Fundamental Interactions and exotic nuclei

(Part II)

Oscar Naviliat-Cuncic

National Superconducting Cyclotron Laboratory
and Department of Physics and Astronomy
Michigan State University

NSCL

Department of Physics and Astronomy

NSF

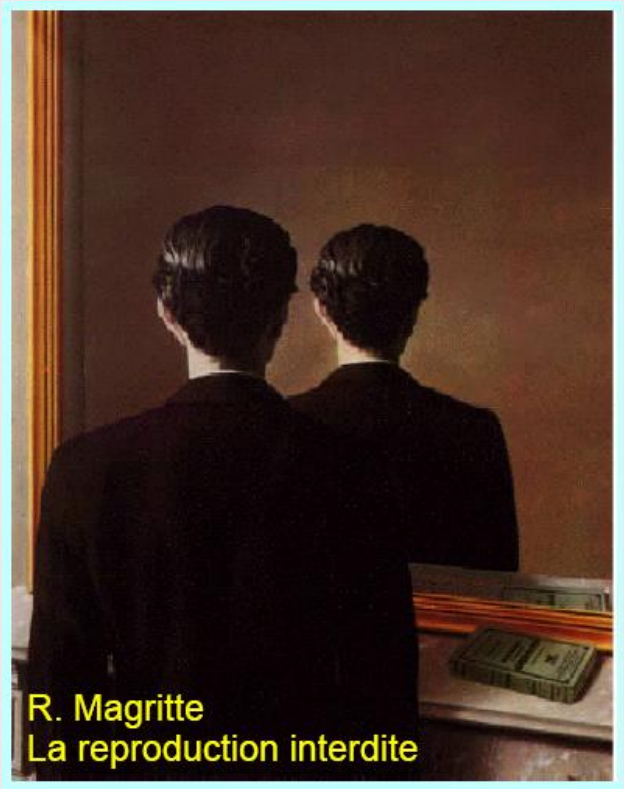
MICHIGAN STATE UNIVERSITY

Scope and Plan

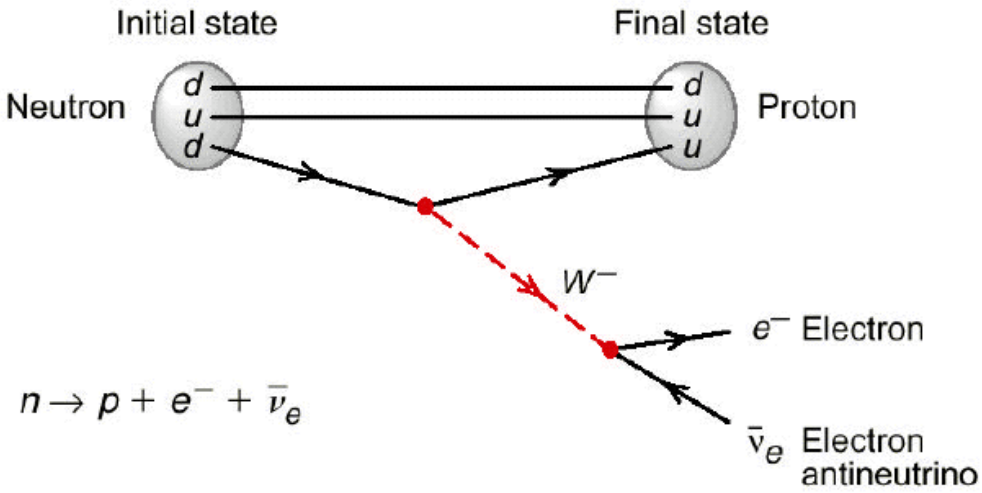
• Overview of selected topics in nuclear beta decay that probe some of the foundations of the Standard Model.
• (not a review).

1. Short reminder of the Standard Model building blocks
2. Phenomenology of the Weak Interactions
3. The Universality of the WI; quark mixing and the test of the Unitarity of the CKM matrix
4. Searches for deviations from maximal parity violation
5. Searches for violations of time reversal invariance

Searches for deviations from maximal parity violation



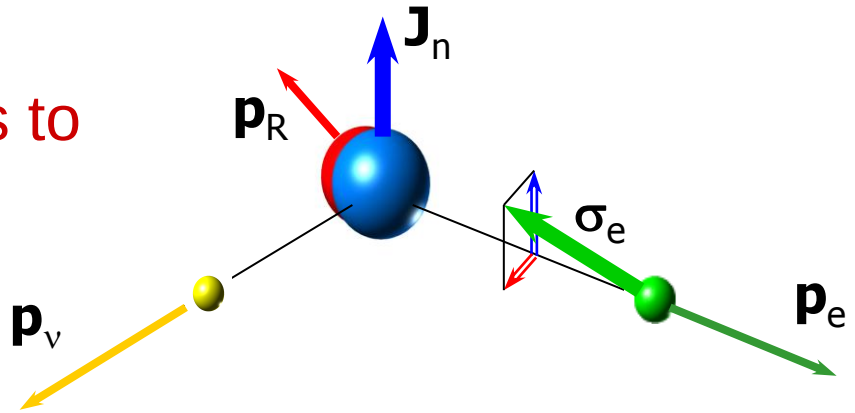
Beta decay correlations



- What we imagine to occur at the quark-lepton level

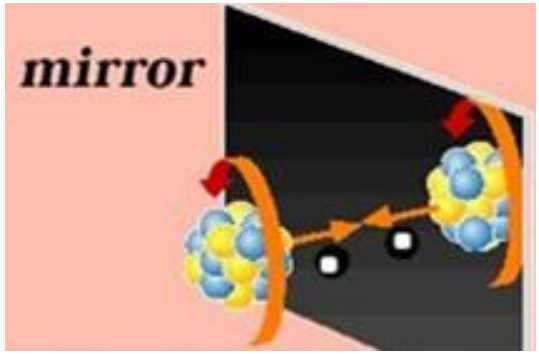
- What we actually have access to (experimentalist toolbox)

We can form many “correlations” between kinematic vectors



Parity transformation

P **space inversion** $\boldsymbol{r} \rightarrow -\boldsymbol{r}$



(idem “mirror symmetry” if rotational invariance holds)

axial vector $\boldsymbol{J} \rightarrow \boldsymbol{J}$ (invariant)

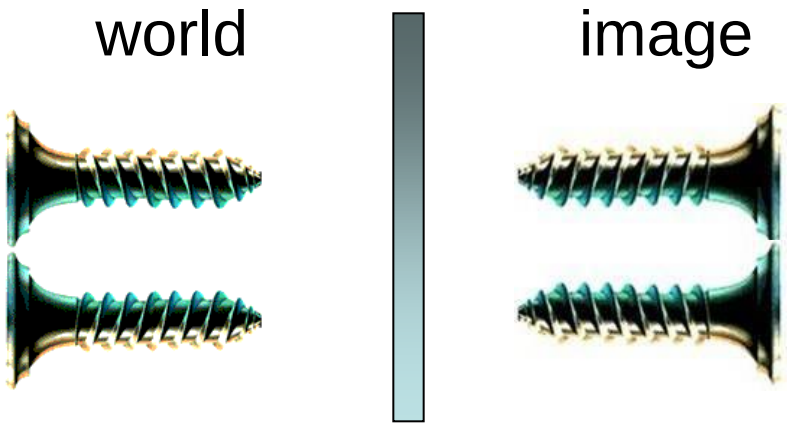
polar vector $\boldsymbol{p} \rightarrow -\boldsymbol{p}$ (changes sign)

Pseudo-scalar quantities (change sign)

$(\boldsymbol{J} \cdot \boldsymbol{p})$ *"decay asymmetry"* $A\ (\mathbf{J} \cdot \mathbf{p}_e)/E_e$

$(\boldsymbol{\sigma} \cdot \boldsymbol{p})$ *"longitudinal polarization"* $G\ (\sigma_e \cdot \mathbf{p}_e)/E_e$

Invariance and violation



L R 50% 50% 50% 50% L R

invariance

90% 10% 10% 90%

violation

100% 0% 0% 100%

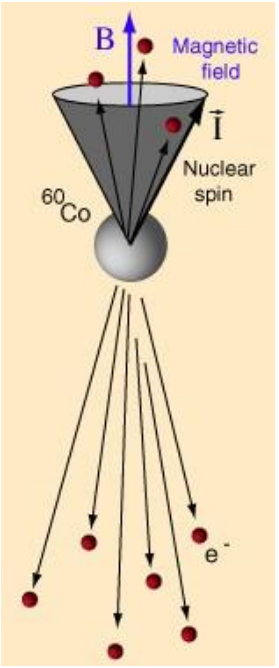
maximal violation

Discovery of parity violation

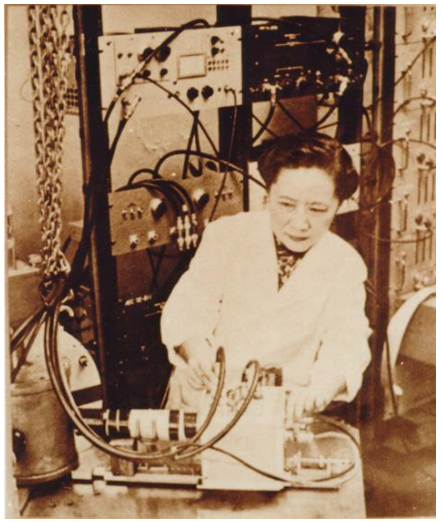
Measurement of the beta decay asymmetry from polarized ^{60}Co

$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$$

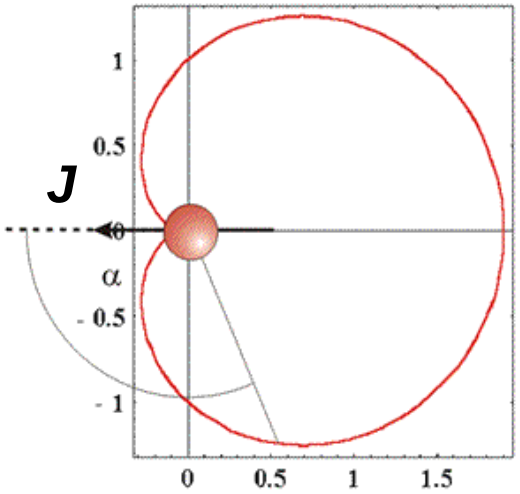
$$A\ (\mathbf{J}\cdot\mathbf{p}_e)/E_e$$



Mme. C.S.Wu



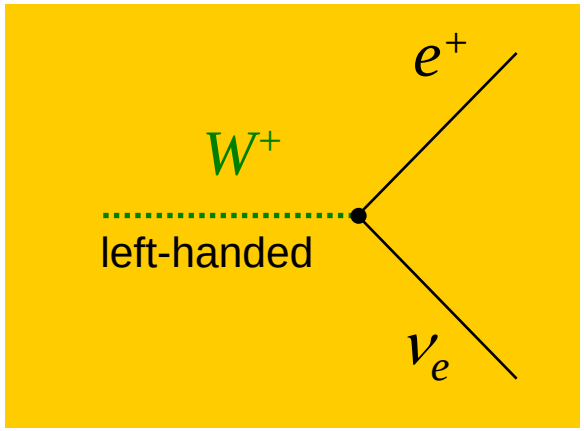
The angular distribution of electrons is not isotropic in space



Parity violation in the Standard Model

- Parity violation is incorporated in the SM and is assumed to be MAXIMAL

- Charged weak currents are only mediated by LEFT-handed weak bosons: RIGHT-handed weak bosons are assumed not to exist.



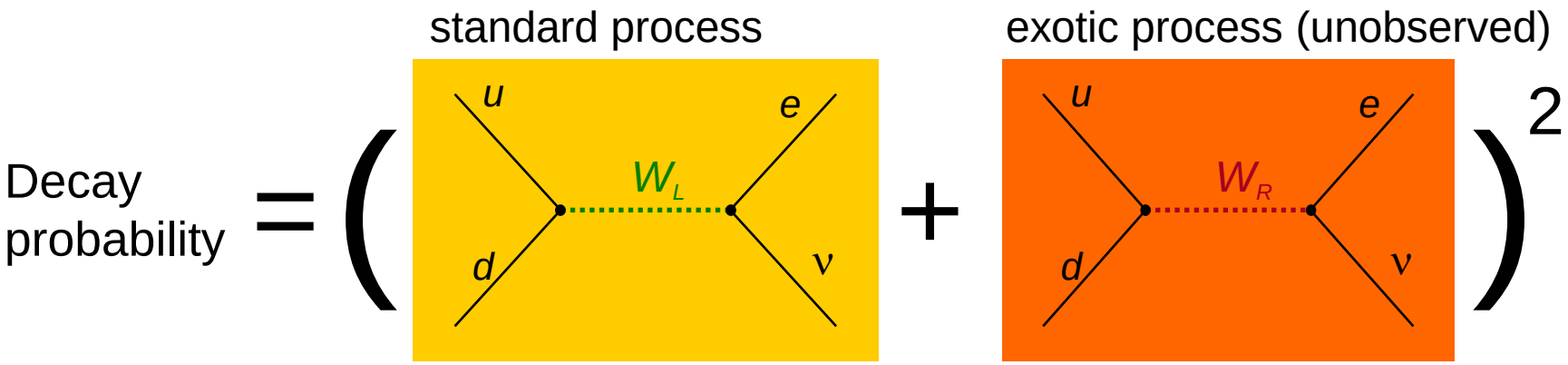
$$\propto \gamma^{\mu}(1-\gamma^{5})$$

- All experiments so far are consistent with the assumption of MAXIMAL parity violation.

Left-Right symmetry restoration

- Is LR symmetry restored at very high energy ?
- Was the primordial Universe LR-symmetric ?
- Do right-handed charged weak bosons exist at all ?

If RH bosons exist they could mix with the LH ones

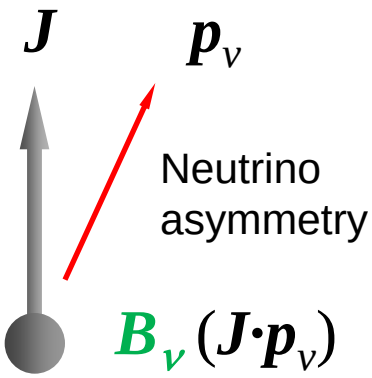


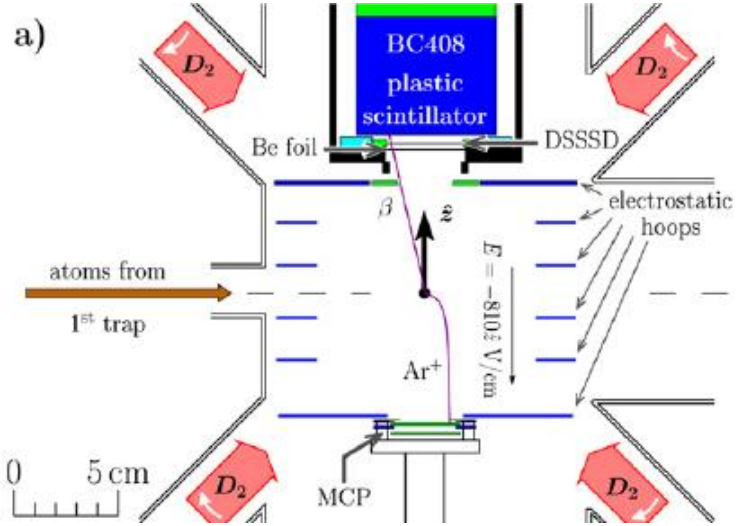
Remember: effects of new bosons go like $\rightarrow \left(\frac{g_R^2}{m_R^2}\right)^2$

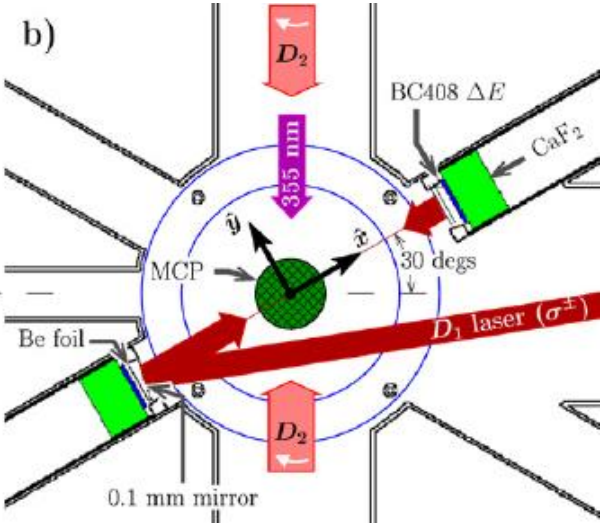
Measurement of B_ν in ^{37}K decay

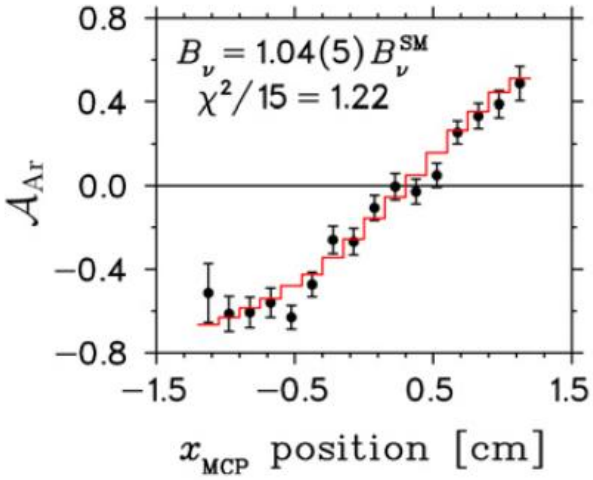
TRIUMF

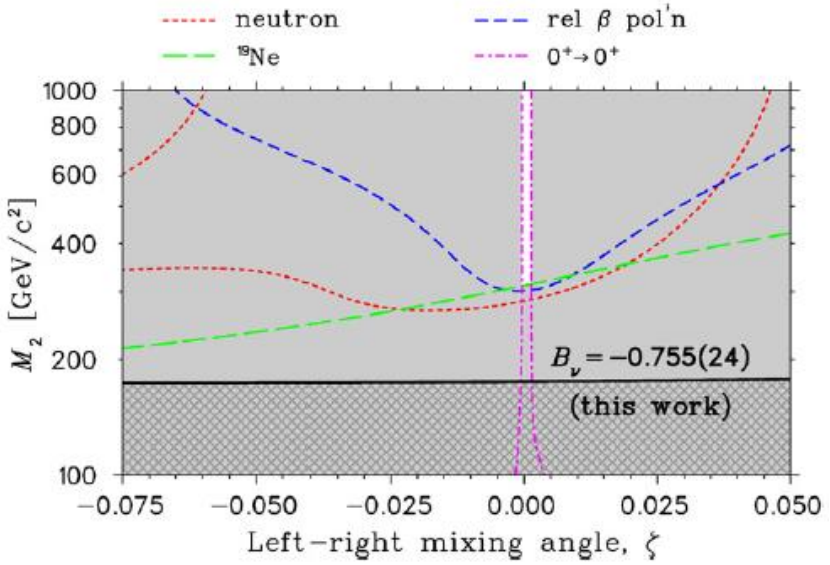
D.Melconian et al., PLB 649 (2007) 370





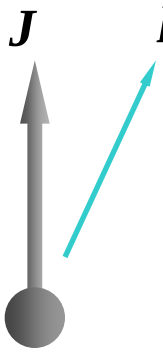






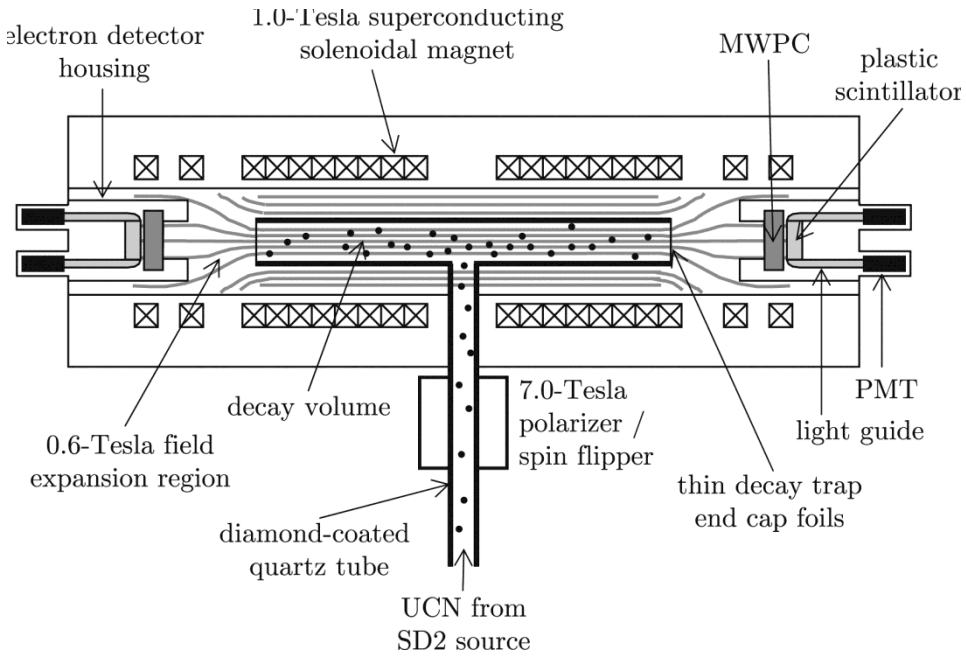
Measurement of A_β in neutron decay

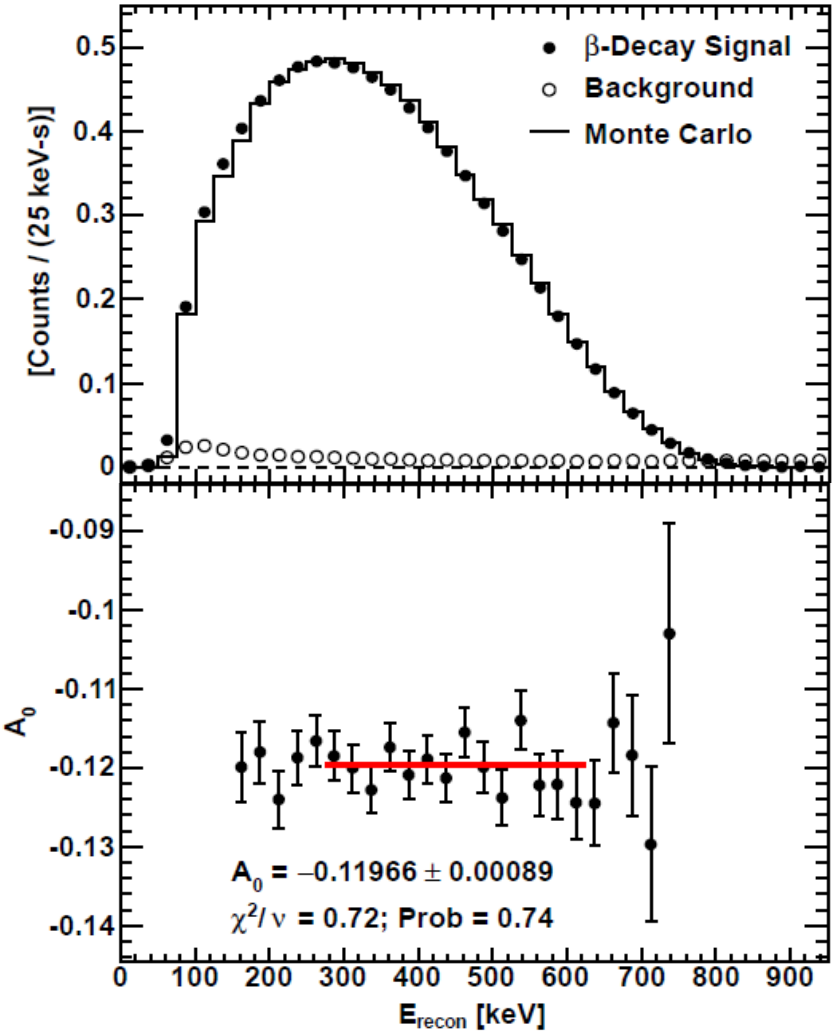
B. Plaster et al., arXiv:1207.5887v1



Beta asymmetry

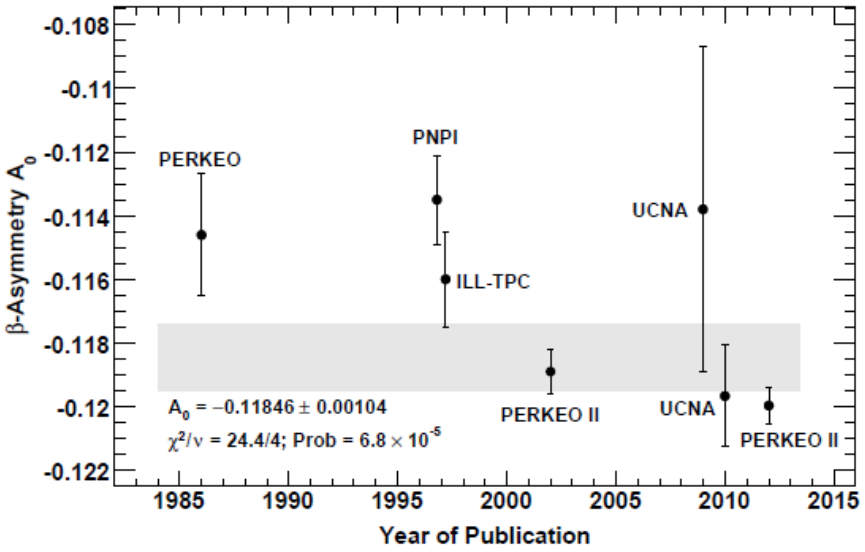
LANL / UCNA



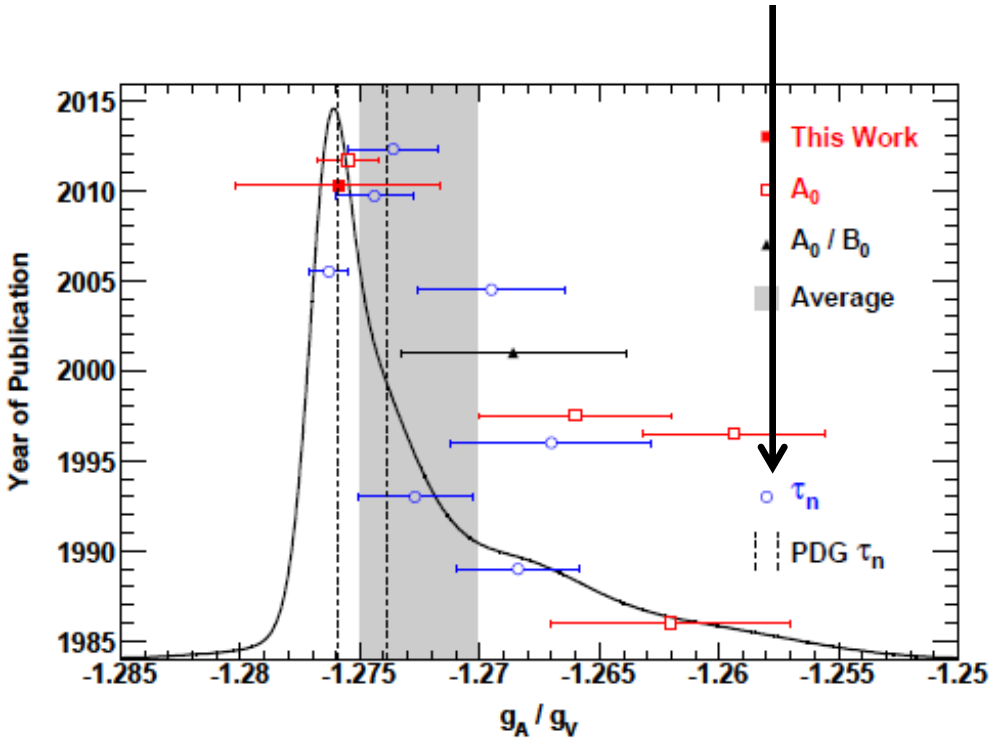


Status of A_β in neutron decay

B. Plaster et al., arXiv:1207.5887v1



Assuming V_{ud} from pure Fermi transitions



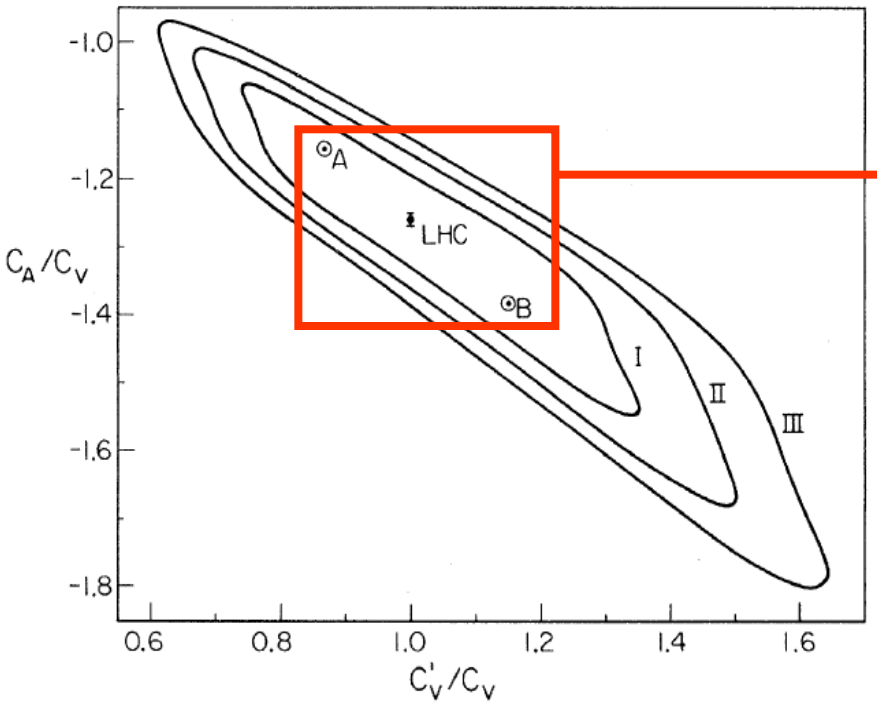
General trend toward smaller values of g_A/g_V

Progress on phenomenological couplings

Maximal parity violation imposes $C'_V = C_V$

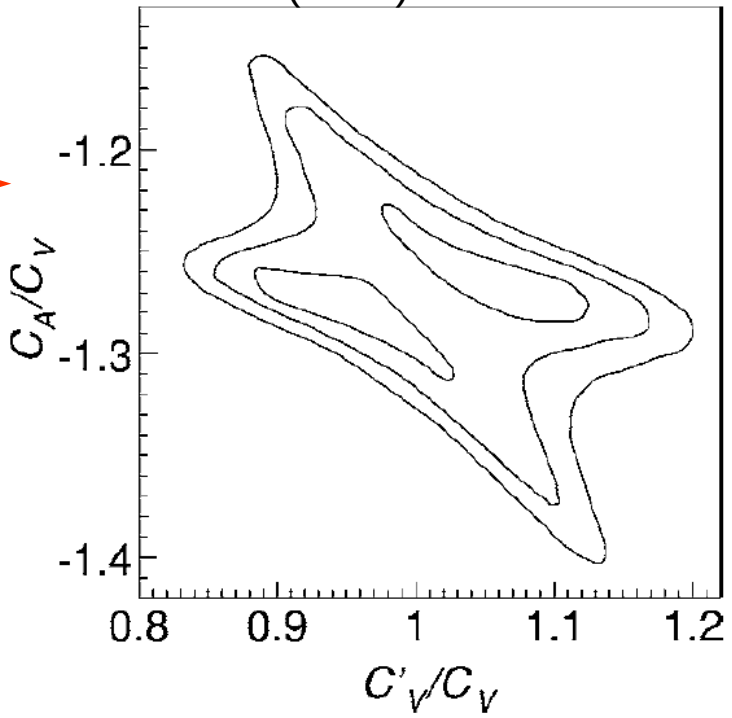
First “global” adjustment by H. Paul, 1970 (69 data values)

Boothroyd, Markey, Vogel, 1984
PRC **29** (1984) 603



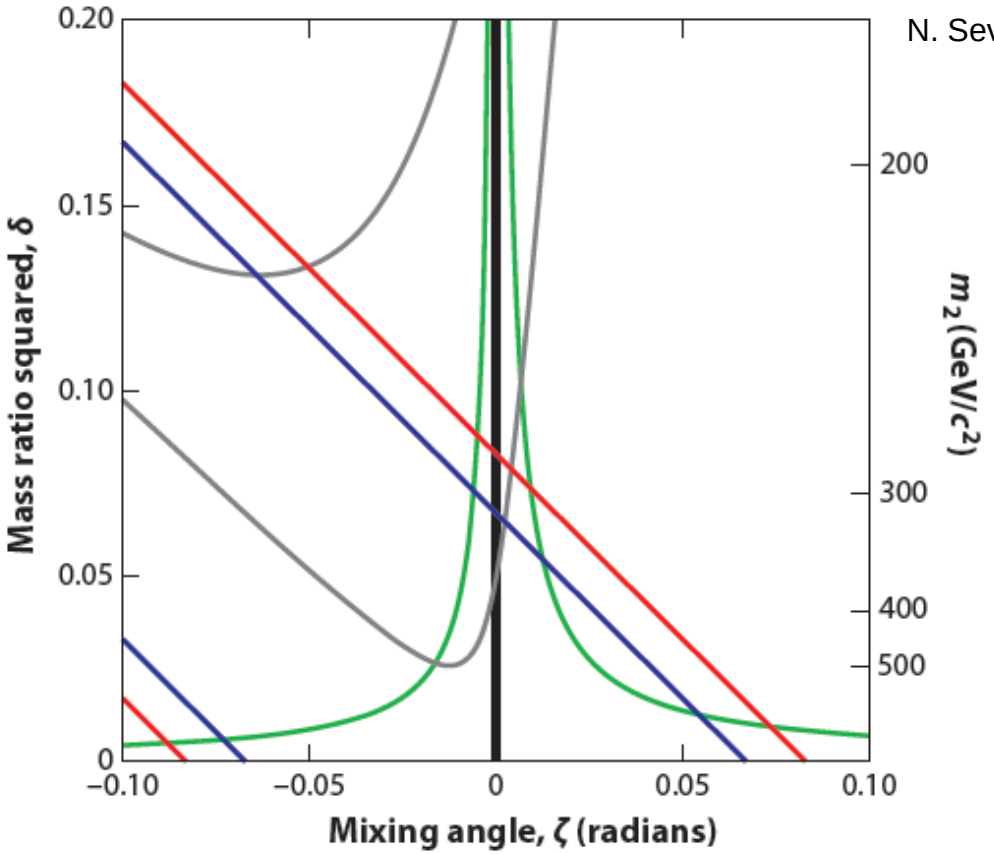
69-1+28 = 96 data values

Severijns, Beck, Naviliat-Cuncic, 2006
RMP **78** (2006) 991



96-(61+13)+34 = 56 data values

Constraints on right-handed bosons

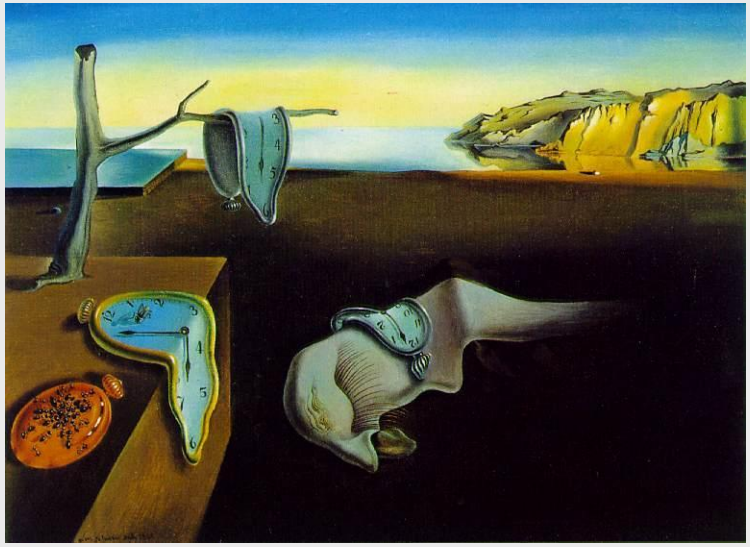


N. Severijns and O.N-C, Annu.Rev.Nucl.Part.Sci. 61 (2011) 23

Figure 4

Constraints on the right-handed current parameters δ and ζ from measurements of different observables in nuclear β decay, including the test of unitarity of the quark-mixing matrix (*black*) (14); measurements of the β-asymmetry parameter in the decays of ^{19}Ne (*gray*) (25, 88), ^{114}In (39), and ^{60}Co (40) (*red*); relative measurements of the longitudinal polarization of β particles in pure Fermi (F) and Gamow-Teller (GT) transitions (P_F/P_{GT}) (*green*) (100, 101); and relative measurements of the longitudinal polarization of β particles emitted from polarized nuclei (*blue*) (105–107). The regions bounded by the colored lines are allowed.

Searches for violations of time reversal invariance



S. Dali
La persistencia de la memoria

Time reversal

T Time reversal $t \rightarrow -t$

axial vector $\boldsymbol{J} \rightarrow -\boldsymbol{J}$ (changes sign)

polar vector $\boldsymbol{p} \rightarrow -\boldsymbol{p}$ (changes sign)

P-even, T-odd correlation: $D\,\vec{J}\cdot(\vec{p}_e \times \vec{p}_\upsilon)/E_e E_\upsilon$

P-odd, T-odd correlation: $R\,\vec{\sigma}_e \cdot (\vec{J} \times \vec{p}_e)/E_e$

Do not probe the same physics

Coeff.	***P***	***T***	***TRV phase***
R	Odd	Odd	T-A, S-V
D	Even	Odd	V-A
E_1	Odd	Odd	V-A

A TRV interaction manifest by the presence of complex couplings

General context

- CP violation has so far only been observed in *K* and *B* meson decays.

- Measured effects can be accounted for in the SM (with 3 quark generations) via the CP-violating phase of the CKM matrix.

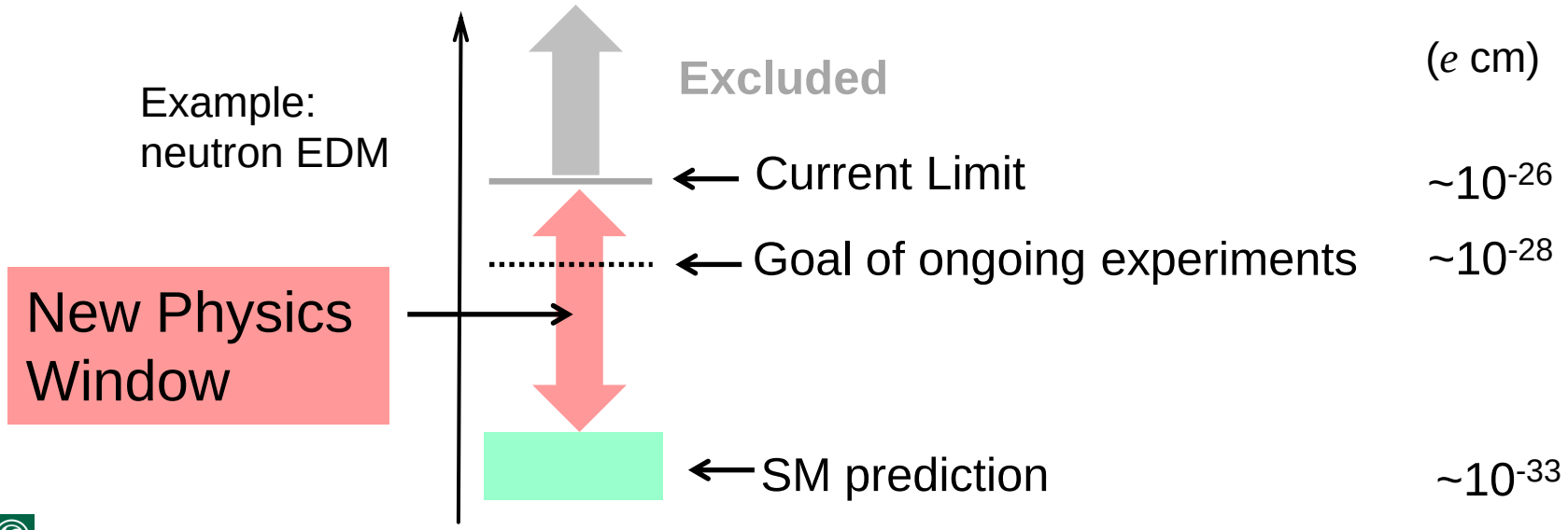
- The size of the standard CP-violating mechanism is however too small to account for the matter-antimatter asymmetry in the Universe.

- New mechanisms of CP violation must exist.

Experiments at low energies

- Under CPT invariance: CP violation = T violation: look at T-violating properties (nEDMs or correlations in weak decays).

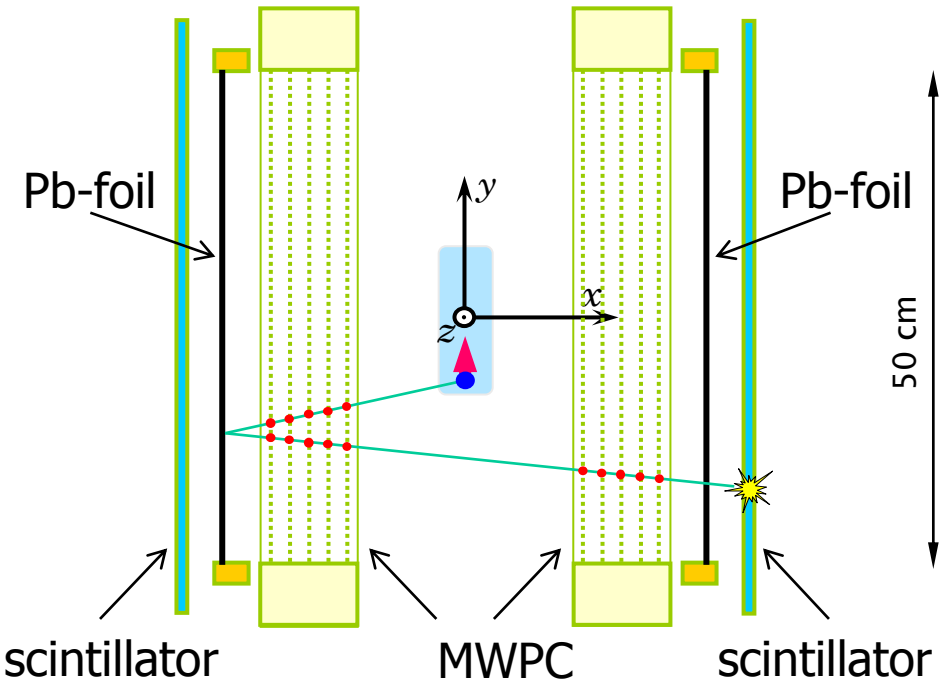
- In processes or properties involving the u,d quarks, effects due to the standard CP violating phase are strongly suppressed (out of experimental reach): large window to search for new physics



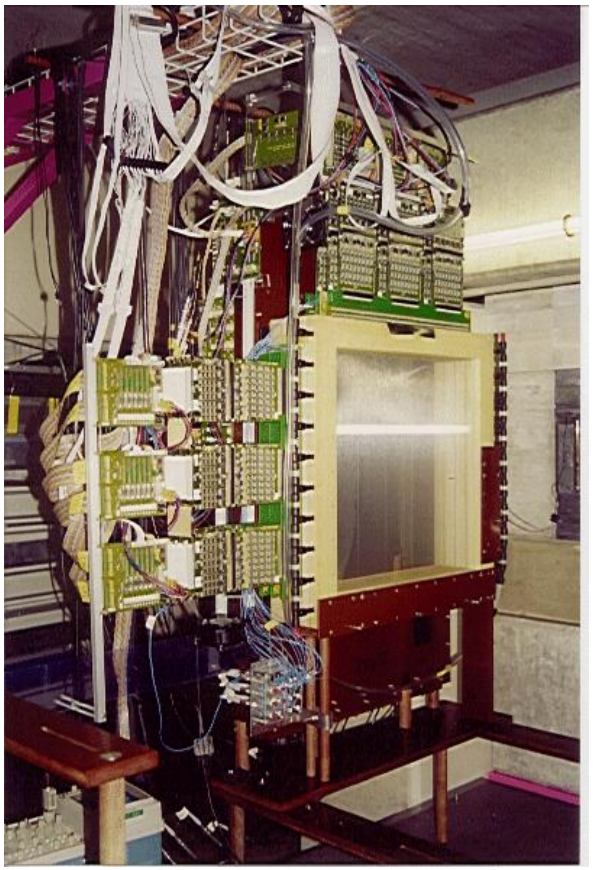
Measurement of R in neutron decay

A. Kozela et al. PRC 85 (2012) 045509

$R\ \sigma_e \cdot (\mathbf{J} \times \mathbf{p}_e)/E_e$ Maximal sensitivity for mutually perpendicular vectors



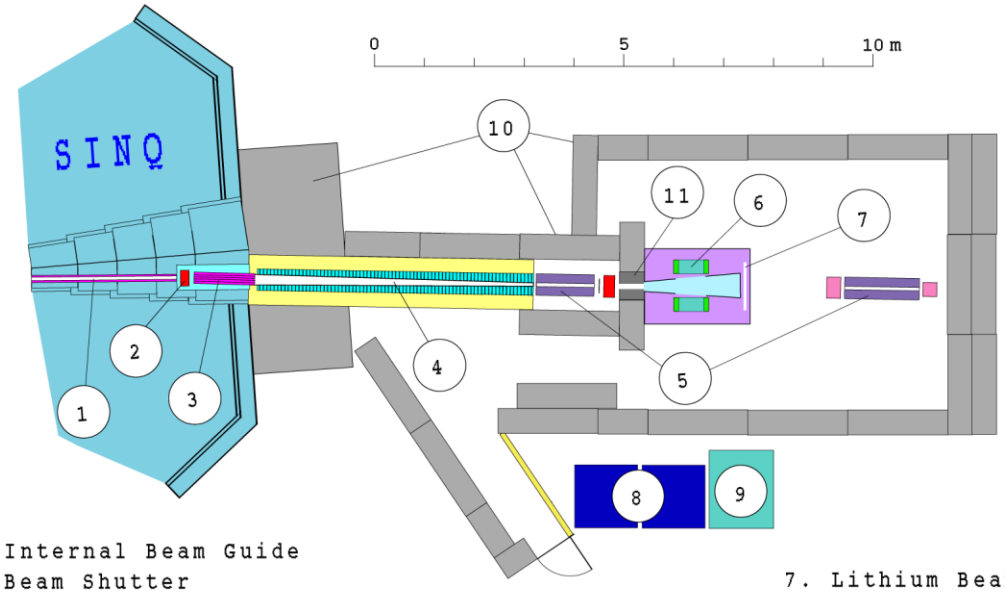
- Transverse polarization analysis by Mott scattering on Pb-foil



- Tracking of electrons in low-mass, low-Z MWPC
- Identification of Mott events by vertex
- Frequent neutron spin flipping
- Foil IN/OUT measurements

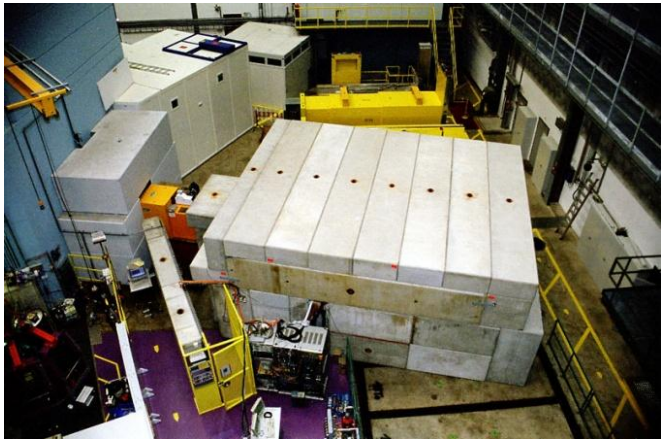
FUNSPIN area at PSI

- Polarized cold neutron beam at the Paul Scherrer Institute



1. Internal Beam Guide
2. Beam Shutter
3. Polarizer
4. Focusing Guide
5. Spin Flippers
6. Neutron Decay Detection System
7. Lithium Beam Dump
8. Electronics
9. Gas System
10. Radiation Shields
11. Boron/Lithium Collimator

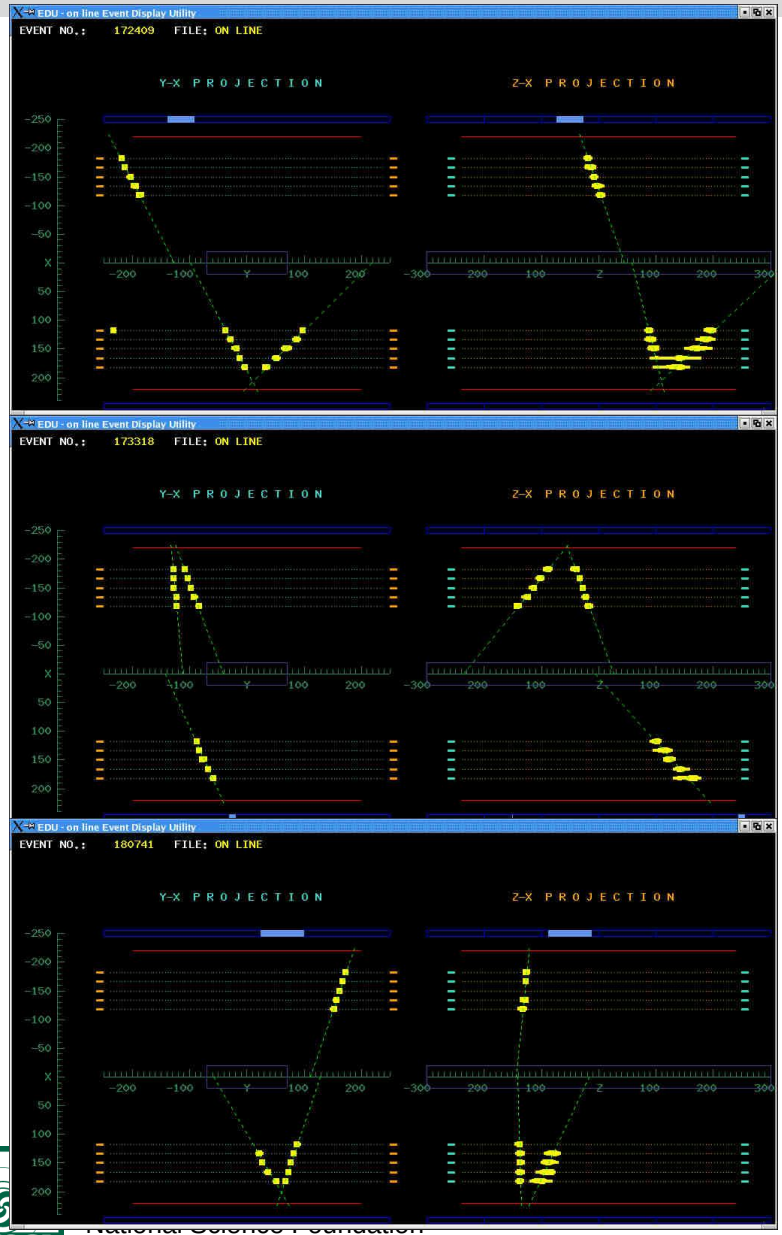
Figure 4: Layout of the Polarized Cold Neutron Facility at PSI.



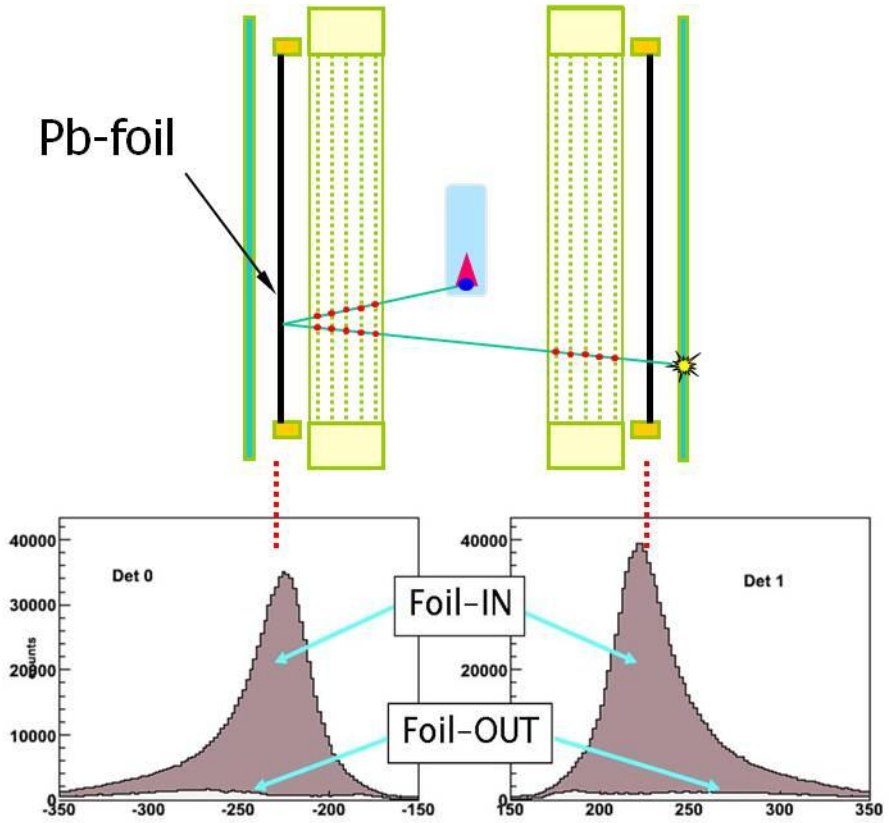
$I_n \approx 10^{10}\ s^{-1}$

$P_n \approx 90\%$

Golden events



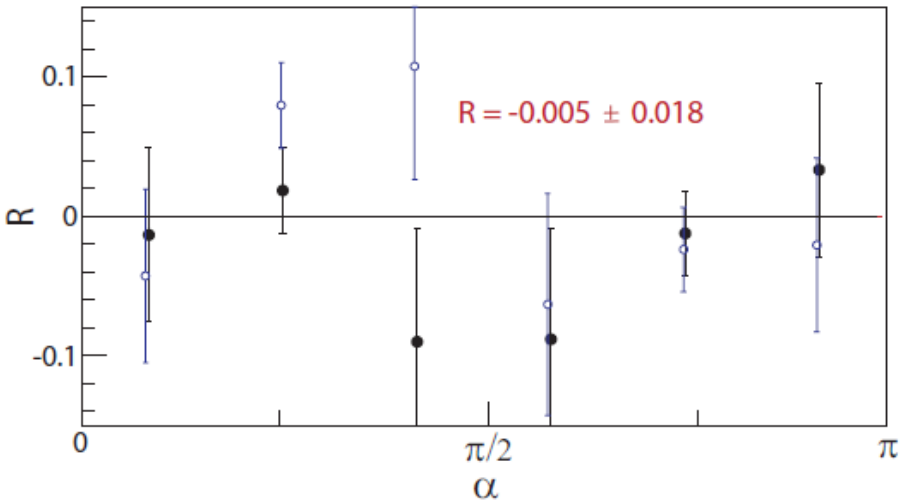
- Vertex identification

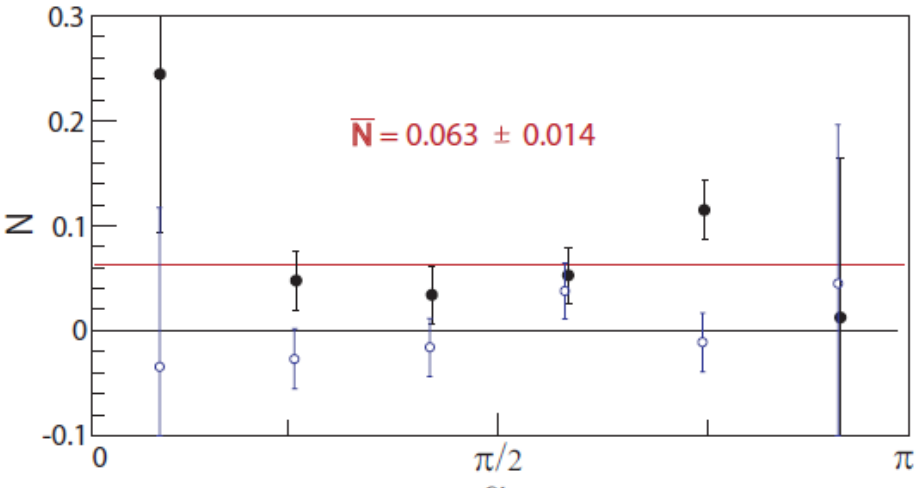


Results

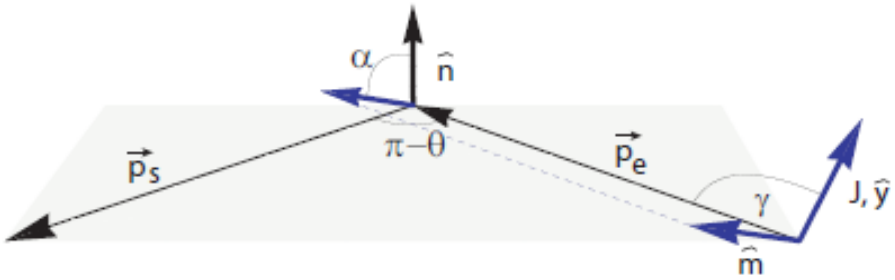
2007 data

A. Kozela et al. PRC 85 (2012) 045509





The setup is also sensitive to a TRI correlation ("N") that provides a control of the polarimeter



R_{exp} = 0.004(12+5) N_{exp} = 0.067(11+4)

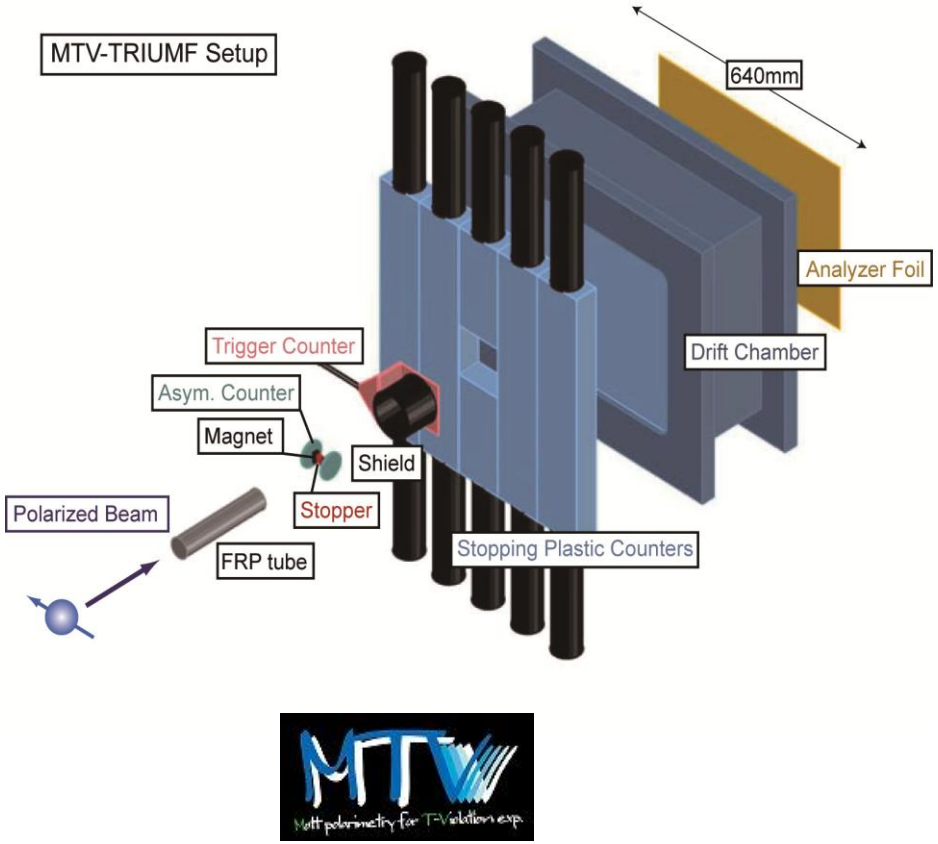
R_{FSI} = 0.0006(2) N_{FSI} = 0.068(1)

Measurement of R in ^{8}Li decay

Rikkyo-U, KEK/TRIMF(Jiro Murata et al.): Started at KEK-TRIAC (2008), moved to ISAC-TRIUMF (2009)

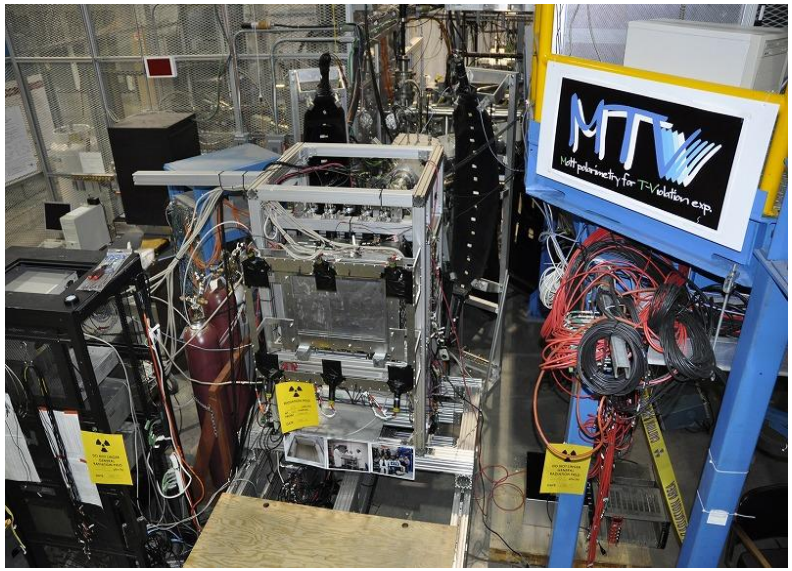
Determines the transverse polarization of electron emitted from polarized nuclei

$$R\,\vec{\sigma}_e \cdot \left(\vec{J} \times \vec{p}_e\right) / E_e$$



^{8}Li from ISAC

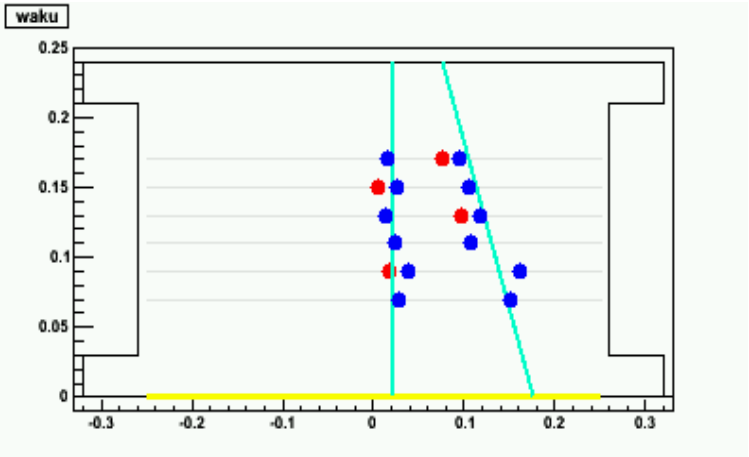
- Beam 10^{7} pps @ 28 keV
- 80% polarization (optically pumped)
- 10 μm Al in 500 G

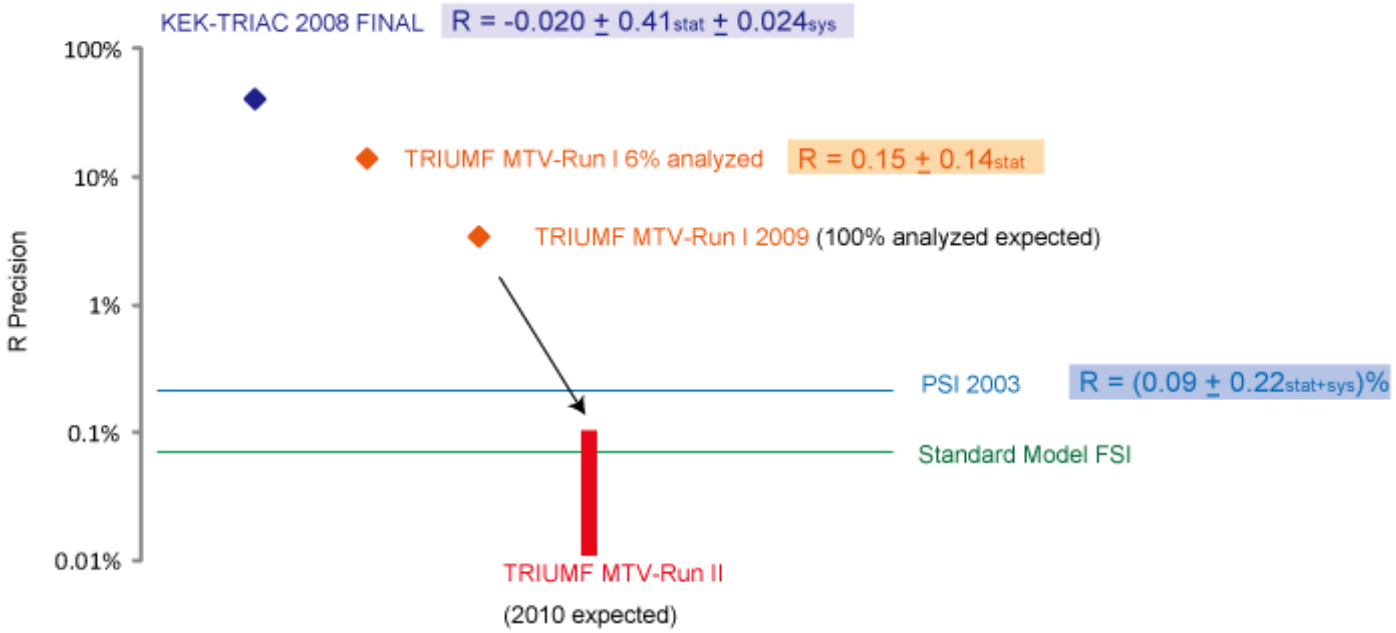


(in progress)

Projected sensitivity

- Production run Nov.2010



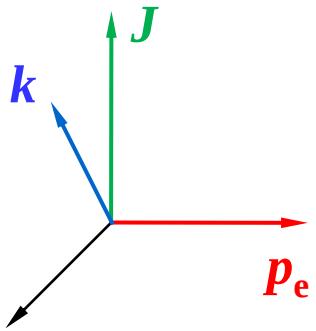


Five-fold TRV correlation

(K. Minamisono et al.)

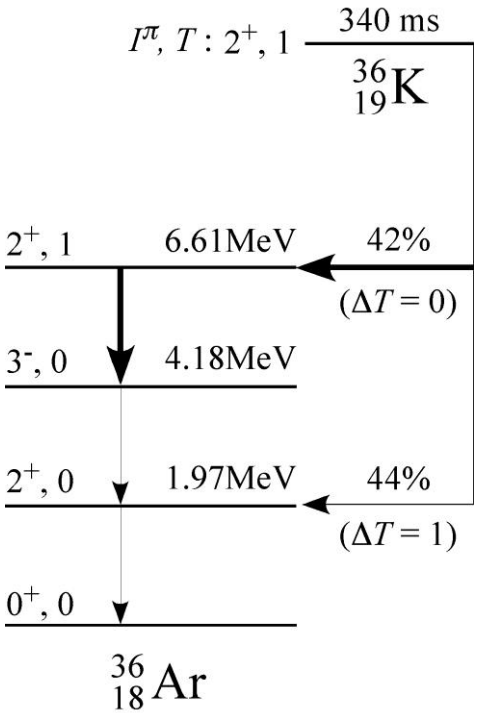
$$W_{\beta-\gamma} \propto 1 - AE_1 \left(\boldsymbol{J}\cdot\boldsymbol{p}\times\boldsymbol{k}\right)\left(\boldsymbol{J}\cdot\boldsymbol{k}\right)$$

"nuclear alignment" –β–γ directional correlation



- Needs mixed F/GT transition
- Complementary to R and D coefficients

(Following suggestion by A. Young et al. PRC52 (1995) R464.)

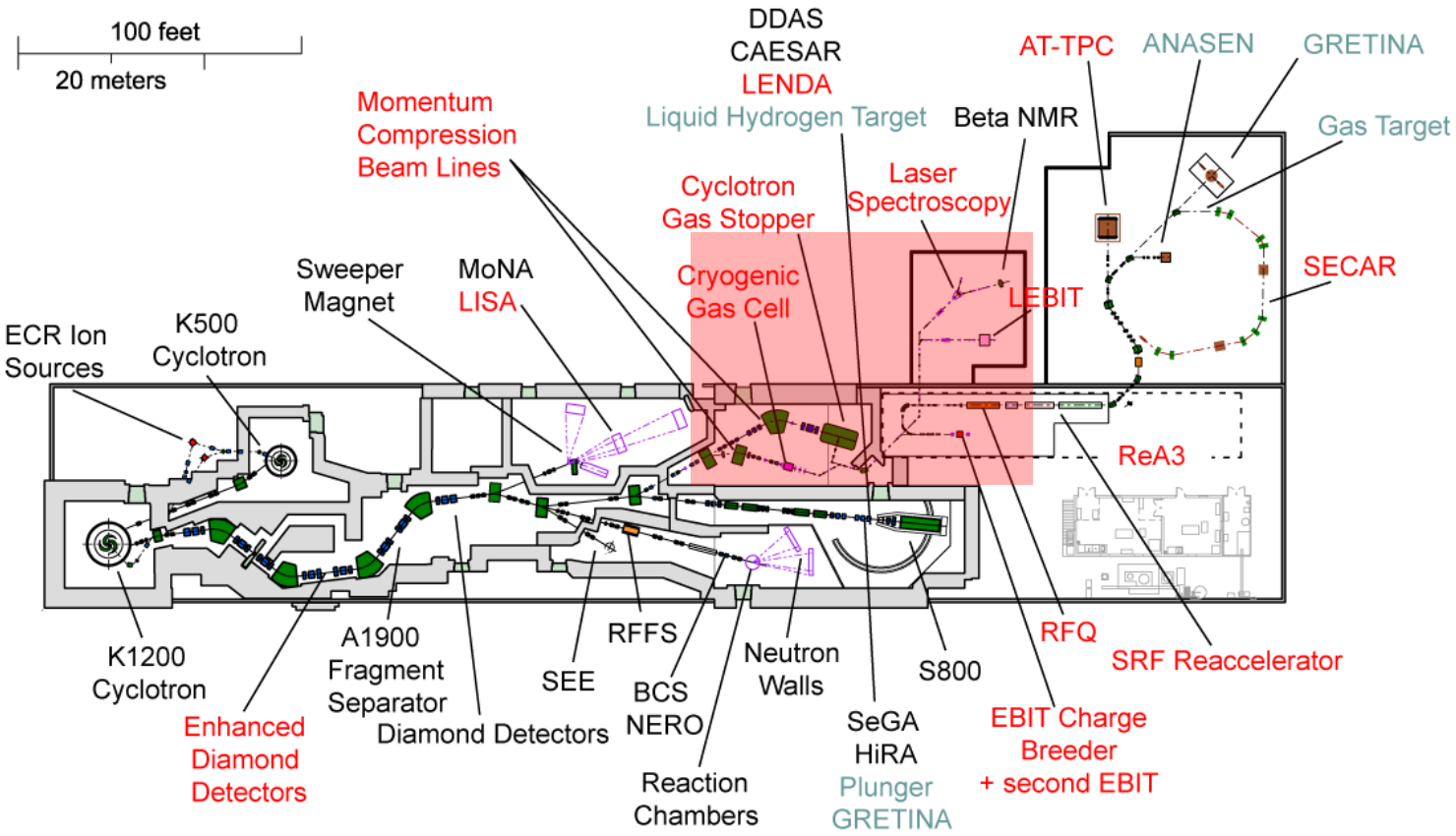


- Mixed transition (signal)
- GT transition (control)

Requirements

- High production rate: >10^6/s
- Large nuclear alignment (optical pumping)
- Highly efficient segmented Ge detector array

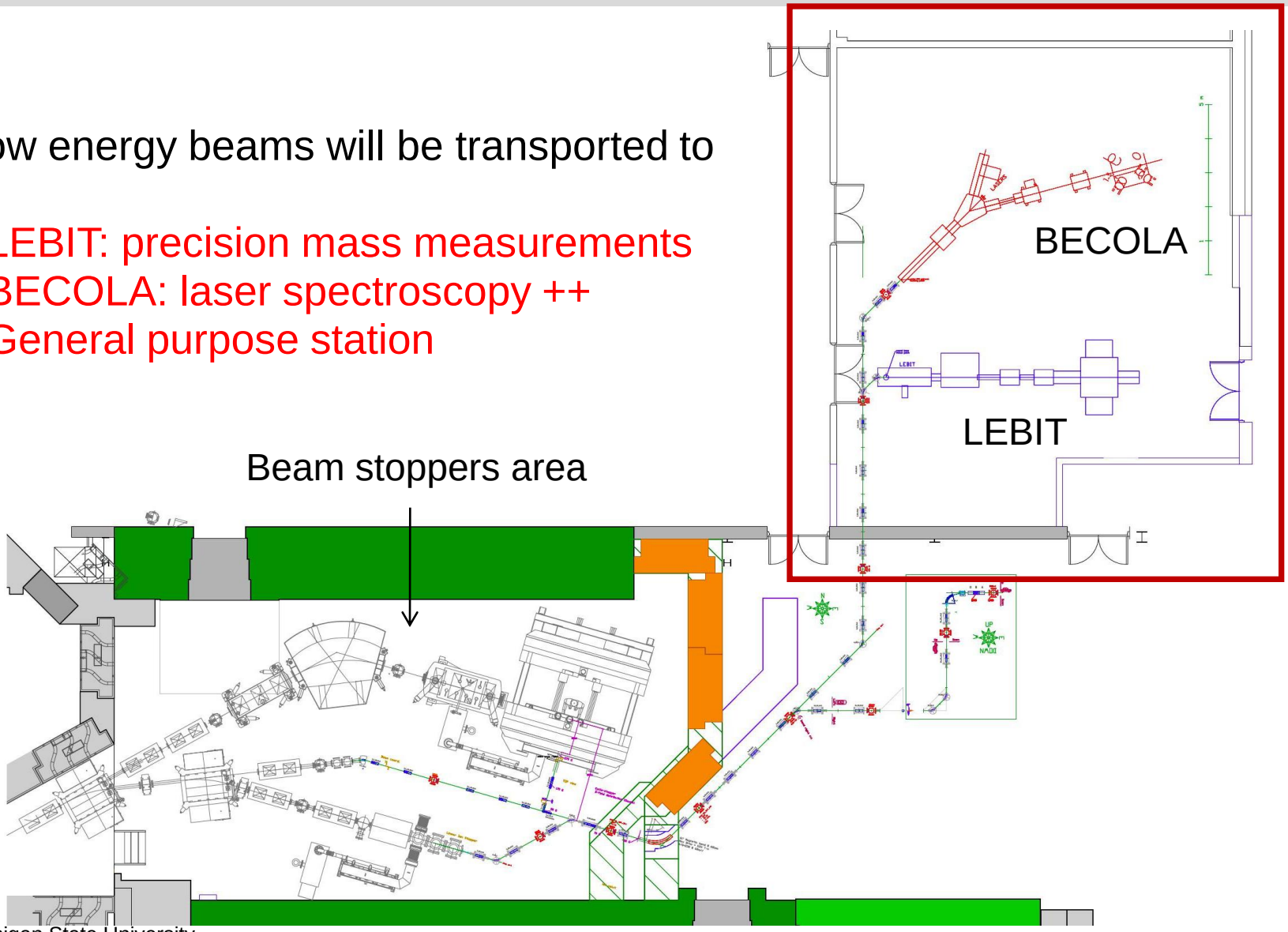
New polarized beam line at NSCL



Low energy beam area

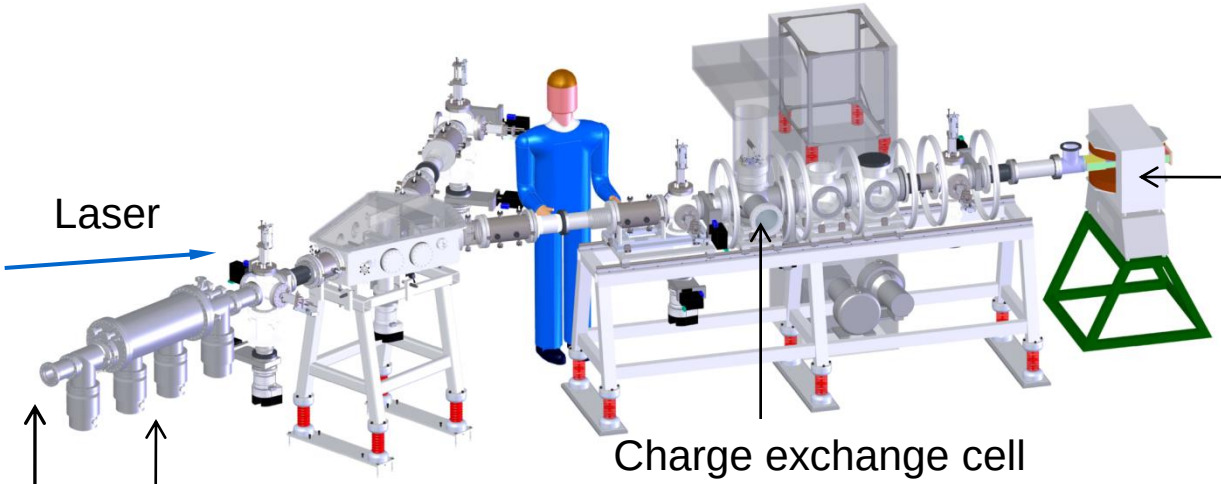
Low energy beams will be transported to

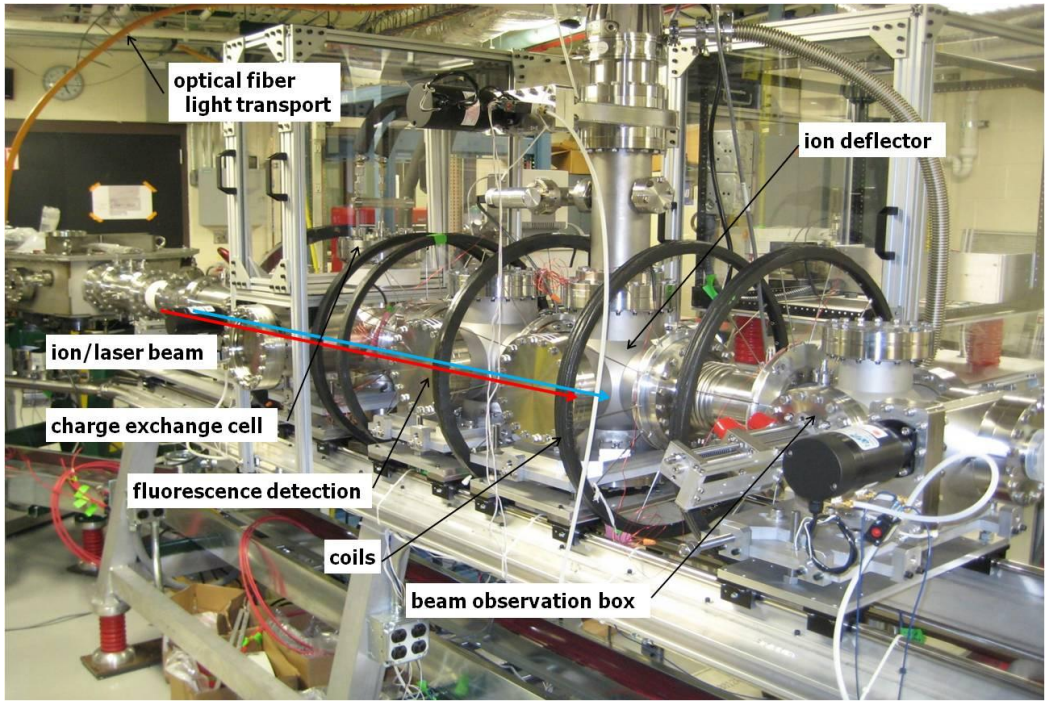
- LEBIT: precision mass measurements
- BECOLA: laser spectroscopy ++
- General purpose station



BECOLA@NSCL

BEam COoling and LAser Soectroscopy , P. Mantica, K. Minamisono et al.)





Commissioned with off-line ion source

Take away

- Sensitive tests of maximal parity violation and time reversal invariance have been obtained in measurements of correlations in nuclear and neutron decays.

- Searches for possible right-handed bosons in nuclear beta decay exclude mass ranges below 330 GeV/c^2.

- The *R* triple correlation coefficient has been measured in neutron decay for the first time. The result is consistent with SM predictions.

- New measurements of triple and five-fold correlations in nuclei use (or plan to use) optically pumped polarized beams.

Further readings

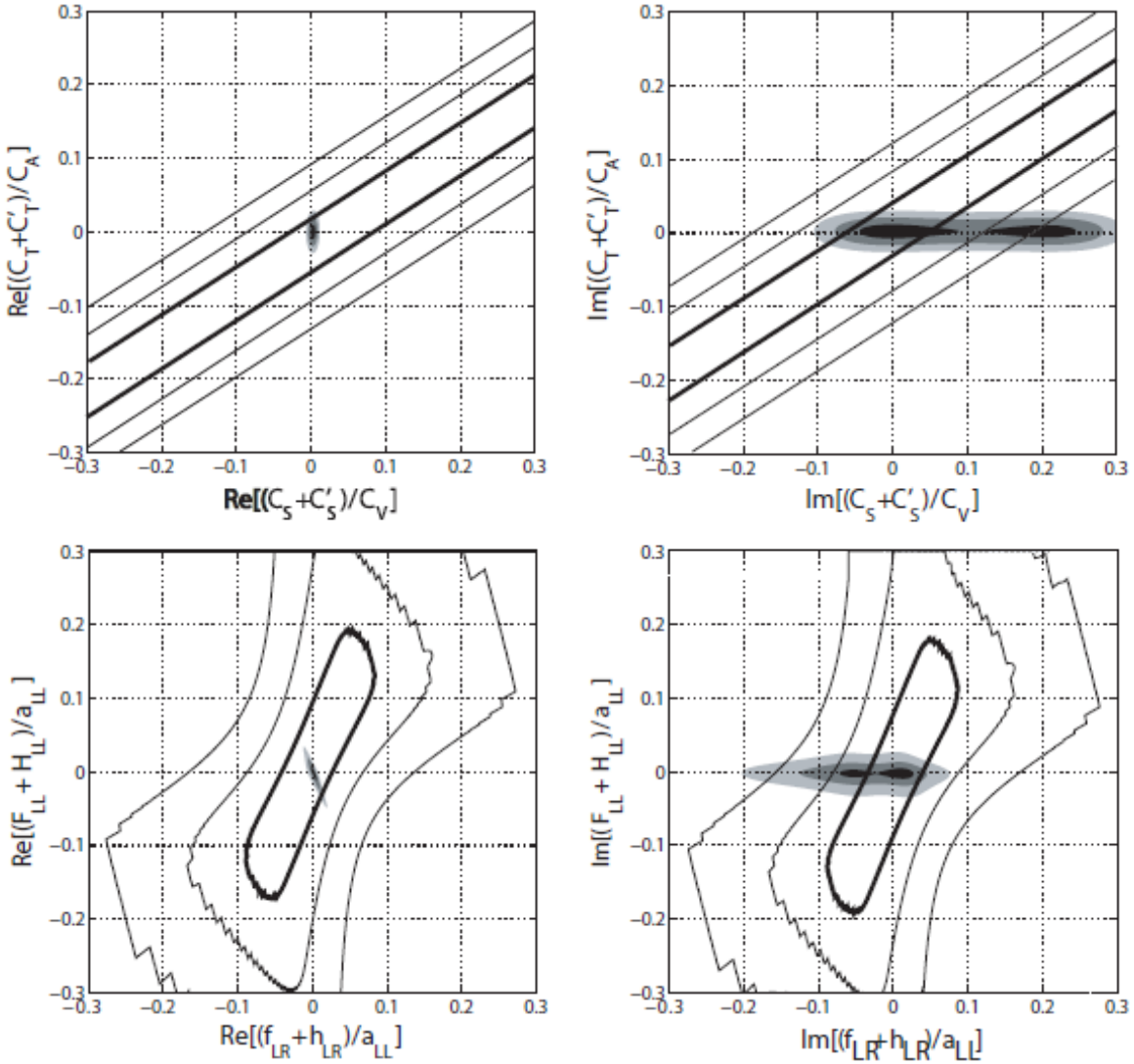
- *The Physics of Time Reversal*,

R. Sachs,
University of Chicago Press, 1987

- *Neutron beta decay,*

J.S. Nico,
J. Phys. G: Nucl. Part. Phys. 36 (2009) 104001

Constraints on exotic couplings



A. Kozela et al. PRC 85 (2012) 045509