Production of hyper-nuclei and exotica using UrQMD and a coalescence model

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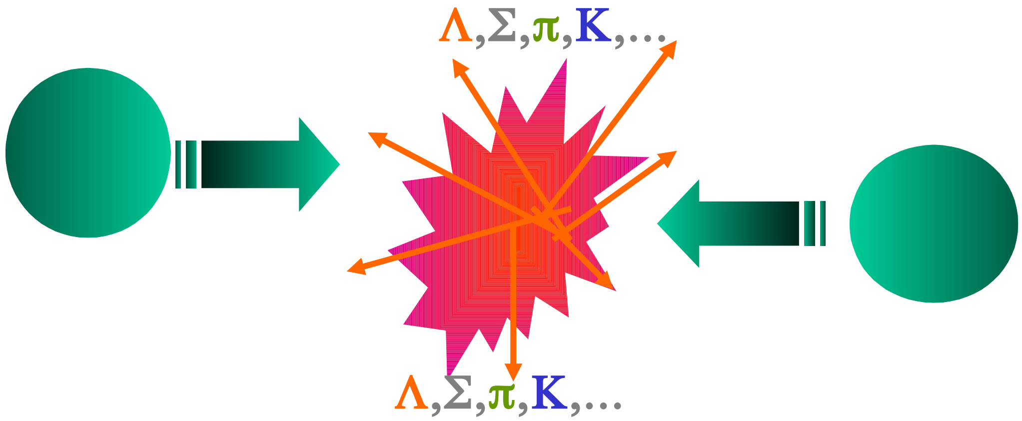
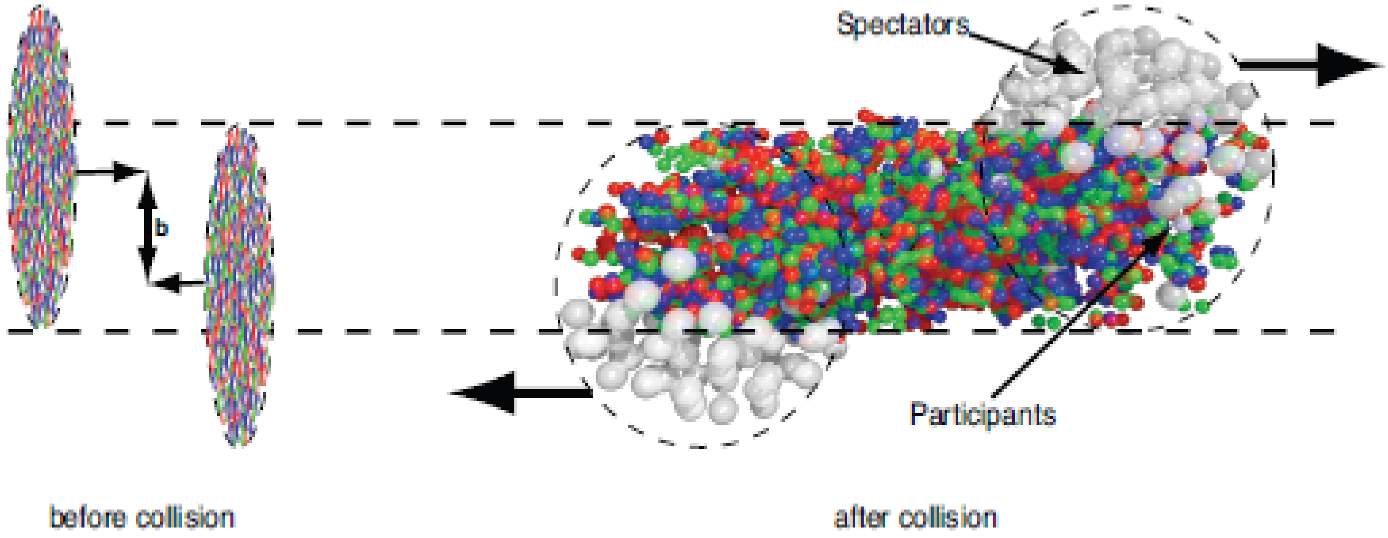
EMMI Workshop
“Anti-matter, hyper-matter and exotica production at the LHC”

Turin, Italy.
November 6-10 , 2017

Relativistic collisions of hadrons and ions



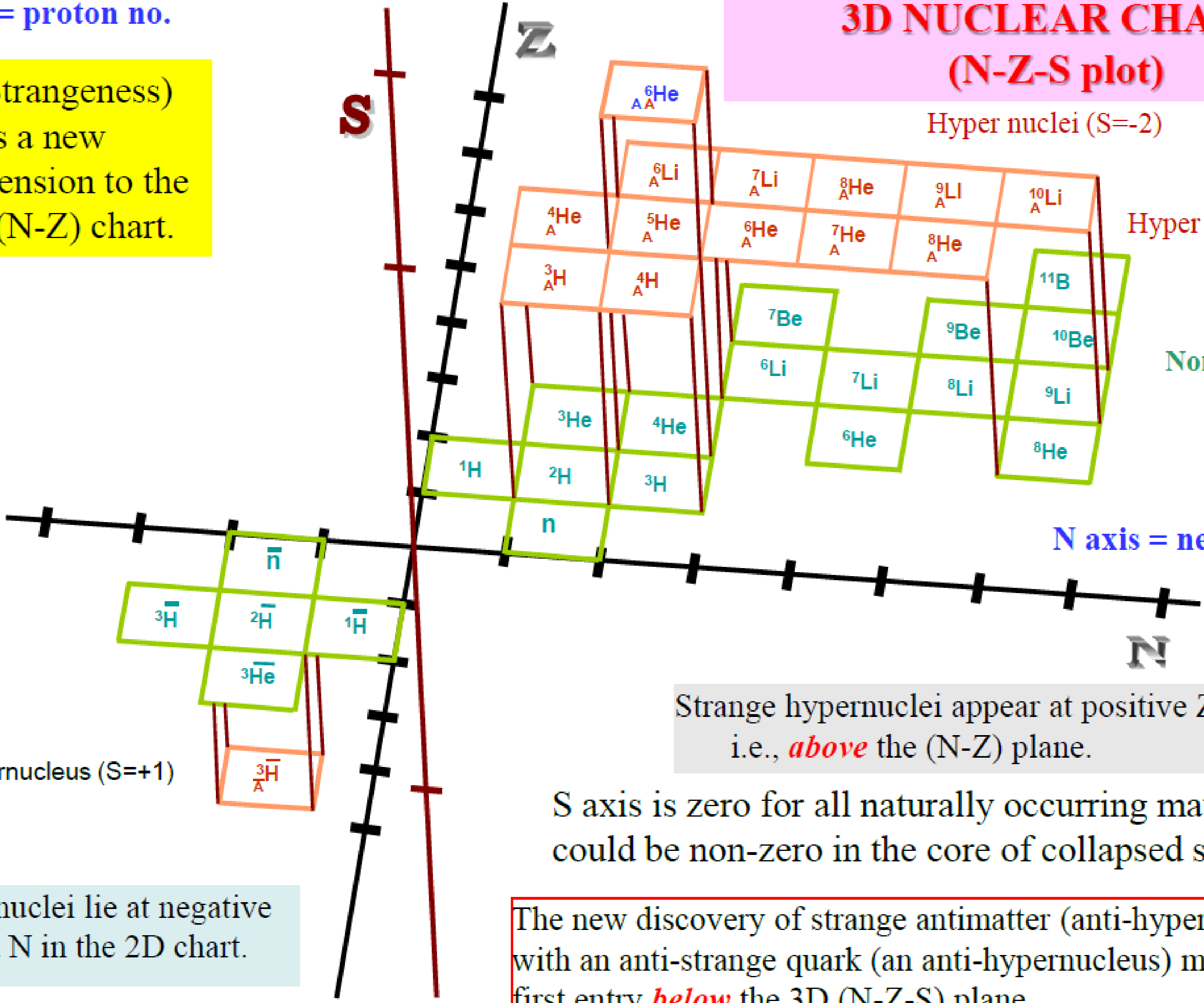
Production of hypernuclei in central and peripheral HI collisions



3D NUCLEAR CHART
(N-Z-S plot)

Z axis = proton no.

S (Strangeness) adds a new dimension to the 2D (N-Z) chart.



Hyper nuclei (S=-2)

Hyper nuclei (S=-1)

Normal nuclei

N axis = neutron no.

Hypernucleus (S=+1)

Strange hypernuclei appear at positive Z, N and S i.e., ***above*** the (N-Z) plane.

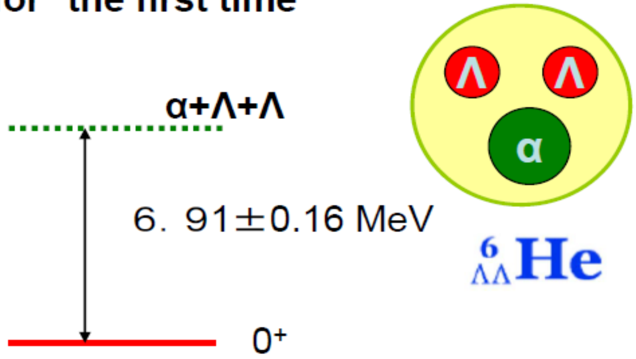
S axis is zero for all naturally occurring matter, but could be non-zero in the core of collapsed stars.

Anti-nuclei lie at negative Z and N in the 2D chart.

The new discovery of strange antimatter (anti-hyper-triton) with an anti-strange quark (an anti-hypernucleus) marks the first entry ***below*** the 3D (N-Z-S) plane.

(K^-, K^+) reactions
Ξ^- hyperons at the emulsion

Uniquely identified without ambiguity for the first time



Possible mechanism of this reaction:

$$\Xi^- + {}^{12}C \longrightarrow {}^{13}_{\Lambda\Lambda}B^* \longrightarrow {}^{6}_{\Lambda\Lambda}He \ldots$$

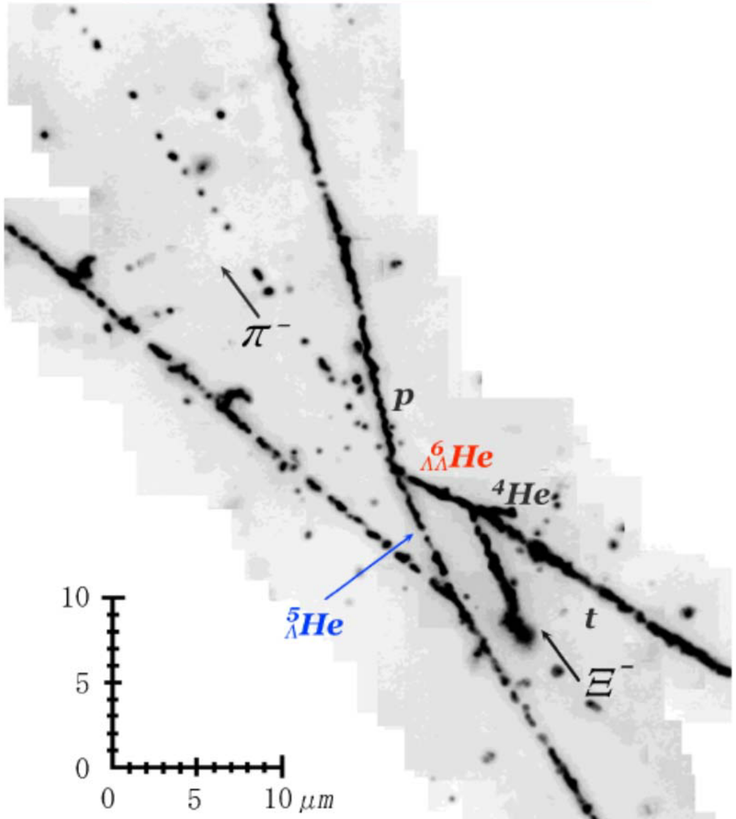
Break-up of excited hyper-system (~28MeV)
[Fermi-Break-up calculated probability~0.01]

A.Sanchez Lorente et al., Phys. Lett. B697 (2011)222

$^{6}_{\Lambda\Lambda}$He double-hypernucleus

Unique interpretation!!

$$\boxed{\begin{array}{l} \Xi^- + {}^{12}C \longrightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t \\ {}^{6}_{\Lambda\Lambda}He \longrightarrow {}^{5}_{\Lambda}He + p + \pi^- \end{array}}$$



"NAGARA" event

presented by E373(KEK-PS) on Jan.2001

H. Takahashi *et al.*, PRL 87, 212502-1 (2001)

Central collisions of relativistic ions

Production of $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ in central 11.5 GeV/c Au+Pt heavy ion collisions

PHYSICAL REVIEW C 70, 024902 (2004)

(AGS)

Rapidity 1.6–2.6
p_t(GeV/c) 0–1.5

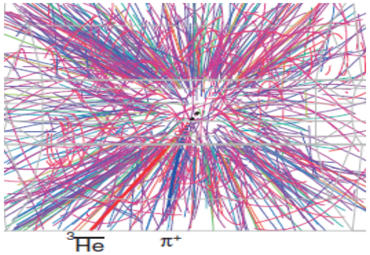
coalescence mechanism

N_{event} 13.5×10^9
N_{count} 1220 ± 854

$^{3}_{\Lambda}H$

STAR collaboration (RHIC):

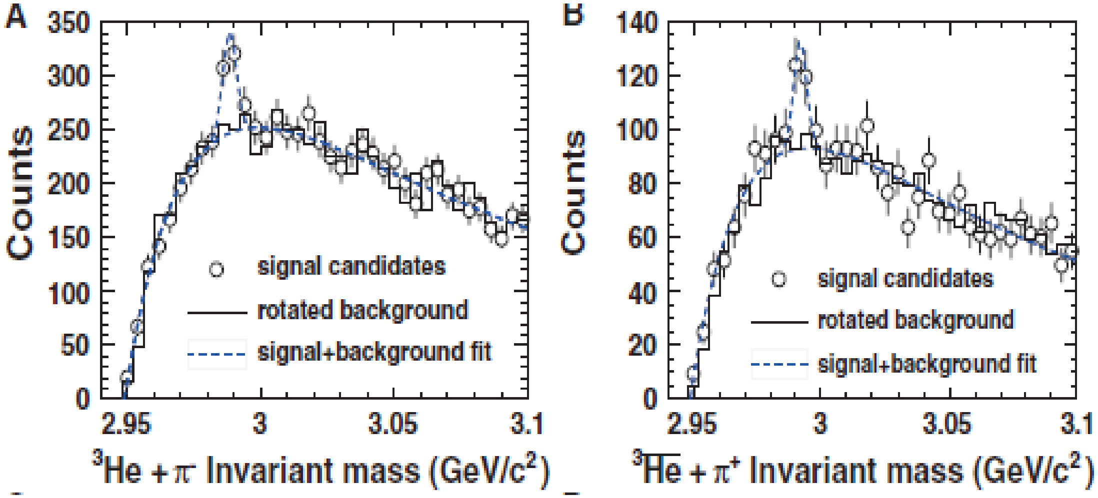
Science, 238 (2010) 58



Au + Au collisions at 200 A GeV

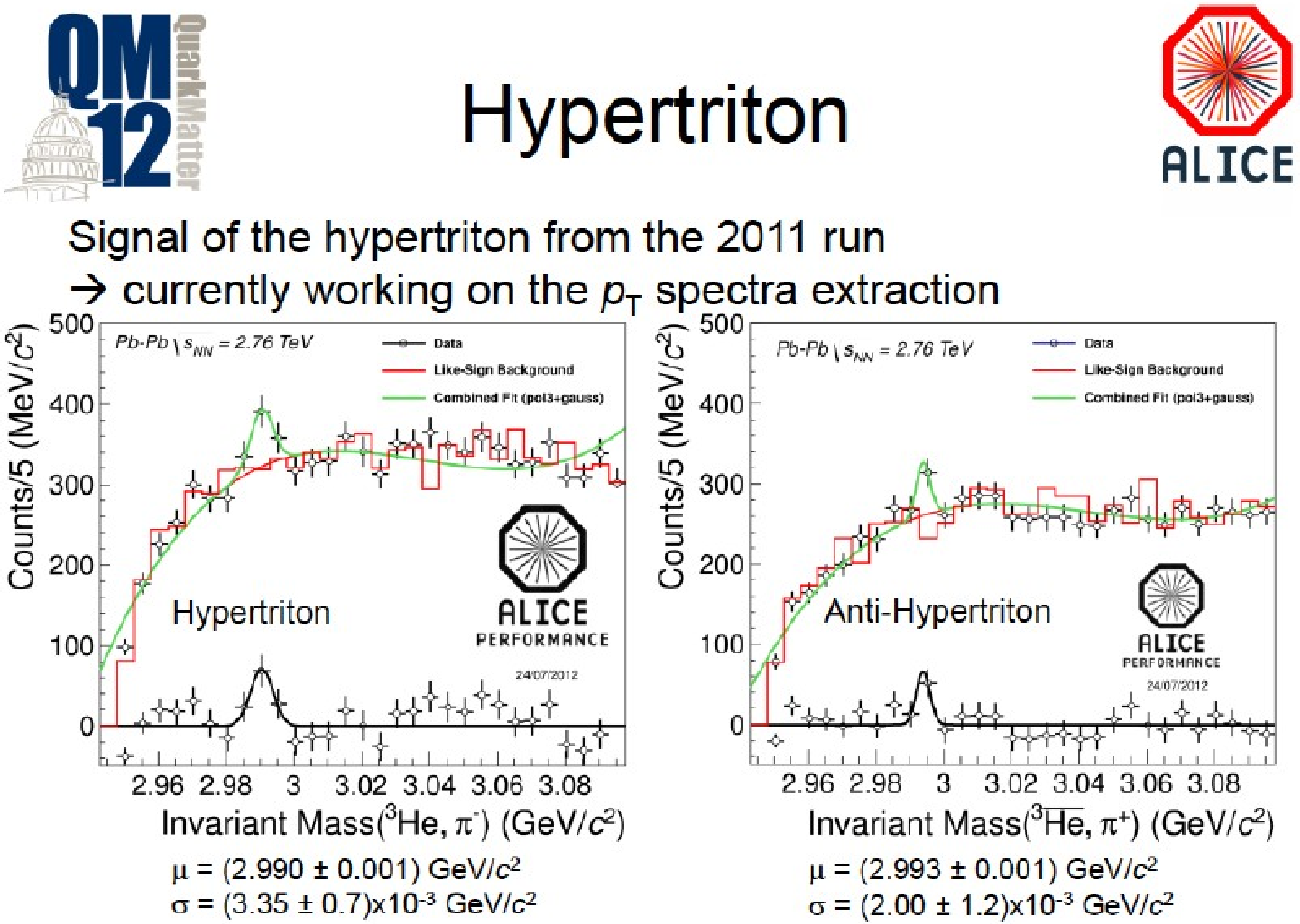
gas-filled cylindrical Time Projection Chamber

70 ± 17 antihypertritons ($^{3}_{\bar{\Lambda}}\overline{H}$) and 157 ± 30 hypertritons ($^{3}_{\Lambda}H$).



B. Doenigus et al., Nucl. Phys. A904-905 (2013) 547c

ALICE’s observation for (anti-)hypertriton



Hypertriton

Signal of the hypertriton from the 2011 run

→ currently working on the p_T spectra extraction

μ = (2.990 ± 0.001) GeV/c^2

σ = (3.35 ± 0.7)x10^{-3} GeV/c^2

μ = (2.993 ± 0.001) GeV/c^2

σ = (2.00 ± 1.2)x10^{-3} GeV/c^2

UrQMD PHSD DCM GiBUU

Production mechanisms of exotic nuclear species including anti-matter, hyper-matter in relativistic HI and hadron collisions:

- Production of all kind of particles (anti- , strange, charmed ones) in individual binary hadron collisions. Effects of nuclear medium can be included.
- Secondary interactions and rescattering of new-born particles are taken into account. (Looks as partial ‘thermalization’.)
- Coalescence of all-possible baryons into composite (exotic, anti- , hyper-) nuclear species.
- Capture of produced baryons by big excited nuclear residues.

Statistical decay of excited residues into new nuclei

- Multifragmentation into small nuclei (high excitations),
- Evaporation and fission of large nuclei (low excitations),
- (Fermi-) Break-up of small nuclei into lightest ones.

A.Botvina, J.Steinheimer, E.Bratkovskaya, M.Bleicher, J.Pochodzalla, PLB742(2015)7

Coalescence of Baryons (CB) Model :

Development of the coalescence for formation of clusters of all sizes

1) Relative velocities between baryons and clusters are considered,
if $(|\mathbf{V}_b-\mathbf{V}_A|)<\mathbf{V}_c$ the particle b is included in the A-cluster.
2) Step by step numerical approximation.

3) In addition, coordinates of baryons and clusters are considered,
if $|\mathbf{X}_b-\mathbf{X}_A|<R*A**(1/3)$ the particle b may be included in A-cluster.
4) Spectators' nucleons are always included in the residues.

Combination of transport UrQMD model with CB:

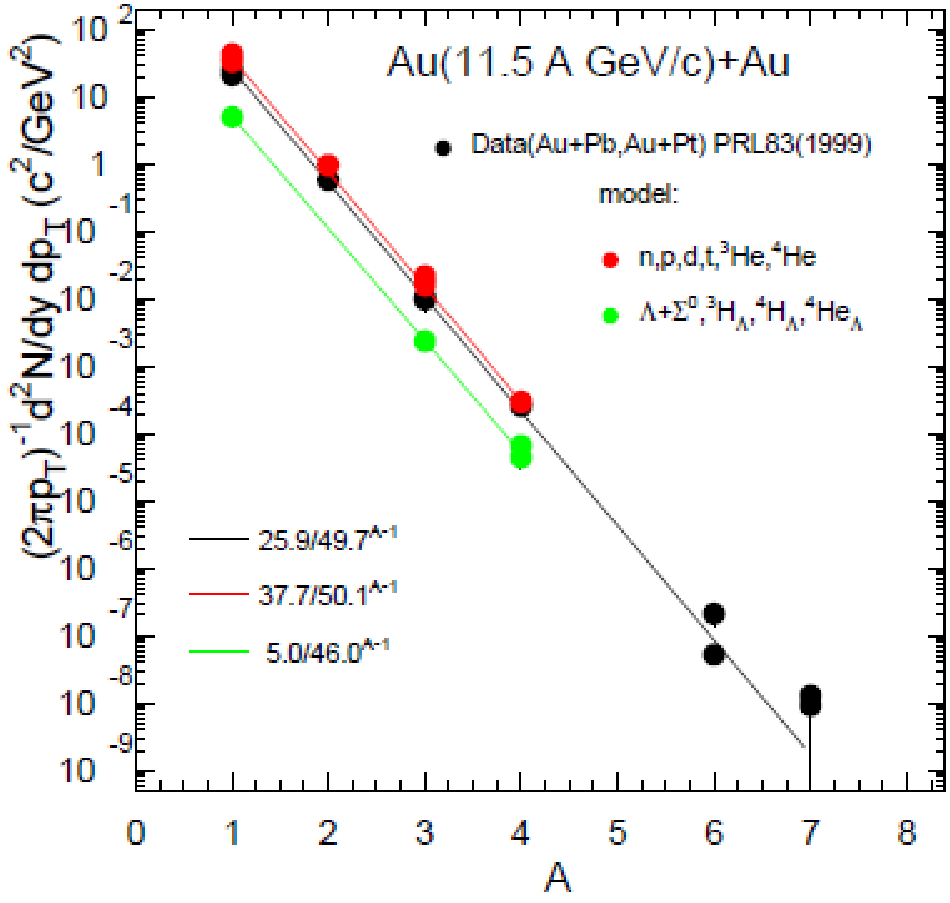
Investigation of fragments/hyperfragments at all rapidities !
(connection between central and peripheral zones)

Production of light nuclei in central collisions : Au+Au

DCM and UrQMD calculations - J.Steinheimer et al., Phys. Lett. B**714**, 85 (2012)

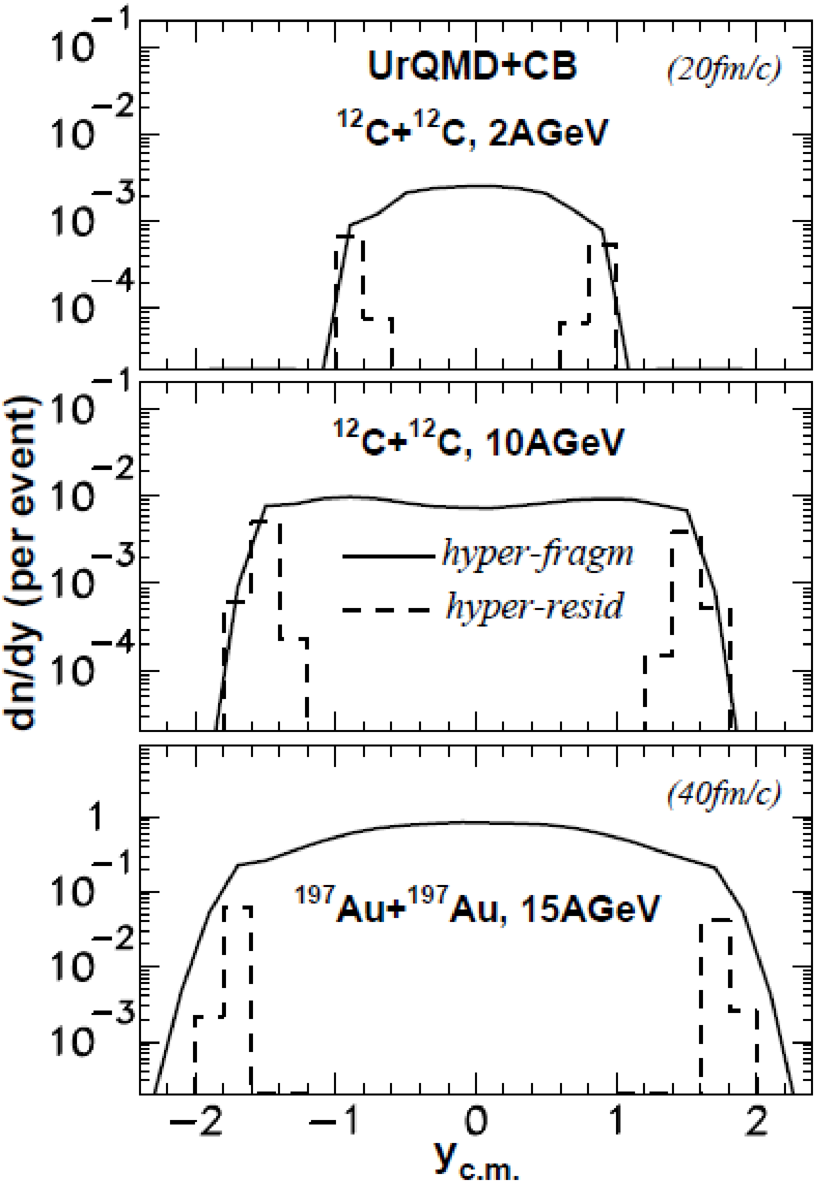
DCM versus experiment :
coalescence mechanism

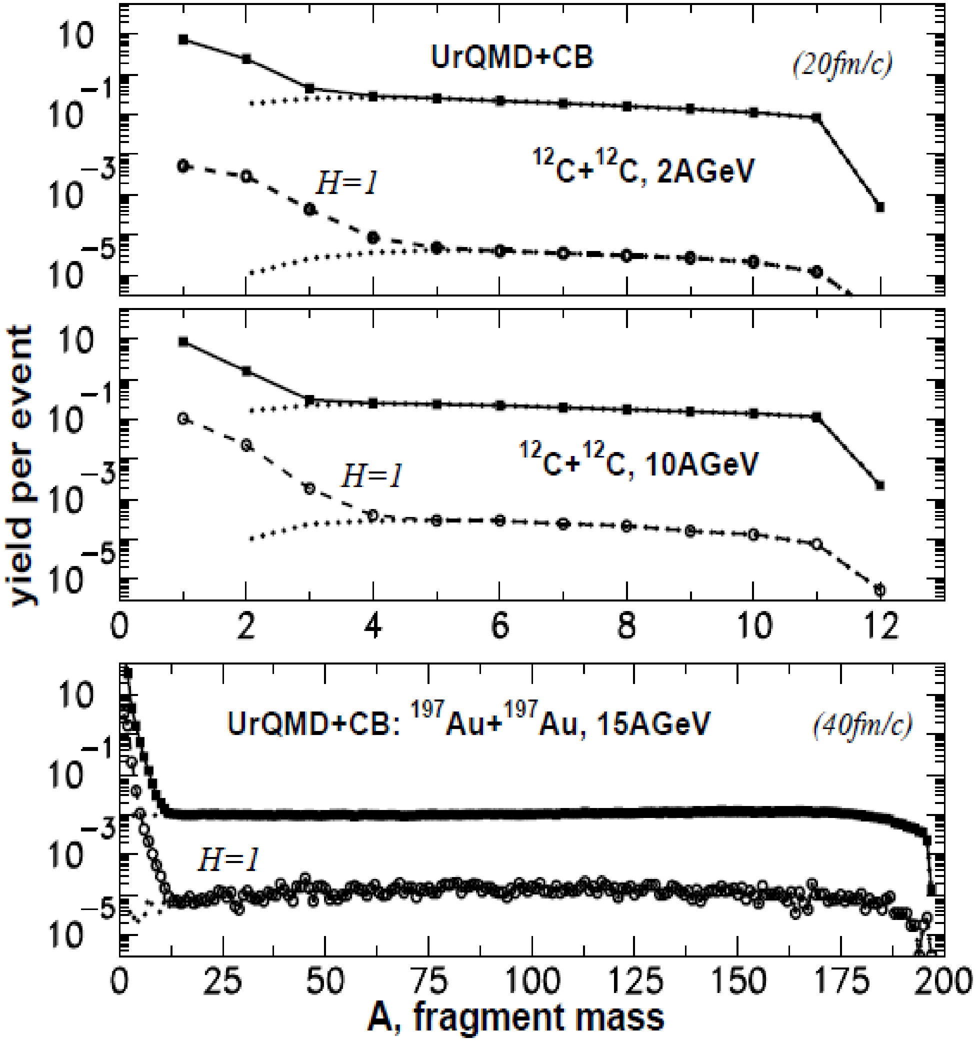
It is not possible to
produce big nuclei !



A.Botvina, J.Steinheimer, E.Bratkovskaya, M.Bleicher, J.Pochodzalla, PLB742, 7 (2015)

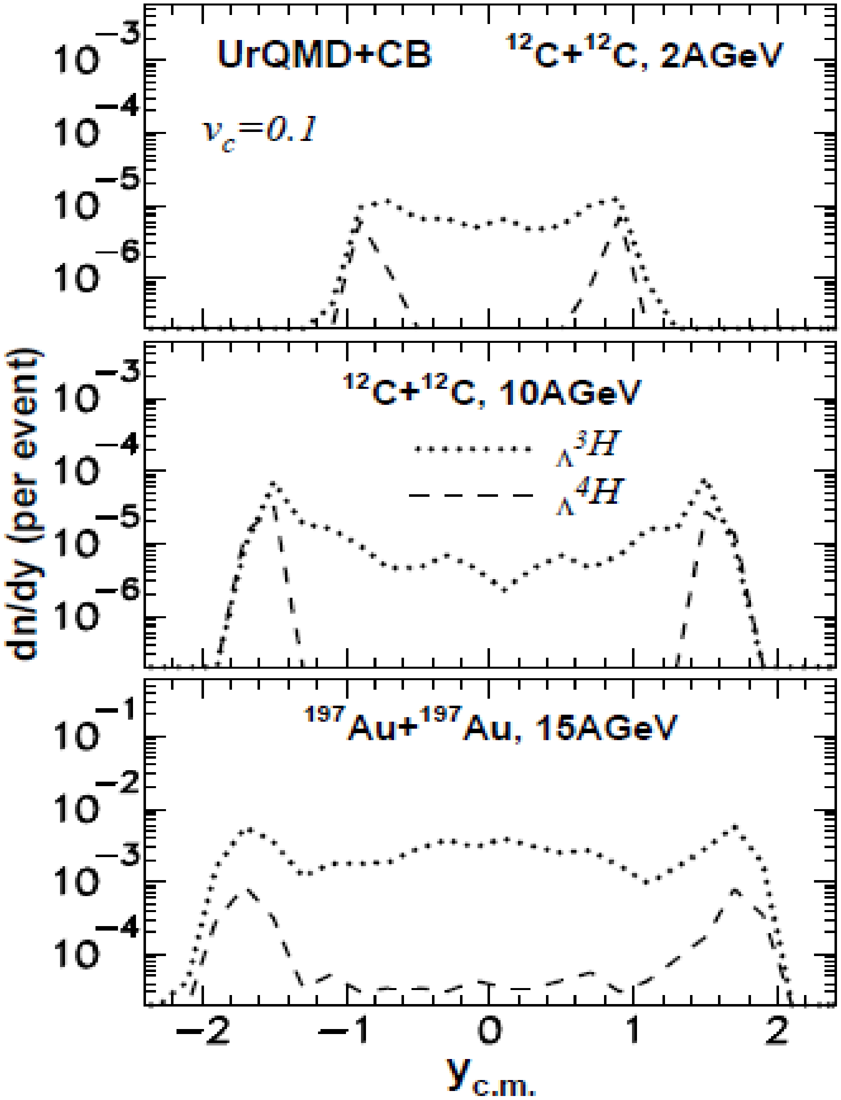
normal- and hyper-fragments; hyper-residues @ target/projectile rapidities





Because of secondary interactions the maximun of the fragments production is shifted from the midrapidity. Secondary products have relatively low kinetic energies, therefore, they can produce clusters and hypernuclei with higher probability.

A.Botvina,
J.Steinheimer,
E.Bratkovskaya,
M.Bleicher,
J.Pochodzalla,
PLB742, 7 (2015)

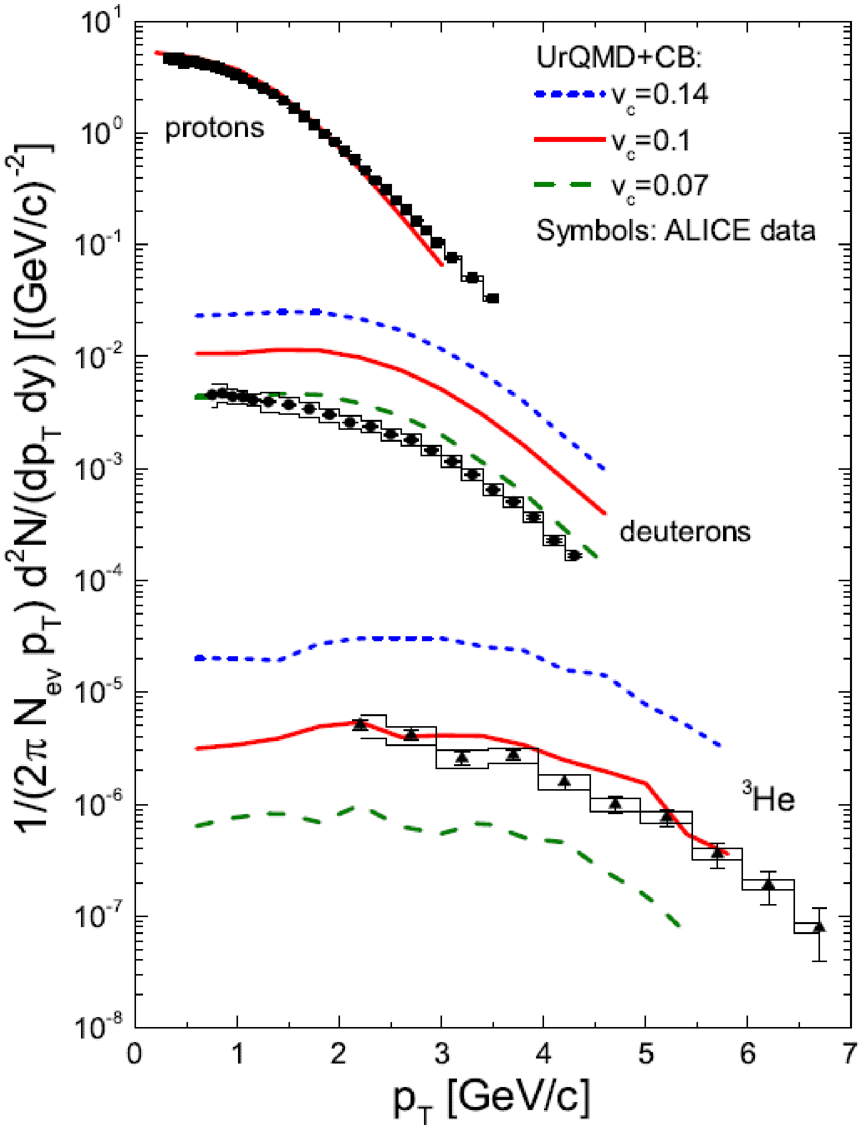


Production of light nuclei at LHC energies (ALICE):

Botvina, Steinheimer, Bleicher : UrQMD + CB - Phys. Rev. C96, 014913 (2017)

Hybrid approach
at LHC energies:
UrQMD+
(hydrodynamics)+
coalescence

Central collisions:
Pb on Pb at the center
of mass energy -
2.76 A TeV .
Rapidity range:
from -0.5 to +0.5



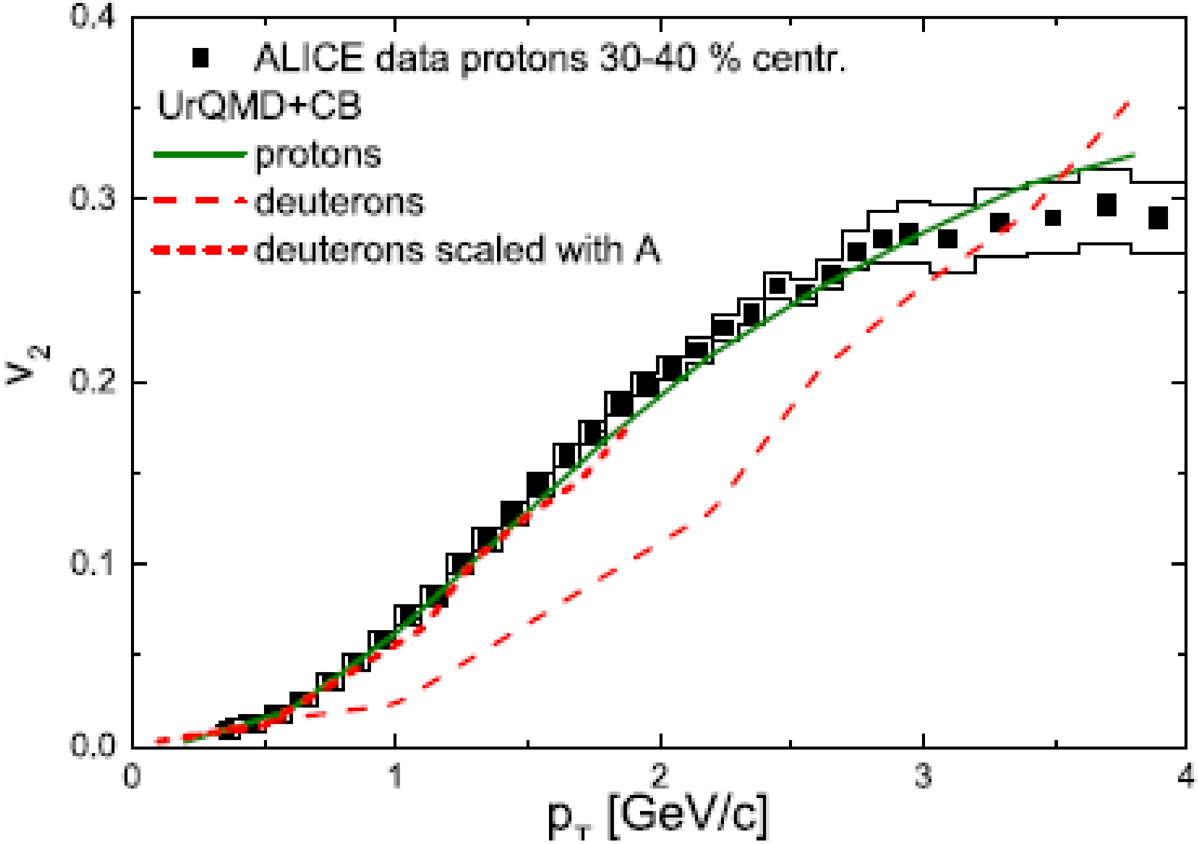
Elliptic flow of protons and deutrons at LHC energies (ALICE experiment):

Hybrid approach
at LHC energies:
UrQMD+
coalescence

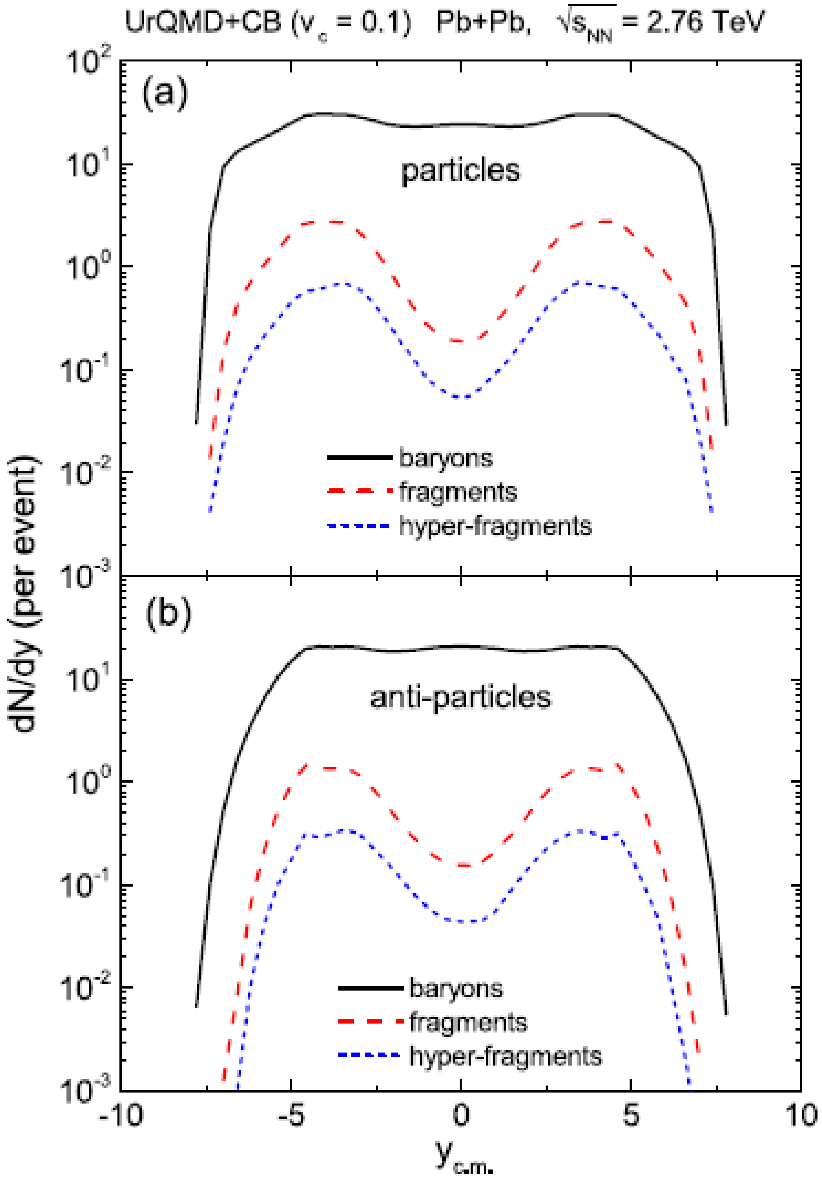
$$v_2 = \langle (P_x^2 - P_y^2)/P_T^2 \rangle$$

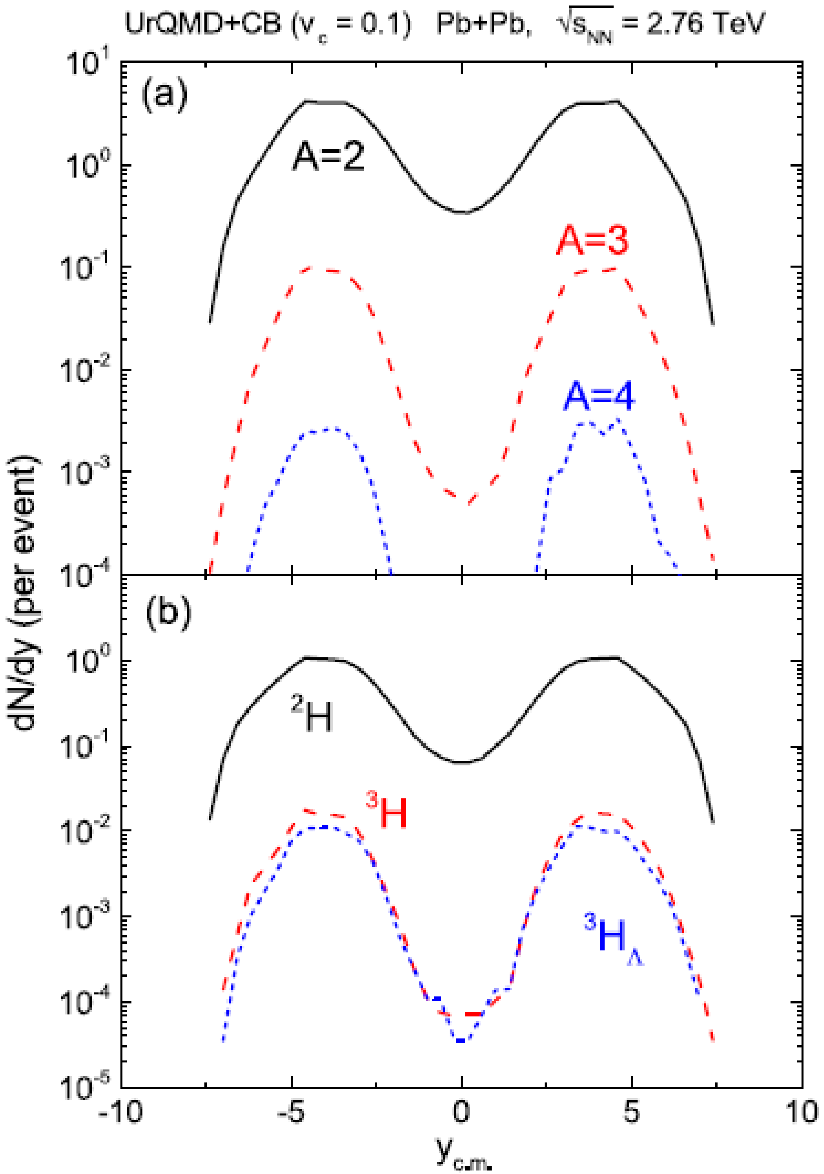
Coalescence scaling

v_2/A versus P_T/A



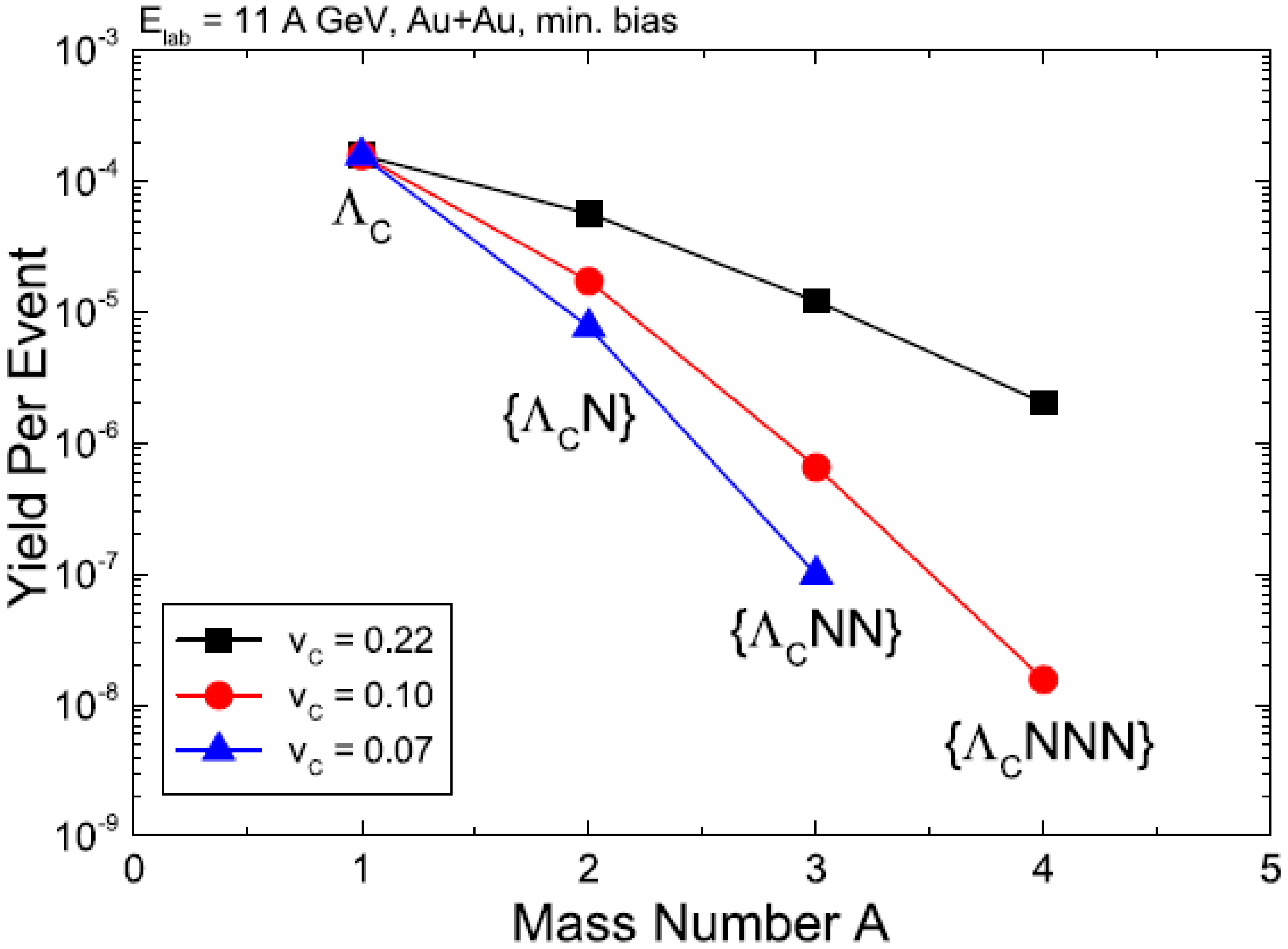
Particle production for all rapidities (at LHC): UrQMD+CB





Charmed nuclei production at FAIR energies : coalescence ?

Steinheimer, Botvina, Bleicher : UrQMD + CB - Phys. Rev. C95, 014911 (2017)



Statistical approach for fragmentation of hyper-matter

$$Y_{\rm AZH} = g_{\rm AZH} V_f \frac{A^{3/2}}{\lambda_T^3} \exp\left[-\frac{1}{T} \left(F_{AZH} - \mu_{AZH} \right) \right]$$

$$\mu_{AZH} = A\mu + Z\nu + H\xi$$

mean yield of fragments with mass number ***A***, charge ***Z***, and **Λ**-hyperon number ***H***

$$F_{AZH}(T,V) = F_A^B + F_A^S + F_{AZH}^{\rm sym} + F_{AZ}^C + F_{AH}^{\rm hyp}$$

$$F_A^B(T) = \left(-w_0 - \frac{T^2}{\varepsilon_0} \right) A \quad ,$$

liquid-drop description of fragments: bulk, surface, symmetry, Coulomb (as in Wigner-Seitz approximation), and hyper energy contributions

J.Bondorf et al., Phys. Rep. **257** (1995) 133

$$F_A^S(T) = \beta_0 \left(\frac{T_c^2 - T^2}{T_c^2 + T^2} \right)^{5/4} A^{2/3} \quad ,$$

$$F_{AZH}^{\rm sym} = \gamma \frac{(A - H - 2Z)^2}{A - H} \quad ,$$

parameters ≈ Bethe-Weizsäcker formula:

$w_0 = 16$ MeV, $\beta_0 = 18$ MeV, $T_c = 18$ MeV

$\gamma = 25$ MeV $\qquad \varepsilon_0 \approx 16$ MeV

$$\sum_{AZH} A Y_{\rm AZH} = A_0, \sum_{AZH} Z Y_{\rm AZH} = Z_0, \sum_{AZH} H Y_{\rm AZH} = H_0.$$

chemical potentials are from mass, charge and *H*yperon number conservations

$$F_{AH}^{\rm hyp} = E_{sam}^{\rm hyp} = H \cdot (-10.68 + 48.7/(A^{2/3})).$$

-- C.Samanta et al. J. Phys. G: 32 (2006) 363 (motivated: single **Λ** in potential well)

$$F_{AH}^{\rm hyp} = (H/A) \cdot (-10.68A + 21.27A^{2/3}).$$

-- liquid-drop description of hyper-matter

A.S.Botvina and J.Pochodzalla, Phys. Rev.C76 (2007) 024909

Connection between coalescence and thermal models (Eur. Phys. J A17, 559 (2003)):

Coalescence mechanism:

$$\frac{d^3\langle N_A\rangle}{d\bar{p}_n^3} \simeq \left(\frac{4\pi}{3}p_0^3\right)^{A-1}\left(\frac{d^3\langle N_1\rangle}{d^3\bar{p}_n}\right)^{A}$$

Assume initial Maxwell-Boltzmann distribution, then

$$\langle N_A\rangle \simeq \left(\frac{4\pi}{3}p_0^3\right)^{A-1}\frac{\langle N_1\rangle^{A}}{(2\pi m_n T)^{3/2(A-1)}A^{3/2}}.$$

On the other hand, from thermal models one can obtain:

$$\langle N_A\rangle = \langle N_1\rangle^{A}\left(\frac{\lambda_T^3}{V}\right)^{A-1}A^{3/2}\exp\left(-\frac{B_A}{T_A}\right)$$

We get connection between coalescence parameter and fragment binding energy

$$\frac{4\pi p_0^3 V}{3h^3} \simeq \left(A^3\cdot\exp\left(-\frac{B_A}{T_A}\right)\right)^{1/(A-1)}$$

Conclusions

Collisions of relativistic ions and hadrons with nuclei are promising reactions for novel research of hypernuclei, anti-nuclei, and exotic nuclei. These processes are theoretically confirmed with various models.

Mechanisms of formation of hypernuclei in peripheral reactions: Strange baryons (Λ, Σ, Ξ, …) produced in particle collisions can be transported to the spectator residues and captured in nuclear matter. Another mechanism is the coalescence of baryons leading to light clusters, including hyper- and anti-matter, will be effective at all rapidities. At LHC energies this mechanism can lead to predominant production of large exotic species outside midrapidity.

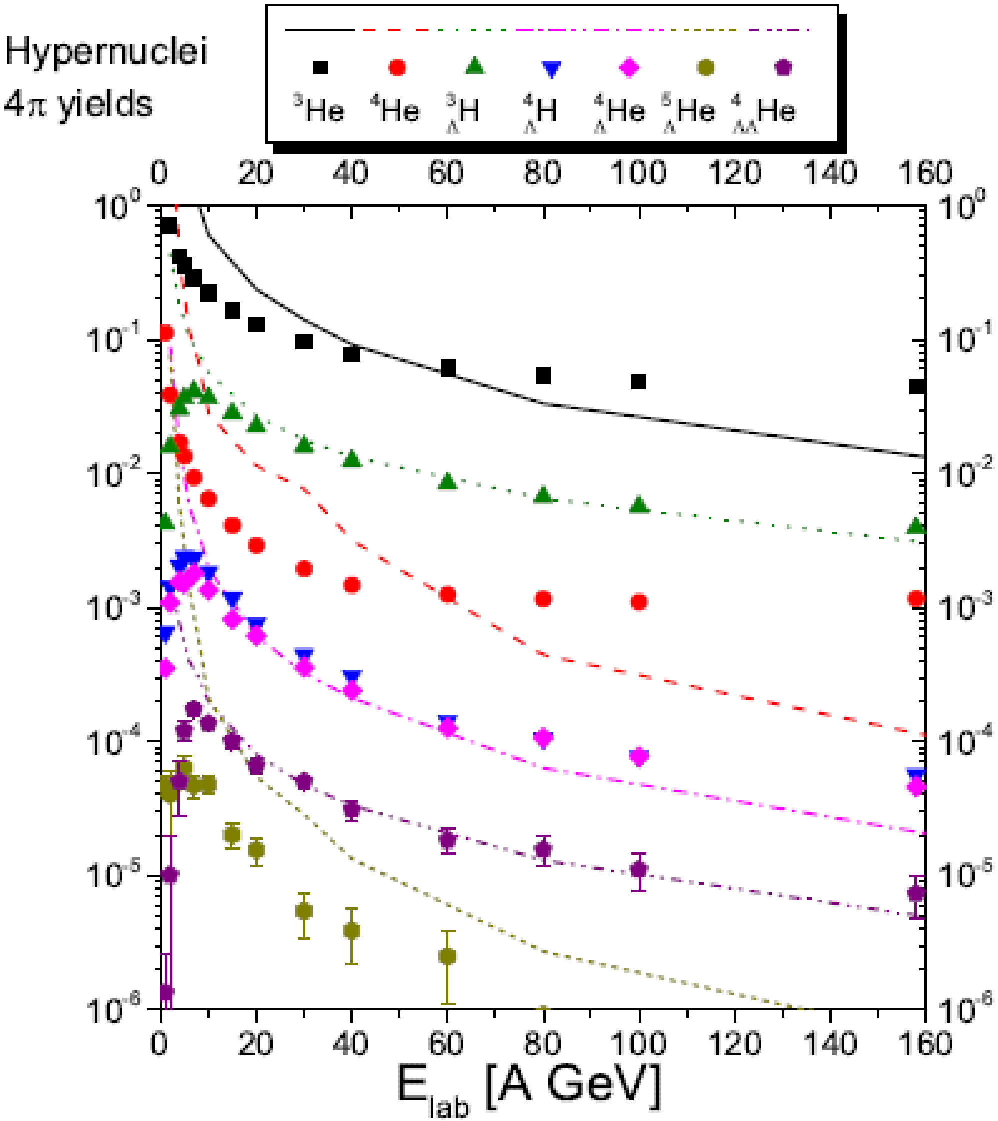
Advantages over other reactions: in the spectator matter there is no limit on sizes and isotope content of produced exotic nuclei; probability of their formation may be high; a large strangeness can be deposited in nuclei.
Correlations (unbound states) and lifetimes can be naturally studied.
EOS of hypermatter at subnuclear density and hyperon interactions in exotic nuclear matter can be investigated.

Production of light nuclei in central collisions : Au+Au

DCM and UrQMD calculations - J.Steinheimer et al., Phys. Lett. B**714**, 85 (2012)

DCM + coalescence
and
hybrid approach :
UrQMD + thermal
hydrodynamics

Symbols - DCM →
Lines - UrQMD



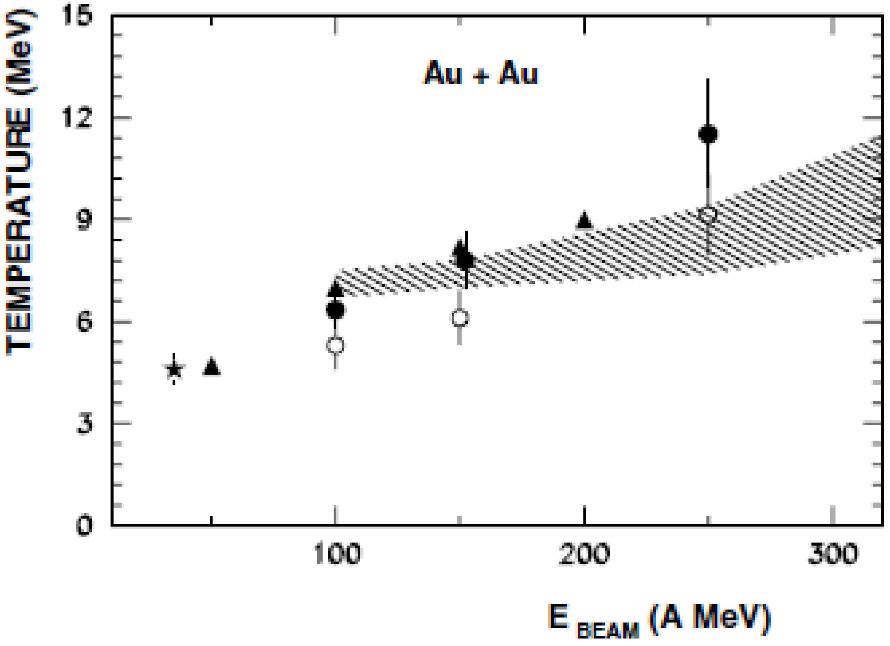
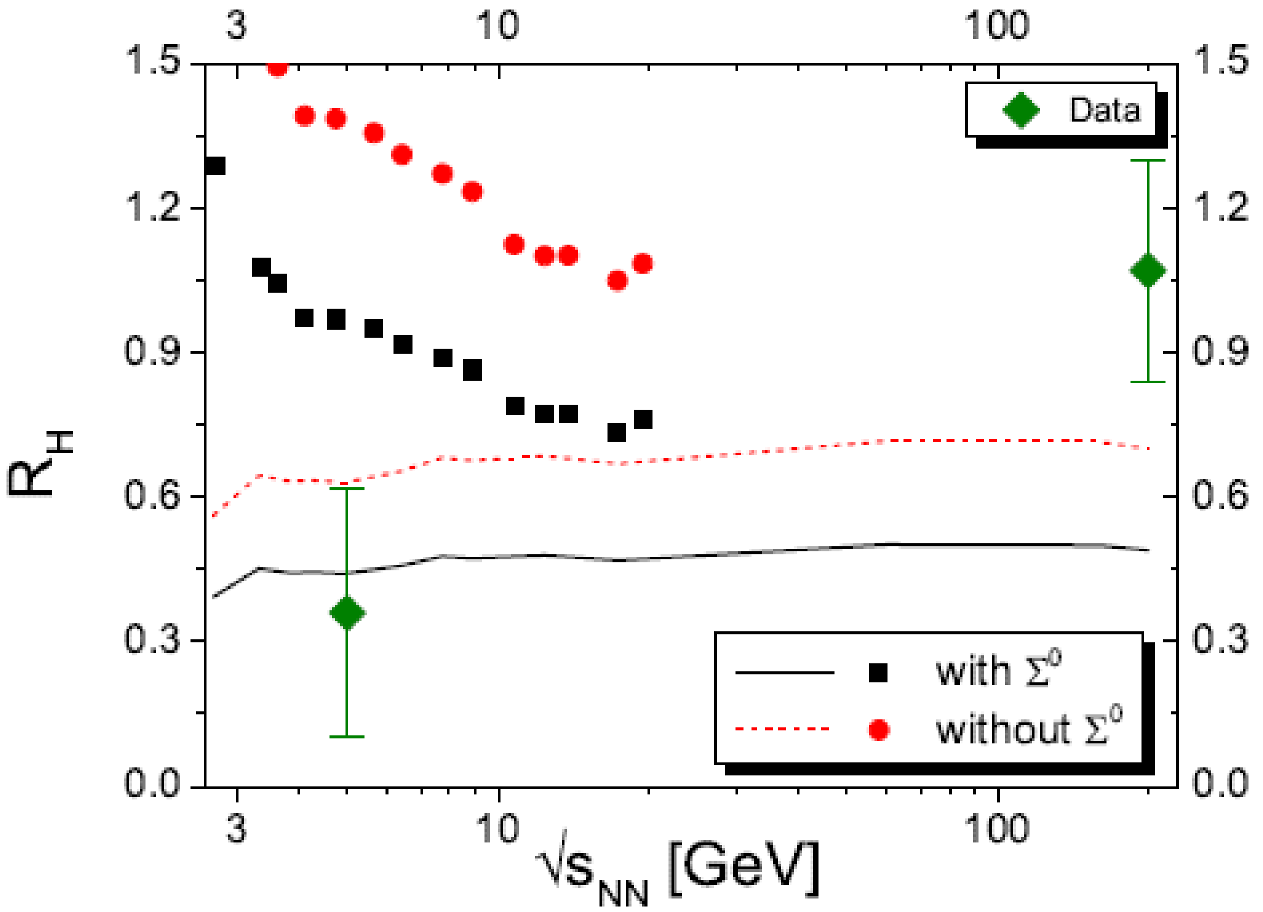


Fig. 5. Temperatures as a function of the beam energy. Black dots: isotope temperatures obtained from the yield ratios d/t and ^{3}He/^{4}He (integrated over the particles kinetic energies) [14,15]. Open dots: the same but in the velocity range limited by $v/c \approx 0.3$. Black triangles: the same, taken from [45]. Black asterisk: temperature from ref. [46]. Hatched area: limits of the microcanonical temperature calculated with SMMFC using the input parameters of table 1.

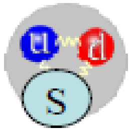
Figure 7: The Strangeness Population Factor $R_H = ({}^3_\Lambda H/{}^3He) \cdot (p/\Lambda)$ as a function of $\sqrt{s_{NN}}$ for most central collisions of Pb+Pb/Au+Au. We compare results from the thermal production in the UrQMD hybrid model (lines) with coalescence results with the DCM model (symbols). The red line and symbols denote values of R_H where the Λ yield has been corrected for the Σ^0 contribution.



$$R_H = {}^3_\Lambda H/{}^3He \cdot p/\Lambda$$

Hyperons: Baryons with Strangeness

Lambda



$\Lambda^0=(uds)$

m(Λ^0) = 1115.683 +/- 0.006 MeV
S = - 1

Quark	Symbol	charge (e)	Strangeness (S)
Up	(u)	2/3	0
Down	(d)	-1/3	0
Strange	(s)	-1/3	-1
Charm	(c)	2/3	0
Bottom	(b)	-1/3	0
Top	(t)	2/3	0

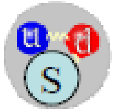
lifetimes of $\sim 1\times10^{-10}$ s

with the exception of Σ^0

whose lifetime is

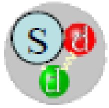
shorter than 1×10^{-19} s

Sigma



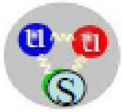
$\Sigma^0=(uds)$

m(Σ^0) = 1192.642 +/- 0.024 MeV
S = - 1



$\Sigma^-=(dds)$

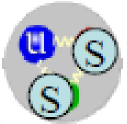
m(Σ^-) = 1197.449 +/- 0.030 MeV
S = - 1



$\Sigma^+(uus)$

m(Σ^+) =1189.37 +/- 0.07 MeV
S = - 1

Cascade or Xi



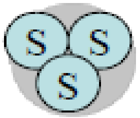
$\Xi^0=(uss)$

m(Ξ^0) = 1314.86 +/- 0.2 MeV
S = - 2

$\Xi^-=(dss)$

m(Ξ^-) = 1321.71 +/- 0.07 MeV
S = - 2

Omega



$\Omega^-=(sss)$

m(Ω^-) = 1672.45 +/- 0.29 MeV
S = - 3

lifetime of $\sim 8.2\times10^{-11}$ s

Why hypernuclei ?

QCD theory development

Micro-laboratory with protons, neutrons, and hyperons;

YN & YY interaction can be investigated (strangeness sector of hadronic EoS); ...

Astrophysics

Hyperons are important for cosmology, physics of neutron stars , "strange stars", black holes, ...

Nuclear physics

Phenomenology: extention of nuclear charts into strangeness, exotic nuclei, limits of nuclear stability

Structure theory -- new degree of freedom for investigating interaction of baryons in nuclei (hyperons - without Pauli blocking)

Reaction theory – new probe for fragmentation of nuclei, phase transitions and EoS in hypermatter and finite hypernuclei