Production of hypernuclei from excited nuclear residues in relativistic ion collisions: New opportunities for BM@N and MPD@NICA

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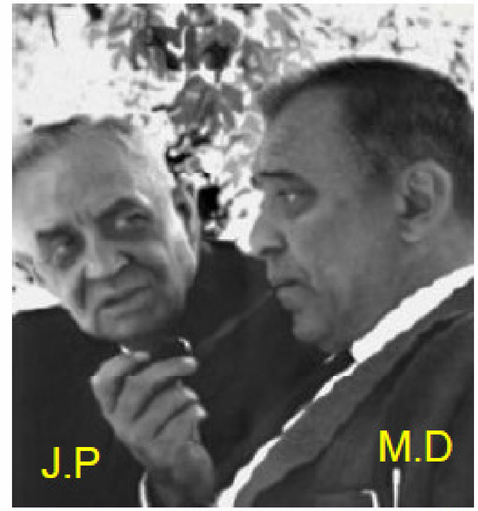
J.Pochodzalla, J.Steinheimer)

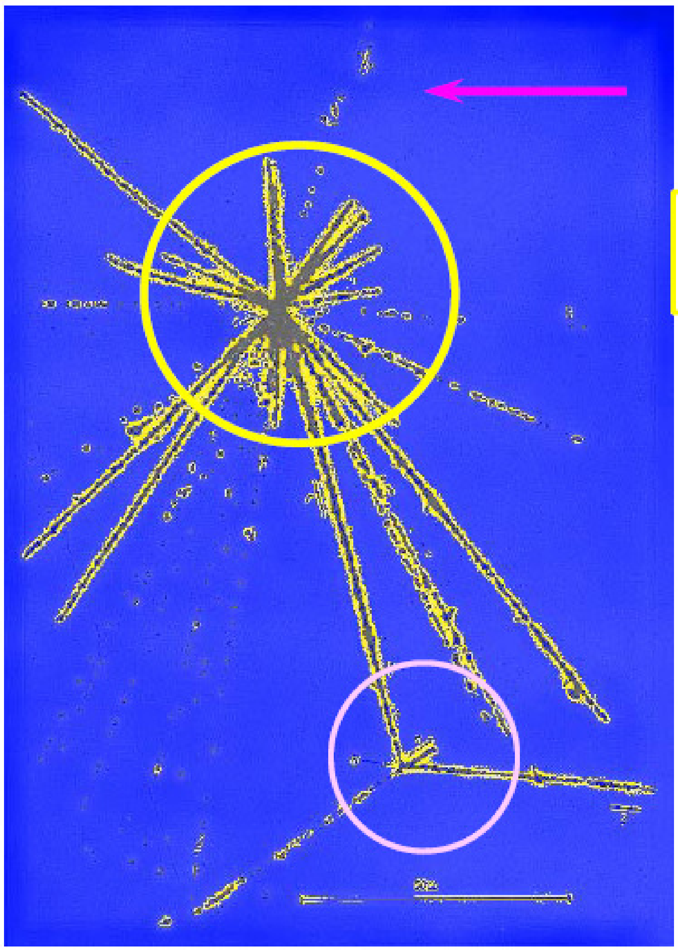
Seminar of BLTP (JINR),
Dubna, Russia
July 7, 2014

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

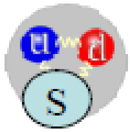
From the first star, 21 Tracks => $9\alpha + 11H + 1\ _{\Lambda}X$

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



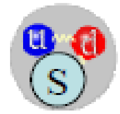
Λ^0=(uds)

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

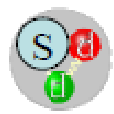
lifetimes of ~1×10^{-10} s
with the exception of Σ^0
whose lifetime is
shorter than 1×10^{-19} s

Sigma



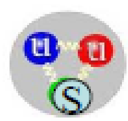
Σ^0=(uds)

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



Σ^-=(dds)

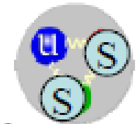
m(Σ^-) = 1197.449 +/- 0.030 MeV
S = - 1



Σ^+(uus)

m(Σ^+) =1189.37 +/- 0.07 MeV
S = - 1

Cascade or Xi



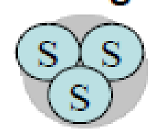
Ξ^0=(uss)

m(Ξ^0) = 1314.86 +/- 0.2 MeV
S = - 2

Ξ^-=(dss)

m(Ξ^-) = 1321.71 +/- 0.07 MeV
S = - 2

Omega



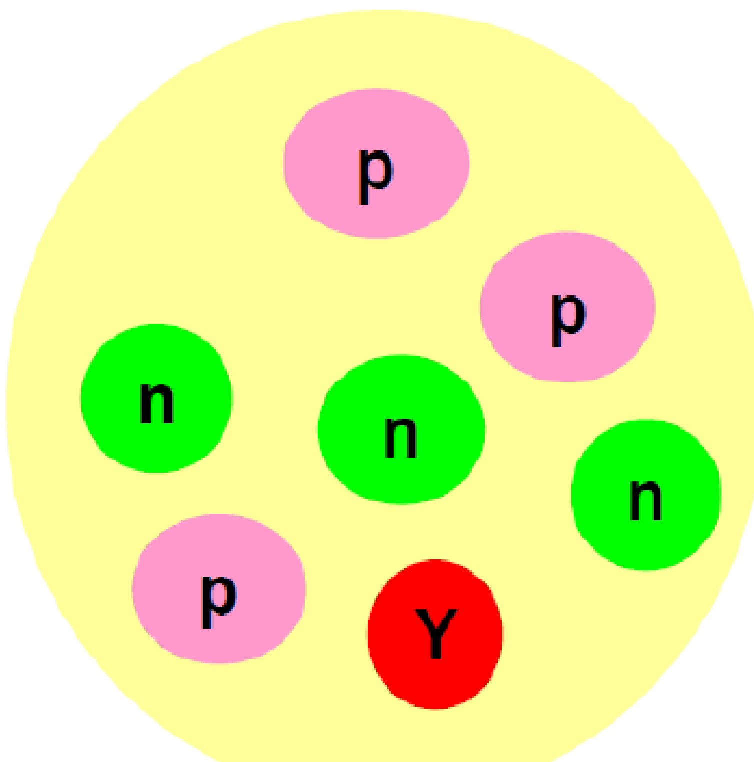
Ω^-=(sss)

m(Ω^-) = 1672.45 +/- 0.29 MeV
S = - 3

lifetime of ~ 8.2×10^{-11} s

Hypernucleus: Hyperons Bound in Nuclei

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



Notation:

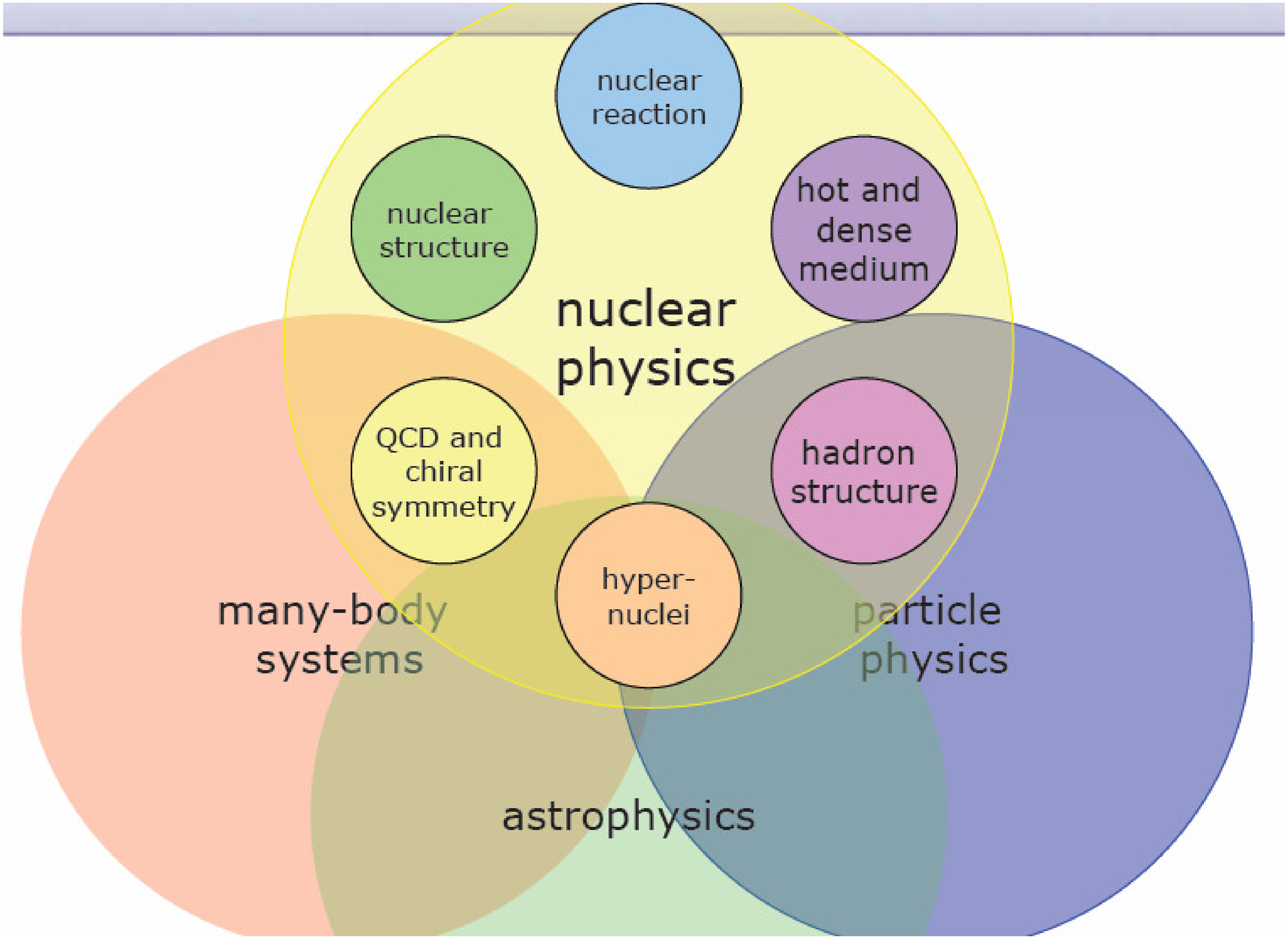
$${}^{A}_{Y}Z$$

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

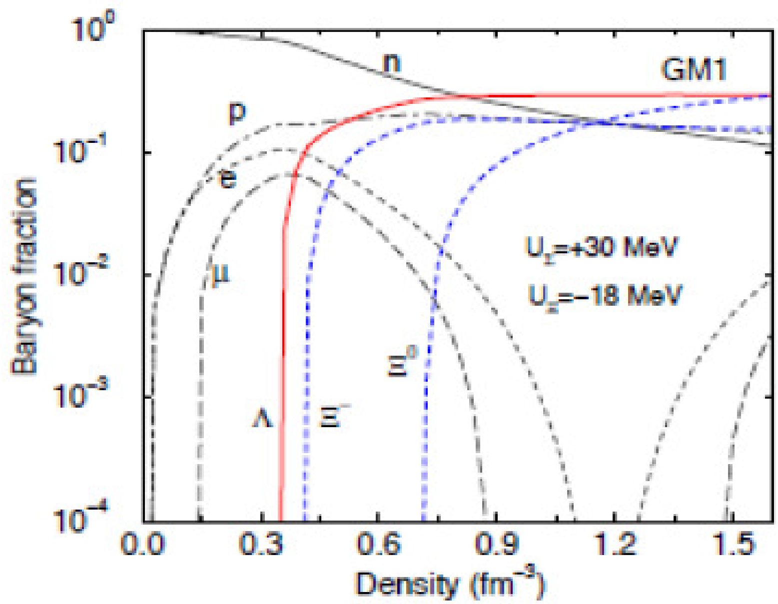
5 decades of hyperons in neutron stars

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).

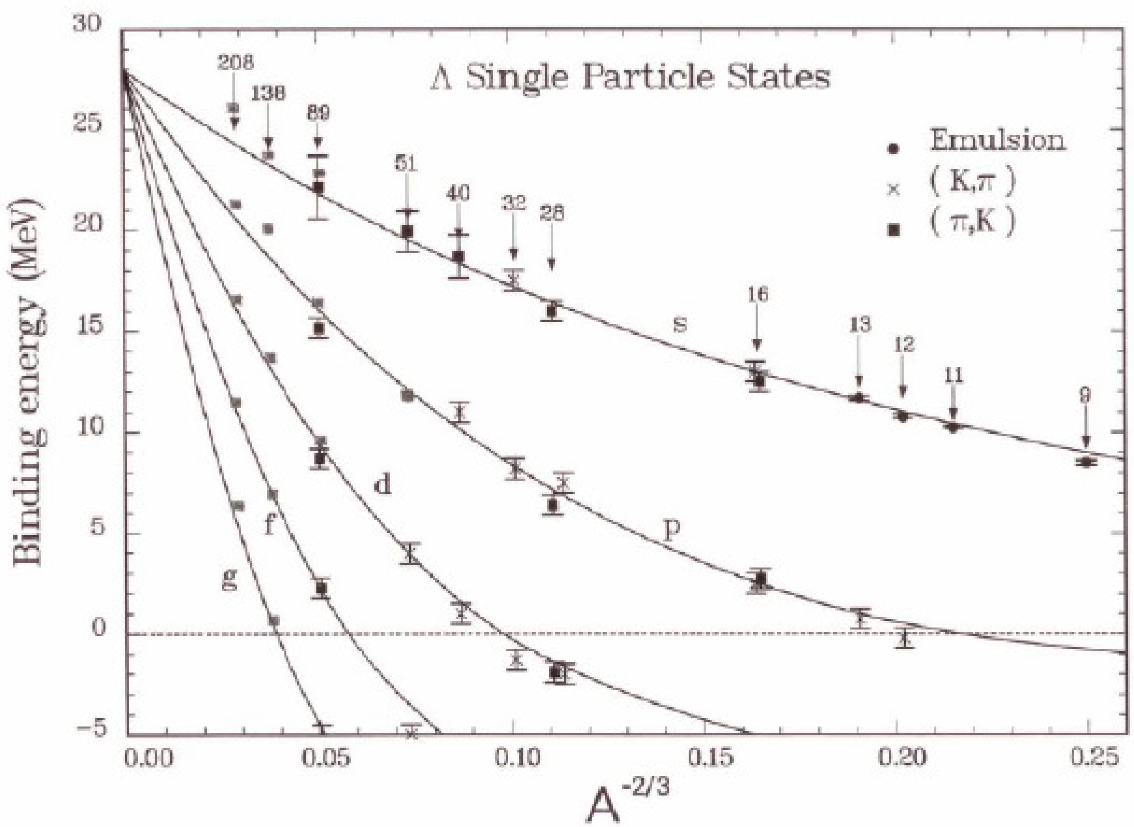
Alastair G.W. Cameron, Astrophysical Journal, vol. 130, p.884 (1959)



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

n-rich hypernucleus is a doorway to n-star

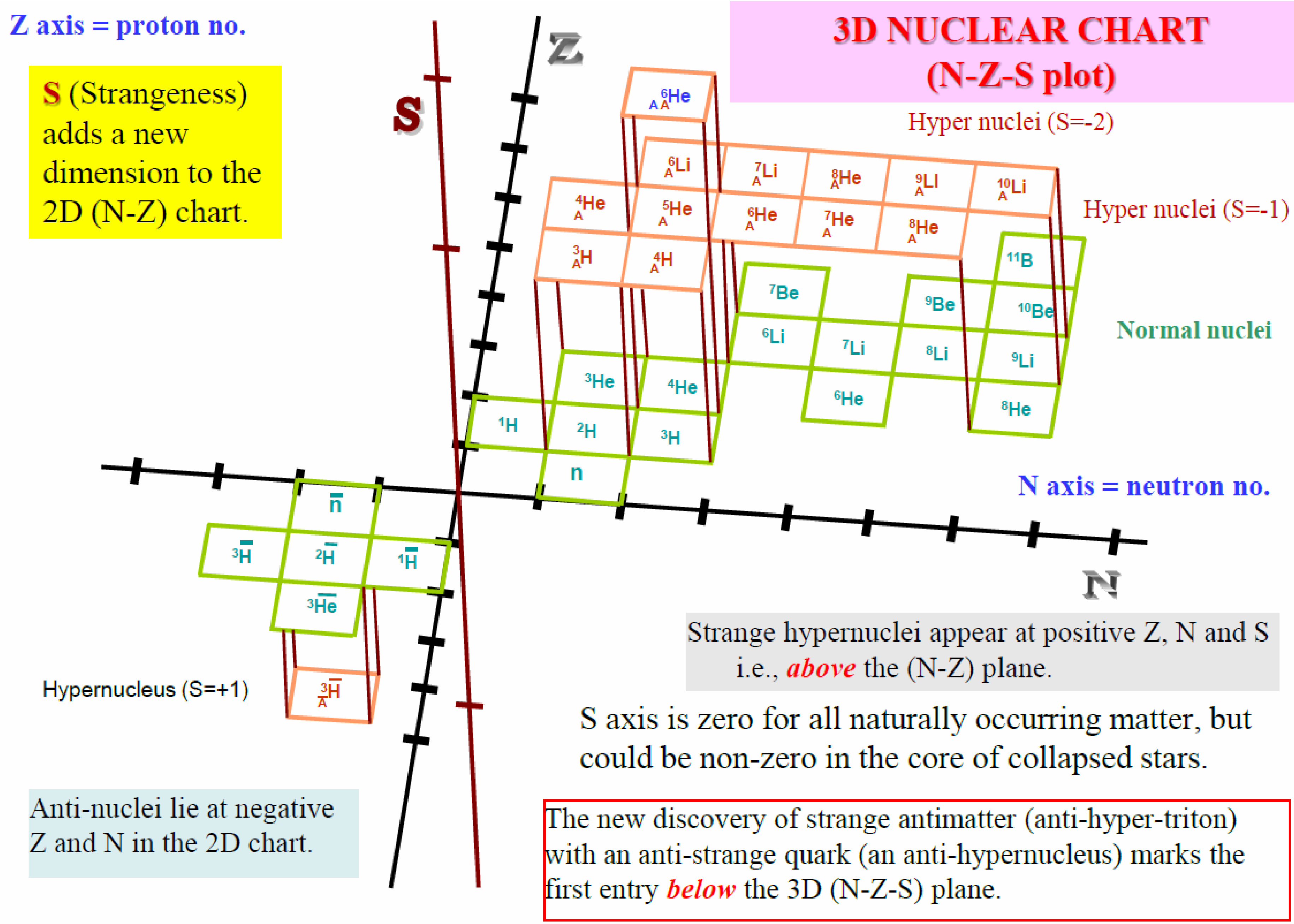
insight into halo nuclear structure through hypernuclei



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


3D NUCLEAR CHART
(N-Z-S plot)
Z axis = proton no.
S (Strangeness) adds a new dimension to the 2D (N-Z) chart.
Z
S
Hyper nuclei (S=-2)
Hyper nuclei (S=-1)
Normal nuclei
N axis = neutron no.
N
$^{6}_{\Lambda\Lambda}$He
$^{6}_{\Lambda}$Li
$^{7}_{\Lambda}$Li
$^{8}_{\Lambda}$He
$^{9}_{\Lambda}$Li
$^{10}_{\Lambda}$Li
$^{4}_{\Lambda}$He
$^{5}_{\Lambda}$He
$^{6}_{\Lambda}$He
$^{7}_{\Lambda}$He
$^{8}_{\Lambda}$He
$^{3}_{\Lambda}$H
$^{4}_{\Lambda}$H
^{11}B
^{7}Be
^{9}Be
^{10}Be
^{6}Li
^{7}Li
^{8}Li
^{9}Li
^{3}He
^{4}He
^{6}He
^{8}He
^{1}H
^{2}H
^{3}H
n
$\bar{n}$
$^{3}\bar{H}$
$^{2}\bar{H}$
$^{1}\bar{H}$
$^{3}\overline{He}$
Hypernucleus (S=+1)
$^{3}_{\bar{\Lambda}}\bar{H}$
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

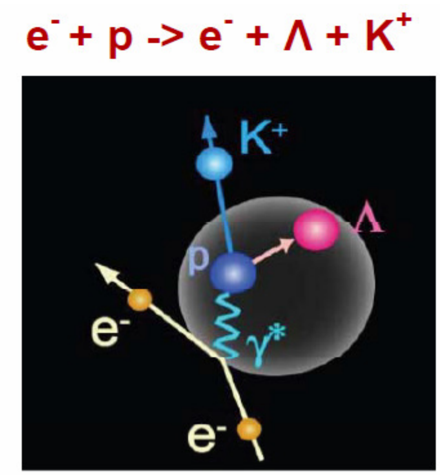
Traditional way for production of hypernuclei:
Conversion of Nucleons into Hyperons
by using hadron and electron beams

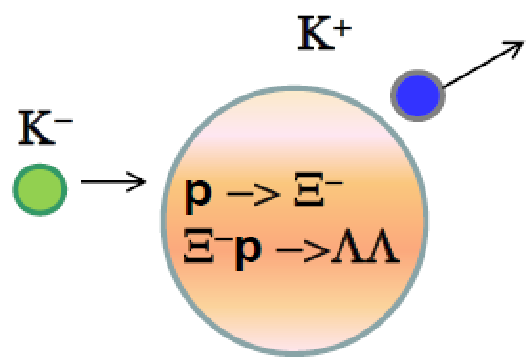
(CERN, BNL, KEK, CEBAF, DAΦNE, JPARC, MAMI, ...)

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 ?

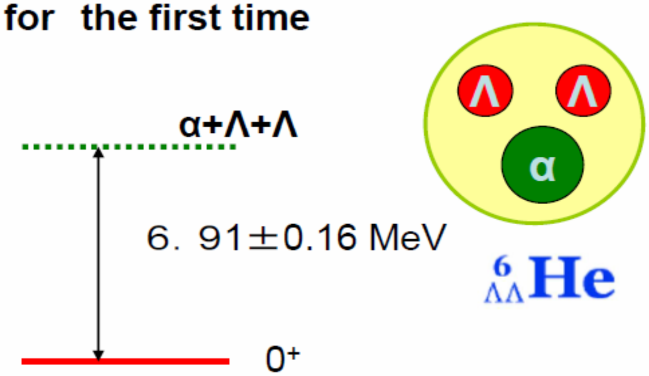




(K^-, K^+) reactions

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)

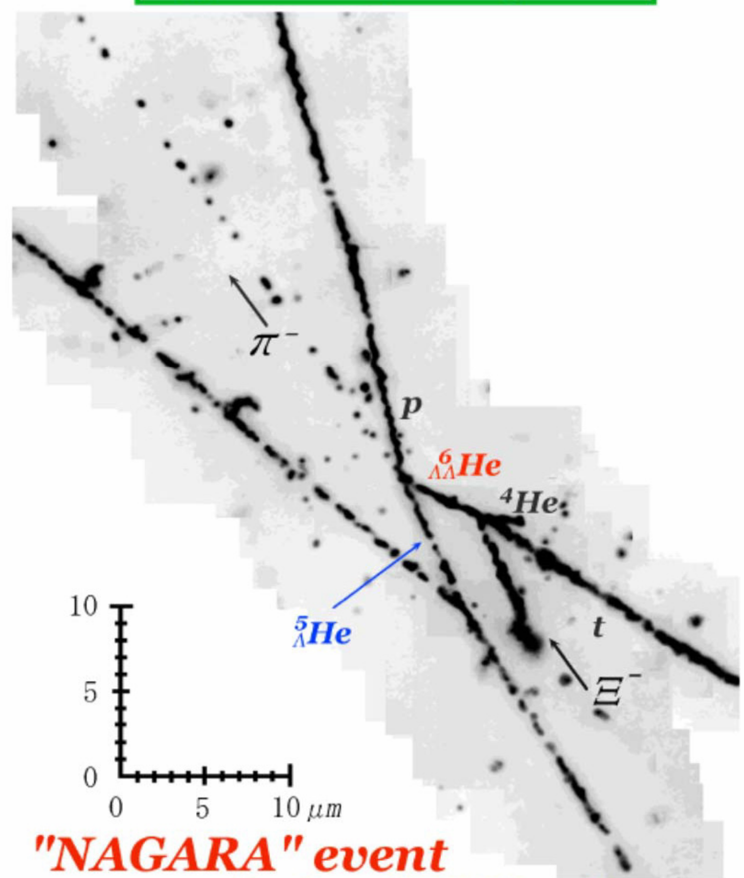
[Fermi-Break-up calculated probability~0.01]

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

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

Unique interpretation!!

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

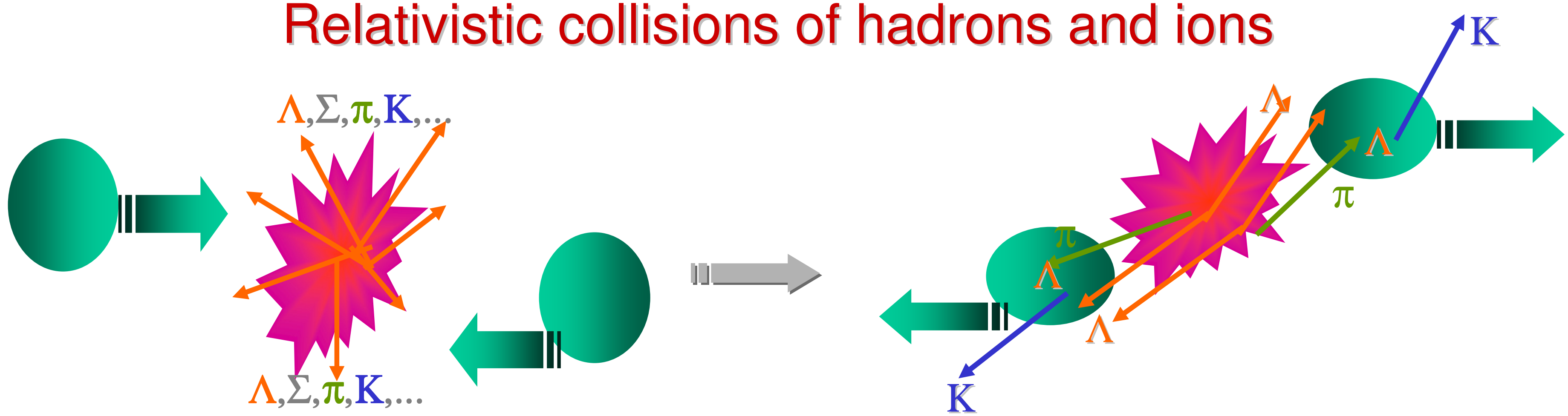


"NAGARA" event

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

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

Relativistic collisions of hadrons and ions

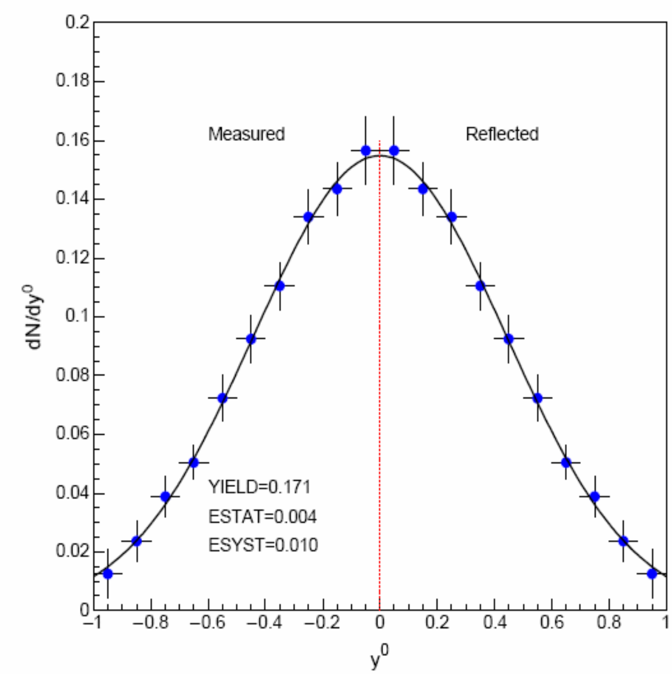


Production of hypermatter in relativistic HI and hadron collisions

- Production of strange particles and hyperons by "participants",
- Rescattering and absorption of hyperons by excited "spectators"

X. Lopez / Progress in Particle and Nuclear Physics 53 (2004) 149–151

Reconstructed Λ rapidity distribution for central ($\sigma_{geo} = 350$ mb) Ni + Ni reactions at 1.93 A GeV.



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

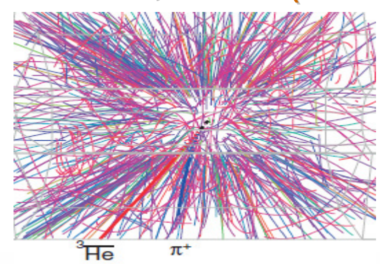
N_{event}	13.5×10^9	${}^{3}_{\Lambda}$H
N_{count}	1220 ± 854	

STAR collaboration (RHIC):

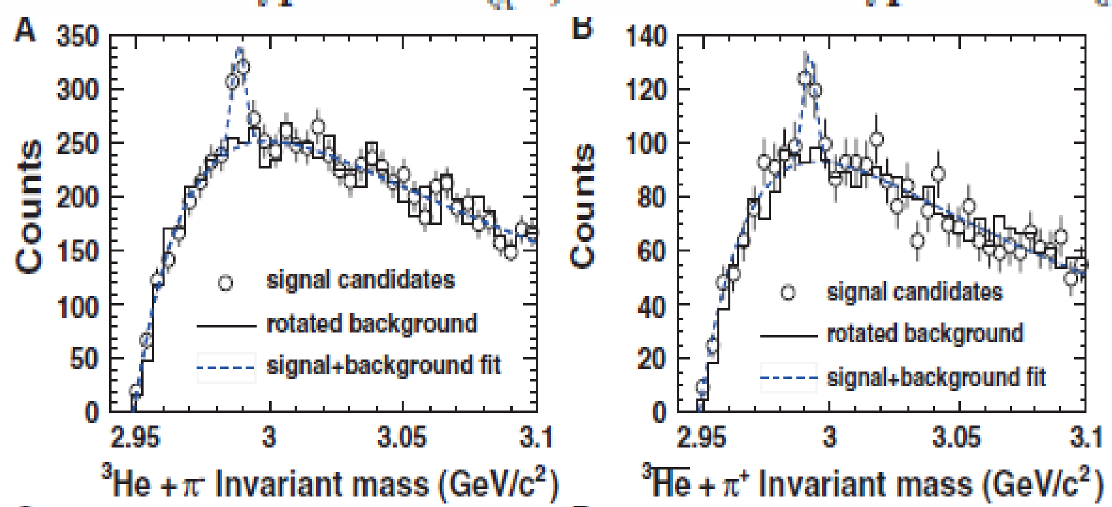
Science, 238 (2010) 58

Au + Au collisions at 200 A GeV

gas-filled cylindrical Time Projection Chamber

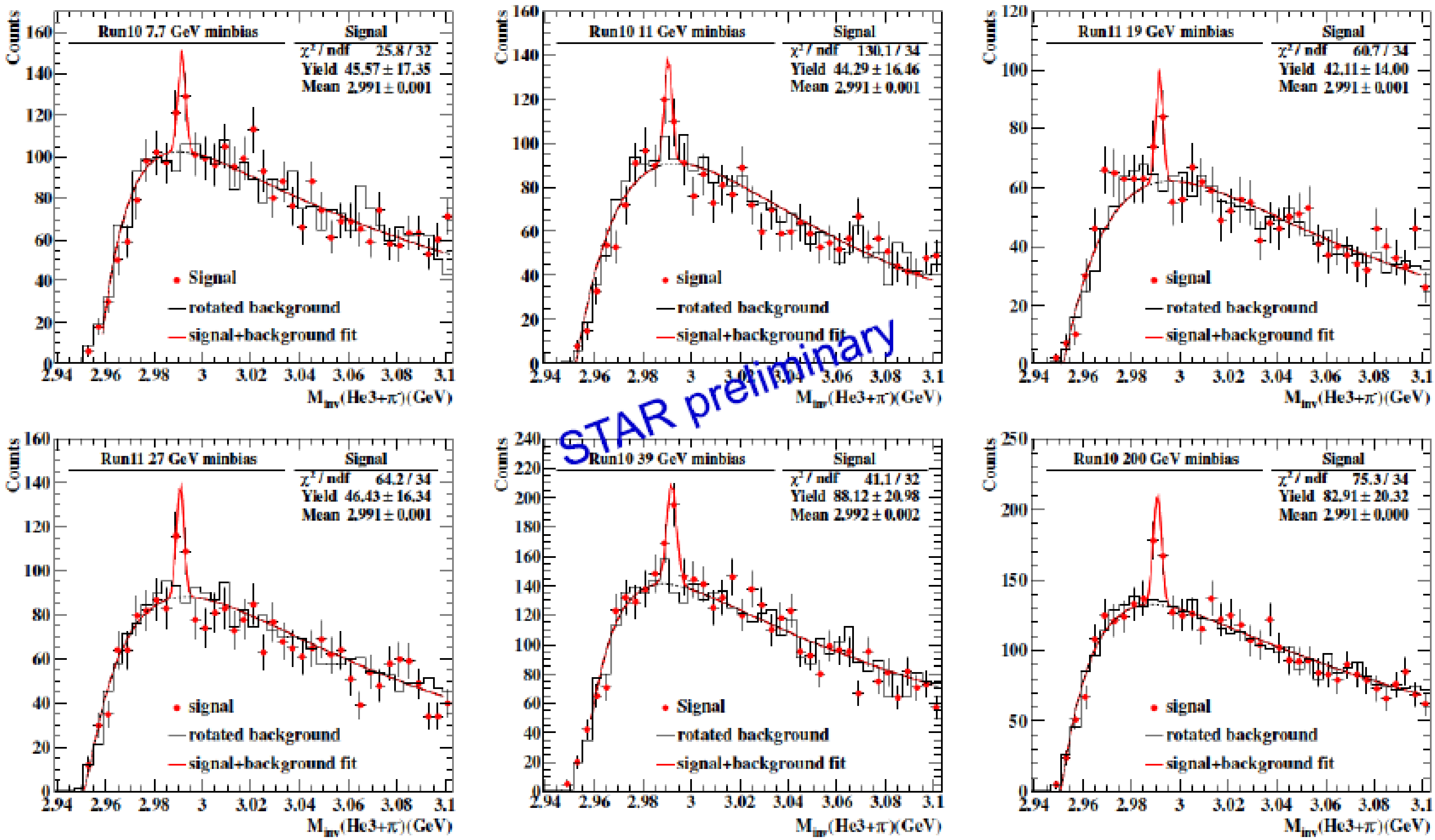


70 ± 17 antihypertritons (${}^{3}_{\bar\Lambda}\overline{H}$) and 157 ± 30 hypertritons (${}^{3}_{\Lambda}$H).



Y.-G. Ma , talk at NUFRA2013 (Kemer, Turkey)

Hypertriton signal from STAR BES at $\sqrt{s_{NN}}$=7.7, 11.5, 19.6, 27, 39, 200GeV



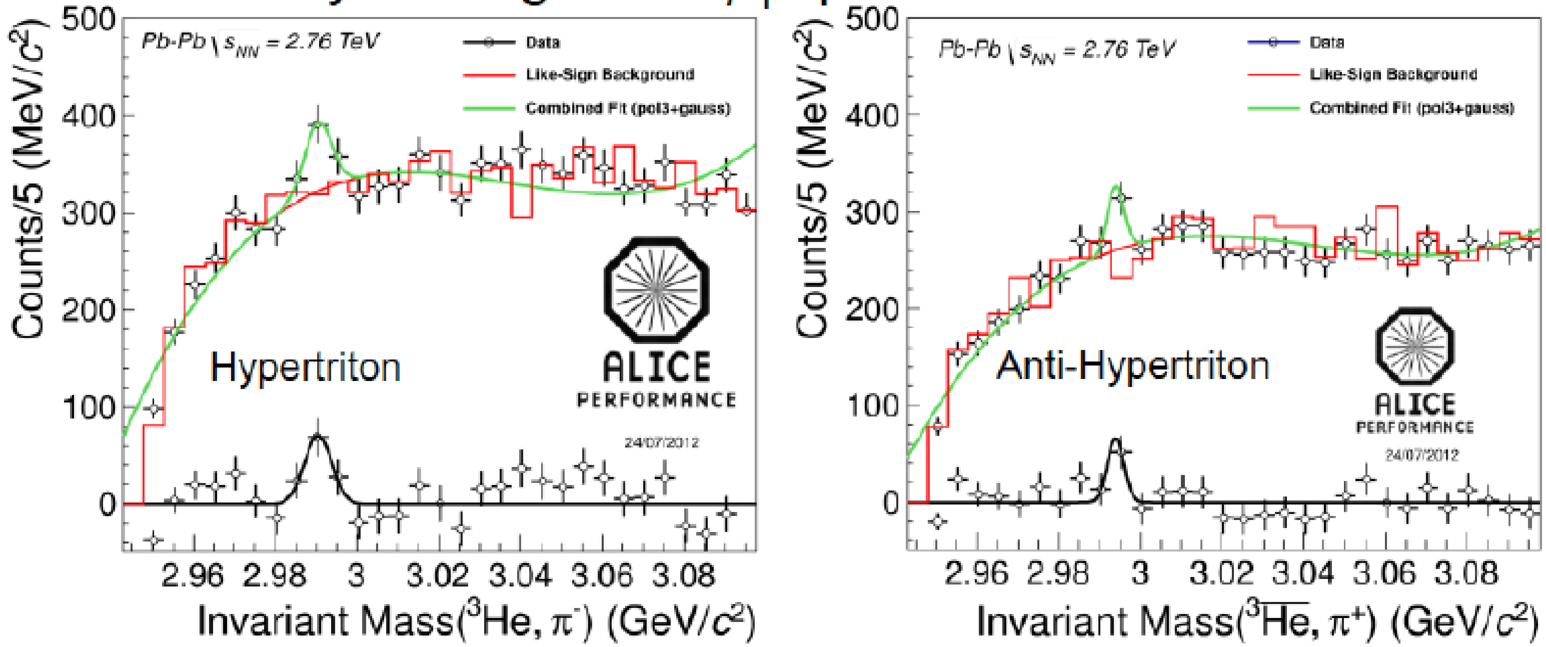
P. Camerini , NUFRA2013 (Kemer, Turkey) ; Nucl. Phys. A904-905 (2013) 547c

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

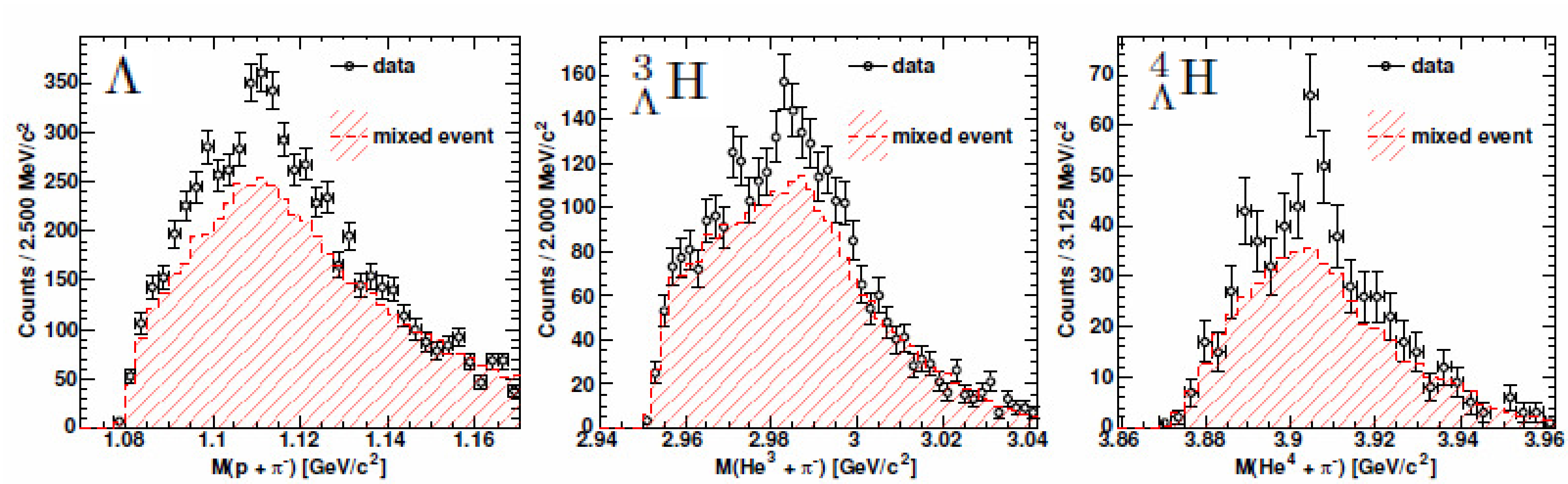
T.Saito, (for HypHI),
NUFRA2011 conference, and
Nucl. Phys. A881 (2012) 218;
Nucl. Phys. A913 (2013) 170.

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

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. Göküzüm[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],

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

Theoretical descriptions of strangeness production within transport codes

old models : e.g., Z.Rudy, W.Casing et al., *Z. Phys.A351(1995)217*
INC, QMD, BUU

GiBUU model: Th.Gaitanos, H.Lenske, U.Mosel , *Phys.Lett. B663(2008)197,*
(+SMM) *Phys.Lett. B675(2009)297*

PHSD model: E.Bratkovskaya, W.Cassing, … *Phys. Rev. C78(2008)034919*

DCM (INC) : JINR version: K.K.Gudima et al., *Nucl. Phys. A400(1983)173, ...*
(+QGSM+SMM) *Phys. Rev. C84 (2011) 064904*

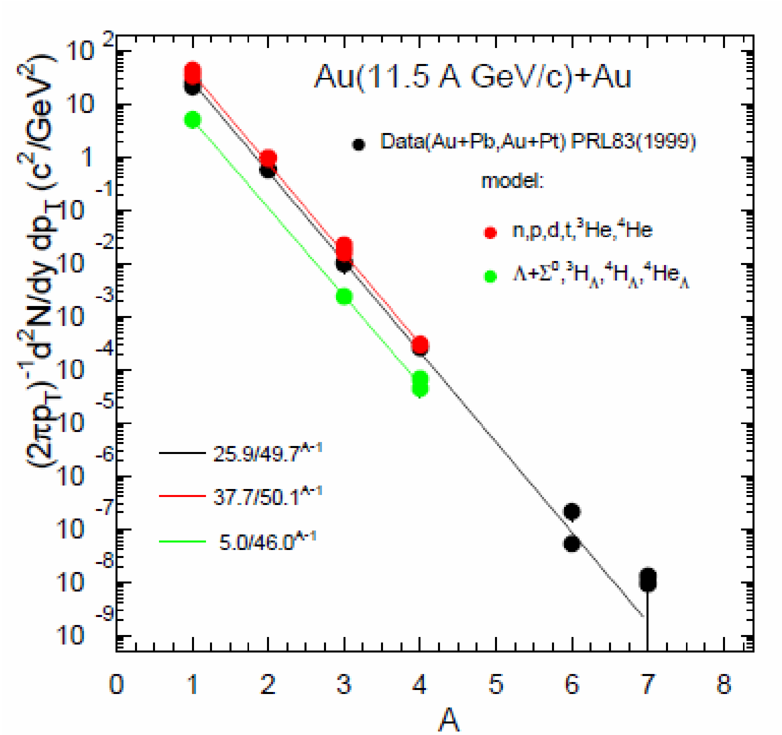
UrQMD approach: S.A. Bass et al., *Prog. Part. Nucl. Phys. 41 (1998)255.*
M.Bleicher et al. *J. Phys.G25(1999)1859, ... ,* J.Steinheimer ...

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

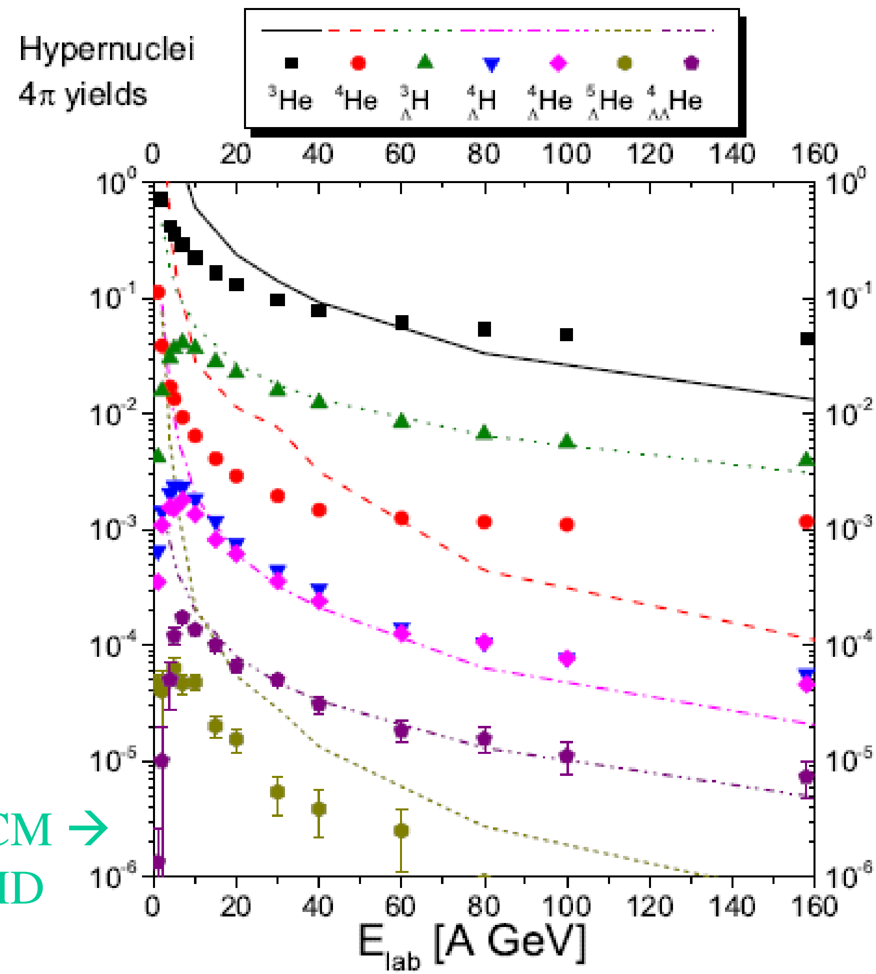
Production of light nuclei in central collisions : Au+Au

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

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.

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)

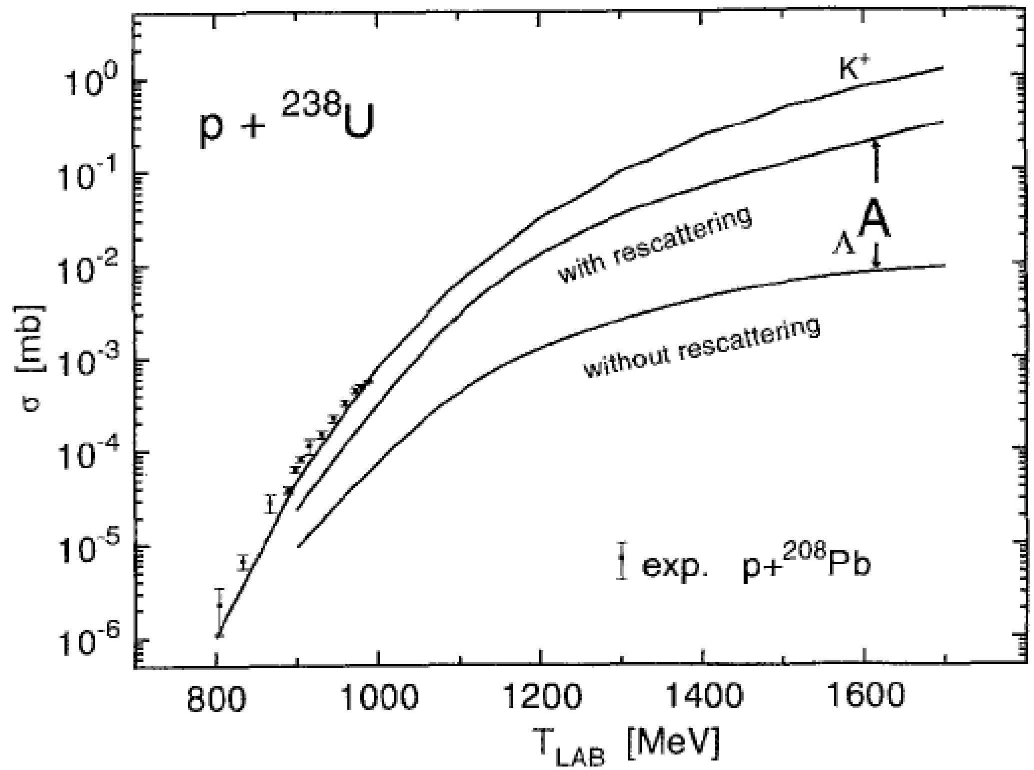


Fig. 5. The energy dependence of the $_{\Lambda}A$ production cross section for the cases with and without Λ hyperon-N rescattering. For relative orientation we also compare the calculated total K^+ cross section with the inclusive K^+ data from [30] for $p + {}^{208}$Pb

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.

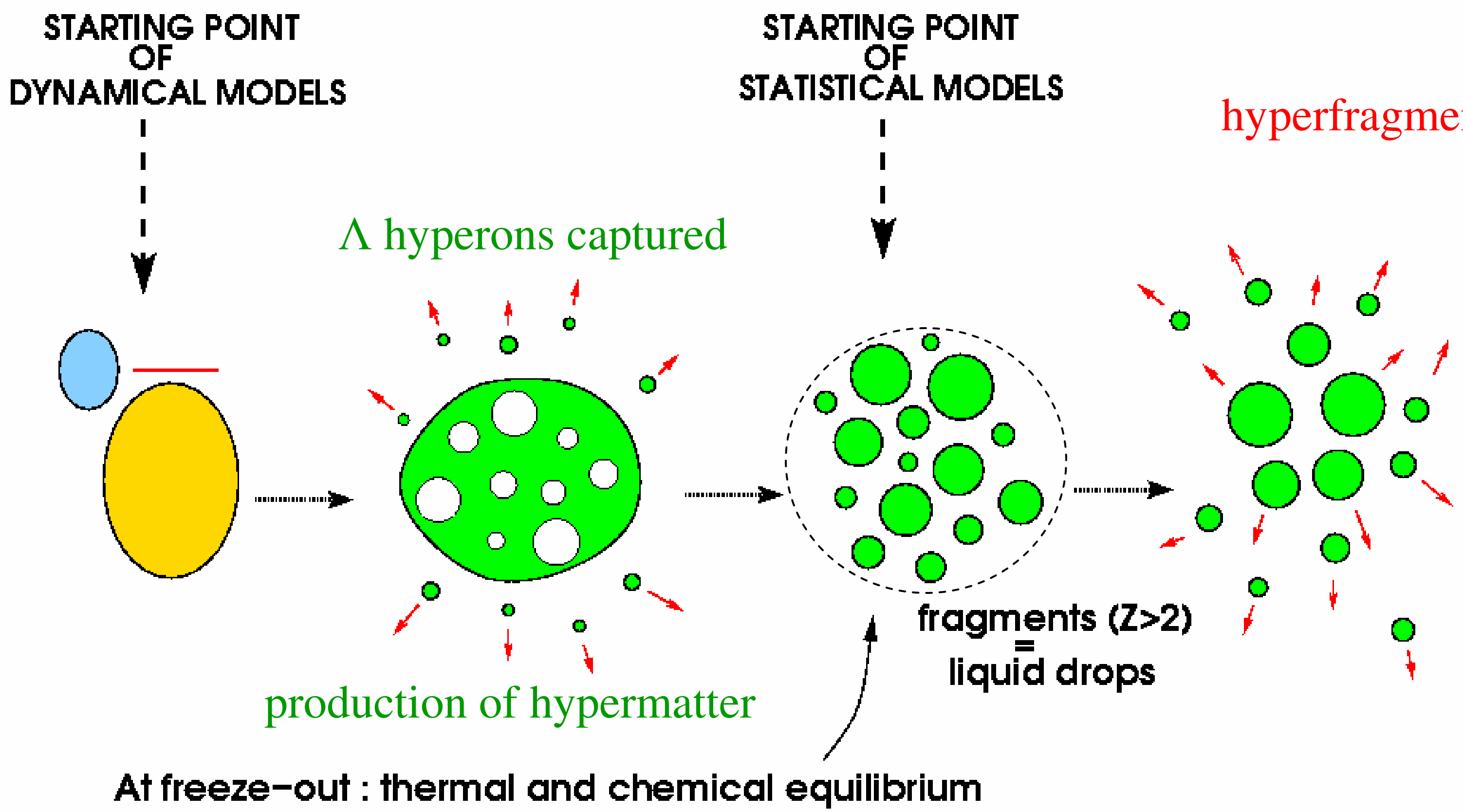
A.S.Botvina and J.Pochodzalla, Phys. Rev.C76 (2007) 024909

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

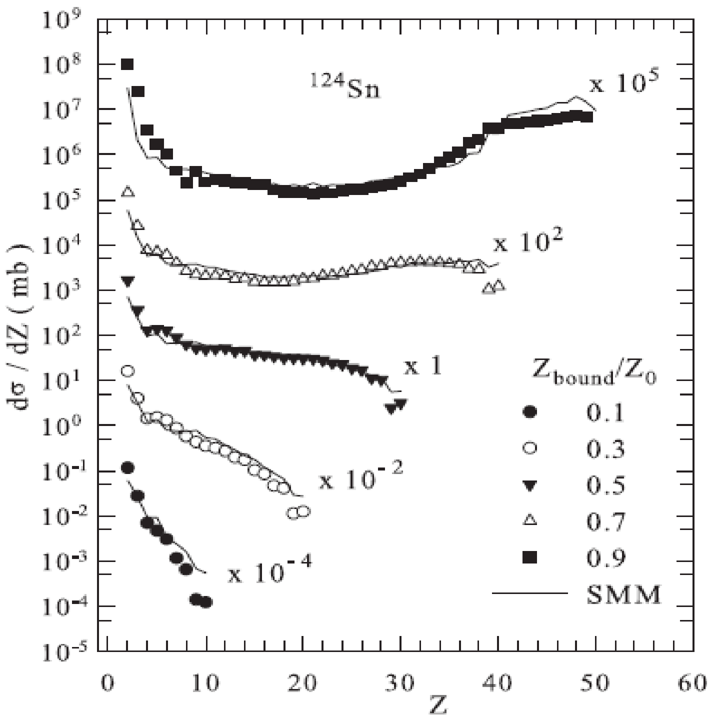


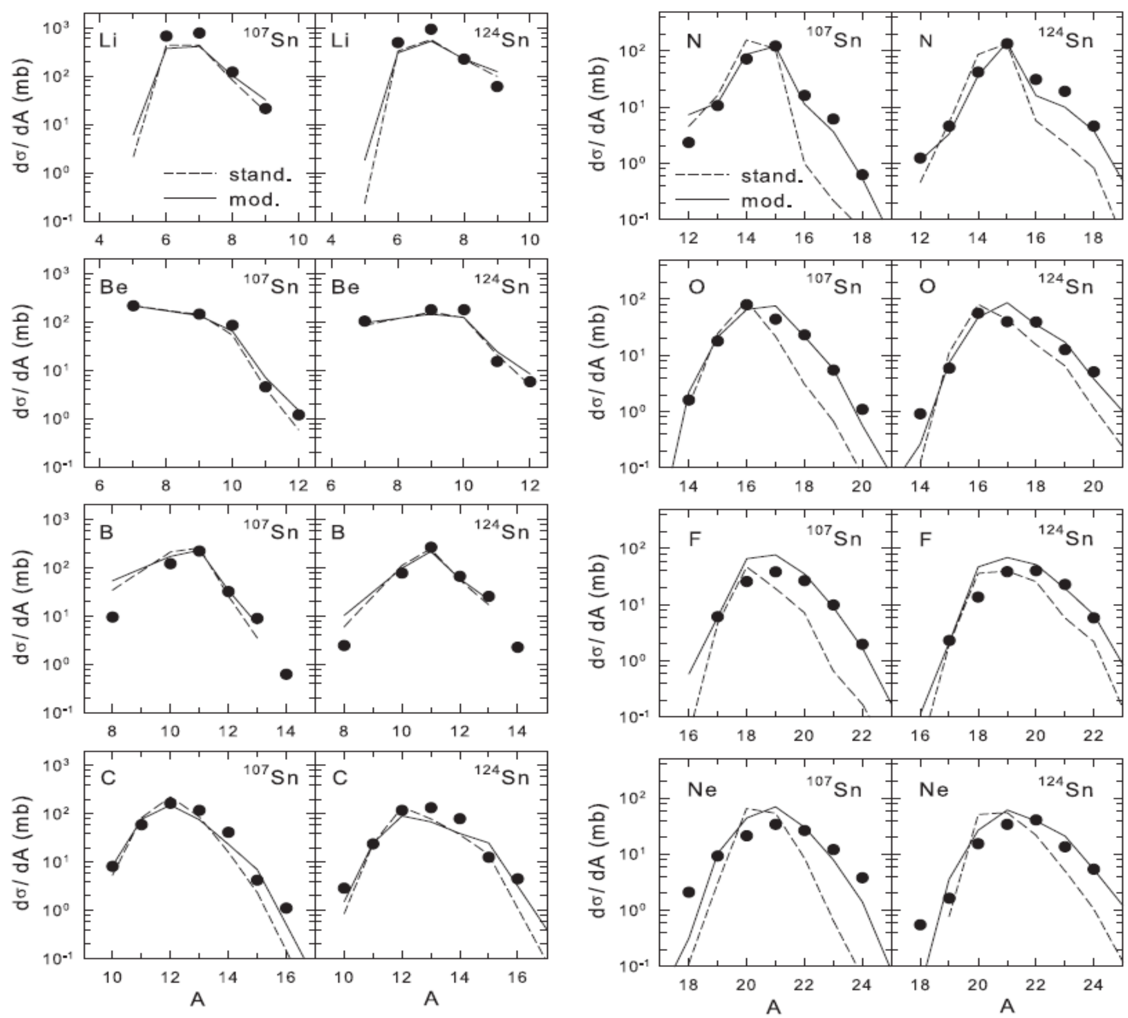
R.Ogul et al. PRC **83,** 024608 (2011) **ALADIN@GSI**

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.





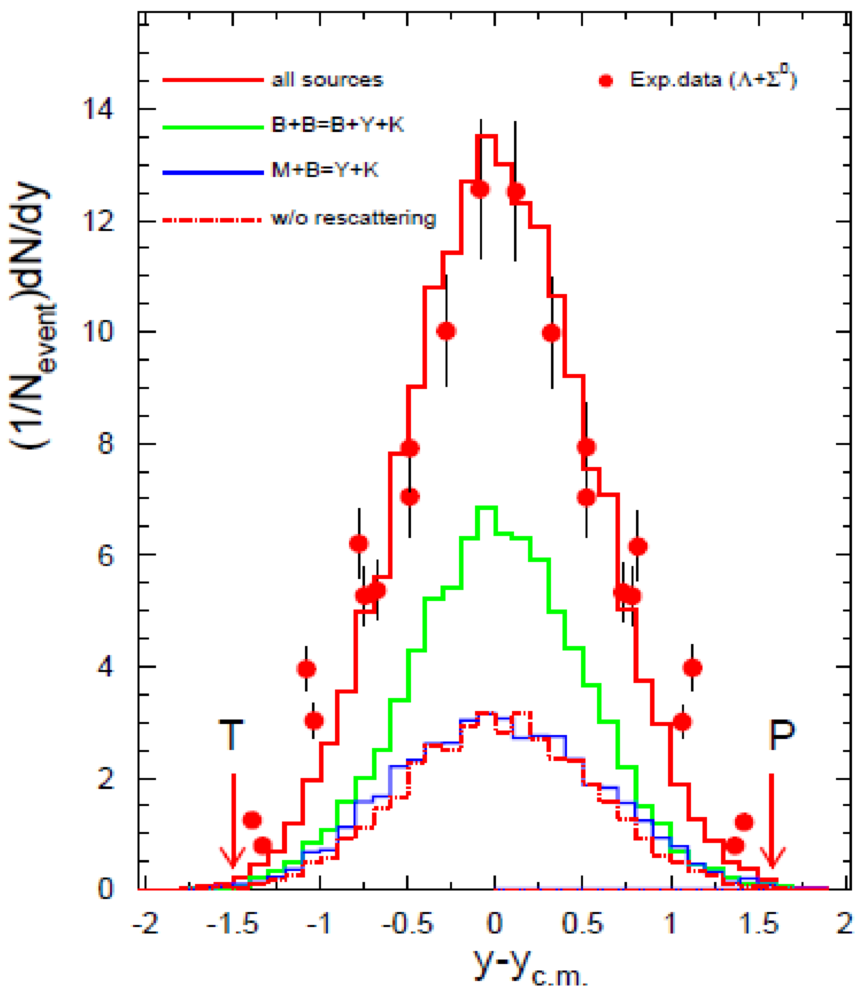
Statistical (chemical) equilibrium is established at break-up of hot projectile residues ! In the case of strangeness admixture we expect it too !

Verification of the models
DCM

Hyperon production
in central collisions
Au(11 A GeV/c)+Au

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

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

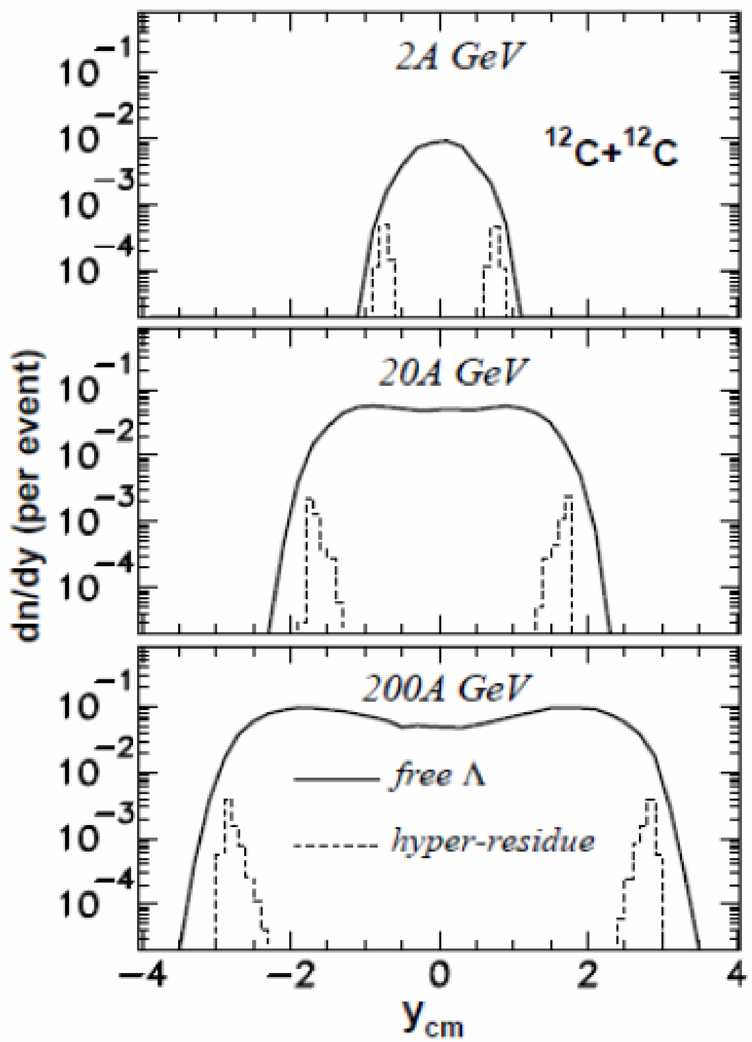


Rapidity distribution of free hyperons and hyper-residues in relativistic ion collisions (DCM calculations)

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

Wide distributions of produced Lambda-hyperons up to spectator rapidities at all incident energies. A stochastic process related to secondary interactions leads to the hyperon capture by residues.

The evolution to a double peak distribution with increasing energy tell us that the Lambda production is mainly caused by secondary processes too.

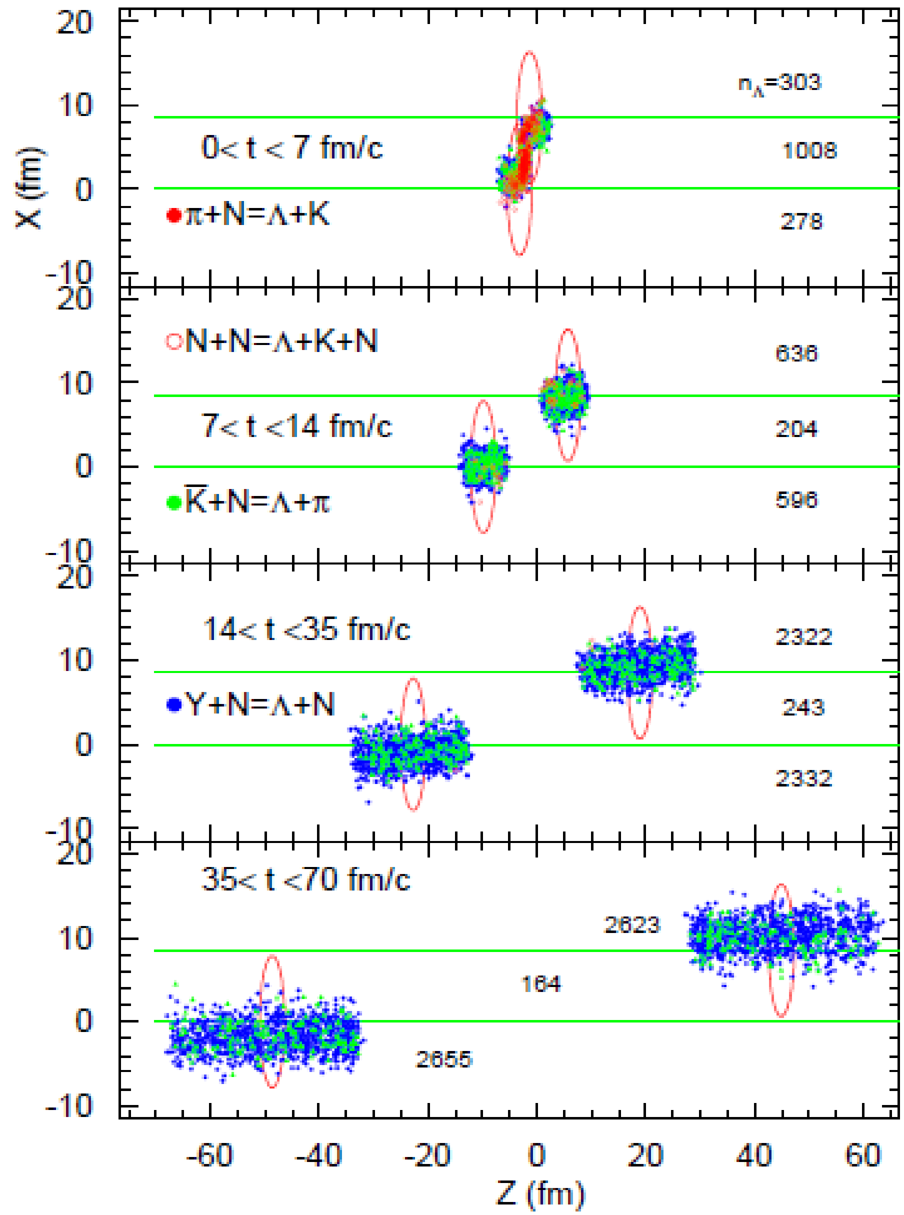


Peripheral relativistic ion collisions: Au (20 A GeV) + Au

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

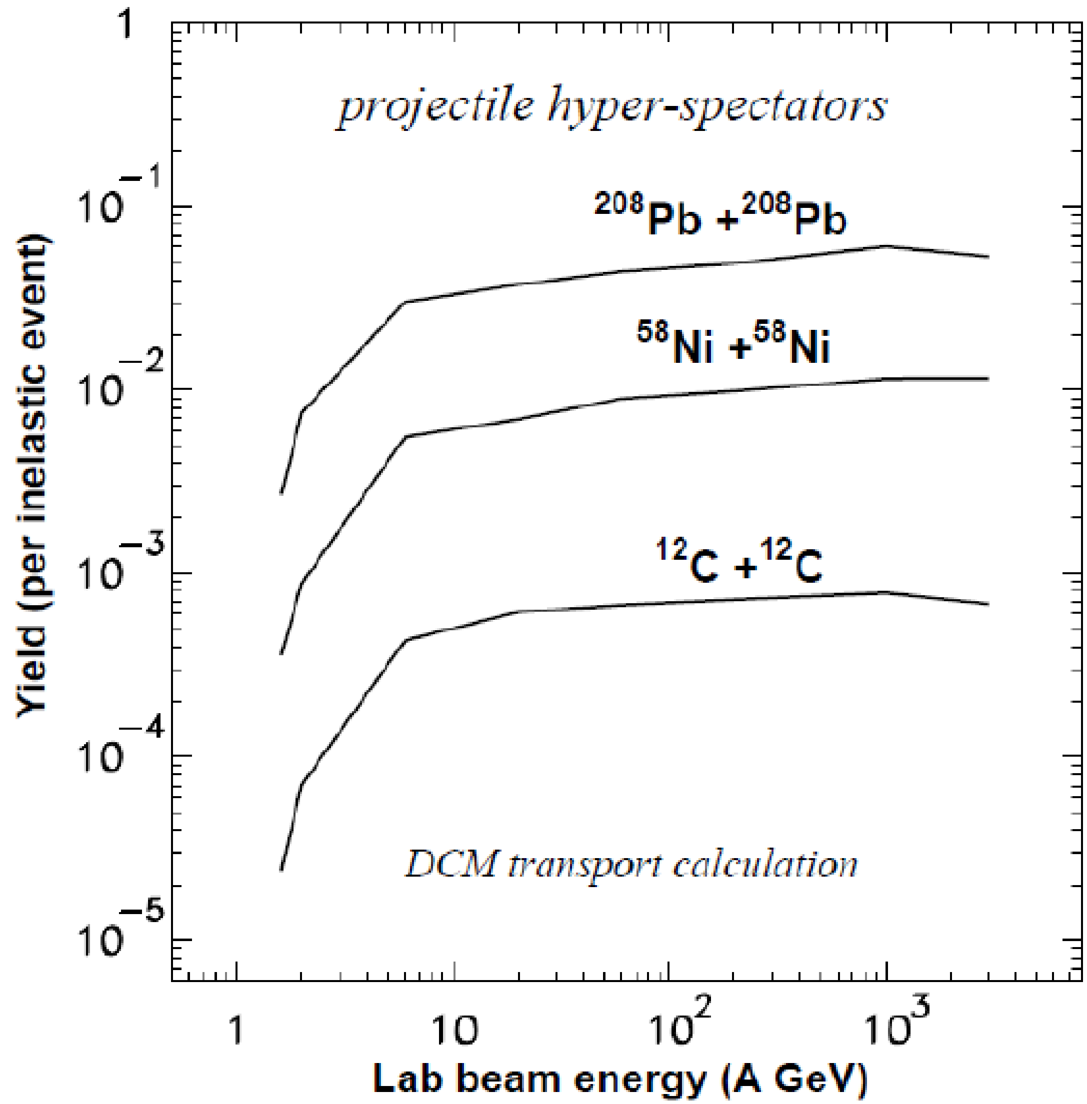
Yield of hypernuclei in peripheral collisions

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

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

Yield is integrated over all impact parameters.

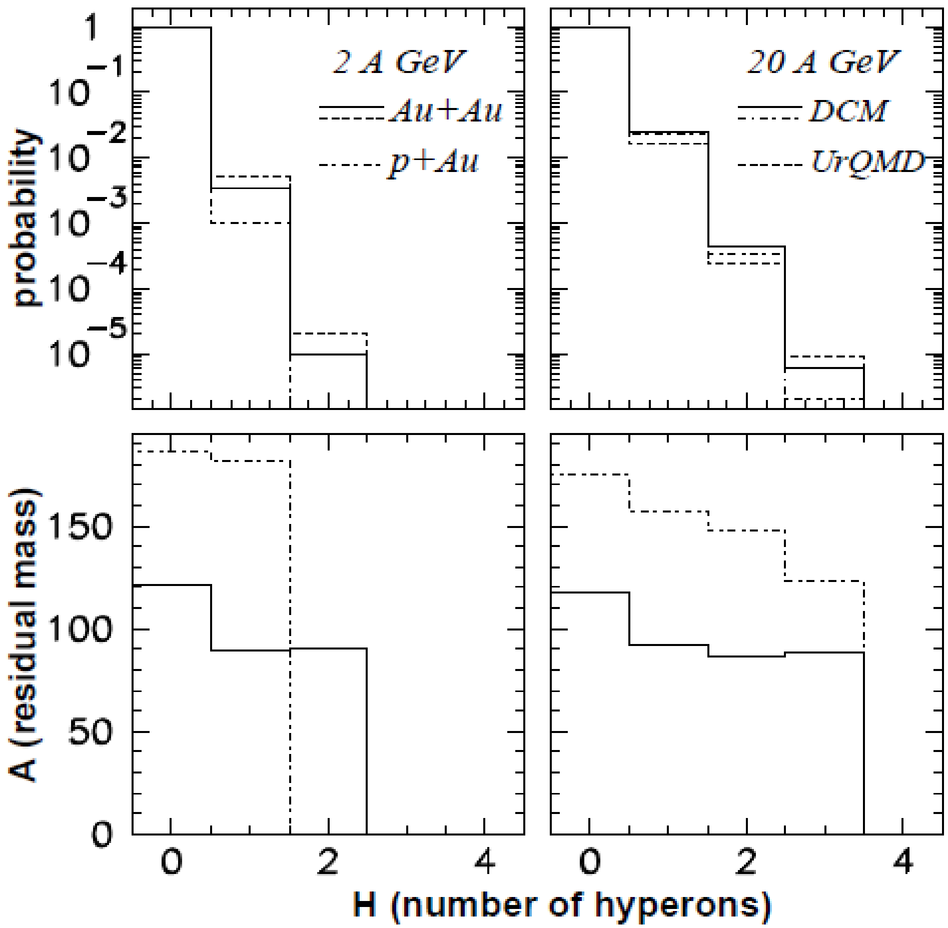
Reactions can be studied at GSI/FAIR and JINR/NICA facilities as well on operating RHIC and LHC.



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



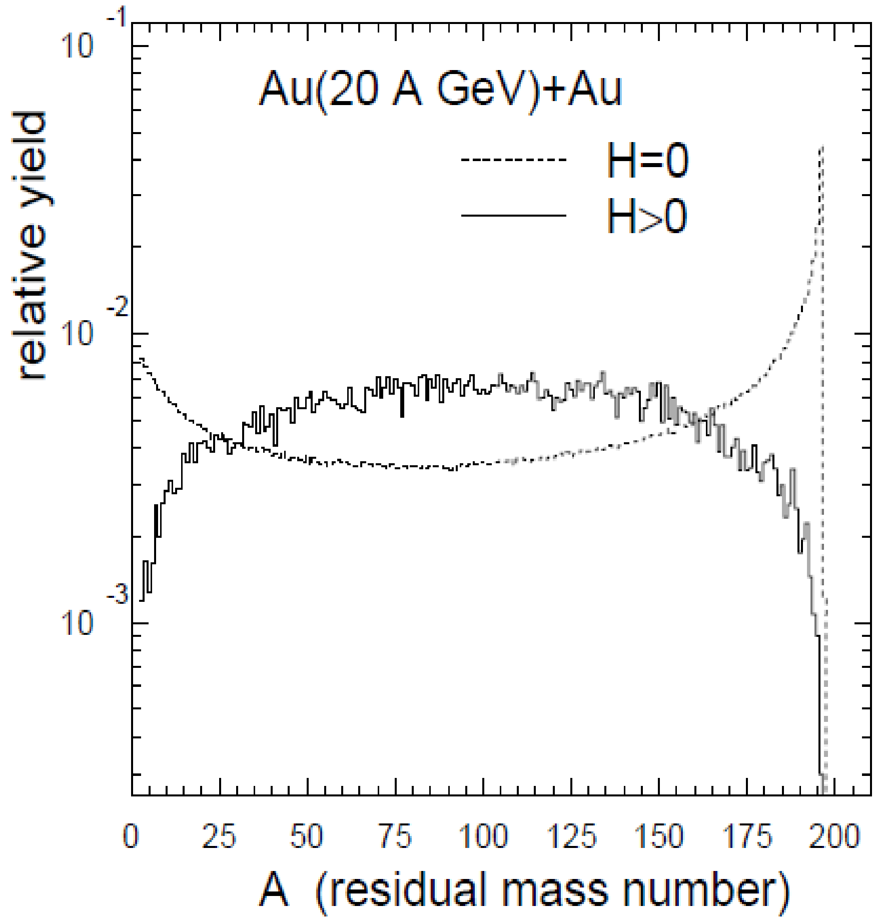
Integrated over all impact parameters

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

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

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)

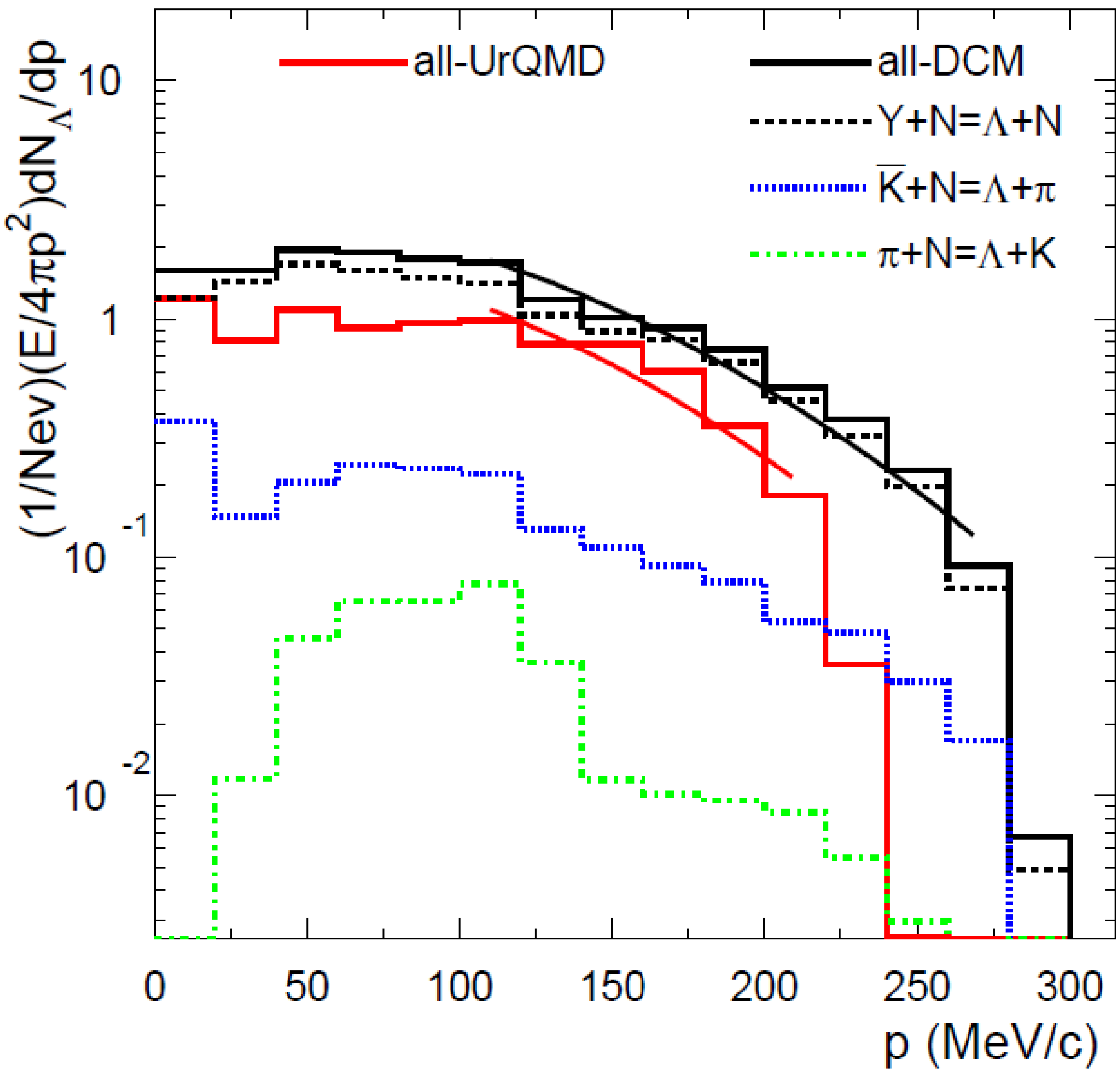


6b : H=0

200mb: H>0

Momentum distribution of Lambda captured in the spectators

(Connection of the potential capture and the coalescence)



W.Neubert and A.S.Botvina, EPJ **A7** , 101 (2000)

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 $(|\mathbf{V}_b - \mathbf{V}_A|^{**}2) < C$ the particle b is included in the A-cluster.
2) Step by step numerical approximation**.**

A.Botvina, E.Bratkovskaya, J.Steinheimer, …

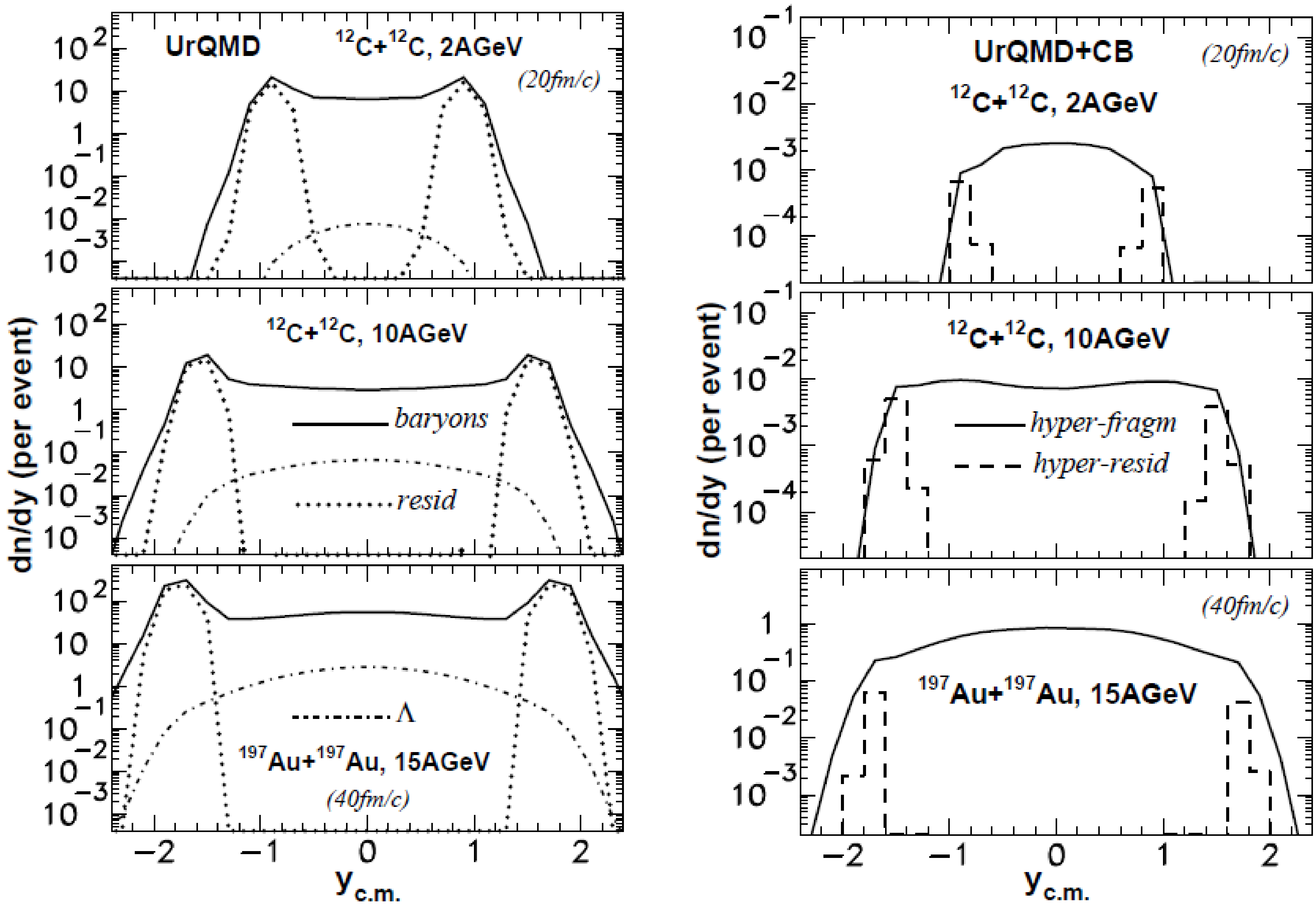
Combination of transport UrQMD and HSD models with CB:

1) 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.
2) Spectators' nucleons are always included in the residues.

Investigation of fragments/hyperfragments at all rapidities !

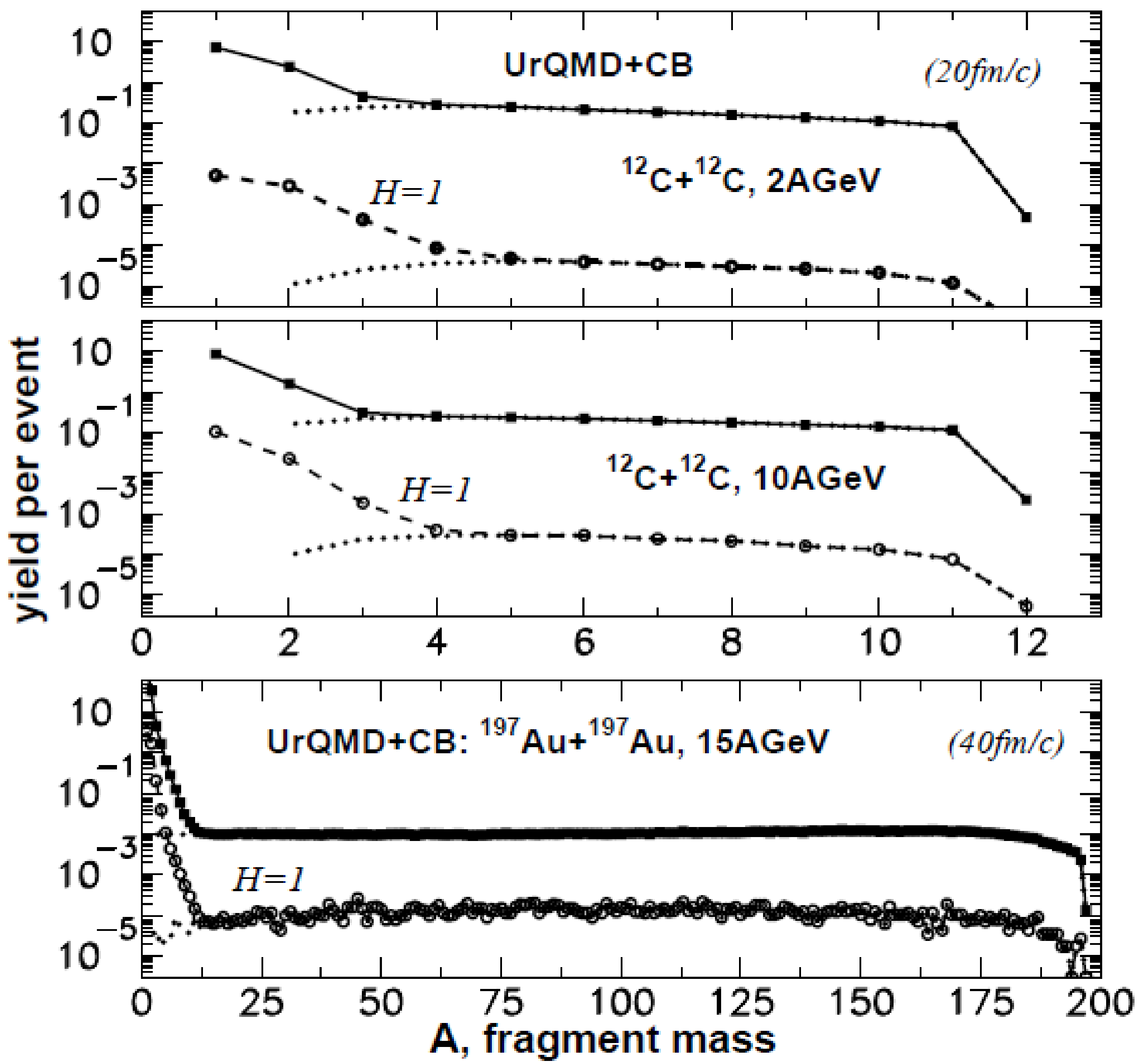
preliminary

baryons, Lambdas, hyper-fragments, hyper-residues



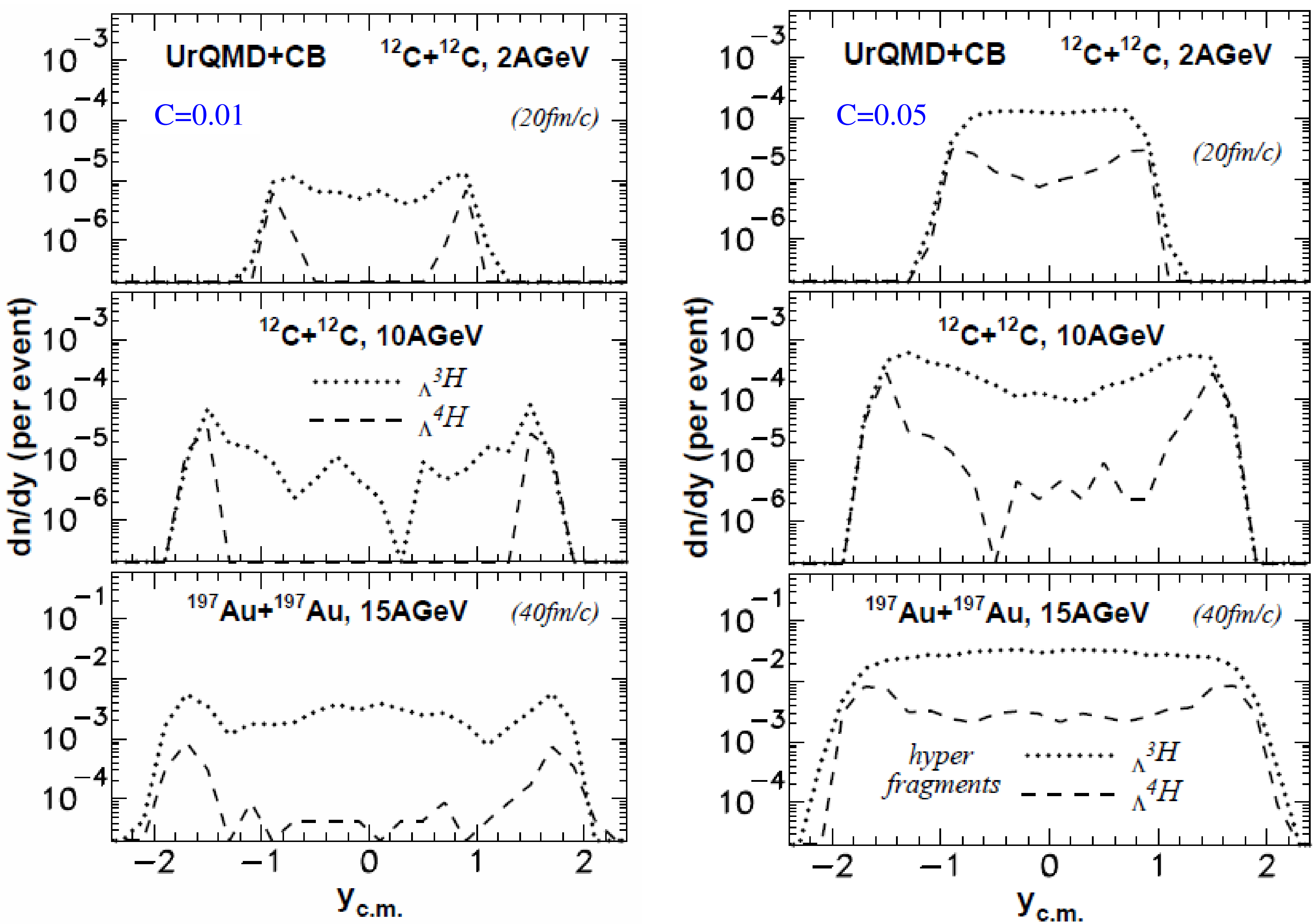
preliminary

normal fragments and hyper-fragments (with residue contribution)



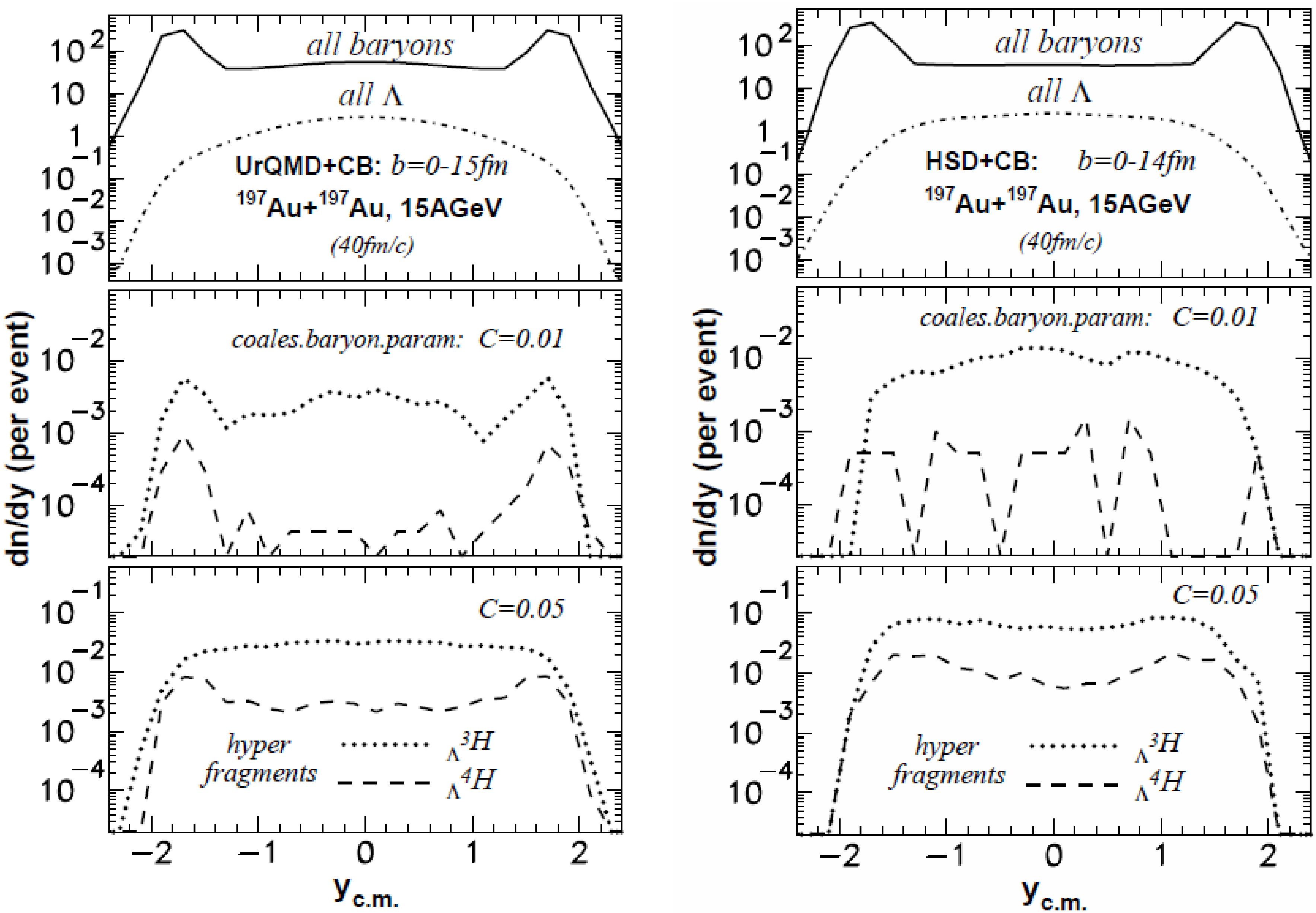
preliminary

light hyper-fragments



preliminary

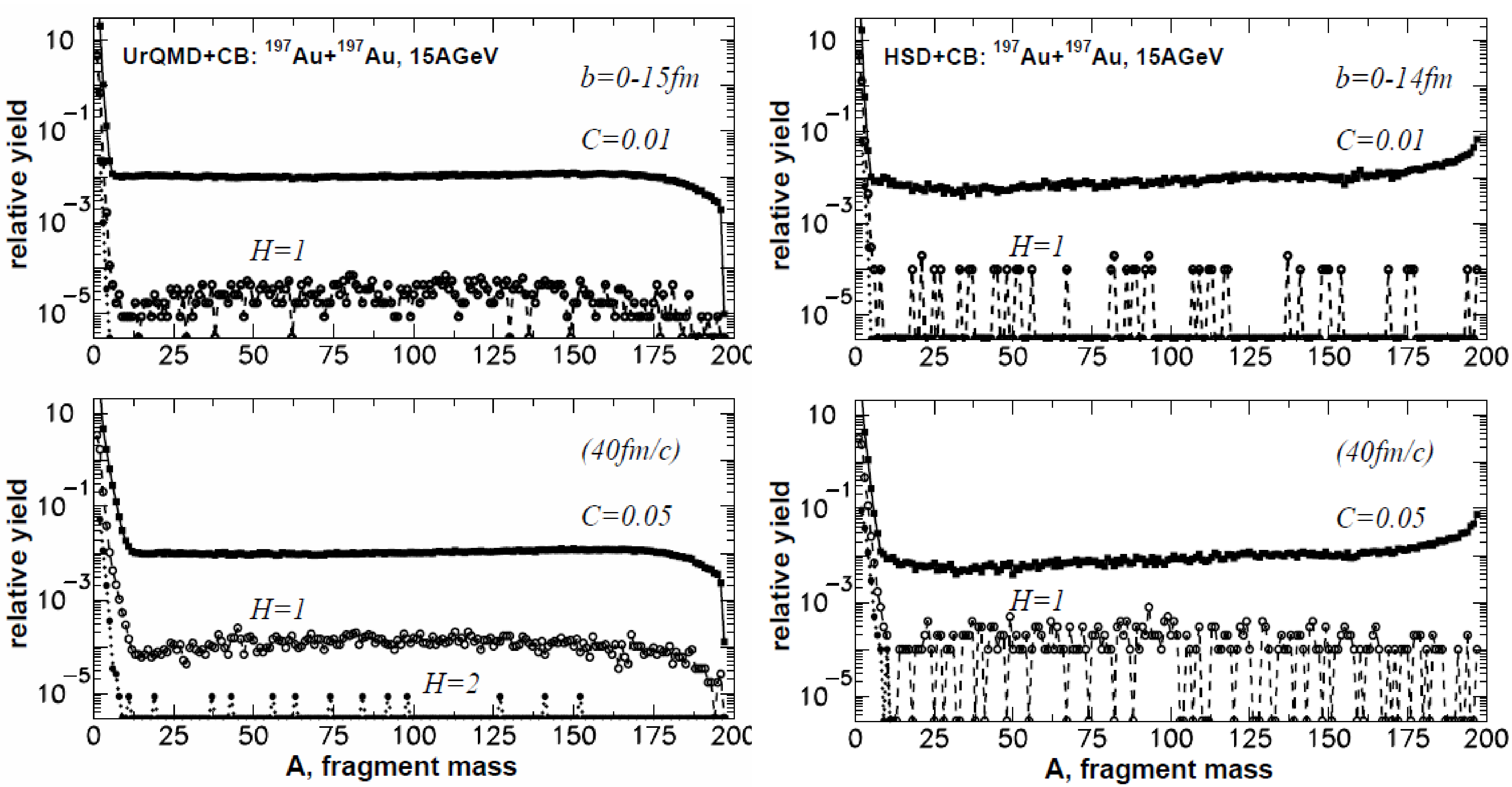
Transport models are consistent (UrQMD, HSD)



preliminary

Transport models are consistent (UrQMD, HSD)

Large fragments and hyperfragments:



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***

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

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

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

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

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

parameters ≈ Bethe-Weizsäcker formula:

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

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

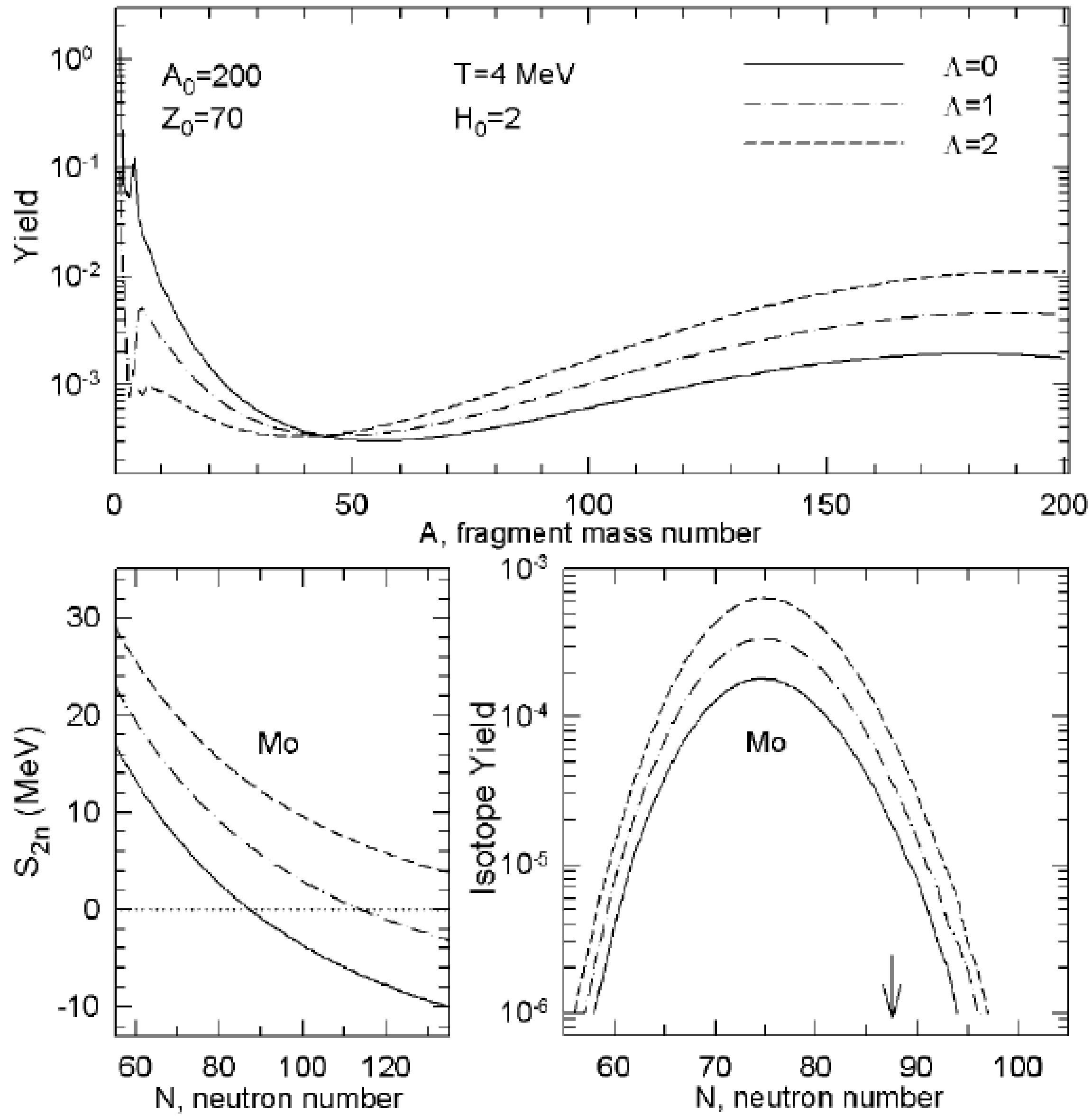
Break-up of excited hyper-residues

Normal nuclei + hypernuclei can be formed via evaporation, fission and multifragmentation processes.

Liquid-gas type phase transition in hyper-matter is expected at subnuclear densities.

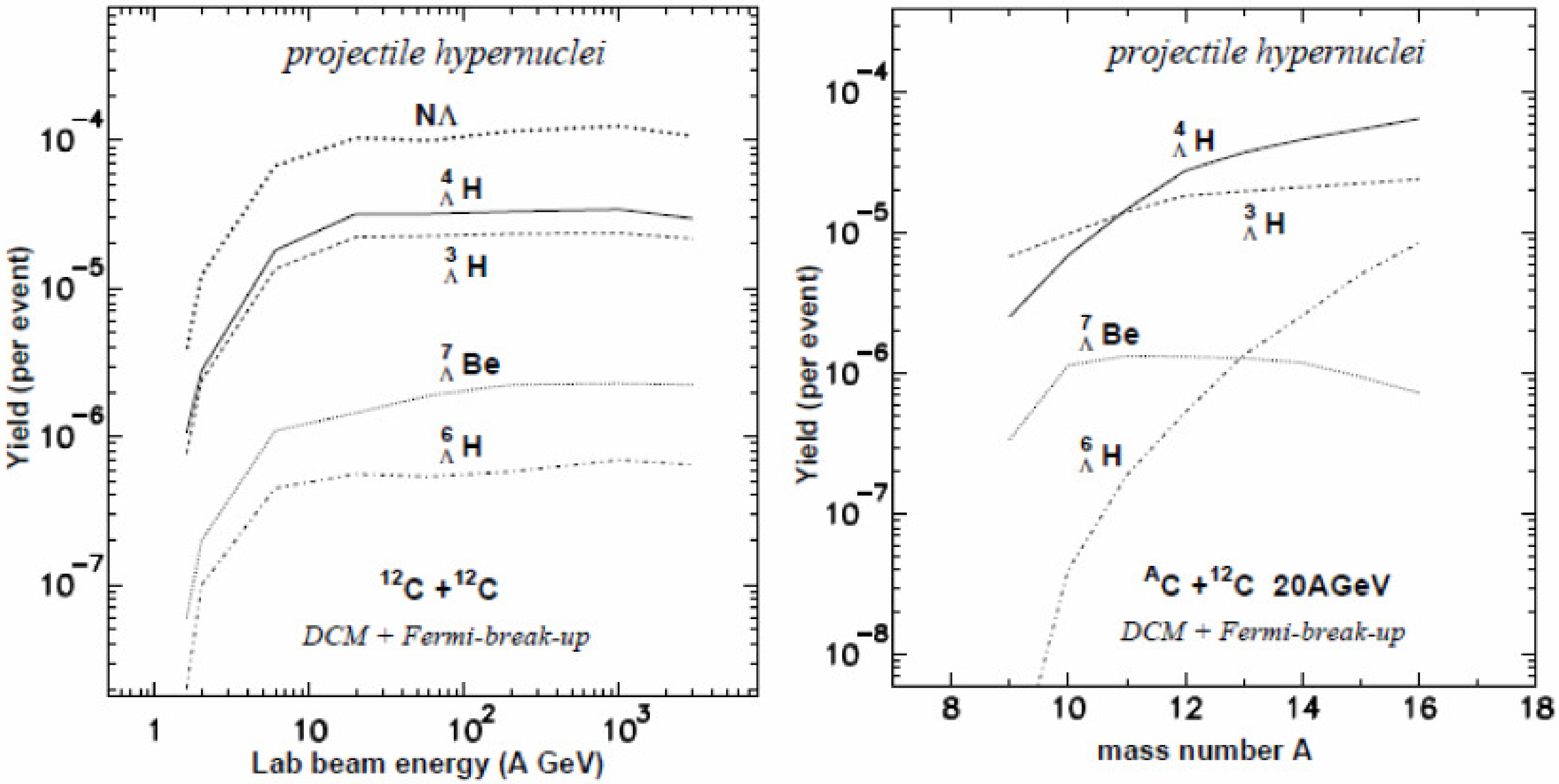
Very broad distributions of nuclei similar to ones in normal nuclear matter. At moderate temperatures hyperons concentrate in large species

Important: formed hypernuclei can reach beyond traditional neutron and proton drip-lines



N.Buyukcizmeci et al., PRC88 (2013) 014611

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.

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Conclusions

Peripheral collisions of relativistic ions and hadrons with nuclei are promising reactions for novel nuclear physics research at BM@N.

A mechanism of formation of hypernuclei:

Relativistic hadron and peripheral ion collisions : Strange baryons (Λ, Σ, Ξ, …) are transported to the spectator residues and are captured in nuclear matter. These strange systems are excited and after decay of such systems hypernuclei of all sizes (and isospin), including exotic weakly-bound states, multi-strange nuclei, and those beyond the drip-lines can be produced.

Advantages over other reactions producing hypernuclei: there is no limit on sizes and isotope content of produced nuclei; probability of their formation is very high; a large strangeness can be deposited in nuclei.
After decay of such hypernuclei exotic normal nuclei can be obtained.
EOS of hypermatter at subnuclear density can be investigated.

Description of elementary interactions in DCM transport code