E12-06-121: Neutron g_2 and d_2

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July 9th, 2021

Outline

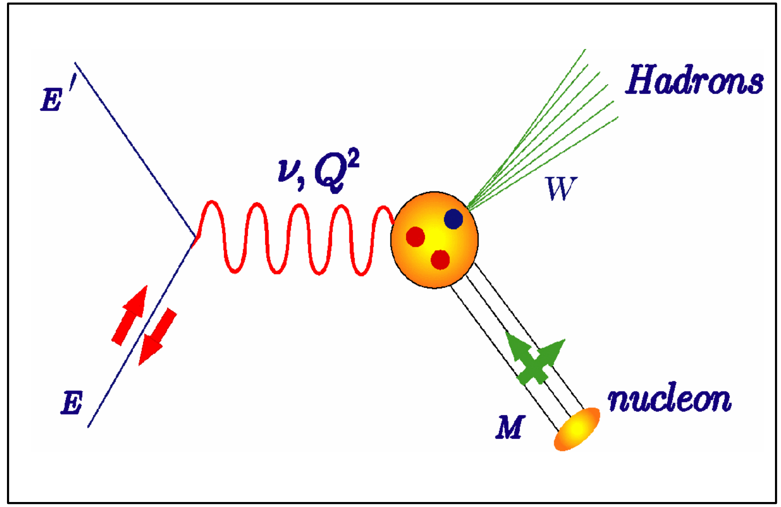
- **Background**

- **The Experiment**
  - Experimental Setup
  - Kinematic Coverage

- **Experimental Data Analysis**
  - Target Polarization Direction Measurement
  - ^{3}He Pressure Extraction
  - Detector Calibration: Cherenkov
  - PID Studies
  - Spectrometer Acceptance Extraction
  - Raw Asymmetry

- **Summary**

Deep Inelastic Scattering



Unpolarized cross section:

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}}\left(\frac{2}{M}F_1(x,Q^2)\sin^2\frac{\theta}{2} + \frac{1}{\nu}F_2(x,Q^2)\cos^2\frac{\theta}{2}\right)$$

- Unpolarized structure functions F_1 and F_2 contain information about the momentum structure of the target nucleon.

Polarized cross section:

$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2 E'}{MQ^2\nu E}\left[(E+E'\cos\theta)g_1(x,Q^2) - \frac{Q^2}{\nu}g_2(x,Q^2)\right] = \Delta\sigma_{\parallel}$$

$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta E'^2}{MQ^2\nu^2 E}\left[\nu g_1(x,Q^2) + 2Eg_2(x,Q^2)\right] = \Delta\sigma_{\perp}$$

- Polarized structure functions g_1 and g_2 encode information about the spin structure of the target nucleon.

Q^2 = 4-momentum transfer squared of the virtual photon

ν = E-E' = energy transfer

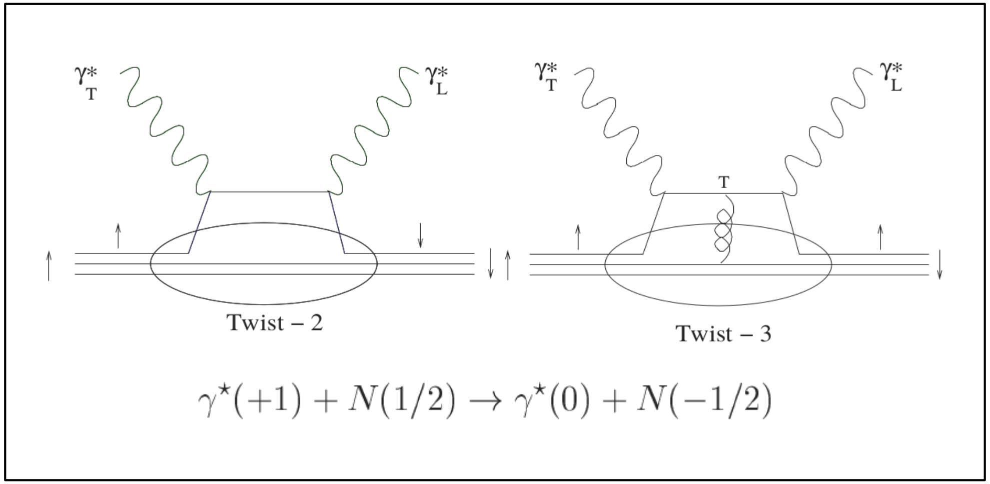
θ = scattering angle

x = Fraction of nucleon momentum carried by the struck quark

g_2 and Quark-Gluon Correlations

- g_2 has no interpretation in naive quark parton model, provides information on quark-gluon correlation.

- g_2 is among the cleanest higher twist observables – contributes to leading order (twist-2 is leading twist) at the transverse spin asymmetry.



$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

- Twist-2 term (*Wandzura & Wilczek*).

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{g_1(y,Q^2)}{y} dy$$

- Twist-3 term with a suppressed twist-2 piece (*Cortes, Pire & Ralston*).

$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left(\frac{m_q}{M} h_T(y,Q^2) - \xi(y,Q^2)\right)\frac{dy}{y}$$

Transversity

Quark-gluon correlation

d_2: Clean Probe of Quark-Gluon Correlations

- d_2 is a clean probe of quark-gluon correlations / higher twist effects - third moment of the linear combination of the spin structure function.

$$d_2(Q^2)=3\int_0^1 x^2[2g_1(x,Q^2)+3g_2(x,Q^2)]dx=3\int_0^1 x^2\bar{g}_2(x,Q^2)dx$$

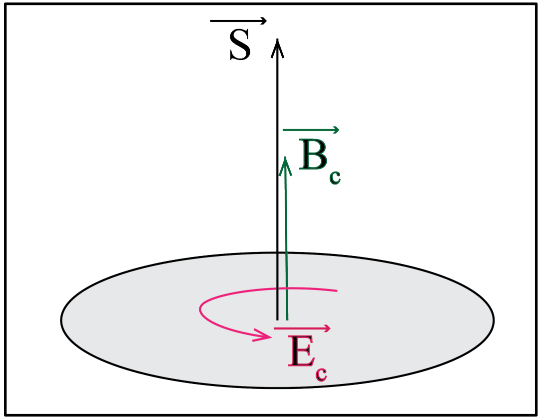
- Related to matrix element in OPE, which represents average transverse color Lorentz force on the struck quark due to the remnant system and it is cleanly computable using Lattice QCD.

- Connected to "color polarizability".

$$\chi_E=\frac{(4d_2+2f_2)}{3} \qquad \chi_B=\frac{(4d_2-f_2)}{3}$$

- f_2 is a twist-4 contribution can be extracted from the first moment of g_1.

$$\Gamma_1=\int_0^1 g_1 dx=\mu_2+\frac{M^2}{9Q^2}(a_2+4d_2+4f_2)+O\left(\frac{\mu^6}{Q^4}\right)$$



Response of the color $\vec{B}$ and $\vec{E}$ field to the nucleon polarization

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  - Raw Asymmetry
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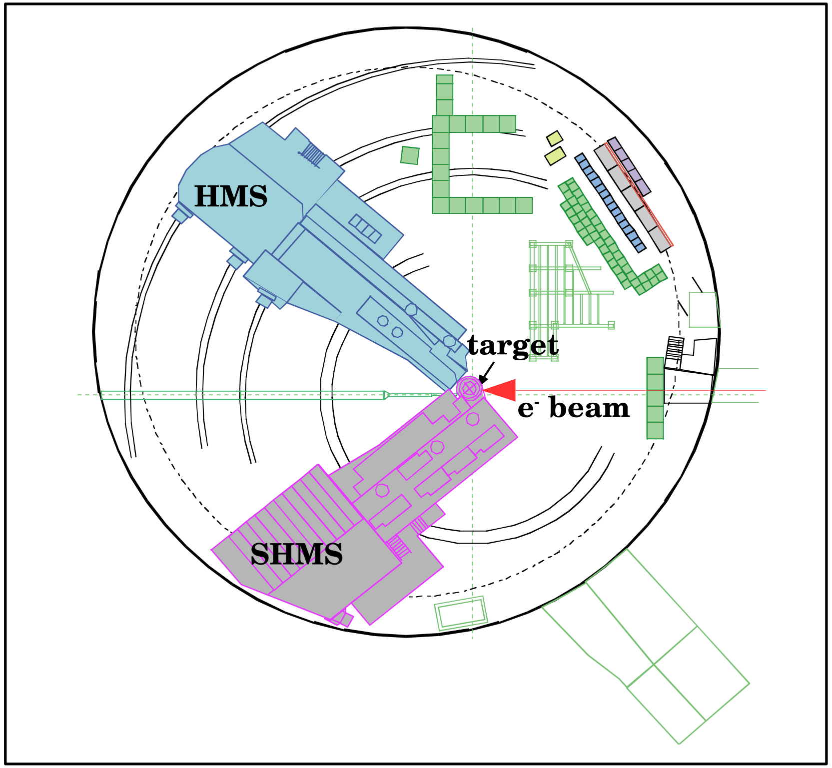
E12-06-121: Experimental Setup

The experiment E12-06-121 (neutron g_2 and d_2) was successfully completed on 21st September, 2020!

Students:

1. Mingyu Chen (Univ. of Virginia)
2. Junhao Chen (William & Mary)
3. Melanie Rehfuss (Temple Univ.)
4. Murchhana Roy (Univ. of Kentucky)



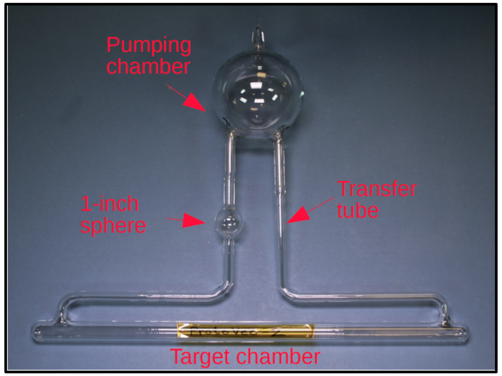
JLab Hall C Layout

Electron Beam :

- Beam energy: 10.38 GeV
- Beam current: 30 μA
- Beam polarization ~ 85% (~3% uncertainty)

Polarized ^{3}He target:

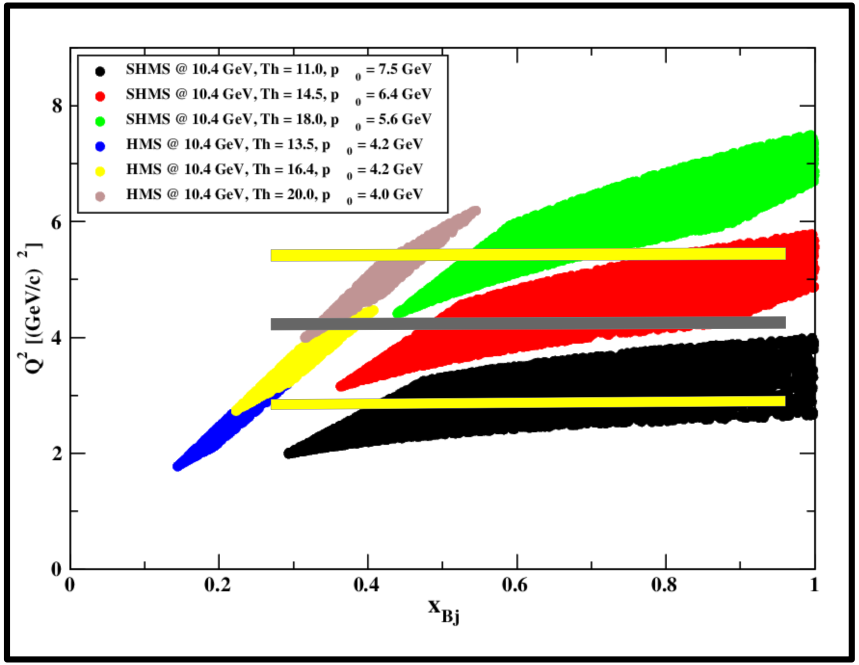
- 40 cm long ^{3}He cell.
- Target polarization: ~ 45% (~3% uncertainty)



Spectrometers:

- Super High Momentum Spectrometer (SHMS)
- High Momentum Spectrometer (HMS)
- Used for the first time for extended target

E12-06-121: Kinematic Coverage



5-pass running					
HMS Production					
Setting	P_o (GeV/c)	Angle	x	Q^2 (GeV^2/c^2)	W (GeV)
A	4.2	13.5°	0.207	2.414	3.178
B	4.2	16.4°	0.305	3.554	2.993
C	4.0	20.0°	0.418	5.018	2.806
SHMS Production					
Setting	P_o (GeV/c)	Angle	x	Q^2 (GeV^2/c^2)	W (GeV)
X	7.5	11.0°	0.527	2.866	1.859
Y	6.4	14.5°	0.565	4.240	2.036
Z	5.6	18.0°	0.633	5.701	2.046

- Above coverage reflects 25% reduction relative to Proposal to accommodate Accelerator schedule. Accelerator performance difficulties during run limited final data collected to:
  - Complete: Kin A, C, X, Z (Calib + Long + Transverse)
  - Partial: Kin B, Y (Calib + Long)
- Collected ~70% of required 1-pass data mostly ^{3}He longitudinal elastic.

1-pass running			
Kinematic Setting	Spectrometer	P_o (GeV/c)	Angle
^{3}He elastic	SHMS	-2.12	8.5°
		-2.129	13°
	HMS	-2.082	17°
		-2.082	11.7°

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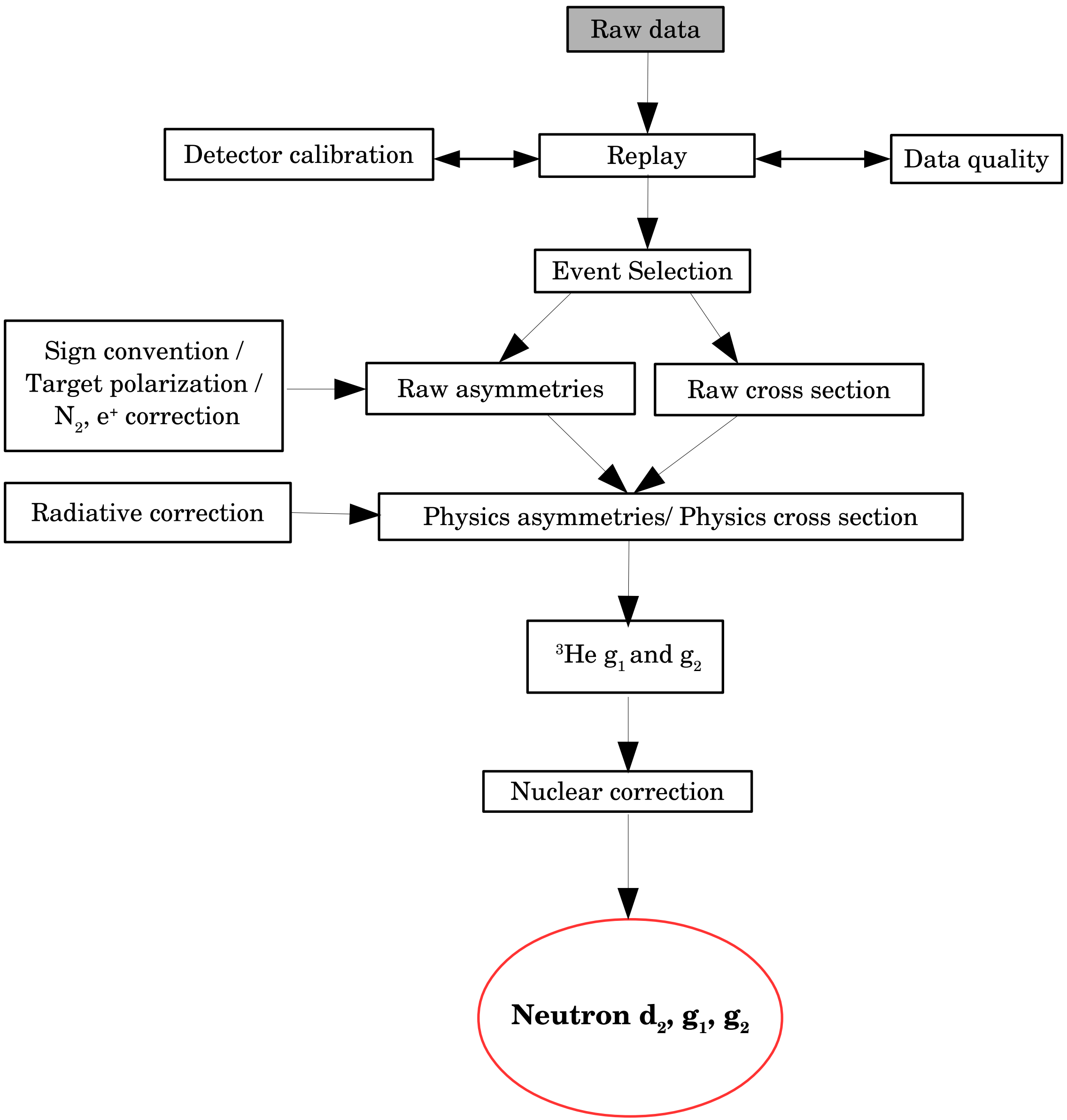
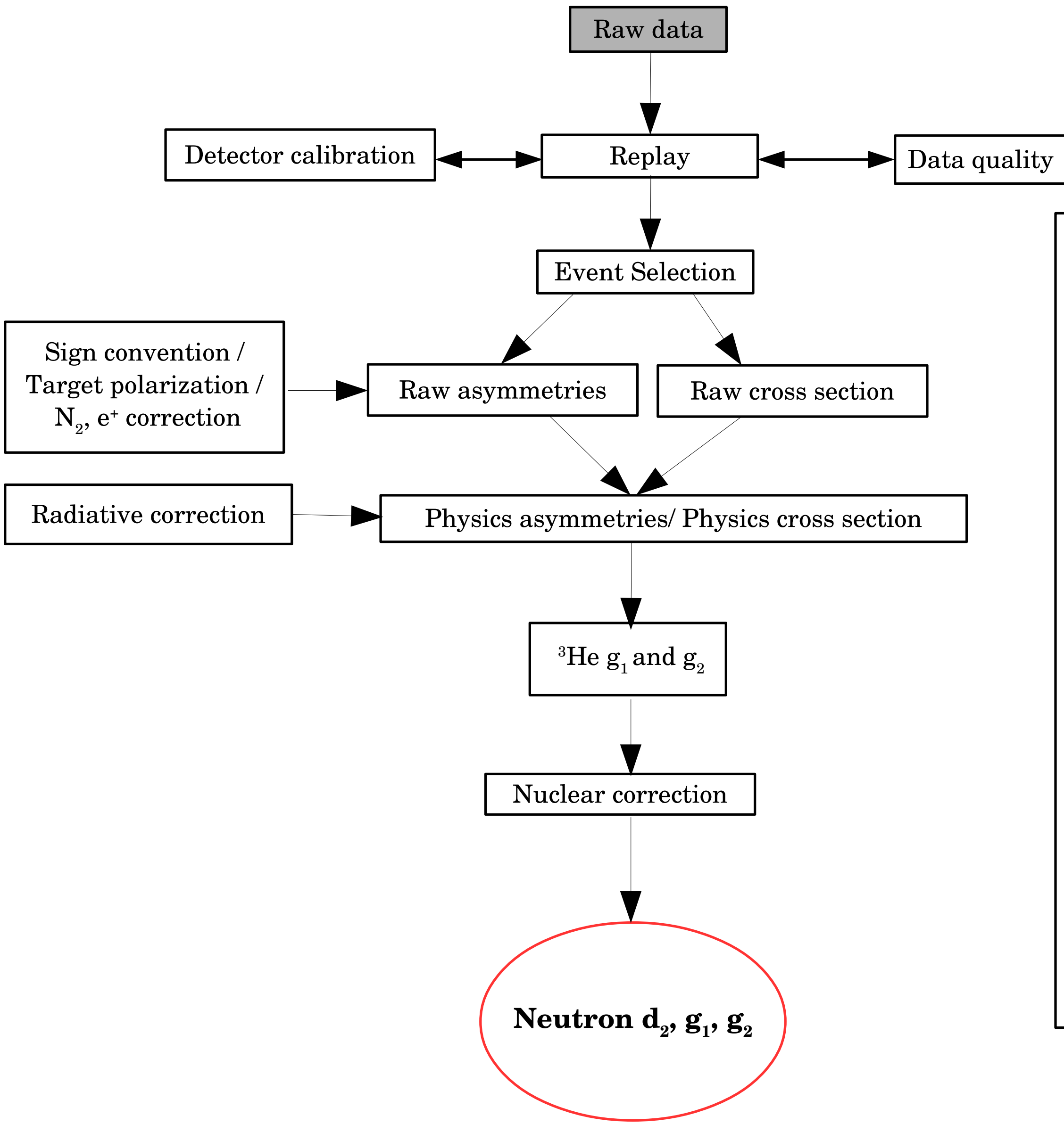
Analysis Flowchart



Analysis Flowchart



Analysis Goal:

- Extract **unpolarized cross section (σ_0)** and **electron asymmetries ($A_\parallel$, $A_\perp$)** to determine spin structure functions g_1 and g_2.

$$g_1 = \frac{MQ^2}{4\alpha^2}\frac{2y}{(1-y)(2-y)}\sigma_0\left[A_\parallel + \tan\left(\frac{\theta}{2}\right)A_\perp\right]$$

$$g_2 = \frac{MQ^2}{4\alpha^2}\frac{2y}{(1-y)(2-y)}\sigma_0\left[-A_\parallel + \frac{1+(1-y)\cos(\theta)}{(1-y)\sin(\theta)}A_\perp\right]$$

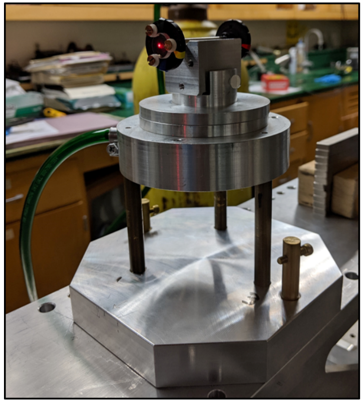
- Access g_1 and g_2 from the **polarized cross section difference**.

$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2 E'}{MQ^2\nu E}\left[(E+E'\cos\theta)g_1(x,Q^2) - \frac{Q^2}{\nu}g_2(x,Q^2)\right] = \Delta\sigma_\parallel$$

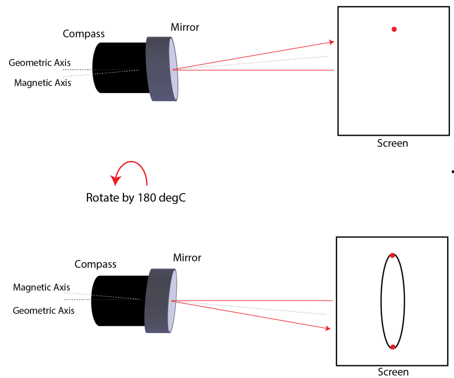
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta E'^2}{MQ^2\nu^2 E}\left[\nu g_1(x,Q^2) + 2E g_2(x,Q^2)\right] = \Delta\sigma_\perp$$

Target Polarization Direction Measurement

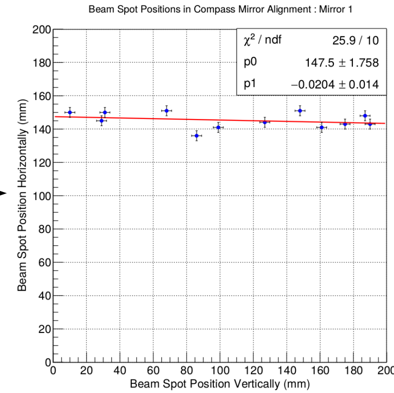
Goal: Measure the direction of the target magnetic field in the Hall C coordinate system precisely within ±0.1°



The air-floated compass

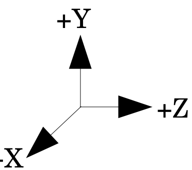


Compass mirror alignment



Horizontal error from mirror 1 alignment: ±0.06° (September 2020)

- The magnetic field direction was measured for all four polarization direction at three different locations along target length
- Measured twice : March, 2020 and September, 2020

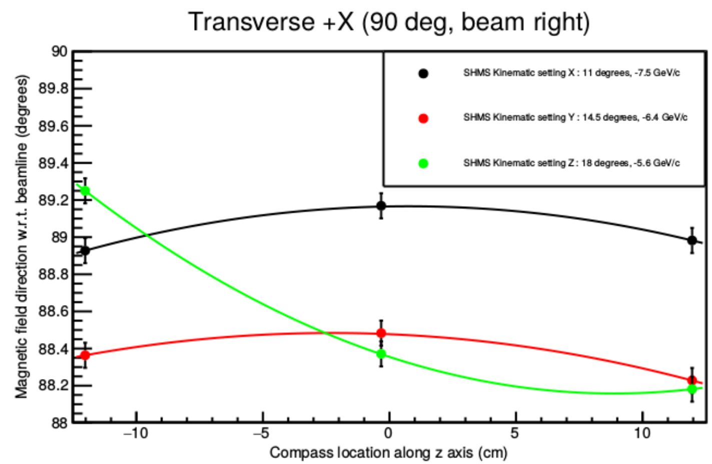


Systematic uncertainties:

1. Error in determining the angle (θ) the magnetic field makes with beam line: ~ ±(0.01°-0.03°)
2. Errors from the compass mirror alignment (θ_M): ~ ±(0.04°-0.08°)
3. Finite laser beam spot size: ~ ±0.006°
4. Position of incident laser beam on the compass mirror: ~ ±0.01°

Current Status:

- Data analysis has been completed for each set of measurements
- Still need to finalize the total uncertainty

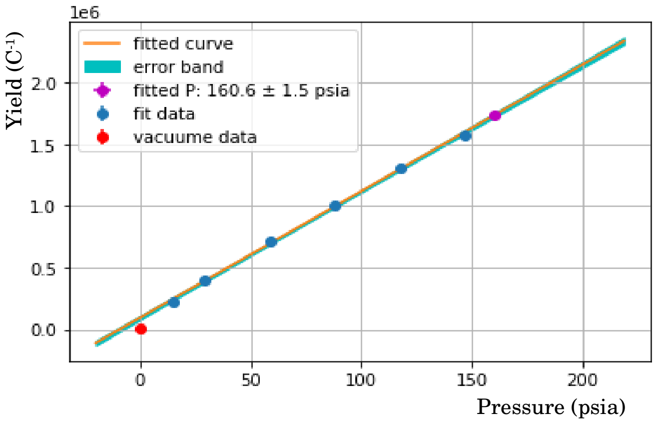


Example results from compass measurements (September 2020)

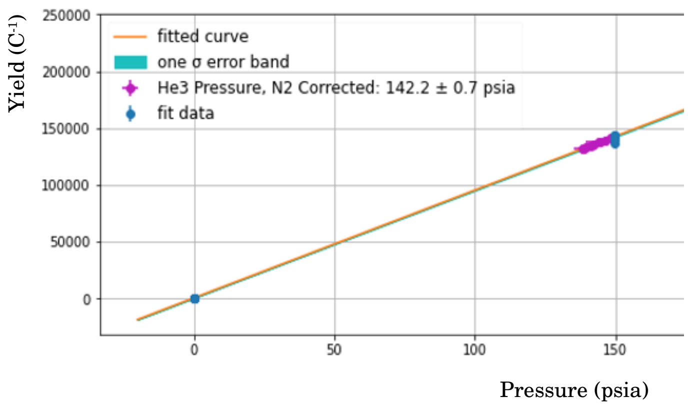
^{3}He Pressure Extraction

Slide Courtesy: J. Chen

Pressure Extraction using 1-Pass Runs



Pressure Extraction using DIS Runs



Method:

Using the yield-pressure curves of ^{3}He and N_2 reference cell runs to extract the ^{3}He pressure in polarized target cell.

Current Status:

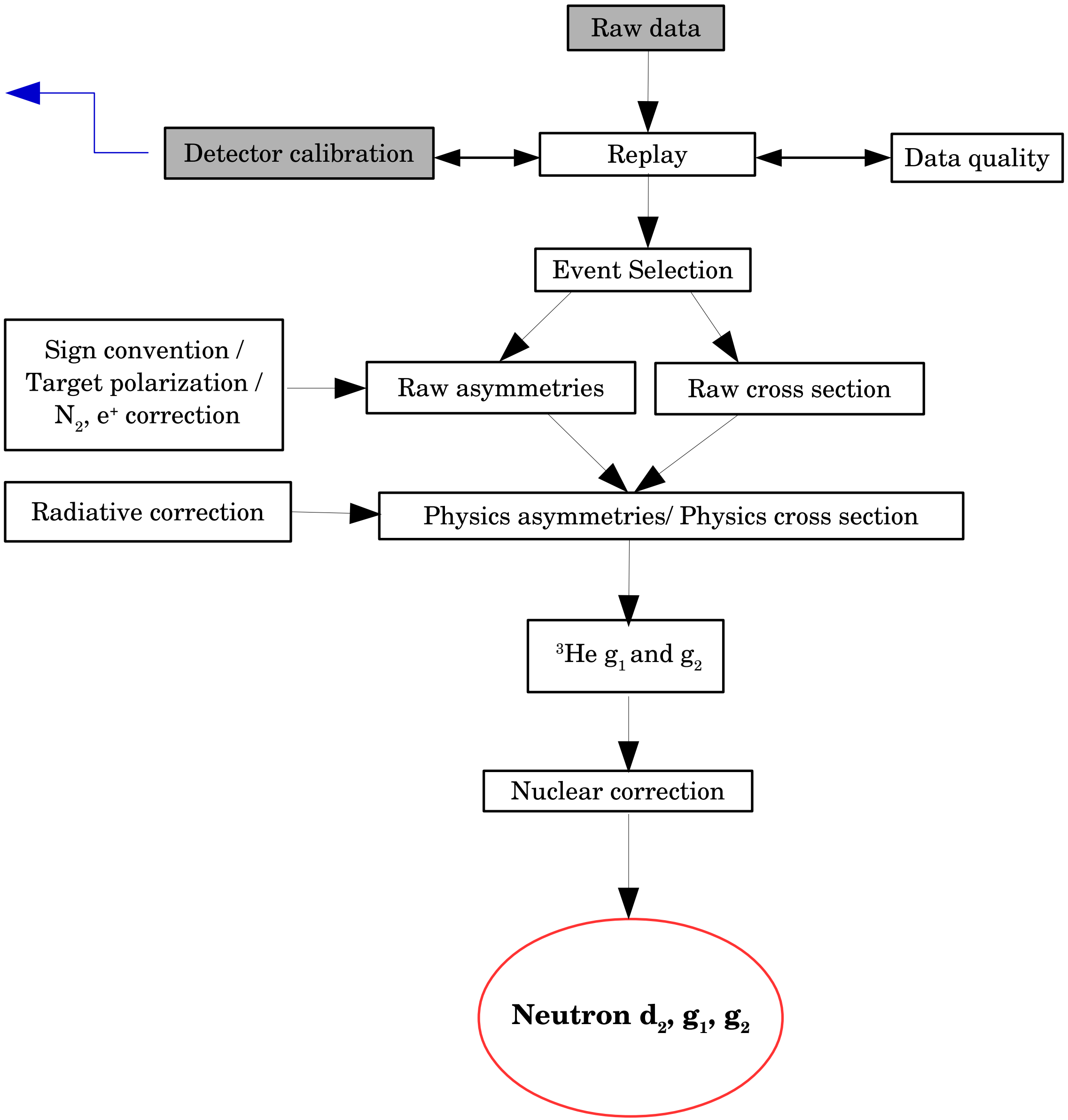
- Got preliminary results for all production cells used in the A_1^n and d_2^n experiments.
- Still need to finalize systematic errors.

Pressure Extraction Results

Cell Name	Filling Density 3He/N2 (amagat)	PC/TC temperature in Production (°C)	PC/TC/TT Volume (cc)	TC He3/N2 Pressure in Production (psia)	1-Pass 12/2019 HMS: 11.7° -2.148 GeV/c (psia)	1-Pass 09/2020 SHMS: 8.5° -2.129 GeV/c (psia)	SHMS: 30° -2.6 GeV/c (psia)	SHMS: 30° -3.4 GeV/c (psia)	SHMS: 18° -5.6 GeV/c (psia)
Briana	6.938/0.1177	240/30	PC: 289.5 TC: 99.88 TT: 26.97	He3: 161.9 N2: 2.75	160.6 ± 1.5	NA	NA	NA	142.2 ± 0.7
Dutch	7.759/0.1102	240/30	PC: 297.15 TC:111.87 TT: 32.52	He3: 179.3 N2: 2.55	NA	NA	NA	191.1 ± 2.0	NA
Big Brother	7.093/0.1120	240/30	PC: 293.82 TC: 100.76 TT: 32.6	He3: 165.5 N2: 2.59	NA	NA	174.1 ± 1.0	178.5 ± 1.6	NA
Tommy	7.76/0.13	240/30	PC: 284 TC: 110 TT: 33	He3: 178.8 N2: 3.0	NA	170.0 ±1.0	NA	NA	157.0 ± 0.6

Analysis Status

1. Hodoscope (M. Chen)
2. Drift Chamber (J. Chen)
3. Cherenkov (M. Roy)
4. Calorimeter (M. Rehfuss)



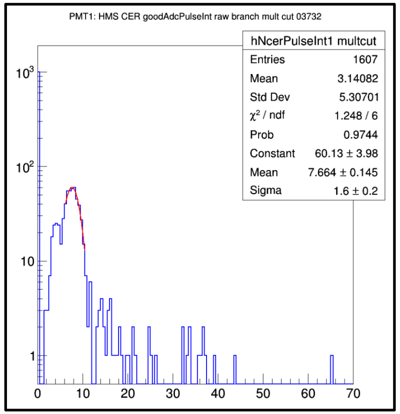
Detector Calibration: Cherenkov

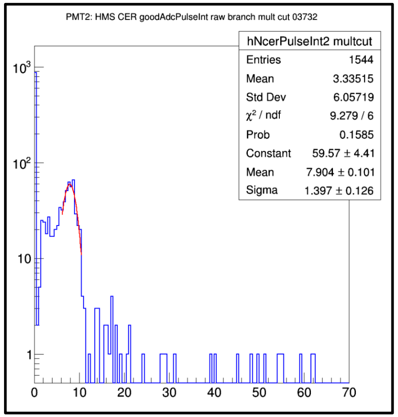
What is Cherenkov calibration?

How much charge (in pC) the PMT will output when one single photoelectron is extracted from the photocathode.

HMS Run 3732

Fit the clear single photo electron peak in goodAdcPulseInt (multiplicity==1) with Gaussian function





Calibration Constants:

- HMS: $1/\mu$

  1/7.664, 1/7.904

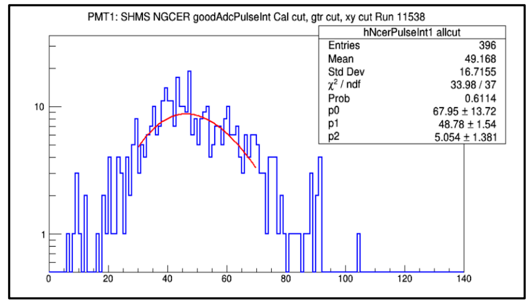
- SHMS: $1/p_2$

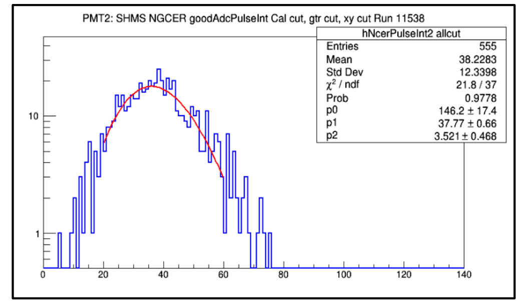
  1/5.054, 1/3.521, 1/4.419, 1/3.788

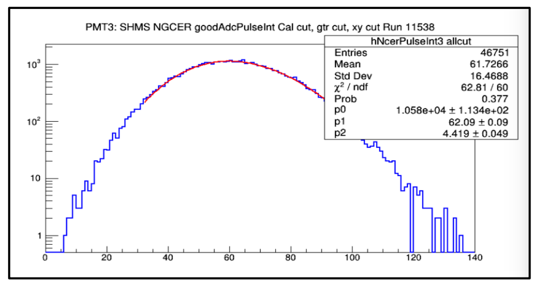
SHMS Run 11538

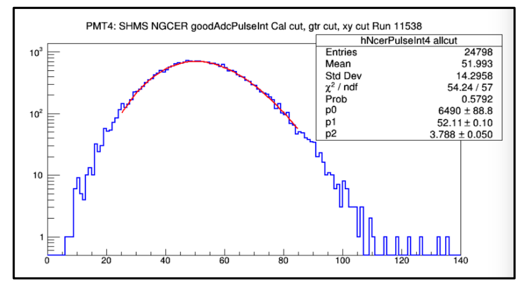
Fit goodAdcPulseInt (multiplicity==1) with: $p_0\left(\frac{p_1}{p_2}\right)^{\frac{x}{p_2}} \frac{\exp\left(\frac{-p_1}{p_2}\right)}{Gamma\left(\frac{x}{p_2}+1\right)}$

$1/p_2$: Calibration constant









Cuts Used:

- -10< P.gtr.dp < 22 (Delta cut for SHMS)
- 0.8 < P.cal.etottracknorm < 1.4 to choose electrons
- X & Y cuts at the mirror planes.

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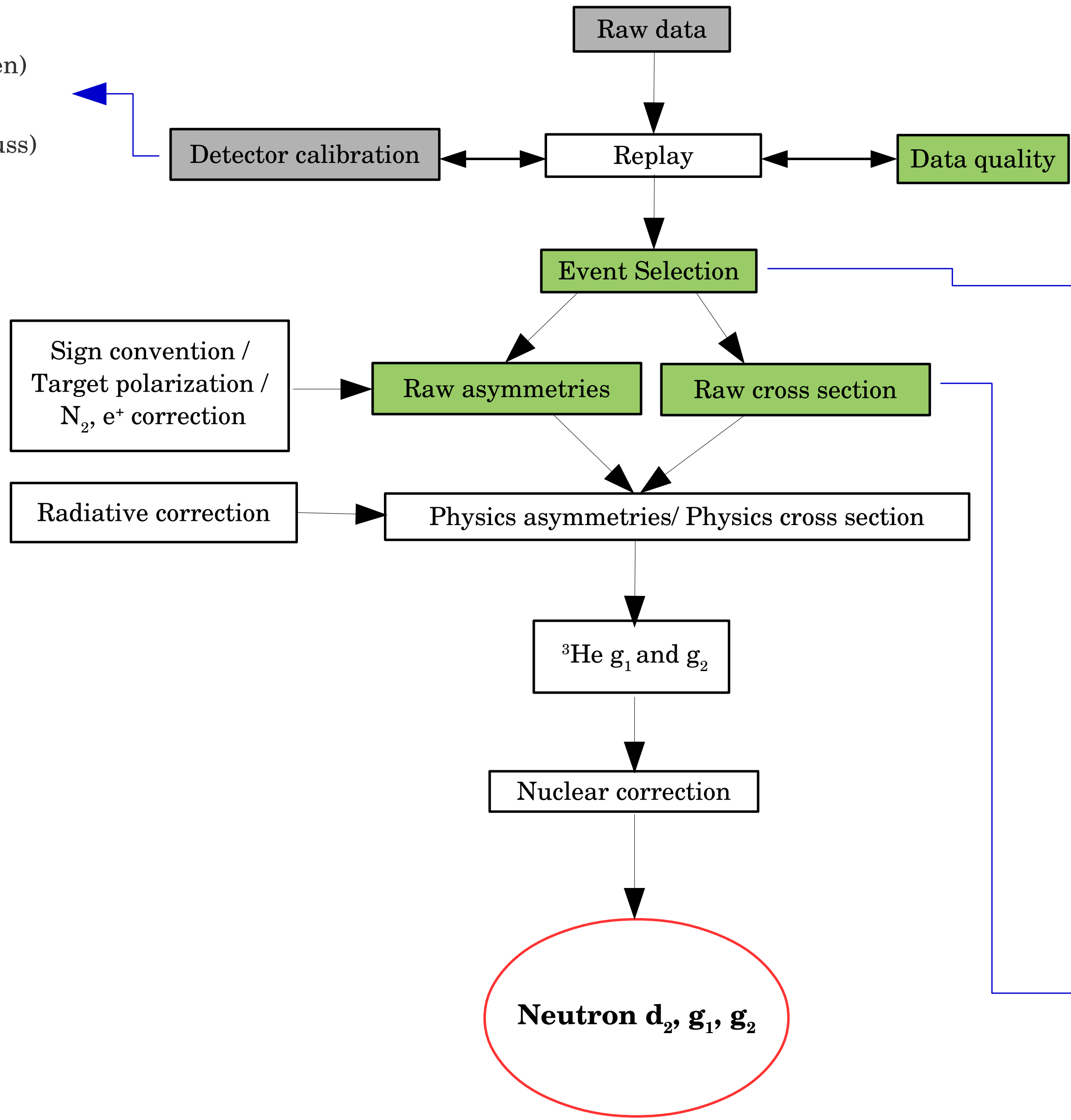
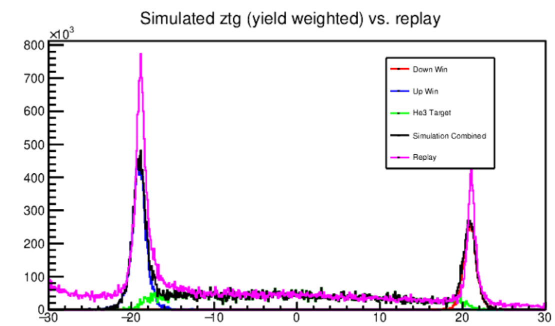
3. Cherenkov (M. Roy)
4. Calorimeter (M. Rehfuss)



1. Beam Trips and Beam Quality
2. Detector live time
3. Short runs

1. Target window cuts (M. Chen)
2. PID studies (M. Rehfuss)
3. Acceptance cuts for SHMS and HMS magnets (M. Roy)



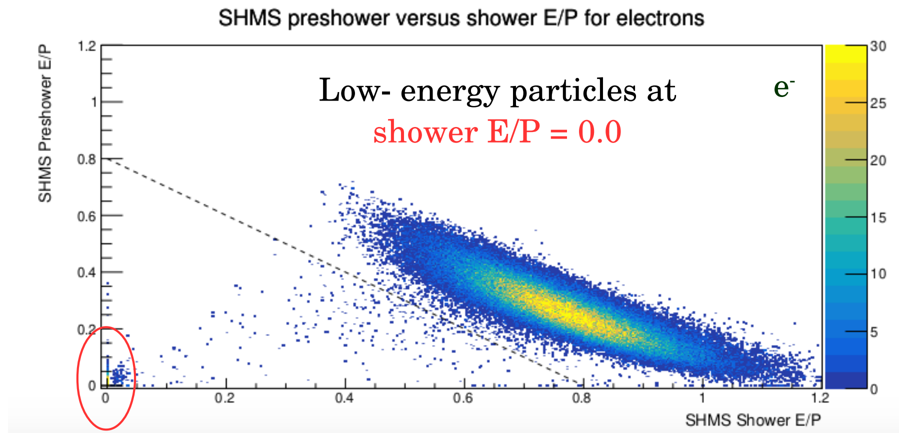
Comparison of MC simulation and data HMS-A (charge normalized yield)

1. Acceptance correction method
2. Monte Carlo Ratio Method (M. Roy)

PID: Calorimeter Efficiency & Pion Rejection

SHMS 11445
DIS, ^{3}He @ 90°
E_p= -5.6 GeV, 18°

Low-energy electrons are surviving the Cherenkov cut but not making the total calotimeter cut (dying in the pre-shower)



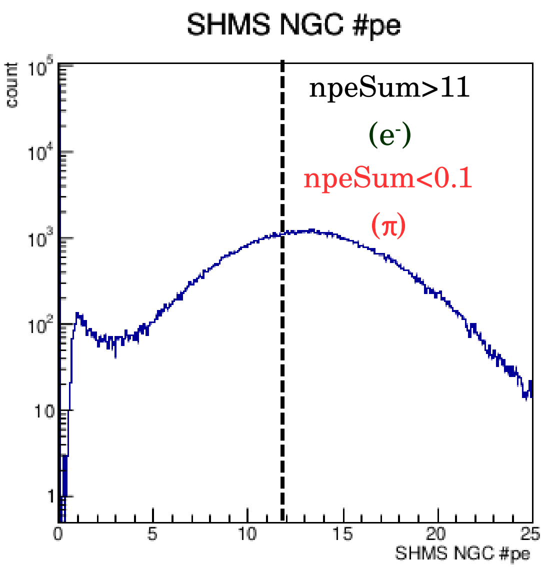
Calorimeter

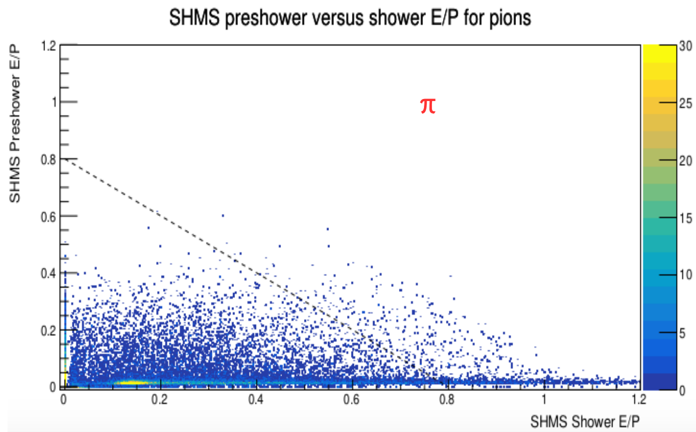
Step 1b

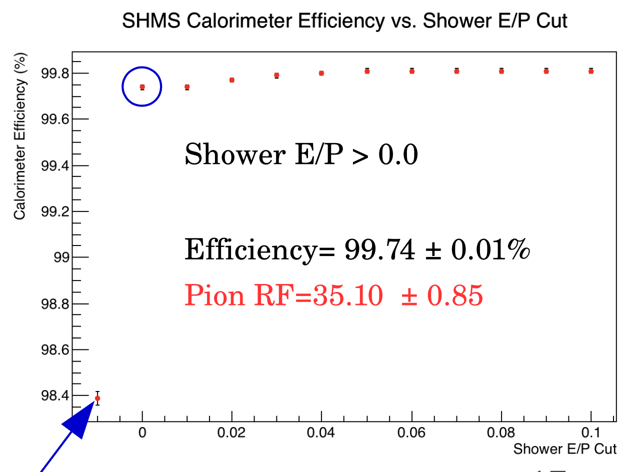
To ensure we are counting only good electrons, impose **a cut on the shower energy > 0.0**

Step 1a

Use the NGC npe sum cut to determine π and e^- samples.







No shower E/P cut

Slide Courtesy: M. Rehfuss

PID: Calorimeter Efficiency & Pion Rejection

SHMS 11445
DIS, ^{3}He @ 90°
E_p= -5.6 GeV, 18°

Calorimeter

Acceptance Cuts:
-10 < P.gtr.dp < 22
abs(P.gtr.ph) < 0.07
abs(P.gtr.th) < 0.05
abs(P.react.z) < 22

Sample Cuts:
NGC npeSum > 11
&& Shower E/P > 0 (e^-)
NGC npeSum < 0.1 (π)

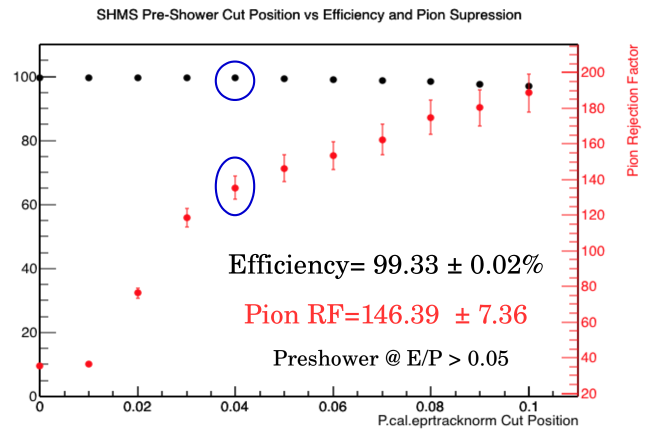
PID Cuts: Total E/P > 0.8

Step 2

Determine how many π and e^- pass the total E/P cut

Efficiency= 99.74 ± 0.01%
Pion RF=35.10 ± 0.85
@ Total E/P > 0.8

Add a preshower cut to the PID cut for a PRF boost

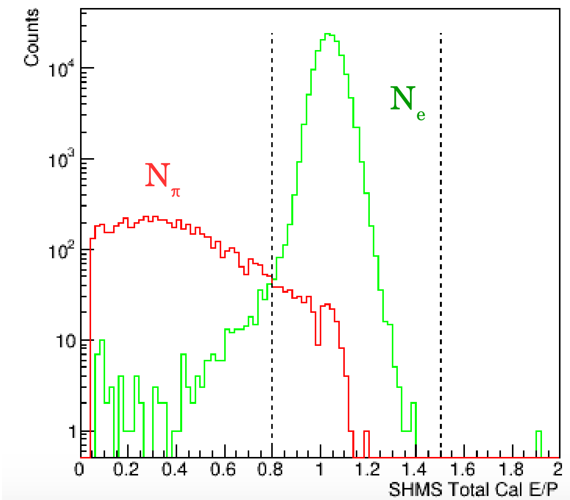


Pion Contamination with a Preshower Cut

Pion contamination= N_π / N_e

PID Cuts: Preshower E / P > 0.05

npeSum > 11 && shower E / P > 0
npeSum < 0.1



Spec	P_0 (GeV/c)	Cherenkov Cut	Cherenkv Efficiency	PRF	Calorimeter Cut	Calorimeter Efficiency	PRF	Combined Pion Cont.
SHMS	5.6	npe>2	99.82±0.01%	21.00±0.55	Total E/P > 0.8 Pre E/P > 0.05	99.33±0.03%	146.36±7.36	0.012%
SHMS	6.4	npe>2	99.80±0.01%	N/A	Total E/P > 0.8 Pre E/P > 0.05	99.33±0.02%	103.24±4.51	0.102%
SHMS	7.5	npe>2	99.73±0.01%	N/A	Total E/P > 0.8	99.29±0.01%	28.11±1.13	0.101%
HMS	4.0	npe>1	99.85±0.02%	36.27±0.20	Total E/P >0.8	99.11±0.02%	82.88±1.27	0.063%

PC from Calorimeter Only: 0.26%

Histogram is integrated over [0.80,1.50] to find percentage of pions in electron sample

(1/PRF) @ 2 npeSum cut from NGC study:
(1/21.00)

PC from Calorimeter + NGC: 0.01%

Slide Courtesy: M. Rehfuss

Cross Section Extraction

- Extract cross section by the following methods:

1. Acceptance correction method

$$\frac{d\sigma}{d\Omega dE'} = \frac{Y(E',\theta)}{\left[(\Delta E\,\Delta\Omega).\,A(E',\theta).\,L\right]}$$

Where,

$Y(E',\theta)$: efficiency corrected electron yield

L : Integrated Luminosity

$A(E',\theta)$: Acceptance for bin ← Determined from simulation!

$A(E',\theta)$ is the probability that a particle will make it through the spectrometer.

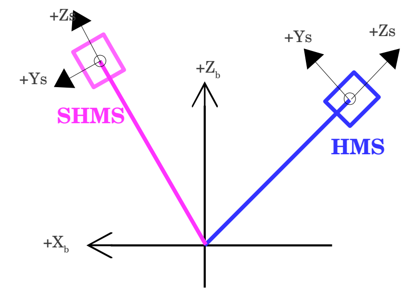
2. Monte Carlo ratio method

$$\frac{d\sigma}{d\Omega dE'} = \sigma^{mod} \cdot \frac{Y(E',\theta)}{Y_{MC}(E',\theta)}$$

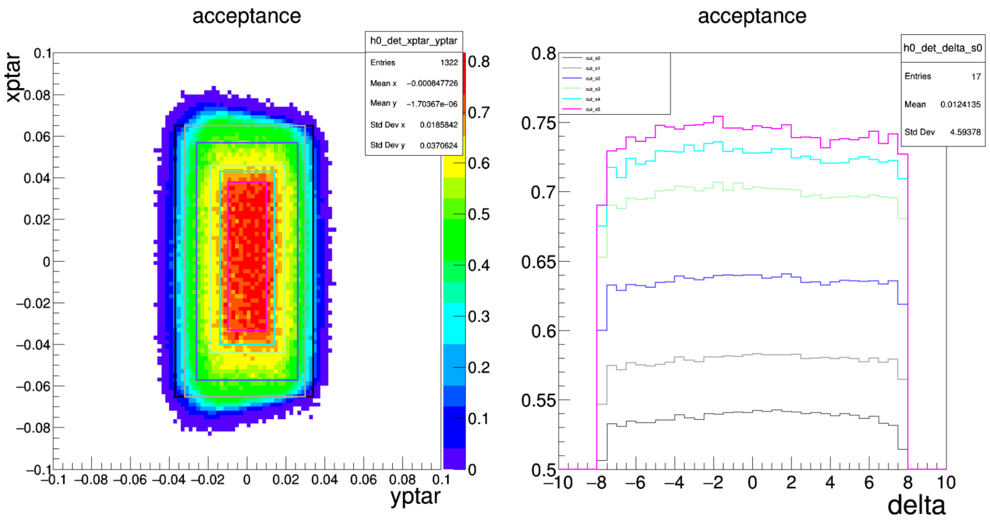
- → Use cross section model (σ^{mod})
- → Assume, $A_{MC} = A$

Spectrometer Acceptance Study

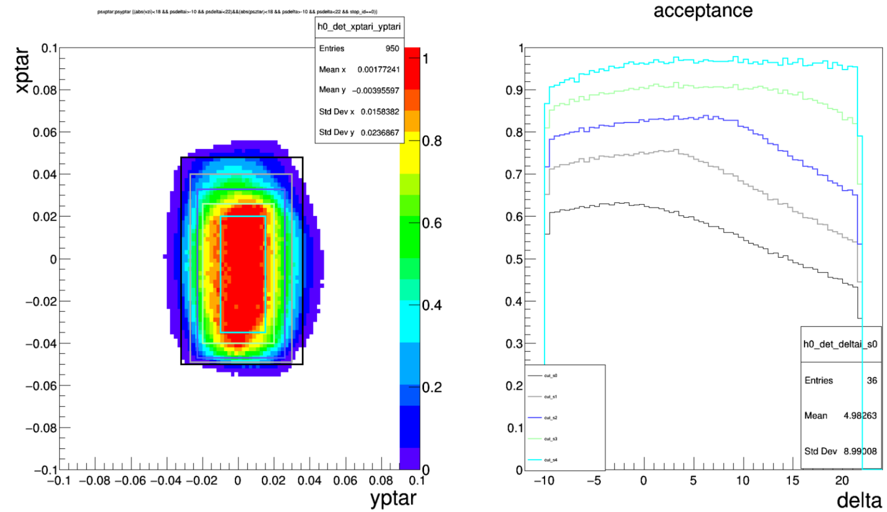
- Acceptance = n_detected / n_thrown
- Generate 1-D delta acceptance for different xptar, yptar rectangular cuts from Monte Carlo Simulation



HMS Kin-C
20 deg, -4.0 GeV/c



SHMS Kin-C
18 deg, -5.6 GeV/c



Cuts applied:

Thrown variable: abs(vzi) < 18 && abs(hsdeltai)<8

Recon variable: abs(vzi) < 18 && abs(hsdeltai)<8 && abs(hsztar) < 18 && abs(hsdelta)<8 && stop_id==0

Cuts applied:

Thrown variable: abs(vzi) < 18 && psdeltai>-10 && psdeltai<22

Recon variable: abs(vzi) < 18 && psdeltai>-10 && psdeltai<22 && abs(psztar) < 18 && psdelta>-10 && psdelta<22 && stop_id==0

Spectrometer Acceptance Study

*Ongoing work

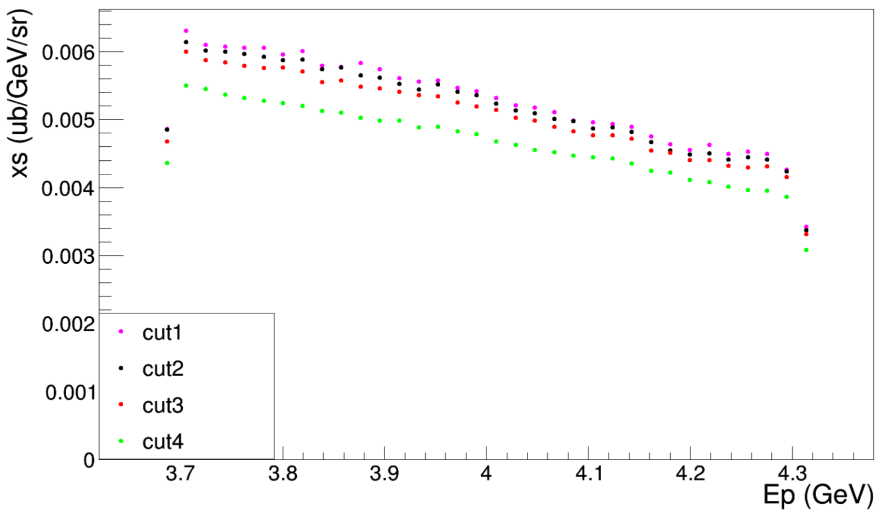
- Simulated yield is generated using cross section model F1F2IN09.
- **Cross section is extracted from the simulated yield** for the **different sets of acceptance cuts** to check the uncertainty in acceptance extraction.

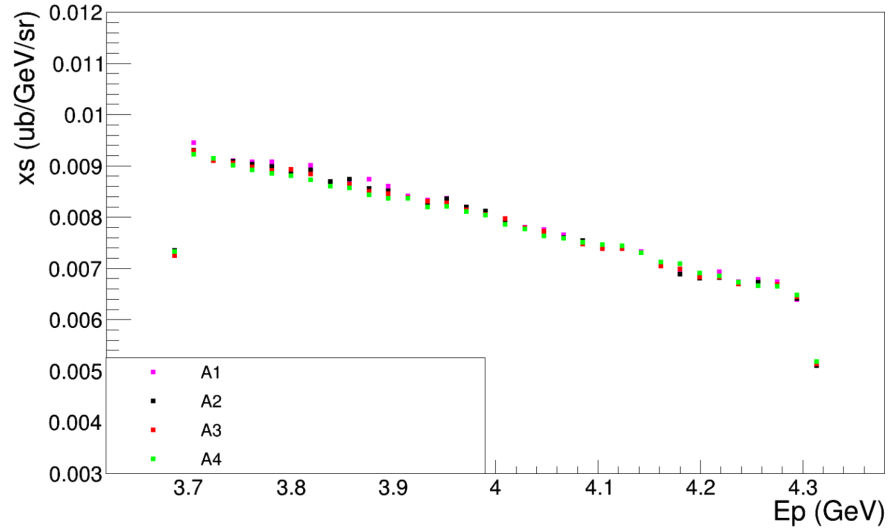
HMS Kin-C
20 deg, -4.0 GeV/c

Theta-Phi cuts	Acceptance
Cut1: theta<38.0 && theta>-33.0 && phi<10.0 && phi>-10.0	A1: 0.739502
Cut2: theta<43.0 && theta>-40.0 && phi<14.0 && phi>-14.0	A2: 0.723254
Cut3: theta<46.0 && theta>-44.0 && phi<19.0 && phi>-19.0	A3: 0.696565
Cut4: theta<57.0 && theta>-57.0 && phi<26.0 && phi>-26.0	A4: 0.634232

Uncorrected: $$\frac{d^2\sigma}{dE'd\Omega} = \frac{Yield * e}{\rho_{He3} * length_{target} * \Delta E' * \Delta\Omega}$$

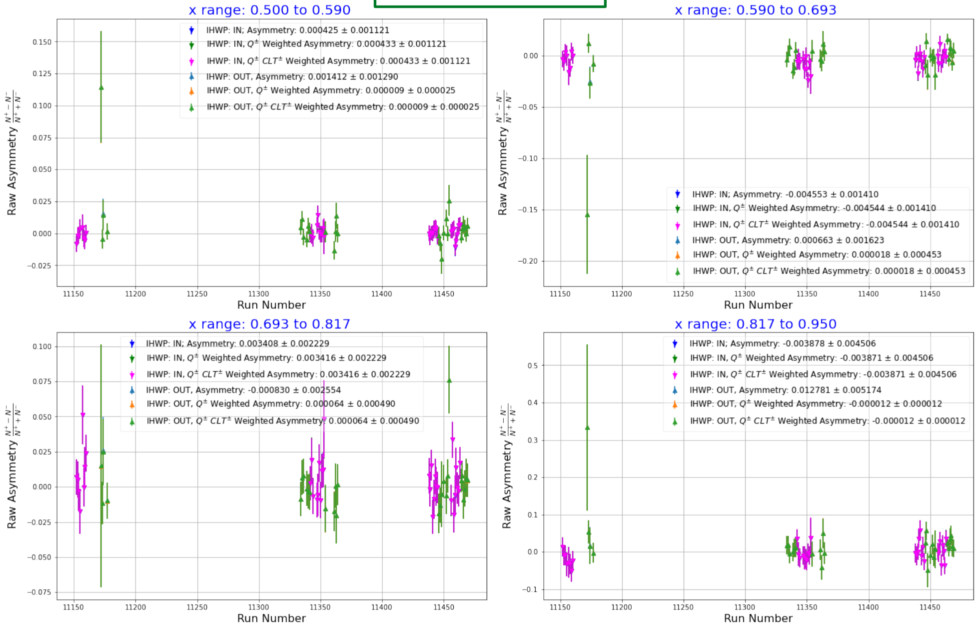
Acceptance corrected: $$\frac{d^2\sigma}{dE'd\Omega} = \frac{Yield * e}{A * \rho_{He3} * length_{target} * \Delta E' * \Delta\Omega}$$



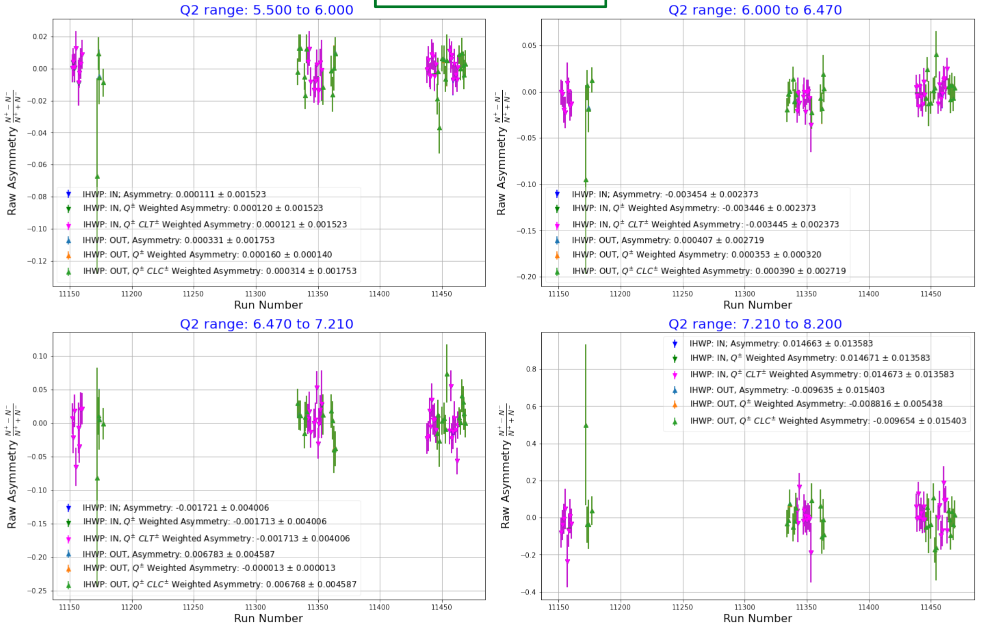


Raw Asymmetry

x binned asymmetry



Q2 binned asymmetry



Raw Asymmetry : $(N^{+}-N^{-}) / (N^{+}+N^{-})$

Current Status:

- Skim through all the runs and got the raw asymmetries for each run
- Still checking some problematic runs

Slide Courtesy: J. Chen

Outline

- **Background**

- **The Experiment**
  - Experimental Setup
  - Kinematic Coverage

- **Experimental Data Analysis**
  - Target Polarization Direction Measurement
  - ^{3}He Pressure Extraction
  - Detector Calibration: Cherenkov
  - PID Studies
  - Spectrometer Acceptance Extraction
  - Raw Asymmetry

- **Summary**

Summary

- Completed: Detector Calibrations, Pressure Curve Study, PID Studies, Spectrometer Acceptance.
- Ongoing: Window Dilution Study, Raw Asymmetry and Raw Cross-section Extraction.
- Finally, d_2^n will be calculated for three constant Q^2 values and g_2^n will provide information on higher twist effects or quark gluon correlation.

Acknowledgments

Thanks to all the collaborators, shift takers, JLab alignment group and other JLab staff for making the experiment successful.

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Mingyu Chen

Supporting Documentations

- Polarized Helium-3 Experiments wiki (2019/2020)
  https://hallcweb.jlab.org/wiki/index.php/Polarized_Helium-3_Experiments

- Proposals
  - https://hallcweb.jlab.org/wiki/images/c/cb/PR12-06-121.pdf
  - https://hallcweb.jlab.org/wiki/images/1/1a/D2n_HallC_PAC36-update_v2.pdf

- Polarized ^{3}He Target
  - https://hallcweb.jlab.org/wiki/index.php/Pol_He-3_Target_Information
  - https://www.jlab.org/indico/event/351/session/1/contribution/9/material/slides/0.pdf

- E06-014 (2009 d_2^n experiment) wiki
  - https://hallaweb.jlab.org/wiki/index.php/Analysis_resources_for_d2n

Back-up Slides

Particle Identification (PID) Studies

We're measuring an asymmetry, so we need **clean electron** detection

The SHMS & HMS have two independent detectors for PID:

Combined Pion Rejection Factor = $PRF_{cherenkov} * PRF_{calorimeter}$

1. The **Gas Cherenkov**

$$Cherenkov\ Efficiency = \frac{electron\ sample\ that\ passed\ the\ Cherenkov\ cut}{electron\ sample\ selected\ with\ the\ Calorimeter}$$

$$Cherenkov\ PR\ Factor = \frac{pion\ sample\ selected\ with\ the\ Calorimeter}{pion\ sample\ that\ passed\ the\ Cherenkov\ cut}$$

→ e^-, π samples determined by the Calorimeter, Cherenkov used for PID

2. The Lead-Glass **Calorimeter**

$$Calorimeter\ Efficiency = \frac{electron\ sample\ that\ passed\ the\ Calorimeter\ (total\ \&\ preshower)\ cut}{electron\ sample\ selected\ with\ the\ Cherenkov}$$

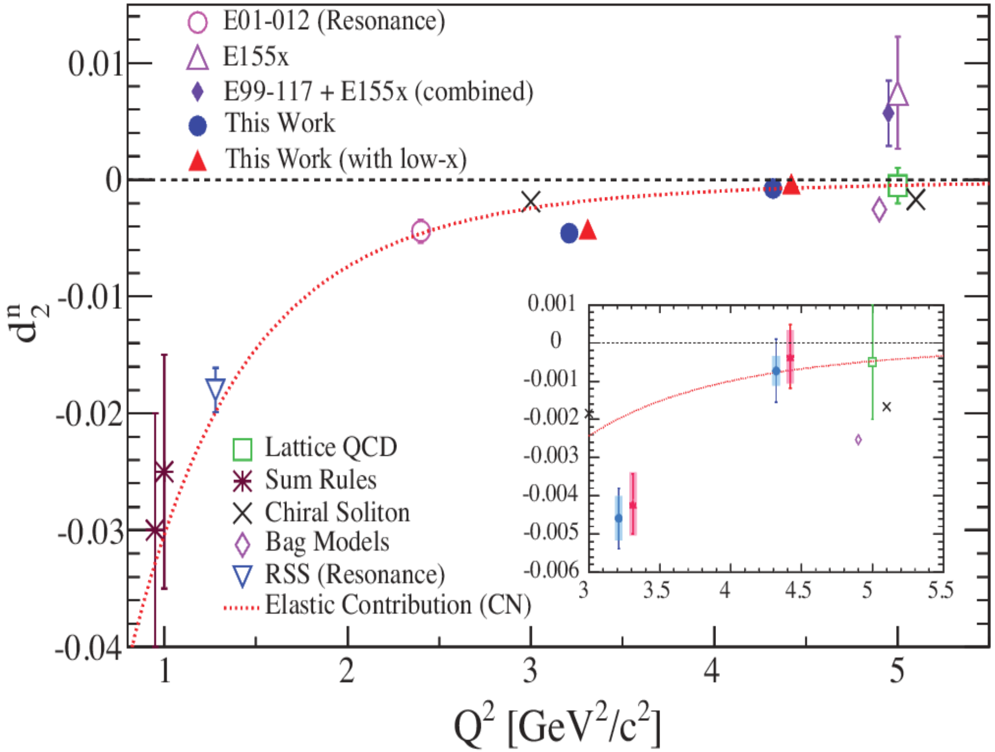
$$Calorimeter\ PR\ Factor = \frac{pion\ sample\ selected\ with\ the\ Cherenkov}{pion\ sample\ that\ passed\ the\ Calorimeter\ (total\ \&\ preshower)\ cut}$$

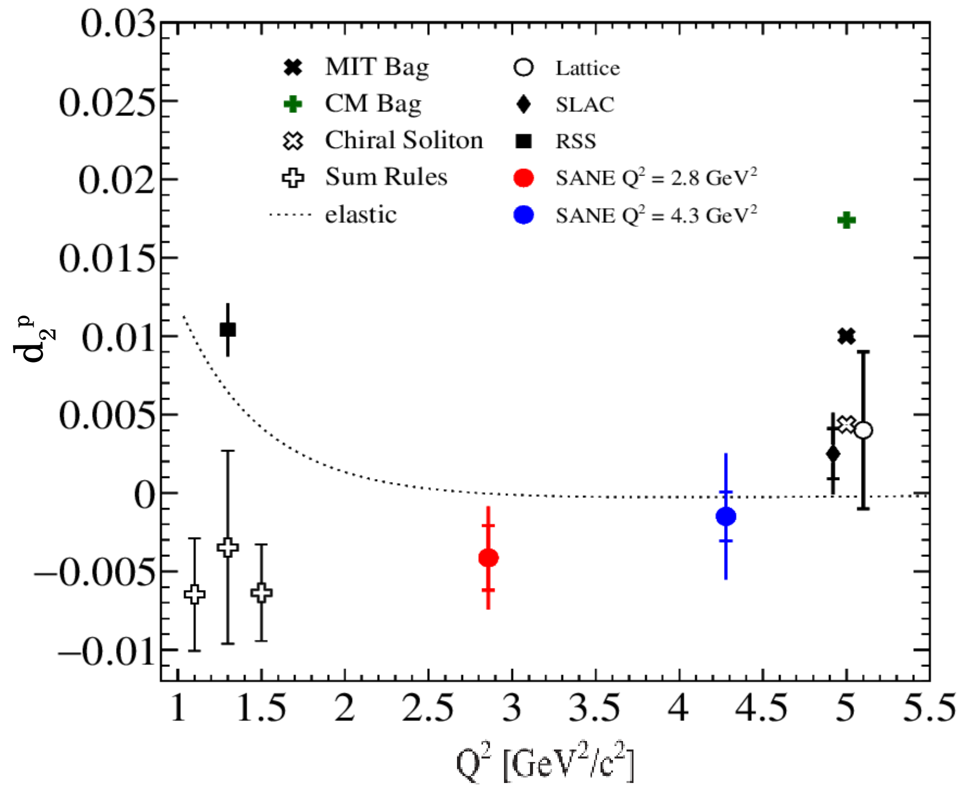
→ e^-, π samples determined by the Cherenkov, Calorimeter used for PID

Existing results: d_2 for proton and neutron

Hint of a negative d_2^n, negative twist-3 at moderate $Q^2 \sim 3$ $(GeV/c)^2$ was noted in E06-014 at JLab.

Posik et al., 10.1103/PhysRevLett.113.022002 (d_2^n, color force extraction)
Flay et al., 10.1103/PhysRevD.94.05200 (Archival paper: g_1^n, g_2^n, d_2^n)
Parno, et al., 10.1016/j.physletb.2015.03.067 (A_1^n)





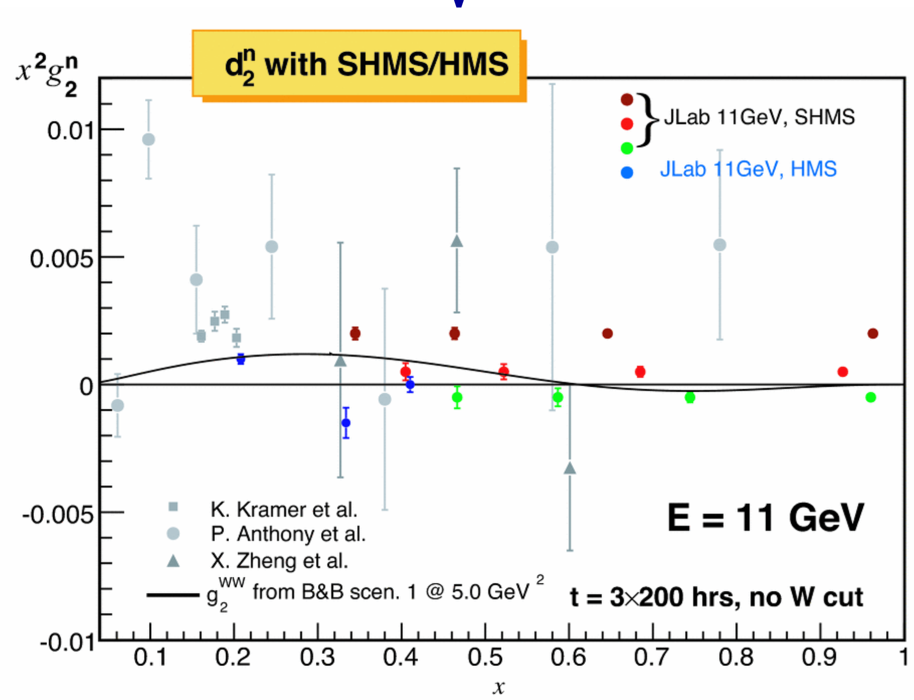
Similar hint of negative twist-3 (dips below CN elastic) in d_2^p data was noted in SANE experiment.

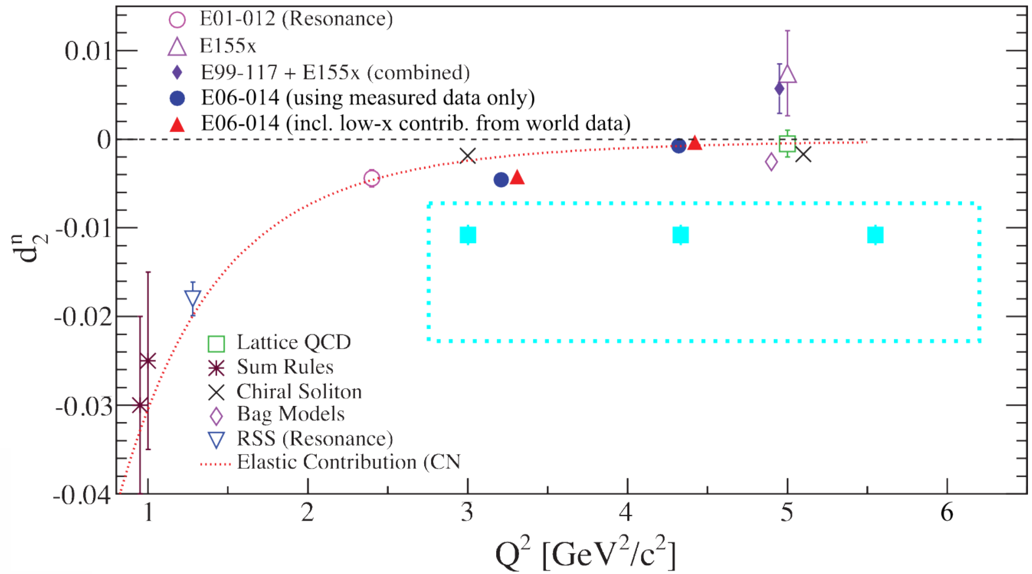
Armstrong et al., PRL 122, 022002 (2019)

E12-06-121: Projected Results

Projection of $x^2 g_2^n$ over broad range of x.

Points are vertically offset from zero along lines that reflect different (roughly) constant Q^2 values from 2.5Ð 6 GeV^2.





Projected results for d_2^n at truly constant Q^2 = 3, 4.3 and 5.6 GeV^2/c^2.

In this region,

- Models are thought to be accurate.
- Direct overlap with 6 GeV Hall A measurements.

E12-06-121: Rate estimates

HMS Kin.	theta (deg)	E' (GeV)	Q^2 (GeV^2)	x	W (GeV)	e^- rate (Hz)	π^- rate (Hz)	$t_{\parallel}$ (Hz)	$t_{\perp}$ (Hz)	ΔA_{raw} (par) (10^{-4})	ΔA_{raw} (perp) (10^{-4})
A	13.5	4.2	2.474	0.216	3.14	3083	2973	8.06	116.9	2.71	0.7
B	16.4	4.2	3.643	0.318	2.948	179	100.3	9.6	115.4	4.48	1.297
C	20	4	5.018	0.418	2.806	39	13.9	11.2	113.8	8.91	2.8

SHMS Kin.	theta (deg)	E' (GeV)	Q^2 (GeV^2)	x	W (GeV)	e^- rate (Hz)	π^- rate (Hz)	$t_{\parallel}$ (Hz)	$t_{\perp}$ (Hz)	ΔA_{raw} (par) (10^{-4})	ΔA_{raw} (perp) (10^{-4})
X	11	7.5	2.866	0.527	1.859	3153	5.29	9.6	115.4	2.51	0.723
Y	14.5	6.4	4.24	0.565	2.036	528.2	5.62	11.38	113.6	5.63	1.78
Z	18	5.6	5.701	0.633	2.046	80.82	1.06	12.85	112.1	13.5	4.58

- The tables have a first estimate of the expected rates and error in raw asymmetries for the different kinematics (B. Sawatzky, W. Korsch).

Input parameters and assumptions →

E [GeV]	l_{tgt} [cm]	ρ_{tgt} (fill) [amg]	ρ_{tgt} (T-corr.) [amg]	P_{tgt}	P_{beam}	I [μA	Be [mil]	GE180 [μm]	A_{charge} [ppm]
10.4	40	8.26	10.56	0.50	0.80	30	10	280	200

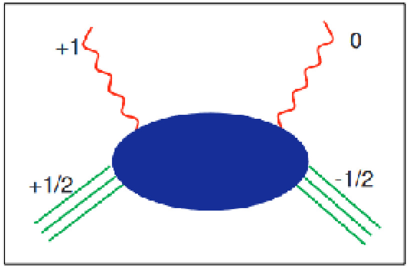
Assumptions:

- SHMS
  - SHMS acceptance: 50 cm, −15%, +25% (relative to p_0)
  - N_2 density of 1.4×10^{19} cm^{-3}
  - $\Delta P_{tgt} = 0$
  - $\Delta P_{beam} = 0$
  - $\Delta A_{charge} = 0$
- HMS
  - HMS acceptance: 10 cm, −10%, +10% (relative to p_0)
  - N_2 density of 1.4×10^{19} cm^{-3}
  - $\Delta P_{tgt} = 0$
  - $\Delta P_{beam} = 0$
  - $\Delta A_{charge} = 0$

Twist Expansion

- Quark electromagnetic current in forward Compton amplitude,

$$T_{\mu\nu} = i \int d^4z\, e^{iqz} < N \left| T \left(j_\mu(z) j_\mu(0) \right) \right| N >$$



- Operator product expansion (OPE) : $j_\mu(z) j_\mu(0) = \sum C_{\mu_1 \ldots \mu_n} \mathcal{O}_{d,n}^{\mu_1 \ldots \mu_n}$

$\mathcal{O}_{d,n}^{\mu_1 \ldots \mu_n}$: Local quark gluon operators with mass dimension d and spin dimension n

- Dimension Analysis : $C_{\mu_1 \ldots \mu_n} \mathcal{O}_{d,n}^{\mu_1 \ldots \mu_n} \longrightarrow \frac{q_{\mu_1}}{Q} \ldots \frac{q_{\mu_n}}{Q} Q^{2-d} M^{d-n-2} p^{\mu_1} \ldots p^{\mu_n}$

$$\rightarrow \frac{P.q}{Q^n} Q^{2-d} M^{d-n-2}$$

$$\rightarrow \left(\frac{1}{x}\right)^n \left(\frac{Q}{M}\right)^{2+n-d}$$

$$\rightarrow \left(\frac{1}{x}\right)^n \left(\frac{Q}{M}\right)^{2-t}$$

	Quark	Gluon
d	3/2	2
n	1/2	1
t	1	1

Twist, t = d-n

Systematic Error Table

Item description	Subitem description	Relative uncertainty
Target polarization		1.5 %
Beam polarization		3 %
Asymmetry (raw)		
	• Target spin direction (0.1°)	$< 5 \times 10^{-4}$
	• Beam charge asymmetry	$<$ 50 ppm
Cross section (raw)		
	• PID efficiency	$<$ 1 %
	• Background Rejection efficiency	$\approx$ 1 %
	• Beam charge	$<$ 1 %
	• Beam position	$<$ 1 %
	• Acceptance cut	2-3 %
	• Target density	$<$ 2%
	• Nitrogen dilution	$<$ 1%
	• Dead time	$<$ 1%
	• Finite Acceptance cut	$<$ 1%
Radiative corrections		$\leq$ 5 %
From ^{3}He to Neutron correction		5 %
Total systematic uncertainty (for both $g_2^n(x,Q^2)$ and $d_2(Q^2)$)		$\leq$ 10 %
Estimate of contributions to d_2 from unmeasured region	$\int_{0.003}^{0.23} \tilde{d}_2^n \, dx$	4.8×10^{-4}
Projected absolute statistical uncertainty on d_2		$\Delta d_2 \approx 5 \times 10^{-4}$
Projected absolute systematic uncertainty on d_2 (*assuming* $d_2 = 5 \times 10^{-3}$)		$\Delta d_2 \approx 5 \times 10^{-4}$

Neutron Asymmetries from ^{3}He

- $$A_1^n = \frac{1}{P_n}\frac{F_2^{3He}}{F_2^n\left(1+\frac{0.056}{P_n}\right)}\left(A_1^{3He} - 2P_p\left(1-\frac{0.014}{2P_p}\right)\frac{F_2^p}{F_2^{3He}}\,A_1^p\right)$$

- $$A_2^n = \frac{1}{P_n}\frac{F_2^{3He}}{F_2^n\left(1+\frac{0.056}{P_n}\right)}\left(A_2^{3He} - 2P_p\left(1-\frac{0.014}{2P_p}\right)\frac{F_2^p}{F_2^{3He}}\,A_2^p\right)$$

- $$\frac{g_1^n}{F_1^n} = \frac{1}{P_n}\frac{F_2^{3He}}{F_2^n\left(1+\frac{0.056}{P_n}\right)}\left(\frac{g_1^{3He}}{F_1^{3He}} - 2P_p\left(1-\frac{0.014}{2P_p}\right)\frac{F_2^p}{F_2^{3He}}\frac{g_1^p}{F_1^p}\right)$$

- $$\frac{g_2^n}{F_1^n} = \frac{1}{P_n}\frac{F_2^{3He}}{F_2^n\left(1+\frac{0.056}{P_n}\right)}\left(\frac{g_2^{3He}}{F_1^{3He}} - 2P_p\left(1-\frac{0.014}{2P_p}\right)\frac{F_2^p}{F_2^{3He}}\frac{g_2^p}{F_1^p}\right)$$

P_p, P_n : Effective proton and neutron polarizations in ^{3}He