Upcoming at Jlab up to 2027-2028 (Hall A and Hall A -> Hall C)

G.M. Urciuoli

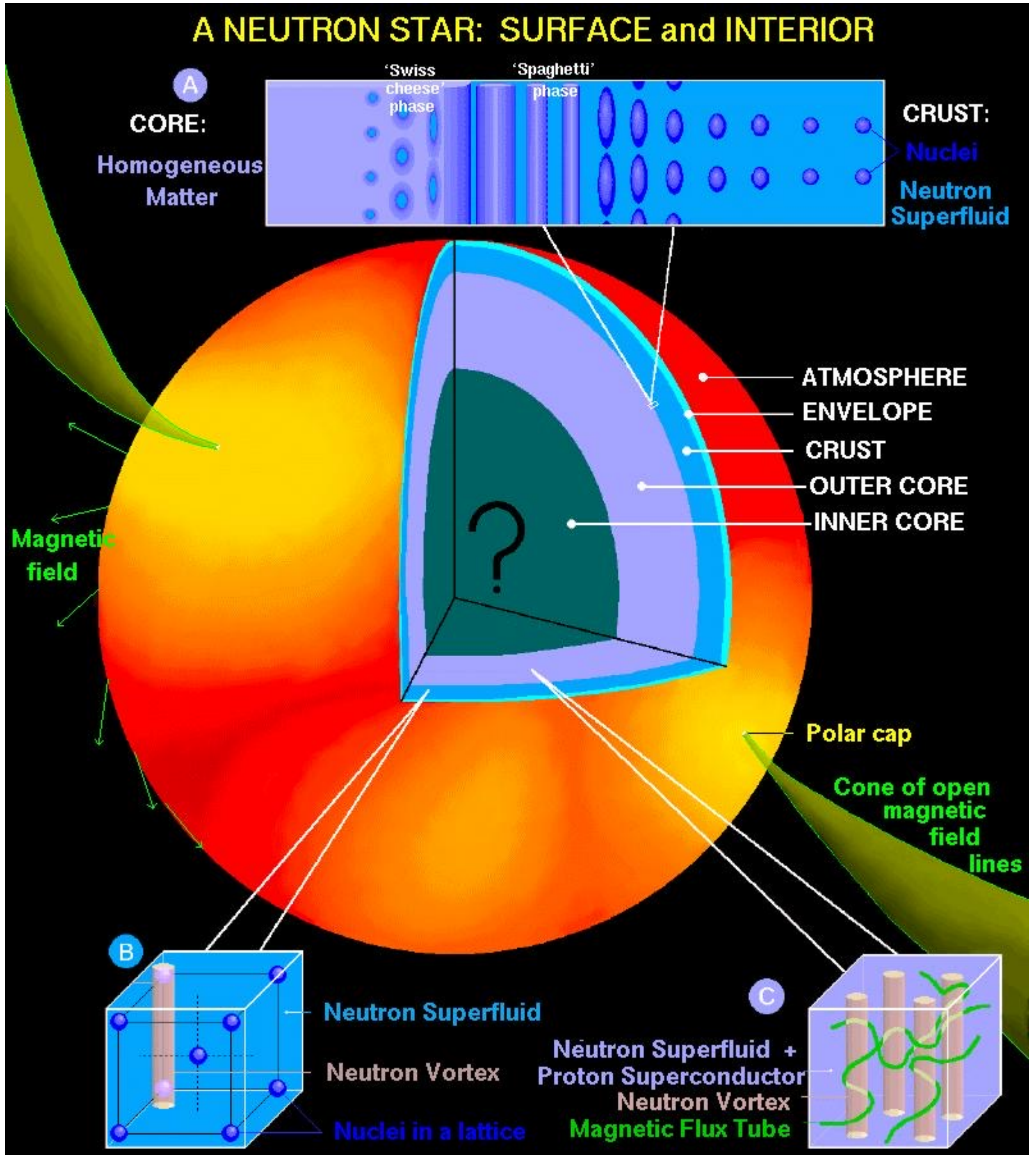
- Neutron Star structure (Hypernuclear spectroscopy)

- Moller experiment

Why Study Neutron Stars?

Frontiers in particle, nuclear, condensed matter, plasma, hydro physics, QED, and general relativity

Core composition is unknown:
Nucleons?
Hyperons?
Quark matter?



http://www.astroscu.unam.mx/neutrones/NS-picture/NStar/NStar-I.gif

Matter in NS cores reaches several times nuclear density

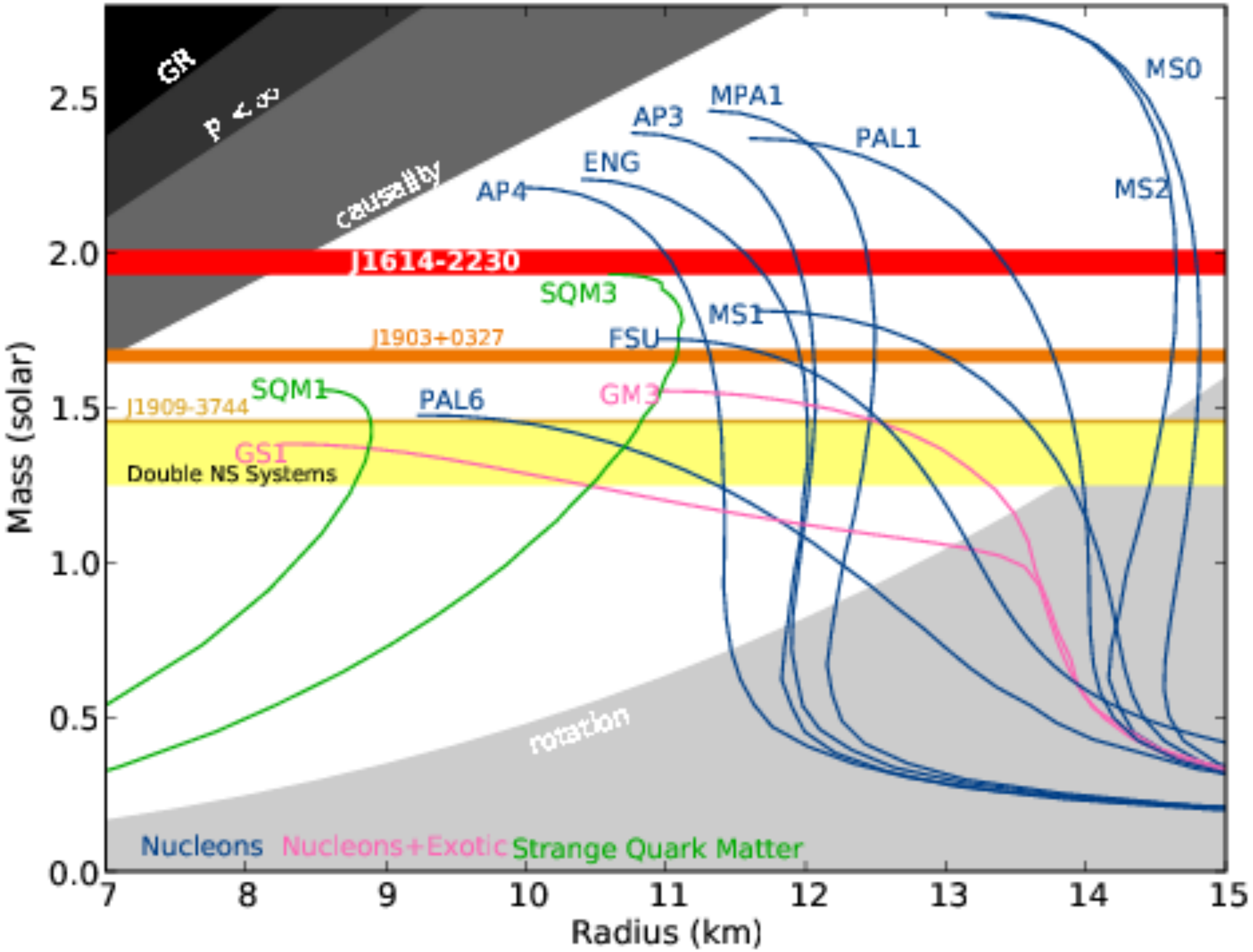
It is very neutron rich, unlike nuclei

It is also very cold: $kT \ll E_F$
$T \sim 10^9$ K is cold!

From Cole Miller's Talk on **PREX/CREX and Astronomical Observations of Neutron Stars** **at** 2023 Summer Hall A/C Meeting

NS masses

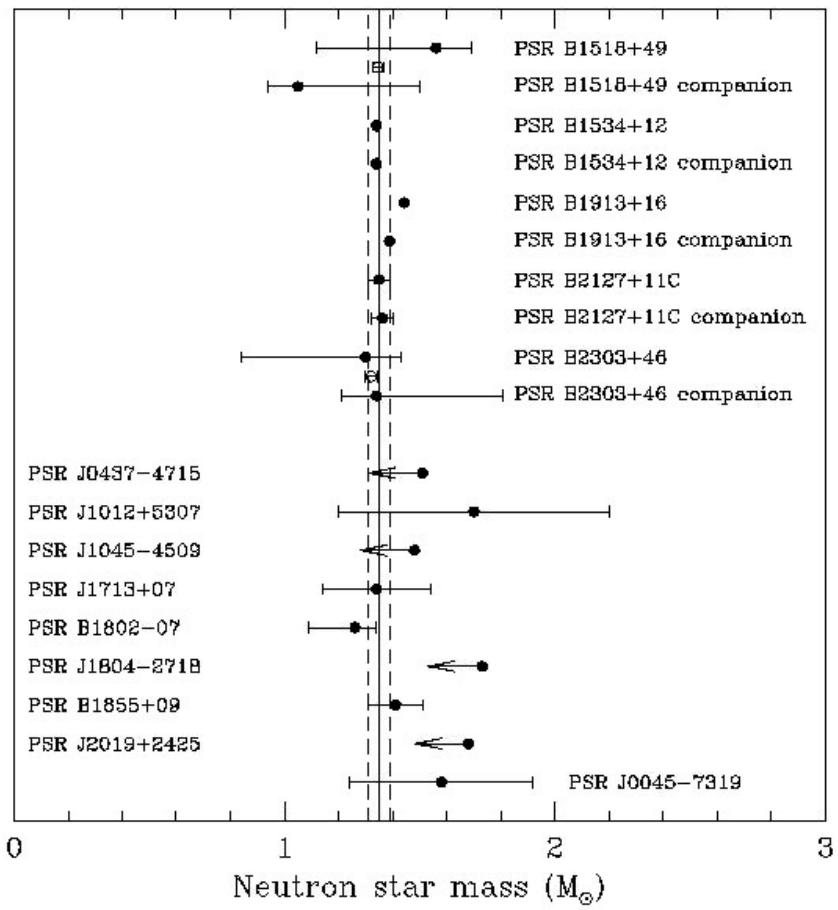
- A given equation of state (EOS) P(ε)
  (P is pressure, ε is total mass-energy density) predicts M(R)
  Assume equilibrium
- Also predicts maximum mass
- Viable EOS must accommodate largest measured mass



Demorest et al. 2010

Double NS Masses

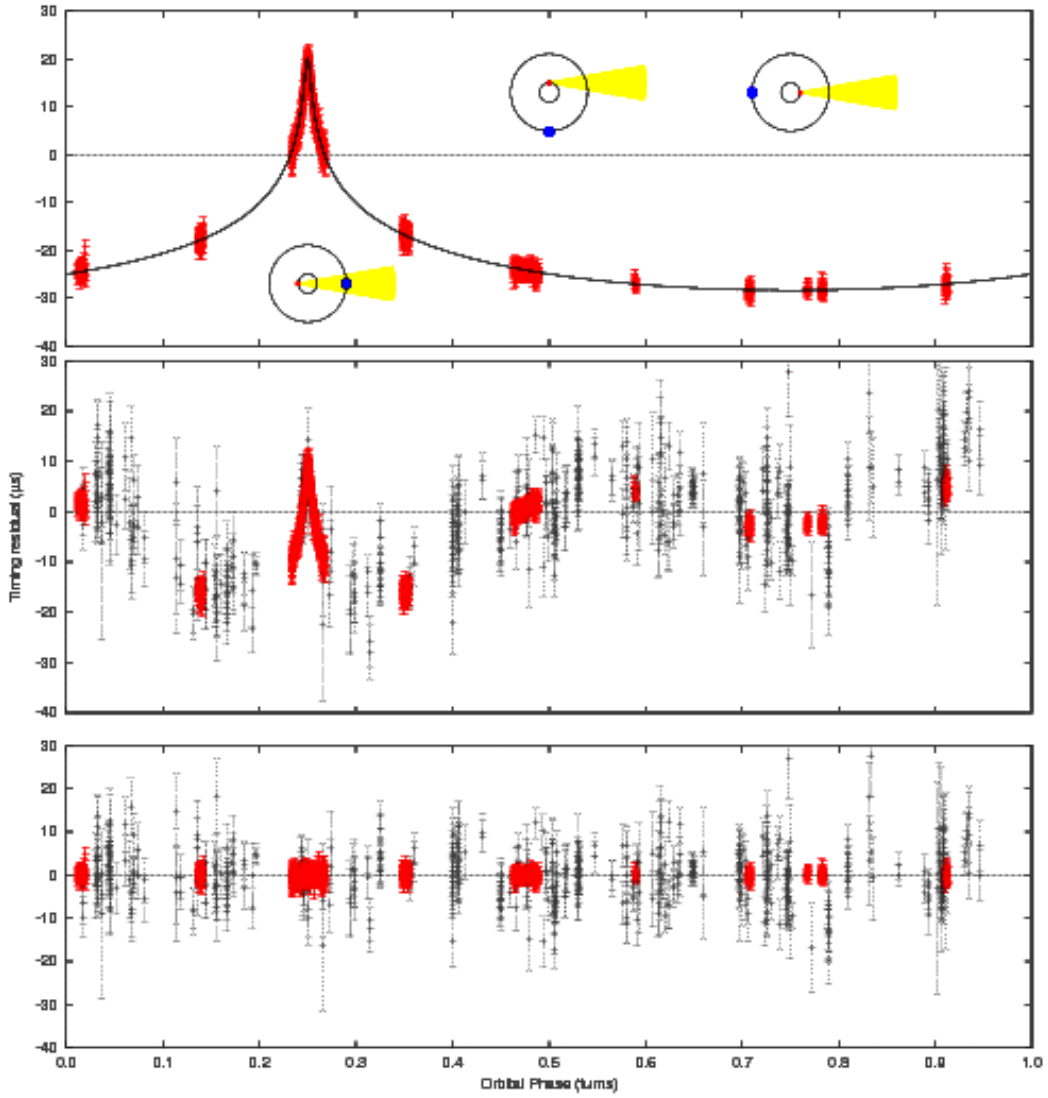
- Very tightly clustered
  M=1.35+−0.1 M_{sun}
- Does this indicate a very low upper limit on masses?
- Or are formation conditions just similar?



http://www.lsw.uni-heidelberg.de/users/mcamenzi/NS_Mass.jpg

~2 M_{sun} Neutron Stars

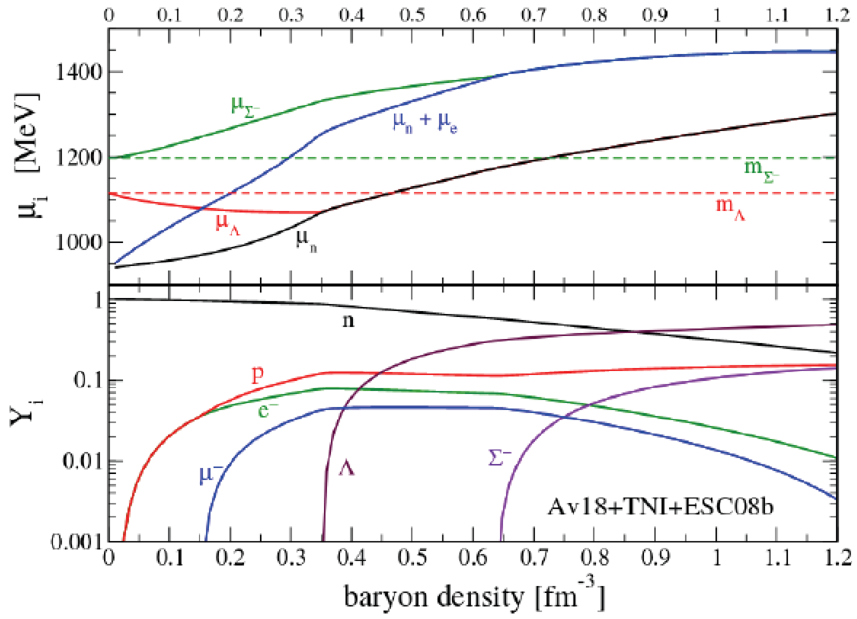
- J1614−2230, 1.908+−0.016
  Demorest et al. 2010
- J0348+0432, 2.01+−0.04 M_{sun}
  Antoniadis et al. 2013
- J0740+6620, 2.08+−0.07
  Cromartie et al. 2019
- Eliminate EOS that are too soft, i.e., whose pressure is too low at the relevant densities



Demorest et al. 2010

The Shapiro delay is a general-relativistic increase in light travel time through the curved space-time near a massive body. For highly inclined (nearly edge-on) binary millisecond radio pulsar systems, this effect allows us to infer the masses of both the neutron star and its binary companion to high precision. Here we present radio timing observations of the binary millisecond pulsar J1614-2230 that show a strong Shapiro delay signature. We calculate the pulsar mass to be (1.97+/-0.04)M_{solar}

Hyperons are expected to appear in their core at r ~ (2-3)r_o when m_N is large enough to make conversion of N to Y energetically favorable. However, this results in a reduction of the Fermi pressure exerted by the baryons and a softening of the equation of state (EOS). As a consequence, the maximum mass determined by the equilibrium condition between gravitational and nuclear forces is reduced. Most of EOS of matter containing strangeness predict a maximum neutron star mass of about 1.5 solar masses. However, the recent measurements of neutron star masses as big as 2 solar masses require a much stiffer EOS (Hyperon puzzle).



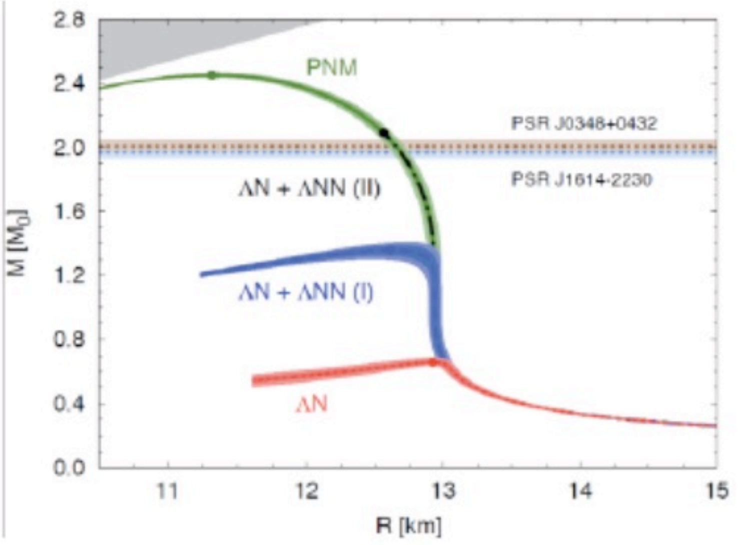
The hypothesis that Neutron Star masses cannot be greater than 1.5 solar masses derived from the assumption that the attractive interaction between Λ and nucleons, experimentally confirmed only at the normal nuclear density (ρ_0), holds true also when one deals with higher density nuclear matter.

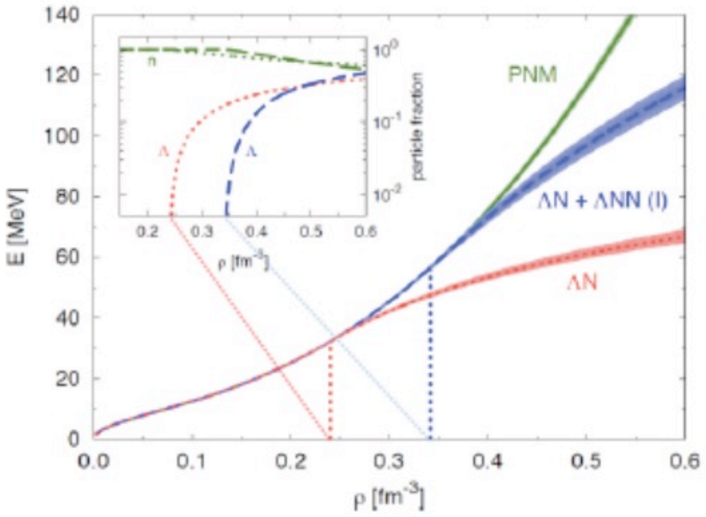
To solve the hyperon puzzle it has been suggested that three body forces could provide additional repulsion making the EOS stiffer enough.

This hypothesis is justified by the observation that realistic *NN* interaction models, which describe all the *NN* scattering data and light nuclei (by adding attractive *NNN* 3BF), fail to reproduce the nuclear saturation density ρ_0. This indicates that a repulsive, short-range 3BF is present in the interaction between nucleons.

It is natural to hence to postulate a similar repulsive Λ*NN* (and ΛΛ*N*, ΛΛΛ) interaction.

However, this has to be proved experimentally!



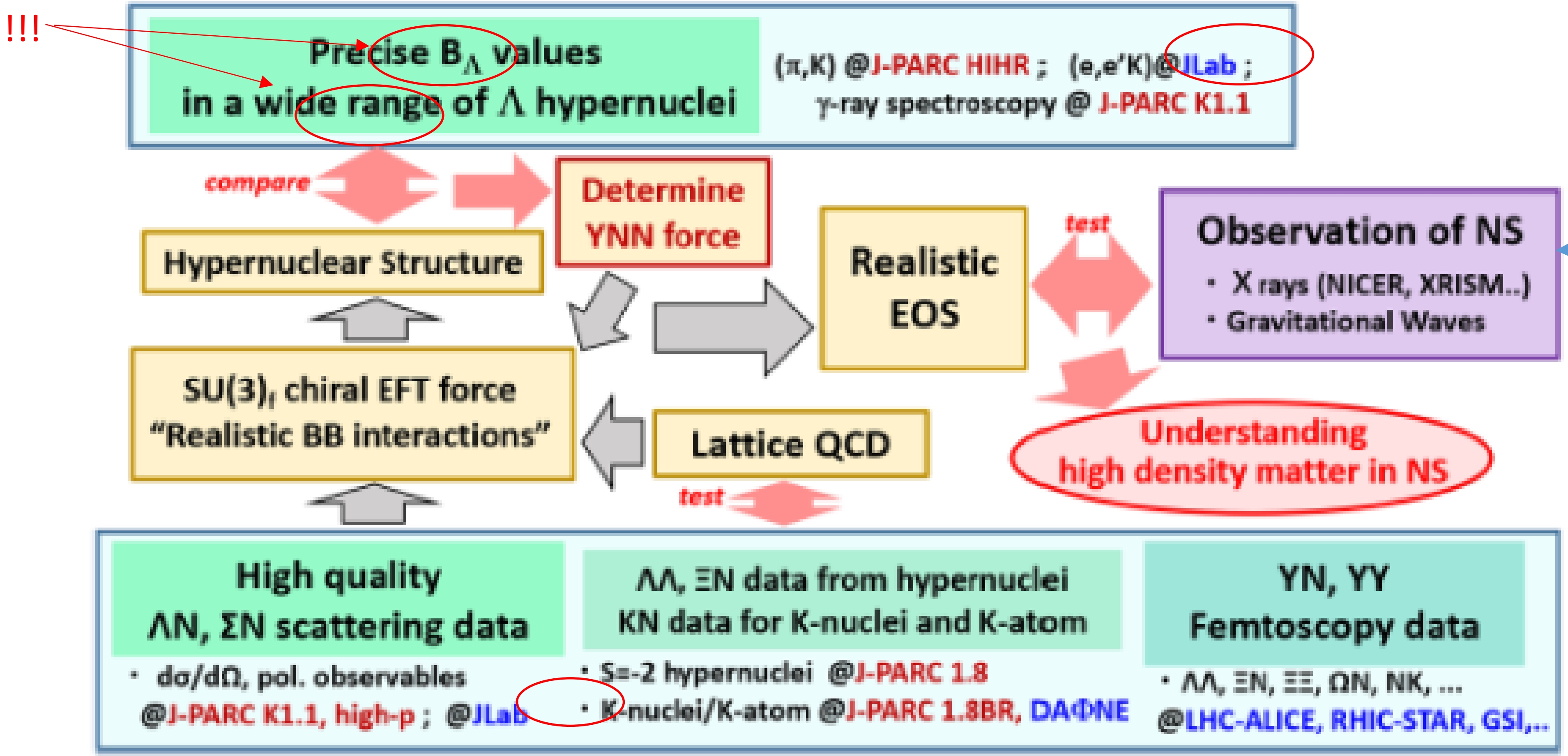


D.Lonardoni *et al.*, Phys. Rev. Lett. 114, 092301 (2015) (AFDMC)

How can we solve the hyperon puzzle?

Why is the hypernuclear spectroscopy program at Jlab so important?

Why is very important to determine ${}^{208}_{\Lambda}Tl$ binding energies in addition to ${}^{40}_{\Lambda}K$ ${}^{48}_{\Lambda}K$ ones?



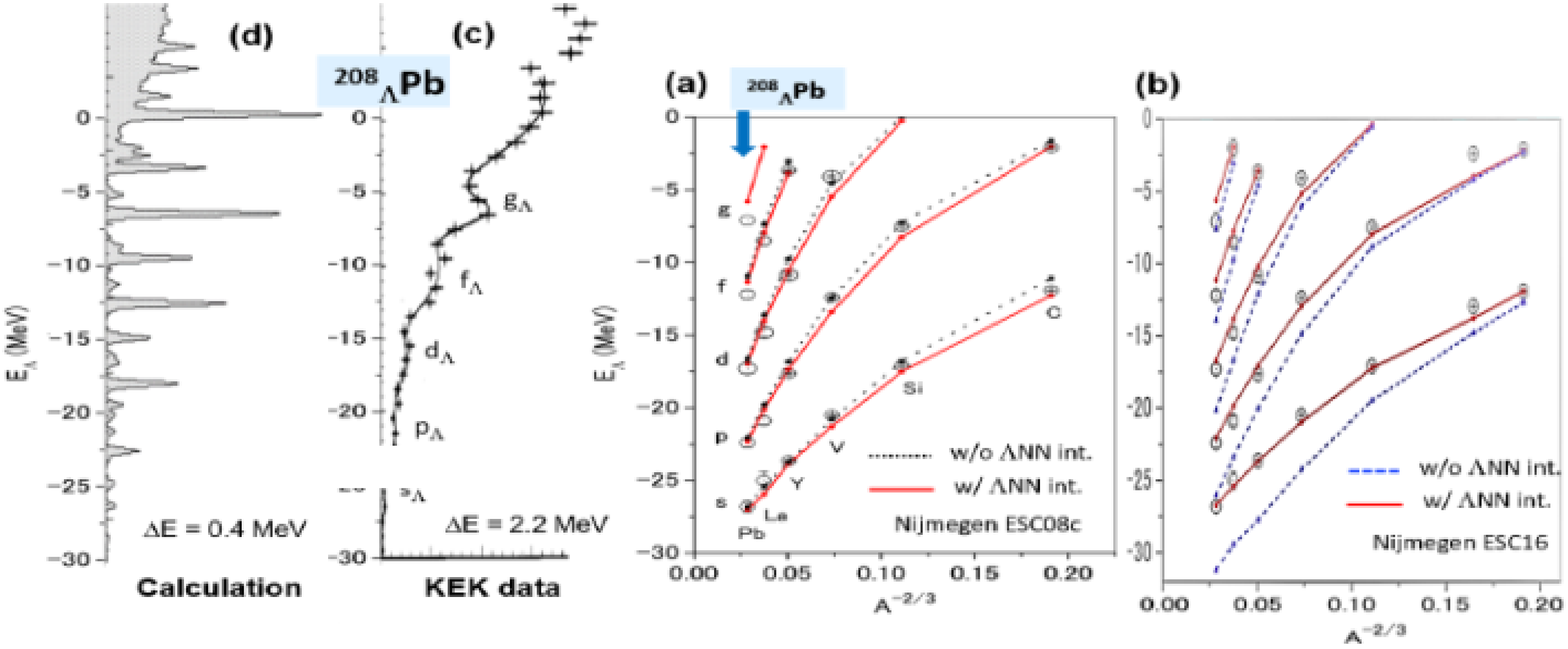
Radii of neutron stars together with their masses can be inferred from combination of multimessenger data.

From Tamura's HYP2022 Proceedings

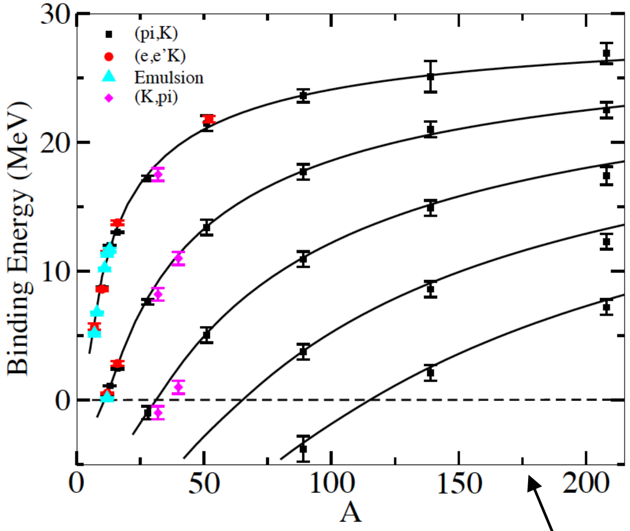
Precise B_Λ values:

@Jlab:

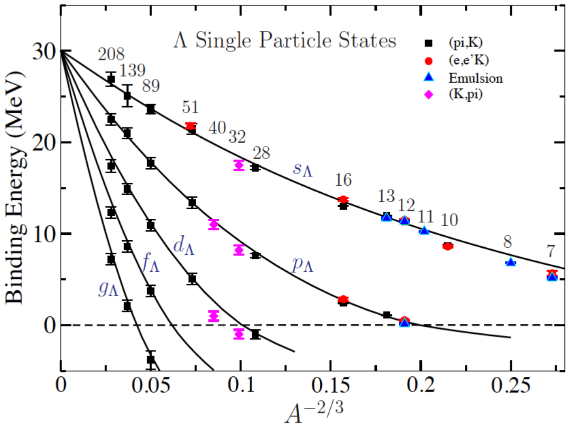
- Precise binding measurement
- High resolution apparatus



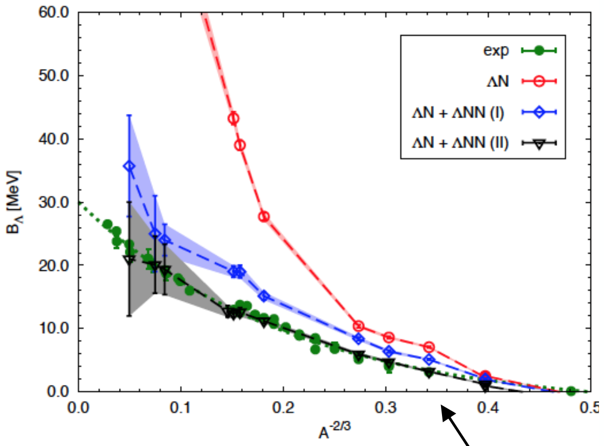
Precise B_Λ values in a wide range of Λ hypernuclei

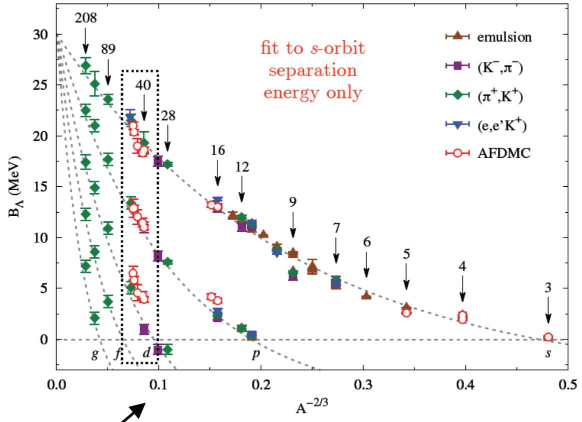


Update: Millener, Dover, Gal PRC 38, 2700 (1988)



Woods-Saxon $V = 30.05$ MeV, $r = 1.165$ fm, $a = 0.6$ fm



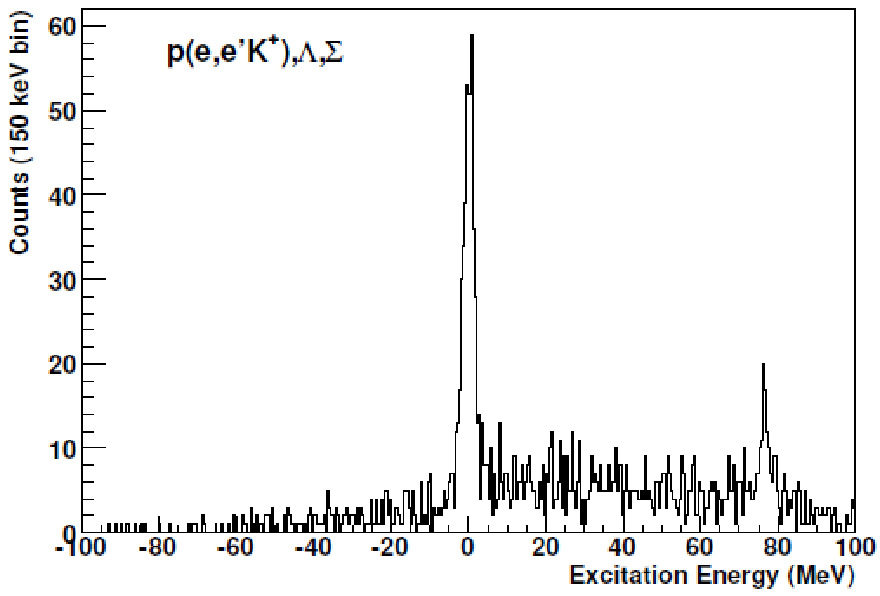


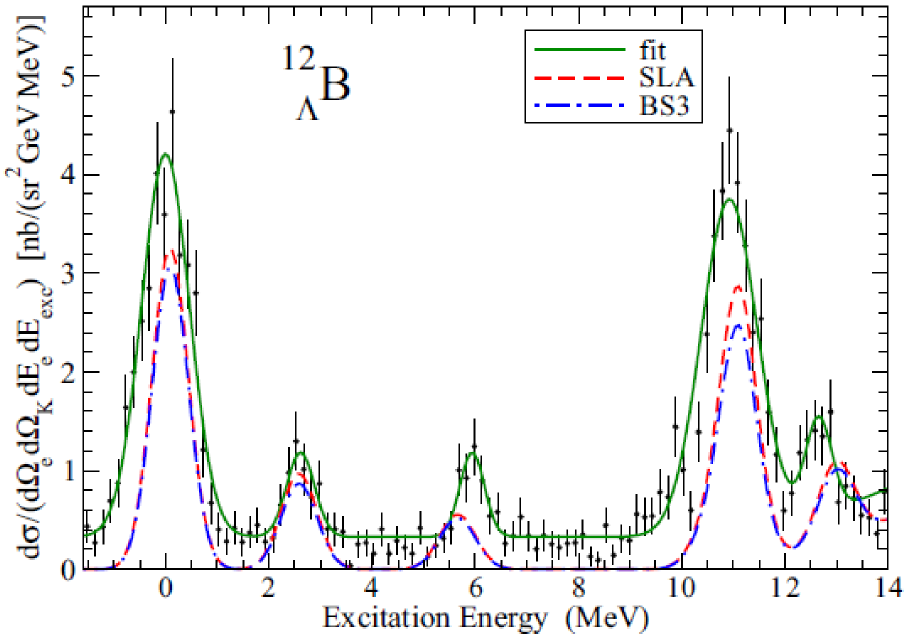
D. L. and F. Pederiva, arXiv:1711.07521

The spacing of the single-particle energies as a function of *A* put more constraints on the theoretical fits.

A satisfactory description of the hyperon separation energies in a wide mass range and for the Λ occupying different single particle state orbitals (s, p and d wave) has be obtained recently by auxiliary field diffusion Monte Carlo (AFDMC), using a phenomenological interaction in which the two-body potential has been fitted on the existing Λp scattering data and with the inclusion of the three-body ΛNN force. However, these potential models predicting relatively small differences in the Λ separation energies of hypernuclei give dramatically different results as for the properties of the infinite medium

Features of the hypernuclear spectroscopy performed through ${}^{A}Z(e,e'K^{+})^{A}_{\Lambda}(Z-1)$ reactions:





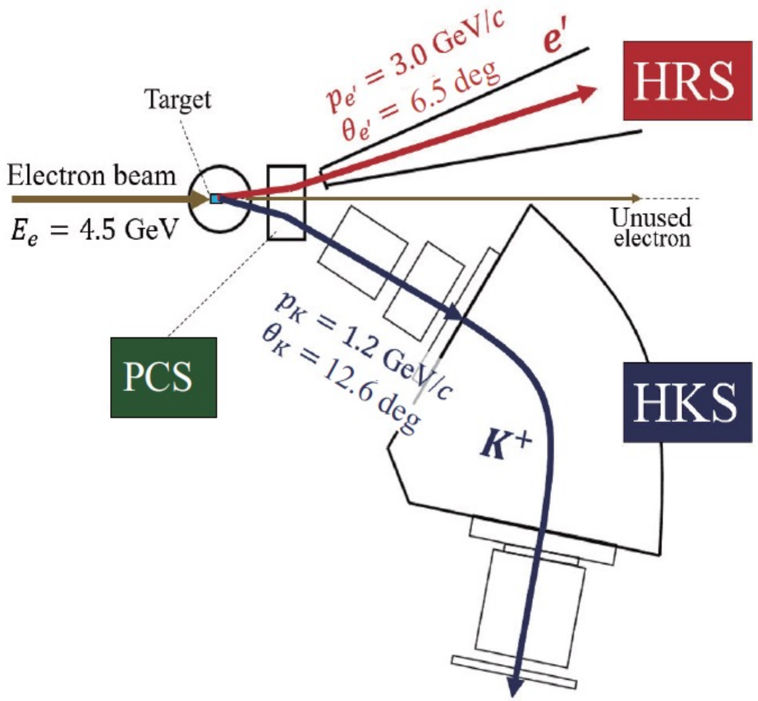
Energy calibration

Thanks to the availability of Hydrogen targets and hence to the possibility to determine the excitation energy spectrum of the reaction: ${}^{1}H(e,e'K^{+})\Lambda,\Sigma$ it is possible to obtain very good energy calibration and hence to determine very precisely binding energies

Energy resolution:

thanks to high resolution spectrometers and the high monochromatic incident electron beam sub-MeV energy resolutions were obtained at Jlab

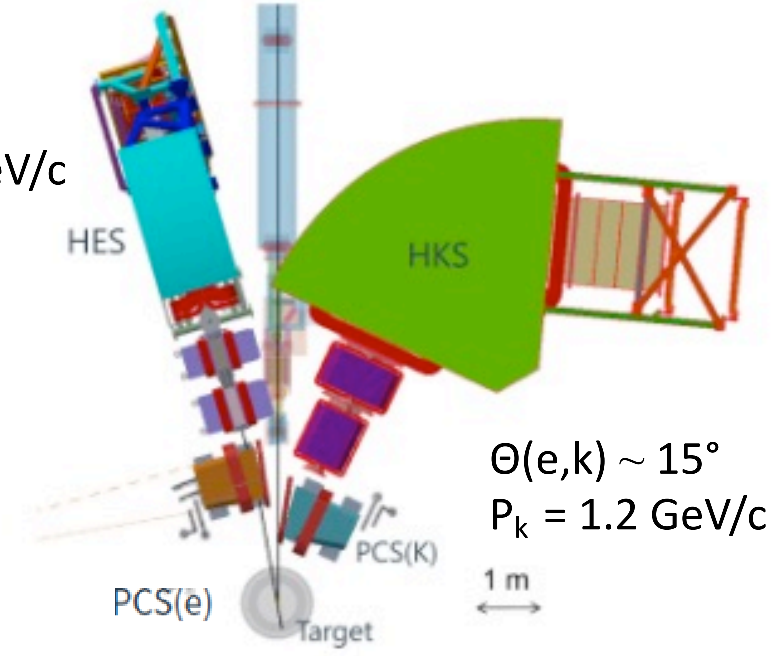
Experimental setup and kinematics as originally planned (the experiment was supposed to run in Hall A)



Beam	$\Delta p/p$ E_e	$< 1 \times 10^{-4}$ FWHM 4.5 GeV
PCS + HRS (e')	D(PCS) + QQDQ	
	$\Delta p/p$	2.6×10^{-4} FWHM
	$p_{e'}$	3.0 GeV$/c \pm 4.5\%$
	$\theta_{ee'}$	6.5 ± 1.5 deg
	Solid angle $\Omega_{e'}$	2.4 msr
PCS + HKS (K^+)	D(PCS) + QQD	
	$\Delta p/p$	4.2×10^{-4} FWHM
	p_K	1.2 GeV$/c \pm 10\%$
	θ_{eK}	12.6 ± 4.5 deg
	Solid angle Ω_K	7 msr
	Optical length	12 m
	K^+ survival ratio	26%

The new Experimental setup and kinematics after moving in Hall C

$\Theta(e,e') \sim 8°$
$P_{e'} = 0.84$ GeV/c

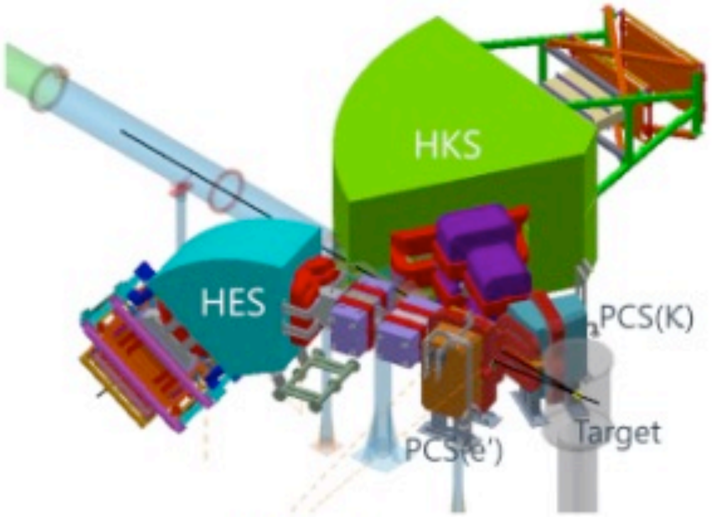


$\Theta(e,k) \sim 15°$
$P_k = 1.2$ GeV/c

(a) Top view

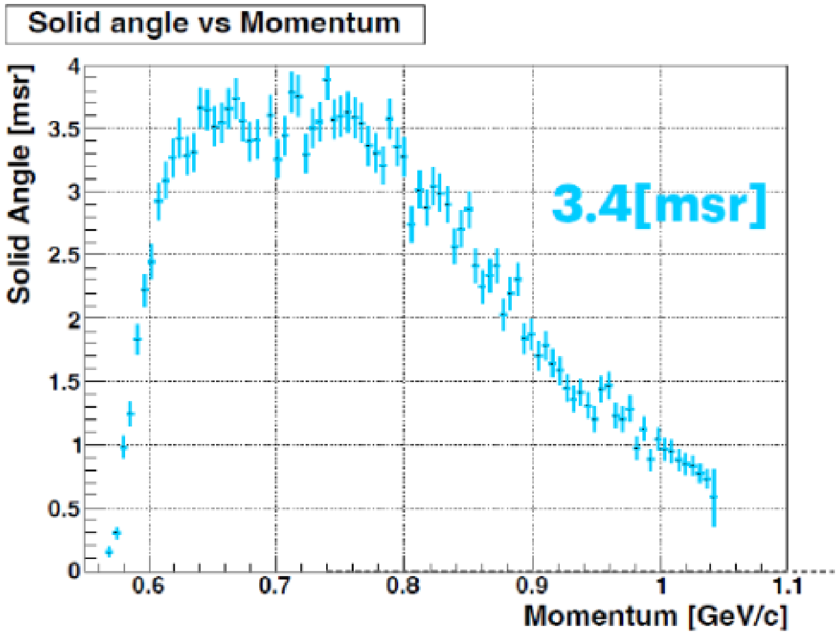
e

$E_e \sim 2.24$ GeV

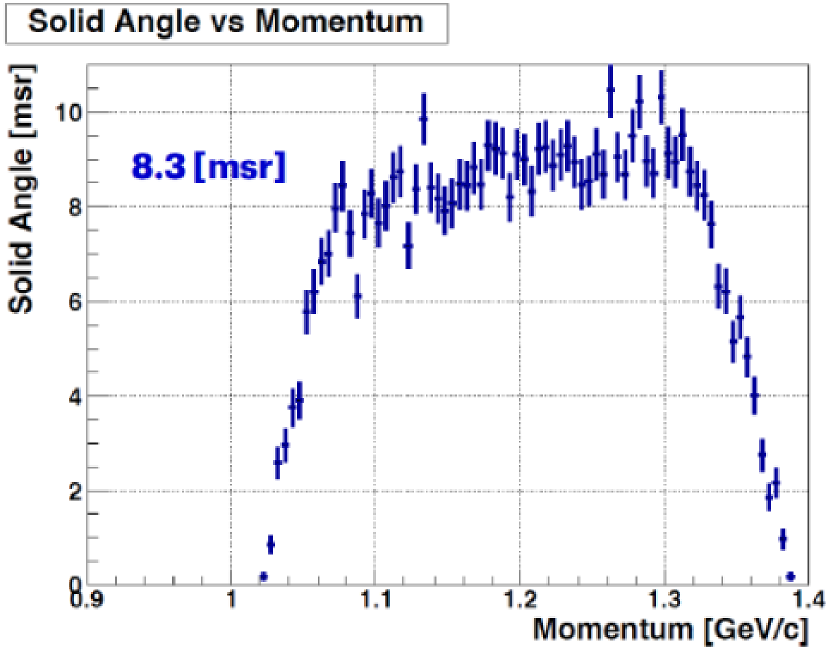


(b) Bird's eye view

Beam	Energy E_e (GeV)	2.240
	Energy stability $\Delta E_e/E_e$	3×10^{-5}
PCS + HES	Central momentum P_e (GeV/c)	0.744
	Central angle $\theta_{e,e'}$ (deg)	8
	Solid angle $\Delta\Omega_{e'}$ (msr)	3.4
	Momentum resolution $\Delta P_{e'}/P_{e'}$	4.4×10^{-4}
PCS + HKS	Central momentum P_K (GeV/c)	1.200
	Central angle θ_K (deg)	15
	Solid angle $\Delta\Omega_K$ (msr)	8.3
	Momentum resolution $\Delta P_K/P_K$	2.9×10^{-4}

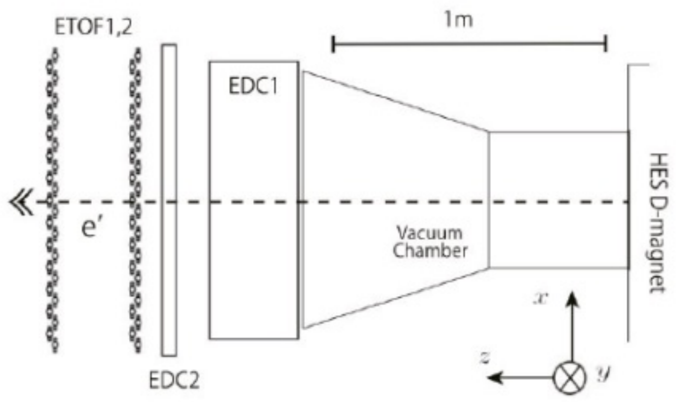


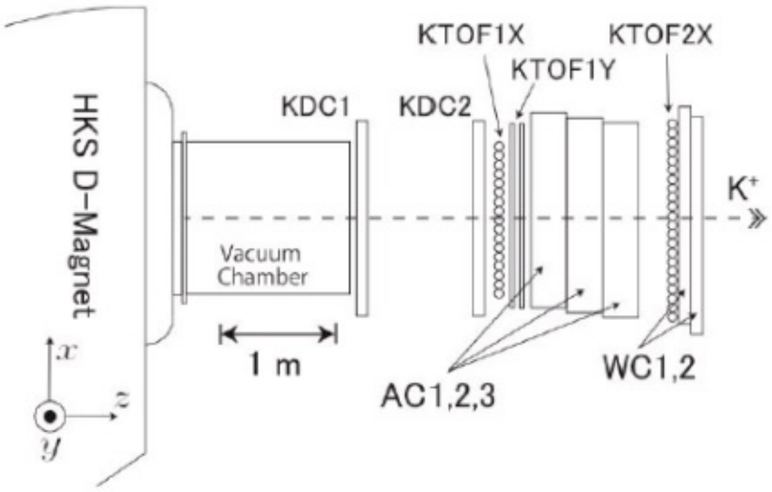
(a) PCS + HES (electron arm)



(b) PCS + HKS (kaon arm)

Detector setup





HES

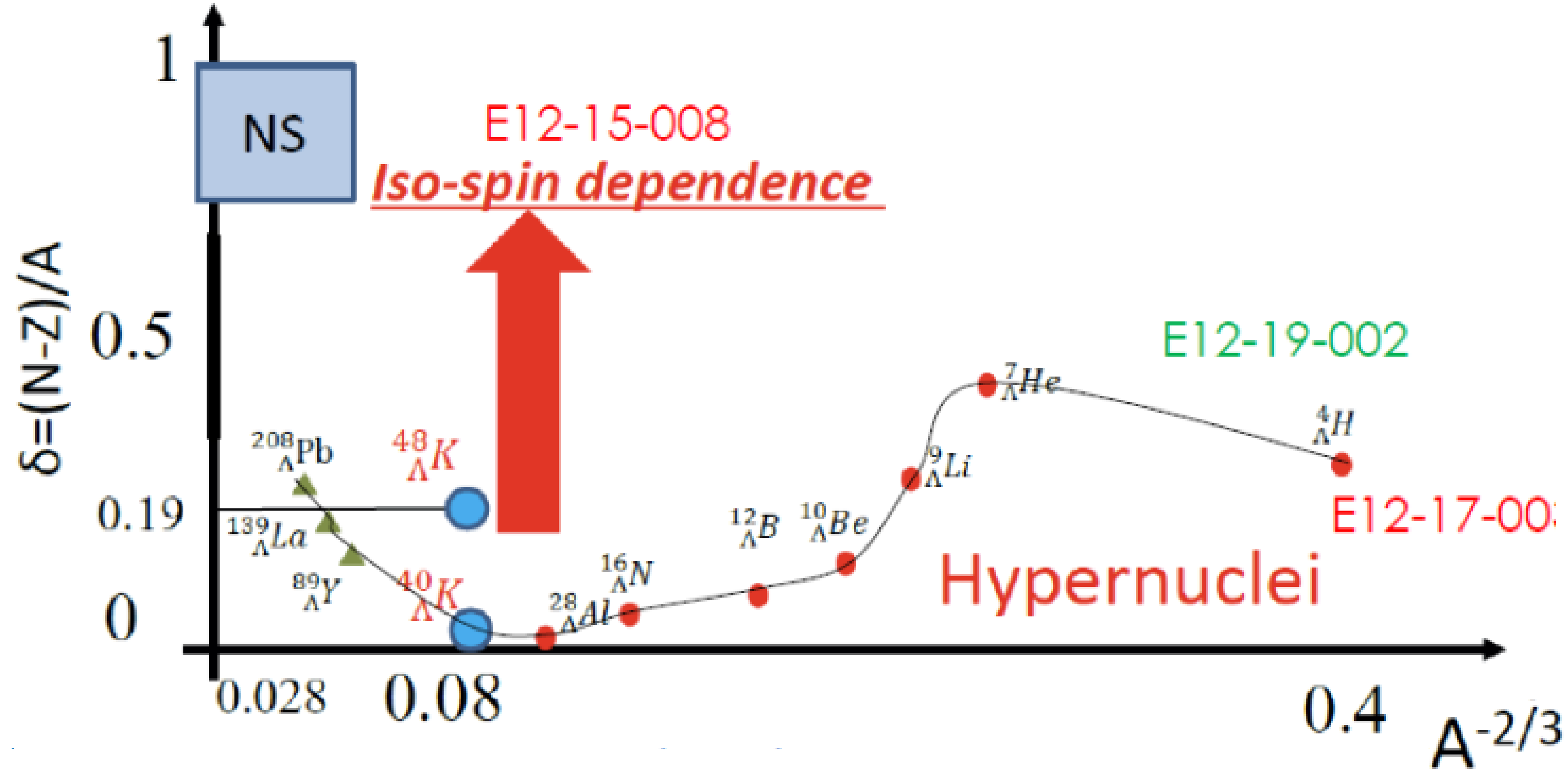
HKS

The detector setup of the experiment E12-20-013 at Jlab is the same as the one employed by the other hypernuclear experiments planned in Hall C (see Toshi's and Sho's talks) but the target used.

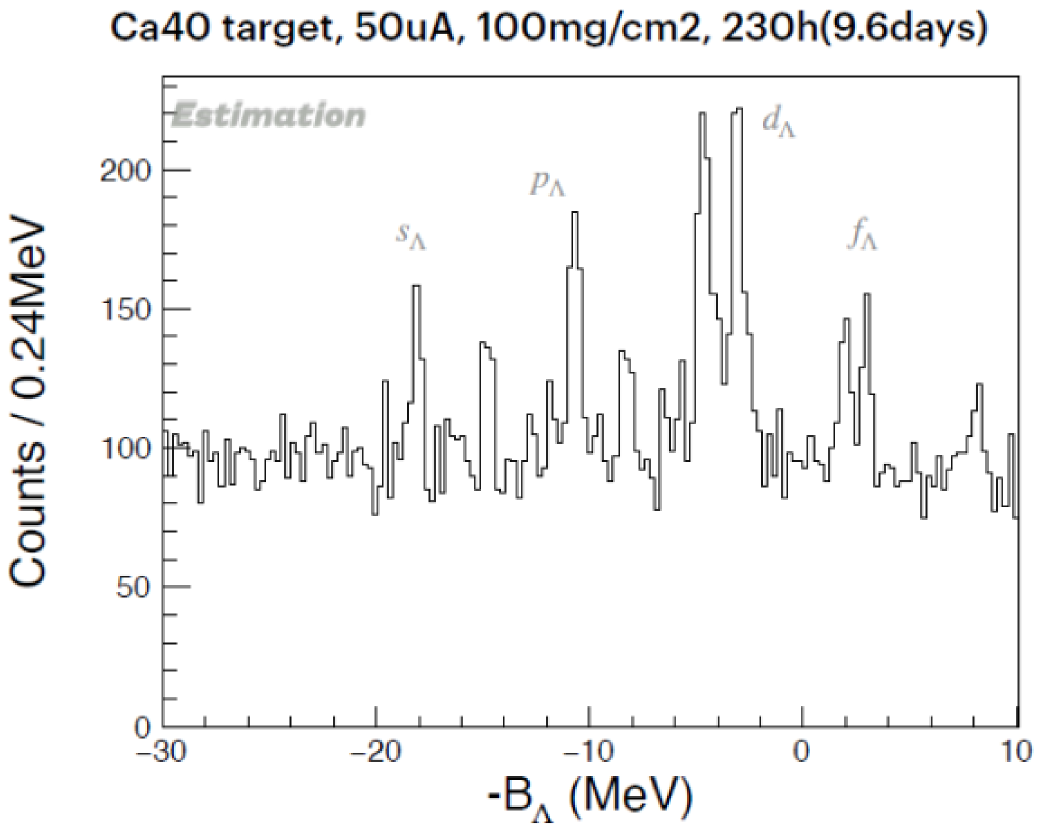
Experiment E12-15-008 at Jlab:

An isospin dependence study of the Lambda-N interaction through the high precision spectroscopy of Lambda hypernuclei with electron beam

Spokesperson:
F. Garibaldi, T. Gogami, S.N. Nakamura, P. Markowitz, S. Nagao,
J. Reinhold, L. Tang, G. M. Urciuoli



1
NS
E12-15-008
Iso-spin dependence
δ=(N-Z)/A
0.5
E12-19-002
$^{7}_{\Lambda}He$
$^{4}_{\Lambda}H$
$^{208}_{\Lambda}Pb$
$^{48}_{\Lambda}K$
$^{9}_{\Lambda}Li$
0.19
E12-17-00
$^{139}_{\Lambda}La$
$^{12}_{\Lambda}B$
$^{10}_{\Lambda}Be$
$^{16}_{\Lambda}N$
$^{89}_{\Lambda}Y$
$^{40}_{\Lambda}K$
Hypernuclei
$^{28}_{\Lambda}Al$
0
0.028
0.08
0.4
$A^{-2/3}$



Ca40 target, 50uA, 100mg/cm2, 230h(9.6days)
Estimation
s_Λ
p_Λ
d_Λ
f_Λ
Counts / 0.24MeV
$-B_\Lambda$ (MeV)

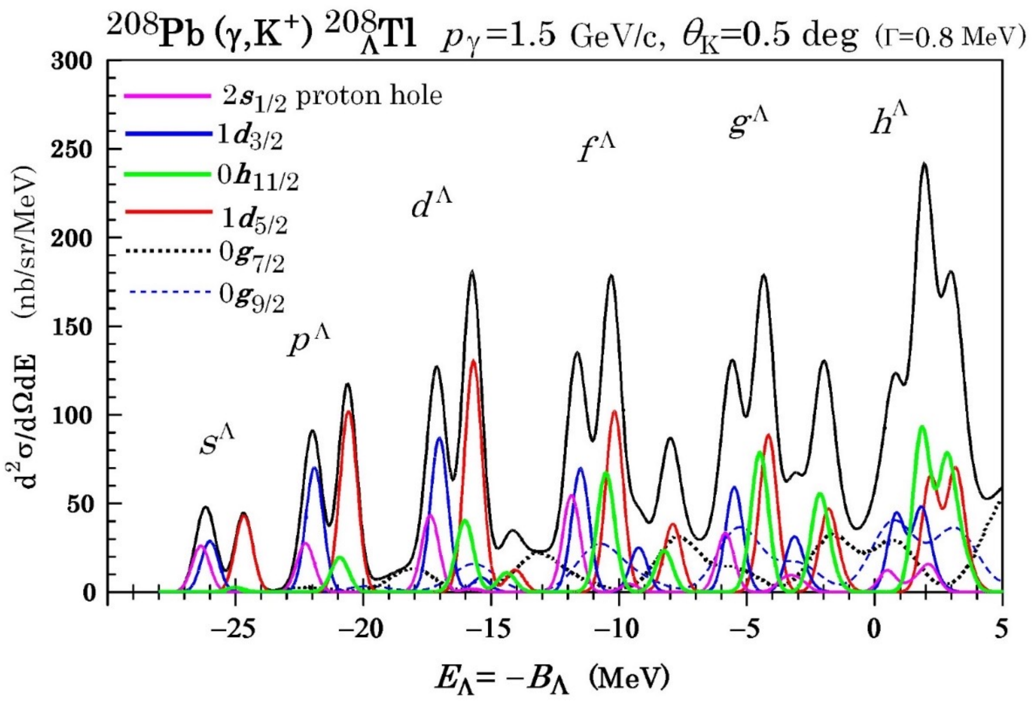
Experiment E12-20-013 at Jlab:

studying Λ interactions in nuclear matter with the $^{208}Pb(e,e'K^+)^{208}_{\Lambda}Tl$ reaction

Spokespersons:

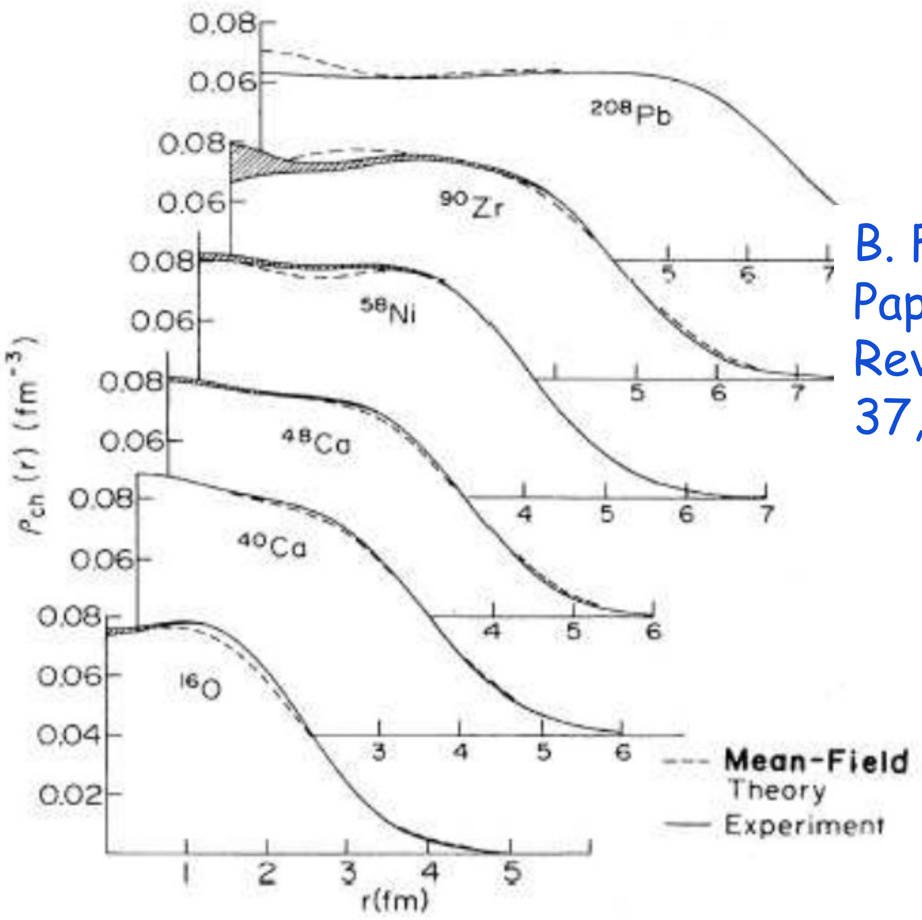
F. Garibaldi, O. Benhar Noccioli, T. Gogami, P. Markowitz, S. Nakamura, J. Reinhold, L. Tang, G. Urciuoli

The expected spectrum: theoretical calculation



Millener-Motoba calculations performed for the kinematics of the experiment E12-20-013 using the Saclay Lyon elementary amplitudes. The Λ is assumed to be weakly coupled to the proton-hole states of ^{207}Tl strongly populated in (e,e'p) or (d,3He) reactions on ^{208}Pb. The Λ single-particle energies were calculated from a Woods-Saxon well fitted to energies derived from the $^{208}Pb(\pi^{+},K^{+})^{208}_{\Lambda}Pb$

Λ interactions in a uniform nuclear medium (1)

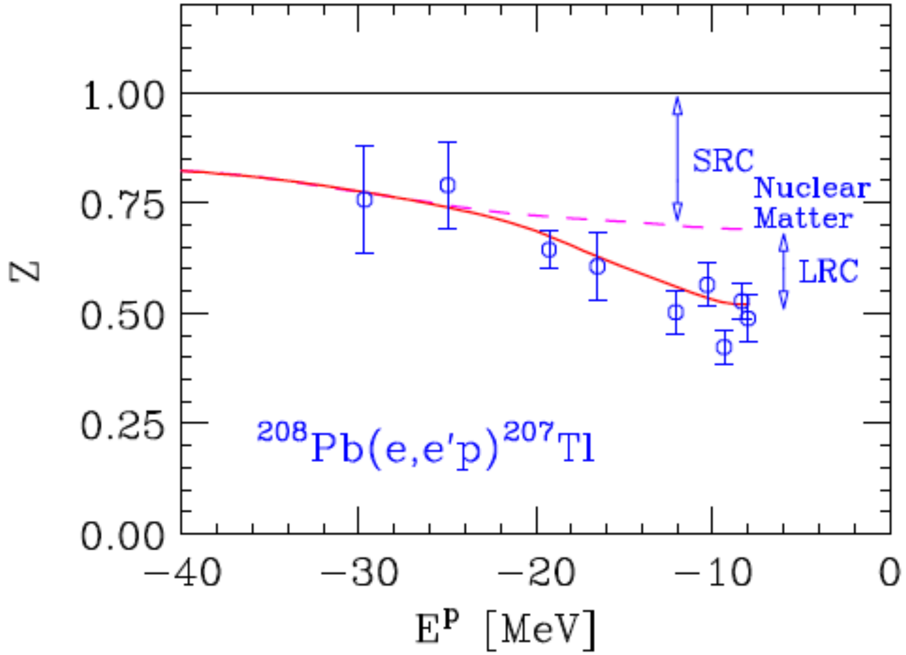


B. Frois and C.N. Papanicolas, Ann. Rev. Nucl. Part. Sci. 37, 133 (1987)

The measured charge density distribution of ^{208}Pb clearly shows that the region of nearly constant density accounts for a very large fraction (~70 %) of the nuclear volume, thus suggesting that its properties largely reflect those of uniform nuclear matter in the neutron star

The validity of this conjecture has been long established by a comparison between the results of theoretical calculations and the data extracted from the ^{208}Pb(e,e´p)^{207}Tl cross sections measured at NIKHEF in the 1990s

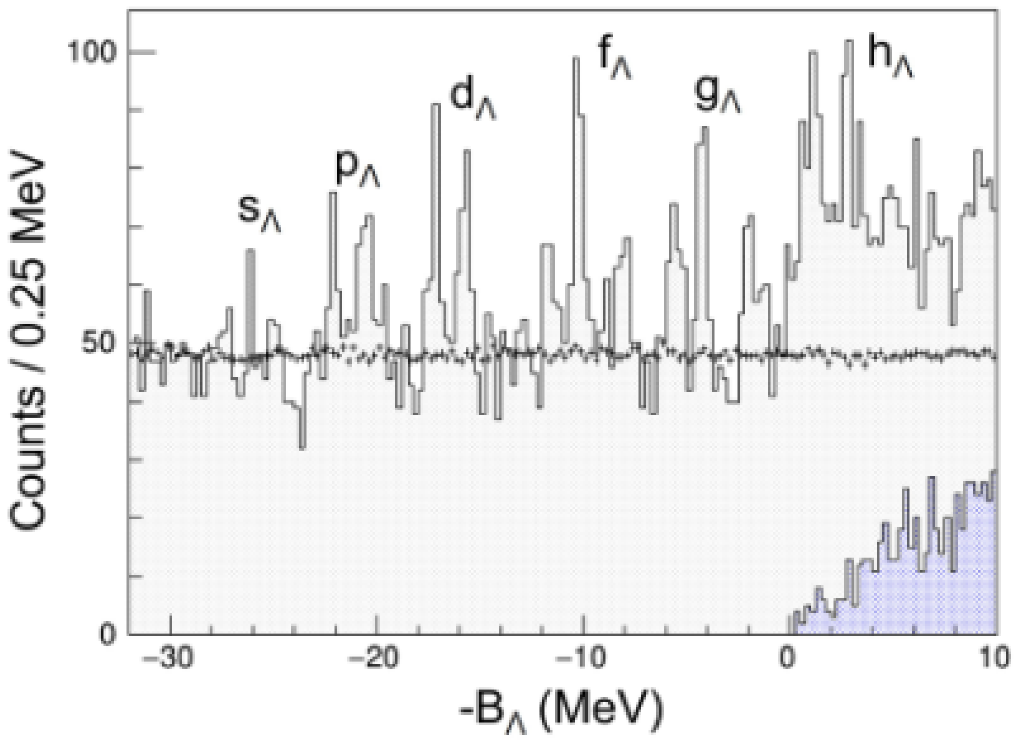
Λ interactions in a uniform nuclear medium (2)



The energy dependence of the spectroscopic factors extracted from the measured $^{208}Pb(e,e'p)^{207}Tl$ cross sections compared to the theoretical results shows that short-range correlations appear to be the most important mechanism leading to the observed quenching of the spectroscopic factor, while surface and shell effects only play an important role in the vicinity of the Fermi surface

Deeply bound protons in the ^{208}Pb ground state are largely unaffected by finite size and shell effects and behave as if they were in nuclear matter

The expected spectrum:
Montecarlo simulations



Expected binding-energy spectrum for the $^{208}Pb(e,e'K^+)^{208}_{\Lambda}Tl$ reaction with the resolution of 0.6MeV in FWHM. Beam time of 480 hours with the beam intensity of 25 μA is assumed.

Expected binding energy spectrum resolution: 0.6 MeV

Expected $|\Delta B_\Lambda| < 100$ keV (≈ 50 keV)

Experiment Beam Time requests

12-15-008

An isospin dependence study of the Lambda-N interaction through the high precision spectroscopy of Lambda hypernuclei with electron beam

Target (Hyper Nucleus)	Beam current (μA)	Target thickness (mg/cm^2)	Assumed cross section (nb/sr)	Expected yield (/h)	Num. of events	Req. beamtime (hours)	B.G. rate (/MeV/h)	S/N	Comments
CH_2	2	500	1000	8.62	1000	120	0.03	290	Calibration
^{6}Li	50	150	10	1.51	—	—	0.86	1.7	Separate LoI
^{9}Be	50	150	10	1.01	—	—	0.84	1.25	Separate LoI
^{11}B	50	150	30	2.47	—	—	0.96	2.57	Separate LoI
^{12}C	50	150	90	6.79	1100	168	1.20	5.67	Calibration
^{27}Al	50	150	60	3.88	330	168	1.06	1.87	Calibration
Subtotal						456			Calibration
^{40}Ca ($^{40}_{\Lambda}$K)	50	150	50	1.13	520	456	2.41	0.47	Physics
^{48}Ca ($^{48}_{\Lambda}$K)	50	150	50	0.94	520	552	1.89	0.50	Physics
Subtotal						1008			Physics
Total						1464			

E12-20-013

studying Λ interactions in nuclear matter with the $^{208}Pb(e,e'K^+)^{208}_{\Lambda}Tl$ reaction

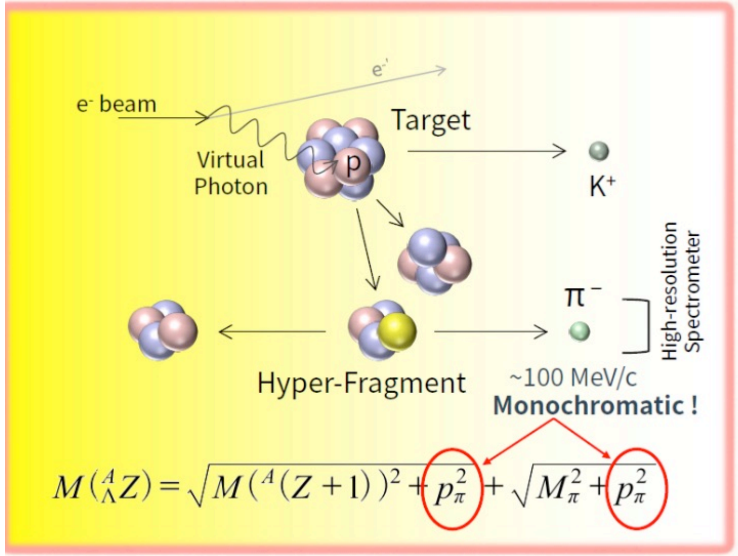
Yields estimation and beam time requirement.

Target and objective hypernucleus	Beam current (μA)	Target thickness (mg/cm^2)	Assumed cross section (nb/sr)	Expected Yield (/hour)	Num. of events	Req. beamtime (hours)	B.G. Rate (/MeV/h)	S/N (±4 σ)	Comments
CH_2	2	500	200	19	1000	54	0.05	252	Calibration
^{6,7}Li	50	100	10	5.4	150	28	1.3	4.9	Calibration
^{9}Be	100	100	10	36	300	9	4.7	8.8	Calibration
^{10,11}B	25	100	10	16	150	19	0.29	33	Calibration
^{12}C	100	100	100	54	2000	37	4.4	17	Calibration
Subtotal for calibration						147			
^{208}Pb	**25**	**100**	**80(g.s.)**	**0.3**	**145**	**480**	**0.1**	**21**	**Production**

Likely experiment E12-20-013 beam time request has to be increased

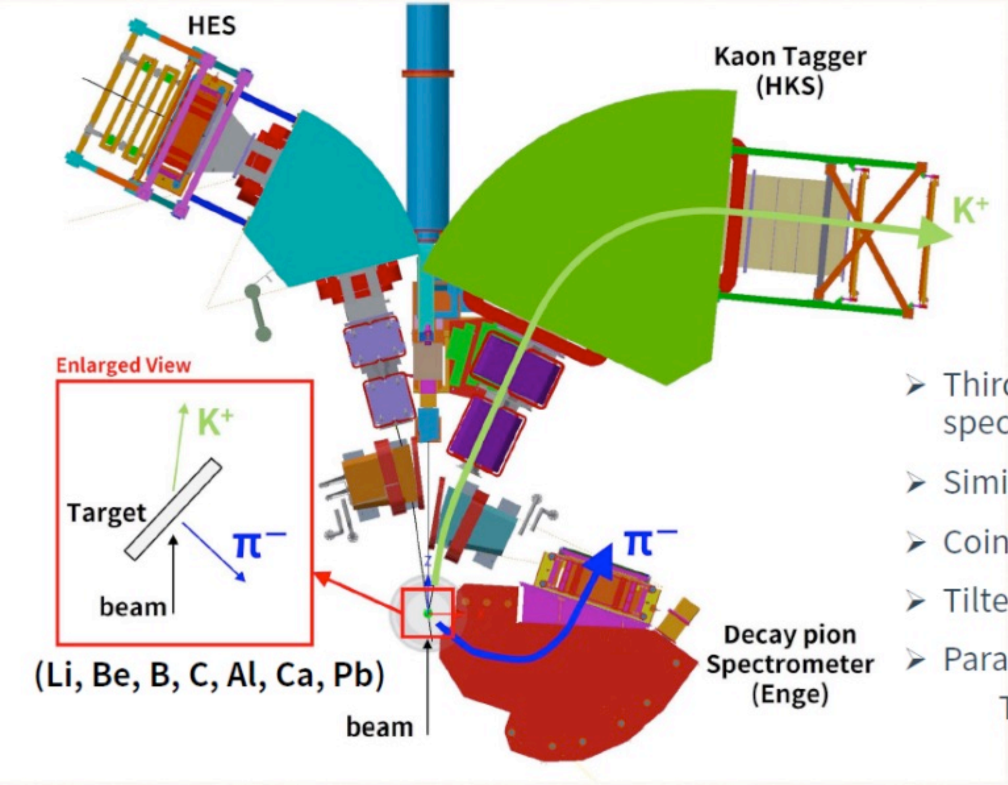
LOI12-23-011

High-resolution spectroscopy of light hypernuclei with the decay-pion spectroscopy

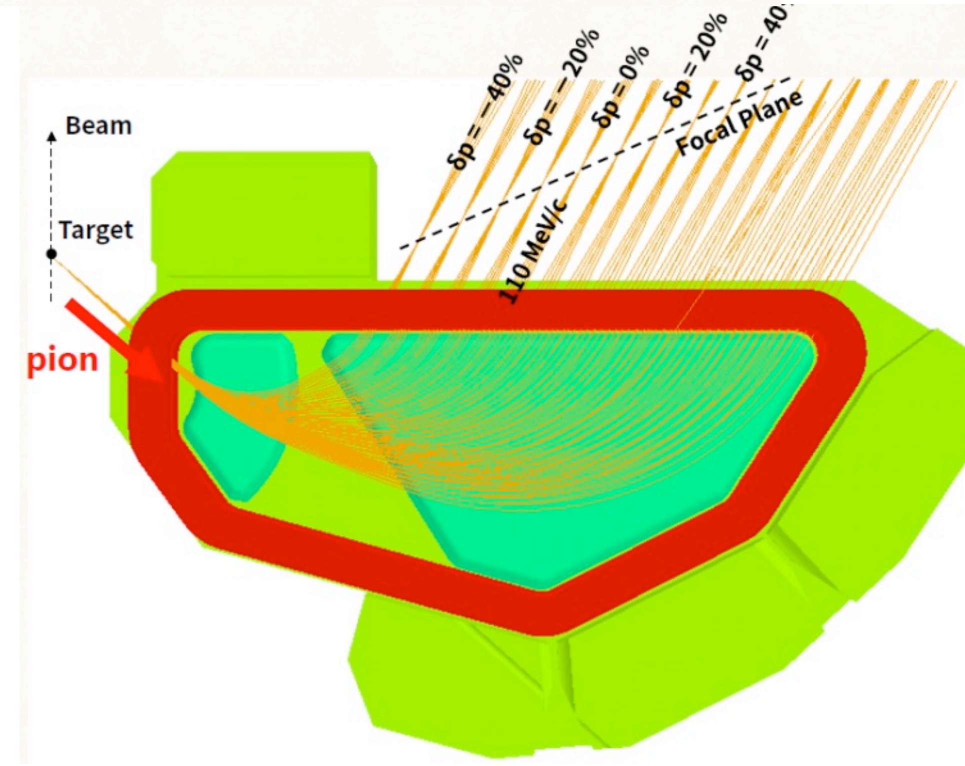


$$M({}^{A}_{\Lambda}Z) = \sqrt{M({}^{A}(Z+1))^2 + p_\pi^2} + \sqrt{M_\pi^2 + p_\pi^2}$$

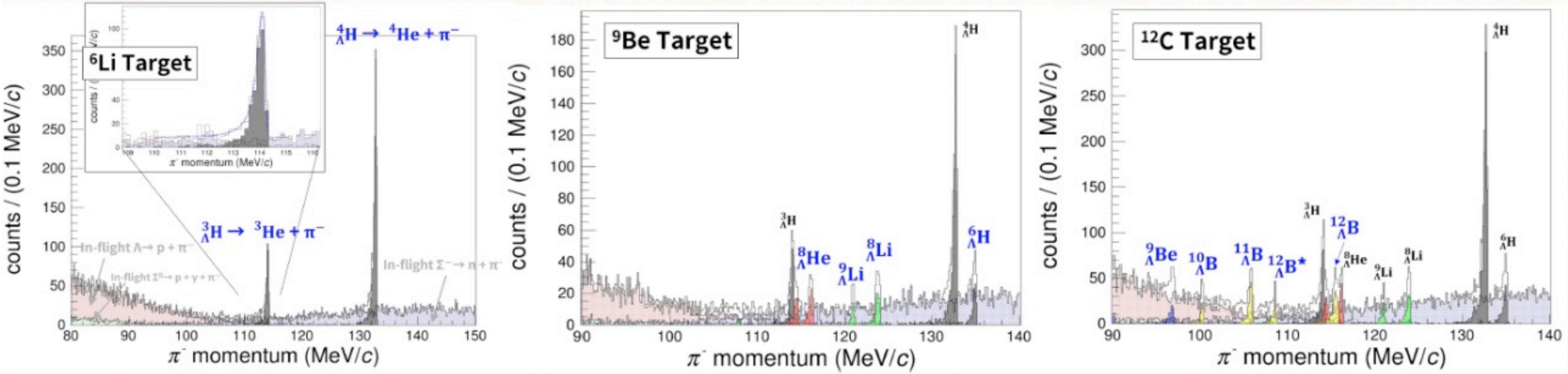
- High-resolution & High-precision hypernuclear mass spectroscopy
  - Stopping in a target
  - Two-body decay with π^- & nucleus → hypernuclear ground-state
- Momentum resolution Δp ~ 0.1 MeV/c
- Mass precision ΔM ~ 0.01 MeV/c²
- Good calibration sources
- Tagging Kaon



- Third spectrometer (Enge) as a decay-pion spectrometer
- Similar concept to MAMI exp.
- Coincidence measurement of "π⁻, K⁺"
- Tilted targets
- Parallel exp. with the (e,e'K⁺) exp.
  Trigger "HES⊗HKS ⊕ Enge⊗HKS"



The expected spectra



- 300 keV/c (FWHM) peak resolution, <keV precision for $^4{}_\Lambda$H (stability check is available)
- Yields were estimated by using MAMI results, AMD calc. [Y.Nara's calc. in A.Kawachi Ph.D thesis (U-Tokyo)], and shell-model calc[NPA 489 (1988) 683.].
- Li target: Measurement of s-shell hypernuclei. Benchmark
- Be target: Interesting n-rich hypernuclei
- C target: Additional p-shell hypernuclei

LOI12-23-013

Study of charge symmetry breaking in p-shell hypernuclei

determine the energies of ground-state peaks of ${}^{6}_{\Lambda}$He, ${}^{9}_{\Lambda}$Li, and ${}^{11}_{\Lambda}$Be with the accuracy of $|\Delta B_{\Lambda}^{\text{total}}| = 70$ keV for the study of CSB.

Electron-beam experiment at JLab (VP) — Emulsion experiment (E)
Hadron-beam experiment at J-PARC (H) — γ-ray experiment (Y)

Hypernucleus			T<0	T=0	T>0	CSB study Now	New JLab	J-PARC
s-shell	dNΛ	(0^{+})	${}^{4}_{\Lambda}$H		${}^{4}_{\Lambda}$He	○	○	○
		(1^{+})	new			△	●	●
p-shell	αNΛ		${}^{6}_{\Lambda}$He new		${}^{6}_{\Lambda}$Li new			●
	αNNΛ		${}^{7}_{\Lambda}$He	${}^{7}_{\Lambda}$Li*	${}^{7}_{\Lambda}$Be	○	○	○
	αdNΛ		${}^{8}_{\Lambda}$Li		${}^{8}_{\Lambda}$Be	○	○	○
	αdNNΛ		${}^{9}_{\Lambda}$Li new	${}^{9}_{\Lambda}$Be	${}^{9}_{\Lambda}$B		●	●
	ααNΛ		${}^{10}_{\Lambda}$Be		${}^{10}_{\Lambda}$B new			●
	ααNNΛ		${}^{11}_{\Lambda}$Be new	${}^{11}_{\Lambda}$B new	${}^{11}_{\Lambda}$C		●	●
	ααdNΛ		${}^{12}_{\Lambda}$B		${}^{12}_{\Lambda}$C new			●

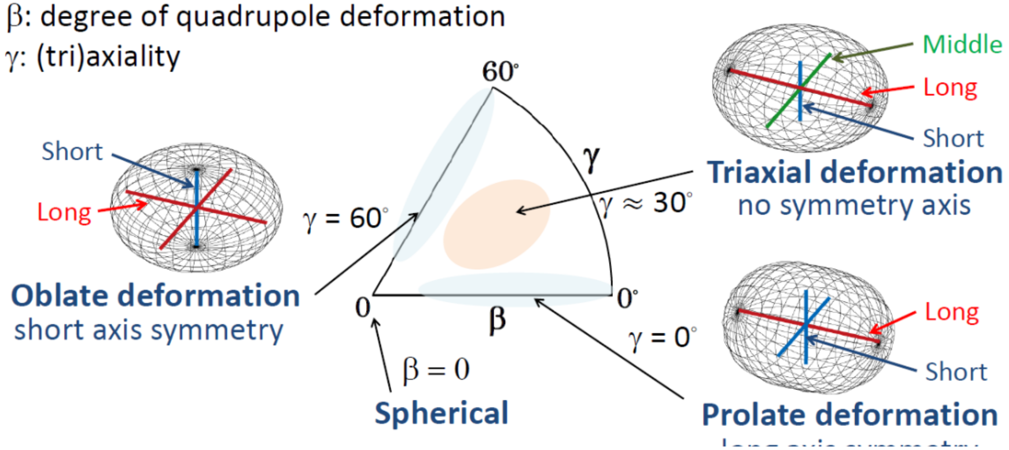
LOI12-23-016

Study of a triaxially deformed nucleus using a Lambda particle as a probe

Description of nuclear deformation

◆Nuclear quadrupole deformation (β,γ)

- β: degree of quadrupole deformation
- γ: (tri)axiality



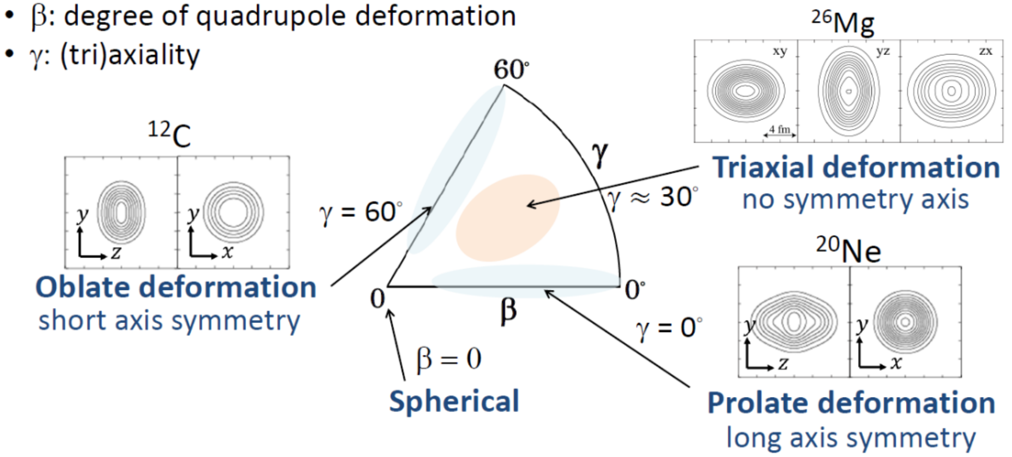
What is expected in deformed Λ hypernuclei

- **Deformation change**
  - Λ particle can change nuclear deformation
- **Difference of B_Λ depending on nuclear deformation**
  - Energy shifts in excitation spectra
- **Coupling of Λ to deformed nuclei shows unique structure**
  - For example, rotational band, mixing of configuration, … etc.

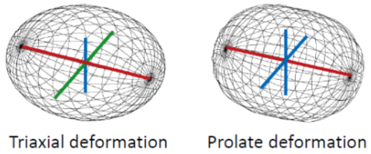
Description of nuclear deformation

◆Nuclear quadruple deformation (β,γ)

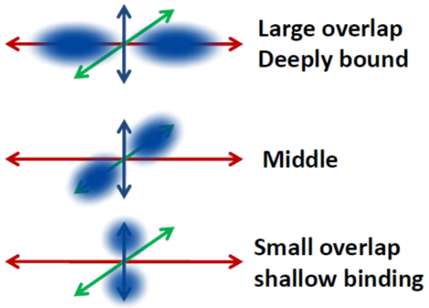
- β: degree of quadrupole deformation
- γ: (tri)axiality



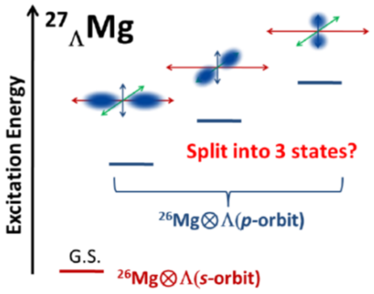
Triaxial deformation



If nucleus is triaxially deformed,
***p*-states can split into 3 different state**



Candidate: Mg hypernuclei



Observing the 3 different *p*-states is strong evidence of triaxial deformation

LOI Beam Time requests

LOI12-23-011

High-resolution spectroscopy of light hypernuclei with the decay-pion spectroscopy

Parasitically running

LOI12-23-013

Study of charge symmetry breaking in p-shell hypernuclei

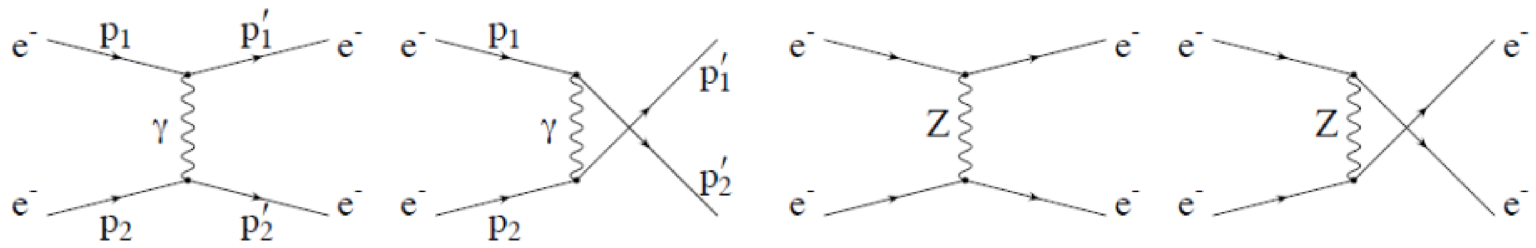
Reaction	Assumed cross section [/(nb/sr)]	Necessary beam time (/days) $I^{30}_{\rm beam} = 30\ \mu$A	$I^{50}_{\rm beam} = 50\ \mu$A	Ratio $[t(I^{50}_{\rm beam})/t(I^{30}_{\rm beam})]$ $(\times 1.7)$
$^{6}{\rm Li}(e,e'K^+)^{6}_{\Lambda}{\rm He}$	10	7	5	
$^{9}{\rm Be}(e,e'K^+)^{9}_{\Lambda}{\rm Li}$	7.6	19.5	14	$\times\frac{1}{1.4} = 0.71$
$^{11}{\rm B}(e,e'K^+)^{11}_{\Lambda}{\rm Be}$	30	3.5	2.5	

LOI12-23-016

Study of a triaxially deformed nucleus using a Lambda particle as a probe

Target (Hyper Nucleus)	Beam current (μA)	Target thickness (mg/cm^2)	Assumed cross section (nb/sr)	Expected yield (/h)	Num. of events	Req. beamtime (hours)	B.G. rate (/MeV/h)	S/N	Comments
CH_2 (Λ, Σ^0)	2	500	1000	8.62	1000	120	0.03	290	Calibration
^{12}C ($^{12}_{\Lambda}$B)	50	150	90	6.79	1100	168	1.20	5.67	Calibration
Subtotal						—			Combined with E12-15-008
^{27}Al ($^{27}_{\Lambda}$Mg)	50	100	10 (p^{Λ})	0.22	150	672	0.78	0.19	Physics
Total						672			

The MOLLER experiment will measure the parity-violating asymmetry (A_{PV}) (that is the fractional difference between right- and left-handed electrons) in the scattering of longitudinally polarized electrons on unpolarized target electrons

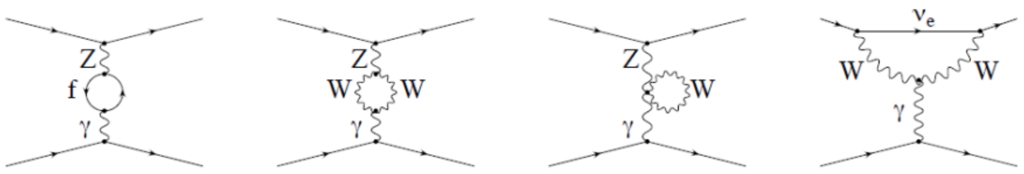


Feynman diagrams for Møller experiment at tree level

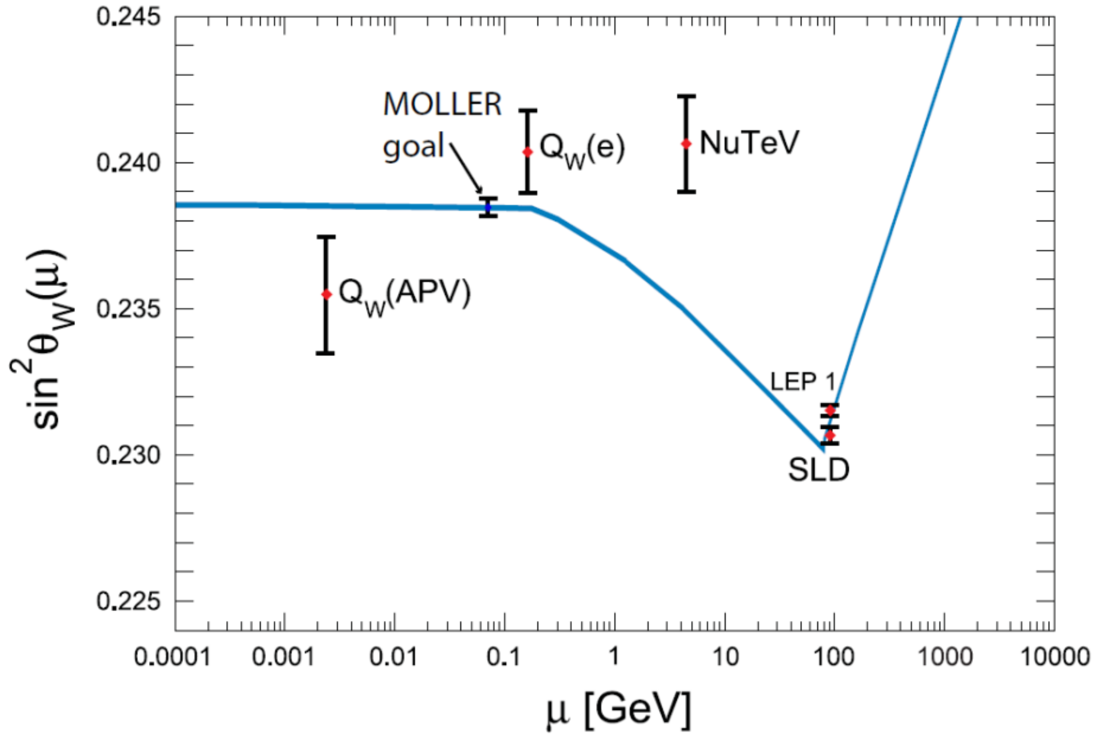
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{4\sin^2\theta}{(3+\cos^2\theta)^2}Q_W^e = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{2y(1-y)}{1+y^4+(1-y)^4}Q_W^e$$

Q_W^e is the weak charge of the electron, proportional to the product of the electron's vector and axial-vector couplings to the Z^0 boson. The electroweak theory prediction at tree level in terms of the weak mixing angle is $Q_W^e = 1 - 4\sin^2\theta_W$

α fine structure constant; E the incident beam energy;
m the electron mass, θ the scattering angle in the center of mass frame,
y = 1 – E'/E; E' the energy of one of the scattered electrons.



Significant 1-loop radiative corrections



The electroweak theory prediction at tree level for Q_W^e ($Q_W^e = 1 - 4\sin^2\theta_W$) is modified at the 1-loop level and becomes dependent on the energy scale at which the measurement is carried out ($\sin^2\theta_W$ runs)".

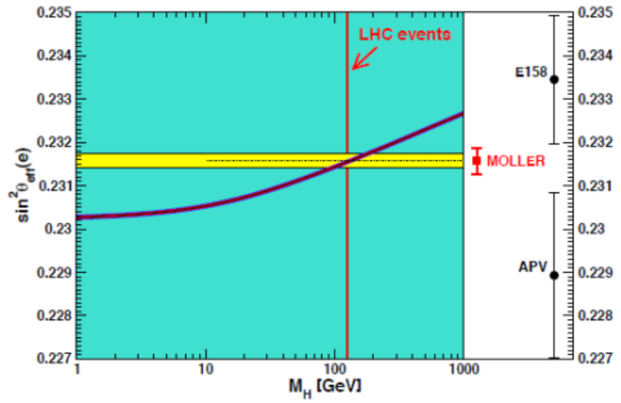
At MOLLER energy scale, Q_W^e ~ 0.0435. This is a 42% change of Q_W^e tree level value of ~ 0.075 (when evaluated at M_Z).

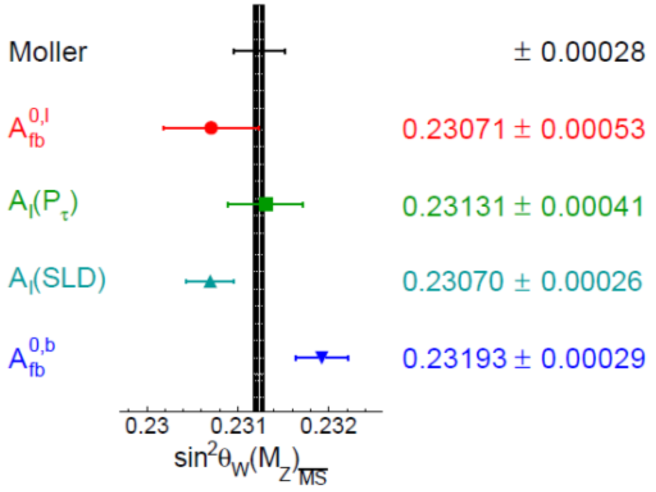
The prediction for the A_{PV} measured by MOLLER is 33 parts per billion (ppb). MOLLER goal is to measure this quantity with a precision of 0.7 ppb, achieving a 2.4% precise measurement of Q_W^e.

The reduction in the numerical value Q_W^e leads to increased fractional accuracy in the determination of the weak mixing angle of ~ 0.1%

The fact that theoretical uncertainties for the purely leptonic Møller Parity Violation are well under control has to be stressed.

Search for Physics Beyond the Standard Model (3)





$\sin^2\theta_W$ vs m_H. The yellow band is the world average. The black points are the two most precise measurements at $Q^2 \ll M_Z^2$.The projected MOLLER error is shown in red.

The four best $\sin^2\theta_W$ measurements and the projected error of the MOLLER proposal. The black band represents the theoretical prediction for m_H = 126 GeV.

A variety of BSM dynamics, can have a significant impact on low Q^2 observables while having much reduced impact on corresponding measurements made at colliders. This is because interference effects are highly suppressed on top of the Z^0 resonance. The MOLLER measurement would achieve a sensitivity of $\delta(\sin^2\theta_W)$= 0.00028. The projected uncertainty from forward-backward asymmetries after 300 fb^{-1}
integrated luminosity at the LHC is a systematics limited $\delta(\sin^2\theta_W)$ = 0.00036, with the dominant error being from parton distribution function (PDF) uncertainties.

Search for Physics Beyond the Standard Model (4)

(Complementarity between MOLLER and LHC, first scenario)

- If the LHC observes an anomaly, the MOLLER experiment will provide important constraints to choose among possible BSM scenarios which could to explain the anomaly.
- For example, if the particle predicted by the Minimal Supersymmetric Standard Model were observed, it would be very important to determine if they were generated through radiative loop effects (R-parity conserving) or tree-level interactions (R-parity violating). In fact, RPC would imply that the lightest supersymmetric particle is stable and therefore it would be an obvious candidate for the non-baryonic dark matter which is needed to understand galactic-scale dynamics. On the other hand, RPV would imply that neutrinos are Majorana particles. The RPV and RPC models generate effects of opposite sign in the weak charge, observable by MOLLER.

Search for Physics Beyond the Standard Model (5)

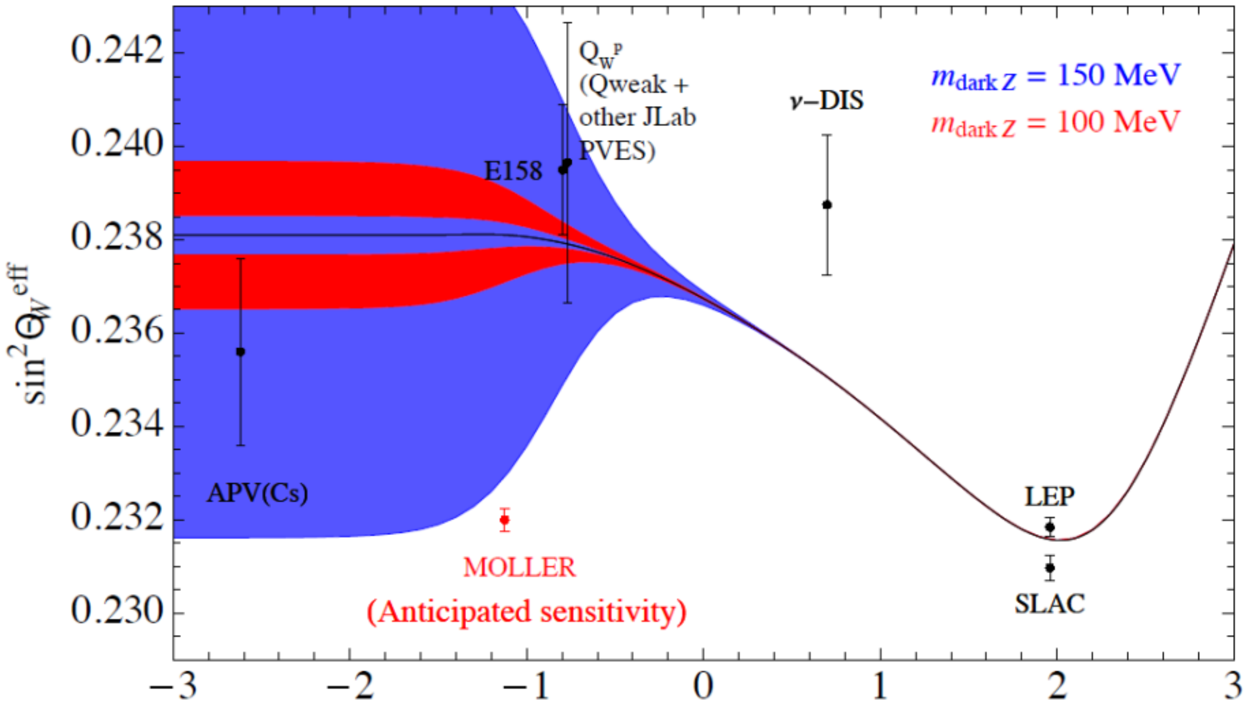
(Complementarity between MOLLER and LHC, second scenario)

- If the LHC continues to agree with the Standard Model with high luminosity running, the MOLLER experiment, thanks to its measurement at low Q^2, can still discover signatures of new physics not detectable by LHC but supposed to exist by theoreticians, like:
- Compressed supersymmetry
- Lepton number violating amplitudes mediated by doubly charged scalars ➔ extended Higgs sector models containing complex triplet representations of SU(2).
- And ….

Search for Physics Beyond the Standard Model (6)

(Complementarity between MOLLER and LHC, second scenario, continued)

Dark photon search.



Experiments measuring Parity Violating Electron Scattering (PVES) improved constantly their techniques. This allows us, today, to measure extremely small Parity violating Asymmetry (APV)

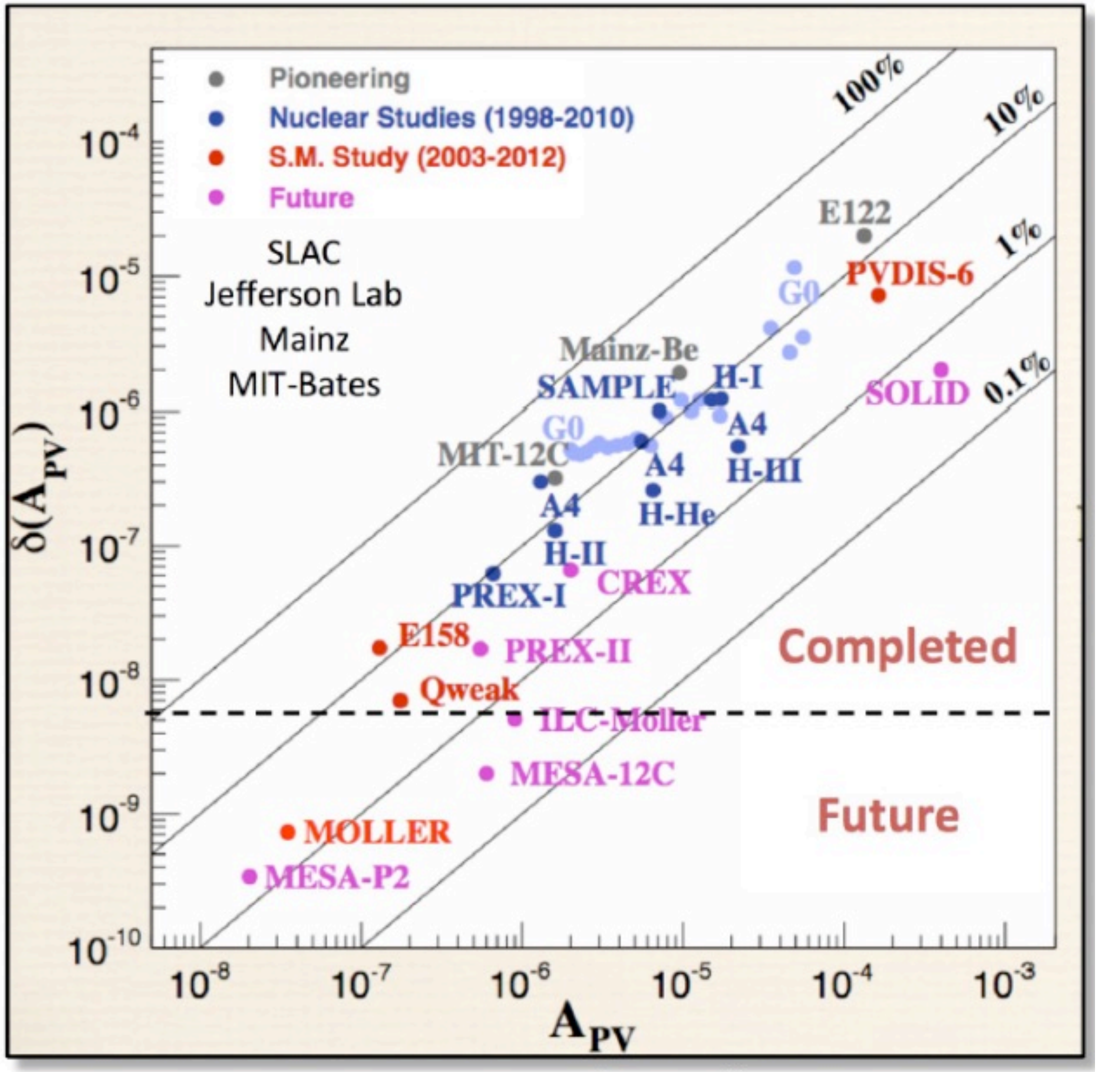
Pioneering (1978) early SM tests
SLAC E122 PVDIS – Prescott *et al.* A = -152 ppm
Bates ^{12}C, Mainz Be

Strange Form Factors (1998 –2009)
SAMPLE, HAPPEX, G0, A4
A ~ 1 – 50 ppm

Standard Model Tests (2003 - 2018)
SLAC E158 Moller: A = - 131 ppb
(13% precision on electron's weak charge)
JLAB Qweak: A = -230 ppb

Neutron radii: (2012-2022)
JLab: PREX-I, PREX-II, CREX

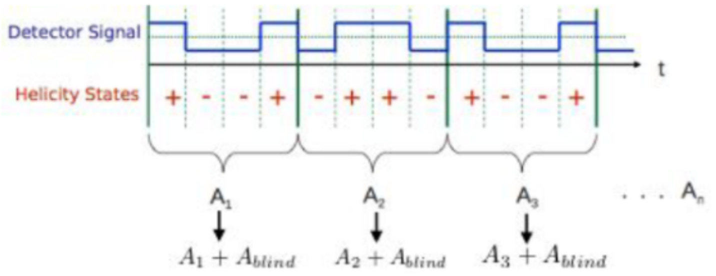
Future: Standard Model, hadron structure studies:
MOLLER: A = - 35 ppb
Goal: 2.5% precision on electron's weak charge



JLab E12-09-005: The Measurement of a Lepton-Lepton Electroweak Reaction (MOLLER)

Parameter	Value
E [GeV]	≈ 11.0
E' [GeV]	2.0 - 9.0
θ_{cm}	50°-130°
θ_{lab}	0.26°-1.2°
$< Q^2 >$ [GeV^2]	0.0058
Maximum Current [μA]	70
Target Length (cm)	125
ρ_{tgt} [g/cm^3] (T= 20K, P = 35 psia)	0.0715
Max. Luminosity [cm^{-2} sec^{-1}]	$2.4 \cdot 10^{39}$
σ [μBarn]	≈ 60
Møller Rate @ 65 μA [GHz]	≈ 134
Statistical Width(1.92 kHz flip) [ppm/pair]	≈ 91
Target Raster Size [mm]	5 x 5
Production running time	344 PAC-days = 8256 hours
ΔA_{raw} [ppb]	≈ 0.54
Background Fraction	≈ 0.10
P_{beam}	$\approx 90\%$
$< A_{pv} >$ [ppb]	≈ 32
$\Delta A_{stat} / < A_{expt} >$	2.1%
$\delta(\sin^2 \theta_W)_{stat}$	0.00023

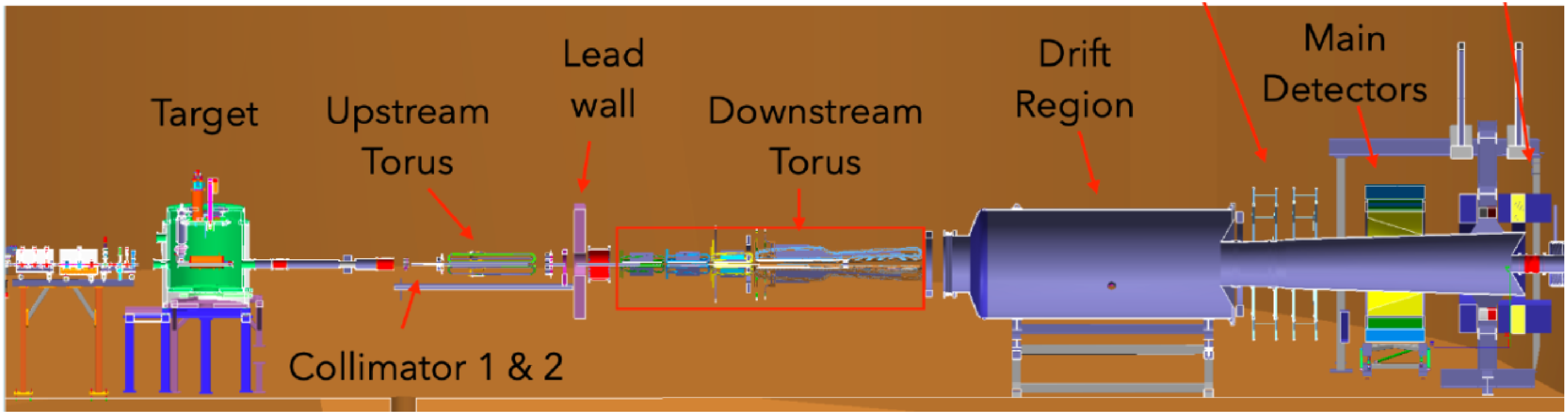
MOLLER CDR

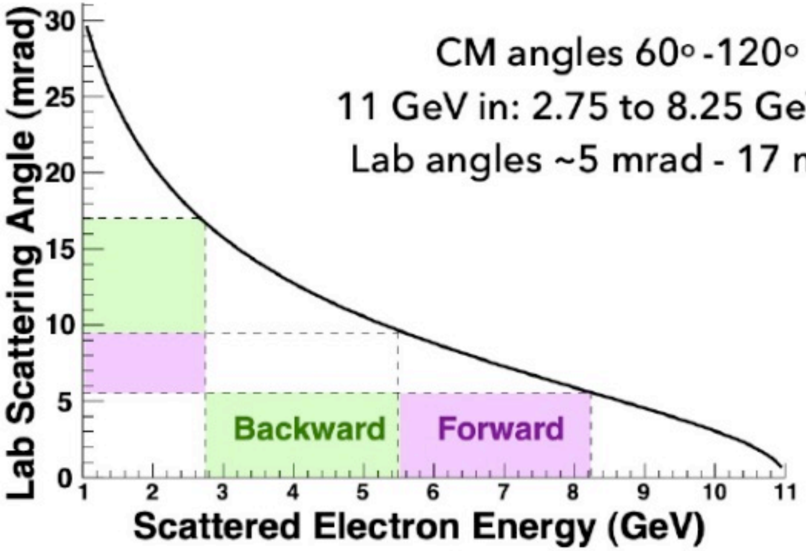


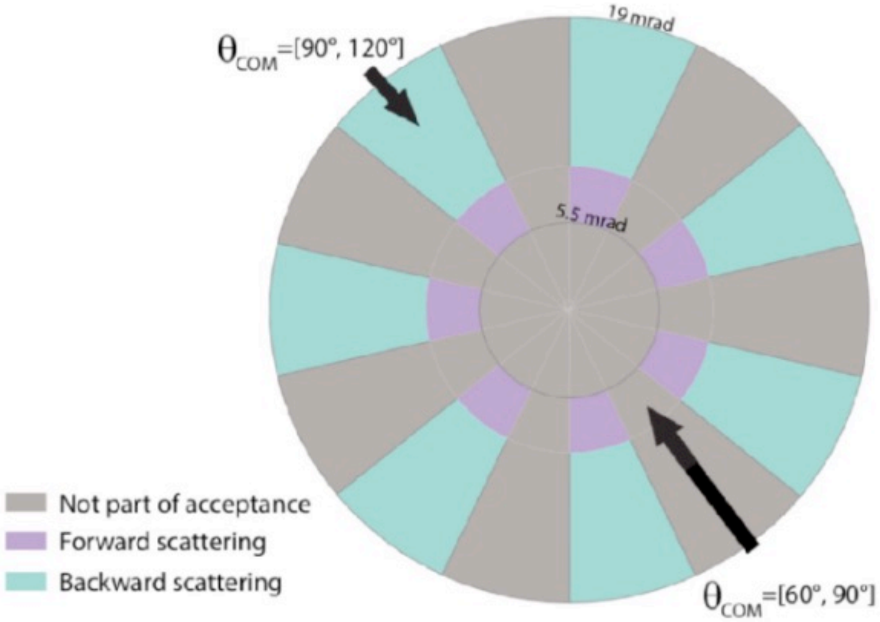
- Integrate counts over each helicity state at 1.92 kHz
- Yields normalized to the Beam Charge Monitors

- counting statistical width = **91 ppm** , to keep the beam intensity measurement an insignificant source of noise:
  BCM resolution ~ **10 ppm**

Experimental apparatus

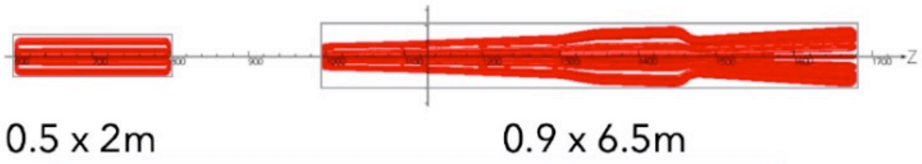



CM angles 60° -120°
11 GeV in: 2.75 to 8.25 GeV out
Lab angles ~5 mrad - 17 mrad
Lab Scattering Angle (mrad)
Scattered Electron Energy (GeV)
Backward
Forward
0
5
10
15
20
25
30
1
2
3
4
5
6
7
8
9
10
11


19 mrad
5.5 mrad
θCOM=[90°, 120°]
θCOM=[60°, 90°]
Not part of acceptance
Forward scattering
Backward scattering

Magnet Concept

long and skinny



Focus Moller electrons from full acceptance (3 – 8 GeV) to tight radial location on detectors