Predictions towards the LHC energies with hybrid dynamical and coalescence models for hyper-nuclei, anti-nuclei, and exotica

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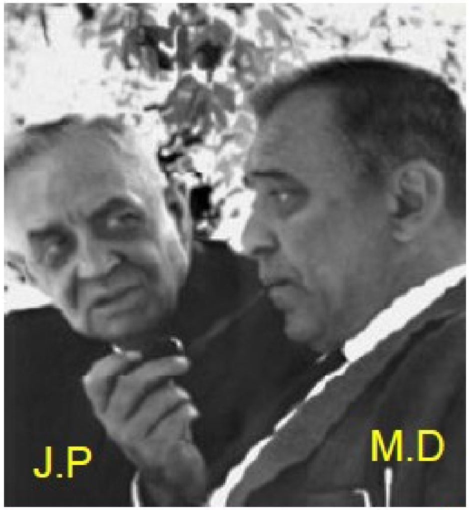
***EMMI Workshop*: Anti-matter, hyper-matter and exotica production at the LHC.**

CERN, Geneva, Switzerland

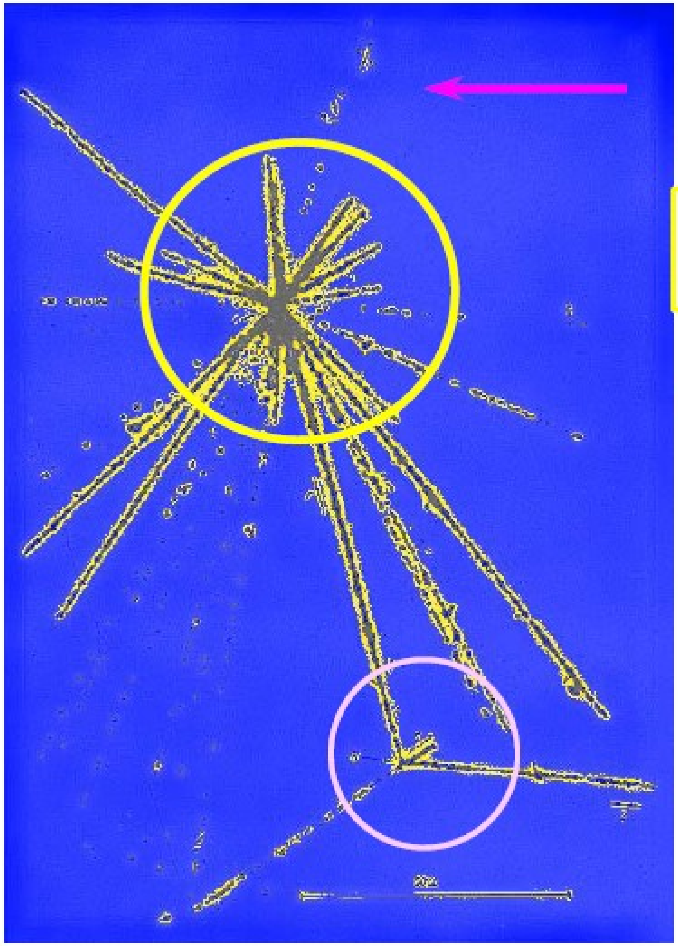
July 20-22, 2015

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 !**

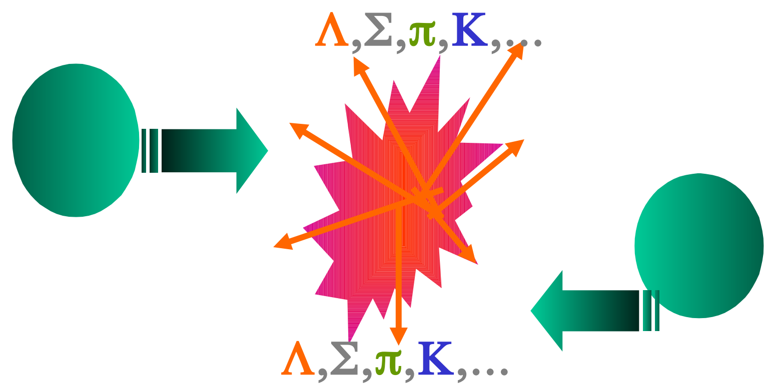
All nuclear fragments stop in the emulsion after a short path

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)

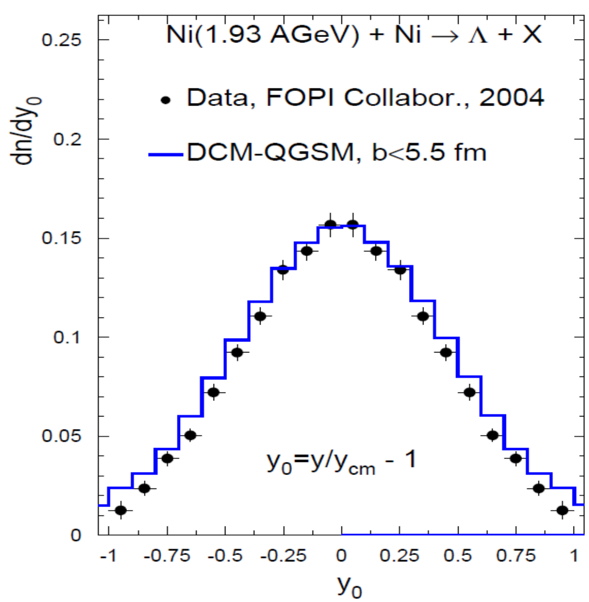
This particular nuclear fragment, and the others obtained afterwards in similar conditions, were called **hyperfragments or hypernuclei.**

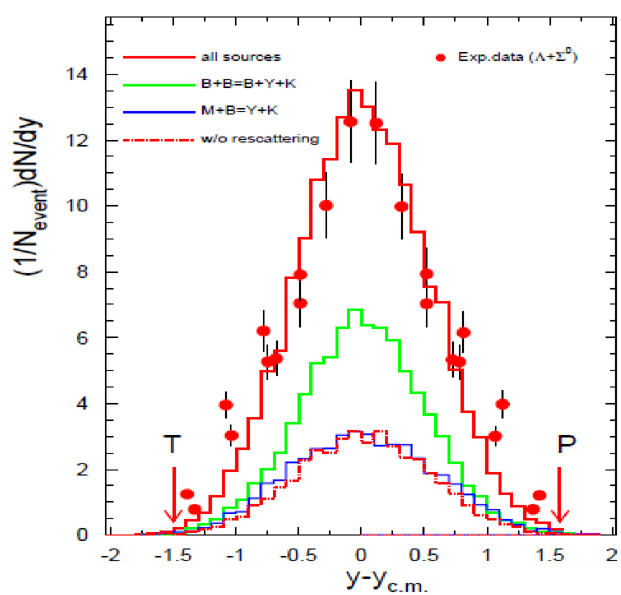
Relativistic collisions of hadrons and ions



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 : 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: $BB \to BYK$, $B\pi \to YK$, ... (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 $\Lambda+N \to N+N$.

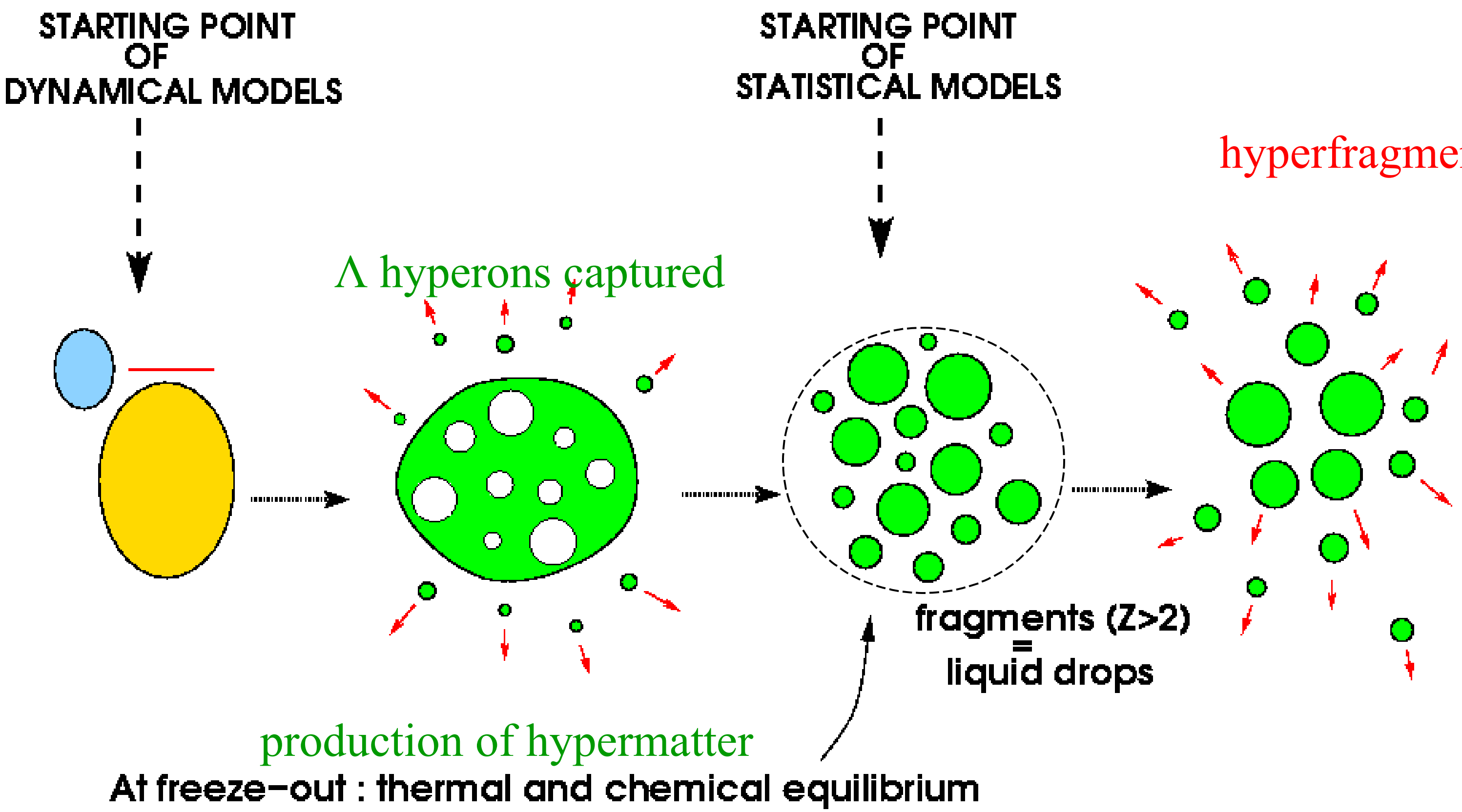
A.S.Botvina and J.Pochodzalla, Phys. Rev.C76 (2007) 024909

Production of excited spectator nuclear matter with Lambda hyperons

In these reactions we expect analogy with

multifragmentation in intermediate and high energy nuclear reactions

nuclear matter with strangeness



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

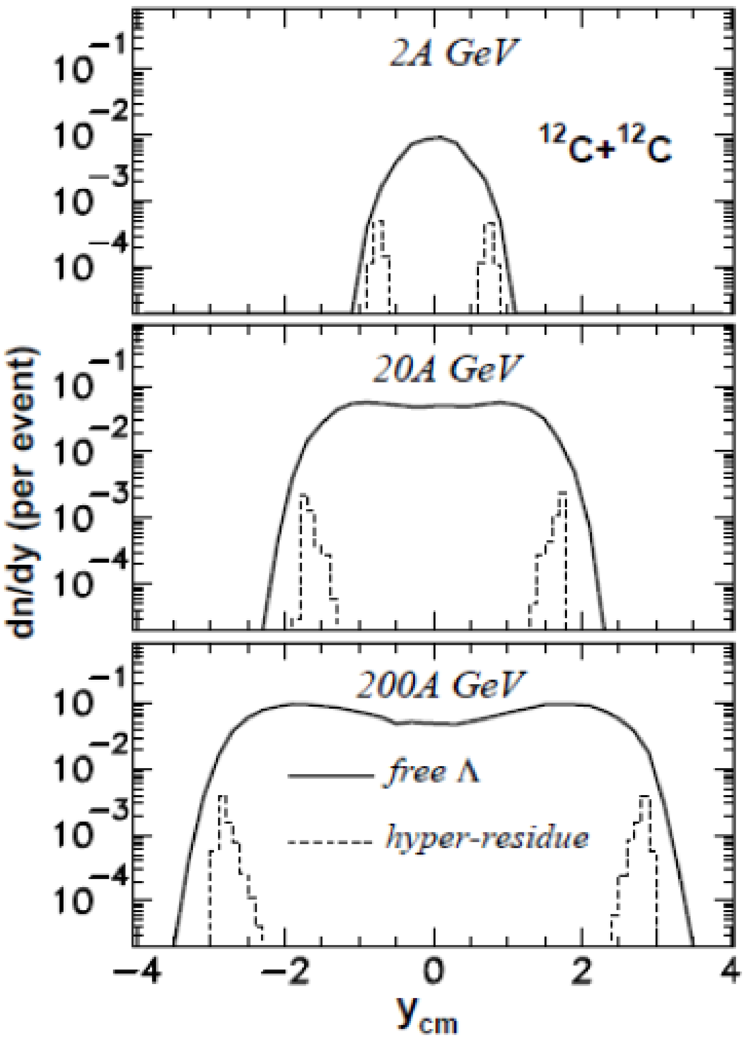
ABSORPTION of LAMBDA :

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.

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.

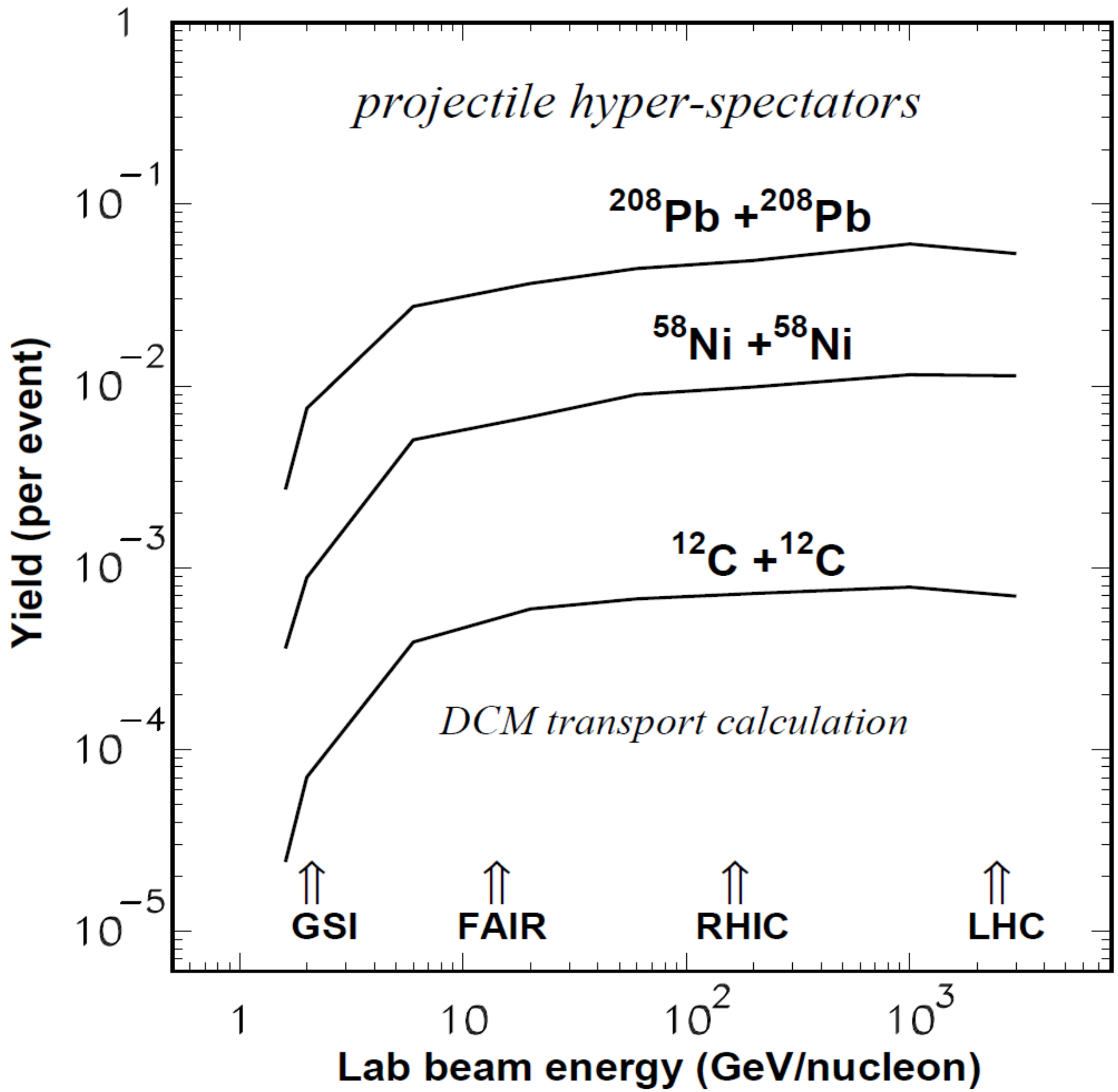
Yield of hypernuclei in peripheral collisions

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.

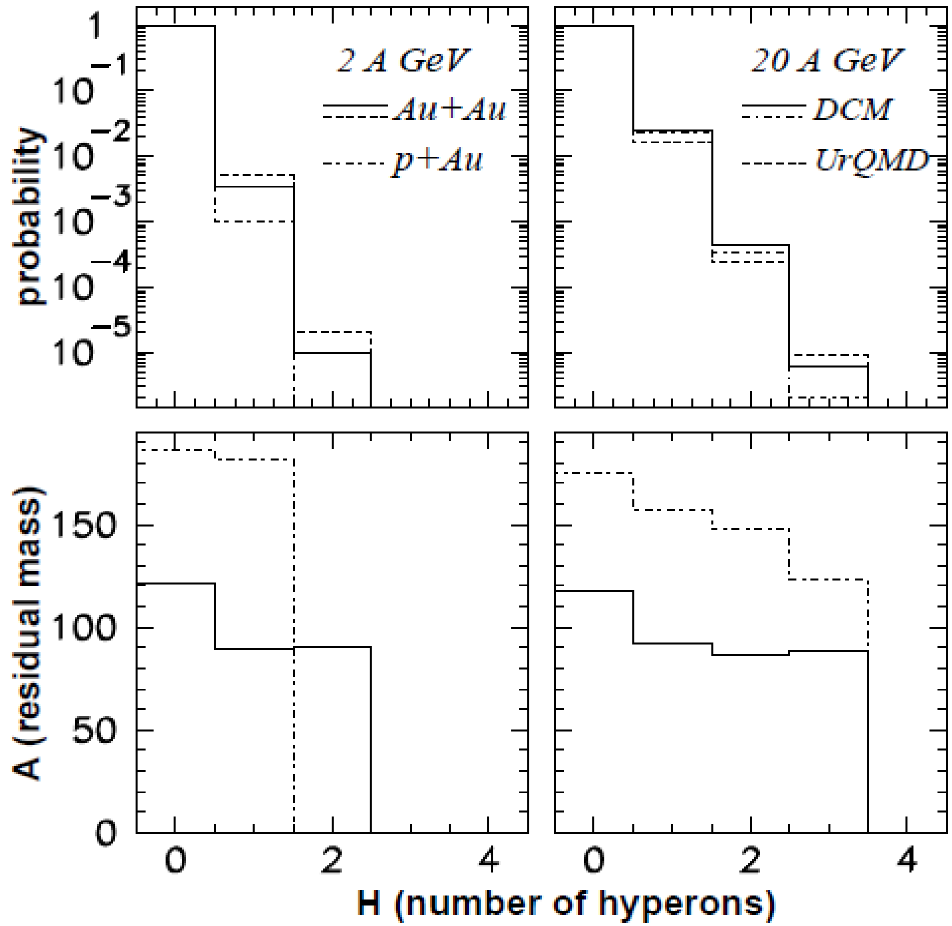
Reactions can be studied at GSI/FAIR and JINR/NICA facilities as well as on operating RHIC and LHC (fixed target experiments).



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



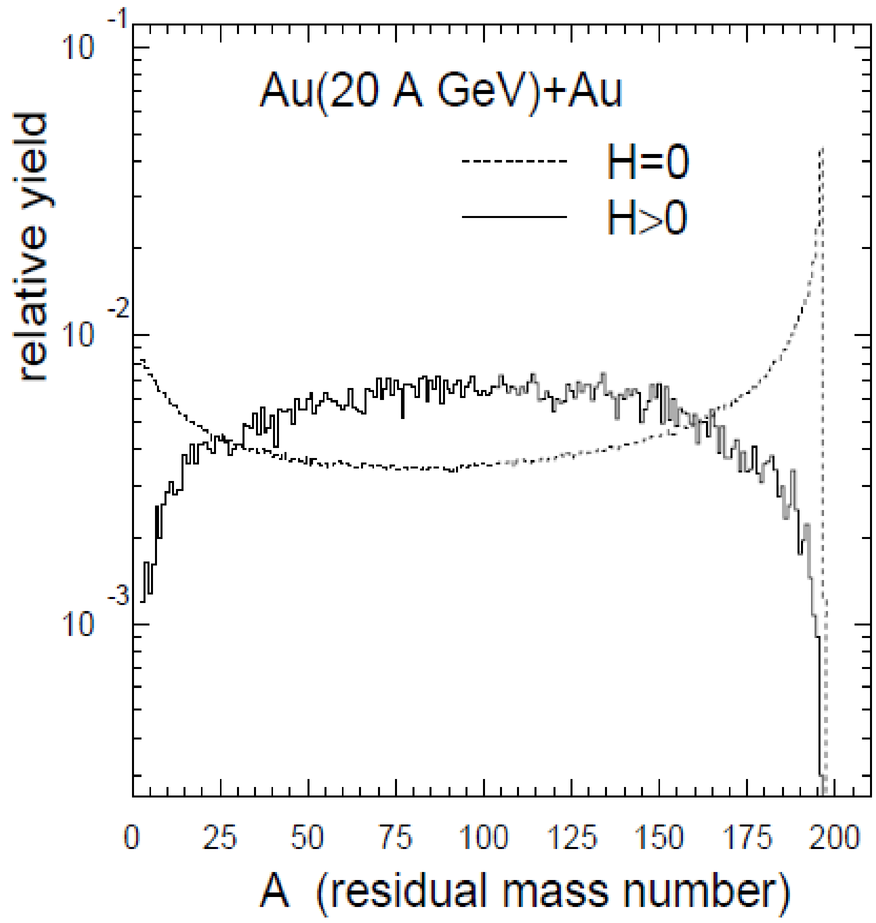
Integrated over all impact parameters

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

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

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)

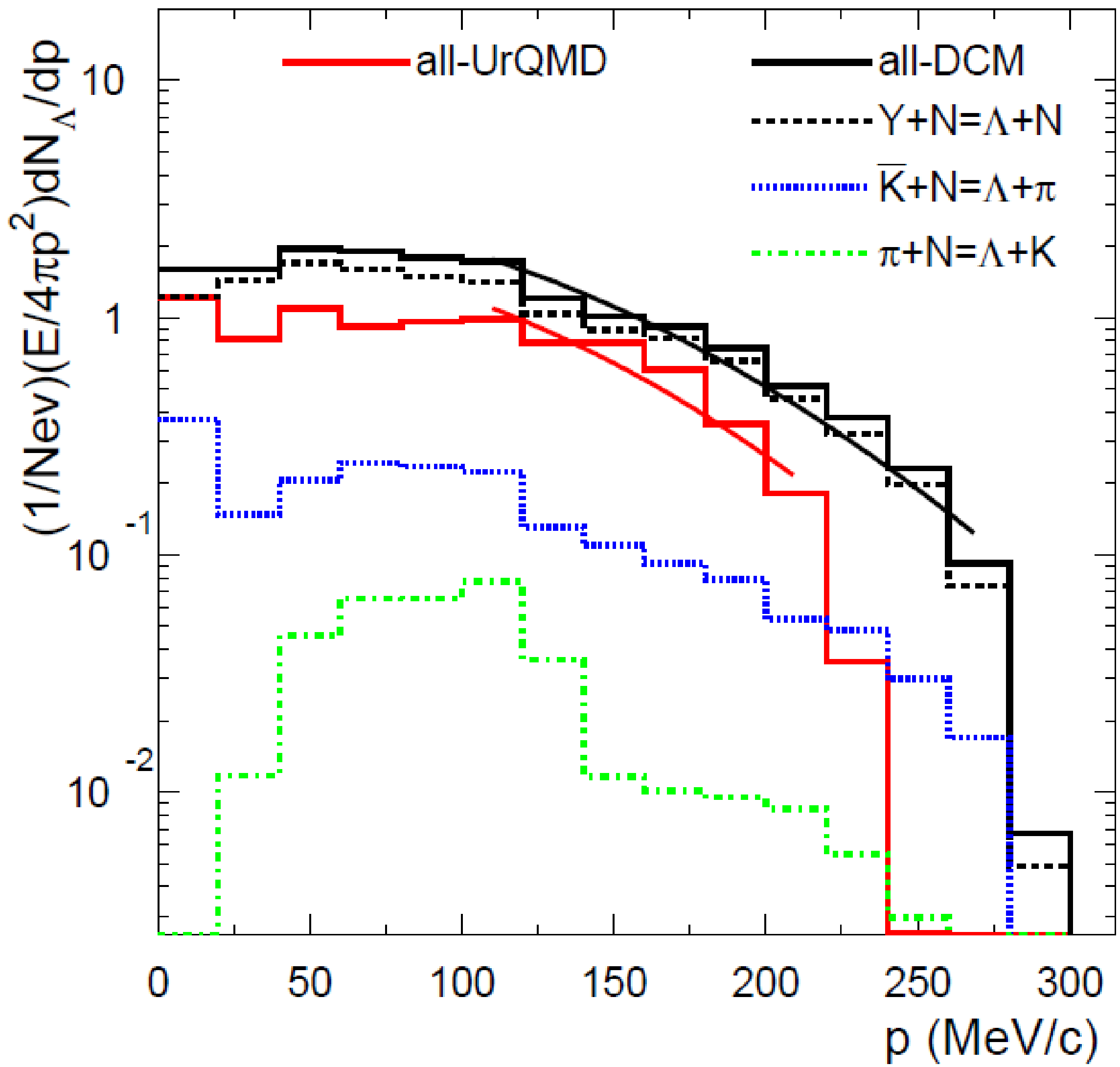
Coalescence of baryons

momenta:

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

coordinates:

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



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.

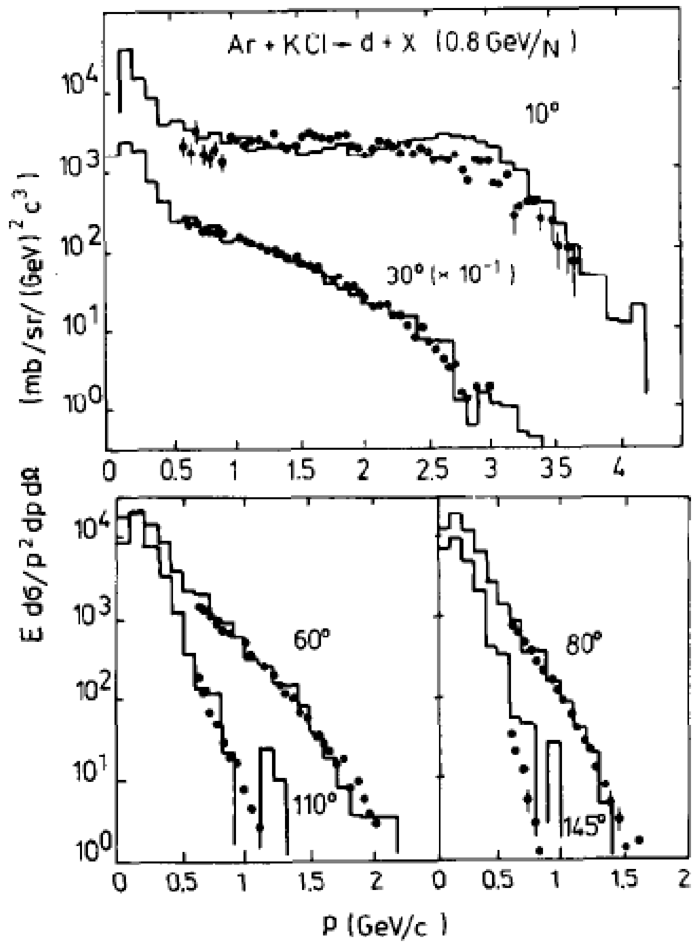
Combination of transport UrQMD and HSD models with CB:

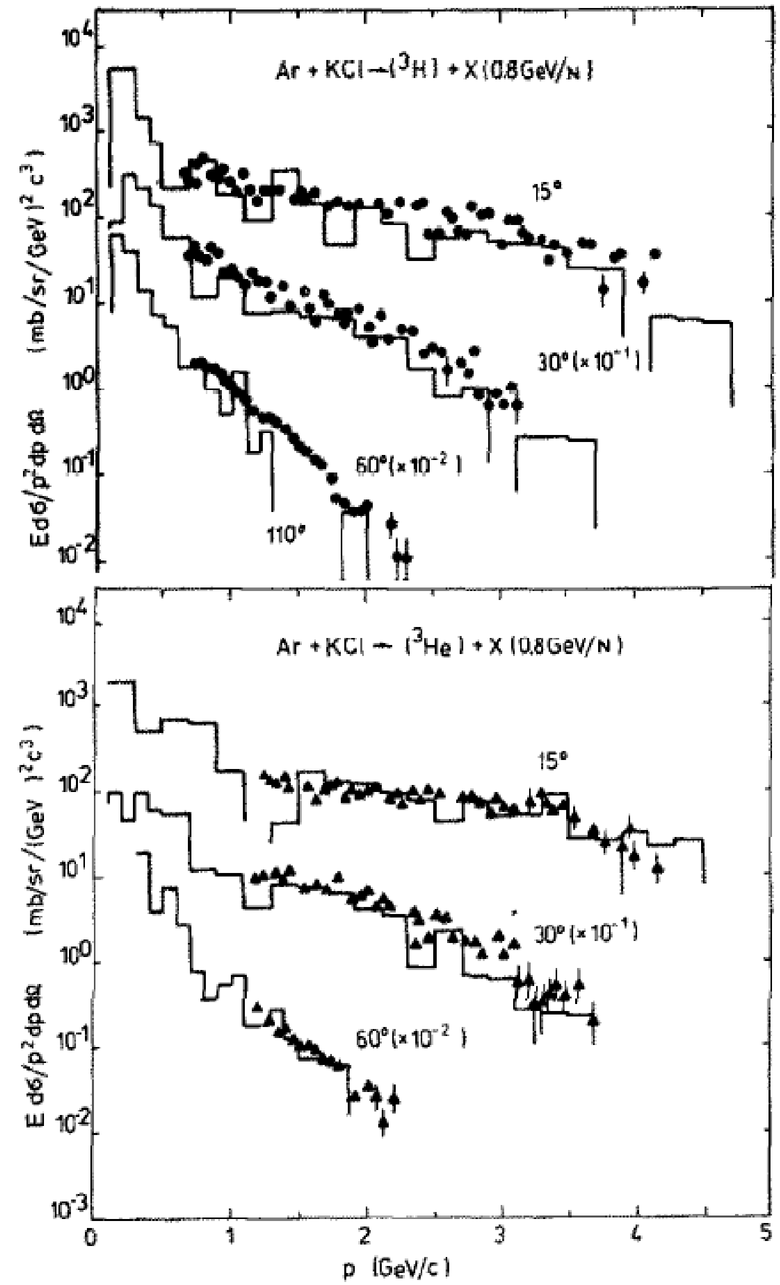
Investigation of fragments/hyperfragments at all rapidities !
(connection between central and peripheral zones)

DCM + Coalescence

momentum: $\left| P_i - P_0 \right| \le P_c$

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

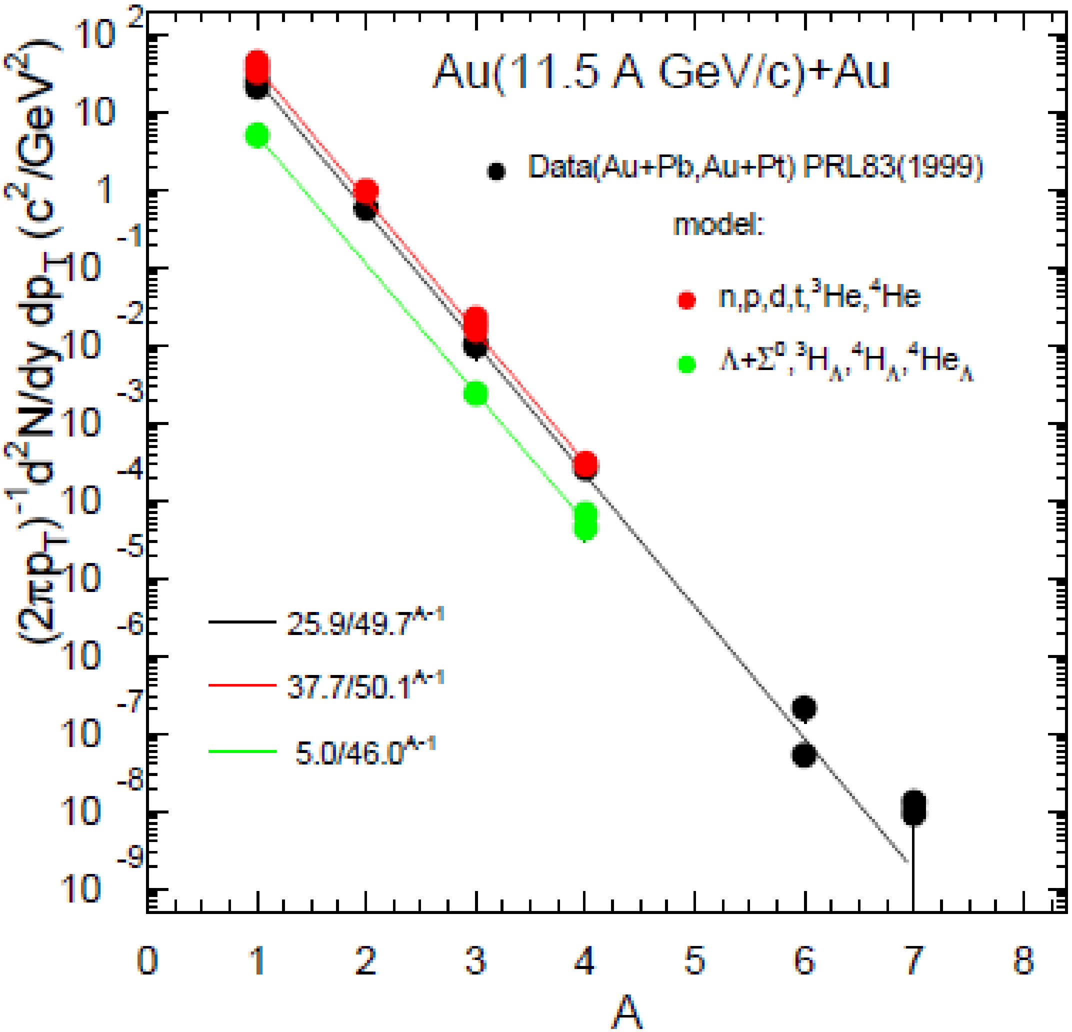




DCM + coalescence --- verification

Coalescence of baryons

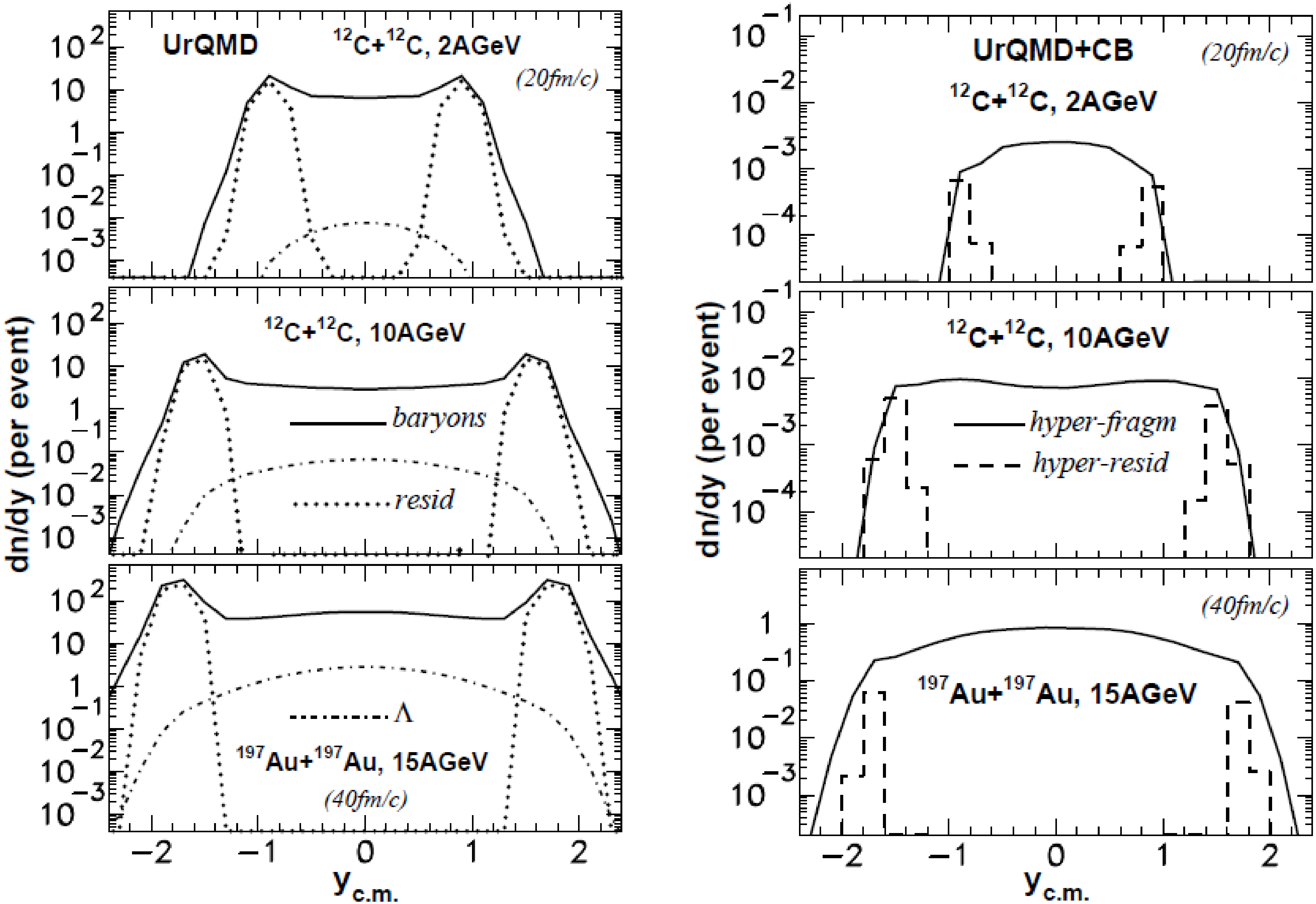
momenta: $|P_i - P_0| \leq P_c$



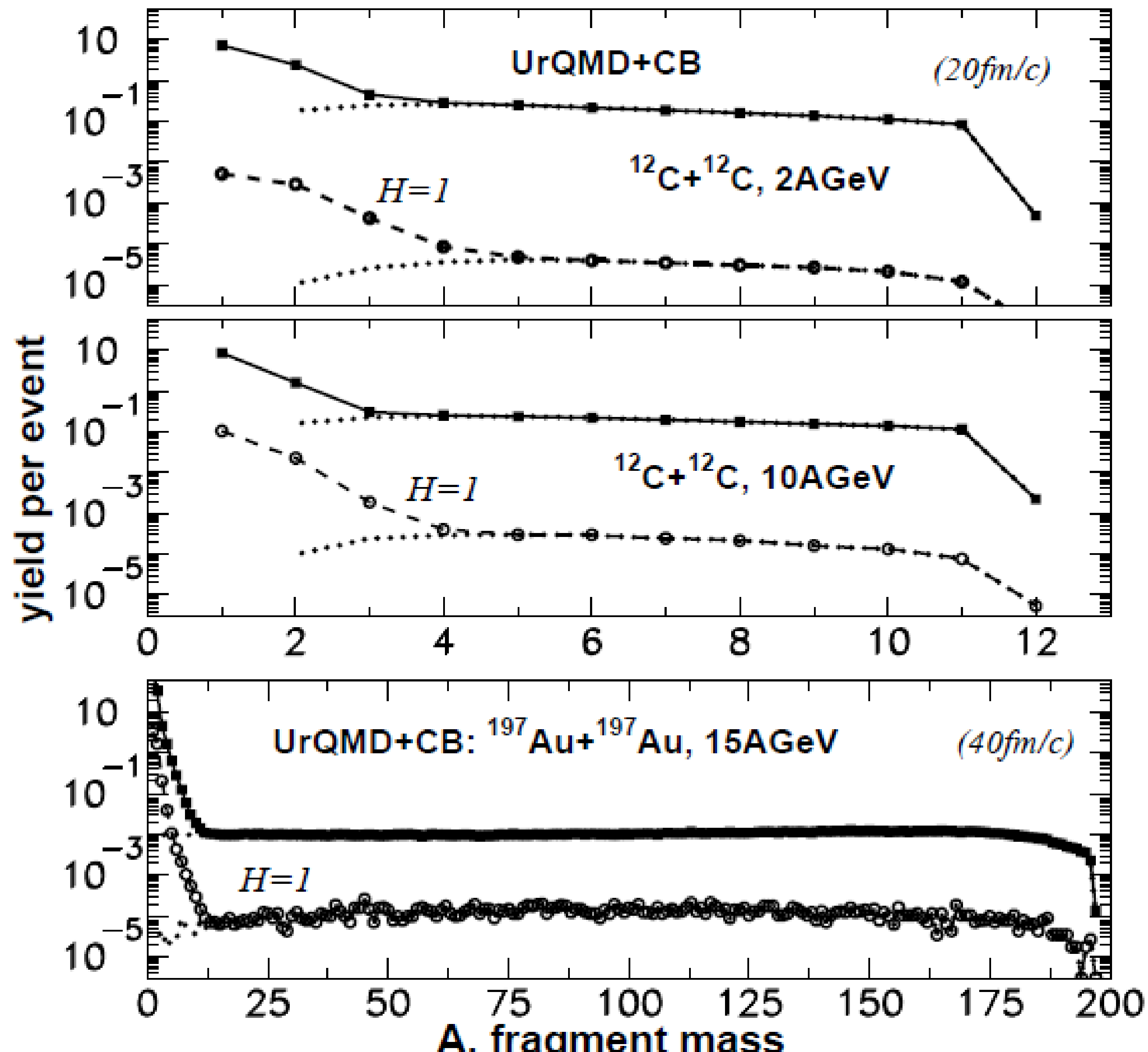
J.Steinheimer, K.Gudima, A.Botvina, I.Mishustin, M.Bleiher, H.Stoecker, Phys. Lett. B**714**, 85 (2012)

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

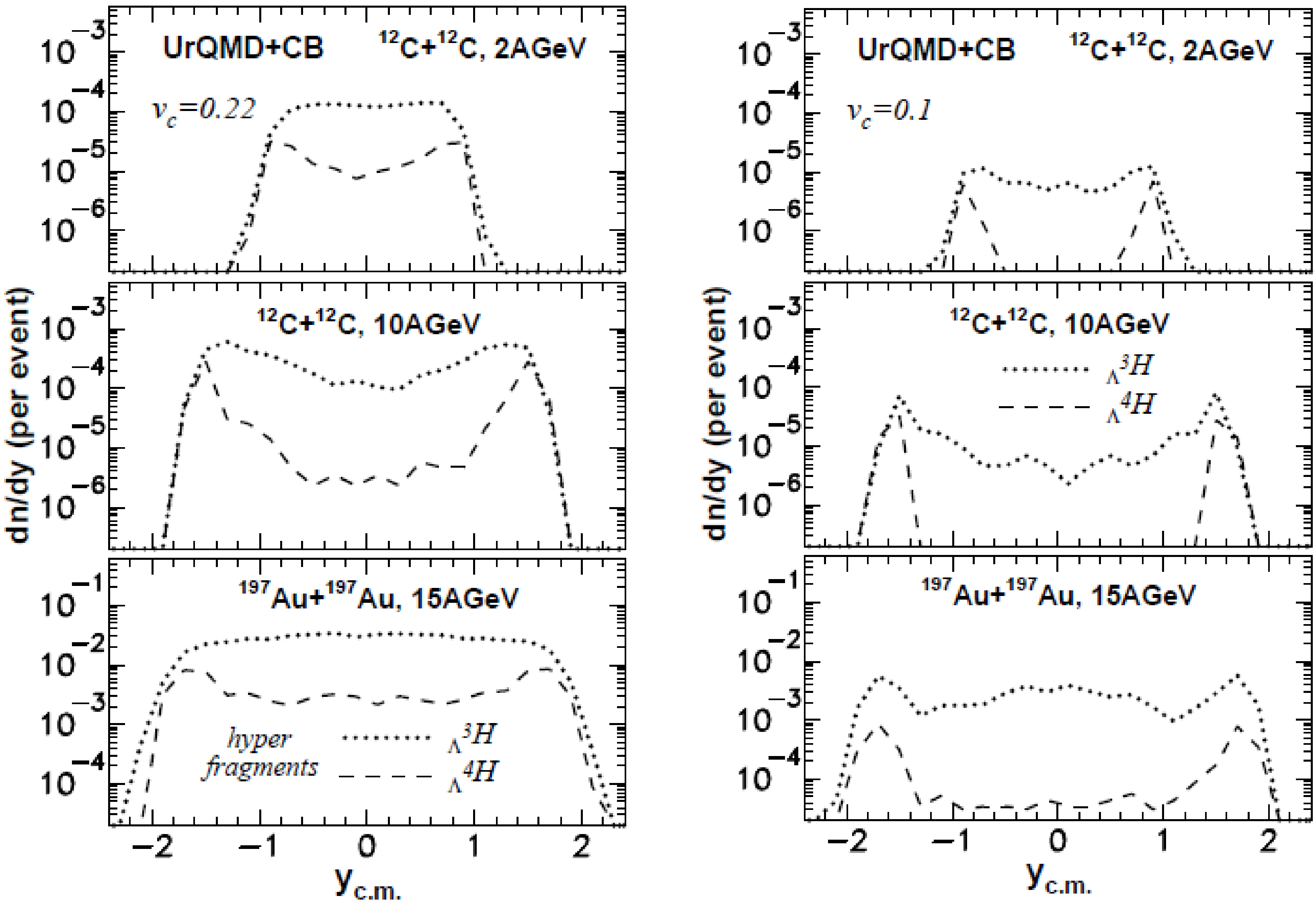
baryons, Lambdas, hyper-fragments, hyper-residues



normal fragments and hyper-fragments (with residue contribution)

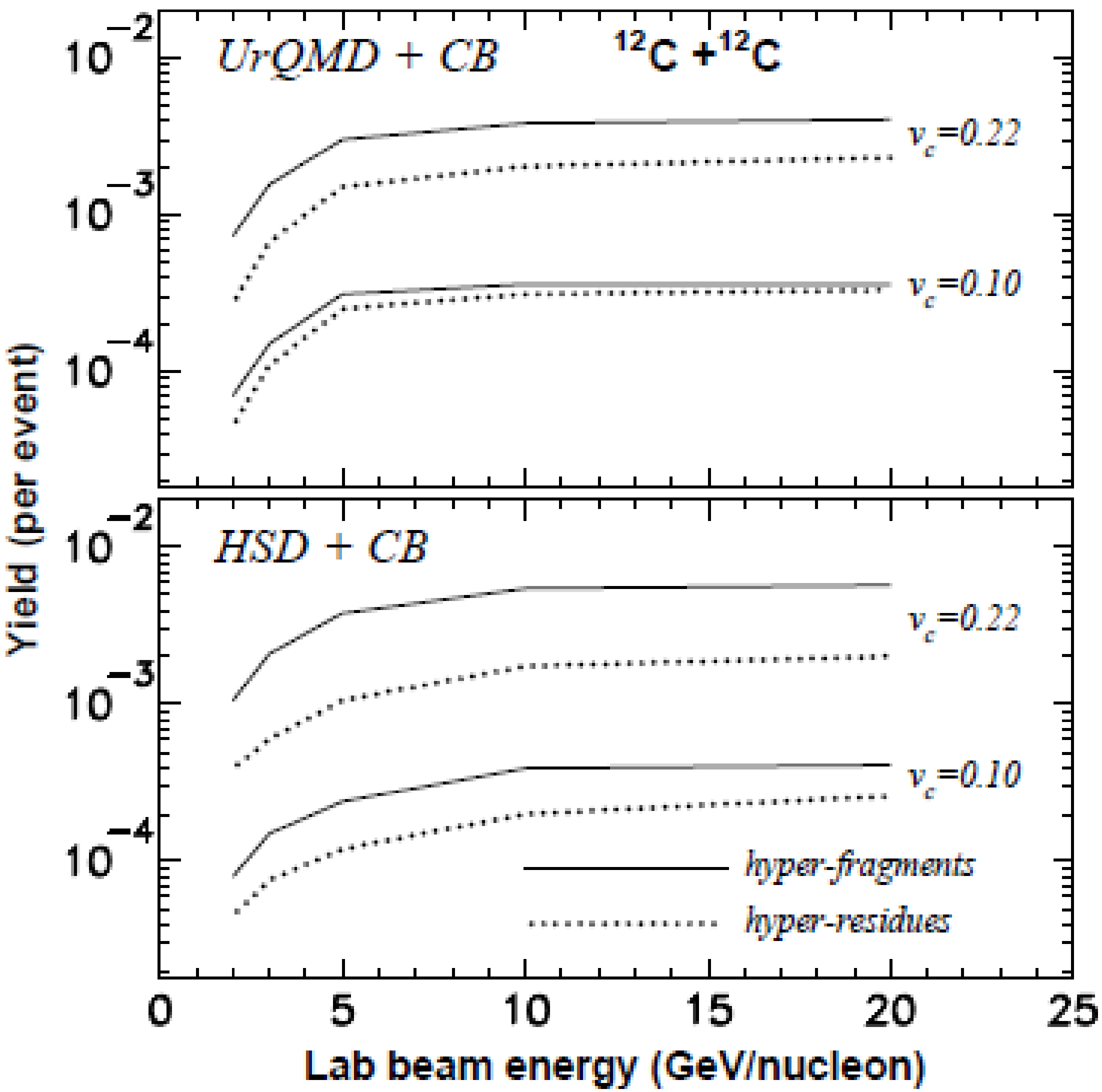


light hyper-fragments



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

Transport models are consistent (UrQMD, HSD)

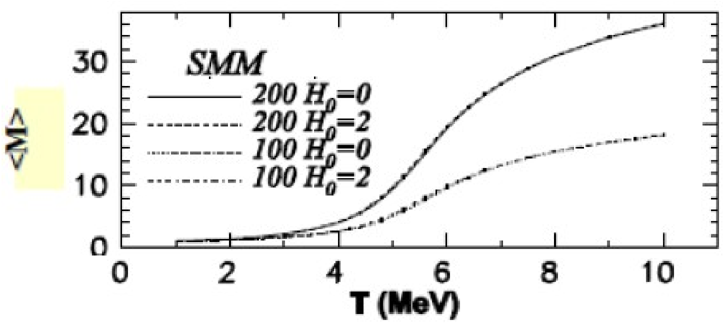


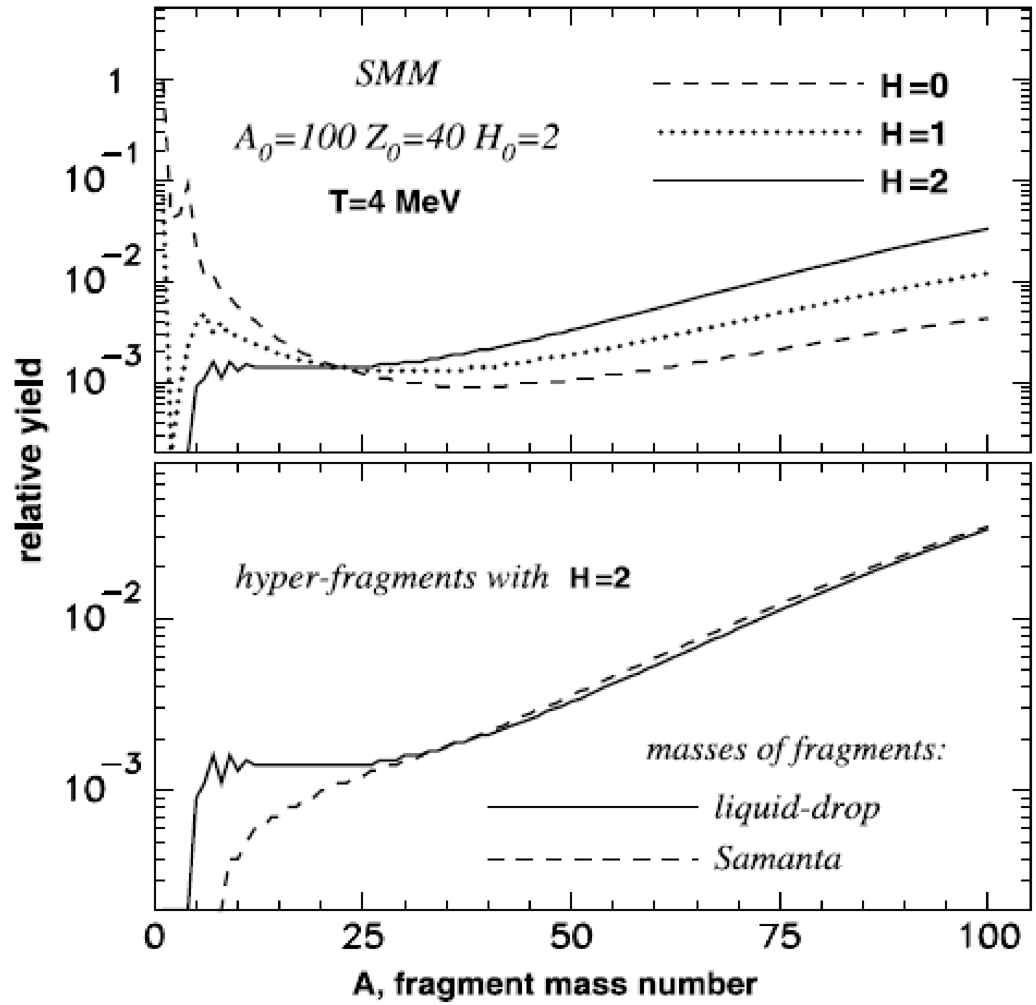
Multifragmentation of excited hyper-sources

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



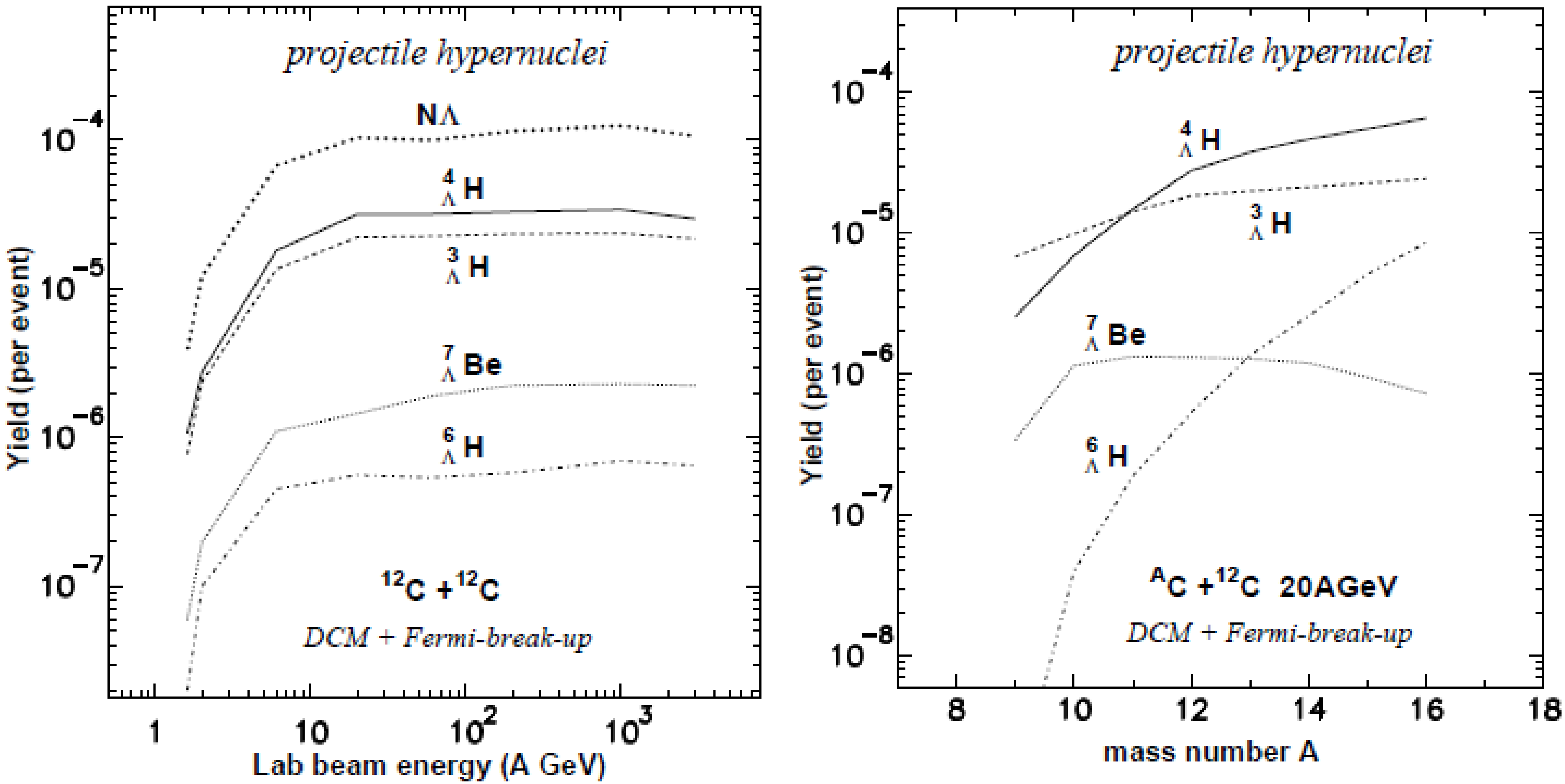


However, there are essential differences in properties of produced fragments !

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].

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

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

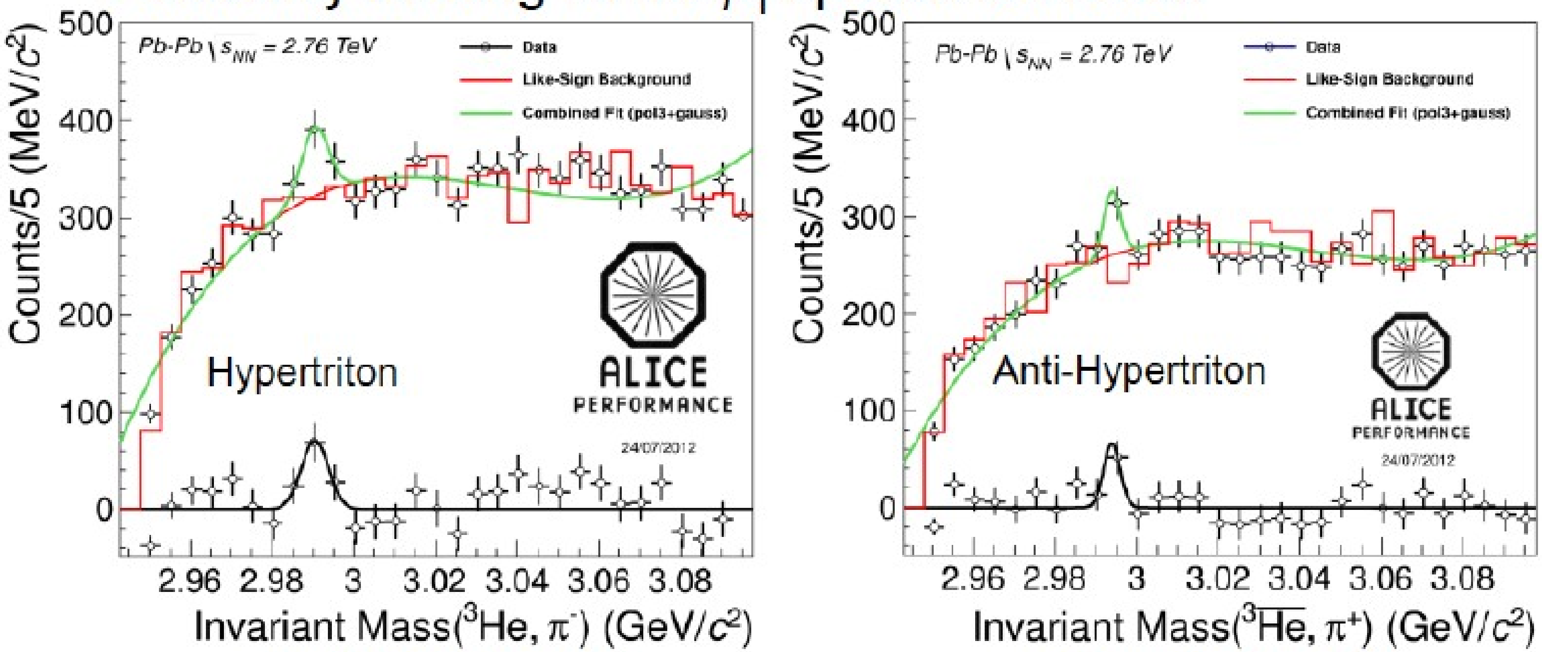
B. Doenigus et al., Nucl. Phys. A904-905 (2013) 547c

ALICE's observation for (anti-)hypertriton

Hypertriton

Signal of the hypertriton from the 2011 run

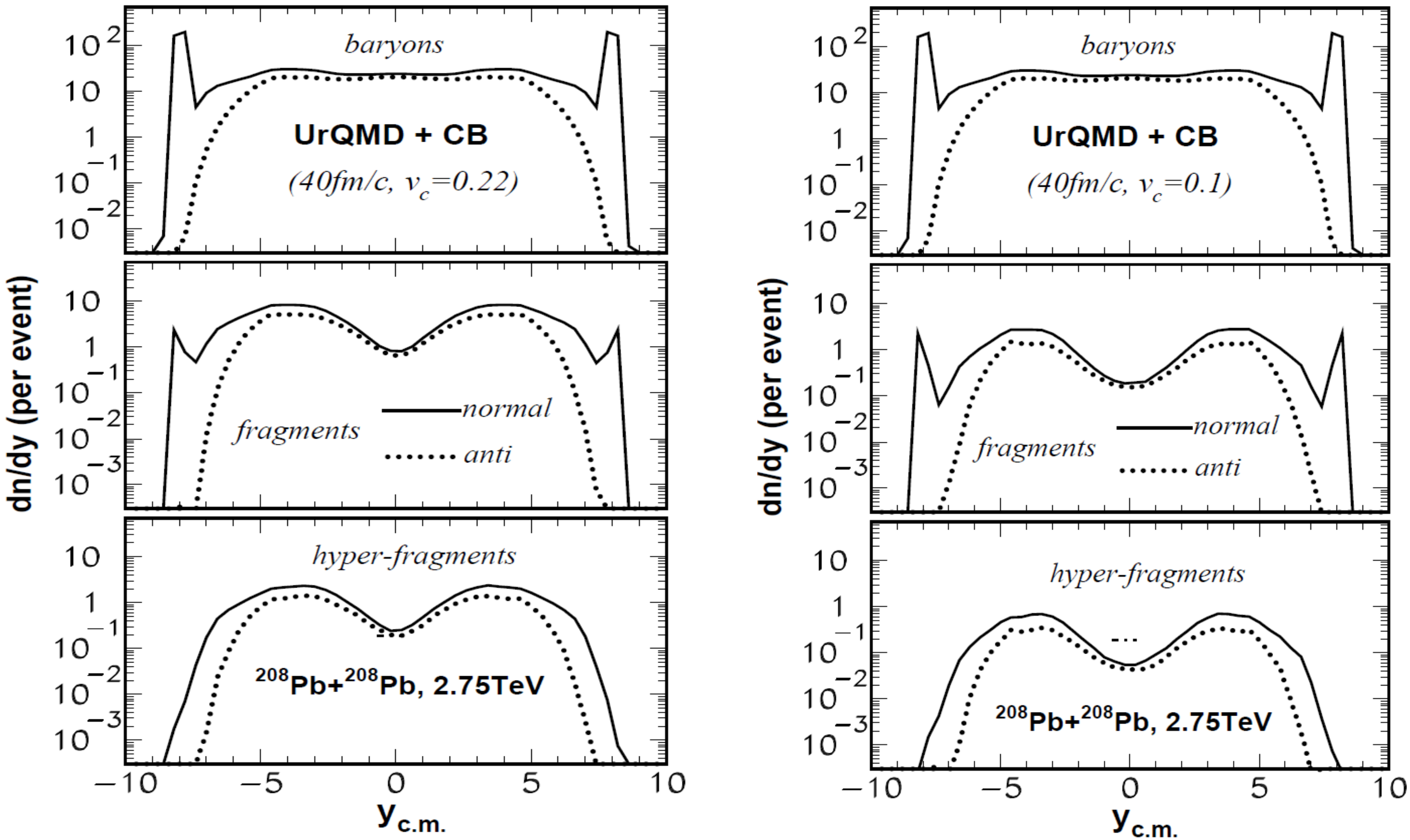
→ currently working on the p_T spectra extraction



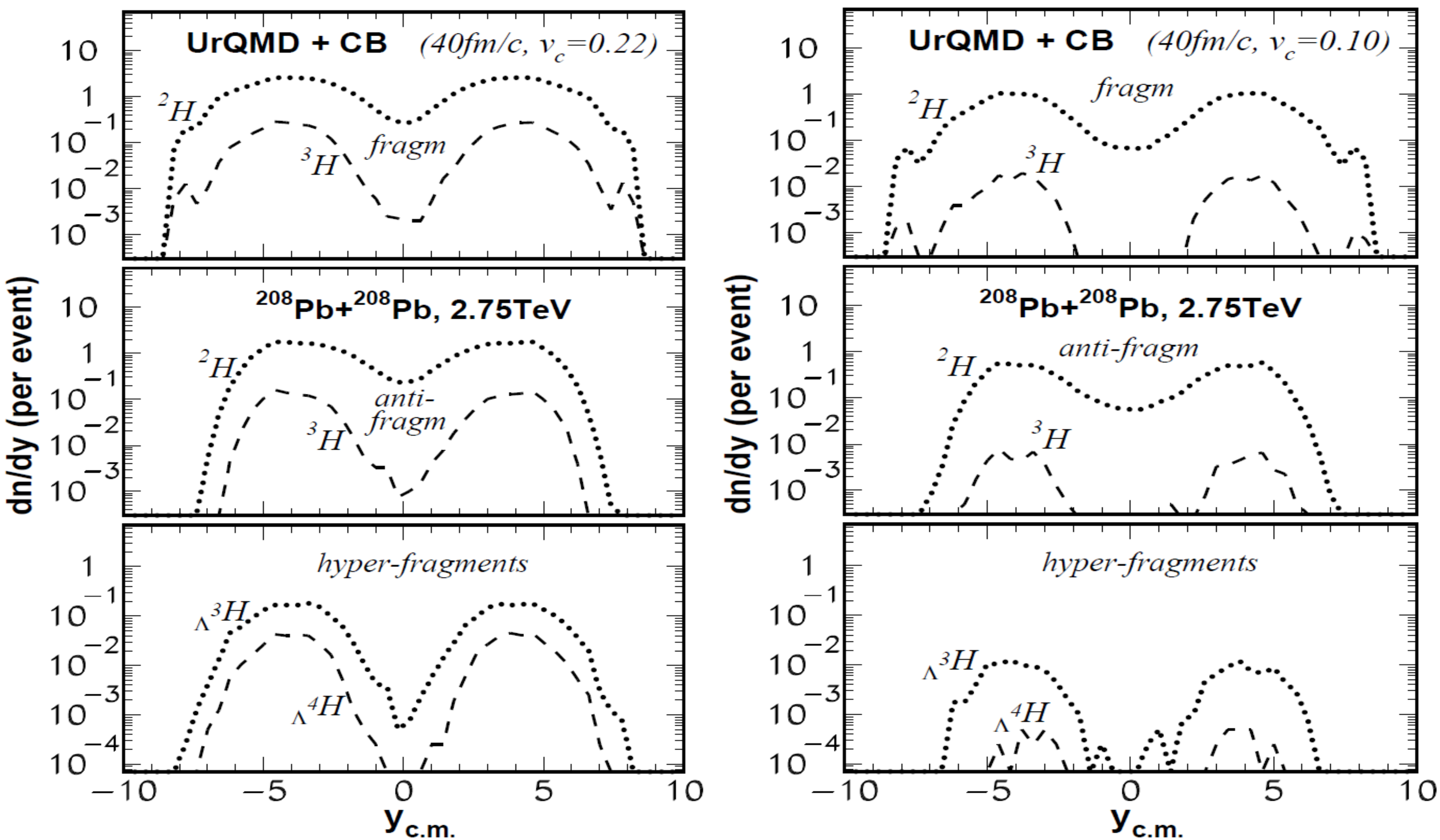
$\mu = (2.990 \pm 0.001)$ GeV/c^2
$\sigma = (3.35 \pm 0.7) \times 10^{-3}$ GeV/c^2

$\mu = (2.993 \pm 0.001)$ GeV/c^2
$\sigma = (2.00 \pm 1.2) \times 10^{-3}$ GeV/c^2

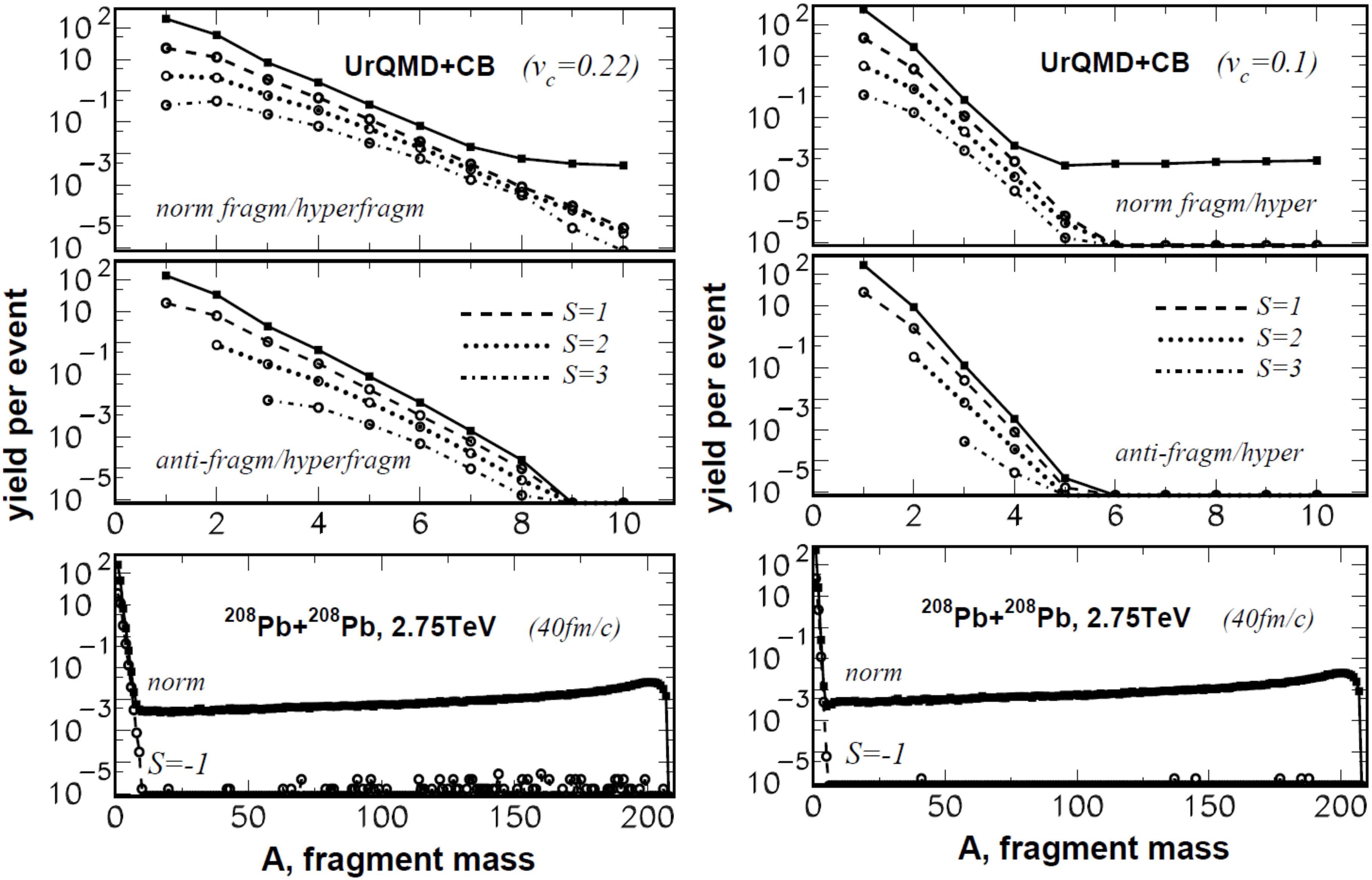
UrQMD + CM calculations for the LHC collider: 208Pb + 208Pb at 2.75 A TeV (preliminary)



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.



Mass distributions of produced fragments: Combining Ξ and Omega with nucleons may lead to exotica production (shown, preliminary, for normal fragments only)



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.

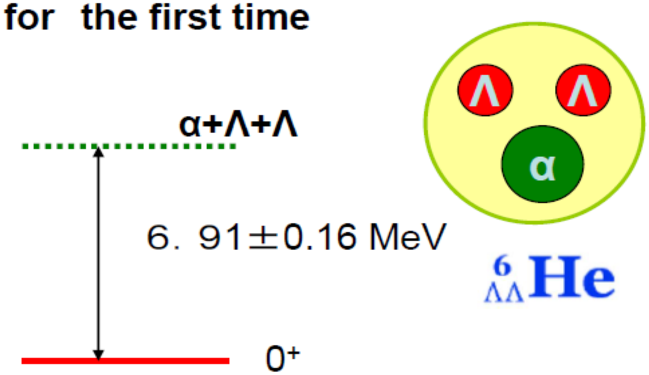
Mechanisms of formation of hypernuclei in peripheral reactions: Strange baryons (Λ, Σ, Ξ, …) produced in particle collisions can be transported to the spectator residues and captured in nuclear matter. Another mechanism is the coalescence of baryons leading to light clusters, including anti-matter, will 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.

(K^-, K^+) reactions

Ξ^- hyperons at the emulsion

Uniquely identified without ambiguity for the first time



Possible mechanism of this reaction:

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

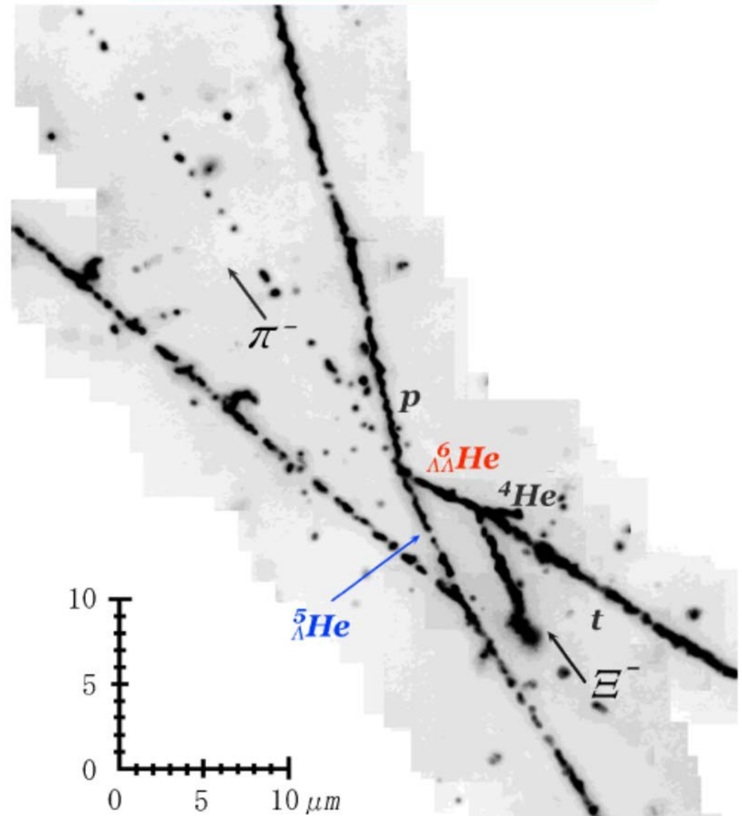
Break-up of excited hyper-system (~28MeV)
[Fermi-Break-up calculated probability~0.01]

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)

Nuclear reactions: production mechanisms for hypernuclei

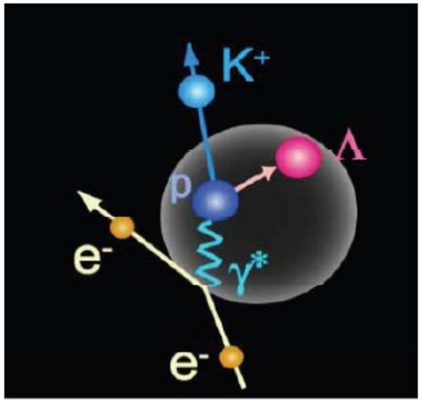
Traditional way for production of hypernuclei:

Conversion of Nucleons into Hyperons

by using hadron and electron beams

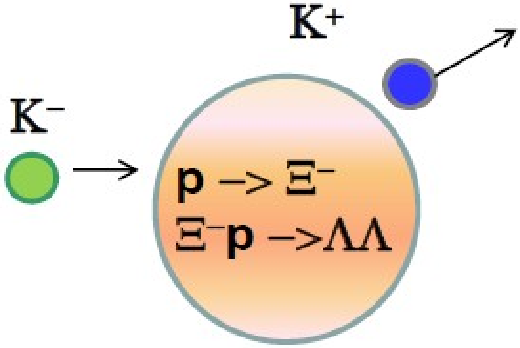
(CERN, BNL, KEK, CEBAF, DAΦNE, JPARC, MAMI, ...)

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



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.



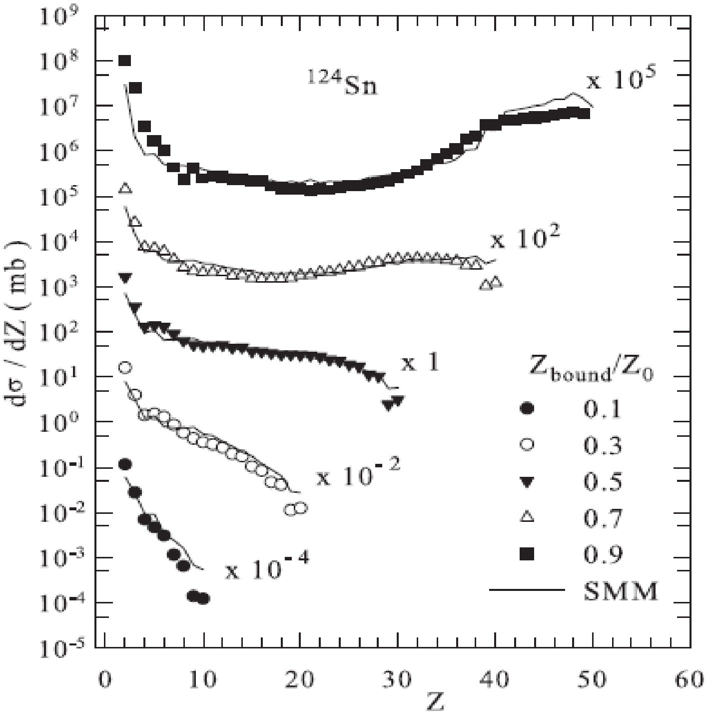
What reactions can be used to produce exotic strange nuclei and nuclei with many hyperons ?

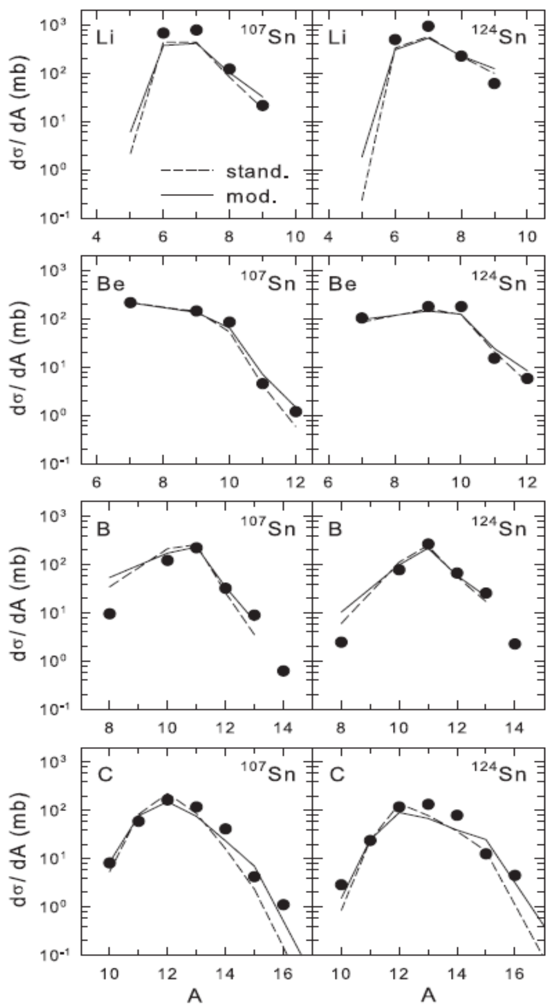
R.Ogul et al. PRC **83,** 024608 (2011) **ALADIN@GSI**

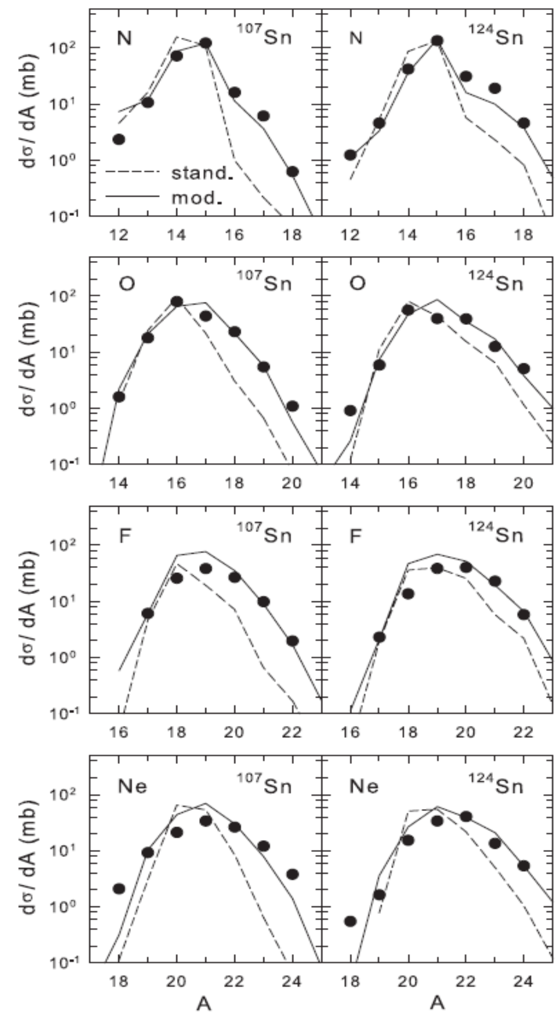
Isospin-dependent multifragmentation of relativistic projectiles

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.





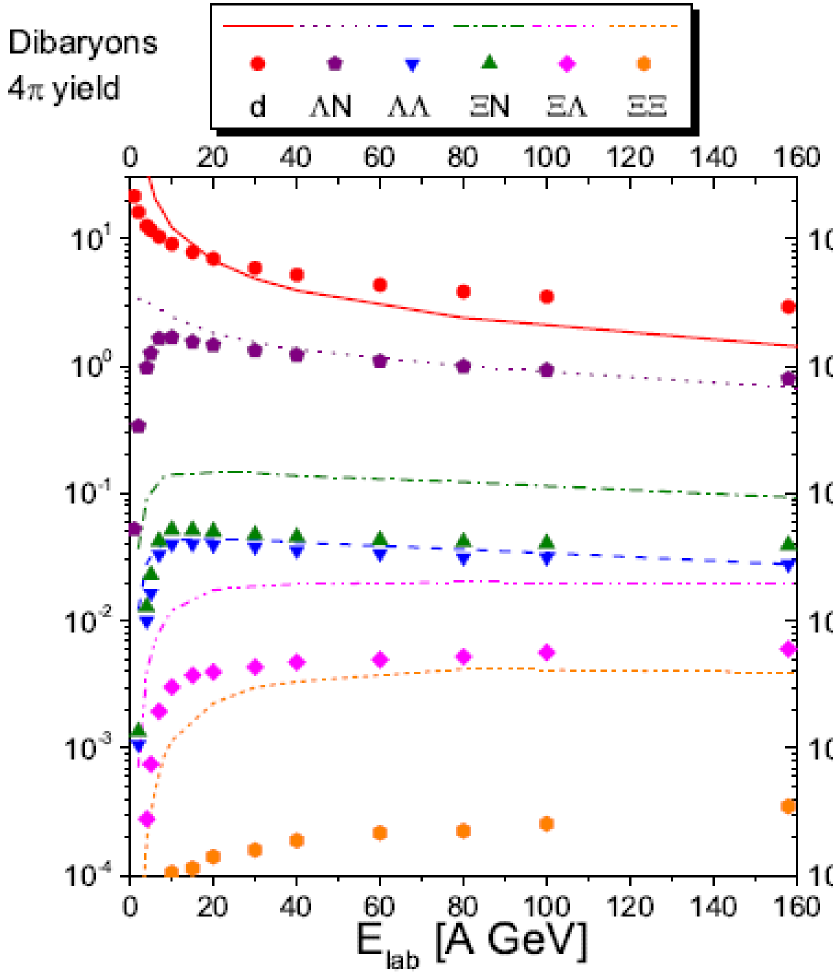


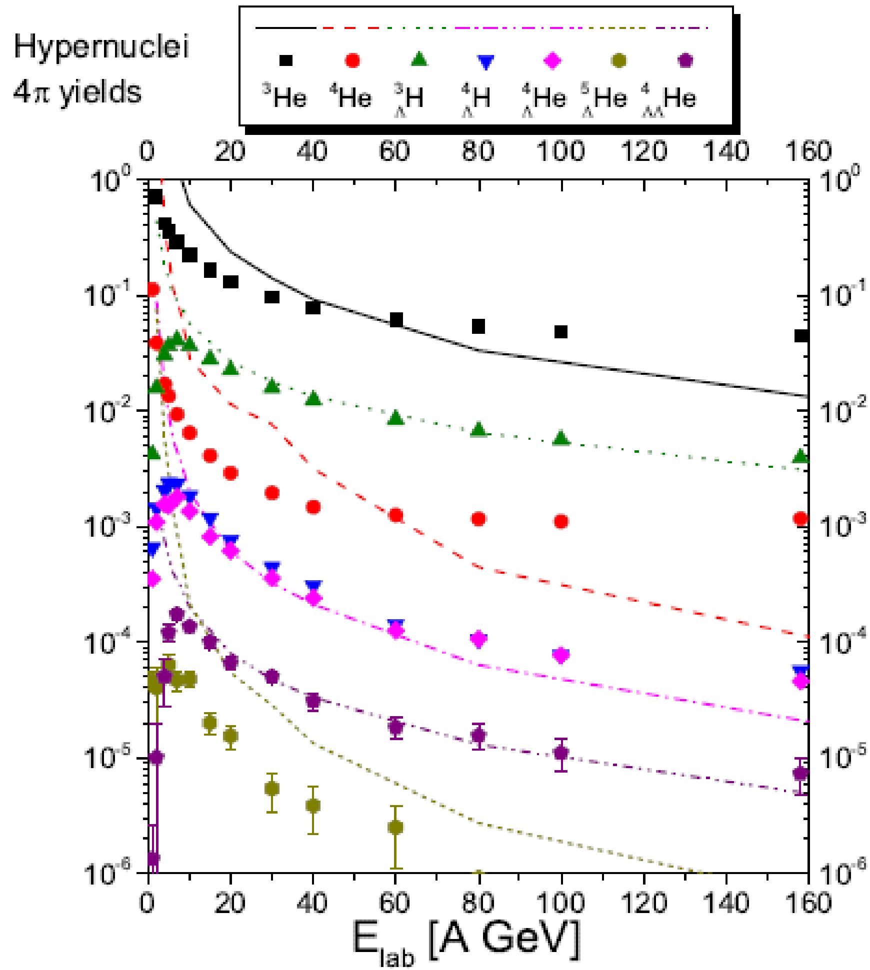
Statistical (chemical) equilibrium is established at break-up of hot projectile residues ! In the case of strangeness admixture we expect it too !

Production of light nuclei in central collisions : Au+Au

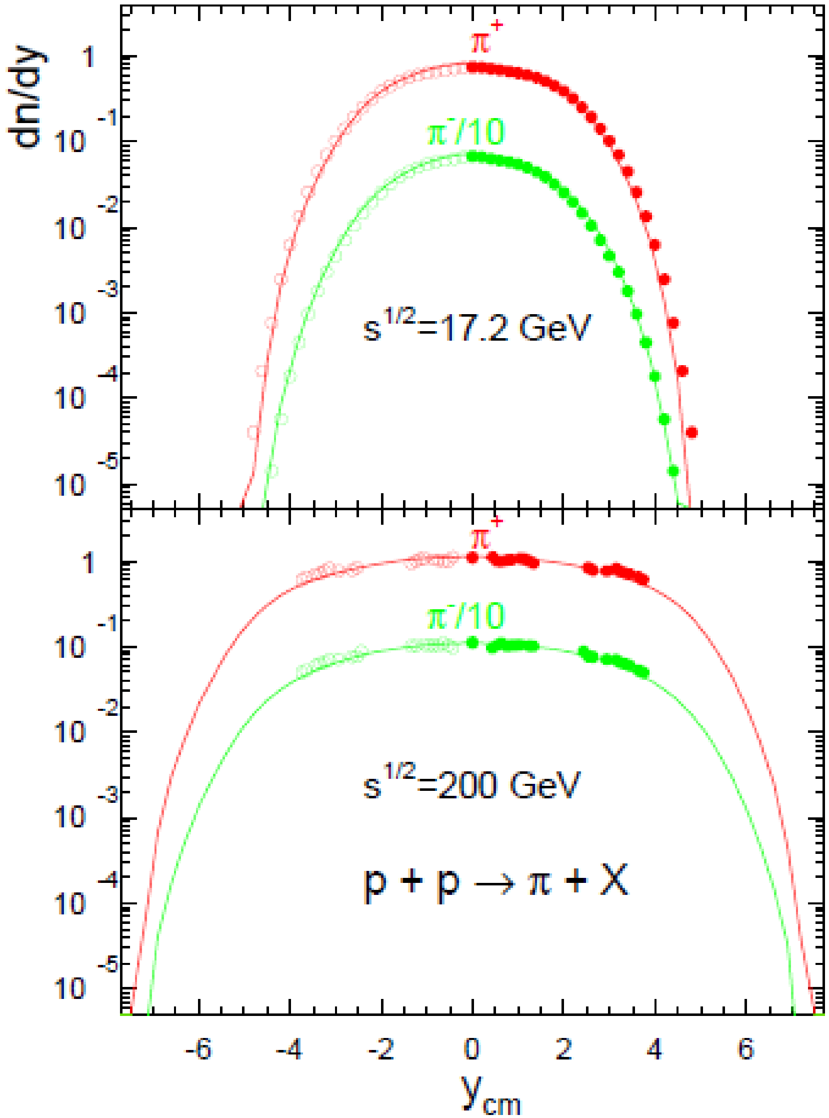
DCM and UrQMD calculations - J.Steinheimer et al., Phys. Lett. B**714**, 85 (2012)

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





Description of elementary interactions in DCM transport code



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

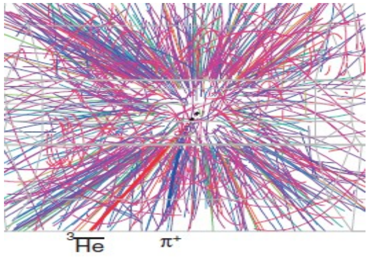
N_{event}	13.5×10^{9}	${}^{3}_{\Lambda}H$
N_{count}	1220±854	

STAR collaboration (RHIC):

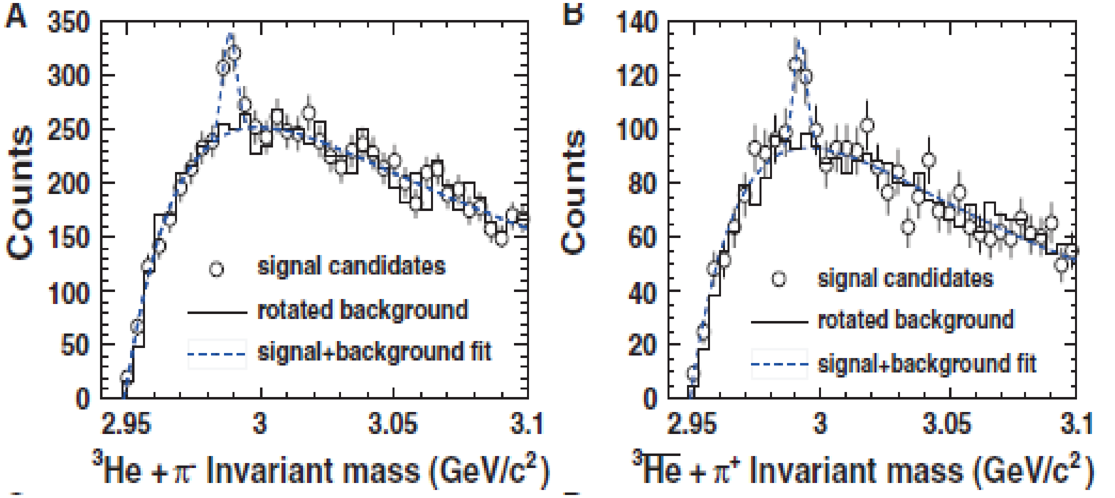
Science, 238 (2010) 58

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 (${}^{3}_{\Lambda}H$).



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

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 ?

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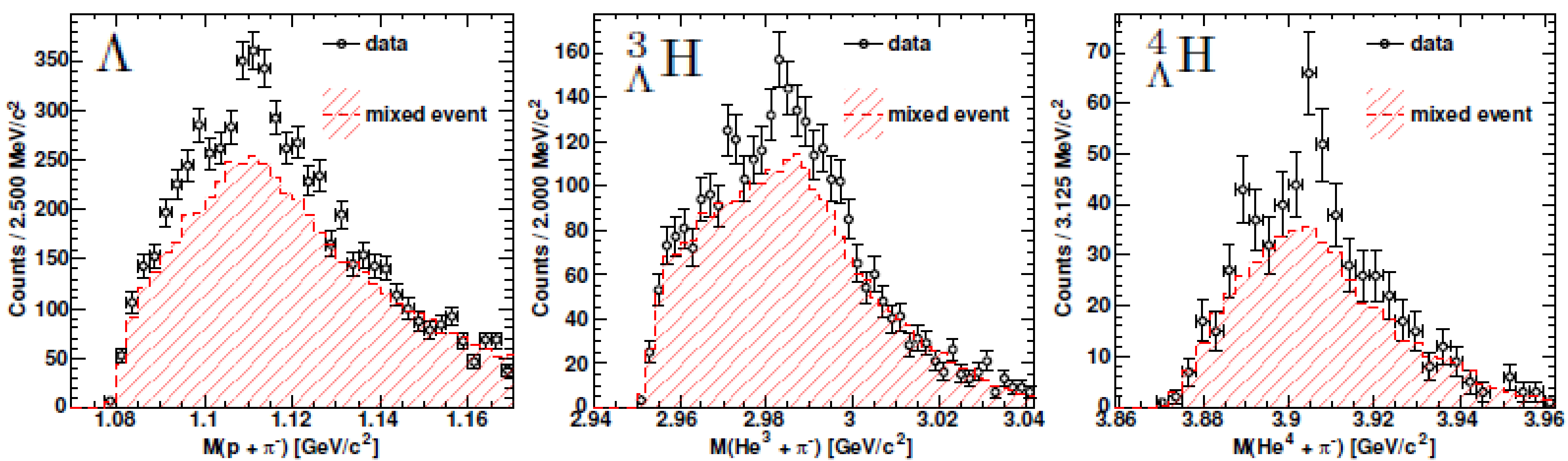
Projectile fragmentation: ^{6}Li beam at 2 A GeV on ^{12}C target



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