Status of Measurements with Cold and Ultracold Neutrons

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CKM Matrix & Neutron Decay

$$|V_{ud}|^2 = \frac{(4908.7 \pm 1.9)s}{\tau(1+3\lambda^2)}$$

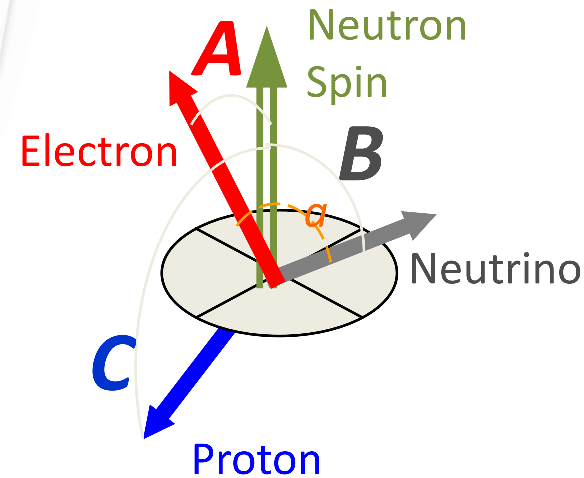
Marciano , Sirlin PRL 96 (2006)

- **Neutron lifetime τ**

- Ratio of coupling constants

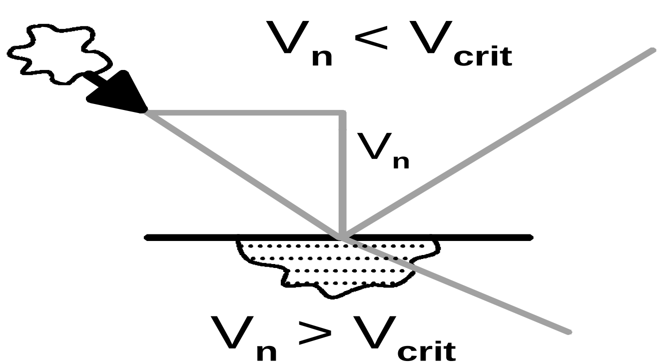
  $$\lambda = g_A / g_V$$

  from **angular correlations**



Neutron Classification

- **Cold neutron**
  - moderated in thermal bath (e.g. liquid D_2)
  - E ~ 3 meV, T ~ 40 K, v ~ 800 m/s, λ~ 0.5nm
  - high flux densities: $2 \cdot 10^{10}\ s^{-1}\ cm^{-2}$
  - Decay rate of $10^{6} s^{-1}$ per metre
- **Ultracold neutron (UCN)**
  - E < 300 neV, T ~ 1 mK, v < 7 m/s, λ > 60nm
  - Reflect from surfaces under any incident angle : storable
  - Moderate densities: 30 cm^{-3}



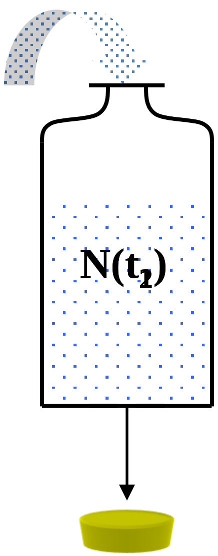
Fermi potential	~ **100 neV**
Gravity $\Delta E = m_n g \Delta h$	~ **100 neV** / meter
Magnetic field $\Delta E = \mu_n B$	~ **60 neV** / Tesla

Measurements of the neutron lifetime τ_n

Storage experiments with UCN

"counting the survivors"

"UCN bottle"



$$\frac{1}{\tau_m} = \frac{1}{t_2 - t_1} \cdot \ln \frac{N(t_1)}{N(t_2)}$$

$$\frac{1}{\tau_m} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{wall}} + \frac{1}{\tau_{leak}} + \frac{1}{\tau_{vacuum}} + \ldots$$

→ 0 (experiment)

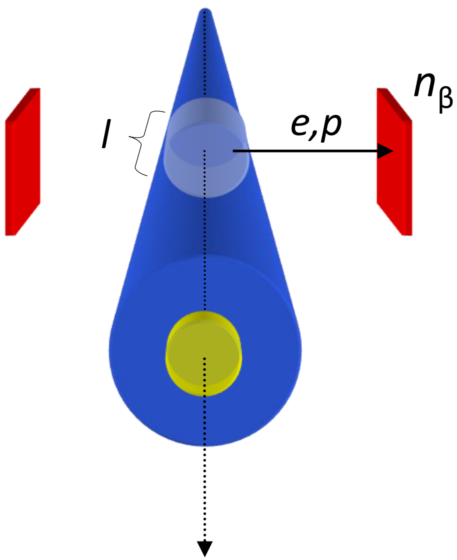
$$\frac{1}{\tau_{wall}} = \mu \cdot v_{eff}$$ → 0 (extrapolation)

$$\Rightarrow \quad \frac{1}{\tau_m} = \frac{1}{\tau_\beta}$$

relative measurements

In-beam experiments with cold neutrons

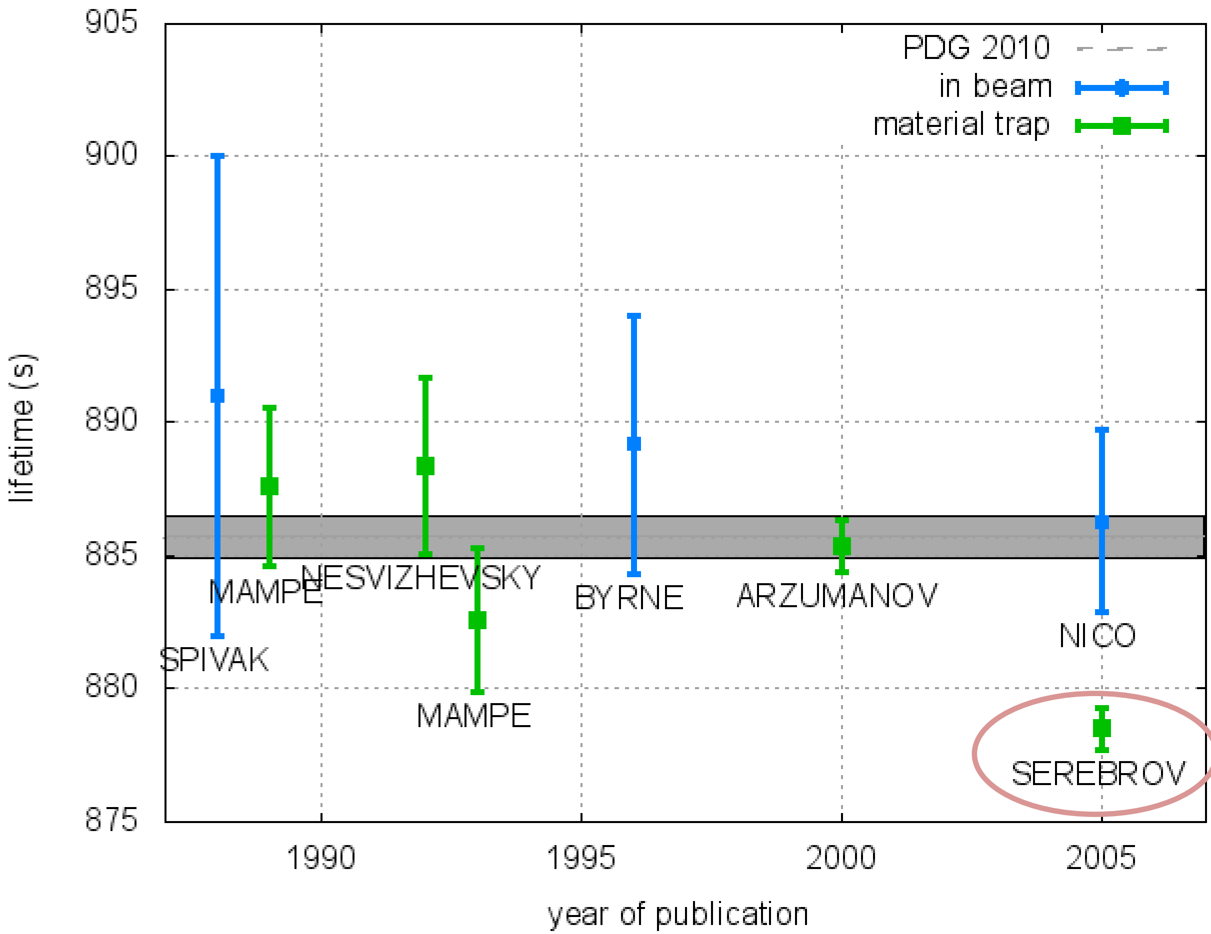
"counting the dead"



$$n_\beta = \frac{dN}{dt} = -\frac{N_0}{\tau_n} e^{-\frac{l}{v \cdot \tau_n}}$$

absolute measurements

PDG 2010: Neutron lifetime



$$\tau_{PDG} = 885.7\ (8)\text{s}$$

Not considered in average due to 6.5σ deviation from previous average

"Until this major disagreement is understood our present average of 885.7 ± 0.8 s must be suspect." PDG 2010

Neutron Lifetime: MAMBO II

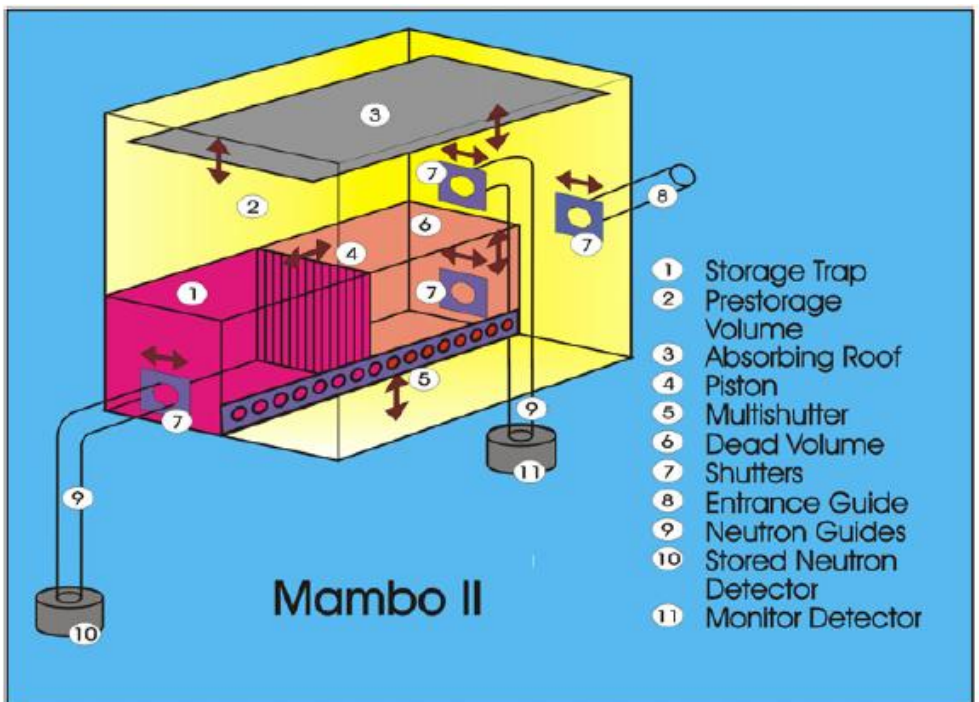
Newest result: Pichlmaier et al., Phys. Lett. B (2010), in press

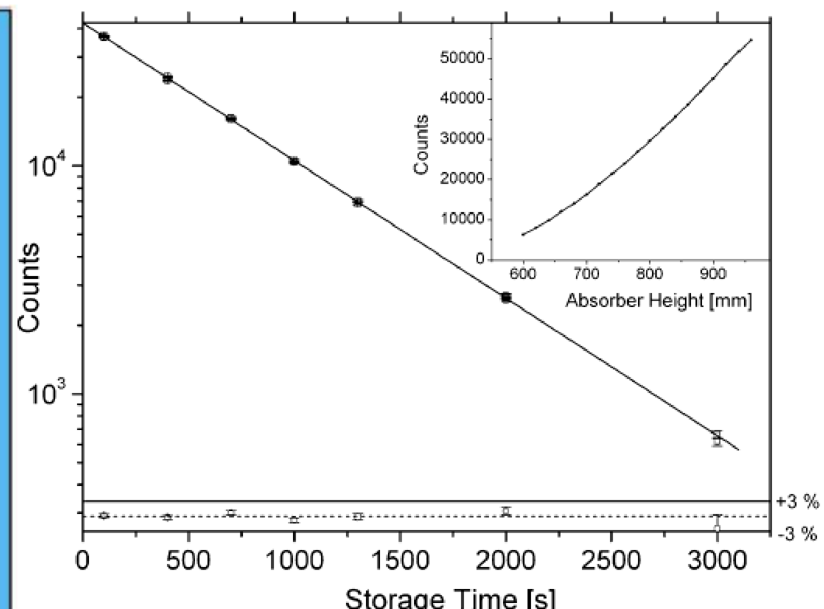
- Pre-storage volume to prepare UCN spectrum

  50neV – max. 90neV, well below surface Fermi potential of 103neV

- Careful selection of storage times:

  constant number of wall interactions when changing trap geometry: spectrum changes cancel





Neutron Lifetime: MAMBO II

Result: $\tau_n = (880.7 \pm 1.3 \pm 1.2)$ s

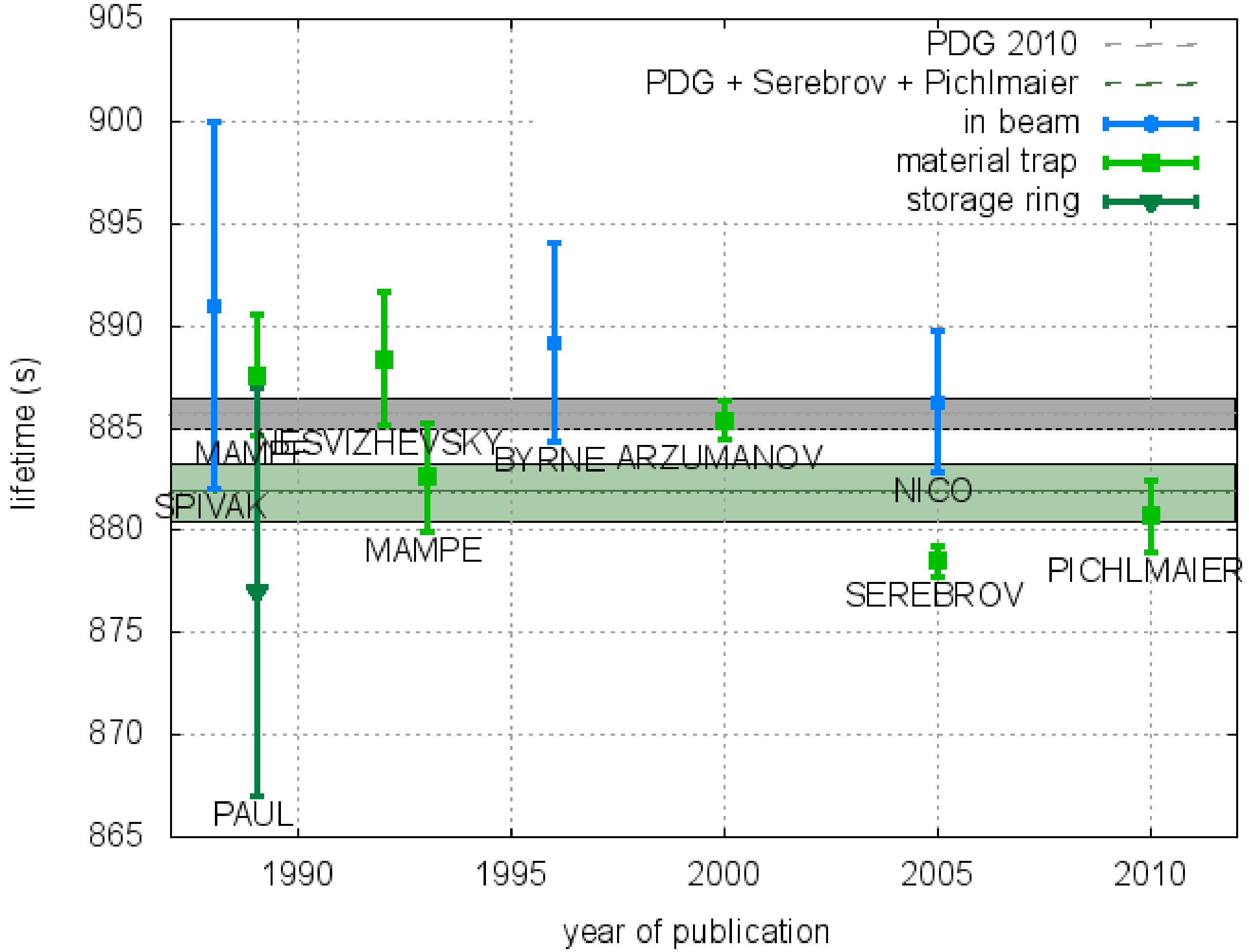
- below the PDG 2010 average of 885.7(0.8)s by 2.5σ
- above Serebrov et al. (2005) result of 878.5(0.9)s by 1.1σ

Kind of uncertainty	Shift in τ_n	Uncertainty $\Delta\tau_n$
Length of trap	–	0.7 s
Volume by Fomblin	–	0.3 s
Residual gas	$+0.7 \cdots +1.4$ s	0.4 s
Loss coefficient f	–	0.4 s
Shape of μ	–	0.5 s
Mean emptying time	+0.3 s	0.5 s
Temp. gradient 22 °C	–	0.1 s
Temp. gradient 4 °C, 10 °C	–	$<$ 0.3 s

"Our MAMBO II result makes the PDG2008 present average of the neutron lifetime value even more 'suspect'. To resolve this issue new and improved measurements are required using different methods including almost loss free UCN storage by magnetic traps" Pichlmaier et al., Phys.Lett.B (2010)

Status Neutron Lifetime

Including **all** results with $\delta\tau$ < 10s



$$\tau_{beam} = 887.6 \pm 2.7s$$

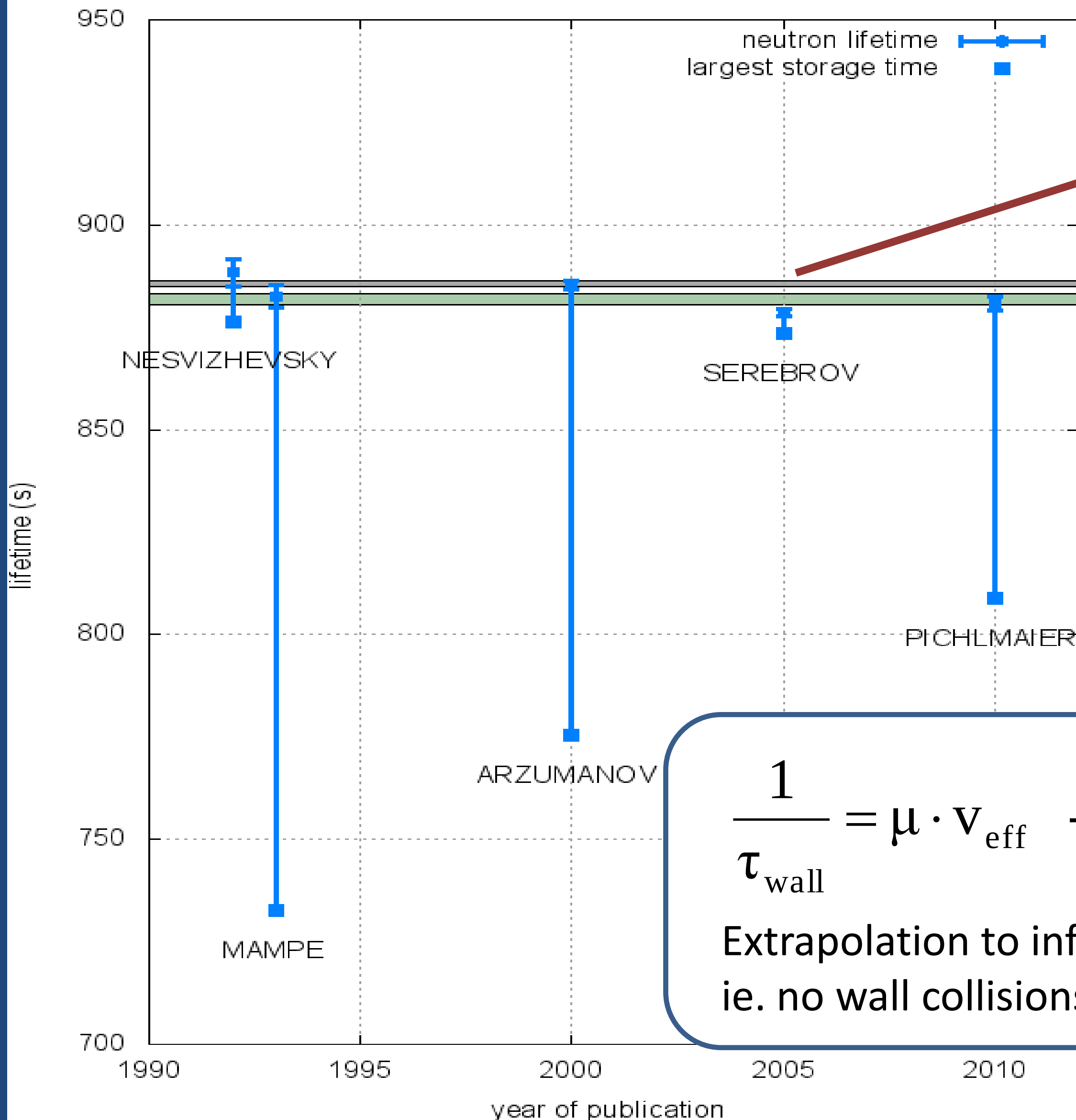
$$\tau_{PDG} = 885.7 \pm 0.8s$$

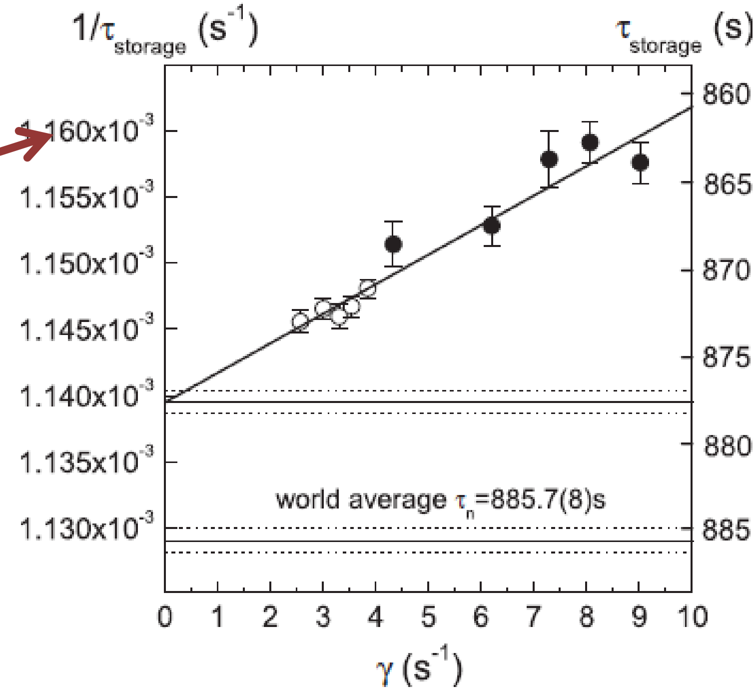
$$\tau_{all} = 881.8 \pm 1.4s$$

Pichlmaier et al., Phys.Lett.B (2010), in press

Dubbers & Schmidt, Rev.Mod.Phys (2010), in press

Status Neutron Lifetime





$$\frac{1}{\tau_{wall}} = \mu \cdot v_{eff} \rightarrow 0 \text{ (extrapolation)}$$

Extrapolation to infinite storage volume, ie. no wall collisions

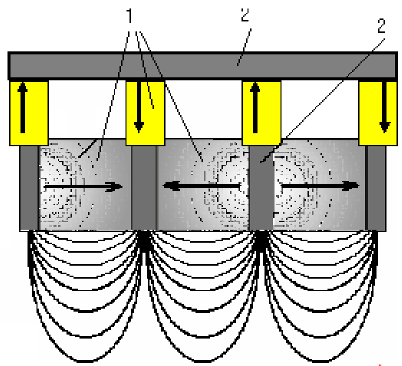
Magnetic confinement

- For μ_n = -60.3 neV/T, a 2T field generates a 120 neV barrier.
- Force due to field gradient, $F = -\mu\,(dB/dz)$, repels only one spin state.
- Use permanent magnets: V. Ezhov et al., J. Res. Natl. Inst. Stand. Technol. 110 (2005)

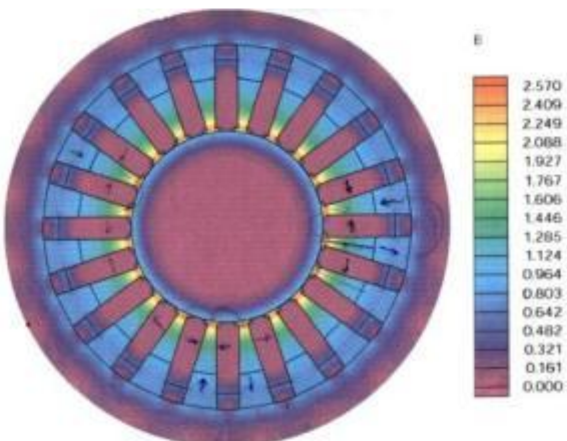
- **Step 1: 1D confinement**

  1 – permanent magnets

  2 – magnetic poles



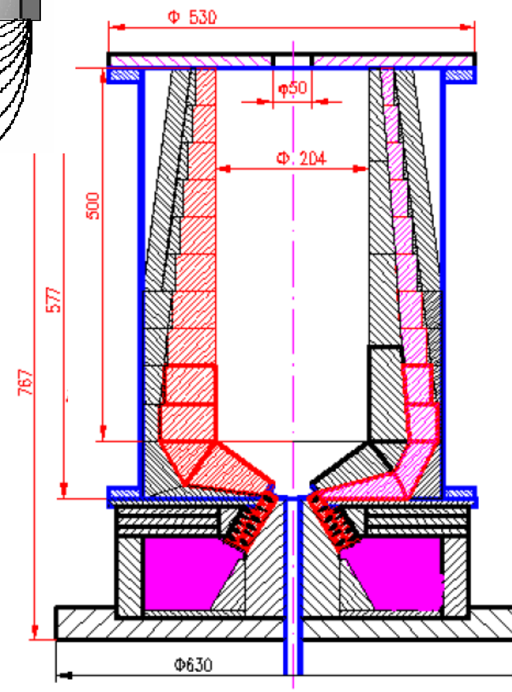
- **Step 2: 2D confinement**



(O. Naviliat-Cuncic)

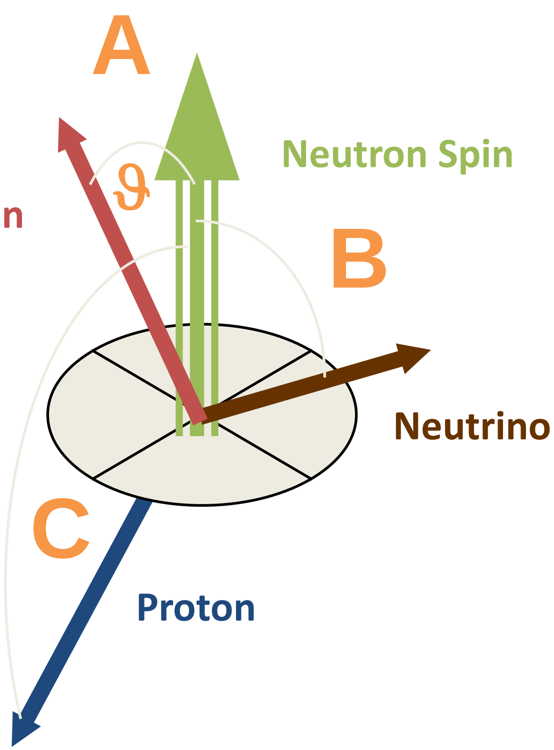
- **Step 3: 3D confinement**

  - top (gravity)
  - bottom (magnetic shutter)



Correlation Coefficients

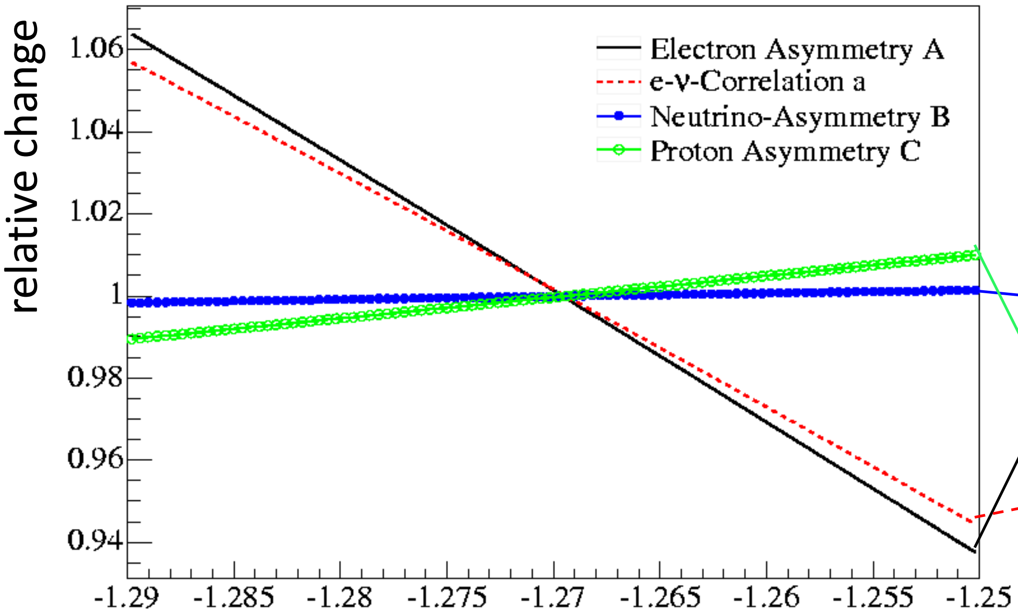
$$d\omega \propto G_F^2 \, |V_{ud}|^2 \, F(E) \left(1 + a \, \frac{\mathbf{p}_e \mathbf{p}_\nu}{E E_\nu} + b \, \frac{m_e}{E} + \langle \mathbf{s}_n \rangle \left[A \, \frac{\mathbf{p}_e}{E} + B \, \frac{\mathbf{p}_\nu}{E_\nu} + D \, \frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E E_\nu} \right] \right)$$



Some recent results and measurements:

A	P-odd	**UCNA, Liu et al. (2010), arXiv:1007.3790**
		UCNA, Pattie et al., PRL 102 (2009)
		PERKEO III – measurement 2009
		PERKEO II, Abele, Prog.Part.Nucl.Phys 60 (2008)
B	P-odd	PERKEO II, Schumann et al., PRL 99 (2007)
C	P-odd	PERKEO II, Schumann et al., PRL 100 (2008)
a		Byrne et al., J. Phys. G 28 (2002)
		***a*Spect** – measurement 2008, 2011
		aCorn – running
D	T-odd	TRINE, Soldner et al., PLB 581 (2004)
		emiT, Lising et al., PRC 62 (2000)
G		Kozela et al., PRL 102 (2009)
N		
R	T-odd	

Determination of $\lambda = g_A/g_V$



$\lambda = g_A/g_V$

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

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

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

$$C = x_C(A+B)$$

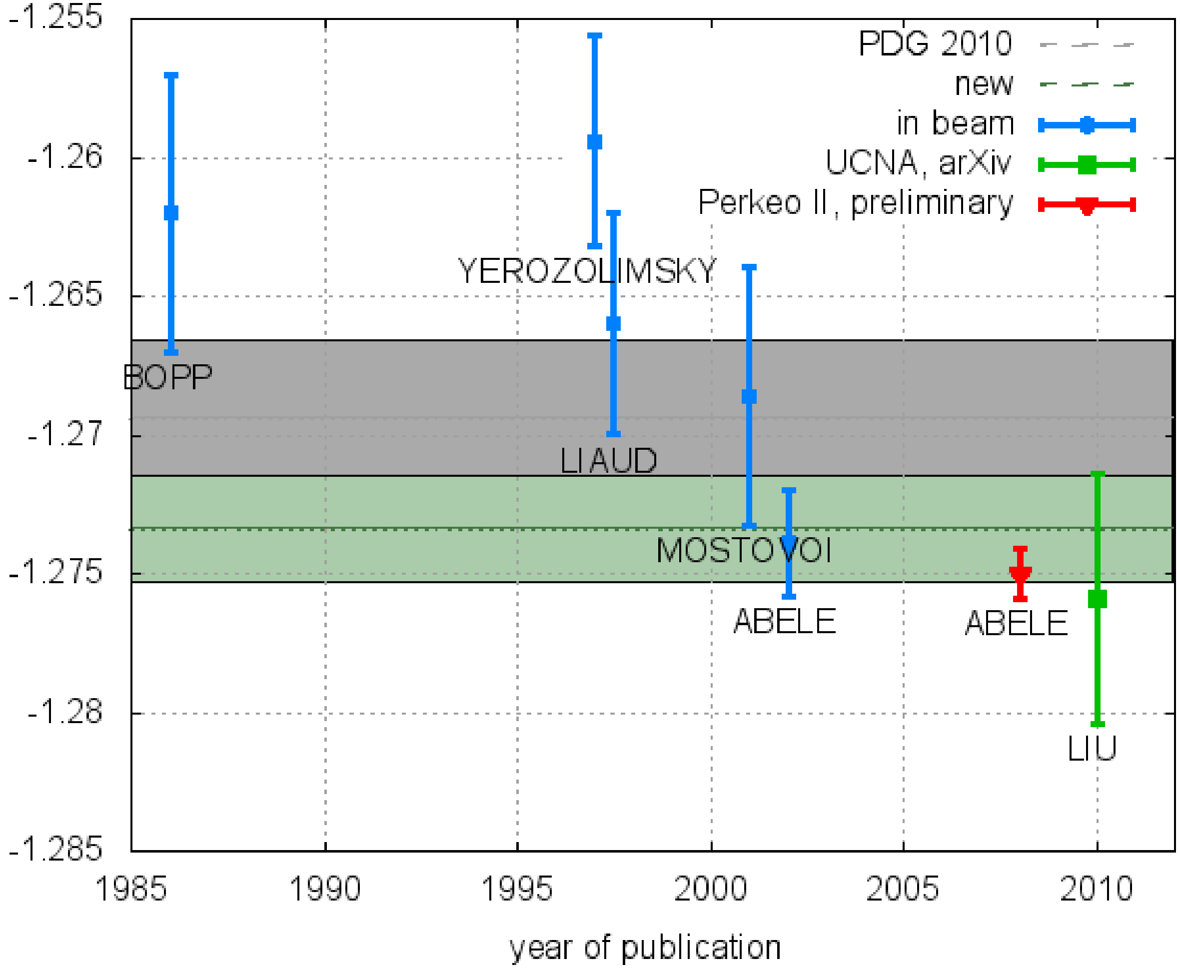
$A_{PDG} = -0.1173 \pm 0.0013$ 1.1%

$B_{PDG} = 0.9807 \pm 0.0030$ 0.3%

$C = -0.2377 \pm 0.0026$ 1.1%

$a_{PDG} = -0.103 \pm 0.004$ 3.9%

Status $\lambda = g_A/g_V$



PDG average:
-1.2694(28), S=2.0

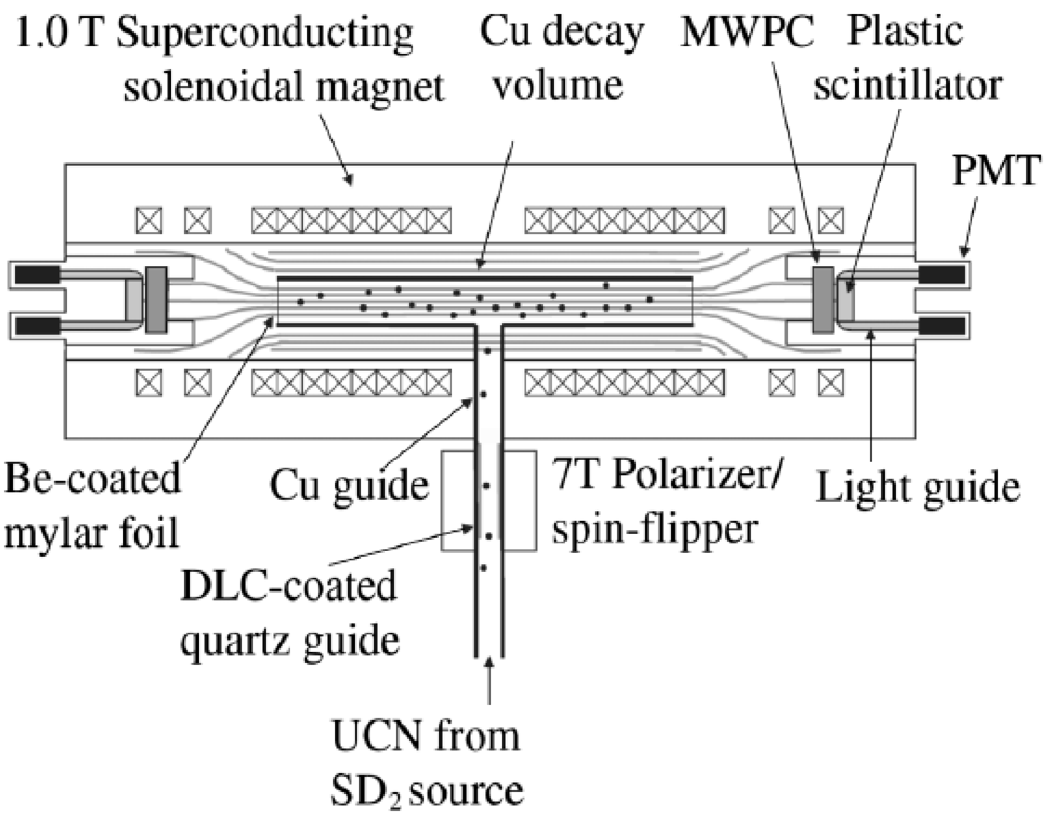
including new data:
-1.2734(19), S=2.3

λ_{UCNA} = -1.2759(+41)(-45)

λ_{Perkeo} = -1.2750(9)

New measurements have much smaller **systematic corrections** on A of O(1%) (Perkeo II, UCNA)

Beta Asymmetry A: UCNA



$$A_{\exp} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}} = \tfrac{1}{2}\tfrac{v}{c} PfA$$

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

Active volume: 3m, Ø12.4cm, limited to Ø9cm

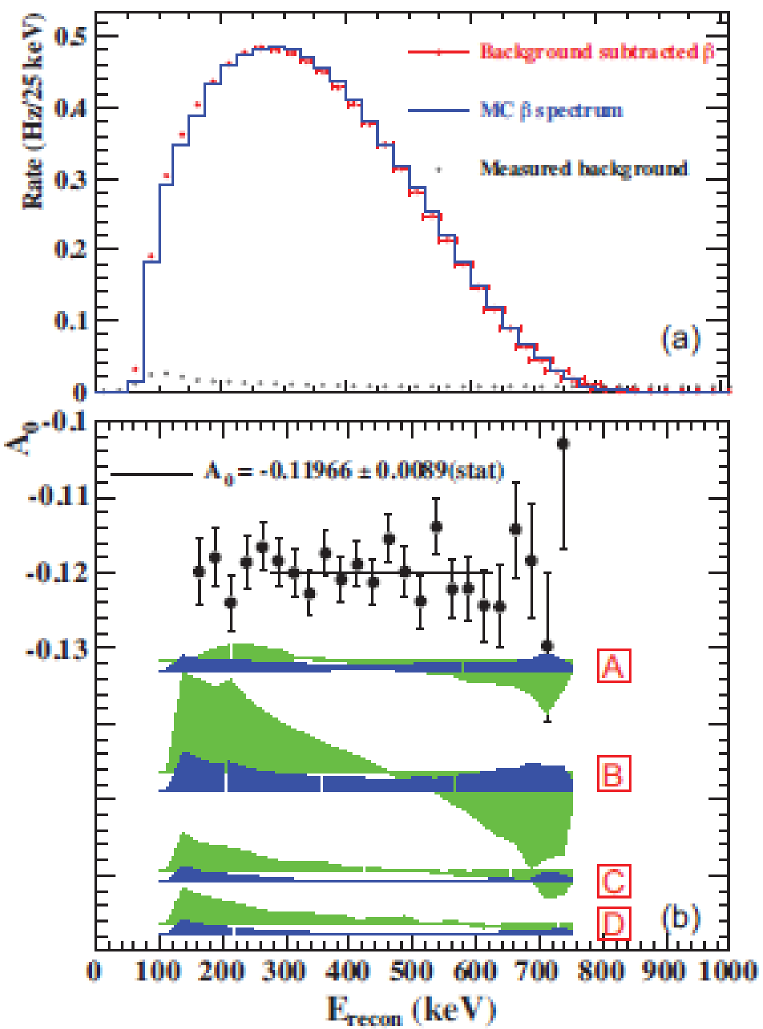
Benefits of UCN:

- Small number of UCN, but long observation time: low neutron induced background
- High neutron polarization 100.0(-5)%

Drawback:

- Windows to define active volume: backscattering and energy loss

Beta Asymmetry A: UCNA

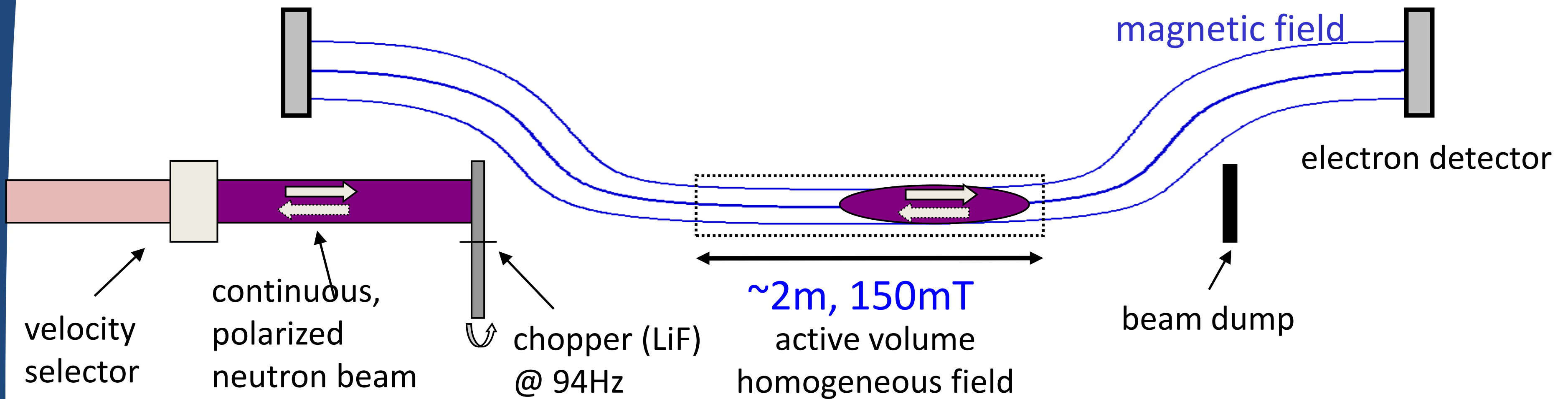


A = -0.1197(9)$_{stat}$(+12)(-14)$_{sys}$
λ = -1.2759(+41)(-45)

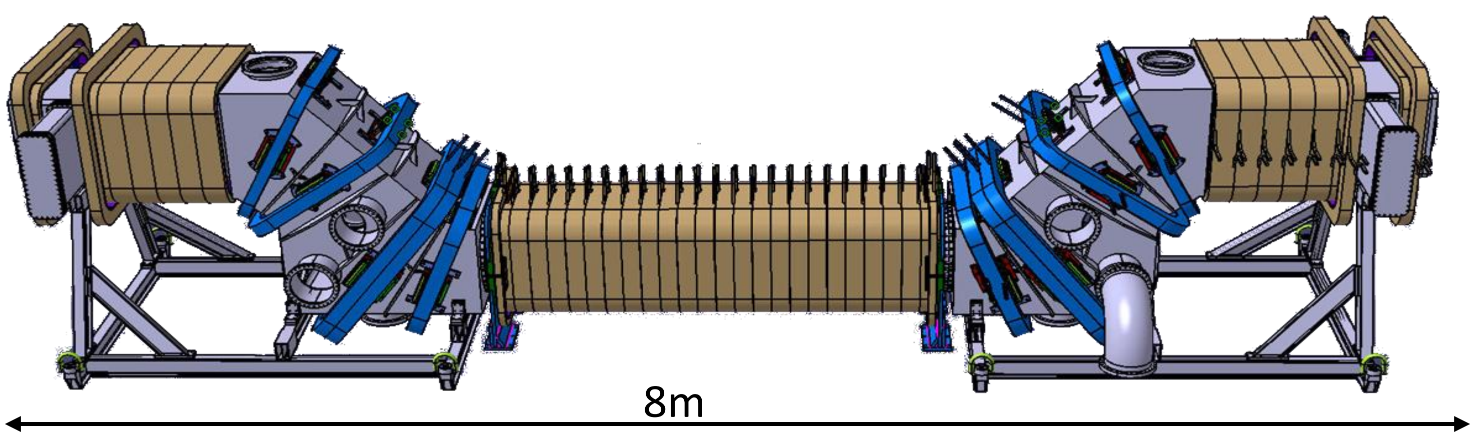
- Blind analysis (±5% spread)
- S/B ~ 40 in fit region

- Leading errors wrt A:
  - Polarization +0.52% -0%
  - Energy response linearity 0.47%
  - Muon veto efficiency 0.3%
  - Live time uncertainty 0.24 %
  - Fiducial cut 0.24 %
  - Gain fluctuation 0.2%
  - Magnetic non-uniformity +0.2% -0%
- Corrections
  - Recoil order -1.79%
  - Radiative corrections 0.1%

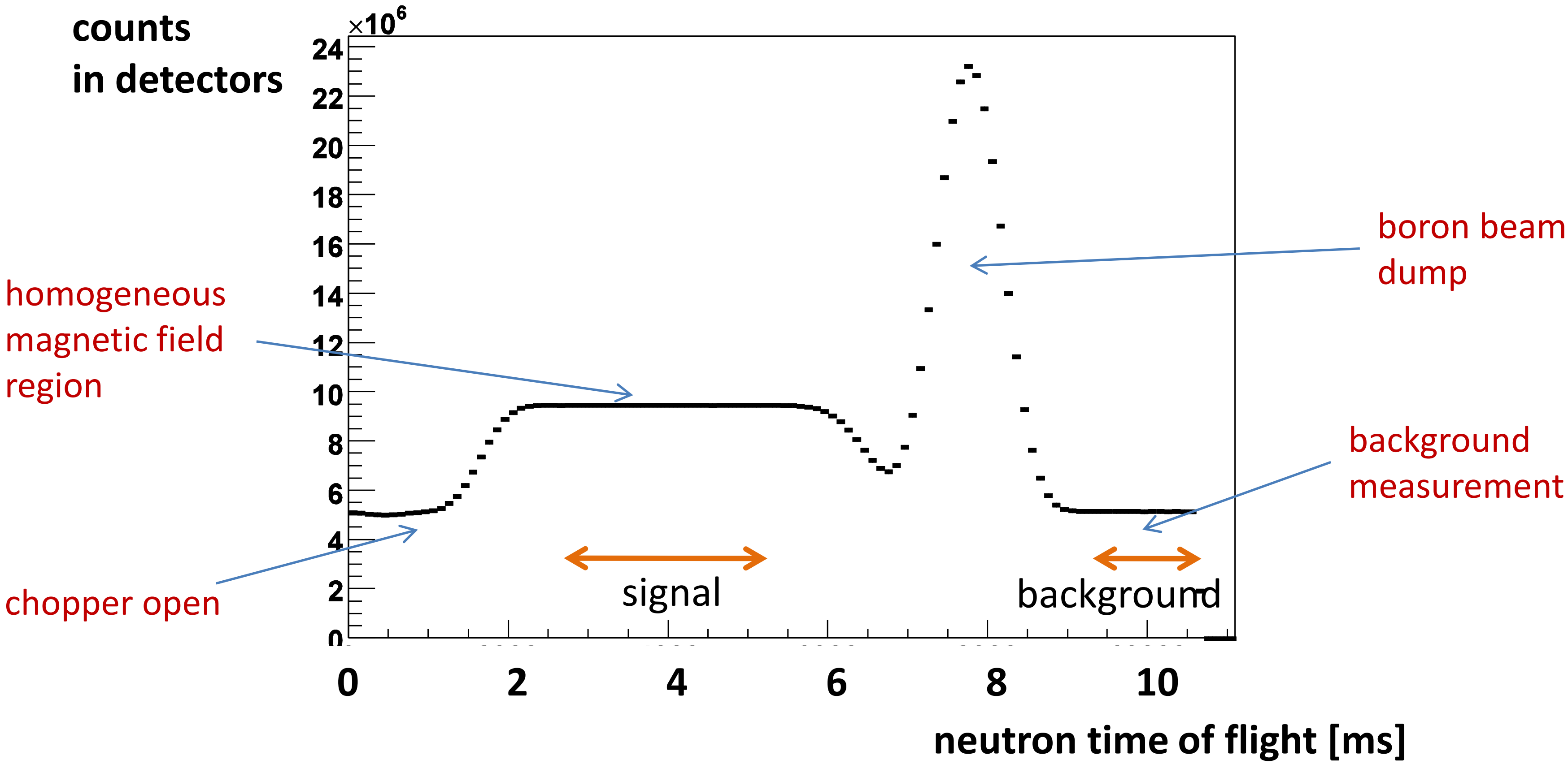
Perkeo III: Beta Asymmetry in a Pulsed Cold Neutron Beam



- Signal and background measured under the *same conditions*
  ⟶ background can be *fully subtracted*
- Edge-free projection onto detectors: full 2 x 2π detection without distortions

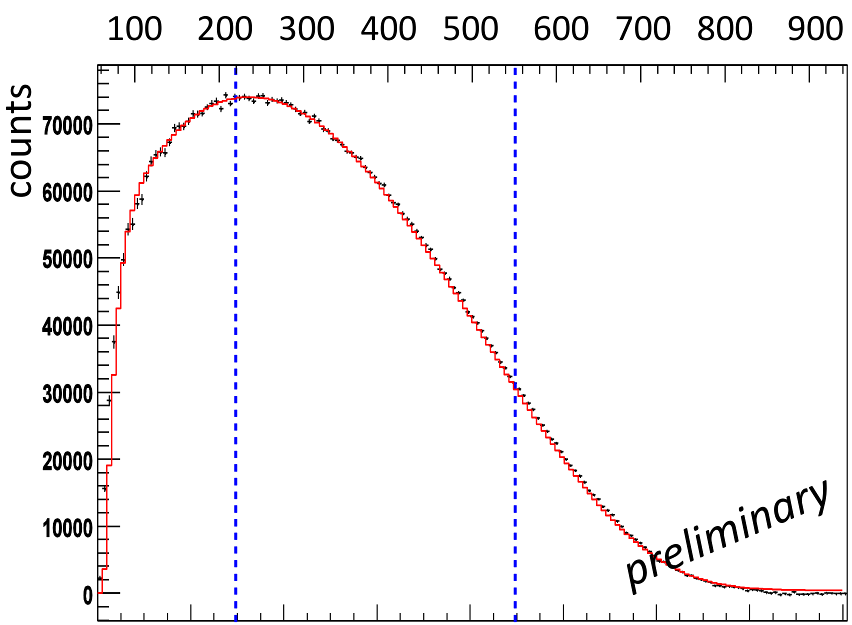


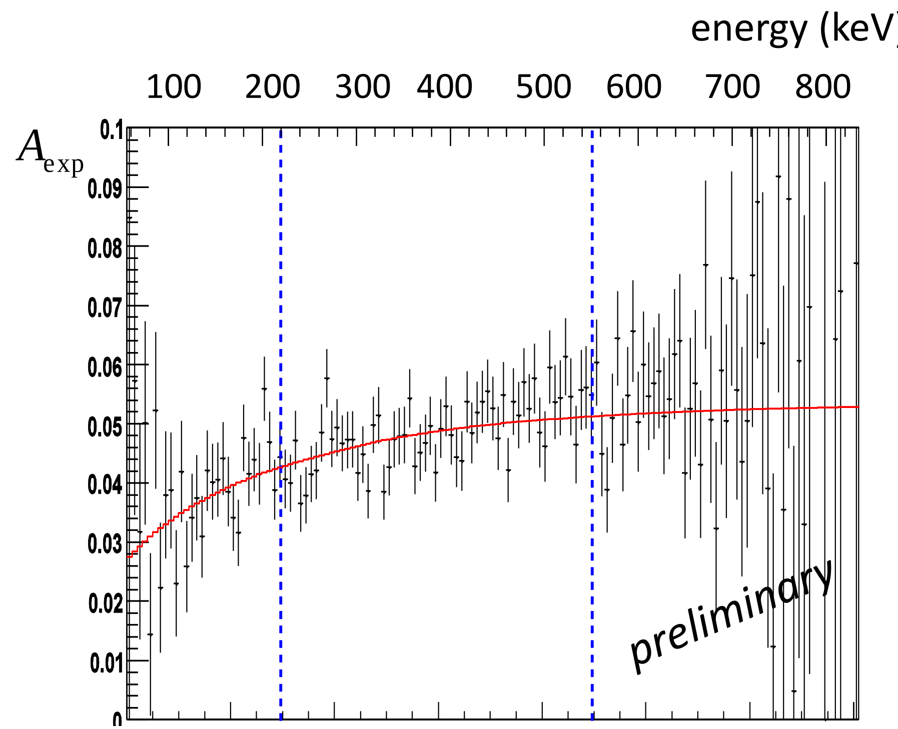
Perkeo III:Time of Flight Spectrum



Perkeo III: First Results

18h of data, downstream detector:



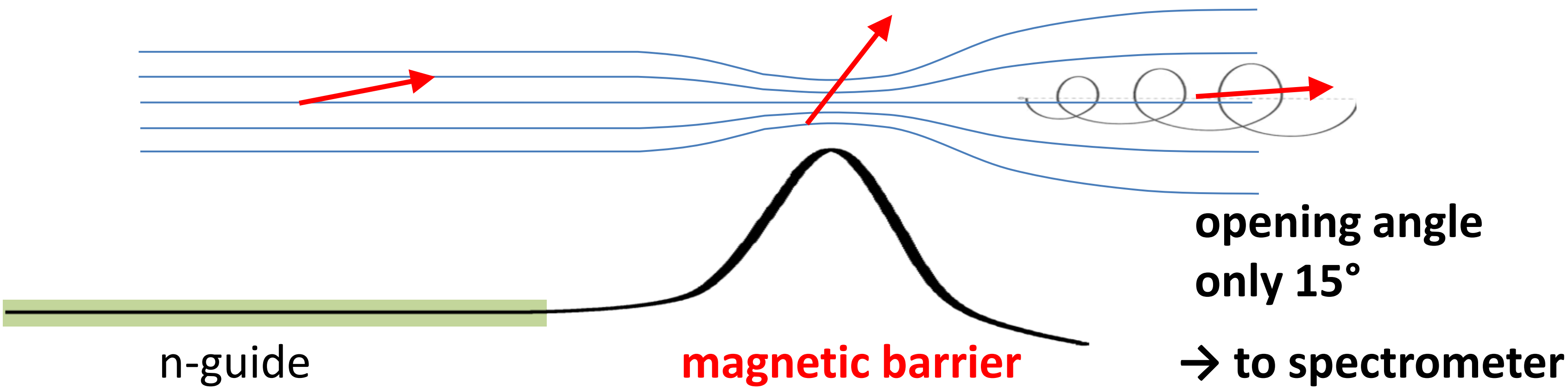


Statistical precision ΔA/A ~ 1% / day
Total statistical error : < 0.2%
Every single systematic error 0.1%

$$A_{exp} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}} = \frac{1}{2} A \frac{v}{c} P f$$

Blind analysis: during data analysis neutron polarization P and correction due to magnetic mirror are not known

PERC: a neutron decay facility



- active volume within a 8m **long neutron guide**
  - Maximum use of available neutron phase density:
  - Decay rates up to ~10^6 s^{-1} / metre (continuous, unpolarised)
- Superconducting **magnetic field** (2T)
  - electron and proton extraction
- **Magnetic barrier** (~8T) to limit e/p phase space
- Dubbers et al., NIM A 596: all systematic errors O(10^{-4})
- **User facility** will be installed at the research reactor FRM-II, Munich;

Status Neutron Experiments

- **Lifetime**
  - new average: **τ = 881.8(14), S=2.7**
  - need clarification by magnetic storage experiments!
  - new projects: Ezhov et al., improved version of Azurmanov et al.,
    + half a dozen more!
- **Ratio of coupling constants λ**
  - new average: **λ = -1.2734(19), S=2.3**
  - expect results from electron-neutrino correlation *a* : aSpect, aCORN
  - result from Perkeo III in 2011, improved UCNA results
  - new projects: Nab, abBA, PERC, ...

PDG	$V_{ud} = 0.9746\,(2)_{RC}(4)_{\tau}(18)_{\lambda}$
PDG + new results	$V_{ud} = 0.9743\,(2)_{RC}(8)_{\tau}(12)_{\lambda}$

Reviews: S. Paul, NIM A 661 (2009); (lifetime)
H. Abele, Prog.Part.Nucl.Phys (2008); J.S. Nico, J.Phys.G 36 (2009);
D. Dubbers & M.G. Schmidt, Rev.Mod.Phys (2010)