"New Physics" in neutron decay – BRAND experiment

Search for Time Reversal Violation

by measurement of angular correlations in neutron decay

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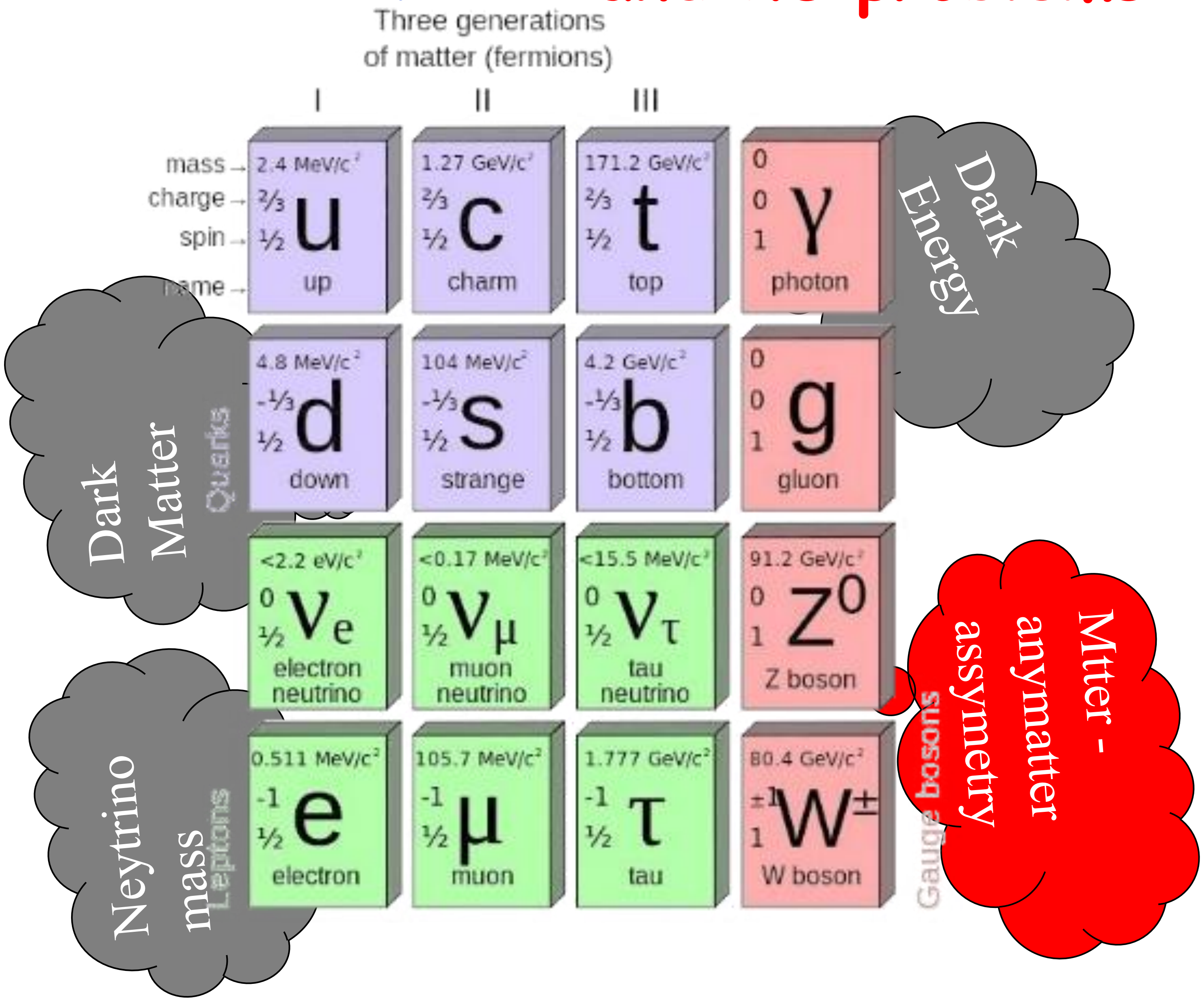
Standard Model and its problems



Time reversal violation

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

$$\begin{pmatrix} 1-½\lambda^2 & \lambda & A\lambda^3 \varrho e^{i\delta_{KM}} \\ -\lambda & 1-½\lambda^2 & A\lambda^2 \\ A\lambda^3\left[1-\varrho e^{-i\delta_{KM}}\right] & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

  - Many orders of magnitude to small to account for observed matter-antymatter 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 ($d_n \approx 2.9 \cdot 10^{-26}$ ecm $\Rightarrow \theta < 10^{-9}$) ... „Strong CP problem”

- Final state interactions (FSI)

TRV in weak interaction?

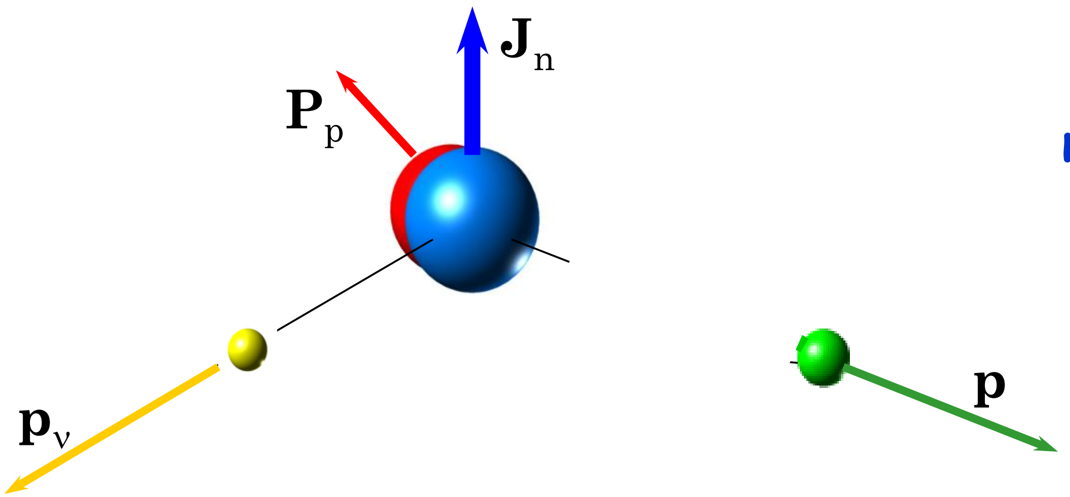
- General form of Lorenz-invariant Hamiltonian of weak ineraction for *n decay:*

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

- Standard Model: V-A interaction, ($C_V = C'_V = 1$, $C_A = C'_A = \lambda = -1.27$, 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

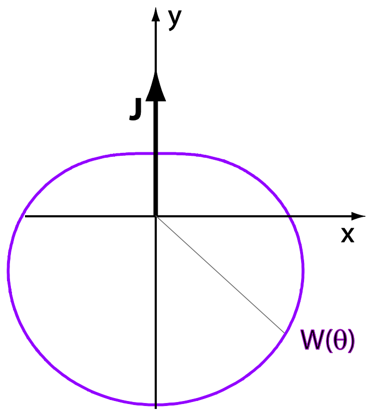


(~885.7s)

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

$T\,\sigma = -\,\sigma$

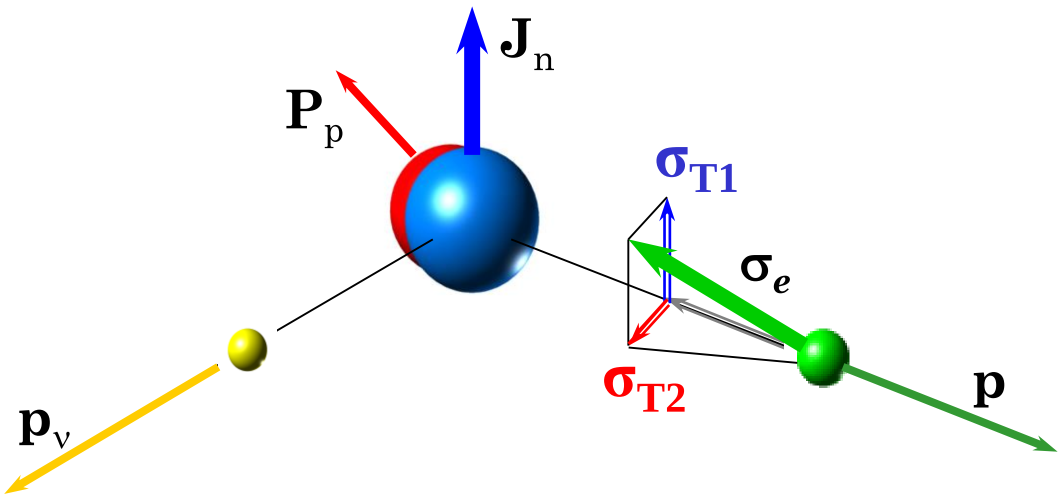
$$W(\theta, E) \propto 1 + A\,\frac{\vec{J}\cdot\vec{p}}{E} + \cdots$$



A- *decay* asymmetry (-0.1173)

R, *N* – correlation coefficients

Angular correlations in neutron decay



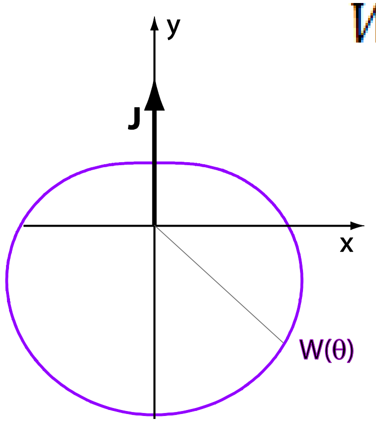
(~885.7s)

n -> p e $\bar{\nu}_e$ + 782 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)

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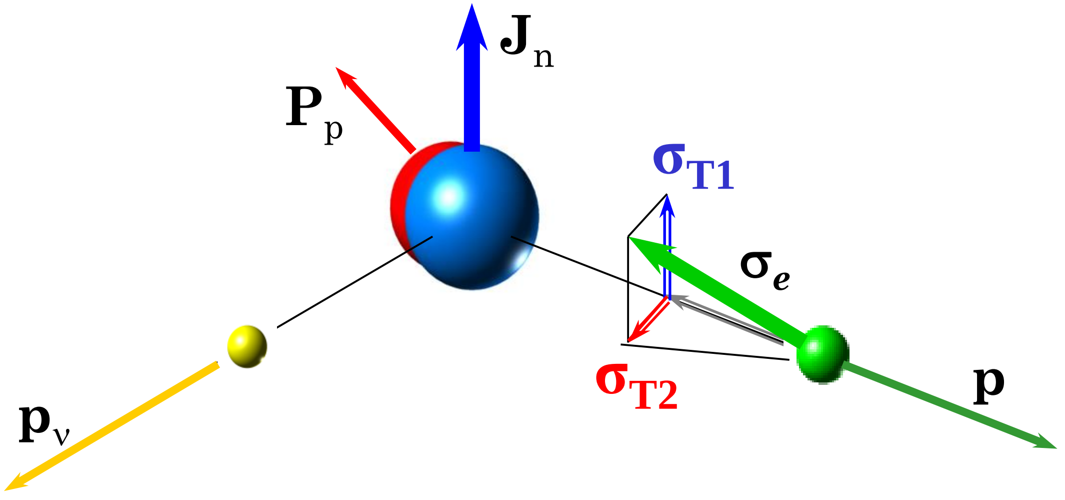
Angular correlations in neutron decay



PDG:

$$W(J,\sigma,E,E_\nu,p,q) \propto 1 + \overset{=-0.103(4)}{a}\frac{p\cdot q}{E\ E_\nu} + b\frac{m}{E} + \frac{\langle J\rangle}{j}\left(\overset{=-0.1188(7)}{A}\frac{p}{E} + \overset{=0.9807(30)}{B}\frac{q}{E_\nu} + \overset{=-0.2377(25)}{C}\frac{q}{E_p} + \overset{=-0.0001(2)}{D}\frac{p\times q}{E\ E_\nu}\right) +$$

$$\sigma\left(G\frac{p}{E} + H\frac{q}{E_\nu} + K\frac{p}{E+m}\frac{p\cdot q}{E\ E_\nu} + L\frac{p\times q}{E\ E_\nu}\right) +$$

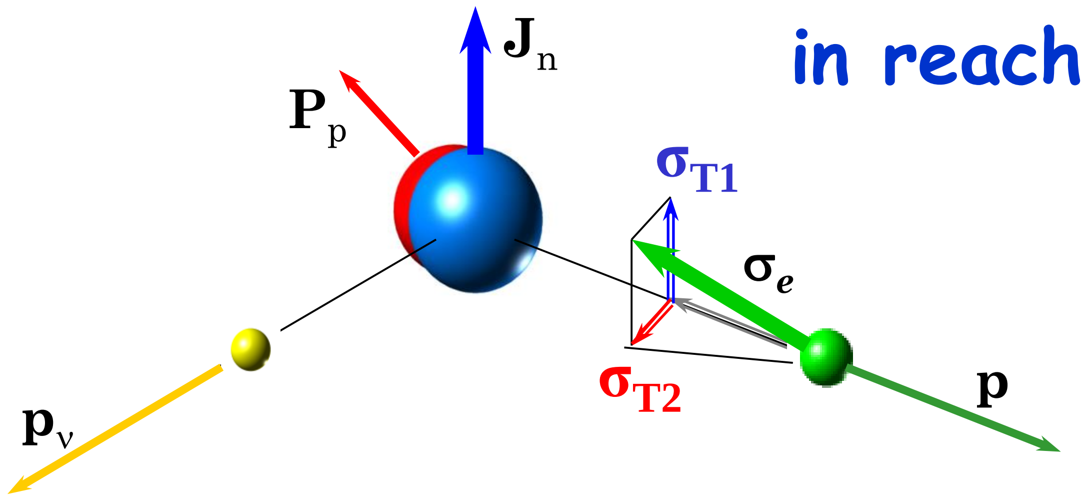
$$\frac{\langle J\rangle}{j}\left(N\frac{\sigma}{E} + Q\frac{\vec{p}}{E}\frac{\vec{p}\cdot\sigma}{E+m} + R\frac{p\times\sigma}{E} + S\,\sigma\frac{p\cdot q}{E\ E_\nu} + T\,q\frac{\sigma\cdot p}{E\ E_\nu}\right) +$$

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

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

Angular correlations in neutron decay

in reach of BRAND experiment



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

Why neutron decay?

- Easiest and most accurate transition from measured observables to basic constants of weak interaction
- No nuclear structure effects.
  - Fermi and Gamow-Teller matrix elements known exactly,

    $M_F = 1$, $M_{GT} = \sqrt{3}$.
- Small and accurately known corrections for final state interaction, recoil…
  - In final state only proton, charge 1 – small Coulomb interaction.
  - No corrections due to atomic electrons orbitals.
  - Small decay asymmetry.
  - Small decay energy.
- Consists of u and d quarks

Correlation coefficients and exotic interactions, general form

TRV

$$X = X_{SM} + X_{FSI} + c_{\mathrm{Re}\,S}\,\mathrm{Re}\,\boldsymbol{S} + c_{\mathrm{Re}\,T}\,\mathrm{Re}\,\boldsymbol{T} + c_{\mathrm{Im}\,S}\,\mathrm{Im}\,\boldsymbol{S} + c_{\mathrm{Im}\,T}\,\mathrm{Im}\,\boldsymbol{T}$$

where:

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

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

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

$$G = -1$$

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

$$Q = 2\lambda\frac{1+\lambda}{1+3\lambda^2}$$

$$b=D=H=L=N=R=S=U=W=0$$

$$N_{fsi} = \frac{m}{E}\cdot\frac{2\lambda(1-\lambda)}{1+3\lambda^2} = -\frac{m}{E}\cdot A$$

$$R_{fsi} = \frac{\alpha\, m}{p}\cdot\frac{2\lambda(1-\lambda)}{1+3\lambda^2} = -\frac{\alpha\, m}{p}\cdot A$$

$$\boldsymbol{S} = \frac{C_S + C_S'}{C_V}$$

$$\boldsymbol{T} = \frac{C_T + C_T'}{C_A}$$

and $c_{\mathrm{Re}\,S}$, $c_{\mathrm{Re}\,T}$, $c_{\mathrm{Im}\,S}$, $c_{\mathrm{Im}\,T}$

are functions of $\lambda = \dfrac{C_A}{C_V}$ and kinematical quantities

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

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

Leading order

No recoil

Point charge

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

† $(|C_S|^2+|C'_S|^2)/2$ instead of ReS and $(|C_T|^2+|C'_T|^2)/2$ instead of ReT, respectively

Courtesy of K. Bodek

nTRV experiment results (exclusion plots)

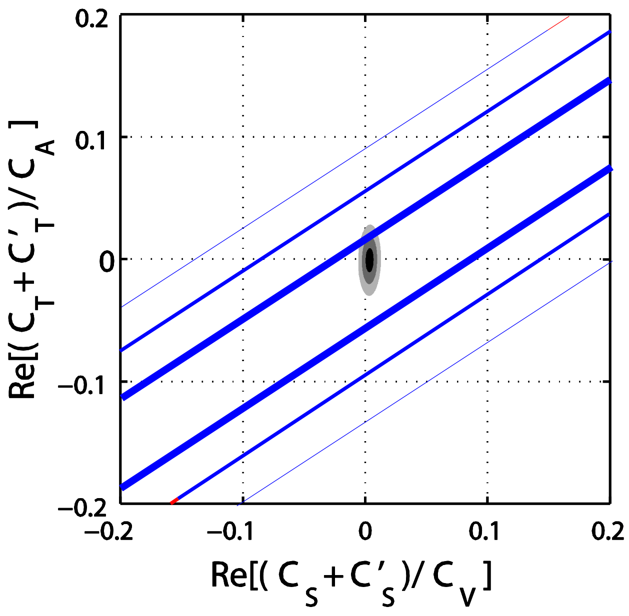
$$N \approx 0.276 \cdot Re(S) + 0.335 \cdot Re(T) - A \cdot \frac{m}{E} \qquad N_{FSI} \sim 0.068 \pm 6 \cdot 10^{-4}$$

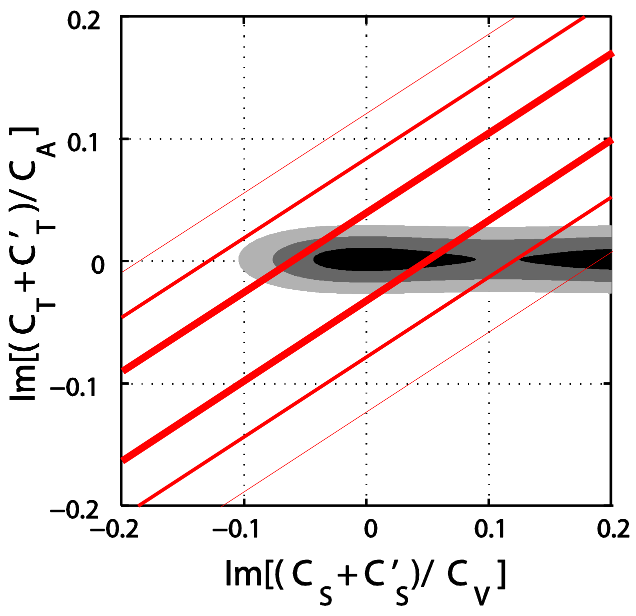
$$R \approx 0.276 \cdot Im(S) + 0.335 \cdot Im(T) - A \cdot \frac{\alpha\, m}{p} \qquad R_{FSI} \sim 0.0006 \pm 6 \cdot 10^{-6}$$

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

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

Existing limitations and our result





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

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

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

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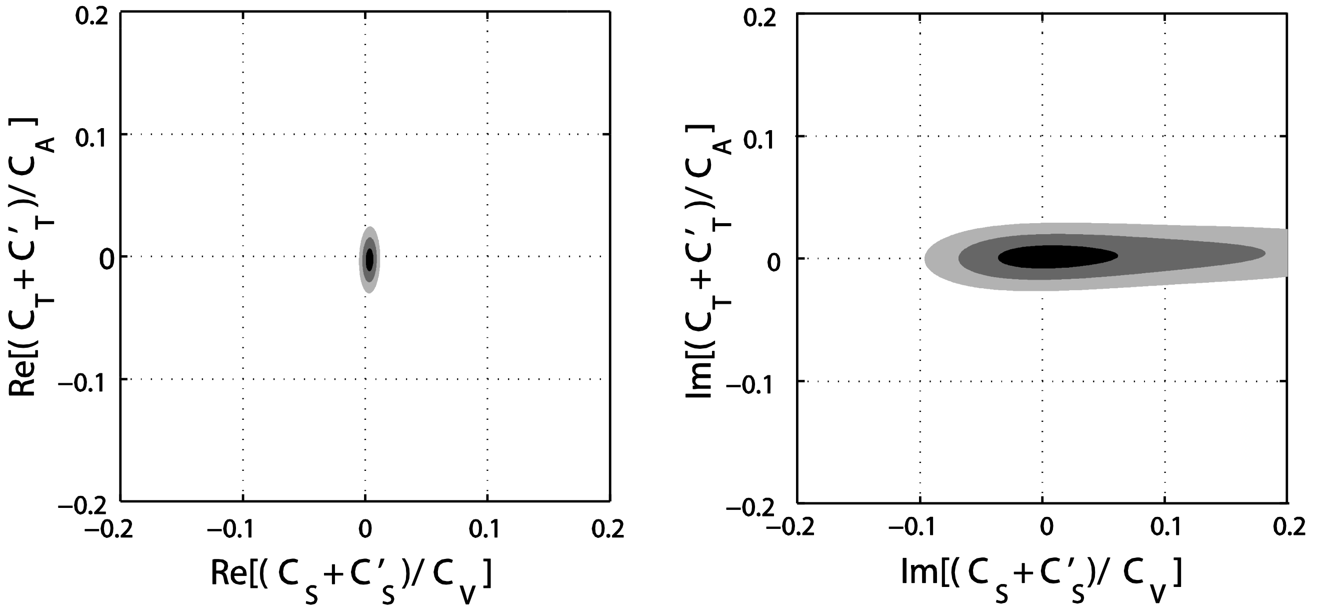
$$R \approx 0.276 \cdot Im(S) + 0.335 \cdot Im(T) - A \cdot \frac{\alpha\, m}{p} \qquad R_{FSI} \sim 0.0006 \pm 6 \cdot 10^{-6}$$

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

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

Existing limitations and our result



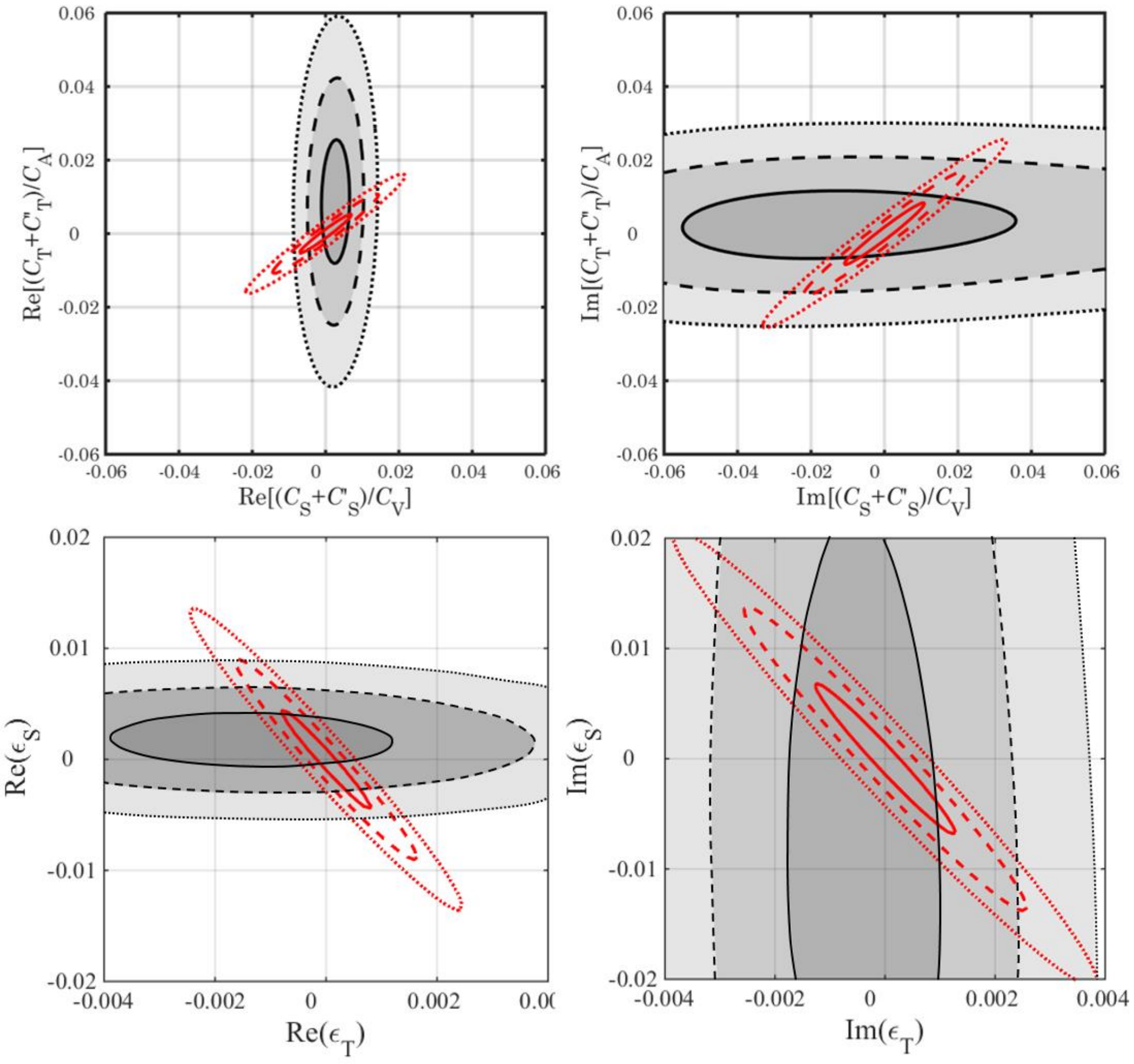
A.Kozela at al .,
Phys. Rev C **85**, 045501(2012)

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

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

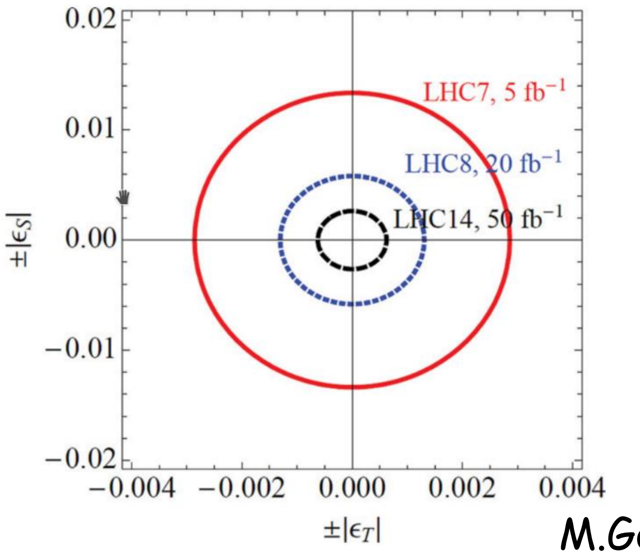
BRaND experiment projections (exclusion plots for accuracy $5 \cdot 10^{-4}$)

Courtesy of K. Bodek



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

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.

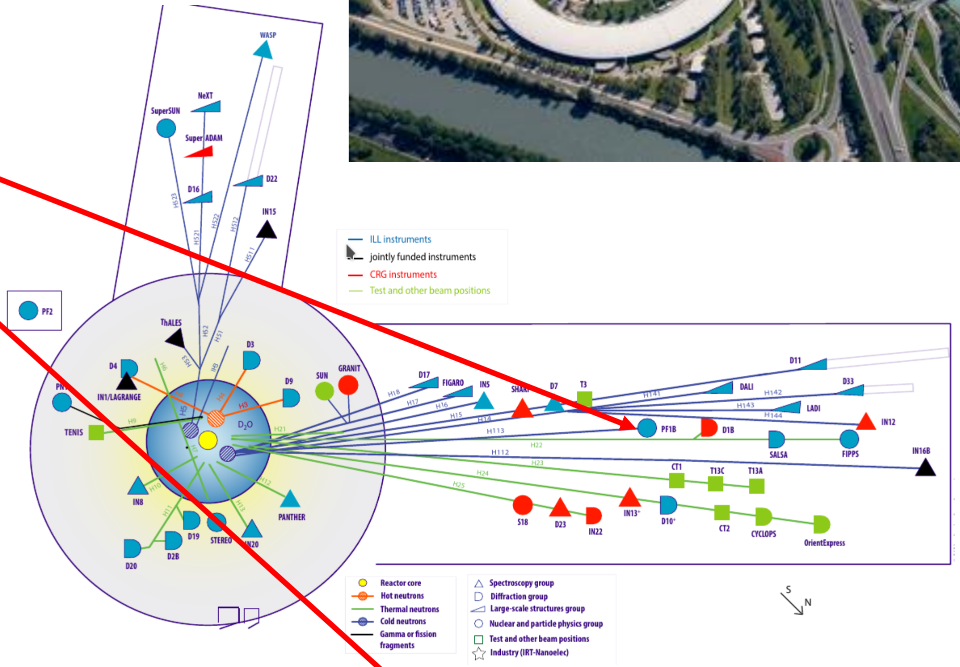
BRAND experiment – vectors we need

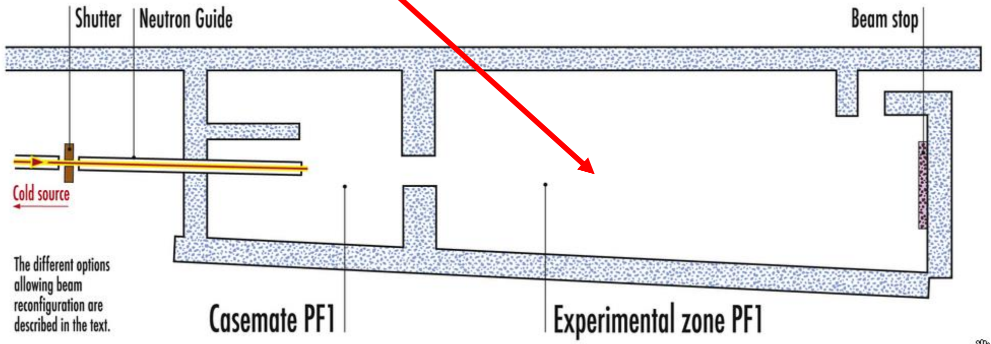
- Neutron spin
- Electron momentum
- Transverse electron polarization
- Proton momentum

Neutron spin: polarized cold neutron beam

Homogenous spin holding magnetic field

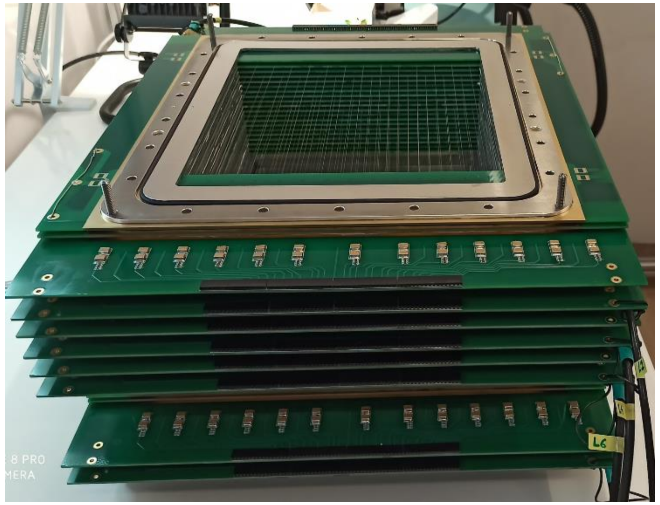
- PF1b areal at ILL, Grenoble
- Polarization > 99.7% (80%)
- “Cold”: mean wavelength ~4.3 Å
- Intensity 2 10^9 n/cm^2/s
- Cross section 6x6 cm^2
- Beam divergence ~1%
- Vacuum in decay chamber (He)

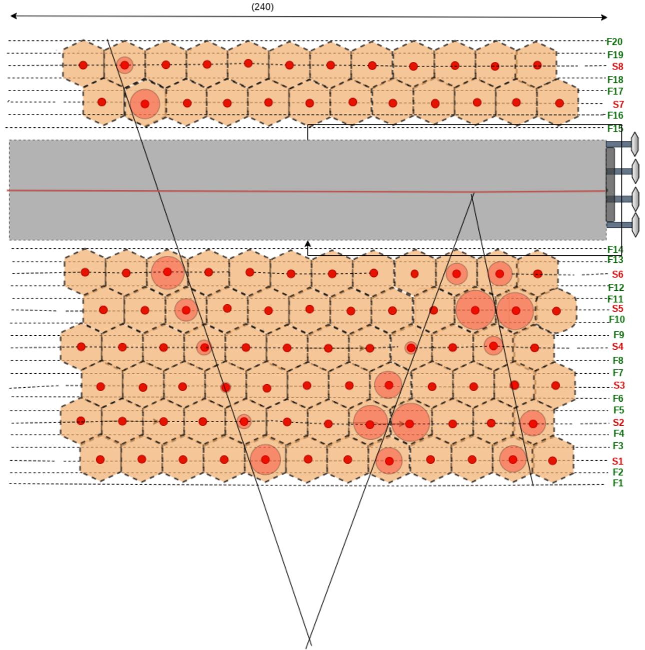


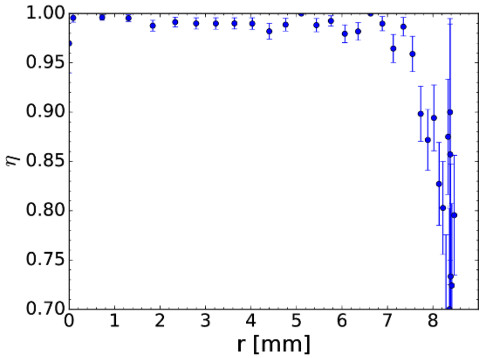


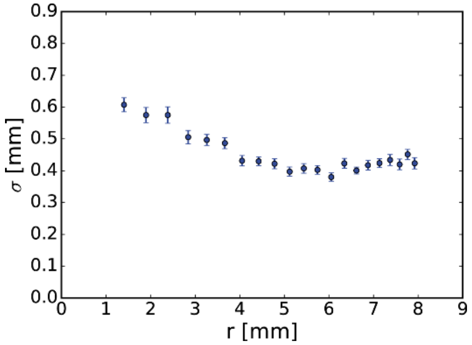
Electron momentum

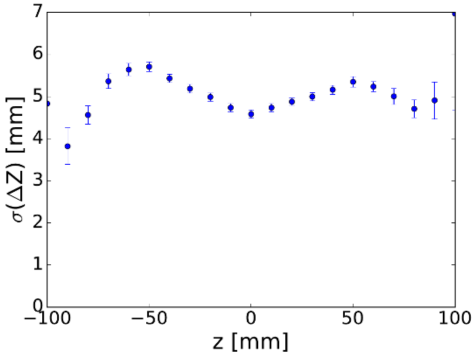
- Electron end-point-energy 782 keV
- Electron tracker based on multiwire drift chamber
  - Better position resolution from drift time (x5)
  - Charge division readout (less planes x2 and comparable resolution)
- Hexagonal cell geometry (less wires x2)
- Gas mixture 1/4/95 alcohol/isobutan/He (almost x2)
- Efficiency ~97%





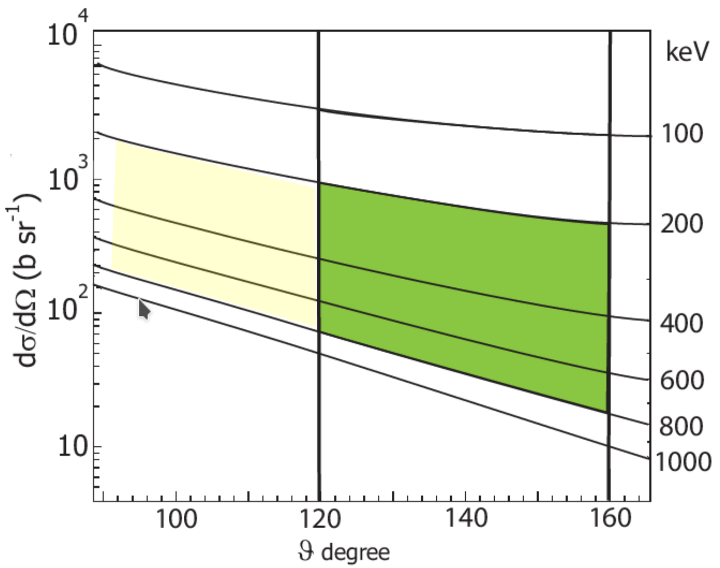


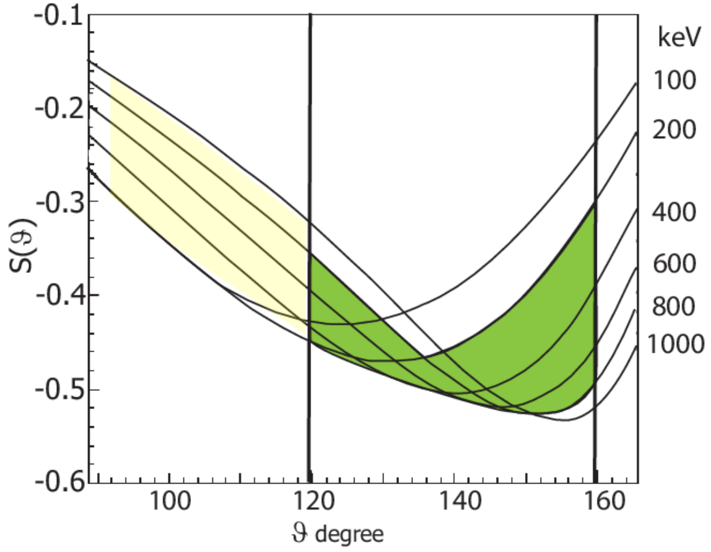


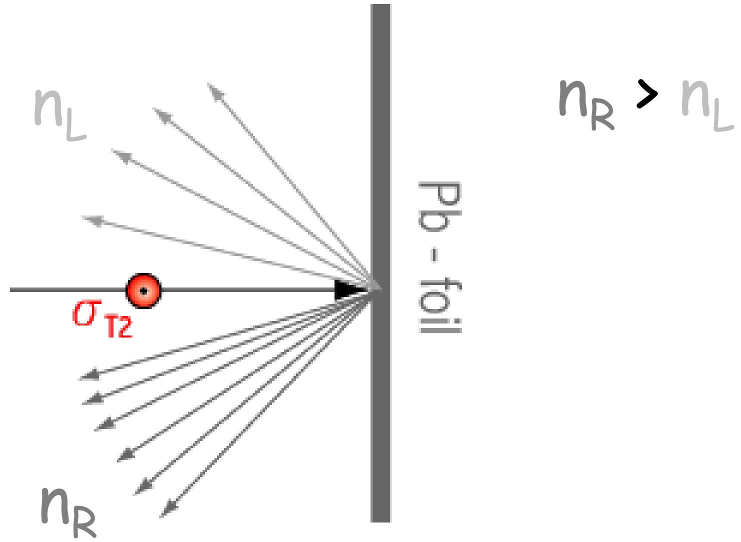


Transverse electron polarization

- Electron tracking and polarization analysis
- Mott polarimetry
- Backscattering from heavy nuclei (Pb, Au, U)



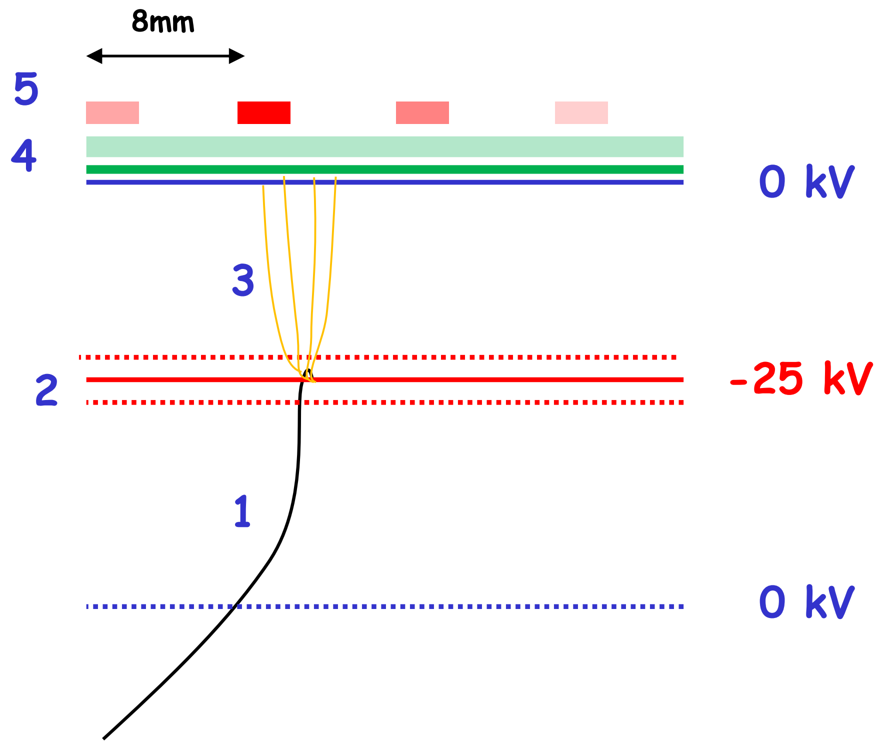




Proton detection

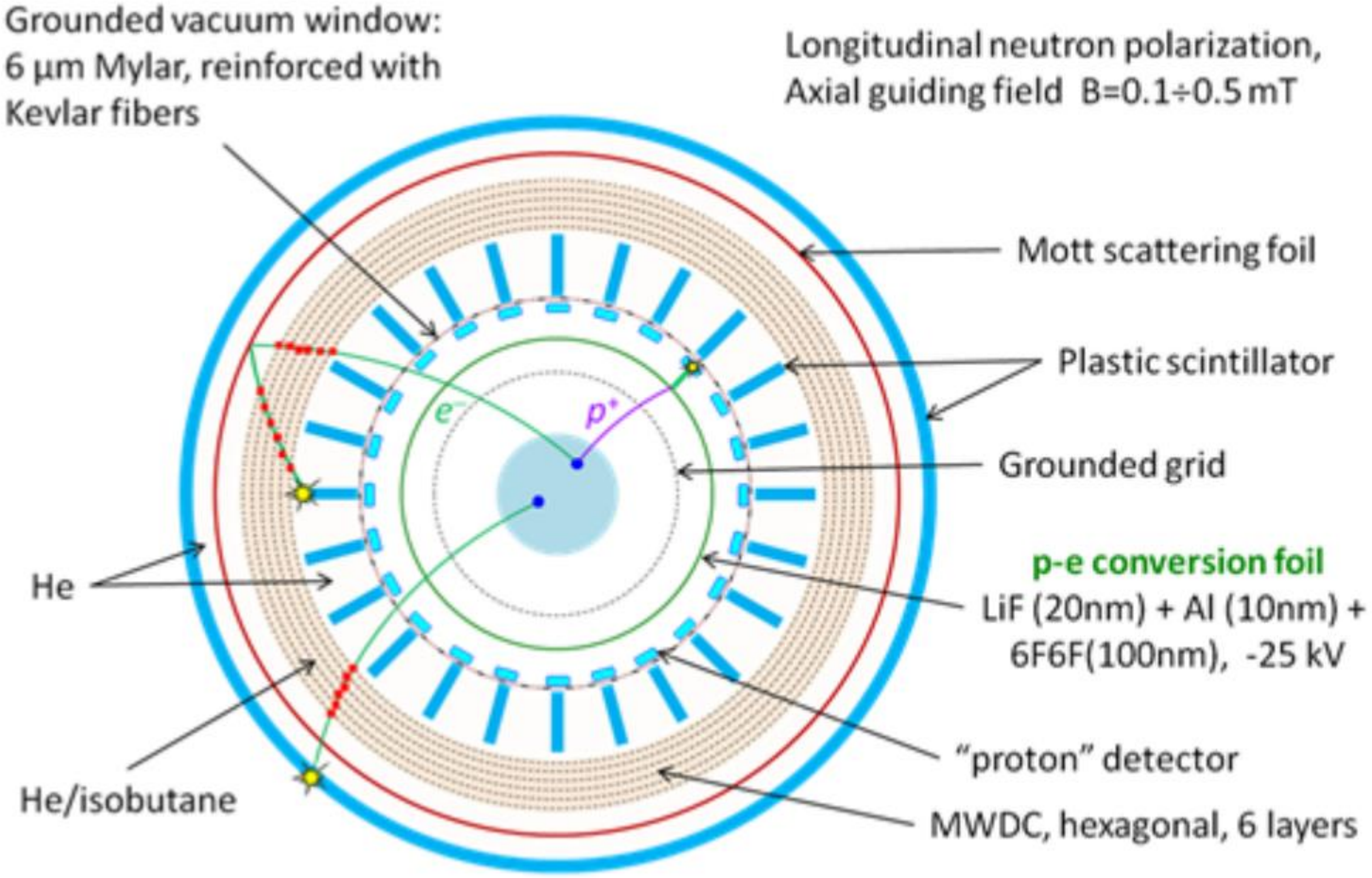
- Proton end-point energy 750 eV
- Problem of neutralization – good vacuum $<10^{-4}$
- Preacceleration in electric field (1)
- Conversion to electrons (~10)
- 110 nm converter foil (2)

  80nm 6F6Fpoliamid + 20nm LiF + 10nm Al
- Acceleration of electrons (~200keV) (3)
- Measurement in thin scintillator (35 μm) (4)
- Not sensitive to direct electrons from neutron decay
- Position sensitive light detection SiPM (5)



Brand – the principle

Initial design

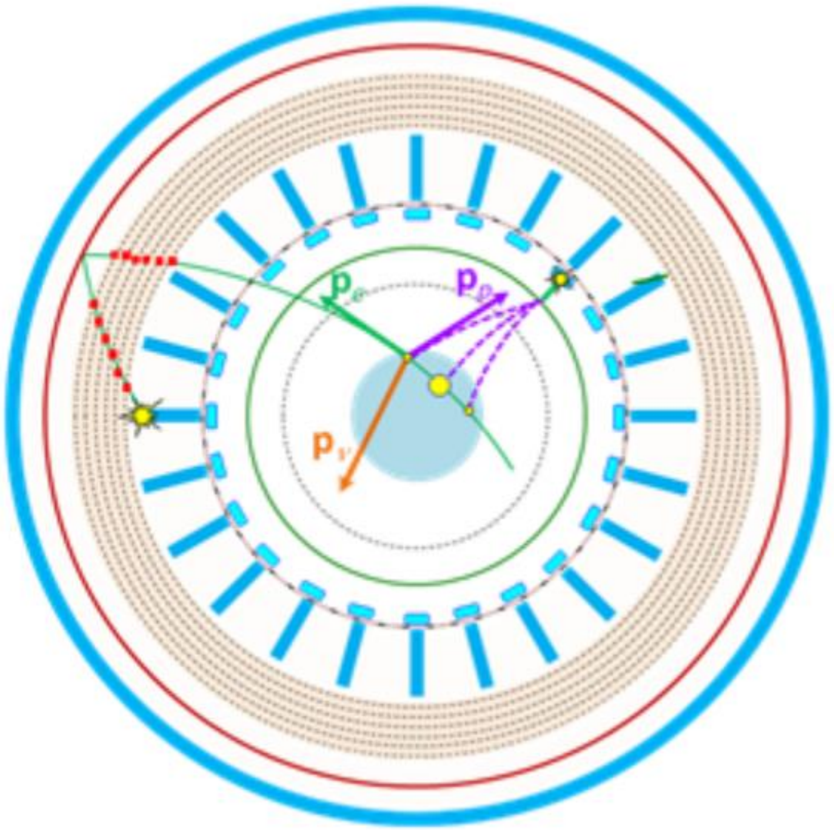


Courtesy of K. Bodek

Proton momentum reconstruction

Initial design

Principle of vertex reconstruction with
3-body kinematics

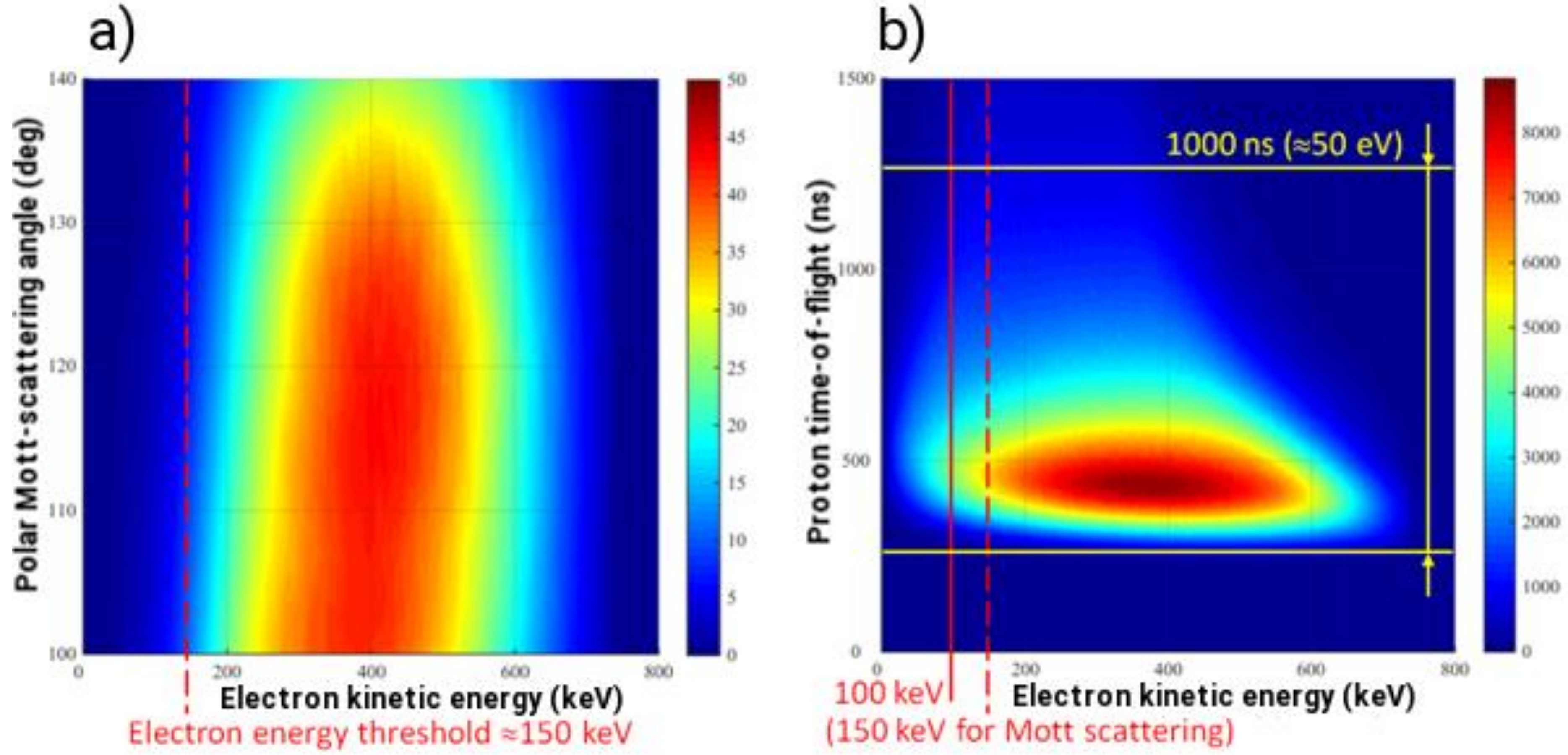


Courtesy of K. Bodek

Neutron decay point must coincide with electron trajectory and neutron beam

For each point along electron trajectory we have both electron and proton momentum. Weights can be constructed accounting for beam density distribution and kinematical fit results.

BRAND figure-of-merit

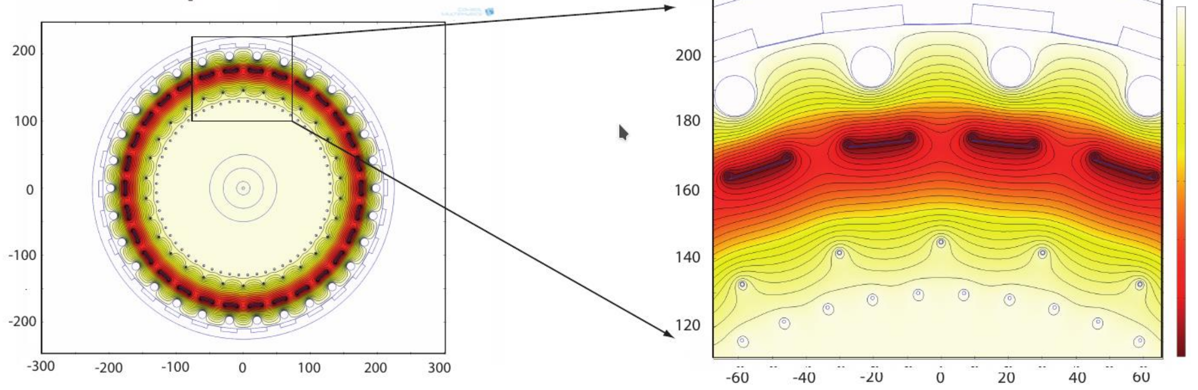


Courtesy of K. Bodek

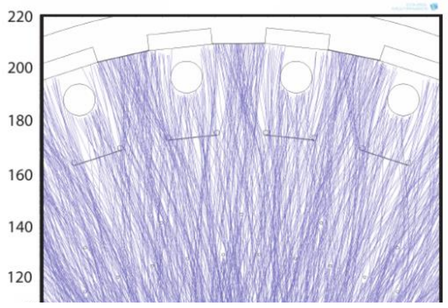
Monte-Carlo simulations with realistic field (COMSOL)

- Influence on electron and proton transport (angular resolution, efficiency)
- Different potential grids configurations
- Focusing effects
- backscattering from chamber walls (different materials)

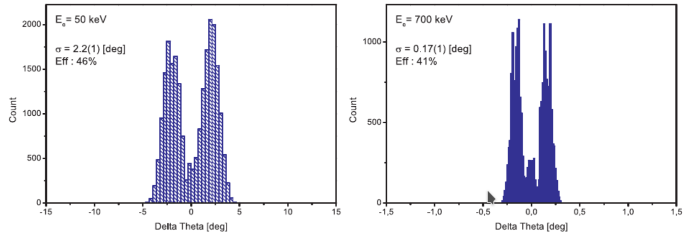
Electric potential



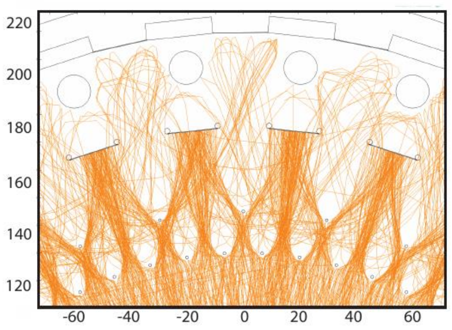
Tracking of decay electrons



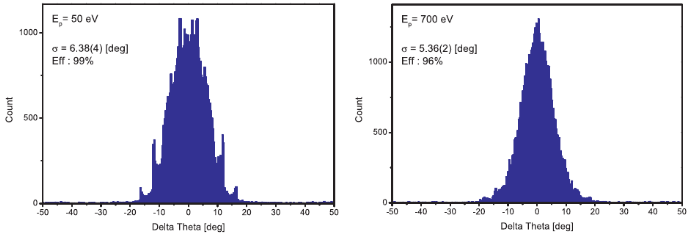
Approximately 43% of all decay electrons leave the vacuum chamber changing their original direction by less than 4 degree

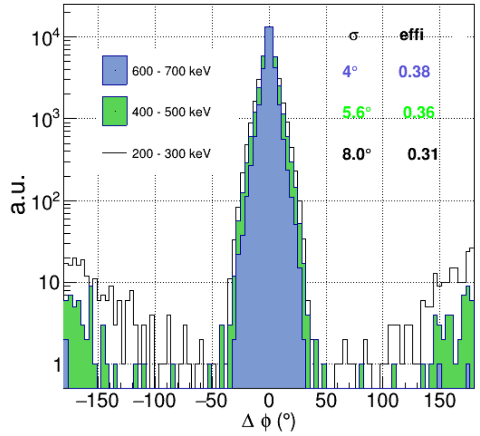


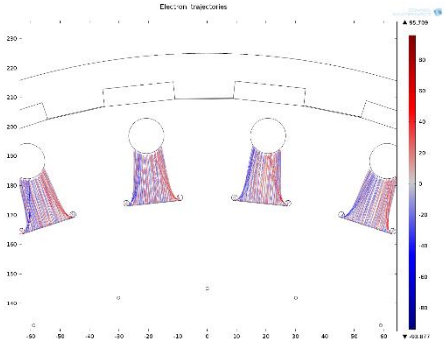
Tracking of decay protons



More than 95% of all decay protons reach the conversion foil changing their original direction by less than 15 degrees

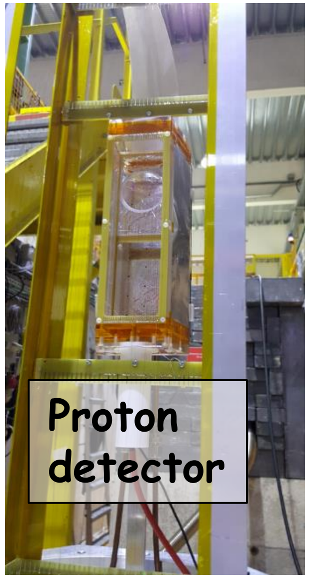


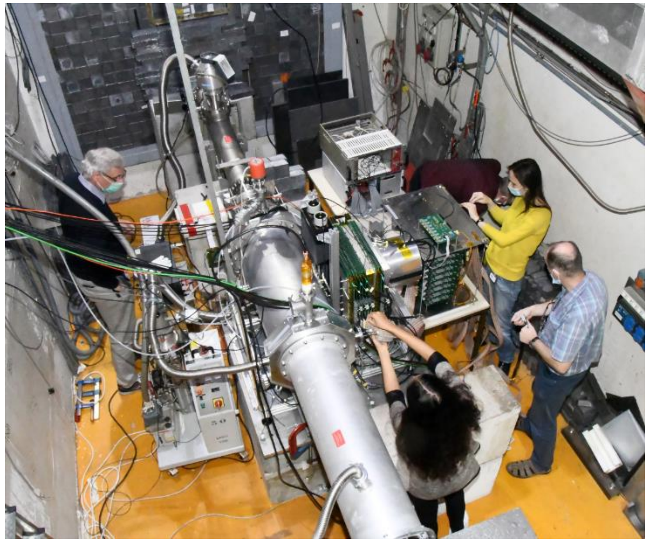


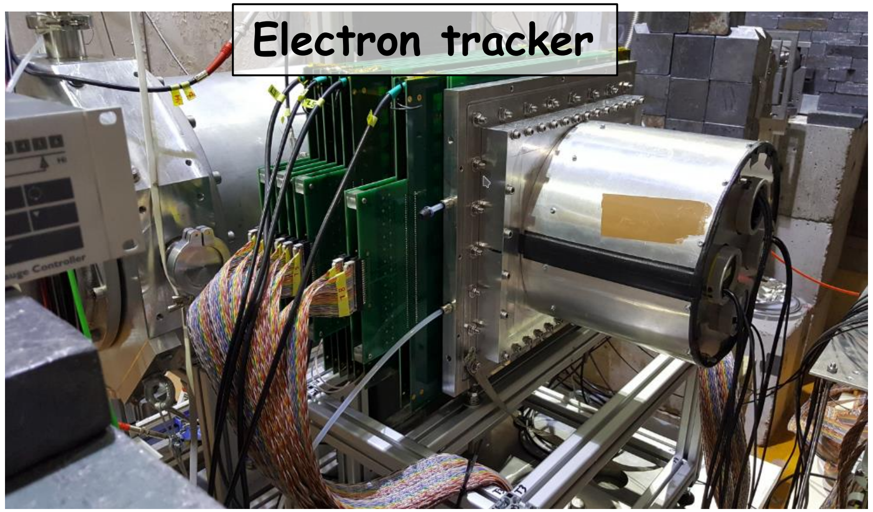


1'st experimental run in ILL, Grenoble September 2020

- Test of the setup in real conditions
  - Electron tracker installation
  - Vacuum chamber with thin windows
  - proton detector and converter foil
  - Upgraded beam polarizer
  - New front-end electronics
  - New data acquisition system

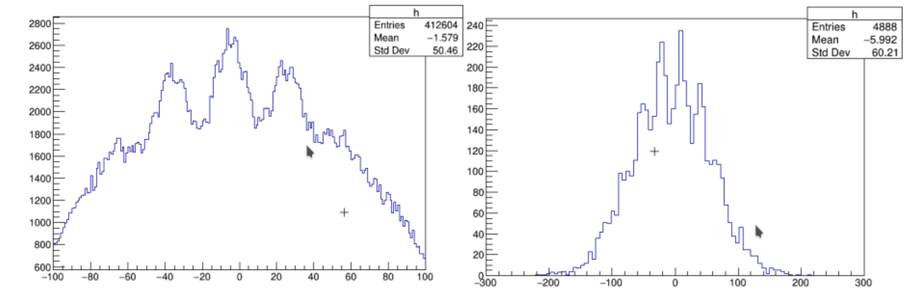


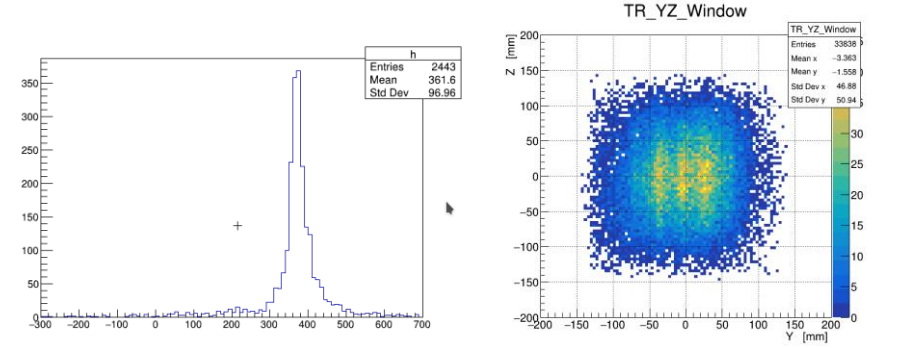


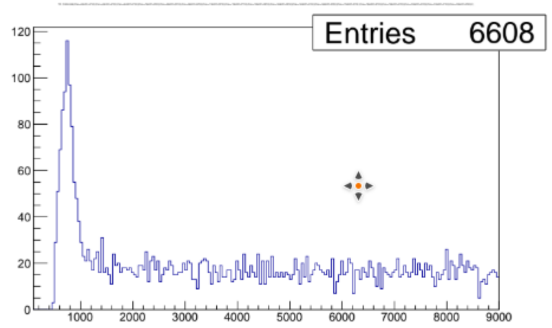


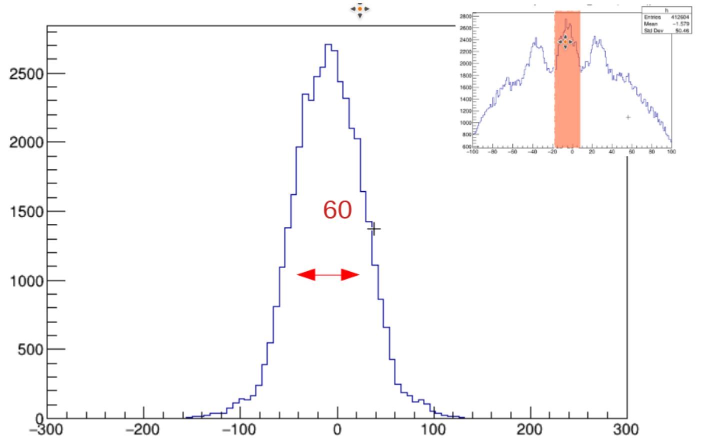
Results of the test run 2020

- All components were functioning
- DAQ worked well (~200GB collected)
- Low level of beam related background confirmed
- Electron tracking in progress, but first results obtained:
  - Distribution at vacuum chamber window
  - Reconstruction of Matt scattering vertices
  - Proton detector amplitude signals
  - Proton detector coincidences with electrons



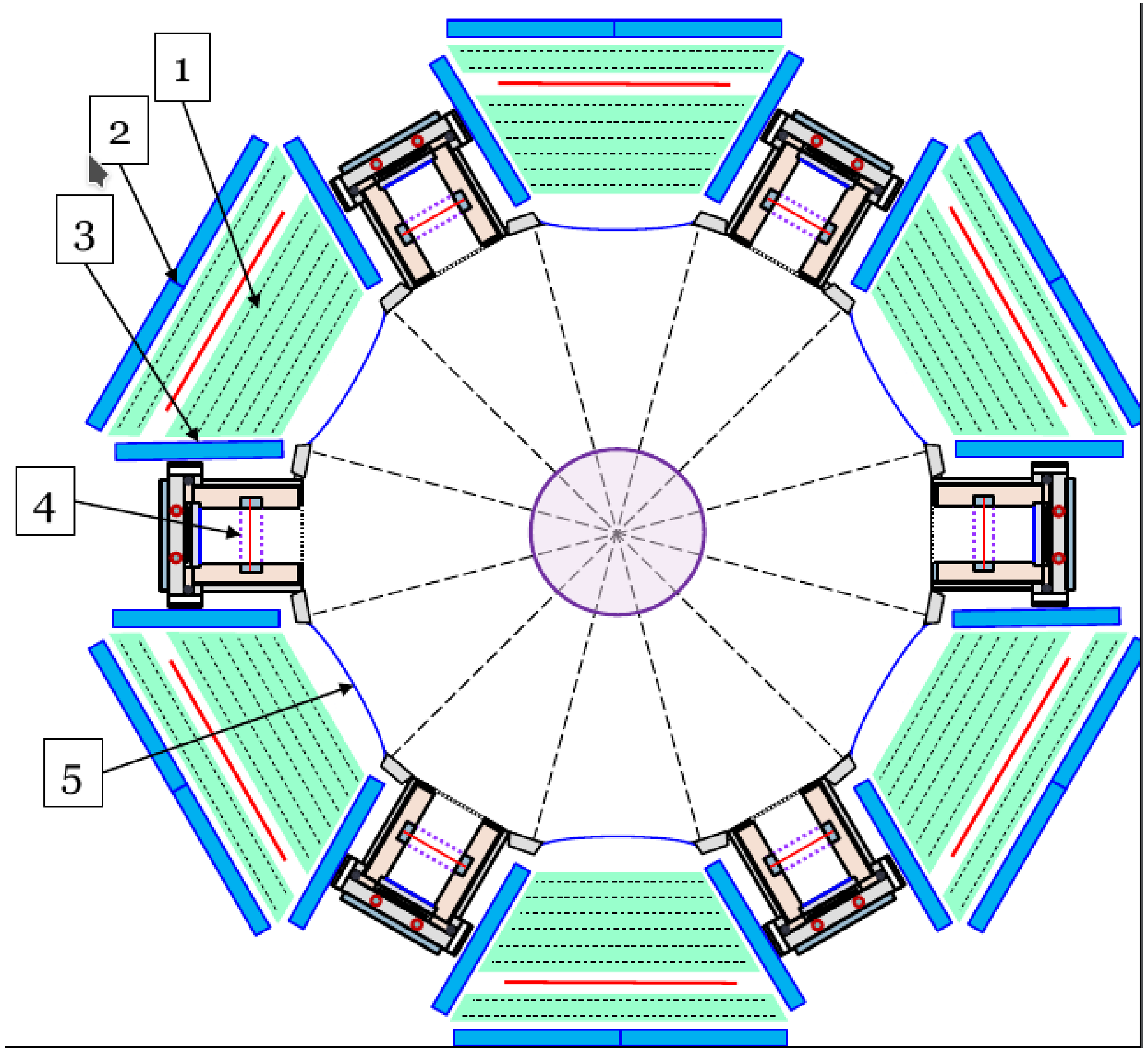






New concept of the final setup?

1. Electron tracker
2. Scintillator for direct electrons
3. Scintillator for Mot scattered electrons
4. proton detector
5. Vacuum chamber window



Outlook

- 4 weeks long data taking run in June-July 2021 including:
  - Spin holding magnetic field
  - Large vacuum chamber window for electrons
  - 4-6 times larger surface of proton converter foil
  - Rearranged Mott event triggering scintillators in order to significantly increase accepted angular range
  - New functionality of trigger board
  - Noise reduction of front-end-electronics
- Final detector design and realization of 1/6 of the full detector 2021-2023, precision compared to nTRV: factor 2÷3 stat. and syst.
- Realization of full detector, precision compared to nTRV: factor ~20 stat., 5 syst.

Thank You