Antihyperons in Nuclei (with PANDA)

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On behalf of the PANDA collaboration

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Outline

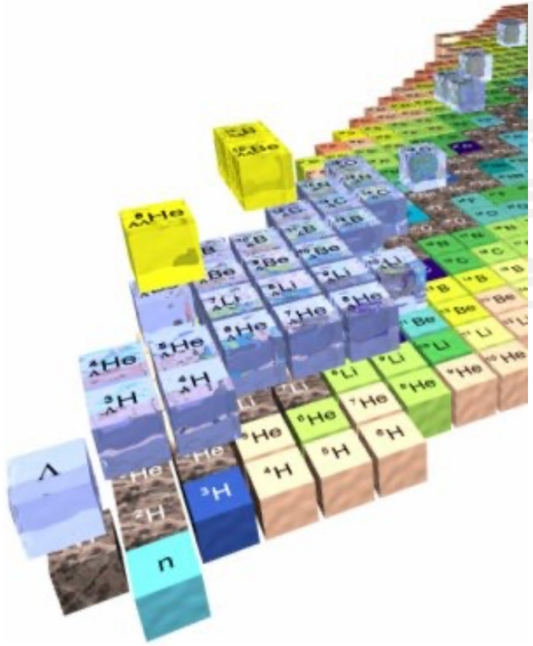
- Motivation
- The PANDA detector
- Antihyperons in nuclei
- Neutron skin measurements
- Hyperatom spectroscopy
- Double-strange hypernuclei
- Summary

Hyperon Puzzle

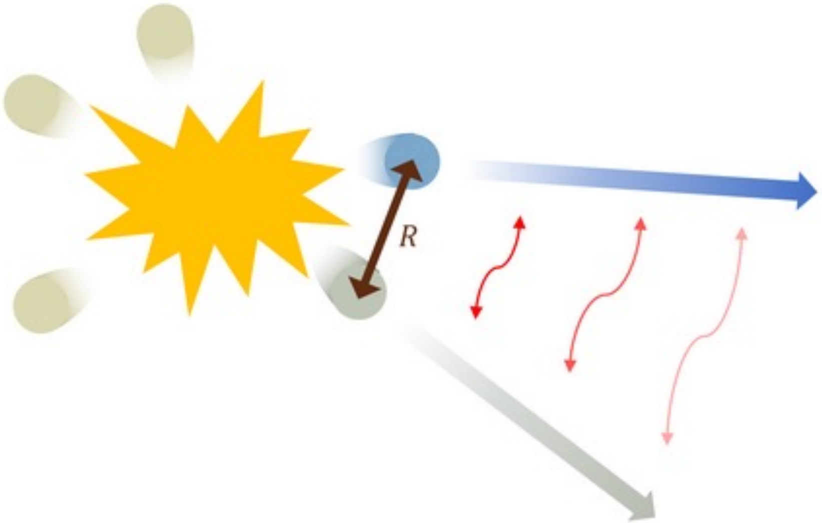
- Neutron stars among the most enigmatic objects in the Universe
- Extreme conditions: Masses of up to 2 solar masses, but radii as low as approx. 10 km
- Formation and fate determined by Equation of State (EoS)
- Gravity, strong force, and Pauli principle compete
  - Rapid increase of chemical potential at centre
  - Conversion of nucleons to hyperons energetically favourable
  - ➢ Relief of Fermi pressure softens EoS, reducing maximum mass to 1.4 solar masses
  - ➢ Contradiction → Hyperon Puzzle

Experimental approaches to hyperon few-body interaction

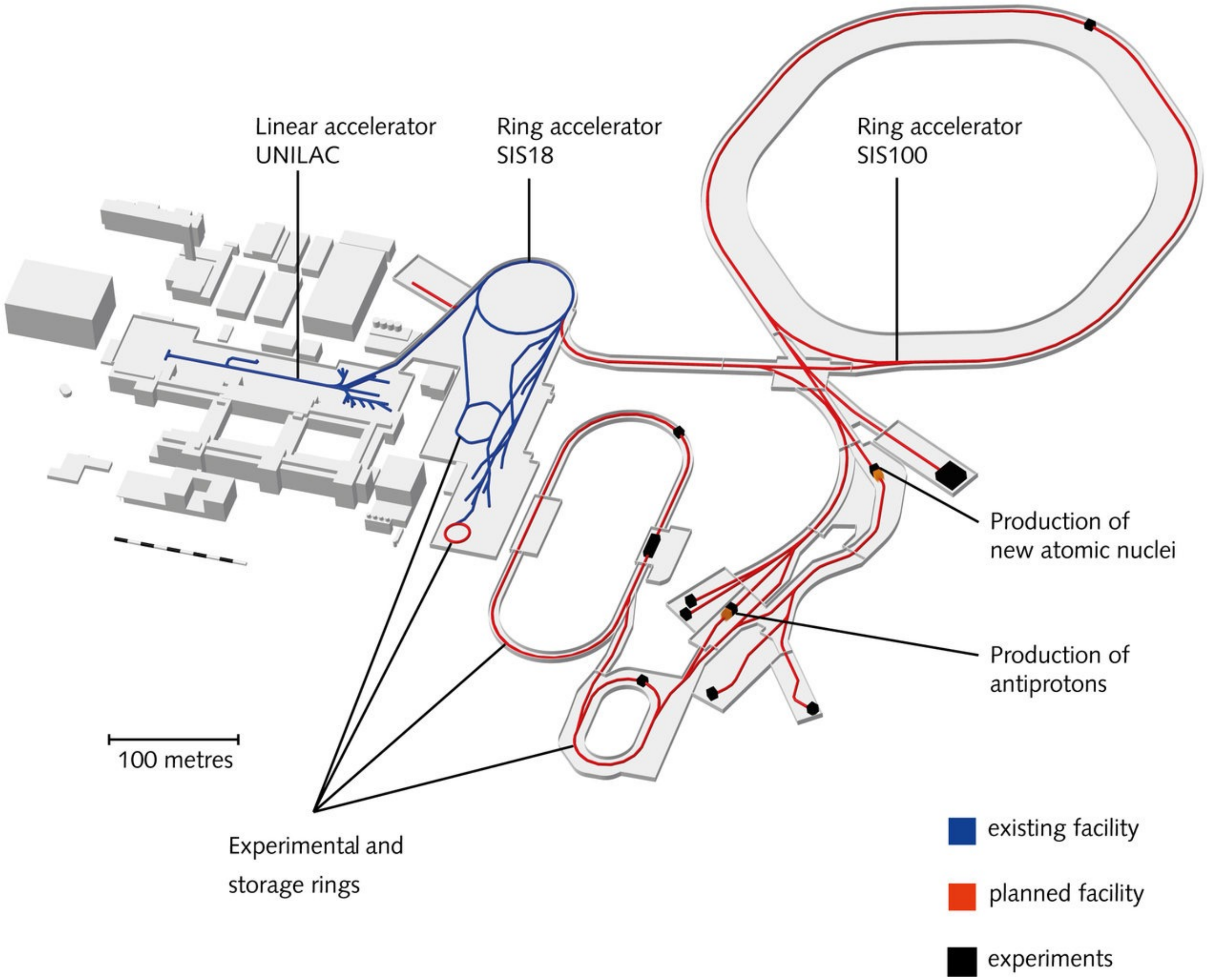
- Hypernuclei
  - 2+3-body forces
  - High-precision γ-ray spectroscopy
  - Spin-dependent forces
  - ➢ Significant contribution to solving hyperon puzzle



- Hyperon femtoscopy
  - Low-energy scattering parameters
  - NY and YY pairs
  - E.g. ALICE and HADES

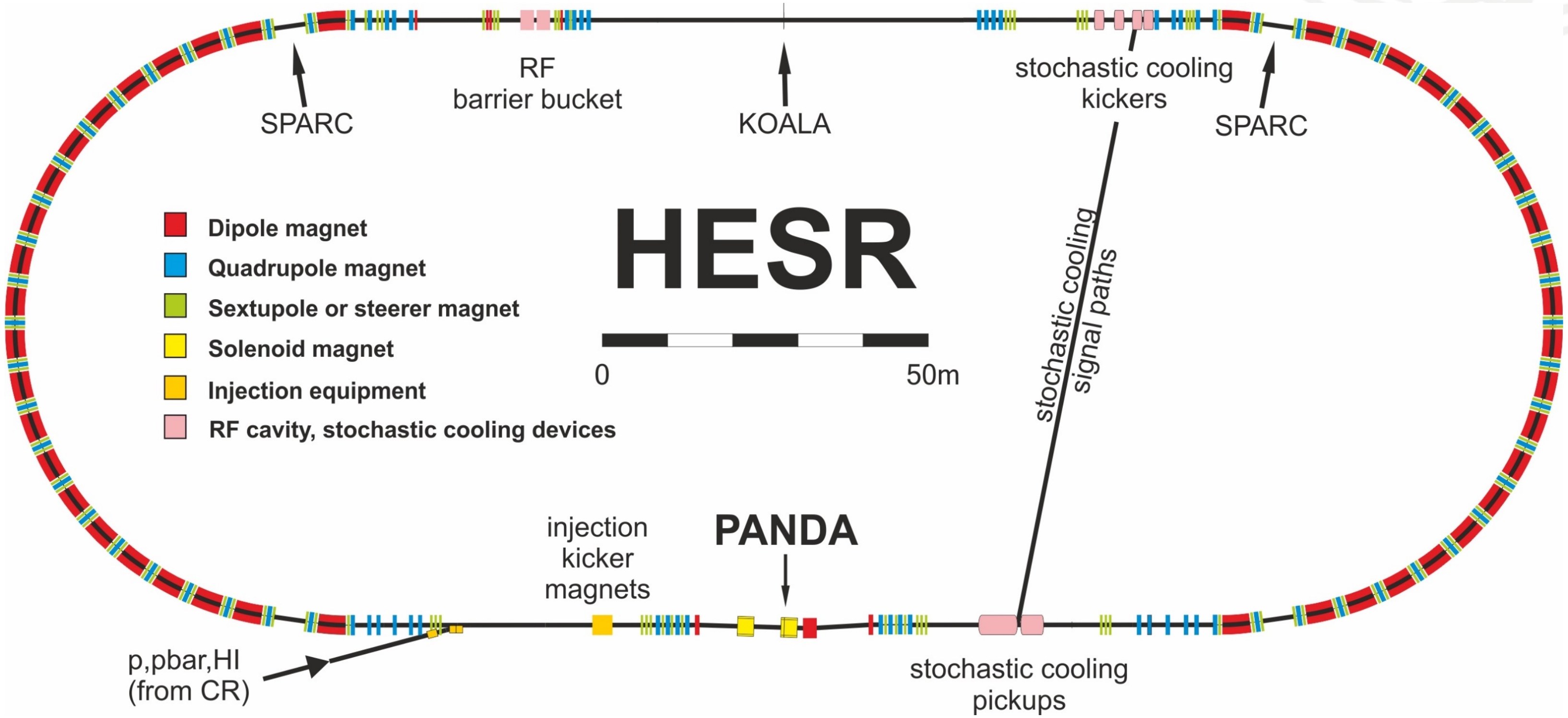


Facility for Antiproton and Ion Research (FAIR)

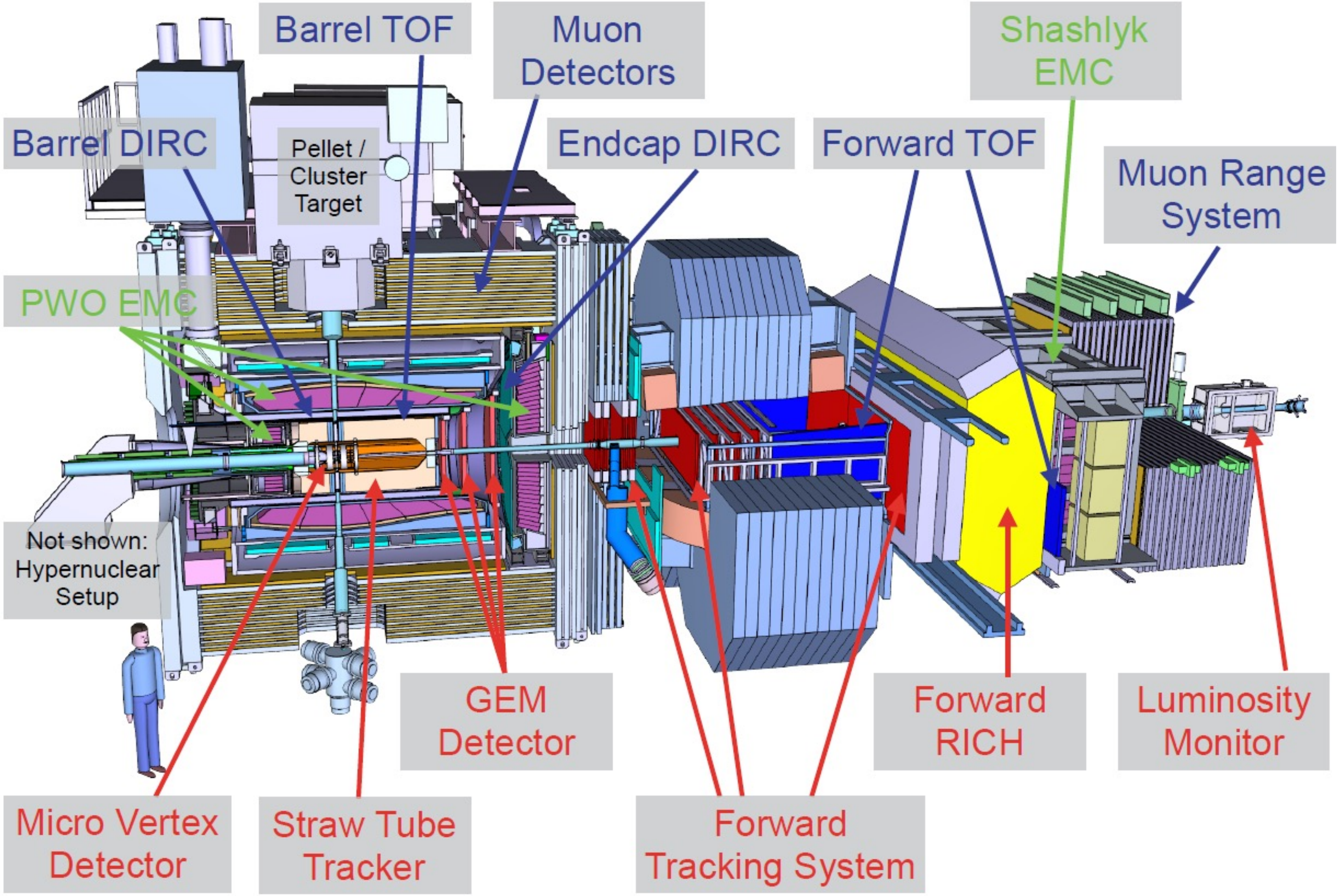


High Energy Storage Ring (HESR)

- Anti-protons with $1.5 < p_{beam} < 15\ \mathrm{GeV}/c$
- Internal targets
  - Cluster-jet and pellet ($\bar{p}p$)
  - Foils ($\bar{p}A$)
- Luminosity
  - Design $\sim 2 \cdot 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Phase One $\sim 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Quasi-continuous beam



PANDA – full setup



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PANDA is a strangeness factory

- Simulation studies of single- and double-strange hyperons*
  - Exclusive measurements of
    - $\bar{p}p \to \bar{\Lambda}\Lambda, \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$
    - $\bar{p}p \to \bar{\Sigma}^0\Lambda, \Lambda \to p\pi^-, \bar{\Sigma}^0 \to \bar{\Lambda}\gamma, \bar{\Lambda} \to \bar{p}\pi^+$
    - $\bar{p}p \to \bar{\Xi}^+\Xi^-, \Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^-, \bar{\Xi}^+ \to \bar{\Lambda}\pi^+, \bar{\Lambda} \to \bar{p}\pi^+$
  - Ideal pattern recognition and PID
  - Background using Dual Parton Model

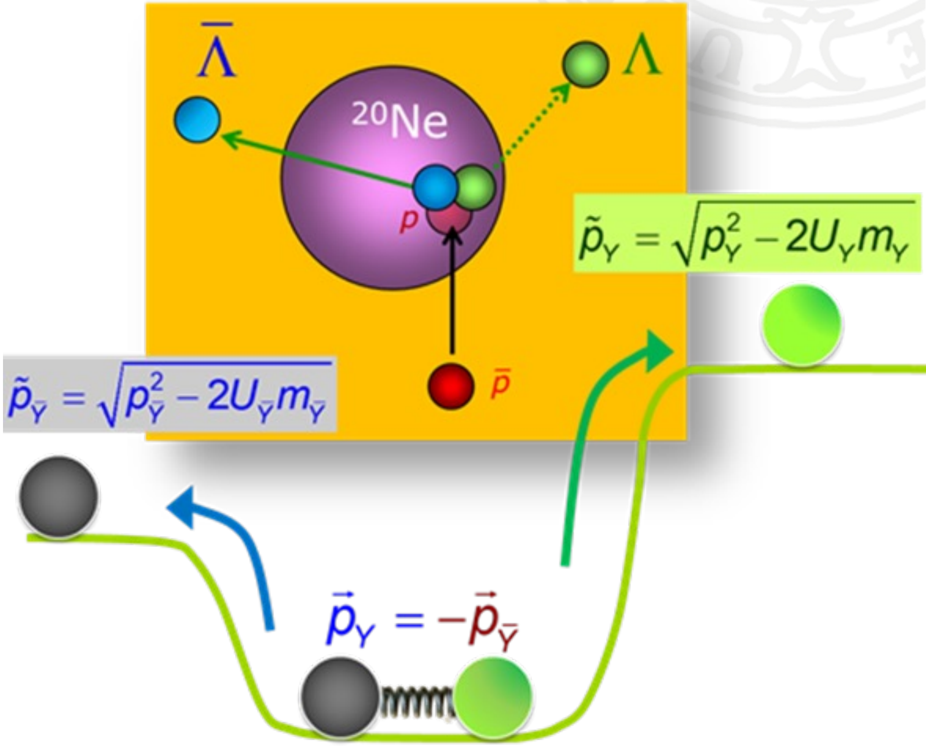
p_{beam} (GeV/c)	Reaction	$\sigma(\mu b)$	$\varepsilon(\%)$	Rate (s^{-1}) @ 10^{31} cm^{-2}s^{-1}	S/B	Events / day
1.64	$\bar{p}p \to \bar{\Lambda}\Lambda$	64.0	16.0	44	114	$3.8 \cdot 10^6$
1.77	$\bar{p}p \to \bar{\Sigma}^0\Lambda$	10.9	5.3	2.4	>11**	207000
6.0	$\bar{p}p \to \bar{\Sigma}^0\Lambda$	20	6.1	5.0	21	432000
4.6	$\bar{p}p \to \bar{\Xi}^+\Xi^-$	~ 1	8.2	0.3	274	260000
7.0	$\bar{p}p \to \bar{\Xi}^+\Xi^-$	~ 0.3	7.9	0.1	65	86000

** 90% C.L.

*By W. Ikegami Andersson (PhD thesis, Uppsala 2020) and G. Perez Andrade (Master thesis, Uppsala 2019)

Antihyperons in nuclei

- Baryon-antibaryon interaction can be studied by correlation functions (e.g. ALICE)
- PANDA: effective optical potential of $\overline{\Lambda}$ by exclusive $^{20}\mathrm{Ne}(\bar{p},\overline{\Lambda}\Lambda)$ reaction
- Abundant production of $\overline{Y}Y$ pairs near threshold
- Probe transport models for heavy ions, e.g. combining relativistic mean field models with momentum dependent interactions

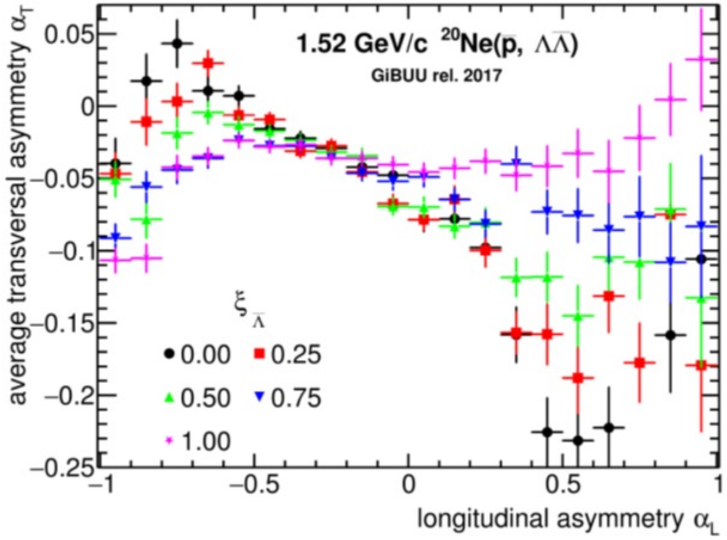


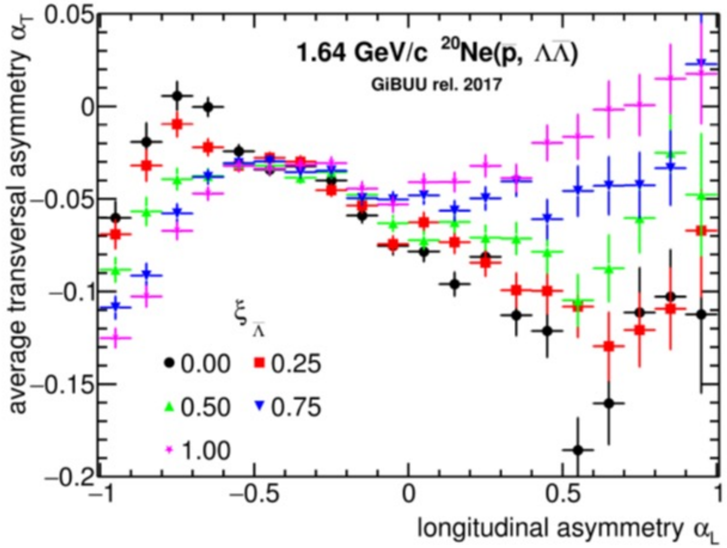
Antihyperons in nuclei

- Measure asymmetry of $\bar{Y}$ and Y

$$\alpha_T = \frac{p_T(Y) - p_T(\bar{Y})}{p_T(Y) + p_T(\bar{Y})}, \alpha_L = \frac{p_L(Y) - p_L(\bar{Y})}{p_L(Y) + p_L(\bar{Y})}$$

- Momentum asymmetries relate to $\bar{Y}$ interaction potential
- Possible within one hour of data taking
- PANDA unique





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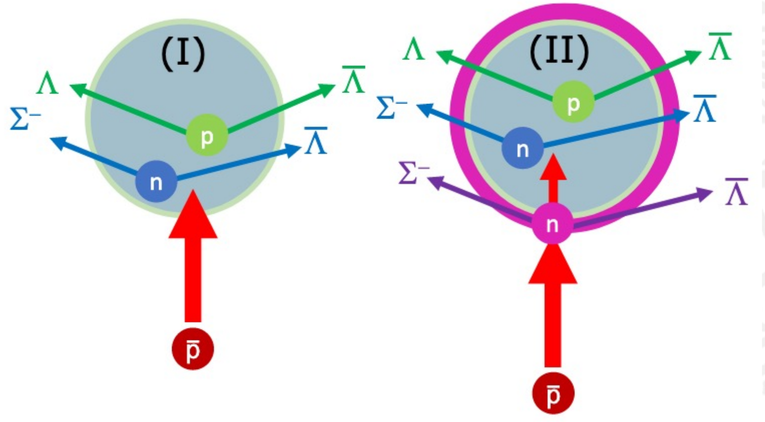
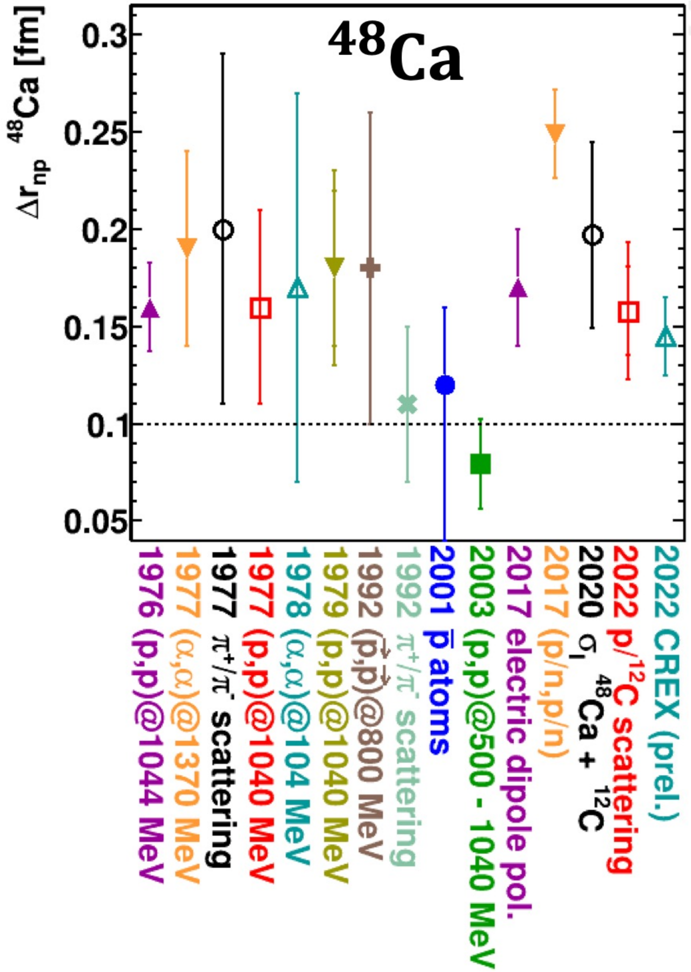
Probing neutron skin

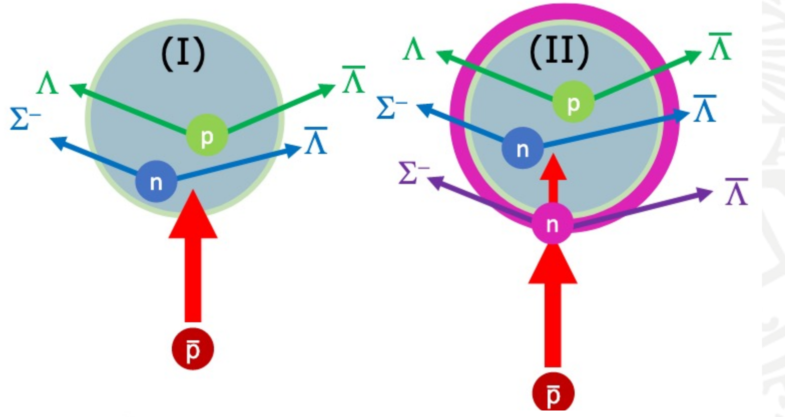
- Many different approaches
  - Hadronic probes
  - Electromagnetic probes
  - Weak interaction
  - Astrophysical observations
- The interesting case of ^{48}Ca
  - Measure skin difference to ^{40}Ca
  - Ab-initio calculations possible

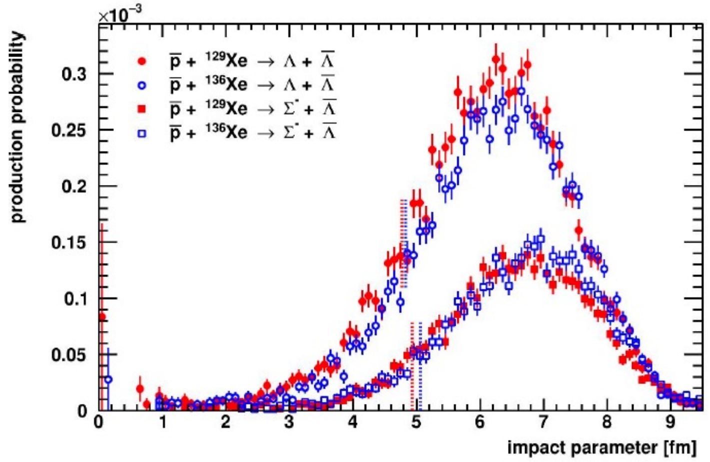


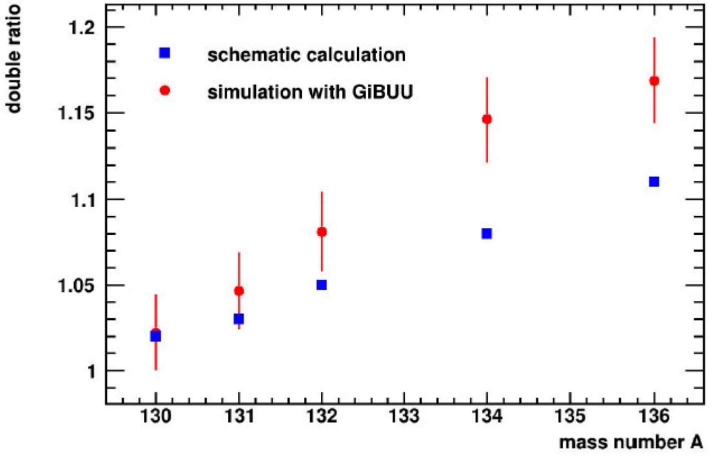


Probing neutron skin

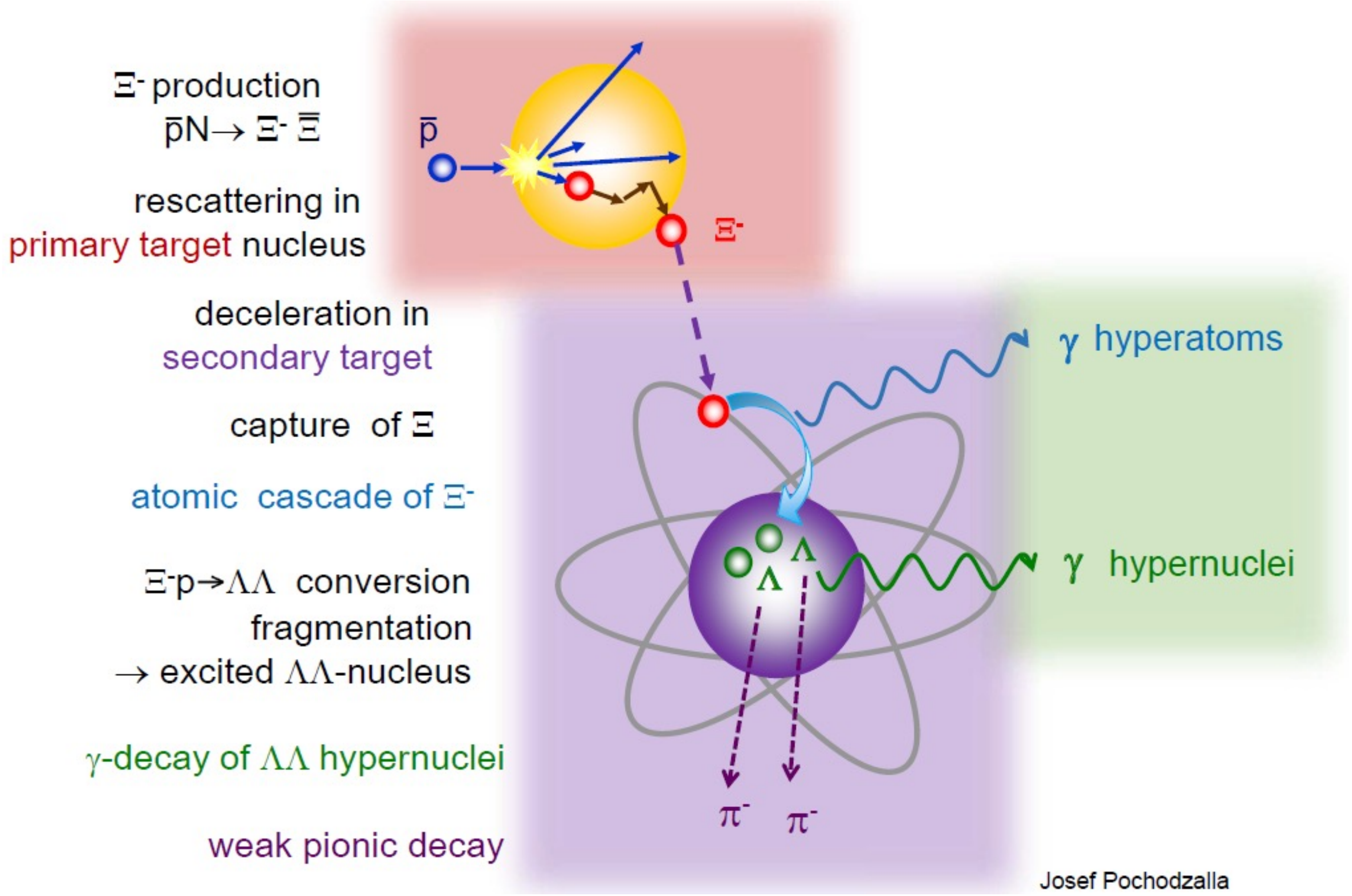
- $\Lambda\bar{\Lambda}$ only in $\bar{p}p$, $\Sigma^-\bar{\Lambda}$ only in $\bar{p}n$
- Double ratio of probabilities
  $$DR = \frac{p^{II}_{\Sigma^-\bar{\Lambda}}/p^{II}_{\Lambda\bar{\Lambda}}}{p^{I}_{\Sigma^-\bar{\Lambda}}/p^{I}_{\Lambda\bar{\Lambda}}} = \frac{1+p_{\mathrm{abs}}}{1-p_{\mathrm{abs}}}$$
- p_{abs}: antiproton absorption probability, related to integrated skin density
- Study evolution of neutron skin thickness for isotope chains, e.g. $^{129-136}\mathrm{Xe}$
- Adds to systematic uncertainties of hyperatom observables
- Preprint: arxiv:2209.03875



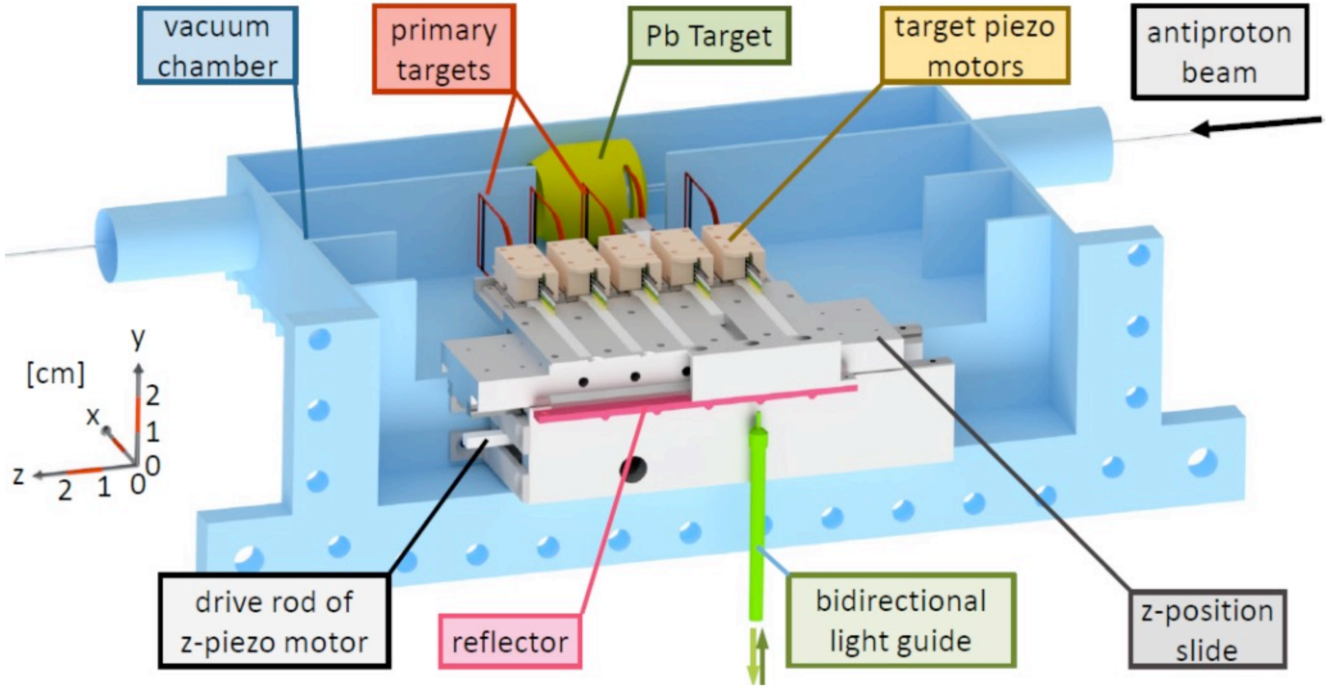


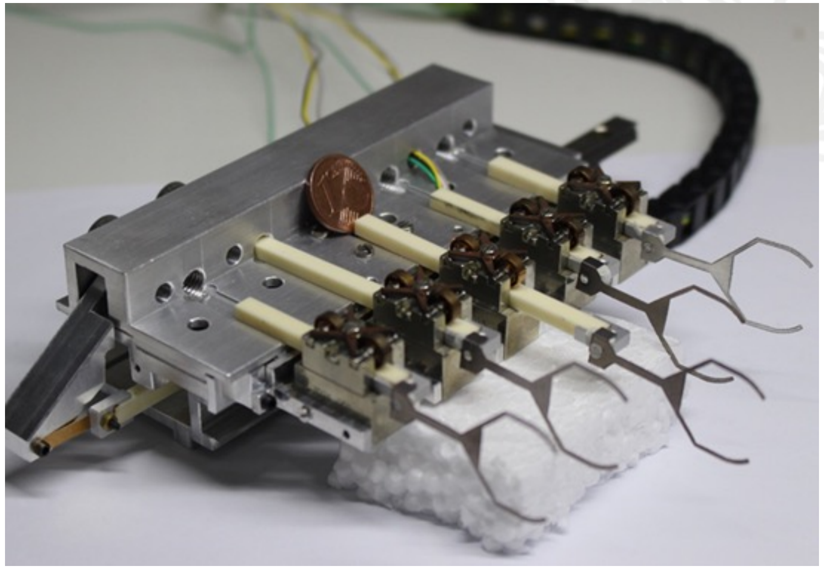


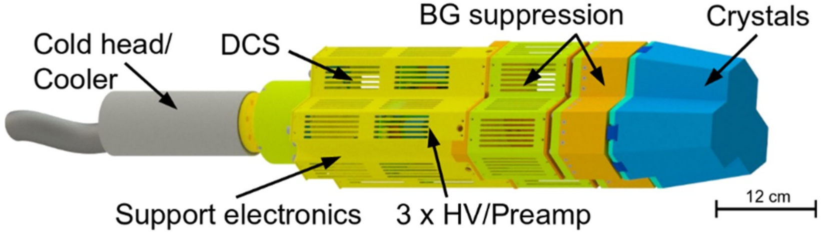
Hyperatoms and hypernuclei



Hyperatoms and hypernuclei

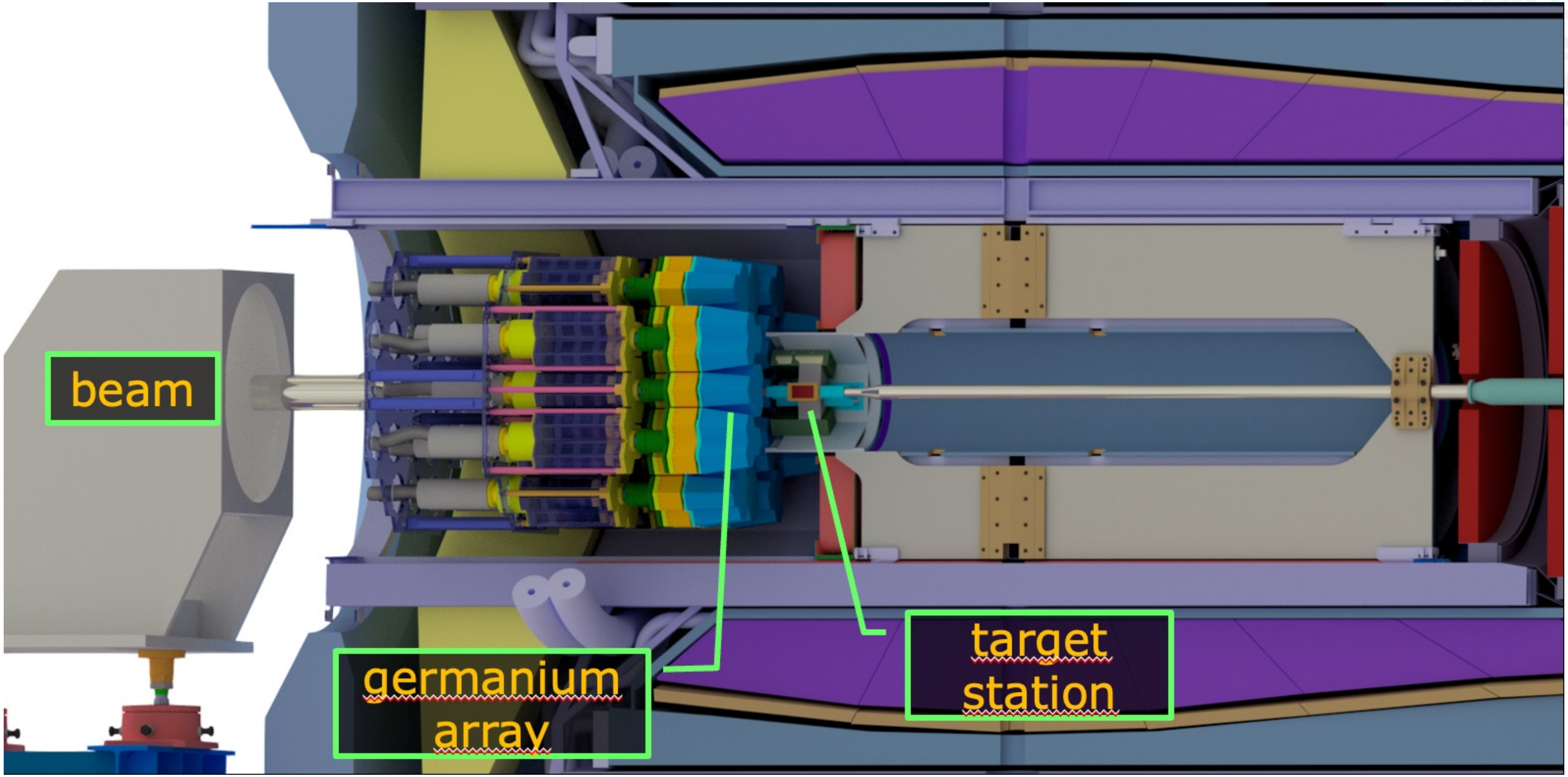






- Target positioning resolution: $5\mu m$
- Repeatibility: $\pm 18\mu m$ (14000 measurements, requirement: $300\mu m$)
- Preprint: arxiv:2303.13359

Hyperatoms and hypernuclei



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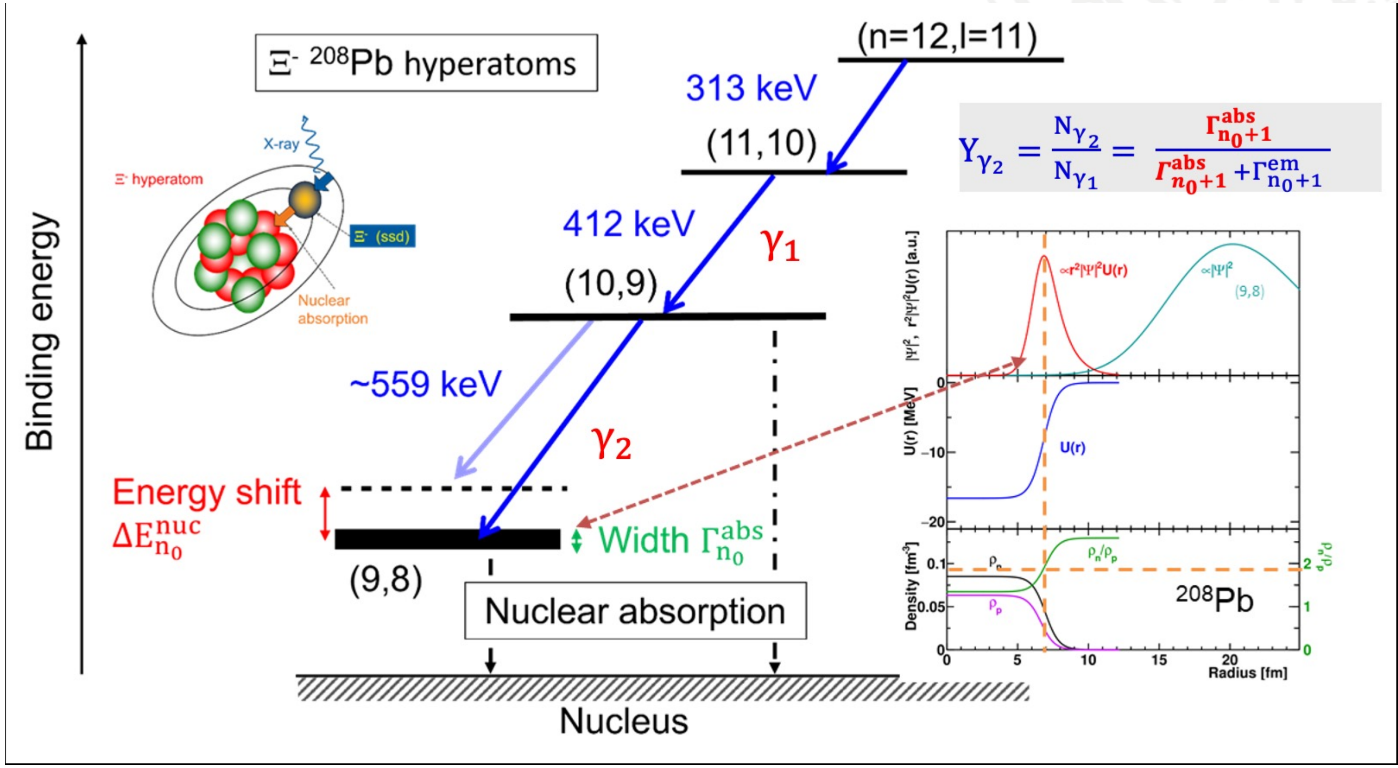
X-ray spectroscopy of Ξ^- hyperatoms

- Observe nuclear cascade
- Shift of low atomic level sensitive to ΞA potential near the nuclear surface
- Different neutron/proton content for different nuclei → isospin dependence of ΞA force
- PANDA unique



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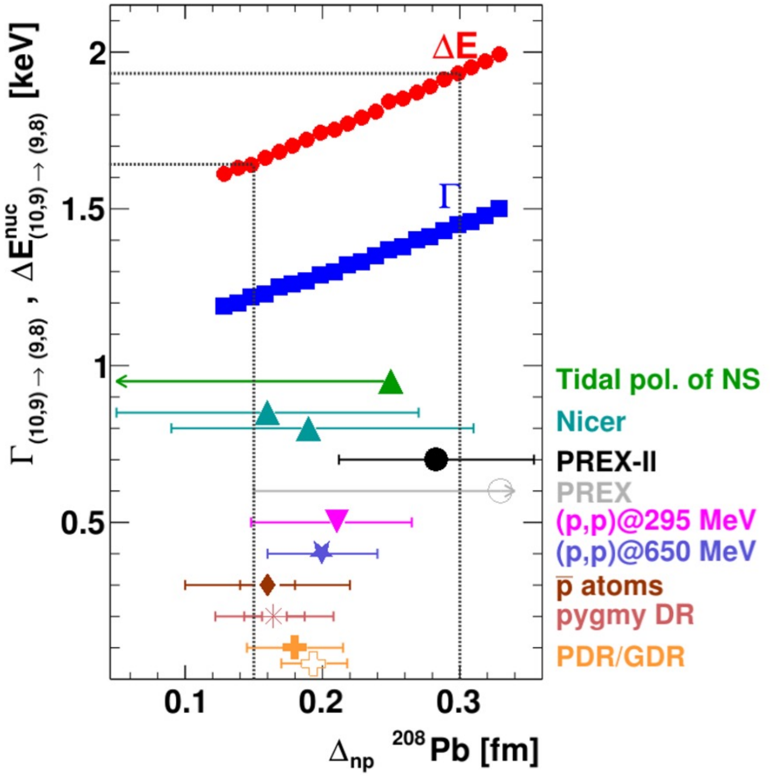
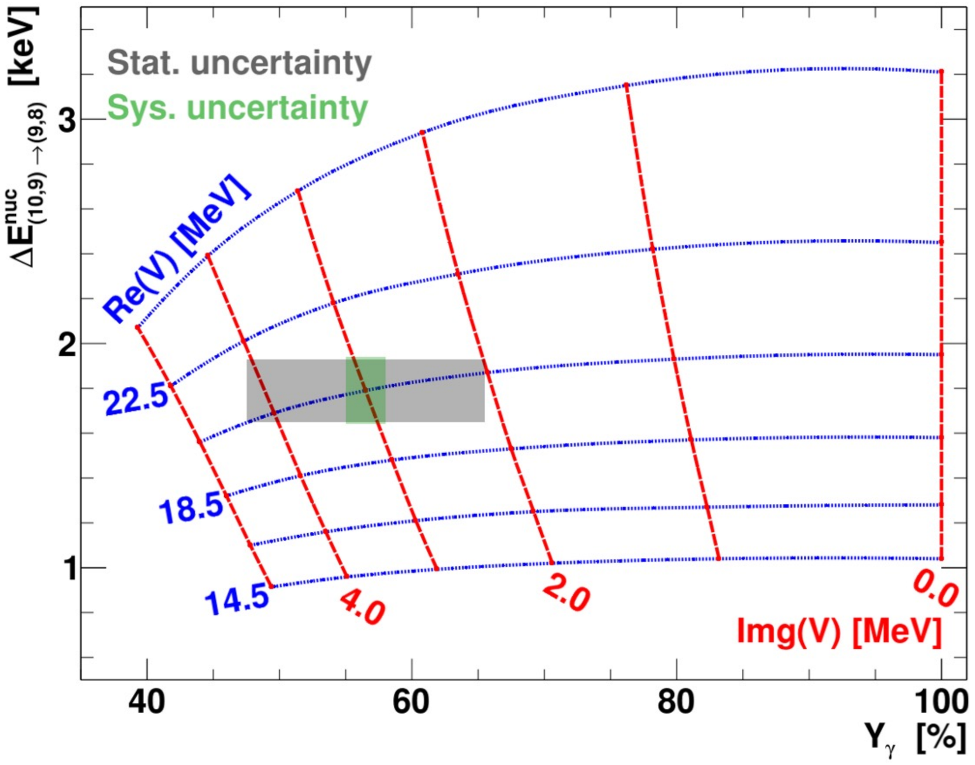
Sensitivity to nuclear structure

- Systematic uncertainties due to uncertainty of neutron skin thickness
- Best known nucleus: $^{208}\mathrm{Pb}$





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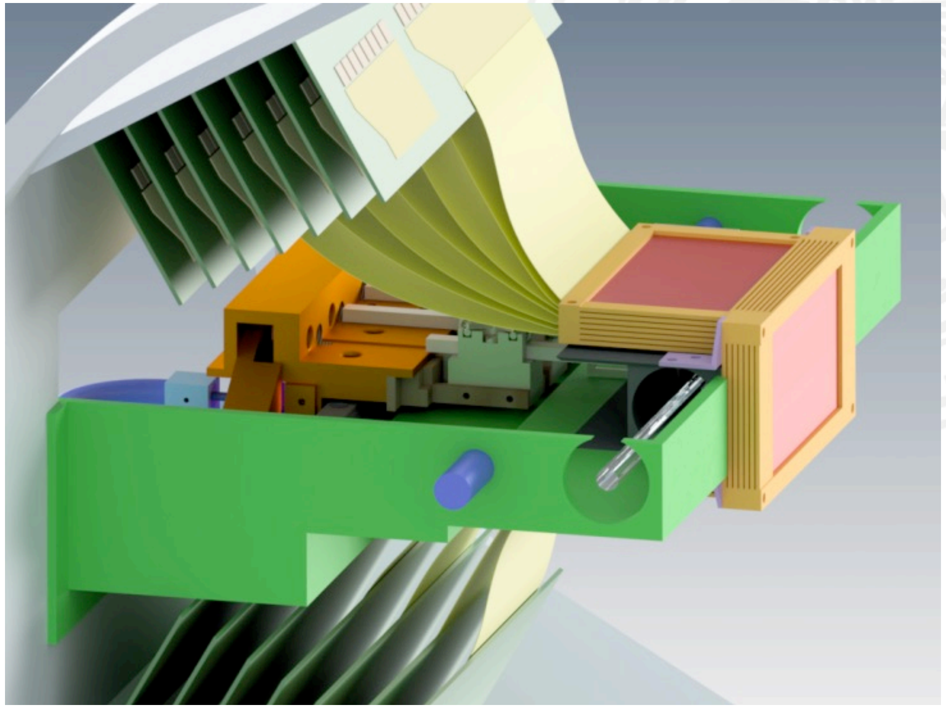
$\Lambda\Lambda$ hypernuclei

- Active secondary target
  - Boron-μStrip sandwich
- Form excited $\Lambda\Lambda$ hypernuclei by Ξ^- capture
- Measure $_{\Lambda\Lambda}X$ γ-transitions and momentum correlations
- Explore structure of light, double-strange hypernuclei
- Study few-body forces in baryonic matter



Nuclei	E_x (MeV)	J^P	production probability ^{9}Be	^{10}B	^{11}B	^{nat}B	^{12}C
$^{4}_{\Lambda\Lambda}$H	0.0	1^+	0.00866	0.02410	0.00000	0.00472	0.0000
$^{5}_{\Lambda\Lambda}$H	0.0	$\frac{1}{2}^+$	0.02120	0.02209	0.03199	0.03005	0.00633
$^{5}_{\Lambda\Lambda}$He	0.0	$\frac{1}{2}^+$	0.00000	0.00330	0.00000	0.00065	0.00000
$^{6}_{\Lambda\Lambda}$He	0.0	0^+	0.02350	0.03175	0.00977	0.01408	0.03304
$^{7}_{\Lambda\Lambda}$He	0.0	$\frac{3}{2}^-$	0.10201	0.03038	0.04407	0.04139	0.00649
$^{8}_{\Lambda\Lambda}$He	0.0	0^+	0.01880	0.00445	0.00490	0.00481	0.00000
	1.80	2^+	0.08201	0.01846	0.02351	0.02252	0.00000
$^{9}_{\Lambda\Lambda}$He	0.0	$\frac{3}{2}^-$	0.00426	0.00017	0.00292	0.00238	0.00000
	2.92	$\frac{5}{2}^-$	0.01859	0.00021	0.00435	0.00354	0.00000
$^{7}_{\Lambda\Lambda}$Li	0.0	$\frac{3}{2}^-$	0.00016	0.00635	0.00000	0.00124	0.00000
$^{8}_{\Lambda\Lambda}$Li	0.0	1^+	0.01055	0.01991	0.00233	0.00578	0.00209
	1.36	3^+	0.01998	0.03976	0.00212	0.00950	0.00150
	5.63	2^+	0.00617	0.01747	0.00000	0.00342	0.00000
$^{9}_{\Lambda\Lambda}$Li	0.0	$\frac{3}{2}^-$	0.02199	0.03041	0.03948	0.03770	0.02574
	0.73	$\frac{1}{2}^-$	0.01079	0.01452	0.01803	0.01734	0.01236
	4.55	$\frac{7}{2}^-$	0.03997	0.04398	0.04528	0.04502	0.04207
	5.96	$\frac{5}{2}^-$	0.02870	0.02975	0.02907	0.02920	0.02864
$^{10}_{\Lambda\Lambda}$Li	0.0	2^+	0.00000	0.00702	0.03799	0.03192	0.00000
	0.98	1^+	0.00000	0.00404	0.02138	0.01798	0.00000
	2.255	3^+	0.00000	0.00929	0.04422	0.03737	0.00000
$^{9}_{\Lambda\Lambda}$Be	0.0	$\frac{3}{2}^-$	0.00000	0.00497	0.00003	0.00100	0.00000
	0.71	$\frac{1}{2}^-$	0.00000	0.00227	0.00001	0.00045	0.00000

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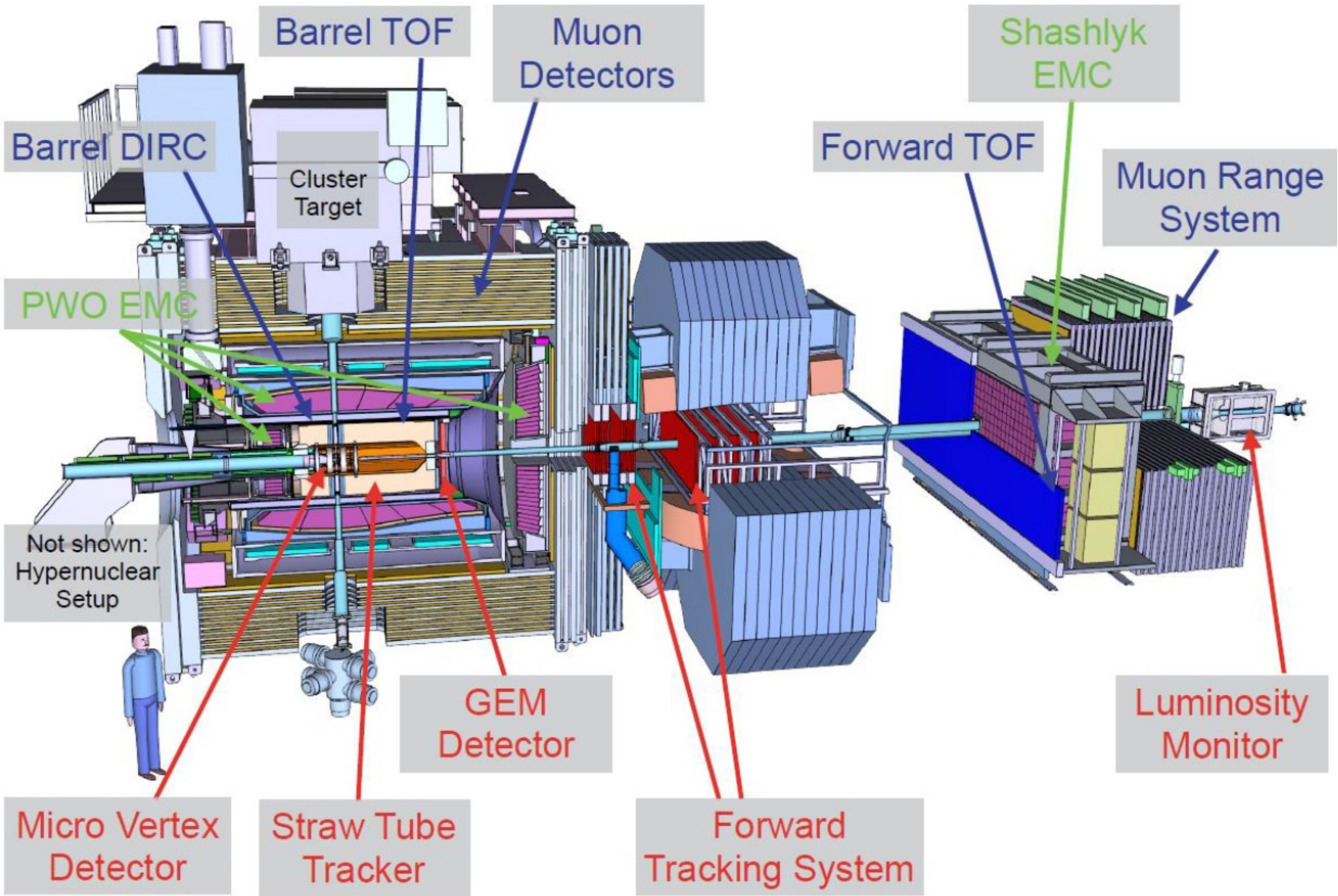
Summary

- PANDA excellent tool for hypernuclear physics from the start
- Explore strong interaction in the nuclear periphery
- Observables relate to equation of state of neutron stars
- Key topics
    - Antihyperon potential in cold baryonic matter
    - Hyperatoms: Ξ^- potential in neutron-rich environments
    - Structure of $\Lambda\Lambda$ hypernuclei

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093.

Thank you for your attention!

PANDA – Phase One setup



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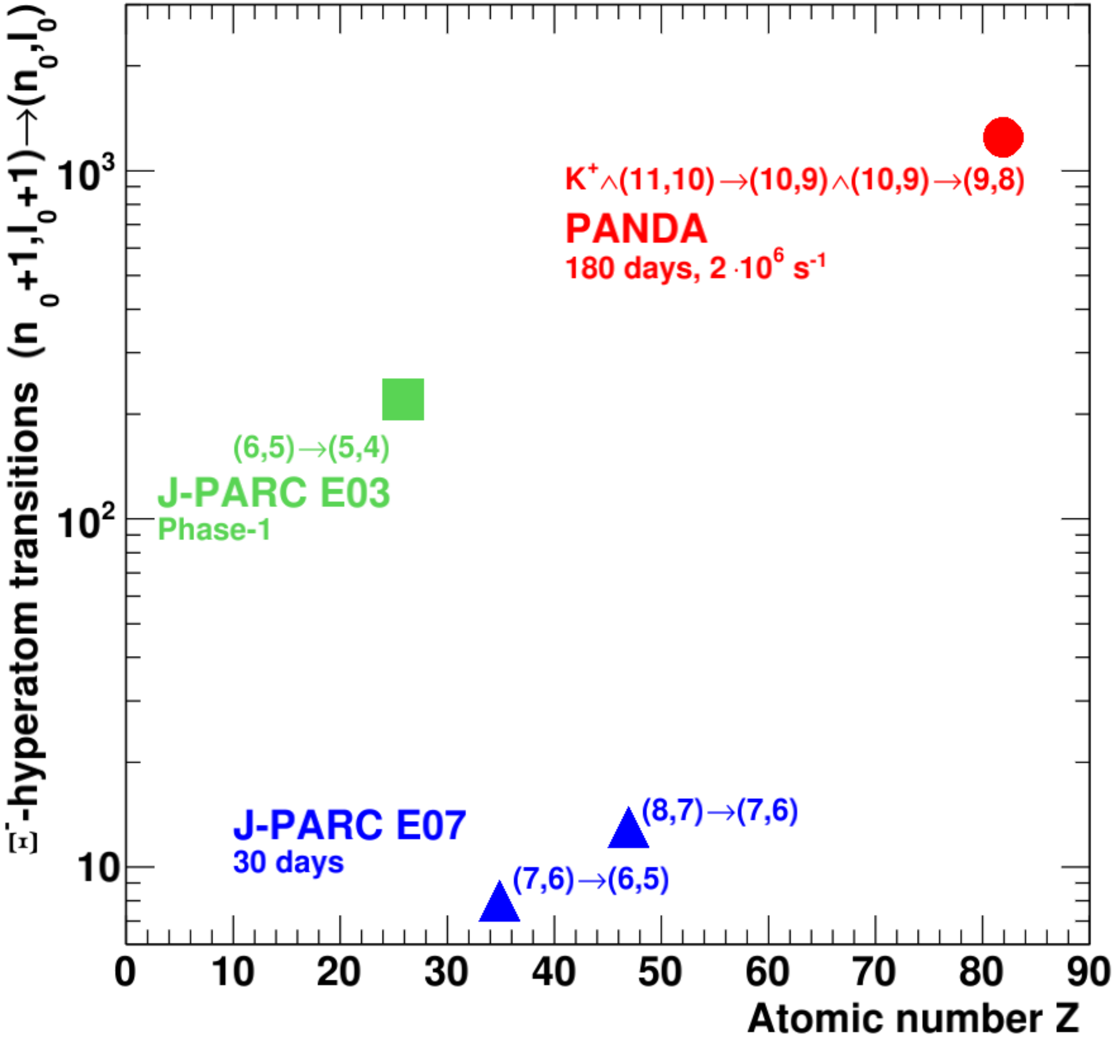
Prospects

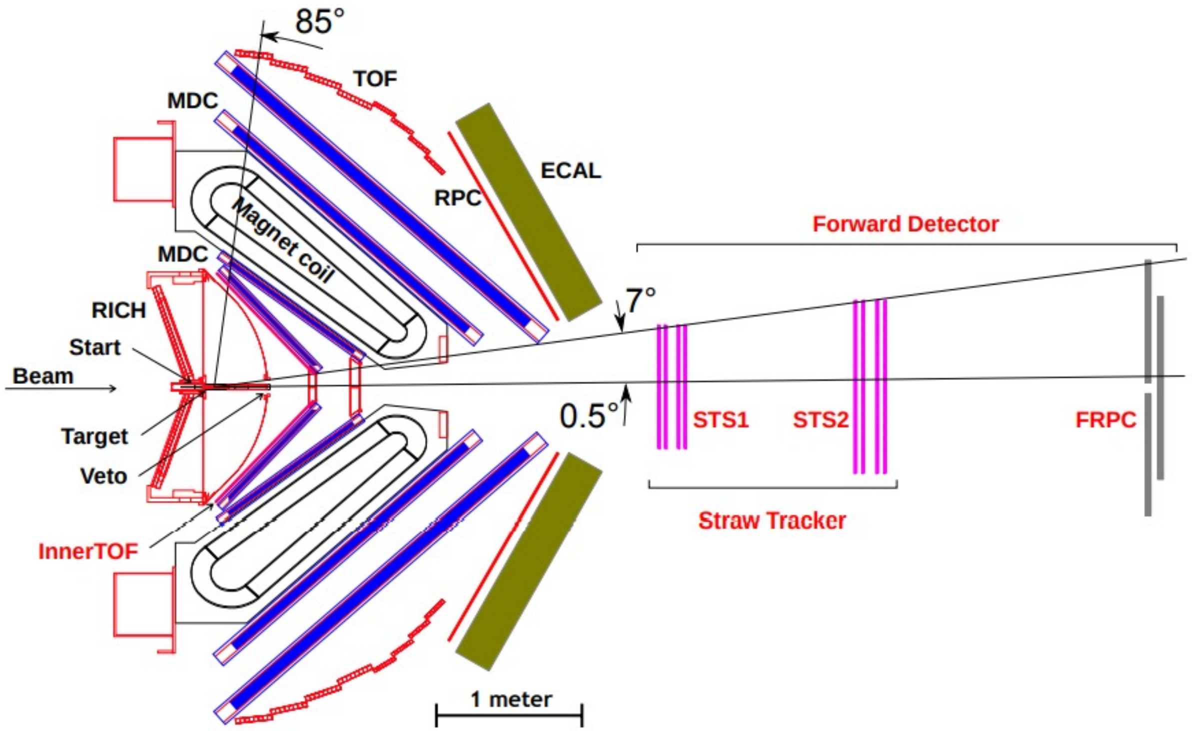
- JPARC
  - Kaon beam
  - Extended target (cm)
  - $\frac{\rho_n}{\rho_p} \sim 1$
- PANDA
  - Stored antiproton beam
  - Thin secondary target (mm)
  - $\frac{\rho_n}{\rho_p} \sim 2$
- PANDA has unique explanatory potential

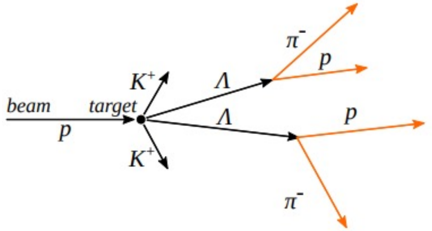


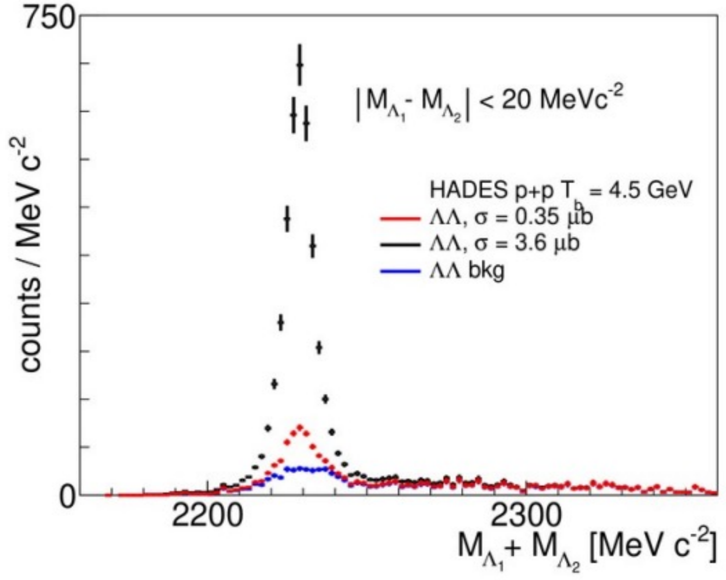
Components in EoS

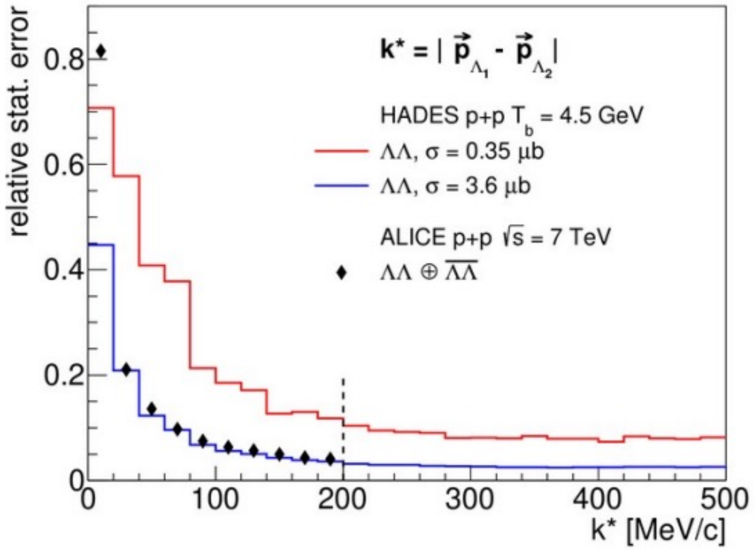
- Strong interaction in the confinement domain
- Three-body forces
  - Nucleon-nucleon-hyperon (NNY)
  - Nucleon-hyperon-hyperon (NYY)
  - ➢Could be repulsive → counteract softening of EoS
- Two-body force
  - Nucleon-hyperon (NY)
  - Hyperon-hyperon (YY)
  - ➢Repulsive core would stiffen EoS or make hyperon presence energetically unfavourable
- Data on hyperon interaction too scarce to constrain theoretical models

HADES / PANDA Phase 0









- 2022 beam time: p+p@4.5 GeV
  - Data analysis ongoing
- Opportunity for YN and YY interaction studies
- High sensitivity in low energy region

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