Joint ESS ILL User Meeting, 5-7 October 2022, Lund, Sweden

BRAND – search for exotic couplings in weak interactions using the transverse electron polarization in the decay of free neutrons

On behalf of the BRAND Collaboration

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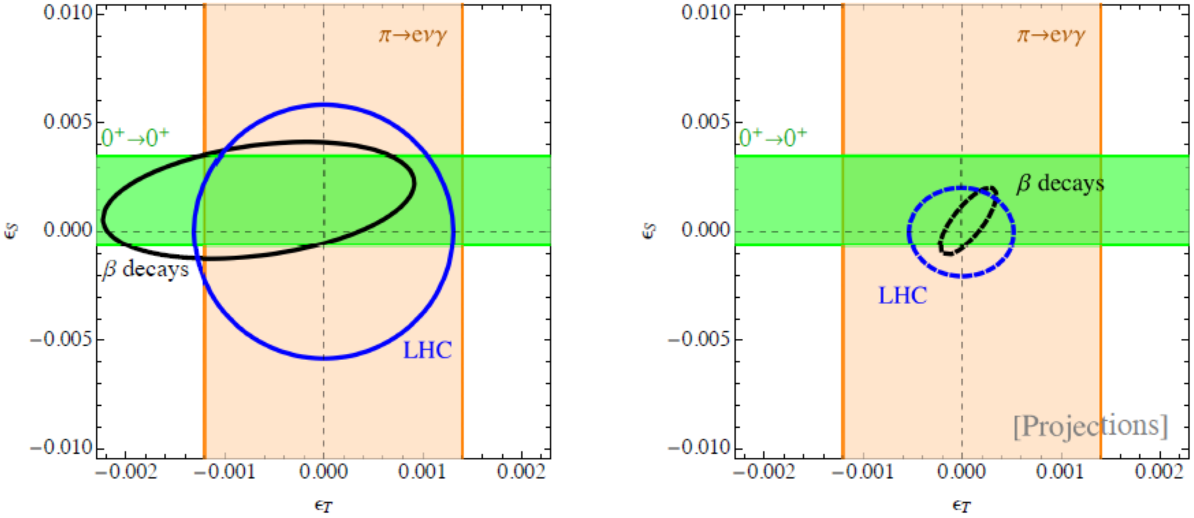
Searches for BSM physics in EW sector

- Searches for new particles (on-shell) in High Energy experiments
- Searches for deviations (from SM) of low energy observables (off-shell) in precision experiments
- *EFT – language to communicate and compare results*

V. Cirigliano et al., Nucl. Phys. B 830 (2010)
T. Bhattacharya et al., Phys. Rev. D 85 (2012)
V. Cirigliano et al., JHEP 1302 (2013)
M.González-Alonso et al., Ann. Phys. 525 (2013)
M.González-Alonso et al., Phys. Rev. Lett. 112 (2014)
D. Dubbers et al., Ann. Rev. Nucl. Part. Sci 71, (2021) 139
V. Cirigliano et al., Phys. Rev. Lett. 123, 051801 (2019)
S. Ando et al., Phys. Lett. B 595 (2004) 250
V. Cirigliano et al., Progr. Part. Nucl. Phys. 71 (2013) 93
A. Falkowski et al., JHEP 126 (2021)

- Global fit using superallowed $0^+ \to 0^+$ transitions, neutron- and nuclear decays compared to LHC $pp \to e$+MET+X
- **In β-decays, neutron plays a prominent role !**

M.González-Alonso et al., Progr. Part. Nucl. Phys. 104 (2019) 165



Nucleon-level effective couplings

- Lee-Yang effective Lagrangian (leading order, low momentum transfer):

$$\begin{aligned} -\mathcal{L}_{n\to pe^-\bar\nu_e} \;=\;& \bar p\, n\ \left(C_S \bar e \nu_e - C_S' \bar e \gamma_5 \nu_e\right) \\ &+ \bar p \gamma^\mu n \left(C_V \bar e \gamma_\mu \nu_e - C_V' \bar e \gamma_\mu \gamma_5 \nu_e\right) \\ &+ \bar p \sigma^{\mu\nu} n \left(C_T \bar e \sigma_{\mu\nu_e} \nu_e - C_T' \bar e \sigma_{\mu\nu} \gamma_5 \nu_e\right) \\ &- \bar p \gamma^\mu \gamma_5 n \left(C_A \bar e \gamma_\mu \gamma_5 \nu_e - C_A' \bar e \gamma_\mu \nu_e\right) \\ &+ \bar p \gamma_5 n\ \left(C_P \bar e \gamma_5 \nu_e - C_P' \bar e \nu_e\right) + \text{h.c.}\ . \end{aligned}$$

$$C_i,\ C_i'\ \left(i \in \{V, A, S, T\}\right)$$

$$C_i \;=\; \frac{G_F}{\sqrt{2}} V_{ud}\, \overline{C}_i$$

$$\langle p|\bar u \Gamma d|n\rangle = g_\Gamma\, \bar\psi_p \Gamma \psi_n$$

- Effective nucleon-level couplings can be expressed in parton-level parameters:

$$\begin{aligned} \overline{C}_V &= g_V \left(1 + \epsilon_L + \epsilon_R + \tilde\epsilon_L + \tilde\epsilon_R\right) \\ \overline{C}_V' &= g_V \left(1 + \epsilon_L + \epsilon_R - \tilde\epsilon_L - \tilde\epsilon_R\right) \\ \overline{C}_A &= -g_A \left(1 + \epsilon_L - \epsilon_R - \tilde\epsilon_L + \tilde\epsilon_R\right) \\ \overline{C}_A' &= -g_A \left(1 + \epsilon_L - \epsilon_R + \tilde\epsilon_L - \tilde\epsilon_R\right) \end{aligned}$$

$$\begin{aligned} \overline{C}_S &= g_S\ \left(\epsilon_S + \tilde\epsilon_S\right) \\ \overline{C}_S' &= g_S\ \left(\epsilon_S - \tilde\epsilon_S\right) \\ \overline{C}_P &= g_P\ \left(\epsilon_P - \tilde\epsilon_P\right) \\ \overline{C}_P' &= g_P\ \left(\epsilon_P + \tilde\epsilon_P\right) \\ \overline{C}_T &= 4\, g_T\ \left(\epsilon_T + \tilde\epsilon_T\right) \\ \overline{C}_T' &= 4\, g_T\ \left(\epsilon_T - \tilde\epsilon_T\right) \end{aligned}$$

- *Form factors are the key ingredients for translation of hadron-level coupling constants to parton-level parameters $\Rightarrow$ from Lattice QCD*

Neutron β-decay in Standard Model

- Only 2 SM parameters establish neutron β decay:

$$H = \frac{G_{\mathrm{F}}}{\sqrt{2}} V_{ud} \quad \bar{p} \left\{ \gamma_\mu \left(1 + \lambda \gamma_5\right) + \frac{\mu_{\mathrm{p}} - \mu_{\mathrm{n}}}{2 m_{\mathrm{p}}} \sigma_{\mu\nu} q^\nu \right\} n \;\; \bar{e} \gamma^\mu \left(1 - \gamma_5\right) \nu_{\mathrm{e}}$$

V_{ud} – CKM matrix element

$\lambda \equiv \frac{g_{\mathrm{A}}}{g_{\mathrm{V}}}$ – axial-to-vector coupling constant ratio

- Can be extracted from:
  - Neutron lifetime

f – phase space factor
δ_{R} – radiative correction (model independent)
Δ_{R} – radiative correction (model dependent)

$$\boxed{\tau^{-1} = \frac{G_{\mathrm{F}}^2 m_e^2}{2\pi^3} \left|V_{ud}\right|^2 f \left(1 + \delta_{\mathrm{R}}\right)\left(1 + \Delta_{\mathrm{R}}\right)\left(1 + 3\lambda^2\right)}$$

  - Angular distribution of decay products (correlation coefficients)

Neutron β-decay correlations

- For polarized neutrons, measuring electron- and proton-momentum and transverse electron polarization:

$$d\Gamma \sim 1 + \boldsymbol{a}\frac{\mathbf{p}_e}{E_e}\cdot\frac{\mathbf{p}_{\bar{\nu}}}{E_{\bar{\nu}}} + \boldsymbol{b}\frac{m_e}{E_e} + \frac{\langle \mathbf{J}\rangle}{J}\cdot\left[\boldsymbol{A}\frac{\mathbf{p}_e}{E_e} + \boldsymbol{B}\frac{\mathbf{p}_{\bar{\nu}}}{E_{\bar{\nu}}} + \boldsymbol{D}\frac{\mathbf{p}_e}{E_e}\times\frac{\mathbf{p}_{\bar{\nu}}}{E_{\bar{\nu}}}\right]$$

$$\boxed{\begin{aligned} &+ \boldsymbol{\sigma}_\perp\cdot\left[\boldsymbol{H}\frac{\mathbf{p}_{\bar{\nu}}}{E_{\bar{\nu}}} + \boldsymbol{L}\frac{\mathbf{p}_e}{E_e}\times\frac{\mathbf{p}_{\bar{\nu}}}{E_{\bar{\nu}}} + \boldsymbol{N}\frac{\langle \mathbf{J}\rangle}{J} + \boldsymbol{R}\frac{\langle \mathbf{J}\rangle}{J}\times\frac{\mathbf{p}_e}{E_e}\right] \\ &+ \boldsymbol{\sigma}_\perp\cdot\left[\boldsymbol{S}\frac{\langle \mathbf{J}\rangle}{J}\frac{\mathbf{p}_e}{E_e}\cdot\frac{\mathbf{p}_{\bar{\nu}}}{E_{\bar{\nu}}} + \boldsymbol{U}\frac{\mathbf{p}_{\bar{\nu}}}{E_{\bar{\nu}}}\frac{\langle \mathbf{J}\rangle}{J}\cdot\frac{\mathbf{p}_e}{E_e} + \boldsymbol{V}\frac{\mathbf{p}_{\bar{\nu}}}{E_{\bar{\nu}}}\times\frac{\langle \mathbf{J}\rangle}{J}\right]\end{aligned}}$$

$\mathbf{p}_e$ - electron momentum $\mathbf{p}_\nu$ - neutrino momentum

$\boldsymbol{\sigma}$ - electron spin projection direction

- All correlation coefficients can be expressed as **combinations** of real and imaginary parts of exotic (**scalar** and **tensor**) couplings:

$$\boxed{X = X_{V\text{-}A} + X_{\mathrm{FSI}} + c_{\mathrm{Re}\,S}\,\mathrm{Re}\boldsymbol{S} + c_{\mathrm{Re}\,T}\,\mathrm{Re}\boldsymbol{T} + c_{\mathrm{Im}\,S}\,\mathrm{Im}\boldsymbol{S} + c_{\mathrm{Im}\,T}\,\mathrm{Im}\boldsymbol{T}}$$

$\boldsymbol{S} = \frac{C_S + C_S'}{C_V}$, $\boldsymbol{T} = \frac{C_T + C_T'}{C_A}$, $c_{\mathrm{Re}\,S}, c_{\mathrm{Re}\,T}, c_{\mathrm{Im}\,S}, c_{\mathrm{Im}\,T}$ – functions of $\lambda = C_A/C_V$ and kinematical quantities

Neutron β-decay correlations at ESS

Proposed experiment	**Measurement**	**Quantity**	**Last measured**	**Current value / limit**	**Statistical uncertainty (1σ) @ANNI [100 days]**
	$n \rightarrow p + e + \bar{\nu}_e$				
ep/n	A	Beta asymmetry	PERKEO III@PF1B 2019 [255]	$-0.11985 \pm 0.00017 \pm 0.00012$	1×10^{-5}
ep/n	C	Proton asymmetry	PERKEO II@PF1B 2008 [292]	$-0.2377 \pm 0.0010 \pm 0.0024$	1×10^{-4}
ep/n	a	e-$\bar{\nu}_e$ correlation from p recoil spectrum	*a*SPECT@PF1B 2020 [257]	-0.10430 ± 0.00084	1×10^{-4}
ep/n	b	Fierz interference from beta asymmetry	PERKEO III@PF1B 2020 [256]	$0.017 \pm 0.020 \pm 0.003$	6×10^{-4}
CRES	b	Fierz interference from beta spectrum	UCNA@UCN-LANL 2017 [380]	$0.067 \pm 0.005^{+0.090}_{-0.061}$	1×10^{-4}
BRAND	a	e-$\bar{\nu}_e$ correlation from e-p correlation	*a*CORN@NG-C 2021 [297]	$-0.10758 \pm 0.00136 \pm 0.00148$	5×10^{-5}
BRAND	B	Neutrino asymmetry	PERKEO II@PF1B 2007 [291]	$0.9802 \pm 0.0034 \pm 0.0036$	5×10^{-5}
BRAND	D	Triple correlation D	emiT@NG-6 2012 [294]	$(-0.94 \pm 1.89 \pm 0.97) \times 10^{-4}$	5×10^{-5}
BRAND	R	Triple correlation R	nTRV@FUNSPIN [278]	$(4 \pm 12 \pm 5) \times 10^{-3}$	1×10^{-3}
BRAND	N	σ_n-$\sigma_{e,\perp}$ Correlation	nTRV@FUNSPIN [278]	$0.067 \pm 0.011 \pm 0.004$	1×10^{-3}
BRAND	H, L, S, U, V	Other correlations with $\sigma_{e,\perp}$	unmeasured	unmeasured	1×10^{-3}

B
R
A
N
D

"*Fundamental Physics at the European Spallation Source*" – to be published

Sensitivity factors for scalar and tensor couplings

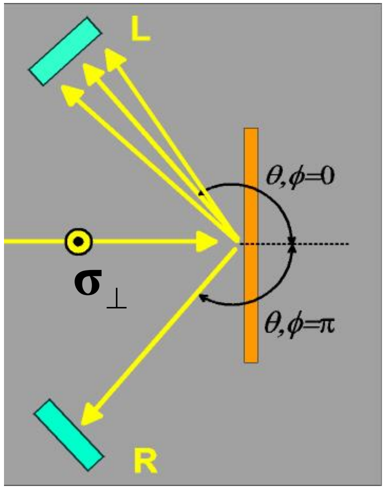
(Lee-Yang Lagrangian, no RH neutrinos, leading order, no recoil, point charge, ideal detectors)

	SM (λ)	FSI (λ)	c(Re$\mathcal{S}$)	c(Re$\mathcal{T}$)	c(Im$\mathcal{S}$)	c(Im$\mathcal{T}$)
a	-0.1048	0	-0.1714[†]	0.1714[†]	-0.0007	+0.0012
b	0	0	+0.1714	+0.8286	0	0
A	-0.1172	0	0	0	-0.0009	+0.0014
B	+0.9876	0	-0.1264	+0.1945	0	0
D	0	0	+0.0009	-0.0009	0	0
H	+0.0609	0	-0.1714	+0.2762	0	0
L	0	-0.0004	0	0	+0.1714	-0.2762
N	+0.0681	0	-0.2176	+0.3348	0	0
R	0	+0.0005	0	0	-0.2176	+0.3348
S	0	-0.0018	+0.2176	-0.2176	0	0
U	0	0	-0.2176	+0.2176	0	0
V	0	0	0	0	-0.2176	+0.2172

[*] Kinematical factor averaged over $E_{\mathrm{e}}^{\mathrm{kin}} \in (200,782)\,\mathrm{keV}$, $E_{\mathrm{p}}^{\mathrm{kin}} \in (50,760)\,\mathrm{eV}$, $\theta_{\mathrm{e}} \in (45^{o},135^{o})$, $\theta_{\mathrm{p}} \in (30^{o},150^{o})$.

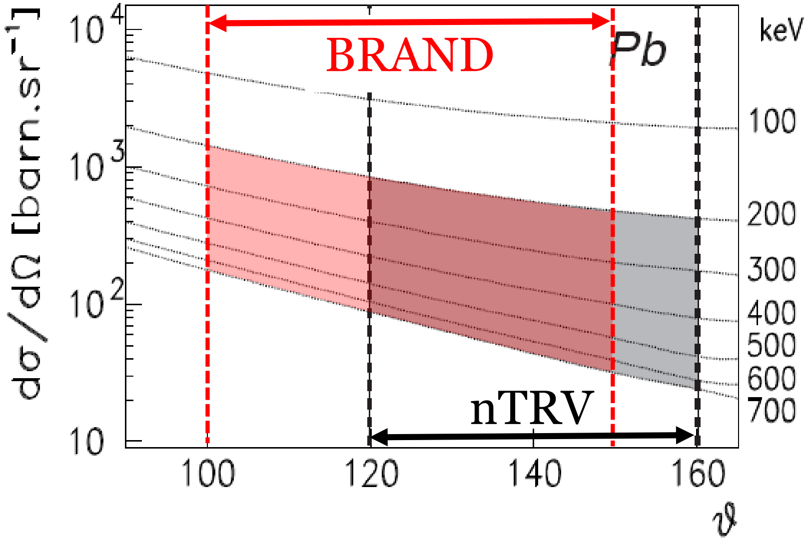
[†] $(|C_S|^2+|C'_S|^2)/2$ instead of ReS and $(|C_T|^2+|C'_T|^2)/2$ instead of ReT, respectively

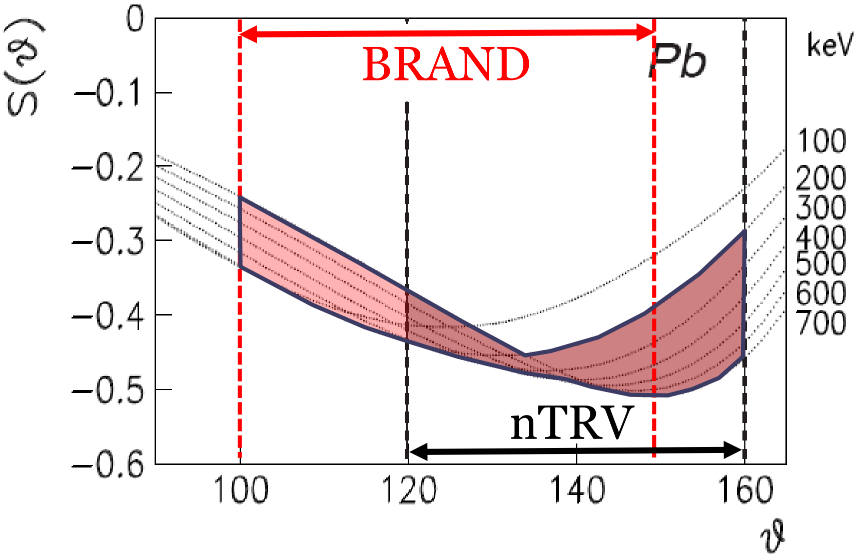
Electron spin analysis



- Mott scattering:
  - Analyzing power caused by spin-orbit force
  - ***P*** and ***T*** conserving (electromagnetic process)
  - Sensitive **exclusively** to the transverse polarization
- *Electron polarization can be determined only in well controlled electric and **low magnetic fields***

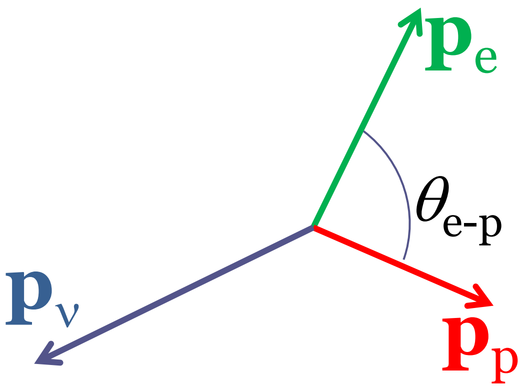
$$\frac{N_L - N_R}{N_L + N_R} = \frac{\langle \boldsymbol{\sigma}_\perp \rangle}{\sigma} S(\theta)$$

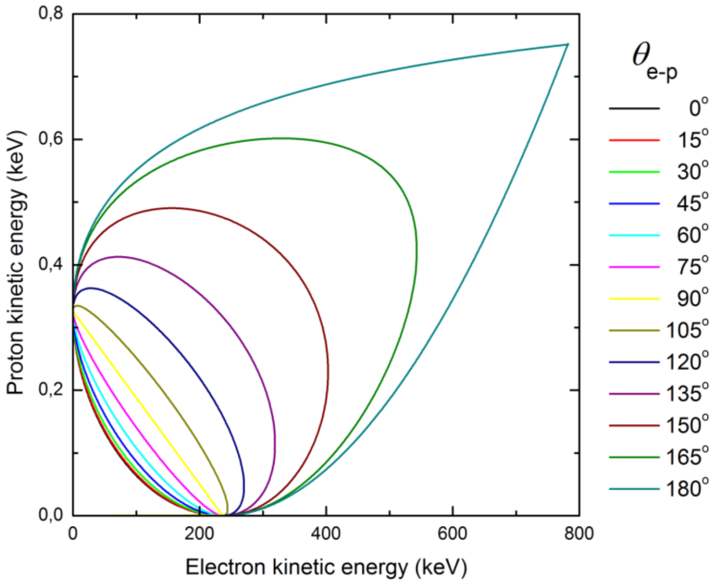




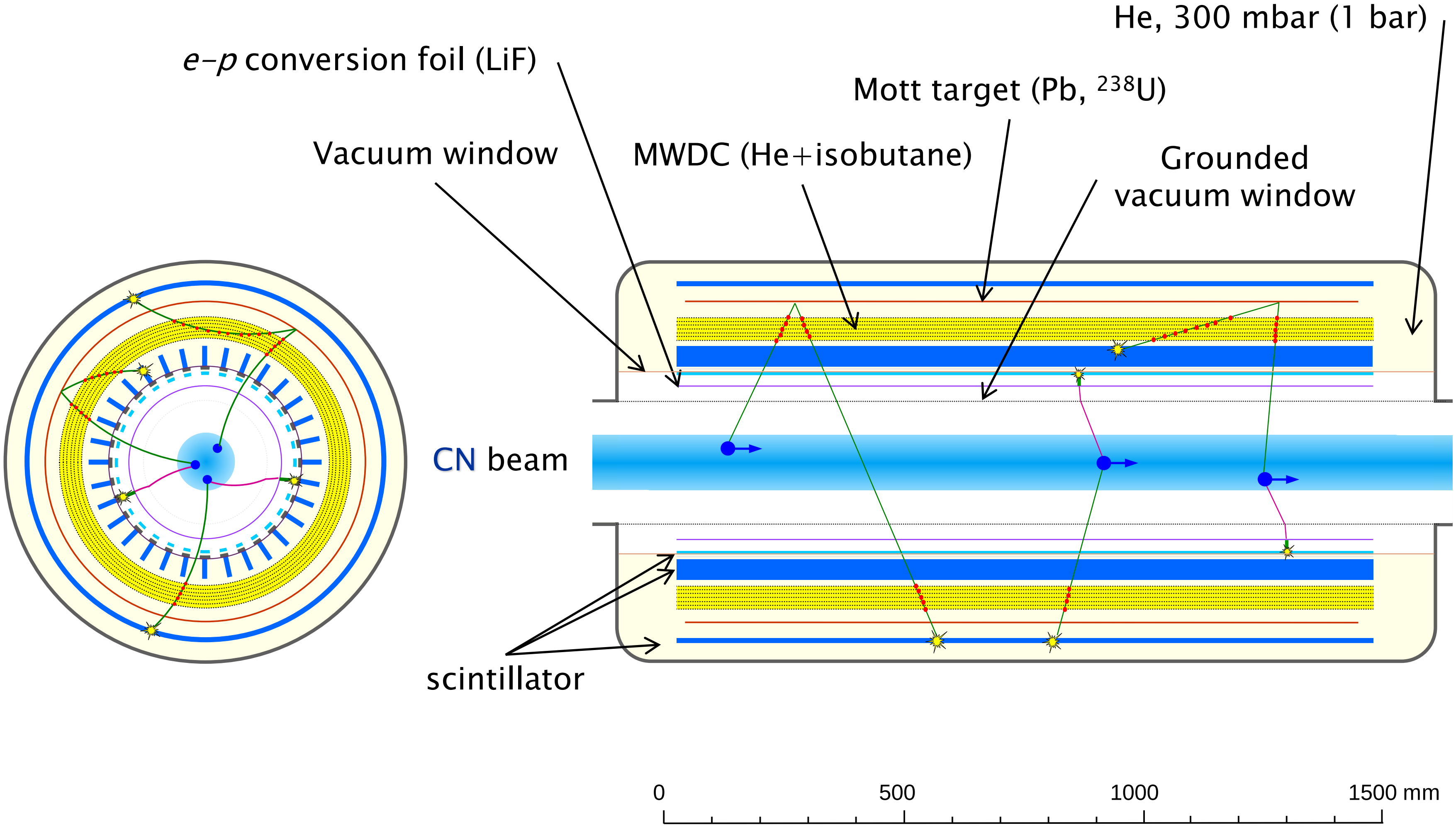
Electron tracking, vertex reconstruction

- Unavoidable for electron spin analysis in Mott scattering for diffused and weak decay sources like e.g. cold neutron beam
- Direct measurement of geometry factors (depending on detector acceptance and efficiency)
- Reduces gamma background in electron energy detector
- Allows for implementation of corrections based on parameter maps (e.g. effective Sherman function corrected for target thickness variation and for angle of incidence)
- Allows for accurate gain balance of large plastic scintillators
- Improves diagnostics of beam in fiducial volume





BRAND - concept



He, 300 mbar (1 bar)

e–*p* conversion foil (LiF)

Mott target (Pb, ^{238}U)

Vacuum window

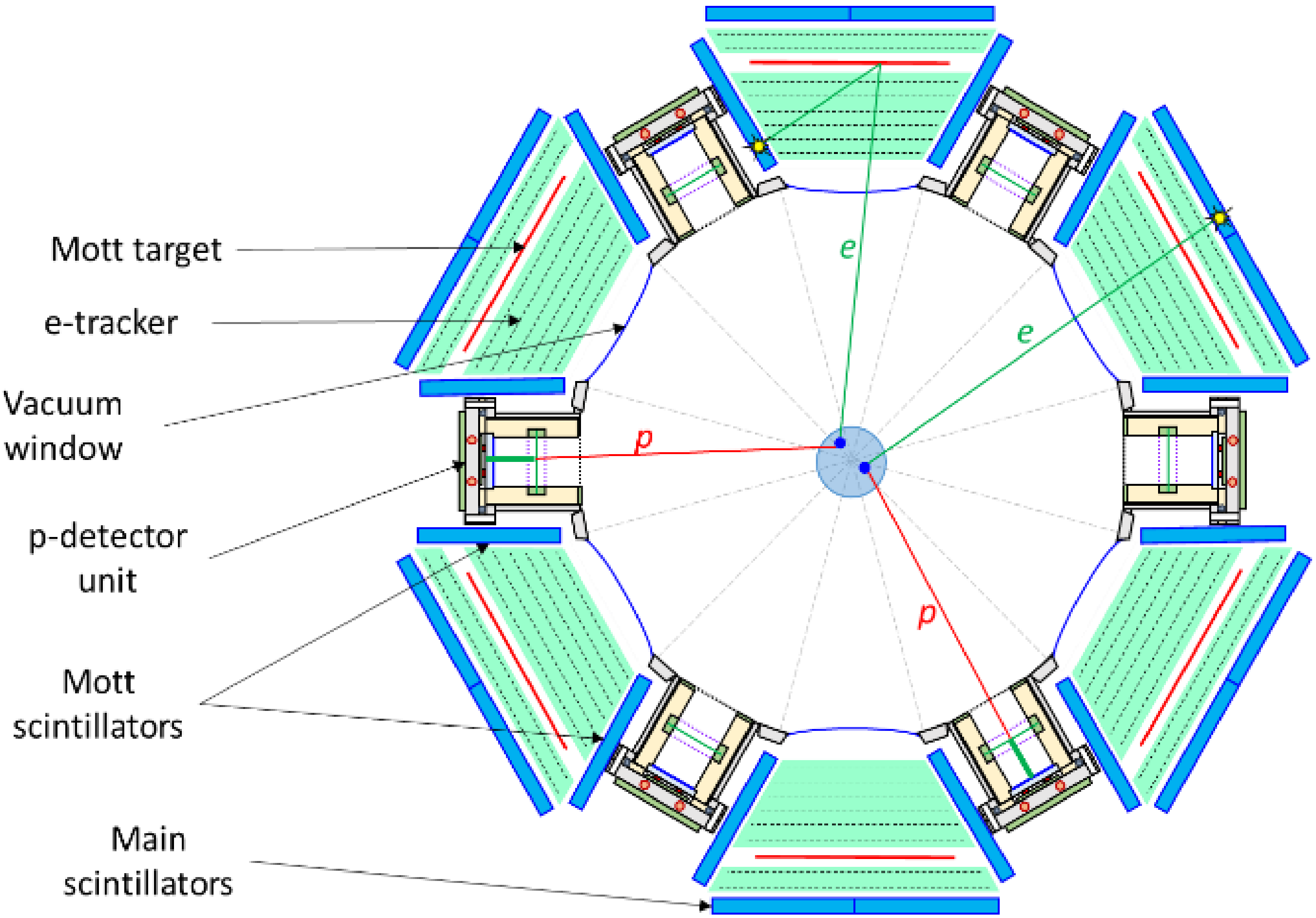
MWDC (He+isobutane)

Grounded vacuum window

CN beam

scintillator

BRAND detecting system - modular design


Mott target

e-tracker

Vacuum window

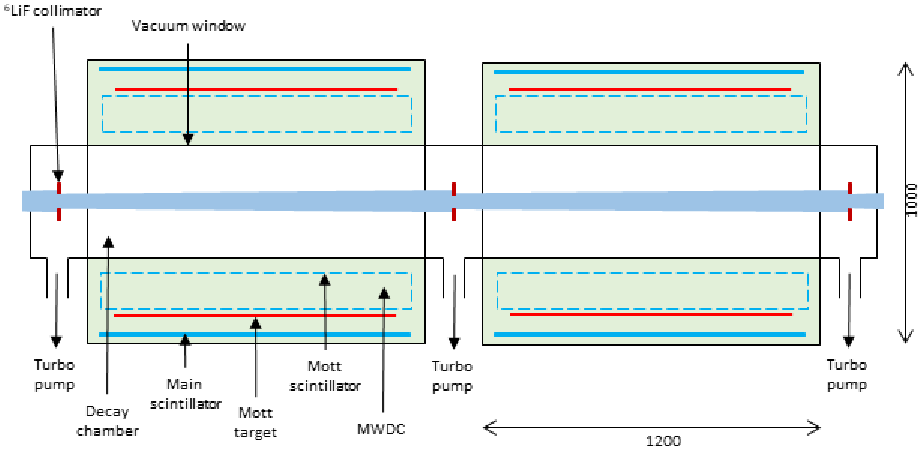
p-detector unit

Mott scintillators

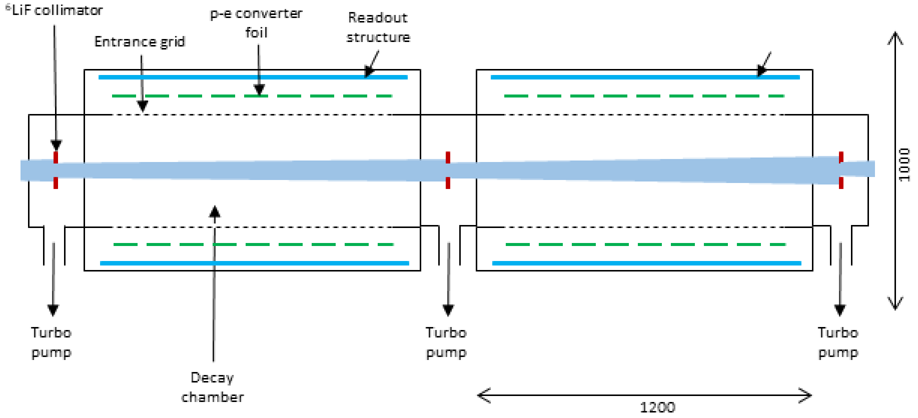
Main scintillators

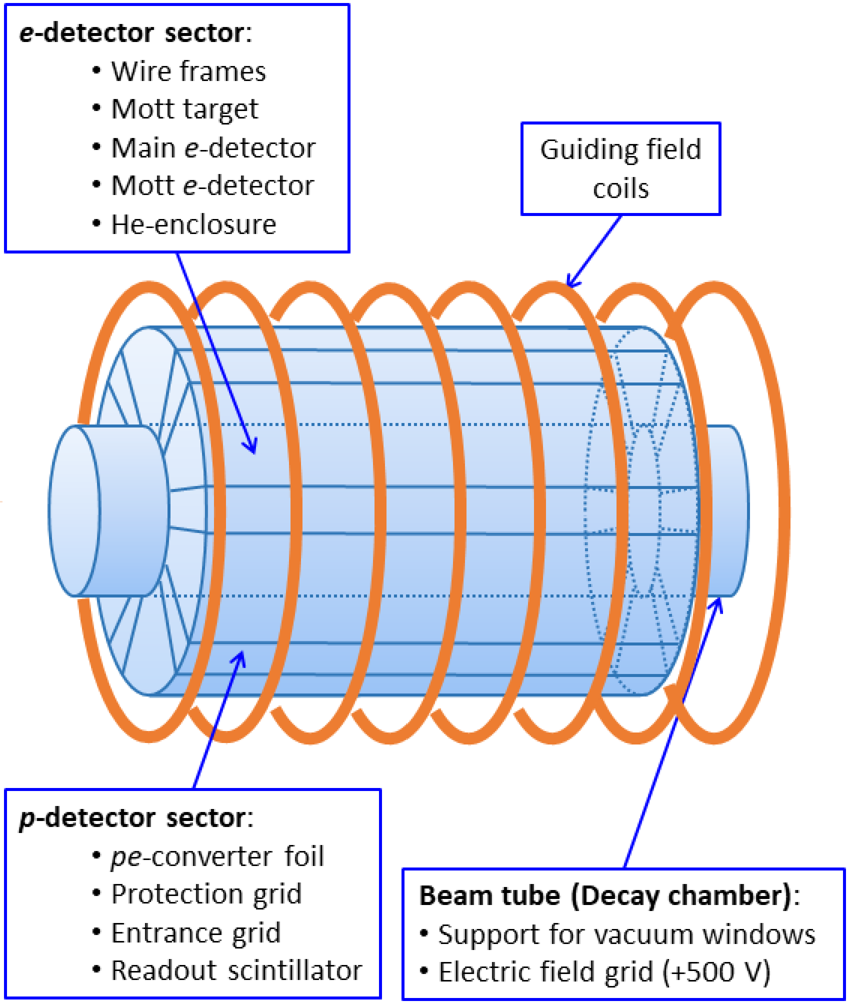
BRAND detecting system - modular design

BRAND segments – vertical cross section



BRAND segments – horizontal cross section





***e*-detector sector**:
- Wire frames
- Mott target
- Main *e*-detector
- Mott *e*-detector
- He-enclosure

Guiding field coils

***p*-detector sector**:
- *pe*-converter foil
- Protection grid
- Entrance grid
- Readout scintillator

Beam tube (Decay chamber):
- Support for vacuum windows
- Electric field grid (+500 V)

BRAND – methods, expected performance, strategy

- ❑ Experimental methods:
  - Measure decay electrons and *e*-*p* coincidences
  - Electron tracking in hexagonal, low *Z*, low pressure MWDC
  - *p*-*e* conversion followed by *e* detection in scintillator (ToF, position)
  - Decay vertex reconstruction
  - Electron spin analysis by Mott scattering (vertex reconstruction)

- ❑ BRAND is based on experimentally verified methods (nTRV@PSI)

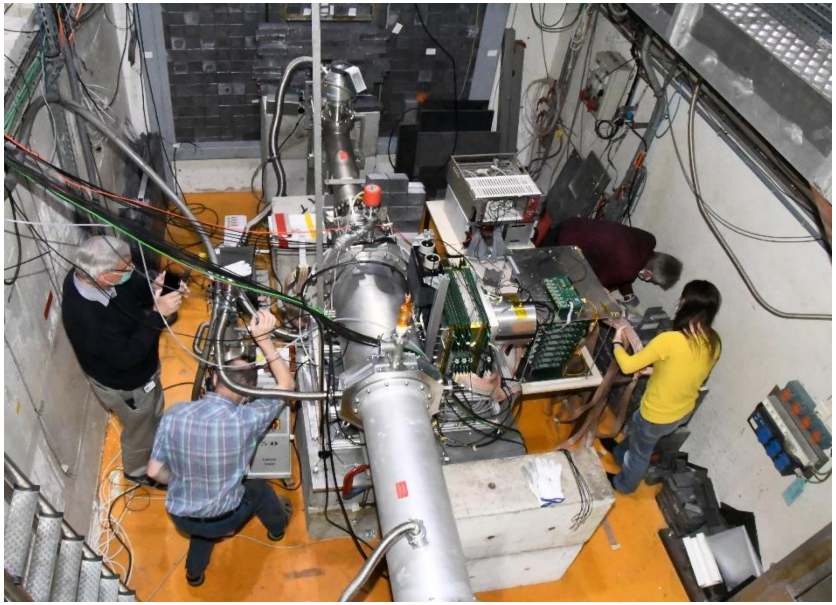
- ❑ Overall systematic uncertainty floor achieved in nTRV@PSI:
  - *N* correlation: 4×10^{-3}
  - *R* correlation: 5×10^{-3}

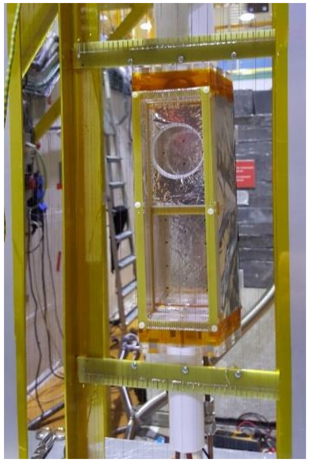
- ❑ Gradual improvement of exp. accuracy (systematic uncertainty):

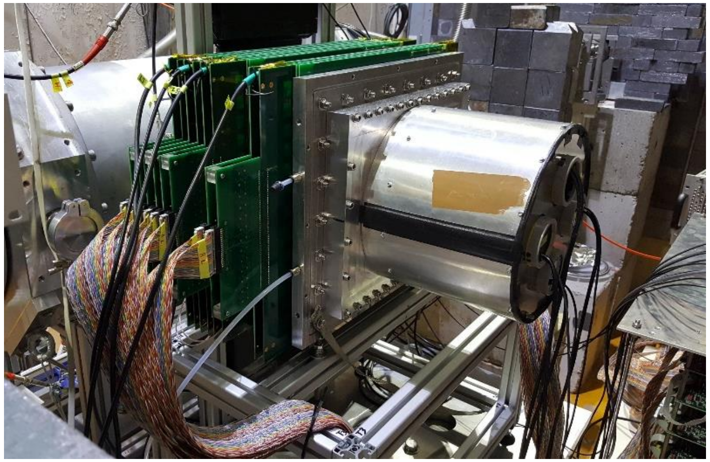
4×10^{-3}	→	2×10^{-3}	→	1×10^{-3}	→	5×10^{-4}
nTRV (PSI)		**BRAND-1 (ILL)**		**BRAND-2 (ILL/ESS ?)**		**BRAND-3 (ESS)**

BRAND-0 test measurement - goals

- Electron tracker
- Proton detector
- Front end and DAQ
- Vacuum window
- Beam intensity profile
- Beam induced background

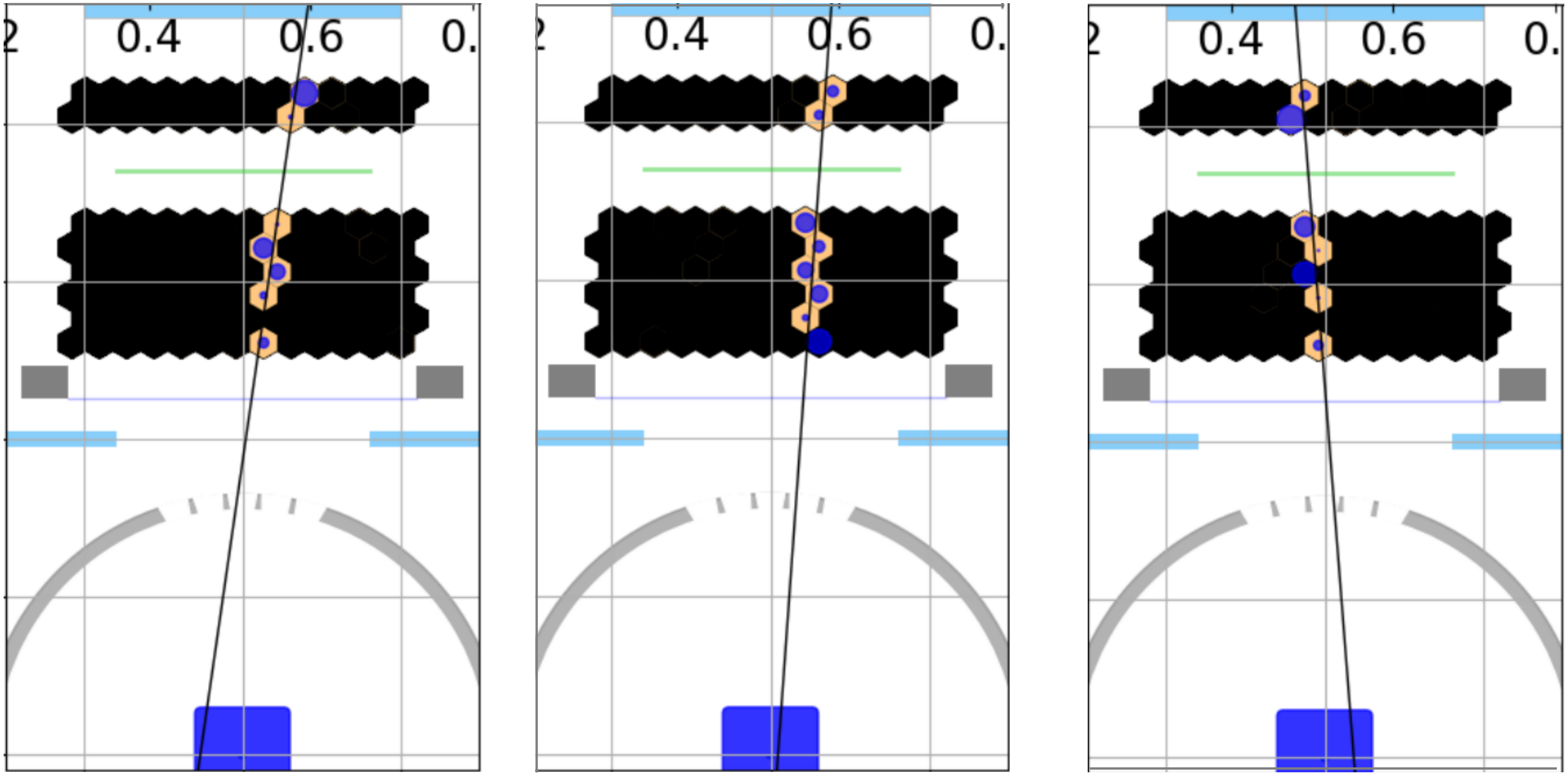






Electron tracker

- ☐ Tracks of decay electrons reconstructed from drift time – snapshot of event display

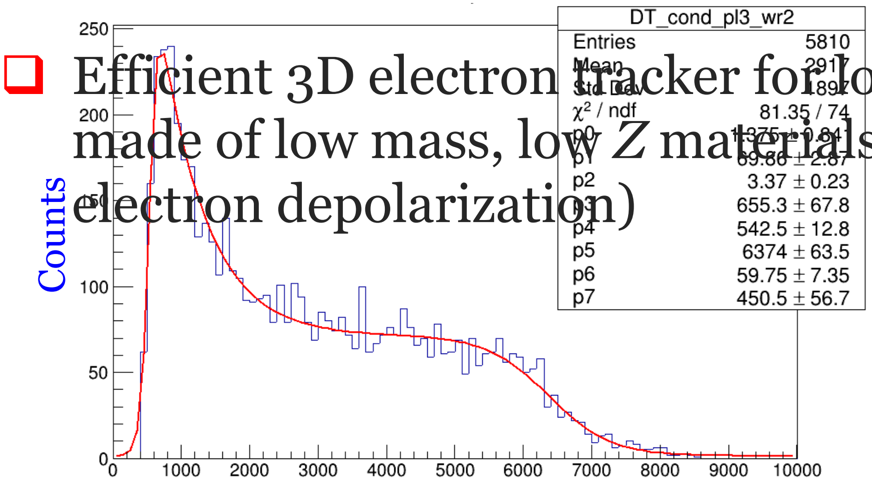


Electron tracker

Data: ILL 2020

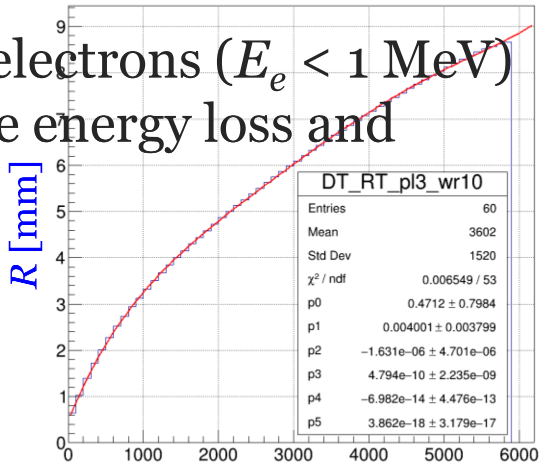
- Efficient 3D electron tracker for low energy electrons ($E_e < 1$ MeV) made of low mass, low Z materials (minimize energy loss and electron depolarization)

Drift-time spectrum

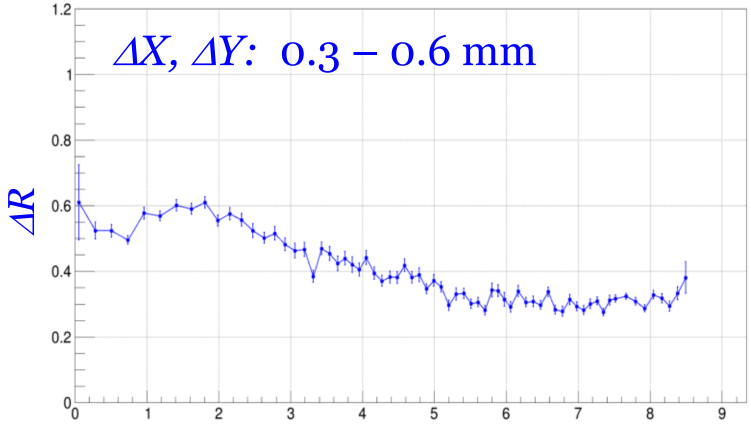


Drift time [×0.1 ns]

Calibration *R*-*t* curve

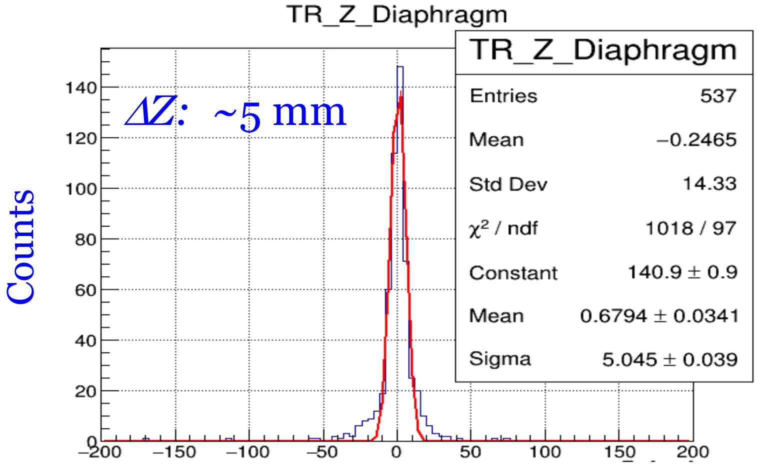


Drift time [×0.1 ns]



ΔX, *ΔY*: 0.3 – 0.6 mm

R - distance from cell center [mm]

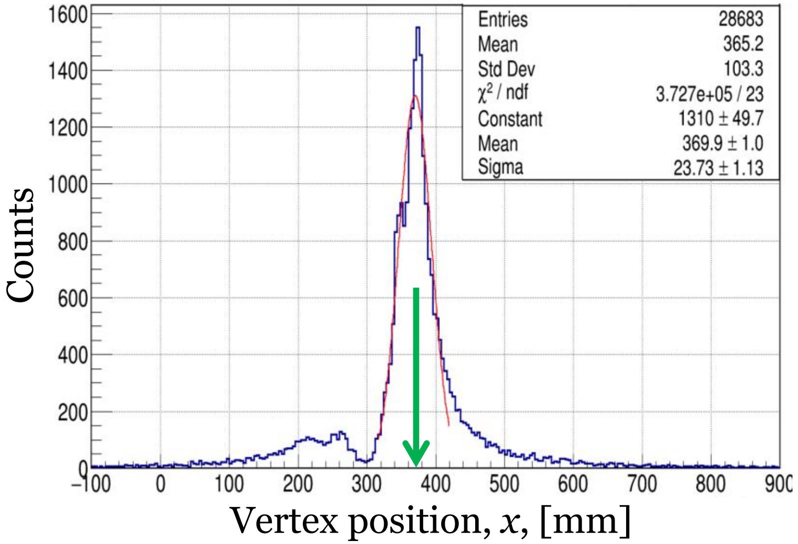


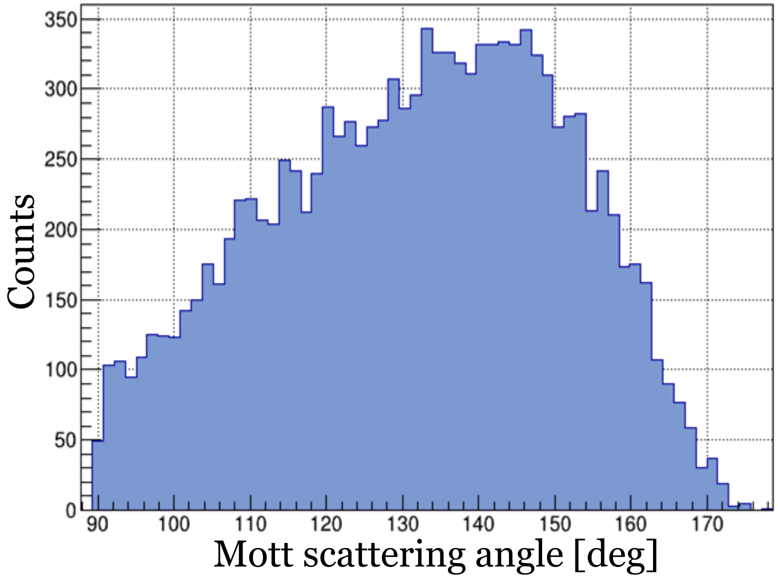
ΔZ: ~5 mm

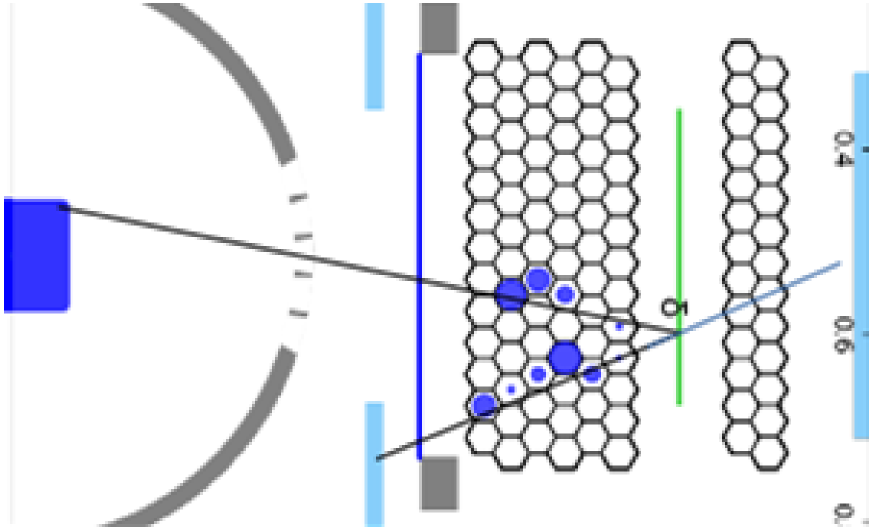
Z-coordinate – along wires [mm]

Electron tracker – Mott scattering events

Data: ILL 2020

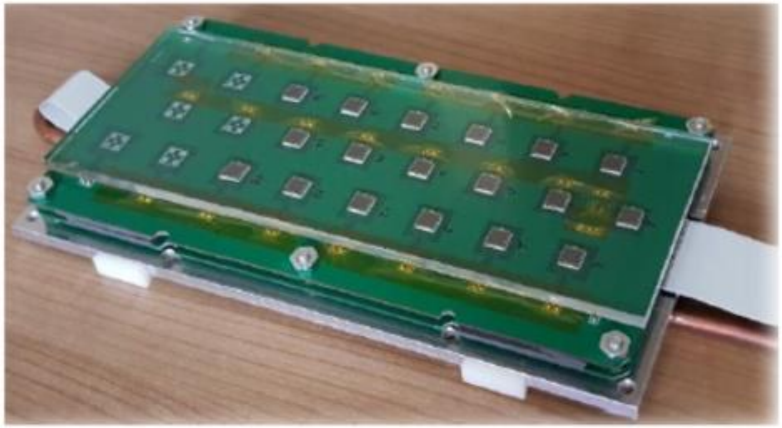


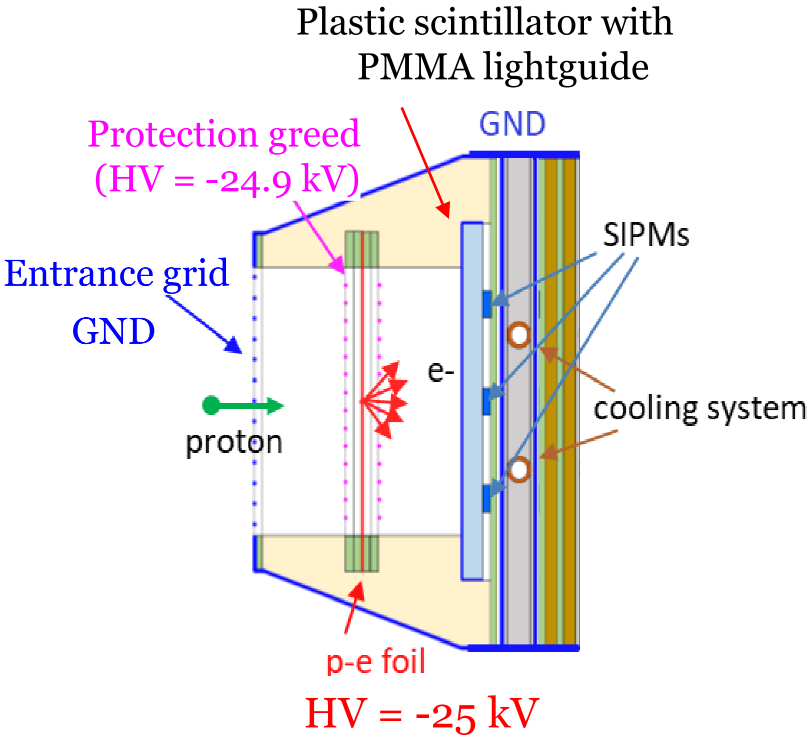




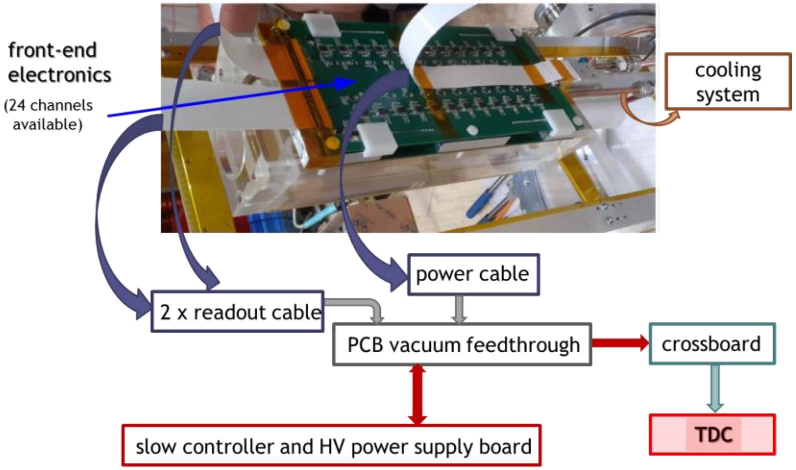
Proton detector

- ☐ 25 µm thick plastic scintillator attached to 4 mm thick lightguide
- ☐ SIPMs light readout with cooling system
- ☐ Charge sensitive preamplifiers



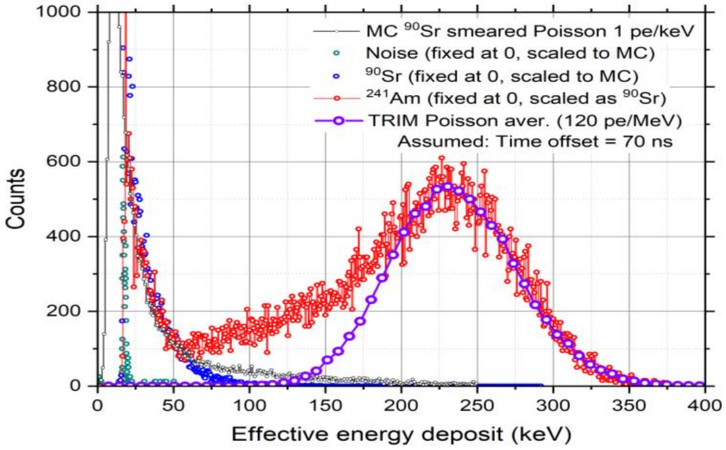


Front-end electronics, slow controller and DAQ connection

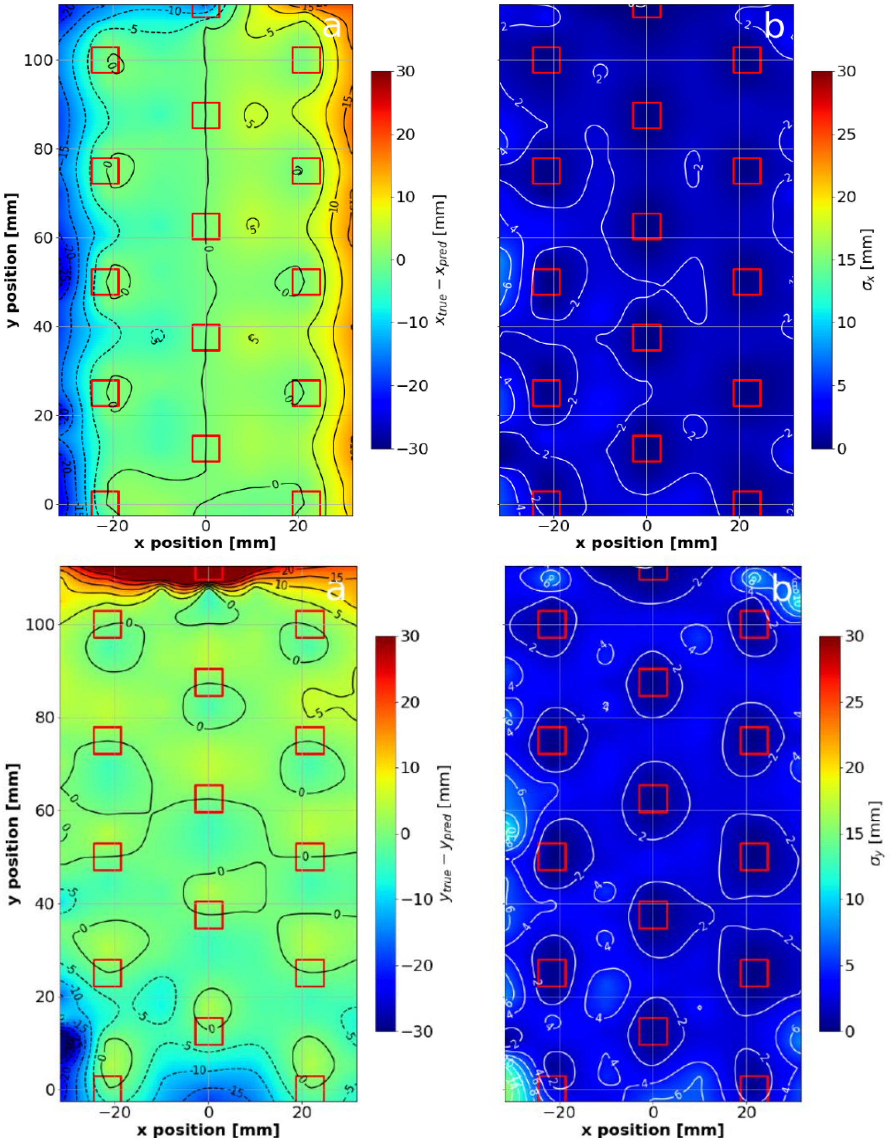


Proton detector

- ❑ 25 µm thick plastic scintillator attached to 4 mm thick lightguide
- ❑ Light readout with temperature stabilized SiPMs
- ❑ Charge sensitive preamplifiers with charge-to-time conversion
- ❑ Gain balance of SiPMs and energy calibration using ^{241}Am source
- ❑ Hit position reconstructed from light intensity (pulse height) distribution using the centroid method



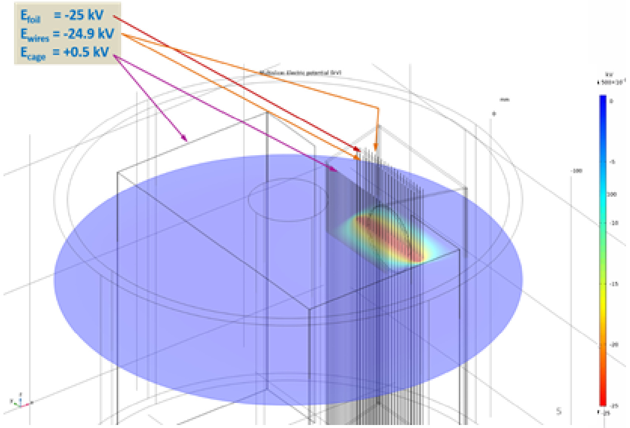
Hit position resolution $\Delta x, \Delta y \approx 5$ mm



Proton detector – test with neutron beam

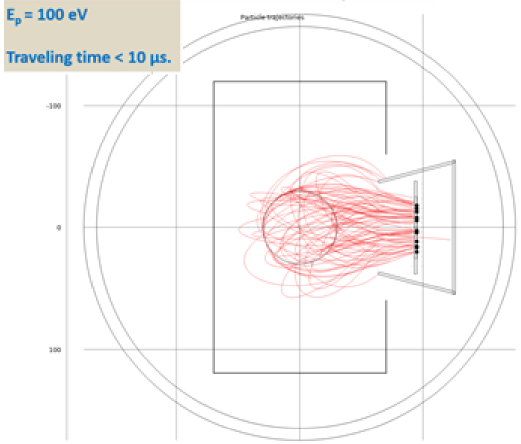
COMSOL simulation of proton transport

Electric potential



E_{foil} = -25 kV
E_{wires} = -24.9 kV
E_{cage} = +0.5 kV

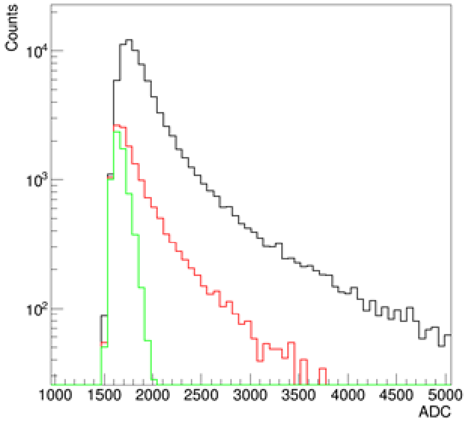
Generation of protons



E_p = 100 eV

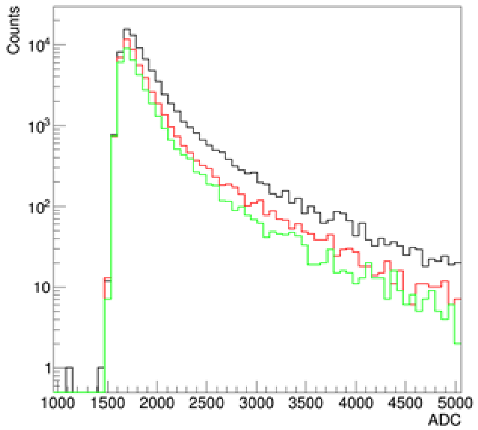
Traveling time < 10 µs.

Recoil protons registered by prototype detector



Influence of the high voltage of p-e foil on the detection of protons

HV_cf = - 6 kV
HV_cf = -10 kV
HV_cf = -15 kV



Influence of the potential cage voltage on the detection of protons

HV_cage = 0 V
HV_cage = 200 V
HV_cage = 500 V

Conclusions and prospects

- ❑ **BRAND** project offers exploration of the transverse electron polarization correlation coefficients ***R***, ***N***, ***H***, ***L***, ***S***, ***U***, ***V*** in neutron β-decay (***H***, ***L***, ***S***, ***U***, ***V*** were never measured before)
- ❑ Combined impact of ***R***, ***N***, ***H***, ***L***, ***S***, ***U***, ***V*** on BSM physics: access to both REAL and IMAGINARY parts of exotic week couplings with compltetely different systematics than in ep/n experiments
- ❑ "**HE approach**": tracking, vertex reconstructrion; measure in low magnetic field to access transverse electron polarization
- ❑ Simultaneous measurement of "classical" coefficients ***a***, ***A***, ***B*** and ***D*** will provide consistency check and comparison of systematic effects specific to **high**– and **low**–magnetic field techniques
- ❑ Experiment is challenging and not free of risks, however, most of critical techniques were experimentaly verified in pioneering project **nTRV@PSI**
- ❑ First runs with prototype detectors confirm feasibility of proposed techniques – further R&D and tests ongoing
- ❑ R&D and initial data taking with minimal setup at ILL; Ultimate setup and major data collection at ESS

BRAND Collaboration

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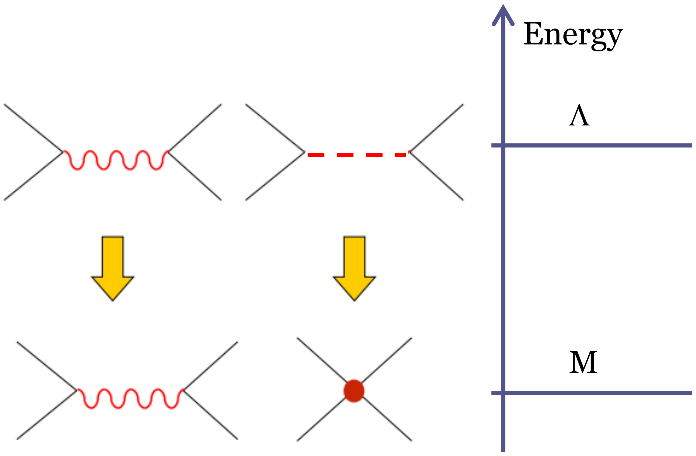
Backup slides

EFT approach in β-decay



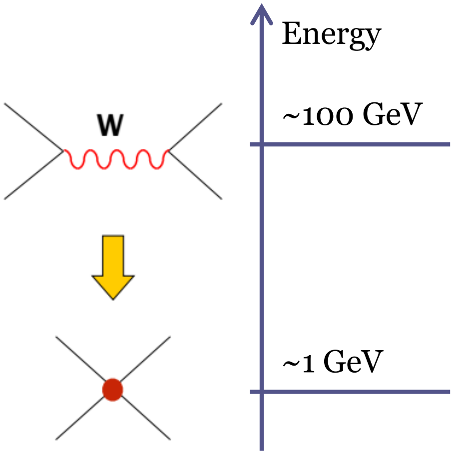
- For experiments at energy significantly lower than BSM scale (Λ_i):

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{1}{\Lambda_i^2}\mathcal{L}_i \approx \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum \alpha_i \mathcal{O}_i^{(6)}$$

$\mathcal{O}_i^{(6)}$ – dimension-6 operators

α_i – *Wilson coefficients* $\alpha_i = \Lambda^2 f_i\left(g_{\text{BSM}}, M_{\text{BSM}}\right)$

Observables for $E << \Lambda$: $\mathcal{R} = \mathcal{R}_0\left(1 + \frac{\mathcal{O}(M)}{\Lambda} + \frac{\mathcal{O}\left(M^2, E^2, ME\right)}{\Lambda^2} + \ldots\right)$



- Semi-leptonic processes, partonic level, exchanged W-boson is heavy – SM interaction Lagrangian takes the contact (V-A)×(V-A) form

$$\mathcal{L}_{\text{SM}} = -\frac{G_F V_{ud}}{\sqrt{2}}\,\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$$

Limits from high energy

- Electrons and missing transverse energy (MET) channel

$$\sigma(pp \to e + \mathrm{MET} + X)$$

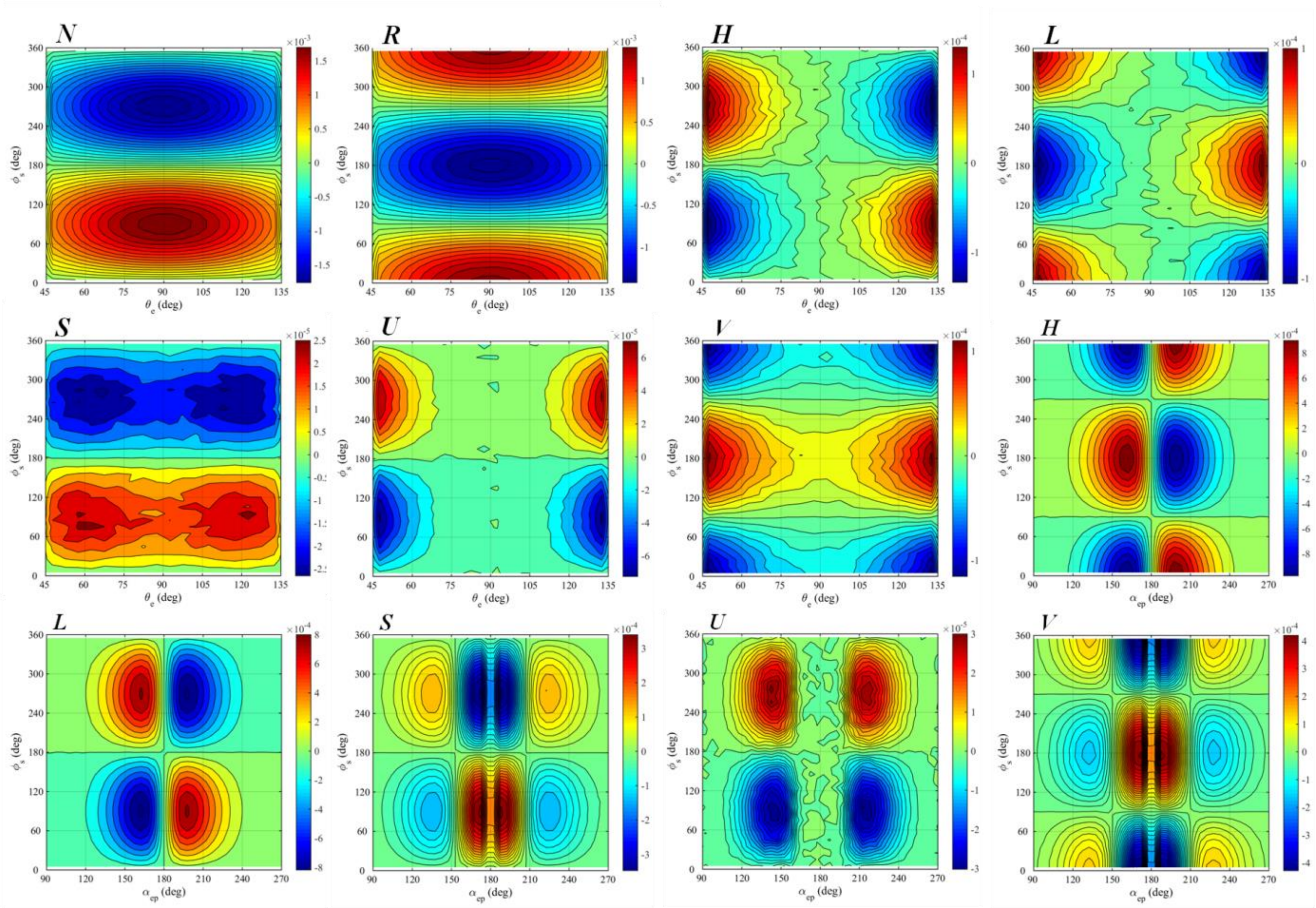
- Underlying partonic process is the same as in β-decay $(\bar{u}d \to e\bar{\nu})$
- If BSM particles are too heavy to be produced on-shell → EFT analysis appropriate
- Express weak scale Lagrangian in terms of EFT parameters and calculate cross section

$$\begin{aligned} \sigma(m_T > \overline{m}_T) \quad = \quad & \sigma_W \left[\left| 1 + \epsilon_L^{(v)} \right|^2 + |\tilde{\epsilon}_L|^2 + |\epsilon_R|^2 \right] \\ & -2\,\sigma_{WL}\,\mathrm{Re}\left(\epsilon_L^{(c)} + \epsilon_L^{(c)} \epsilon_L^{(v)^*} \right) + \sigma_R \left[|\tilde{\epsilon}_R|^2 + |\epsilon_L^{(c)}|^2 \right] \\ & + \sigma_S \left[|\epsilon_S|^2 + |\tilde{\epsilon}_S|^2 + |\epsilon_P|^2 + |\tilde{\epsilon}_P|^2 \right] + \sigma_T \left[|\epsilon_T|^2 + |\tilde{\epsilon}_T|^2 \right] \end{aligned}$$

Planning

	BRAND I	**BRAND II**	**BRAND III**
Site	ILL	ILL (ESS ?)	ESS
Time	3 – 4 years	3 – 4 years	5-6 years
Pressure	Ambient	Ambient	300 mbar
Mott target	Pb (Au)	Pb (Au)	Depleted U
Coverage of azimuthal angle	1/6	Full	Full
Statistical precision (goal)			
A	0.0008	0.00008	0.000016
a, B, D	0.005	0.0005	0.0001
R, N	0.01	0.001	0.0002
H, L, S, U, V	0.02	0.002	0.0004
Systematic errors			
R, N, H, L, S, U, V	0.002	0.001	0.0005

BRAND – kinematical sensitivity maps



Sensitivity maps for the *N*, *R*, *H*, *L*, *S*, *U* and *V* coefficient as a function of the polar electron angle θ_e or the relative electron-proton angle and the azimuthal spin projection angle ϕ_s (arbitrary units). Irregularities in contours are due to limited statistics in simulations. The kinematical acceptance is defined by:

$$E_\mathrm{e}^\mathrm{kin} \in (200, 782)\,\mathrm{keV},\ E_\mathrm{p}^\mathrm{kin} \in (50, 760)\,\mathrm{eV},\ \theta_\mathrm{e} \in (45^o, 135^o),\ \theta_\mathrm{p} \in (30^o, 150^o).$$

Electron polarization – dominant systematics

- ☐ **Momentum rotation in external electric field**
  - In uniform field step of 30 kV, incident energy of 100 keV and angle of incidence of 45°, momentum vector rotates by about 12°
  - Effect decreases with increasing energy and decreasing angle of incidence
  - Effect cancels to 1st order for symmetric barrier or if symmetrically sampled (left-right)
- ☐ **„*g*-2 effect”**
  - 7 mrad per revolution de-synchronization between spin and momentum
  - For magnetic field strength <1 mT (guiding field in BRAND) – can be corrected for
- ☐ *Electron polarization can be determined only in well controlled electric and **low magnetic** fields*
- ☐ **Electron depolarization by multiple Coulomb scattering**
  - Dominant contribution from Mott target
  - Effective Sherman function – MC transport code based on ELSEPA physics input (F. Salvat, et al., Comput. Phys. Comm. 165 (205) 157)

Theoretical corrections (SM)

☐ Final State Interaction (FSI)

- Exist calculations sufficient for ***a***, ***b***, ***A***, ***B***, ***D***, ***R*** and ***N*** coefficients measurements with accuracy of $\mathbf{10^{-4}}$
- For ***H***, ***L***, ***S***, ***U*** and ***V*** coefficients **FSI** correction exist only in lowest order (point charge) approximation

☐ Recoil order corrections (ROC)

- Main contribution from Weak Magnetism
- No **ROC** exist for ***H***, ***L***, ***S***, ***U*** and ***V***

☐ Mott scattering – Sherman function

- Theoretical accuracy on the level 10^{-4} is ultimately required

V. Gudkov, et al., Phys. Rev. C 77, 045502 (2008).
A.N. Ivanov et al., Phys. Rev. C 95, 055502 (2017).
A.N. Ivanov et al., Phys. Rev. C 98, 035503 (2018).
M. Gorchtein, priv. communication