Formation of hypernuclei in relativistic ion collisions

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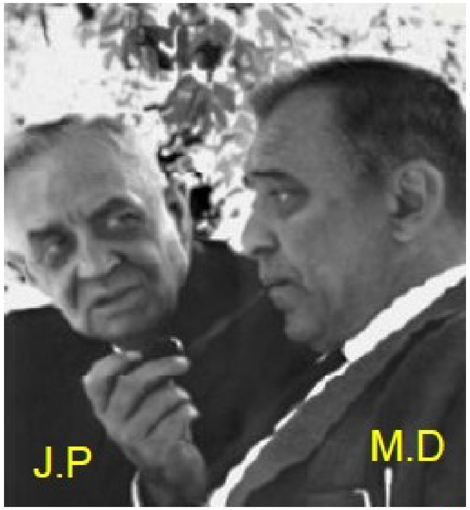
(Collaboration with M.Bleicher, N.Buyukcizmeci, E.Bratkovskaya,
K.Gudima, J.Pochodzalla, J.Steinheimer)

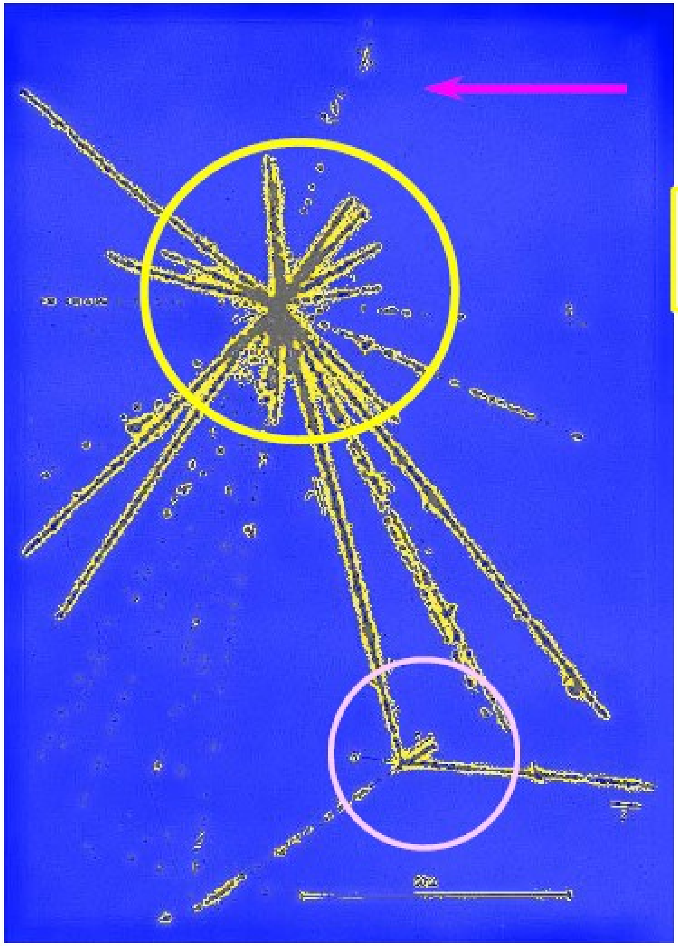
Workshop on hypernuclei,
CEA-Saclay DSM, Saclay, France
January 19-21, 2016

Discovery of a Strange nucleus: Hypernucleus

M. Danysz and J. Pniewski, Philos. Mag. 44 (1953) 348

First-hypernucleus was observed in a stack of photographic emulsions exposed to cosmic rays at about 26 km above the ground.





Incoming high energy proton from cosmic ray

colliding with a nucleus of the emulsion, breaks it in several fragments forming a star. **Multifragmentation !**

All nuclear fragments stop in the emulsion after a short path

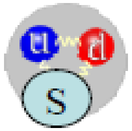
From the first star, 21 Tracks => $9\alpha + 11H + 1\ {}_{\Lambda}X$

The fragment ${}_{\Lambda}X$ disintegrates later , makes the bottom star. Time taken ~ 10^{-12} sec (typical for weak decay)

This particular nuclear fragment, and the others obtained afterwards in similar conditions, were called **hyperfragments or hypernuclei.**

Hyperons: Baryons with Strangeness

Lambda



$\Lambda^0=(uds)$

$m(\Lambda^0)$ = 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

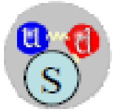
lifetimes of $\sim 1\times10^{-10}$ s

with the exception of Σ^0

whose lifetime is

shorter than 1×10^{-19} s

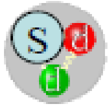
Sigma



$\Sigma^0=(uds)$

$m(\Sigma^0)$ = 1192.642 +/- 0.024 MeV

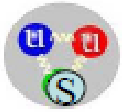
S = - 1



$\Sigma^-=(dds)$

$m(\Sigma^-)$ = 1197.449 +/- 0.030 MeV

S = - 1

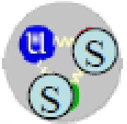


$\Sigma^+(uus)$

$m(\Sigma^+)$ =1189.37 +/- 0.07 MeV

S = - 1

Cascade or Xi



$\Xi^0=(uss)$

$m(\Xi^0)$ = 1314.86 +/- 0.2 MeV

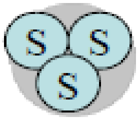
S = - 2

$\Xi^-=(dss)$

$m(\Xi^-)$ = 1321.71 +/- 0.07 MeV

S = - 2

Omega



$\Omega^-=(sss)$

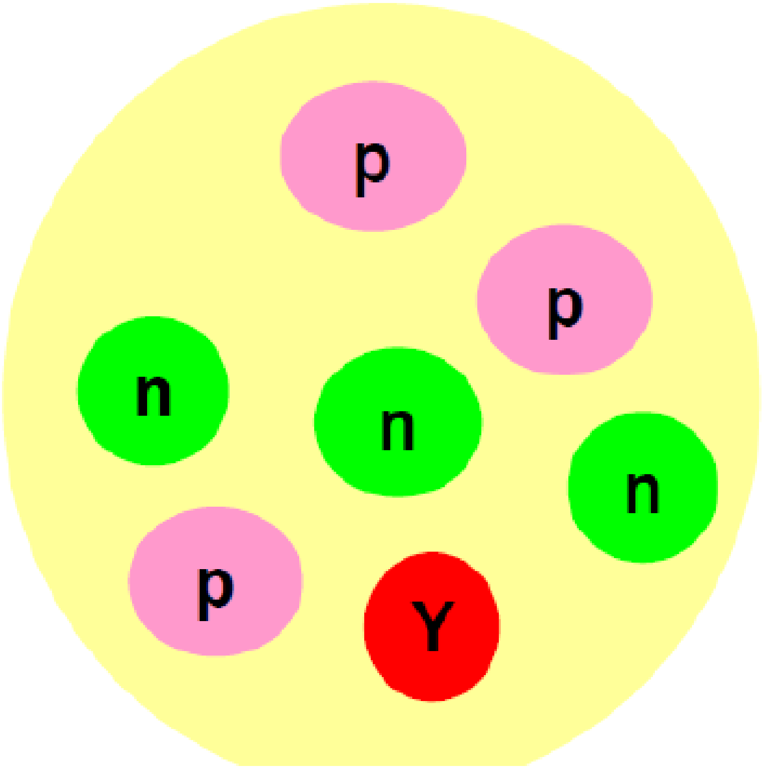
$m(\Omega^-)$ = 1672.45 +/- 0.29 MeV

S = - 3

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

Hypernucleus: Hyperons Bound in Nuclei

Hypernucleus: consists of nucleons (n, p) + hyperon (Y)



Notation:

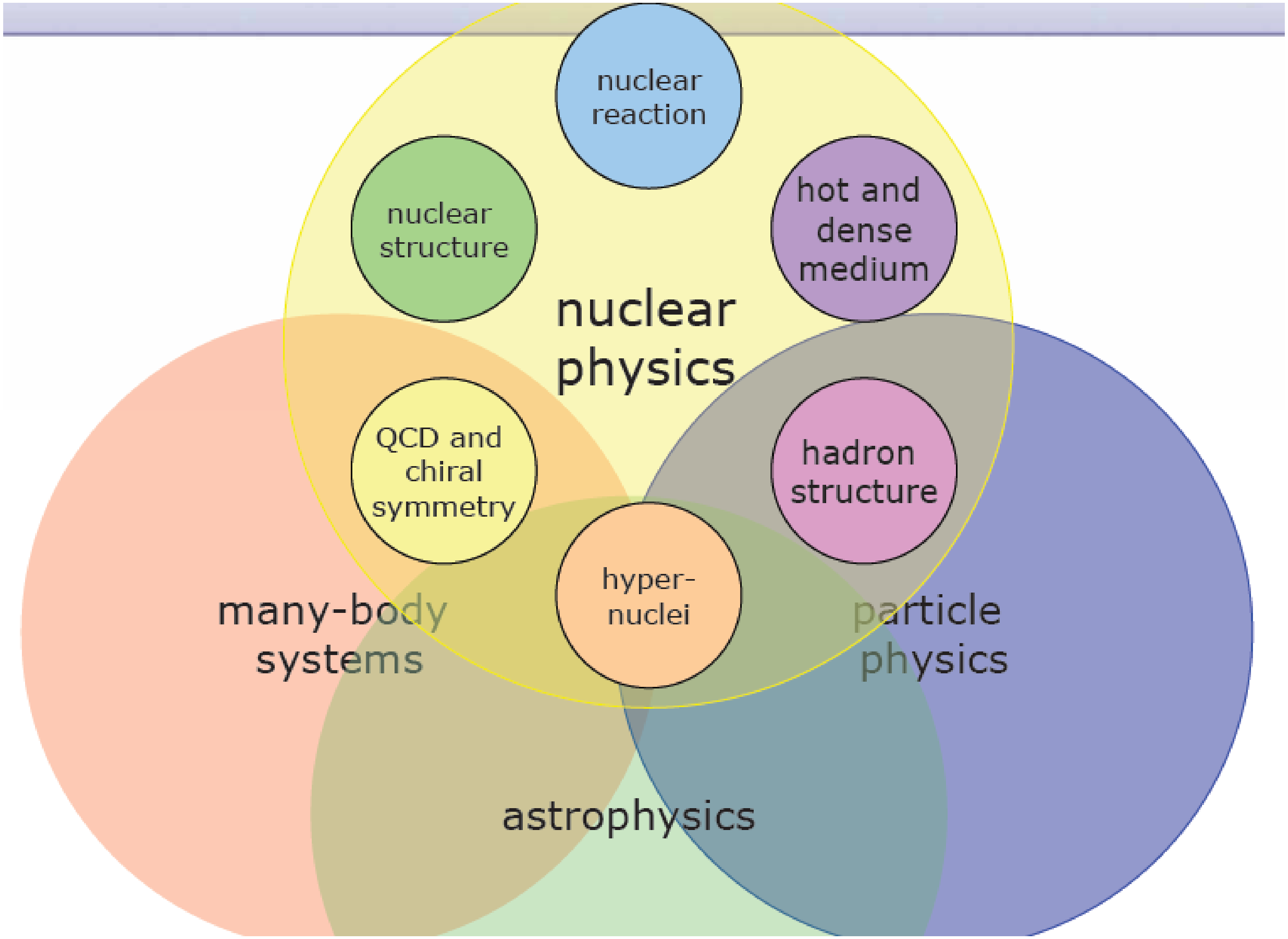
$${}^{A}_{Y}Z$$

Y = Hyperon

$Z = Z_p + (N_Y \cdot q_Y)$

$A = N_n + N_p + N_Y$

Hypernuclei within the research fields



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, ...

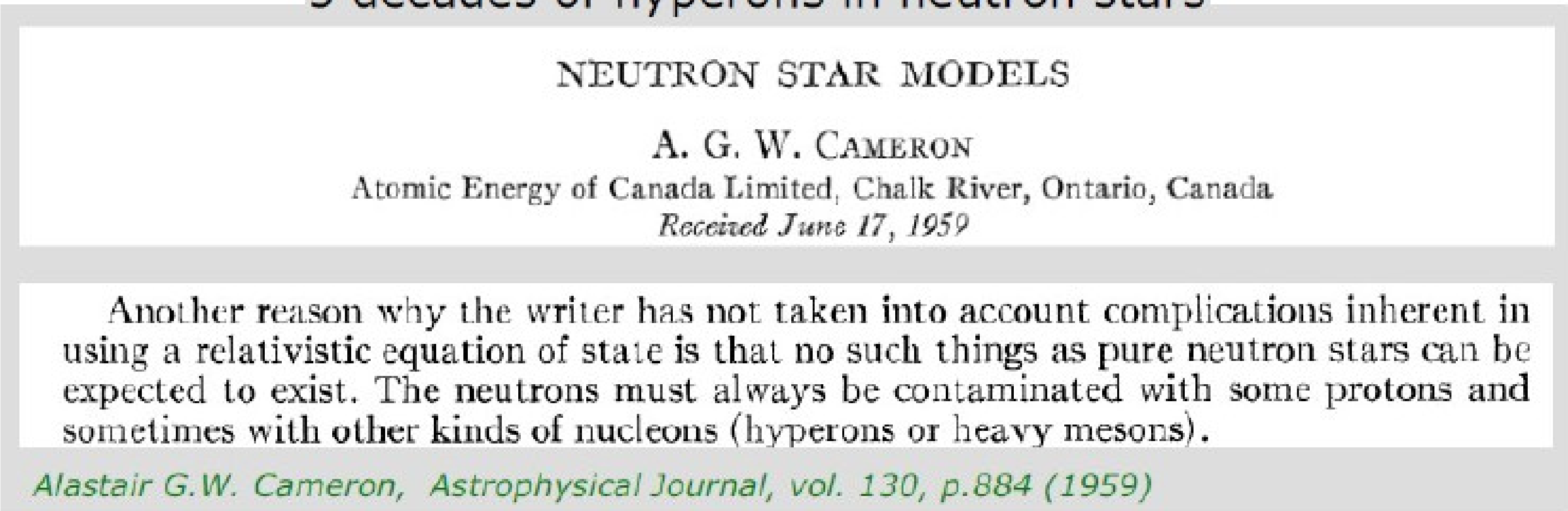
Nuclear physics

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

5 decades of hyperons in neutron stars

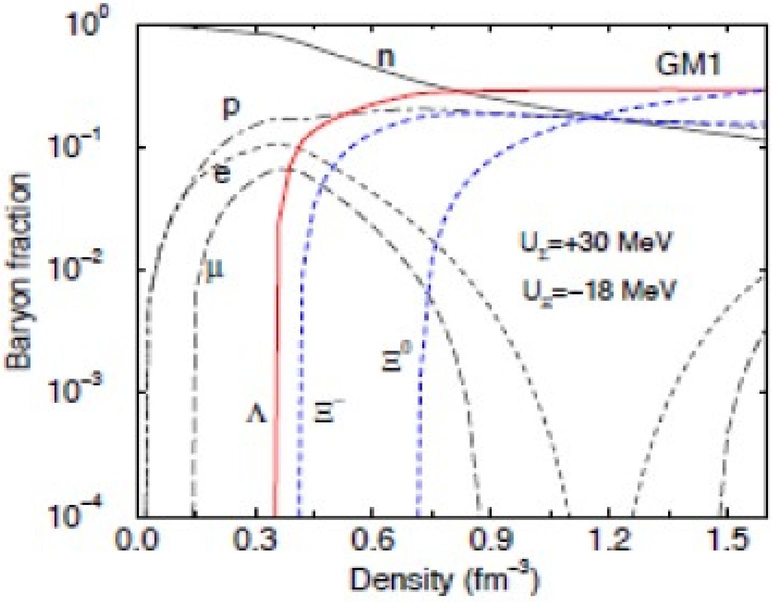


NEUTRON STAR MODELS

A. G. W. CAMERON
Atomic Energy of Canada Limited, Chalk River, Ontario, Canada
Received June 17, 1959

Another reason why the writer has not taken into account complications inherent in using a relativistic equation of state is that no such things as pure neutron stars can be expected to exist. The neutrons must always be contaminated with some protons and sometimes with other kinds of nucleons (hyperons or heavy mesons).

Alastair G.W. Cameron, Astrophysical Journal, vol. 130, p.884 (1959)



J. Schaffner-Bielich, Nucl. Phys. A804 (2008) 309

n-rich hypernucleus is a doorway to n-star

^{5}H

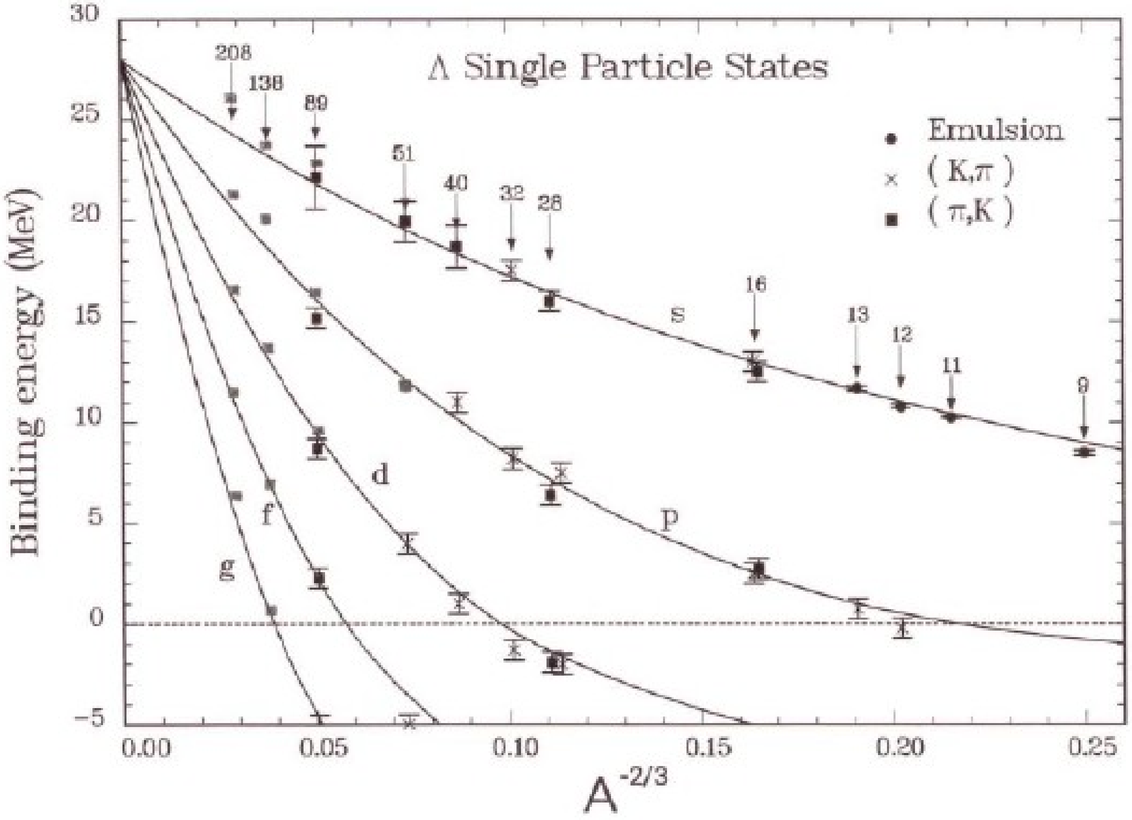
unbound exotic nucleus

glue-like role of Λ-hyperon

$^{6}_{\Lambda}H$

bound exotic hypernucleus

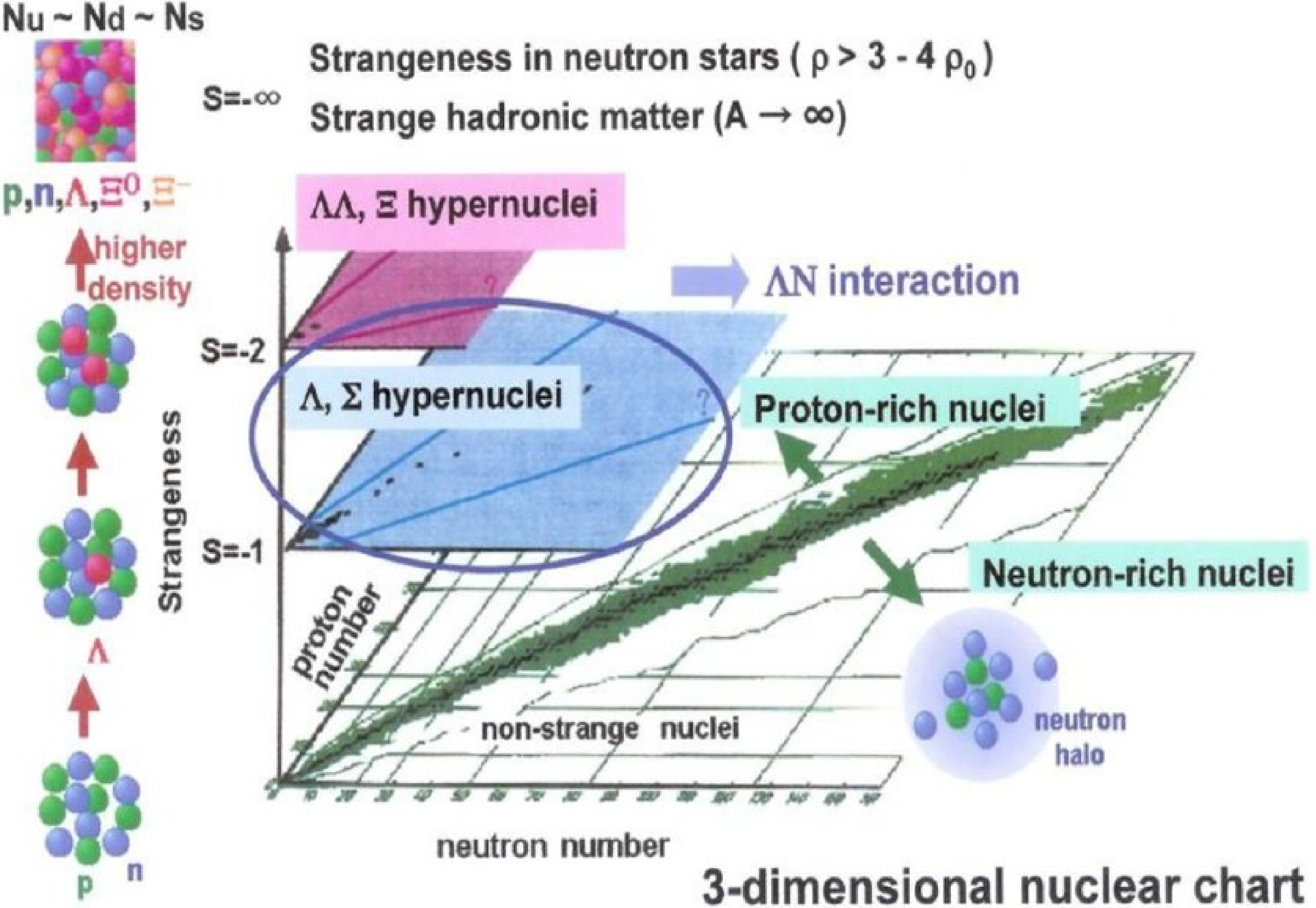
insight into halo nuclear structure through hypernuclei



Hyperon can be put deep inside - no Pauli blocking

In heavy nuclei effects of the additional hyperon binding will be larger:

Production of nuclei beyond the drip lines



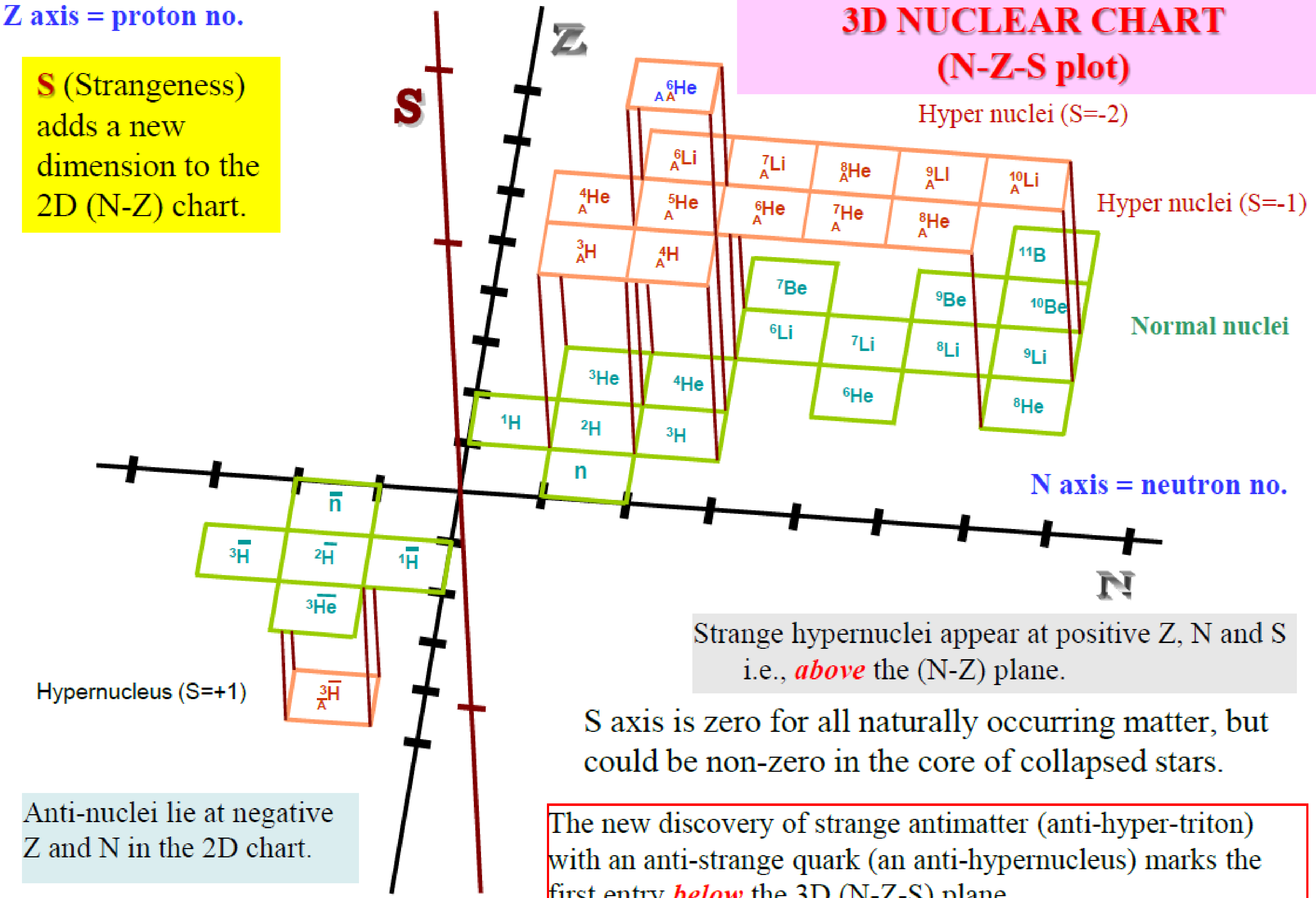
Strangeness in neutron stars ($\rho > 3 - 4\,\rho_0$)

Strange hadronic matter ($A \rightarrow \infty$)

3-dimensional nuclear chart

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

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



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.

Nuclear reactions: production mechanisms for hypernuclei

Traditional way for production of hypernuclei:

Conversion of Nucleons into Hyperons

by using hadron and electron beams

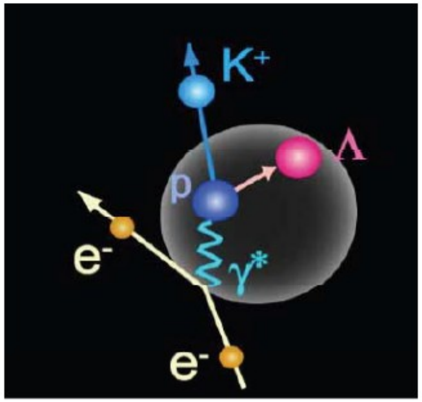
(CERN, BNL, KEK, CEBAF, DAΦNE, JPARC, MAMI, ...)

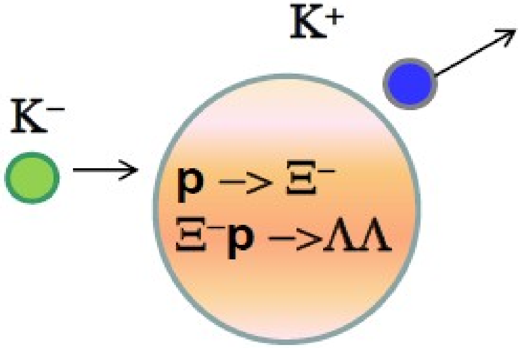
Advantages: rather precise determination of masses
(e.g., via the missing mass spectroscopy) :
good for nuclear structure studies !

Disadvantages: very limited range of nuclei in A and Z can beinvestsigated; the phase space of the reaction is narrow (since hypernuclei are produced in ground and slightly excited states), so production probability is low; it is difficult to produce multi-strange nuclei.

What reactions can be used to produce exotic strange nuclei and nuclei with many hyperons ?

$e^- + p \to e^- + \Lambda + K^+$

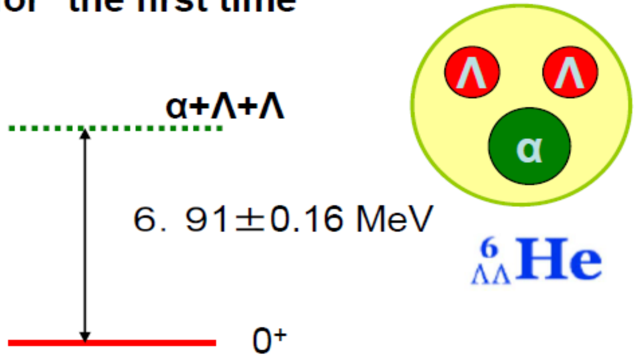




(K^-, K^+) reactions

Ξ^- hyperons at the emulsion

Uniquely identified without ambiguity for the first time



Possible mechanism of this reaction:

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

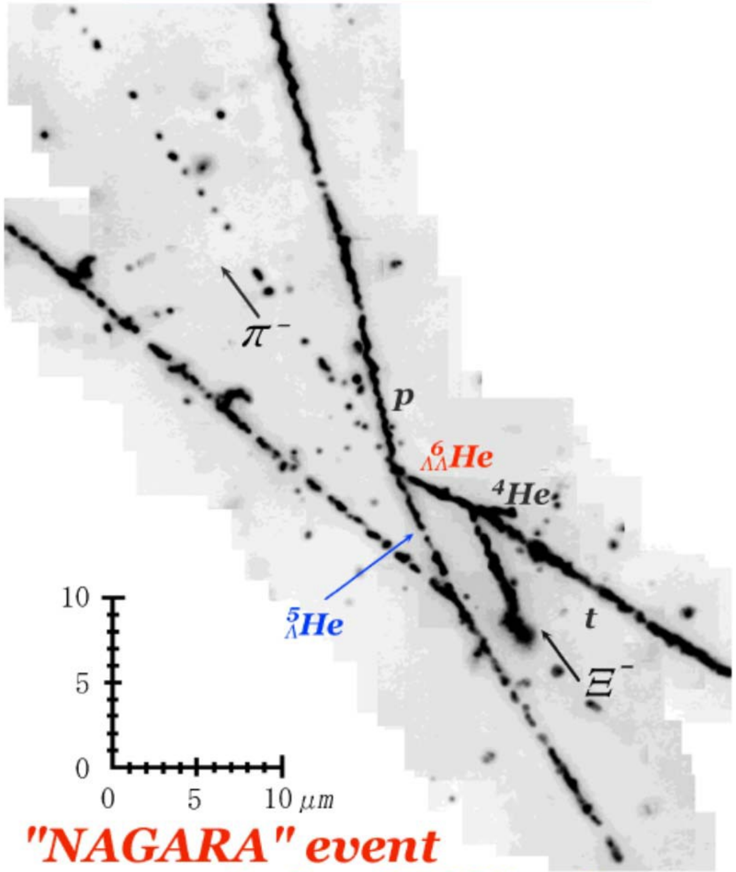
Break-up of excited hyper-system (~28MeV)
[Fermi-Break-up calculated probability~0.01]

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

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

Unique interpretation!!

$$\Xi^- + {}^{12}\mathrm{C} \longrightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t$$
$${}^{6}_{\Lambda\Lambda}\mathrm{He} \longrightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^-$$

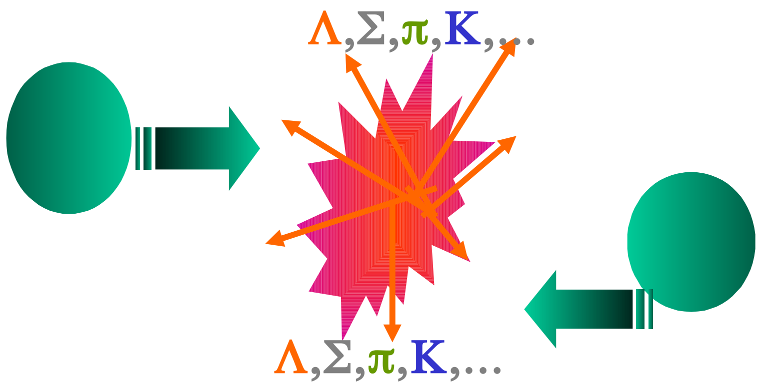


"NAGARA" event

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

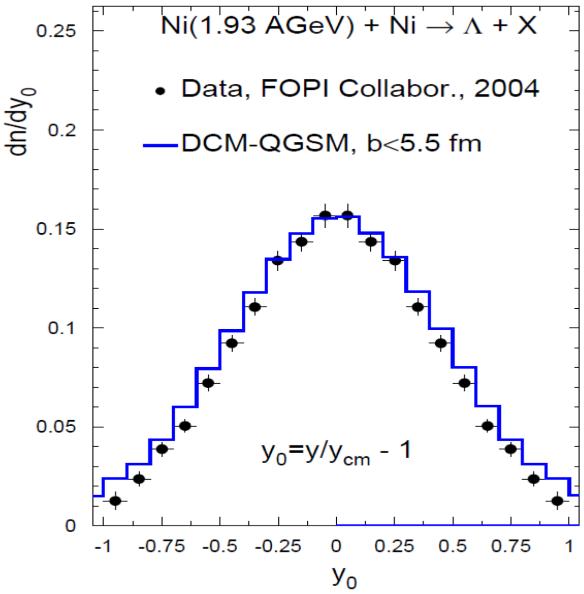
H. Takahashi *et al.*, PRL 87, 212502-1 (2001)

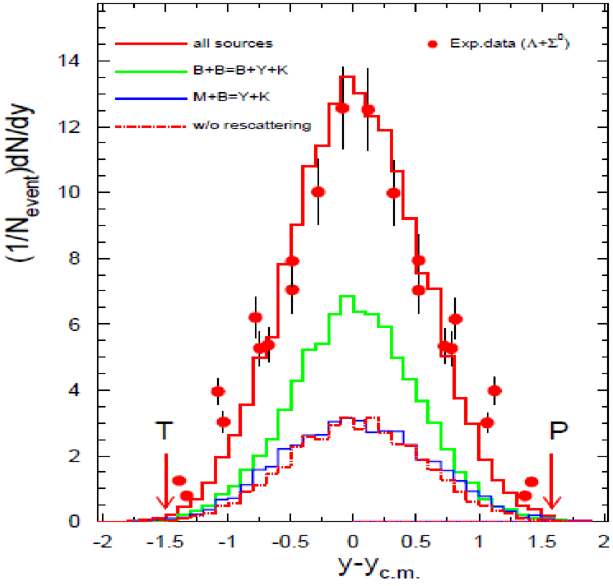
Relativistic collisions of hadrons and ions



Production of hypermatter in relativistic HI and hadron collisions

- Production of strange particles and hyperons by "participants",
- Rescattering and absorption of hyperons by excited "spectators",
- Coalescence of produced baryons.





S.Albergo et al.,
E896:
PRL88(2002)062301

Au(11AGeV/c)+Au

Calculation: DCM
PRC**84**(2011)064904

Wide rapidity distribution of produced Λ!

Theoretical descriptions of strangeness production within transport codes

old models : *INC, QMD, BUU*	e.g., Z.Rudy, W.Casing et al., *Z. Phys.A351(1995)217*
GiBUU model: *(+SMM)*	Th.Gaitanos, H.Lenske, U.Mosel , *Phys.Lett. B663(2008)197,* *Phys.Lett. B675(2009)297*
PHSD model:	E.Bratkovskaya, W.Cassing, … *Phys. Rev. C78(2008)034919*
DCM (INC) : *(+QGSM+SMM)*	JINR version: K.K.Gudima et al., *Nucl. Phys. A400(1983)173, ...* *Phys. Rev. C84 (2011) 064904*
UrQMD approach:	S.A. Bass et al., *Prog. Part. Nucl. Phys. 41 (1998)255.* M.Bleicher et al. *J. Phys.G25(1999)1859, ...* , J.Steinheimer ...

Main channels for production of strangeness in individual hadron- nucleon collisions: $BB \rightarrow BYK$, $B\pi \rightarrow YK$, ... (like $p+n \rightarrow n+\Lambda+K^+$, and secondary meson interactions, like $\pi+p \rightarrow \Lambda+K^+$). Rescattering of hyperons is important for their capture by spectators. Expected decay of produced hyperons and hypernuclei: 1) mesonic $\Lambda \rightarrow \pi+N$; 2) in nuclear medium nonmesonic $\Lambda+N \rightarrow N+N$.

Physical picture of peripheral relativistic HI collisions:

nucleons of projectile interact with nucleons of target, however, in peripheral collisions many nucleons (spectators) are not involved. All products of the interactions can also interact with nucleons and between themselves. The time-space evolution of all nucleons and produced particles can be calculated with transport models.

All strange particles: Kaons, Lambda, Sigma, Xi, Omega
are included in the transport models

ABSORPTION of LAMBDA :

The residual spectator nuclei produced during the non-equilibrium stage may capture the produced Lambda hyperons if these hyperons are (a) inside the nuclei and (b) their energy is lower than the hyperon potential in nuclear matter (~30 MeV). In the model a depletion of the potential with reduction of number of nucleons in nucleus is taken into account by calculating the local density of spectator nucleons.

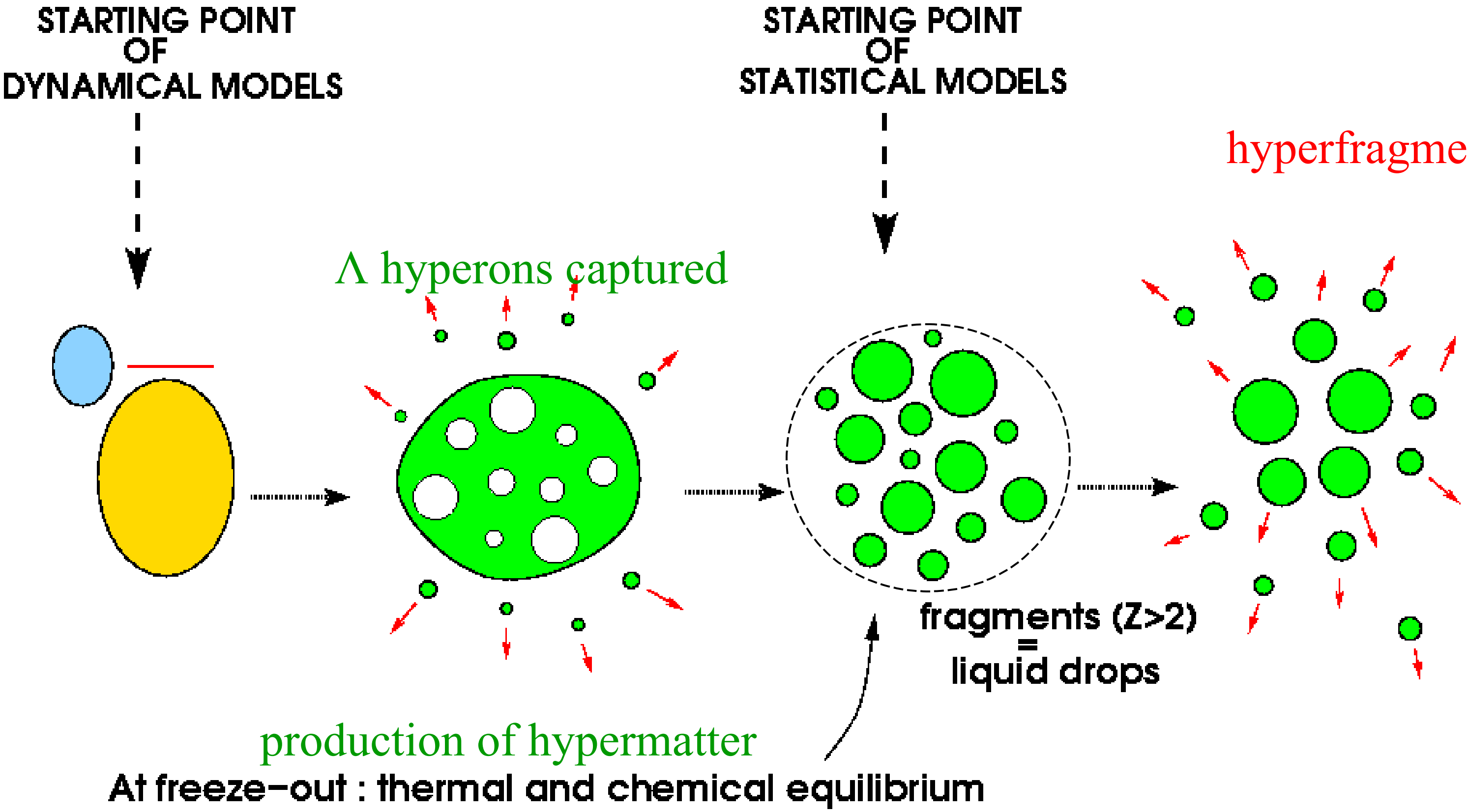
A.S.Botvina and J.Pochodzalla, Phys. Rev.C76 (2007) 024909

Generalization of the statistical de-excitation model for nuclei with Lambda hyperons

In these reactions we expect analogy with

multifragmentation in intermediate and high energy nuclear reactions

+ nuclear matter with strangeness



STARTING POINT
OF
DYNAMICAL MODELS

STARTING POINT
OF
STATISTICAL MODELS

hyperfragments

Λ hyperons captured

fragments (Z>2)
=
liquid drops

production of hypermatter

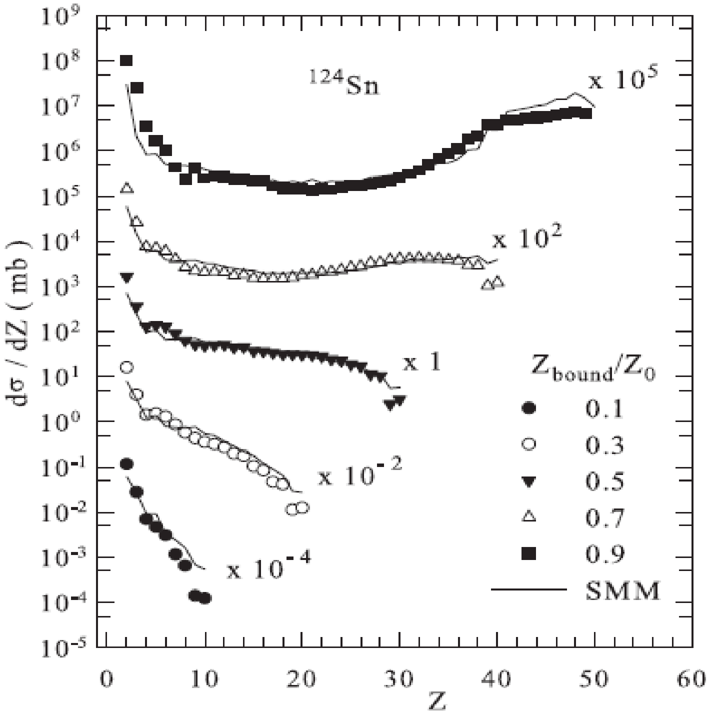
At freeze-out : thermal and chemical equilibrium

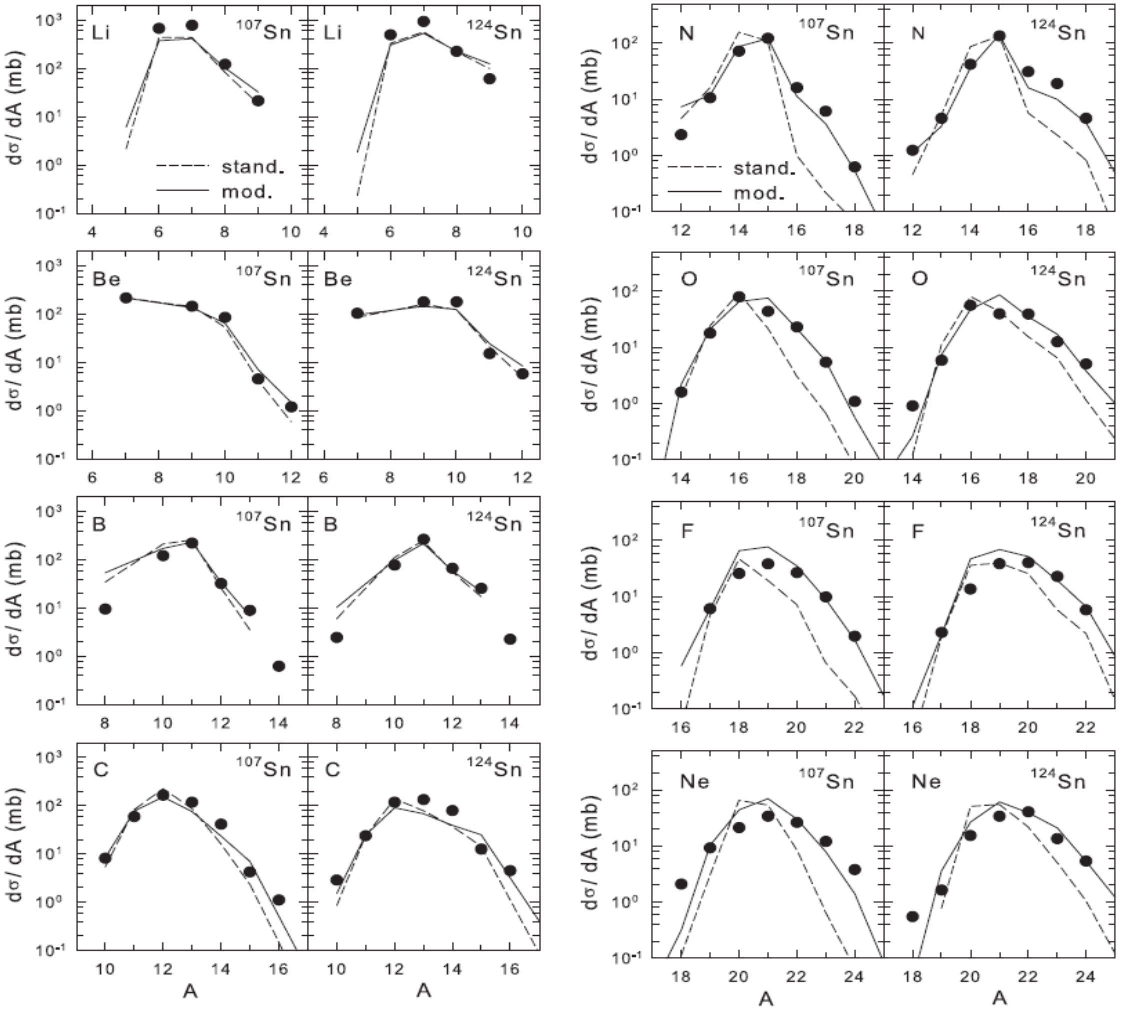
R.Ogul et al. PRC **83,** 024608 (2011)   **ALADIN@GSI**

Isospin-dependent multifragmentation of relativistic projectiles

124,107-**Sn**, 124-**La** (600 A MeV) + **Sn** → projectile (multi-)fragmentation

Very good description is obtained within Statistical Multifragmentation Model, including fragment charge yields, isotope yileds, various fragment correlations.





Statistical (chemical) equilibrium is established at break-up of hot projectile residues ! In the case of strangeness admixture we expect it too !

With heavy ion collisions E_{beam} >1.6AGeV
(since NN-->ΛKN energy threshold ~ 1.6 GeV)
we can obtain

Relativistic Hypernuclei – in peripheral collisions

Effective lifetime: longer by Lorentz factor γ
200 ps → 600 ps with $\gamma=3$ (2AGeV)
200 ps → 4 ns with $\gamma=20$ (20AGeV)

=> Detection of their decay products becomes feasible : target and hyper-fragment decay zones are separated in space, particle vertex methods can be used. At large γ direct separation of hypernuclei is possible.

Additional advantages of HI: Hypernuclei with multiple strangeness and exotic (e.g. neutron-rich) hypernuclei can be produced.

HypHi experimental program at GSI and FAIR

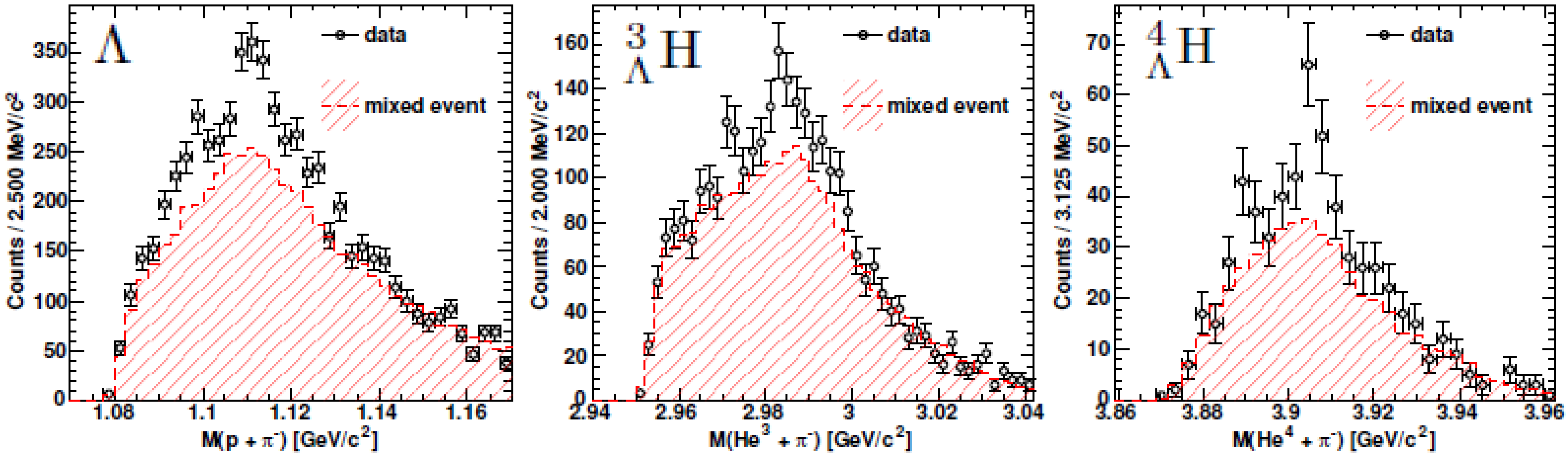
T.Saito, (for HypHI),
NUFRA2011 conference, and
Nucl. Phys. A881 (2012) 218;
Nucl. Phys. A913 (2013) 170.

Production of hypernuclei in peripheral HI collisions: The HypHI project at GSI

T.R. Saito[a,b,c], D. Nakajima[a,d], C. Rappold[a,c,e], S. Bianchin[a], O. Borodina[a,b], V. Bozkurt[a,f], B. Gökjüzüm[a,f], M. Kavatsyuk[g], E. Kim[a,h], Y. Ma[a,b], F. Maas[a,b,c], S. Minami[a], B. Özel-Tashenov[a], P. Achenbach[b], S. Ajimura[i], T. Aumann[a], C. Ayerbe Gayoso[b], H.C. Bhang[f], C. Caesar[a], S. Erturk[f], T. Fukuda[j], E. Guliev[h], Y. Hayashi[k], T. Hiraiwa[k], J. Hoffmann[a], G. Ickert[a], Z.S. Ketenci[f], D. Khaneft[a,b], M. Kim[h], S. Kim[h], K. Koch[a], N. Kurz[a], A. Le Fevre[a,l], Y. Mizoi[j], M. Moritsu[k], T. Nagae[k], L. Nungesser[b], A. Okamura[k], W. Ott[a], J. Pochodzalla[b], A. Sakaguchi[m], M. Sako[k], C.J. Schmidt[a], M. Sekimoto[n], H. Simon[a], H. Sugimura[k], T. Takahashi[n], G.J. Tambave[g], H. Tamura[o], W. Trautmann[a], S. Voltz[a], N. Yokota[k], C.J. Yoon[h], K. Yoshida[m],

C. Rappold et al.,
Phys. Rev. C88 (2013) 041001:
Λnn bound state ?

Projectile fragmentation: ^{6}Li beam at 2 A GeV on ^{12}C target



For the first, they have also observed a large correlation of $^2\mathrm{H} + \pi^-$
i.e., considerable production of Λn bound states

Λ-Hypernucleus formation in proton-nucleus reactions

Z.Rudy, W.Casing et al., *Z. Phys. A351(1995)217*

BUU approach (Λ-potential in matter ~ 30 MeV)

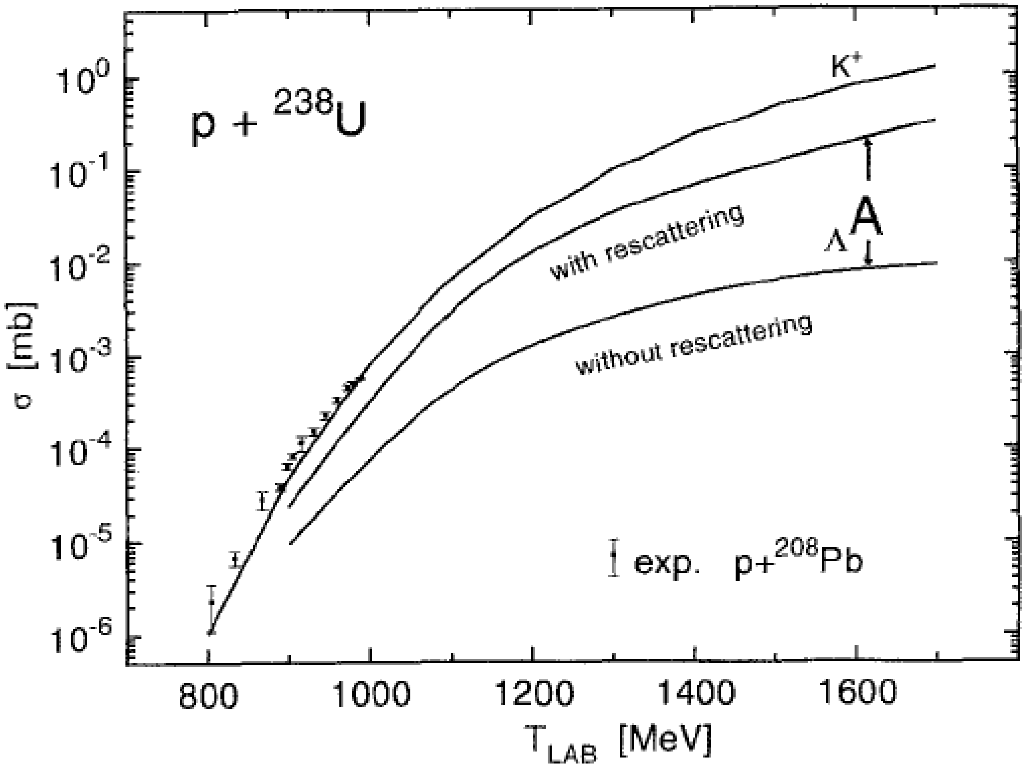


Fig. 5. The energy dependence of the $_\Lambda A$ production cross section for the cases with and without Λ hyperon-N rescattering. For relative orientation we also compare the calculated total K^+ cross section with the inclusive K^+ data from [30] for $p + {}^{208}$Pb

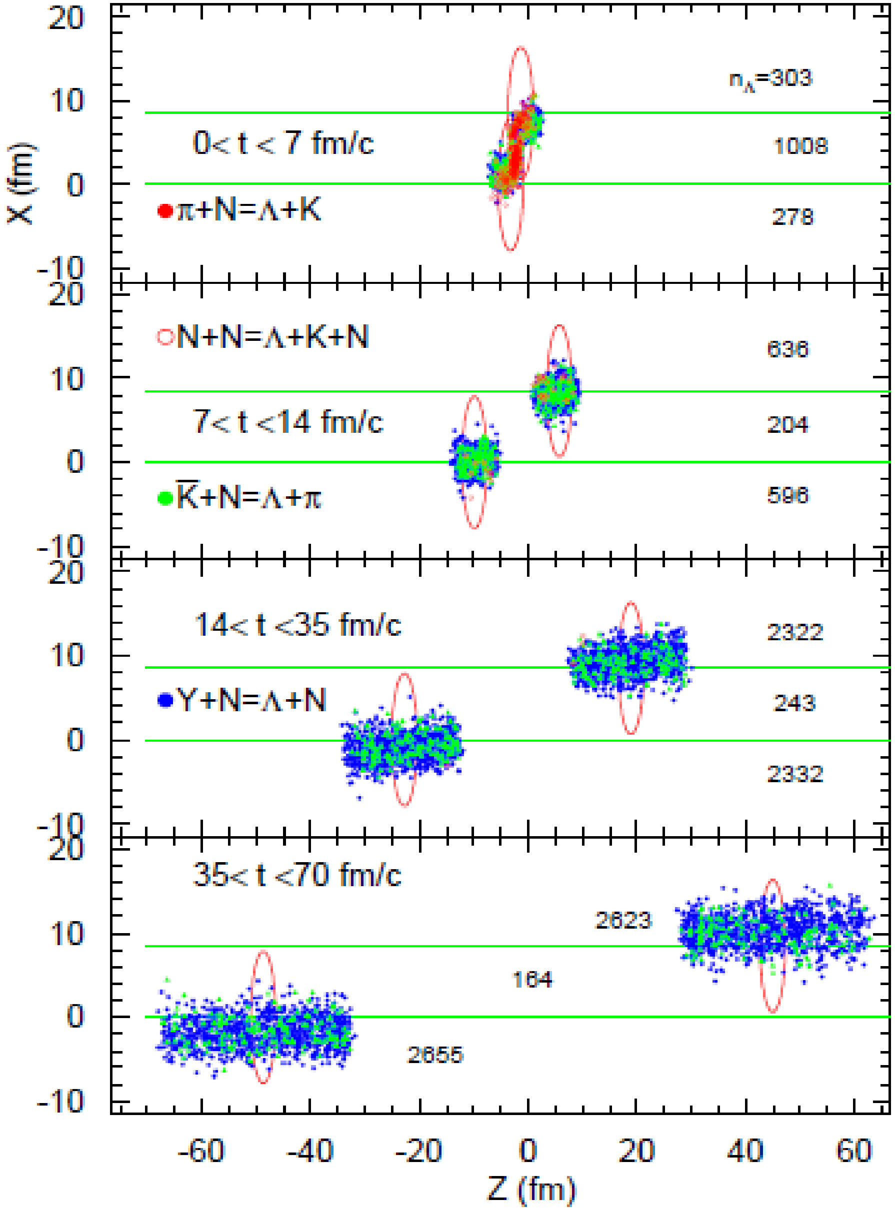
However, lifetime of these hypernuclei is too short ~200 p*s*, experimental identification using products of their decay is very difficult, because of background of other particles.

Peripheral relativistic ion collisions: Au (20 A GeV) + Au

impact parameter= 8.5fm

Absorption of Lambda hyperons by residual nuclei within DCM and UrQMD model description

(times/coordinates of the absorption are given on the panels)

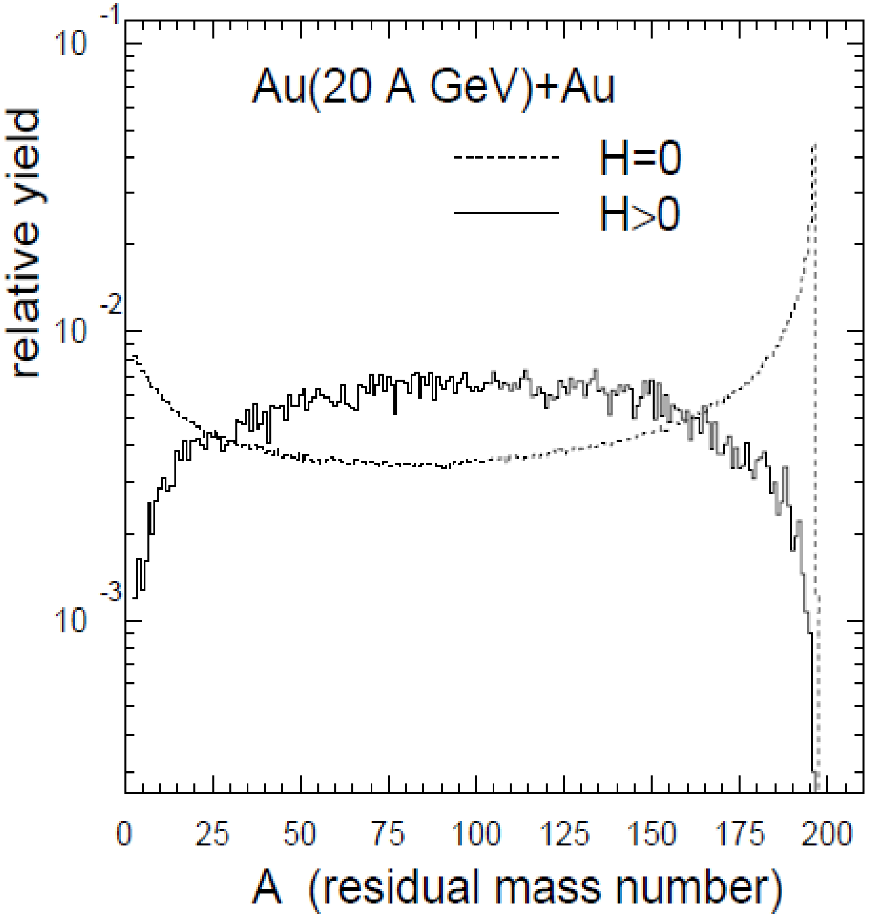


Secondary interactions of the particles dominates in the process.

A.S.Botvina, K.K.Gudima, J.Steinheimer, M.Bleicher, I.N.Mishustin.
PRC 84 (2011) 064904

Masses of projectile residuals produced after DCM

different hyper-residuals (with large cross-section) can be formed (from studies of conventional matter: expected temperatures - up to 5-8 MeV)



6b : H=0

200mb: H>0

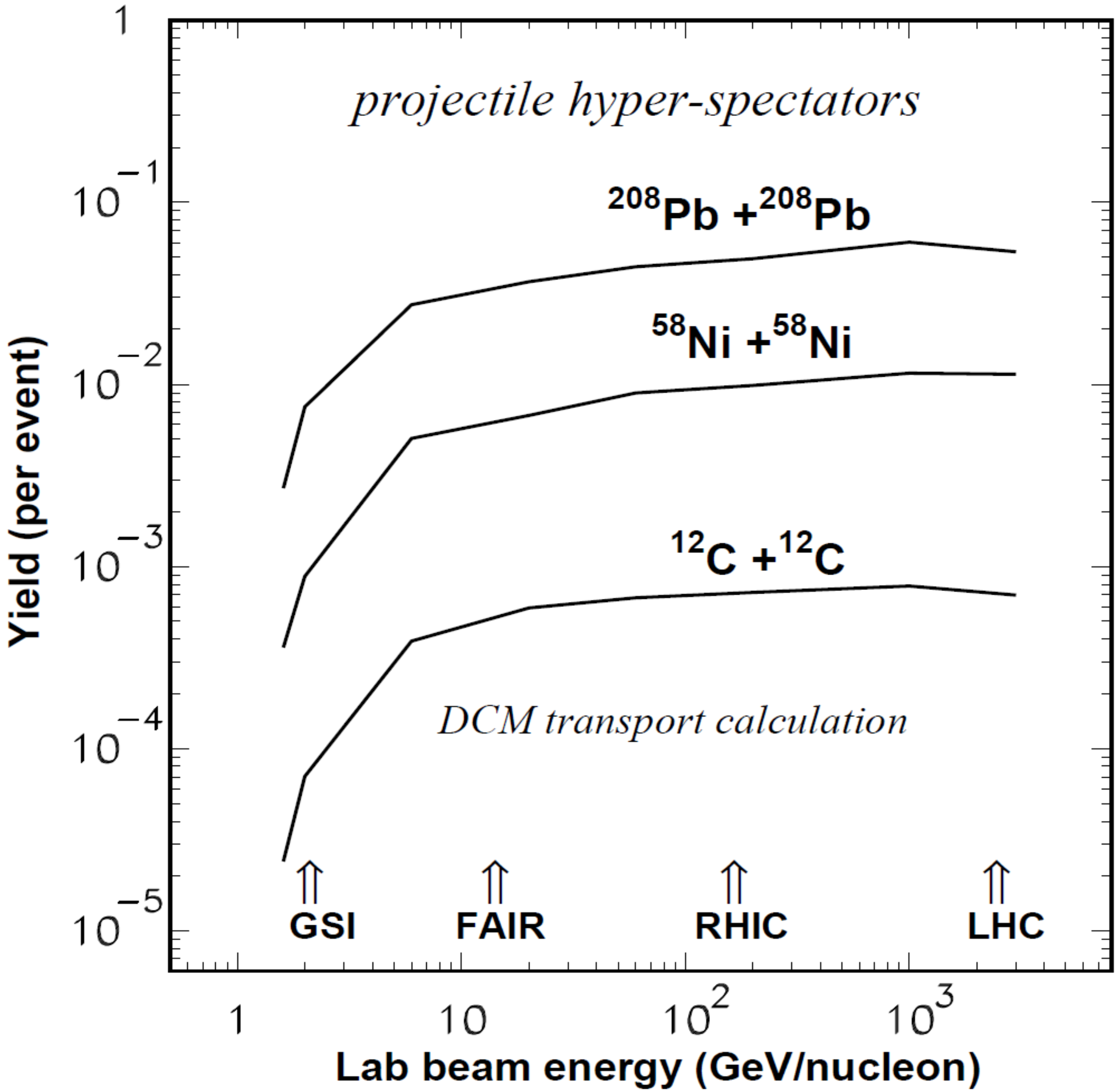
Yield of hypernuclei in peripheral collisions

A.S.Botvina, K.K.Gudima, J.Pochodzalla (PRC88, 054605, 2013)

Threshold behavior with saturation at high energies (for single hypernuclei)

Yield is integrated over all impact parameters.

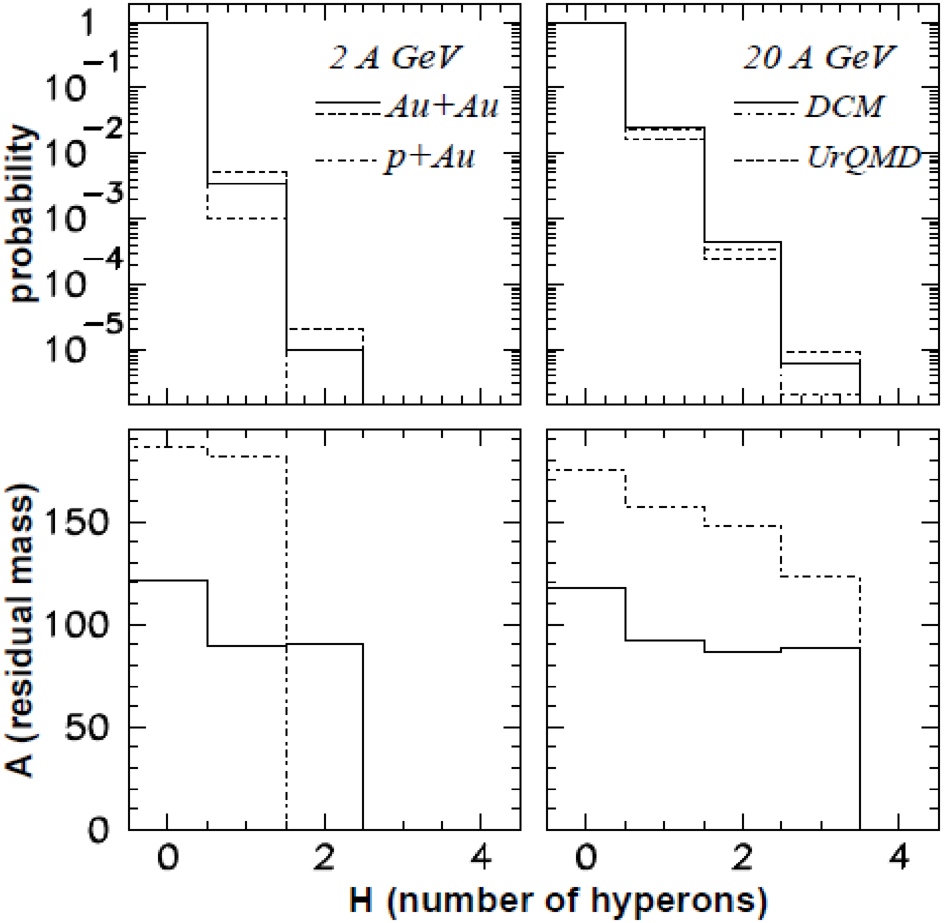
Reactions can be studied at GSI/FAIR and JINR/NICA facilities as well as on operating RHIC and LHC (fixed target experiments).



A.S.Botvina, K.K.Gudima, J.Steinheimer, M.Bleicher, I.N.Mishustin. PRC 84 (2011) 064904

projectile residuals produced after non-equilibrium stage

total yield of residuals with single hyperons ~1% , with double ones ~0.01%, at 2 GeV per nucleon, and considerably more at 20 GeV per nucleon



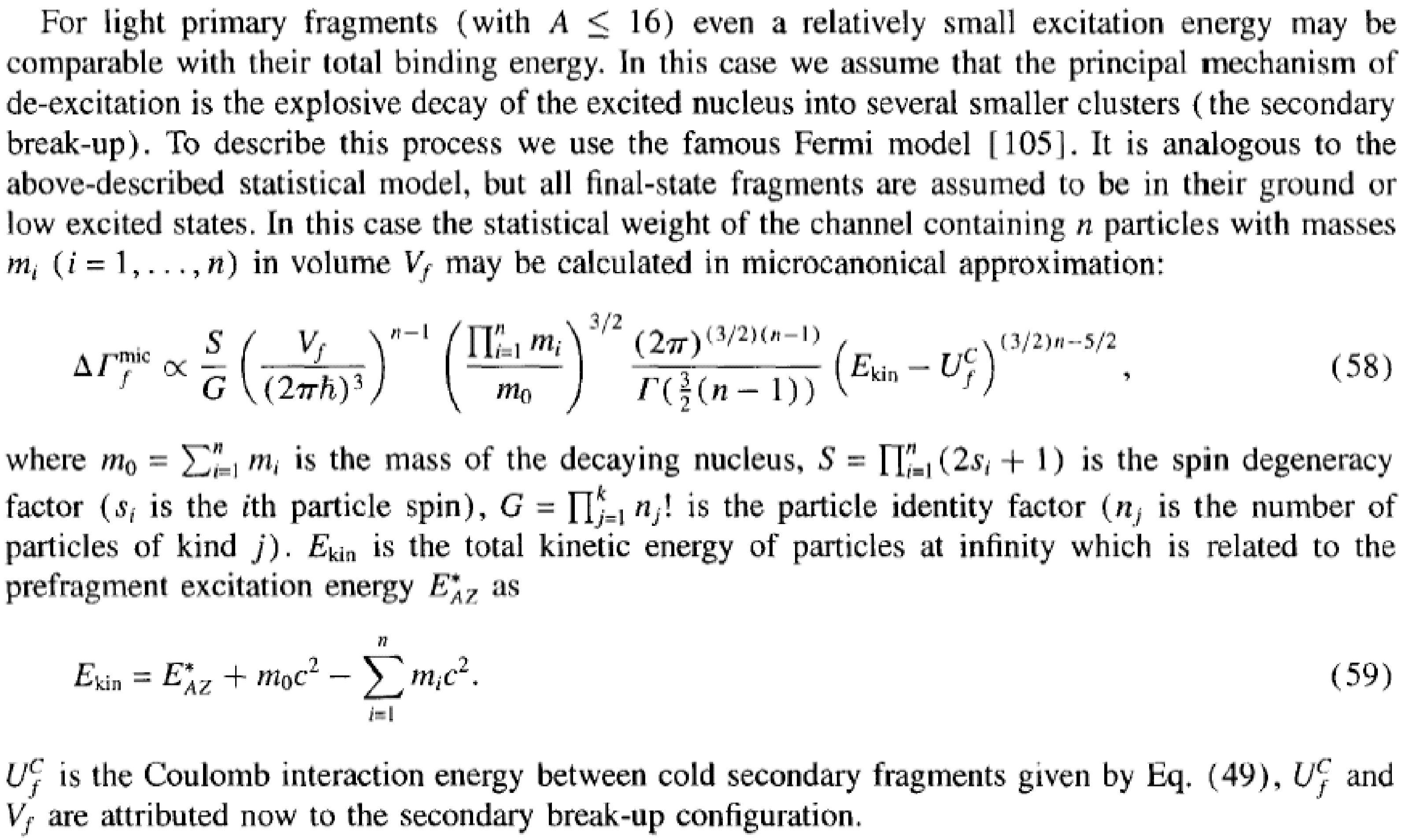
Integrated over all impact parameters

Formation of multi-strange nuclear systems (H>2) is possible!

The disintegration of such sytems can lead to production of exotic hypernuclei.

De-excitation of hot light hypernuclear systems

A.Sanchez-Lorente, A.S.Botvina, J.Pochodzalla, Phys. Lett. B697 (2011)222



For light primary fragments (with $A \leq 16$) even a relatively small excitation energy may be comparable with their total binding energy. In this case we assume that the principal mechanism of de-excitation is the explosive decay of the excited nucleus into several smaller clusters (the secondary break-up). To describe this process we use the famous Fermi model [105]. It is analogous to the above-described statistical model, but all final-state fragments are assumed to be in their ground or low excited states. In this case the statistical weight of the channel containing n particles with masses m_i $(i = 1, \ldots, n)$ in volume V_f may be calculated in microcanonical approximation:

$$\Delta\Gamma_f^{\rm mic} \propto \frac{S}{G}\left(\frac{V_f}{(2\pi\hbar)^3}\right)^{n-1}\left(\frac{\prod_{i=1}^{n} m_i}{m_0}\right)^{3/2}\frac{(2\pi)^{(3/2)(n-1)}}{\Gamma(\frac{3}{2}(n-1))}\left(E_{\rm kin}-U_f^C\right)^{(3/2)n-5/2}, \qquad (58)$$

where $m_0 = \sum_{i=1}^{n} m_i$ is the mass of the decaying nucleus, $S = \prod_{i=1}^{n}(2s_i+1)$ is the spin degeneracy factor (s_i is the ith particle spin), $G = \prod_{j=1}^{k} n_j!$ is the particle identity factor (n_j is the number of particles of kind j). $E_{\rm kin}$ is the total kinetic energy of particles at infinity which is related to the prefragment excitation energy E^*_{AZ} as

$$E_{\rm kin} = E^*_{AZ} + m_0c^2 - \sum_{i=1}^{n} m_ic^2. \qquad (59)$$

U_f^C is the Coulomb interaction energy between cold secondary fragments given by Eq. (49), U_f^C and V_f are attributed now to the secondary break-up configuration.

Generalization of the Fermi-break-up model: new decay channels with hypernuclei were included ; masses and spins of hypernuclei and their excited states were taken from available experimental data and theoretical calculations

After absorption of Ξ^-
an excited ${}^{13}_{\Lambda\Lambda}\mathrm{B}$
is formed, and it decays

Calculations with the
Fermi-break-up

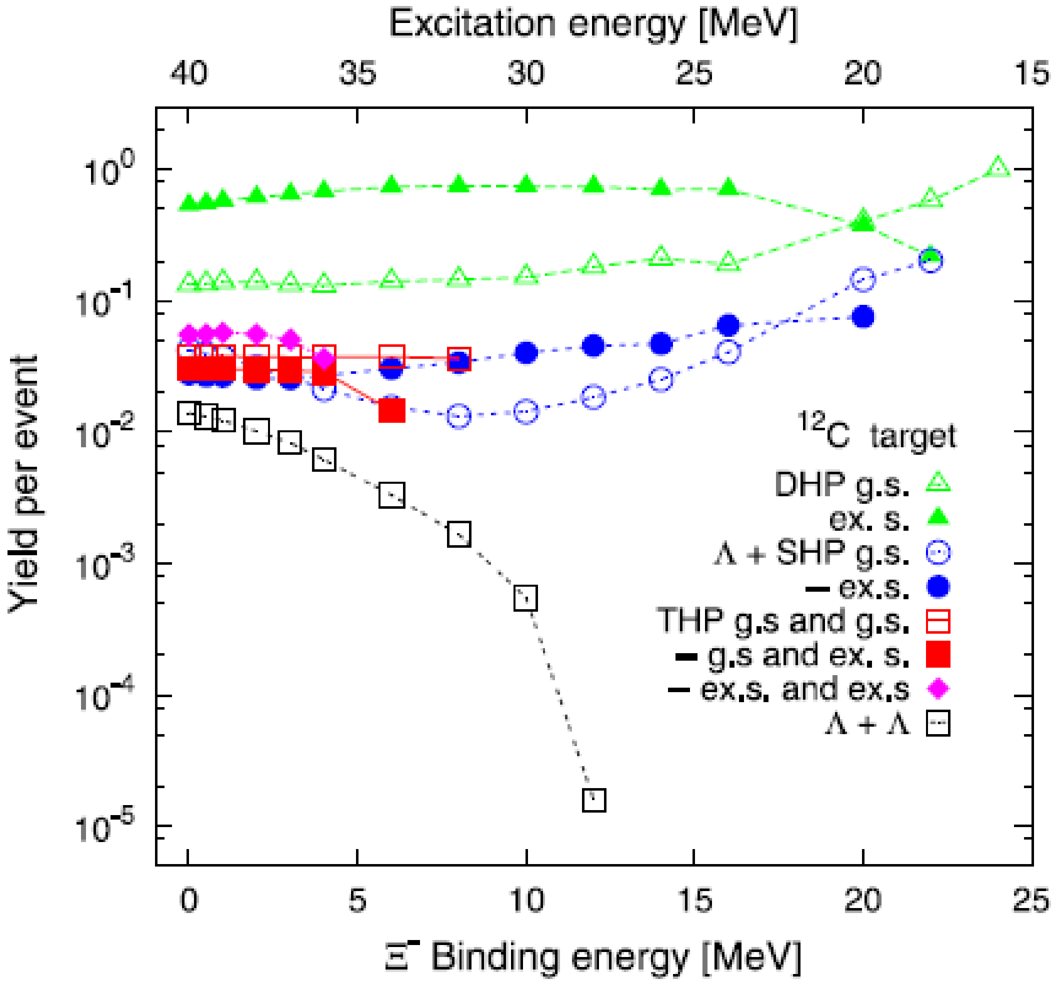


Fig. 1. Predicted production probability of ground (g.s.) and excited states (ex.s.) in one single (SHP), twin (THP) and double hypernuclei (DHP) after the capture of a Ξ^- in a ^{12}C nucleus and its conversion into two Λ hyperons. The lower and upper scale shows the binding energy of the captured Ξ^- and the excitation energy of the initial ${}^{13}_{\Lambda\Lambda}\mathrm{B}$ nucleus, respectively.

Absorption of Ξ-minus may lead to production of H-dibaryons:

Consider: absorptions of Ξ^- by ^{7}Li and by ^{3}He,

leading to the formation of $^{8}_{\Lambda\Lambda}\mathrm{He}^*$ and $^{4}_{\Lambda\Lambda}\mathrm{H}^*$

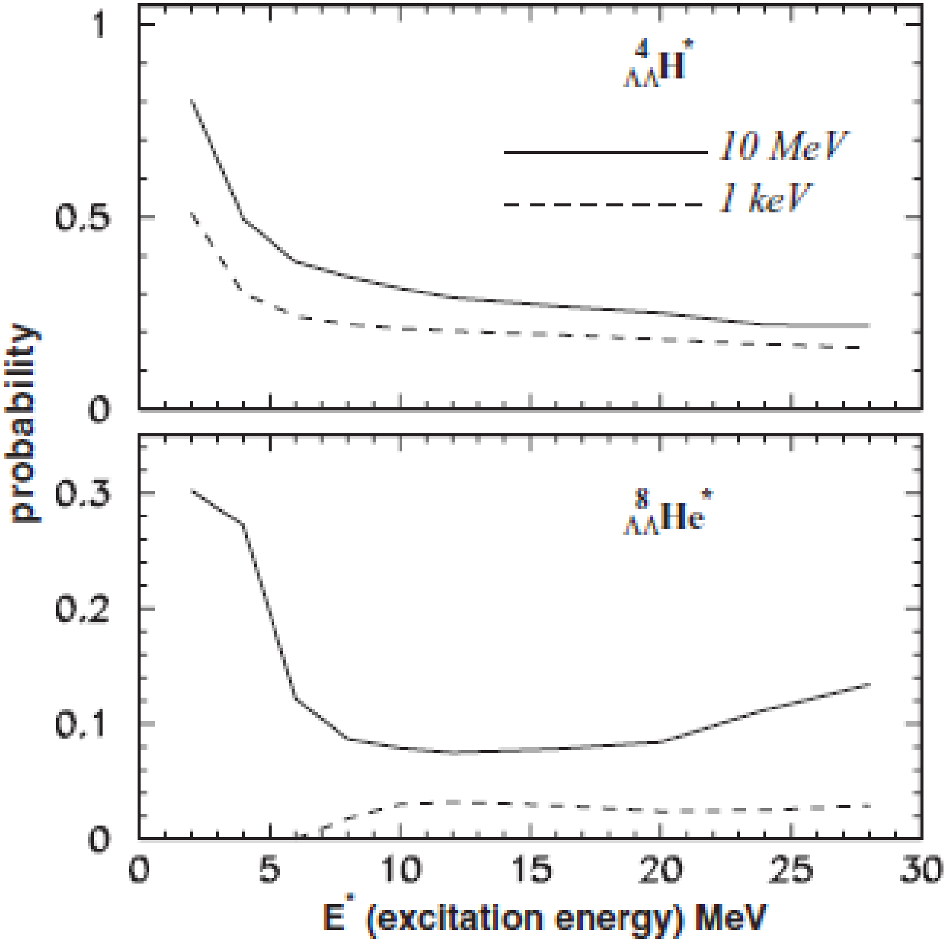
($\Xi^- p \rightarrow \Lambda\Lambda$ with release of 28 MeV)

The following disintegration of these nuclei calculated with the Fermi-Break-up model yields many normal and strange fragments, including exotic ones, if they exist. Different binding energies of H-dibaryons was assumed, from strongly bound to nearly unbound. In all cases the yield is considerable !

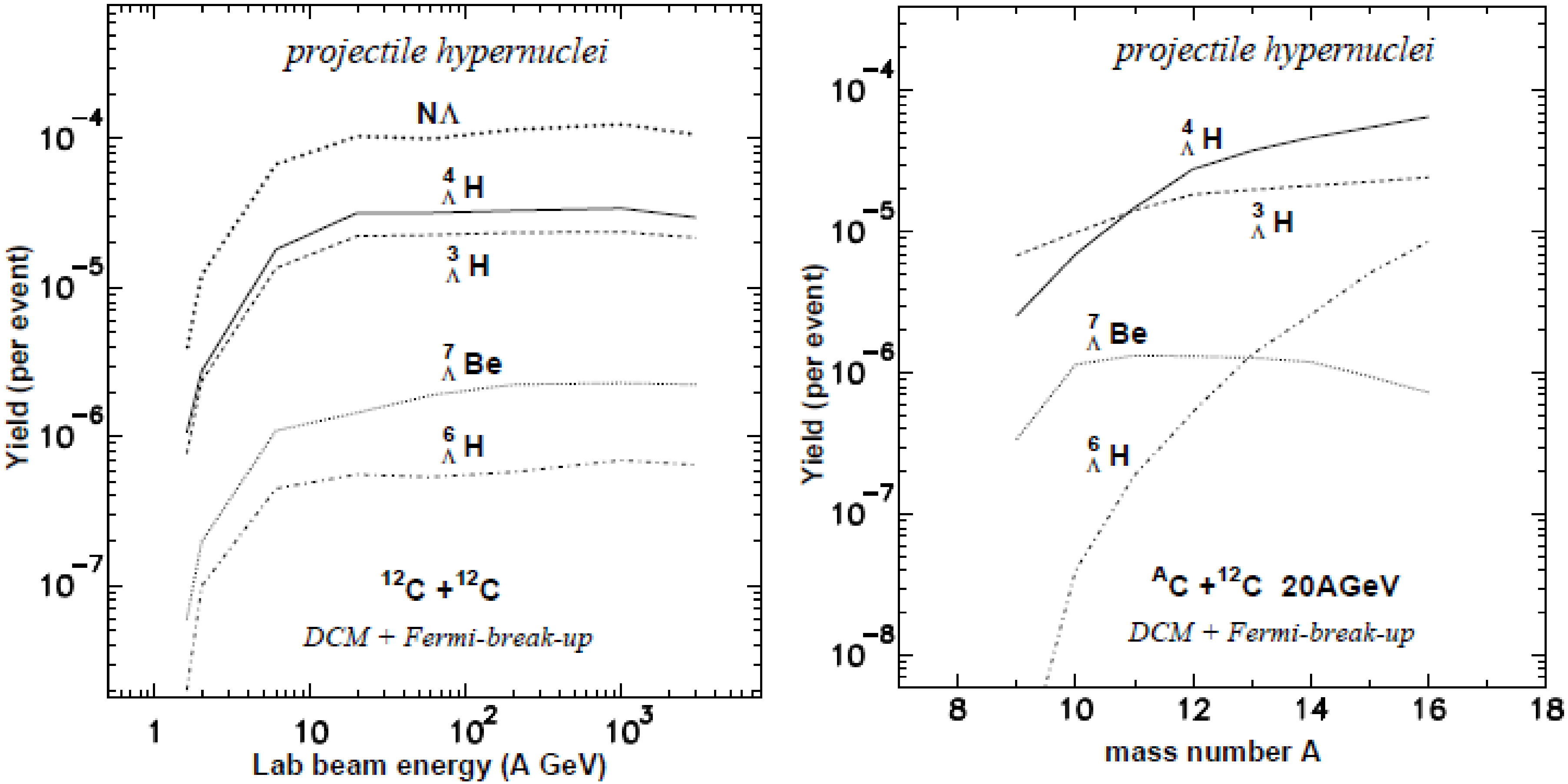
The nuclear reaction theory can show the most efficient experimental way for searching for specific species.

A.S.Botvina, I.N.Mishustin, J.Pochodzalla,
Phys. Rev. C86, 011601 (2012).

H-dibaryon (ΛΛ bound state) yield



Production of light hypernuclei in relativistic ion collisions



One can use exotic neutron-rich and neutron-poor projectiles, which are not possible to use as targets in traditional hyper-nuclear experiments, because of their short lifetime. Comparing yields of hypernuclei from various sources we can get info about their binding energies and properties of hyper-matter.

A.S.Botvina, K.K.Gudima, J.Pochodzalla, PRC 88, 054605, 2013

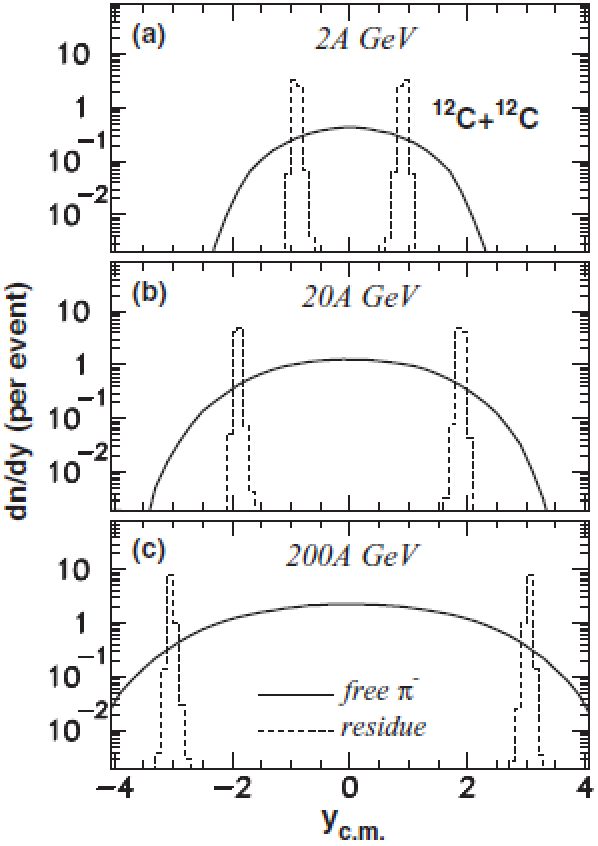


FIG. 7. Rapidity distributions in the system of center of mass $y_{\mathrm{c.m.}}$ of free π^- (solid curves) and projectile and target spectator residues (dashed histograms) normalized per one inelastic event in ^{12}C + ^{12}C interactions. Top (a), middle (b), and bottom (c) panels are for collisions with 2, 20, and 200 GeV per nucleon energy, respectively, as calculated with the DCM.

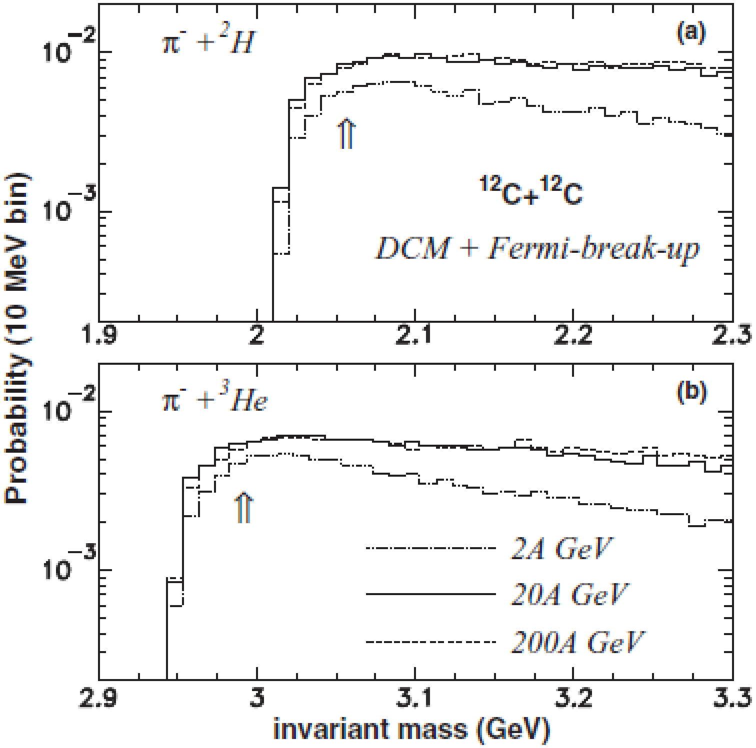


FIG. 8. (a) Invariant mass distributions of the π^- plus ^{2}H pairs and (b) the π^- plus ^{3}He pairs obtained in carbon-carbon collisions at energies of 2 GeV per nucleon (dotted histograms), 20 GeV per nucleon (solid histograms), and 200 GeV per nucleon (dashed histograms). The event by event calculations are performed within the DCM and Fermi breakup models. The count number of the pairs in 10-MeV bins of invariant mass are normalized per inelastic event and noted as probability. Arrows mark the invariant masses corresponding to an NΛ bound state and to $^3_\Lambda$H nuclei.

Momentum distribution of Lambda captured in the spectators

(Connection of the potential capture and the coalescence)

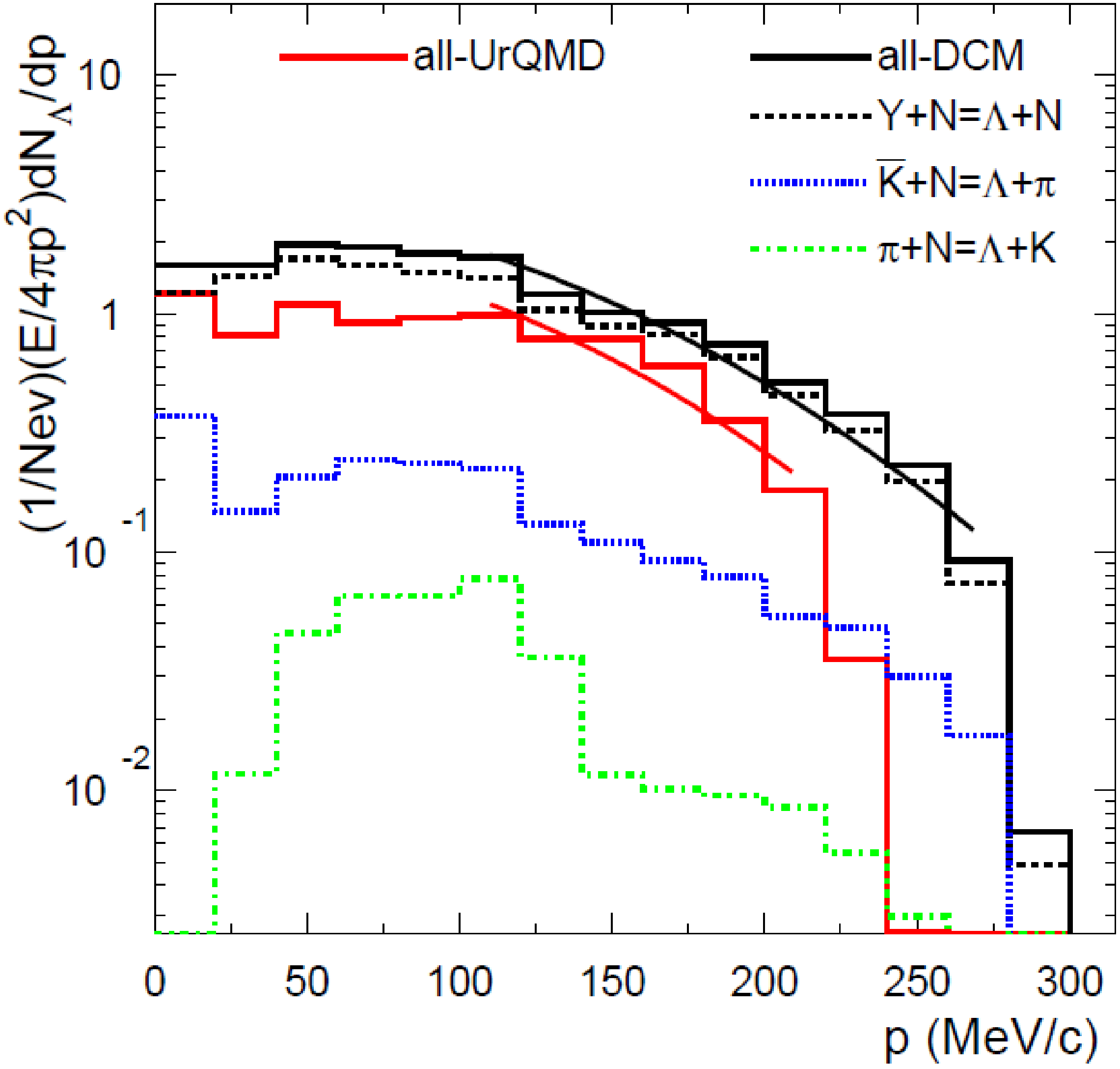
Coalescence of baryons

momenta:

$$\left| \mathbf{P}_{i} - \mathbf{P}_0 \right| \le \mathbf{P}_{c}$$

coordinates:

$$\left| \mathbf{X}_{i} - \mathbf{X}_0 \right| \le \mathbf{X}_{c}$$



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

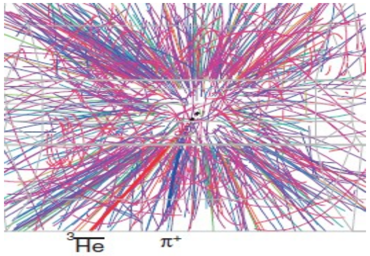
N_{event}	13.5×10^{9}	${}^{3}_{\Lambda}$H
N_{count}	1220±854	

STAR collaboration (RHIC):

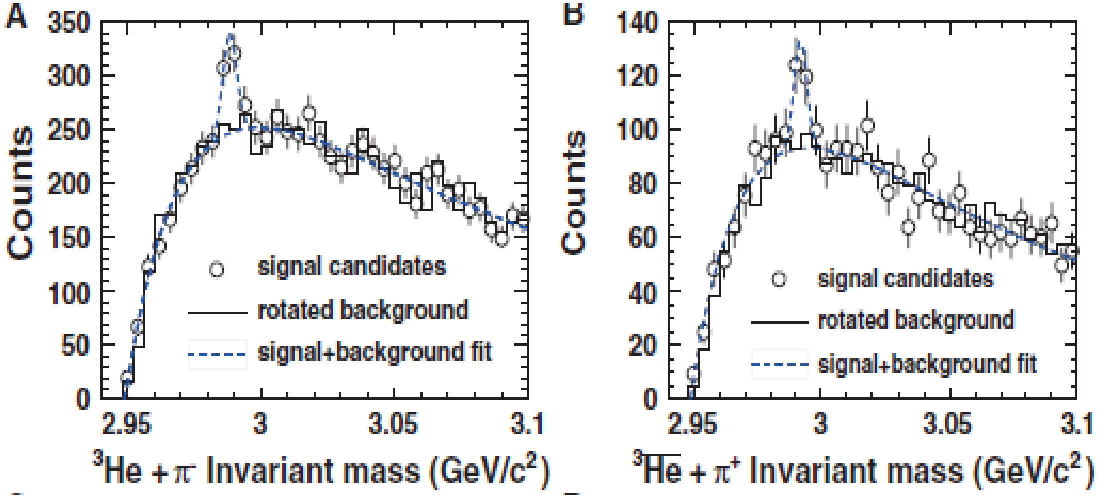
Science, 238 (2010) 58

Au + Au collisions at 200 A GeV

gas-filled cylindrical Time Projection Chamber

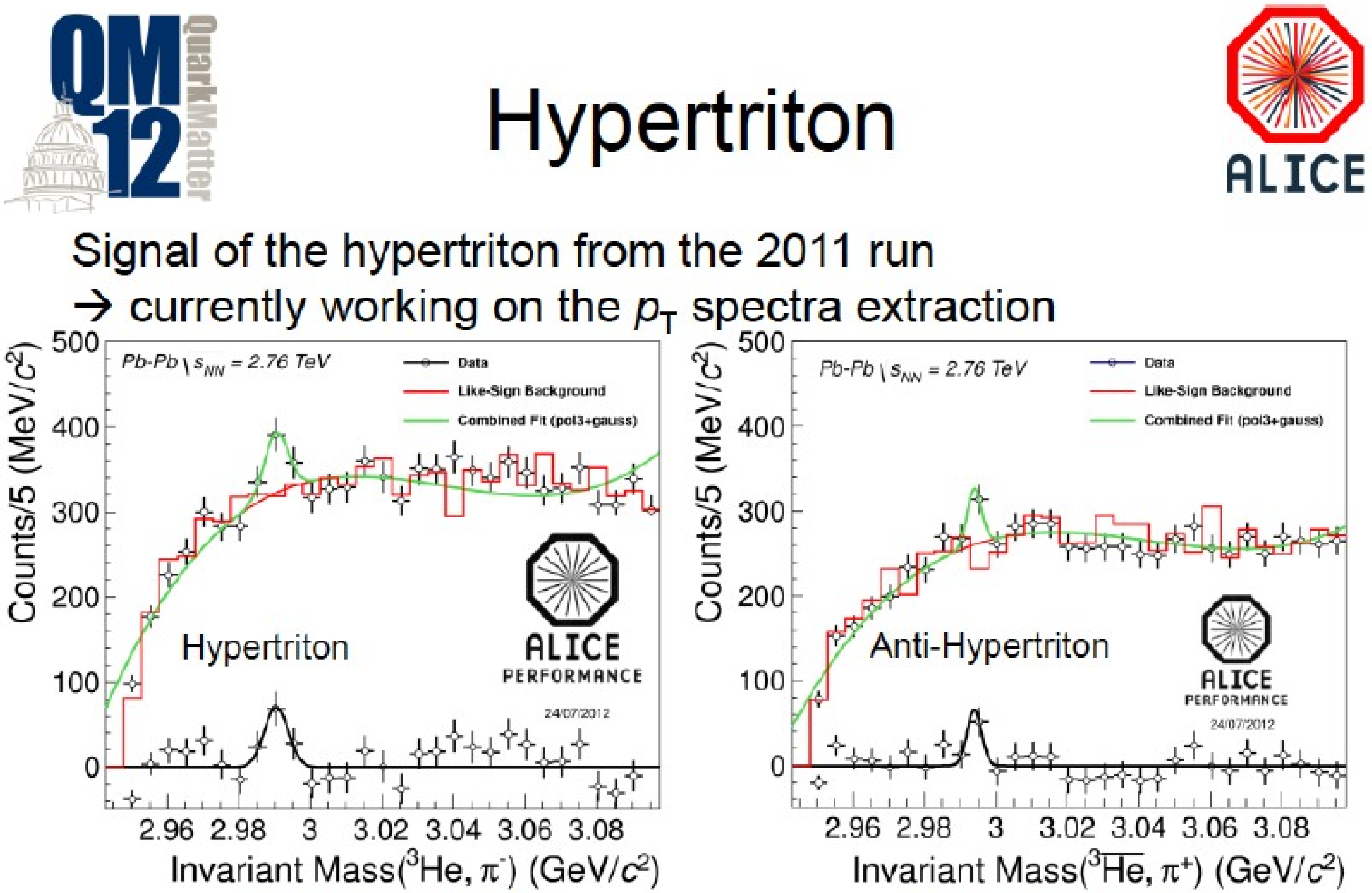


70 ± 17 antihypertritons (${}^{3}_{\bar{\Lambda}}\overline{\text{H}}$) and 157 ± 30 hypertritons (${}^{3}_{\Lambda}$H).



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

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 (|**V**b-**V**A|)<**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 |**X**b-**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 and HSD models with CB:

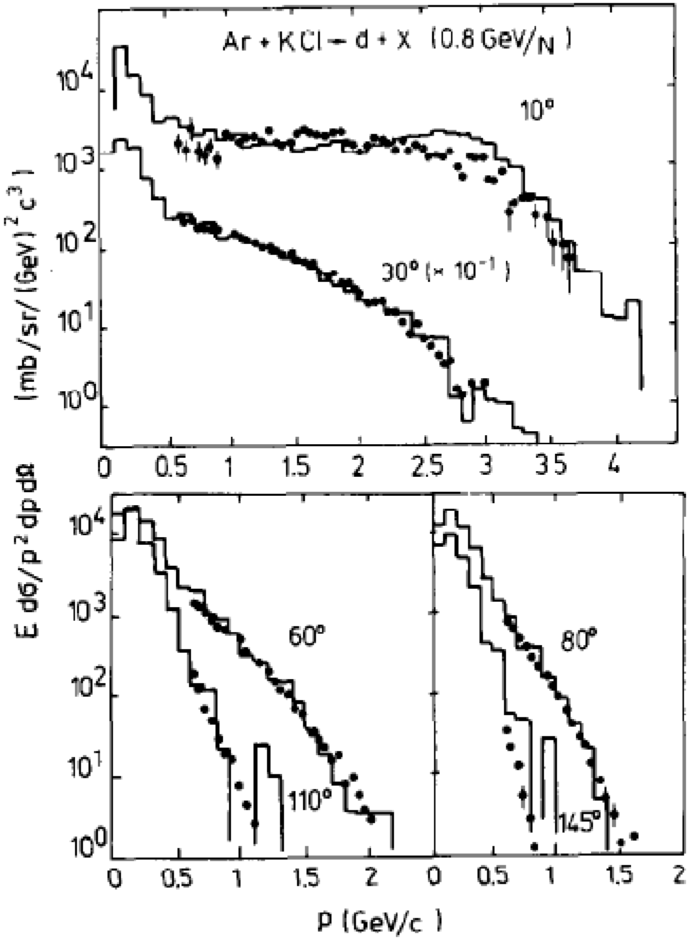
Investigation of fragments/hyperfragments at all rapidities !
(connection between central and peripheral zones)

HI collisions at intermediate energies

DCM + Coalescence

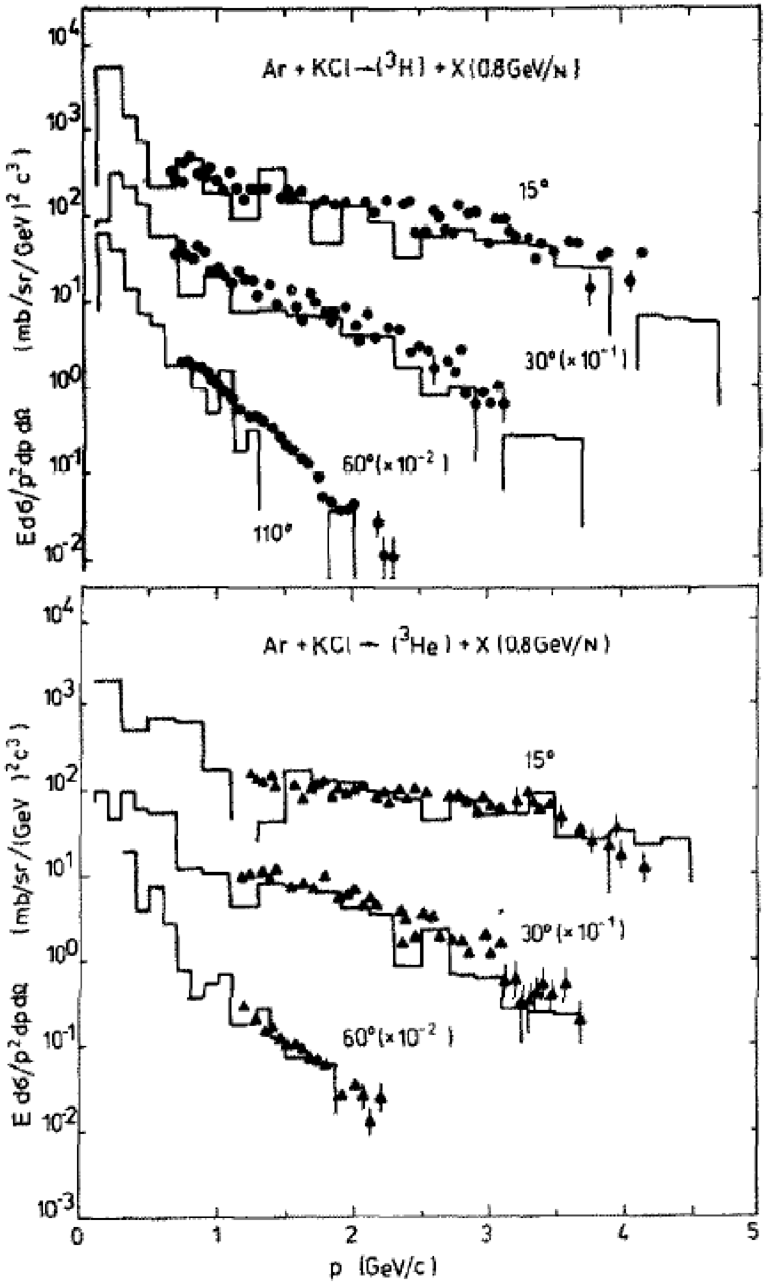
momentum: $\left| \mathbf{P}_{i} - \mathbf{P}_{0} \right| \leq \mathbf{P}_{c}$

V.Toneev, K.Gudima,
Nucl. Phys. A400 (1983)173c



Deutrons:
Pc=90 MeV/c

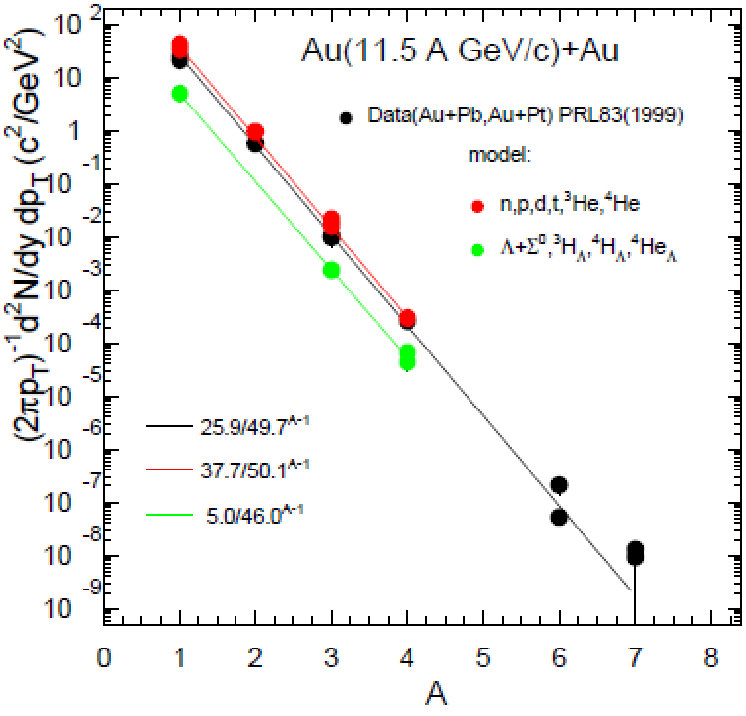
A=3:
Pc=110 MeV/c



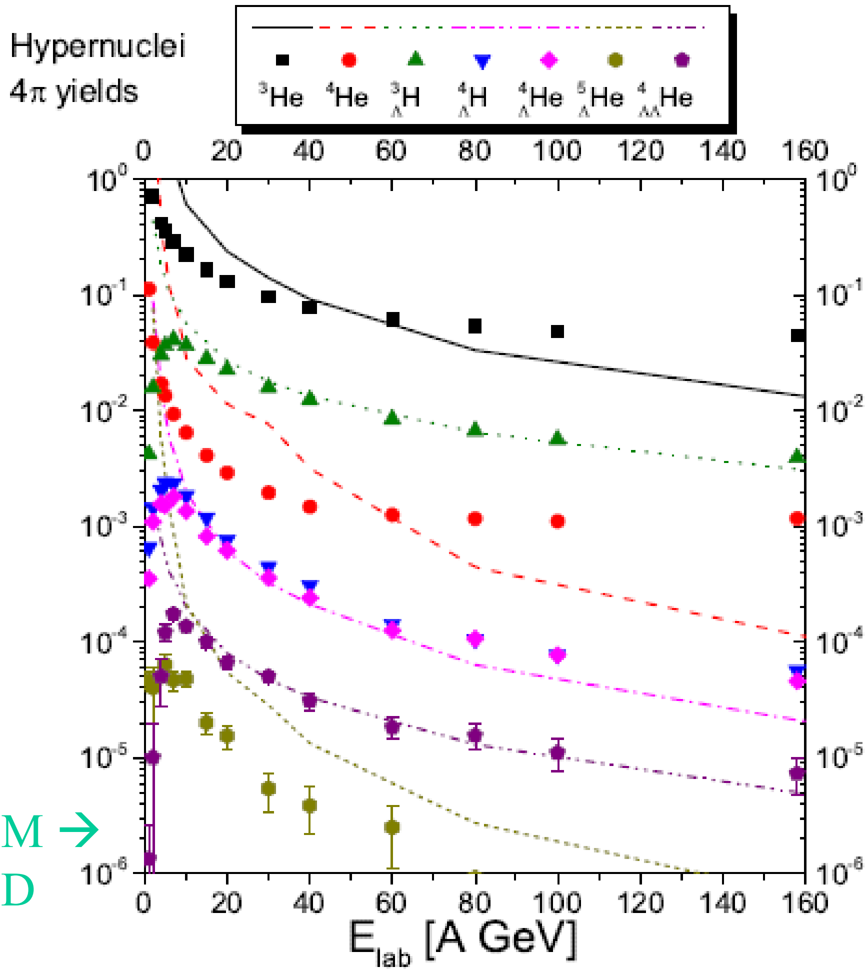
Production of light nuclei in central collisions : Au+Au

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

DCM versus experiment : coalescence mechanism



Also predictions for hybrid approach : UrQMD + thermal hydrodynamics



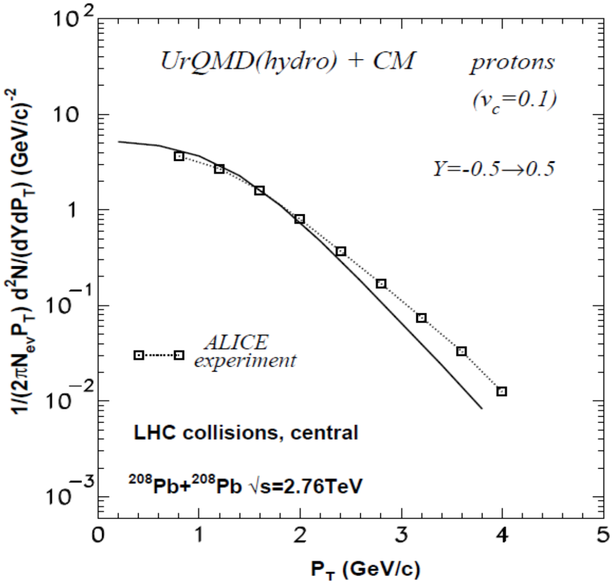
It is not possible to produce big nuclei !

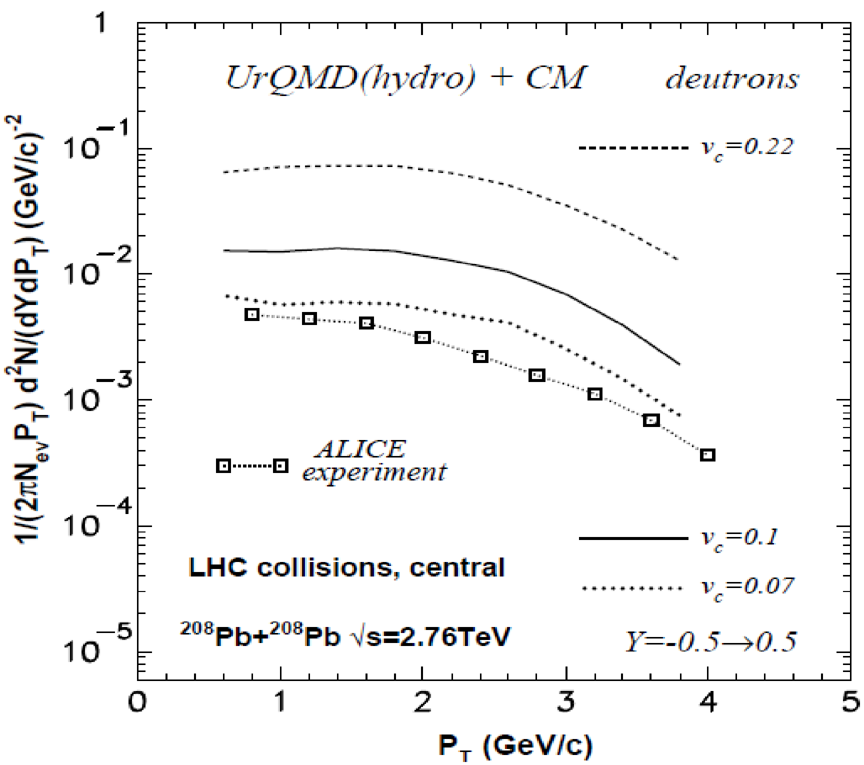
Symbols - DCM →
Lines - UrQMD

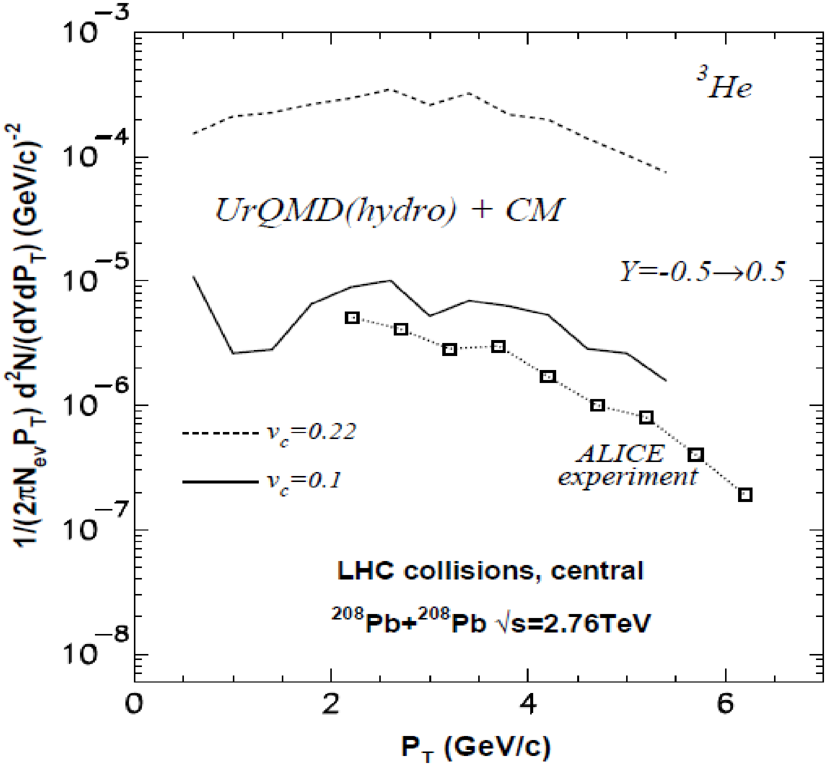
PRELIMINARY:

UrQMD + CB model calculations:
(LHC collider) 208Pb + 208Pb at 2.76 A TeV

ALICE: arXiv: 1303.0737v3 (2014)
arXiv: 1506.08951v1 (2015)

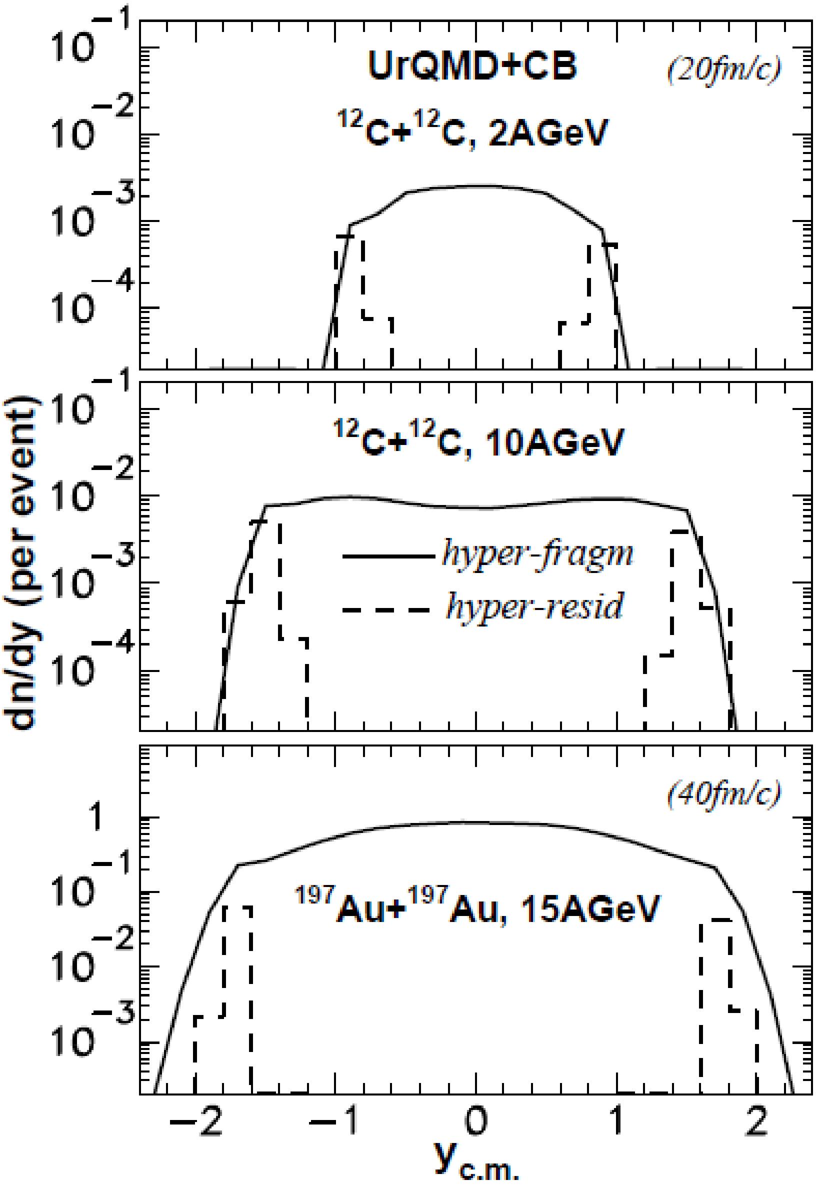


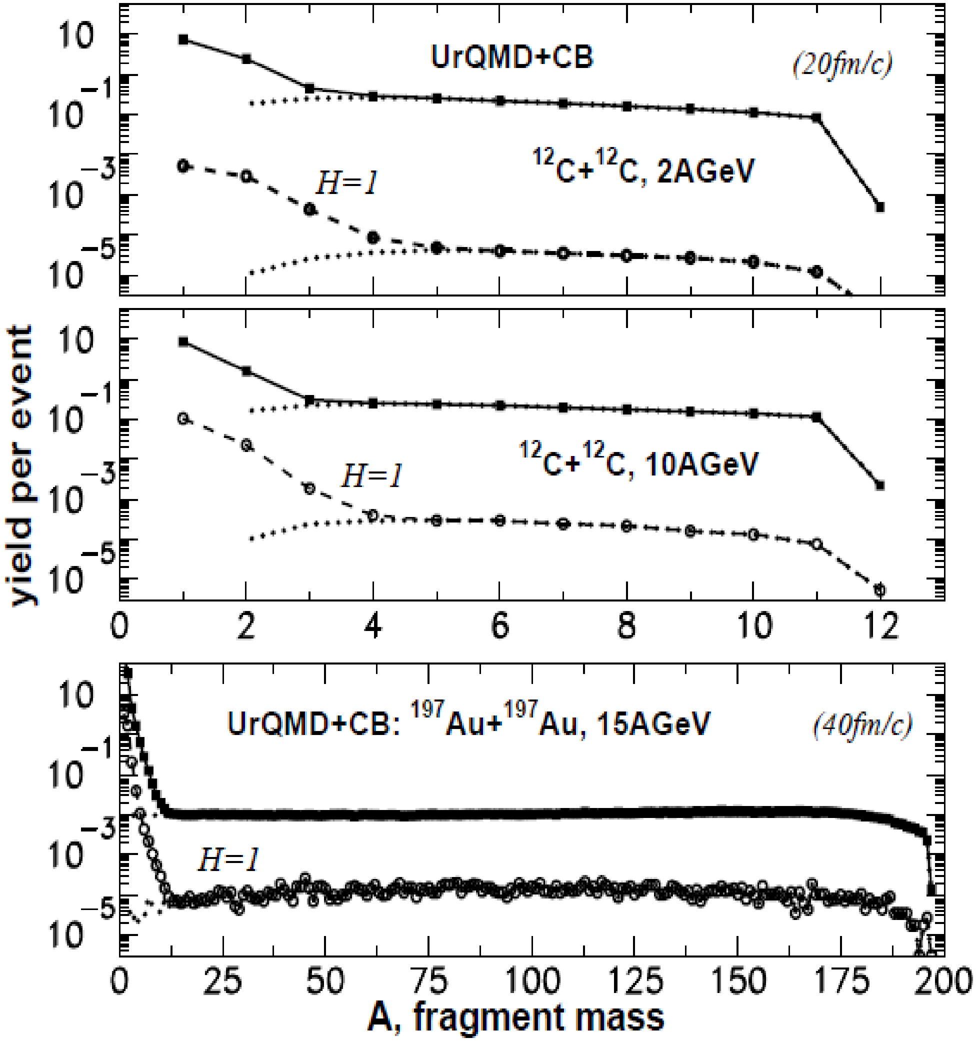




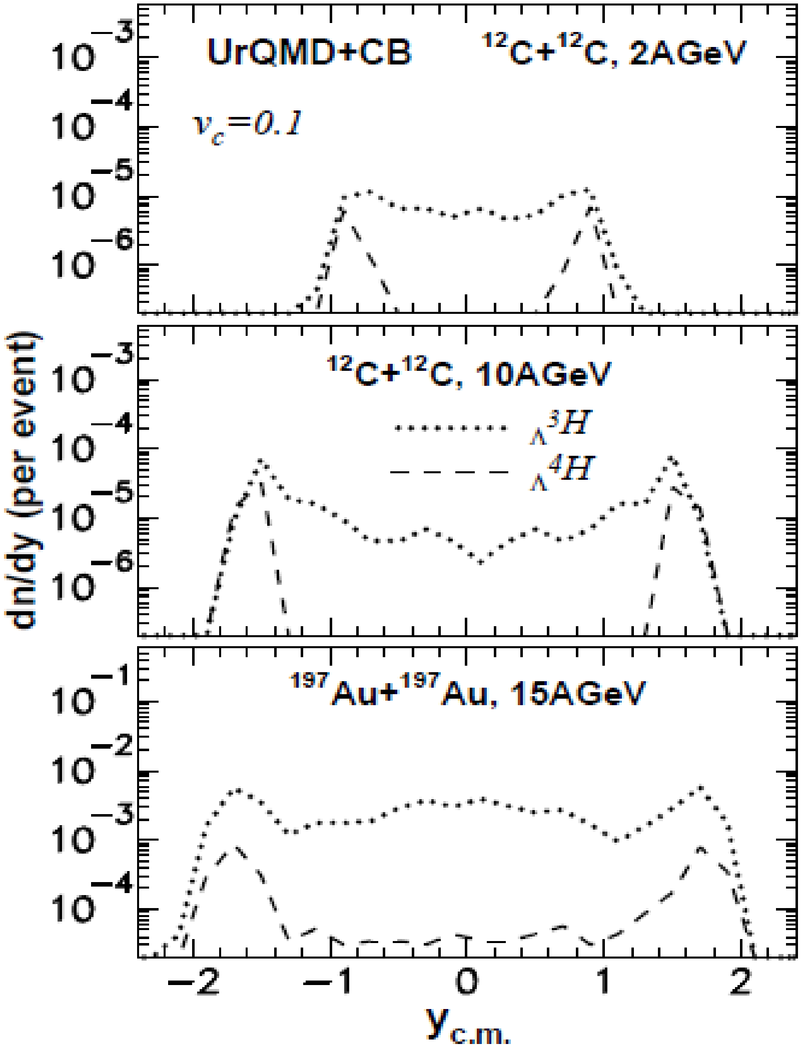
A.Botvina, J.Steinheimer, E.Bratkovskaya, M.Bleicher, J.Pochodzalla, PLB742(2015)7

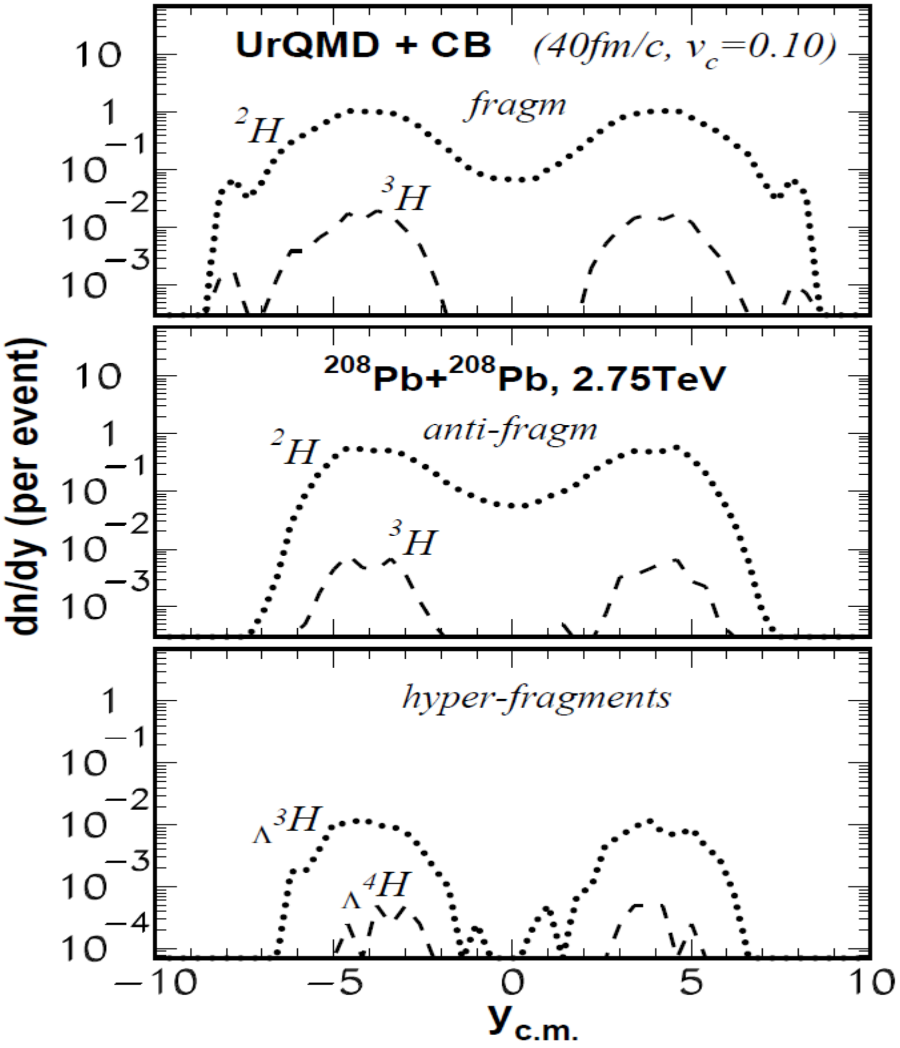
normal fragments, hyper-fragments, hyper-residues





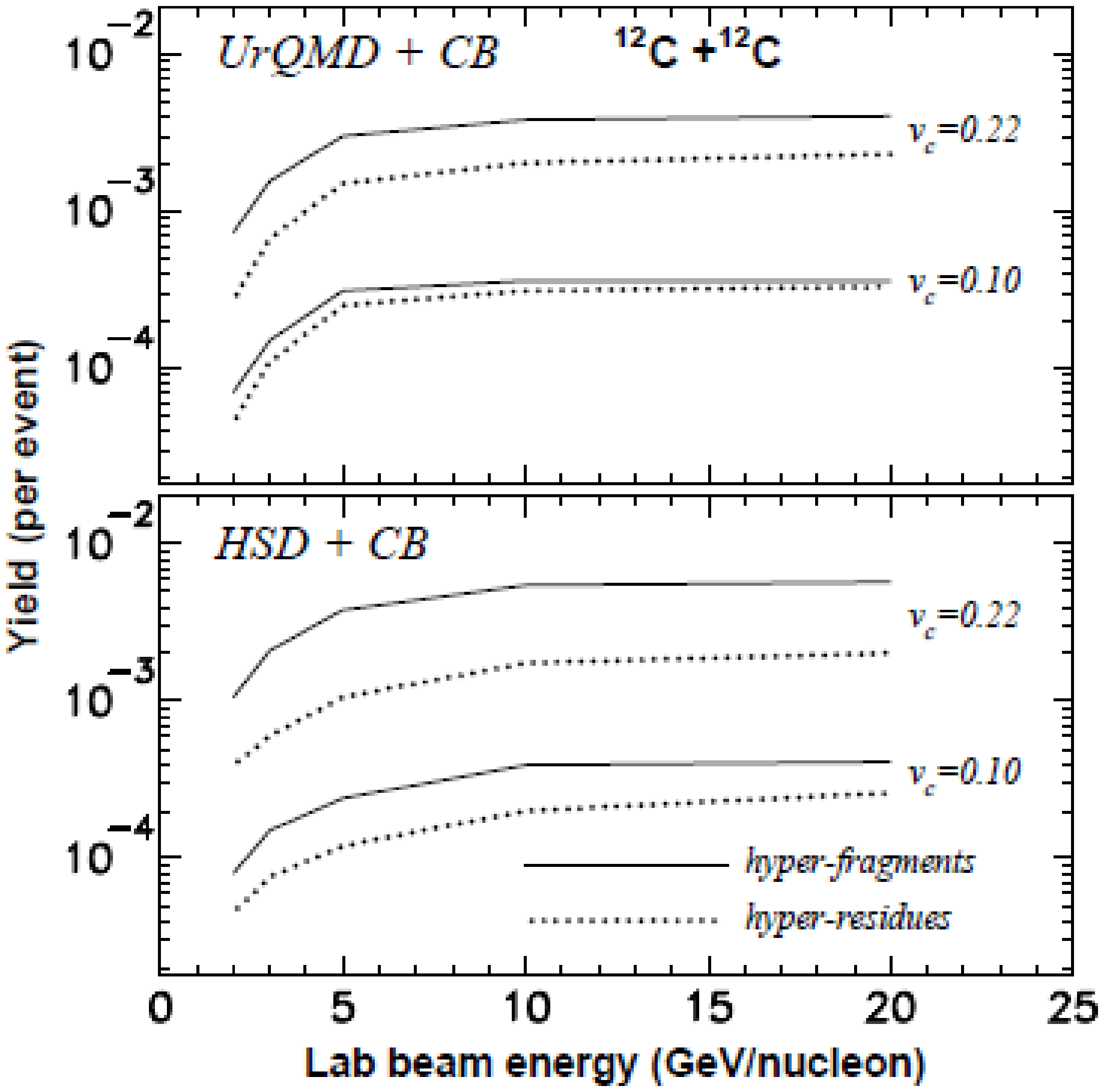
Because of the secondary interactions the maximun of the fragments production is shifted from the midrapidity. Secondary products have relatively low kinetic energies, therefore, they can produce clusters with higher probablity (even for light fragments/hyper-fragments).





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

Transport models are consistent (UrQMD, HSD)



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 anti-matter, will be effective at all rapidities. These exotic systems are presumably excited and after their decay novel hypernuclei of all sizes (and isospin), including exotic weakly-bound states, multi-strange nuclei, anti-nuclei can be produced.

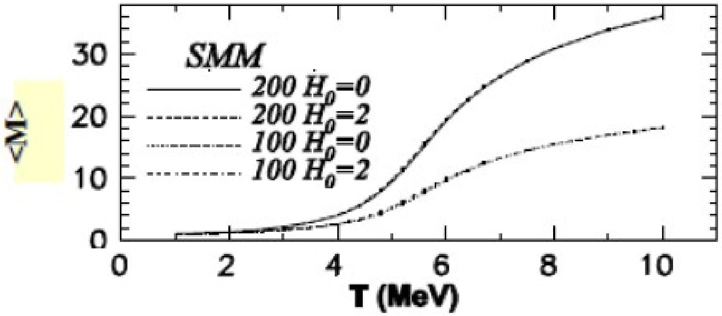
Advantages over other reactions: in the spectator matter there is no limit on sizes and isotope content of produced exotic nuclei; probability of their formation may be high; a large strangeness can be deposited in nuclei.
Correlations (unbound states) and lifetimes can be naturally studied.
EOS of hypermatter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

Multifragmentation of excited hyper-sources

H_0 is the number of hyperons in the system

General picture depends weakly on strangeness content (in the case it is much lower than baryon charge)

Mean multiplicity



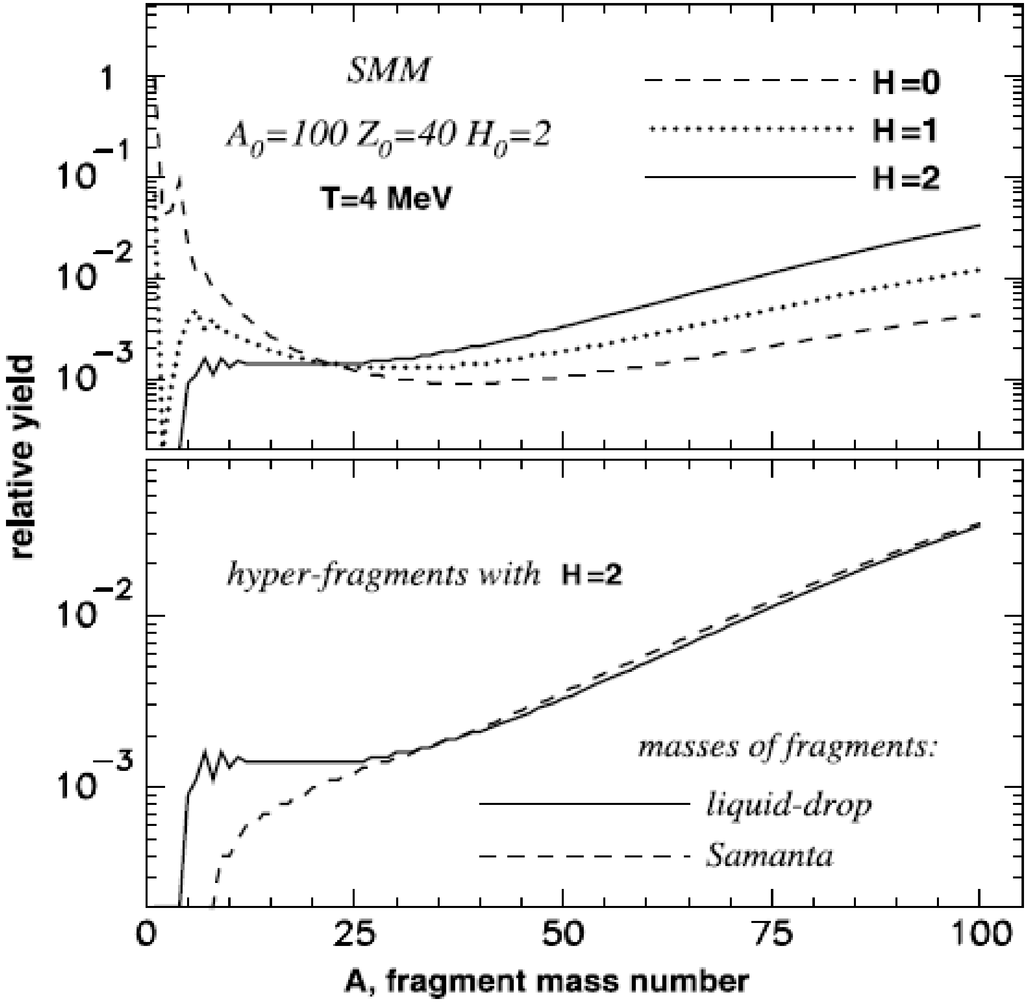


Fig. 3. Multifragmentation of an excited double-strange system with mass number 100 and charge 40, at temperature 4 MeV. Top panel – yield of fragments containing 0, 1, and 2 Λ hyperons. Bottom panel – effect of different mass formulae with strangeness on production of double hyperfragments [13].

However, there are essential differences in properties of produced fragments !

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