Update on the Montreal X-17 Project

G. Azuelos[1,2] , B. Broerman[3] , D. Bryman[2,4] , W.C. Chen[1] , H.N. da Luz[5] , L. Doria[6] , A. Gupta[1] , L-A. Hamel[1] , M. Laurin[1] , K. Leach[7] , G. Lefebvre[1] , J-P. Martin[1] , F. Nadeau[1], A. Robinson[1] , N. Starinski[1] , R. Sykora[5] , D. Tiwari[8], U. Wichoski[9,10,11], V. Zacek[1]

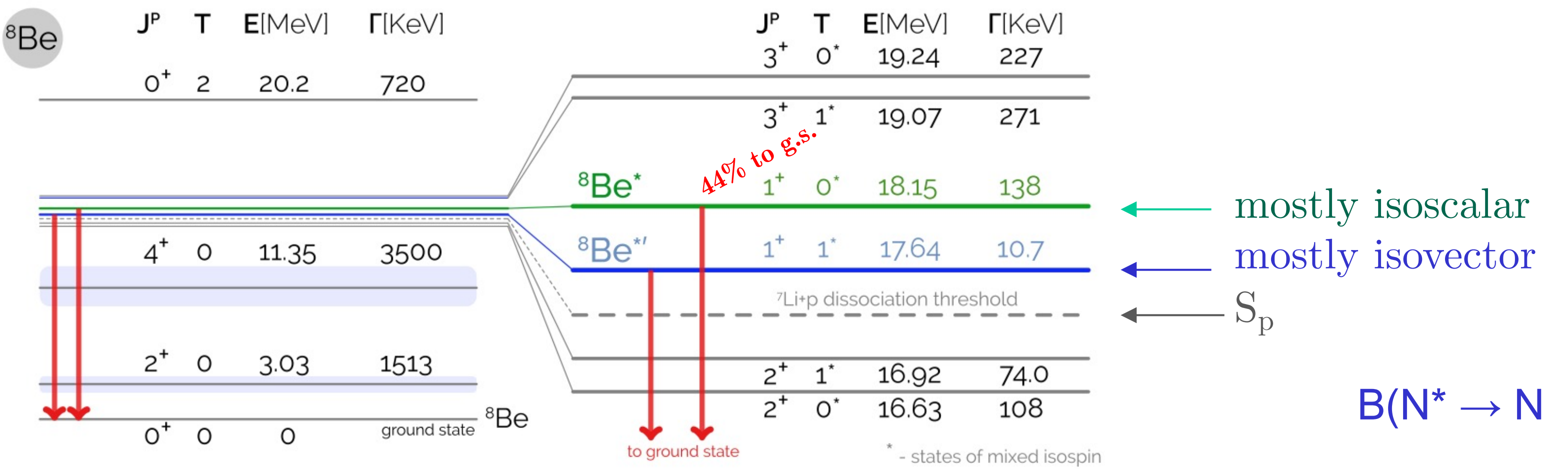
[1] Université de Montréal, Canada
[2] TRIUMF, Canada
[3] Queen's University, Canada
[4] University of British Columbia, Canada
[5] Czech Technical University, Czech Republic
[6] Johannes Gutenberg University of Mainz, Germany
[7] Colorado School of Mines, USA
[8] University of Regina, Canada
[9] Laurentian University, Canada
[10] SNOLAB, Canada
[11] Carleton University, Canada

Outline:

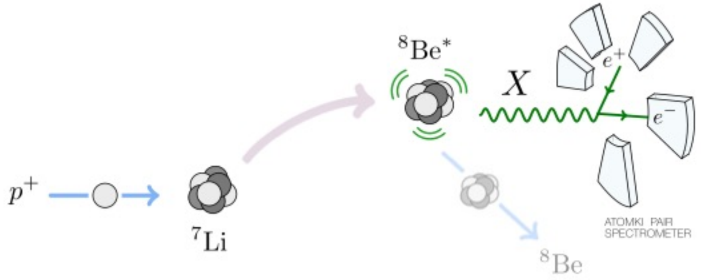
- Introduction:
  - Brief reminder of motivation for the search
- Basic experimental setup
  - scintillator ring
  - MWPC
  - target
- Tests and Simulations

DARKLIGHT @ TRIUMF Advanced Rare Isotope Laboratory (ARIEL)
Collaboration Meeting
May 31 - June 2, 2023

Internal Pair Creation in ^8Be

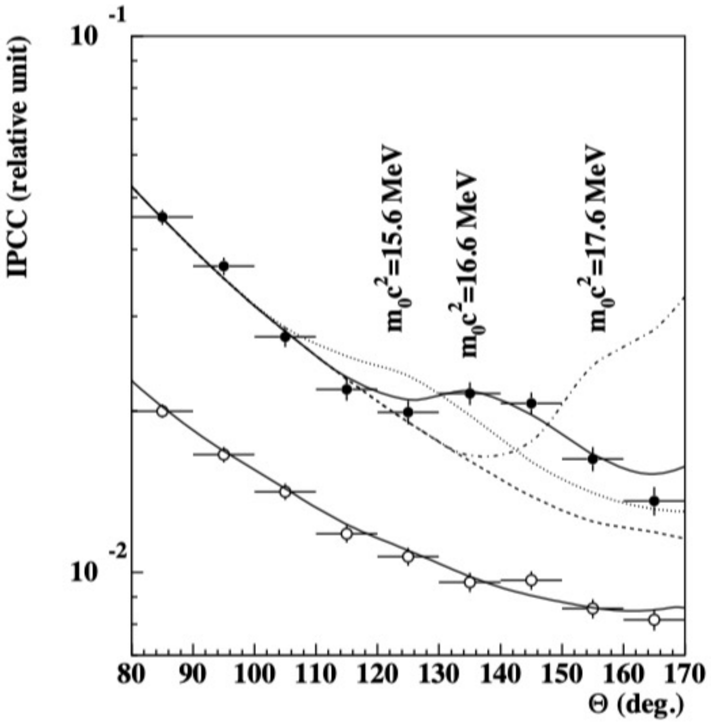


$B(N^* \rightarrow N\gamma) = 1.4 \times 10^{-5}$



figures borrowed from: Feng et al., Phys. Rev. D 95, 035017 (2017) , arXiv:1608.03591

ATOMKI result on ^{8}Be, 2016



For a transition energy of 18.15 MeV an opening angle of 140° betweeen e^+ and e^- corresponds to a mass of 16.7 MeV

from: *Krasznahorkay AJ, et al., Phys Rev Lett 2016;116(4); arXiv:1504.01527*

S/B appear to be ~ 0.7 ?

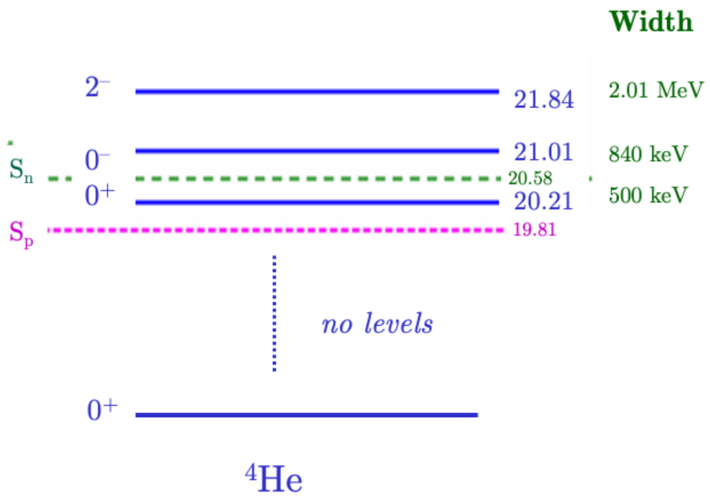
<u>18.15 MeV resonance (M1: $1^+ \rightarrow 0^+$)</u>

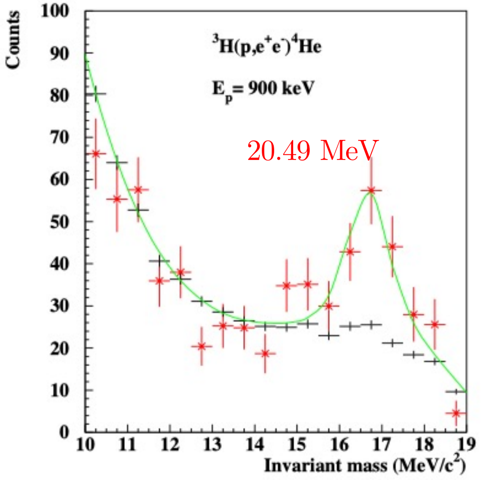
- IPC coefficient: 3.9 x 10^{-3}
- $\frac{B(X\rightarrow e^+e^-)}{B(^8Be^*\rightarrow\gamma)}$ = 5.8 x 10–6 (Atomki)

$\Bigg\}$ $\frac{B(X\rightarrow e^+e^-)}{B(^8Be^*\rightarrow e^+e^-)}$ = 1.5 x 10^{-3}

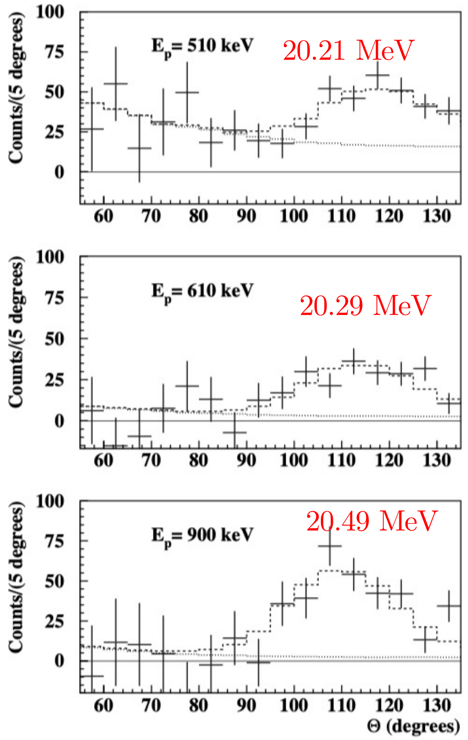
now BR = 3.4-5.8E-06,

ATOMKI result on ^{4}He





Krasznahorkay AJ et al., arXiv:1910.10459



Krasznahorkay AJ et al, *Phys.Rev.C* 104 (2021) 4, 044003, arXiv:2104.10075

E0 transition ($0^+ \rightarrow 0^+$)
mixed 0^+ and 0^-

TABLE I. Internal Pair Creation Coefficients (IPCC), X17 Boson branching ratios (Bx), masses of the X17 particle, and confidences derived from the fits.

E_p	IPCC	B_x	Mass	Confidence
(keV)	$\times 10^{-4}$	$\times 10^{-6}$	(MeV/c^2)	
510	2.5(3)	6.2(7)	17.01(12)	7.3σ
610	1.0(7)	4.1(6)	16.88(16)	6.6σ
900	1.1(11)	6.5(20)	16.68(30)	8.9σ
Averages		5.1(13)	16.94(12)	
^{8}Be values		6	16.70(35)	

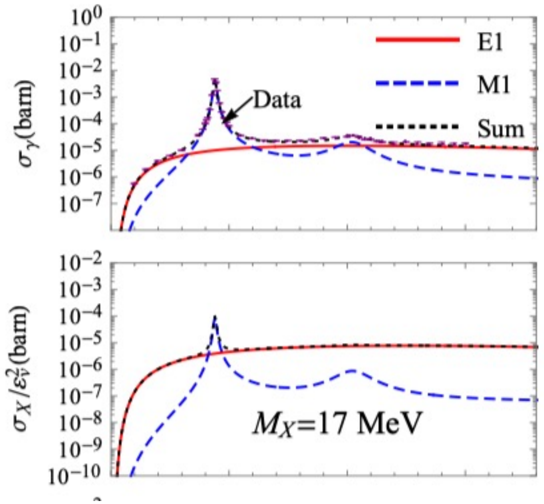
Theoretical speculations/calculations...

Scalar (0^+)? Pseudoscalar (0^-)?, Vector (1^-)? Axial-vector (1^+)?

$$\epsilon_u \sim -0.5 \times \epsilon_d = 3.7 \times 10^{-3}$$

- J.L. Feng et al. Phys. Rev. Lett. 117, 071803 (2016); Phys. Rev. D 95, 035017 (2017), Phys.Rev. D 102, 036016 (2020)
  - favor vector gauge boson (not dark photon) coupling not proportional to electric charge
  - protophobic, from constraints from $\pi^0 \longrightarrow Z\gamma$ results of NA48/2 experiment
- Ellwanger and Moretti JHEP 11 39 (2016)
  - possible pseudoscalar $J^\pi = 0^-$
- X. Zhang and G. Miller Phys. Lett. B773 159 (2017)
  - improved nuclear model
  - nuclear form factor does not explain anomaly
- Kozaczuk et al., Phys.Rev.D 95 (2017) 11, 115024
  - axial-vector X17 explains isoscalar transition (18.15 MeV) and absence of isovector (17.64 MeV)
- Luigi Delle Rose et al. Phys. Rev. D 96, 115024 (2017); Phys. Rev. D 99 055022 (2019); Frontiers in Physics 7 73 (2019)
  - consider pseudoscalar 0^- or axial-vector Z'
    - possibly embedded in BSM models
- J.L. Feng, T.M.P. Tait and C.B. Verharen, Phys. Rev.D 102, 036016 (2020)
  - protophobic model consistent with ^{4}He result
  - consider also ^{12}C
- X. Zhang and G. A. Miller, Phys. Lett. B 813 (2021), 136061
  - protophobic hypothesis: X17 capture dominated by E1 direct capture without going through any nuclear resonance
  - smooth energy dependence that occurs for all proton beam energies above threshold.
- M. Viviani et al. Phys. Rev. C 105, 014001 (2022)
  - χEFT
  - systematic study of the cross section as function of both the opening angle and electron energy to discriminate among the different hypotheses regarding the nature of X17.

N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	—	$\mathcal{O}_{4P}^{(0)}$ (27)	$\mathcal{O}_{5P}^{(1)}$ (37)	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)
^{12}C(17.23)	1^-	$\mathcal{O}_{4P}^{(0)}$ (27)	—	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)	$\mathcal{O}_{5P}^{(1)}$ (37)
^{4}He(21.01)	0^-	—	$\mathcal{O}_{3S}^{(0)}$ (39)	—	$\mathcal{O}_{4P}^{(1)}$ (40)
^{4}He(20.21)	0^+	$\mathcal{O}_{3S}^{(0)}$ (39)	—	$\mathcal{O}_{4P}^{(1)}$ (40)	—



ATOMKI result on ^{12}C

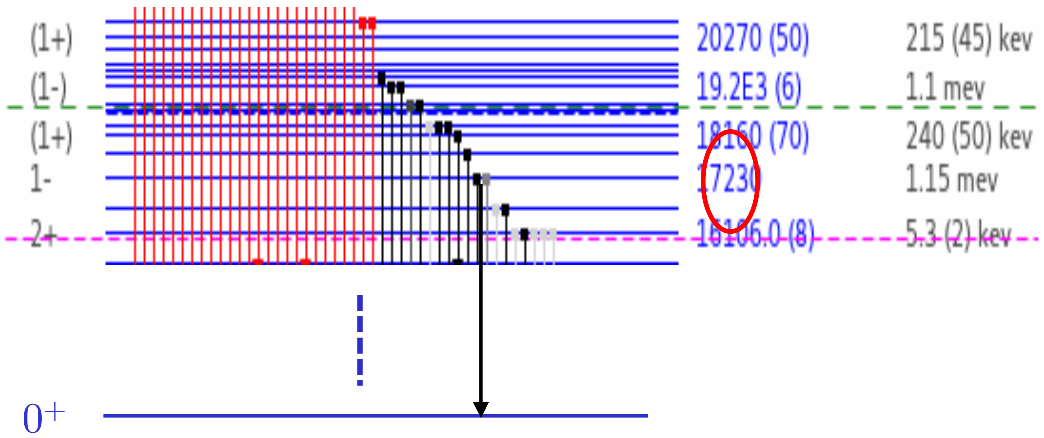
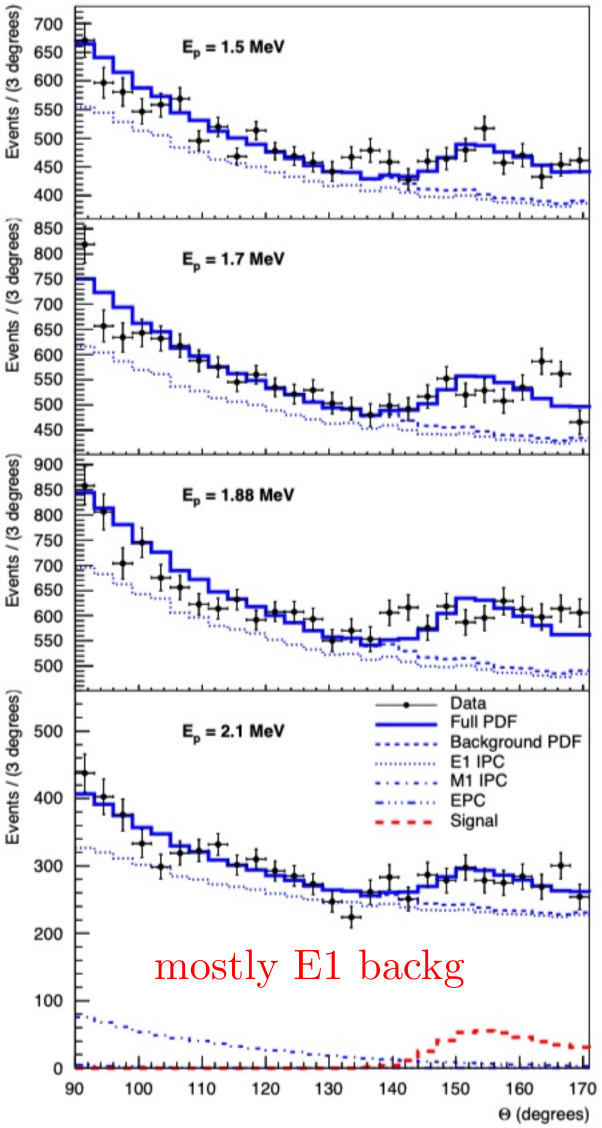


TABLE I. X17 branching ratios (B_x), masses, and confidences derived from the fits.

E_p	B_x	Mass	Confidence
(MeV)	$\times 10^{-6}$	(MeV/c^2)	
1.5	2.7(2)	16.62(10)	8σ
1.7	3.3(3)	16.75(10)	10σ
1.88	4.1(4)	16.94(10)	11σ
2.1	4.7(9)	17.12(10)	6σ
Averages	3.4(3)	16.86(17)	
Previous [1]	5.8	16.70(30)	
Previous [21]	5.1	16.94(12)	
Predicted [16]	3.0		

Krasznahorkay AJ, *et al.*,
Phys.Rev.C 106 (2022) 6, L061601, arXiv:2209.10795



Dominated by direct proton capture (E1)

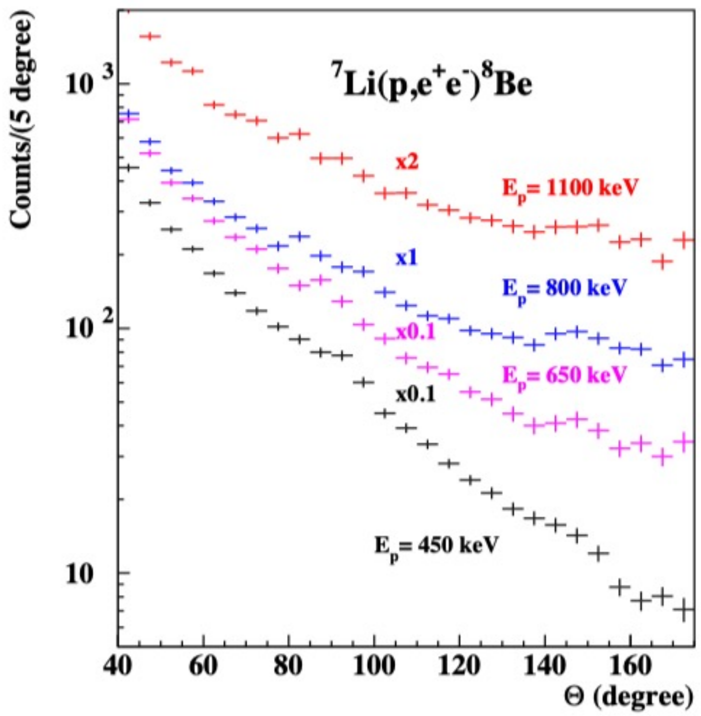


FIG. 3. Angular correlations of the e^+e^- pairs for the "Signal" region. Symbols with error bars indicate experimental data measured in the $^7Li(p,\gamma)^8Be$ reaction at different proton beam energies.

TABLE I. The fitted mass [m(X17)] and the integrated yields I(X17), I(E1) and I(M1) of the X17 and the E1 and the M1 contributions. The ratio of I(X17)/I(E1) is also listed [B(X17)].

E_p (keV)	m(X17) (MeV/c^2)	I(X17)	I(E1)	I(M1)	B(X17)
450	16.6(3)	43(49)	30(25)	79(2)	1.4(16)
650	16.94(14)	24(16)	46(5)	32(4)	0.5(3)
800	16.81(9)	33(10)	62(4)	5.9(4)	0.53(14)
1100	17.11(12)	28(8)	66(2)	15(1)	0.41(13)

N.J. Sas et al., arXiv:2205.07744

X17 produced at all energies above 17.6 MeV resonance

- contradicts previous measurement
- explained as
    - better background fit
    - proton beam energy loss in thick target, causing increased background

Dark photon constraints

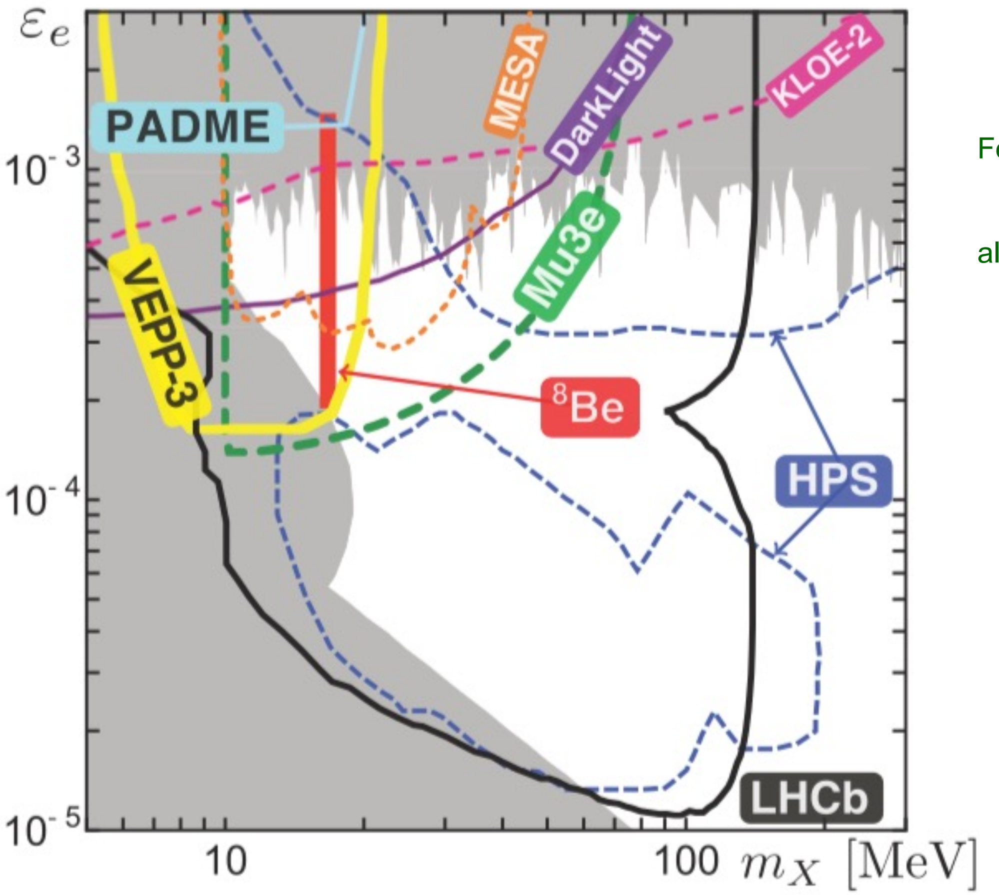
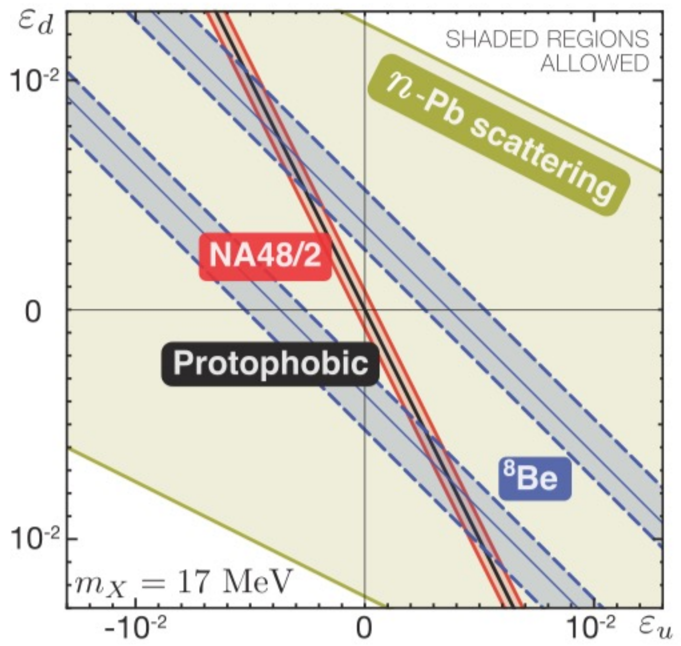


FIG. 6. The ^{8}Be signal region, along with current constraints (gray) and projected sensitivities of future experiments in the (m_X, ε_e) plane. Updated from Ref. [7]. Note $\mathrm{Br}(X \to e^+e^-) = 1$ is assumed.

Feng JL, et al., PhysRevD 95 (2016) (035017).
arXiv:1608.03591

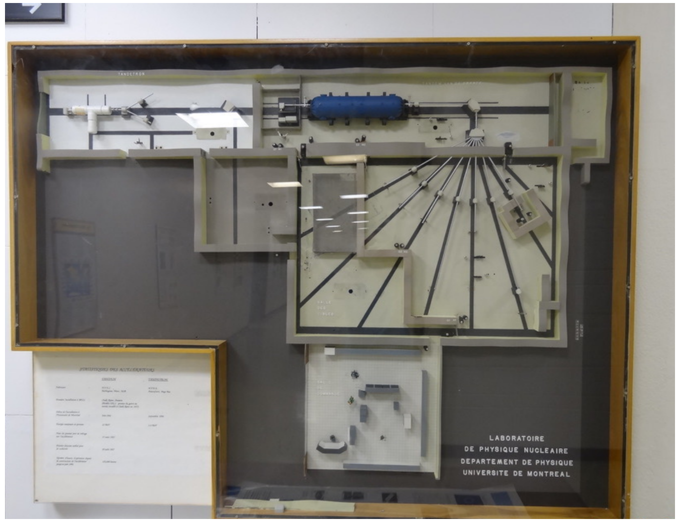
also: *Phys.Rev.Lett.* 117 (2016) 7, 071803 (arXiv:1604.07411)



The Montreal Facility

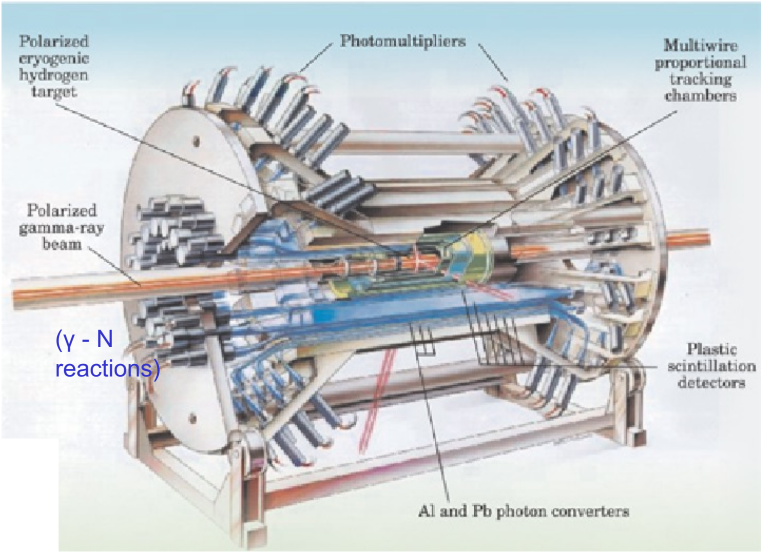
UdeM 6 MV Tandem
Van de Graaff

- 2 μA proton beam on target (possibly up to 20 μA)
- E - resolution of 2 keV for E_p = 0.4 - 1 MeV

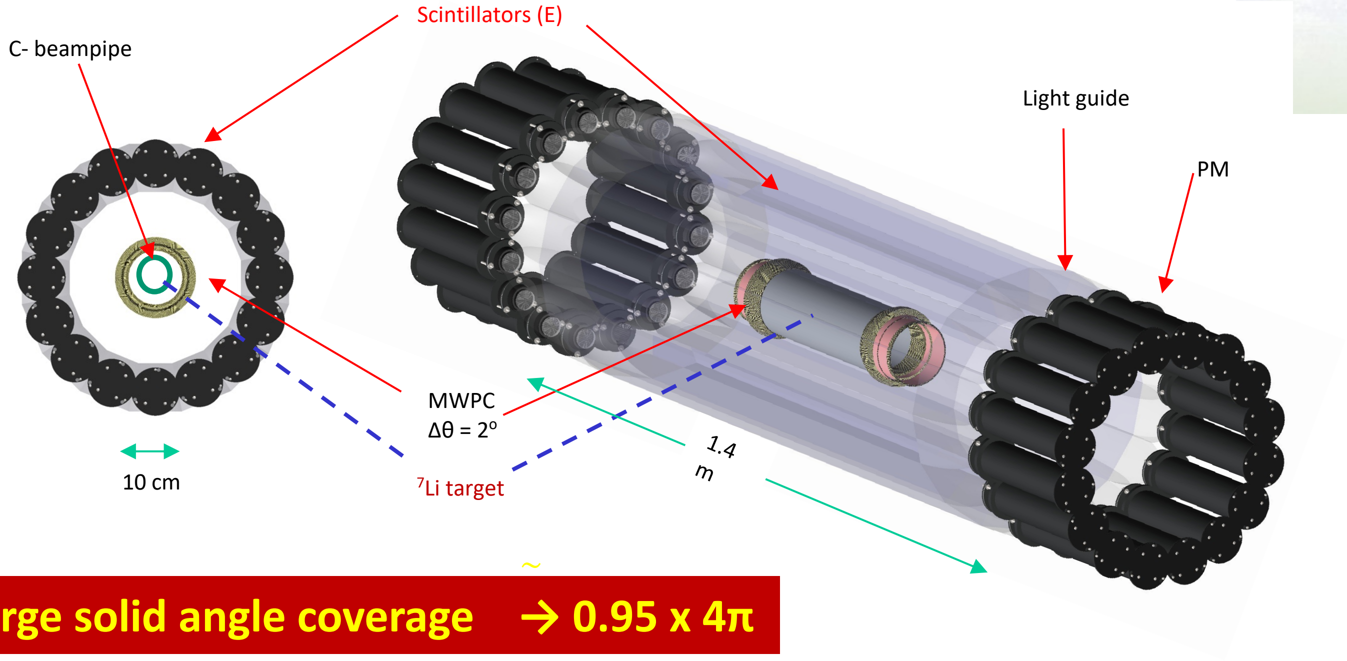


The Montreal X-17 Project

- Use parts of the DAPHNE experiment (Saclay/Mainz)
  - *Many thanks to L. Doria & U. Mainz!*
- Tracking MWPC chamber & 16 scintillators (NE102A)
- Scints & MWPC from U. Mainz → now @ Montreal
- Phototubes and some ADC/TDC's borrowed from TRIUMF

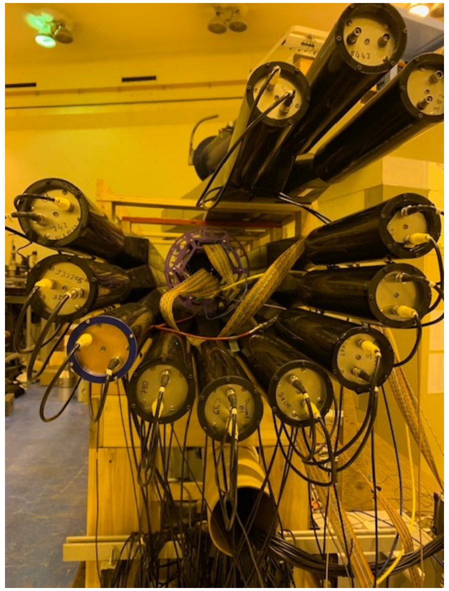


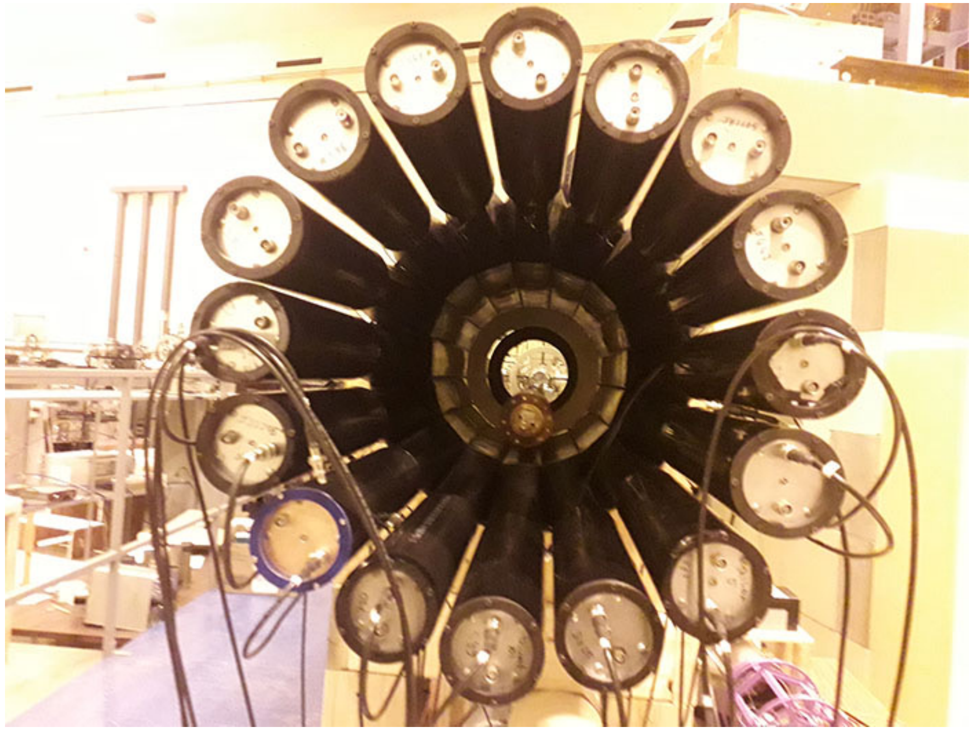
Daphne experiment:
polarized gamma rays on polarized nuclei

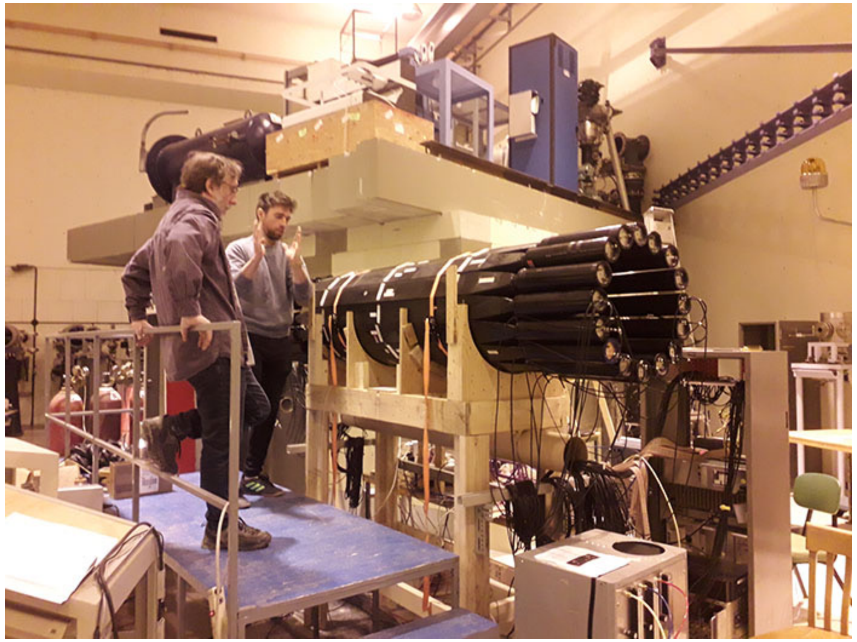


Large solid angle coverage → 0.95 x 4π

Scintillators







- all scintillator bars instrumented
- pmt gains approximately adjusted
  - will be fine-tuned offline by software

Example of scintillator signals from localized hits

(4-fold coincidences from Cosmic Rays)

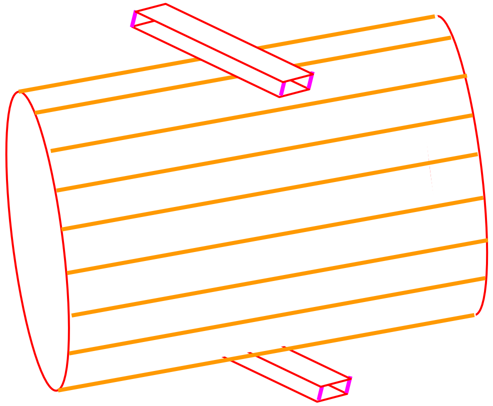
- determine attenuation length:

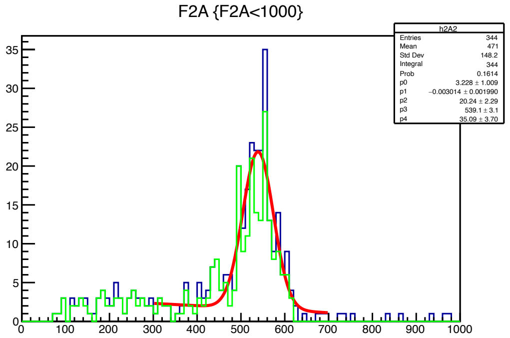
  $e^{-\mu x}, \mu = 0.1 - 0.2\ m^{-1}$

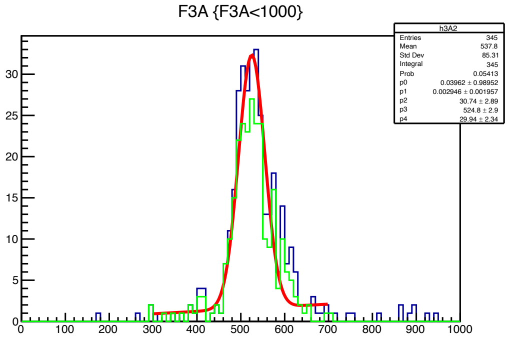
  $\Rightarrow \sim 80\%$ signal over length of sc. bar

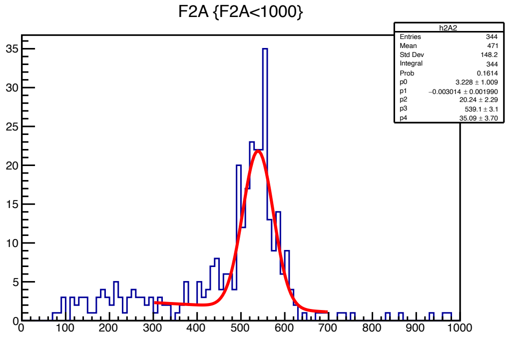
  - consistent with DAPHNE measurement (0.17 m^{-1})*

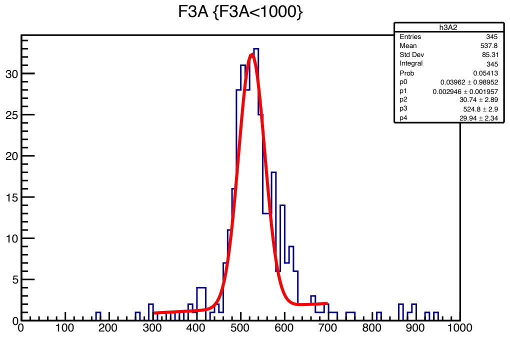
    * Oliver Jahn, dissertation, Mainz 2005
- adjust gains

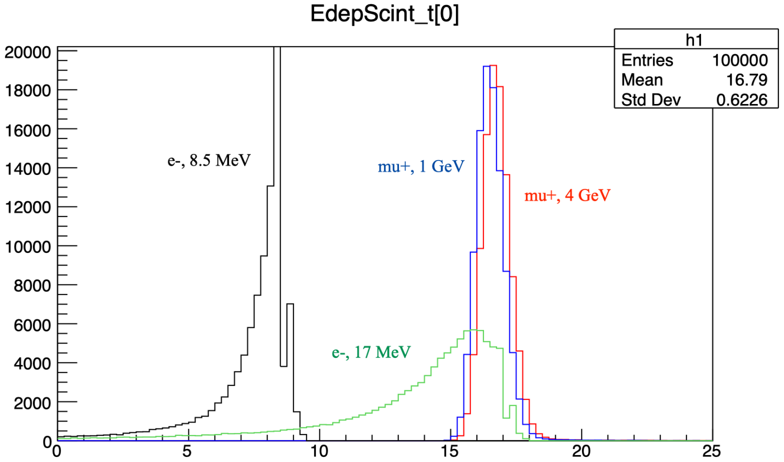




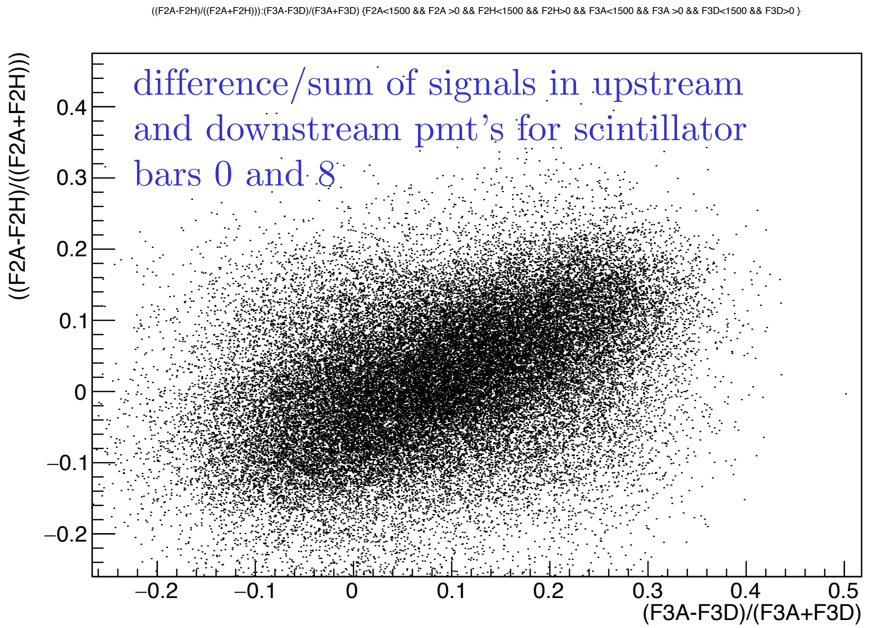








- Position resolution along scintillator bars
  - useful to resolve hit ambiguities
  - estimated from
    - time difference of upstream and downstream pmt's
      - approximately 8 ns for 1 m => ~ 10-15 cm for 1 ns timing resolution
    - amplitude difference



The DAPHNE Tracking Chamber

- Inner wire chamber only
  - ID 12 cm / OD 14 cm - Length 36 cm
  - Cathode-anode distance: 4 mm;
  - 192 Anode wires:
    - 20 μm diam;
    - radius 6.4 cm
    - spacing: 2mm (1.9°)
  - 60/68 cathode strips
    - radius: 6.0 and 6.8 cm
    - at 45° wrt wires;
    - width 4mm, 0.5 mm separation
  - Low density material to avoid EPC!
- Gas mixture:
  74% Ar, 26% CO_2
- Angular res.: $\Delta\theta \sim 2^o$ (FWHM)

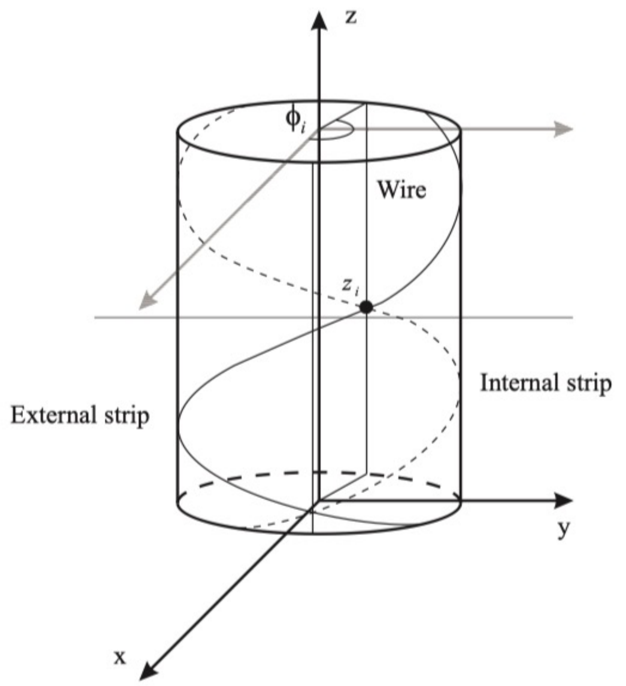


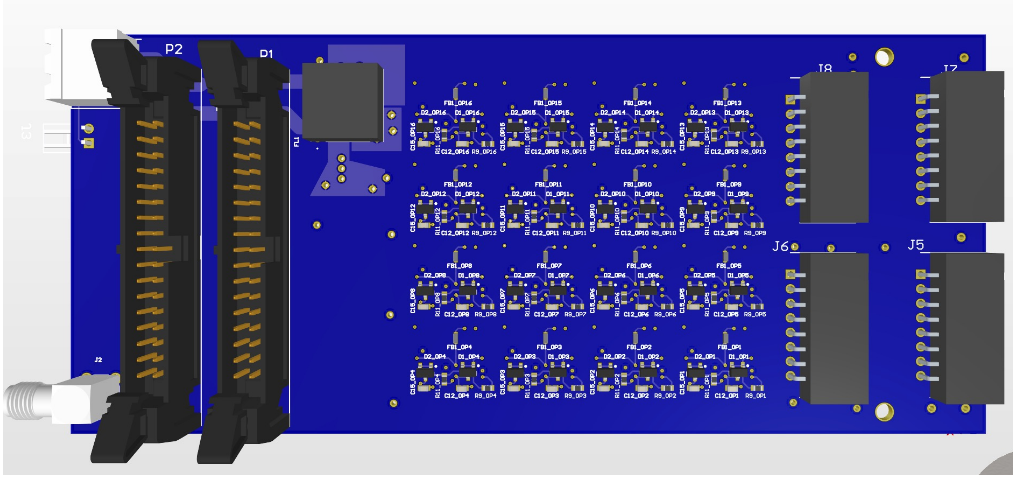
Figure 2.11. MWPC: Reconstruction of the impact point of a traversing particle.

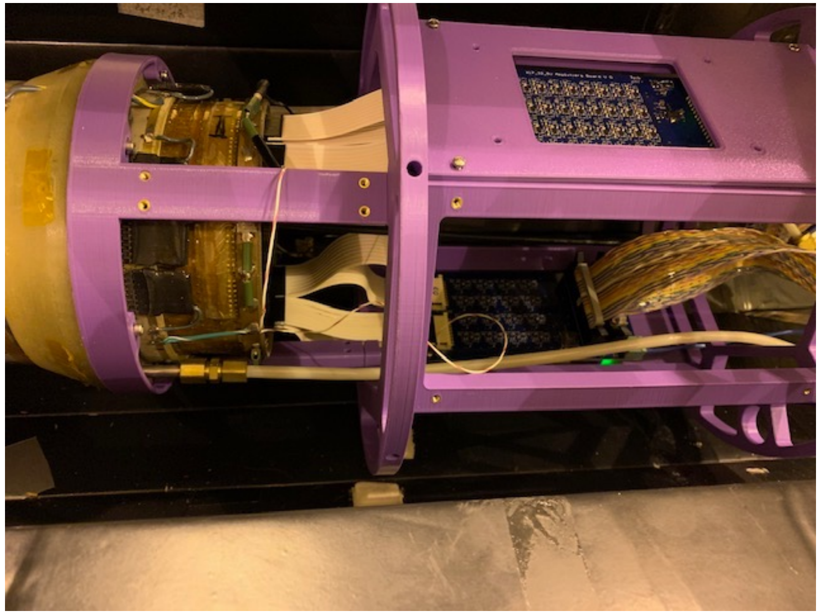
Dissertation, Oliver Jahn, Mainz (2005)

Preamplifiers – designed by J-P Martin

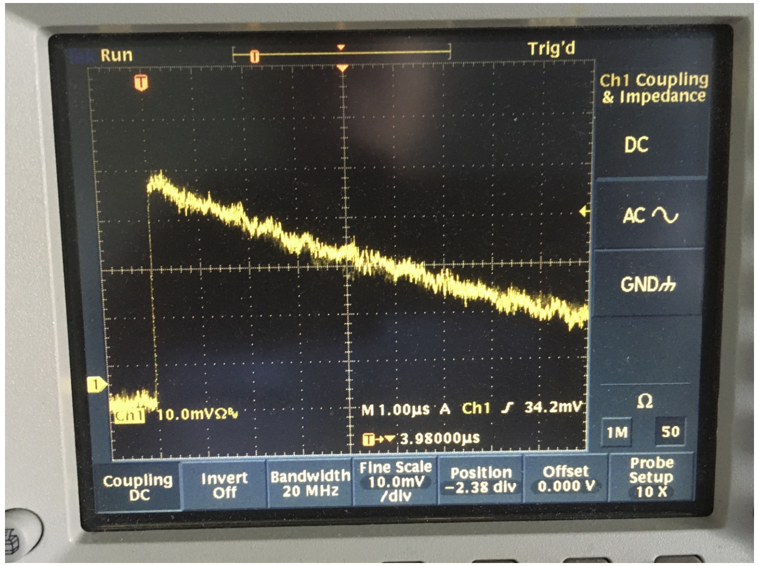
- 32 channels per card
- Nominal gain: 1V / picocoulomb (no load)
- Charge decay RC : 10 µs. (neglecting coupling RC)
- Series output impedance: 27 ohms
- Series coupling capacitance: 100 nF
- Output: twisted pair ribbon
  - 1 side grounded
  - 100 Ω termination at load
- Intended DAQ device:
  - VF48 Module
  - Differential input, 100 Ω

Power: 5V, 0.3A (total)





Here, preamps are connected on top and bottom and the chamber is triggered by CR's from scintillators above and below



With 50 mV tail pulse (500 fC Nominal)

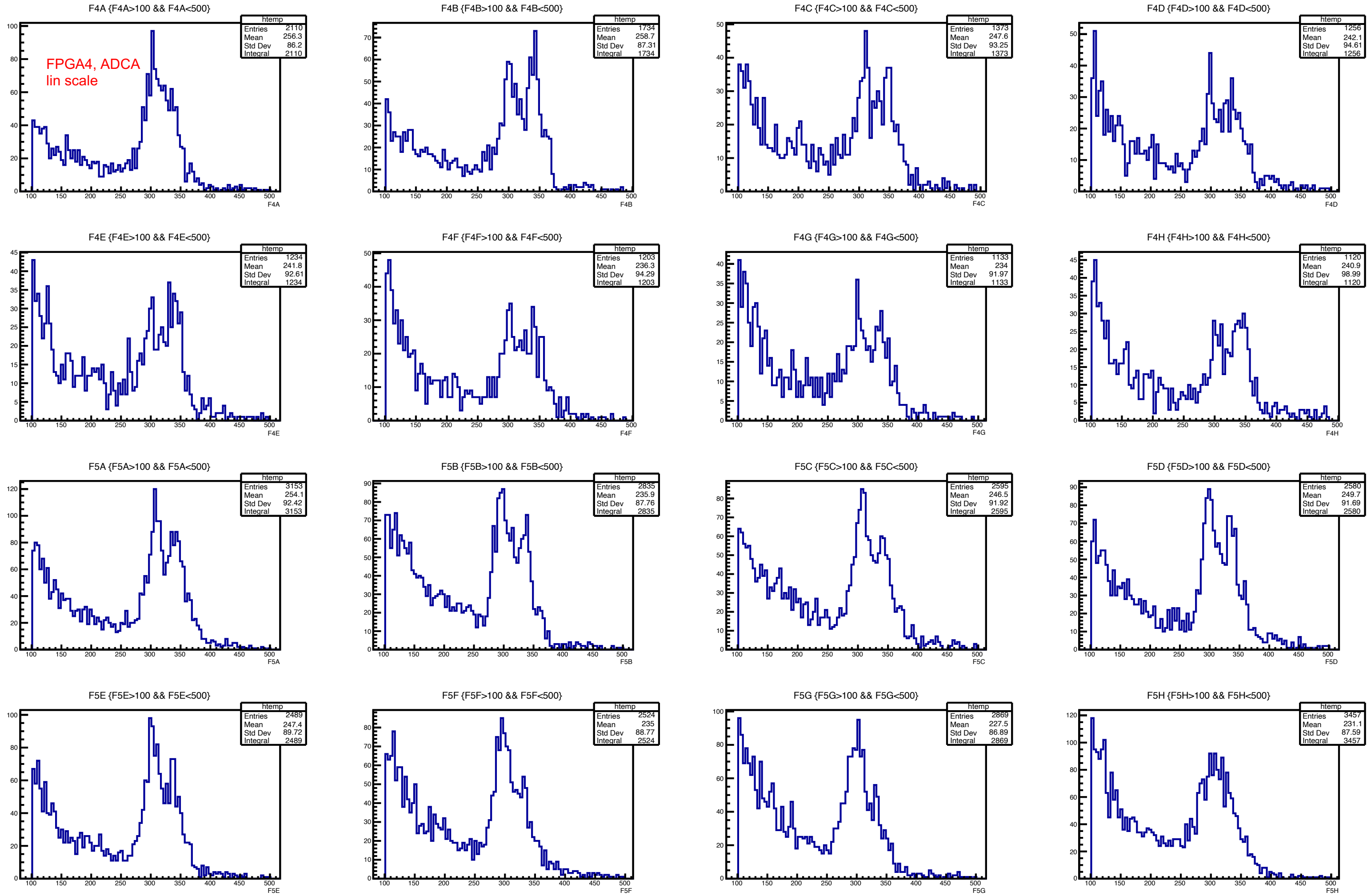
Signal Processing

- Done with Digital Signal Processing firmware in VF48
  - VF48 modules designed by J-P Martin
  - 16-tap Finite Impulse Response (FIR) digital filter; ‘triangular unipolar response’ to a step function
  - frequency: 50 MHz
  - Continuous moving window :
    - Sum of samples n to n-7
    - Minus sum of samples n-8 to n-15
    - Result divided by 4
    - Max/min of values is calculated in the window aperture => Charge evaluator.

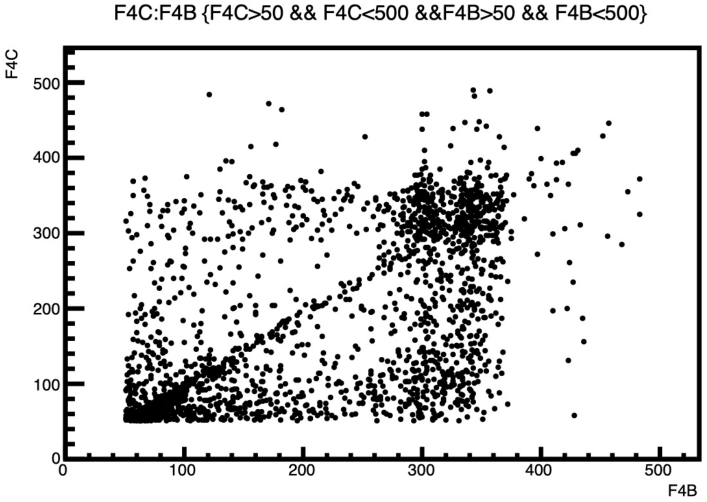
- NOTE: the same algorithm is applied also to the very short PMT anode signals
  - This produces bipolar output signals
  - The charge is evaluated for both polarit
  - (Q+ minus Q–)/2 is the variable kept in the data packets

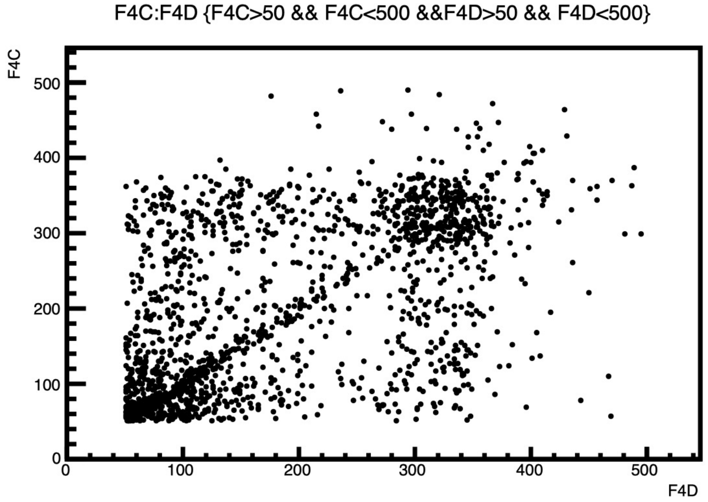
Cosmic Ray signals in MWPC

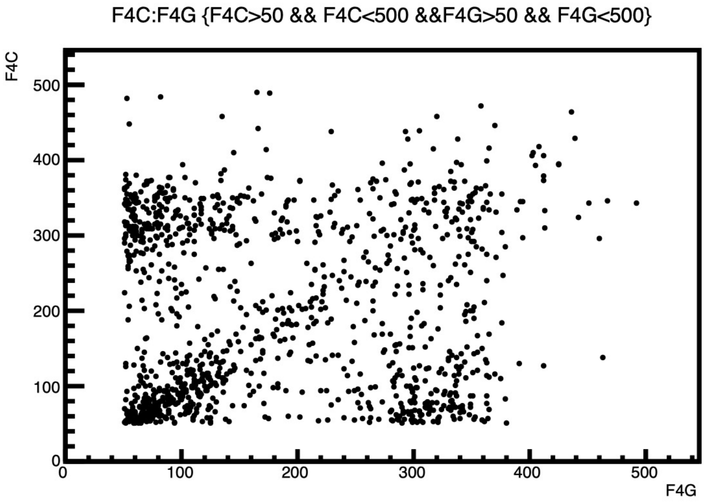
- Wire chamber: wire signals
  - trigger from cosmic rays through scintillators

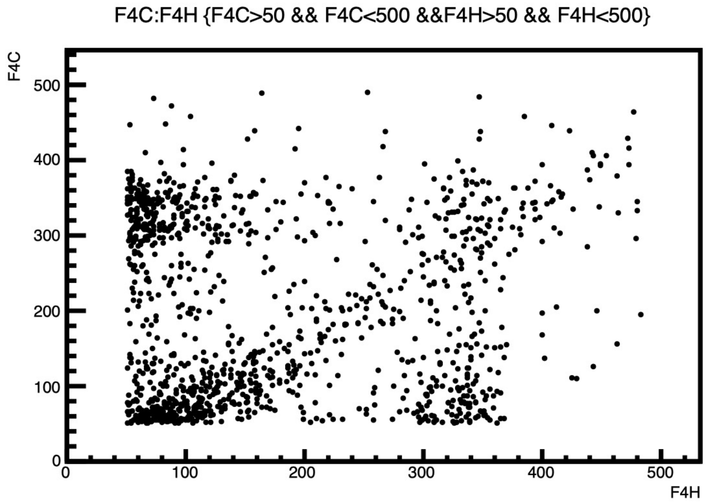


Correlations, mostly between adjacent wires



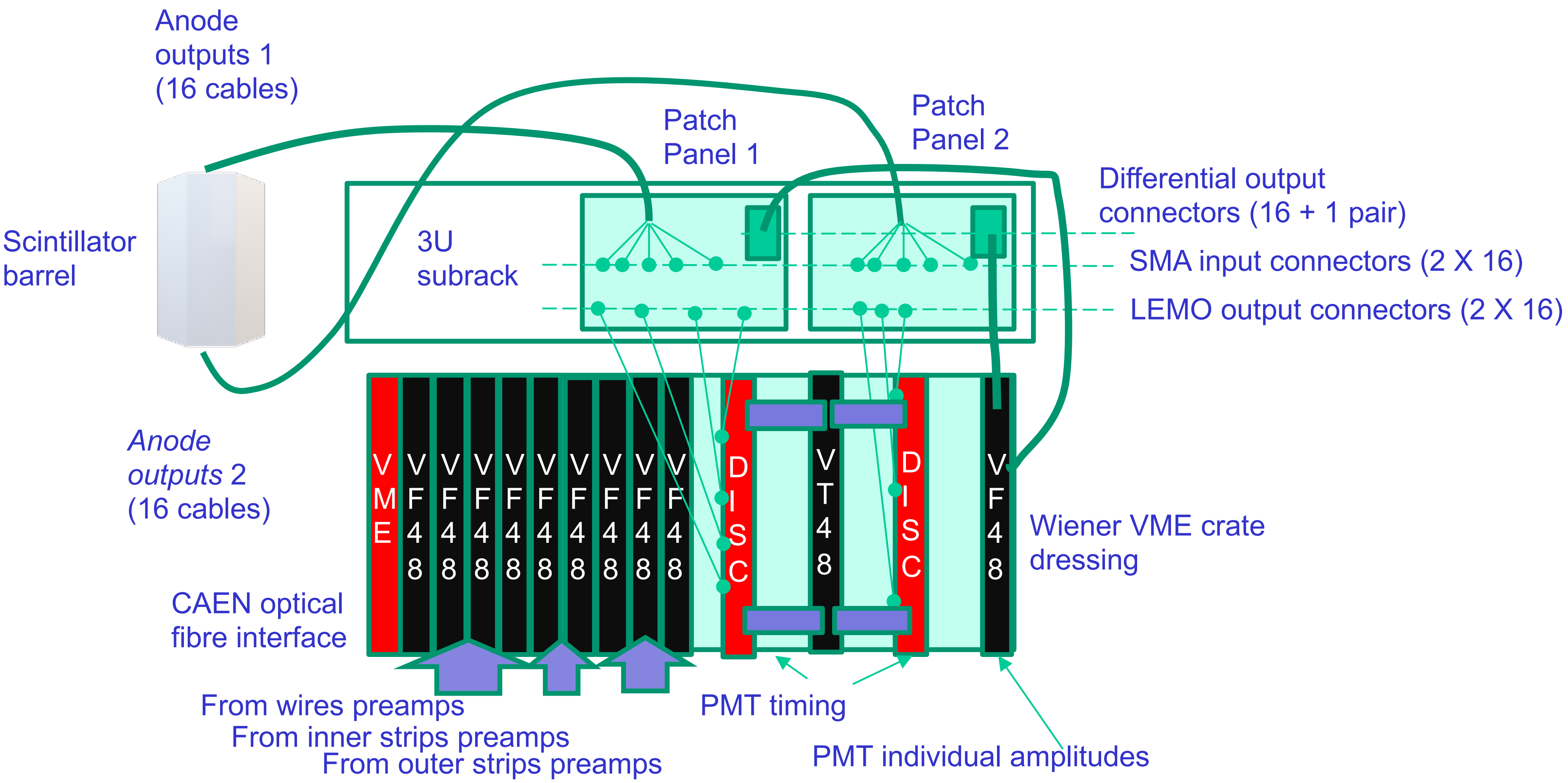




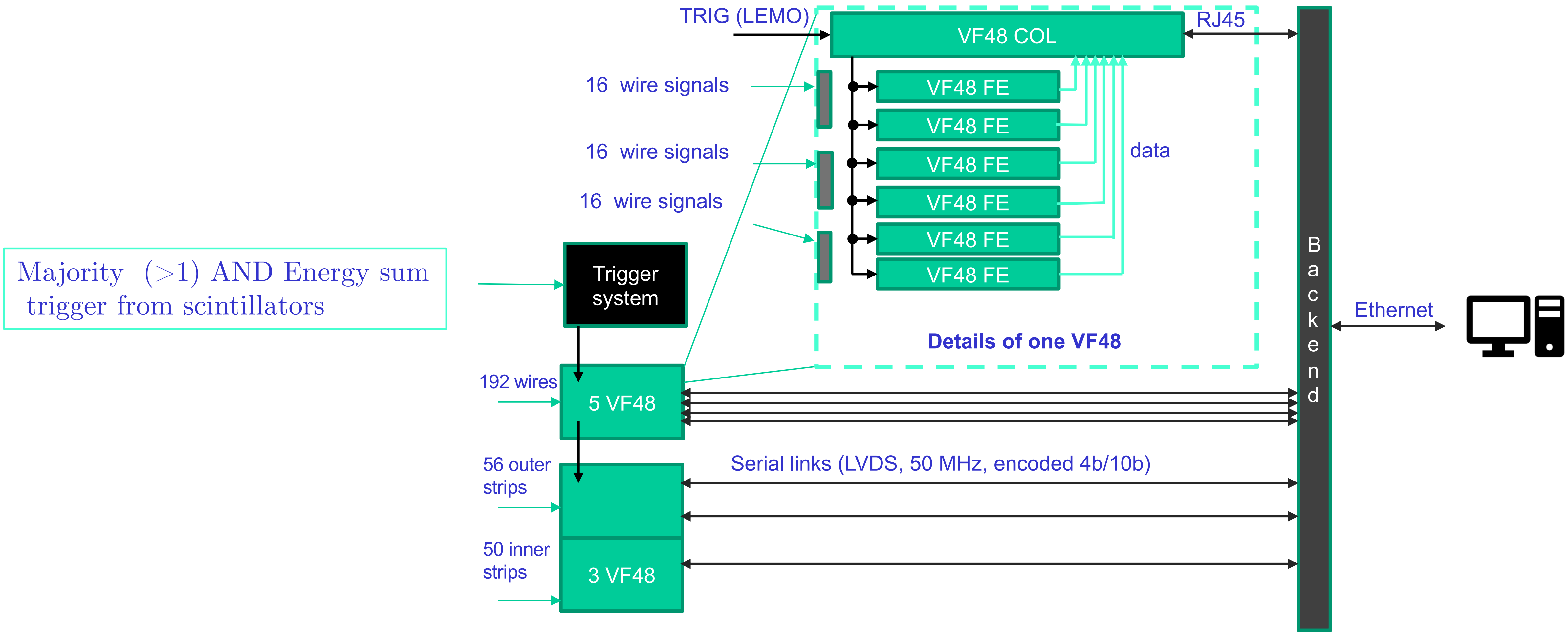


Data Acquisition System

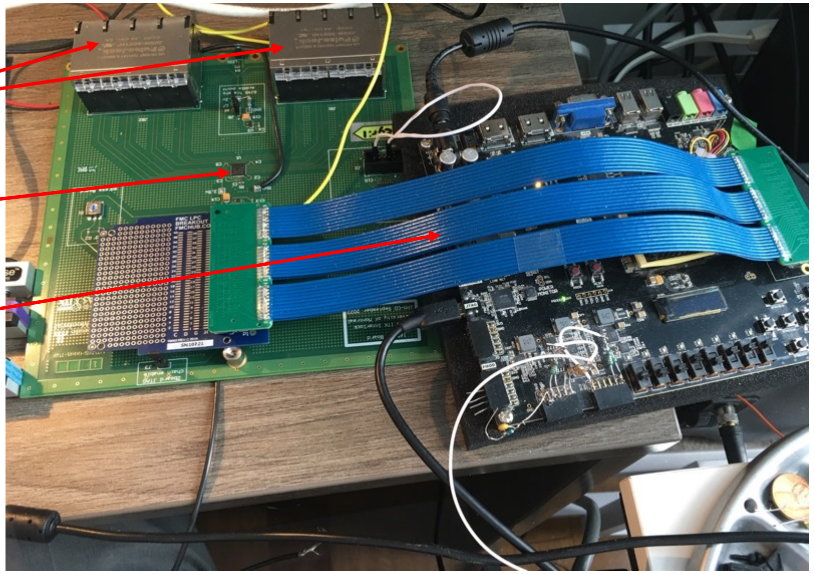
as planned 1 1/2 year ago



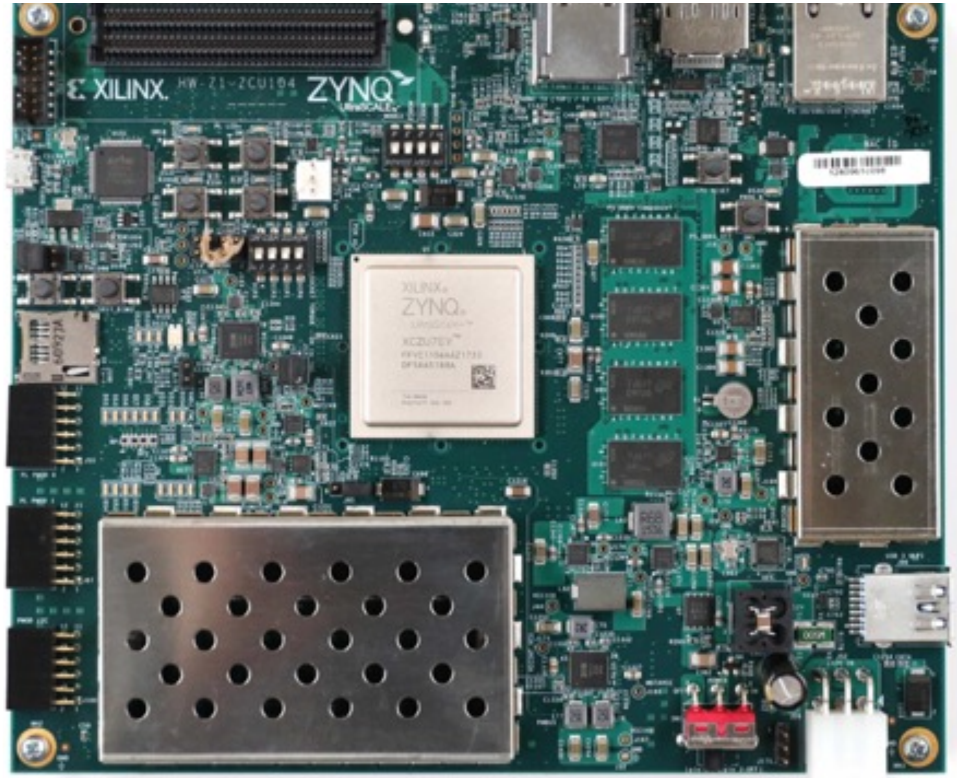
Elements of the DAQ system



Backend



16-port Back-end interface card (16X RJ45 to FMC) shown on a test bench



Xilinx development board to be used for the <u>backend</u> (ZCU104)

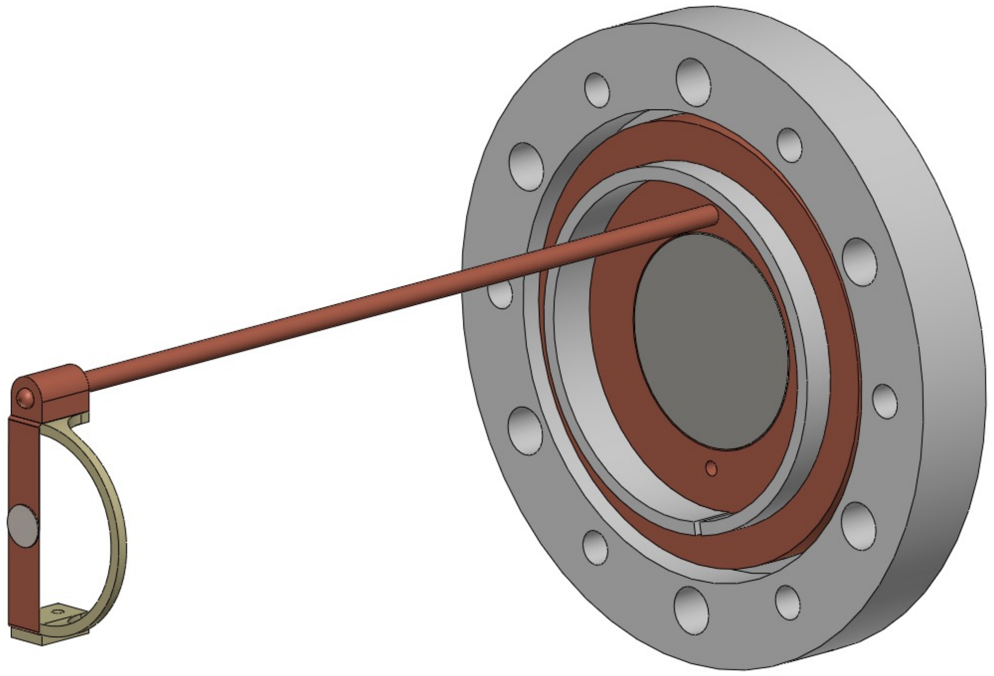
Store hit pattern of wires and strips if

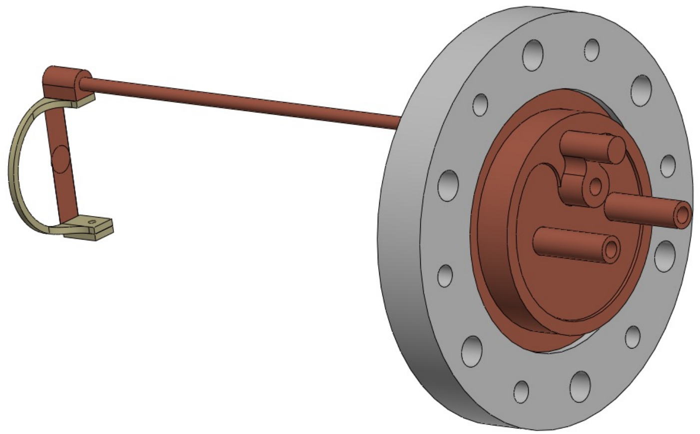
- scintillator trigger (at least 2 scints. and > 4 MeV sum)
- at least 2 wire clusters
- at least 2 strip clusters

- Can handle the 16 ports and clocks of the interface card
- FNC low density connector
- Ultrascale FPGA with 6 software processors
- Local SD disk (SATA)
- Pentalinux
- Ethernet and USB ports

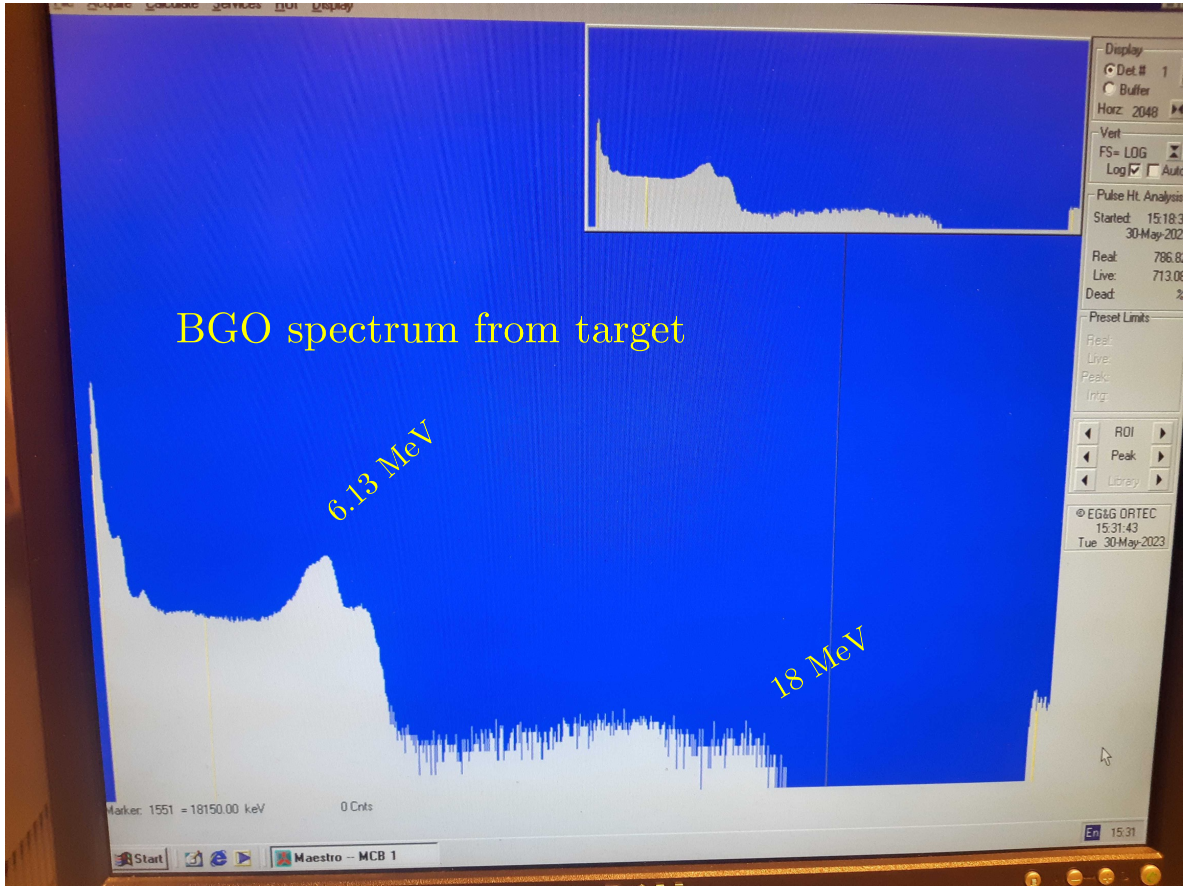
Target holder

- 1” long, 2” OD copper heat exchanger, water cooled
- Cu brazed (Ag) heat pipe support
- 4 mm x 150 mm heat pipe
  - Rated 20W @ effective length
  - 1 uA proton @ 1 MeV = 1W
    - Goal 20 uA beam -> 20W max of heat
- Substrate 1/4” x 1,25” x 0,001” thick, 1/4” diameter LiF target
- Brass screw to hold target and ease target replacement
- High temperature plastic support to hold target flat
- Tantalum beam stop disc





Beam test

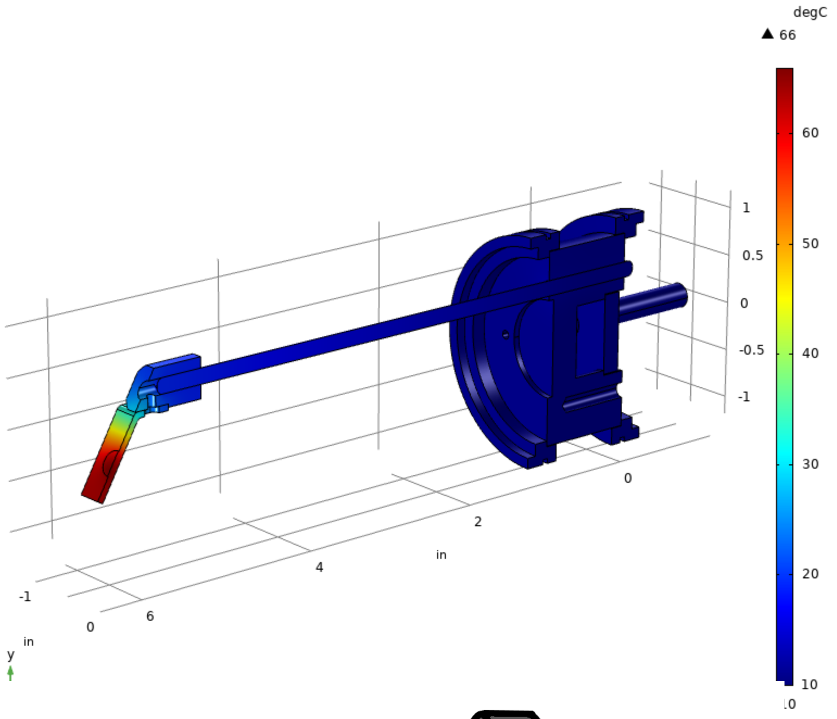


Yesterday:

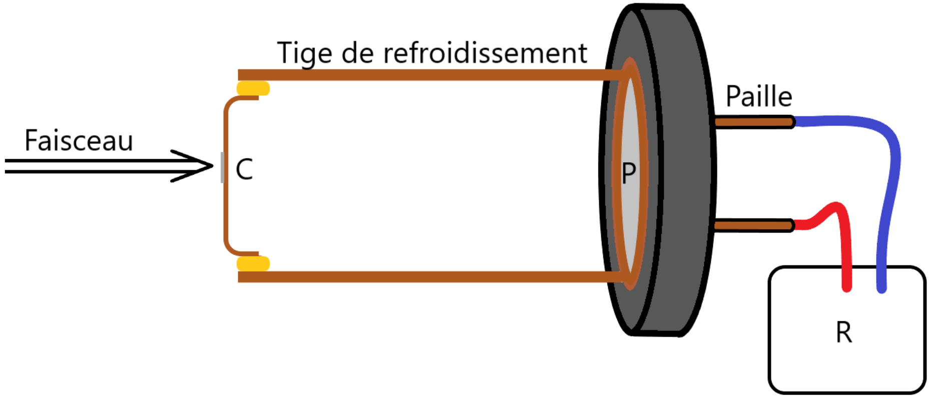
- 1.04 MeV beam bombarding LiF target
- all 16 scintillators irradiated with ^{8}Be* γ's and 6.1 MeV γ's from ^{19}F(p,αγ)^{16}O
- 6 MeV peak at channel ~ 200
- muons from CR's (17 MeV) at ch ~ 600

COMSOL simulations

- Heat transfer module
  - No radiation
  - No outside air natural convection
- Heat pipe
  - Effective thermal conductivity
    - 24 000 W/(m*K)
- Water cooling to 10° C
- Target temp below 70° C
  - 20 W heat at target from 20 uA beam (Li melts at 180°C)

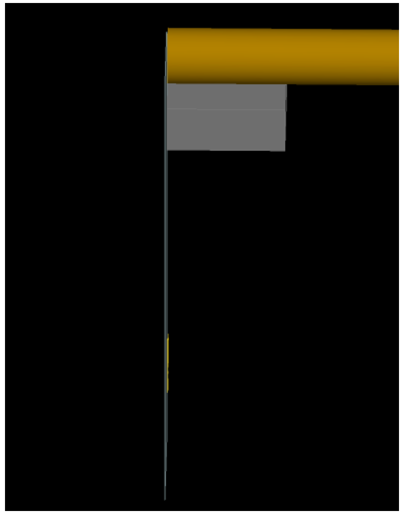


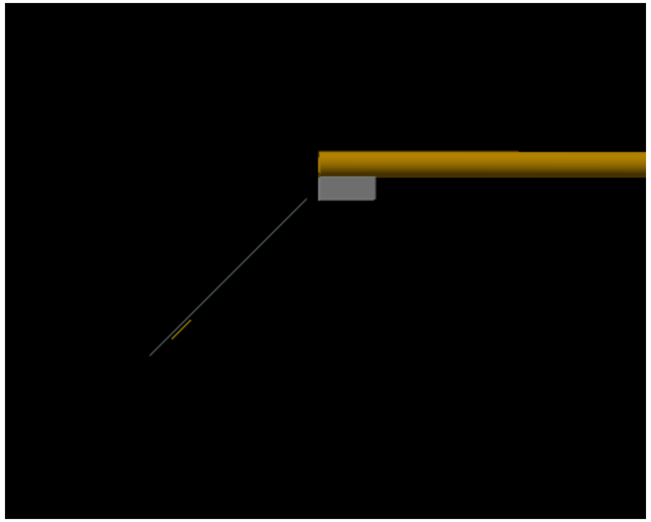
- preliminary tests of heat
  - measured overheating
  - needs to be revised

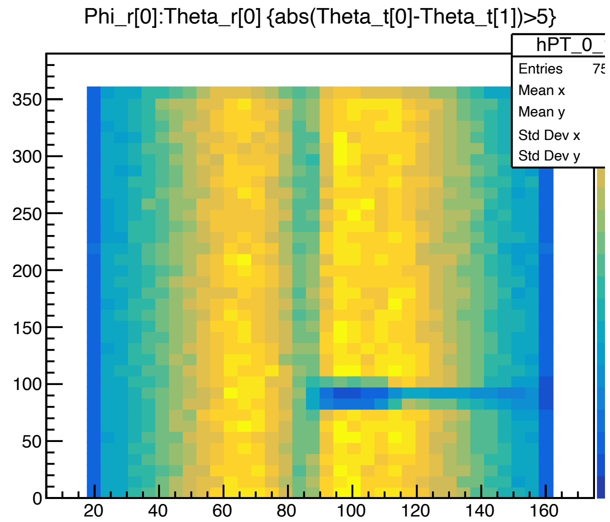


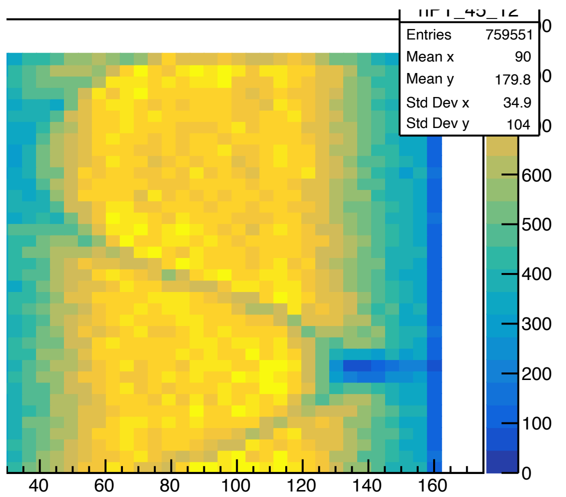
Target orientation

Loss of geometrical acceptance due to supporting foil

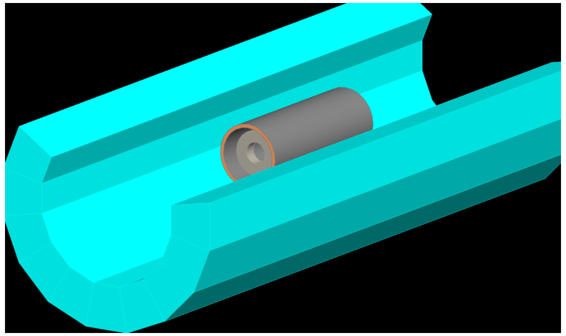


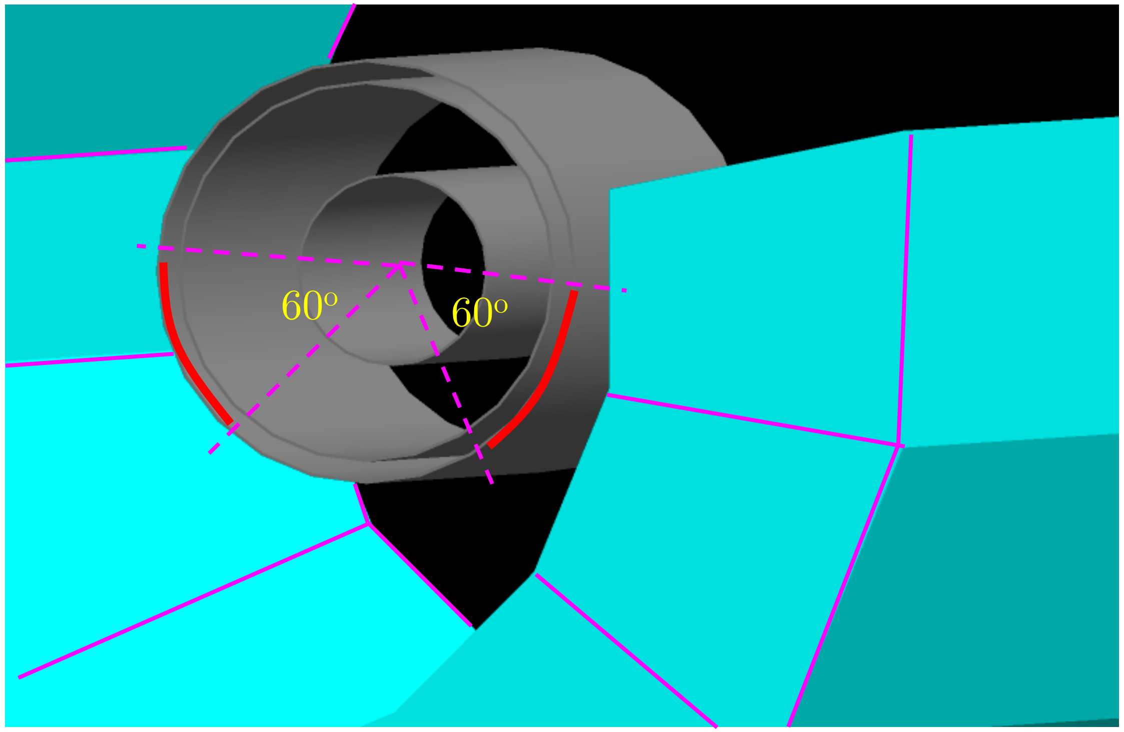


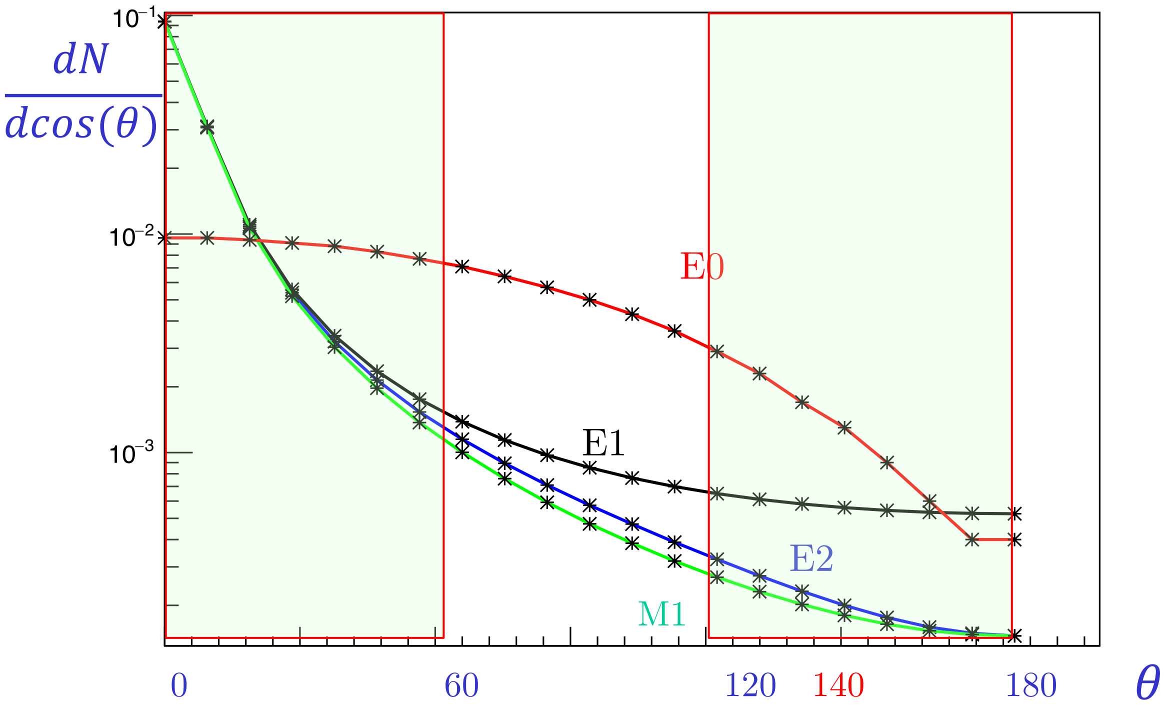




Test set-up



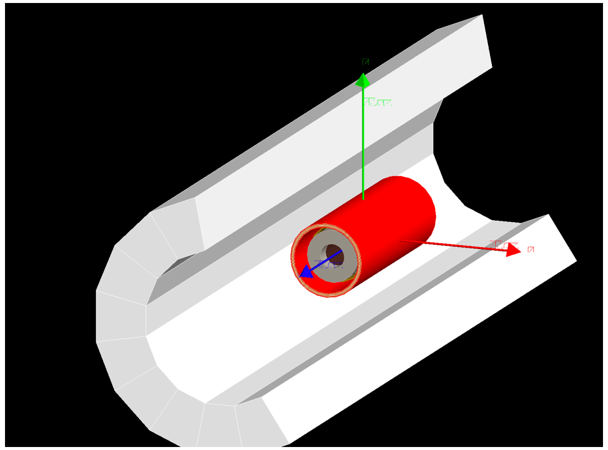


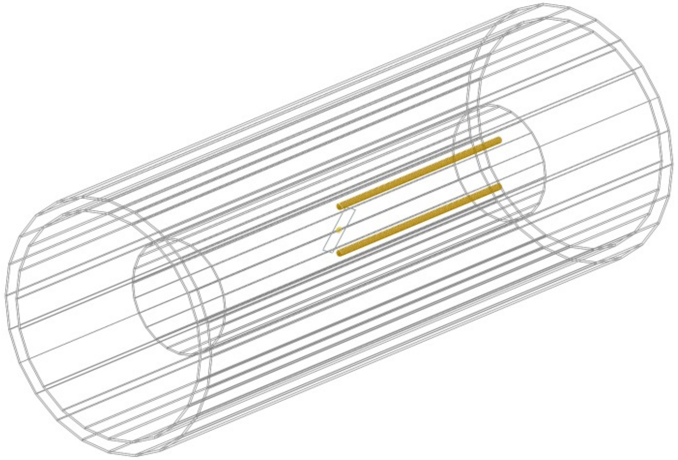


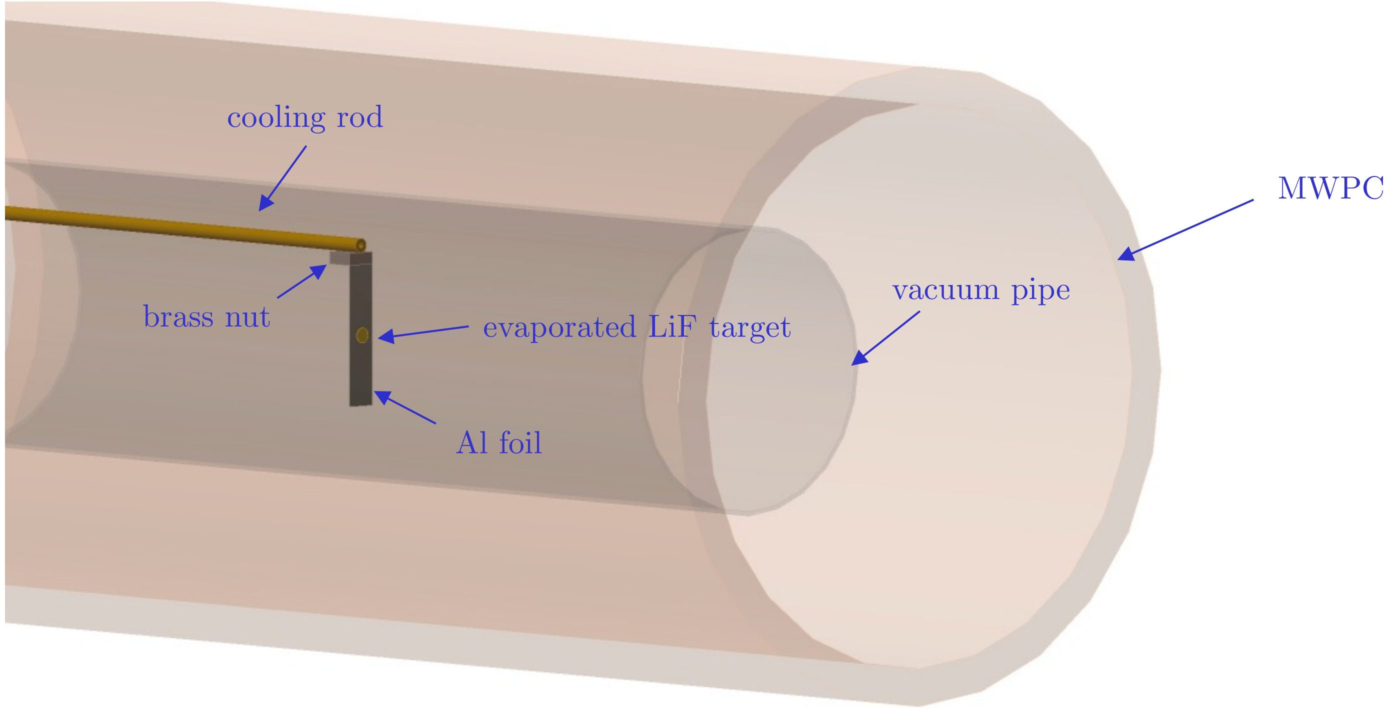
Planning initial run with 2 sectors of 60 degrees

- cover angular range 0°-60° and 120°-180°
- test full chain measurement and DAQ
- first tests and calibrations with 6.15 MeV photons from $^{19}F(p,\alpha\gamma)^{16}O$
- measure rates

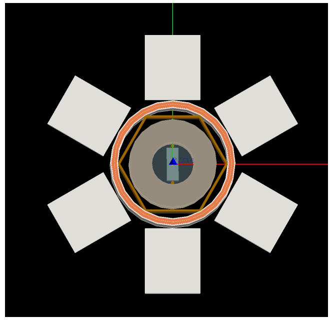
Monte Carlo simulation with Geant4



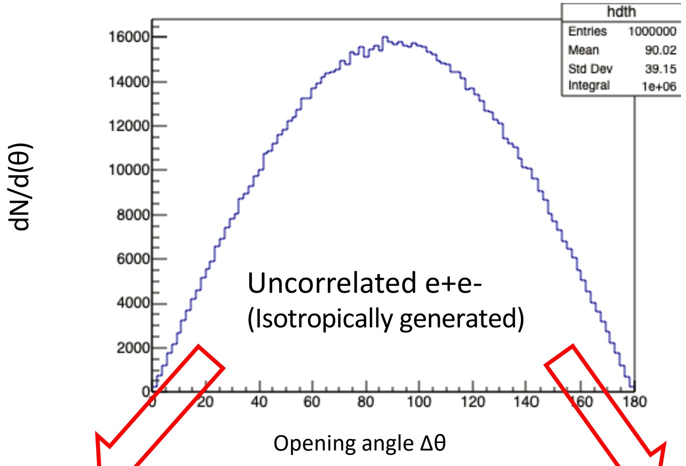


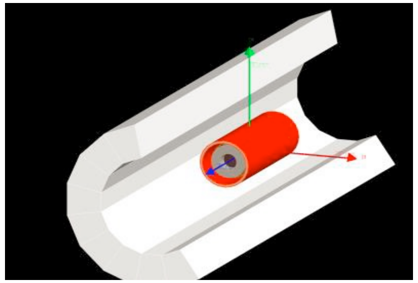


Geometrical Acceptance



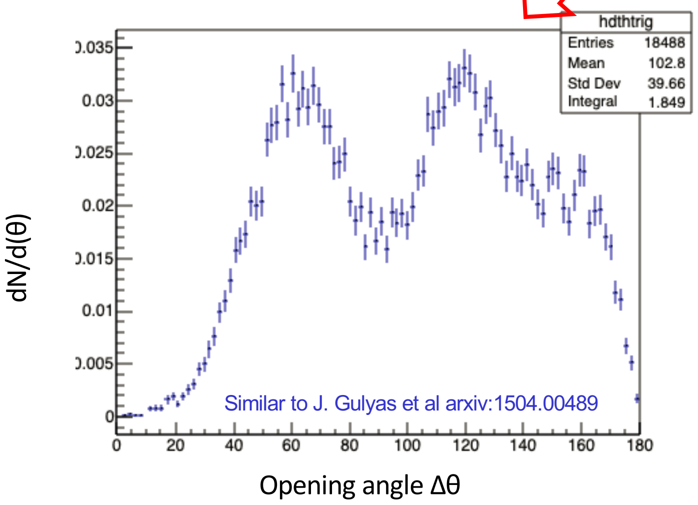
ATOMKI geometry

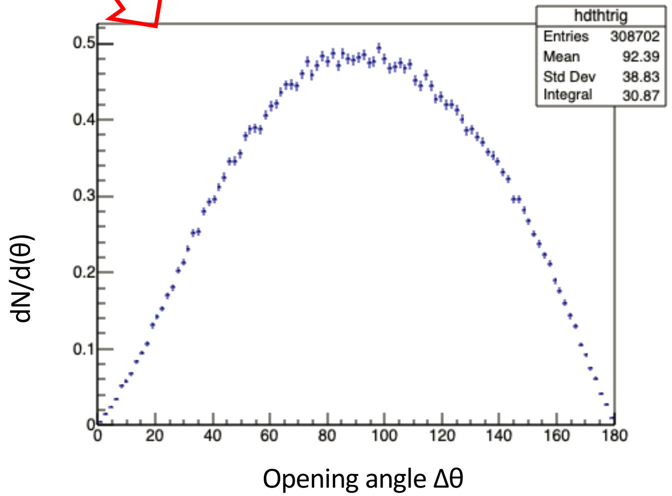


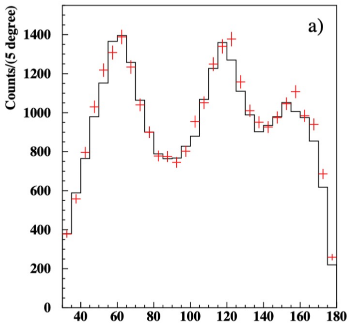


Montreal geometry

[Gulyás J, et al.](), [A.J. Krasznahorkay et al.]()







Angular dependence

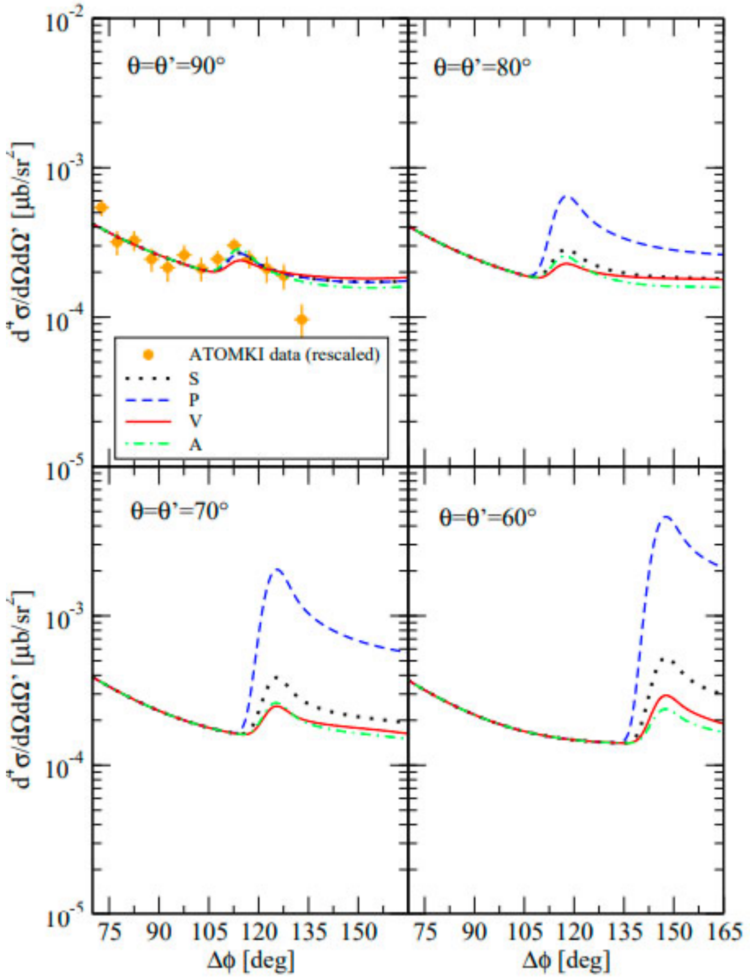


FIG. 6. The four-fold differential cross section for the $^3H(p,e^-e^+)^4He$ process at 0.90 MeV incident proton energy for the configuration in which the e^+ and e^- momenta are emitted at angles $\theta=\theta'$ with respect to the incident proton momentum, and as function of the difference $\Delta\phi = \phi' - \phi$.

If X17 produced in direct E1-capture (^4He,^{10}B..)

Angular distribution of the e^+e^- pair depends on the X17 quantum numbers

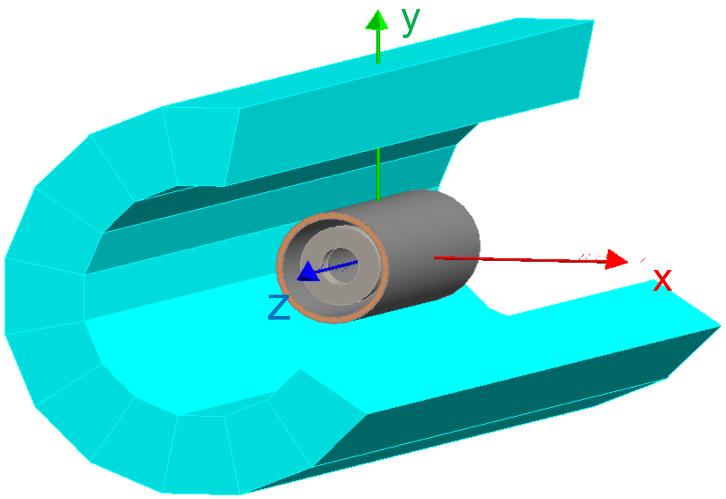
Large angular acceptance allows discrimination btw. different decay modes

Motivation for a large ang. acceptance experiment!

M. Viviani et al. Phys. Rev. C 105, 014001 (2022)

Monte Carlo simulation with Geant4
Assumed parameters

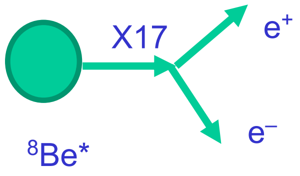
- MWPC
  - angular resolution: 2^o
- Scintillator bars:
  - energy resolution ~ $7\,\%/\sqrt{E(MeV)}$
  - position resolution: ~ 10 cms FWHM in z direction from energy sharing and time difference at the two ends

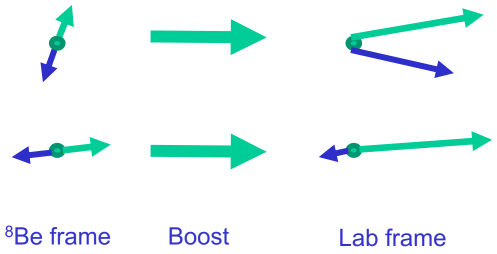


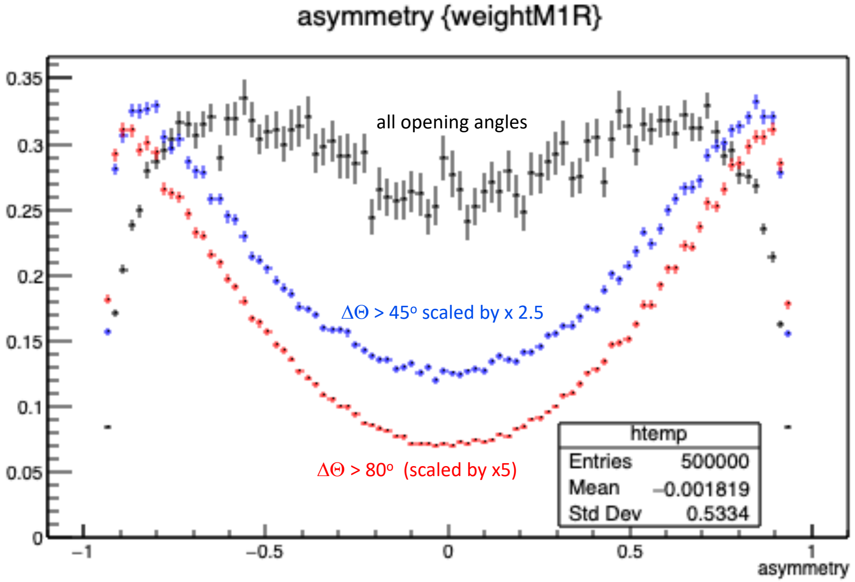
- Calibration/resolution of scintillators ongoing
  - scintillator bars tested for light output and light attenuation length
  - phototubes tested with LED's for gain and stability

3 basic observables for e^+e^- pair

- opening angle
  - heavy particle → small boost → large opening angle
- asymmetry: $y \equiv \frac{|E_1 - E_2|}{E_1 + E_2}$
  - for low m_{ee}, large opening angles correlated with large asymmetry.
- invariant mass m_{ee}
  - preselection of large m_{ee} removes a lot of background and fake signals



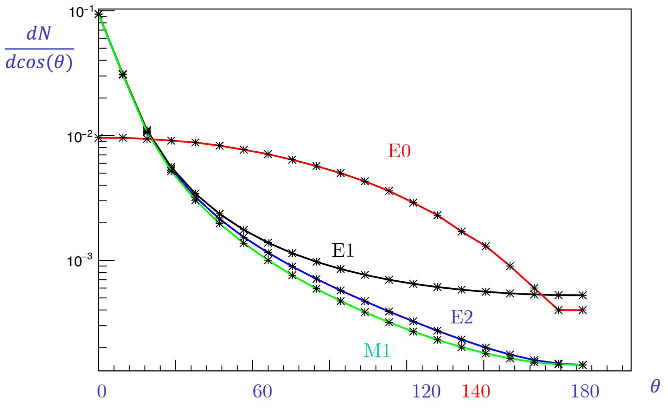


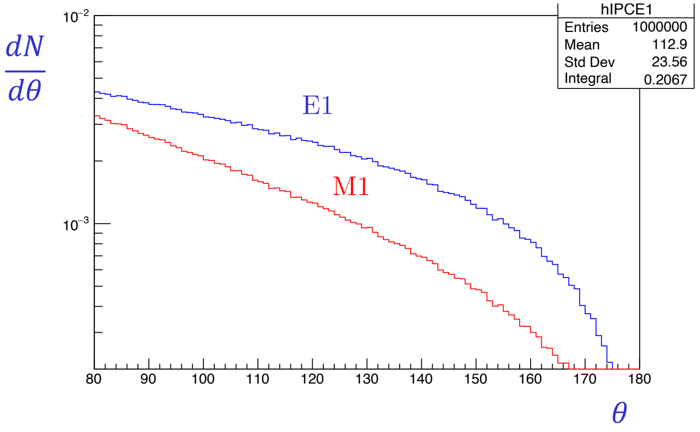


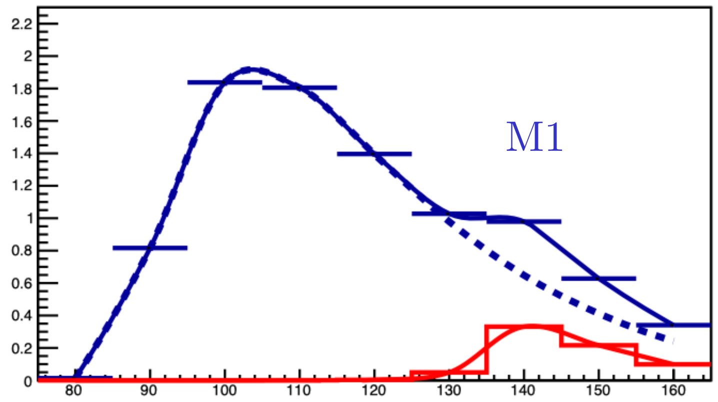
Simulation – 8Be* (IPC & X17)

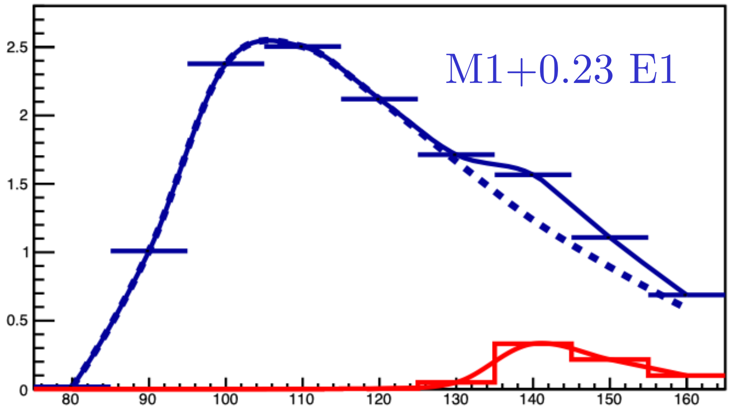
- Reconstructed opening angle
  - asymmetry < 0.5
  - $m(e^+e^-) > 12$ MeV
  - assumes $\frac{B(X \to e^+e^-)}{B(^8Be^* \to \gamma)} = 5.8 \times 10{-}6$

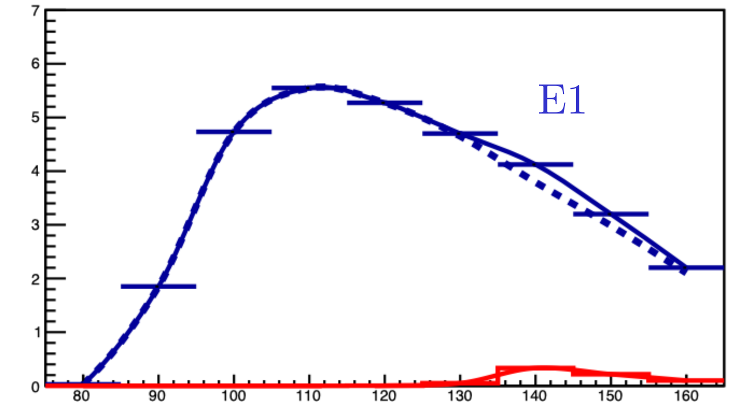
    or $\frac{B(X \to e^+e^-)}{B(^8Be^* \to e^+e^-)} = 1.5 \times 10^{-3}$
- strong dependence on E1/M1 ratio
  - due to higher IPC coefficient for E1 than for M1 at high θ
    - assuming same X/γ BR implies higher background at high θ for E1 transition
    - but in region of interest, experimentally: S/B ~ 0.7





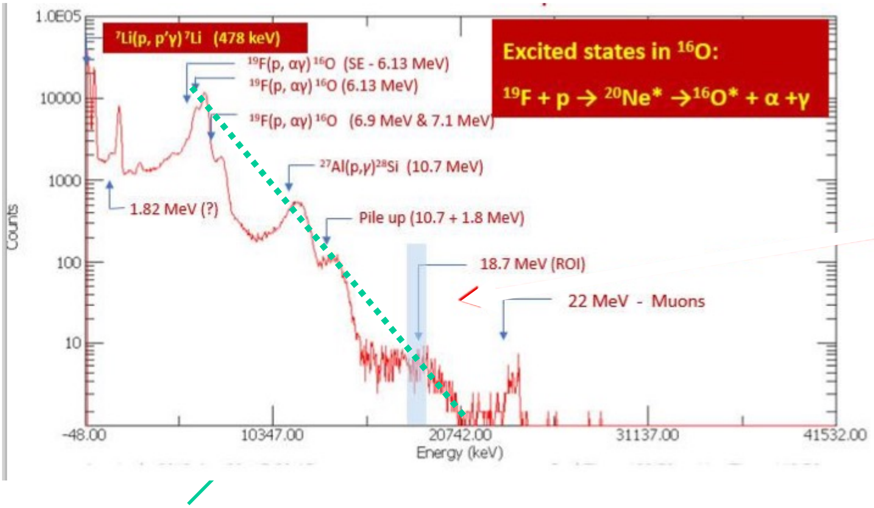






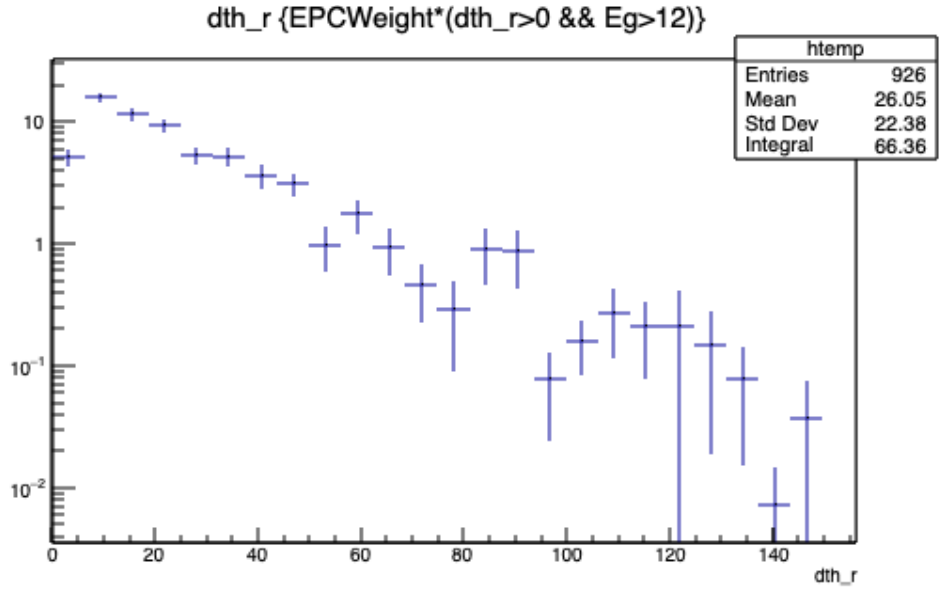
EPC simulation

Rough spectrum of gamma rays



approximate as an exponential

log_10 (N) ~ -0.233 * E + 5.42

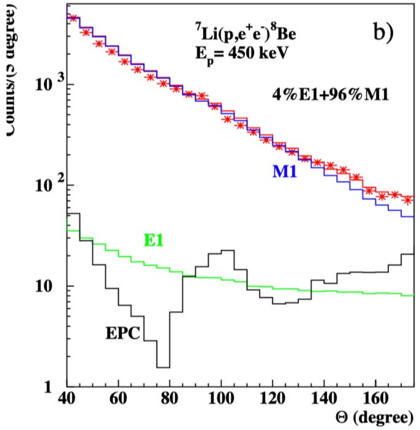


Reconstructed opening angle of e^+e^-,from EPC, *requiring*

E_{e+e-} > 12 MeV for 10^6 photons above 6.1 MeV generated

→ *very few events in region of interest*

→ *unknown rate of photons ...*



Gulyás J, et al. , A.J. Krasznahorkay et al.

Signal rates

- Measured BGO rates @ I_p = 2μA extrapolated to 0.9 x 4π – coverage:

E_γ = 478 keV: $R_\gamma = 5.7 \times 10^5\ s^{-1}$

B(IPC/γ) = 3.9×10^{-3}

$$\frac{\sigma\,^7Li(p,\gamma)^8Be^*}{\sigma\,^7Li(p,\gamma)^7Li} = 7.5\times10^{-4}$$

R_{IPC} (18.2 -> GS) = $1.7\ s^{-1}$

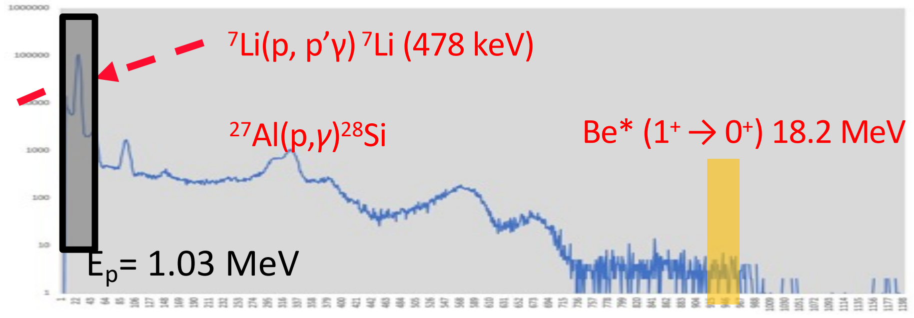
cuts on y, ROI — Geant4

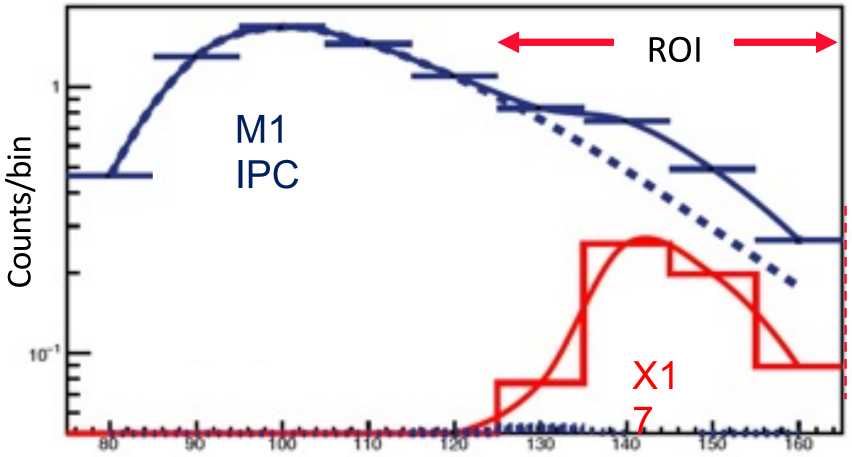
R_{IPC} (in ROI) $= 15\ h^{-1}$

R_{X17} (in ROI) $= 9\ h^{-1}$

(Data taking 1 - 2 weeks @ I_p = 2μA)

(Expected $R_{trigger}(\gamma\gamma)$ (E_γ > 6 MeV; $E_1 \wedge E_2$) = 30 Hz)





Consistent with ATOMKI's measurement: (5μA for 50 hrs) - N.J. Sas et al., arXiv:2205.07744

Conclusions

- X17 experiment setup progressing
  - Scintillator bars instrumented and mounted
    - tested with cosmic rays
    - gains adjusted and calibration approximately measured
    - good signals
  - MWPC
    - large solid angle gives uniform angular response
      - helps in determination of nature of X17
    - prototype preamplifiers fully tested
      - signals in wires and strips
      - ready for production
    - good progress in DAQ system
  - Simulations
    - Geant4 simulation of boson, IPC, cosmic rays
    - EPC simulation needs beam test results of gamma ray spectrum and rates
- prospects
  - Eventually extend to other states & nuclei: ^{10}B(17.8, 19.3), ^{4}He (22 MeV), ^{12}C(17.2)
  - Giant Resonance? (bombard at 4-5 MeV, but high neutron flux)

backup

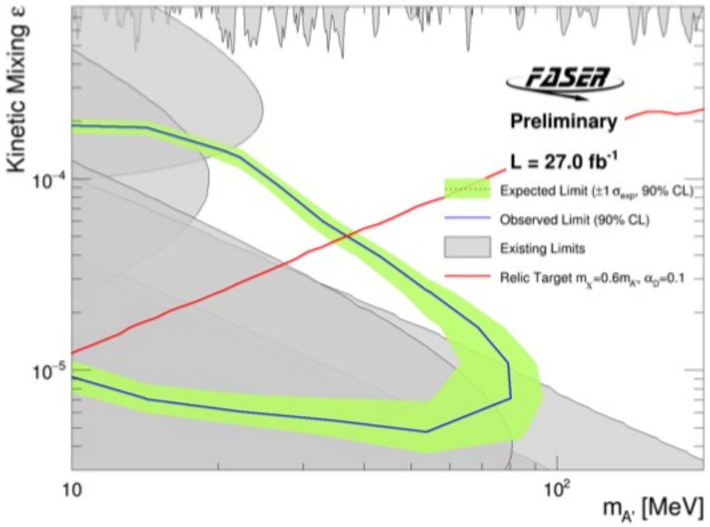


Figure 2 – The 90% confidence level exclusion contour in the dark photon model parameter space. Regions excluded by previous experiments are shown in grey[12]. The red line shows the region of parameter space which yields the correct dark matter relic density, with the assumptions discussed in the main text.

arXiv:2305.08665

Krasznahorkay AJ et al,

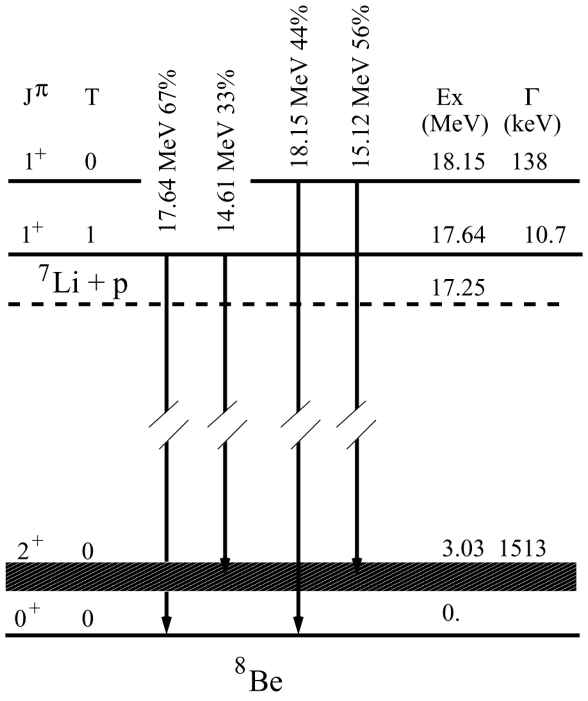


Figure 1: *The most relevant 8Be states and their spin-parities J^{π}, isospins T, excitation energies Ex, and decay widths Γ from Ref. [23]. Decays of the ^{8}Be 18.15 MeV state to the ground state of ^{8}Be exhibit anomalous internal pair creation.*

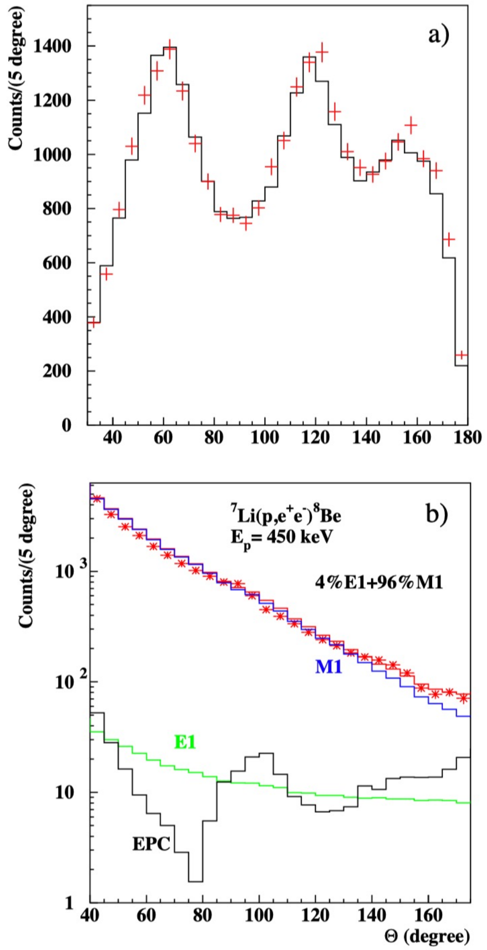


FIG. 1. a) Detector response for the setup as a function of correlation angle (θ) for isotropic emission of e^+e^- pairs (red crosses) compared with the results of the Monte Carlo simulations (black line histogram) as explained in the text. b) e^+e^- angular correlations obtained for the 17.6 MeV transition of ^{8}Be by using thin target backing compared to the simulations performed for E1 and M1 IPC, as well as for the EPC created by the γ-rays on the different materials around the target.

Krasznahorkay AJ, *et al.*,
Phys.Rev.C 106 (2022) 6, L061601, arXiv:2209.10795