A High Precision 5 MeV Mott Polarimeter

Jefferson Lab Mott Team

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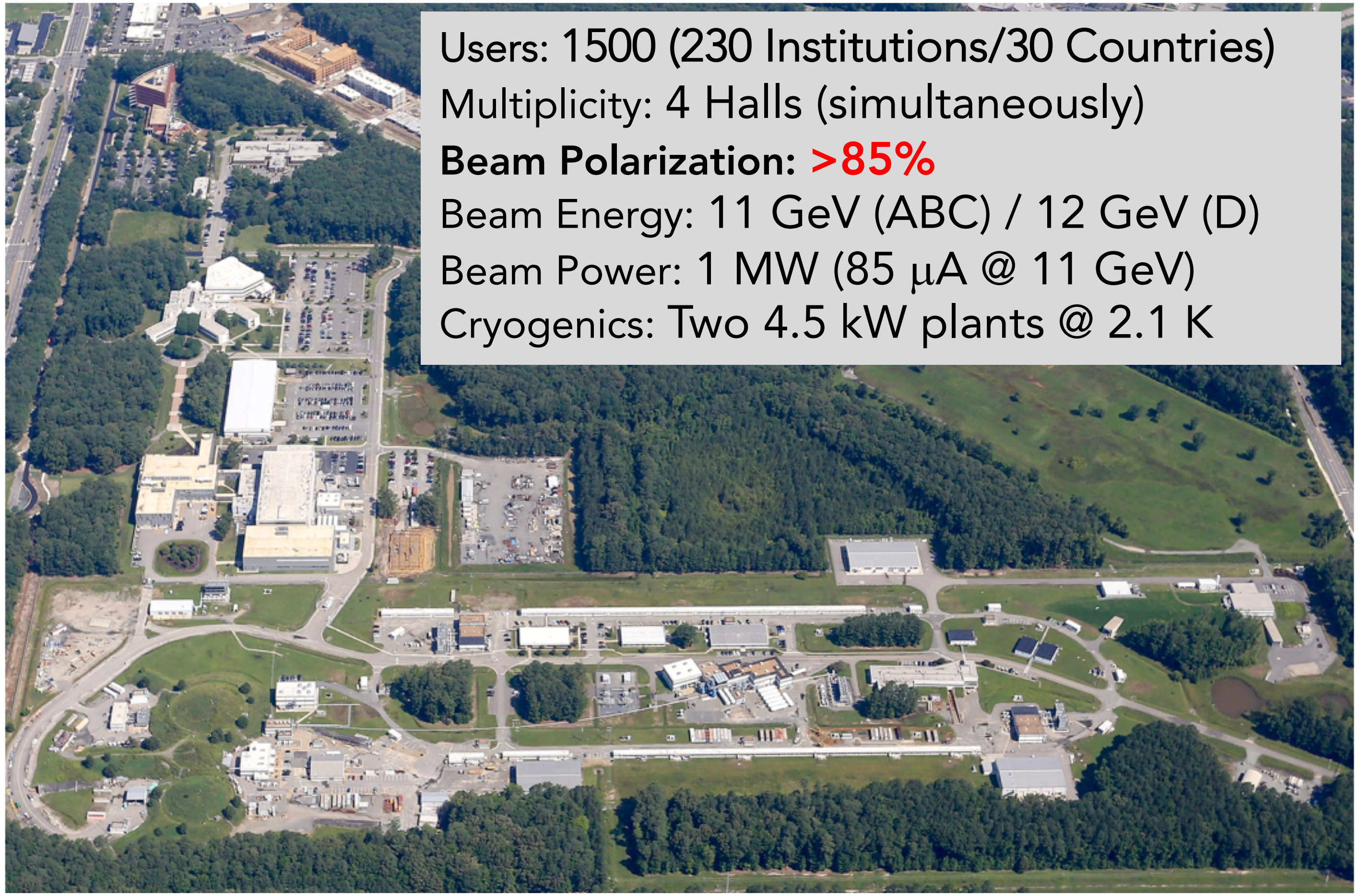
SPIN2021, 17-22 October 2021, Matsue, Japan

CEBAF @ Jefferson Lab

Many of the highest impact experiments performed at Jefferson Lab have relied on spin-polarized electron beams.



Users: 1500 (230 Institutions/30 Countries)
Multiplicity: 4 Halls (simultaneously)
Beam Polarization: >85%
Beam Energy: 11 GeV (ABC) / 12 GeV (D)
Beam Power: 1 MW (85 μA @ 11 GeV)
Cryogenics: Two 4.5 kW plants @ 2.1 K

HAPPEX – Nucleon strangeness
K.A. Aniol, et al., Phys. Rev. C **69,** 065501 (2004)
K.A. Aniol, et al., Phys. Lett. B **635**, 275 (2006)
K.A. Aniol, et al., Phys. Rev. Lett. **96**, 022003 (2006)

G^0 – Nucleon strange quark distribution
D. S. Armstrong, et al., Phys. Rev. Lett. **95**, 092001-1-5 (2005)

Q_{weak} – Test of the Standard Model
D. Androic, et al., Phys. Rev. Lett. **111**, 141803 (2013)

G_E/G_M – Proton electric/magnetic factor
A. J. R. Puckett, et al., Phys. Rev. C **96** (2017) 055203

PREx – Lead Radius Experiment
C. Horowitz, et al., Phys. Rev. C **63**, 025501 (2001)
See D. Jones' talk at this conference

CREx – Calcium weak Radius Experiment
See Y. Tian's talk at this conference

High energy electron polarimeters at CEBAF

Unsurprisingly **electron polarimetry is a very important technology** at Jefferson Lab, and there are many polarimeters.

Table 6. Møller polarimeters.

Polarimeter	Beam energy (GeV)	Arms	Optics	$(dP/P)_{syst}$ Target	Full
SLAC[60]	48	1	D	1.7%	2.7%
SLAC[61]	16, 29	2	D	2.3%	2.4%
MAMI[57]	0.850	2	Q	2.0%	9.0%
MAMI[16,68]	0.850–1.50	2	D	0.6%	1.6%
Bates[58]	0.250, 0.574	1	Q	1.25%	6.0%
Bates[59]	0.868	2	Q	1.5%	2.9%
ELSA[69]	1.0–3.3	2	D	1.9%	2.0%
JLab, A[70]	0.85–6	2	QQD	1.5%	1.7%
JLab, A[70]	0.85–6	2	QQD	0.35%	0.9%
JLab, B[71]	0.85–6	2	QQ	1.4%	3.0%
JLab, C[65] (ideal)	0.85–6	2	QQ	0.3%	0.5%
JLab, C[72] (Q-Weak)	1.16	2	QQ	0.3%	0.8%

Table 8. Comparison of properties and systematic uncertainties of high precision Compton polarimeters (SLD,[86,106] JLab Hall A[103] and JLab Hall C[82]).

	SLD	Hall A (photon)	Hall C (electron)
Properties			
Beam energy	45.6 GeV	3 GeV	1.16 GeV
Endpoint A_{long}	74.7%	5.21%	4.06%
Laser system	532 nm, pulsed	1064 nm, FP cavity	532 nm, FP cavity
Detector	Cherenkov	GSO	Diamond strip
Scheme	Multiphoton	Integrating	Differential
Uncertainties		dP/P (%)	
Laser polarization	0.10	0.80	0.18
Detector response (linearity, gain)	0.20	0.48	0.1
Analyzing power determination	0.40	0.13	0.27
DAQ and electronics related	0.20	N/A	0.48
Total	0.50	0.94	0.59

MOLLER (0.8 – 3.0 %)

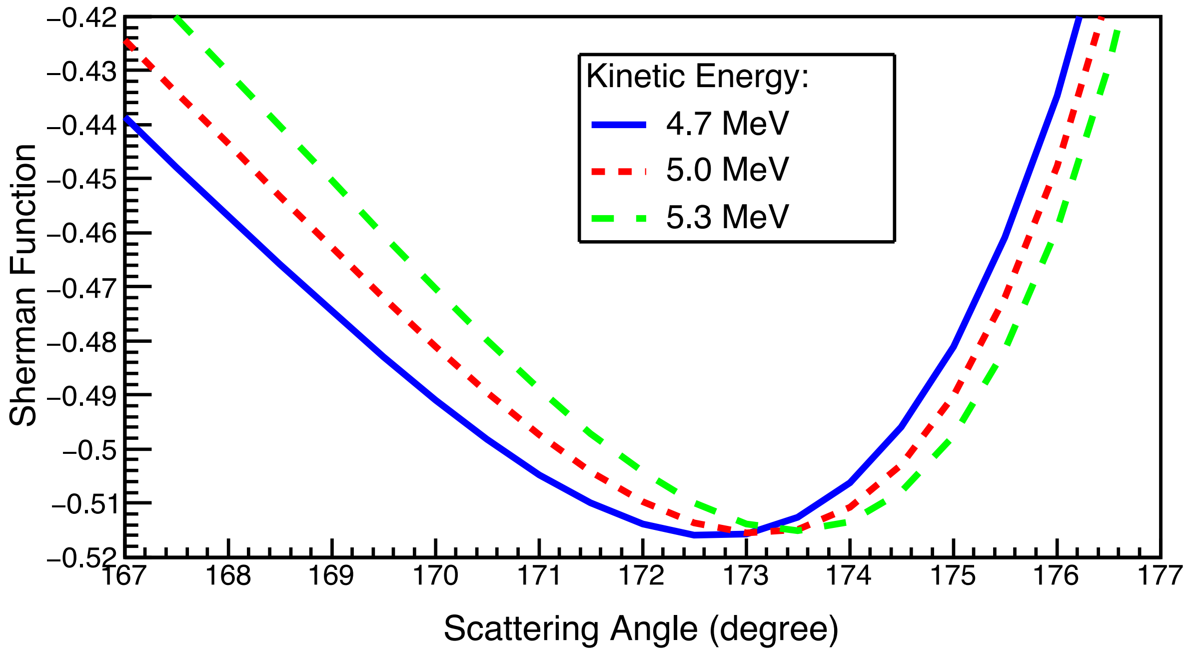
COMPTON (0.59 – 0.94 %)

K. Aulenbacher, E. Chudakov, D. Gaskell, J. Grames, and K.D. Paschke, "*Precision electron beam polarimetry for next generation nuclear physics experiments*", International Journal of Modern Physics E, **27**, 7 (2018)

Injector MeV energy Mott scattering polarimeter

Mott polarimetry exploits **elastic scattering asymmetry** of spin polarized electrons from nuclear Coulomb field.

$$\sigma(\theta) = I(\theta)\,[1 + S(\theta)\mathbf{P}\cdot\mathbf{n}]$$

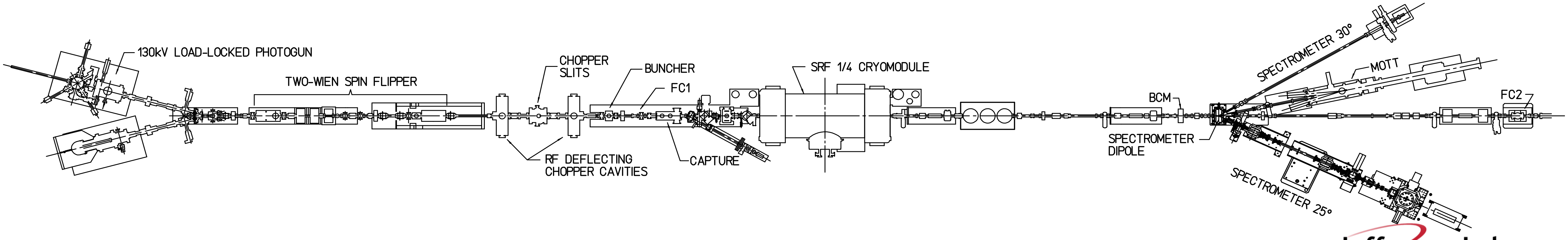


Benefits of MeV energy Mott

- Larger analyzing power
- Smaller cross-section
- Free standing targets
- Systematics suppressed (more on this later)

Historical JLab performance

- Measuring spin-polarization of photocathodes
- Calibrating injector spin rotators
- Study from 2000 reported 1.1% accuracy (conservatively 1-2%)



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High accuracy Mott polarimetry

The **dominant uncertainty** in the measured **parity-violating asymmetry** in the scattering of longitudinally polarized electrons from nuclear or electron targets is on the **beam polarization**.

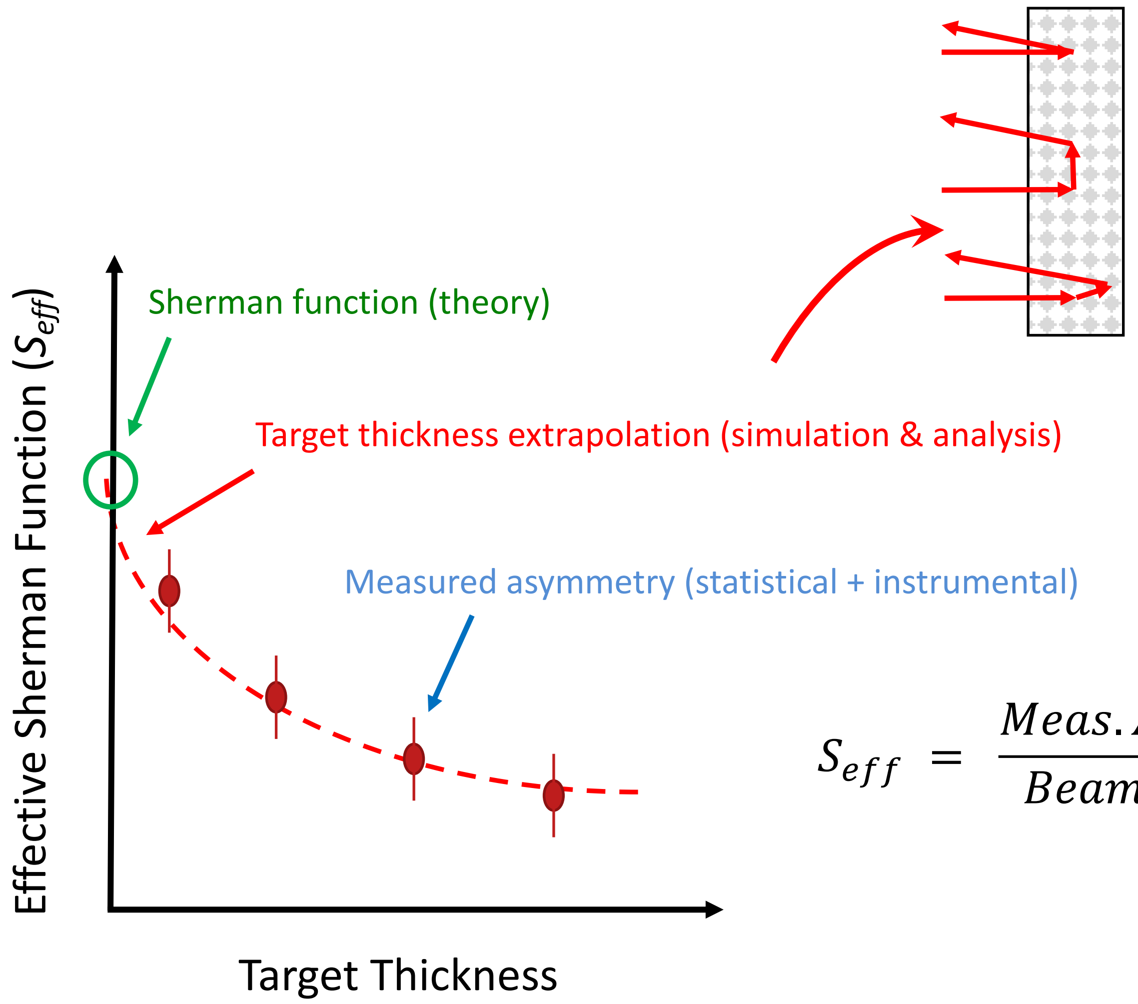
Next generation of parity-violations experiments are significantly more challenging, with polarimetry requirements **below 1%**, but as **low as 0.3 – 0.5 %.**

- **Moller**: e^- - H (JLab)
- **P2**: e^- - H (MESA)
- **SoLID/PV-DIS**: e^- - ^{2}H (JLab)

In support of JLab's mission to achieve **<0.5% accuracy** we embarked on a multi-year strategy to test our 5 MeV Mott polarimeter.

Our strategy for a precision of the MeV energy Mott polarimeter

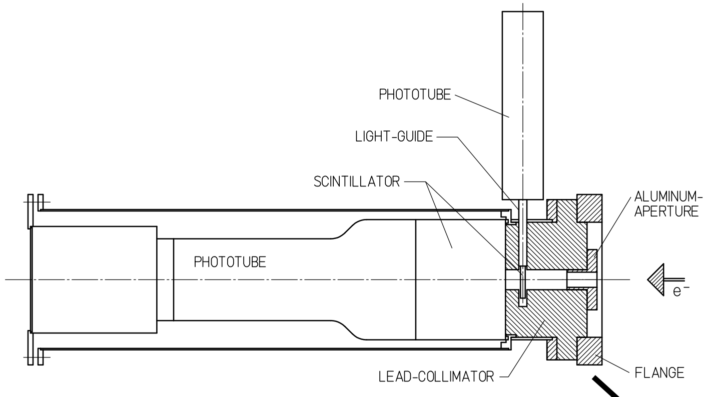
1. Careful selection of elastic events originating only from the target
2. Precise characterization of beam and instrumental uncertainties
3. Improving extrapolation to a single-atom of zero thickness
4. Modern arguments on the single-atom Sherman function
5. Test what we learned with further techniques & measurements



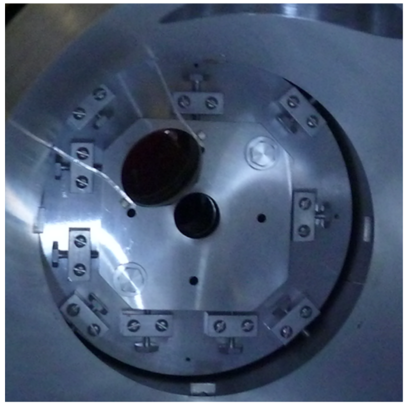
$$S_{eff} = \frac{Meas.Asym.}{Beam\ Pol.}$$

Step 1 – Improve and prepare Mott scattering chamber

Checked and repaired each detector package, comprised of both E (e-) and ΔE (photon veto) detector

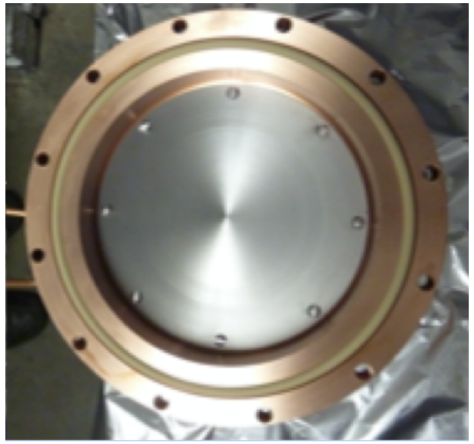


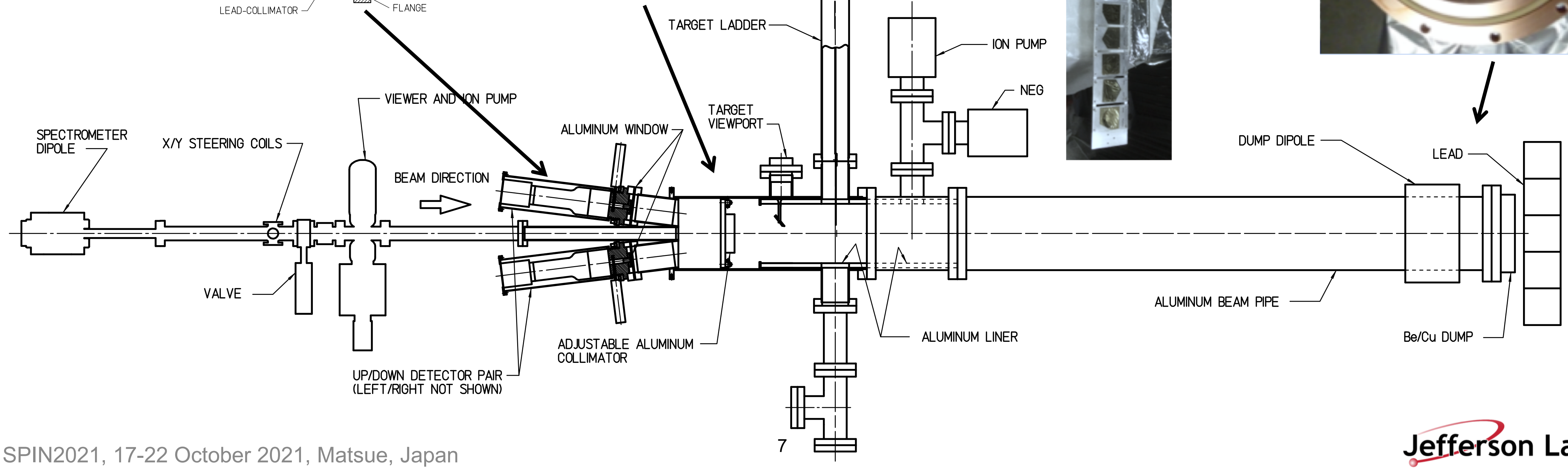
Re-surveyed adjustable collimator system



Loaded 10 gold foils, each with a sibling for thickness measurement

Replaced Al dump with Be plate to reduce e- backscatter and Cu radiator end flange





Step 1 – Improve and prepare Mott scattering chamber

Used **10 foils** used with nominal thicknesses ranging from **50 nm to 1000 nm**, with duplicates at 50 and 350 nm

- Measured thickness of sibling foils (destructive) using Field Emission Secondary Electron Microscopy
- Uncertainties due to FESEM resolution & reproducibility, variation across sample and imaging
- Thickness consistent with vendor (Lebow in Chicago)
- Measurement uncertainty (5%) agrees with vendor siblings

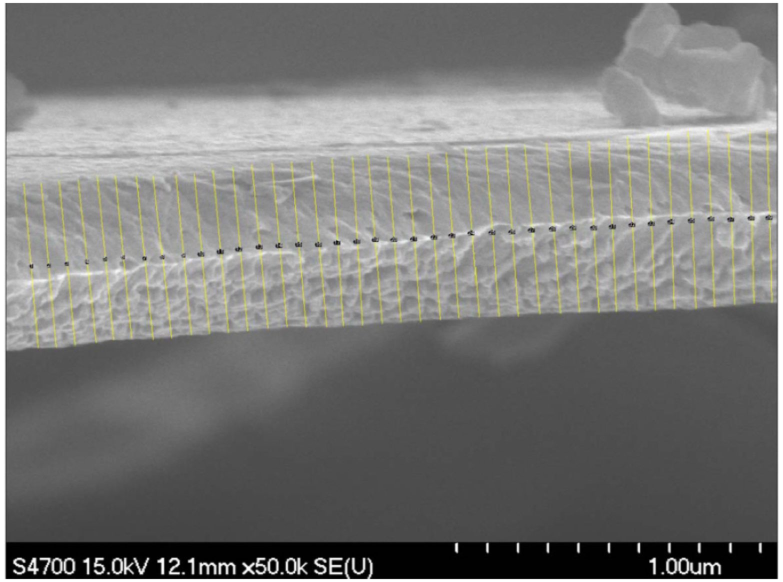
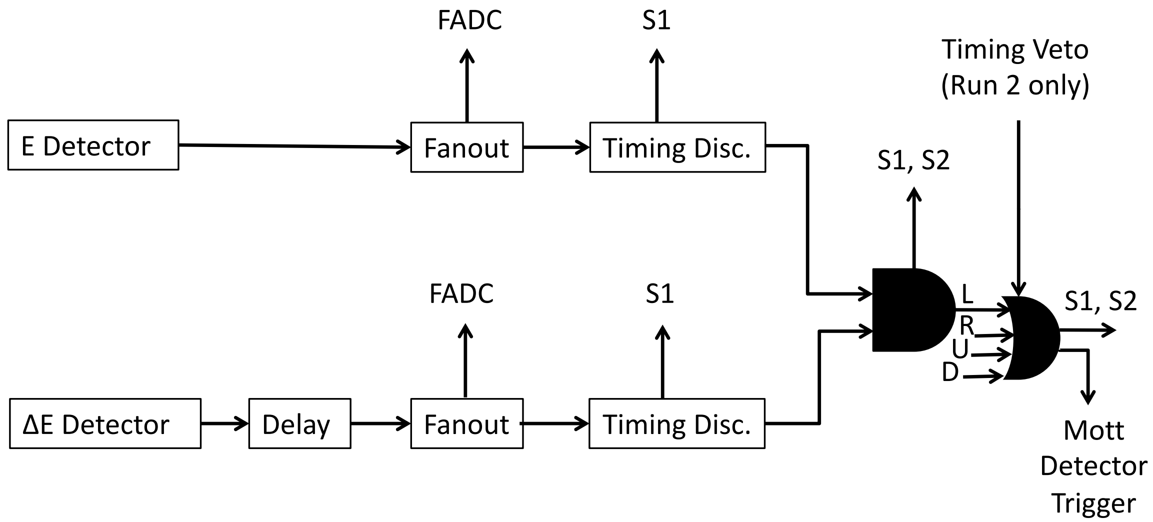


TABLE IV. Summary of purchased target foils and their FESEM measured thicknesses and corresponding uncertainty.

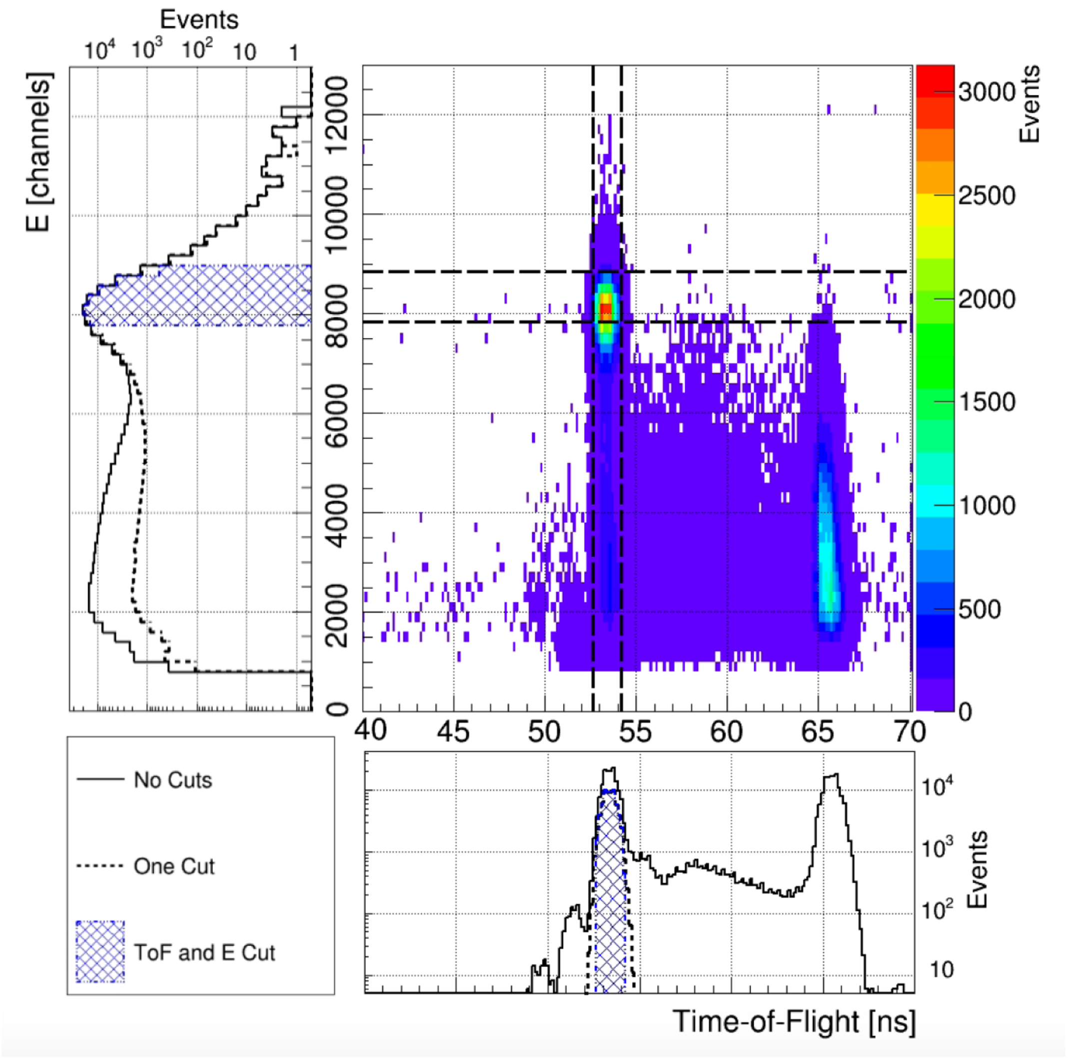
Lebow thickness (nm)	1000	870	750	625	500	355	225	50
FESEM thickness (nm)	943.7	836.8	774.5	561.2	482.0	389.4	215.2	52.0
FESEM uncertainty (nm)	59.8	44.2	41.9	31.0	27.7	22.1	11.7	4.7
Image analysis (nm)	29.0	7.1	9.1	8.0	9.7	4.5	1.9	2.3
FESEM resolution (nm)	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Same image reanalysis (nm)	22.6	12.4	13.3	10.2	9.7	9.2	3.8	2.9
Lebow sibling 5% (nm)	47.2	41.8	38.7	28.2	24.1	19.5	10.8	2.6

Step 1 – Fine tune the Data Acquisition & Analysis Chain



Data acquisition system collects coincidence event data

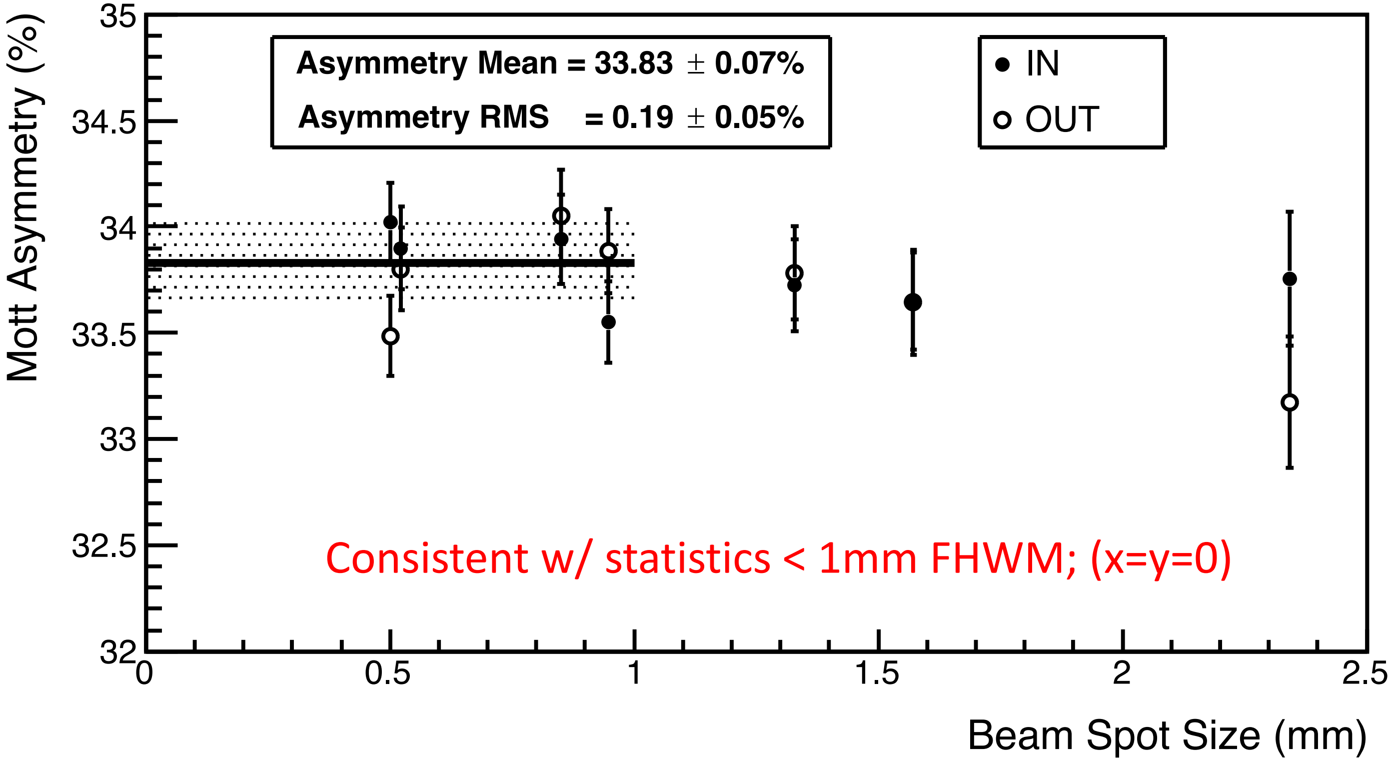
- **Flash ADC** samples energy spectra (<10 kHz)
- **Timing** resolution 34 psec, width of peak 380 psec
- **Beam helicity & current** are sampled, tagged to events
- Event data analyzed off-line in three step process (described in gory detail in PRC article)



Systematic uncertainty 0.1% on Energy and Timing cuts (see PRC article)

Step 2 – Precise characterization of beam and instrumental systematics

- **Sensitivity to beam size**
- Sensitivity to beam position
- Sensitivity to beam current
- Reproducibility
- Slow helicity reversal
- Beam Energy & Acceptance



Step 2 – Precise characterization of beam and instrumental systematics

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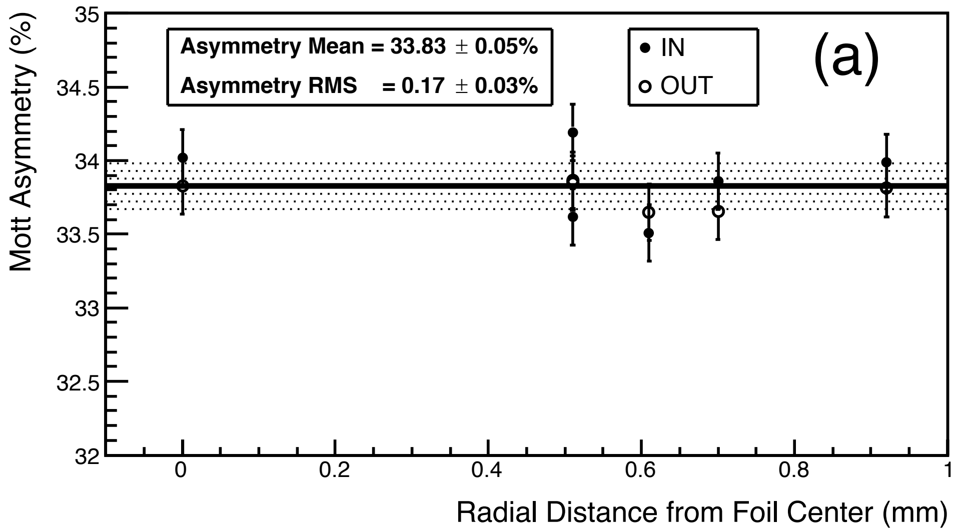
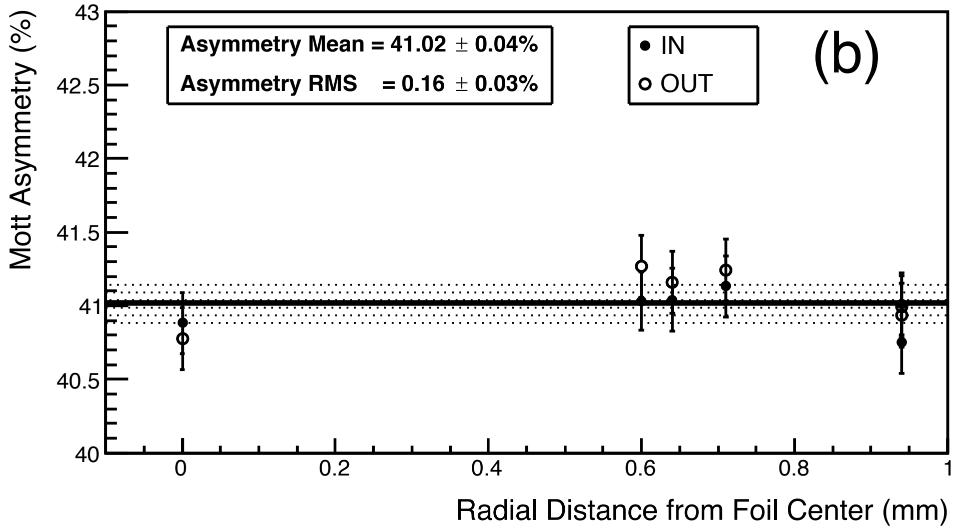
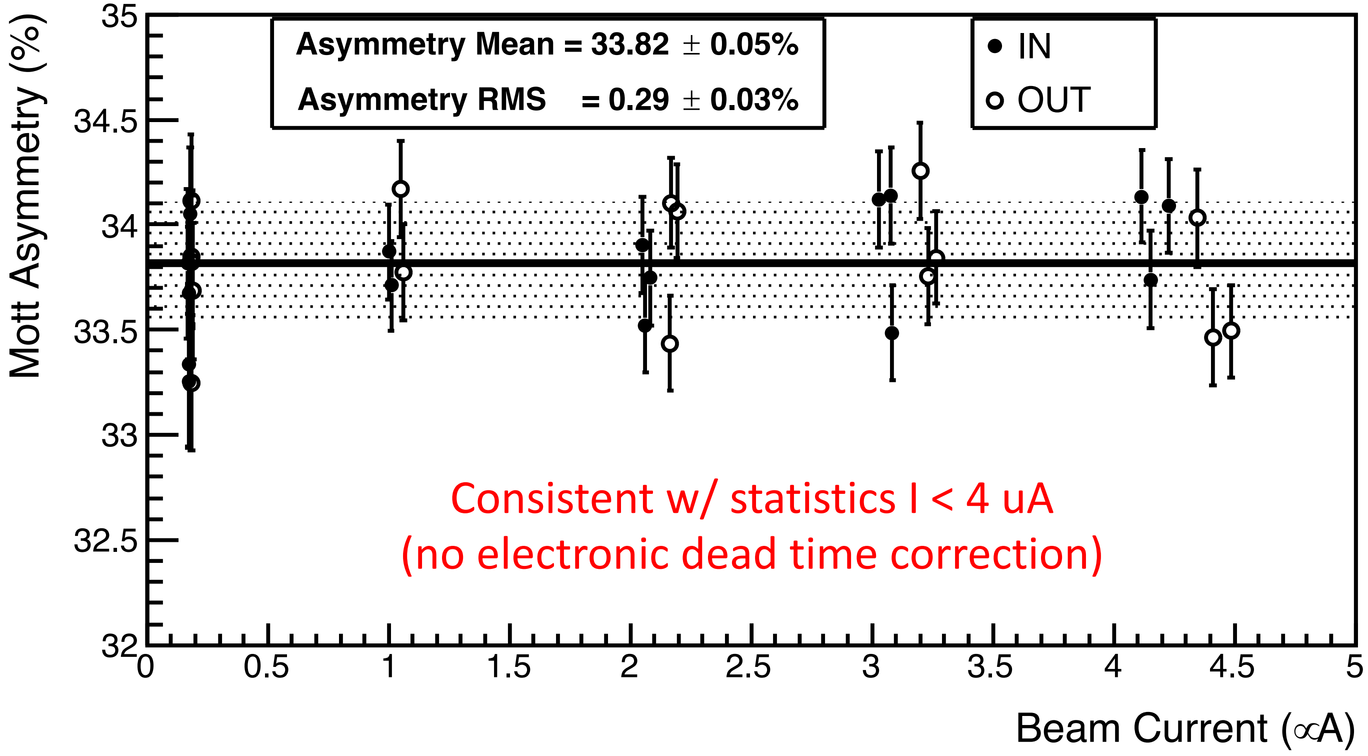


Consistent w/ statistics R < 1mm; (size < 0.5 mm FWHM)



Step 2 – Precise characterization of beam and instrumental systematics

- Sensitivity to beam size
- Sensitivity to beam position
- **Sensitivity to beam current**
- Reproducibility
- Slow helicity reversal
- Beam Energy & Acceptance



Step 2 – Precise characterization of beam and instrumental systematics

- Sensitivity to beam size
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- Sensitivity to beam current
- **Reproducibility**
- Slow helicity reversal
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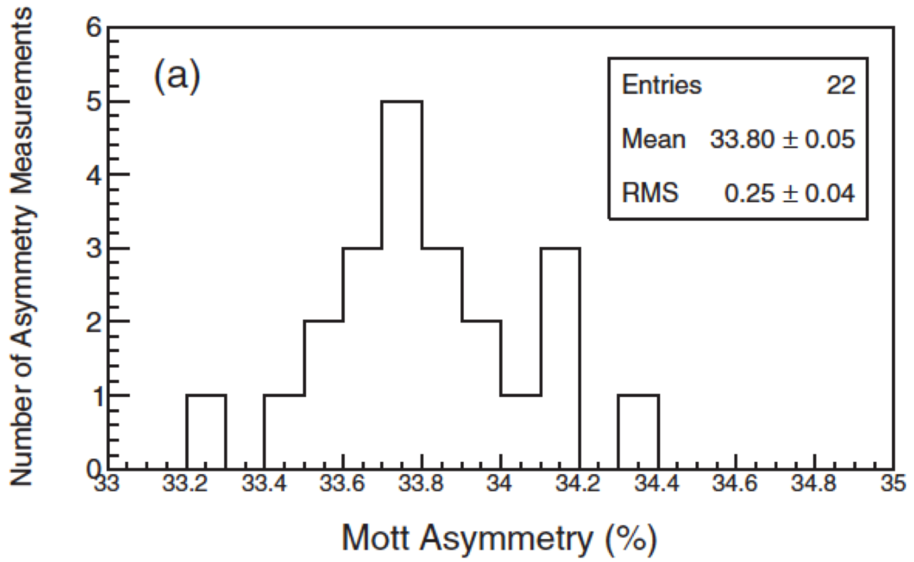
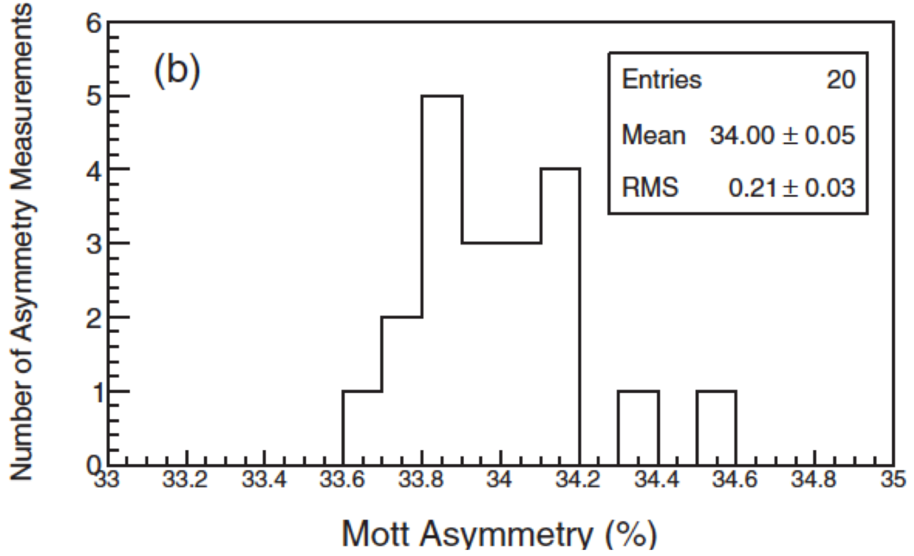


Interleave 1um foil throughout each rum => RMS < run stat. 0.25%



Step 2 – Precise characterization of beam and instrumental systematics

- Sensitivity to beam size
- Sensitivity to beam position
- Sensitivity to beam current
- Reproducibility
- **Slow helicity reversal**
- Beam Energy & Acceptance

Half of data collected with a $\lambda/2$ waveplate IN or OUT.

Statistical ratio for all measurements

Run1	1.0022 +/- 0.0020
Run2	1.0017 +/- 0.0021

Laser polarization >99.8 +/- 0.1 %

Laser polarization systematic uncertainty (0.10%)

Step 2 – Precise characterization of beam and instrumental systematics

- Sensitivity to beam size
- Sensitivity to beam position
- Sensitivity to beam current
- Reproducibility
- Slow helicity reversal
- **Beam Energy & Acceptance**

Beam energies for Runs 1 & 2

Run1	E = 4.806 +/- 0.097 MeV (2.0%)
Run2	E = 4.917 +/- 0.013 MeV (0.3%)

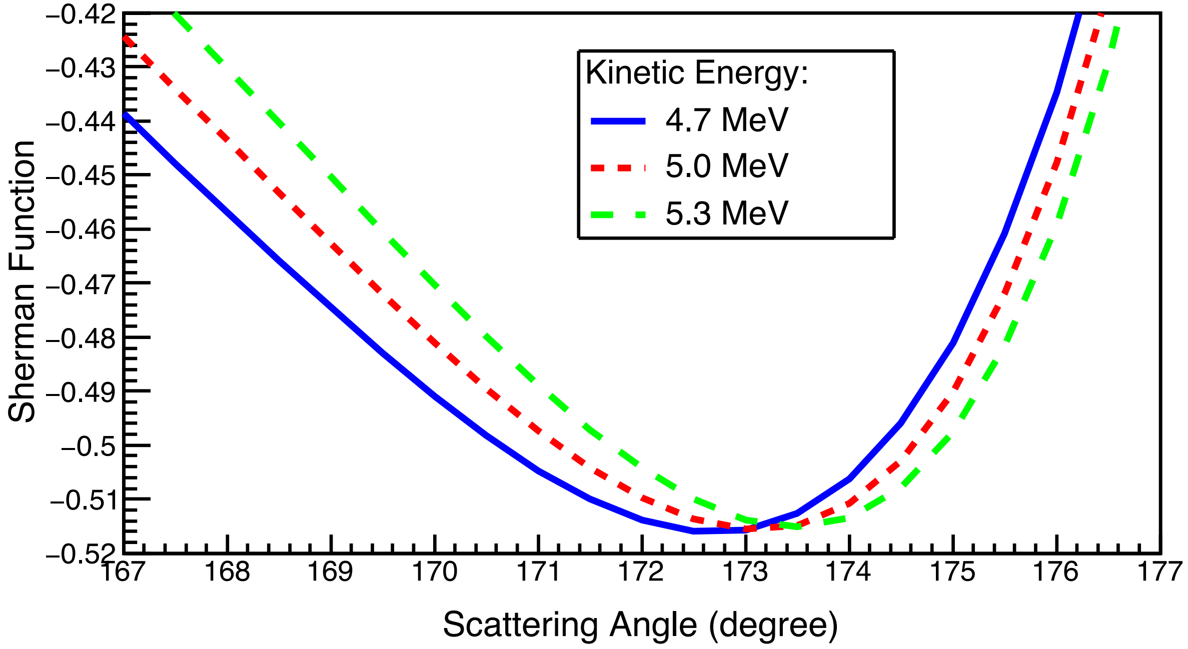
Energy spread (dispersive region)

Runs 1,2	$\sigma_E/E < 4$ keV

Detector Acceptance

Runs 1,2	$\theta = 172.6$ deg ($d\Omega = 0.232$ msr)

Systematic uncertainty 0.2% on Sherman function (0.514 +/- 0.001)



Step 2 – Precise characterization of beam and instrumental systematics

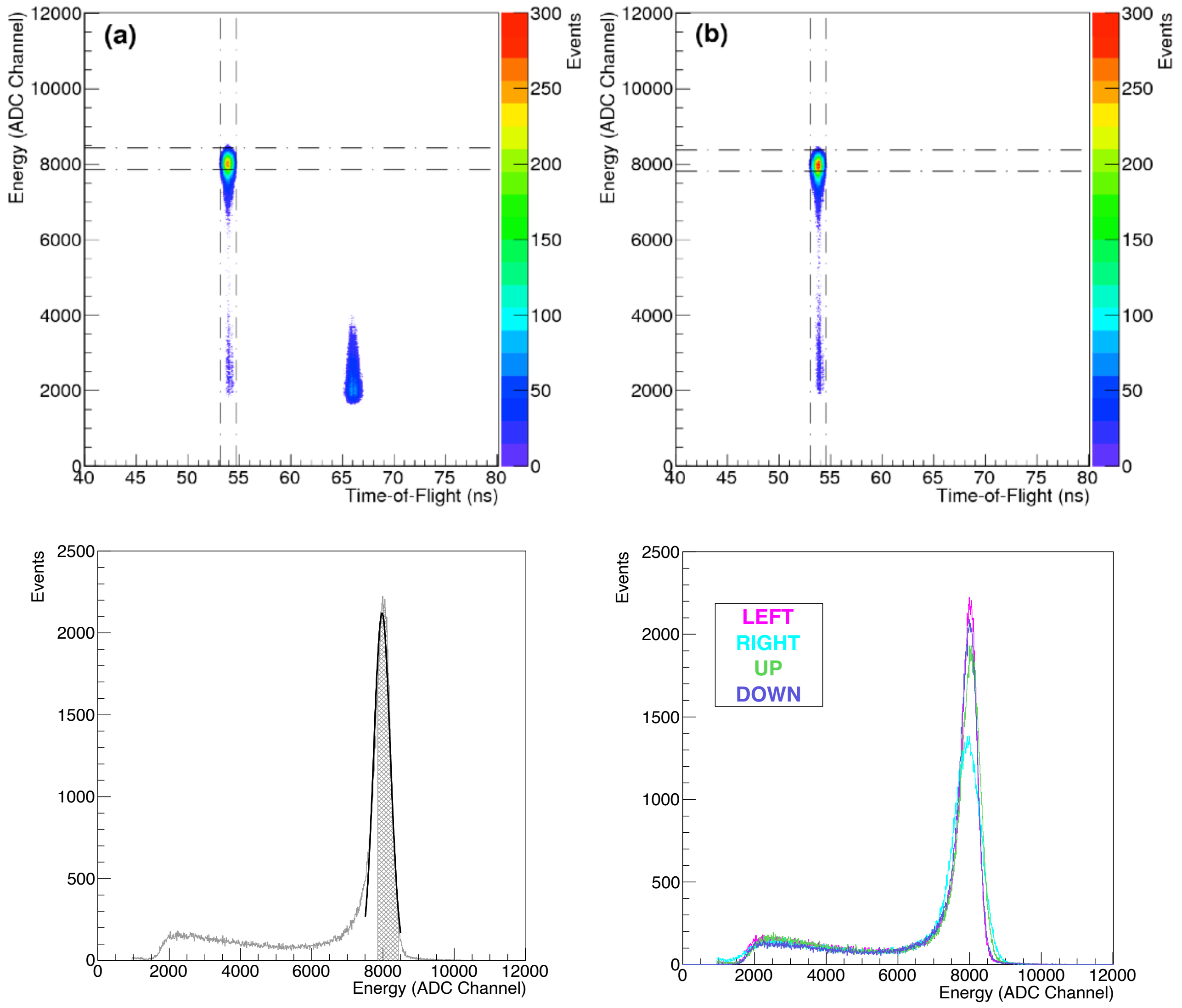
Experiment was done twice, with **10 months** in between

Run 1

- GaAs/GaAsP => **#1**
- Spin vertical => **L/R arms**
- Timing => **TDC**
- Energy => **4.806 +/- 0.097 MeV**

Run 2

- GaAs/GaAsP => **#2**
- Spin horizontal => **U/D arms**
- Timing => **hardware veto**
- Energy => **4.917 +/- 0.013 MeV**



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Step 3 – Improving zero thickness extrapolation

- **No known functional form** to account precisely for multiple-elastic scattering

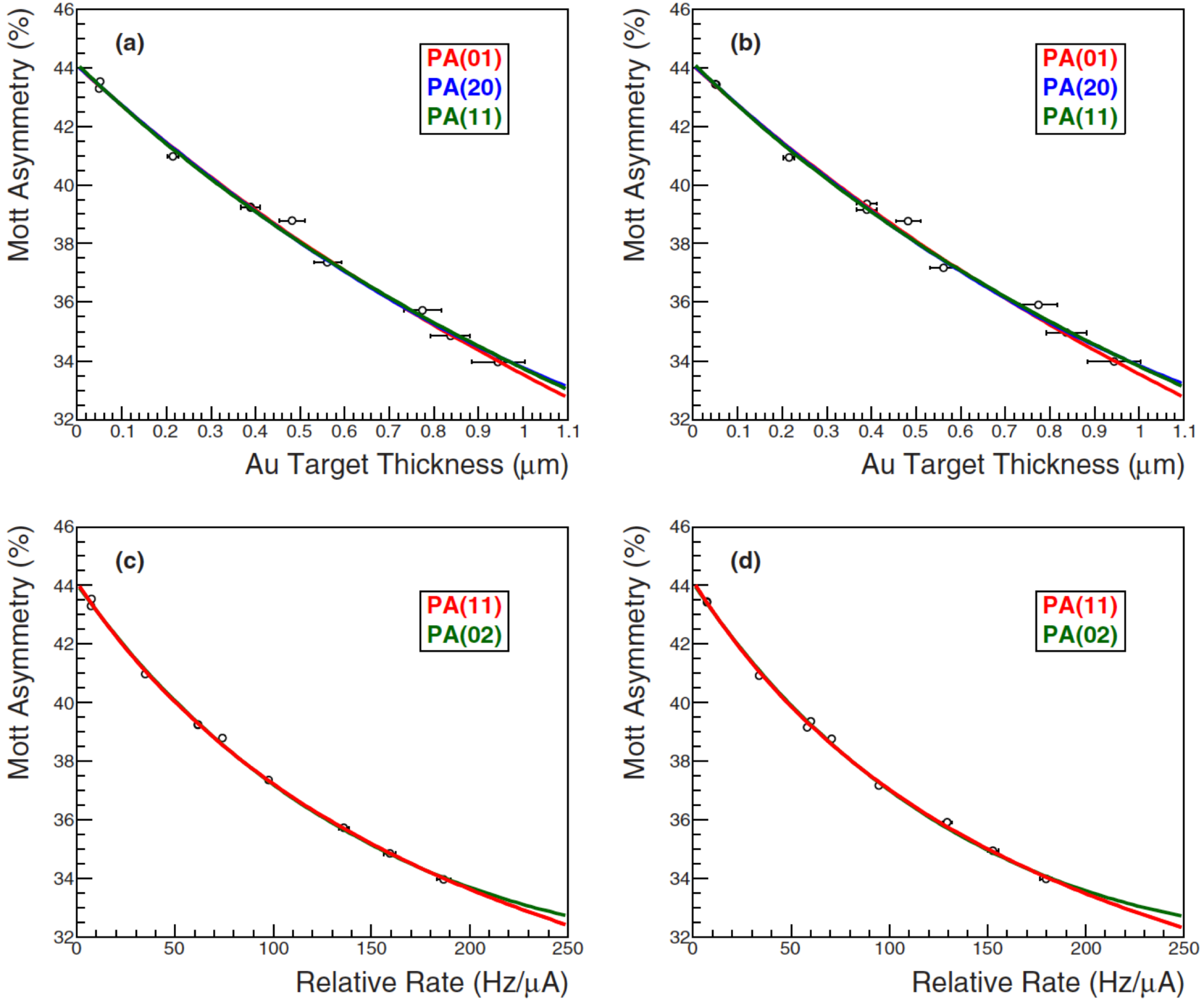
Purely single – $A(t) = A(0)/(1+\beta t)$.

And double – $A(t) = A(0)[(1+\alpha t)/(1+\beta t)]$

- We **apply method of Padé approximates** to determine the statistically allowed polynomial

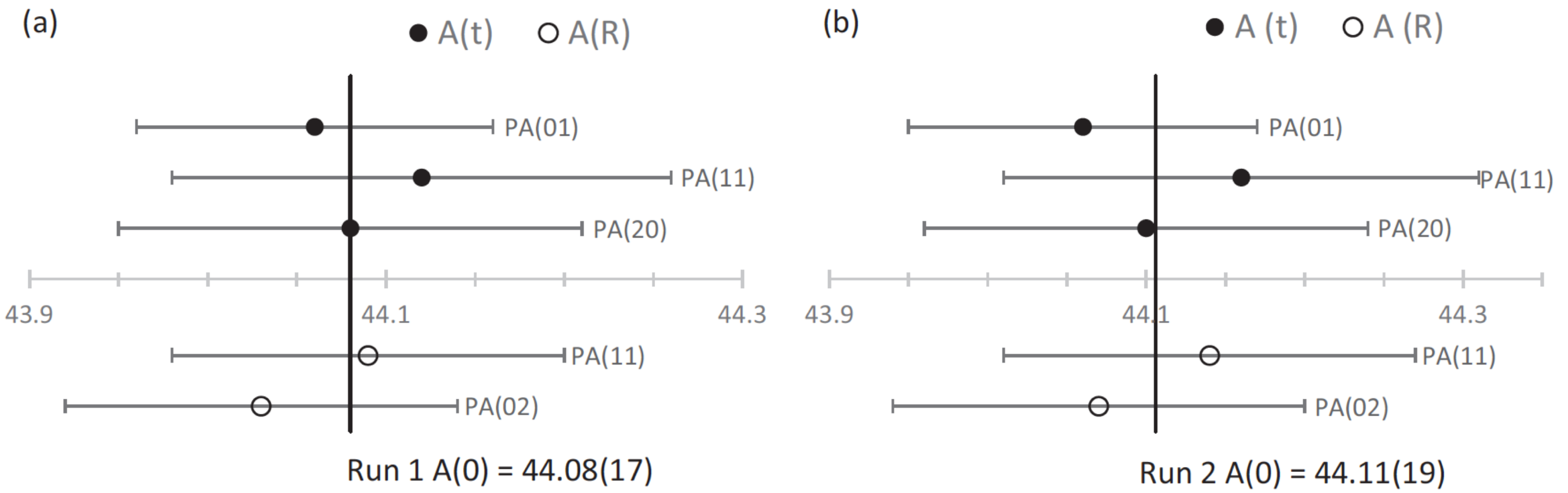
$$A = A(0)\frac{(1 + a_1 t + a_2 t^2 + a_3 t^3 + \cdots\cdots + a_m t^m)}{1 + b_1 t + b_2 t^2 + b_3 t^3 + \cdots\cdots + b_n t^n}.$$

- **High statistical precision** in relative scattering rate due to well known beam currents used



Step 3 – Improving zero thickness extrapolation

- Padé analysis **rejects fits** based on poor **reduced chi-squared** values and outcomes of **F-tests**
- Good agreement with *most* traditional forms (1,0) <u>(0,1)</u> <u>(1,1)</u> <u>(0,2)</u> <u>(2,0)</u>
- Our final reported values are **weighted average over all accepted fits** (no human biasing)



P(e-) = 85.72 ± 0.19%

P(e-) = 85.72 ± 0.21%

Step 4 – Single-atom Sherman function

See X. Roca-Maza Eur. Phys. Lett. **120** 33002 (2017) &
Salvat F., Jablonski A. and Powell C. J., Comput. Phys. Commun., 165 (2005) 157.

Relativistic (Dirac) partial-wave calculations from a local central interaction potential *V*(*r*)

$$\left[\imath\vec{\alpha}\cdot\vec{\nabla}+\beta m+V(r)\right]\Psi(r)=E\Psi(r)$$
$$V(r)=V_{\rm Coul}(r)+V_{\rm ex}(r)-\imath W_{\rm abs}$$

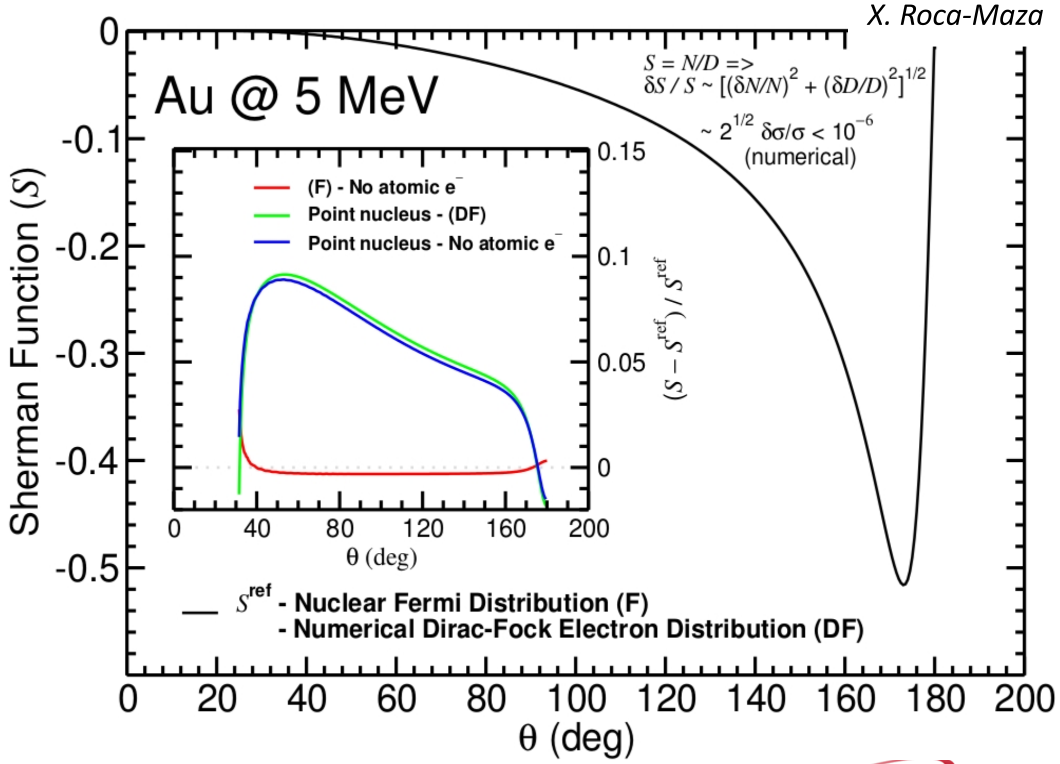
solution →

$$\frac{d\sigma}{d\Omega}=|f(\theta)|^2+|g(\theta)|^2,$$
$$S(\theta)\equiv\imath\frac{f(\theta)g^*(\theta)-f^*(\theta)g(\theta)}{|f(\theta)|^2+|g(\theta)|^2}$$

Scattering amplitudes (f and g) and dσ/dΩ are estimated from the convergence of partial-wave series, typically the numerical error in S(θ) is about 10^{-6} or smaller.

Effects in the Sherman function *S*(*θ*):

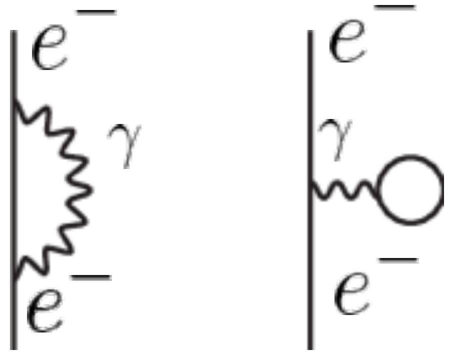
- $\rho_{ch} \rightarrow V_{coul}(r)$ **~0.1%** depends on using a realistic Nuclear Model
- Electron exchange potential $V_{ex}(r)$ is **~few ‰ if neglected**
- Inelastic contributions $W_{abs}(r)$ **<0.1% if neglected**
- Screening from atomic electrons **few % if neglected**
- Radiative corrections do not amount to more than a 0.5% (**estimated!**).



Step 4 – Single-atom Sherman function

Radiative corrections give the **largest contributions** to the **theoretical uncertainty** in the Sherman function in the few-MeV energy range.

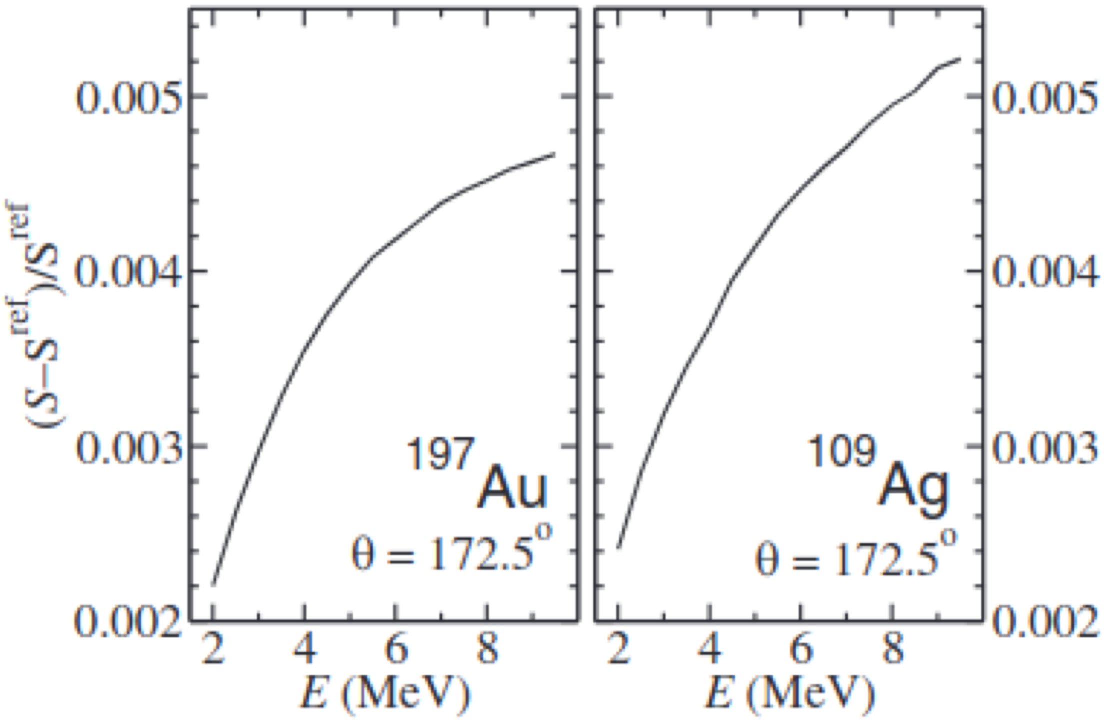
Leading QED corrections of the order of $\alpha^2 Z$ are the **self-energy** **(left)** and **vacuum polarization** (right). Both are predicted to **increase with energy** and **display a Z dependence**, but have **opposite sign and cancel** one another.



SE **VP**

X. Roca-Maza Eur. Phys. Lett. **120** 33002 (2017)

Vacuum polarization effects

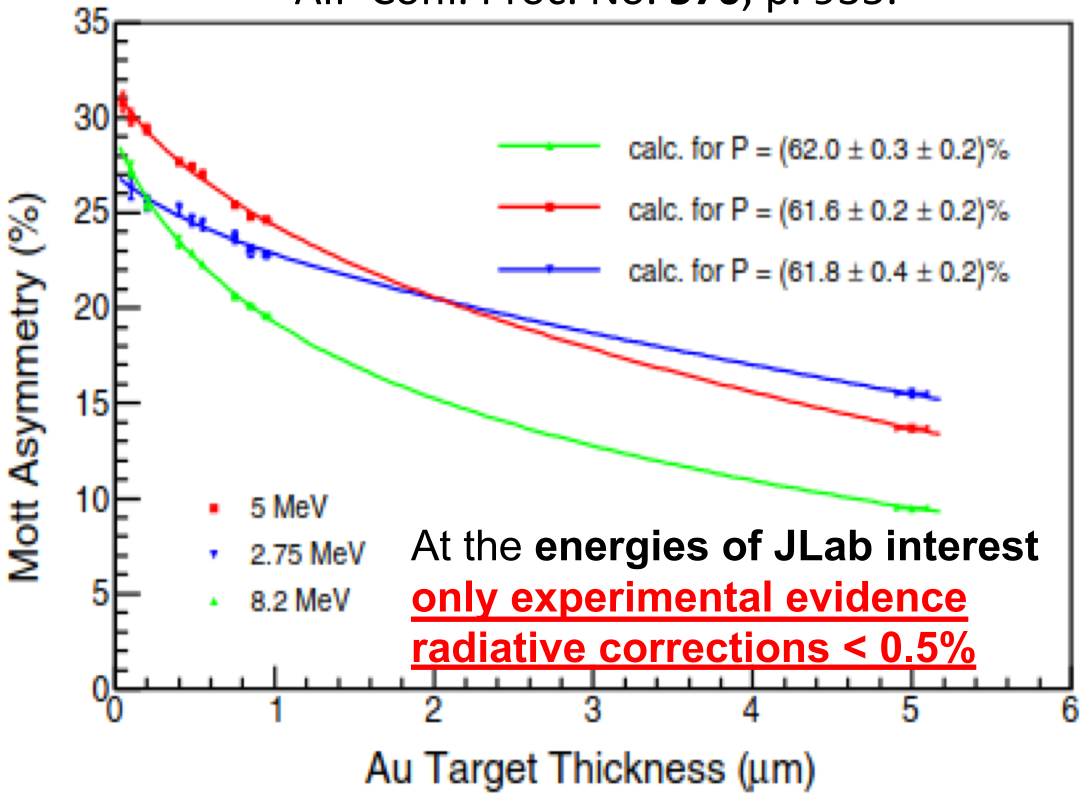


Measuring the Mott asymmetry from foils of **different Z** and with **different Energy** **bounds the theoretical uncertainty**.

Step 4 – Single-atom Sherman function

Experimental evidence supports the net effect of these **corrections largely cancel** (as theoretically anticipated).

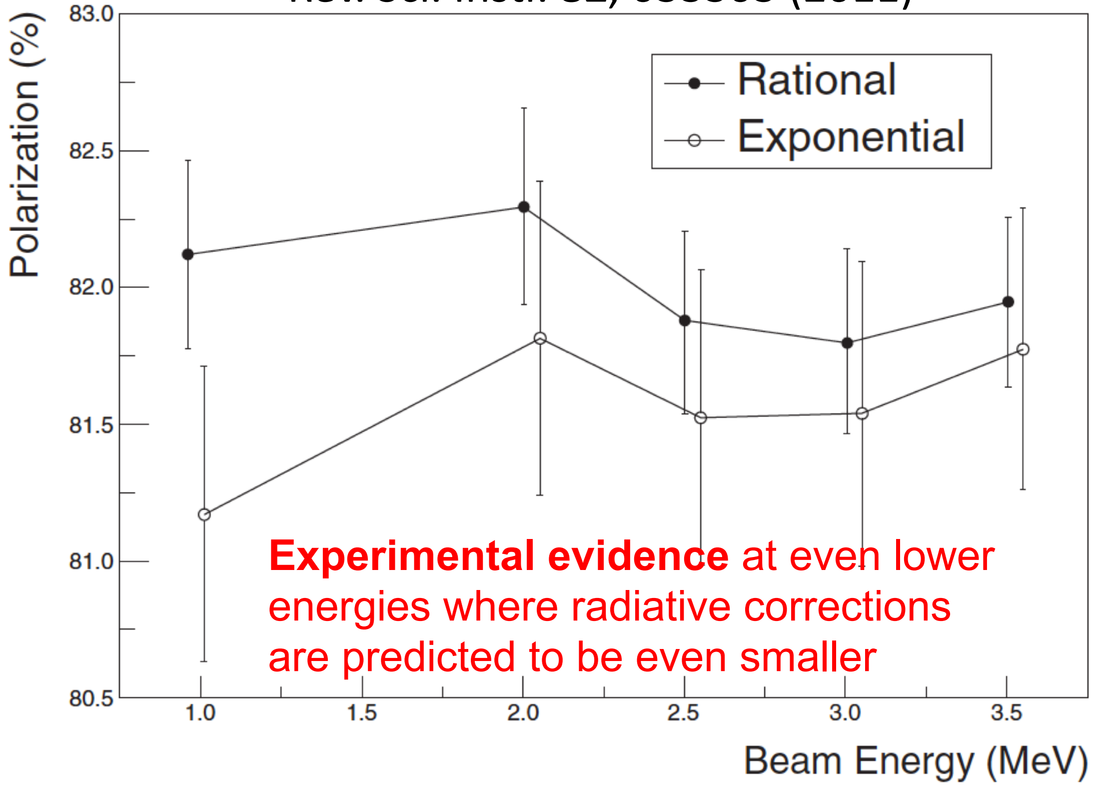
M. Steigerwald, SPIN2000
AIP Conf. Proc. No. **570**, p. 935.



At the **energies of JLab interest** **only experimental evidence radiative corrections < 0.5%**

* **No radiative corrections** were included in the analysis of the Sherman function at these **three energies**.

V. Tioukine, K Aulenbacher, and E. Riehn,
Rev. Sci. Instr. **82**, 033303 (2011)



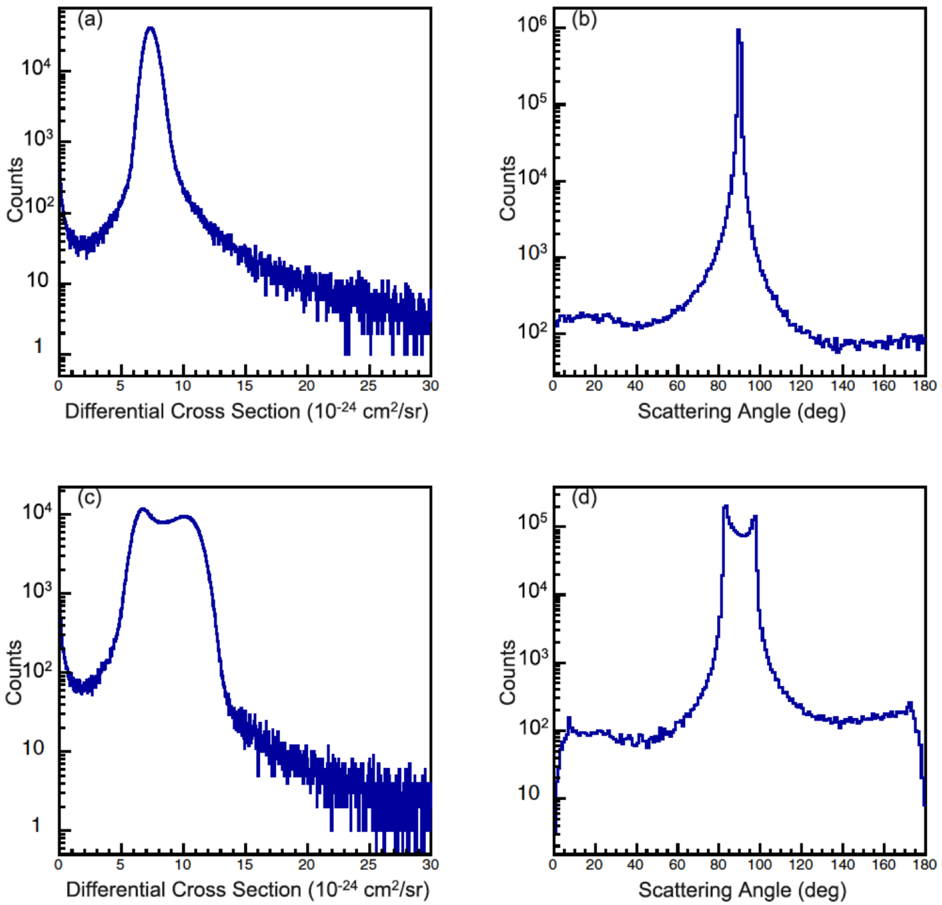
Experimental evidence at even lower energies where radiative corrections are predicted to be even smaller

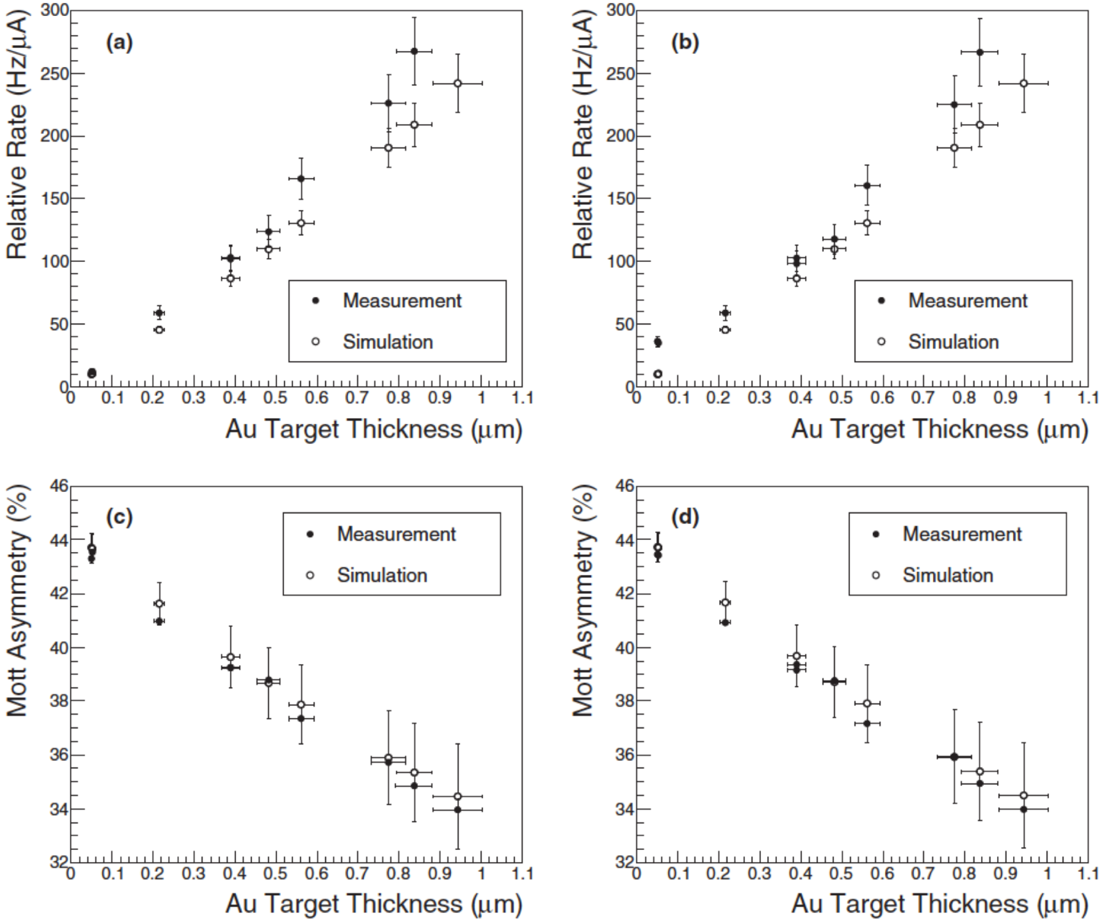
Step 5 – Further techniques & measurements

- Sophisticated **Monte-Carlo techniques** used to compute **scattering from "thick" targets** into detector acceptance
- **Simulations in good agreement with experimental data** => confirms functional form from first principles

Single Scattering

Double Scattering



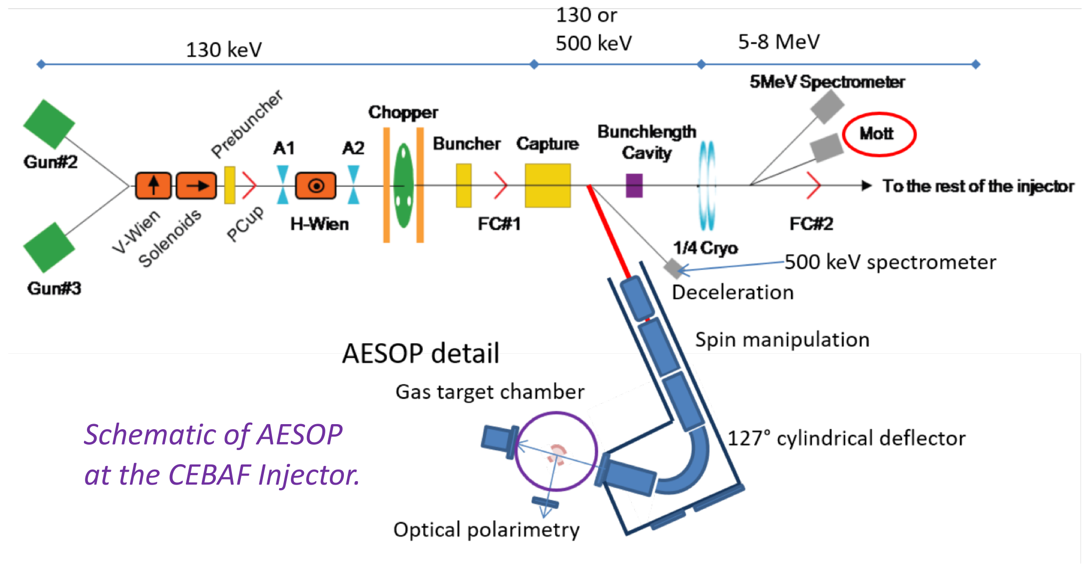


Refer interested read to the journal article (too many details to discuss here)

Step 5 – Further techniques & measurements

Accurate Electron Spin Optical Polarimeter (AESOP) is a project at the University of Nebraska-Lincoln **using optical fluorescence** to measure electron spin polarization**.**

- **Goal** is achieving an overall **accuracy of 0.3%** (T.J.Gay *et al.* Phys. Rev. A **65**, 2341).
- Two papers published on AESOP optical polarimeter systematic effects (Trantham *et al.*, *Appl. Opt.* **59**, 2715 (2020) and Foreman and Gay, *Measurement Sci. and Tech*. in press)
- Construction of **AESOP polarimeter** with GaAs source is **about 50% complete**.



Schematic of AESOP at the CEBAF Injector.

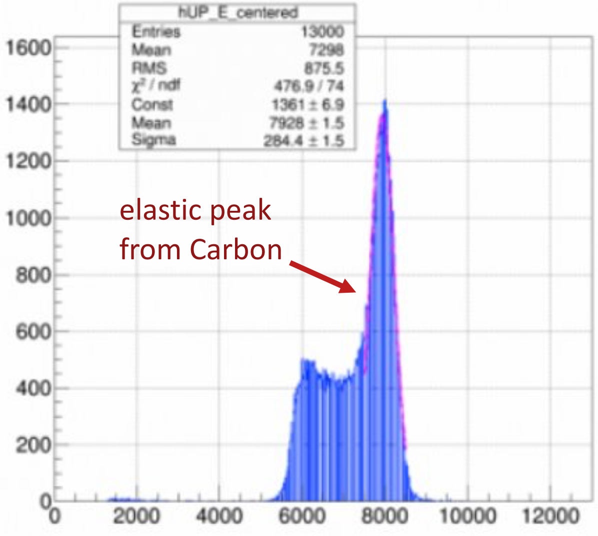
Mott Diamond Target experiment is a project between Jefferson Lab and industry partner Euclid BEAMLABS to **test radiative corrections** by scattering from **low-Z** carbon targets using **high current** electron beams

- First **exploratory tests** using diamond targets at CEBAF performed summer of **2021**
- Developing **Phase II proposal** for a **new polarimeter** to operate efficiently with low-Z targets

euclid BEAMLABS

Carbon (diamond)

Gold (foil)



Conclusions

Multi-year effort concluded

Great team to work with, a lot of diversity to accomplish our goals

Results published last year (with more details) in **Phys. Rev. C**

Achieved total uncertainty **0.61%**

Exploring strategy to achieve an uncertainty of **<0.5%**

PHYSICAL REVIEW C **102**, 015501 (2020)

High precision 5 MeV Mott polarimeter

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[3]*Department of Mechanical and Aerospace Engineering, Old Dominion University, Norfolk, Virginia 23529, USA*
[4]*Physics Department, George Washington University, Washington, DC 20052, USA*
[5]*Jorgensen Hall, University of Nebraska, Lincoln, Nebraska 68588, USA*

TABLE III. Uncertainty budget for the 5 MeV Mott polarimeter.

Contribution to the total uncertainty	Value
Theoretical Sherman function	0.50%
Target thickness extrapolation	0.25%
Systematic uncertainties	0.24%
Energy cut (0.10%)	
Laser polarization (0.10%)	
Scattering angle and beam energy (0.20%)	
Total	0.61%