The emiT Experiment: A Search for Time-reversal Symmetry Violation in Polarized Neutron Beta Decay

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Jumping right in......

- Baryon asymmetry implies C, CP (or T) violation.
  but SM CP violation is MANY orders of mag. too small.

- No strong 1st order phase transition in SM.

- Neutrino mass??

Time reversal exchanges initial and final states, but also complex conjugates

$$Tf(t)T^{-1} = f^*(-t)$$

$$[p, x] = -i\hbar$$

- Standard Model while pretty darn good, isn't complete.

(and in particular there must be additional sources of CP violation)

- Adding new physics will generally add phases and so interference effects can produce T violation.

Symmetries: tests of T invariance

Electric Dipole Moment (EDM) Experiments

Electron	$< 1.6 \times 10^{-27}$ e·cm	B. C. Reagan *et al.*
Neutron	$< 2.9 \times 10^{-26}$ e·cm	C. A. Baker *et al.*
Hg	$<< 2.1 \times 10^{-28}$ e·cm??	M. V. Romalis *et al.*

- often make use of combinations of three kinematic variables
- require competing amplitudes with a relative phase

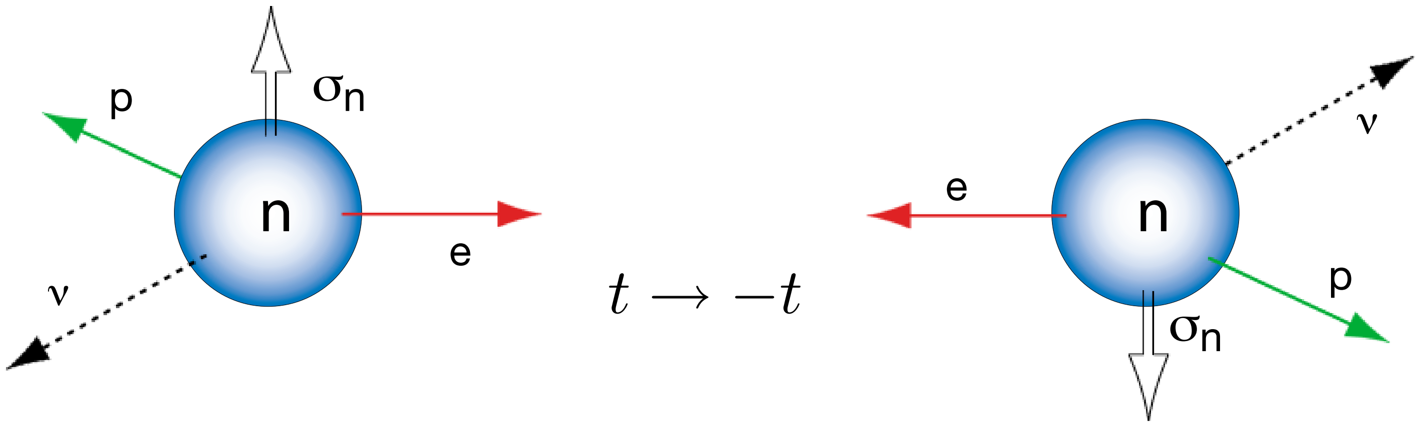
Kaon Decay
Hyperon Decay
Ternary Fission

Nuclear Beta Decay Experiments

$L\sigma_e \bullet (p_e \times p_\nu)$ $R\sigma_n \bullet (\sigma_e \times p_e)$ $D\sigma_n \bullet (p_e \times p_\nu)$

^{8}Li	$R = (0.9 \pm 2.2) \times 10^{-3}$	J. Sromicki *et al.*
^{19}Ne	$D = (4 \pm 8) \times 10^{-4}$	A. L. Hallin *et al.*
Neutron	$D = -(2.8 \pm 7.1) \times 10^{-4}$ $D = (-0.6 \pm 1.2(\text{stat.}) \pm 0.5(\text{syst.})) \times 10^{-3}$	T. Soldner *et al. Phys. Lett. B* ***581*** *(2004)* emiT I *Phys. Rev. C* ***62*** *055501 (2000)*

Polarized Neutron Decay



$$\frac{d\omega}{dE_e d\Omega_e d\Omega_\nu} = G(E_e)\left(1 + a\frac{p_e \cdot p_\nu}{E_e E_\nu} + \sigma_n \cdot \left(A\frac{p_e}{E_e} + B\frac{p_\nu}{E_\nu} + D\frac{p_e \times p_\nu}{E_e E_\nu}\right)\right)$$

Measurable & non-zero

T-odd, P-even

- ❶ *D* = -2.8 ± 7.1 x 10^{-4} *TRINE*

Not quite T reversal; Initial and final states are *not* reversed: final state interactions

- ❶ $|D_{f.s.}| = 2.6 \times 10^{-5}$ ^{19}Ne ~ 2.6 × 10^{-4} p/p_{max}

Polarized Neutron Decay

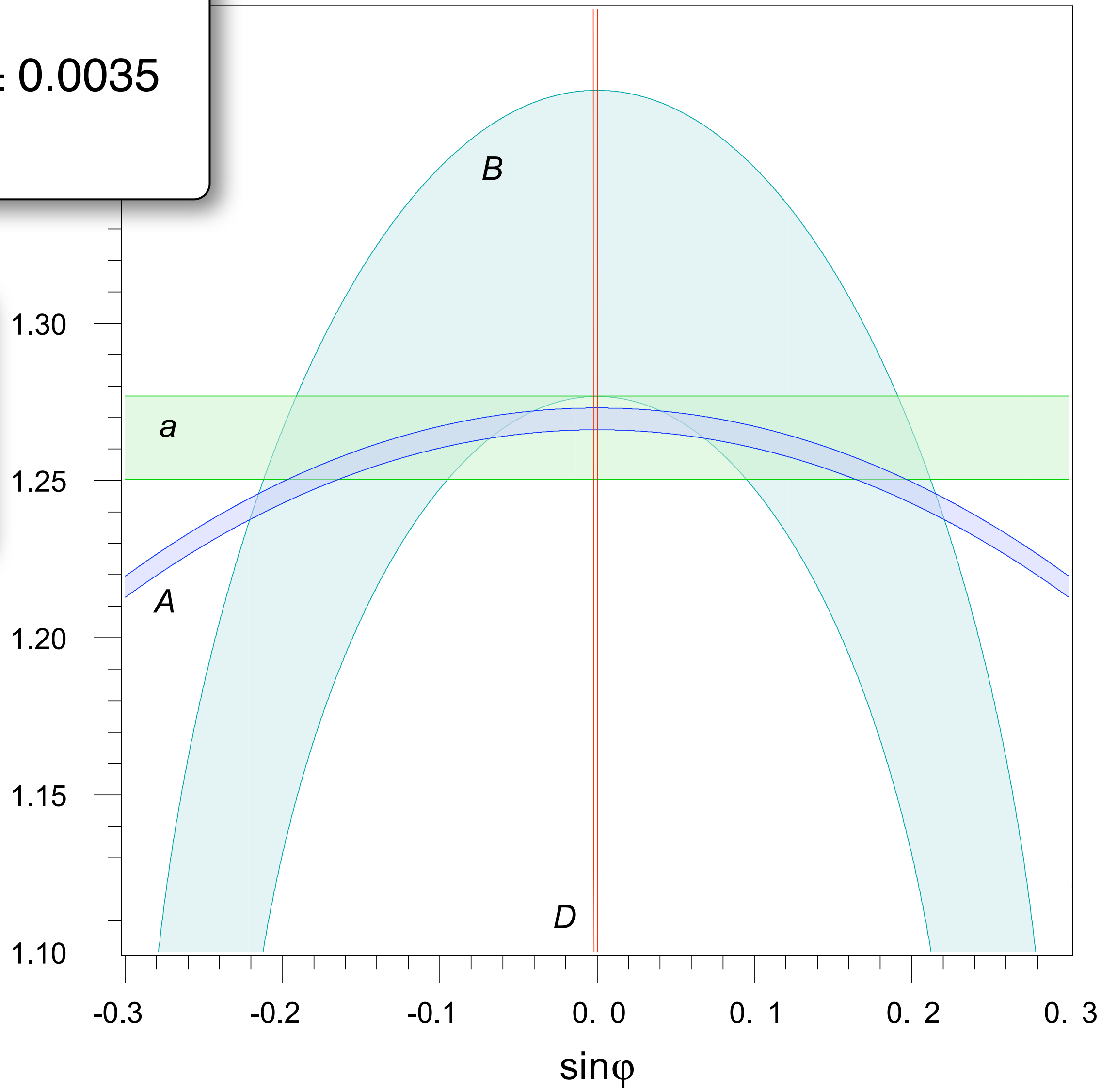
The observables, a, A, B, etc..., allow important tests of the Standard Model V-A Theory

$$\lambda \equiv \left|\frac{g_A}{g_V}\right| e^{-i\phi} \approx 1.2670 \pm 0.0035$$

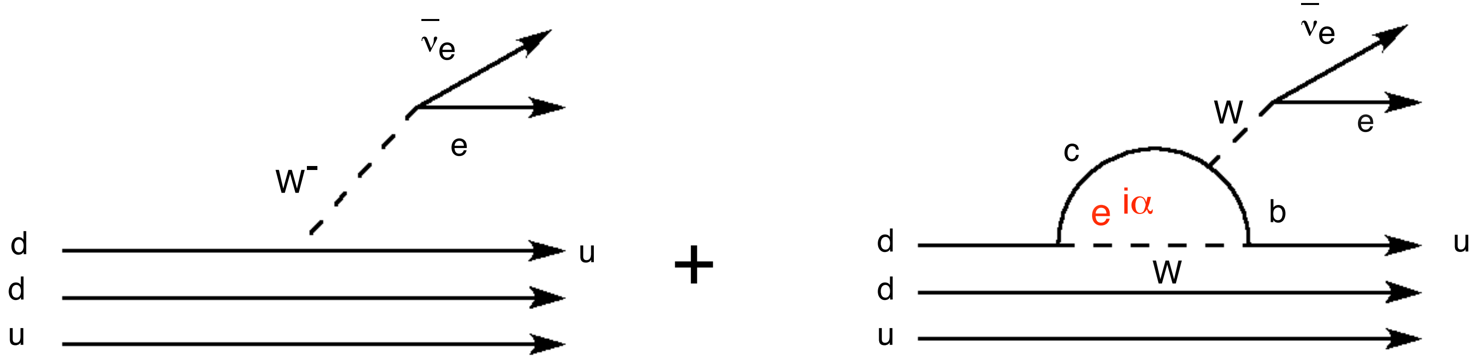
$$A = -2\frac{|\lambda|^2 + |\lambda|\cos\phi}{1+3|\lambda|^2}$$

T-odd (P-even) triple correlation:

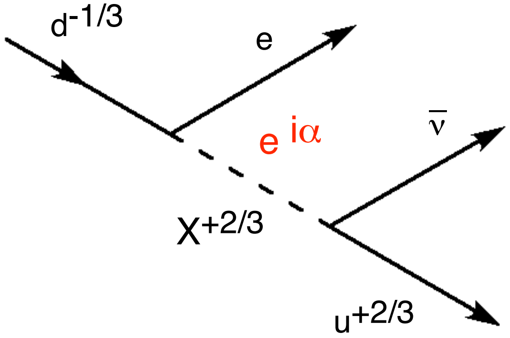
$$D = 2\frac{|\lambda|\sin\phi}{1+3|\lambda|^2}$$



Polarized Neutron Decay: Possible Sources of T Violation



Standard Model



Super-symmetry

L-R symmetric

Lepto-quarks

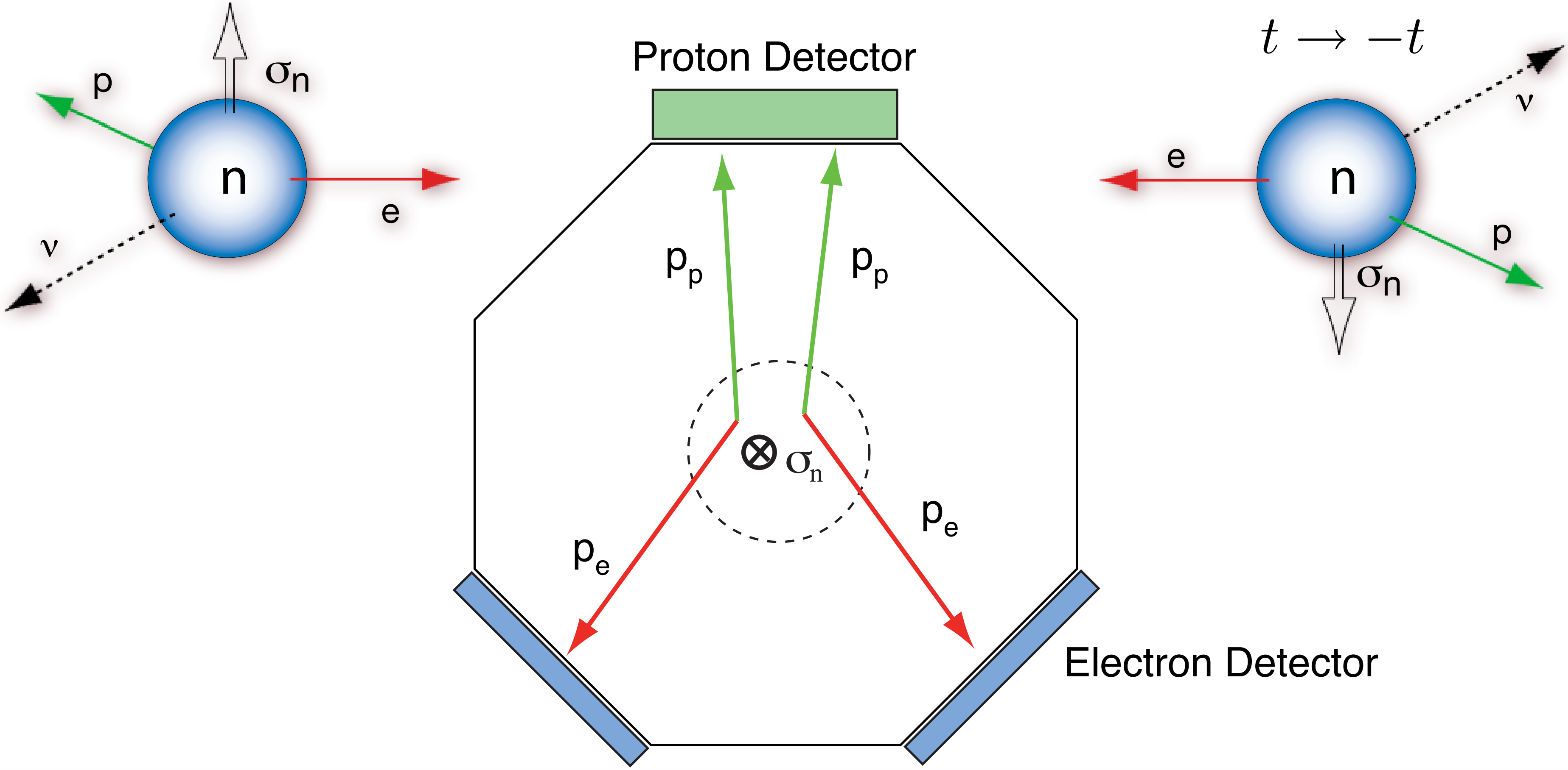
Theory	*D*
1. Kobayashi-Maskawa Phase	$< 10^{-12}$
2. Theta-QCD	$< 10^{-14}$
3. Supersymmetry	$\leq 10^{-7} – 10^{-6}$
4. Left-Right Symmetry	$\leq 10^{-6} – 10^{-5}$
5. Exotic Fermion	$\leq 10^{-6} – 10^{-5}$
6. Leptoquark	present limit

Table 1. Constraints on *D* based on other T-odd observables. Limits 2-5 are from EDM measurements in mercury

Polarized Neutron Decay

$$\sigma_n \cdot (p_e \times p_p)$$

$$t \rightarrow -t$$



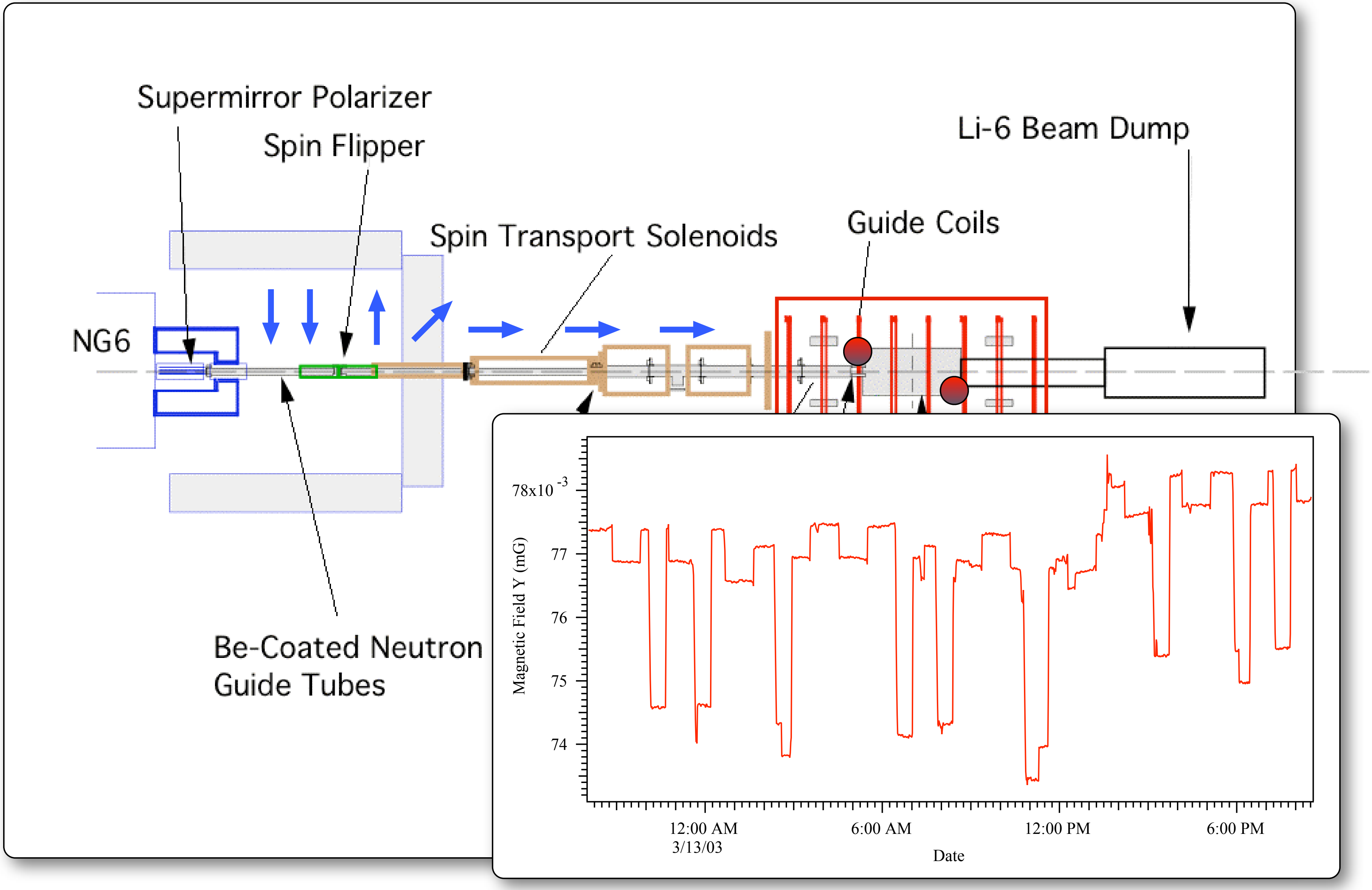
Difficulties

- proton endpoint 750 eV (requires acceleration)
- Neutron lifetime (requires intense source)
- Tight control of magnetic fields

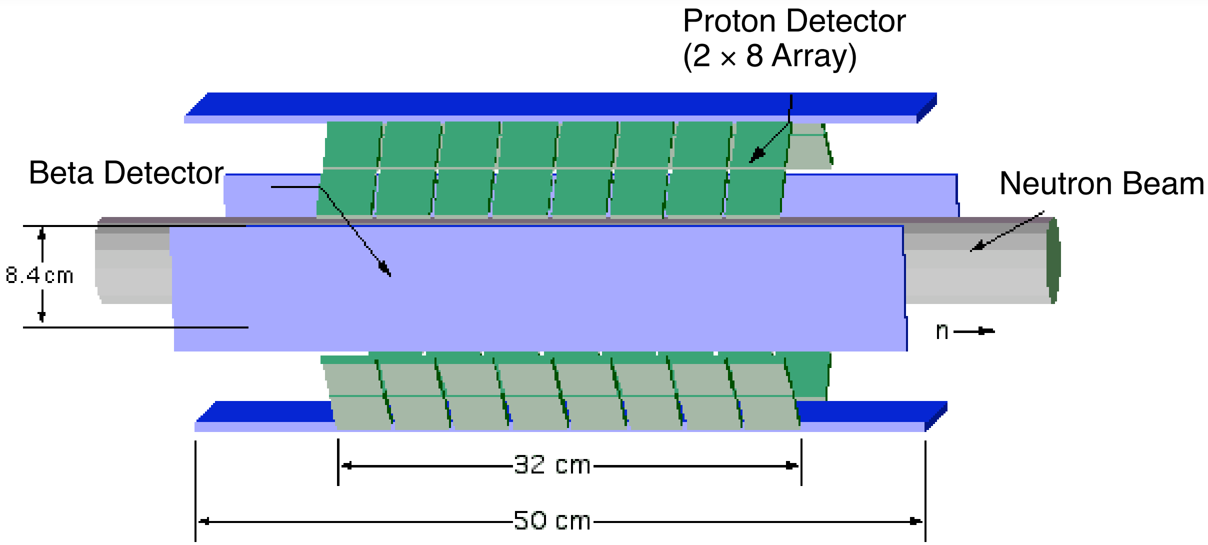
Advantages

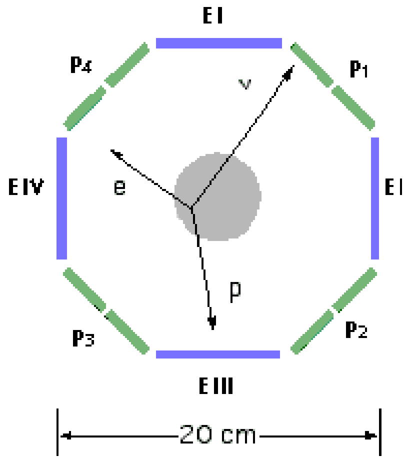
- Delayed coincidence
- Simple physics

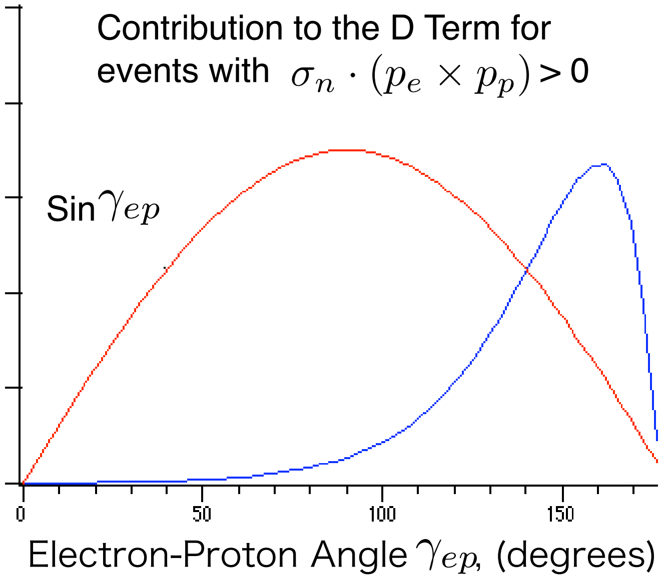
emiT Beamline



emiT Detector: basic concept and design criteria



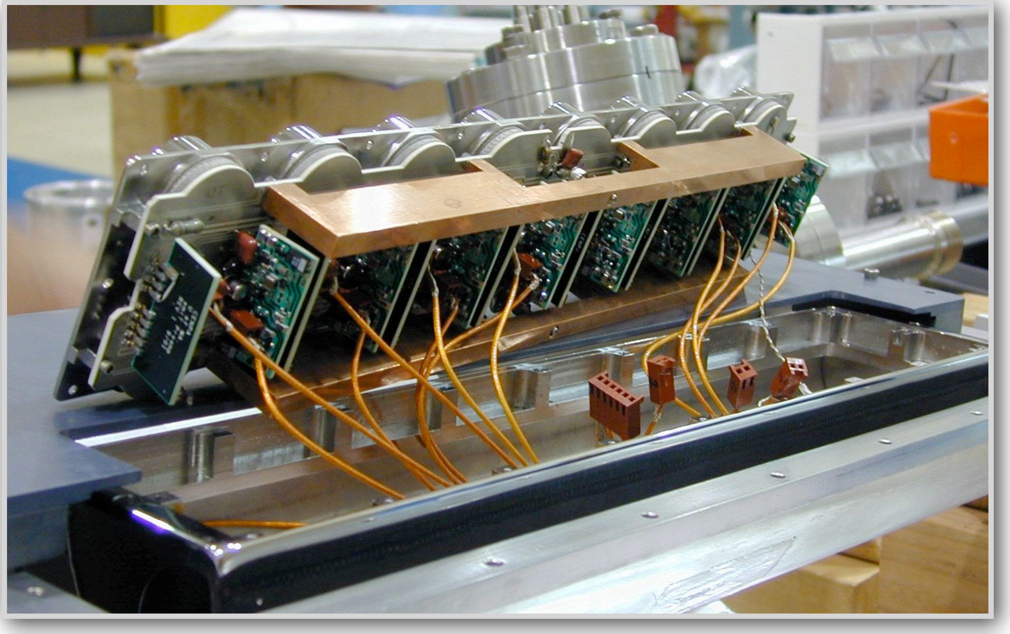


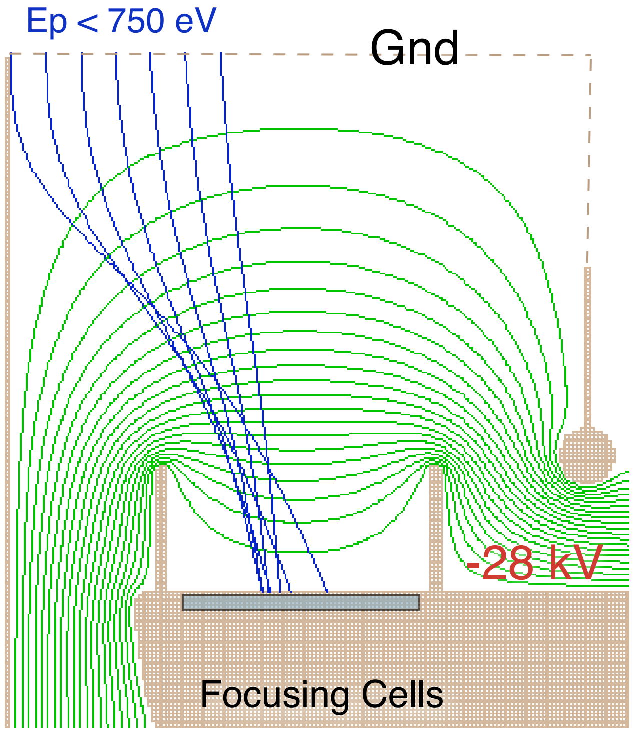


- Statistical precision requires highest possible coincidence rate
- High continuous neutron flux (1.7 x 10^8 cm^{-2} s^{-1} at “C2” collimator)
- Symmetrical, segmented detector to minimize or cancel instrumental asymmetries that could yield false coincidences
- Detector geometry to maximize sensitivity to $D\sigma_n \cdot (p_e \times p_\nu)$
  (minimize sensitivity to other terms in decay distribution)

emiT gained a factor of three increase in “effective” beam flux over previous “right angle” geometry beam experiments

emiT Detector: Proton Paddle Assembly





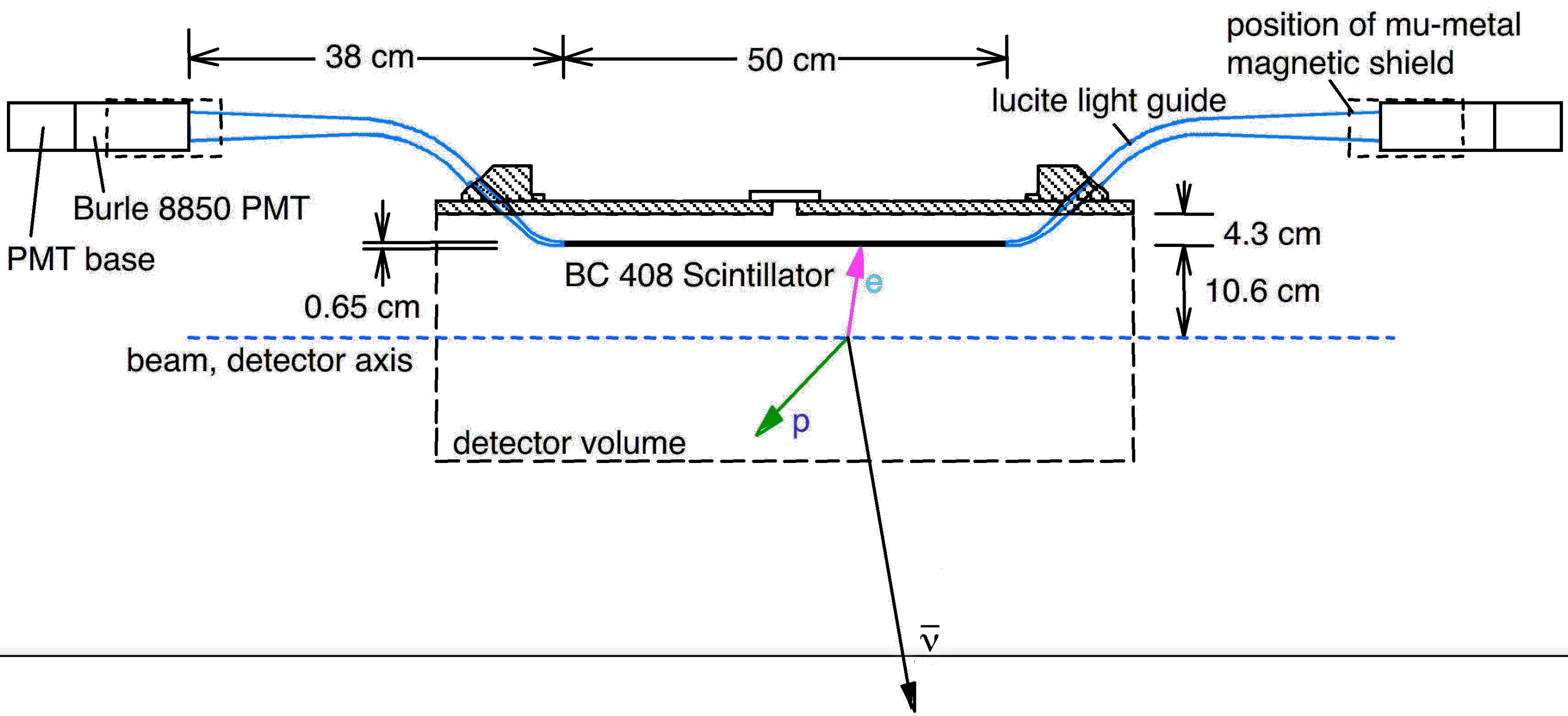
Focusing efficiency reaches 90%
(Voltage Dependent)

Required detector area reduced by ~ 80%

Surface barrier detectors

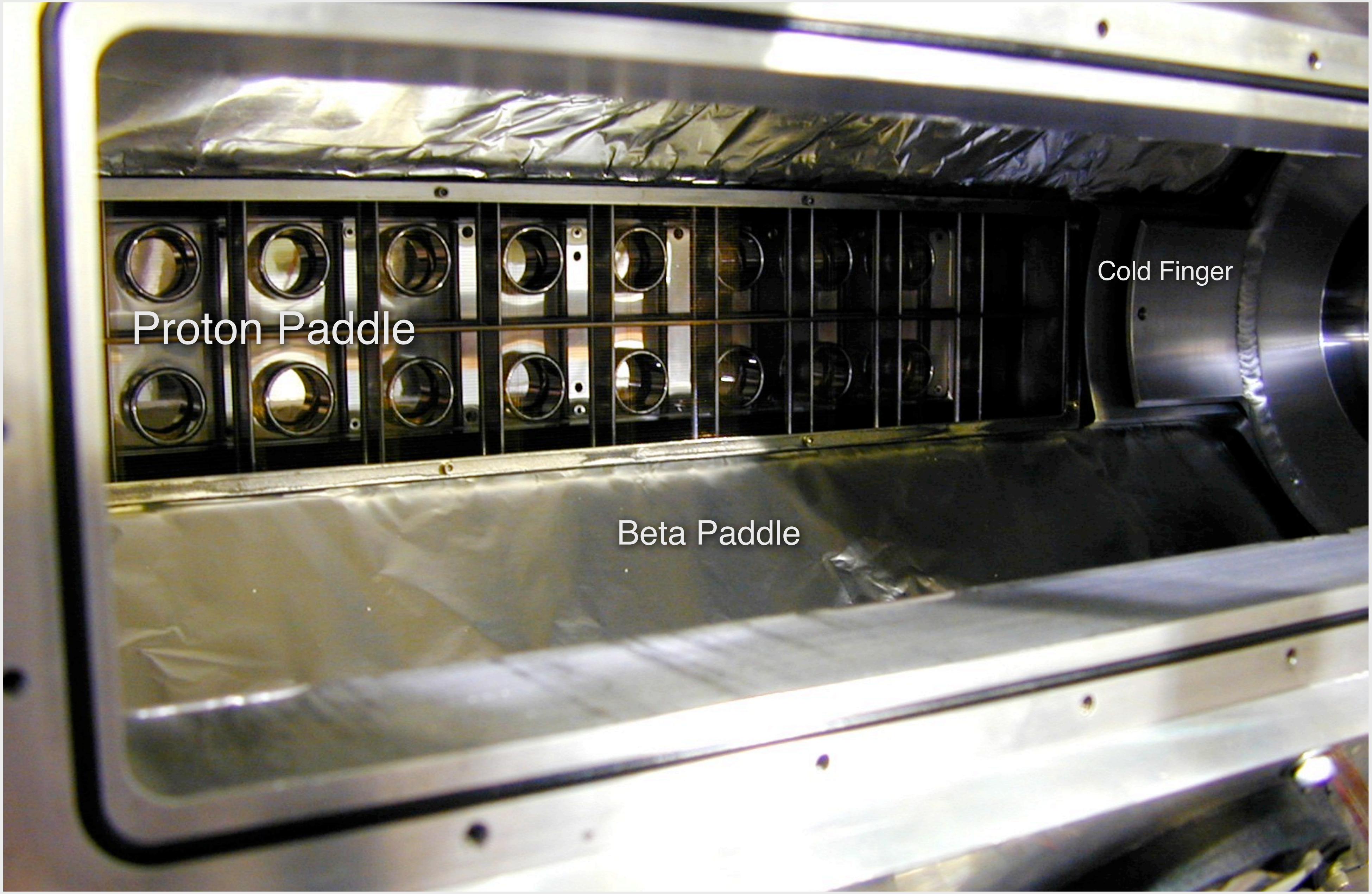
- 20 μg Au (less energy loss)
- 300 mm^2 active area
- 300 μm depletion depth
- Room temperature leakage current ~ μA

emiT Detector: Beta detectors (4 panels and support hardware)

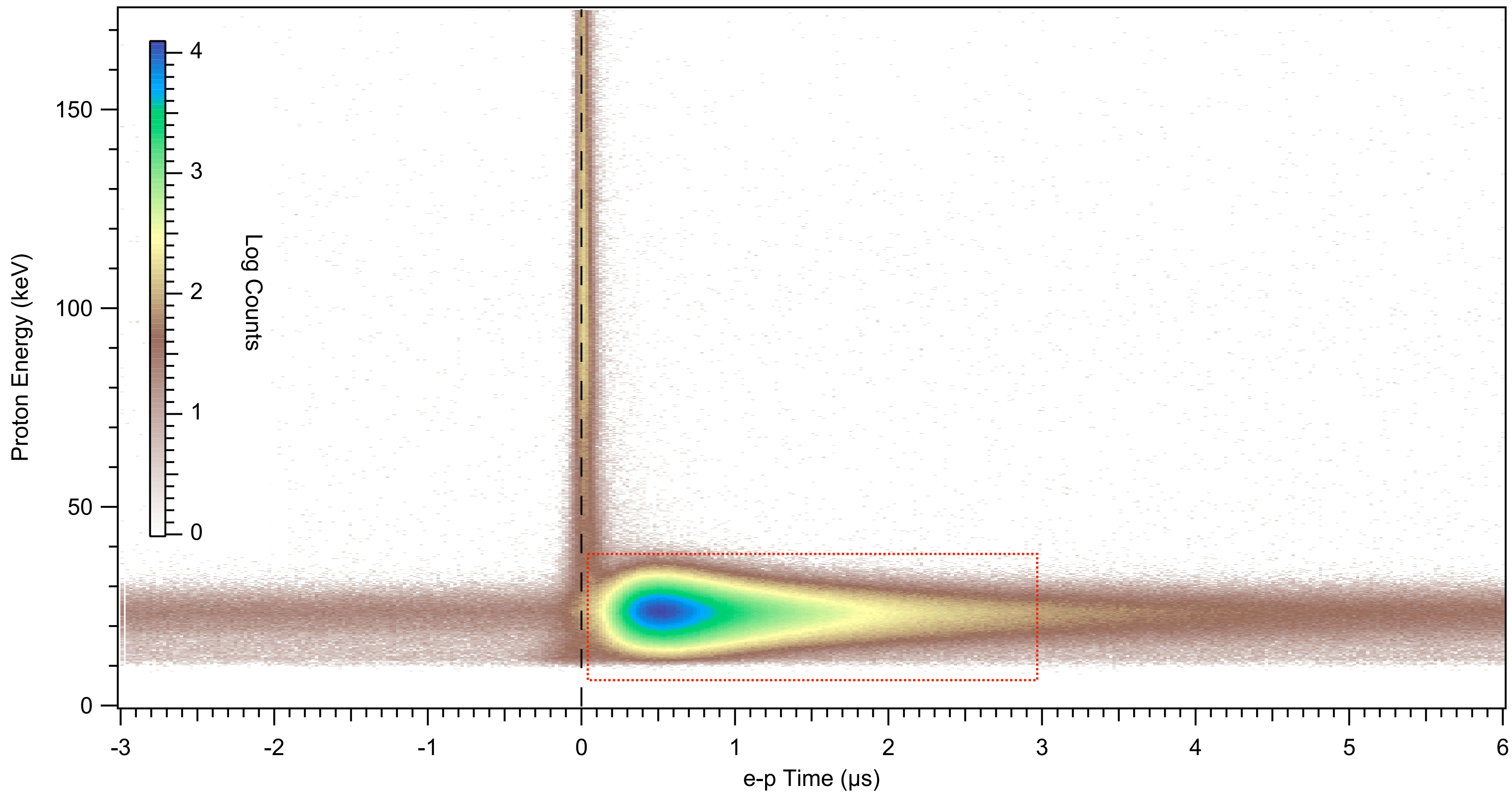


- 0.1 ns timing resolution (Pulse arrival time may be used to determine position)
- Thresholds (35-50 keV) (Software cut on geometric mean)
- Resolution ~18% at 1 MeV
- Cosmic ray muons deposit ~ 1.42 MeV (well separated)
- Overall rate 300 s^{-1} per paddle (Signal to accidental ~ 1 to 1)

emiT Detector: Interior View

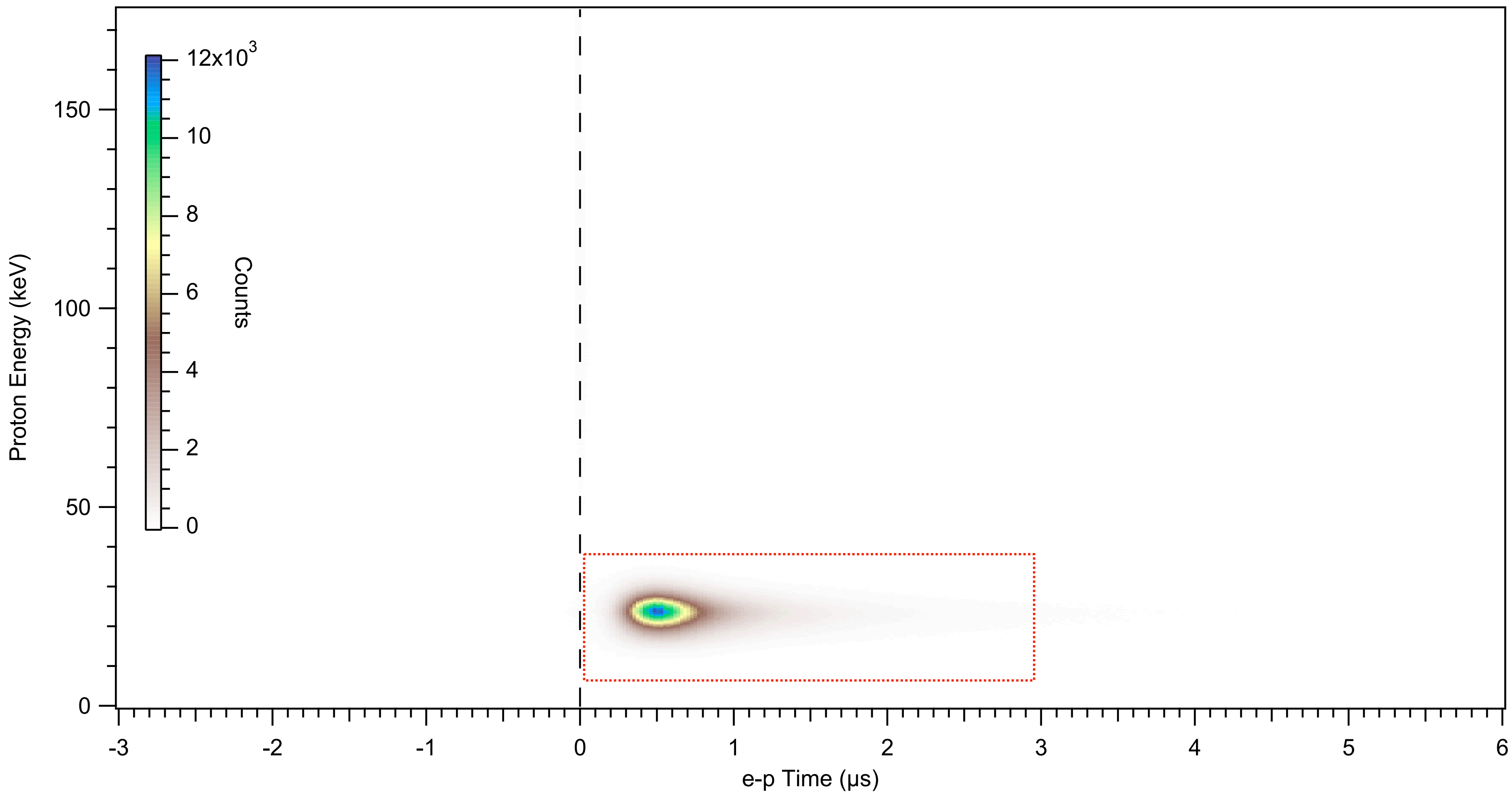


emiT: flitered coincidence data



- 3 Hz singles per proton Surface Barrier det
- 0.55 Average coincidence rate per pair
- 25 Hz average coincidence rate
- Essentially no high voltage noise (Modified focusing assembly)
- Signal to noise better than 100/1
- Clear separation of cosmic Landau peak

emiT: flitered coincidence data



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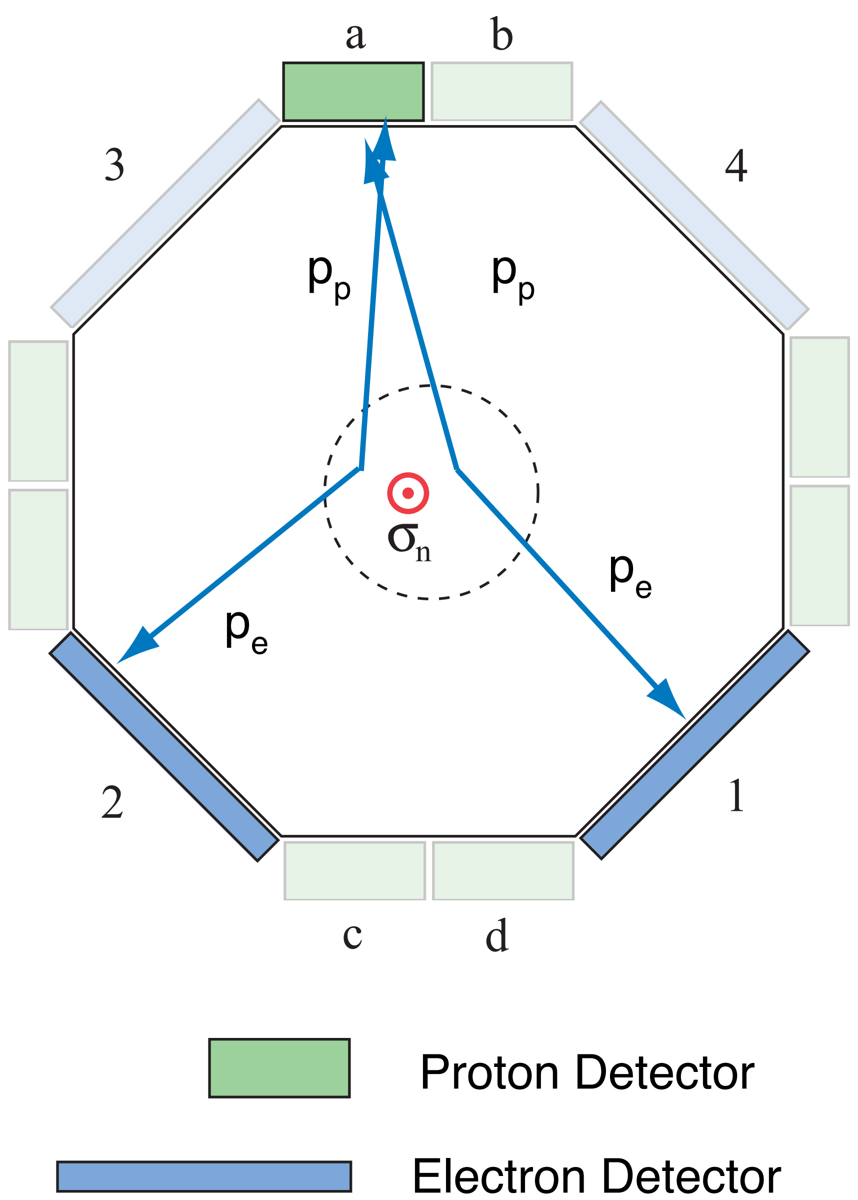
emiT: signal extraction



Efficiency independent ratio,

$$w^{a1} = \frac{N_+^{a1} - N_-^{a1}}{N_+^{a1} + N_-^{a1}}$$

w is sensitive to *D*, but also to *A*, *B*

Define a parameter,

$$v^{a2,a1} = \frac{1}{2}(w^{a2} - w^{a1})$$

For a symmetric uniform detector,

$$v^{a2,a1} = PD\vec{K}_D^a \cdot \hat{z}$$

Instrumental constant

$$\propto \int \frac{p_e \times p_p}{E_e E_p} d\Omega_a d\Omega_2 dV_{beam}$$

Systematics: Overview

- ❶ Polarization, Flux, Clock Variations (proportional to D)
  - Beam flux stable to about a percent

$$D_{false}(\Delta\Phi) = \frac{\Delta\Phi}{2\Phi_{avg}}(AK_A + BK_B)PD$$

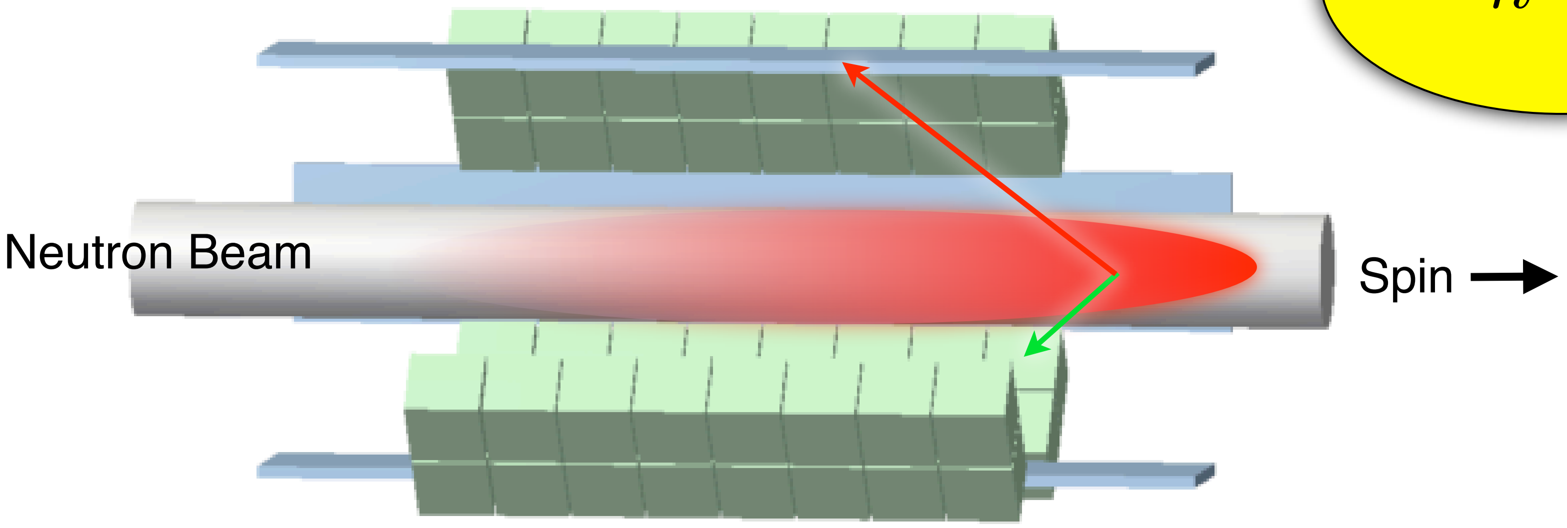
  - Spin flip efficiency 95±5%

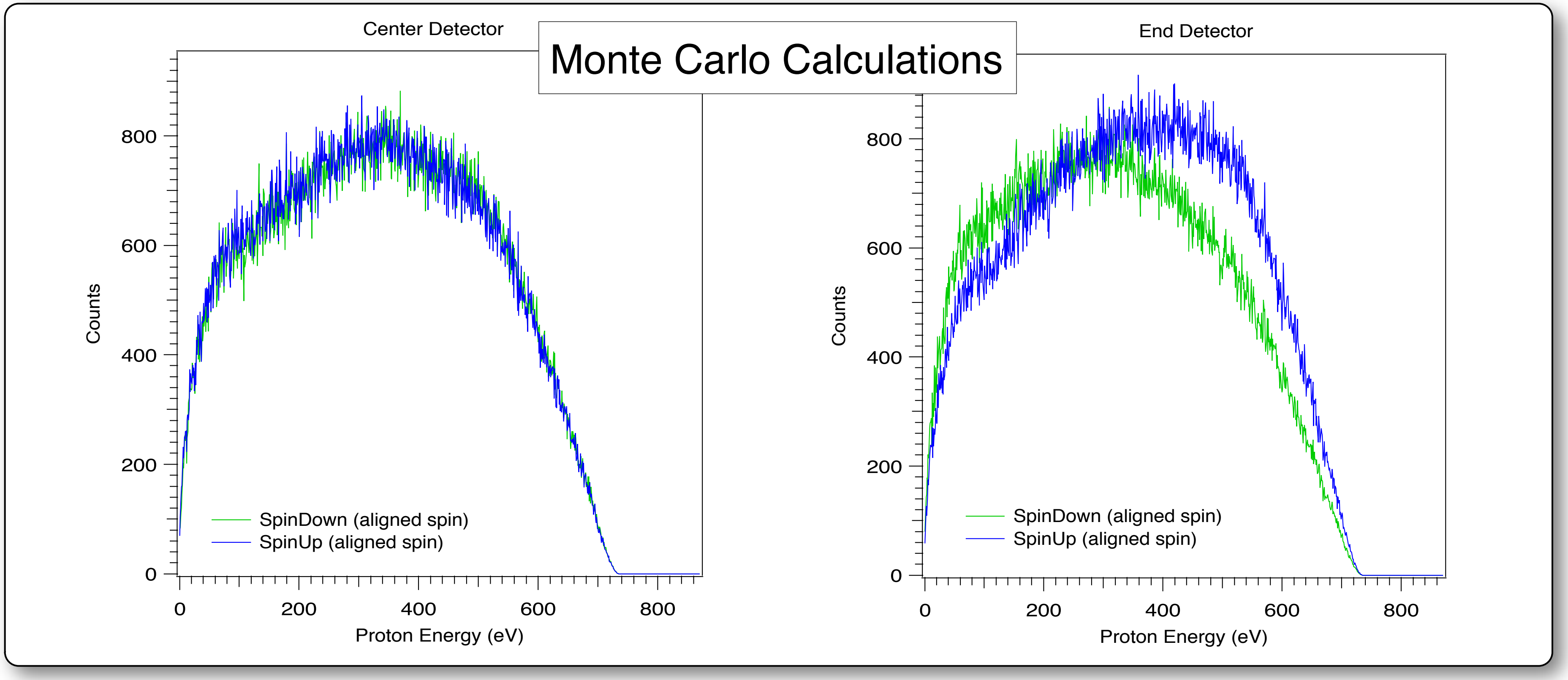
$$D_{false}(\Delta P) = \frac{\Delta P}{2}(AK_A + BK_B)PD$$

- ❶ Initial polarization misalignment and spin precession
  - Average over polychromatic beam washes out effect
- ❶ Electron backscattering
  - approximately 3% of events at 135°
- ❶ Spin state dependent proton energy spectrum
  - Energy shift of up to 100 eV due to recoil and focusing effects
- ❶ Misalignments (with detector symmetry - in general takes two working in conjunction)

Systematics: spin dependent energy spectrum

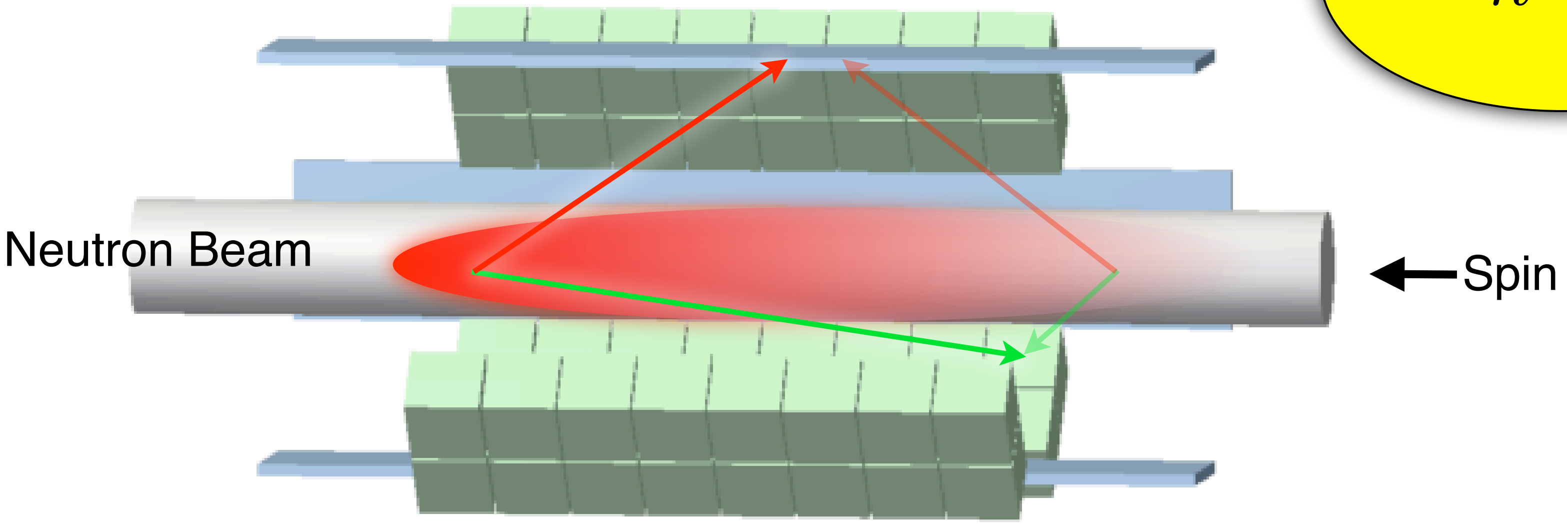
$$A\sigma_n \cdot \frac{p_e}{E_e}$$

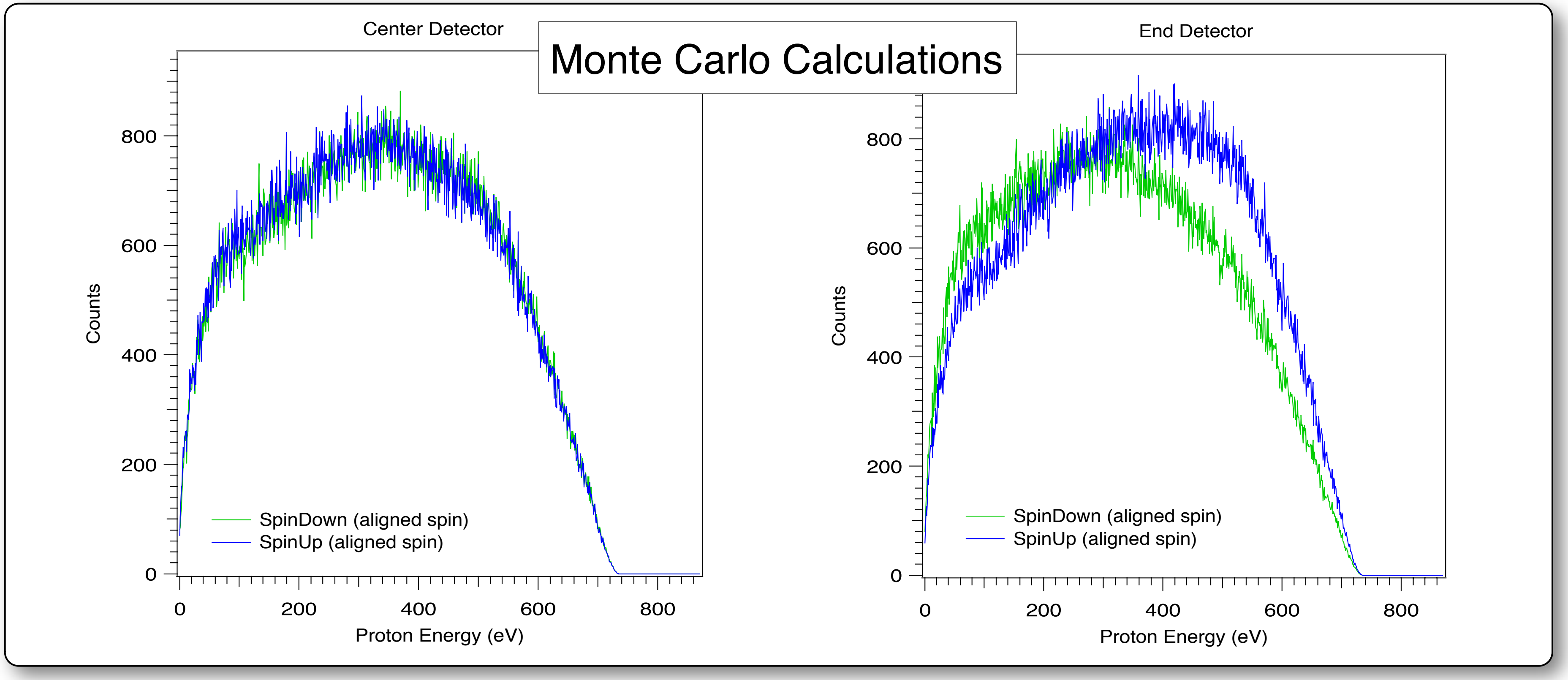



Monte Carlo Calculations

Systematics: spin dependent energy spectrum

$$A\sigma_n \cdot \frac{p_e}{E_e}$$

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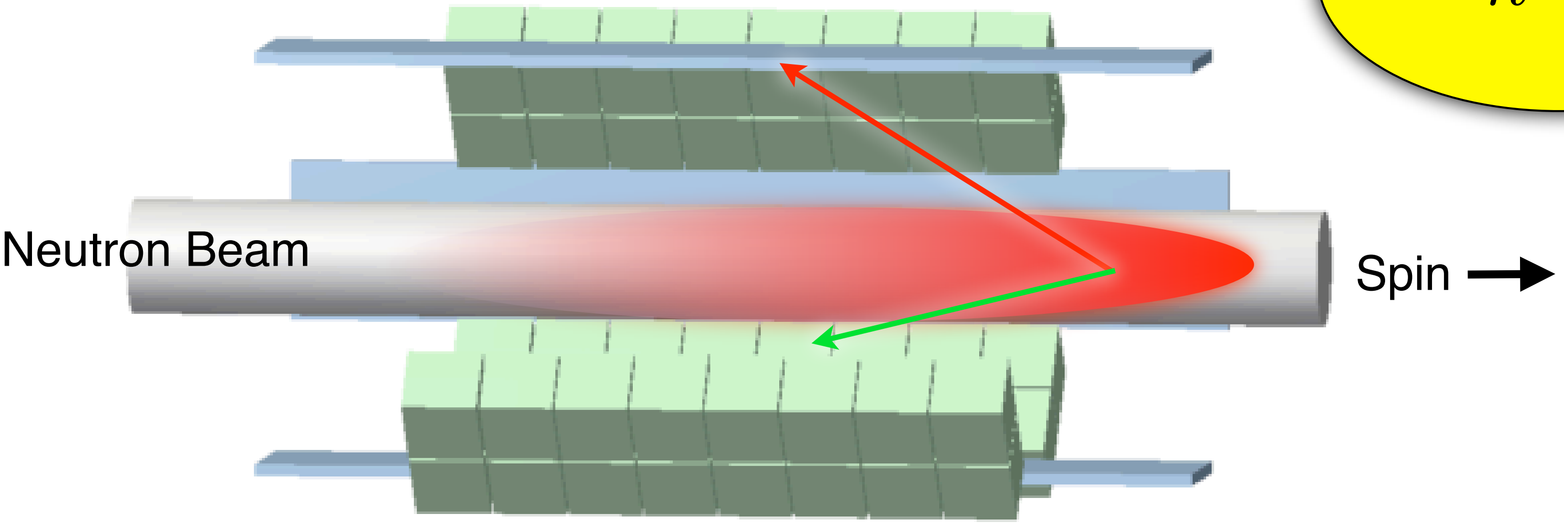

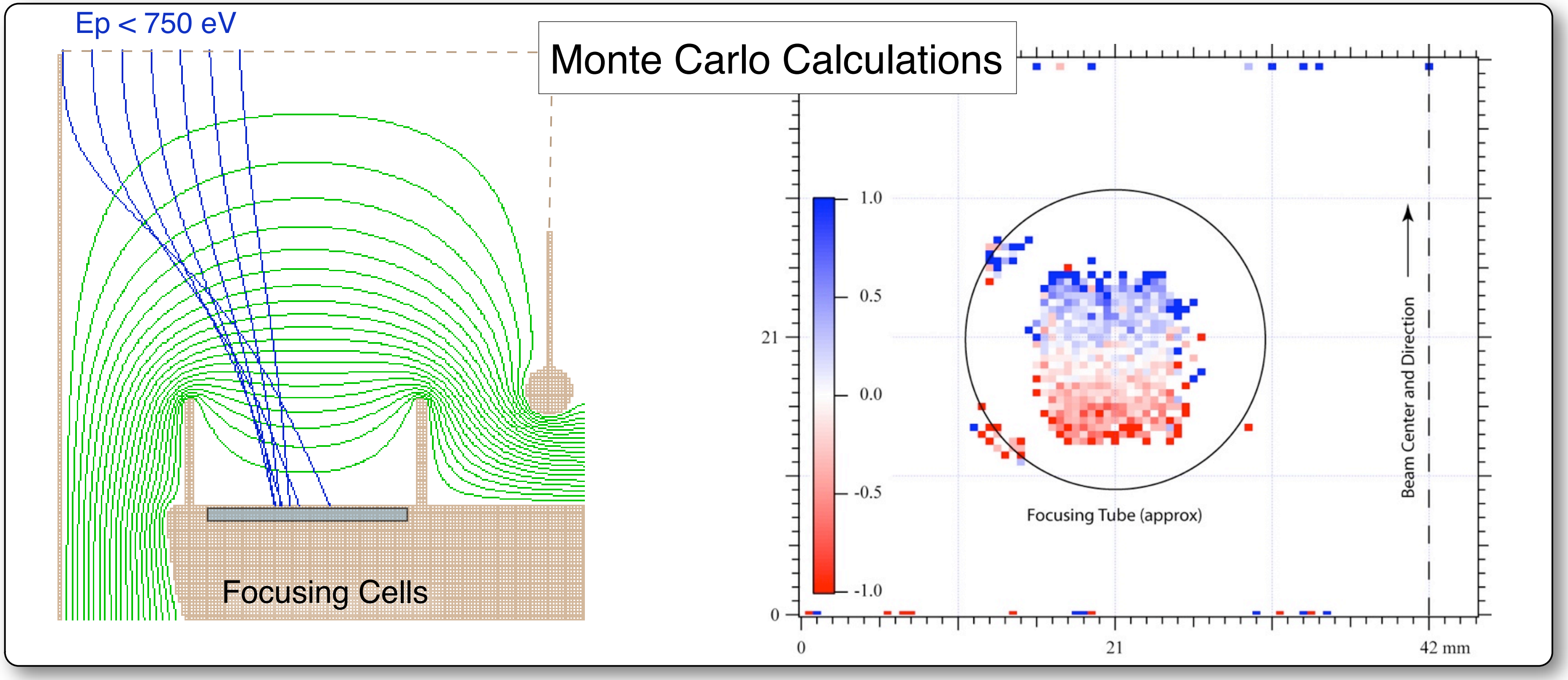

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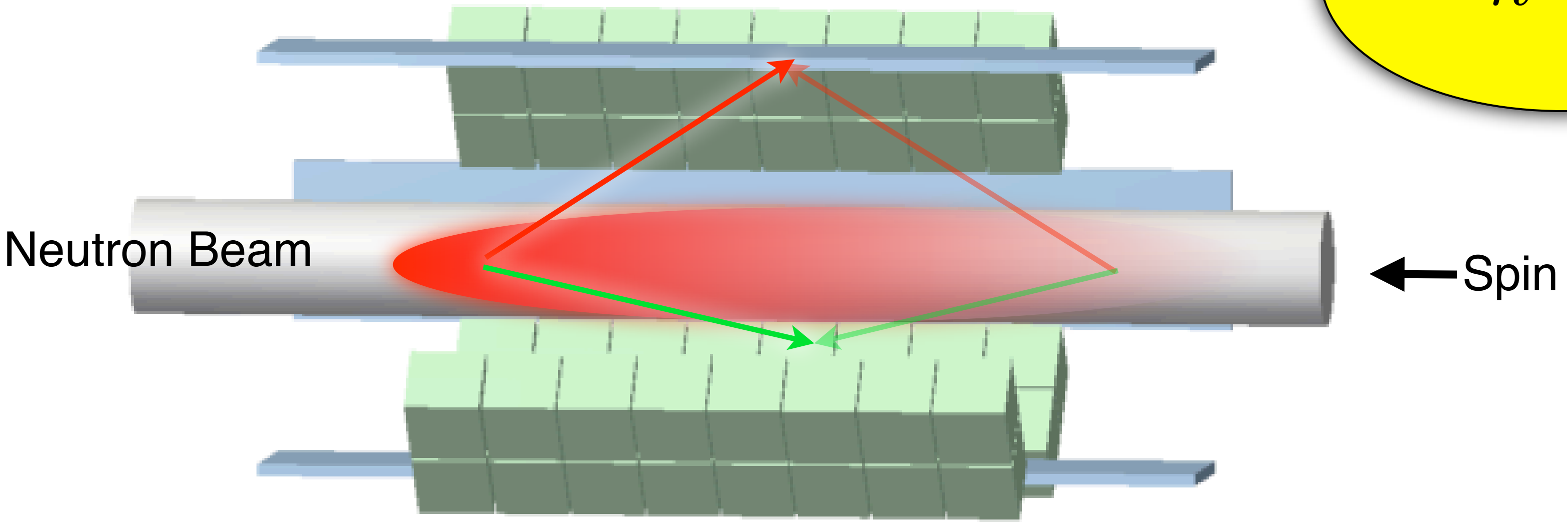

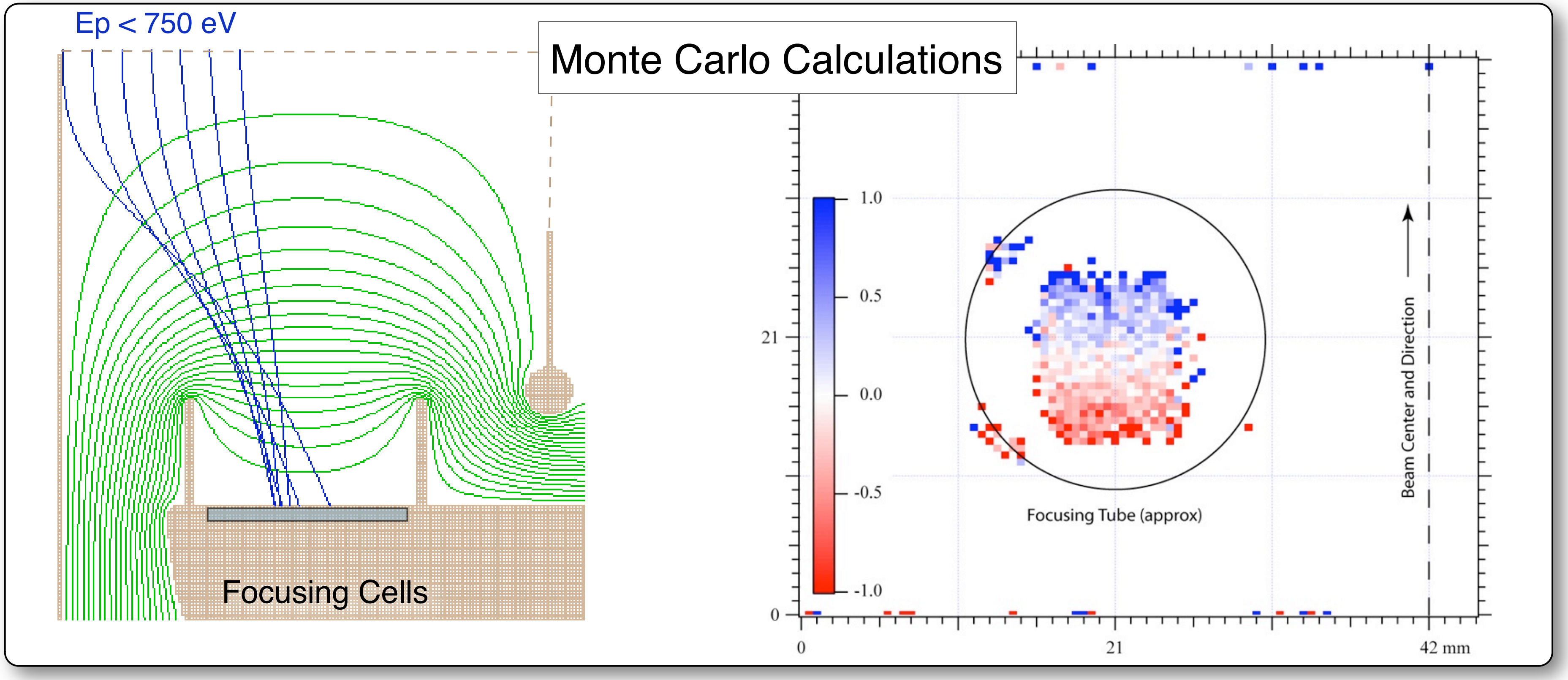
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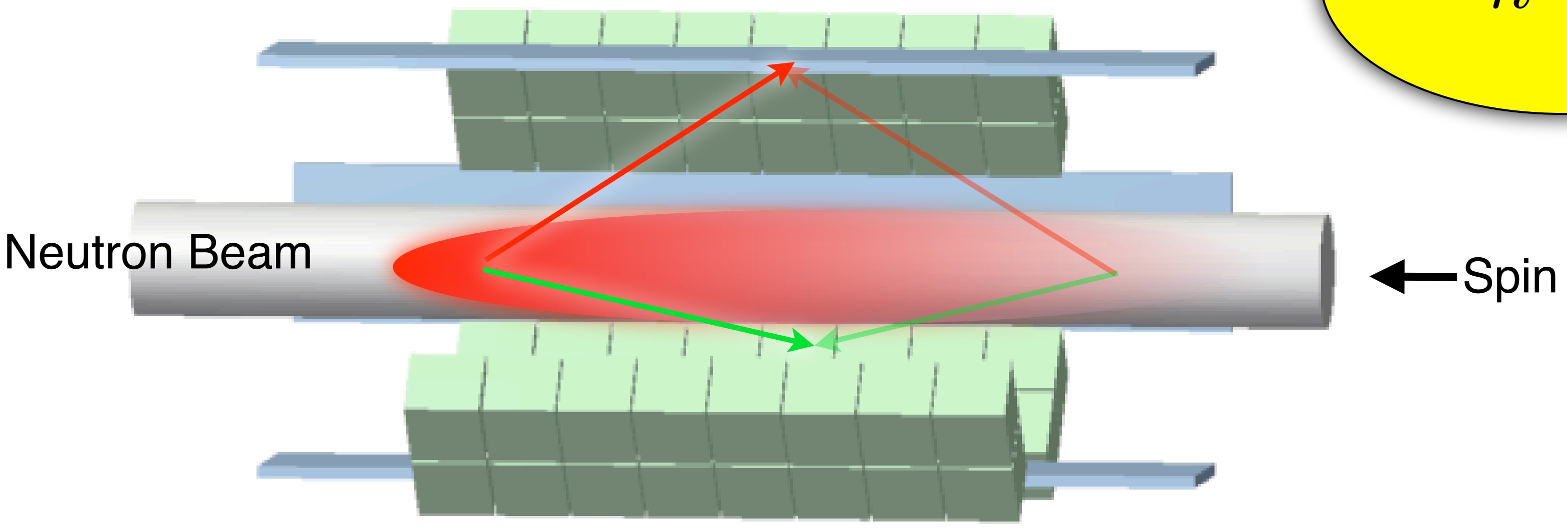
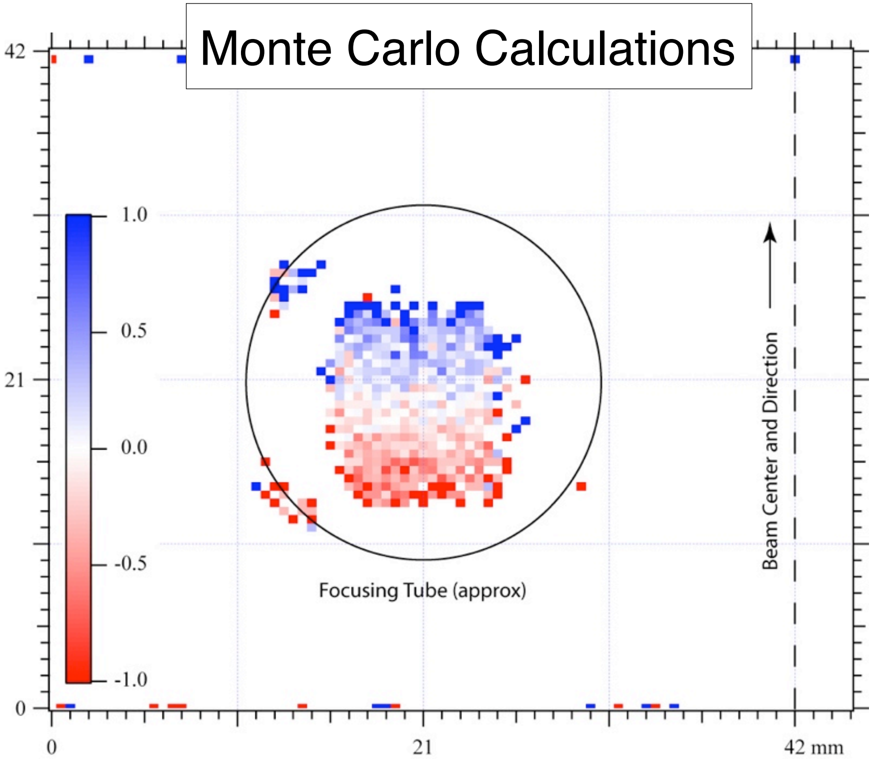
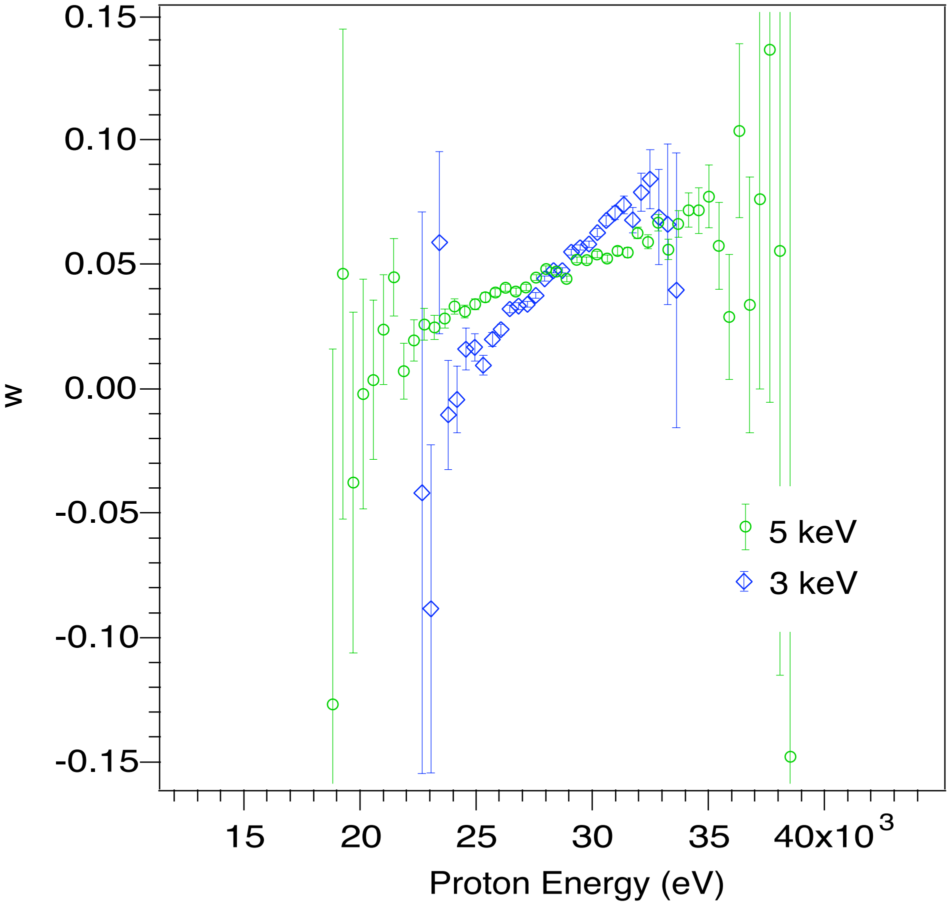


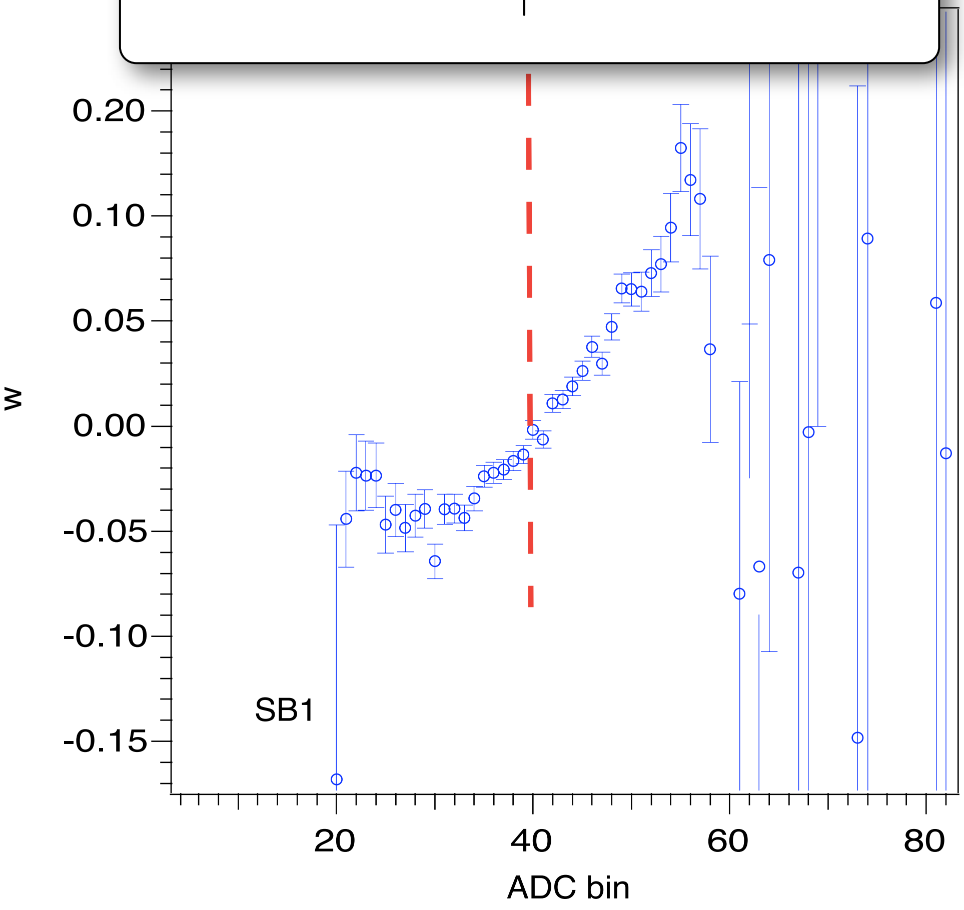

Monte Carlo Calculations

Systematics: spin dependent energy spectrum

$$w^{a1} = \frac{N_+^{a1} - N_-^{a1}}{N_+^{a1} + N_-^{a1}}$$

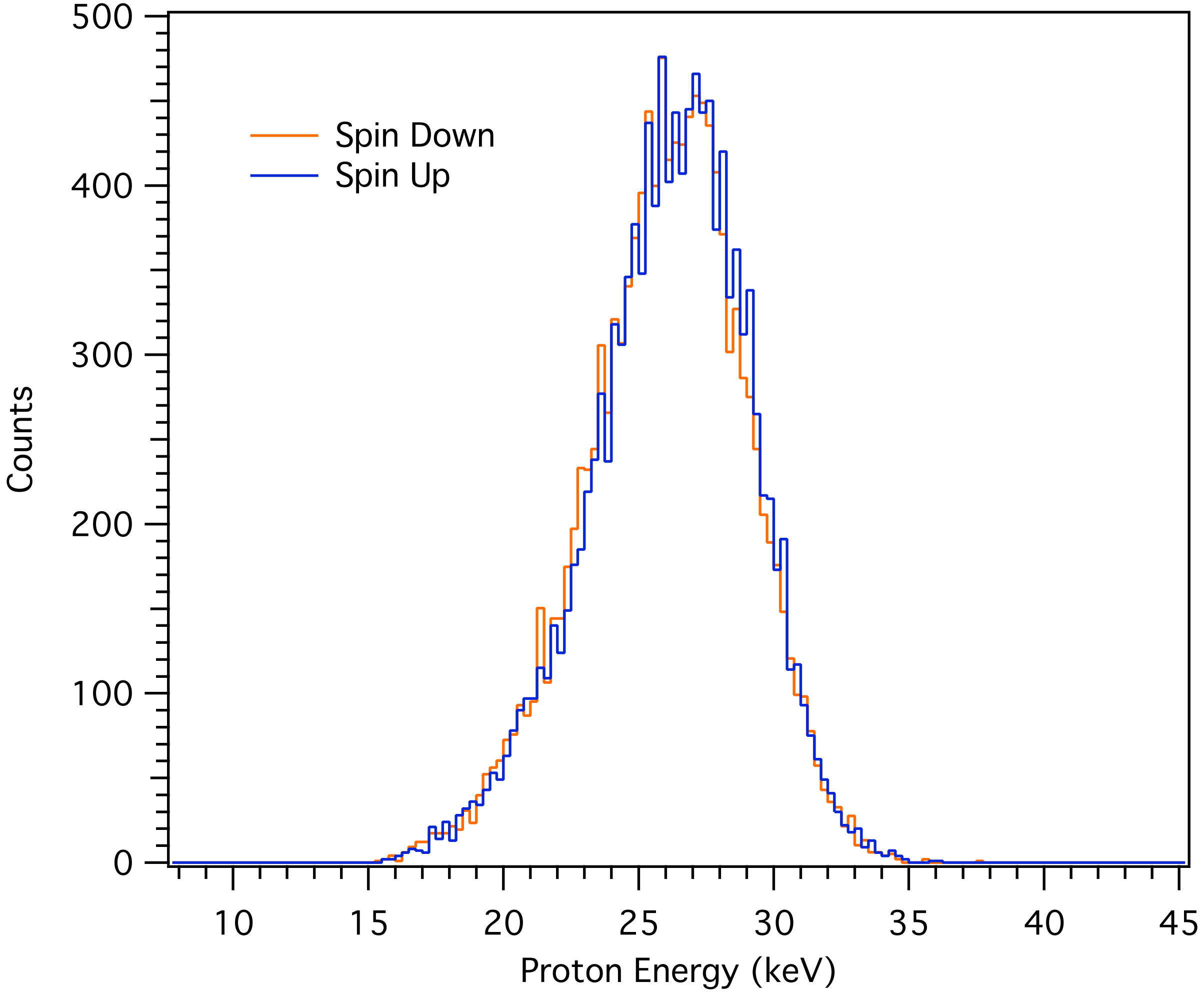


Monte Carlo Calculations



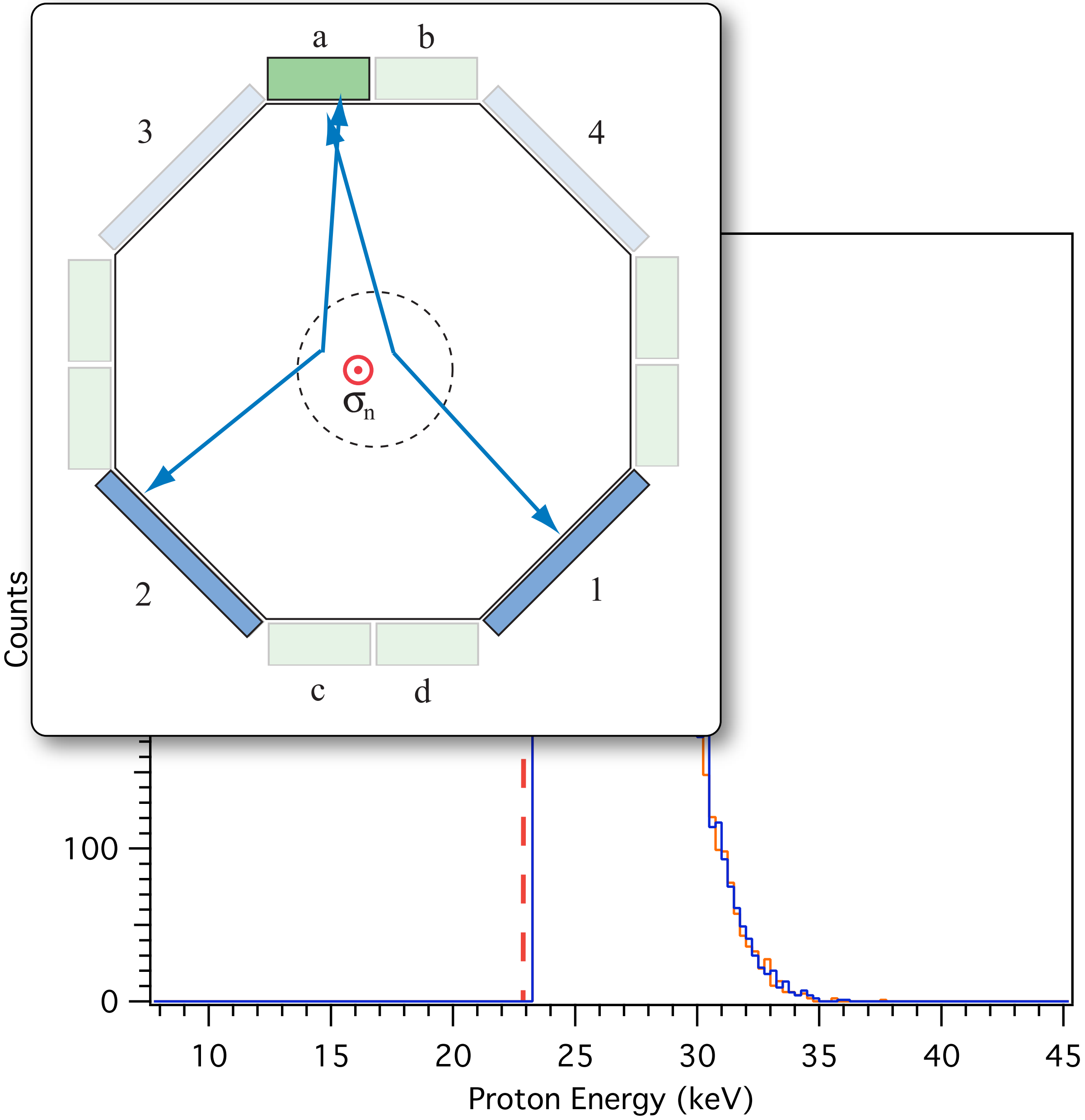
Data

Systematics: spin dependent energy spectrum



Shift of 159 eV

Systematics: spin dependent energy spectrum



Shift of 159 eV

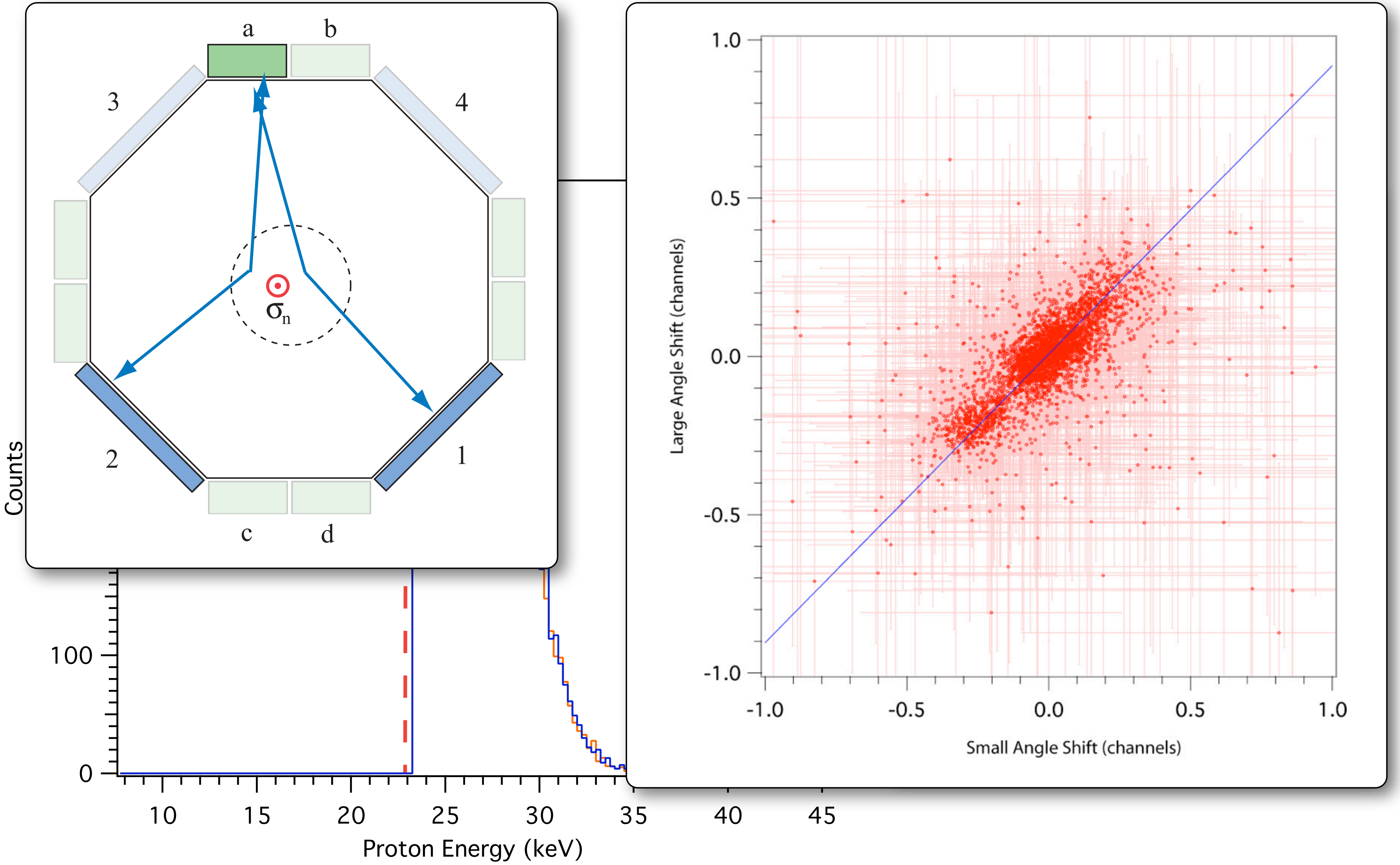
With a threshold of 23 keV

$w_{false} = 0.0079$

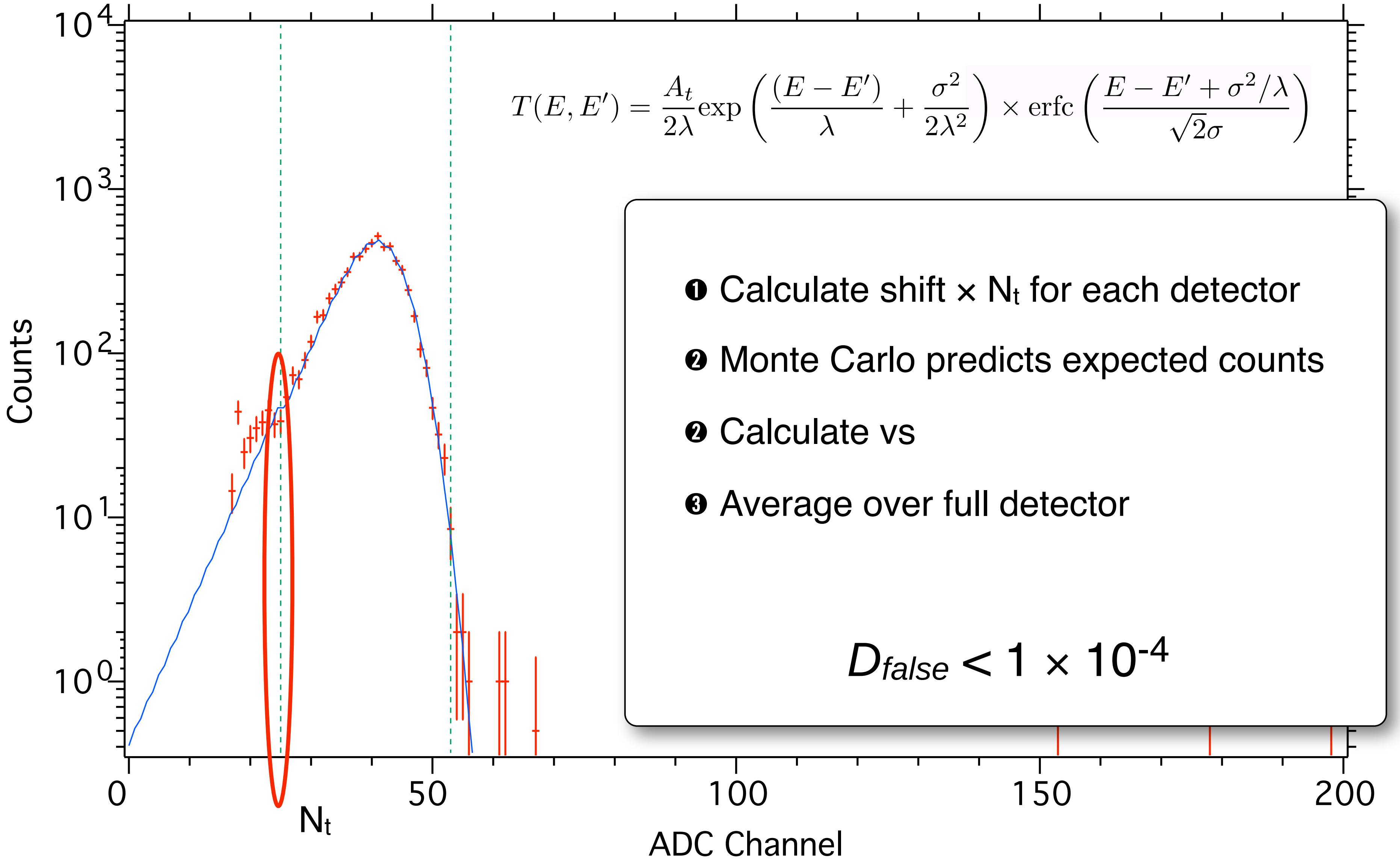
$$v^{a2,a1} = \frac{1}{2}(w^{a2} - w^{a1})$$

$$v^{a2,a1} = PD\vec{K}^{a}_{D} \cdot \hat{z}$$

Systematics: spin dependent energy spectrum



Systematics: spin dependent energy spectrum

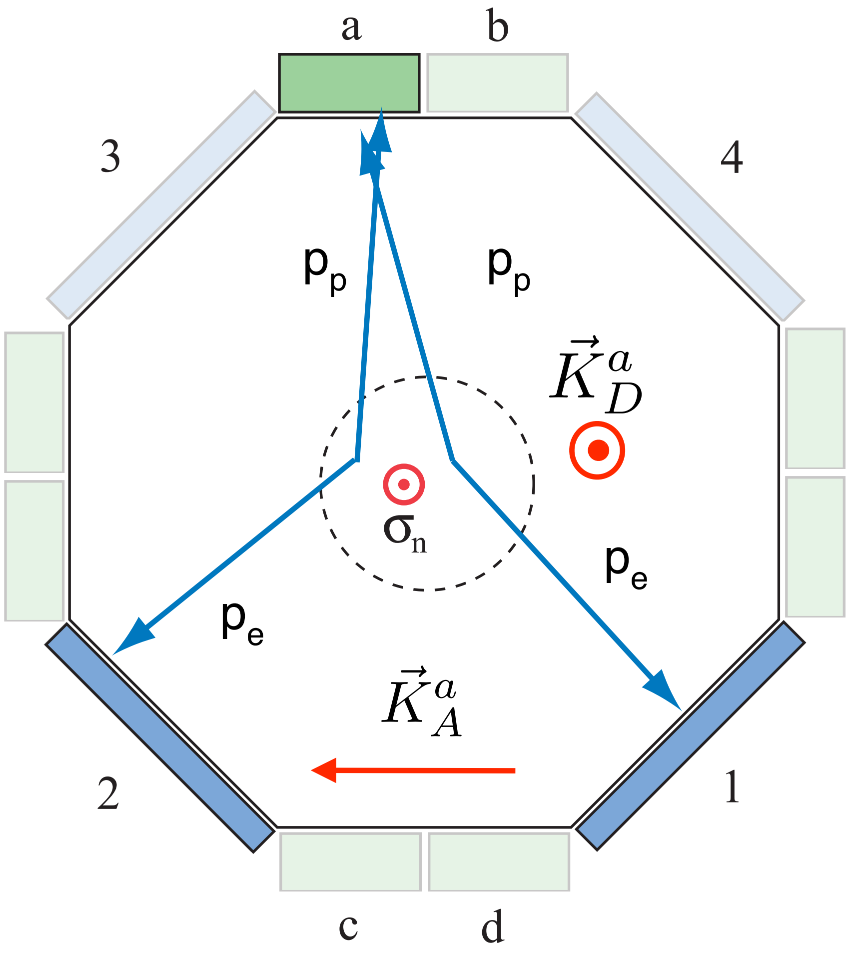


$$T(E,E') = \frac{A_t}{2\lambda} \exp\left(\frac{(E-E')}{\lambda} + \frac{\sigma^2}{2\lambda^2}\right) \times \mathrm{erfc}\left(\frac{E-E'+\sigma^2/\lambda}{\sqrt{2}\sigma}\right)$$

- ❶ Calculate shift × N_t for each detector
- ❷ Monte Carlo predicts expected counts
- ❷ Calculate vs
- ❸ Average over full detector

$D_{false} < 1 \times 10^{-4}$

emiT: signal extraction



Efficiency independent ratio,

$$w^{a1} = \frac{N^{a1}_{+} - N^{a1}_{-}}{N^{a1}_{+} + N^{a1}_{-}}$$

w is sensitive to *D*, but also to *A*, *B*

Define a parameter,

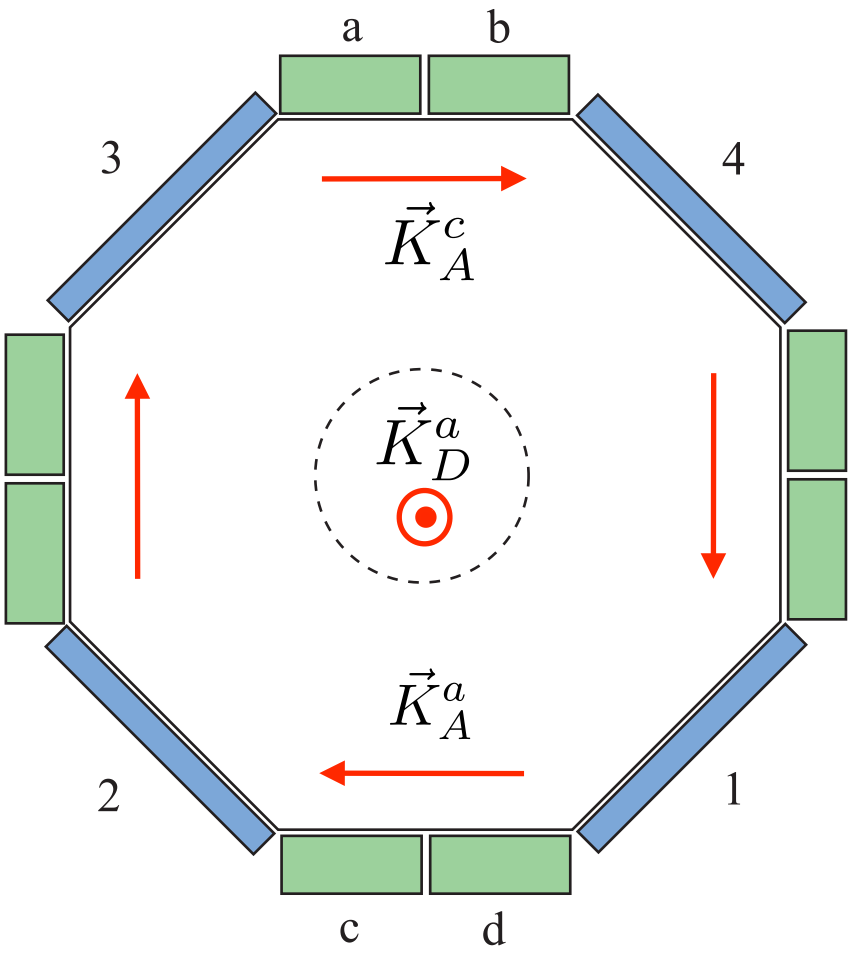
$$v^{a2,a1} = \frac{1}{2}(w^{a2} - w^{a1})$$

For a real detector,

$$v^{a2,a1} = \frac{1}{2} P \hat{\sigma}_n \cdot (D(\vec{K}^a_D) + A(\vec{K}^a_A) + B(\vec{K}^a_B))$$

Systematics: Asymmetric Transverse Polarization (Tilt ATP)

$$v^{a2,a1} = \frac{1}{2} P \hat{\sigma}_n \cdot \left(D(\vec{K}^a_D) + A(\vec{K}^a_A) + B(\vec{K}^a_B) \right)$$



$D_{false} = 0$

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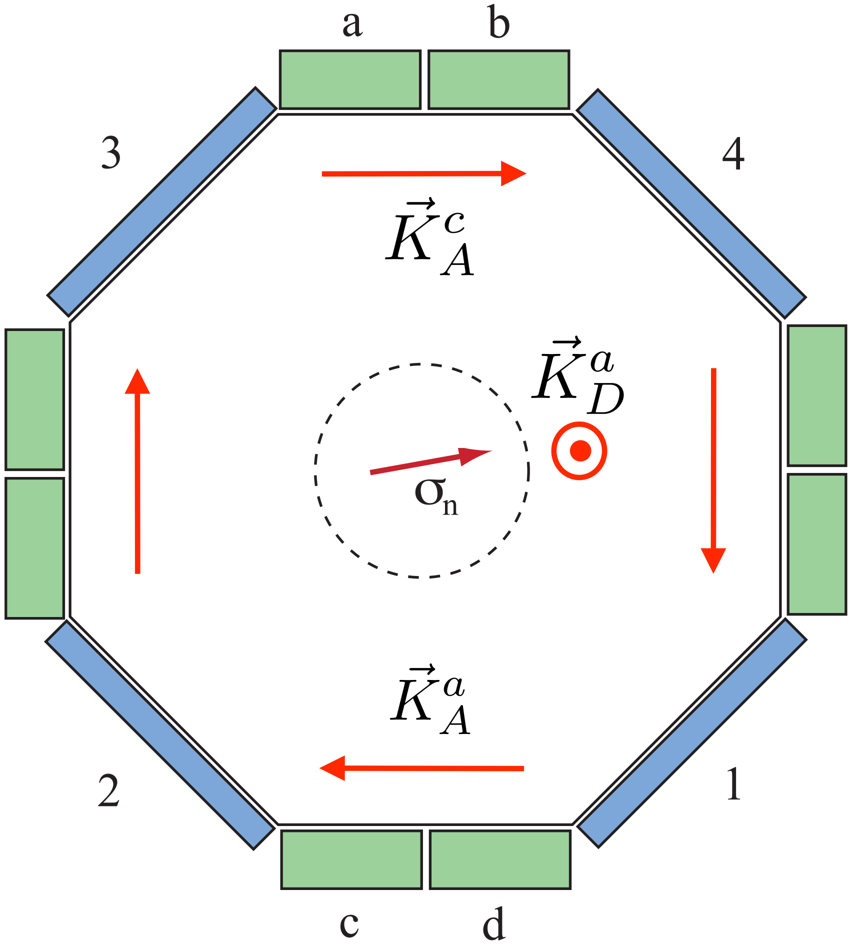

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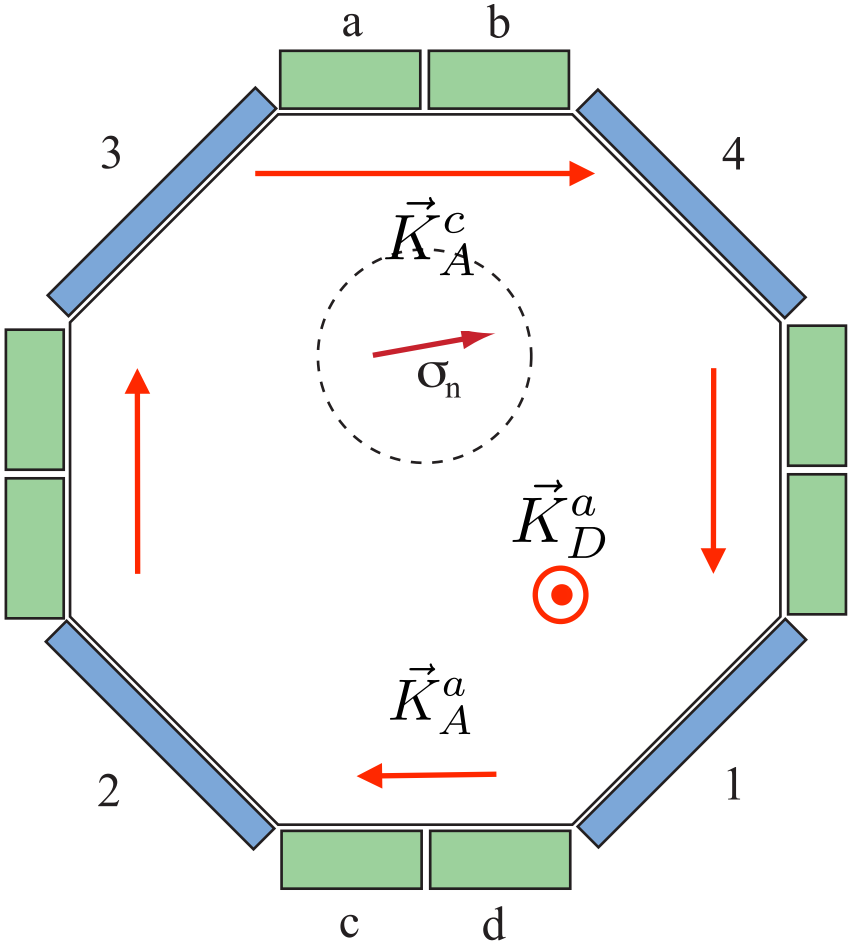


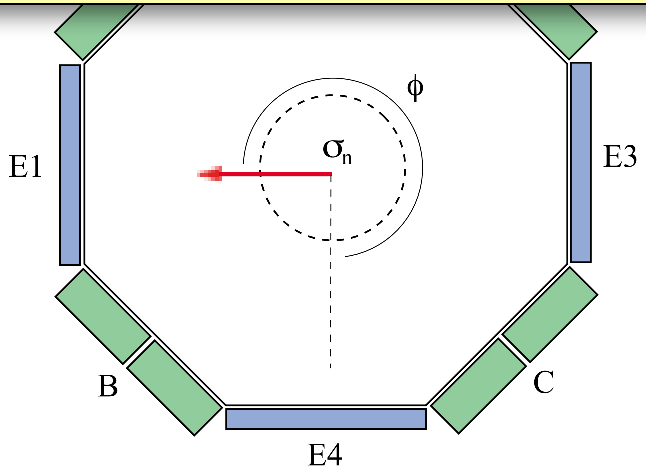
Monte Carlo
15 mrad polarization tilt,
beam displacement 5mm:
$D_{false} \sim 1\times10^{-4}$

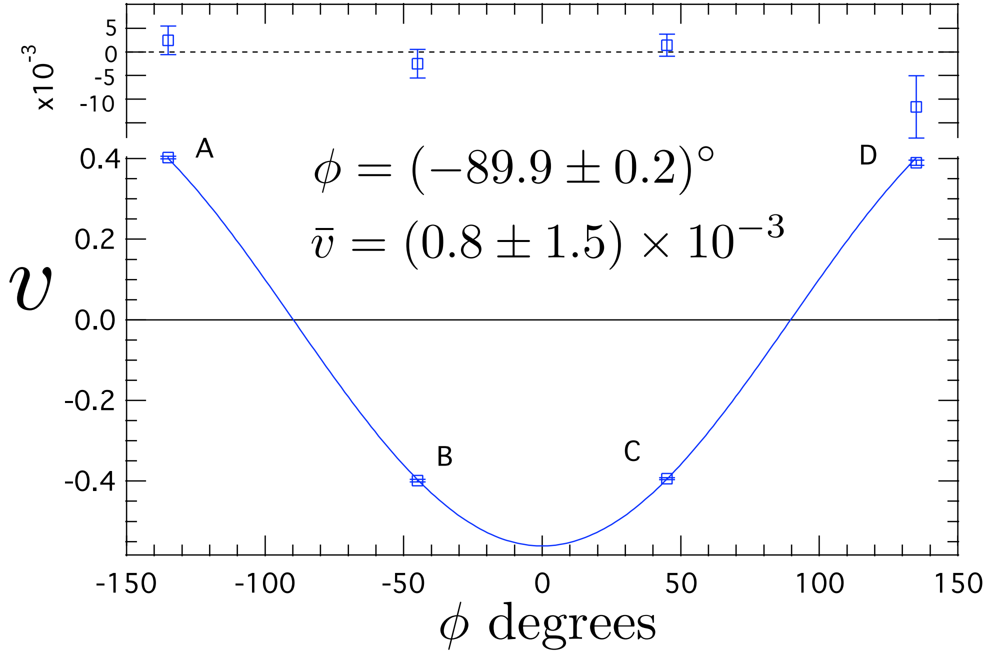
$D_{false} \neq 0$

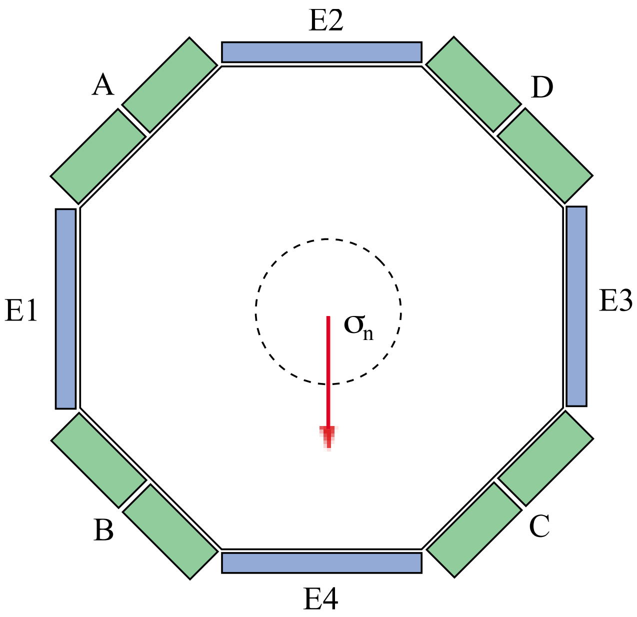
Two perpendicular asymmetries do *not* cancel

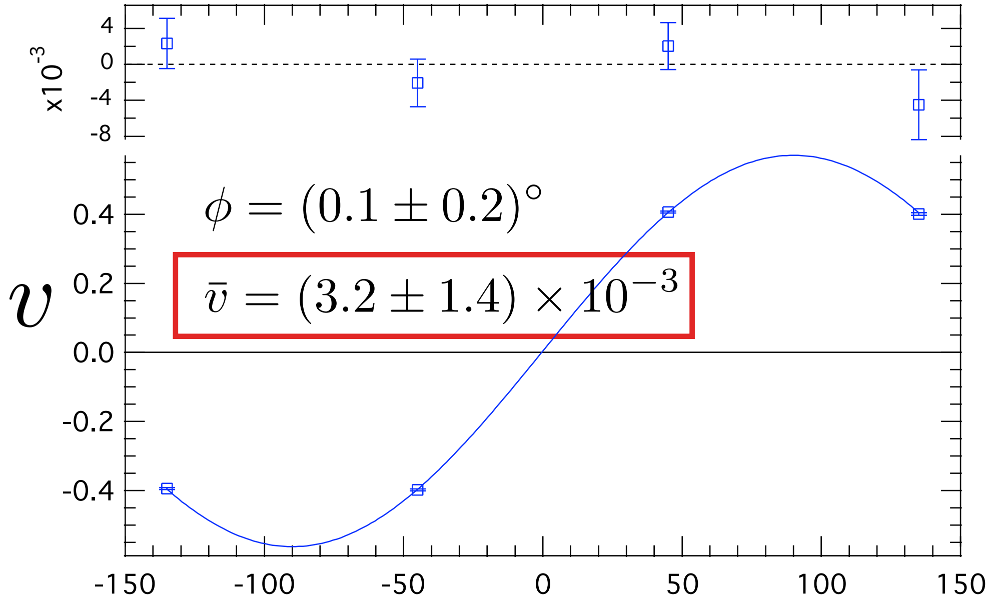
Systematics: Asymmetric Transverse Polarization (Tilt ATP)

Intentional field rotation
(Maximal polarization misalignment)





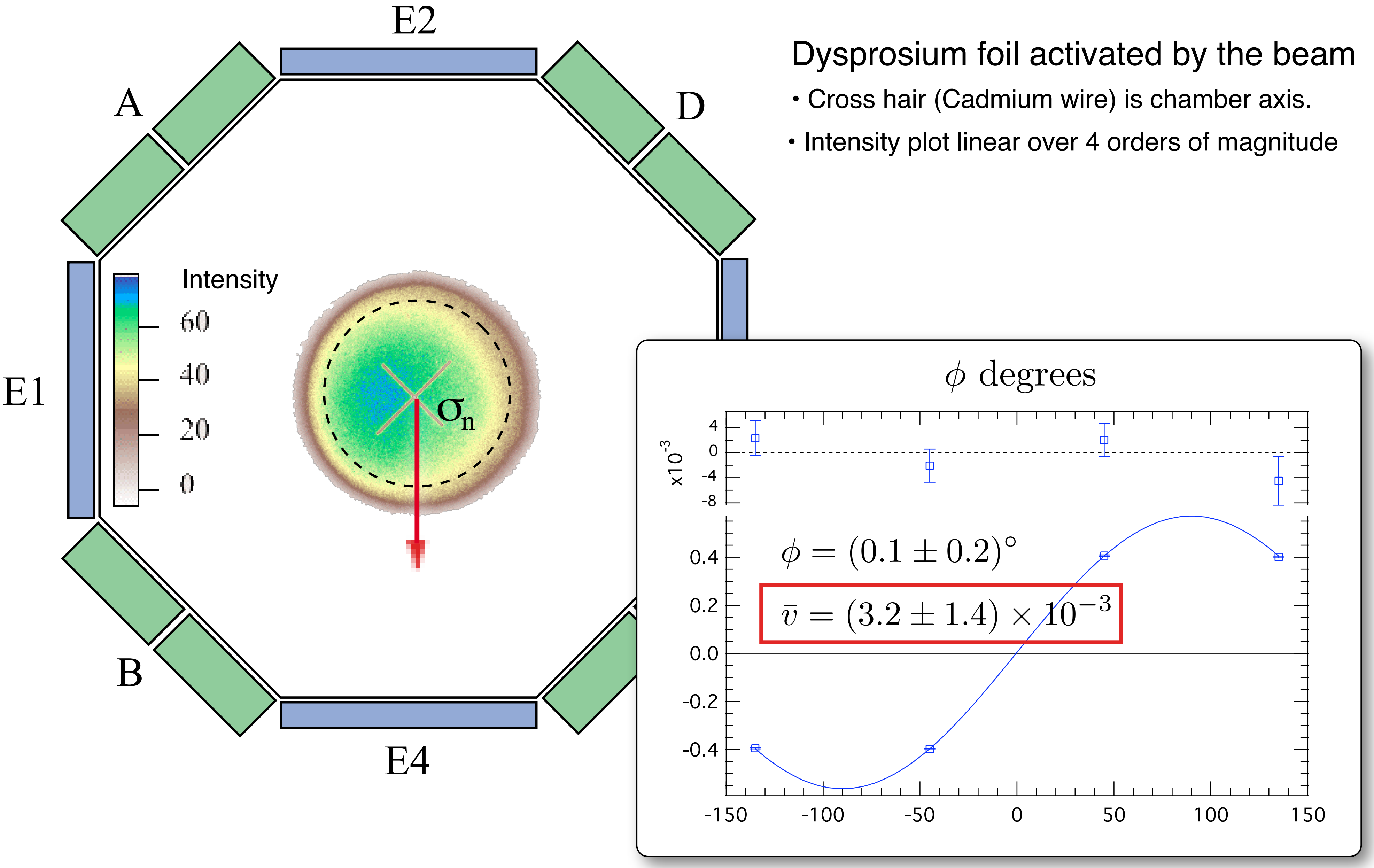




Systematics: Measured Intensity Distribution (Tilt ATP)

Dysprosium foil activated by the beam

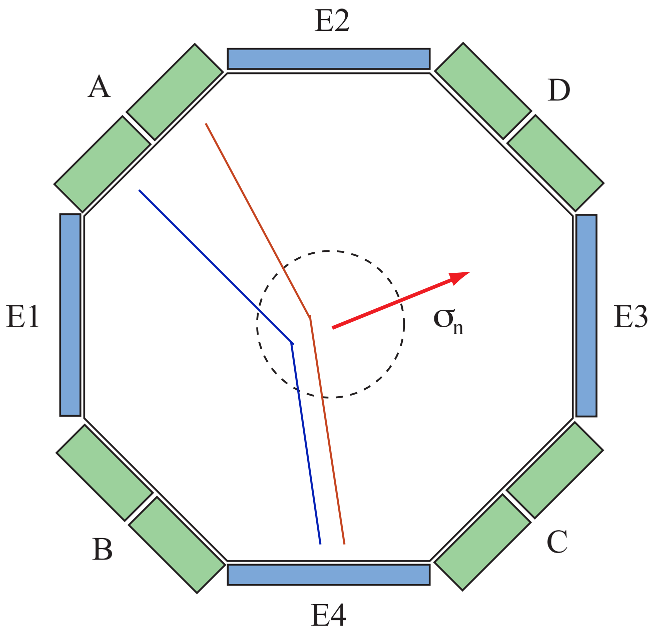
- Cross hair (Cadmium wire) is chamber axis.
- Intensity plot linear over 4 orders of magnitude



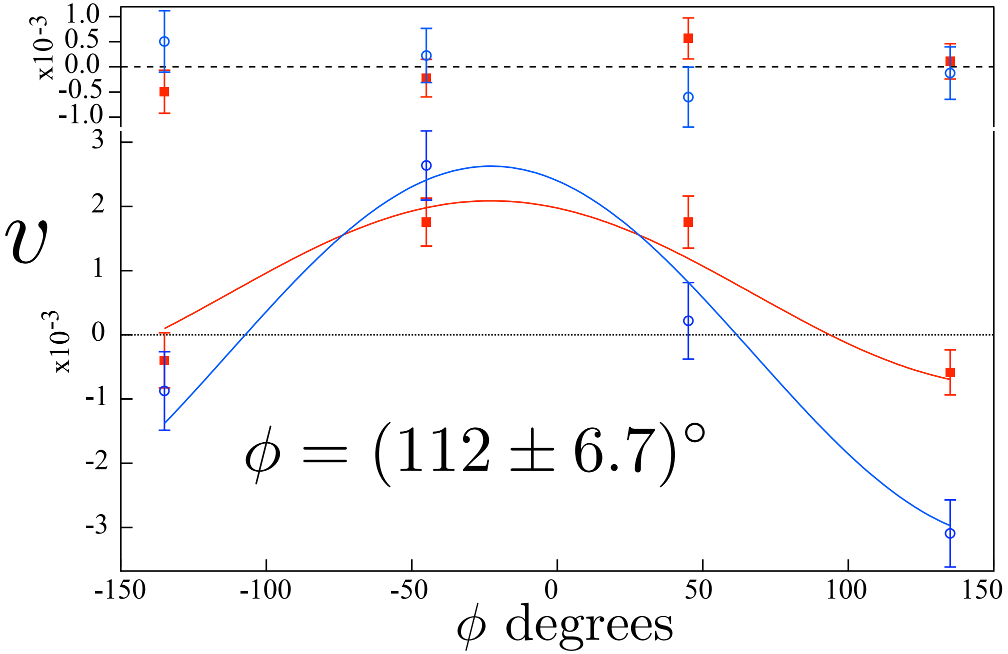
$$\phi = (0.1 \pm 0.2)^\circ$$

$$\boxed{\bar{v} = (3.2 \pm 1.4) \times 10^{-3}}$$

Systematics: Measured Intensity Distribution (Tilt ATP)



22 days of data (7% of total)



Implied misalignment;

Large angle: 4 ± 0.5 mrad

Small angle: 5 ± 0.5 mrad

$$\bar{v} = (3.2 \pm 1.4) \times 10^{-3}$$

from previous slide

$$D_{ATP} = (5.7 \pm 2.6) \times 10^{-6}$$

(preliminary cuts)

Conclusions

- Currently blind: checking cuts/finalizing systematics
- Over 350 million coincidence events collected
- *Preliminary* treatment of systematic effects indicate all are below 1×10^{-4}

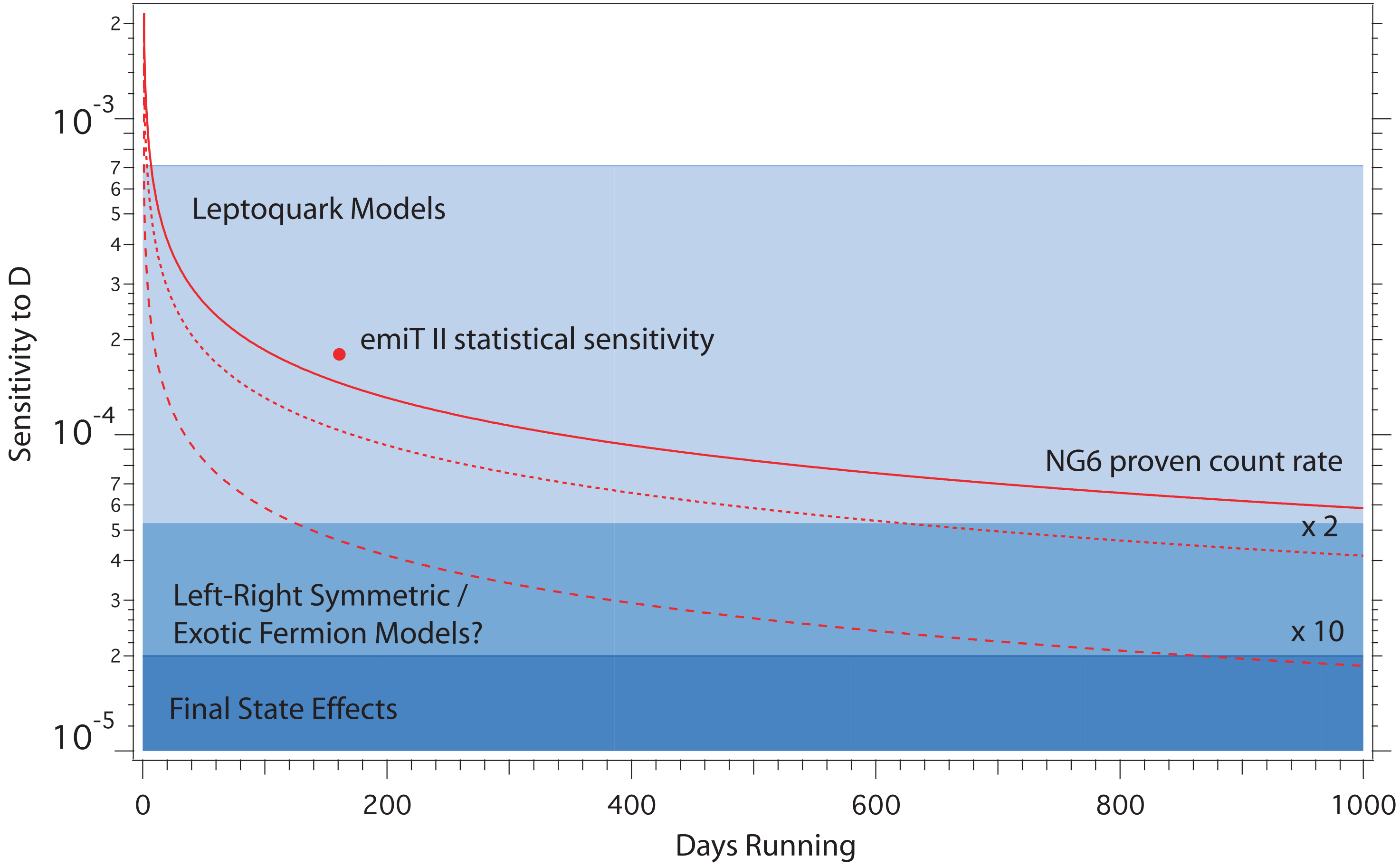
• Spin Dependent Spectra	$< 1 \times 10^{-4}$
• Twist ATP	$< 1 \times 10^{-5}$
• Electron backscattering	$< 1 \times 10^{-5}$
• Tilt ATP	$< 6 \times 10^{-6}$
• Spin depen. background	$< 1 \times 10^{-6}$
• Flux variations	$< 2 \times 10^{-4} \bullet D$
• Polarization variations	$< 2 \times 10^{-4} \bullet D$
• Flip clock	$< 1 \times 10^{-12} \bullet D$

Expected statistical sensitivity of $D \sim 2 \times 10^{-4}$

- Data analysis VERY near completion

Which, because of nuclear matrix elements involved will be the *most* sensitive test of T (D) invariance in beta decay (e.g. ^{19}Ne)

Future Possibilities



Current apparatus could reach 5 x 10^{-5} with reasonable upgrades

❶ Leptoquarks/Exotic Fermions/L-R symmetry

In principle one could *measure* the FSE

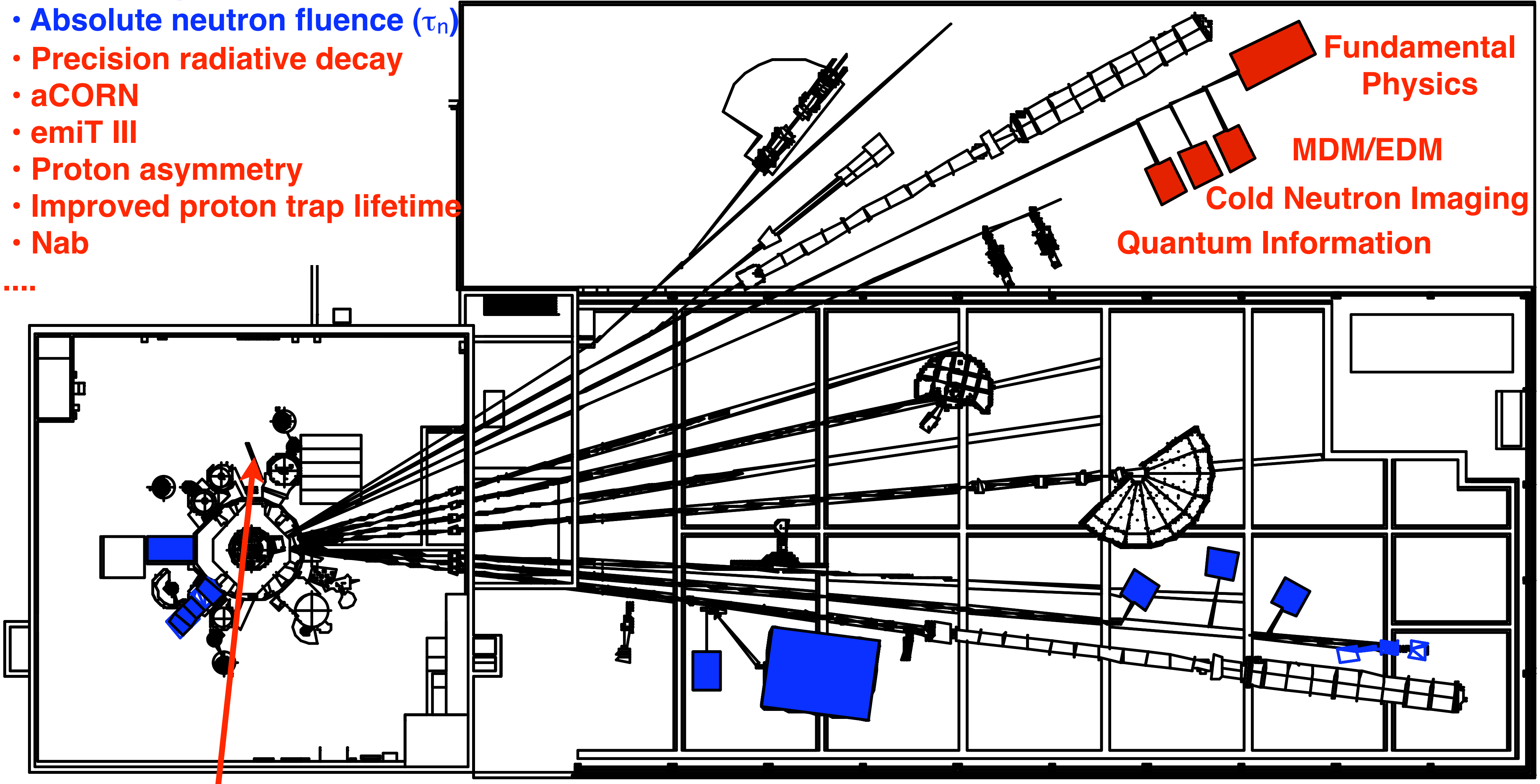
❷ Leptoquarks/Exotic Fermions/L-R symmetry + Scalar and Tensor Currents

Future Possibilities

Physics Program:

- UCN n lifetime
- Neutron spin rotation
- Absolute neutron fluence (τ_n)
- Precision radiative decay
- aCORN
- emiT III
- Proton asymmetry
- Improved proton trap lifetime
- Nab

....



Proposed New Guide Hall
(conceptual design)

Fundamental Physics

MDM/EDM

Cold Neutron Imaging

Quantum Information

New Cold Source

🟦 Existing (or in progress)
🟥 Proposed