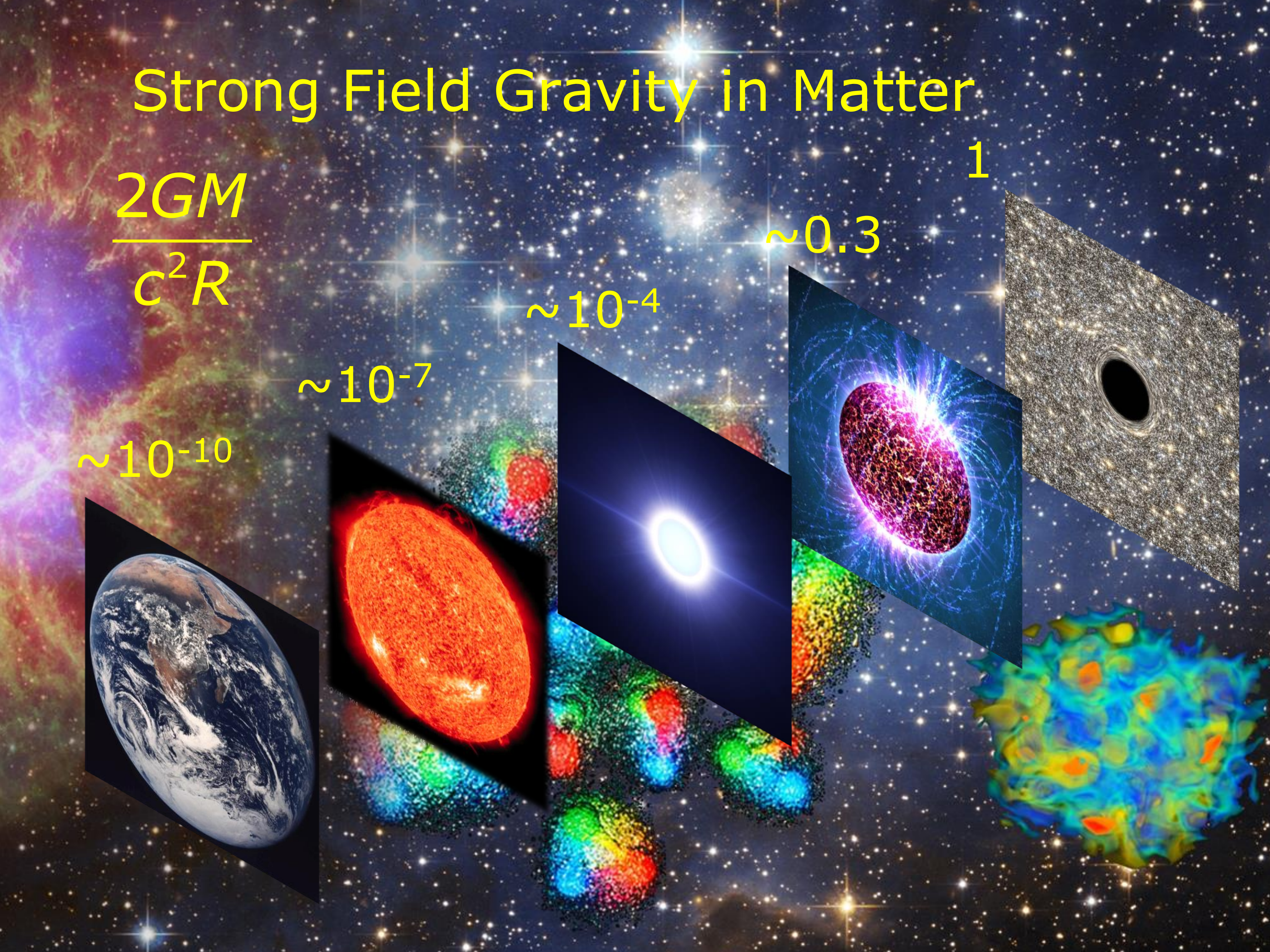

Strong Field Gravity in Matter
$\frac{2GM}{c^2R}$
$\sim 10^{-10}$
$\sim 10^{-7}$
$\sim 10^{-4}$
~ 0.3
1

Hypernuclei in Heavy Ion Collisions:
Observations - Opportunities - Outlook

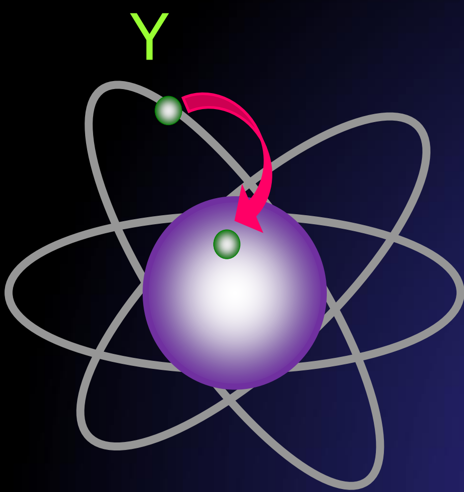
-
Josef Pochodzalla

JGU Mainz & Helmholtz-Institut Mainz

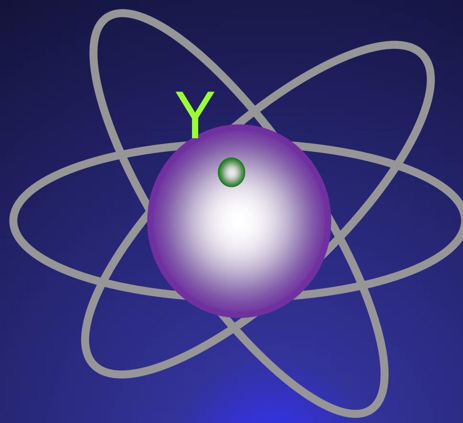
- **Production of Hypernuclei**
- **Hypernuclei from Hot Participants' zone**
- **Hypernuclei from Cold Spectators**
- **Prospects: Study of S=-2 Systems**

Strangeness Nuclear Physics

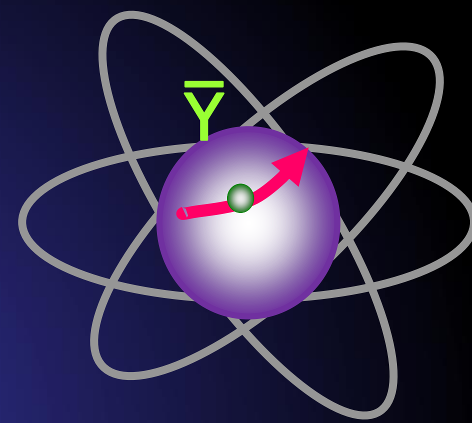
= Strangeness in cold nuclei



hyperatoms



hypernuclei



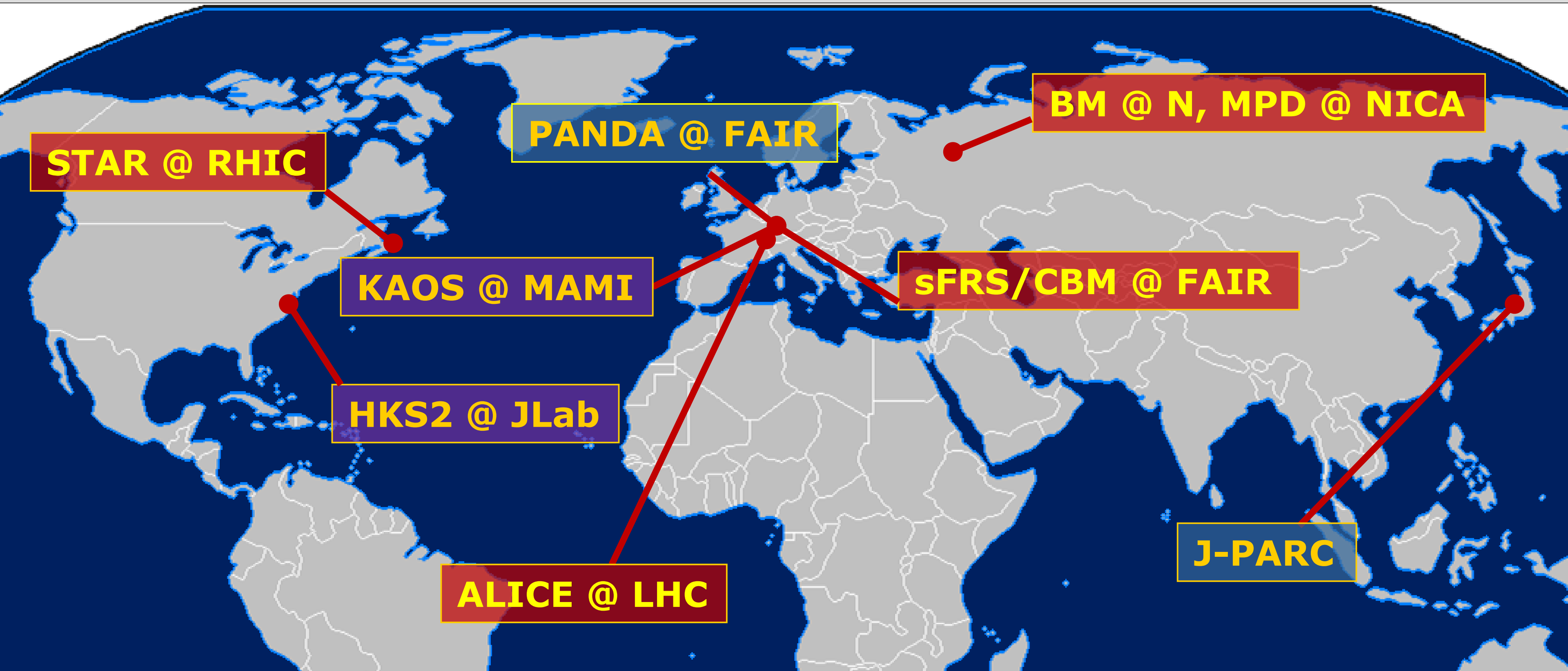
(anti)hyperon
scattering

Recent Progress in Strangeness and Charm Hadronic and Nuclear Physics
Edts. A. Gal and JP
Nucl. Phys. A **954**, 1–2 (2016)

Theoretical considerations for HI:
PRC **86**, 011601(R) (2012)
PRC **88**, 054605 (2013)
PLB **742**, 7 (2015)
Eur. Phys. J. **52**, 242 (2016)
PRC **94**, 054615 (2016)
PRC **95**, 014902 (2017)

JP PLB **669**, 306 (2008)
Sanchez *et al.*, PLB 749, 421 (2015)

Hypernuclear Activities



Tools
- heavy ion beams
- electron beams
- photon beams
- meson beams
- antiproton beams

Methods
- missing mass studies
- invariant mass studies
- γ-spectroscopy
- π-spectroscopy
- FSI

Observables
- masses
- excitation spectrum
- lifetimes
- branching rations
- cross section

Hypernuclear Activities

Tools

- heavy ion beams
- electron beams
- photon beams
- meson beams
- antiproton beams

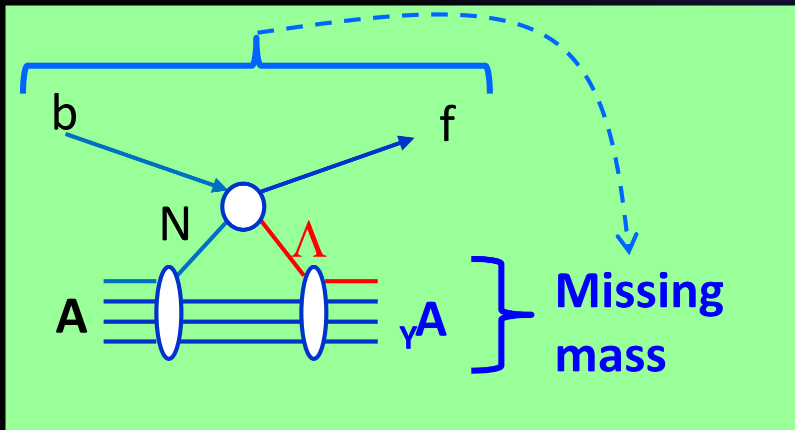
Methods

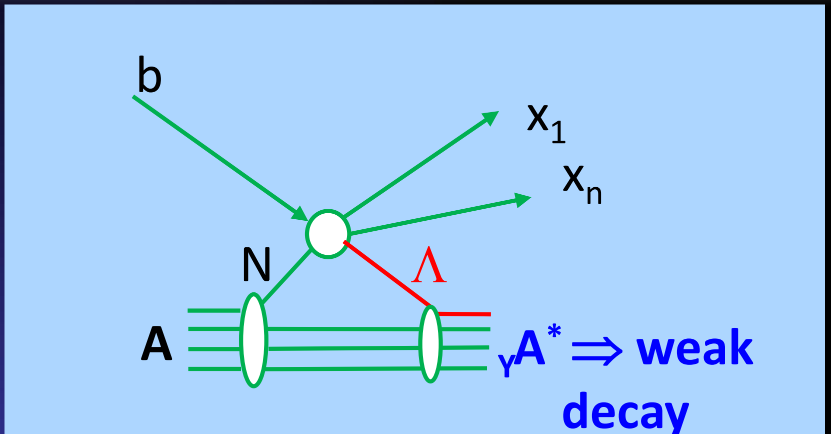
- missing mass studies
- invariant mass studies
- γ-spectroscopy
- π-spectroscopy
- FSI

Observables

- masses
- excitation spectrum
- lifetimes
- branching rations
- cross section

The twofold way to hypernuclei



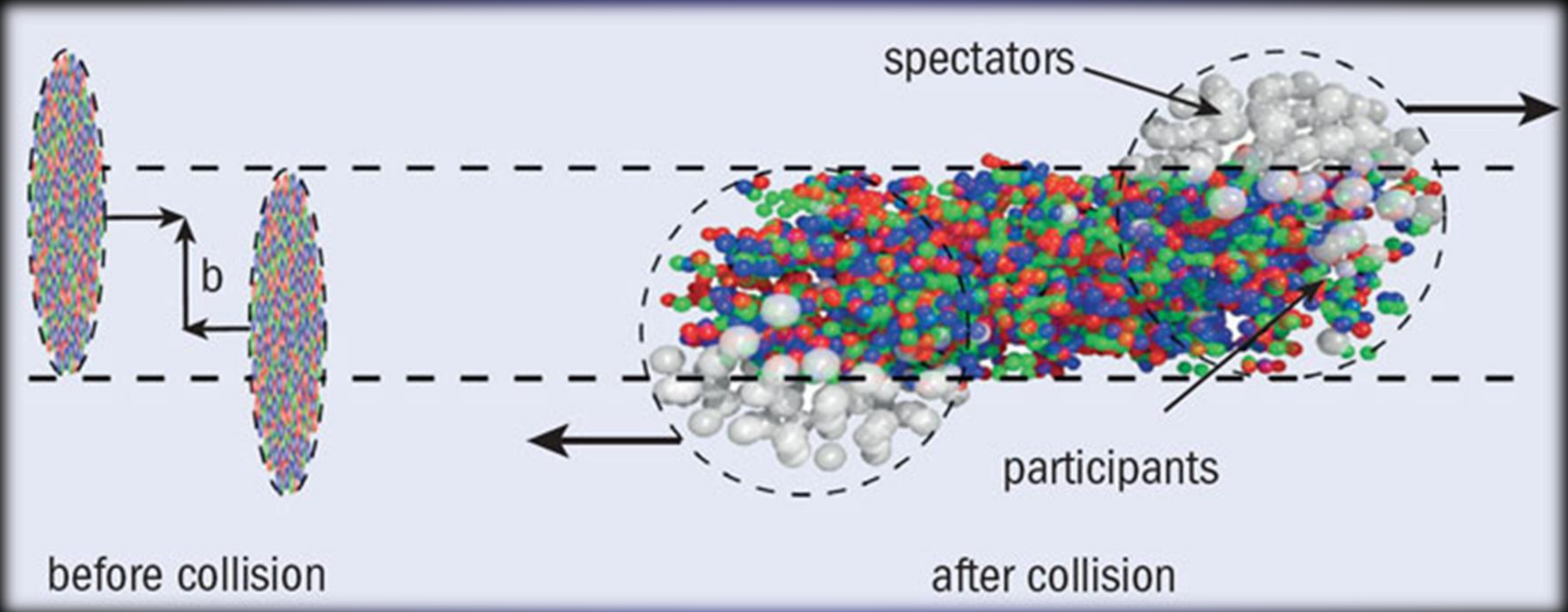


- **DIRECT PRODUCTION SPECTROSCOPY**
  - missing mass in two-body kinematics
- **Examples**
  - strangeness production (π^+, K^+), (π^-, K^0)
  - strangeness exchange (K^-, π^-), (K^-, π^0), (K^-, K^+)
  - electroproduction $(e, e'K^+)$, (γ, K^+)

- **DECAY SPECTROSCOPY**
  - γ-decay of excited states
  - π from weak decay
  - charged fragments
- **Examples**
  - nuclear emulsions
  - heavy ion reactions
  - antiproton induced reactions
  - continuum excitation in $(e, e'K^+)$

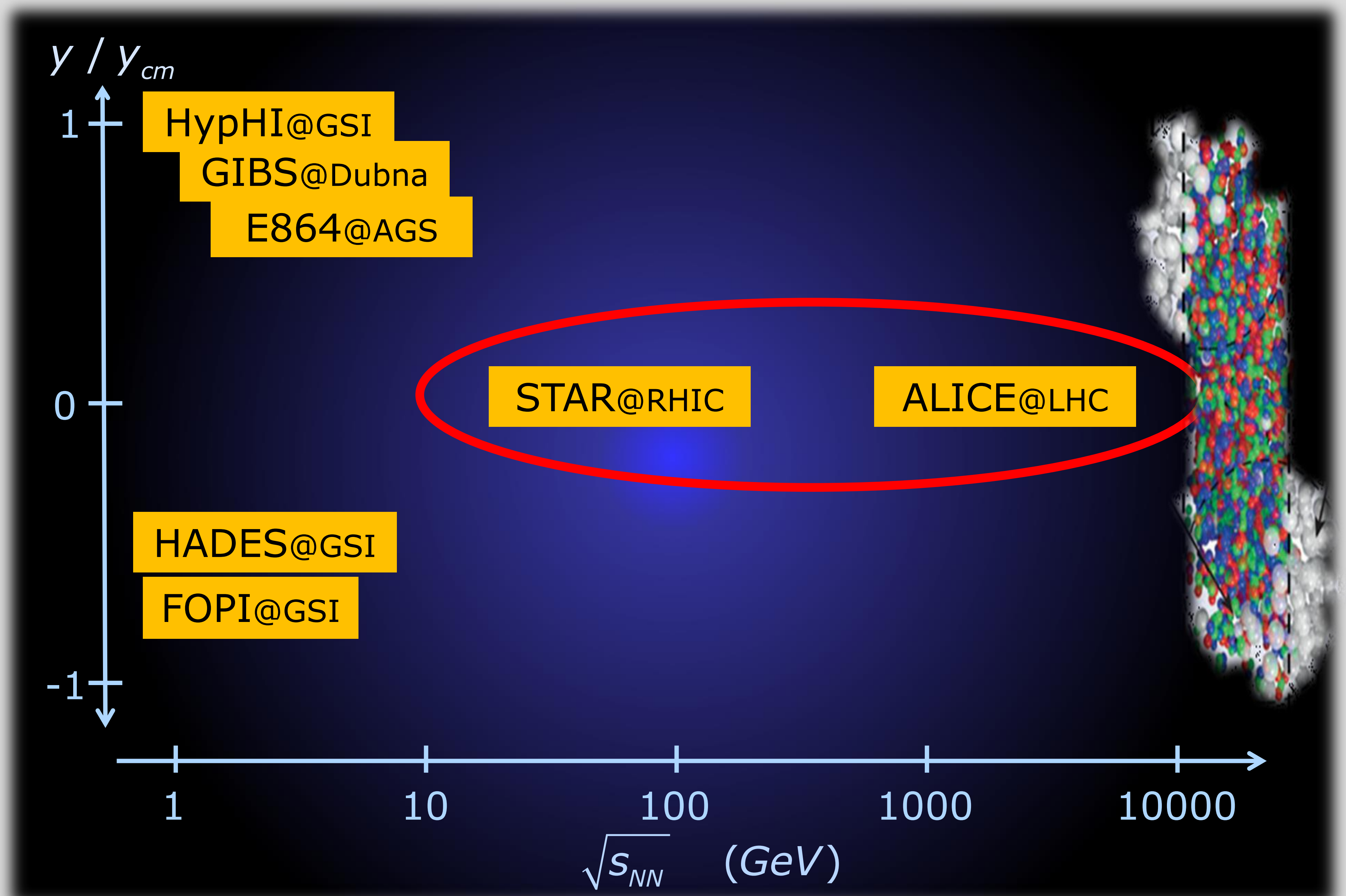
40 Years Participant-Spectator Model

J. Knoll et al. Nucl. Phys. **A304** (1978) 298.
M. Guylassy et al., Phys. Rev. Lett. **40** (1978) 298.

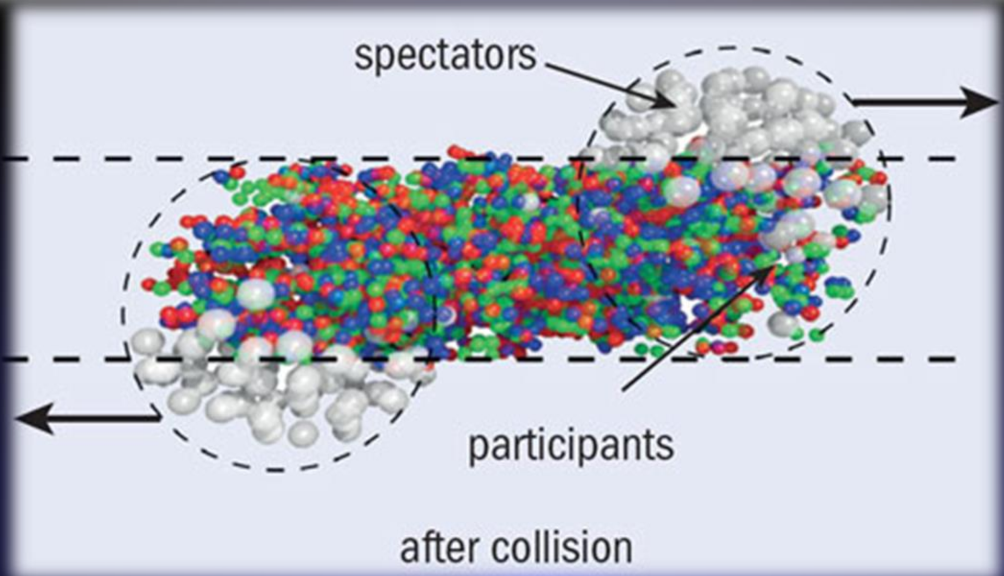


CERN

Present Hypernuclei HI Experiments



Hypernuclei from Participants‘ zone

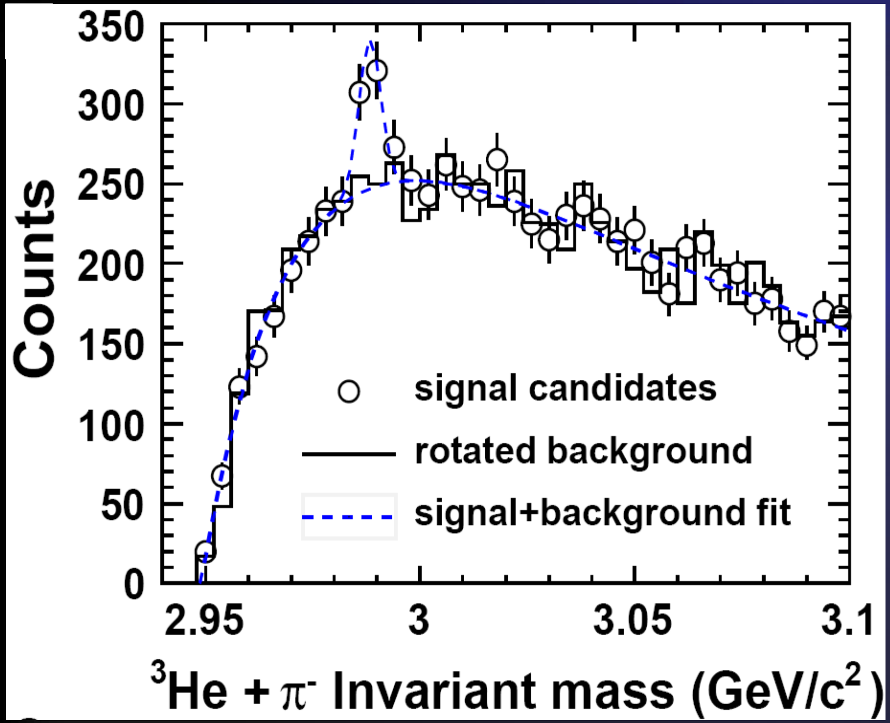


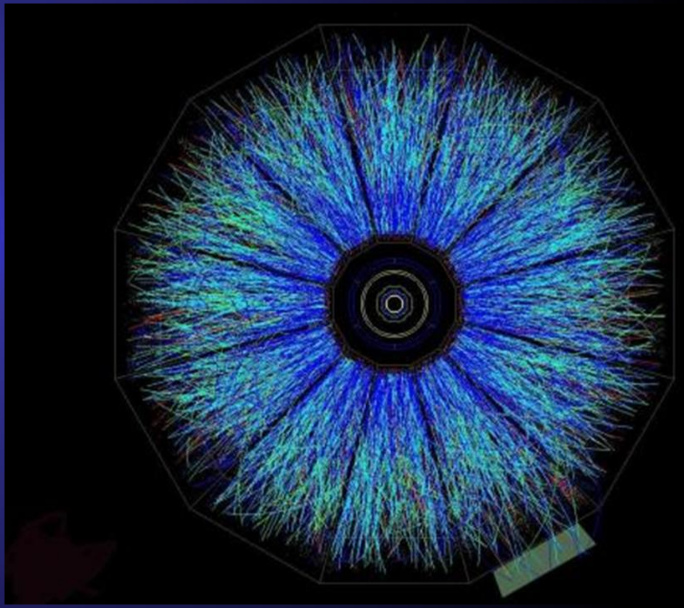
- PARTICIPANT MATTER
- high excitation energy
- expansion
- hadrons and antihadrons
- baryons and mesons
- COALESCENCE
- light hypernuclei
- strangeness as tracer of fragment formation
- lifetime

$^{3}_{\Lambda}H$ at STAR

- STAR@RHIC : Au+Au at 200AGeV
  - ~10^8 minimum bias events, ~$2\cdot10^7$ central events
  - 157±30 hypertritons 70±17 antihypertritons

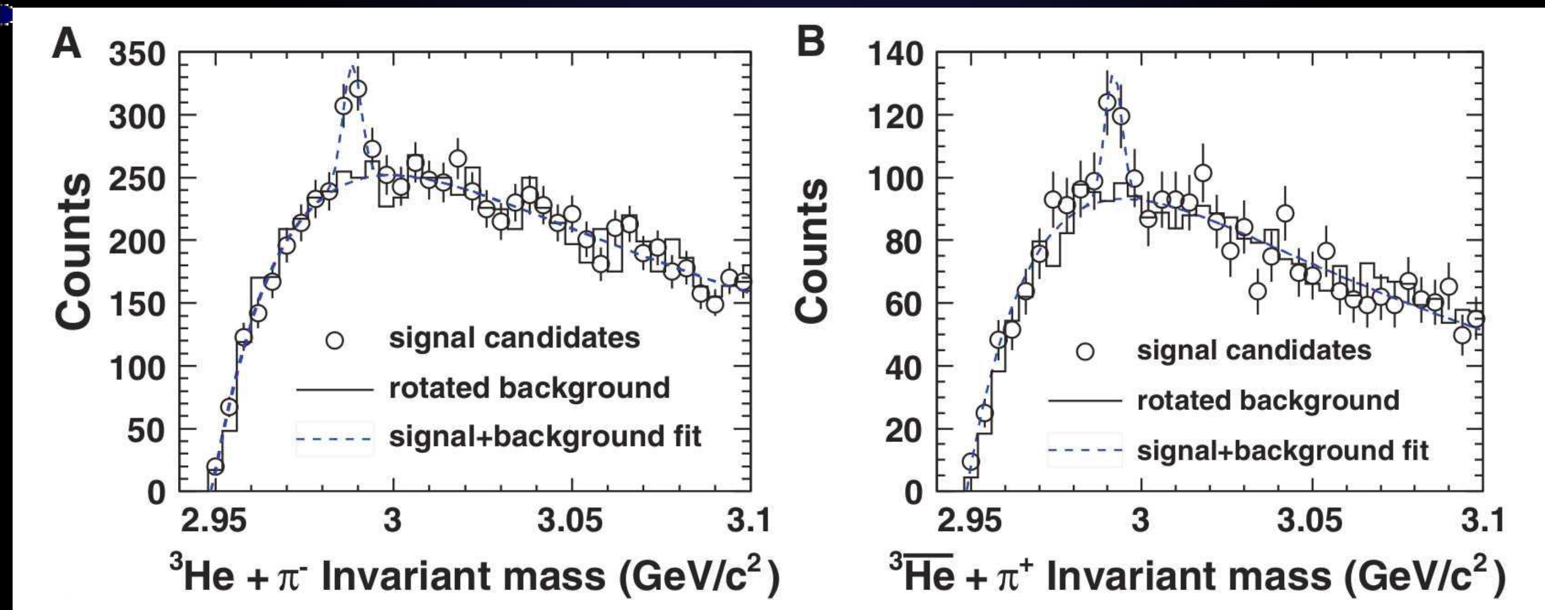
STAR collaboration, NATURE **328** (2010)





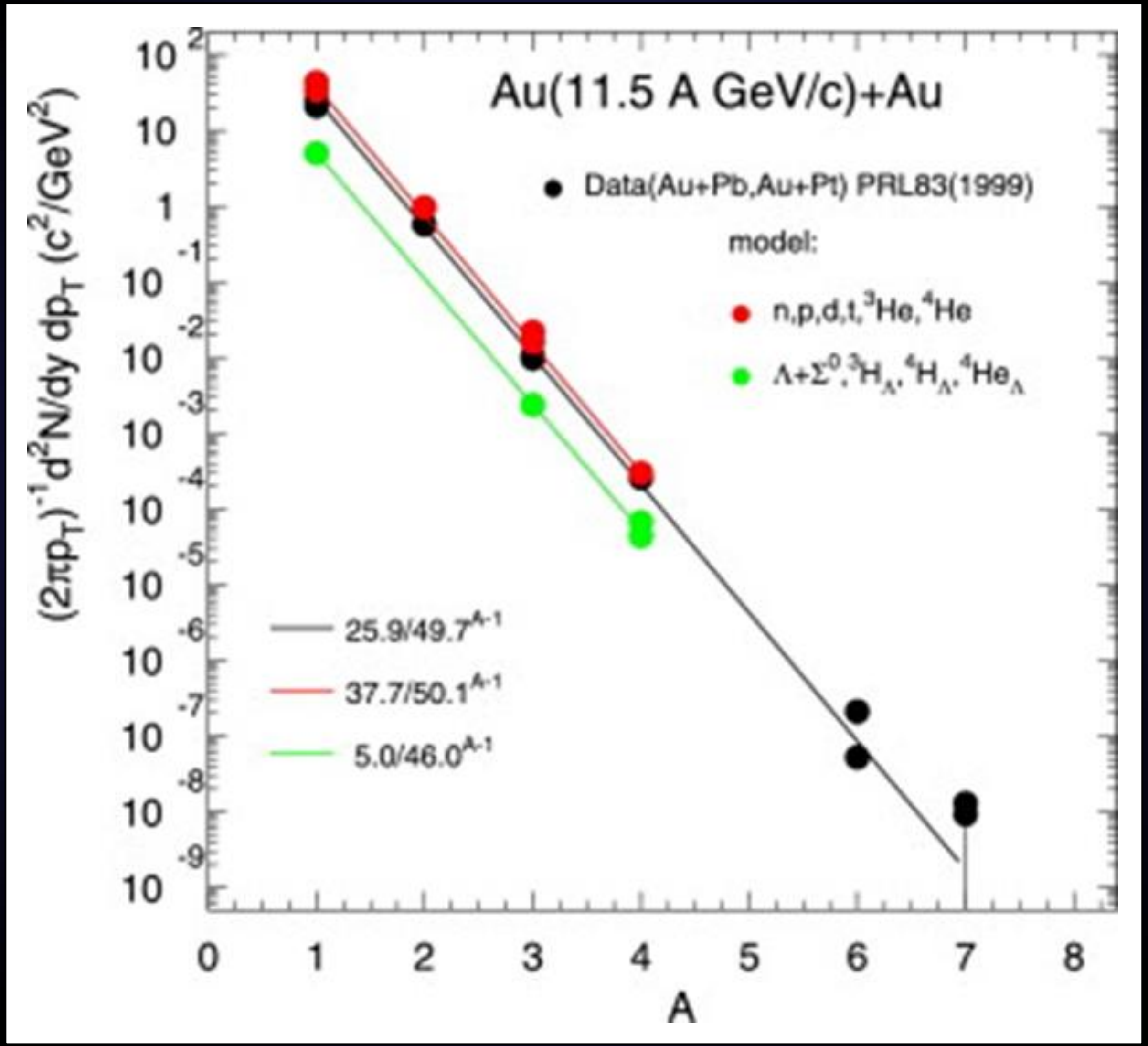
- background shape determined from rotated background analysis
- Mass: 2.990 ± 0.001 GeV; Width (fixed): 0.0025 GeV.

Observation of Anti-hypernuclei



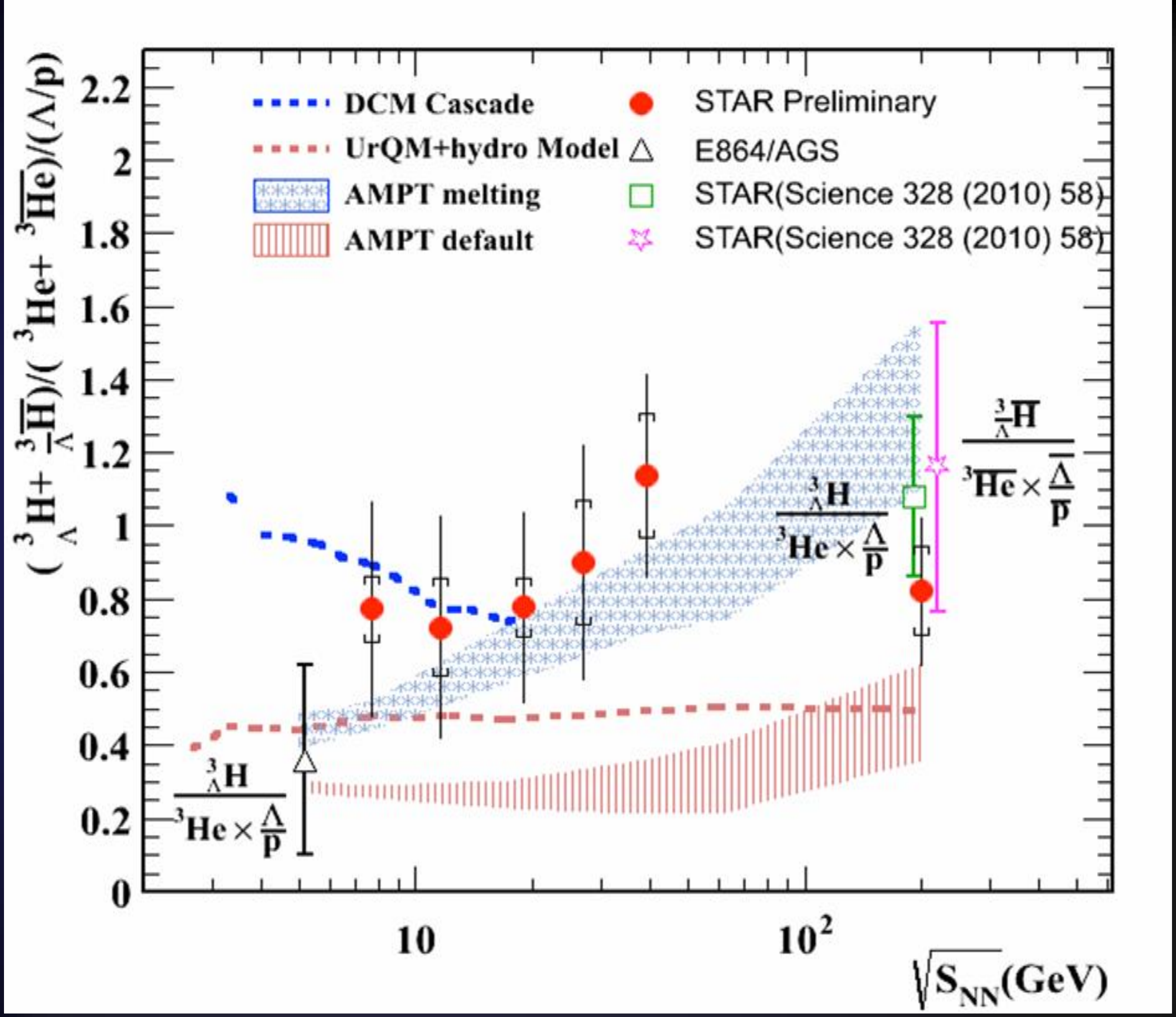
Experiment	Reaction	$\langle y/y_{cm} \rangle$	$\sqrt{s_{NN}}$ [GeV]	$^3_\Lambda$H	$^3_{\overline{\Lambda}}\overline{H}$	$^4_\Lambda$H
E864	Au+Pt	0.3	5.0	1220±854	-	-
HADES	Ar+KCl	-0.45	2.6	$\frac{^3_\Lambda H}{N_\Lambda} < 2.5 \cdot 10^{-2}$	-	-
STAR	Au+Au	0	7.7-200	≈400	≈200	-
ALICE	Pb+Pb	0	2760	≈124	≈90	-

Penalty for heavy fragments



Strangeness Population Factor

$$\frac{\overbrace{(np\Lambda)}^{^3_\Lambda H} / \Lambda}{\underbrace{(npp)}_{^3He} / p}$$

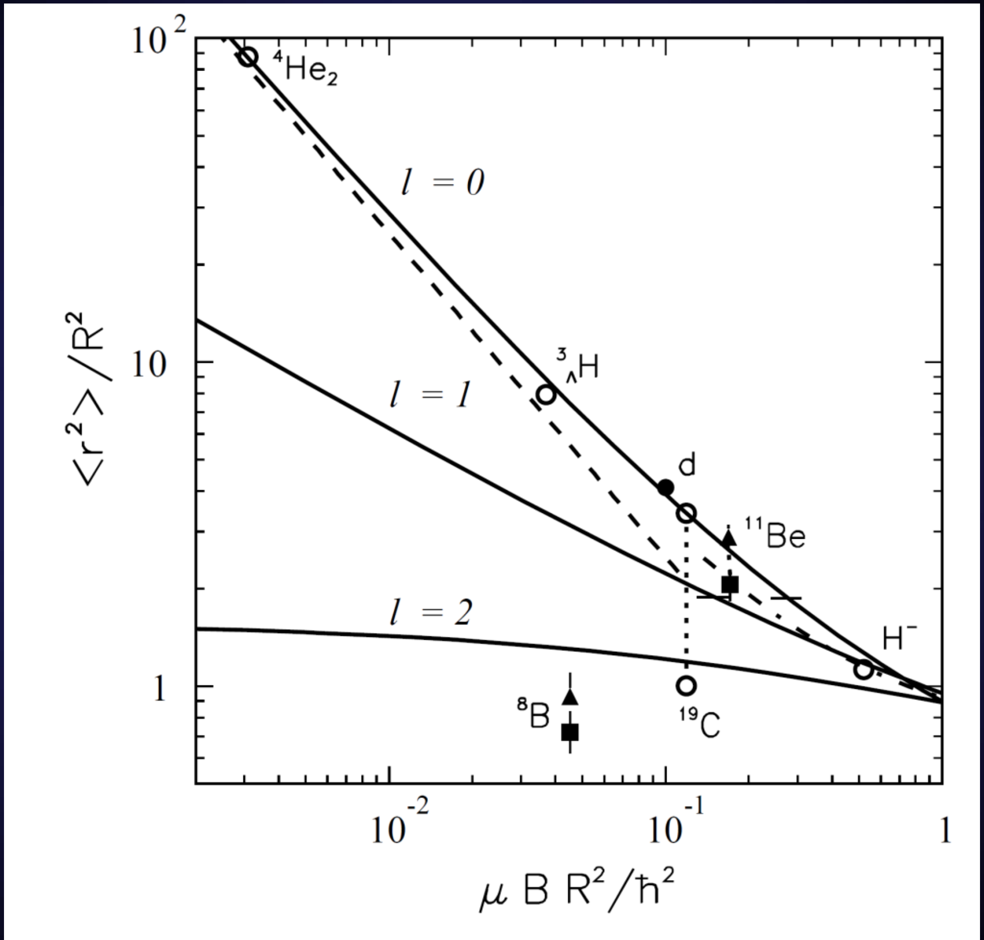


ALICE

$^3_\Lambda H$: a Quantum Halo

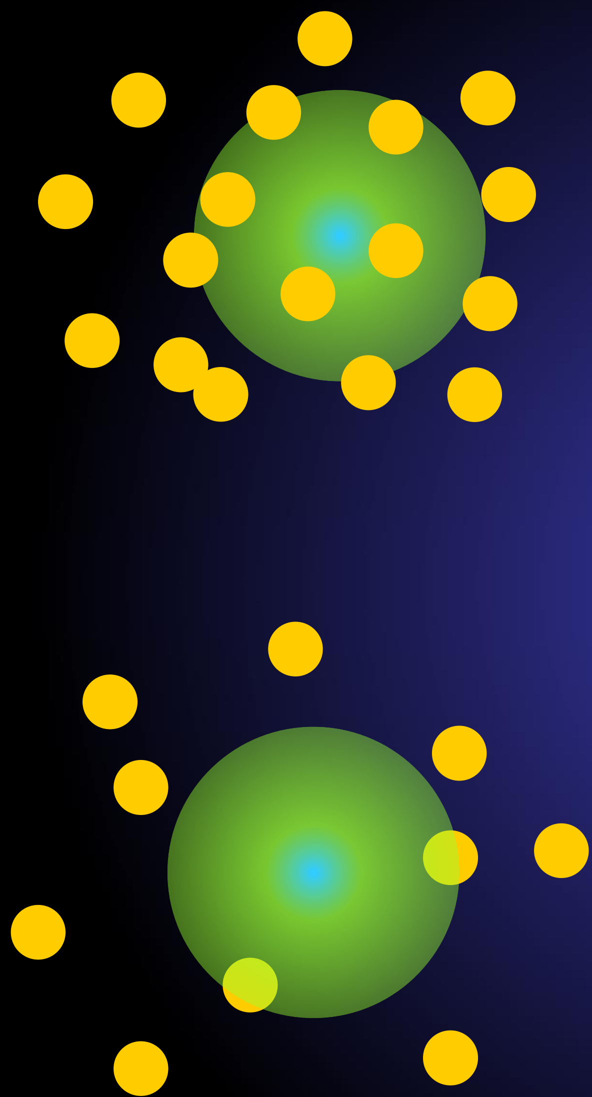
- K.Riisager,D.V.FedorovandA.S.Jensen, Europhys. Lett 49, 547 (2000)

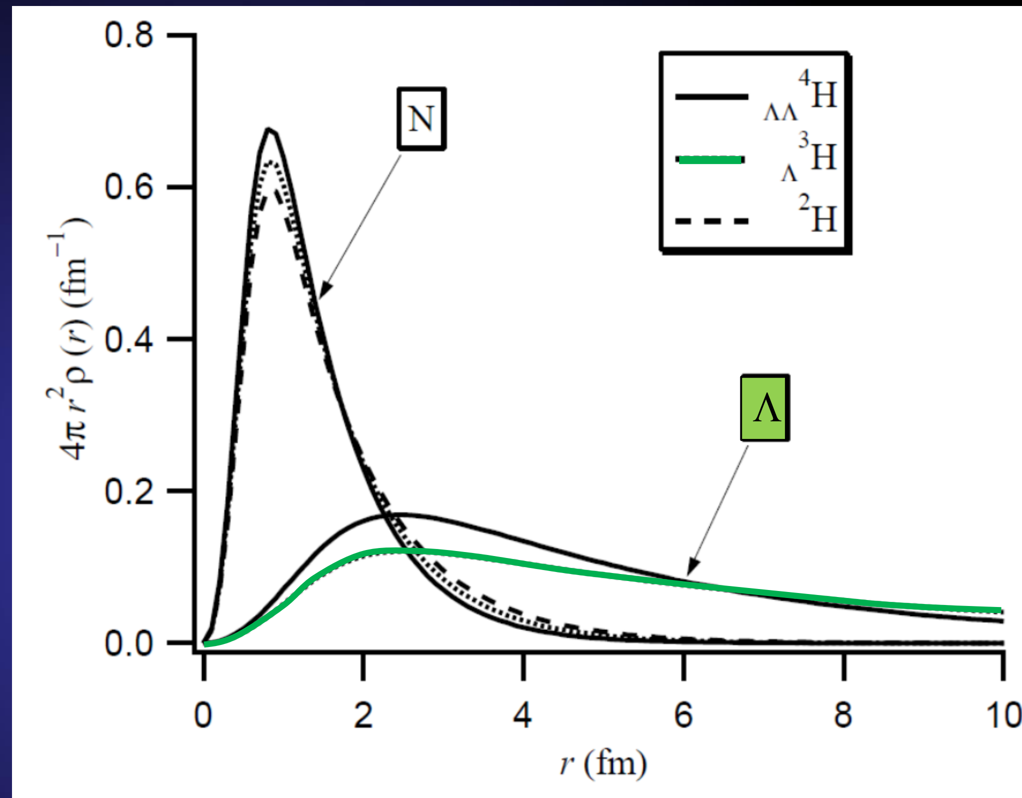
ratio of halo and core-potential square radii



scaled separation energy

Hadronic Debey Screening

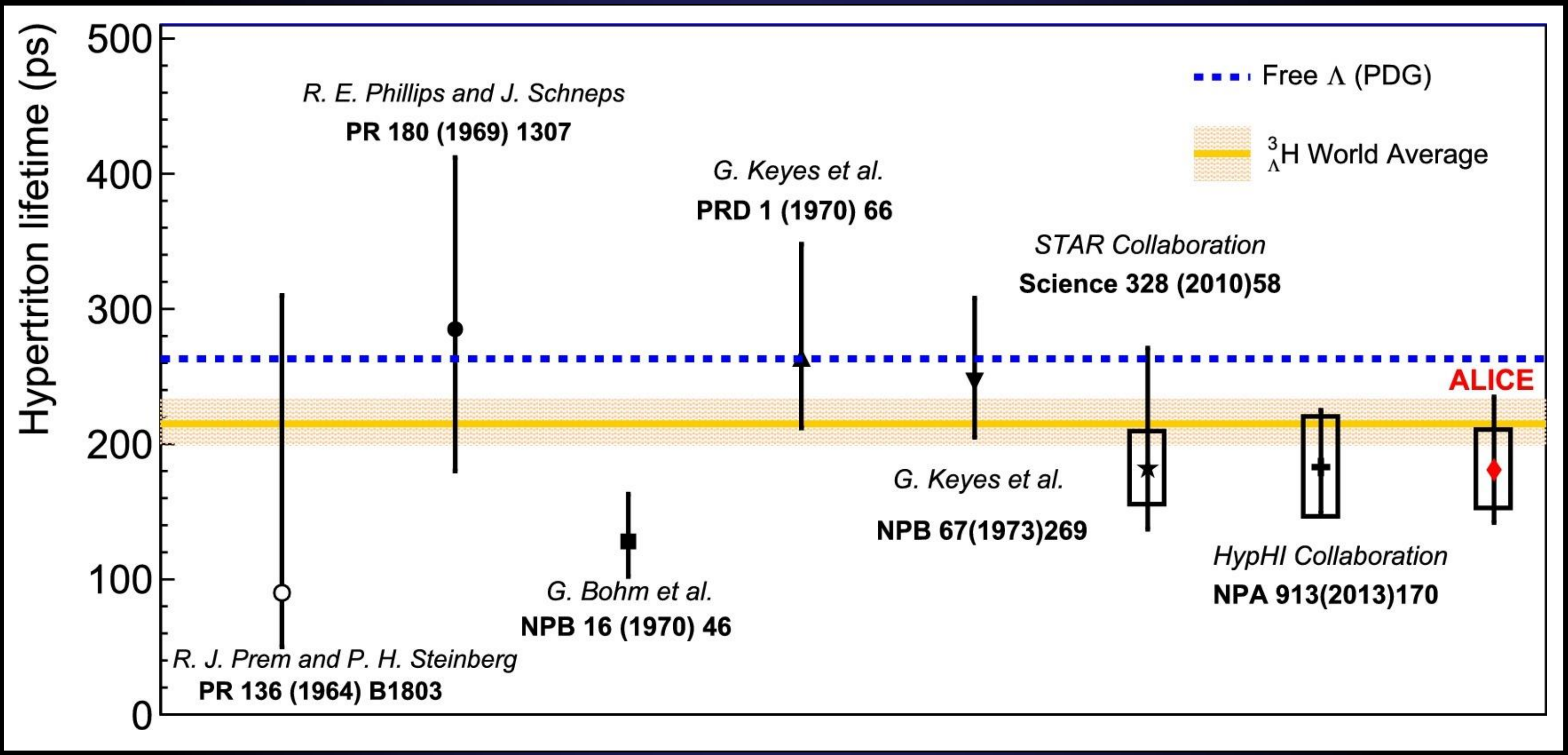




H. Nemura et al., Prog. Theor. Phys. **103** (2000)

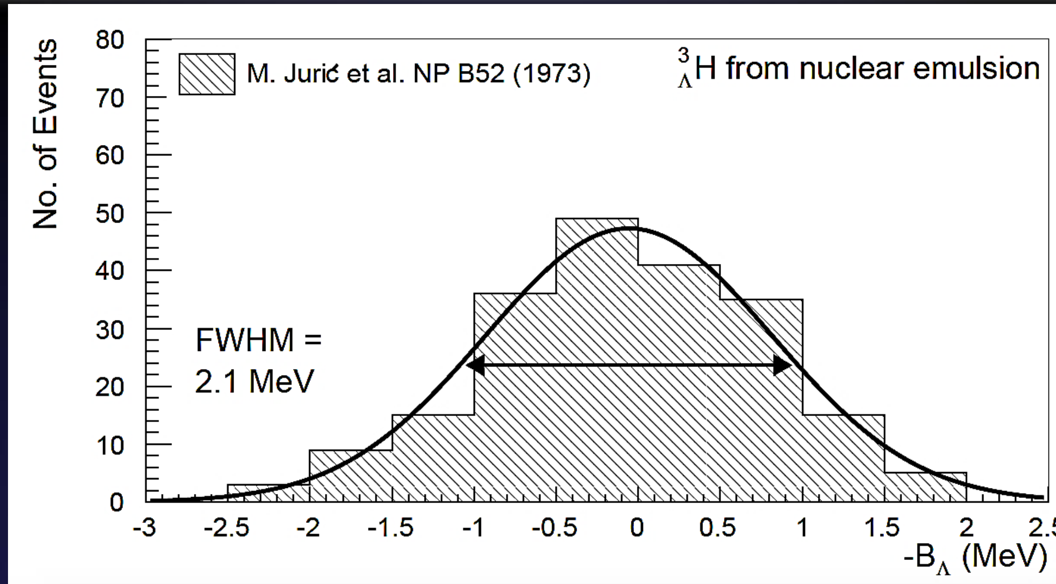
$\Rightarrow$ $^{4}_{\Lambda}$H might help to distinguish the scenarios

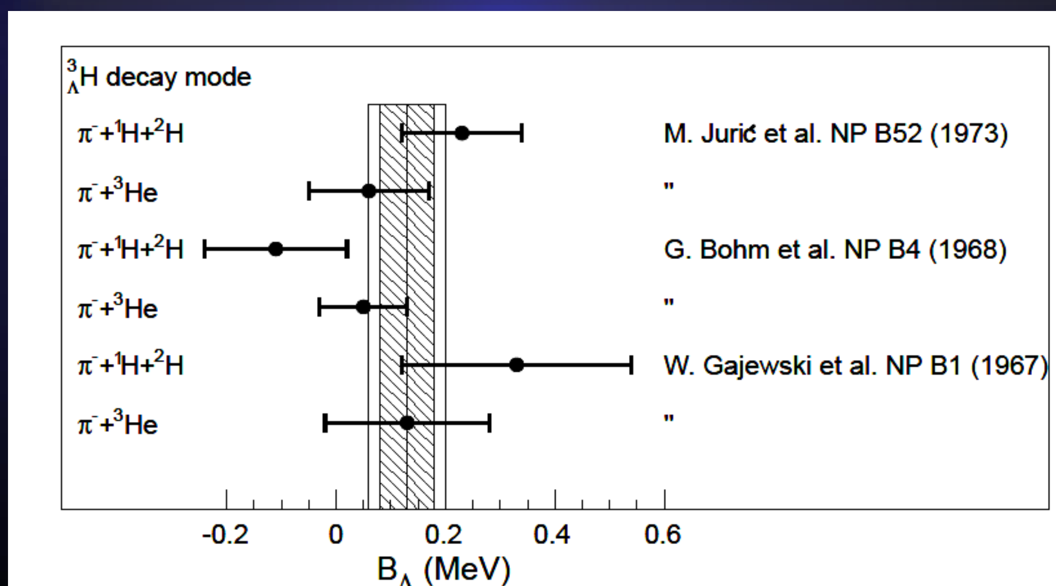
The Hypertriton Puzzle



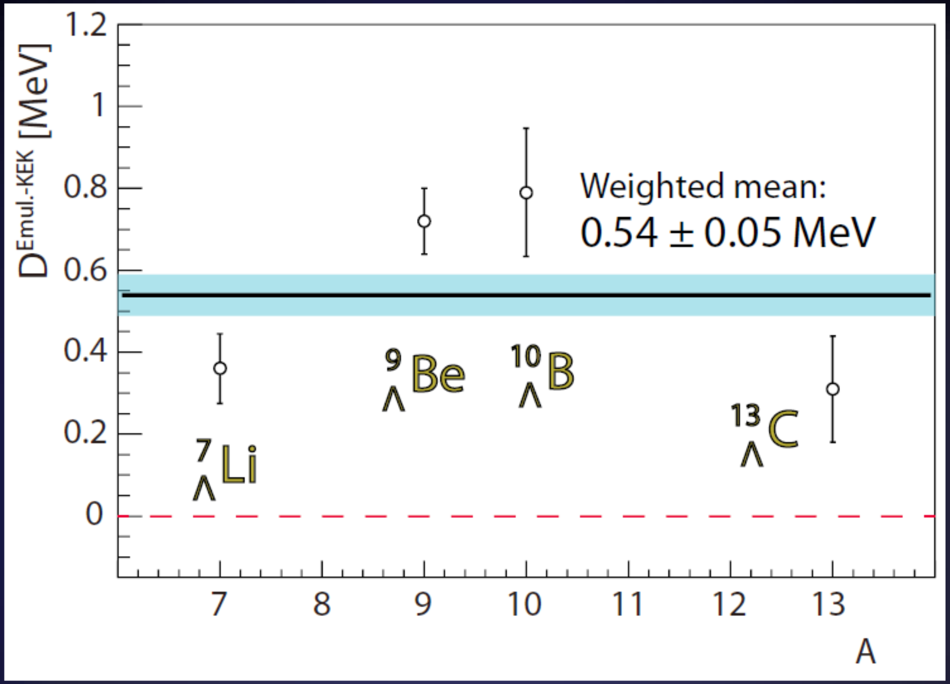
ALICE, Phys. Lett. B **764,** 360 (2016)

The $^{3}_{\Lambda}$H Binding Energy





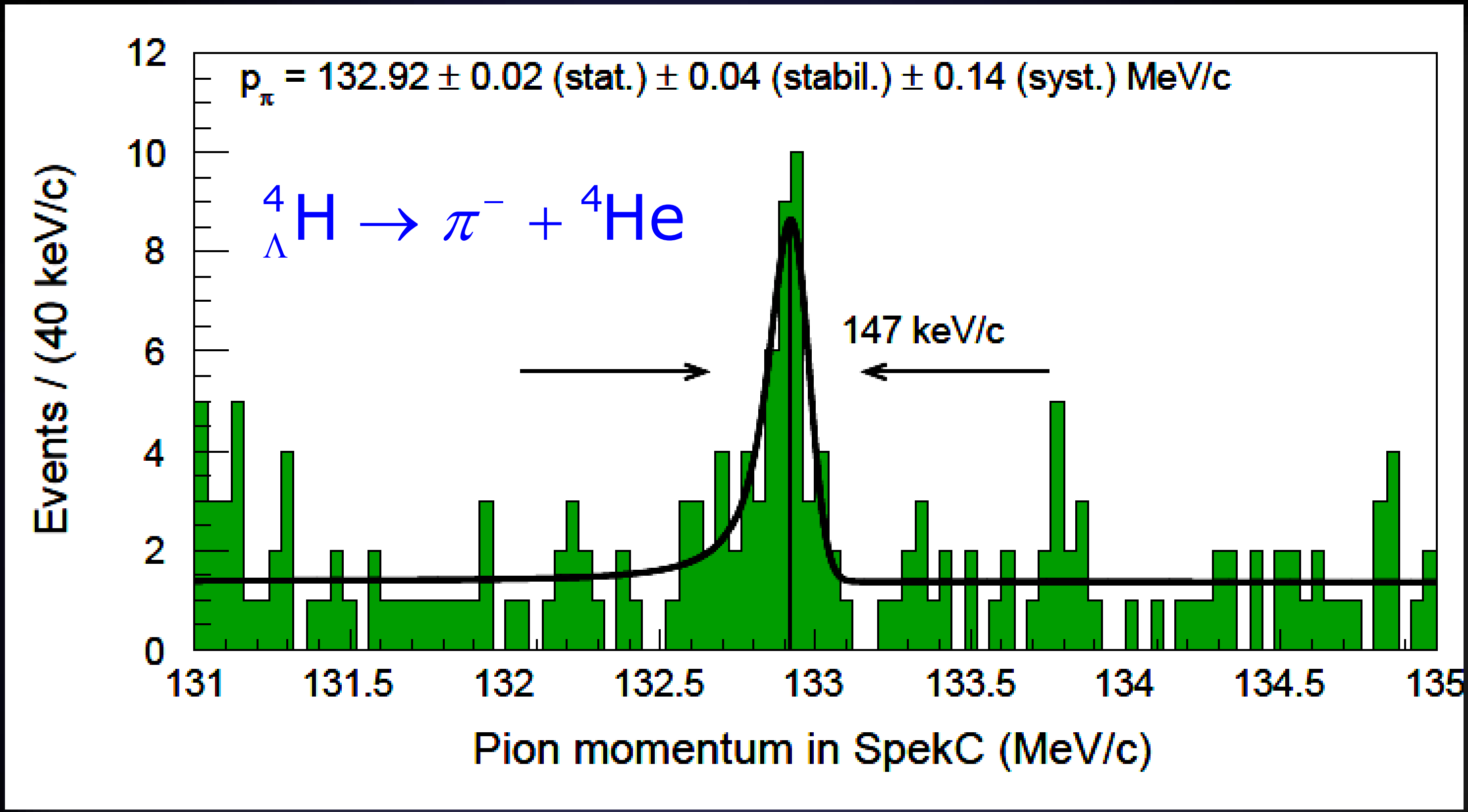
The $^3_\Lambda H$ problem



Gogami et al. PRC (2016)

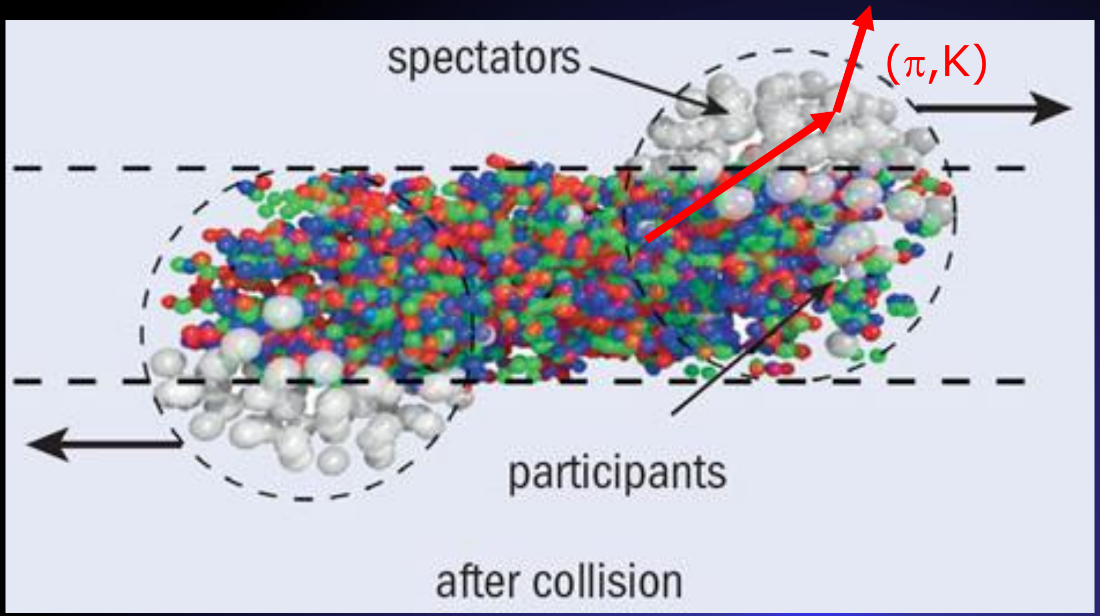
⇒ need precision measurement of $^3{}_\Lambda H$ to solidify experimental basis
⇒ pion spectroscoy at MAMI

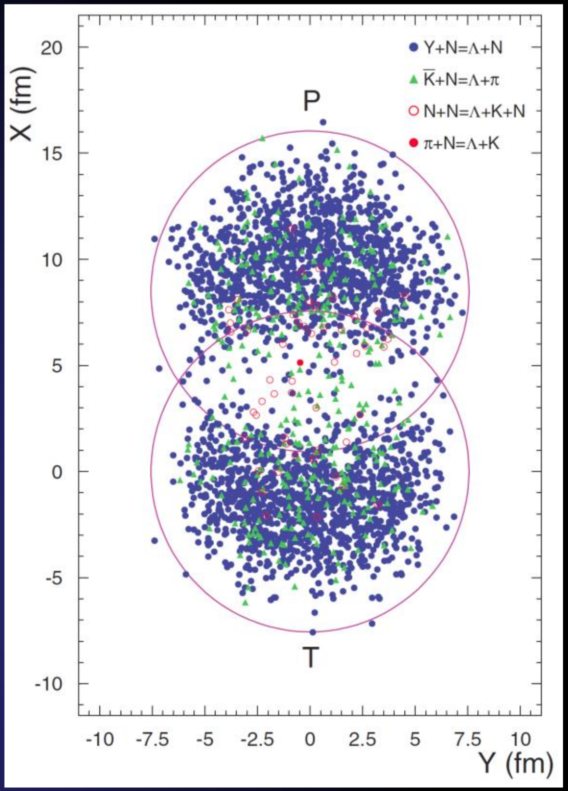
High resolution π-Spectrocopy @MAMI



- Main systematic error due to uncertainty of the absolute MAMI beam energy $\Rightarrow$ interference of coherent undulator radiation
- improved luminosity by $\times 50$ with Li target

Spectator zone



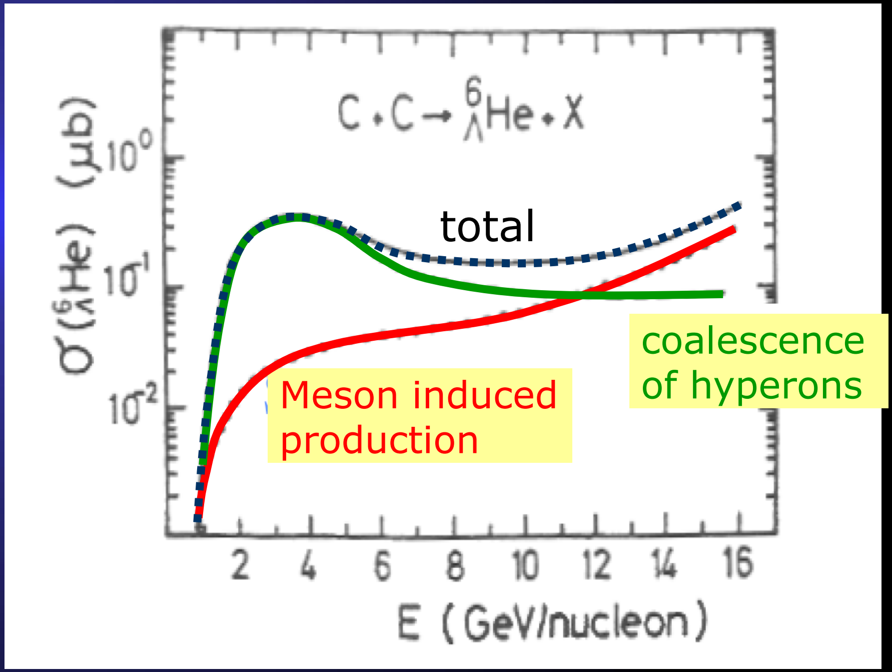


A. Botvina *et al*., PRC 84, 064904 (2011)

- SPECTATOR MATTER
- moderate excitation energy
- hyperons produced by rescattering
- capture of hyperons
- no antibaryons
- MULTIFRAGMENTATION

Relativistic Hypernuclei

- Many predictions based on coalescence model or Fermi breakup
  - M. Sano, INS-PT-31 (1982), M. Wakai, H. Bando and M. Sano, PRC 38, 748 (1988)
  - J. Aichelin and K. Werner, PLB 274, 260 (1992), S. Hirenzaka, T. Suzuki and I. Tanihata, PRC 48, 2403 (1993), M. Sano and M. Wakai, PTP Suppl. 117, 99 (1994)
  - Botvina *et al*….
- General features
  - local maximum at ~4AGeV
  - single Λ-hypernuclei ~0.1μb
  - $\Lambda\Lambda$-hypernuclei ~0.01 nb



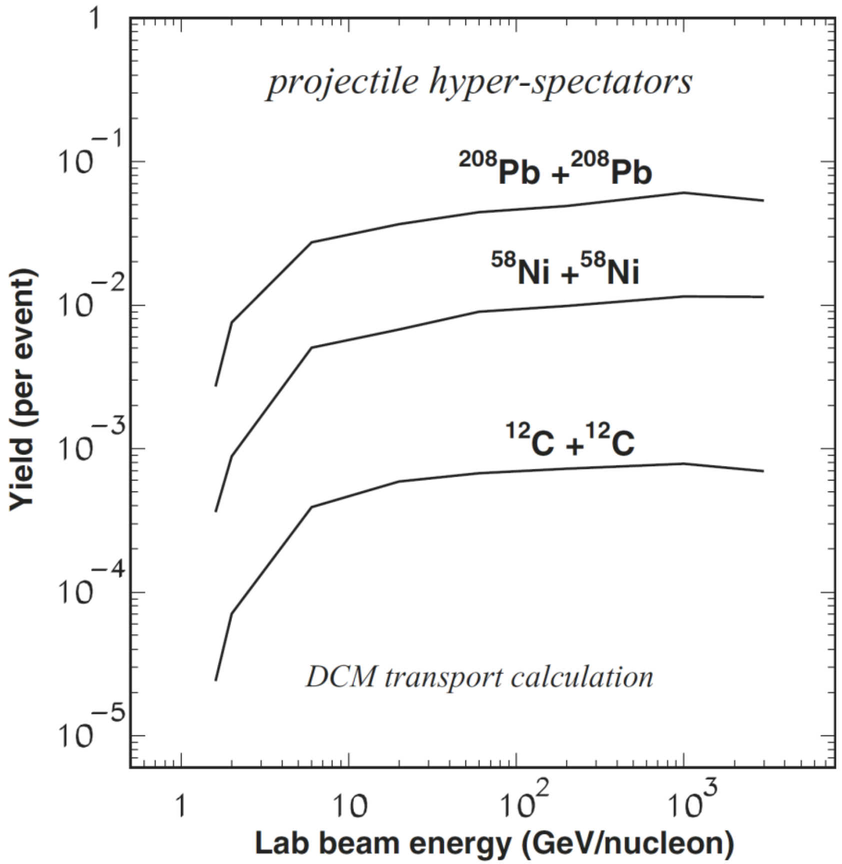


FIG. 2. Yields of hyperresidues of projectiles in collisions of ^{12}C, ^{58}Ni, and ^{208}Pb beams with the same targets, as a function of the incident energy. The DCM calculations are integrated over all impact parameters and normalized to one inelastic collision event.

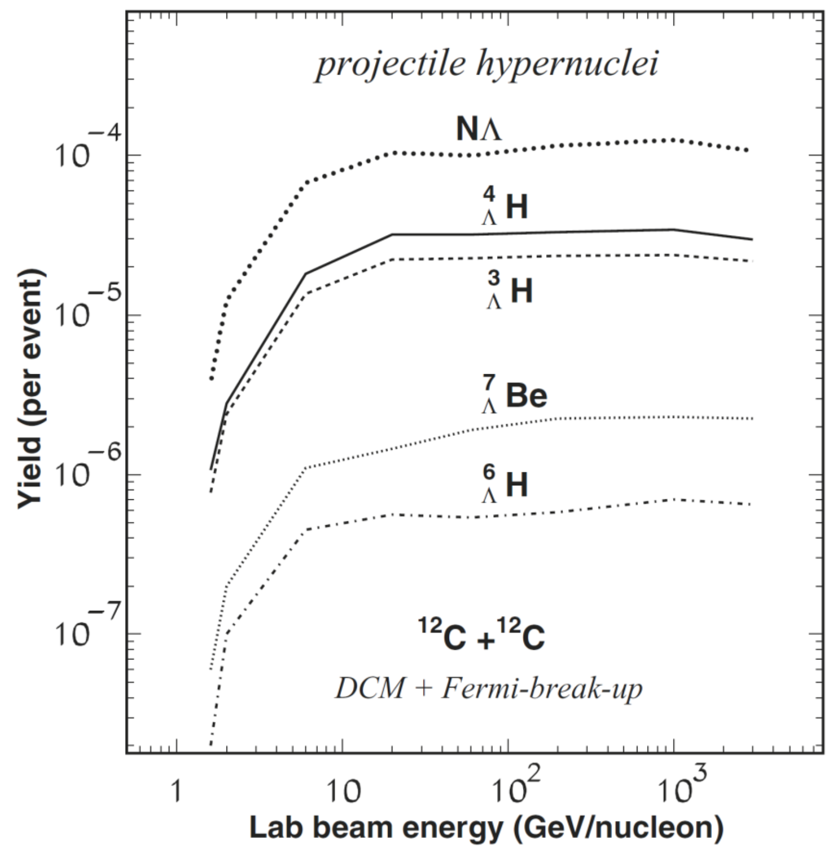
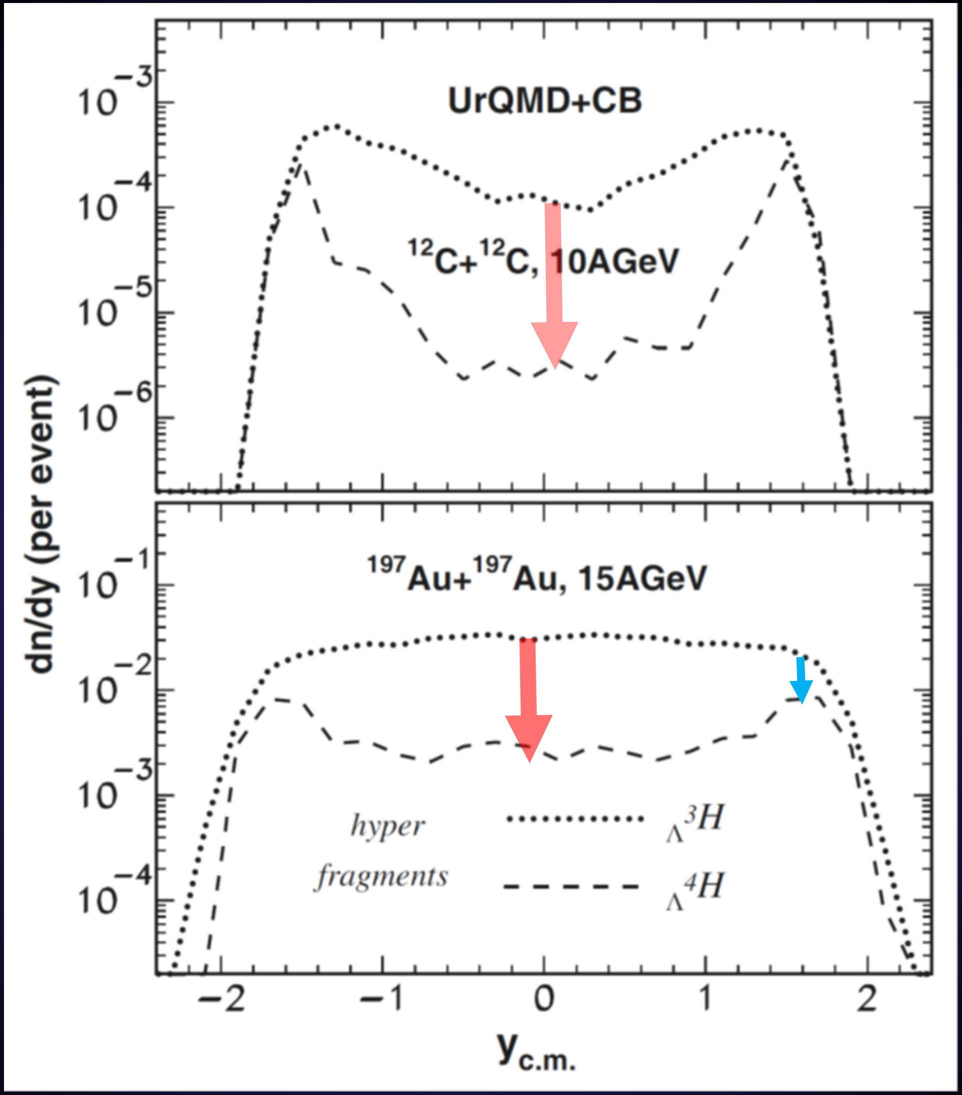


FIG. 5. Yields of particular hypernuclei (see figure and the text) obtained from projectile residues in collisions of ^{12}C with ^{12}C versus projectile energy in laboratory system. The hybrid DCM and FBM calculations are integrated over all impact parameters and normalized to one inelastic collision event.

PRC 88, 054605 (2013)

Central vs. peripheral collisions

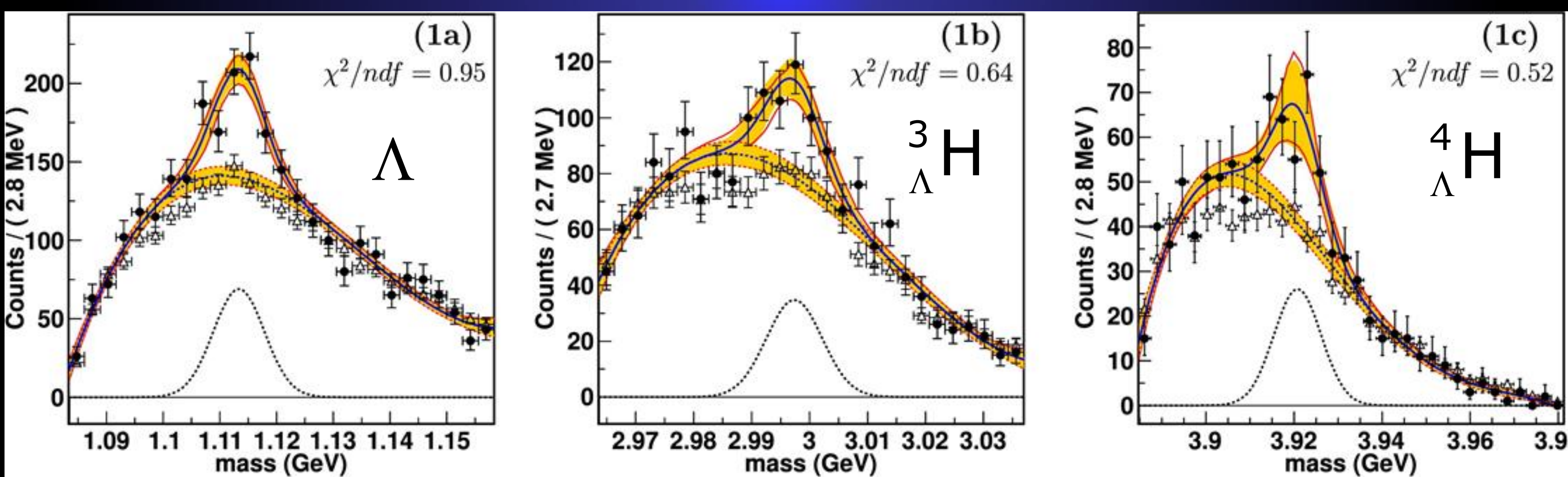


Eur. Phys. J. 52, 242 (2016)

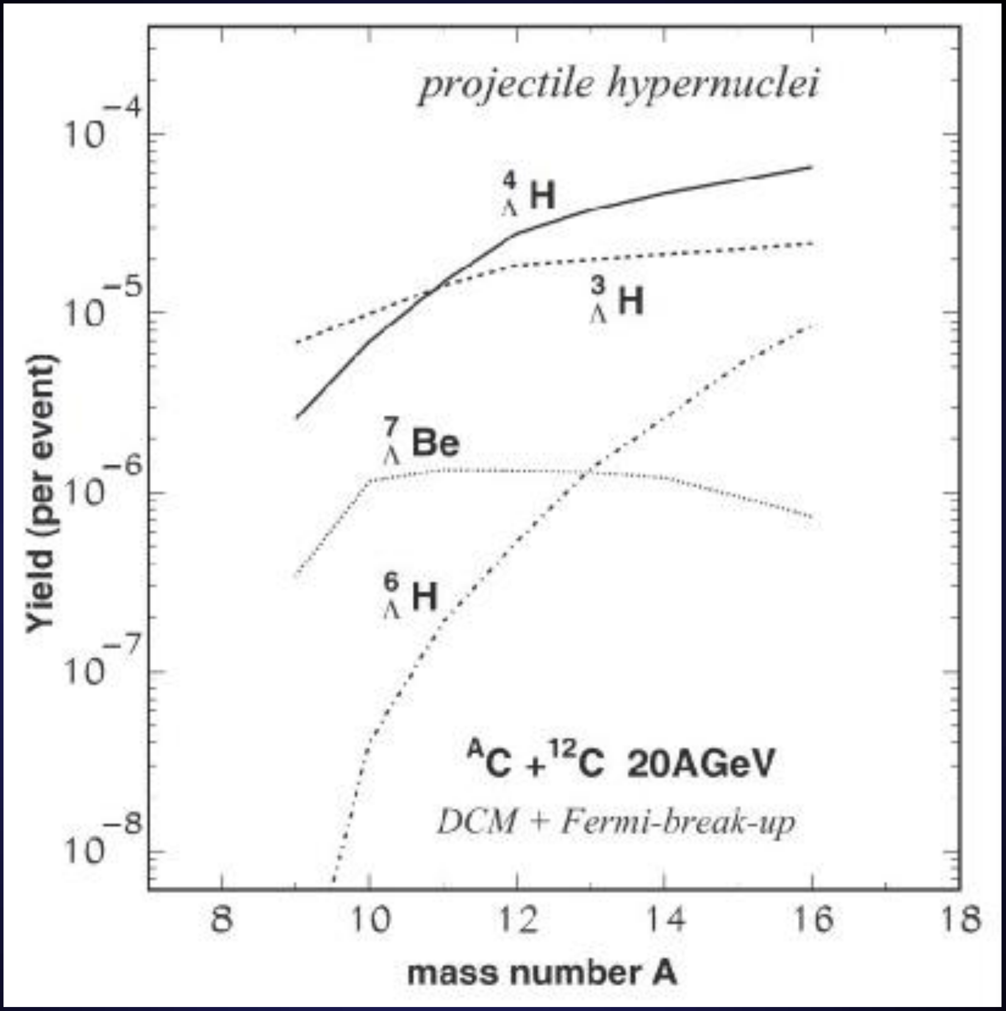
HYBS @ Dubna and HYPHI @ GSI

HIM Helmholtz-Institut Mainz

Experiment	Reaction	$\langle y/y_{cm} \rangle$	$\sqrt{s_{NN}}$ [GeV]	${}^{3}_{\Lambda}$H	$\overline{{}^{3}_{\Lambda}H}$	${}^{4}_{\Lambda}$H
E864	Au+Pt	0.3	5.0	1220±854	-	-
HADES	Ar+KCl	-0.45	2.6	$\frac{{}^{3}_{\Lambda}H}{N_{\Lambda}}$ <2.5·10^{-2}	-	-
STAR	Au+Au	0	7.7-200	≈400	≈200	-
ALICE	Pb+Pb	0	2760	≈124	≈90	-
HYBS Dubna	^{3,4}He, ^{6,7}Li+C		2.8-3.6	2/few events	-	18/22
HYPHI	^{6}Li+^{12}C	1	2.7	178±31	-	66±14



Secondary HI beams @ FAIR



PRC 88, 054605 (2013)

- ⇒ neutron or proton rich hypernuclei @ sFRS

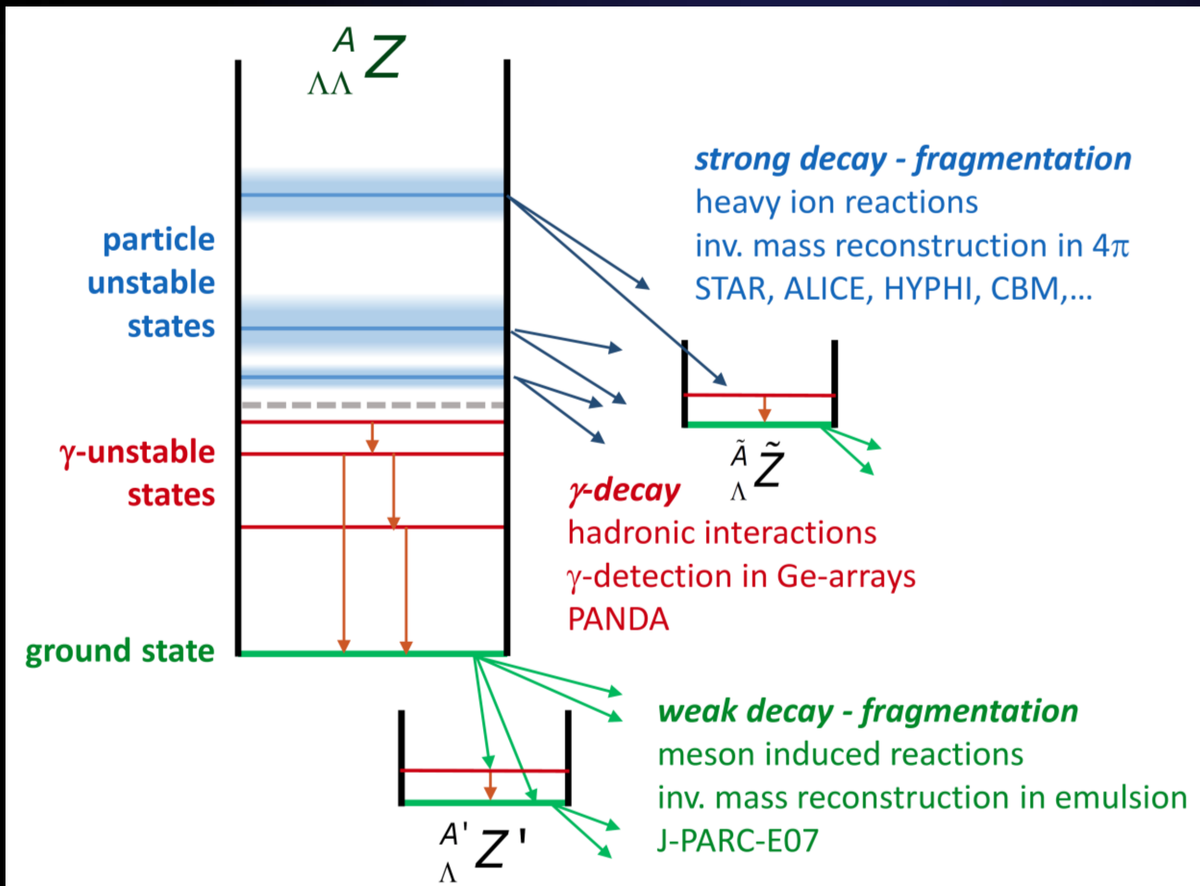
Double Hypernuclei are Shy

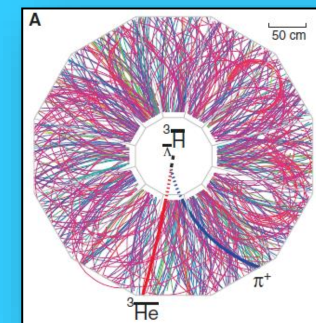
Nucleus	$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z)$ (MeV)	Experiment	Reference	Remark
${}^{10}_{\Lambda\Lambda}$Be	4.3 ± 0.4	Danysz (1963)	[77, 78] [74]	K^{-} + nuclear emulsion; $\Delta B_{\Lambda\Lambda}$ consistent with NAGARA if decay to ${}^{9}_{\Lambda}$Be* at E$_x \approx 3$ MeV [81, 11]
${}^{6}_{\Lambda\Lambda}$He	4.7 ± 0.6	Prowse (1966)	[198]	K^{-} + nuclear emulsion only schematic drawing
${}^{10}_{\Lambda\Lambda}$Be or ${}^{13}_{\Lambda\Lambda}$B	-4.9 ± 0.7 0.6 ± 0.8	KEK-E176 (1991) Aoki event	[20, 245] [88, 24, 172]	hybrid-emulsion (K^{-},K^{+})$\Xi^{-}_{stopped}$
${}^{6}_{\Lambda\Lambda}$He	0.67 ± 0.17	KEK-E373 (2001) NAGARA event	[226, 172] [11]	hybrid emulsion
${}^{10}_{\Lambda\Lambda}$Be or ${}^{10}_{\Lambda\Lambda}$Be*	-1.65 ± 0.15	KEK-E373 (2001) DEMACHIYANAGI event	[10, 172] [11]	$B_{\Lambda\Lambda}$ consistent with Danysz if E$_x \approx 2.8$ MeV
${}^{6}_{\Lambda\Lambda}$He or ${}^{11}_{\Lambda\Lambda}$Be*	3.77 ± 1.71 3.95 ± 3.00 or 4.85 ± 2.63	KEK-E373 (2003) MIKAGE event	[227, 11]	
${}^{12}_{\Lambda\Lambda}$Be or ${}^{11}_{\Lambda\Lambda}$Be*	2.00 ± 1.21 2.61 ± 1.34	KEK-E373 (2010) HIDA event	[172, 11]	

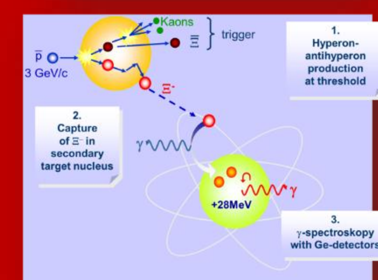
$\Xi^{-}p \rightarrow \Lambda\Lambda + 28$MeV

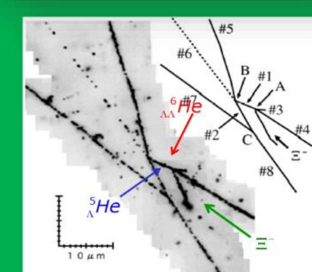
S=-2 systems

- Ξ capture and $\Xi^- p \to \Lambda$ ⇒ ΛΛ hypernuclei J-PARC, FAIR
- ΛΛ coalescence ⇒ ΛΛ hypernuclei HI



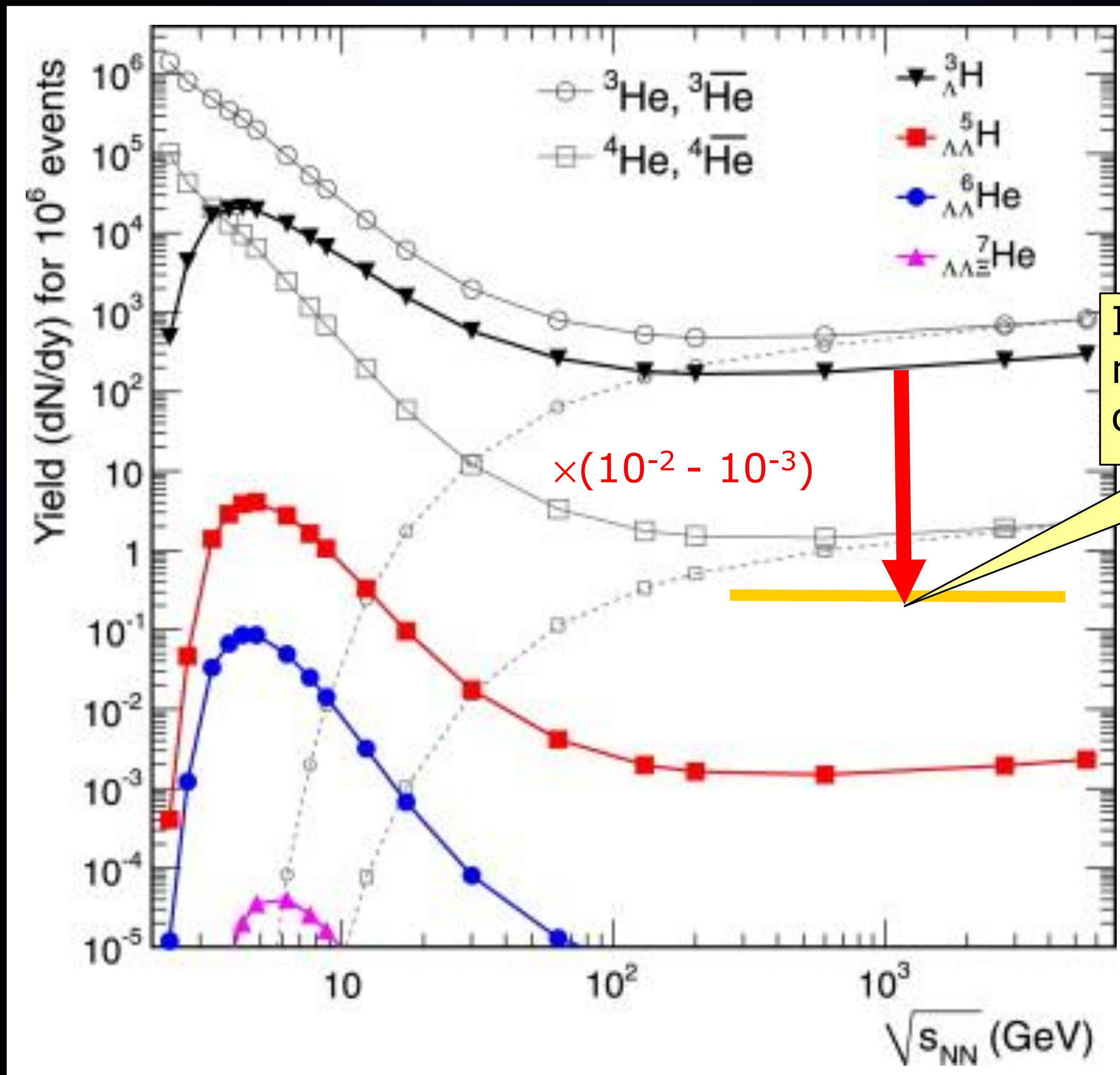






- missing mass (K^-, K^+) reactions ⇒ Ξ bound state J-PARC
- Ξ capture ⇒ Ξ atoms J-PARC, FAIR

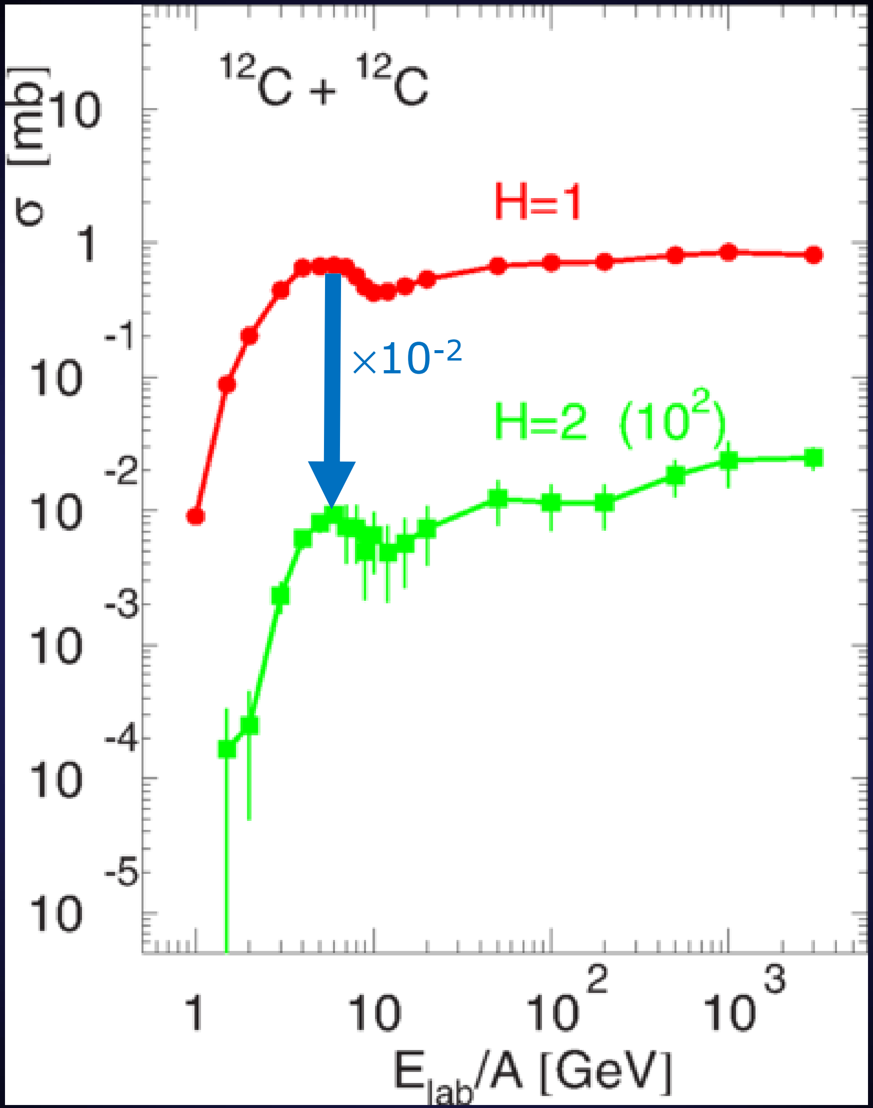
Double Hypernuclei at ALICE ?



If $^4_{\Lambda\Lambda}$H is stable, it might be just observable

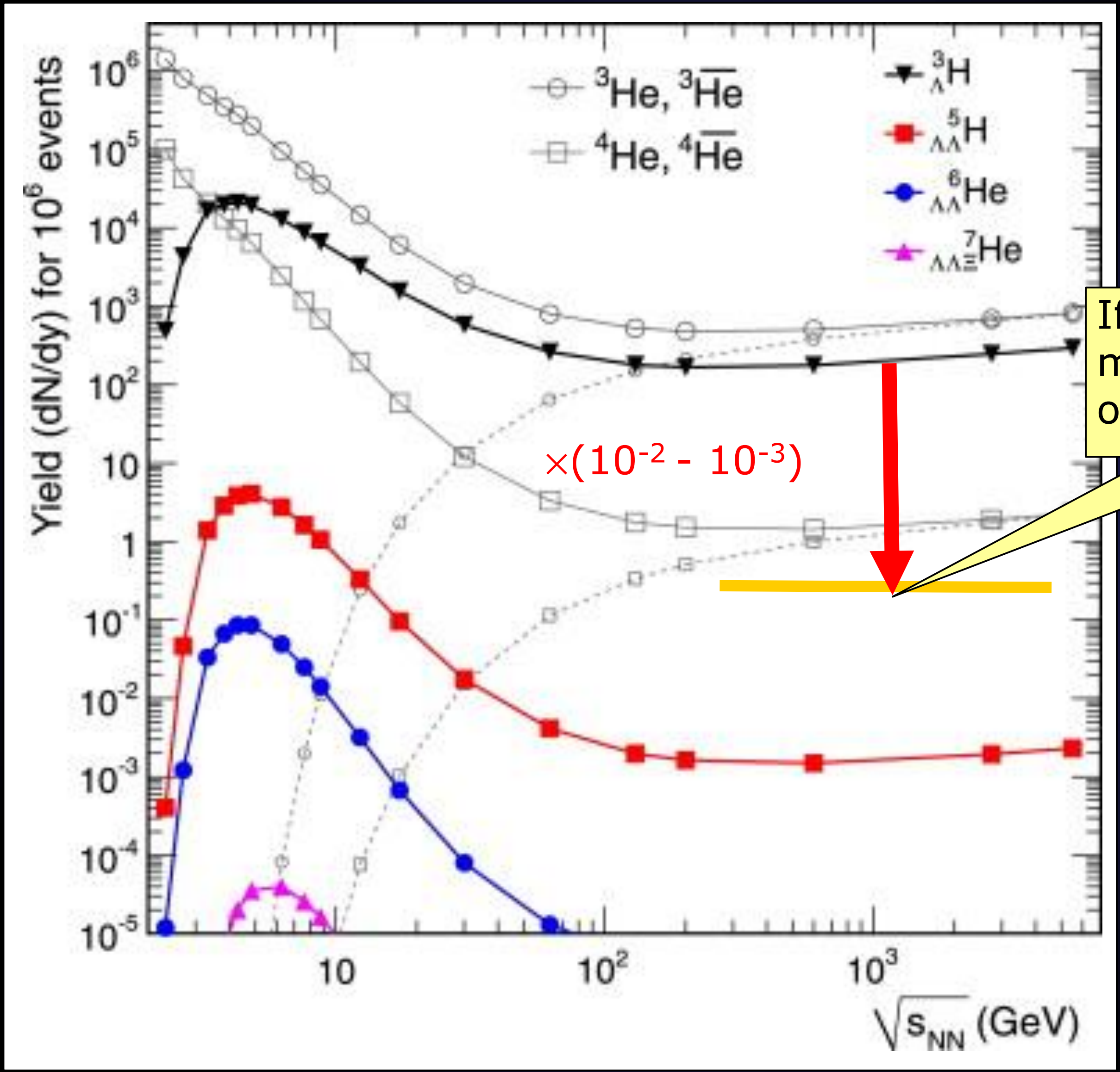
A. Andronic, P. Braun-Munzinger, J. Stachel. H. Stöcker

Double Hypernuclei in Peripheral HI



Phys. Rev. C 95, 014902 (2017)

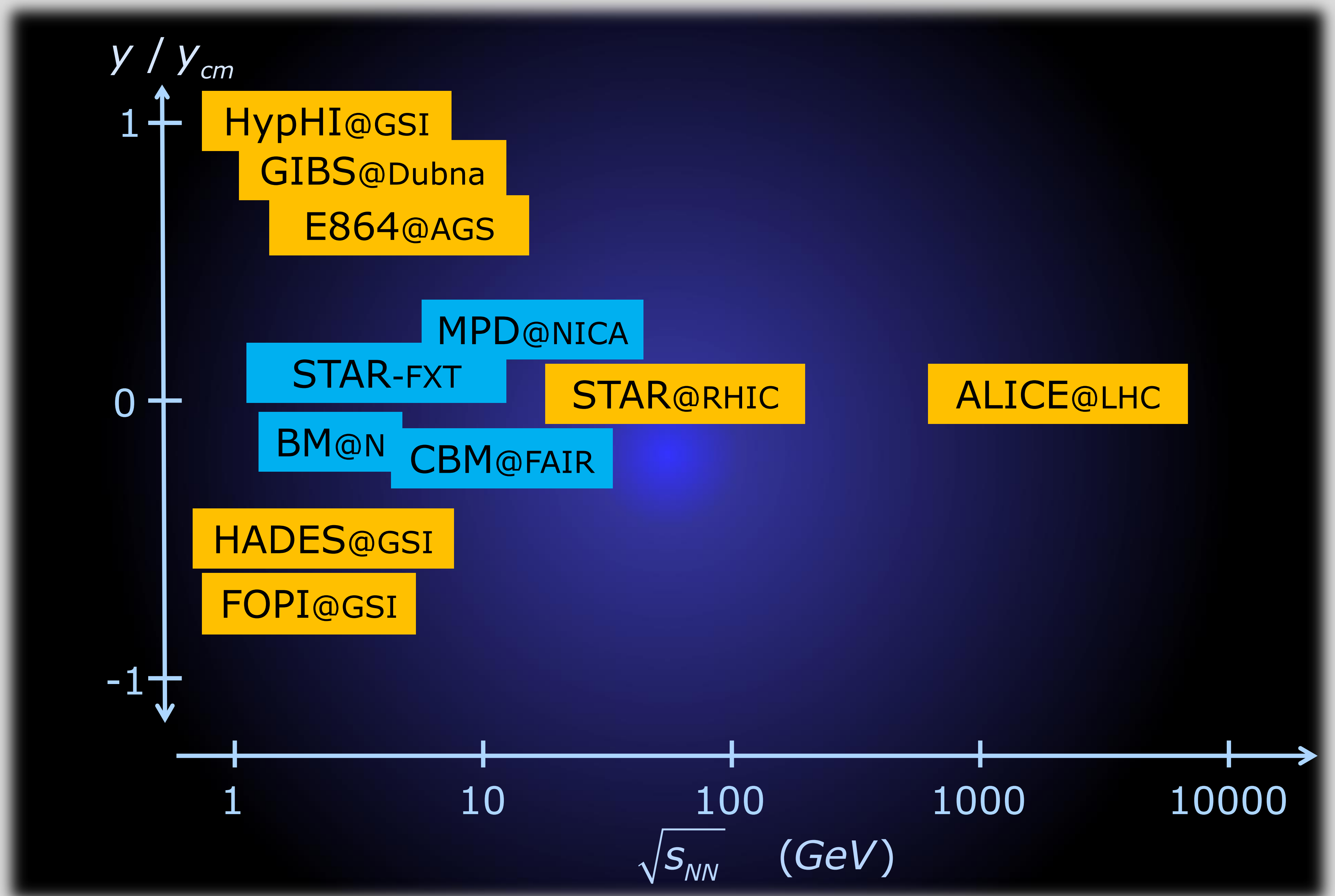
Double Hypernuclei at ALICE ?



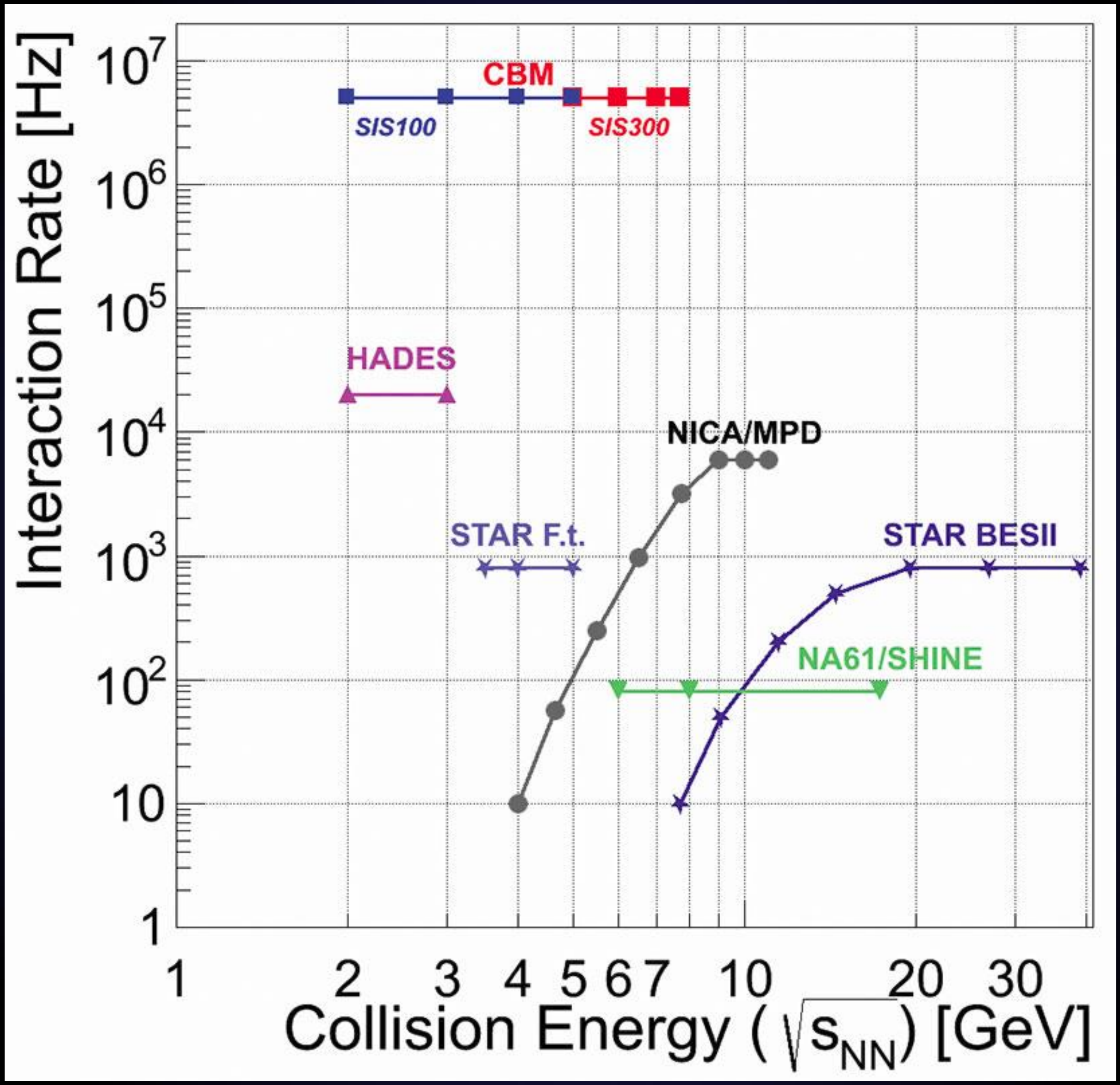
If $^4_{\Lambda\Lambda}$H is stable, it might be just observable

A. Andronic, P. Braun-Munzinger, J. Stachel. H. Stöcker

Future HI Experiments



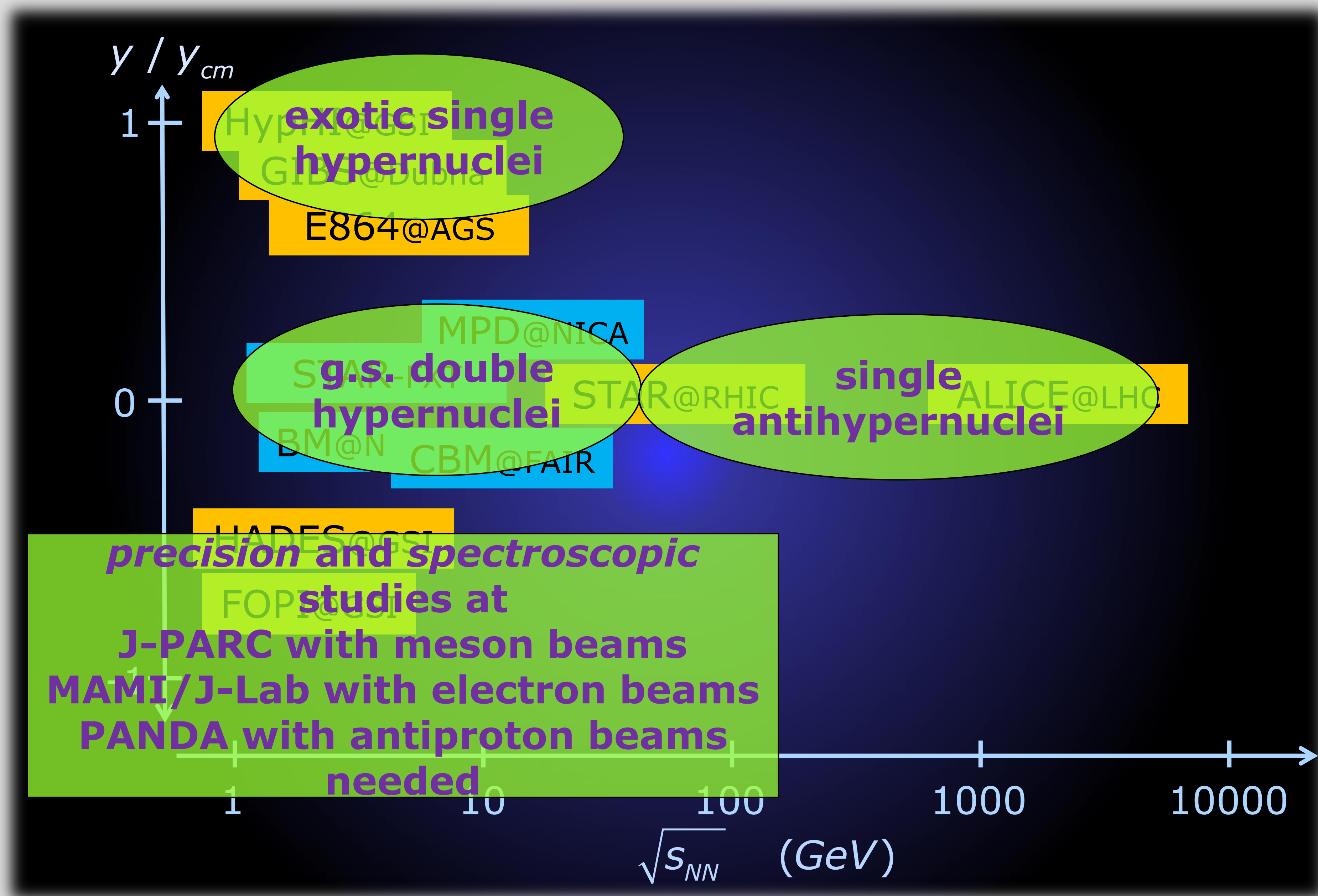
Interaction Rate



JG|U

Hypernuclei in HI

HIM Helmholtz-Institut Mainz




Thank you

Missing Mass & Decay Spectroscopy

Cosmic ray interactions (Emulsion)
Heavy Ion (HypHI, STAR, ALICE, CBM…)
Precission Pion Spectroscopy (MZ)
Antiprotons

Proton Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
10						$^{17}_{\Lambda}$Ne	$_{\Lambda}$ …e	$^{19}_{\Lambda}$Ne	$^{20}_{\Lambda}$Ne	$^{21}_{\Lambda}$Ne	$^{22}_{\Lambda}$Ne	$^{23}_{\Lambda}$Ne	$^{24}_{\Lambda}$Ne	$^{25}_{\Lambda}$Ne	$^{26}_{\Lambda}$Ne	$^{27}_{\Lambda}$Ne	$^{28}_{\Lambda}$Ne	$^{29}_{\Lambda}$Ne	$^{30}_{\Lambda}$Ne	$^{31}_{\Lambda}$Ne
9						$^{16}_{\Lambda}$F	$^{17}_{\Lambda}$F	$^{18}_{\Lambda}$F	$^{19}_{\Lambda}$F	$^{20}_{\Lambda}$F	$^{21}_{\Lambda}$F	$^{22}_{\Lambda}$F	$^{23}_{\Lambda}$F	$^{24}_{\Lambda}$F	$^{25}_{\Lambda}$F	$^{26}_{\Lambda}$F	$^{27}_{\Lambda}$F	$^{28}_{\Lambda}$F	$^{29}_{\Lambda}$F	$^{30}_{\Lambda}$F
8				$^{13}_{\Lambda}$O	$^{14}_{\Lambda}$O	$^{15}_{\Lambda}$O	$^{16}_{\Lambda}$O	$^{17}_{\Lambda}$O	$^{18}_{\Lambda}$O	$^{19}_{\Lambda}$O	$^{20}_{\Lambda}$O	$^{21}_{\Lambda}$O	$^{22}_{\Lambda}$O	$^{23}_{\Lambda}$O	$^{24}_{\Lambda}$O	$^{25}_{\Lambda}$O	$^{26}_{\Lambda}$O	$^{27}_{\Lambda}$O		
7				$^{12}_{\Lambda}$N	$^{13}_{\Lambda}$N	$^{14}_{\Lambda}$N	$^{15}_{\Lambda}$N	$^{16}_{\Lambda}$N	$^{17}_{\Lambda}$N	$^{18}_{\Lambda}$N	$^{19}_{\Lambda}$N	$^{20}_{\Lambda}$N	$^{21}_{\Lambda}$N	$^{22}_{\Lambda}$N	$^{23}_{\Lambda}$N	$^{24}_{\Lambda}$N				
6			$^{10}_{\Lambda}$C	$^{11}_{\Lambda}$C	$^{12}_{\Lambda}$C	$^{13}_{\Lambda}$C	$^{14}_{\Lambda}$C	$^{15}_{\Lambda}$C	$^{16}_{\Lambda}$C	$^{17}_{\Lambda}$C	$^{18}_{\Lambda}$C	$^{19}_{\Lambda}$C	$^{20}_{\Lambda}$C	$^{21}_{\Lambda}$C						
5			$^{9}_{\Lambda}$B	$^{10}_{\Lambda}$B	$^{11}_{\Lambda}$B	$^{12}_{\Lambda}$B	$^{13}_{\Lambda}$B	$^{14}_{\Lambda}$B	$^{15}_{\Lambda}$B	$^{16}_{\Lambda}$B	$^{17}_{\Lambda}$B	$^{18}_{\Lambda}$B								
4		$^{7}_{\Lambda}$Be	$^{8}_{\Lambda}$Be	$^{9}_{\Lambda}$Be	$^{10}_{\Lambda}$Be	$^{11}_{\Lambda}$Be	$^{12}_{\Lambda}$Be	$^{13}_{\Lambda}$Be	$^{14}_{\Lambda}$Be	$^{15}_{\Lambda}$Be										
3		$^{6}_{\Lambda}$Li	$^{7}_{\Lambda}$Li	$^{8}_{\Lambda}$Li	$^{9}_{\Lambda}$Li	$^{10}_{\Lambda}$Li	$^{11}_{\Lambda}$Li	$^{12}_{\Lambda}$Li												
2	$^{4}_{\Lambda}$He	$^{5}_{\Lambda}$He	$^{6}_{\Lambda}$He	$^{7}_{\Lambda}$He	$^{8}_{\Lambda}$He	$^{9}_{\Lambda}$He														
1	$^{3}_{\Lambda}$H	$^{4}_{\Lambda}$H																		

Neutron Number

$n \to \Lambda:$ (K^-,π^-), (K^-_{stop},π^-), (π^+,K^+)

$p \to \Lambda:$ $(e,e'K^+)$, (K^-_{stop},π^0)

$pp \to n\Lambda:$ (π^-,K^+)