Design of the detection system for the HyperMu experiment

Laura Šinkūnaitė
on behalf of CREMA collaboration

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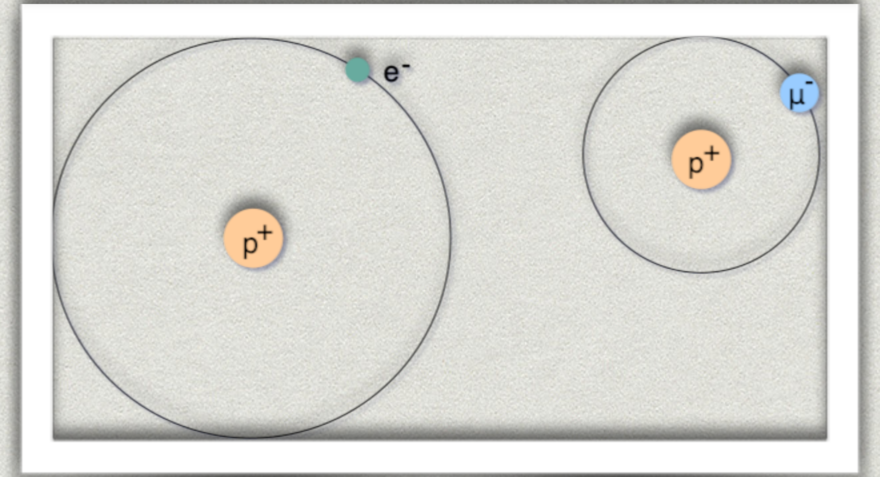
Introduction

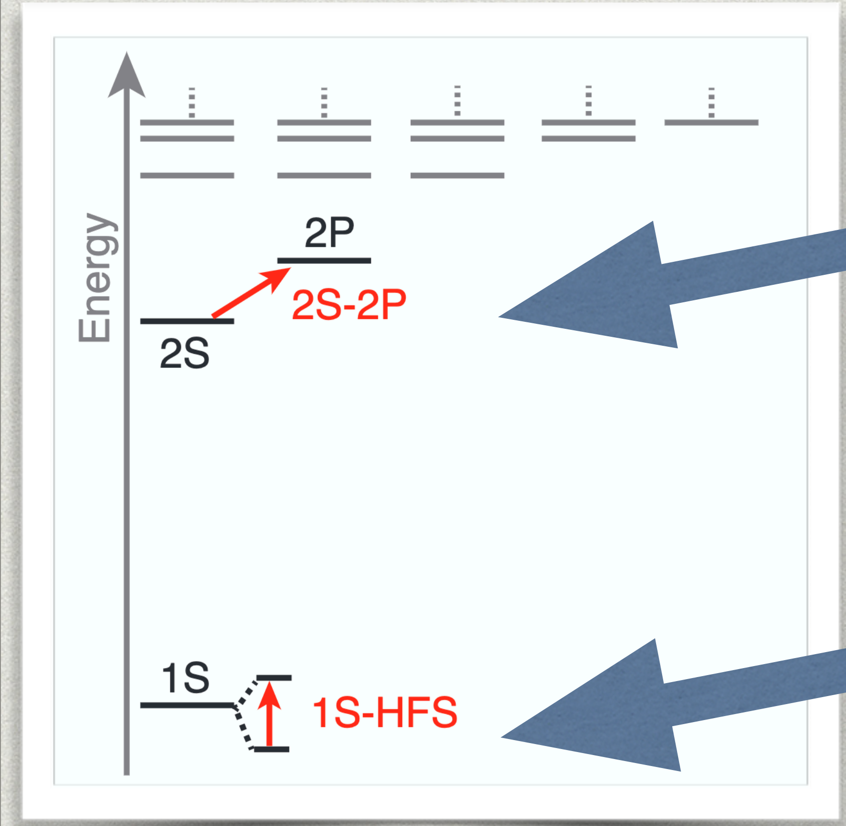
$$|\Psi(r=0)|^2 \propto m_r^3$$

Hydrogen



Muonic hydrogen

Proton radius puzzle



Charge radius

$$< r_p^2 > = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}|_{Q^2=0}$$

Zemach radius (in progress)

$$r_z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left[G_E(Q^2)\frac{G_M(Q^2)}{1+\kappa_P} - 1\right]$$

Theory I

Correction of hadronic vacuum polarisation and weak interaction

$$\Delta E^{HFS}_{theor} = E^F(1 + \Delta_{QED} + \Delta_{TPE} + \Delta_{Weak+HVP})$$

Fermi energy

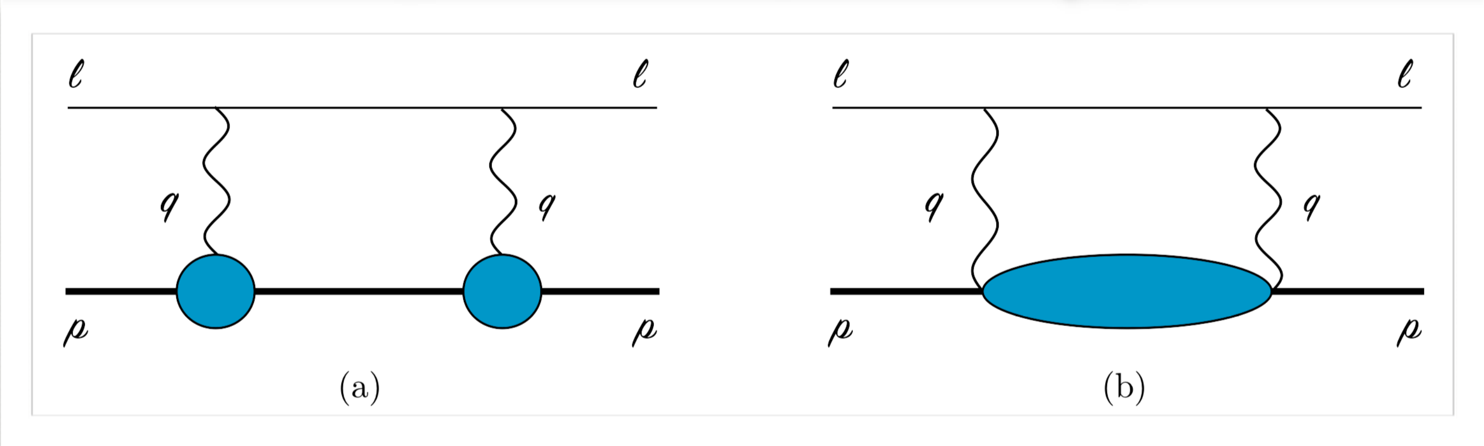
$$E^F = \frac{8}{3}\alpha^4 \frac{\mu_p m_\mu^2 m_p^2}{(m_\mu + m_p)^3}$$

QED contribution

TPE contribution

Theory II

$$\Delta_{TPE} = \Delta_Z + \Delta_{recoil} + \Delta_{pol}$$



Elastic contribution to TPE (Zemach)

Inelastic contribution to TPE

$$\Delta_Z = \frac{8Z\alpha m_r}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left(G_E(Q^2)\frac{G_M(Q^2)}{1+\kappa_p} - 1\right) = -2(Z\alpha)m_r R_Z$$

Zemach radius

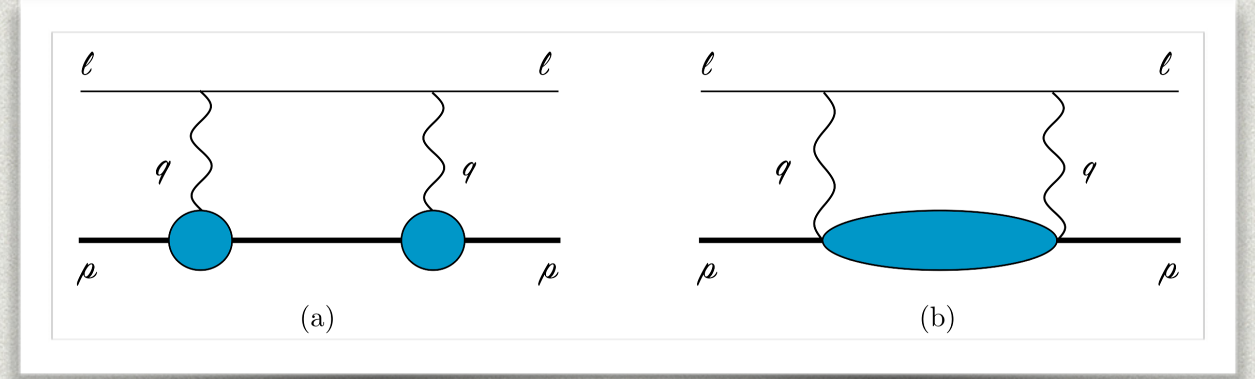
$$R_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left(G_E(Q^2)\frac{G_M(Q^2)}{1+\kappa_p} - 1\right)$$

Zemach radius (non-relativistically)

$$R_Z = \int d^3\mathbf{r}\,|\mathbf{r}|\int d^3\mathbf{r}'\rho_E(\mathbf{r}-\mathbf{r}')\rho_M(\mathbf{r}')$$

Motivation

Two-photon exchange contribution

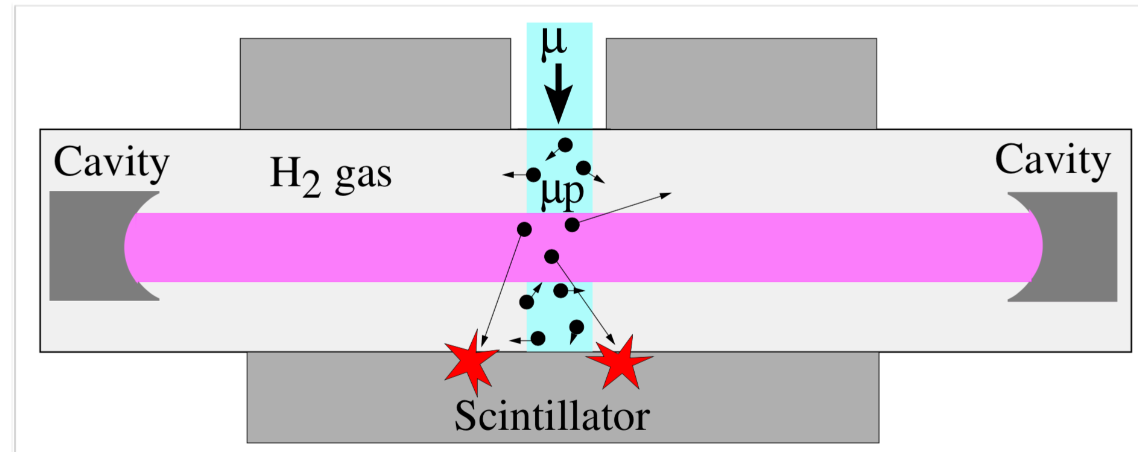


By measuring 1S-HFS transition with 1 ppm accuracy, the TPE contribution could be evaluated with a relative accuracy of 1×10^{-4}.

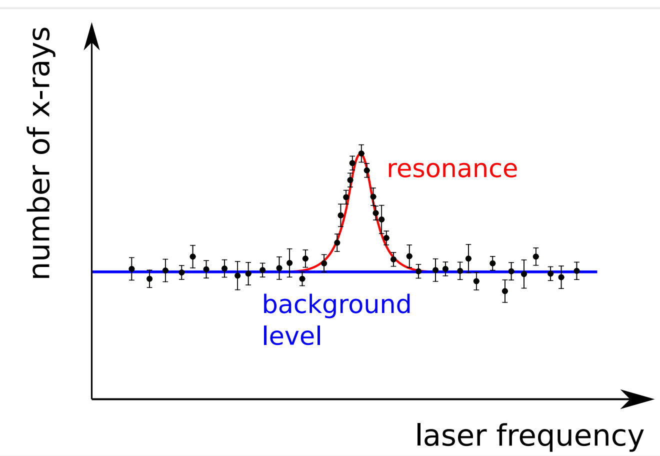
- Increased understanding of the low-energy structure of the proton.
- Benchmark for chiral perturbation theory, dispersion-based approaches, and lattice QCD.
- Test of lepton universality.

Principle

1. Formation
2. De-excitation
3. Laser excitation
4. Collisional de-excitation
5. Diffusion
6. At the wall
7. Detection

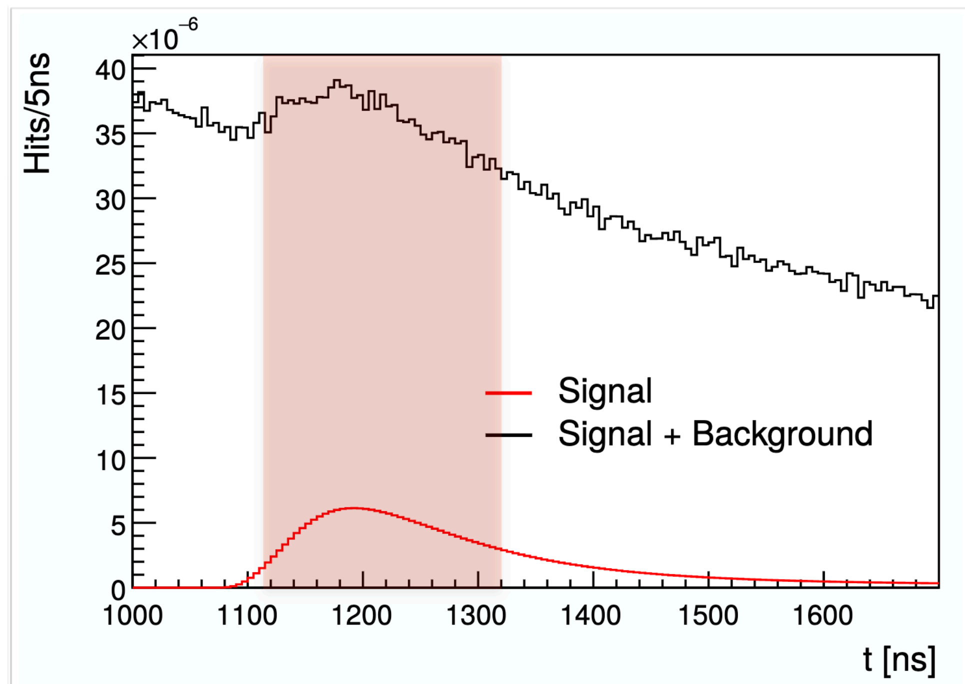


$$
\begin{aligned}
\mu\mathrm{p} + \mathrm{Au} \quad \rightarrow \quad & \mu\mathrm{Au}^* + \mathrm{p} \\
& \quad \downarrow \\
& \mu\mathrm{Au} + \text{X-rays} \\
& \quad \downarrow \\
& \nu + \ldots + \text{neutrons} + \gamma + p, d, \alpha
\end{aligned}
$$



Signal and background

Signal: MeV X-rays detected within a time window Δt.



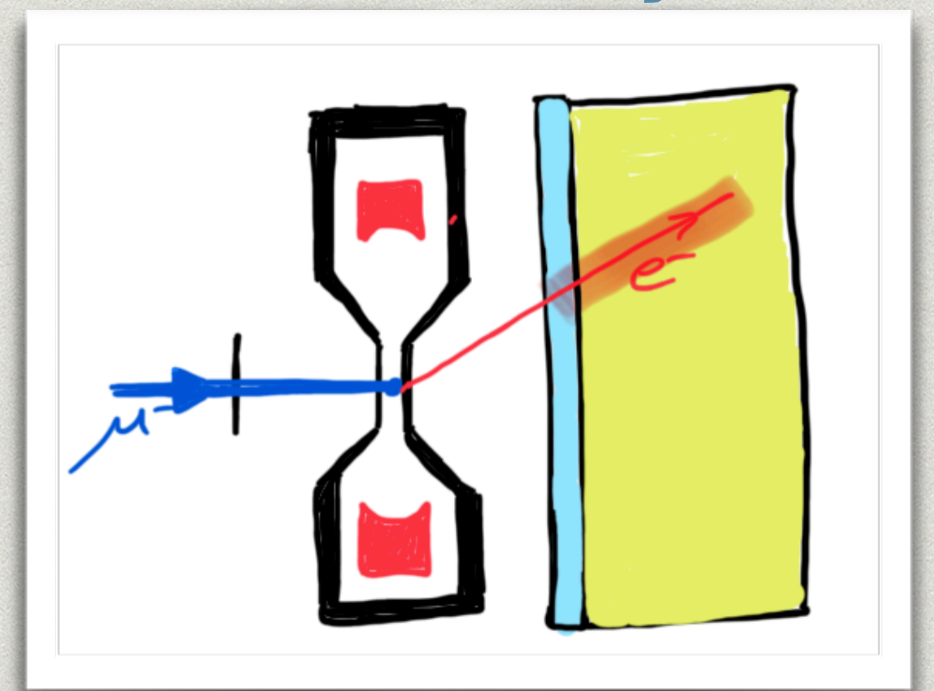
Intrinsic background: non-laser excited μp atoms that diffuse to the target walls within Δt.

Erroneous background: electrons produced when the muon decays. $\mu^- \rightarrow e^- \nu_\mu \overline{\nu}_e$

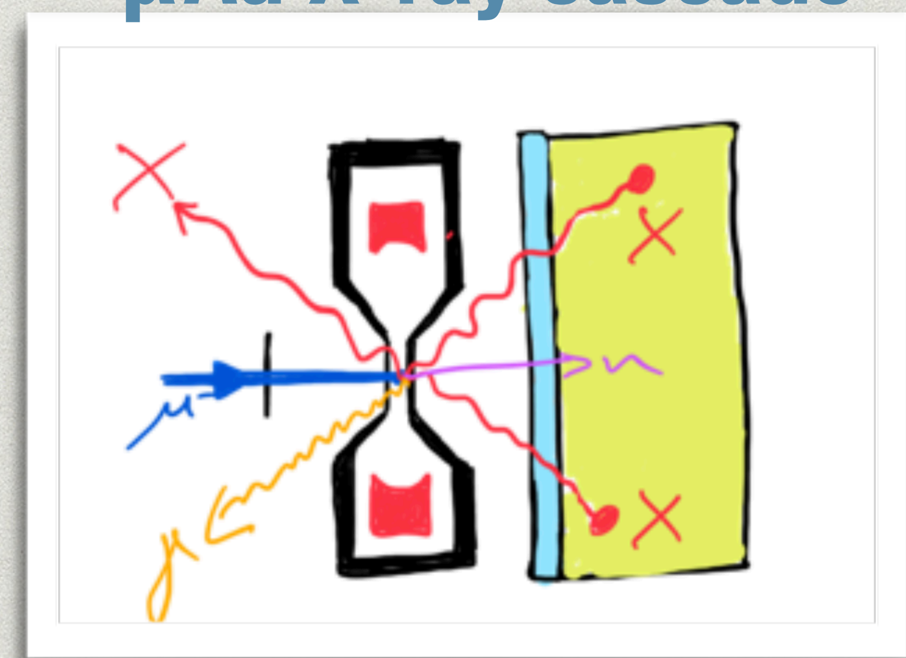
30 x more electrons than cascade events

What is it all about?

Muon decay



μAu X-ray cascade



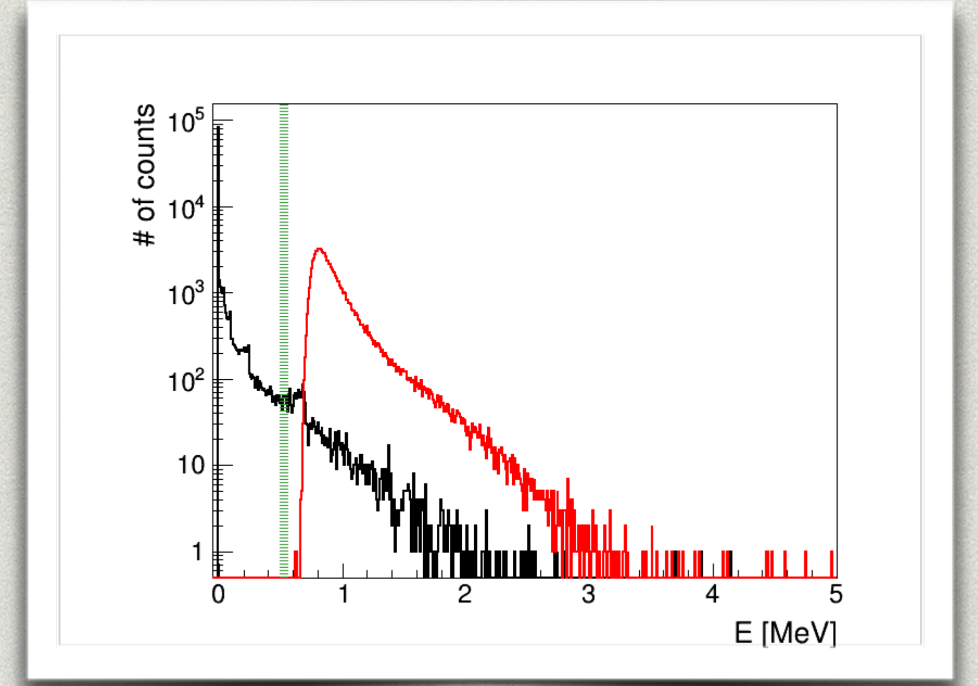
Muonic gold (μAu) X-ray cascade

Muon decay

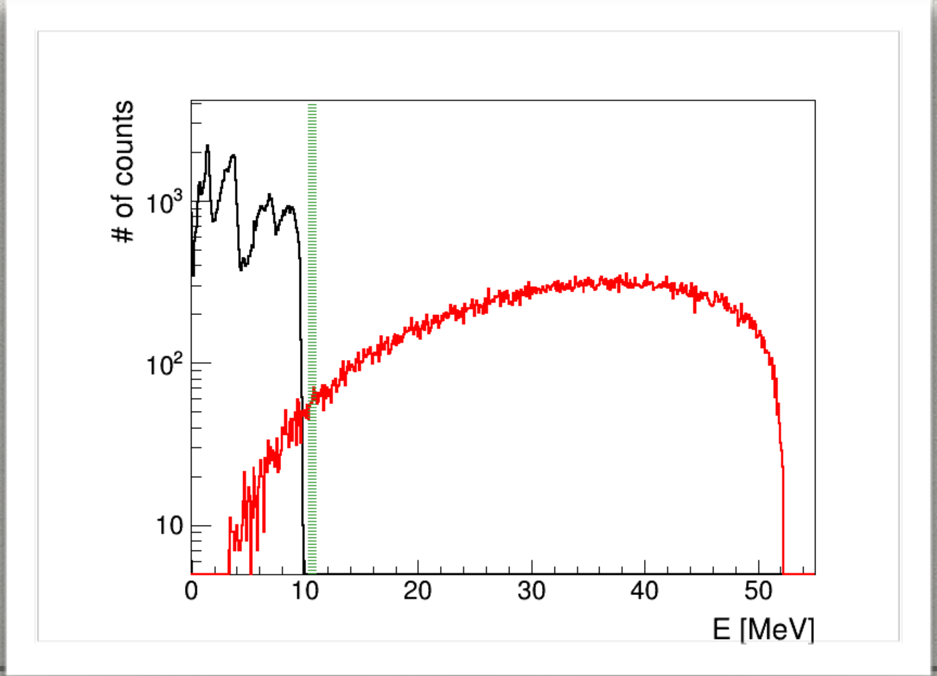
$\mu^- \rightarrow e^- \nu_\mu \overline{\nu_e}$

Theoretical energy threshold

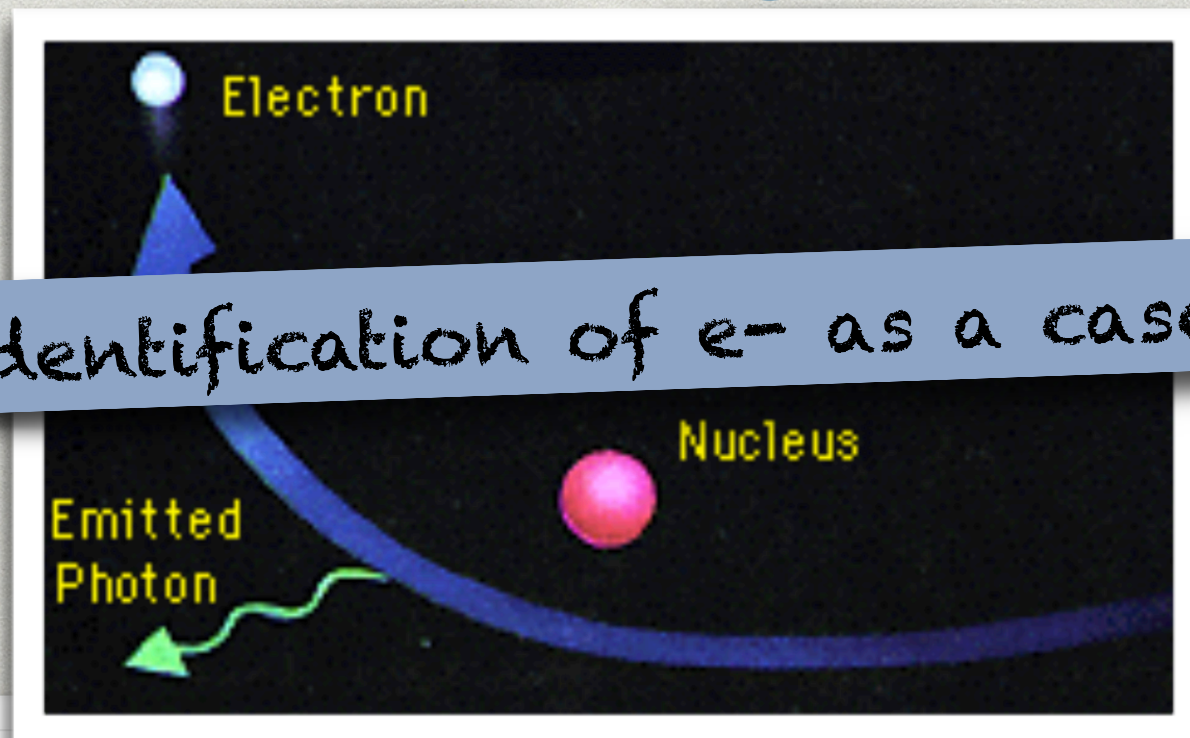
5-mm plastic scintillator



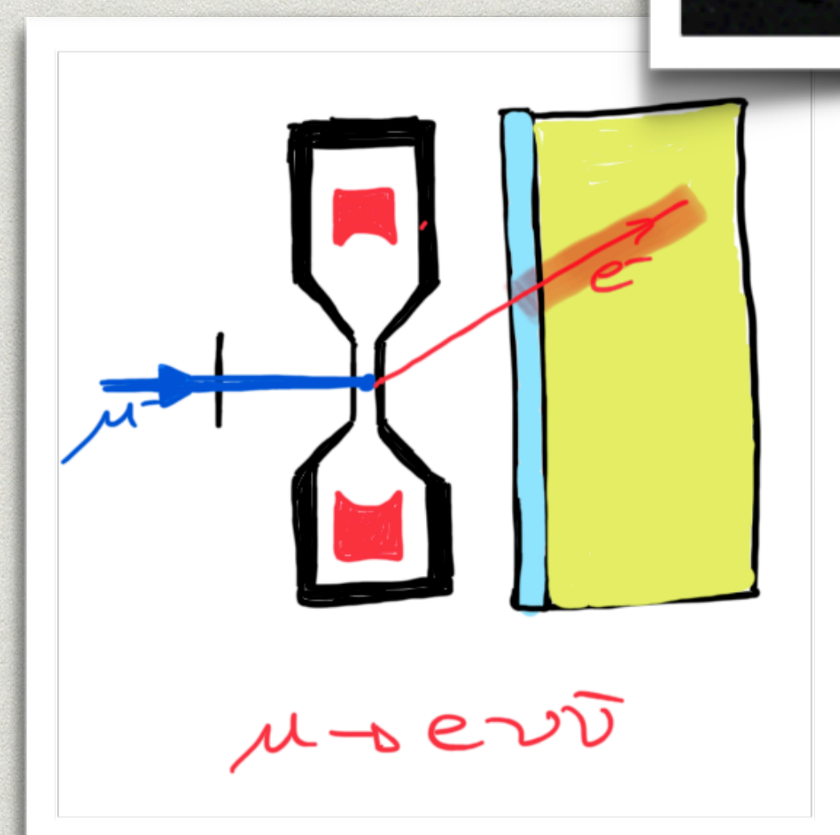
250-mm plastic scintillator

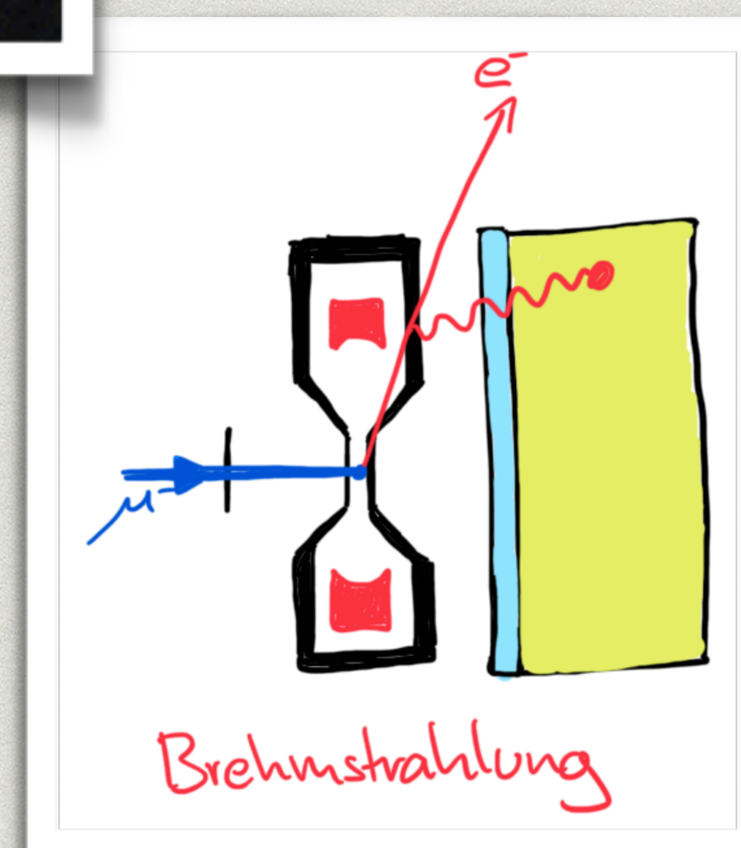


Bremsstrahlung

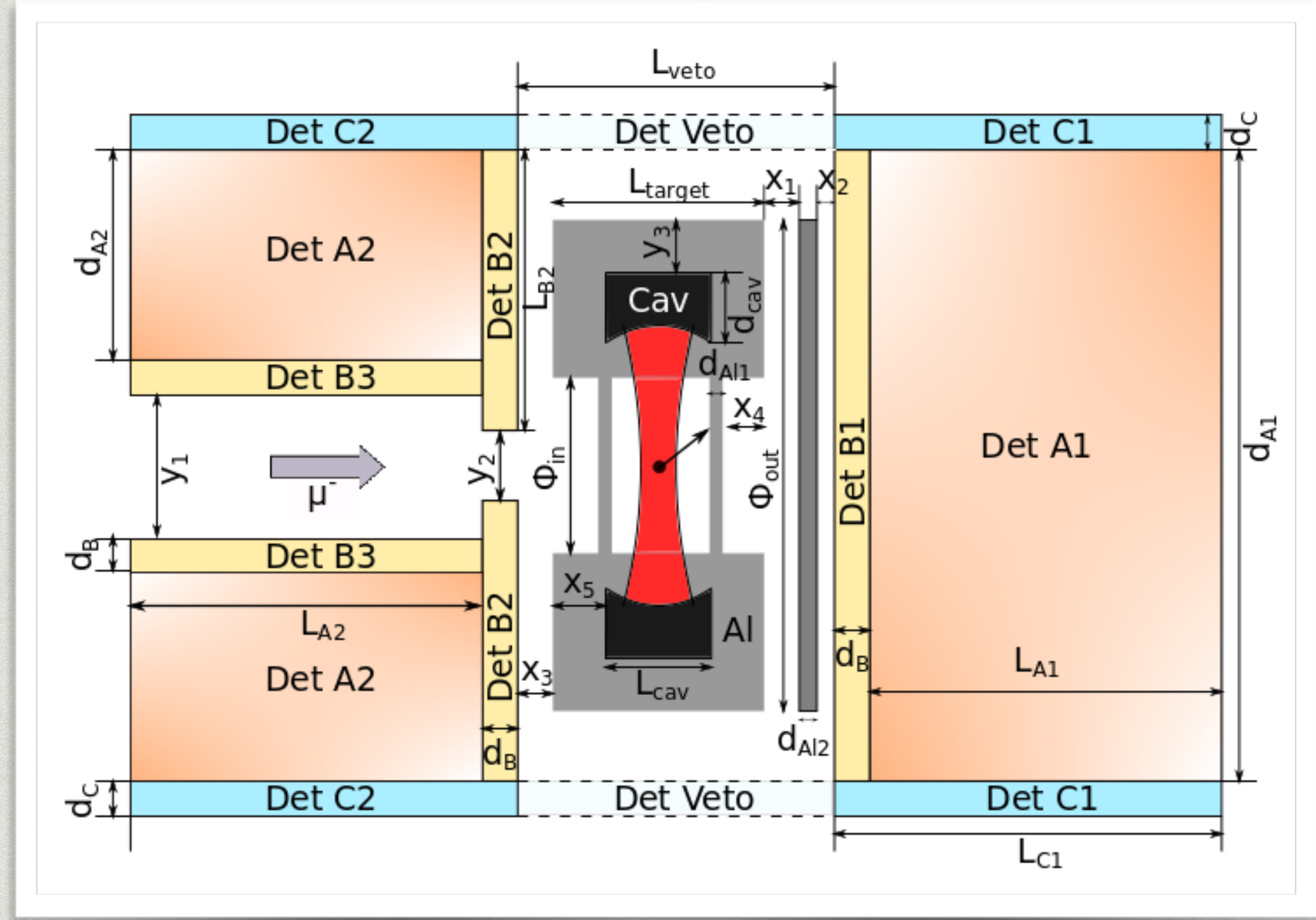


False identification of e- as a cascade event





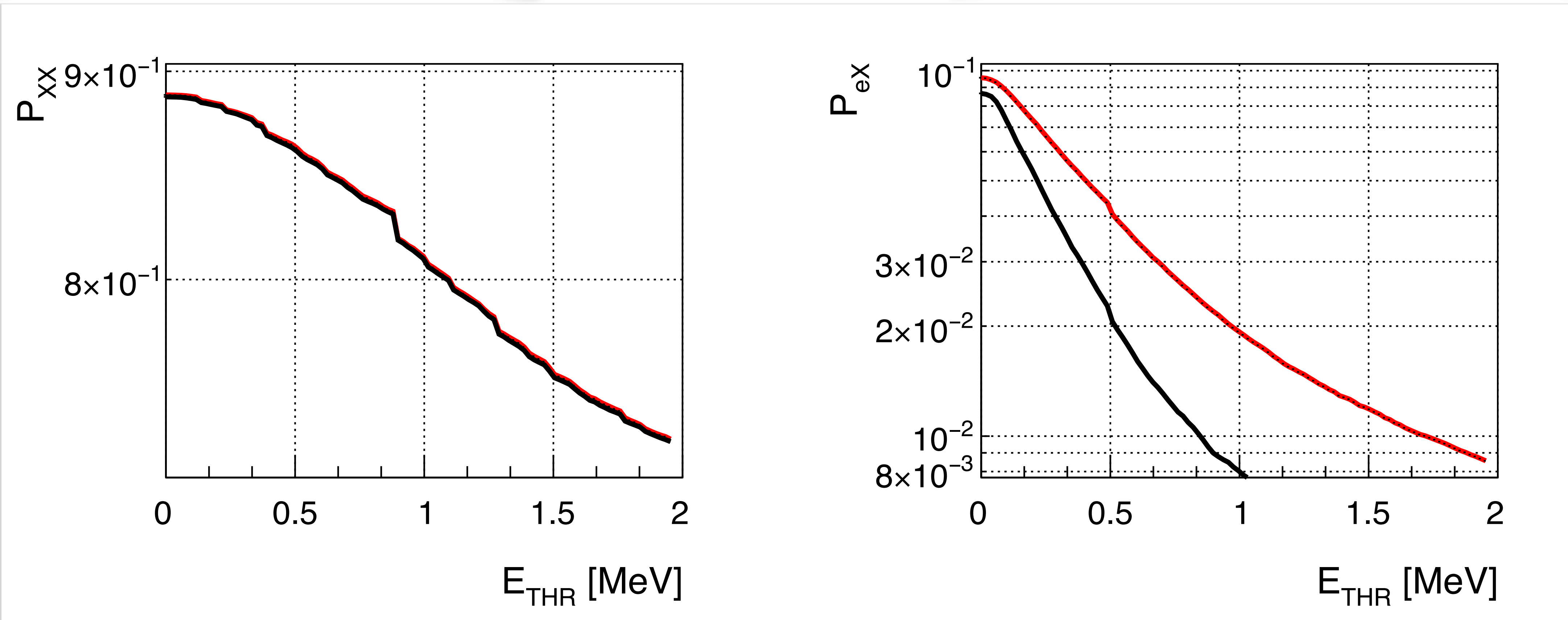
Detection system



MC simulations

P_{XX}: μAu cascade detection efficiency

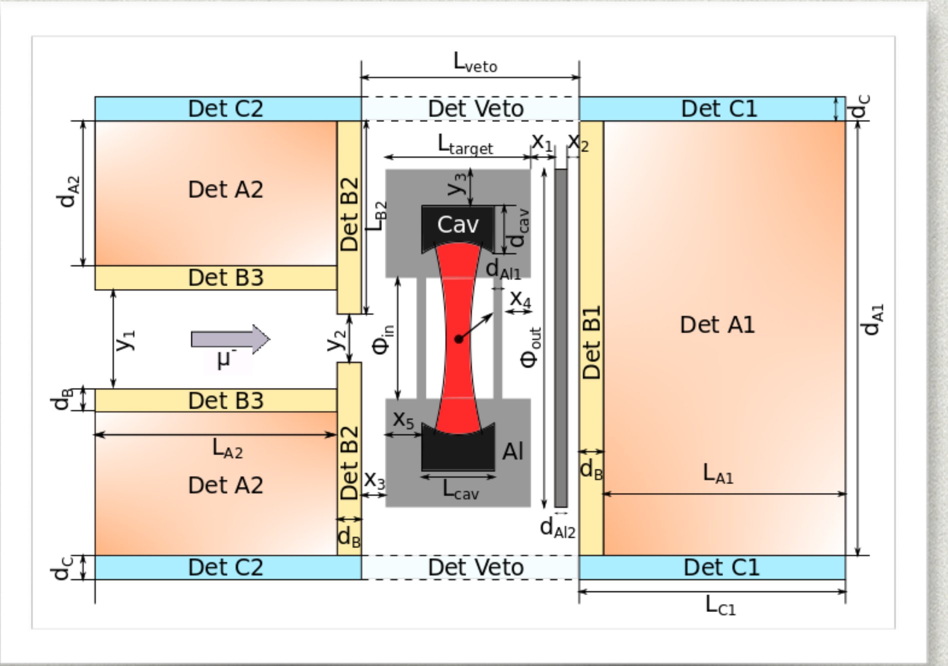
P_{eX}: probability to misidentify e^- as X-ray



Target cavity is made of glass

Target cavity is made of copper

Detector budget

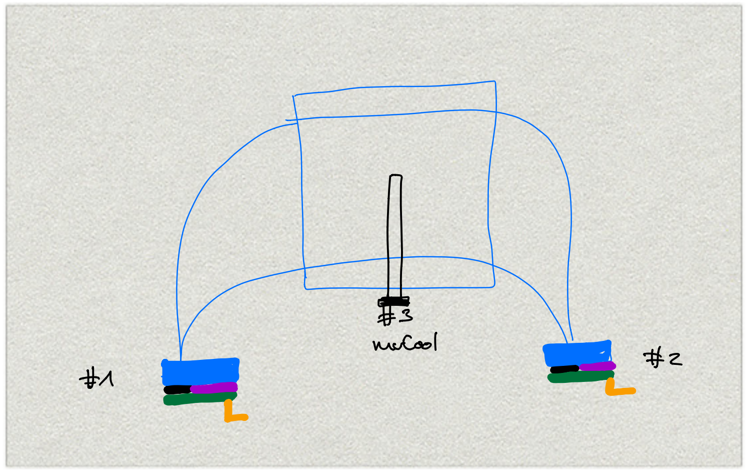


- **2** x 250-mm x 250-mm x 5-mm plastic scintillators readout with fibres
- **1** x 400-mm x 400-mm x 10-mm plastic scintillator readout with fibres
- **1** x 20-mm x 20-mm x 0.05-mm plastic scintillator readout with GAPDs as an entrance detector
- **1** x 400-mm x 400-mm x 350-mm big plastic scintillator readout with 5 PMTs
- **16** x BGO crystals readout with individually-attached PMTs
- **1** x 150-mm plastic scintillator with a hole of the ⌀=36-mm readout with GAPDs
- **1** x 450-mm x 450-mm multi-wire chamber with 25-μm wires in Ar-gas

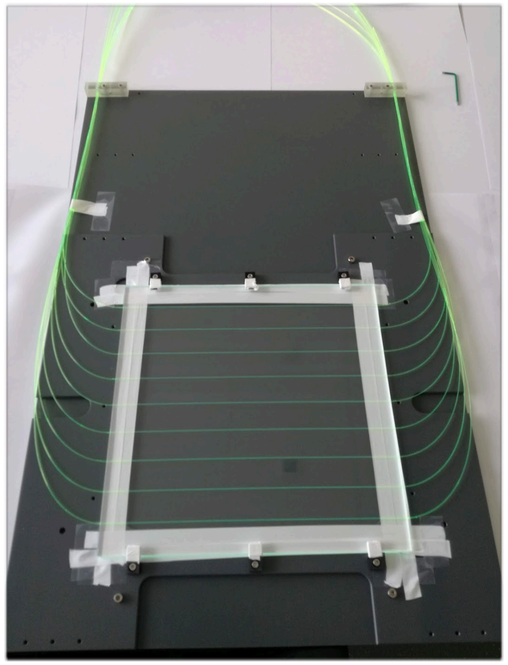
23 detectors to produce, calibrate, and synchronise!

R&D of the WLSF detectors

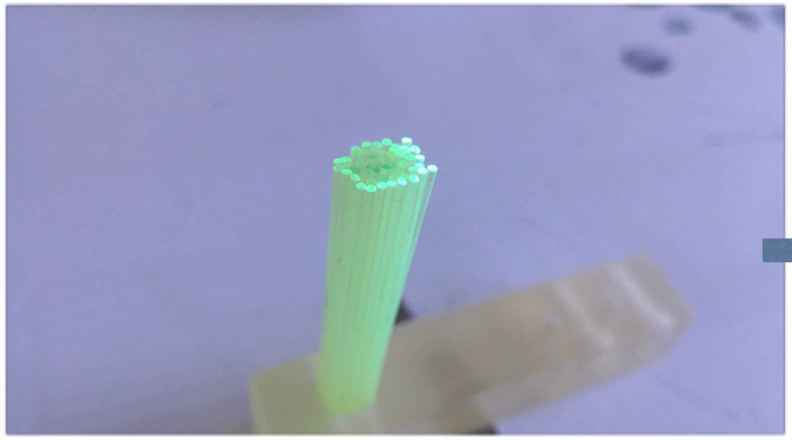
1. Design



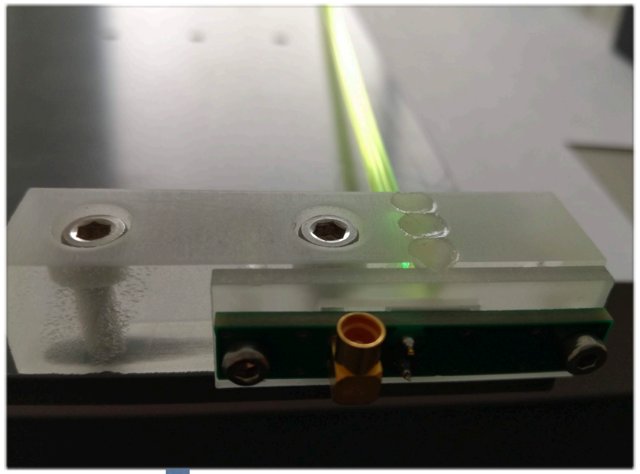
2. Gluing



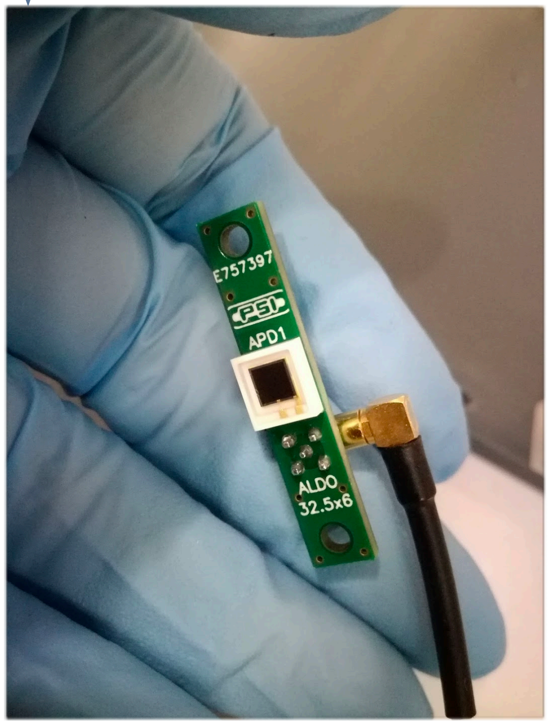
3. Fixing



4. Gluing

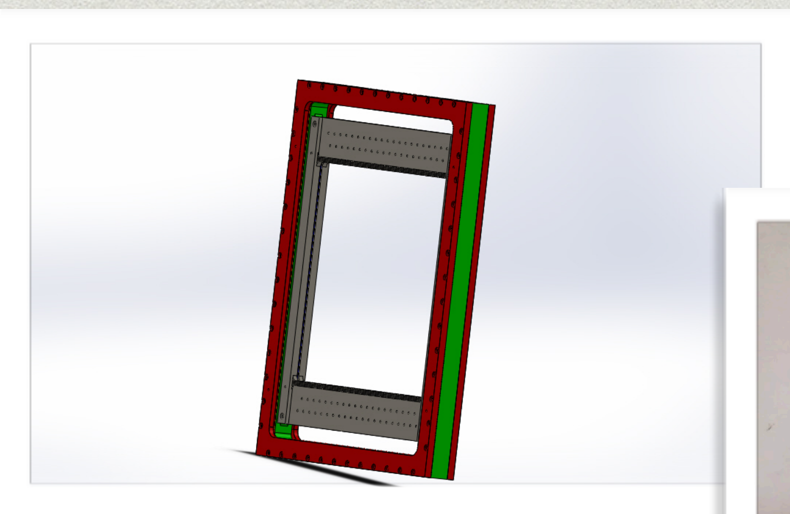


5. Polishing



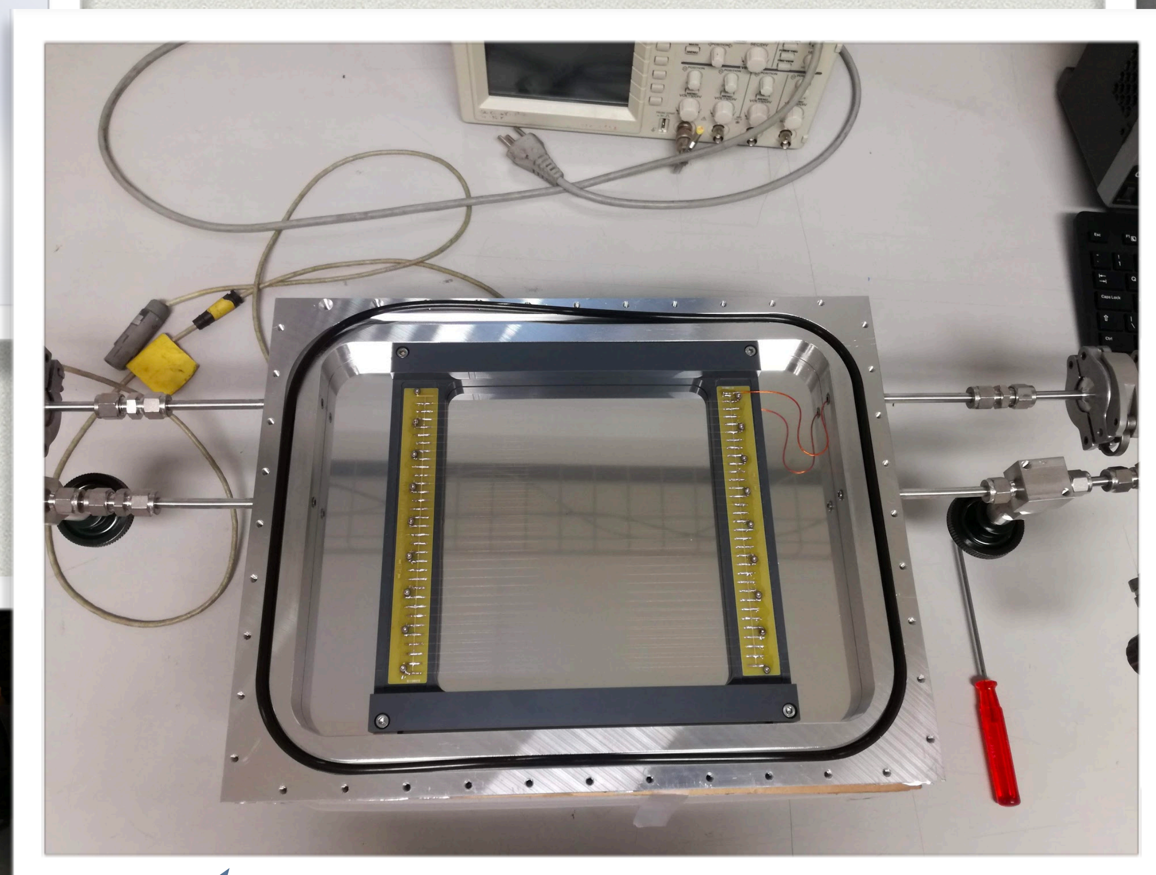
6. Testing

R&D: Multi-wire gas chamber

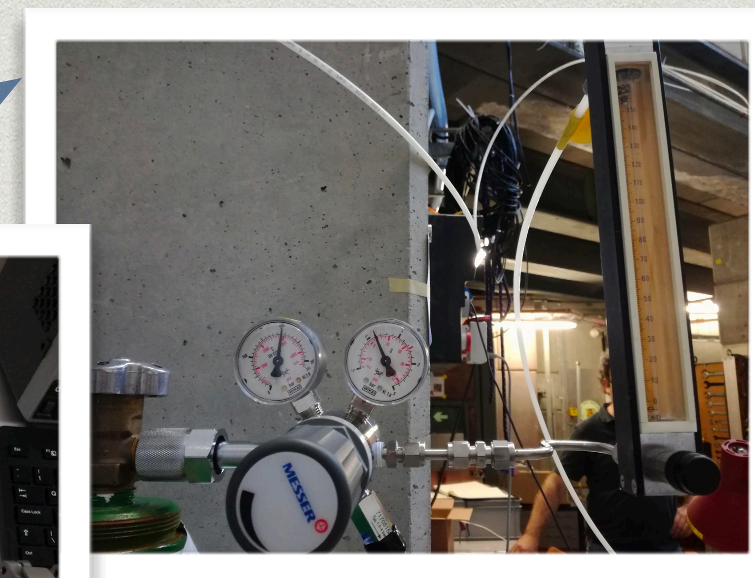


1. Design

2. Soldering



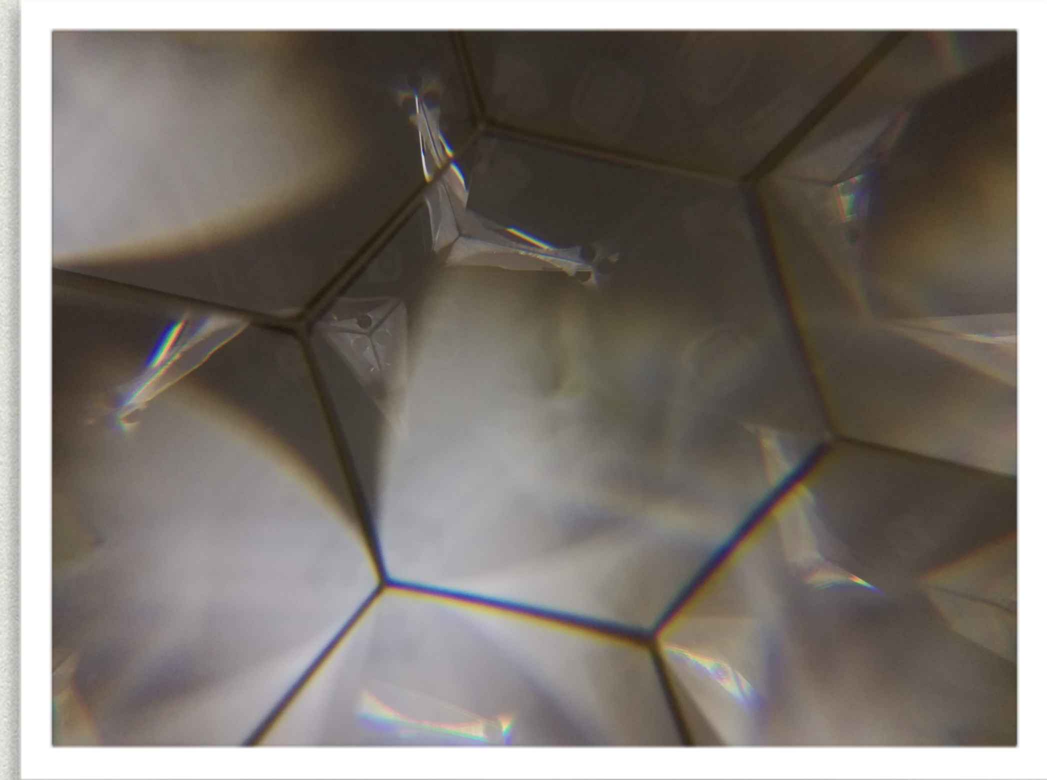
3. Inlets and HV



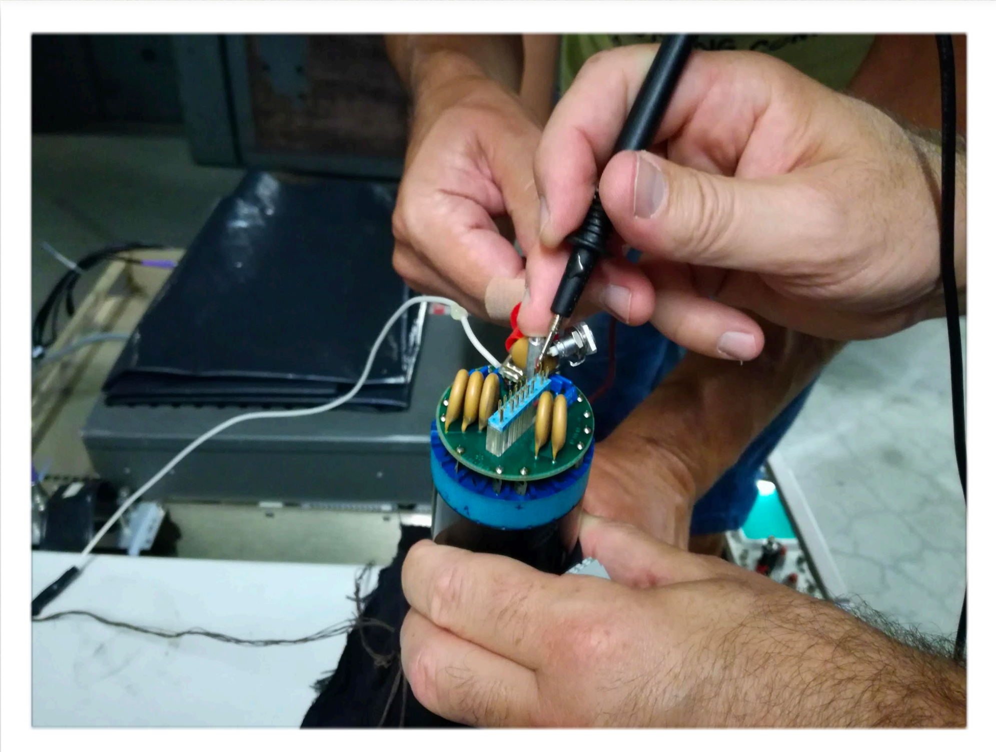
4. Ar-gas

5. Testing

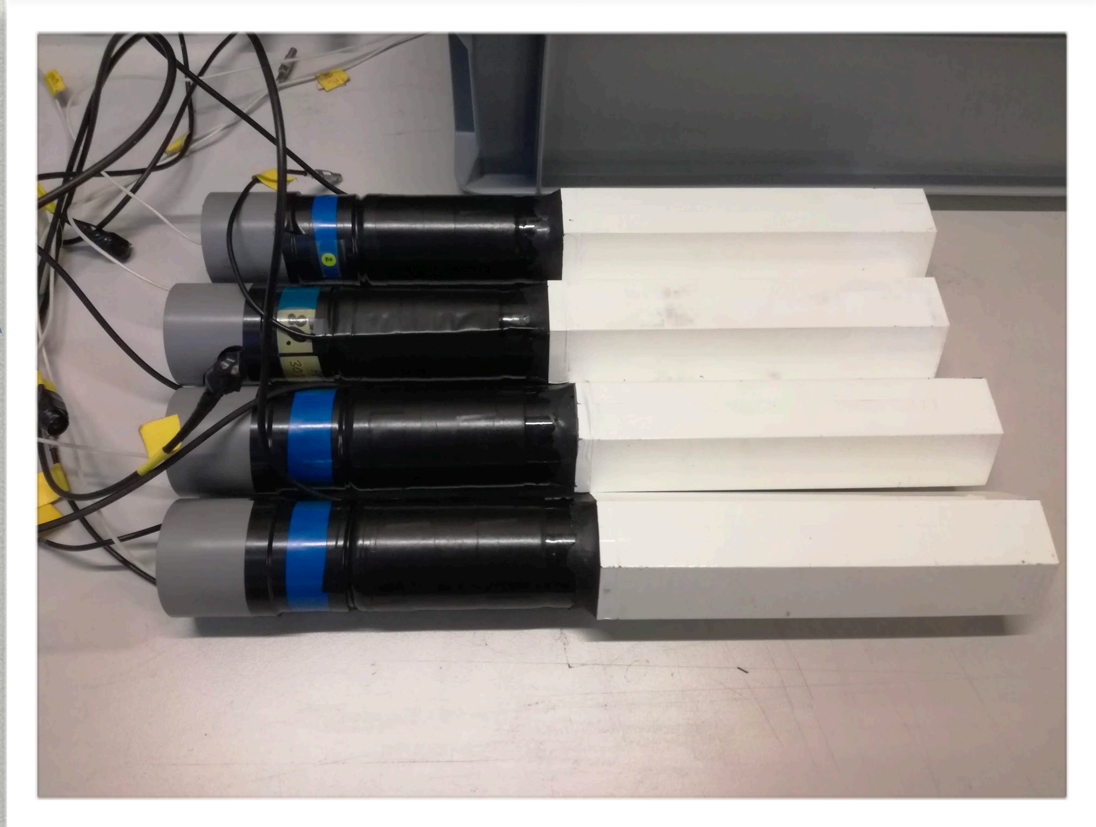
BGO repair



Checking for any damage of the crystal



Testing the performance of the PMT



Defining optimal operational parameters

Conclusions

- Complex detection system is needed to detect MeV X-ray cascade and to distinguish it from the electrons.
- Individual elements of the detection system are being realised.
- The full detection system is going to be tested in 5 weeks at PSI.