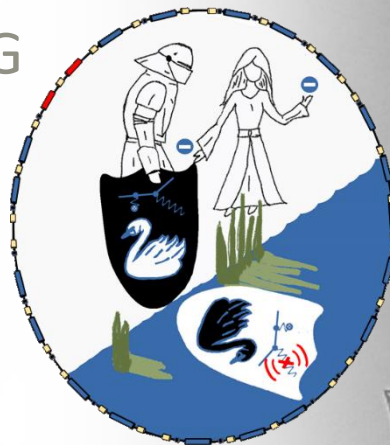


CMF RA4 KICKOFF MEETING THE LOHENGRIN EXPERIMENT AT THE ELSA ACCELERATOR



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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 $\rightarrow$ “**dark photon**”
- minimal model: SM + DM + $U(1)_D \rightarrow$ introduce coupling between DS and SM through **kinetic mixing**

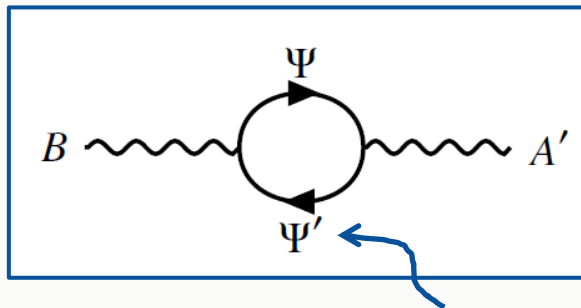
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_D + \mathcal{L}_{\text{SM} \otimes D}$$

$$\mathcal{L}_D \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - g_D A'_\mu J_D^\mu$$

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



$$\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu - \boxed{A'_\mu(\epsilon e J_{\text{EM}}^\mu + g_D J_D^\mu)}$$

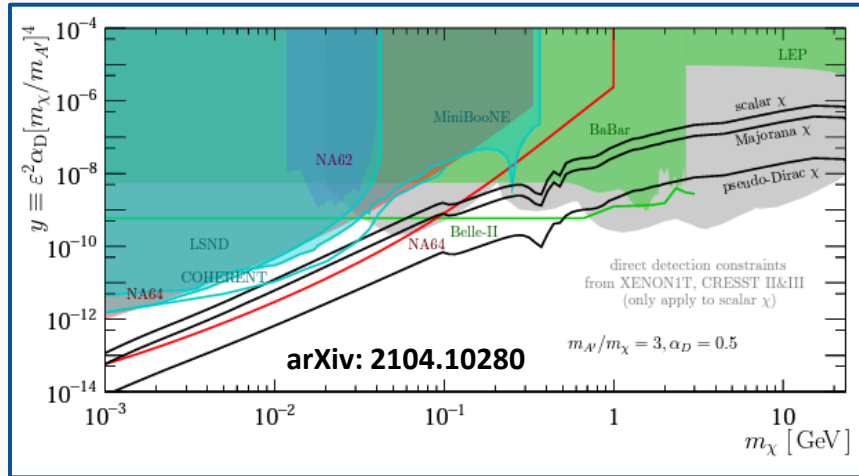
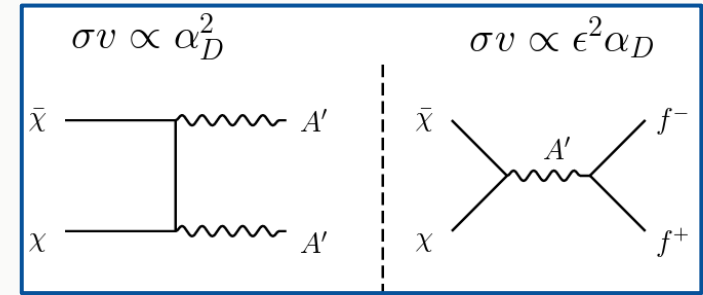


some heavy particles charged under both $U(1)_D$ and $U(1)_Y$

$$\begin{aligned} m_A^2 &= 0 \\ m_Z^2 &= m_Z^2 \left(1 + \varepsilon_Y^2 \frac{m_Z^2 s_W^2}{m_Z^2 - m_{A'}^2} \right) \\ m_{A_D}^2 &= m_{A'}^2 \left(1 + \varepsilon_Y^2 \frac{m_Z^2 c_W^2 - m_{A'}^2}{m_Z^2 - m_{A'}^2} \right) \end{aligned}$$

DARK MATTER – DARK PHOTONS

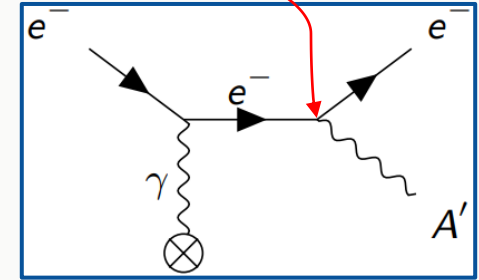
- “invisible” dark photons: $m_{A'} > 2m_\chi$:
 - dark matter annihilation through s-channel A' into fermions
 - production of dark photon at accelerators: **no visible signal**



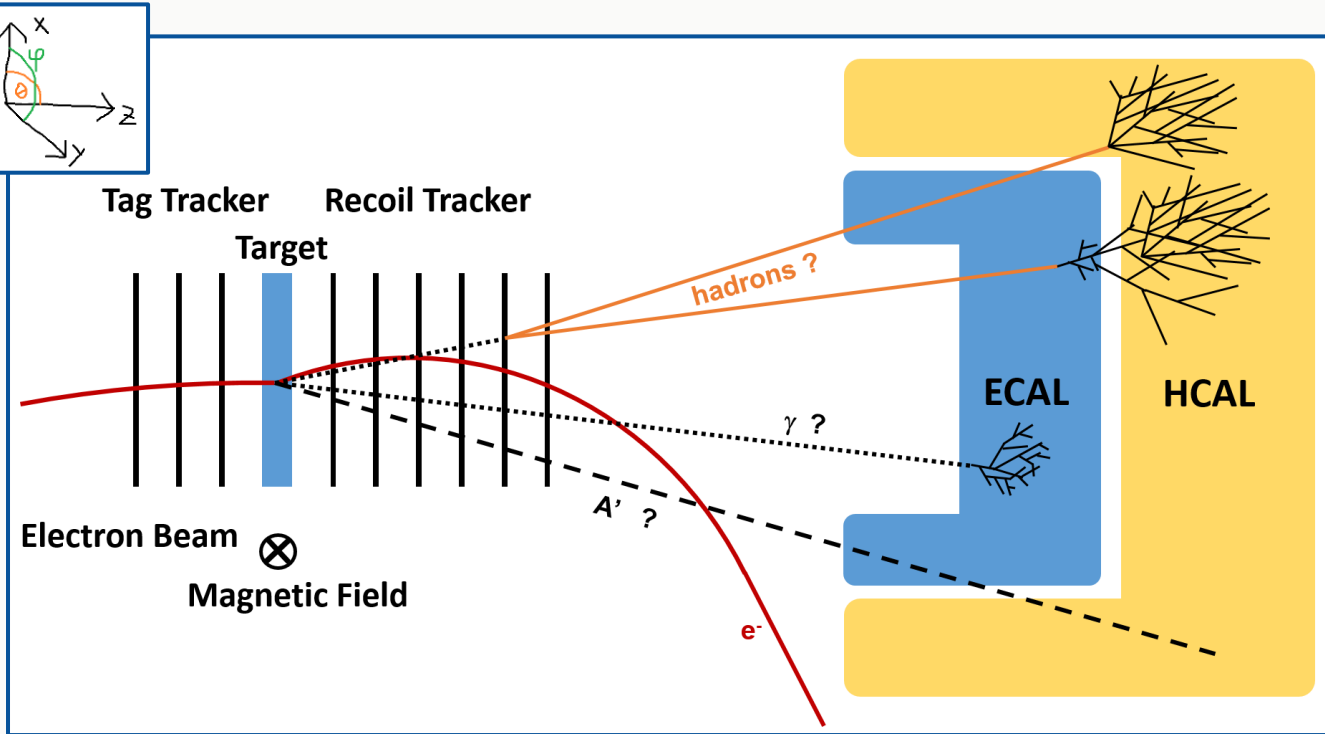
- collider searches, beam dump experiments (with and without direct detection) and direct detection experiments
- in particles for DM masses < 1 GeV ($m_{A'} < 3$ GeV): **sizeable gap to relic target**

FIXED TARGET DARK PHOTON SEARCH

$$\mathcal{M} \propto \varepsilon$$

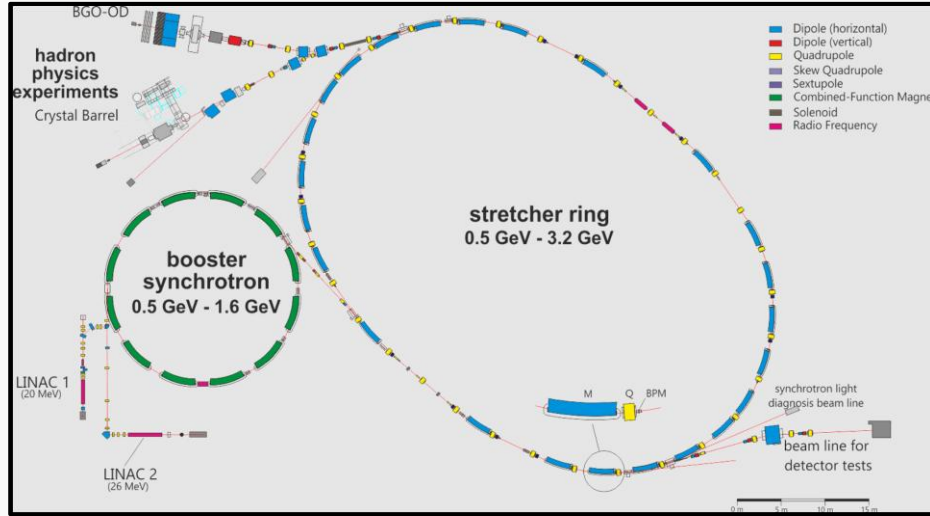


- electron beam on fixed target
- SM processes:
 - bremsstrahlung
 - electro-nuclear reaction
 - photo-nuclear reaction
- depending on $m_{A'}$ and ε :
occasional radiation of dark photon: **dark bremsstrahlung with large energy loss**



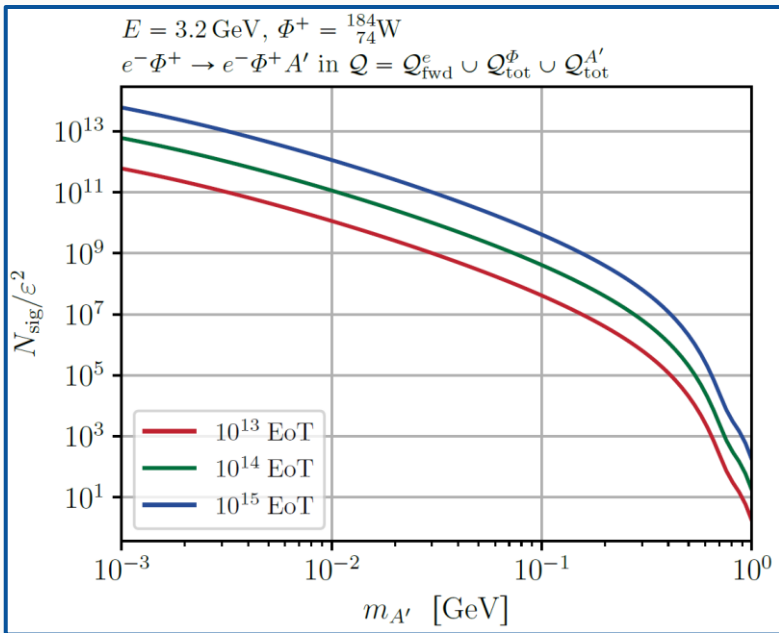
inspired by the LDMX experiment: [arXiv:1808.05219](https://arxiv.org/abs/1808.05219)

ELSA – ELEKTRONEN STRETCHER ANLAGE



- ability to extract $\mu \leq 1$ electrons per 2 ns bunch
- electron energy up to **3.2 GeV**, $\sigma_E = 0.08\%$
- 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

$m_{A'}$ [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?

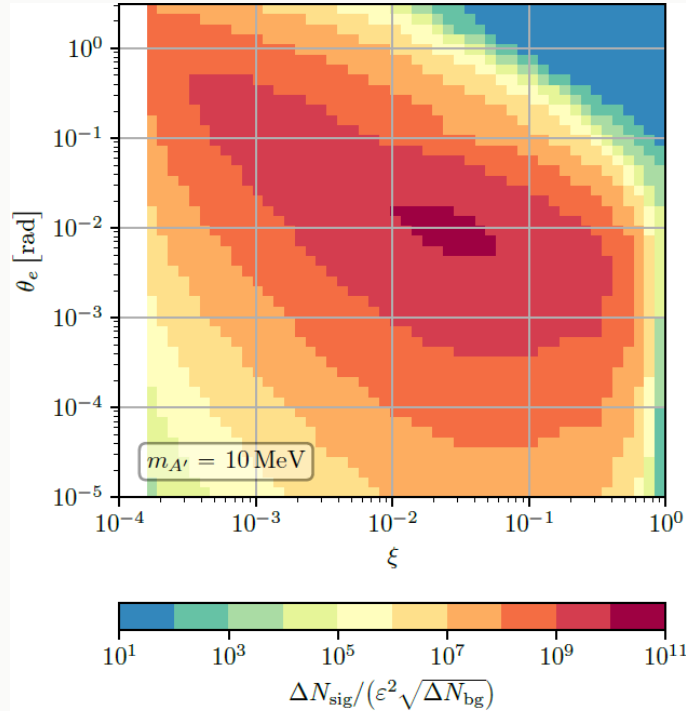
- target interval for $m_{A'}$: 10 MeV – 100 MeV
- assuming basic ECAL veto and only dominant SM BG

$$E = 3.2 \text{ GeV}, \Phi^+ = {}^{184}_{74}\text{W}$$

$$e^- \Phi^+ \rightarrow e^- \Phi^+ A' \text{ in } \mathcal{Q} = \mathcal{Q}_{\text{bin}}^e \cup \mathcal{Q}_{\text{tot}}^\Phi \cup \mathcal{Q}_{\text{tot}}^{A'}$$

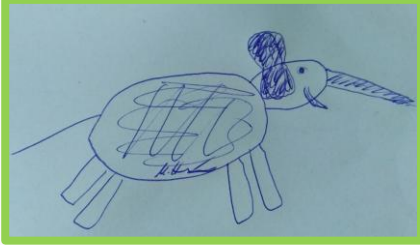
$$e^- \Phi^+ \rightarrow e^- \Phi^+ \gamma \text{ in } \mathcal{Q} = \mathcal{Q}_{\text{bin}}^e \cup \mathcal{Q}_{\text{tot}}^\Phi \cup \mathcal{Q}_{\text{ECAL+IRc}}^\gamma$$

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



DARK PHOTON SEARCH AT ELSA: LOHENGRIN

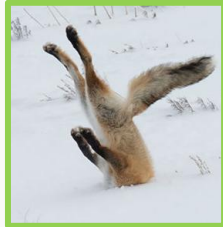
model used in this presentation



two equally likely options for the final thing



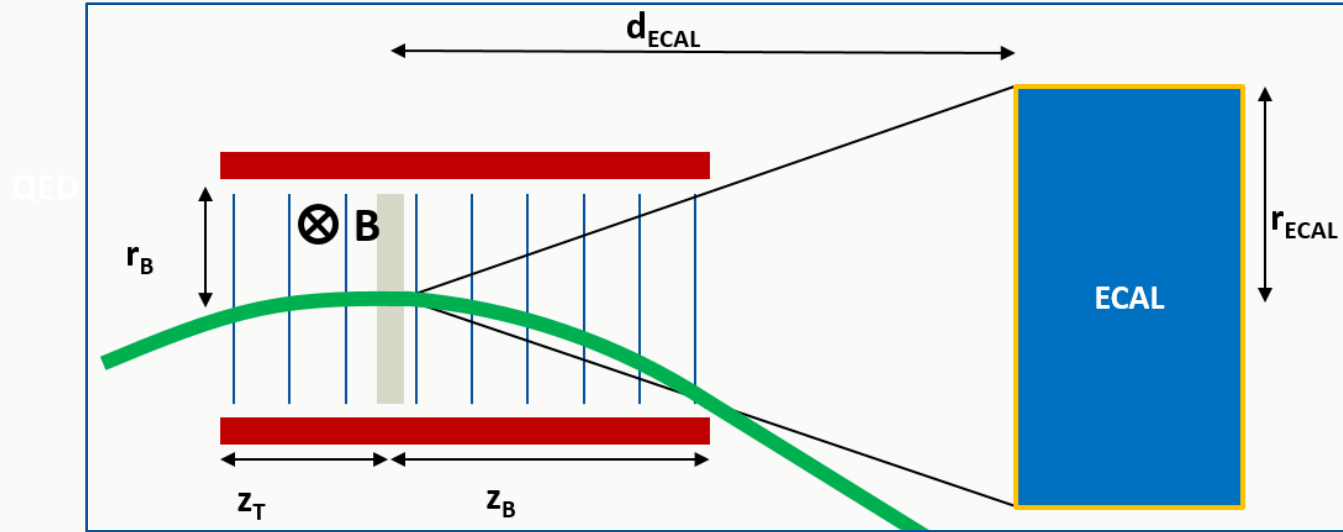
hopefully not the final thing



(almost) certainly not the final thing



LAYOUT OPTIMISATION



baseline parameters:

$$r_B = 0.1 \text{ m}$$

$$B = 0.9 \text{ T}$$

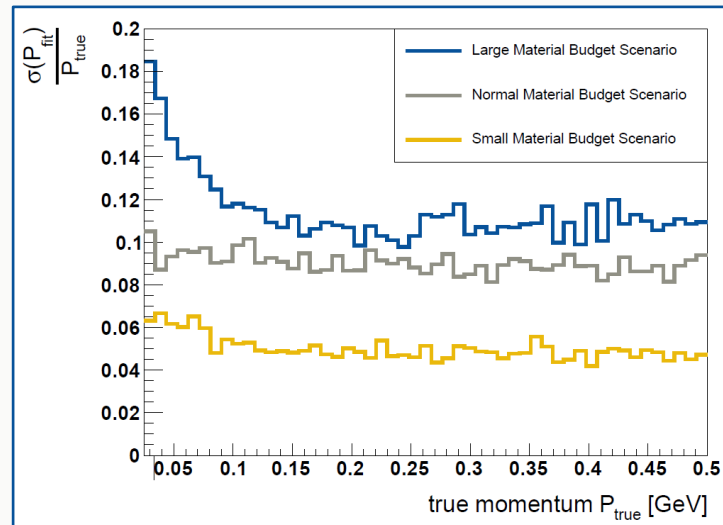
$$d_{ECAL} = 3.5 \text{ m}$$

$$z_B = 1.0 \text{ m}$$

$$r_{ECAL} = 0.24 \text{ m}$$

TRACKING DETECTOR

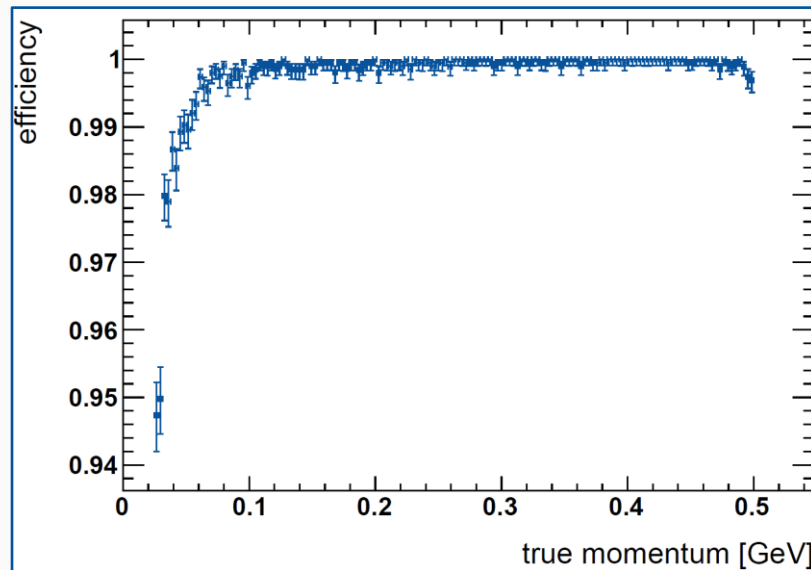
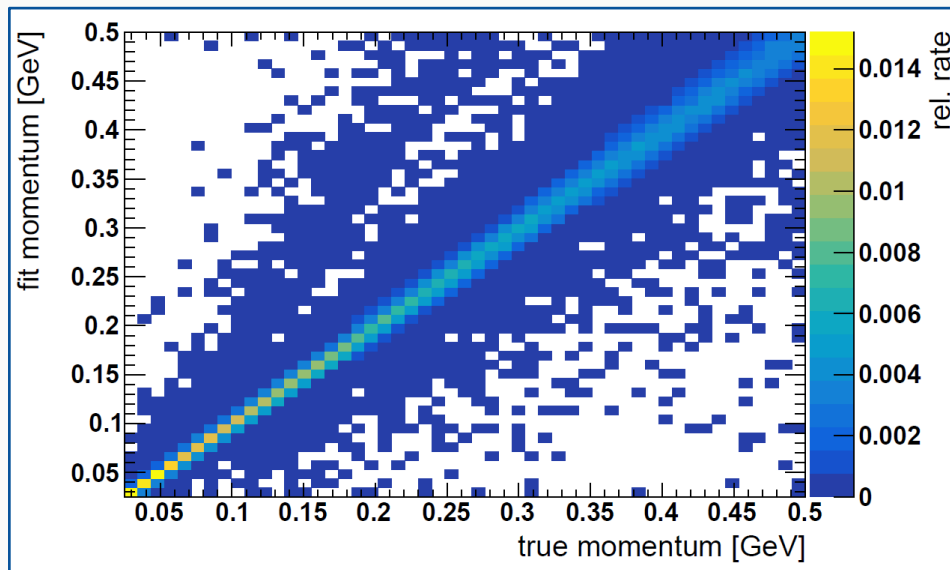
- **tracking detector**
 - reasonable per pixel hit rate
 - **low material budget** is key for tracking low momentum electrons
- estimated performance using **TJ Monopix2** like tracking ASICs
 - **DMAPS** in Tower Jazz 180nm technology
 - **33.04 x 33.04 μm^2** pixels
 - can be thinned to **50-100 μm**
 - **2x2 ASICs** per tracking plane
- tracking performance estimated using **ACTS** for a telescope geometry



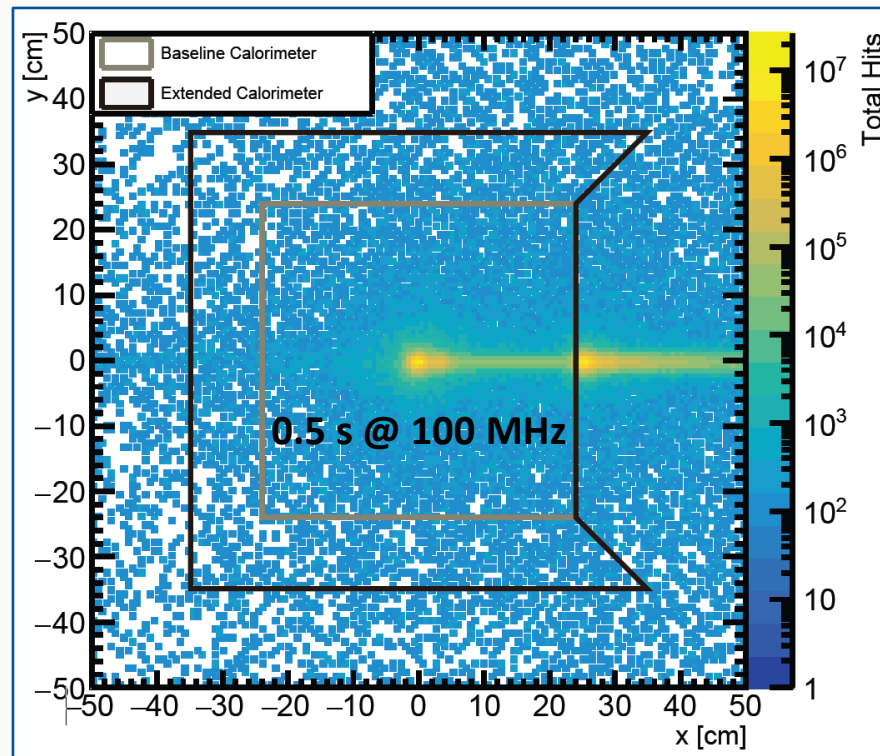
Layer	Target	1	2	3	4	5	6	7	8	9
z Position [mm]	2000	1810	1840	1900	2010	2030	2045	2070	2100	2130

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

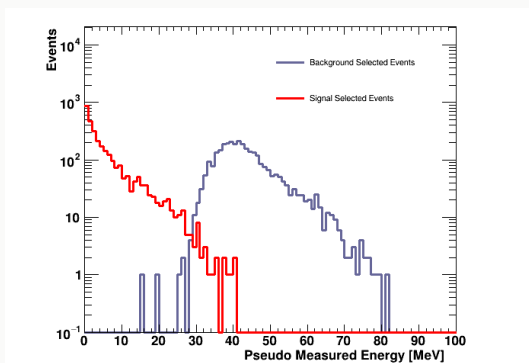


- ECAL used as **photon veto**
 - high rate of photons in the same cells
 - QED bremsstrahlung
 - baseline choice: **CALICE SiW ECAL**
 - max hit rate per cell: **40 MHz** in central cells
 - mostly **low energy** photons
 - need to identify **low rate high energy photons** in those cells
- need **fast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

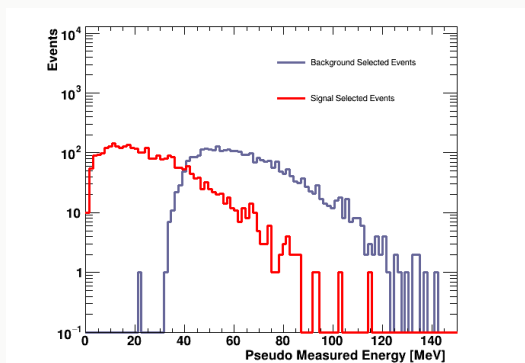


THE ECAL – SIGNAL PROCESSING

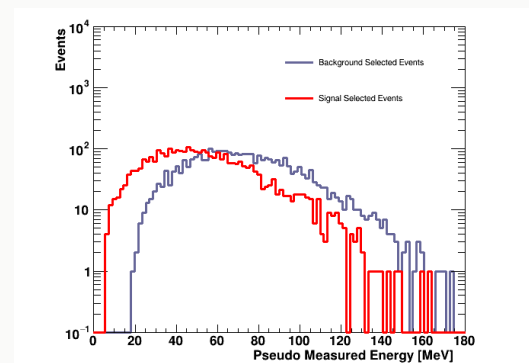
- **idealized assumptions** for readout ASIC: fast preamplifier, discharged after each event
- otherwise, **SCIROC2A like characteristics**, in particular CRRC shaper (time constant τ)



- $\tau = 10$ ns
- $th = 18$ MeV
- $\varepsilon = 81\%$



- $\tau = 30$ ns
- $th = 18$ MeV
- $\varepsilon = 68\%$



- $\tau = 60$ ns
- $th = 18$ MeV
- $\varepsilon = 5\%$

ESTIMATING SENSITIVITY

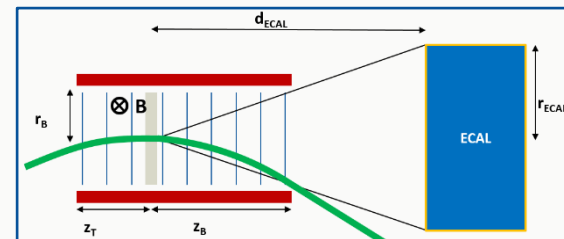
– candidate signal region

- ==1 electron in initial state
- ==1 charged track, compatible with electron hypothesis with $25 \text{ MeV} < E_e < 75 \text{ MeV}$, in final state
- no significant energy deposition above background level in ECAL
- no significant energy deposited in hadron calorimeters

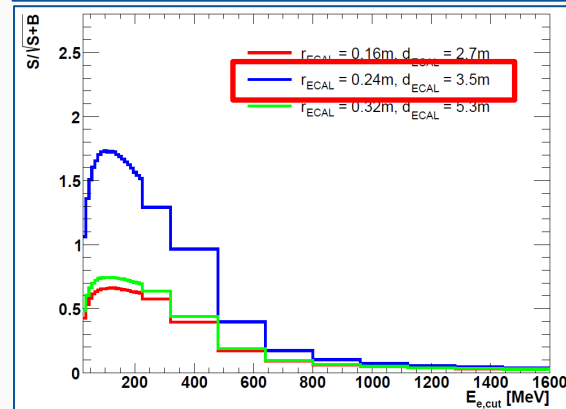
– considering **baseline magnet scenario** with **baseline ECAL scenario**

- main background expected to stem from **out-of-acceptance SM QED**
- **hadronic backgrounds** are difficult to estimate → next slides

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

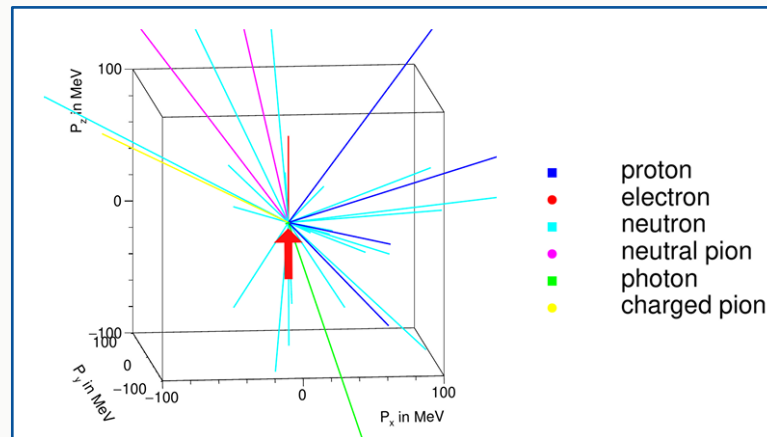
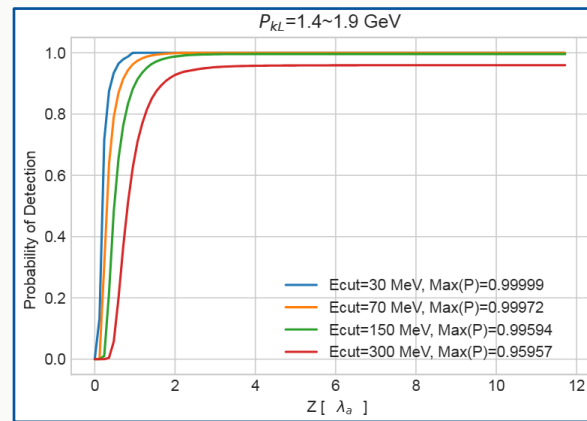
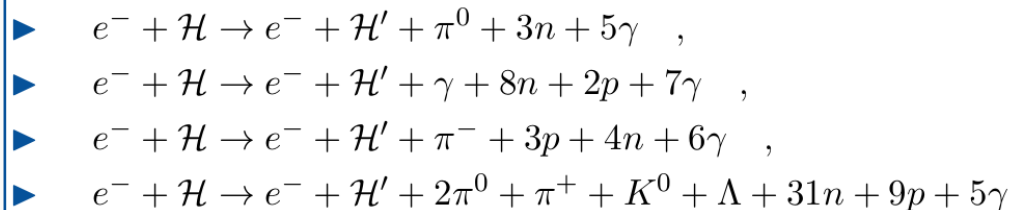


- **pessimistic:** $B = 0.6 \text{ T}, z_B = 0.6 \text{ m}$
- **baseline:** $B = 0.9 \text{ T}, z_B = 1.0 \text{ m}$
- **optimistic:** $B = 1.2 \text{ T}, z_B = 1.2 \text{ m}$



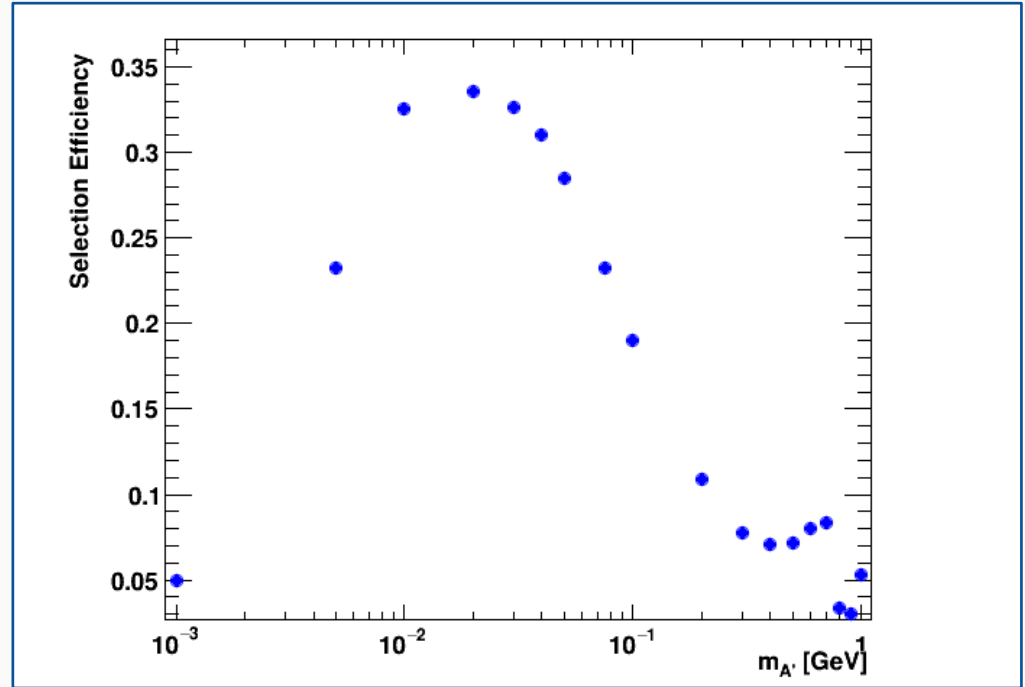
HADRONIC BACKGROUNDS

- 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

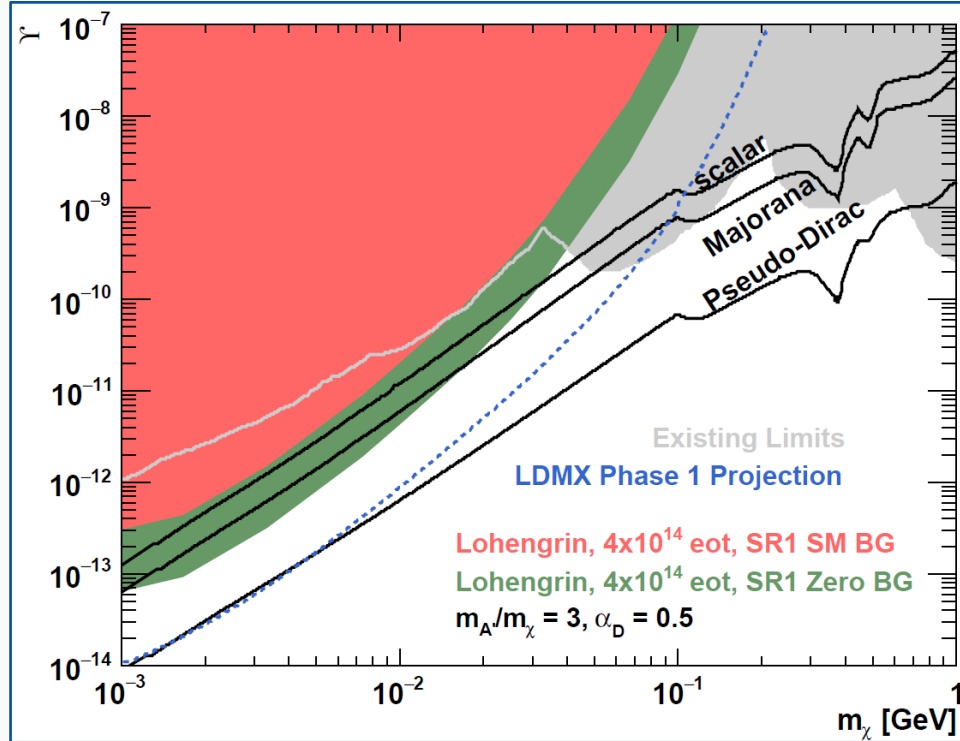


ESTIMATING SENSITIVITY

- **signal selection efficiency**, including
 - trigger efficiency
 - electron reconstruction efficiency
 - calorimeter veto efficiency
 - offline cuts
- **achieve reasonable signal efficiency** for targeted mass interval

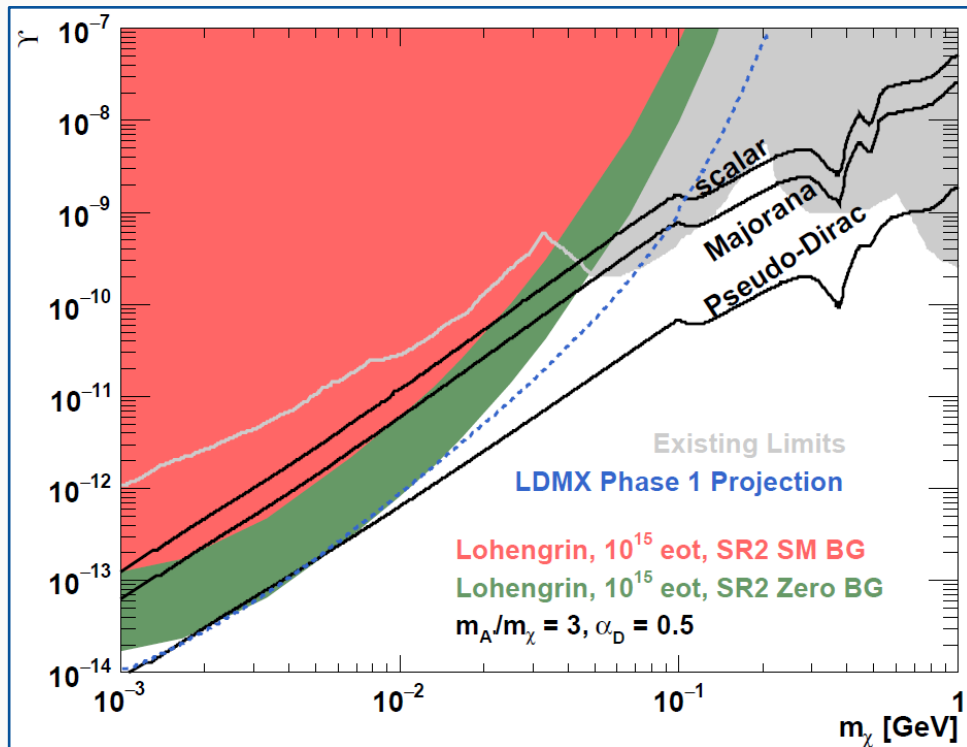


ESTIMATING SENSITIVITY



- **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

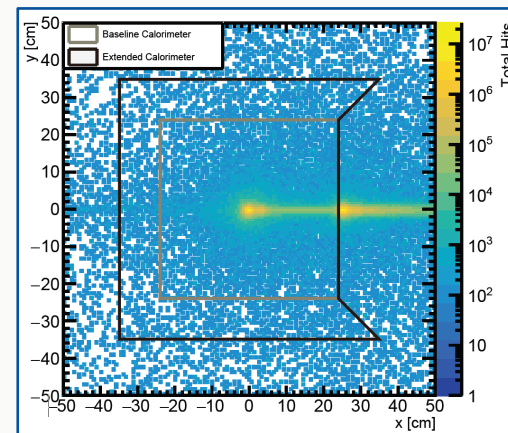
ESTIMATING SENSITIVITY



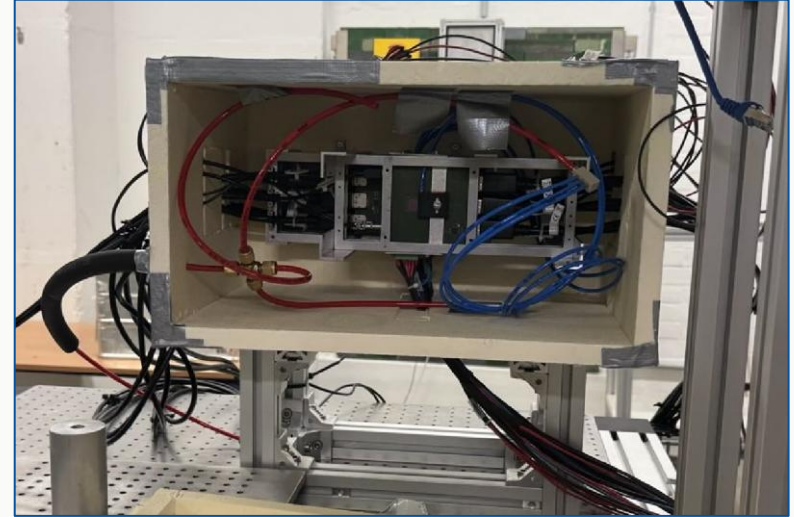
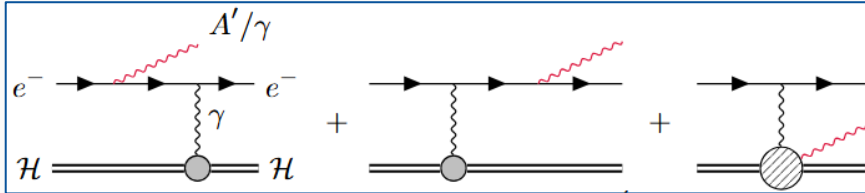
– possible improvements

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

“slot” in ECAL
could drastically
reduce QED
background



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





– **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

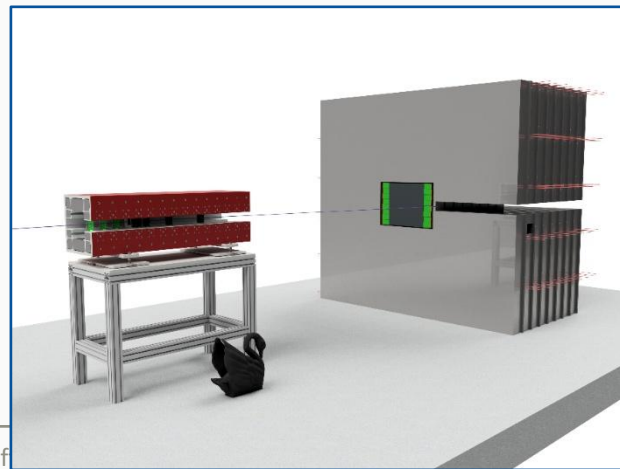
existing components



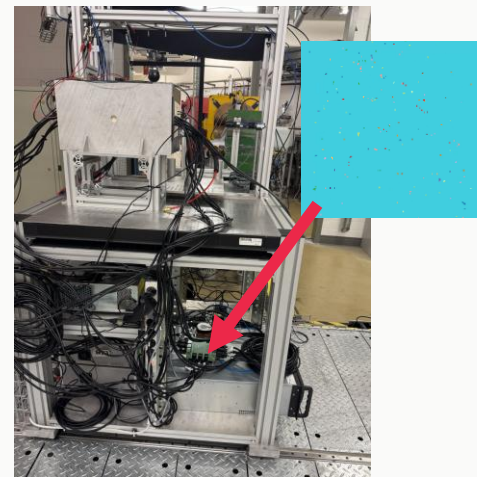
requires detector R&D

– **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
- ...



- **Lohengrin simulation framework – Perceval being set up**
 - plan to run some further simulation studies for EN backgrounds (target moved closer towards boundaries of magnet)
 - tracker and ECAL timing studies
 - HCAL layout and design
 - studying a simple scintillator based L0 trigger instead of ultra-fast hit-or
- **towards feeding AI engines for L1 trigger with DMAPS data**
 - testing rate capabilities of Xilinx Versal with Timepix3 telescope
 - construction of TJMonopix2 (-derivative) telescope, read out by AI engines
- **exploring options for the ECAL**



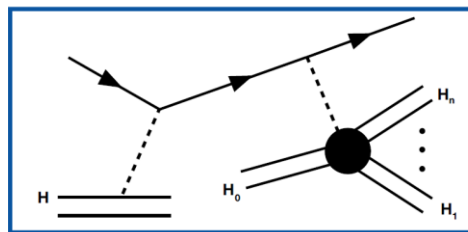
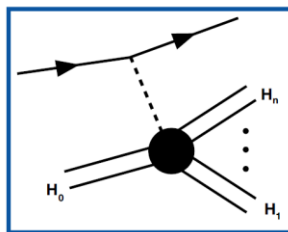
backup

ELECTRON SCATTERING

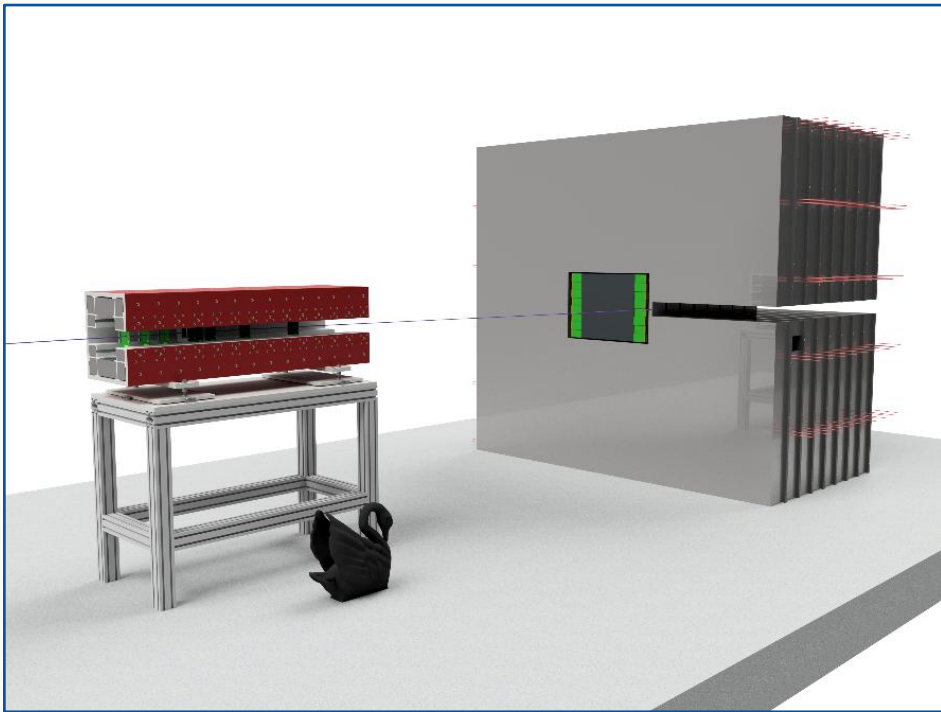
- dominant process by far: **SM bremsstrahlung**
 - about 1% of all events with a **hard photon**

$$i\mathcal{M}(e^- \mathcal{H} \rightarrow e^- \mathcal{H} \{A', \gamma\}) = \underbrace{e^- \rightarrow e^- \gamma}_{\text{Bethe-Heitler}} + \underbrace{e^- \rightarrow e^- \gamma}_{\text{Bethe-Heitler}} + \underbrace{e^- \rightarrow e^- \gamma}_{\text{VCS}}$$

- 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



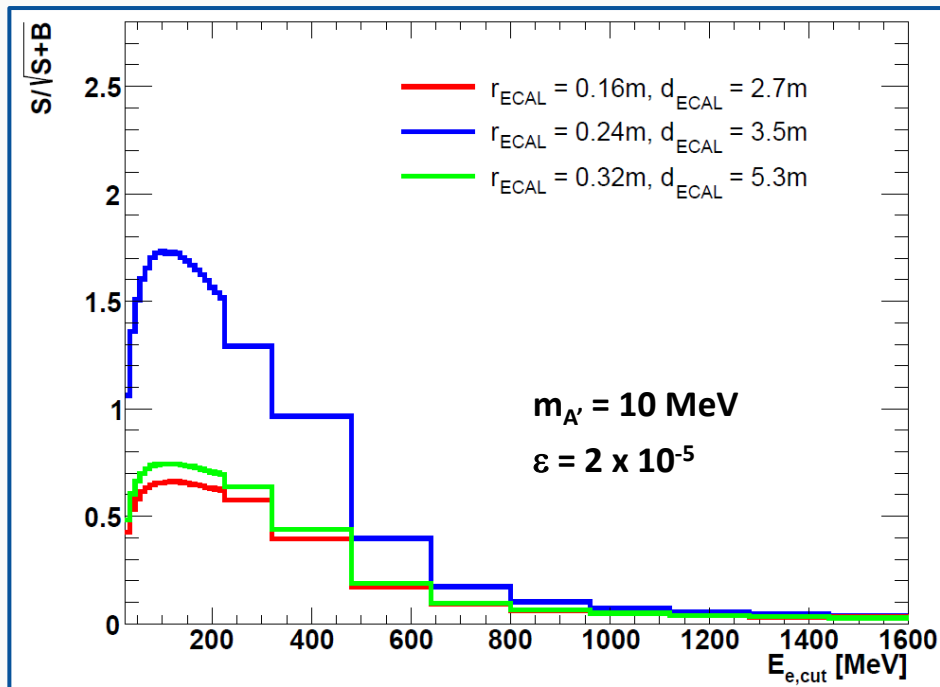
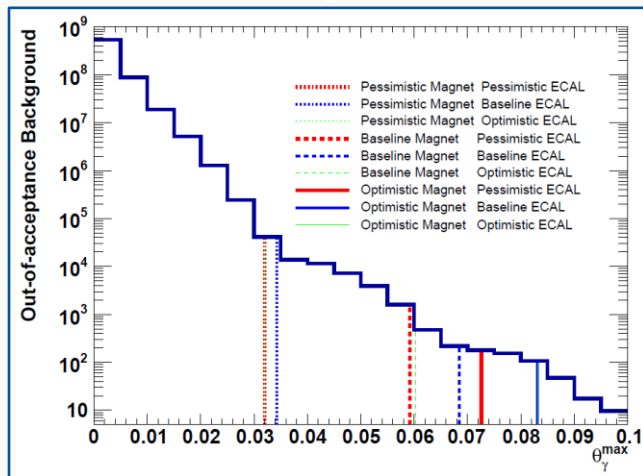
- overall layout
 - trackers in **strong magnetic field**
 - **high Z, 10% X_0** target (tungsten)
 - **ECAL veto** for high energy photons
 - **HCAL veto** for hadrons
- event rate: single electrons on target at **100 MHz**
- **general requirements**
 - high resolution, **fast and thin tracker**
 -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

LAYOUT OPTIMISATION

Magnet scenarios:

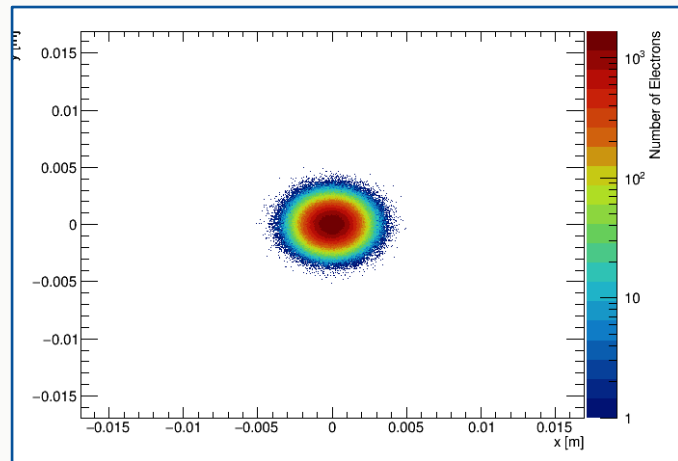
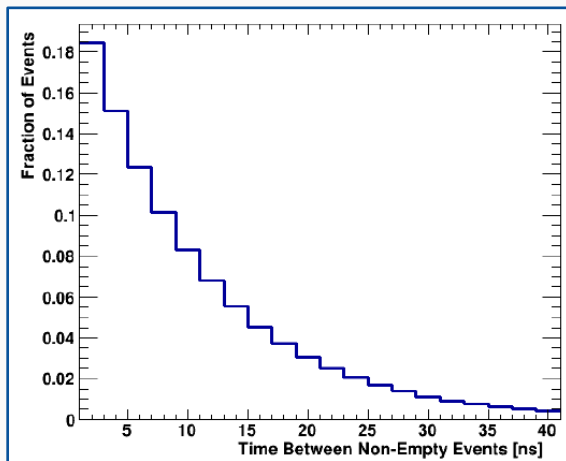
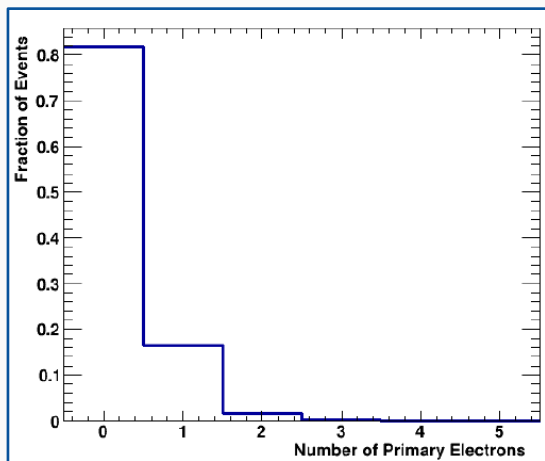
- pessimistic: $B = 0.7 \text{ T}$, $z_B = 0.6 \text{ m}$
- baseline: $B = 0.9 \text{ T}$, $z_B = 1.0 \text{ m}$
- optimistic: $B = 1.2 \text{ T}$, $z_B = 1.2 \text{ m}$

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



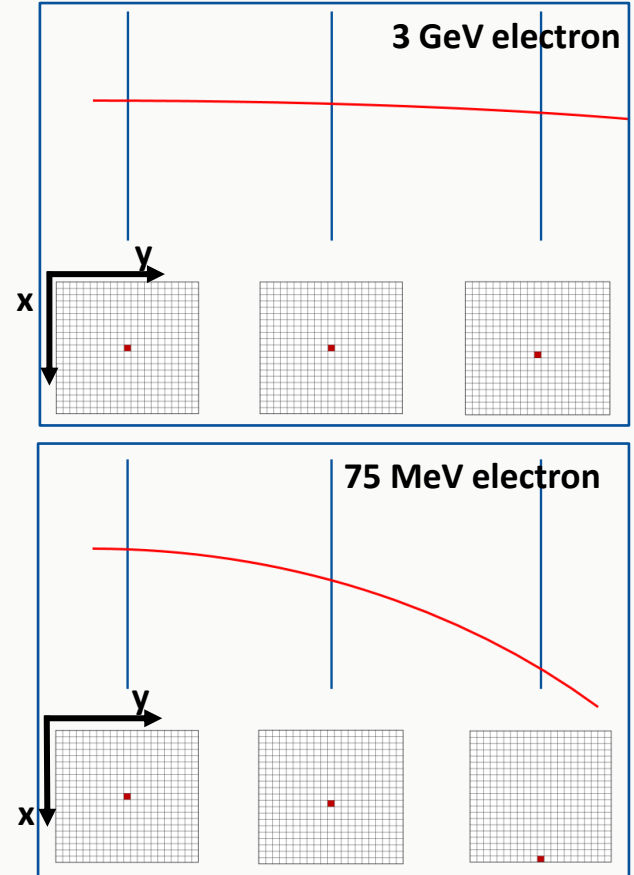
BEAM STRUCTURE

- 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, $\nu_{\text{eff}} = 100$ MHz
- beamspot on target: $\sigma_x = \sigma_y = 1\text{mm}$, $\sigma'_x = \sigma'_y = 0.8$ mrad



- 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 $z=1\text{cm}$
AND
 - hit in plane at $z=7\text{cm}$ with $x > 3.1\text{mm}$
OR
 - hit in plane at $z=4.5\text{cm}$ with $x > 2.3\text{mm}$
OR
 - hit in plane at $z=3\text{cm}$ with $x > 1.99\text{ mm}$
- Total Rate: 1.7 MHz



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

