
$^{3}_{\Lambda}H$	5 GeV	10 wks	1	0.5	100	9×10^4
$^{4}_{\Lambda}He$	5 GeV	10 wks	0.4	0.5	100	1×10^4

[Tetyana Galatyuk, QM 2018]

Λ spin interaction with external fields

$$H_{\rm spin}^{\omega} = -\frac{g_{\omega\Lambda}}{m_\Lambda}\beta\,\boldsymbol{S}\cdot\boldsymbol{B}_\omega - i\,\frac{g_{\omega\Lambda}}{4m_\Lambda^2}\boldsymbol{S}\cdot\boldsymbol{\nabla}\times\boldsymbol{E}_\omega - \frac{g_{\omega\Lambda}}{2m_\Lambda^2}\boldsymbol{S}\cdot\boldsymbol{E}_\omega\times\boldsymbol{p} \qquad (3)$$

where $\beta = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ is the usual Dirac 4x4 matrix.

When acting on the spinors of Λ and anti-Λ they result in opposite signs whereas the second and third terms have the same sign.

The second and third terms contribute to the usual nuclear spin-orbit energy.

[J. Kapusta & L.P. Cs., in preparation]