Precise measurement of d_2^n as a function of Q^2

On behalf of the A_1^n/d_2^n Collaboration

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DIS2026
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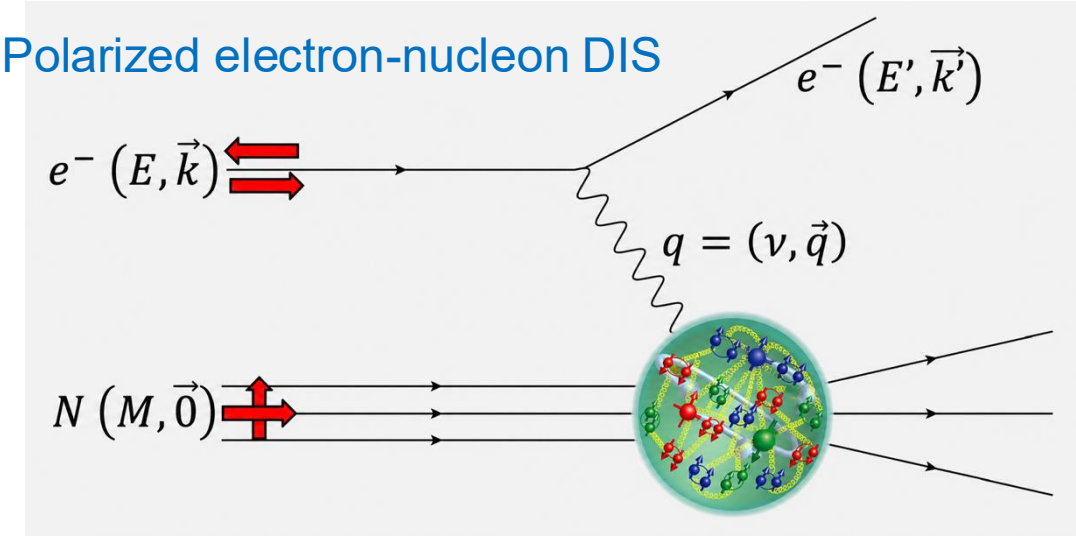
Polarized electron-nucleon DIS

Polarized electron-nucleon DIS



$$\begin{cases} \nu = E - E' \\ Q^2 \equiv -q^2 = 4EE' \sin^2\left(\frac{\theta}{2}\right) \\ x = \frac{Q^2}{2M\nu} \end{cases}$$

Polarized cross section difference

$\sigma^{\uparrow,\Uparrow}$: Electron spin parallel to its momentum; Target spin parallel to the electron momentum

$\sigma^{\downarrow,\Rightarrow}$: Electron spin anti-parallel to its momentum; Target spin perpendicular to the electron momentum

$$\frac{d^2\sigma^{\downarrow,\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\uparrow,\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2}{Q^2}\frac{E'}{E}\frac{1}{M\nu}\left[(E + E'\cos\theta)\, g_1\left(x,Q^2\right) - \frac{Q^2}{\nu} g_2\left(x,Q^2\right)\right]$$

$$\frac{d^2\sigma^{\downarrow,\Rightarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\uparrow,\Rightarrow}}{d\Omega dE'} = \frac{4\alpha^2}{Q^2}\frac{E'^2}{E}\sin\theta\cos\phi\left[\frac{1}{M\nu} g_1\left(x,Q^2\right) + \frac{2E}{M\nu^2} g_2\left(x,Q^2\right)\right]$$

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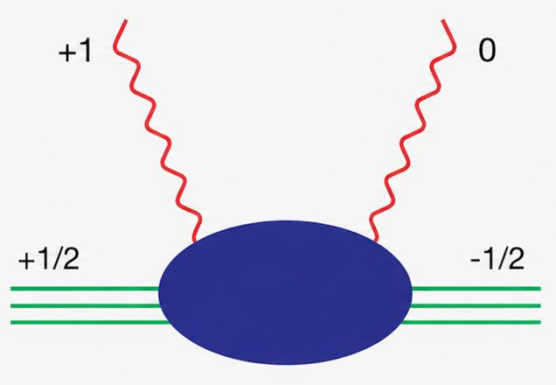
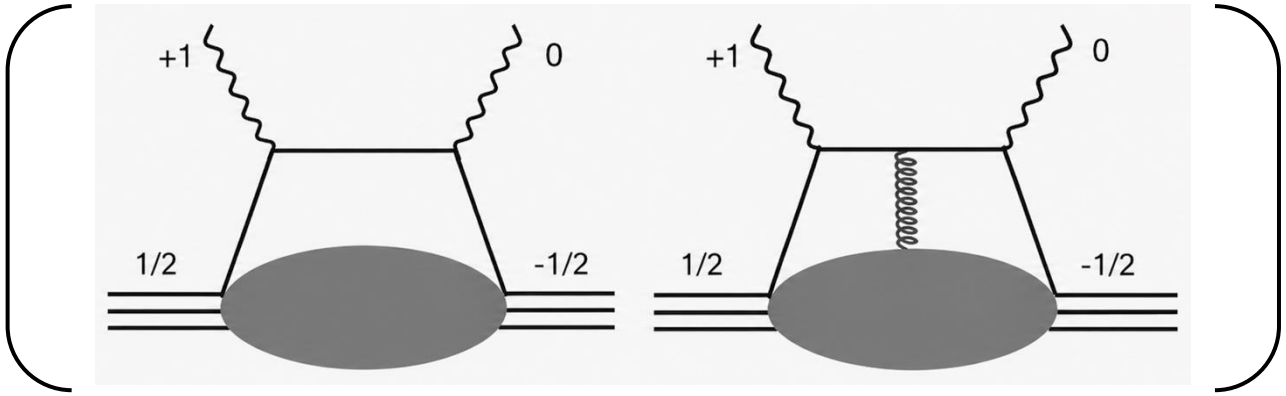
Spin structure function g_2



$$\gamma^*(+1) + N(+1/2) \rightarrow \gamma^*(0) + N(-1/2)$$



twist-2 higher-twist

$$g_2(x,Q^2) = \underbrace{g_2^{WW}(x,Q^2)}_{\text{twist-2}} + \underbrace{\bar{g}_2(x,Q^2)}_{\text{higher twist}}$$

S. Wandzura and F. Wilczek, PLB 72B, 195 (1977).

$$\begin{cases} g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{dy}{y} g_1(x,Q^2) \\ \bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left[\underbrace{\frac{m_q}{M} h_T(y,Q^2)}_{\text{transversity (suppressed)}} + \underbrace{\xi(y,Q^2)}_{\text{quark-gluon correlation}}\right]\frac{dy}{y} \end{cases}$$

- g_2 provides a unique opportunity to study the quark-gluon correlation inside the nucleon.
- We can access the quark-gluon correlation by studying the difference between g_2 and g_2^{WW}.

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Twist-3 matrix element d_2

- d_2 is defined by a third moment of a linear combination of g_1 and g_2.

$$d_2(Q^2) = \int_0^1 x^2 \left[2g_1(x, Q^2) + 3g_2(x, Q^2)\right] dx$$

- d_2 is related to a specific twist-3 matrix element involving local operators of quark and gluon fields.

$$2MP^+P^+S^x d_2 = g\langle P, S|\bar{\psi}(0)\gamma^+ G^{+y}(0)\psi(0)|P, S\rangle$$

quark-gluon correlation nucleon

nucleon rest frame

$$F^y(0) \equiv \langle P, S|\bar{\psi}(0)\gamma^+ G^{+y}(0)\psi(0)|P, S\rangle$$

$$= -M^2 d_2,$$

- d_2 represents an average color Lorentz force acting on the struct quark due to the remnant diquark system during the DIS process.

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Determination of g_1, g_2, and d_2

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

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

$$\begin{cases} A_\parallel \equiv \dfrac{\sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\downarrow\Uparrow} + \sigma^{\uparrow\Uparrow}} \\ A_\perp \equiv \dfrac{\sigma^{\downarrow\Rightarrow} - \sigma^{\uparrow\Rightarrow}}{\sigma^{\downarrow\Rightarrow} + \sigma^{\uparrow\Rightarrow}} \end{cases}$$

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

- g_1, g_2, and d_2 can be evaluated by measuring unpolarized cross section and double spin asymmetries $A_\parallel$ and $A_\perp$.
- How precisely the d_2 is measured in the experiment depends on
  - how broad x range the data covers and
  - how constant Q^2 is across that x range.

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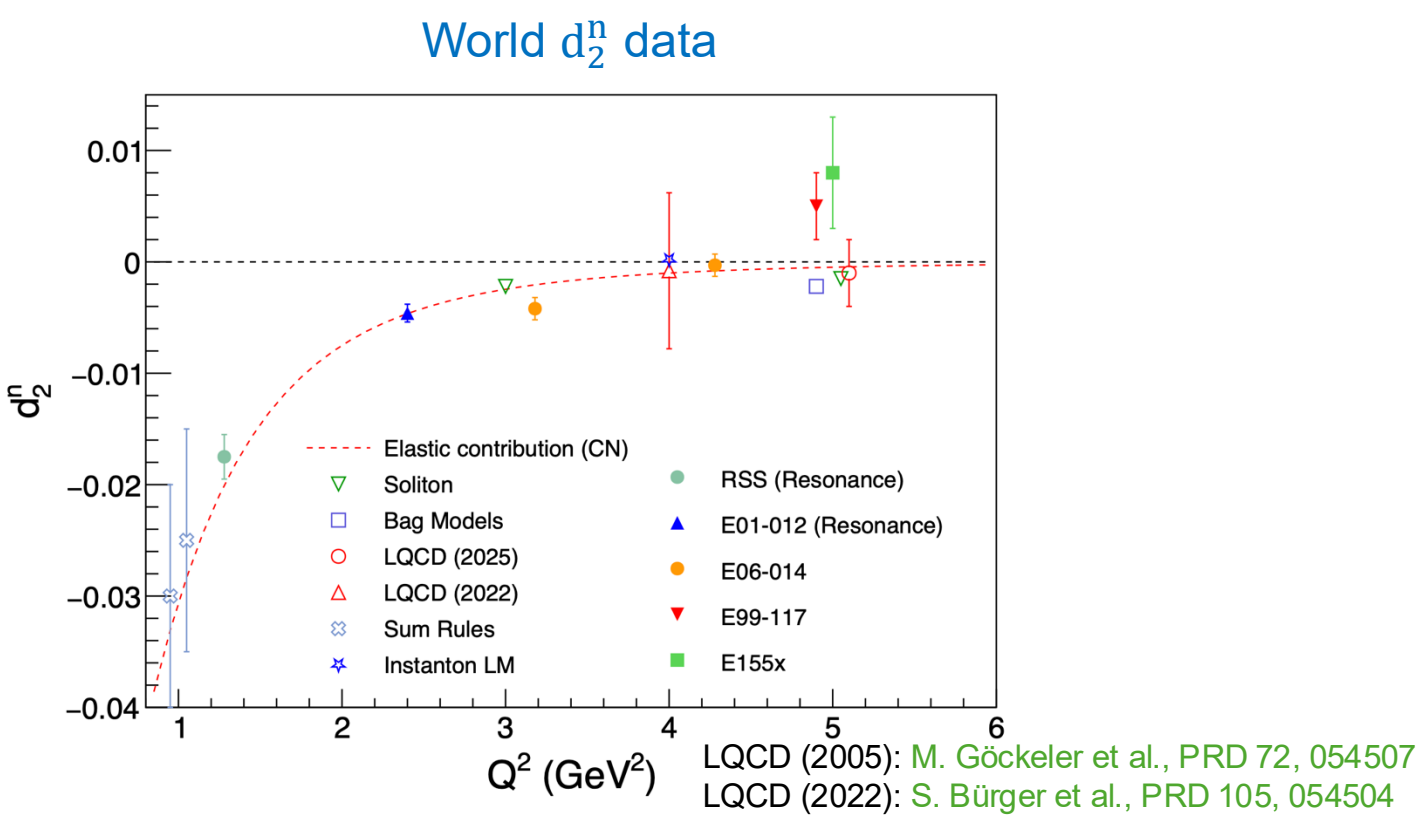
World d_2^n data



LQCD (2005): M. Göckeler et al., PRD 72, 054507
LQCD (2022): S. Bürger et al., PRD 105, 054504

- At intermediate and low $\langle Q^2 \rangle$, the experimental data points show reasonable agreement with the model predictions at nearby Q^2.
- However, at higher $\langle Q^2 \rangle$~5 GeV^2, they do not seem to be in reasonable agreement.
- Although the uncertainties of the higher $\langle Q^2 \rangle$ data points are large, this discrepancy suggests the need for more precise d_2^n measurement at high Q^2.

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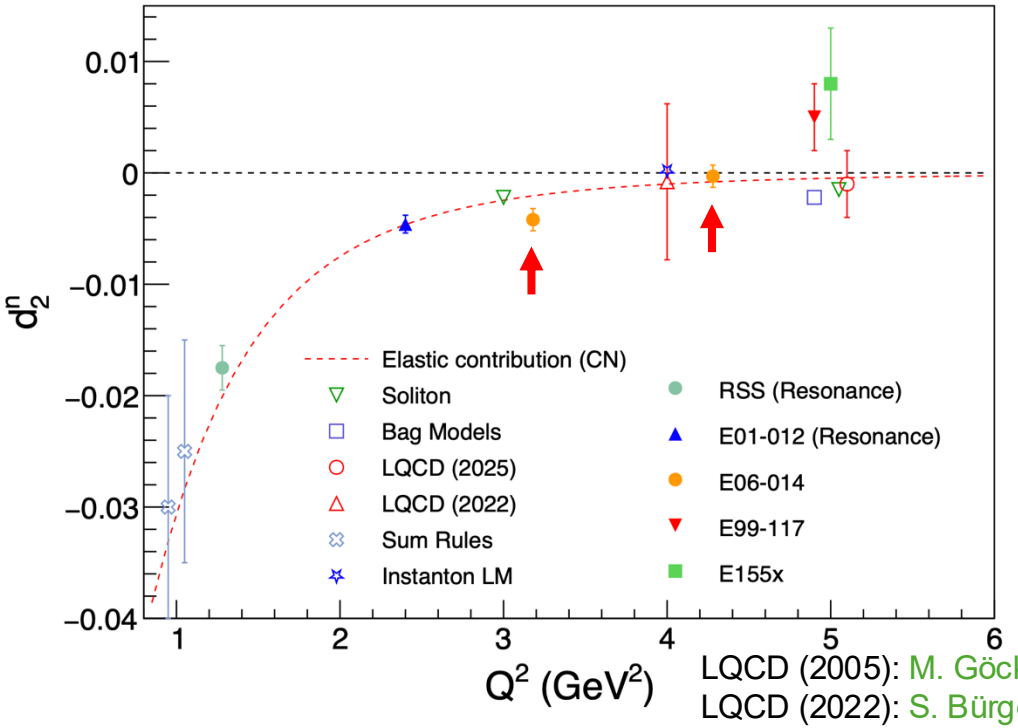
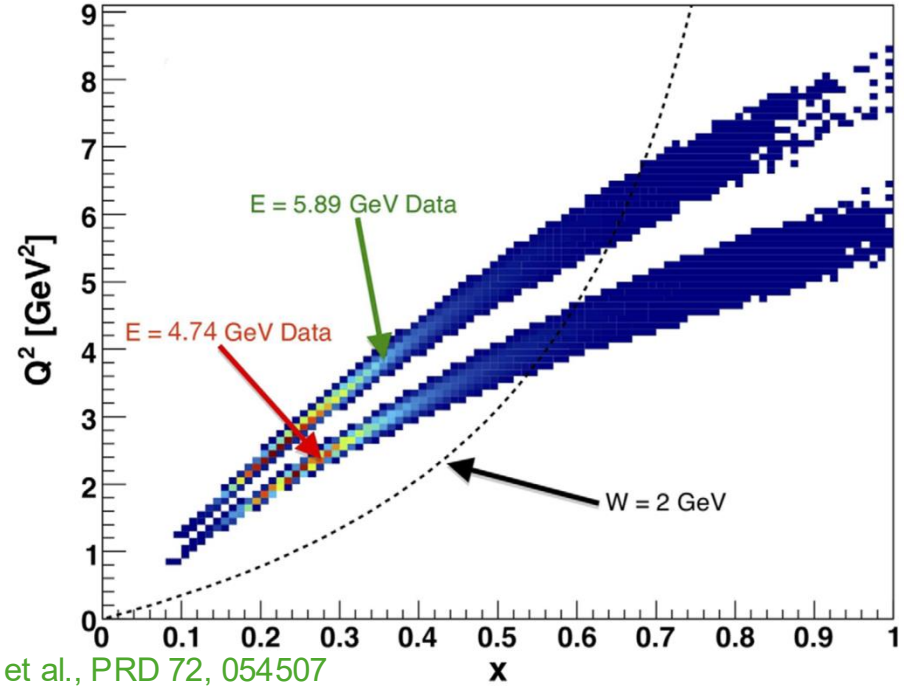
World d_2^n data

World d_2^n data



Measured (x, Q^2) at E06-014



LQCD (2005): M. Göckeler et al., PRD 72, 054507
LQCD (2022): S. Bürger et al., PRD 105, 054504

- All the previous measurements took data over a broad Q^2 range.
- It suggests the need for more precise d_2^n measurement with nearly constant Q^2.

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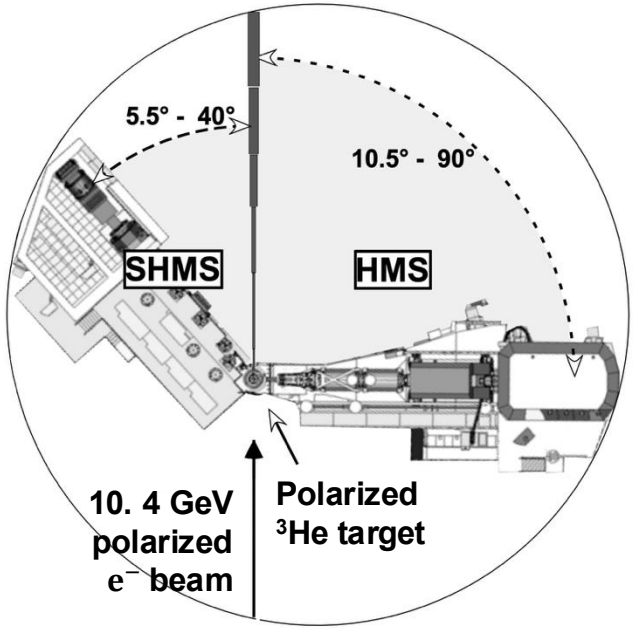
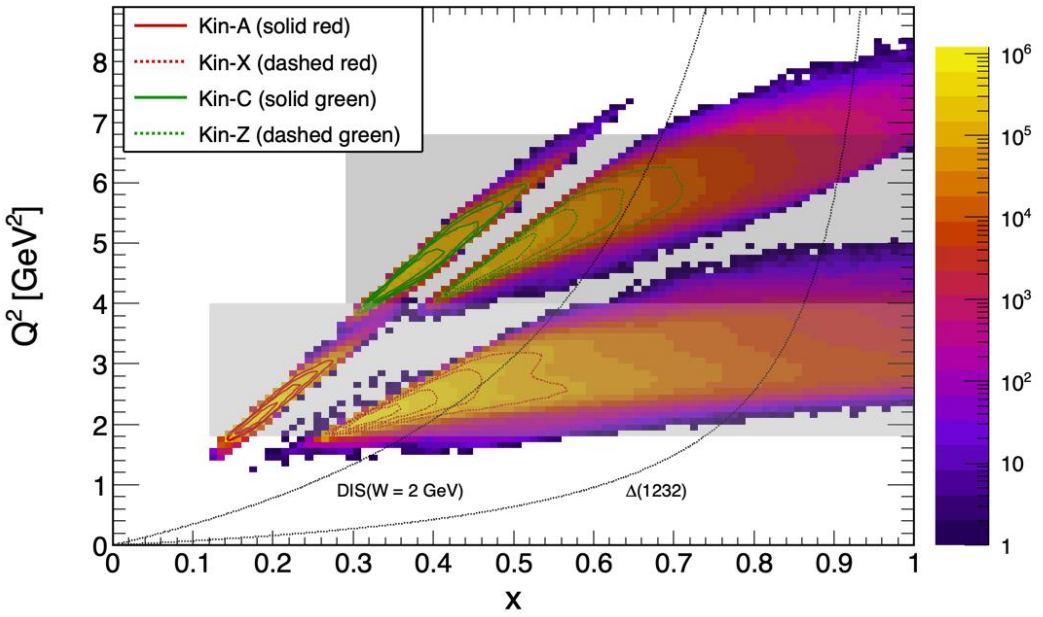
E12-06-121 experiment

SHMS & HMS



Measured (x, Q^2)



SHMS

Setting	p_0 (GeV/c)	Angle (°)
X	7.5	11.0
Z	5.6	18.0

HMS

Setting	p_0 (GeV/c)	Angle (°)
A	4.2	13.5
C	4.0	20.0

- To provide significantly improved d_2^n values at intermediate and high Q^2, we ran a dedicated experiment, E12-06-121, in 2020 at Jefferson Lab in Hall C.
- We can extract the d_2^n with the highest precision achieved so far by integrating the spin structure functions over the broad x range at nearly constant Q^2.
- Q^2 evolution of the precisely measured d_2^n will provide a strict test of Lattice QCD.

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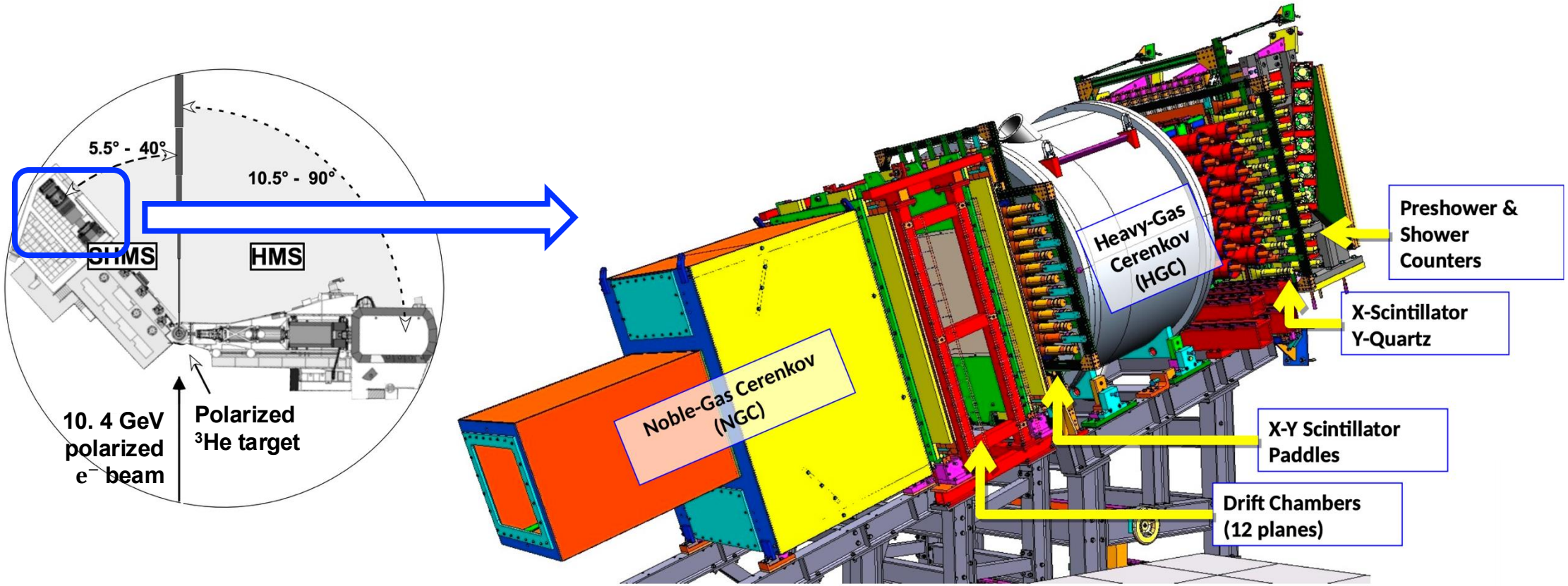
Super High Momentum Spectrometer (SHMS)



- The Cherenkov counters and EM calorimeters separate scattered electrons from pion and kaon background.
- The drift chambers provide the tracking information.
- The hodoscopes provide the trigger and timing information.

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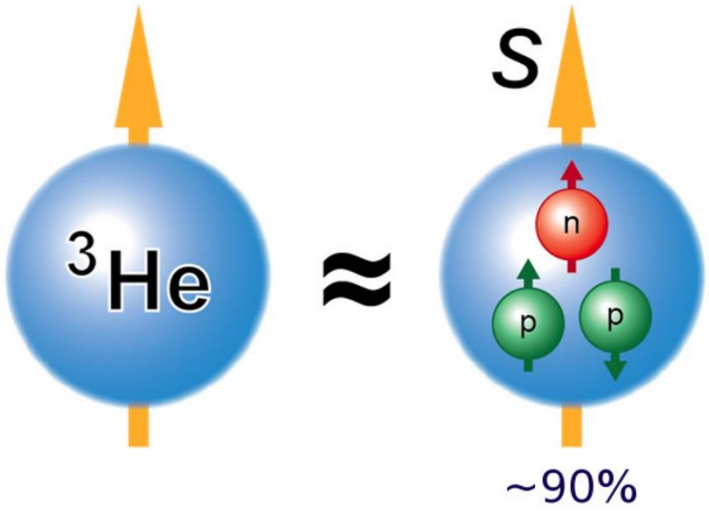
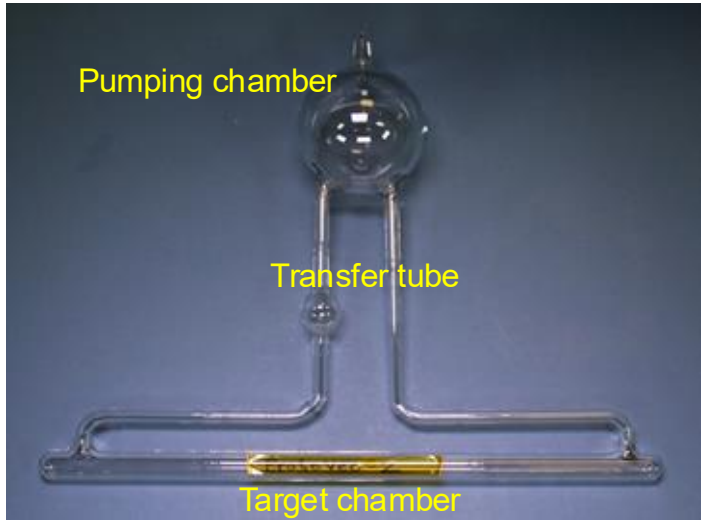
Polarized ^{3}He target system

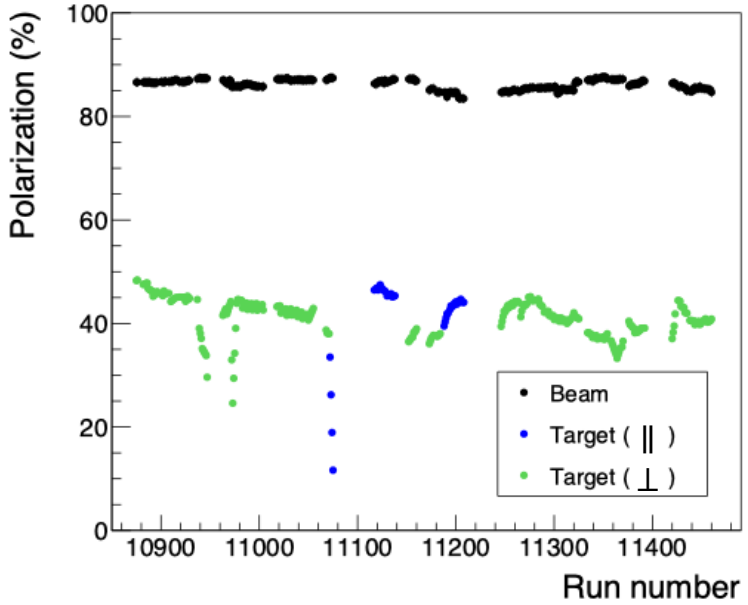
Polarized ^{3}He



Target cell



Polarizations



- The polarized ^{3}He target can be used as an effective polarized neutron target.
- The polarized ^{3}He gas is actively delivered to the target chamber by the temperature difference between two transfer tubes.
- The target polarization was quite stable at 41.32 $\pm$ 4.12% regardless of the polarization direction, even under the highest luminosity condition achieved so far.

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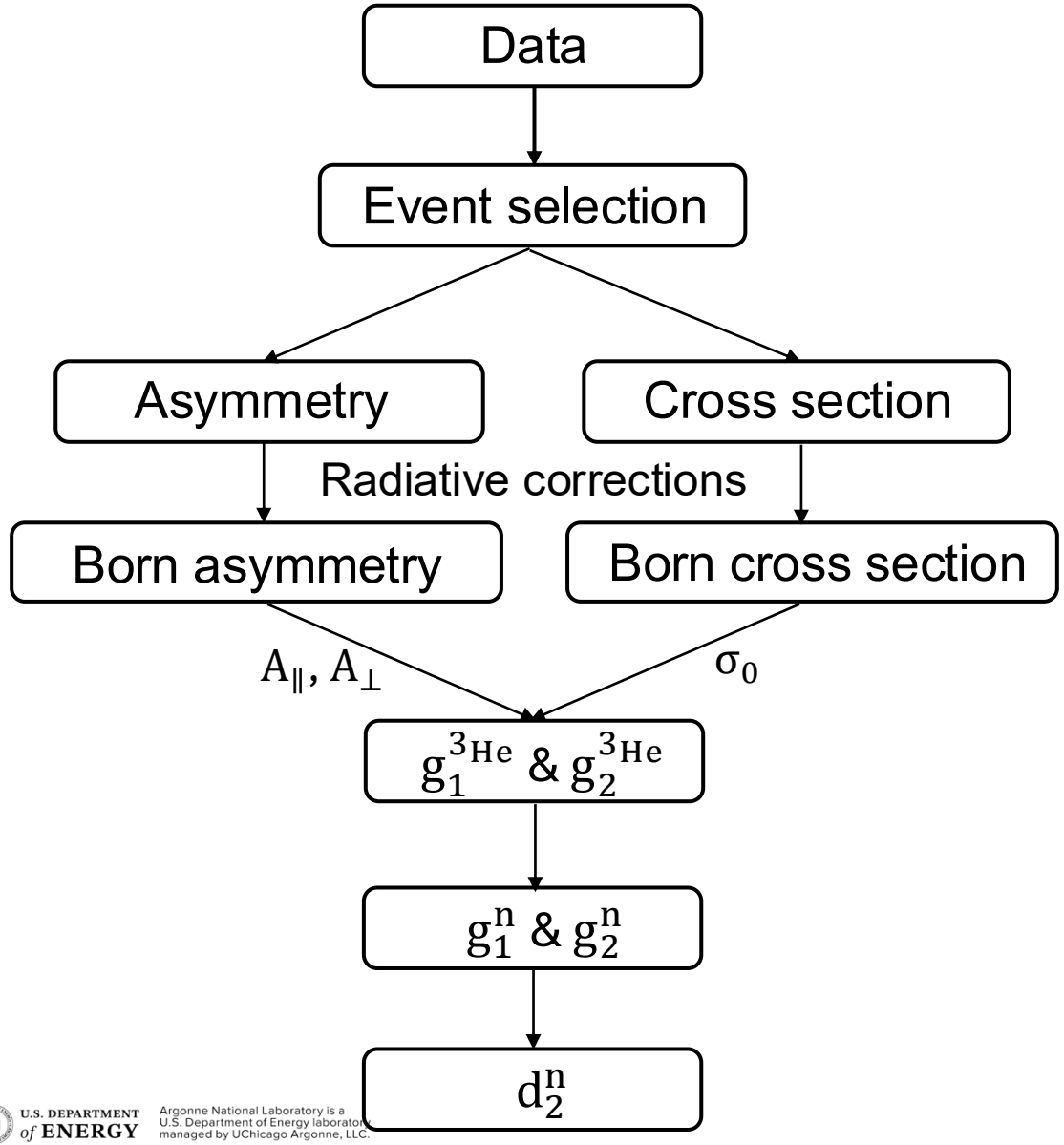
Analysis flow



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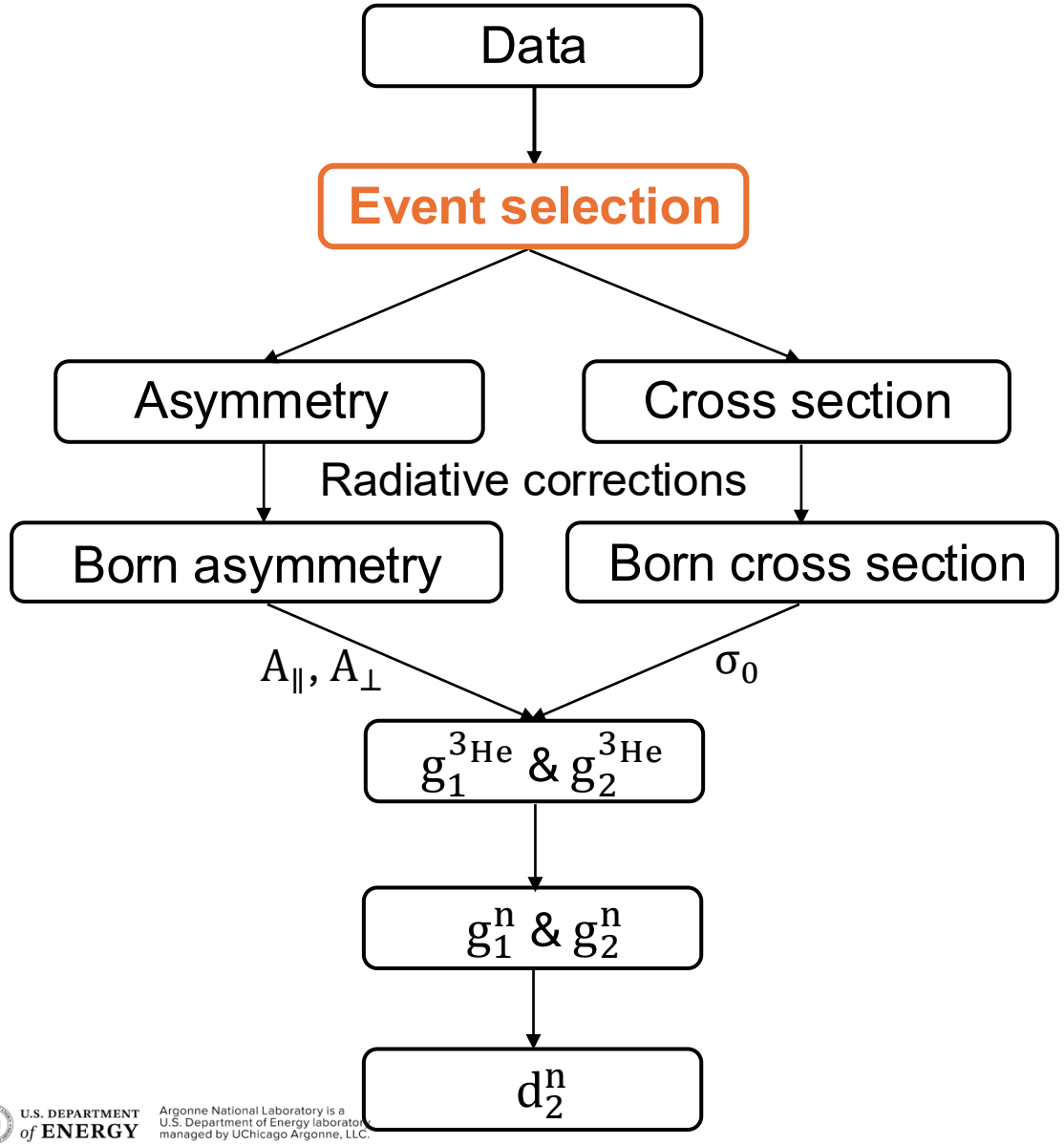
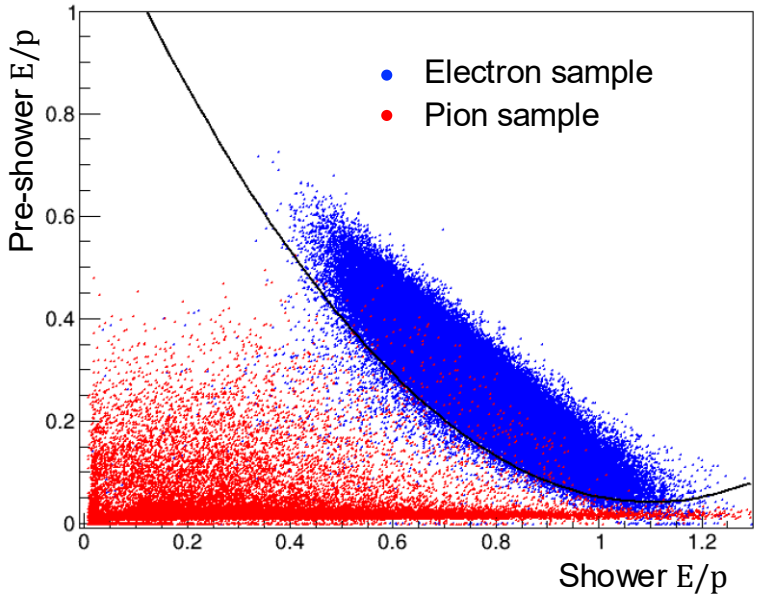
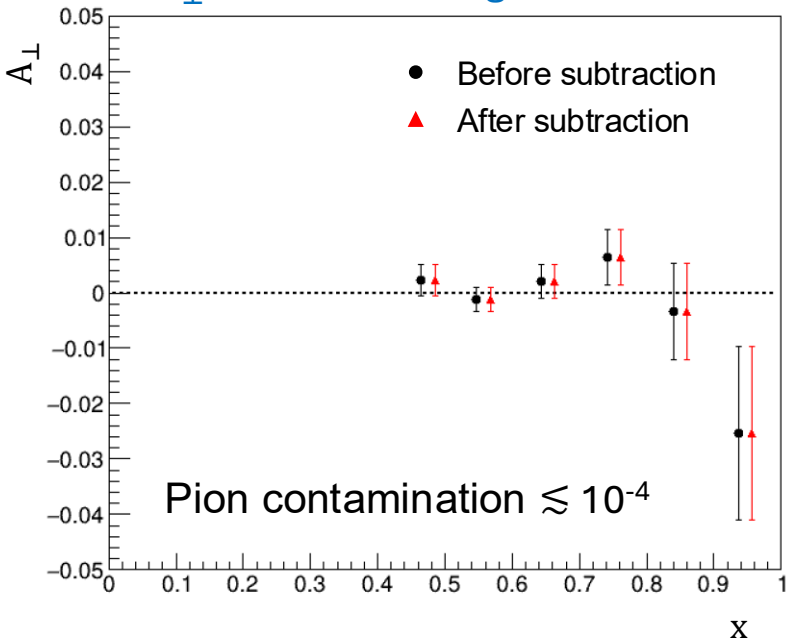


e/π separation



$A_\perp$ before/after Bkg. subtraction



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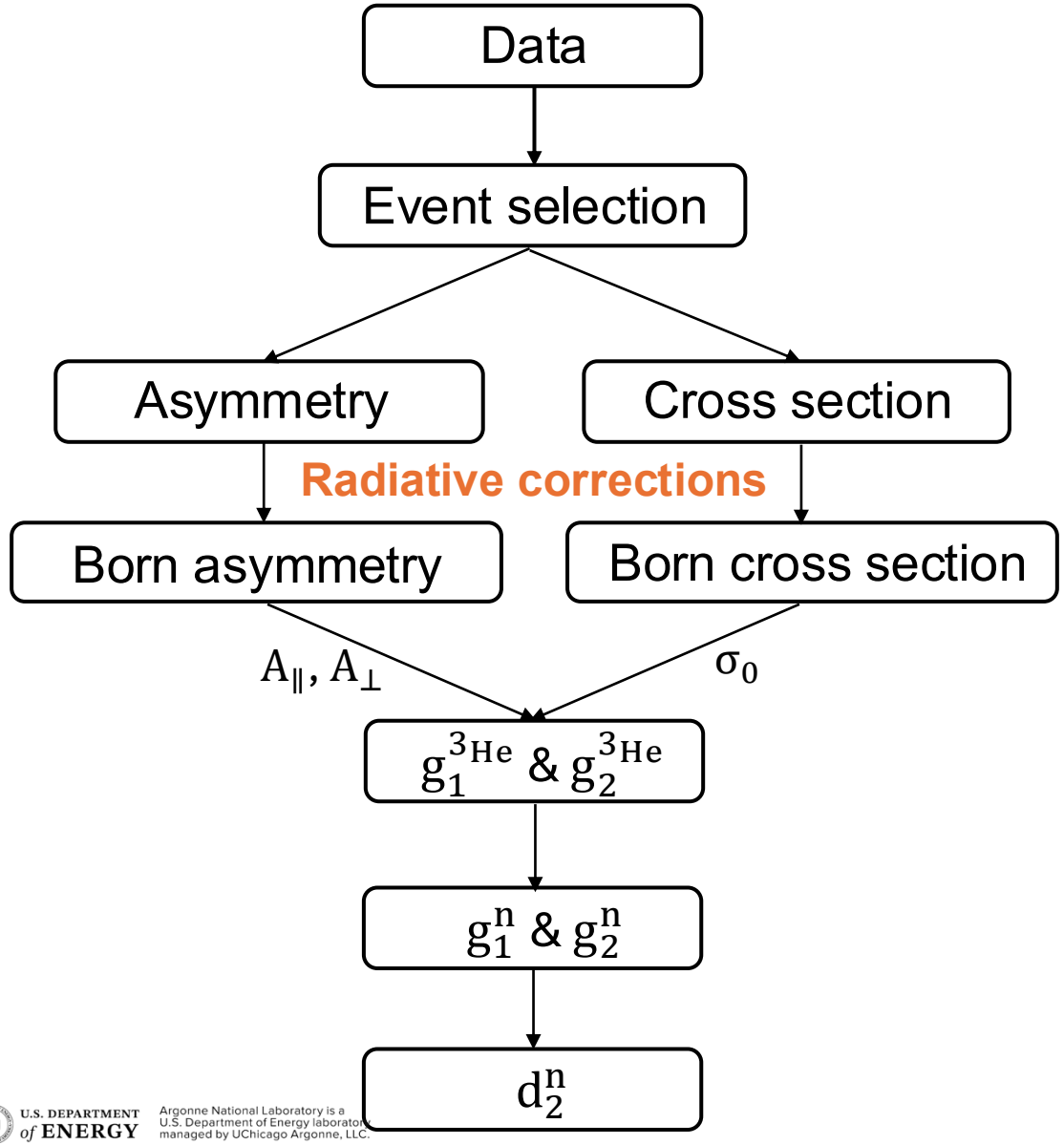
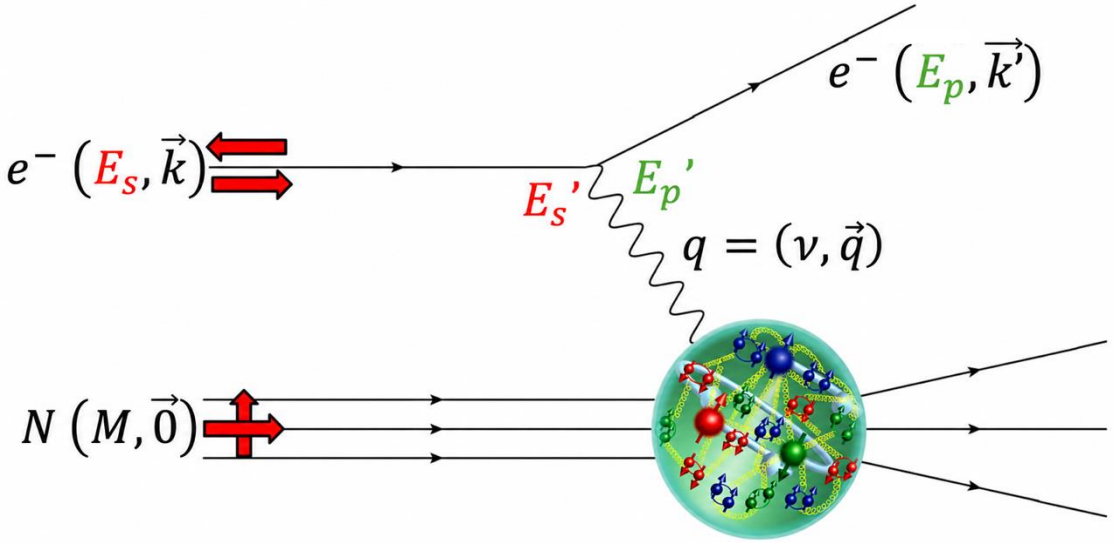
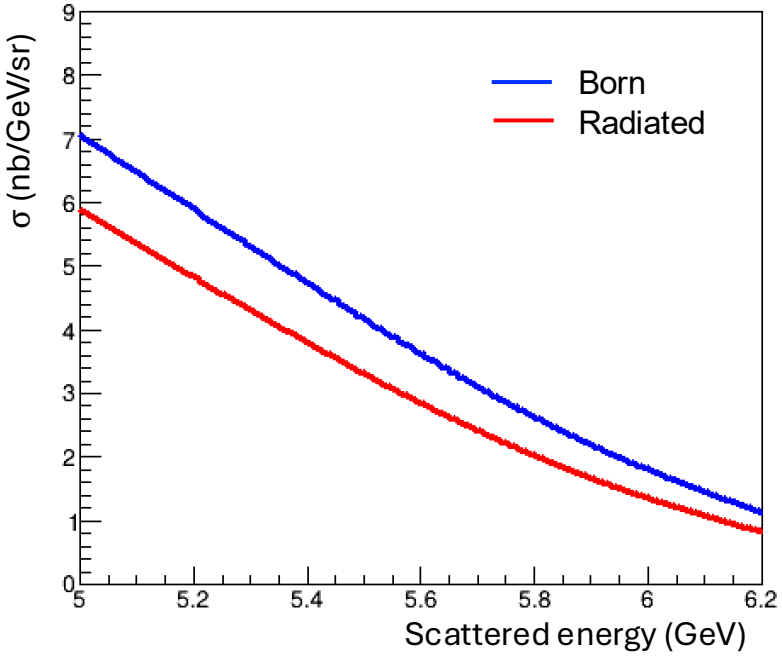
Analysis flow





Born & Radiated cross sections



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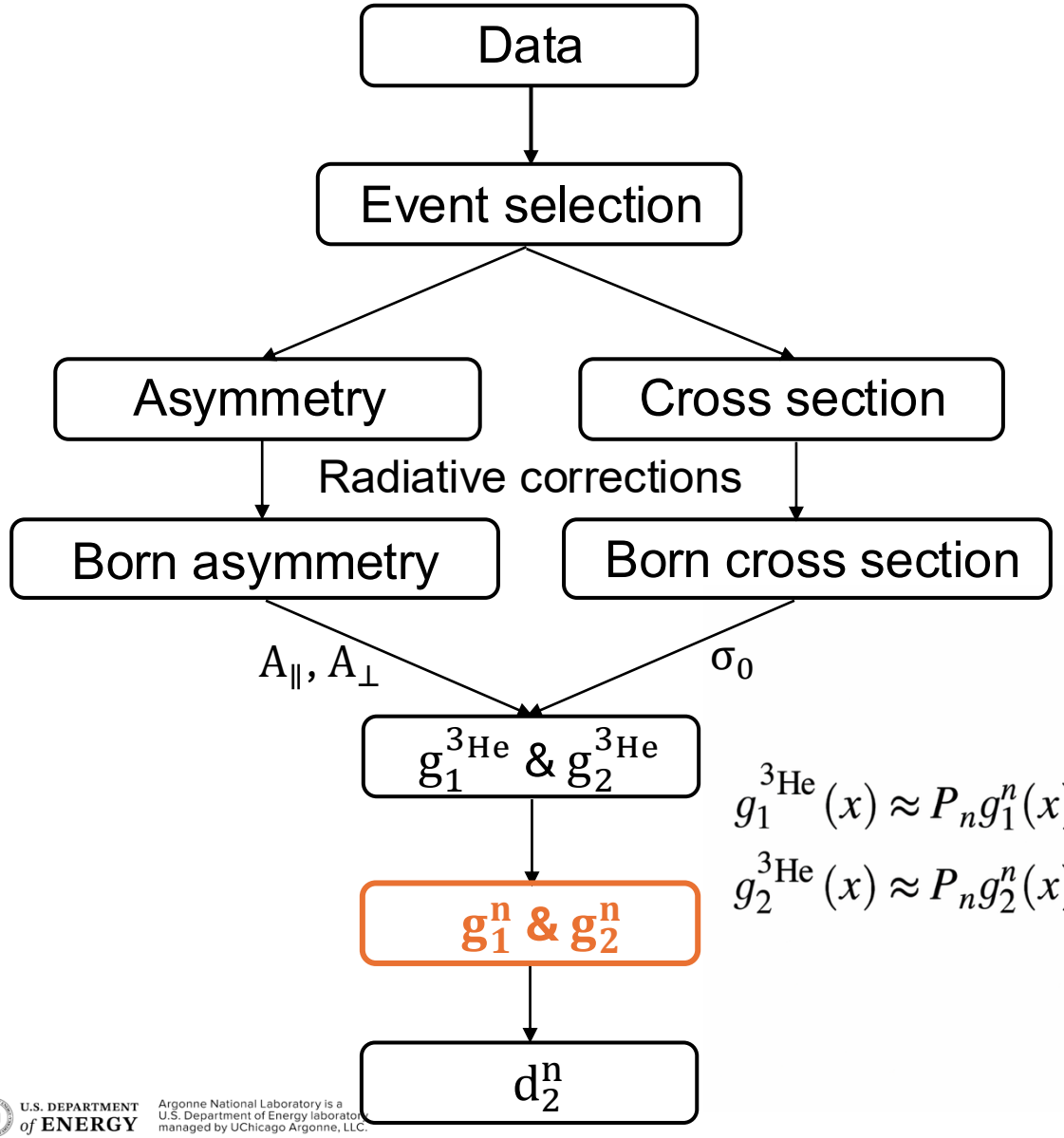
Analysis flow



$$g_1^{^3\mathrm{He}}(x) \approx P_n g_1^n(x) + 2P_p g_1^p(x) - 0.014\left[g_1^p(x) - 4g_1^n(x)\right]$$

$$g_2^{^3\mathrm{He}}(x) \approx P_n g_2^n(x) + 2P_p g_2^p(x) - 0.014\left[g_2^p(x) - 4g_2^n(x)\right]$$

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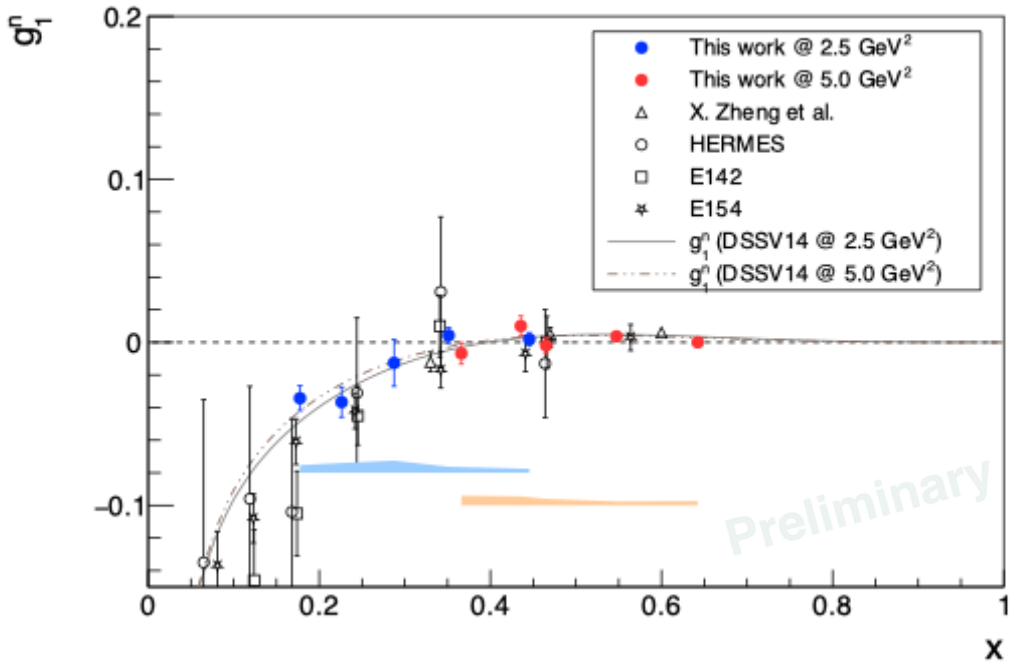
g_1^n results



- Systematic uncertainties due to beam and target polarizations, analysis cuts, and radiative corrections were included.
- Our g_1^n results are consistent with the previous measurements and model predictions.
- No higher-twist effect was observed in g_1^n as expected.

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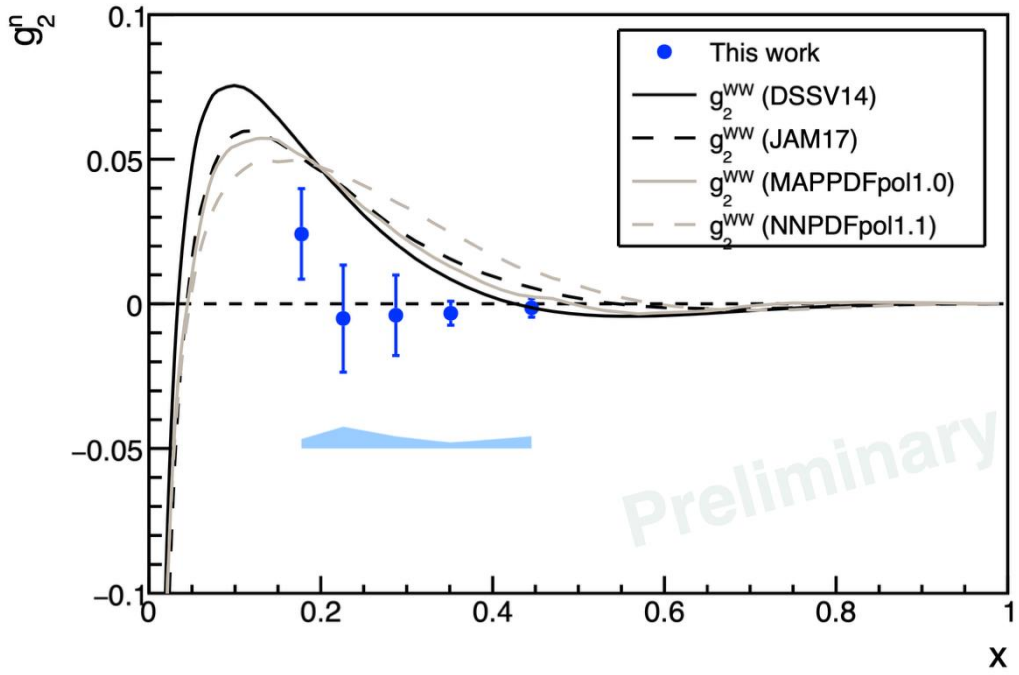
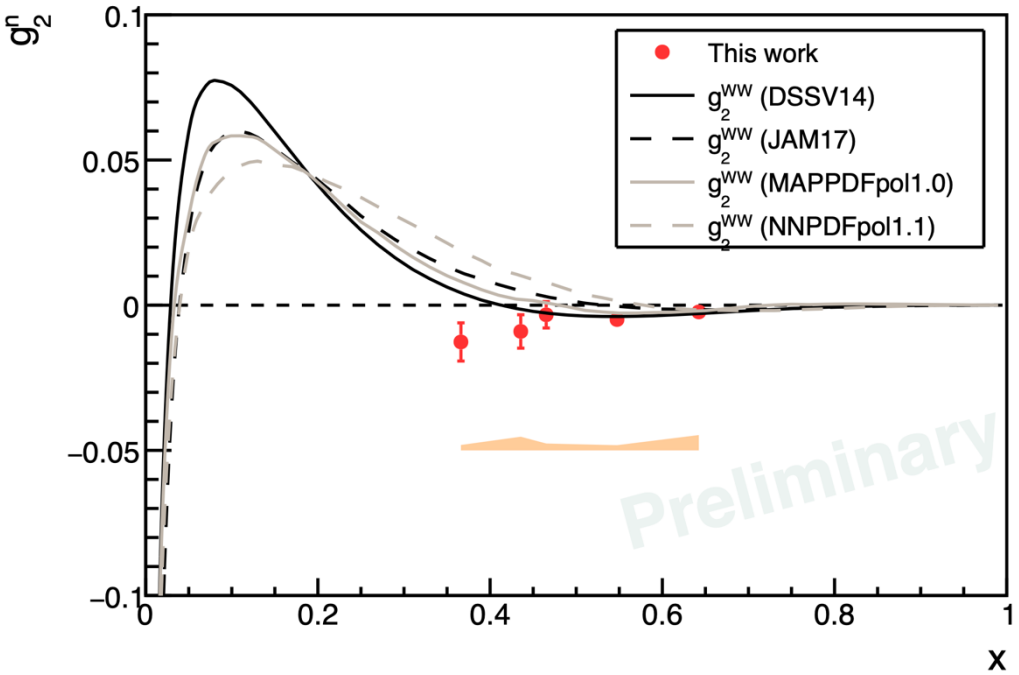
g_2^n results

$\langle Q^2 \rangle = 2.5\ GeV^2$



$\langle Q^2 \rangle = 5.0\ GeV^2$



- In $x > 0.4$, g_2^n is consistent with g_2^{WW}.
- However, in $x < 0.4$, data seems to show a negative deviation from g_2^{WW} at intermediate Q^2, and even at high Q^2.

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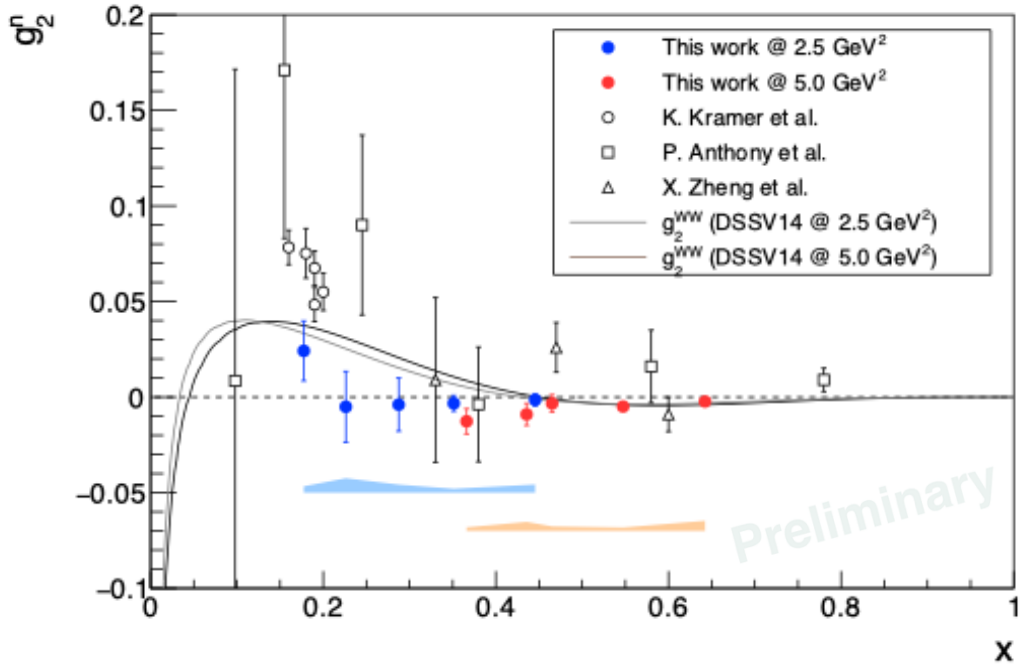
g_2^n results



- At low Q^2, g_2^n shows a positive deviation from g_2^{WW}. However, as Q^2 increases, the data appear to suggest a negative deviation.
- Our results will significantly improve the world g_2^n data at intermediate and high Q^2.

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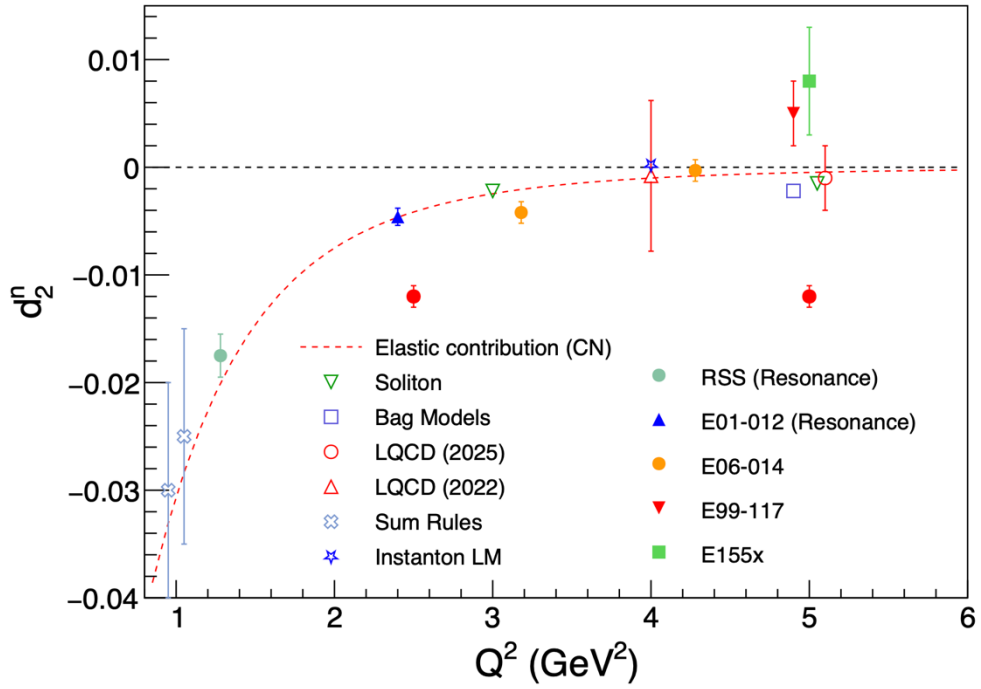
Projected statistical uncertainty for d_2^n



- We will also provide precise d_2^n values at intermediate and high Q^2.
- The statistical uncertainties indicate that d_2^n can be extracted with high precision.

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Summary

- We can study the quark-gluon correlation inside the nucleon by measuring g_2^n and d_2^n.
- To measure the g_2^n and d_2^n values precisely at intermediate and high Q^2, we measured polarized electron-^{3}He scattering over the broad x range at two nearly constant Q^2.
- We are first completing the data analysis at DIS region.
  - The g_1^n results are consistent with the previous measurements and model predictions.
  - The g_2^n values appear to show negative deviations from g_2^{WW}.
- The precise d_2^n values will also be extracted.

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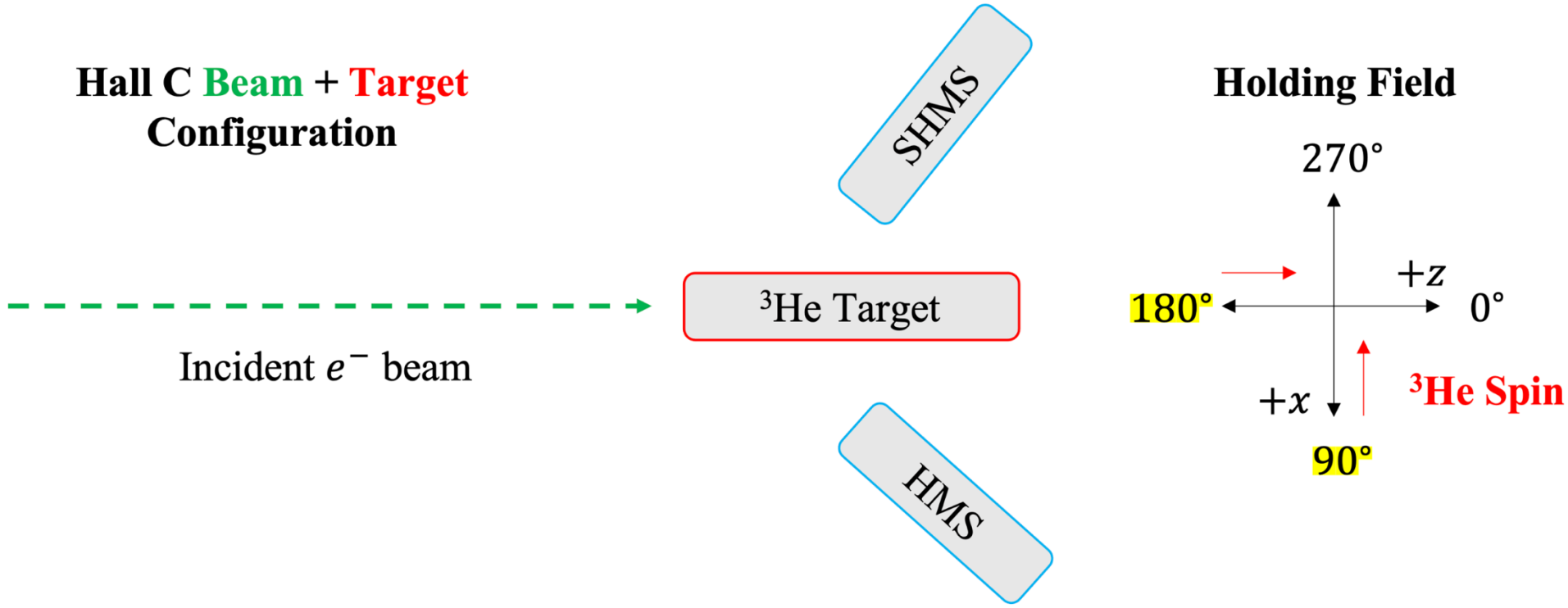
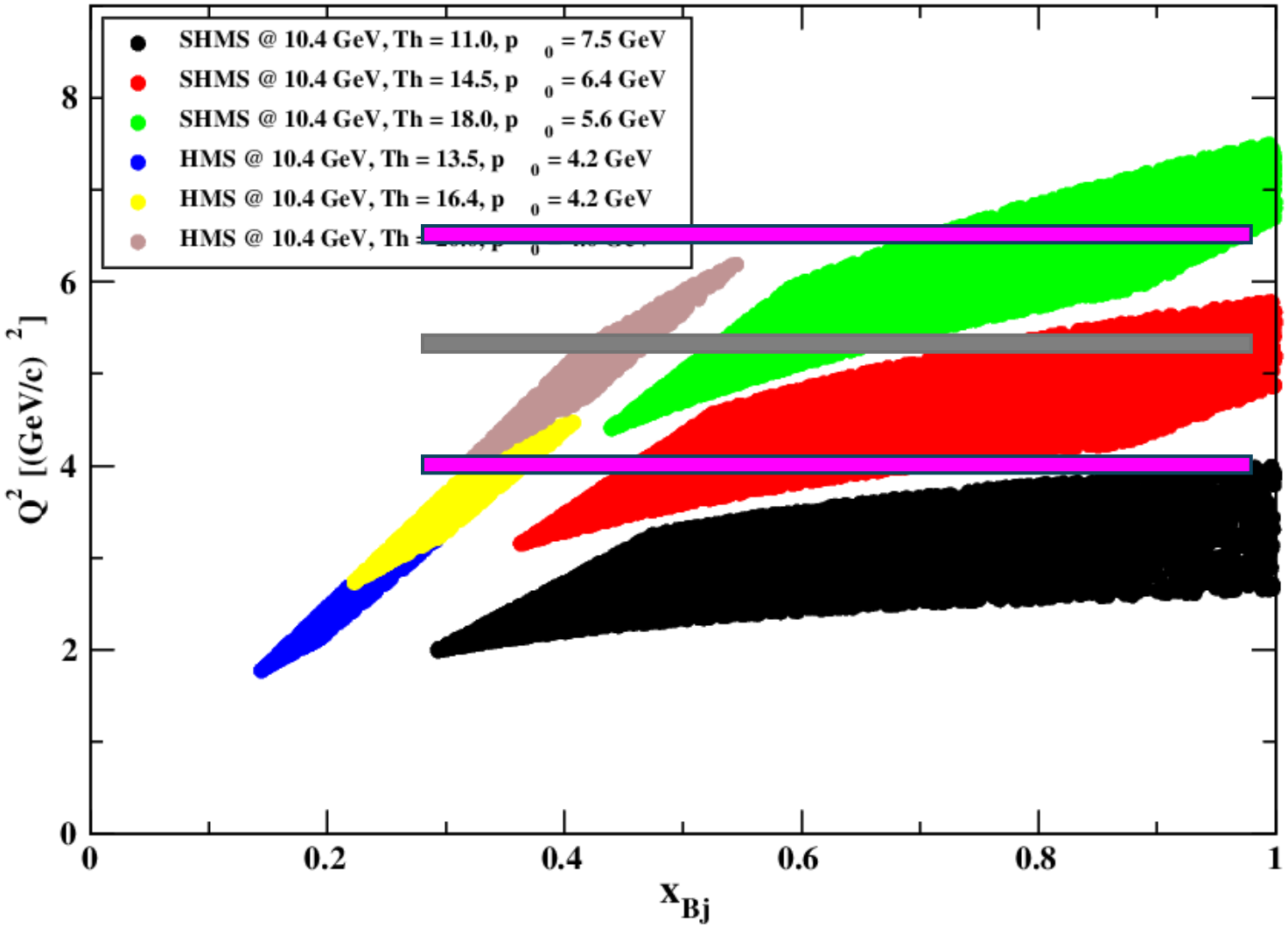
Backup

Spin directions



Original plan at proposal



	HMS		
	Setting	P_0(GeV/c)	Angle(°)
✓	A	4.2	13.5
✗	B	4.2	16.4
✓	C	4.0	20.0

	SHMS		
	Setting	P_0(GeV/c)	Angle(°)
✓	X	7.5	11.0
✗	Y	6.4	14.5
✓	Z	5.6	18.0

SHMS & HMS

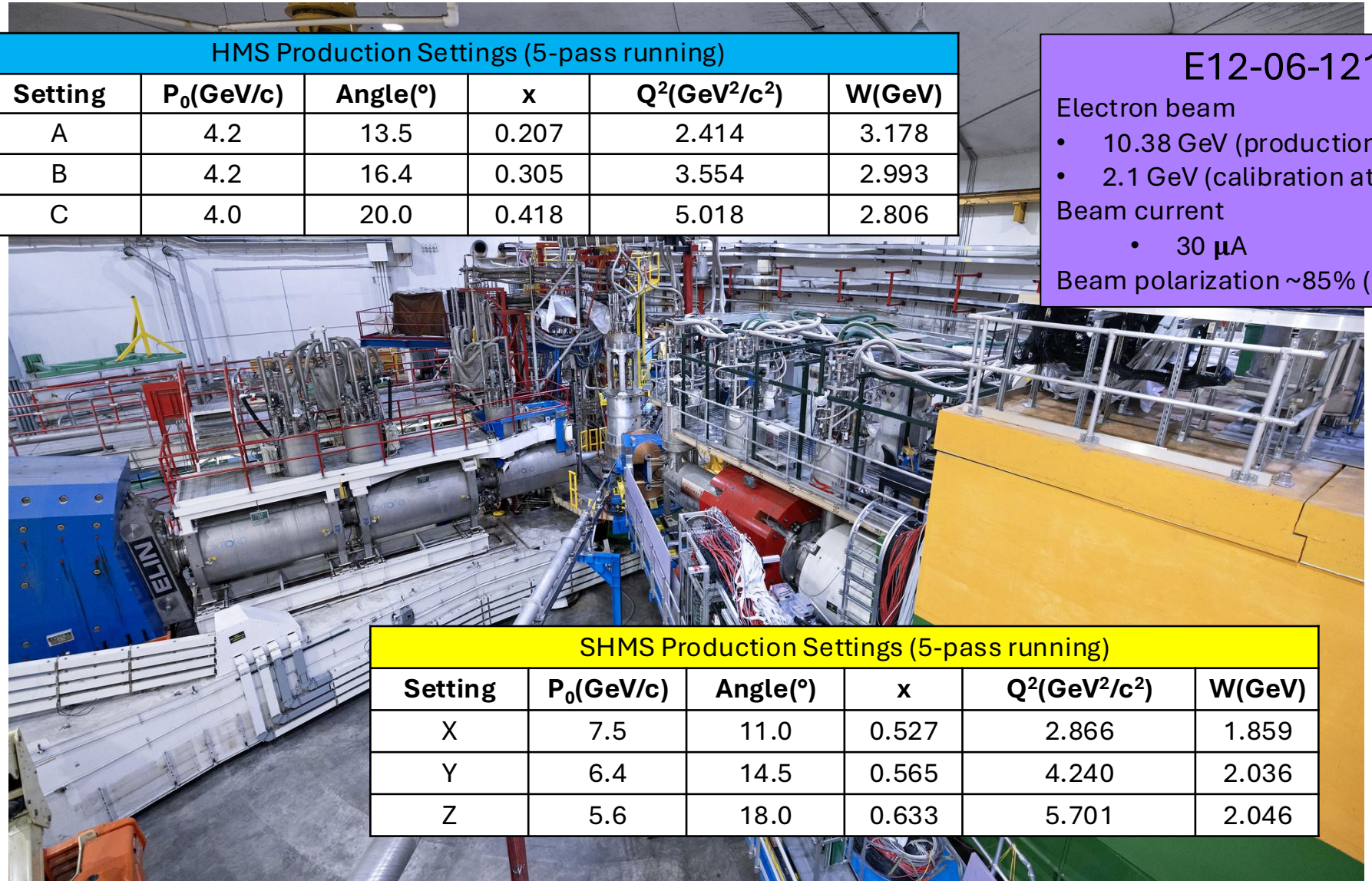
HMS Production Settings (5-pass running)					
Setting	**P_0(GeV/c)**	**Angle(°)**	**x**	**Q^2(GeV^2/c^2)**	**W(GeV)**
A	4.2	13.5	0.207	2.414	3.178
B	4.2	16.4	0.305	3.554	2.993
C	4.0	20.0	0.418	5.018	2.806

E12-06-121 d2n

Electron beam
- 10.38 GeV (production at 5 pass)
- 2.1 GeV (calibration at 1 pass)

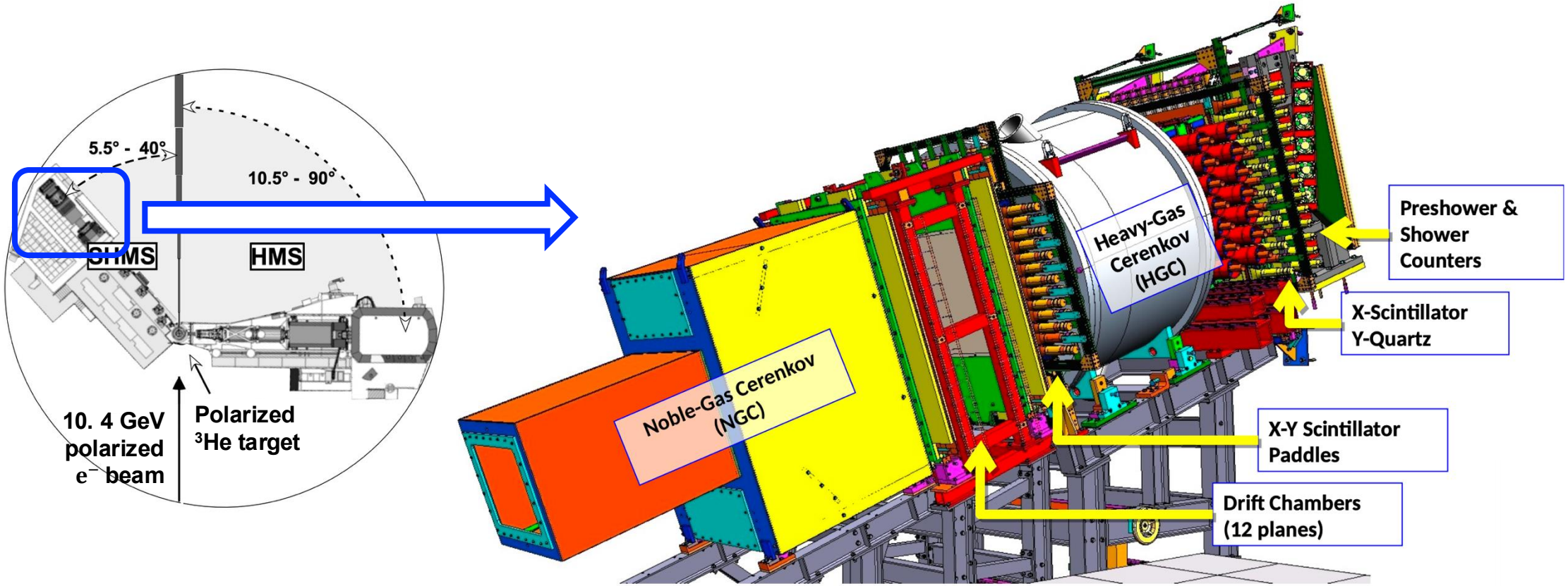
Beam current
- 30 μA

Beam polarization ~85% (3% accuracy)



SHMS Production Settings (5-pass running)					
Setting	**P_0(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

Super High Momentum Spectrometer (SHMS)



- The Cherenkov counters and EM calorimeters separate scattered electrons from pion and kaon background.
- The drift chambers provide the tracking information.
- The hodoscopes provide the trigger and timing information.

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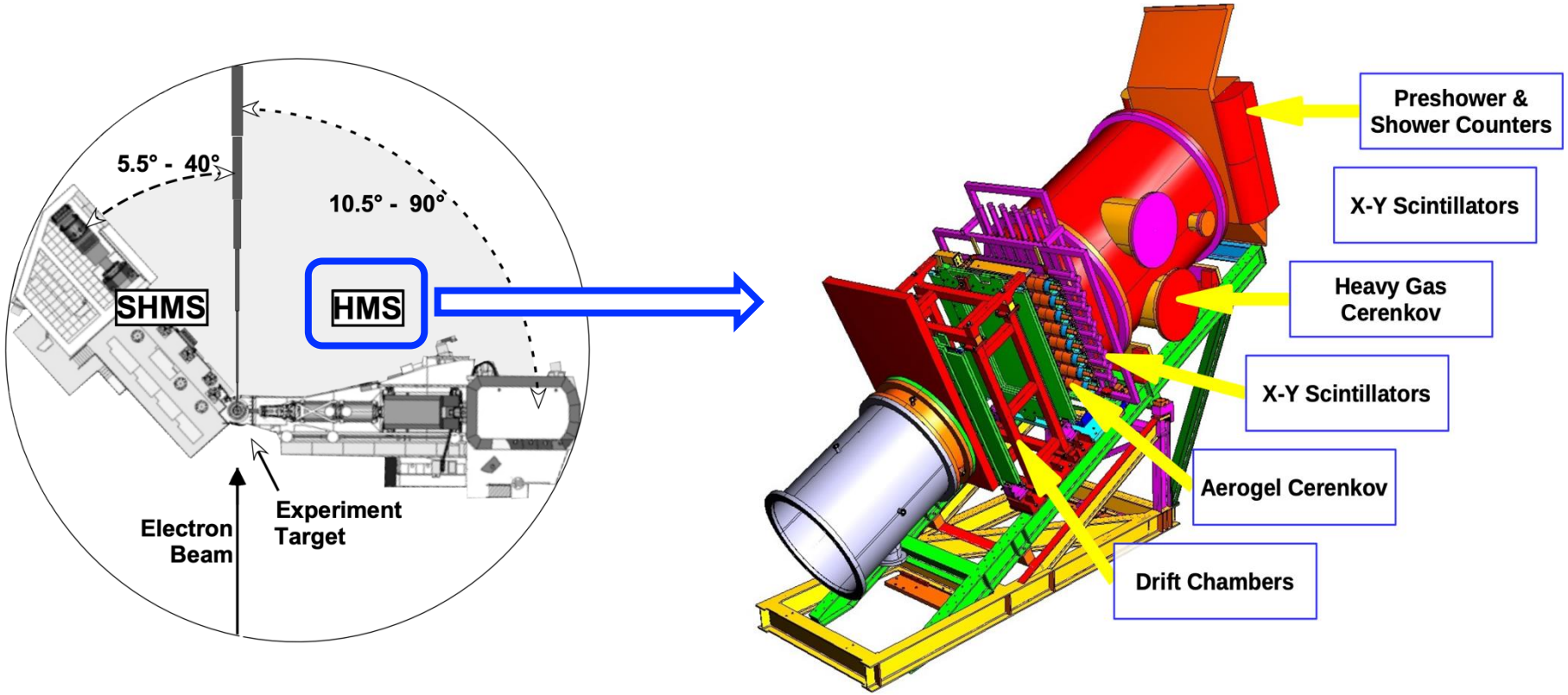
High Momentum Spectrometer (HMS)



- The two hodoscope planes provide the trigger for data acquisition, reference time, and ToF.
- The drift chamber provides the tracking information to reconstruct the particle momentum.
- The Aerogel Cherenkov detector and the lead-glass calorimeters are also used for PID.

Target & Polarization

How to polarize ^{3}He

^{85}Rb

↓ Optical pumping

^{85}Rb (e^--polarized)

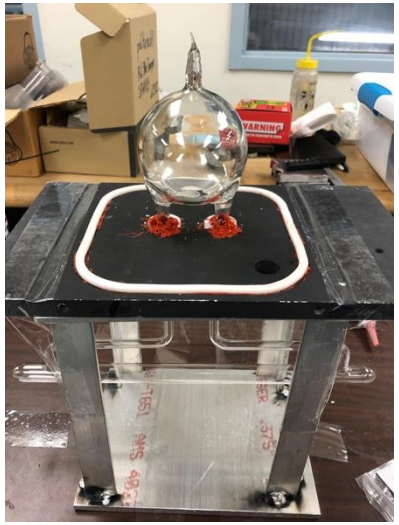
↓ Spin exchange

^{39}K (e^--polarized)

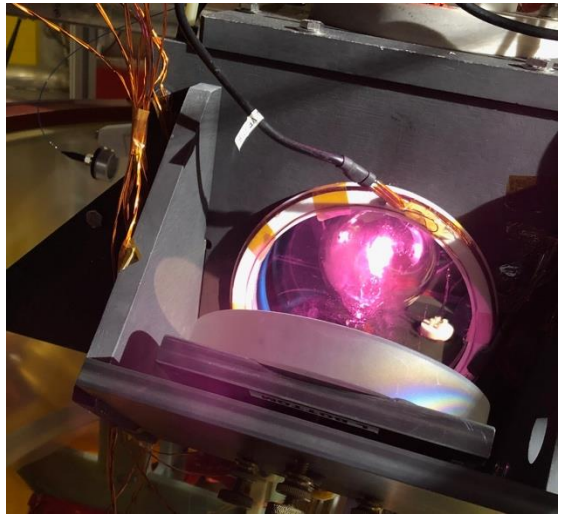
↓ Spin exchange

Polarized ^{3}He

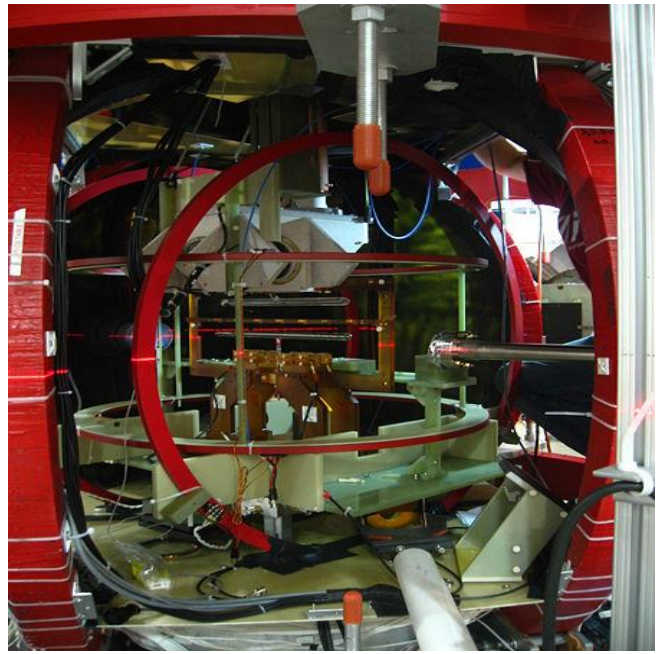
Target cell



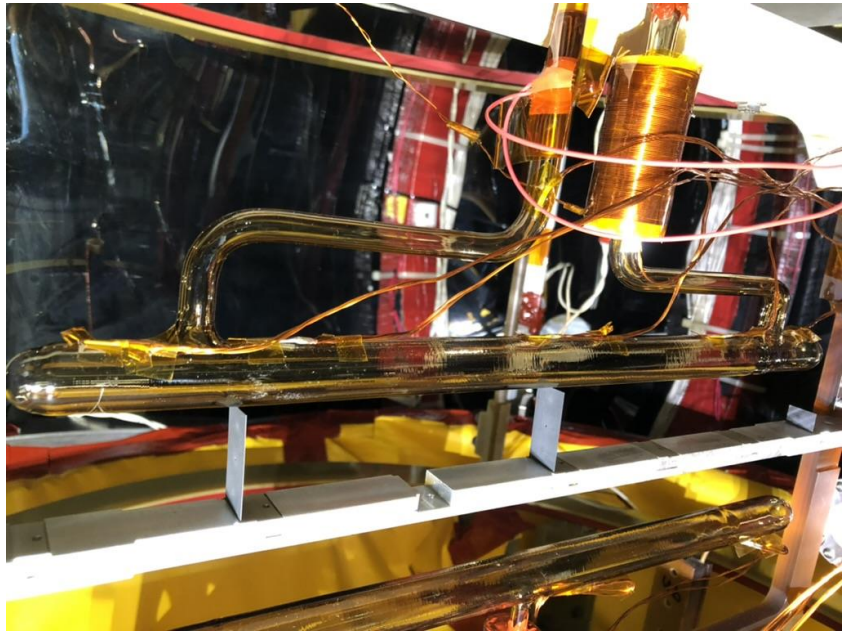
Target oven



Target system



Side view



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