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COSPT MEETING

THE LOHENGRIN EXPERIMENT AT ELSA

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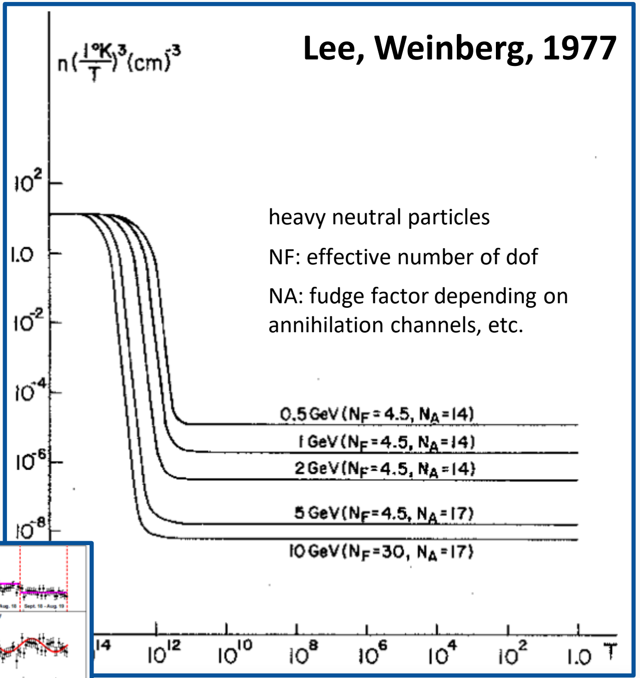
J. Heinrichs, J. Kaminski, M. Lupberger, T. Schiffer, P. Schwäbig, M. Schürmann, S. Vashishta

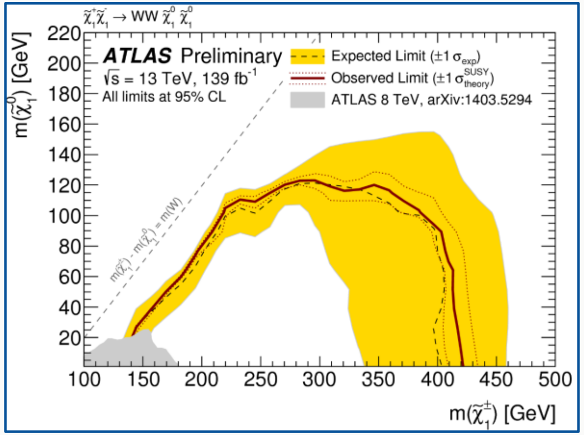
OUTLOOK

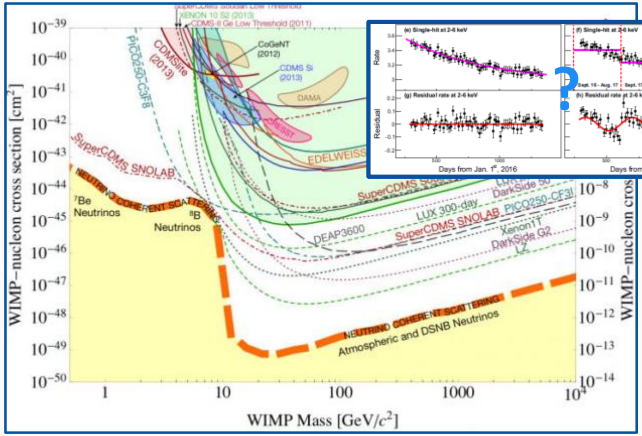
- dark sectors with a dark photon as an explanation for dark matter
- production of dark photons through dark bremsstrahlung
- physics potential of a fixed target experiment at the ELSA accelerator in a dark photon benchmark model
- the Lohengrin experiment
  - principle setup and discovery reach of the experiment
  - technological options
  - next steps

DARK MATTER - WIMPS?



- 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

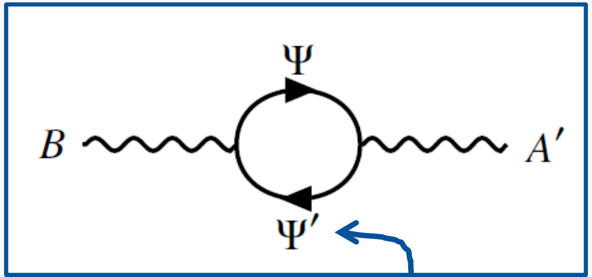
- dark matter from light particles?
  - need a fitting interaction between dark matter and SM sector
  - models with vector or scalar portals → can tune interaction strength to get right relic density
- one of the more simple models: massive boson from spontaneously broken $U(1)_D$ as portal → "dark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

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

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

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

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



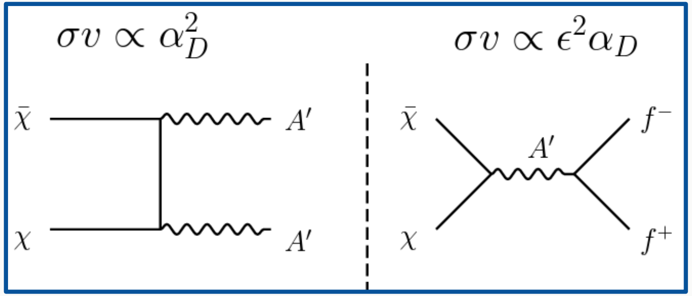
some heavy particles charged under both $U(1)_D$ and $U(1)_Y$

$$m^2_A = 0$$

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

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

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

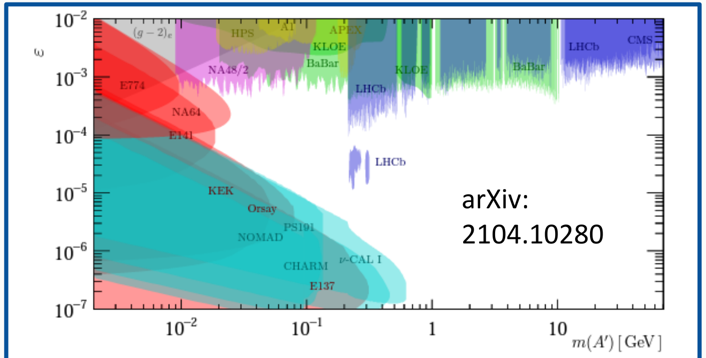
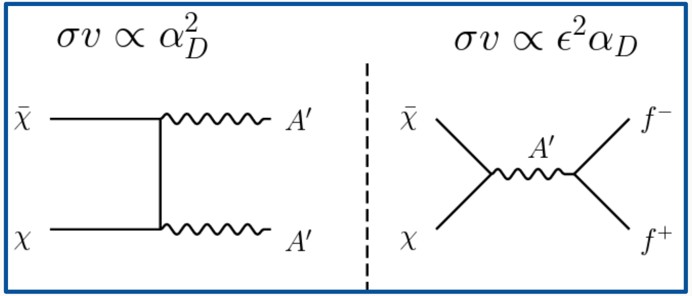


Figure 3

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.

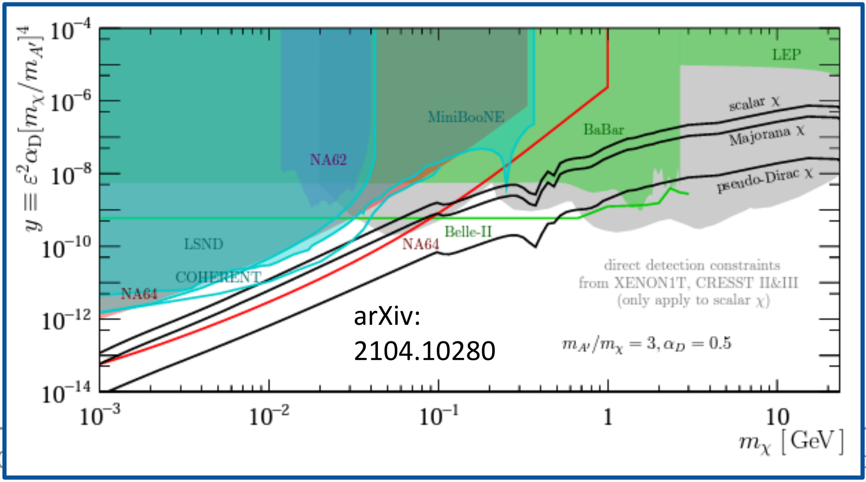
- prompt A' decays:
  - irreducible $\gamma \rightarrow$ ff background $n(A' \to \ell^+\ell^-) = \varepsilon^2 n(\gamma^* \to \ell^+\ell^-)\mathcal{F}(m_{A'})/2\Delta m$
- displaced A' decays
  - $\tau_{A'} \propto [\varepsilon^2\, m_{A'}]^{-1}$
  - beam dump experiments with baselines up to O(100m)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

DARK MATTER – DARK PHOTONS



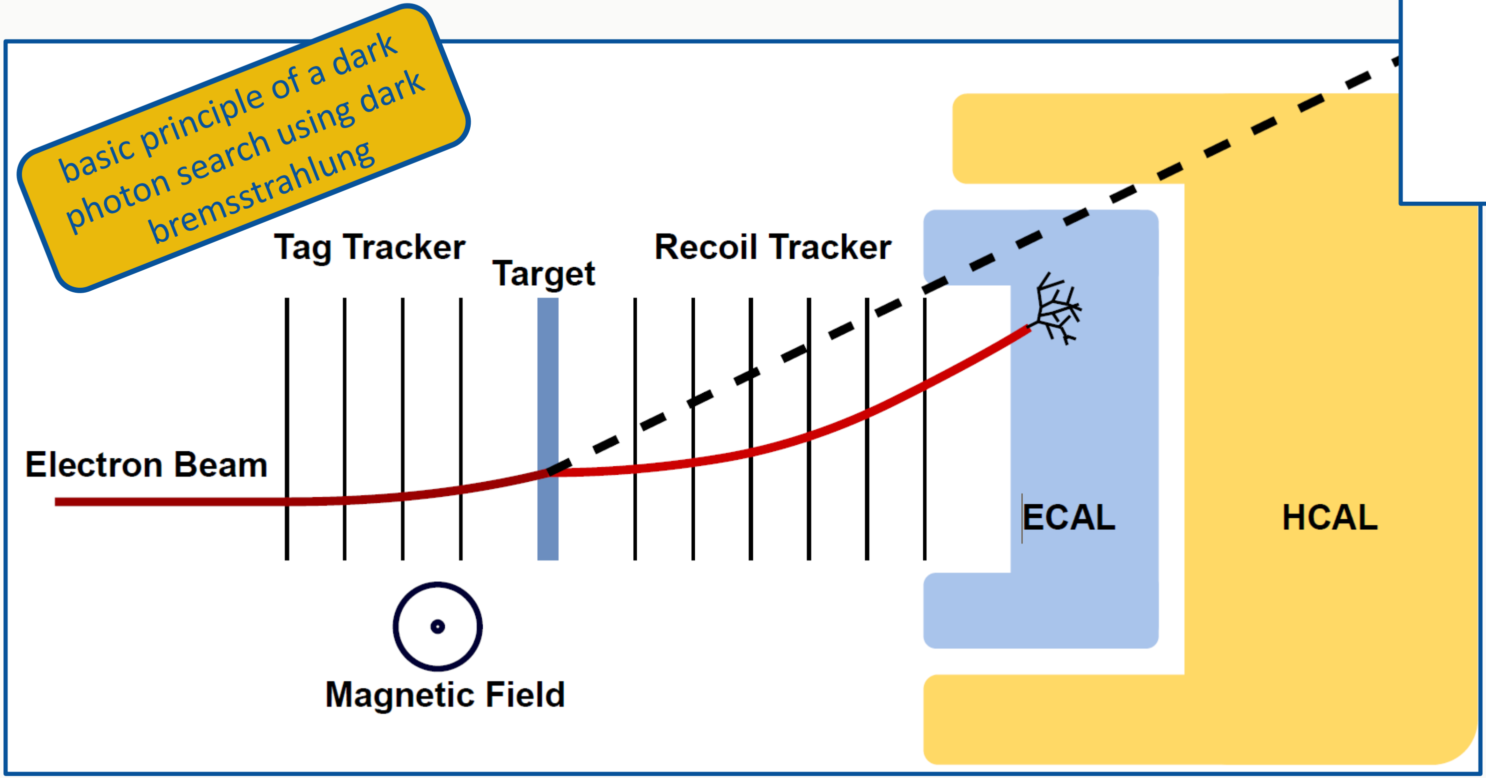
- dark photon phenomenology
  - fundamental distinction: “visible” and “invisible” dark photons
  - **“invisible” dark photons: $m_{AD} > m_\chi$:**
    - dark matter annihilation through s-channel A’ into fermions
    - once produced, dark photon and its decay products do not necessarily produce any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

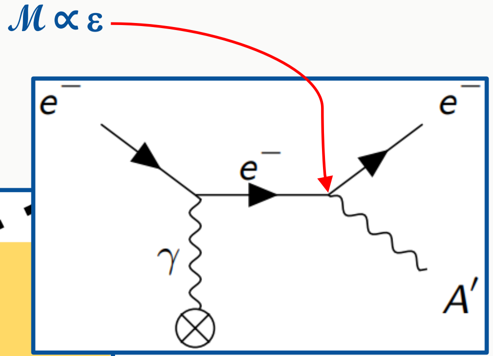
$n_{vis} / n_{invis} \propto \varepsilon^2$



- 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

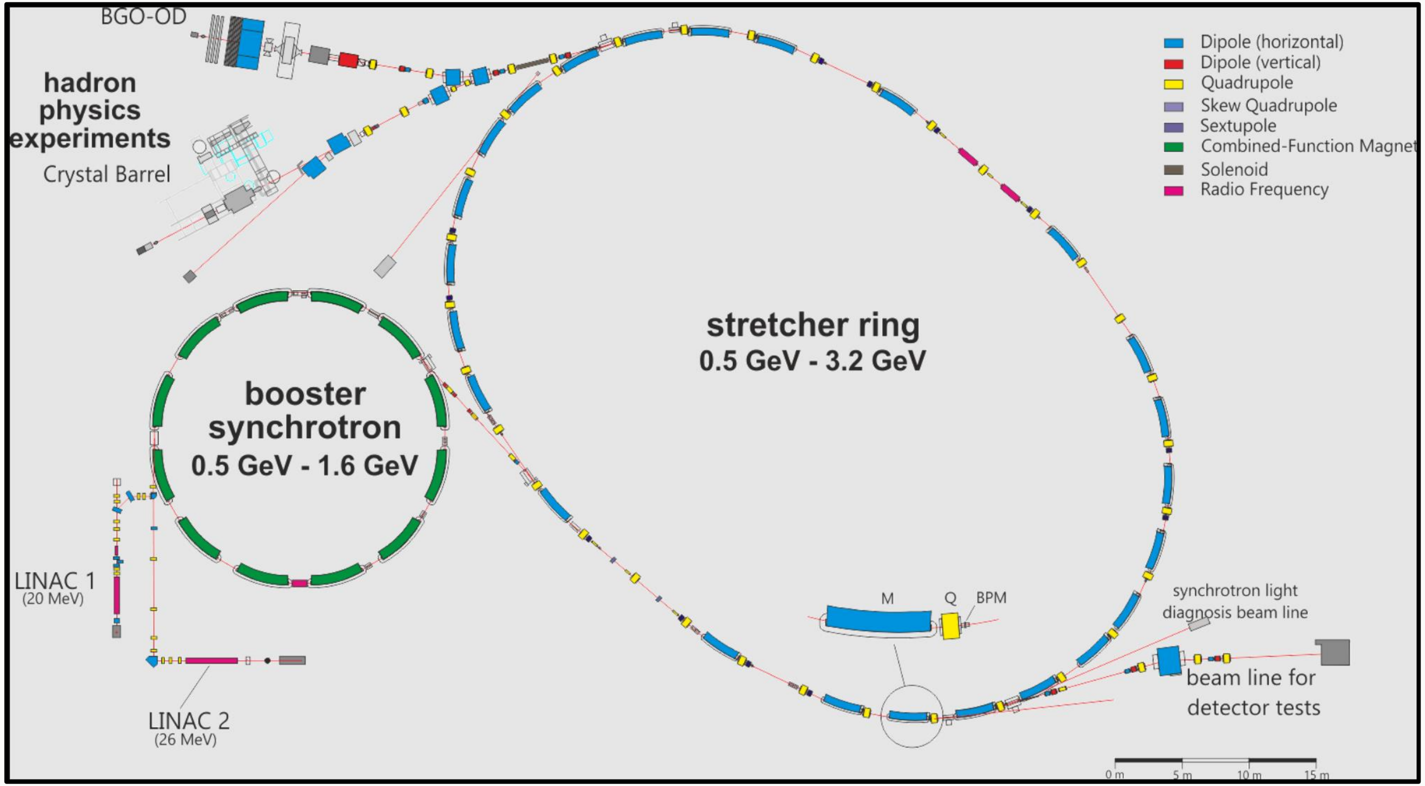
FIXED TARGET DARK PHOTON SEARCH





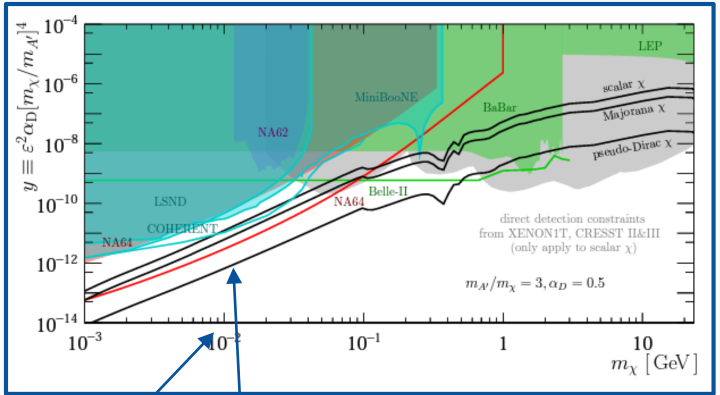
- electron beam on fixed target (~10% X0)
- dominant reaction: SM bremsstrahlung, sometimes subsequent electro-nuclear or photo-nuclear reaction
- depending on $m_{A'}$ and ε: occasional radiation of dark photon

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**

DARK PHOTON PRODUCTION AT ELSA



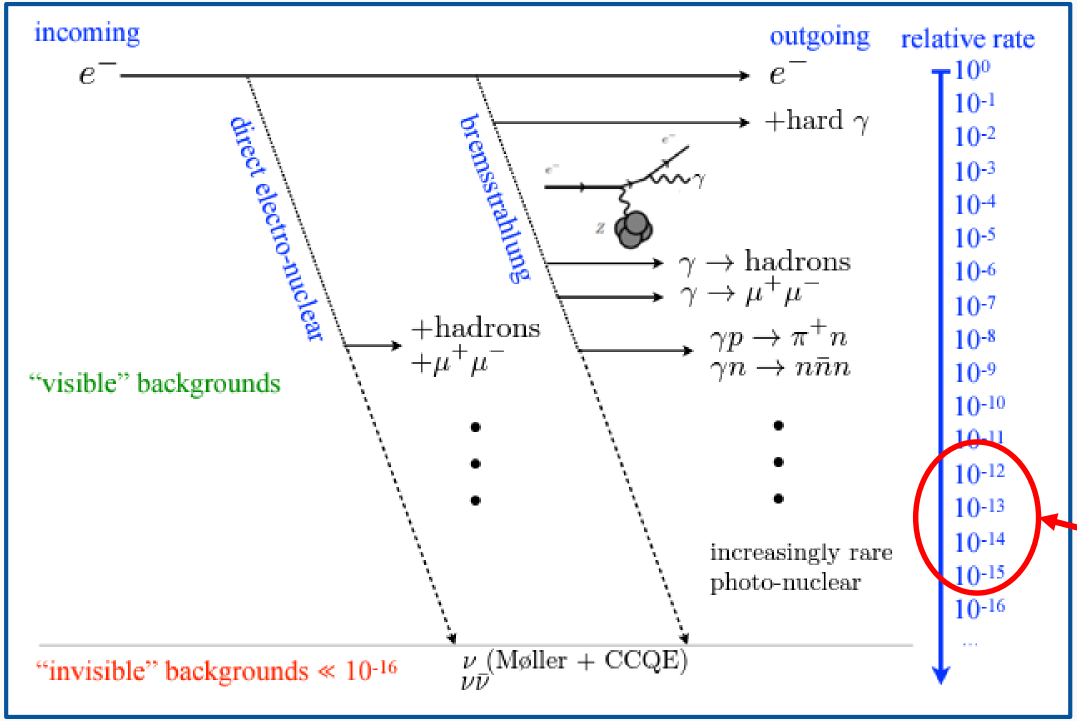
– how many electrons on target do we need (10% X0 tungsten target) to produce 1 dark photon with right "relic target properties"? (**EoT_1**)

– how many days would the experiment have to run in order to produce 100 dark photons at 100 MHz EoT rate, assuming a 50% duty cycle? (**$t_{100}2$**)

	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 hope to find dark photons at ELSA with the right properties if we can control our backgrounds!

EVENT RATES



- 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!

highly efficient photon veto is required!

TOWARDS A DP SEARCH AT ELSA

- goal posts are set
  - can we – and if yes, how – realise an experiment at ELSA that has sensitivity to light dark photons within a reasonable time period?
  - timely construction and commissioning of experiment?
    - use as much existing hardware as possible
    - simplify where possible
    - design newly required components by building on existing R&D work
  - we have studied a few aspects of such an experiment at ELSA with small team
    - basic sensitivity estimate shows that such a dark bremsstrahlung experiment at ELSA has the potential to close a sizeable gap in the dark photon parameter space!

Martin Schürmann

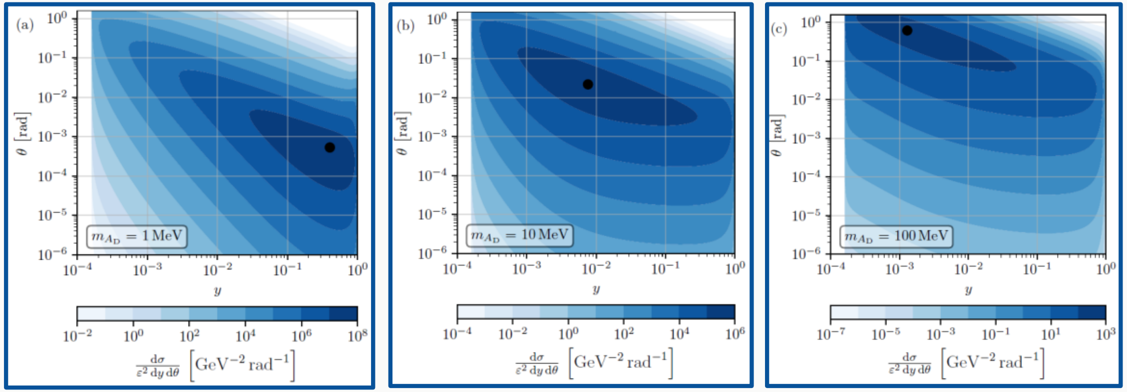
LOHENGRIN - LAYOUT AND SENSITIVITY

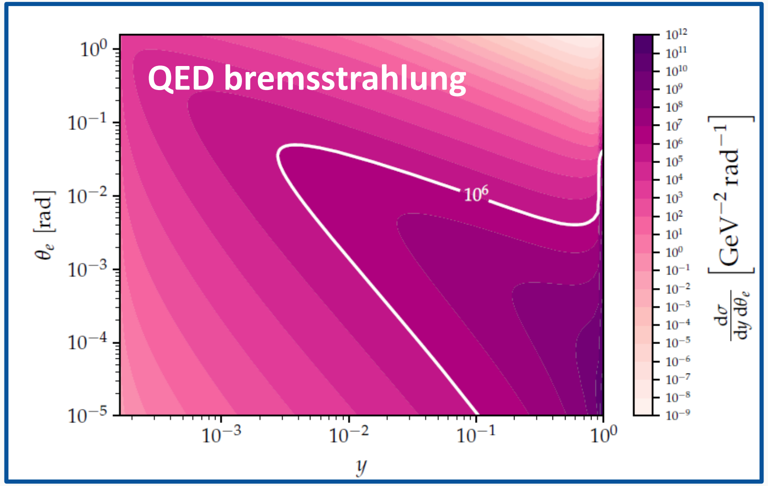
$y = E_e$ / Ebeam
$x = E_\gamma$ / Ebeam (SM only)

- "coarse-tuning" the experiment
  - using dedicated code to calculate the expected number of SM bremsstrahlung events where
    - $y \in [y_{min}; y_{max}]$
    - $\theta_e \in [\theta_{e\,min}; \theta_{e\,max}]$
    - $x \in [x_{min}; x_{max}]$
    - $\theta_\gamma \in [\theta_{\gamma\,min}; \theta_{\gamma\,max}]$

can already guess potential signal regions:

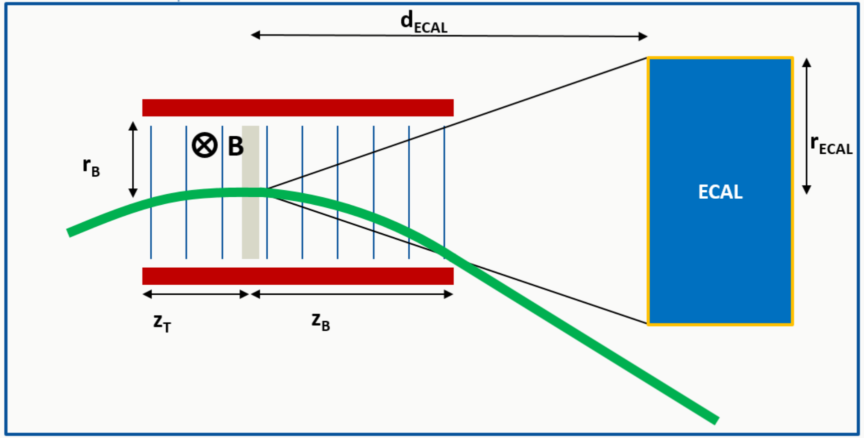
- (very) low y
- high scattering angle? → more signal events, but for fixed, low y, also more potential background events





LOHENGRIN – LAYOUT AND SENSITIVITY

- ELSA delivers electrons with an extremely narrow energy distribution (σ_E = 0.08%)
- build a basic tag tracker to identify number of electrons per extraction
- limit the readout rate of the ECAL → use strong magnetic field to bend electrons around the ECAL, use only tracking information to identify electrons in the final state



- use ECAL to measure photons and other EM interacting particles, not the electrons
  - impact of limited ECAL coverage is not entirely understood at this point
- assume there is a HCAL that can efficiently veto all forward hadrons

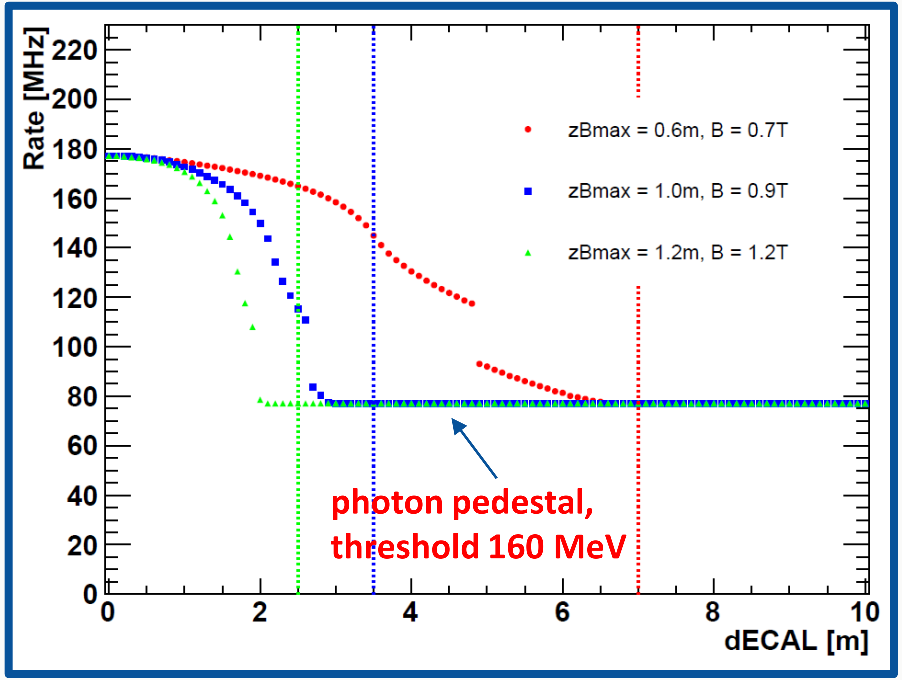
LOHENGRIN – LAYOUT AND SENSITIVITY

- decided to study 3 benchmark scenarios for a start
  - all assuming rECAL = 0.16 m

    1) zBmax = 0.6 m
       B = 0.7 T
       dECAL = 7 m

    2) zBmax = 1.0 m
       B = 0.9 T
       dECAL = 3.5 m

    3) zBmax = 1.2 m
       B = 1.2 T
       dECAL = 2.5 m



rBmax [m]	zBmax [m]	$\theta_\gamma^{max} = \theta_\gamma^{ECAL}$ [rad]	d_{ECAL} [m]	r_{ECAL} [m]	B [T]	θ_e(zBmax, y=1)	r_e(zBmax) [m]	r_e(dECAL) [m]
0.1	0.6	0.165	7	1.167	0.7	0.039	0.012	0.264
0.1	1.0	0.100	3.5	0.350	0.9	0.084	0.042	0.254
0.1	1.2	0.083	2.5	0.208	1.2	0.135	0.081	0.258

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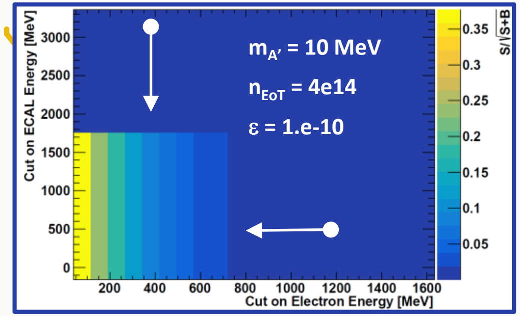
LOHENGRIN – LAYOUT AND SENSITIVITY

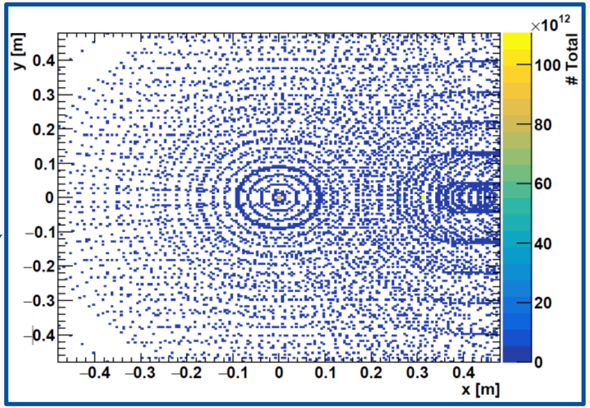
- **tentative Signal Region** defined using
  - outgoing electron momentum (p and θ)
  - energy of photons that hit the ECAL

  - **<u>Lohengrin SR:</u>**
    - **very** tight cut on outgoing electron energy
    - moderate cut on ECAL energy
    - ECAL covering a large polar angle crucial for efficient veto on fake missing E backgrounds

  - the study was conducted using coarsely binned cross-sections
    - estimates are 0^{th} order estimate



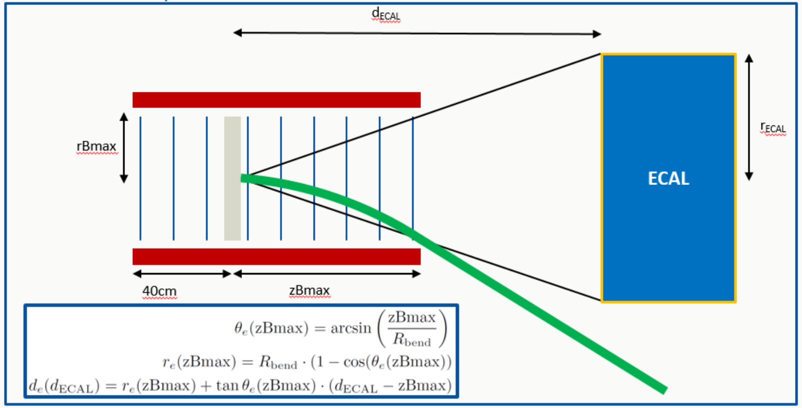
rECAL	0.16	0.24	0.32
SMBG	11506	293	48
S for S/sqrt(S+B) = 1	108	18	7



photons and electrons hitting the ECAL in Benchmark 2

LOHENGRIN – SENSITIVITY REACH ESTIMATE

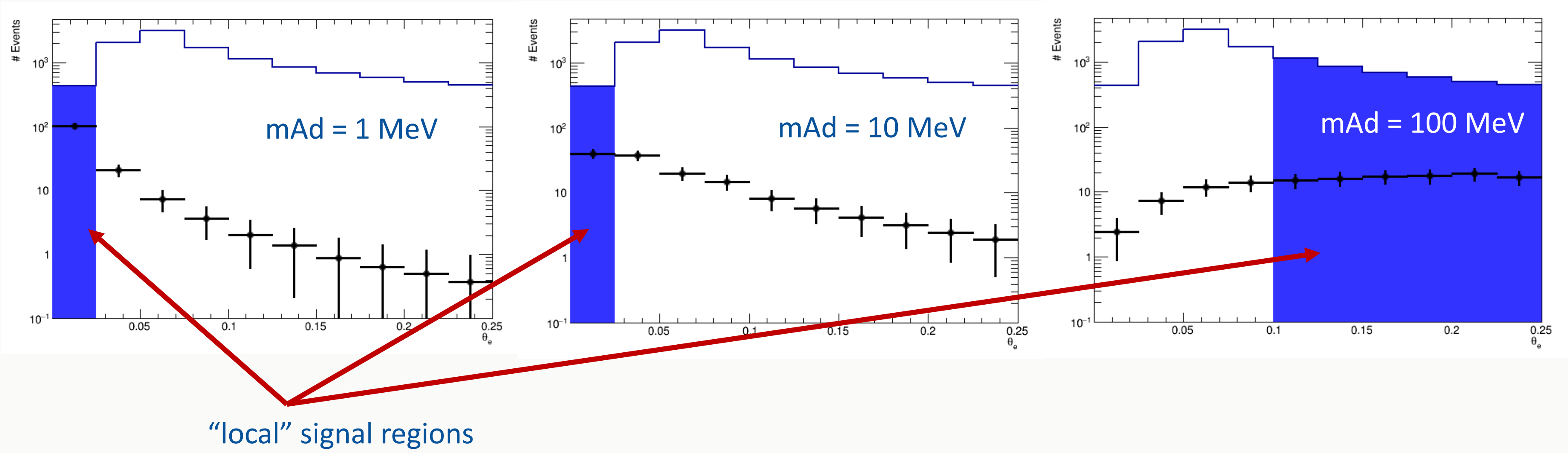
- results for benchmark 2
  - mixture of optimistic and conservative choices
- tentative signal region
  - y < 0.024
    - E_e < ~ 75 MeV
    - bending radius in 0.9 T magnetic field R = 0.5m
    - difficult!
  - E_{ECAL} < 640 MeV
  - possibly a mA' dependent, two-sided cut on θ_e
    - "global" SR without this cut
    - "local" SR including this cut



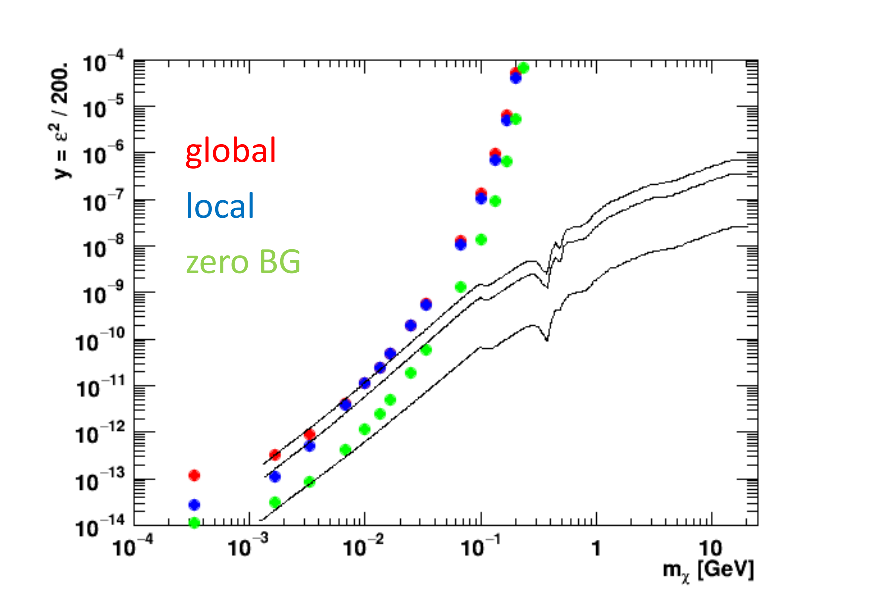
rBmax = 0.1 m
zBmax = 1.0 m
dECAL = 3.5 m
rECAL ∈ (0.16 m, 0.24 m, 0.36 m)
B = 0.9 T

LOHENGRIN - SENSITIVITY REACH ESTIMATE

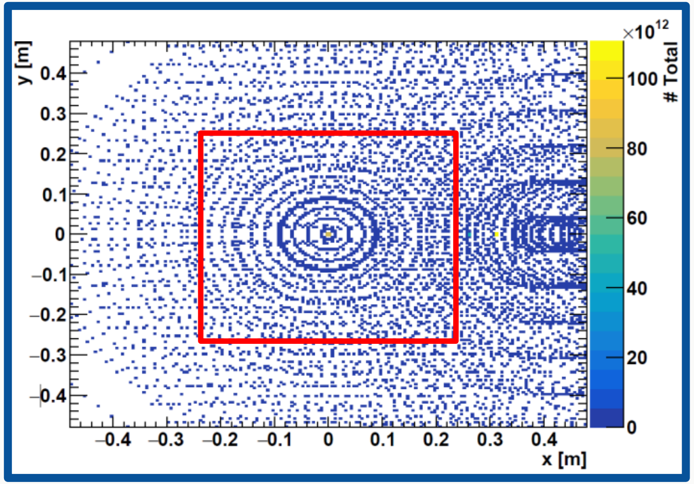
- benchmark 2, rECAL = 0.16m, various DM masses
  - ε^2 set to value for which $S/\sqrt{(S+B)} = 1$ for the $\theta_e < 0.25$



LOHENGRIN - SENSITIVITY REACH ESTIMATE

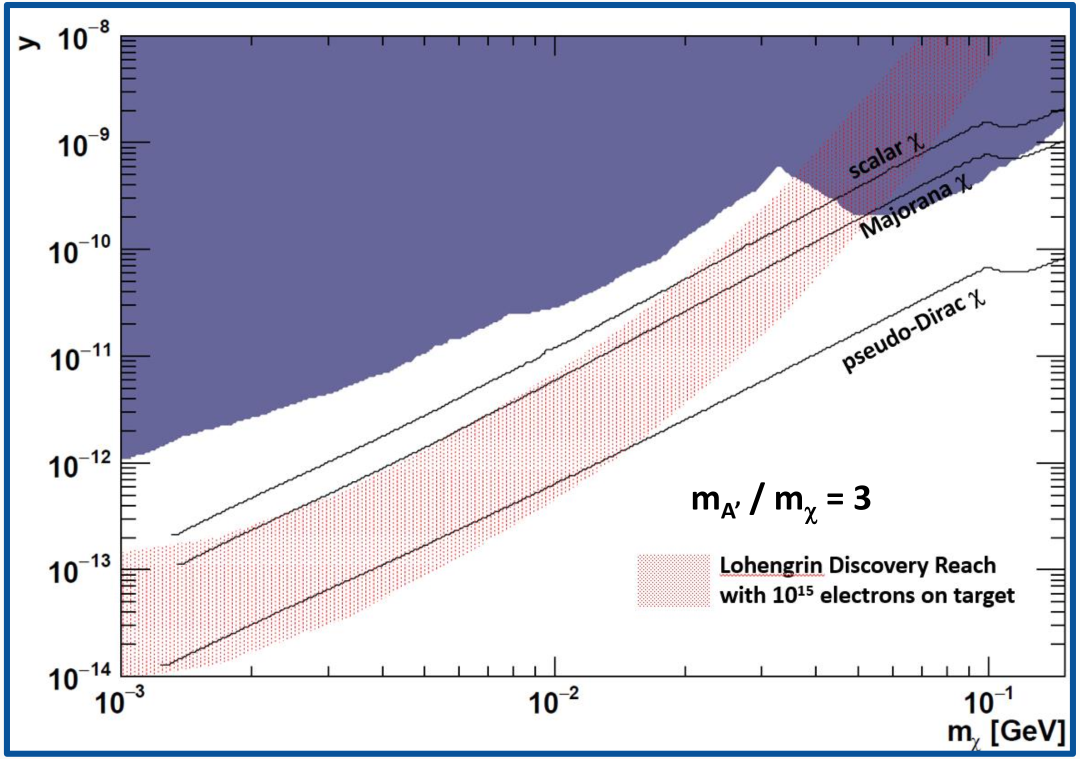


Benchmark 2



example for sensitivity with a mid-sized ECAL (24x24 cm^2) in benchmark 2 assuming 4x10^{14} EoT

LOHENGRIN - SENSITIVITY REACH ESTIMATE



- depending on how well we meet our targets and how many electrons on target we can collect, we expect that Lohengrin has the potential to close the gap between existing limits and the relic density target for dark photon masses of 1 MeV – 40 MeV for scalar and Majorana dark matter, and possibly even for pseudo-Dirac dark matter

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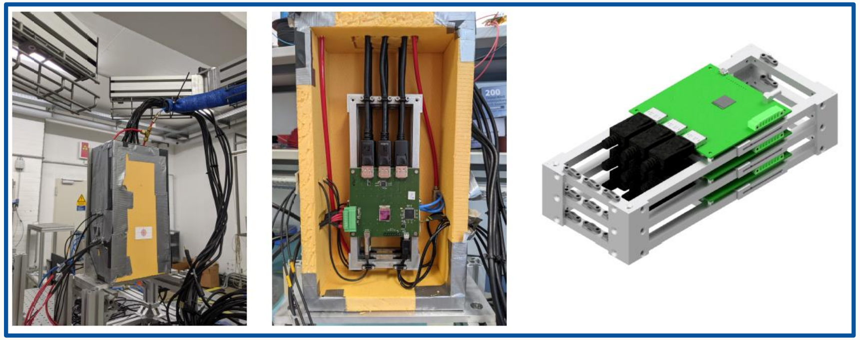
LOHENGRIN - RATE TESTS WITH TIMEPIX3 MINITRACKER

Leonie Richarz
Markus Gruber
Tobias Schiffer

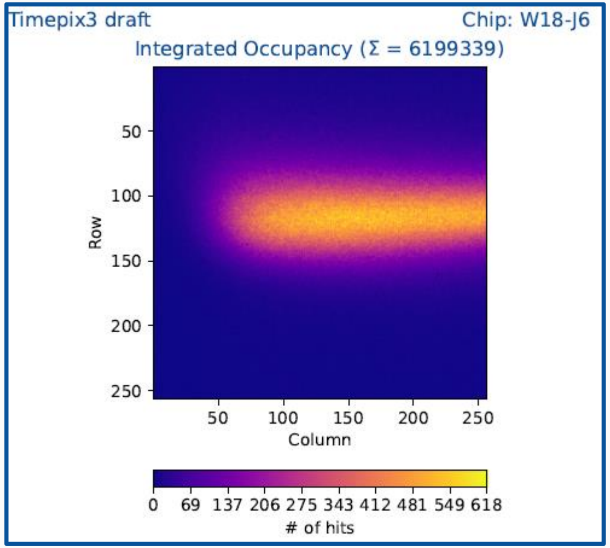
- feasibility study for the tracker:
  - production of a mini-tracker using untriggered TimePix3 silicon modules with beam telescope
    - used in ELSA testbeam area
    - rate capabilities of TimePix3 tested
    - first analysis of multiple scattering done



LOHENGRIN - RATE TESTS WITH TIMEPIX3 MINITRACKER

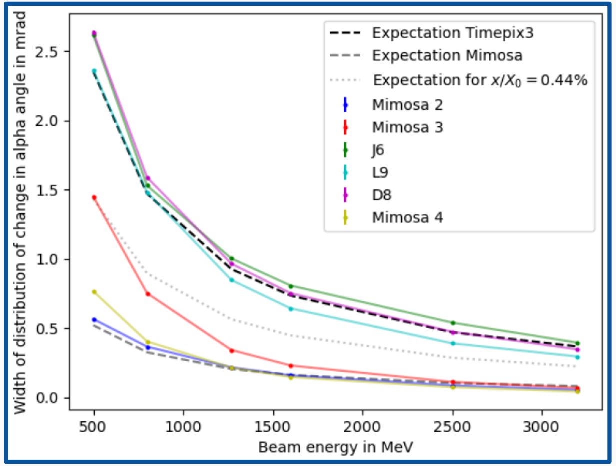
Leonie Richarz
Markus Gruber
Tobias Schiffer

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



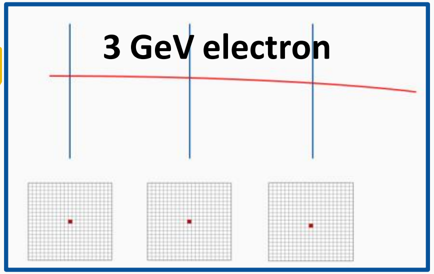
2.5 GeV electron beam, 100 kHz

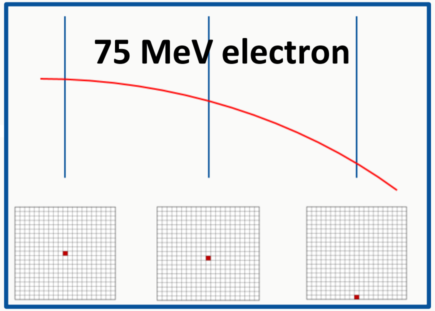
rate in kHz	energy in GeV	length	settings	remarks
2.00	2.50	10 min	nominal	ok
10.00	2.50	7 min	nominal	ok
50.01	2.50	2,5 min	nominal	ok
100.60	2.50	30 s	nominal	ok
500.00	2.50	30 s	nominal	ok
1000.00	2.50	30 s	thr: 4 150	ok
1000.00	2.50	30 s	thr: 4 200	some errors
750.00	2.50	30 s	nominal	ok
875.00	2.50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



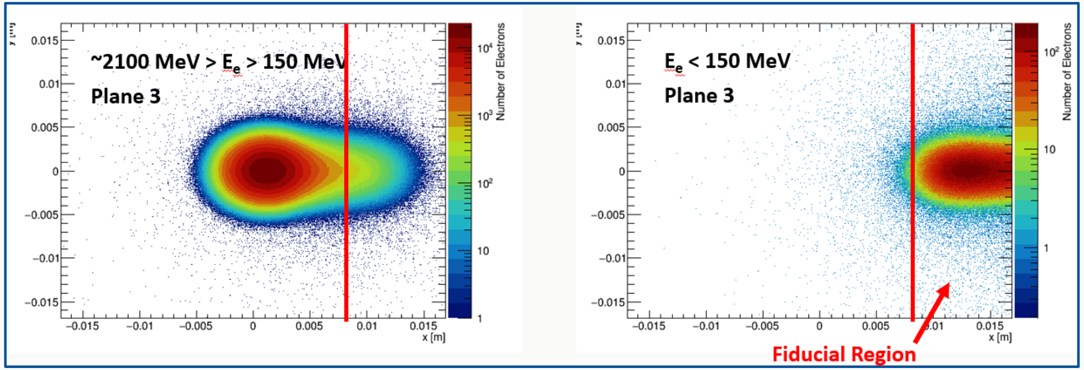
- tests with Timepix3 minitracker with and without ANEMONE telescope
  - lower than expected maximum rate (bottleneck in software)
  - tracking resolution not perfectly understood yet (MS? track reco?)

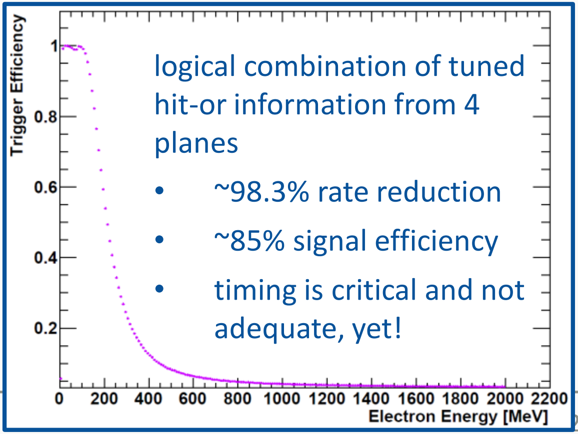
LOHENGRIN – ULTRAFAST LOW MOMENTUM TRACK TRIGGER





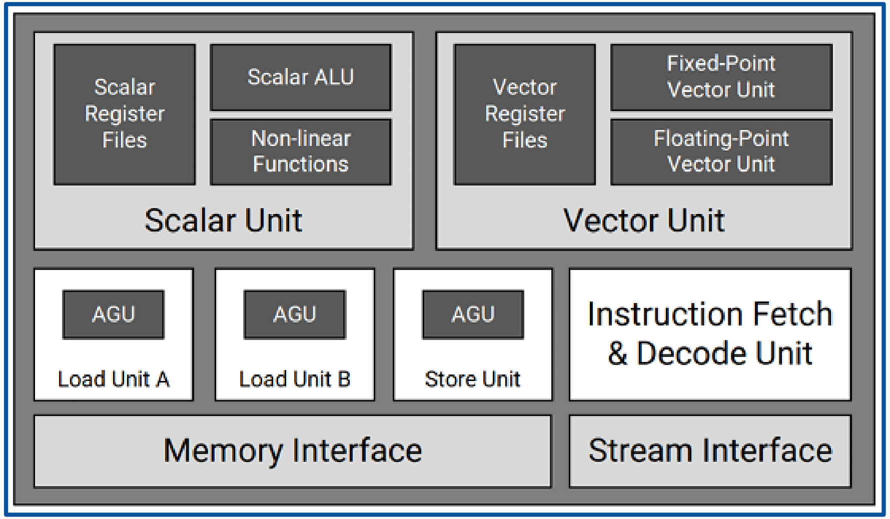
- low energy electrons → can expect significant impact from multiple scattering
  - ultrathin tracking detector required
- 100 MHz is too much for the ECAL → use "low momentum track trigger"
  - ultrafast tracking detector required
- looking into a (significant) upgrade of the TJ Monopix2 ASIC
  - ASIC provides a hit-or that can be connected to a configurable part of the pixel matrix
  - a simple, coincidence based hit-or trigger can be used to significantly reduce the readout rate for all detectors

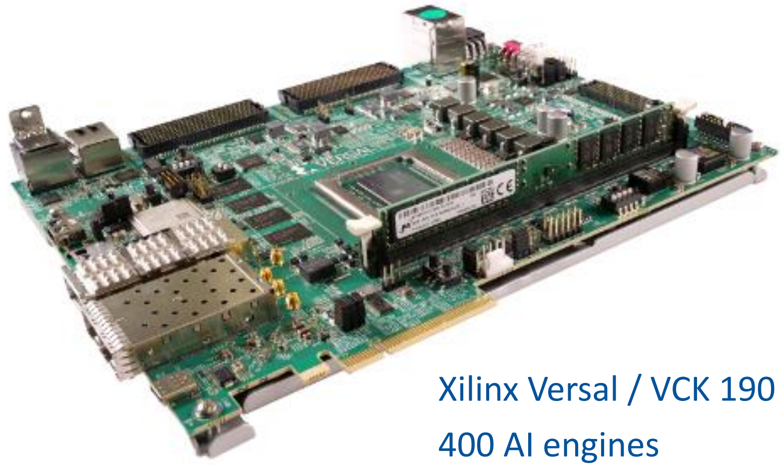




LOHENGRIN - ADVANCED HARDWARE TRACK TRIGGER

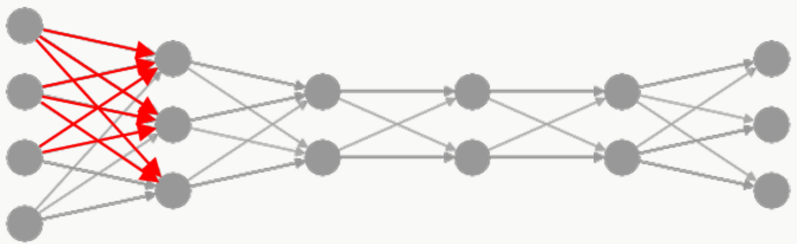
- use of AI engine driven track trigger for Lohengrin 2nd stage?
  - pattern recognition for multi-track events
  - implementation of track building and track fitting, e.g. Kalman filter





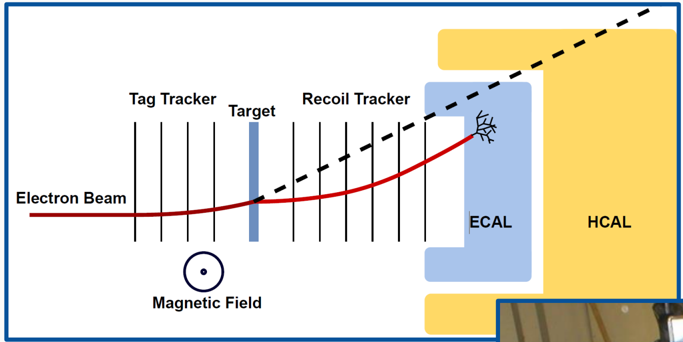
Xilinx Versal / VCK 190

400 AI engines

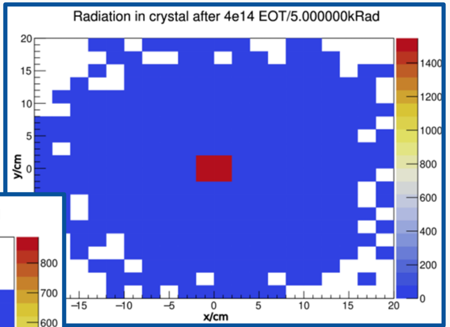


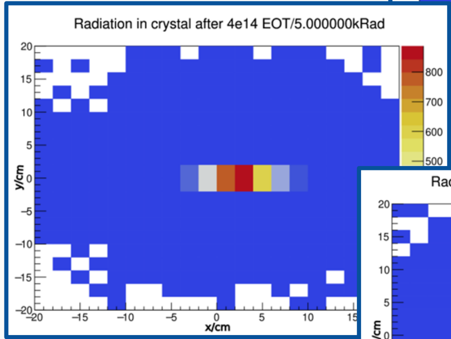
Jan Heinrichs
Christoph Schmidt

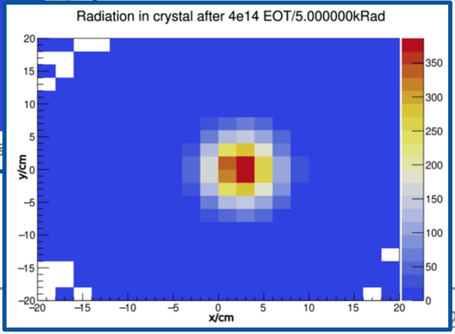
LOHENGRIN - ECAL

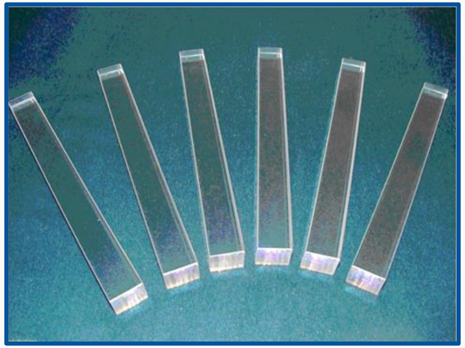


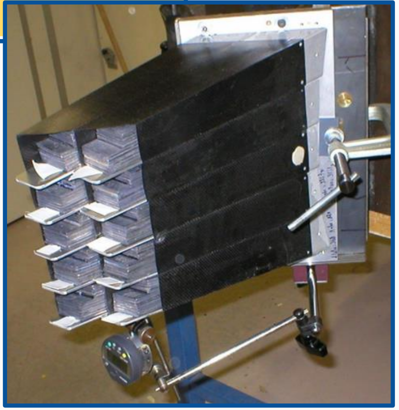
- second detector of interest: electromagnetic calorimeter
  - ECAL from $PbWO_4$ crystals?
    - 500 kHz readout rate achievable
    - radiation hardness ~50 Gy











assuming a B-field of 0.5 T

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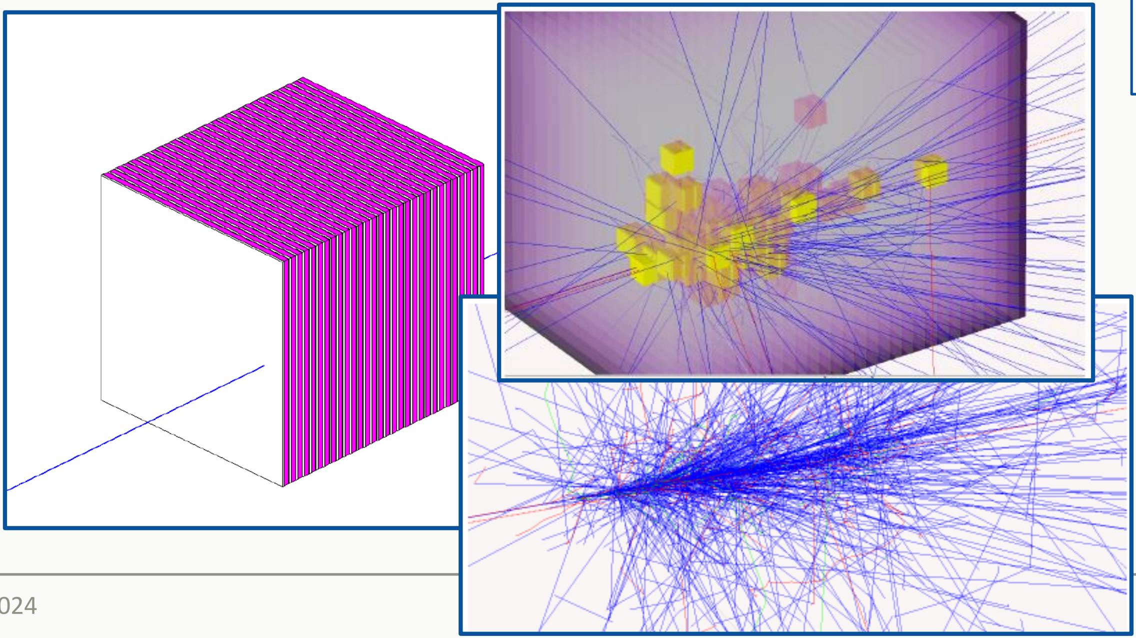
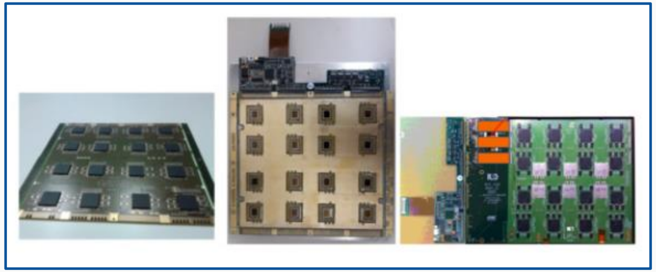
LOHENGRIN - ECAL

Jan Heinrichs
Dirk Zerwas
Roman Pöschl
Jihane Maalmi
Dominique Breton

- implementation of ECAL in simulation: CALICE
  - CALICE ECAL looks like a promising candidate for the Lohengrin ECAL
  - inclusion of a simple 15 layer ECAL in the Lohengrin simulation

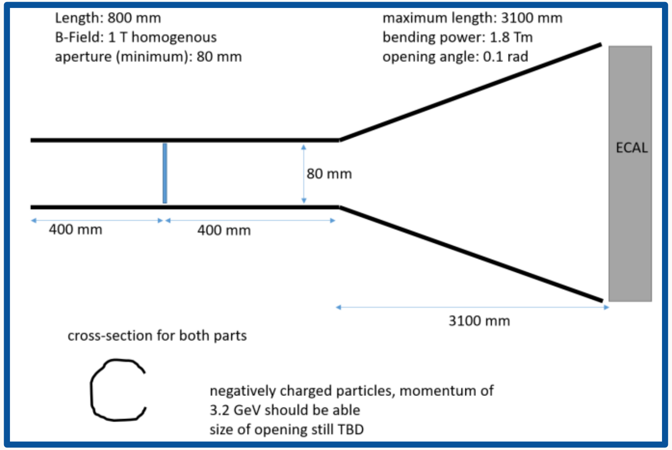


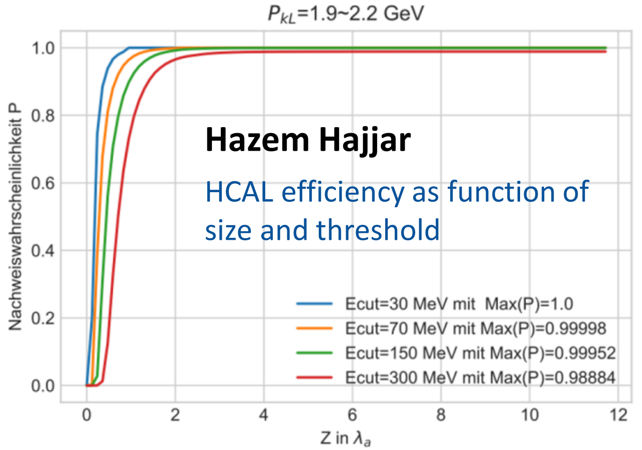


- 5.5 x 5.5 mm2 silicon pixels
- modular design, 16 readout chips per ~16x16 cm2 plane
- chips can buffer integrated readout data for some time
- implementation of a “clear command” for use of Lohengrin DAQ strategy under study

NEXT STEPS

- implementation of ACTS in Lohengrin tracking
  - development of low momentum energy tracking algorithm?
- closer look at the manget system that is required for Lohengrin
  - permanent iron dominated design might meet all requirements
- feasibility study for CALICE SiW ECAL
  - rate capabilities (beam test at ELSA)
  - readout logic and implementation of fast clear based on trigger
- detailed study for HCAL requirements
  - moderately sized HCAL might be enough for efficient veto
- derivation of detailed requirements for tracker ASICs
  - number, delay, shape of hit-or signal
  - timing analysis of tracking information





Hazem Hajjar

HCAL efficiency as function of size and threshold

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SUMMARY

- Lohengrin experiment at ELSA motivated by dark sector searches
  - physics potential reaches beyond dark photon models
- sensitivity is expected to surpass existing limits and be competitive with other planned experiments (e.g. LDMX)
- powerful tracking detector could enable the experiment using existing calorimeters with minimal(?) modifications