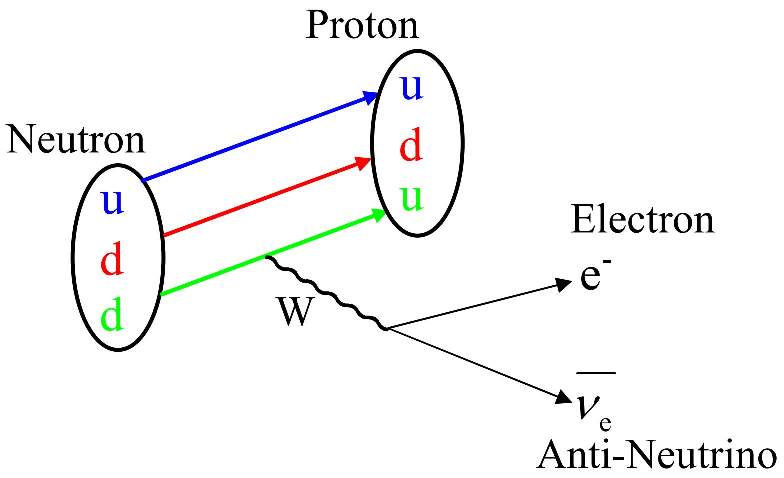
Neutron Beta Decay Correlations:
Part 1: …within the Standard Model

Stefan Baeßler



UNIVERSITY of VIRGINIA

Thanks for contributions from:
H. Abele, K.Bodek, G. Konrad, B. Märkisch, P. Mumm, J. Nico, S. Paul, D. Počanić, M. Schumann,
T. Soldner, F. Wietfeldt, A. Young

Outline

Part 1: Contributions to the Standard Model

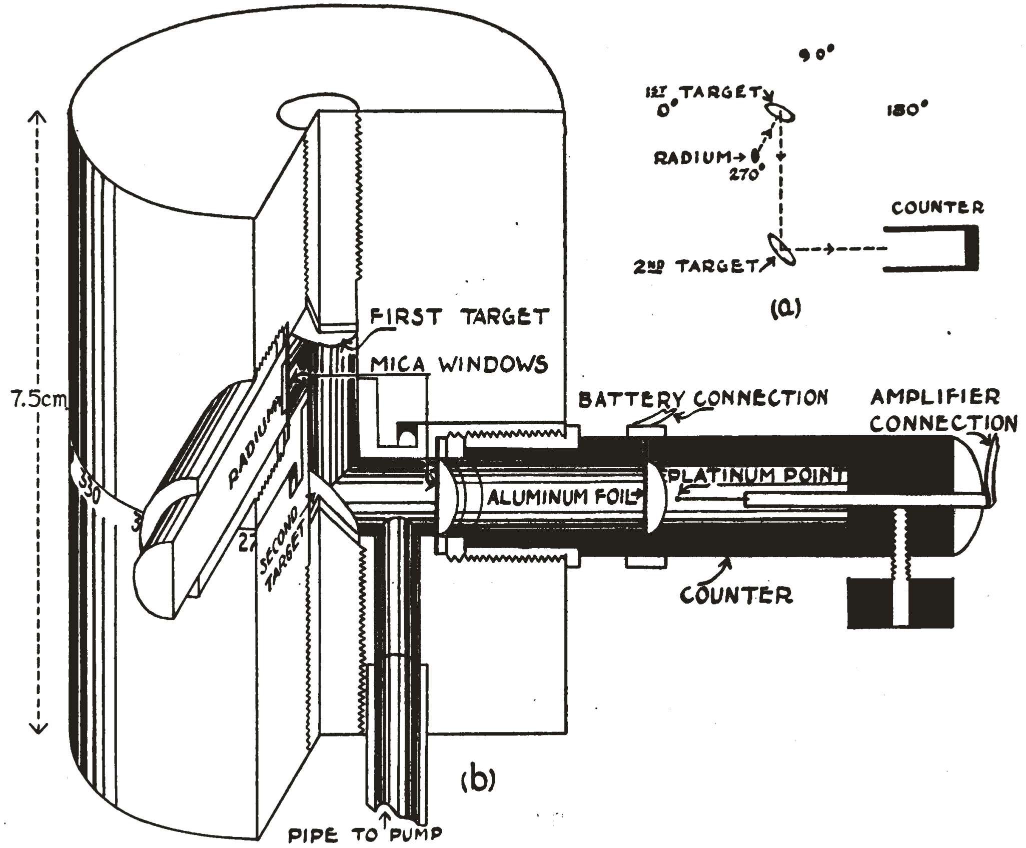
1. Beta Decay: The study of Parity Violation
2. Measurement of the Beta Asymmetry
3. Measurement of the Neutrino Electron Correlation

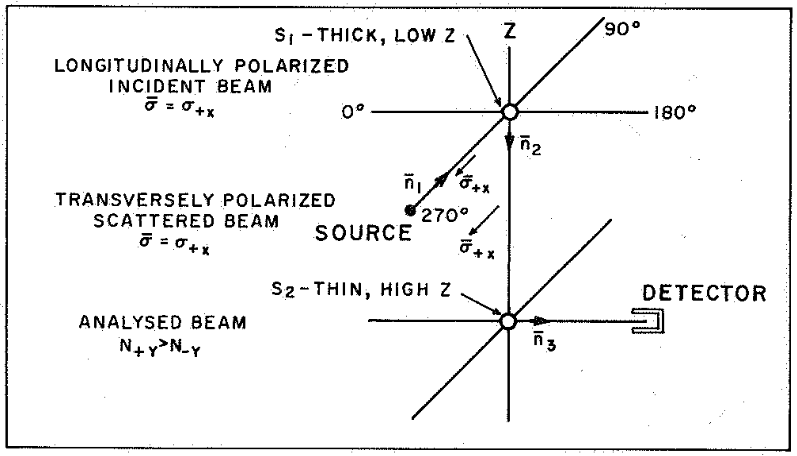
Part 2: Searches for physics beyond the Standard Model

…

(First) discovery of Parity Violation (1928)

R.T. Cox et al., PNAS 14, 544 (1928):



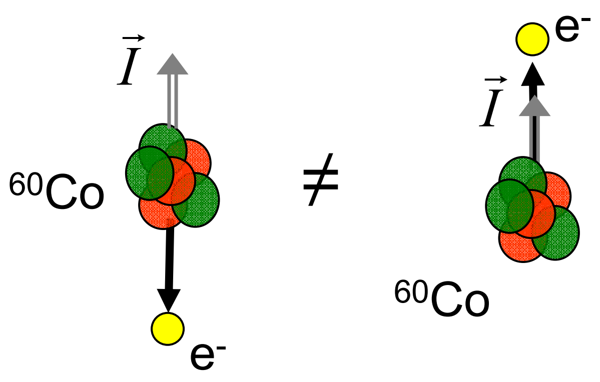


Assumption: Scattering probability depends on spin orientation (that was known for X rays). This is correct, but the reason (Spin-Orbit Interaction) was not discovered yet.
Aim: Prove that an electron is a vector particle.
Result: Asymmetry of count rate for 90 deg / 270 deg found, was not deemed to be important. Later experiments continued with electrons from a hot filament.

The Beta Decay Hamiltonian

Finally: Parity Violation found by Wu et al, 1956

Now: Construction of Parity-Violating Hamiltonian, which couples leptons and hadrons



$$H_{\text{weak,elementary}} = \frac{G_{\text{F}}}{\sqrt{2}} \left\langle u \middle| \underbrace{\gamma^{\mu} - \gamma^{\mu}\gamma^{5}}_{V-A} \middle| d' \right\rangle \left\langle e^{-} \middle| \underbrace{\gamma_{\mu} - \gamma_{\mu}\gamma_{5}}_{V-A} \middle| \nu_{e} \right\rangle + \text{h.c.}$$

Properties: Helicity of fermions is –v/c, of antifermions is v/c

Complication: Nucleons aren‘t elementary particles:

$$H_{\text{weak}} = \frac{G_{\text{F}} V_{\text{ud}}}{\sqrt{2}} \left\langle p \middle| 1 \cdot \gamma^{\mu} - \lambda \gamma^{\mu}\gamma^{5} \middle| n \right\rangle \left\langle e^{-} \middle| \gamma_{\mu} - \gamma_{\mu}\gamma_{5} \middle| \nu_{e} \right\rangle + \text{h.c.}$$

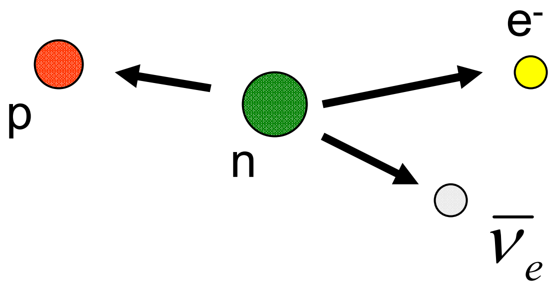
Coupling constants are unknown. Fermi-Transitions: $g_{\text{V}} = G_{\text{F}} \cdot V_{\text{ud}}$

Gamow-Teller-Transitions: $g_{\text{A}} = G_{\text{F}} \cdot V_{\text{ud}} \cdot \lambda$

Observables in Neutron Beta Decay

Fermi's golden rule:

Decay probability $w_{i\to f} = \frac{2\pi}{\hbar}\left|\left\langle f\left|H_{\text{weak}}\right|i\right\rangle\right|^{2}\rho$



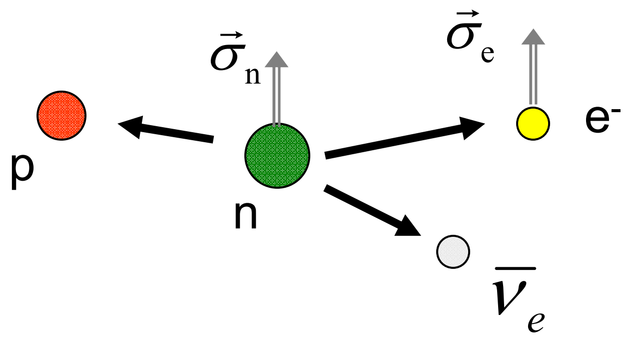
$$\frac{dw}{dE_{\mathrm{e}}} = \frac{2\pi}{\hbar} G_F^2 V_{\mathrm{ud}}{}^2\left(1+3|\lambda|^2\right)\rho\left(E_{\mathrm{e}}\right)$$

Neutron lifetime $\tau_{\mathrm{n}}{}^{-1} = \frac{2\pi}{\hbar} G_F^2 V_{\mathrm{ud}}{}^2\left(1+3|\lambda|^2\right)\int\rho\left(E_{\mathrm{e}}\right)$

Observables in Neutron Beta Decay

Jackson et al., PR 106, 517 (1957):

Observables in Neutron beta decay, as a function of generally possible coupling constants (assuming only Lorentz-Invariance)



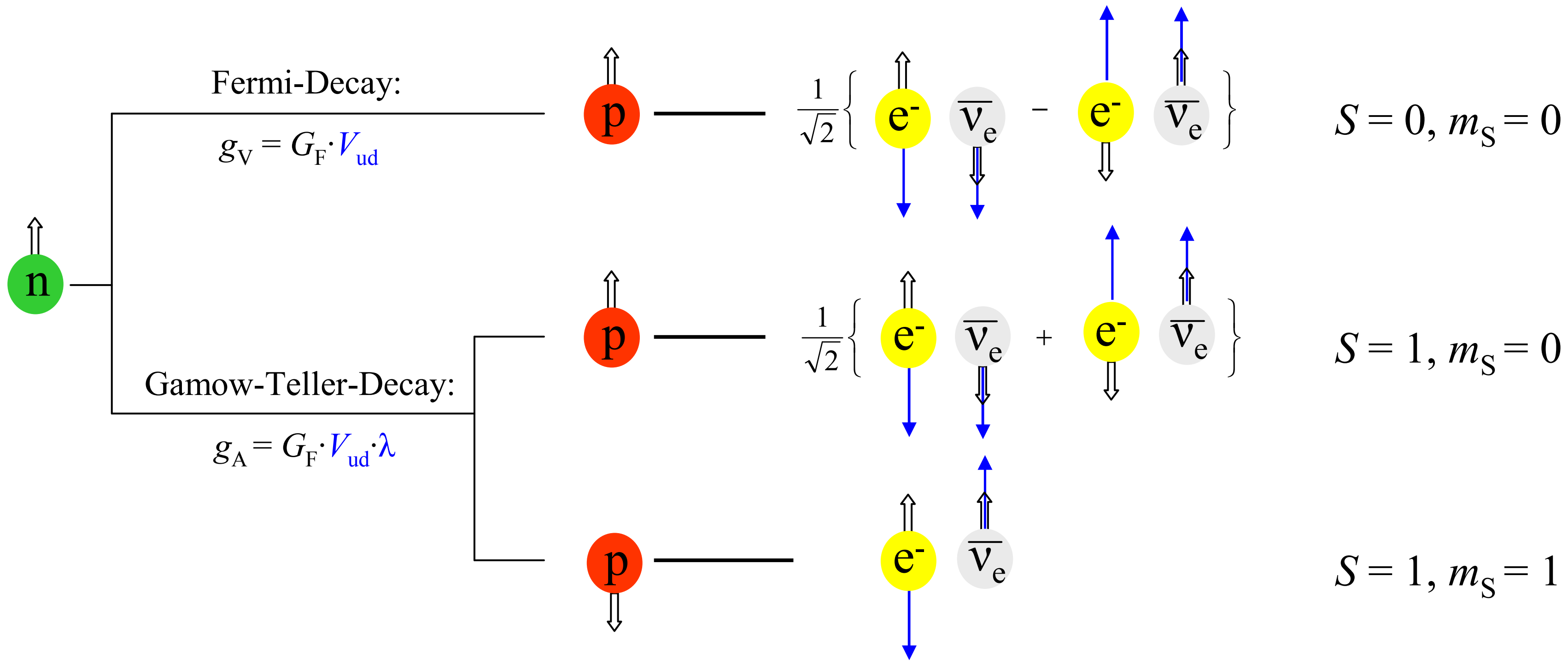
$$dw \propto \rho(E_{\mathrm{e}}) \cdot \left(1+3|\lambda|^2\right) \cdot \left\{1 + a\frac{\vec{p}_{\mathrm{e}} \cdot \vec{p}_\nu}{E_{\mathrm{e}} E_\nu} + b\frac{m_{\mathrm{e}}}{E_{\mathrm{e}}} + \vec{\sigma}_{\mathrm{n}} \cdot \left(A\frac{\vec{p}_{\mathrm{e}}}{E_{\mathrm{e}}} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_{\mathrm{e}} \times \vec{p}_\nu}{E_{\mathrm{e}} E_\nu}\right)\right\}$$

Beta-Asymmetry $A = -2\frac{|\lambda|^2 + \mathrm{Re}\,\lambda}{1+3|\lambda|^2}$

Neutrino-Electron-Correlation $a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}$

Neutron lifetime $\tau_{\mathrm{n}}^{-1} = \frac{2\pi}{\hbar} G_F^2 V_{\mathrm{ud}}^{\ 2} \left(1+3|\lambda|^2\right) \int \rho(E_{\mathrm{e}})$

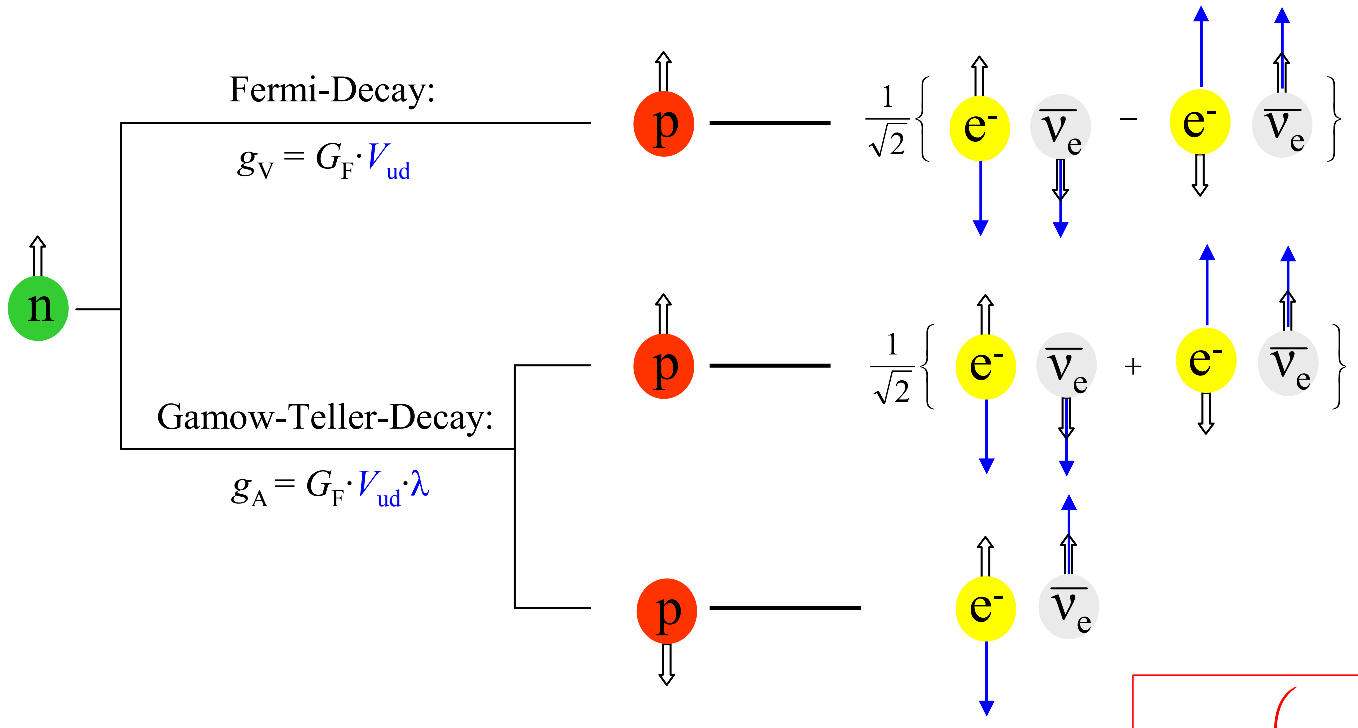
The Standard Model Parameters V_{ud} and λ



Two unknown parameters, g_A and g_V, need to be determined in 2 experiments

1. Neutron-Lifetime: $\tau_n^{-1} \propto \left(g_V^2 + 3g_A^2\right)$ $\tau_n \approx 885\ \mathrm{s}$

The Standard Model Parameters V_{ud} and λ



$A = 0$

$A = 0$

$A = -1$

$$\boxed{dw \propto \left(1 + A\frac{v}{c}\cos\left(p_e, \sigma_n\right)\right)}$$

Two unknown parameters, g_A and g_V, need to be determined in 2 experiments

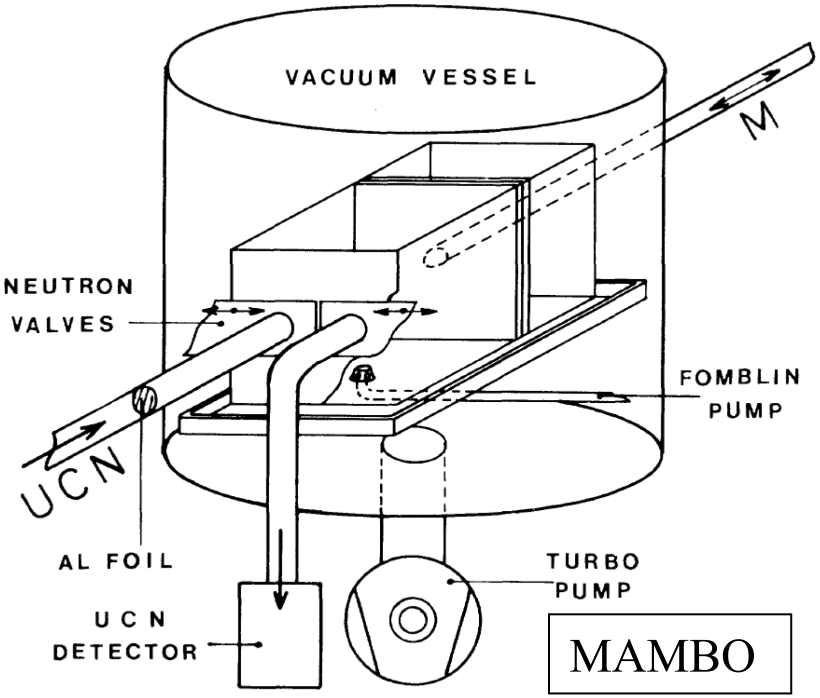
1. Neutron-Lifetime: $\tau_n^{-1} \propto \left(g_V^2 + 3g_A^2\right)$ $\tau_n \approx 885\ \mathrm{s}$

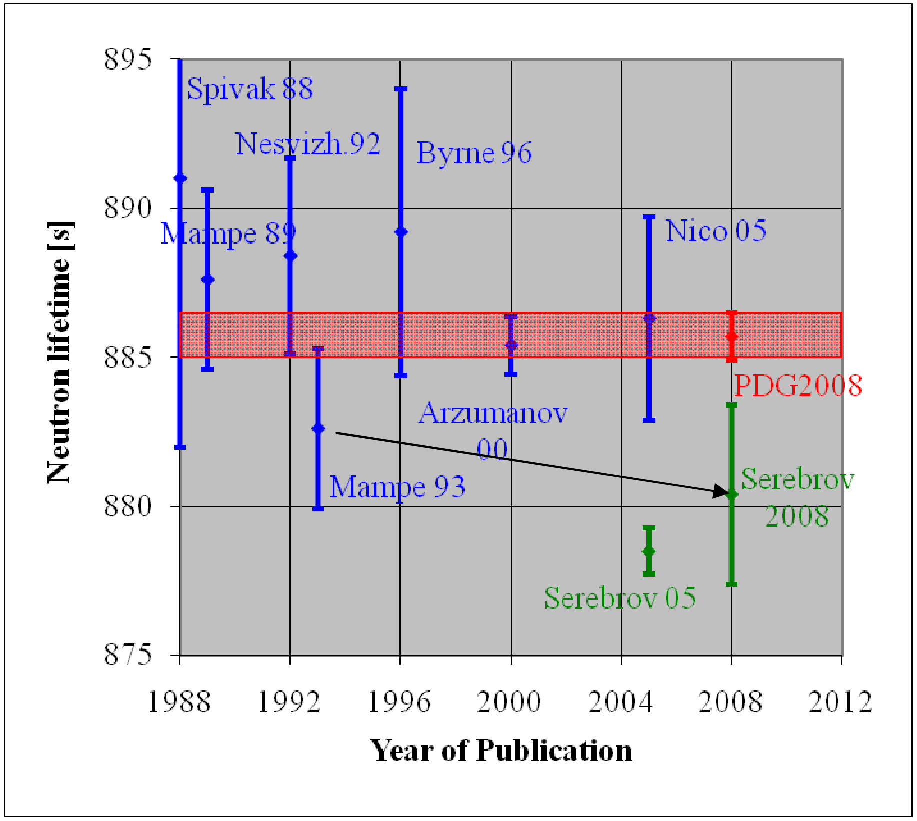
2. Beta-Asymmetry: $A = -2\frac{\lambda^2 + \lambda}{1 + 3\lambda^2} \approx -0.1$ $\lambda = \frac{g_A}{g_V}$

Neutron Lifetime Measurements

Decrease of Neutron Counts N with storage time t: $N(t) = N(0)\exp\{-t/\tau_{\text{eff}}\}$

$1/\tau_{\text{eff}} = 1/\tau_\beta + 1/\tau_{\text{wall losses}}$





Many new attempts underway, mostly with magnetic bottles:
Under (at least) construction: Ezhov et al. (ILL, PNPI Gratchina), Bowman et al. (LANL), Paul et al. (TUM, PSI)

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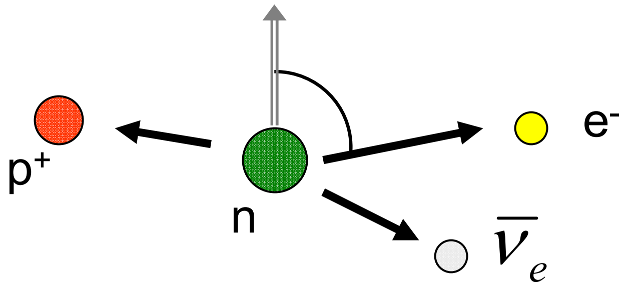
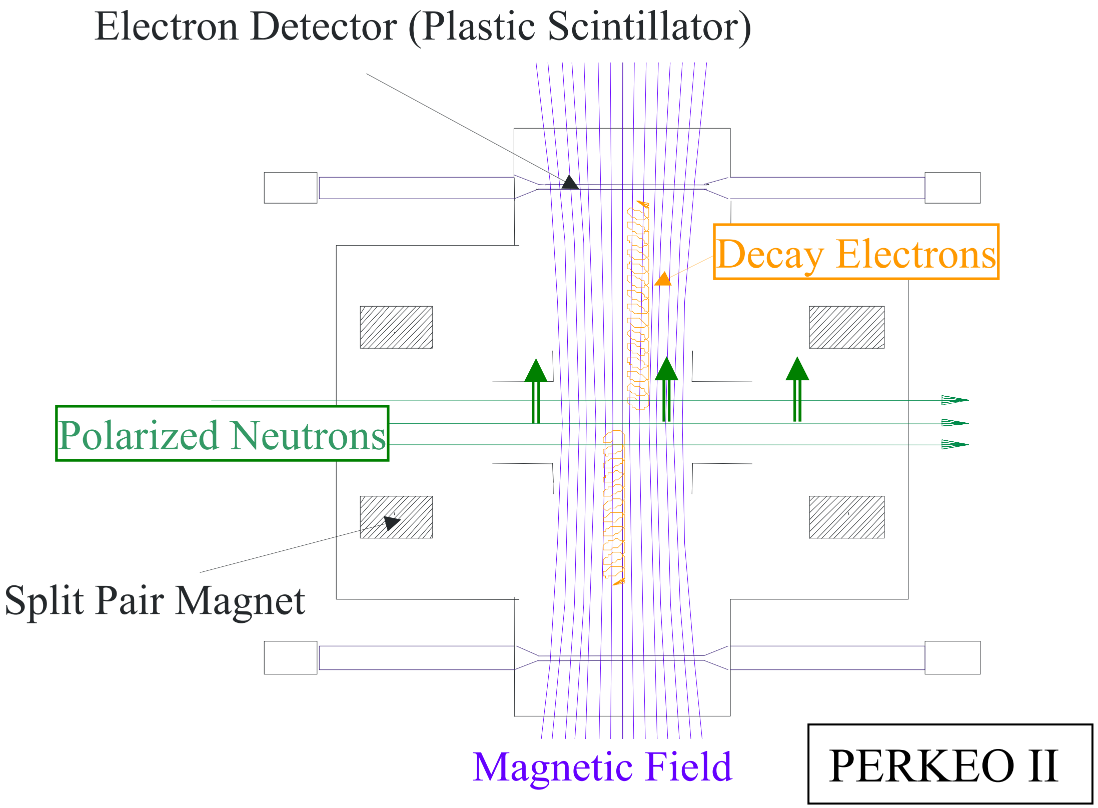
The Beta Asymmetry: PERKEO II



$$dw \propto \left(1 + A\frac{v}{c}\cos\left(p_e,\sigma_\text{n}\right)\right)$$

Experimental Reality:

- Flip neutron spin, don’t compare detectors!
- Two detectors still needed to suppress electron backscattering.



Electron Detector (Plastic Scintillator)

Decay Electrons

Polarized Neutrons

Split Pair Magnet

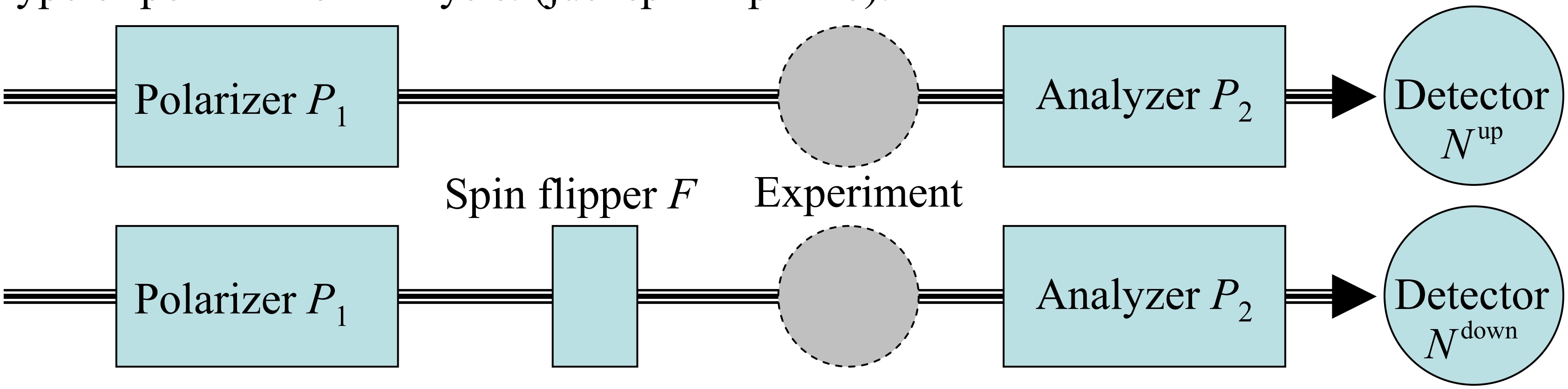
Magnetic Field

PERKEO II

$$\frac{N_\text{up} - N_\text{down}}{N_\text{up} + N_\text{down}} = A\frac{v}{c}\left\langle\cos\left(p_e,\sigma_\text{n}\right)\right\rangle Pf$$

On the motivation to achieve high polarization

Easiest type of polarization analysis: (just spin flip ratio):



Polarizer P_1

Analyzer P_2

Detector N^{up}

Spin flipper F

Experiment

Polarizer P_1

Analyzer P_2

Detector N^{down}

Spin flip ratio: $R = \dfrac{N^{\text{up}}}{N^{\text{down}}} = \dfrac{1+P_1P_2}{1-P_1P_2+P_1P_2f} \doteq \left[\dfrac{1}{2}(1-P_1)+\dfrac{1}{2}(1-P_2)+(1-f)\right]^{-1}$

Result: The spin flip ratio sets a lower limit on the efficiency of devices, even if one couldn’t tell individual numbers for P_1, P_2, or f. If this lower limit is close to 100%, the precision of any scheme used to determine the efficiencies individually doesn’t have to be high. Most experimental errors (Background, Depolarization) cause the true polarization to be even higher than the lower limit given by the spin flip ratio.

Note: Modification of spin flip ratio if analyzer is He-cell (opposite polarization)

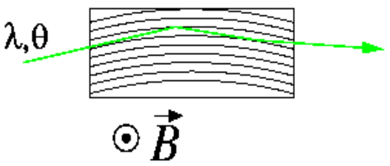
Problems of polarization measurement: Inhomogeneities of polarization and spin flip efficiency

Supermirror: … with position, angle, wavelength

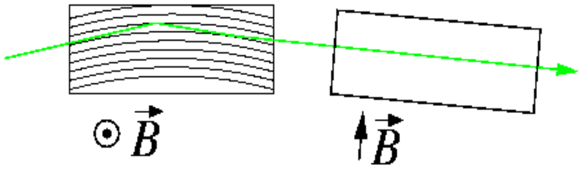
He-3: … with wavelength, time

Beam polarization with crossed supermirrors

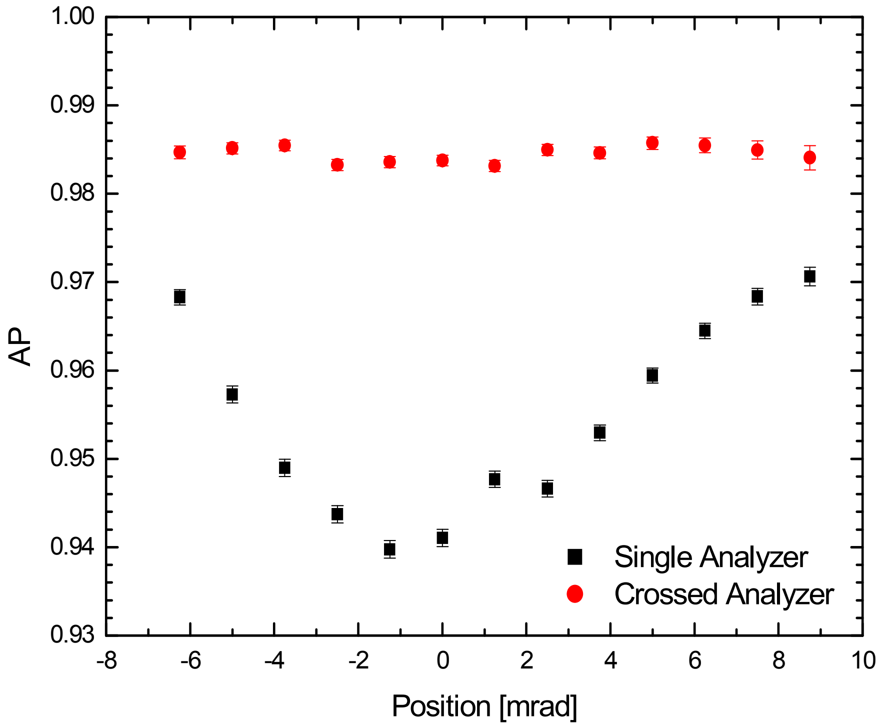
Supermirror polarizer



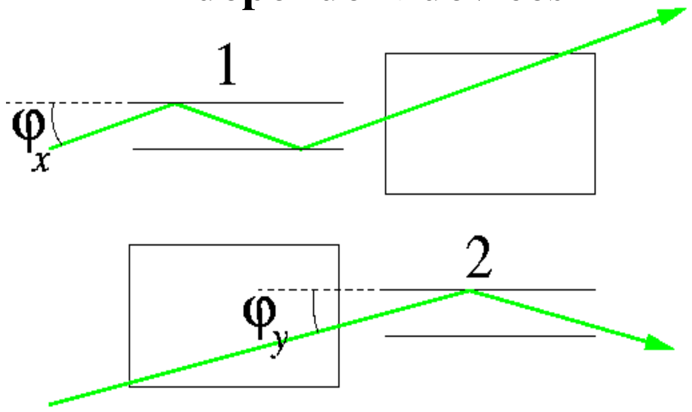
The crossed geometry



Angular dependence



Independent devices



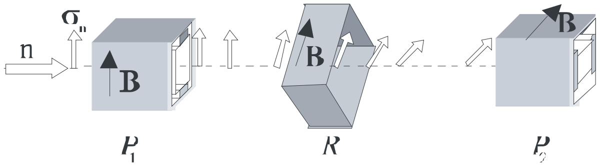
$$P_{12}=\frac{P_1+P_2}{1+P_1P_2}$$

$$\approx 1-\frac{1}{2}(1-P_1)(1-P_2)$$

M. Kreuz et al., NIM A 547, 583 (2005)

Neutron beam polarization for PERKEO II

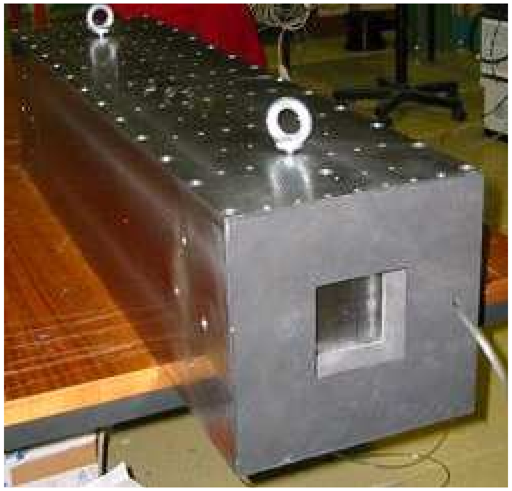
1. Beam polarization: Crossed supermirrors Kreuz et al., NIM A 547, 583 (2005)



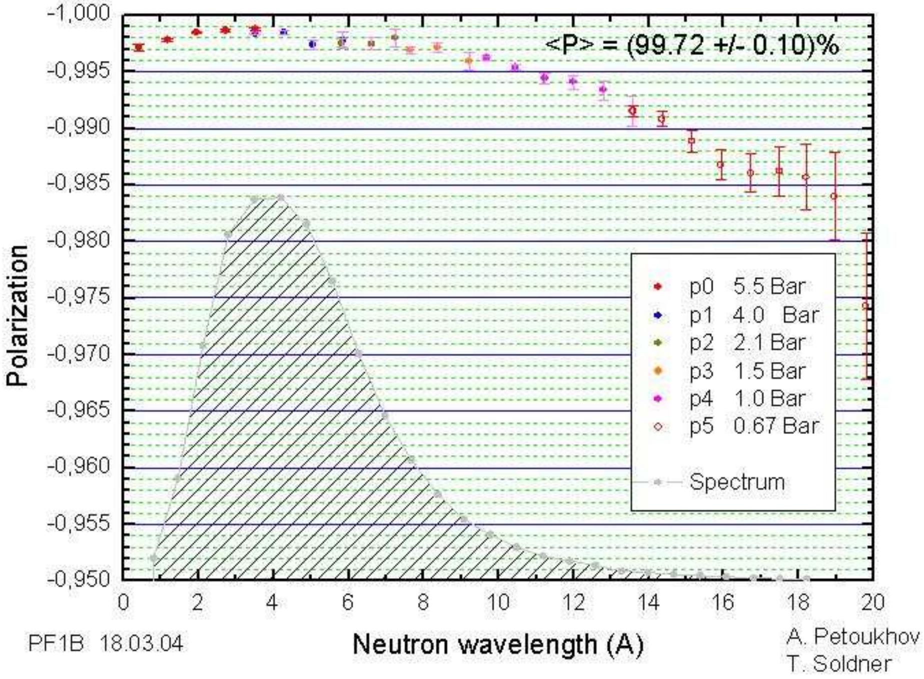
2. Spin flip through adiabatic fast passage
3. Polarization analysis behind experiment with 2nd spin flipper and black He-3 analyzer

Result: M. Schumann et al., PRL 99, 191803 (2007)

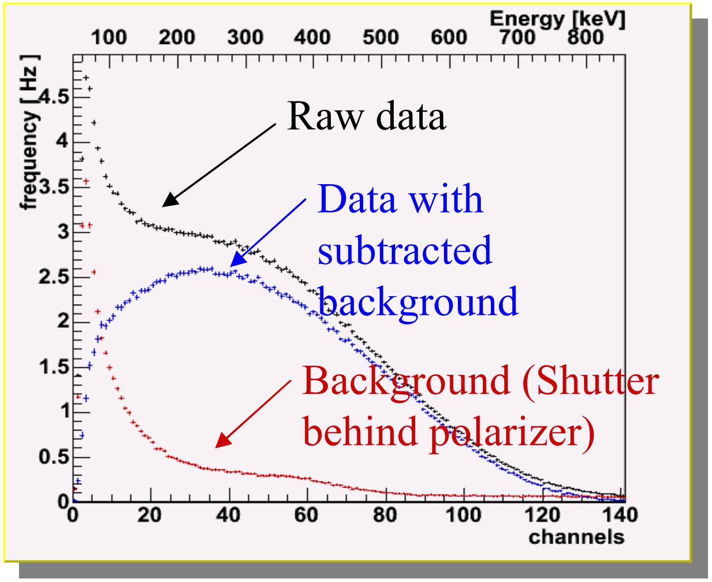
- Spin flip efficiency *f* = 100.0(1)%
- Beam polarization *P* = 99.7(1)%
- No position dependence of *f* or *P*
- No time dependence of *f* or *P*



Above: Polarizer, below: Results

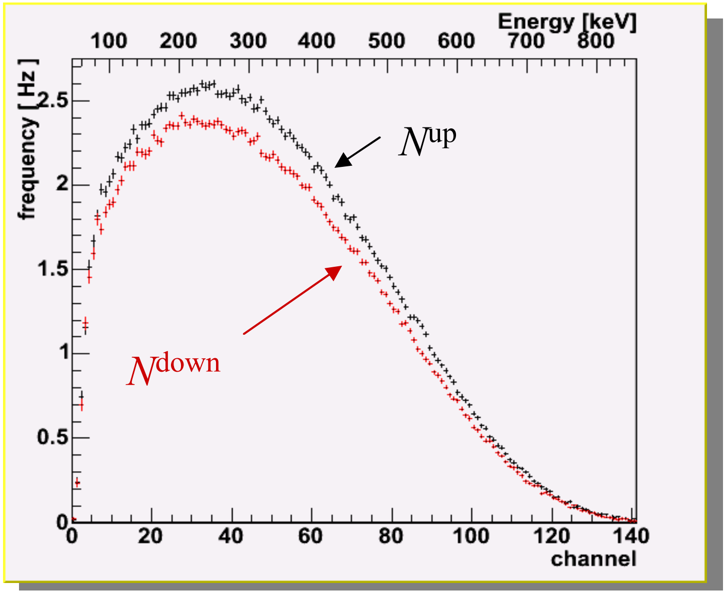


PERKEO II: Results


Raw data

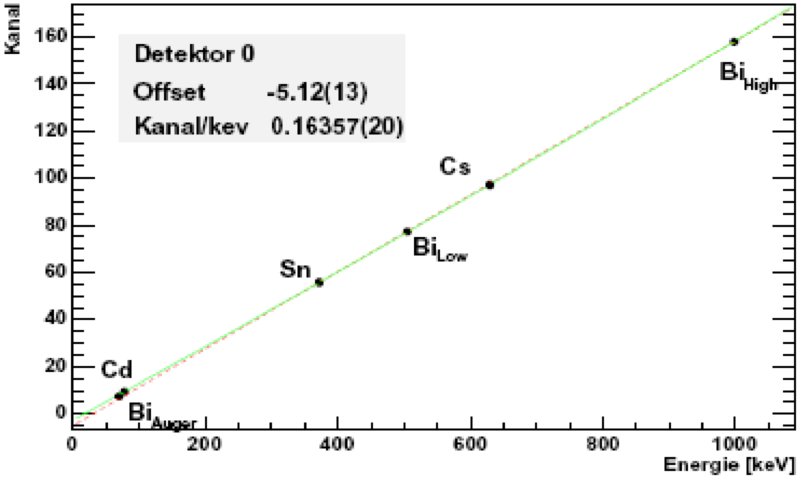
Data with subtracted background

Background (Shutter behind polarizer)


N^{up}

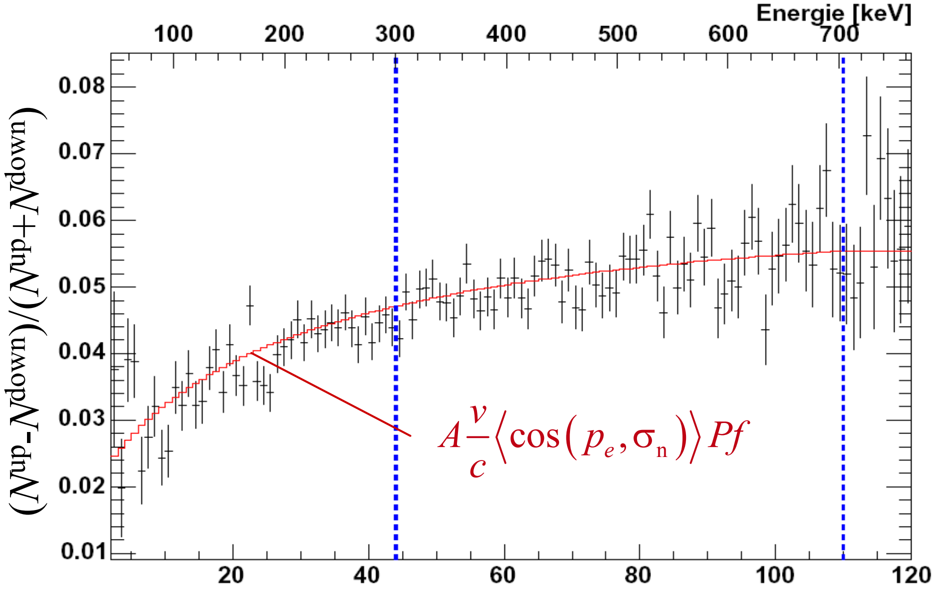
N^{down}

Calibration: Conversion electron sources


Detektor 0

Offset -5.12(13)

Kanal/kev 0.16357(20)


$A\frac{v}{c}\langle\cos(p_e,\sigma_n)\rangle Pf$

Uncertainty Budget PERKEO II, last run

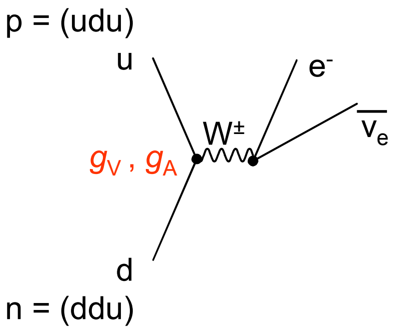
Error Analysis	**Correction**	**Uncertainty PERKEO II**
Statistical uncertainty		0.26%
Background	0.1%	0.1%
Neutron beam polarization	0.3 %	0.1%
Spin flip efficiency	0%	0.1%
Magnetic mirror effect	0.11%	0.01%
Edge Effect	-0.22%	0.05%
Detector response		0.18%
…		

H. Abele, 2009, preliminary

Beam time	**Result**	**Publication**
1995	$A = -0.1189(12)$	Phys. Lett. B 407, 212 (1997)
1997	$A = -0.1189(7)$	Phys. Rev. Lett. 88, 211801 (2002)
2004	$A = -0.1198(5)$ (preliminary) → $\lambda = -1.2762(13)$	

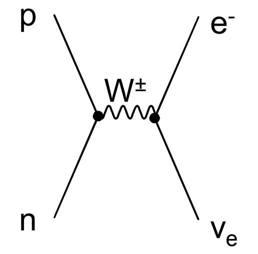
Coupling Constants of the Weak Interaction

Coupling Constants in Neutron Decay

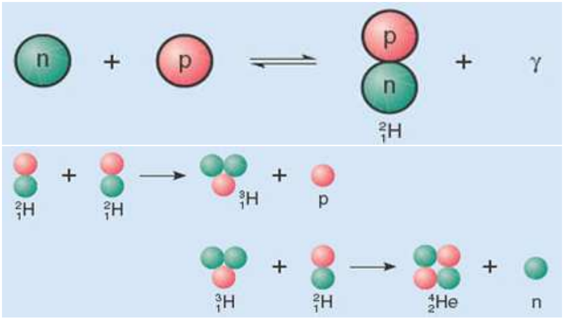


$$n \rightarrow p + e^- + \bar{\nu}_e$$

Primordial Nucleosynthesis

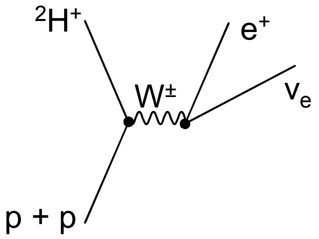


$$n + \nu_e \leftrightarrow p + e^-$$



Start of Big Bang Nucleosynthesis, Primordial ^{4}He abundance

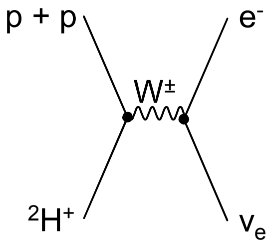
Solar cycle



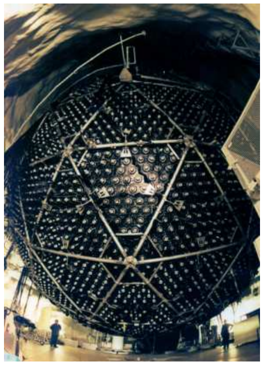
$$p + p \rightarrow {}^2H^+ + e^+ + \nu_e$$

Start of Solar Cycle, determines amount of Solar Neutrinos

Neutrino Detection (SNO, CC)

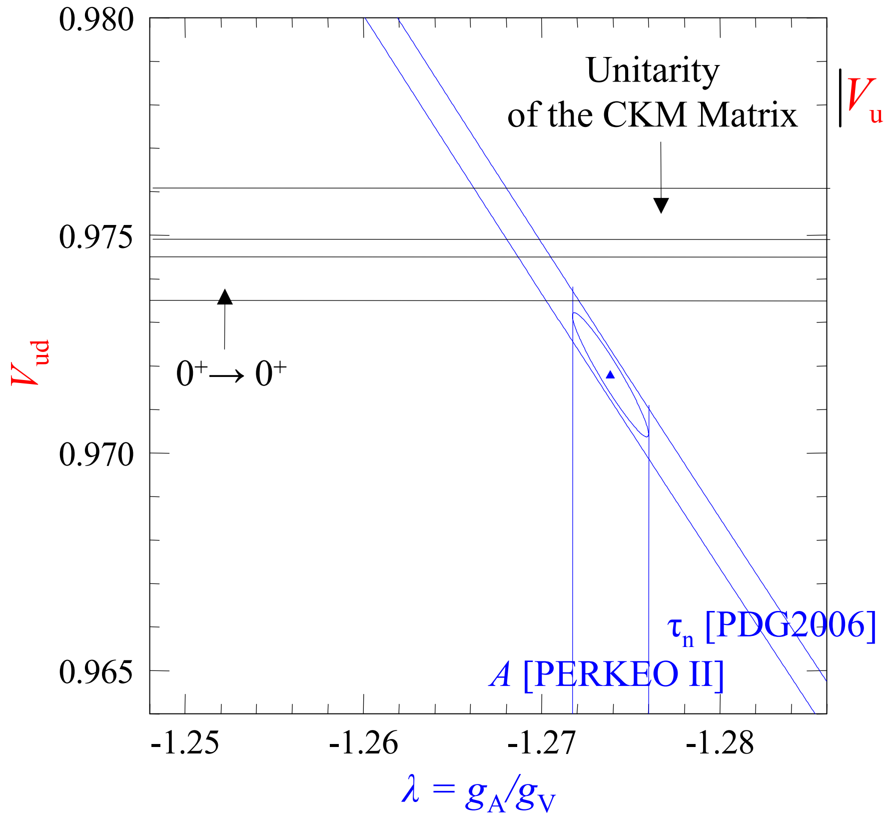


$$\nu_e + {}^2H^+ \rightarrow p + p + e^-$$



Efficiency of Neutrino Detectors

Unitarity: Situation 2004



$$|V_{ud}| = \sqrt{1 - |V_{us}|^2 + |V_{ub}|^2}$$

Fermi-Transition: $g_V = G_F \cdot V_{ud}$

Gamow-Teller-Transition: $g_A = G_F \cdot V_{ud} \cdot \lambda$

Neutron Measurements needed:

- Neutron lifetime τ_n

$$\tau_n^{-1} \propto G_F^2 V_{ud}^2 \left(1 + 3|\lambda|^2\right) \quad ; \lambda = g_A/g_V$$

- Beta Asymmetry $A(\lambda)$

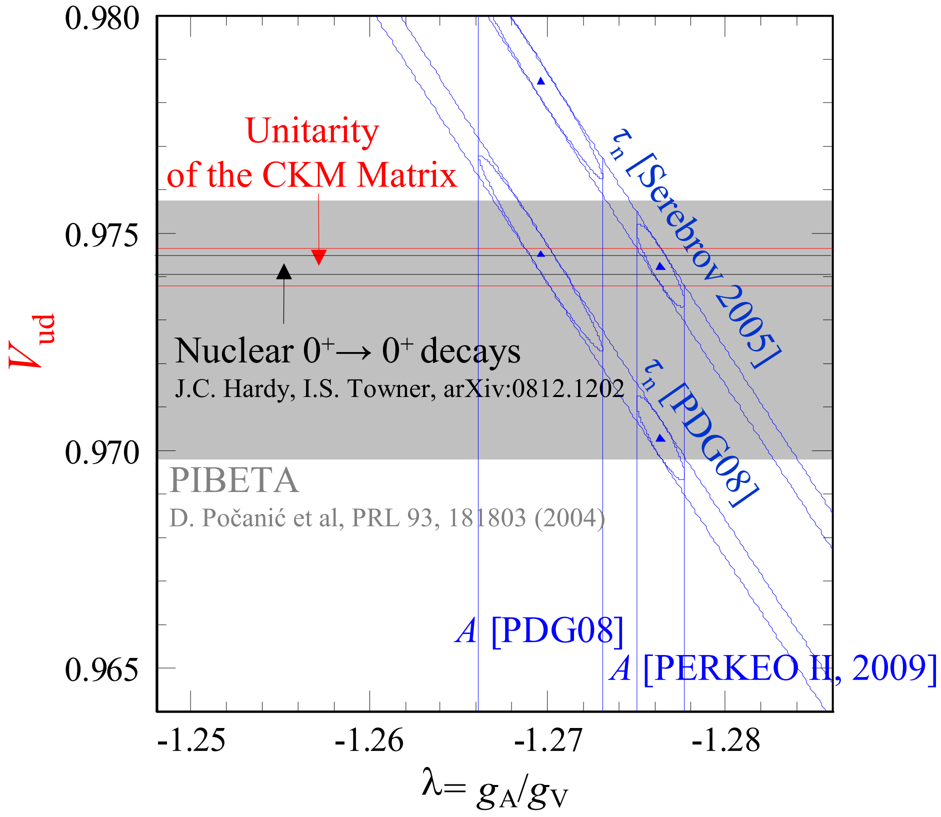
$$A = -2\frac{|\lambda|^2 + \mathrm{Re}\,\lambda}{1 + 3|\lambda|^2}$$

- Neutrino-Electron-Correlation $a(\lambda)$

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

Unitarity 2008

$$|V_{ud}| = \sqrt{1 - |V_{us}|^2 + |V_{ub}|^2}$$



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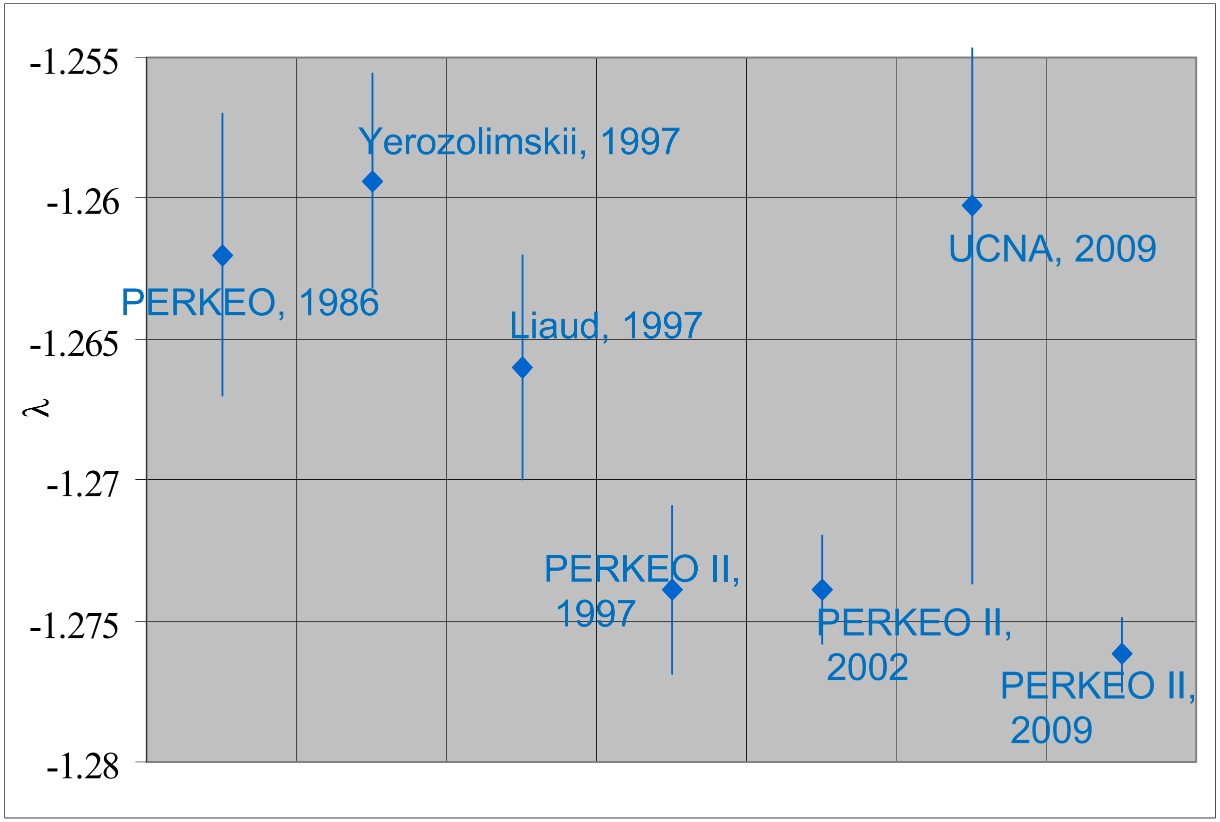
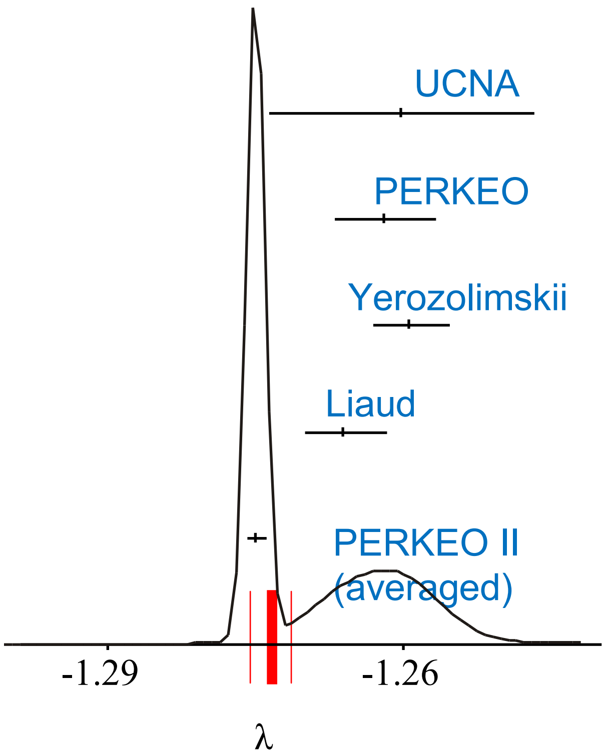
Neutron lifetime discrepancies have to be sorted out.

To make A not limiting for neutron-based determination of V_{ud}: $\Delta A/A < 0.2\%$ needed

Determination of $\lambda = g_A/g_V$ from A



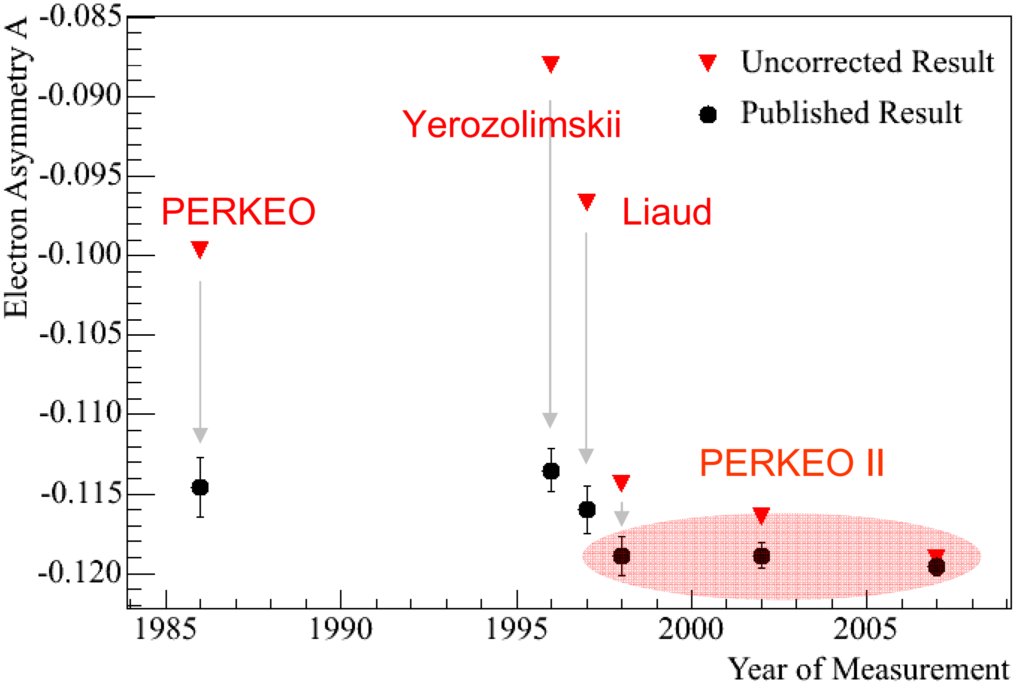


Probability of disagreement between beta asymmetry measurements due to statistical fluctuations:

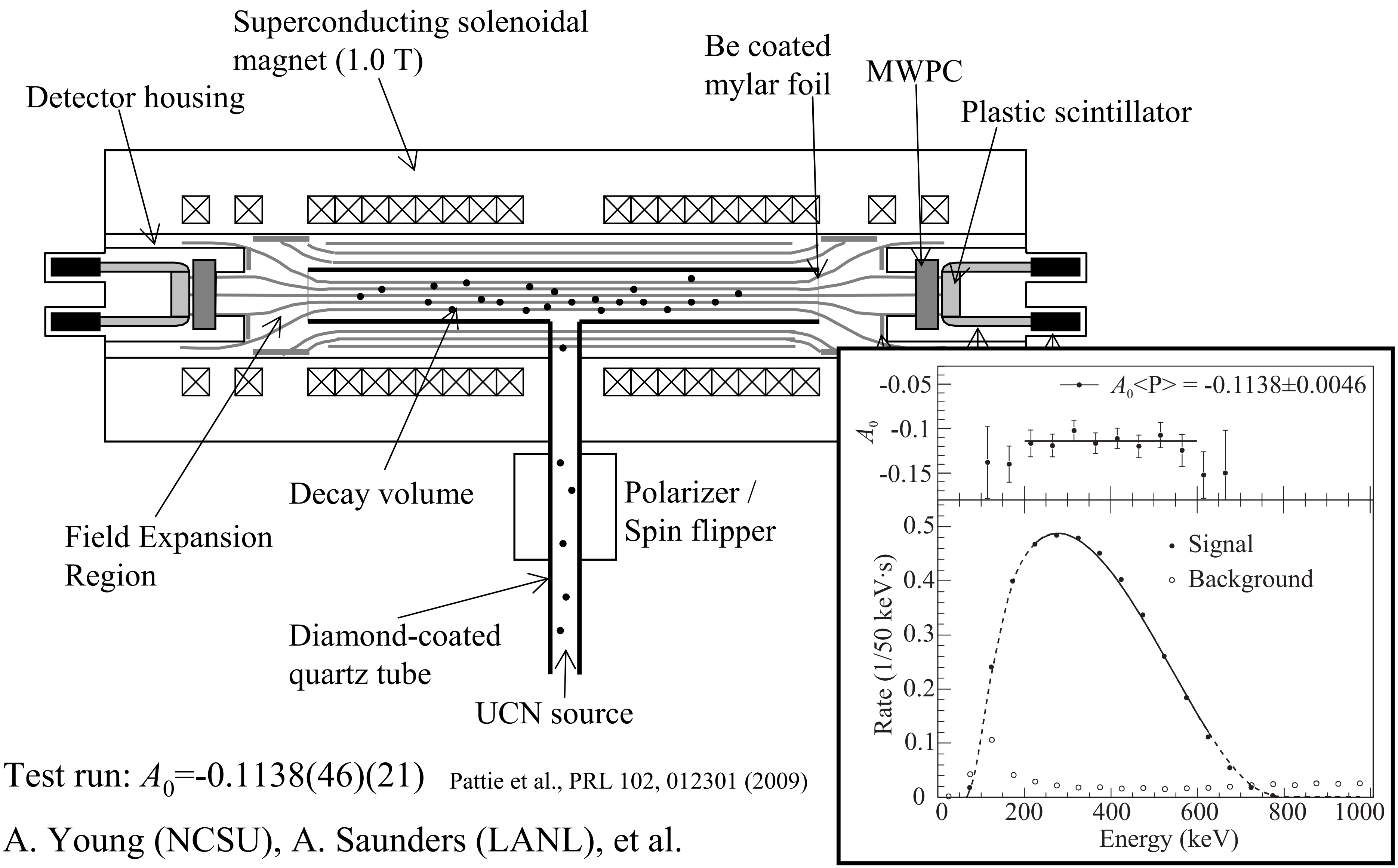
$P = 2.7\times10^{-5}$ (4.2 σ)

Maybe in PDG2010: “The most recent results from PERKEO II are so far from other results that it makes no sense to include them in the average. It is up to workers in this field to resolve this issue ??? (THIS IS NOT A SERIOUS PROPOSAL!)

Corrections in Beta asymmetry measurements



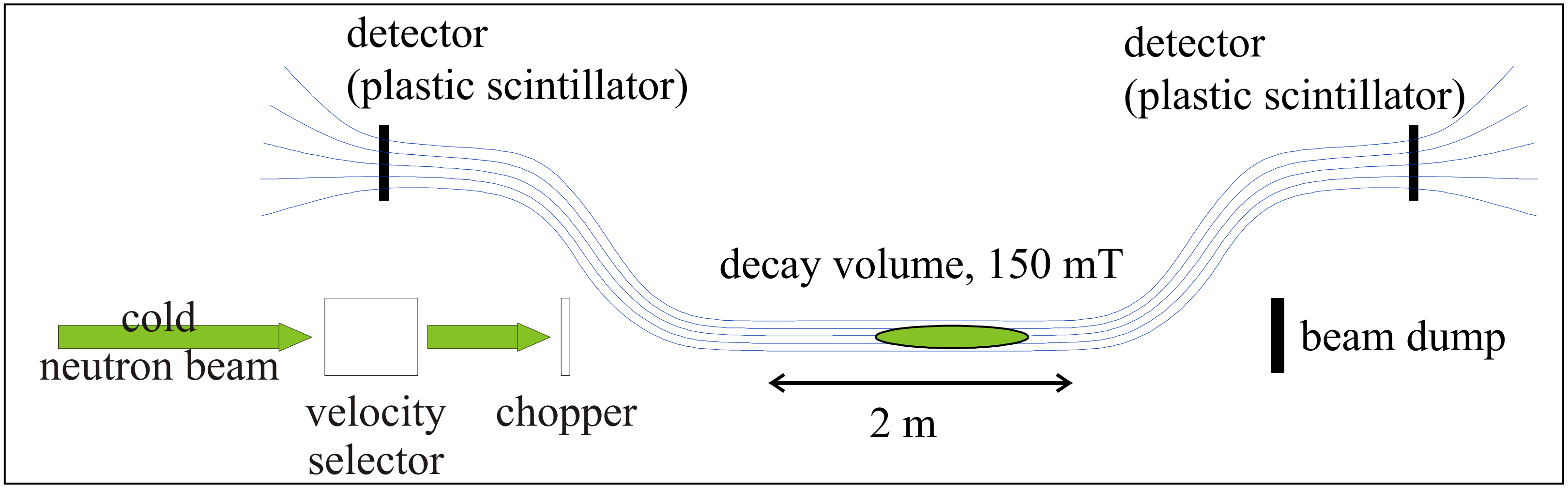
New attempts: UCNA (ultracold neutrons)



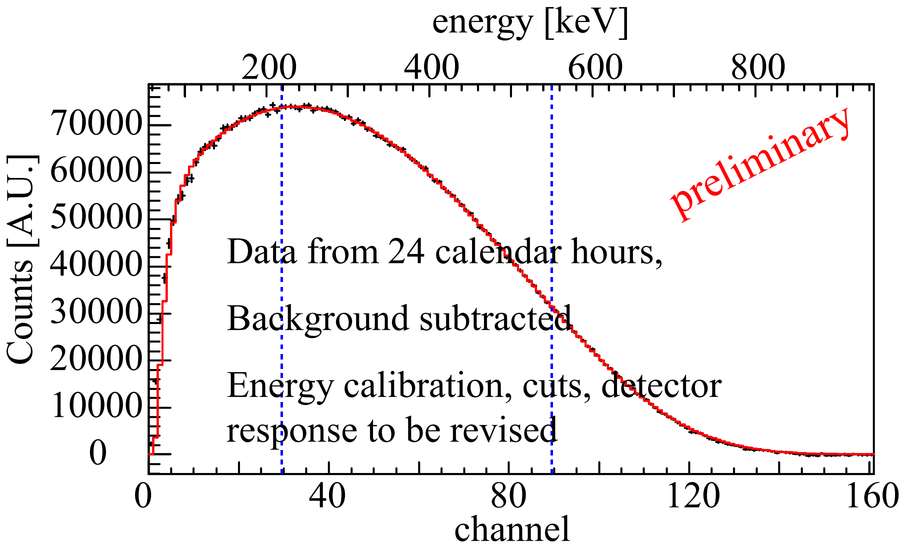
Test run: A_0=-0.1138(46)(21) Pattie et al., PRL 102, 012301 (2009)

A. Young (NCSU), A. Saunders (LANL), et al.

Next generation: PERKEO III



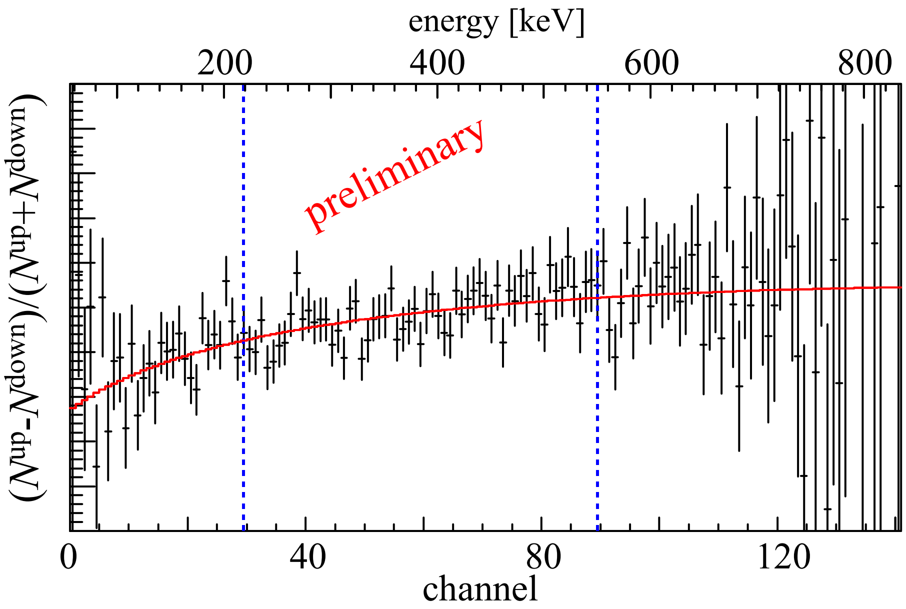
B. Maerkisch, D. Dubbers (Heidelberg), H. Abele (Vienna), T. Soldner (ILL) et al.



Data from 24 calendar hours,

Background subtracted

Energy calibration, cuts, detector response to be revised



New observable: Weak magnetism

Hadronic current at $q \neq 0$:

$$H_{\text{weak}} = G_{\text{F}} V_{\text{ud}} \left\langle p \middle| 1 \cdot \gamma^{\mu} - \lambda \gamma^{\mu} \gamma^{5} + i \frac{\mu_{\text{p}} - \mu_{\text{n}}}{2 m_{\text{p}}} \sigma^{\mu\nu} q_{\nu} + \ldots \middle| n \right\rangle$$

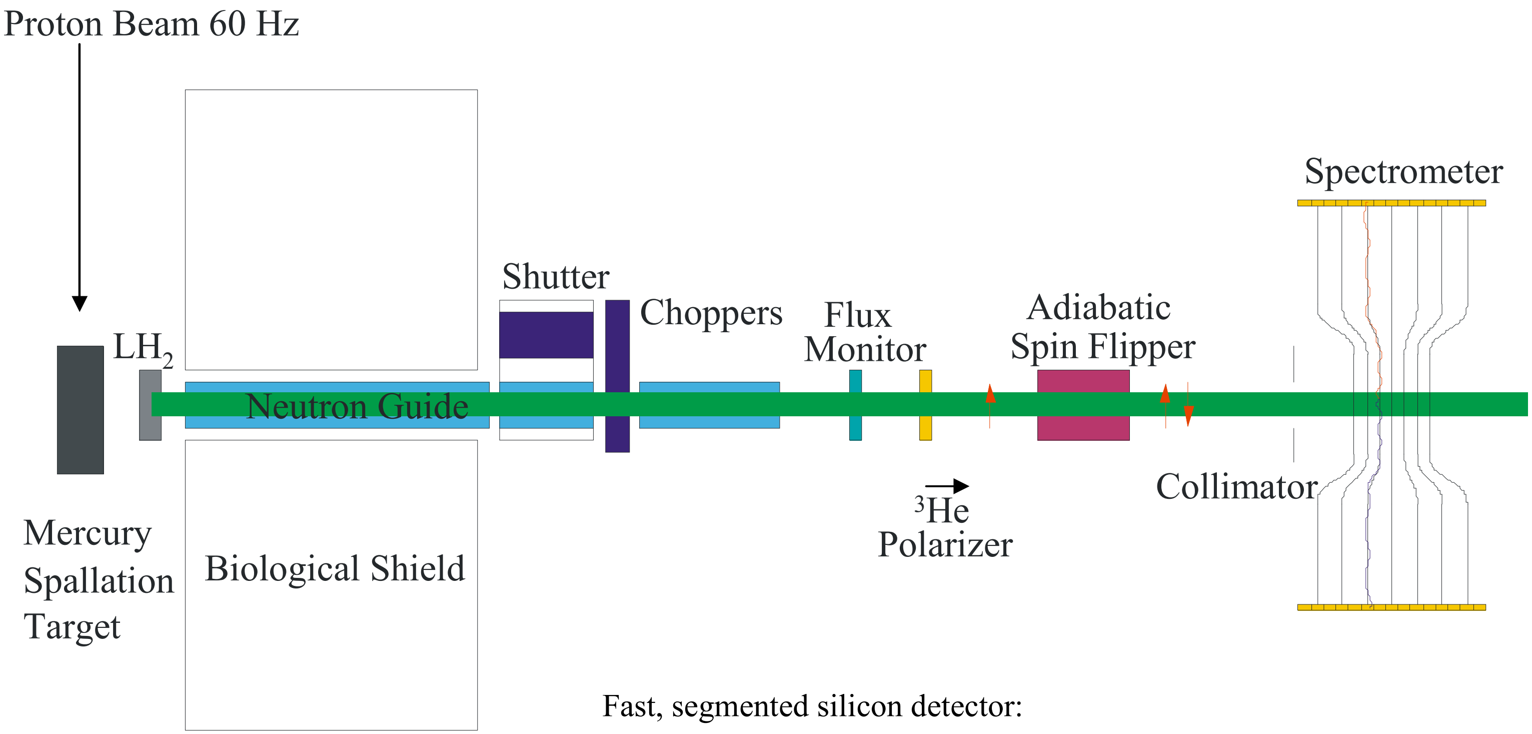
$$\cdot \left\langle e^{-} \middle| \gamma_{\mu} - \gamma_{\mu} \gamma_{5} \middle| \nu_{e} \right\rangle$$

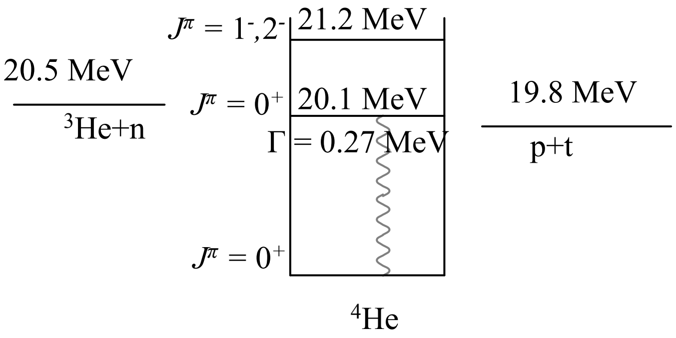
weak magnetism

1. First determination in mirror nuclei: Slightly different decay rates due to weak magnetism
2. Determination in hyperons: Not always according to Standard Model
3. New: Determination from beta asymmetry spectrum

$$A(E) = A_{0} \left[1 + c + \underbrace{a_{\text{WM}} \left(\lambda, \frac{\mu_{\text{p}} - \mu_{\text{n}}}{2} \right)}_{\approx 2\%} \right]$$

New attempts at SNS: abBA / Nab / PANDA





Fast, segmented silicon detector:

S. Wilburn (LANL),

D. Bowman (ORNL),

S.B. et al.

Outline

Part 1: Contributions to the Standard Model

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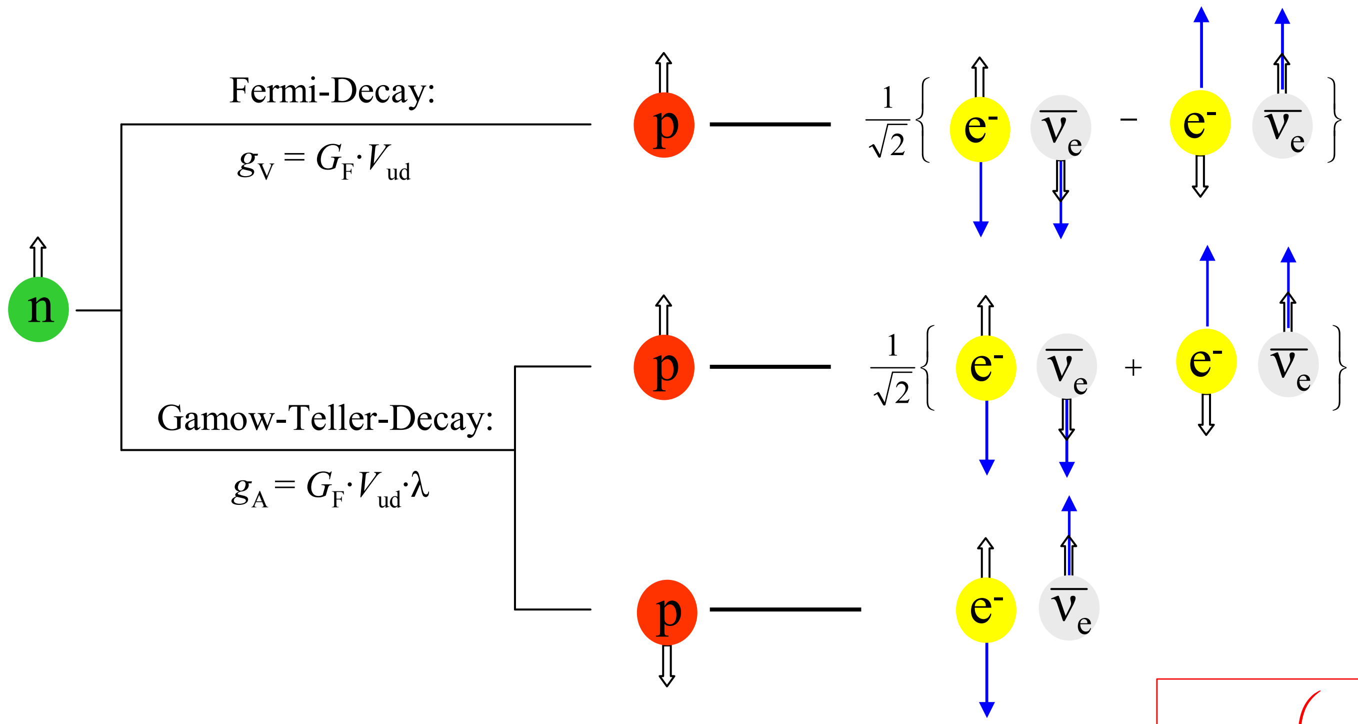
Part 2: Searches for physics beyond the Standard Model

…

Determination of the Coupling Constants



Fermi-Decay:

$g_V = G_F \cdot V_{ud}$

Gamow-Teller-Decay:

$g_A = G_F \cdot V_{ud} \cdot \lambda$

$a = 1$

$a = 1$

$a = -1$

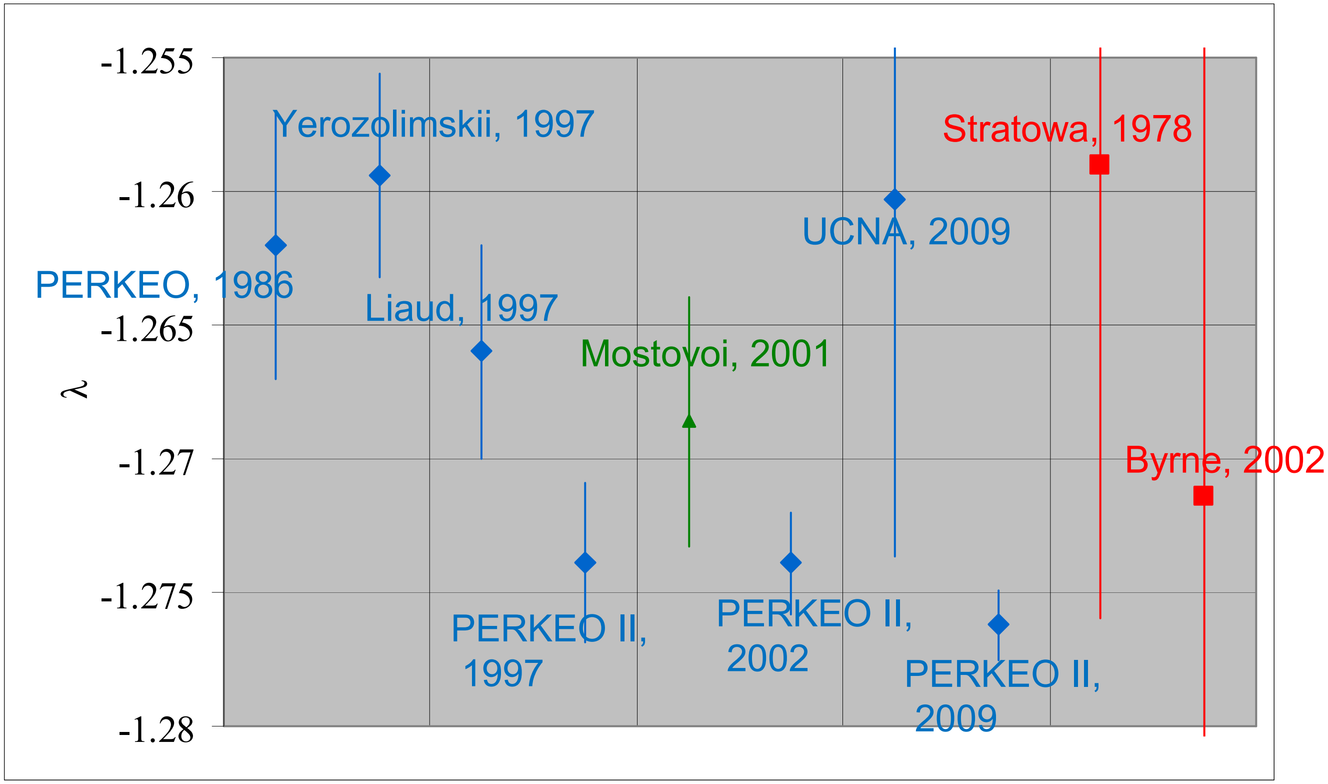
$$\boxed{dw \propto \left(1 + a\frac{v}{c}\cos\left(p_e, p_{\bar{\nu}_e}\right)\right)}$$

Two unknown parameters, g_A and g_V, need to be determined in 2 experiments

1. Neutron-Lifetime: $\tau_n^{-1} \propto \left(g_V^2 + 3g_A^2\right)$ $\tau_n \approx 885\ \mathrm{s}$

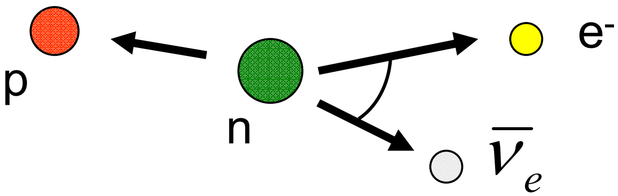
2b. Neutrino-Electron-Correlation *a*: $a = \dfrac{1-\lambda^2}{1+3\lambda^2} \sim -0.1$ $\lambda = \dfrac{g_A}{g_V}$

Determination of λ = g_A/g_V



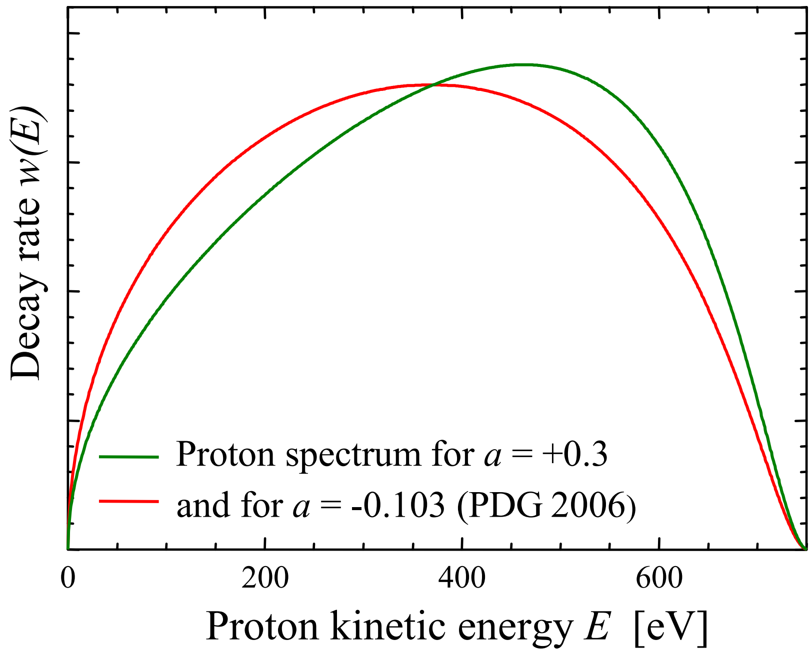
- A measurement of *a* is independent of possible unknown errors in *A*, systematics are entirely different.
- Present experiments have $\Delta a/a \sim 5\%$, an order of magnitude improvement is desirable

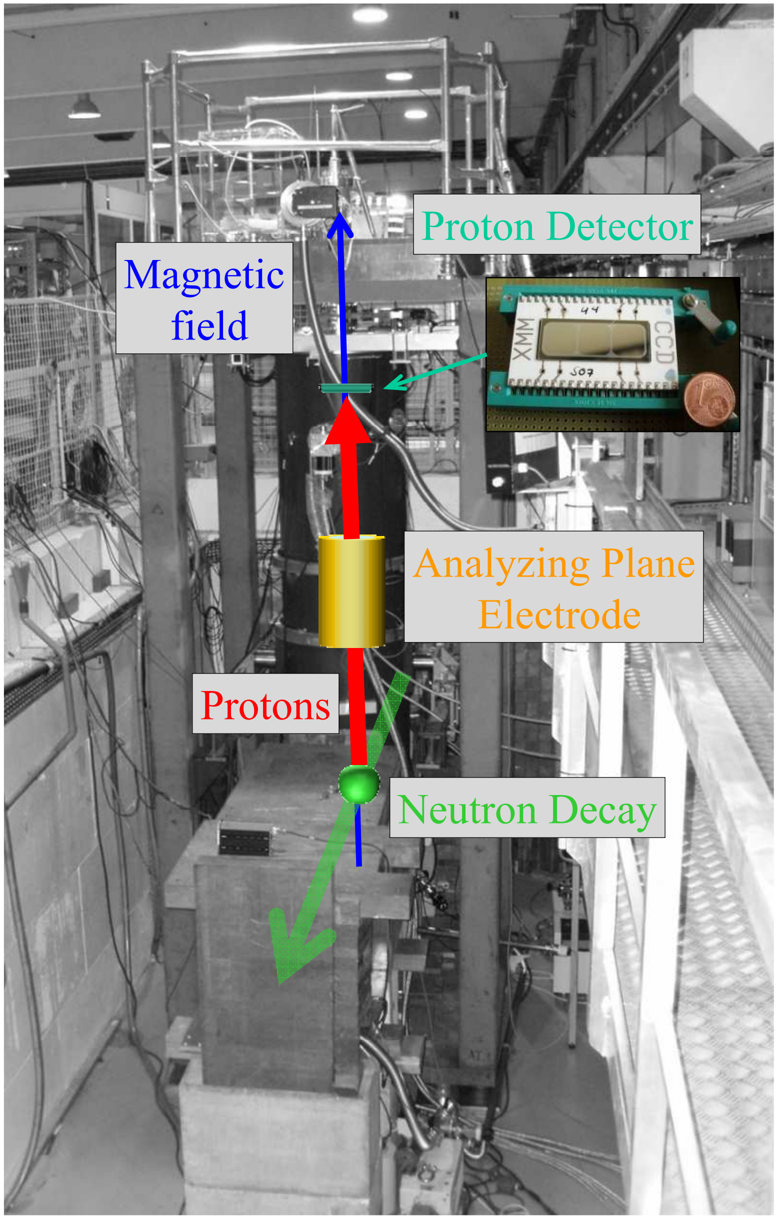
aSPECT (Mainz, Munich, ILL, Virginia)



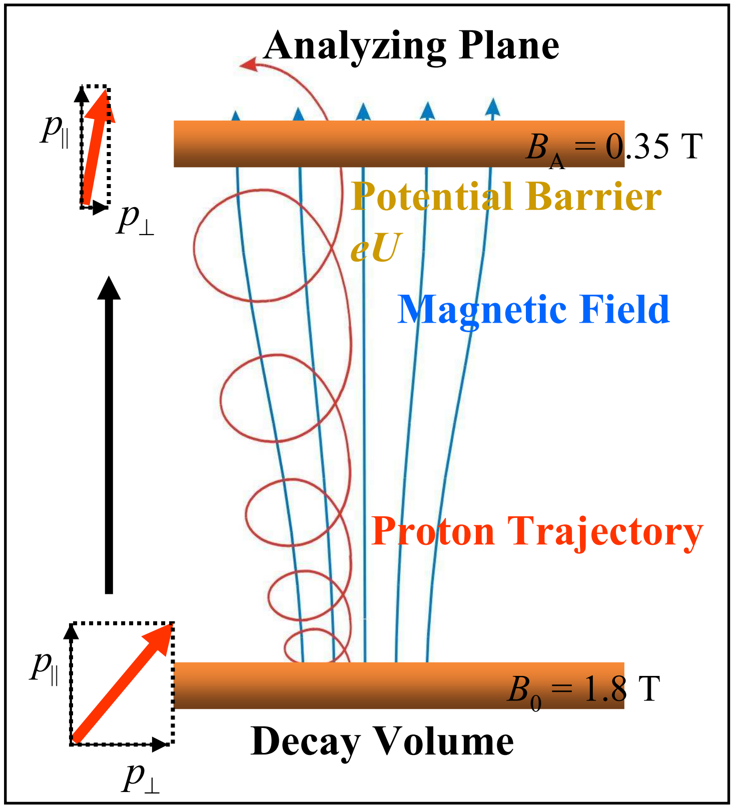
$$dw \propto \left(1 + a\frac{v}{c}\cos\left(p_e, p_{\bar{\nu}_e}\right)\right)$$

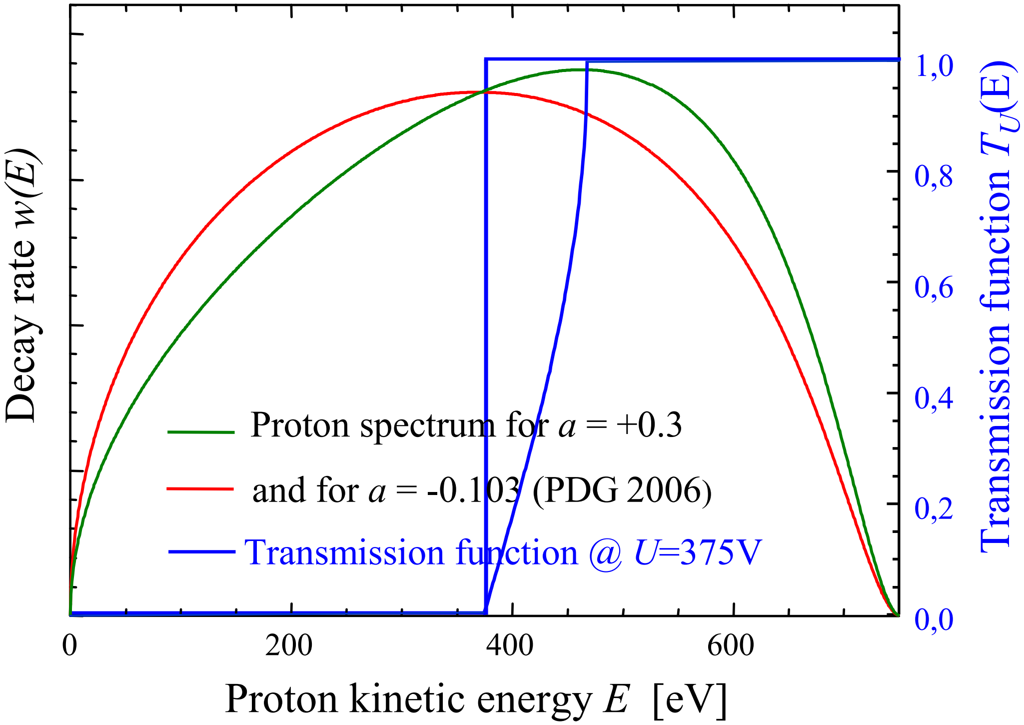
Sensitivity of the Proton Spectrum to *a*:





Principle of a Retardation Spectrometer



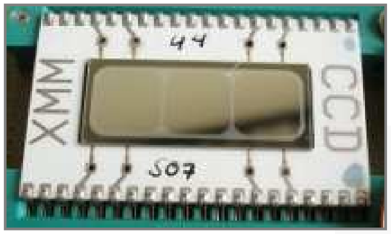


Transmission function $T_U(E)$ in the adiabatic limit:

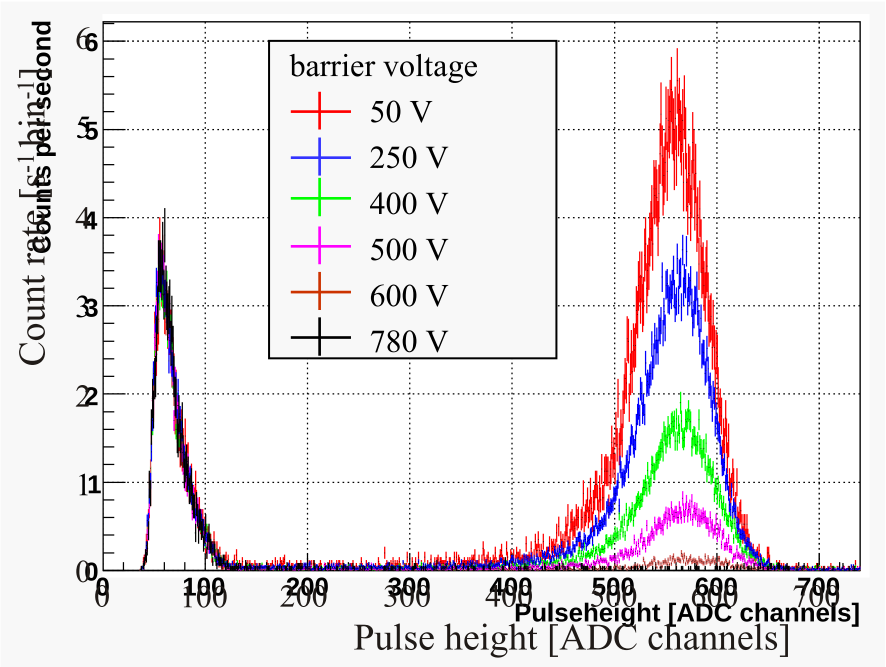
$$T_U(E) = \begin{cases} 0 & ; \quad E < eU \\ 1 - \sqrt{1 - B_0/B_A\left(1 - eU/E\right)} & ; \quad \text{otherwise} \\ 1 & ; \quad E > eU/\left(1 - B_A/B_0\right) \end{cases}$$

First results of 2008 beamtime @ ILL

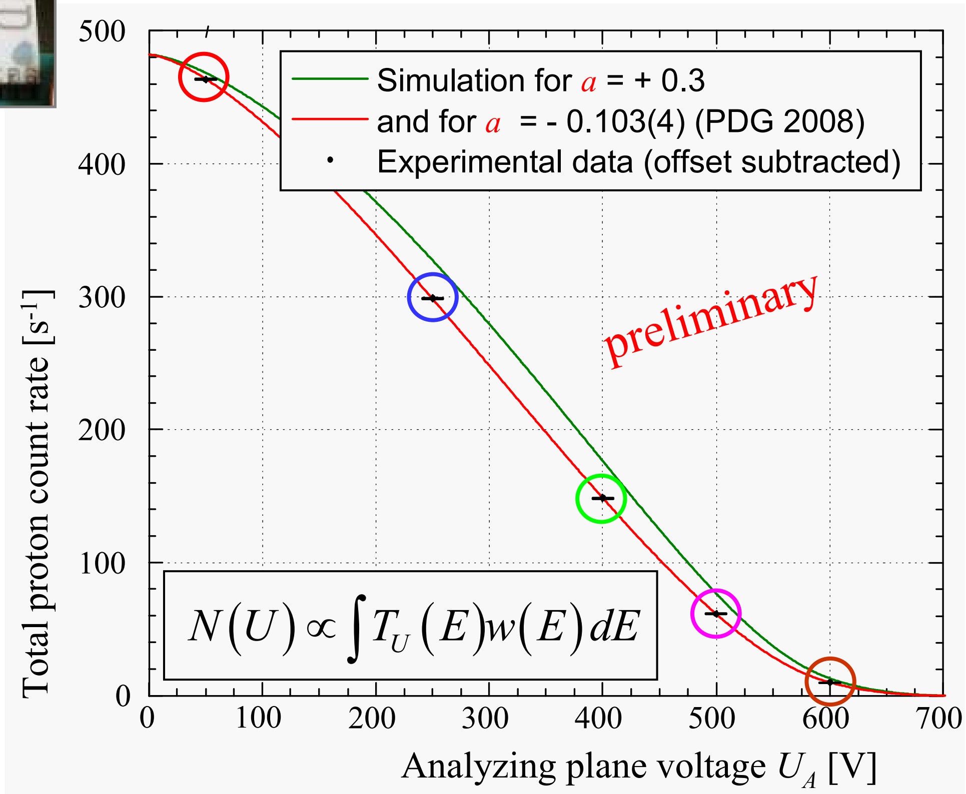
Silicon drift detector,
at -15kV



Pulse height spectrum:

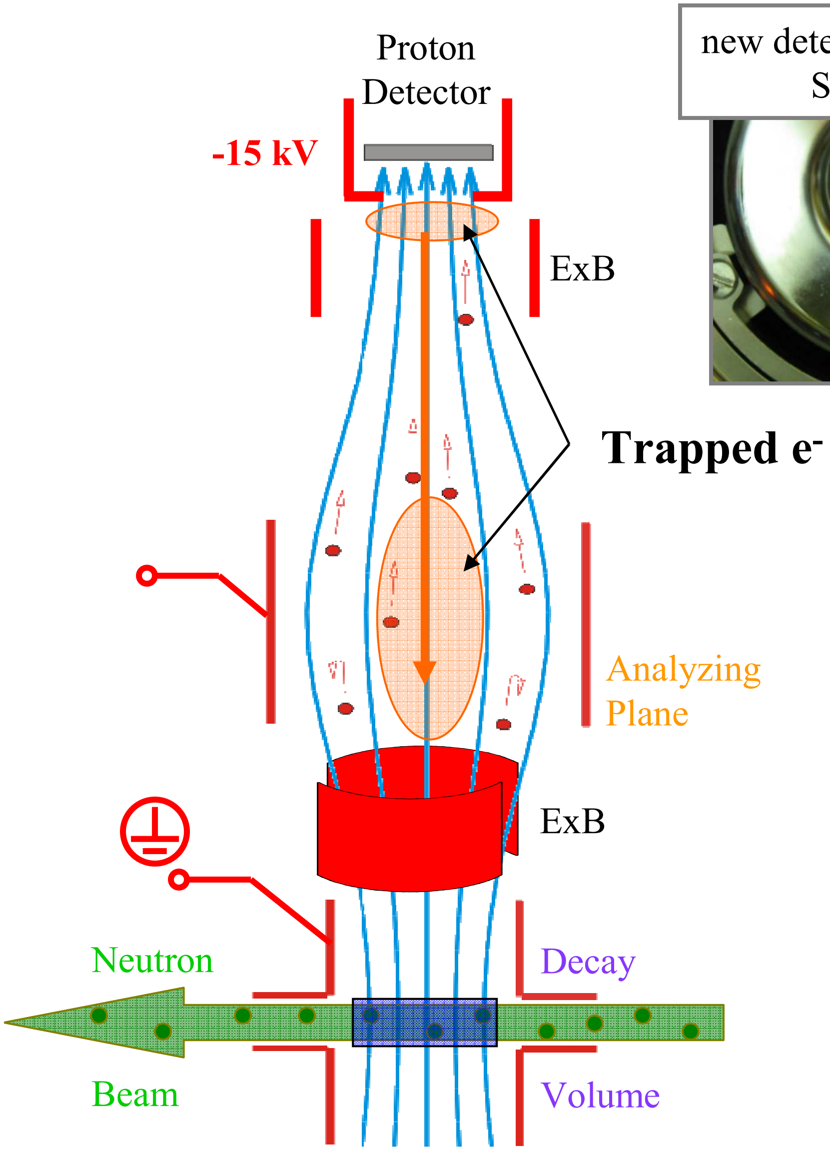


Integrated Proton Spectrum:

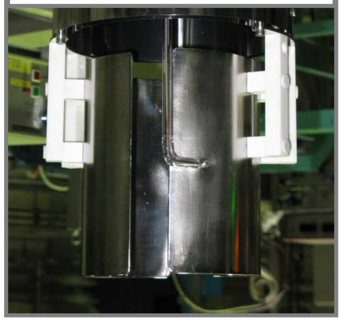


- 470 counts per second at $U_A = 50$ V (one detector pad)
- Statistical sensitivity on a about 2 % per 24 hours measurement time
- Background stable

Trapping problems solved

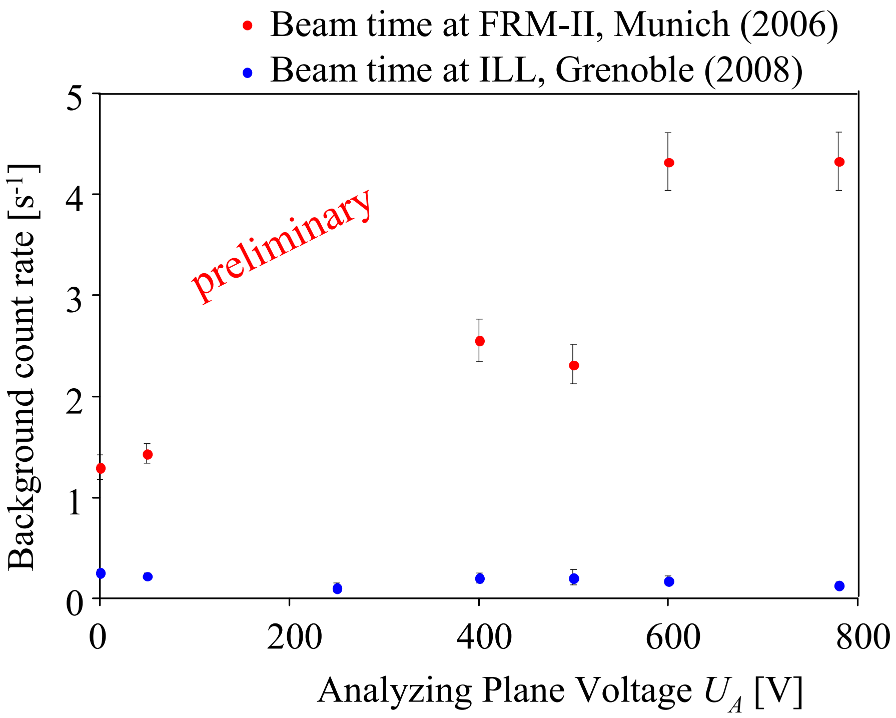



new detector -HV electrode,
SDD detector

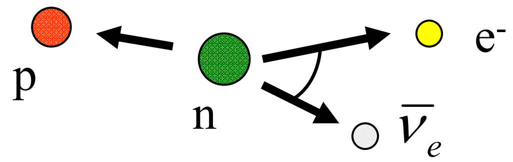

new ExB electrode


Internal getter pumps

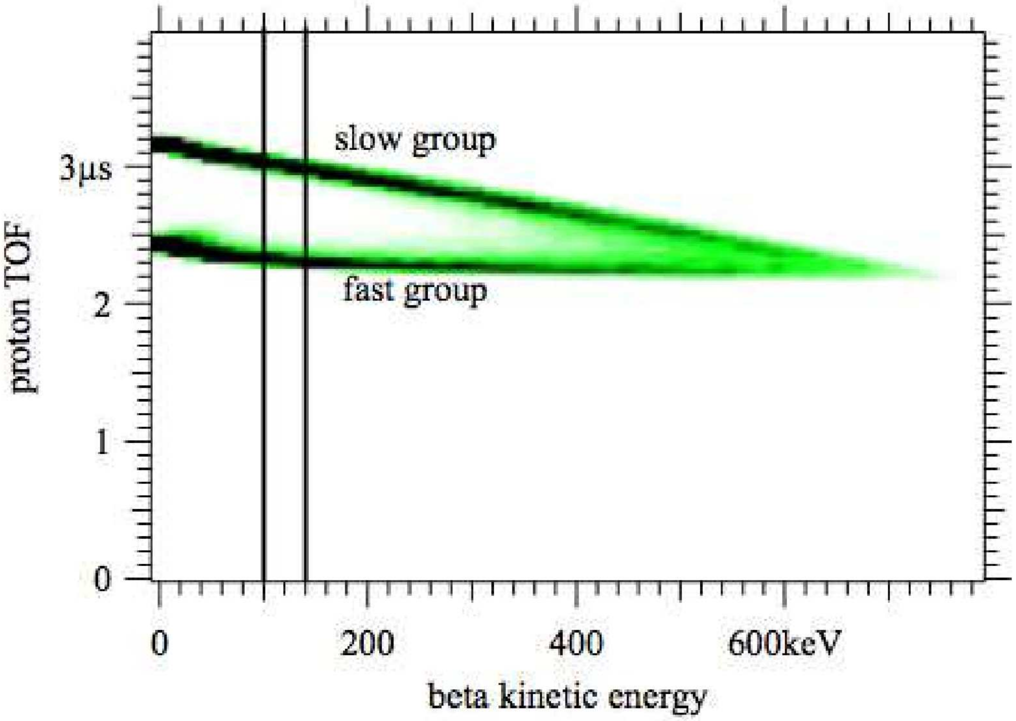
Measurements without neutron beam

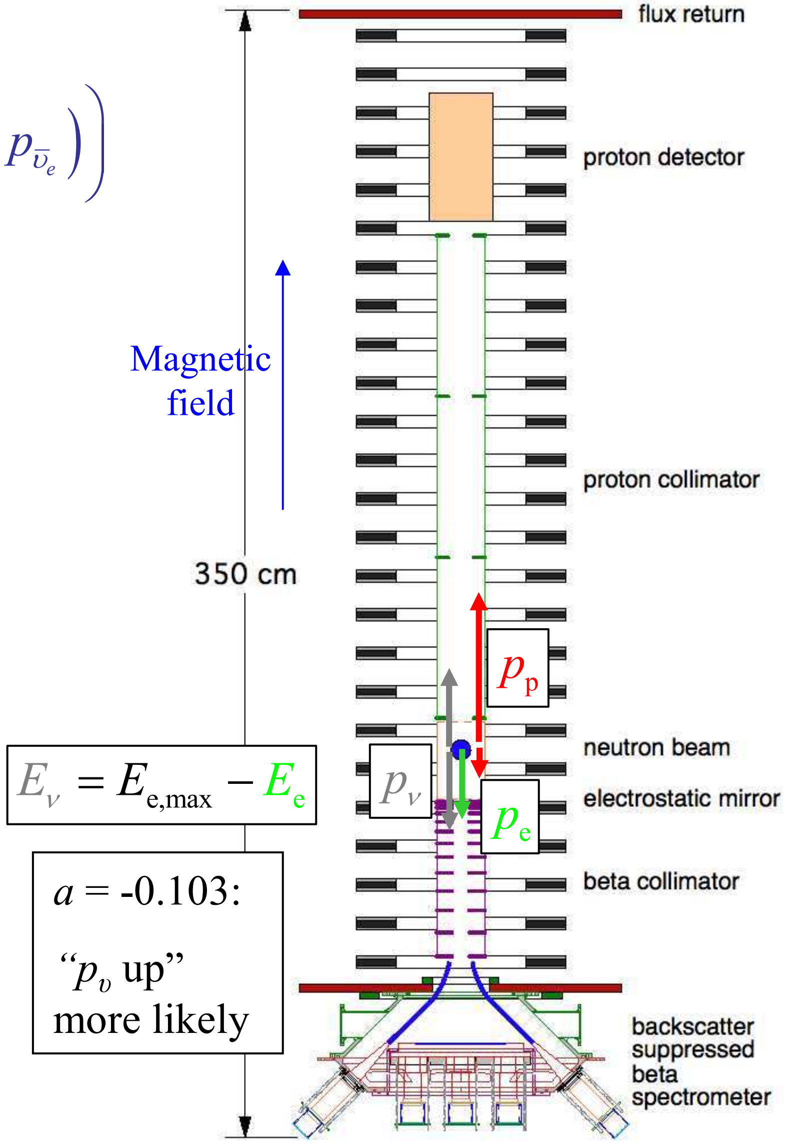


aCORN



$$w(E) \propto \left(1 + a\frac{v}{c}\cos\left(p_e, p_{\bar{\nu}_e}\right)\right)$$





$E_\nu = E_{e,\max} - E_e$

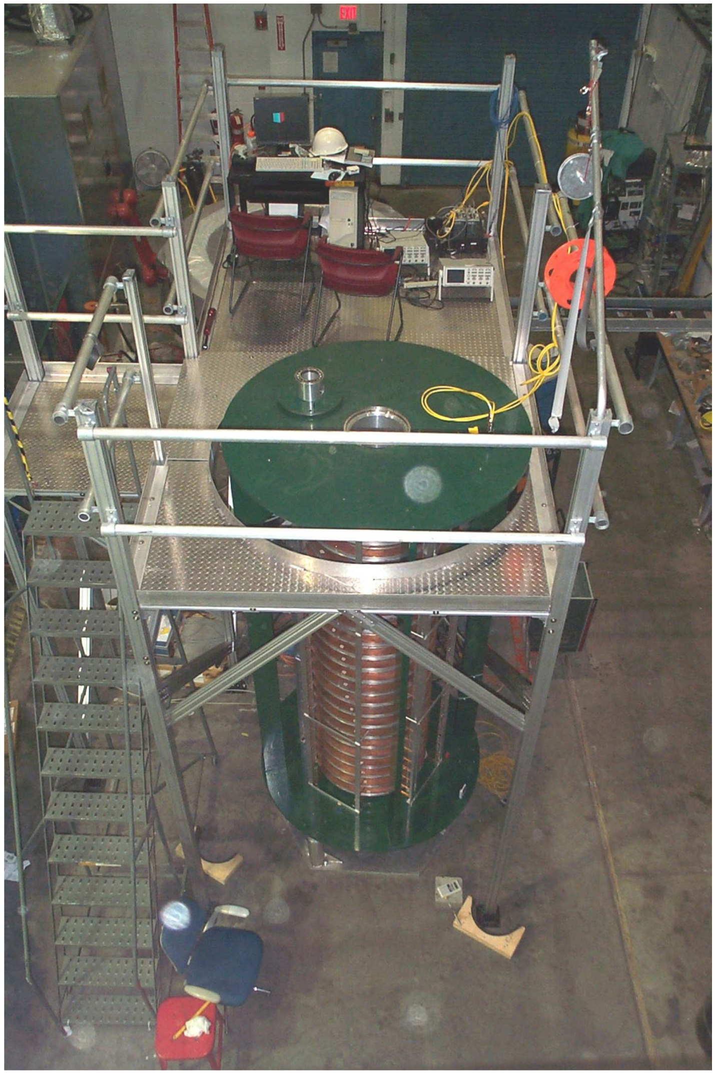
a = -0.103:

"p_υ up" more likely

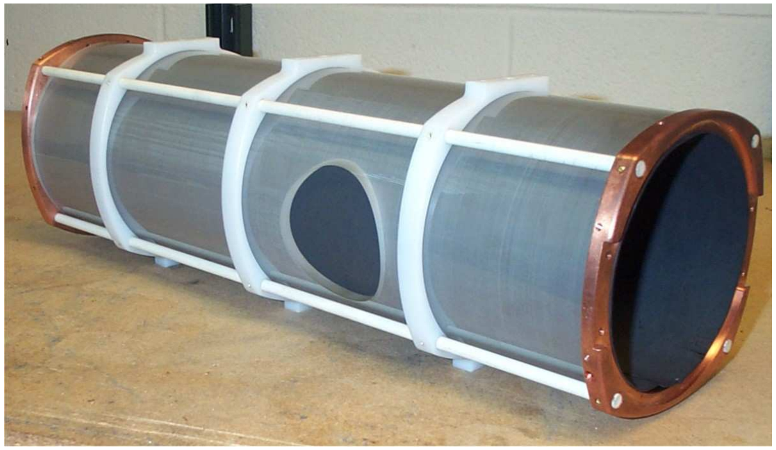
Aim: $\Delta a/a \sim 2\%$, maybe 0.5% after NIST upgrade

Tulane (F. Wietfeldt), Indiana, NIST, et al.

aCORN @ IUCF



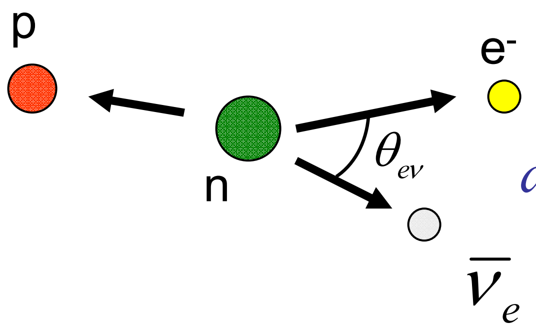
Magnet+Yoke



Decay volume electrode

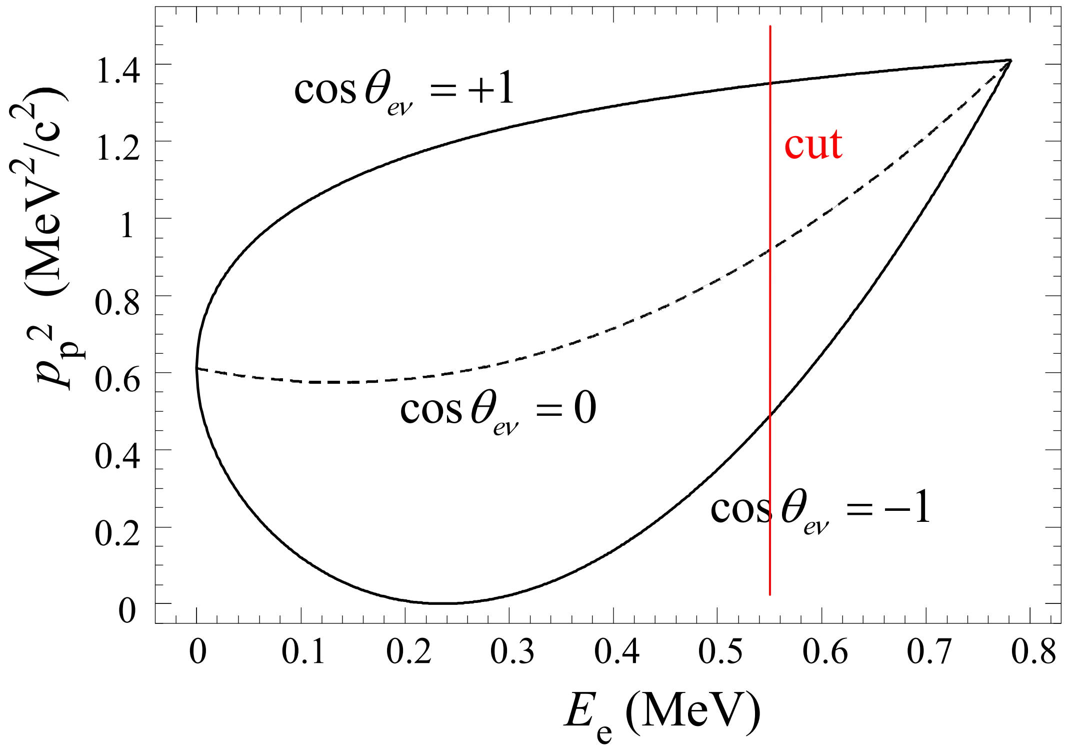
Collimator

The $\cos\theta_{e\nu}$ spectrometer Nab @ SNS



$$dw \propto \left(1 + a\frac{v}{c}\cos\theta_{e\nu}\right)$$

electron and proton phase space



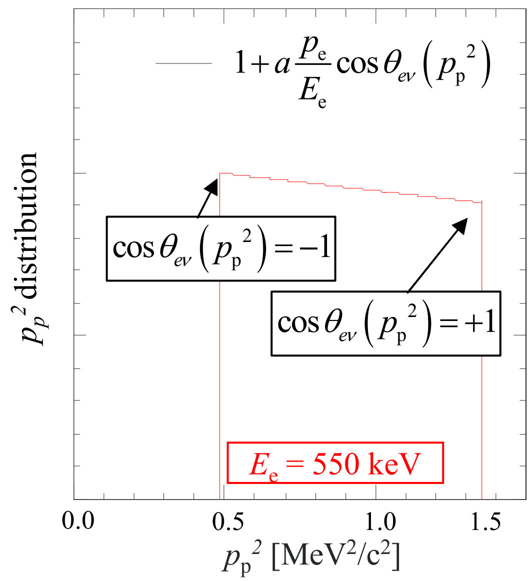
Kinematics:

- Energy Conservation

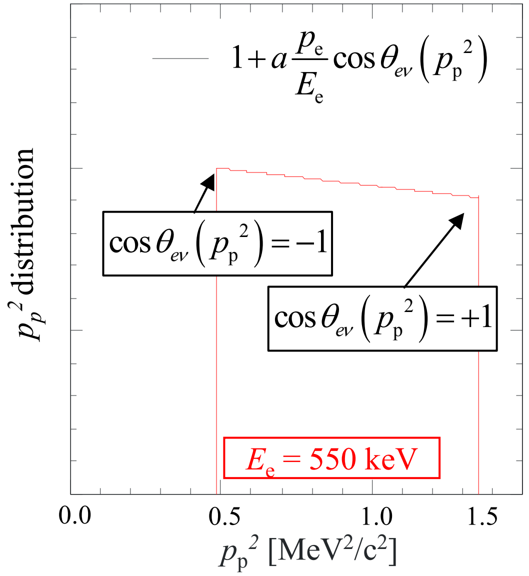
$$E_\nu = E_{e,\max} - E_e$$

- Momentum Conservation

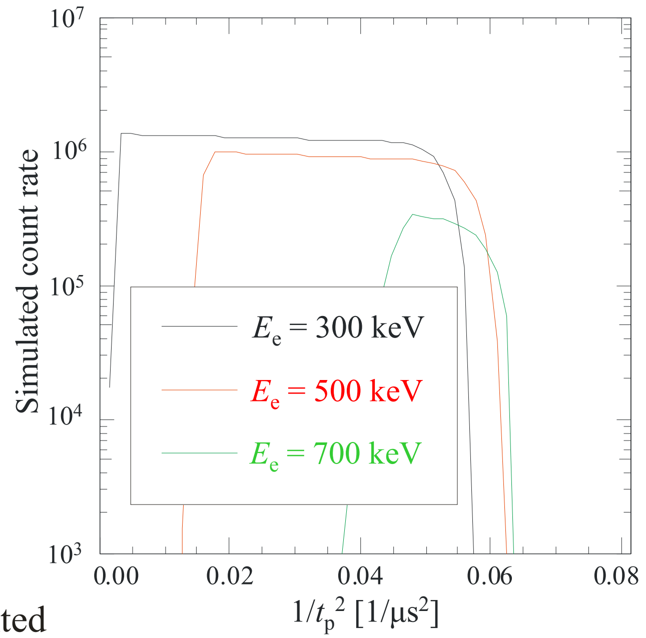
$$p_p^{\,2} = p_e^{\,2} + p_\nu^{\,2} + 2 p_e p_\nu \cos\theta_{e\nu}$$

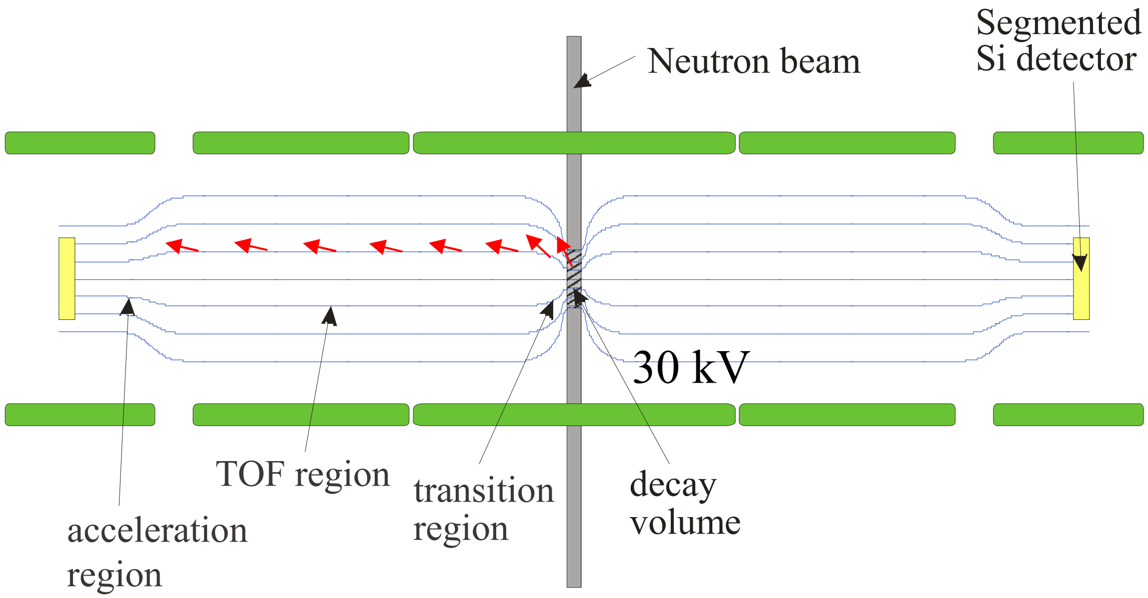


The cosθ$_{e\nu}$ spectrometer Nab @ SNS



$$t_p = \frac{m_p}{p_p}\int\frac{dz}{\cos\theta_p(z)}$$



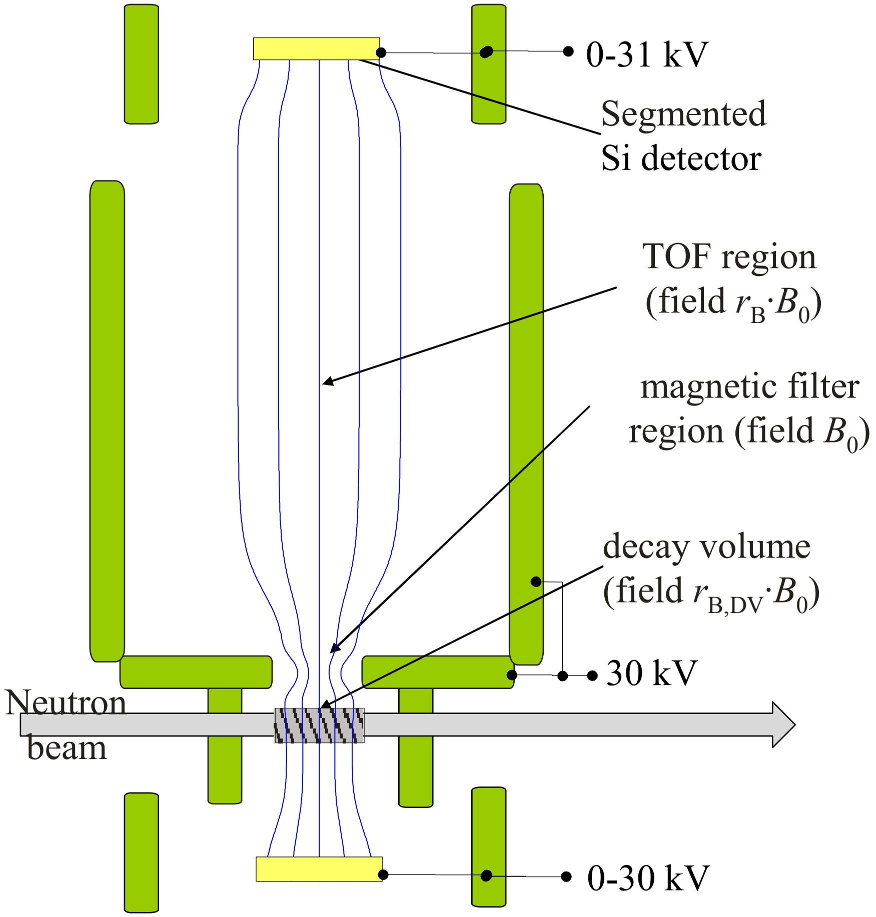


- Spectrometer and detector shared with abBA
- Background suppression through coincidences
- Aim: $a \sim 0.1\%$

D. Pocanic, S.B. (Virginia),

D. Bowman (ORNL), et al.

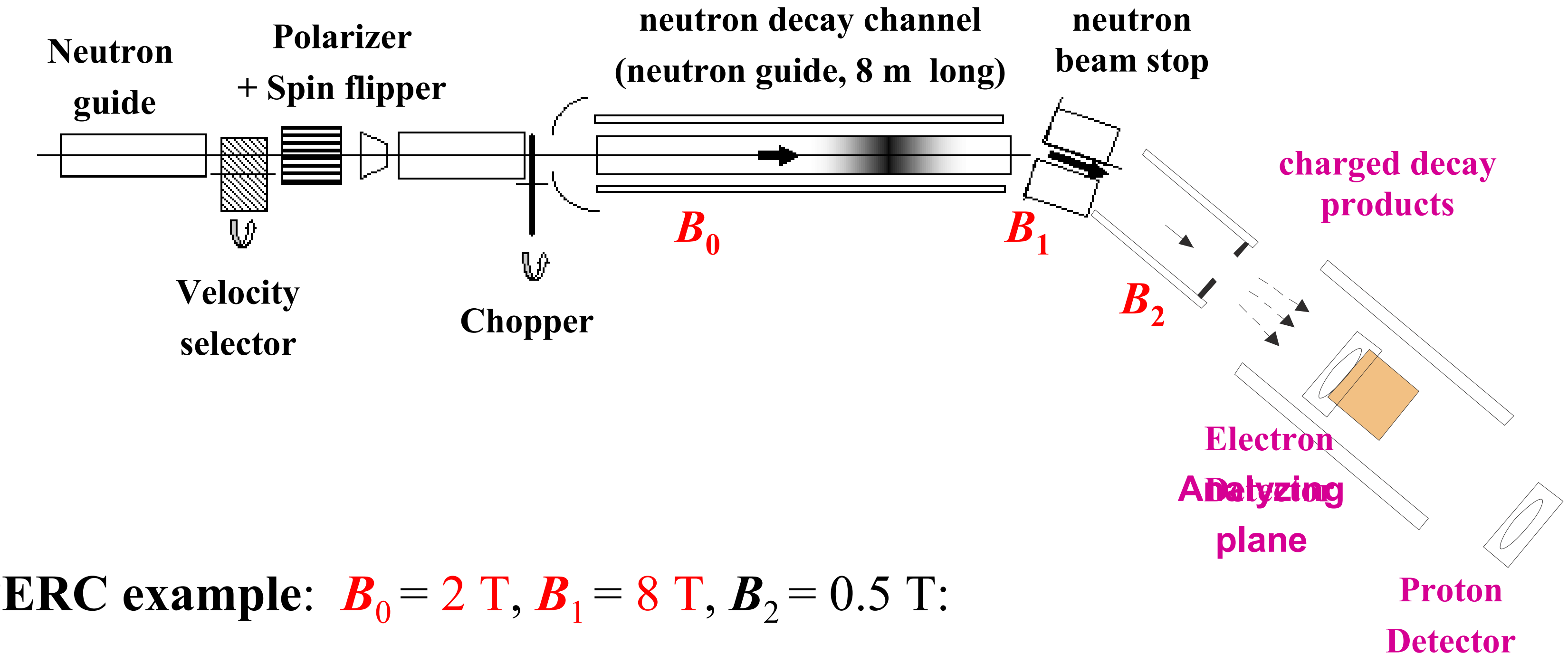
The asymmetric version of Nab @ SNS



Advantages of asymmetric configuration:

- Reduced sensitivity to electrostatic potential inhomogeneities
- Statistical: Bigger decay volume vs. Angular acceptance
- Detection function: Improved flight path length
- Avoidance of deep Penning trap
- Polarized experiment (abBA, PANDA) still possible

Future in Europe (@ILL or FRM-2): PERC



PERC example: $B_0 = 2$ T, $B_1 = 8$ T, $B_2 = 0.5$ T:

count rates:		beam time:
70000 s^{-1},	continuous unpolarized n-beam	½ h
14000 s^{-1},	continuous beam polarized to 98%	2 h
6000 s^{-1},	pulsed unpolarized beam	10 h
370 s^{-1},	pulsed beam polarized to 99.7%	4 d

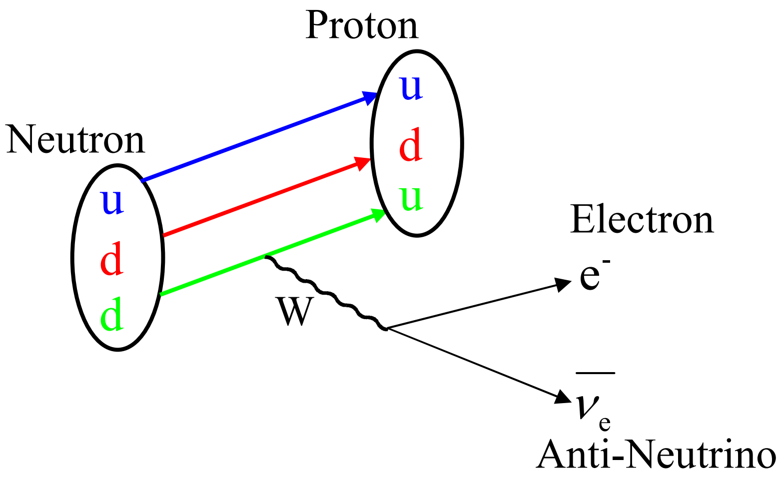
for ~10^{-4} statistical error

Dubbers et al., NIM A 596, 238 (2008)

Neutron Beta Decay Correlations:
Part 2: …beyond the Standard Model

Stefan Baeßler

UNIVERSITY of VIRGINIA



Thanks for contributions from:
H. Abele, K.Bodek, G. Konrad, B. Märkisch, P. Mumm, J. Nico, S. Paul, D. Počanić, T. Soldner, F. Wietfeldt, A. Young

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5. Bound Beta Decay

General Beta Decay Hamiltonian

$$H_{\mathrm{if}} = \frac{2G_{\mathrm{F}}V_{\mathrm{ud}}}{\sqrt{2}} \sum_{j\in\{\mathrm{V,A,S,T}\}} L_j \langle p|\Gamma_j|n\rangle \langle e^-|\Gamma_j \underbrace{\frac{1-\gamma_5}{2}|\nu_e\rangle}_{\text{Left-handed neutrino}} + R_j \langle p|\Gamma_j|n\rangle \langle e^-|\Gamma_j \underbrace{\frac{1+\gamma_5}{2}|\nu_e\rangle}_{\text{Right-handed neutrino}}$$

with operators: $\Gamma_{\mathrm{V}} = \gamma_\mu \;;\; \Gamma_{\mathrm{A}} = i\gamma_\mu\gamma_5 \;;\; \Gamma_{\mathrm{S}} = 1 \;;\; \Gamma_{\mathrm{T}} = \dfrac{i\left[\gamma_\mu,\gamma_\nu\right]}{2\sqrt{2}}$

Standard Model: $L_{\mathrm{V}} = 1 \;;\; L_{\mathrm{A}} = \lambda \;;\; L_{\mathrm{S}} = L_{\mathrm{T}} = R_V = R_{\mathrm{A}} = R_{\mathrm{S}} = R_{\mathrm{T}} = 0$

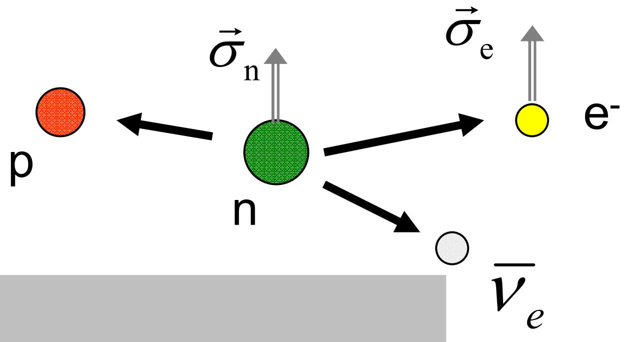
Neutron lifetime: $\tau_{\mathrm{n}} \propto \Big(\underbrace{|L_{\mathrm{V}}|^2 + 3|L_{\mathrm{A}}|^2}_{\text{Standard Model: } 1+3\lambda^2} + \underbrace{|L_{\mathrm{S}}|^2 + 3|L_{\mathrm{T}}|^2 + |R_{\mathrm{V}}|^2 + 3|R_{\mathrm{A}}|^2 + |R_{\mathrm{S}}|^2 + 3|R_{\mathrm{T}}|^2}_{\text{Standard Model: } 0} \Big)$

Beta Asymmetry: $A = \dfrac{2\,\mathrm{Re}\left(-|L_{\mathrm{A}}|^2 - L_{\mathrm{V}}L_{\mathrm{A}}^{\;*} + |L_{\mathrm{T}}|^2 + L_{\mathrm{S}}L_{\mathrm{T}}^{\;*} + |R_{\mathrm{A}}|^2 + R_{\mathrm{V}}R_{\mathrm{A}}^{\;*} - |R_{\mathrm{T}}|^2 - R_{\mathrm{S}}R_{\mathrm{T}}^{\;*}\right)}{|L_{\mathrm{V}}|^2 + 3|L_{\mathrm{A}}|^2 + |L_{\mathrm{S}}|^2 + 3|L_{\mathrm{T}}|^2 + |R_{\mathrm{V}}|^2 + 3|R_{\mathrm{A}}|^2 + |R_{\mathrm{S}}|^2 + 3|R_{\mathrm{T}}|^2}$

Neutrino Electron Correlation: $a = \dfrac{|L_{\mathrm{V}}|^2 - |L_{\mathrm{A}}|^2 - |L_{\mathrm{S}}|^2 + |L_{\mathrm{T}}|^2 + |R_{\mathrm{V}}|^2 - |R_{\mathrm{A}}|^2 - |R_{\mathrm{S}}|^2 + |R_{\mathrm{T}}|^2}{|L_{\mathrm{V}}|^2 + 3|L_{\mathrm{A}}|^2 + |L_{\mathrm{S}}|^2 + 3|L_{\mathrm{T}}|^2 + |R_{\mathrm{V}}|^2 + 3|R_{\mathrm{A}}|^2 + |R_{\mathrm{S}}|^2 + 3|R_{\mathrm{T}}|^2}$

Glück et al., NPA 593, 125 (1995), Jackson, PR 106, 517 (1957)

More observables: Fierz Interference Term



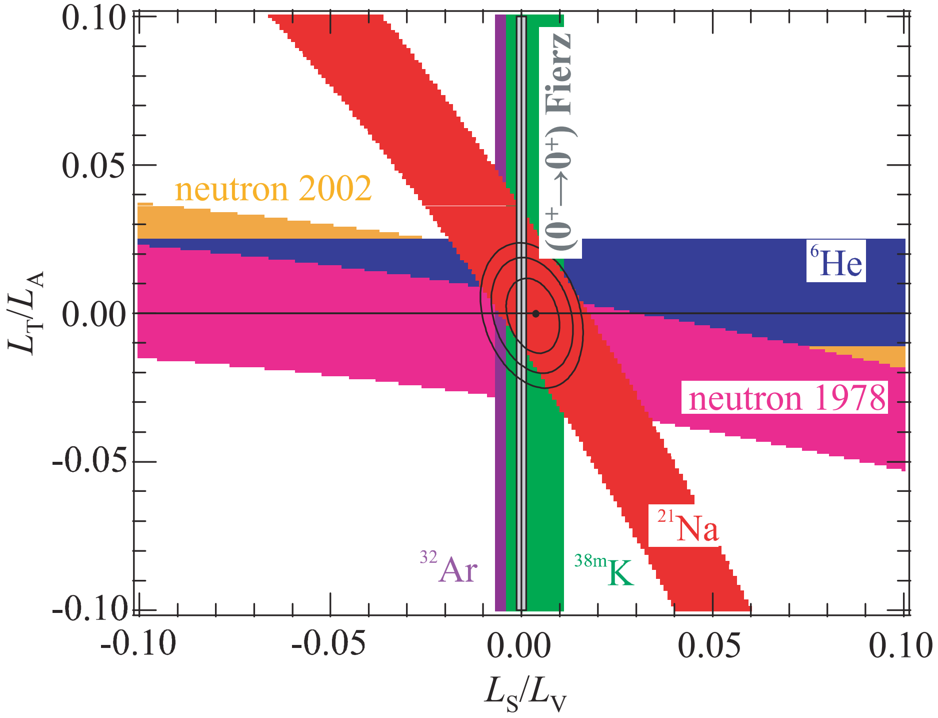
Jackson et al., PR 106, 517 (1957):

$$dW \propto \rho\left(E_\text{e}\right)\cdot\left\{1 + a\frac{\vec{p}_\text{e}\cdot\vec{p}_\nu}{E_\text{e}E_\nu} + b\frac{m_\text{e}}{E_\text{e}} + \vec{\sigma}_\text{n}\cdot\left(A\frac{\vec{p}_\text{e}}{E_\text{e}} + B\frac{\vec{p}_\nu}{E_\nu} + N\vec{\sigma}_\text{e} + D\frac{\vec{p}_\text{e}\times\vec{p}_\nu}{E_\text{e}E_\nu} + \ldots + R\frac{\vec{p}_\text{e}\times\vec{\sigma}_\text{e}}{E_\text{e}}\right)\right\}$$

Fierz-Interference Term: $b = \dfrac{2\,\mathrm{Re}\left(L_\text{S}L_\text{V}^{*} + 3L_\text{A}L_\text{T}^{*} + R_\text{S}R_\text{V}^{*} + 3R_\text{A}R_\text{T}^{*}\right)}{\left|L_\text{V}\right|^2 + 3\left|L_\text{A}\right|^2 + \left|L_\text{S}\right|^2 + 3\left|L_\text{T}\right|^2 + \left|R_\text{V}\right|^2 + 3\left|R_\text{A}\right|^2 + \left|R_\text{S}\right|^2 + 3\left|R_\text{T}\right|^2}$

- Signal expected for left-handed scalar and tensor interaction (neutrino is left-handed, electron is right-handed). Could be caused by leptoquarks or charged Higgs bosons.
- Signal expected for MSSM: $b \sim 10^{-3}$ (Ramsey-Musolf, 2007)
- Not measured (directly) in neutron beta decay (detector, background), Nab might be able to.
- Tight bound for scalar part from superallowed decays

Search for left-handed scalar and tensor currents



(Time reversal invariance assumed)

Based on P.A. Vetter et al.,
PRC **77,** 035502 (2008)

- Most stringent limit comes from superallowed nuclear decays (missing energy dependence of partial lifetime due to Fierz Term:

$$dW \propto \rho(E_e)\cdot\left(1+b\frac{m_e}{E_e}\right)$$

- Approximation: Extracted correlation coefficients (a, A, …), where the analysis assumes $b = 0$, are in general

$$\frac{a}{1+b\left\langle\frac{m_e}{E_e}\right\rangle},\frac{A}{1+b\left\langle\frac{m_e}{E_e}\right\rangle},\ldots$$

- Better if experimentalists would discuss the non-V-A case (correct electron energy dependence, possible influence of b on systematics).

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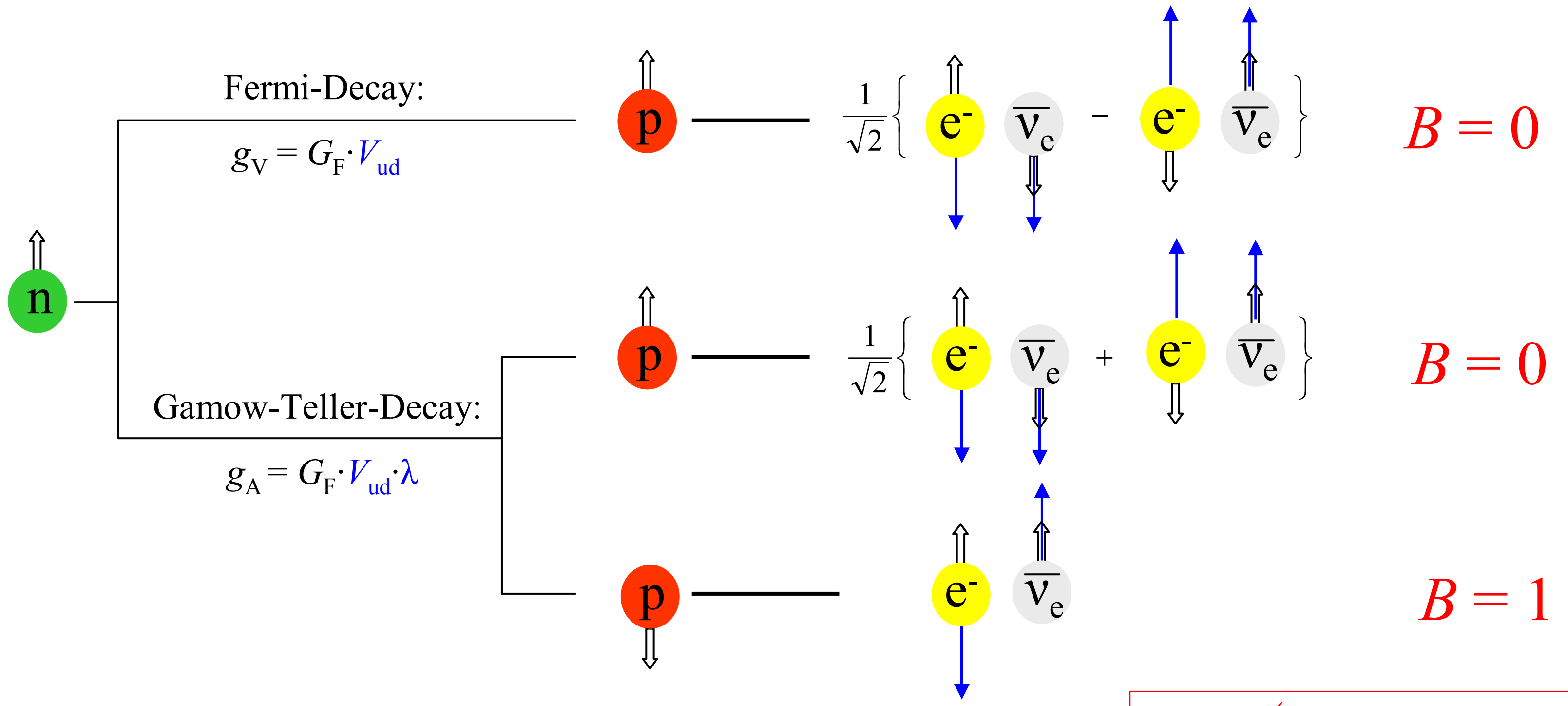
The neutrino asymmetry *B*



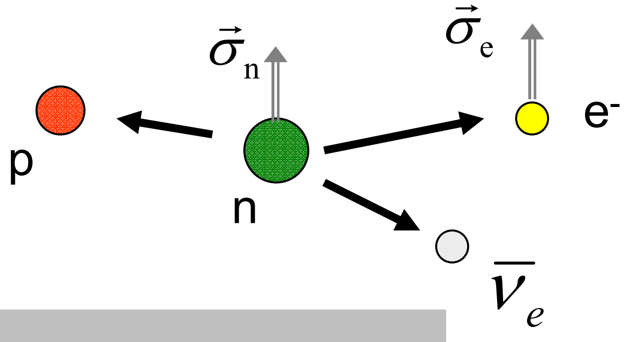
$$\boxed{dw \propto \left(1 + B\cos\left(p_\nu, \sigma_\text{n}\right)\right)}$$

g_A and g_V can be determined with *B* and τ_n (as before) but one is not very sensitive

Neutrino Asymmetry: $$B = 2\frac{\lambda^2 - \lambda}{1 + 3\lambda^2} \approx 0.98 \qquad \lambda = \frac{g_A}{g_V}$$

This can be turned around to look for deviations from the Standard Model (e.g., right-handed W bosons)

More observables: Neutrino Asymmetry



Jackson et al., PR 106, 517 (1957):

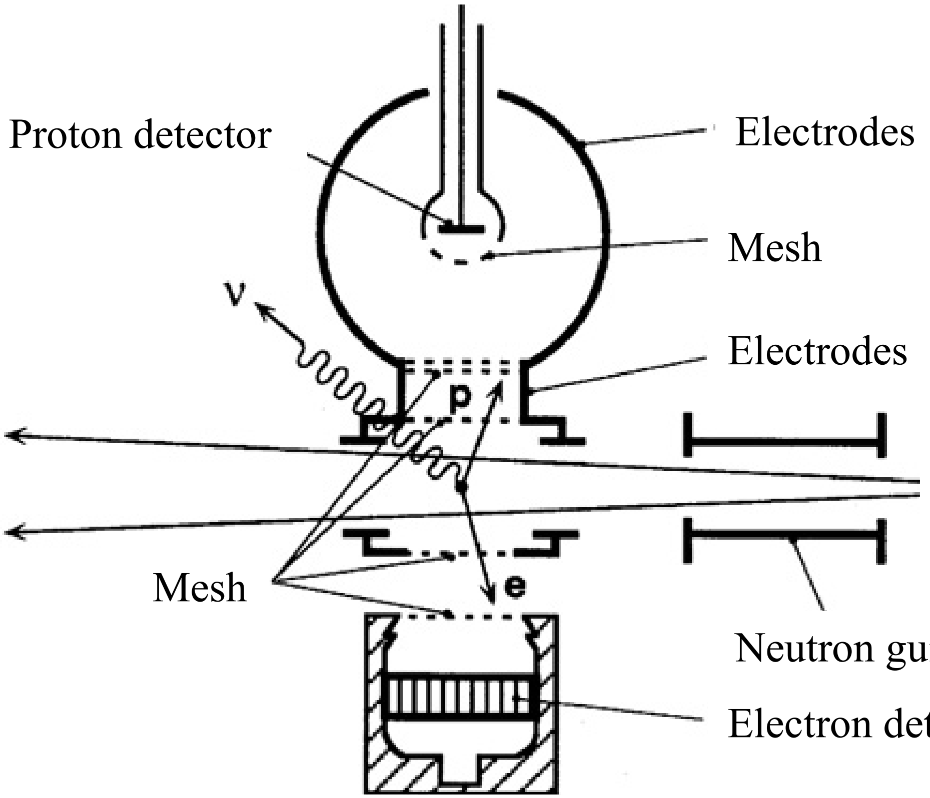
$$dW \propto \rho\left(E_e\right)\cdot\left\{1 + a\frac{\vec p_e\cdot\vec p_\nu}{E_eE_\nu} + b\frac{m_e}{E_e} + \vec\sigma_n\cdot\left(A\frac{\vec p_e}{E_e} + B\frac{\vec p_\nu}{E_\nu} + N\vec\sigma_e + D\frac{\vec p_e\times\vec p_\nu}{E_eE_\nu} + \ldots + R\frac{\vec p_e\times\vec\sigma_e}{E_e}\right)\right\}$$

Neutrino-Asymmetry

$$B = \frac{2\,\mathrm{Re}\left(\left|L_A\right|^2 - L_VL_A^{\,*} + \left|L_T\right|^2 - L_SL_T^{\,*} - \left|R_A\right|^2 + R_VR_A^{\,*} - \left|R_T\right|^2 + R_SR_T^{\,*}\right)}{\left|L_V\right|^2 + 3\left|L_A\right|^2 + \left|L_S\right|^2 + 3\left|L_T\right|^2 + \left|R_V\right|^2 + 3\left|R_A\right|^2 + \left|R_S\right|^2 + 3\left|R_T\right|^2} + \frac{2\,\mathrm{Re}\left(-L_SL_A^{\,*} - L_VL_T^{\,*} + 2L_AL_T^{\,*} + R_SR_A^{\,*} + R_VR_T^{\,*} - 2R_AR_T^{\,*}\right)}{\left|L_V\right|^2 + 3\left|L_A\right|^2 + \left|L_S\right|^2 + 3\left|L_T\right|^2 + \left|R_V\right|^2 + 3\left|R_A\right|^2 + \left|R_S\right|^2 + 3\left|R_T\right|^2}\cdot\frac{m_e}{E_e}$$

Signal expected for MSSM at $\Delta B \sim 10^{-3}$ (Ramsey-Musolf, 2007)

The neutrino asymmetry *B* from PNPI



Proton detector

Electrodes

Mesh

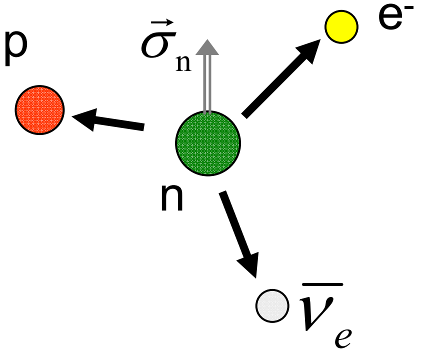
Electrodes

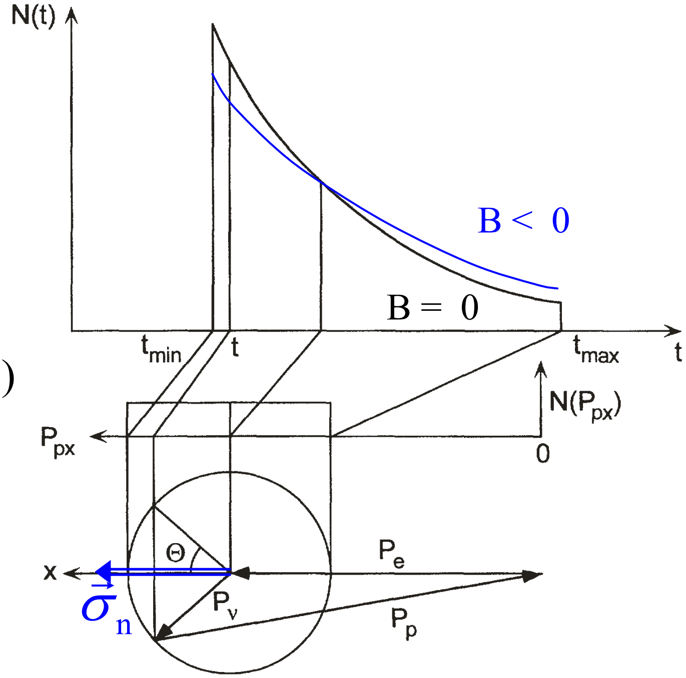
Neutrons

Mesh

Neutron guide

Electron detector (MCP)

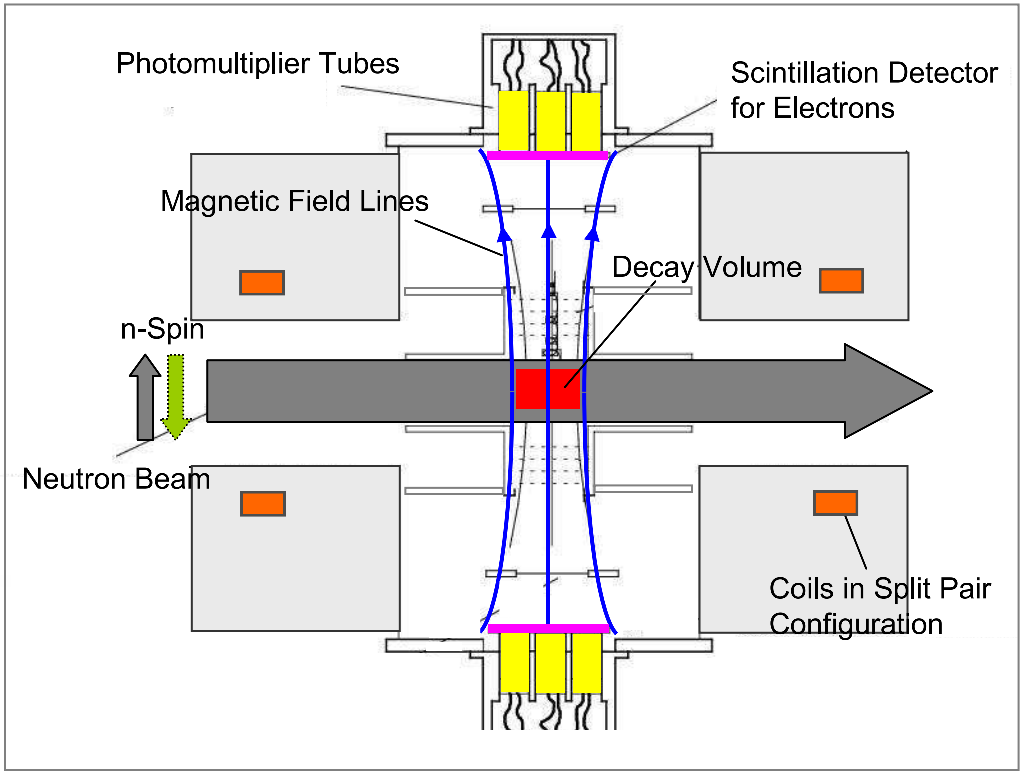


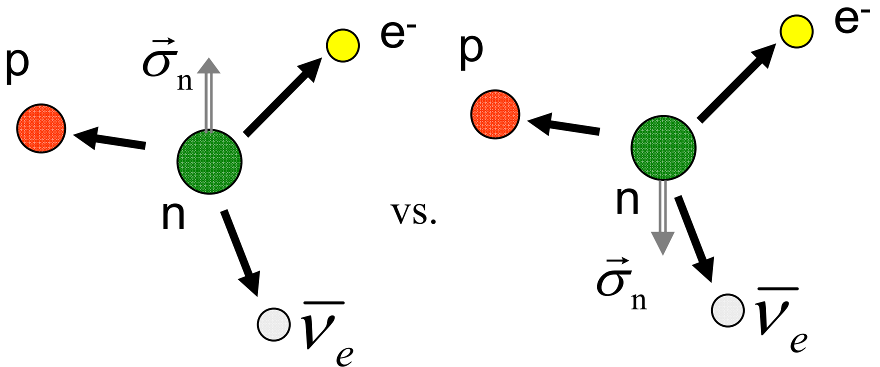


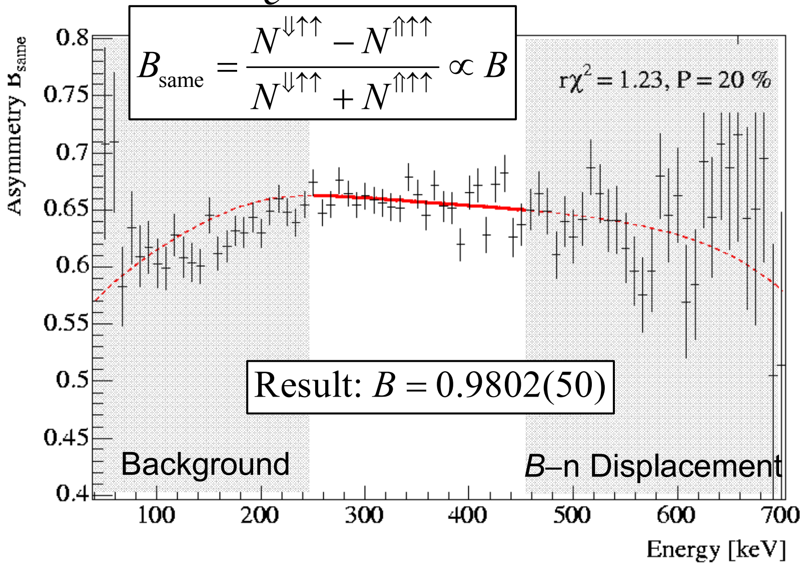
Result: $B = 0.9821(40)$

A. Serebrov et al., JETP 86, 1074 (1998)

The neutrino asymmetry *B* from PERKEO II







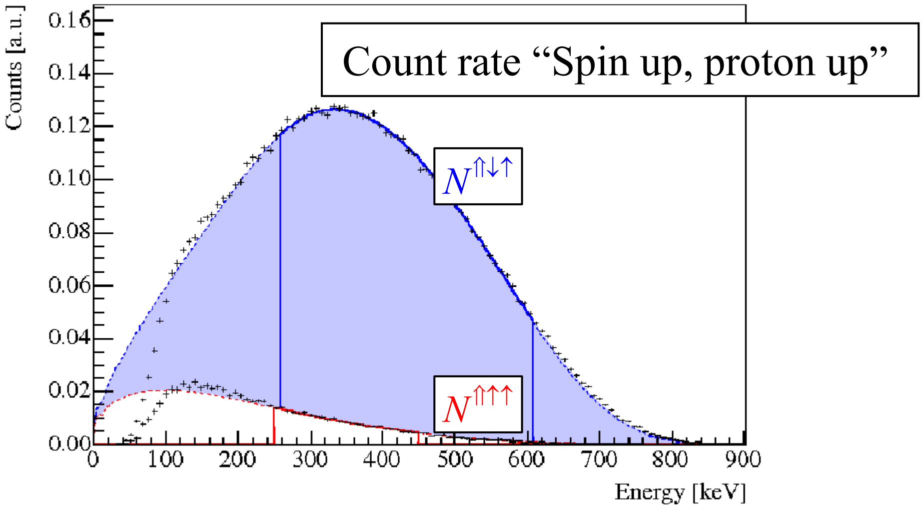
Combine both *B* values with *A* (PERKEO II) and τ_n (own average):

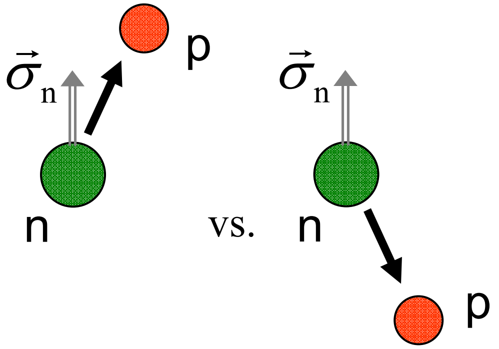
→ Limit on right-handed W boson: $m(W_R) > 296$ GeV/c^2 M. Schumann et al., PRL 99, 191803 (2007)

Compare with limits from D0 (assuming left- and right handed coupling constants are equal):

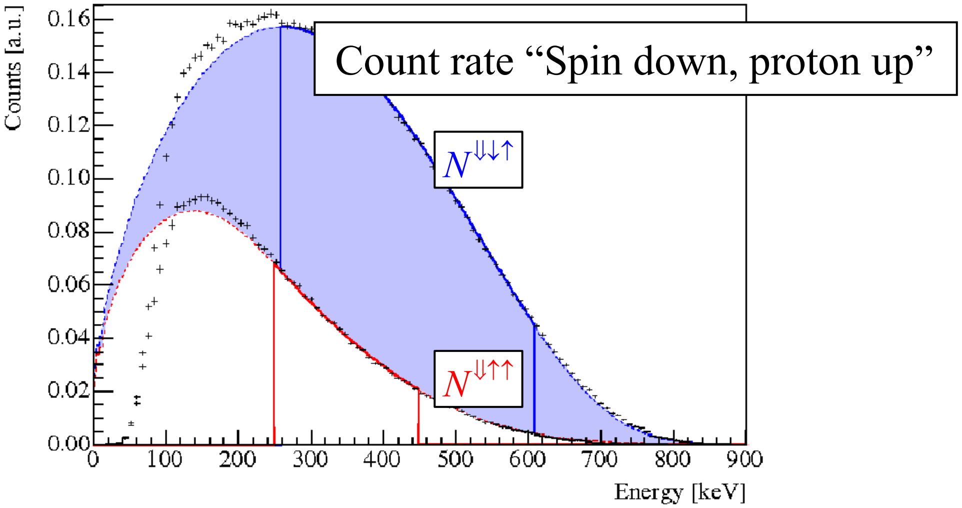
$m(W_R) > 1000$ GeV/c^2 V.M. Abazov et al., PRL 100, 031804 (2008)

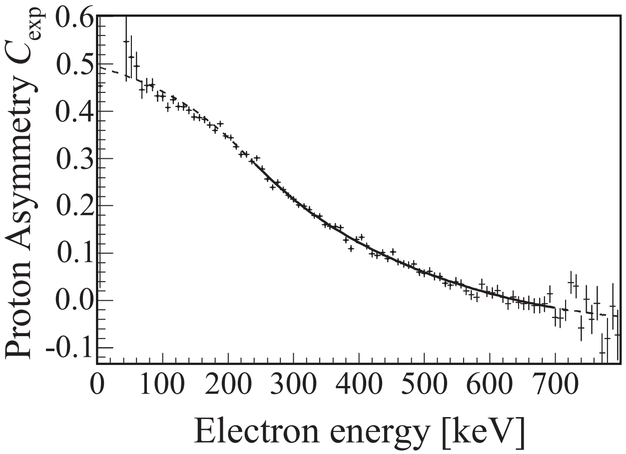
The proton asymmetry *C* from PERKEO II


Count rate “Spin up, proton up”



$$C_{\exp} = \frac{\left(N^{\Uparrow\uparrow\uparrow} + N^{\Uparrow\downarrow\uparrow}\right) - \left(N^{\Downarrow\uparrow\uparrow} + N^{\Downarrow\downarrow\uparrow}\right)}{\left(N^{\Uparrow\uparrow\uparrow} + N^{\Uparrow\downarrow\uparrow}\right) + \left(N^{\Downarrow\uparrow\uparrow} + N^{\Downarrow\downarrow\uparrow}\right)}$$

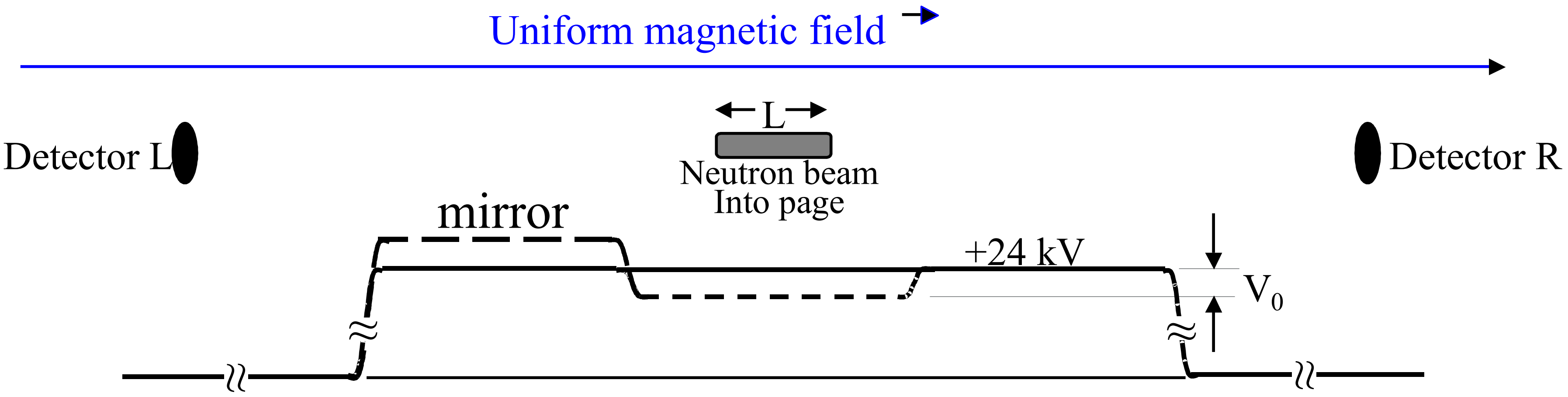

Count rate “Spin down, proton up”

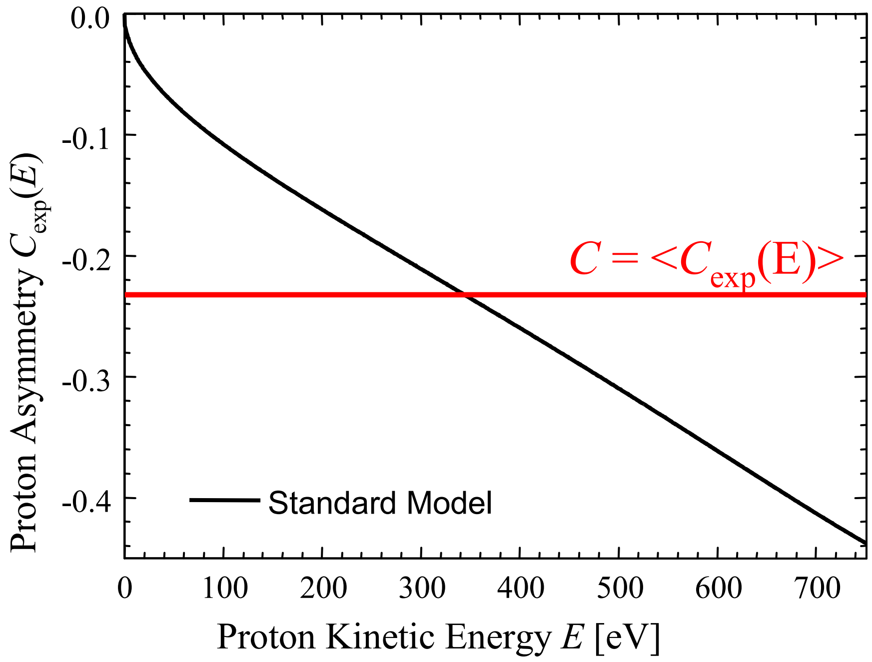


- Result: $C = \int C_{\exp} dE_e = -0.2377(26)$ M. Schumann et al., PRL 100, 151801 (2008); in SM: $C = -0.27484\left(A + B\right)$

(PERKEO-II measurement of *B* not independent of PERKEO-II measurement of *C*)

The proton asymmetry *C* from PANDA





A similar measurement is planned with aSPECT

T. Chupp (Michigan), S.B., et al.

Outline

Part 1: Contributions to the Standard Model

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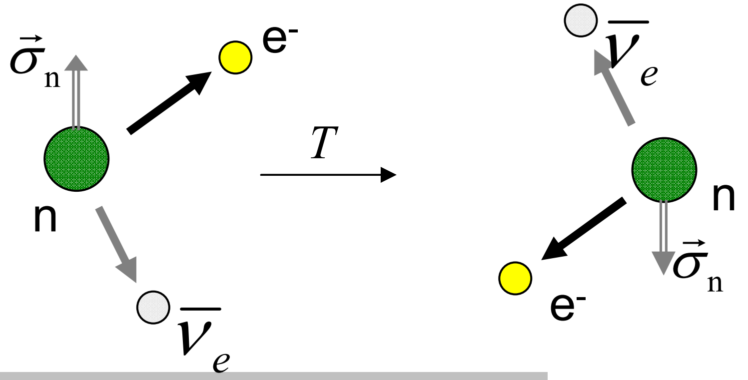
More observables: Triple correlation



Jackson et al., PR 106, 517 (1957):

$$dW \propto \rho(E_\mathrm{e})\cdot\left\{1 + a\frac{\vec{p}_\mathrm{e}\cdot\vec{p}_\nu}{E_\mathrm{e}E_\nu} + b\frac{m_\mathrm{e}}{E_\mathrm{e}} + \vec{\sigma}_\mathrm{n}\cdot\left(A\frac{\vec{p}_\mathrm{e}}{E_\mathrm{e}} + B\frac{\vec{p}_\nu}{E_\nu} + N\vec{\sigma}_\mathrm{e} + D\frac{\vec{p}_\mathrm{e}\times\vec{p}_\nu}{E_\mathrm{e}E_\nu} + \ldots + R\frac{\vec{p}_\mathrm{e}\times\vec{\sigma}_\mathrm{e}}{E_\mathrm{e}}\right)\right\}$$

Triple correlation $D = 2\frac{\mathrm{Im}\,\lambda}{1+3|\lambda|^2}$

- A non-zero *D* coefficient violates Time reversal symmetry.

  → complex contribution in Hamiltonian. In SM only in high order

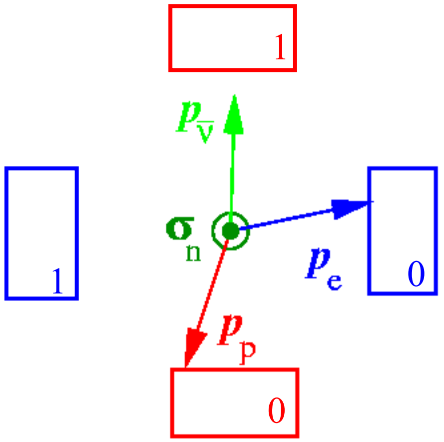
- Final state effects give $D \sim 10^{-5}$

- Serves to restrict leptoquark extensions to the Standard Model

Measurement of the *D* coefficient with TRINE-β

$$D\vec{\sigma}_{\mathrm{n}} \frac{\vec{p}_{\mathrm{e}} \times \vec{p}_{\nu}}{E_{\mathrm{e}} E_{\nu}} = D\vec{\sigma}_{\mathrm{n}} \frac{\vec{p}_{\mathrm{e}} \times \left(-\vec{p}_{\mathrm{e}} - \vec{p}_{\mathrm{p}}\right)}{E_{\mathrm{e}} E_{\nu}} = -D\vec{\sigma}_{\mathrm{n}} \frac{\vec{p}_{\mathrm{e}} \times \vec{p}_{\mathrm{p}}}{E_{\mathrm{e}} E_{\nu}}$$

Principle Setup



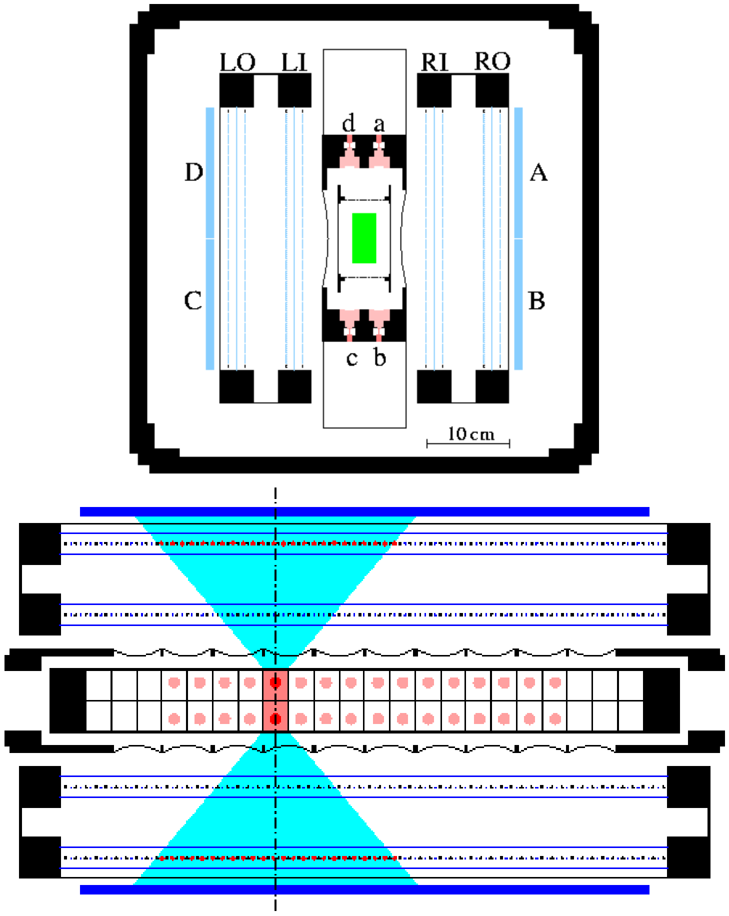
$$\alpha^{00} = \frac{N^{\uparrow}_{\mathrm{e0,p0}} - N^{\downarrow}_{\mathrm{e0,p0}}}{N^{\uparrow}_{\mathrm{e0,p0}} + N^{\downarrow}_{\mathrm{e0,p0}}} = D\mathbf{P}\boldsymbol{\kappa}_D$$

But: Imperfect alignment gives too high sensitivity to *A* and *B*.

Better use the following combination:

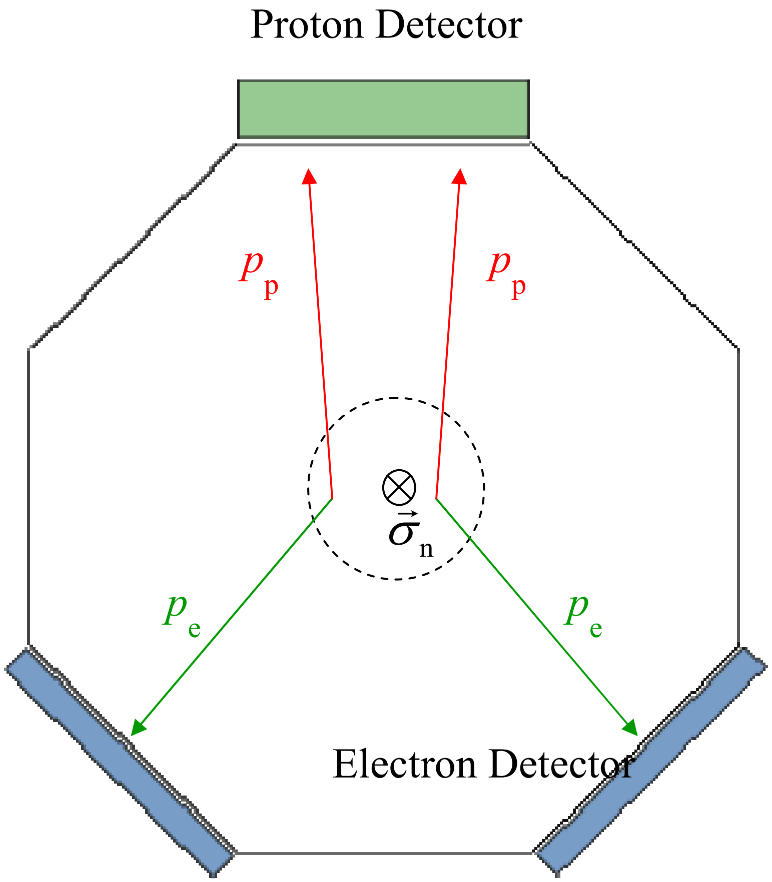
$$D = \frac{\alpha^{00} - \alpha^{01} - \alpha^{10} + \alpha^{11}}{4P\kappa_D^{00}}$$

Real Setup

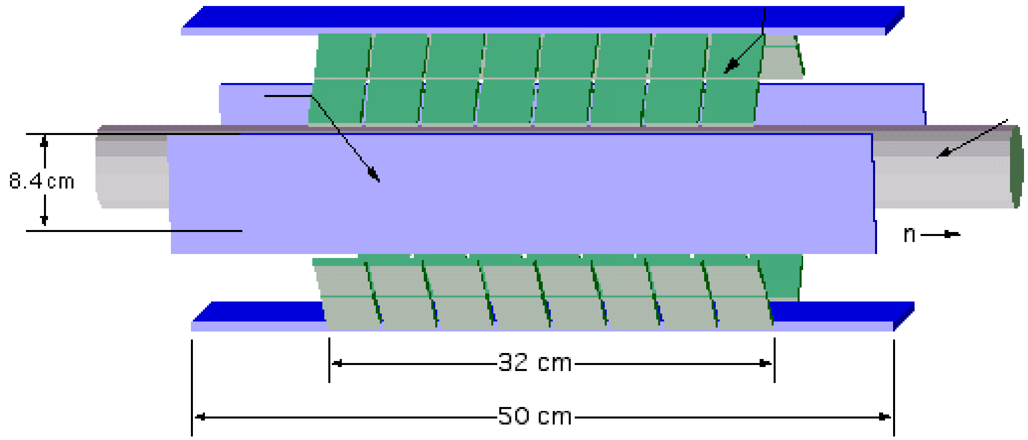


Result: $D = (-2.8 \pm 7.1) \times 10^{-4}$ T. Soldner et al., PLB 581, 49 (2004)

Measurement of the *D* coefficient with EMIT



Extract *D* from asymmetry with left detector minus right detector to suppress unwanted dependencies on other correlations.

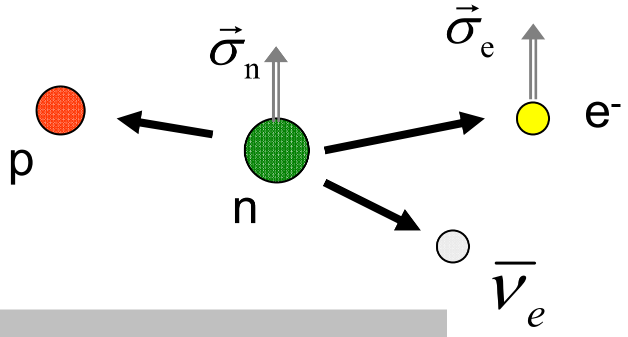


- Statistically favorable geometry
- Detection of protons with surface barrier detectors at -28 kV (Earlier: PIN diodes), electrons with scintillators
- First results published $D = (-6 \pm 13) \times 10^{-4}$ (EMIT I)

L. Lising et al., PRC 62, 055501 (2000)

- Difficult systematics if beam polarization is not homogeneous
- EMIT-2 is still being analyzed, result for *D* at several times 10^{-4} expected

More Pseudo T violation: R/N correlation



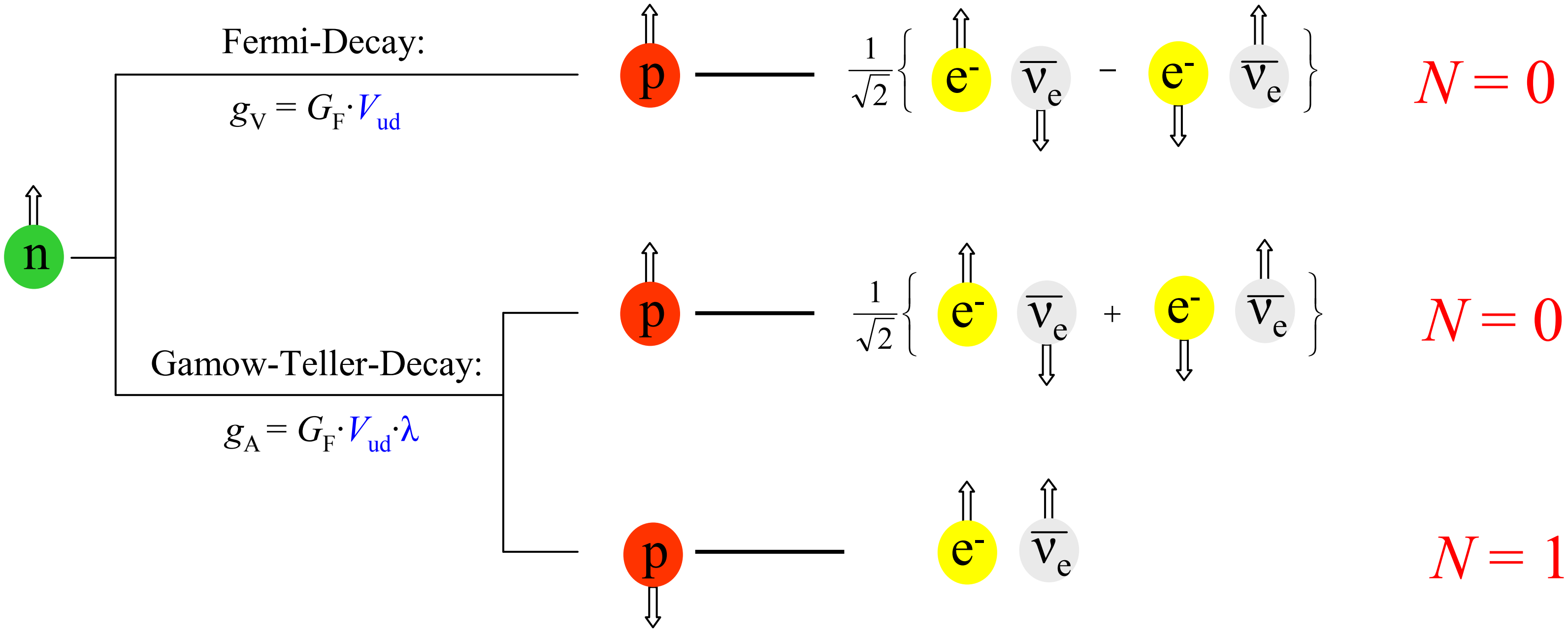
Jackson et al., PR 106, 517 (1957):

$$dW \propto \rho\left(E_\mathrm{e}\right)\cdot\left\{1 + a\frac{\vec{p}_\mathrm{e}\cdot\vec{p}_\nu}{E_\mathrm{e}E_\nu} + b\frac{m_\mathrm{e}}{E_\mathrm{e}} + \vec{\sigma}_\mathrm{n}\cdot\left(A\frac{\vec{p}_\mathrm{e}}{E_\mathrm{e}} + B\frac{\vec{p}_\nu}{E_\nu} + N\vec{\sigma}_\mathrm{e} + D\frac{\vec{p}_\mathrm{e}\times\vec{p}_\nu}{E_\mathrm{e}E_\nu} + \ldots + R\frac{\vec{p}_\mathrm{e}\times\vec{\sigma}_\mathrm{e}}{E_\mathrm{e}}\right)\right\}$$

Electron polarization $N = \sqrt{1-\left(\frac{v}{c}\right)^2}\,A$

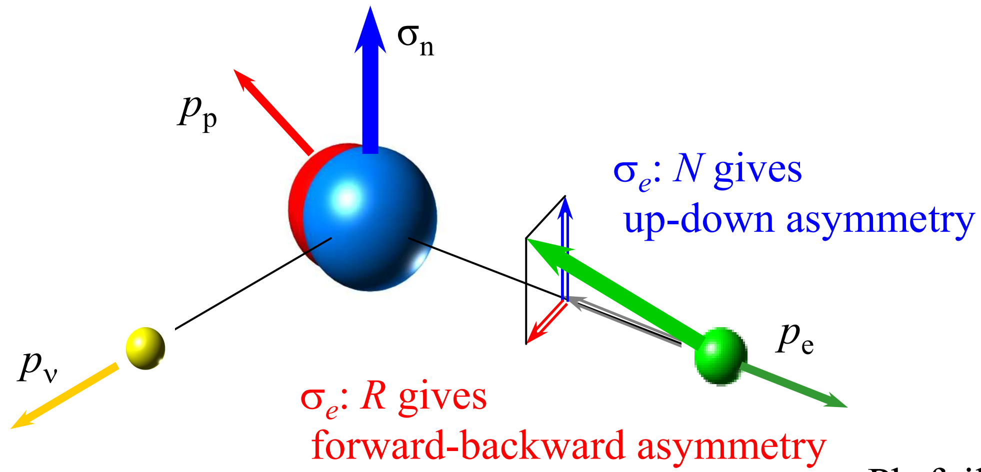
- Standard-Model: $N_\mathrm{SM} = 0.07$; $R_\mathrm{SM} = 0.0066 \sim 0$
- Scalar or Tensor Interactions lead to deviations (Leptoquarks, charged Higgs, Sleptons in SUSY)
- Of special interest: R, as it is Time-Reversal violating, measures imaginary part of coupling constants

The Standard Model Parameters V_{ud} and λ

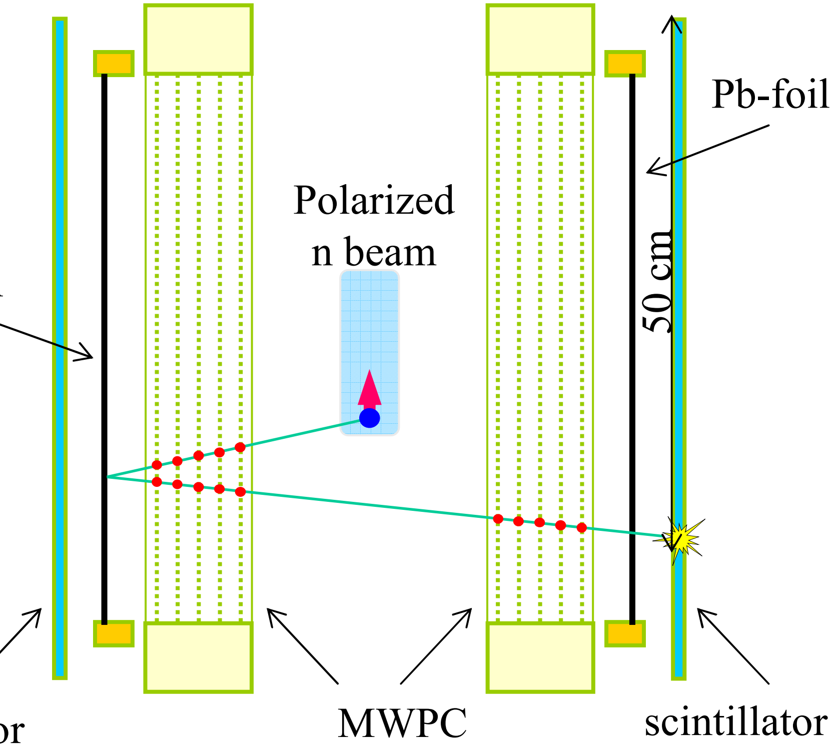


$$\boxed{dw \propto \left(1 + N \cos\left(\sigma_e, \sigma_{\mathrm{n}}\right)\right)}$$

R/N correlation



Detection of electron polarization through Mott scattering in Pb foil: The probability of having a V track is electron spin dependent.



Result:

$$N_{\mathrm{exp}} = 0.056(11)(5)$$

$$\left(N_{\mathrm{SM}} = 0.066\right)$$

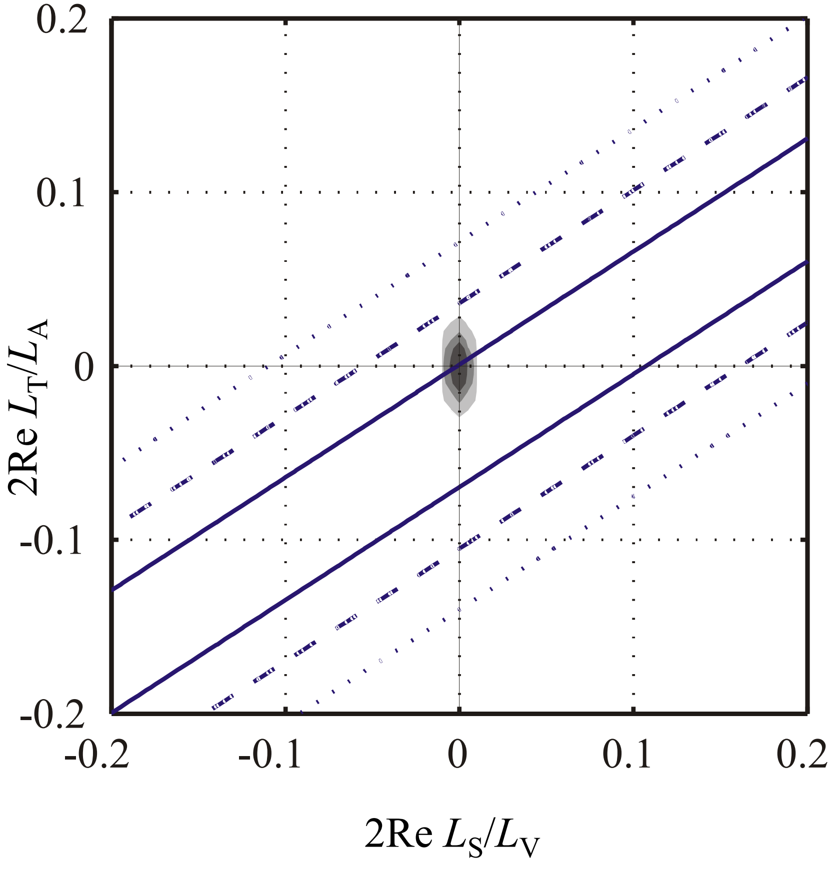
$$R_{\mathrm{exp}} = 0.008(15)(5)$$

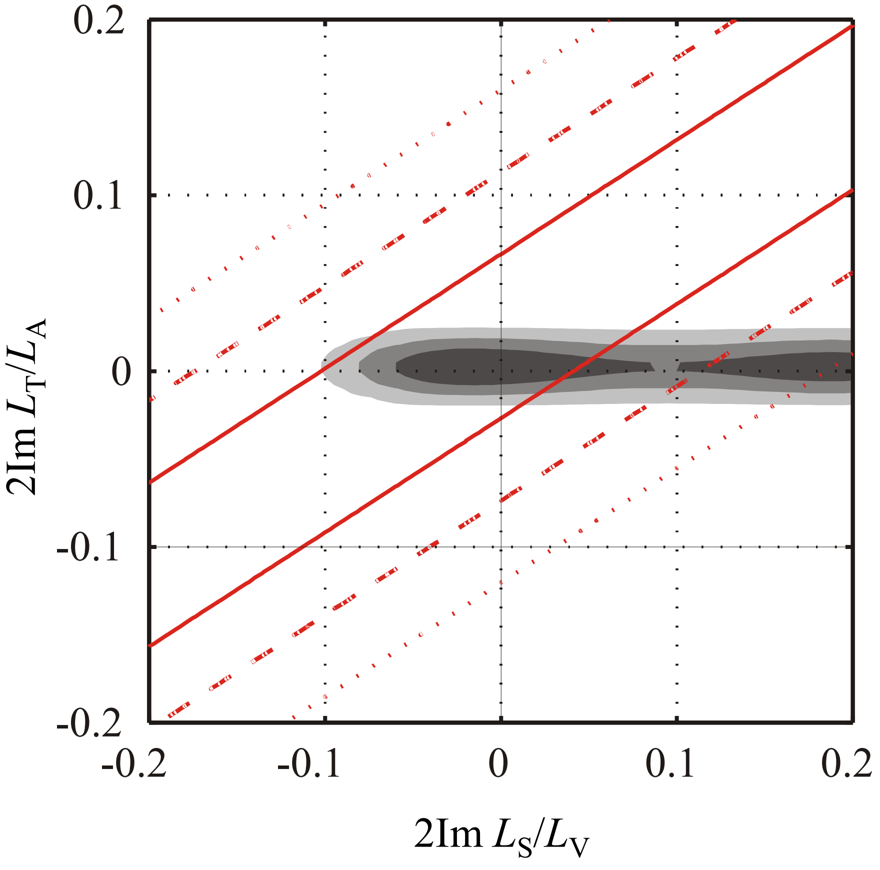
$$\left(R_{\mathrm{SM}(FSI)} = 0.00066\right)$$

K. Bodek (Cracow), Villigen, CAEN, Leuven, Kattowice,

Bodek et al., Phys. Rev. Lett. 102, 172301 (2009)

R/N correlation and implications on S/T couplings





Grey: Other limits from neutrons and nucleons

N. Severijns et al., RMP 78, 991 (2006)

Based on Bodek et al., Phys. Rev. Lett. 102, 172301 (2009)

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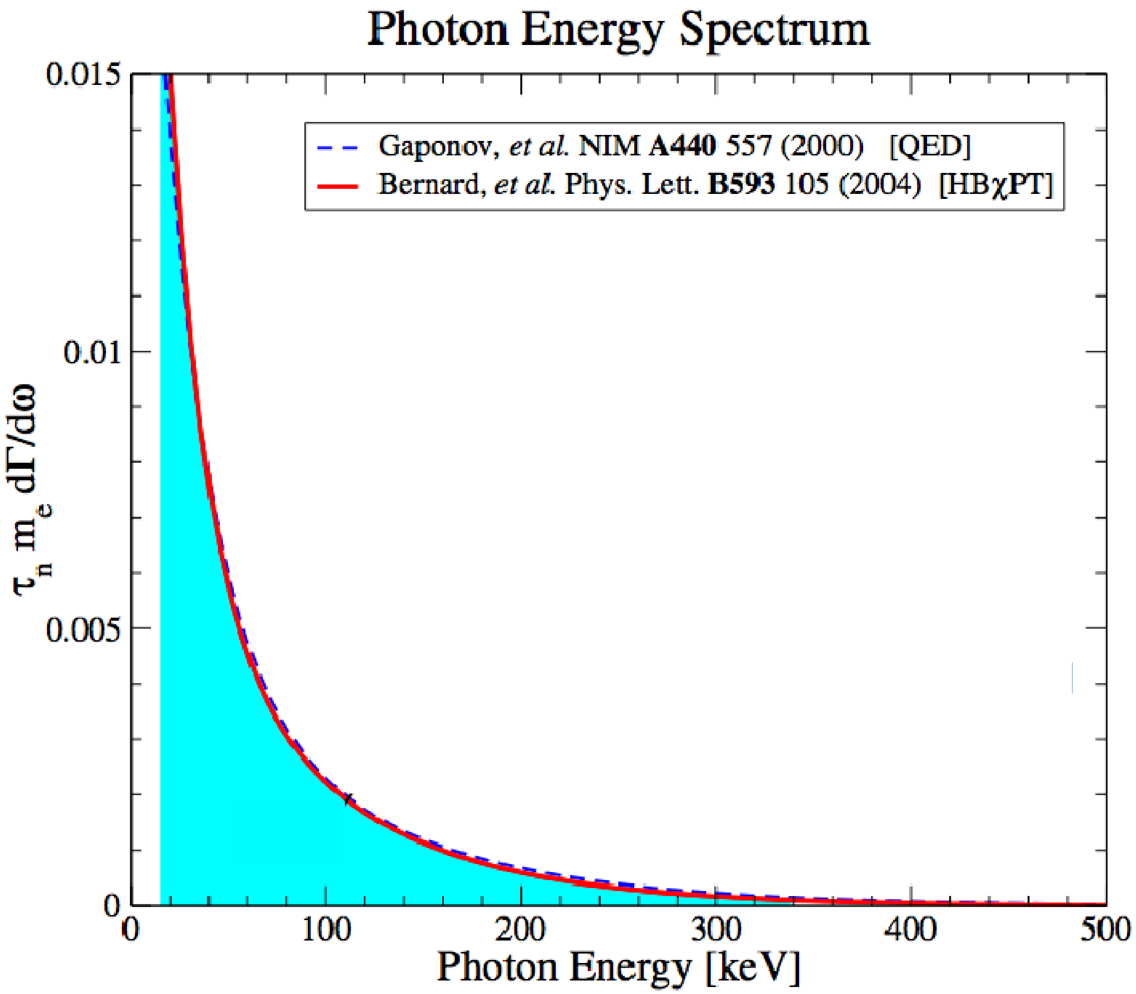
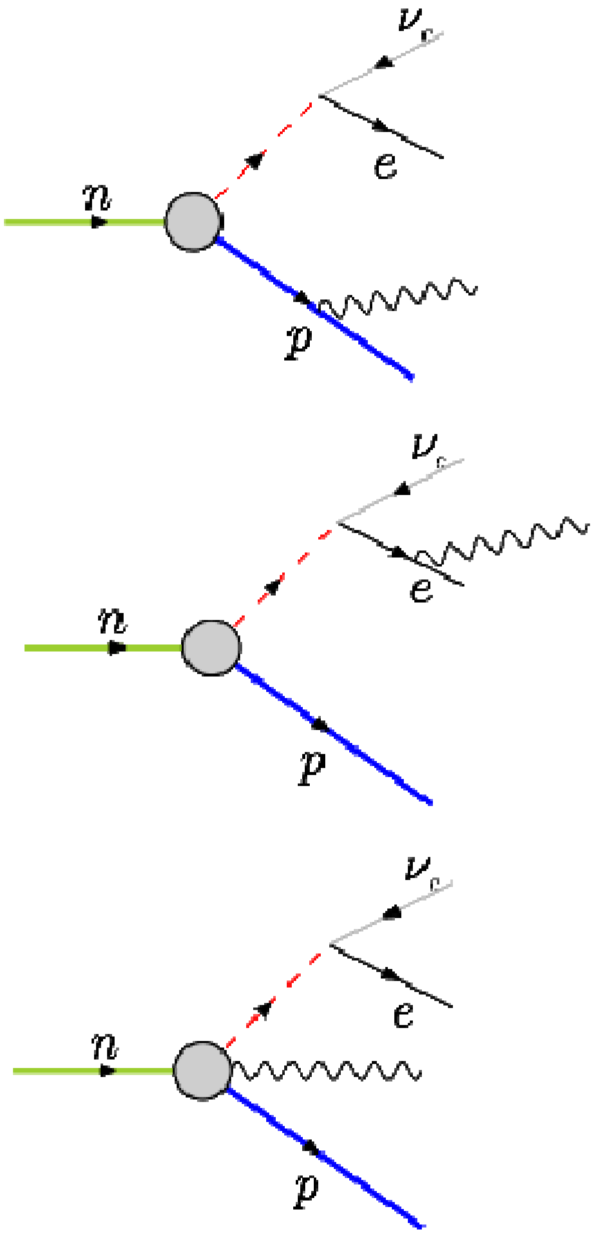
Motivation: Neutron radiative decay



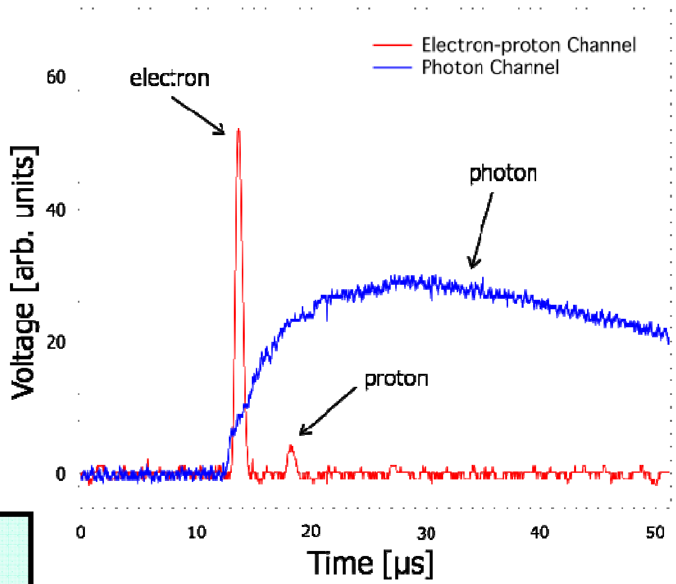


Measurement @ NIST: Neutron radiative decay

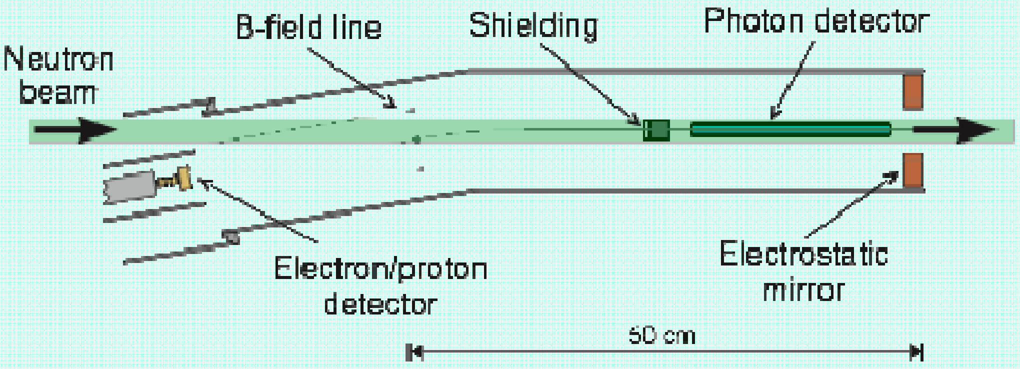
$$n \rightarrow p + e^- + \bar{\nu}_e + \gamma$$

- Previously unmeasured process in a fundamental semileptonic decay. Testing QED in a weak process.

- Groundwork for other investigations: new correlations, photon polarization, corrections O(0.5%).



RDK I operated at NIST NCNR cold neutron source. Measured e-Y coincidences followed by delayed proton.



Measured branching ratio:

$BR_{\text{RDK I}} = (3.13 \pm 0.34) \times 10^{-3}$

$BR_{\text{QED}} = 2.81 \times 10^{-3}$

J. Nico et al., Nature 444, 1059 (2006)

Measurement goal of current run: 1%

Collaboration: NIST, Tulane, Maryland, Michigan, Sussex, Arizona State

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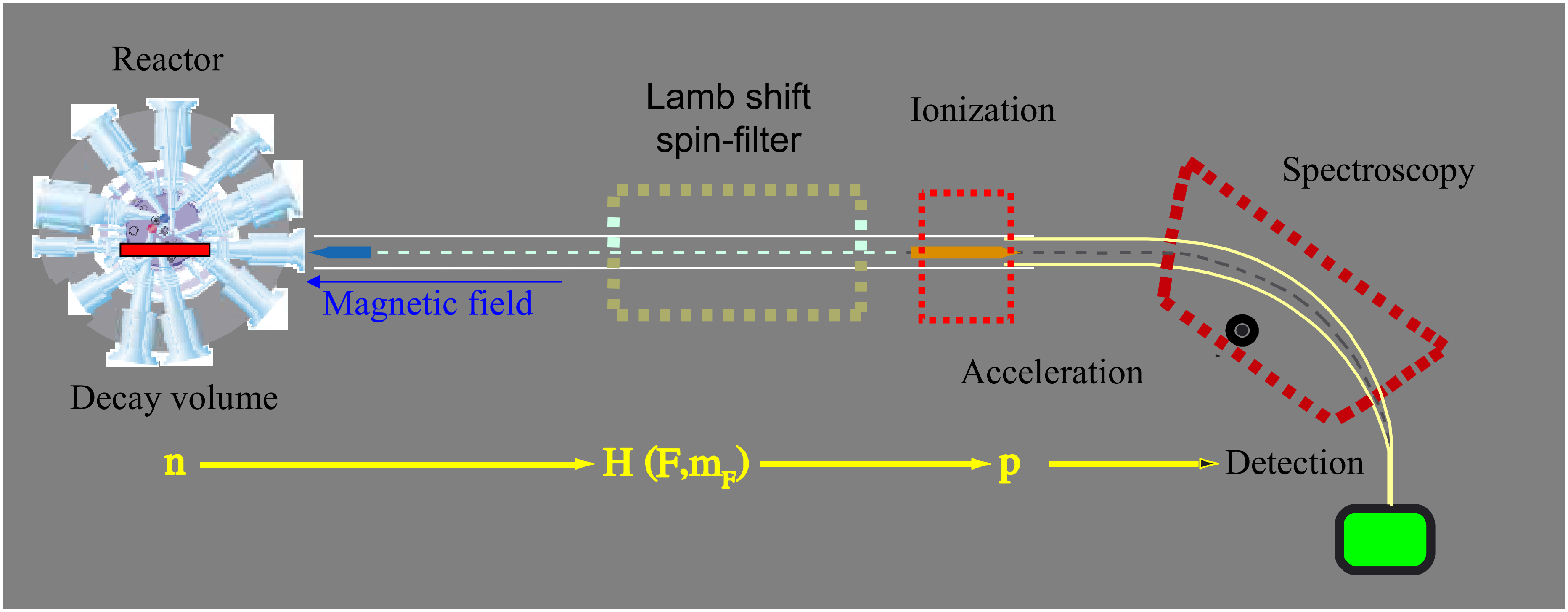
Neutron decay into hydrogen



Reactor

Lamb shift spin-filter

Ionization

Spectroscopy

Magnetic field

Acceleration

Decay volume

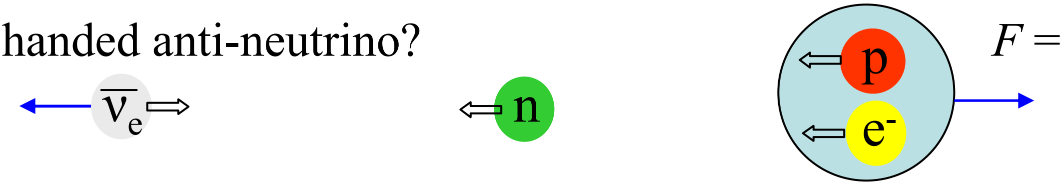
$n \longrightarrow H\,(F, m_F) \longrightarrow p \longrightarrow$ Detection

Production rate: ~ 4×10^{-6}, only 10% end up in 2s state (needed for spin state analysis)

$$p(H) = -p(\bar{\nu}_e) \qquad H(H) = \frac{\sigma(H)\cdot p(H)}{|\sigma(H)|\cdot|p(H)|} = 0, -H(\bar{\nu}_e)$$

Left-handed anti-neutrino?

$F = 1$, $m_F = -1$



Other application: Search for scalar and tensor couplings, which influence occupation numbers of spin states

W. Schott et al., EPJ A 30, 603 (2006)

Summary

- Rich experimental program with the study of neutron decay correlations

- New physics might be found with precision measurements. Maybe soon!

- Main problem: Neutron lifetime disagreement

Thank you for your interest !!