Aspects of the Physics Program at Jefferson Lab's Halls A, B, and C

- General Overview and Instrumentation
- **Physics Highlights** from Halls A, B, and C

- **J/ψ Near-Threshold Production** in Hall B
- **Strangeness Production** in Hall B
- **Hypernuclear Physics** in Hall C

Patrick Achenbach
Jefferson Lab

June 2o24

Complementing the talks of

- Lubomir Pentchev: Threshold charmonium production at Jlab

- Yordanka Ilieva: Hyperon physics at JLab

Jefferson Lab Operating the 12-GeV CEBAF

Cryogenic refrigeration plant

CEBAF at 12-GeV schematics

Superconducting niobium radiofrequency cavities

Cryomodules in the accelerator tunnel

Recirculation arcs

Linearly pol. photon beam

D

A

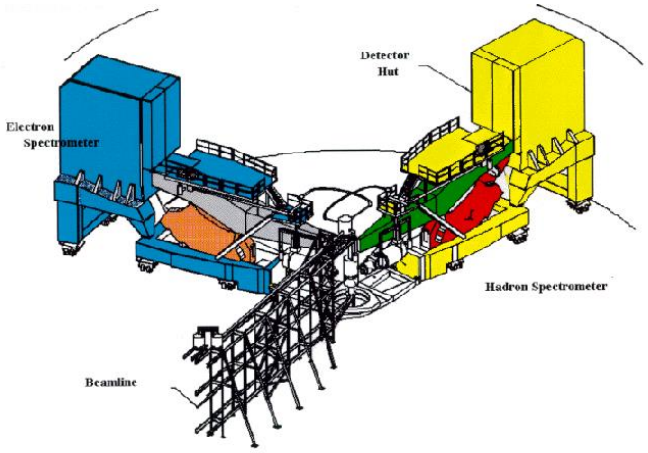
B

C

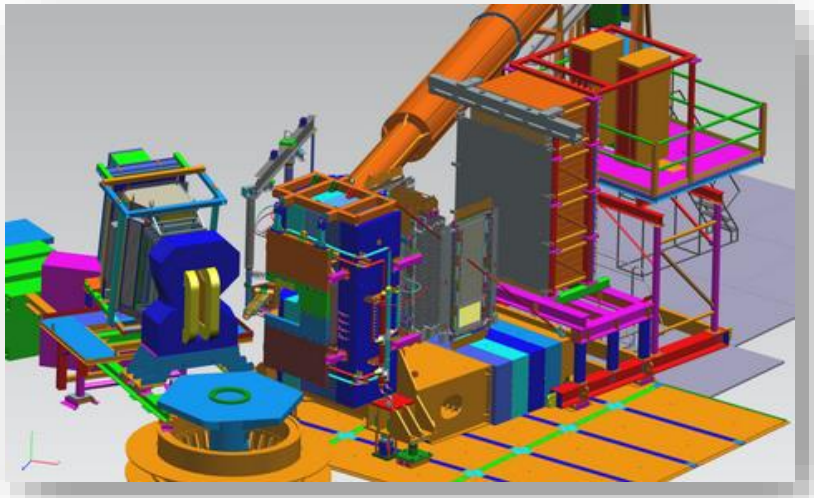
3 electron beams, cw, E_{max}= 10.6 GeV, P ~ 90%

Spectrometers and Instruments in Halls A, B, and C

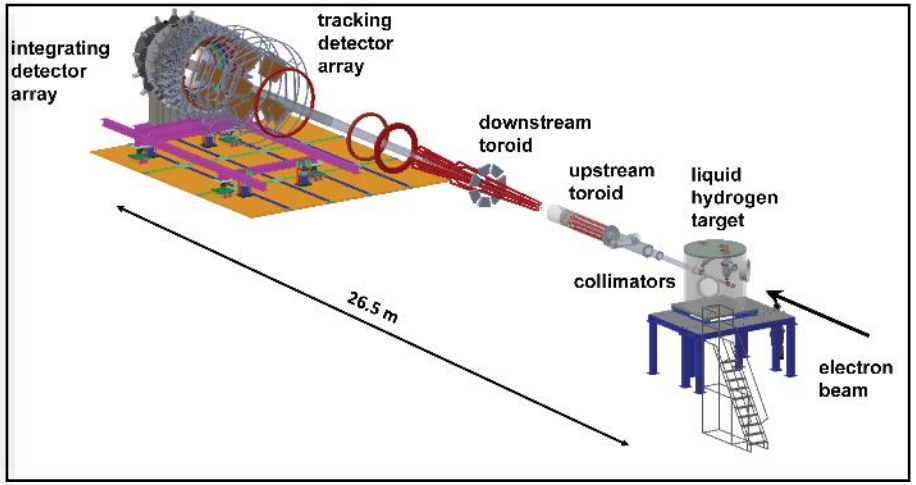
L+R HRS **Hall A**



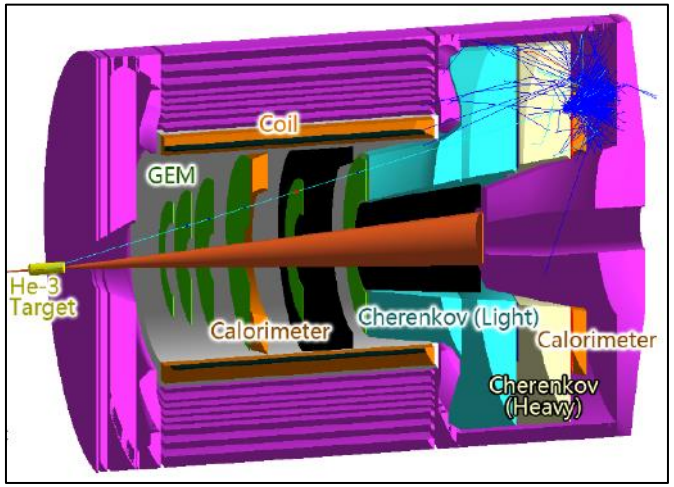
BigBite & SBS **Hall A**



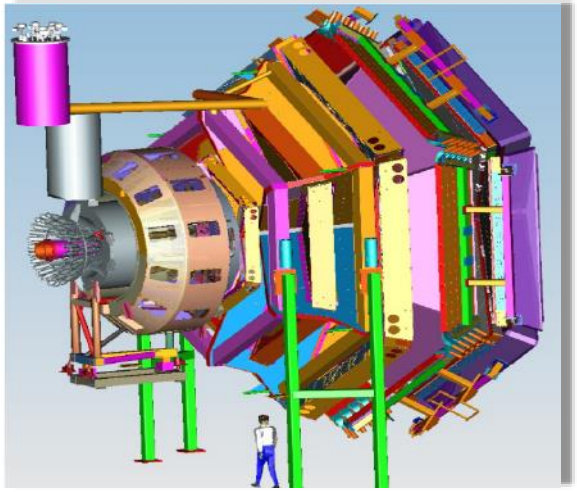
MOLLER **To come in Hall A**



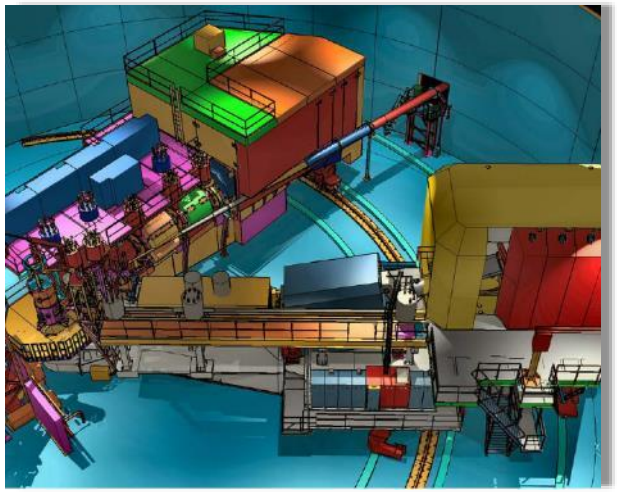
SOLID **Proposed in Hall A**



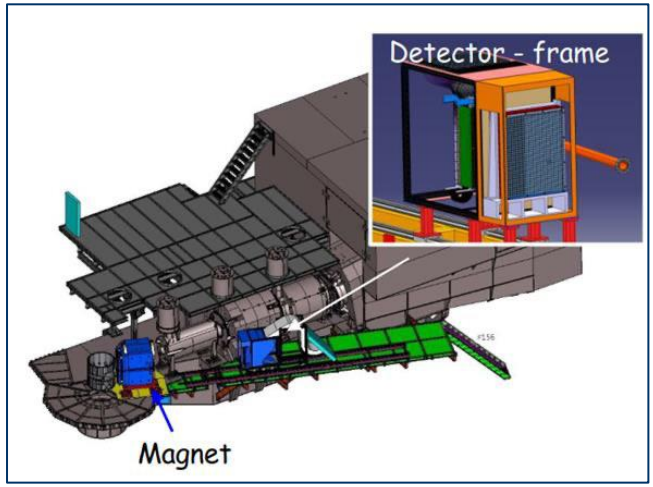
CLAS12 **Hall B**



HMS & SHMS **Hall C**



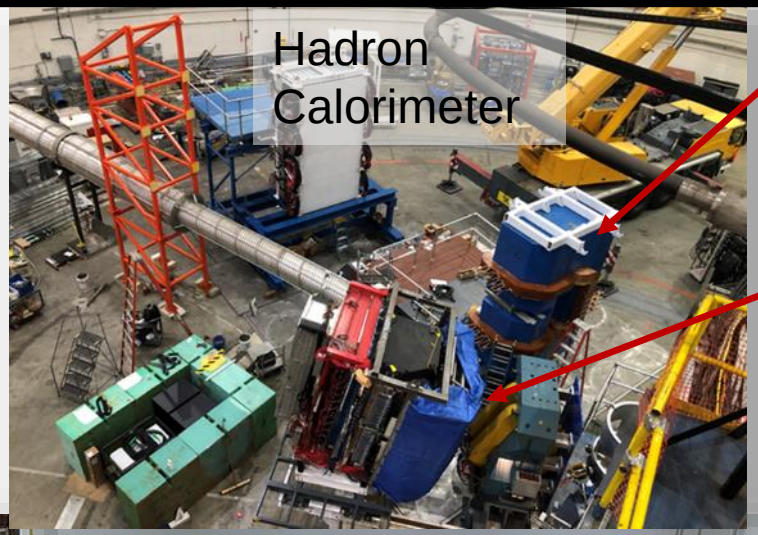
NPS **Hall C**



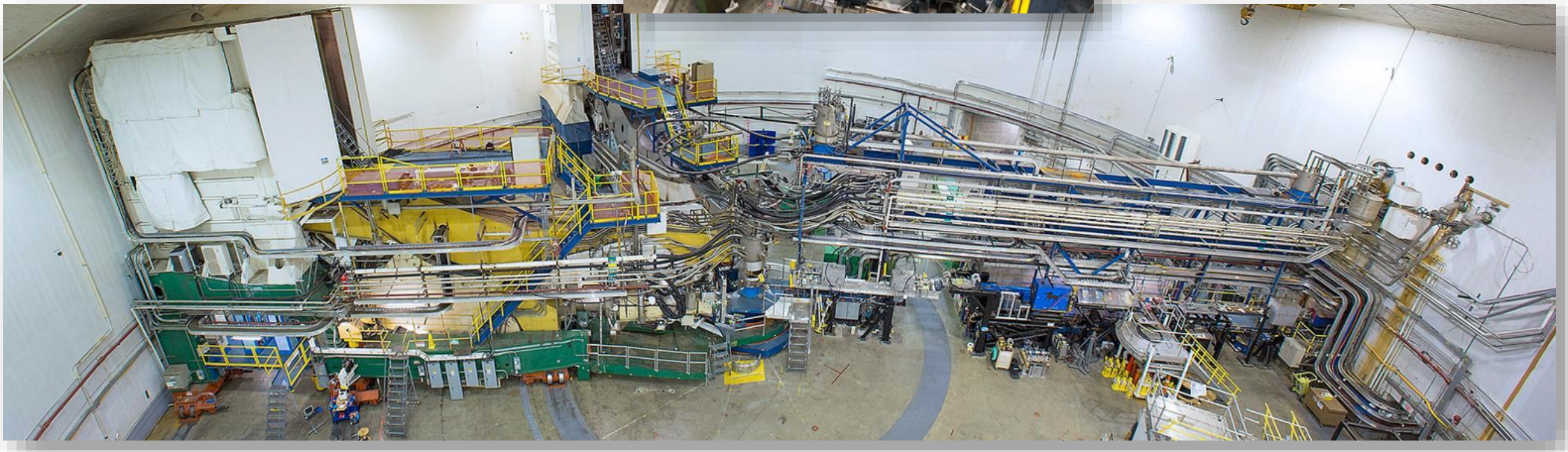
Hall A

Hall A: High-Resolution and BigBite Spectrometers

- Two identical QQDQ High-Resolution spectrometers: **Right and Left HRS**
  - $\Delta p/p = 10^{-4}$, $\Delta\Omega$ = 6 msr
  - Angular range θ = 12.5° − 150°
  - Dipole septa to access θ < 12.5°
- Luminosity up to 10^{39} cm^{-2} s^{-1}
- LH2, LD2 targets, solid and gas targets



- **SuperBigBite** Spectrometer
  - Dipole magnet, 1.7 T-m
  - $\Delta\Omega$ = 70 msr
  - Proton/neutron separation
- **BigBite** Spectrometer
  - Indexed dipole magnet
  - $\Delta p/p$ = 1-2%
  - $\Delta\Omega$ = 15 − 40 msr



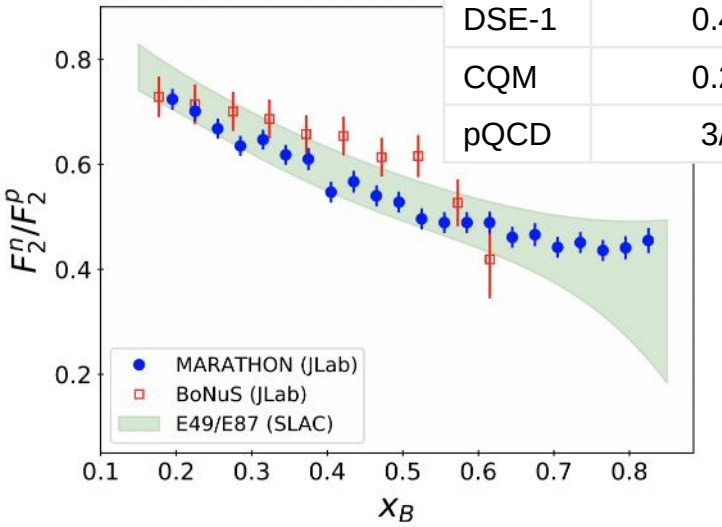
Hall A: Highlights from Experiments

- **Precise Determination of the Nucleon F_2^n/F_2^p at Large x_B**

- **Electron DIS from mirror nuclei** ^{3}H and ^{3}He gives unique access to neutron/proton ratio

- Testing predictions of variety of QCD models

Model	F_2^n/F_2^p at x=1
SU(6)	2/3
NJL	0.43
DSE-1	0.49
CQM	0.25
pQCD	3/7

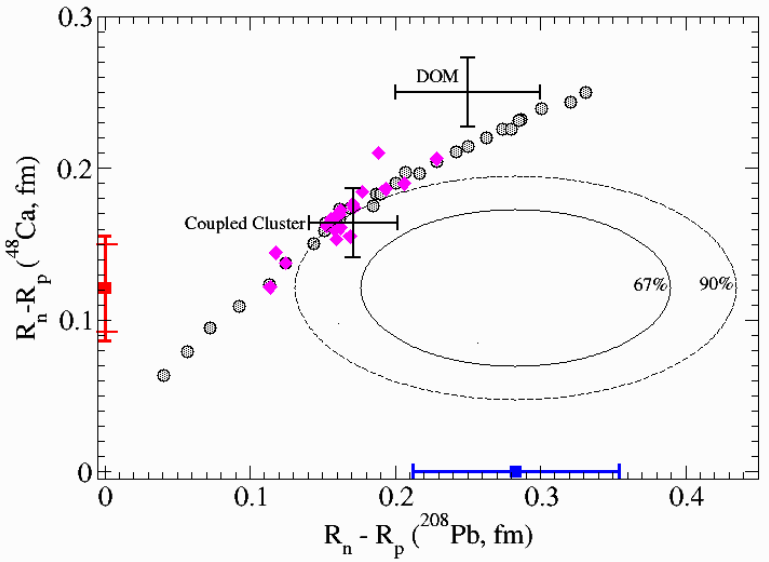


[D. Abrams *et al.* (Jefferson Lab Hall A Tritium Collaboration), Phys. Rev. Lett. 128, 132003 (2022)]

- **From Nuclei to Neutron Stars**

- **Parity-violating electron scattering** measurement of neutron skins in comparison to nuclear models and ab-initio calculations

- Models used in calculation of neutron star mass limits



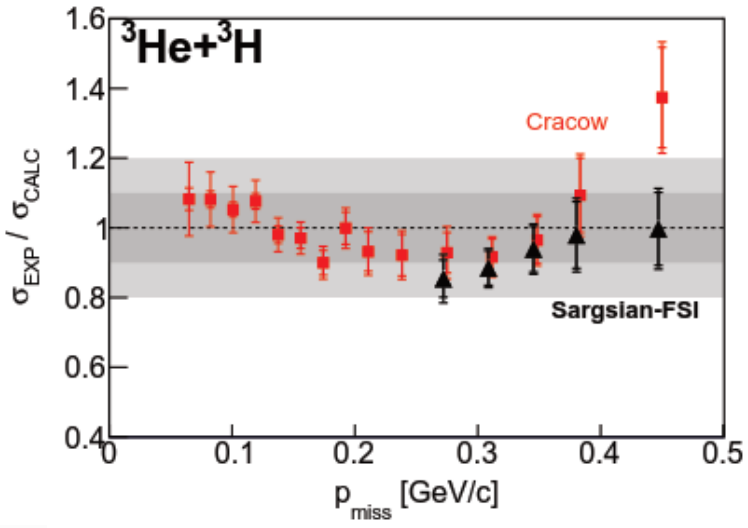
[D. Adhikari et al. (CREX Collaboration), Phys. Rev. Lett. 129, 042501 (2022)]

- **Test of State-of-the-Art Ab-Initio 3-Nucleon Calculations**

- ^{3}H,^{3}He(*e,e'p*) **three-body breakup reaction** cross sections

- Sensitive to QE scatttering

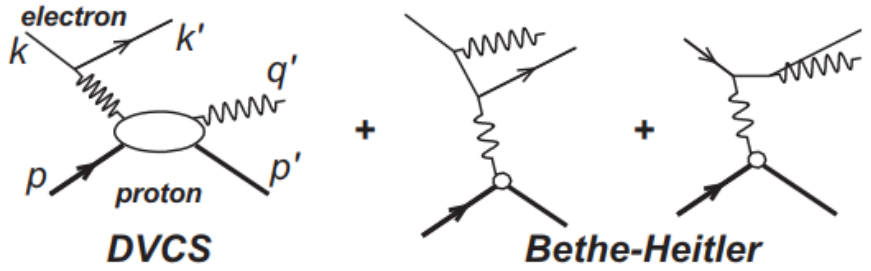
- Ratio of iso-scalar cross section measurements to theory validated up to p_{miss} = 0.5 GeV/*c*

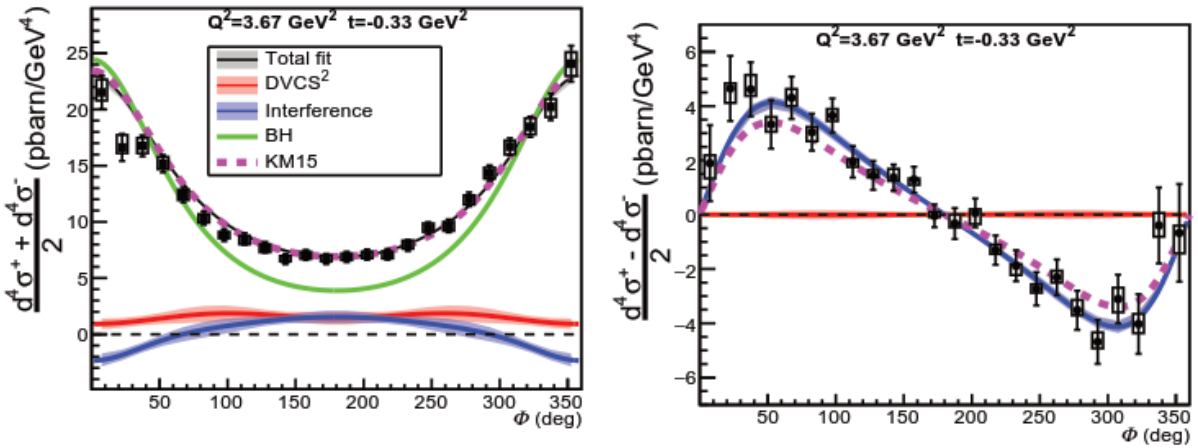


[R. Cruz-Torres *et al.* (Jefferson Lab Hall A Tritium Collaboration), Phys. Rev. Lett. 124, 212501 (2020)]

Hall A: Highlights from Experiments

- PbF_2 calorimeter to detect photons in coincidence with electrons in LHRS for measurement of helicity-dependent cross sections in **deeply virtual Compton scattering** to extract GPDs

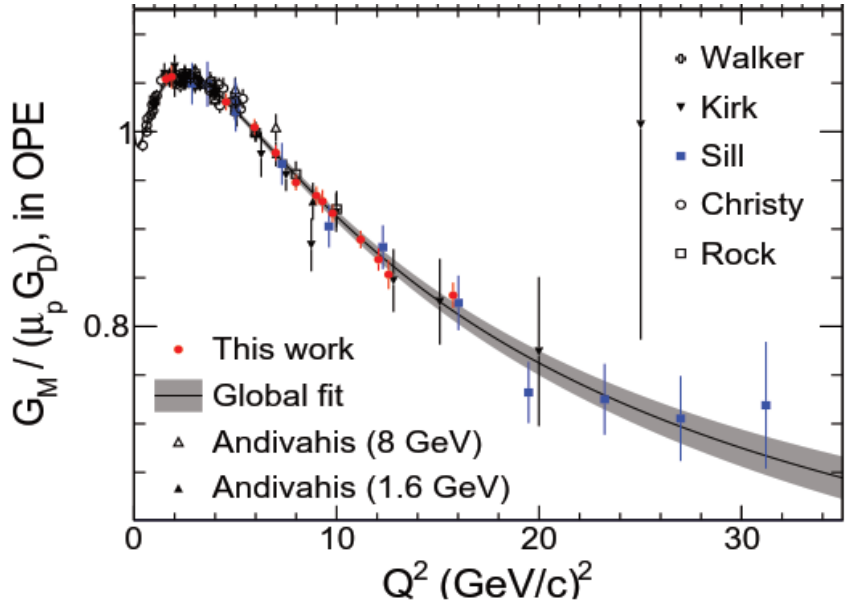




[F. Georges et al. (Jefferson Lab Hall A Collaboration), Phys. Rev. Lett. 128, 252002 (2022), https://arxiv.org/abs/2201.03714]

- RHRS **Rosenbluth separation** measurement of **proton magnetic form factor**, G_M, up to momentum transfers of $Q^2 = 16$ (GeV/c)^2

- Difference to polarization data attributed to hard two-photon exchange (TPE) effects



[M. E. Christy et al., Phys. Rev. Lett. 128, 102002 (2022), https://arxiv.org/abs/2103.01842]

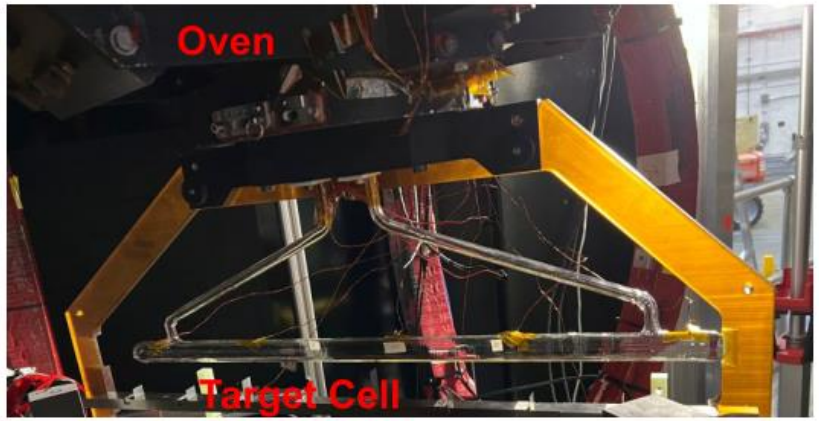
Hall A: Highlights from Experiments

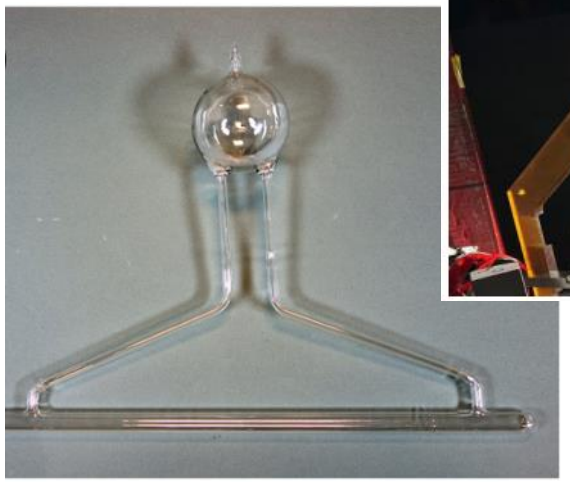
- Measurement of **neutron electric form factor**, G_E, by beam-target asymmetry

$$A_N = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

- Beam polarization 85% and currents up to 50 μA
- Target length 60 cm and polarization 45−55%

Use high luminosity + open geometry + GEM detectors

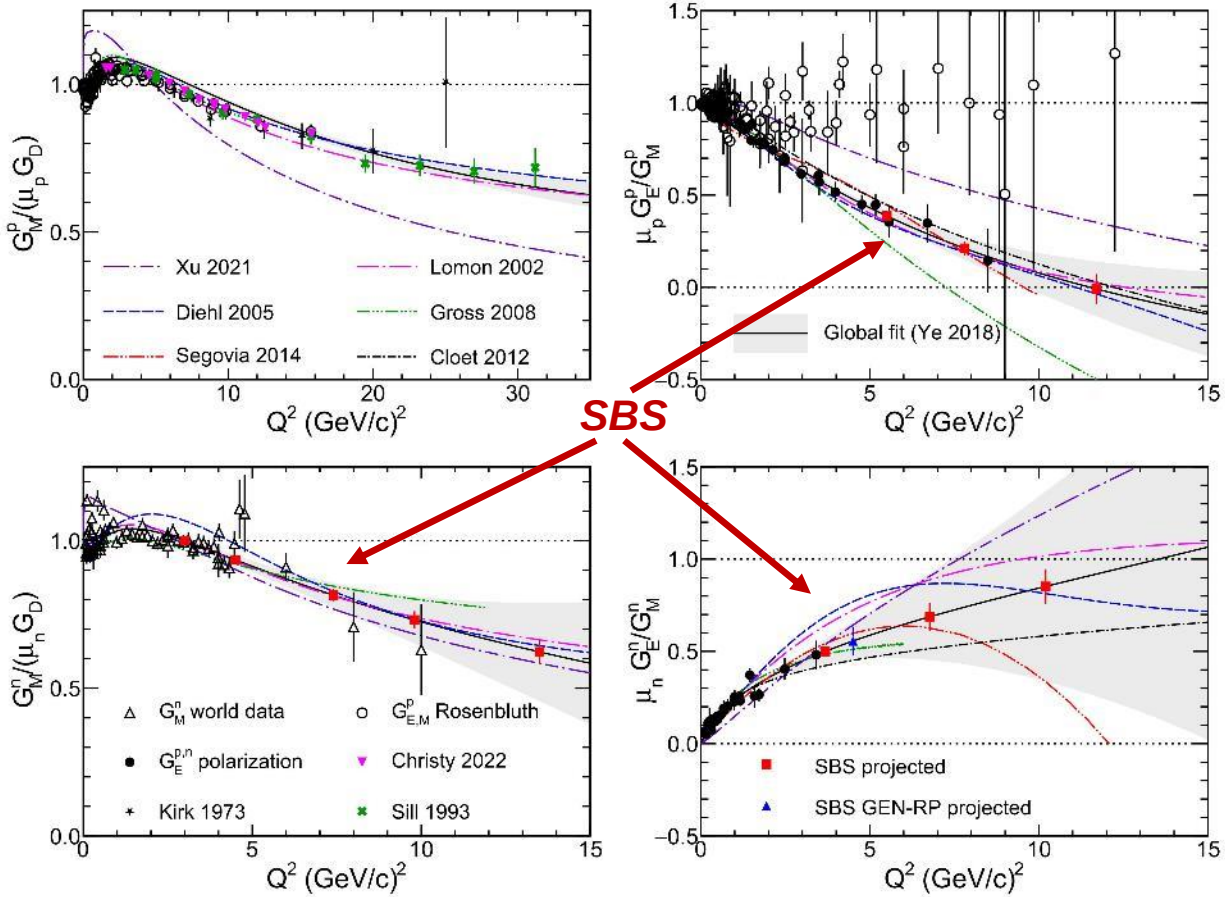




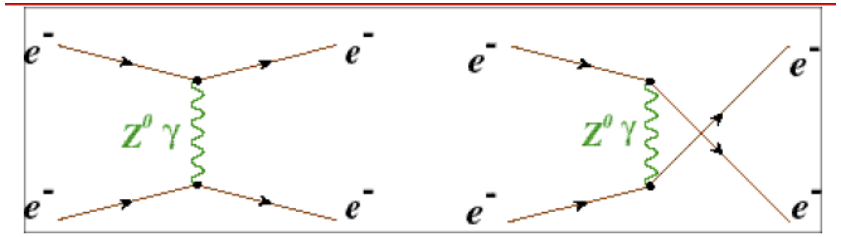
Polarized helium-3 target as effective polarized neutron

Accessing Nucleon Form Factors at Large Q^2

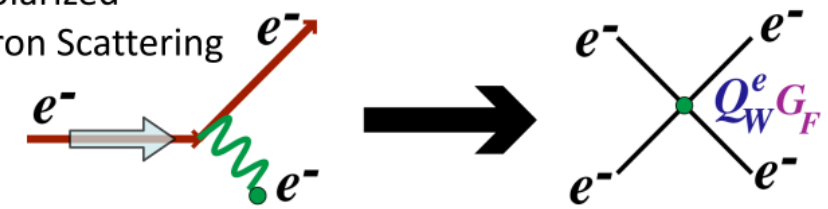
- **Proton G_M** published from data with H target
- **Neutron G_M** data taken in Fall 2021 with D target
- **Neutron G_E** completed in Fall 2023 with He target
- **Proton G_E** to run in fall 2024



Hall A: Future MOLLER Experiment



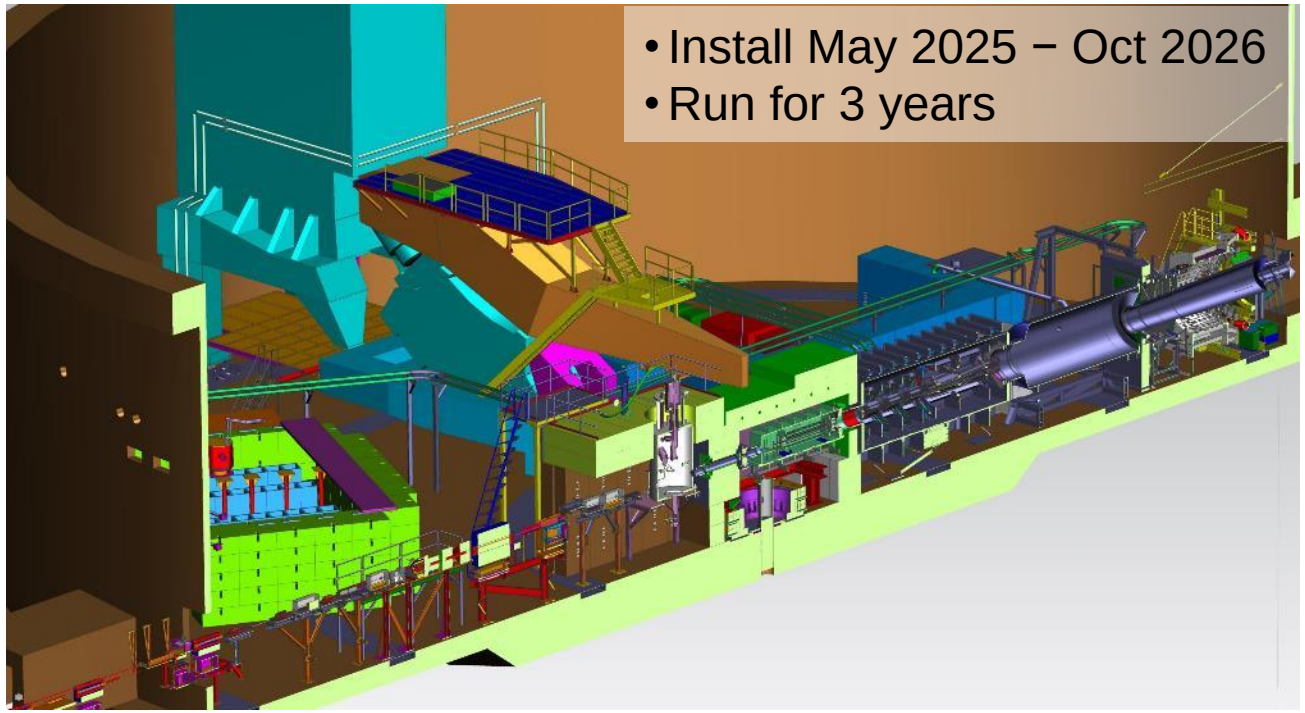
Fixed Target Polarized
Electron-Electron Scattering



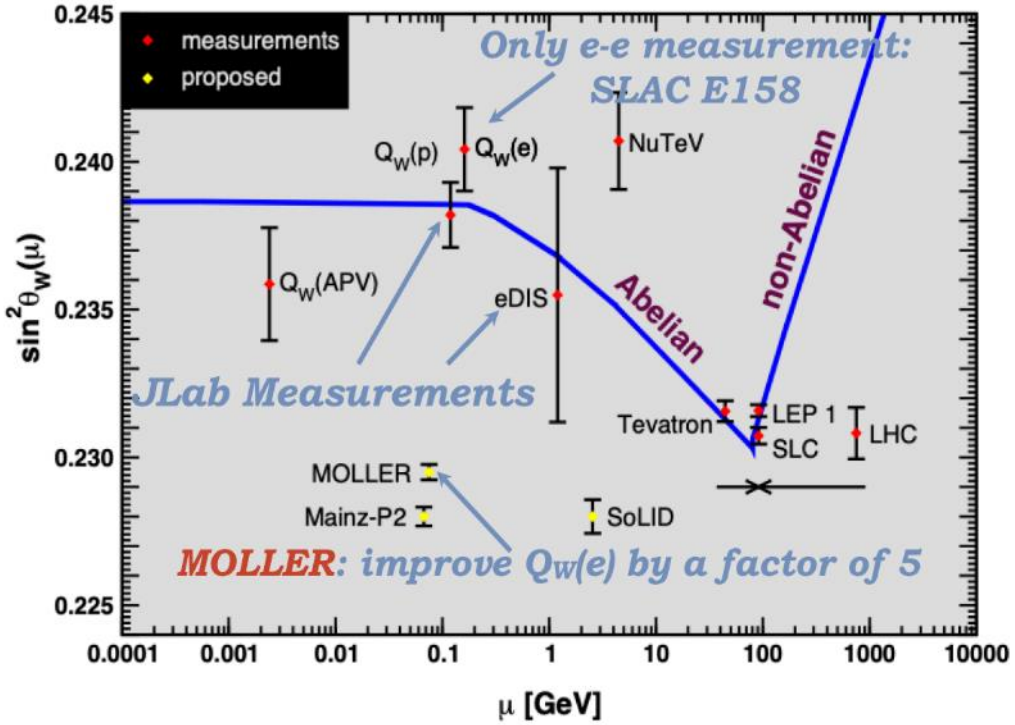
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -mE \frac{G_F}{\sqrt{2}\pi\alpha} \frac{16 \sin^2\Theta}{(3+\cos^2\Theta)^2} Q_W^e$$

$$Q_W^e = 1 - 4\sin^2\theta_W \sim 0.075$$

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5 \text{ TeV}$$



$\delta(\sin^2\theta_W) = \pm 0.00023$ (stat.) ± 0.00012 (syst.)



Hall A: SoLID - The QCD Intensity Frontier

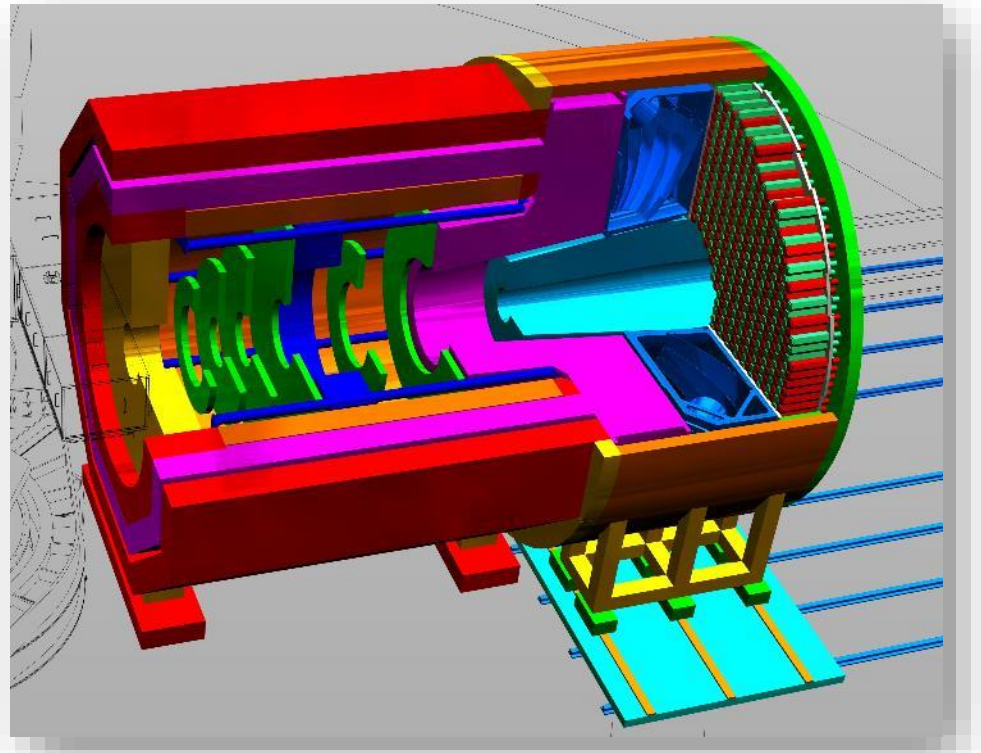
High Luminosity
$10^{37\text{-}39}$ /cm^2/s
[>100x CLAS12][>1000x EIC]

+

Large Acceptance
Full azimuthal ϕ coverage

SoLID will have the ***unique*** capability to **explore** QCD landscape while **complementing** other key facilities

- 3D momentum imaging of a relativistic strongly interacting confined system - TMDs (**nucleon spin**)
- Superior sensitivity to the differential electro- and photo-production cross section of J/ψ near threshold (**gluon field and proton mass**)
- Pushing the phase space in the search of new physics and of hadronic physics

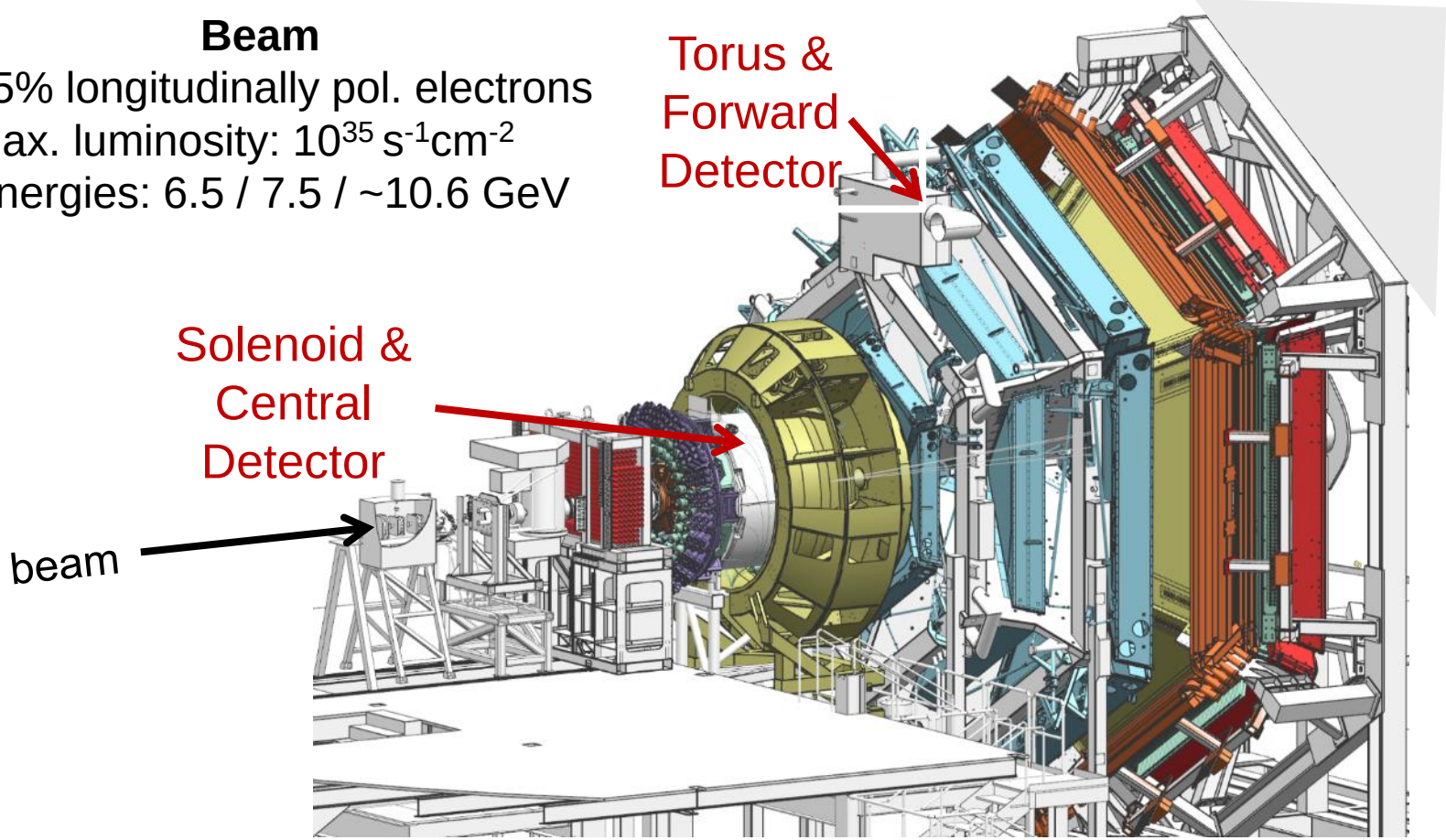


Hall B

Hall B: The CLAS12 Spectrometer for 12 GeV

Beam

- 85% longitudinally pol. electrons
- Max. luminosity: 10^{35} $s^{-1}cm^{-2}$
- Energies: 6.5 / 7.5 / ~10.6 GeV

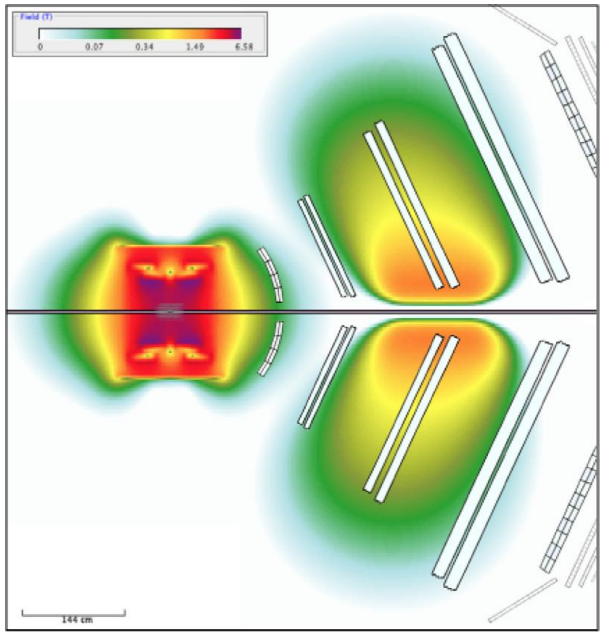


[V.D. Burkert et al., Nucl. Inst. and Meth. A 959, 163419 (2020)]

Targets (org. by Run Groups)

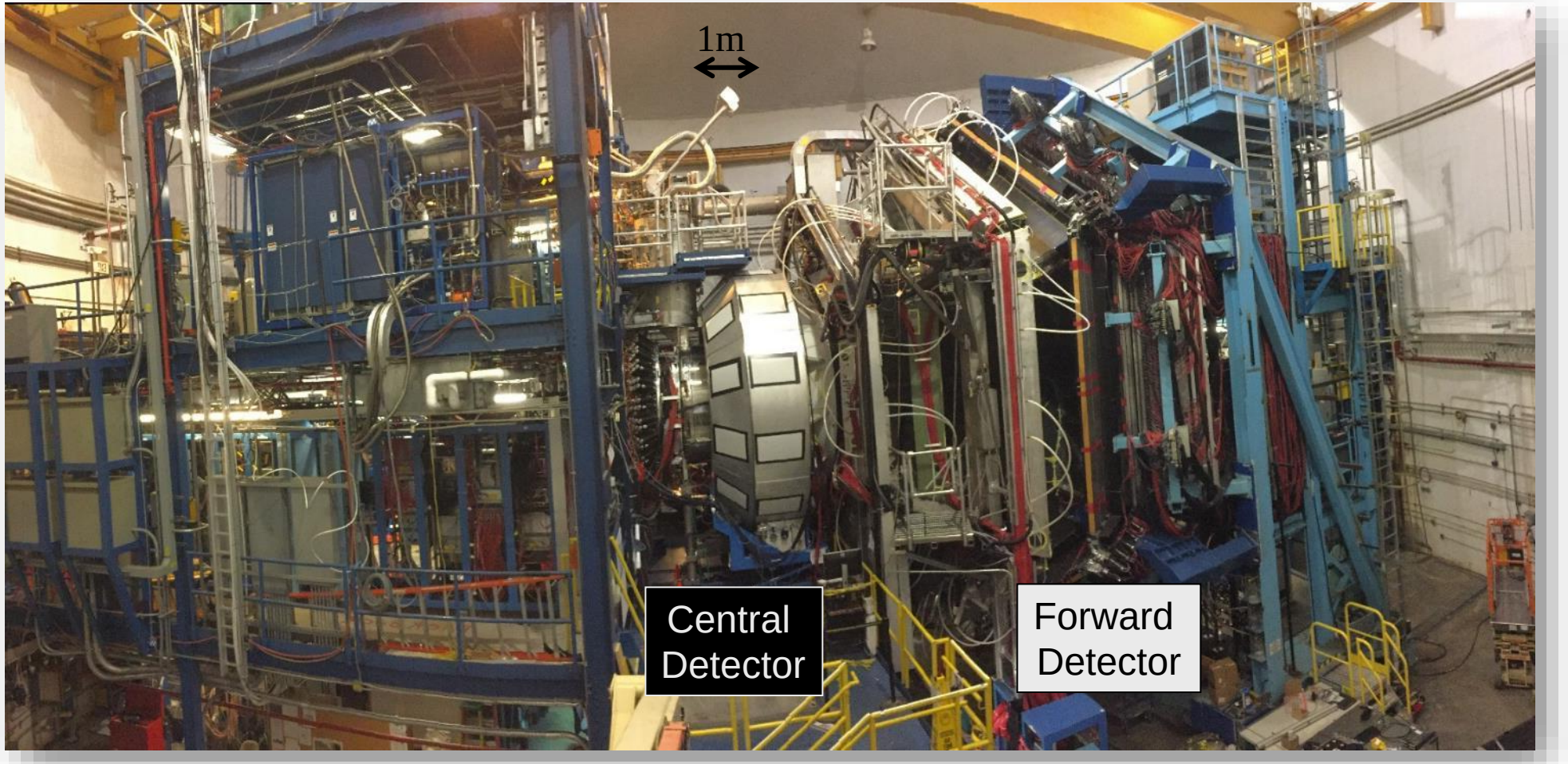
- Proton (RG-A/K)
- Deuteron (RG-B)
- Nuclei (RG-M/D/E)
- Long. pol. NH_3/ND_3 (RG-C)

Magnetic Field



Large-acceptance multi-purpose spectrometer

Hall B: Side View of The CLAS12 Spectrometer



Electron beam →

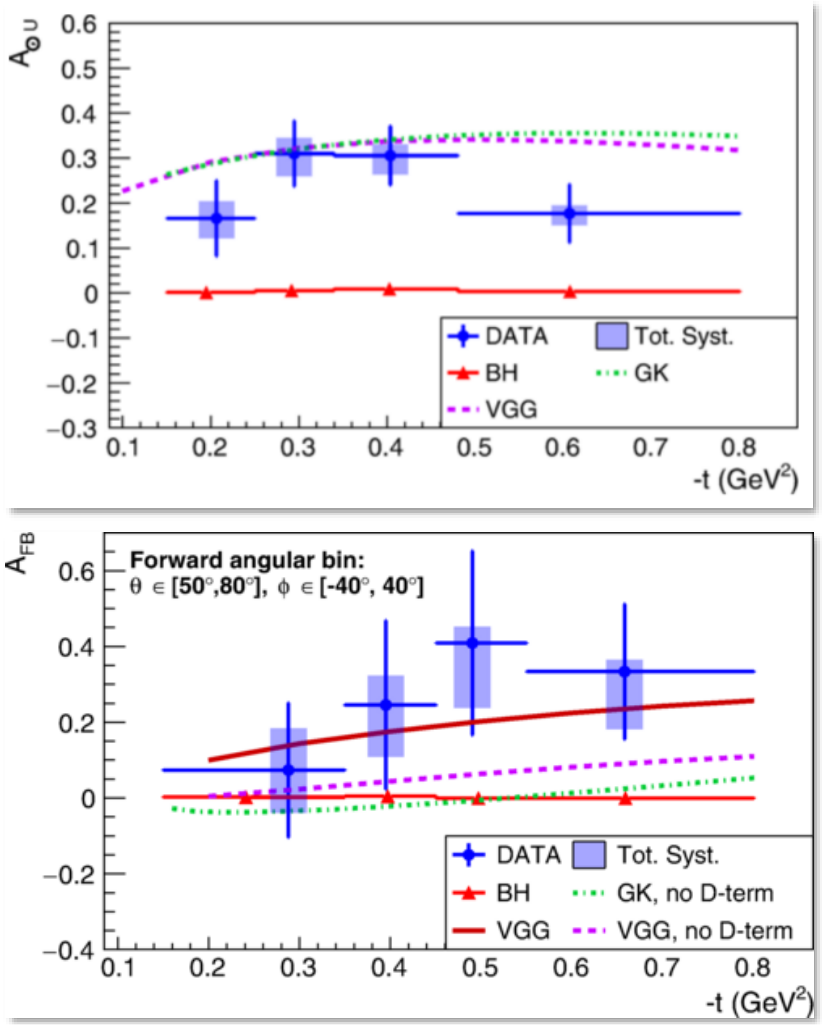
Hall B: Highlights from Experiments

First measurement of time-like Compton scattering processes

- Test of GPD universality via beam spin asymmetry that is sensitive to **imaginary part of the Compton form factors**

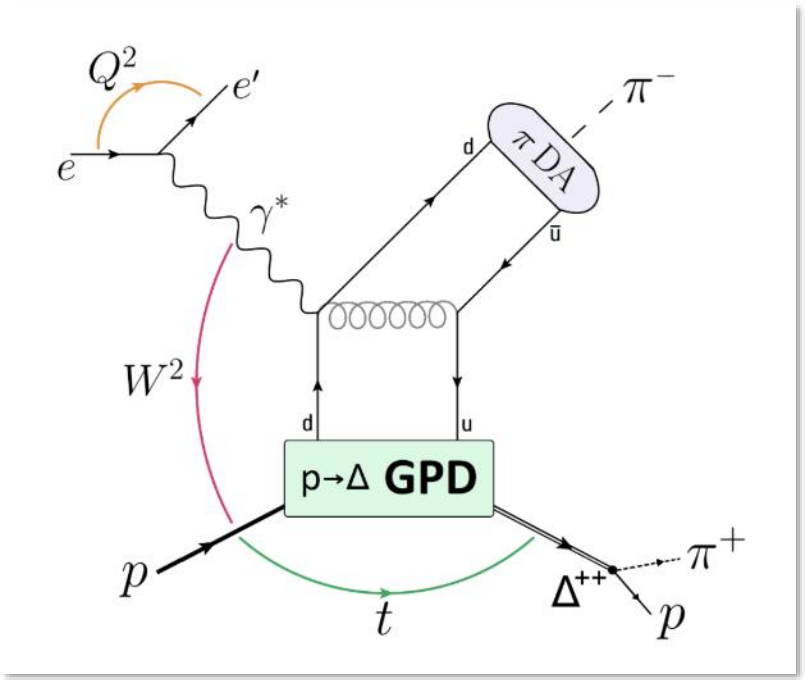
Qualitatively New Steps in Studying the 3D Structure of the Proton

- Access to **real part of Compton form factors** via forward/backward asymmetry and thus to *D*-term in parametrization of GPDs that links to the mechanical properties of the proton



[P. Chatagnon *et al.* (CLAS Collaboration), Phys. Rev. Lett. 127, 262501 (2021)]

Hall B: Highlights from Experiments

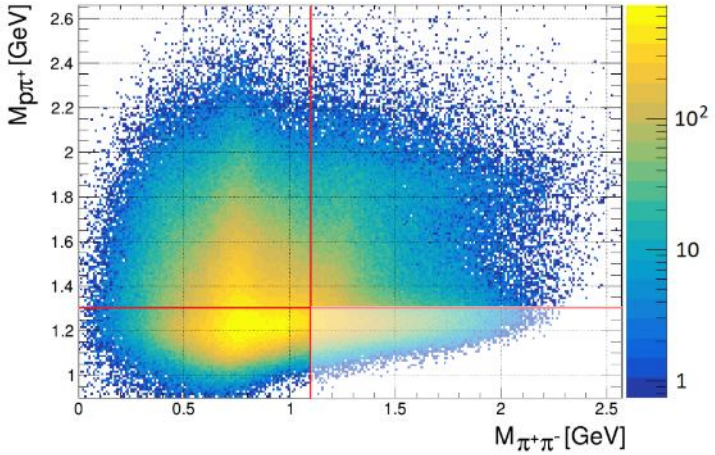


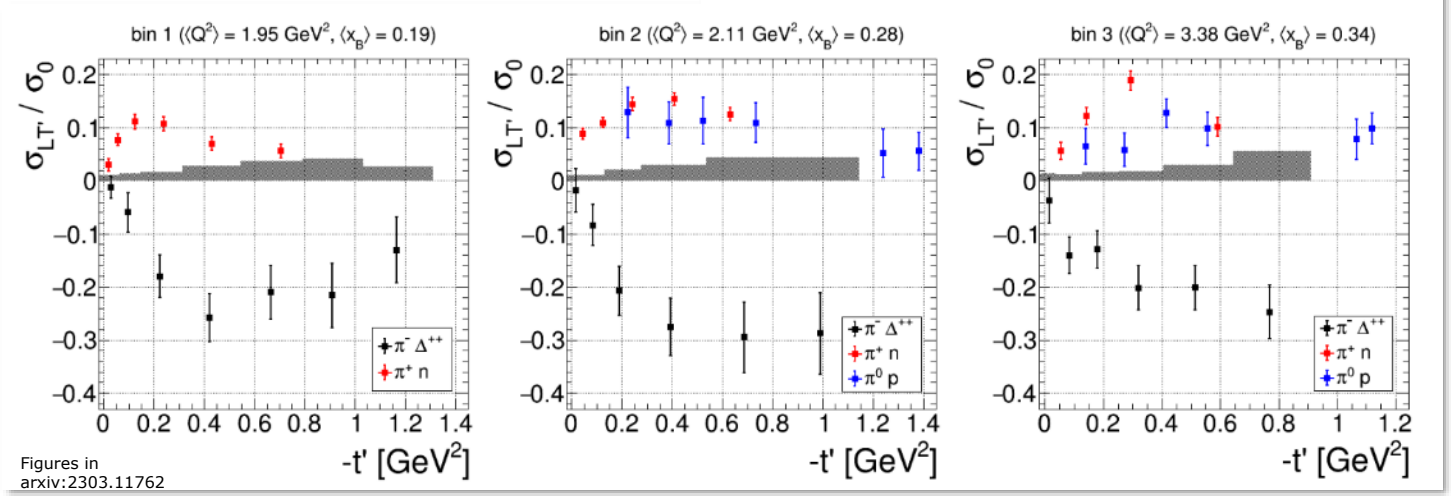
First Measurement of a Transition GPD in the N to Δ++ Reaction

Exploratory measurement of beam-spin asymmetries to access transition GPDs in N → Δ processes:

- $ep \rightarrow e' p \pi^-(\pi^+)$
- Access to *d*-quark content
- No other world data

$$BSA = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi+\epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi}$$

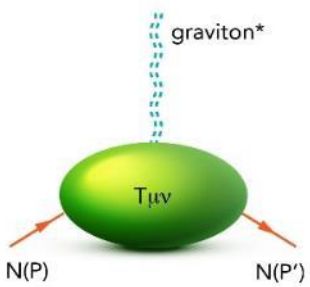




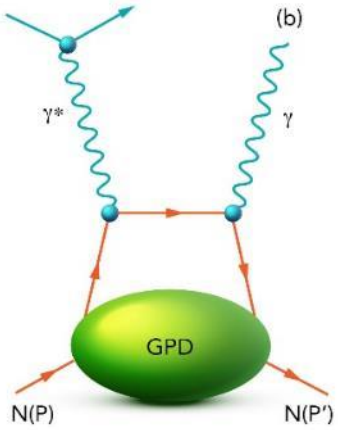
Figures in arxiv:2303.11762

[S. Diehl *et al.* (CLAS Collaboration), Phys. Rev. Lett. 131, 021901 (2023)]

Hall B: Highlights from Experiments



Graviton coupling to the proton

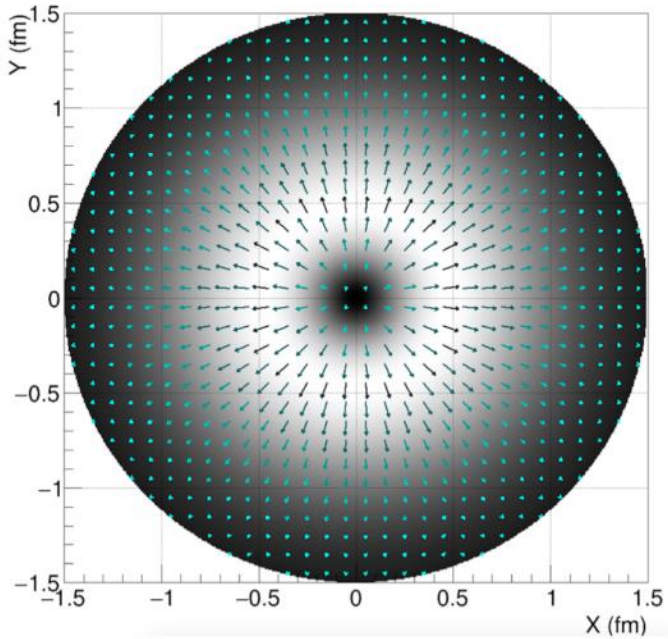


Deeply Virtual Compton Scattering (DVCS)

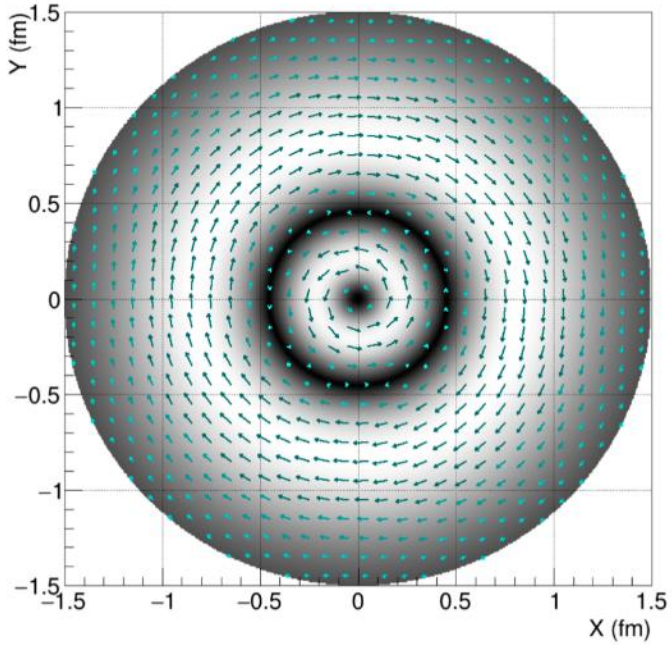
$$\int \mathrm{d}x\, x\,[H(x,\xi,t) + E(x,\xi,t)] \;=\; 2J(t)$$

$$\int \mathrm{d}x\, x H(x,\xi,t) \;=\; M_2(t) + \frac{4}{5}\xi^2 d_1(t),$$

Distribution of forces in the proton



Left: normal forces



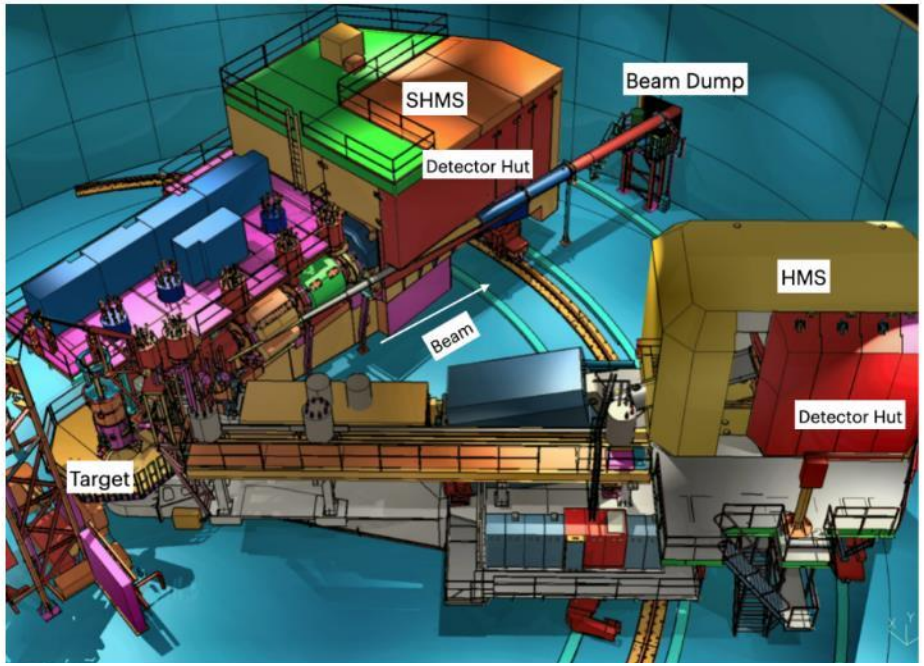
Right: tangential forces

[V. D. Burkert, L. Elouadrhiri, F. X. Girod, C. Lorcé, P. Schweitzer, and P. E. Shanahan, Rev. Mod. Phys. 95, 041002 (22 Dec 2023)]

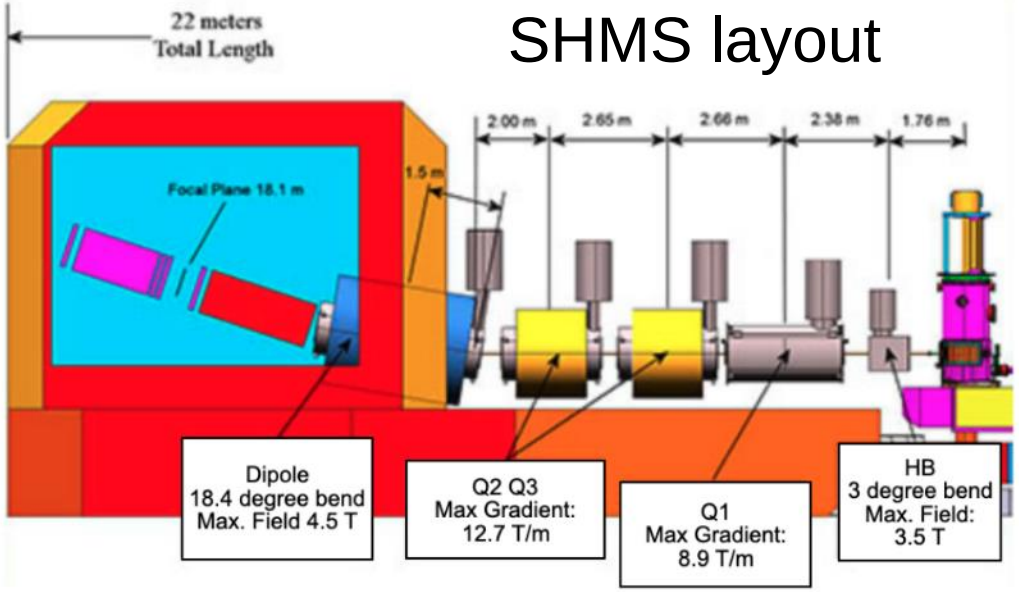
Hall C

Hall C: Small Acceptance Spectrometers for High Luminosity

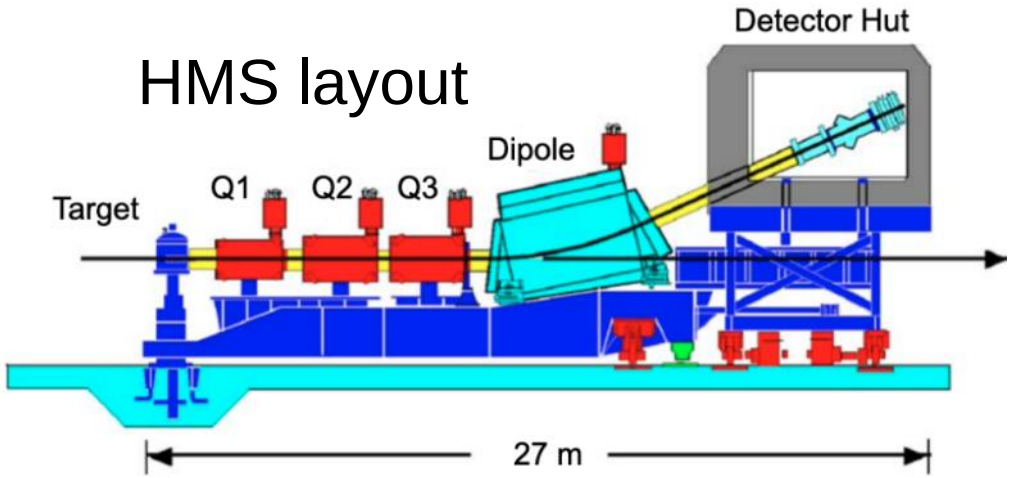
Parameter	HMS Design	SHMS Design
Range of Central Momentum	0.4 to 7.4 GeV/c	2 to 11 GeV/c
Momentum Acceptance δ	$\pm 10\%$	-10% to $+22\%$
Momentum Resolution	$0.1\% - 0.15\%$	$0.03\% - 0.08\%$
Scattering Angle Range	10.5 to 90 degrees	5.5 to 40 degrees
Horizontal Angle Acceptance	± 32 mrad	± 18 mrad
Vertical Angle Acceptance	± 85 mrad	± 50 mrad
Solid Angle Acceptance	8.1 msr	> 4 msr
Horizontal Angle Resolution	0.8 mrad	0.5 – 1.2 mrad
Vertical Angle Resolution	1.0 mrad	0.3 – 1.1 mrad
Target resolution (ytar)	0.3 cm	0.1 - 0.3 cm
Maximum Event Rate	2 kHz	10 kHz
Max. Flux within Acceptance	~ 5 MHz	~ 5 MHz



SHMS layout



HMS layout



Hall C: Neutral Particle Spectrometer (NPS)

- 1080 $PbWO_4$ crystals
- 0.6 Tm sweeping magnet
- F250ADC sampling electronics
- Large opening angle beam pipe
- SHMS as carriage for rotation

Simplest process: e + p → e' + p + γ (DVCS)

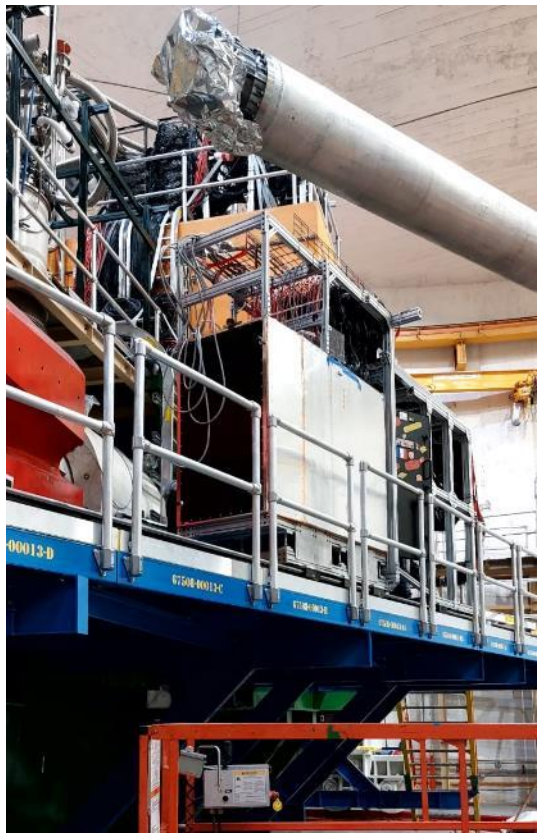
E12-13-010 DVCS measurements follow up on measurements in Hall A:

- Scaling of the Compton Form Factor
- Rosenbluth-like separation of DVCS:

$$\sigma = |BH|^2 + \mathrm{Re}\left[\underset{\sim E_{beam}^2}{DVCS^{\perp}}\ BH\right] + \underset{\sim E_{beam}^3}{|DVCS|^2}$$

- L/T separation of π^0 production

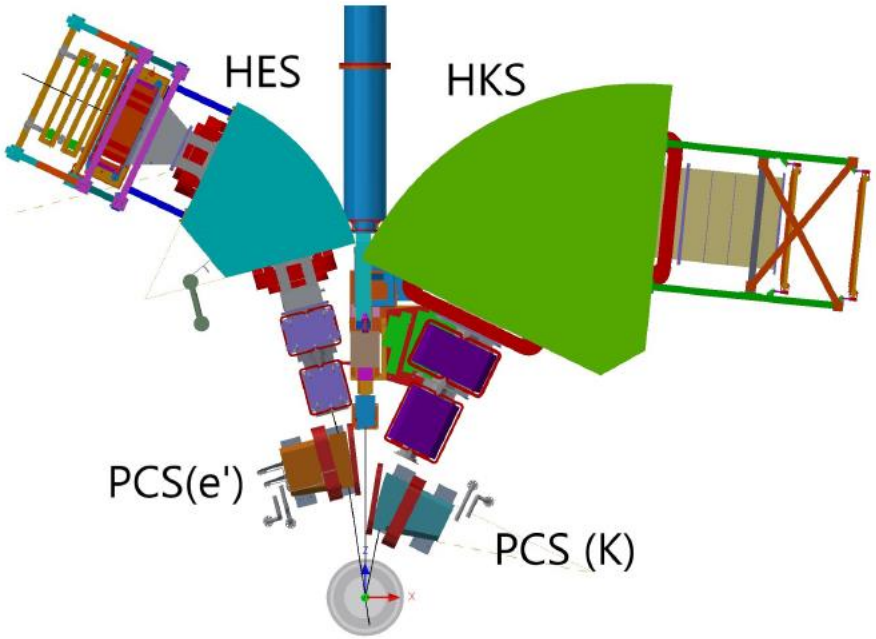
E12-13-007 goal: Measure the basic SIDIS cross sections of π^o production off the proton, including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate(*) flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

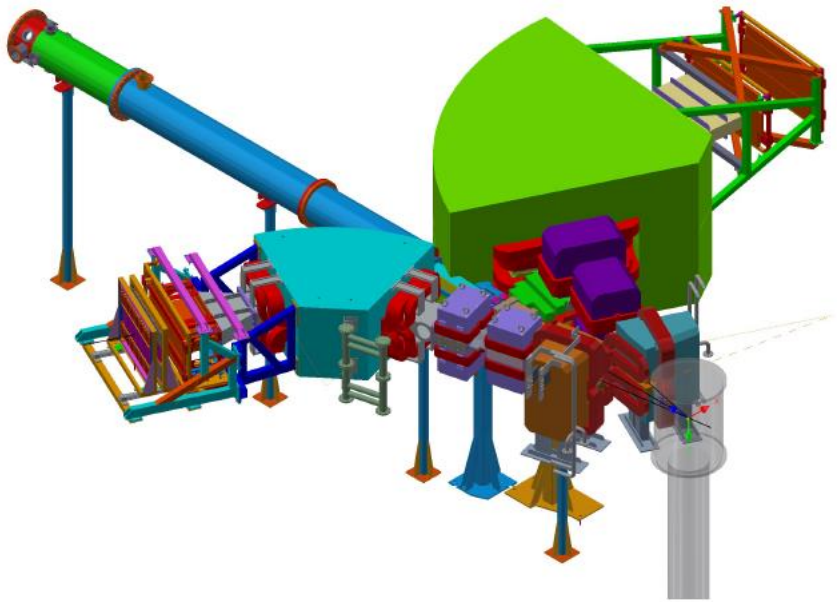


Hall C: Hypernuclear Experimental Setup

	Updated
Experimental Hall	Hall-C
Beam Energy [/(GeV)]	2.240
Electron spectrometer	HES
Bending direction	Horizontal
Central momentum [/(GeV/c)]	0.74
Kaon spectrometer	HKS
Bending direction	Horizontal
Central momentum [/(GeV/c)]	1.20

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}



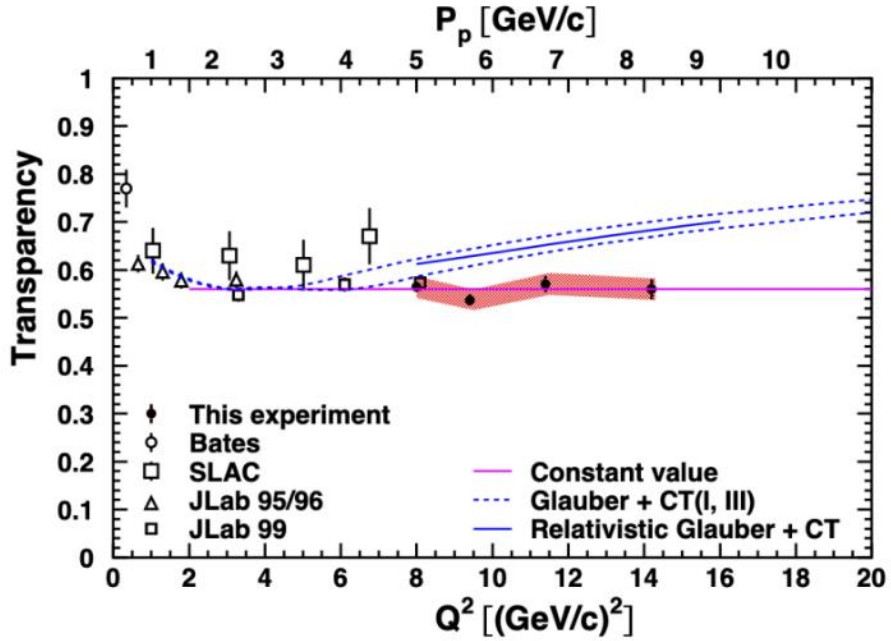


Hall C: Highlights from Experiments

- **No Sign of Color Transparency for Protons Traversing Nuclei**

- Unique prediction of QCD that hadrons are produced as point-like configurations in nuclei experiencing little interactions

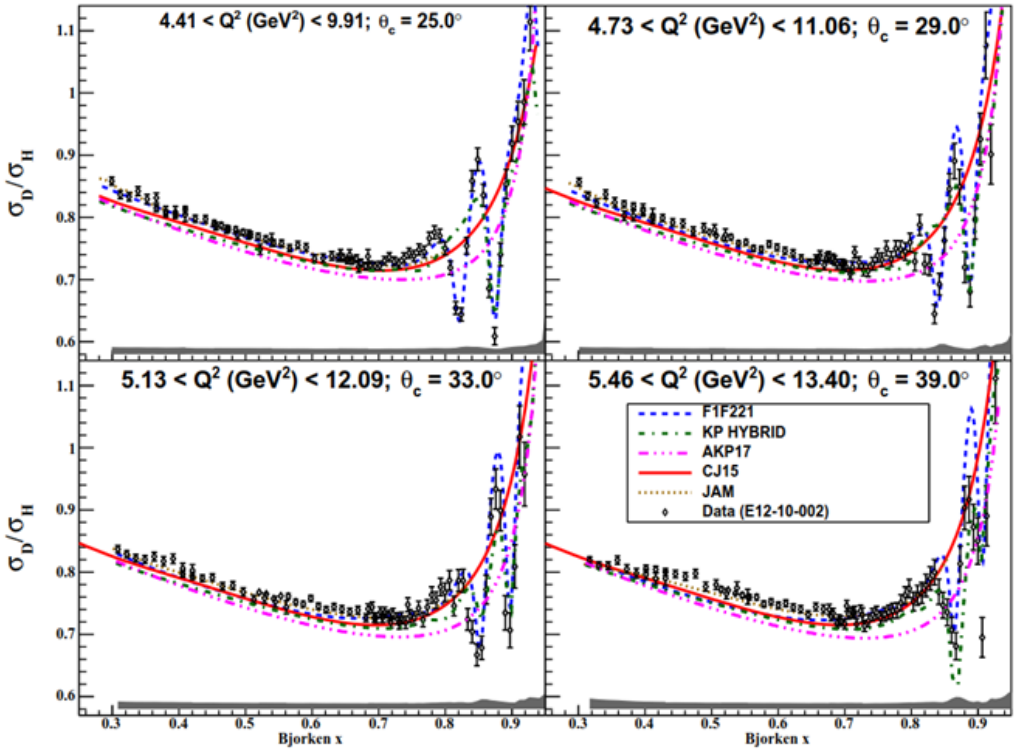
- Color Transparency seen in other reactions, but ruled out for protons



[D. Bhetuwal et al. (for the Hall C Collaboration), Phys. Rev. Lett. 126, 082301 (2021)]

- **Constraining PDFs at Large x_B**

- Measurement of F_2 for H, D
- Significant impact on valence PDFs in global fits



[D. Biswas et al. (for the Hall C Collaboration)]

J/ψ Near-Threshold Production in Hall B

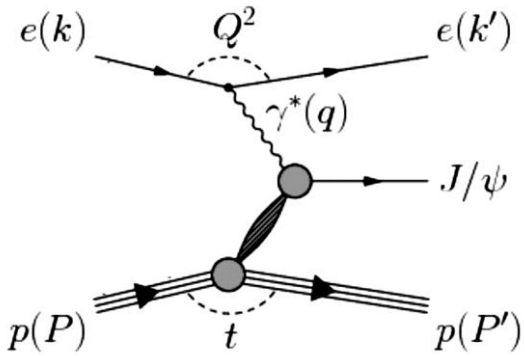
J/ψ Near-Threshold Production off the Proton and Neutron

CLAS12 took data on **J/ψ near-threshold photoproduction** off a proton and a deuterium target:

$e\ p \rightarrow$ e' J/ψ p $\rightarrow$ (e') l+l-p (RG-A)

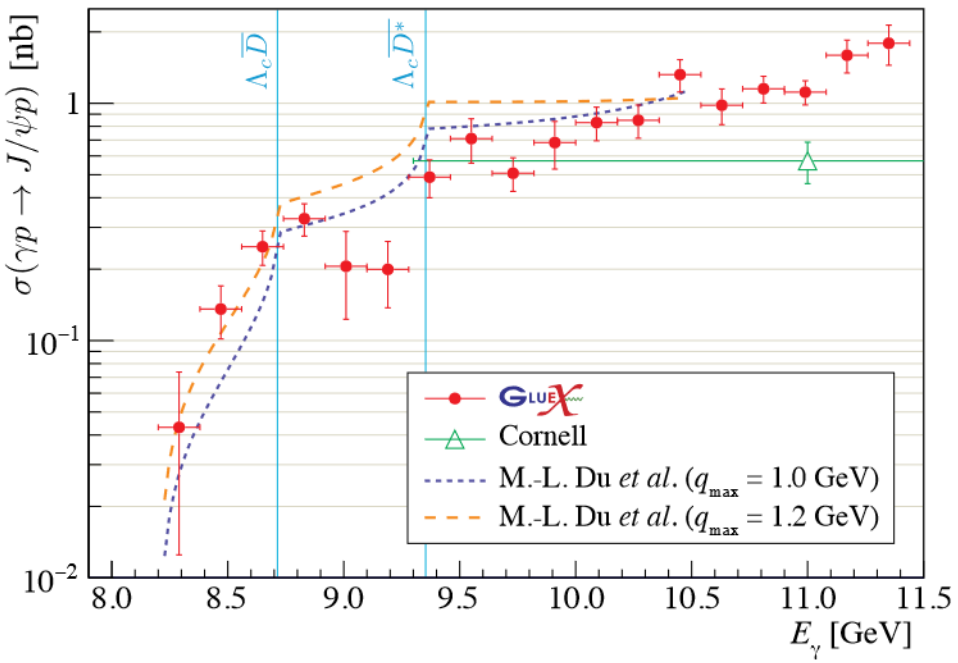
$e\ p_{\text{bound}} \rightarrow$ e′ J/ψ p $\rightarrow$ (e') l+l-p (RG-B)

$e\ n_{\text{bound}} \rightarrow$ e! J/ψ n $\rightarrow$ (e') l+l-n (RG-B)



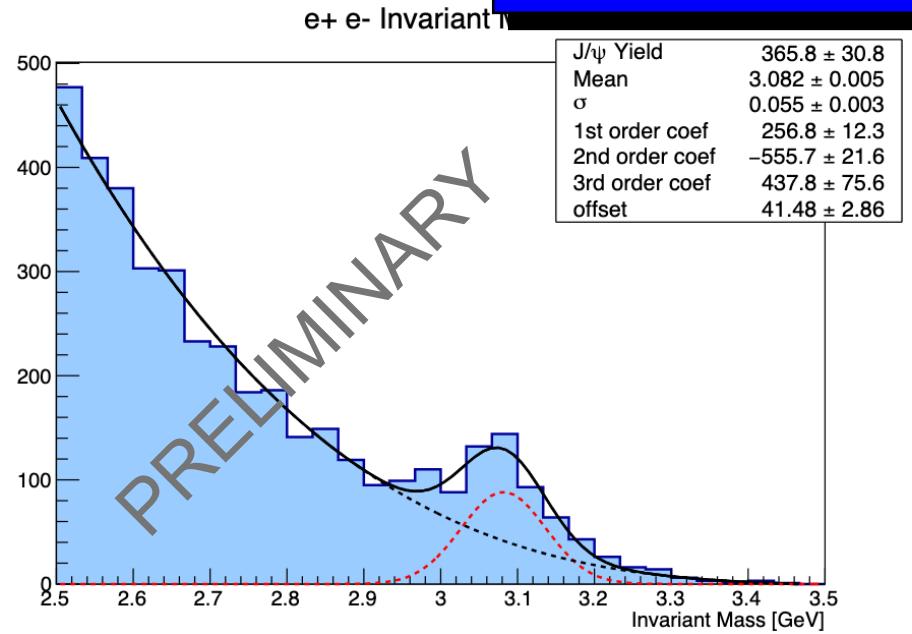
- First measurement on bound neutron and proton in deuteron
- New constraints on open-charm contributions to cross section
- Testing the isospin invariance of production mechanism

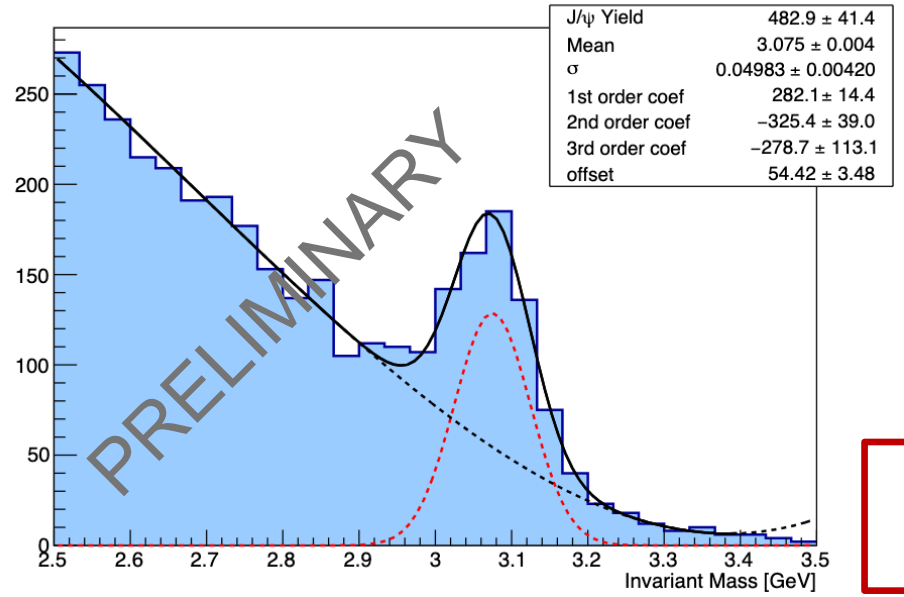
See talk by Lubomir Pentchev on GFF extraction from first moments of GPDs by relating the scattering amplitude to the gluon GPDs



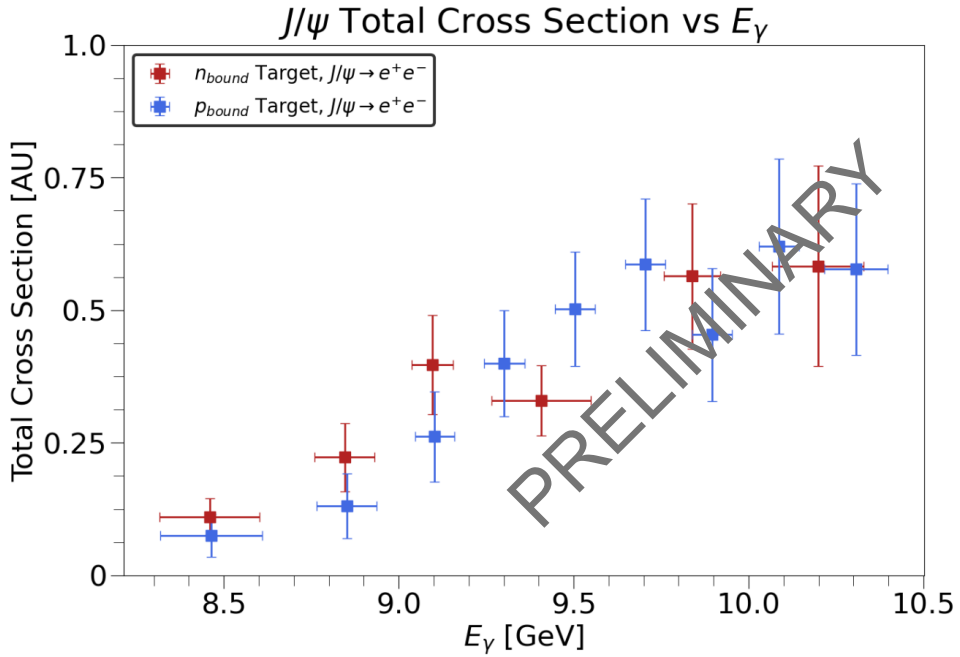
[Du et al. EPJ C80, 1053 (2020)]

Cross Section Determination





- Lepton and hadron identification in Forward Detector
- Radiative and momentum-dependent corrections, fiducial cuts
- Momentum selection in Q^2 and missing mass
- Fits to the invariant mass spectra

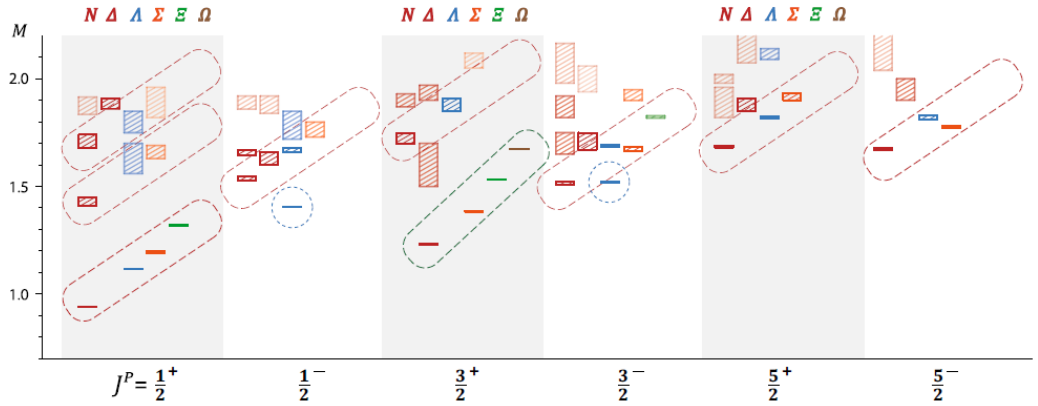


Good agreement between cross section on proton and neutron suggests isospin invariant production mechanism

Strangeness Production in Hall B

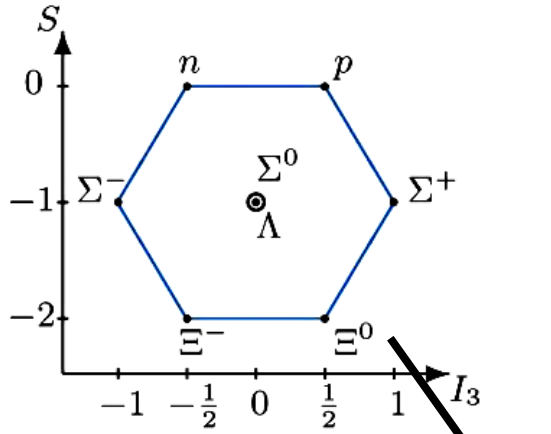
Electroproduction of the Very Strangest Baryons

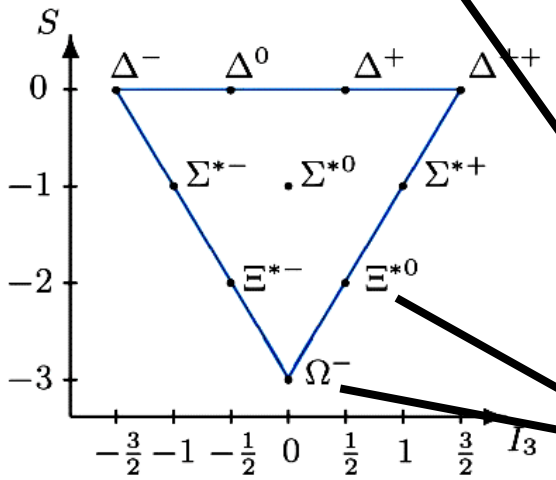
- **Study of S = −2 and −3 baryons with the CLAS12 detector**

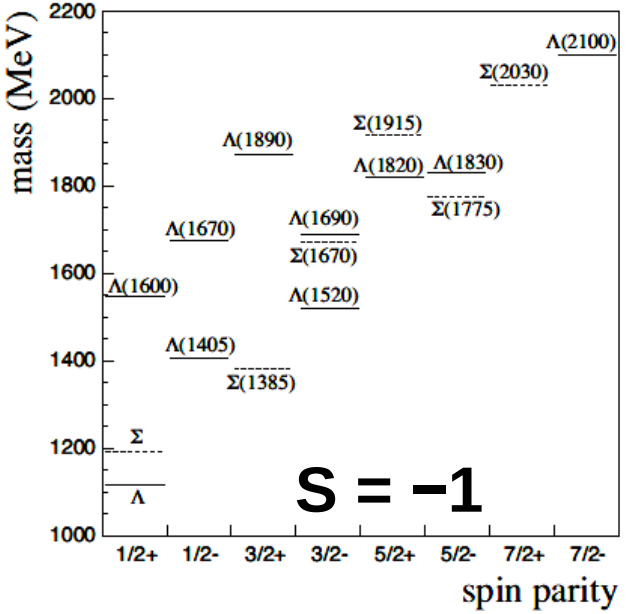


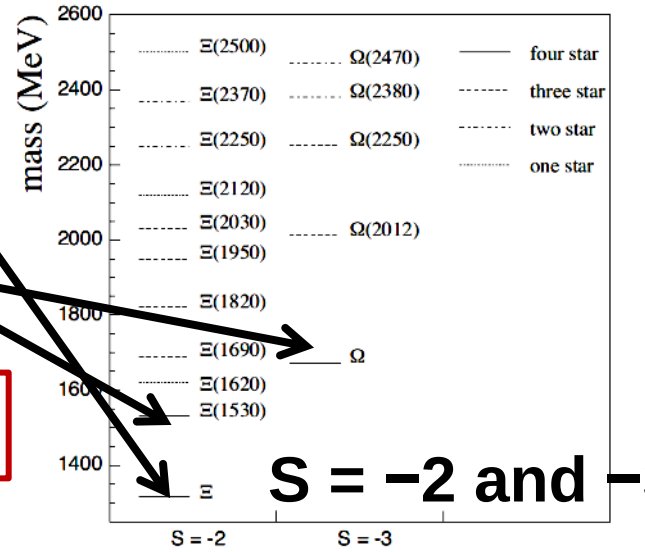
- **Ω baryon is unique** but simple *I* = 0 system of 3 strange quarks: place to study internal structure of baryons

- Little known of **excited Ω and Ξ baryons**
  - Only 2 Ω and 6 Ξ states well-established
  - Even fewer spin-parity assignments
  - SU(3) flavor multiplets are incomplete









The art of spectroscopy

Strategies to Access Multi-Strange Baryons

- **Production** processes:

  $ep \rightarrow e'K^+K^+\Xi^{-(*)}$

  $ep \rightarrow e'K^+K^+K^0\,\Omega^-$

- **Decay** processes:

  $\Omega^- \rightarrow (\Lambda \rightarrow p\pi-)K^-, \Xi^0\pi-$

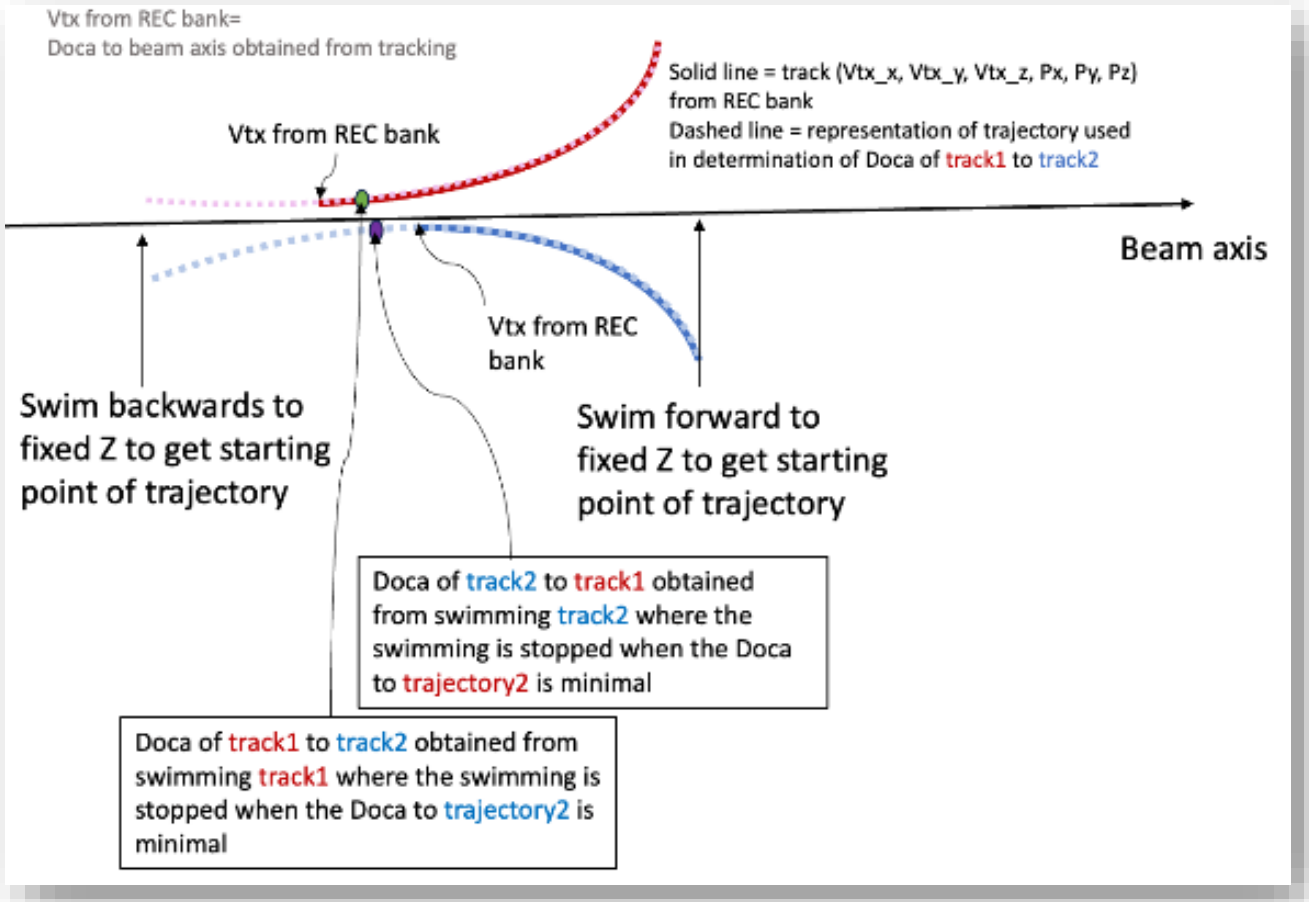
  $\Xi^* \rightarrow \Xi\pi$

  $\Xi \rightarrow (\Lambda \rightarrow p\pi-)\pi$

- **Multiparticle charged final states**:
  - High efficiency
  - Good kaon PID

- Cross sections small, background high:

Displaced vertices



[V. Ziegler, in progress]

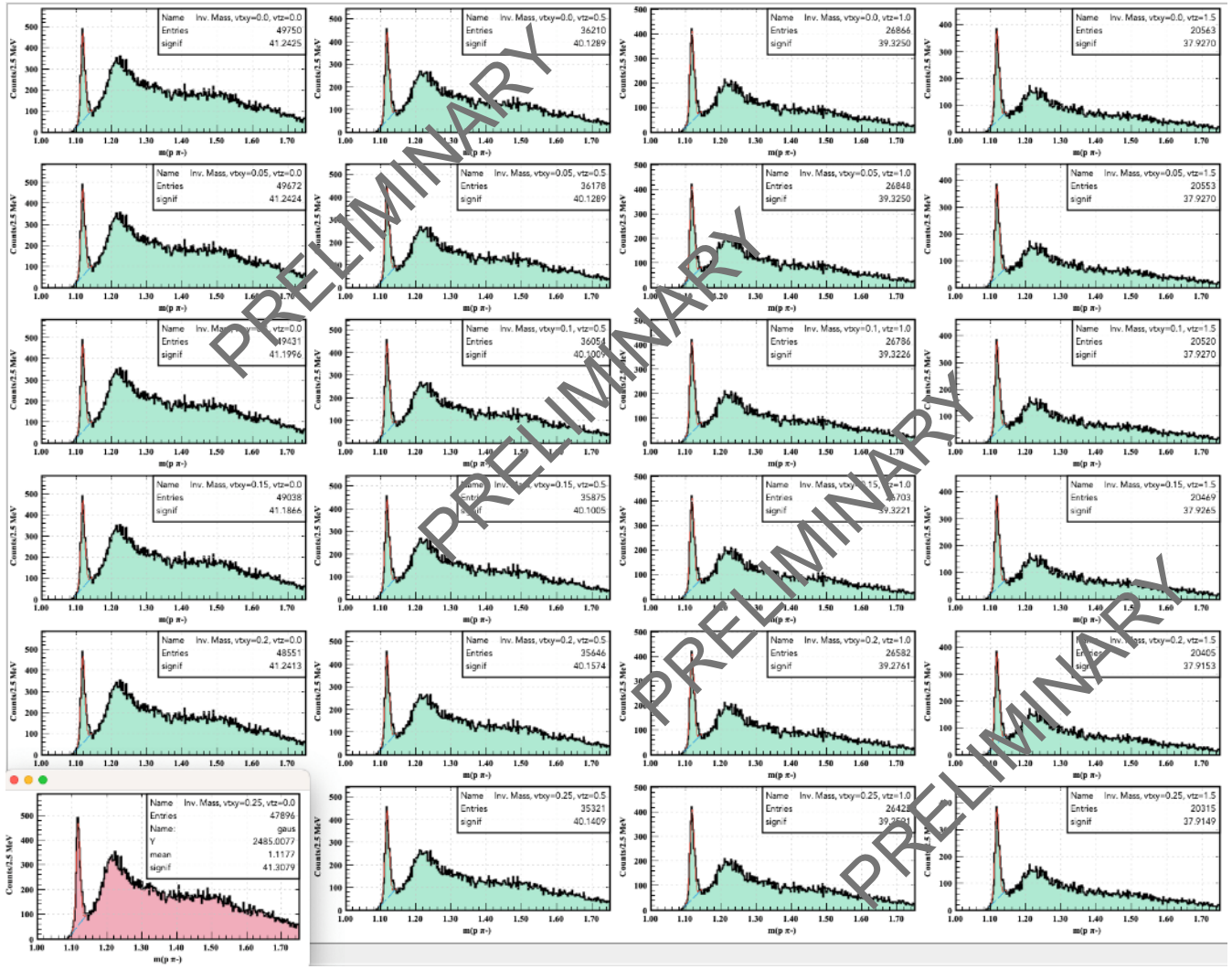
Identification of Weak Decays

ed → e'K+(Λ→pπ−)n

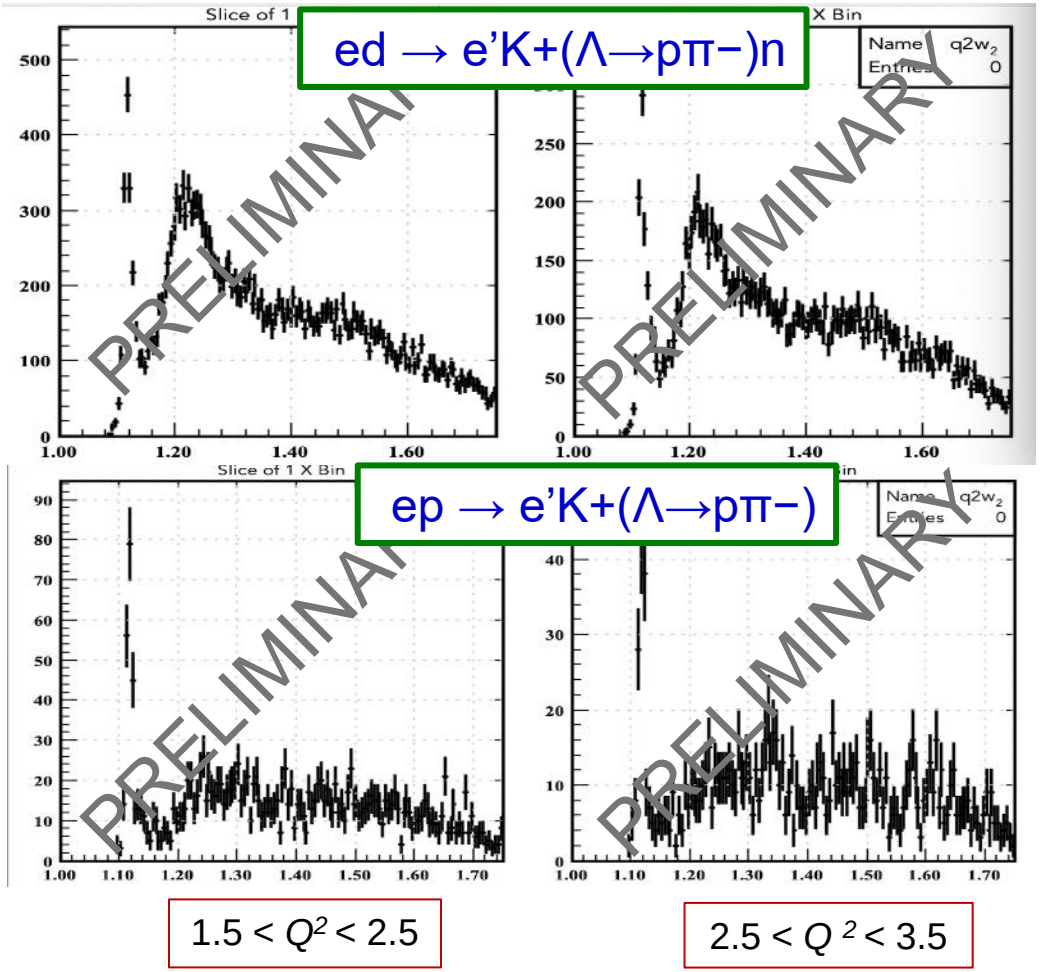
Dependence on vertex displacement

long. vertex displ.

trans. vertex displ.



Study of dependence on momentum transfer Q^2

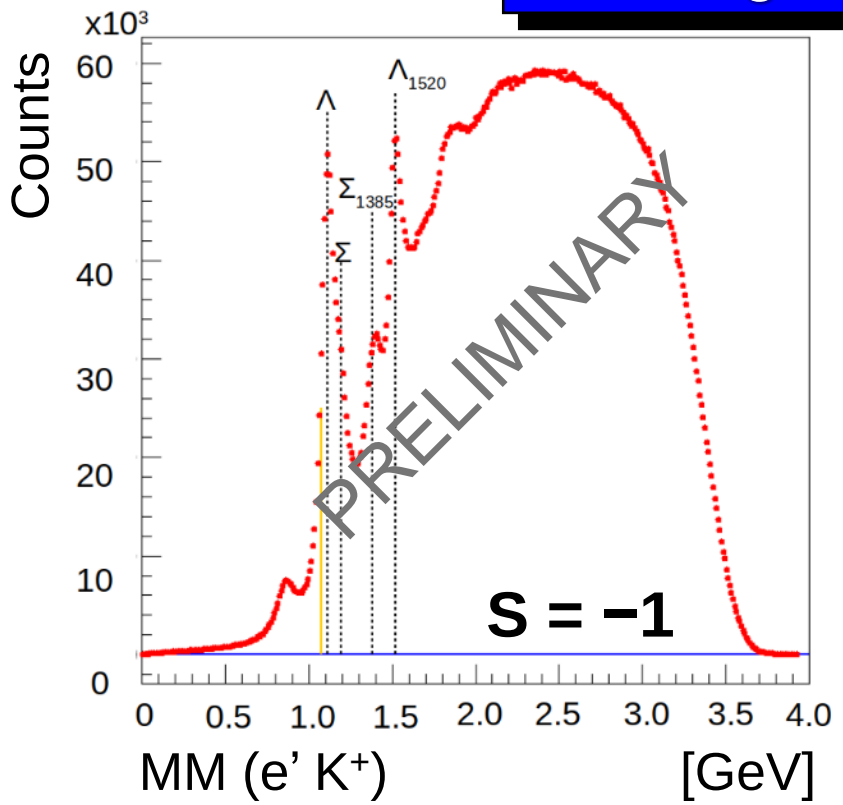


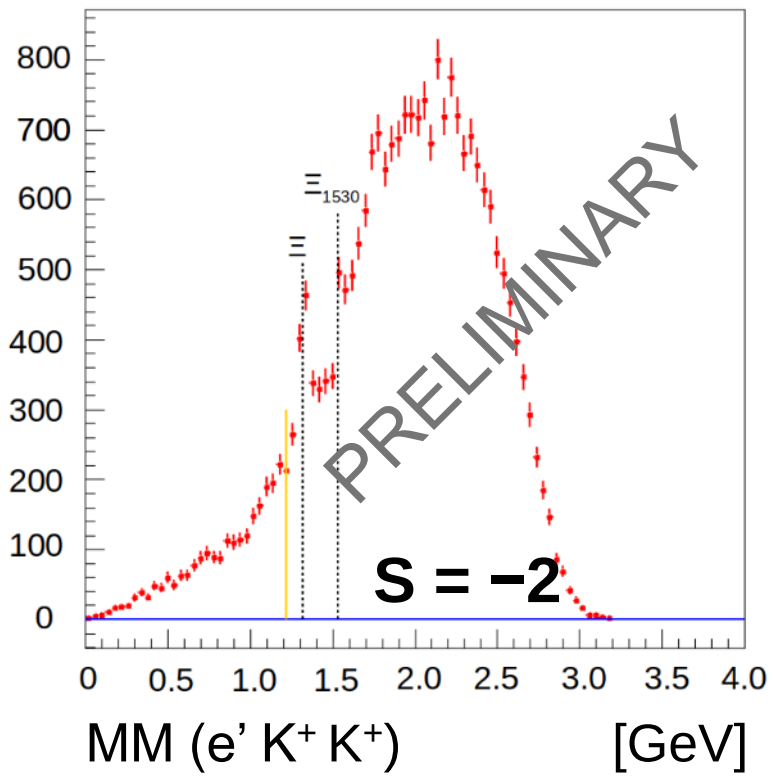
$1.5 < Q^2 < 2.5$

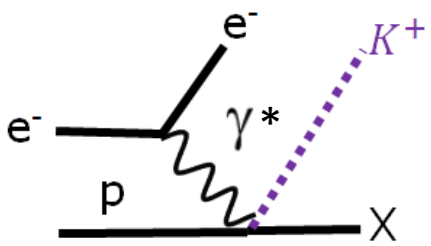
$2.5 < Q^2 < 3.5$

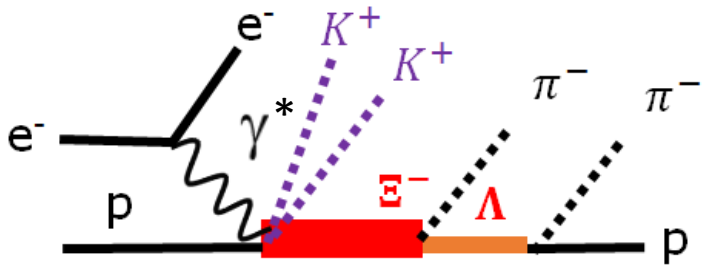
[V. Ziegler, in progress]

Strangeness and Multi-Strangeness Production









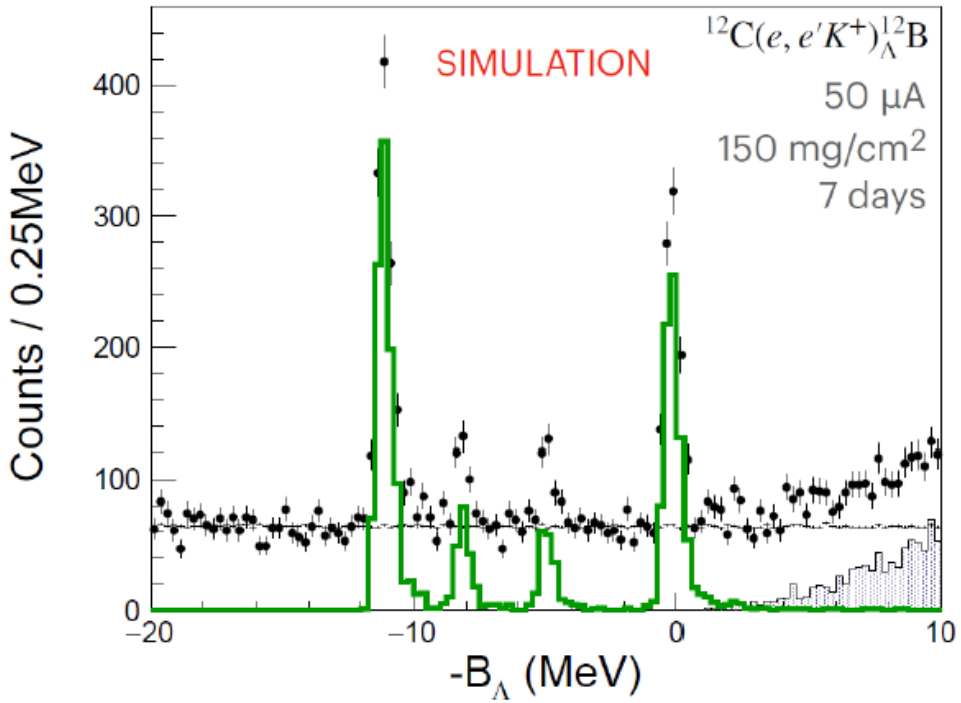
- Search for **excited Ξ states**
- Measurement of **quantum numbers** and mass splittings of Ξ doublets
- Study of beam polarization transfer and induced polarization of ground state Ξ
- Experiments at JLab **complementary** with J-PARC Ξ spectroscopy experiments

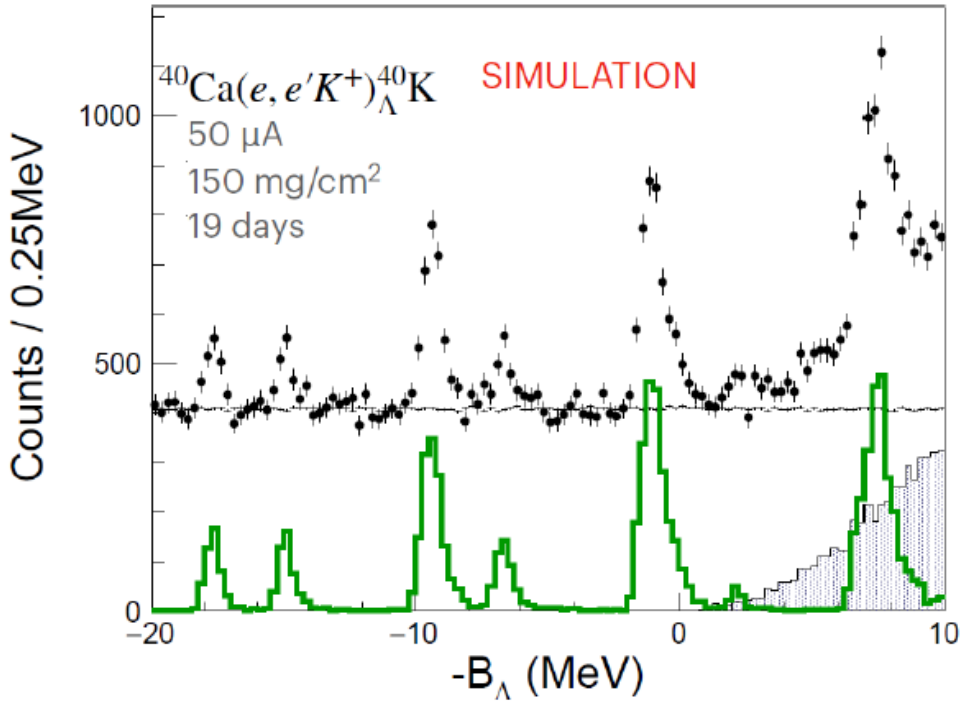
[U York, in progress, presented by E. Pasyuk at RG-A Retreat, CNU, 18 Oct. 2023]

Hypernuclear Physics in Hall C

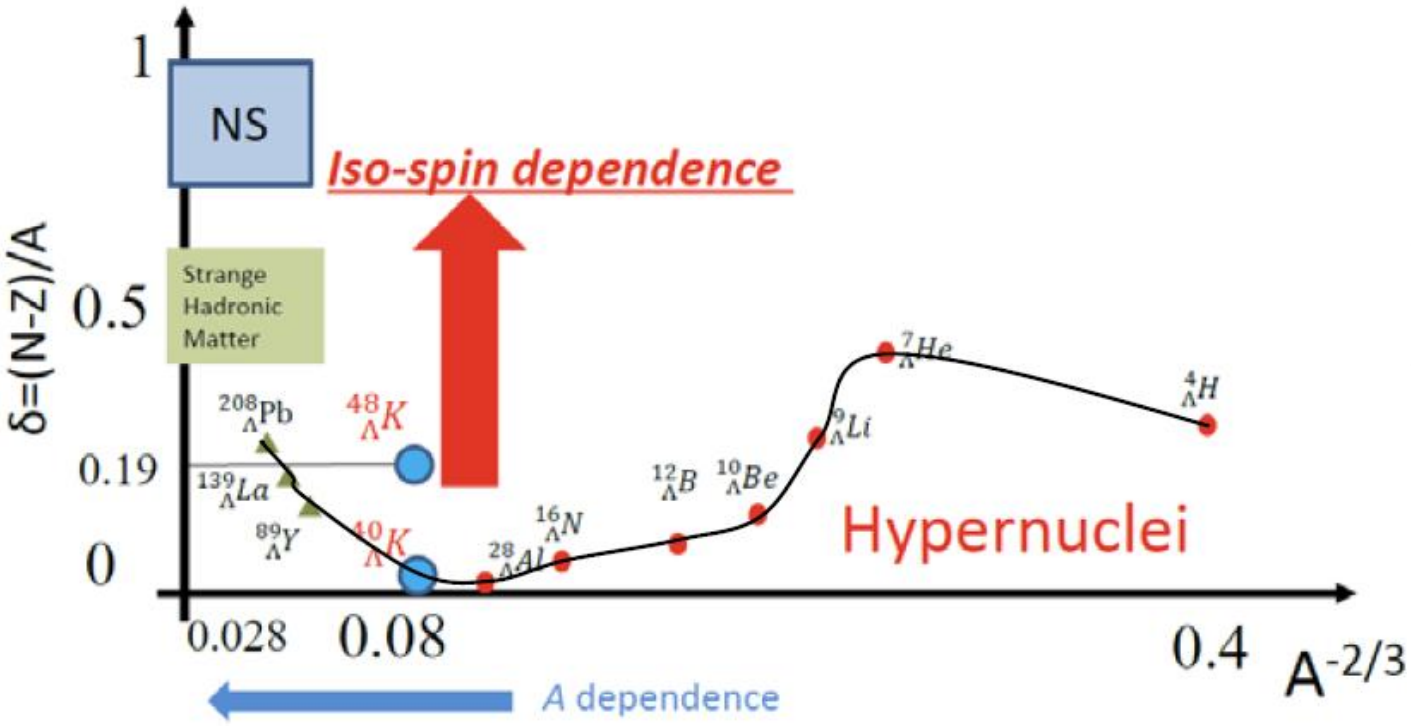
Study of Light and Medium-Mass Hypernuclei

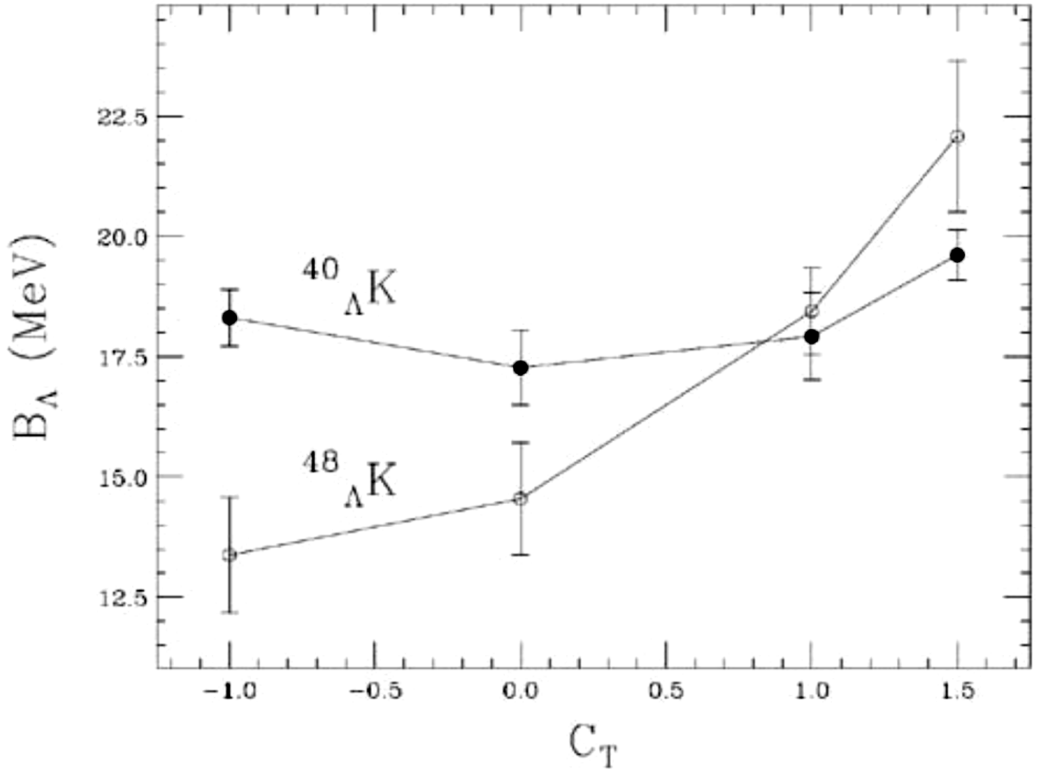
Target	CH_2	^{6}Li	^{9}Be	^{11}B	^{12}C	^{27}Al	^{40}Ca	^{48}Ca
Hyperon/Hypernucleus	Λ	$^{6}_{\Lambda}$He	$^{9}_{\Lambda}$Li	$^{11}_{\Lambda}$Be	$^{12}_{\Lambda}$B	$^{27}_{\Lambda}$Mg	$^{40}_{\Lambda}$K	$^{48}_{\Lambda}$K
Target thickness [/(mg/cm^2)]	500	150	150	150	150	150	150	150
Cross section [/(nb/sr)]	1000	10	10	30	90	60	50	50
Beam intensity [/(μA)]	2	50	50	50	50	50	50	50
Yield (g.s.) [/(/h)]	8.6	1.5	1.0	2.5	6.8	2.0	1.1	0.9
Acc. BG [/(/MeV/h)]	0.03	0.86	0.84	0.96	1.2	1.8	2.4	1.9





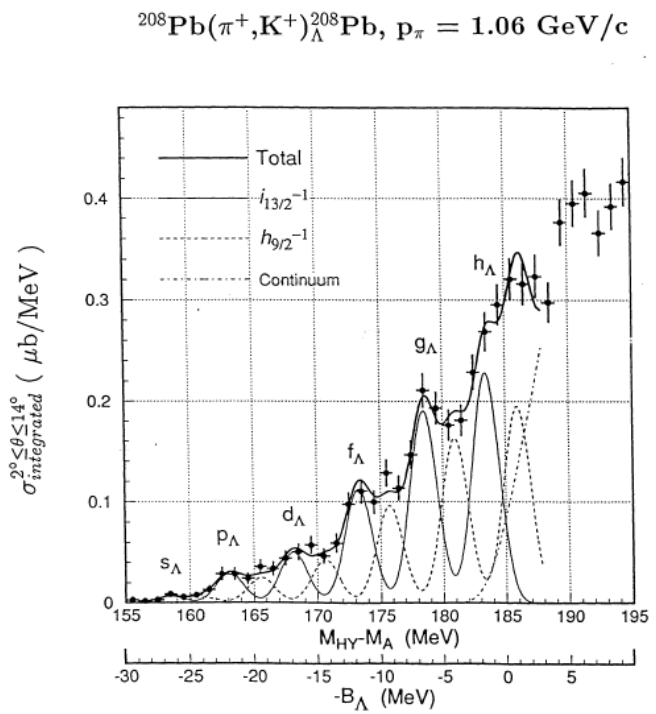
Study of YN Isospin-Dependence

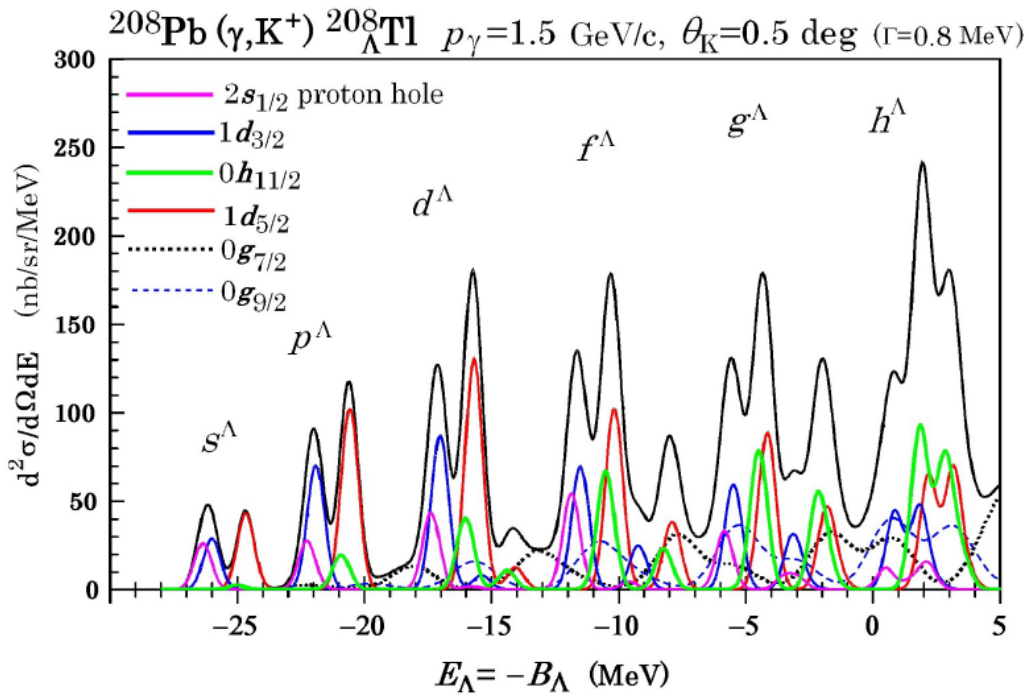




Current experimental information in this mass region cannot provide ANY information on the possible **isospin dependence** of hypernuclear forces

Study of Heavy Hypernuclei

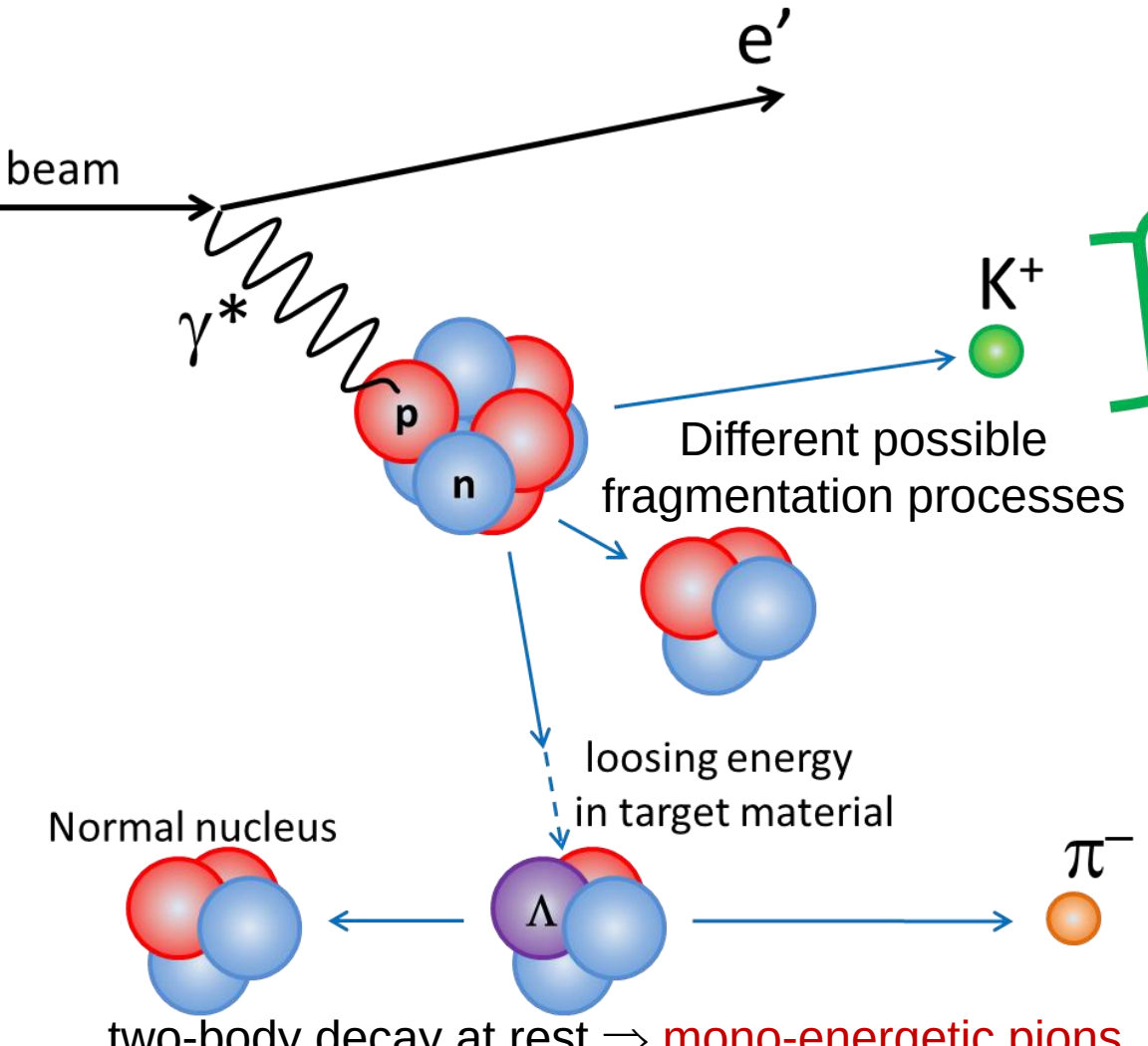




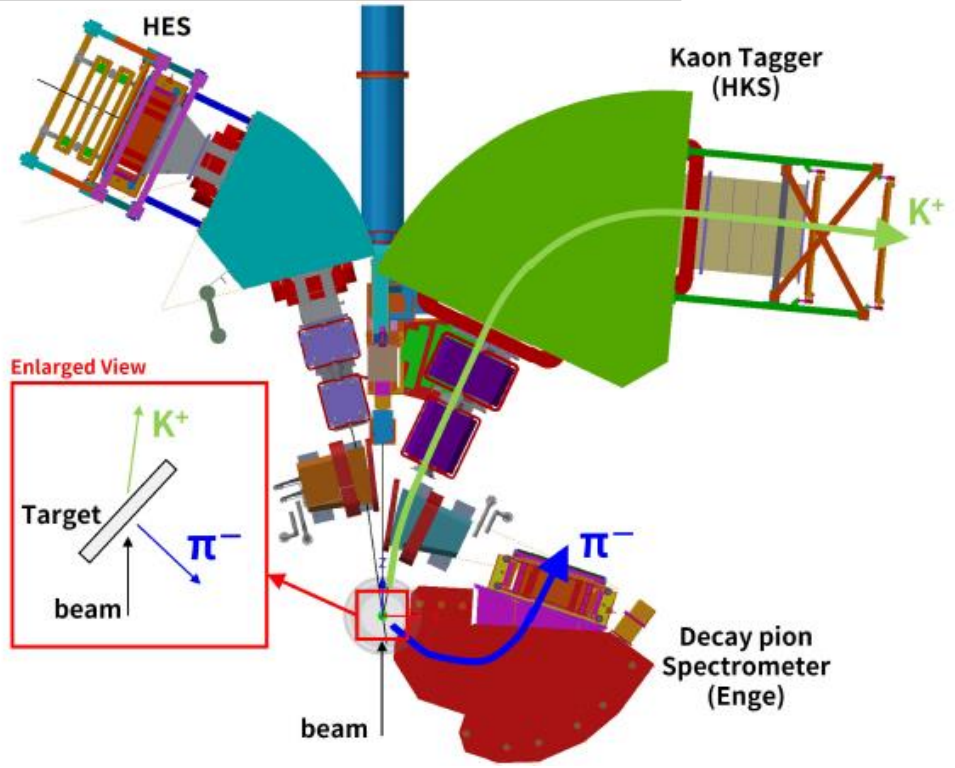
Due to extended region of constant density and large neutron excess **heavy hypernuclei** provide best available proxy of neutron star matter

Heavy hypernuclei provide an environment, in which **three-body interactions** are expected to play an important role

Hyperfragment Decay-Pion Spectroscopy with Electron Beams

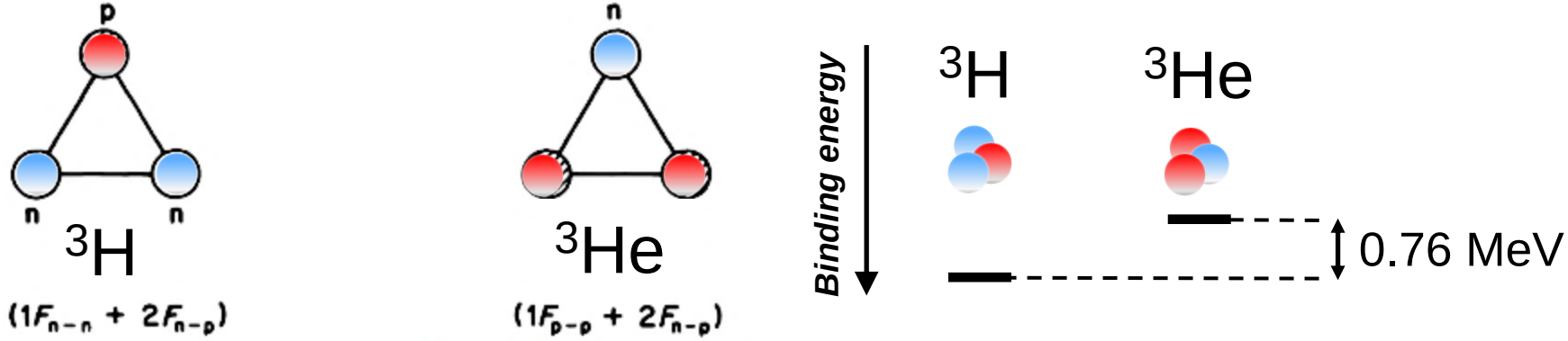


$$M_{\mathrm{HYP}} = \sqrt{M_{\mathrm{ncl}}^2 + p_{\pi^-}^2} + \sqrt{M_{\pi^-}^2 + p_{\pi^-}^2}$$



Target	Thickness		Hypernuclei
	(mm)	(mg/cm^2)	
^{6}Li	2.8	150	$^{3,4}_{\Lambda}$H
^{9}Be	0.8	150	$^{3,4,6}_{\Lambda}$H, $^{7,8}_{\Lambda}$He, $^{7,8,9}_{\Lambda}$Li, $^{8}_{\Lambda}$Be
^{11}B	0.7	150	$^{3,4,6}_{\Lambda}$H, $^{7,8}_{\Lambda}$He, $^{7,8,9}_{\Lambda}$Li, $^{8}_{\Lambda}$Be
^{12}C	0.9	150	$^{3,4,6}_{\Lambda}$H, $^{7,8}_{\Lambda}$He, $^{7,8,9}_{\Lambda}$Li, $^{8}_{\Lambda}$Be, $^{9,10,11,12}_{\Lambda}$B
^{27}Al	0.6	150	s, p, sd-shell hypernuclei?
^{40,48}Ca	1.0	150	s, p, sd-shell hypernuclei?
^{208}Pb	0.13	150	s, p, sd-shell hypernuclei?

Charge Symmetry Breaking in Nuclei



$M(^3\mathrm{H}) =$	2808.921	$B(^3\mathrm{H}) =$	8.482
$M(^3\mathrm{He}) =$	2808.391	$B(^3\mathrm{He}) =$	7.718
$\Delta M^3 =$	−0.530	$\Delta B^3 =$	−0.764

… can be studied in mirror nuclei after correcting for Coulomb effects

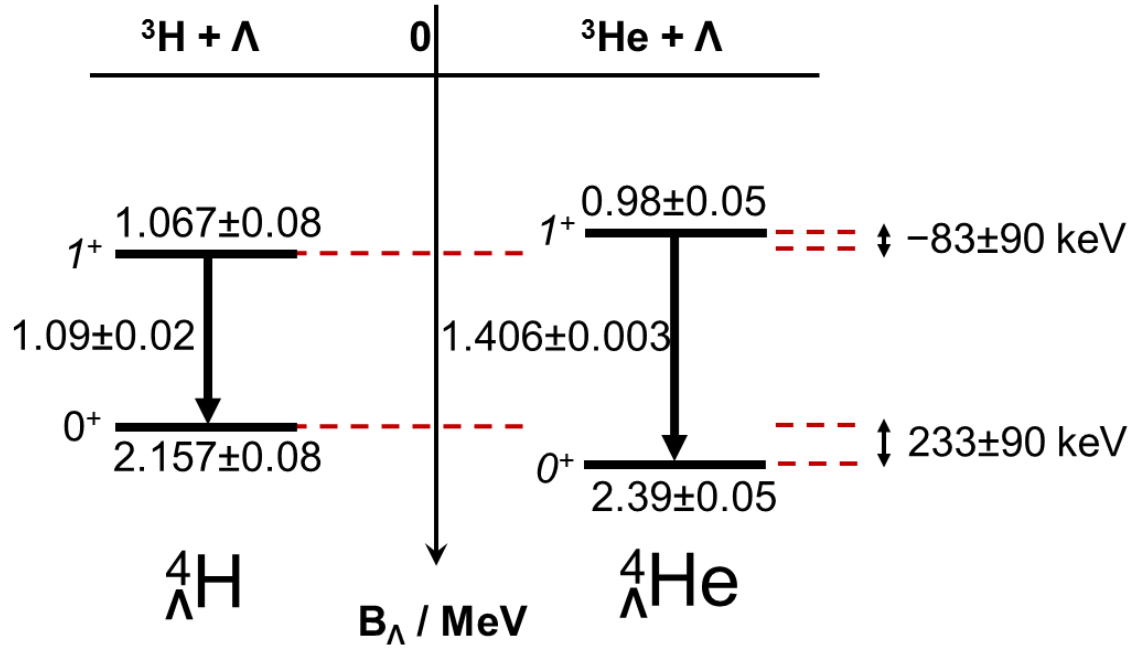
… is dominated by electromagnetic effects

… nuclear part very small, ~ 80 keV in case of ^{3}H - ^{3}He

… is well understood and reproduced by theory using ρ^0-ω mixing

[R. Machleit et al., Phys. Rev. C 63, 034005 (2001)]

Charge Symmetry Breaking in Hypernuclei

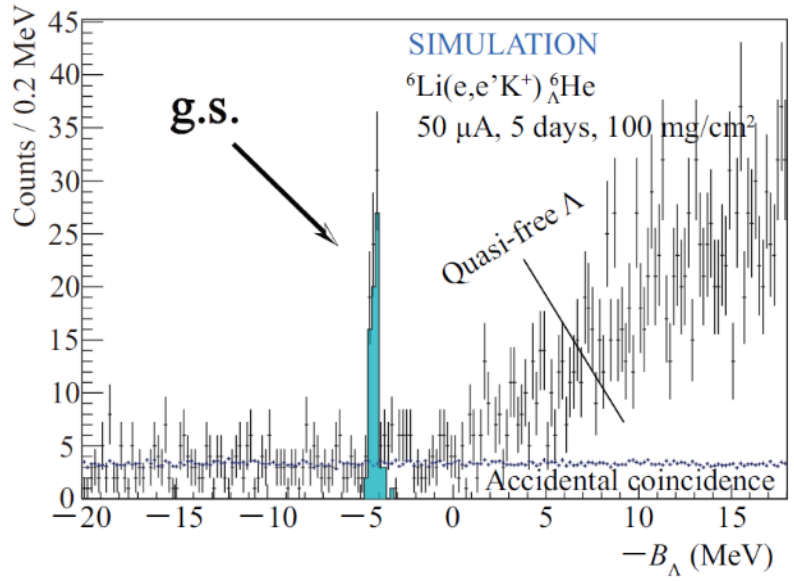


[F. Schulz et al. (A1 Collab.), NPA 954, 149 (2016)]

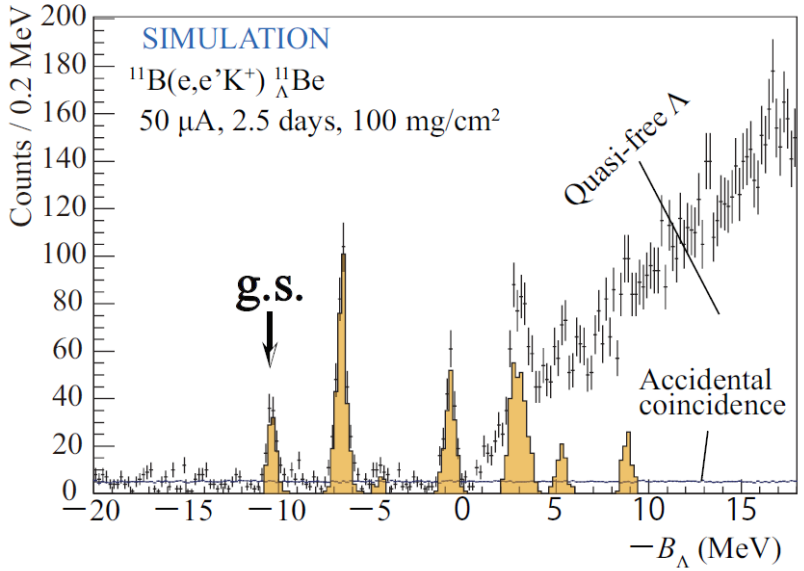
- Is CSB in the $A = 4$ system a feature of spin-dependent interactions?
- Is CSB a general feature of SU(3) interactions in light systems?

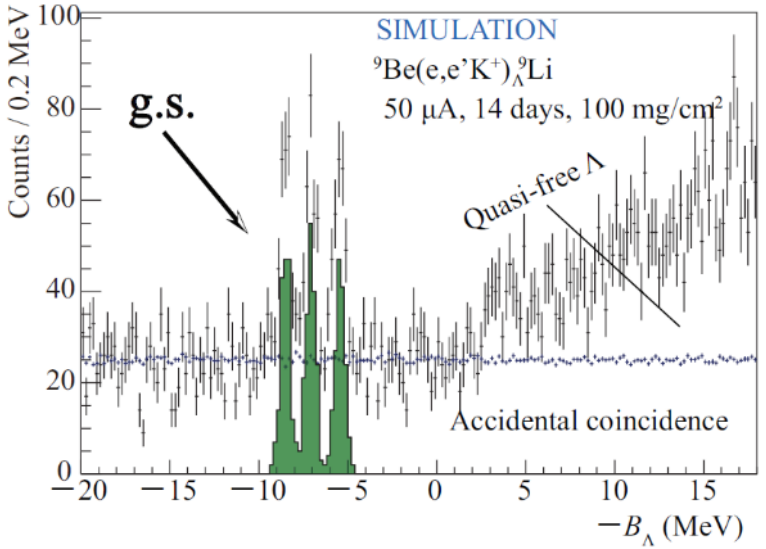
Answers can only be found in systematic studies across different nuclei

Study of Hypernuclear Isospin Multiplets

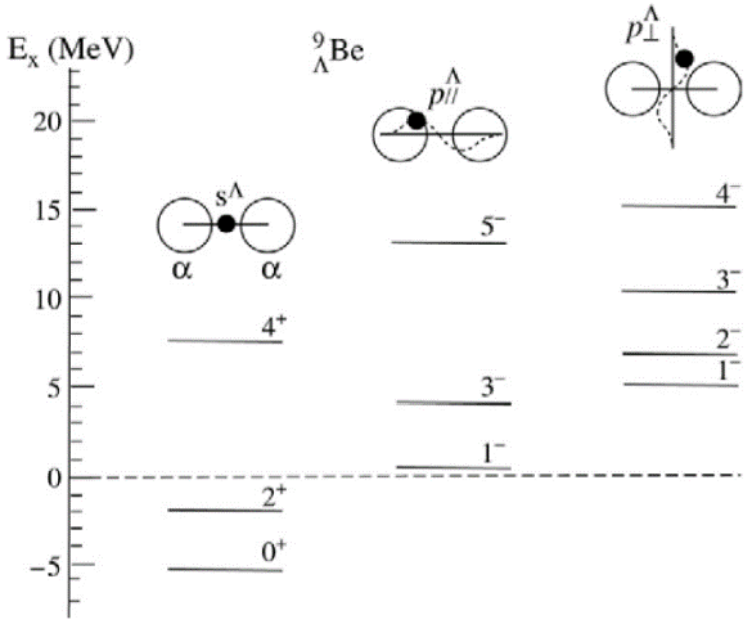


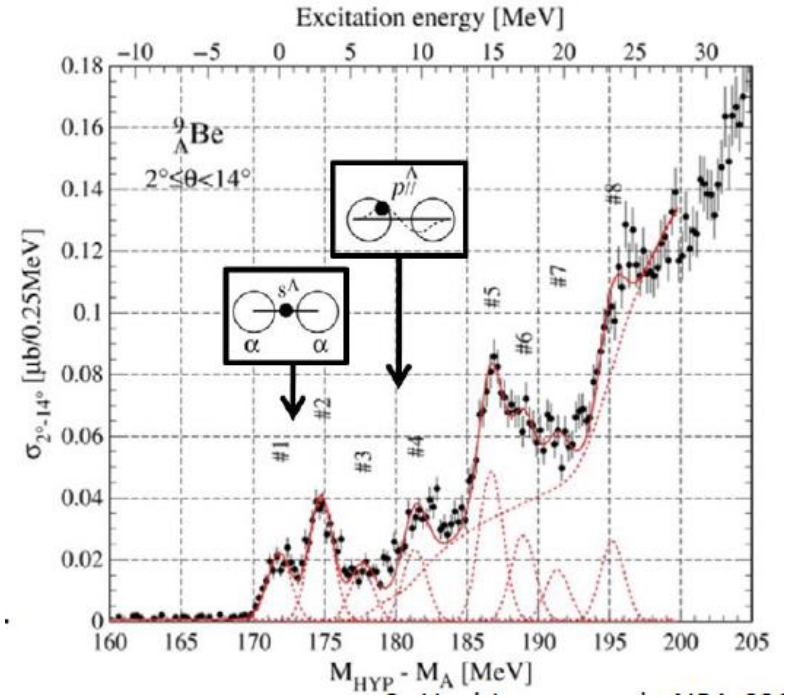
Reaction	Target thickness [/(g/cm^2)]	Beam current (/μA)	Assumed cross section [/(nb/sr)]	Yield per day
$^{6}\mathrm{Li}(e,e'K^{+})^{6}_{\Lambda}\mathrm{He}$	100	50	10	24
$^{9}\mathrm{Be}(e,e'K^{+})^{9}_{\Lambda}\mathrm{Be}$			7.6	12
$^{11}\mathrm{B}(e,e'K^{+})^{11}_{\Lambda}\mathrm{B}$			30	39





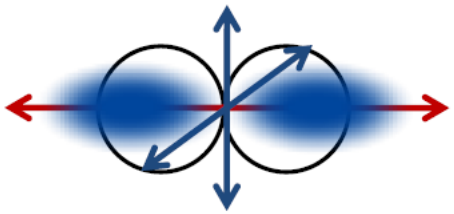
Genuine Hypernuclear States





Genuine hypernuclear states:

***p* orbit parallel to 2α (long axis)**

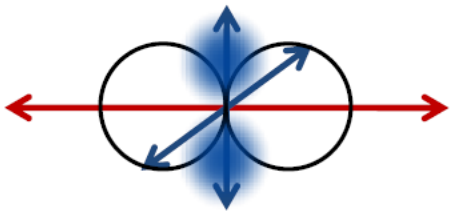


Large overlap

Deeply bound

^{9}Be analog states:

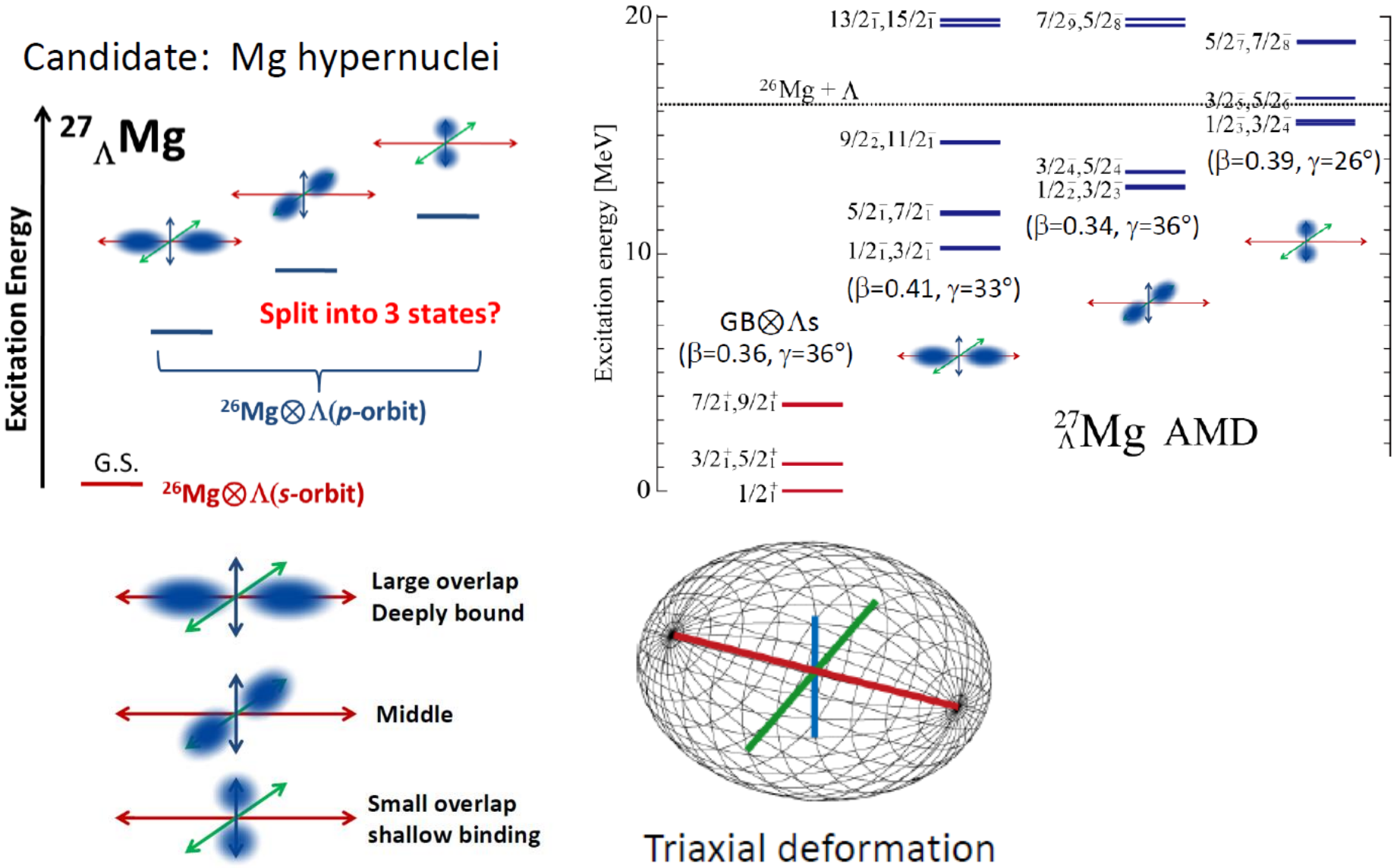
***p* orbit perpendicular to 2α (short axes)**



Small overlap

Shallowly bound

States in Triaxially Deformed Hypernuclei



Summary

- General Overview and Instrumentation

  JLab hosts existing or planned new equipment at the luminosity frontier

- **Physics Highlights** from Halls A, B, and C

  At CEBAF a groundbreaking experimental program has been developed

- **J/ψ Near-Threshold Production** in Hall B

  First measurement with CLAS12 on the bound proton and bound neutron

- **Strangeness Production** in Hall B

  CLAS12 aims for first observation of Ω baryon in electroproduction

- **Hypernuclear Physics** in Hall C

  Study of isospin dependence and charge symmetry breaking in hypernuclei uniquely reveals features of nuclear interactions