“BSM physics” in neutron decay

Search for Time Reversal Violation

by measurement of angular correlations in neutron decay

– nTRV and BRAND experiments

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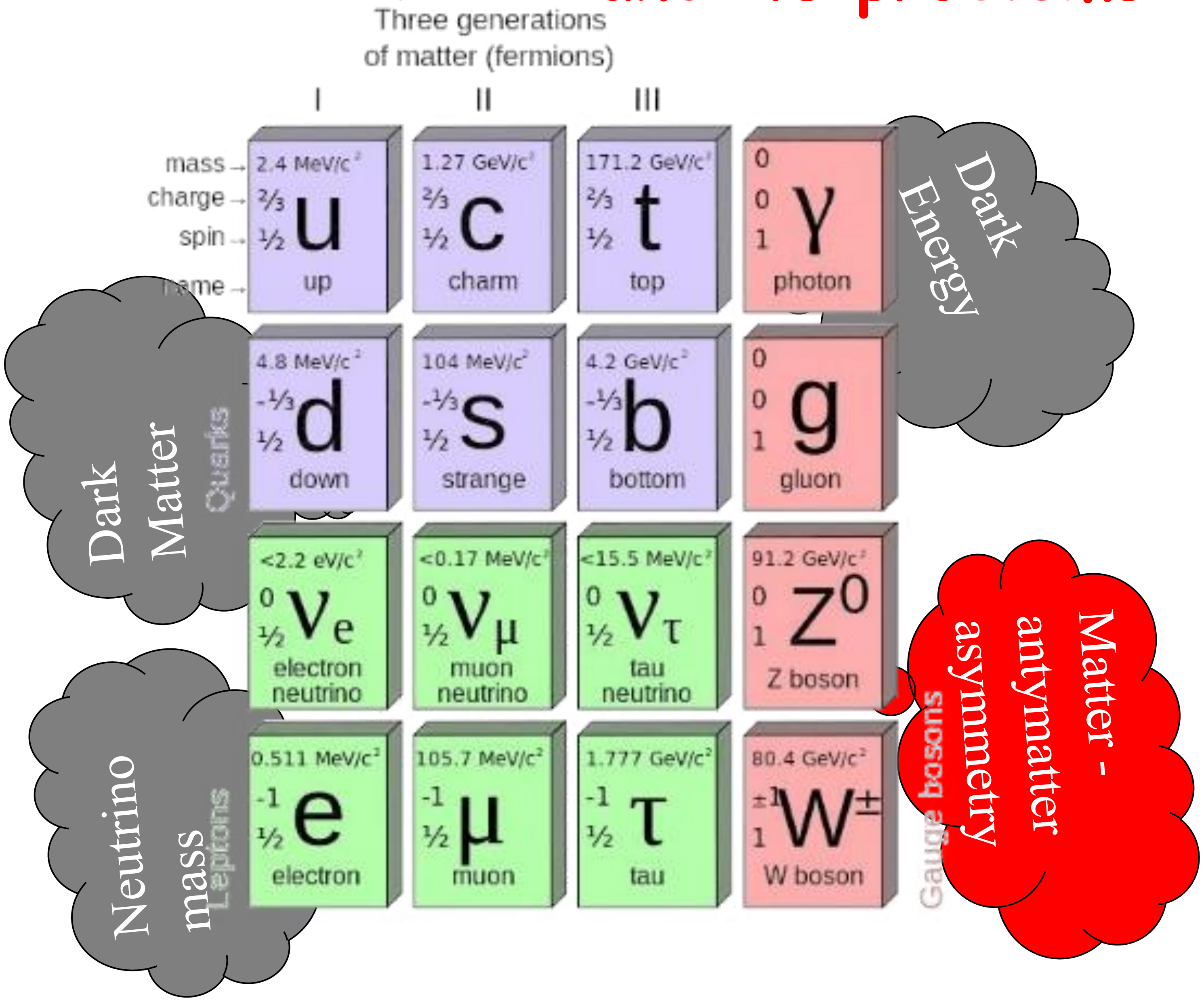
Standard Model and its problems



Time reversal violation

- Cabibbo-Kobayashi-Maskawa matrix:
  - TRV parametrized by complex phase δ_{KM},

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3\varrho e^{i\delta_{KM}} \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3\left[1-\varrho e^{-i\delta_{KM}}\right] & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

  - Many orders of magnitude to small to account for observed matter-antimatter asymmetry …

- θ-term in effective Lagrangian of strong interactions

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \theta \cdot q(x)$$

  - Generates unobserved nEDM ($d_n \approx 1.8 \cdot 10^{-26}$ ecm $\Rightarrow \theta < 10^{-9}$) … „Strong CP problem"

- Final state interactions (FSI)

TRV in weak interaction?

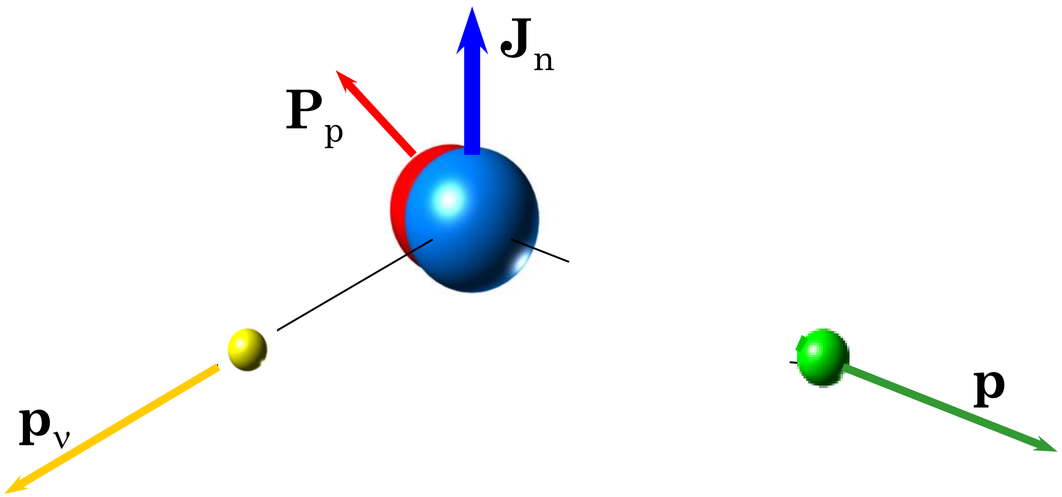
- General form of Lorenz-invariant Hamiltonian of weak interaction for *n decay:*

$$H = \bar{e}\gamma_\lambda (C_V + C'_V\gamma_5)\nu_e\bar{p}\gamma^\lambda n + \bar{e}\gamma_\lambda\gamma_5 (C_A + C'_A\gamma_5)\nu_e\bar{p}\gamma^\lambda\gamma_5 n$$
$$+ \bar{e}(C_S + C'_S\gamma_5)\nu_e\bar{p}n + \bar{e}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}(C_T + C'_T\gamma_5)\nu_e\bar{p}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}n$$
$$+ \bar{e}\gamma_5 (C_P + C'_P\gamma_5)\nu_e\bar{p}\gamma^5 n + H.c.$$

C_i ,C_i'- 19 real param.

- Standard Model: V-A interaction, (C_V= C'_V=1, C_A= C'_A = $\lambda \approx -1.27$, rest is 0), but actual experimental limitations are finite, on % level and may provide missing source of TRV.
- More accurate limitations on C_i – more precise tests of proposed extensions of Standard Model: Left-Right Symmetric Models, Leptoquark exchange, Supersymmetric Models ...

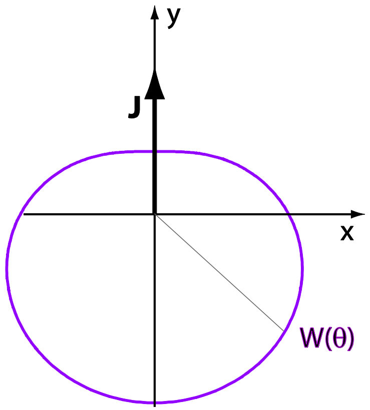
Angular correlations in neutron decay



(~885.7s)

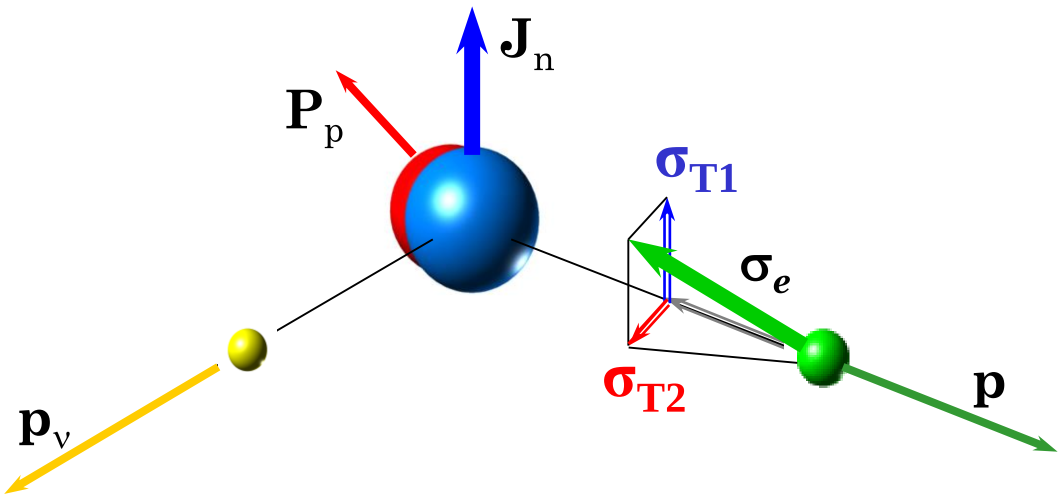
$n \rightarrow p\, e\, \bar{\nu}_e \;+\; 782$ keV

$$W(\theta, E) \propto 1 + A\,\frac{\vec{J}\cdot\vec{p}}{E} + \cdots$$



A- *decay* asymmetry (-0.1173)

Angular correlations in neutron decay



(~885.7s)

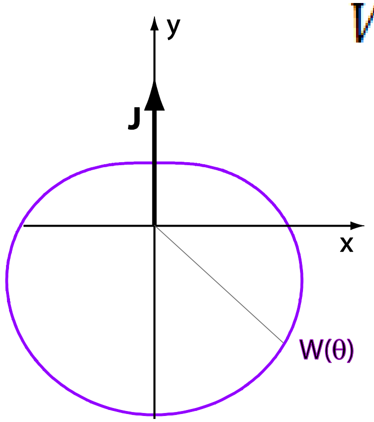
$n \rightarrow p\ e\ \bar{\nu}_e + 782\ \mathrm{keV}$

T p = - p

T σ = - σ

T J = - J

$$W(\theta, E, \sigma_T) \propto 1 + A\,\frac{\vec{J}\cdot\vec{p}}{E} + N\,\vec{J}\cdot\hat{\sigma} + R\,\frac{\vec{J}\cdot\vec{p}\times\hat{\sigma}}{E} + \cdots$$



A- *decay* asymmetry (-0.1173)

R, N – correlation coefficients

Why neutron?

- Long lifetime (886 sec, good and bad…).
- Decays by weak interaction (known from TRV).
- No effects from nuclear or atomic structure (for free neutrons exact value of M_F, M_{GT}).
- It is neutral… (application of high electric fields possible).
- Small decay asymmetry A and small charges involved in decay => (small and precisely known final state interaction correction).
- Made of u and d quark (very small effect from CKM-matrix).

Correlation coefficients N, R and exotic interactions

- Allowing for nonzero exotic couplings in weak interaction (Jackson at al., 57):

$$N \approx 0.276 \cdot Re(S) + 0.335 \cdot Re(T) - A \cdot \frac{m}{E}$$

$$R \approx 0.276 \cdot Im(S) + 0.335 \cdot Im(T) - A \cdot \frac{\alpha m}{p}$$

N_{FSI}~$0.068 \pm 6 \cdot 10^{-4}$

R_{FSI}~$0.0006 \pm 6 \cdot 10^{-6}$

$$T = \frac{C_T + C'_T}{C_A}$$

$$S = \frac{C_S + C'_S}{C_V}$$

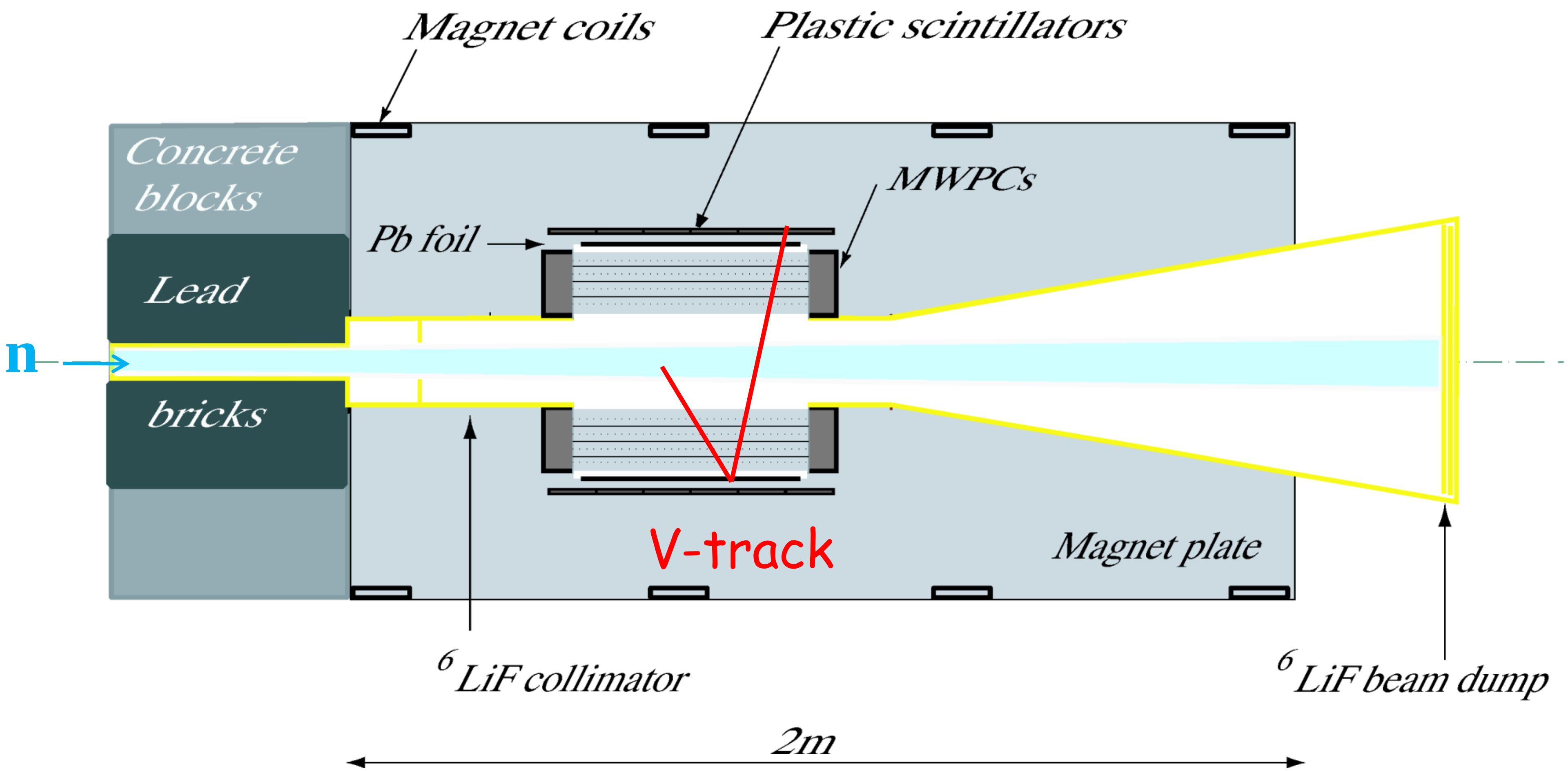
Beyond Standard Model:
S, T – relative strength of scalar and tensor couplings

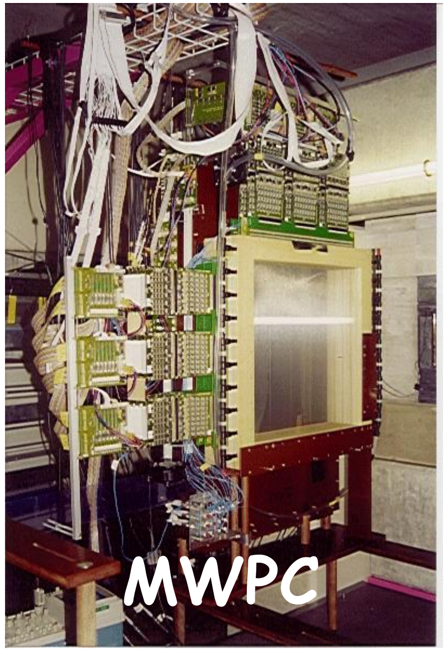
Standard Model
Final state interaction

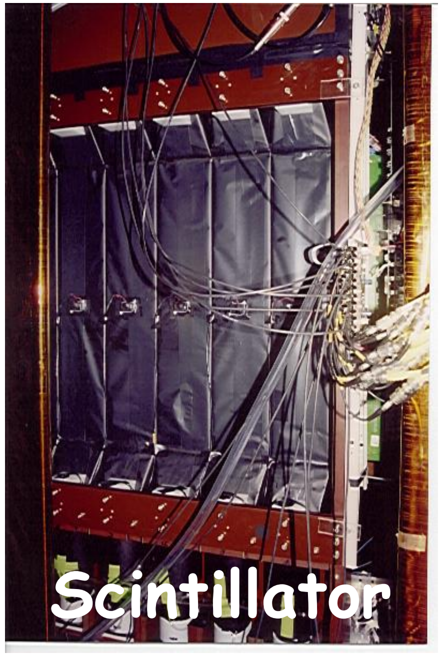
- N measurement: detector test (Re(S), Re(T) known well from other experiments).
- If measured R≠0 ⇒ new mechanism of T(CP) violation, limit on Im(C_S) i Im(C_T).

nTRV experimental setup - top view

PSI, Villigen 2004-2007







nTRV experiment results (exclusion plots)

$$N \approx 0.276 \cdot Re(S) + 0.335 \cdot Re(T) - A \cdot \frac{m}{E} \qquad N_{FSI} \sim 0.068 \pm 6 \cdot 10^{-4}$$

$$R \approx 0.276 \cdot Im(S) + 0.335 \cdot Im(T) - A \cdot \frac{\alpha\, m}{p} \qquad R_{FSI} \sim 0.0006 \pm 6 \cdot 10^{-6}$$

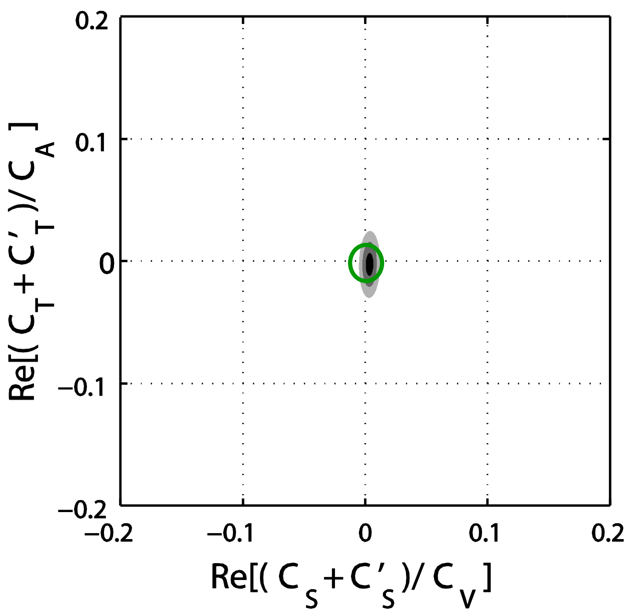
Consistent with Standard Model

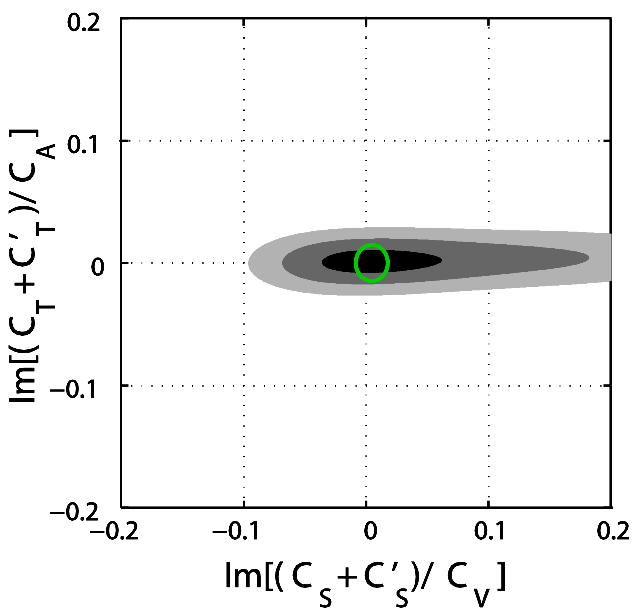
where:

$$T = \frac{C_T + C'_T}{C_A}$$

$$S = \frac{C_S + C'_S}{C_V}$$

Existing limitations and our result





A.Kozela at al ., Phys. Rev C **85**, 045501(2012)

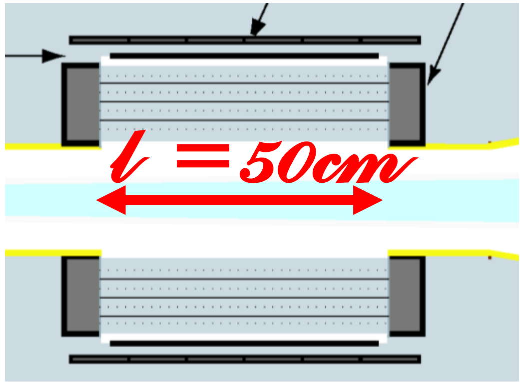
$$N = (62 \pm 12 \pm 5) \cdot 10^{-3}$$

$$R = (4 \pm 12 \pm 5) \cdot 10^{-3}$$

Stat+syst

What next?

- Increasing accuracy by a factor of two: 15 months of measurement.
- Better strategy: increase the length of the detector

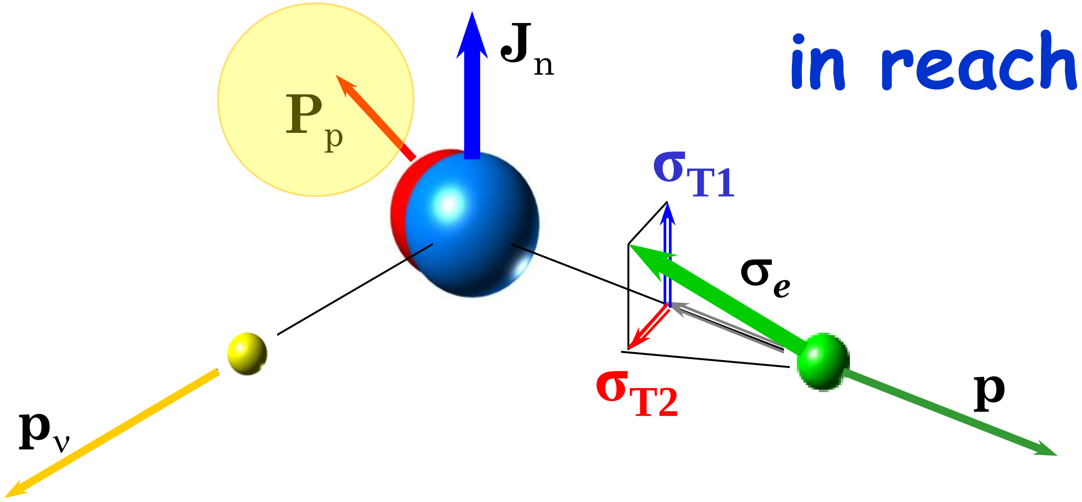


gain factor more than l^3

- No money for both, but …
- 2018: BRAND experiment received support from NCN

Angular correlations in neutron decay

in reach of BRAND experiment



PDG:

$$W(\boldsymbol{J},\boldsymbol{\sigma},E,E_\nu,\boldsymbol{p},\boldsymbol{q}) \propto 1 + \overset{=-0.106(3)}{a}\frac{\boldsymbol{p}\cdot\boldsymbol{q}}{E\,E_\nu} + \boxed{b}\frac{m}{E} + \frac{\langle \boldsymbol{J}\rangle}{j}\left(\overset{=-0.1196(2)}{A}\frac{\boldsymbol{p}}{E} + \overset{=0.9807(30)}{B}\frac{\boldsymbol{q}}{E_\nu} + \overset{=-0.2377(25)}{C}\frac{\boldsymbol{q}}{E_p} + \overset{=-0.00012(20)}{D}\frac{\boldsymbol{p}\times\boldsymbol{q}}{E\,E_\nu}\right) +$$

$$\boldsymbol{\sigma}_T\left(H\frac{\boldsymbol{q}}{E_\nu} + L\frac{\boldsymbol{p}\times\boldsymbol{q}}{E\,E_\nu} + N\frac{\langle \boldsymbol{J}\rangle}{j} + R\frac{\langle \boldsymbol{J}\rangle}{j}\times\frac{\boldsymbol{p}}{E}\right) +$$

$$\boldsymbol{\sigma}_T\left(S\frac{\langle \boldsymbol{J}\rangle}{j}\frac{\boldsymbol{p}\cdot\boldsymbol{q}}{E\,E_\nu} + U\frac{\langle \boldsymbol{J}\rangle}{j}\frac{\boldsymbol{p}\cdot\boldsymbol{q}}{E\,E_\nu} + V\frac{\boldsymbol{q}}{E_\nu}\times\frac{\langle \boldsymbol{J}\rangle}{j}\right)$$

A.Kozela at al.,
Phys. Rev Lett **102**, 172301(2009)

H, L, S, U, V: never measured

Correlation coefficients and exotic interactions, sensitivity factors

	SM (λ)	FSI (λ)	c(ReS)	c(ReT)	c(ImS)	c(ImT)
a	-0.104793	0	-0.171405†	0.171405†	-0.000727	+0.001171
b	0	0	+0.171405	+0.828595	0	0
A	-0.117233	0	0	0	-0.000923	+0.001420
B	+0.987560	0	-0.126422	+0.194539	0	0
D	0	0	0	0	+0.000923	-0.000923
H	0	+0.060888	-0.171405	+0.276198	0	0
L	0	-0.000444	0	0	+0.171405	-0.276198
N	0	+0.068116	-0.217582	+0.334815	0	0
R	0	+0.000497	0	0	-0.217582	+0.334815
S	0	-0.001845	+0.217582	-0.217582	0	0
U	0	0	-0.217582	+0.217582	0	0
V	0	0	0	0	-0.217582	+0.217582

J.D.Jackson, SB Treiman, HW Wyld, Nucl.Phys, 4206-212, 1957

Leading order

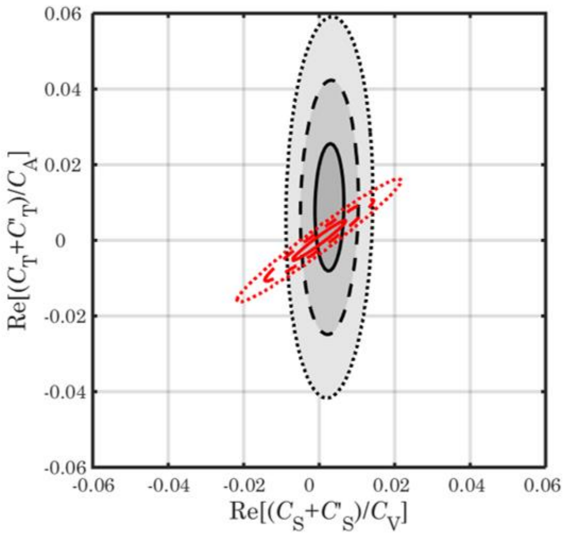
No recoil

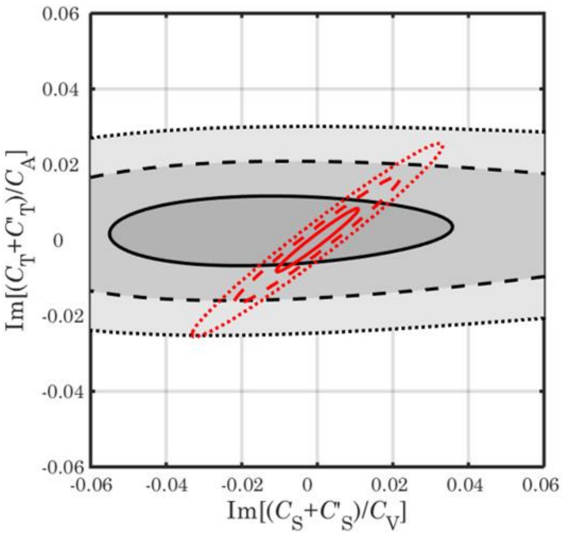
Point charge

* Kinematical factor averaged over electron kinetic energy E_k = (200,783) keV

BRaND experiment projections (exclusion plots for accuracy $5\cdot 10^{-4}$)

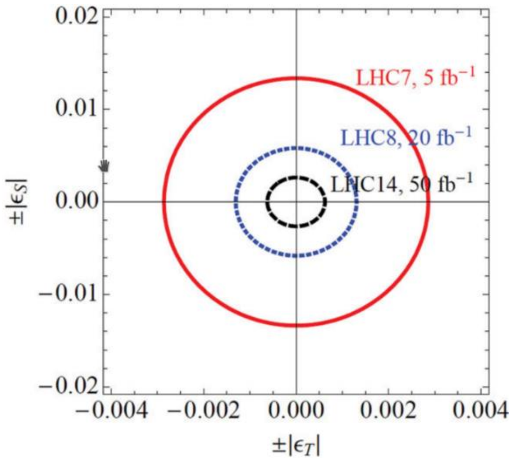
Courtesy of K. Bodek





$$W(\boldsymbol{J},\boldsymbol{\sigma},E,E_\nu,\boldsymbol{p},\boldsymbol{q}) \propto 1 + a\frac{\boldsymbol{p}\cdot\boldsymbol{q}}{E\,E_\nu} + b\frac{m}{E} + \frac{\langle \boldsymbol{J}\rangle}{j}\left(A\frac{\boldsymbol{p}}{E} + B\frac{\boldsymbol{q}}{E_\nu} + C\frac{\boldsymbol{q}}{E_p} + D\frac{\boldsymbol{p}\times\boldsymbol{q}}{E\,E_\nu}\right) +$$
$$\boldsymbol{\sigma}_T\left(H\frac{\boldsymbol{q}}{E_\nu} + L\frac{\boldsymbol{p}\times\boldsymbol{q}}{E\,E_\nu} + N\frac{\langle \boldsymbol{J}\rangle}{j} + R\frac{\langle \boldsymbol{J}\rangle}{j}\times\frac{\boldsymbol{p}}{E}\right) +$$
$$\boldsymbol{\sigma}_T\left(S\frac{\langle \boldsymbol{J}\rangle}{j}\frac{\boldsymbol{p}\cdot\boldsymbol{q}}{E\,E_\nu} + U\frac{\langle \boldsymbol{J}\rangle}{j}\frac{\boldsymbol{p}\cdot\boldsymbol{q}}{E\,E_\nu} + V\frac{\boldsymbol{q}}{E_\nu}\times\frac{\langle \boldsymbol{J}\rangle}{j}\right)$$

Transition from $C_{T,S}$ and $C'_{T,S}$ to $\epsilon_{S,T}$ via EFT
T.Bhattacharya at al .,Phys. Rev D **85**, 054512(2012)



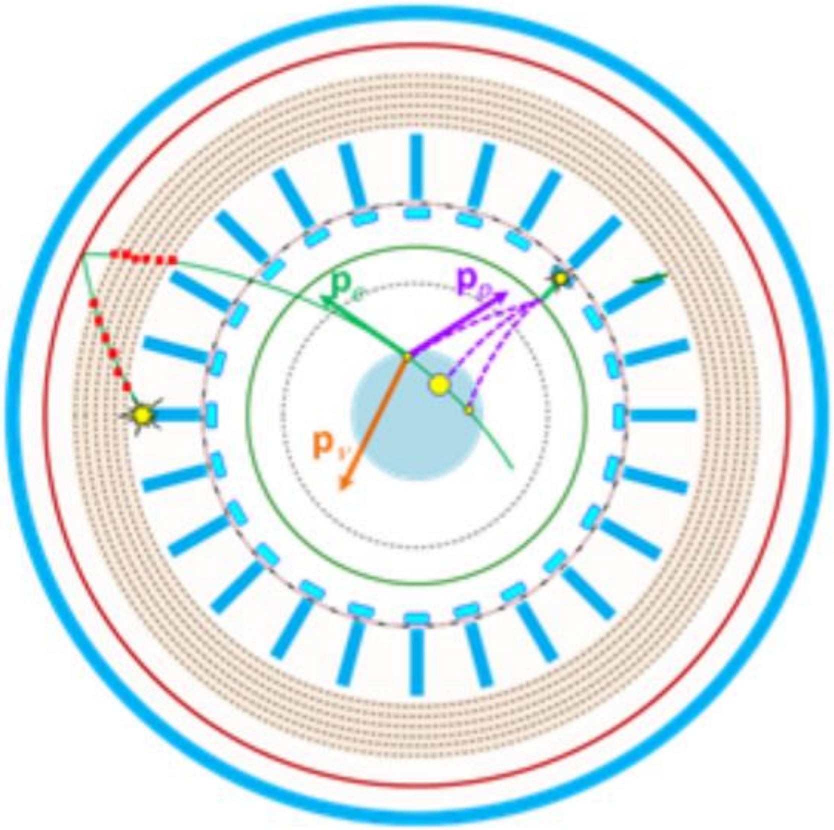
M.Gonzalez-Alonso at al.

BRAND experiment – vectors we need

- Neutron spin
- Electron momentum
- Transverse electron polarization
- Proton momentum

- Exclusive kinematics

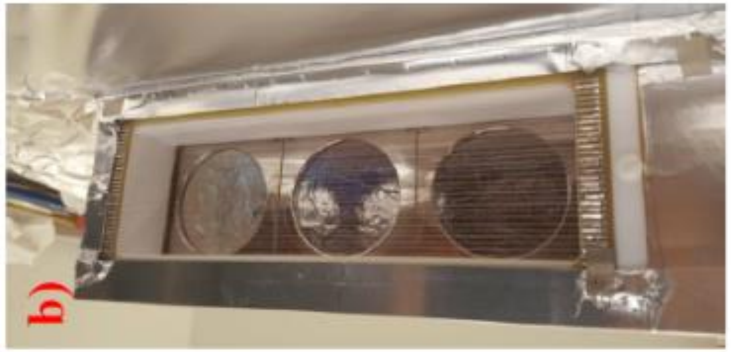
Principle of vertex reconstruction with 3-body kinematics

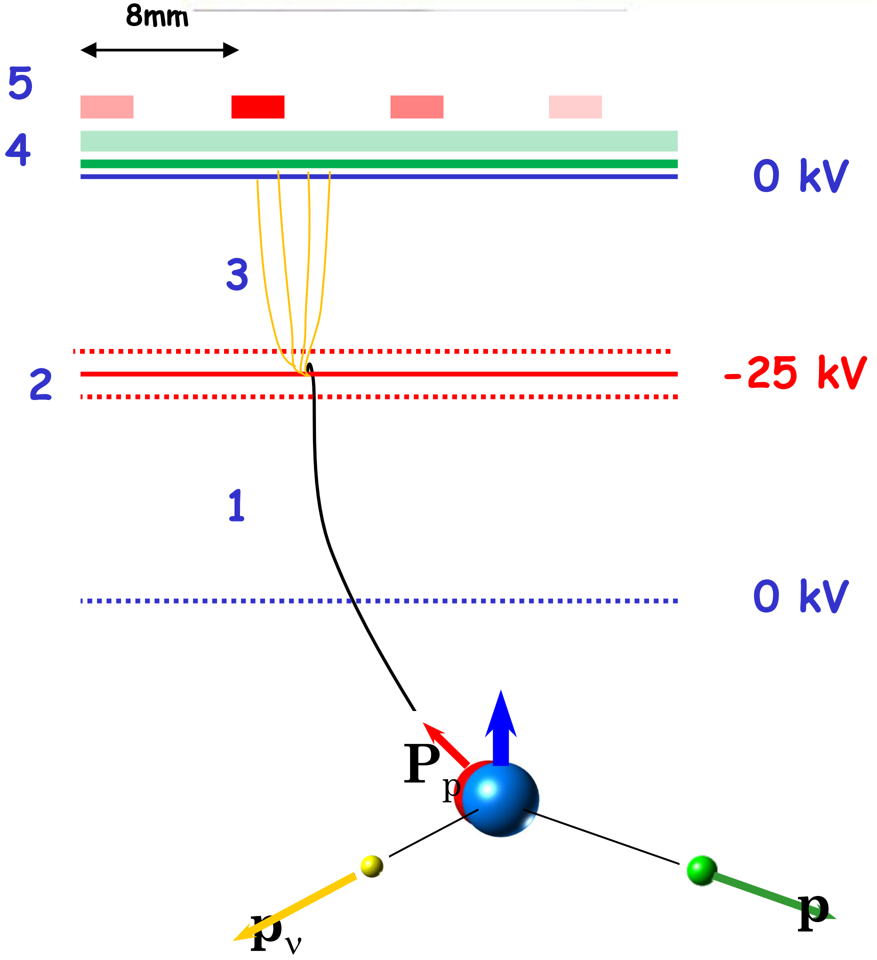


Proton detection

- Proton end-point energy 750 eV
- Problem of neutralization – good vacuum <10^{-4}
- Preacceleration in electric field (1)
- Conversion to electrons (~10)
- 110 nm converter foil (2) Albert Young, USA

  80nm 6F6Fpoliamid + 20nm LiF + 10nm Al
- Acceleration of electrons (25keV) (3)
- Measurement in thin scintillator (35 µm) (4)
- Not sensitive to direct electrons from neutron decay
- Position sensitive light detection SiPM (5)

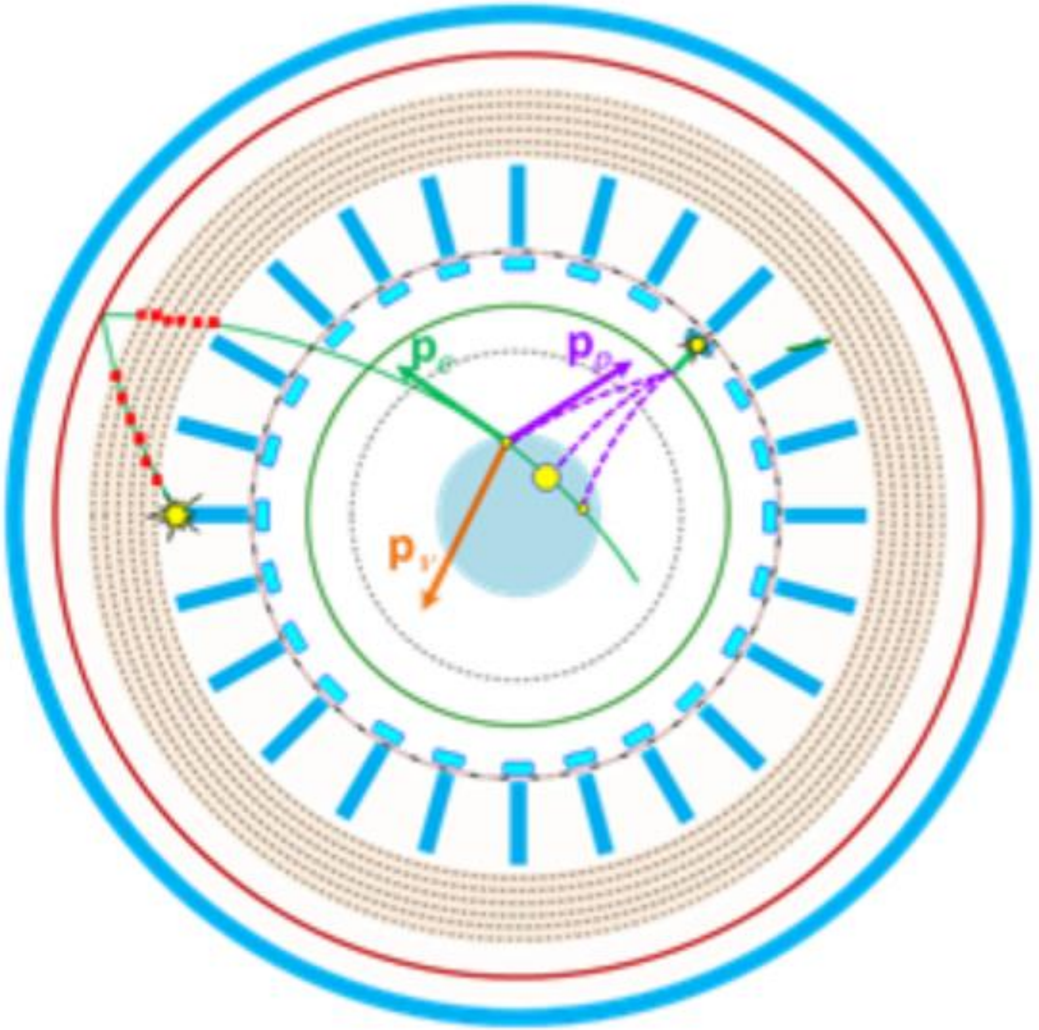




Proton momentum

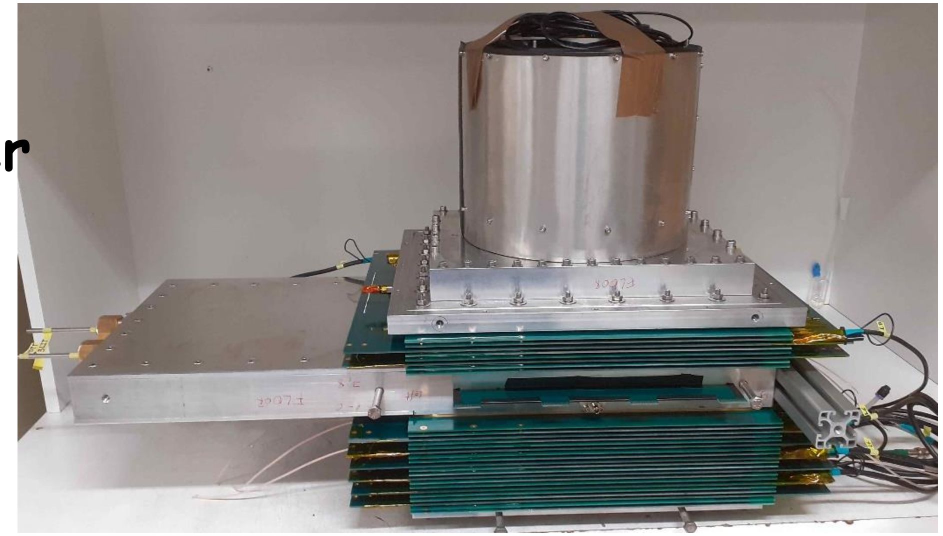
- Position sensitive proton measurement -> emission angles
- Electron momentum + n-beam volume -> vertex reconstruction
- Precise timing -> proton time-of-flight
- Overdetermined kinematic -> kinematic fit to improve knowledge of proton momentum

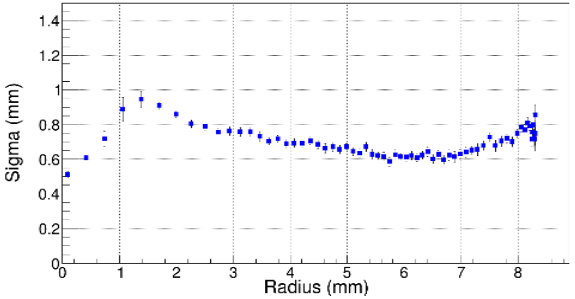
Principle of vertex reconstruction with 3-body kinematics

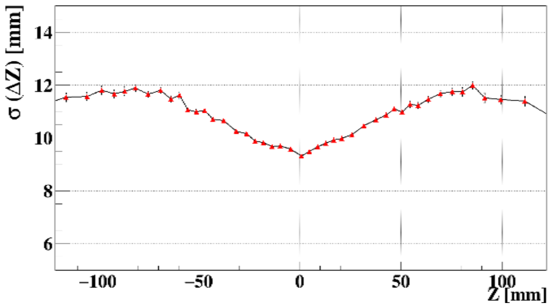


Electron tracking

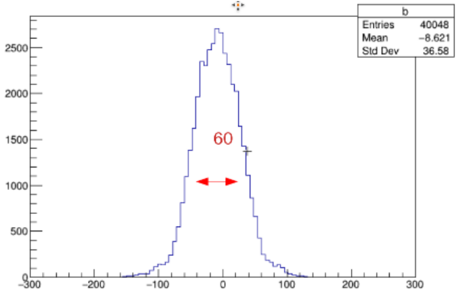
- Electron end-point-energy 782 keV
- Electron tracker based on multiwire drift chamber
  - Better position resolution from drift time
  - Charge division method (less planes x2)
- Hexagonal cell geometry (less wires x2)
- Gas mixture 1/4/95 alcohol/isobutan/He
- Efficiency ~97%

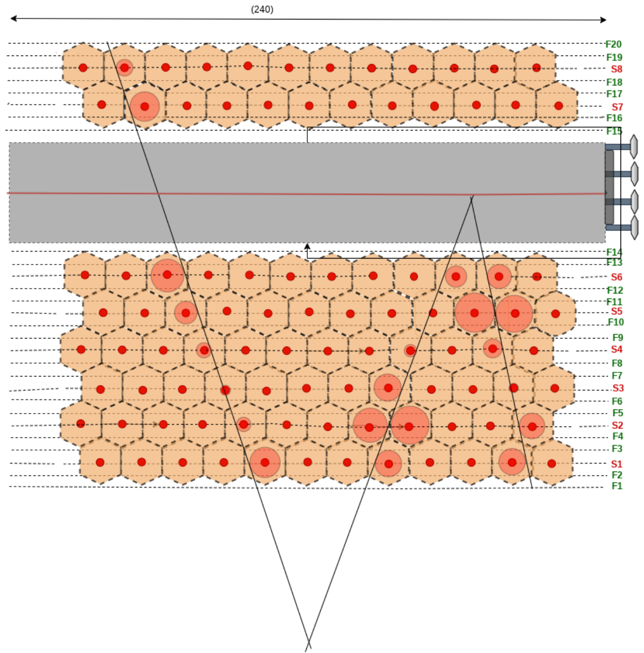






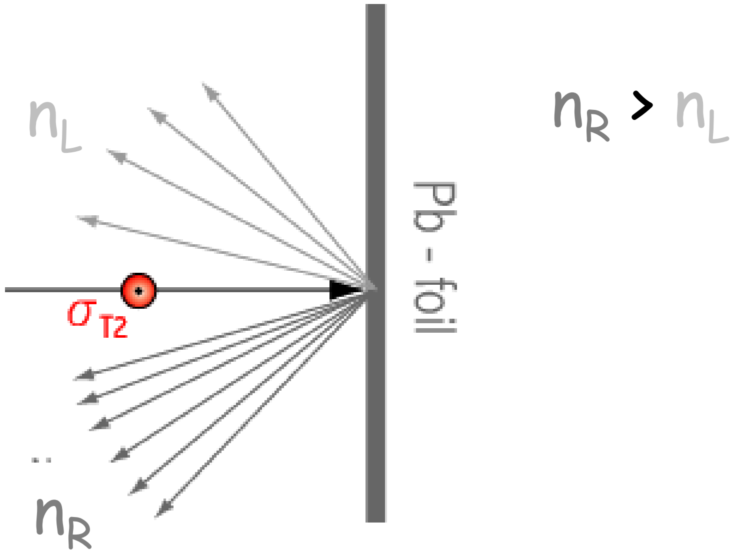
Beam profile



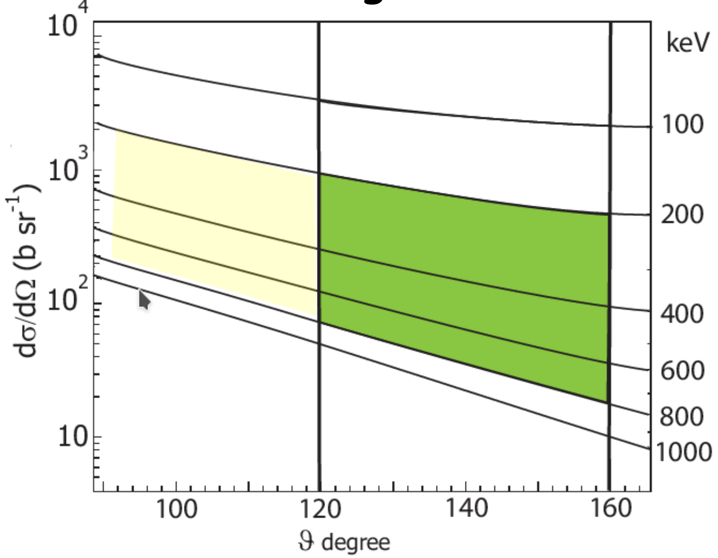


Transverse electron polarization

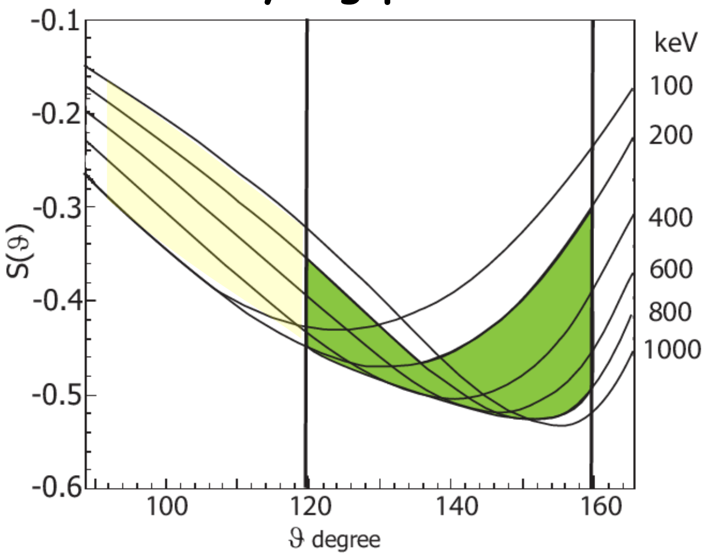
- Mott polarimetry
- Asymmetry due to spin-orbit interaction
- Backscattering from heavy nuclei (Pb, Au, U)
- Increased scattering angle range (compared to nTRV)



Mott scattering cross section



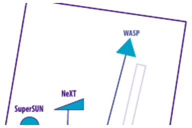
Analyzing power

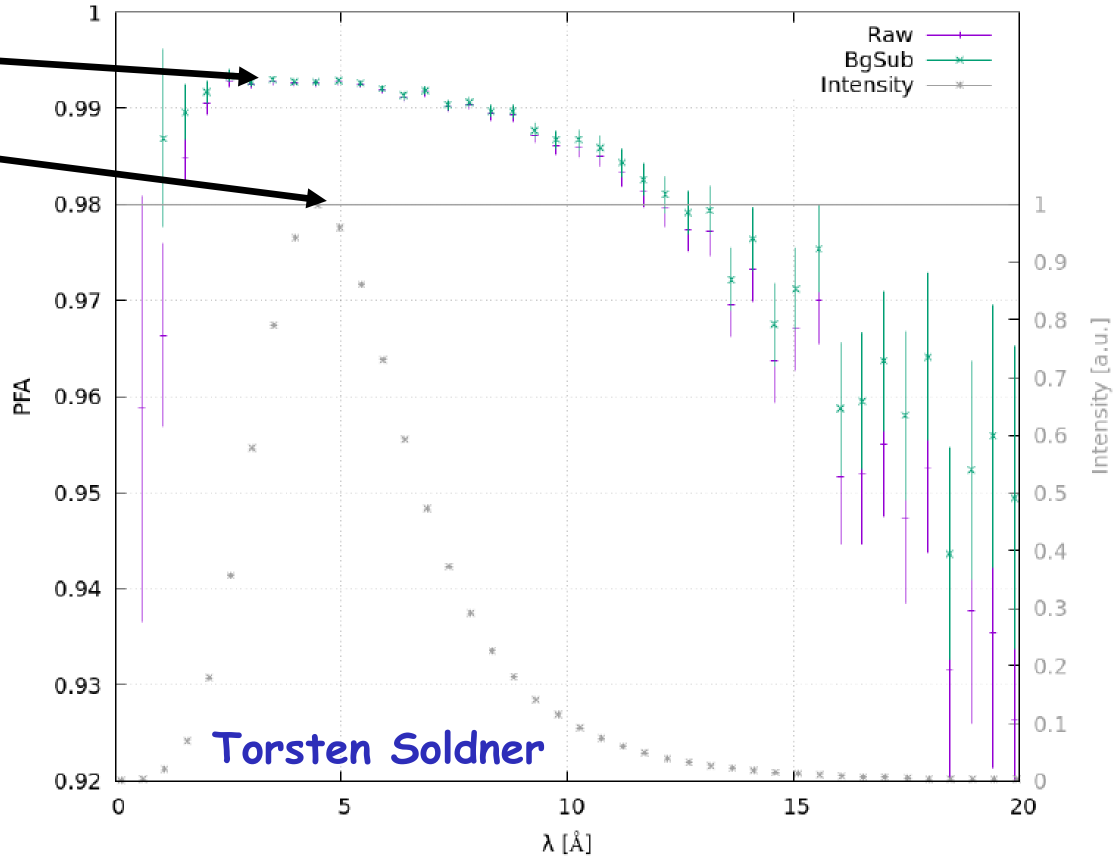


Neutron spin: polarized cold neutron beam

Homogenous spin holding magnetic field

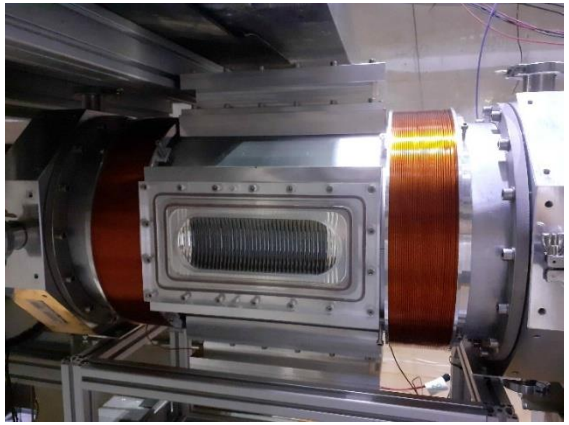
- PF1b areal at ILL, Grenoble
- Polarization > 99.2%
- “Cold”: mean wavelength ~4.3 Å
- Intensity 2 10^9 n/cm^2/s
- Cross section 6x6 cm^2
- Beam divergence ~1%
- Vacuum in decay chamber

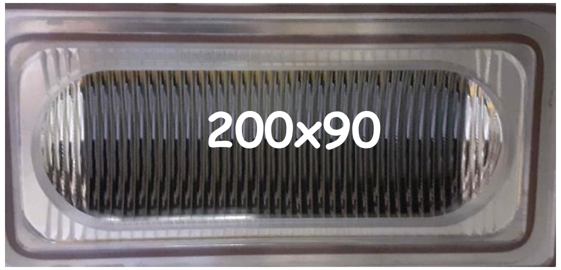




Test runs performed at ILL, Grenoble 2020, 2021 - summary

- **Test of the prototype in real conditions**
  - Upgraded beam polarizer installed
  - Decay chamber integrated with the beam line
  - Neutron spin holding magnetic field and Earth field compensation
  - Vacuum chamber with large thin window (4.5μm foil, Kevlar reinforced) pressure $<10^{-5}$mb
  - Small beam related background observed





- **Data analysis finished, serious problems identified:**
  - Difficult SiPM gain matching for proton detector
  - Problem with custom made Charge-to-Time converter
  - More selective trigger logic must be implemented

Summary

- Neutron decay – perfect laboratory for BSM physics searches
- Correlation coefficients of neutron decay important for TRV effects, may be used to strengthen limits on scalar and tensor couplings of weak interaction
- First measurement of N- and R-correlations in neutron decay successfully finished (nTRV)
- Its successor (BRAND) aimed at simultaneous measurement of 11 correlation coefficients is in early stage

Thank You