Neutron β-decay study with the spectrometer *a*SPECT

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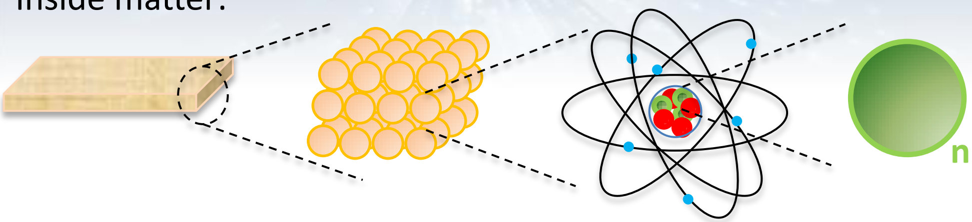
24th – 28th August 2015, Strasbourg

Neutron β-decay in particle physics

- **The β-decay**
  - The correlation coefficients
  - Within/beyond the Standard Model

Inside matter:



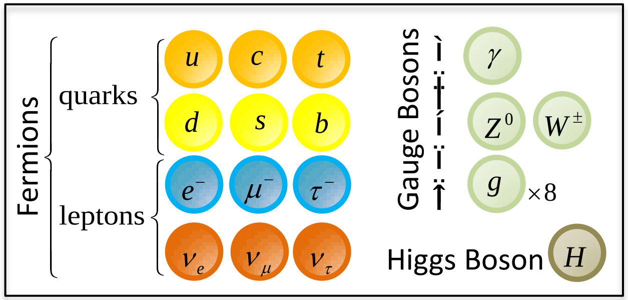
The neutron:

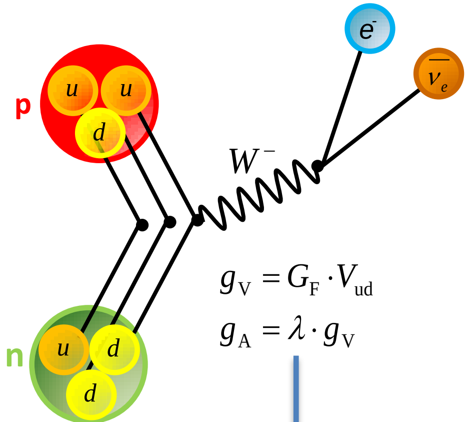
- 1932, discovery
- Mn = 939.565 MeV/c^2
- q = $(-0.4 \pm 1.1)\cdot 10^{-21}$ e
- ½ spin

Free neutron:

- $\tau_n \approx (880.3 \pm 1.1)$ s
- $n \rightarrow p + e^- + \overline{\nu}_e + 782.3\ \mathrm{keV}$

Further down:





$$g_V = G_F \cdot V_{ud}$$
$$g_A = \lambda \cdot g_V$$

Within the Standard Model formalism, the β-decay is the conversion of a *down* quark into an *up* quark via the emission of a W^- boson.

The Cabbibo-Kobayashi-Maskawa matrix:

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

Weak interaction process described by the *V-A* theory and is governed by two free parameters:

$$V_{ud} \quad \text{and} \quad \lambda = \frac{g_A}{g_V}$$

Both currents occur in neutron decay.

Differential decay rate:

(Jackson *et al.*, PR 106, 517, 1957)

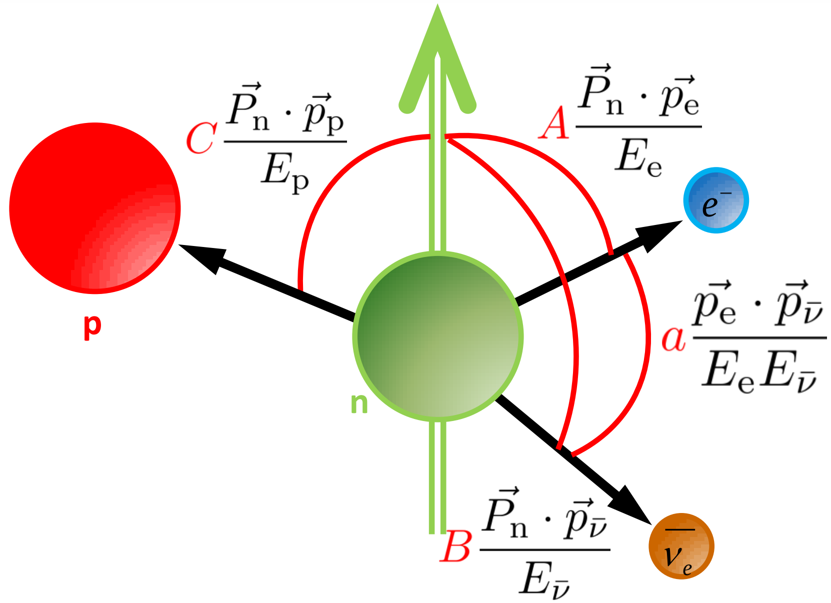
$$\frac{dW}{dW_e dW_n dE_e} \propto 1 + b\frac{m_e}{E_e} + a\frac{\vec{P}_e \cdot \vec{P}_{\overline{\nu}_e}}{E_e E_{\overline{\nu}_e}} + \vec{P}_n \left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_{\overline{n}}}{E_{\overline{n}}} + D\frac{\vec{p}_e \times \vec{p}_{\overline{\nu}_e}}{E_e E_{\overline{\nu}_e}} \right]$$

Within the Standard Model:

The coefficients are expressed in term of the weak coupling constants ratio:

$$\lambda = \frac{g_A}{g_V}$$

- ➢ $e^- - \overline{\nu}_e$ angular correlation coefficient: $a = \frac{1-\lambda^2}{1+3\lambda^2}$
- ➢ e^- beta asymmetry: $A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2}$
- ➢ $\overline{\nu}_e$ antineutrino asymmetry: $B = +2\frac{\lambda^2-\lambda}{1+3\lambda^2}$
- ➢ p proton asymmetry: $C = x_C \frac{4\lambda}{1+3\lambda^2}$



- ➢ Another measurable parameter: the neutron lifetime, $\tau_n \approx (880.3 \pm 1.1)$ s

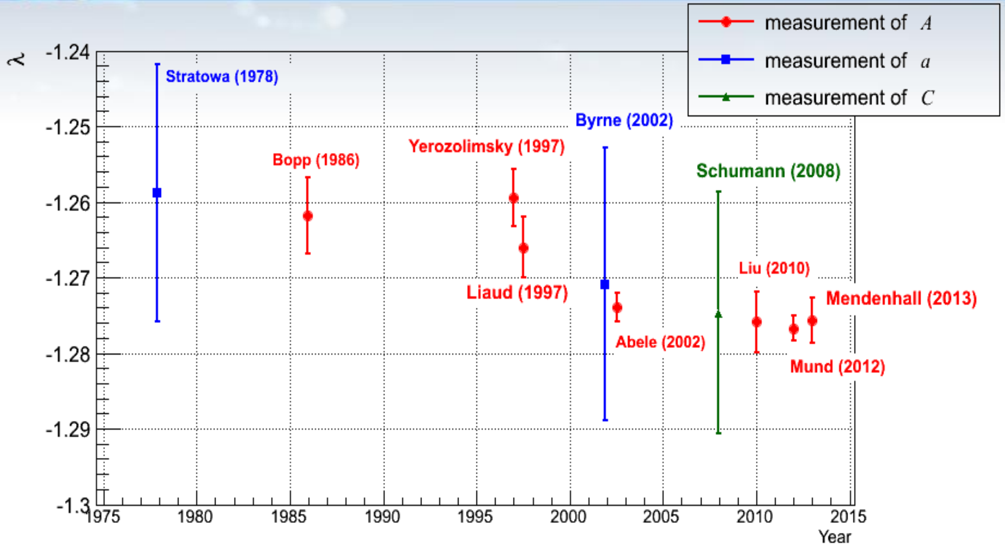
K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014)

Contribution to test the Standard Model:

Determination of the ratio λ with different experimental systematics.

Sensitivities towards $\lambda = -1.2694(28)$:

$$\frac{da}{d/} = 0.298, \quad \frac{dA}{d/} = 0.374, \quad \frac{dB}{d/} = 0.076, \quad \frac{dC}{d/} = -0.124$$



The ratio λ is used with the neutron lifetime τ_n to calculate the first element of Cabbibo-Kobayashi-Maskawa matrix.

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

Unitarity test of the CKM matrix: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

- ➢ Non-unitarity could indicate a new quarks generation.

Search for new physics beyond the Standard Model:

$$a = \frac{1}{\xi}\left(|L_V|^2 - |L_S|^2 + |L_T|^2 - |L_A|^2 + |R_V|^2 - |R_S|^2 + |R_T|^2 - |R_A|^2\right)$$

$$A = \frac{2}{\xi}\mathrm{Re}\left(-|L_A|^2 - L_V L_A^* + |L_T|^2 + L_S L_T^* + |R_A|^2 + R_V R_A^* - |R_T|^2 - R_S R_T^*\right)$$

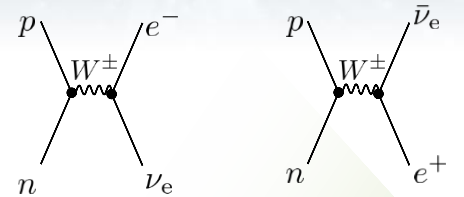
...

- ➢ Different sensitivity to new physics,
- ➢ Searches for scalar *S* and tensor *T* currents,
- ➢ Possible contribution of right-handed interaction to the weak process, new gauge boson…

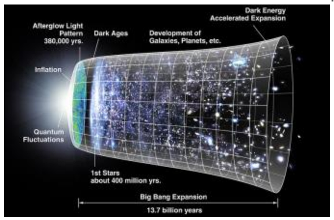
N. Severijns, M. Beck, O. Naviliat-Cuncic, Reviews of Modern Physics, 2006, 78, 991

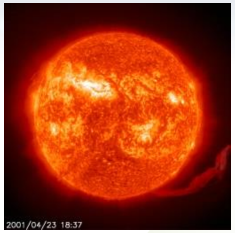
Beyond the theory:

Primordial nucleosynthesis

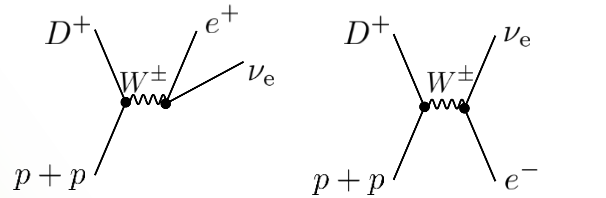


$n + \nu_e \rightarrow p + e^-$ $\quad n + e^+ \rightarrow p + \bar{\nu}_e$

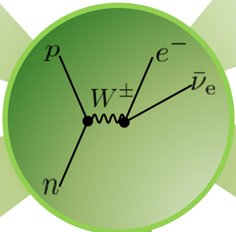




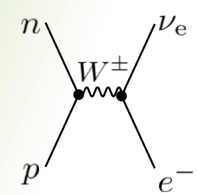
Solar cycle



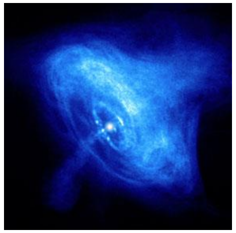
$p + p \rightarrow D^+ + e^+ + \nu_e$ $\quad p + p + e^- \rightarrow D^+ + \nu_e$



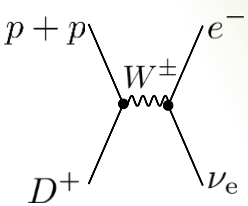
Neutron star formation



$p + e^- \rightarrow n + \nu_e$



Neutrino detection



$\nu_e + D^+ \rightarrow p + p + e^-$

Pion decay
W and *Z* bosons production
…

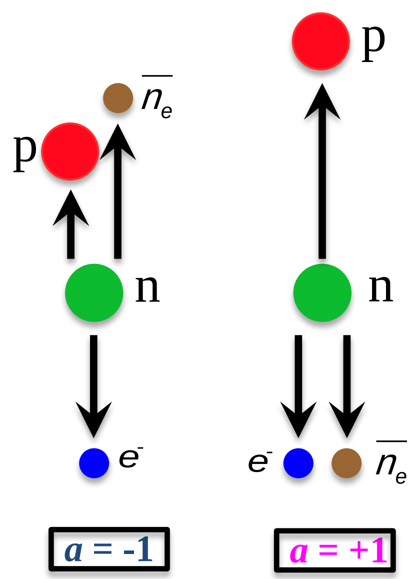
The Universe in a ~~nutshell~~… neutron !

The experiment *a*SPECT

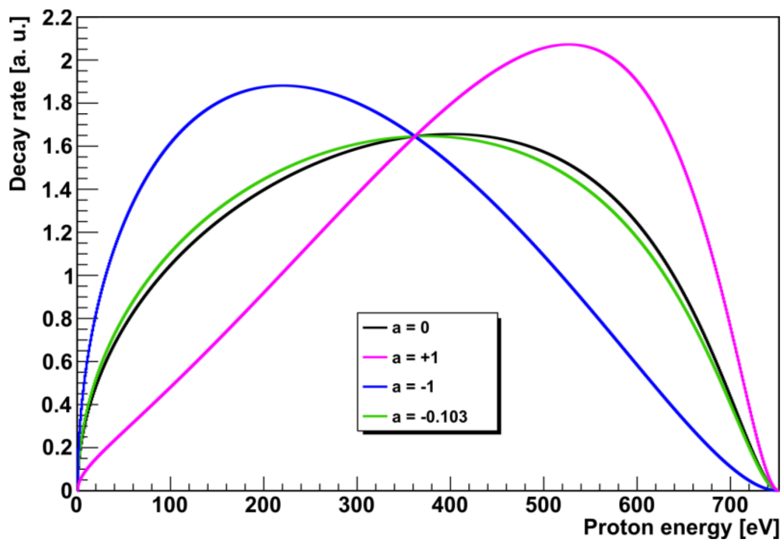
Measurement of the electron-antineutrino angular correlation coefficient *a*:

- ➢ Last determination in 2002 by Byrne *et al.* ➔ $\Delta a/a$ = 5% Byrne et al., J. Phys. G. Nucl. Part. Phys. 28 (2002) 1325-1349
- ➢ The aim of the experiment *a*SPECT ➔ $\Delta a/a$ = 0.3%
- ➢ Difficulty: the antineutrino is hard to detect.

Kinematics description:



The coefficient is tied to the shape of the proton recoil spectrum which is theoretically described by $W(T)$.



$$W(T) \propto g_1(T) + a \times g_2(T)$$

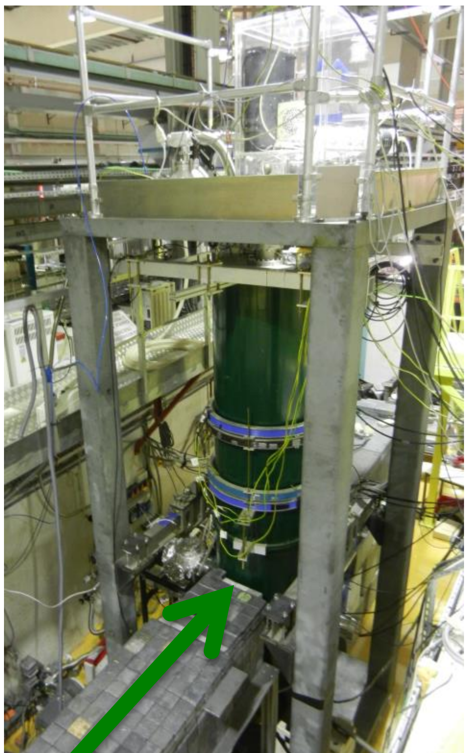
The actual world average value for *a* is -0.103.

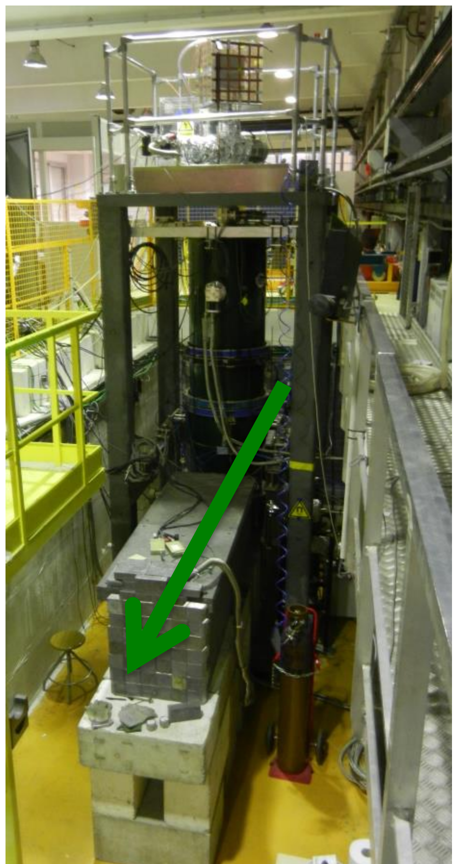
The endpoint of the proton energy is **751.4 eV**.

⇒ High-precision measurement of the coefficient *a* can be realised from a high-precision measurement of the proton recoil spectrum.

Neutron source at the ILL:

High-flux reactor (58 MW) delivers a cold neutron beam in the zone PF1b ($\phi_n = 2\cdot10^{10}$ $cm^{-2}\cdot s^{-1}$).

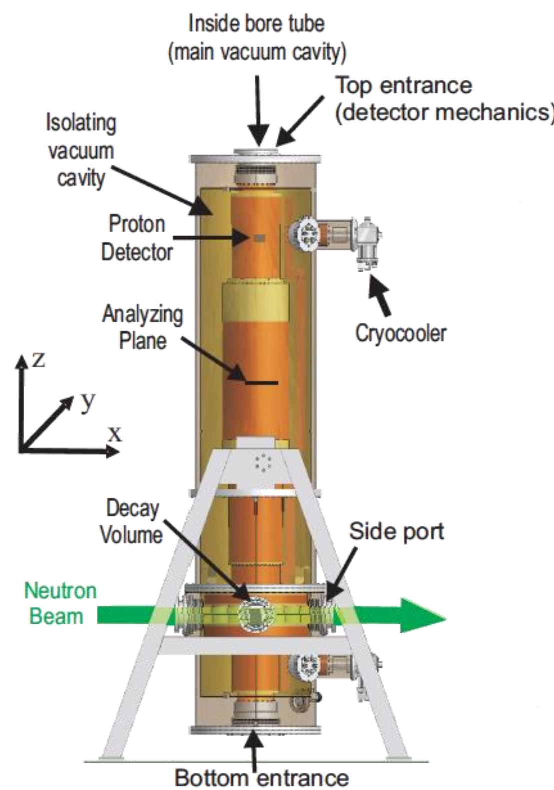


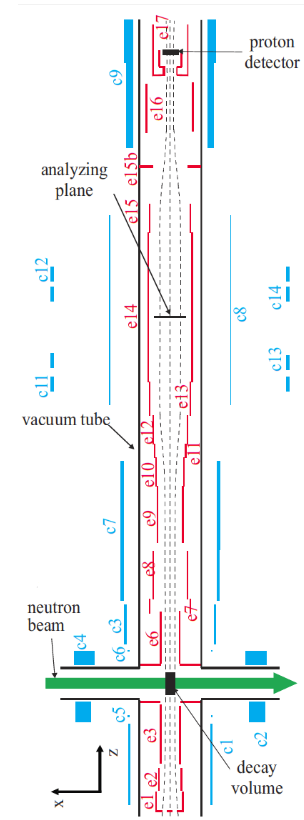


*a*SPECT:

Cryostat (Ø= 0.76 m ; h = 3.3 m) with a central bore tube (Ø= 200 mm):

- ➢ T ≈ 70 K,
- ➢ P ≈ 10^{-9} mbar.

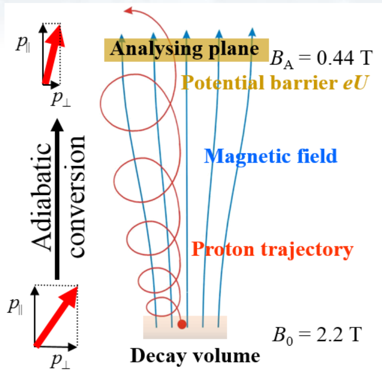




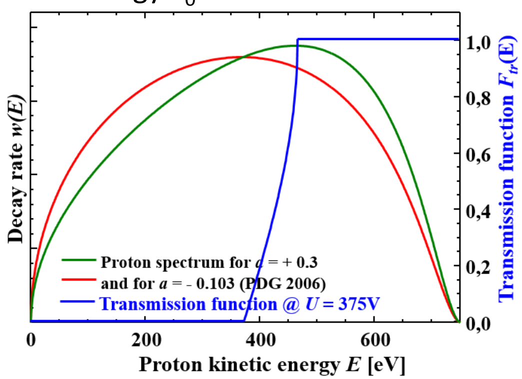
Set of electrodes inside the bore tube surrounded by a set of superconducting coils.

Measurement of the proton recoil:

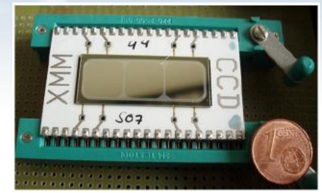
Adiabatic conversion: The momentum of the proton is transferred to its parallel component.



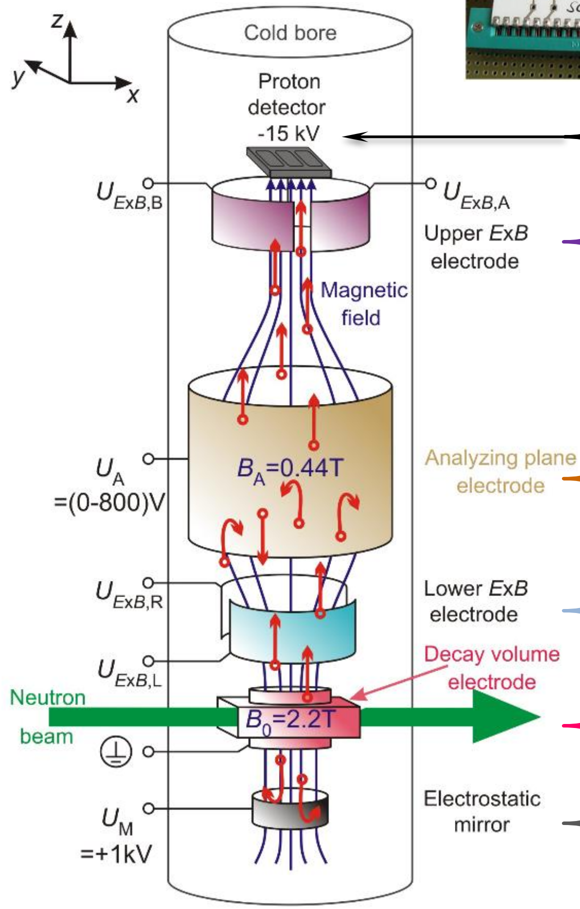
The transmission function:
In the adiabatic limit the condition for a proton to overcome the AP depends on the kinetic energy T_0.



$$F_{tr}(T_0) = \begin{cases} 0 & \text{if } T_0 < eU \\ 1 - \sqrt{1 - \frac{1}{r_B}\left(1 - \frac{eU}{T_0}\right)} & \text{otherwise} \\ 1 & \text{if } T_0 > eU/(1 - r_B) \end{cases}$$



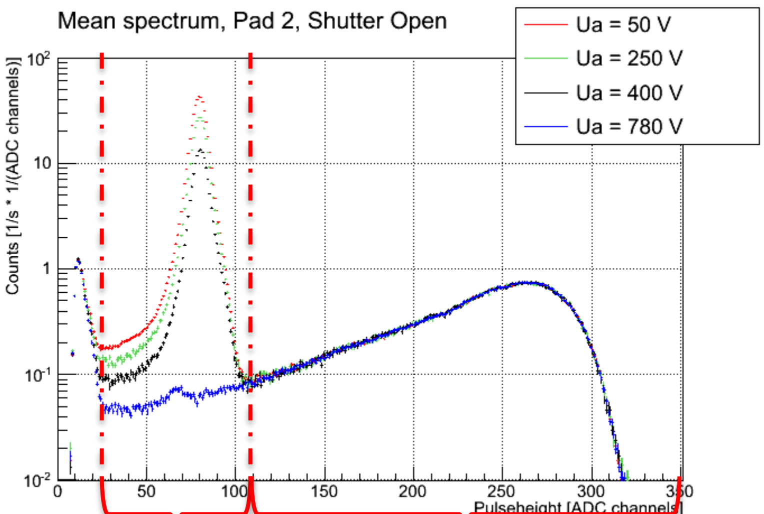
Silicon Drift Detector:
3 pads of 10x10 mm^2 each.



- Protons accelerated and detected.
- Ensure proton transport against increasing magnetic field.
- Proton energy selection by applying a variable potential barrier.
- Remove trapped positively charged particles between AP and EM.
- Emitted protons guided by magnetic field.
- Detection in a solid angle of **4π**.

Pulseheight spectra:

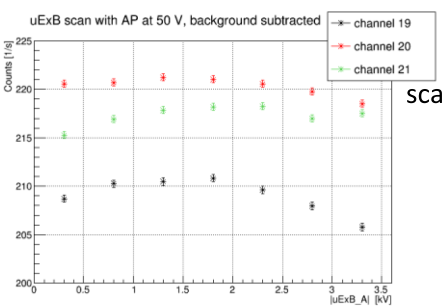
Measurement with different voltages Ua for the potential barrier at AP.



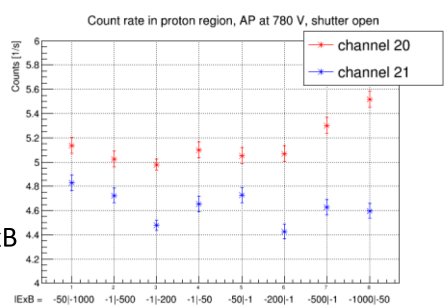
Proton region **Electron region**

Integration + Analysis, simulations, corrections

Test the systematics effects with different configurations and settings.



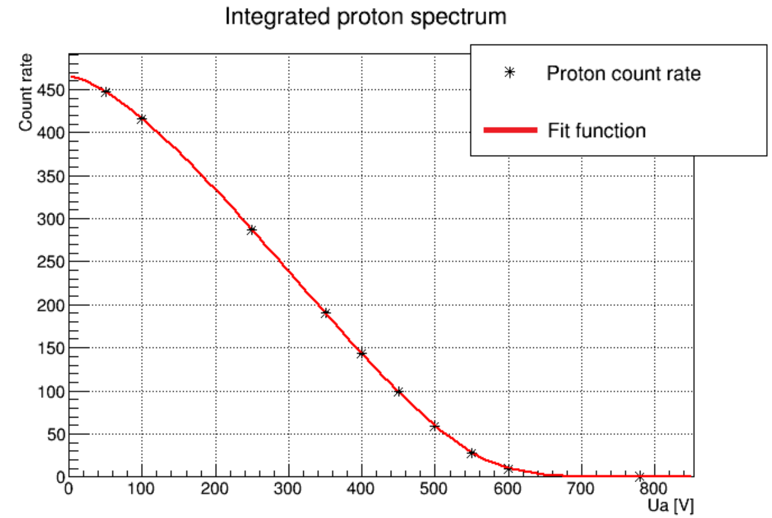
scan uExB



scan lExB

Integrated proton spectrum:

The fit function is built with the transmission function F_{tr} and the theoretical proton energy spectrum W:



$$\rho_{tr}(U_A) = N_0 \int_0^{T_{max}} F_{tr}(T) \cdot W(T) \cdot dT$$

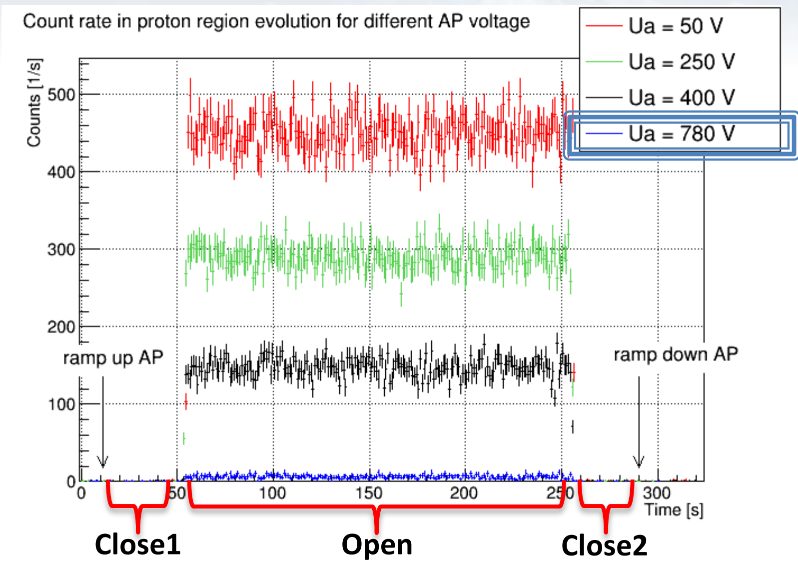
Free parameters:

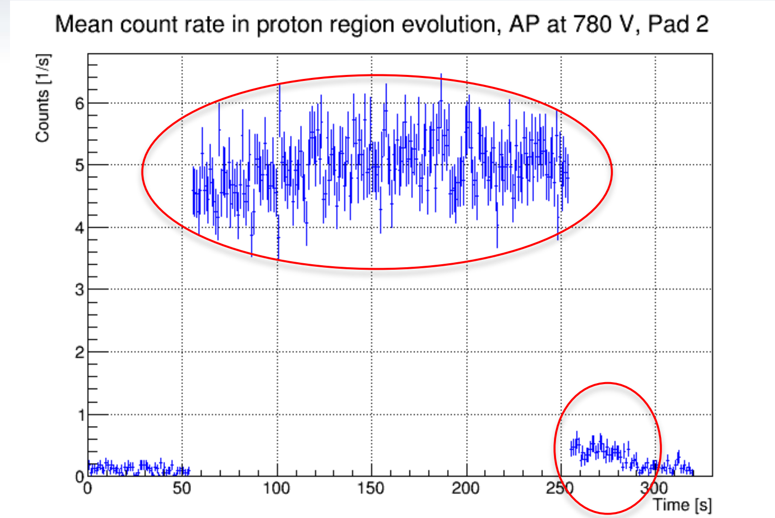
- ➢ N_0 count rate with U_A at 0 V,
- ➢ Coefficient a.
- ➢ Offset (⇔ constant background)

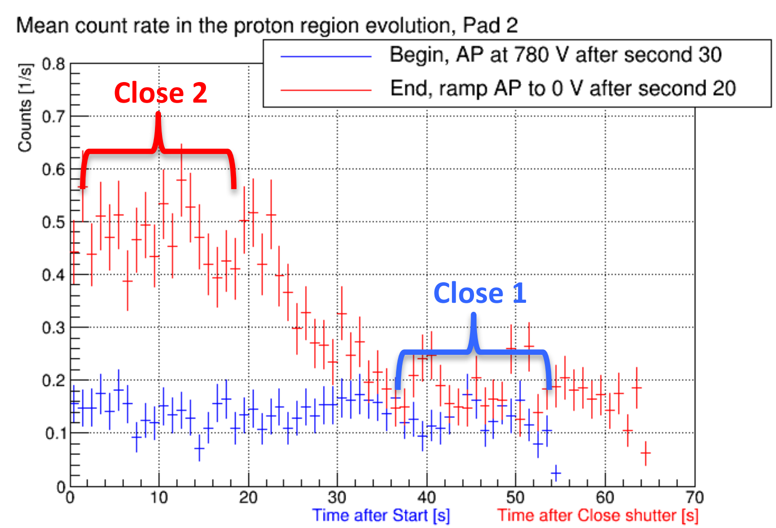
Background investigations

- **Measurement**
  - New approach for the characterization
  - Reduction of the background

Measurement time sequence:







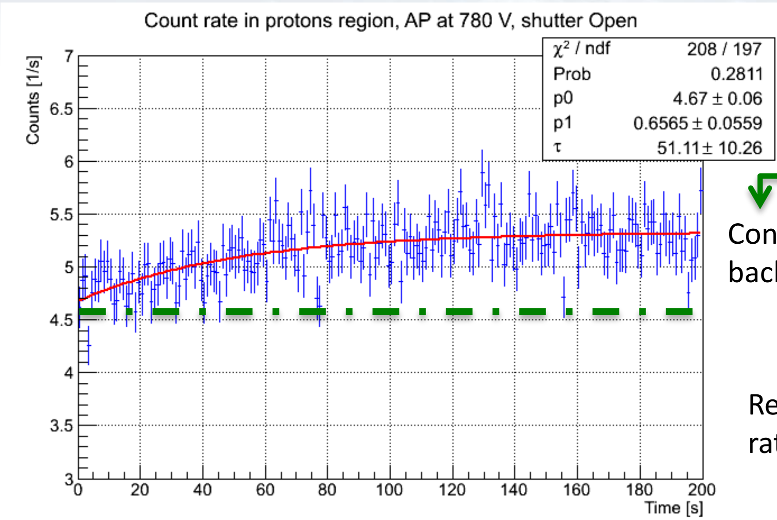
The background is measured by setting the AP voltage at 780 V.
All protons from the DV are blocked.
Pulseheight region dominated by spontaneous electrons.

But:

$\Rightarrow$ During shutter open: increase of the count rate,

$\Rightarrow$ After closing shutter (close2): “residual” count rate.

Dependence on the shutter open time:

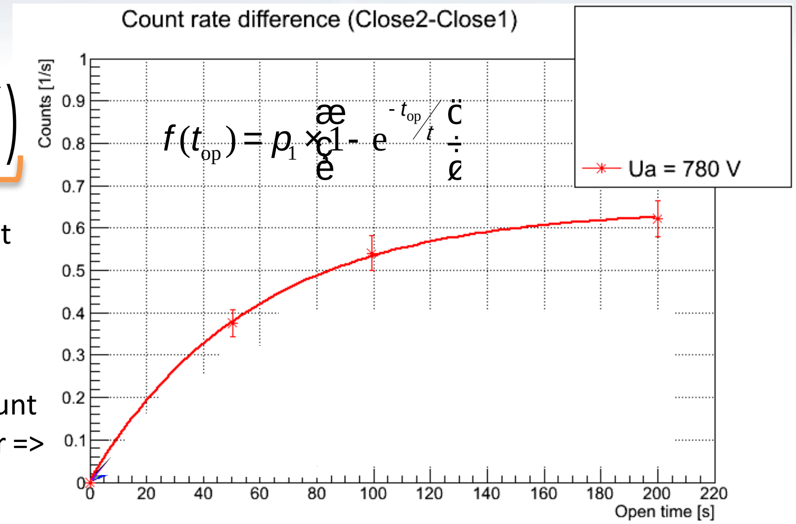


This evolution can be described by:

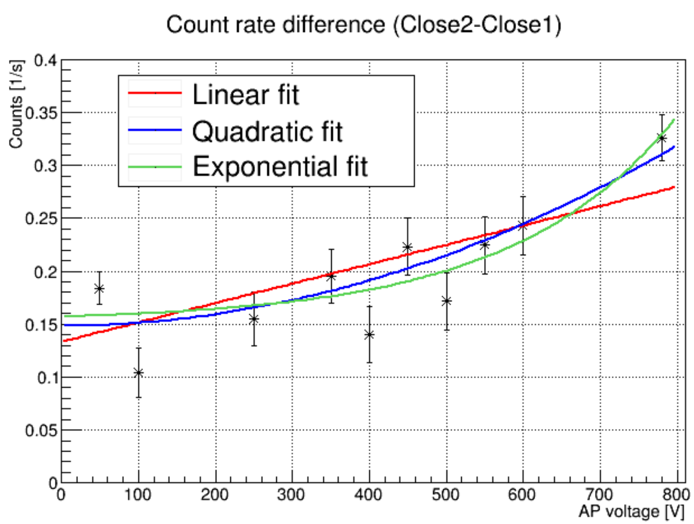
$$f(t) = p_0 + p_1 \times \left(1 - e^{-t/\tau}\right)$$

Constant background — Non-constant background

Related to the “residual” count rate after closing the shutter =>



Dependence on the AP voltage Ua:



The “residual” count rate which is dependent on the AP voltage Ua.

This AP-dependence can be approximated by different fit:

- ✓ Linear $b + c \times U_A$
- ✓ Quadractic $b + c \times U_A^2$
- ✓ Exponential $b + c \times \exp(U_A / d)$

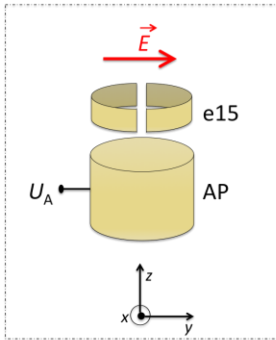
Non-constant background depends on the shutter open time t_{op} and the AP voltage U_A:

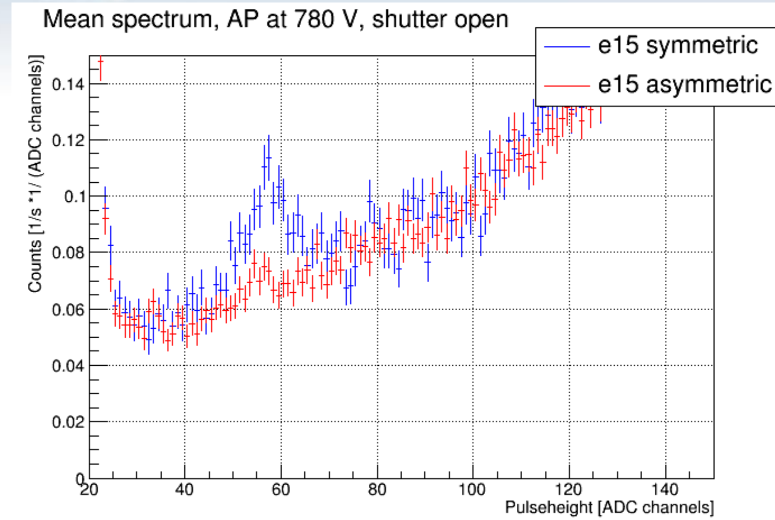
$$BG(U_A, t_{op})$$

Technical solution:

The non-constant background is probably related to trapped charged particles above the AP electrode.

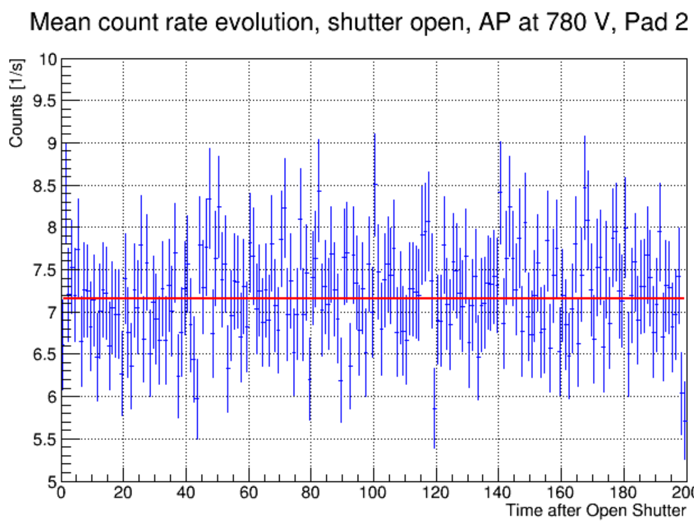
The electrode e15 above the AP was tested in asymmetric settings.

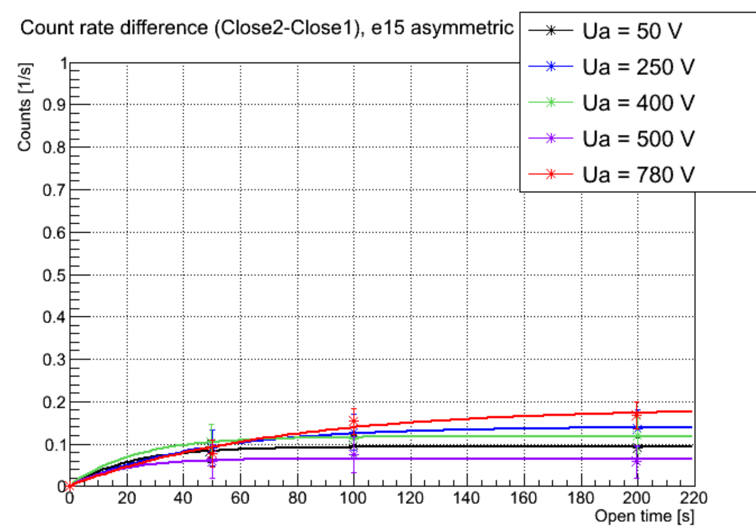




Reduction of the time-dependence:
the fit function tends to a constant.

Reduction of the AP-dependence:
the "residual" count rate tends to be constant





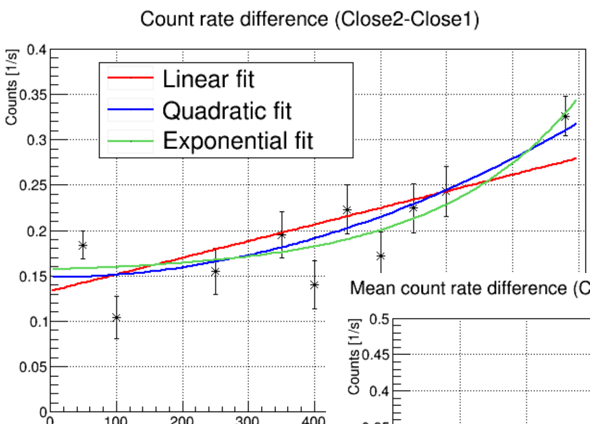
Mathematical description:

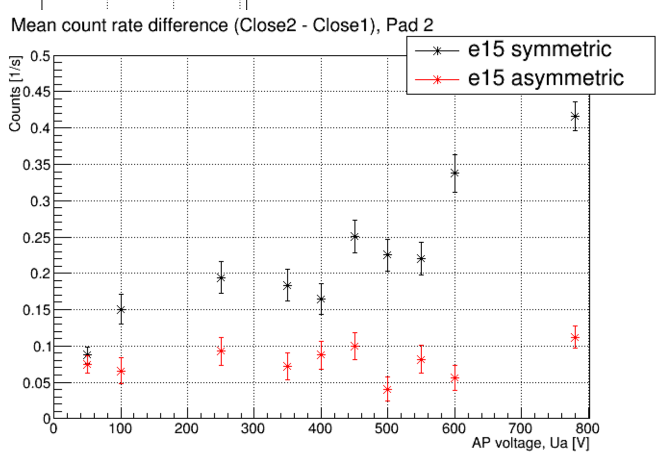
An equation to calculate the amount of the non-constant background for each AP voltage and each open time for the shutter.

$$BG(U_A, t_{op}) = \int_0^{t_{op}} p_1 \cdot (1 - e^{-t/\tau})\, dt$$

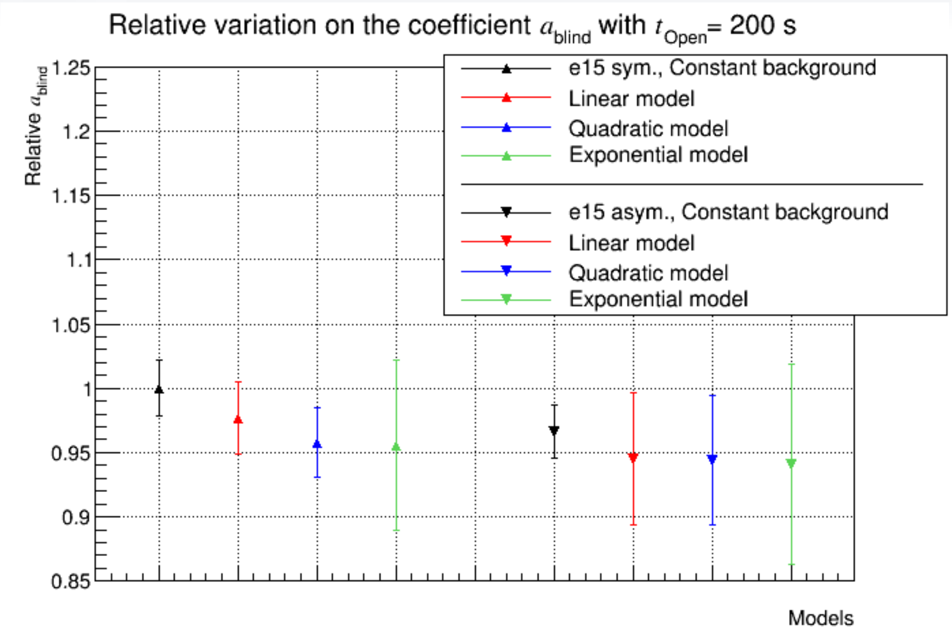
$$= p_1(U_A) \cdot \left(t_{op} - \tau \cdot (1 - e^{-t_{op}/\tau}) \right)$$

$\Rightarrow p_1(Ua)$ from the description of shutter Open at 780 V and the description of the AP-dependence of Close2-Close1.





Subtraction of the non-constant background:



Shift on a_{blind} from the value without background correction:

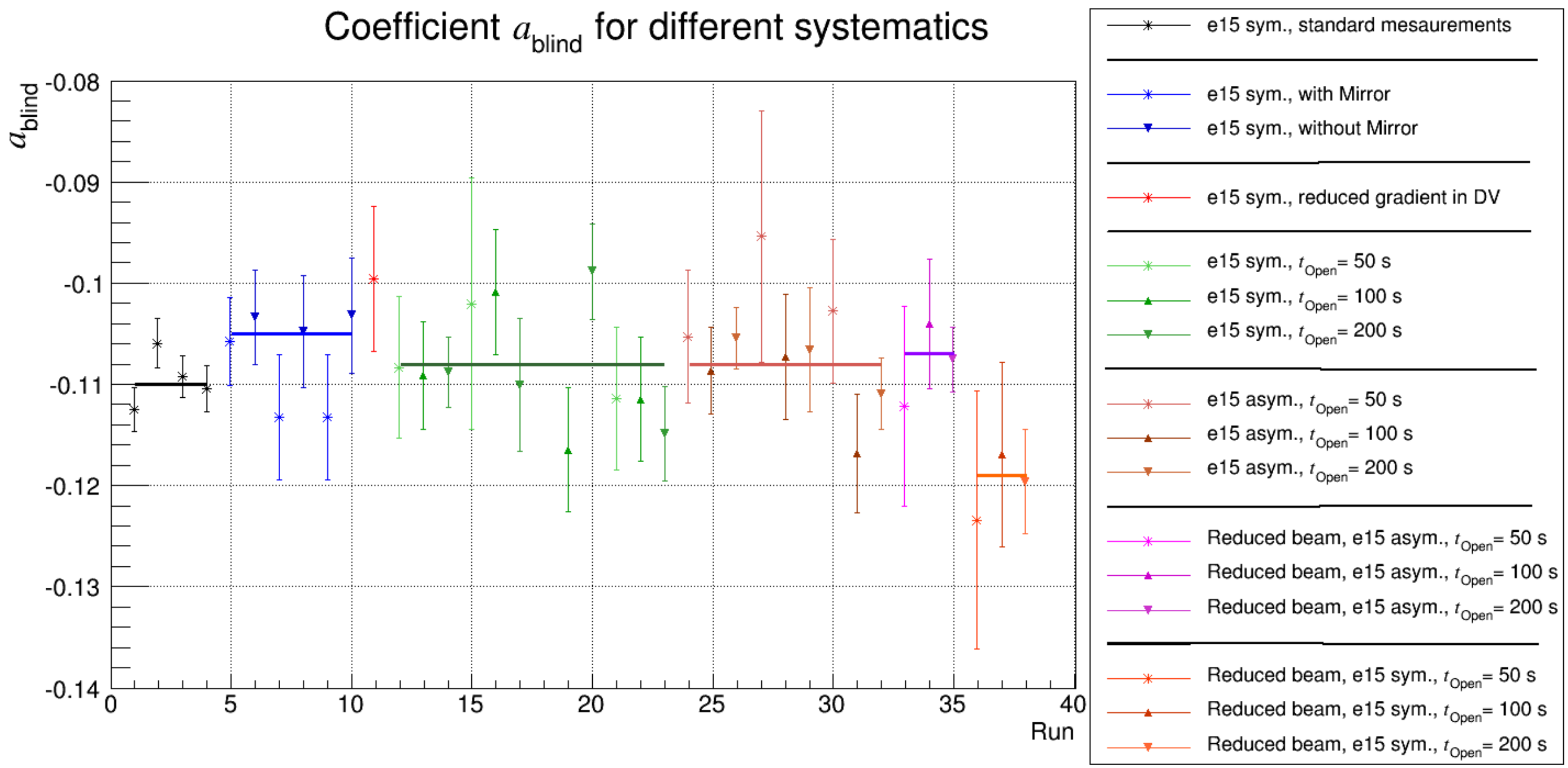
- ➢ with e15 sym., and with quad./exp. models: about 3-4%.
- ➢ with e15 asym. and without correction: about 3%.

Systematics on the coefficient *a*

- ✓ Background correction
- ➢ **Systematics variations of the coefficient *a***

Preliminary results the coefficient *a*:

The following values are obtained for one pad of the detector and without any corrections.



⇒ Encouraging results: $\mathbf{(\Delta a_{blind}/a_{blind})_{stat.}}$ of **1%** and $\mathbf{(\Delta a_{blind}/a_{blind})_{syst.}}$ of about **5%**.

⇒ $(\Delta a_{blind}/a_{blind})_{syst.}$ should be reduced by considering corrections: background, edge effect, …

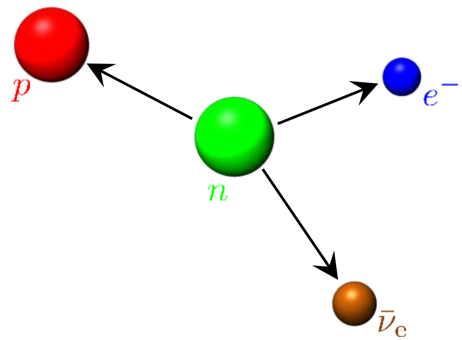
Conclusion and outlook

Test of the Standard Model at low-energy:

- Weak coupling constants ratio λ and 1st element of the CKM matrix
- Contribution to the unitarity test of the CKM matrix,
- Search for new physics beyond the Standard Model.

New analysis for the background:

- Characterization of different backgrounds,
- Models for the non-constant background,
- Electrode e15 as a dipole to reduce it.



Encouraging preliminary results:

- $(\Delta a_{blind}/a_{blind})_{stat.}$ of 1%
- $(\Delta a_{blind}/a_{blind})_{syst.}$ of 5%
- Non-constant background correction about 3-4%

Reach 1% of accuracy for the coefficient *a*:

- Ongoing data analysis and simulation,
- Quantification of other systematics effects and their correction

Future:

- New beam time with *a*SPECT: measurement of the coefficient *a*, measurement of the coefficient *C* (with polarized neutron beam).
- New neutron source at the European Spallation Source (ESS) at Lund: long pulsed neutron beam.

Thanks for your attention

Backup
β-decay rules

$$^{A}_{Z}N \rightarrow {}^{A}_{Z-1}M + e^{-} + \overline{\nu}_e$$

Theory of Fermi (1934): point-like interaction with hadronic and leptonic currents.

$$J_{\mu}^{had}(x) = \overline{\Psi}_p(x)\gamma_{\mu}\Psi_n(x) \qquad J_{\mu}^{lep}(x) = \overline{\Psi}_e(x)\gamma_{\mu}\Psi_{\nu}(x)$$

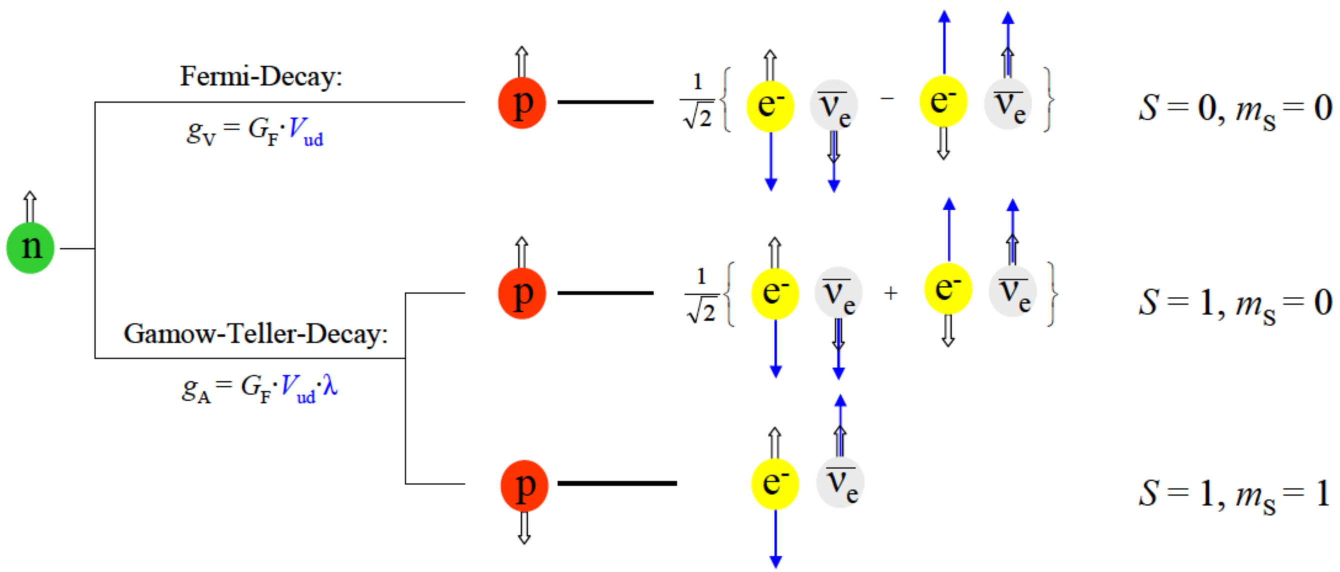
Theory by Gamow and Teller (1936): five possible current-current interaction.

$\overline{\Psi}\Psi$	Scalar (S)	$\overline{\Psi}\gamma_{\mu}\gamma_{\nu}\Psi$	Tensor (T)
$\overline{\Psi}\gamma_{\mu}\Psi$	Vector (V)	$\overline{\Psi}\gamma_5\gamma_{\mu}\Psi$	Axial-vector (A)
$\overline{\Psi}\gamma_5\Psi$	Pseudo-scalar (P)		

Selection rules for the β-transitions:

- $J_M - J_N = 0$ and $S_{lept} = 0$ ⟶ Fermi decay ⟶ Scalar and Vector couplings
- $J_M - J_N = 0, 1$ and $S_{lept} = 1$ ⟶ Gamow-Teller decay ⟶ Tensor and Axial-vector coupling

Parity violation in β-decay found by Wu *et al.* (1957): only left-handed components of Vector and Axial-vector currents.



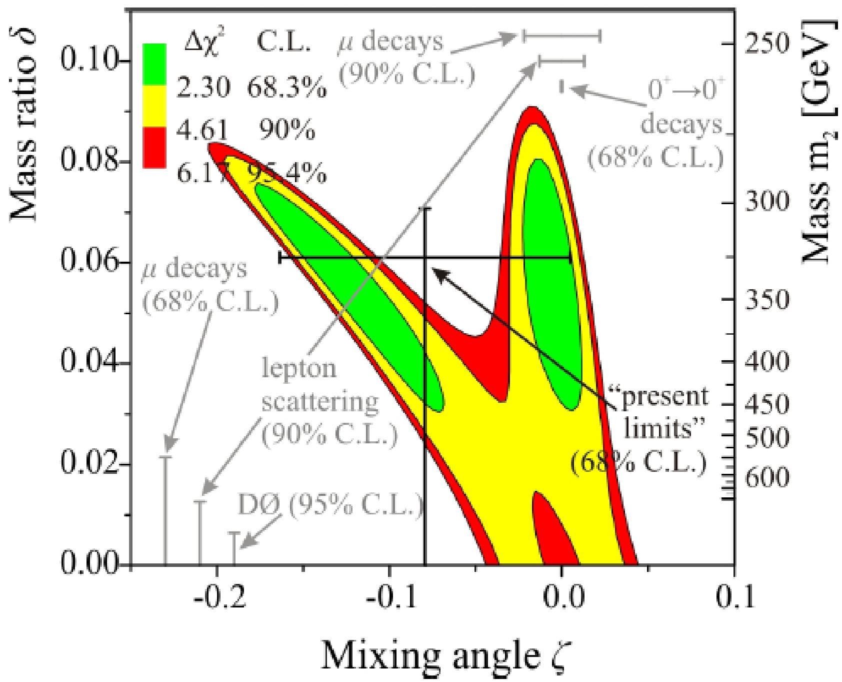
S. Baeßler, « Neutron beta decay correlations », Summer School on the Fundamentals of Neutron Scattering, NIST Center for Neutron Research, 2009.

Backup
Beyond the Standard Model

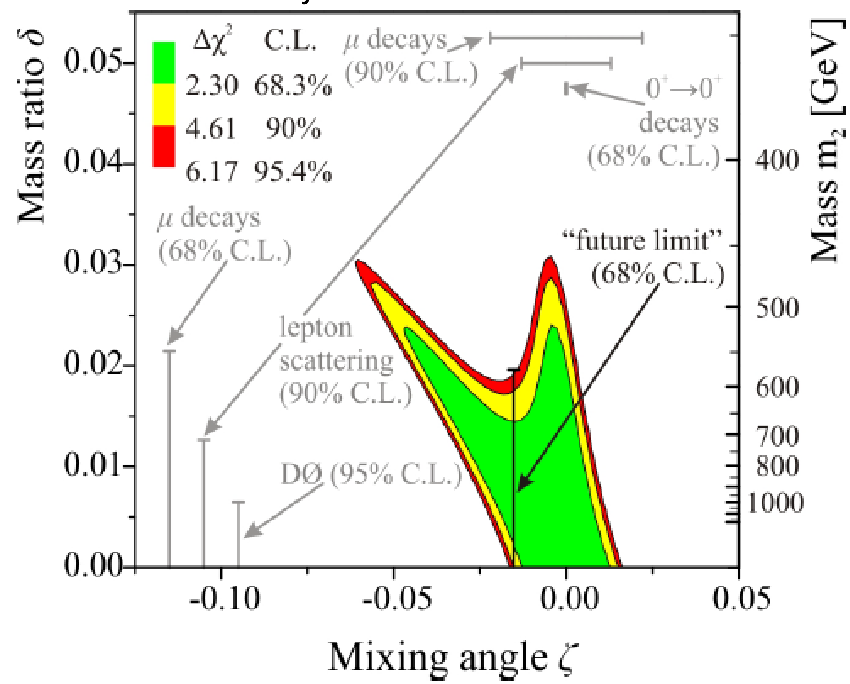
One example concerning new physics : predictions for right-handed *W* boson.

$$\begin{pmatrix} W_1 \\ W_2 \end{pmatrix} = \begin{pmatrix} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_L \\ W_R \end{pmatrix}$$

Current limits



Projected future limits



G. Konrad, W. Heil, S. Baeßler, D. Počanić, F. Glück , "Impact of neutron decay experiments on non-standard model physics", World Scientific, November 2, 2012

Backup
The correlation coefficients

Recent results for the coefficients:

Coeff.	Value	Experiments	Comments
A	-0.11952(110)	UCNA (Mendenhall *et al.*, 2013)	At LNL with polarized UCN. Detector of electrons by low-pressure multiwire proportional chamber
	-0.11996(58)	PERKEO II (Mund *et al.*, 2012)	At ILL with polarized cold neutrons. Detection of electrons by two plastic scintillator detector.
B	0.9802(50)	PERKEO II (Schumann *et al.*, 2007)	At ILL with polarized cold neutrons. Protons and electrons are detected in coincidence.
C	-0.2377(26)	PERKEO II (Schumann *et al.*, 2008)	At ILL with polarized cold neutrons. Protons and electrons are detected in coincidence.
a	−0.1054(55)	Spectrometer (Byrne *et al.*, 2002)	Proton recoil spectrum using a cryogenic ion trap.

Ongoing experiments with neutron:

- aCORN for *a* at NIST by detecting protons and electrons in coincidence,
- *a*SPECT for *a* at ILL by measuring the proton recoil spectrum,
- PERKEO III for *A, a* and *C* at ILL by measuring protons and electrons.

Ongoing experiments with nuclei:

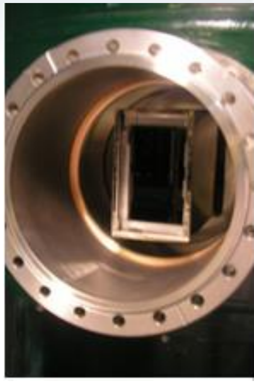
- WITCH at ISOLDE (CERN): measurement of the coefficient *a* in the β-decay of ^{35}Ar,
- LPCTrap at SPIRAL (GANIL): measurement of the coefficient *a* in the β-decay of $^{6}He^{1+}$, $^{35}Ar^{1+}$, $^{19}Ne^{2+}$

Backup
Installation of *a*SPECT at the ILL

The PF1b zone is shared by several fundamental physics experiments.





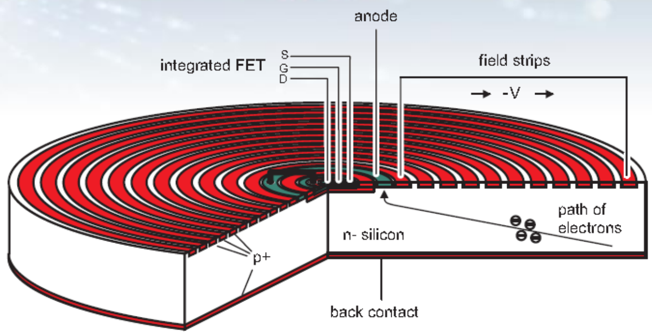


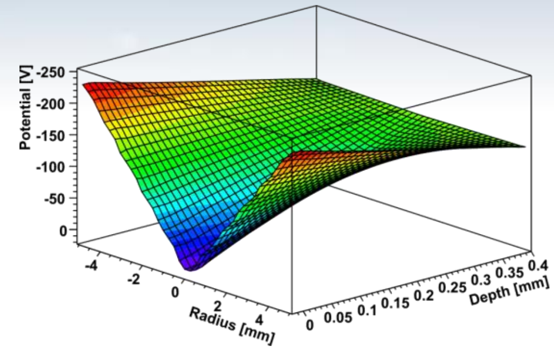

Backup
Low-energy proton detection

The Silicon Drift Detector:

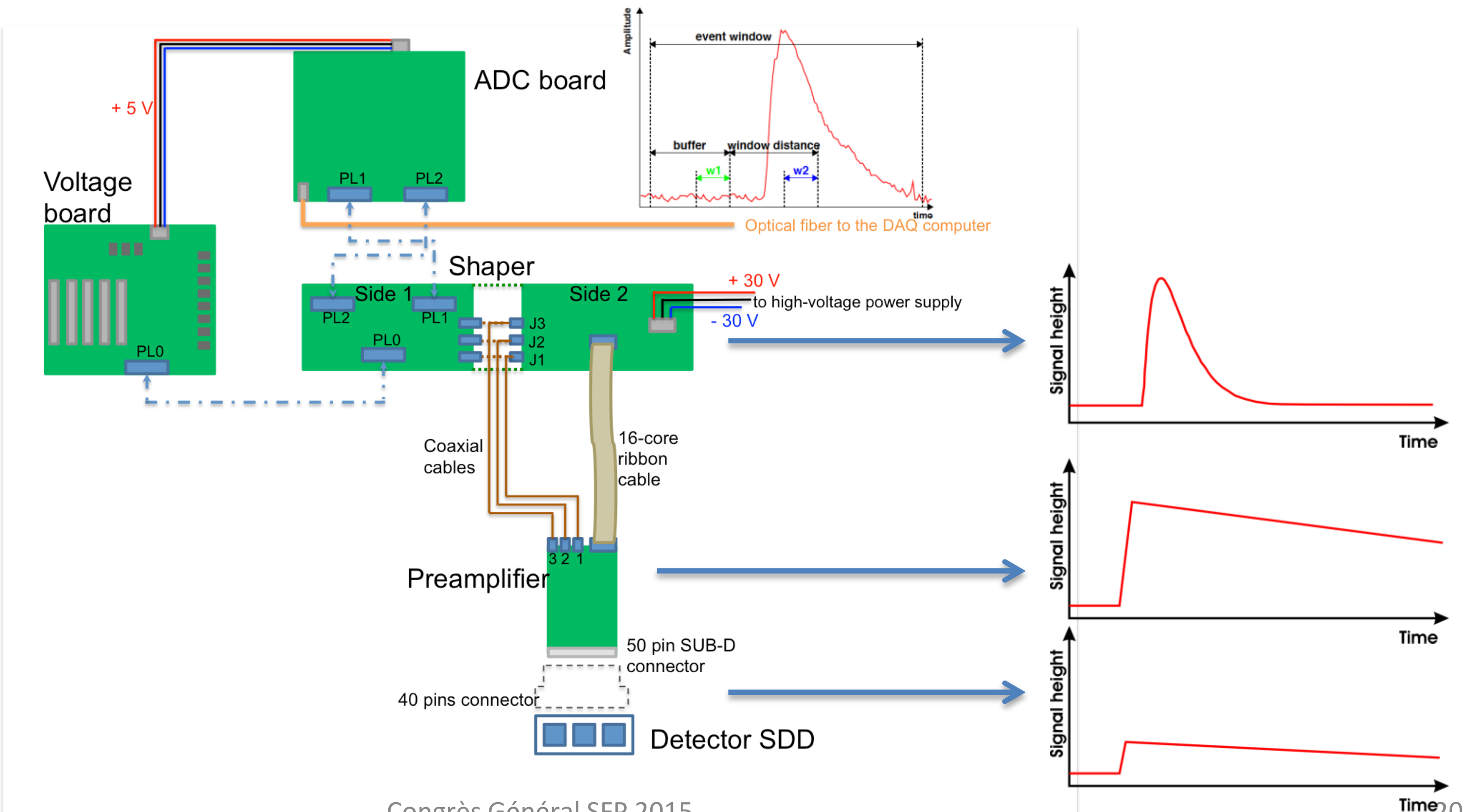
Semi-conductor based on the principle of the sidewards depletion (P. Lechner et *al.*, 1996).

Formation of a potential valley where electrons drift toward the anode.





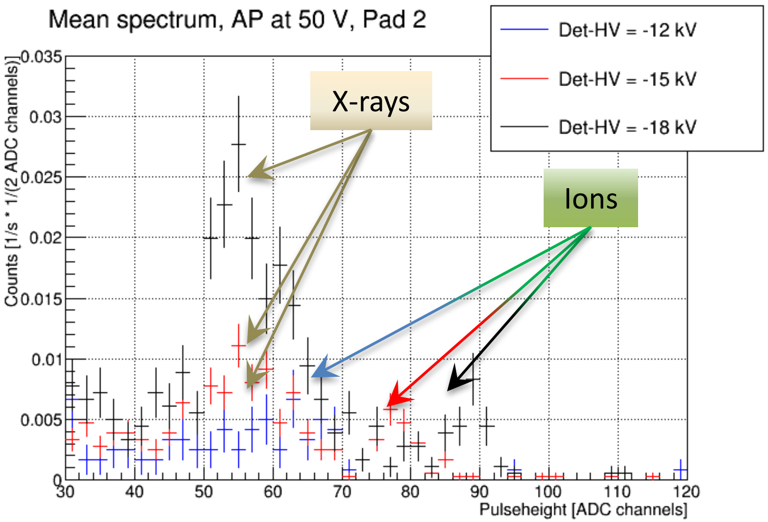
The electronic processing:

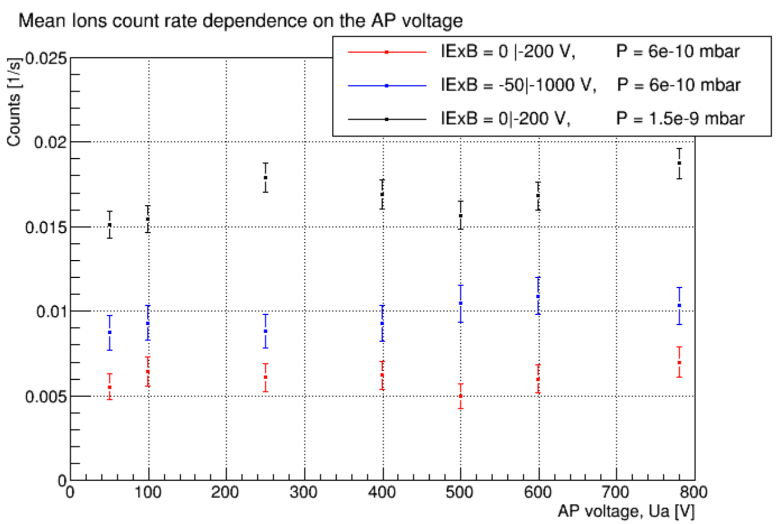


Backup
The "internal" background

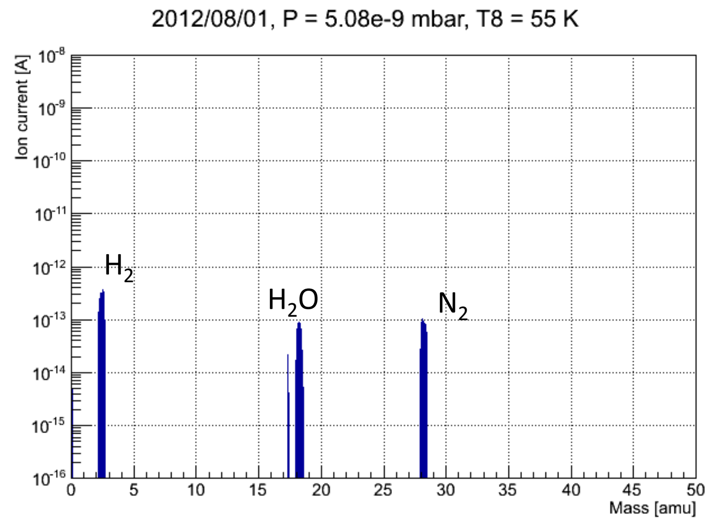
Offline measurements in 2012:

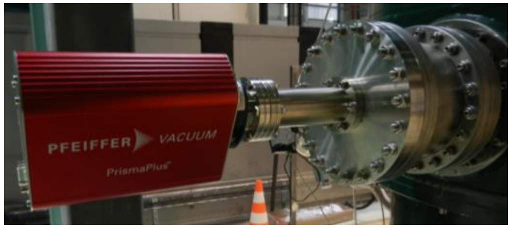
Variation of the acceleration voltage allowed to identify the peaks.





Analysis of the vacuum with a mass spectrometer.



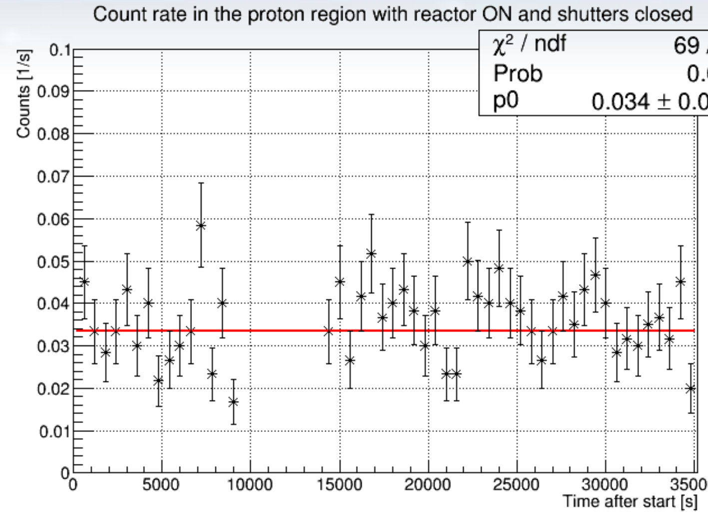


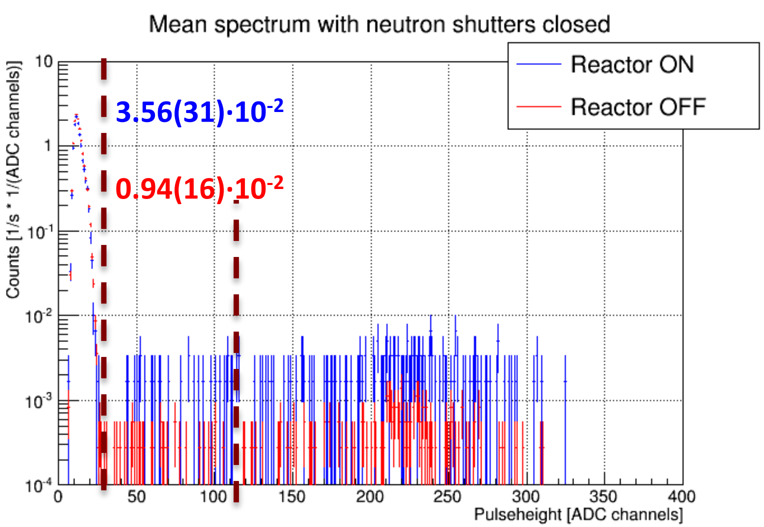
With IExB in **standard** configuration:
- ✓ Lower count rate,
- ✓ Negligible AP-dependence.

With **deteriorated** vacuum:
- ✓ Higher count rate,
- ✓ AP-dependence more pronounced.

Backup
The environmental background

The PF1b zone is surrounded by several neutron guides and experimental zones:



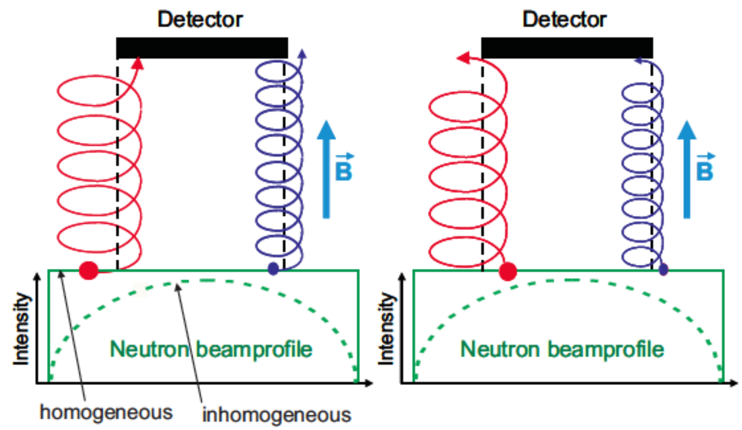


- ✓ Some fluctuations seemed to correspond to an action of neighbouring zones,
- ✓ This can superpose the “internal” background,
- ✓ **0.02 s^{-1}** of difference in count rate in the worst case.

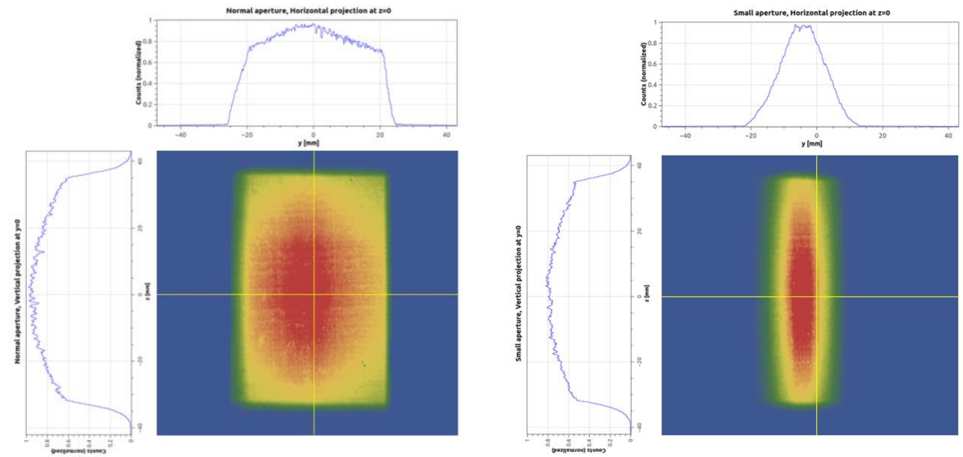
Backup
The edge effect

Example of the edge effect in *a*SPECT.

This is related to the size difference between the detector and the width of the neutron beam profile.

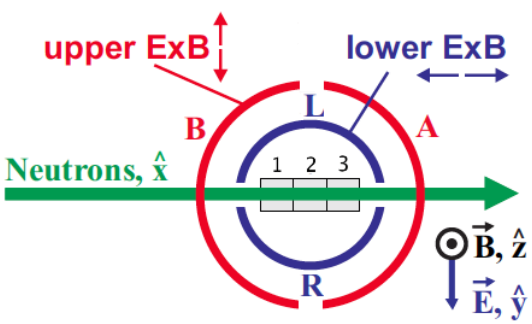


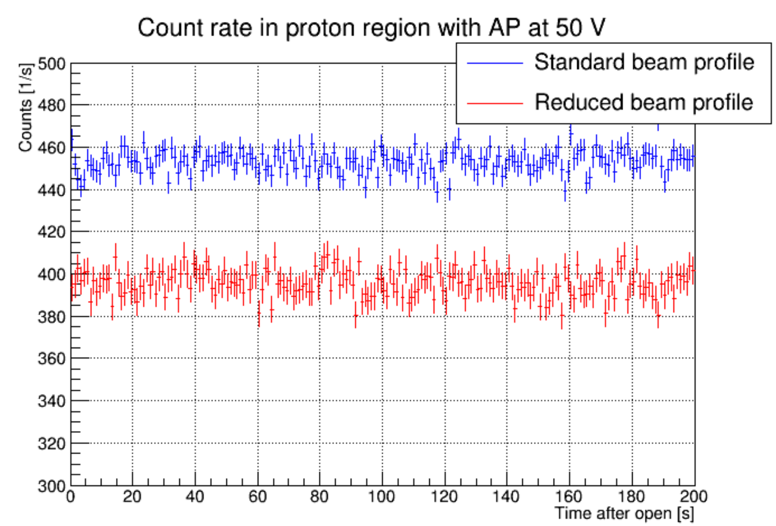
Standard beam profile. Reduced beam profile.



Additional parameters participating to the edge effect:

- Settings of the electrodes uExB and e15,
- Position and orientation of the detector.

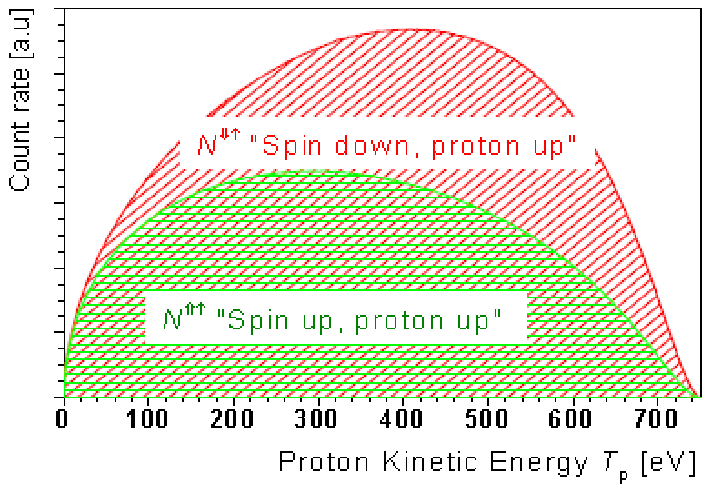


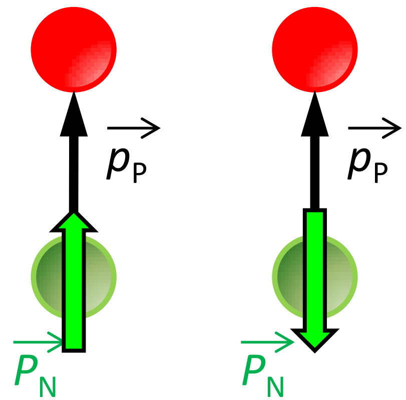


The proton asymmetry

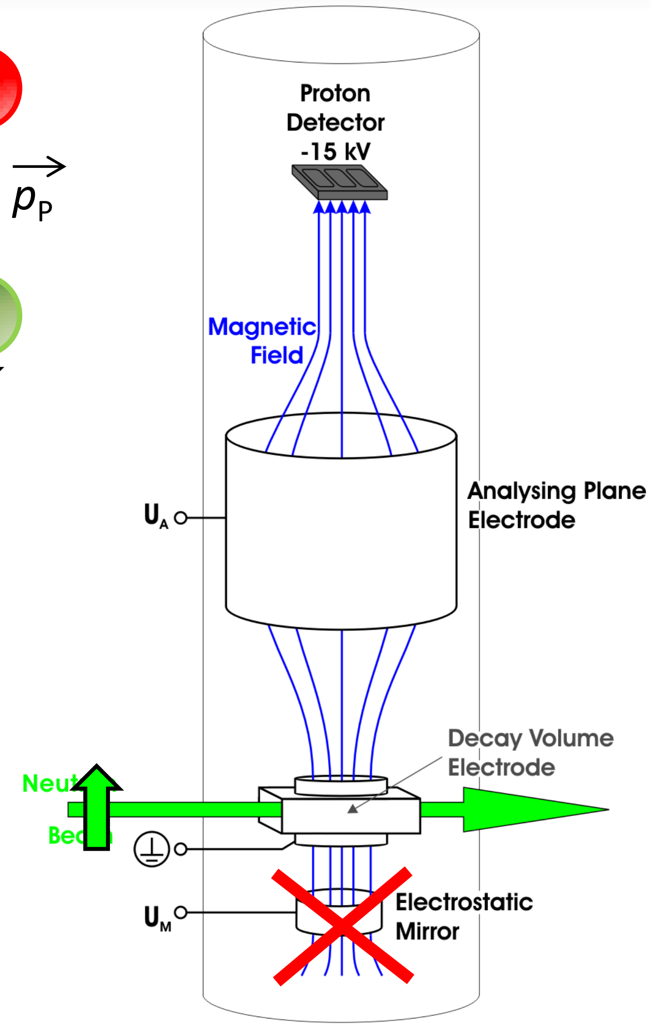
Perspectives with *a*SPECT:

The spectrometer would be used with a polarized neutron beam.





$$C_{exp} = \frac{N^{\text{Ý-}} - N^{\text{ß-}}}{N^{\text{Ý-}} + N^{\text{ß-}}} = \frac{1}{2}C$$



Considerations:

- 10 days measurements (by alternating the spin orientation),
- Detector with 5 pads to increase the statistics,

Estimation on the coefficient *C*: $\left(\Delta C / C\right)_{stat} \approx 0.08\%$

Backup
The new neutron source

European Spallation Source (ESS) in Lund, Sweden:

- pulsed neutron beam => new systematics,
- long pulses of 2.86 ms at a frequency of 14 Hz.

EUROPEAN SPALLATION SOURCE


Photo credit: ESS AB