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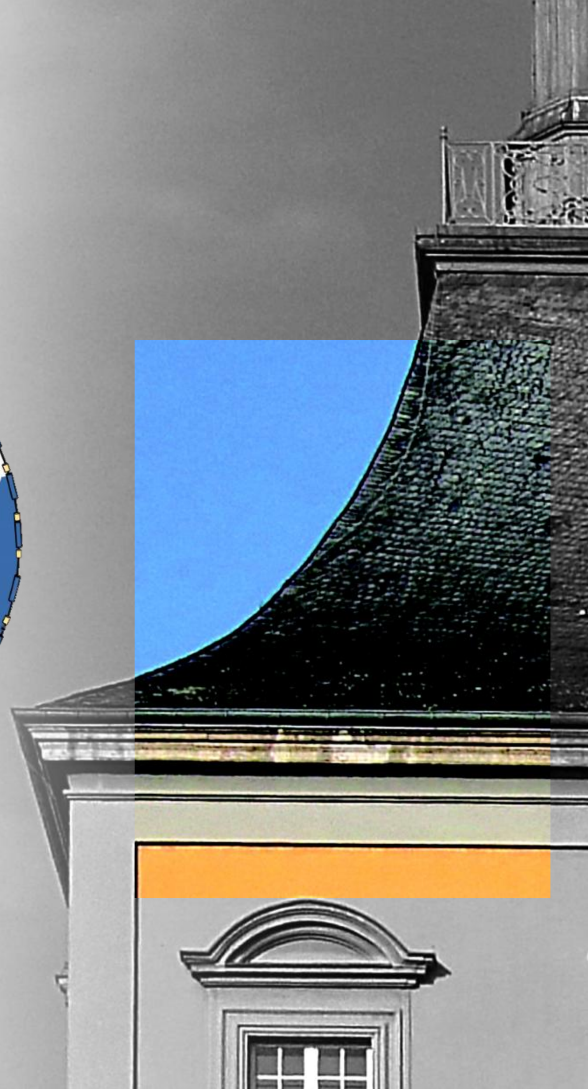
EPS HEP MARSEILLE 2025

THE LOHENGRIN EXPERIMENT AT THE ELSA ACCELERATOR



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OUTLINE

- Motivation for Lohengrin: Light Dark Matter
- General Principle of Lohengrin
- Design of the Lohengrin Experiment
- Expected Sensitivity of the Lohengrin Experiment
- The Way Forward

DARK MATTER – WISPS AND LDM

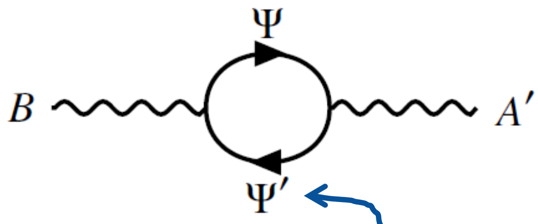
- **light dark matter**?
  - interaction between dark matter and standard model
  - **portals**: tune coupling for right relic density
- simple model: massive boson from spontaneously broken $U(1)_D$ as portal → **“dark photon”**
- minimal model: SM + DM + $U(1)_D$ → introduce coupling between DS and SM through **kinetic mixing**

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{D} + \mathcal{L}_{SM\otimes D}$$

$$\mathcal{L}_{D} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_{\mu}A'^{\mu} - g_{D}A'_{\mu}J^{\mu}_{D}$$

$$\mathcal{L}_{SM\otimes D} = -\frac{\sin\varepsilon_Y}{2}F'_{\mu\nu}B^{\mu\nu}$$

$$\mathscr{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{m^2_{A'}}{2}A'_{\mu}A'^{\mu} - \boxed{A'_{\mu}(\epsilon e J^{\mu}_{EM}} + g_D J^{\mu}_{D})$$



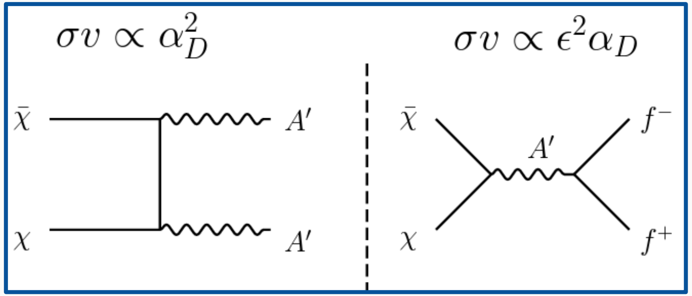
some heavy particles charged under both $U(1)_D$ and $U(1)_Y$

$$m_A^2 = 0$$

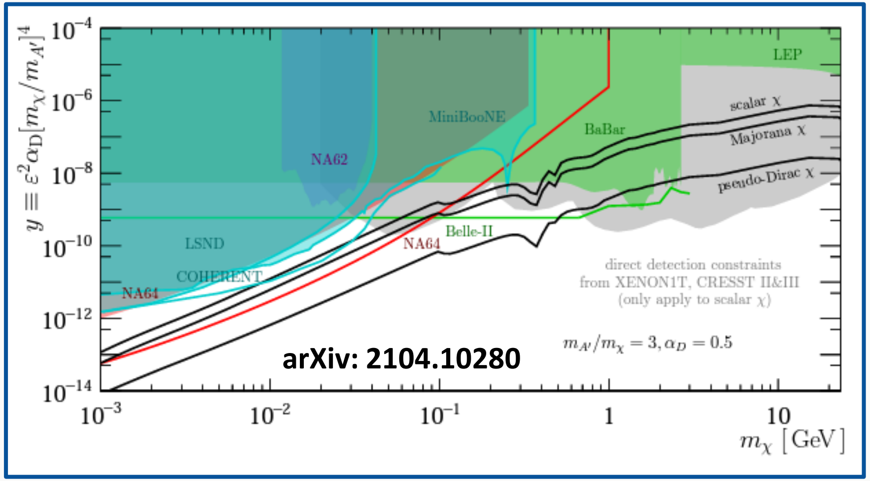
$$m_{\tilde{Z}}^2 = m_Z^2\left(1 + \varepsilon_Y^2\frac{m_Z^2 s_W^2}{m_Z^2 - m_{A'}^2}\right)$$

$$m_{A_D}^2 = m_{A'}^2\left(1 + \varepsilon_Y^2\frac{m_Z^2 c_W^2 - m_{A'}^2}{m_Z^2 - m_{A'}^2}\right)$$

DARK MATTER – DARK PHOTONS



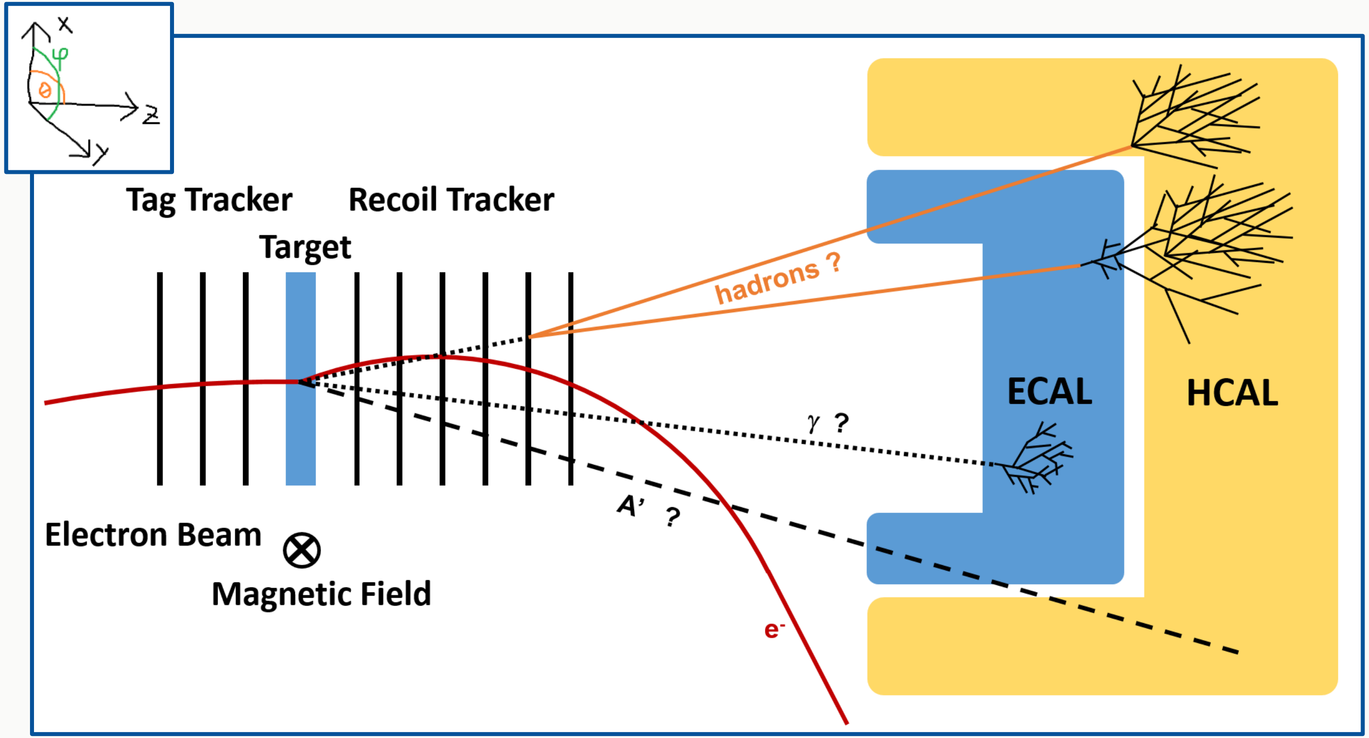
- "invisible" dark photons: $m_{A'} > 2m_\chi$:
  - dark matter annihilation through s-channel A' into fermions
  - production of dark photon at accelerators: **no visible signal**



- collider searches, beam dump experiments (with and without direct detection) and direct detection experiments

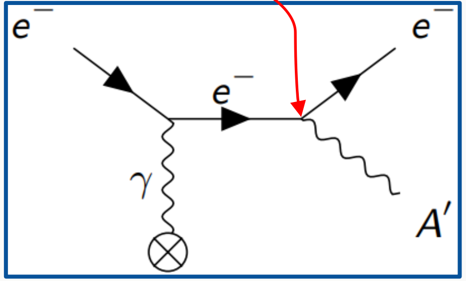
- in particles for DM masses < 1 GeV ($m_{A'}$ < 3 GeV): **sizeable gap to relic target**

FIXED TARGET DARK PHOTON SEARCH



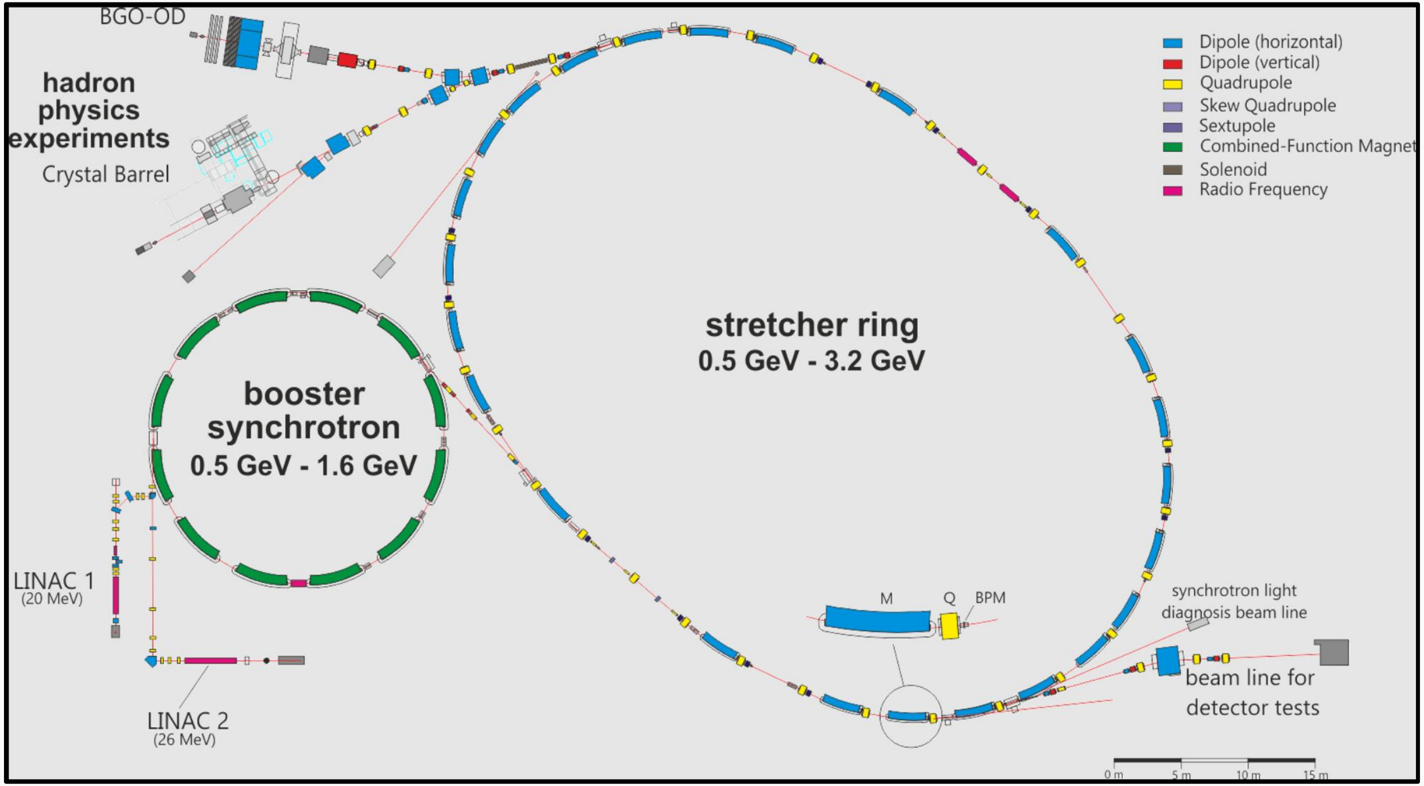
inspired by the LDMX experiment: [arXiv:1808.05219]

$\mathcal{M} \propto \varepsilon$



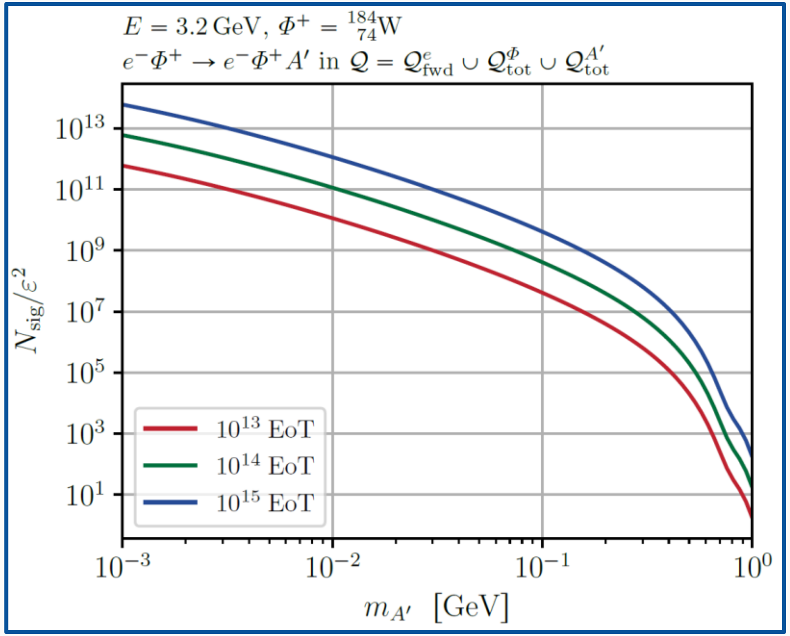
- electron beam on fixed target
- SM processes:
  - bremsstrahlung
  - electro-nuclear reaction
  - photo-nuclear reaction
- depending on $m_{A'}$ and ε: occasional radiation of dark photon: **dark bremsstrahlung with large energy loss**

ELSA – ELEKTRONEN STRETCHER ANLAGE



- ability to extract **$\mu \leq 1$** electrons per 2 ns bunch
- electron energy up to **3.2 GeV, σ_E = 0.08%**
- enough for the production of light weight dark photons

DARK PHOTON PRODUCTION AT ELSA



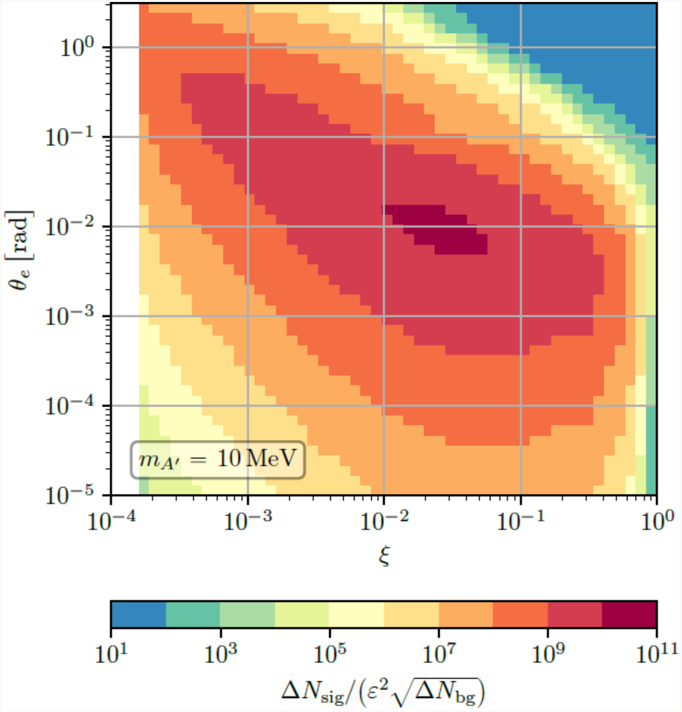
tungsten target, thickness: 0.1 X_0

- relic target predicts coupling strength between 10^{-12} and 10^{-7} for dark photon masses between 1 MeV and 1 GeV

mA' [MeV]	ε^2 (scalar χ)	ε^2 (majorana χ)	ε^2 (pseudo-dirac χ)
4.5	4.3×10^{-11}	2.2×10^{-11}	2.9×10^{-12}
10	2.0×10^{-10}	9.8×10^{-11}	1.3×10^{-11}
100	2.6×10^{-8}	1.2×10^{-8}	1.2×10^{-9}
1000	5.4×10^{-7}	2.7×10^{-7}	2.5×10^{-8}

- need high rate of electrons on target, **O(100 MHz)**:
- can expect between **100 and a O(1000) dark photon events** for masses **up to 100 MeV** during 100 days of beam time at ELSA
- need **excellent background rejection**

WHERE TO LOOK FOR DARK PHOTONS?

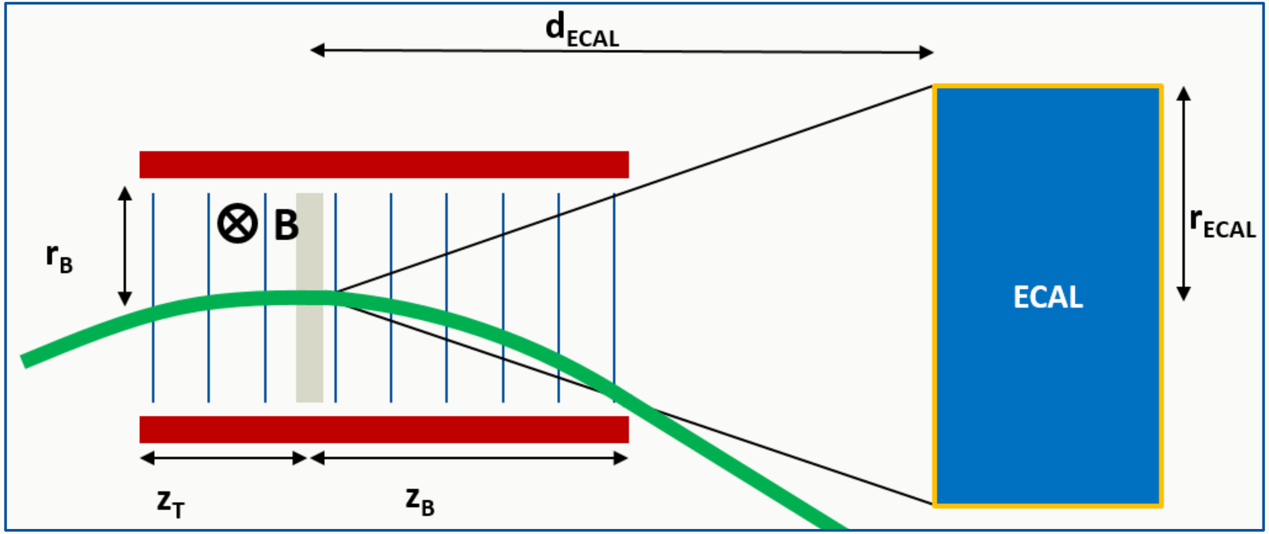


- target interval for mA': 10 MeV – 100 MeV
- assuming basic ECAL veto and only dominant SM BG

$$E = 3.2\,\mathrm{GeV},\ \Phi^+ = {}^{184}_{74}\mathrm{W}$$
$$e^-\Phi^+ \to e^-\Phi^+ A' \text{ in } \mathcal{Q} = \mathcal{Q}^e_{\mathrm{bin}} \cup \mathcal{Q}^{\Phi}_{\mathrm{tot}} \cup \mathcal{Q}^{A'}_{\mathrm{tot}}$$
$$e^-\Phi^+ \to e^-\Phi^+ \gamma \text{ in } \mathcal{Q} = \mathcal{Q}^e_{\mathrm{bin}} \cup \mathcal{Q}^{\Phi}_{\mathrm{tot}} \cup \mathcal{Q}^{\gamma}_{\overline{\mathrm{ECAL+IRc}}}$$

- should look in **final states with electrons that lost most of their energy** in the target
  - use low momentum electron trigger!

LAYOUT OPTIMISATION



baseline parameters:

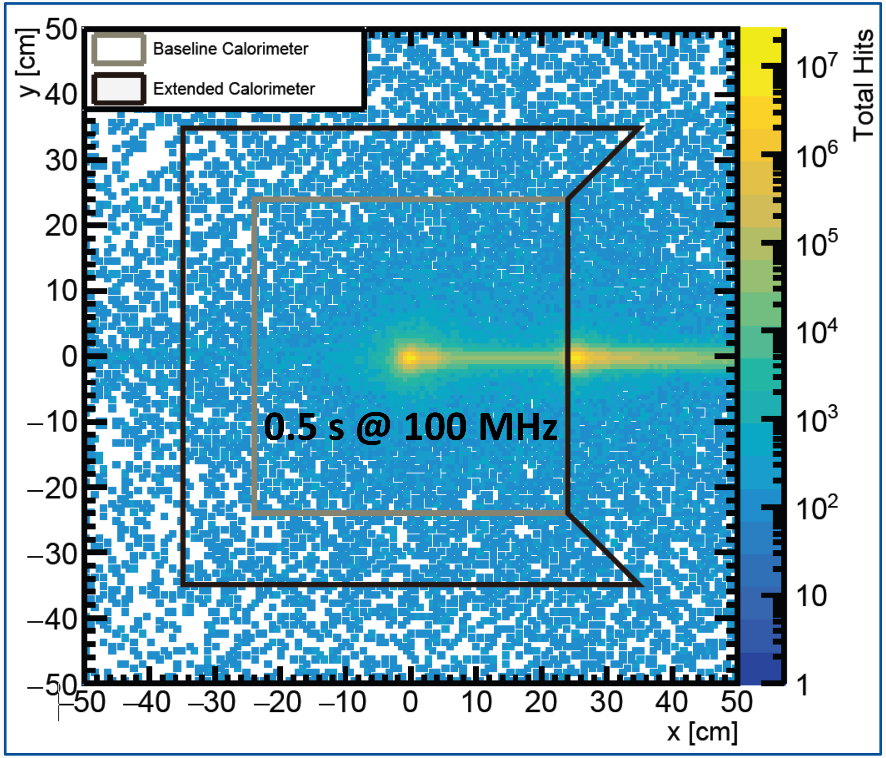
r_B = 0.1 m B = 0.9 T d_{ECAL} = 3.5 m

z_B = 1.0 m r_{ECAL} = 0.24 m

THE ECAL

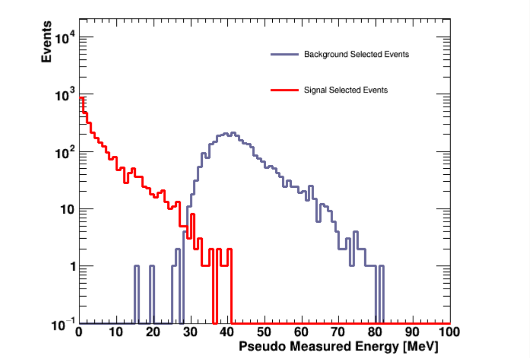
- ECAL used as **photon veto**
  - high rate of photons in the same cells
- baseline choice: **CALICE SiW ECAL**
- max hit rate per cell: **40 MHz** in central cells
  - mostly **low energy** photons
  - need to identify **low rate high energy photons** in those cells

→ need **fast signal processing** in ECAL

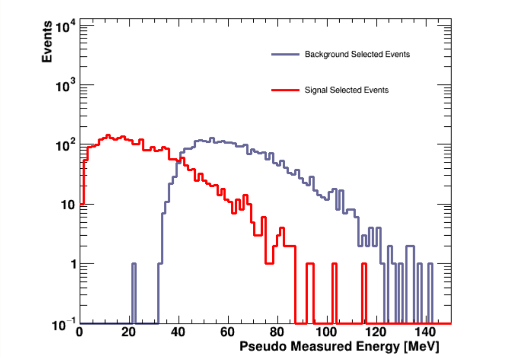


THE ECAL – SIGNAL PROCESSING

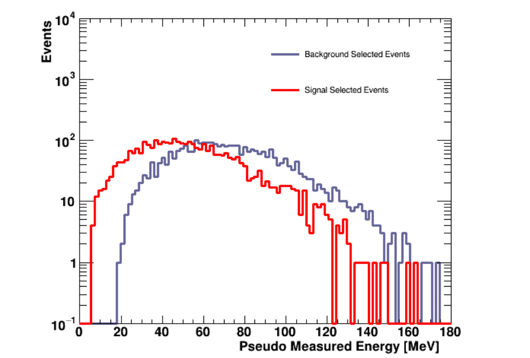
- **idealized assumptions** for readout ASIC: fast preamplifier, discharged after each event
- otherwise, **SCIROC2A like characteristics**, in particular CRRC shaper (time constant τ)



- τ = 10 ns
- th = 18 MeV
- ε = 81%



- τ = 30 ns
- th = 18 MeV
- ε = 68%

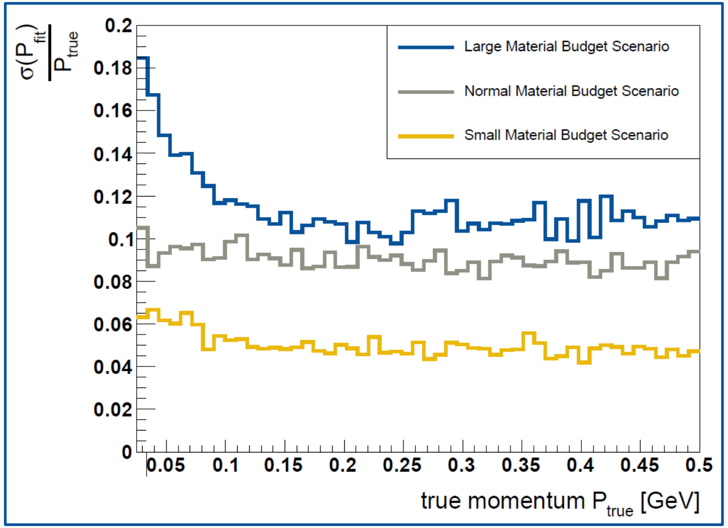


- τ = 60 ns
- th = 18 MeV
- ε = 5%

TRACKING DETECTOR

- **tracking detector**
  - reasonable per pixel hit rate
  - **low material budget** is key for tracking low momentum electrons

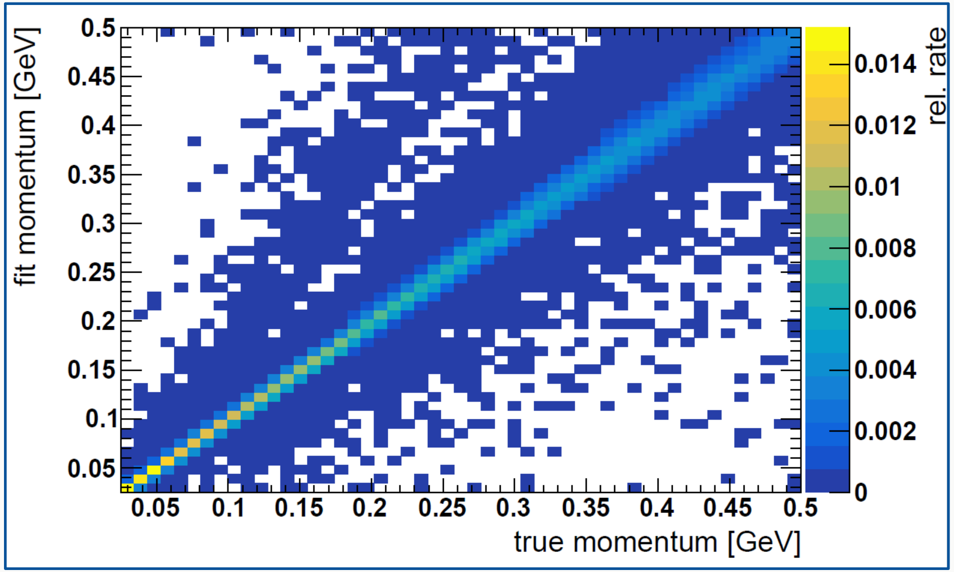
- estimated performance using **TJ Monopix2** like tracking ASICs
  - **DMAPS** in Tower Jazz 180nm technology
  - **33.04 x 33.04 μm²** pixels
  - can be thinned to **50-100 μm**
  - **2x2 ASICs** per tracking plane
- tracking performance estimated using **ACTS for a telescope geometry**

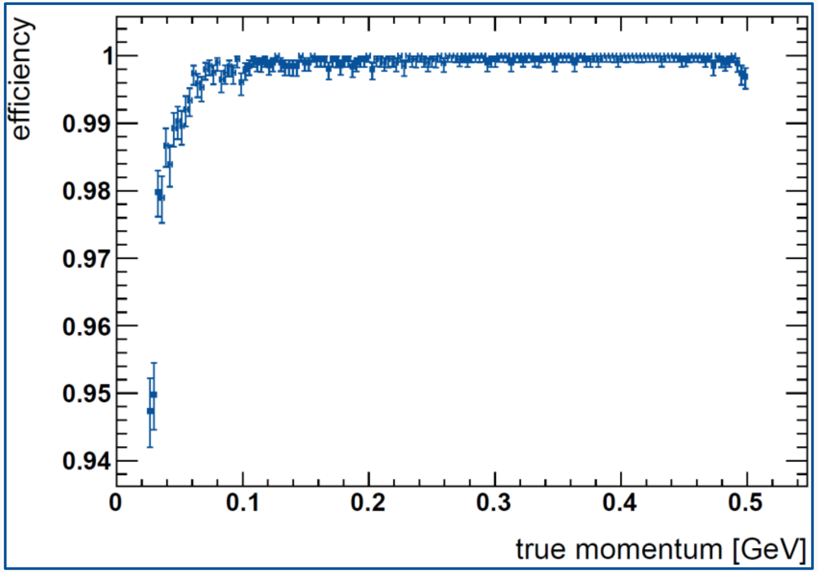


Layer	Target	1	2	3	4	5	6	7	8	9
z Position [mm]	2000	1810	1840	1900	2010	2030	2045	2070	2100	2130

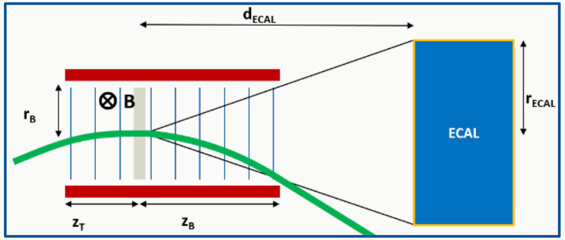
TRACKING DETECTOR

- **tracker performance** (single events)
  - visible branch due to **hard scattering in tracking planes** → importance of thin tracker!
  - reasonable **efficiency down to 25 MeV** → vanilla algorithm, improvements may be possible





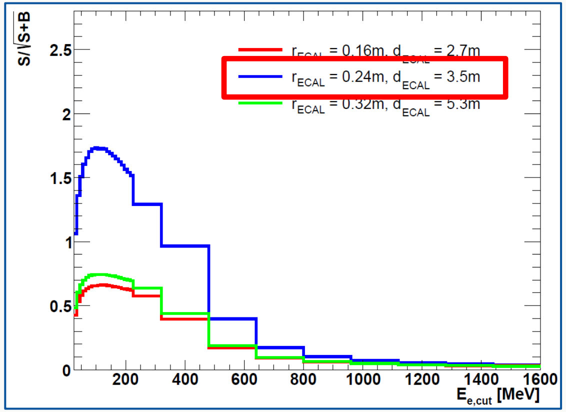
ESTIMATING SENSITIVITY



- **candidate signal region**
  - ==1 electron in initial state
  - ==1 charged track, compatible with electron hypothesis with 25 MeV < E_e < 75 MeV, in final state
  - no significant energy deposition above background level in ECAL
  - no significant energy deposited in hadron calorimeters

- pessimistic: $B = 0.6\,\mathrm{T}$, $z_B = 0.6\,\mathrm{m}$
- baseline: $B = 0.9\,\mathrm{T}$, $z_B = 1.0\,\mathrm{m}$
- optimistic: $B = 1.2\,\mathrm{T}$, $z_B = 1.2\,\mathrm{m}$

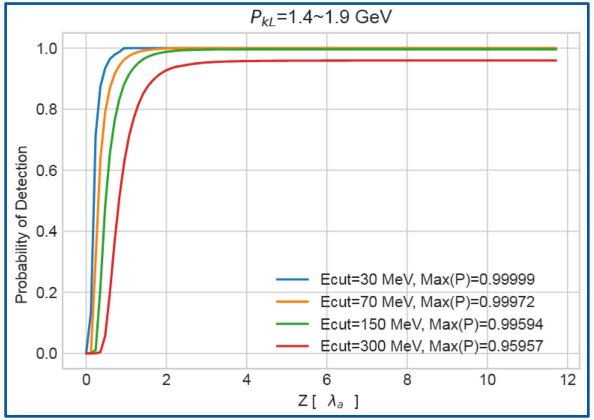
- considering **baseline magnet scenario** with **baseline ECAL scenario**
  - main background expected to stem from **out-of-acceptance SM QED**
  - **hadronic backgrounds** are difficult to estimate → next slides



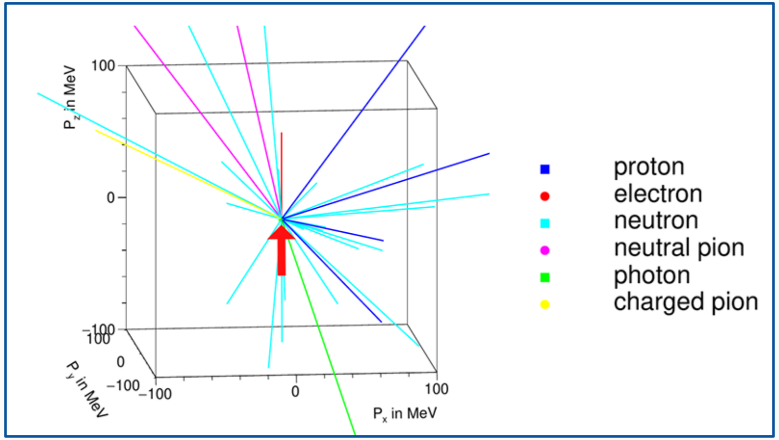
$4 \cdot 10^{14}$ EoT	number of γ	$m_{A'} = 1\,\mathrm{MeV}$ $\varepsilon = 1.2 \cdot 10^{-6}$	$m_{A'} = 10\,\mathrm{MeV}$ $\varepsilon = 1.4 \cdot 10^{-5}$	$m_{A'} = 100\,\mathrm{MeV}$ $\varepsilon = 1.6 \cdot 10^{-4}$
total $\xi < 0.95$	$3.1 \cdot 10^{14}$	26	80	27
$p_e < 75\,\mathrm{MeV}$, $\theta_e < 0.25\,\mathrm{rad}$	$1.0 \cdot 10^{12}$	1.3	26	5.1
$E^{\gamma}(\theta_{\gamma} < 0.07) < 640\,\mathrm{MeV}$	293	1.3	26	5.1

HADRONIC BACKGROUNDS

- limited sample size MC
  - 10^7 electron-nuclear and 10^7 photon-nuclear interactions
  - **no events survive all SR cuts**
- estimate is limited by the **sample size & issues found with Geant4**
  - FLUKA as an alternative to Geant4
- expect somewhat **isotropic distribution of FS hadrons**
  - set the expectation to 10 events in the SR (arbitrary number)
  - very conservative compared to LDMX for example



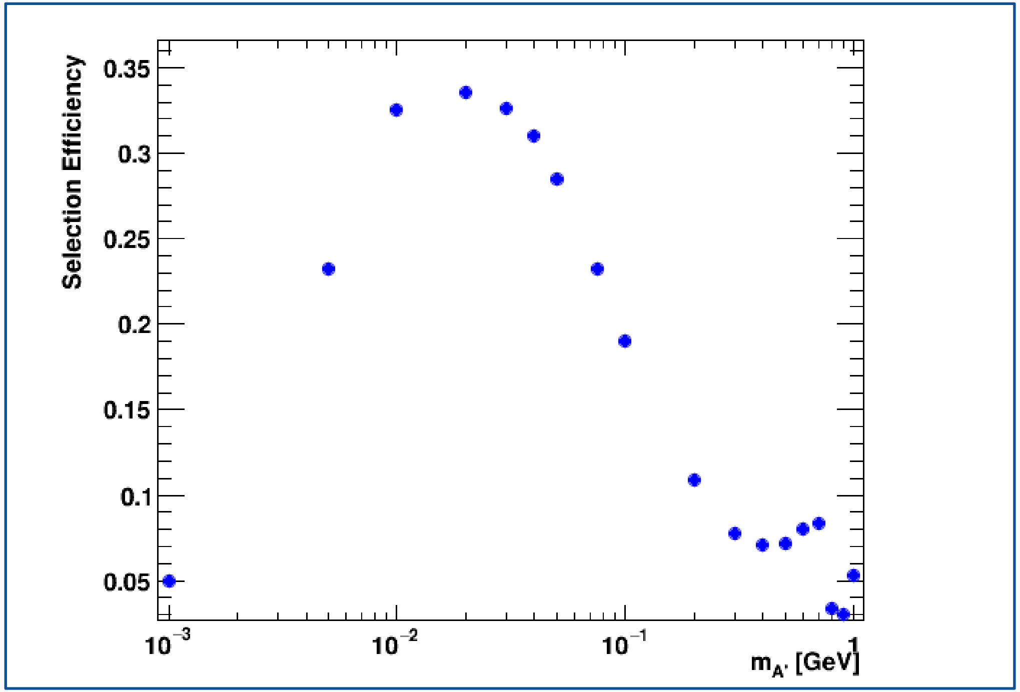
- $e^- + \mathcal{H} \to e^- + \mathcal{H}' + \pi^0 + 3n + 5\gamma$,
- $e^- + \mathcal{H} \to e^- + \mathcal{H}' + \gamma + 8n + 2p + 7\gamma$,
- $e^- + \mathcal{H} \to e^- + \mathcal{H}' + \pi^- + 3p + 4n + 6\gamma$,
- $e^- + \mathcal{H} \to e^- + \mathcal{H}' + 2\pi^0 + \pi^+ + K^0 + \Lambda + 31n + 9p + 5\gamma$



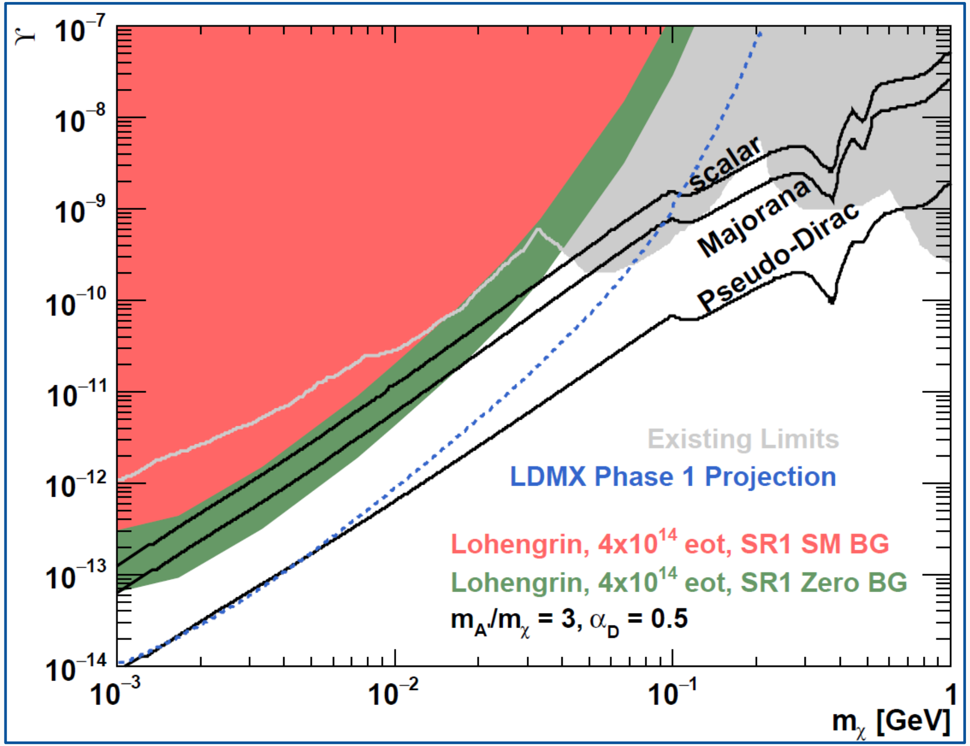
ESTIMATING SENSITIVITY

- **signal selection efficiency**, including
  - trigger efficiency
  - electron reconstruction efficiency
  - calorimeter veto efficiency
  - offline cuts

- **achieve reasonable signal efficiency** for targeted mass interval

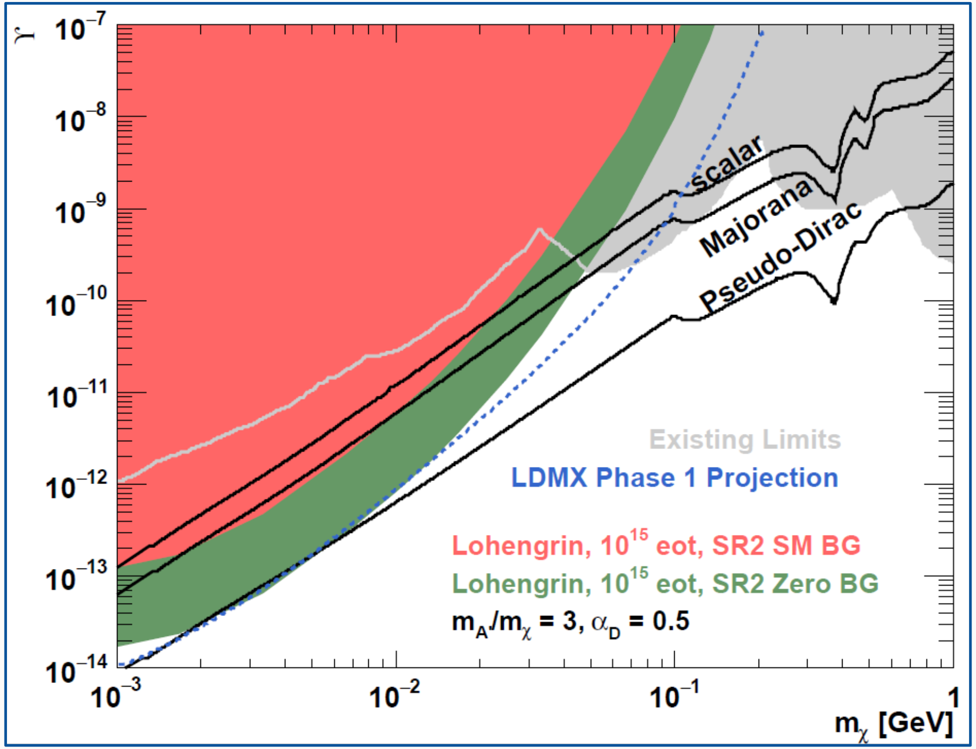


ESTIMATING SENSITIVITY



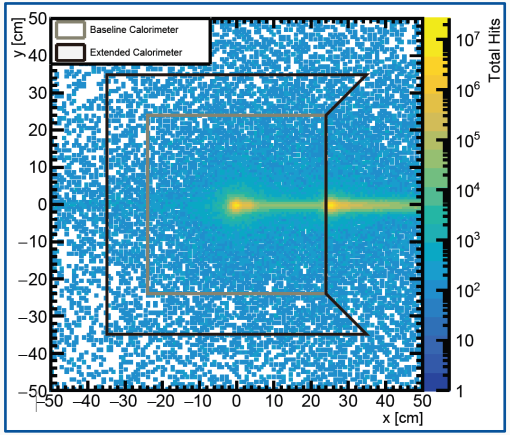
- **conservative estimates:**
  - sensitivity approaches relic target for scalar dark matter with 4×10^{14} electrons on target
- **reduction of out-of-acceptance backgrounds**
  - could expand the reach beyond relic target for scalar and majorana DM
- **comparison to similar proposed experiments:**
  - lower center of mass energy at ELSA

ESTIMATING SENSITIVITY



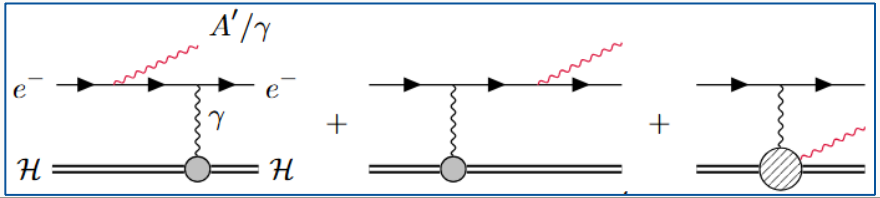
- **possible improvements**
  - **moderate** increase in luminosity
  - **low momentum** electron reconstruction
  - **enhanced coverage** for veto calorimeters

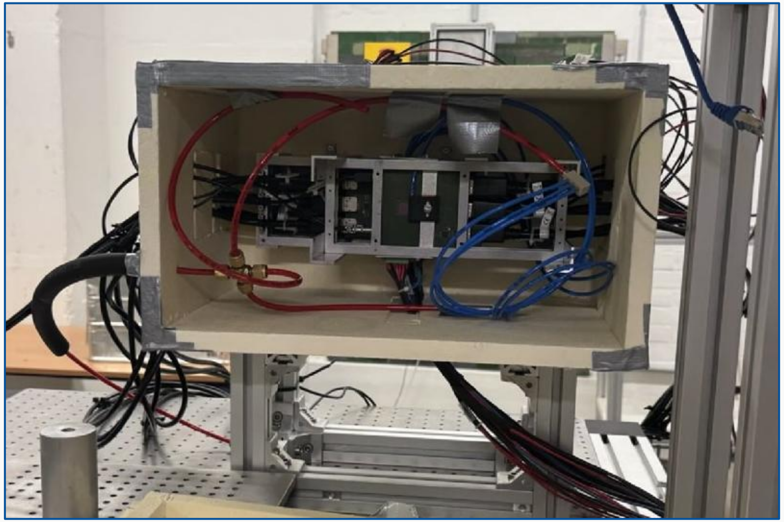
"slot" in ECAL could drastically reduce QED background



LOHENGRIN – STATUS

- **feasibility study published** in EPJC Eur. Phys. J. C (2025) 85: 600
- currently **running beam test** for second trigger stage
  - test pattern recognition and rate capabilities
  - inclusion of target in the setup
- **improving estimates:**
  - virtual compton scattering
  - hadronic backgrounds





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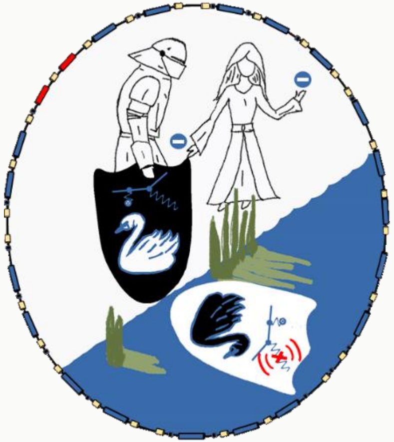
LOHENGRIN - ROADMAP

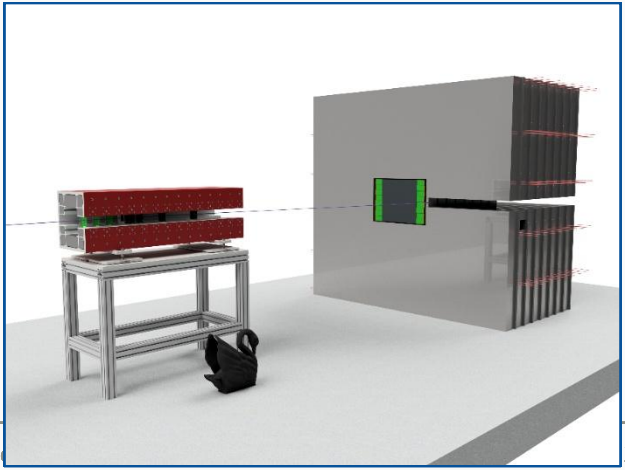


- **phased setup** of experiment at ELSA, starting with components from existing hardware
  - **phase 1:** (low-rate) test to establish the (non)relevance of VCS
  - **phase 2:** (medium-rate) test with hadron counter to support estimation of hadronic backgrounds
  - **phase 3:** first dark photon search run

existing components

requires detector R&D

- **offline integration, layout and design optimisation**
  - finalise requirements for tracker and ECAL
  - improvement of tracking algorithm
  - investigation of alternative triggering strategies
  - design and test of suitable tracker, ECAL and HCAL
  - . . .



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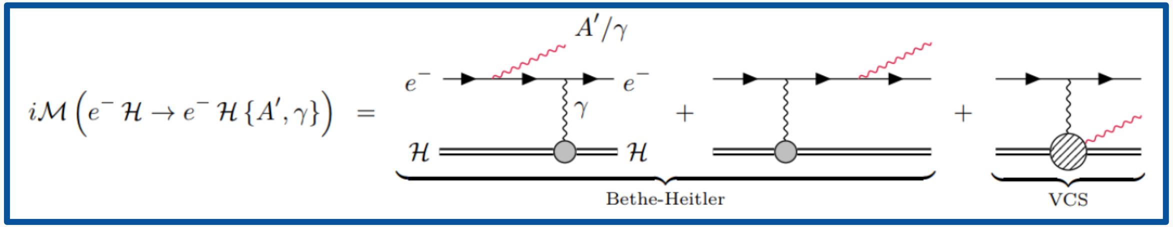
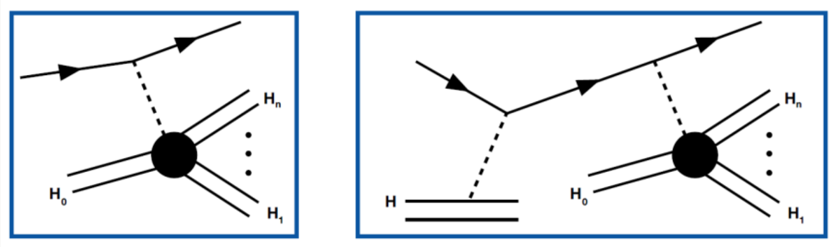
backup

ELECTRON SCATTERING

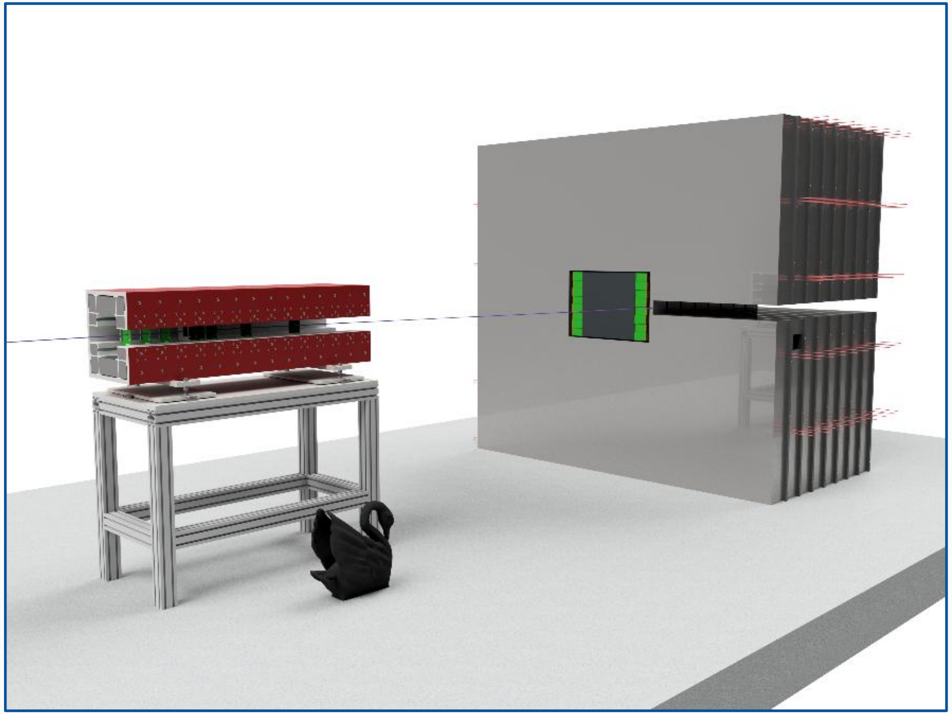
- dominant process by far: **SM bremsstrahlung**
  - about 1% of all events with a **hard photon**



- rare **electro-nuclear** and **photo-nuclear** events:
  - rate about 10^{-6}: **1-2 high energy hadrons**, many low energy photons



LOHENGRIN – CONCEPTION OF LAYOUT AND OPTIMISATION



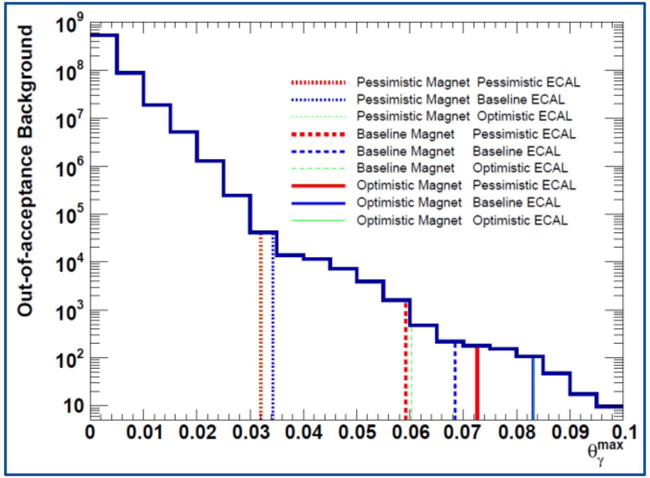
- overall layout
  - trackers in **strong magnetic field**
  - **high Z, 10% X_0** target (tungsten)
  - **ECAL veto** for high energy photons
  - **HCAL veto** for hadrons
- event rate: single electrons on target at **100 MHz**
- **general requirements**
  - high resolution, **fast and thin tracker**
  - calorimeter with **fast signal processing**
  - highly **efficient hadron calorimeter**

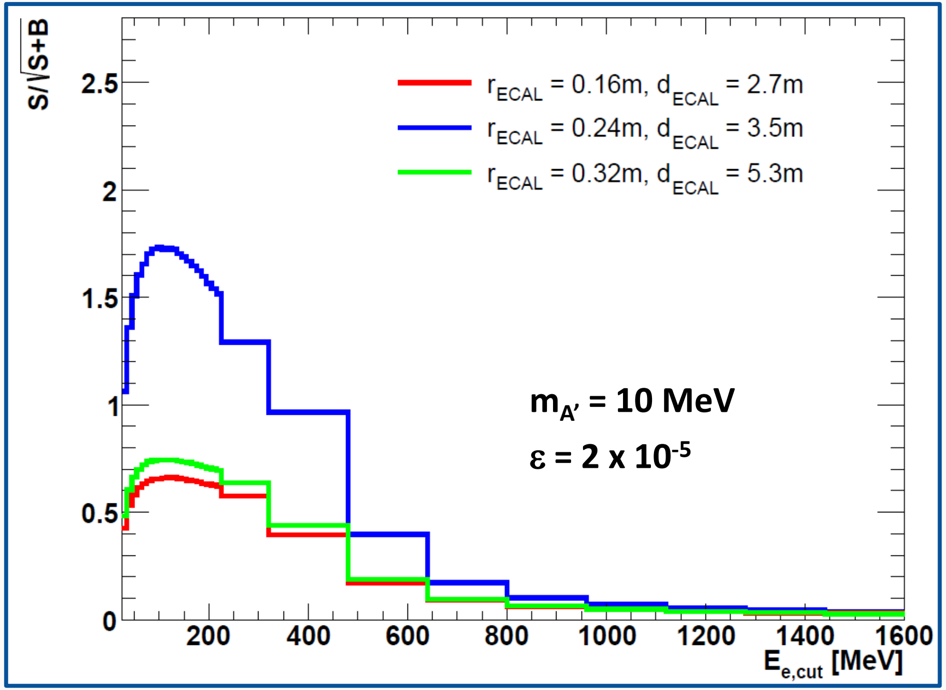
LAYOUT OPTIMISATION

Magnet scenarios:

- pessimistic: $B = 0.7\,\mathrm{T},\ z_B = 0.6\,\mathrm{m}$
- baseline: $B = 0.9\,\mathrm{T},\ z_B = 1.0\,\mathrm{m}$
- optimistic: $B = 1.2\,\mathrm{T},\ z_B = 1.2\,\mathrm{m}$

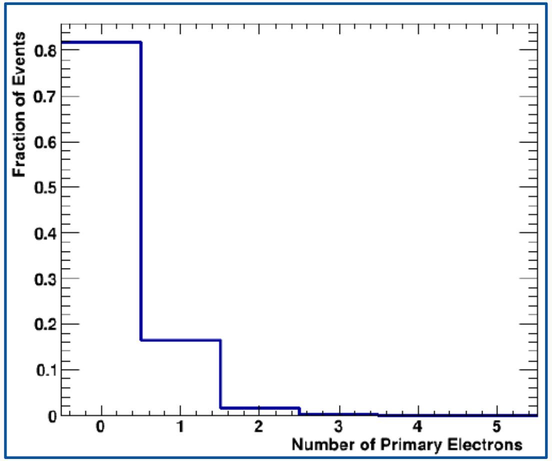
- **baseline scenario** is feasible. in comparison:
  - **optimistic scenario** desirable, feasibility unclear
    - photon acceptance limited
  - **pessimistic scenario** probably not good enough

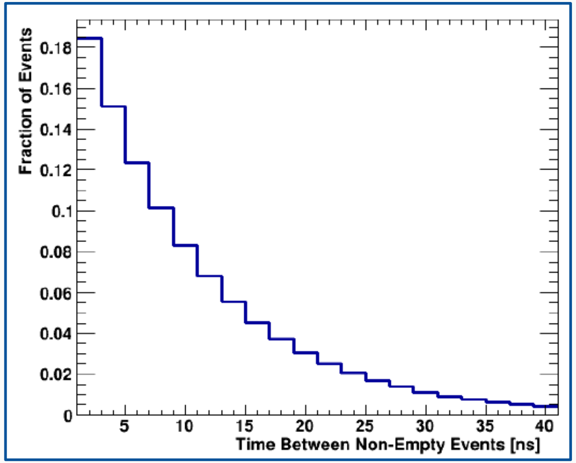


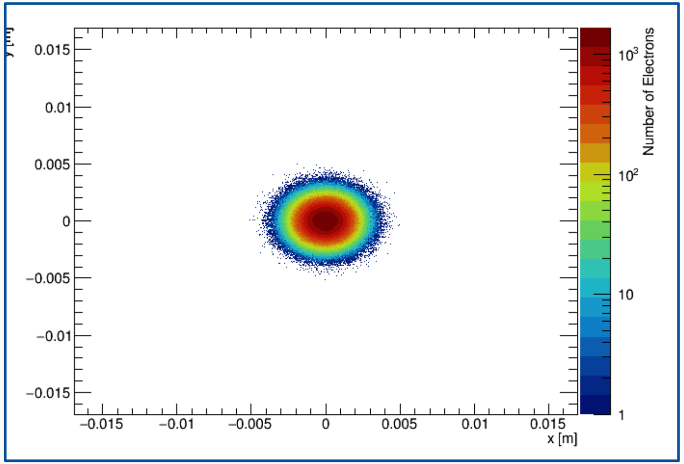


BEAM STRUCTURE

- extract electrons from ELSA at a rate of up to 500 MHz
- high energy resolution, 0.08%
- extract on average one electron every 5th cycle, ν_{eff} = 100 MHz
- beamspot on target: $\sigma_x = \sigma_y$ = 1mm, $\sigma'_x = \sigma'_y$ = 0.8 mrad







TRIGGER SYSTEM

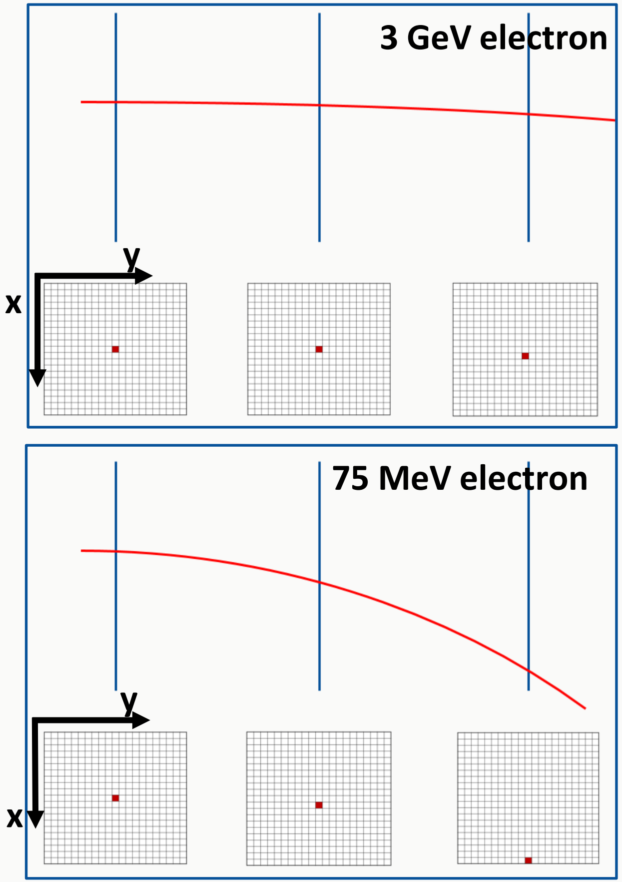
- TJ Monopix2 has a fast hit-or signal
  - sensitive part of pixel matrix can be configured
  - could be used for a low energy electron trigger

- hit in plane at z=1cm

  AND
  - hit in plane at z=7cm with x > 3.1mm

    OR
  - hit in plane at z=4.5cm with x > 2.3mm

    OR
  - hit in plane at z=3cm with x > 1.99 mm
- Total Rate: 1.7 MHz



TRIGGER SYSTEM

- estimated trigger efficiency
  - good efficiency for low energy electrons, but slow turn-off
  - structure in scattering angles due to magnetic field