GEN Data Analysis Summary

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SBS Collaboration Meeting

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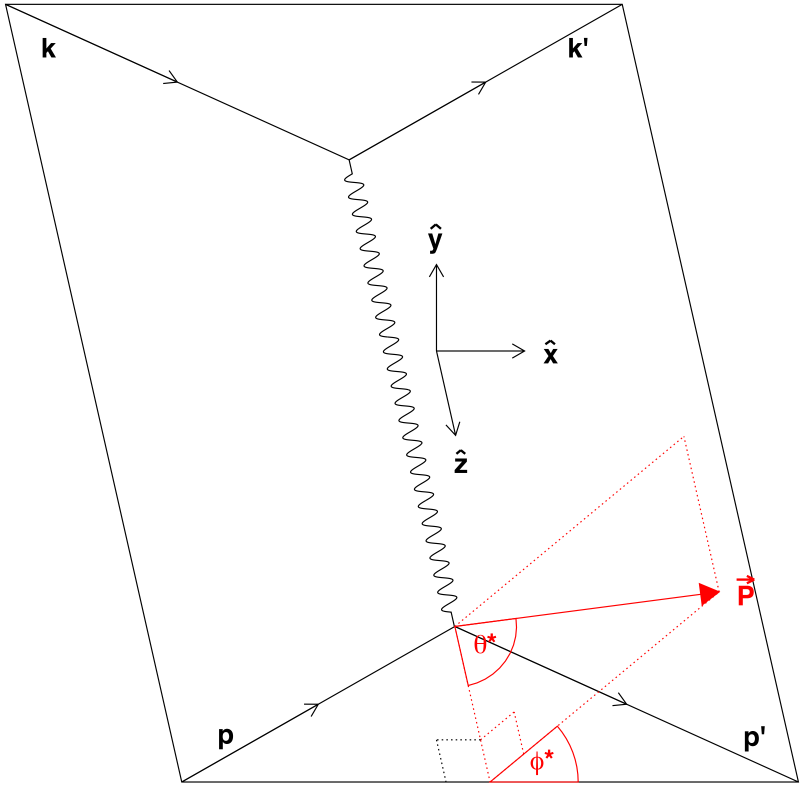
Outline

- Overview of double-spin asymmetry technique for G_E^n/G_M^n
- SBS GEN overview
- Differences between GMN and GEN analyses
- Comparison between E02-013 (”GEN-1”) and E12-09-016 (“GEN-2”)
- Issues and challenges for GEN-2 analysis

Polarization Observables in Elastic $eN \to eN$ Scattering



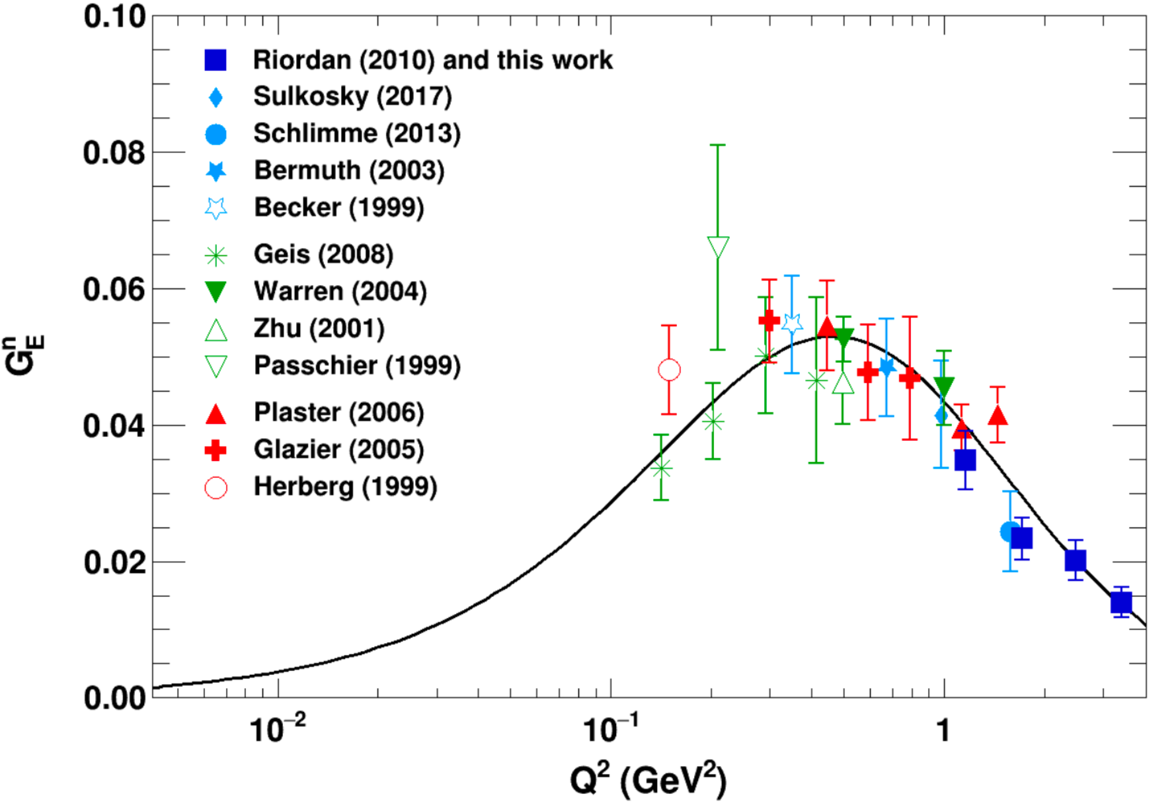
Standard coordinate system and angle definitions for nucleon polarization components in $eN \to eN$

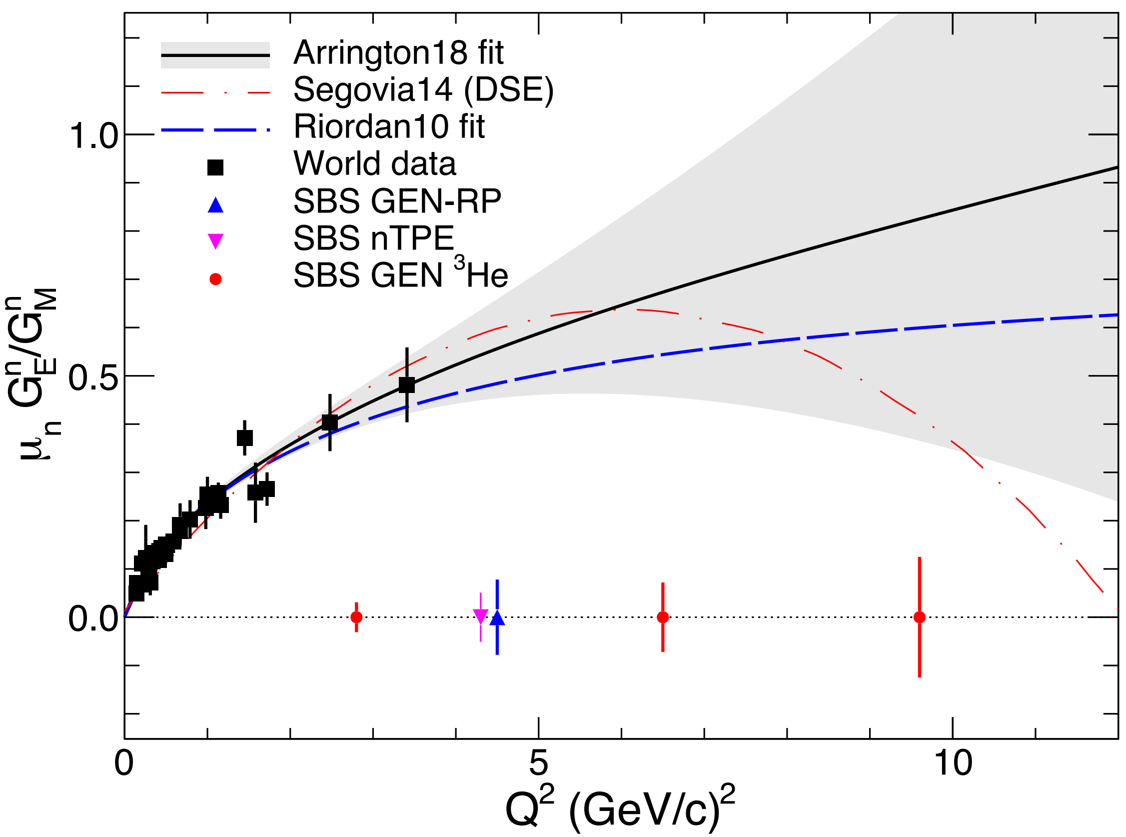
$$
\begin{aligned}
A_{eN} &\equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = P_{\mathrm{beam}} P_{\mathrm{targ}} \left[A_t \sin\theta^* \cos\phi^* + A_\ell \cos\theta^* \right] \\
\boxed{A_t} & \boxed{= -\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}} \frac{r}{1+\frac{\epsilon}{\tau} r^2}} \\
A_\ell &= -\frac{\sqrt{1-\epsilon^2}}{1+\frac{\epsilon}{\tau} r^2} \\
r &\equiv \frac{G_E}{G_M} \\
P_t &= P_{beam} A_t \\
P_\ell &= -P_{beam} A_\ell \\
\frac{G_E}{G_M} &= -\frac{P_t}{P_\ell} \sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}} = -\frac{P_t}{P_\ell} \frac{E_e + E'_e}{2M} \tan\left(\frac{\theta_e}{2}\right)
\end{aligned}
$$

Target spin is oriented to measure this asymmetry in ^{3}He(e,e'n)!

- Polarized beam-polarized target double-spin asymmetry or polarization transfer observables in OPE are sensitive to the electric/magnetic form factor *ratio*, giving enhanced sensitivity to $G_E(G_M)$ for large (small) values of Q^2, as compared to the Rosenbluth method

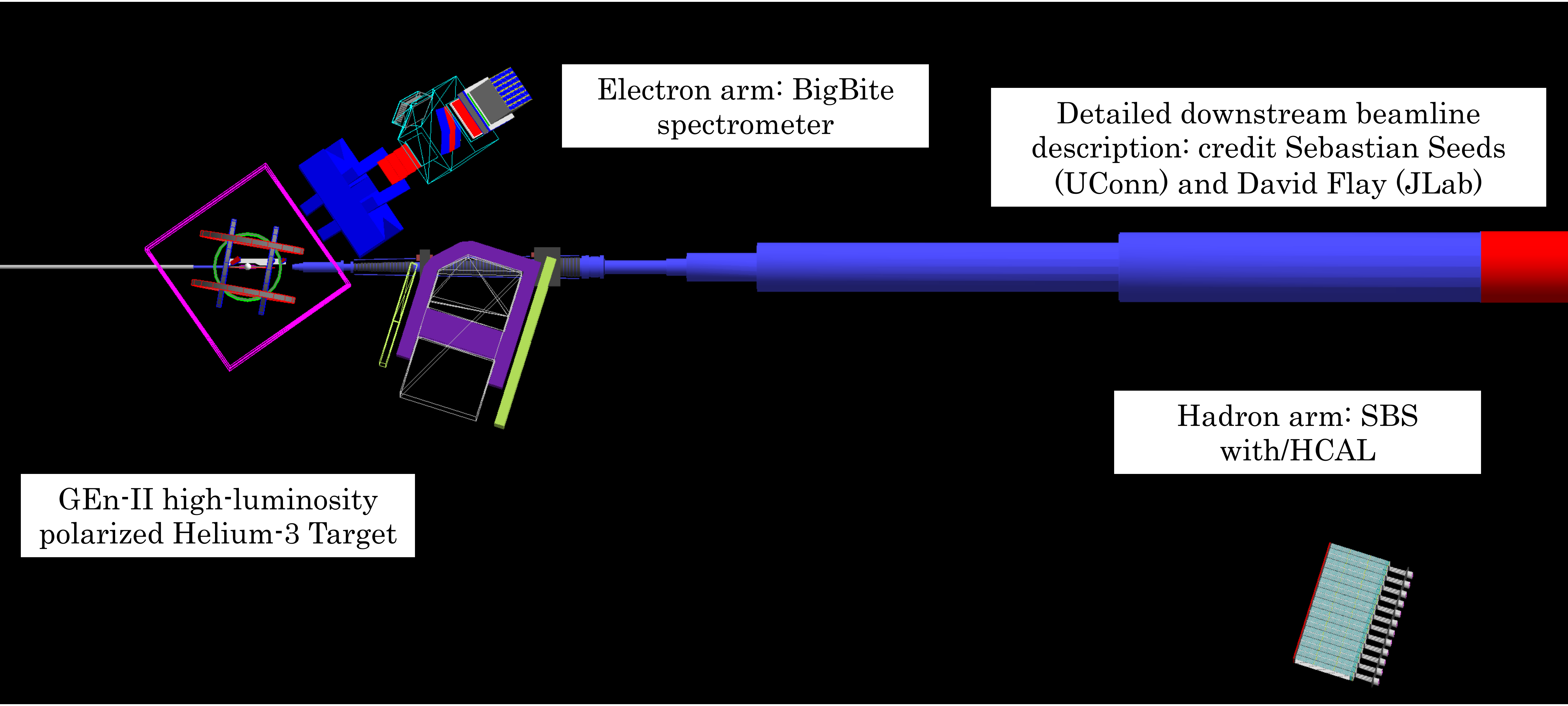
Neutron FFs—GEN





- Left (from Obrecht *et al.*, in preparation): G_E^n from polarization observables (color-coded by observable): Polarized Helium-3 target asymmetry, Deuteron recoil polarimetry, Polarized deuterium target asymmetry.
    - See Freddy Obrecht Ph.D. thesis: https://opencommons.uconn.edu/dissertations/2045/
- Right: GEN world data with projected SBS results, including already-collected Helium-3 data at 3 and 6.5 GeV^2

GEN in *g4sbs*: Overview



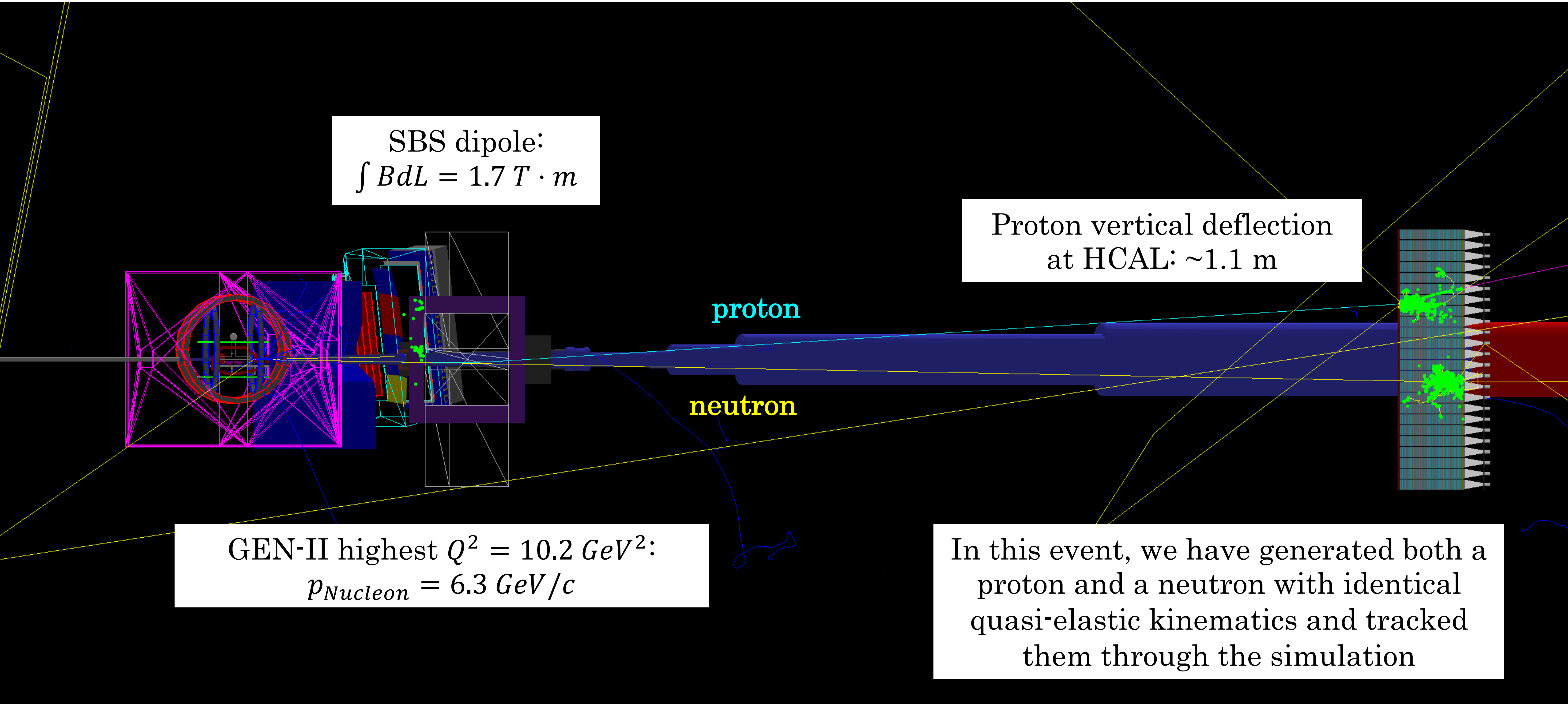
Electron arm: BigBite spectrometer

Detailed downstream beamline description: credit Sebastian Seeds (UConn) and David Flay (JLab)

Hadron arm: SBS with/HCAL

GEn-II high-luminosity polarized Helium-3 Target

GEN simulations: nucleon charge ID



SBS dipole:
$\int BdL = 1.7\ T \cdot m$

Proton vertical deflection at HCAL: ~1.1 m

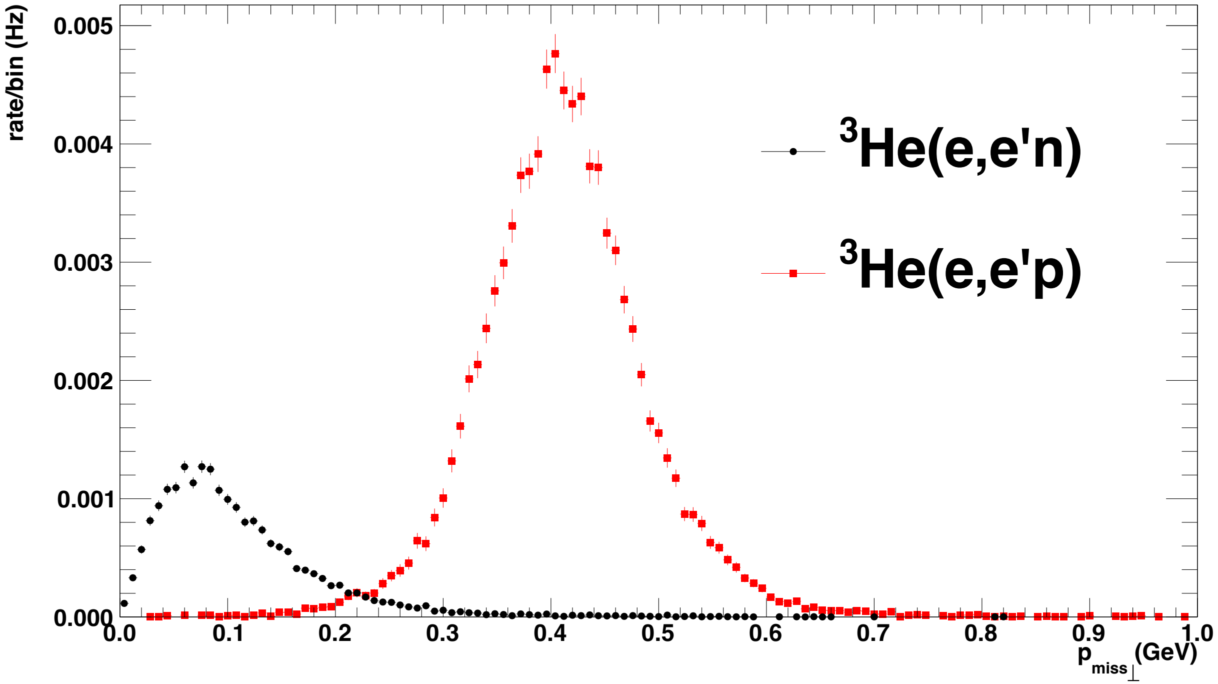
GEN-II highest $Q^2 = 10.2\ GeV^2$:
$p_{Nucleon} = 6.3\ GeV/c$

In this event, we have generated both a proton and a neutron with identical quasi-elastic kinematics and tracked them through the simulation

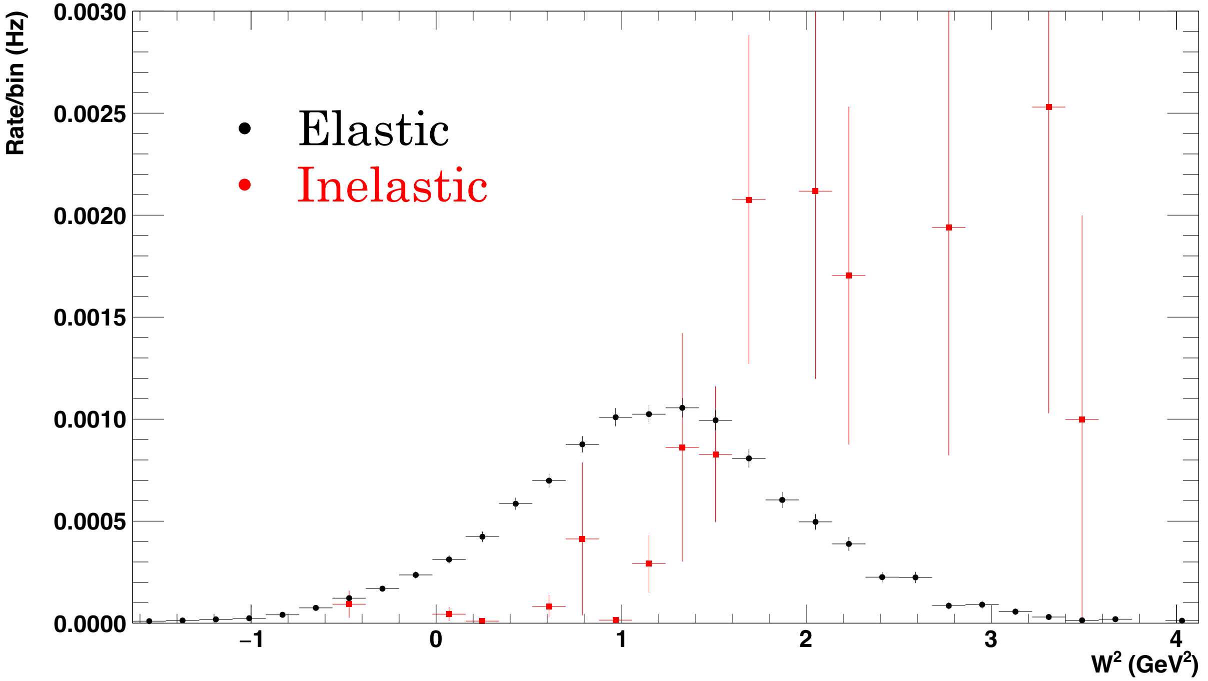
Key differences between GMN/GEN experiments/analyses

- For GEN, we don’t care about precise knowledge of HCAL detection efficiency or acceptance→main interest is (e,e’n) asymmetry
  - Always operate at SBS maximum field to achieve maximum n/p separation
  - Use coincidence trigger between HCAL and BigBite to reduce event and data rate
- Set HCAL as far from target as possible to maximize TOF resolution of neutron velocity (without reducing acceptance)
- Goal is to select quasi-elastic (e,e’n) events with smallest possible contamination (however, statistics are extremely challenging, so we can’t use arbitrarily tight cuts!)
- Fermi smearing on ^{3}He significantly worse than on ^{2}H → Inelastic contamination is a much more significant problem for physics analysis (however, inelastic asymmetries will be measured much more precisely than elastic), ESPECIALLY at large Q^2

Quasi-elastic Event Selection in MC ($Q^2 = 10.2\ GeV^2$)



- *np* separation for quasi-elastics based on missing perp. momentum
- Expected contamination from quasi-elastic protons negligible for canonical cut of $p_\perp < 0.1$ GeV

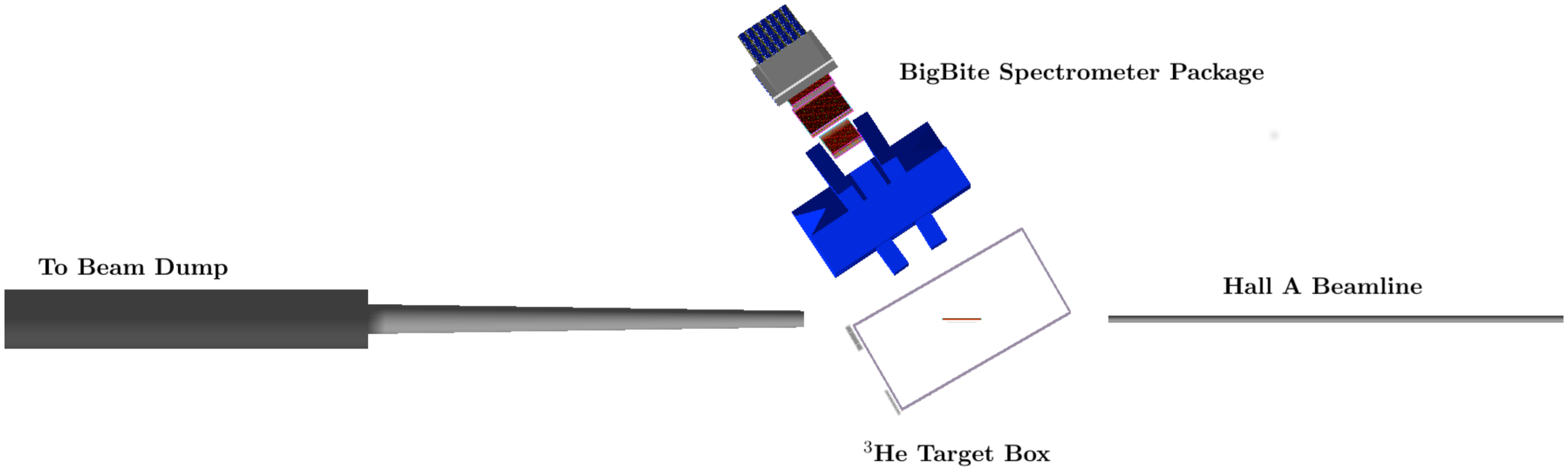


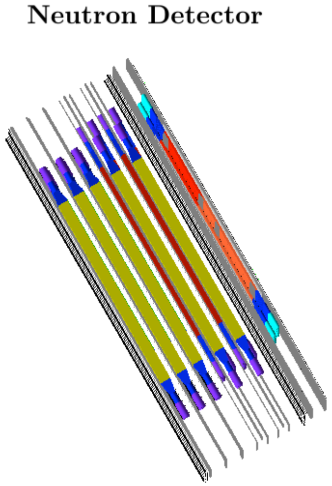
- PRELIMINARY: For $W^2 < 1.6$ GeV², we estimate fractional inelastic contamination of $26 \pm 8\%$ (consistent with original proposal estimate of ~25%) assuming TOF resolution of 1 ns, after cuts.
- Inelastic asymmetry can be measured precisely and corrected for; with much higher statistics than elastic asymmetry

GEN-1 versus GEN-2

See Freddy Obrecht thesis:
https://opencommons.uconn.edu/dissertations/2045/

Experiment E02-013 (GEN-1) layout (in GEANT4)

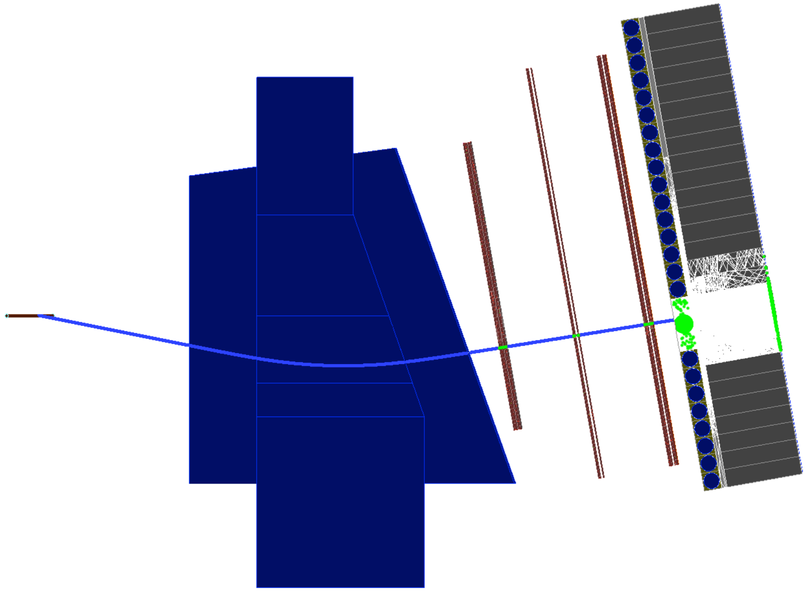


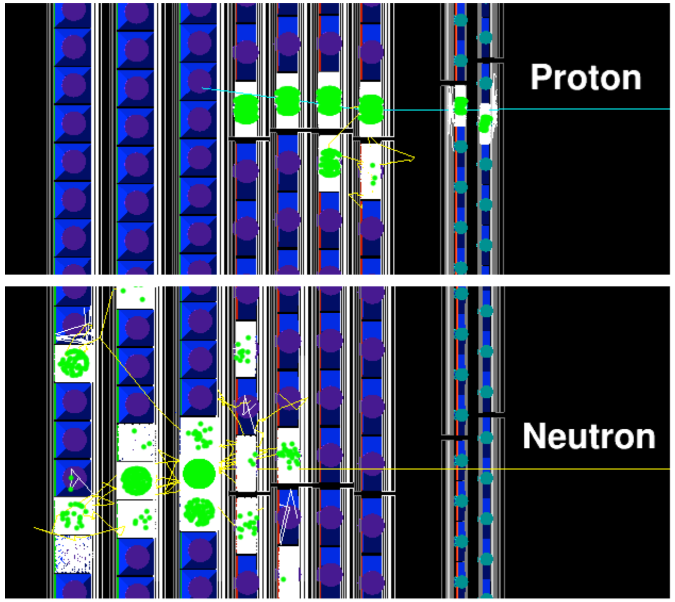


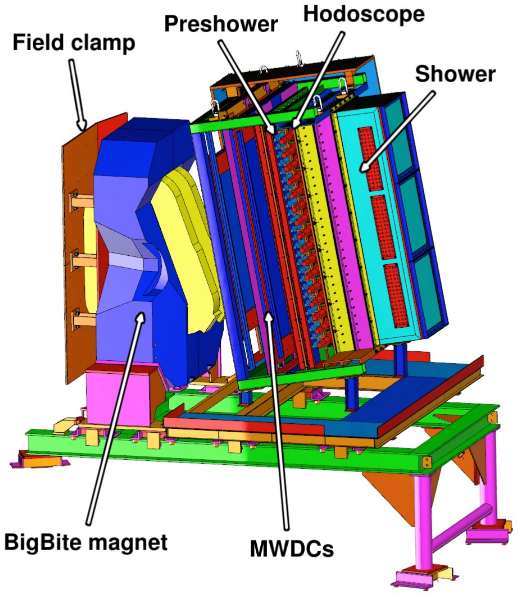
Q^2 [GeV^2]	Days	E_b [GeV]	θ_{BB} [deg]	θ_{NA} [deg]
1.16	8	1.519	-56.3	35.74
1.72	9	2.079	-51.6	35.74
2.48	19	2.640	-51.6	30.25
3.41	33	3.291	-51.6	25.63

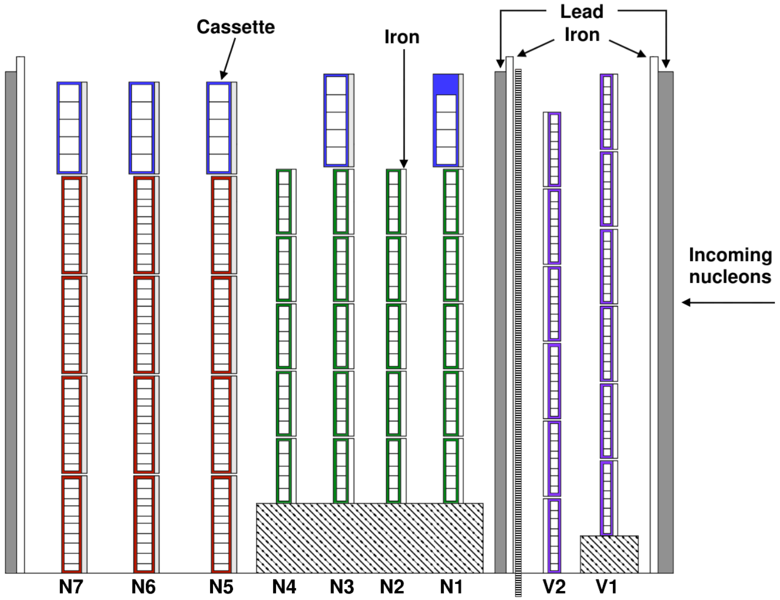
E02-013 Kinematics: lowest Q^2 not included in PRL 2010 publication

Electron and Nucleon Detection

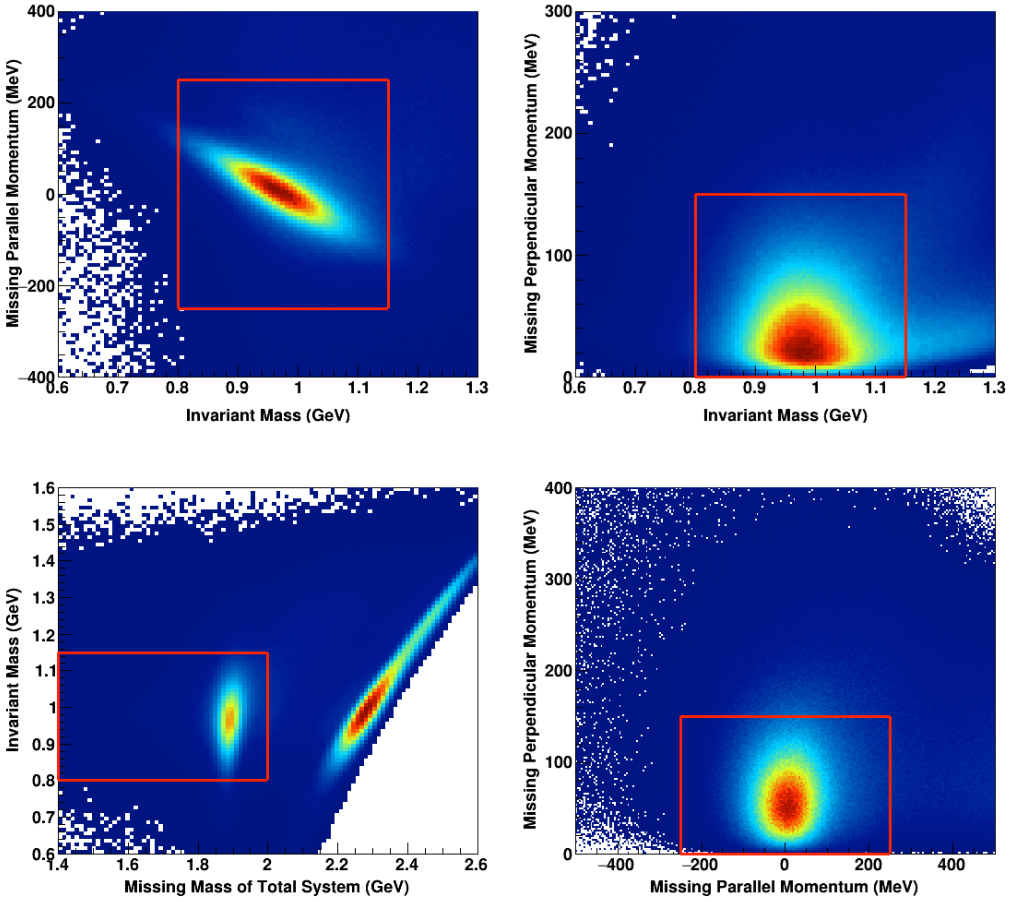




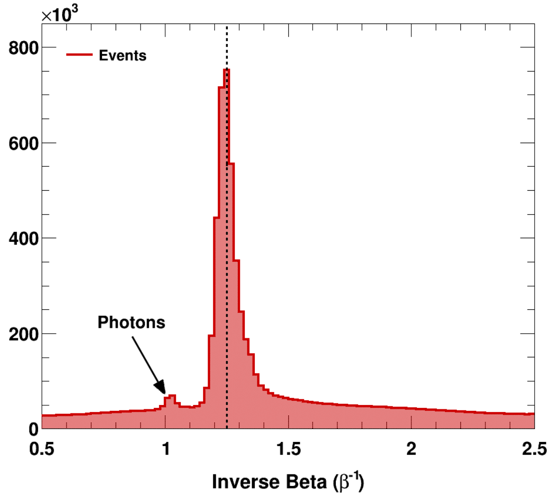




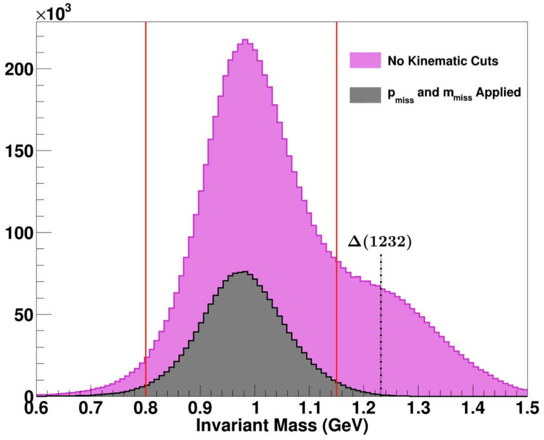
Quasi-elastic Event Selection: ^{3}He data, $Q^2 = 1.16$ GeV^2



- Three main cuts to select the coincidence quasi-elastic channel: Invariant mass W, missing parallel and perpendicular momentum, and ”missing mass”



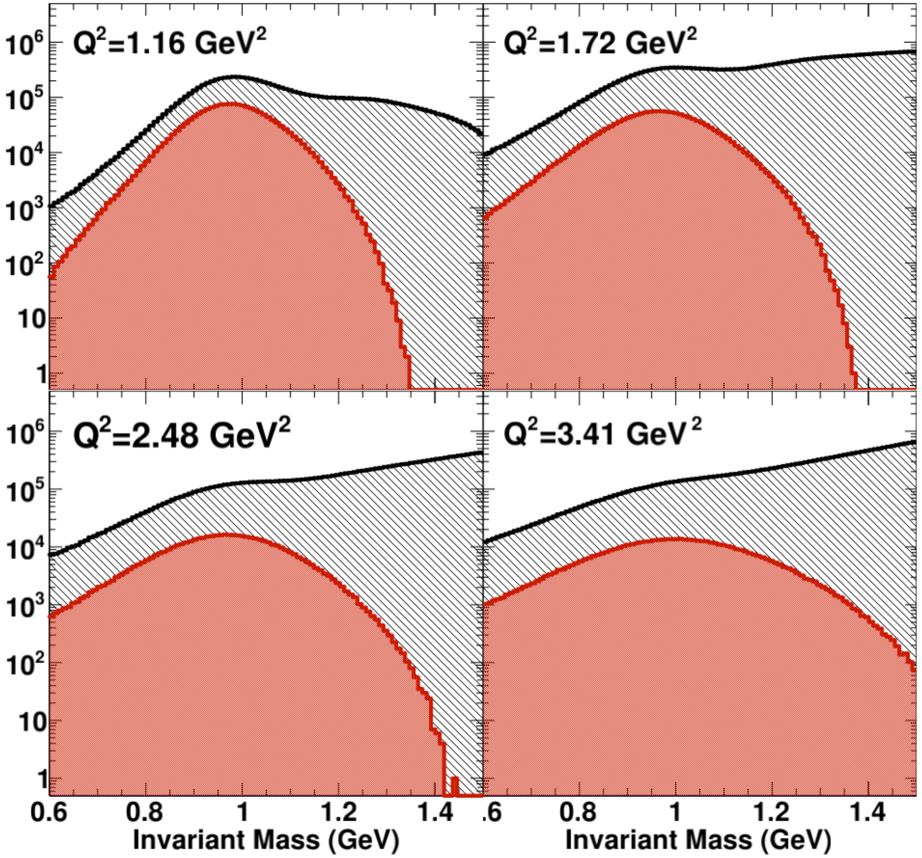
- Nucleon identification and momentum reconstruction via time-of-flight

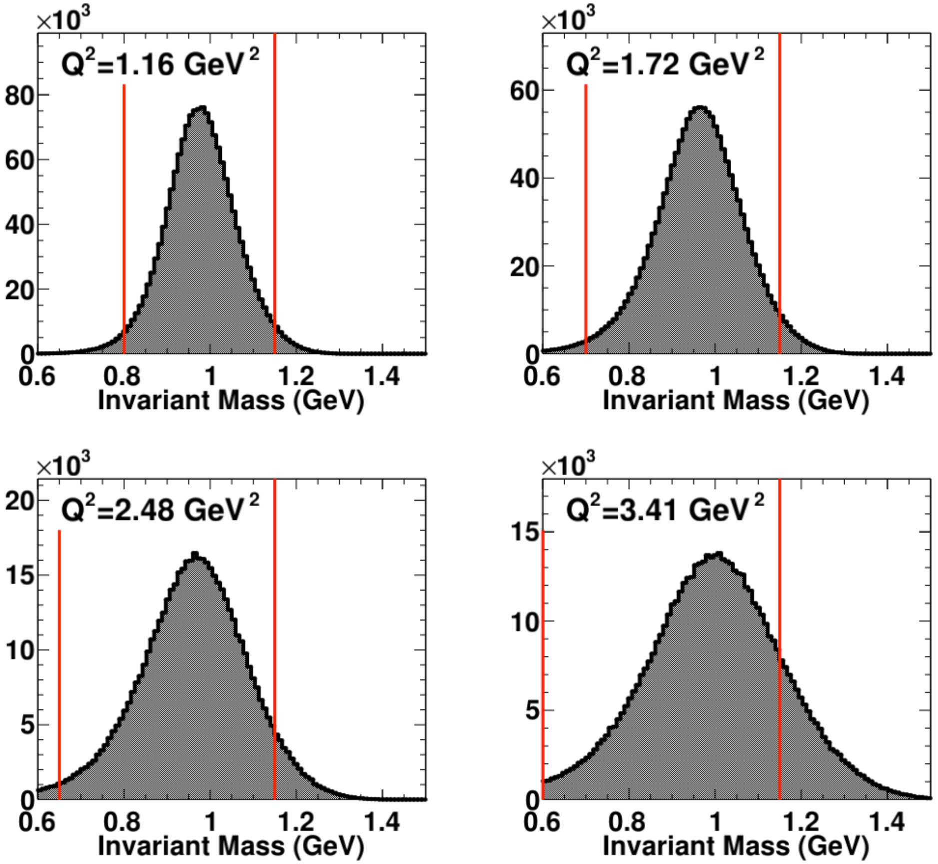


$Q^2 = 1.16\ \mathrm{GeV}^2$

- W distribution before and after cuts

Quasi-elastic coincidence event selection: All kinematics





- Width of quasi-elastic W distribution due to Fermi smearing increases with Q^2.
- Inelastic scattering yield relative to quasi-elastic also increases with Q^2.
- Nevertheless, two-arm coincidence and exclusivity cuts result in a very clean selection of QE events at all four Q^2

Raw Asymmetries

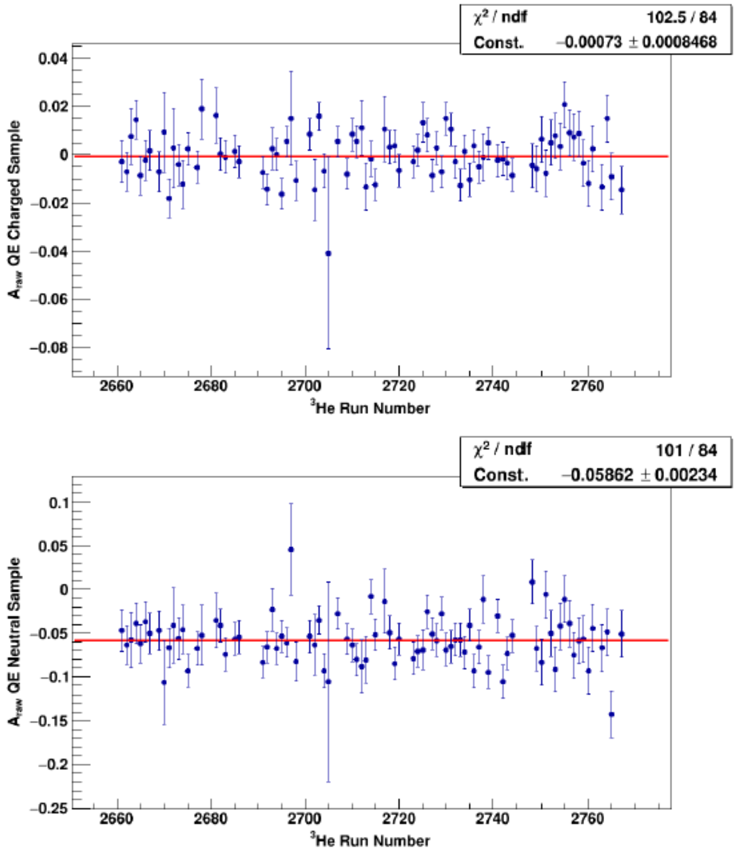


Fig. 5.62: The raw asymmetry for the QE charged (top panel) and uncharged (bottom panel) samples over the ^{3}He data set. The raw asymmetry for the charged sample is expected to be much smaller than the uncharged sample.

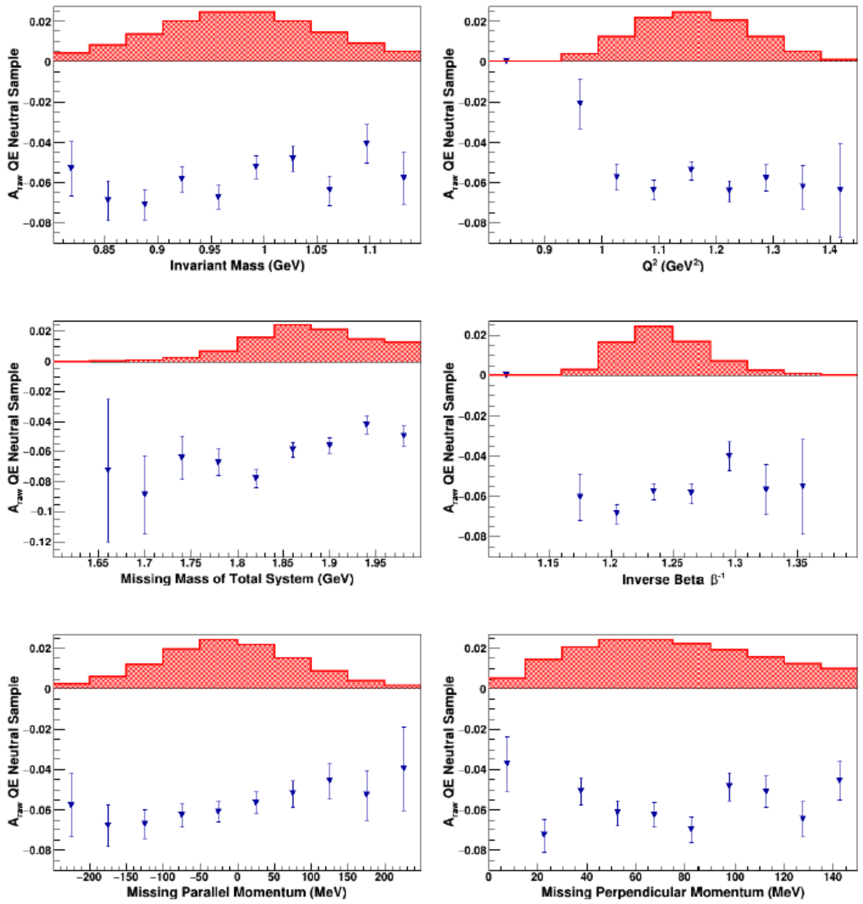
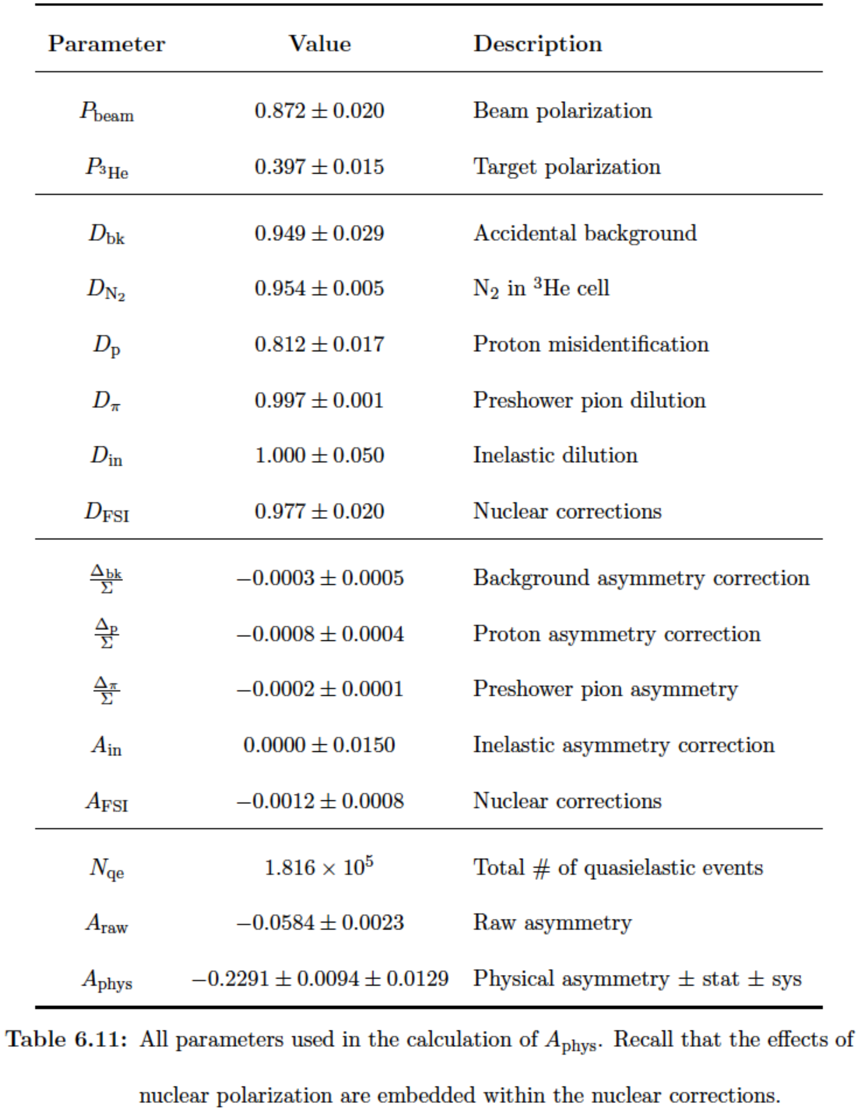


Fig. 5.63: A comparison of A_{raw} to important kinematic variables which are represented by the shaded red regions and have been scaled to fit; therefore, the y-axis is arbitrary for kinematic relations.

Raw asymmetry to ”physics” asymmetry—Summary of Dilution Factors/Corrections



Parameter	Value	Description
P_{beam}	0.872 ± 0.020	Beam polarization
$P_{^3\text{He}}$	0.397 ± 0.015	Target polarization
D_{bk}	0.949 ± 0.029	Accidental background
D_{N_2}	0.954 ± 0.005	N_2 in ^{3}He cell
D_{p}	0.812 ± 0.017	Proton misidentification
D_{π}	0.997 ± 0.001	Preshower pion dilution
D_{in}	1.000 ± 0.050	Inelastic dilution
D_{FSI}	0.977 ± 0.020	Nuclear corrections
$\frac{\Delta_{\text{bk}}}{\Sigma}$	-0.0003 ± 0.0005	Background asymmetry correction
$\frac{\Delta_{\text{p}}}{\Sigma}$	-0.0008 ± 0.0004	Proton asymmetry correction
$\frac{\Delta_{\pi}}{\Sigma}$	-0.0002 ± 0.0001	Preshower pion asymmetry
A_{in}	0.0000 ± 0.0150	Inelastic asymmetry correction
A_{FSI}	-0.0012 ± 0.0008	Nuclear corrections
N_{qe}	1.816×10^5	Total # of quasielastic events
A_{raw}	-0.0584 ± 0.0023	Raw asymmetry
A_{phys}	$-0.2291 \pm 0.0094 \pm 0.0129$	Physical asymmetry ± stat ± sys

Table 6.11: All parameters used in the calculation of A_{phys}. Recall that the effects of nuclear polarization are embedded within the nuclear corrections.

- Most significant dilution factors:
  - Accidental coincidence background
  - Nitrogen dilution
  - Proton misidentification
- Others include FSI, inelastic contamination, and BigBite pions. The latter two are basically negligible for GEN-1

Nuclear corrections—Mainly FSI

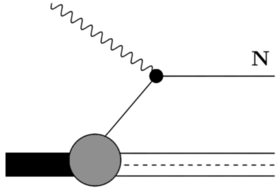


Figure A

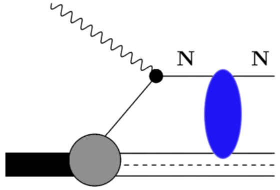


Figure B

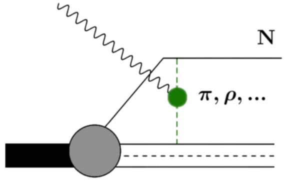


Figure C

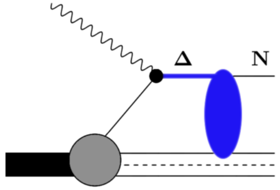
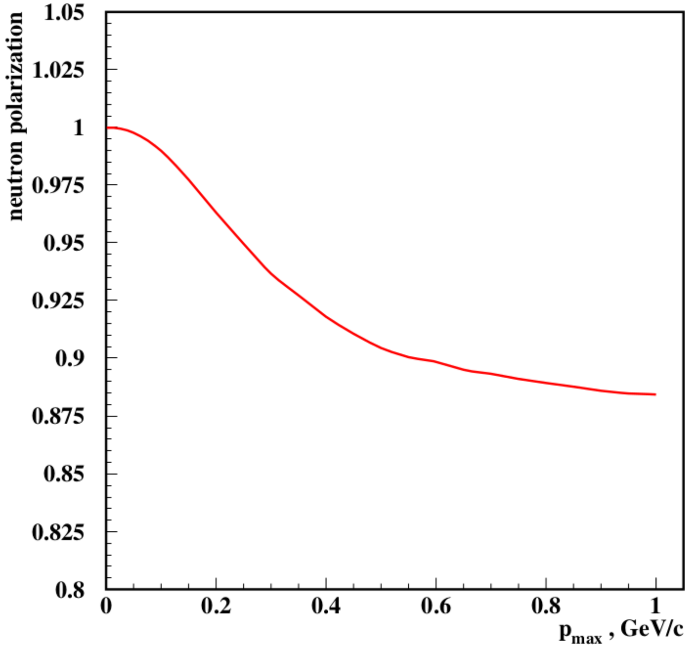


Figure D

- Nuclear corrections calculated within Generalized Eikonal Approximation framework
  - Cross section/asymmetry calculation code provided by Misak Sargsian (FIU)
  - Event-by-event MC simulation folded with experimental acceptance—lots of numerical integration, computationally expensive! (Much easier to do with 2019 JLab scientific computing facilities than 2009)
- A: PWIA
- B: FSI/charge-exchange
- C: Meson Exchange Currents
- D: Isobar Configurations
- Diagrams “A” and “B” dominant in E02-013 kinematics
- Exclusivity selection increases effective neutron polarization from the canonical 86% (of P_{He}) in the inclusive case to 96% in the coincidence—quasi-elastic case.



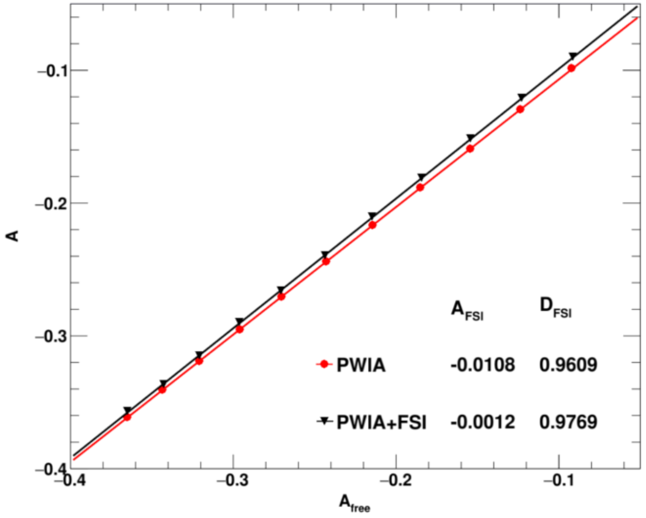


Table of corrections, GEN-1 data

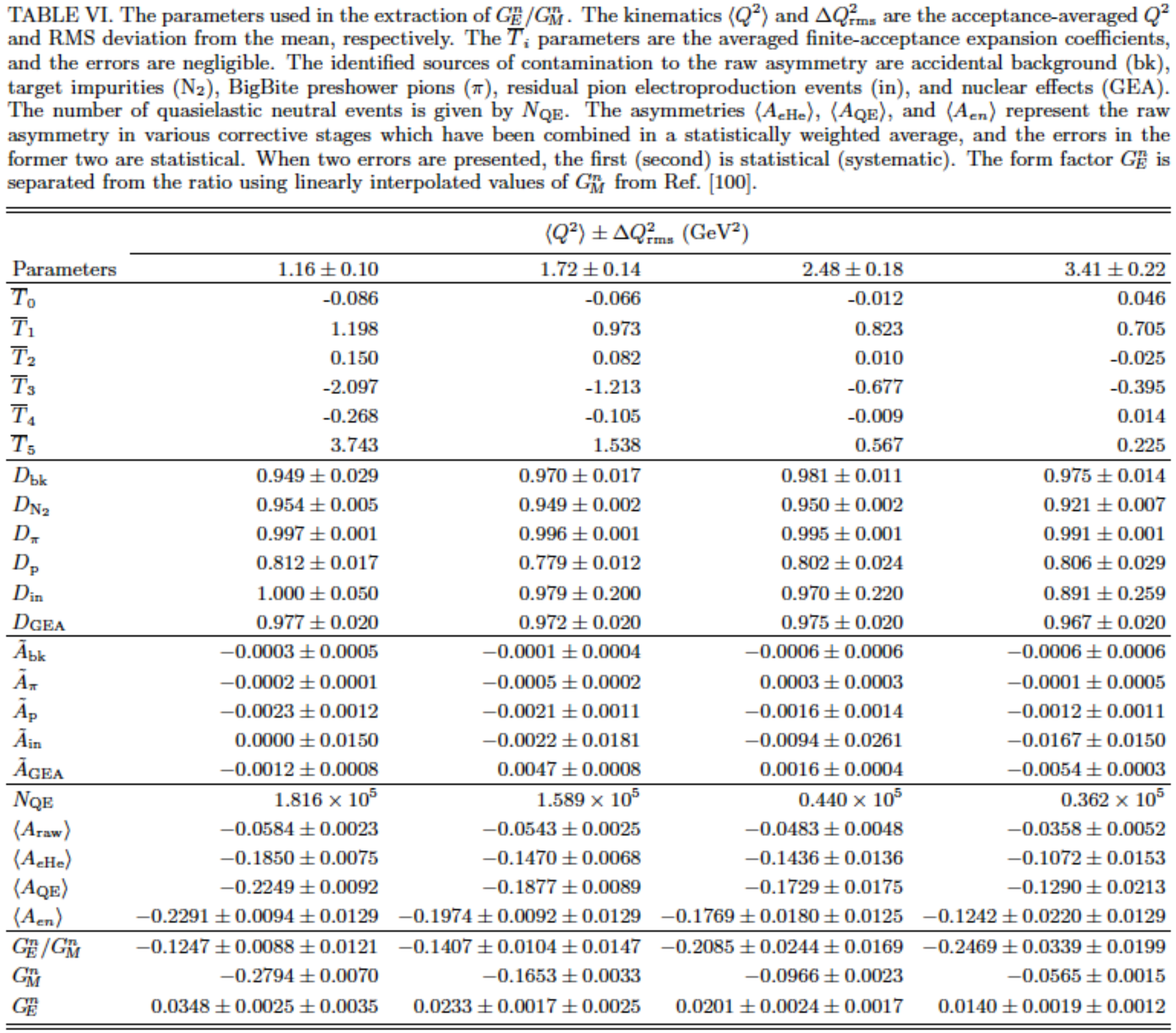


TABLE VI. The parameters used in the extraction of G_E^n/G_M^n. The kinematics $\langle Q^2\rangle$ and $\Delta Q^2_{\mathrm{rms}}$ are the acceptance-averaged Q^2 and RMS deviation from the mean, respectively. The $\overline{T}_i$ parameters are the averaged finite-acceptance expansion coefficients, and the errors are negligible. The identified sources of contamination to the raw asymmetry are accidental background (bk), target impurities (N_2), BigBite preshower pions (π), residual pion electroproduction events (in), and nuclear effects (GEA). The number of quasielastic neutral events is given by N_{QE}. The asymmetries $\langle A_{\mathrm{eHe}}\rangle$, $\langle A_{\mathrm{QE}}\rangle$, and $\langle A_{\mathrm{en}}\rangle$ represent the raw asymmetry in various corrective stages which have been combined in a statistically weighted average, and the errors in the former two are statistical. When two errors are presented, the first (second) is statistical (systematic). The form factor G_E^n is separated from the ratio using linearly interpolated values of G_M^n from Ref. [100].

	$\langle Q^2\rangle \pm \Delta Q^2_{\mathrm{rms}}$ (GeV^2)			
Parameters	1.16 ± 0.10	1.72 ± 0.14	2.48 ± 0.18	3.41 ± 0.22
T_0	-0.086	-0.066	-0.012	0.046
$\overline{T}_1$	1.198	0.973	0.823	0.705
$\overline{T}_2$	0.150	0.082	0.010	-0.025
$\overline{T}_3$	-2.097	-1.213	-0.677	-0.395
$\overline{T}_4$	-0.268	-0.105	-0.009	0.014
T_5	3.743	1.538	0.567	0.225
D_{bk}	0.949 ± 0.029	0.970 ± 0.017	0.981 ± 0.011	0.975 ± 0.014
$D_{\mathrm{N_2}}$	0.954 ± 0.005	0.949 ± 0.002	0.950 ± 0.002	0.921 ± 0.007
D_{π}	0.997 ± 0.001	0.996 ± 0.001	0.995 ± 0.001	0.991 ± 0.001
D_{p}	0.812 ± 0.017	0.779 ± 0.012	0.802 ± 0.024	0.806 ± 0.029
D_{in}	1.000 ± 0.050	0.979 ± 0.200	0.970 ± 0.220	0.891 ± 0.259
D_{GEA}	0.977 ± 0.020	0.972 ± 0.020	0.975 ± 0.020	0.967 ± 0.020
$\tilde{A}_{\mathrm{bk}}$	-0.0003 ± 0.0005	-0.0001 ± 0.0004	-0.0006 ± 0.0006	-0.0006 ± 0.0006
$\tilde{A}_{\pi}$	-0.0002 ± 0.0001	-0.0005 ± 0.0002	0.0003 ± 0.0003	-0.0001 ± 0.0005
$\tilde{A}_{\mathrm{p}}$	-0.0023 ± 0.0012	-0.0021 ± 0.0011	-0.0016 ± 0.0014	-0.0012 ± 0.0011
$\tilde{A}_{\mathrm{in}}$	0.0000 ± 0.0150	-0.0022 ± 0.0181	-0.0094 ± 0.0261	-0.0167 ± 0.0150
$\tilde{A}_{\mathrm{GEA}}$	-0.0012 ± 0.0008	0.0047 ± 0.0008	0.0016 ± 0.0004	-0.0054 ± 0.0003
N_{QE}	1.816×10^5	1.589×10^5	0.440×10^5	0.362×10^5
$\langle A_{\mathrm{raw}}\rangle$	-0.0584 ± 0.0023	-0.0543 ± 0.0025	-0.0483 ± 0.0048	-0.0358 ± 0.0052
$\langle A_{\mathrm{eHe}}\rangle$	-0.1850 ± 0.0075	-0.1470 ± 0.0068	-0.1436 ± 0.0136	-0.1072 ± 0.0153
$\langle A_{\mathrm{QE}}\rangle$	-0.2249 ± 0.0092	-0.1877 ± 0.0089	-0.1729 ± 0.0175	-0.1290 ± 0.0213
$\langle A_{\mathrm{en}}\rangle$	$-0.2291 \pm 0.0094 \pm 0.0129$	$-0.1974 \pm 0.0092 \pm 0.0129$	$-0.1769 \pm 0.0180 \pm 0.0125$	$-0.1242 \pm 0.0220 \pm 0.0129$
G_E^n/G_M^n	$-0.1247 \pm 0.0088 \pm 0.0121$	$-0.1407 \pm 0.0104 \pm 0.0147$	$-0.2085 \pm 0.0244 \pm 0.0169$	$-0.2469 \pm 0.0339 \pm 0.0199$
G_M^n	-0.2794 ± 0.0070	-0.1653 ± 0.0033	-0.0966 ± 0.0023	-0.0565 ± 0.0015
G_E^n	$0.0348 \pm 0.0025 \pm 0.0035$	$0.0233 \pm 0.0017 \pm 0.0025$	$0.0201 \pm 0.0024 \pm 0.0017$	$0.0140 \pm 0.0019 \pm 0.0012$

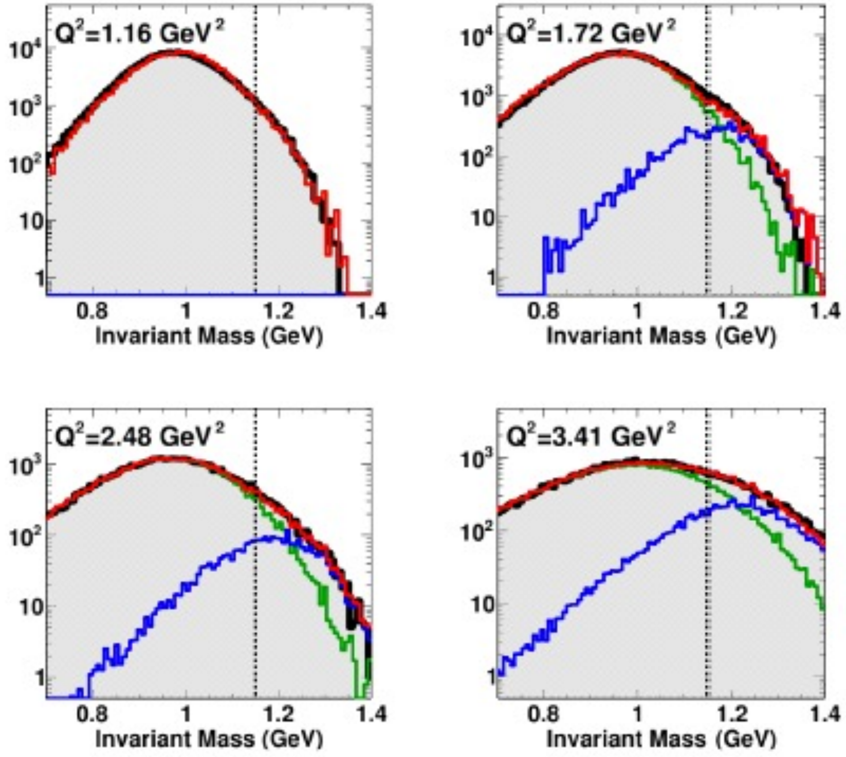


FIG. 22. (color online) The QE neutral sample (black) is compared to the simulation (red) where pion electroproduction events (blue) are generated using the unitary isobar model `MAID`. Simulated QE events are indicated by a green line, and the dotted line represents the upper-bound $W < 1.15$ GeV cut to be applied for inelastic suppression.

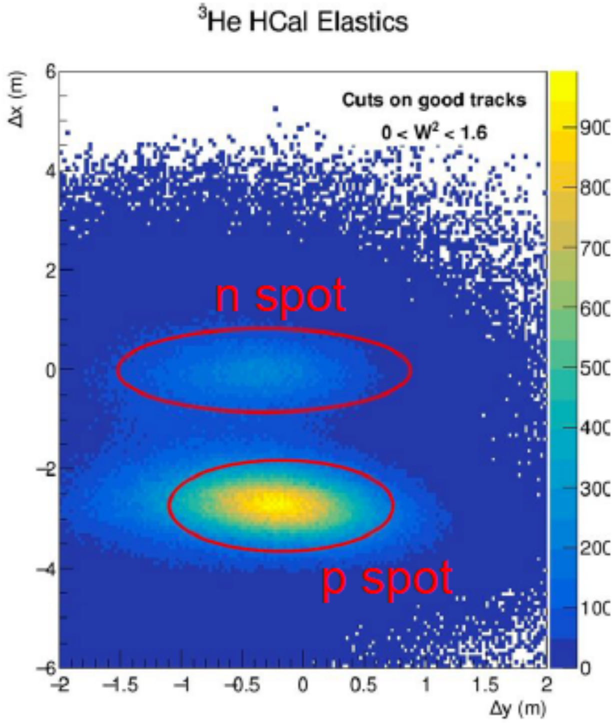
Figure from Obrecht *et al.*, (in preparation)

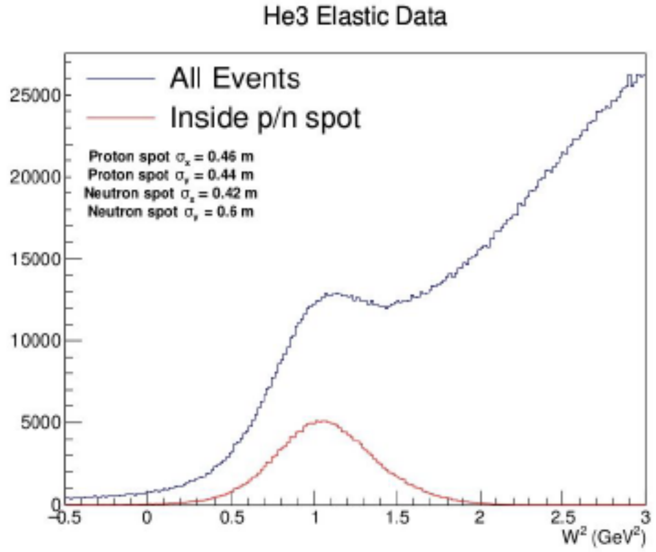
GEN-2 vs GEN-1 key differences and challenges

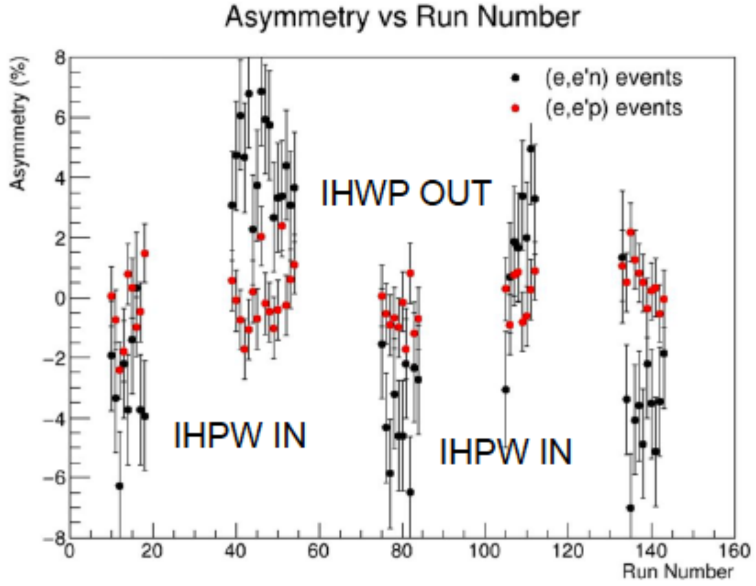
- In *principle,* GEN-2 proton dilution due to misidentification as neutron *should* be much less than in GEN-1 due to magnetic deflection of protons
- In *practice,* we will still need to worry about this, due to very significant inelastic contamination (inelastic protons can look like neutrons) and ~6X higher proton yield from ^{3}He compared to neutron yield (~3X larger cross section and two protons in Helium-3 to one neutron), Fermi motion, and reduction (enhancement) of n (p) acceptance due to HCAL vertical offset above beam height
- Time-of-flight resolution with HCAL not as good as BigHand, and high-Q^2 nucleons have $\beta \rightarrow 1$, worse resolution of missing parallel (and perp) momentum
- Statistics are extremely challenging due to very small elastic cross section
- Target and beam polarimetry and target spin orientation → similar systematics.
- Physics results will most likely be statistics limited for Kin. 3 and Kin. 4

Elastic Event Selection, Q^2 = 2.9 GeV

- Neutron/proton separation in HCal.
- Selection on spots gives good elastic peak.
- Asymmetry flips for as IHWP flips, as expected.





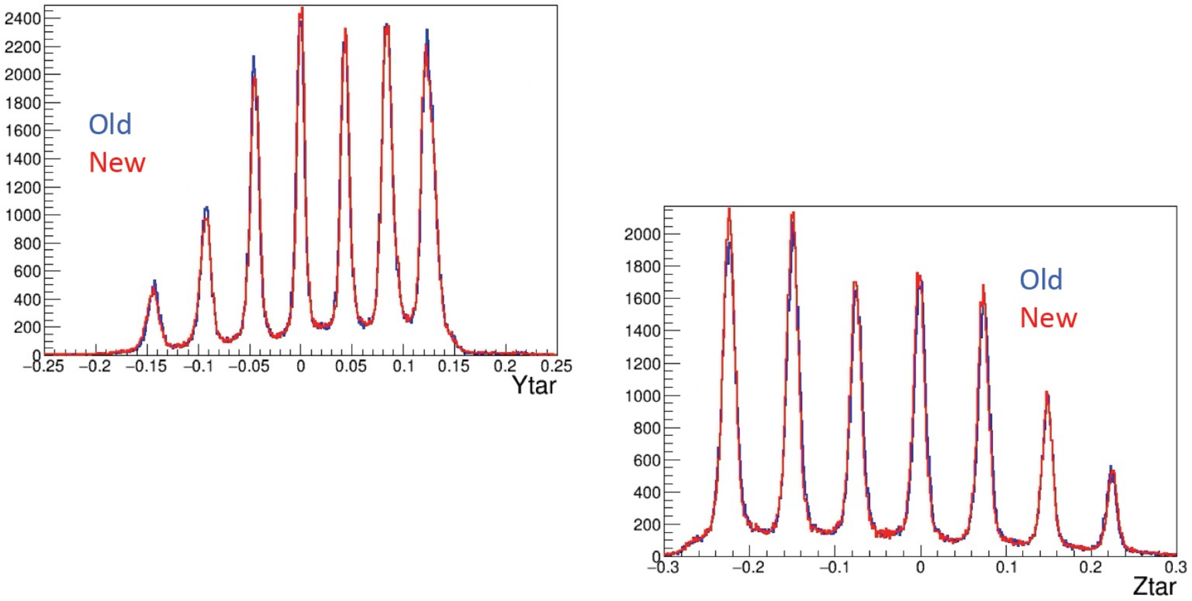


Backups

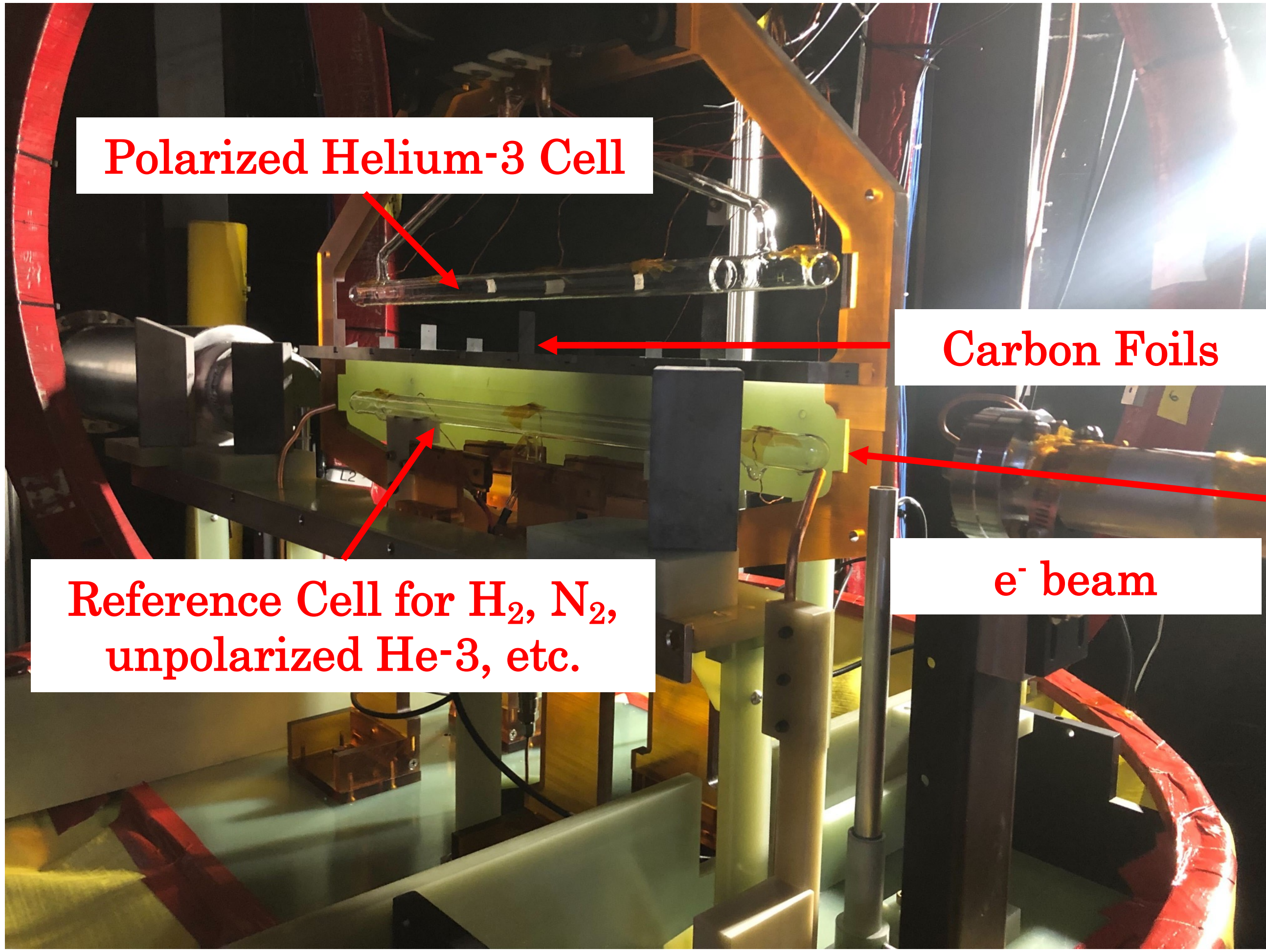
GEN Optics calibration (by Holly)

https://sbs.jlab.org/cgi-bin/DocDB/private/ShowDocument?docid=344

Comparing the old and new reconstruction.



- Lessons learned from GMN experience allow “pretty good” starting optics model for BigBite from simulation



Polarized Helium-3 Cell

Carbon Foils

Reference Cell for H_2, N_2, unpolarized He-3, etc.

e^- beam