ISOLDE Workshop and Users Meeting, December 15, 2021

Weak Interaction Studies with ^{32}Ar Decay

Federica Vera Cresto

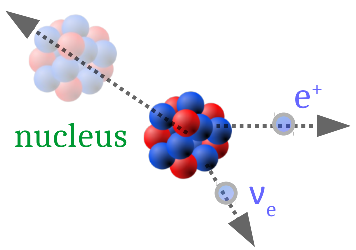
on behalf of the WISArD Collaboration

The Standard Model of weak interaction

Nuclear β decay can be described through the following Lorentz-invariant hamiltonian:

Hadronic terms **Leptonic terms**

$$
\begin{aligned}
H_\beta = \frac{G_F}{\sqrt{2}} V_{ud} \Big[& \left(\bar{\psi}_p \gamma_\mu \psi_n\right)\left(\bar{\psi}_e \gamma^\mu \left(C_V + C'_V \gamma_5\right) \psi_\nu\right) \\
- & \left(\bar{\psi}_p \gamma_\mu \gamma_5 \psi_n\right)\left(\bar{\psi}_e \gamma^\mu \gamma_5 \left(C_A + C'_A \gamma_5\right) \psi_\nu\right) \\
+ & \left(\bar{\psi}_p \psi_n\right)\left(\bar{\psi}_e \left(C_S + C'_S \gamma_5\right) \psi_\nu\right) \\
+ & \frac{1}{2} \left(\bar{\psi}_p \sigma_{\lambda\mu} \psi_n\right)\left(\bar{\psi}_e \sigma^{\lambda\mu} \left(C_T + C'_T \gamma_5\right) \psi_\nu\right) \\
+ & h.c.
\end{aligned}
$$



Operators

- **coupling constants**
- **γ matrices**

STANDARD MODEL: V-A theory

- Only vector and axial-vector contributions: $C_V = 1$, $C_A = -1.27$ $C_S = C_S' = C_T = C_T' = 0$
- No time-reversal symmetry violation: C_V, C_V', C_A, C_A' real
- Maximal parity violation: $C_V = C_V'$ and $C_A = C_A'$

BEYOND STANDARD MODEL

- Search for deviation from β-theory → scalar and tensor contribution?

The Standard Model of weak interaction (2)

Information on the theoretical coupling constants can be retrieved experimentally from the expression of the β-decay rate:

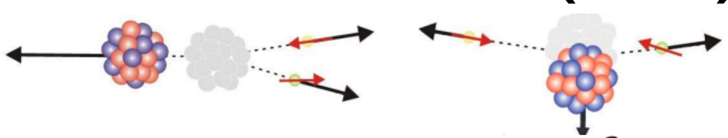
$$d\Gamma = \boxed{d\Gamma_0}\left(1 + \boxed{a}\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + \boxed{b}\frac{m_e}{E_e}\right)^{(1)}$$

Phase space factor

β-ν angular correlation coefficient

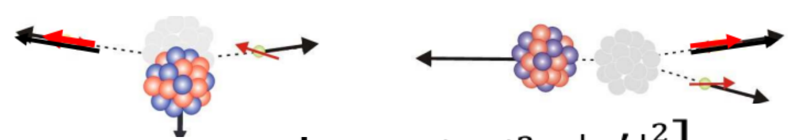
Fierz coefficient (= 0 in SM)

Pure Fermi transitions (s = 0)



$$a_F \cong 1 - \frac{|C_S|^2 + |C_S'|^2}{|C_V|^2}$$

Pure Gamow-Teller transitions (s = 1)



$$a_{GT} \cong -\frac{1}{3}\left[1 - \frac{|C_T|^2 + |C_T'|^2}{|C_A|^2}\right]$$

SM: vector current
- Preferred emission angle: θ = 0°
- Maximum recoil energy

BSM: scalar current
- Preferred emission angle: θ = 180°
- Minimum recoil energy

SM: axial-vector current
- Preferred emission angle: θ = 180°
- Minimum recoil energy

BSM: tensor current
- Preferred emission angle: θ = 0°
- Maximum recoil energy

(1) J.D. Jackson, S.B. Treiman, H.W. Wyld: Nucl. Phys. **4**, 206 (1957)

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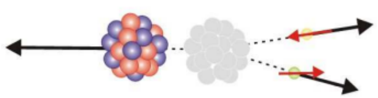

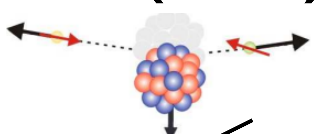

$$a_F \cong 1 - \cancel{\frac{|C_S|^2 + |C_S'|^2}{|C_V|^2}} \quad \text{SM}$$

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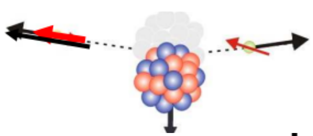

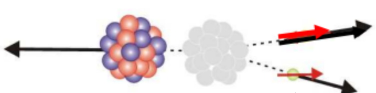

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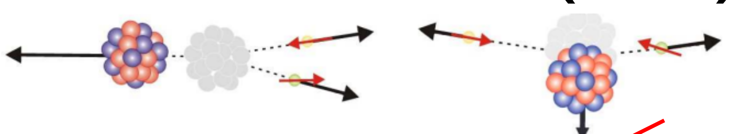

$$b'_F \simeq \pm \frac{\Gamma m_e}{E_e} \cancel{Re\left(\frac{C_S + C'_S}{C_V}\right)} \quad \text{SM}$$

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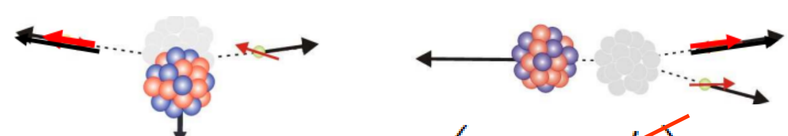

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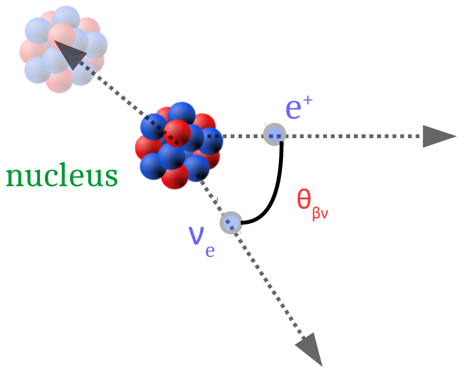

a coefficient determined from experiment

$\theta_{\beta\nu}$ not directly measurable (no neutrino detection)

WISArD (Weak Interaction Studies with ^{32}Ar Decay)

- Fermi and Gamow-Teller transition
- β-delayed proton emission

$$\tilde{a} \approx \frac{a}{1 + b\langle m_e / E_e \rangle}$$

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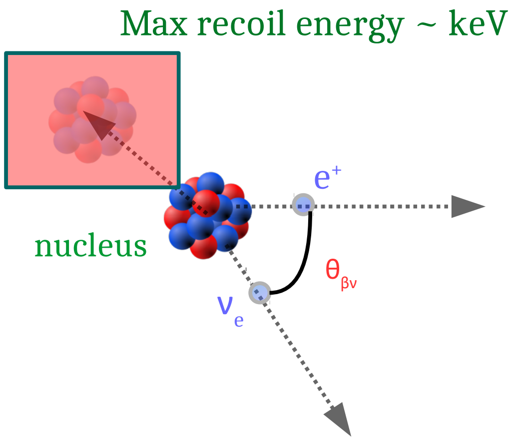

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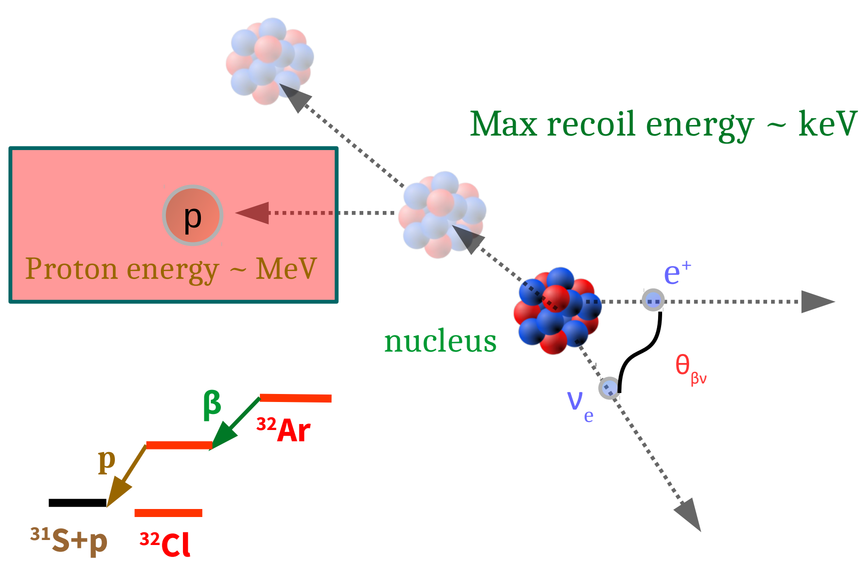

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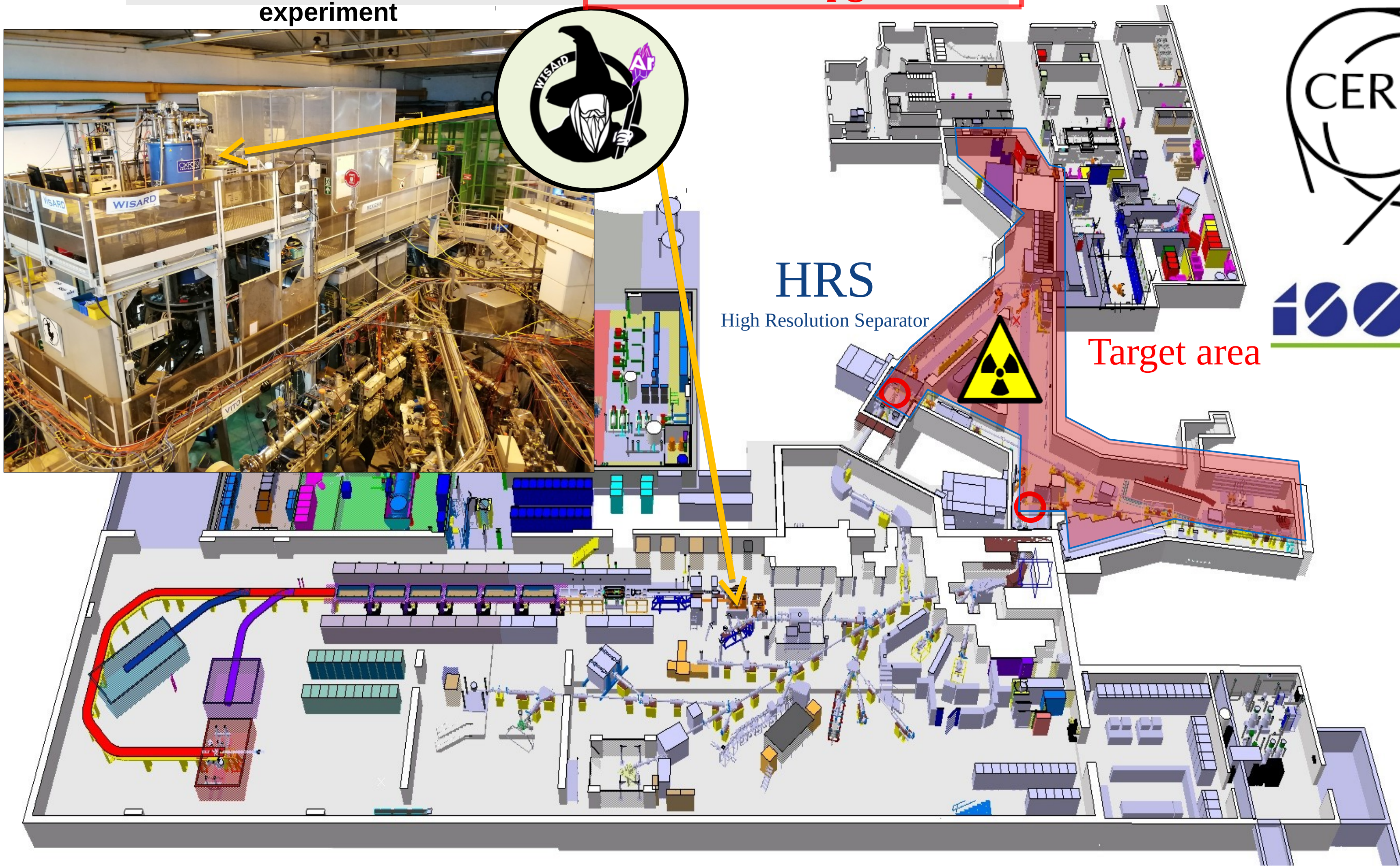
WISArD experimental campaign – October 2021

2018	2019	2020	2021	2022

Proof-of-principle experiment

WISArD upgrade

Foreseen run

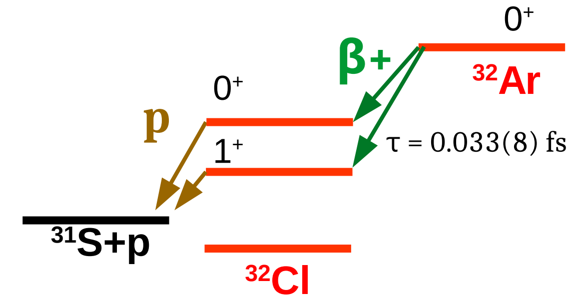


María J G Borge and Klaus Blaum, J. Phys. G: Nucl. Part. Phys. 45 (2018) 010301

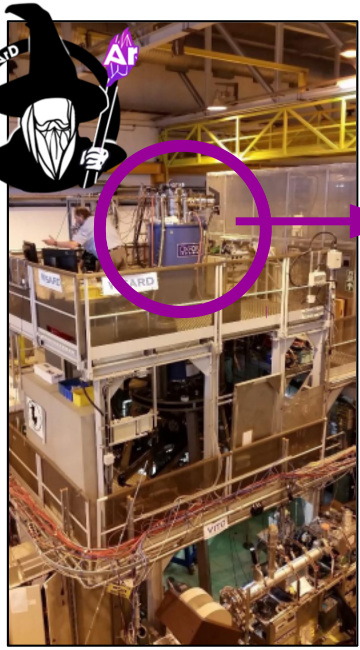
WISArD – Weak Interaction Studies with ^{32}Ar Decay

EXPERIMENTALLY

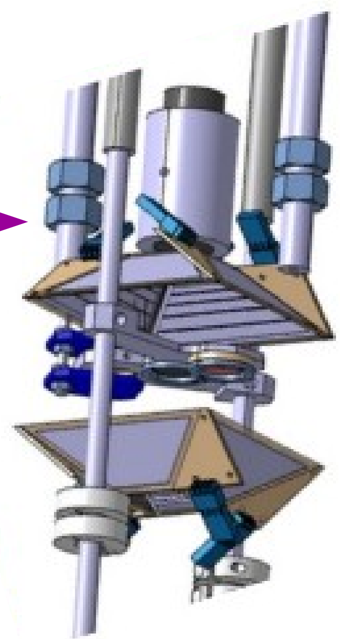
- ^{32}Ar nuclei initially at rest in the catcher foil
- **β^{+}- decay**
  → e^{+} emitted → B field → plastic scintillator
- **Nucleus recoils and emits a proton** immediately after
  → p emitted → 8 Si detectors (symmetrical to the catcher foil)
- **Detection of p in coincidence with the e^{+}**



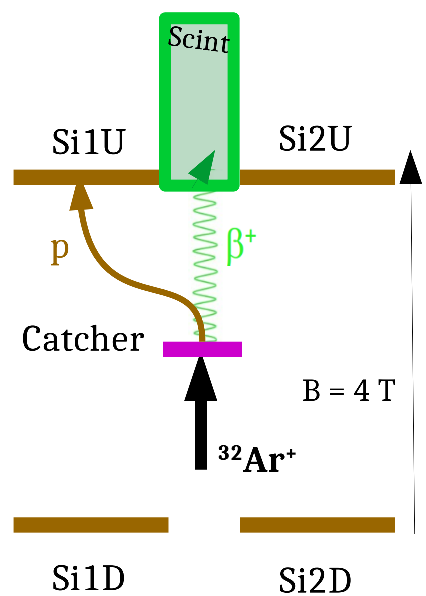
^{32}Ar simplified decay scheme



ISOLDE hall, CERN



WISArD detectors



e^{+} and p can be emitted in the same or opposite direction

↓

measure the proton energy shift (linear function of ã)

↓

limits on exotic coupling constants

A proof-of-principle was realized in November 2018

$\tilde{a}_{F} = 1.007(32)_{(stat)}(25)_{(sys)}$ [1]

$\tilde{a}_{GT} = -0.222(86)_{(stat)}(16)_{(sys)}$ [1]

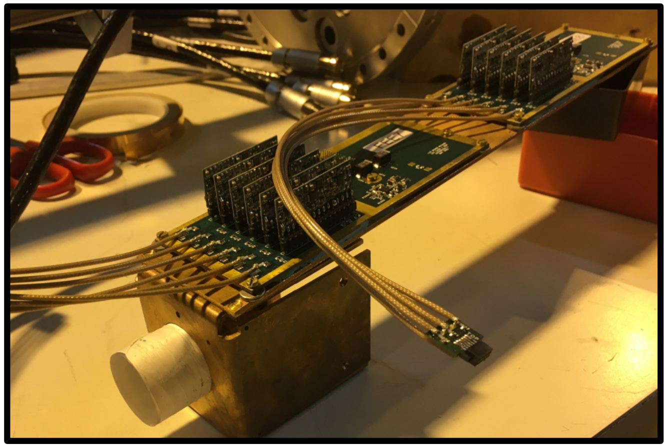
‰ precision to reach

(1) V. Araujo-Escalona et al. arXiv:1906.05135 [nucl-ex]

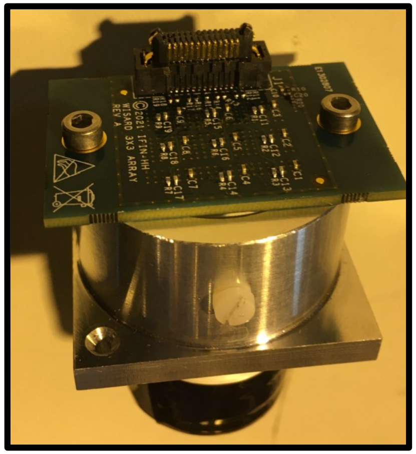
WISArD – experimental set-up

A significant upgrade of the existing experimental set-up has been performed through the past three years:

- significant **improvement in beam transmission** through WISArD beamline (from ~15% up to ~90% in 2021)
- completely new detection set-up (**SiPMs** + silicon detectors) installed in Sept. 2021



Plastic scintillator mounted on its cube copper support



SiPM matrix optically coupled to the scintillator

WISArD tower bottom view. The SiPM matrix is visible

Upgrade @ POP experiment:

- Plastic scintillator (r=1.5 cm, L=5 cm) + matrix 3x3 Onsemi J-Series SiPMs sensors (IFIN)
- FASTER DAQ trigger @ 3 cells fired at the same time

  → almost eliminating fake signals coming not from β-particles hitting and releasing energy inside the scintillator but due to the noise of a single SiPM cell

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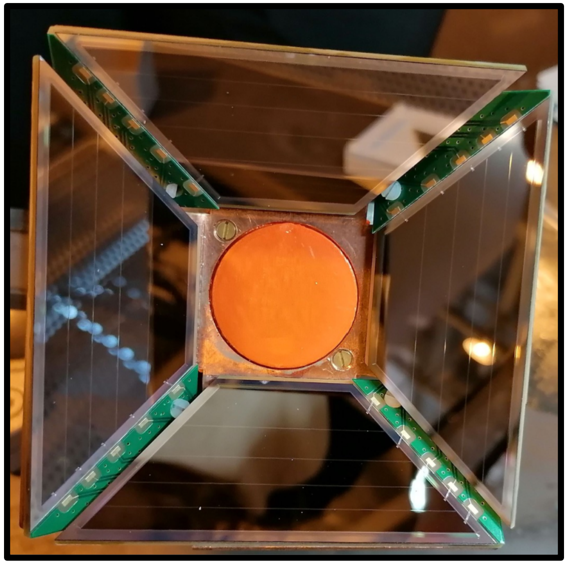
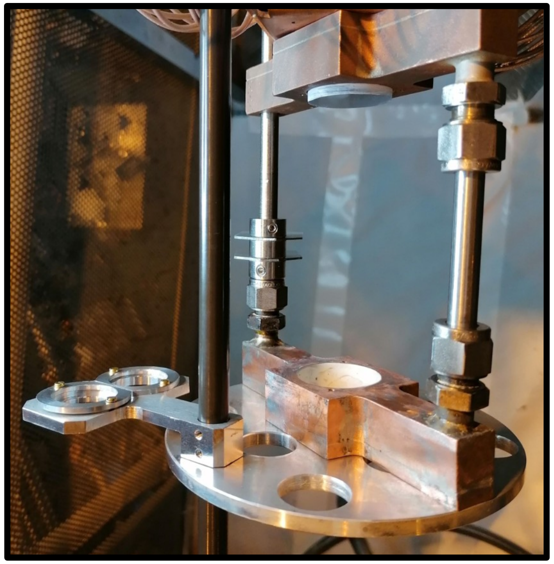
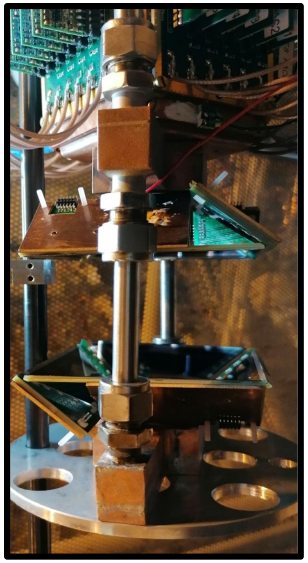


8 trapezoidal silicon detectors (5 strips each)





Silicon detectors assembling

Upgrade @ POP experiment:

- Pyramidal disposition of Si detectors → gained about x5 factor in angular coverage
- Detectors and preamps actively cooled at ~-30°C (glycol cooling system) → more stability

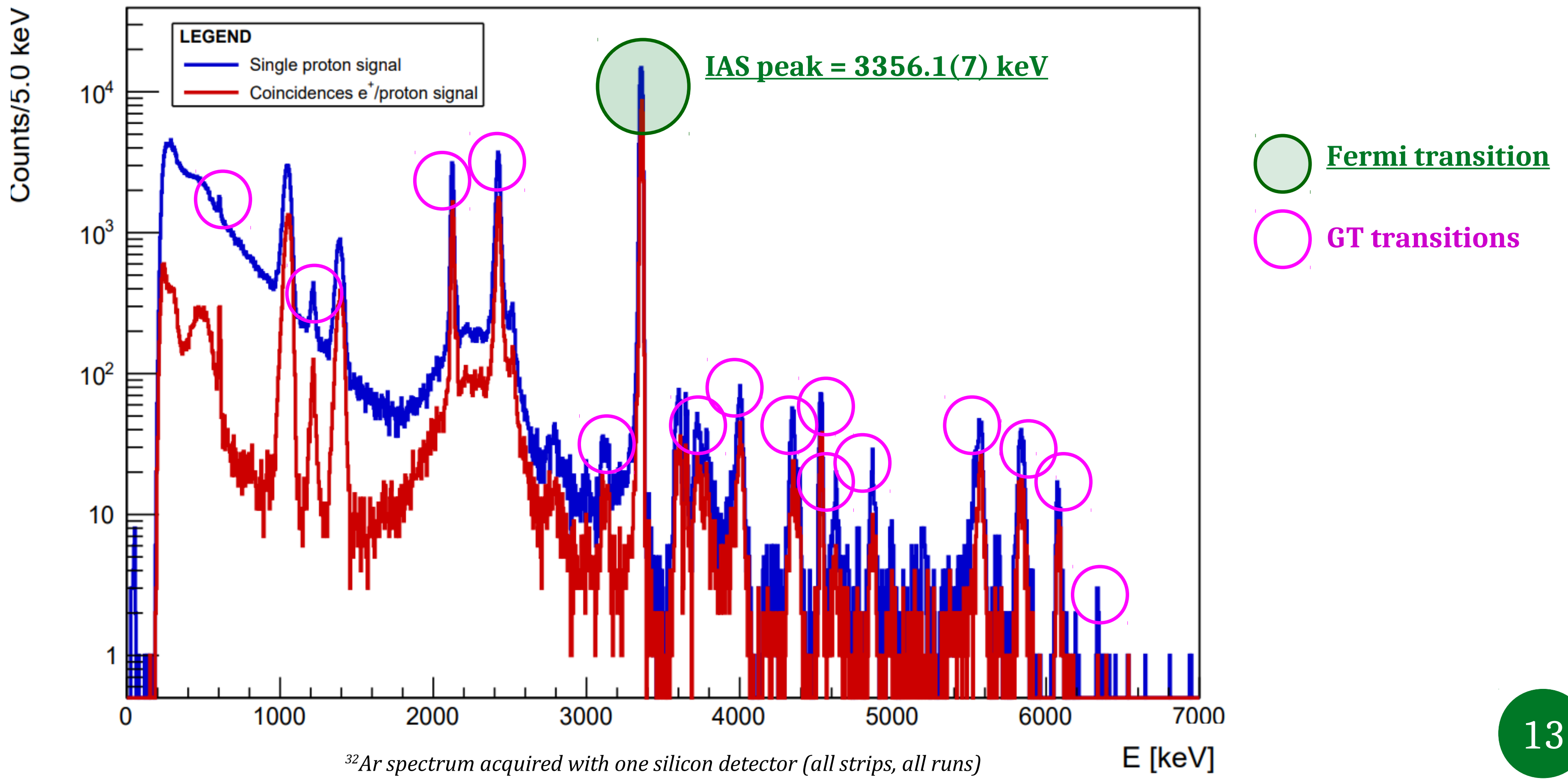
WISArD Oct. 2021 – preliminary results

- 10 shifts, ~61 h data taking, 63 runs acquired → mostly ^{32}Ar, few hours ^{33}Ar
- ^{32}Ar initially produced with ~100 pps → factor 10 less that ISOLDE production yields
  → retuning of beam through REX and target heating → gained a x3 in beam production
- Most of SiDet working correctly (despite discharges in a beamline PDT)
- Already **higher statistics** (x2.5) and **better energy resolution** ($\sigma_p \approx 15$ keV, $\sigma_{e+p} \approx 10$ keV) with respect to the proof of principle experiment (despite short beamtime allocated)

WISArD Oct. 2021 – preliminary results

- Energy calibrations for all the 48 silicon detectors (8 SiDet x (5 strips + 1 rear) each)
- Summed proton spectra for both single and coincident signals (detector by detector)

- **SiDet energy resolution between 7 and 15 keV** (35 keV in 2018 proof-of-principle exp)



[32]Ar spectrum acquired with one silicon detector (all strips, all runs)

Proton energies can be found in B- Blank et al., arXiv:2101.06422 [nucl-ex] (2021)

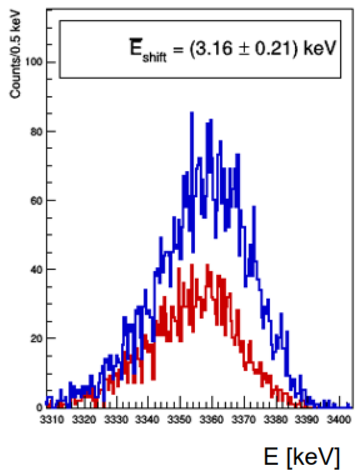
WISArD Oct. 2021 – preliminary results

Proton energy shifts + statistical uncertainties determined for all SiDets (IAS region)

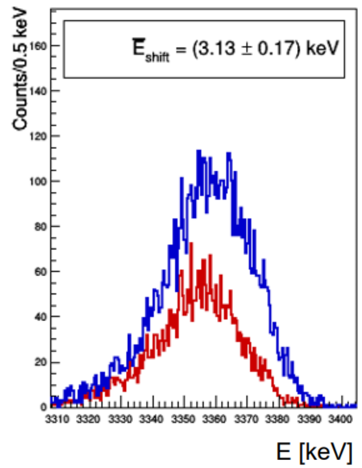
Upper detectors

Shift towards lower energies

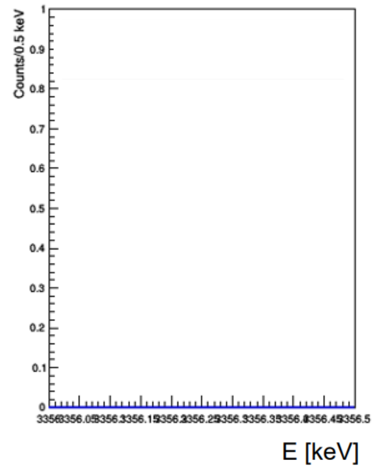
SiDet 1



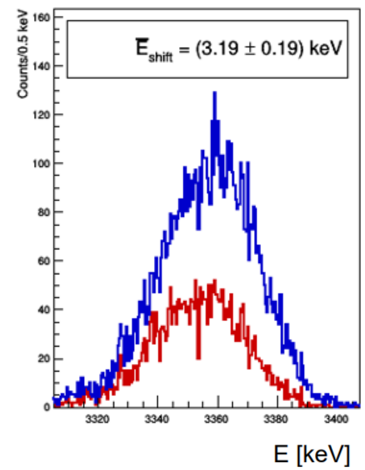
SiDet 2



SiDet 3



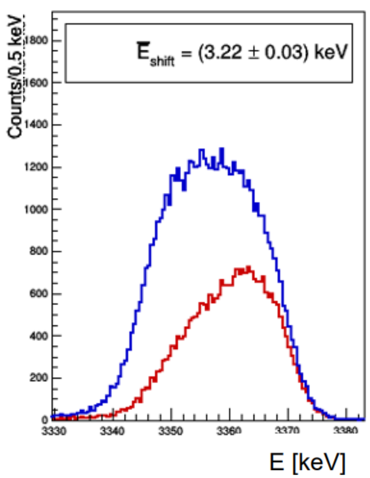
SiDet 4



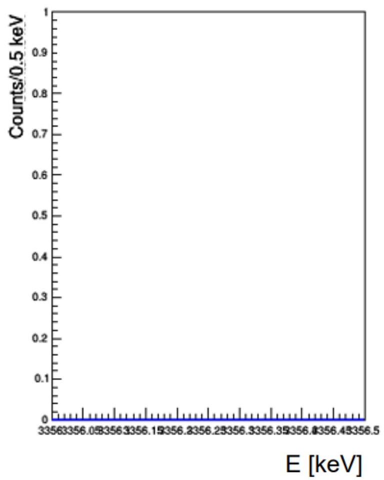
Lower detectors

Shift towards higher energies

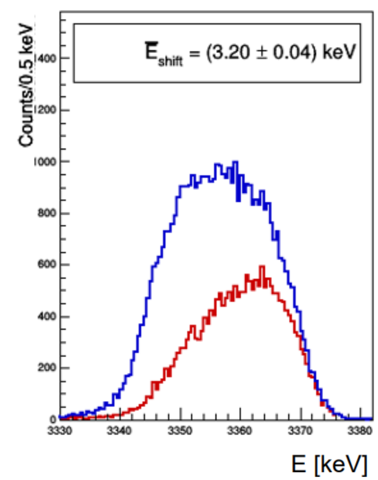
SiDet 5



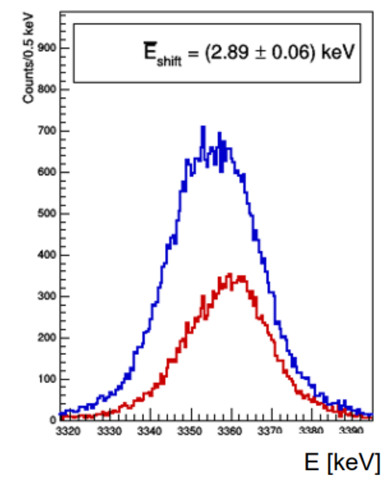
SiDet 6



SiDet 7

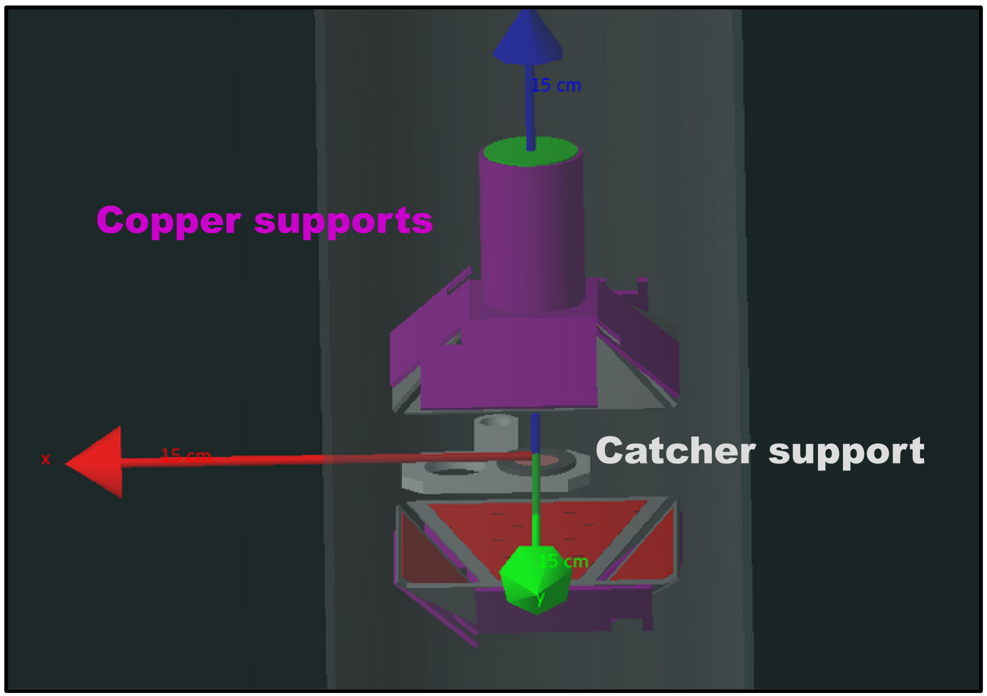


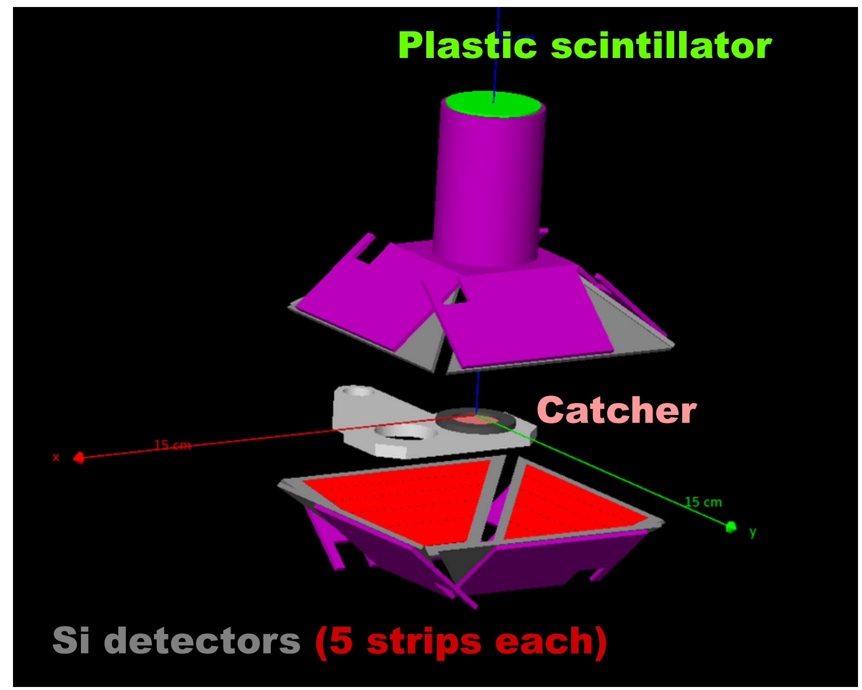
SiDet 8



New WISArD Geant4 simulations

New WISArD set-up implemented within the G4 simulations
→ new 8 Si detectors (5 strips each): thin dead layer (~ 60 nm)
→ measured with alpha beam @ AIFIRA (CENBG)





→ implemented CRADLE++ output files as event generator for the ^{32}Ar decay
→ implemented possibility to simulate the real WISArD magnetic field (measured in February 2021) as an alternative to the classic numerical algorithms

G4 OUTPUTS WILL BE COMPARED TO THE MIRROR PENELOPE ONES[1]

(1) Collaboration with Texas A&M University

WISArD – outlook

- Despite the short beamtime allocated, problems in beam production and transmission

Completely new experimental set-up:

- Higher statistics with respect of proof-of-principle experiment (x2.5)
- Significant improvement in the sensitivity experiment (x2.1)

- Encouraging preliminary results
- Comparison with Geant4 simulations and analysis of systematic errors
- New request for additional beamtime (24 shifts) in one further run in 2022

Reach the level of few ‰ precision in the determination of $\tilde{a}$ in 2022


Thanks
for your attention
P. Alfaurt, D. Atanasov, B. Blank, F. Cresto, L. Daudin, X. Fléchard,
J. Giovinazzo, E. Liénard, G. Quéméner, M. Pomorski,
N. Severijns,S. Vanlangendonck, M. Versteegen,
D. Zakoucky

BACKUP SLIDES

Physics beyond the SM – electroweak sector

$$a_{\beta\nu}^{F} \simeq 1 - \frac{|C_S|^2 + |C_S'|^2}{C_V^2} \qquad a_{\beta\nu}^{GT} \simeq -\frac{1}{3}\left[1 - \frac{|C_T|^2 + |C_T'|^2}{C_A^2}\right]$$

$$b_F' \simeq \pm \frac{\Gamma m_e}{E_e} Re\left(\frac{C_S + C_S'}{C_V}\right) \qquad b_{GT}' \simeq \pm \frac{\Gamma m_e}{E_e} Re\left(\frac{C_T + C_T'}{C_A}\right)$$

$$\mathcal{F}t_i \equiv ft_i\,(1 + \delta_{R,i}')\,(1 + \delta_{NS,i} - \delta_C) = \frac{K}{G_F^2\, V_{ud}^2\,(1 + \Delta_R^V)\,\left[1 + (f_{A,i}/f_{V,i})\,\rho_i^2\right]}$$

Physics beyond the SM – electroweak sector

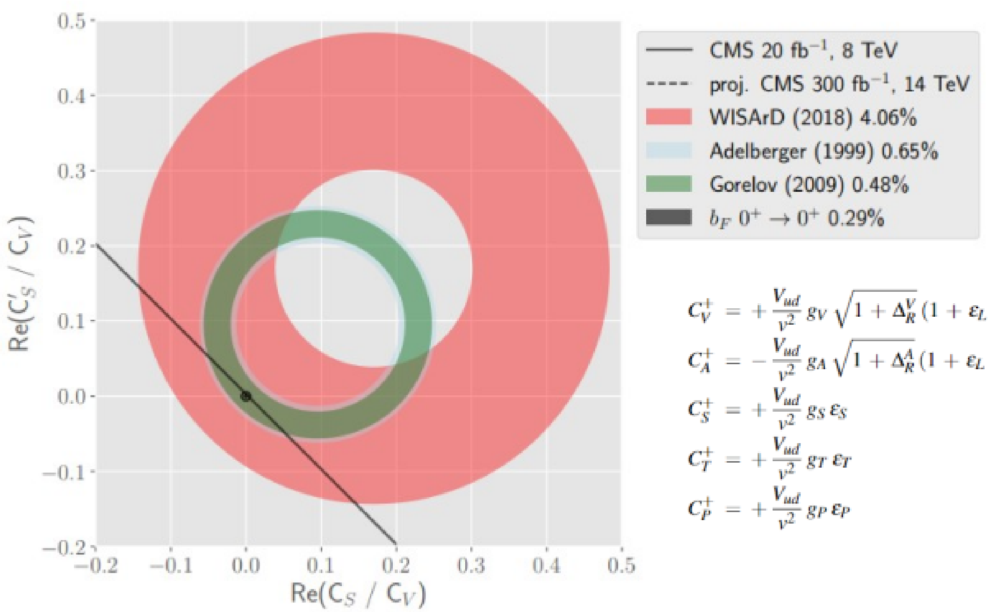
$$W_L = \cos\zeta W_1 + \sin\zeta W_2 \qquad\qquad W_R = -\sin\zeta W_1 + \cos\zeta W_2 \qquad (1.48)$$

Further constraints on right-handed currents from low-energy physics come from longitudinal positron polarization experiments, neutron decay, longitudinal polarization of positrons emitted by polarized nuclei and the Ft-values of the superallowed 0+ −→0+ transitions.

F. Cresto

Physics beyond the SM – electroweak sector

$$
\begin{aligned}
&\mathcal{L}_{quark-level} \supset \\
&-\frac{V_{ud}}{v^2}\Big[(1+\varepsilon_L)\,\overline{\psi_e}\gamma_\mu\psi_{\nu,L}\cdot\overline{\psi_u}\gamma^\mu(1-\gamma_5)\psi_d + \tilde{\varepsilon}_L\,\overline{\psi_e}\gamma_\mu\psi_{\nu,R}\cdot\overline{\psi_u}\gamma^\mu(1-\gamma_5)\psi_d \\
&+\varepsilon_R\,\overline{\psi_e}\gamma_\mu\psi_{\nu,L}\cdot\overline{\psi_u}\gamma^\mu(1+\gamma_5)\psi_d + \tilde{\varepsilon}_R\,\overline{\psi_e}\gamma_\mu\psi_{\nu,R}\cdot\overline{\psi_u}\gamma^\mu(1+\gamma_5)\psi_d \\
&+\frac{1}{4}\varepsilon_T\,\overline{\psi_e}\sigma_{\mu\nu}\psi_{\nu,L}\cdot\overline{\psi_u}\sigma^{\mu\nu}(1-\gamma_5)\psi_d + \frac{1}{4}\tilde{\varepsilon}_T\,\overline{\psi_e}\sigma_{\mu\nu}\psi_{\nu,R}\cdot\overline{\psi_u}\sigma^{\mu\nu}(1+\gamma_5)\psi_d \\
&+\varepsilon_S\,\overline{\psi_e}\psi_{\nu,L}\cdot\overline{\psi_u}\psi_d + \tilde{\varepsilon}_S\,\overline{\psi_e}\psi_{\nu,R}\cdot\overline{\psi_u}\psi_d - \varepsilon_P\,\overline{\psi_e}\psi_{\nu,L}\cdot\overline{\psi_u}\gamma_5\psi_d - \tilde{\varepsilon}_P\,\overline{\psi_e}\psi_{\nu,R}\cdot\overline{\psi_u}\gamma_5\psi_d\Big] \\
&+h.c.
\end{aligned}
\tag{1.47}
$$

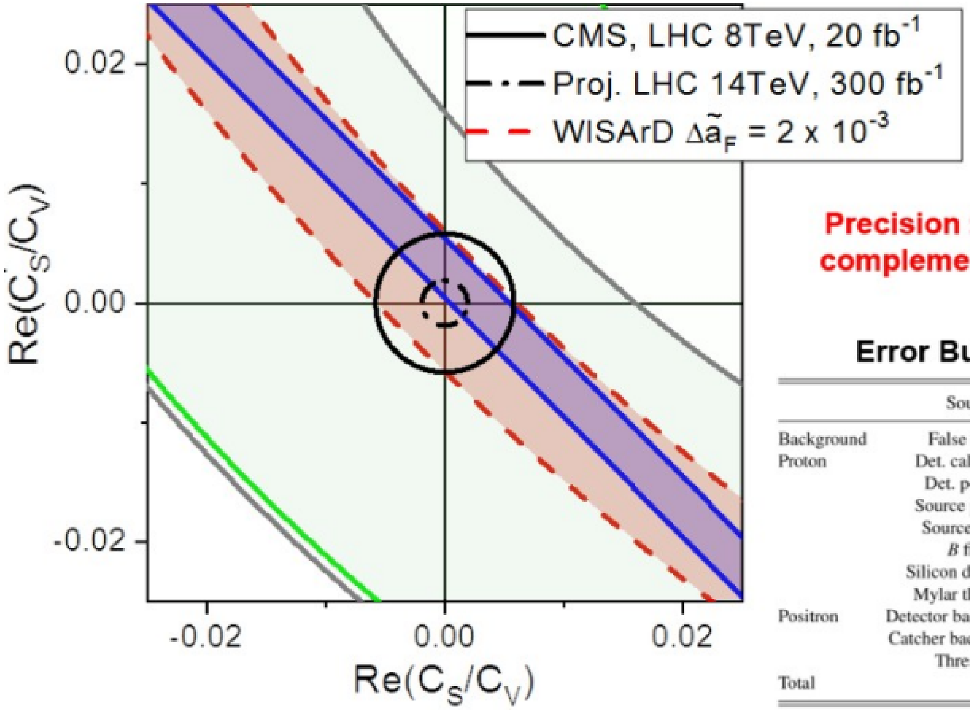


$$
\begin{aligned}
C_V^+ &= +\frac{V_{ud}}{v^2}g_V\sqrt{1+\Delta_R^V}\,(1+\varepsilon_L+\varepsilon_R) & C_V^- &= +\frac{V_{ud}}{v^2}g_V\sqrt{1+\Delta_R^V}\,(\tilde{\varepsilon}_L+\tilde{\varepsilon}_R) \\
C_A^+ &= -\frac{V_{ud}}{v^2}g_A\sqrt{1+\Delta_R^A}\,(1+\varepsilon_L-\varepsilon_R) & C_A^- &= +\frac{V_{ud}}{v^2}g_A\sqrt{1+\Delta_R^A}\,(\tilde{\varepsilon}_L-\tilde{\varepsilon}_R) \\
C_S^+ &= +\frac{V_{ud}}{v^2}g_S\,\varepsilon_S & C_S^- &= +\frac{V_{ud}}{v^2}g_S\,\tilde{\varepsilon}_S \\
C_T^+ &= +\frac{V_{ud}}{v^2}g_T\,\varepsilon_T & C_T^- &= +\frac{V_{ud}}{v^2}g_T\,\tilde{\varepsilon}_T \\
C_P^+ &= +\frac{V_{ud}}{v^2}g_P\,\varepsilon_P & C_P^- &= +\frac{V_{ud}}{v^2}g_P\,\tilde{\varepsilon}_P
\end{aligned}
\tag{A.7}
$$

Physics beyond the SM – electroweak sector

- gamma-rays shifts of 18Ne (1997) and 14O (2003)
- recoiling ions: 37K (TRIUMF); beta.mixed of 21Na at Berkeley

Scalar couplings - future

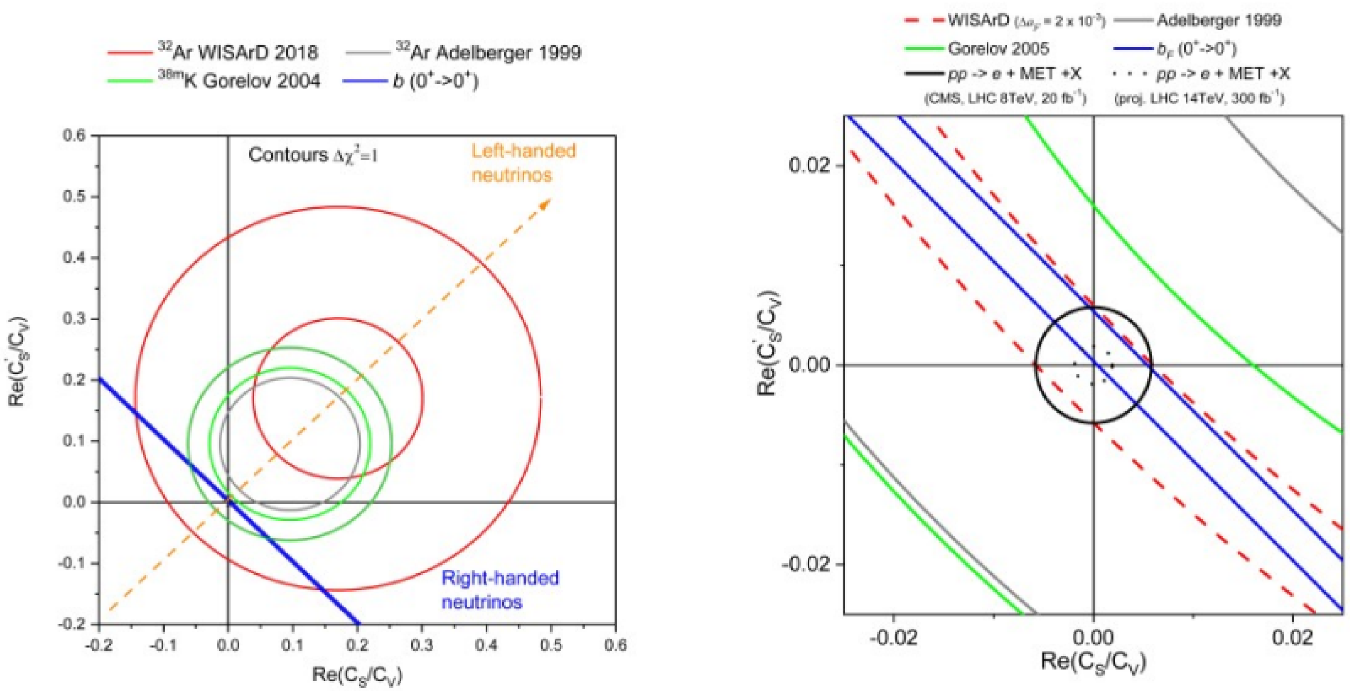


Precision ≤ 0.1% needed to complement LHC searches!

Error Budget NOV2018

	Source	Uncertainty	$\Delta\tilde{a}_F$ x1E-3
Background	False coinc.	8%	<1
Proton	Det. calibration	0.2%	9
	Det. position	1 mm	<1
	Source position	3 mm	3
	Source radius	3 mm	1
	B field	1%	<1
	Silicon dead layer	0.3 μm	5
	Mylar thickness	0.15 μm	2
Positron	Detector backscattering	15%	2
	Catcher backscattering	15%	21
	Threshold	12 keV	8
Total			25

Physics beyond the SM – electroweak sector



(a) Present constraints.

(b) Projected limits.

Figure 4: Exclusion plots for the scalar coupling constants. (a) Present picture from correlation measurements in nuclear beta decay (b) Projections of WISArD reaching a precision of 0.1%, showing that at this precision it will remain competitive to high-energy physics.

B5

Physics beyond the SM – electroweak sector

Beamtime Request - summary

$\tilde{a}_F = 1.007(32)_{stat}(25)_{syst}$ $\quad$ N^{2021}_{coinc} ~ 290 x N^{2018}_{coinc} = 2.9E7

	2018	2021	Gain	Shifts (8h)
Resolution (keV)	35	10	2.1	-
Yield (pps)	~1700	~4000	2.35	-
Transport efficiency (%)	12	70	5.8	-
Detector geometry (%)	8	40	5	-
Beamtime Duration (h)	35	144	4.1	18
Calibration ^{33}Ar				3
Stable beam + TISD				3
TOTAL				24

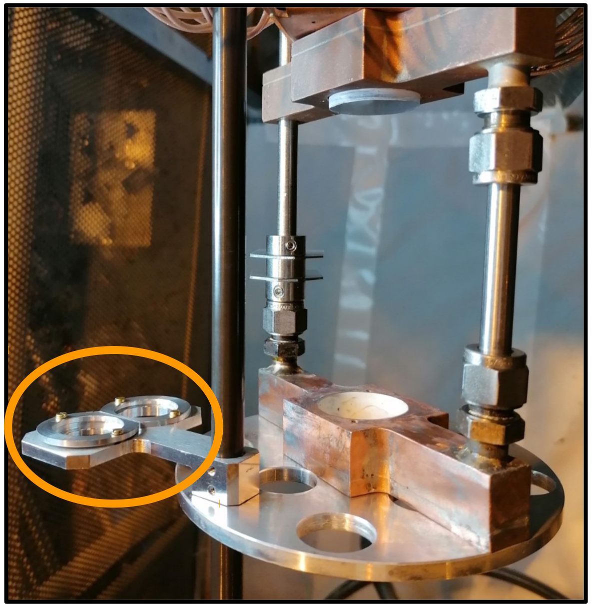
Summary table presented at the INTF Committee in 2020

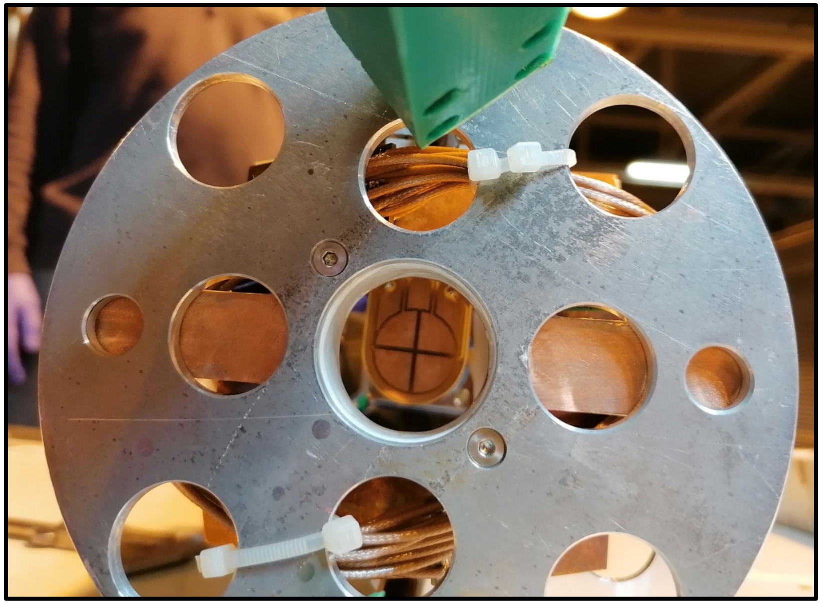
WISArD campaign – beam implantation & calibration

- Calibration tests with 4-α source
- Incoming ^{32}Ar and ^{33}Ar radioactive beam → implanted on an aluminum foil
  → tests with 0.8 μm and 6 μm thickness foils

same as 2018 POP
reducing contribution from backscattered electrons

Catcher and source support





Segmented FC

- Incoming beam intensity measured via segmented Faraday cup

Systematic uncertainties

Total systematic uncertainties on $\tilde{a}_{F,\,GT}$ have to be reduced by at least an order of magnitude

→ measurements at the ~‰ level of precision needed to set **new** stringent **limits** on the possible existence of the exotic **coupling constants** (scalar and tensor ones)

Syst. contribution	Error source	Uncertainty	$\Delta\tilde{a}_F$ (‰)	$\Delta\tilde{a}_{GT}$ (‰)
background	false coincidences	8%	< 1	2
protons	detector calibration	0.2%	9	6
	detector position	1 mm	< 1	1
	silicon dead layer	0.3 μm	5	7
	source position	3 mm	3	2
	source radius	3 mm	1	1
	B field	1%	< 1	< 1
	Mylar thickness	0.15 μm	2	3
positrons	detector backscattering	15%	2	1
	catcher backscattering	15%	21	11
	detection threshold	12 keV	8	4
Total			**25**	**16**

(1)

[(1)] V. Araujo-Escalona et al. arXiv:1906.05135 [nucl-ex]

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(2)

Reduction in thickness
Measurements WISArD magnet
Measurements ion implantation profile

- new Si detectors
- new Si detector geometrical disposition
- dedicated tests with AIFIRA @ CENBG

[2] V. Araujo-Escalona et al. arXiv:1906.05135 [nucl-ex]

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Total			**25**	**16**

(2)

Dedicated experimental campaign with independent set-ups in order to constraint the Geant4 simulations

B10

[2] V. Araujo-Escalona et al. arXiv:1906.05135 [nucl-ex]

β-backscattering tests - State-of-the-art

Different β-backscattering test benches to reproduce different relative angles between detectors and incoming particles:

Electron spectrometer (Nov. 2019 - ...)

data analyzed and compared with G4 simulations:

- fairly good agreement with the experimental data
- evaluation of backscattering coefficient @ E, θ_{inc}

PROS: → selection of monoenergetic e- beam
→ high intensity

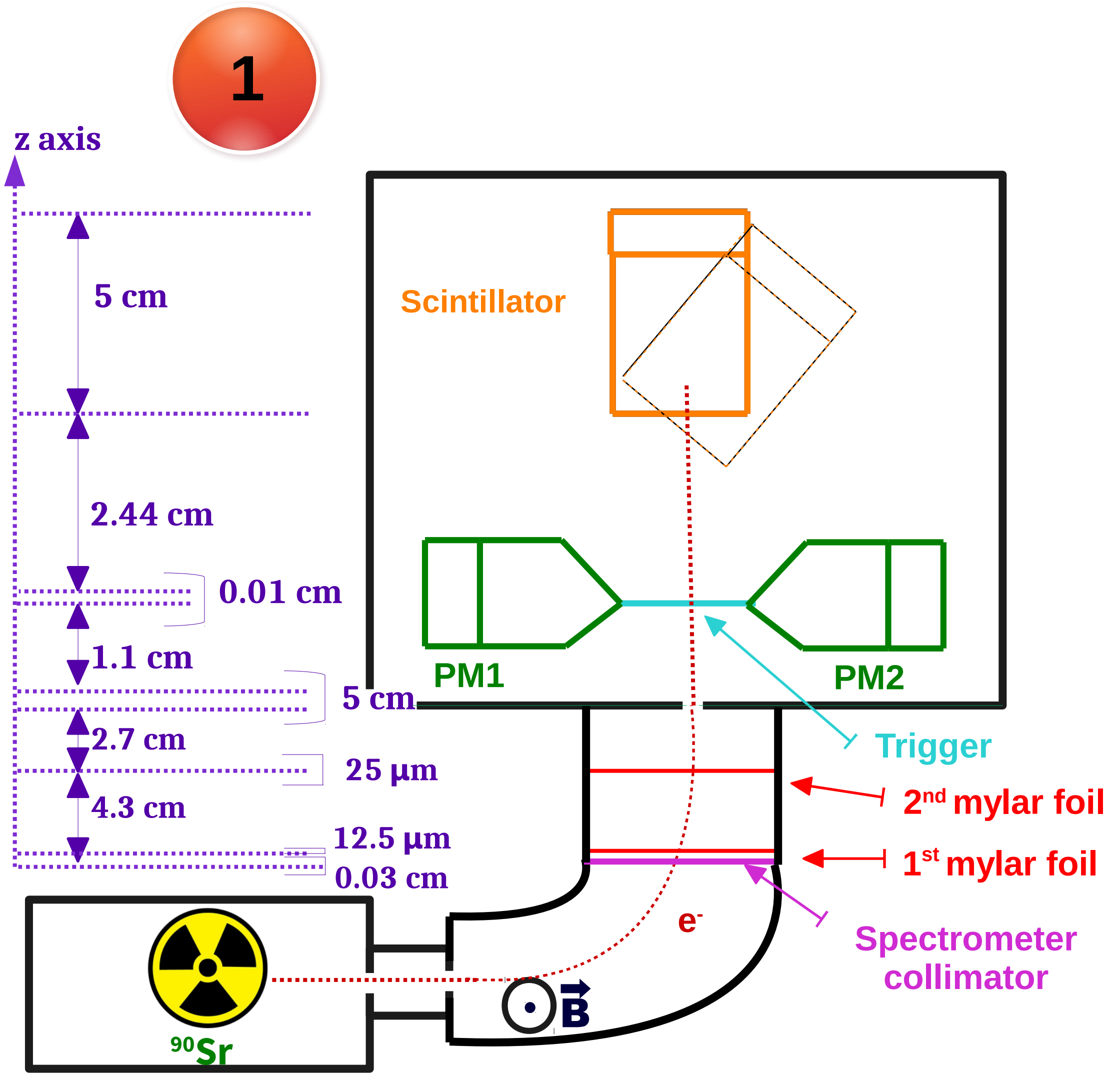
CONS: → measurements taken at atmospheric pressure

New dedicated set-up (2021, ongoing)

- feasibility study through Geant4 simulations
- currently data taking

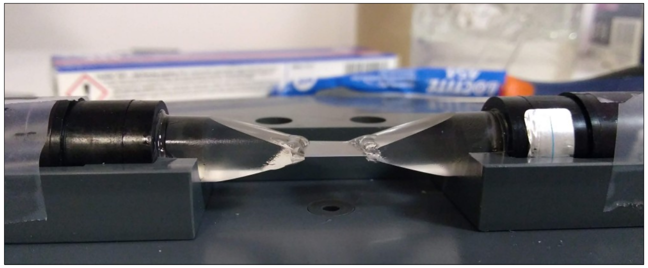
PROS: → measurements taken in primary vacuum
→ employment of radioactive sources

β-backscattering tests @ e- spectrometer



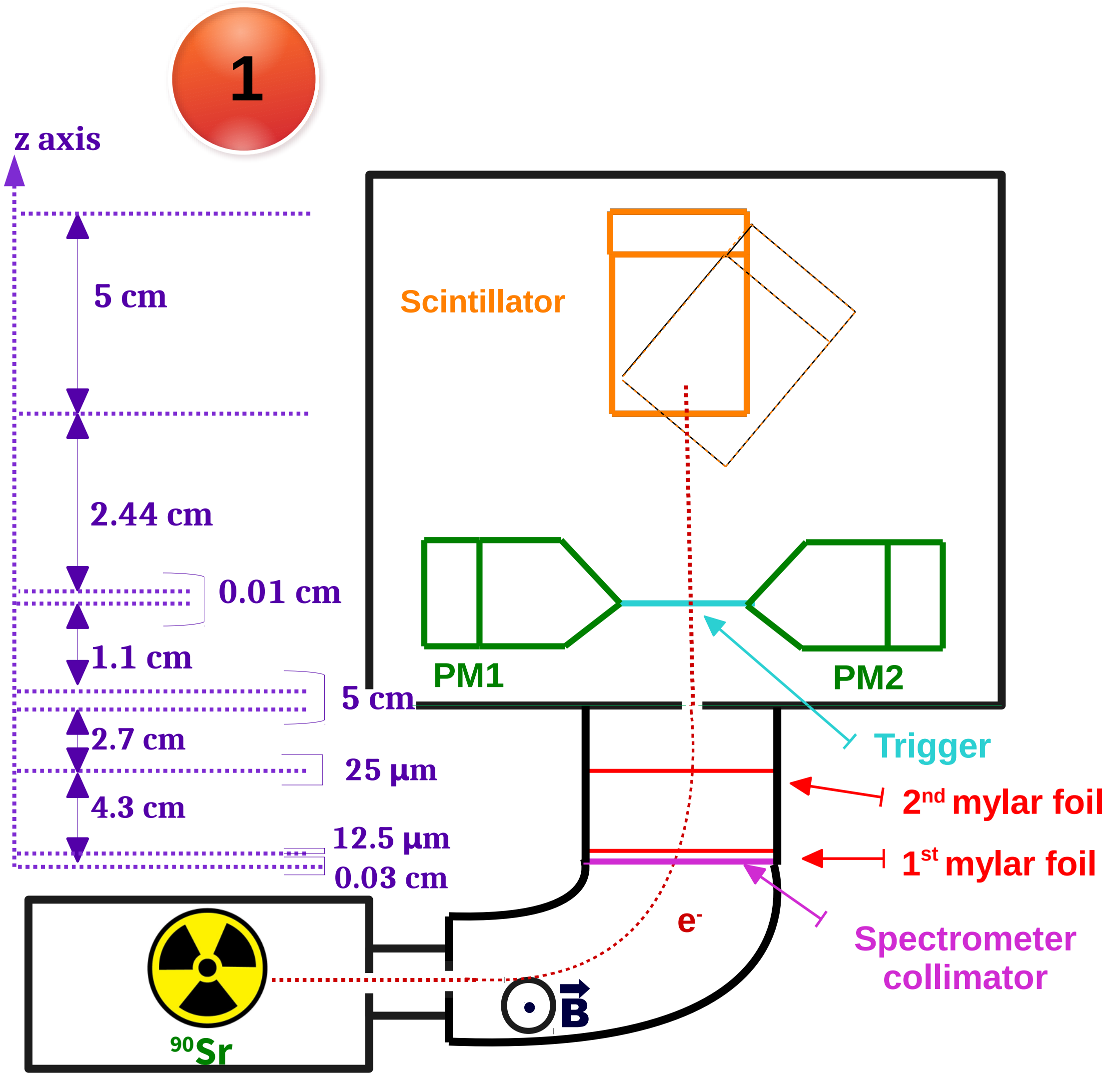
- <u>Source ^{90}Sr:</u>
  - $Q_\beta(^{90}Sr) = 0.55$ MeV → $Q_\beta(^{90}Y) = 2.3$ MeV
  - Monoenergetic electrons via B field
  - Collimator (radius = 0.2 cm)
  - E_{e-} = 0.7 – 1.8 MeV

- <u>Black box:</u>
  - Air (no vacuum)
  - Trigger on e-
    - plastic scintillator
    - 100 µm thickness
  - \+ 2 optical guides coupled with PMs



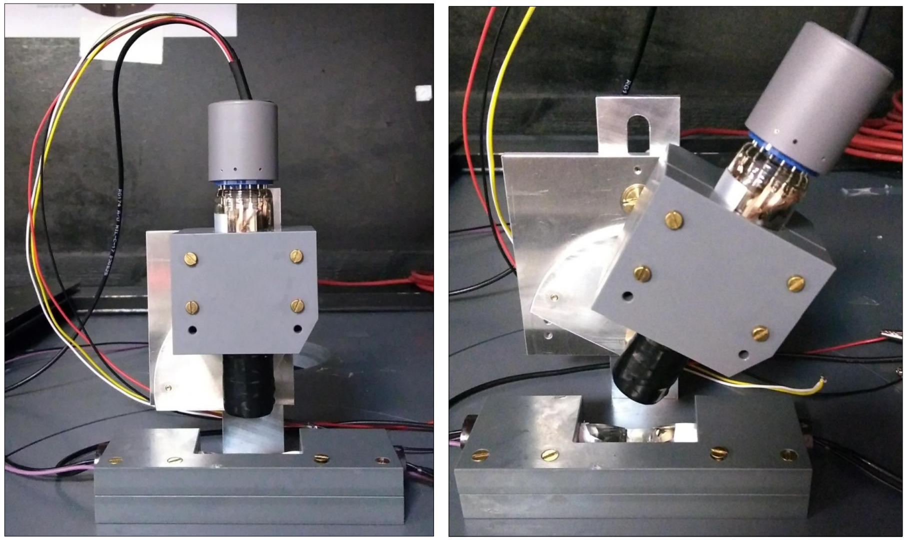
Electron trigger with optical guides and PMs

β-backscattering tests @ e- spectrometer



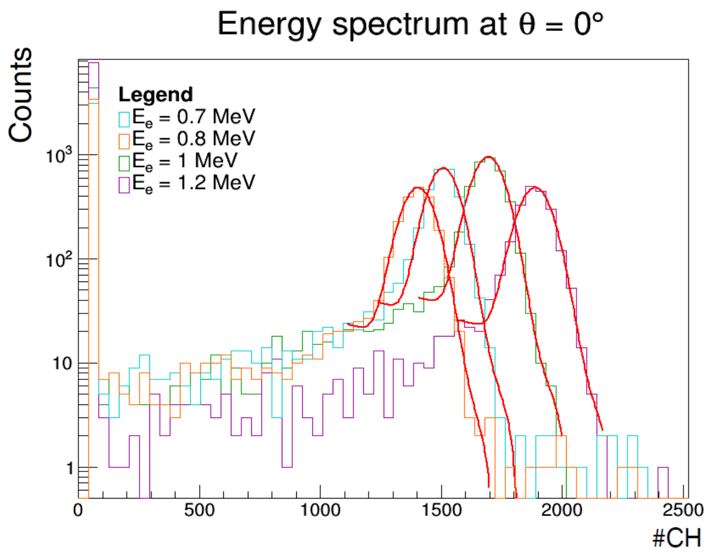
- <u>Black box:</u>
  - Plastic scintillator (rotatable)
    - radius = 1 cm
    - length = 5 cm

→ collecting data with different electron incident angles (θ = 0°, 20°, 40°)



Plastic scintillator fixed on a rotatable support

β-backscattering tests @ e- spectrometer



EXPERIMENTAL MEASUREMENTS

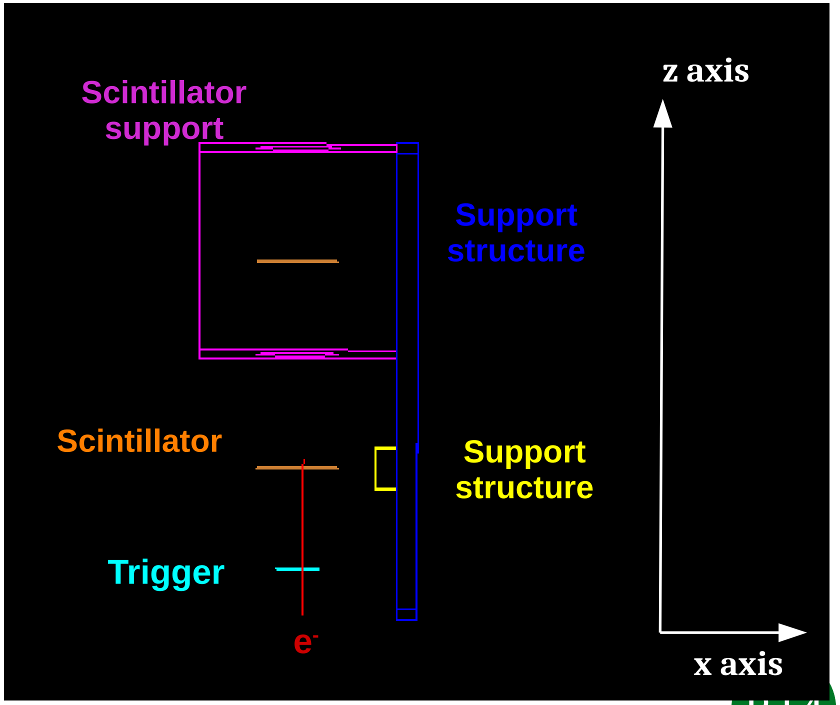
- 13 runs varying 0.7 MeV < E_e < 1.8 MeV at different incident angles with respect to the scintillator (0°,20°,40°)

DATA ANALYSIS

- Reconstruction of the ADC spectra
- Gaussian+background fits
  - → μ → energy calibration
  - → σ → used to apply resolution to G4 simulations

G4 SIMULATIONS

- Each run simulated by using 8 different *PhysicsLists*

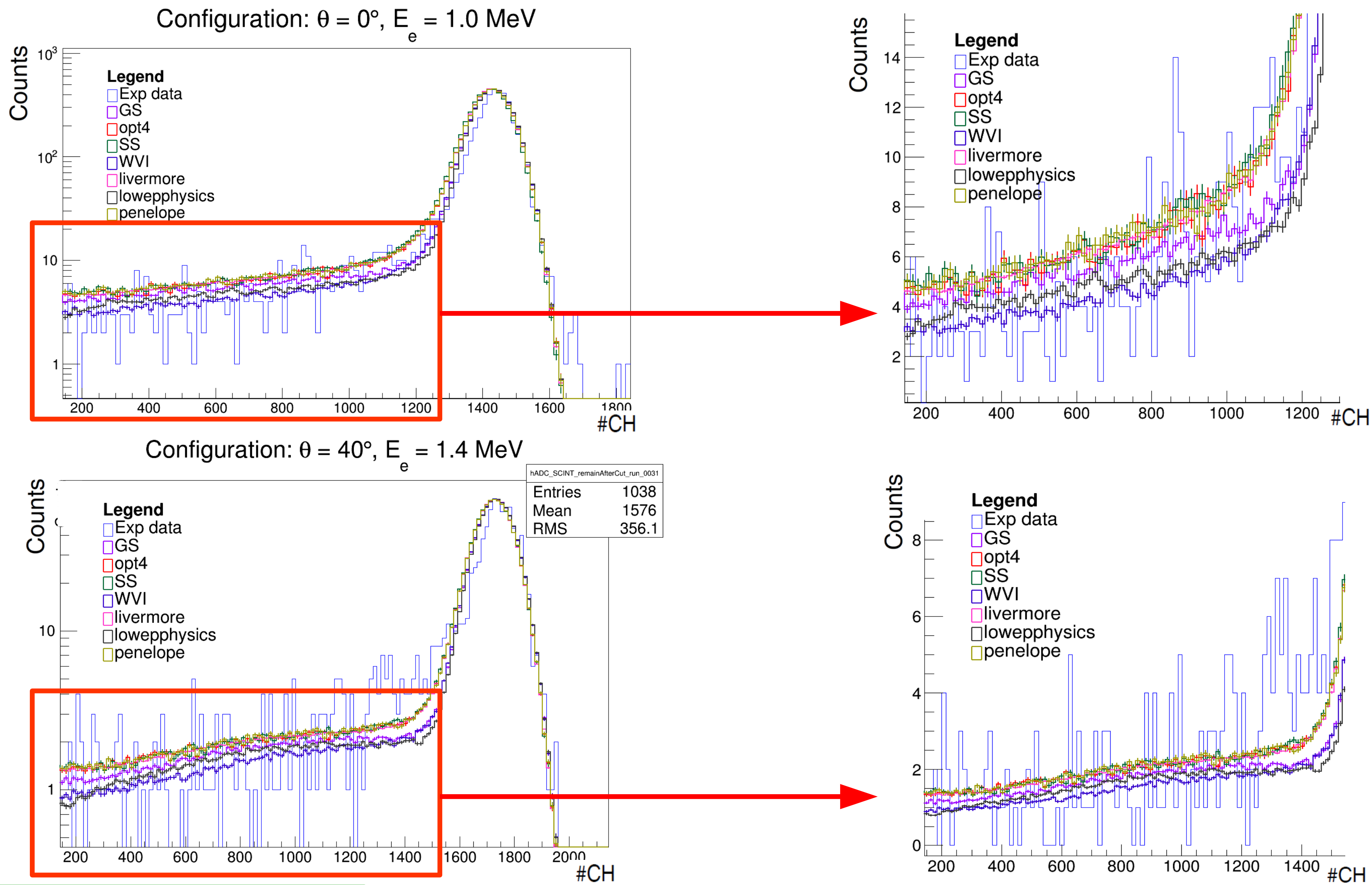


COMPARISON EXP/G4 SIMULATIONS

- β-backscattering coefficients computed (± stat. ± syst.)

β-backscattering tests @ e- spectrometer

EXAMPLES (LOWEST AND HIGHEST θ_{INC}):



QUALITATIVELY:

- GS and SS describe better the experimental spectra

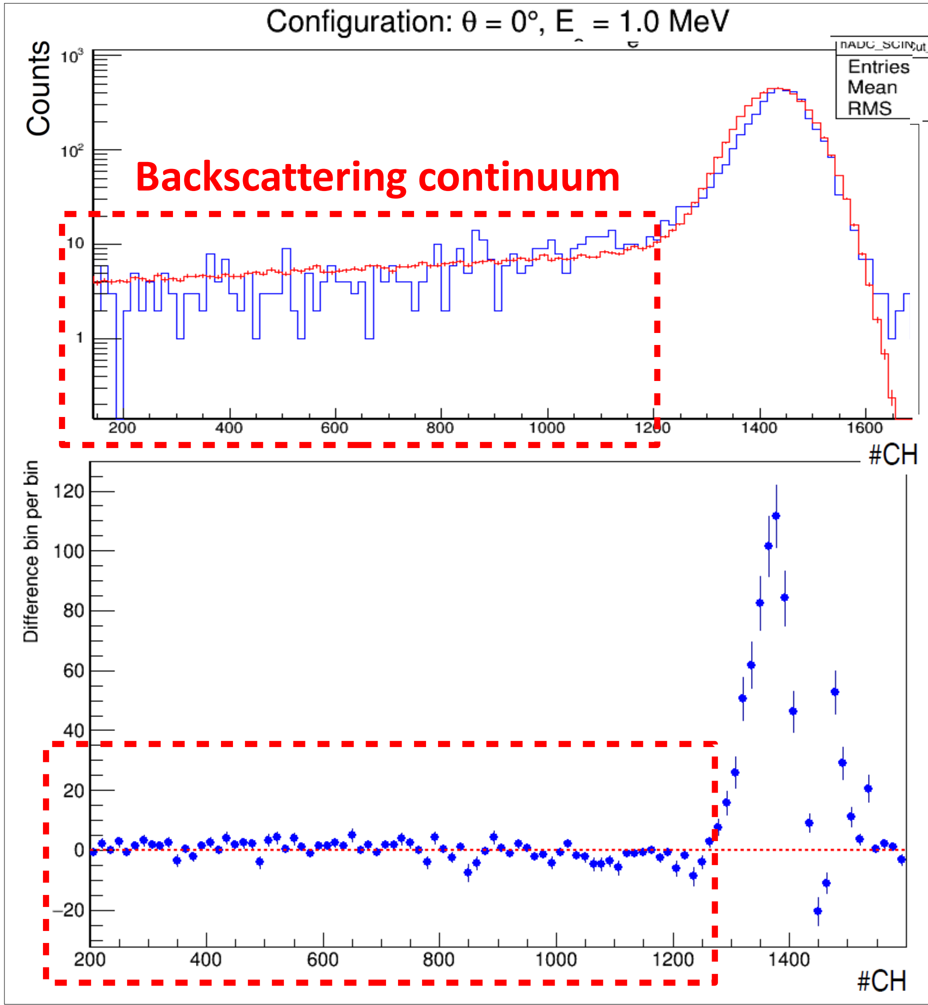
F. Cresto

β-backscattering tests @ e- spectrometer

QUANTITATIVELY:

→ **Residual plots**
→ **Backscattering coefficient experimental/simulated spectra**

<u>EXAMPLE:</u> E_e = 1 MeV, θ = 0°



Configuration: θ = 0°, E_e = 1.0 MeV

Physics List used: GS

Backscattering ratio exp (%):

8.58 +/- 0.45 (stat.) +/- 0.51 (syst.)

Backscattering ratio simu (%):

7.76 +/- 0.04 (stat.) +/- 0.49 (syst.)

F. Cresto

β-backscattering tests @ e- spectrometer

QUANTITATIVELY:

→ **Residual plots**
→ **Backscattering coefficient experimental/simulated spectra**

- Qualitatively → best reproduction with GS and SS PhysicsList
- Quantitatively?

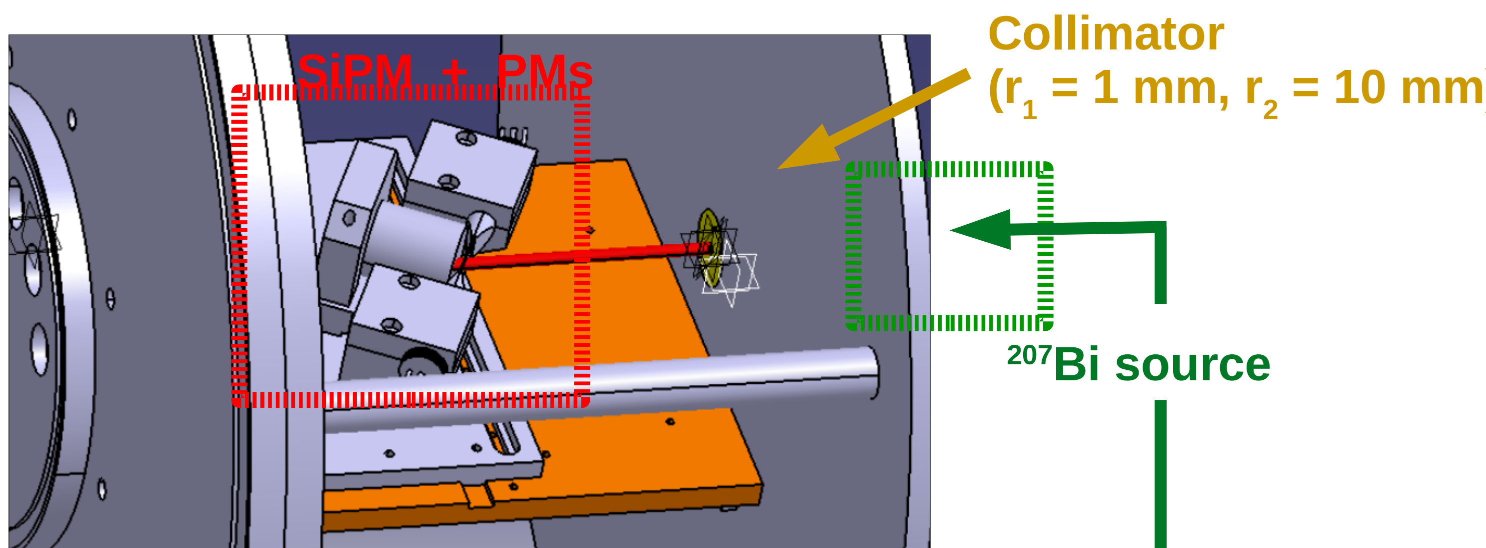
Exp. spectrum
Simu. spectrum

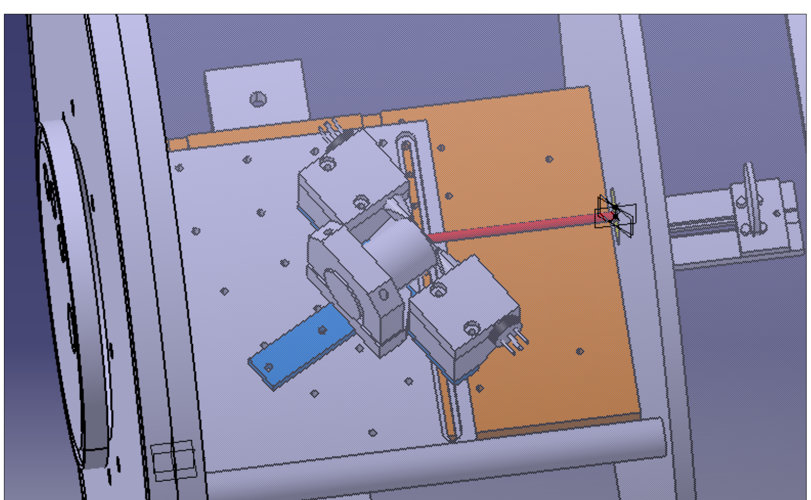
	Run name + PhysicsList	Backscattering coefficient (%) Value	Stat.	Syst.
E_e = 1.0 MeV, θ = 0°	hADC_SCINT_remainAfterCut_run_0011	8.58	0.45	0.51
	run_0011_GS	7.76	0.04	0.49
	run_0011_opt4	8.88	0.05	0.41
	run_0011_SS	9.17	0.05	0.40
	run_0011_WVI	6.40	0.03	0.61
	run_0011_lowepphysics	6.84	0.03	0.57
	run_0011_penelope	9.05	0.05	0.40
E_e = 1.0 MeV, θ = 20°	hADC_SCINT_remainAfterCut_run_0013	9.87	0.48	0.44
	run_0013_GS	9.23	0.04	0.42
	run_0013_opt4	10.48	0.06	0.35
	run_0013_SS	10.67	0.06	0.34
	run_0013_WVI	7.82	0.04	0.50
	run_0013_lowepphysics	8.39	0.04	0.47
	run_0013_penelope	10.84	0.06	0.34
E_e = 1.4 MeV, θ = 40°	hADC_SCINT_remainAfterCut_run_0031	17.14	1.40	1.14
	run_0031_GS	13.75	0.05	1.38
	run_0031_opt4	15.14	0.06	1.20
	run_0031_SS	15.12	0.06	1.20
	run_0031_WVI	11.93	0.04	1.62
	run_0031_lowepphysics	12.89	0.05	1.50
	run_0031_penelope	15.23	0.06	1.19

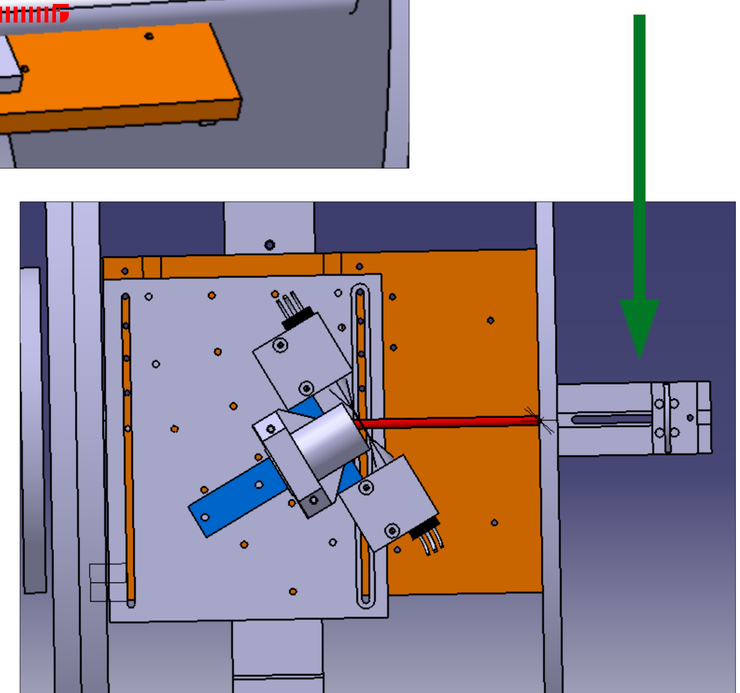
β-backscattering tests @ new set-up

A second dedicated set-up to study the electron backscattering has been conceived:

2







β-backscattering tests @ new set-up

Data taking completed, energy calibration done, G4 simulations performed
Started data analysis and quantitative comparison to Geant4 simulations