Has the neutral double hypernucleus ${}^{4}_{\Lambda\Lambda}n$ been observed?

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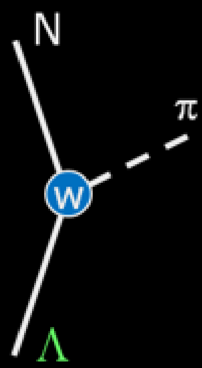
Physics Letters B 790, 502-508 (2019)

Falk Schupp
Helmholtz Institute Mainz

INPC 2019
Glasgow

Weak decay of Λ in nuclei

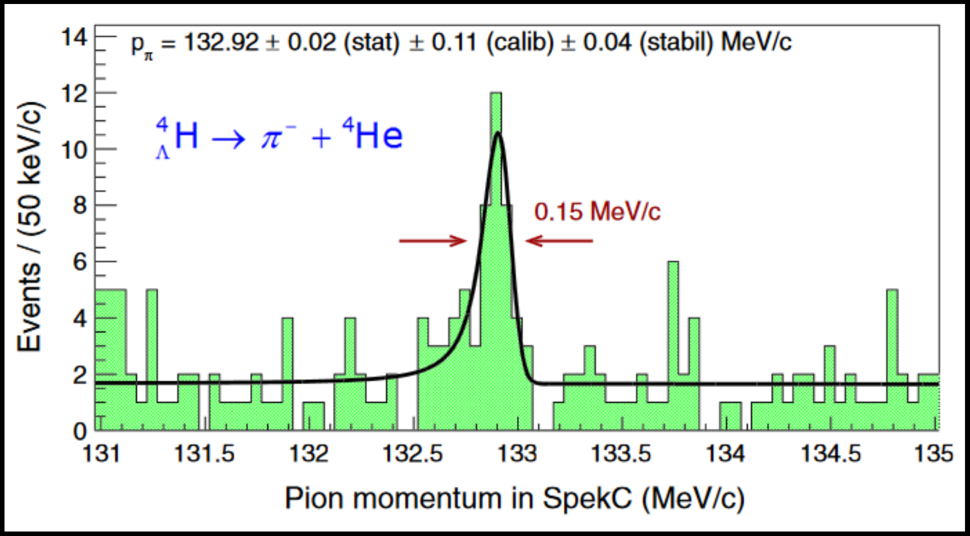
Free Λ decay



$\Lambda \rightarrow p\pi^-$: **101 MeV/c** (64%)

$\Lambda \rightarrow n\pi^0$: **104 MeV/c** (36%)

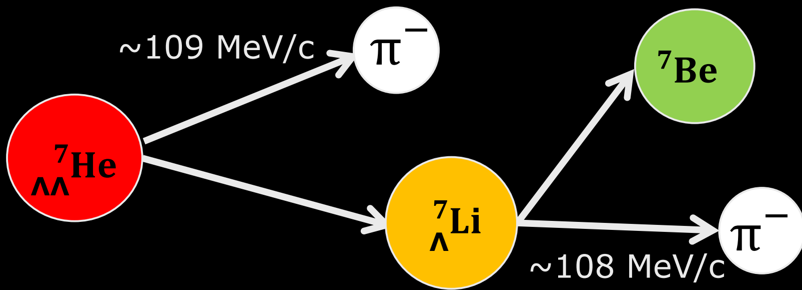
Weak pionic two-body decay in light hypernuclei

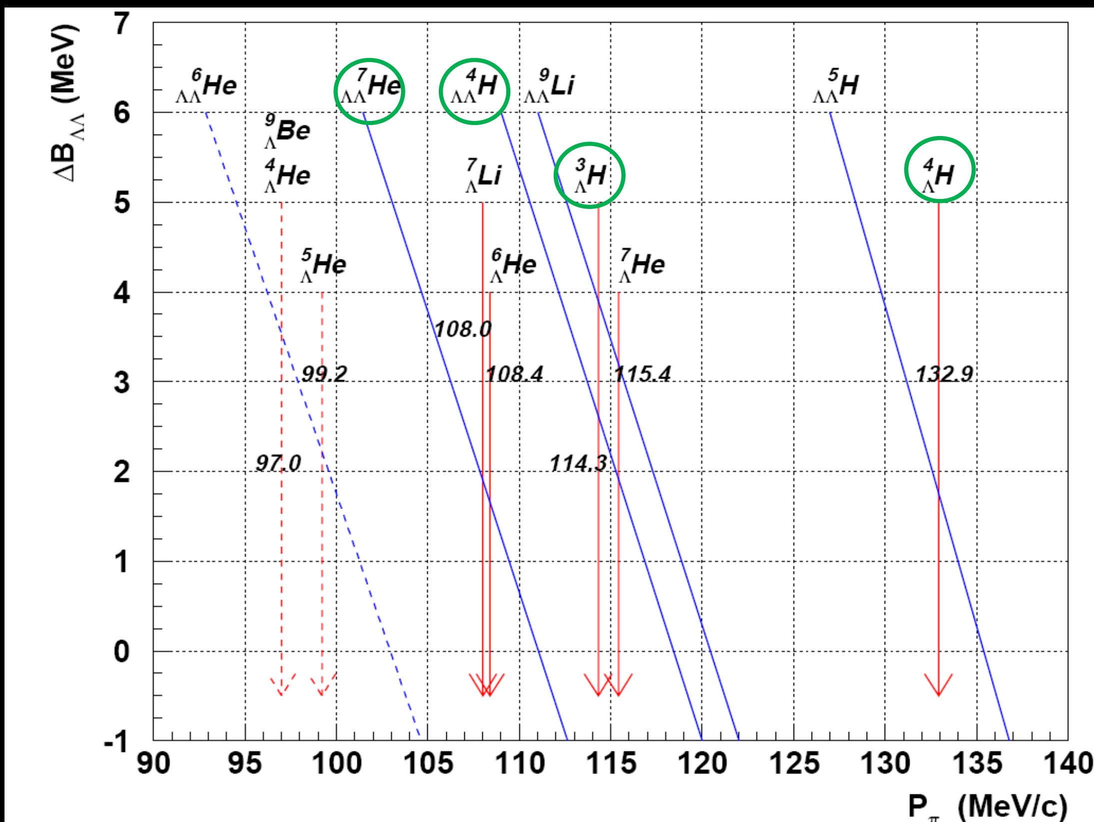


A. Esser et al., Phys. Rev. Lett. 114, 232501 (2015)

- Two-body decays → Sharp pion momenta

Sequential decay of ΛΛ hypernuclei





J. K. Ahn *et al.*, Phys. Rev. Lett. 87, 132504 (2011)

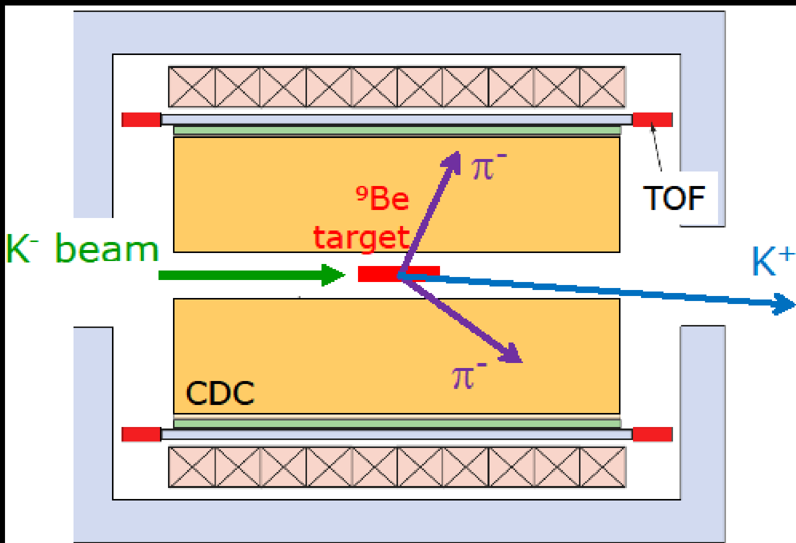
- Sequential pionic two-body decay of double ΛΛ hypernuclei will produce pairs of sharp pion momenta

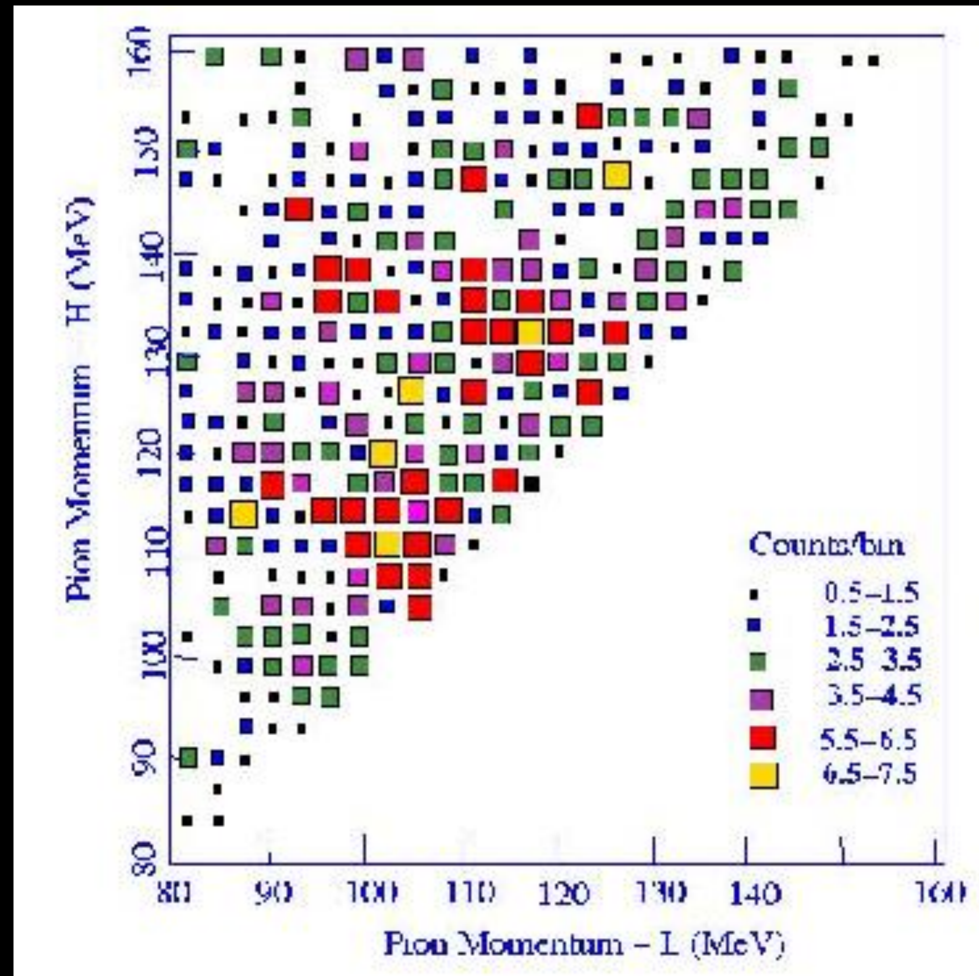
- Double hypernuclei mass depends on the not well known Λ-Λ binding energy $\Delta B_{\Lambda\Lambda}$

  → Momentum of first pion uncertain

The E906 puzzle

J. K. Ahn *et al.*, Phys. Rev. Lett. 87, 132504 (2011)





- Double strangeness exchange reaction (K^-,K^+) in ^{9}Be target
- Measured momenta of two correlated pions

Two dominant structures:

(104, 114) MeV/c : ${}^{4}_{\Lambda\Lambda}\mathrm{H}$; More likely ${}^{7}_{\Lambda\Lambda}\mathrm{He}$

(114, 133) MeV/c : ${}^{3}_{\Lambda}\mathrm{H} + {}^{4}_{\Lambda}\mathrm{H}$

S. D. Randeniya and E. V. Hungerford, Phys. Rev. C 76, 064308 (2007)

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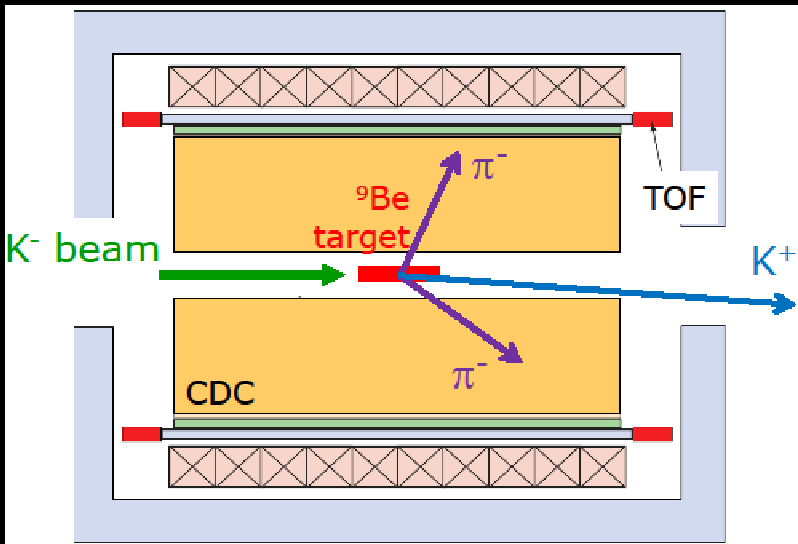

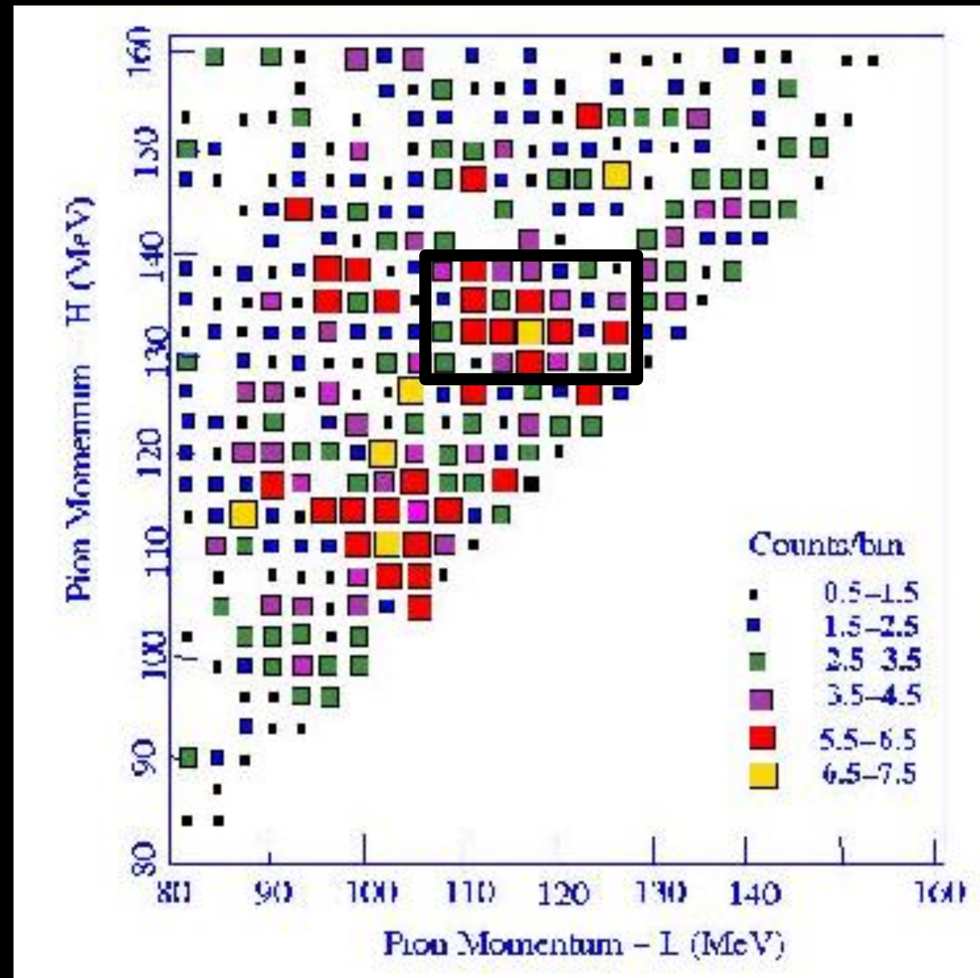

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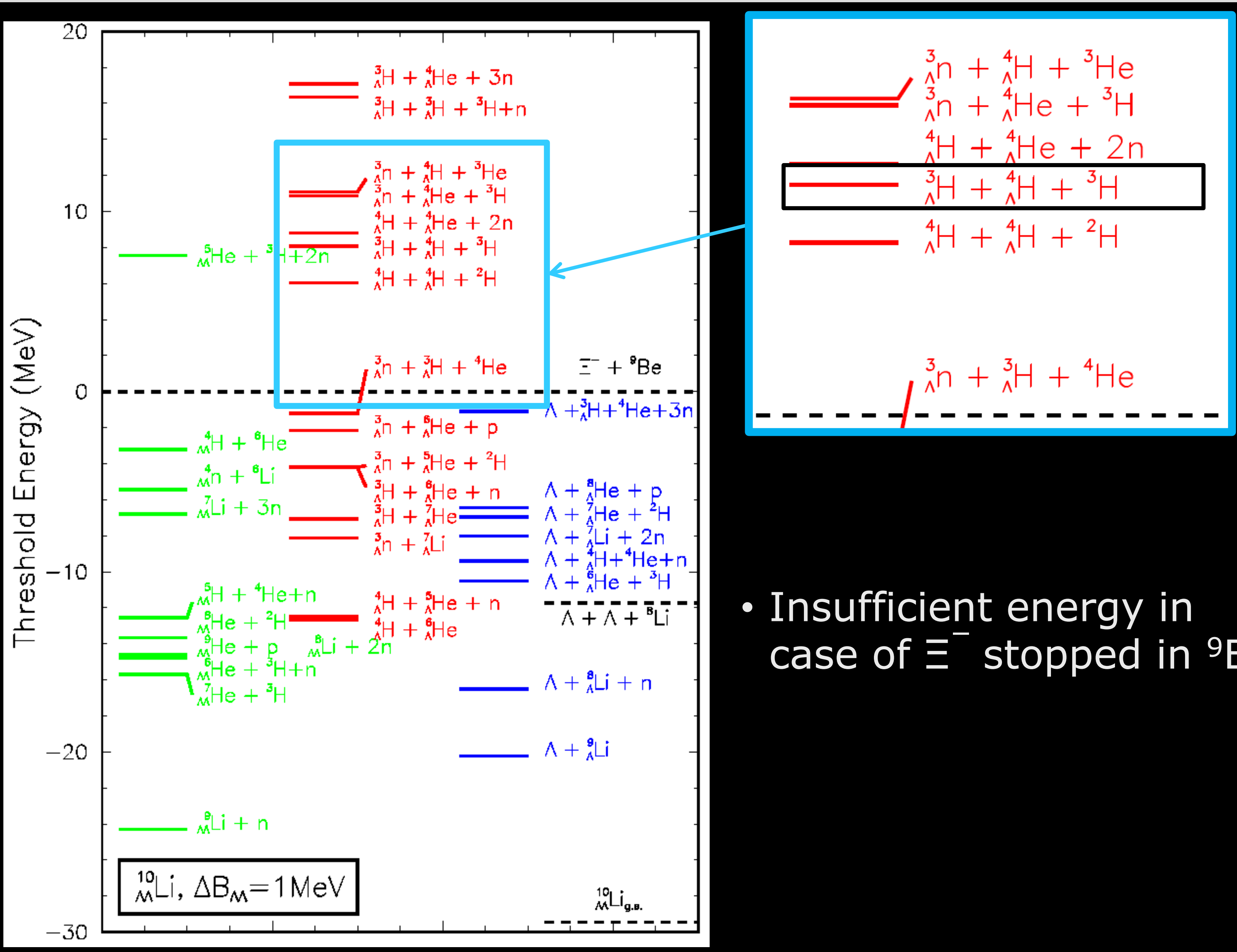
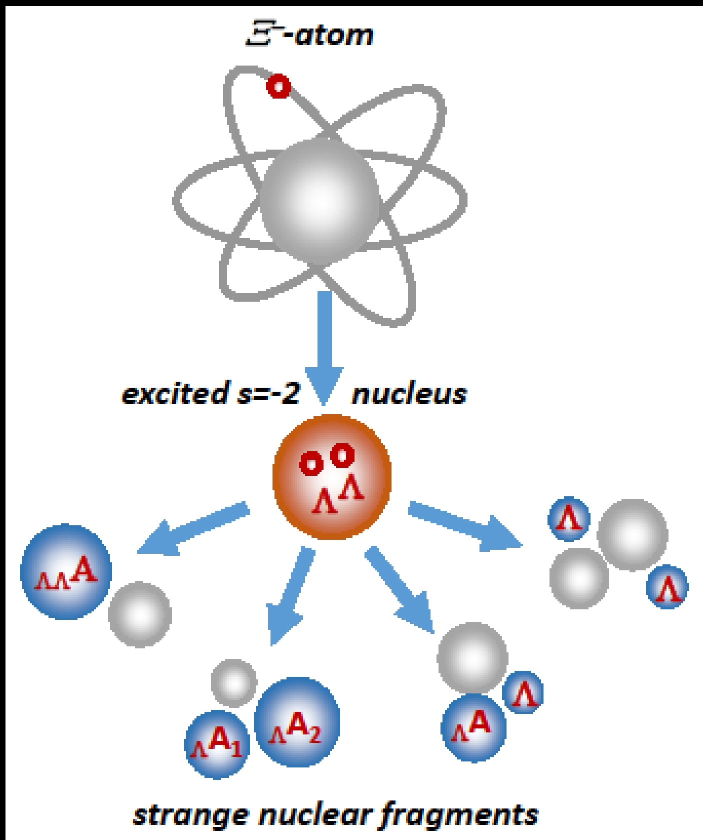
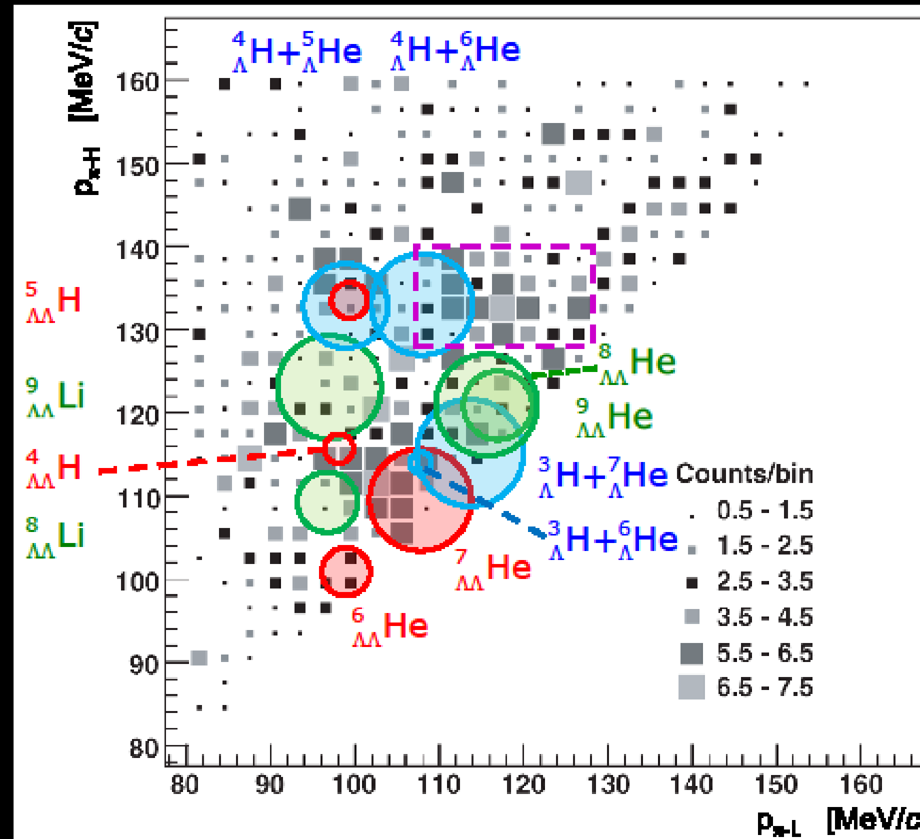
Why not $^{3}_{\Lambda}H + ^{4}_{\Lambda}H$?



- Insufficient energy in case of Ξ^- stopped in ^{9}Be

Simulation of Ξ^-_{rest} + ^{9}Be using SMM

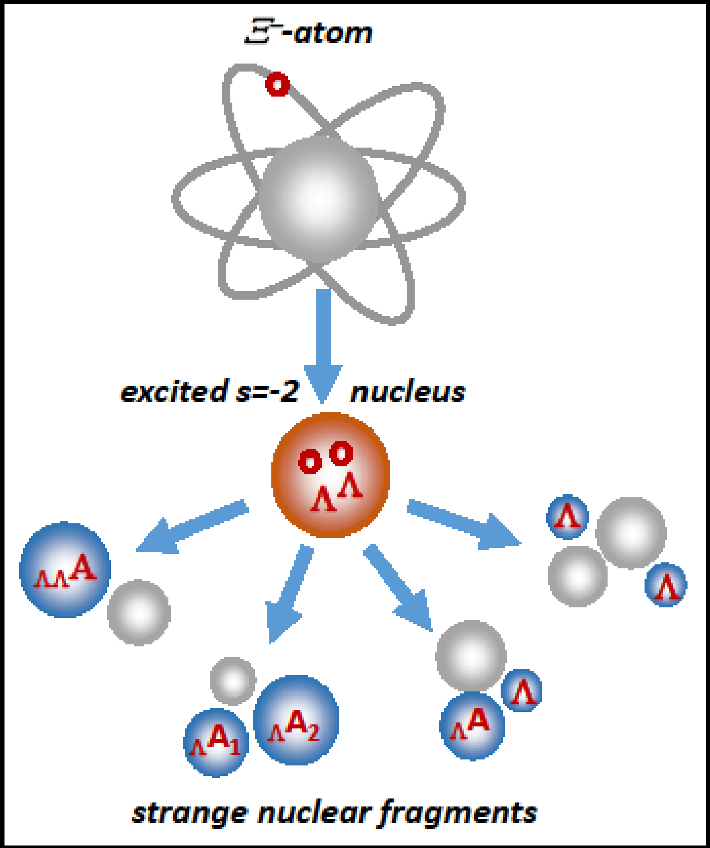


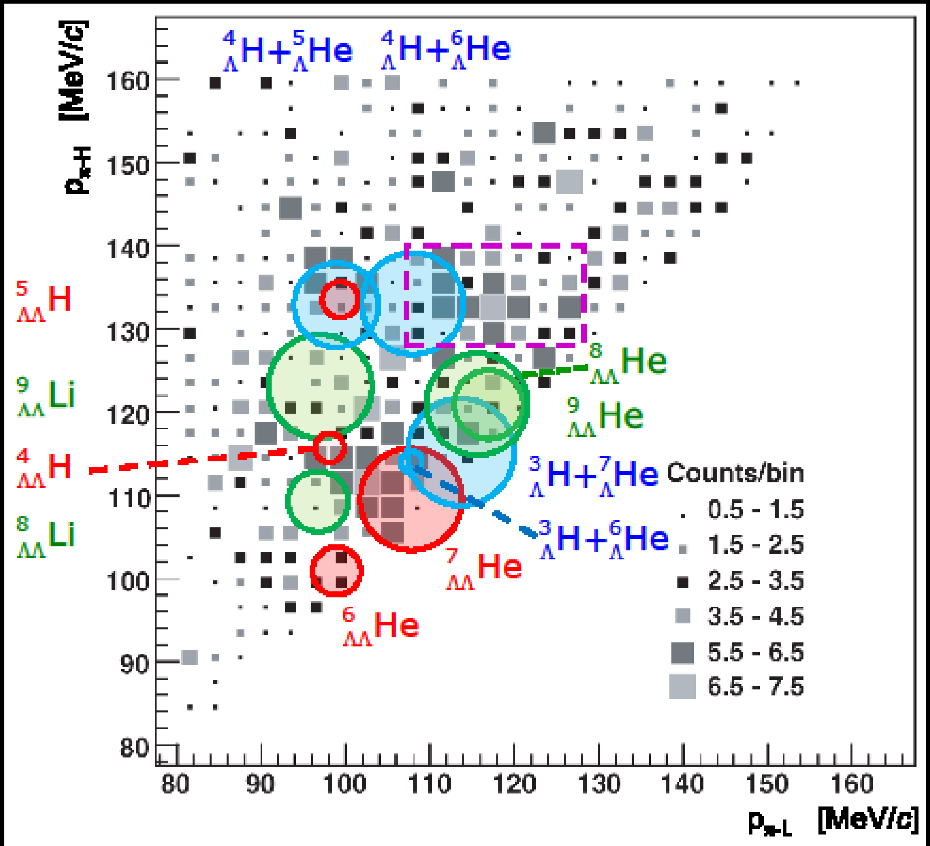


- Micro-canonical statistical multifragmentation model
    - Extended to strangeness

      A. S. Botvina, J. Pochodzalla, Physical Review C 76, 024909 (2007)
- Area of circles proportional to production yields
- Center given by pion momenta in two-body decays ($\Delta B_{\Lambda\Lambda}$ = 1 MeV)
- Branching ratios for pionic two-body decay not taken into account

Simulation of $\Xi^-_{rest} + {}^9Be$ using SMM

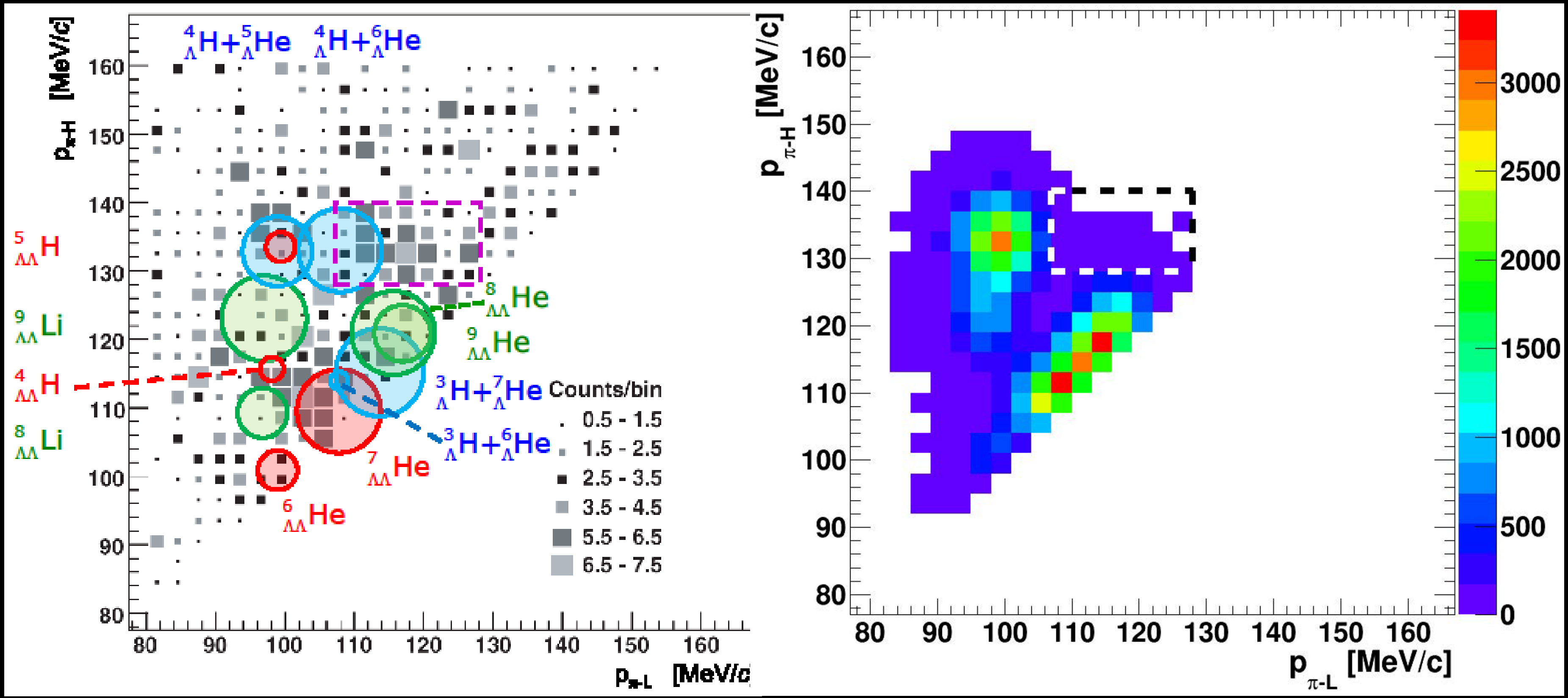




- No production channel can explain area of interest
- Note: $^7_{\Lambda\Lambda}He$ is far more likely to reproduce the first dominant structure

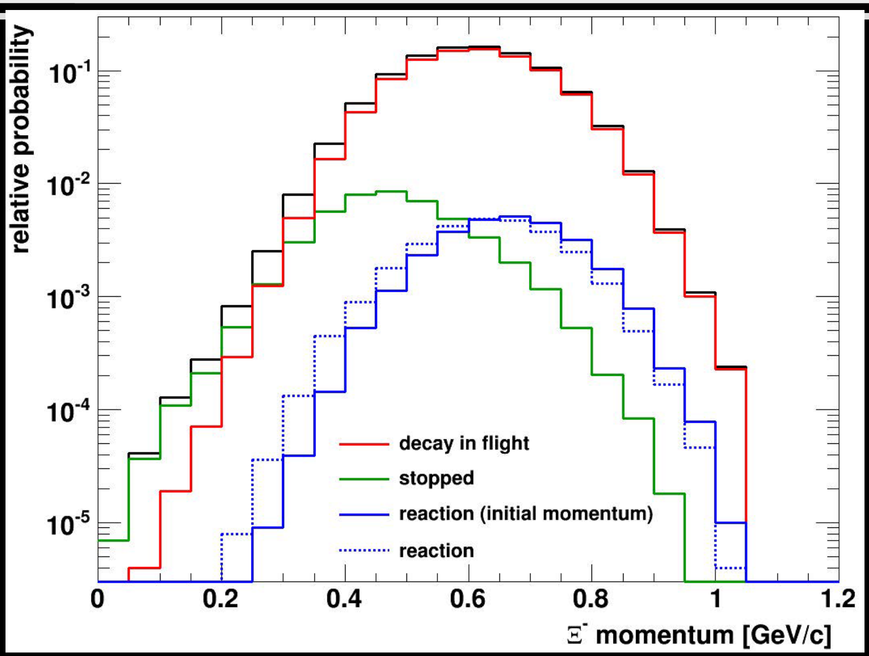
Simulation of $\Xi^-_{rest} + {}^9Be$ using SMM

- Including:
  - Pionic two-body decay branching ratios
  - E906 momentum resolution



- Known nuclei cannot produce a signal in the area of interest of E906

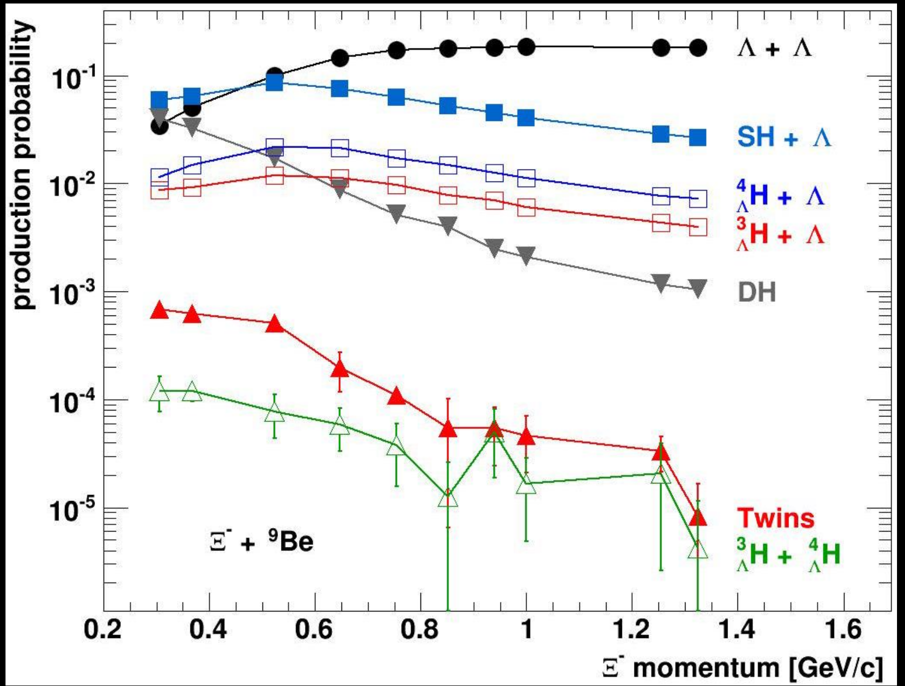
Simulations of energetic $\Xi^- + {}^9Be$ nuclear reactions



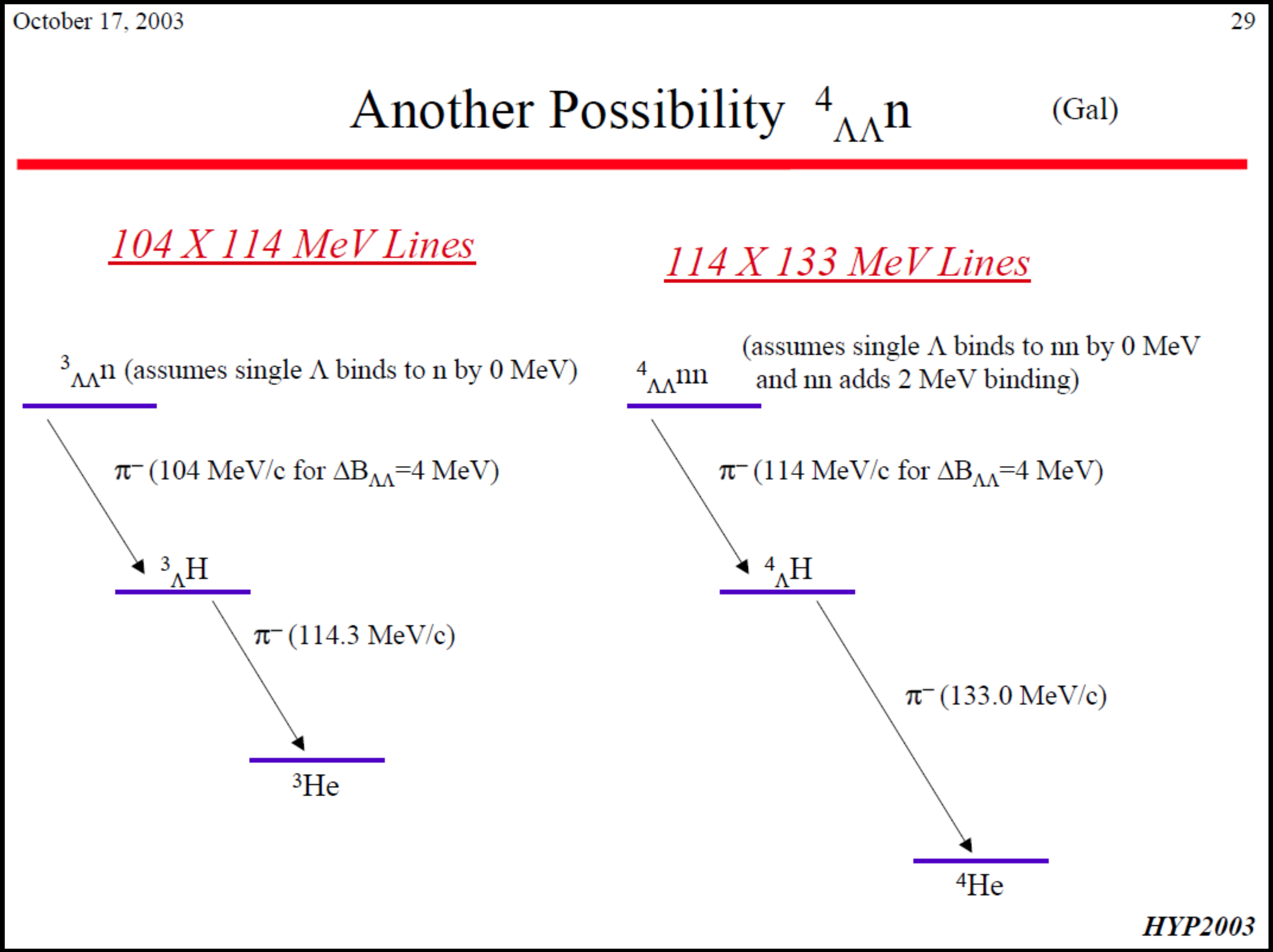
- Simulations using GEANT4
- Possible cases
  - Decay in flight
  - Stopped in target
  - Nuclear reactions

- Nuclear reactions simulated with GiBUU

- Total probability: both graphs folded
- Resulting production probability of $P({}^3_\Lambda H + {}^4_\Lambda H) = 1.6 \cdot 10^{-6}$
- Two orders of magnitude too low to match experimental observation

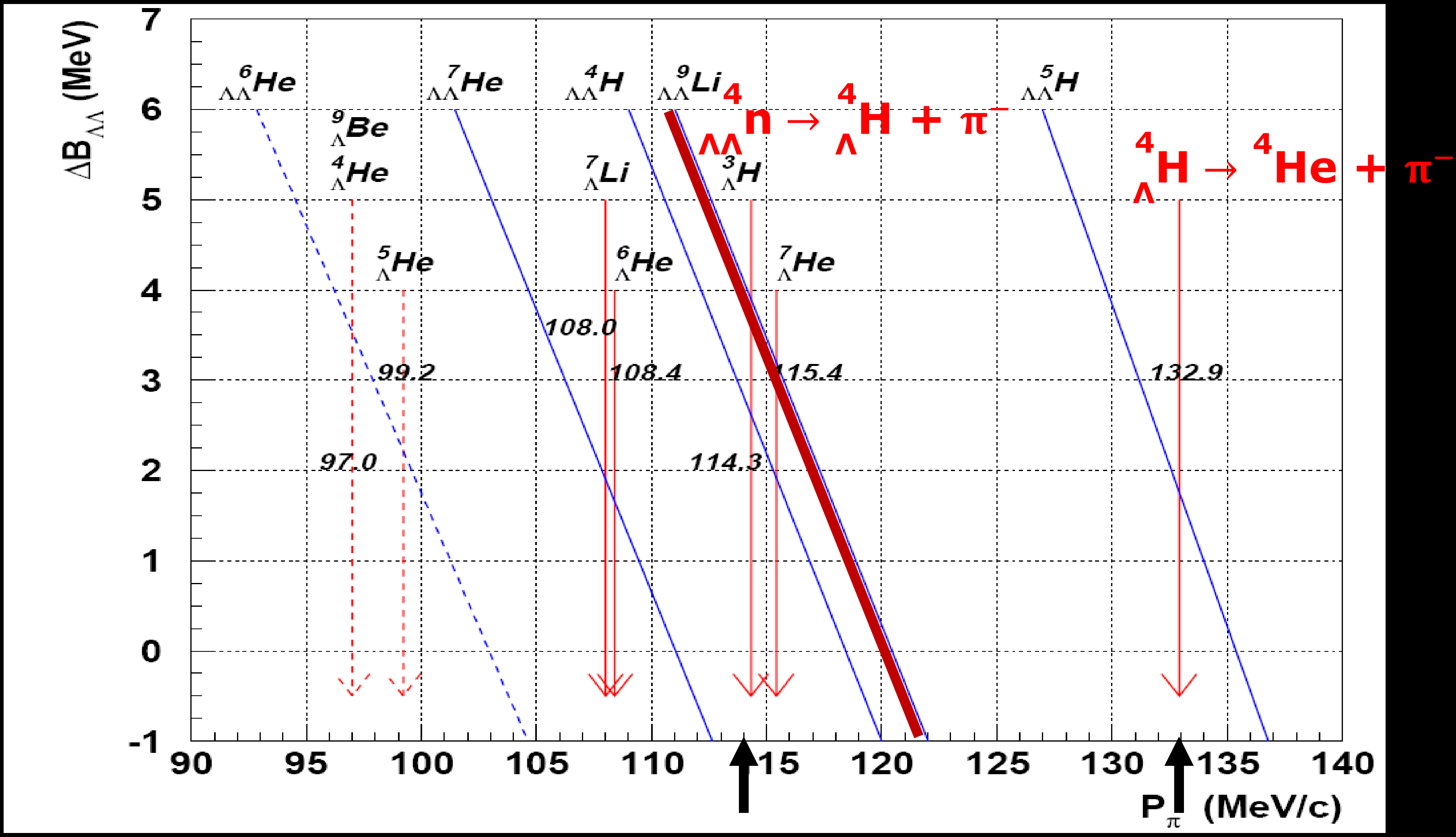


Can $^{4}_{\Lambda\Lambda}n$ solve the puzzle?



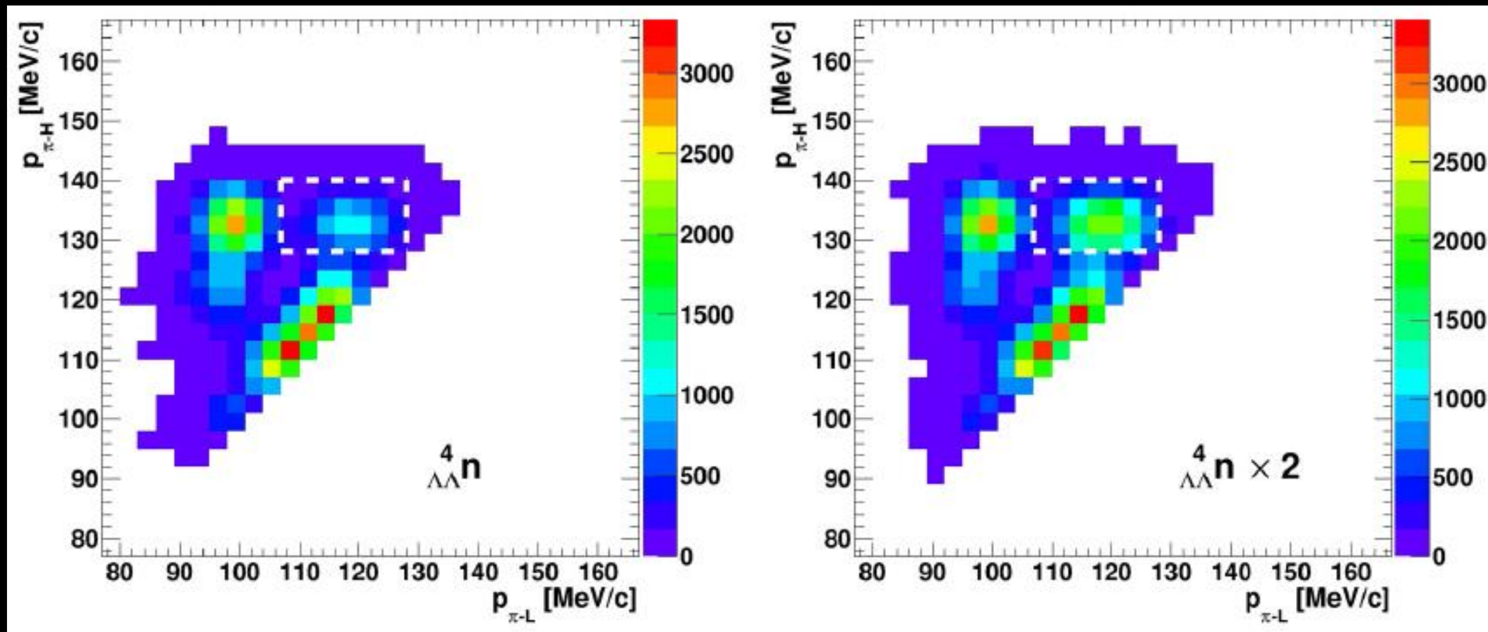
P. Pile, Production of hypernuclei at the AGS, talk given at VIII International Conference on Hypernuclear and Strange, Particle Physics (HYP2003).

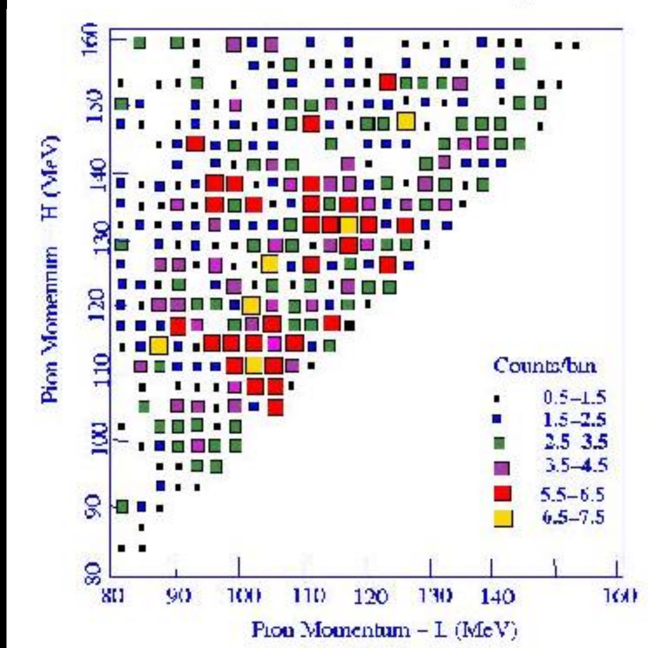
Can $^{4}_{\Lambda\Lambda}n$ solve the puzzle?



Decay of $^{4}_{\Lambda\Lambda}n$ would yield pion momenta in the observed region (114,133) MeV/c

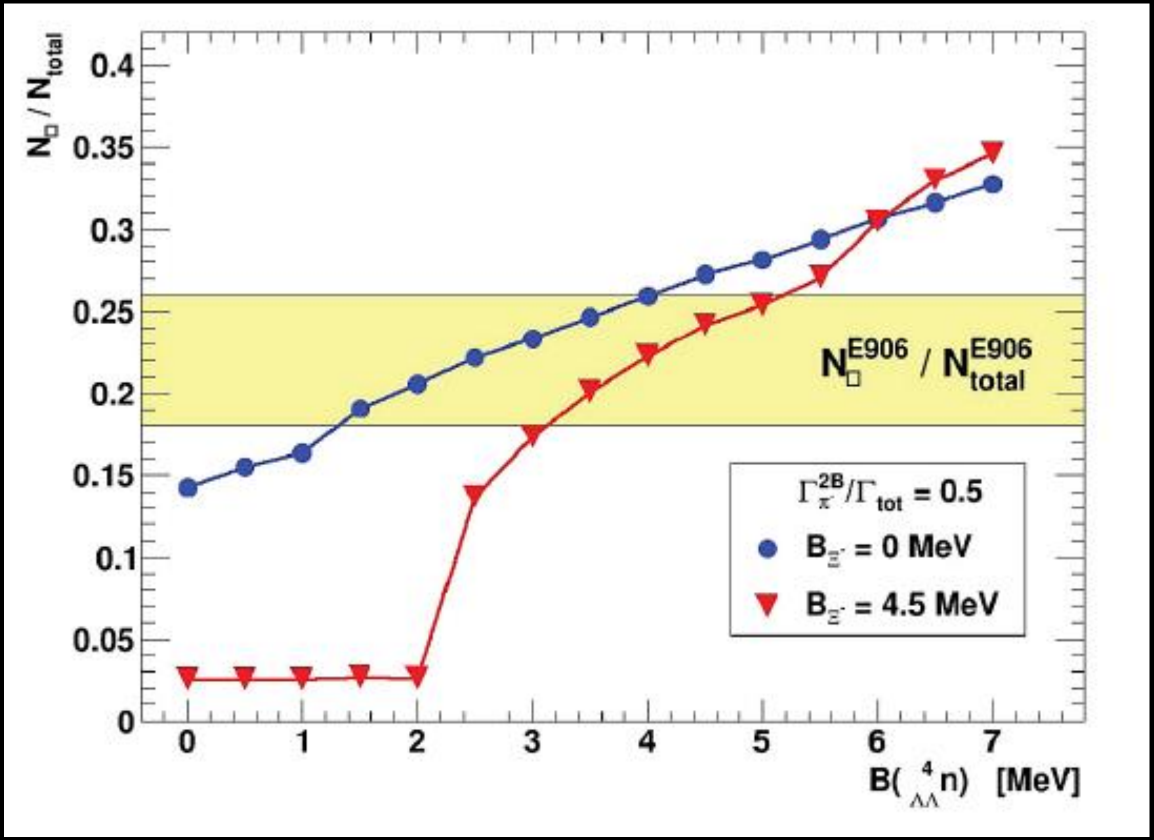
Can $^{4}_{\Lambda\Lambda}n$ solve the puzzle?





- SMM with $^{4}_{\Lambda\Lambda}n$ taken into account
- $^{4}_{\Lambda\Lambda}n$ with 25% (left) and 50% (right) pionic two-body branching ratios

Can $^{4}_{\Lambda\Lambda}n$ solve the puzzle?



- Relative signal strength in area of interest
- Yellow band marks experimental value of E906
- For branching ratio of 50%

- Good agreement found for $^{4}_{\Lambda\Lambda}n$ binding energies between 1.5 - 4 MeV

Is ${}^{4}_{\Lambda\Lambda}n$ bound ?

- ${}^{4}_{\Lambda\Lambda}n$ may be bound
  - Calculation still rather schematic

  J.-M. Richard, Q. Wang, and Q. Zhao, Phys. Rev. C 91, 014003 (2015)

- ${}^{4}_{\Lambda\Lambda}n$ not bound
  - Calculation using pionless effective field theory
  - „Far from being bound"

  L. Contessi, M. Schäfer, N. Barnea, A. Gal, J. Mareš, The onset of ΛΛ hypernuclear binding, arXiv:1905.06775 [nucl-th]

Conclusion

- Decays of ${}^{4}_{\Lambda\Lambda}n$ could indeed solve the E906 puzzle
- Present work should not be considered as a direct proof
- Most consistent explanation at the moment
- Experimentally ${}^{4}_{\Lambda\Lambda}n$ challenging to detect
    - Current J-PARC E07 emulsion experiment
    - Newly developed „vertex picker“ scanning system
- Further discussions and experimental activities needed to solve the E906 puzzle

Thank you for your attention.

Backup 1

HIM HELMHOLTZ Helmholtz Institut Mainz

Table 2
Probability per produced Ξ^- for different $S = -2$ channels by nuclear $\Xi^- + {}^9Be$ reactions and by stopped Ξ^- hyperons. Here, SH (DH) stands for single (double) hypernucleus, respectively. In case of the stopped Ξ^- process a capture $\times$ conversion probability for producing excited $\Lambda\Lambda$ nuclear systems of 5% was taken into account. The probabilities in the last 5 columns are multiplied by 10^4.

process	probability [%]	model	$\Lambda+\Lambda$	Λ+SH	SH+SH	DH	${}^3_\Lambda H + {}^4_\Lambda H$
$\Xi^- + {}^9Be$	2.83	GiBUU	37.2	20.9	0.070	3.23	0.016
stopped Ξ^-	4.65×0.05	SMM ${}^{10}_{\Lambda\Lambda}Li^*$	0.525	6.365	6.659	9.699	0

Backup 2

Table 1

Accessible decay channels with twin-hypernuclei (upper rows) or $\Lambda\Lambda$-hypernuclei (lower rows) of an excited $^{10}_{\Lambda\Lambda}Li^*$ hyperfragment which was formed after capture of a stopped Ξ^- by a ^9Be nucleus. The pion momenta and the branching ratios are given for two-body π^- decays. The neutral nucleus $^{4}_{\Lambda\Lambda}n$ has not been observed yet and its stability is controversial [17,29]. Also the $^{3}_{\Lambda}n$ [3] needs further confirmation. Both hypernuclei are not included in the production probability calculations shown in Fig. 1 and column 7.

decay channels		π^- decay momenta (MeV/c)		two-body π^- branching ratios		production probability			
						no neutral	only $^{3}_{\Lambda}n$	only $^{4}_{\Lambda\Lambda}n$	$^{3}_{\Lambda}n$+ $^{4}_{\Lambda\Lambda}n$
$^{3}_{\Lambda}n \to {}^{3}H+\pi^-$	$^{3}_{\Lambda}H \to {}^{3}He+\pi^-$	119	114	0.25	0.249	–	0.0002	–	0.0002
$^{3}_{\Lambda}n \to {}^{3}H+\pi^-$	$^{5}_{\Lambda}He \to {}^{4}He+p+\pi^-$	119	99	0.25	0.17	–	0.0121	–	0.0120
$^{3}_{\Lambda}n \to {}^{3}H+\pi^-$	$^{6}_{\Lambda}He \to {}^{6}Li+\pi^-$	119	108	0.25	0	–	0.0012	–	0.0011
$^{3}_{\Lambda}n \to {}^{3}H+\pi^-$	$^{7}_{\Lambda}Li \to {}^{7}Be+\pi^-$	119	108	0.25	0.24	–	0.2421	–	0.2380
$^{3}_{\Lambda}H \to {}^{3}He+\pi^-$	$^{3}_{\Lambda}H \to {}^{3}He+\pi^-$	114	114	0.249	0.249	0.0001	0.0001	0.0001	0.0001
$^{3}_{\Lambda}H \to {}^{3}He+\pi^-$	$^{5}_{\Lambda}He \to {}^{4}He+p+\pi^-$	114	99	0.249	0.17	0.0001	0.0001	0.0001	0.0001
$^{3}_{\Lambda}H \to {}^{3}He+\pi^-$	$^{6}_{\Lambda}He \to {}^{6}Li+\pi^-$	114	108	0.249	0	0.0053	0.0039	0.0052	0.0039
$^{3}_{\Lambda}H \to {}^{3}He+\pi^-$	$^{7}_{\Lambda}He \to {}^{7}Li+\pi^-$	114	115	0.249	0.10	0.1112	0.0824	0.1086	0.0806
$^{4}_{\Lambda}H \to {}^{4}He+\pi^-$	$^{5}_{\Lambda}He \to {}^{4}He+p+\pi^-$	133	99	0.51	0.17	0.0716	0.0533	0.0701	0.0524
$^{4}_{\Lambda}H \to {}^{4}He+\pi^-$	$^{6}_{\Lambda}He \to {}^{6}Li+\pi^-$	133	108	0.51	0	0.0981	0.0727	0.0960	0.0716
$^{4}_{\Lambda\Lambda}n \to {}^{4}_{\Lambda}H+\pi^-$	$^{4}_{\Lambda}H \to {}^{4}He+\pi^-$	118	133	0.25	0.51	–	–	0.0227	0.0170
$^{4}_{\Lambda\Lambda}H \to {}^{4}_{\Lambda}He+\pi^-$	$^{4}_{\Lambda}He \to {}^{4}Li+\pi^-$	117	98	0.25	0.19	0.0087	0.0066	0.0085	0.0063
$^{5}_{\Lambda\Lambda}H \to {}^{5}_{\Lambda}He+\pi^-$	$^{5}_{\Lambda}He \to {}^{4}He+p+\pi^-$	134	99	0.20	0.17	0.0209	0.0159	0.0205	0.0153
$^{6}_{\Lambda\Lambda}He \to {}^{5}_{\Lambda}He+p+\pi^-$	$^{5}_{\Lambda}He \to {}^{4}He+p+\pi^-$	101	99	0.17	0.17	0.0234	0.0174	0.0229	0.0171
$^{7}_{\Lambda\Lambda}He \to {}^{7}_{\Lambda}Li+\pi^-$	$^{7}_{\Lambda}Li \to {}^{7}Be+\pi^-$	109	108	0.14	0.24	0.1022	0.0759	0.1002	0.0747
$^{8}_{\Lambda\Lambda}He \to {}^{8}_{\Lambda}Li+\pi^-$	$^{8}_{\Lambda}Li \to {}^{8}Be+\pi^-$	116	124	0.13	0.027	0.1005	0.0745	0.0983	0.0733
			120		0.148				
$^{9}_{\Lambda\Lambda}He \to {}^{9}_{\Lambda}Li+\pi^-$	$^{9}_{\Lambda}Li \to {}^{9}Be+\pi^-$	117	121	0.11	0.1	0.0229	0.0130	0.0224	0.0167
$^{7}_{\Lambda\Lambda}Li \to {}^{7}_{\Lambda}Be+\pi^-$	$^{7}_{\Lambda}Be \to {}^{7}B+\pi^-$	101	96	0.14	0	0.0002	0.0001	0.0002	0.0001
$^{8}_{\Lambda\Lambda}Li \to {}^{8}_{\Lambda}Be+\pi^-$	$^{8}_{\Lambda}Be \to {}^{8}B+\pi^-$	109	97	0.13	0	0.0369	0.0273	0.0359	0.0269
$^{9}_{\Lambda\Lambda}Li \to {}^{9}_{\Lambda}Be+\pi^-$	$^{9}_{\Lambda}Be \to {}^{9}B+\pi^-$	123	97	0.11	0.14	0.1012	0.0753	0.0990	0.0748