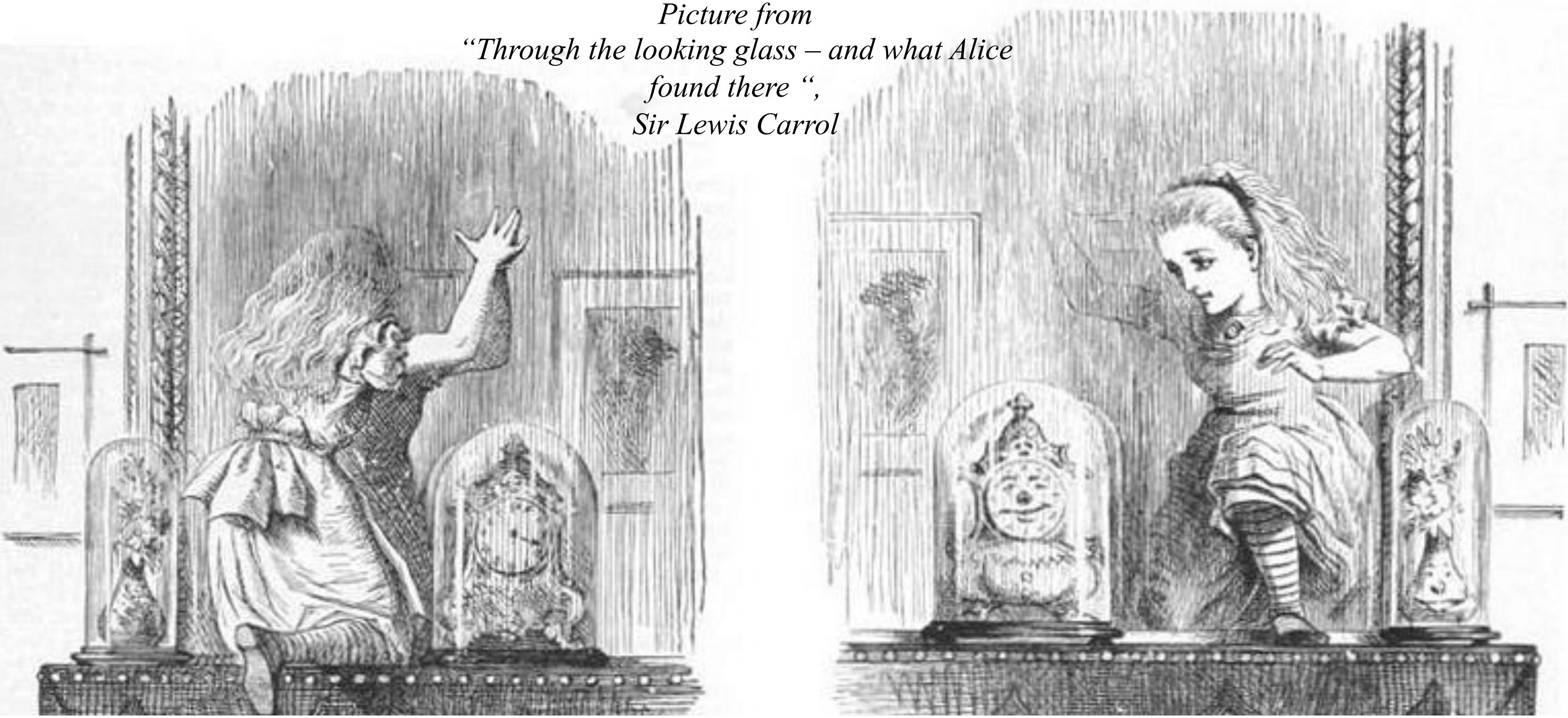
Picture from
"Through the looking glass – and what Alice found there ",
Sir Lewis Carrol



Stored Antiprotons: a versatile Tool to study (anti)hyperons in nuclear matter

Emmi Workshop 2015, 20-22 July CERN, Geneva

Alicia Sanchez Lorente
Josef Pochodzalla

HIM Helmholtz-Institut Mainz

JG|U

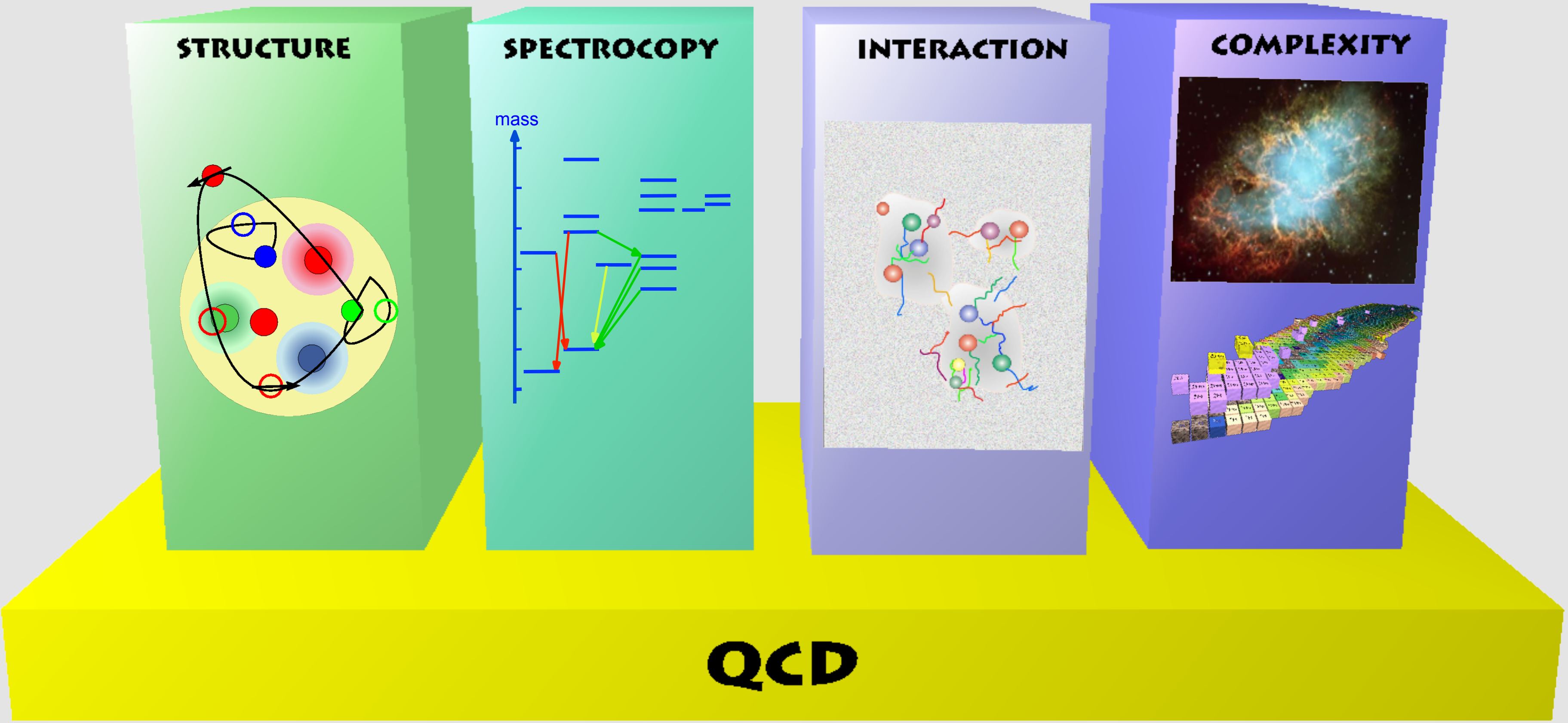
Strangeness in Nuclei

...a unique laboratory for strong interactions and baryon structure

from hyperatoms
to hyperonstructure

(anti)hadrons
in nuclei

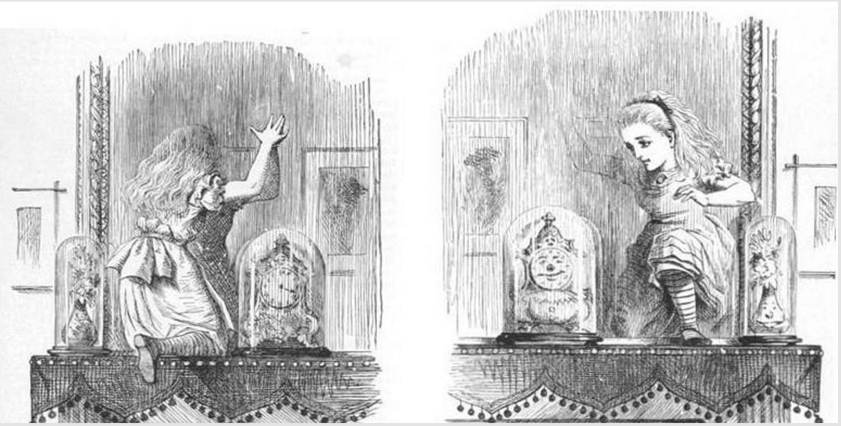
multistrange
hypernuclei



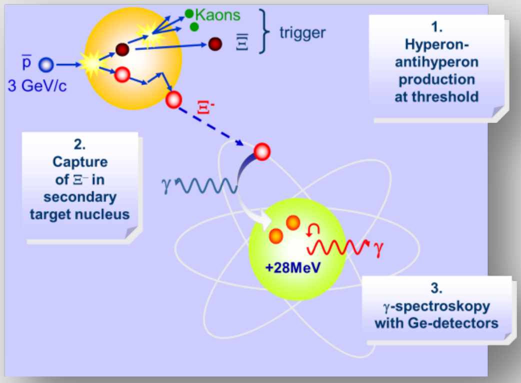
Importance of $\bar{p}$ reactions for hypernuclear production in Heavy Ions

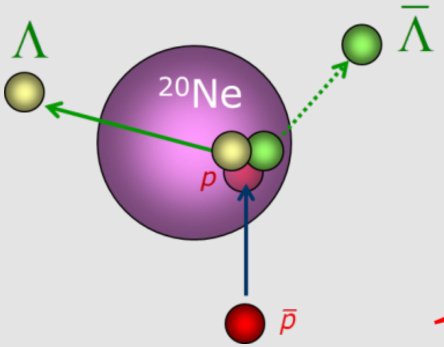
- Important for HI :Production mechanism
  - Lifetime
  - Exotic hypernuclei (*A. Botvina´s talk*)
  - Resonances

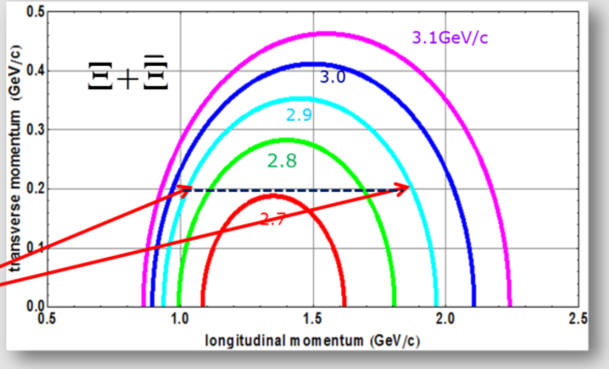
  Inner structure not accesible



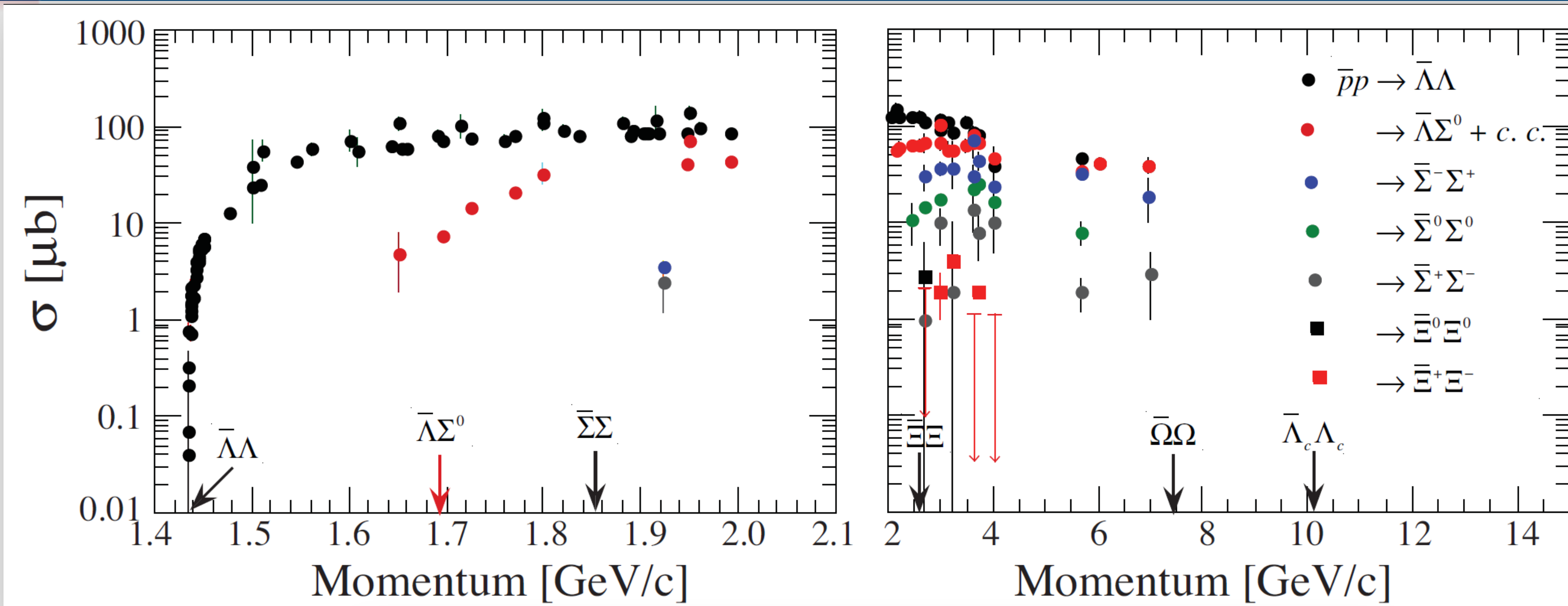
- Missing pieces:
  - Precission spectroscopy of single and double Λ hypernuclei
  - Behaviour of (anti)hyperons in matter
  - Secondary scattering of momentum tagged hyperons and antihyperons







Stored $\bar{p}$ – a Factory for strange *and* charmed $Y\bar{Y}$-Pairs

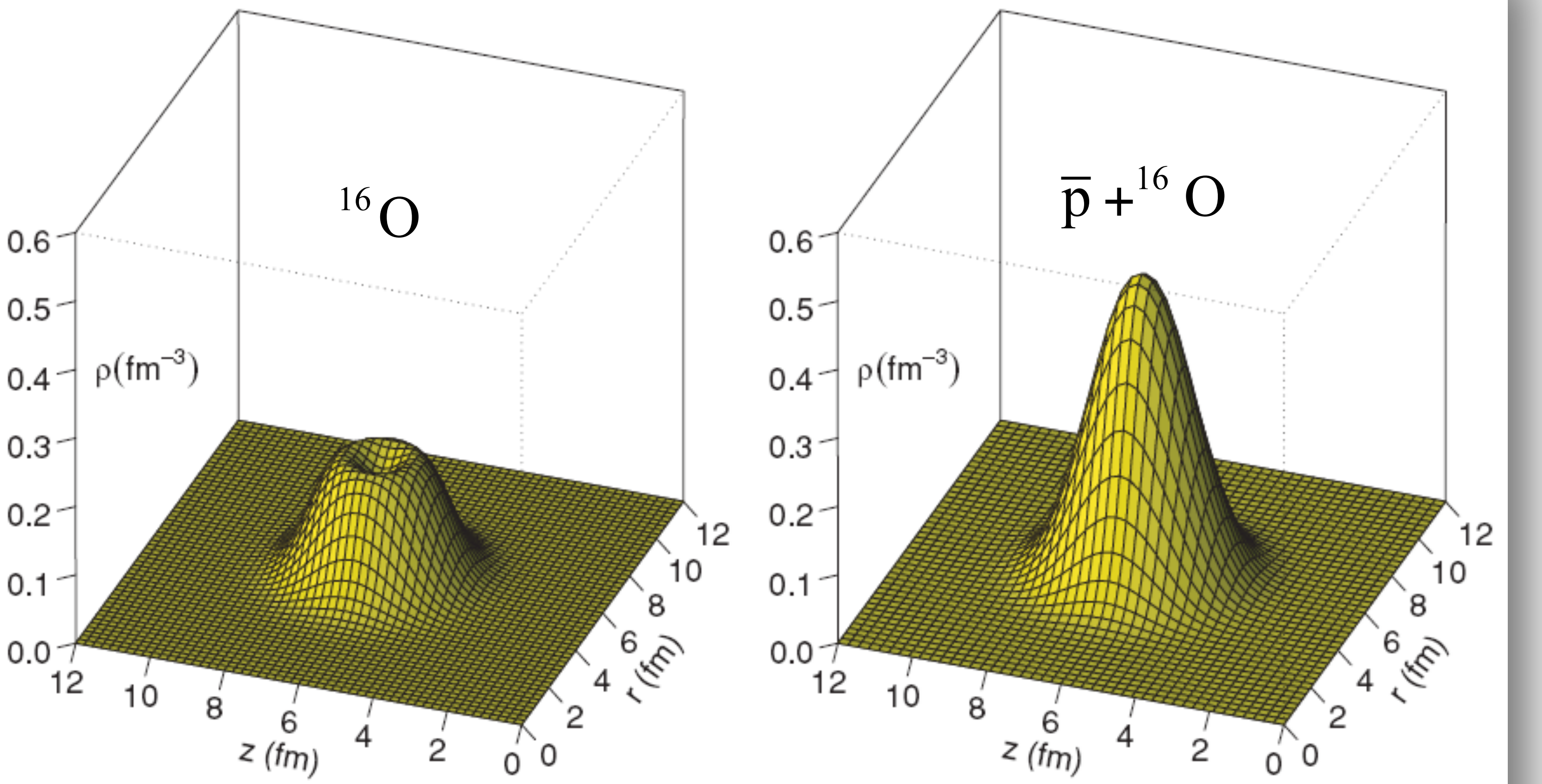


$\bar{\text{P}}$ANDA

Production Rates (1-2 (fb)$^{-1}$/y)

Final State	cross section	# reconstr. events/y
Meson resonance + anything	100μb	10^{10}
$\Lambda\bar{\Lambda}$	50μb	10^{10}
$\Xi\bar{\Xi}$ ($\to_{\Lambda\Lambda}$A)	2μb	10^8 (10^5)
$D\bar{D}$	250nb	10^7
J/ψ ($\to e^+e^-, \mu^+\mu^-$)	630nb	10^9
χ_2 ($\to J/\psi+\gamma$)	3.7nb	10^7
$\Lambda_c\bar{\Lambda}_c$	20nb	10^7
$\Omega_c\bar{\Omega}_c$	0.1nb	10^5

Cold compression by antibaryons ?



nucleon density in the ^{16}O nucleus (left) and in the bound $\overline{p}$ + ^{16}O system (right)

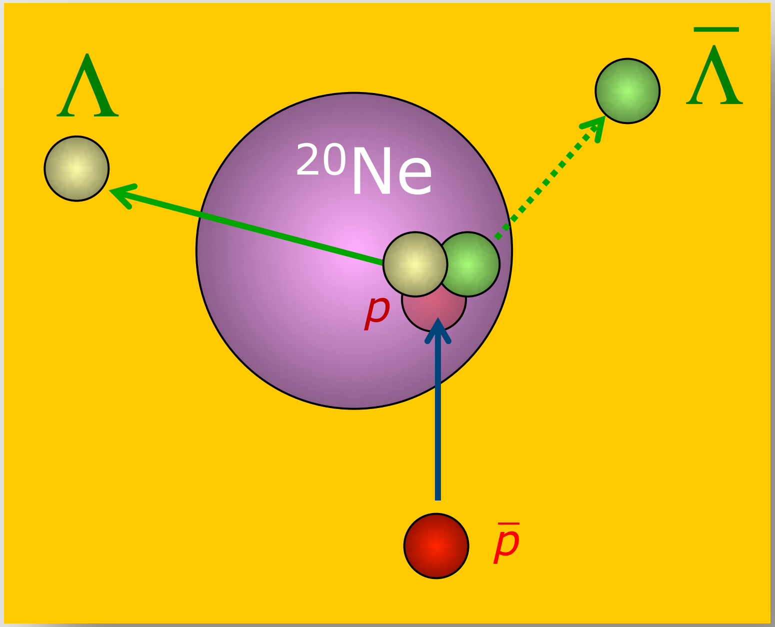
I. N. Mishustin, L. M. Satarov, T. J. Bürvenich, H. Stöcker, and W. Greiner

PHYSICAL REVIEW C **71**, 035201 (2005)

$\bar{\Lambda}$ Potential (in Neutron Matter)

- exclusive $\bar{p}$+p(A) ⇒ Y+$\bar{Y}$ close to threshold within a nucleus
- Λ and $\bar{\Lambda}$ that leave the nucleus will have different asymptotic momenta depending on the respective potential

J.P., PLB **669** (2008) 306



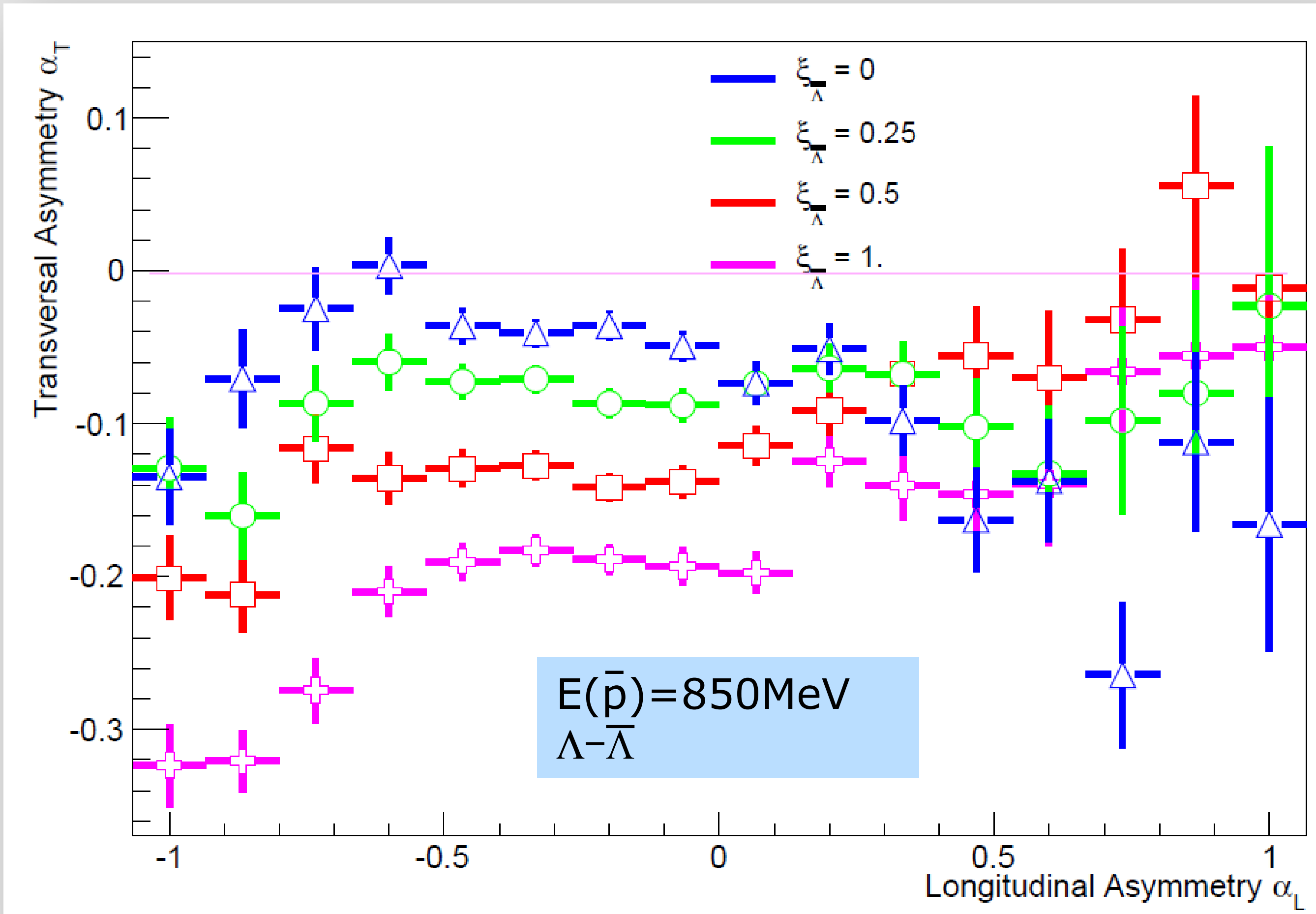
- ⇒ *transverse* momentum close to threshold of *coincident* $Y\bar{Y}$ pairs

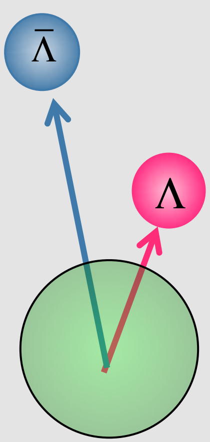
$$\alpha_\perp = \left\langle \frac{p_\perp(\Lambda) - p_\perp(\bar{\Lambda})}{p_\perp(\Lambda) + p_\perp(\bar{\Lambda})} \right\rangle$$

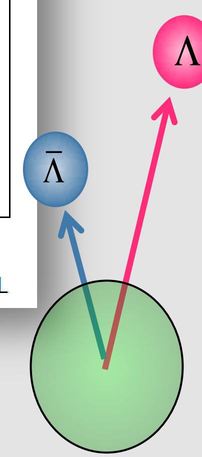
Scan of $\bar{\Lambda}$ Potential with GiBUU

- $U(\bar{\Lambda})$= -449MeV, -225MeV, -112MeV, 0MeV
- All other potentials unchanged

$$\alpha_{\perp} = \left\langle \frac{p_{\perp}(\Lambda) - p_{\perp}(\bar{\Lambda})}{p_{\perp}(\Lambda) + p_{\perp}(\bar{\Lambda})} \right\rangle$$





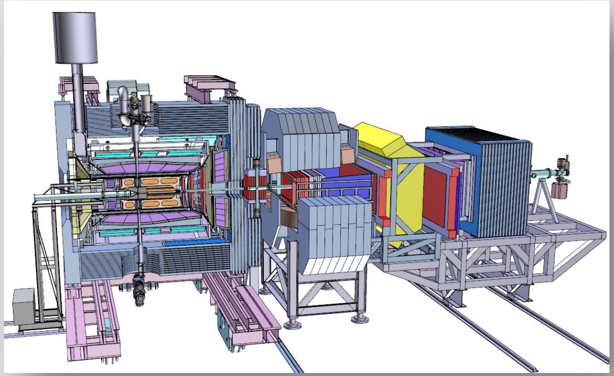


$$\alpha_L = \frac{p_L(\Lambda) - p_L(\bar{\Lambda})}{p_L(\Lambda) + p_L(\bar{\Lambda})}$$

Antihyperon-Hyperon Pairs in $\bar{\text{P}}$ANDA

- We are right now exploring different scenarios
  - different detector availability
  - different solenoid fields (1T, 0.5T,…)

  and other important aspects like
  - luminosity
  - length of typical running period



- Typical (*preliminary*) $\bar{\Lambda}\Lambda$ pair efficiency ≈ 3-5% (better at higher momenta)
- $\bar{\Lambda}+\Lambda$ case
  - ^{nat}Ne target, H for calibration systematic check
  - only charged particle detection easy
  - assume average interactions rate $10^6 s^{-1}$ (~10% of default luminosity)
  - pair reconstruction efficiency ~3%

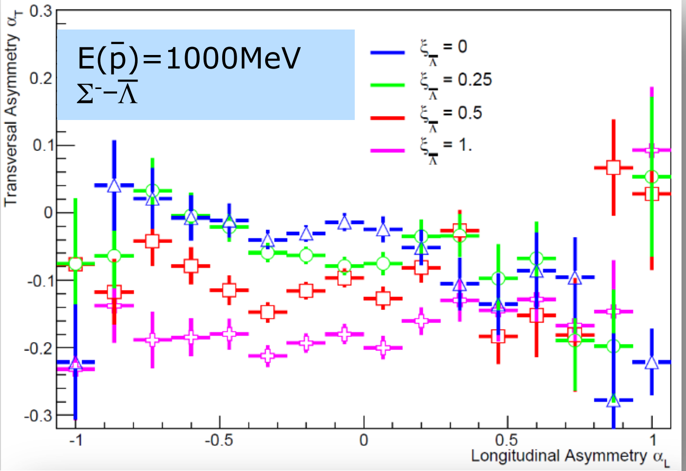
    ⇒ 144k detected $\bar{\Lambda}+\Lambda$ pairs per day ⇒ 10 × GiBUU

  - Moderate data taking period *~14 days Ne target + 7 days p-target*

    ⇒ 130 × present GiBUU simulations (statistics at large α_L)

Other |s|=1 channels @ 1000MeV

- $\bar{p}+p\rightarrow\bar{\Lambda}+\Lambda$ $\bar{p}+p\rightarrow\bar{\Sigma}^0+\Lambda$
- $\bar{p}+n\rightarrow\bar{\Lambda}+\Sigma^-$ $\bar{p}+n\rightarrow\bar{\Sigma}^++\Lambda$
- all antihyperon potentials scaled by same factor



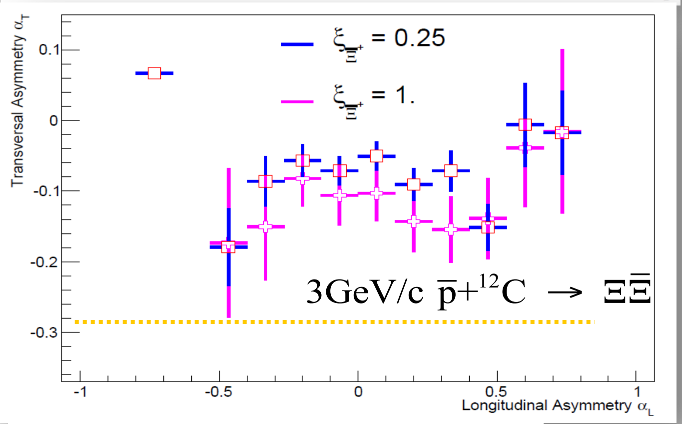
- Future options:
  - Any other pair: Σ-$\bar{\Sigma}$, Ξ-$\bar{\Xi}$, $\Lambda_c\bar{\Lambda}_c$
  - Long lived resonances in nuclei

    $\Lambda(1520)$ (Γ= 15.6 MeV)

    $\Xi(1530)$ (Γ=9.9 MeV)

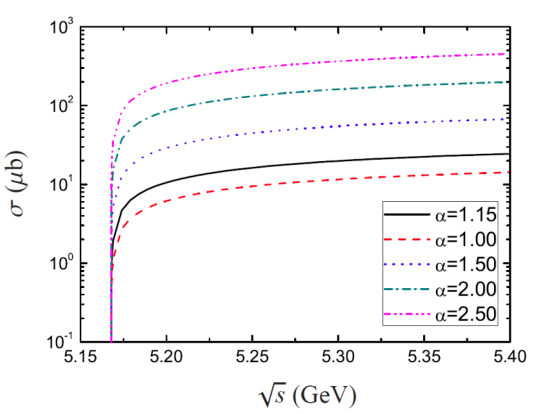
    $\Lambda_c(2880)$ (Γ=5.8MeV)

    (Phys. Rev. D 90, 014014 (2014))



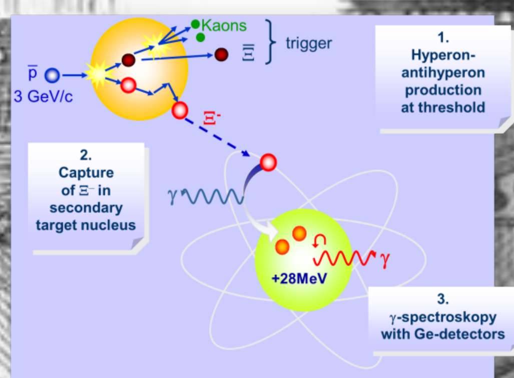
Shopping List:

- Exploring the neutron skin of nuclei
- $K^*/\bar{K}^*$ in nuclei
- Search for Antilambda bound states
- Atomic transitions in heavy hyperonic atoms

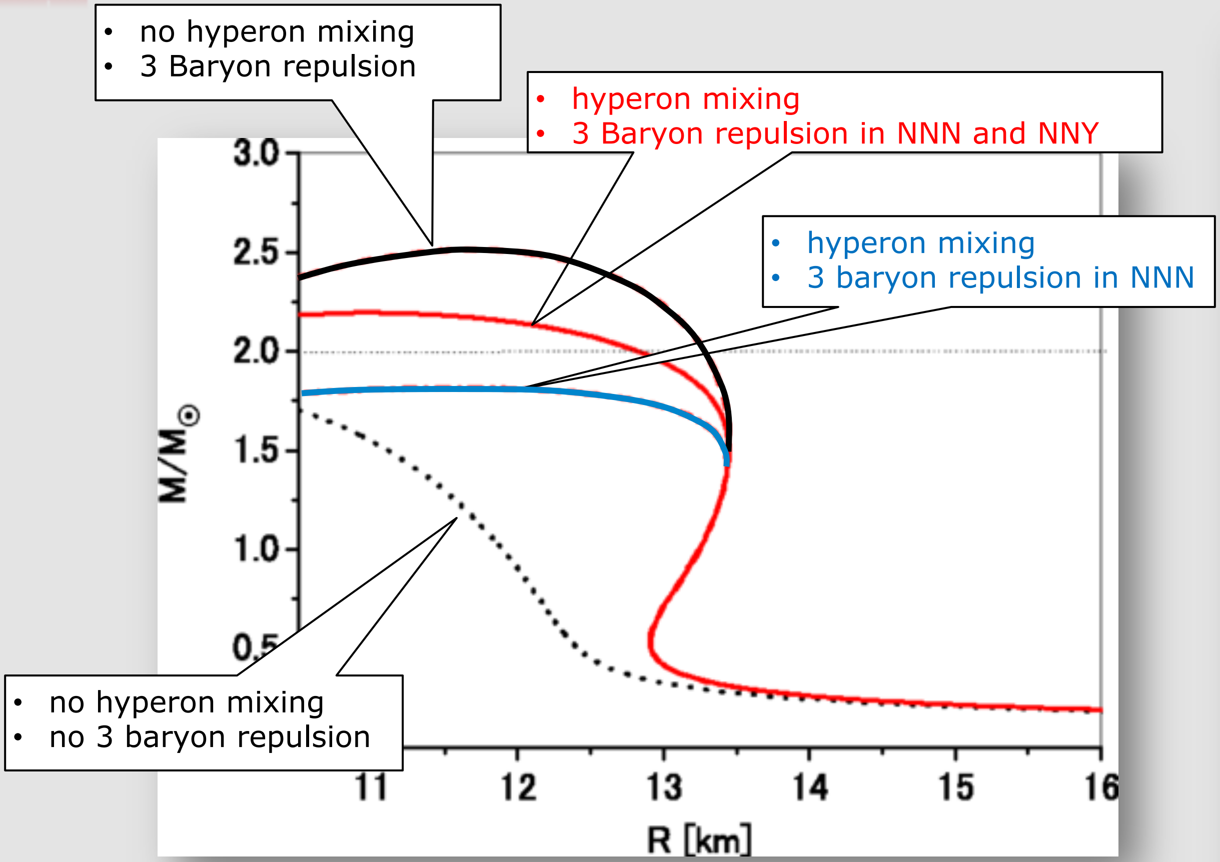


HIGH RESOLUTION γ-SPECTROSCOPY: ΛΛ HYPERNUCLEI

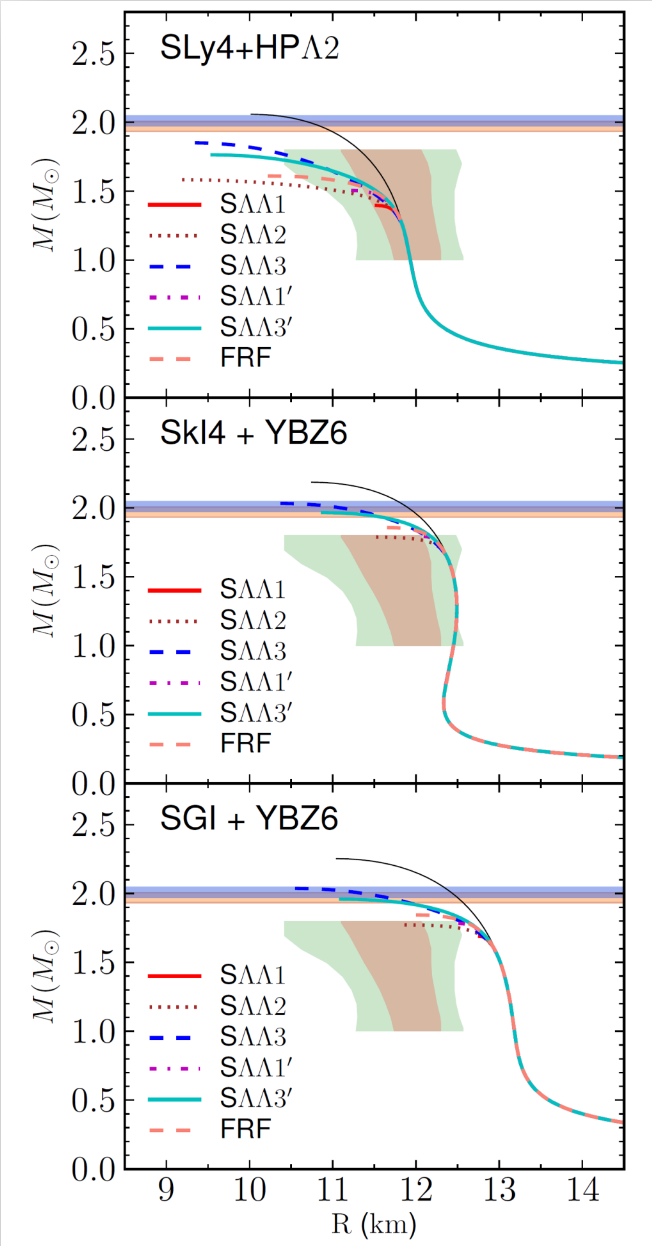
Approaching the hyperonization puzzle



Importance of ΛΛ interaction



Y. Yamamoto, T. Furumoto, N. Yasutake, Th. A Rijken, Phys. Rev. C 90, 045805 (2014)

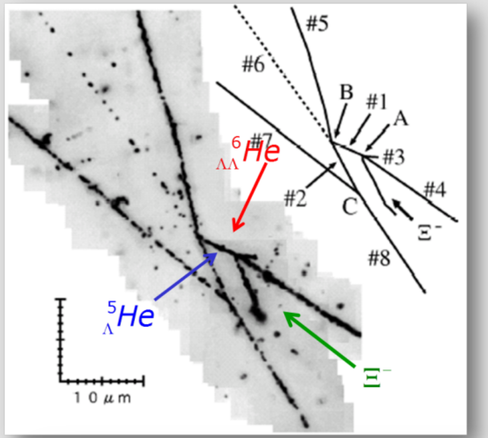


- Full treatment of 3 baryon forces is essential
- ΛΛ interaction is significant
- Uncertainties in the model are due to lacking sufficient data of double-Λ-hypernuclei

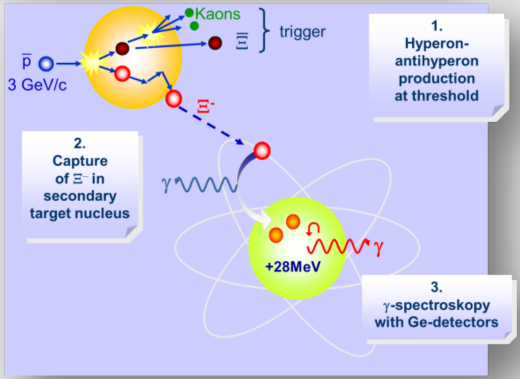
Yeunhwan Lim, Chang Ho Hyun, Kyujin Kwak, and Chang-Hwan Lee, [nucl-th] 18 Dec 2014

Many ways to double hypernuclei

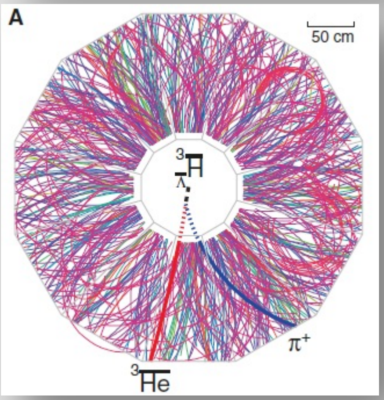
- Ground state masses
  - Hybrid-emulsion technique
  - J-PARC (E07)
  - Goal: factor of 10 compared to existing data



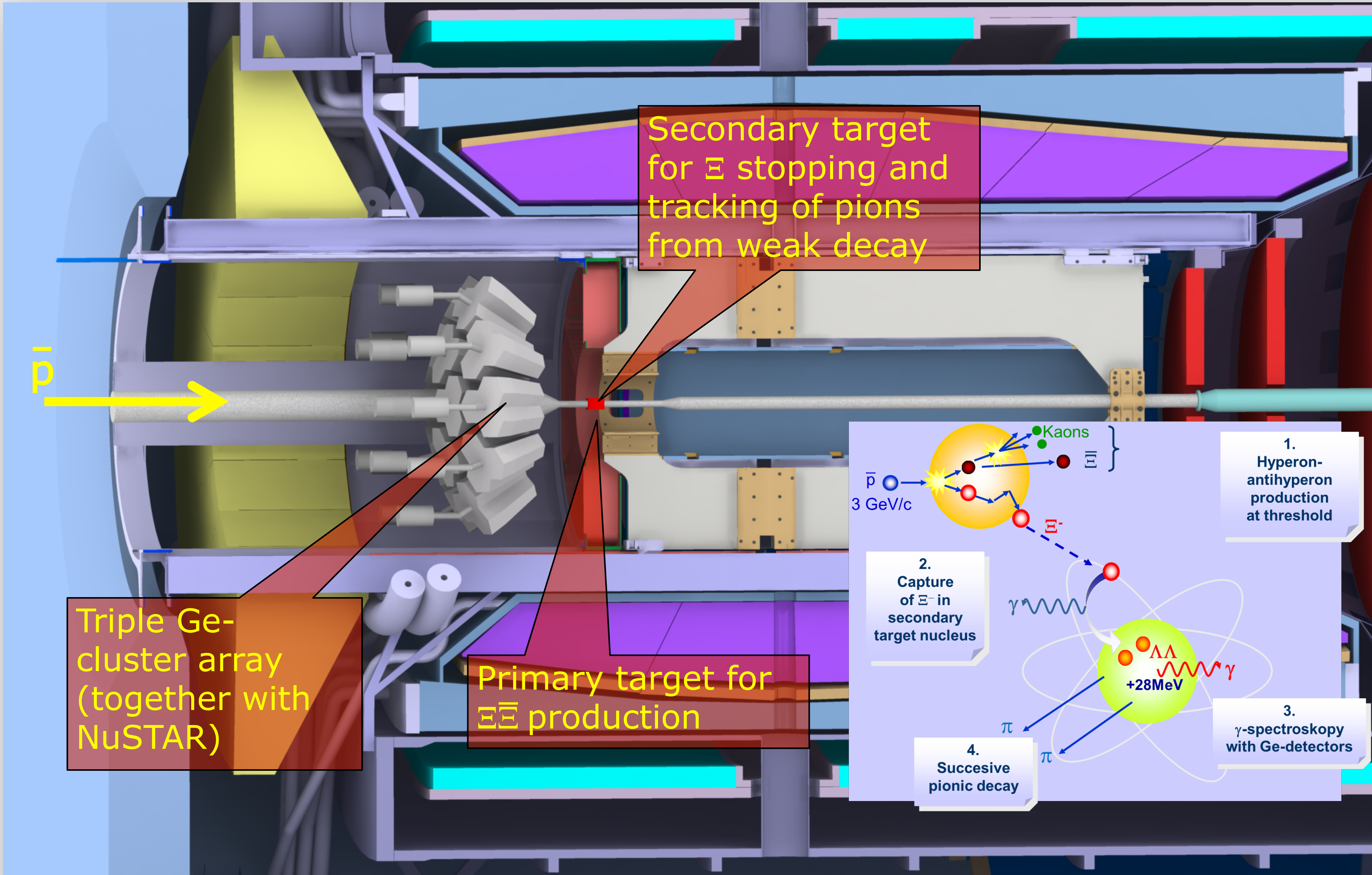
- Excited *particle stable* state spectroscopy
  - γ-spectroscopy
  - $\bar{\mathrm{P}}$ANDA@FAIR



- Excited *particle unstable* resonances, exotic single hypernuclei, lifetime
  - Invariant mass; hypernuclei-Λ correlations
  - CBM, NuSTAR, STAR, ALICE



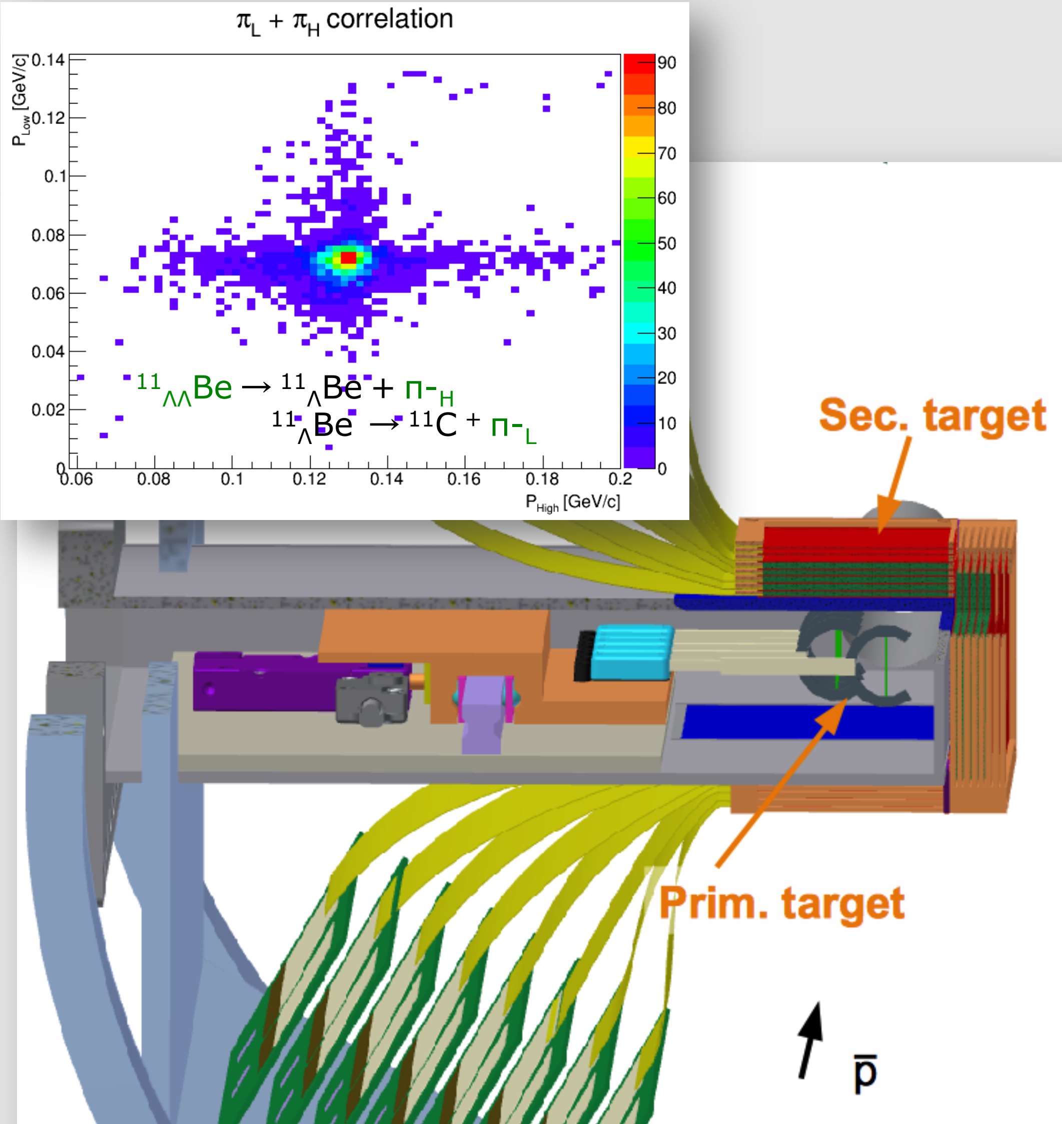
The HYP setup at PANDA

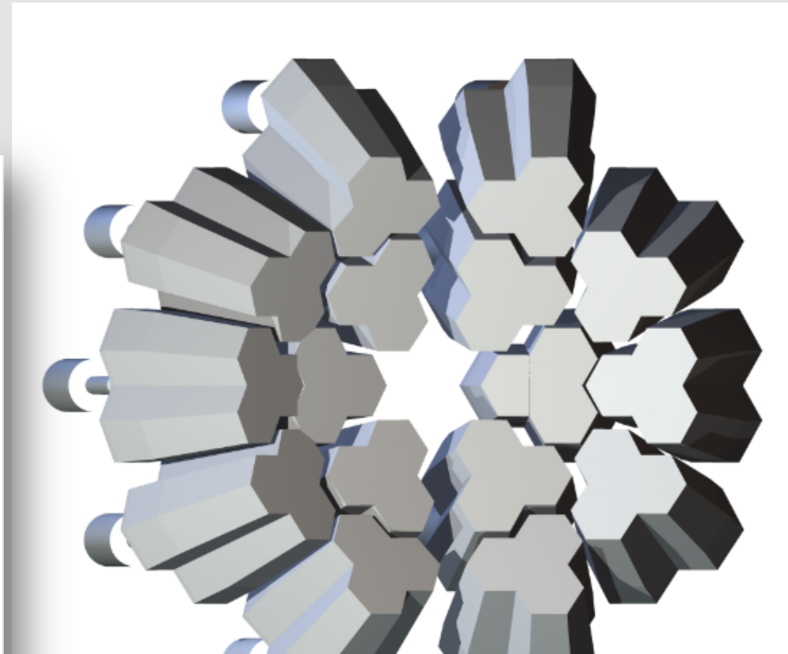


Status and expected count rate

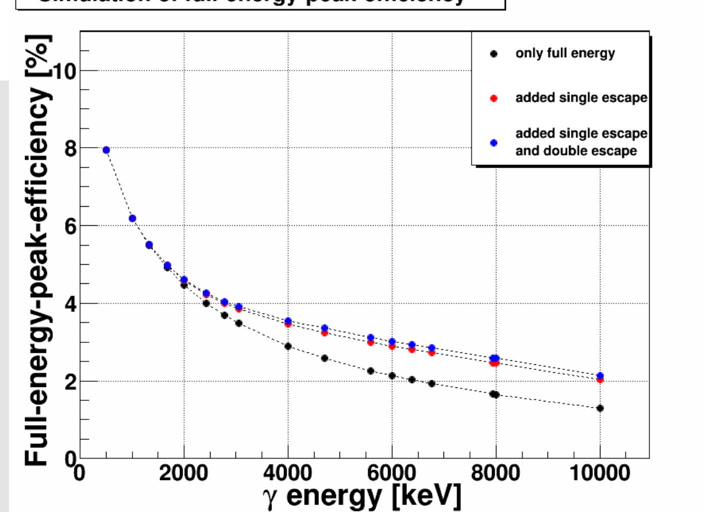
- Primary and Secondar active target

HPGe Cluster Array



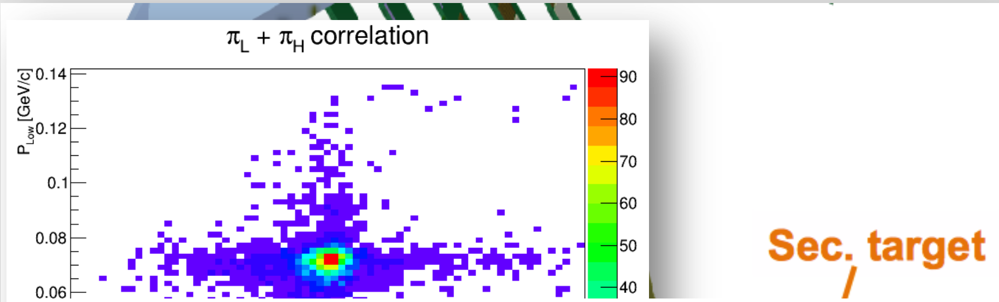


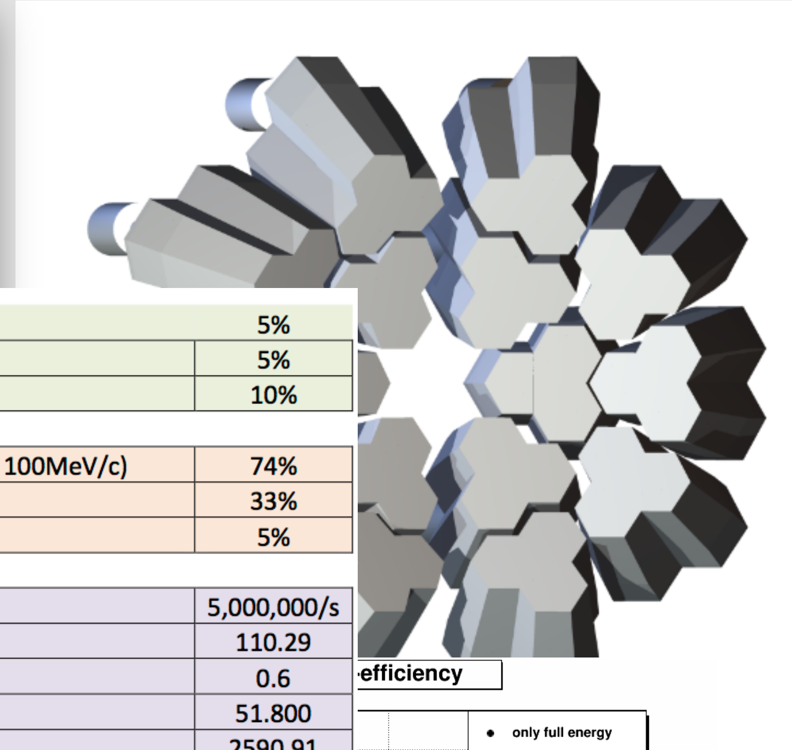
Simulation of full-energy-peak-efficiency



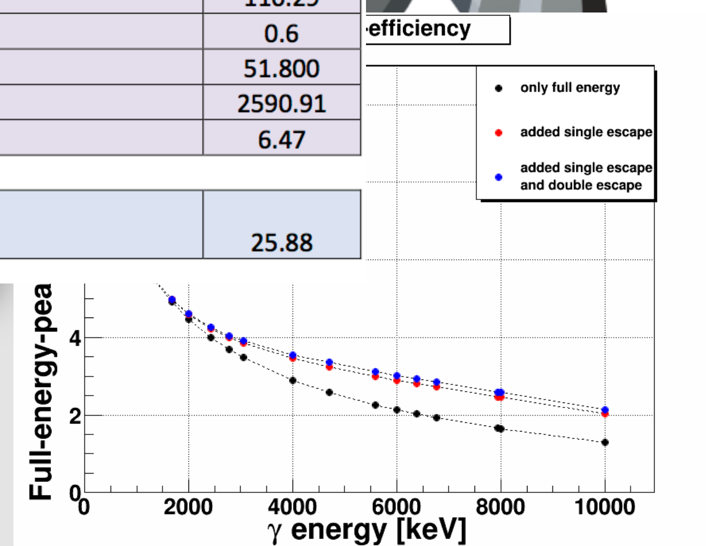
Status and expected count rate

- Primary and Secondar active target HPGe Cluster Array





Process :	Capture and conversion for Xi	5%
	Main channels (which hypernucleus is produced)	5%
	weak decay probability	10%
Detection:	Pion tracking efficiency for pion mom (higher than 100MeV/c)	74%
	Double Pion tracking efficiency	33%
	Gamma Efficiency	5%
Counting rates:	Counting rate at PANDA	5,000,000/s
	Xi-Production per second	110.29
	Stopped Xis per second	0.6
	Stopped Xis per day	51.800
	Double hypernuclei (DHP) production per day	2590.91
	Detected DHP per month	6.47
Measurement period (4 months)	detected single gamma transitions (11LLBe)	25.88



Heavy hyperonic atoms

- Ξ-Atoms
  - Thin secondary targets
  - Identification:
    - Intermediate transitions are accessible
    - π decay

- Ω-Atoms
  - Thin secondary targets
  - Deformation of a baryon
  - few 100 stopped Ω per day
  - Yield(Σ-Pb)≈Yield(Ξ-Pb)

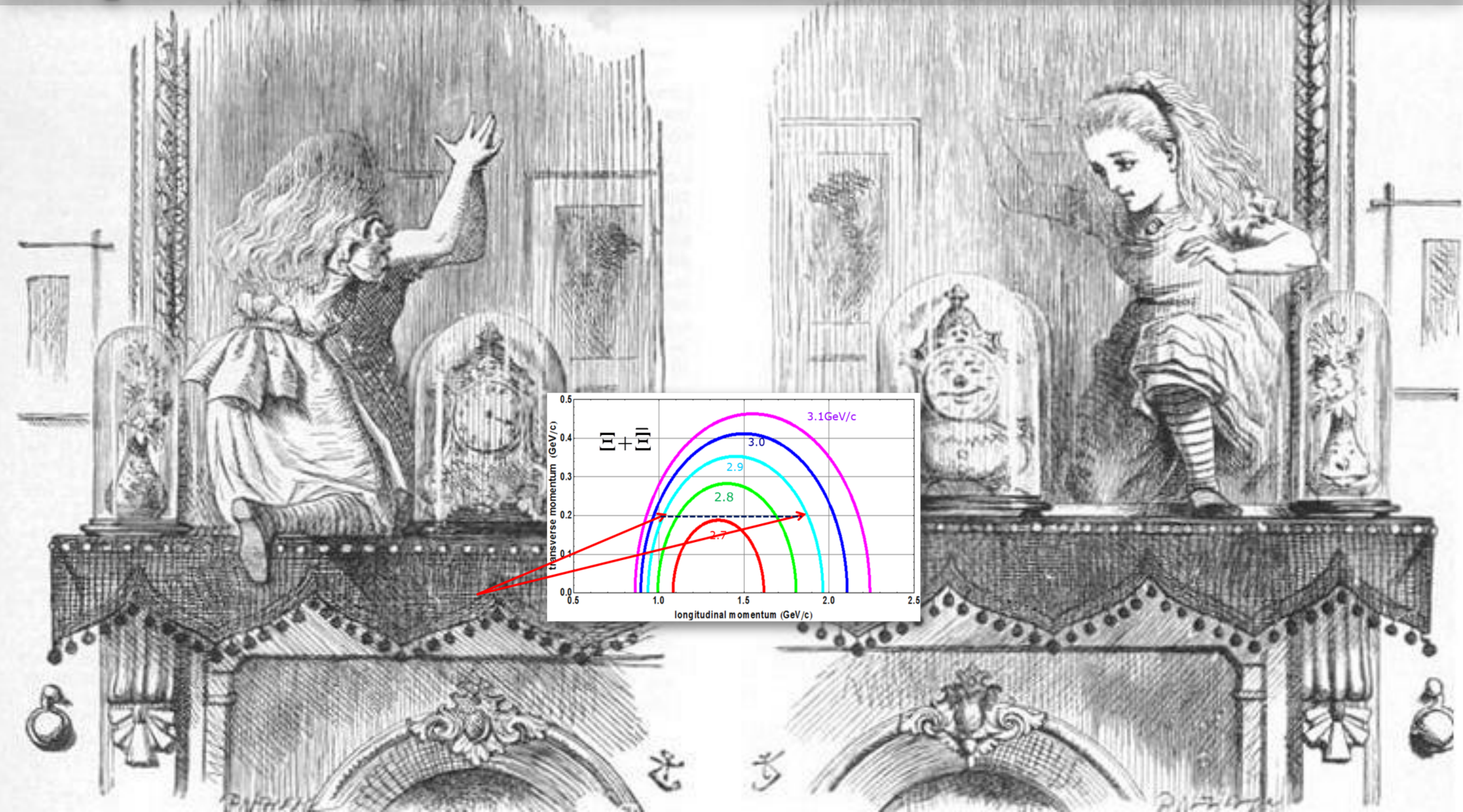
C.J.Batty, E. Friedman, A. Gal, PRC 59, 295 (1999)

  - Capture probability ~10%
  - X-ray detection efficiency ~5%
  - trigger efficiency ($\overline{\Omega}$)

~5000 expected X-rays/month

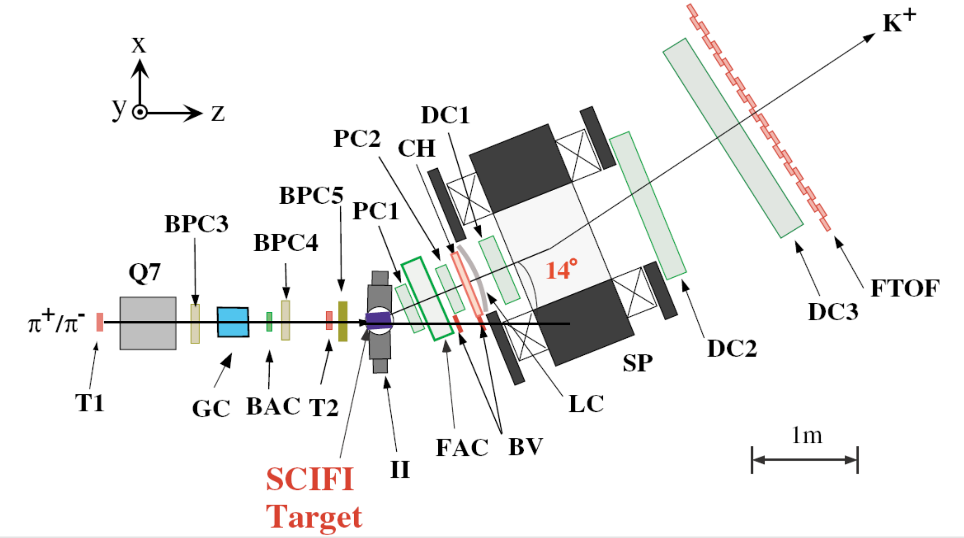
$\bar{p}+p \rightarrow Y - \bar{Y}$ pair production

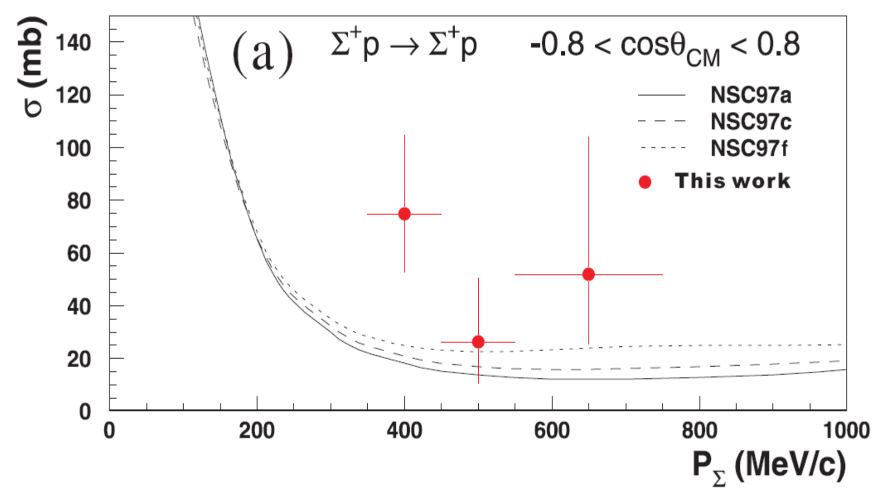
A unique tool to study elementary (anti)hyperon-nucleon interactions



Y N scattering

- low energy baryon-baryon scattering
  - N-N: ~10^4 data points available
  - charged hyperon – proton: scattering in a scintillator target
    - Σ^-p: KEK-PS E289 (π^-,K^+) $\Rightarrow$ 30 events
    - Σ^+p: KEK-PS 251 & KEK-PS E289 (π^+,K^+) $\Rightarrow$ 31 events each
    - Ξ^- p: (K^-,K^+) $\Rightarrow$ 1 candidate

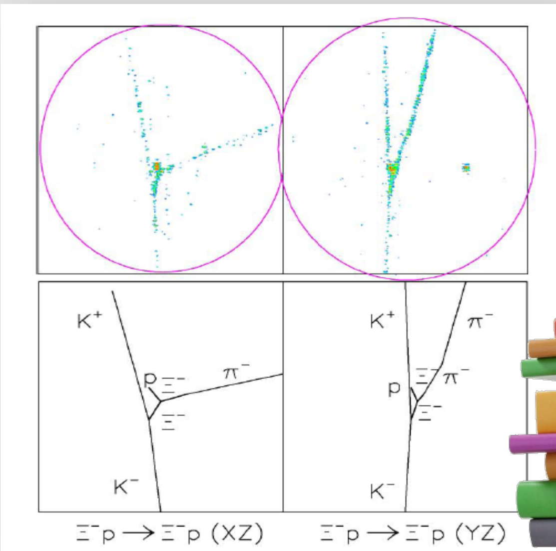


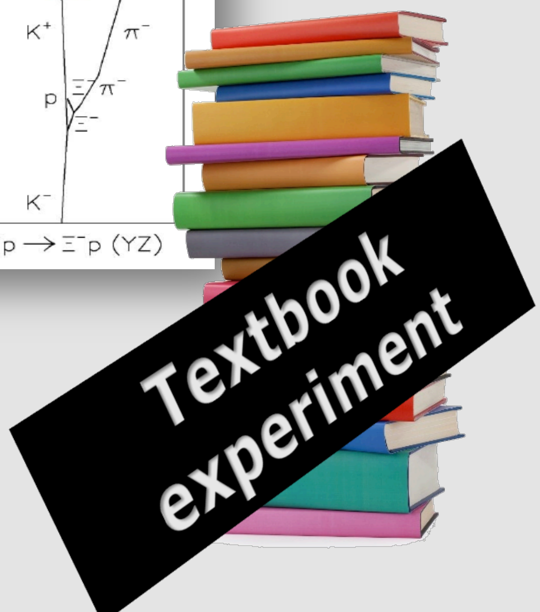


    - JPARC: ~1000 events/day
- hyperon-hyperon final state interaction
  - feasible but difficult to interpret
- PANDA: Tagged hyperon-antihyperon pair production and secondary scattering of hyperons *and* antihyperons

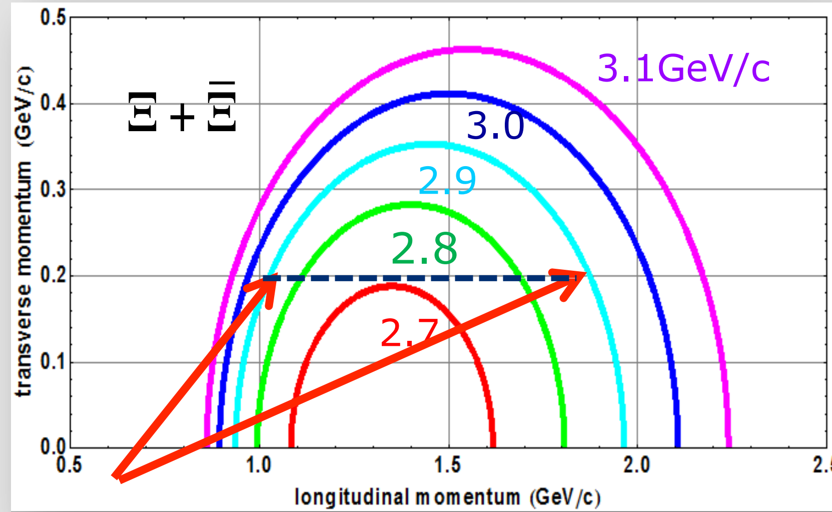
Example: Ξ^- scattering

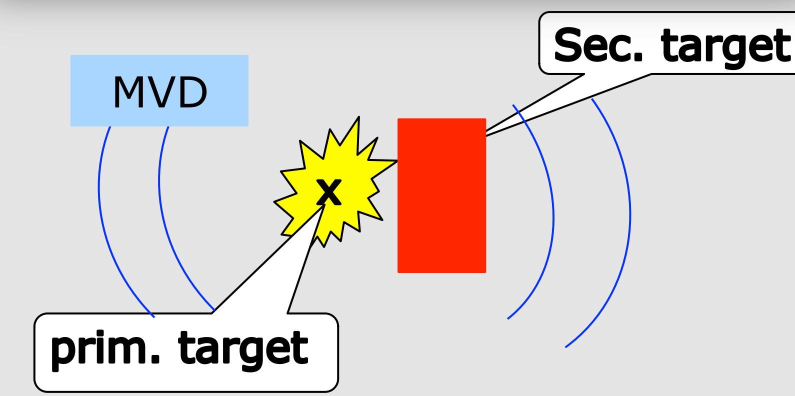
- Ahn et al.





Beyond $\bar{\text{P}}$ANDA: YN, $\bar{\text{Y}}$N scattering





- $\bar{p}+p\rightarrow \bar{Y}+Y$ provides momentum tagged low momentum, polarized hyperon *or* antihyperon beams
- scattering experiment with low momentum (anti)hyperons possible

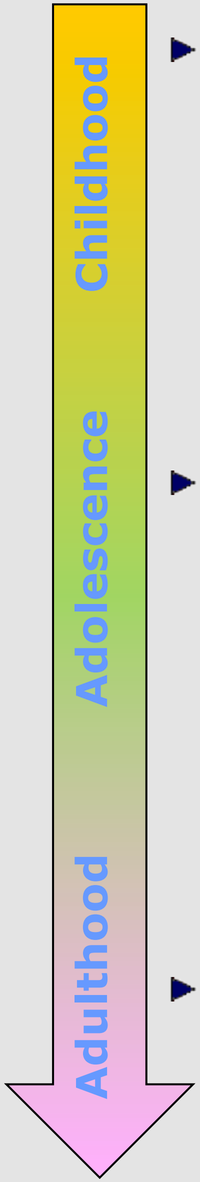
Stored $\bar{p}$ is an excellent and **unique factory tool** for strange and charmed $\bar{Y}Y$ pairs

Stored antiproton beams at FAIR will offer many unique opportunities to study the interactions of hyperons and antihyperons in nuclear systems

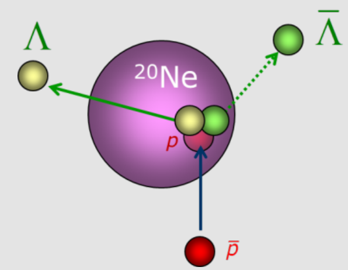
Thank you for your attention

Backup slides

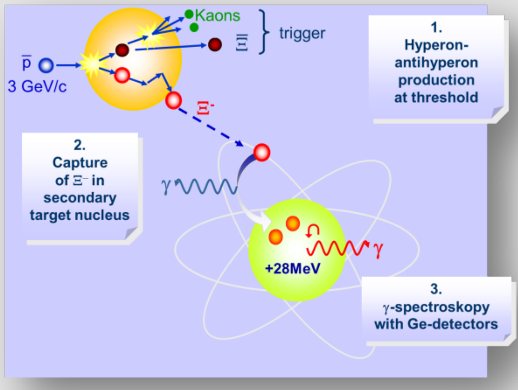
Exploring (anti-)hadron interactions



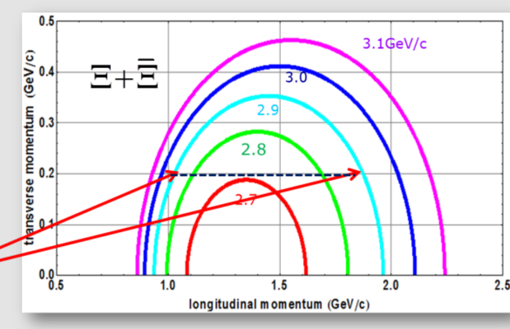
- Antihadrons in atomic nuclei
  - Nuclear potential of antihadrons and hadrons
  - Search for Antilambda bound states
  - Exploring the neutron skin of nuclei
  - $K^*/\bar{K}^*$ in nuclei



- High resolution γ-Spectroscopy
  - Excited particle stable state spectroscopy of light ΛΛ hypernuclei
  - Atomic transitions in heavy hyperonic atoms



- Secondary scattering of momentum tagged hyperons and antihyperons



ANTIHADRONS IN NUCLEI

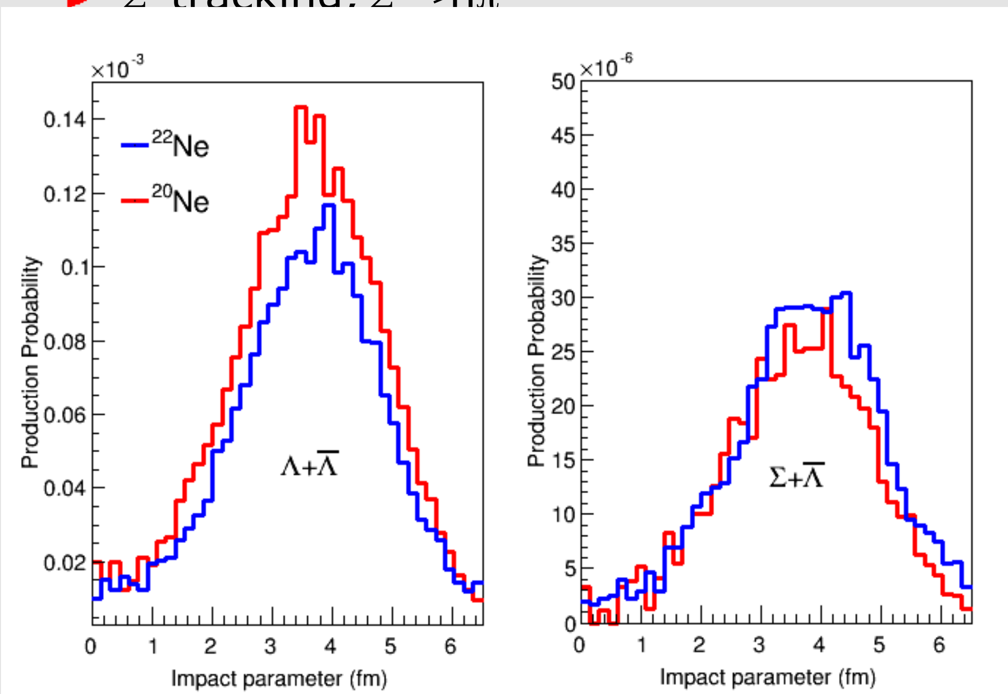
Further Possibilities

Reactions within the Neutron Skin

- $\bar{\Lambda}+\Sigma^-$
  - Ideal probe for interactions in the neutron skin
  - ^{20}Ne; ^{22}Ne, H for calibration; later: ^{86}Kr (36 Protons, 50 Neutrons)
  - Σ^- tracking, $\Sigma^-\rightarrow n\pi^-$

uclei)

0.25



	$\bar{p}+p \rightarrow \bar{\Lambda}+\Lambda$	$\bar{p}+n \rightarrow \bar{\Lambda}+\Sigma^-$
^{20}Ne	18808	3667
^{22}Ne	15733	4516
^{22}Ne/^{20}Ne	0.84	1.23

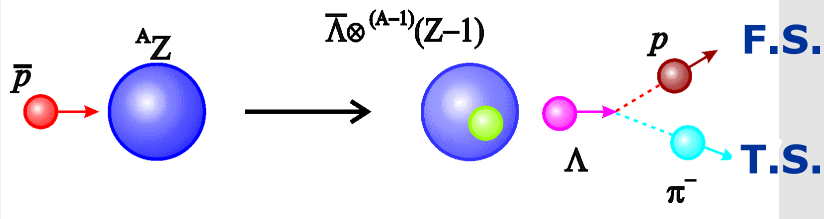
- When going from ^{20}Ne to ^{22}Ne two competing effects
  - more absorption of ingoing $\bar{p}$ in thicker n-skin $\Rightarrow$ less $\bar{\Lambda}\Lambda$ and more $\bar{\Lambda}\Sigma^-$
  - more absorption of outgoing $\bar{\Lambda}$ in thicker n-skin $\Rightarrow$ less $\bar{\Lambda}\Lambda$ and less $\bar{\Lambda}\Sigma^-$
- $\bar{\Lambda}+\Sigma^-$ and $\bar{\Lambda}+\Lambda$ production may probe the neutron skin
- Possibility to explore potentials in neutron-rich environment ?

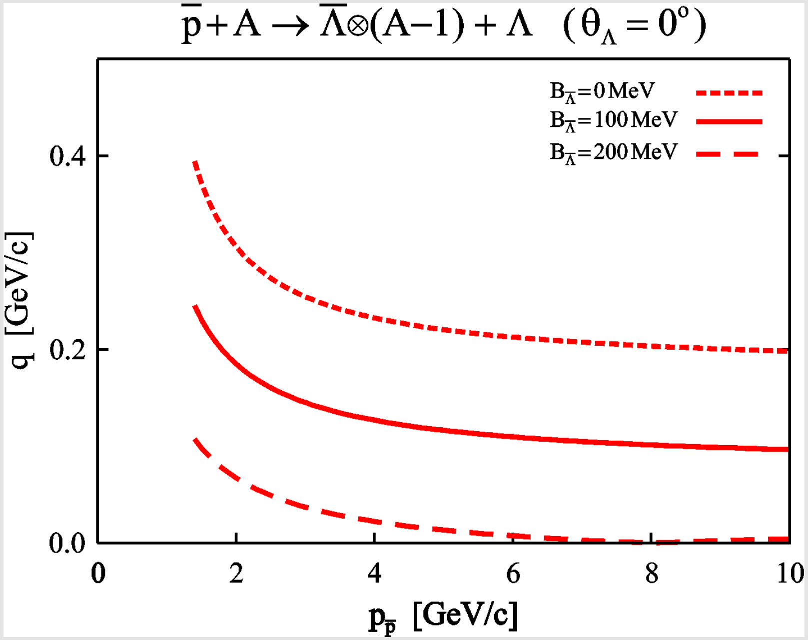
Search for $\overline{\Lambda}$ bound States in Recoilfree Reaction

- Missing mass analysis
- Use of $\bar{p}p \Rightarrow \overline{\Lambda}\Lambda$ at $\theta_\Lambda \sim 0°$ with nuclear proton
- Detect $\Lambda \Rightarrow p\pi^-$ in forward spectrometer beyond the kinematic limit
- Small momentum transfer
- $$\left(\frac{d\sigma}{d\Omega}\right)_{\bar{p}p\to\overline{\Lambda}\Lambda\,\theta_\Lambda\sim 0°} \cong 2\mu b/sr$$

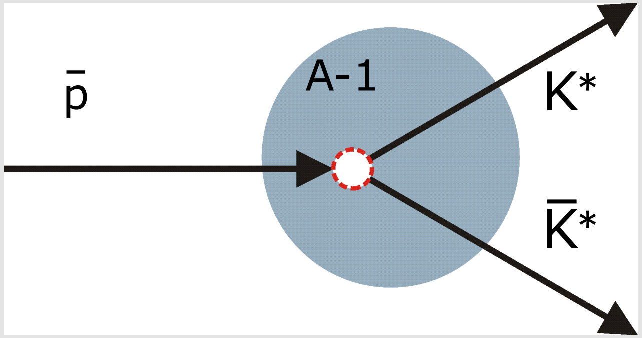
  at p = 1.77 GeV/c

P.D Barnes et al. (LEAR-PS185), PRC 54 (1996) 28

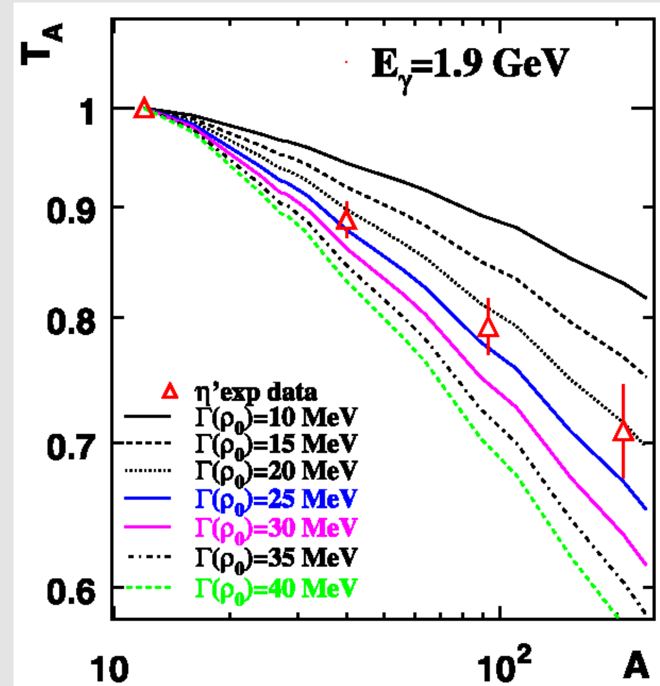




$K^*/\bar{K}^*$ Nuclear Absorption



- Interest from Giessen group
- Measure $K^+\pi^-$ and $K^-\pi^+$ yield for different A
- Nuclear transparency $T_A = \sigma_h(A)/A\sigma_h(p)$
- T_A directly related to the $\mathrm{Im}\Sigma_h$, Γ^*_h , $\sigma_{hN,inel}$
- Recently demonstrated for η'
- could already be done in the start-up phase of PANDA



$\Gamma_{\eta'N} \sim$ 15-25 MeV$\cdot(\rho/\rho_0)$
$\sigma_{\eta'N,inel} \sim$ 6-10 mb
at $\sqrt{s}_{\eta'N} \sim$ 2.0 GeV

M. Nanova *et al.*,
CBELSA/TAPS,
PLB 710 (2012) 600

HIGH RESOLUTION γ-SPECTROSCOPY: Ω ATOMS

reaching for the unthinkable

Deformation of a Baryon

- J=1/2 baryons have no *spectroscopic* quadrupole moment

$$Q_i = \int d^3r\,\rho(r)(3z^2 - r^2)$$

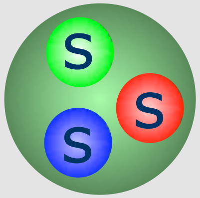
$$Q_s \propto (3J_z^2 - J(J+1)) \xrightarrow[J_z=1/2]{J=1/2} 0$$

- The Ω^- Baryon is the only „elementary" particle whose quadrupole moment can be measured
  - J=3/2
  - long mean lifetime $0.82\cdot 10^{-10}$ s

- Contributions to *intrinsic* quadrupole moment of baryons
  - General: One-gluon exchange and meson exchange
  - Ω: only one-gluon contributions to quadrupole moment

A.J. Buchmann Z. Naturforsch. **52** (1997) 877-940

  - e.g. within SU(3) limit $m_u/m_s=1$



$$Q_\Omega = Q_\Delta(gluon)$$

A very strange Atom

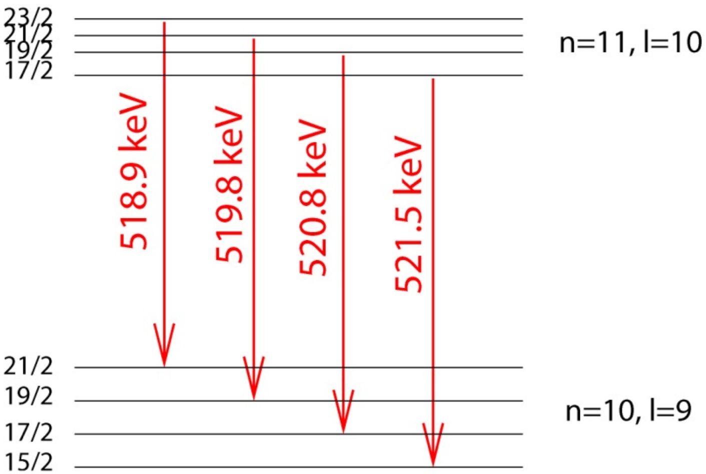
- hyperfine splitting in Ω-atom
  $\Rightarrow$ electric quadrupole moment of Ω

spin-orbit	$\Delta E_{ls} \sim (aZ)^4\, l \cdot m_\Omega$
quadrupole	$\Delta E_\Theta \sim (aZ)^4 Q m^3_\Omega$

R.M. Sternheimer, M. Goldhaber, Phys. Rev. A 8, 2207 (1973)

M.M. Giannini, M.I. Krivoruchenko, Phys. Lett. B 291, 329 (1992)

- prediction Q_Ω = (0 - 3.1) 10^{-2} fm^2
  - E(n=11, l=10 $\rightarrow$ n=10, l=9) ~ 520 keV
    - calibration with 511keV line!
  - ΔE_Θ ~ few tenth of keV for Pb

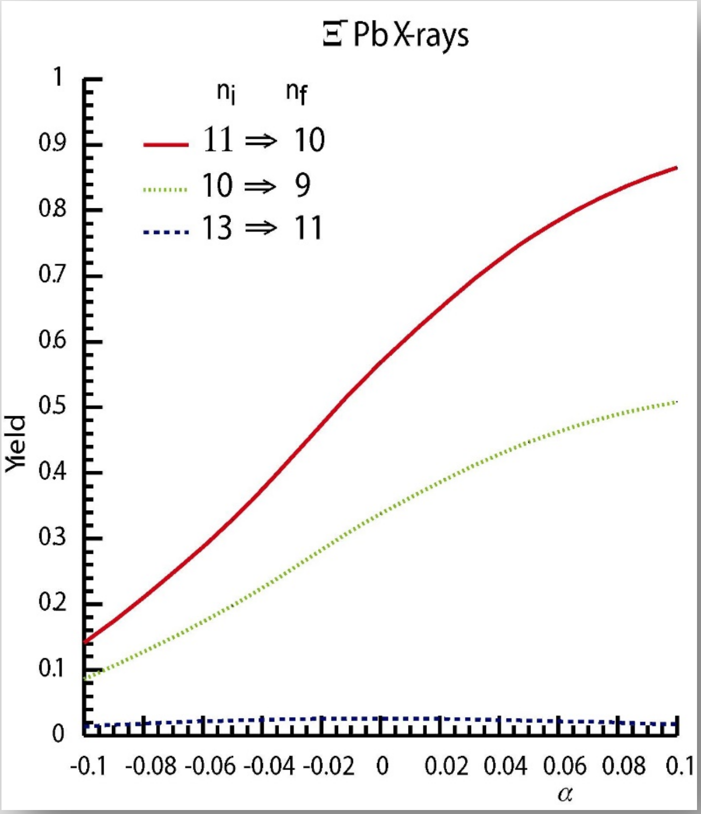


Q_Ω=0.02fm^2

Experimental details –*PANDA-HYP*

- few 100 stopped $\bar{\Omega}$ per day
- Yield(Σ-Pb)≈Yield(Ξ-Pb)
  C.J.Batty, E. Friedman, A. Gal, PRC 59, 295 (1999)
- capture probability ~10%
- X-ray detection efficiency ~5%
- trigger efficiency ($\bar{\Omega}$)
- ...

~10 observed X-rays/month



$$p_{initial}(l) = (2l+1)\cdot e^{\alpha l}$$

- Ξ-atoms factor 500 ⇒ early stage of PANDA

Overview: Strangeness in Nuclei

	Physics topic	setup	luminosity requirement	primary target	secondary target	comple-mentarity
Early phase	$\bar{\Lambda}$ in nuclei	PANDA	moderate	Ne, Ar	-	none
	$\bar{\Lambda}$ bound state	PANDA	moderate	Ne, Ar	-	none
	$K^*/\bar{K}^*$ nuclear absorption	PANDA	moderate		-	
	Ξ-atoms	PANDA-HYP	moderate	C (Ti)	heavy	JPARC
Standard conditions	$\bar{\Sigma}$, $\bar{\Xi}$ in nuclei; neutron skin	PANDA	standard	Ne, Ar	-	none
	$\Lambda\Lambda$-hypernuclei (γ-transitions)	PANDA-HYP	standard	C (Ti?)	B (Be, C)	JPARC (g.s.), CBM (p-u. s.)
Future options	heavy Ω-atoms	PANDA-HYP	standard	C (Ti?)	Pb	none
	Λ_c and $\bar{\Lambda}_c$ in nuclei	PANDA	standard	Ne	-	none
	Y and $\bar{Y}$ secondary scattering	PANDA + sec. active target	standard	H	$(CH_2)_n$	JPARC (only Y)