

Free Neutron Decay at PERC: Proton Electron Radiation Channel

Alberto José Saavedra García

FAKT Meeting
Bruck an der Mur
22.02.2024

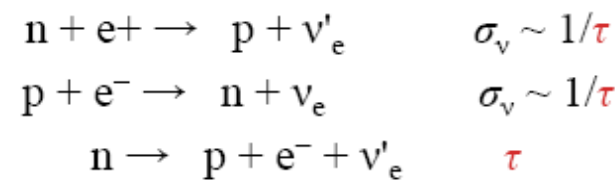
Why Free Neutron Decay?

- Cosmology: primordial nucleosynthesis
- Astronomy: solar physics
- Particle physics: neutrino detectors

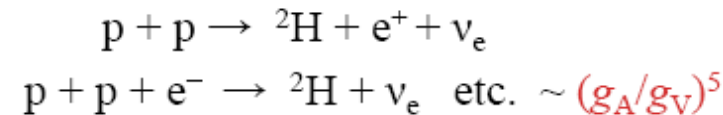
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- CKM matrix element: V_{ud} ($|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1?$)

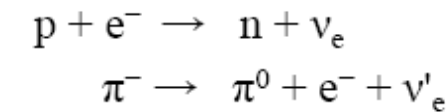
Primordial element formation
(^2H , ^3He , ^4He , ^7Li , ...)



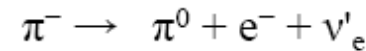
Solar cycle



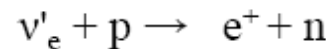
Neutron star formation



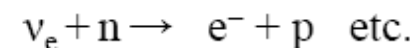
Pion decay



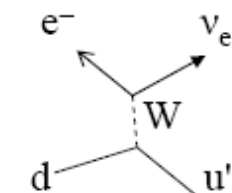
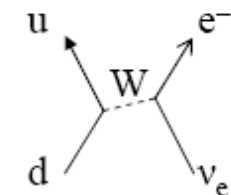
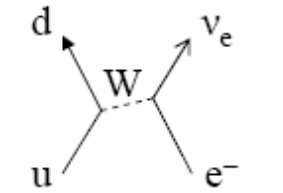
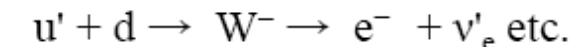
Neutrino detectors



Neutrino forward scattering



W and Z production



Free Neutron Decay: Theory

$$\begin{aligned}
 \mathcal{H} = & \cancel{(\bar{\psi}_p \psi_n)(C_S \bar{\psi}_e \psi_\nu + C'_S \bar{\psi}_e \gamma_5 \psi_\nu)} && \text{Scalar} \\
 & + (\bar{\psi}_p \gamma_\mu \psi_n)(C_V \bar{\psi}_e \gamma_\mu \psi_\nu + C'_V \bar{\psi}_e \gamma_\mu \gamma_5 \psi_\nu) && \text{Vector} \\
 & + \frac{1}{2} \cancel{(\bar{\psi}_p \sigma_{\lambda\mu} \psi_n)(C_T \bar{\psi}_e \sigma_{\lambda\mu} \psi_\nu + C'_T \bar{\psi}_e \sigma_{\lambda\mu} \gamma_5 \psi_\nu)} && \text{Tensor} \\
 & - (\bar{\psi}_p \gamma_\mu \gamma_5 \psi_n)(C_A \bar{\psi}_e \gamma_\mu \gamma_5 \psi_\nu + C'_A \bar{\psi}_e \gamma_\mu \psi_\nu) && \text{Axial-vector} \\
 & + \cancel{(\bar{\psi}_p \gamma_5 \psi_n)(C_P \bar{\psi}_e \gamma_5 \psi_\nu + C'_P \bar{\psi}_e \psi_\nu)} && \text{Pseudoscalar}
 \end{aligned}$$

where: $C_i = (L_i + R_i)$; $C'_i = (L_i - R_i)$

Lee and Yang, *Phys. Rev.* 104 (1956)

Nature seems to favor a V-A linear combination.

In the V-A Theory: $R_A = R_V = 0$

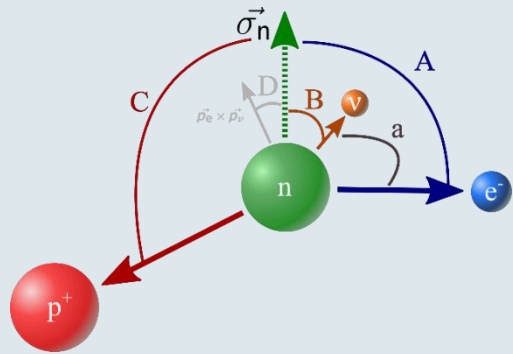
Parity is maximally violated

$$\left. \begin{aligned} C_V &\propto g_V \\ C_A &\propto g_A \end{aligned} \right\} \Rightarrow \lambda \equiv \frac{g_A}{g_V}$$

Free Neutron Decay: Observables

$$d^3\Gamma = \frac{1}{(2\pi)^5} \frac{G_F^2 |V_{ud}|^2}{2} p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu \times \xi \left[1 + a \frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \frac{\langle \mathbf{s}_n \rangle}{s_n} \left(A \frac{\mathbf{p}_e}{E_e} + B \frac{\mathbf{p}_\nu}{E_\nu} + D \frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu} \right) \right]$$

Jackson, Treiman, Wyld, *Phys. Rev.* 106 (1957)



Standard Model: only vector and axial-vector currents

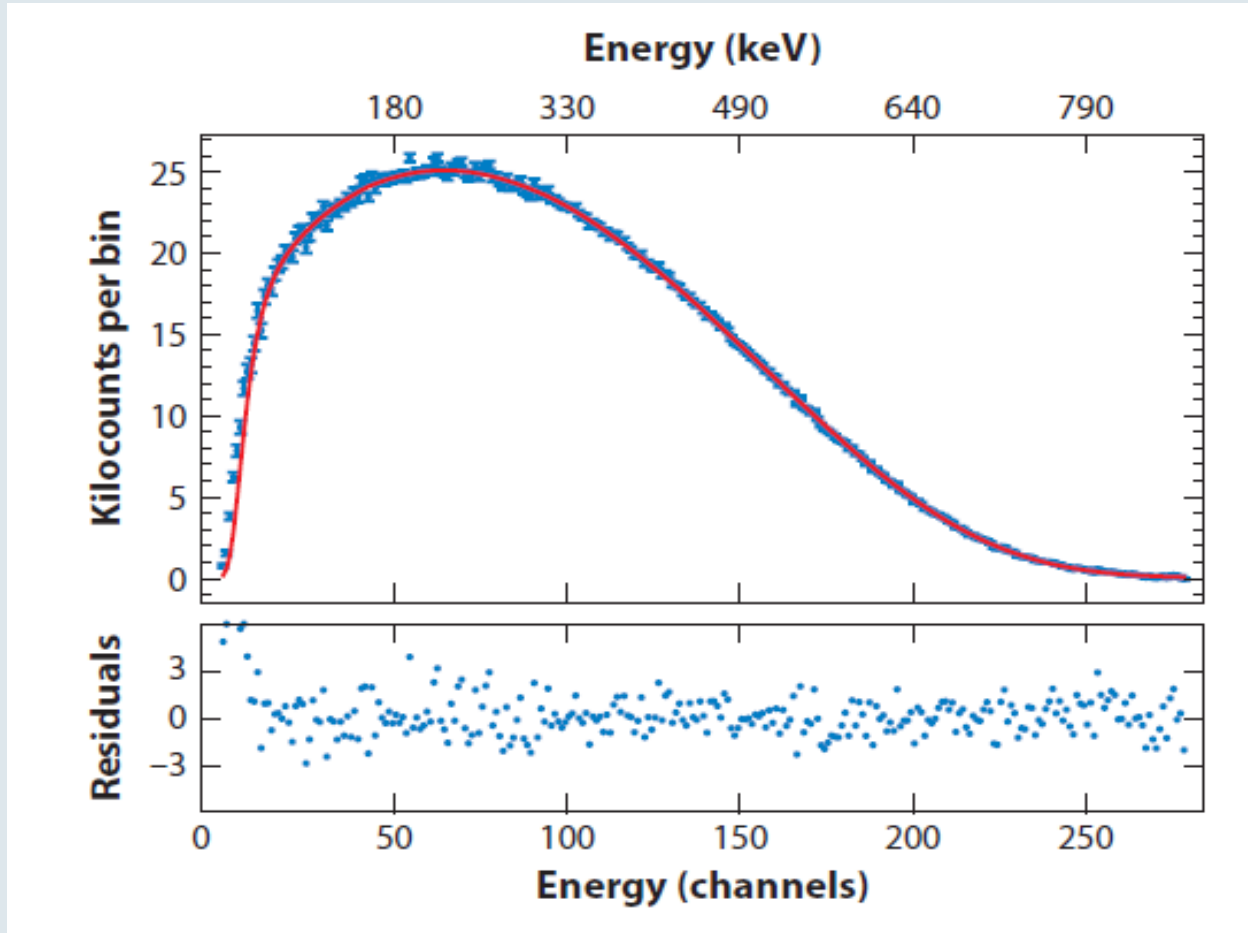


correlation coefficients depend only on λ

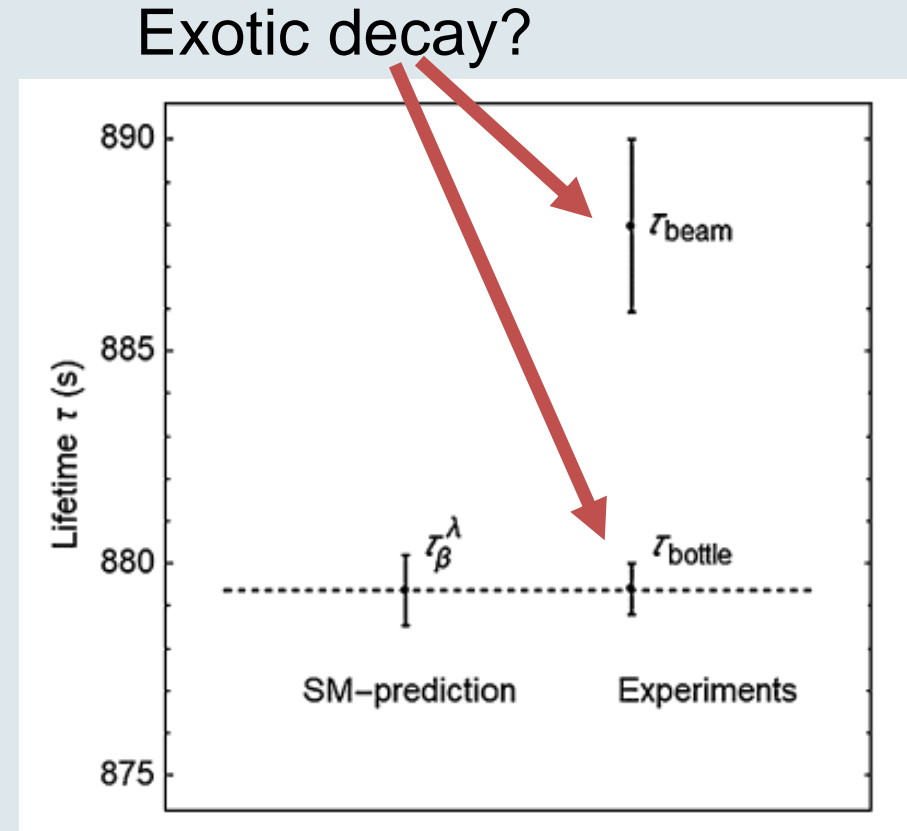
$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \quad A = -2 \frac{|\lambda|^2 + \lambda}{1 + 3|\lambda|^2} \quad B = \frac{|\lambda|^2 - \lambda}{1 + 3|\lambda|^2}$$

$$C = x_C \frac{4\lambda}{1 + 3|\lambda|^2} \quad D = \frac{-2|\lambda| \sin(\phi_{AV})}{(1 + 3\lambda^2)} \quad \lambda = \frac{g_A}{g_V}$$

Parameter:	Name:	P	T
a	Electron-Neutrino Correlation	Even	Even
b	Fierz-Term	Even	Even
A	β -Asymmetry	Odd	Even
B	Neutrino Asymmetry	Odd	Even
C	Proton Asymmetry	Odd	Even
D	Triple Correlation Coefficient	Even 10^{-4}	Odd



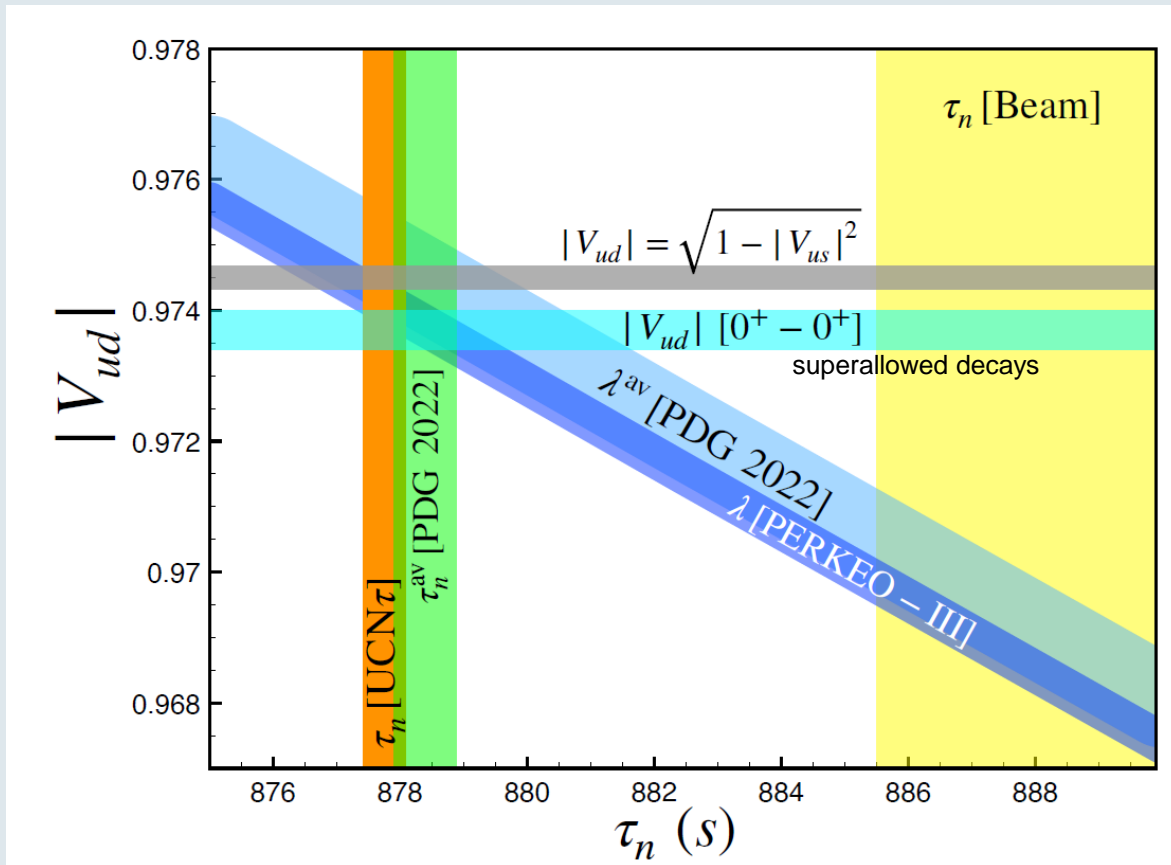
Experimental electron energy spectrum - PERKEO III



Dubbers, Abele et al, *Phys. Lett. B* 791 (2019)

$$\tau_{\beta}^{\lambda} = \frac{5172.3(1.1)s}{1 + 3|\lambda|^2}$$

Free Neutron Decay: V_{ud}



Gorchtein and Seng, *Universe* 9 (2023)

$$|V_{ud}|^2 = \frac{5099.34s}{\tau_n (1 + 3|\lambda|^2)(1 + \Delta V_R)}$$

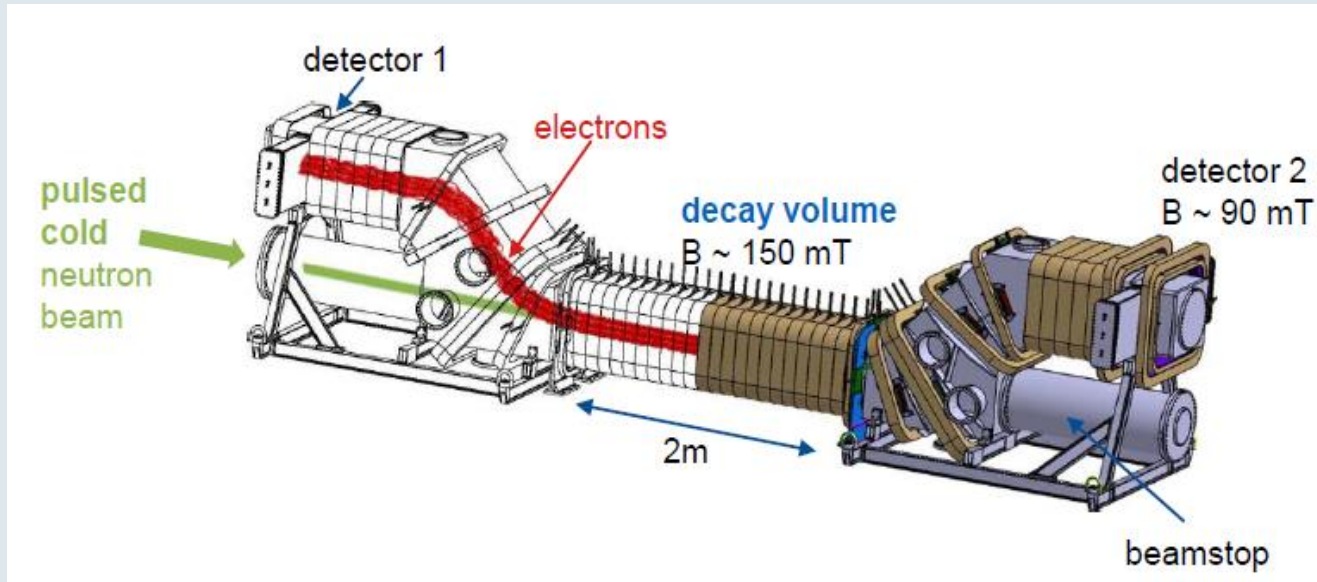
Seng et al, *Phys. Rev. D* 101 (2020)

$$V_{ud} = 0.97413(20)_{\tau_n} (35)_{\lambda} (13)_{RC}$$

$$V_{ud} = 0.97413(43)$$

τ_n : UCN_T, González et al, *Phys. Rev. Lett.* 127 (2021)
 λ : PERKEO III, Märkisch et al, *Phys. Rev. Lett.* 122 (2019)
 Cirigliano et al, *Phys. Lett. B* 838 (2023)

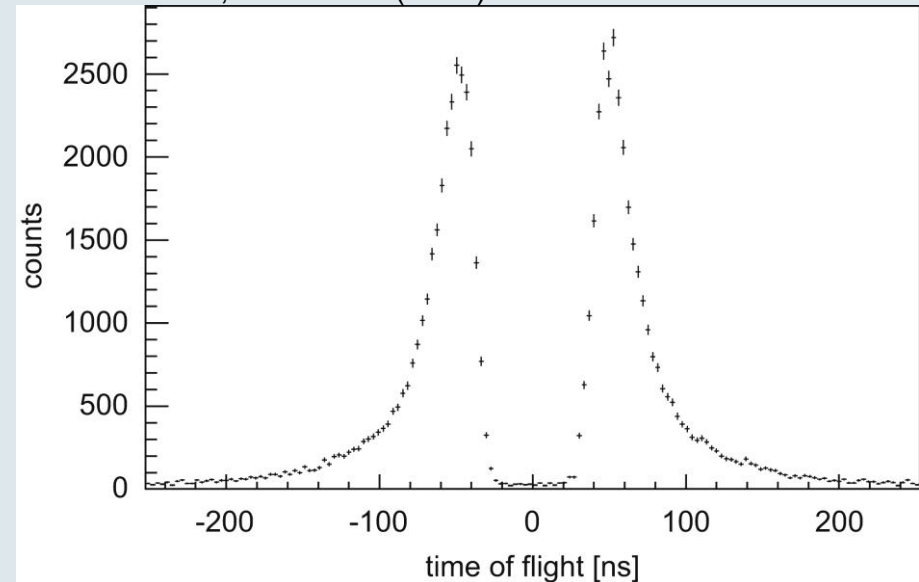
Cabbibo Angle Anomaly!



- BSE guided to opposite detector
- Both detectors read out in coincidence
- Background is measured during every chopper cycle, after the pulse is fully absorbed.
SAME CONDITIONS AS THE SIGNAL

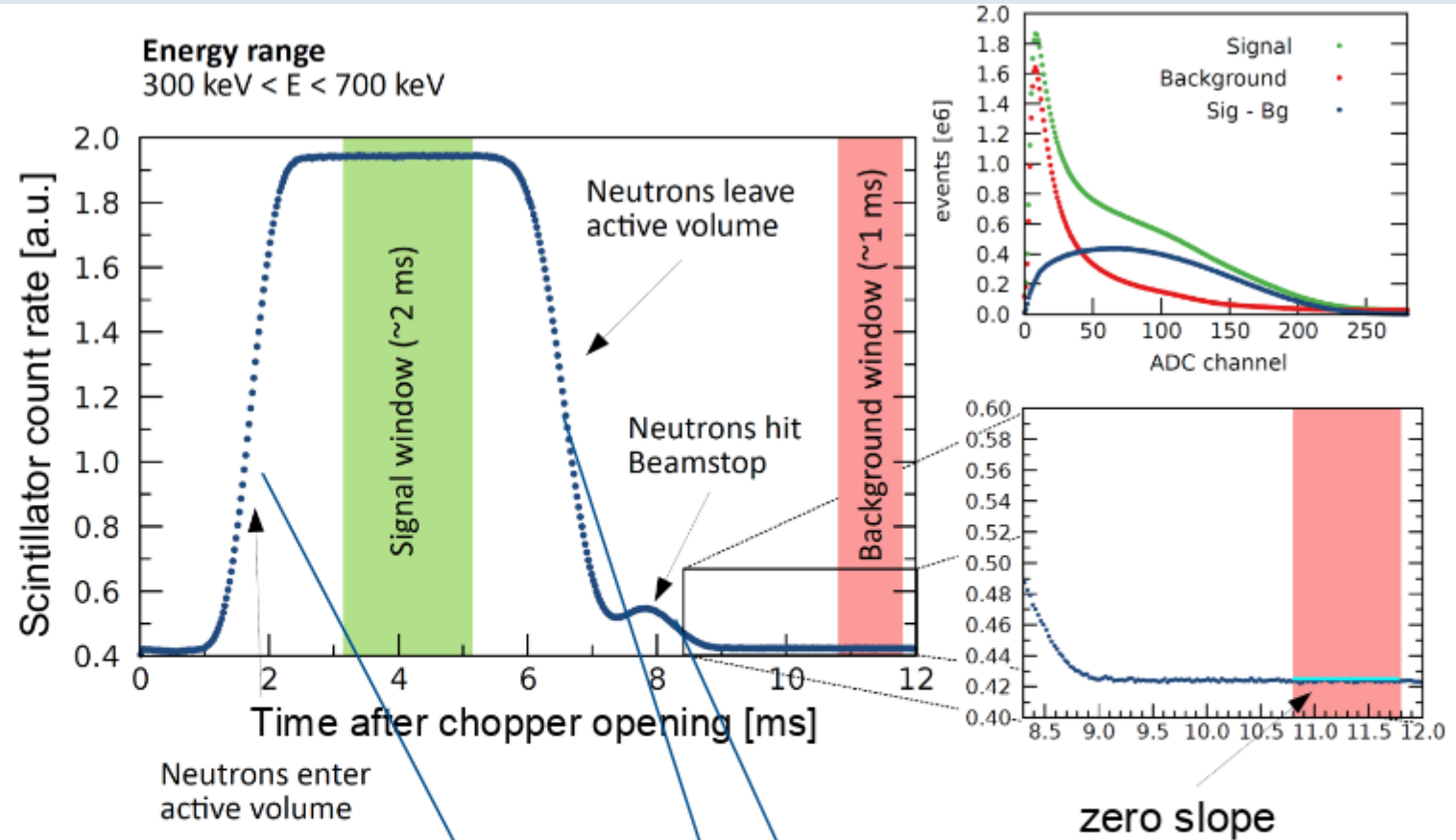
- Holding field for neutron polarization
- Charged decay particles guided towards the detectors (separated from CNB)
- 2 defined hemispheres ensuring $2 \times 2\pi$ solid angle coverage

Märkisch et al, *NIM A* 611 (2009)

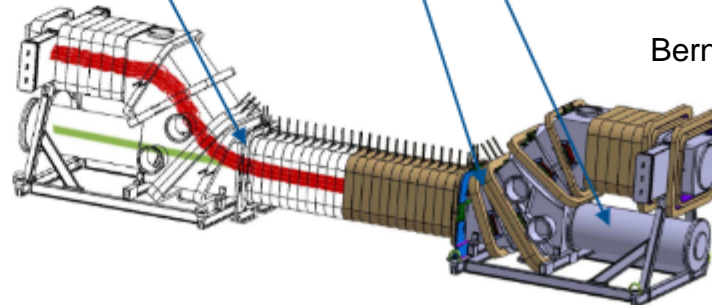


Same background condition in **signal** and **background** time window

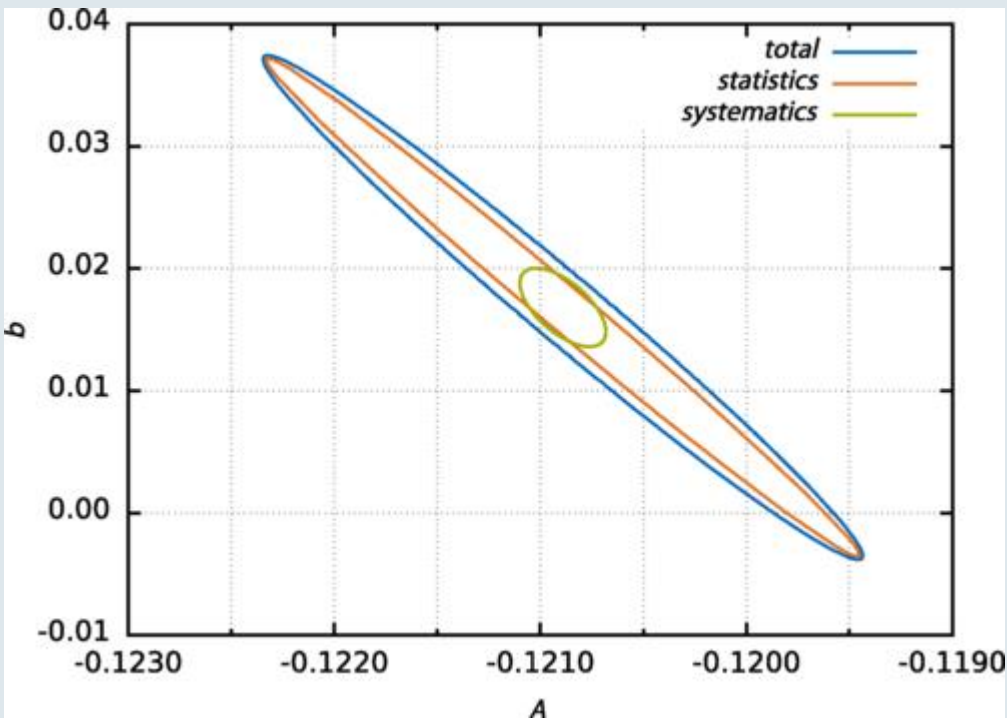
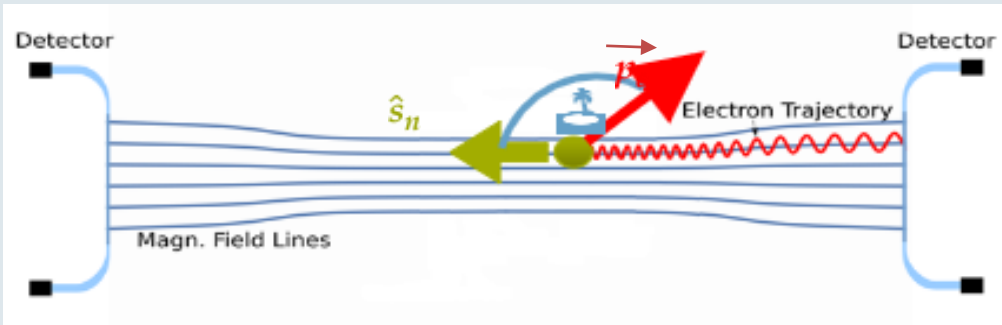
Nearly perfect background subtraction



~800 decays/s in pulsed-unpolarized mode
~200 decays/s in pulsed-polarized mode



Bernert, *Neutron Seminar ATI* (2023)



Saul et al, *Phys. Rev. Lett.* 125 (2020)

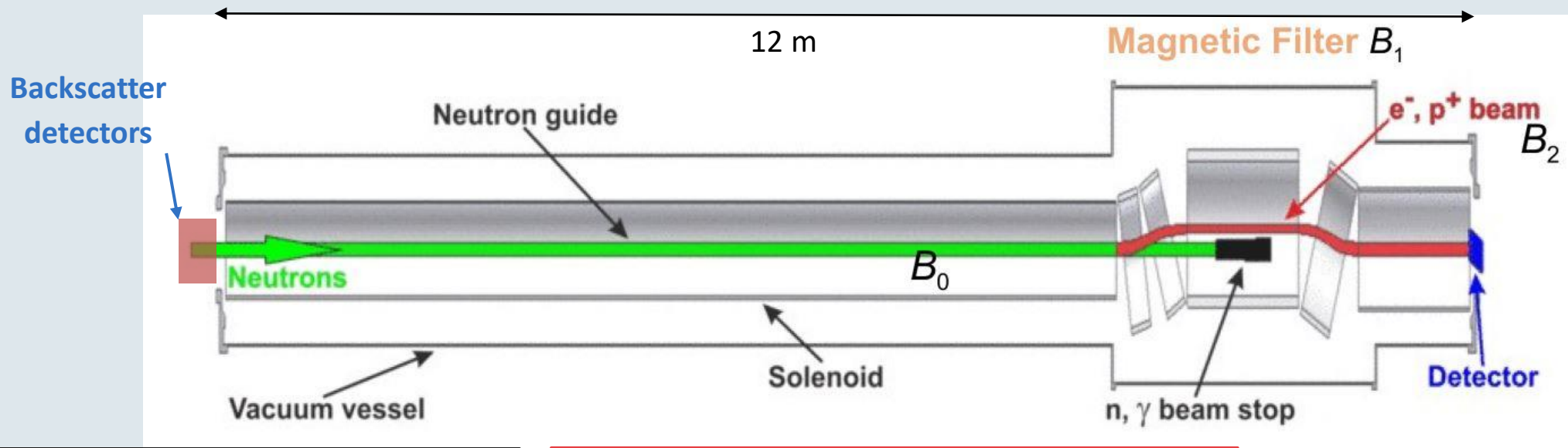
After integrating over the two hemispheres:

$$A_{\text{exp}}(E_e) = \frac{N^{\uparrow}(E_e) - N^{\downarrow}(E_e)}{N^{\uparrow}(E_e) + N^{\downarrow}(E_e)} = \frac{1}{2} A P_n \beta(E_e)$$

Considering the Fierz term $b \neq 0$ (BSM):

$$A_{\text{exp}}(E_e) \rightarrow \frac{A_{\text{exp}}(E_e)}{1 + b \left(\frac{m_e}{E_e} \right)}$$

$$A = -0.1209(15), \quad b = 0.017(21)$$



Superconducting magnets (He cooled)	B_0	0.5 – 1.5 T
	B_1	3 – 6 T
	B_2	0.5 – 1.0 T

Electron/Proton beam:

- Upstream/reflected at filter $\sim 94\%$
- Reach detector unhindered $\sim 4.3\%$

Neutrons:

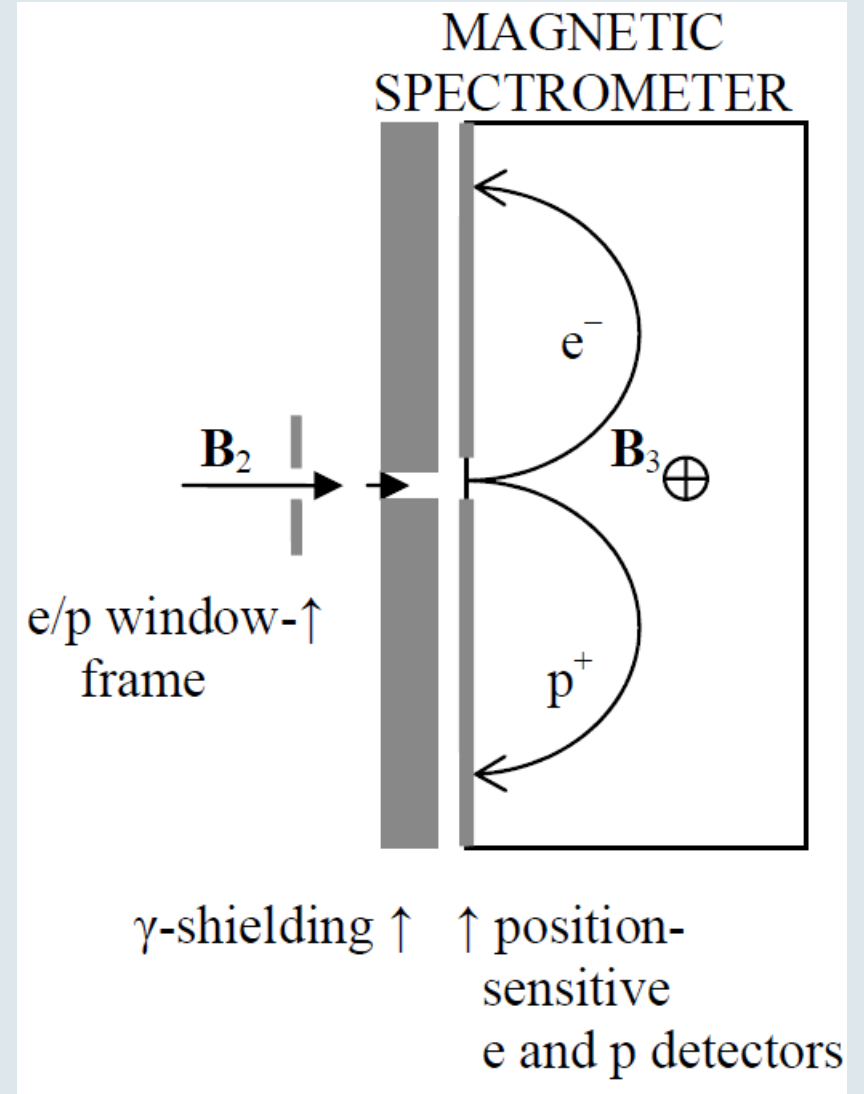
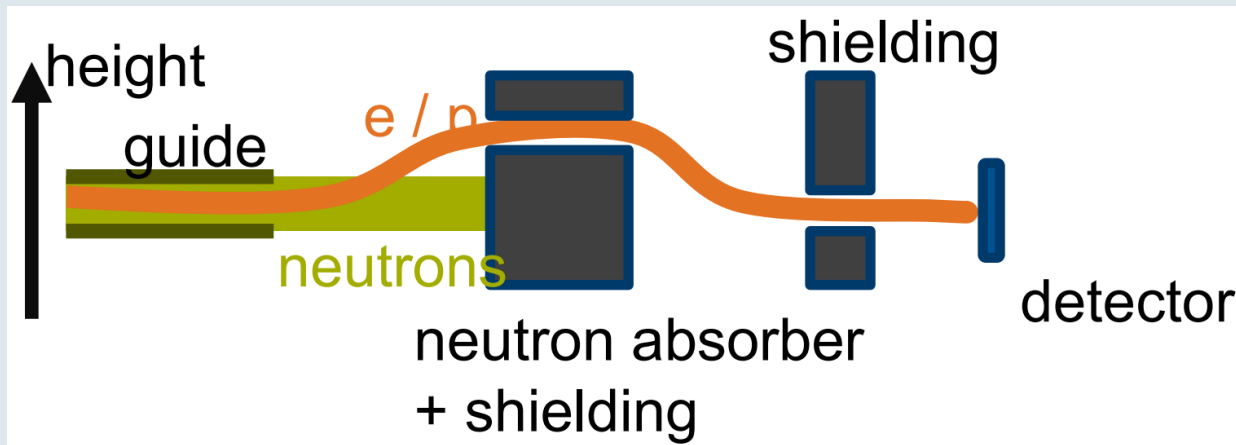
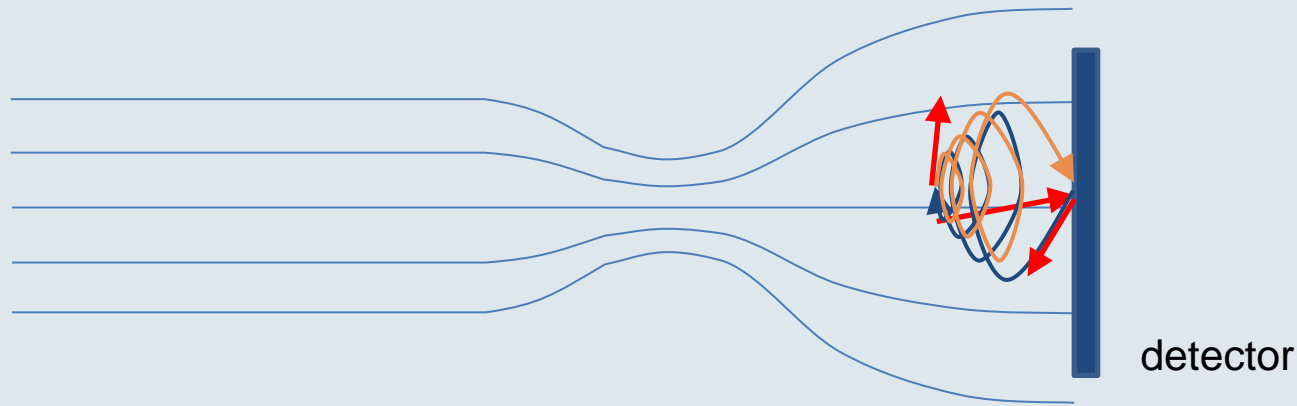
- Cold neutrons
- Flux $\sim 2 \times 10^{10} s^{-1} cm^{-2}$
- Decay rate $\sim 10^4 Hz$ (polarized, pulsed)

Backscatter detectors:

- $\sim 2\%$ of electrons from main detector
- Scintillation detectors with SiPM readout

Detector:

- Scintillation detector with PMT readout
- Silicon detector under development
- Magnetic spectrometer



Delivery of Magnet System September 2021



Setting up the Feeder Tower March 2022





Installation of yoke frame nearing completion. Power distribution installed.

Continually Setting up the Return Yoke



Arranging > 1km of cables



Status of PERC and the MEPHISTO beamline

Instrument: Installation of yoke frame nearing completion.
Power distribution installed.

Beam line: Successful test installation of beam tubes.
Expect transfer of first ~45t of shielding within next weeks.

Infrastructure: Concrete support outside hall east for
helium compressor!!

Equipment:

negligible depolarization of
CuTi verified at ILL

First sample of 2mm thick Si
pixel detector



Goal: magnet *acceptance* tests asap => ready for beam in 2024!

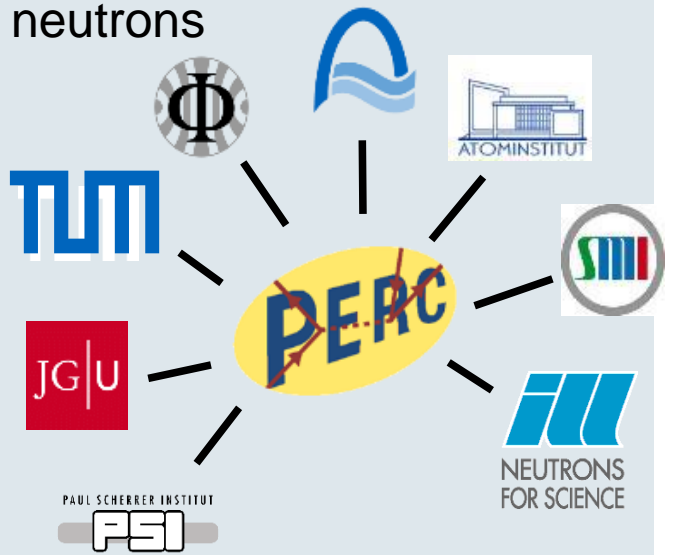
Outlook

- Early 2024:
 - Completion of magnetic shielding
 - Cool-down of the cryostat
 - Magnetic field measurements

- Late 2024:
 - Installation of neutron beamline
 - Detector tests inside PERC with calibration sources
 - First measurements with cold neutrons of thermal beam
- 2025:
 - Measurements with cold neutrons



A. Saavedra (ATI-TU Wien), FAKT 2024



Thank you for your attention!

Hartmut Abele¹, Karina Bernert², Andreas Doblhammer¹, Dirk Dubbers³, Martin Fertl⁴, Ivica Galic¹, José Manuel Gómez Guzmán⁵, Erwin Jericha¹, Christine Klauser^{6,7}, Jens Klenke⁵, Manuel Lebert^{2,5}, Kathrin Lehmann⁵, Bastian Märkisch², Irina Pradler¹, Alberto José Saavedra Garcia¹, Johannes Schilberg¹, Ulrich Schmidt³, Anna Schubert², Torsten Soldner⁷, Bernd Windelband³

Former members:

Jaqueline Erhart¹, Harald Fillunger¹, Werner Heil⁴, Alexander Hollering^{2,5}, Michael Klopff¹, Gertrud Konrad^{1,8}, Max Lamparth², Thorsten Lauer⁵, Wilfried Mach¹, Reinhard Maix^{1,2,3}, Holger Mest³, Thomas Mittelstädt³, Daniel Moser⁸, Alexander Petoukhov⁷, Lukas Raffelt^{2,3}, Nataliya Rebrova³, Christoph Roick², Heiko Saul^{1,2,5}, Romain Viroth⁷, Xiangzun Wang¹, Carmen Ziener¹, Oliver Zimmer⁶

- ¹ Atominstitut, Technische Universität Wien, Austria
- ² Physik-Department, Technische Universität München, Germany
- ³ Physikalisches Institut, Universität Heidelberg, Germany
- ⁴ Johannes Gutenberg-Universität, Mainz, Germany
- ⁵ Forschungs-Neutronenquelle Heinz Maier-Leibnitz, Garching, Germany
- ⁶ Paul Scherrer Institut, Villigen, Switzerland
- ⁷ Institut Laue-Langevin, Grenoble, France
- ⁸ Stefan Meyer Institute for Subatomic Physics, Vienna, Austria

