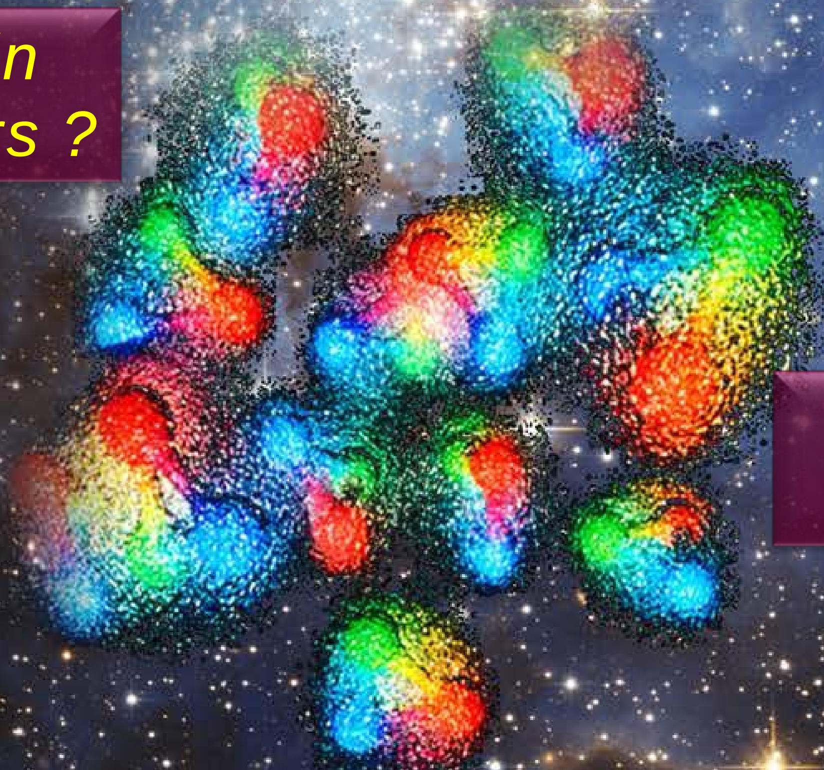
High precision mass measurements of hypernuclei
motivation, achievements and perspectives at MAMI

Josef Pochodzalla

New trends in the low-energy QCD in the strangeness sector: experimental and theoretical aspects
ECT* , October 15th-19th 2012

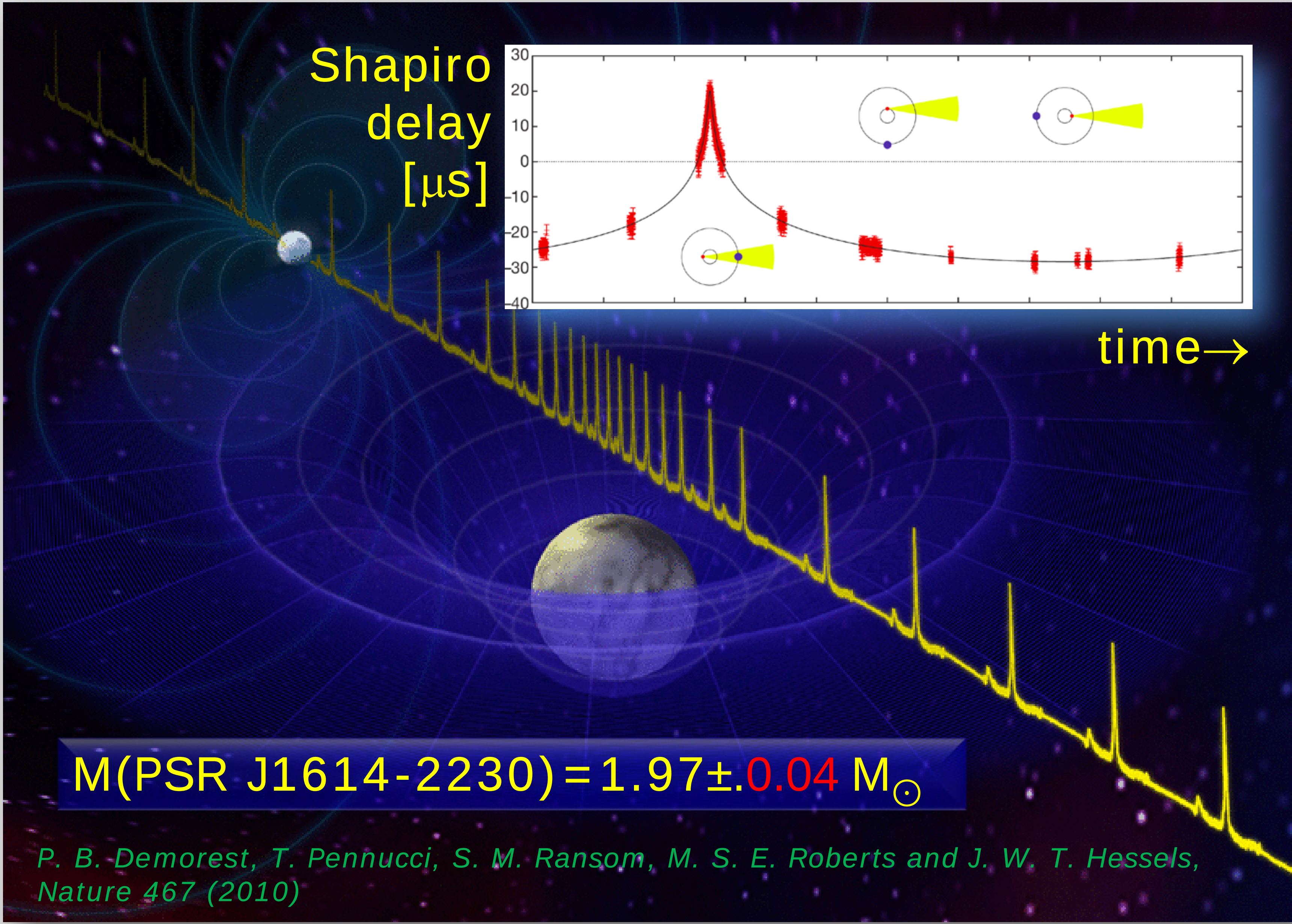
Comprehensive description of strange nuclei in terms of basic principles (QCD) to allow quantitative predictions in regions not directly accessible by experiments

hyperons in neutron stars ?



existence of H-particle ?

A Heavy Neutron Stars

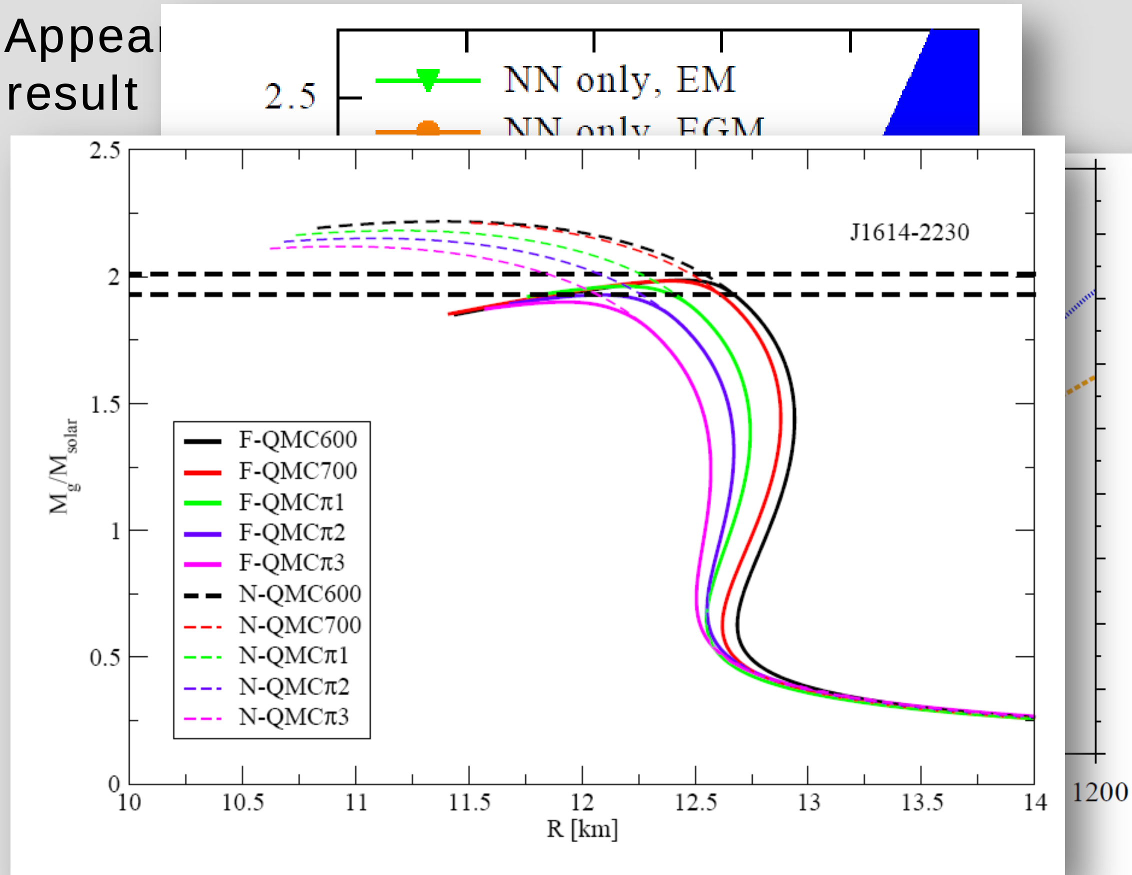


M(PSR J1614-2230) = 1.97±.0.04 $M_{\odot}$

P. B. Demorest, T. Pennucci, S. M. Ransom, M. S. E. Roberts and J. W. T. Hessels, Nature 467 (2010)

The Hyperon Puzzle in Neutron Stars

- Also three (and four) baryon forces are essential for understanding the EOS at high density
- Appea[r]
result



J. R. Stone et al., arXiv:1012.2919v1

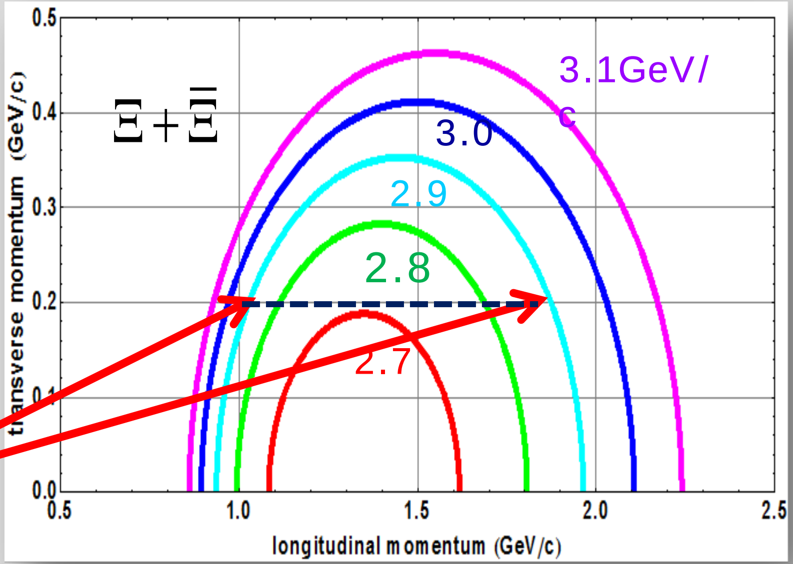
D.L.Whittenbury et al., arXiv:1204.2614

- This causes a dilemma for many EOS but a two solar mass neutron star may still be compatible with the presence of hyperons

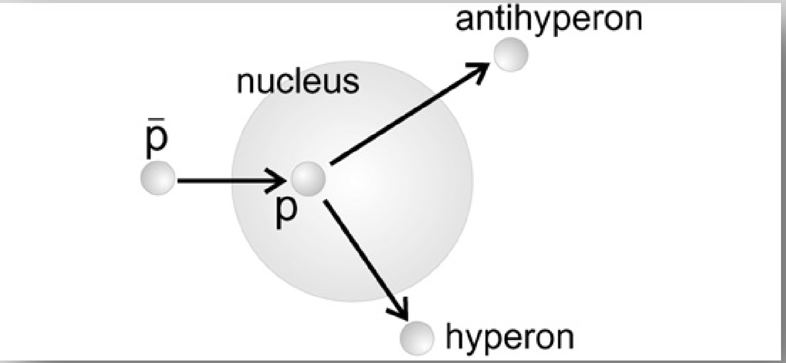
But even if hyperons do *not* appear in neutrons stars, why so ?
⇒ Need a precise understand Y-N, Y-Y, Y-N-N, ... interactions !

Possibilities for studying YN, YNN

- Scattering of hyperons and antihyperons
  → JPARC, PANDA
  - $\bar{p}+p \to \bar{Y}+Y$ provides momentum tagged hyperon or antihyperon beams



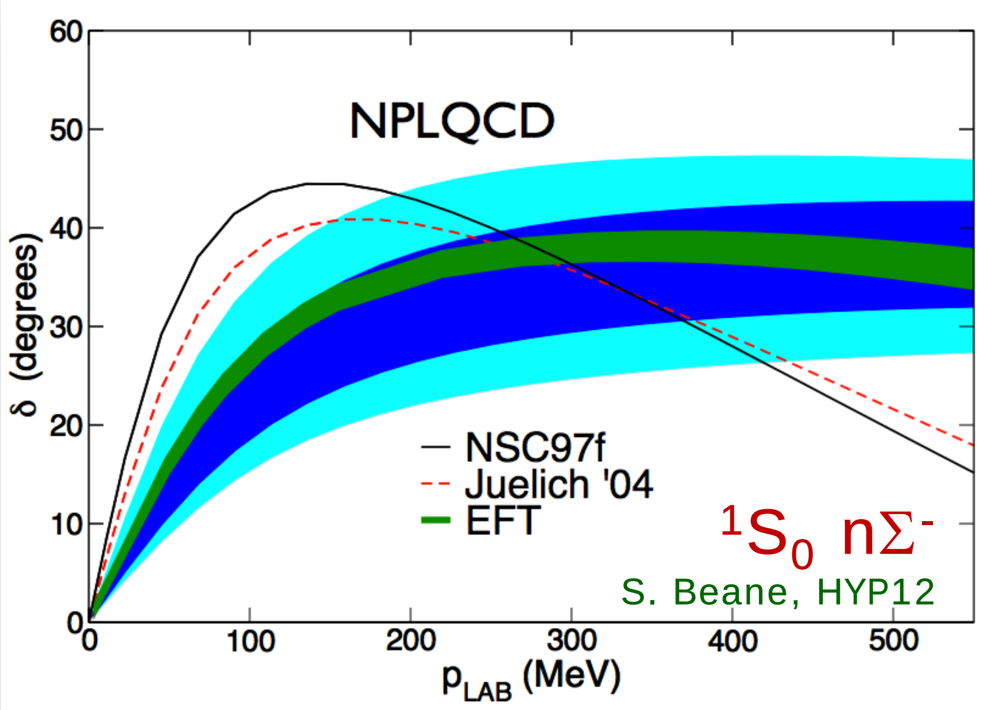
- $\bar{p}+A \to \bar{Y}+Y+X$: (anti)hyperon nuclear potentials from $\bar{Y}+Y$ pair correlations
  → PANDA
  see e.g. PLB 669 (2008) 306

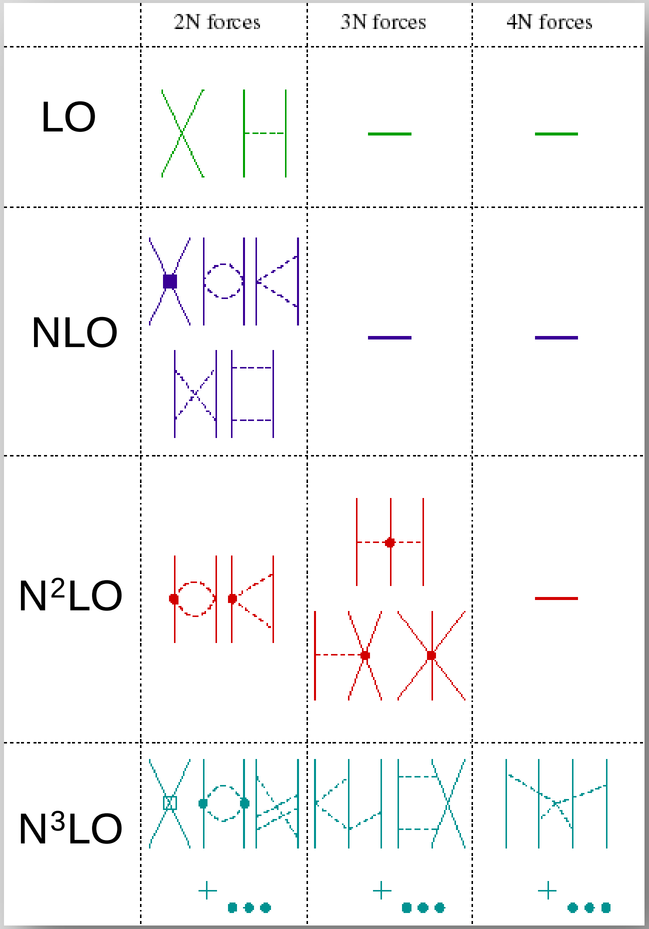


- Hypernuclei !
  - Advantage: YN,YNN,...,YY interaction accessible

Fundamental theories are getting mature...

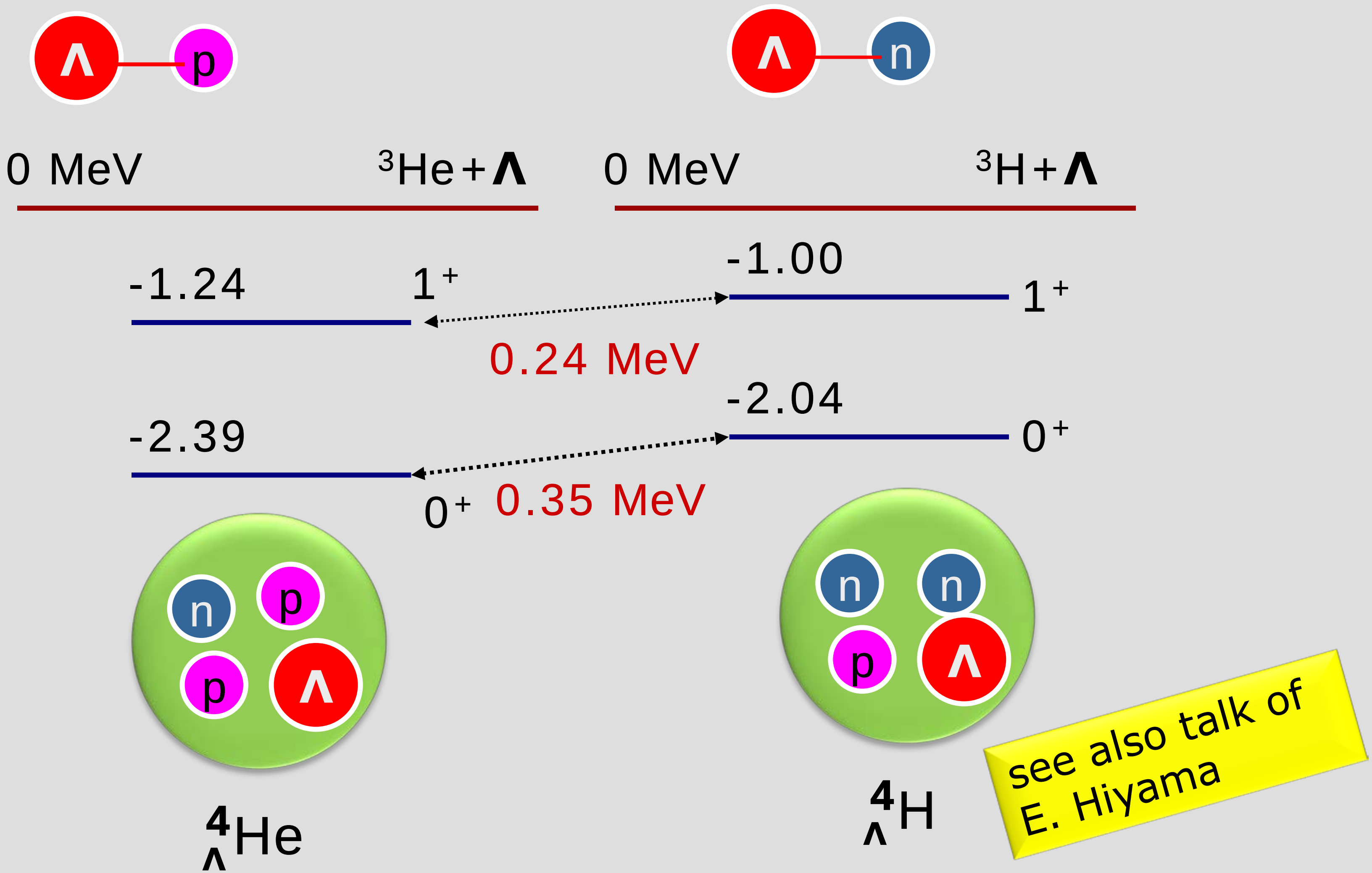
- EFT for relevant degrees of freedom based on symmetries of QCD; provides hierarchy of *consistent* NN, 3N, 4N,... interactions
- Also Lattice QCD makes giant steps towards nuclear physics





E. Epelbaum

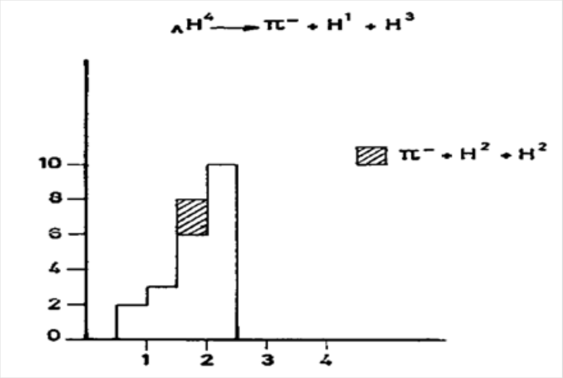
CSB in Strange Nuclei - Experiment

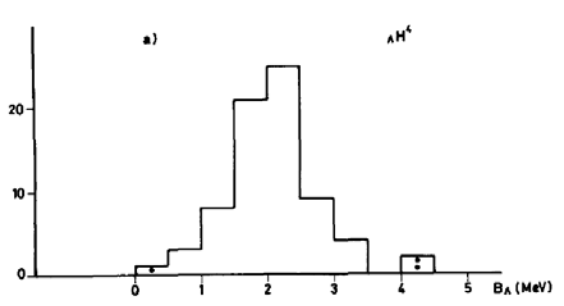


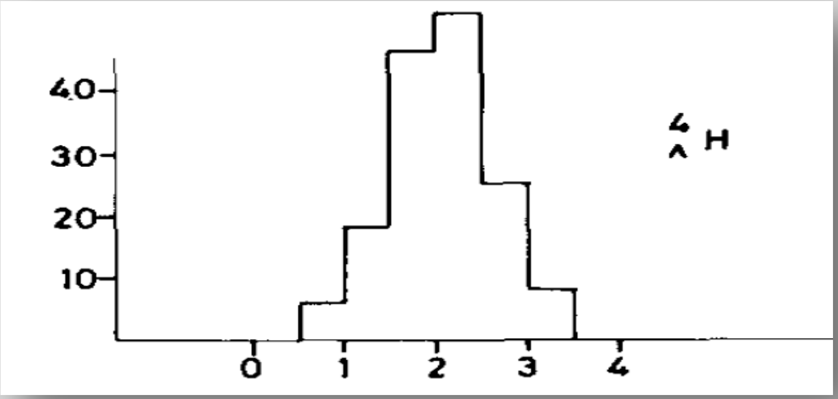
- *A. Nogga (HYP 2012): “CSB for four-body hypernuclei is a puzzle”*
- Precise <100keV information on ground state masses of hypernuclei can serve as a extremely valuable input to determine YN

The experimental situation of $^{4}_{\Lambda}H$

- W. Gajewski *et al*,
  - Nucl. Phys. B1, 105 (1967)
  - 208 (π^- 4He) B_Λ = 2.26±0.07
  - 21 (π^- pt)+2 (π^-dd) B_Λ = 1.86±0.10
- G. Bohm *et al*.,
  - Nucl. Phys. B4, 511 (1968)
  - 552 (π^- ^{4}He) B_Λ = 2.29±0.04
  - 63 (π^- pt)+7 (π^-dd) B_Λ = 2.08±0.06
- M. Juric *et al*., Nucl. Phys. B52, 1 (1973)
  - 56 (π^- pt) B_Λ = 2.14±0.07
  - 11 (π^-ppd) B_Λ = 1.92±0.12

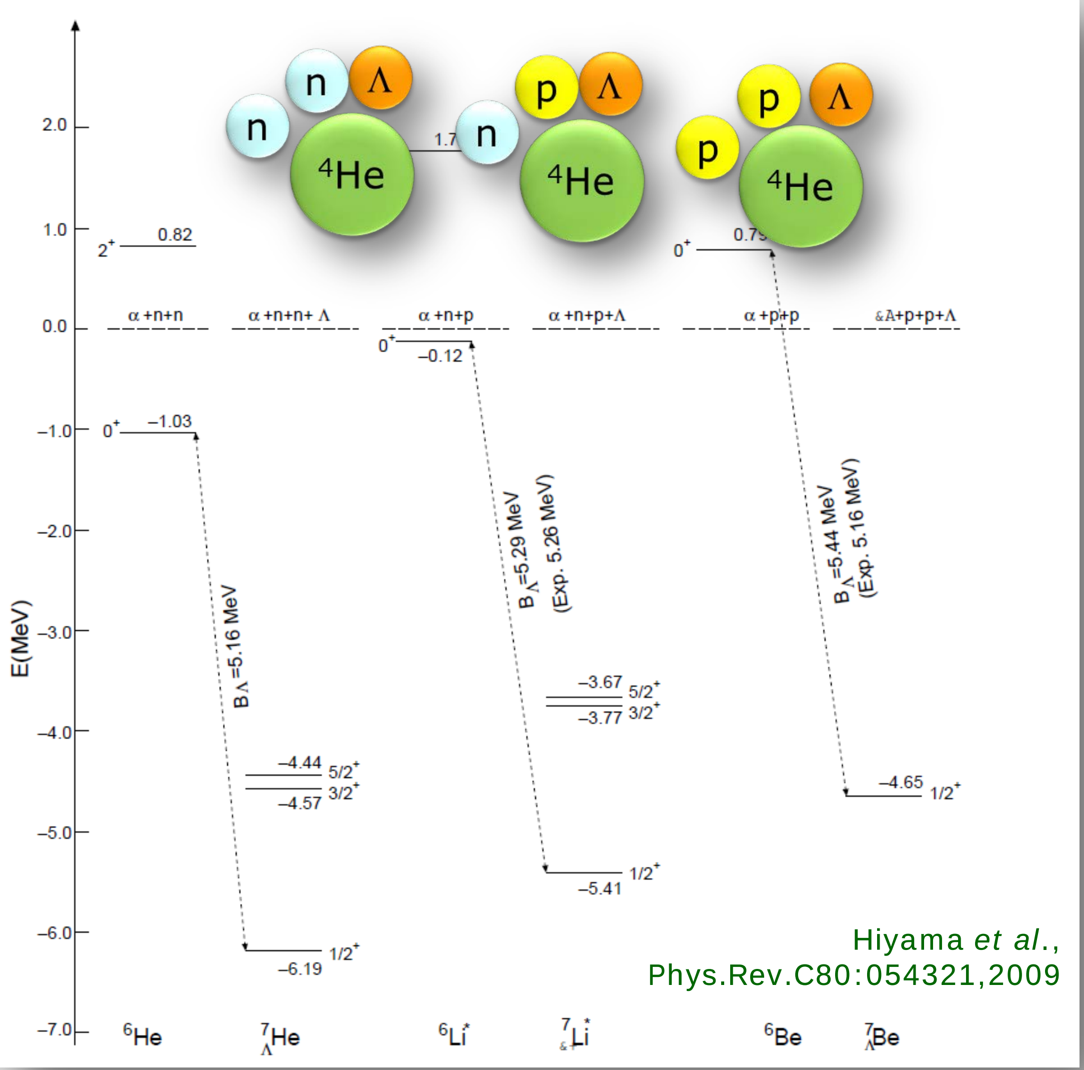






CSB in 3Baryon Forces ?

- CSB $|\Delta E| \sim 100$keV
- 3 baryon force: YNN ?



Hiyama *et al.*,
Phys.Rev.C80:054321,2009

The A=7 Hypernuclei

A NOTE ON THE $_{\Lambda}He^{7}$ HYPERFRAGMENTS

J. PNIEWSKI and M. DANYSZ
Institute of Physics, University of Warsaw, Warsaw
and Institute of Nuclear Research, Warsaw, Poland

Received 16 April 1962

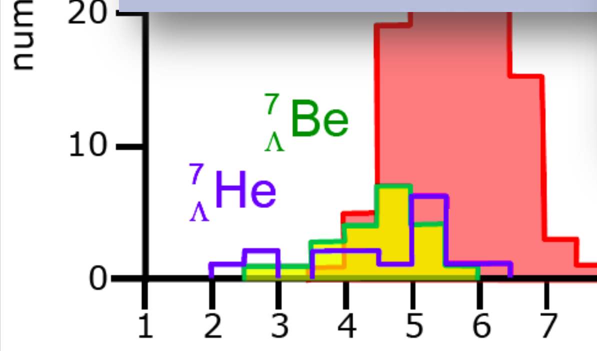
To find a way out of this dilemma, we may consider the spread of B_{Λ} values of $_{\Lambda}He^{7}$ in table 1 to be a genuine effect. If we divide tentatively all the events from this table into two groups in which the hypernuclei are observed to decay with or without a heavy recoil ($A = 6.7$) we notice that for the first group the average Λ^{0} binding energy is:

$$B'_{\Lambda} = (5.1 \pm 0.4)\ \mathrm{MeV}$$

while for the second one:

$$B''_{\Lambda} = (3.2 \pm 0.4)\ \mathrm{MeV}$$

304.810	5.16 ± 0.54
294.107 a)	5.48 ± 0.67
329.107 a)	5.03 ± 0.69



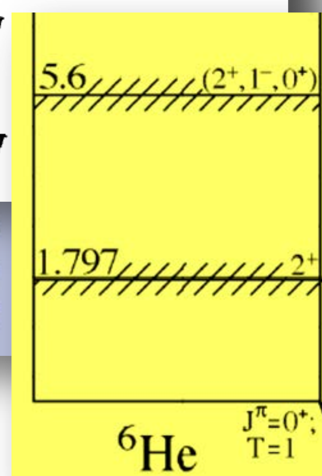
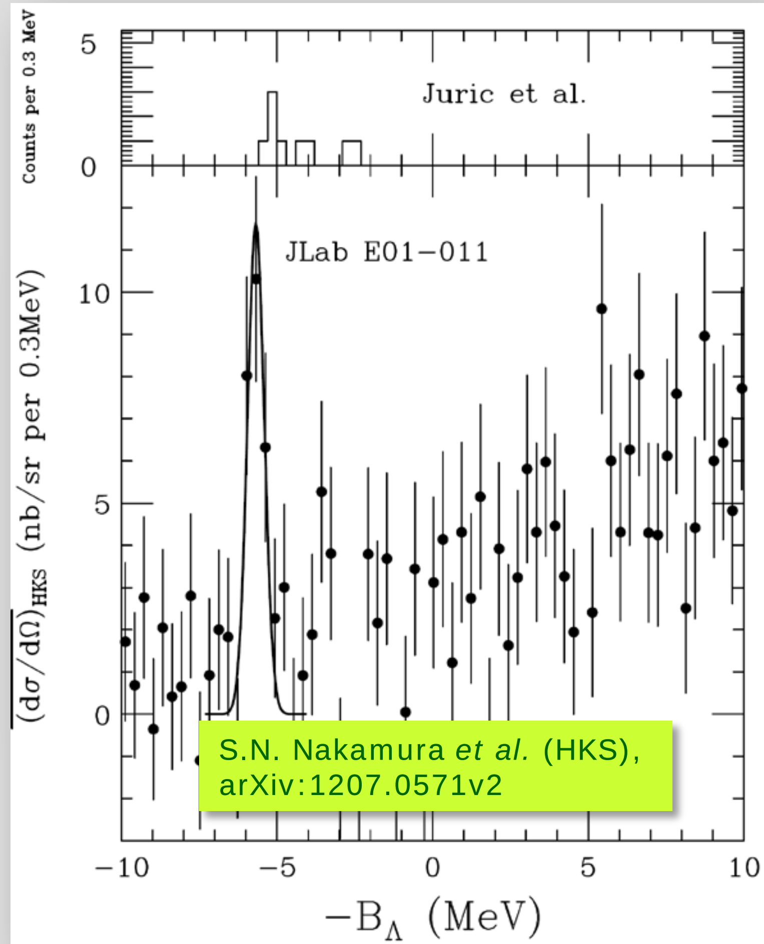


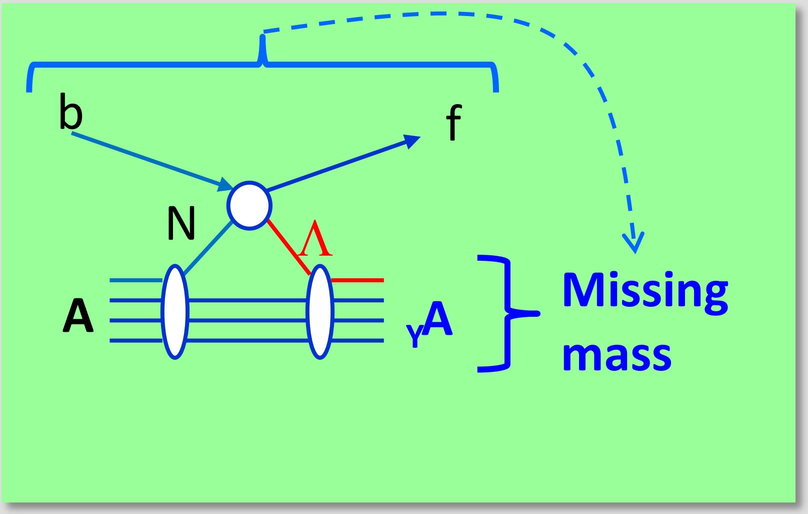
TABLE II. Binding energies of $A = 7, T = 1$ iso-triplets Λ hypernuclei. Errors of E01-011 are statistical and systematic errors.

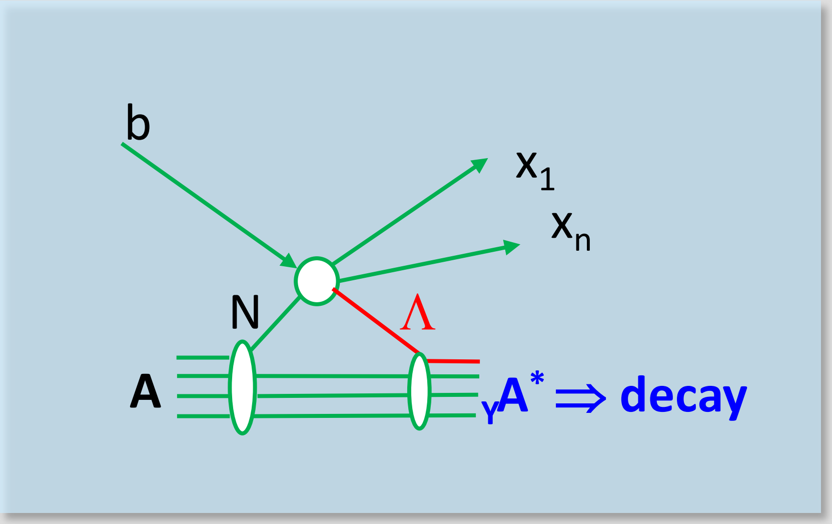
	$^{7}_{\Lambda}$He (E01-011)	$^{7}_{\Lambda}$Li* [2, 13]	$^{7}_{\Lambda}$Be [2]
B_{Λ} (MeV)	$5.68 \pm 0.03 \pm 0.25$	5.26 ± 0.03	5.16 ± 0.08



S.N. Nakamura *et al.* (HKS), arXiv:1207.0571v2

The twofold way

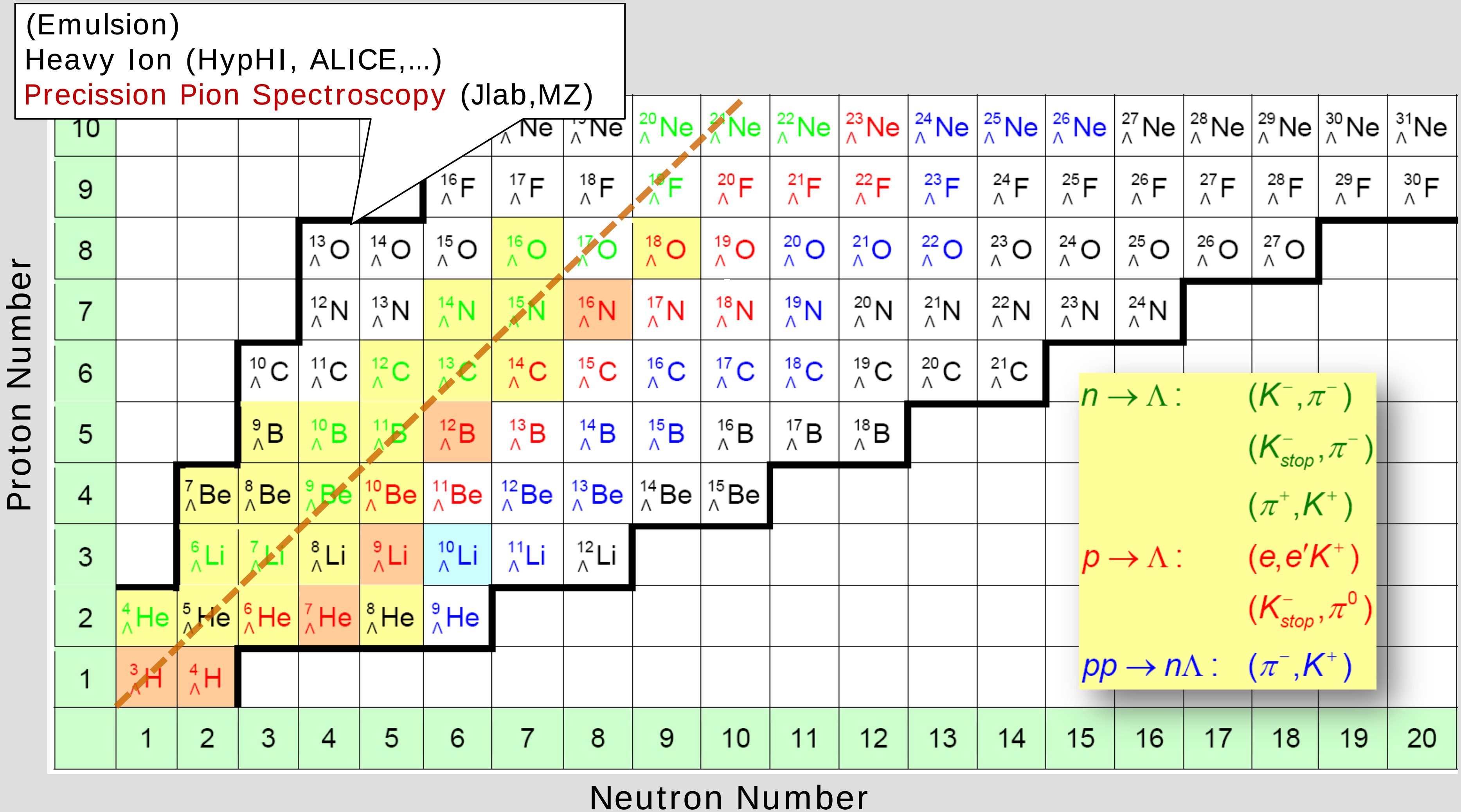




- Direct production spectroscopy
- Examples
  - strangeness production (π^+, K^+), (π^-, K^0)
  - strangeness exchange (K^-, π^-), (K^-, π^0), (K^-, K^+)
  - Electroproduction $(e, e' K^+)$, (γ, K^+)
- Absolute calibration difficult
  - Secondary beams
  - High momenta

- Decay spectroscopy
  - γ-decay of excited states
  - π from two-body weak decay
  - charged fragments
- Examples
  - nuclear emulsions
  - heavy ion reactions
  - antiproton induced reactions
  - continuum excitation in $(e, e' K+)$

Missing Mass Experiments



- Not a single mirror pair can be reached by the same method
- Systematic error >200keV

The achievements

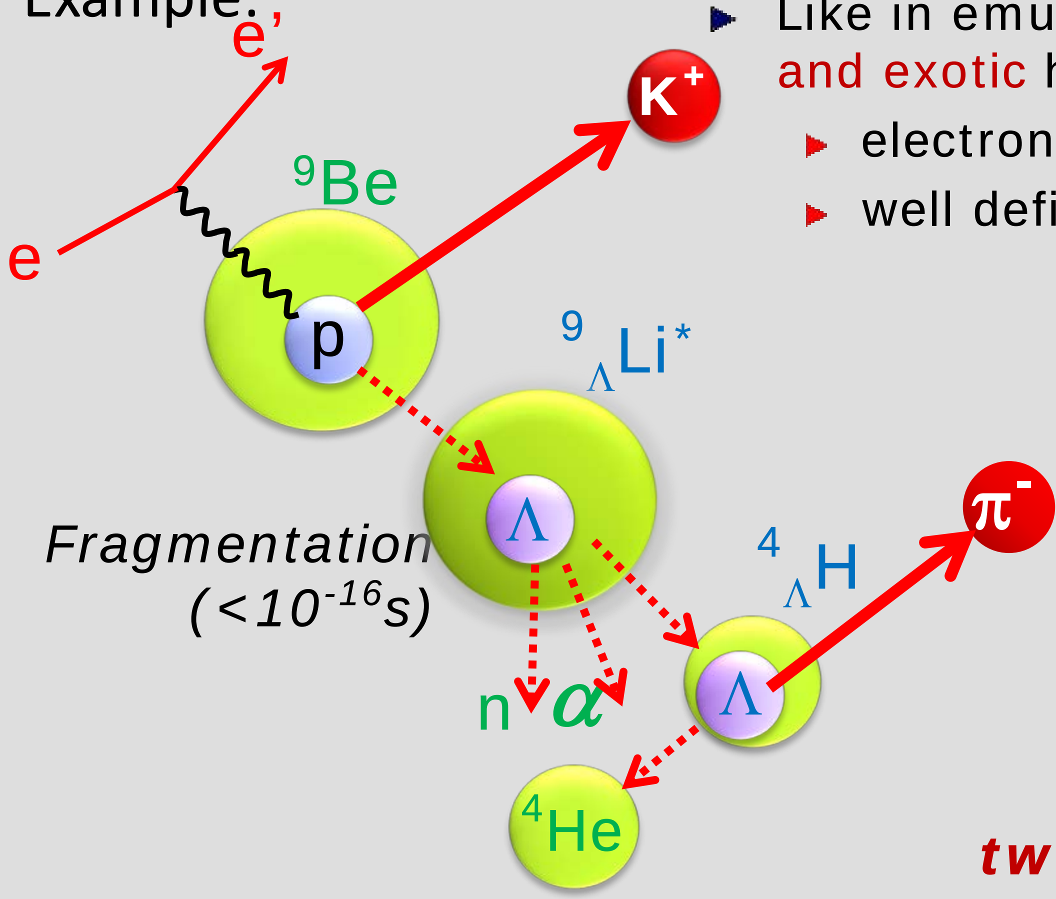
High Resolution Decay Pion Spectroscopy at MAMI

Anselm Esser, Sho Nagao, Florian Schulz

Decay pion spectroscopy

- Two-body decay ⇒ mono-energetic pions
- high resolution: Λ binding energy resolution limited by π^- momentum resolution
- Like in emulsion access to variety of light and exotic hypernuclei, but
  - electronic experiment
  - well defined initial target nucleus

Example:



Weak mesonic
***two-body** decay ($\sim 10^{-10}$s)*
at rest

The prospects

PROTON NUMBER \ NEUTRON NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
12		^{12}C	Target				$^{20}_{\Lambda}Mg$	$^{21}_{\Lambda}Mg$	$^{22}_{\Lambda}Mg$	$^{23}_{\Lambda}Mg$	$^{24}_{\Lambda}Mg$	$^{25}_{\Lambda}Mg$	$^{26}_{\Lambda}Mg$	$^{27}_{\Lambda}Mg$	$^{28}_{\Lambda}Mg$	$^{29}_{\Lambda}Mg$	$^{30}_{\Lambda}Mg$	$^{31}_{\Lambda}Mg$	$^{32}_{\Lambda}Mg$	$^{33}_{\Lambda}Mg$
11		^{9}Be	Target					$^{20}_{\Lambda}Na$	$^{21}_{\Lambda}Na$	$^{22}_{\Lambda}Na$	$^{23}_{\Lambda}Na$	$^{24}_{\Lambda}Na$	$^{25}_{\Lambda}Na$	$^{26}_{\Lambda}Na$	$^{27}_{\Lambda}Na$	$^{28}_{\Lambda}Na$	$^{29}_{\Lambda}Na$	$^{30}_{\Lambda}Na$	$^{31}_{\Lambda}Na$	$^{32}_{\Lambda}Na$
10		^{7}Li	Target			$^{17}_{\Lambda}Ne$	$^{18}_{\Lambda}Ne$	$^{19}_{\Lambda}Ne$	$^{20}_{\Lambda}Ne$	$^{21}_{\Lambda}Ne$	$^{22}_{\Lambda}Ne$	$^{23}_{\Lambda}Ne$	$^{24}_{\Lambda}Ne$	$^{25}_{\Lambda}Ne$	$^{26}_{\Lambda}Ne$	$^{27}_{\Lambda}Ne$	$^{28}_{\Lambda}Ne$	$^{29}_{\Lambda}Ne$	$^{30}_{\Lambda}Ne$	$^{31}_{\Lambda}Ne$
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	$^{3}_{\Lambda}H$	$^{4}_{\Lambda}H$	$^{5}_{\Lambda}H$	$^{6}_{\Lambda}H$	$^{7}_{\Lambda}H$	$^{8}_{\Lambda}H$														
0	ΛN																			

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

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

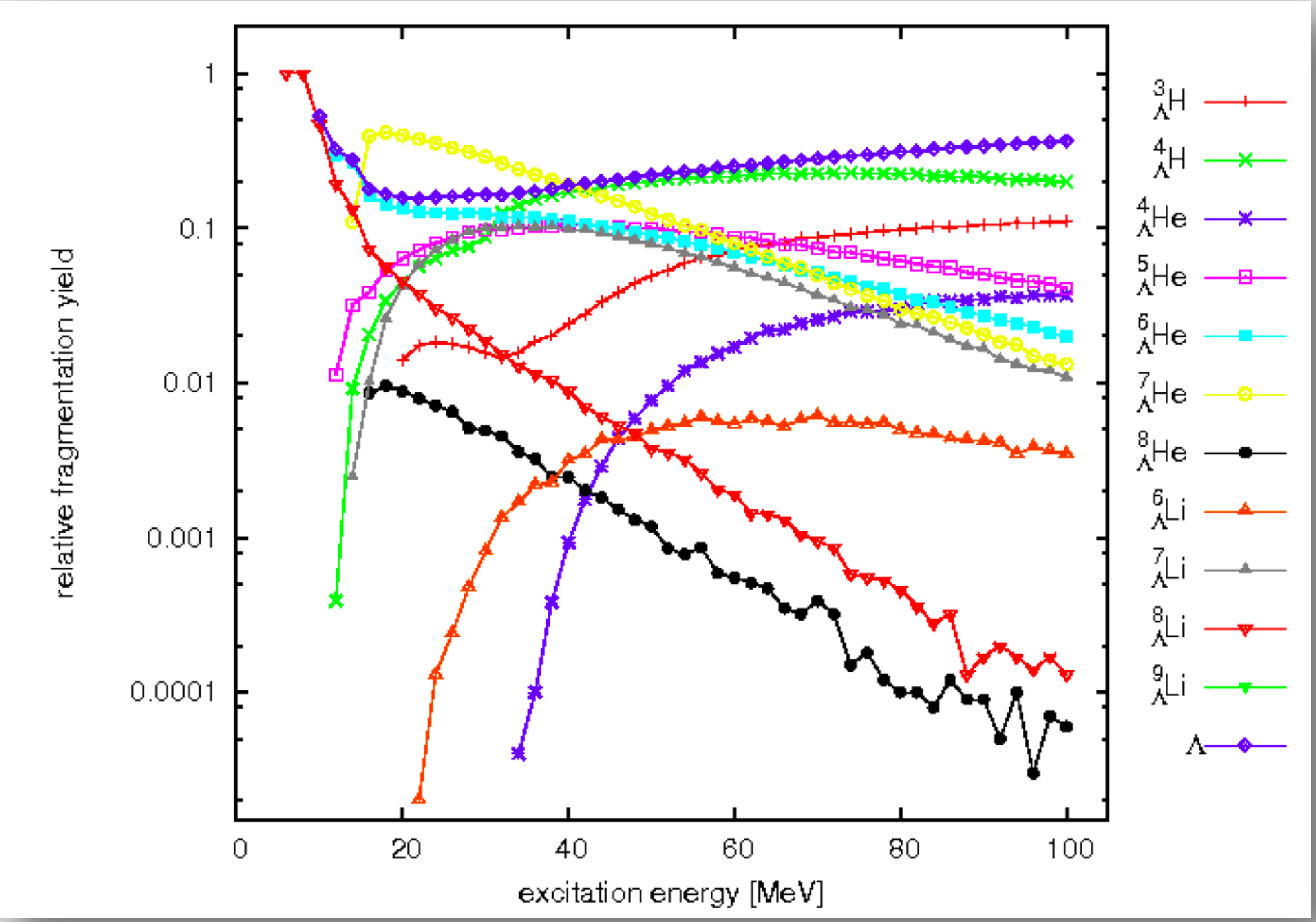
$pp \to n\Lambda$: (π^-,K^+)

PROTON NUMBER

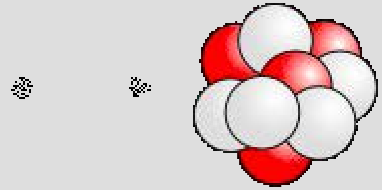
NEUTRON NUMBER

Fermi breakup of excited hypernuclei

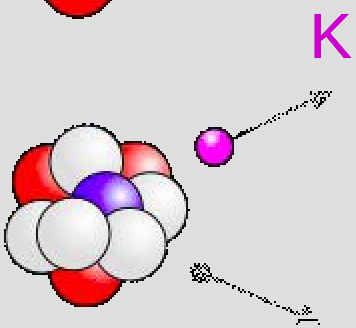
- Decay of ${}^{9}_{\Lambda}Li^*$ (A. Botvina, A. Sanchez, J. P., Physics Letters B 697 (2011) 222)



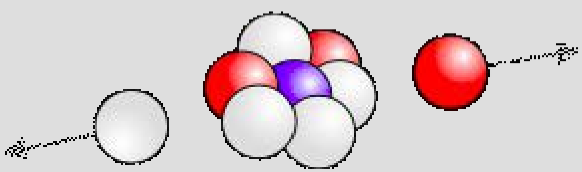
The experiment in a nutshell



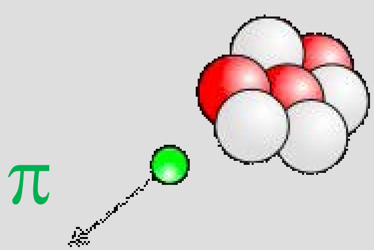
- Electroproduction of excited hypernuclei on ^{9}Be Target



- Event tagging by kaon detection



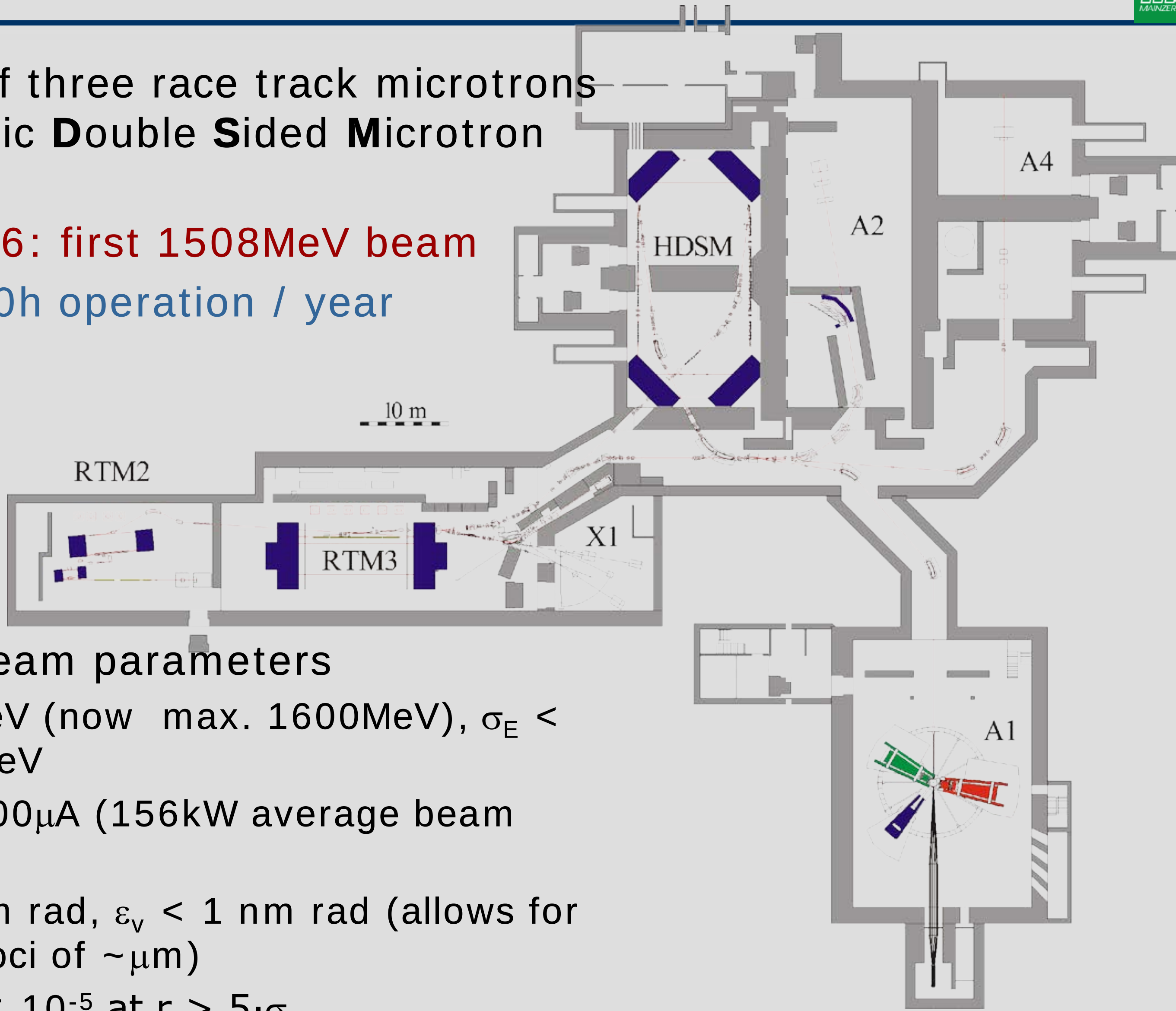
- Fragmentation produces several light hypernuclei



- Mesonic weak decay and groundstate mass reconstruction by spectroscopy of pions from two-body decay

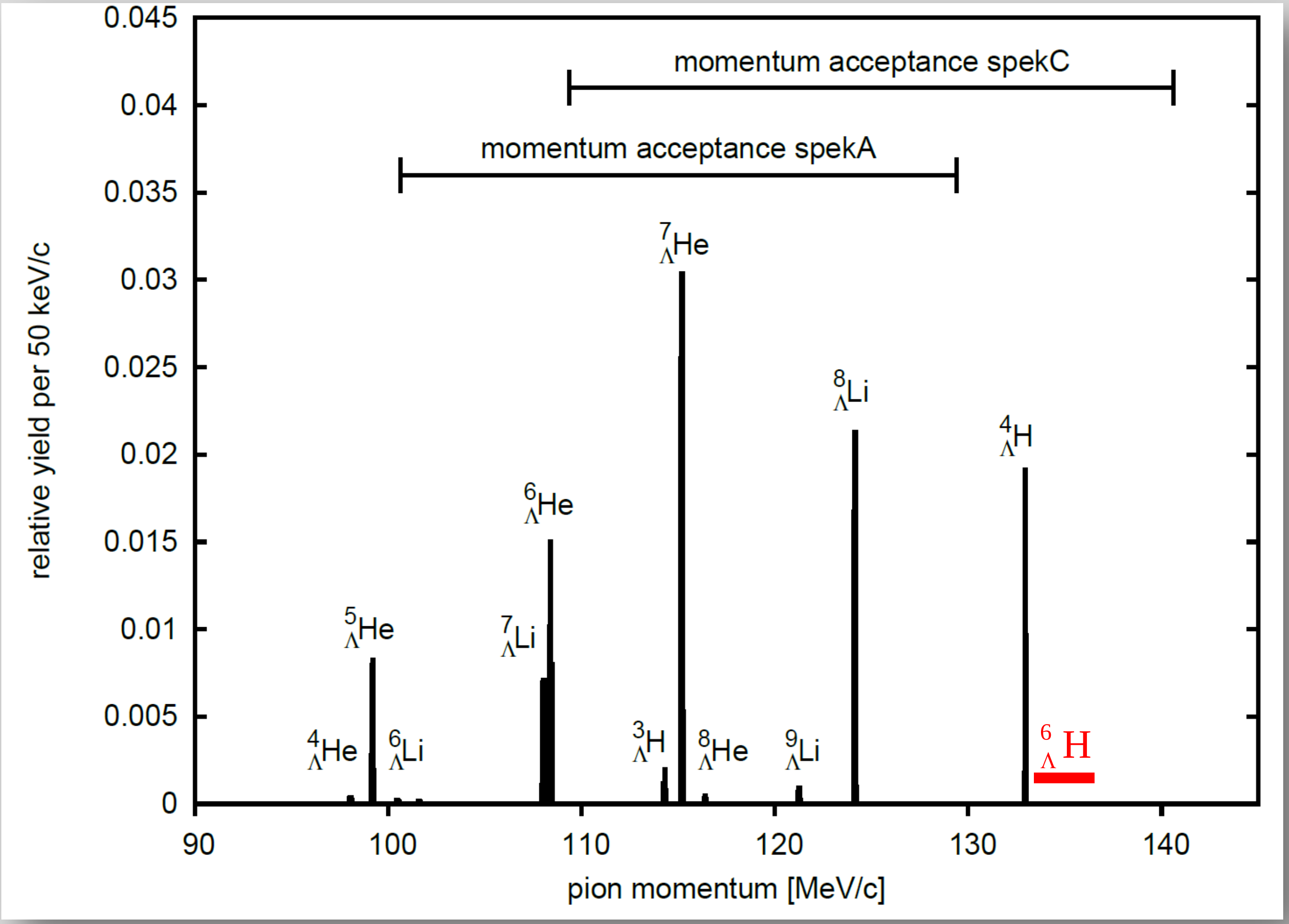
The Mainz Microtron MAMI-C

- Cascade of three race track microtrons + **H**armonic **D**ouble **S**ided **M**icrotron (HDSM)
- 19.12.2006: first 1508MeV beam
- Up to 7000h operation / year



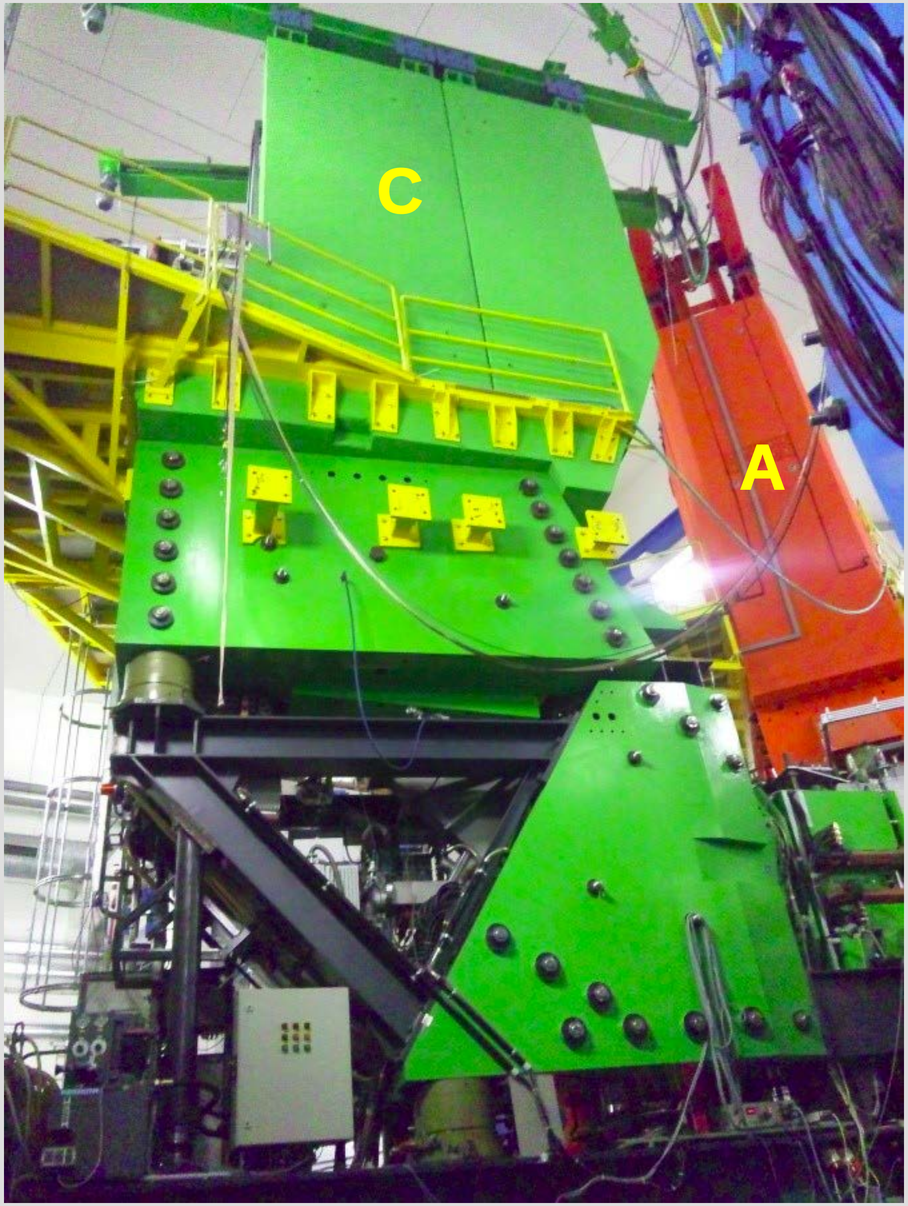
- MAMI-C beam parameters
  - 1508MeV (now max. 1600MeV), σ_E < 0.100MeV
  - max. 100μA (156kW average beam power)
  - ε_h=9 nm rad, ε_v < 1 nm rad (allows for beam foci of ~μm)
  - halo: < 10^{-5} at r > $5 \cdot \sigma_r$

What can be expected

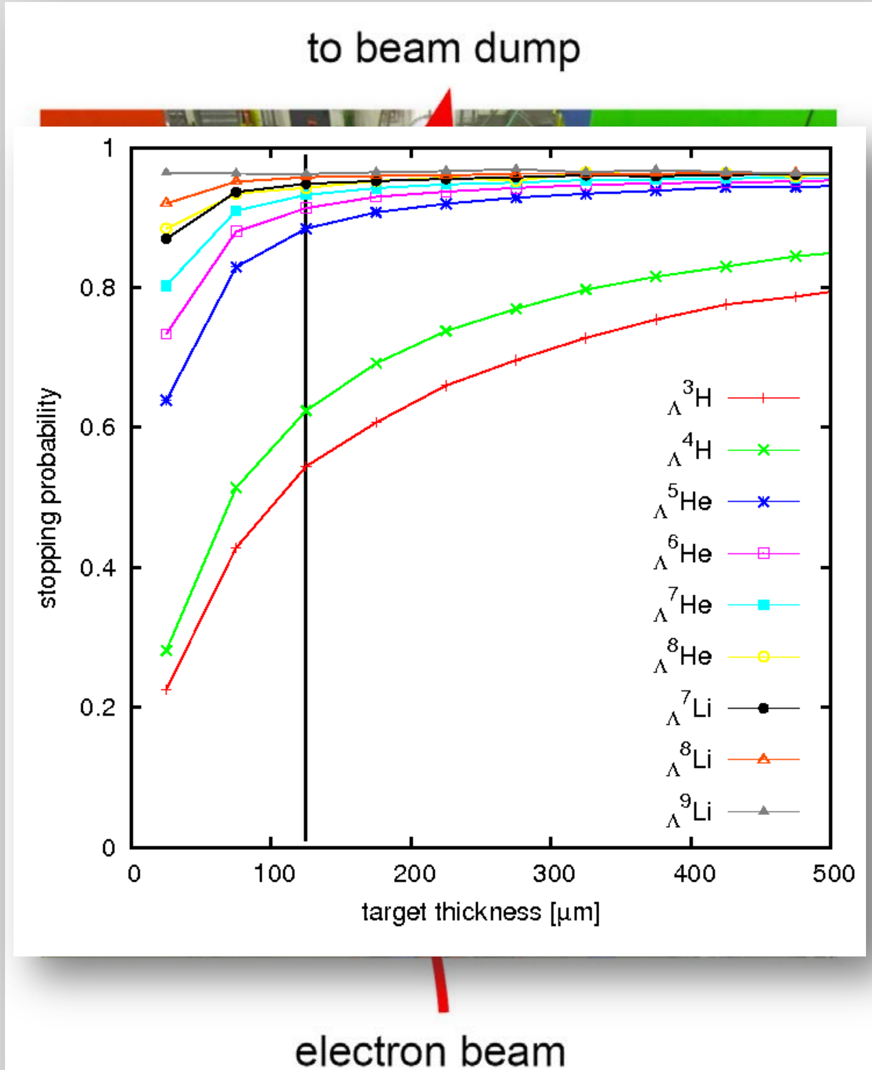


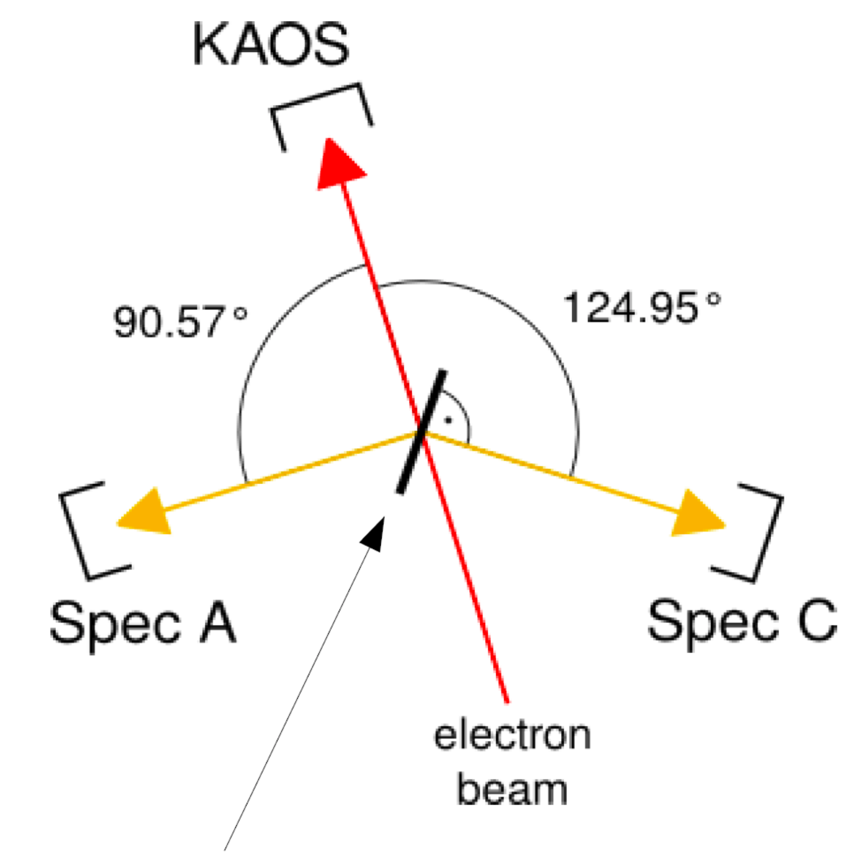
Pion detection

- Spectrometer A (red)
- Spectrometer C (green)
- Momentum resolution
  $\Delta p/p = 10^{-4} \Rightarrow \Delta m < 30 keV/c$
- Solid angle: 28 msr
- Momentum acceptance
  - Spek A: 20%
  - Spek C: 25%
- Length of trajectories
  - Spek A:10.75m
  - Spek C: 8.53m
- Gas threshold Cherenkov detectors for pion/electron separation



Setup of the Pilot run 2011



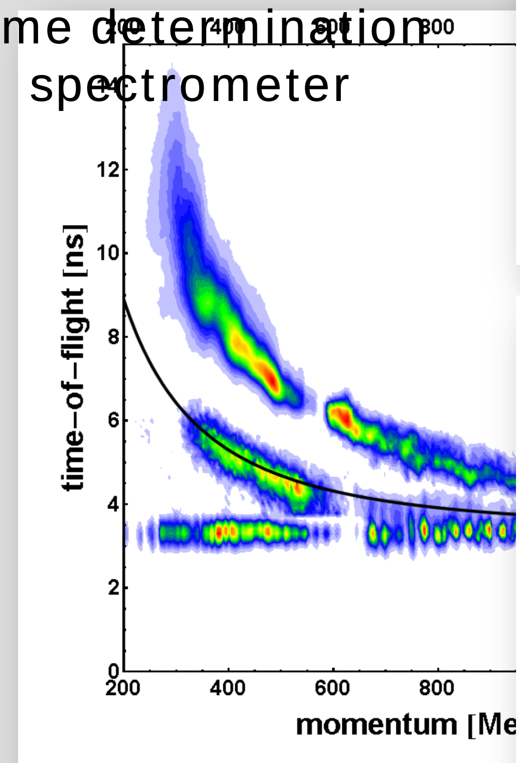


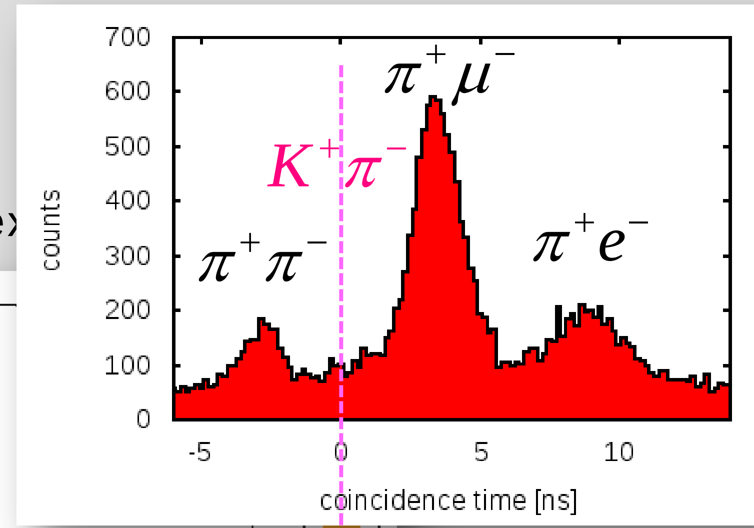
Target rotated 54° wrt beam:

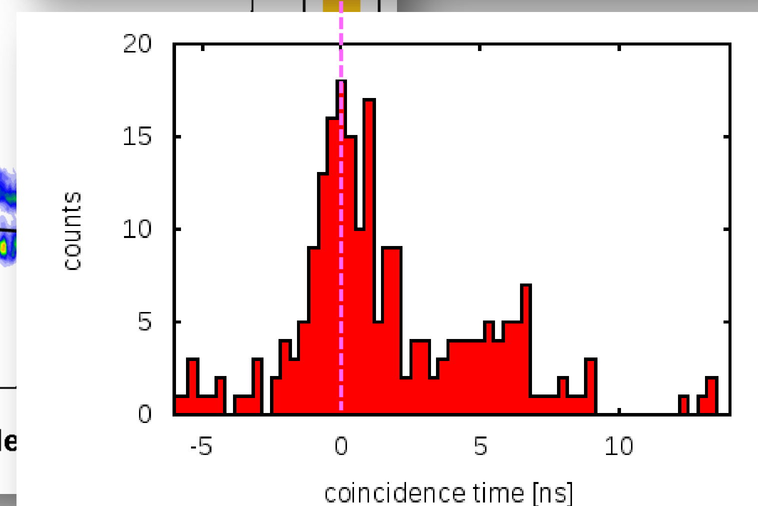
→ Reduced energy loss variation for pions

Data analysis

- Main challenge: Huge positron background at 0° in KAOS produced by bremsstrahlung conversion: $10^6/\mu A$
- Determination of best parameters for kaon selection:
  - Single KAOS arm time-of-flight
  - Specific energy loss
  - Threshold Cherenkov light yield
  - Optimisation of K^+ selection in an ex
- Coincidence time determination from different spectrometer

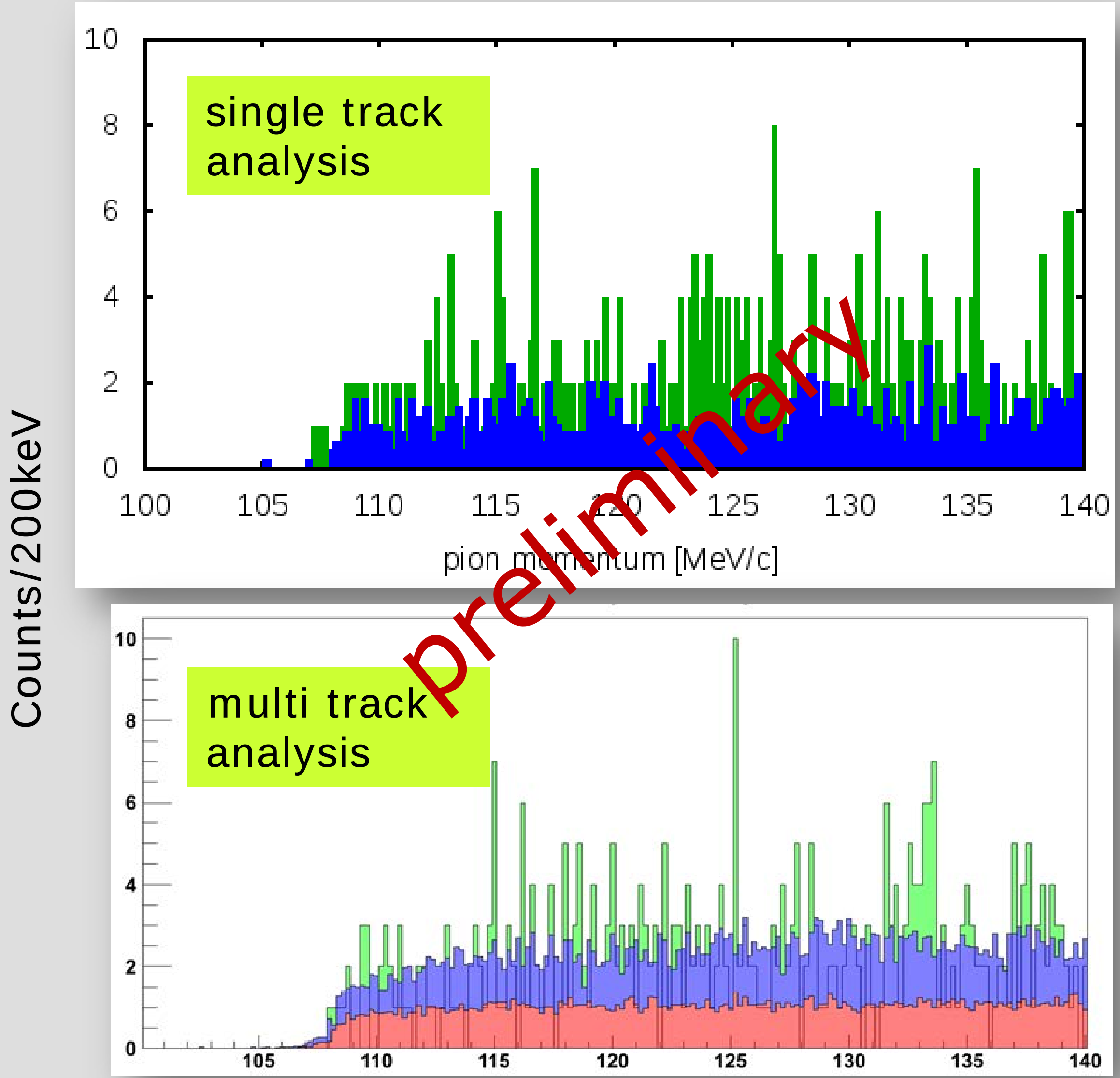






Anselm Esser (PhD Mainz)
Sho Nagao (PhD Sendai)
Florian Schulz (PhD Carl Zeiss fellow)

Decay pion spectroscopy: 2011 run

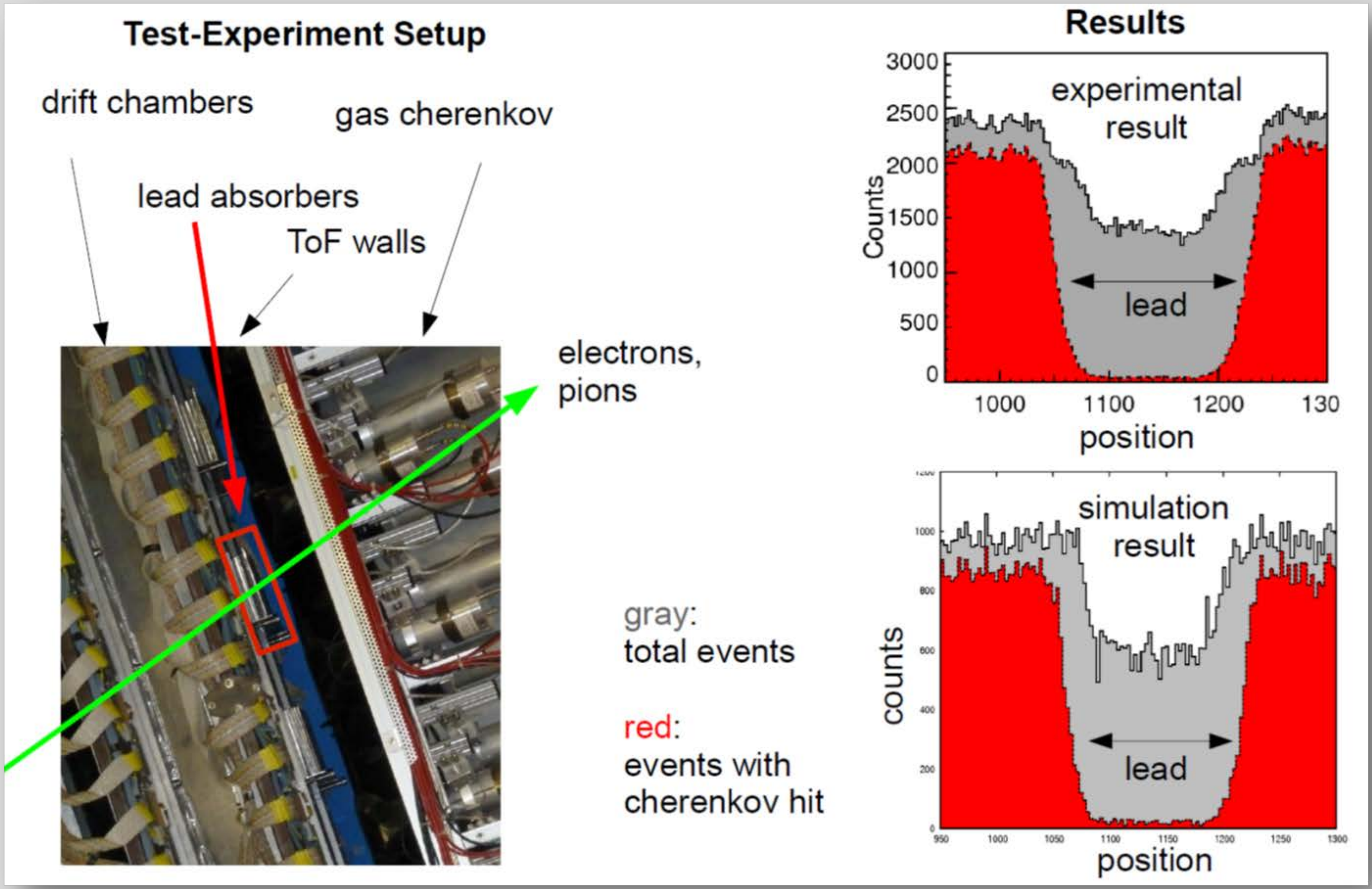


PhD projects
Anselm Esser,
Sho Nagao,
Florian Schulz

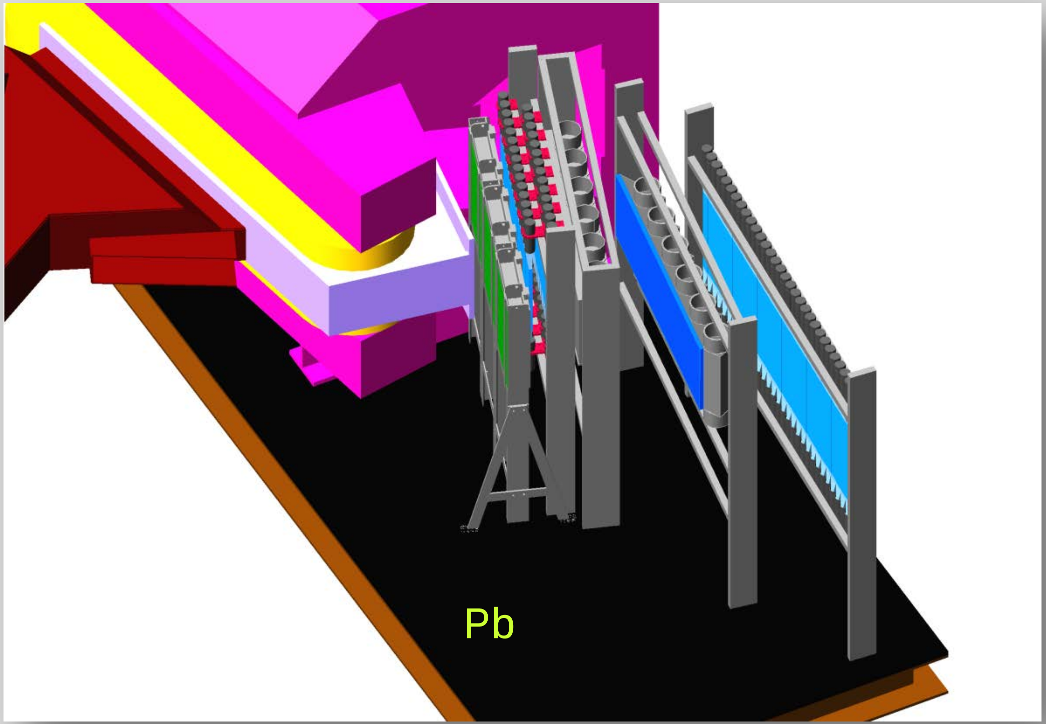
- Promising but not yet conclusive!
- Need better statistics!! (see http://www.nu.to.infn.it/Statistics/...)

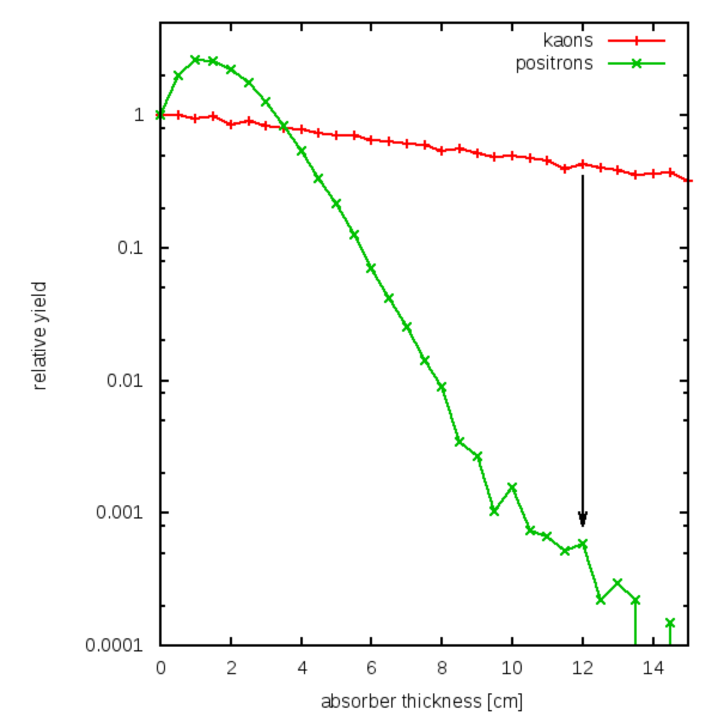
Supression of Positron Background

- Goal Reduction of e⁺ background at increased luminosity
- Lead ρ=11.35 g/cm^2
  - Nuclear interaction length 199.6 g/cm^2
  - Radiation length X0=6.37g/cm^2



Dedicated KAOS setup





- Reduction of background at increased luminosity
- Optimized by GEANT simulations: $I_e = 22\mu A$ $d_{Pb} = 10cm \rightarrow 14cm$
- Additional improvements:
  - 3 TOF walls
  - increased TOF path,
  - 2nd Č-detectors
- Experiment will start October 23rd 2012

Conclusions

- *Precision pion decay spectroscopy offers a unique possibility for precision hypernulcei mass determination throughout the strange periodic system*

- *Hypernuclear program at MAMI has started and will hopefully soon present first physics results*

Collaboration

- **Institut für Kernphysik, Johannes Gutenberg-Universität, Mainz, Germany:** Patrick Achenbach, Carlos Ayerbe, Ralph Böhm, Michael O. Distler, Anselm Esser, Mar Gomez, Alicia Sanchez Lorente, Harald Merkel, Ulrich Müller, Josef Pochodzalla, Takehiko Saito, Björn Sören Schlimme, Matthias Schoth, Florian Schulz, Concettina Sfienti
- **University of Ljubljana and Institut "Josef Stefan", Ljubljana, Slovenia:** Luka Debenjak, Simon Sirca
- **Department of Physics, University of Zagreb, Croatia:** Damir Bosnar, Ivica Friscic
- **Department of Physics, Hampton University, VA, USA:** Liguang Tang
- **Department of Physics, Florida International University, Miami, FL, USA:** Joerg Reinhold
- **Yerevan Physics Institute, Yerevan, Armenia:** Amur Margaryan
- **Department of Physics, Tohoku University, Sendai, Japan:** Osamu Hashimoto, Satoshi N. Nakamura, Kyo Tsukada Toshiyuki Gogami, Sho Nagao
- **GSI, Darmstadt, Germany:** Olga Borodina, Vakkas Bozkurt, Eunhee Kim, Christophe Rappold


NUFRA 2013
September 29th - October 6th 2013
Kemer Turkey
SEVENTH FRAMEWORK PROGRAMME
Joint SPHERE & JSPS meeting
• Fragmentation and multifragmentation reactions in laboratory experiments and astrophysical sites.
• Production mechanisms of nuclear fragments, hypernuclei, and antinuclei.
• Progress in theoretical description of baryon interactions, nuclei, and hypernuclei.
• Equation of state (EOS) of isospin-asymmetric and hyperonic nuclear matter.
• Phase transitions in nuclear collisions at intermediate and high energies.
• Nuclear composition and EOS of supernova matter and neutron stars.
• Evaluation of fragmentation reactions in cancer therapy, transmutation of nuclear waste, and spallation sources.