Decay Station Workshop

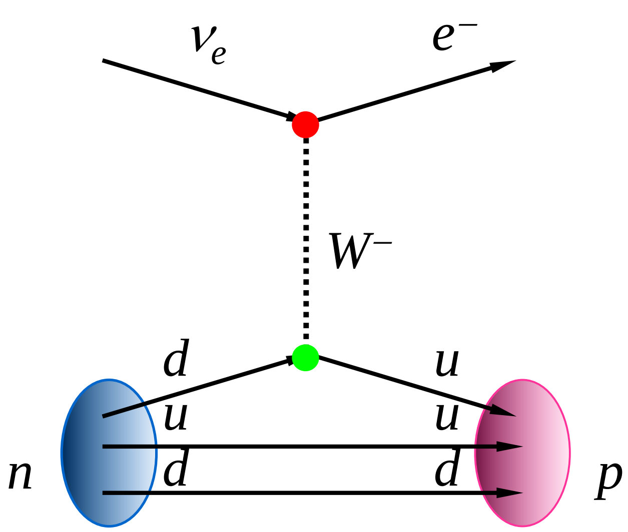
Decay studies for searches of New Physics beyond the Standard Model

Oscar Naviliat-Cuncic
National Superconducting Cyclotron Laboratory
and Department of Physics and Astronomy
Michigan State University

NSCL NSF

MICHIGAN STATE UNIVERSITY

Nuclear beta decay



- At the quark-lepton level is described by *Vector boson exchange with maximal parity violation*.

- Is this all? Are there other bosons? (masses, couplings)

- W_L boson exchange gives rise to phenomenological *V* and *A* couplings (*V-A theory*)

Phenomenology of semi-leptonic processes

Effective Field Theory approach

M. Gonzalez-Alonso, arXiv:1209.0689v1
T. Bhattacharya et al., PRD **85** (2012) 054512
V. Cirigliano et al., Prog. Part. Nucl. Phys. **71** (2013) 93

Assuming the energy scale of new physics (NP) to be at significantly larger energies than those accessible at the LHC, the EFT approach enables to compare constraints from low energy and high energy experiments

$$\frac{1}{M_{NP}^2 + q^2} \rightarrow \frac{1}{M_{NP}^2}$$

Exotic *Scalar* and *Tensor* couplings

Low energy/high energy connection

$$C_S = g_S \varepsilon_S$$
$$C_T = g_T \varepsilon_T$$

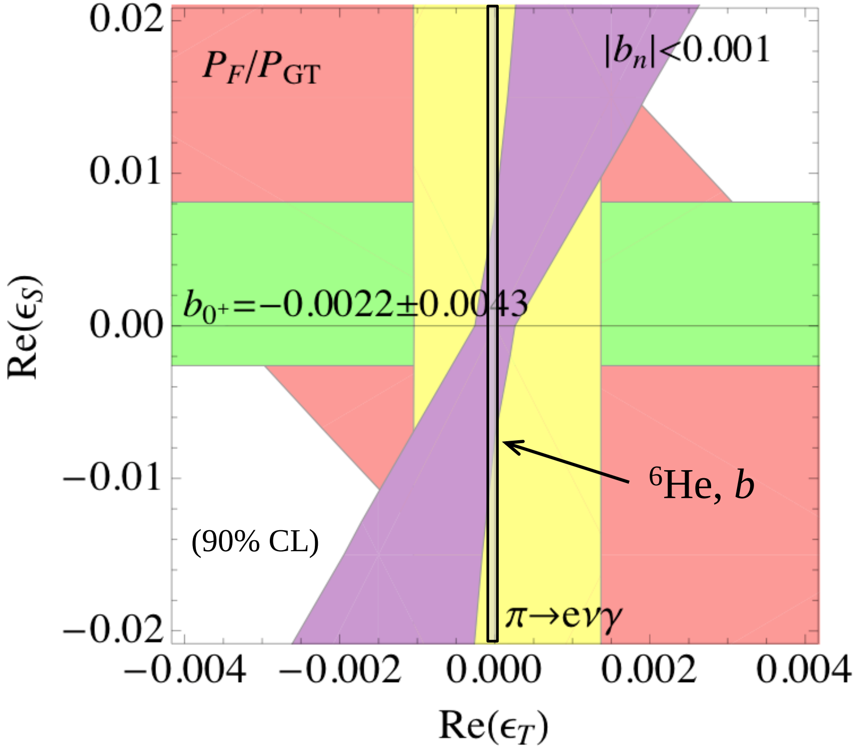
The g's are calculated within QCD and are known to ~10% accuracy

Complementarity with HEP

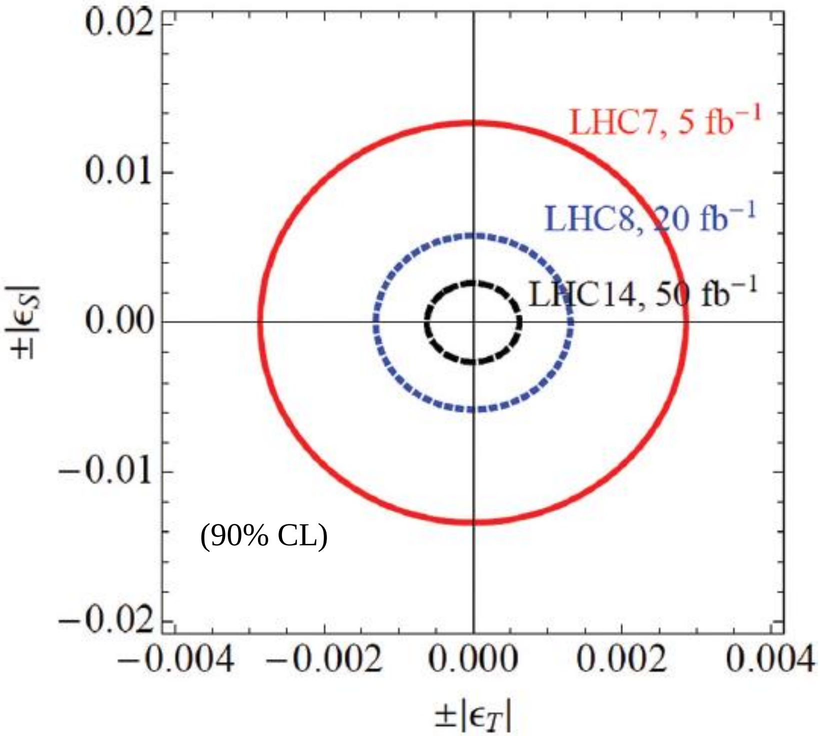
Constraints involving left-handed neutrinos

ONC and M. Gonzalez-Alonso,
Ann. Phys. (Berlin) **525** (2013) 600

Low energy



channel: $pp \to e\,\nu + X$



Updated in
N. Severins, ONC and M. Gonzalez-Alonso,
Prog. Part. Nucl. Phys.

Phenomenology guidance

• Is there any niche left by the LHC to constraint new physics?

• What is the complementarity between low- and high energy searches and which is the required precision for low energy experiments?

M. Gonzalez-Alonso, arXiv:1209.0689v1
T. Bhattacharya et al., PRD **85** (2012) 054512
V. Cirigliano, S. Gardner, B.R, Holstein, Prog. Part. Nucl. Phys. **71** (2013) 93

$$\varepsilon_T \approx 10^{-4}$$

(Current limits from beta decay are at the level $2\text{–}4\times10^{-3}$)

• Largest sensitivity obtained by observables which are linear in the couplings.

Observable and kinematic sensitivity

- The Fierz term in the β spectrum

$$N(W) = pW(W_0 - W)^2 Q(W)\left(1 + \frac{m}{W} b_{GT}\right) S_R(W)$$

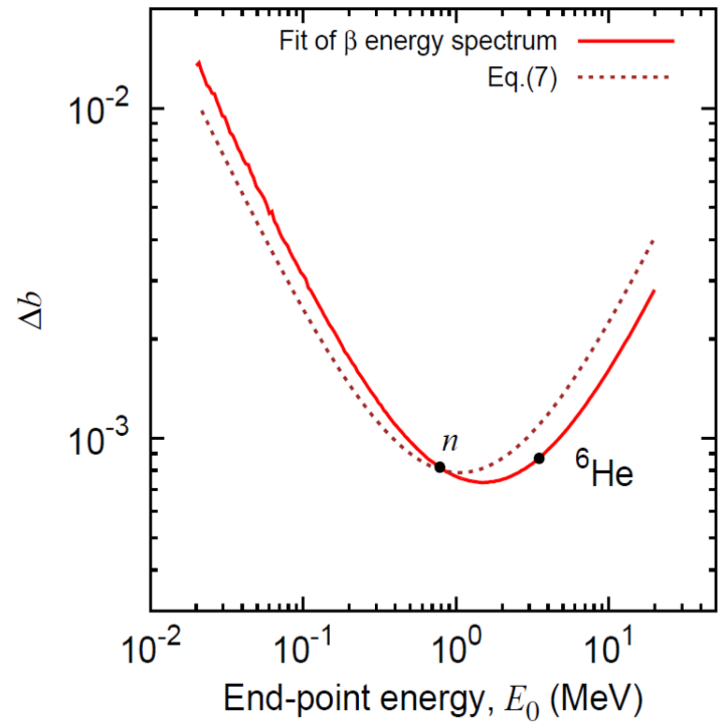
- The Fierz term is linear in the couplings

$$b_{GT} \propto (C_T C_A + C_T' C_A')$$

$$b_{GT} \approx 8\varepsilon_T$$

M. Gonzalez-Alonso and O. N.-C
Phys. Rev. C **94** (2016) 035503

Stat error for 10^8 events

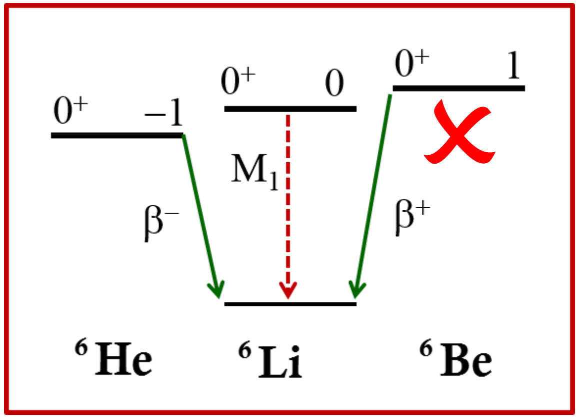


Kinematic sensitivity (^{6}He comparable to neutron decay)

Weak magnetism in ^{6}He decay

- The WM form factor, b_{WM}, can be accurately calculated using the *strong form of CVC* applied to an isospin triplet.

- The WM contributes to all terms of the spectrum shape factor



$$S_R(W) = \left(1 + C_0 + C_1 W + C_{-1}/W\right)$$

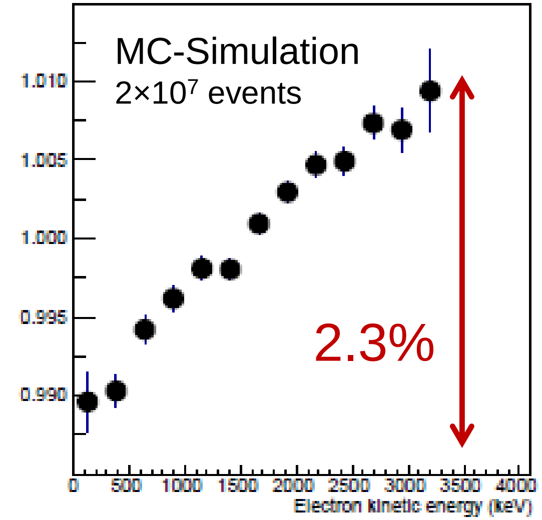
$$C_0 = \frac{2}{3}\frac{W_0}{M}\left(1 + \frac{b_{WM}}{c}\right) = -1.234(14)\ \%$$

$$C_1 = \frac{2}{3M}\left(5 + 2\frac{b_{WM}}{c}\right) = 0.6502(69)\ \%/\mathrm{MeV}$$

$$C_{-1} = -\frac{2m^2}{3M}\left(1 + \frac{b_{WM}}{c}\right) = -0.0802(9)\ \% \times \mathrm{MeV}$$

$$b_{WM}^{SM} = 68.22 \pm 0.79 \qquad c = g_A\left|M_{GT}\right|$$

Effect on the ^{6}He spectrum shape

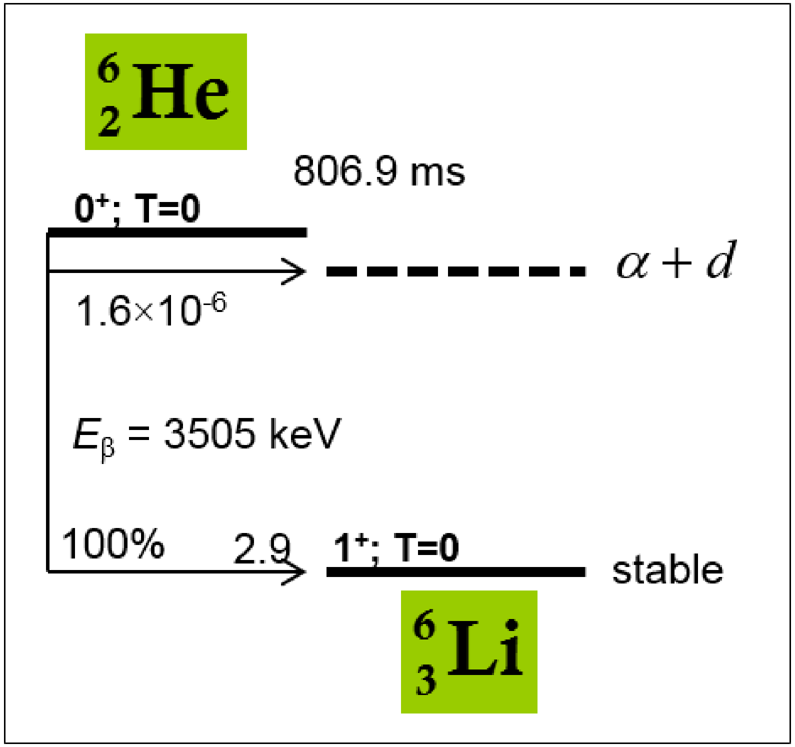


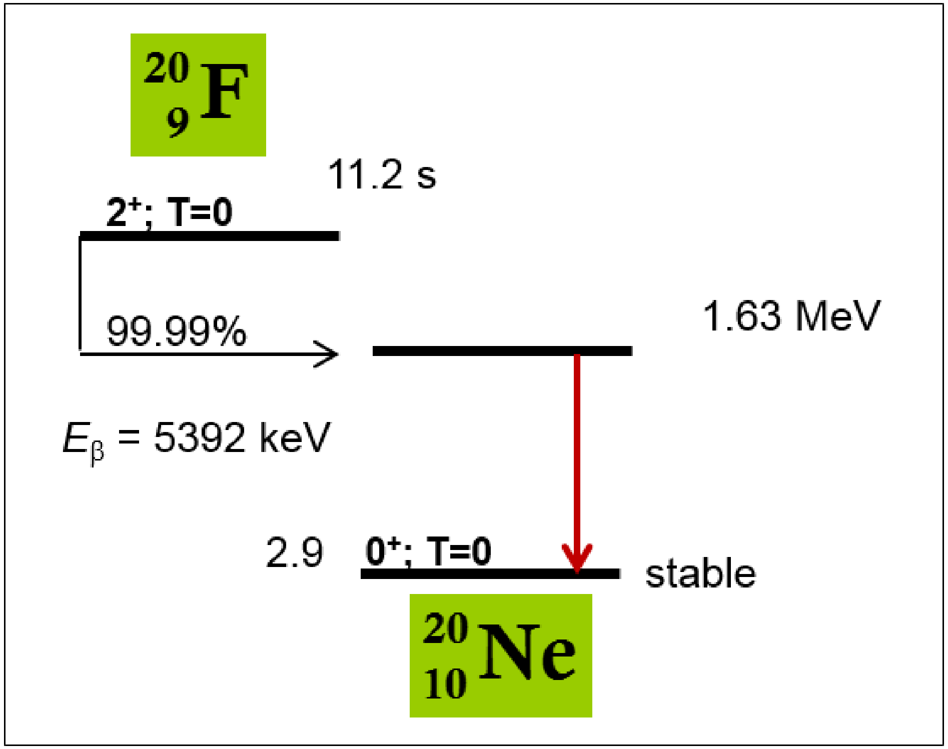
Our first goal

MICHIGAN STATE UNIVERSITY

Selection of candidates

Gamow-Teller decays in isospin triplets



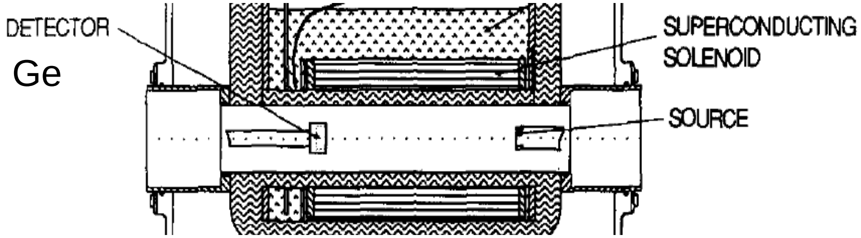


Hadronic effects (*weak magnetism*) are well under control.
(Serve also as a sensitivity test of the experimental technique)

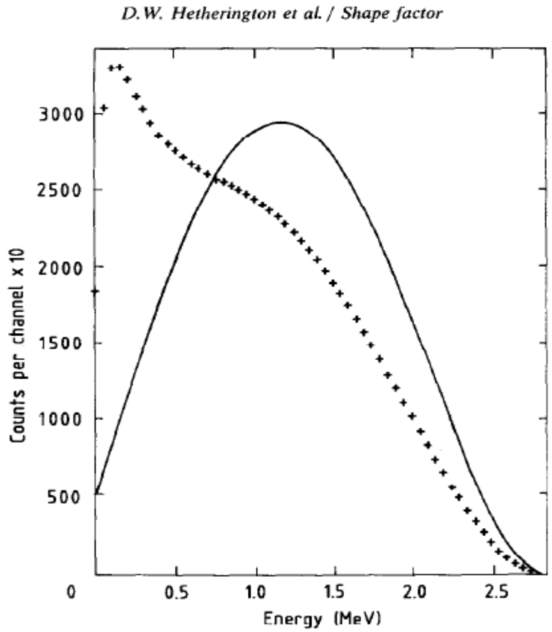
Instrumental effects in β spectra measurements

- What has been limiting such experiments so far?

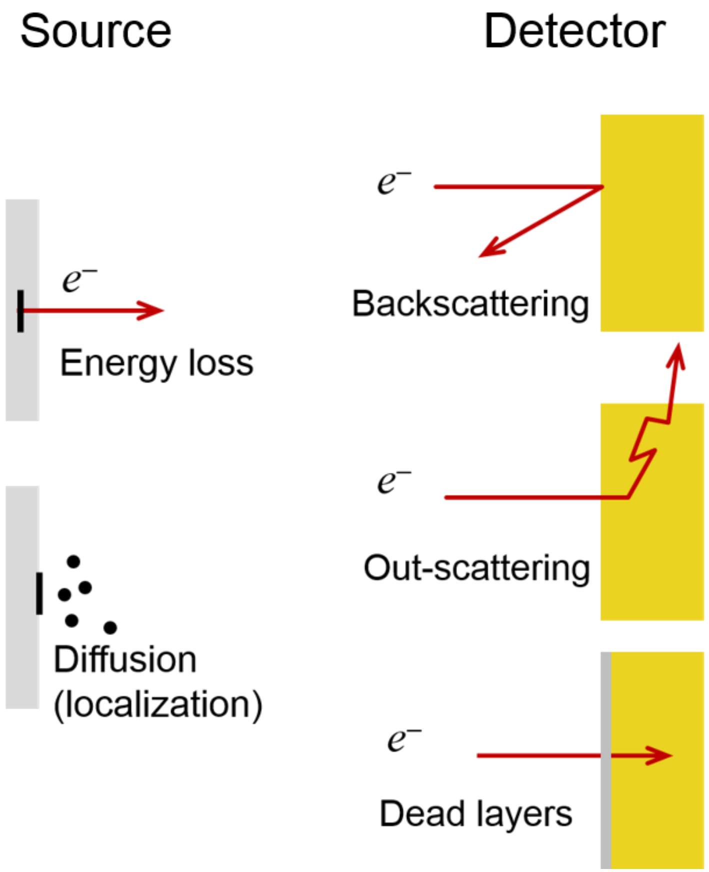
Ge



D.W. Hetherington, A. Alousi and R.M. Moore, NPA **494** (1989) 1

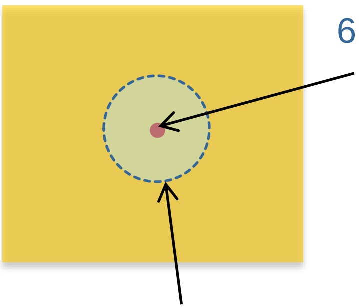


Detector response function for a measurement of the shape in ^{20}F decay



Measurement principle

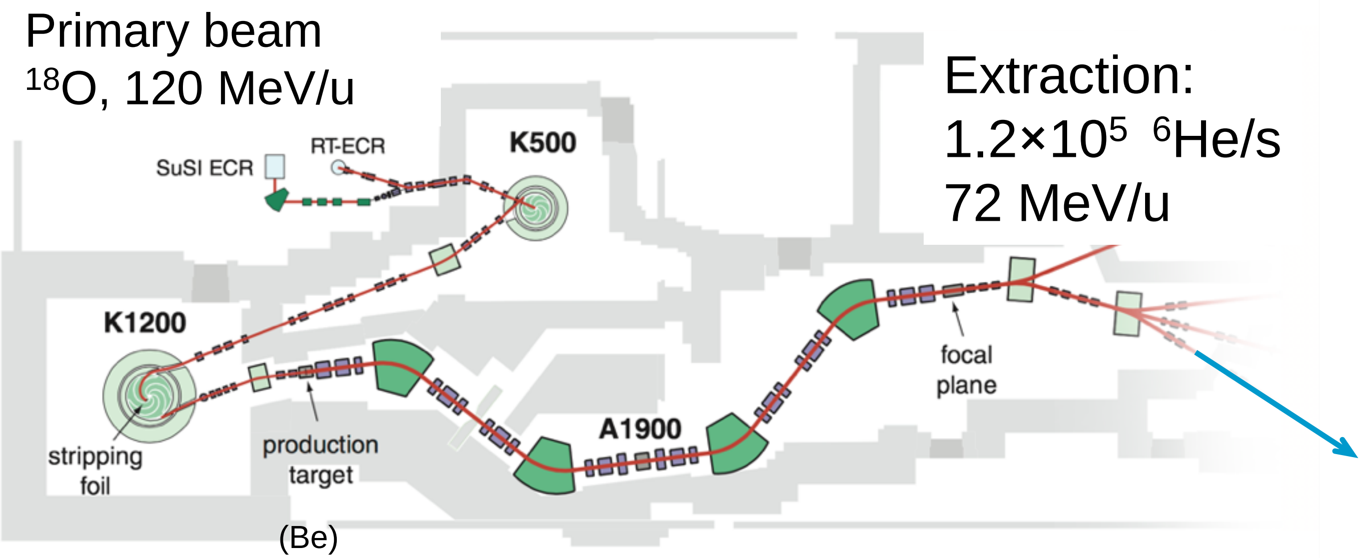
- We have eliminated all those effects using a calorimetric technique



- Requires the appropriate beam energy to implant ions inside a detector.

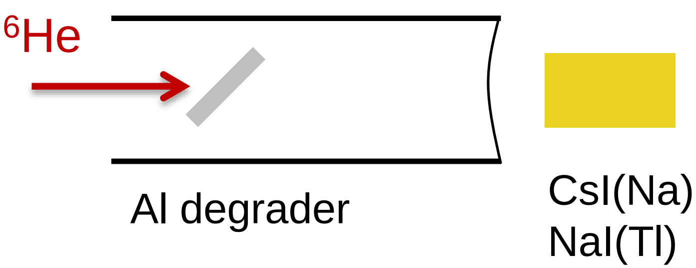
Experiment with implanted ^{6}He at the NSCL

Primary beam
^{18}O, 120 MeV/u

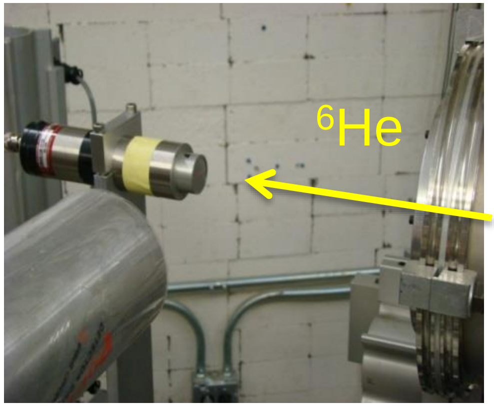


Extraction:
1.2×10^{5} ^{6}He/s
72 MeV/u

- $\Delta p/p$ = 1%
- $\Delta x \times \Delta y$ = 1.5×2 mm^2

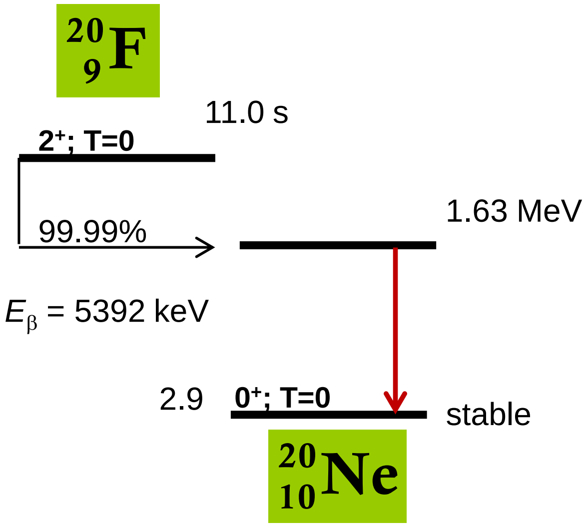


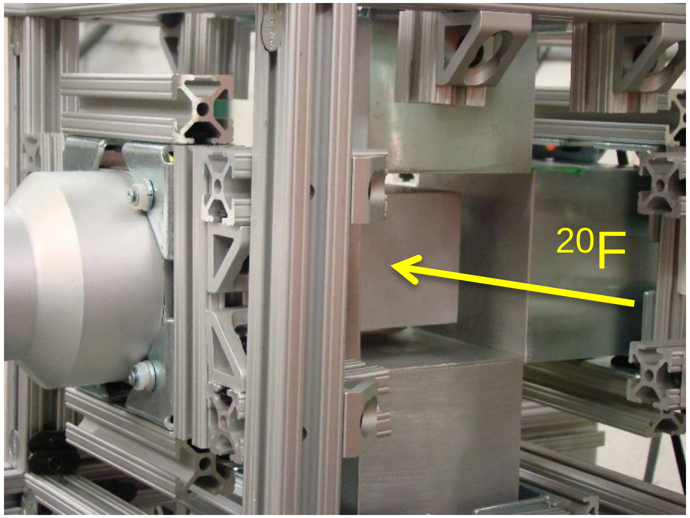
46 MeV/nucleon after degrader



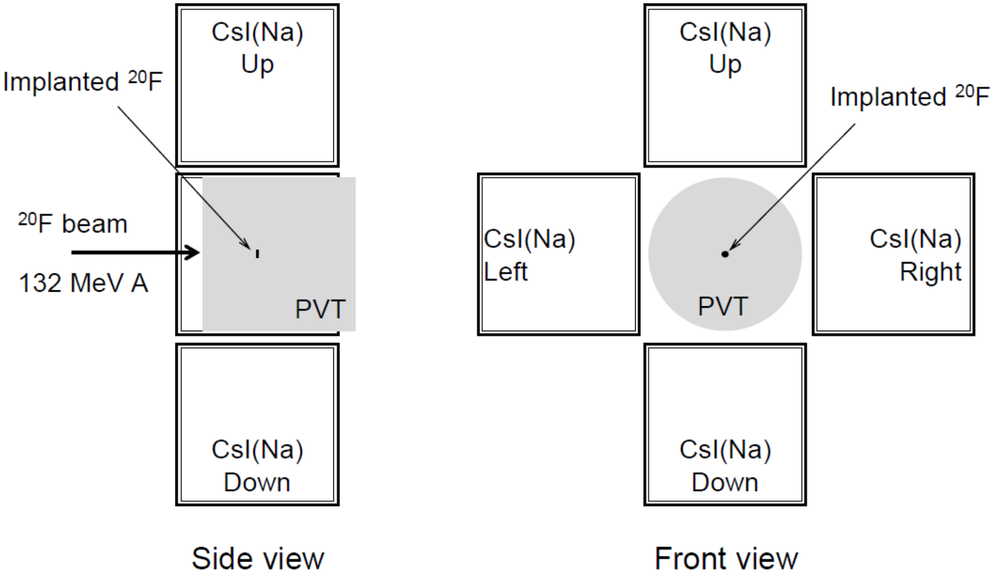
- CsI(Na) (2"×2"×5")
- NaI(Tl) (Ø3"×3")
- (Ø1"×1") CsI(Na)
- (Ø1"×1") NaI(Tl)

Experiment with implanted ^{20}F



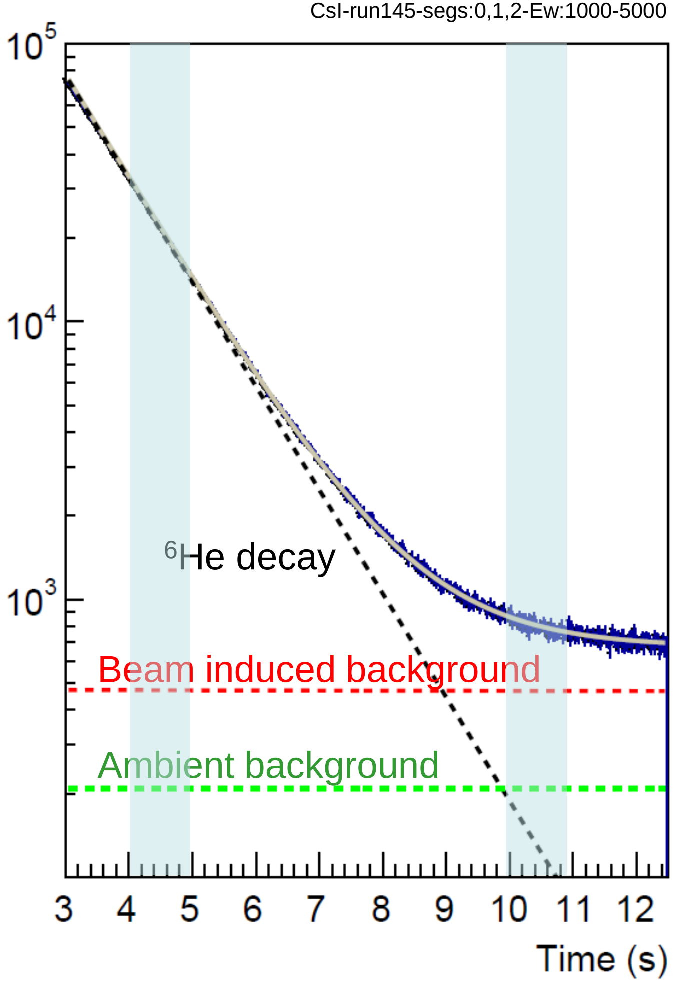


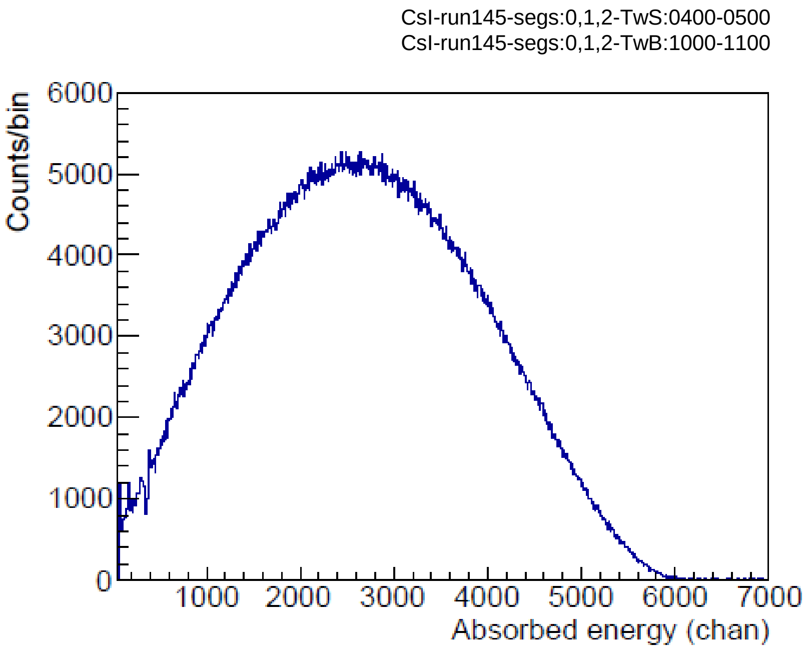
- ^{22}Ne primary beam
- ^{20}F implanted at132 MeV/nucleon
- 4 (3"×3"×3") CsI(Na) for γ
- PVT (Ø3"×3") and (2"×2"×4") CsI(Na) implantation detectors for β



Sample spectra (^{6}He)

Beam ON/OFF sequence





No traces of “short lived” beam induced background

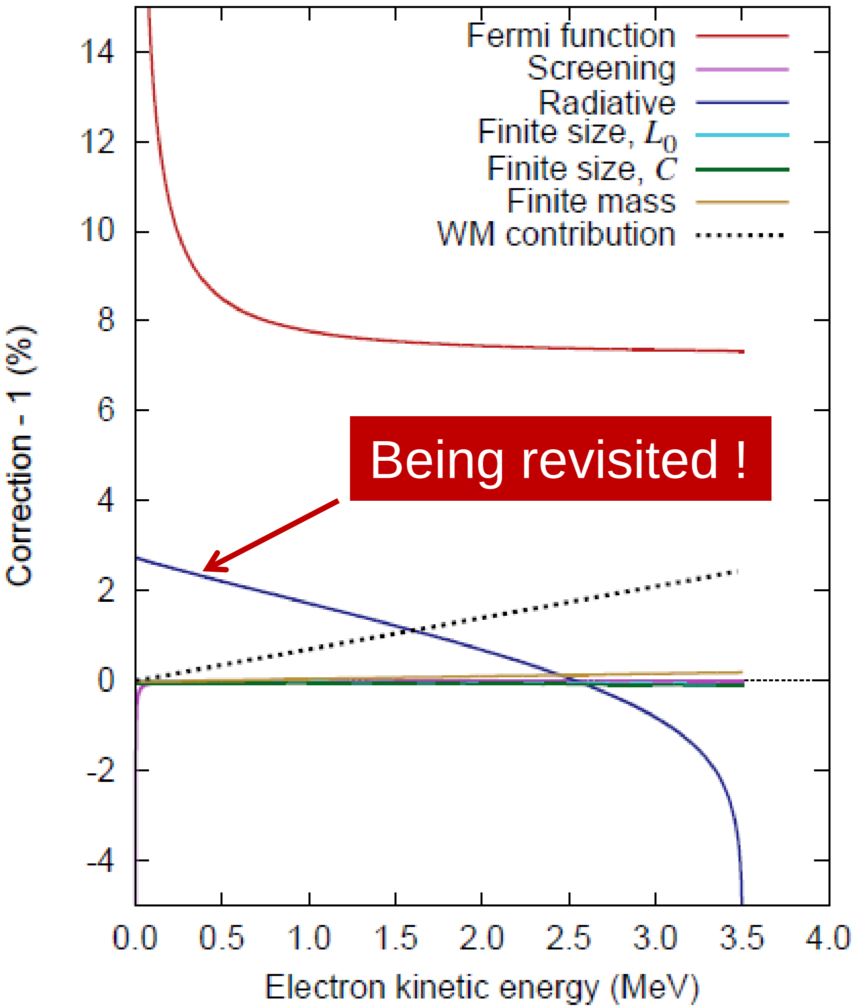
- Collected typically 10^7 events in 1 h run
- Define slices between 3.5 and 5.0 s, with:
  - 10^6 events in each spectrum
  - Rate < 20 kcps
  - S/B > 20

- ~50 spectra with CsI(Na)
- ~50 spectra with NaI(Tl)

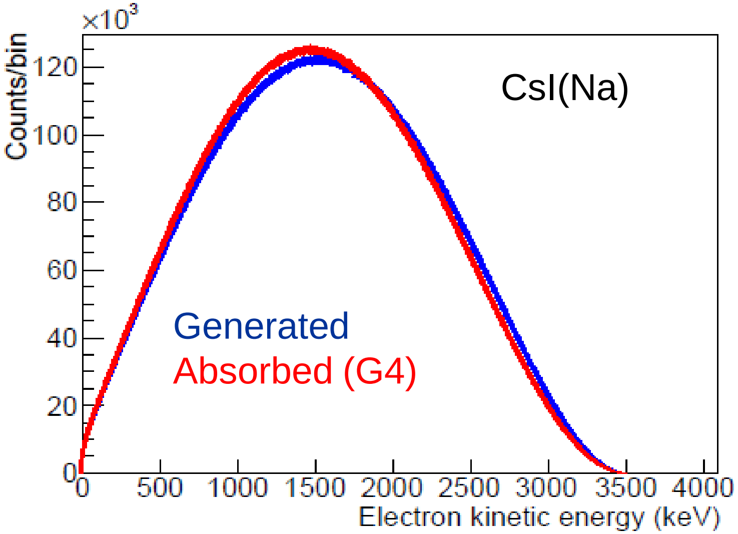
Theoretical spectrum and Geant4 simulation

- EM and radiative corrections

$$Q(W) \propto F(Z,W) \cdot L_0 \cdot C \cdot S \cdot R \cdot M$$



- The measured spectrum is distorted due to the escape of Bremsstrahlung radiation.
- The absorbed energy spectrum was determined using G4 simulations.



X. Huyan et al. NIMA 879 (2018) 134

Systematic effects

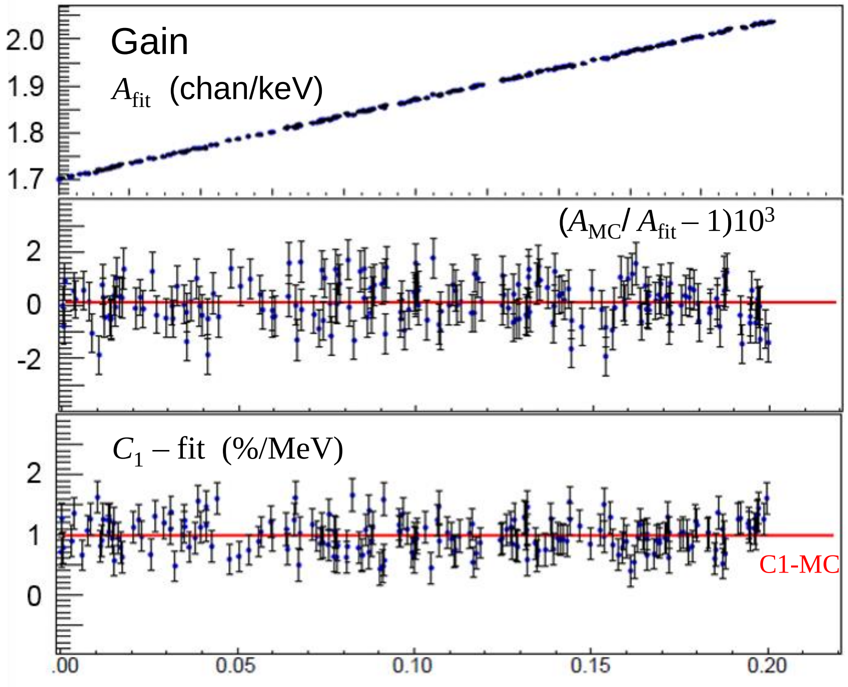
1. Theoretical corrections to beta spectrum	✓
2. Bremsstrahlung escape (Geant4)	✓
3. Detector response function (convolution)	✓
4. "Fast" pile-up (digital DAQ)	✓
5. After-glow pile-up (system gain)	✓
6. Detection system gain (calibration)	✓
7. Calibration offset (base line)	
8. Background subtraction with gain correction	✓
9. Fitting range, histogram binning	✓
10. Detection system linearity (fit model)	

Systematics: gain of detection system

- The technique relies on the extraction of the system gain for each of the ~100 measured spectra ("auto-calibration").

$$N(W) \approx P(W)(1+C_1 W)$$

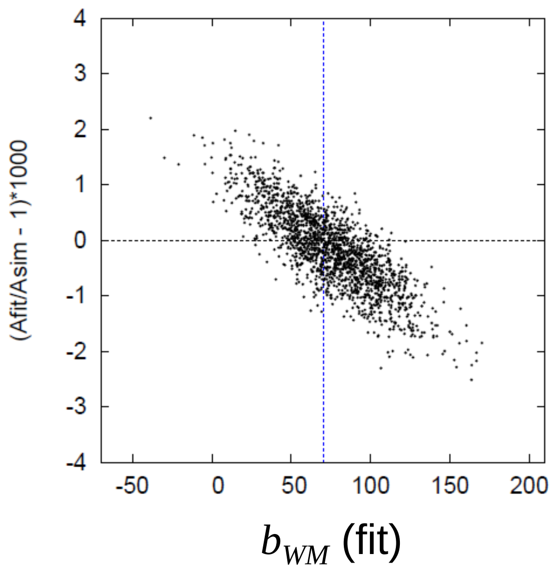
MC simulation: 10^6 events/run



Gain stretch - 1

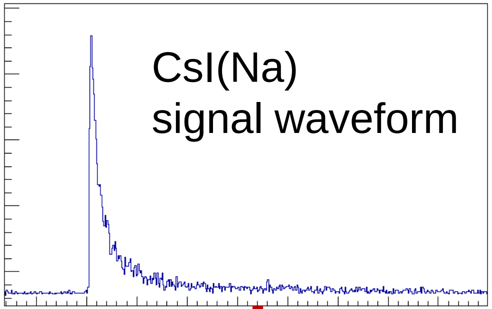
- There is a correlation between individual systematic errors made in the determination of (whatever the value of) the system gain and the form factor.

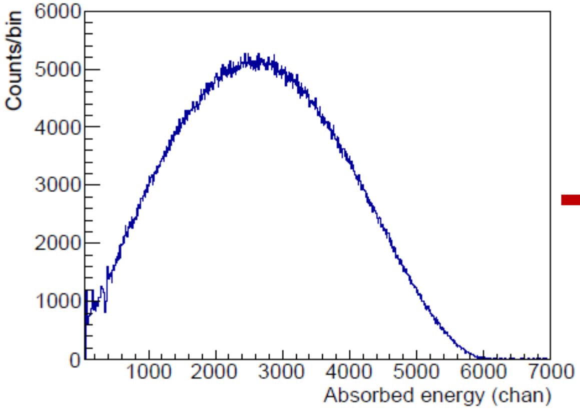
1000 MC runs



- There is no correlation between the actual value of the system gain and the form factor.

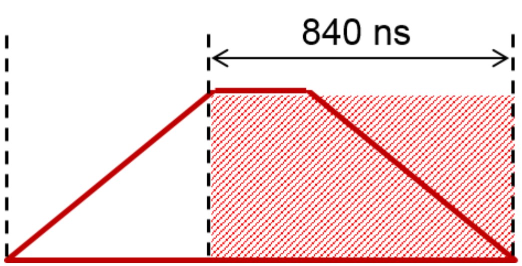
Systematics: "fast" pile-up



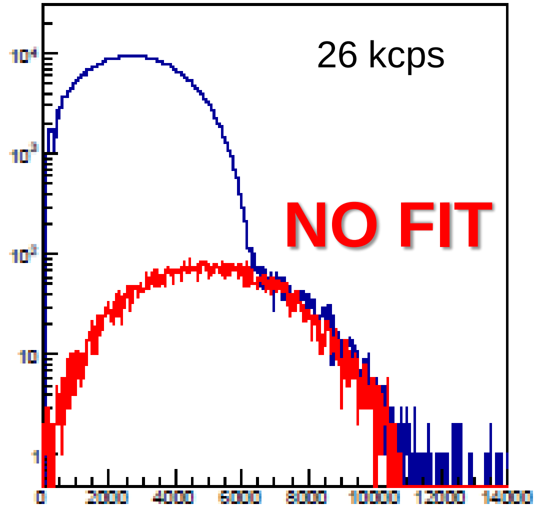


Measured spectrum

Digitizer simulation

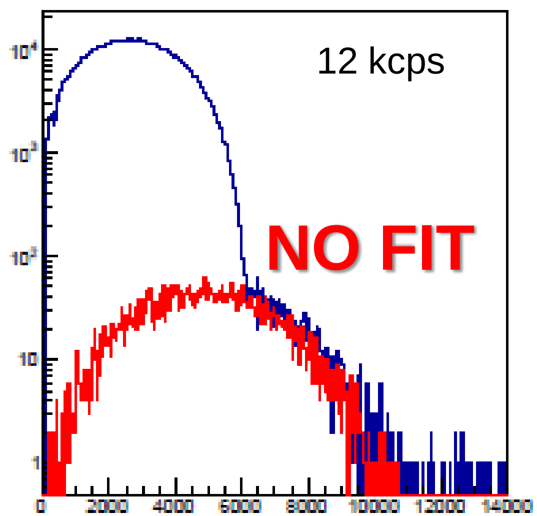


Full pile-up Partial pile-up



Experiment

Pile-up calculation



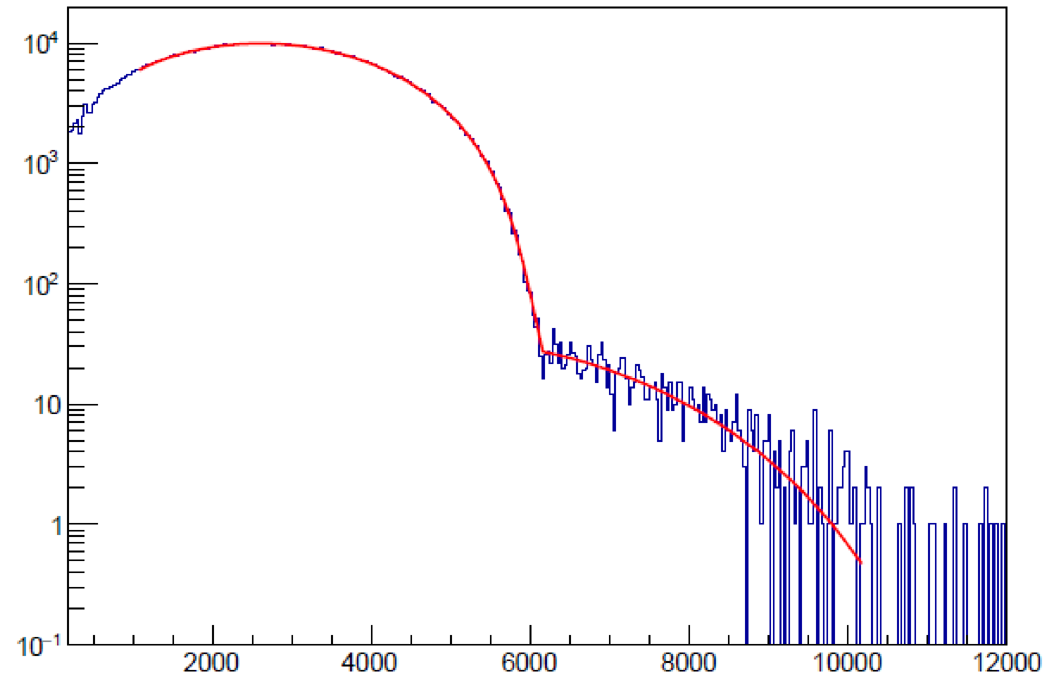
Data analysis: example of Monte-Carlo fit

Fit data with G4 simulated spectra convoluted with the detector response, including pile-up contribution

$$N(W) \approx G(W)(1 + C_0 + C_1 W + C_{-1}/W)$$

Free parameters

- Overall normalization N_0
- b_{WM}
- System gain ($Ch = AE+B$)



Electron energy (chan)

Status and Outlook

• We have performed high statistics measurements of the β spectrum shape in ^{6}He and ^{20}F decays.

• We have analyzed half of the collected data in ^{6}He (CsI detector). This will enable the determination of the weak magnetism form factor with a relative statistical uncertainty of about 8%.

• The comparison of the result with the CVC prediction will provide a sensitivity test of the experimental technique and allow us to perform a first direct measurement of the Fierz term in ^{6}He and ^{20}F.

Collaborators

D.Bazin[1], S. Chandavar[1], A.Gade[1], E, George[3], M.Hughes[1], X.Huyan[1], S.Liddik[1], K.Minamisono[1], S.Noji[1], S.Paulauskas[1], A.Simon[3], P.Voytas[2], D.Weisshaar[1]

[1] *NSCL/Michigan State University MI, USA*
[2] *Wittenberg University, OH, USA*
[3] *University of Notre Dame, IN, USA*