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

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Symmetries........

Continuous symmetries

- Translation / Rotation (lead to conservation laws)

Discrete symmetries

- Parity (Inversion of coordinates)
- Charge conjugation (particles to anti-particles)
- **Time reversal**

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

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

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

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- Strong and electromagnetic interactions both conserve C, P, and T
- Weak interaction violates C and P, but what about combinations?
- No observed violation of CPT to date
- In 1964 CP violation observed in neutral kaons
- CP violation directly observed in kaon decay (KTeV 1999 and NA48 1999)
- CP violation observed in the decay neutral B mesons (Belle and BaBar Collaborations, PRL 2001)

All consistent with a phase in the quark mixing matrix, i.e consistent with the Standard Model

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

So this is the end of the story.....

Baryon Asymmetry....

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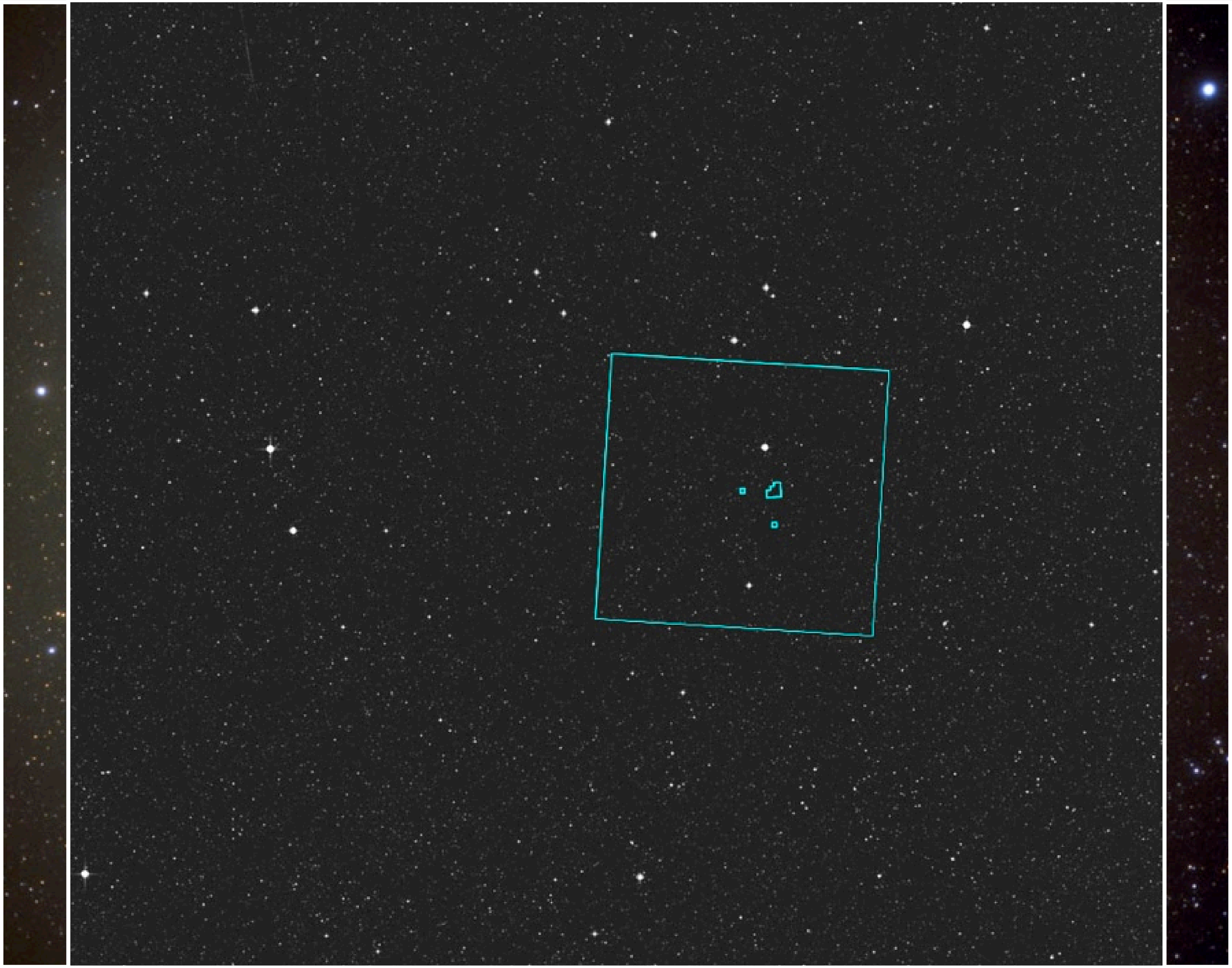
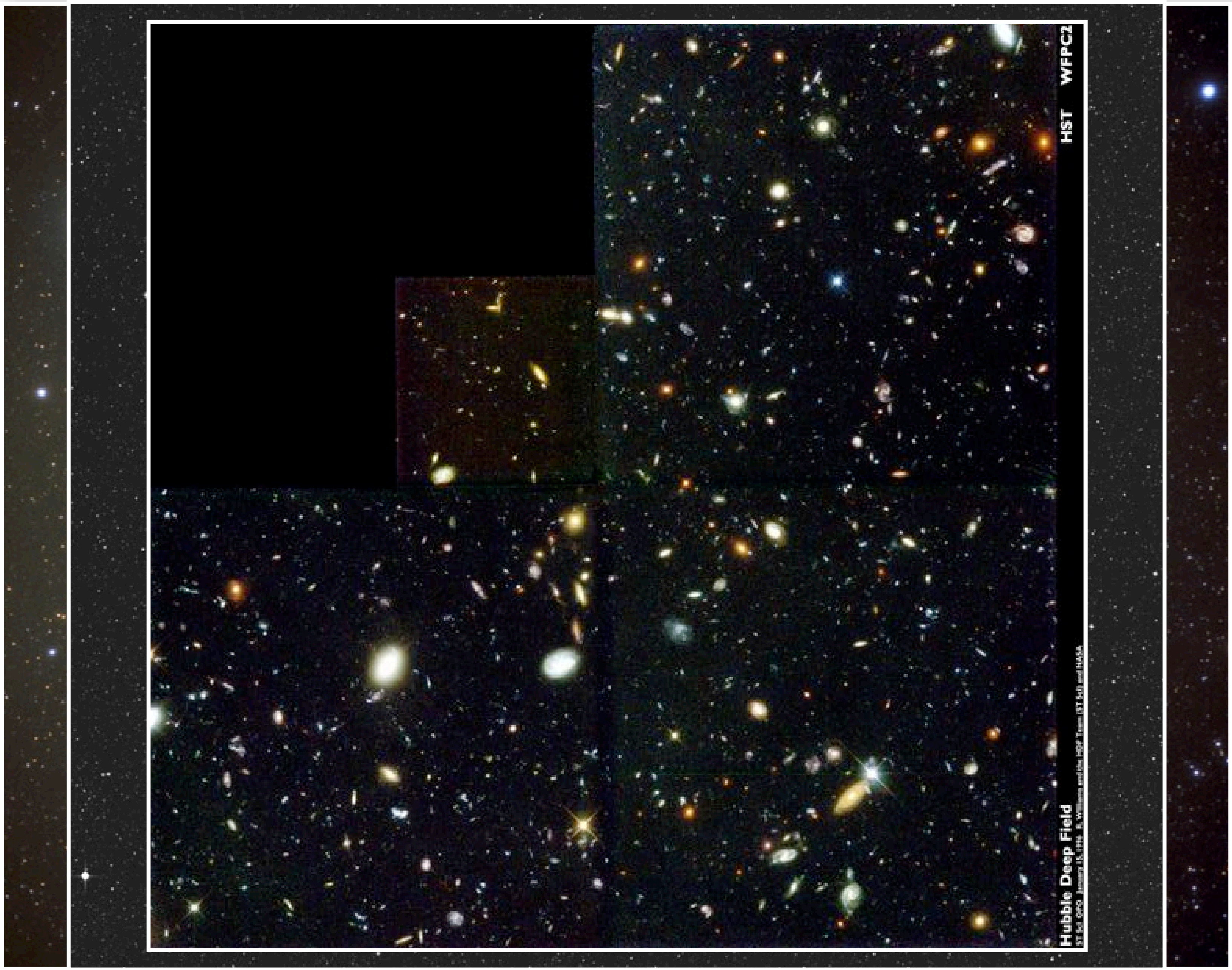


Baryon Asymmetry....



Baryon Asymmetry....

- Baryon asymmetry
  - Cosmic rays give $(\bar{p}/p) \sim 10^{-4}$
  - No evidence of gammas from antiproton annihilation

- A baryon asymmetry requires:
  - lack of thermal equilibrium
  - baryon number violation
  - CP violation

  (If we assume CPT, T violation is implied by CP violation)

- However, the Standard model is MANY orders of magnitude to small !!

  (In the quark sector)

Baryon Asymmetry and a bit more....

- 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??

So while the Standard Model is pretty darn good, isn't complete.

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

There *must* be additional CP 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

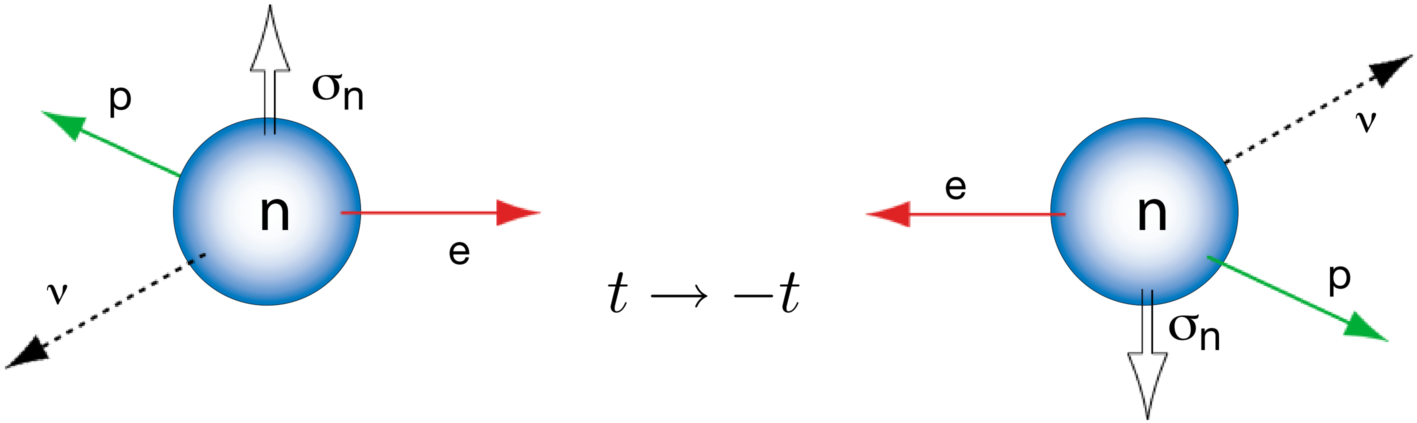
Kaon Decay
Hyperon Decay
Ternary Fission

Nuclear Beta Decay Experiments

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

^{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	$D = -(2.8 \pm 7.1) \times 10^{-4}$	T. Soldner *et al. Phys. Lett. B* ***581*** *(2004)*
	$D = (-0.6 \pm 1.2(\text{stat.}) \pm 0.5(\text{syst.})) \times 10^{-3}$	emiT I *Phys. Rev. C* ***62*** *055501 (2000)*

Polarized Neutron Decay



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

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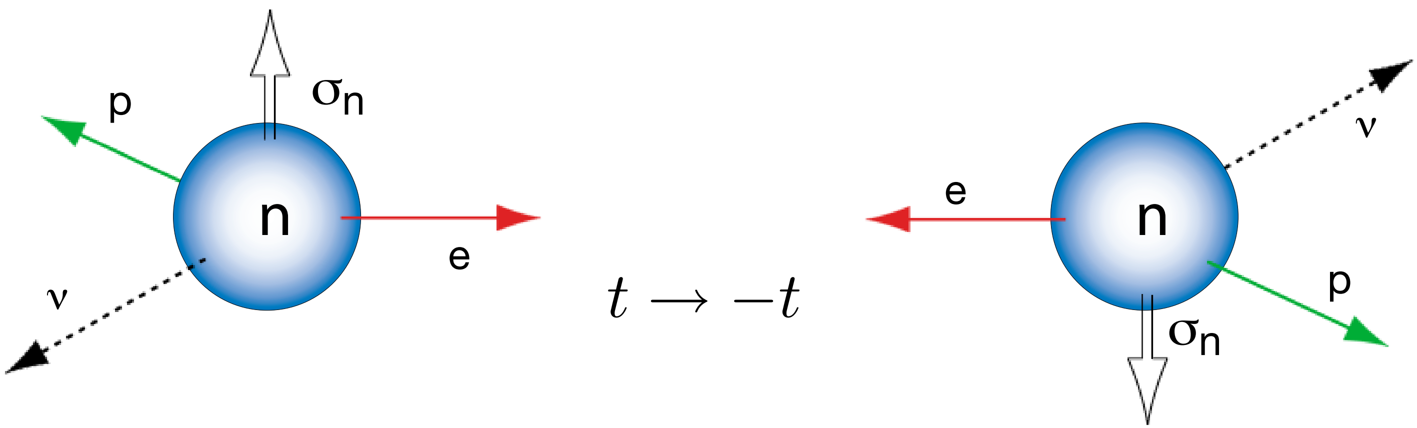

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Measurable & non-zero

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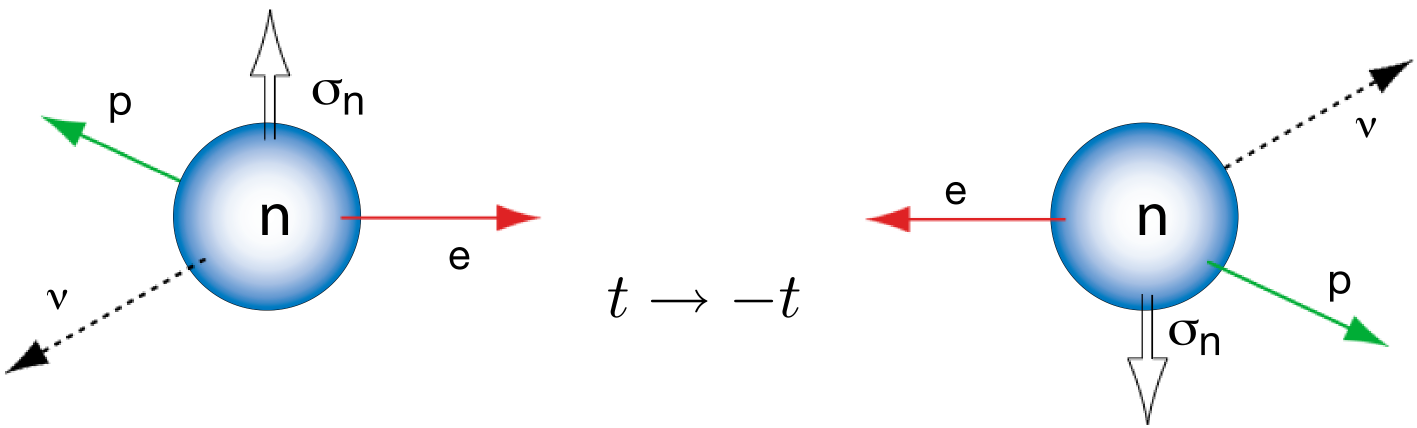

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T-odd, P-even

- $D = -2.8 \pm 7.1 \times 10^{-4}$ *TRINE*

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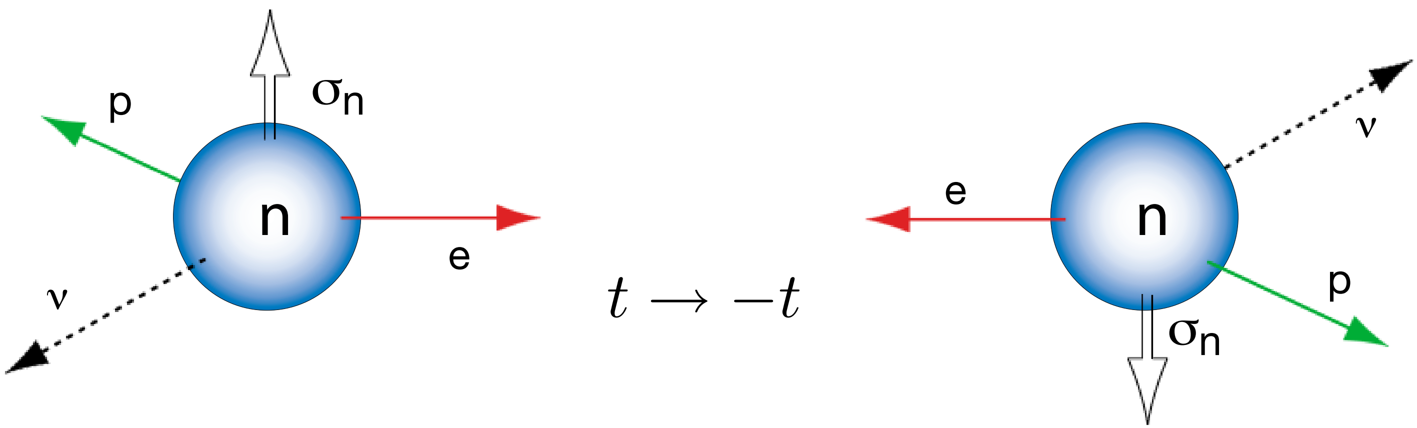

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Not quite T reversal; Initial and final states are *not* reversed: final state interactions

- $|D_{f.s.}| = 1.1 \times 10^{-5}$ $\quad {}^{19}Ne \sim 2.6 \times 10^{-4}\ p/p_{max}$

Polarized Neutron Decay

$$D^{CS} = \frac{m_e}{p_e}\frac{\alpha|\lambda|}{1+3|\lambda|}(b_F + b_{GT})$$

$$|D^{WM}| \approx 1.1 \times 10^{-5} p_e/p_{e(max)}$$

$$|D^{CS}| < 1.6 \times 10^{-5} m_e/p_e$$

w/ 80 keV threshold $|D_{C.S.}| < 3 \times 10^{-5}$

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

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

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Polarized Neutron Decay

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

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

$= -0.1173 \pm 0.0013$

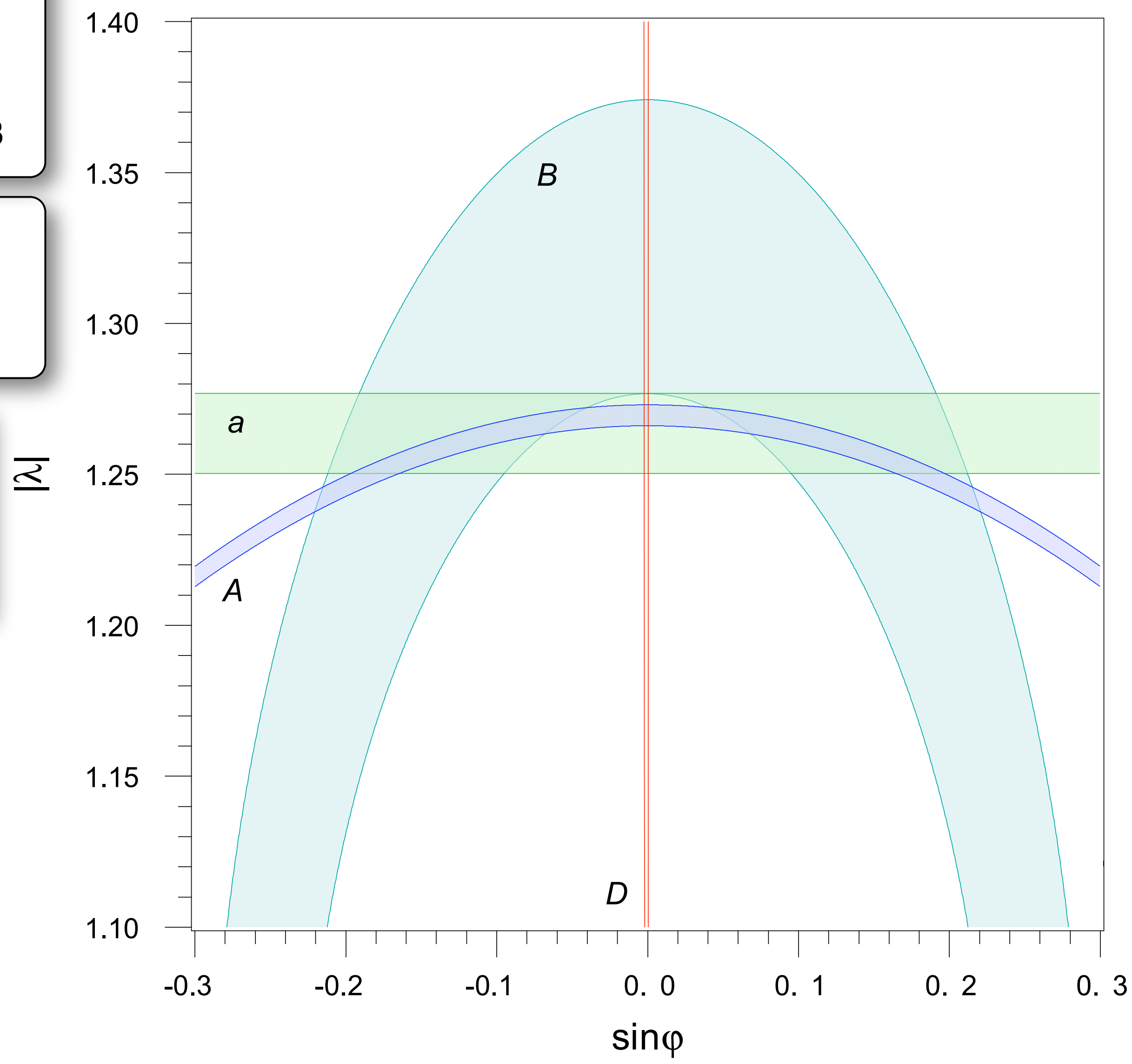
$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}$$ $= -0.103 \pm 0.004$

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

$= 0.981 \pm 0.004$

T-odd (P-even) triple correlation:

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



Polarized Neutron Decay: Possible Sources of T Violation

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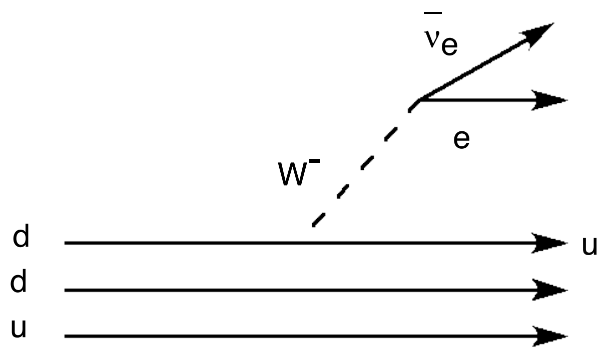

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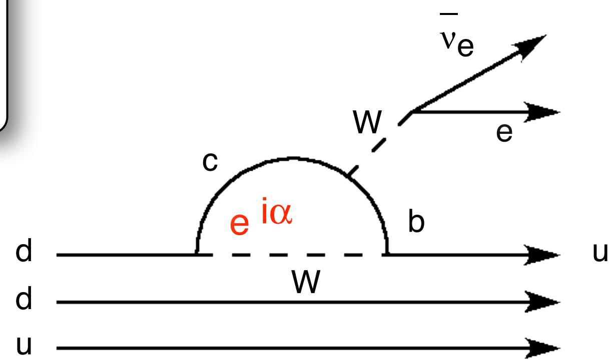
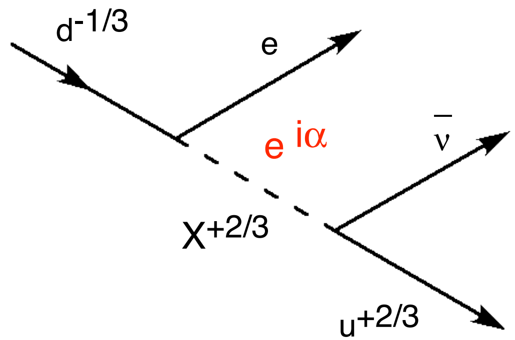


Standard Model



Super-symmetry

L-R symmetric

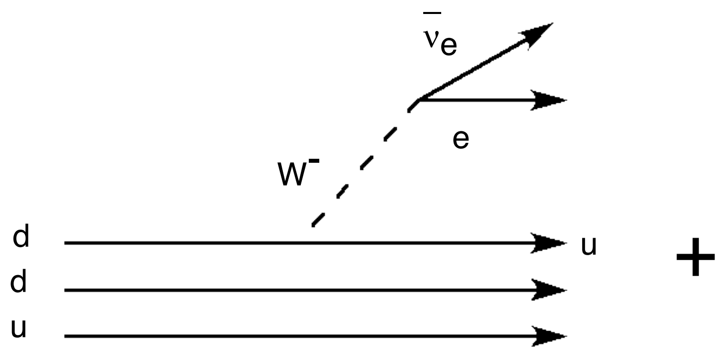
Lepto-quarks

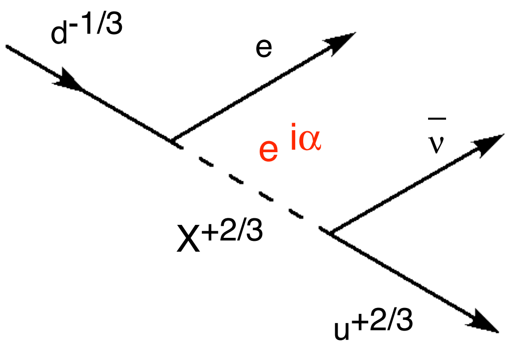
Theory	*D*
1. Kobayashi-Maskawa Phase	$< 10^{-12}$
2. Theta-QCD	$< 10^{-14}$
3. Supersymmetry	$\leq 10^{-7} - 10^{-6}$
4. Left-Right Symmetry	$\leq 10^{-6} - 10^{-5}$
5. Exotic Fermion	$\leq 10^{-6} - 10^{-5}$
6. Leptoquark	present limit

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

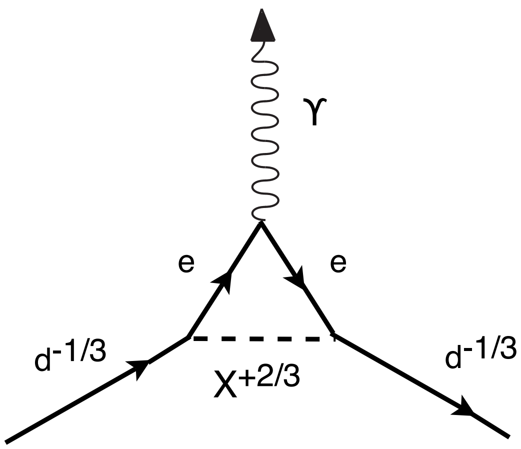
Schiff Moments??

Polarized Neutron Decay: Possible Sources of T Violation





Lepto-quarks
(for D)



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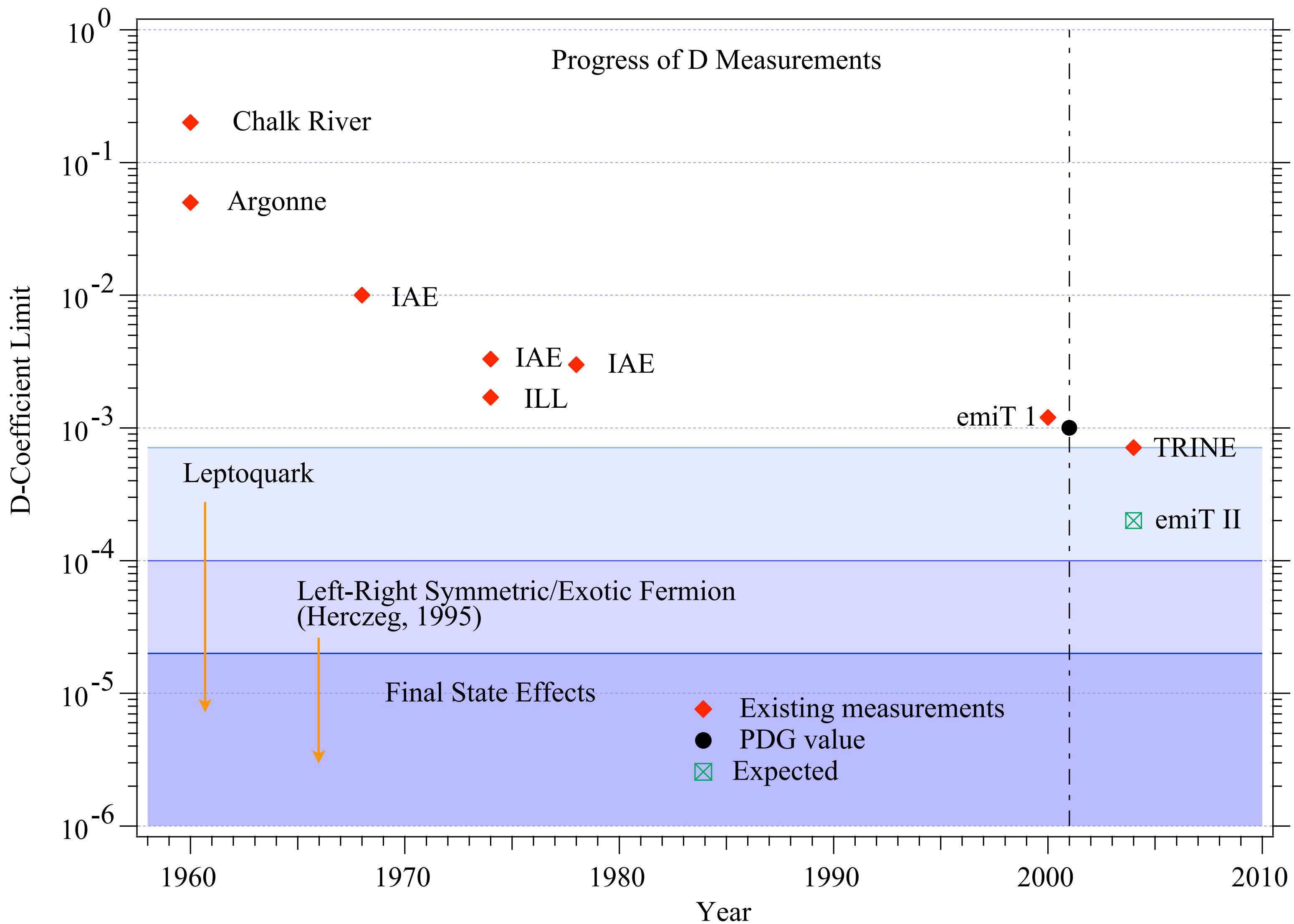
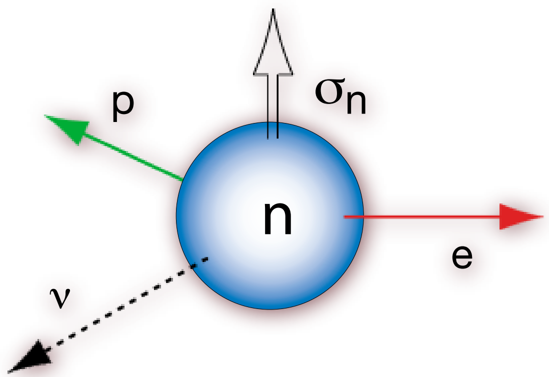
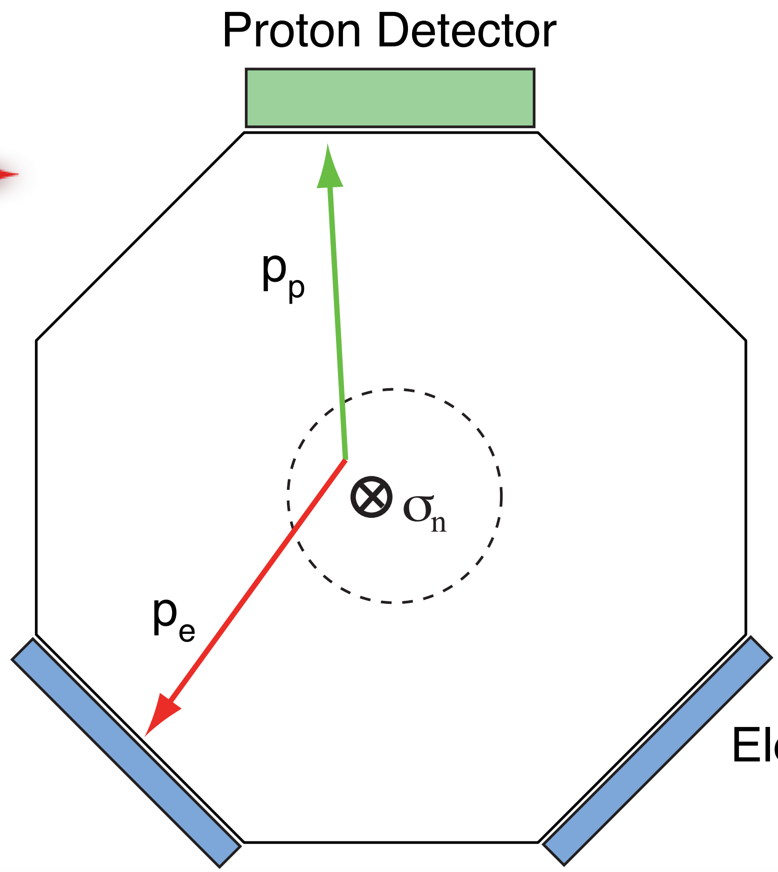
Polarized Neutron Decay: Constraints and History



Polarized Neutron Decay

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





Difficulties

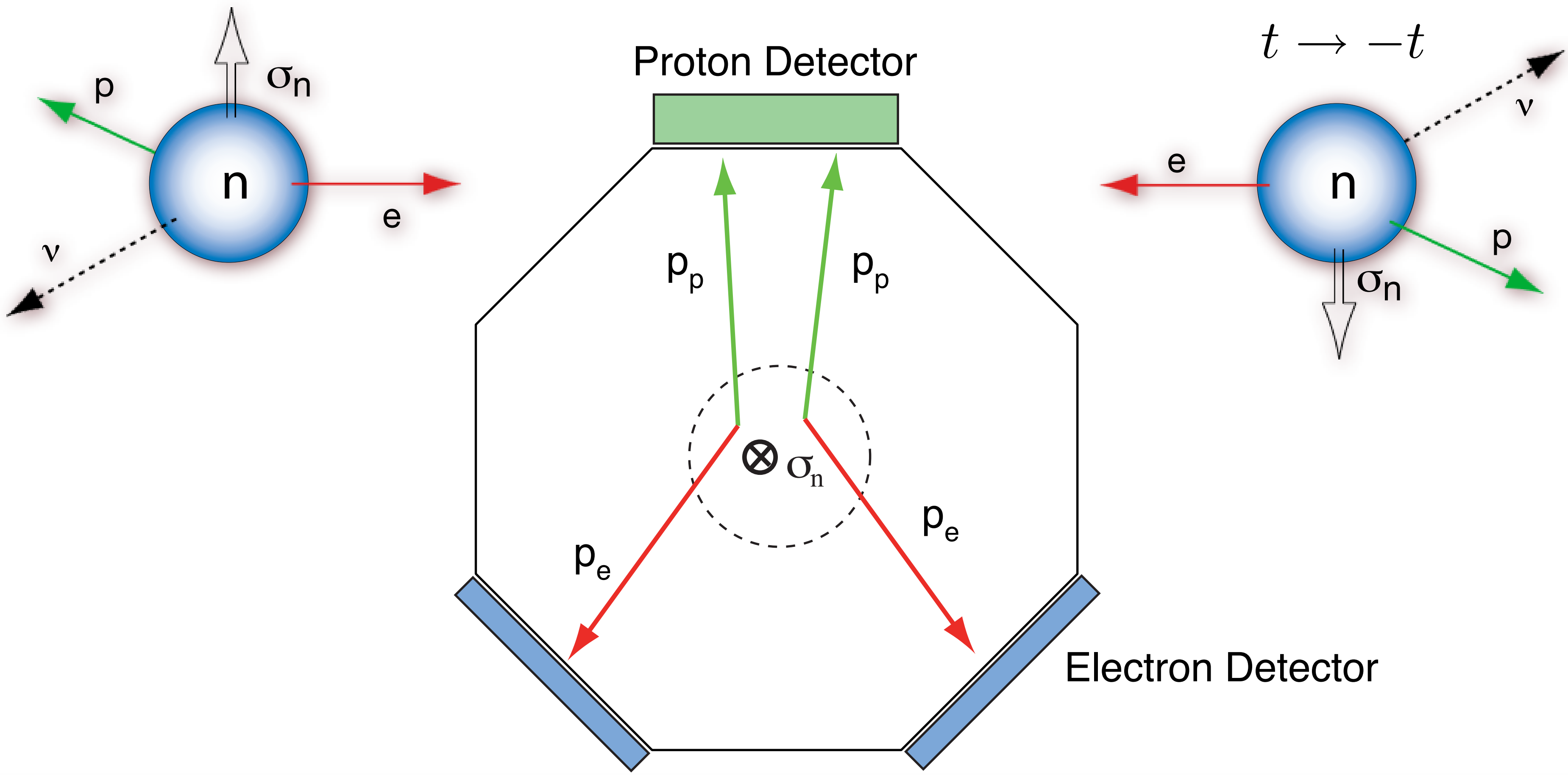
- proton endpoint 750 eV (requires acceleration)
- Neutron lifetime (requires intense source)
- Tight control of magnetic fields

Advantages

- Delayed coincidence
- Simple physics

Polarized Neutron Decay

$$\sigma_n \cdot (p_e \times p_p)$$
$$t \rightarrow -t$$



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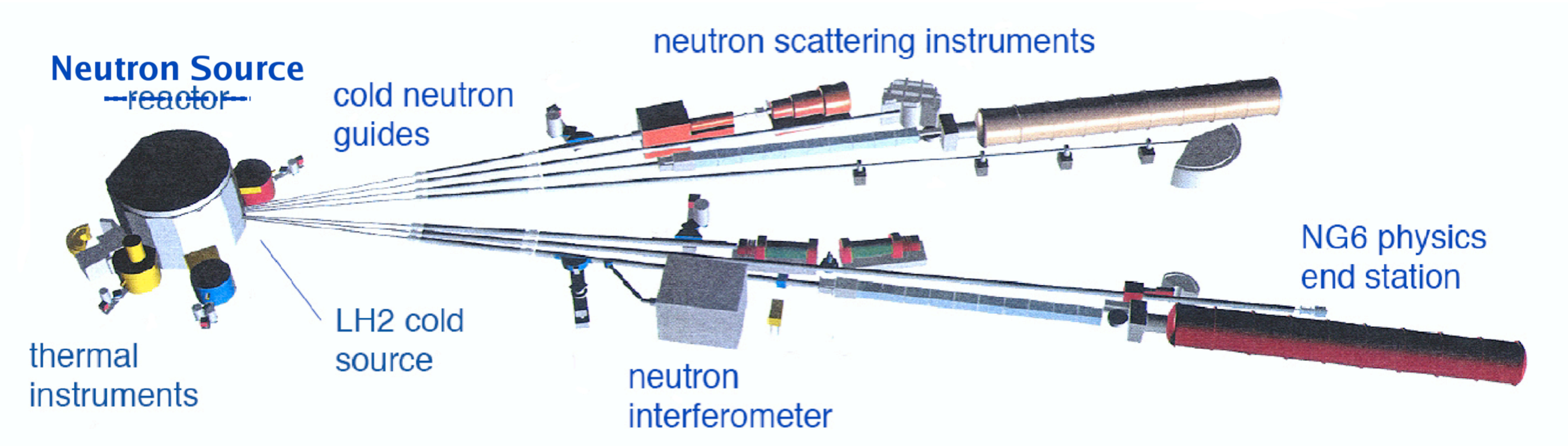
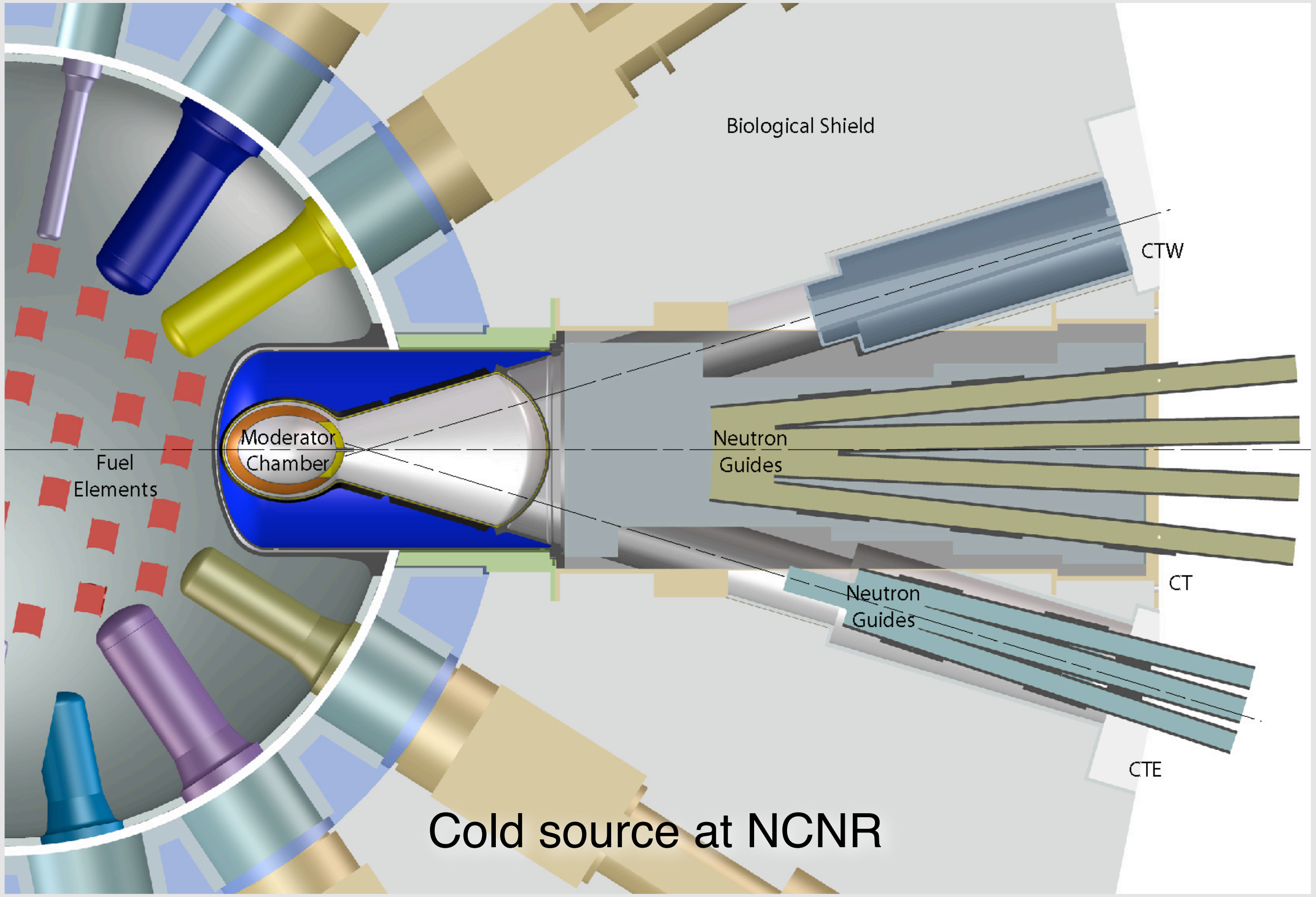
The National Institute of Standards and Technology Center for Neutron Research (NCNR)



Cold Neutrons at NCNR (NIST)

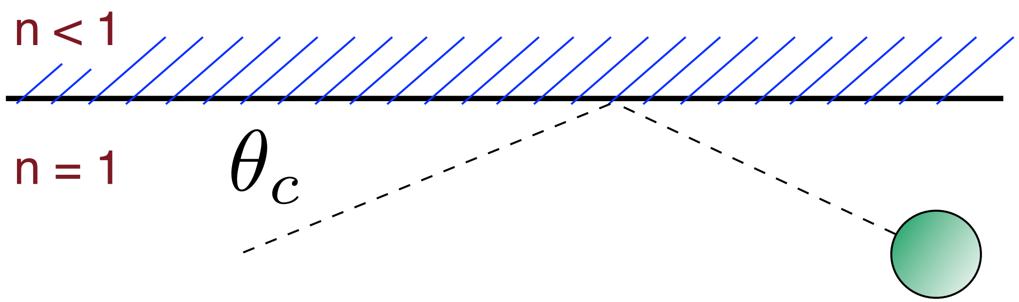


Neutrons partially thermalize in a cold source

- NCNR, liquid hydrogen (eff. 20K)
- Slow neutrons have larger probability of decaying in the detector

- neutron temp ≈ 40 K
- neutron energy ≈ 3.4 meV
- neutron velocity ≈ 800 m s^{-1}
- neutron flux (typ. ≈ 10^9 s^{-1} cm^{-2})

Neutron Polarization and Transport



Neutron Reflection

- Neutrons with glancing angle < θ_c are reflected $\cos\theta_c = n$

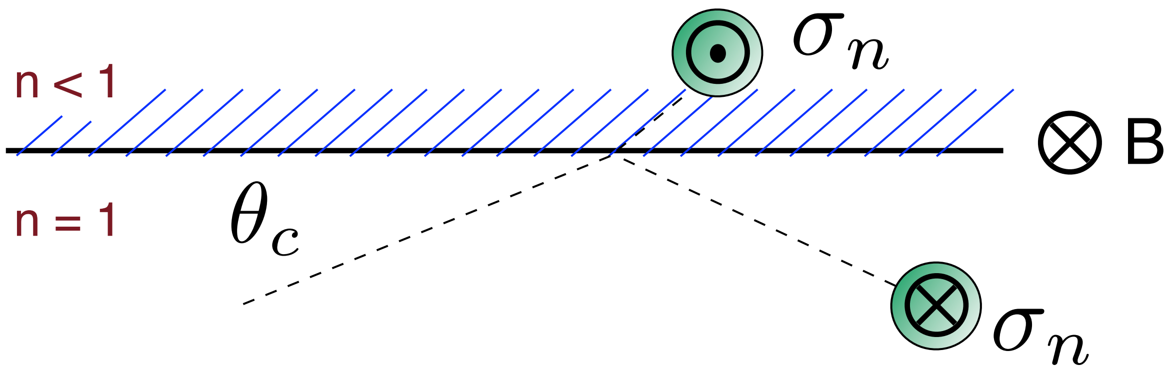
$$n = \sqrt{1 - \frac{V}{E}}$$

Guides transport the neutrons away from the reactor (reduce backgrounds)

- ^{58}Ni, $\theta_c = 2$ mrad/Å
- 6 cm × 15 cm × 60 meters

$$V = \frac{2\hbar^2}{m} N a$$

Neutron Polarization and Transport



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Magnetic materials

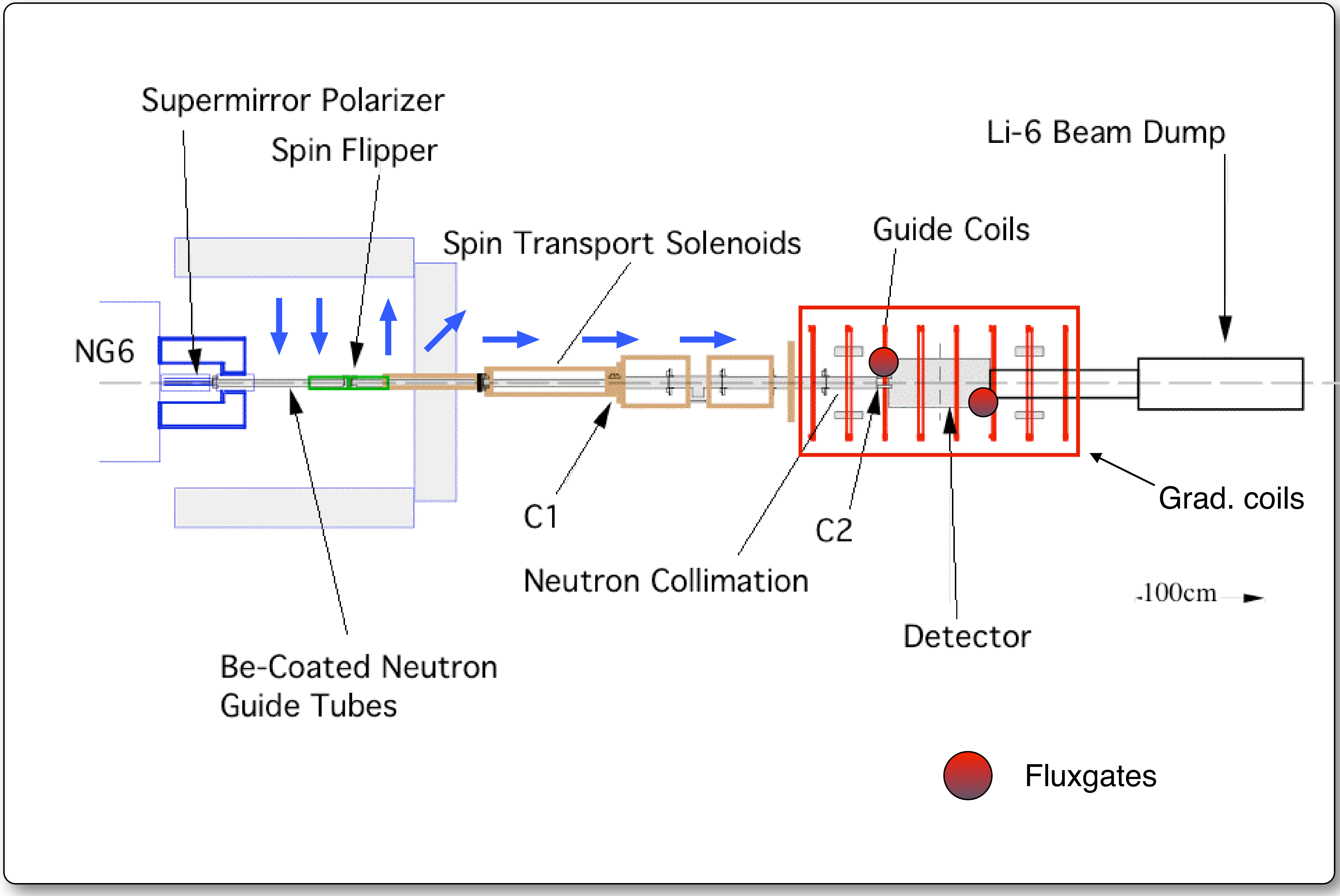
- If |V/E| ≈ |μB/E| only one neutron polarization will be reflected. $$n = \sqrt{1 - \frac{V}{E} \pm \frac{\mu B}{E}}$$

Supermirrors

- Interference from multilayers of magnetic and non-magnetic material reflect neutrons of one spin but not the other.

- Varying layer thickness extends the effective critical angle for reflection over a greater energy range

emiT Beamline



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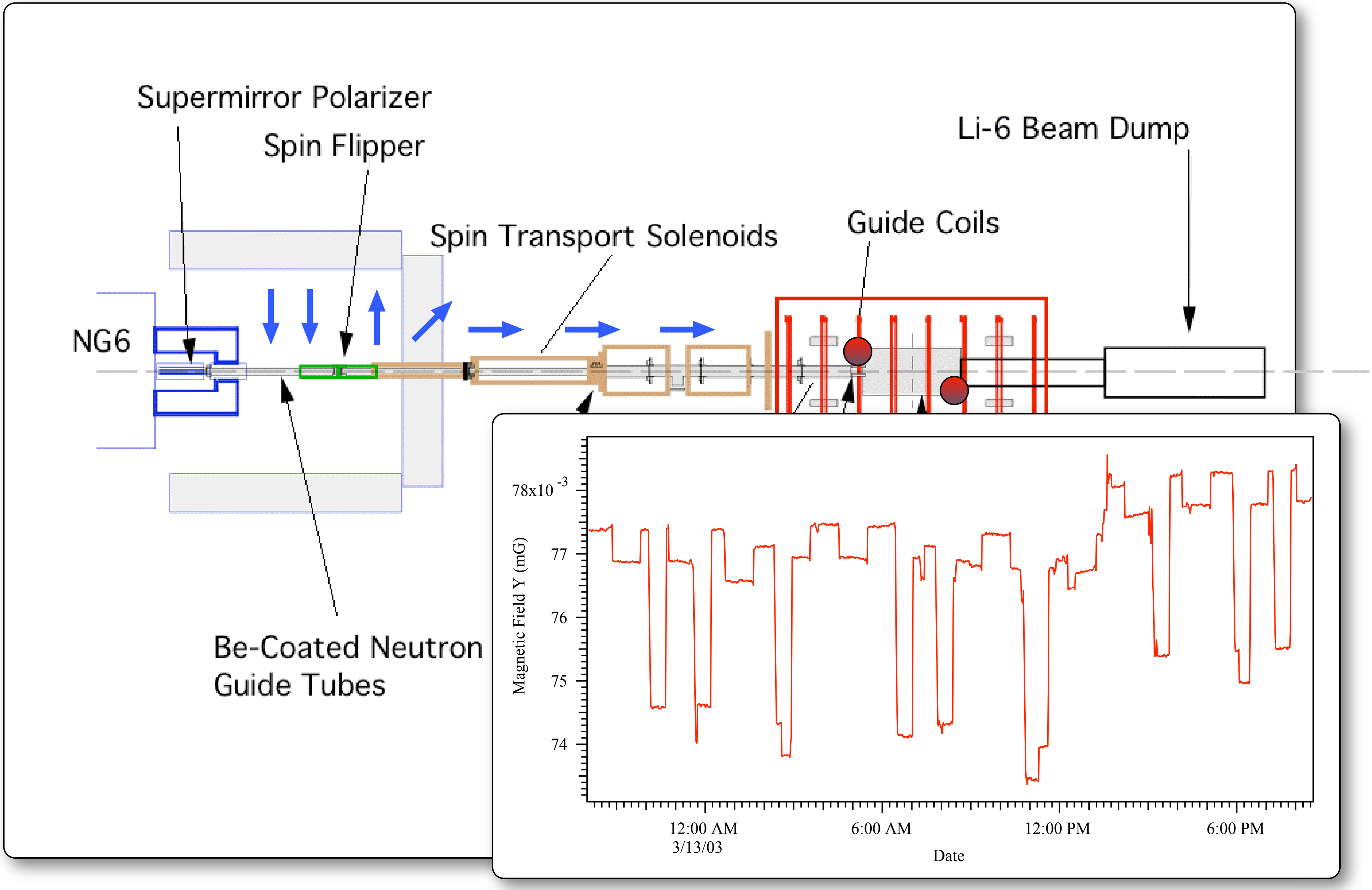
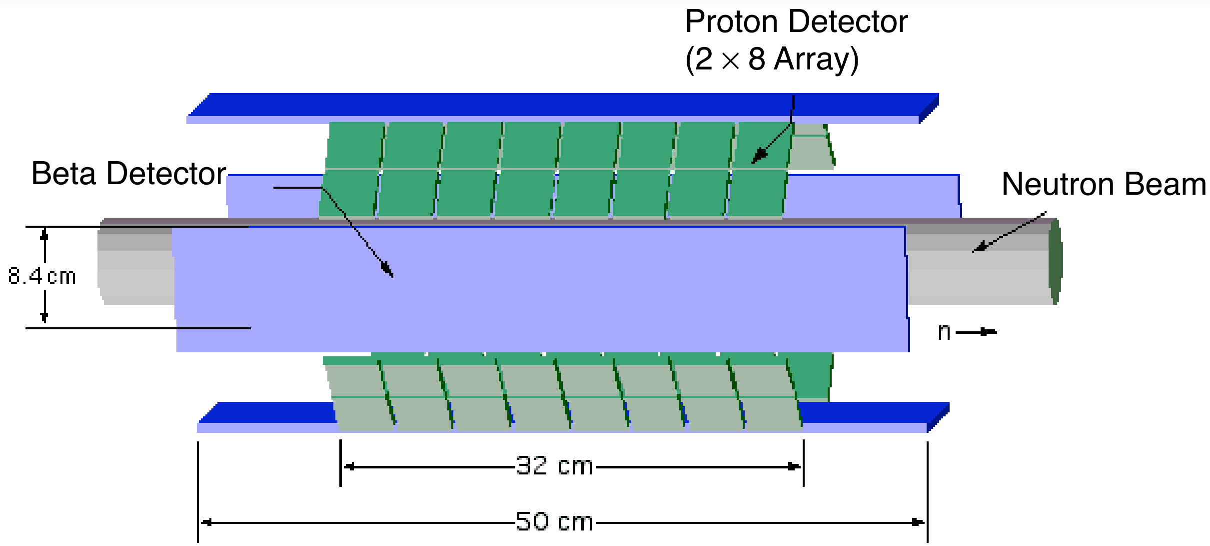
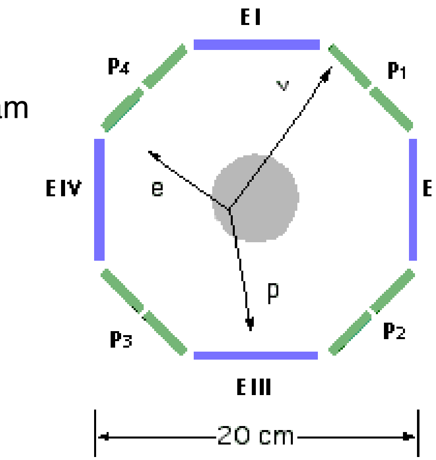
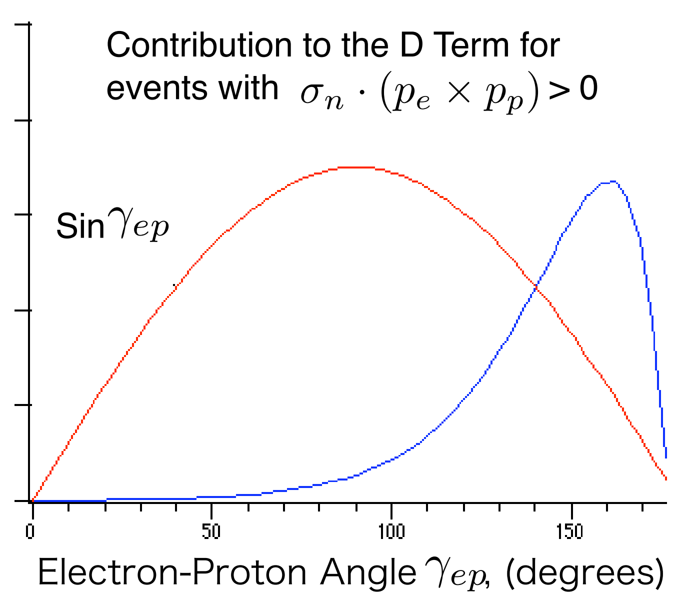


emiT Detector: basic concept and design criteria







- Statistical precision requires highest possible coincidence rate
- High <u>continuous</u> 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 $D\sigma_n \bullet (p_e \times p_\nu)$
  (minimize sensitivity to other terms in decay distribution)

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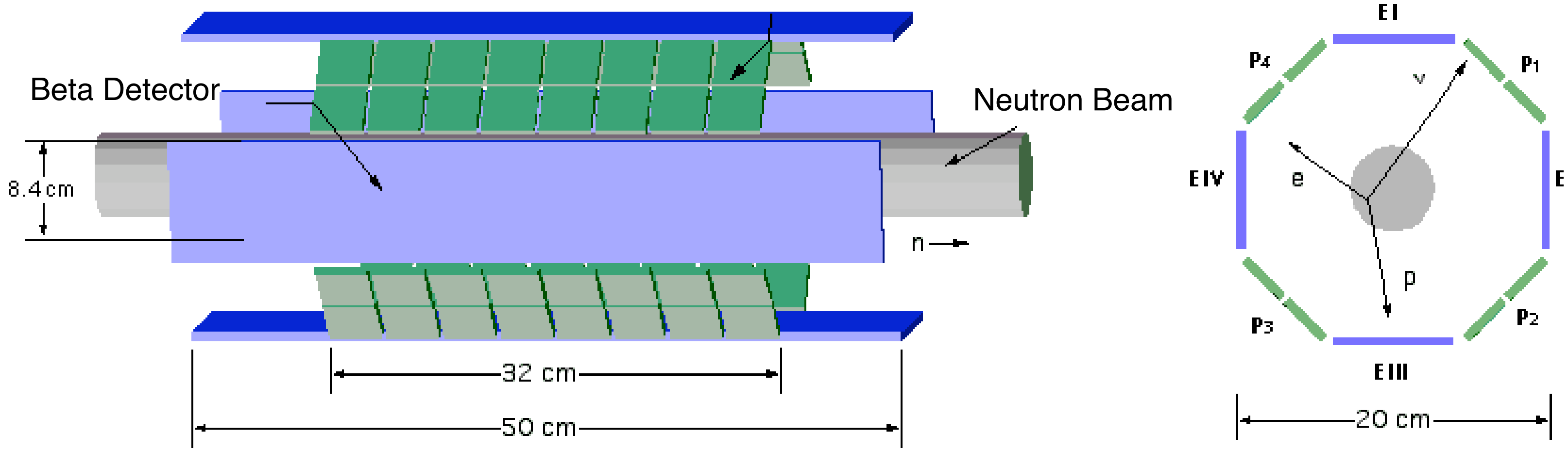

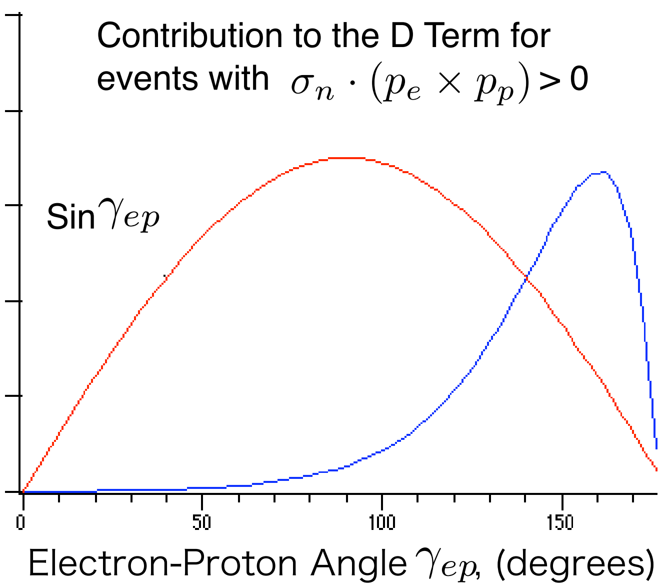

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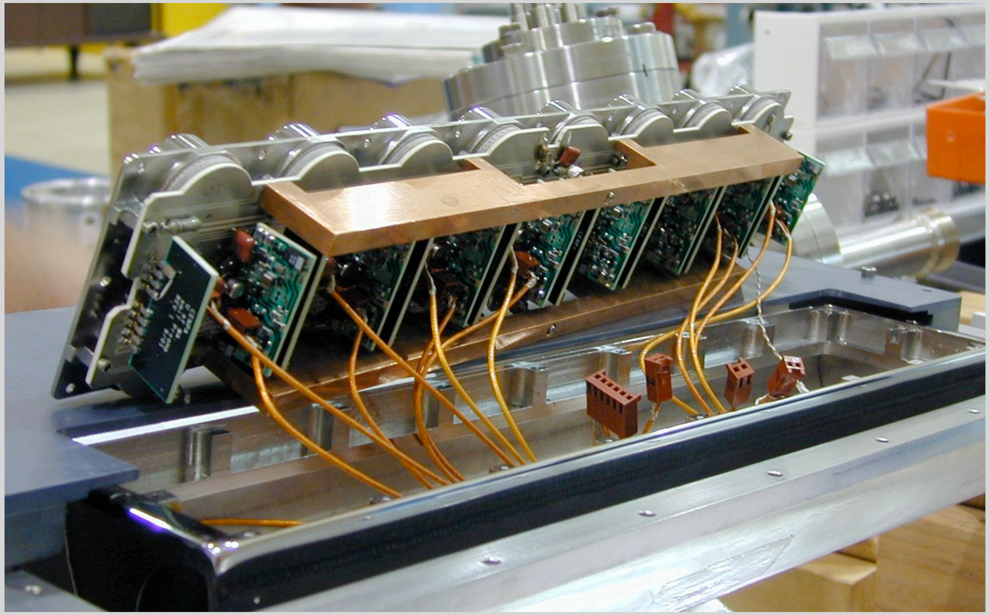
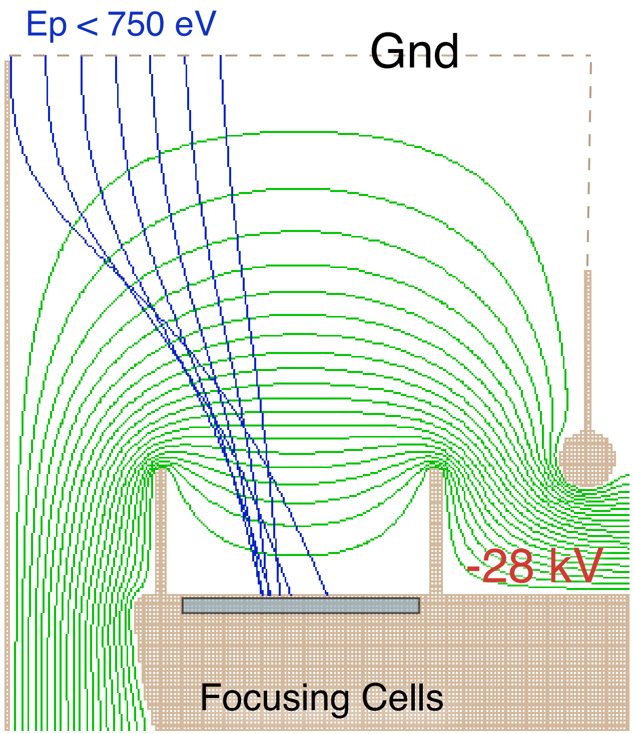
emiT gained a factor of three increase in "effective" beam flux over previous "right angle" geometry beam experiments

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

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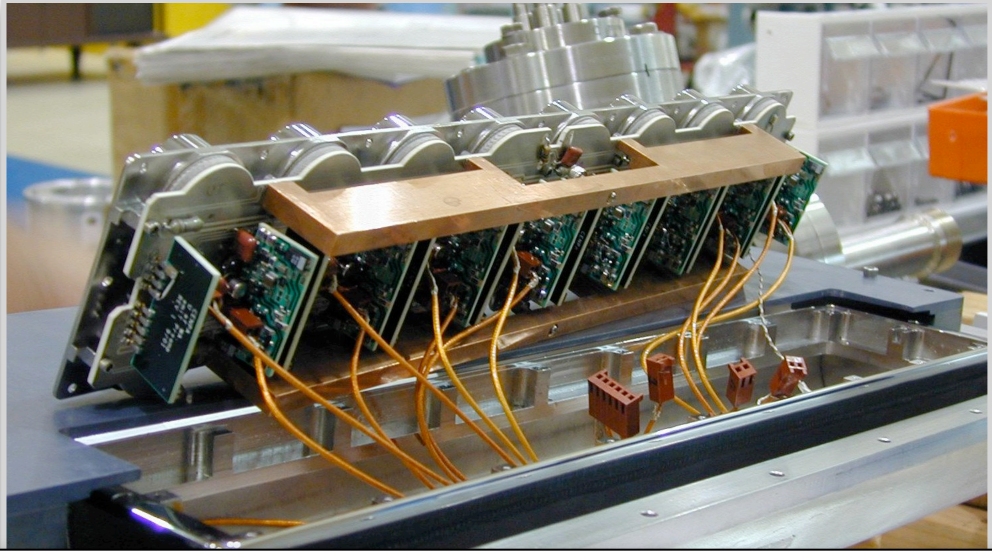

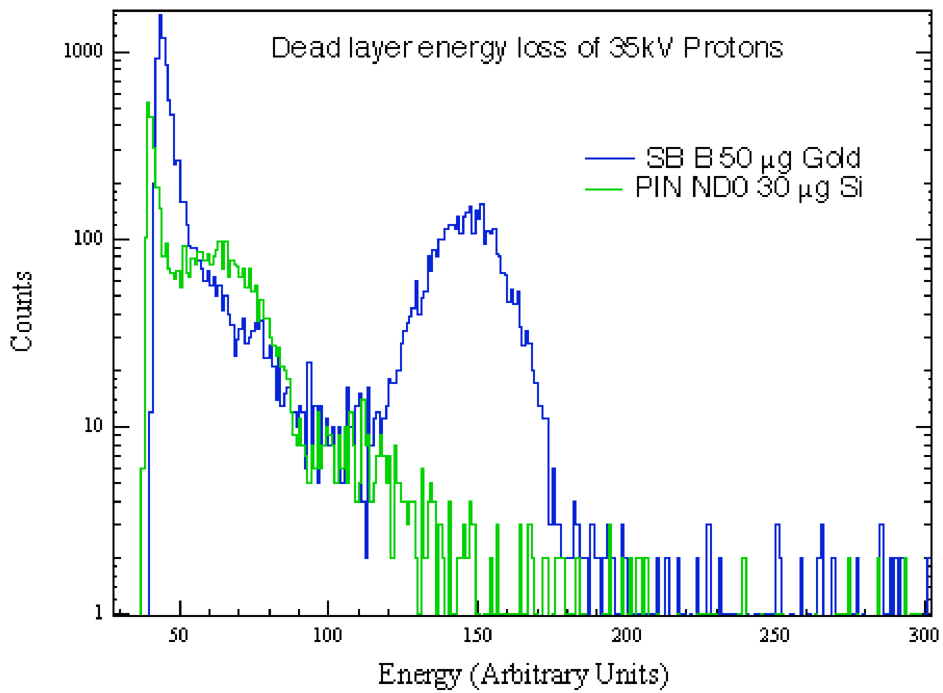

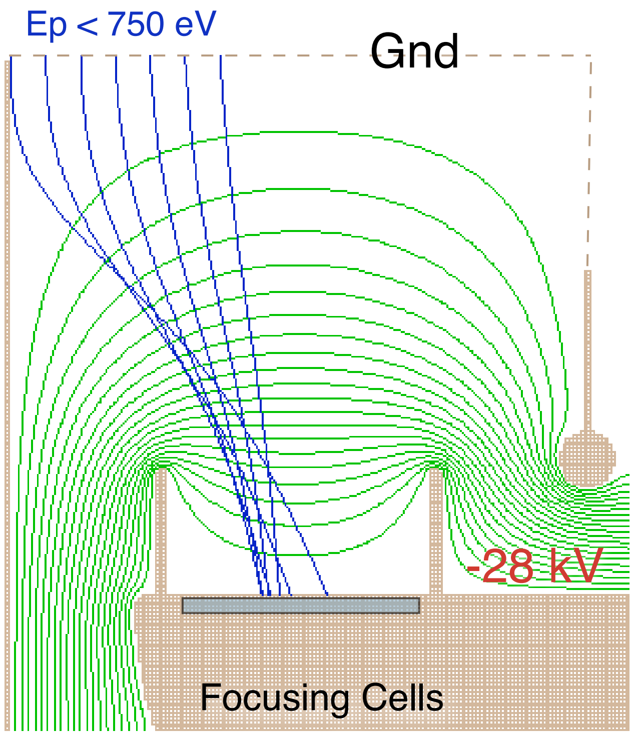

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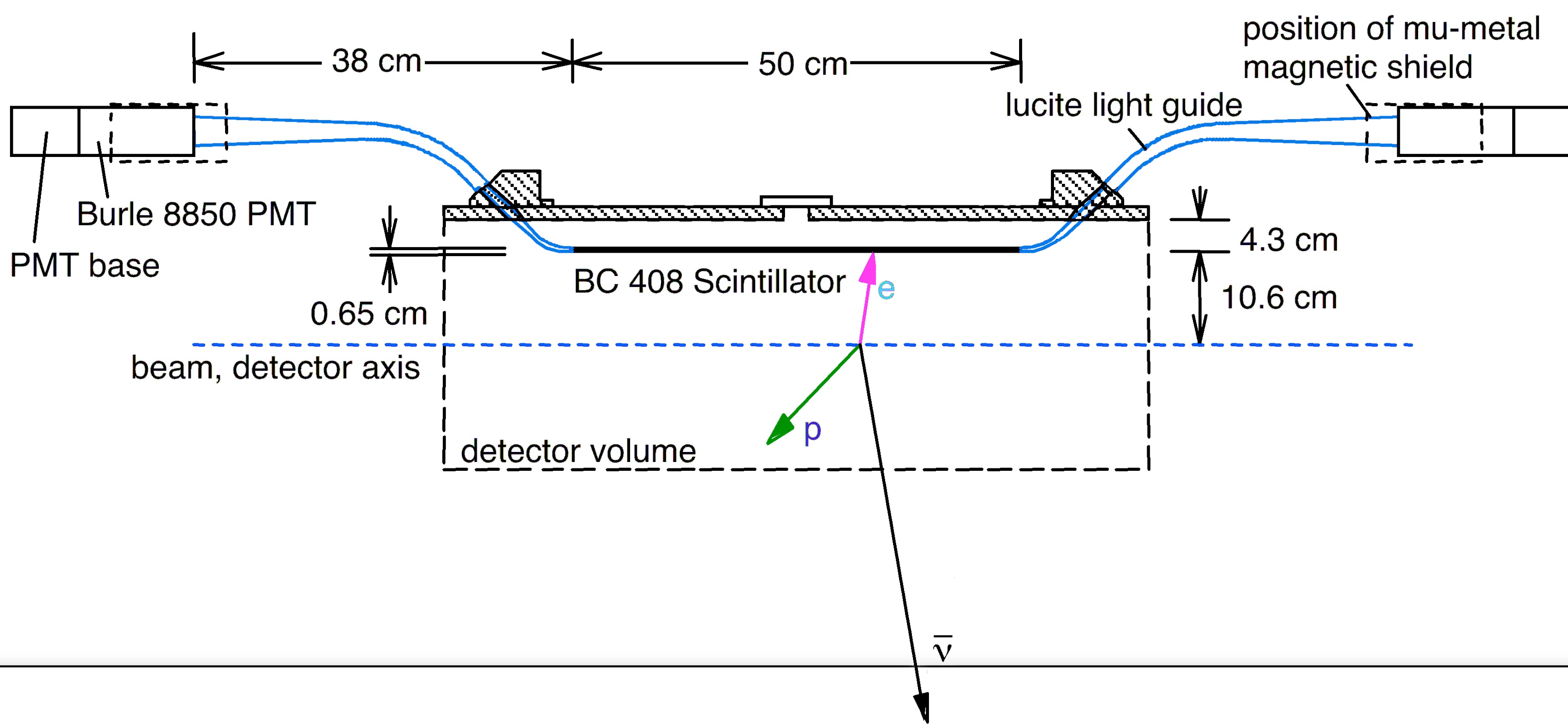
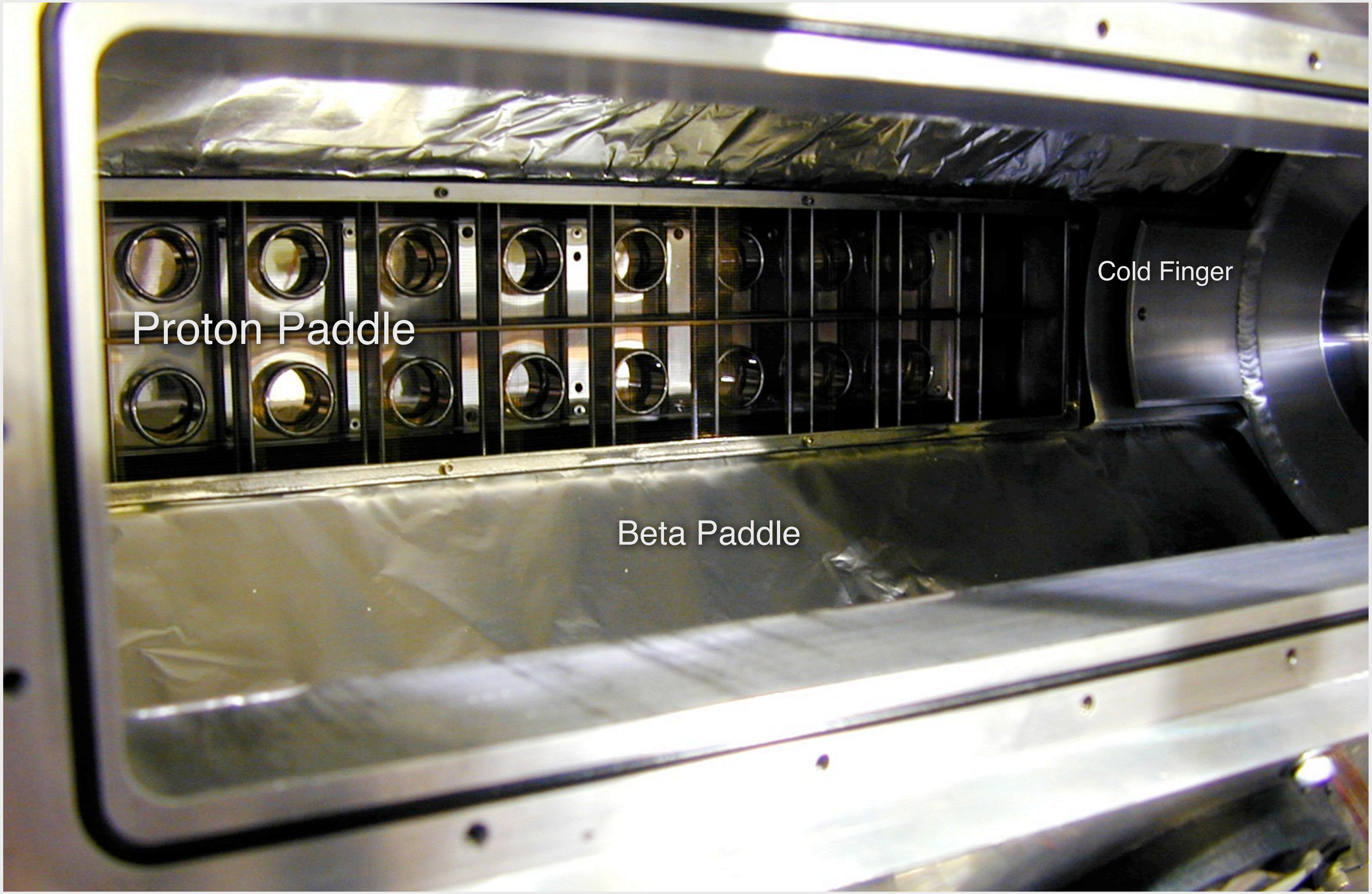
emiT Detector: Beta detectors (4 panels and support hardware)

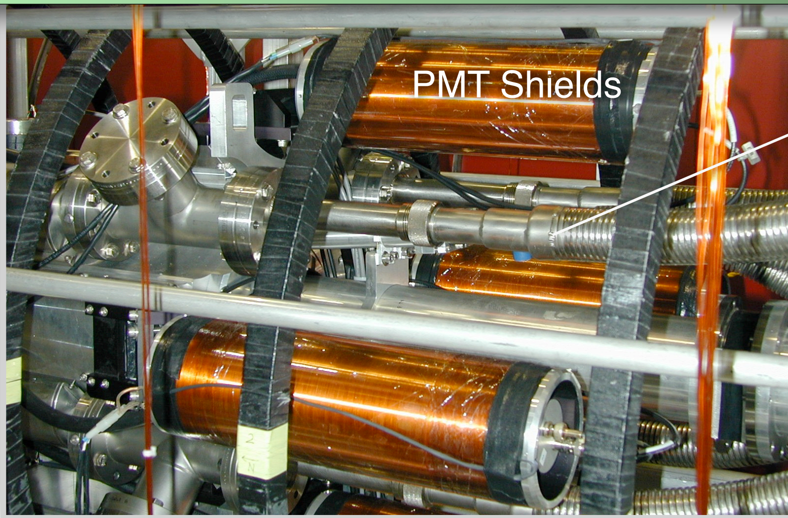


- 0.1 ns timing resolution (Pulse arrival time may be used to determine position)
- Thresholds (70-80 keV) (Software cut on geometric mean)
- Resolution ~18% at 1 MeV
- Cosmic ray muons deposit ~ 1.42 MeV (well separated)
- Overall rate 300 s^{-1} per paddle (Signal to accidental ~ 1 to 1)

emiT Detector: Interior View

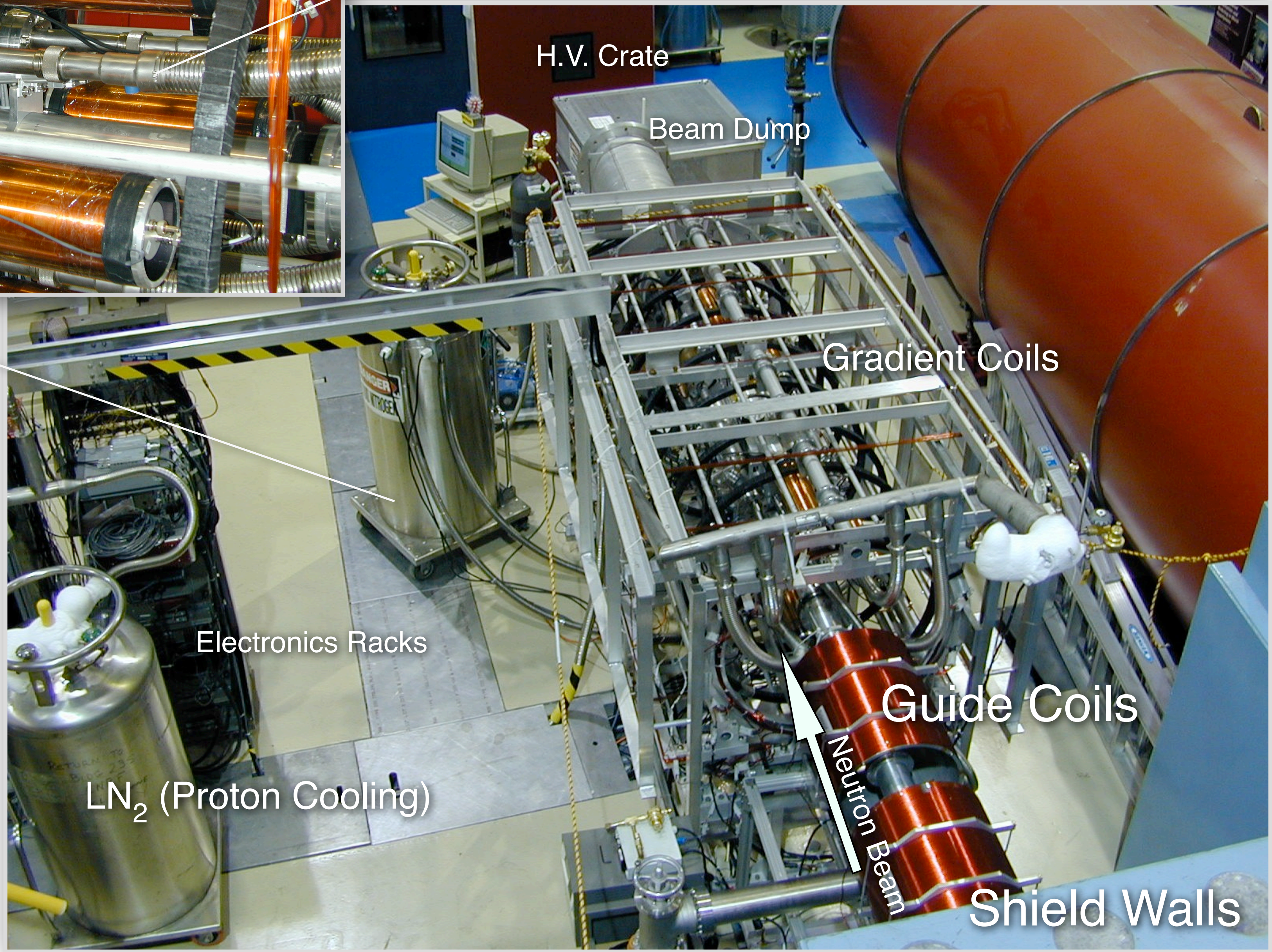


emiT Detector: On The Floor



Proton Detector Cooling

LN_2 (Cold Fingers)



Data Selection

Hardware

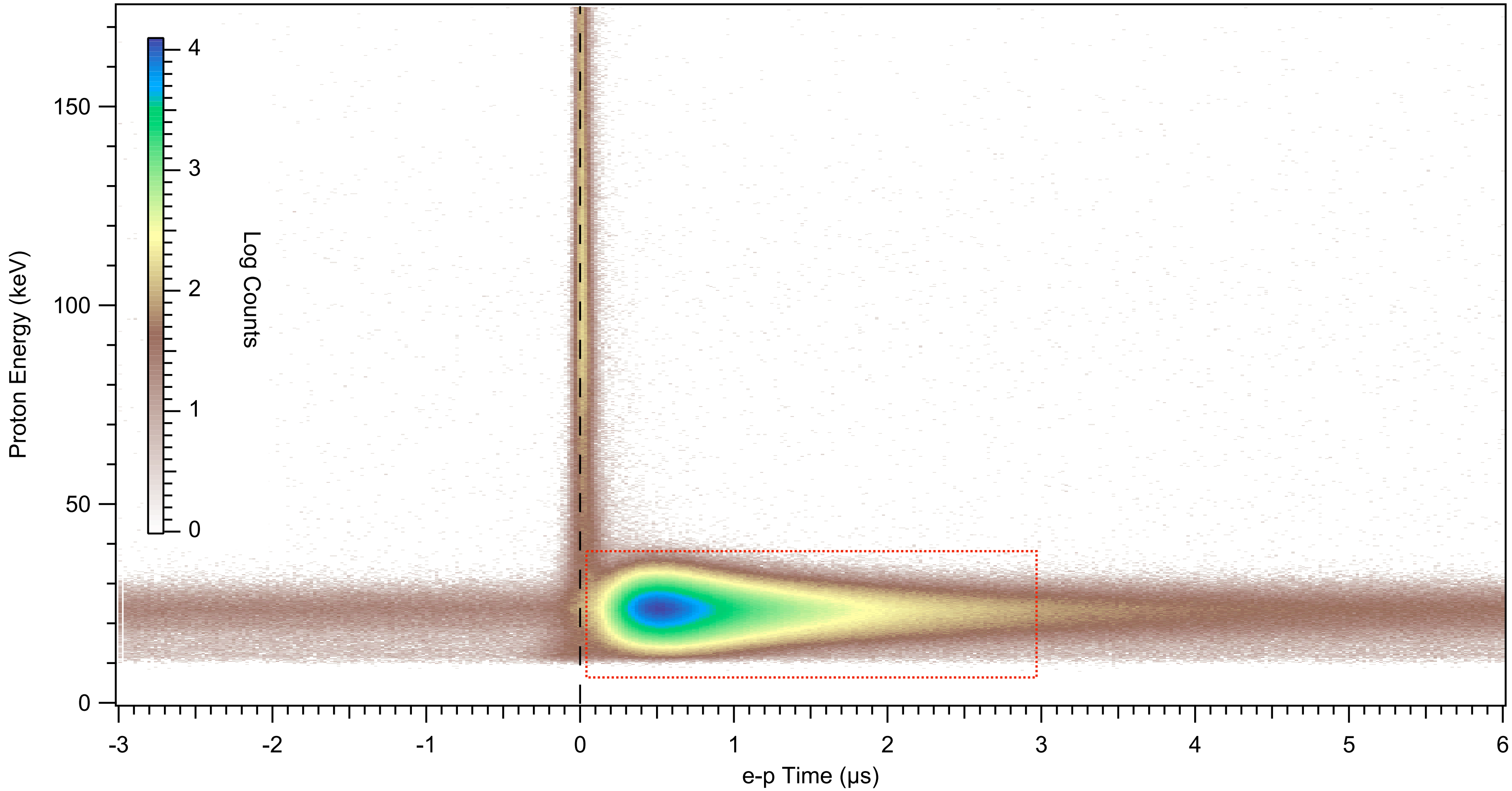
- Beta energy > 30 keV (SPE)
- Beta events separated by > than 5 μs (single tube)
- Coincidence between beta paddle ends within 100 ns (photon transit time)
- Proton energy > 10 keV

Software

- High voltage and leakage current (nominally 28 kV, 0.32 μA)
- Detector bias voltage and leakage current (nominally 65 V, 0.05 μA)
- Spin Flip (greater than 2 ms from flip)
- Cryo-panel fill
- Magnetic fields < 5 mG from nominal value (~ 1mrad)
- Proton energy ~ 10 - 30 keV (somewhat channel dependent)
- Beta energy ~ 35 - 950 keV (geometric mean of both phototubes)
- Proton - beta delay greater than 0.1μs and less than 10μs
- Background subtraction from widow between 0.1μs and 10μs pre-prompt

Coincidences are then binned on spin state enabling calculation of the various ratios

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

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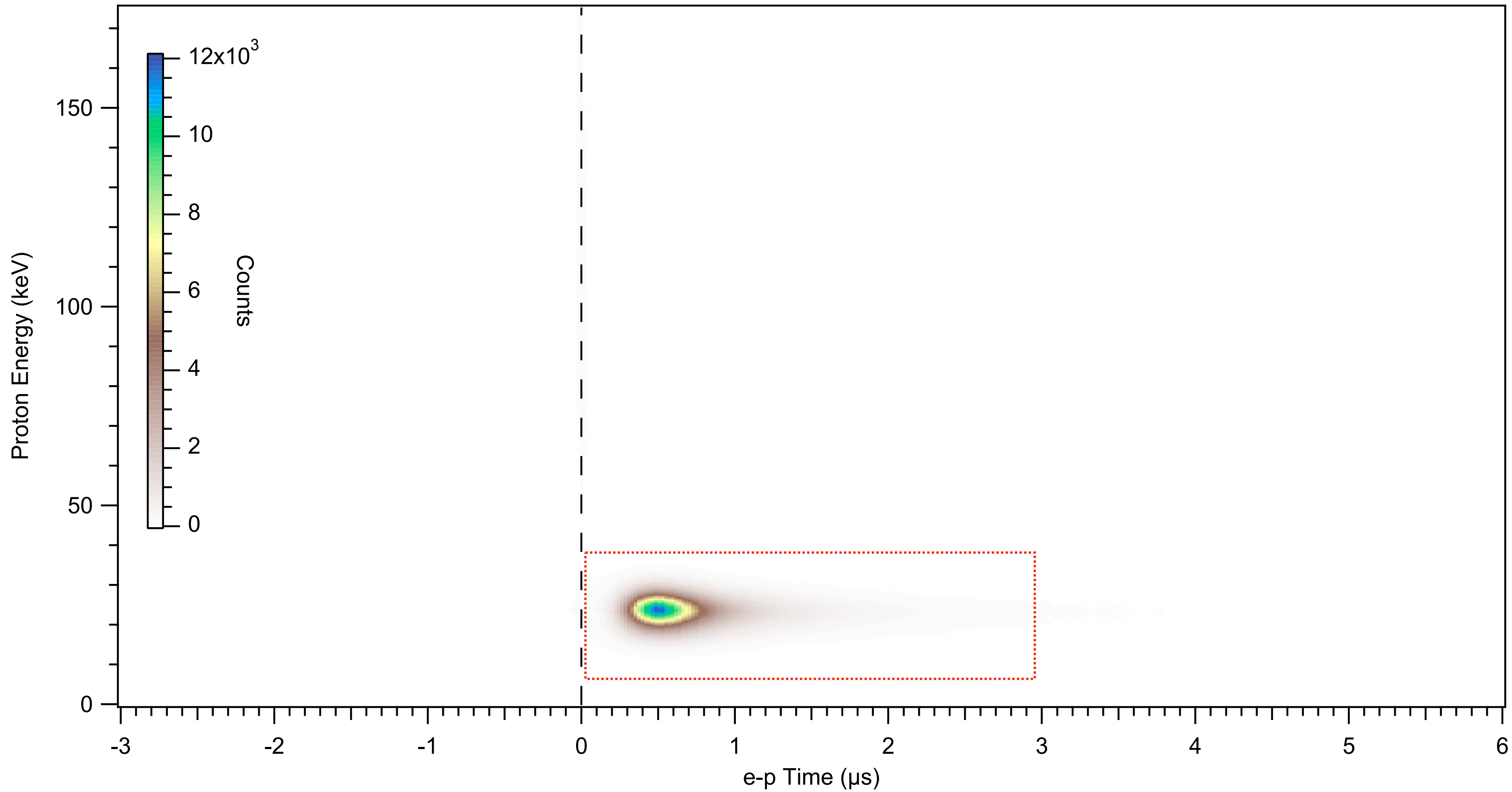

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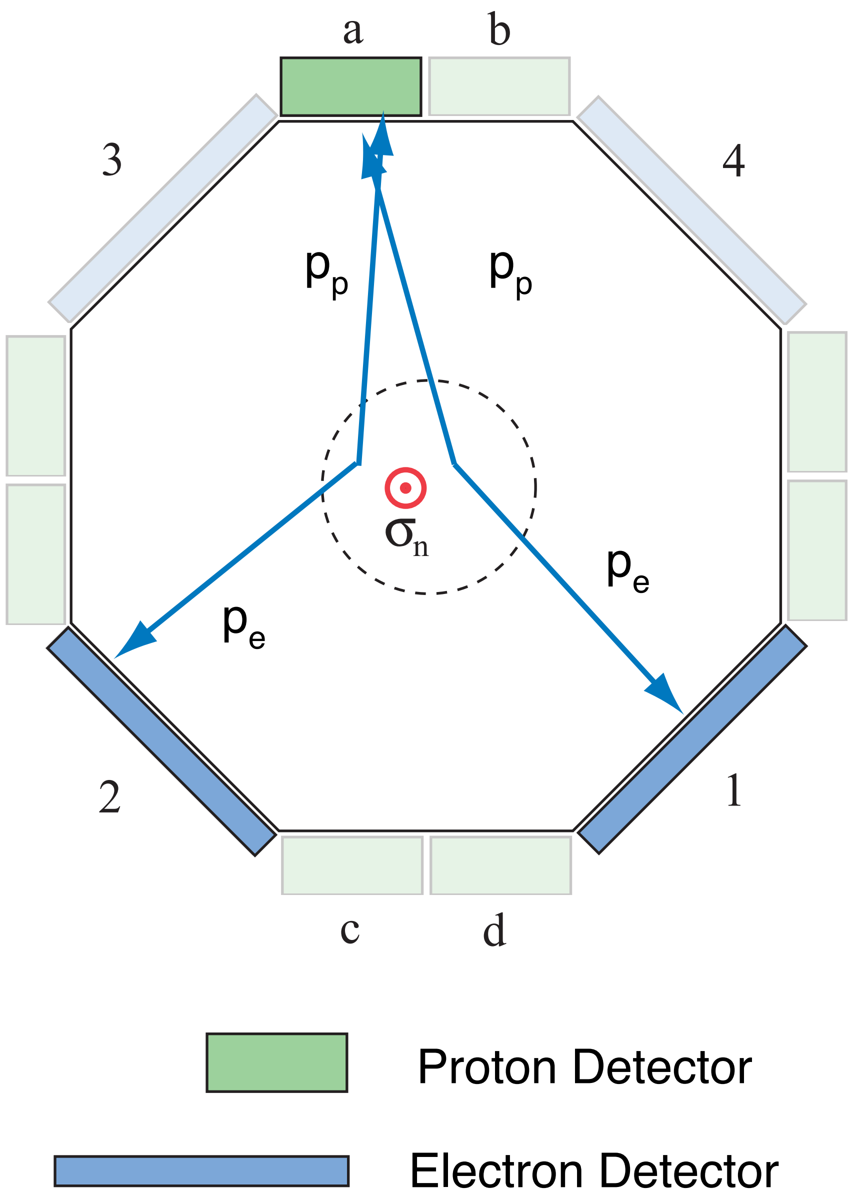

Efficiency independent ratio,

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

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

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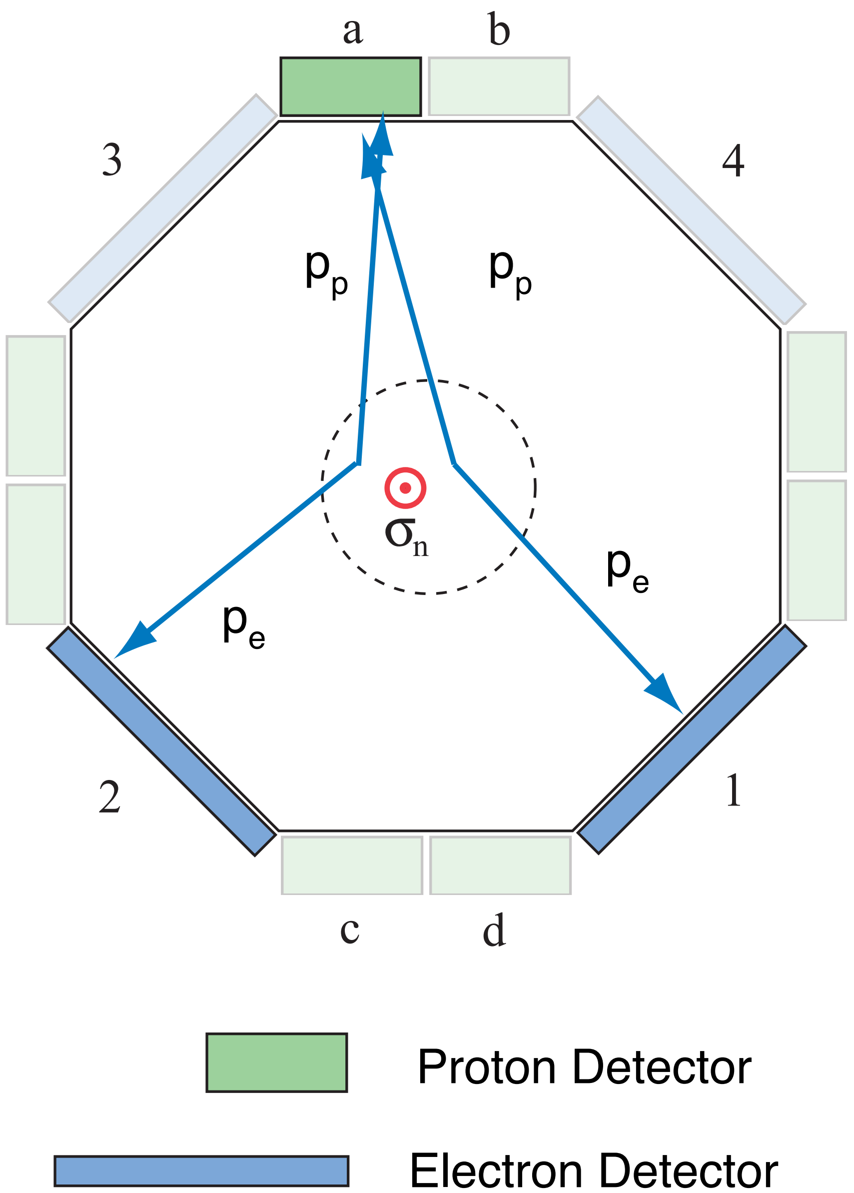

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Instrumental constant

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

Systematics: Overview

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

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

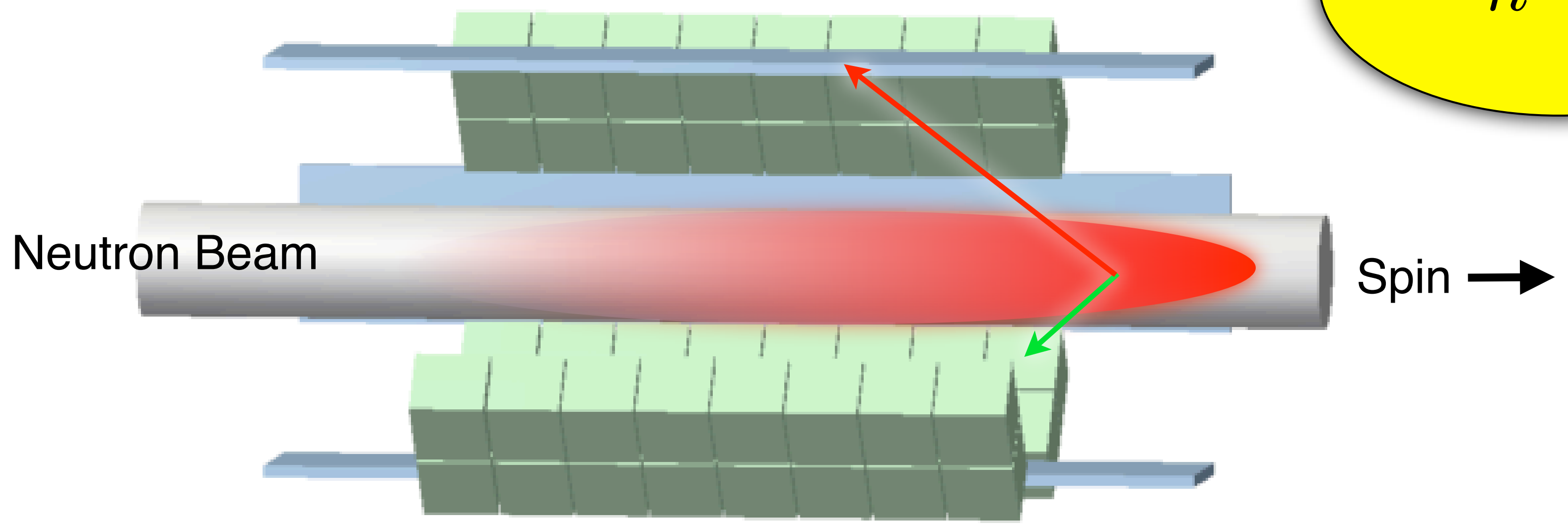
  - Spin flip efficiency 95±5%

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

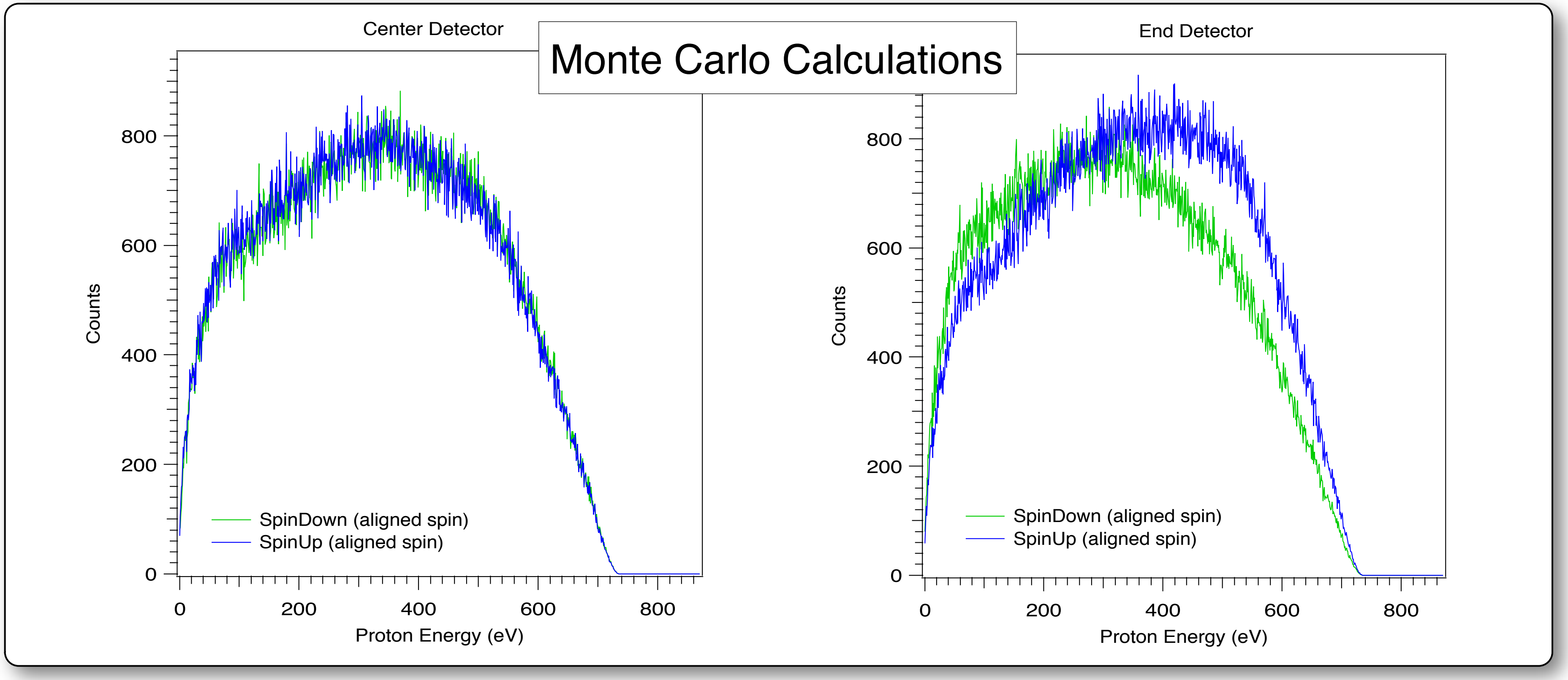
- Initial polarization misalignment and spin precession
  - Average over polychromatic beam washes out effect
- Electron backscattering
  - approximately 3% of events at 135°
- Spin state dependent proton energy spectrum
  - Energy shift of up to 100 eV due to recoil and focusing effects
- Misalignments (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



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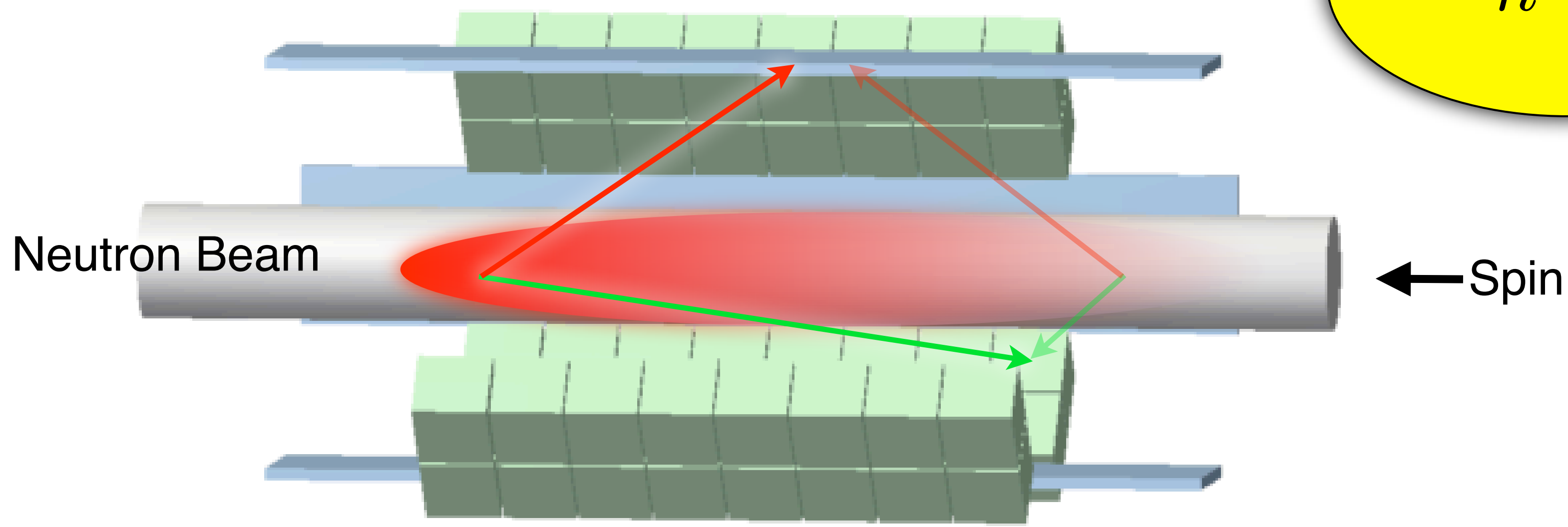

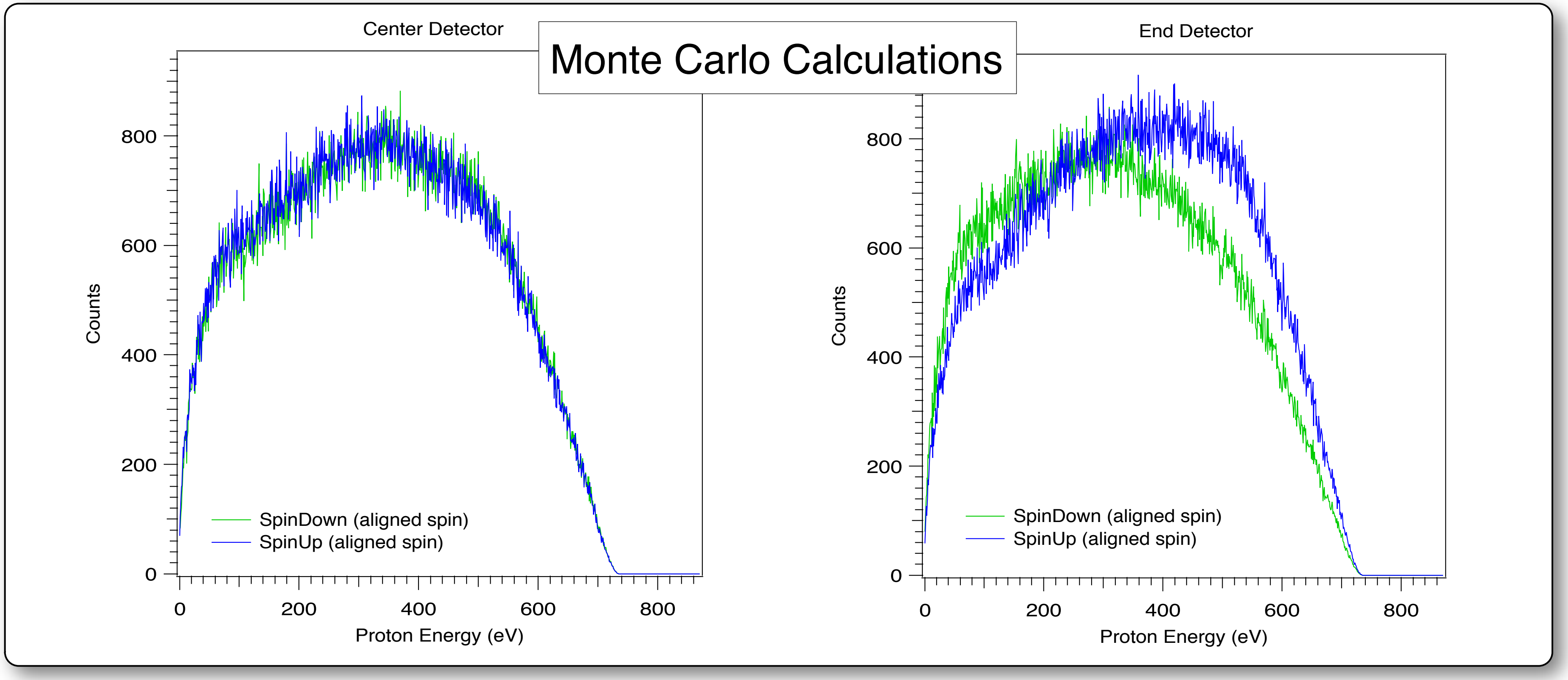

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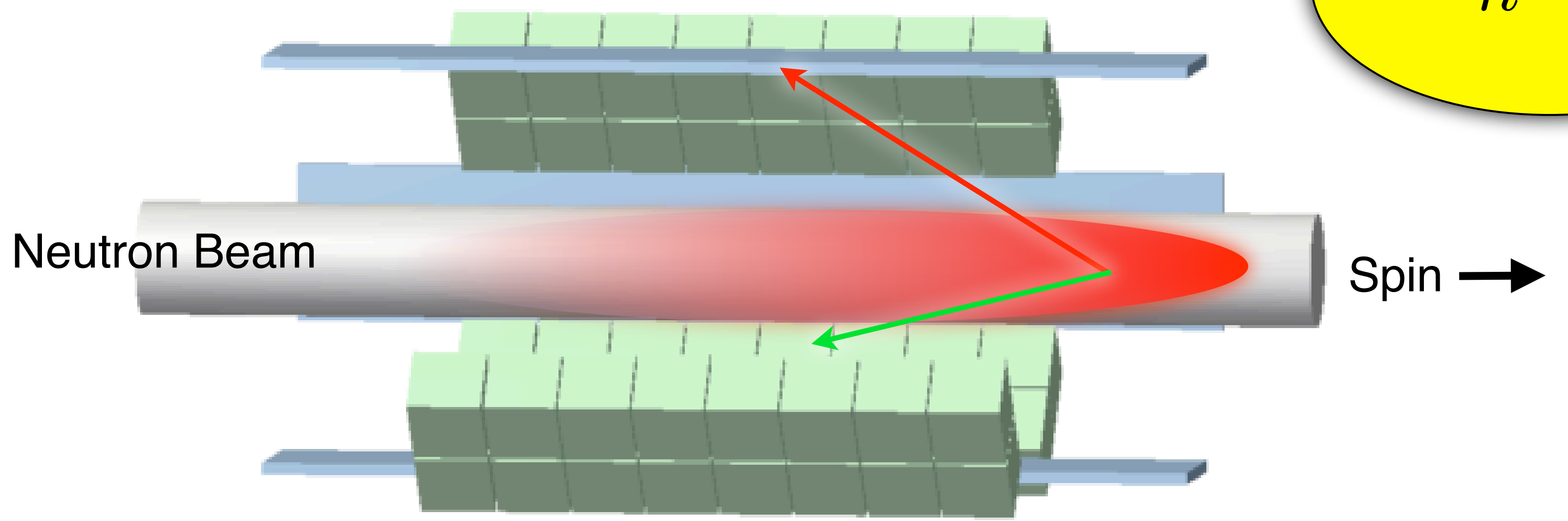

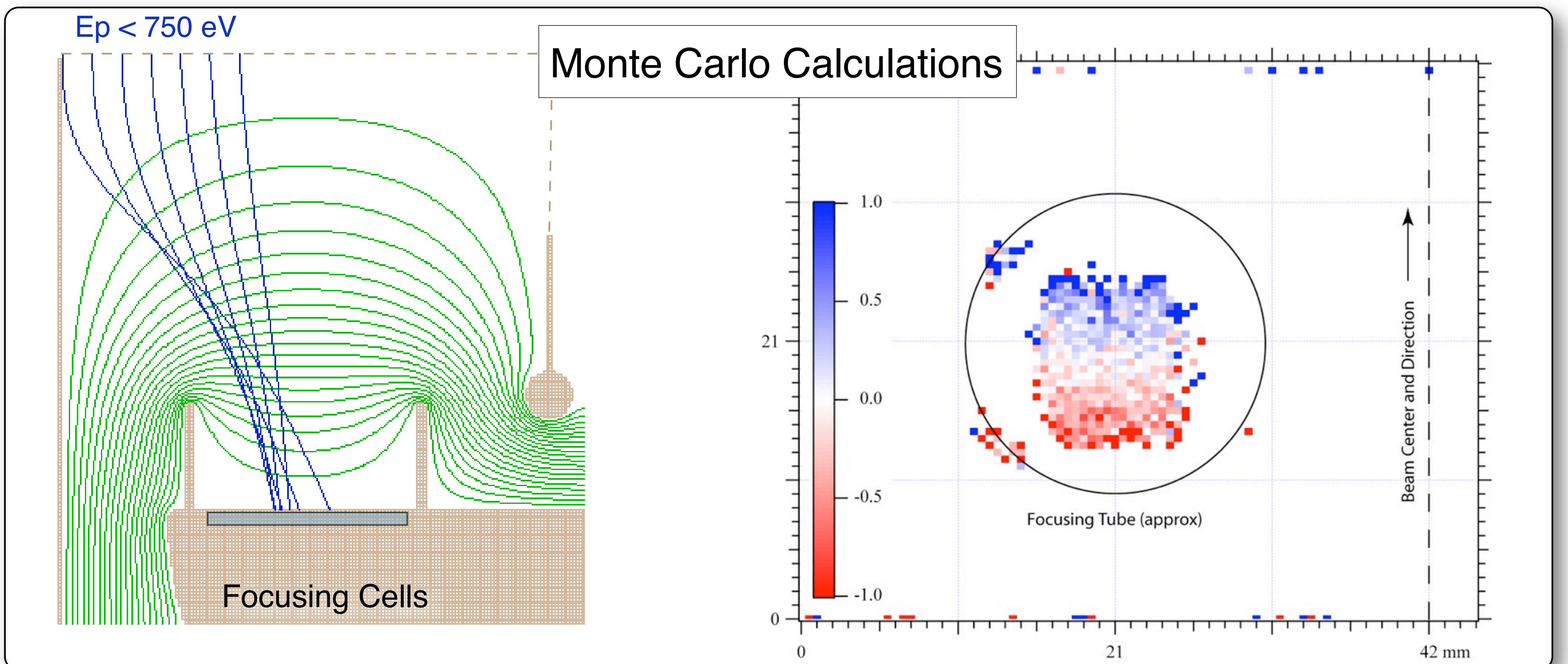

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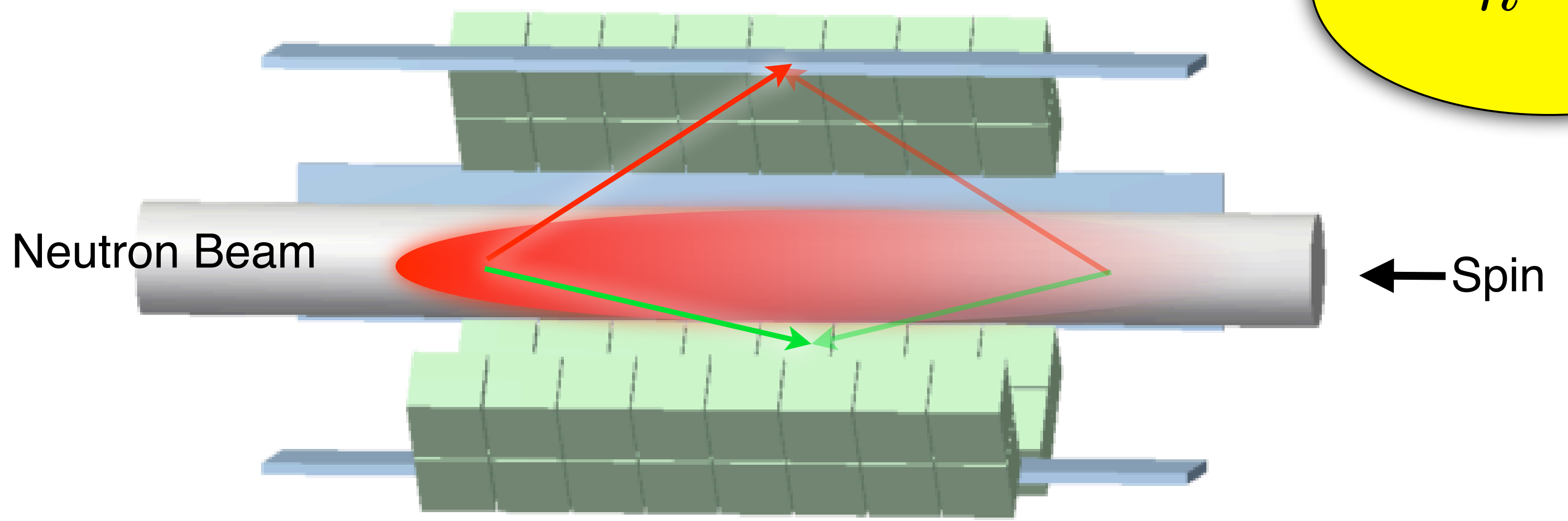

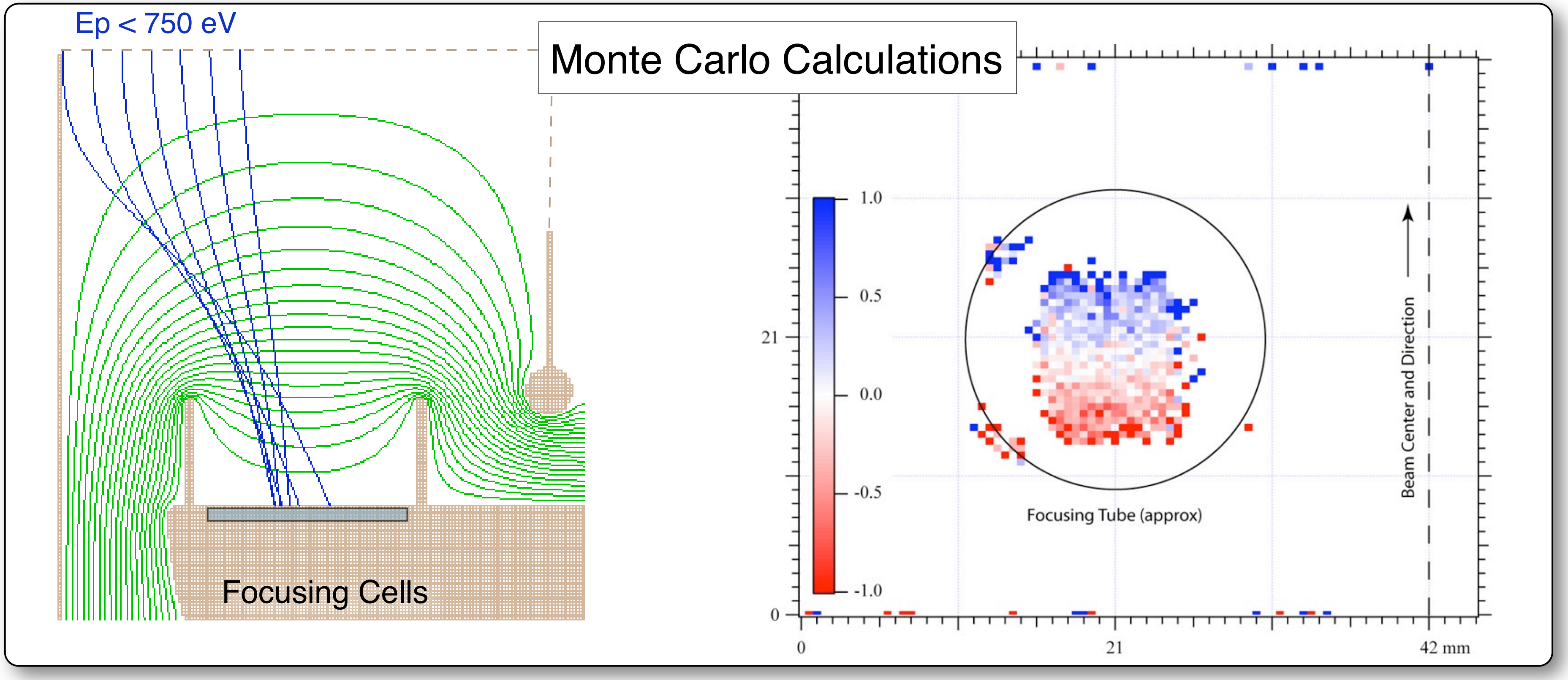

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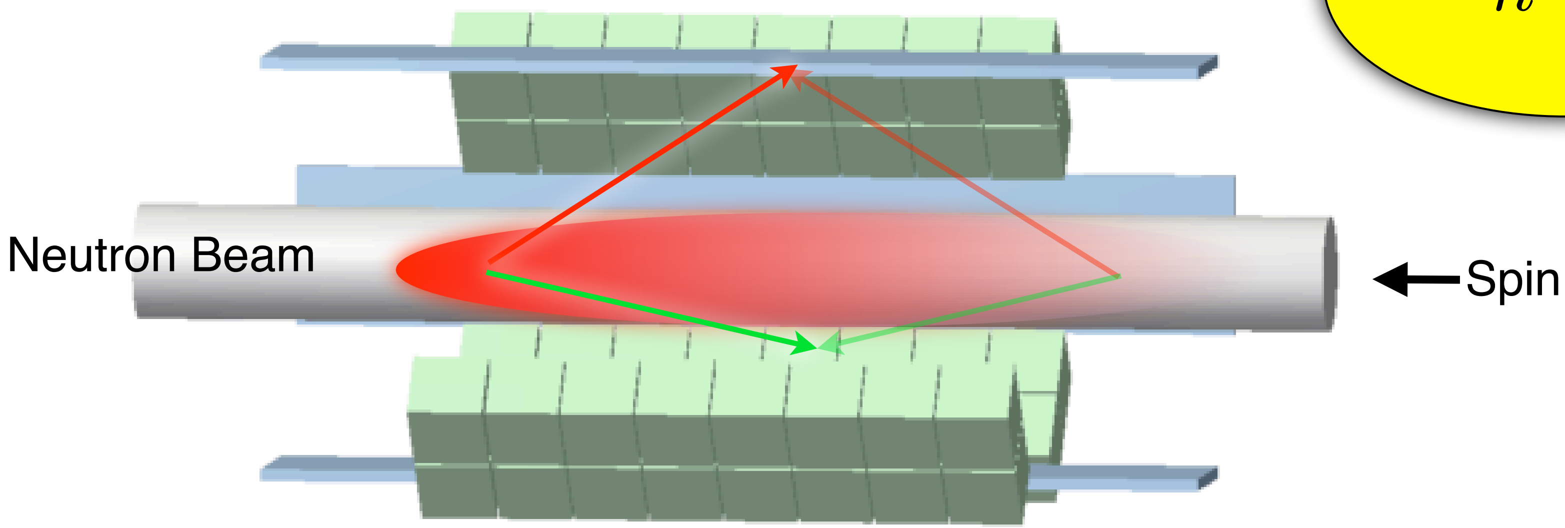

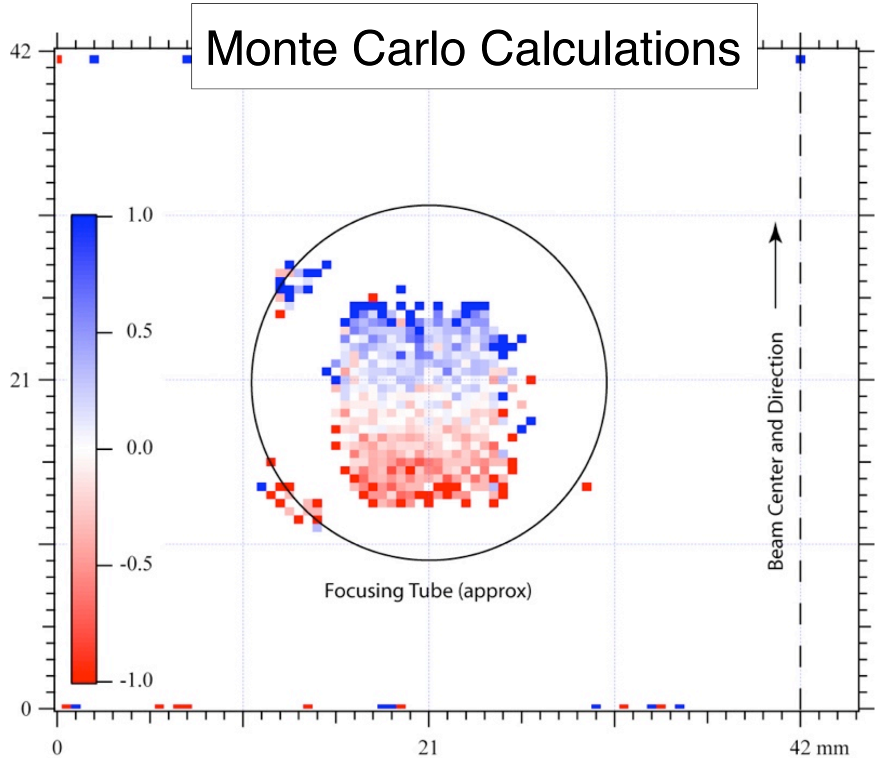

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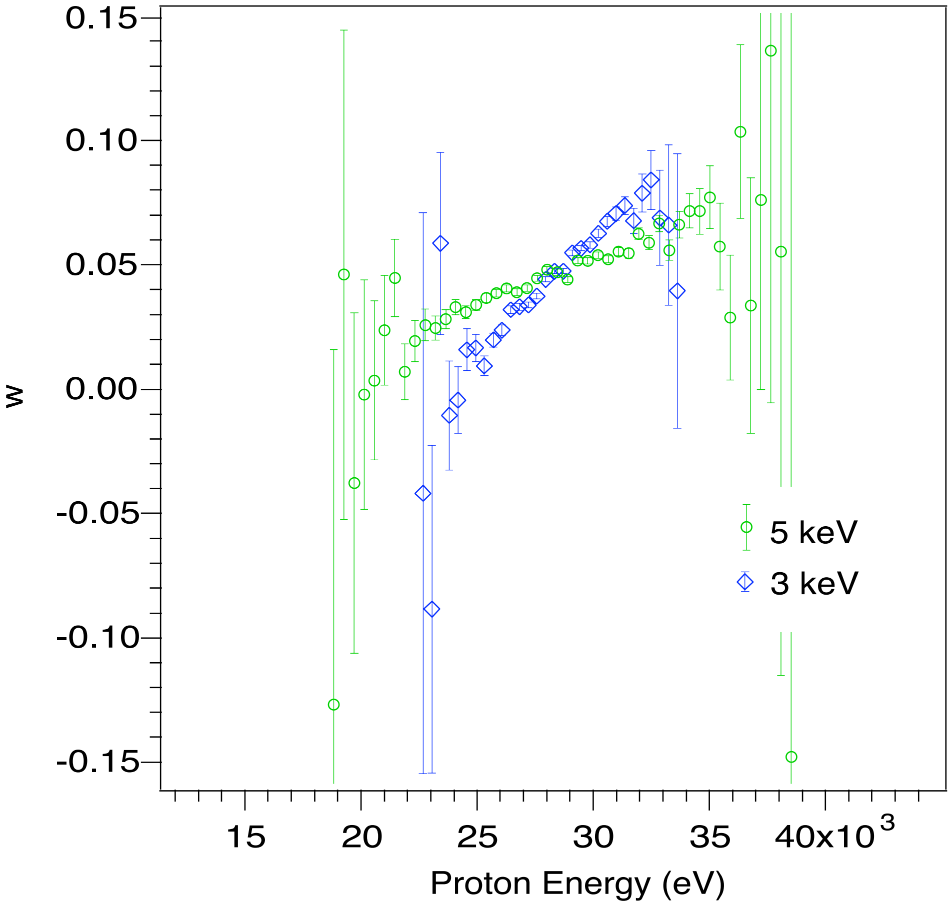

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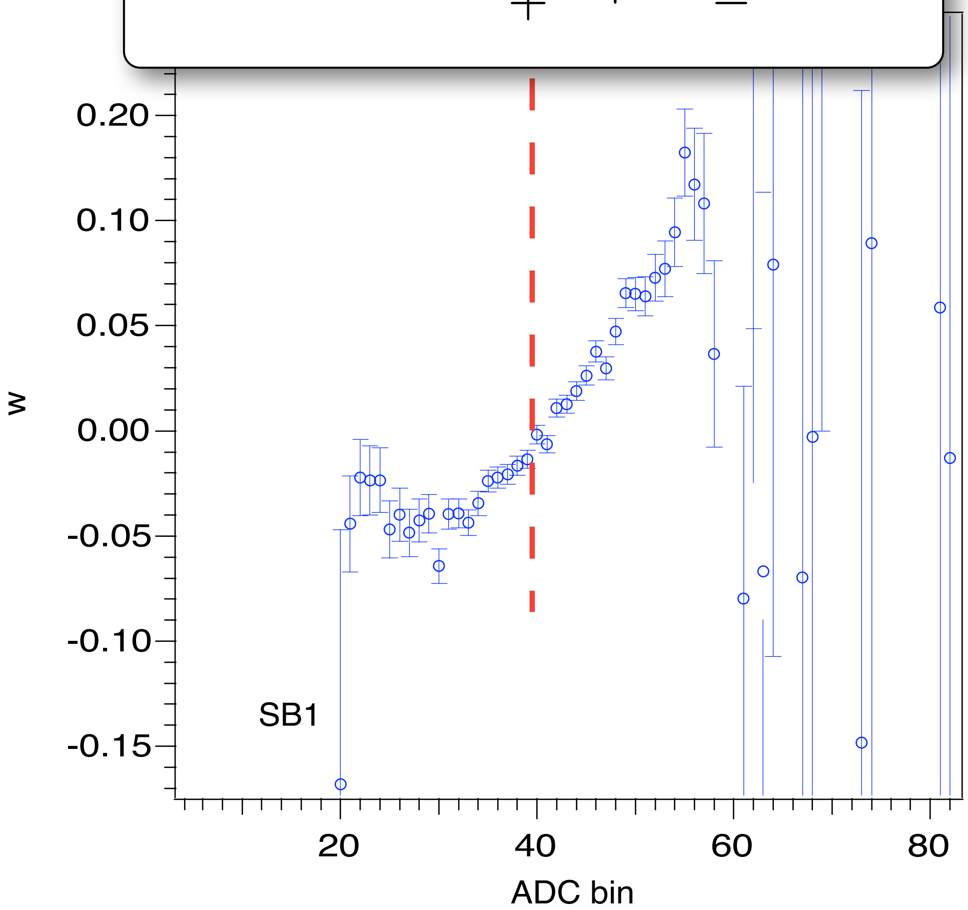
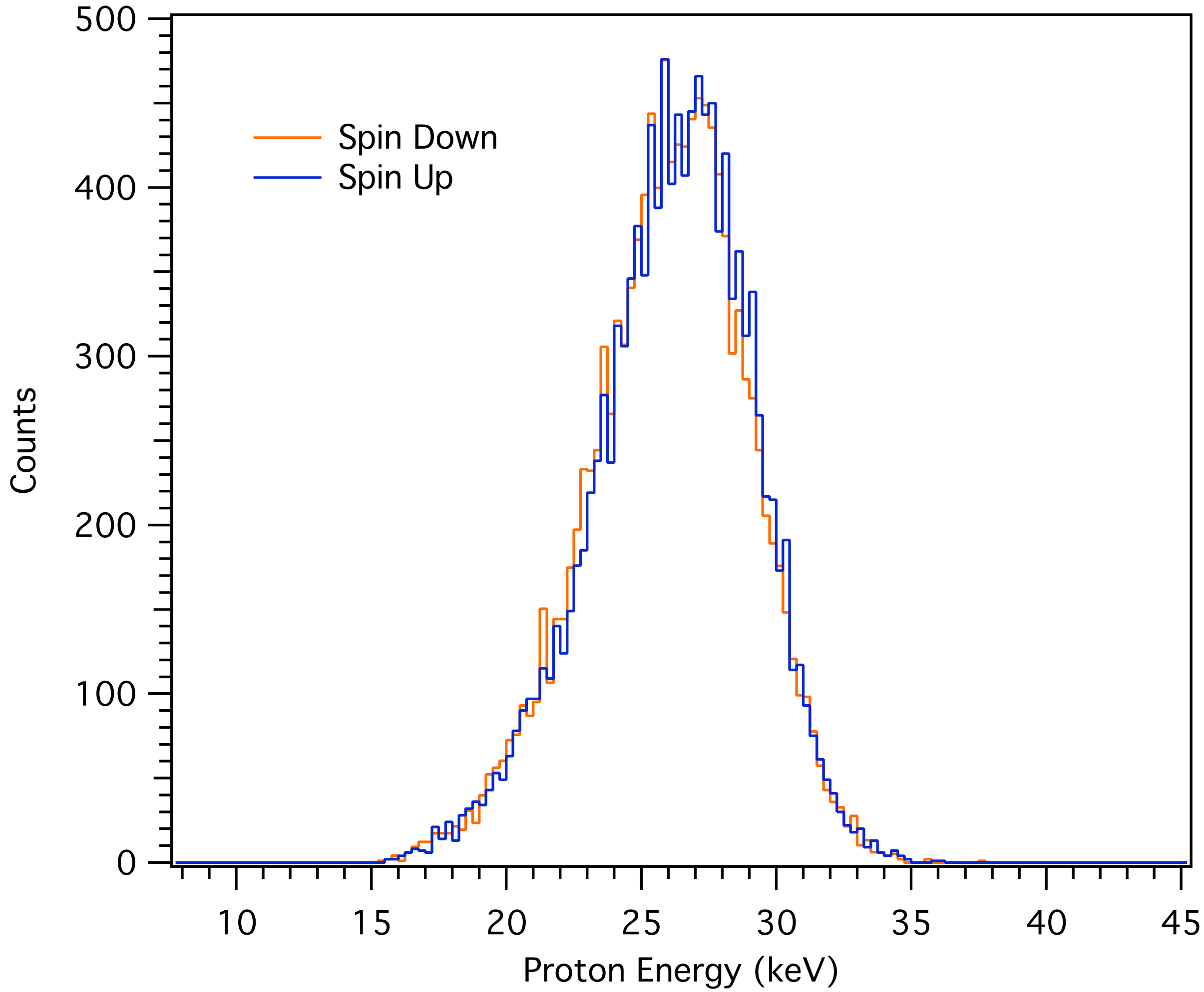


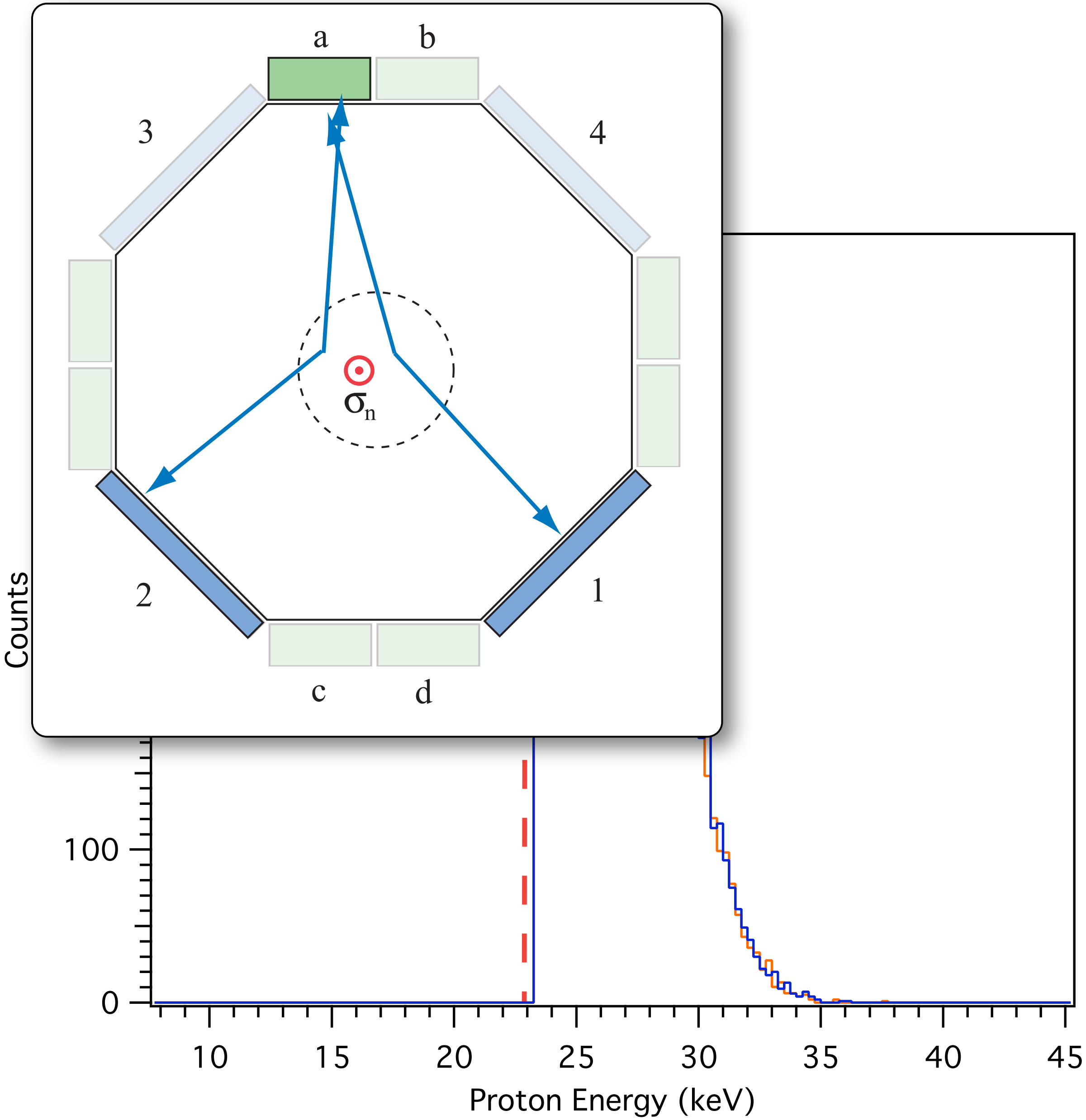
Data

Systematics: spin dependent energy spectrum



Shift of 159 eV

Systematics: spin dependent energy spectrum



Shift of 159 eV

With a threshold of 23 keV

$w_{false} = 0.0079$

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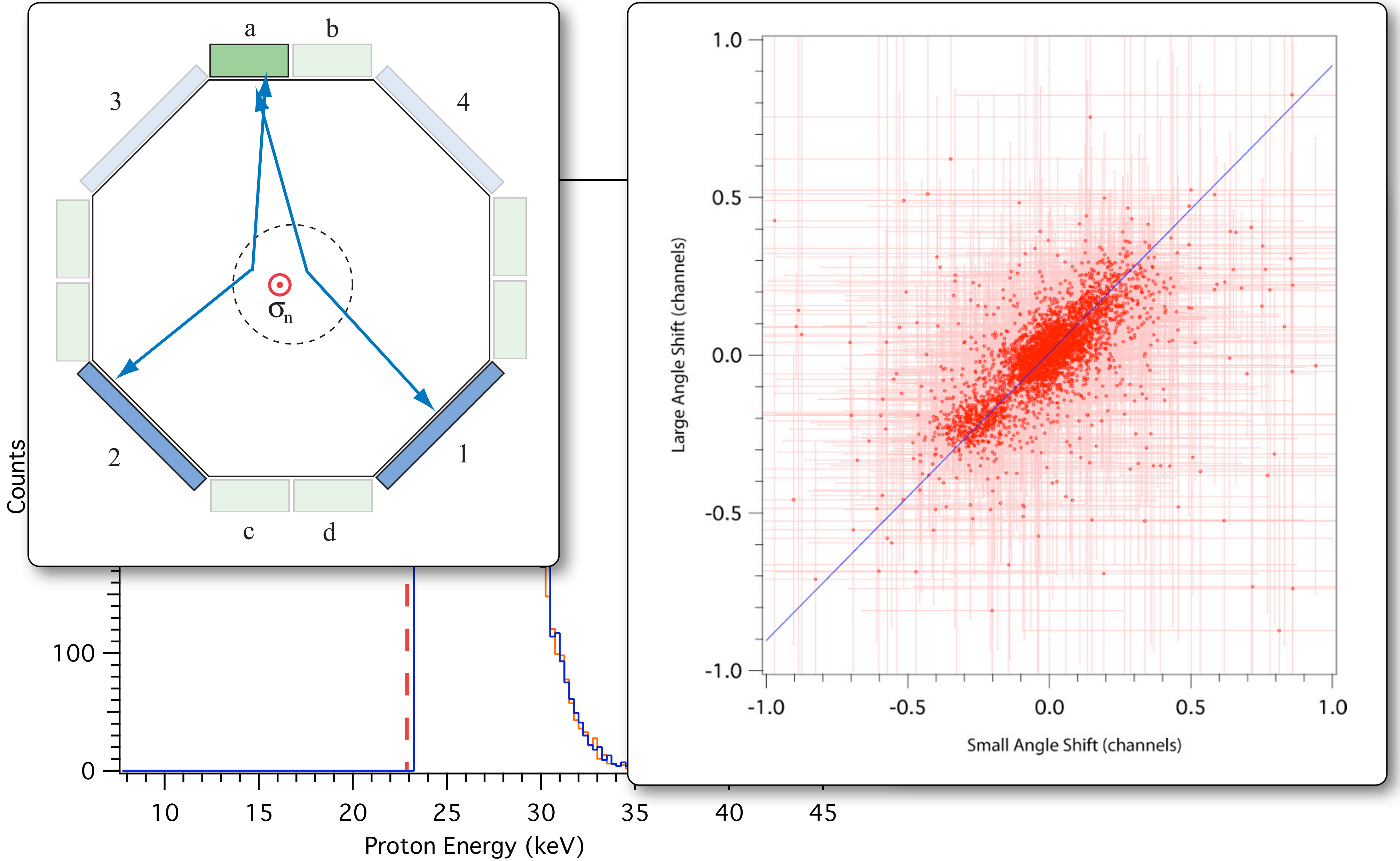
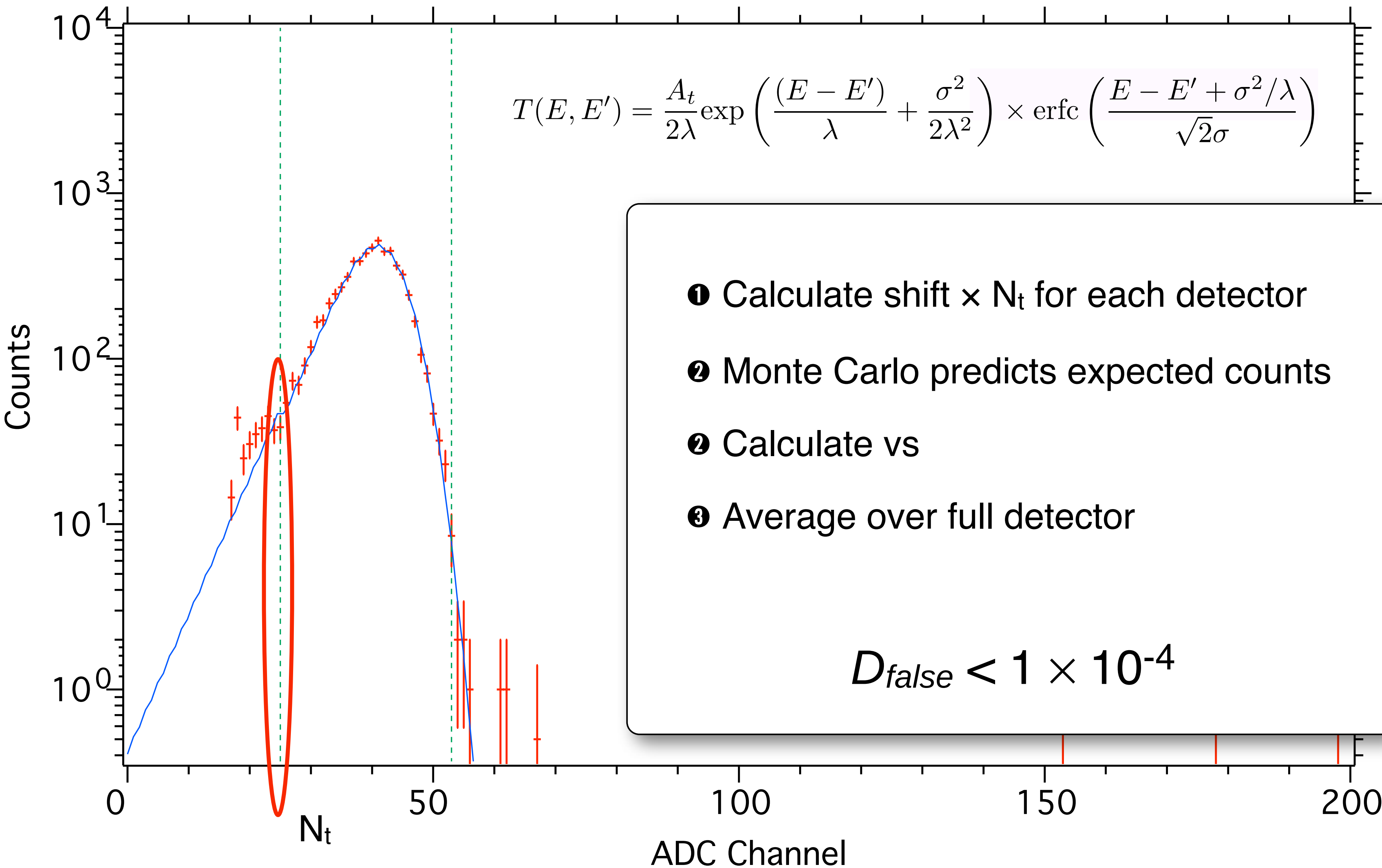
Systematics: spin dependent energy spectrum



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

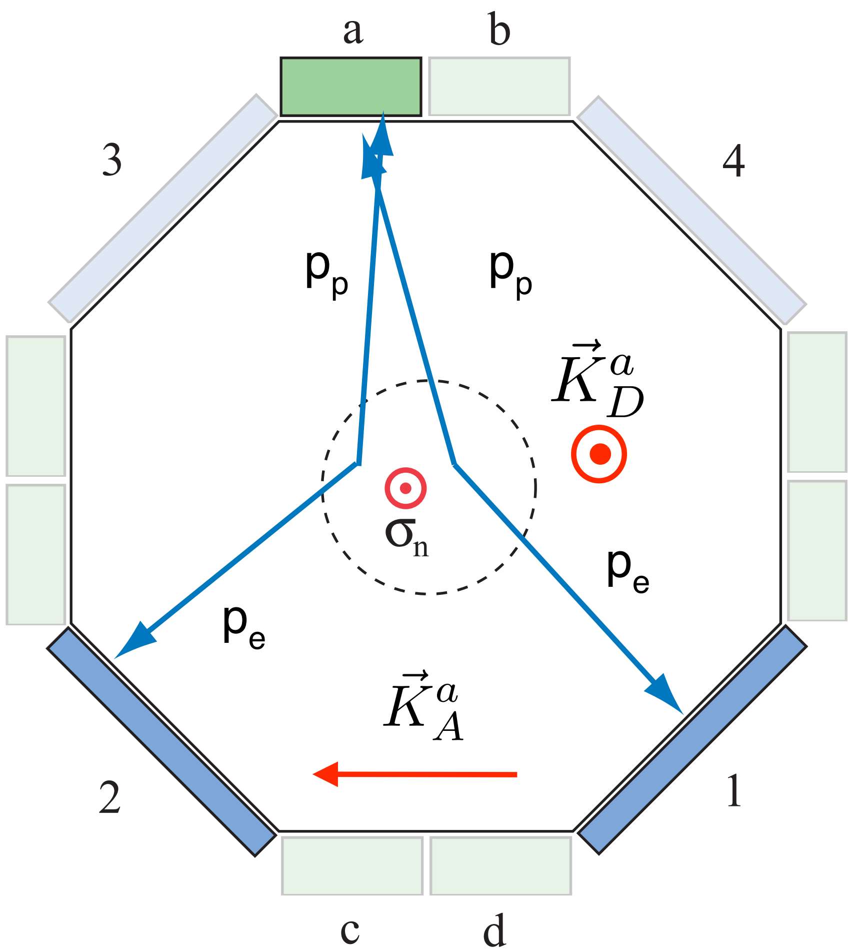
❷ Monte Carlo predicts expected counts

❷ Calculate vs

❸ Average over full detector

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

emiT: signal extraction



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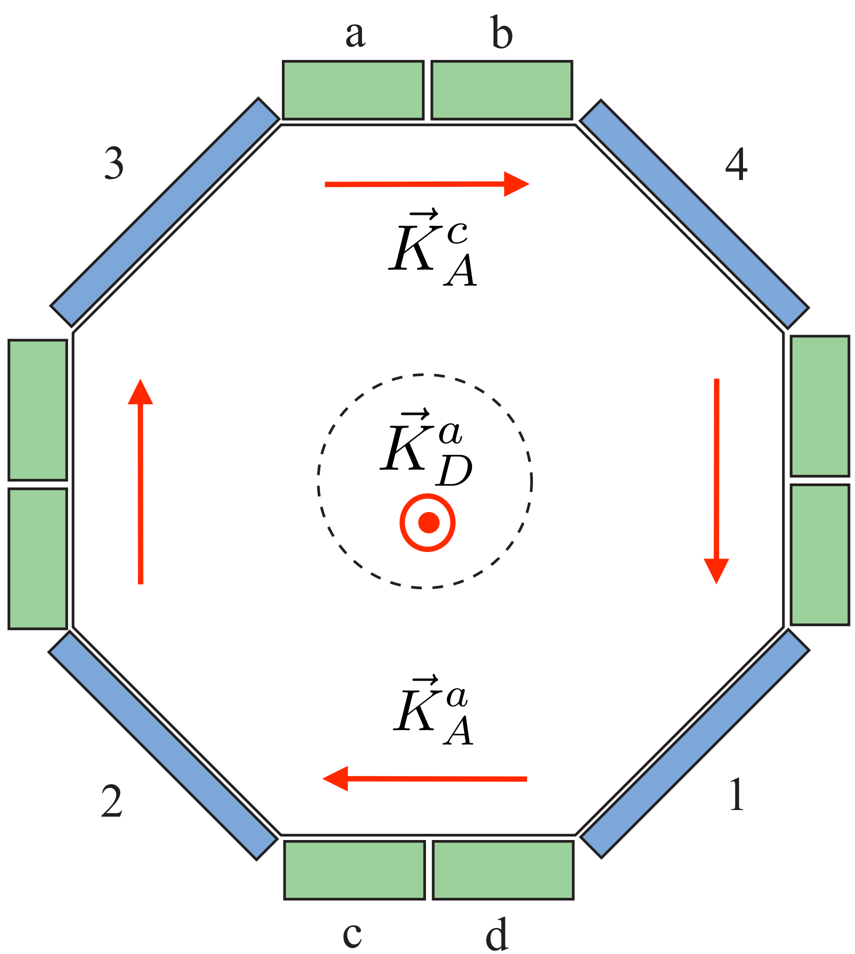
Systematics: Asymmetric Transverse Polarization (Tilt ATP)

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



$D_{false} = 0$

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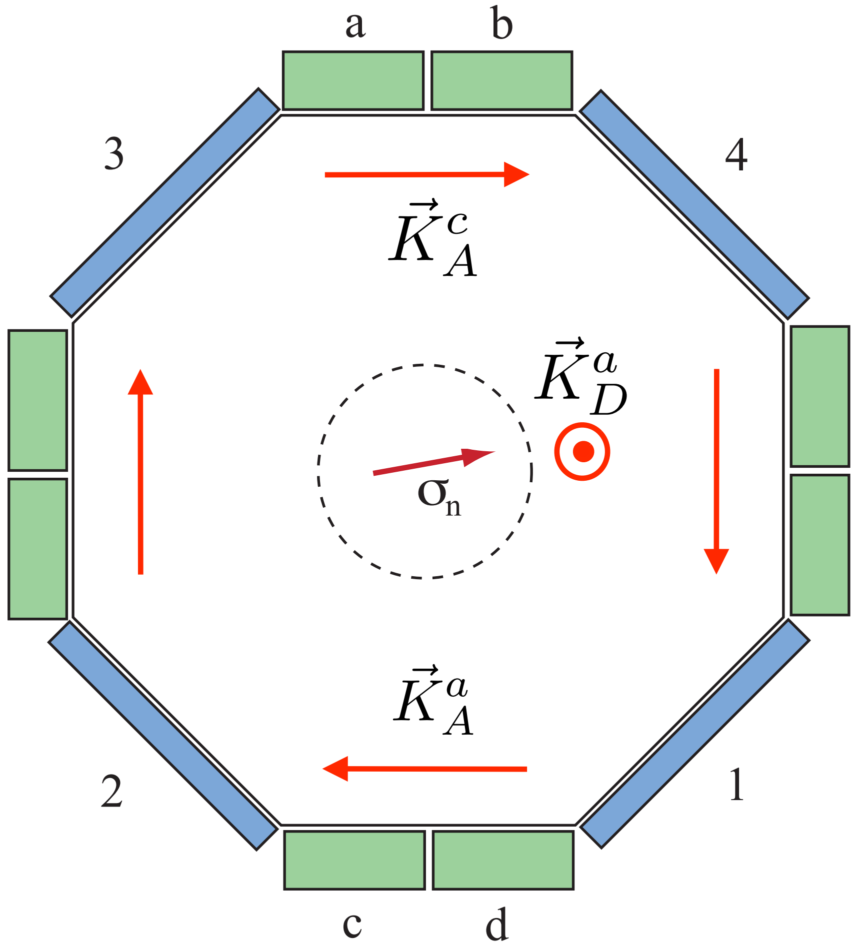

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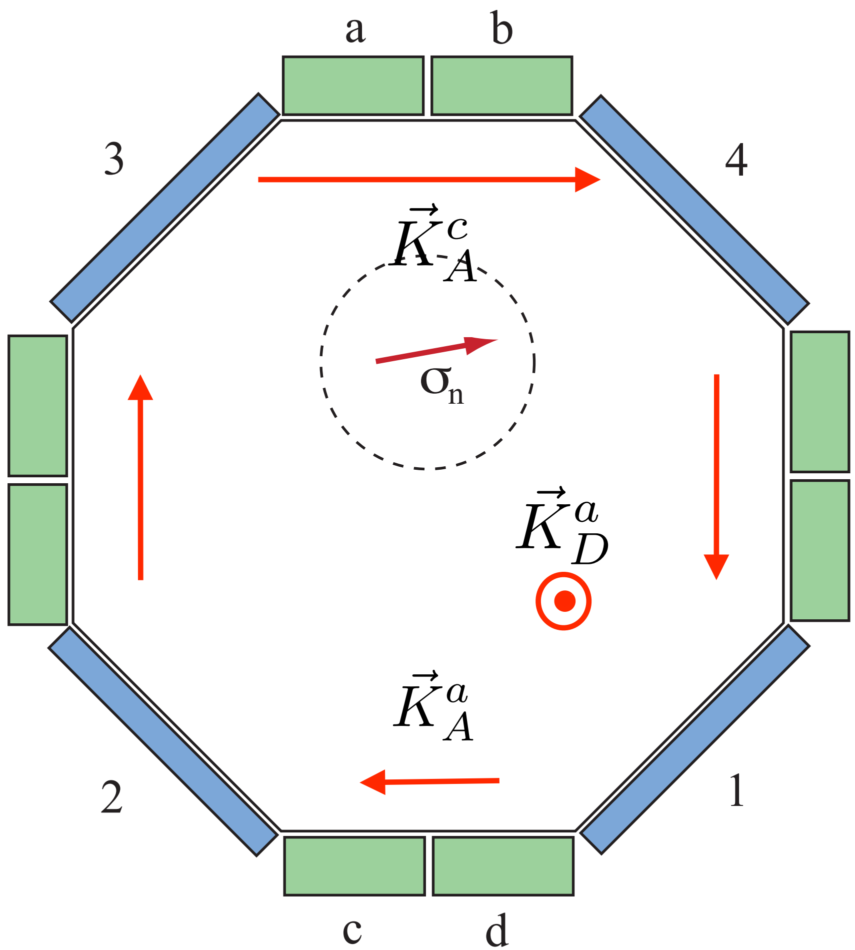


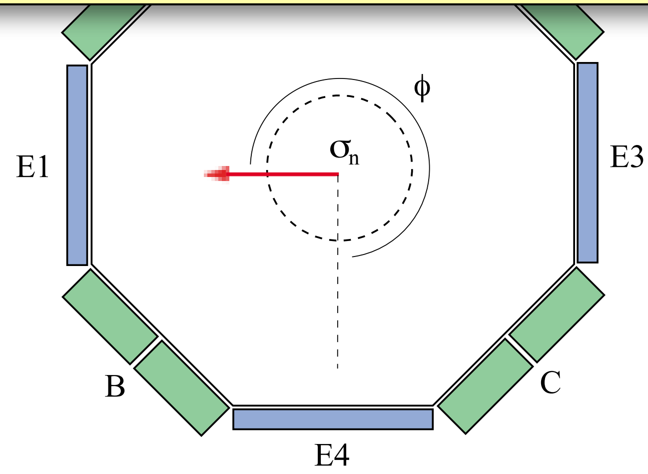
Monte Carlo
15 mrad polarization tilt,
beam displacement 5mm:
$D_{false} \sim 1 \times 10^{-4}$

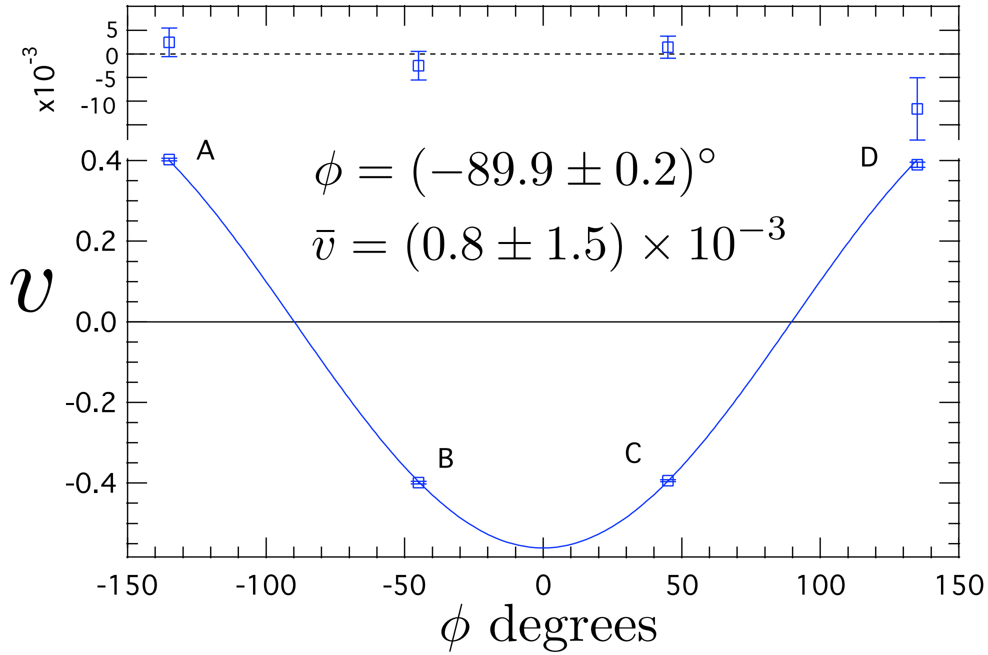
$D_{false} \neq 0$

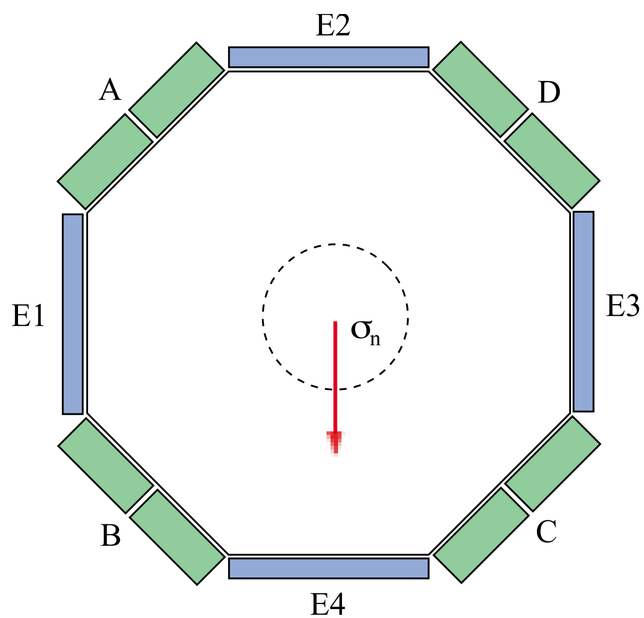
Two perpendicular asymmetries do *not* cancel

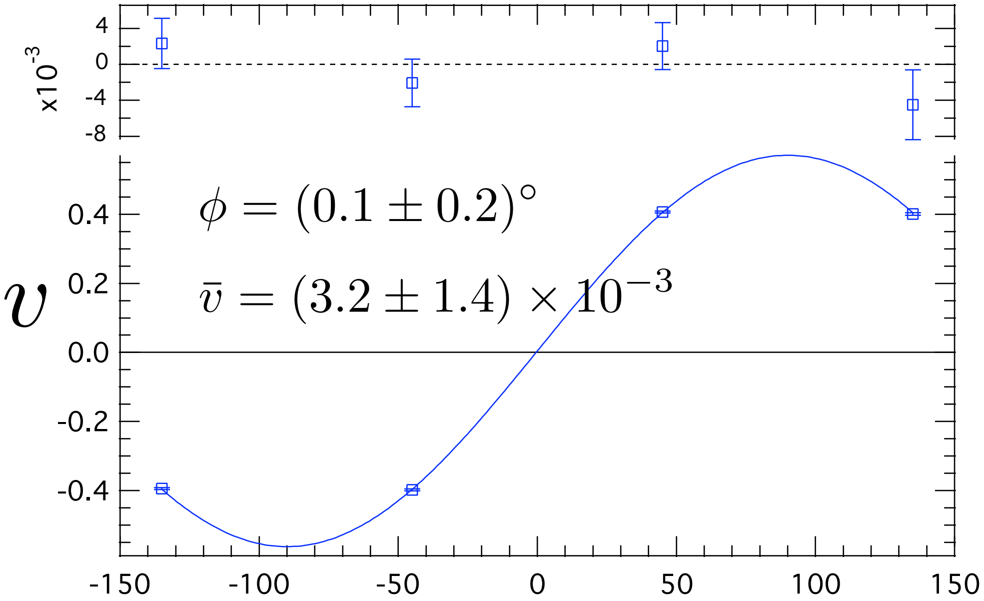
Systematics: Asymmetric Transverse Polarization (Tilt ATP)

Intentional field rotation
(Maximal polarization misalignment)









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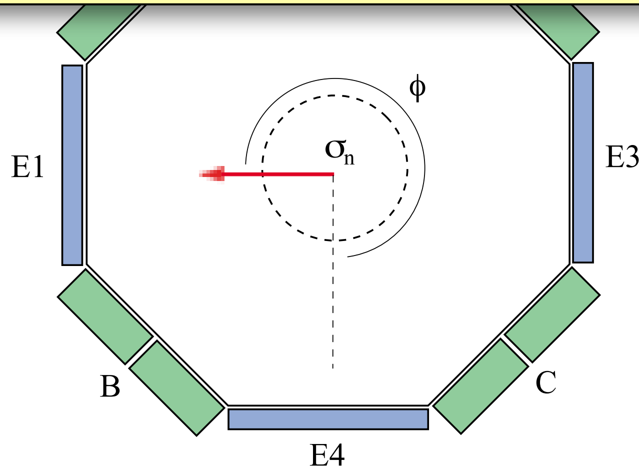
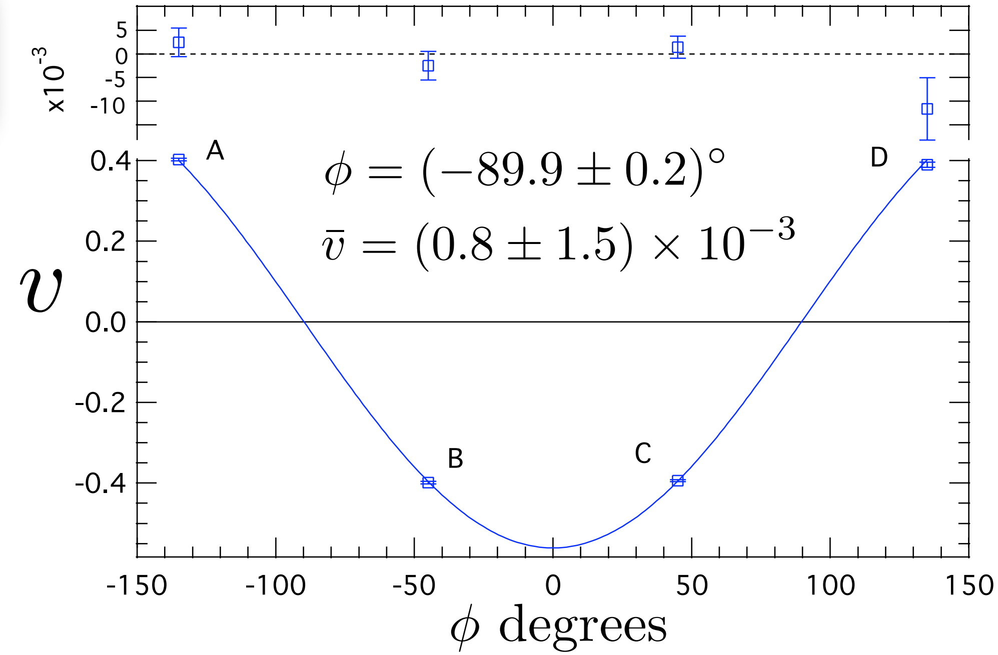
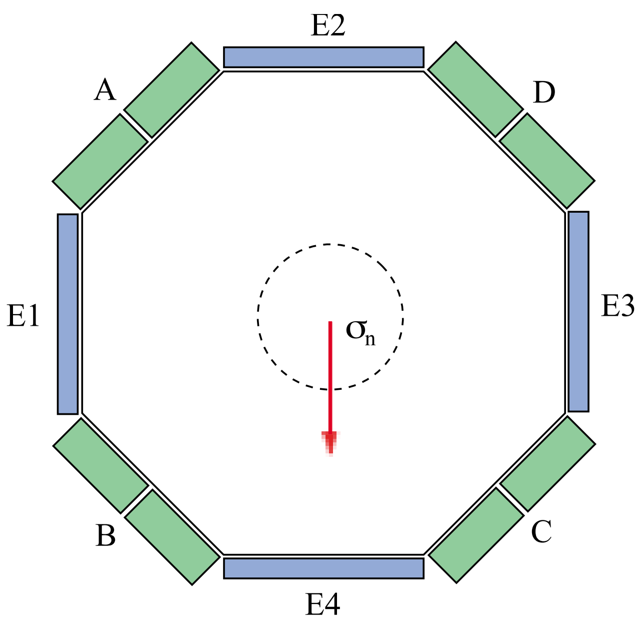
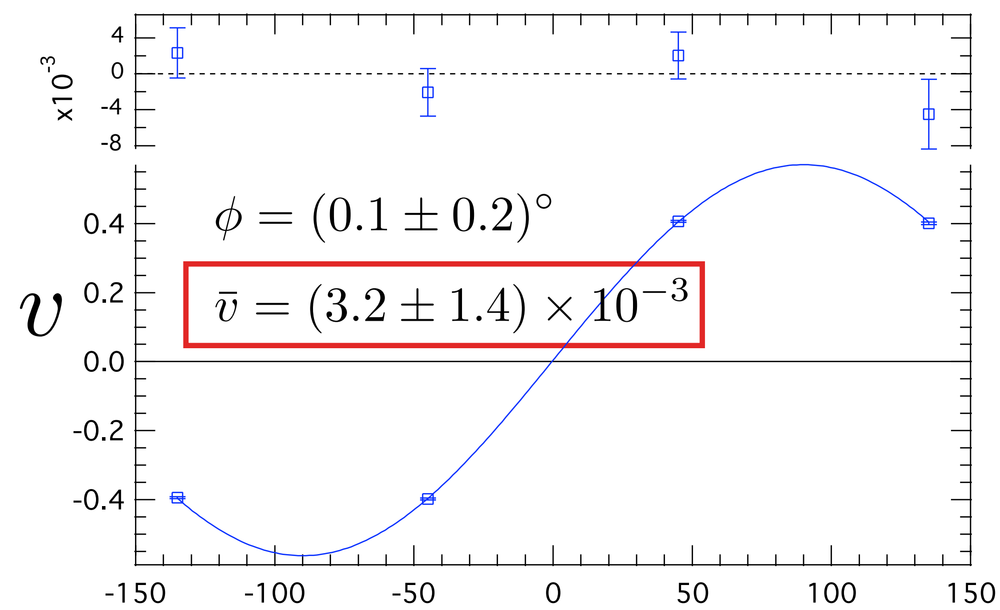
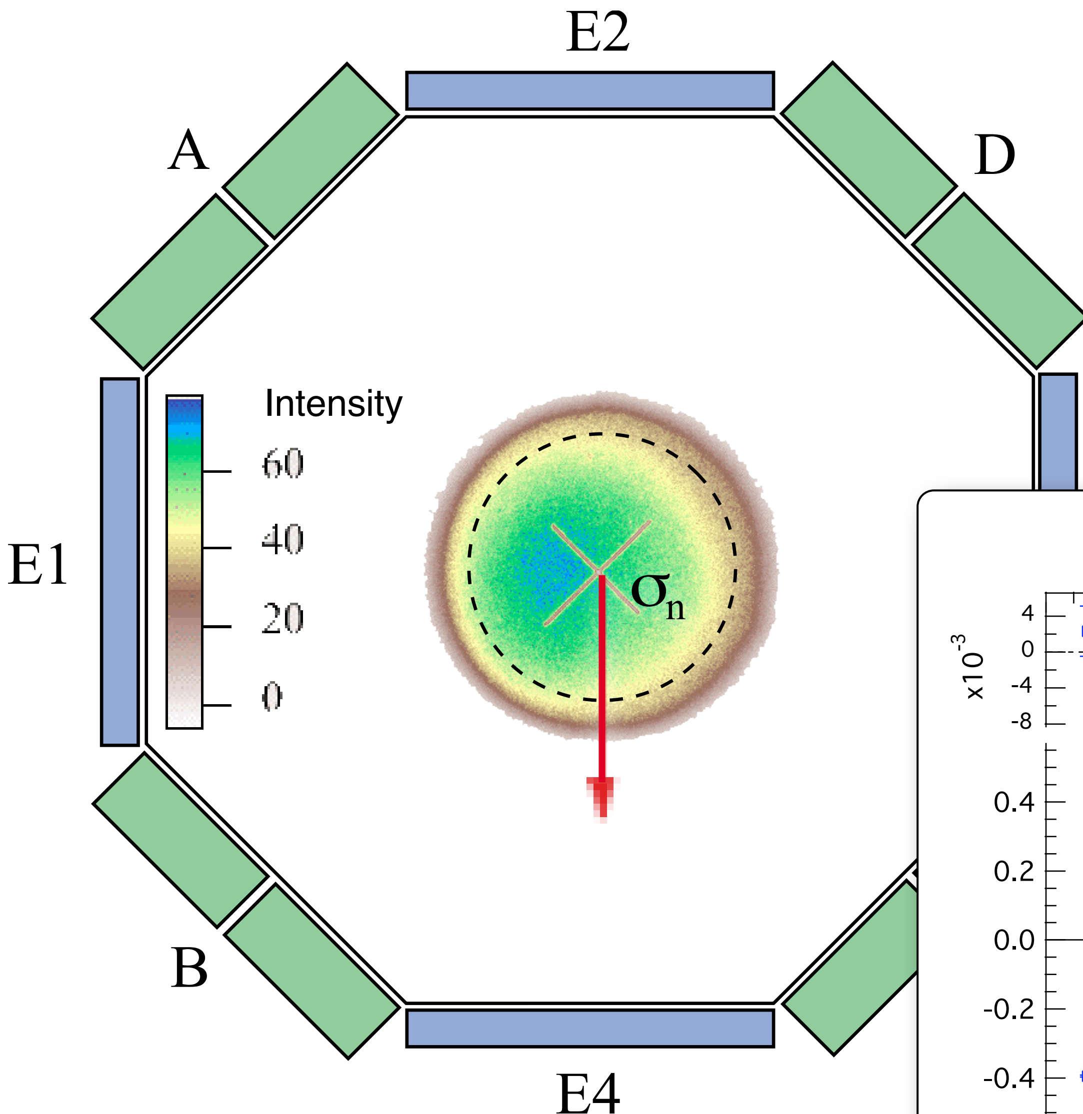






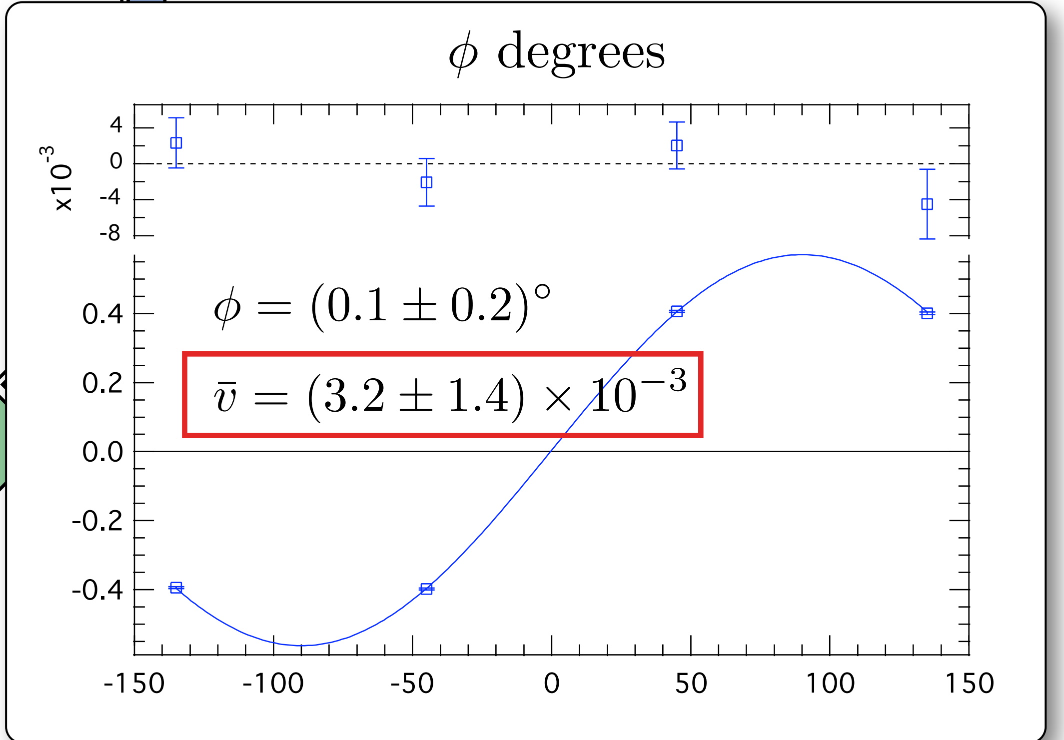


Systematics: Measured Intensity Distribution (Tilt ATP)



Dysprosium foil activated by the beam

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



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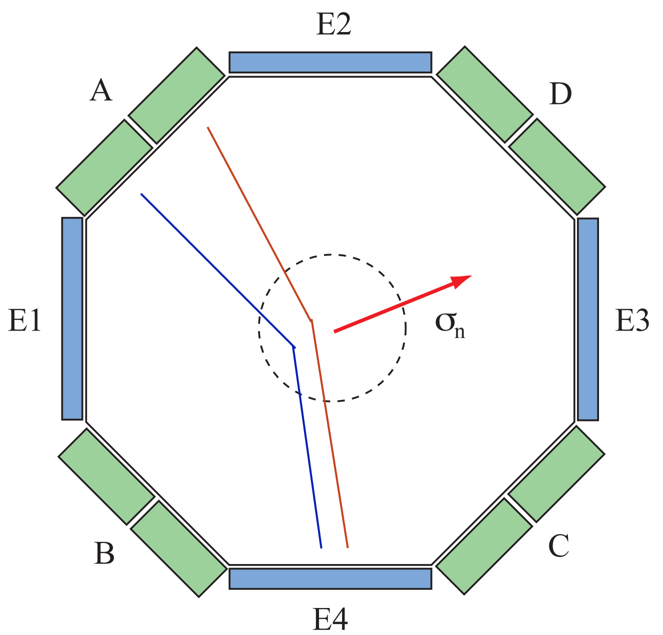
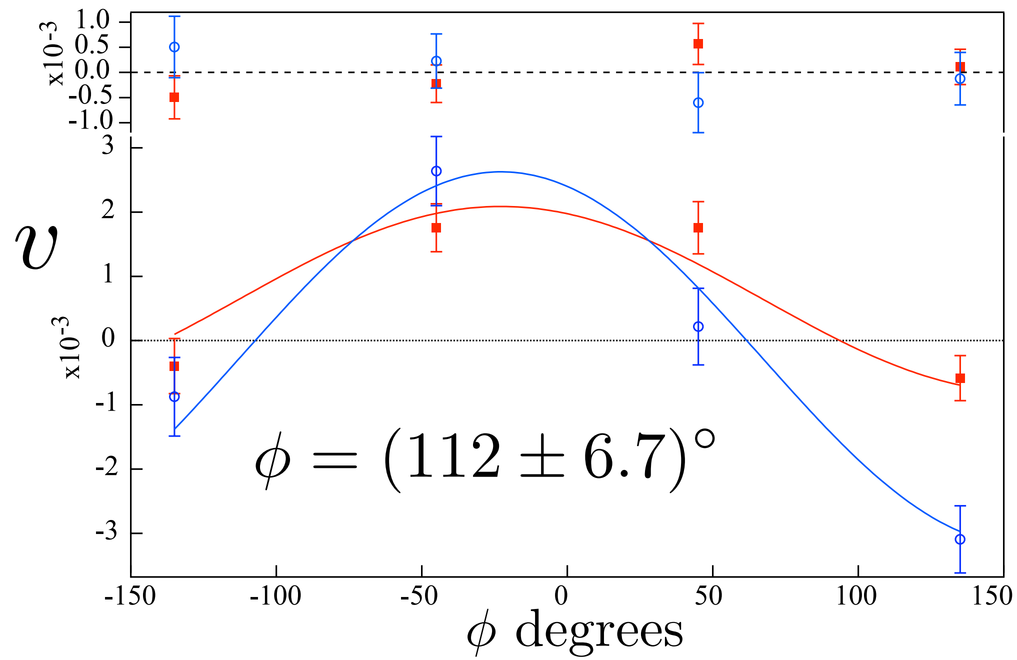


22 days of data (7% of total)



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}

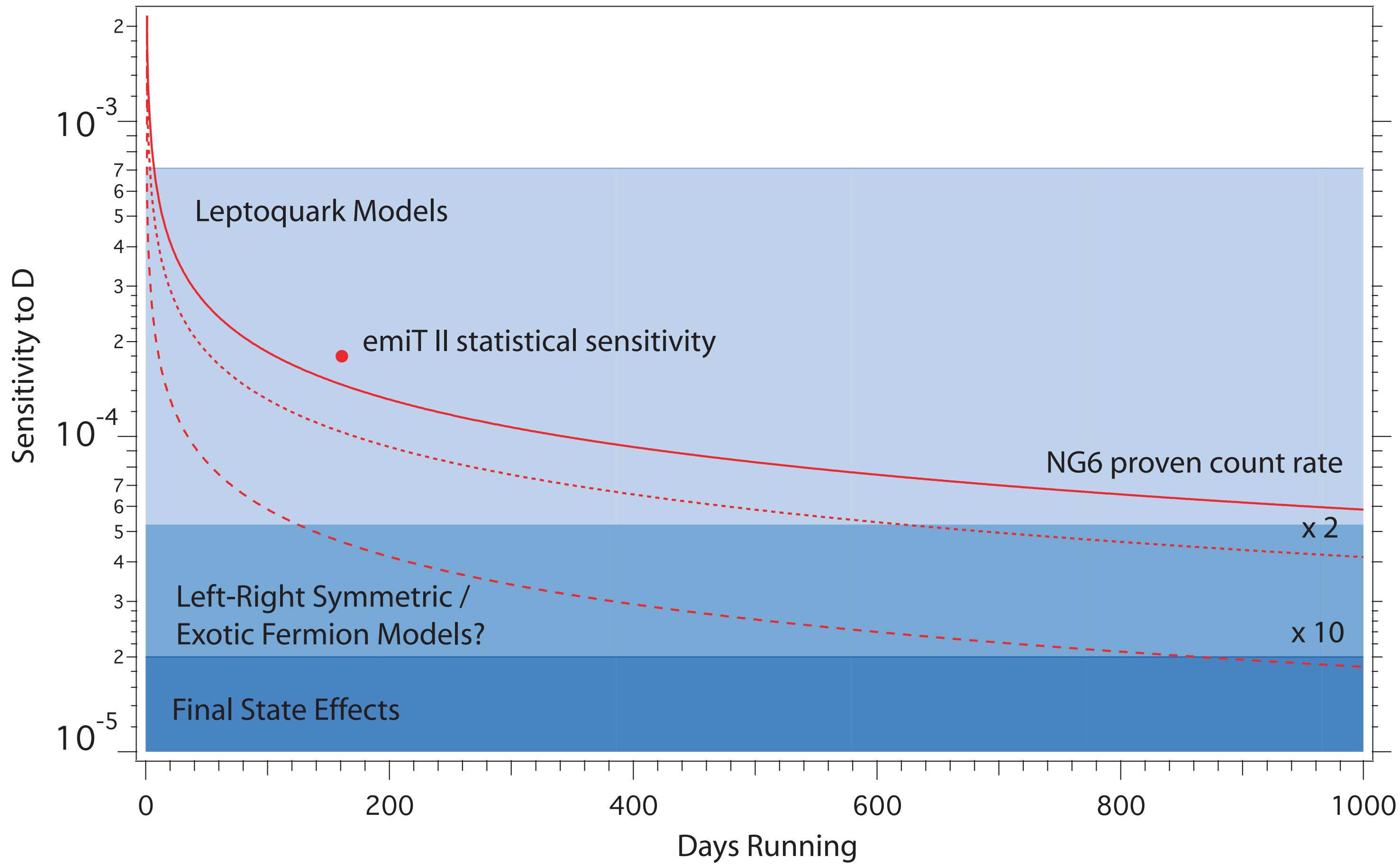
• Spin Dependent Spectra	$< 1 \times 10^{-4}$
• Twist ATP	$< 1 \times 10^{-5}$
• Electron backscattering	$< 1 \times 10^{-5}$
• Tilt ATP	$< 6 \times 10^{-6}$
• Spin depen. background	$< 1 \times 10^{-6}$
• Flux variations	$< 2 \times 10^{-4} \cdot D$
• Polarization variations	$< 2 \times 10^{-4} \cdot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

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

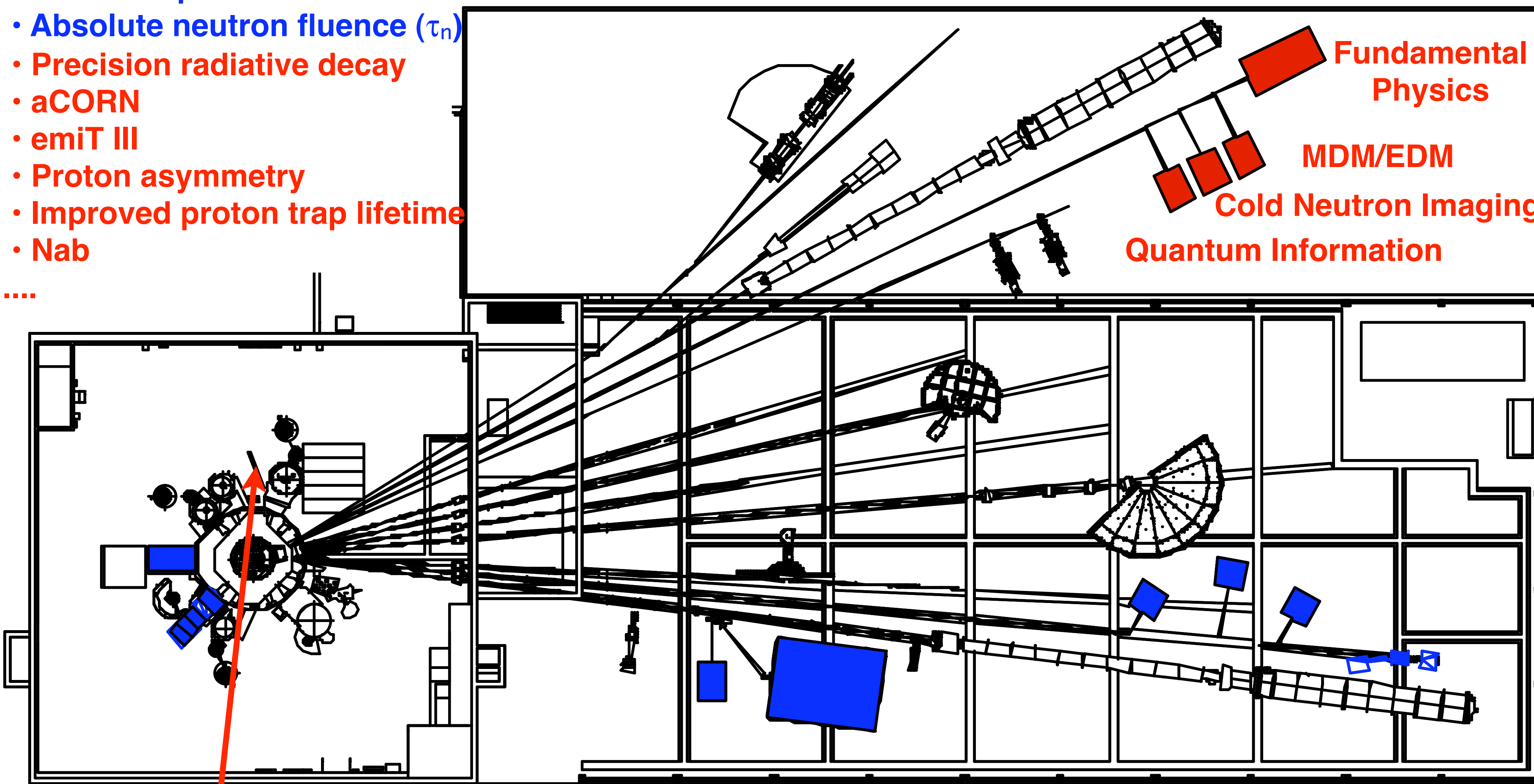
Future Possibilities

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)

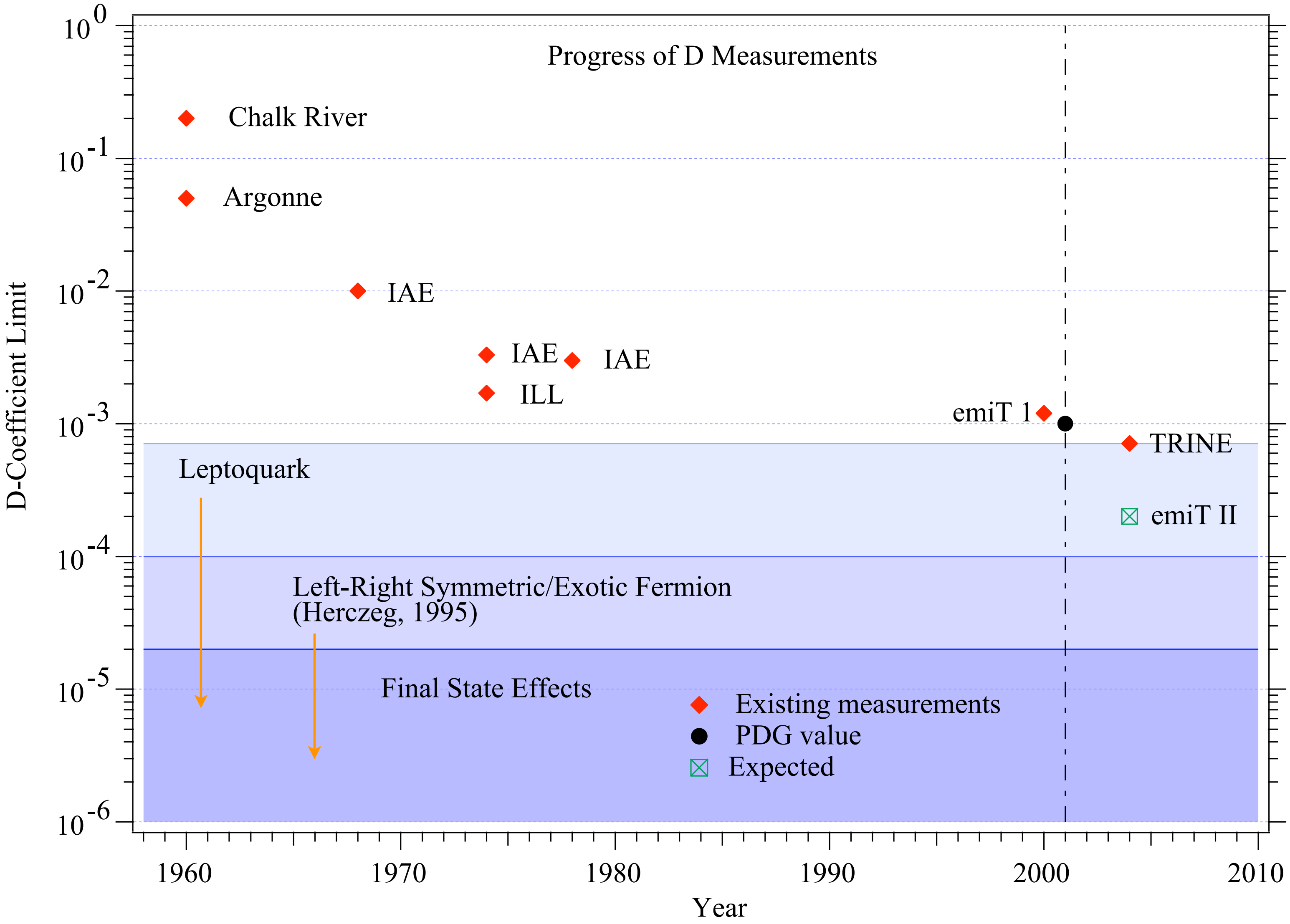


New Cold Source

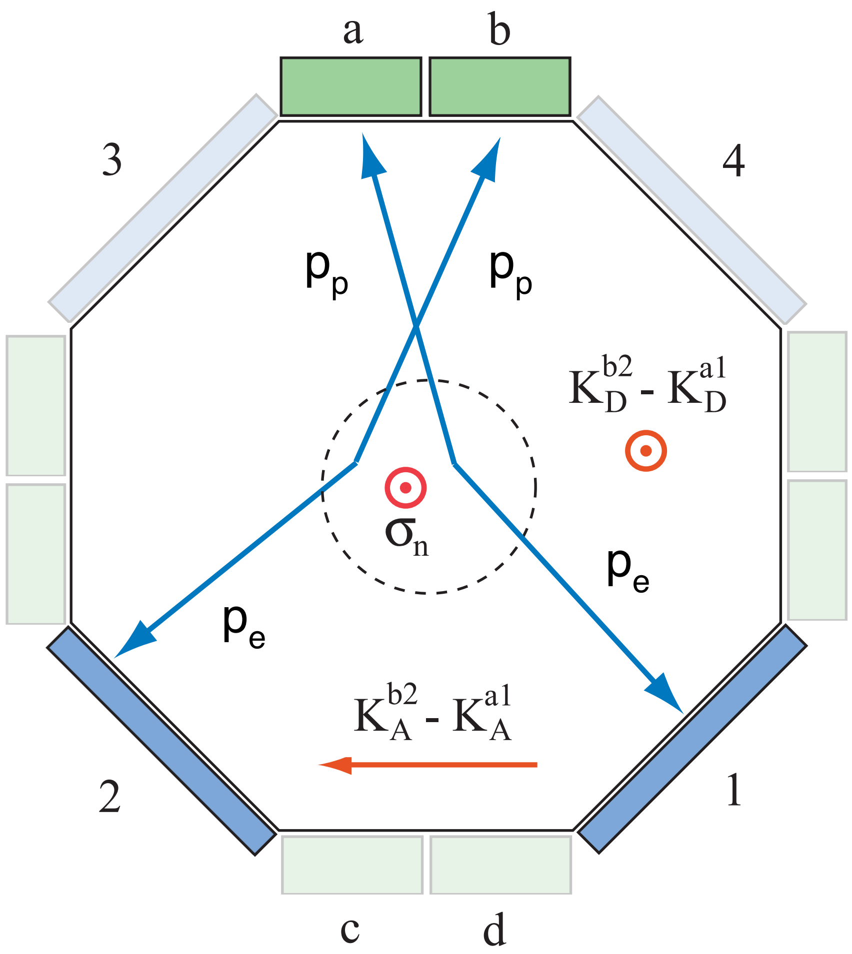
- Existing (or in progress)
- Proposed

-THANK YOU!-

Polarized Neutron Decay: Constraints and History



emiT: signal extraction



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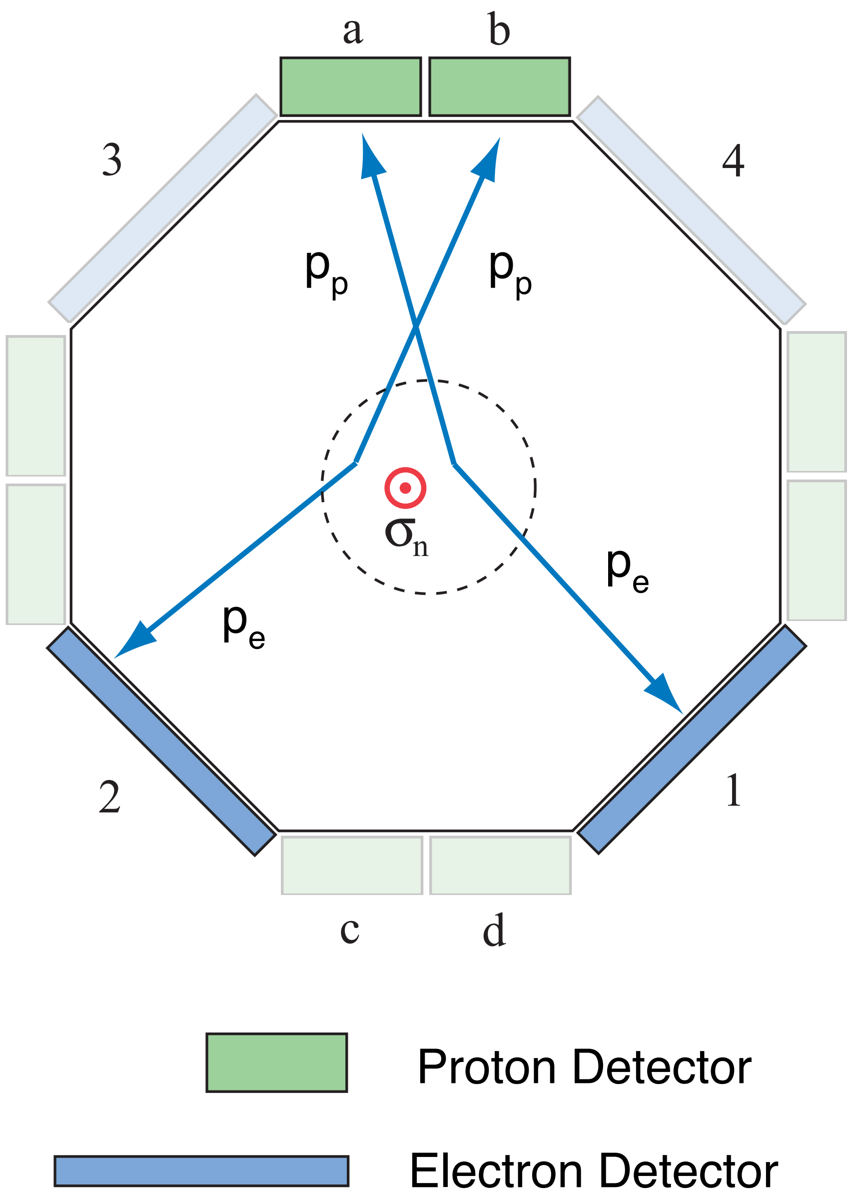
emiT: signal extraction



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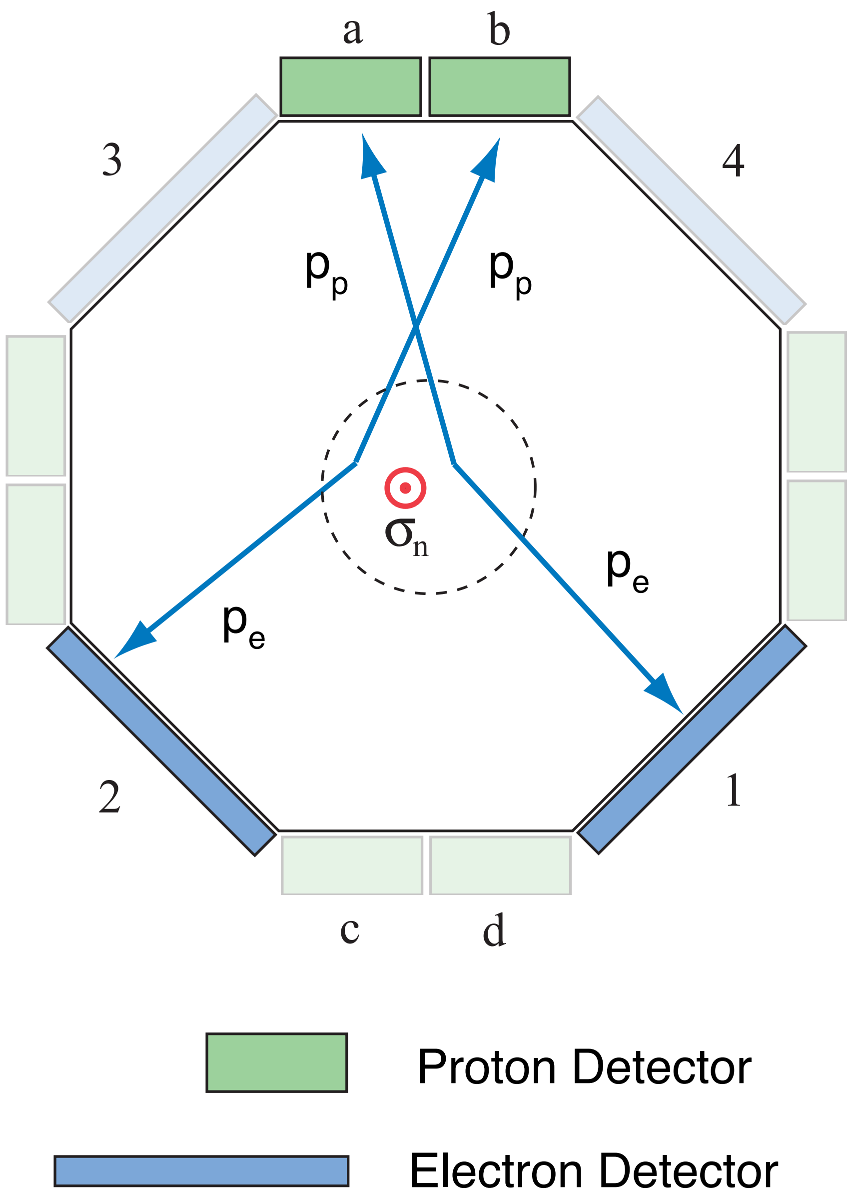

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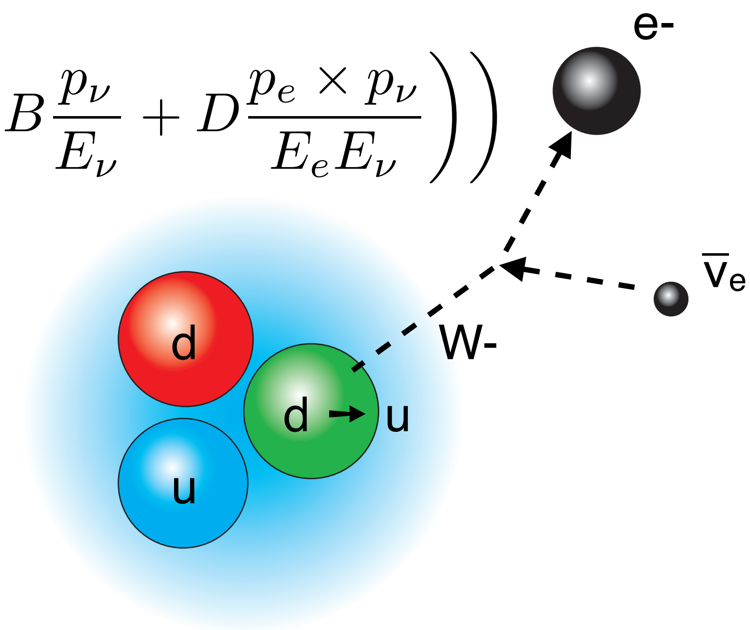
Instrumental constant

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

Fundamental Physics with Neutrons

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



$$\lambda \equiv \left|\frac{g_A}{g_V}\right| e^{-i\phi} = -1.2695 \pm 0.0029$$

$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} = -0.103 \pm 0.004 \qquad A = -2\frac{|\lambda|^2 + |\lambda|\cos\phi}{1 + 3|\lambda|^2} = -0.1173 \pm 0.0013$$

$$B = \frac{|\lambda|^2 - |\lambda|\cos\phi}{1 + 3|\lambda|^2} = 0.981 \pm 0.004 \qquad \tau_n \propto \frac{1}{g_V^2 + 3g_A^2} = 885.7 \pm 0.8$$

Conclusions:

- Successful run carried out from June 2002 - December 2003
- Over 350 million coincidence events collected
- Preliminary treatment of systematic effects indicate all are below 1×10^{-4}
    - Twist ATP $< 1 \times 10^{-4}$
    - Electron backscattering $< 1 \times 10^{-5}$
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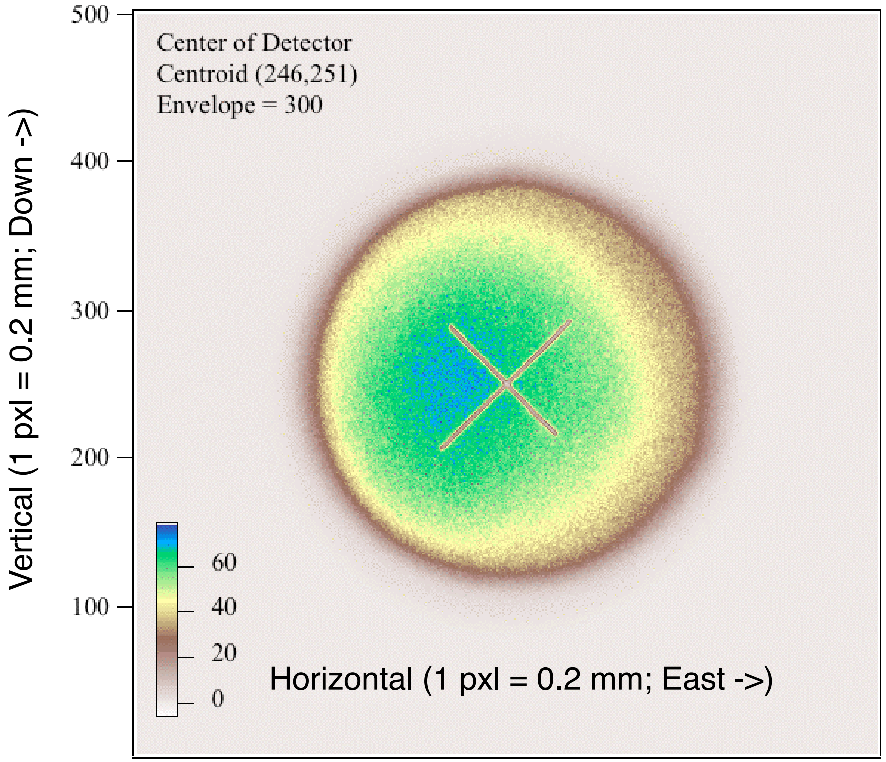
Mumm *et al.*, nucl-ex/0402010 and Rev. Sci. Instru.

Systematics: Characterization of the neutron beam



Improved method of measuring neutron flux

Dysprosium foil activated by the beam

- Cross hair (Cadmium wire), indicates chamber axis.

Scan foil

- Intensity plot linear over 4 orders of magnitude

emiT: completed filtering of primary data set

* Possible misalignment of the the guide field (fluctuations below 3-5 mrad)
* Poor operation of SB detectors/detector system (reduction of some systematic uncertainties)
* Equal counting times in each spin state (and we want the spin state to be well defined)
* Uniform/defined beta events (multiplicity and energy)

Raw events	361.4×10^6	
Decay events	244.8×10^6	67.7%
Background events	3.7×10^6	S/B ≈ 66
Beta energy	35.6×10^6	9.8%
Field monitoring	30.3×10^6	8.4%
Beta multiplicity	17.8×10^6	4.9%
Fission monitors	3.4×10^6	0.9%
Detector bias	2.5×10^6	0.7%
Coil currents	2.7×10^6	0.7%
High voltage	1.2×10^6	0.3%
Spin flip	0.4×10^6	0.1%

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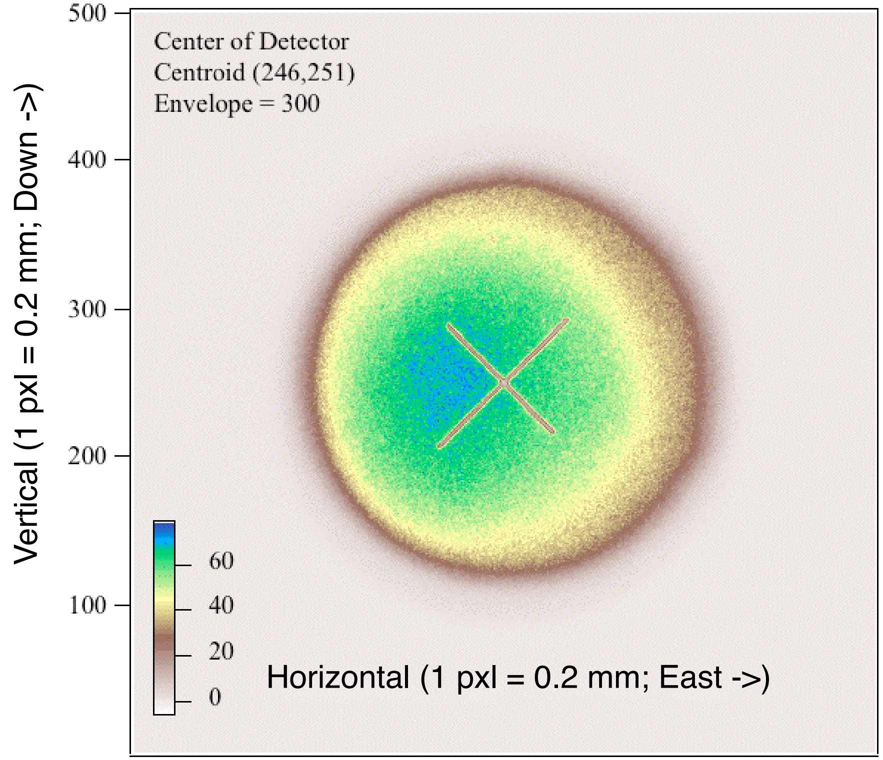

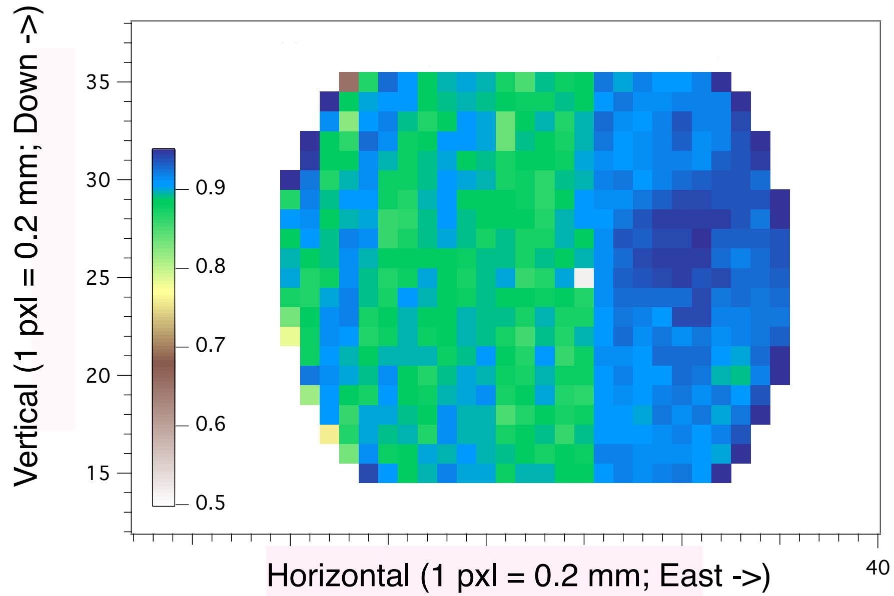

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Polarization asymmetry is equivalent to a beam shift...

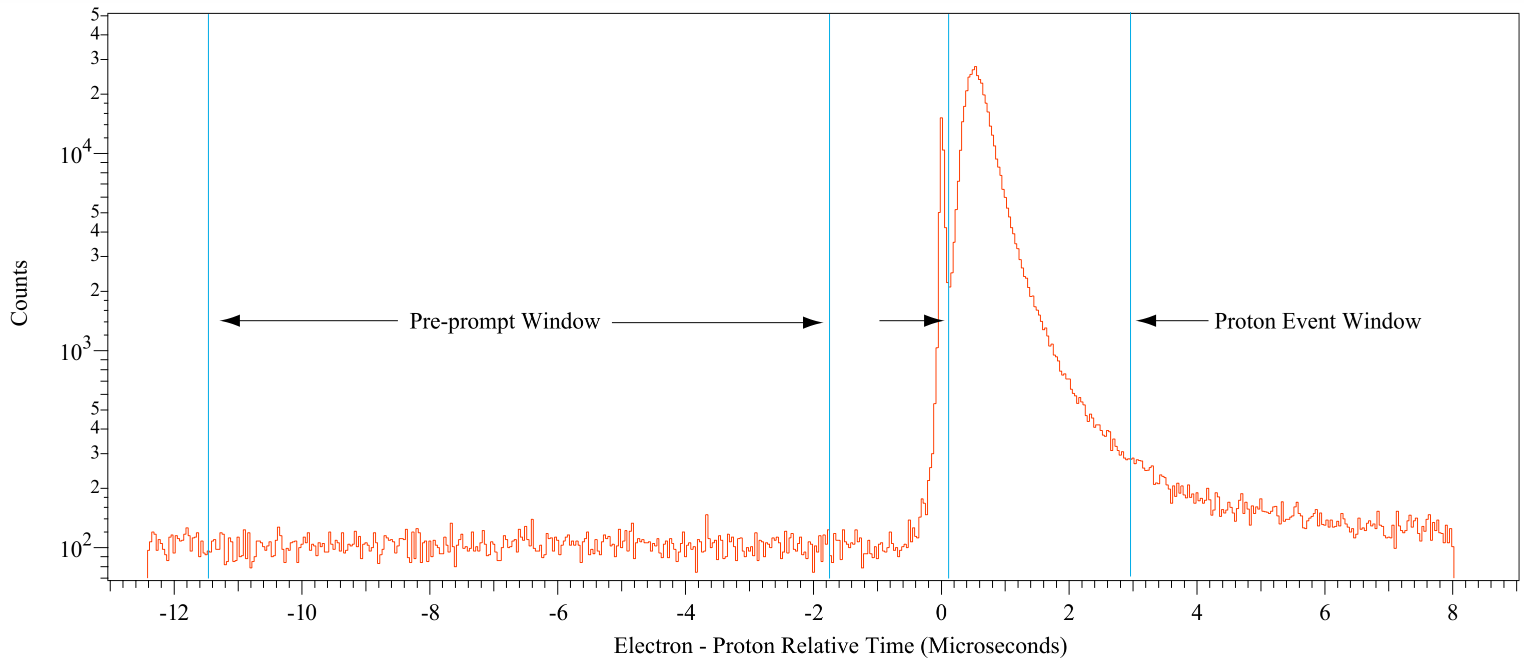
Measuring polarization

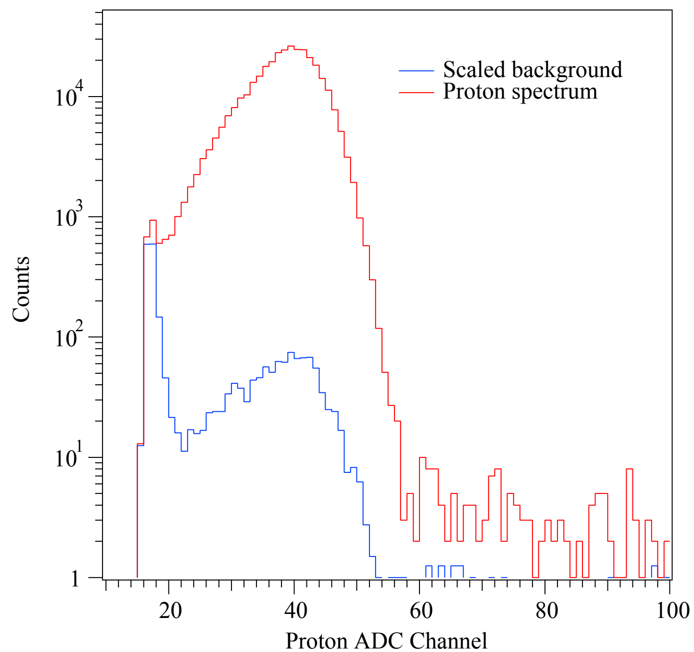
- Second supermirror after the spin flipper

$$P_{SM}P_A = \frac{\Phi_{OFF} - \Phi_{ON}}{\Phi_{ON} - s\Phi_{OFF}}$$

s	spin flipper efficiency
OFF/ON	indicates spin flipper state
PSM	polarizing power of the supermirror
PA	polarizing power of the analyzing mirror

emiT: signal extraction I





Subtract scaled background from summed decay window

Flat pre-prompt window

Decay window determined by maximizing S/N

$$\frac{\sigma_N}{N} = \frac{(s^2\sigma^2_{OFF} + \sigma^2_{ON}(s))^{1/2}}{N_{ON}(s) - sN_{OFF}}$$

Neutron Interactions and Dosimetry Group

Neutron beta-decay

Neutron lifetime

Penning trap - PRC 71, 055502 (2005) - 886.3 +/- 4 s

Ultracold neutron-based measurement in progress

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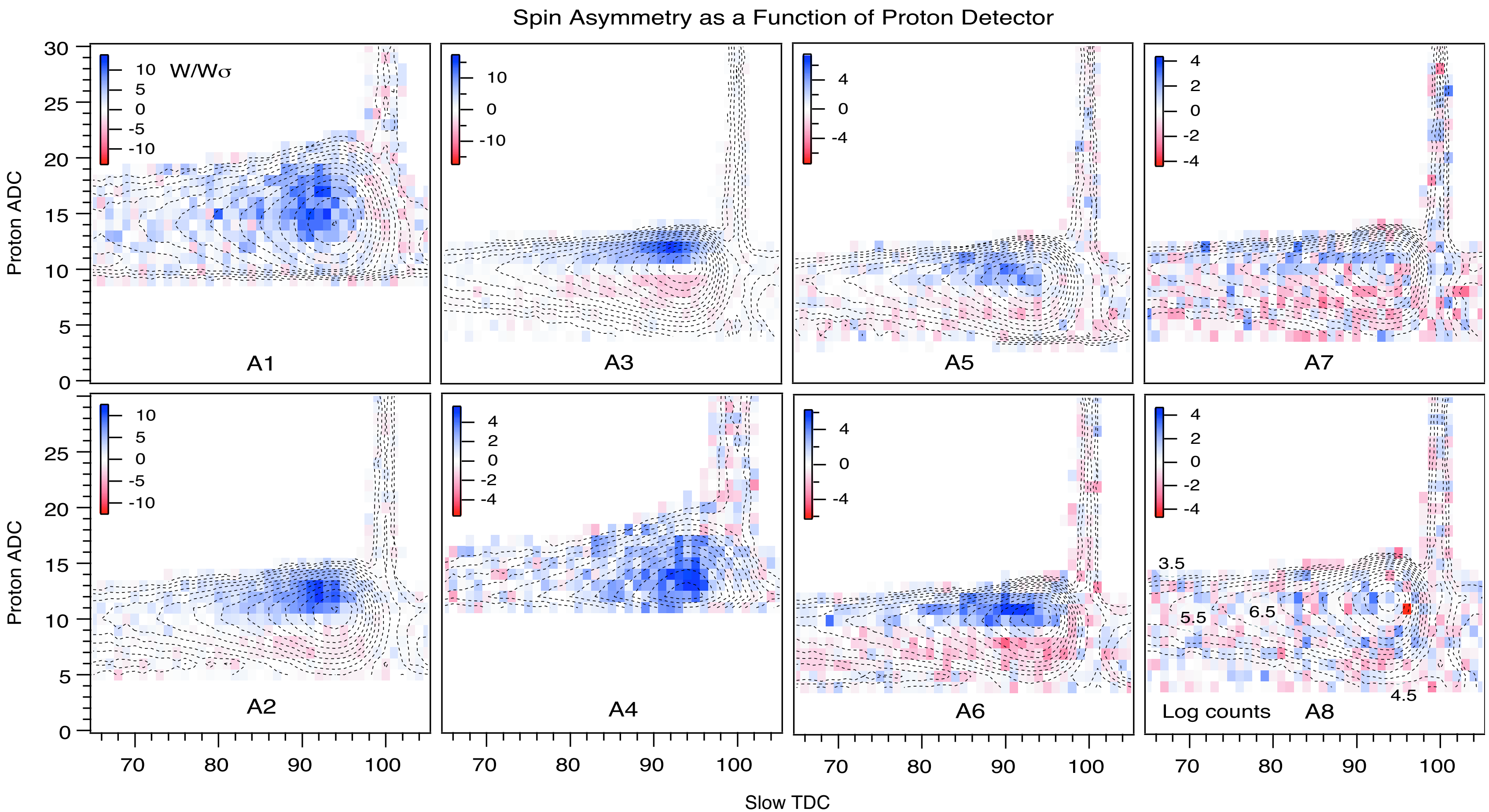
Polarized ^3He neutron spin filters: *NPDGamma at LANL/SNS*

Decay correlation coefficients (A, B, C)

Systematics: Spin dependent proton energy spectrum



Pieter Mumm, DNP 2005, Sept. 22, 2005

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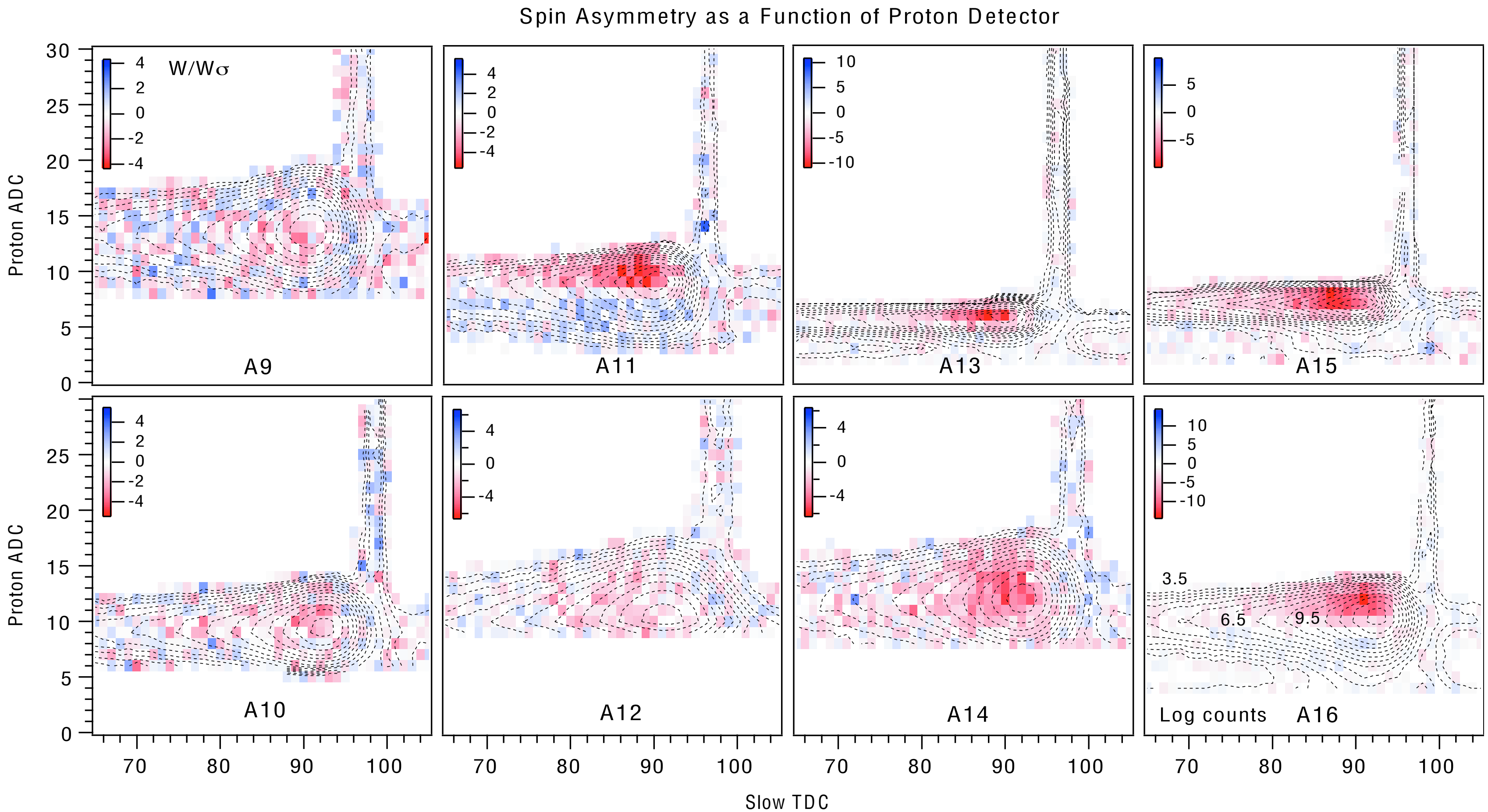


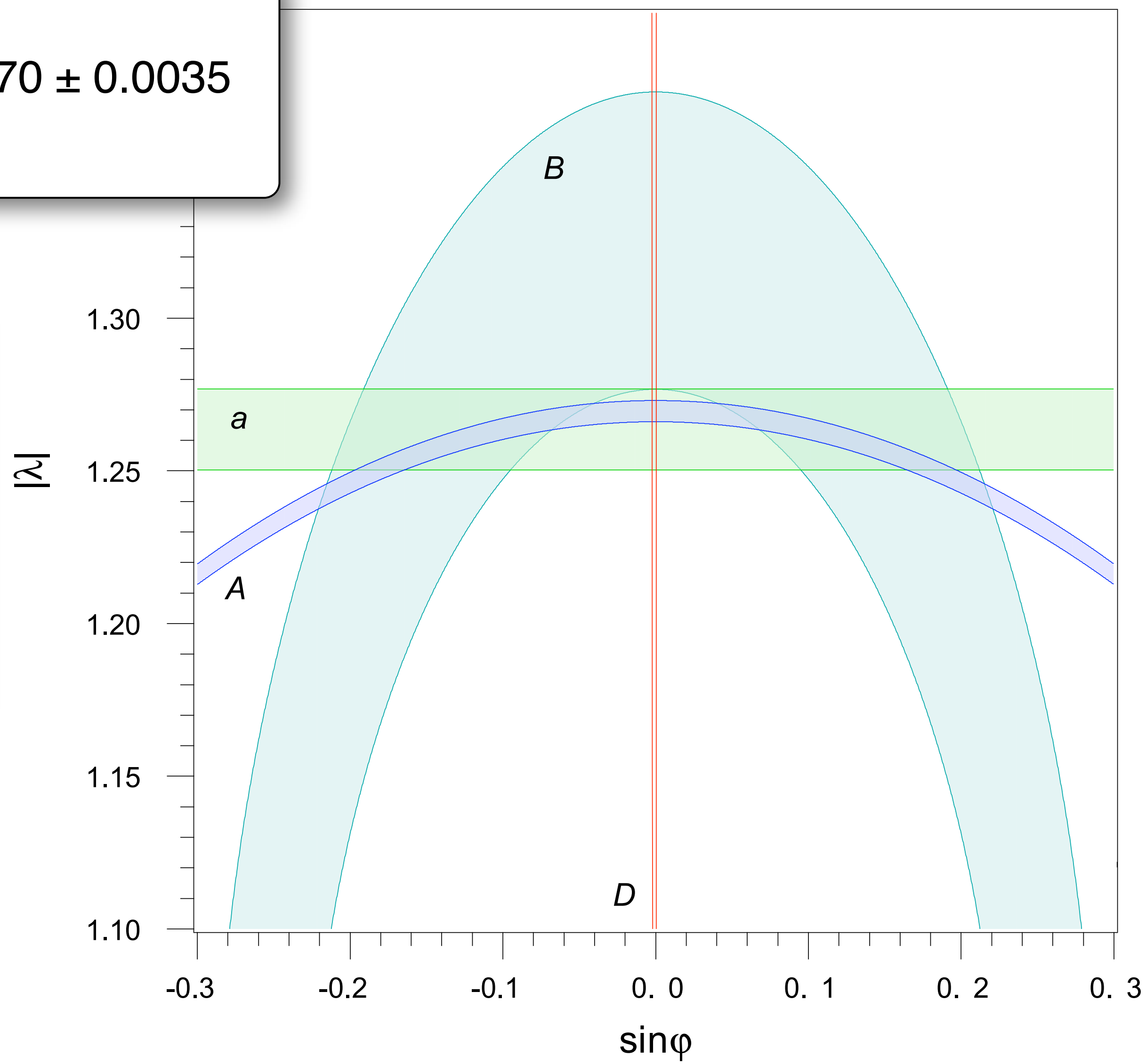
Polarized Neutron Decay

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

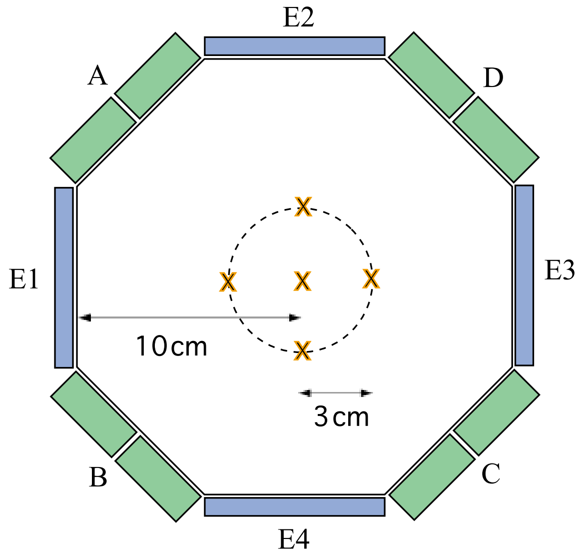
$$\lambda \equiv \left|\frac{g_A}{g_V}\right| e^{-i\phi} \approx 1.2670 \pm 0.0035$$

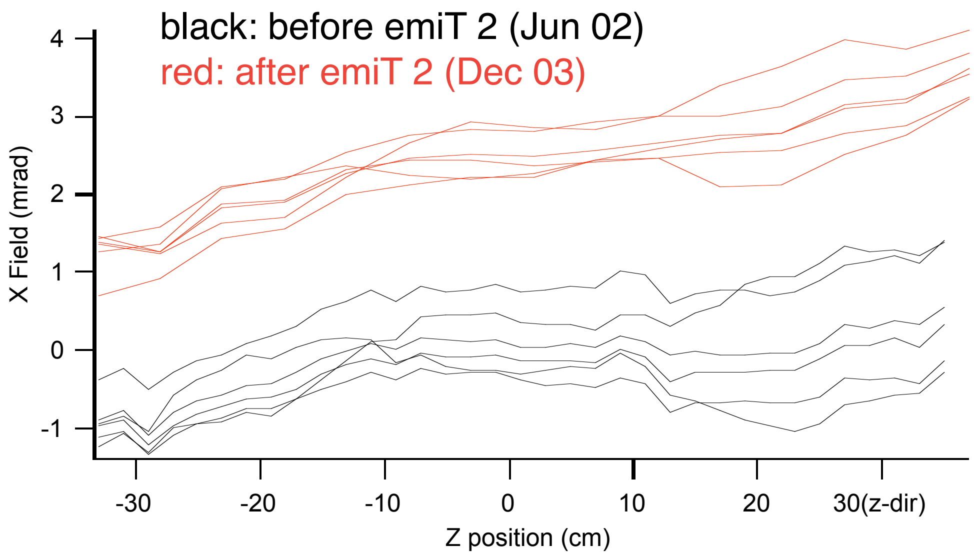
T-odd (P-even) triple correlation:

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

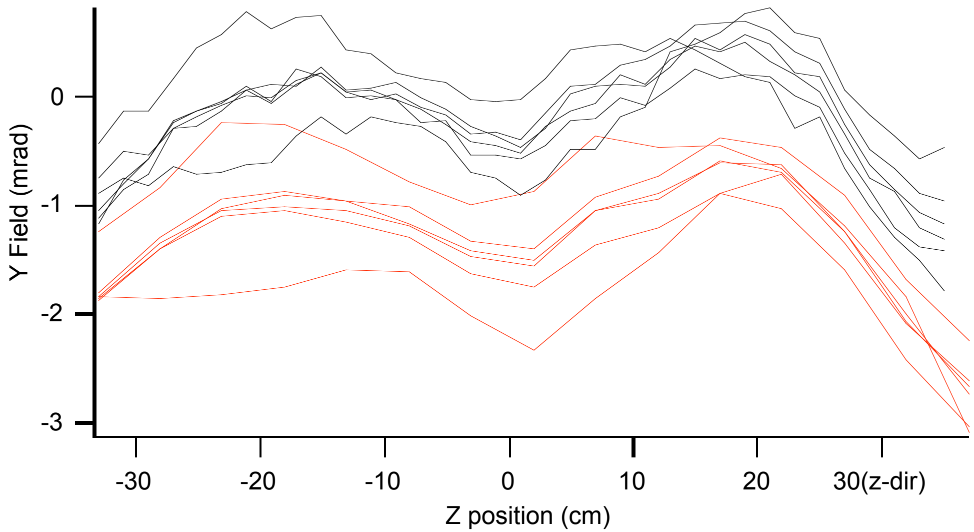


Systematics: Magnetic Field Alignment and Monitoring





Field maps were performed both before and after the emiT 2 run.



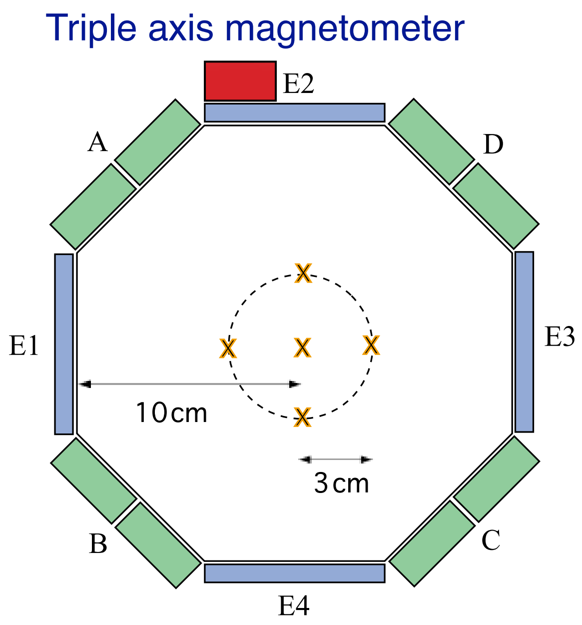
Triple axis magnetometer
(carriage moves in Z axis on aligned rail)

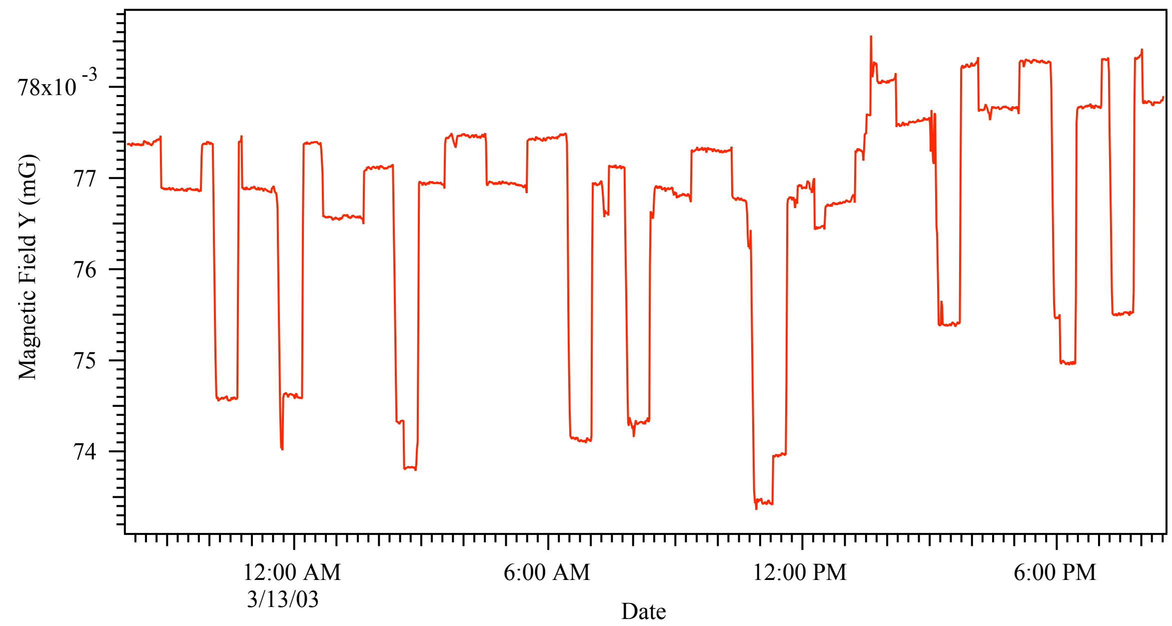
5 maps per set -- central,
3 cm up, down, east, west

rail alignment good to ~2 mrad absolute

Off-beam-axis magnetometers used during runs to continously monitor field integrity

Systematics: Magnetic Field Alignment and Monitoring



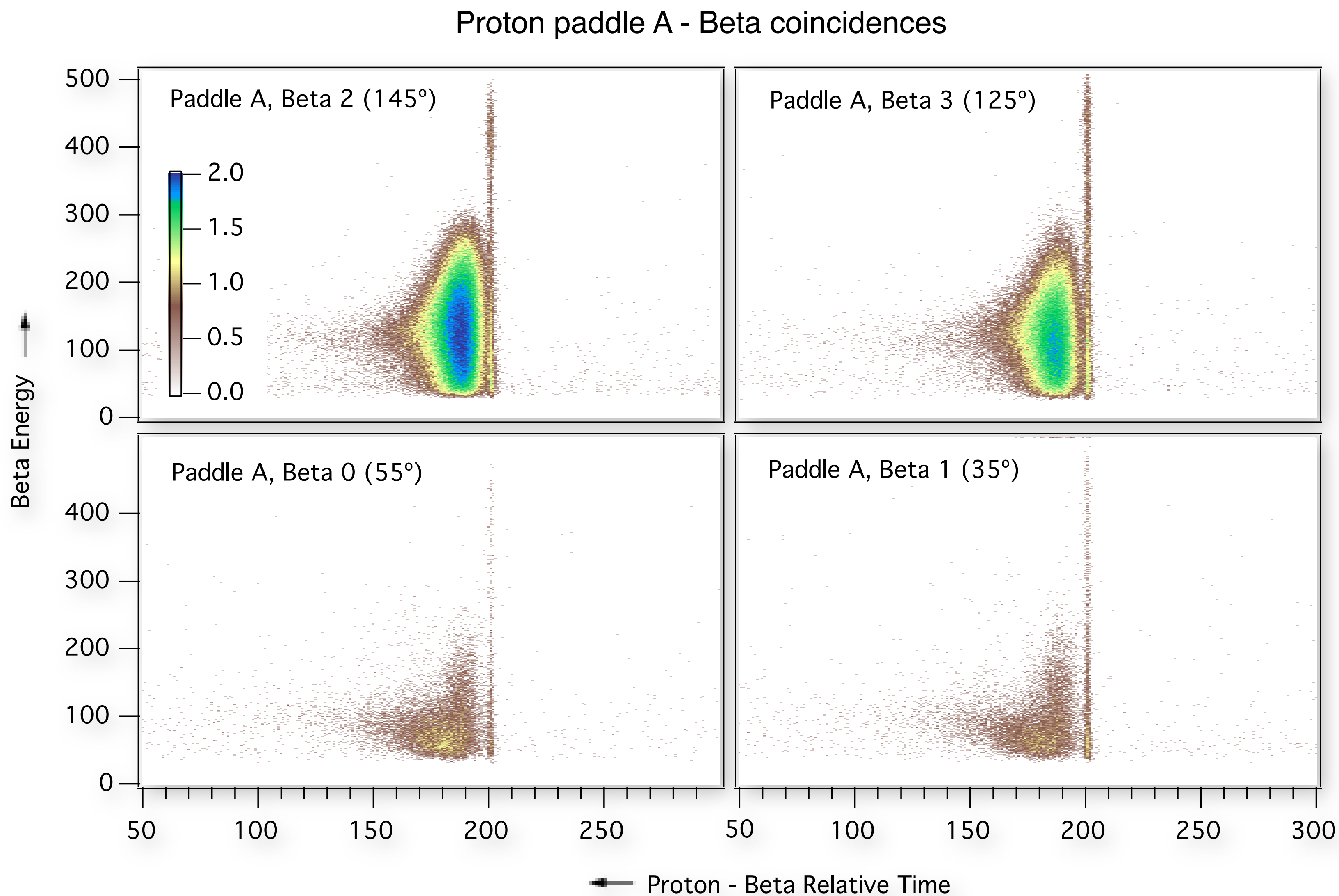


Triple axis magnetometer

Considerable magnetic noise
- Overhead crane
- Other experiments

Cuts made on fields

Systematics: Electron Backscattering

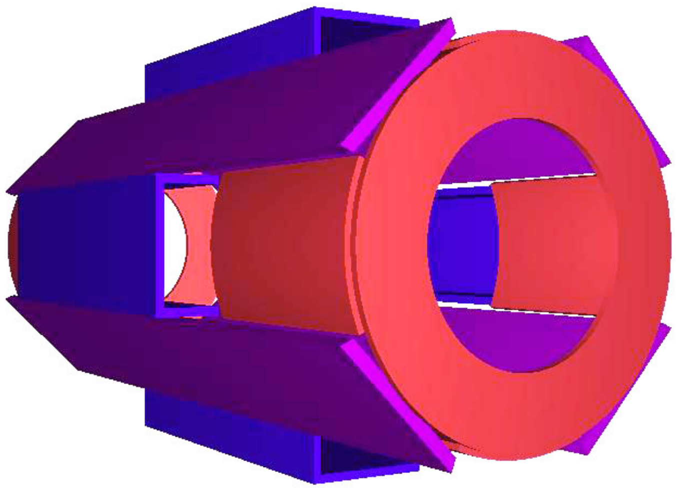


Systematics: Electron Backscattering

MC study in progress

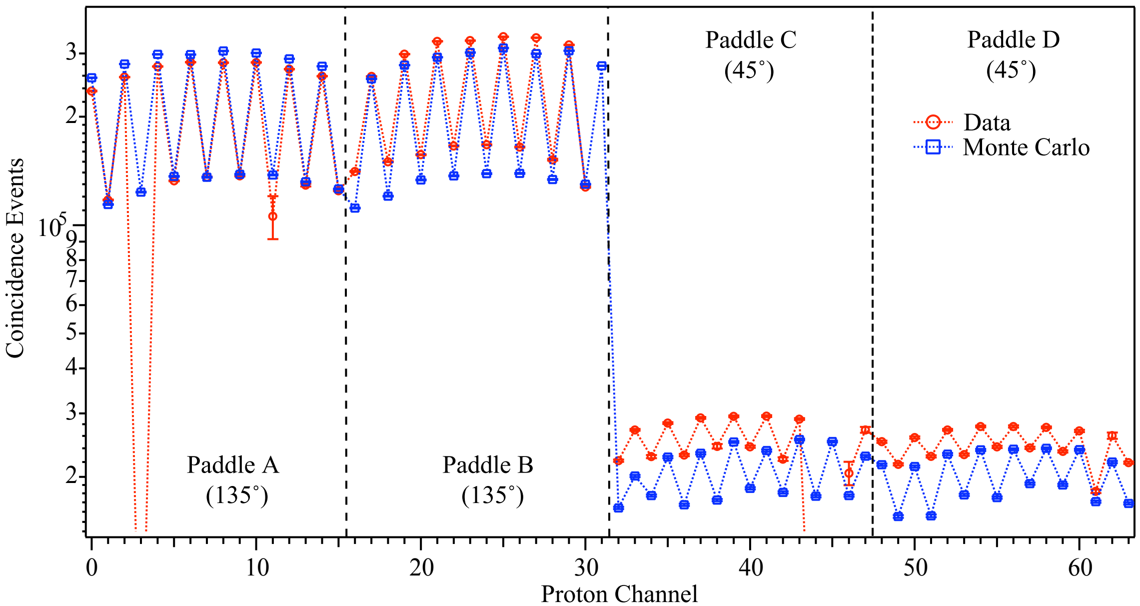
Adding realistic backscattering into the Monte Carlo.

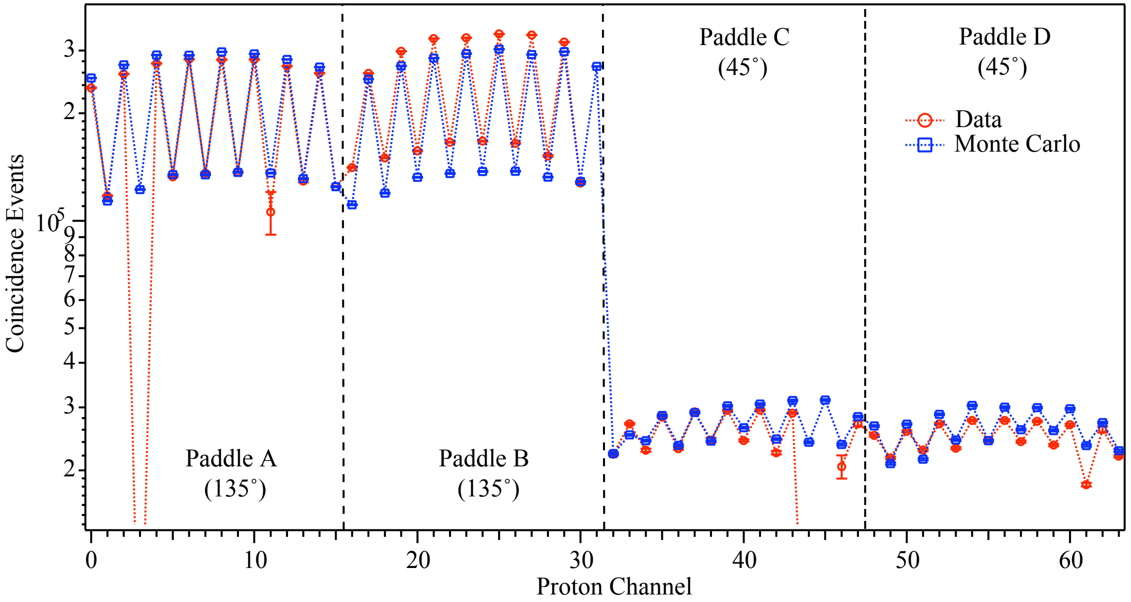
Using Penelope for MC



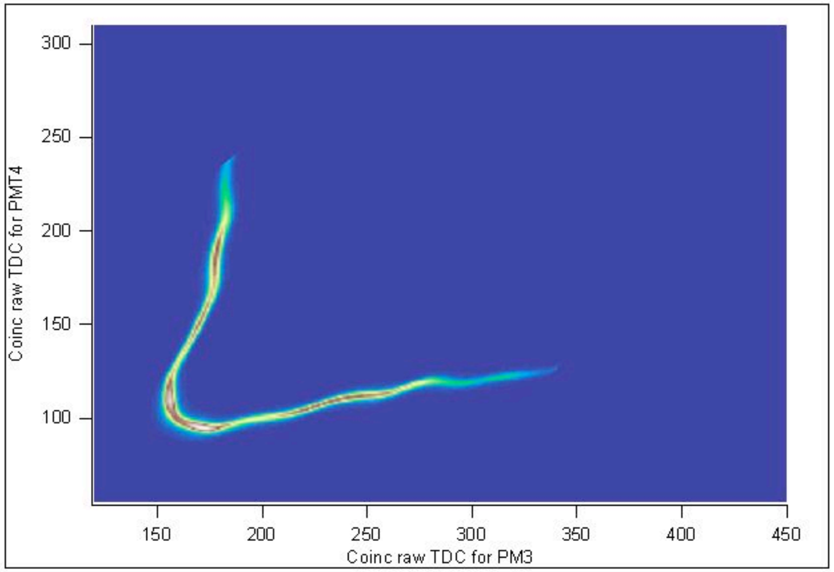
Penelope Geometry

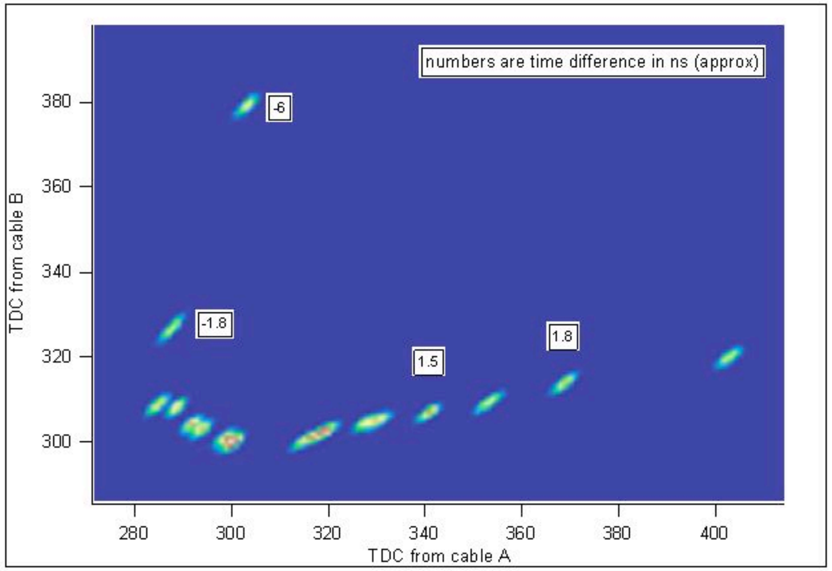
Proton Channel - Beta 3 Coincidences

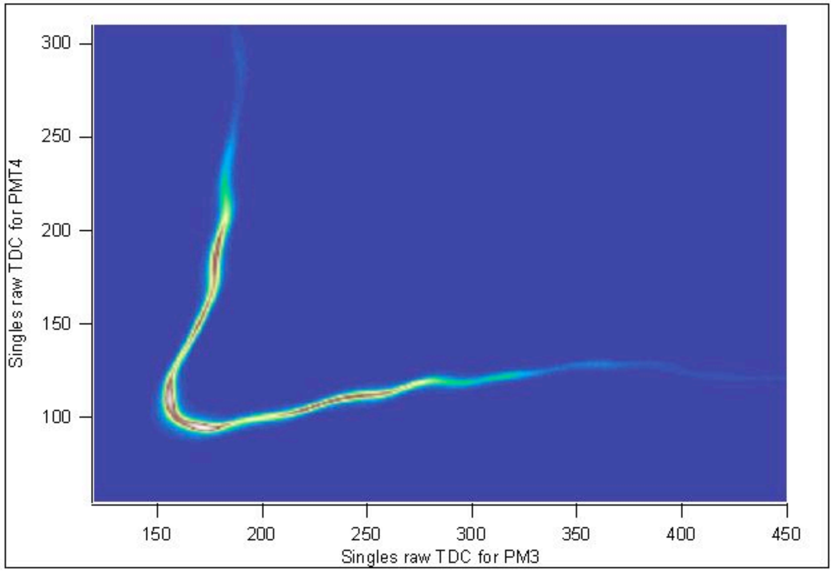


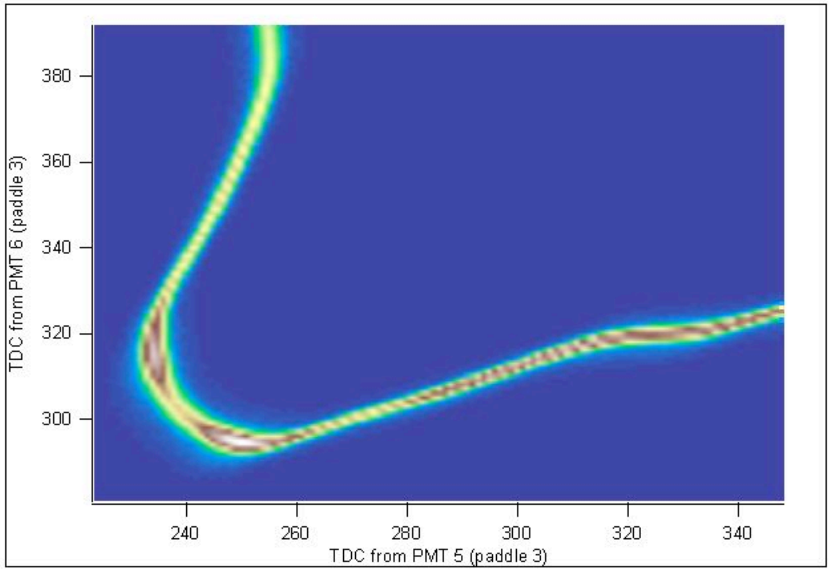


Electron Calibration









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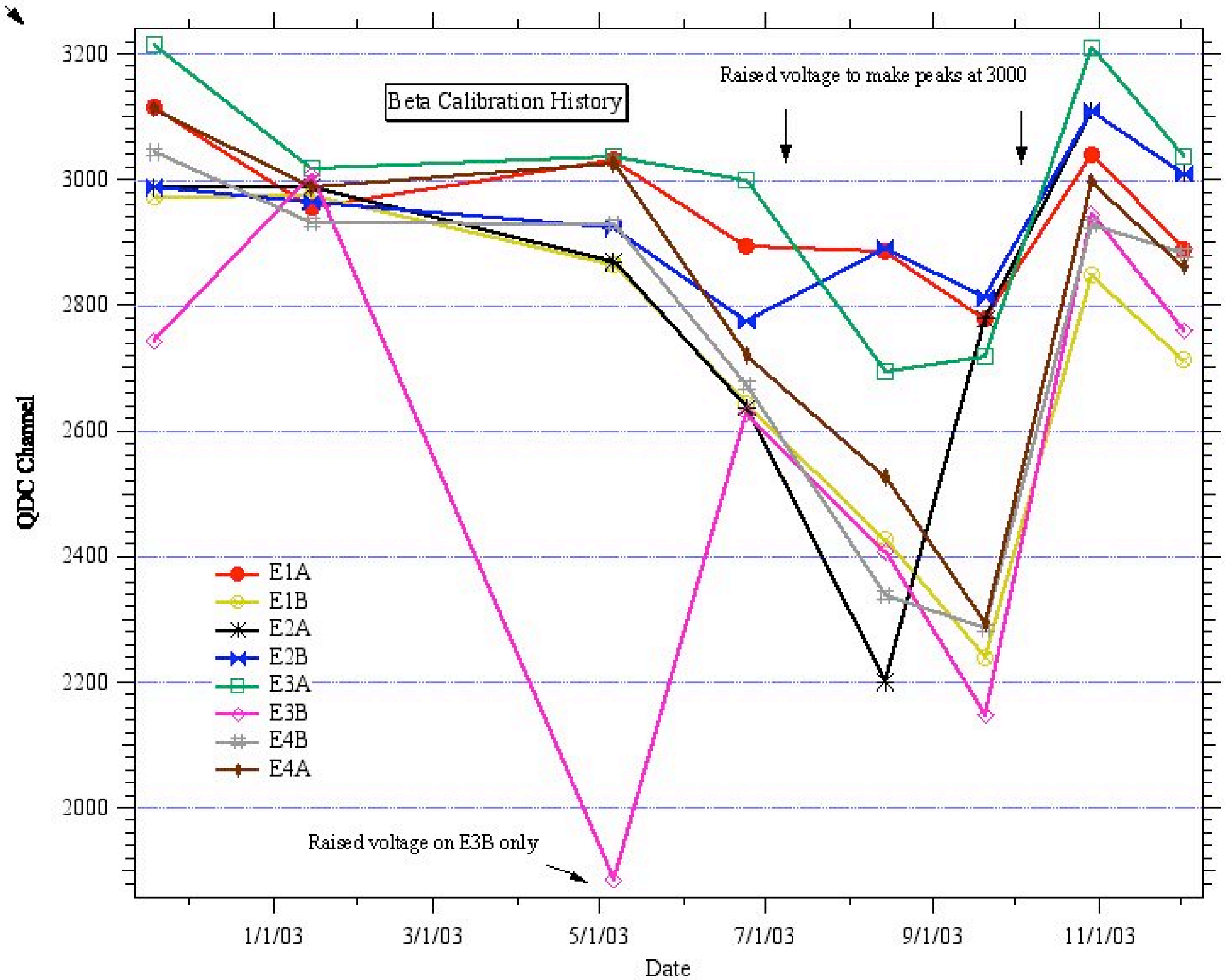


The emiT Experiment: A Search for Time-reversal Invariance Violation in Polarized Neutron Beta Decay

H.P. Mumm, M.S. Dewey, J.S. Nico, and A.K. Thompson
National Institute of Standards and Technology

S.J. Freedman and B.K. Fujikawa
University of California - Berkeley/
Lawrence Berkeley National Laboratory

G.L. Jones
Hamilton College

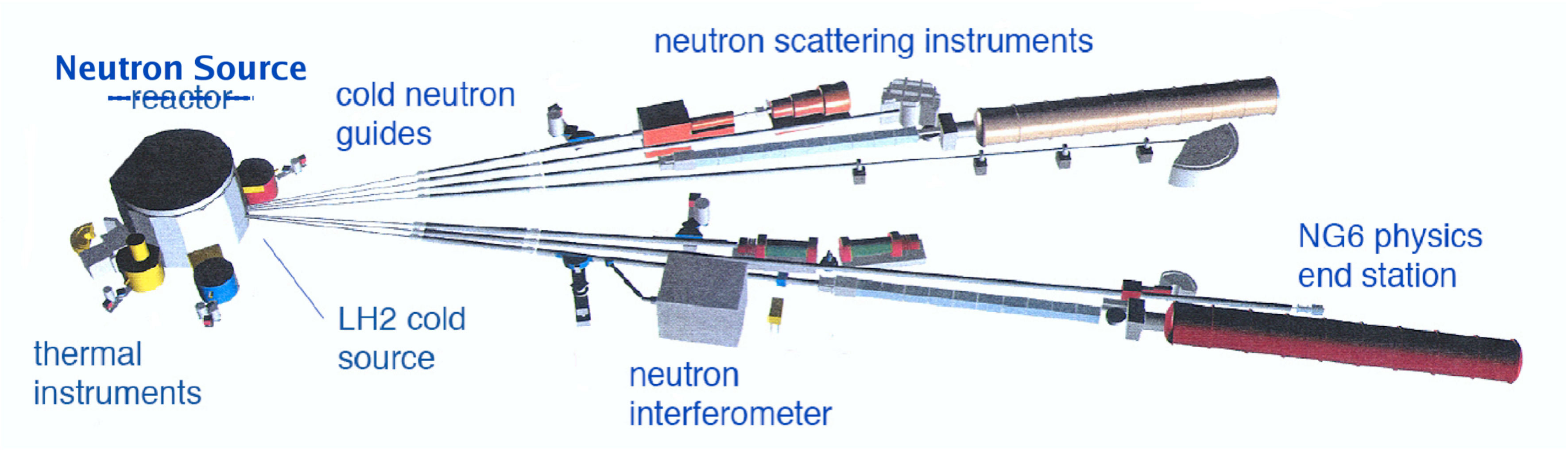
T.E. Chupp and R.L. Cooper
University of Michigan

C. Trull and F.E. Wietfeldt
Tulane University

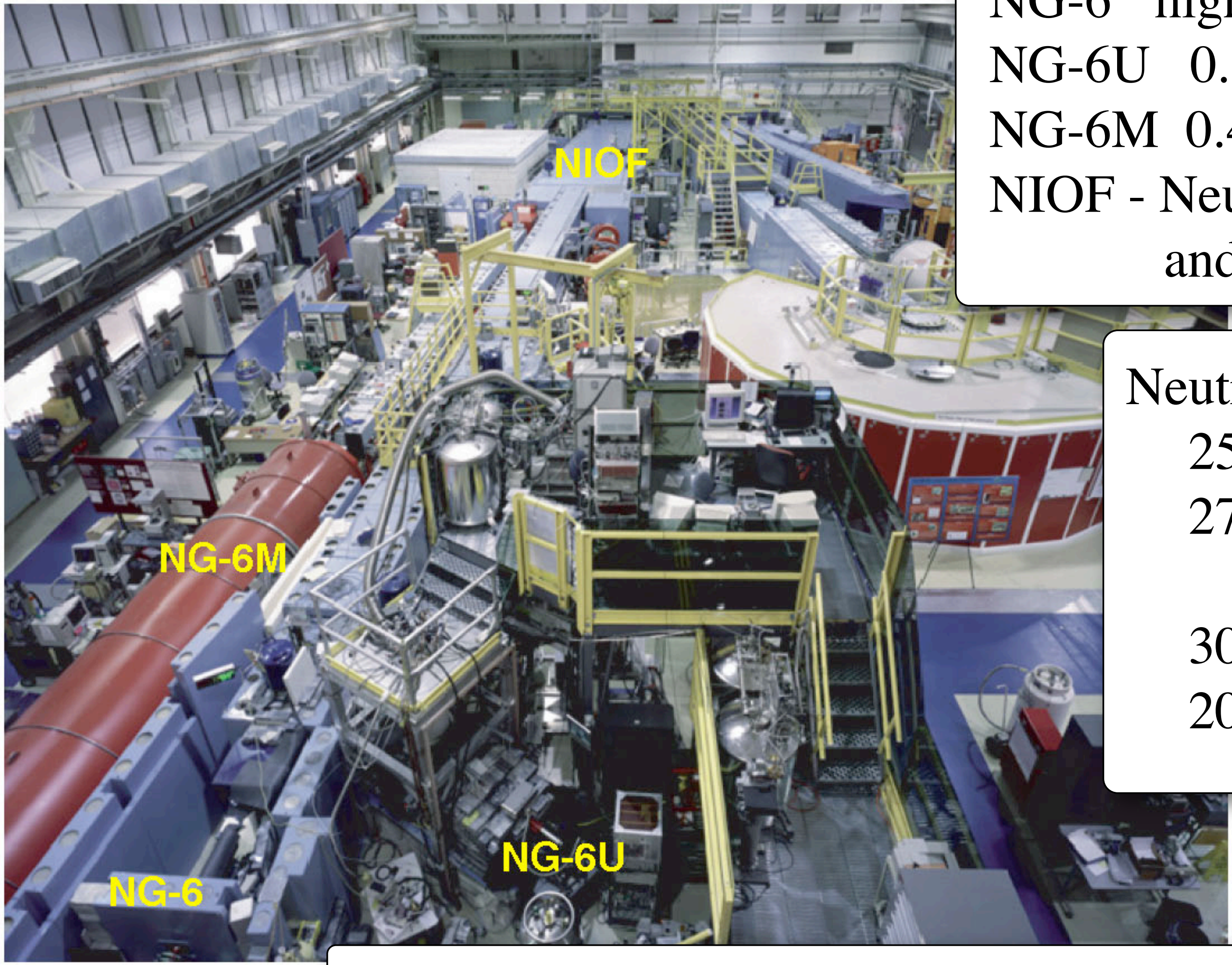
A. Garcia and J.F. Wilkerson
University of Washington

Work supported in part by grants from the DOE, NSF and NIST

The National Institute of Standards and Technology Center for Neutron Research (NCNR)



The National Institute of Standards and Technology Center for Neutron Research (NCNR)



NG-6 high flux
NG-6U 0.89 nm (UCN)
NG-6M 0.495 nm (metrology)
NIOF - Neutron Interferometer and Optics Facility

Neutron physics program:
- 25 postdocs
- 27 grad students
  - so far 19 Ph.D.s
- 30 undergrads
- 20 institutions

Plans for a significant upgrade are underway

Neutron Interactions and Dosimetry Group

Neutron beta-decay

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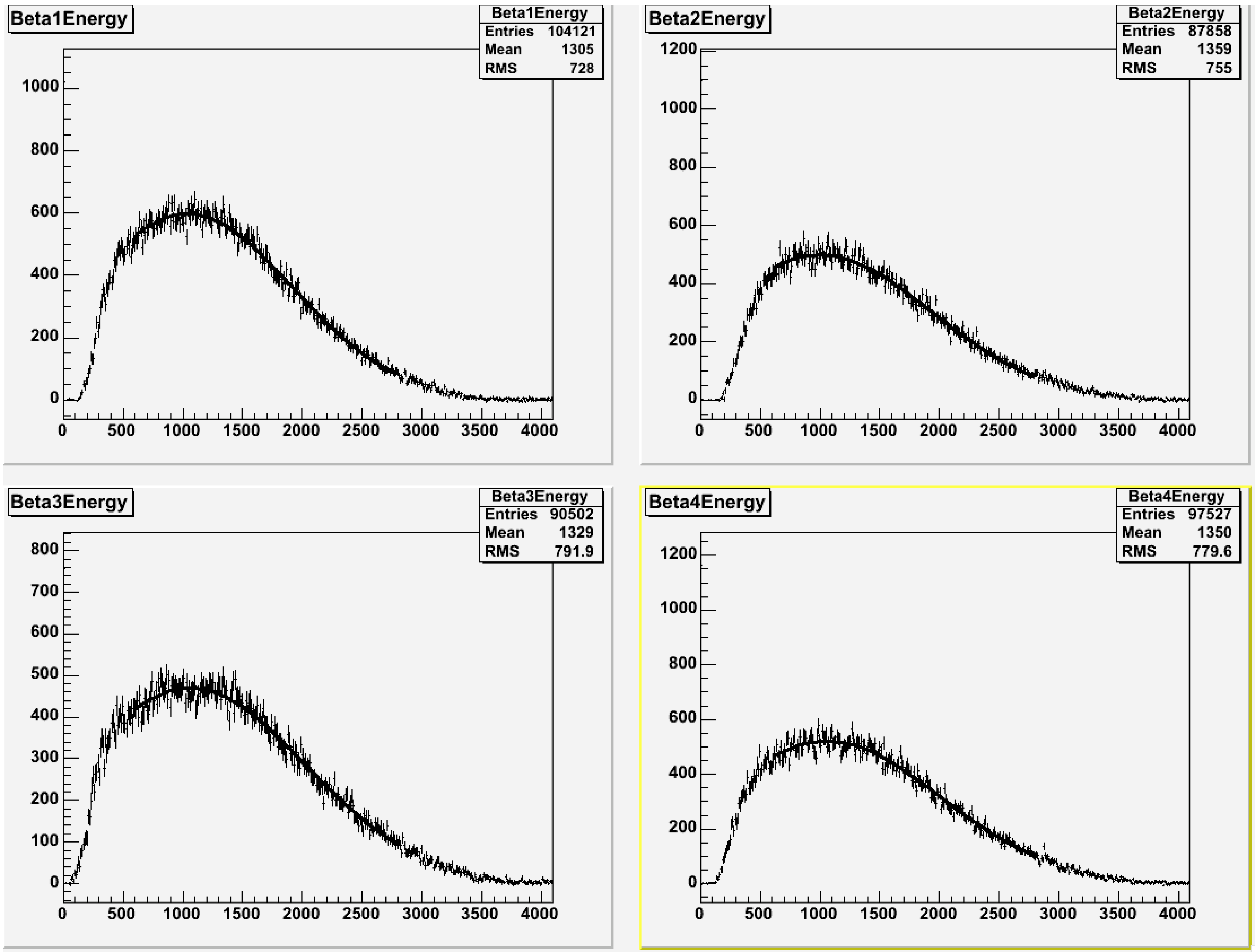
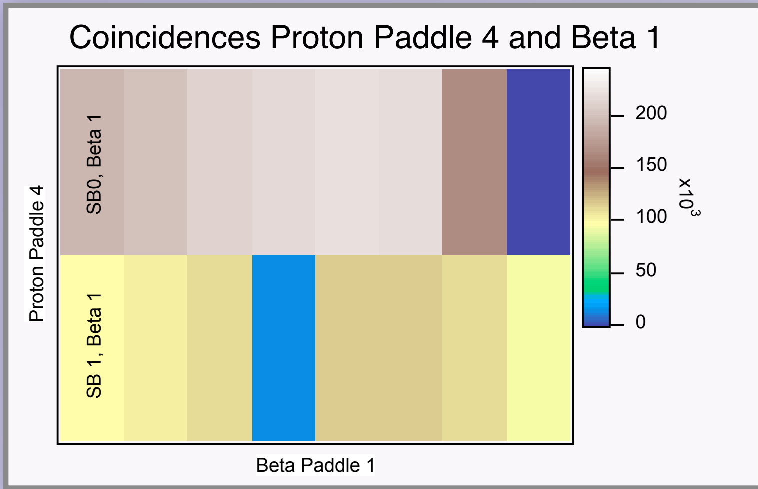
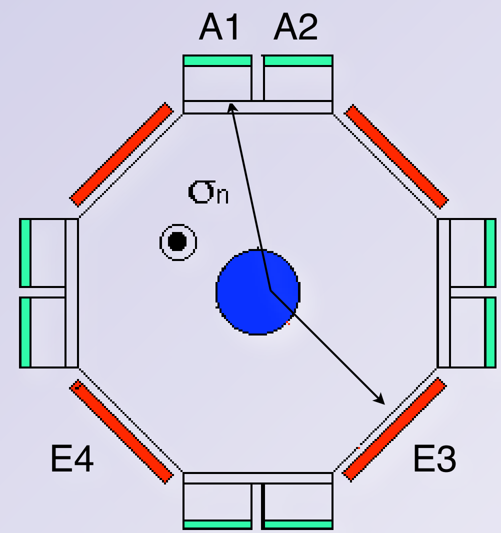
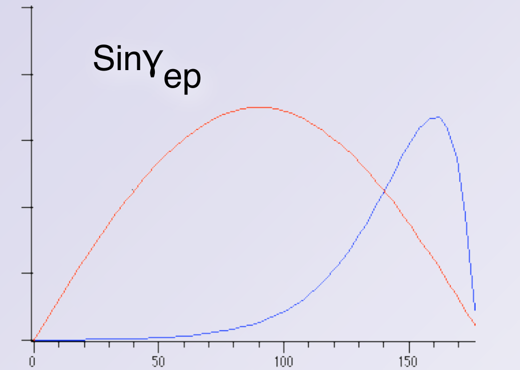


Detector symmetries

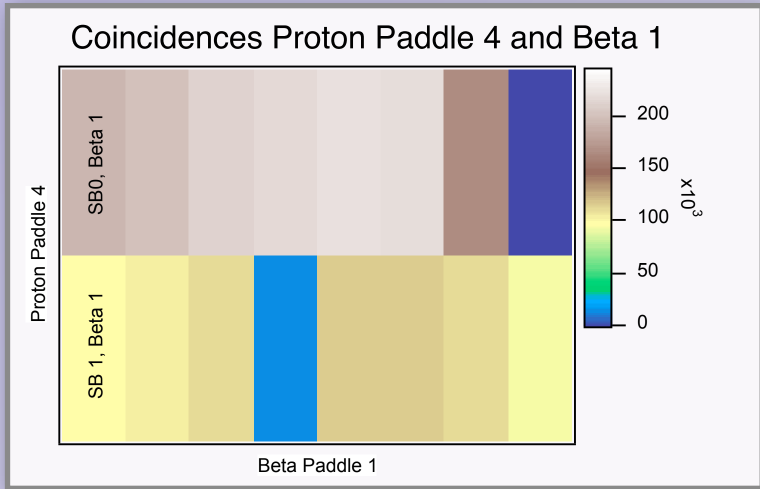


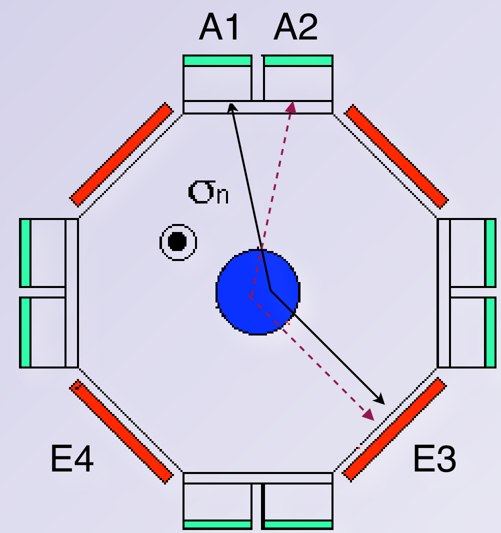


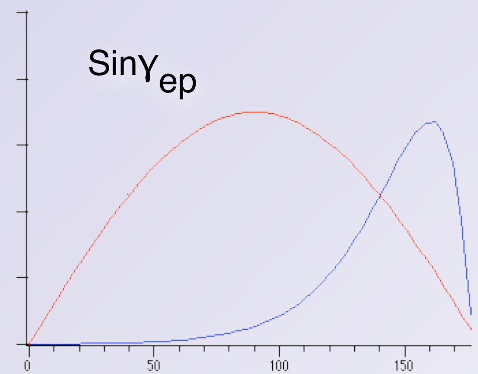


$$\left(\frac{A}{E_e} - \frac{B}{E_\nu}\right)\hat{\sigma}_n \cdot \mathbf{p}_e$$

Detector symmetries







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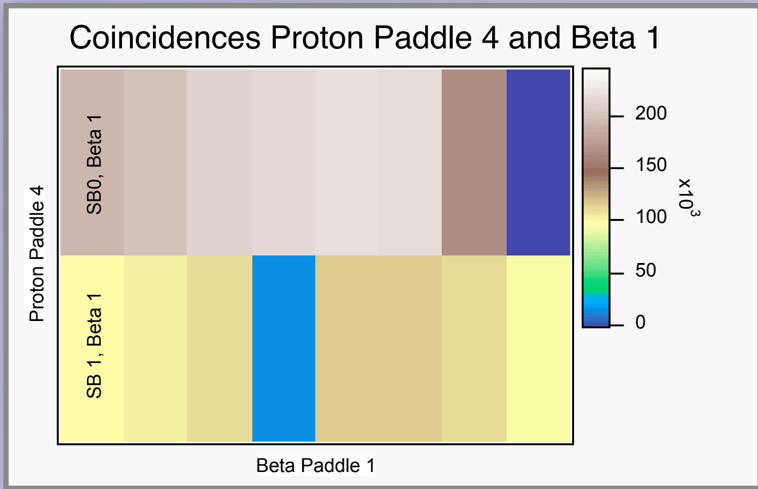
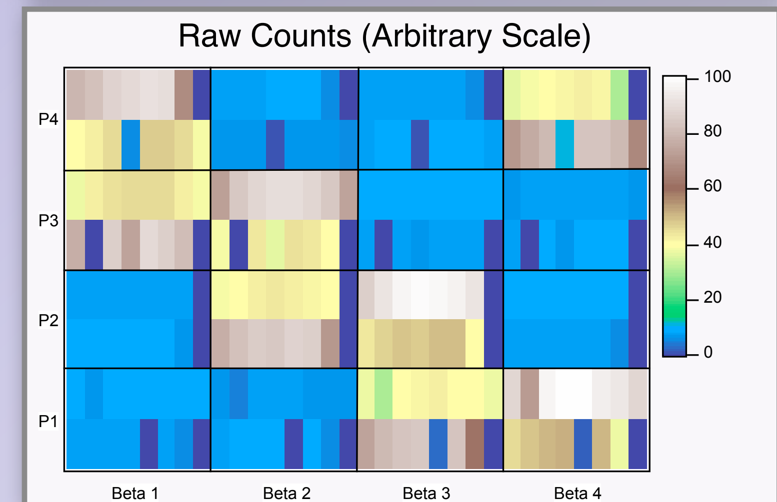
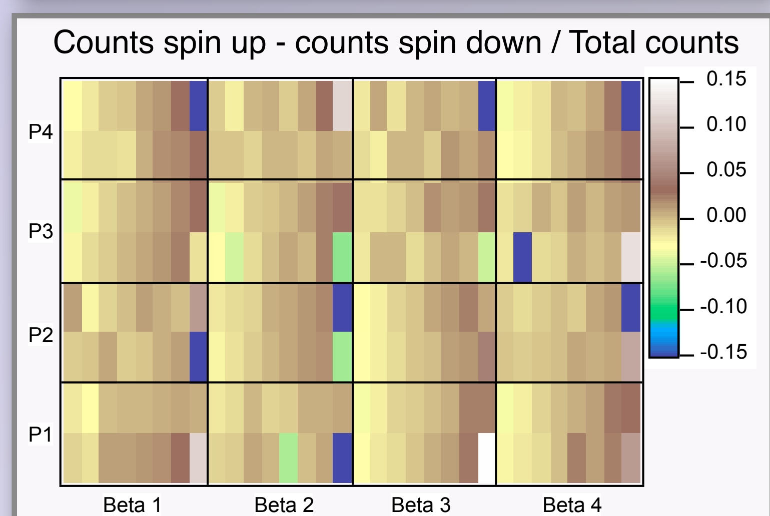
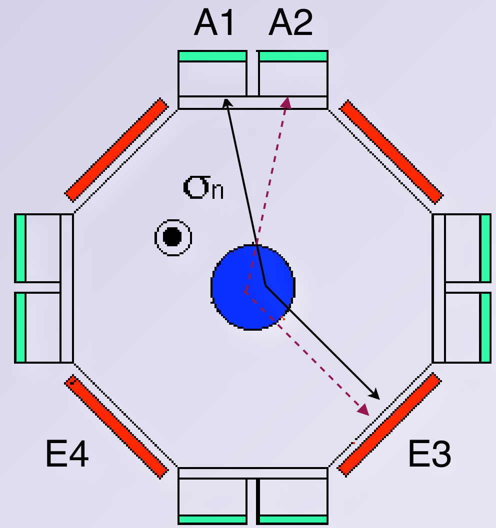
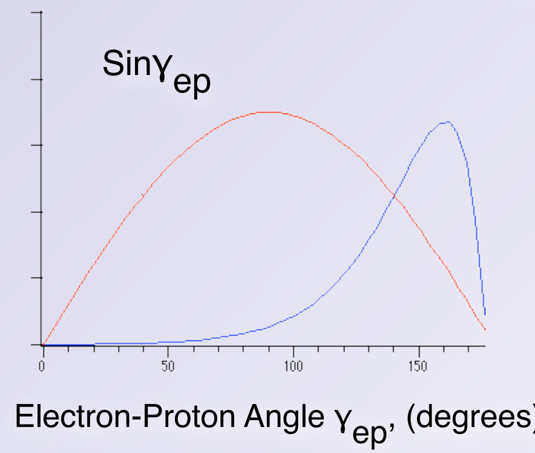










$$\left(\frac{A}{E_e} - \frac{B}{E_\nu}\right)\hat{\sigma}_n \cdot \mathbf{p}_e$$

Symmetries: overview

Discrete symmetries

- Charge conjugation
- Parity
- **Time reversal**

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

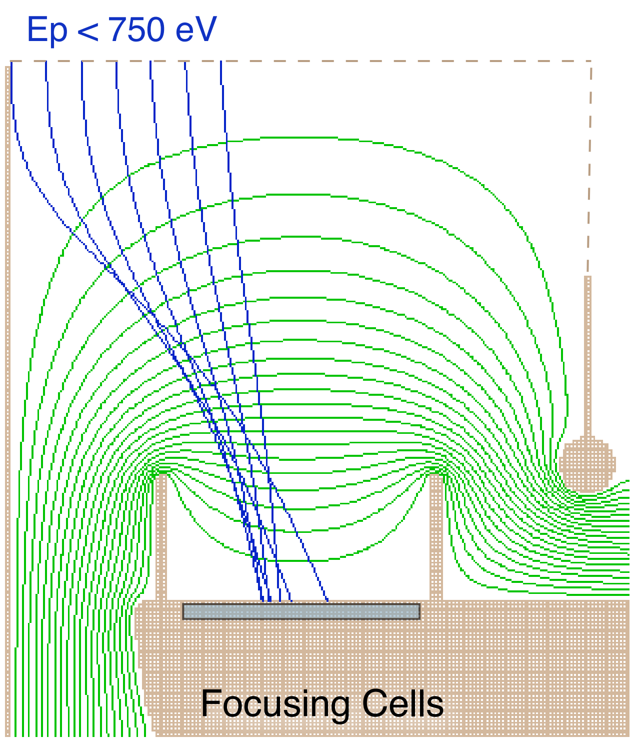
$$T f(t) T^{-1} = f^*(-t)$$

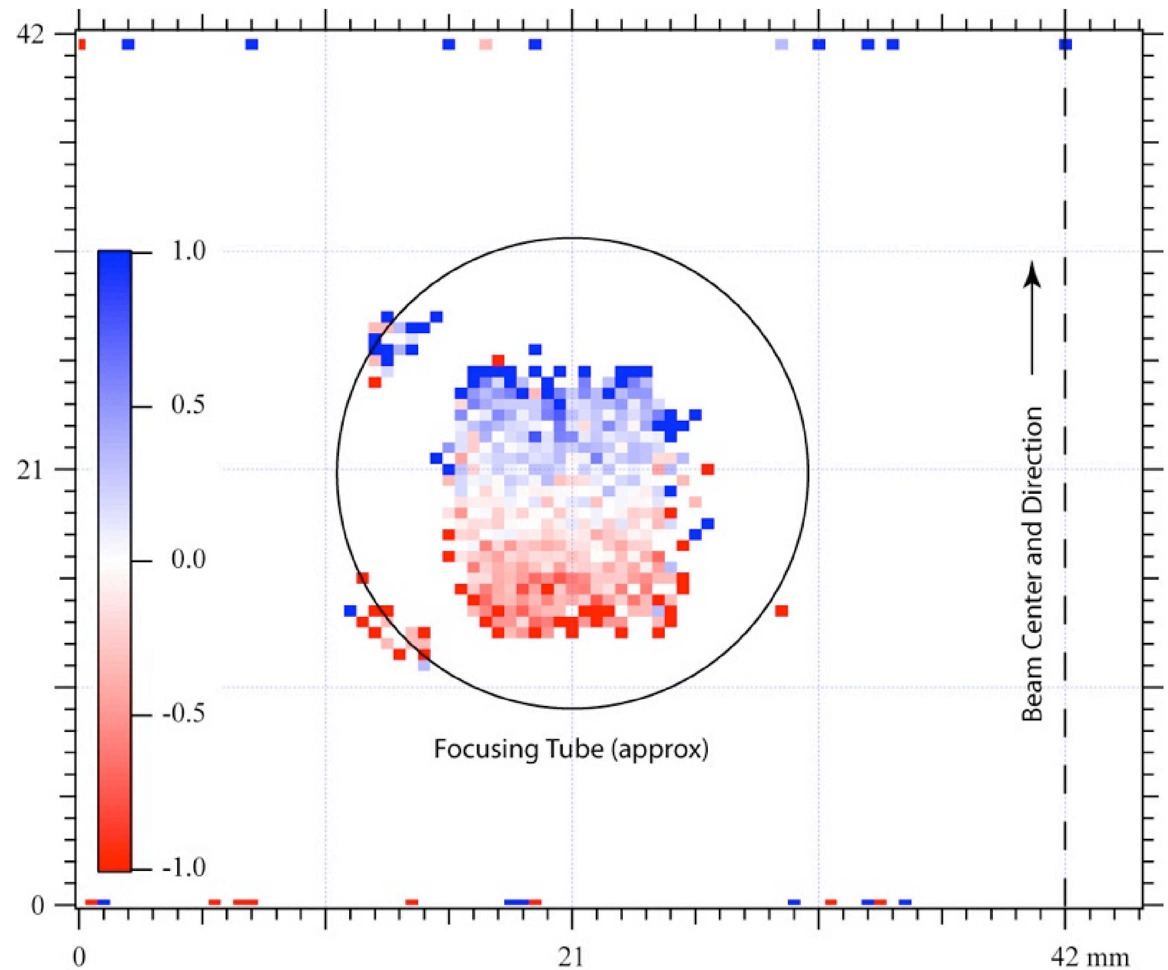
- Strong and electromagnetic interactions both conserve C, P, and T
- Weak interaction violates C and P, but what about combinations?
- No observed violation of CPT to date
- In 1964 CP violation observed in neutral kaons
- Direct CP violation observed in kaon decay (KTeV 1999 and NA48 1999, CPLEAR)
- Recently, CP violation observed in the decay neutral B mesons (Belle and BaBar Collaborations)

This is all consistent with a phase in the quark mixing matrix, i.e consistent with the Standard Model

Systematics: spin dependent energy spectrum

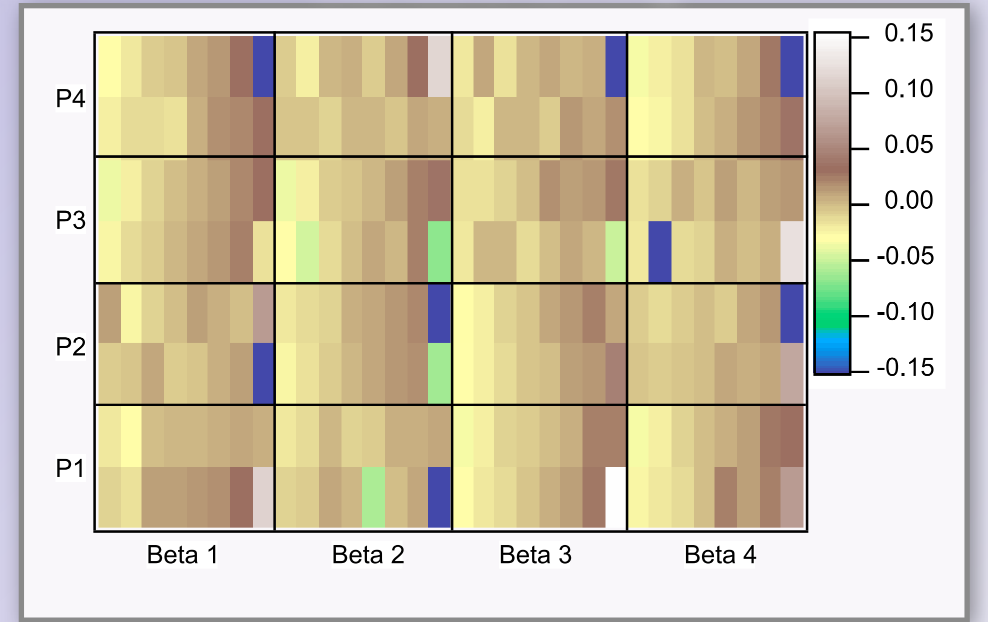
Any proton energy threshold can result in a spin asymmetry



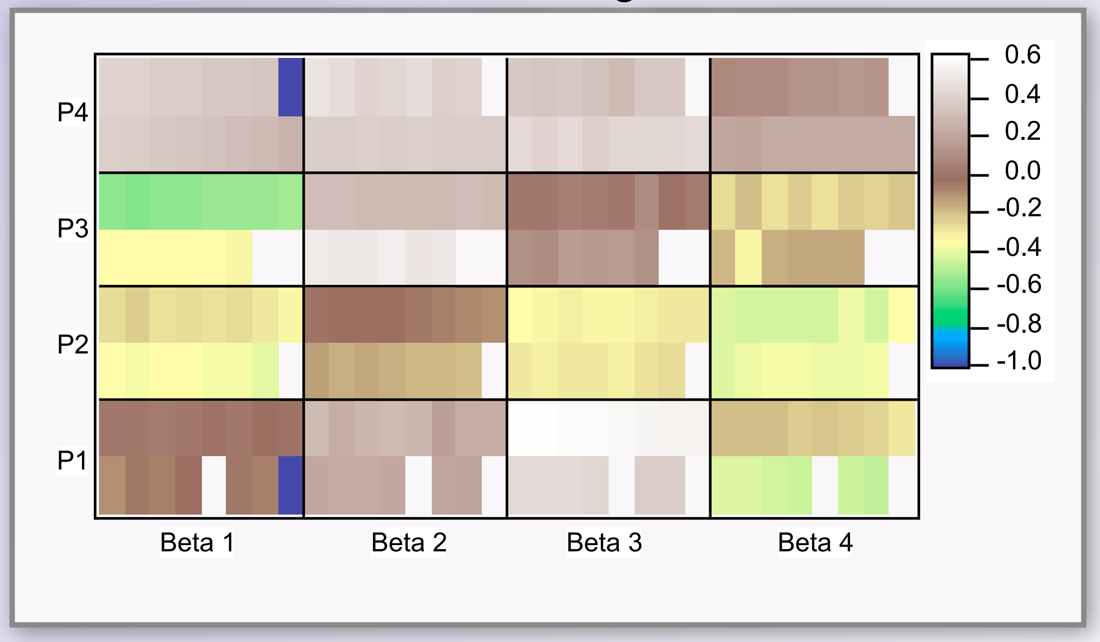


Monte Carlo Calculations

Standard running



Forced misalignment



Systematics: Asymmetric Transverse Polarization

Get status report on SALSA
CLEAN at NIST (what is this guy doing, can I help?)
Ask Dan for a comparison with CDMA, CLEAN should be able to do forward backward (Look up this talk)
How advantageous will this be in this case?
NUSEL at Virginia Tech
Wick is going out for a tour in June (Schedule this?)
(figure out who gave the talk on the neutrino detector, ask John/Karsten about prospects)

Give equation for Datp in terms of beam 2nd moment.
Maybe also give K's for size estimate Datp
compare to below

-end-

emiT systematics: Backscattering spin dependent ~10-4!
NDE
How much does the fit effect result?
(what percentage of spectrum is extrapolated?
compare fit values.....
Get V calculation going!
Must have vs in normal running for defense.
2nd beam moment-> ATP (can I get a nice expression for this?)
scattering by 3He
NEW 2D plot