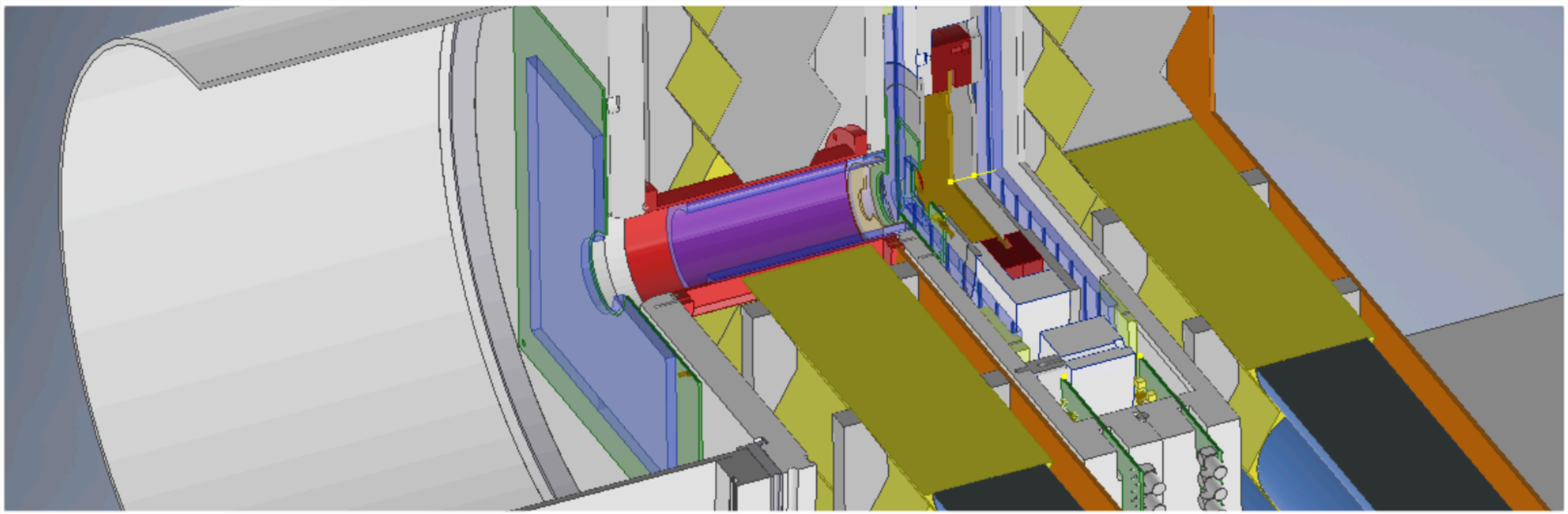


Zürich Physics PhD Student Seminar · 08 - 09.09.2020

Detection System

for the hyperfine-splitting in muonic hydrogen

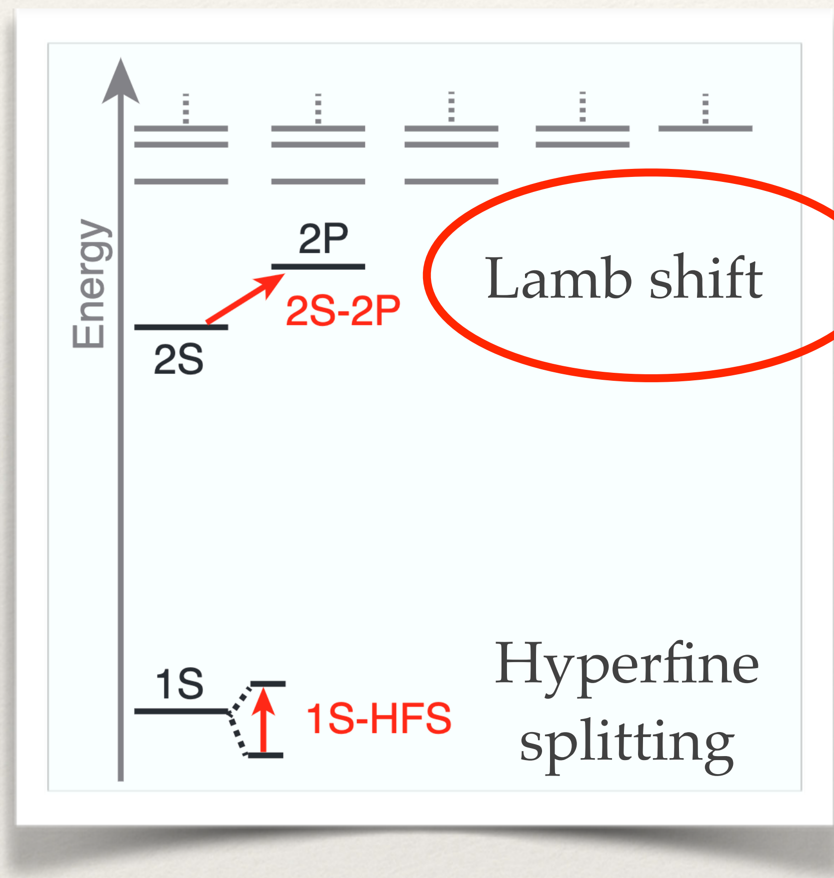
Laura Šinkūnaitė

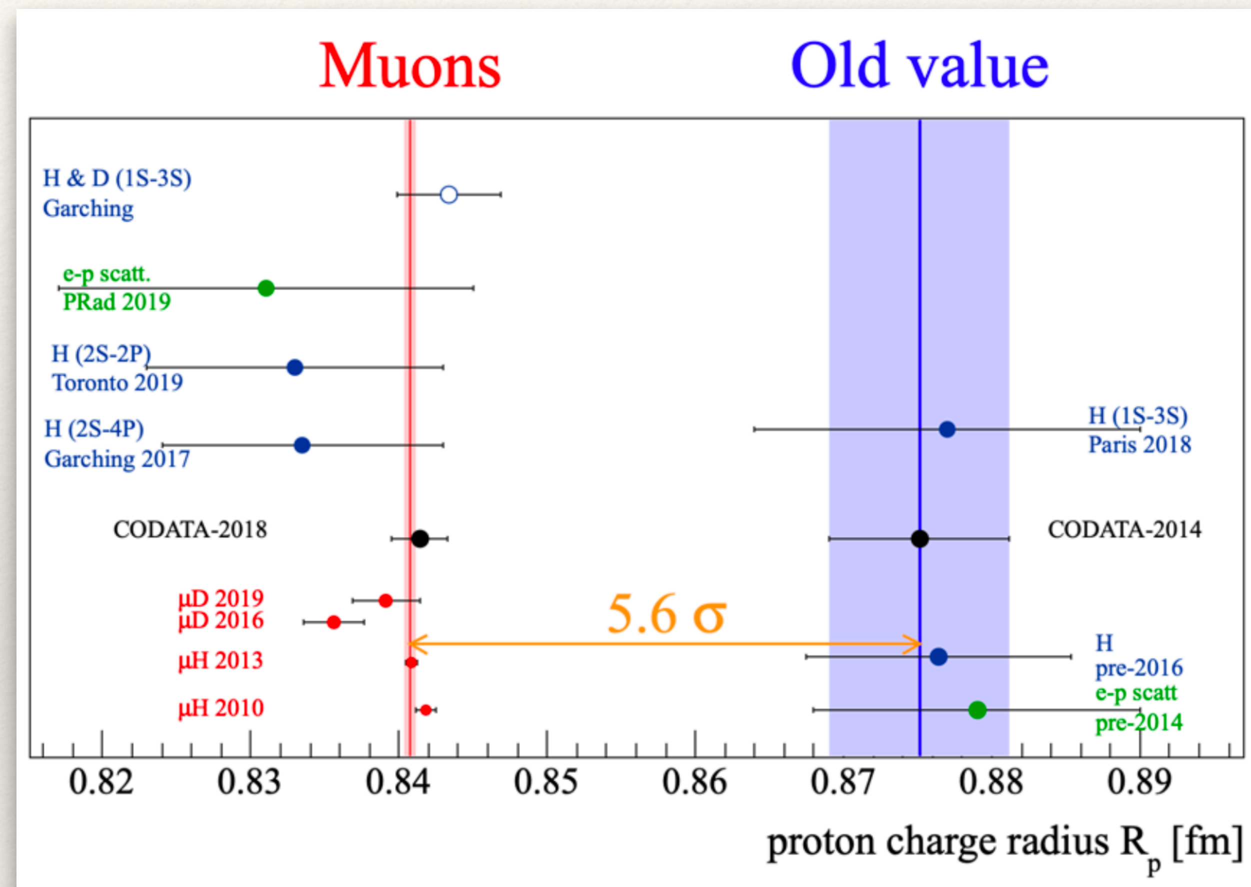
Paul Scherrer Institute

Outline

1. Introduction
2. HyperMu experiment
3. Detection system
4. Preliminary results from Nov' 19
5. Status
6. Summary

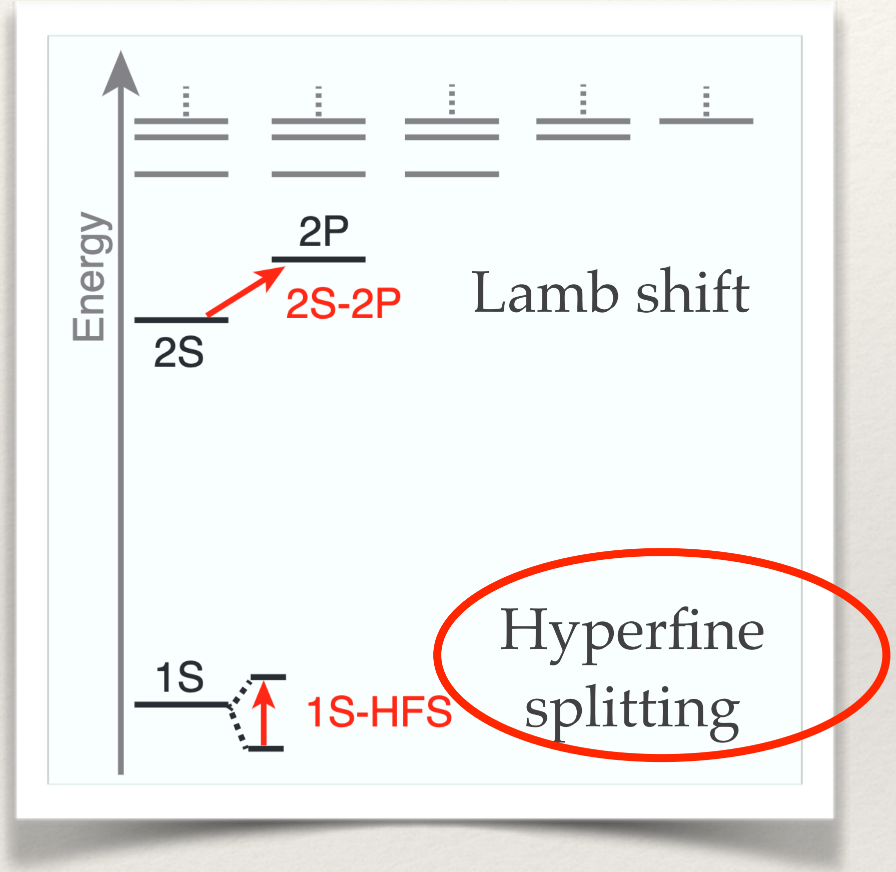
1.1 Proton-Radius Puzzle

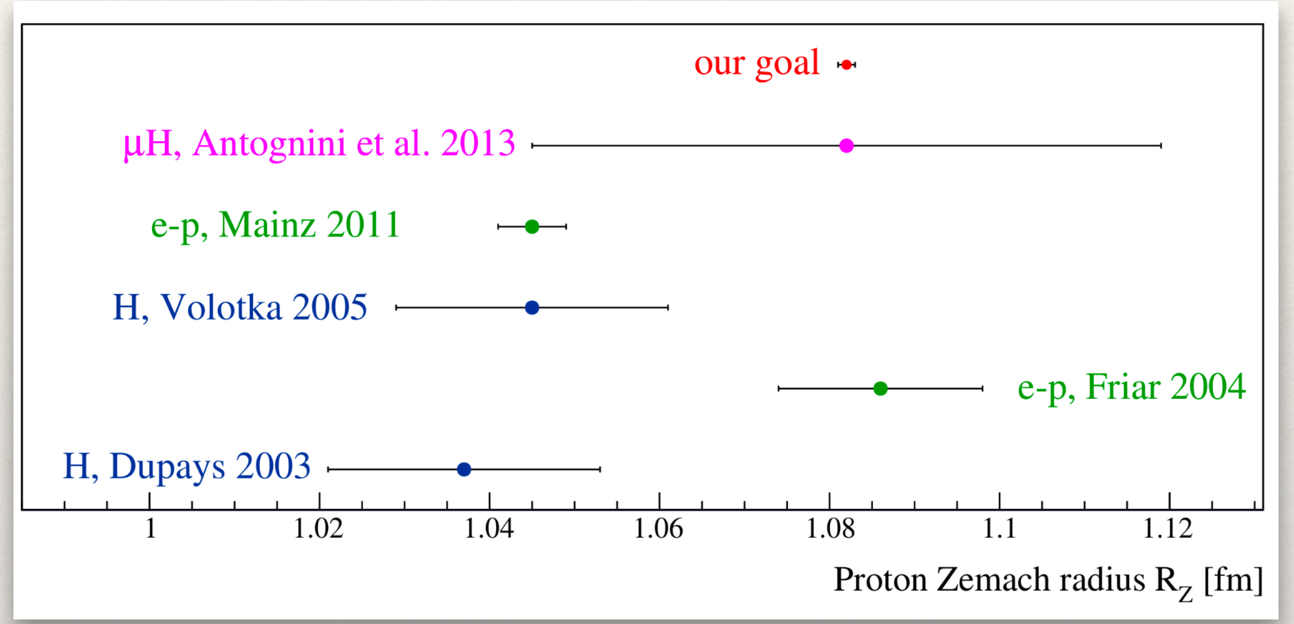




$$< r_p^2 > = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}|_{Q^2=0}$$

1.1 Proton-Radius Puzzle (II)





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

1.2 Zemach radius

- Hyperfine splitting: $$\Delta E^{HFS}_{theor} = E^F(1 + \Delta_{QED} + \Delta_{TPE} + \Delta_{Weak+HVP})$$
- Two-photon exchange (TPE): $$\Delta_{TPE} = \Delta_Z + \Delta_{recoil} + \Delta_{pol}$$
- Zemach contribution (elastic): $$\Delta_Z = \frac{8Z\alpha m_r}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left(G_E(Q^2)\frac{G_M(Q^2)}{1+\kappa_p} - 1\right) = -2(Z\alpha)m_r R_Z$$
- 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-relativistic): $$R_Z = \int d^3\mathbf{r}\,|\mathbf{r}|\int d^3\mathbf{r}'\rho_E(\mathbf{r}-\mathbf{r}')\rho_M(\mathbf{r}')$$

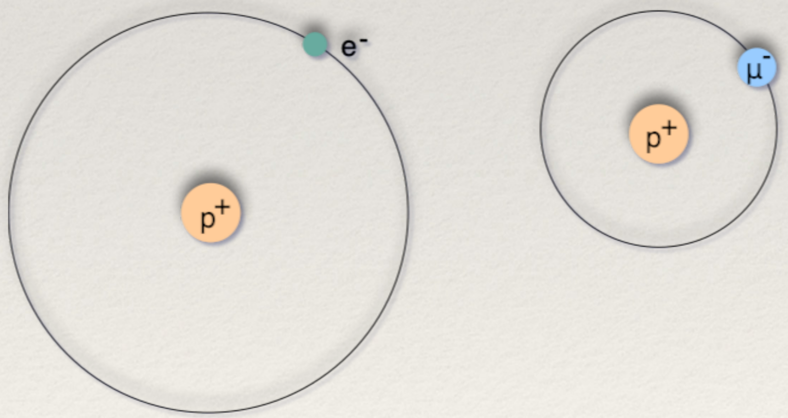
1.3 Motivation

- 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.

2.1 HyperMu Goal

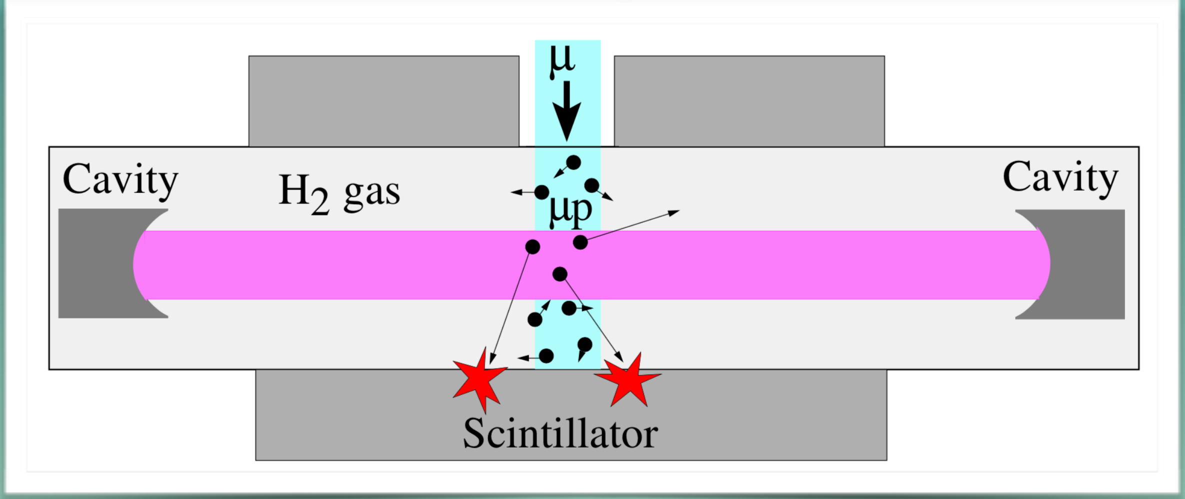
Measurement of the ground-state hyperfine-splitting in muonic hydrogen (μp) with about 1 ppm accuracy by means of laser spectroscopy.

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



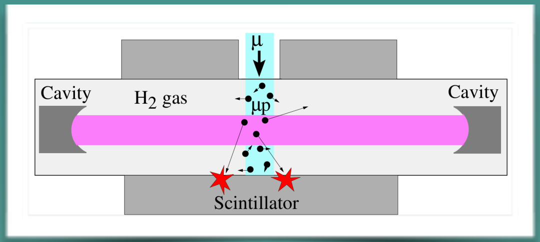
2.2 Working Principle

1. Formation



2.2 Working Principle

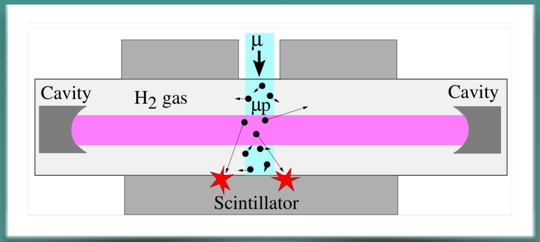
1. Formation



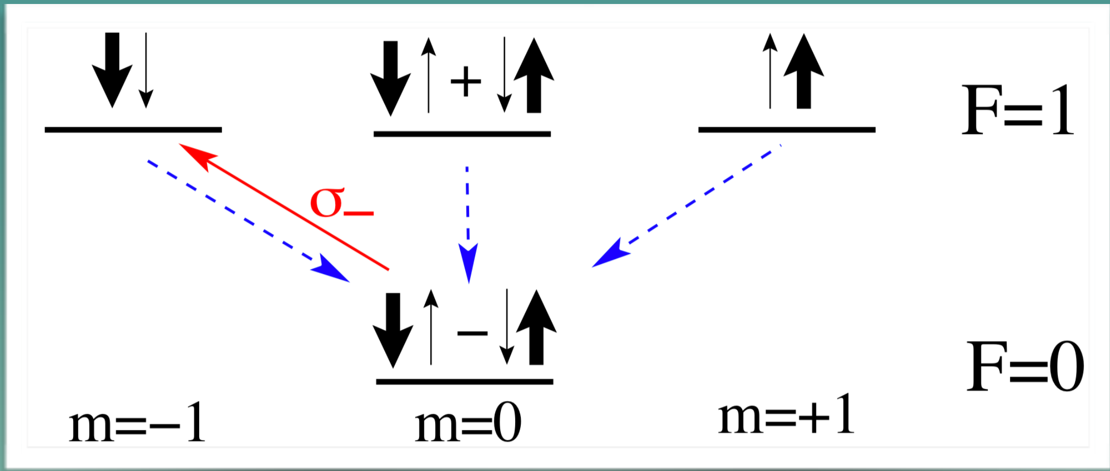
2. De-excitation

2.2 Working Principle

1. Formation



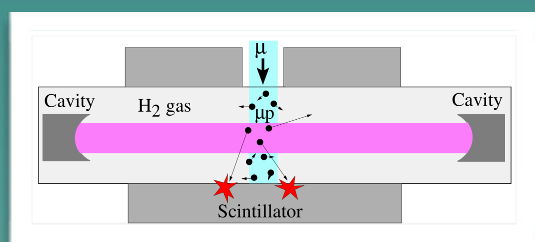
2. De-excitation



3. Laser excitation

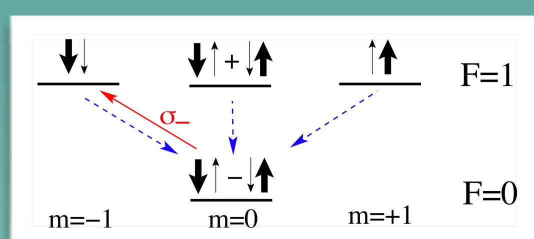
2.2 Working Principle

1. Formation



2. De-excitation

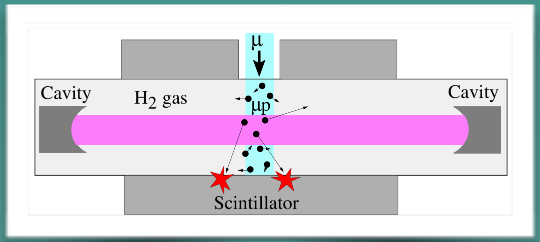
3. Laser excitation



4. Collisional de-excitation

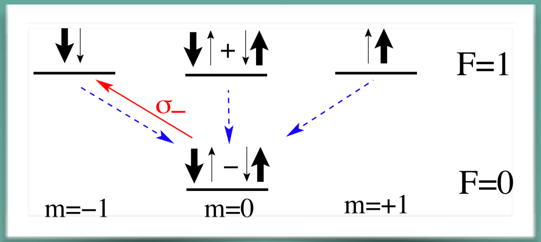
2.2 Working Principle

1. Formation



2. De-excitation

3. Laser excitation

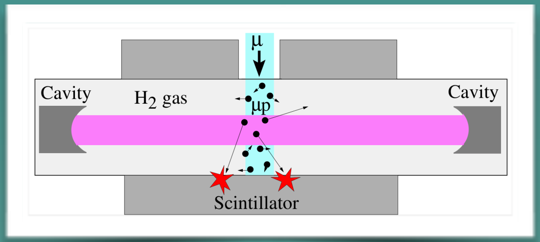


4. Collisional de-excitation

5. Diffusion

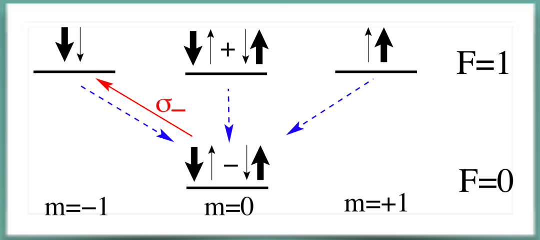
2.2 Working Principle

1. Formation



2. De-excitation

3. Laser excitation



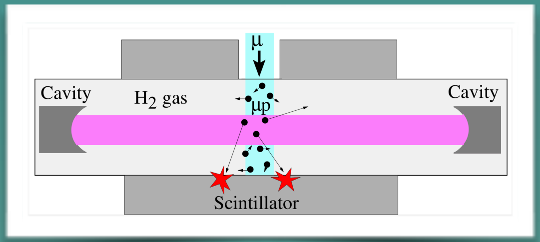
4. Collisional de-excitation

5. Diffusion

6. At the wall

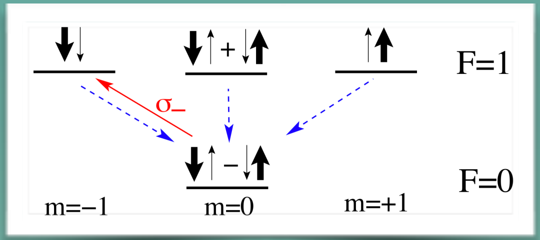
2.2 Working Principle

1. Formation



2. De-excitation

3. Laser excitation

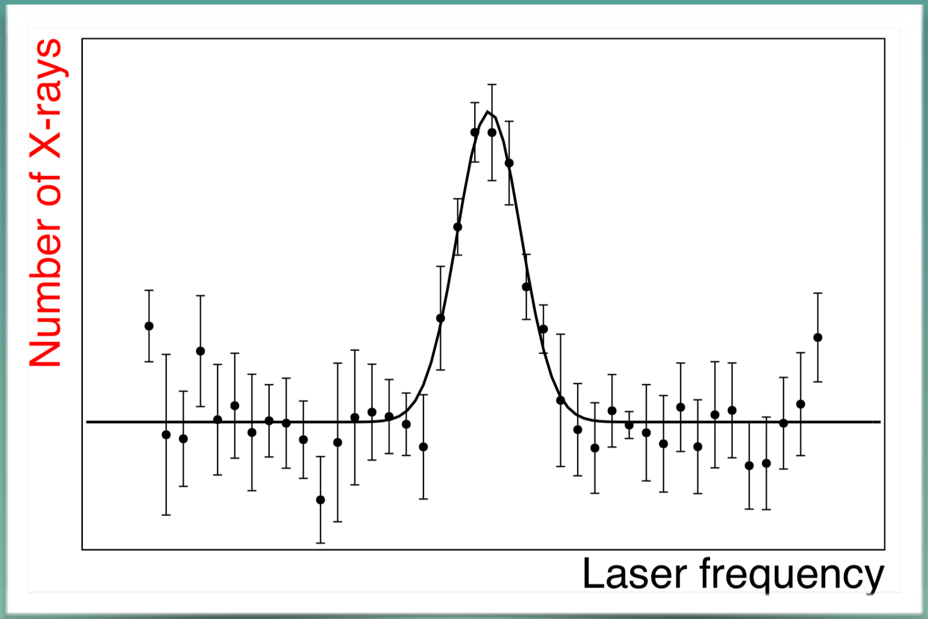


4. Collisional de-excitation

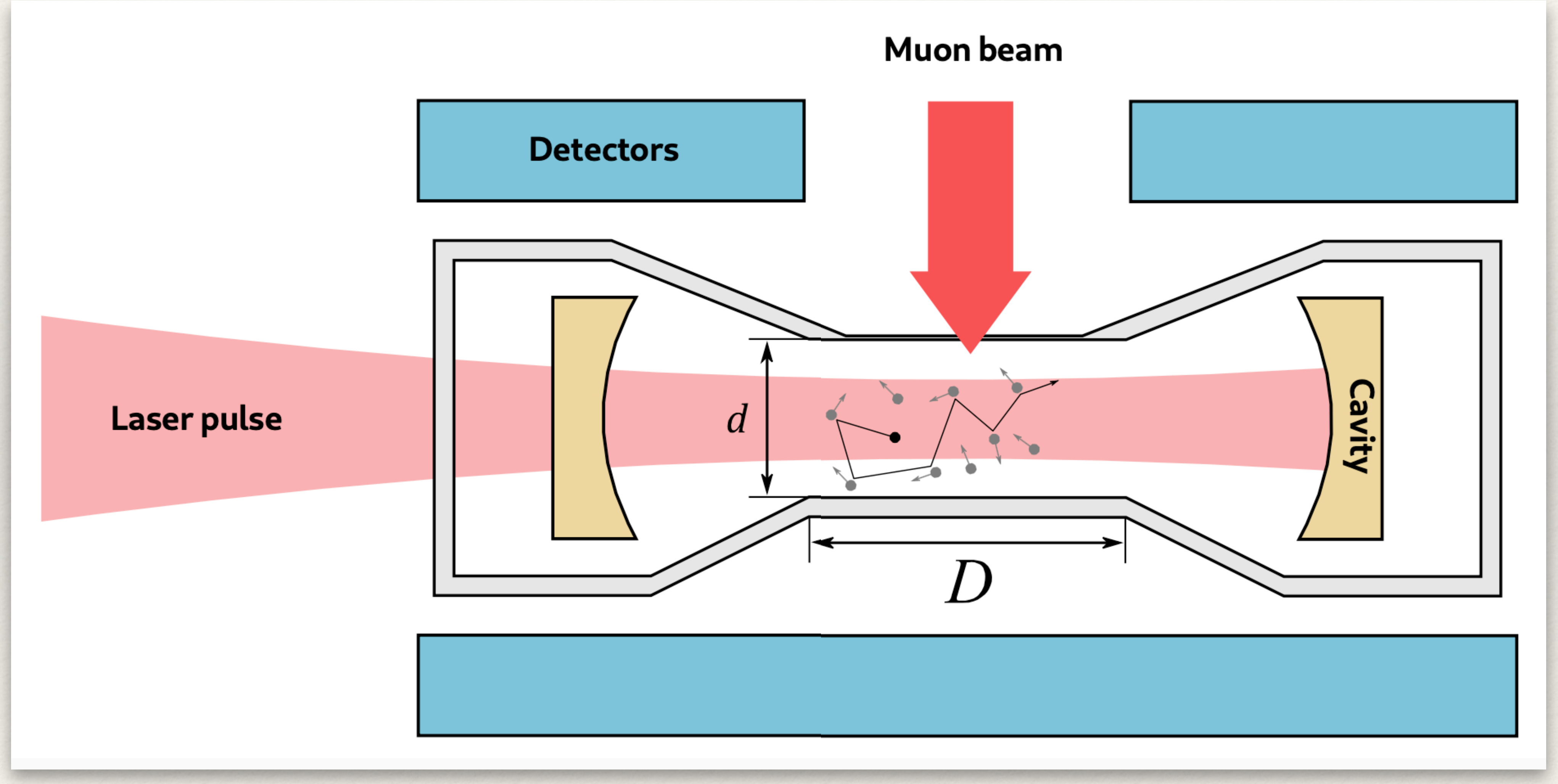
5. Diffusion

6. At the wall

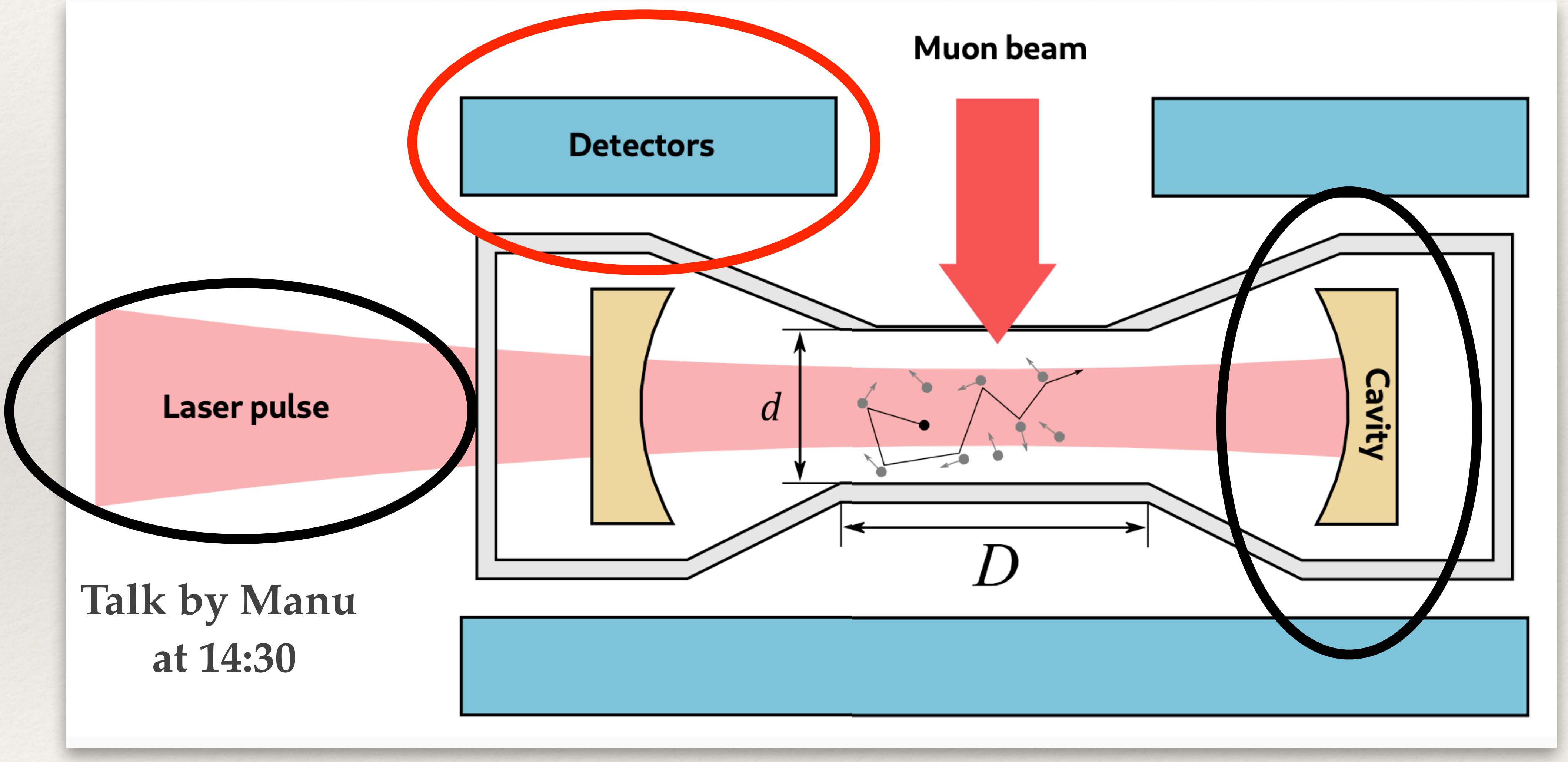
7. Detection



2.3 HyperMu Apparatus



2.3 HyperMu Apparatus

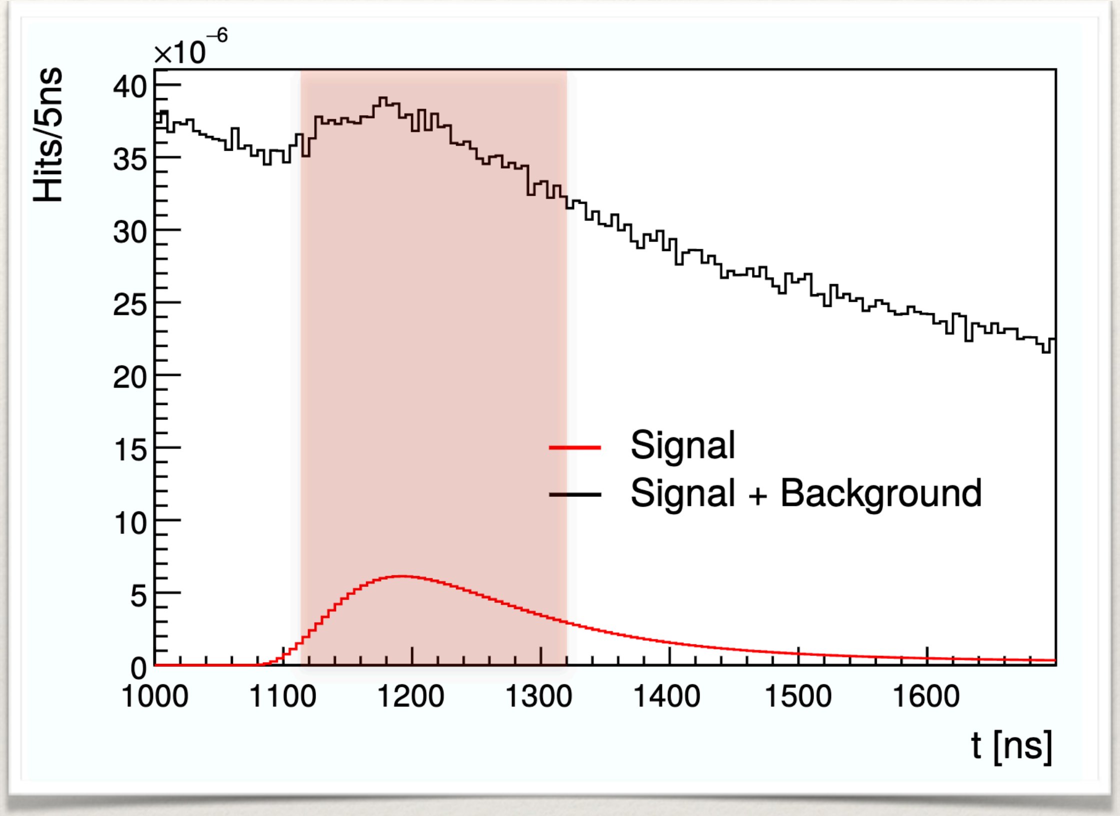


Talk by Manu
at 14:30

3.1 Signal and Background

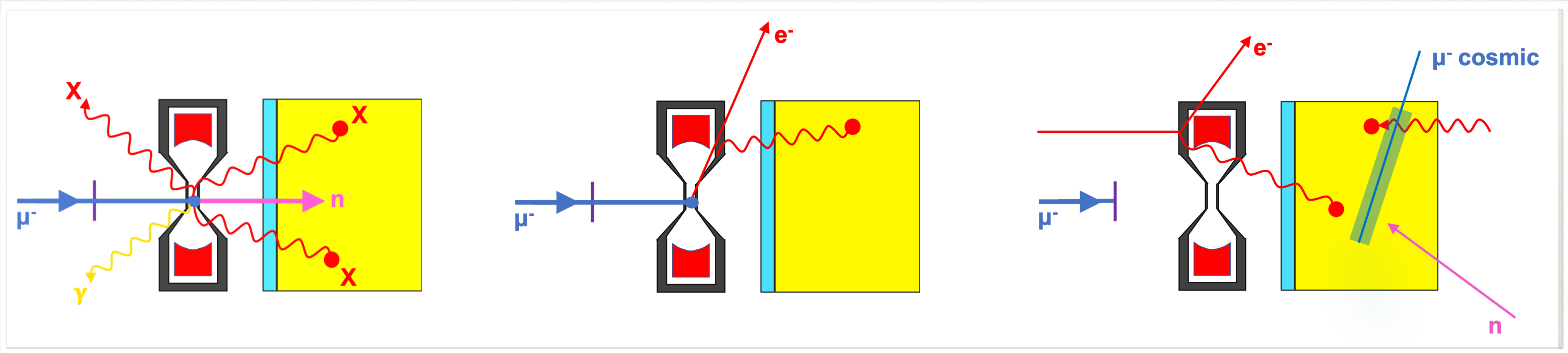
- Signal:
  MeV X-rays detected within a time window Δt.

- Background:
  - Intrinsic (from μp diffusion)
  - Erroneous (bremsstrahlung): electrons produced when the muon decays, $\mu^- \to e^- \nu_\mu \overline{\nu_e}$.
  - Muon-uncorrelated



3.1 Signal and Background (II)

Signal   Bremsstrahlung   Uncorrelated background

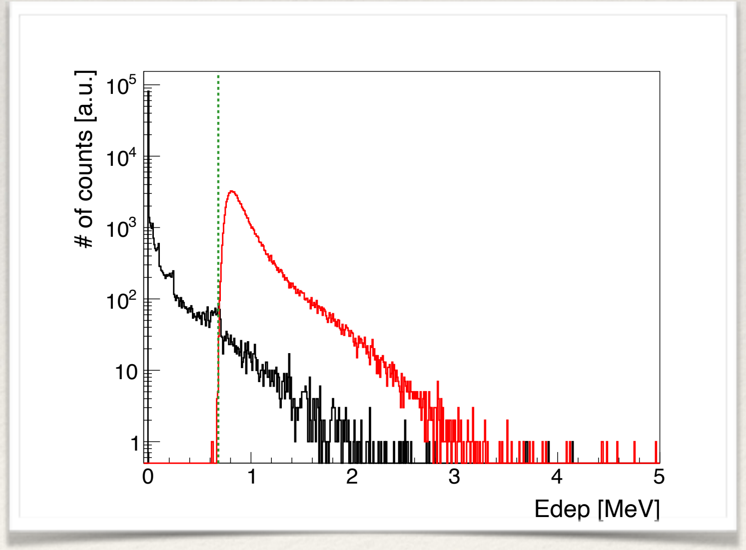


False identification of
e- as cascade event

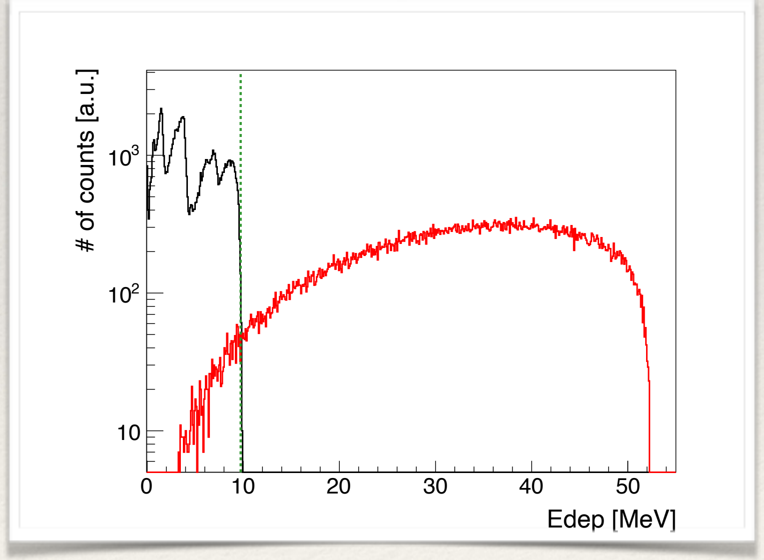
3.2 The Principle

- Use thick scintillators to detect X-rays.
- Use thin scintillators to discriminate electrons from X-rays.
- Muon decay: , muonic-gold X-ray cascade: .

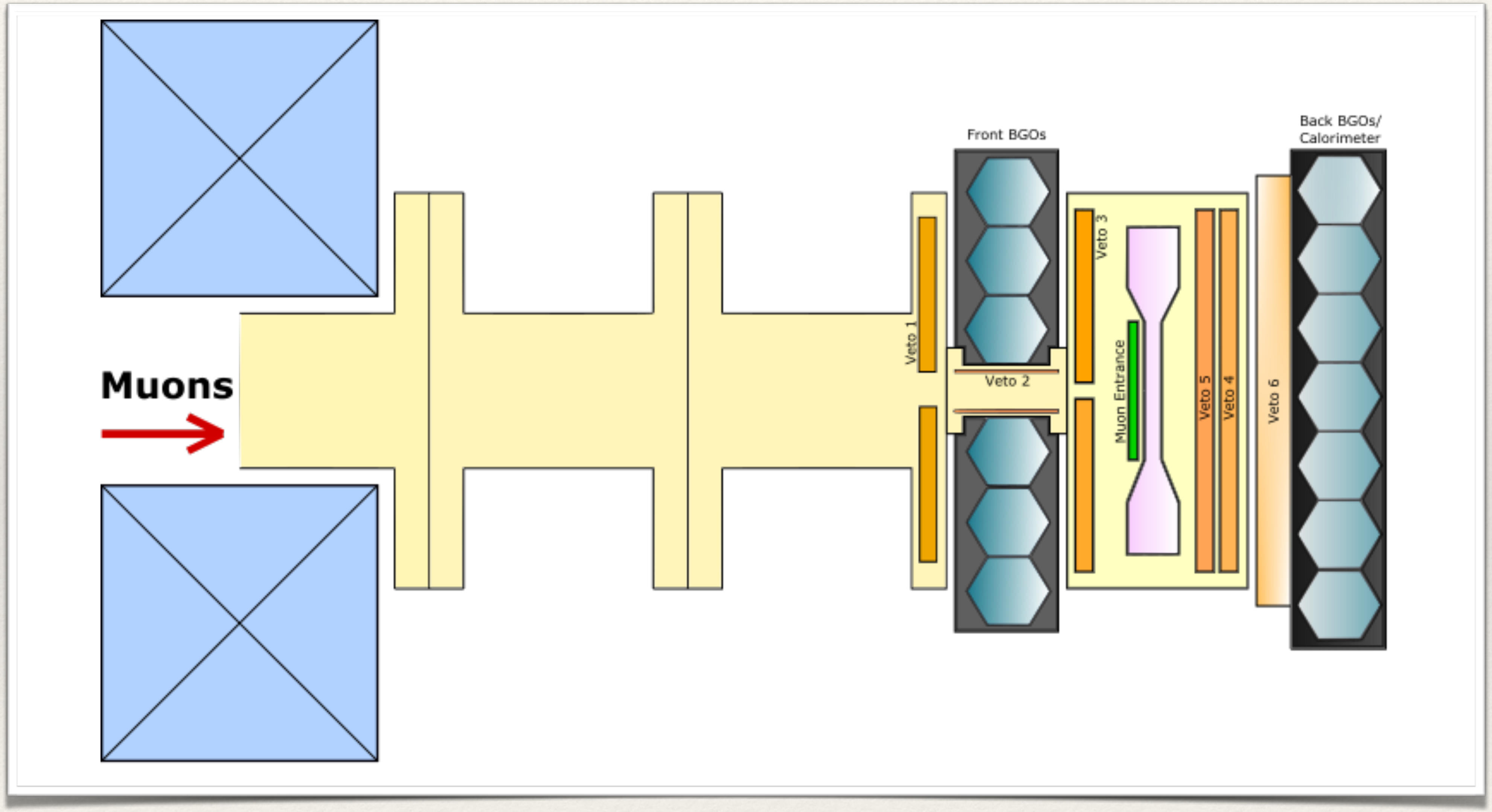
5-mm plastic scintillator



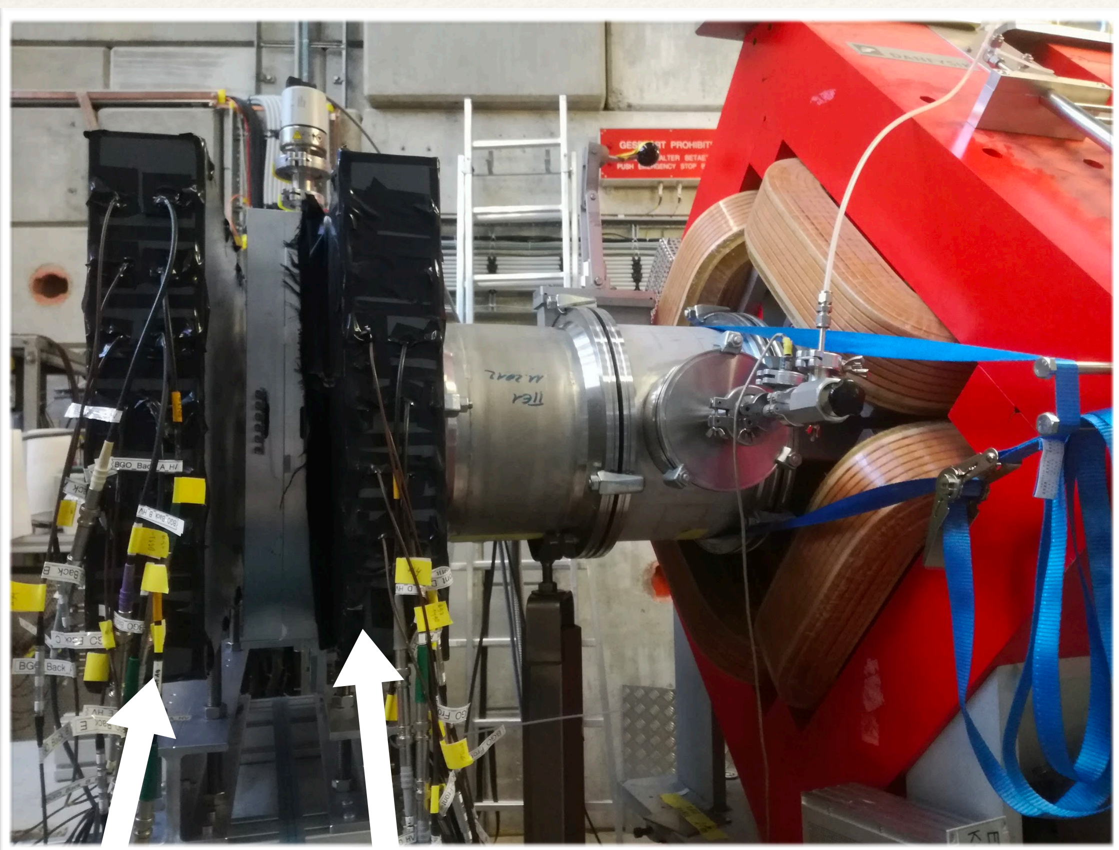
250-mm plastic scintillator



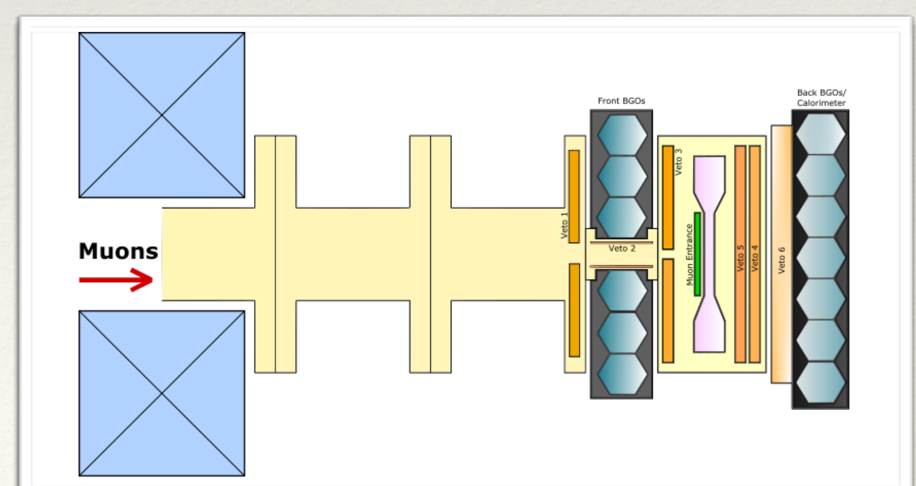
3.3 Detection System Nov' 19



3.3 Detection System Nov’19 (II)



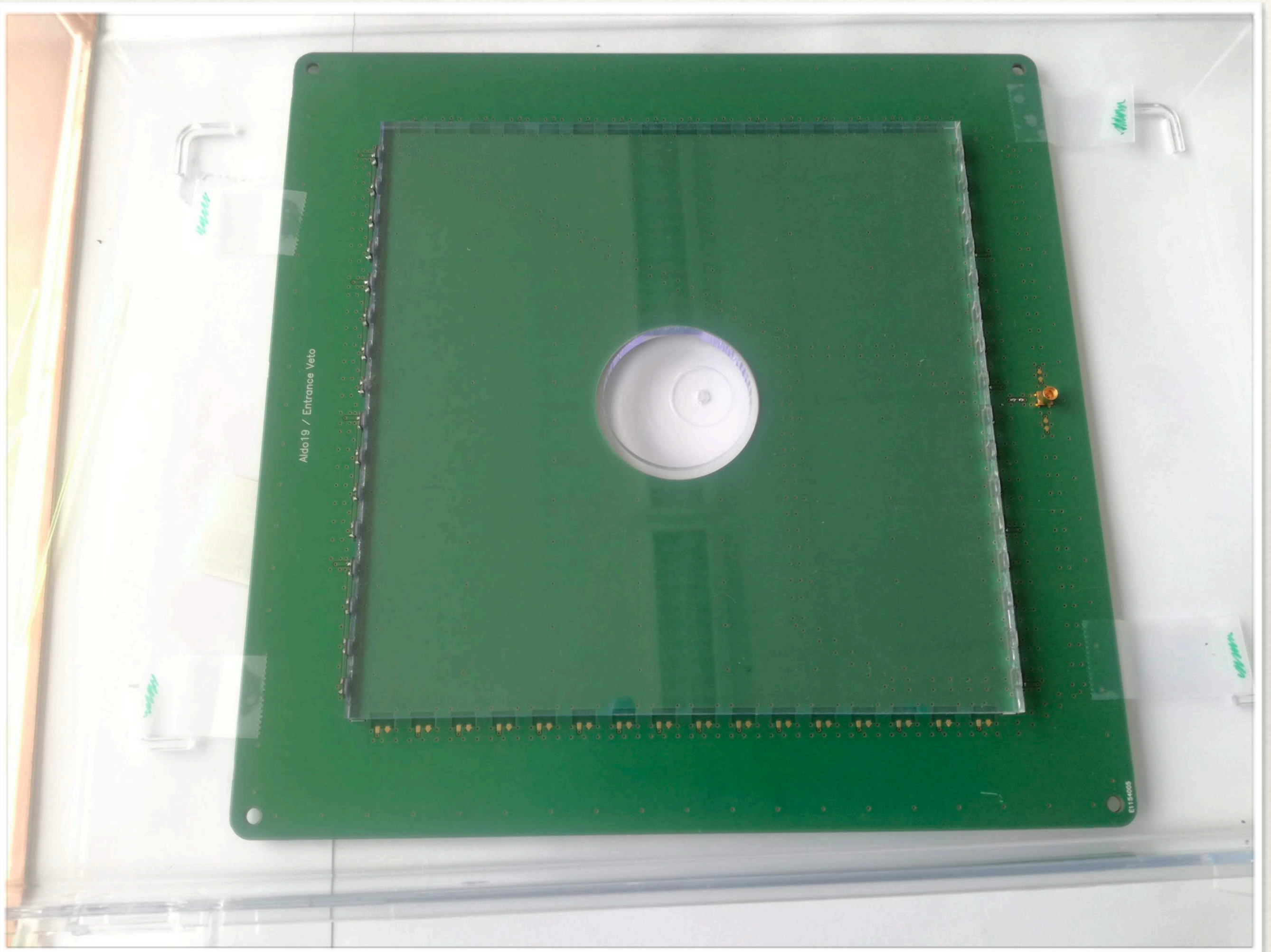
Calorimeter

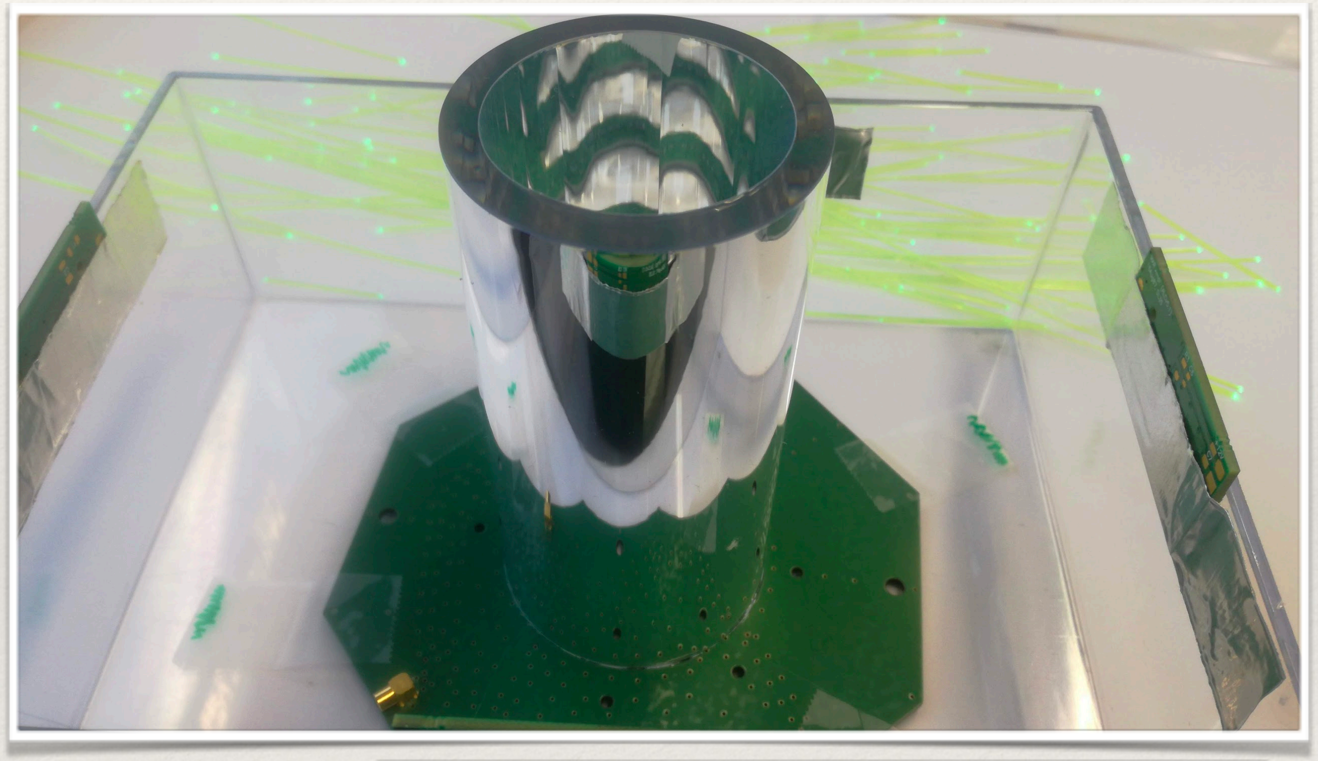


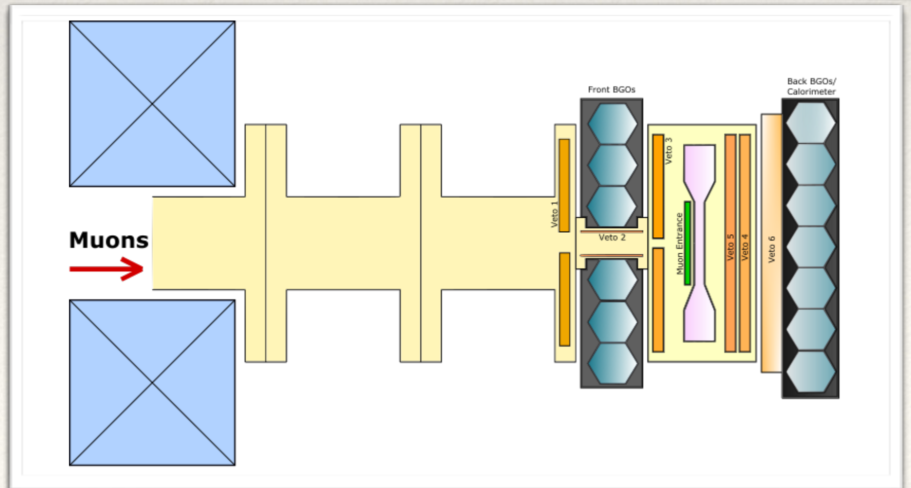
Back BGOs

Front BGOs

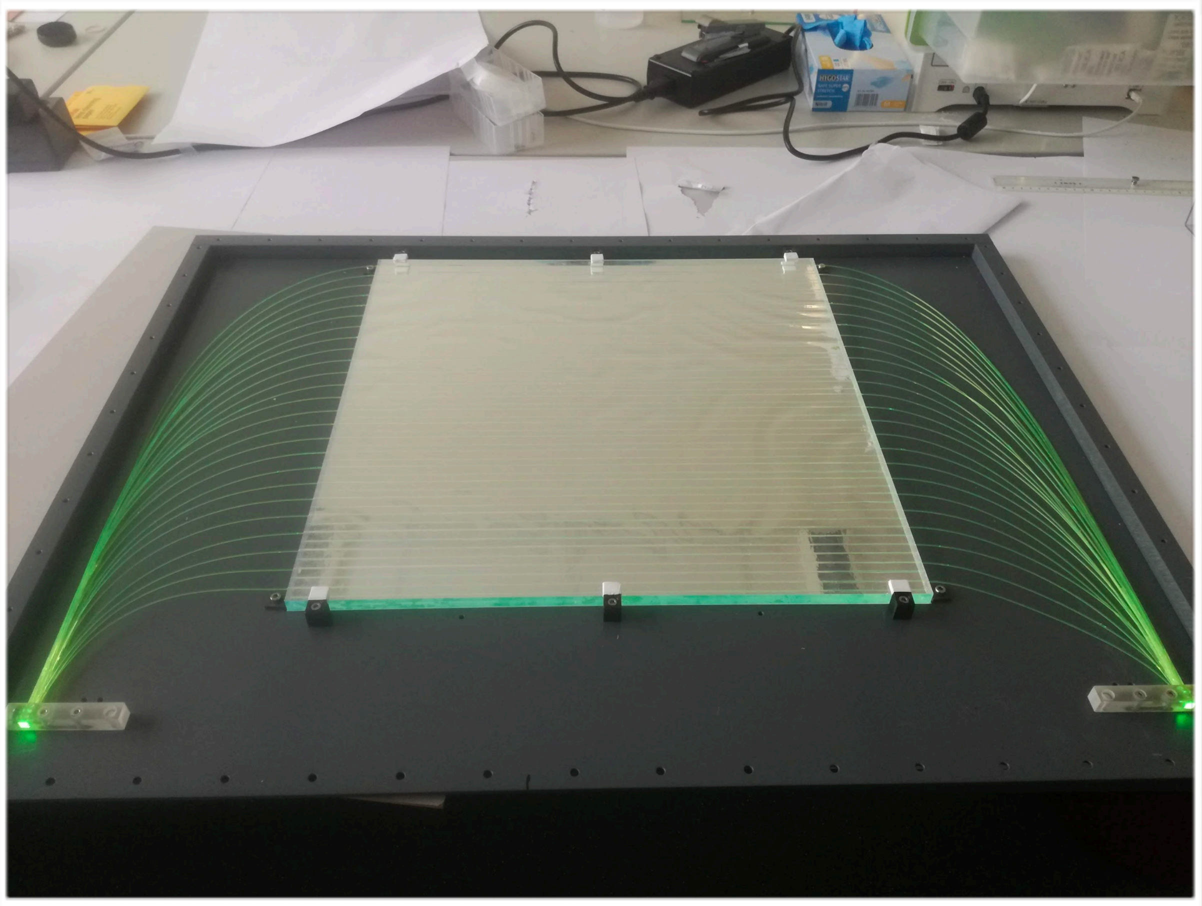
3.4 Plastic Scintillators with GAPDs

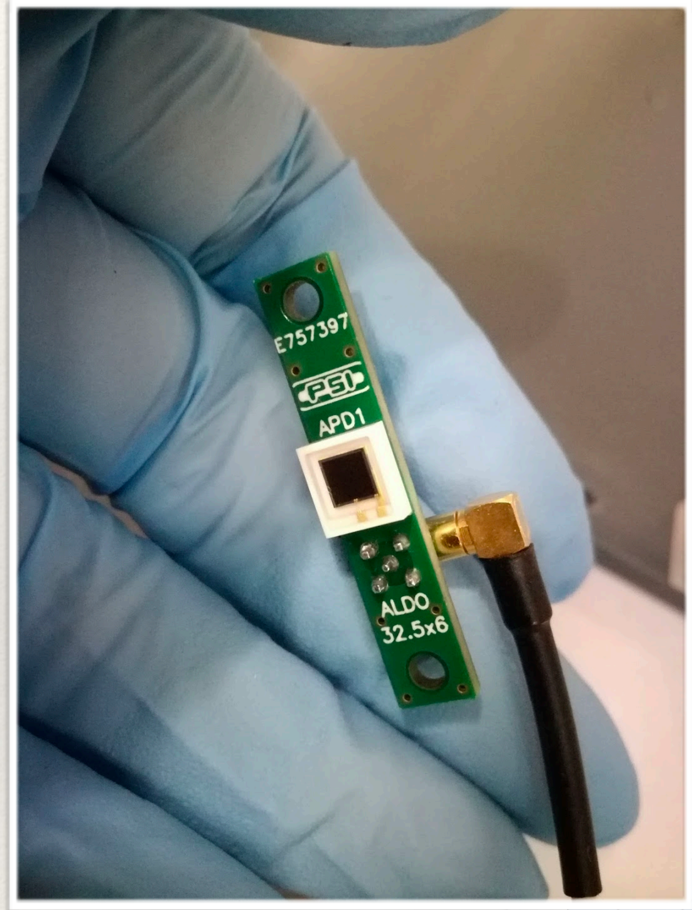


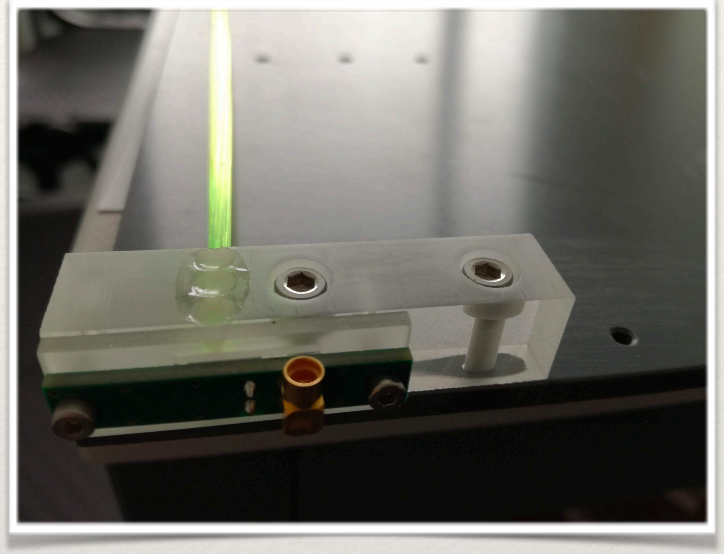


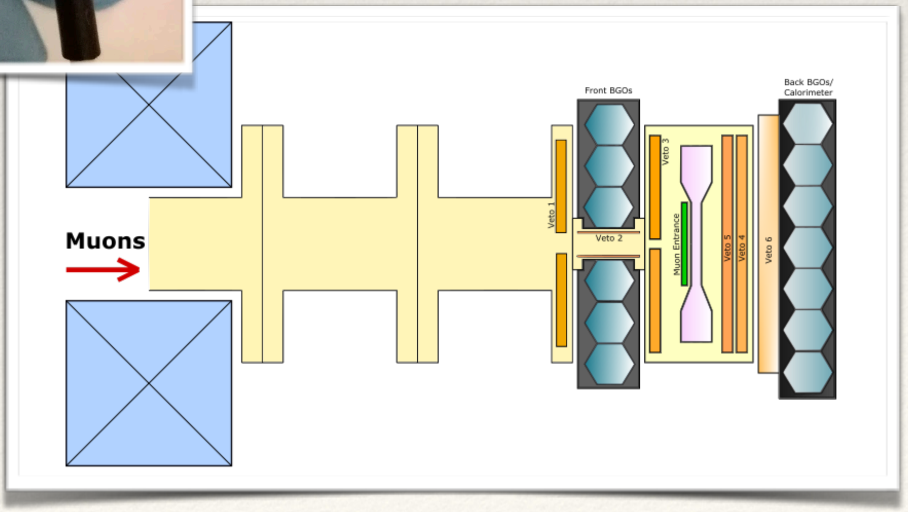


3.5 Plastic Scintillators with WLSFs

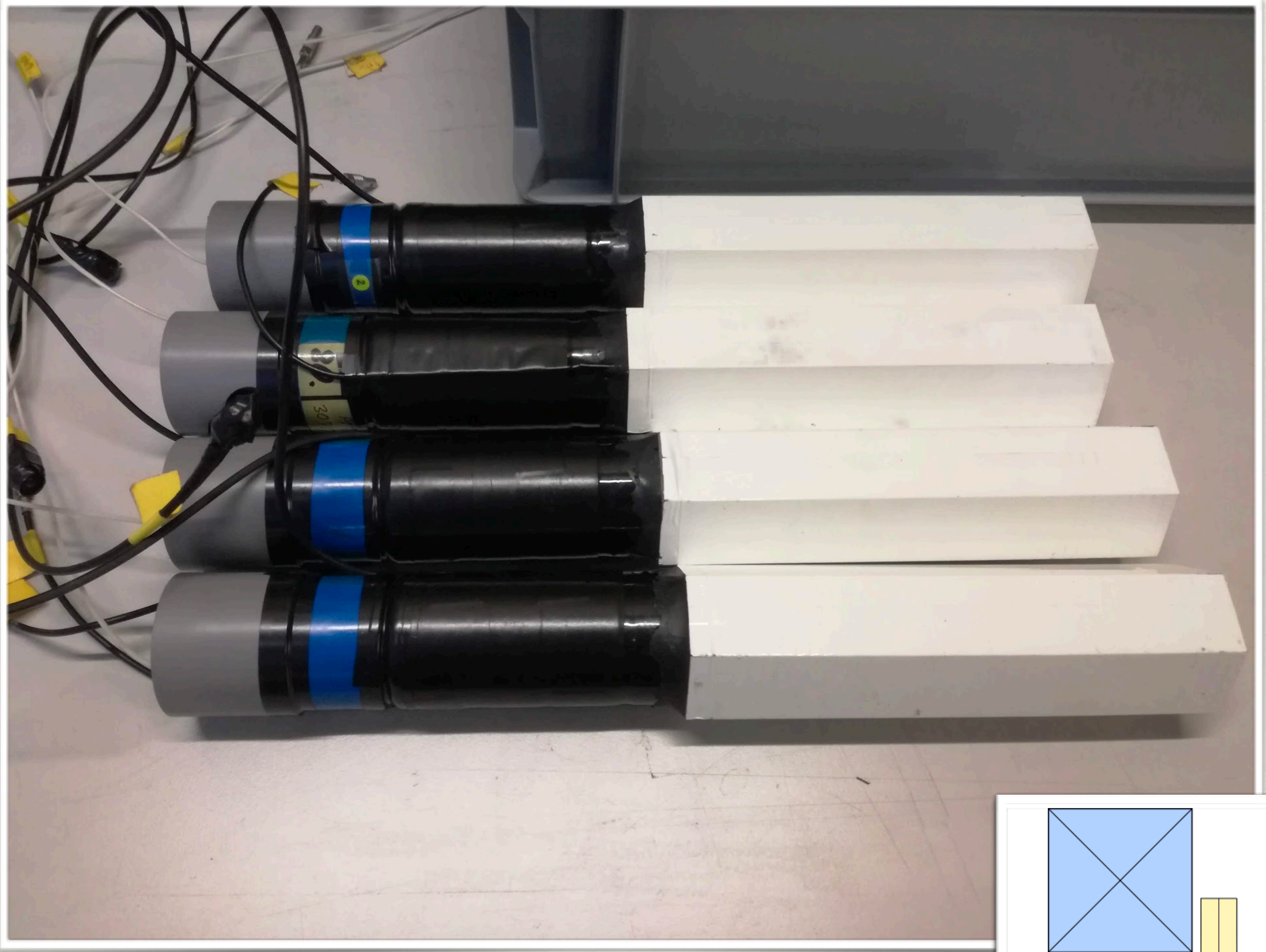


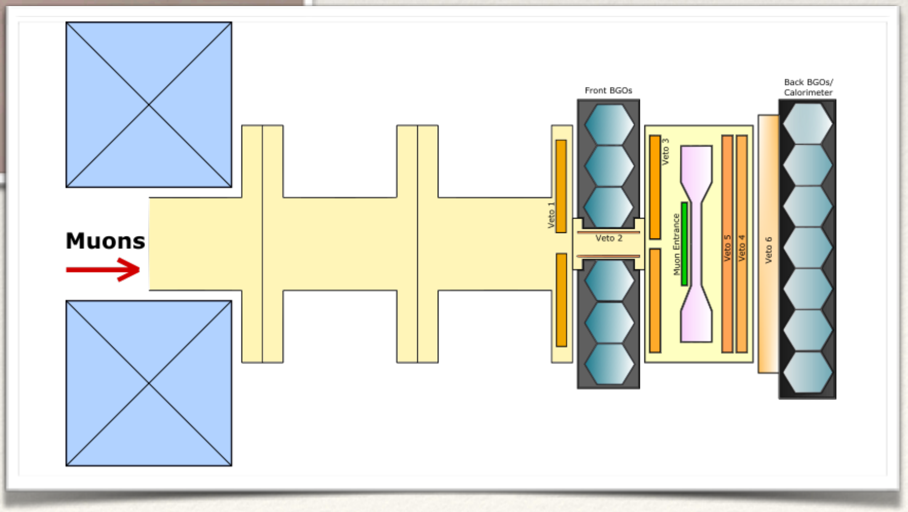




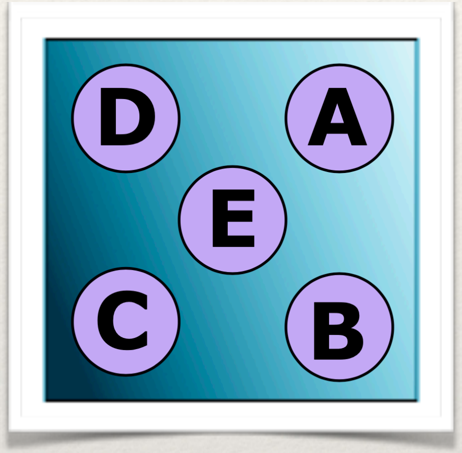


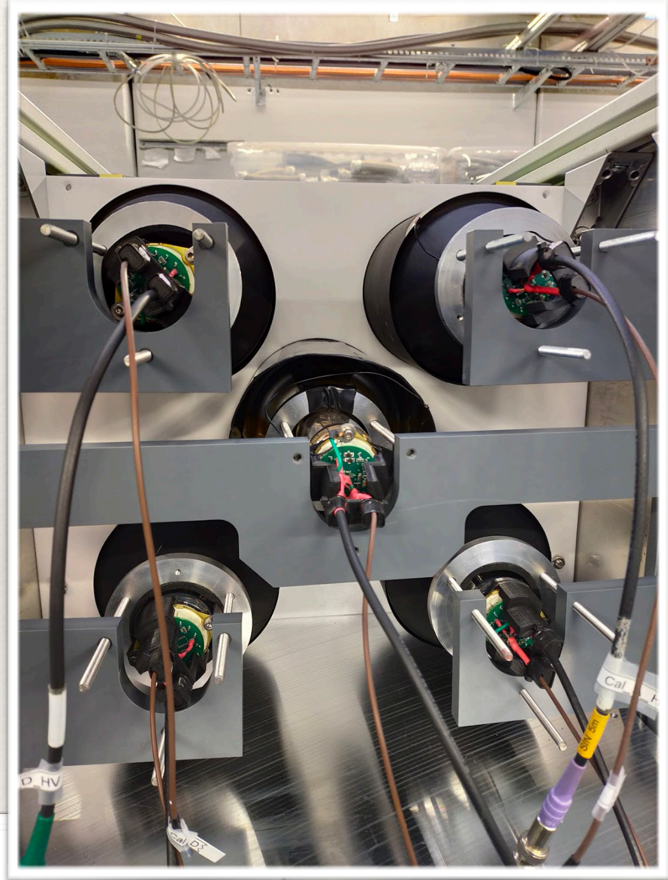
3.6 BGO Crystals

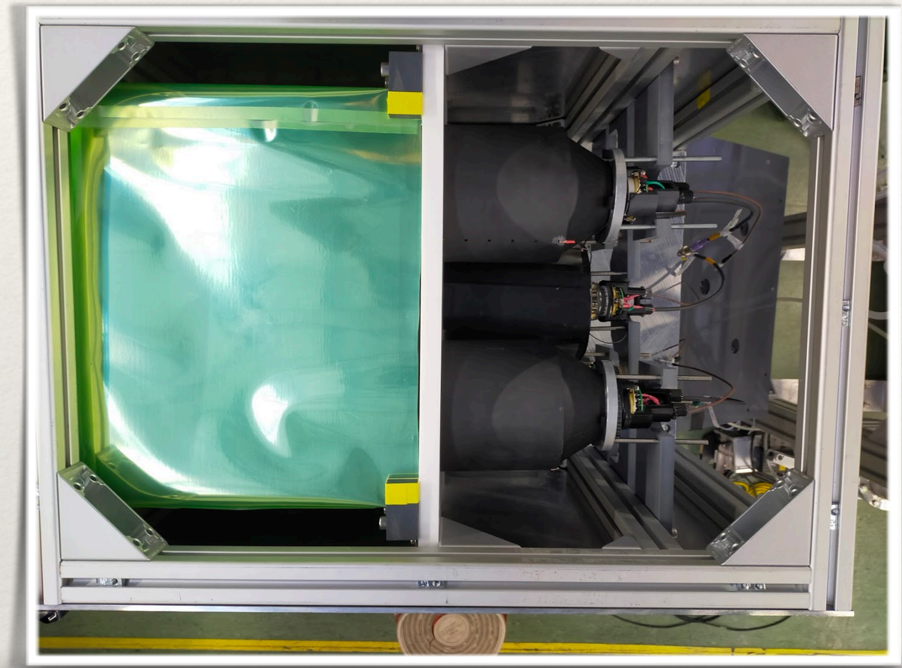


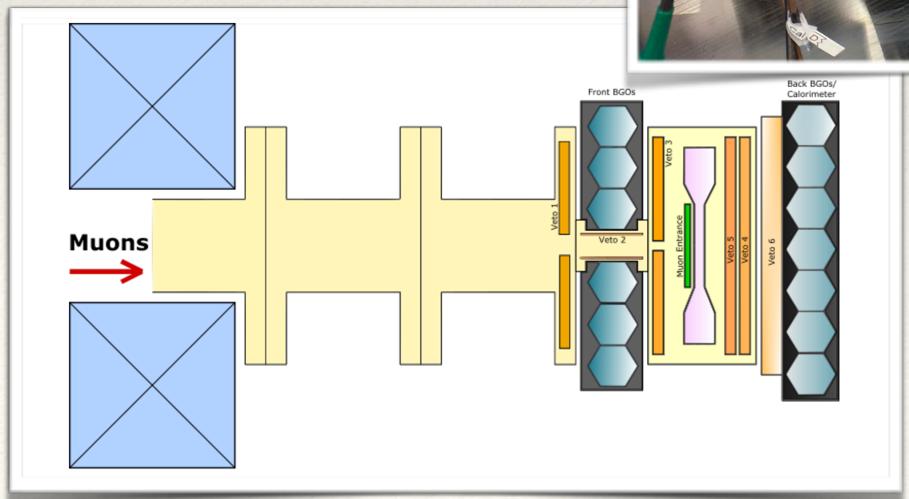


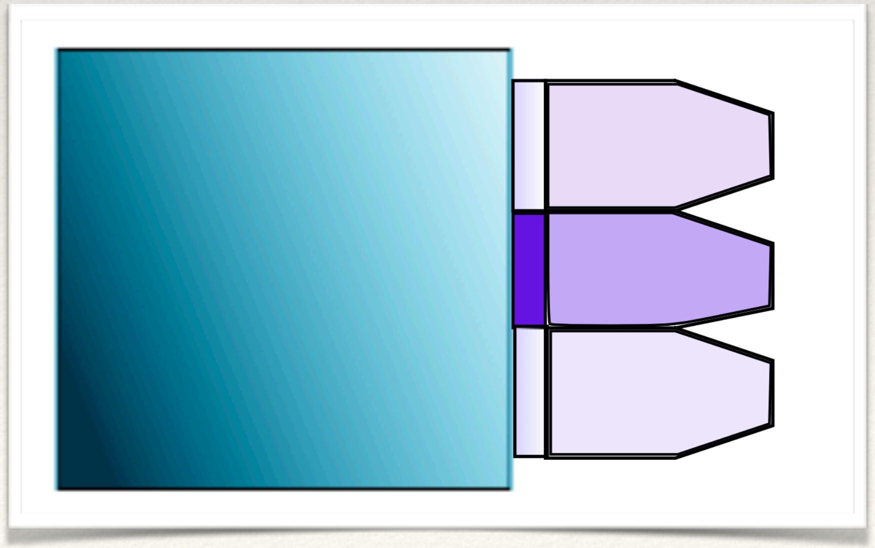
3.7 Calorimeter





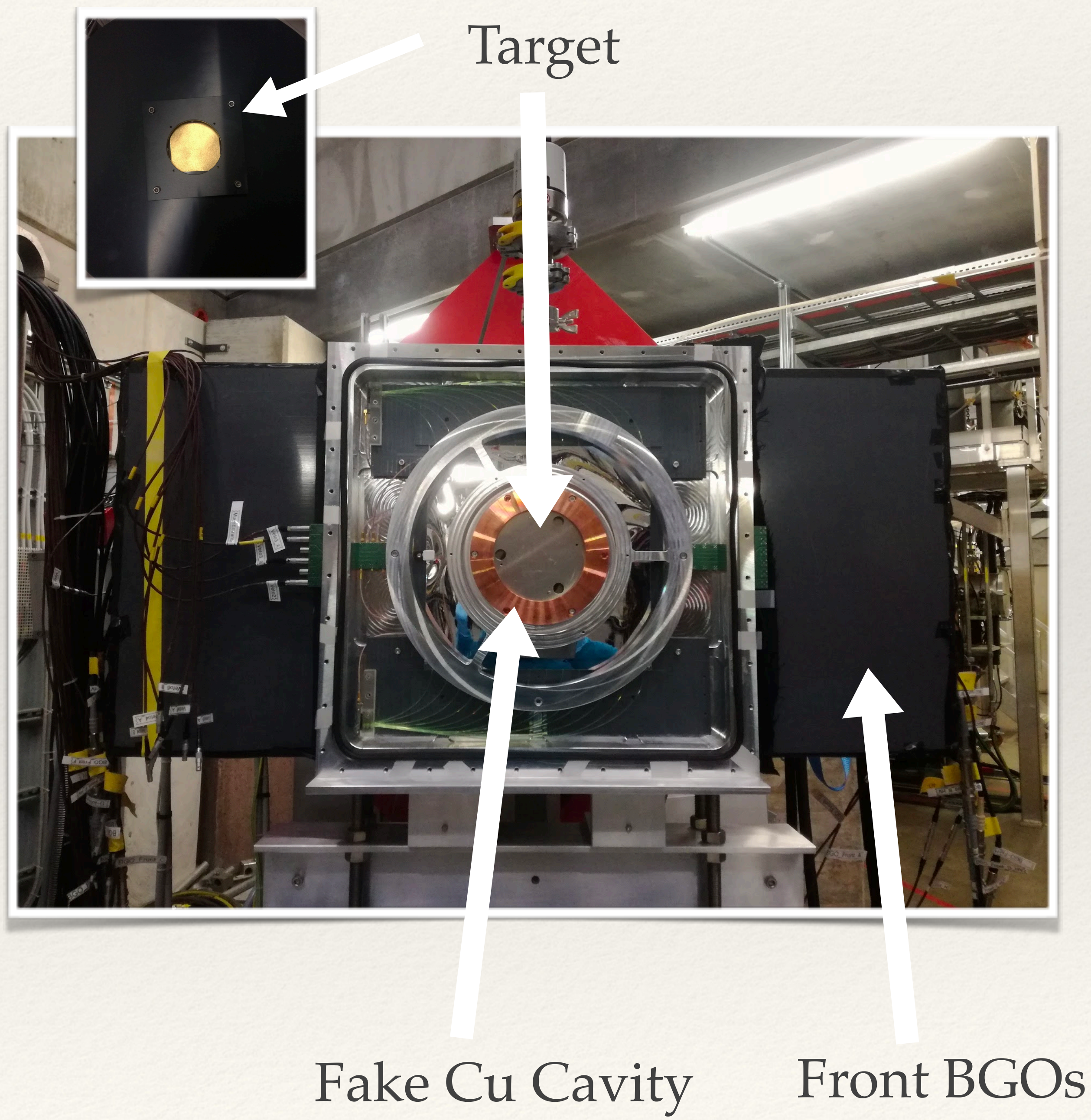






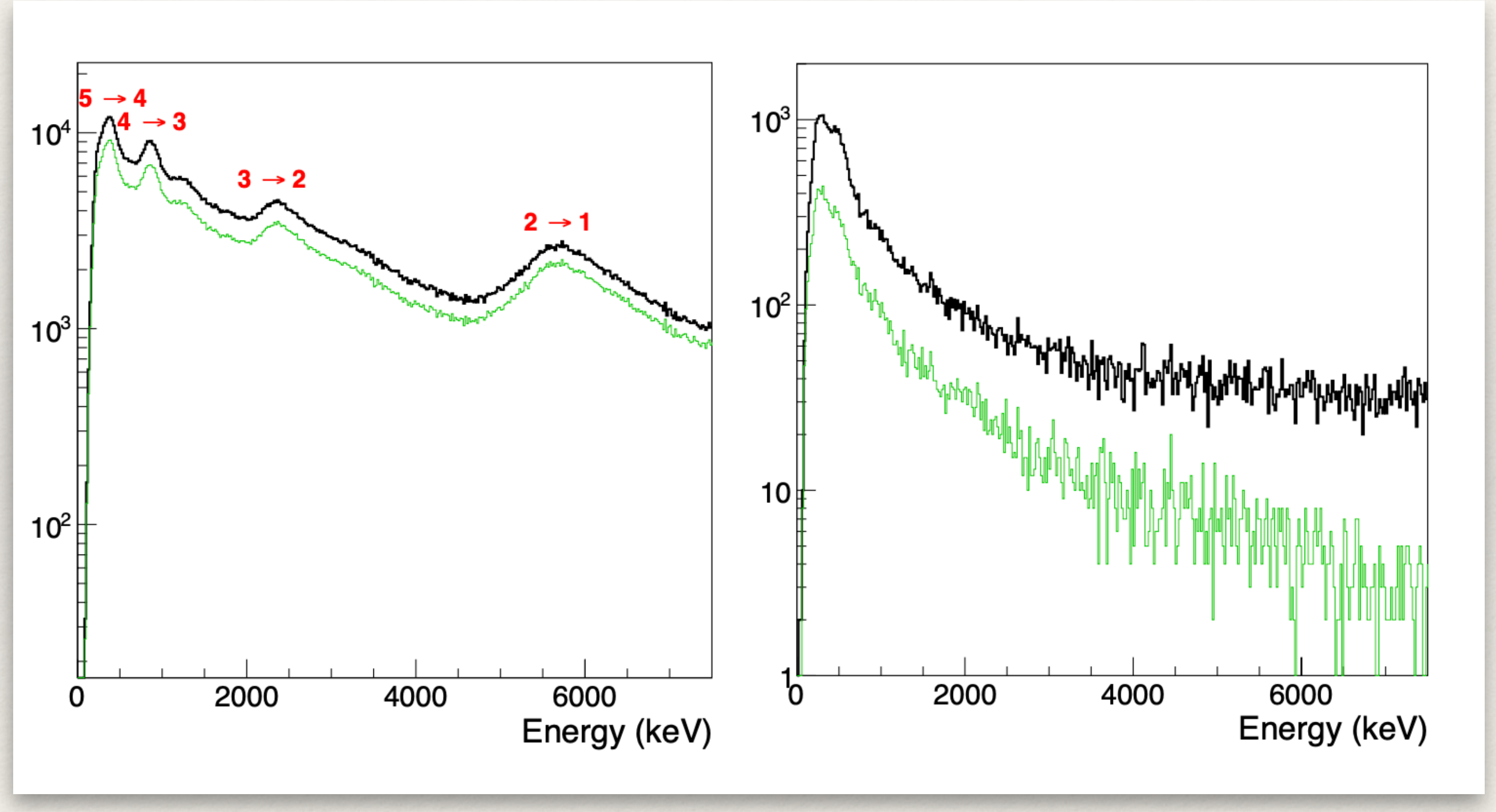
4.1 Test Variables

- P_{XX} = muonic gold (μAu) cascade detection efficiency
  - Target: gold
- P_{eX} = probability to misidentify electron as an X-ray
  - Target: plastic (hydrogen)



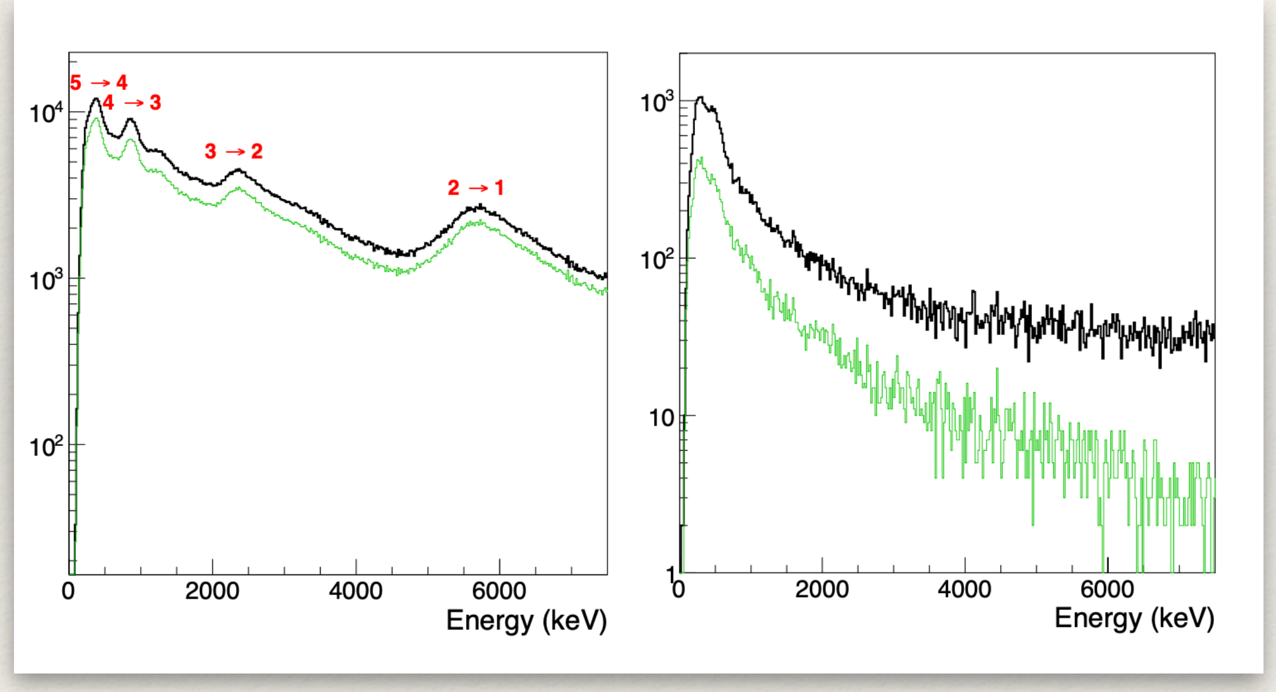
4.2 Preliminary Results

P_{XX} P_{eX}



4.2 Preliminary Results

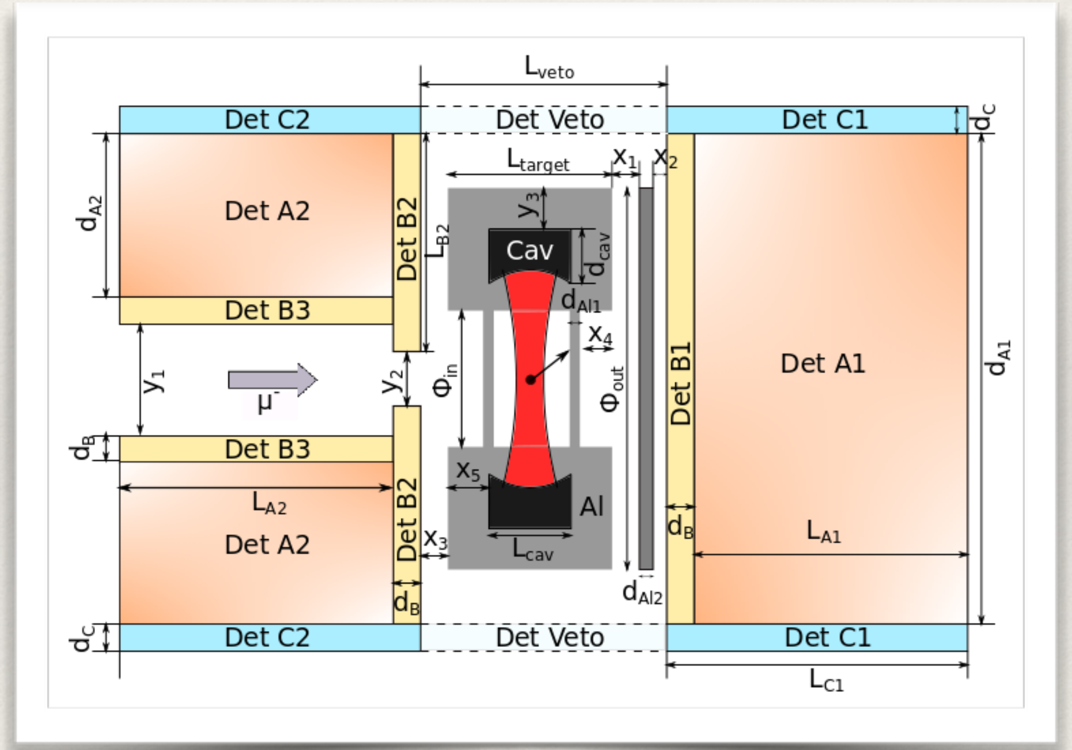
P_{XX} $\qquad$ P_{eX}



Energy range	0.20-7.5 [MeV]	0.65-7.5 [MeV]	2.0-7.5 [MeV]
P_{XX}	0.92	0.76	0.46
P_{eX}	0.121	0.062	0.022

5. Current Status

- Initial simulations for detector development - ✔
- Realisation of the setup - ✔
- Tests of the full setup - ✔
- Analysis - ON!
- Advanced simulations for the optimisation - ON!



6. Summary

- The motivation for studying the proton radius
- Working principle of the HyperMu experiment
- The idea of the HyperMu detection system
- Preliminary results from the Nov’19 beam-time at PSI
- Status update

Backup Slides

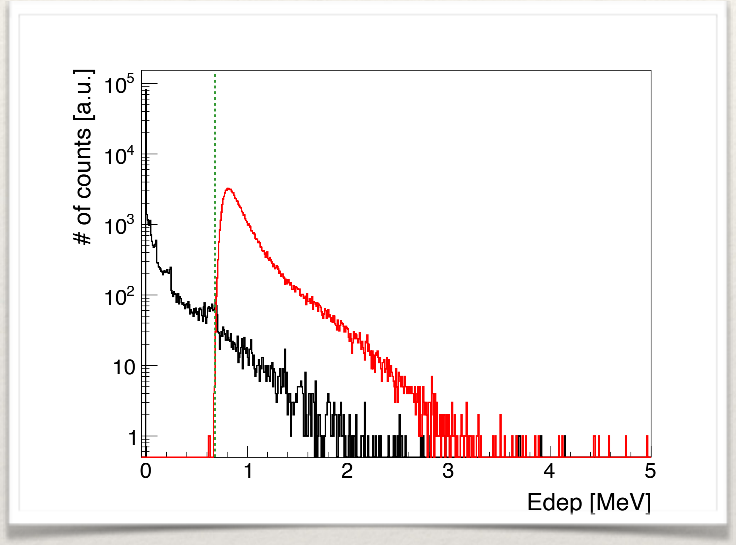
Muonic X-ray Transitions in Gold

Table 1: Energies and probabilities used in the simulations of muonic X-ray transition of gold. Data reproduced from [5,6]

transition n → n'	relative probability / %	energy / MeV
2 → 1	90	5.65
3 → 1	4.5	8.1
4 → 1	0.3	9.0
5 → 1	0.1	9.4
>6 → 1	1.0	9.6
3 → 2	84	2.4
4 → 2	6.0	3.3
5 → 2	1.12	3.7
6 → 2	0.4	3.9
>7 → 2	0.5	4.2
4 → 3	76	0.9
5 → 3	8.0	1.3
6 → 3	2.0	1.5
7 → 3	0.8	1.7
>8 → 3	2.5	1.8
5 → 4	66	0.4
6 → 4	9.0	0.6
7 → 4	3.0	0.5
8 → 4	1.0	0.85
>9 → 4	4.0	0.9
6 → 5	66	0.22
7 → 5	9.0	0.36
8 → 5	3.0	0.45
9 → 5	1.0	0.52
>10 → 5	4.0	0.55
7 → 6	62	0.19
8 → 6	12.0	0.22
9 → 6	4.0	0.29
10 → 6	2.0	0.33
>11 → 6	6.0	0.26

Thin Plastic Scintillator

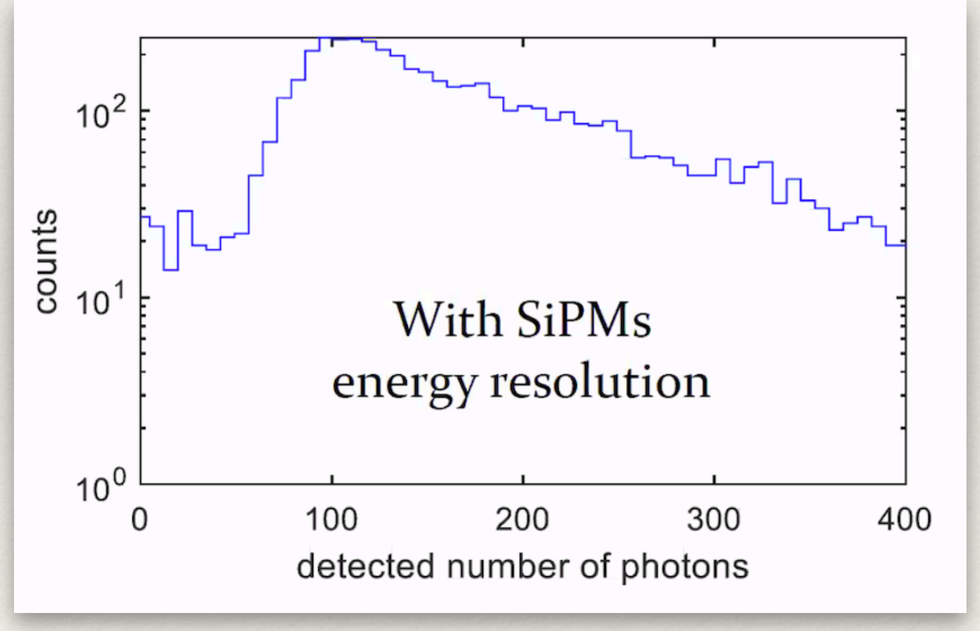
Ideal detector, no resolution



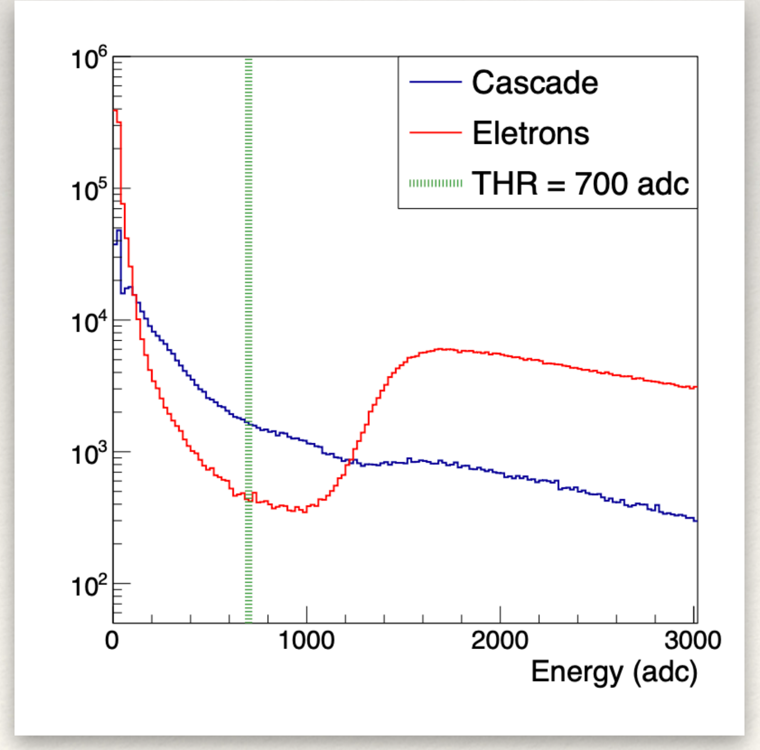
Muon decay:

μAu X-ray cascade:

Realistic detector, no mechanics



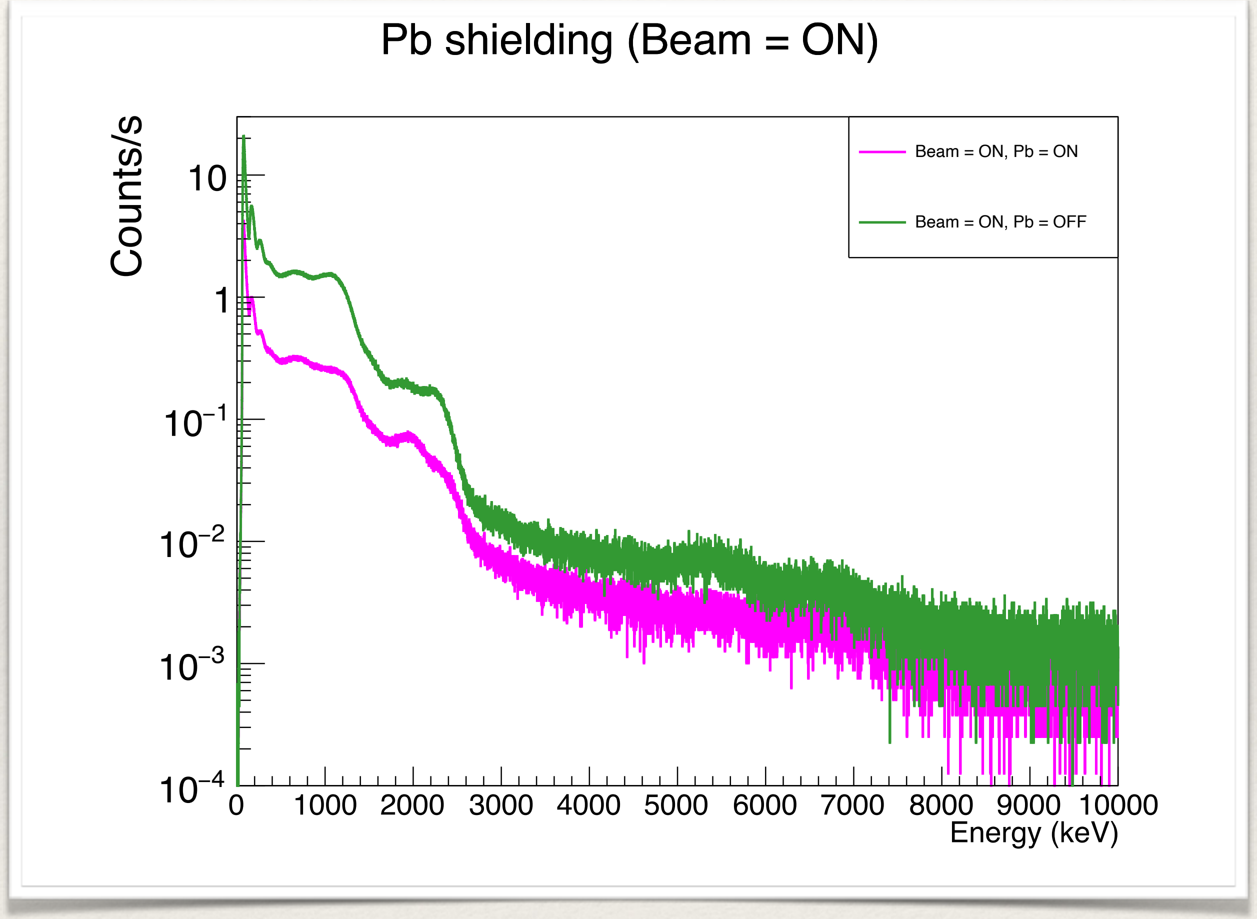
Beam-time results



Lead Shielding

- When the beam is ON:
  - Four times less background counts with the Pb shield when compared to no-shield.

→ Lead shield is useful



Experimental Rates

Energy range	0.20-7.5 [MeV]	0.65-7.5 [MeV]	2.0-7.5 [MeV]
P_{XX}	0.92	0.76	0.46
P_{eX}	0.121	0.062	0.022

R_{signal}	172 [events/h]
$R_{\mathrm{BG}}^{\mathrm{diff}}$	1512 [events/h]
$R_{\mathrm{BG}}^{\mathrm{electron}}$	1010 [events/h]
$R_{\mathrm{BG}}^{\mathrm{unc}}$	504 [events/h]