Precision searches at the intensity frontier with muons at PSI

From MEG II calibration methods to the muEDM positron tracker

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XXXVI cycle

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Today's presentation

- Particle physics at PSI
- The muEDM experiment
  - Introduction and 'frozen spin'
  - Thin scintillators
  - Positron Tracker
- The MEG II experiment
  - Introduction and Cockroft-Walton
  - Liquid Hydrogen target
  - X17 search
- Wrap-up

Today's progress-bar

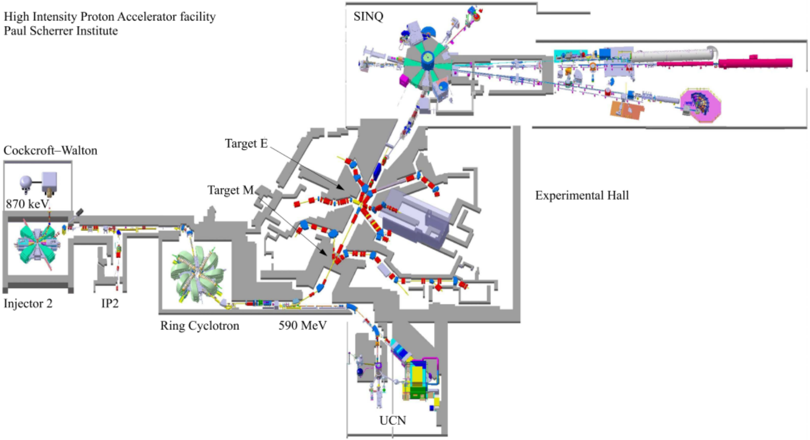
1. Introduction
   - Particle physics at PSI
2. muEDM
   - Experiment
   - Scintillators
     - Tracker
3. MEG II
   - Experiment
     - LH2
     - X17
4. Wrap-up

Paul Scherrer Institute

Paul Scherrer Institute (PSI) is the largest federal research institute in Switzerland

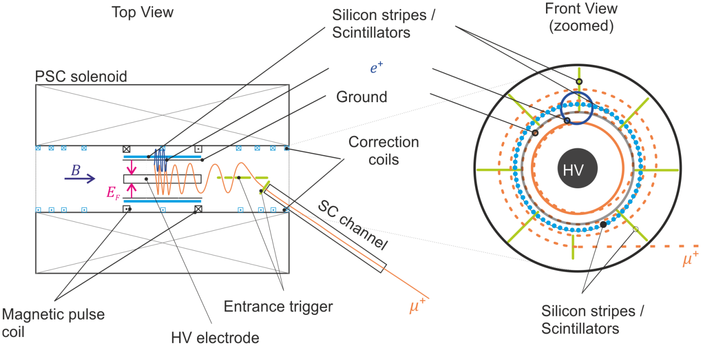
PSI: Beamlines and facilities

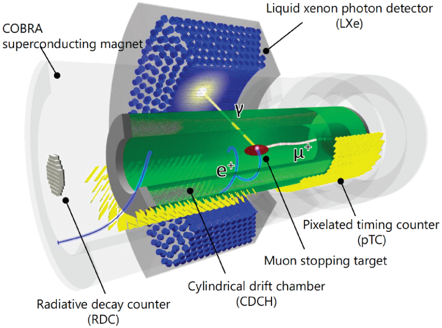
- The most powerful proton accelerator: a power of 1.4 MW and a beam current of over 2 mA
- Used to produce secondary particle beams (μ, π, e): continuous beam up to few$\times 10^8 \mu/s$



PSI: experiments

- Experiments with muons, muonic atoms, neutrons, SwissFEL, SLS, ...
- We will discuss muEDM and MEG II



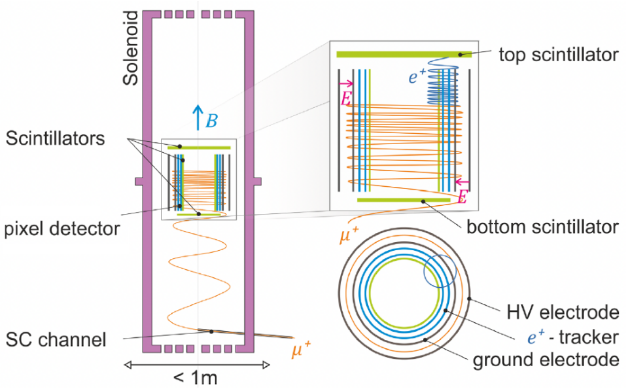


Today's progress-bar

MuEDM in one slide

- g-2 direct limit[a] $d_\mu < 1.8 \times 10^{-19}\,\mathrm{e\,cm}$
- Aim is $6 \times 10^{-23}\,\mathrm{e\,cm}$ using *frozen spin*
- Backwards $\approx 90\%$ polarized μ^+ beam
- Superconducting shielded injection
- Muon *kicked* in a 'virtual' storage ring
- Thin electrodes to freeze the spin
- Positron tracking after the decay
- 'Up-down' asymmetry is the observable

[a]Bennett et al.,PRD80(2009)052008



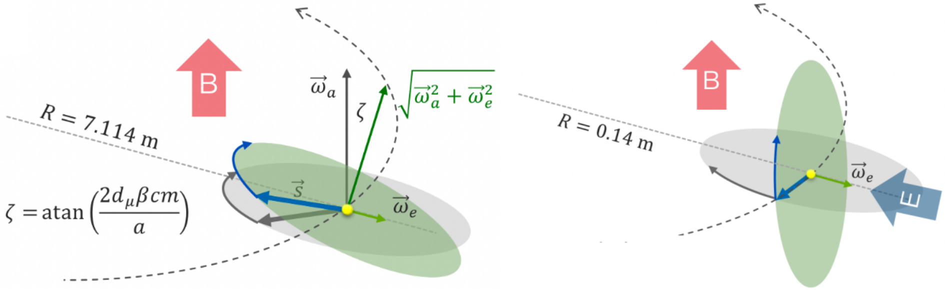
Frozen-spin technique

- MDM and EDM describe the interaction of the spin with EM fields: $\hat{H} = -\mu\hat{\boldsymbol{\sigma}} \cdot \boldsymbol{B} - d\hat{\boldsymbol{\sigma}} \cdot \boldsymbol{E}$
- Thomas-BMT equation gives the precession of the spin

$$\boldsymbol{\Omega} = \boldsymbol{\Omega}_0 - \boldsymbol{\Omega}_c = \underbrace{\frac{q}{m}\left[a\boldsymbol{B} - \cancel{\frac{a\gamma}{\gamma+1}(\boldsymbol{\beta}\cdot\boldsymbol{B})}\boldsymbol{\beta} - \left(a - \frac{1}{\gamma^2-1}\right)\frac{\boldsymbol{\beta}\times\boldsymbol{E}}{c}\right]}_{\text{Anomalous procession, } \omega_a = \omega_L - \omega_c}$$
$$+ \underbrace{\frac{\eta q}{2m}\left[\boldsymbol{\beta}\times\boldsymbol{B} + \frac{\boldsymbol{E}}{c} - \cancel{\frac{\gamma c}{\gamma+1}(\boldsymbol{\beta}\cdot\boldsymbol{E}}\boldsymbol{\beta})\right]}_{\text{Interaction of EDM and relativistic } \boldsymbol{E},\ \omega_a}$$

- Taking $\boldsymbol{p} \perp \boldsymbol{B} \perp \boldsymbol{E}$ the equation is simplified
- Anomalous precession term can be set to zero taking $a\boldsymbol{B} = \left(a - \frac{1}{\gamma^2-1}\right)\frac{\boldsymbol{\beta}\times\boldsymbol{E}}{c}$

Frozen-spin technique



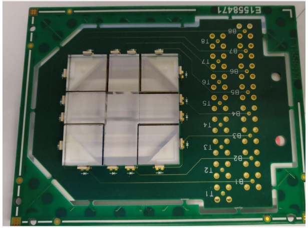
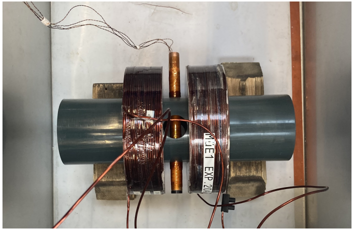
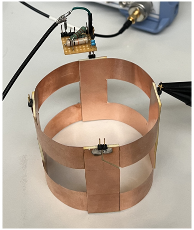
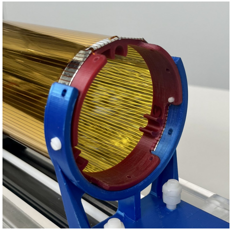
- If $\eta = 0$ the angle between *p* and spin is unchanged $\rightarrow$ *frozen*
- In the presence of an EDM the change in polarization follows
- The net result is a longitudinal build-up of the polarization $\rightarrow$ Direction of the positrons

Take home message

With orthogonal $\boldsymbol{p} \perp \boldsymbol{B} \perp \boldsymbol{E}$ and the adequate fields, EDM translates in a *time-dependent longitudinal* polarization, giving a positrons emission asymmetry

muEDM: Several subsystems

- The project went through many studies and prototypes
  - Beam monitoring to follow beam time variations
  - Superconducting shielded channel to inject the beam
  - Magnetic pulse generator to store the muon
  - Electrodes to freeze the spin
  - ...
- We will discuss:
  - Thin scintillators to trigger the magnetic kick and ToF
  - Few iteration of the positron tracker design

Today's progress-bar

Scintillators for muEDM

- Plastic scintillators
  - Emit light after ionizing radiation
  - Roughly $1 \div 100$ γ/eV of E deposit
- Trigger for the magnetic pulse
  - Thin enough to keep the phase-space
  - Thick enough to have a readable signal
  - $\Rightarrow$ for 28 MeV/c muons $25 \div 200$ μm
- Positron tracker
  - Add layers of lower refractive index to 'filamentous' scintillators to make fibres
  - Less light but collected far from the hit
  - Resolution $\sim$ fibre width ($0.25 \div 1$ mm)

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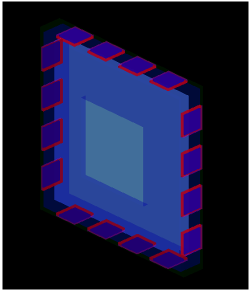
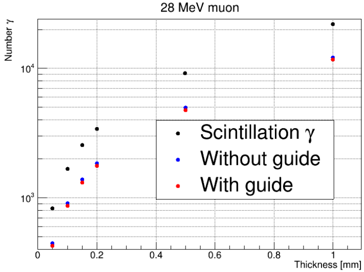
GEometry ANd Tracking (GEANT4)

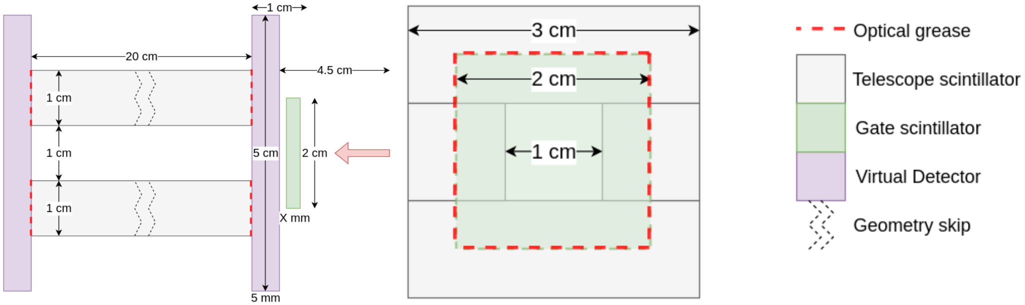
Toolkit to simulate particles-matter interactions
It is step-based and can handle optic simulations
Started with plain scintillators, adding optical grease and SiPM, up to fibres simulations for the tracker



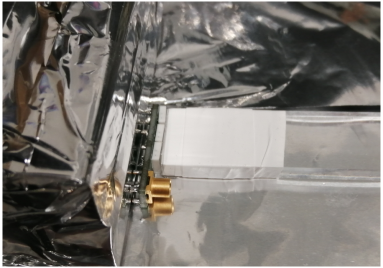
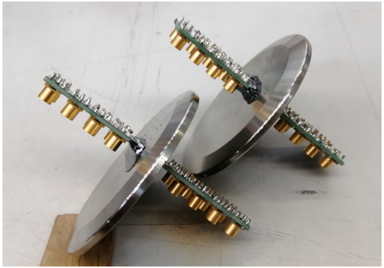
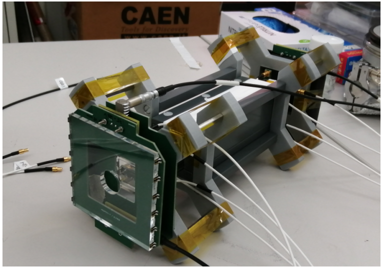


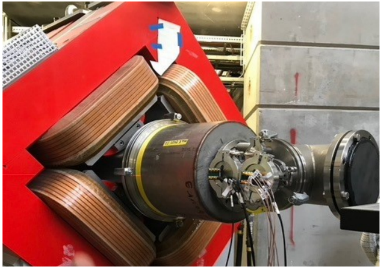
Gate and Telescope

- Key aspect is the triggering of the magnetic pulse to store the muon
- Needs to be reliable, fast, and should not disrupt the muon phase-space
- A single scintillator would be sufficient but needs to be characterized
- A telescope can be used to study the effect of the scintillator on the beam



Gate and Telescope construction

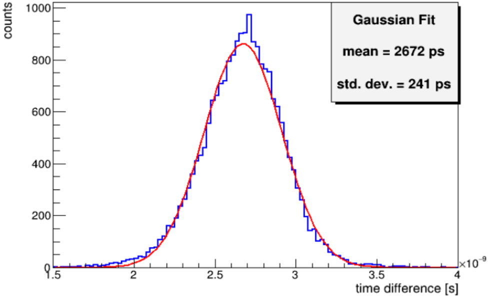
Trigger Patterns

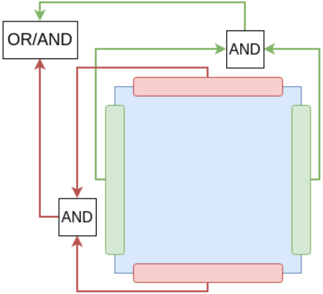
Clear Or All Help

Chn	Pol	P00	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12	P13	P14	P15	P16	P17
CH0	-	•		×	×	×	×	×	×	×	×	×	×	×	×	×	×	•	
CH1	-		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	×	
CH2	-			×			×	•	•							•	•		
CH3	-			×			×	•	•										
CH4	-			×			×			•	•								
CH5	-			×			×			•	•								
CH6	-			×			×					•	•						
CH7	-			×			×					•	•						
CH8	-			×			×							•	•				
CH9	-			×			×							•	•				
CH10	-			•	•				•		•		•		•		•		•
CH11	-																		
CH12	-																		
CH13	-																		
CH14	-																		
CH15	-																		
EXT	-																		

Gate and multi-readout

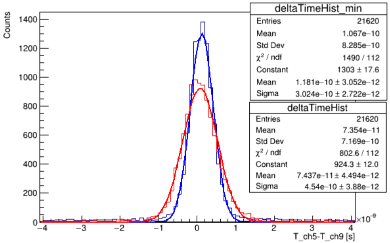
- The *gate* 100 μm is to be tested via an *exit* 200 μm scintillator
- The time resolution is defined by both detectors $\sigma \approx 240$ ps
- The efficiency is limited by the number of total photons generated
- A low -50 mV threshold would allow $\sim 90\%$ efficiency but a high dark noise ~ 150 kHz
- Reading the four sides and adding logic to the trigger would allow for low thresholds

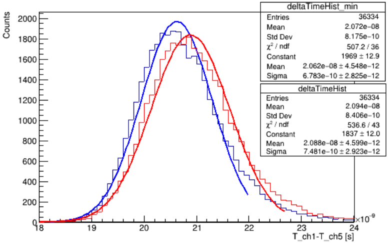


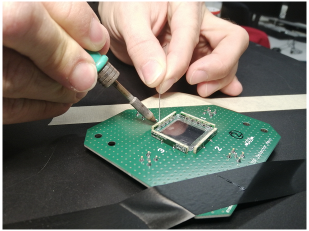


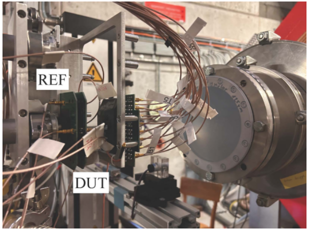
Time of Flight and resolutions

- A ToF can be used to select particle momentum
- The aim is to study the systematic effects of CW CCW
- Requirements are still fuzzy so we tested 100, 50, 25 μm
- Multi-readout is needed to improve the resolution and efficiency
  - AND of more ch to lower the DR $\rightarrow \varepsilon_{100\,\mu\mathrm{m}} > 99,\ 98,\ 96,\ 95\%$
  - We obtained $\sigma \approx 450 \xrightarrow{multi} 350$ ps





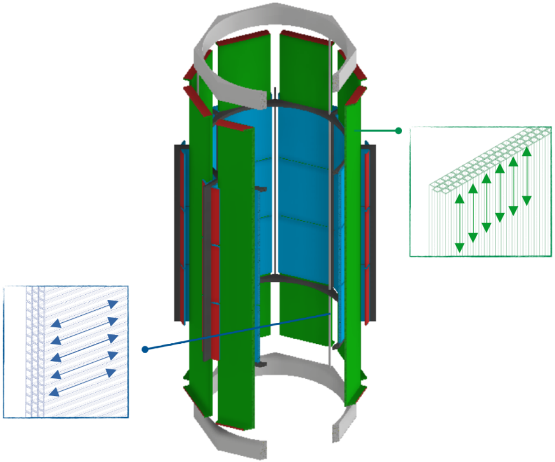




Today's progress-bar

SciFi Tracker

- UK: straw tubes and/or silicon pixels
- Our idea was to add bundles of fibres
  - Fast solution with good spatial resolution
  - ‘Simple’ to construct
  - Potentially a lot of readout
  - Readout not trivial for transverse fibres
- Original design
  - Cylinder of longitudinal external fibres
  - ‘Barrels’ of transverse inner fibres

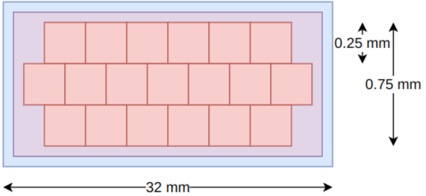


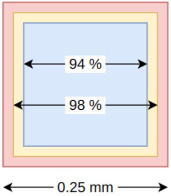
Mildly confusing point

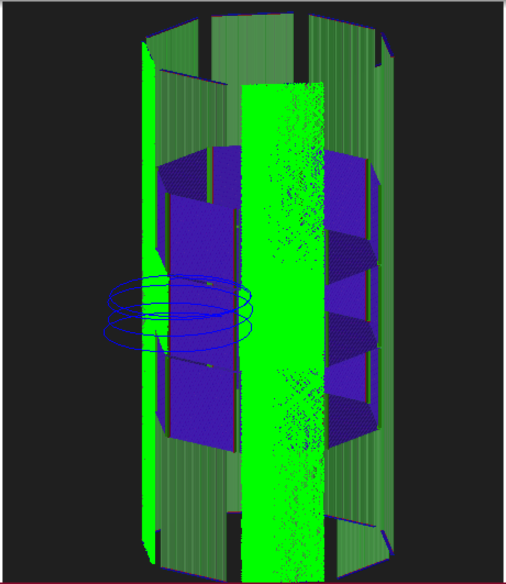
Fibres which run longitudinally have better resolution in the transverse direction and vice versa

SciFi Tracker Geant4

- Bundles of fibres 3cm $\times$ Xcm
  - 3 layers of 0.25mm staggered fibres
  - fibres with core and two layers
- External longitudinal fibres
  - Long as much as needed
- Internal transverse fibres
  - probably 5 layers for 15cm coverage
  - Internal could cover one or more external
- Many channels and challenging to readout

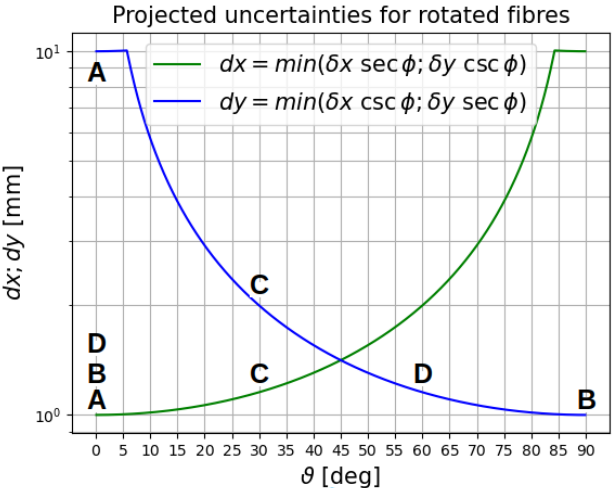


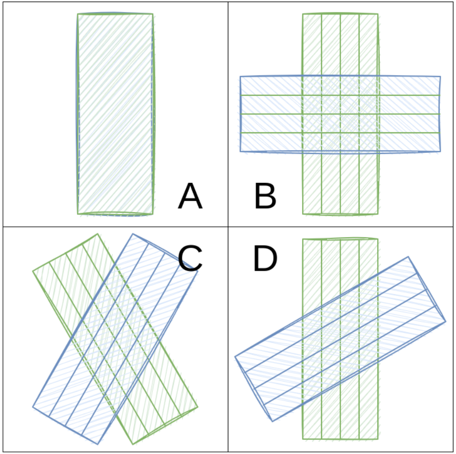




Uncertainties and crossed fibres

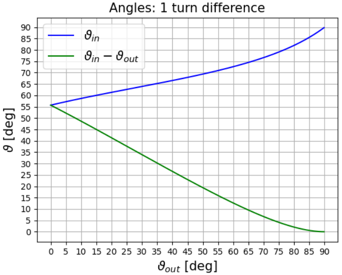
An interesting alternative is to cross fibres to reduce the uncertainties and channels

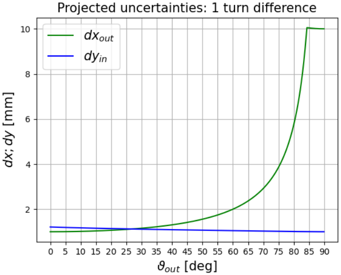


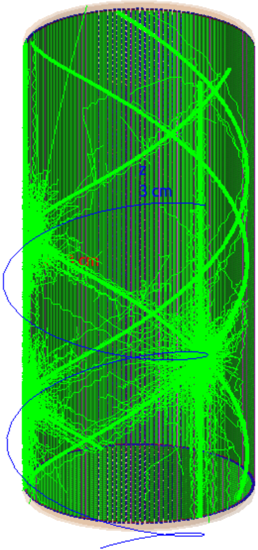


Cyindrical Helicoidal Tracker CHeT

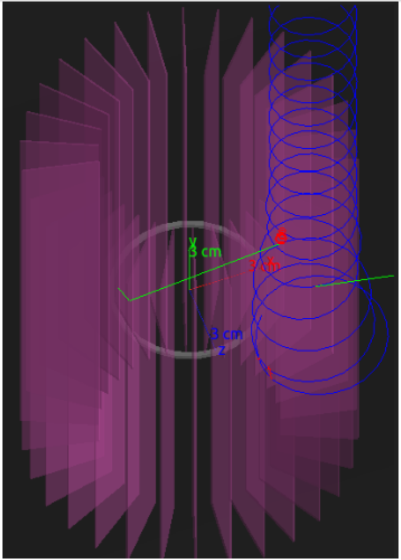
- If we want external readout the fibers must be helicoidal
- Following a cylindrical symmetry we can have crossed layers
- Requiring for 1 turn difference we reduce the chance of *ghost* hits
- Resolutions depend on angles and total length of the cylinder
- Promising design but too few hits to be the only tracker



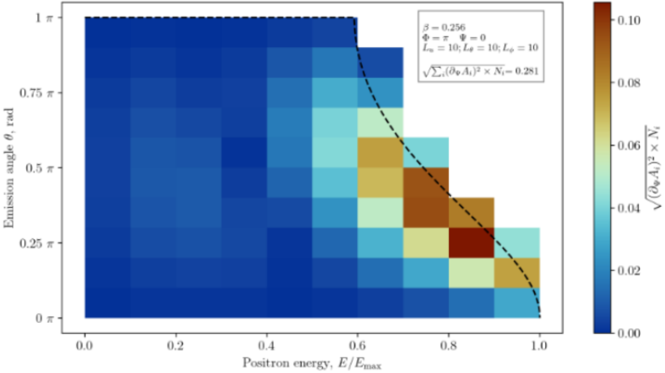




Radial design



- We need a standalone version for Phase I
- Some positrons bring more information
- A purely radial solution was found to be not satisfactory and the current aim is a combo of cylindrical and radial

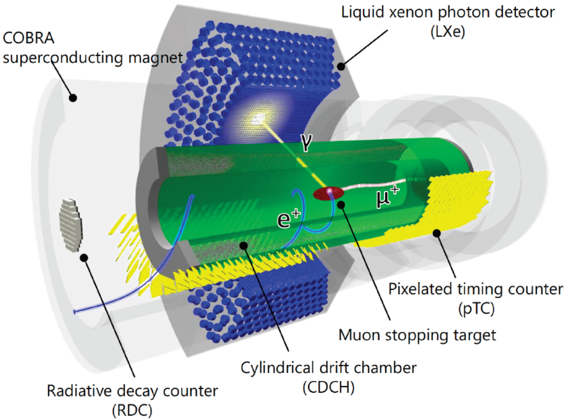


Today's progress-bar

MEG II in one slide

- The process of interest is $\mu \to e\gamma$
- Aim is a sensitivity of 6×10^{-14}[a]
- Positron reconstruction:
  - COnstant Bending RAdius (COBRA)
  - Pixellated Timing Counter (pTC)
  - Cylindrical Drift CHamber (CDCH)
- Liquid Xenon Calorimeter (XEC) for the γ

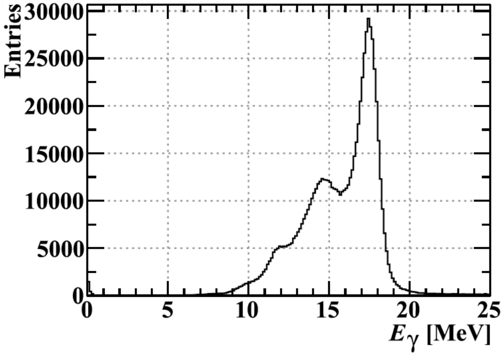
[a] Afanaciev et al., EPJ C(2024)84

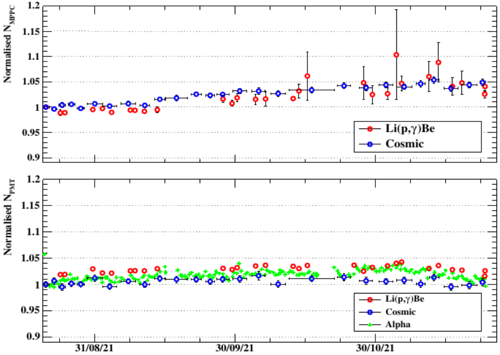


Calibrations of the Liquid Xenon Calorimeter

- 900 Liters of Xe read by MPPCs and PMTs
- Complex and delicate calibrations:
  - CW dedicated runs of ^{7}Li(p, γ)^{8}Be at 17.6 MeV (3/week)
  - Charge EXchange reaction at 55 MeV (1/year)

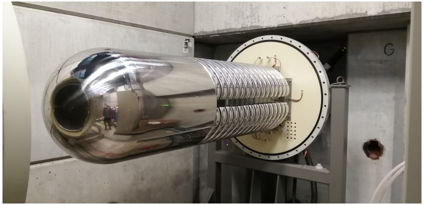
Resolutions	
$\sigma_{E_\gamma}(w)$	2.0/1.8 %
$\sigma_{u,v,w}$	2.5/2.5/5 mm
σ_{t_γ}	65 ps

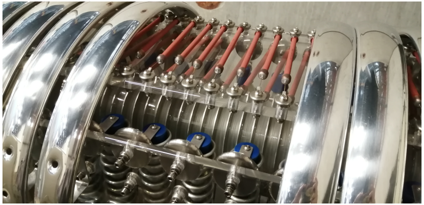




Cockroft-Walton

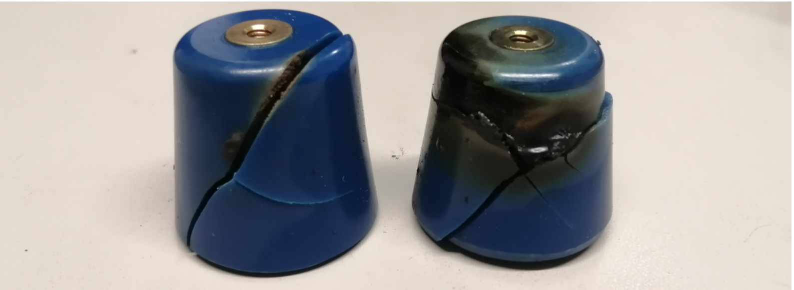
- Used 3/week for the ^{7}Li(p, γ)^{8}Be XEC calibration
- Last year had some issues:
  - Discharges at high voltages
  - Delay in the starting time

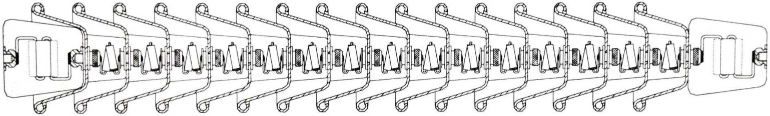




Cockroft-Walton

- Routine tests, like Q-factor and the ‘starting frequency’
- After removing the SF_6 and opening we found the problem
- The substitution of the broken rectifiers solved it

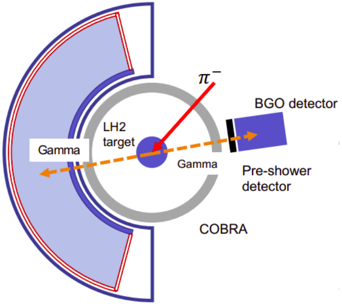


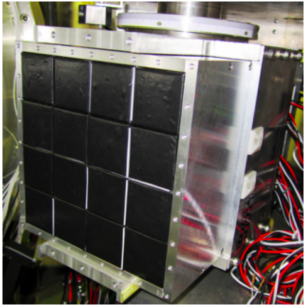


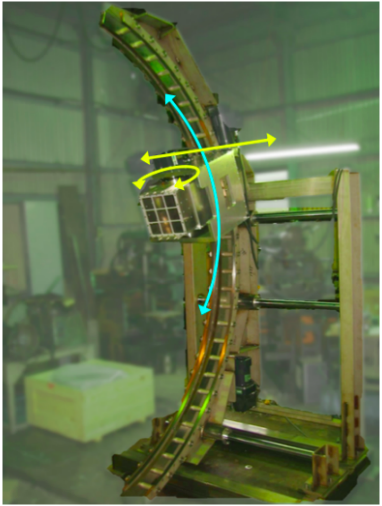
Today's progress-bar

Charge EXchange reaction

- How do we calibrate the XEC at 52 MeV?
- Charge EXchange: $\pi^- p \to \pi^0 n$; $\pi^0 \to \gamma\gamma$
- This process γ flat in $[54.9, 82.9]$ MeV
- Tagging with the BGO, we can select the 55 MeV
  - 16 scintillators of Bismuth germanium oxide $Bi_2Ge_3O_9$





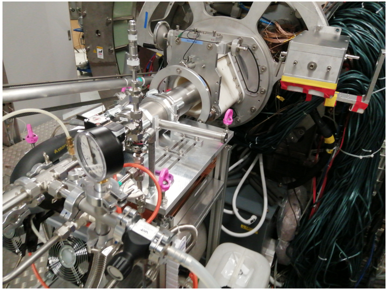


Liquid Hydrogen target

- A 'closed volume' hydrogen circuit, made of a buffer and the target cell at the tip
- A copper cold finger cooled fluxing liquid He in a copper coil and holding the cell
- Vacuum Insulation
- A slow-control system with P and T
- Small differences between iterations

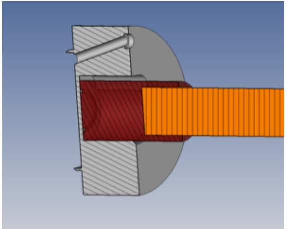
CEX: 2021

- I joined for the tests of the first iteration
- Tests outside the area with hydrogen were not allowed
- Minor adjustments required to start the liquefaction
- Two weeks of CEX with some stability issues



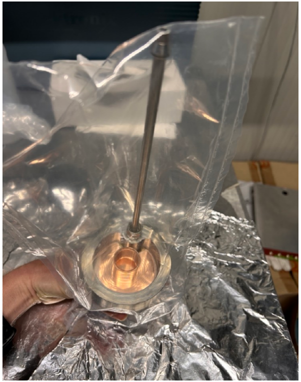
CEX: 2022

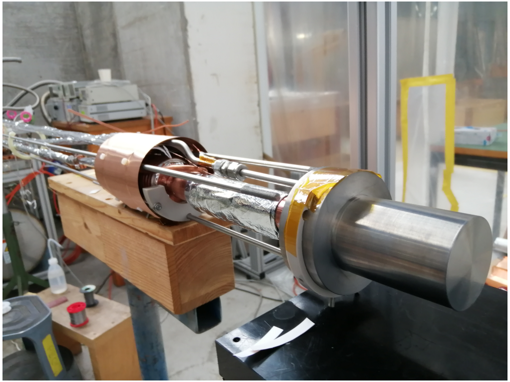
- Learning from the previous year:
  - modified cell for better thermal contact
  - super insulation to reduce heat radiation
  - additional lakeshores to study the system
- The test with hydrogen was allowed
- Two weeks of CEX with fewer stability issues
- Limiting factor: the dewar usage



CEX: 2023

- We opted to ditch the length of the system
- New compact version with new cell design and longer cooler
- Improved thermal shielding, in particular for the cell
- This will bring faster and more stable cooling/liquefaction

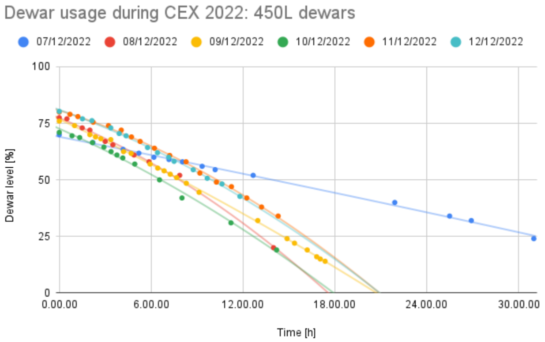


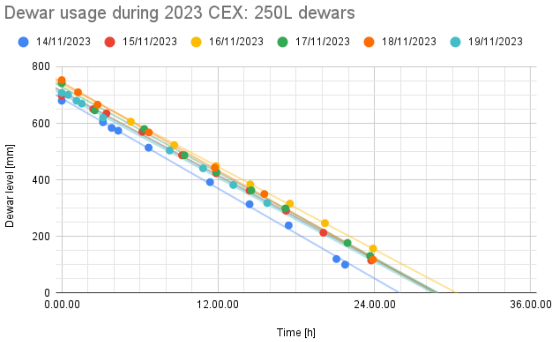


LHe usage

With the last modifications, the dewar usage improved significantly between 2022 and 2023:

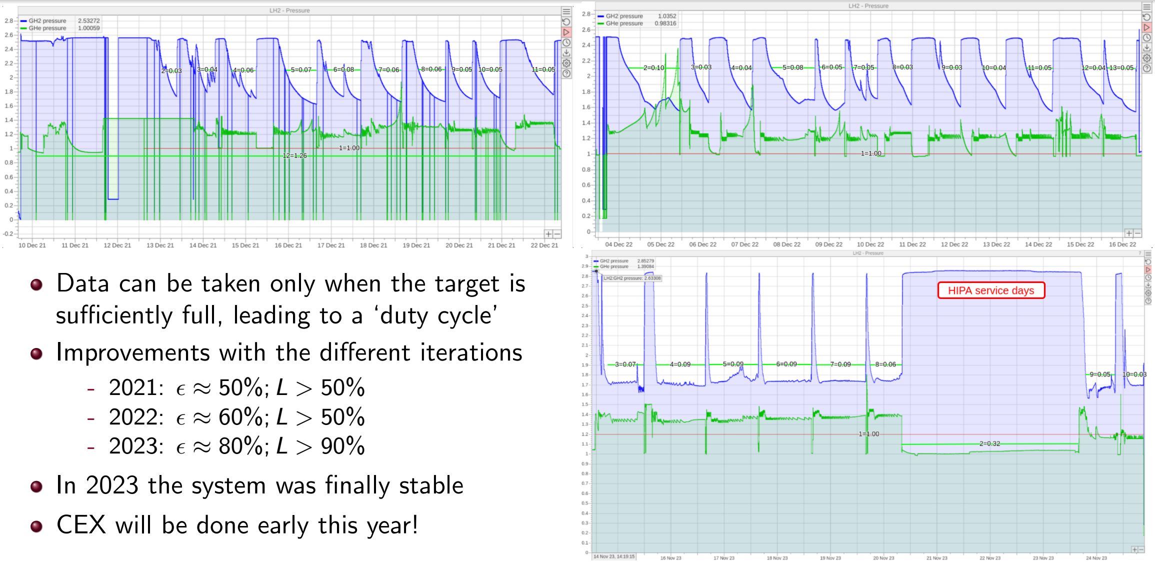
- 2022: varied trends, mostly below 20h for 400L (apart from a 'lucky-day')
- 2023: linear usage over 24h, allowing for simpler planning, with a smaller dewar!





Details of the dewar usage for 2021 not available but similar to 2022

Duty cycle



- Data can be taken only when the target is sufficiently full, leading to a ‘duty cycle’
- Improvements with the different iterations
  - 2021: $\epsilon \approx 50\%$; $L > 50\%$
  - 2022: $\epsilon \approx 60\%$; $L > 50\%$
  - 2023: $\epsilon \approx 80\%$; $L > 90\%$
- In 2023 the system was finally stable
- CEX will be done early this year!

Today's progress-bar

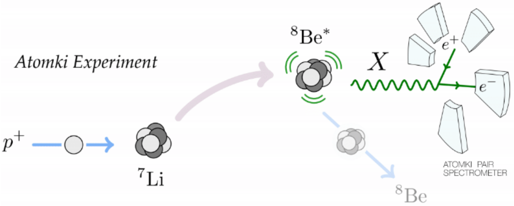
ATOMKI

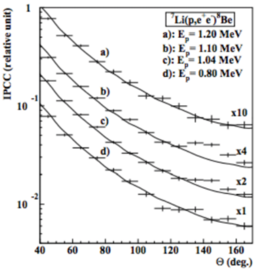
- Internal/External Pair Conversion in $^{7}\mathrm{Li}(\mathrm{p},\gamma)^{8}\mathrm{Be}$
- Excess[a] of IPC at $\sim 140\,\mathrm{deg}$ and $E_p = 1.1$ MeV

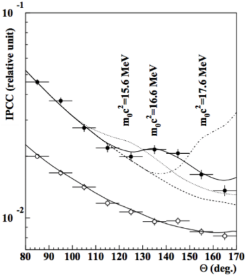
$\Rightarrow$ Explained with a light particle

  - $m_X = 16.95$ MeV
  - $BR(X) = 6 \times 10^{-6}$ (w.r.t. γ)

- A photophobic boson? mediator of fifth force?[b]
- Needs confirmation and a non-planar geometry
- MEG II, with its spectrometer, is a good candidate

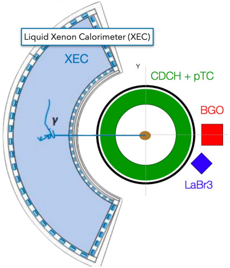


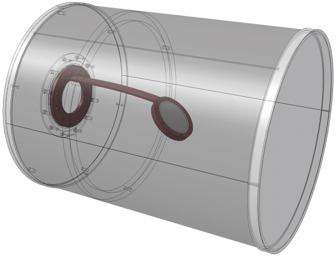


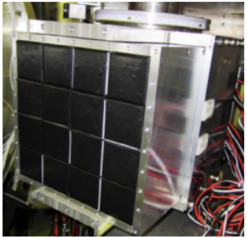


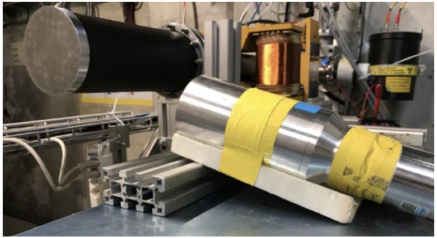
[a] Phys. Rev. Lett. 116, 042501
[b] Phys. Rev. D. 95, 035017

Adapt MEG II to the X17 search







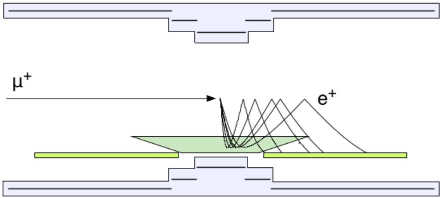


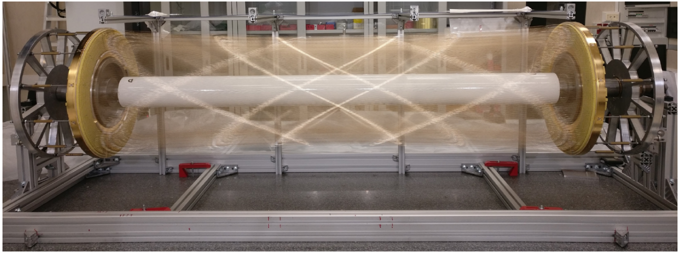
- Carbonfiber vacuum chamber
- Cu target holder for the heat
- LiPON[a] target (instead of LiF)
- BGO to collect the spectra (XEC not always available)
- Additional $LaBr_3$ as reference
- Reduced COBRA field to optimize for 17/2 MeV particles (15%)
- pTC/CDCH to track the pairs

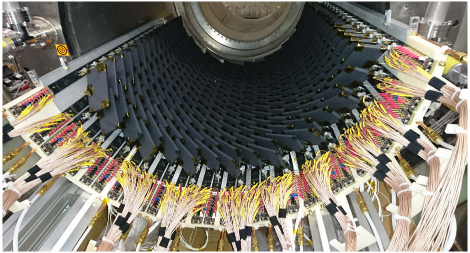
[a]Stable but produced with varying fractions

MEG II's spectrometer and reconstruction

- The COBRA magnet bends the positrons
- The pTC detects them and functions as a trigger
- The CDCH is the core tracker, with 12k wires
- Reconstruction of e^+ in $\vec{B}$ and e^- in $-\vec{B}$
- Pairs are created by applying cuts on these tracks

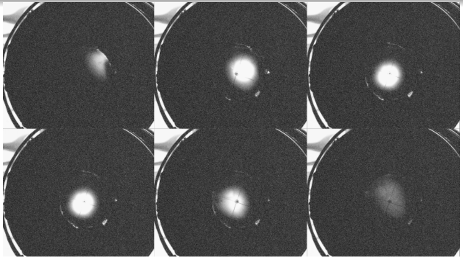


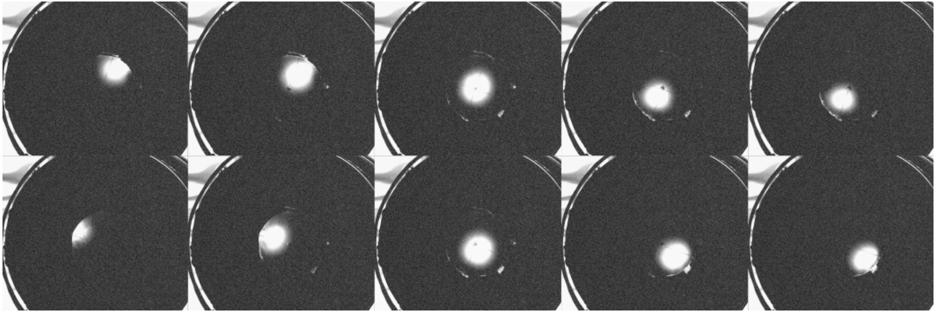




Beamtuning

- MEG's CW holds up to $\sim$ 1080 kV
- A pair of dipoles to center the proton beam
- A quartz to see the position of the beam
- Focus setting per each energy of interest
- Working points for energies in the whole range





BGO Energy Calibration

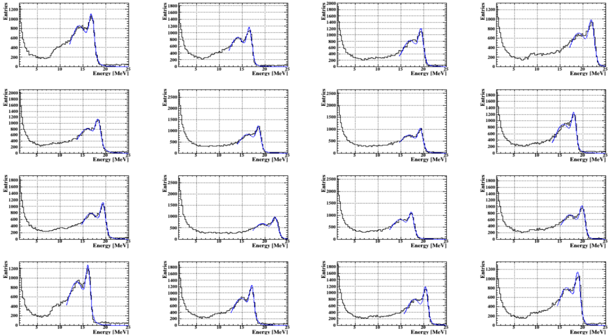
First, let's calibrate the BGO to reconstruct the spectra

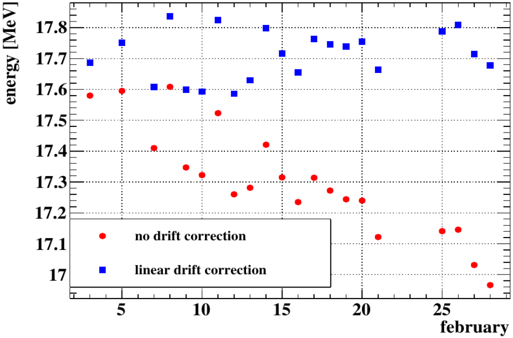
- Cross-calibrate the different crystals
- Calibrate the sum to be at the right energy
- Take leaking into consideration

→ Still a drift, which can be compensated

Photon energy from measured charges

$$E_\gamma = \sum_{j=0}^{15} K_{\text{scale}} \cdot K_{\text{leak}} \cdot a_j \cdot I_j$$

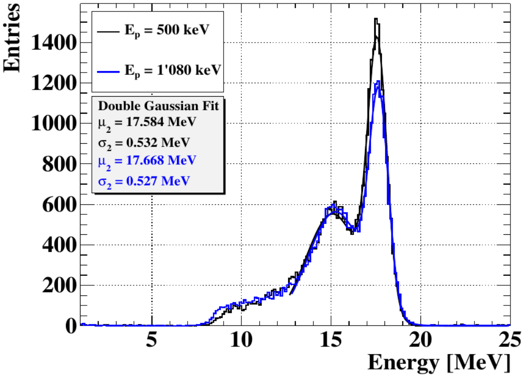


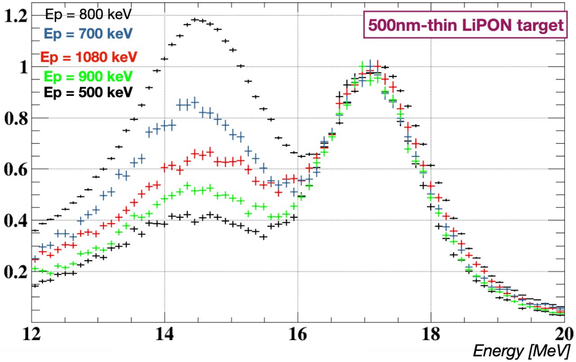


Spectra

- Change the proton energy 500 keV → 1 MeV ⇒ expectation is a 300 keV shift
- The relative height of the 15 vs 18 MeV peaks is not consistent

⇒ The data collected seems to be mostly 17.6 MeV instead of 18.1 MeV
The X17 can still be at $E_p = 500$ keV, and a new data-taking is planned at $E_p = 1080$ keV



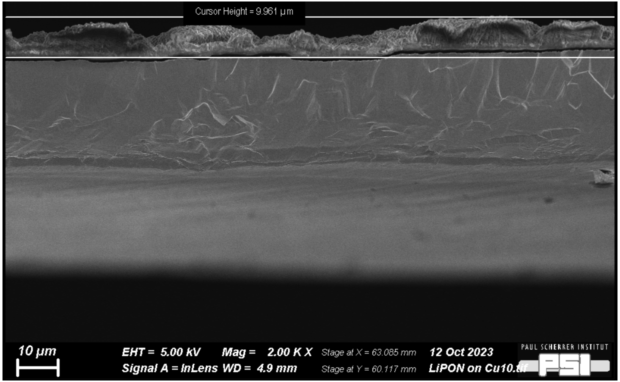


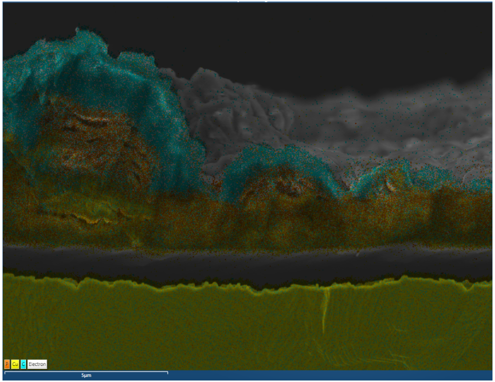
Target analysis

We tried to explain the discrepancies we found analyzing the target:

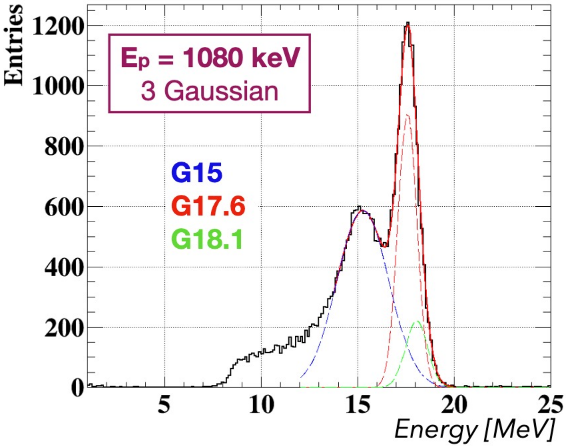
- Thicker [2 $\rightarrow$ 10 μm] and rougher than expected
- Strange layer of Carbon, possibly some form of oxidation

$\Rightarrow$ Possibly contributing, but probably not the main culprit





CW beam particle composition



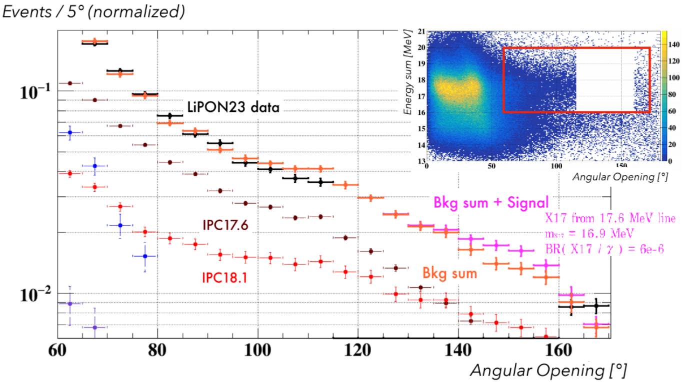
- If calibration and target are ‘ok’...
- Why do we have more 17.6 MeV?
- Current hypothesis is the beam composition
  - 75% H^+, 25% $H_2{}^+$
  - 1 MeV $H_2{}^+ \rightarrow 2 \times 500$ keV $H_1{}^+$

Upcoming 18.1 MeV data-taking

A collimator to prevent $H_2{}^+$ from entering COBRA
Better quality, but smaller, LiPON targets

Likelihood and MonteCarlo

- Likelihood with 5 populations (X17, EPC15, ECP18, IPC15, IPC18) for a FC analysis
- A different method in the study to avoid the MC statistics limits



- MC:
  - production of EPC
  - weighting EPC vs IPC
- Reconstruction:
  - rejection of track/pair fakes
  - dominated by 17.6 MeV line
- Likelihood:
  - extract the PDFs
  - limited statistics

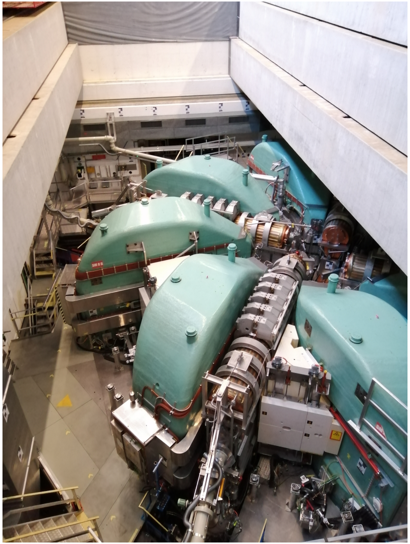
⇒ Getting ready for the unblinding!

Conclusions

- muEDM
  - Gate and Time of Flight
  - Positron Tracker
- MEG II
  - CW for XEC calibrations
  - Liquid Hydrogen target for CEX
  - X17 search

That's all folks!

Thanks to my supervisor, to all the colleagues, and to you for your attention!



Backup: Frozen-spin polarization

- If $\eta = 0$ the angle between p and spin is unchanged $\rightarrow$ *frozen*
- In the presence of an EDM the change in polarization follows

$$\frac{\mathrm{d}\mathbf{\Pi}}{\mathrm{d}t} = \boldsymbol{\omega}_e \times \mathbf{\Pi} = \frac{2d_\mu}{\hbar}(\boldsymbol{\beta} c \times \boldsymbol{B} + \boldsymbol{E}_f) \times \mathbf{\Pi}$$

- The net result is a vertical build-up of the polarization $\rightarrow$ Direction of the positrons

$$|\mathbf{\Pi}(t)| = P(t) = P_0 \sin(\omega_e t) \approx P_0 \omega_e t \approx 2P_0 \frac{d_\mu}{\hbar} \frac{E_f}{a\gamma^2} t$$

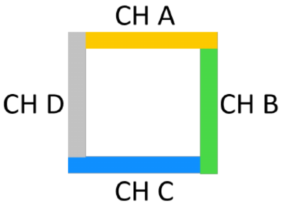
Take home message

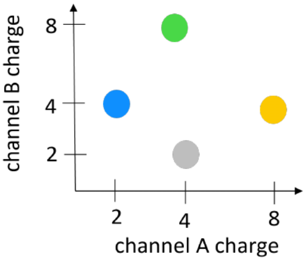
Choosing an orthogonal $\boldsymbol{p} \perp \boldsymbol{B} \perp \boldsymbol{E}$ and the adequate $\boldsymbol{B}$, $\boldsymbol{E}$ fields the existence of EDM translates in a *time-dependent up-down* polarization which in turns translates in an asymmetry in positrons emission direction

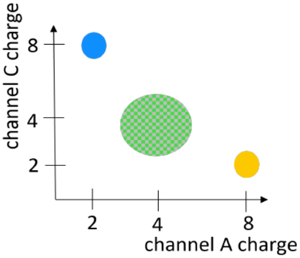
Backup: Cross-talk analysis

Let's understand how cross-talk in the telescope would work:

- Neighbour scintillators: A vs B
  - A yellow - charge in A and some in B
  - B green - charge in B and some in A
  - C blue - some in B and little in A
  - D gray - some in A and little in B
- Opposite scintillators: A vs C
  - A yellow - charge in A and little in C
  - C blue - charge in C and little in A
  - B/D green - some in A and some in C

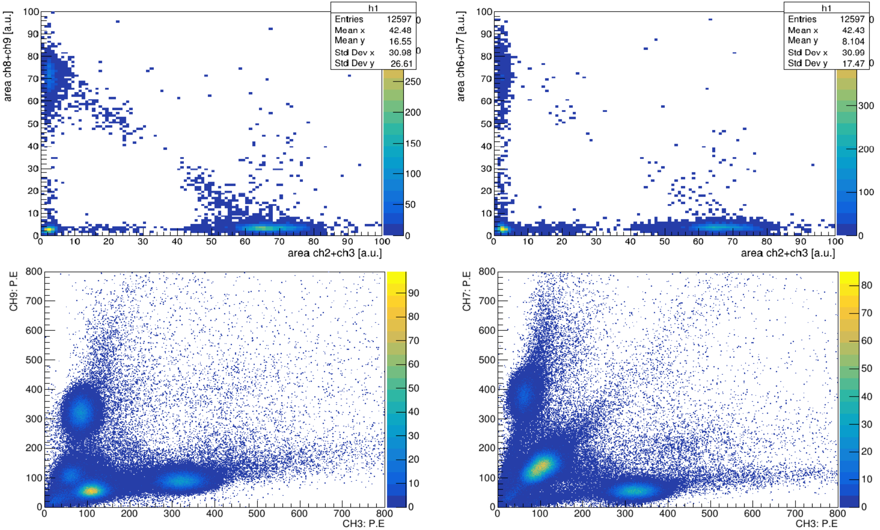






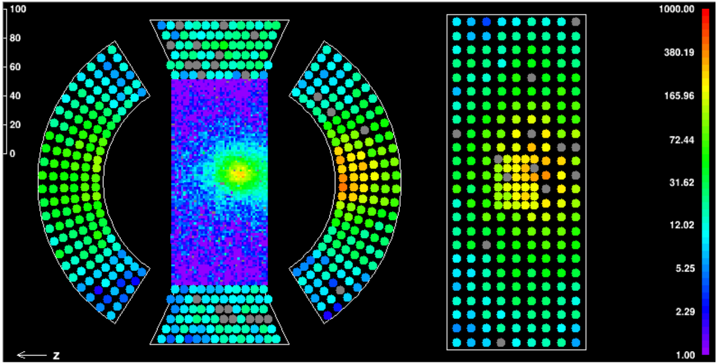
Backup: Cross-talk analysis

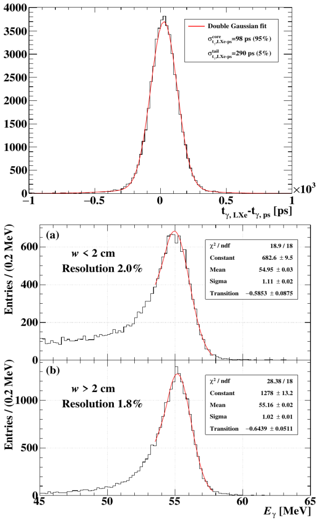
Big distinction, due to the difference in construction between ‘Pisa’ and ‘Shanghai’



Backup: Liquid Xenon Calorimeter

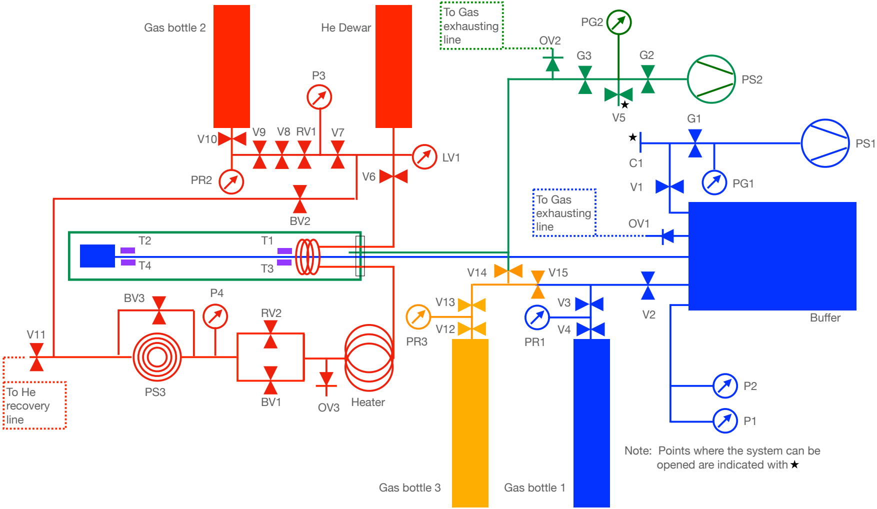
- 900 Liters of Xe read by MPPCs and PMTs
- Complex and delicate calibrations:
  - Frequent runs of CR, LED, α (7/week)
  - CW dedicated runs of ^{7}Li(p, γ)^{8}Be at 17.6 MeV (3/week)
  - Charge EXchange reaction discussed later (1/year)



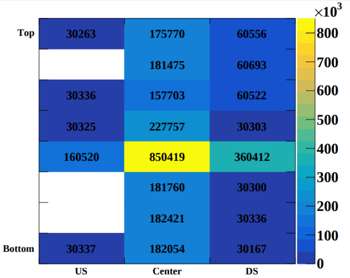


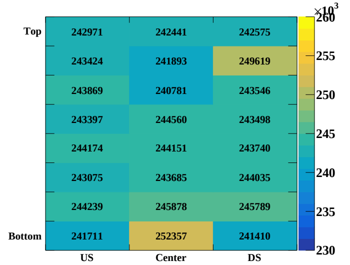
Backup: LH2 circuit

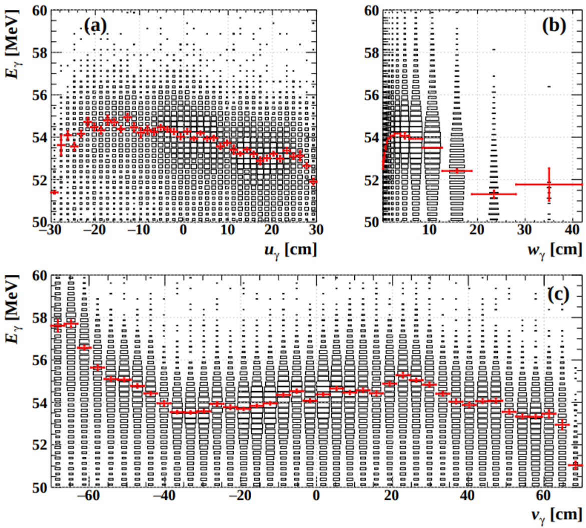
With small differences, the idea behind the circuit stayed the same in the different iterations:
A close-circuit for the Hydrogen, cooled via liquid Helium pressurizing a dewar



Backup: CEX results

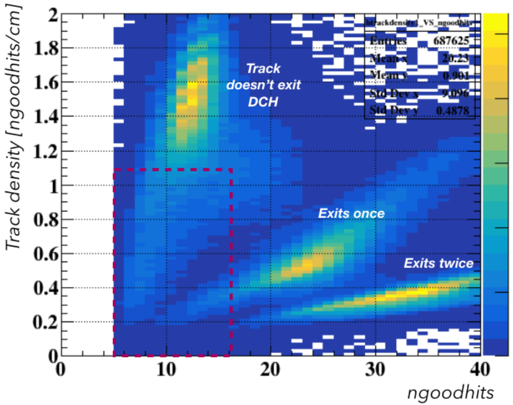






Backup: Pair reconstruction

- Reconstruction of e^+ in $\vec{B}$ is the same as e^- in $-\vec{B}$
- A series of selections:
  - successful propagation to the beam axis
  - at least 10 good hits (ngoodhits)
  - $11 \leq$ ngoodhits $\leq 16 \Rightarrow$ density > 1.1 hits/cm
  - $|z_{vertex} - z_{beamspot}| < 2.5$ cm
  - time order in the hits
  - 1^{st} hit close to vertex than 35 cm
  - Cuts on the *score* = ngoodhits + 10 × hit density
  - no hits with opposite z_{hit}
  - ...
- Most are to reduce the number of *fake-tracks*
- Correction for angle-position correlations
- improved vertexing for the pairs



Backup: Corrections and vertexing

- Angle correlations are found and corrected
- REVE: GENFIT tool to constraint the vertex of the two tracks on the beam-spot