Production of Hypernuclei in Collisions of Relativistic Ions

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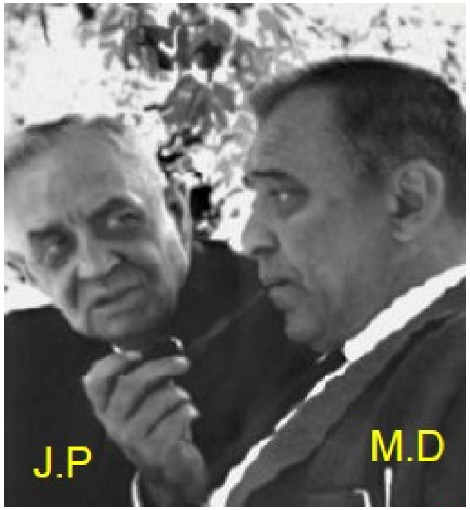
Frankfurt am Main, Germany

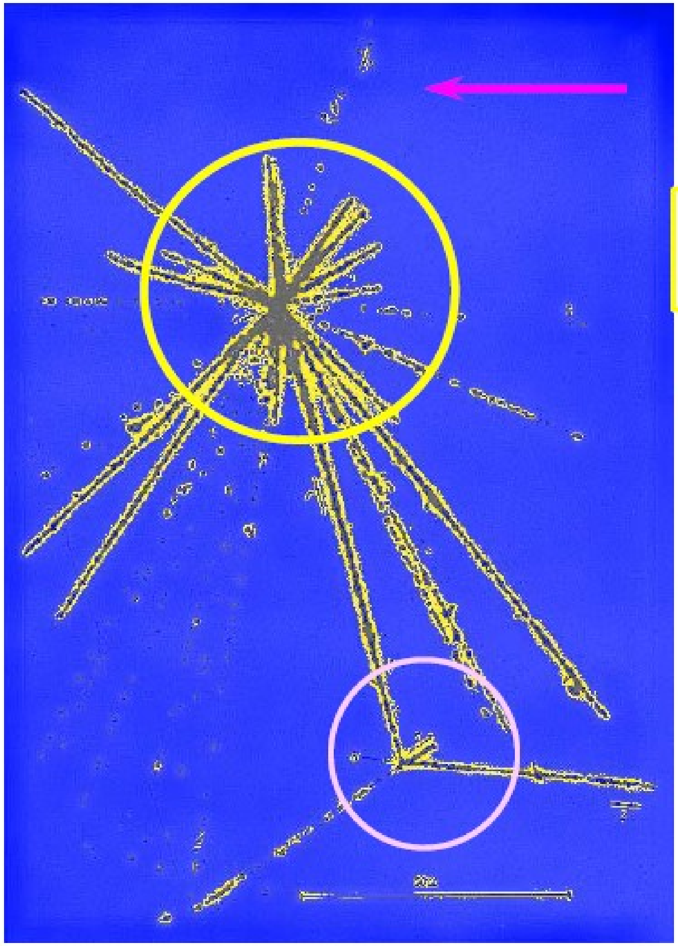
April 2-4, 2012

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

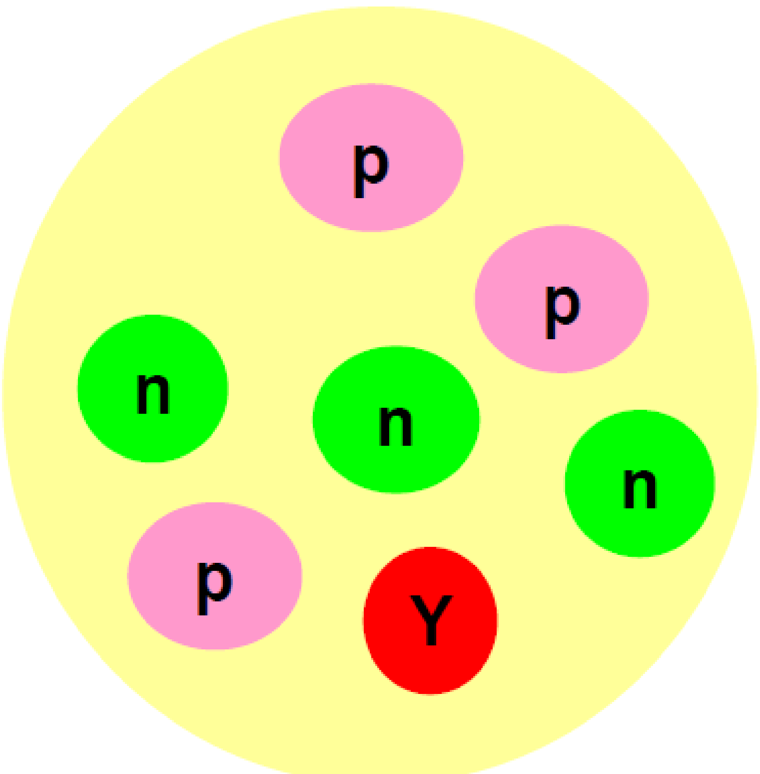
From the first star, 21 Tracks => $9\alpha + 11H + 1\ _{\Lambda}X$

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.**

Hypernucleus: Hyperons Bound in Nuclei

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



Notation:

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

Y = Hyperon

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

$A = N_n + N_p + N_Y$

Why hypernuclei ?

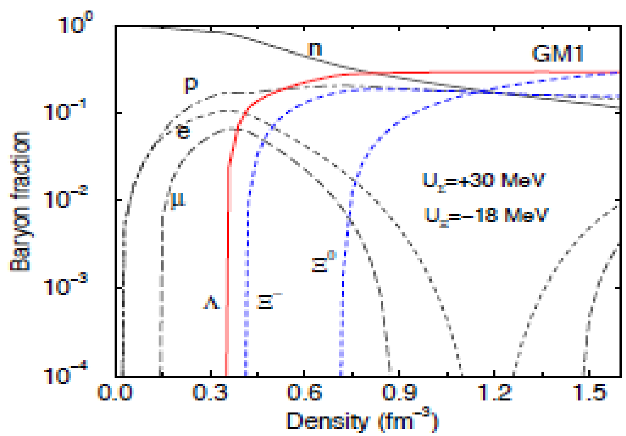
QCD motivated theory development

Micro-laboratory with protons, neutrons, and hyperons; lump of strange matter;

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

Astrophysics

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



Nuclear physics

Extention of nuclear charts into strangeness, limits of nuclear stability, e.g., ...

^5H unbound exotic nucleus

glue-like role of Λ -hyperon

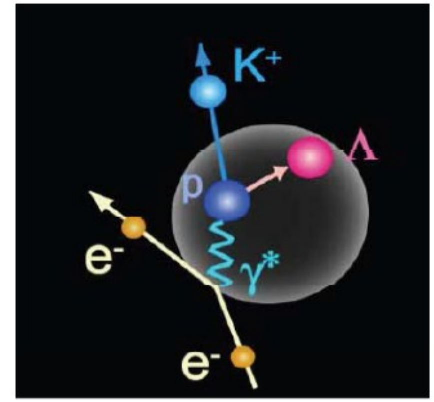
$^6_\Lambda H$ bound exotic hypernucleus

Production of Hypernuclei in Hadron Reactions:

- Single-Λ hypernuclei
- (π^+,K^+), (K^-,π^-), $(e,e'K^+)$
  CERN, BNL, KEK, CEBAF, DAΦNE, JPARC

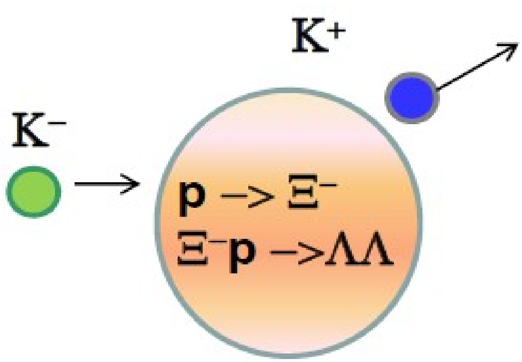
} Conversion: $N \rightarrow \Lambda$

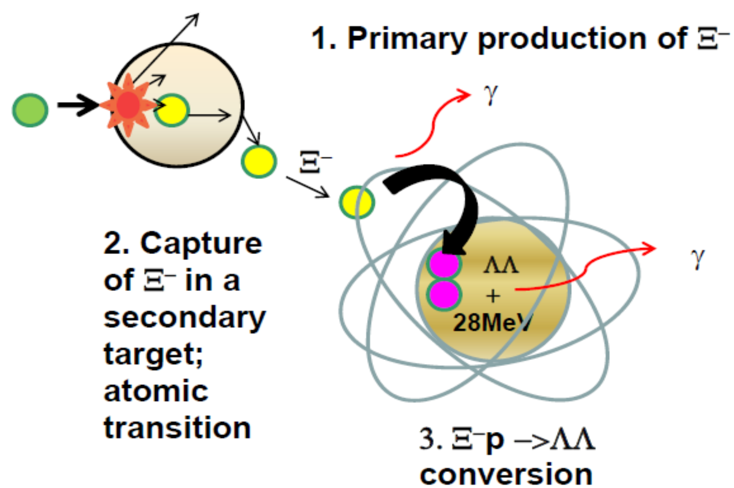
$e^- + p \rightarrow e^- + \Lambda + K^+$



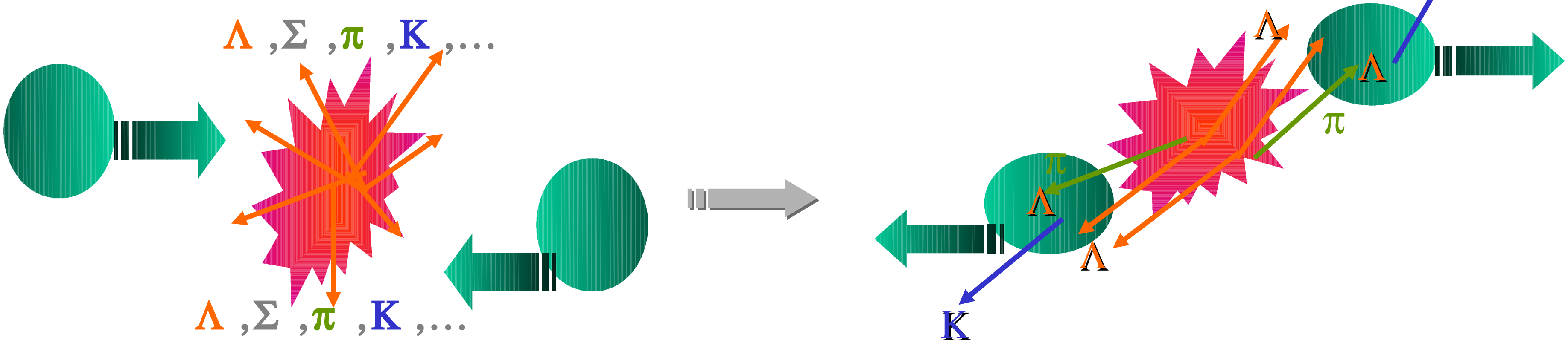
- Double-Λ hypernuclei
- (K^-,K^+)
  BNL, KEK

} Conversion: $p \rightarrow \Xi^-$: $\Xi^- p \rightarrow \Lambda\Lambda$





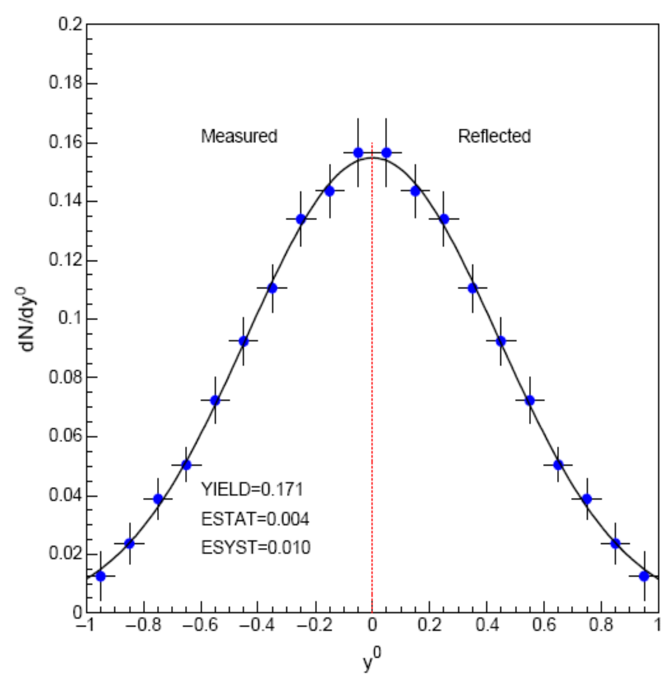
Relativistic Heavy-Ion collisions



- **Production of Hypermatter in Relativistic HIC**
  - Production of many hyperons by "participants",
  - Absorption of hyperons by excited "spectators"

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

Reconstructed Λ rapidity distribution for central ($\sigma_{\rm geo} = 350$ 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

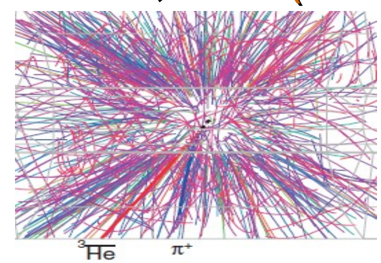
N_{event}	13.5×10^{9}	$^{3}_{\Lambda}H$
N_{count}	1220 ± 854	

STAR collaboration (RHIC):

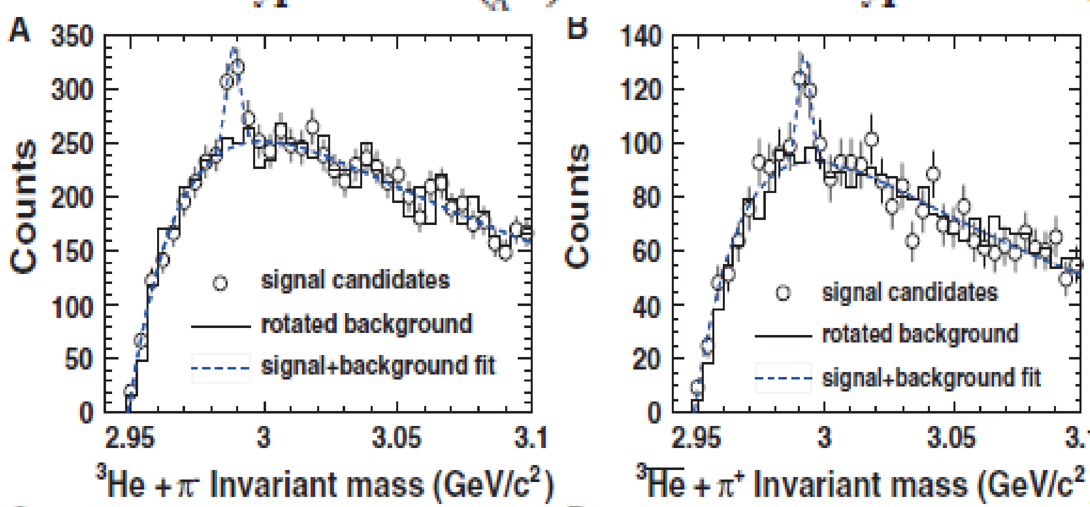
Science, 238 (2010) 58

Au + Au collisions at 200 A GeV

gas-filled cylindrical Time Projection Chamber



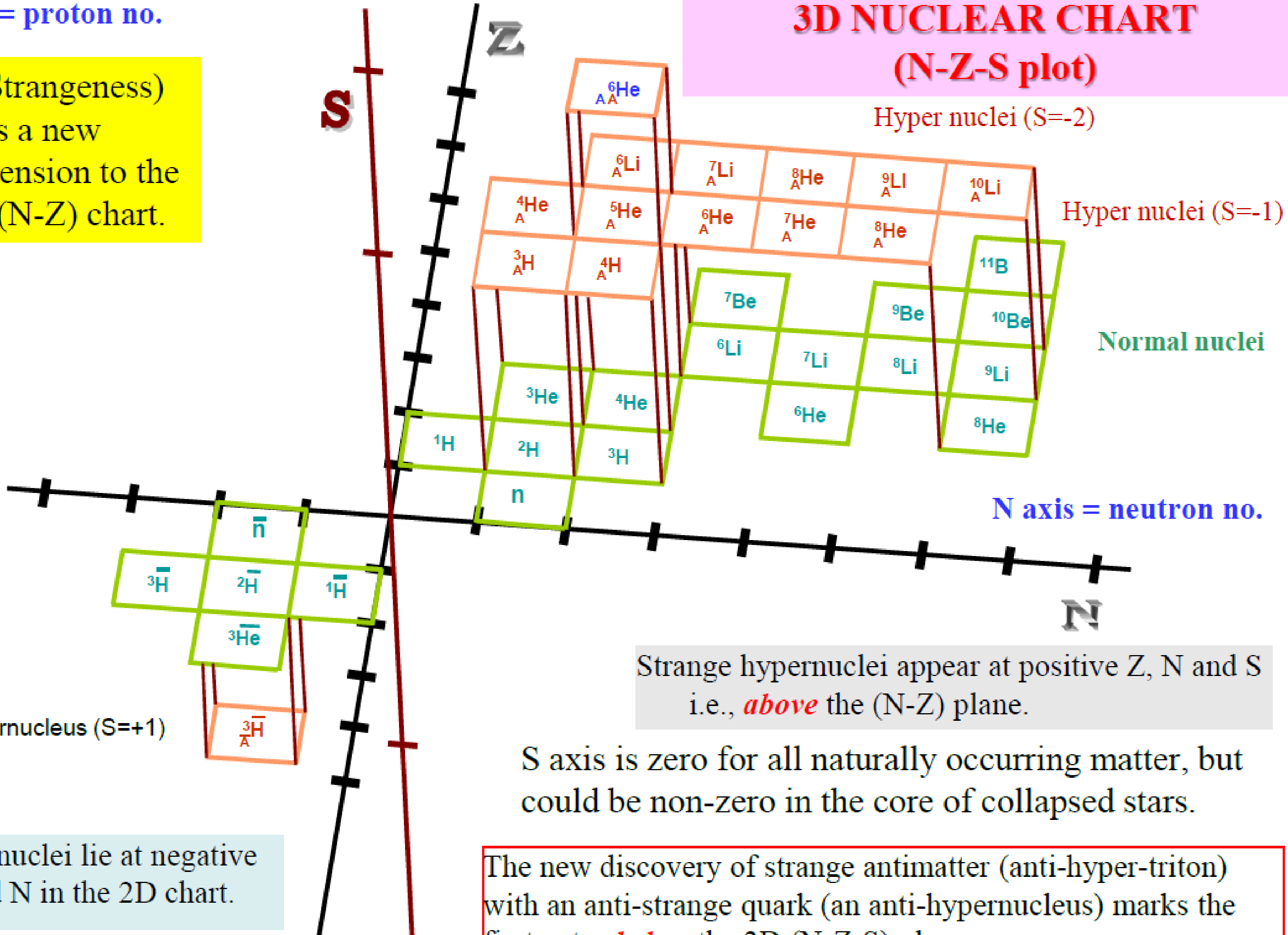
70 ± 17 antihypertritons ($^{3}_{\bar{\Lambda}}\overline{H}$) and 157 ± 30 hypertritons ($^{3}_{\Lambda}H$).



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

Z axis = proton no.

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.

Theoretical descriptions of strangeness production within transport codes

....

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

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

INC approach: JINR version – DCM : K.K.Gudima et al.,
(+QGSM+...) *Nucl. Phys. A400(1983)173, ...*
arXiv:0709.1736 [nucl-th]

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

Main channels for production of strangeness in individual hadron- nucleon collisions: BB→BYK , Bπ →YK, ...

(like p+n→n+Λ+K^+, and secondary meson interactions, like

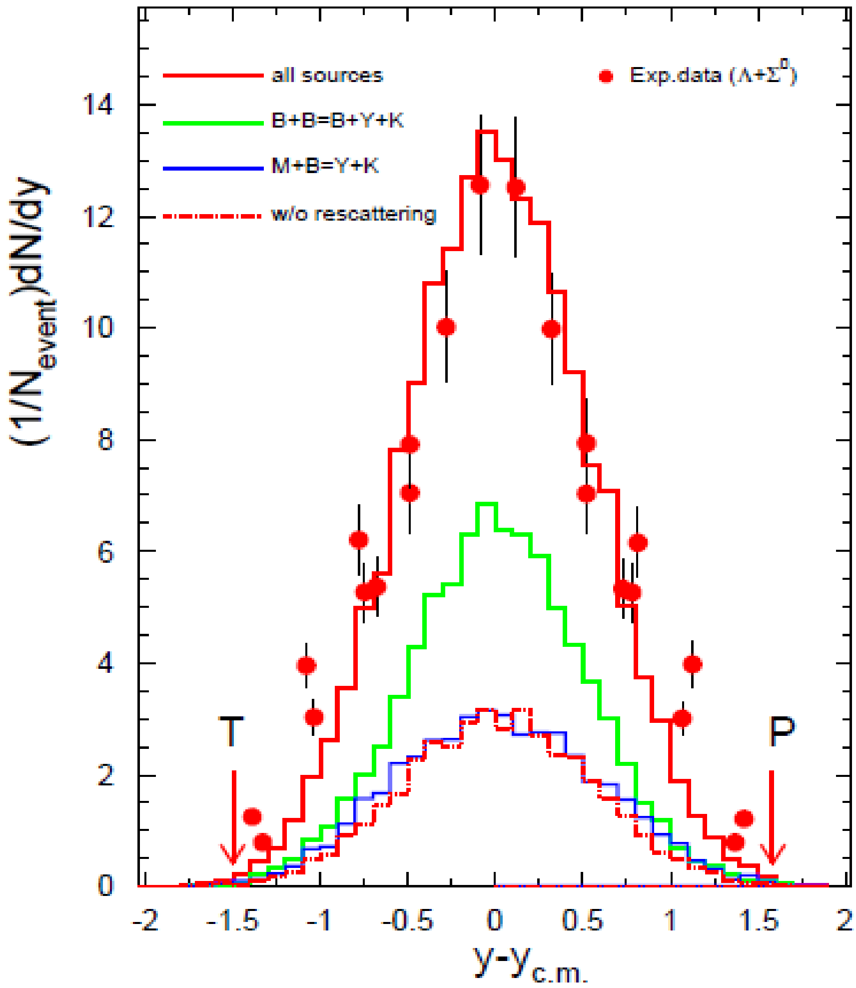
π +p→Λ+K^+). Rescattering of hyperons is important for their capture by spectators. Expected decay of produced hyperons and hypernuclei: 1) mesonic Λ→π +N ; 2) in nuclear medium nonmesonic Λ+N→N+N .

Verification of the models

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

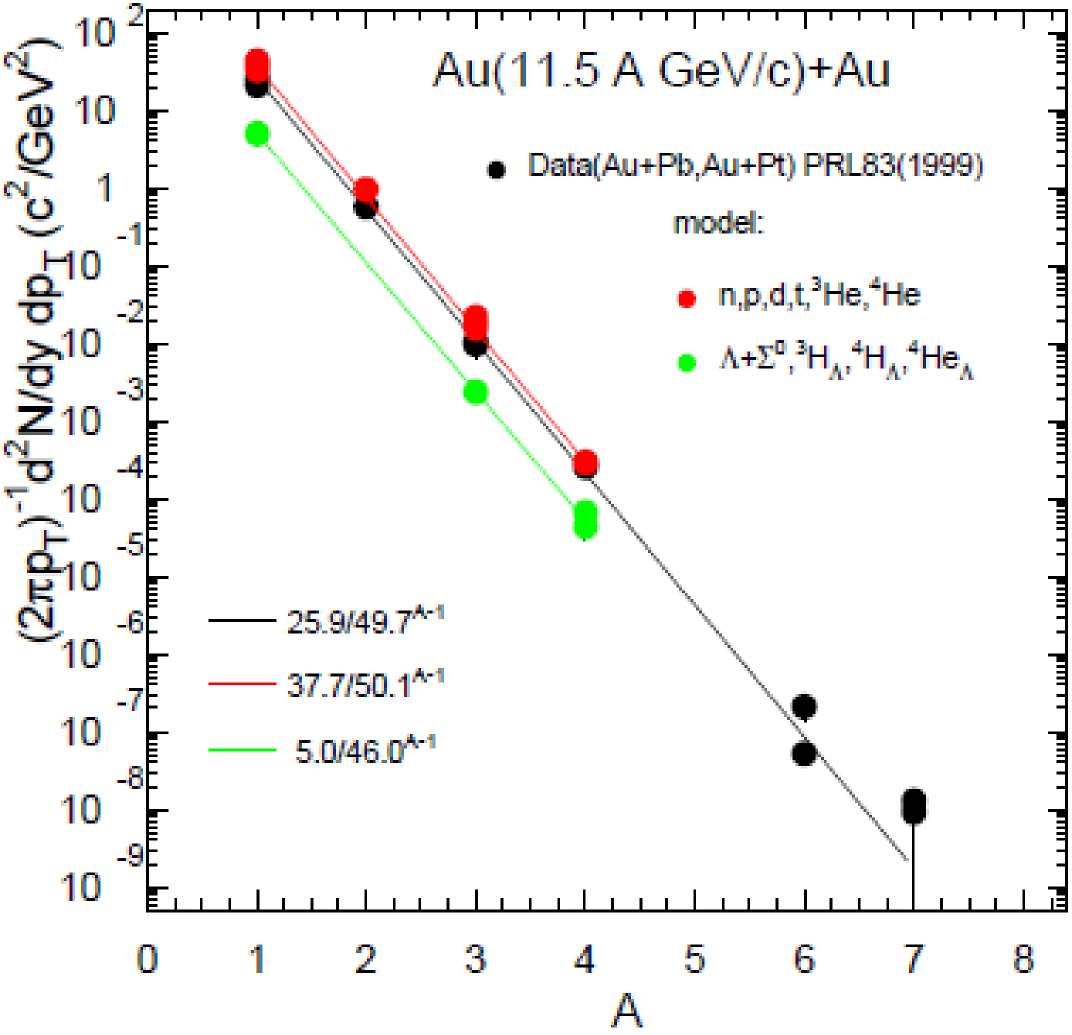


DCM + coalescence --- verification

Coalescence of baryons

momenta: $|\mathbf{P}_i - \mathbf{P}_0| \leq \mathbf{P}_c$

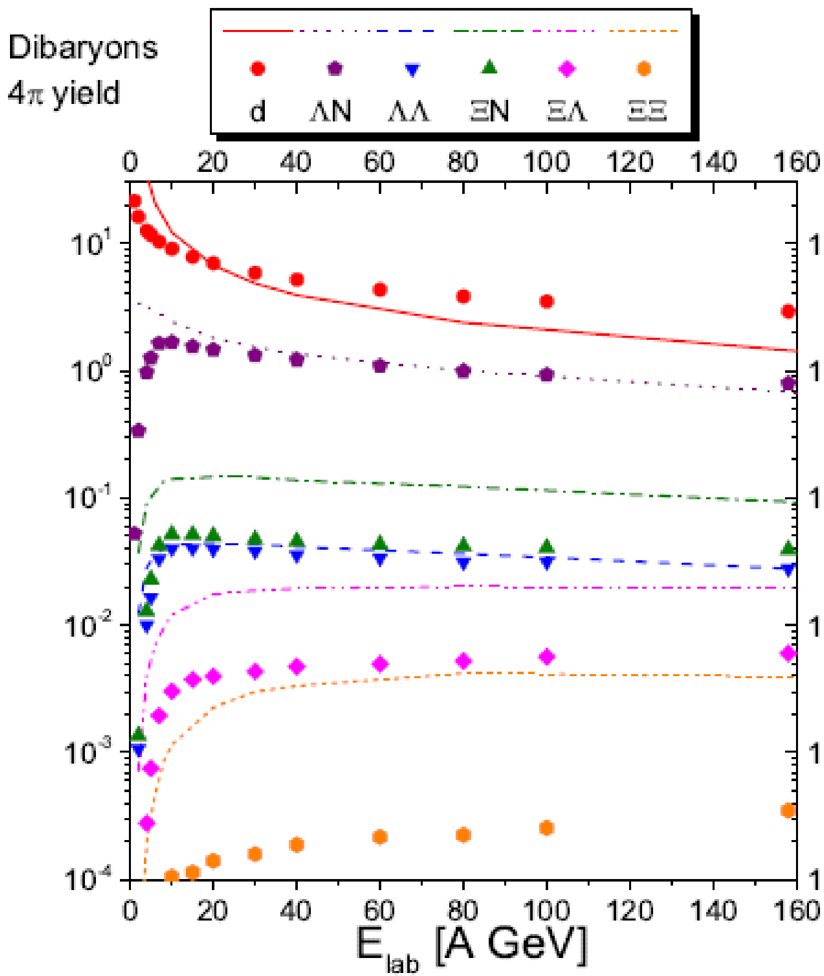
coordinates: $|\mathbf{X}_i - \mathbf{X}_0| \leq \mathbf{X}_c$

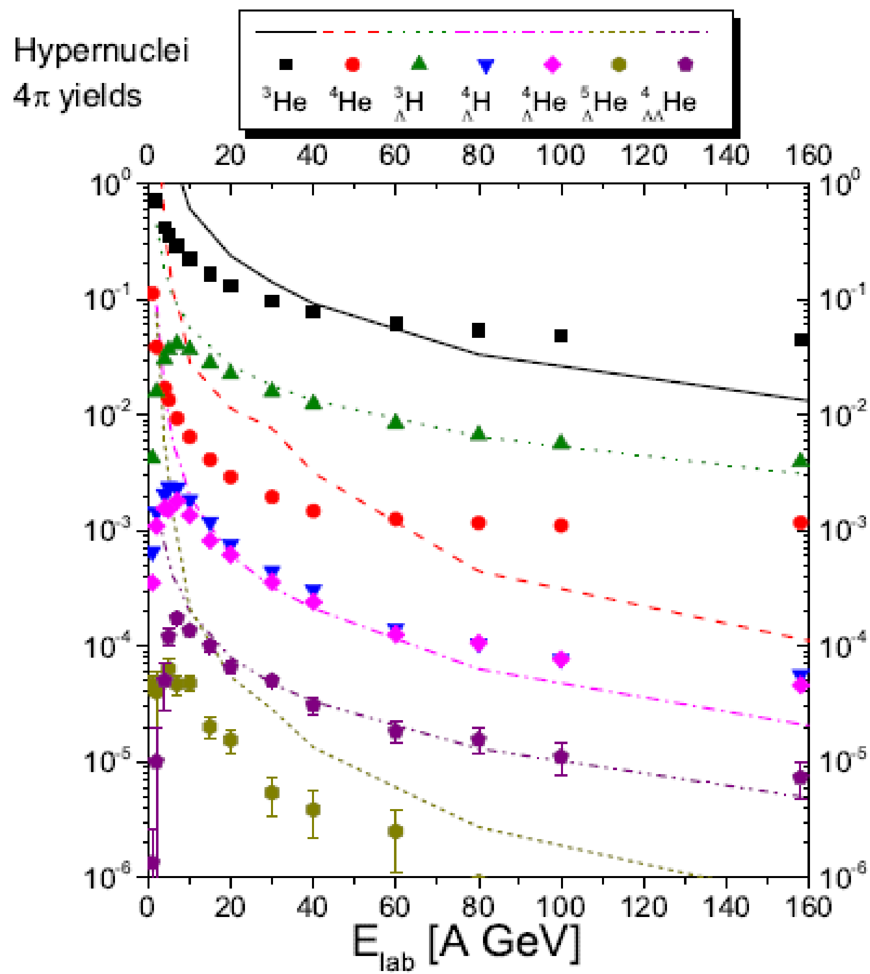


Production of light nuclei in central collisions : Au+Au

DCM and UrQMD calculations - J.Steinheimer et al., arXiv:1203.2547 (2012)

Predictions of hybrid approaches: DCM + coalescence and UrQMD + thermal hydrodynamics. Symbols: DCM. Lines: UrQMD





Problems of description of central collisions

In dynamical approaches: Coalescence parameter can be small if hypernuclei are weakly bound. Difficult to obtain exotic hypernuclei

$p_C=$	5	20	50	90
ΛN	$4.4 \cdot 10^{-4}$	$2.7 \cdot 10^{-2}$	$3.0 \cdot 10^{-1}$	2.1
$\Lambda\Lambda$	$3.0 \cdot 10^{-5}$	$1.2 \cdot 10^{-3}$	$6.6 \cdot 10^{-3}$	$5.6 \cdot 10^{-2}$
ΞN	$< 10^{-6}$	$1.0 \cdot 10^{-3}$	$1.1 \cdot 10^{-2}$	$1.0 \cdot 10^{-1}$
$\Xi\Lambda$	$< 10^{-6}$	$7.4 \cdot 10^{-5}$	$5.8 \cdot 10^{-4}$	$1.0 \cdot 10^{-2}$
$\Xi\Xi$	$< 10^{-6}$	$< 10^{-6}$	$3.8 \cdot 10^{-4}$	$7.2 \cdot 10^{-4}$

Table 2: Dependence of yield of strange dibaryons (per one event) on momentum coalescence parameter (p_C in units of [MeV/c]), in central ($b < 3.5 fm$) Au+Au collisions at 20.4 GeV

In thermal approaches: if statistical equilibrium achieved is sufficient for formation of complex nuclear species?

In all cases: it is not possible to produce big nuclei !

J.Steinheimer, K.Gudima, A.Botvina, I.Mishustin, M.Bleiher, H.Stoecker, arXiv:1203.2547 (2012)

Physical picture of peripheral relativistic HI collisions:

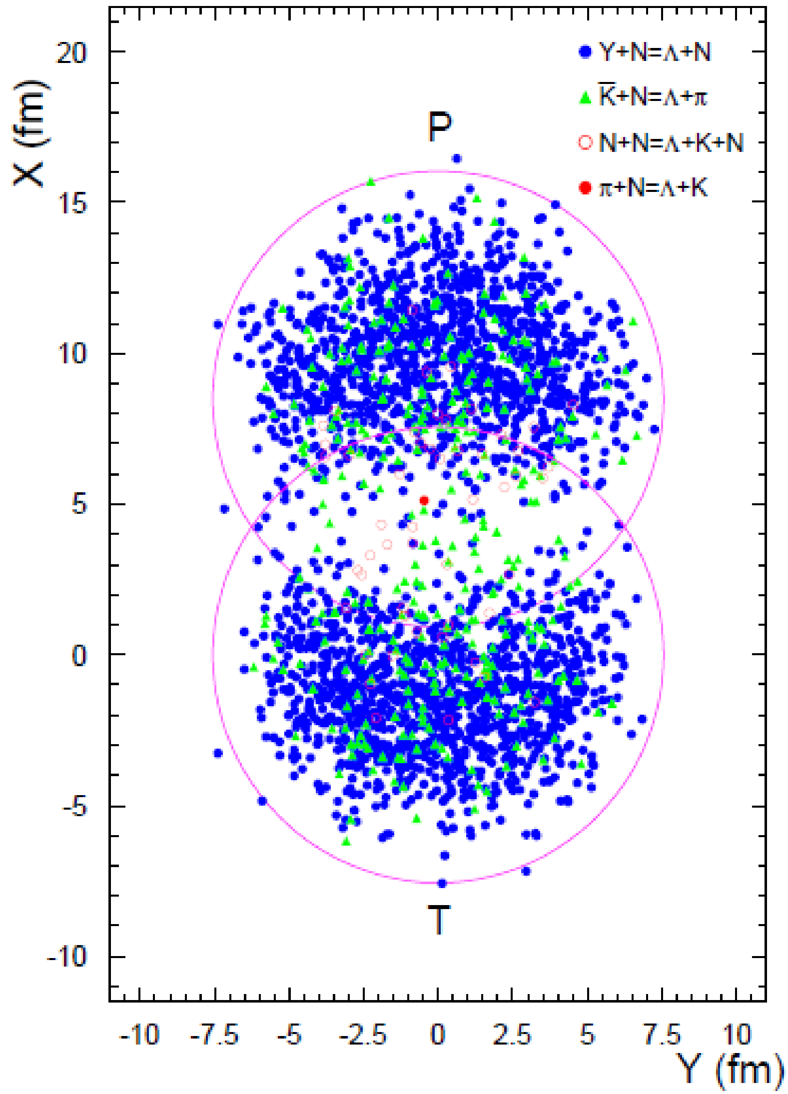
nucleons of projectile interact with nucleons of target, however, in peripheral collisions many nucleons (spectators) are not involved. All products of the interactions can also interact with nucleons and between themselves. The time-space evolution of all nucleons and produced particles is calculated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

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.

Absorption of Lambda hyperons inside residual nuclei after DCM
(different processes leading to Lambda production are noted)



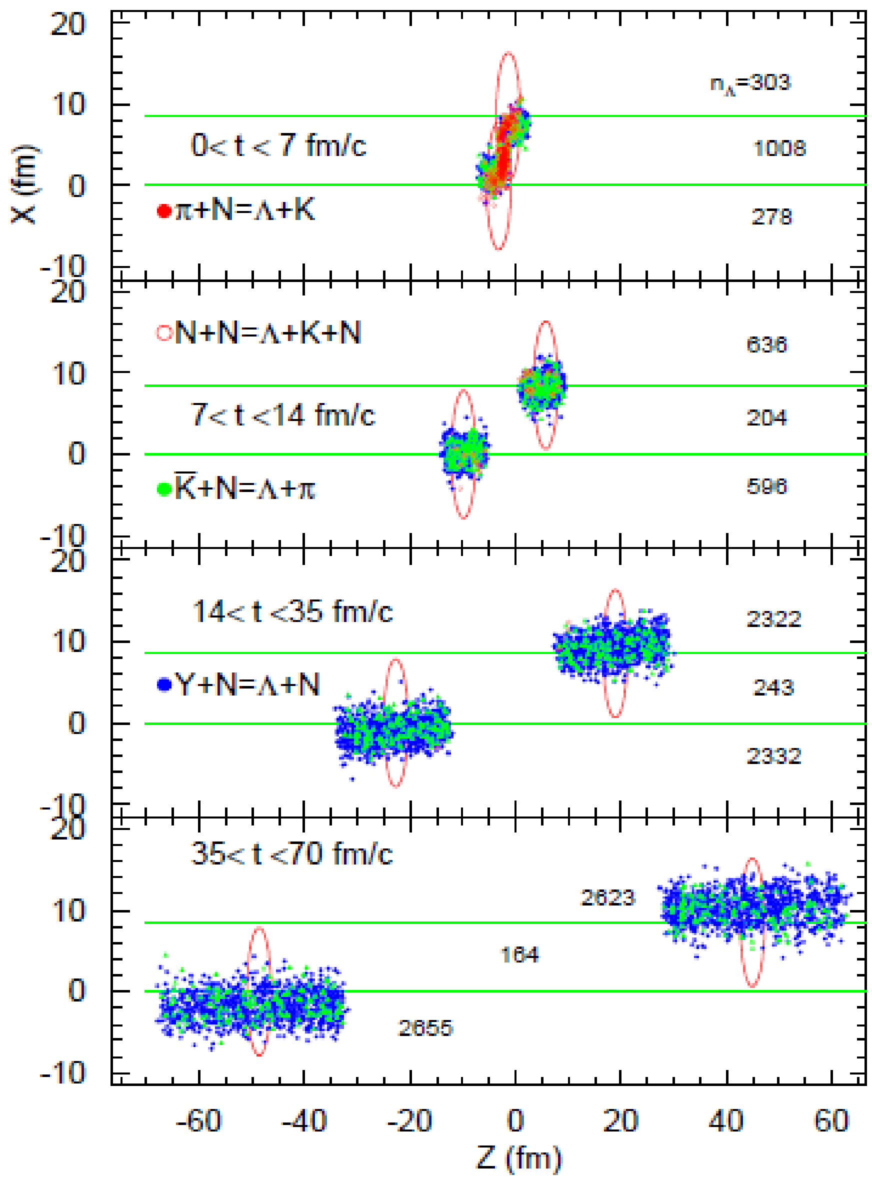
Perpendicular beam axis view

Au (20 A GeV) + Au

impact parameter= 8.5fm

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

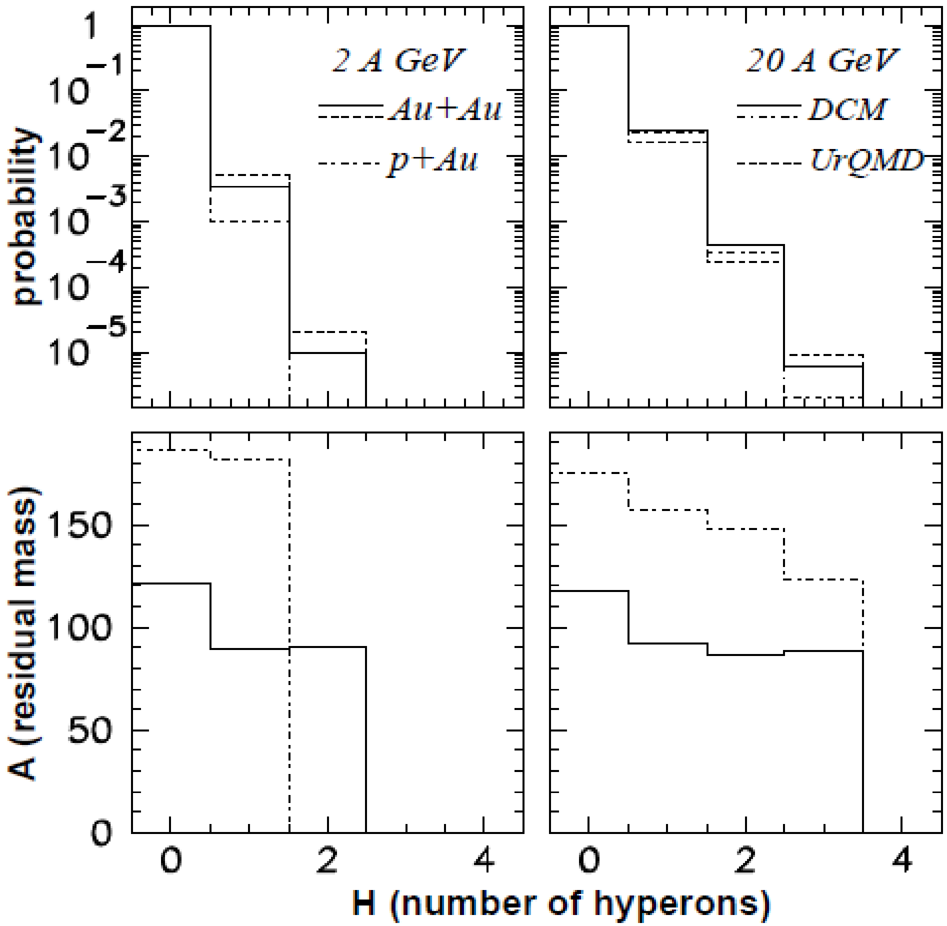
Absorption of Lambda hyperons inside residual nuclei after DCM
(different times and coordinates of absorption are on panels)



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 2.1 GeV per nucleon, and considerably more at 20 GeV per nucleon

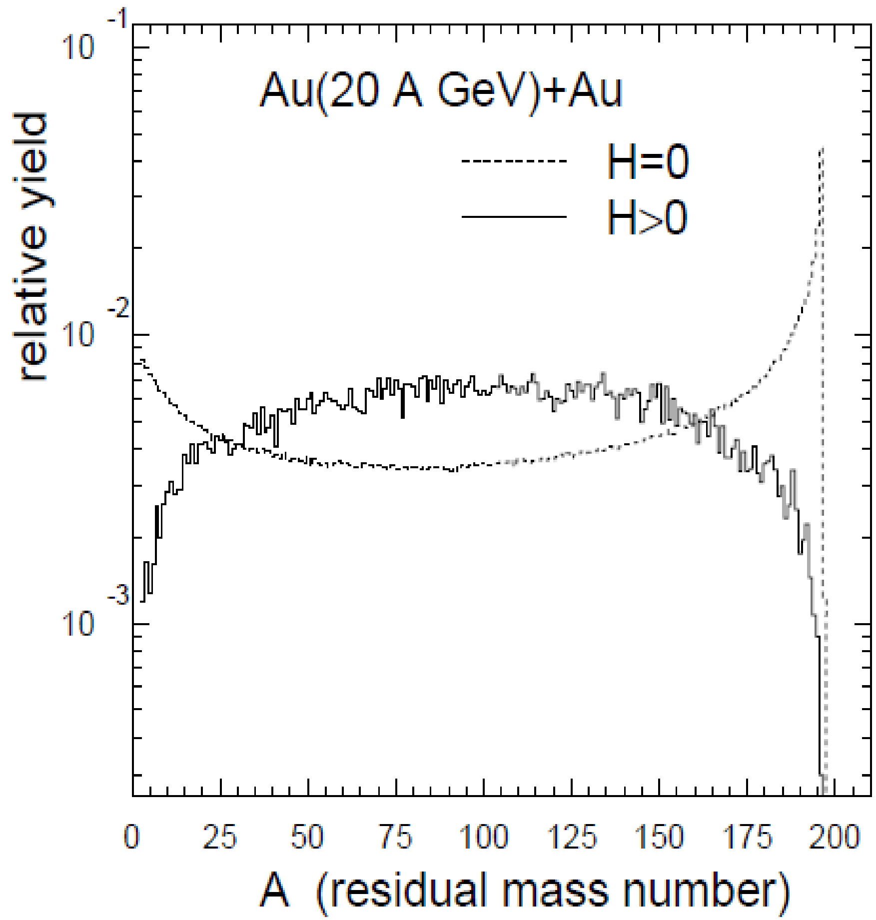


Approximation of local density of nucleons for the hyperon capture.

Integrated over all impact parameters

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

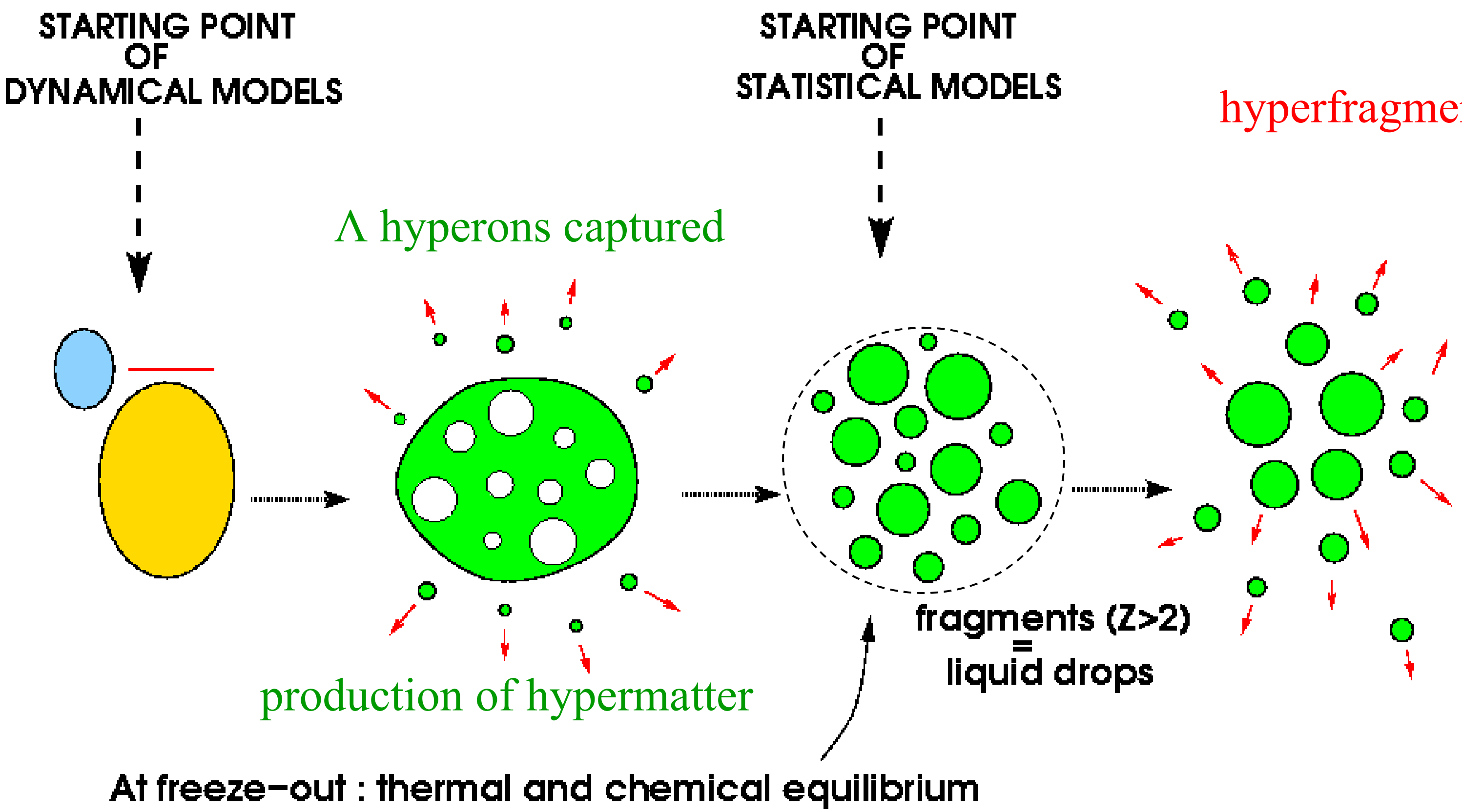
A.S.Botvina and J.Pochodzalla, Phys. Rev.C76 (2007) 024909

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

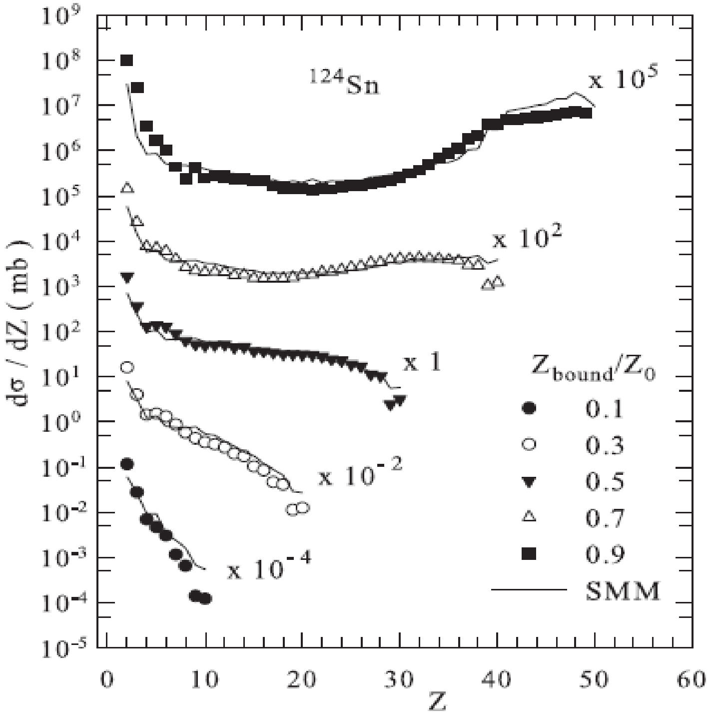


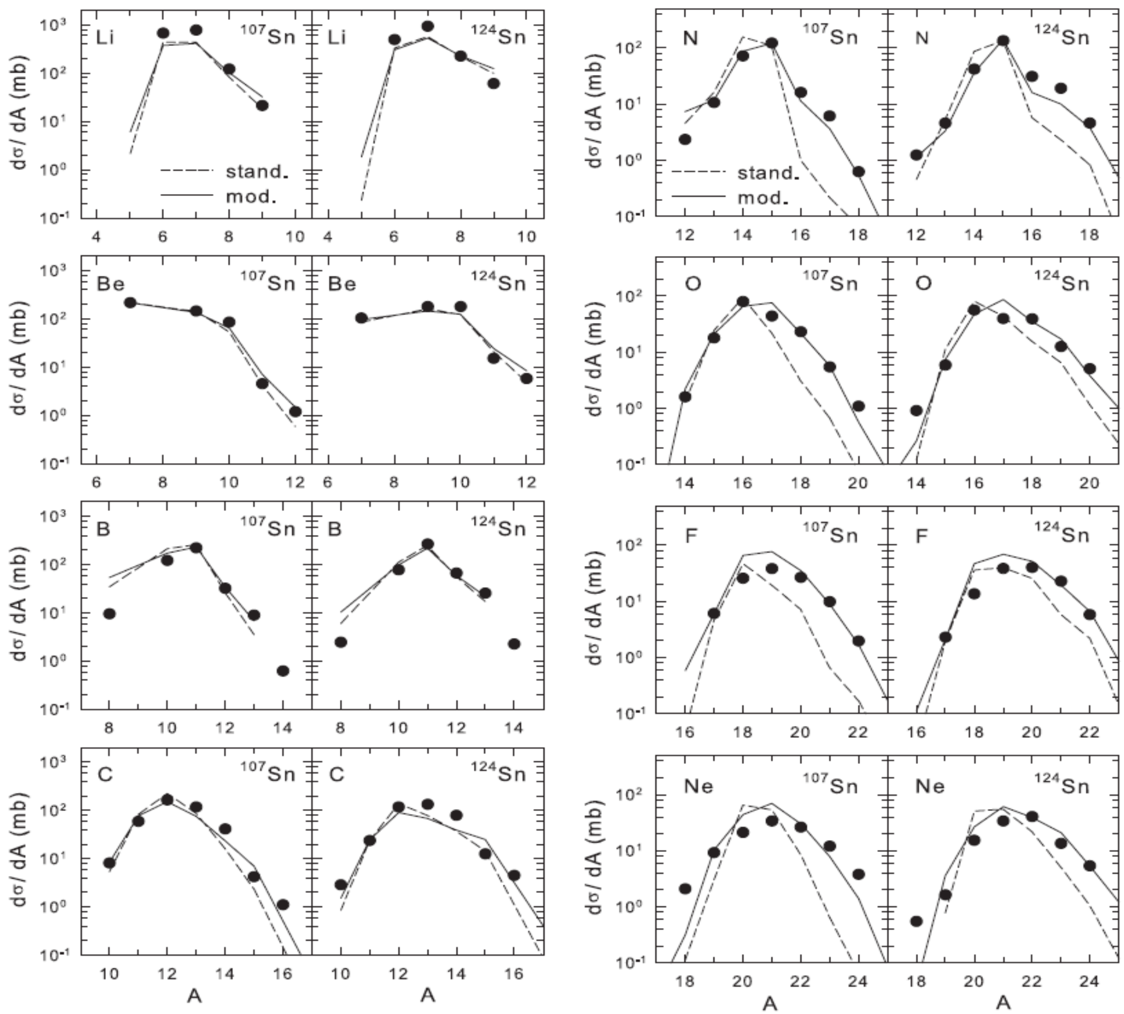
R.Ogul et al. PRC **83,** 024608 (2011) **ALADIN@GSI**

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.





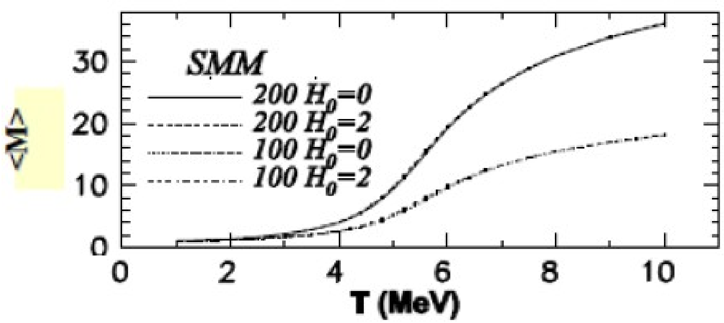
Statistical (chemical) equilibrium is established at break-up of hot projectile residues ! In the case of strangeness admixture we expect it too !

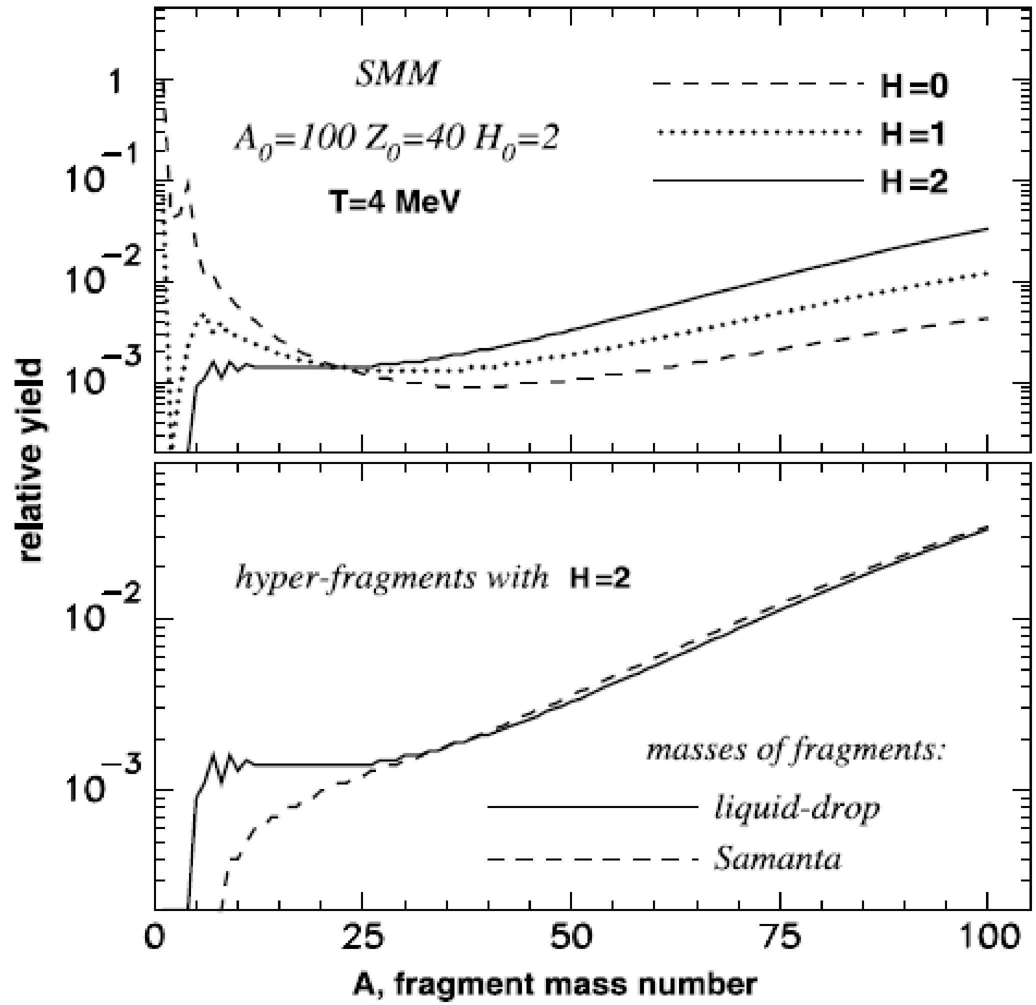
Multifragmentation of excited hyper-sources

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





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

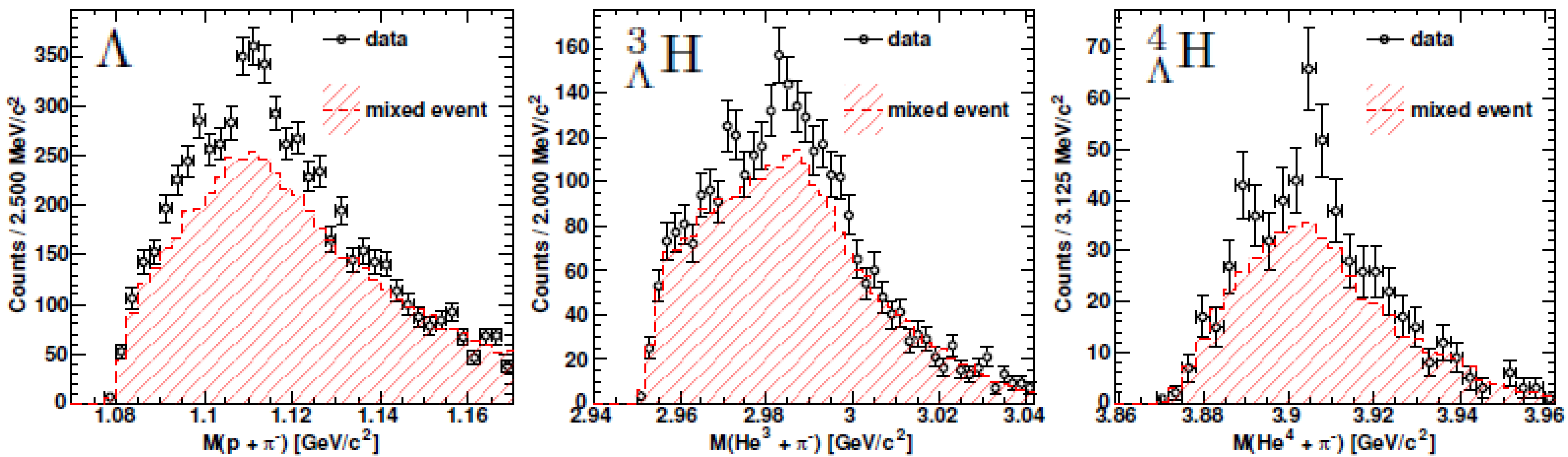
Fig. 3. Multifragmentation of an excited double-strange system with mass number 100 and charge 40, at temperature 4 MeV. Top panel – yield of fragments containing 0, 1, and 2 Λ hyperons. Bottom panel – effect of different mass formulae with strangeness on production of double hyperfragments [13].

T.Saito, (for HypHI), NUFRA2011 conference, and Nucl. Phys. A (2012), doi:10.106/j.nuclphysa.2012.011

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],

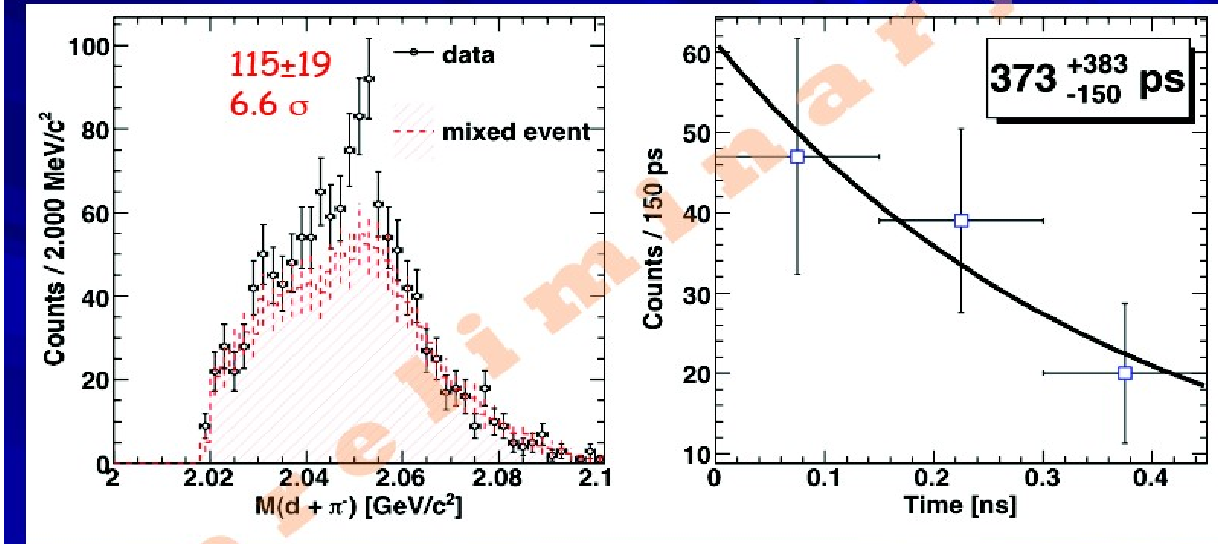
Projectile fragmentation: ^{6}Li beam at 2 A GeV on ^{12}C target



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

T.Saito (for HypHI), NUFRA2011 conference, and ETC* Workshop 'Strange Hadronic Matter' Trento, 2011

$? \to d + \pi^-$



- Calibrated mass: 2.054 - 2.064 GeV/c^2 (n+Λ threshold = 2.055)

Λn bound state ?

Final state / Initial state	p + π^- / Λ	^{3}He + π^- / $^3_\Lambda$H	^{4}He + π^- / $^4_\Lambda$H	d + π^-
Uncalibrated mass	1111.3 ± 0.4	2984.6 ± 0.6	3905.6 ± 0.6	2051.3 ± 0.5
Width	7.3	8.6	5.2	4.8
Peak integral	403 ± 41	178 ± 31	66 ± 14	115 ± 19
Significance in σ	7.1	6.2	5.3	6.6
Known mass	1115.683 ± 0.006 [26]	2991.68 ± 0.05 [3]	3923.03 ± 0.06 [3]	
Measured lifetime	231^{+112}_{-75}	141^{+67}_{-57}	162^{+99}_{-73}	373^{+383}_{-150}
Known lifetime	263.2 ± 2.0 [26]	$246^{+62}_{-41} \pm 27$ [27]	194^{+24}_{-26} [28]	
After the correction of the acceptance and efficiency		1.0	0.17	4.12

It is not possibles to explain yield ratios with a simple coalescence model !

In reactions with light ions:
production of hypernuclei via break-up of excited light strange systems

Generalization of the statistical Fermi break-up model for hypernuclei:
A.Sanchez Lorente, A.S.Botvina and J.Pochodzalla, Phys. Lett. B697 (2011) 222

6Li (2 AGeV) + 12C collisions

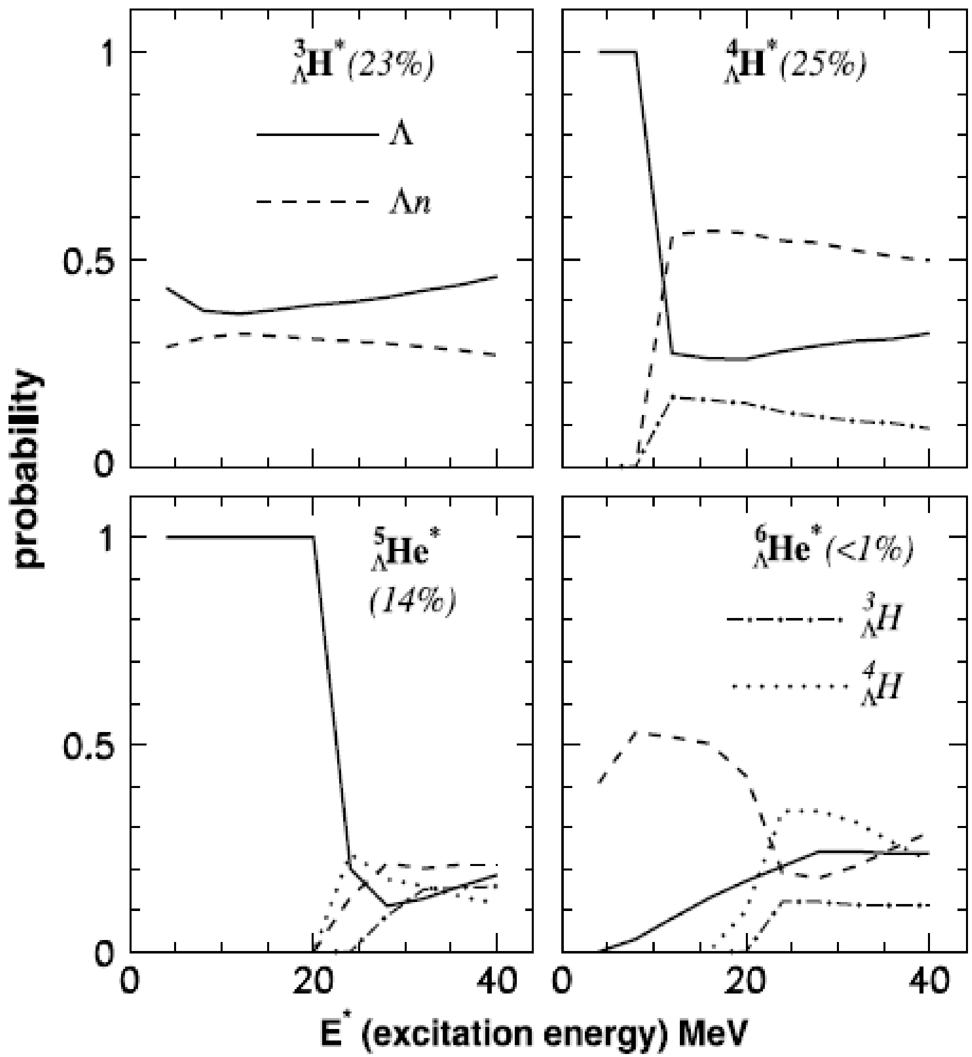
DCM calculations lead to production of light hyper-spectators (from Li) with excitation energies around 1--8 MeV/n.
Their decay produces hyper-nuclei.

A new Lambda-N state was included into the break-up calculations with the bound energy of 50 keV and Spin=1. All known light hypernuclei were also included. Summing-up one can rough estimate the ratio of production of

$$\Lambda N \qquad {}^{3}_{\Lambda}H \qquad {}^{4}_{\Lambda}H$$

as 4.6 : 1 : 0.23

Recent HypHI experiment at GSI,
T.Saito (@NUFRA2011)
----- 4.12 : 1 : 0.17



Conclusions

Two ways for production of hypernuclei in relativistic Ion collisions:

1. Central HI collisions: Very high excitation energy deposited in fireball. Many species (Λ, Σ, Ξ, …) can be produced with high probability. Their interaction may lead to formation of complex fragments and new exotic states. However, probability for production of big clusters, and weakly-bound states may be low. (Also because of high excitation and dynamics.)

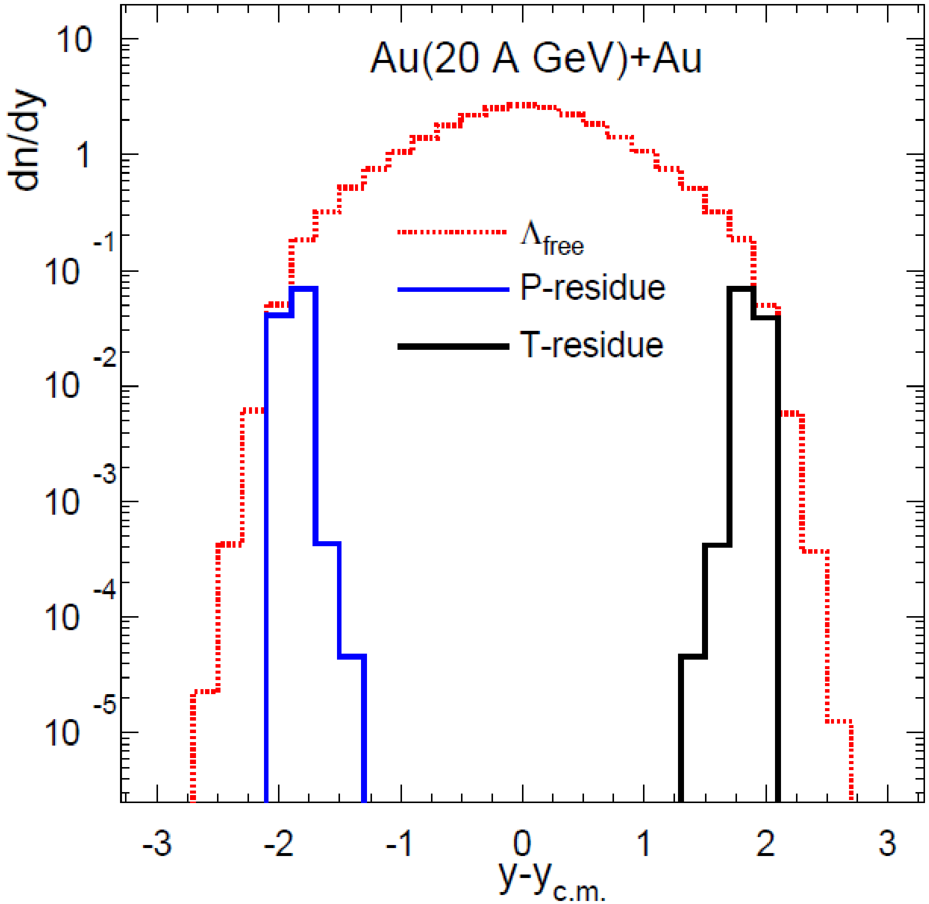
2. Peripheral collisions: Strange hadrons must be transported to the spectator residues, therefore, formation probability of strange nuclear systems is lower. However, such systems are relatively cold and they are in chemical equilibrium respective to cluster formation. Hypernuclei of all sizes (and isospin) and weakly-bound states can be produced. EoS of hypermatter at subnuclear density can be investigated.

Advantages over kaon reactions producing hypernuclei: there is no limit on sizes and isotope content of produced nuclei; relativistic velocities can be used for novel measurements, higher strangeness can be deposited in nuclei.

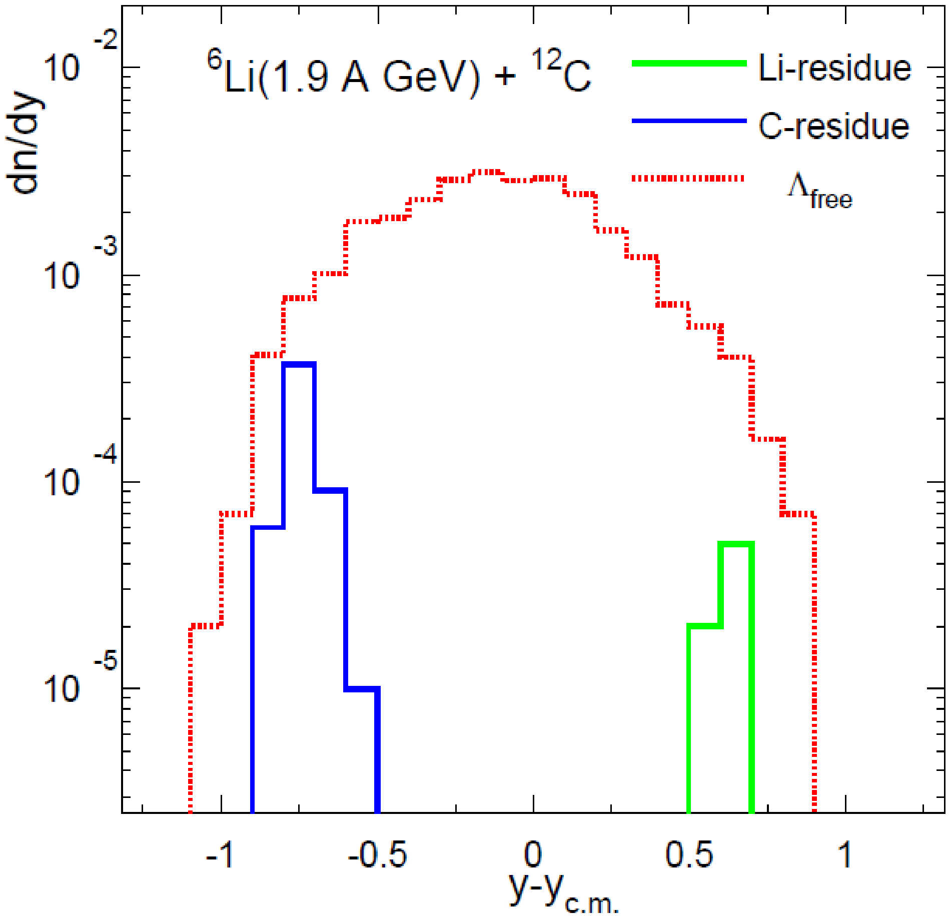
Investigation of hypernuclei in relativistic Ion collisions is very promising !

Rapidity distribution of free Lambda and hyper-residues

Heavy Ion collisions



Light Ion collisions



Statistical approach for fragmentation of hyper-matter

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

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

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

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

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

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

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

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

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

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

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

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

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

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

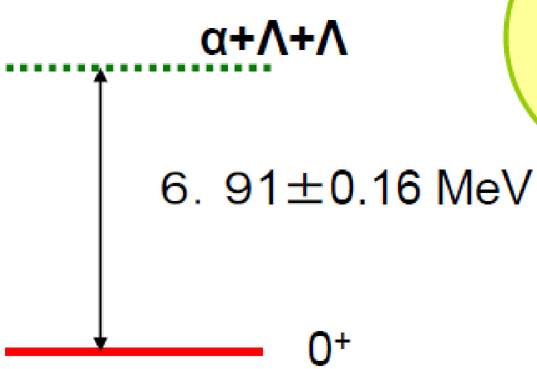
-- liquid-drop description of hyper-matter

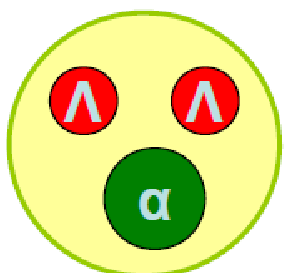
A.S.Botvina and J.Pochodzalla, Phys. Rev.C76 (2007) 024909

(K^-, K^+) reactions

Ξ^- hyperons at the emulsion

Uniquely identified without ambiguity for the first time



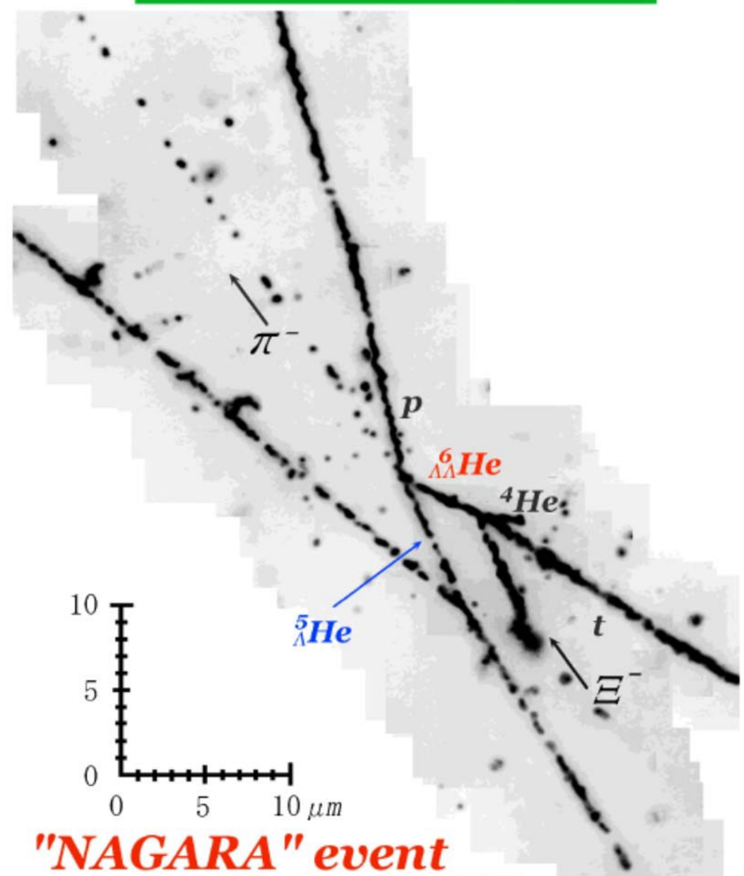


$^{6}_{\Lambda\Lambda}\mathrm{He}$

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

Unique interpretation!!

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



"NAGARA" event

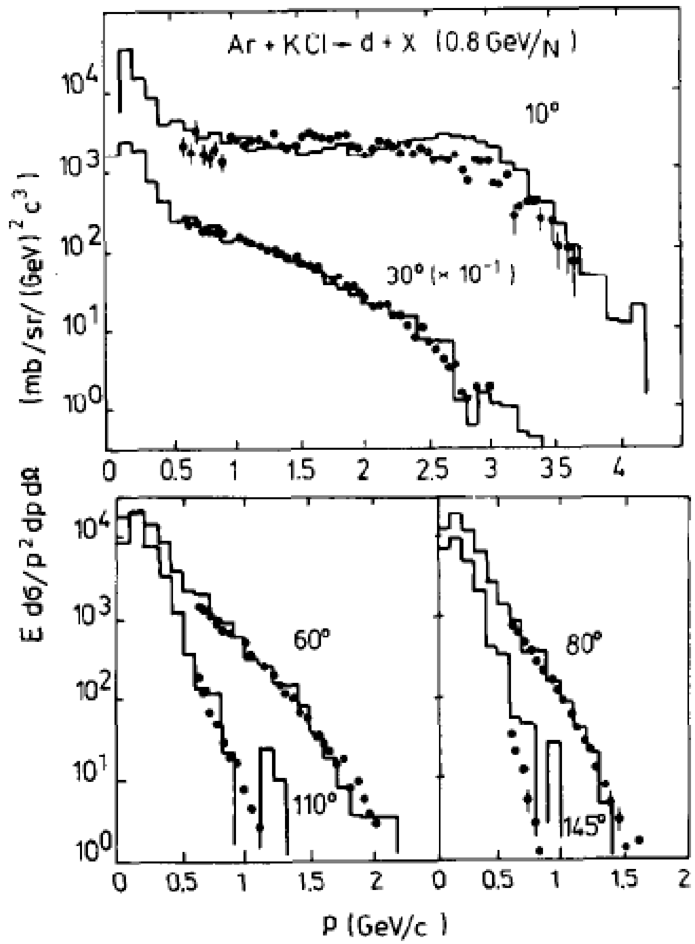
presented by E373(KEK-PS) on Jan.2001

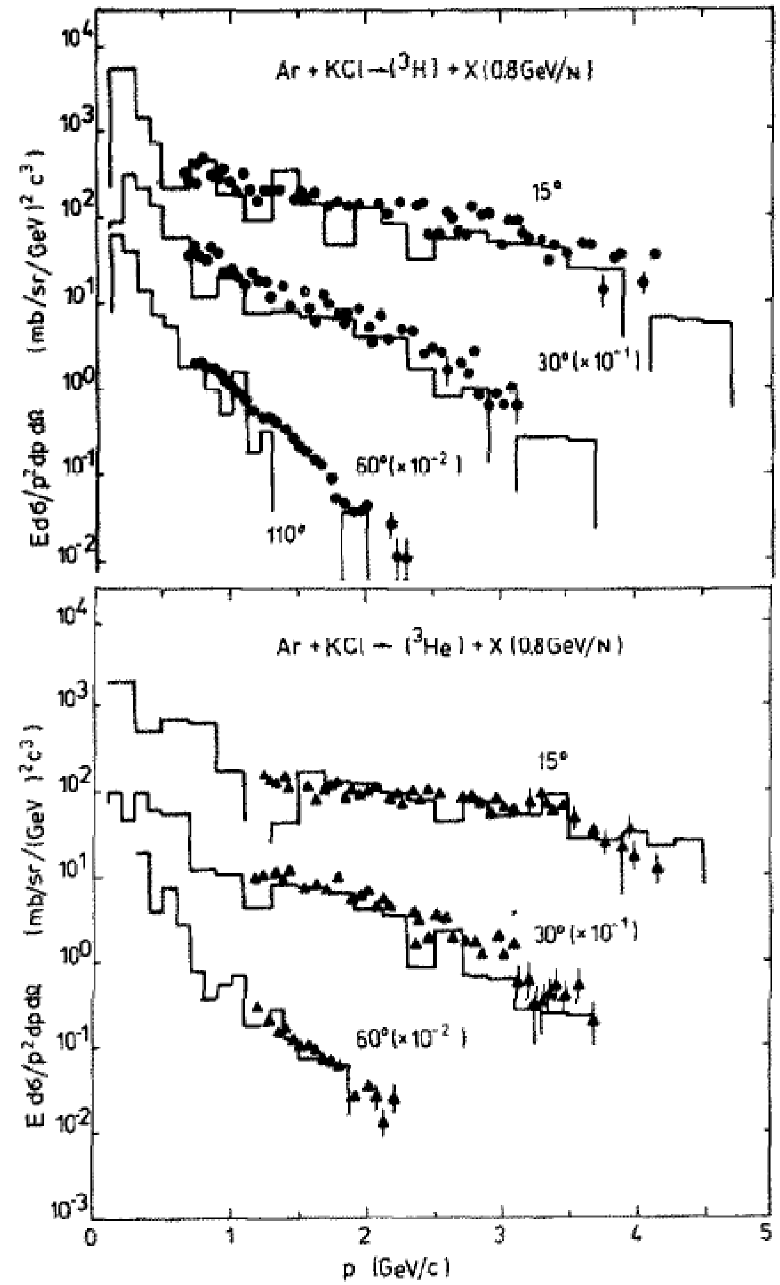
H. Takahashi *et al.*, PRL 87, 212502-1 (2001)

DCM + Coalescence

momentum: $|\mathbf{P}_i - \mathbf{P}_0| \leq \mathbf{P}_c$

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

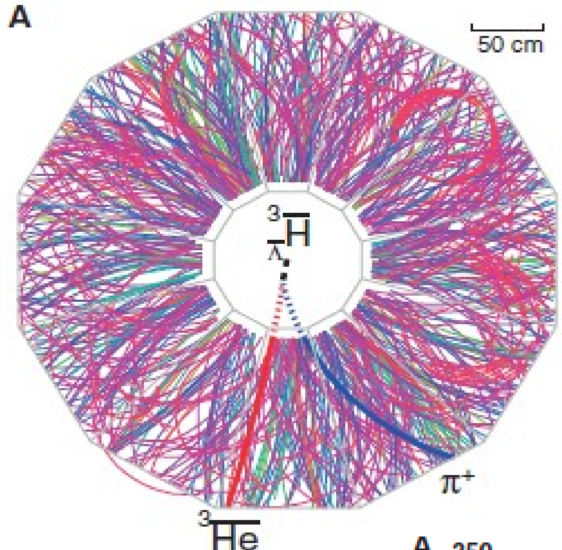


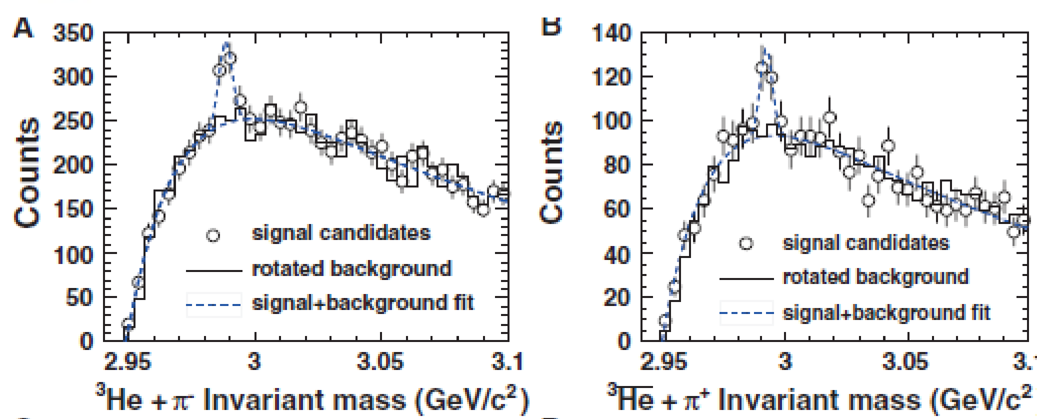


STAR collaboration (RHIC): Science, 238 (2010) 58

Au + Au collisions at 200 A GeV

Fig. 2. A typical event in the STAR detector that includes the production and decay of a $^{3}_{\Lambda}\overline{H}$ candidate: (**A**) with the beam axis normal to the page, (**B**) with the beam axis horizontal. The dashed black line is the trajectory of the $^{3}_{\Lambda}\overline{H}$ candidate, which cannot be directly measured. The heavy red and blue lines are the trajectories of the $^{3}\overline{He}$ and π^{+} decay daughters, respectively, which are directly measured.





With heavy ion collisions $E_{beam} > 1.6$AGeV

(since $NN \rightarrow \Lambda KN$ energy threshold ~ 1.6 GeV)

we can obtain

Relativistic Hypernuclei

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

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:

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

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