Weak Interaction Studies with ^{32}Ar Decay

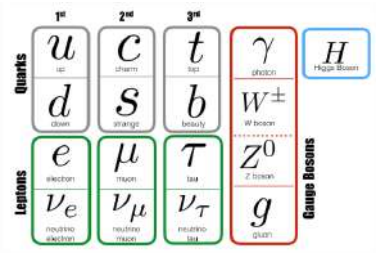
Federica Vera Cresto

on behalf of the WISArD Collaboration

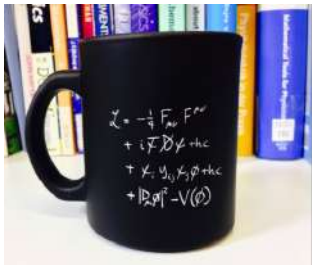
Contents

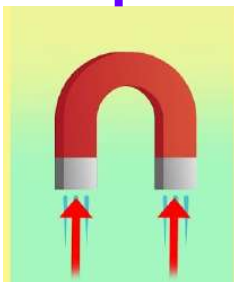
- Motivation
- The WISArD experiment at ISOLDE/CERN
- Experimental campaign @ October 2021
- Preliminary results
- Outlook

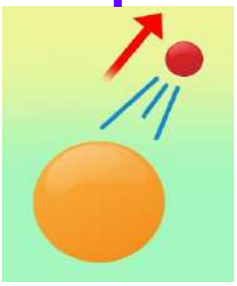
Introduction – SM and beyond



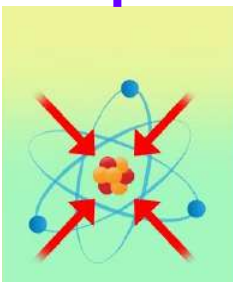
Standard Model (SM)







Electroweak interaction



Strong interaction

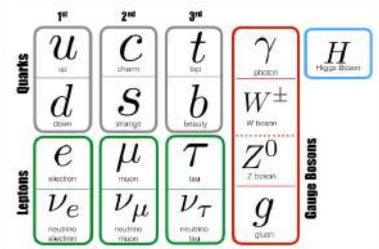
Gravity

Limits →

Gravity?
Dark matter/energy?
Neutrino masses?
Why three families of quarks/leptons?
Are they really the most fundamental particles?
...

→ **Need for further tests of SM**
→ search for possible existence of New Physics (NP) beyond the SM

Introduction – SM and beyond



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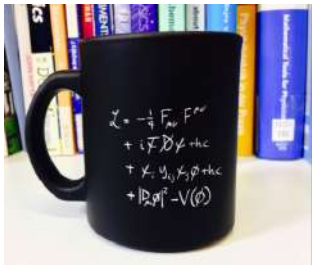

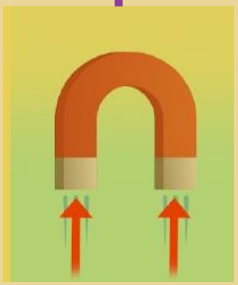

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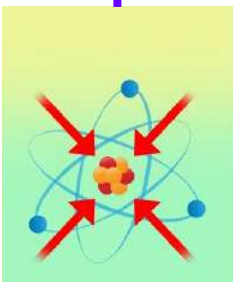

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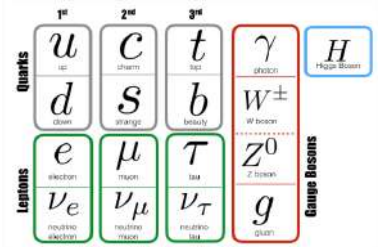

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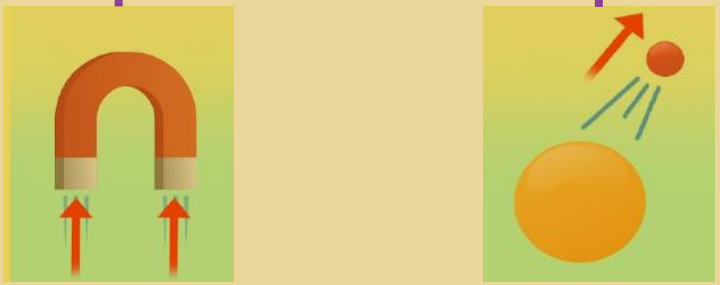


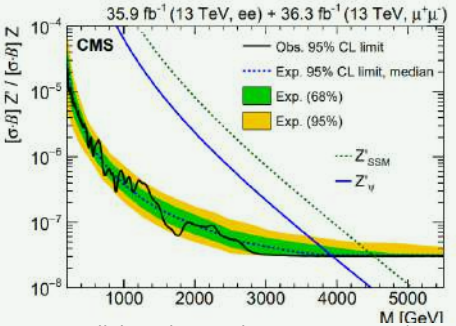
Electroweak interaction

Tests of the SM
in the electroweak sector
can be performed via
complementary approaches

Energy frontier

- LHC …

direct search for possible
new gauge bosons

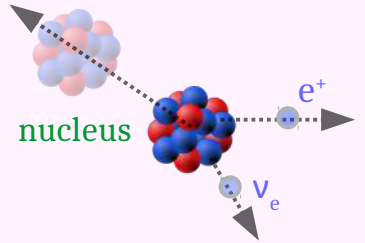


CMS Collaboration, arXiv:1803.06292v2 (2018)

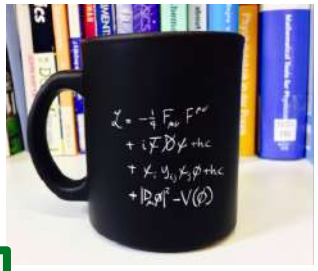
Precision frontier

- Nuclear beta decay

constraints on exotic coupling constants (C_i)



$$C_i \propto \frac{M_W^2}{M_{new}^2}$$



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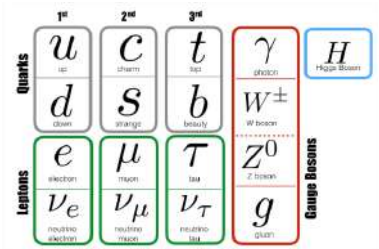

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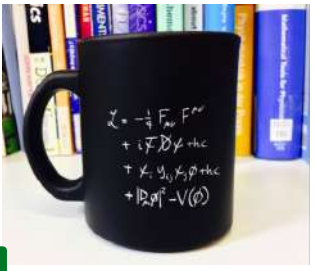

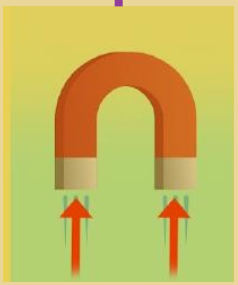

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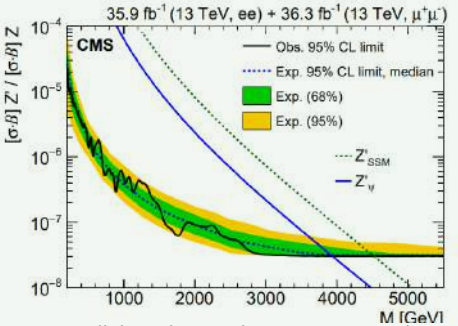

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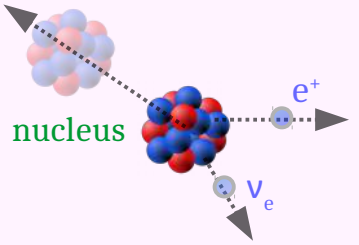


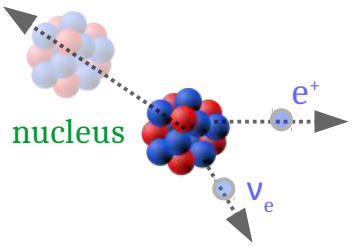
Tests of the SM in the electroweak sector can be performed via complementary approaches

The Standard Model of weak interaction

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

Hadronic terms **Leptonic terms**

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



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

STANDARD MODEL: V-A theory

- Only vector and axial-vector contributions: $C_V = 1$, $C_A = -1.27$ $\quad C_S = C_S' = C_T = C_T' = 0$
- 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?

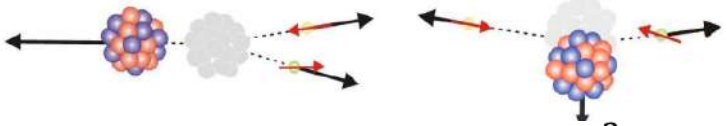
The Standard Model of weak interaction (2)

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

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

Phase space factor | **β-ν angular correlation coefficient** | **Fierz coefficient (= 0 in SM)**

Pure Fermi transitions (s = 0)



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

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

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

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

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

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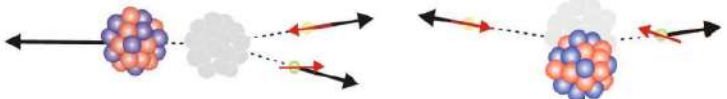

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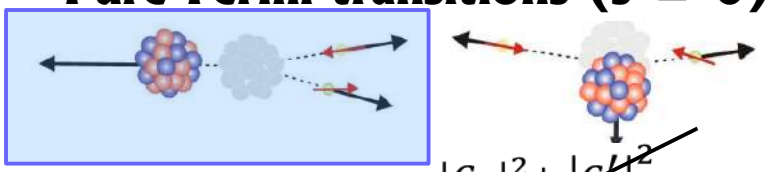

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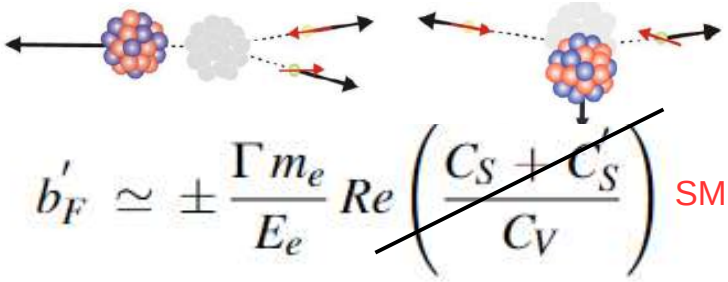

$$b'_F \simeq \pm \frac{\Gamma m_e}{E_e} Re\left(\frac{C_S + C'_S}{C_V} \right)$$ SM

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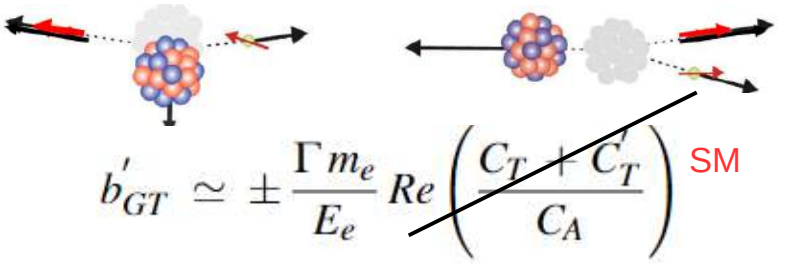

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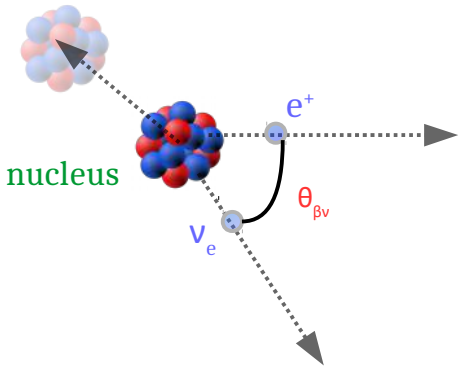

a coefficient determined from experiment

↓

$\theta_{\beta\nu}$ 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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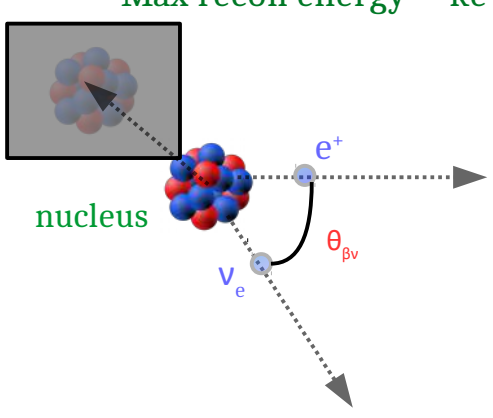

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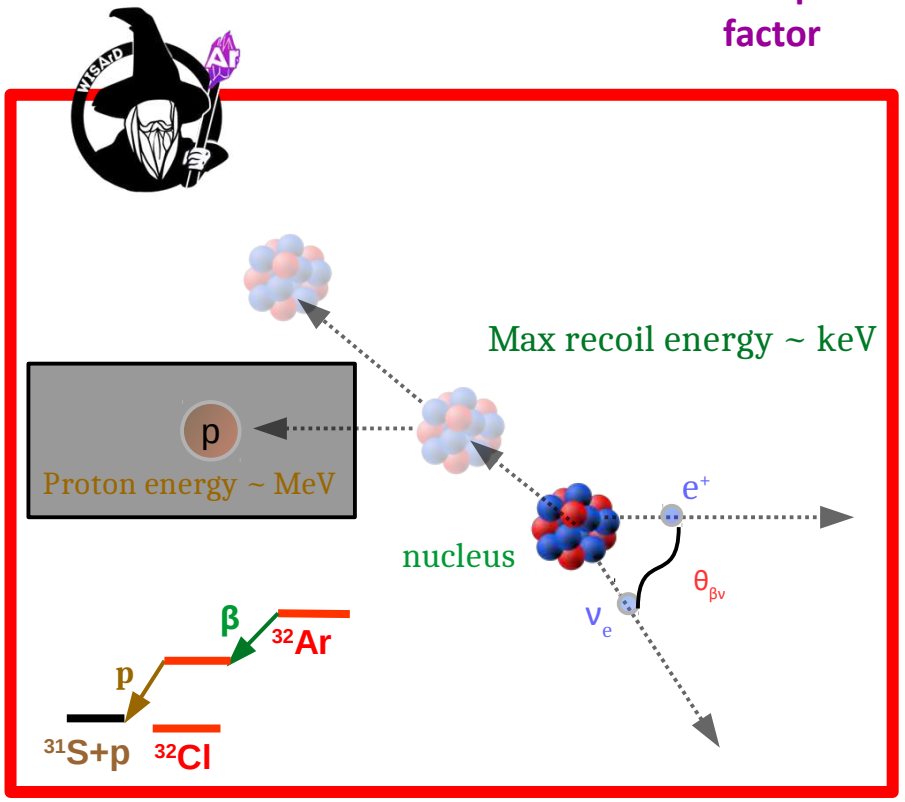

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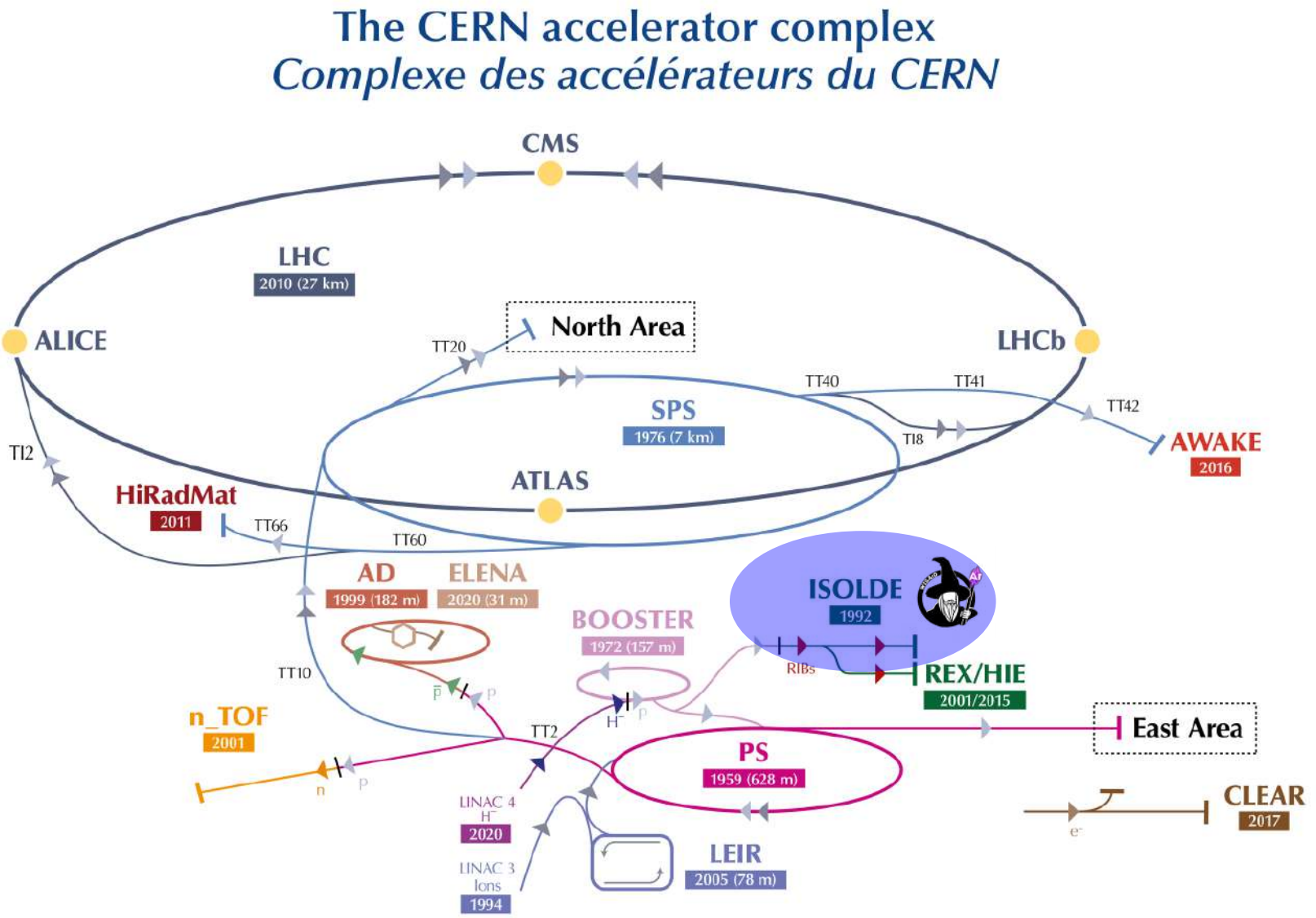
WISArD experimental campaign – October 2021



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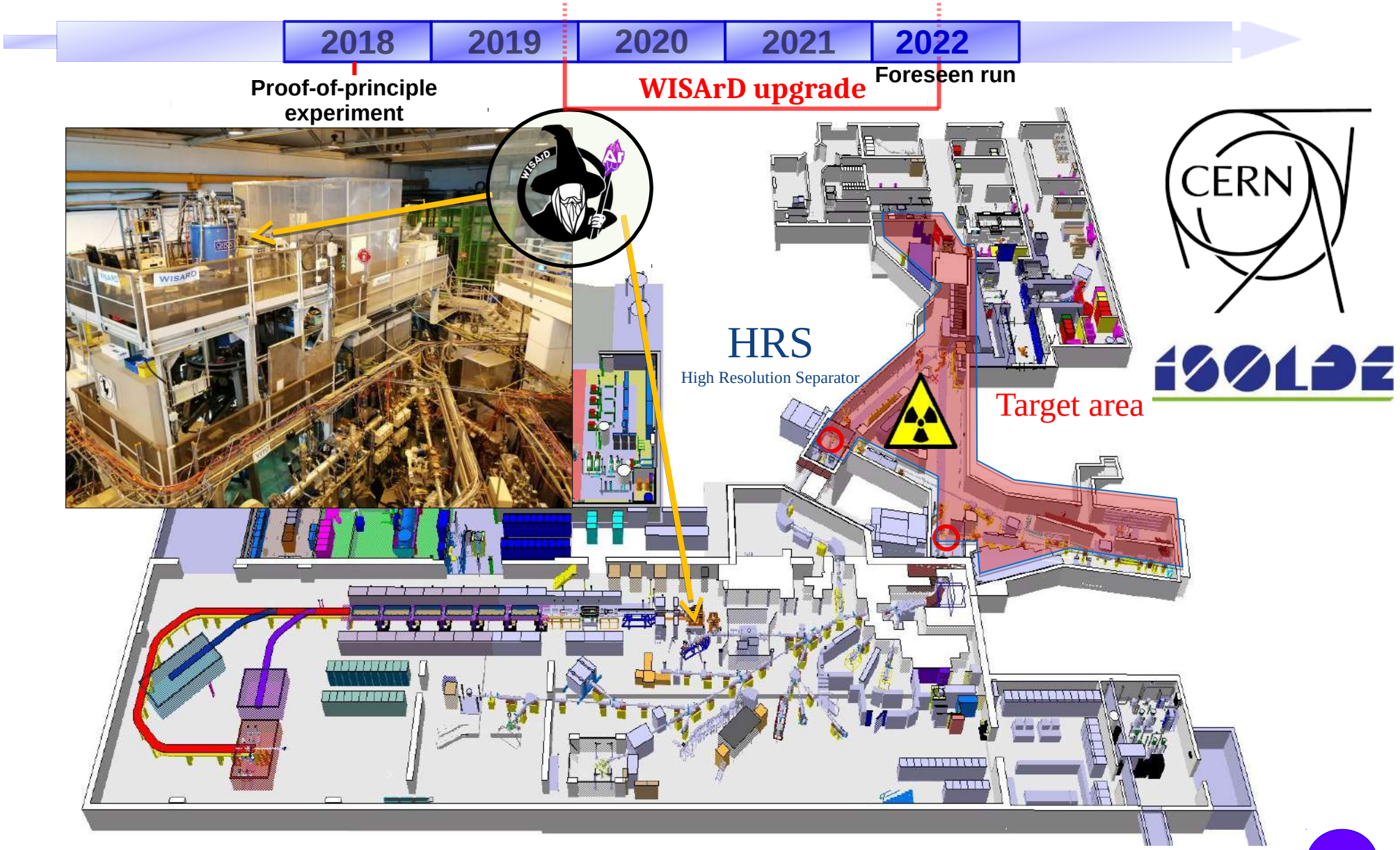
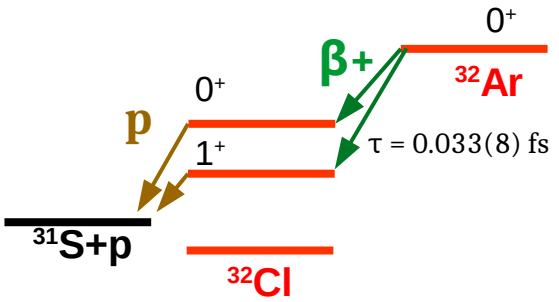


María J G Borge and Klaus Blaum, J. Phys. G: Nucl. Part. Phys. 45 (2018) 010301

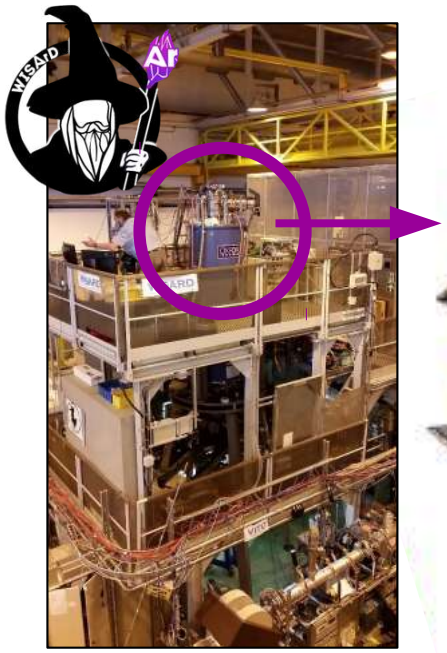
WISArD – Weak Interaction Studies with ^{32}Ar Decay

EXPERIMENTALLY

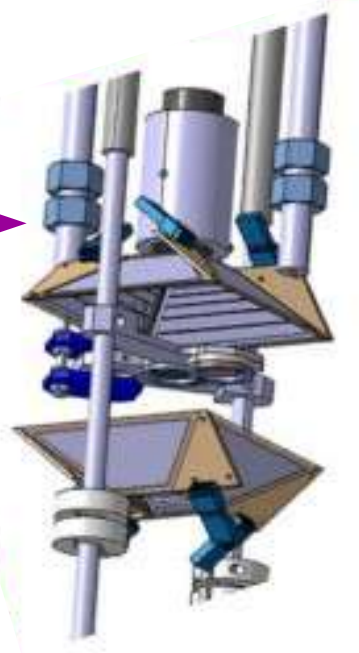
- ^{32}Ar nuclei initially at rest in the catcher foil
- **β^+- decay**
  → e^+ emitted → B field → plastic scintillator
- **Nucleus recoils and emits a proton** immediately after
  → p emitted → 8 Si detectors (symmetrical to the catcher foil)
- **Detection of p in coincidence with the e^+**



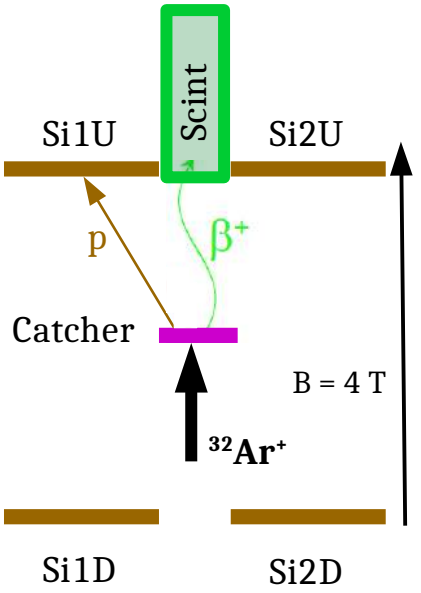
^{32}Ar simplified decay scheme



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

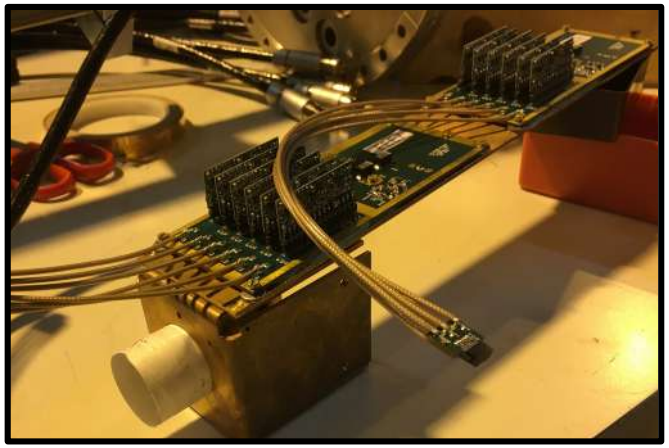
$$\tilde{a}_F = 1.007(32)_{(stat)}(25)_{(sys)}$$
$$\tilde{a}_{GT} = -0.222(86)_{(stat)}(16)_{(sys)}$$

‰ precision to reach

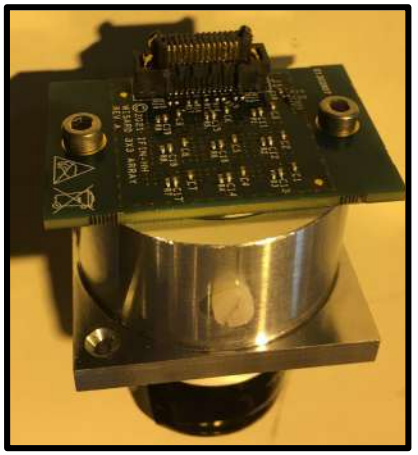
WISArD – experimental set-up

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

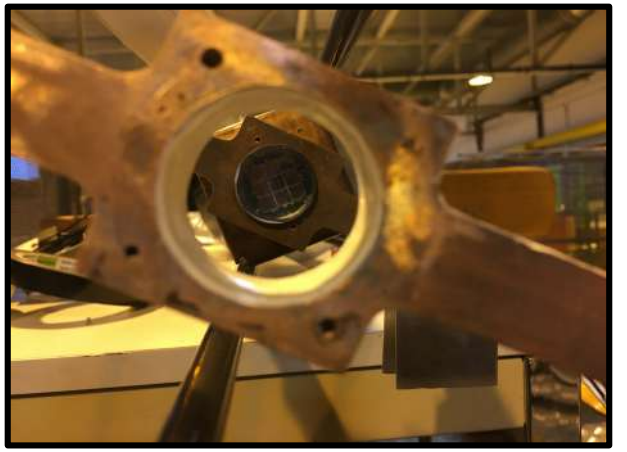
- significantly **improvement in beam transmission** through WISArD beamline (from ~15% up to ~90% in 2021)
- completely new detection set-up (**SiPMs** + silicon detectors) installed in Sept. 2021



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:

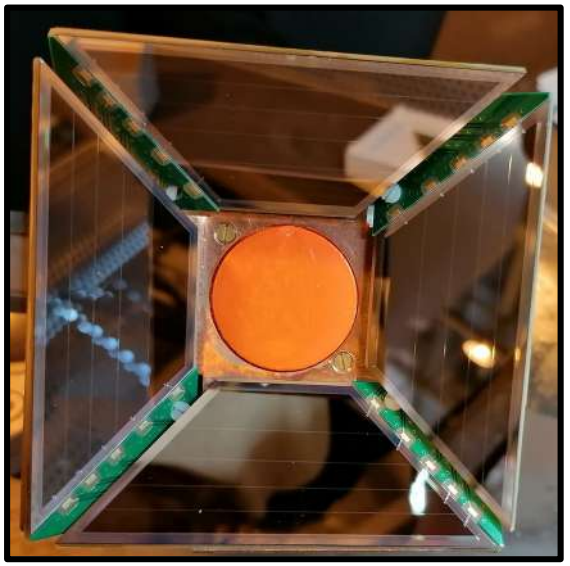
- Plastic scintillator (r=1.5 cm, L=5 cm) + matrix 3x3 Onsemi J-Series SiPMs sensors (IFIN)
- FASTER DAQ trigger @ 3 cells fired at the same time

  → 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

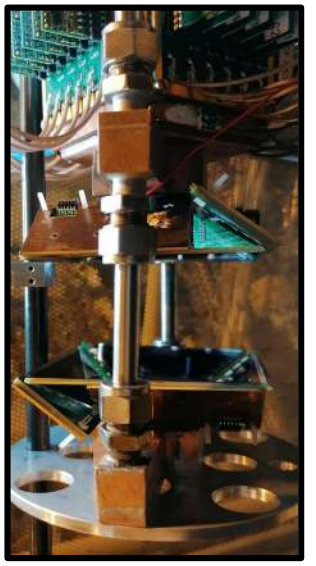
WISArD – experimental set-up

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

- significantly **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



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

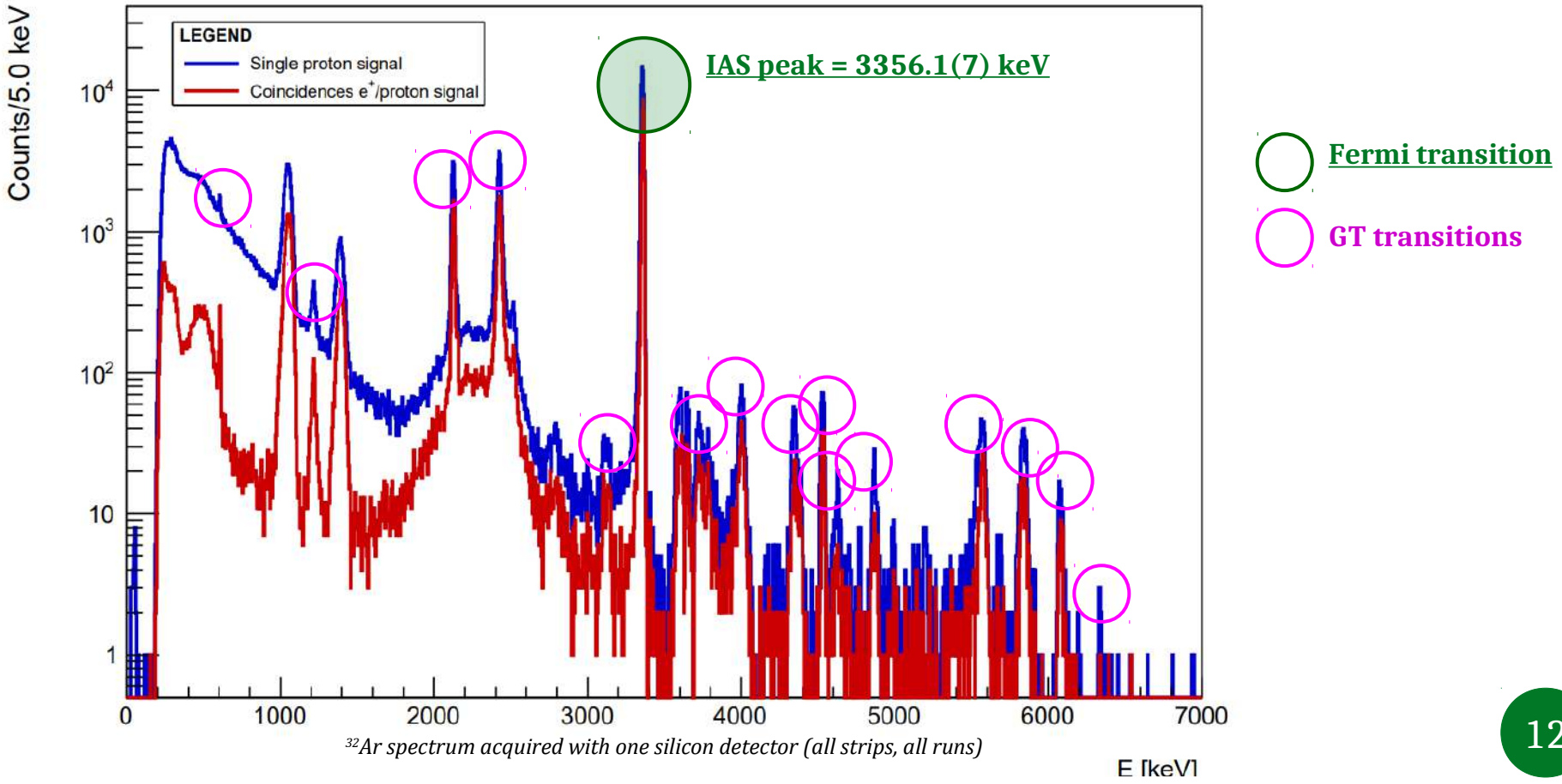
WISArD Oct. 2021 – preliminary results

- 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 => x2.1) 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 6 strips 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)



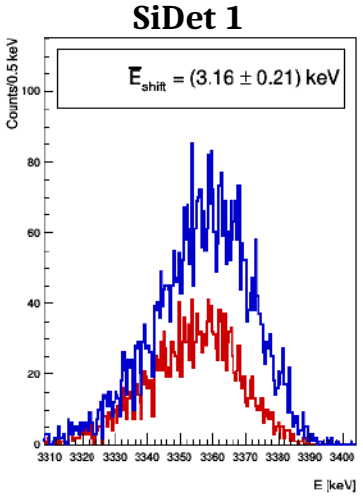
^{32}Ar spectrum acquired with one silicon detector (all strips, all runs)

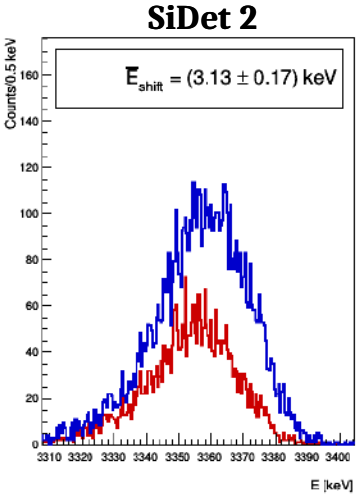
Proton energies can be found in B. Blank et al., arXiv:2101.06422 [nucl-ex] (2021)

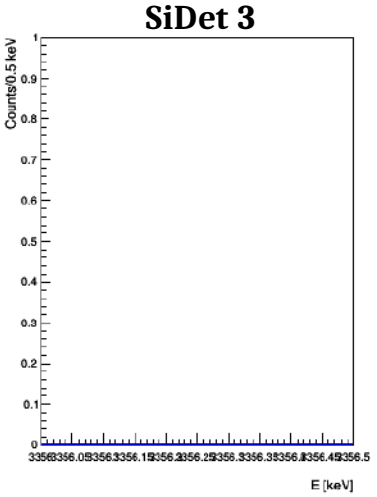
WISArD Oct. 2021 – preliminary results

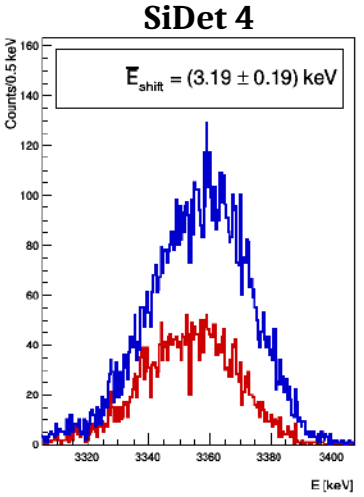
Proton energy shifts + statistical uncertainties determined for all SiDets

Upper detectors



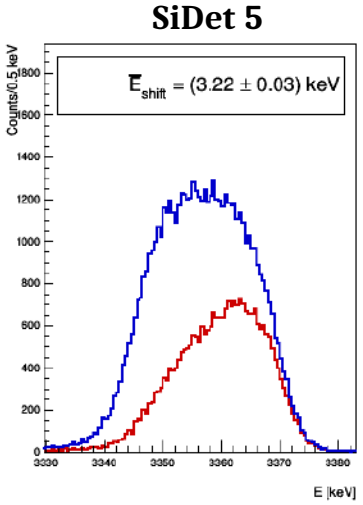


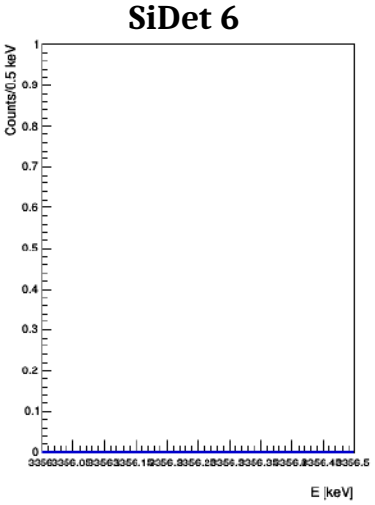


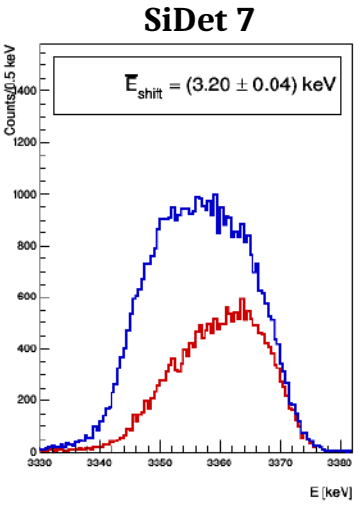


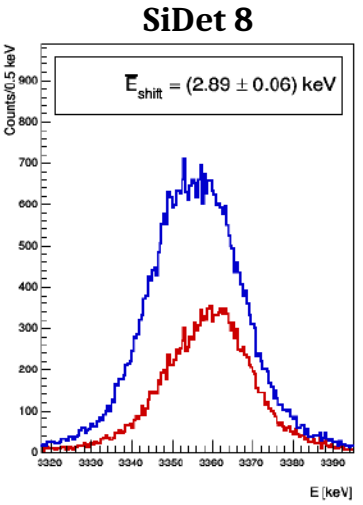
Shift towards lower energies

Lower detectors









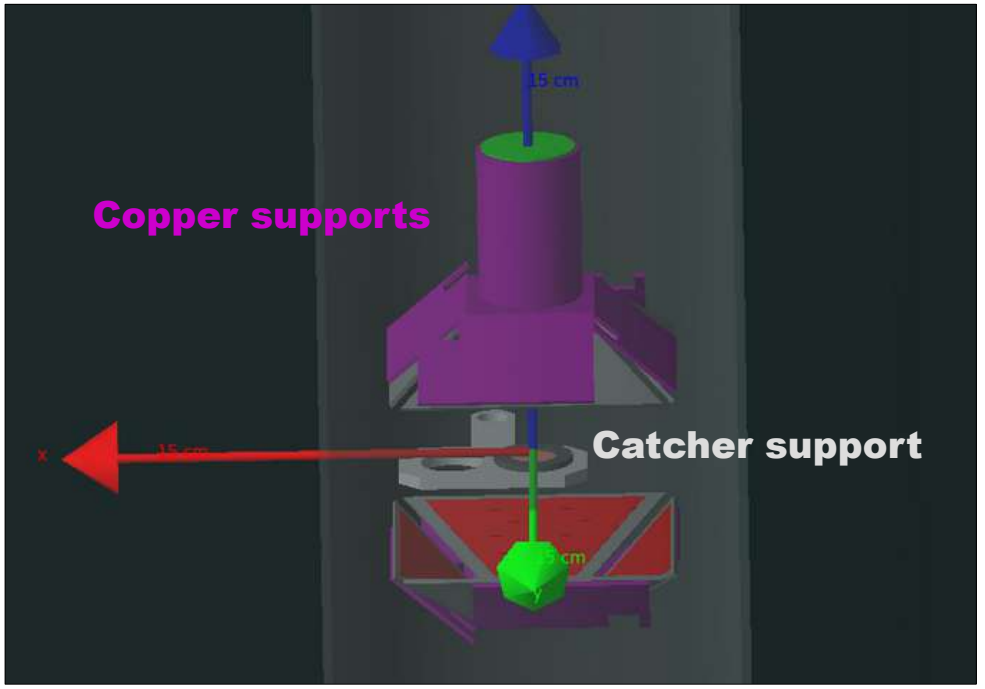
Shift towards higher energies

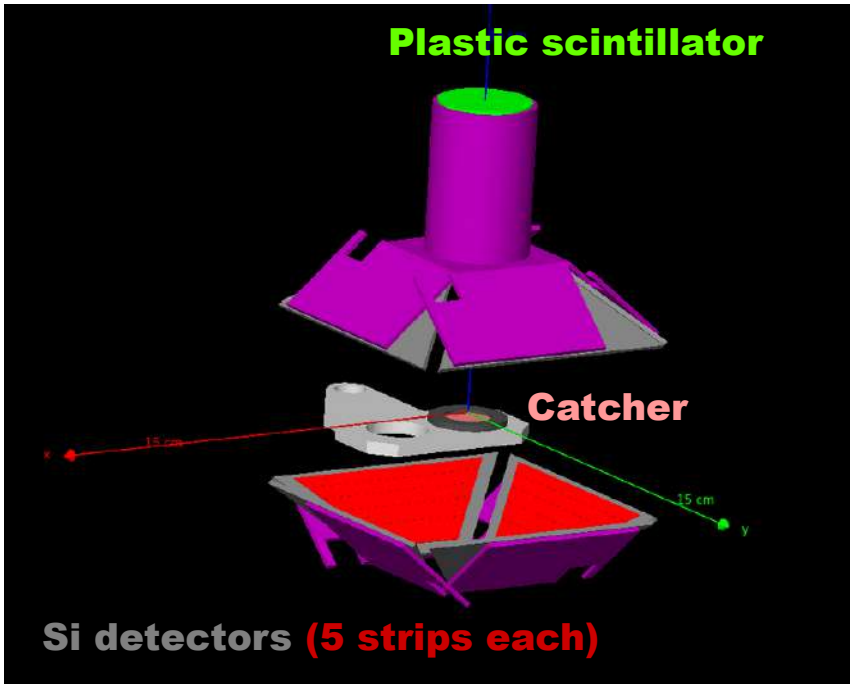
New WISArD Geant4 simulations

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

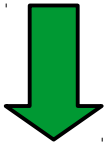
→ implemented possibility to simulate the real WISArD magnetic field (measured in February 2021) as an alternative to the classic numerical algorithms

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

(1) Collaboration with Texas A&M University

WISArD – outlook

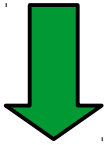
- Despite the short beamtime allocated, problems in beam production and transmission



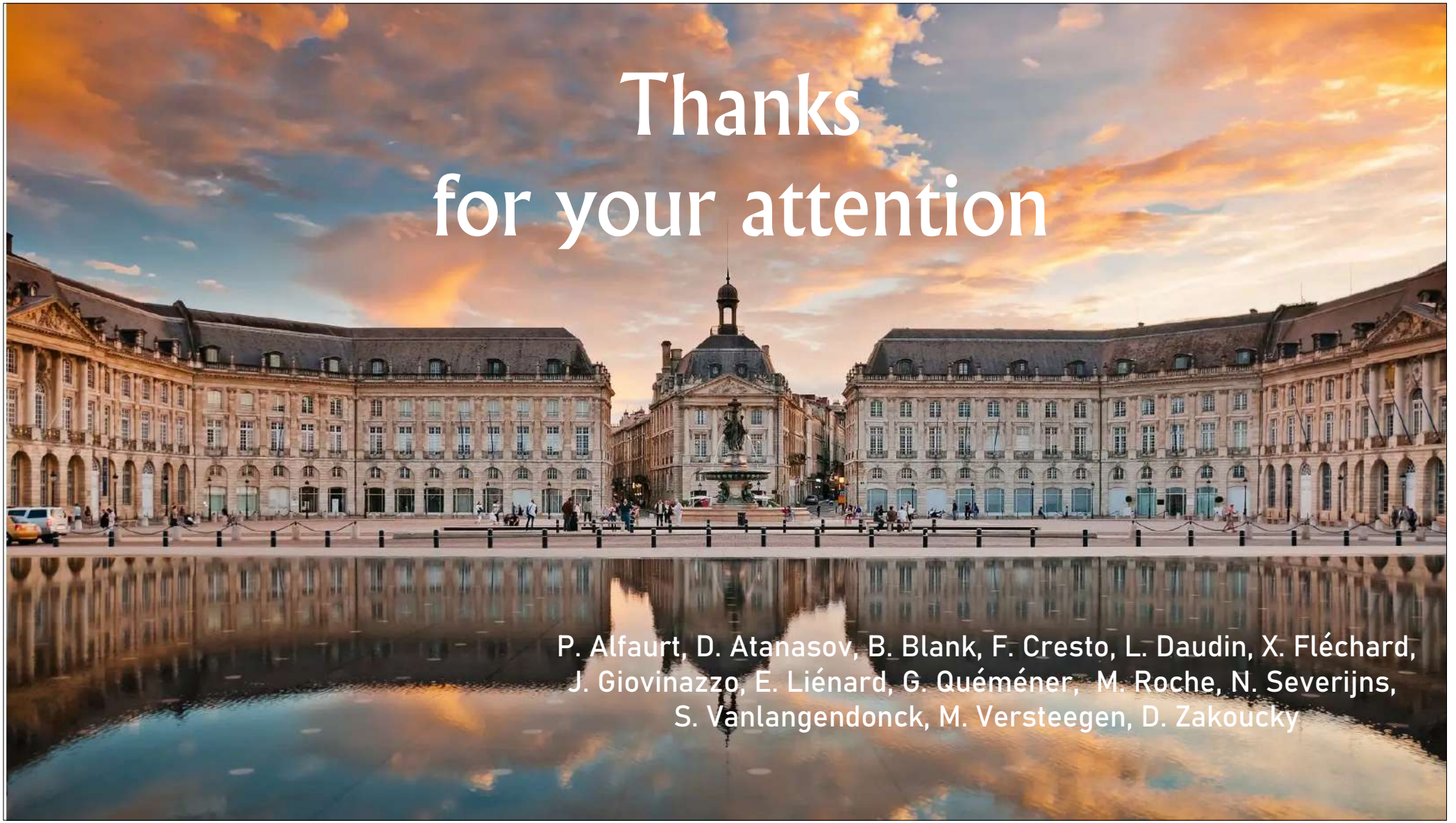
Completely new experimental set-up:

- 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 ã 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. Roche, N. Severijns,
S. Vanlangendonck, M. Versteegen, D. Zakoucky