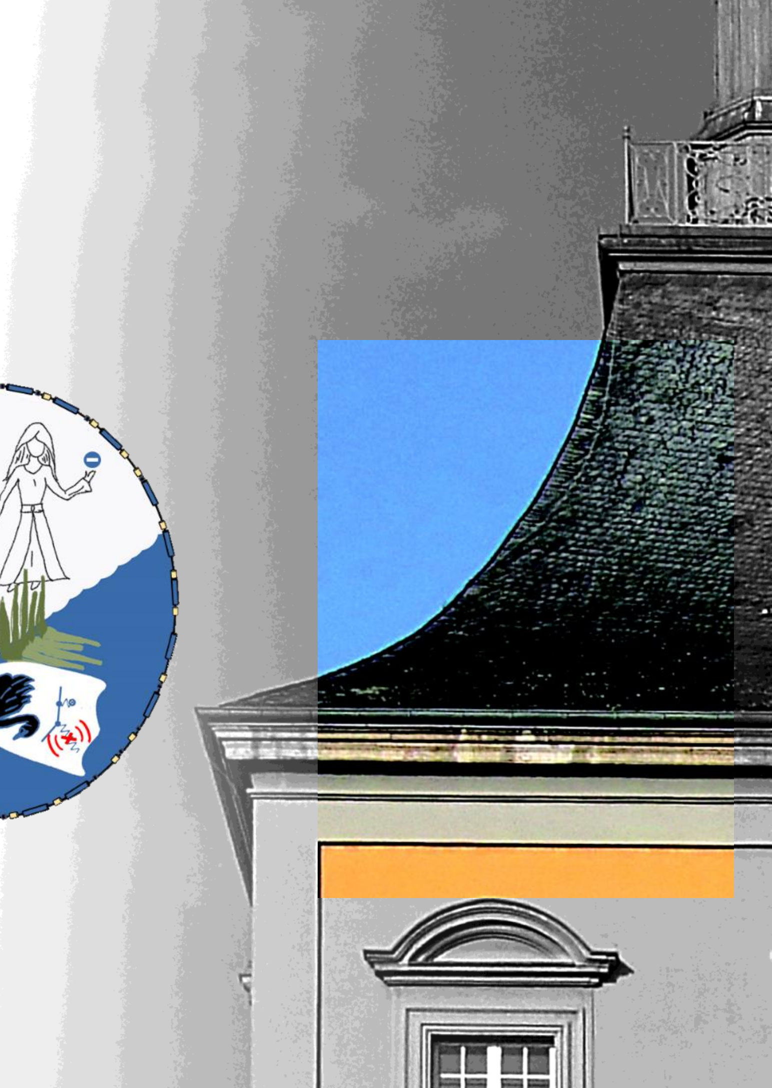
IFIC SEMINAR

THE LOHENGRIN EXPERIMENT AT THE ELSA ACCELERATOR



Matthias Hamer, University of Bonn

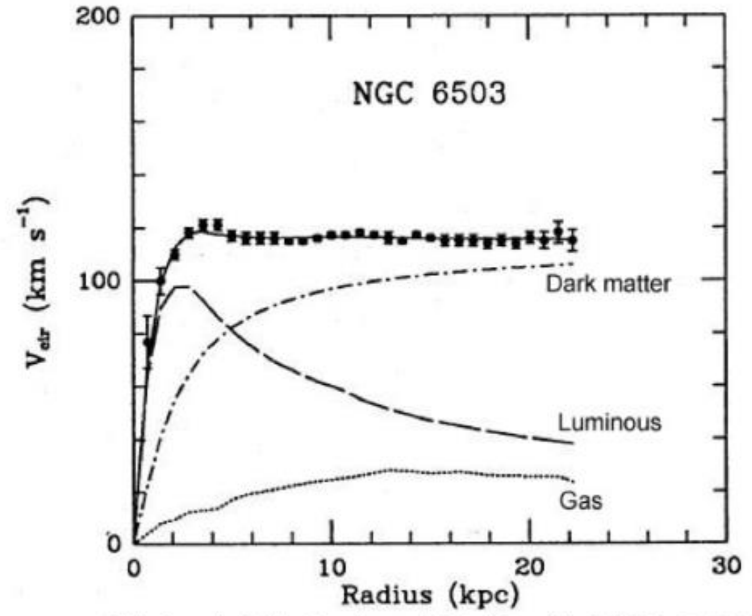
OUTLINE

- 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

$$\langle T\rangle = -\frac{1}{2}\sum_{k=1}^{N}\langle \mathbf{F}_k \cdot \mathbf{r}_k\rangle$$

$$v(r) = \sqrt{G\frac{m(r)}{r}}$$

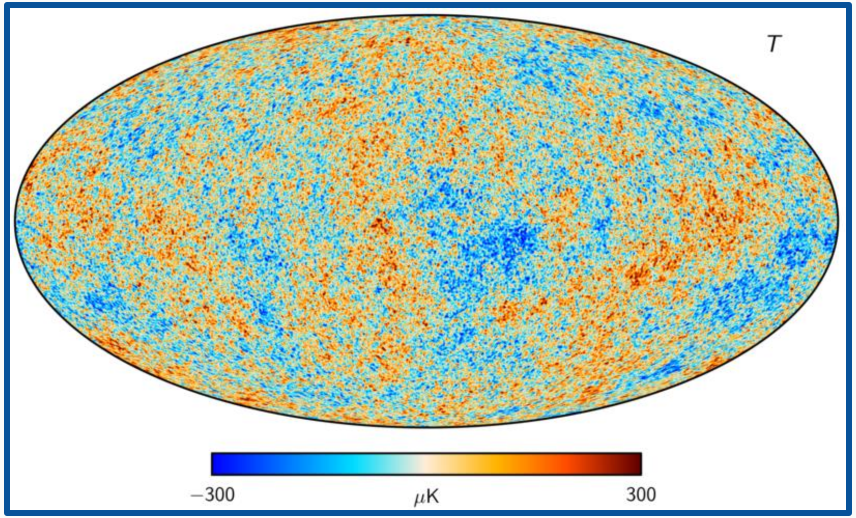


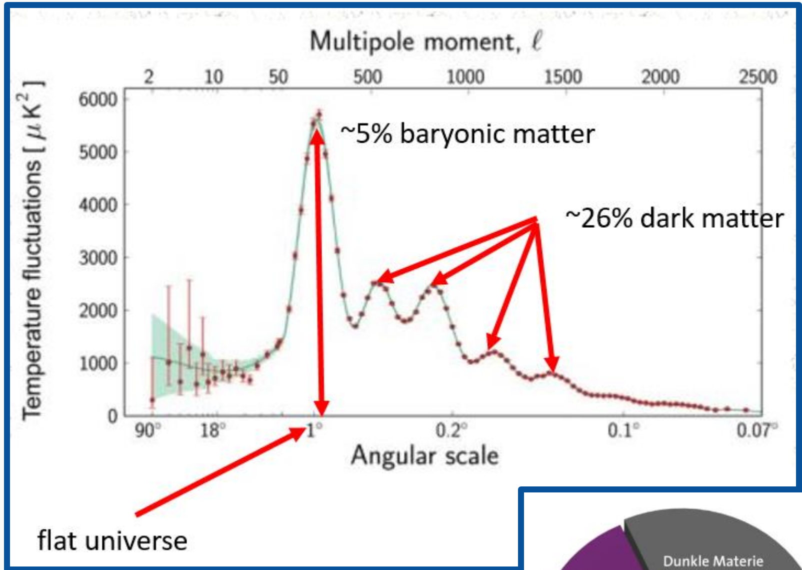
K.G. Begeman, A.H. Broels, R.H. Sanders. 1991. Mon.Not.RAS 249, 523.

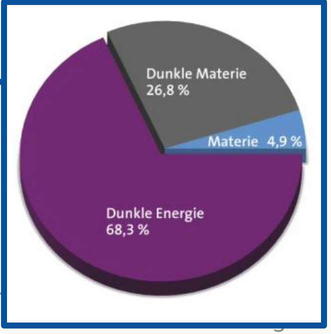
DARK MATTER

"visible matter" (X-ray)
matter distribution (gravitational lensing)

DARK MATTER



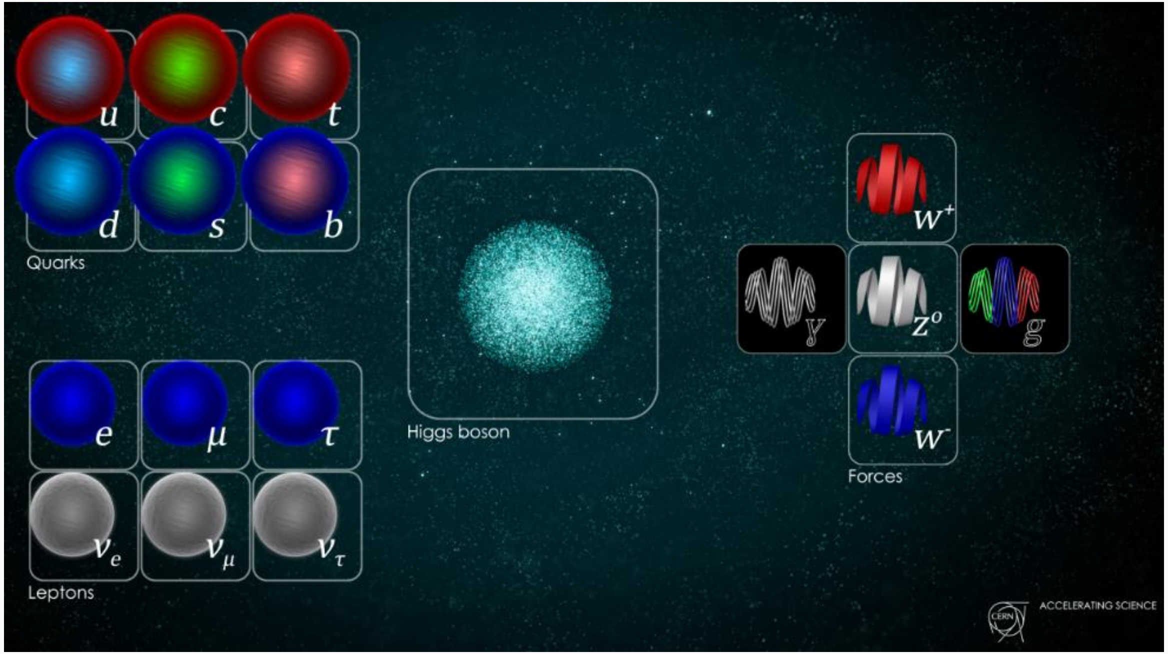




$$T(\theta,\phi) = \sum_{lm} a_{lm} Y_{lm}(\theta,\phi)$$

$$C_l \equiv \langle a_{lm} a^*_{lm} \rangle$$

DARK MATTER – CANDIDATES?



- the SM cannot explain dark matter
  - we require one or multiple extensions to the SM in order to do that!

DARK MATTER - RELIC DENSITY

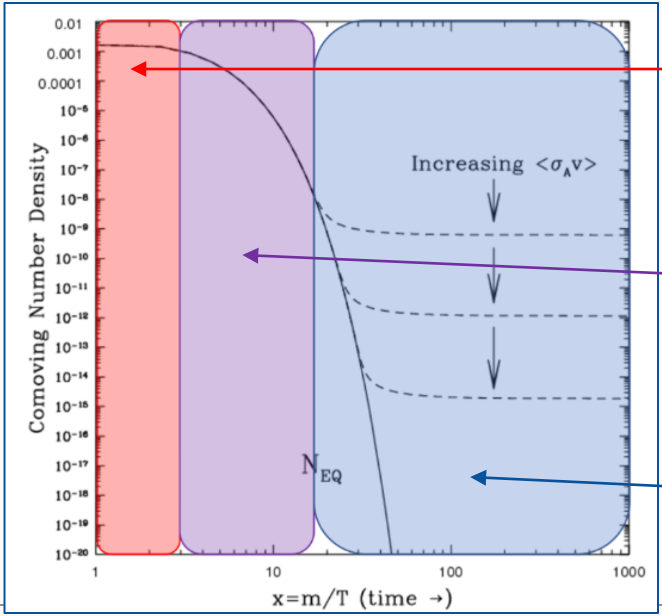
- what do we know about dark matter?
  - no so much, but we can infer some of its properties if we make certain assumptions

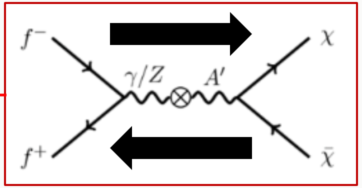
- relic density depends on annihilation cross-section, but not directly on the mass of the dark matter particle

$n_X / s \propto 1/M_X$

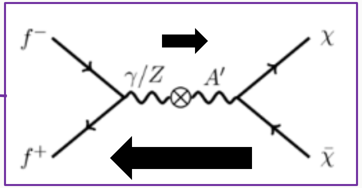
$\Omega \propto M_X * n_X$

- coupling of sole DM candidate → mass of DM candidate

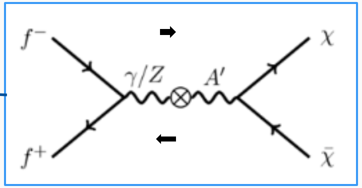




- thermal equilibrium
  - annihilation and production balance



- T dominated region
  - production is suppressed due to available energy



- H dominated region
  - annihilation is suppressed due to number density

DARK MATTER – WIMPS?

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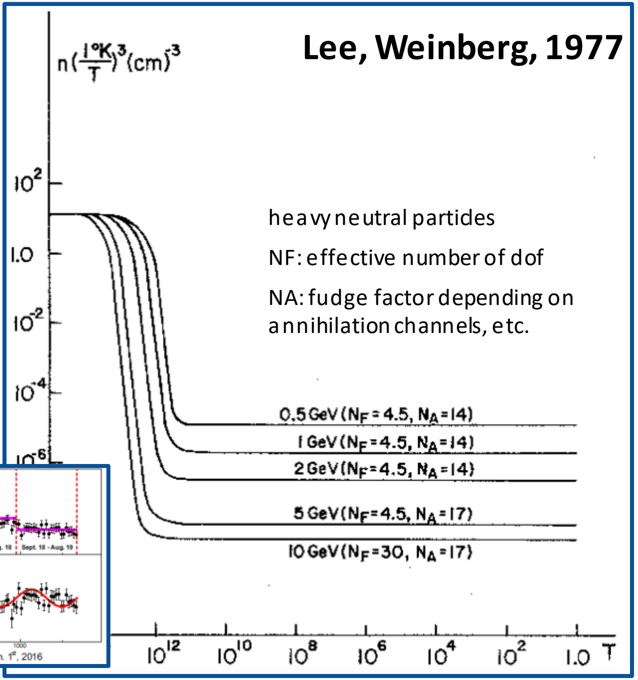
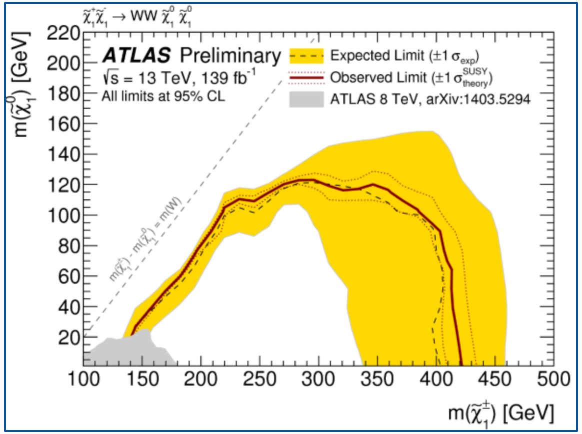
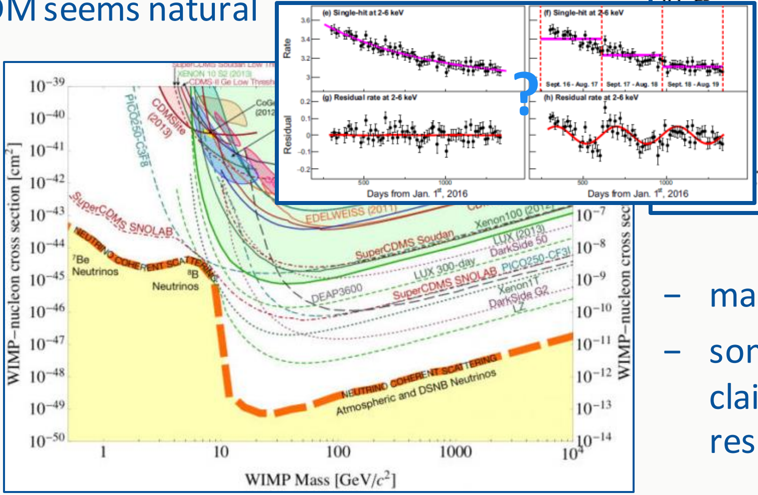
- assuming weak coupling between SM and DM:
  - smaller dark matter mass → smaller annihilation cross-section
  - DM mass is limited in the range of GeV – TeV
  - looking for weak-scale DM seems natural







- many negative results from searches
- some direct detection experiments claim to have found signal, but results are not reproducible

DARK MATTER - WISPS AND LDM

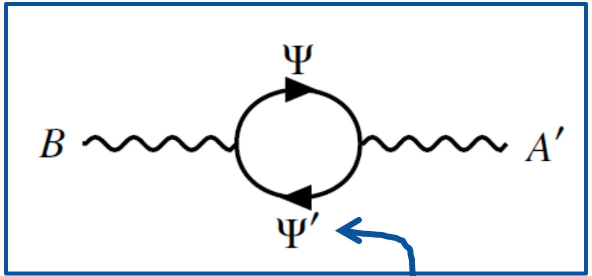
- dark matter from light particles?
  - need a fitting interaction between dark matter and SM sector
  - models with vector or scalar portals → can tune interaction strength to get right relic density
- one of the more simple models: massive boson from spontaneously broken $U(1)_D$ as portal → “dark photon”
- minimal model: SM + DM + $U(1)_D$ → introduce coupling between DS and SM through **kinetic mixing**

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_{\mathrm{D}} + \mathscr{L}_{\mathrm{SM}\otimes\mathrm{D}}$$

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

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

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



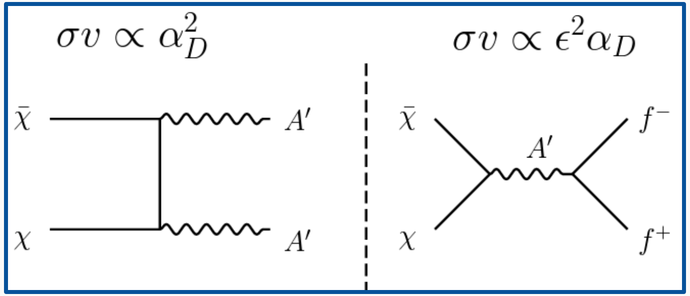
some heavy particles charged under both $U(1)_D$ and $U(1)_Y$

$$m^2_A = 0$$

$$m^2_{\tilde{Z}} = m^2_Z\left(1 + \varepsilon^2_Y\frac{m^2_Z s^2_W}{m^2_Z - m^2_{A'}}\right)$$

$$m^2_{A_D} = m^2_{A'}\left(1 + \varepsilon^2_Y\frac{m^2_Z c^2_W - m^2_{A'}}{m^2_Z - m^2_{A'}}\right)$$

DARK MATTER – DARK PHOTONS



- dark photon phenomenology
  - fundamental distinction: **"visible"** and **"invisible"** dark photons
  - **"visible" dark photons: $m_{AD} < m_\chi$:**
    - dark matter annihilation through pair production of A'
    - A' decays into SM particles, decays into DM kinematically forbidden

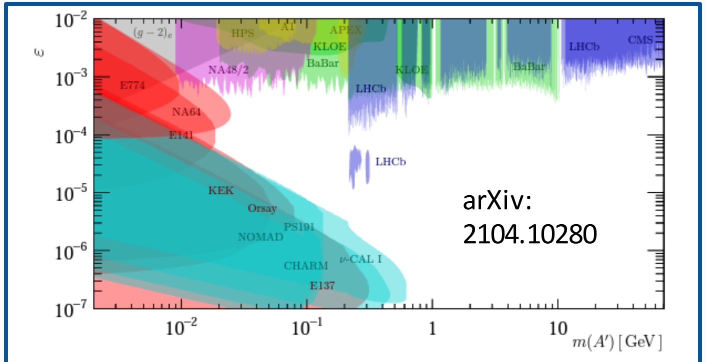


Figure 3
From Ref. (14) made using Ref. (19): Constraints on visible A' decays from electron beam dumps, proton beam dumps, e^+e^- colliders, pp collisions, meson decays, and electron on fixed target experiments. The constraint derived from $(g-2)_e$ is shown in grey (20, 21). The gaps in the prompt limits correspond to regions near the masses of the QCD vector mesons.

- prompt A' decays:
  - irreducible $\gamma \rightarrow$ ff background $n(A' \to \ell^+\ell^-) = \varepsilon^2 n(\gamma^* \to \ell^+\ell^-)\mathcal{F}(m_{A'})/2\Delta m$
- displaced A' decays
  - $\tau_{A'} \propto [\varepsilon^2 m_{A'}]^{-1}$
  - beam dump experiments with baselines up to O(100m)
  - collider searches with displaced vertices

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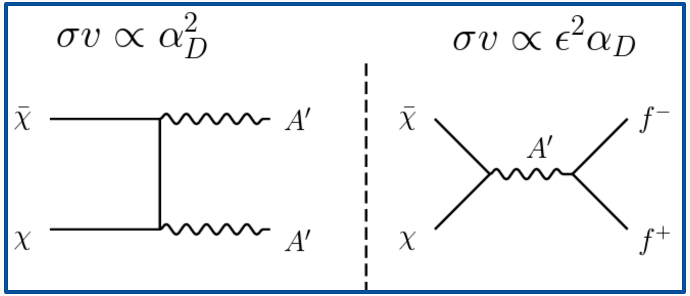
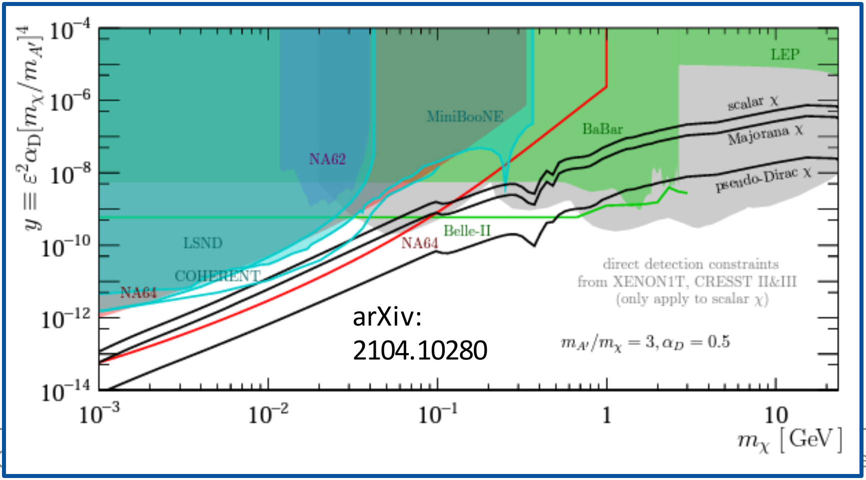
DARK MATTER – DARK PHOTONS



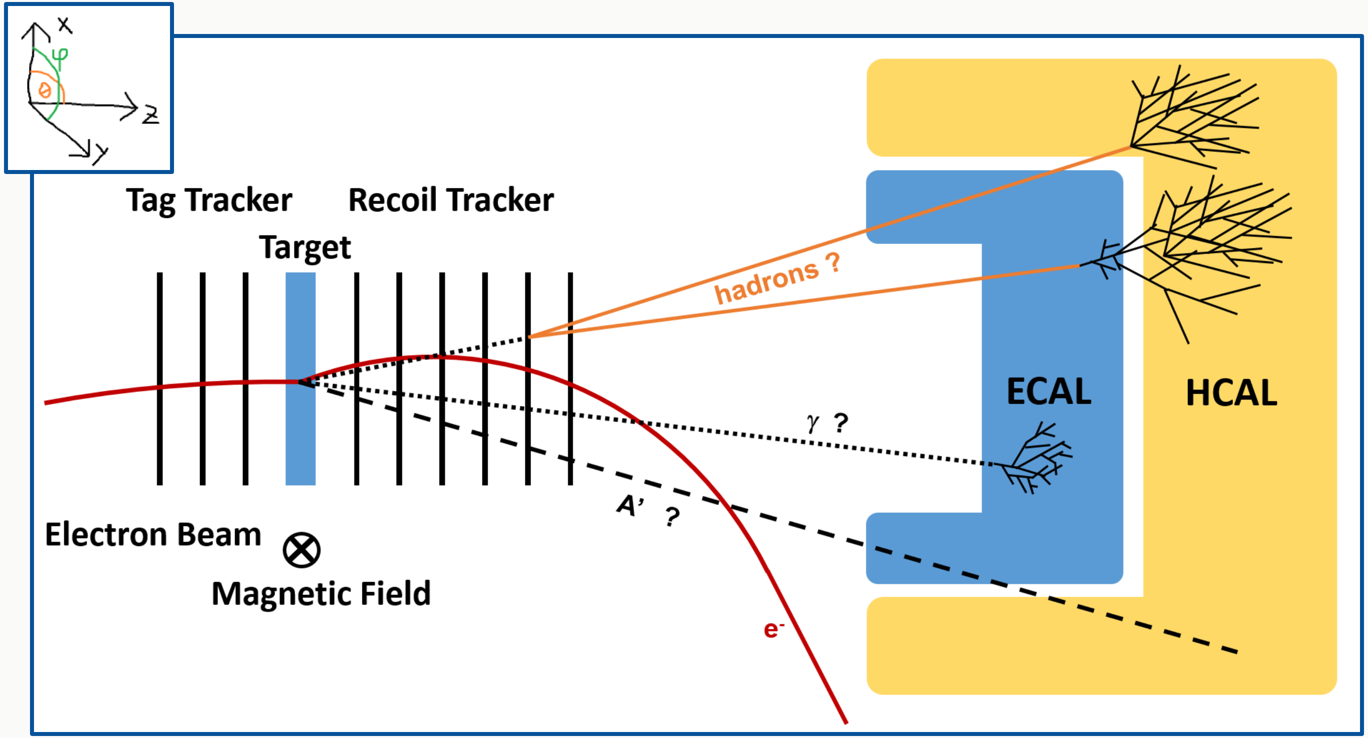
- dark photon phenomenology
  - fundamental distinction: **"visible"** and **"invisible"** dark photons
  - **"invisible" dark photons: $m_{AD} > m_\chi$:**
    - dark matter annihilation through s-channel A' into fermions
    - once produced, dark photon and its decay products do not necessarily produce any detectable signal

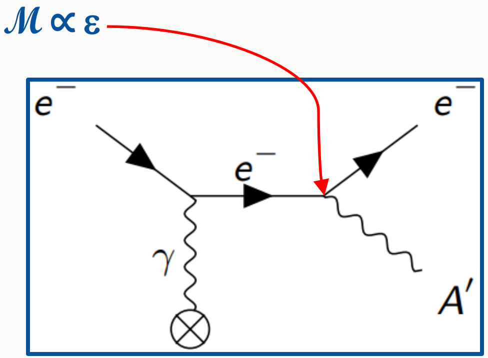
$n_{vis} / n_{invis} \propto \varepsilon^2$



- collider searches, beam dump experiments (with and without direct detection) and direct detection experiments
- in particles for DM masses < 1 GeV, i.e. mA' < 3 GeV, sizeable gap to relic target

FIXED TARGET DARK PHOTON SEARCH





- electron beam on fixed target (~10% X_0)
- dominant reaction: SM bremsstrahlung, sometimes subsequent electro-nuclear or photo-nuclear reaction
- depending on $m_{A'}$ and ε: occasional radiation of dark photon

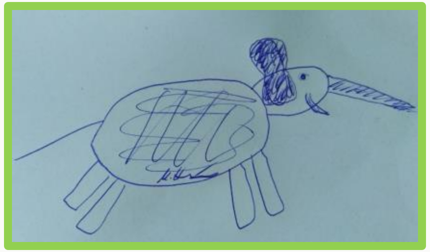
LOHENGRIN - IDEA

- inspired by the proposal for the **LDMX** experiment
  - electron beam-dump experiment with 4-16 GeV electrons and up to ~tens of electrons on target per spill (see arXiv:1808.05219)
    - Phase I: μ_e = 1 @ 50 MHz
    - Phase II+: μ_e = 2-10 @ 50 MHz -200 MHz

- studied the possibility to setup a similar experiment at the ELSA accelerator in Bonn
  - benefit from electron energy resolution of ELSA
  - use clean, single electron events at high rate
  - study orthogonal approach to LDMX calorimeter triggered approach
  - started with guiding principle: build the experiment fast using existing technology
    - have come to the conclusion that some detector R&D is required to be competitive

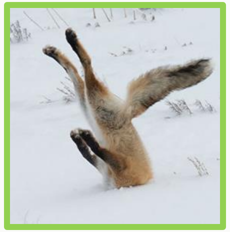
DARK PHOTON SEARCH AT ELSA: LOHENGRIN

model used in this presentation



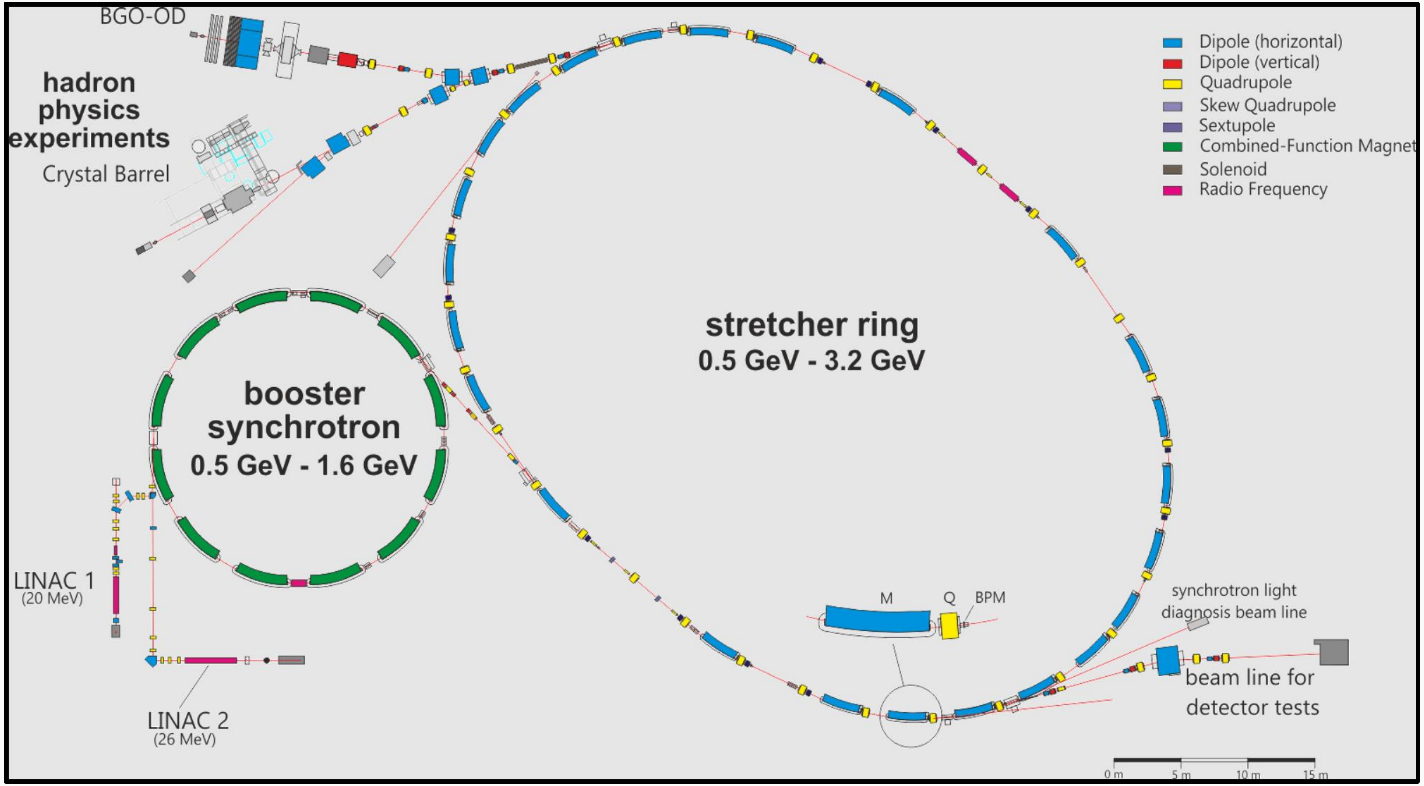
two equally likely options for the final thing

hopefully not the final thing



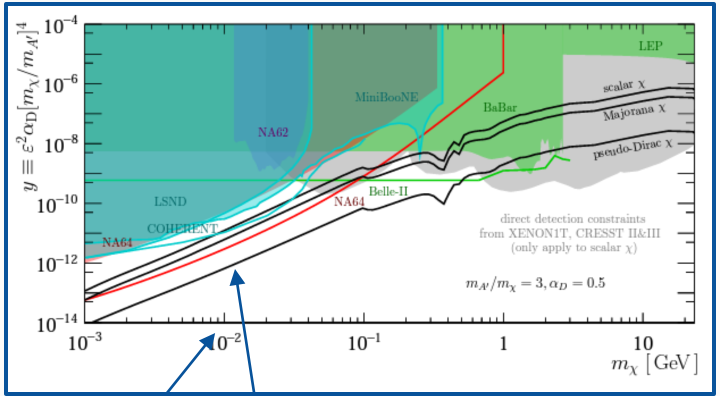
(almost) certainly not the final thing

ELSA - ELEKTRONEN STRETCHER ANLAGE

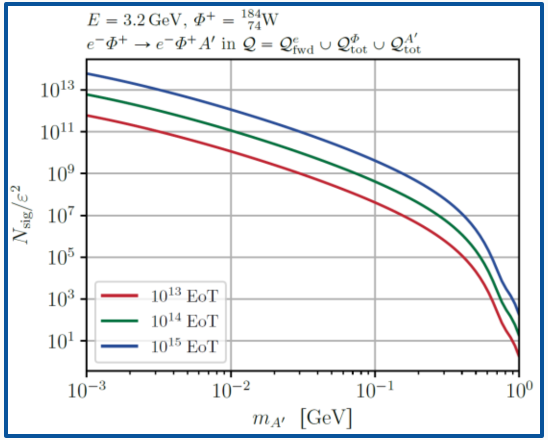


- ability to extract μ = 1 electrons per 2 ns bunch
- electron energy up to 3.2 GeV
- this should be enough to do produce some lightweight dark photons in Bonn!

DARK PHOTON PRODUCTION AT ELSA



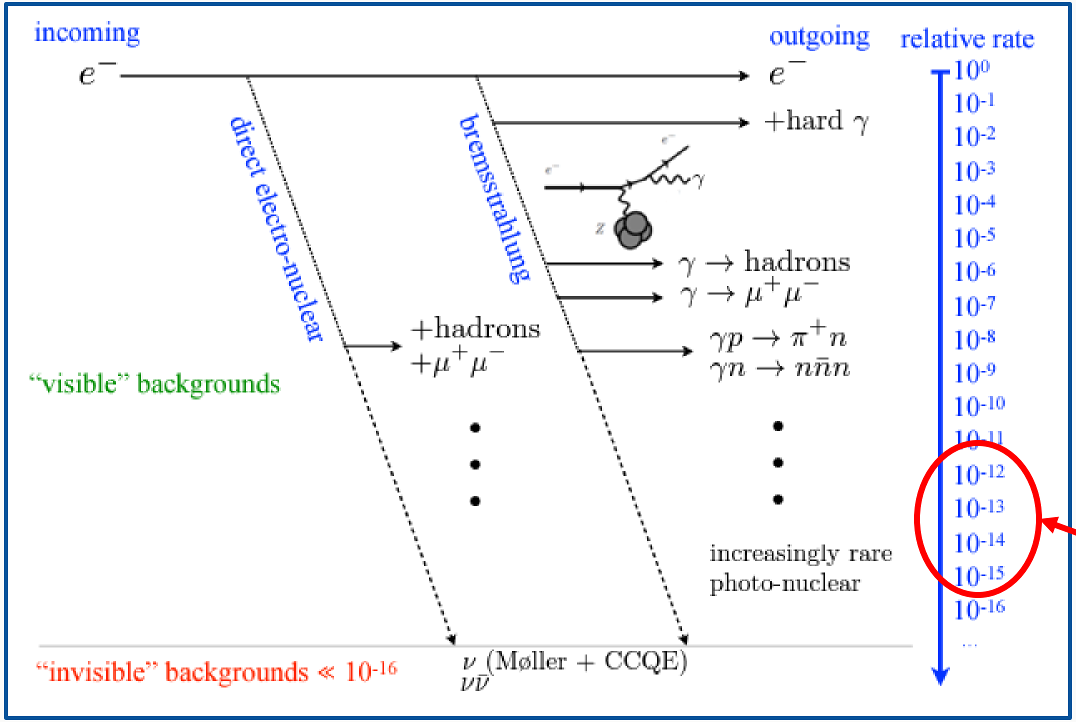
- how many electrons on target do we need to produce 1 dark photon with the right “relic target properties”?
- how many full days of beam time would we need to produce 100 dark photons at 100 MHz EoT rate?



	Scalar			Majorana			Pseudo-Dirac		
mA [Mev]	ε^2	EoT_1	$t_{100}2$ [days]	ε^2	EoT_1	$t_{100}2$ [days]	ε^2	EoT_1	$t_{100}2$ [days]
4.5	4.3E-11	**4.9E+12**	112	2.2E-11	**9.6E+12**	221	2.9E-12	**7.4E+13**	1709
10	2.0E-10	**4.7E+12**	110	9.8E-11	**9.7E+12**	225	1.3E-11	**7.5E+13**	1729
100	2.6E-08	**1.0E+13**	238	1.2E-08	**2.1E+13**	495	1.2E-09	**2.2E+14**	5205
1000	5.4E-07	**1.0E+19**	238388060	2.7E-07	**2.0E+19**	472519191	2.5E-08	**2.2E+20**	5188446020

there is a chance to find dark photons at ELSA with the right properties if we can control our backgrounds!

BACKGROUNDS



- taken from arXiv:1808.05219
- dominant process: SM bremsstrahlung
- relatively rare:
  - photo-nuclear and electro-nuclear reactions producing neutral hadrons
  - neutrino backgrounds generally expected well below signal levels

this is where the music plays!

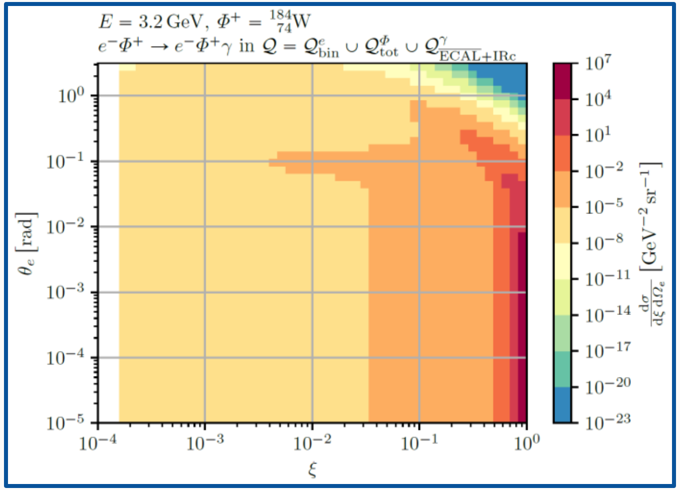
SM QED

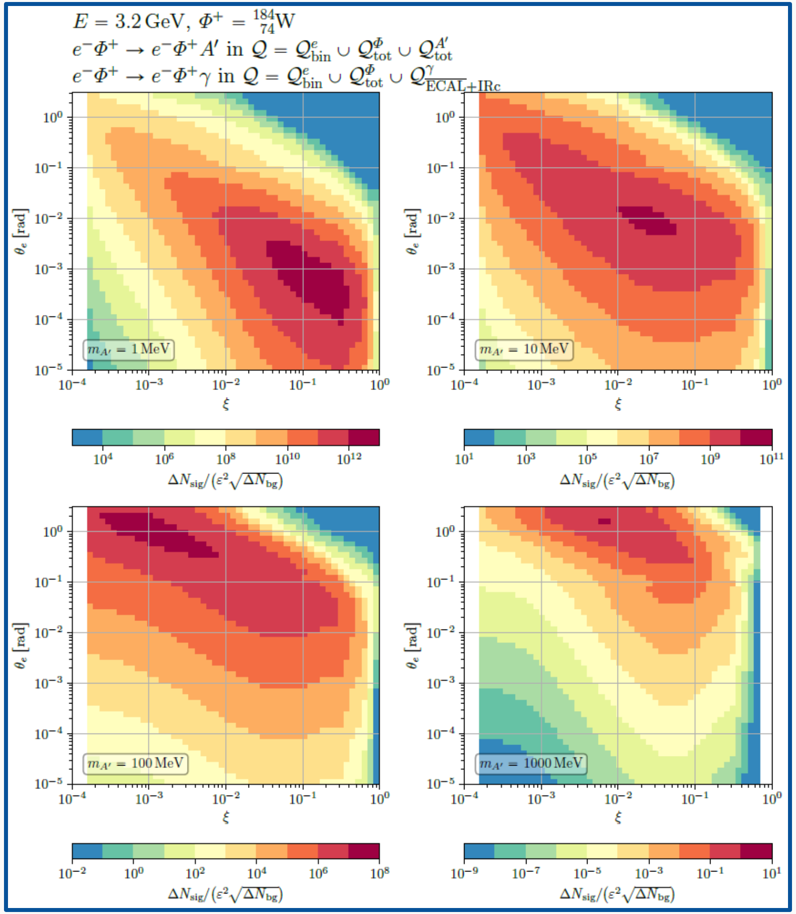
- how to find our dark photon events?
  - need to get rid of all the SM QED events
  - find veto for rare hadronic final states
- where to look best?

FS phase space described by

- e^- scattering angle θ
- e^- energy

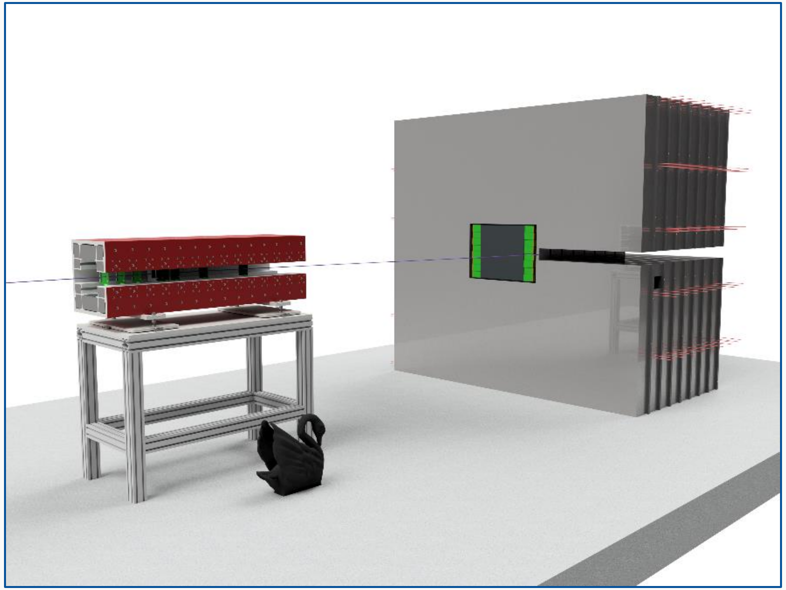
$$\xi = \frac{E_{\mathrm{e,out}}}{E_{\mathrm{e,in}}}$$





LOHENGRIN - CONCEPTION OF LAYOUT AND OPTIMISATION

- goal posts are set
  - looking for events with
    - high energy electron in the initial state
    - low energy electron and nothing else in the final state
  - benefit from clean events
    - → single electrons on target
  - reasonable runtime of experiment
    - → high rate

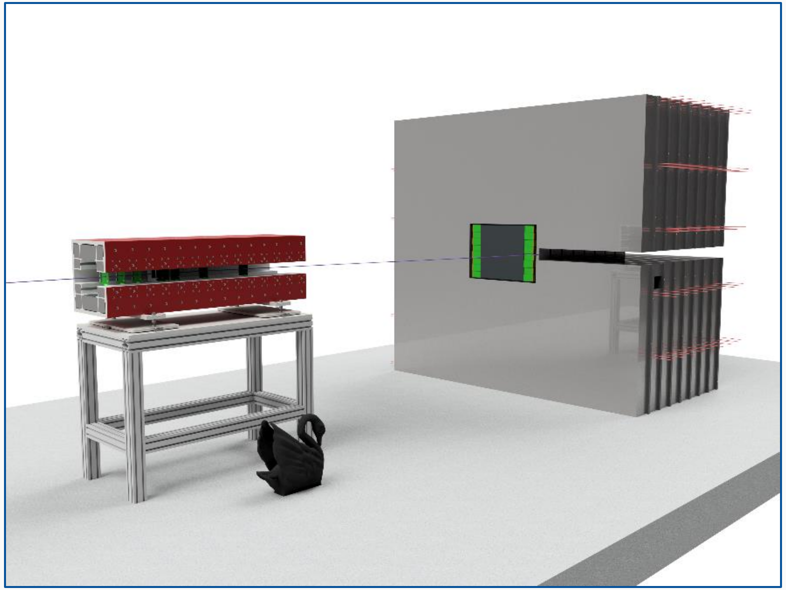


- how to get to a working experiment?
  - sketch requirements
  - do first rough and global determination of key parameters
  - study performance of individual components and optimise

LOHENGRIN - CONCEPTION OF LAYOUT AND OPTIMISATION

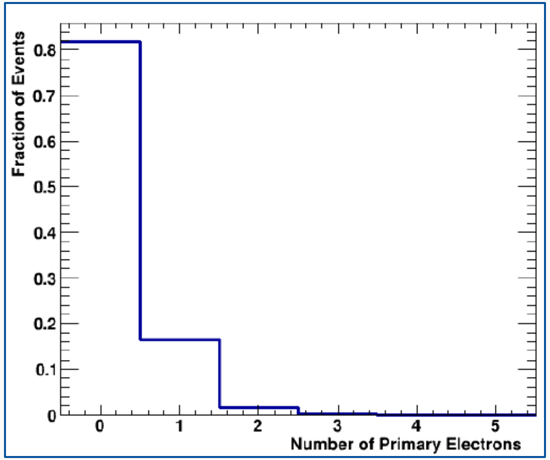
- experimental approach
  - place tracker and target in strong magnetic field
  - use ECAL to veto events with high energy photons
  - use HCAL system to veto events with hadrons

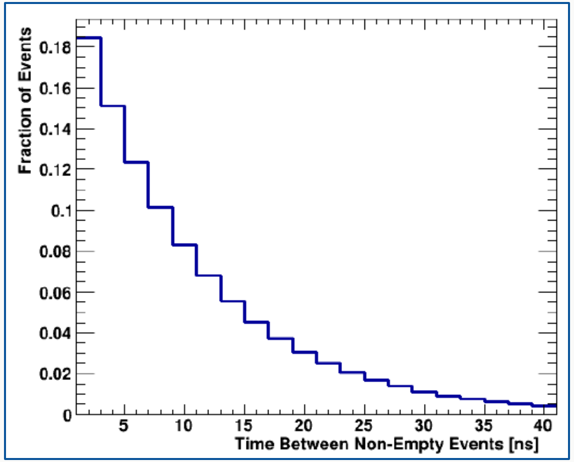
- general requirements
  - high resolution, fast and thin tracker
  - strong magnetic field
  - calorimeter with fast signal processing
  - highly efficient hadron calorimeter

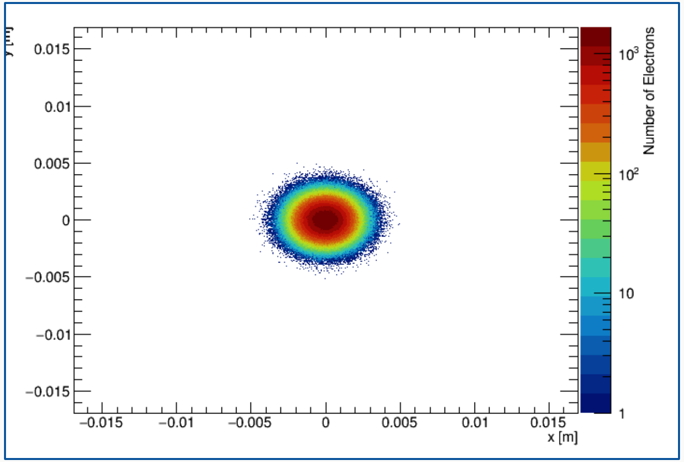


EVENT STRUCTURE

- 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

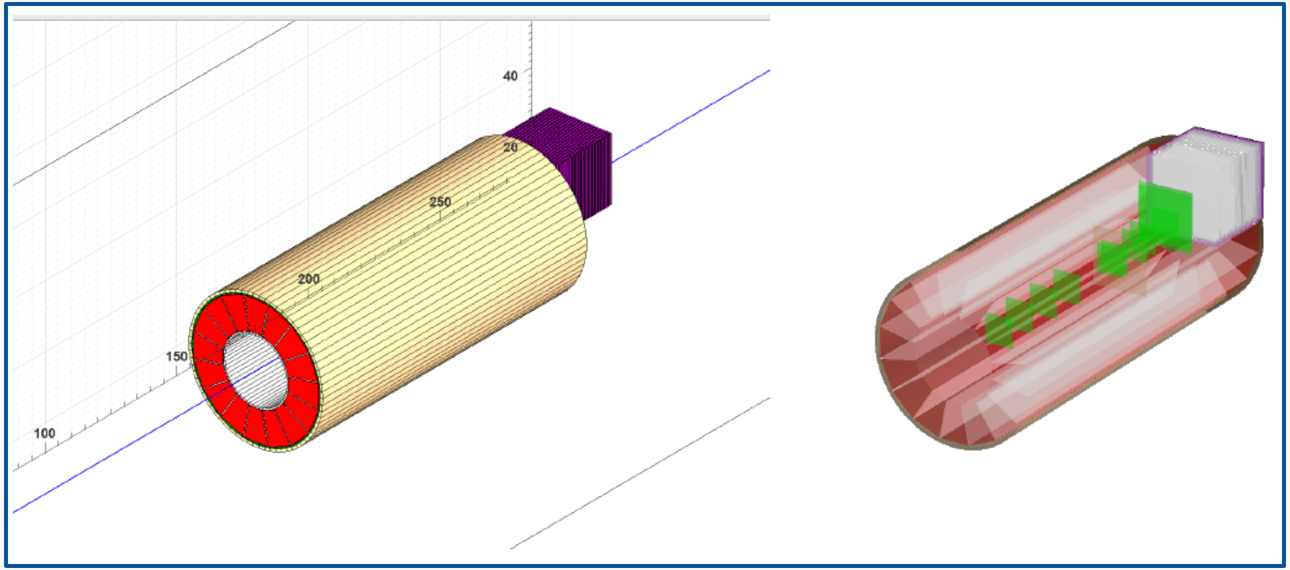




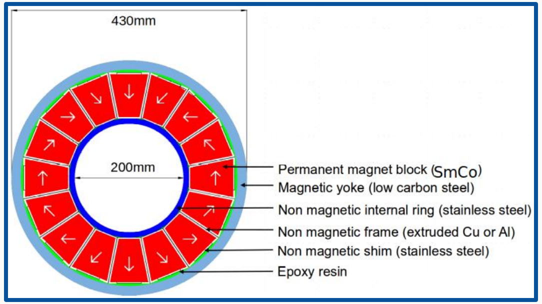


MAGNET

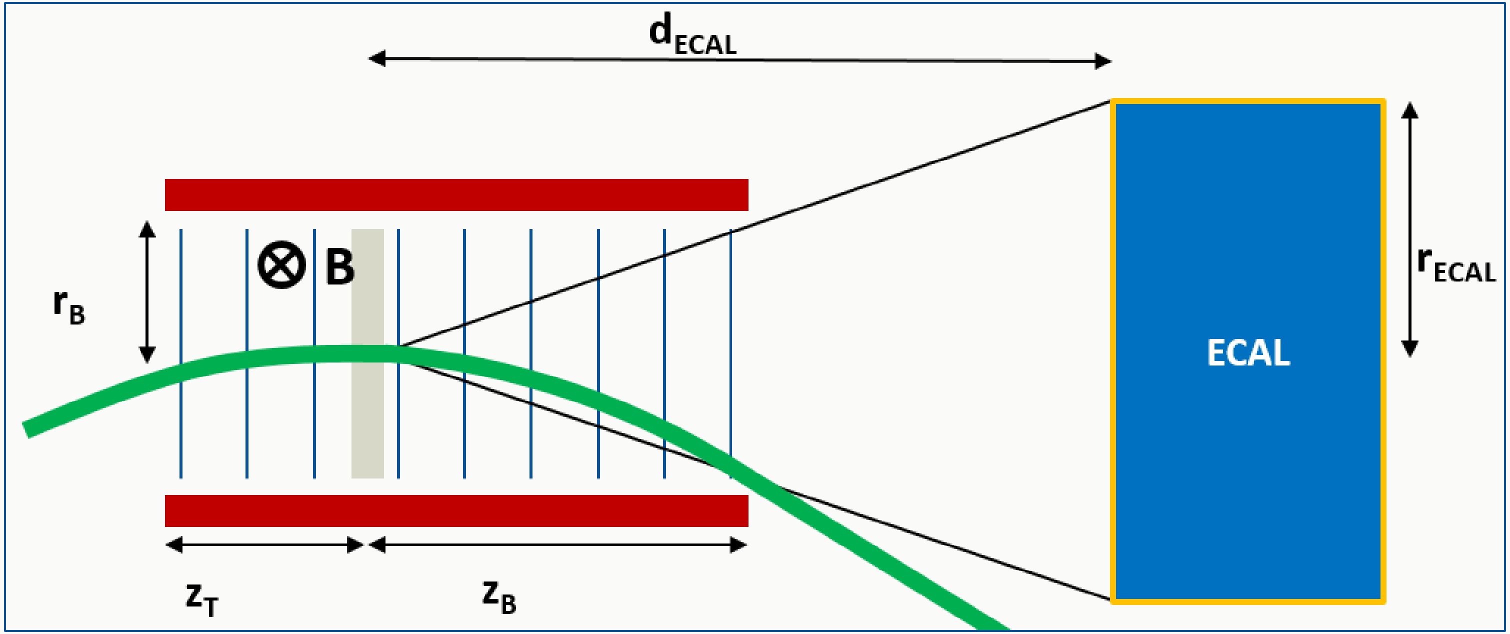
– starting point: FASER magnets



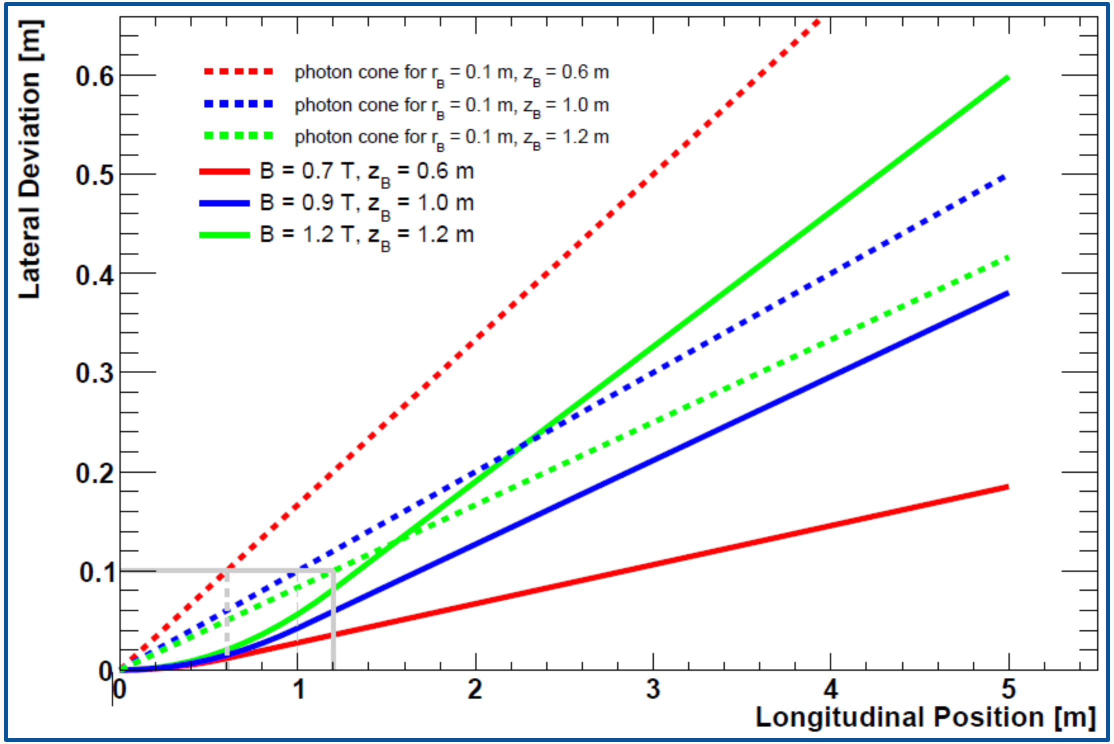
– 1 m long permanent dipole
– 0.5 T orthogonal to beam axis
– similar, iron dominated design could provide magnetic field of ~1T



LAYOUT OPTIMISATION



LAYOUT OPTIMISATION

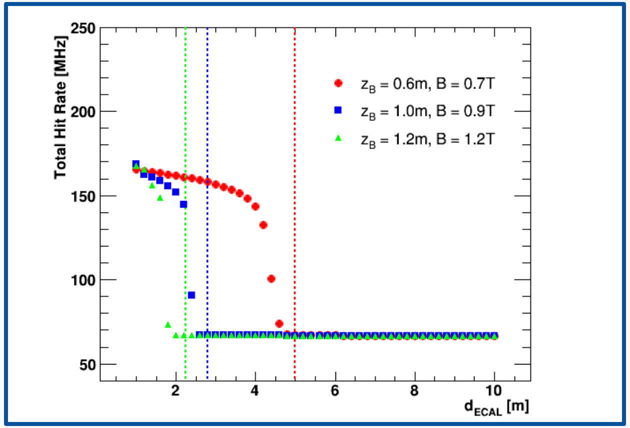


- considering three magnet scenarios
- ECAL coverage for photons determined by
  - maximum opening angle of magnet
  - lateral size of ECAL as function of its distance to target
- smaller coverage → larger out-of-acceptance background for SM QED events
- signal processing of ECAL limits acceptable hit rate

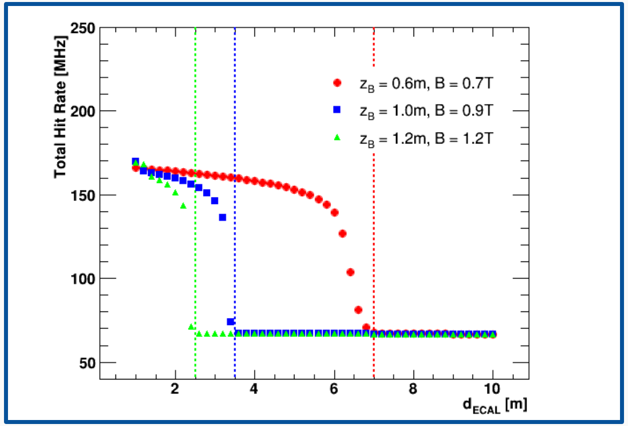
  → bend electron beam around ECAL

LAYOUT OPTIMISATION

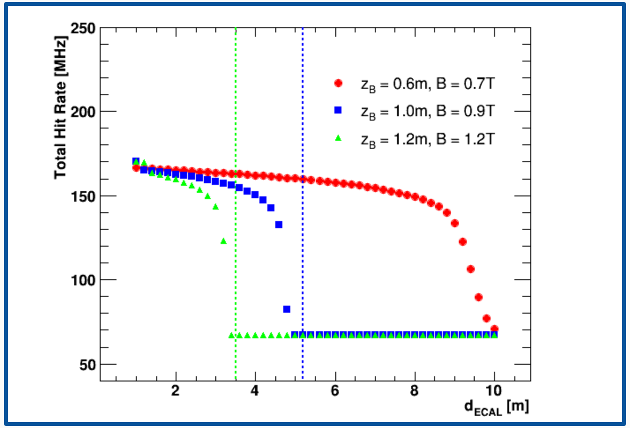
- drop off at large radius as electrons start to miss the ECAL
- stable pedestal at 70 MHz for 10+ MeV photons



d_{ECAL} = 16 cm



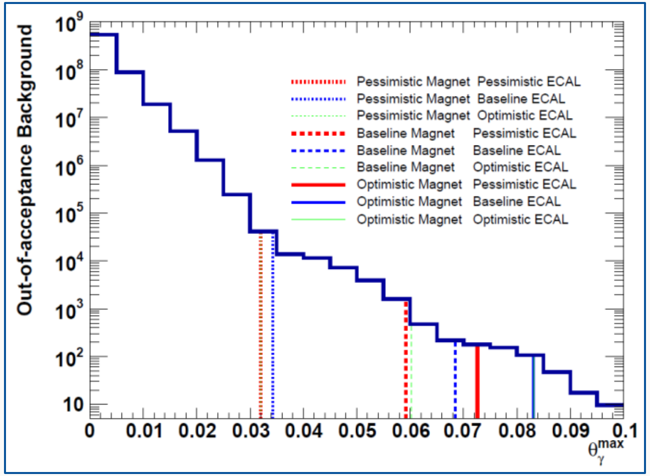
d_{ECAL} = 24 cm

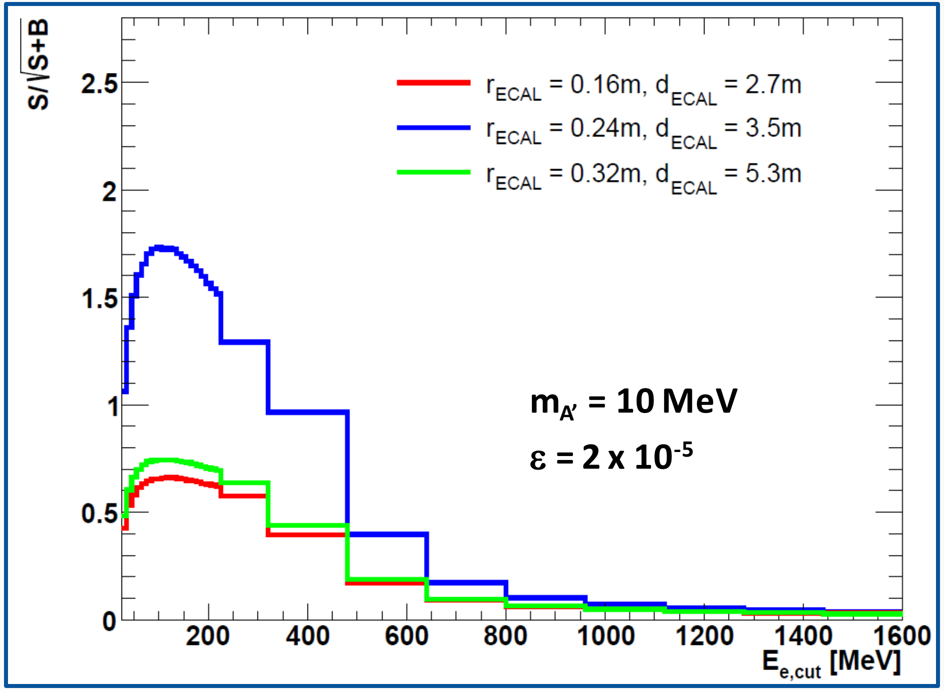


d_{ECAL} = 32 cm

LAYOUT OPTIMISATION

- baseline scenario with intermediate bending power
  - optimistic scenario desirable, feasibility unclear
    - photon acceptance limited
  - pessimistic scenario probably not good enough

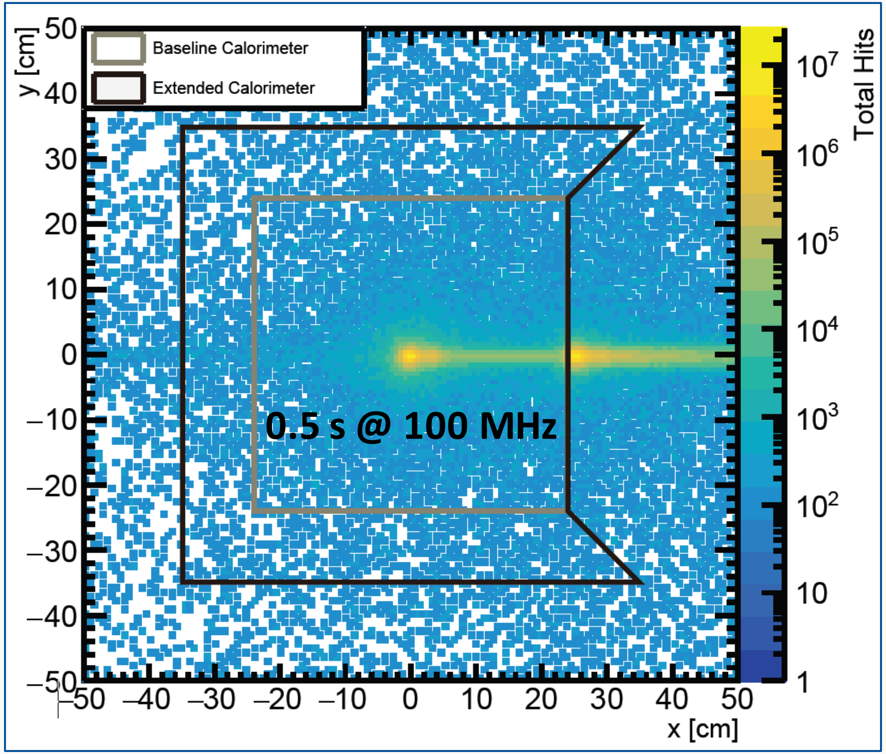




THE ECAL

- ECAL measurement of photons
  - not using ECAL in the conventional way
  - high hit rate of photons in the same cells
- estimated max hit rate per cell, assuming CALICE SiW ECAL like granularity: ~40 MHz in central cells
  - mostly low energy photons
  - need to find the few high energy photons in this sea of high energy photons to effectively veto SM QED events

→ need fast signal processing in ECAL



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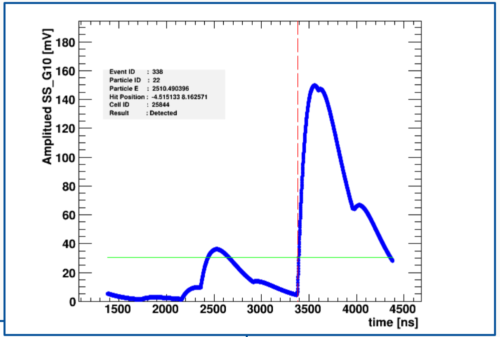
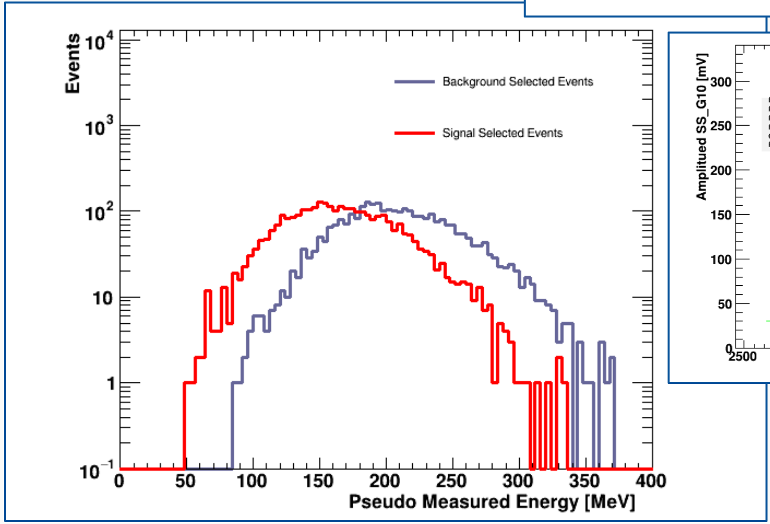
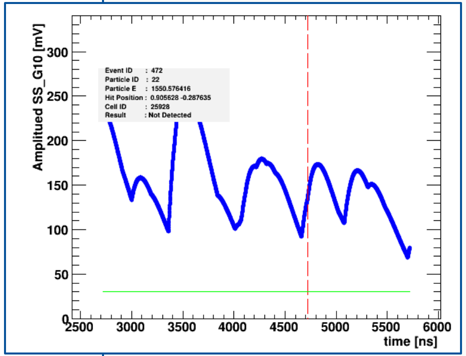
THE ECAL

- assuming SiW ECAL with infinitely fast pre-amplifier that never saturates . . .
- otherwise, SCIROC2a like characteristics, in particular CRRC shaper



- estimated signal efficiency for perfect background suppression:
  - SM QED events, including those with signal like electrons
  - pseudo signal events by removing hard photons from final state
  - with implemented shaping time, signal efficiency very low
  - too much "pile-up"

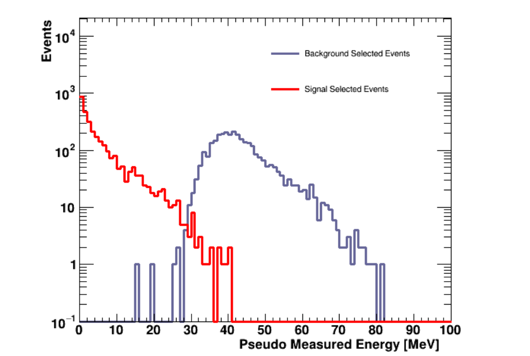




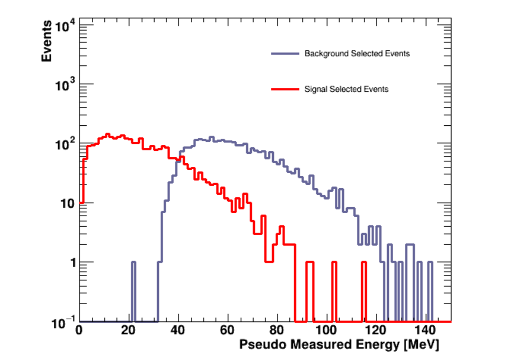
- τ = 180 ns

THE ECAL - SIGNAL PROCESSING

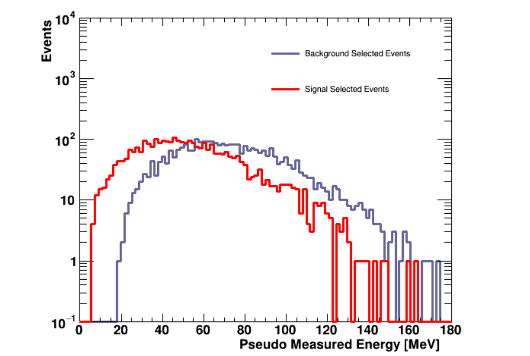
- assuming SiW ECAL with infinitely fast pre-amplifier that never saturates . . .
- otherwise, SCIROC2a like characteristics, in particular CRRC shaper



- τ = 10 ns
- th = 18 MeV
- ε = 81%



- τ = 30 ns
- th = 18 MeV
- ε = 68%

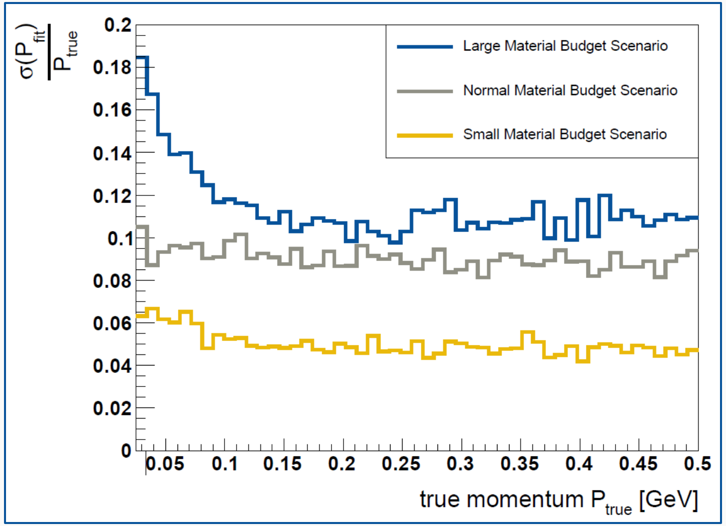


- τ = 60 ns
- th = 18 MeV
- ε = 5%

TRACKING DETECTOR

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

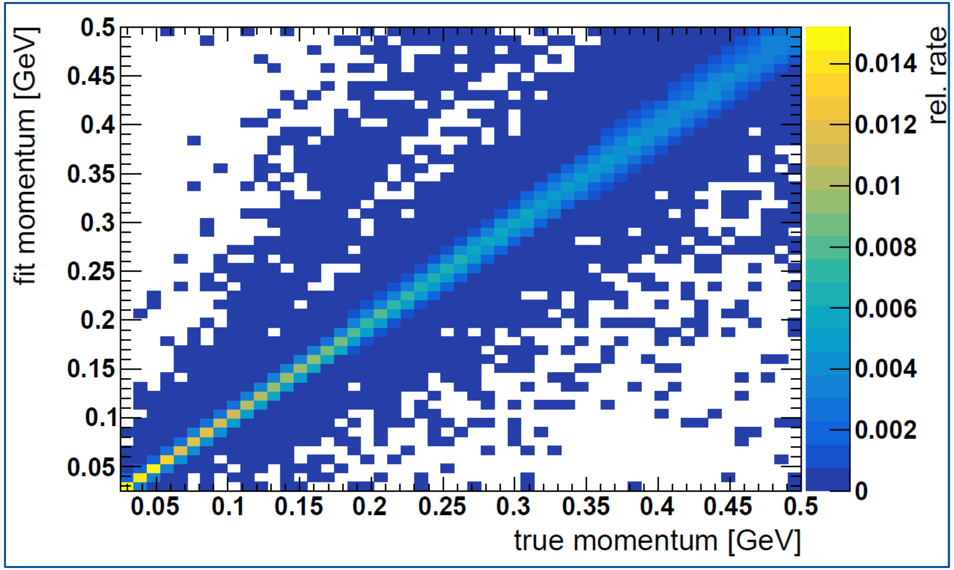
- estimated performance using TJ Monopix2 like tracking ASICs
  - DMAPS in Tower Jazz 180nm technology
  - 33.04 x 33.04 μm^2 pixels
  - can be thinned to 50-100 um
  - assuming modules of 2x2 ASICs per tracking plane
- tracking performance estimated using ACTS for a telescope geometry

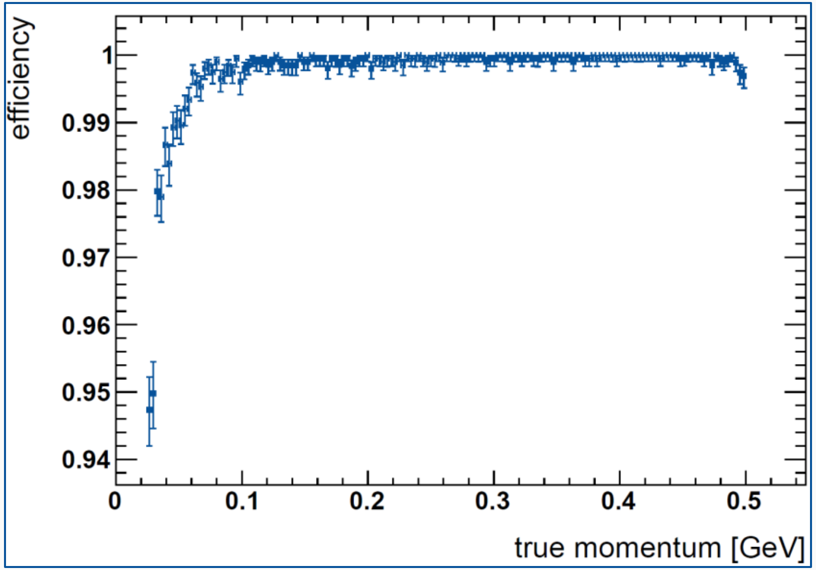


Layer	Target	1	2	3	4	5	6	7	8	9
z Position [mm]	2000	1810	1840	1900	2010	2030	2045	2070	2100	2130

TRACKING DETECTOR

- estimated tracker performance
  - 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

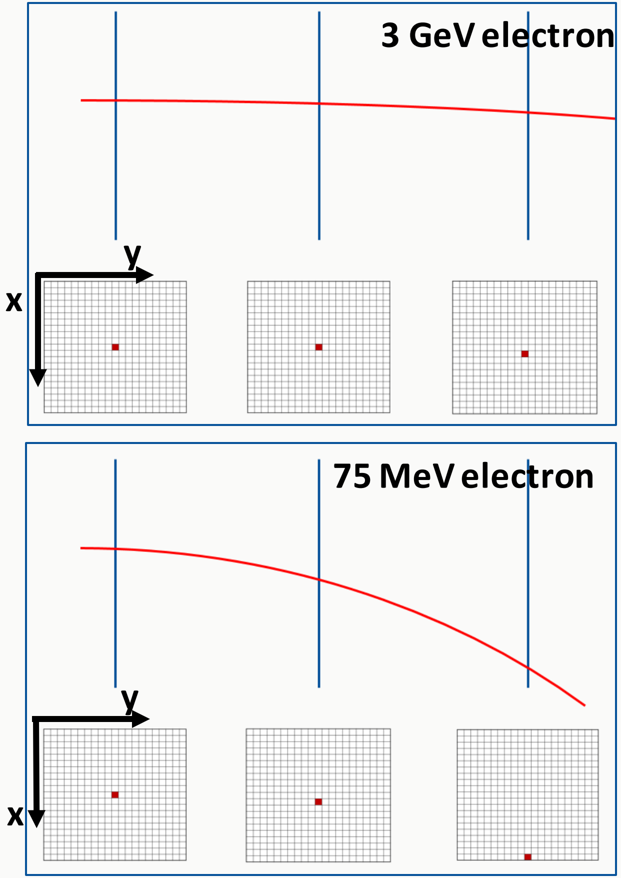




TRIGGER SYSTEM

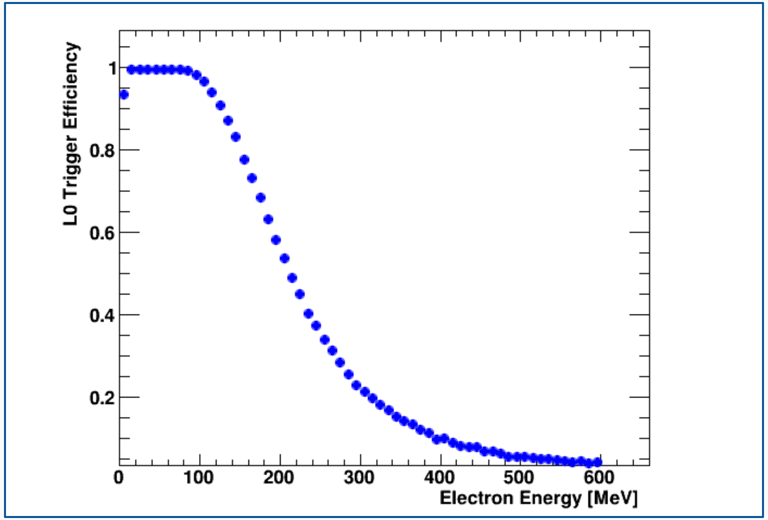
- TJ Monopix2 has a fast hit-or signal
  - sensitive part of pixel matrix can be configured
  - could be used for a low energy electron trigger

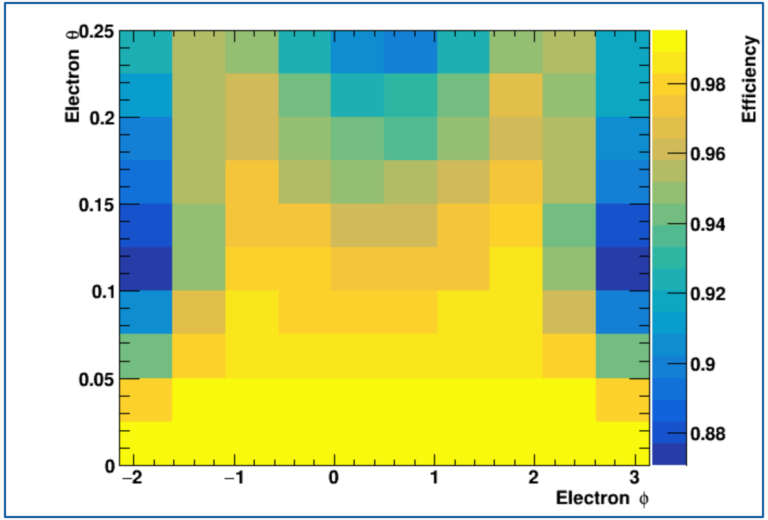
- hit in plane at z=1cm
  AND
  - hit in plane at z=7cm with x > 3.1mm
    OR
  - hit in plane at z=4.5cm with x > 2.3mm
    OR
  - hit in plane at z=3cm with x > 1.99 mm
- Total Rate: 1.7 MHz



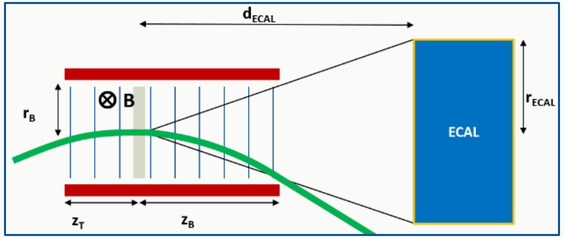
TRIGGER SYSTEM

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



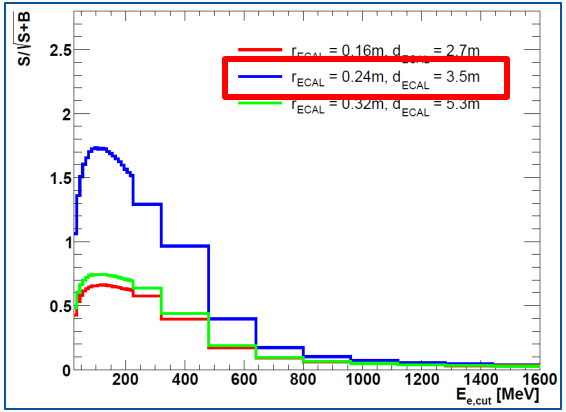


ESTIMATING SENSITIVITY



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

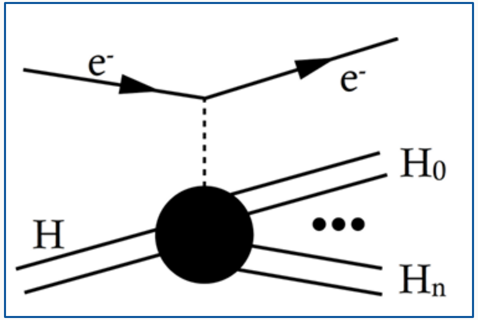
- pessimistic: $B = 0.6\,\mathrm{T}$, $z_B = 0.6\,\mathrm{m}$
- baseline: $B = 0.9\,\mathrm{T}$, $z_B = 1.0\,\mathrm{m}$
- optimistic: $B = 1.2\,\mathrm{T}$, $z_B = 1.2\,\mathrm{m}$



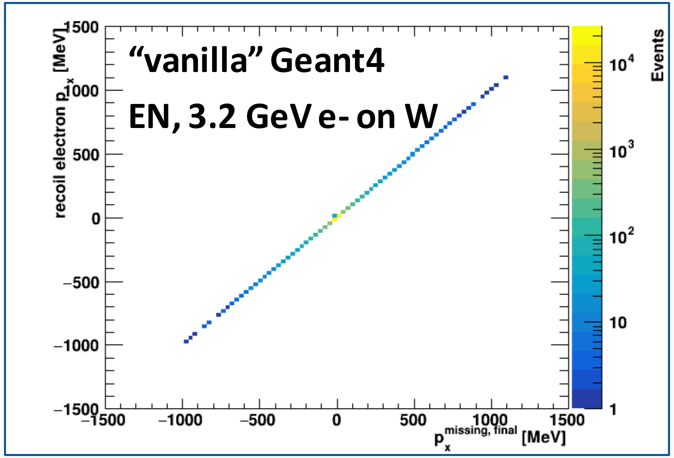
- considering baseline magnet scenario with baseline ECAL scenario
  - main background expected to stem from out-of-acceptance SM QED
  - hadronic backgrounds are difficult to estimate → next slides

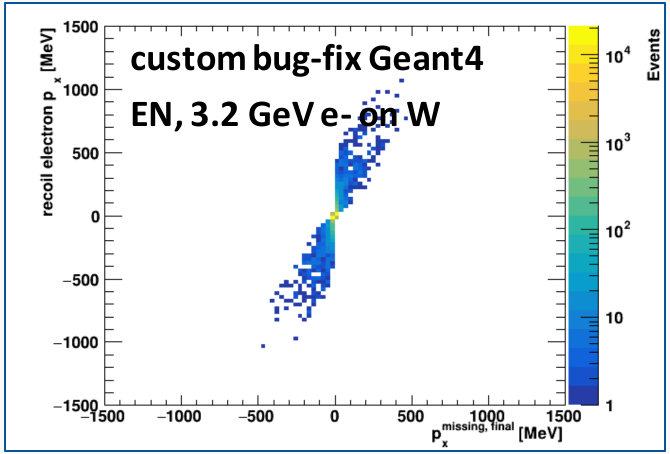
$4 \cdot 10^{14}$ EoT	number of γ	$m_{A'} = 1\,\mathrm{MeV}$ $\varepsilon = 1.2 \cdot 10^{-6}$	$m_{A'} = 10\,\mathrm{MeV}$ $\varepsilon = 1.4 \cdot 10^{-5}$	$m_{A'} = 100\,\mathrm{MeV}$ $\varepsilon = 1.6 \cdot 10^{-4}$
total $\xi < 0.95$	$3.1 \cdot 10^{14}$	26	80	27
$p_e < 75\,\mathrm{MeV}$, $\theta_e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

ESTIMATING SENSITIVITY



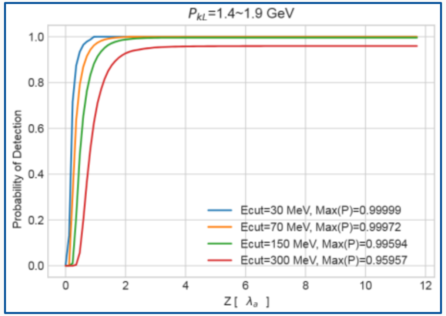
- initially used Geant4 to estimate electron-nuclear and photon-nuclear backgrounds
  - bug in Geant4 produces non-physical results (missing rotation to lab frame)
  - can be fixed in Geant4 source code
  - equivalent photon approximation does not produce reliable results for high q^2 that defines our SR
  - dominant contribution to background is expected to be out-of-acceptance background → important to get kinematic distributions right!



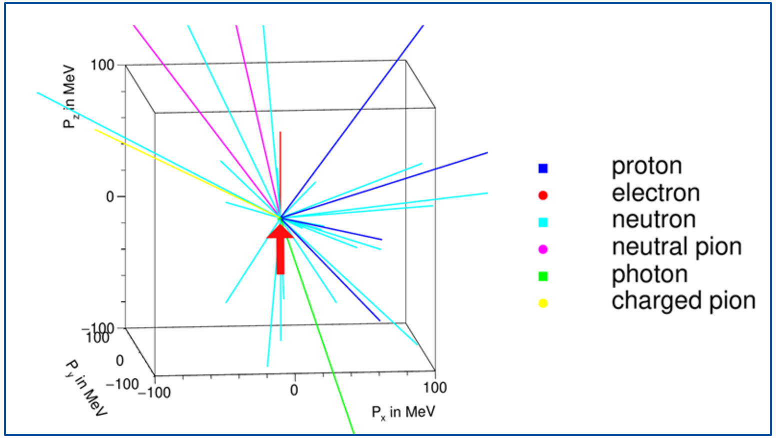


- Geant4 effectively cuts off the photon momentum when transforming the virtual photon into a real photon
- causes momentum imbalance that is pronounced for large values of $|q^2|$

ESTIMATING SENSITIVITY



- have used limited sample size MC to estimate number of background events
  - 10^7 electron-nuclear and 10^7 photon-nuclear interactions in the target and first layer of the ECAL
  - no events survive all SR cuts
- estimate is limited by the sample size → need reliable generator before generating more MC
  - looking into FLUKA as an alternative to Geant4 for the eN interactions
- expect somewhat isotropic distribution of FS hadrons
  - unreasonable to set BG expectation to 0
  - set the expectation to 10 events in the SR (arbitrary number)
  - very conservative compared to LDMX for example

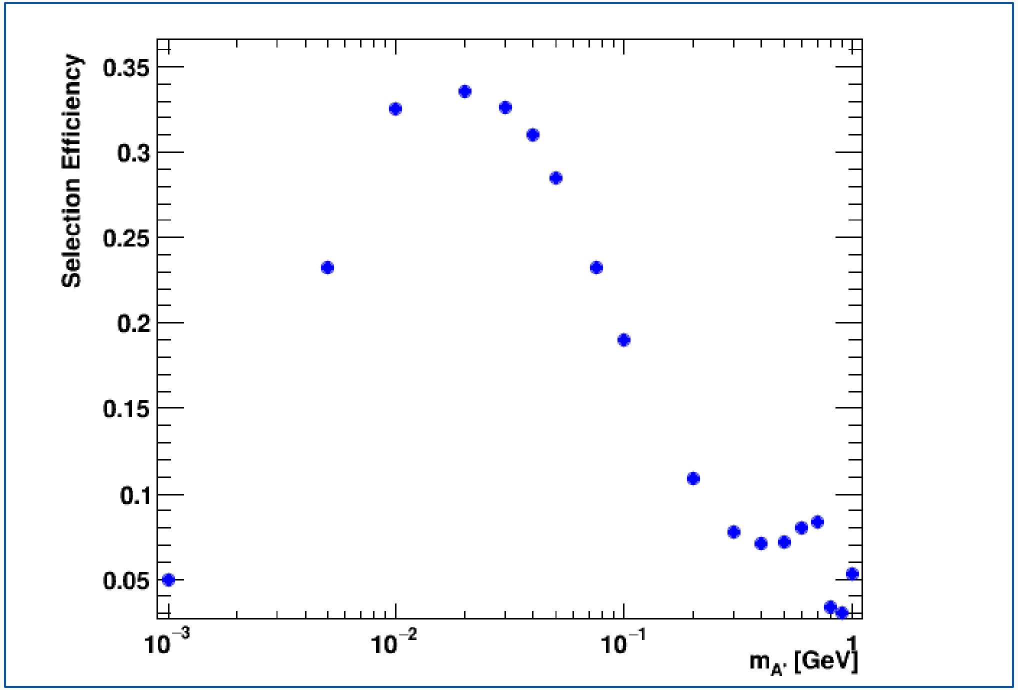


- $e^- + \mathcal{H} \to e^- + \mathcal{H}' + \pi^0 + 3n + 5\gamma$,
- $e^- + \mathcal{H} \to e^- + \mathcal{H}' + \gamma + 8n + 2p + 7\gamma$,
- $e^- + \mathcal{H} \to e^- + \mathcal{H}' + \pi^- + 3p + 4n + 6\gamma$,
- $e^- + \mathcal{H} \to e^- + \mathcal{H}' + 2\pi^0 + \pi^+ + K^0 + \Lambda + 31n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

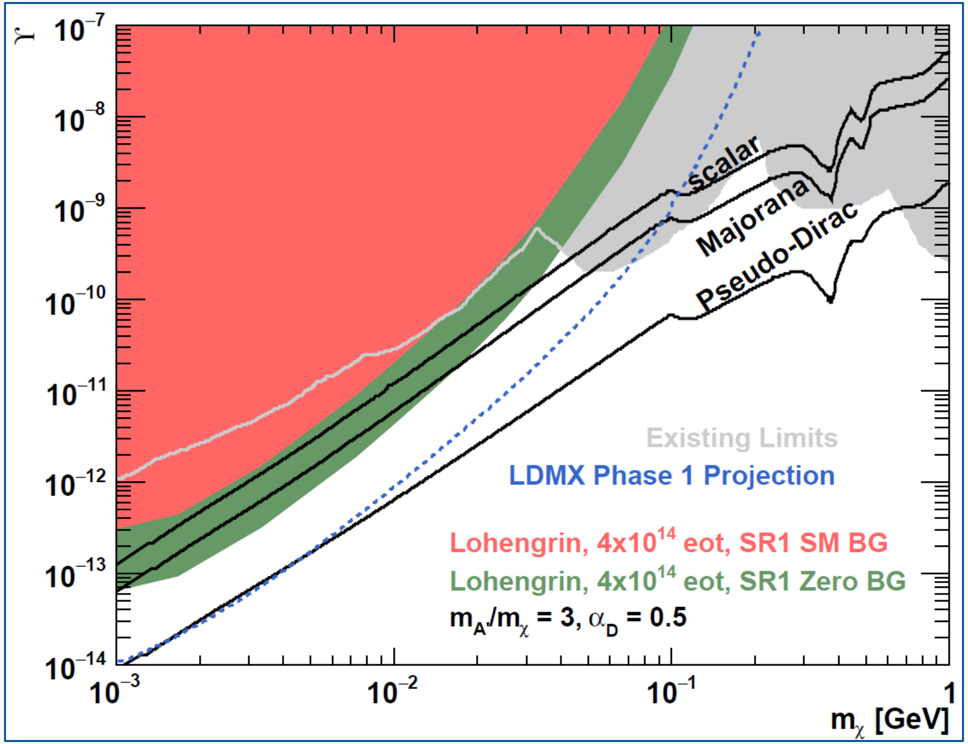
ESTIMATING SENSITIVITY

- signal efficiency, including
  - trigger efficiency
  - electron reconstruction efficiency
  - calorimeter veto efficiency
  - selection efficiency

- achieve reasonable signal efficiency for targeted mass interval

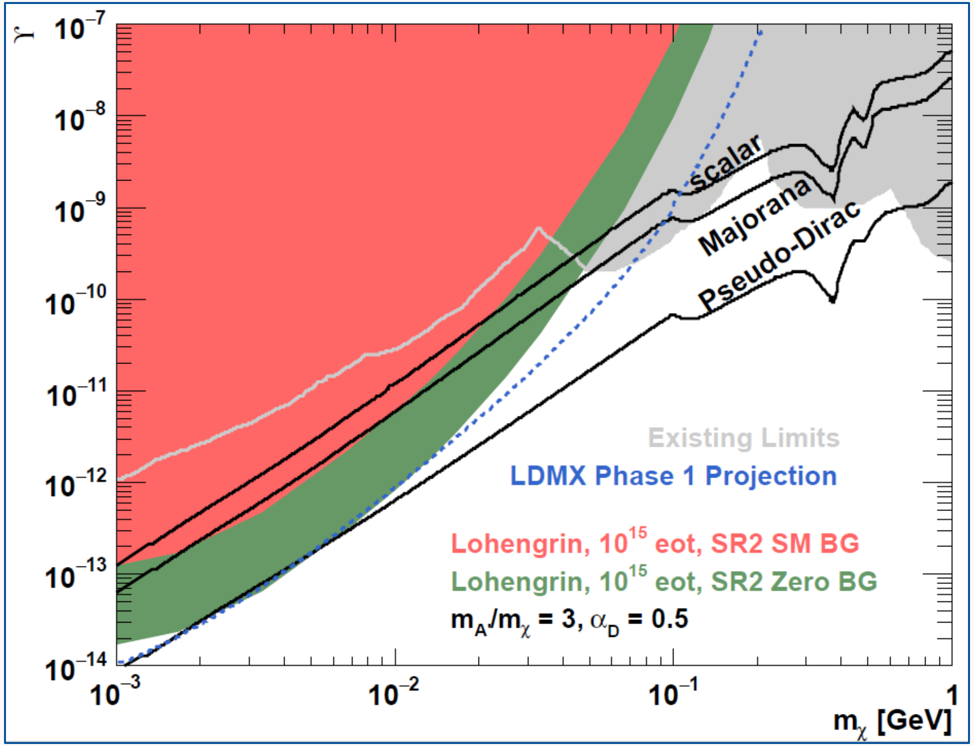


ESTIMATING SENSITIVITY



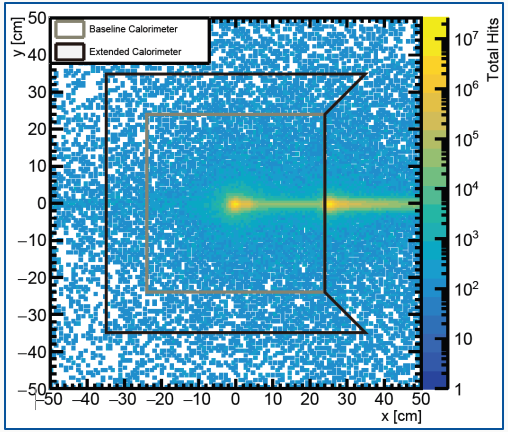
- with conservative estimates, sensitivity approaches relic target for scalar dark matter with $4x10^{14}$ electrons on target
- reduction of out-of-acceptance backgrounds could expand the reach beyond relic target for scenarios with scalar and Majorana dark matter
- lower centre-of-mass energy limits expected sensitivity with respect to the LDMX projection

ESTIMATING SENSITIVITY



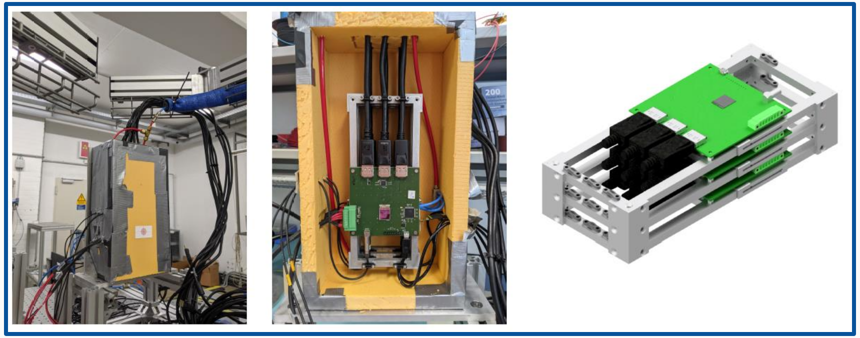
- possible improvements
  - moderate increase in luminosity
  - electron reconstruction down to the lowest energies
  - enhanced coverage for photon and hadron vetos

"slot" in ECAL could drastically reduce QED background



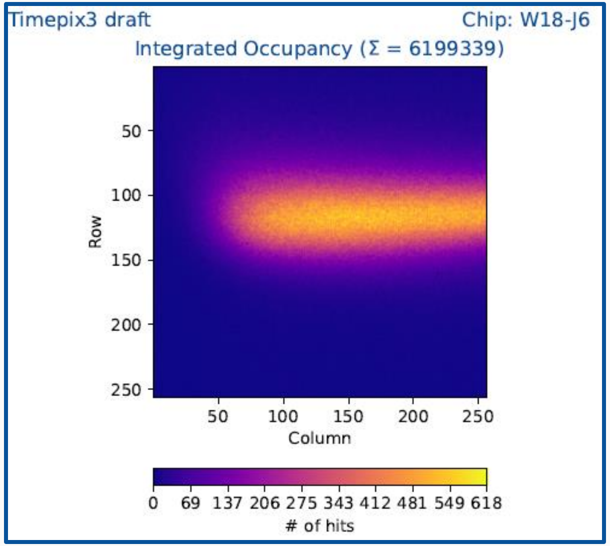
LOHENGRIN - RATE TESTS WITH TIMEPIX3 MINITRACKER

- started focusing on the tracker
  - implementation of a Kalman filter in simulation
  - production of a mini-tracker using untriggered TimePix3 silicon modules with beam telescope
    - rate capabilities of TimePix3 tested
    - first analysis of multiple scattering done



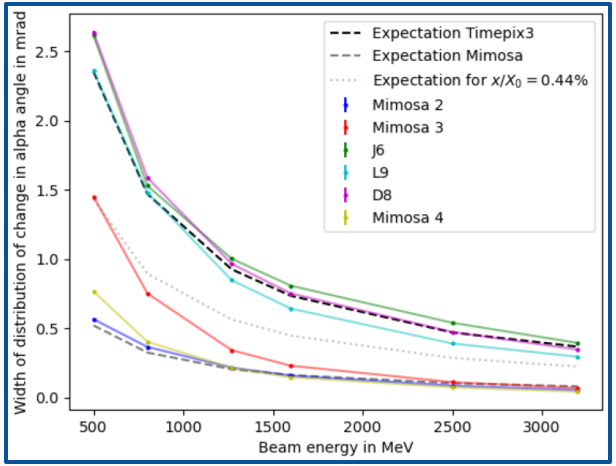
LOHENGRIN - RATE TESTS WITH TIMEPIX3 MINITRACKER

- detector development: tracker
  - first testbeam in 2020 with 3 Timepix3 silicon assemblies



2.5 GeV electron beam, 100 kHz

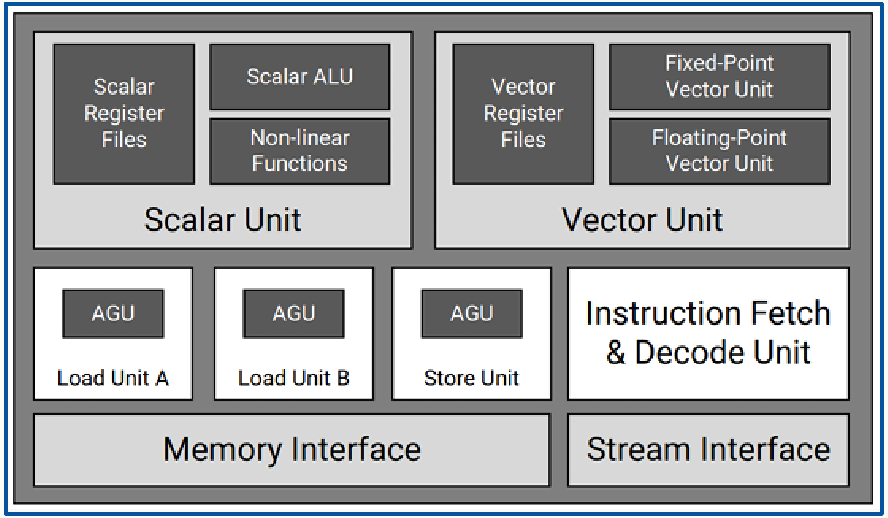
rate in kHz	energy in GeV	length	settings	remarks
2.00	2.50	10 min	nominal	ok
10.00	2.50	7 min	nominal	ok
50.01	2.50	2,5 min	nominal	ok
100.60	2.50	30 s	nominal	ok
500.00	2.50	30 s	nominal	ok
1000.00	2.50	30 s	thr: 4 150	ok
1000.00	2.50	30 s	thr: 4 200	some errors
750.00	2.50	30 s	nominal	ok
875.00	2.50	30 s	nominal	some errors
825.00	2.50	30 s	nominal	ok
850.00	2.50	30 s	nominal	some errors

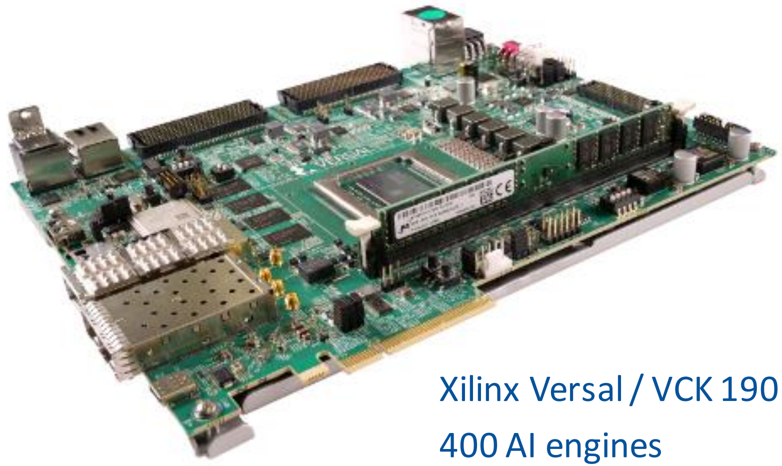


- tests with Timepix3 minitracker with and without ANEMONE telescope
  - lower than expected maximum rate (bottleneck in software)
  - tracking resolution not perfectly understood yet (MS? track reco?)

LOHENGRIN - TRIGGER

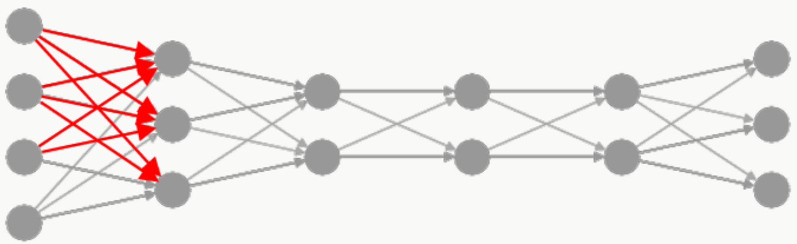
- use of AI engine driven track trigger for Lohengrin?
  - pattern recognition for multi-track events
  - implementation of track building and track fitting, e.g. Kalman filter





Xilinx Versal / VCK 190

400 AI engines

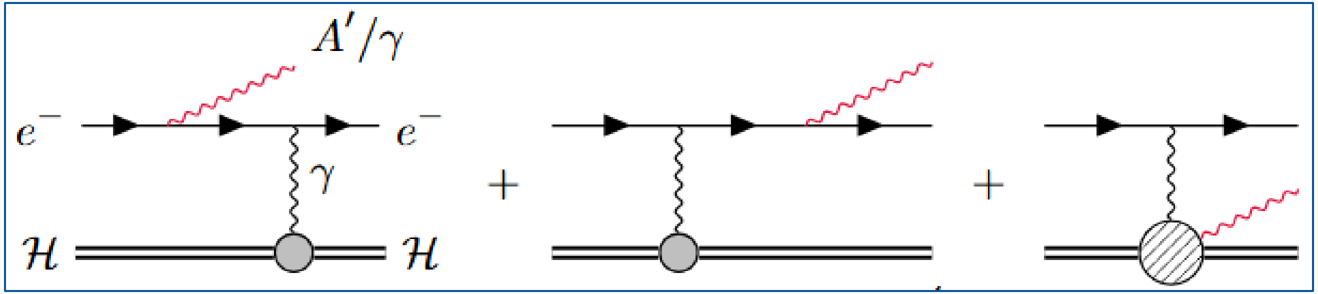


LOHENGRIN - NEXT STEPS

- feasibility study submitted to journal: https://arxiv.org/abs/2410.10956
  - revision will be submitted this week

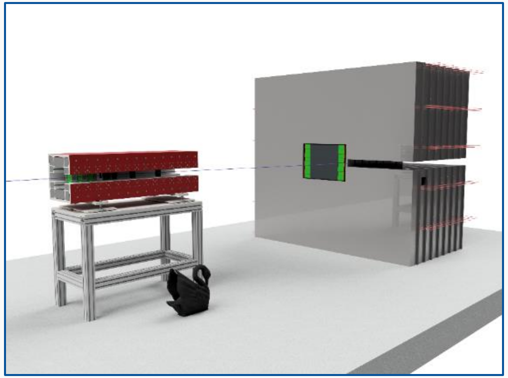
- setting up new beam test for second trigger stage
  - no magnetic field, test pattern recognition and rate capabilities
  - inclusion of target and simple hadron counter in the beam test setup

- improving estimates:
  - virtual compton scattering
  - hadronic backgrounds



LOHENGRIN - ROADMAP

- phased setup of experiment at ELSA
  - development of tracker ASICs and finalisation of experiment layout in the tracking volume
  - improvement of tracking algorithm
  - investigation of alternative triggering strategies (scintillator based trigger?)
  - development of suitable ECAL and readout (fast clear?)
  - design and test of suitable HCAL



- measurements needed for solid background estimates
  - phase 1: high-rate test to establish the (non)relevance of VCS
  - phase 2: high-rate test with hadron counter → improve prediction for EN and PN interactions
  - phase 3: first dark photon search run

collaborators welcome!