UNIVERSITÄT BONN

SECOND DMLAB MEETING

LOHENGRIN EXPERIMENT AT ELSA

P. Bechtle, K. Desch, H. Dreiner, O. Freyermuth, M. Gruber, M. Hamer,
J. Heinrichs, J. Kaminski, M. Lupberger, T. Schiffer, P. Schwäbig, M. Schürmann

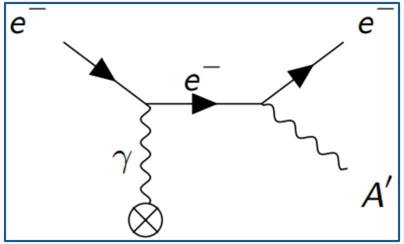
LOHENGRIN IN A NUTSHELL

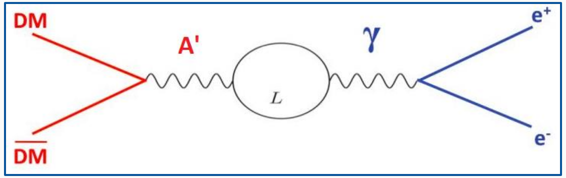
- proposal for a light dark matter search experiment at the ELSA accelerator in Bonn
- sensitive to light dark photons coupling to the SM by kinetic mixing
- inspired by the LDMX experiment, following a different triggering strategy
- production of dark photons through bremsstrahlung by electrons when scattered off a fixed target
- expected sensitivity extends into the cosmologically preferred region for dark photon masses below 100 MeV

DARK MATTER PRODUCTION AT LOHENGRIN

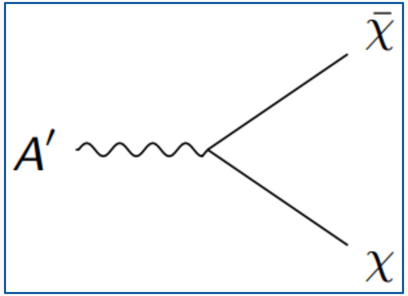
- introduce dark sector with at least one $U(1)_D$ gauge interaction
- coupling to SM through **kinetic mixing** of SM photon with DP

$$\boxed{\mathcal{L}_{DP} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu} - A'_{\mu}(\varepsilon e J^{\mu}_{\mathrm{em}} + g_D J^{\mu}_{D})}$$



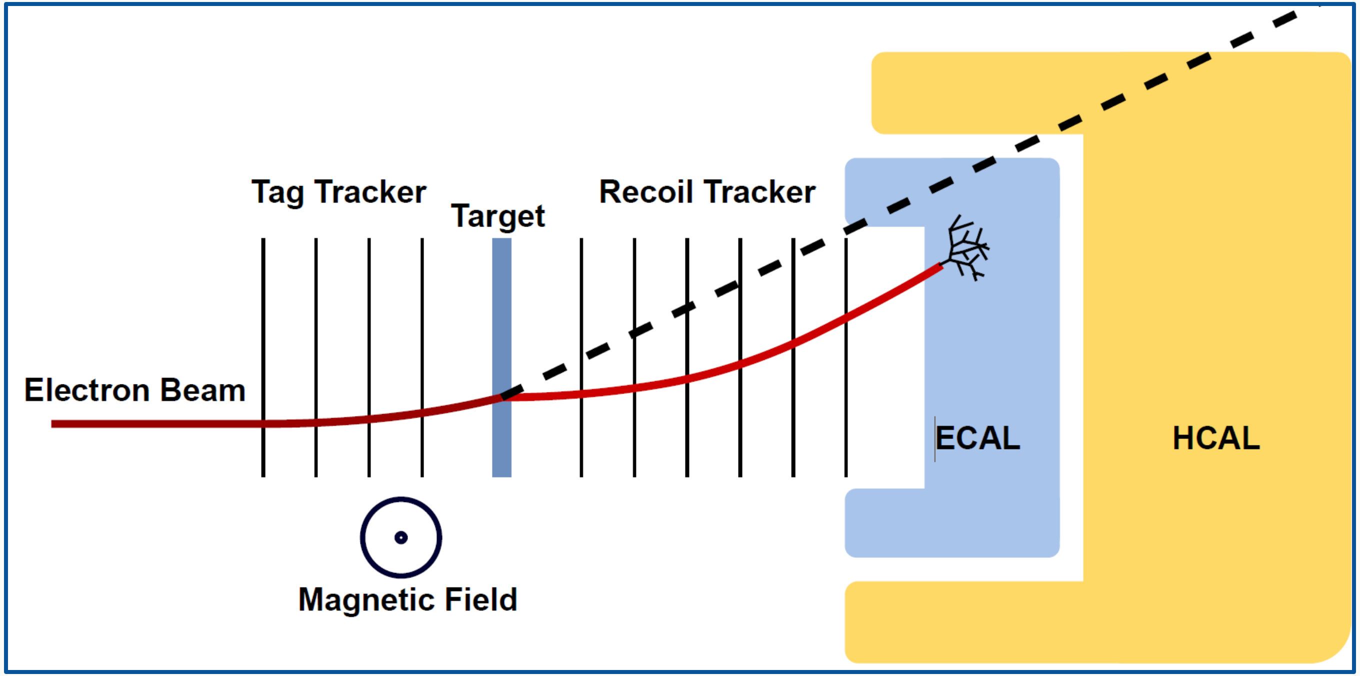


- production of dark photons through **bremsstrahlung**
- key motivation is the search for **invisible** dark photons
  - models with dark matter particles χ with $\mathbf{2m_\chi < m_{A'}}$
  - in general sensitive to models with scalar, Majorana or pseudo-Dirac χ



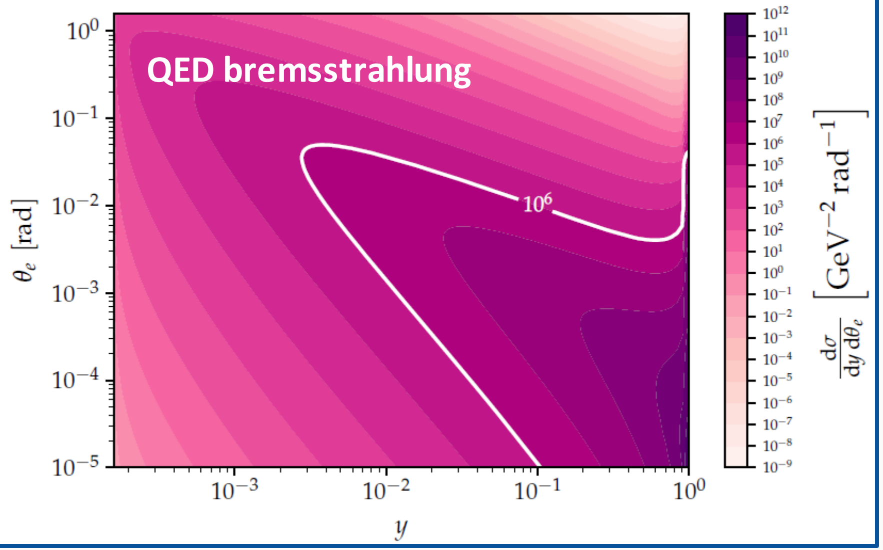
LOHENGRIN IN A NUTSHELL

- 3 GeV electron beam on thin tungsten target
- reconstruction of momentum of incoming and outgoing electron through two tracking detectors in magnetic field
- ECAL for measurement of electron energy and identification of SM bremsstrahlung events
- HCAL for hadronic veto



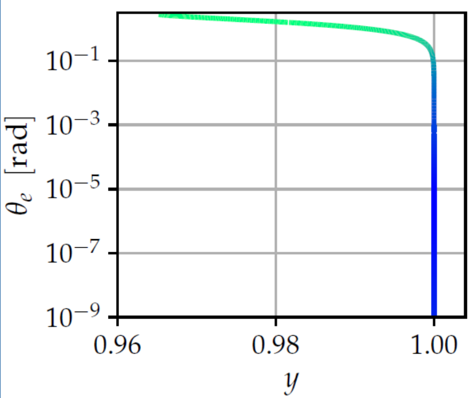
EVENT KINEMATICS

– Lohengrin – event kinematics



– studying the kinematics of the scattered electrons

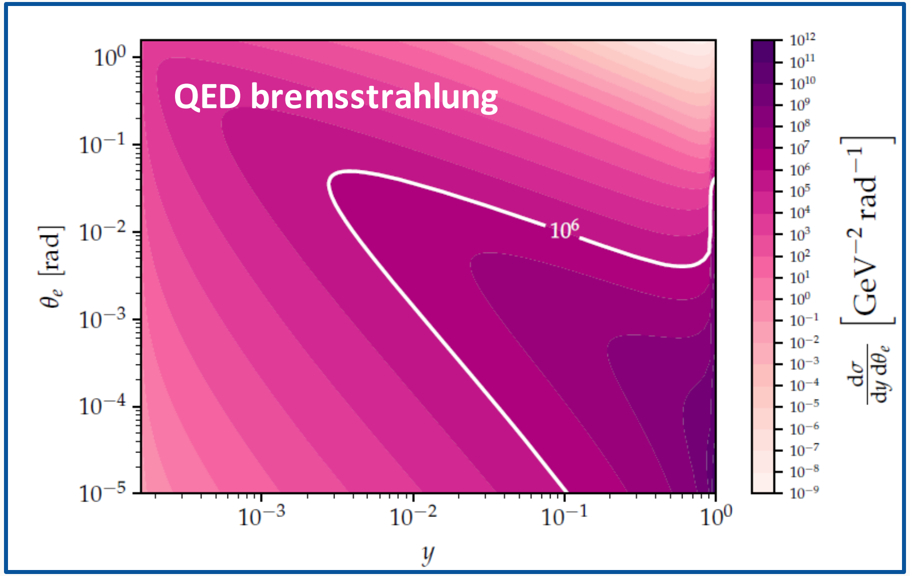
- **y: ratio of recoil electron energy to incident electron energy, y = E'/E**
- **θ_e: scattering angle of electron with respect to incident beam axis**

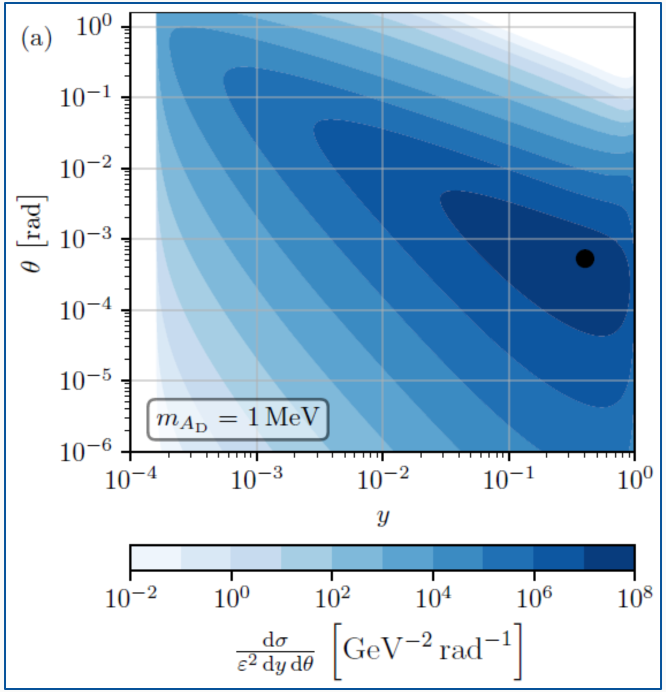


elastic scattering is efficiently vetoed by requiring a minimum energy transfer in the target

LOHENGRIN AT ELSA

- Lohengrin: a light dark matter particle search experiment at ELSA





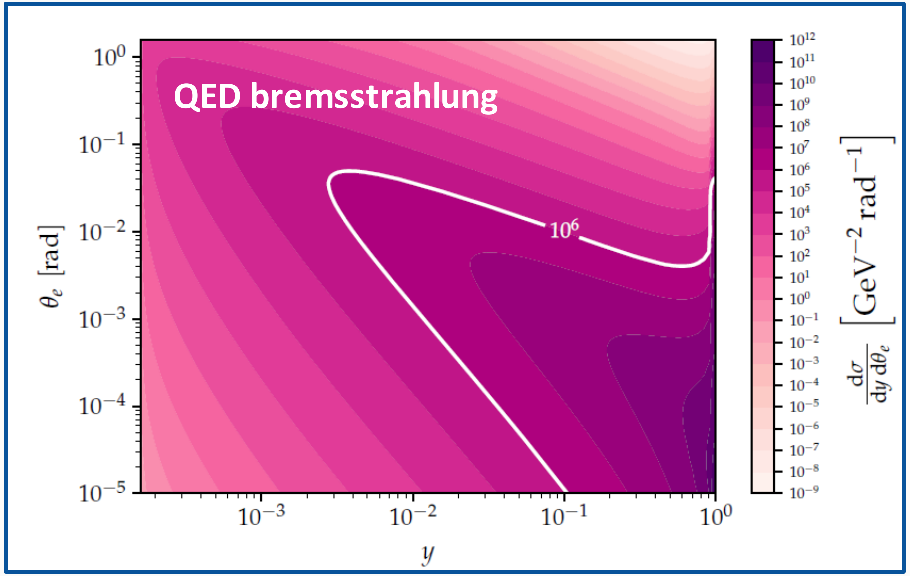
y: ratio of recoil electron energy to incident electron energy, y = E'/E

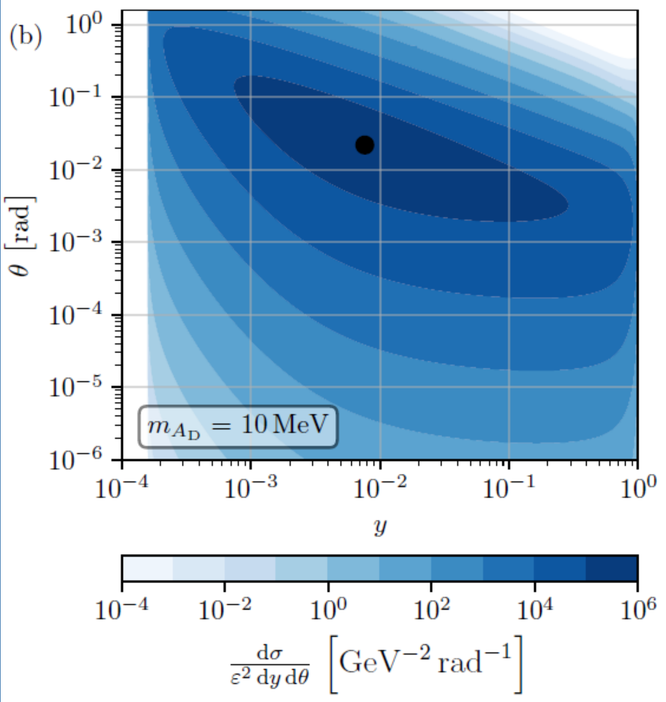
θ_e: scattering angle of electron with respect to incident beam axis

UNIVERSITÄT BONN

LOHENGRIN AT ELSA

- Lohengrin: a light dark matter particle search experiment at ELSA





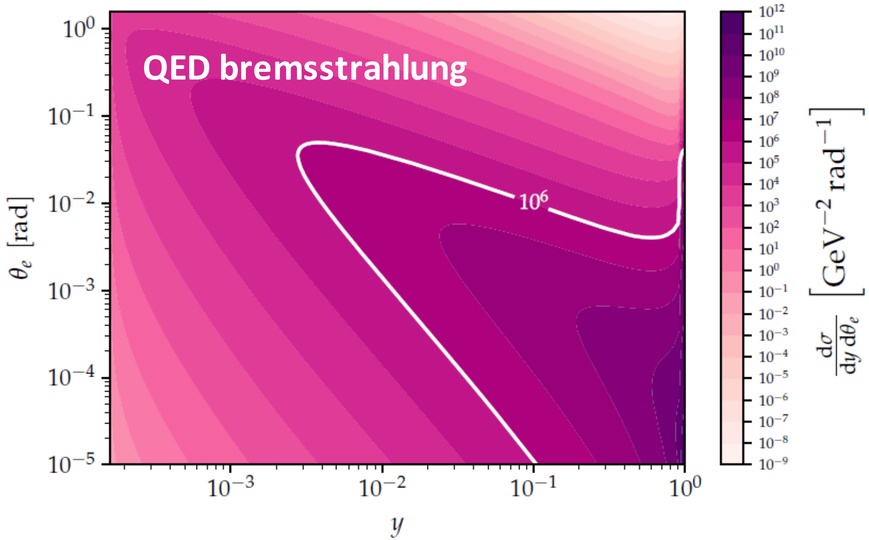
y: ratio of recoil electron energy to incident electron energy, y = E'/E

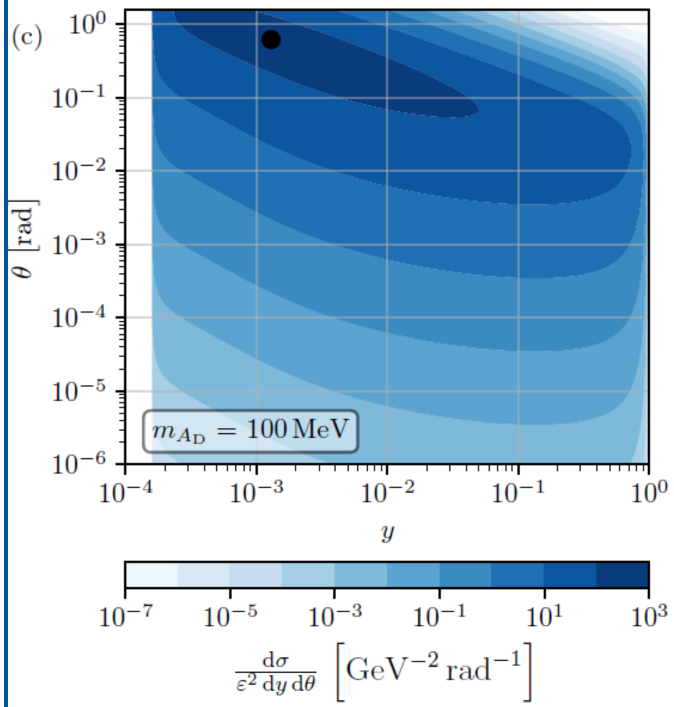
θ_e: scattering angle of electron with respect to incident beam axis

UNIVERSITÄT BONN

LOHENGRIN AT ELSA

- Lohengrin: a light dark matter particle search experiment at ELSA



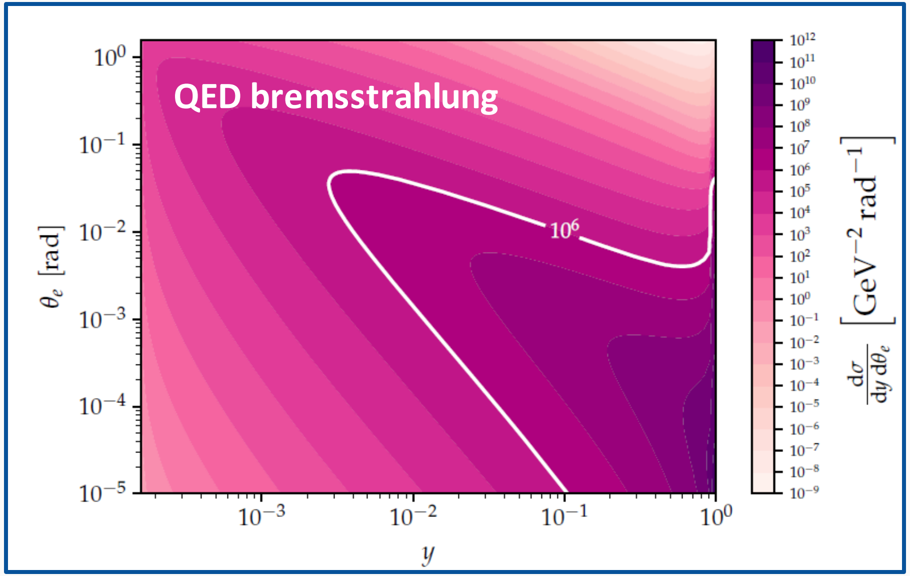


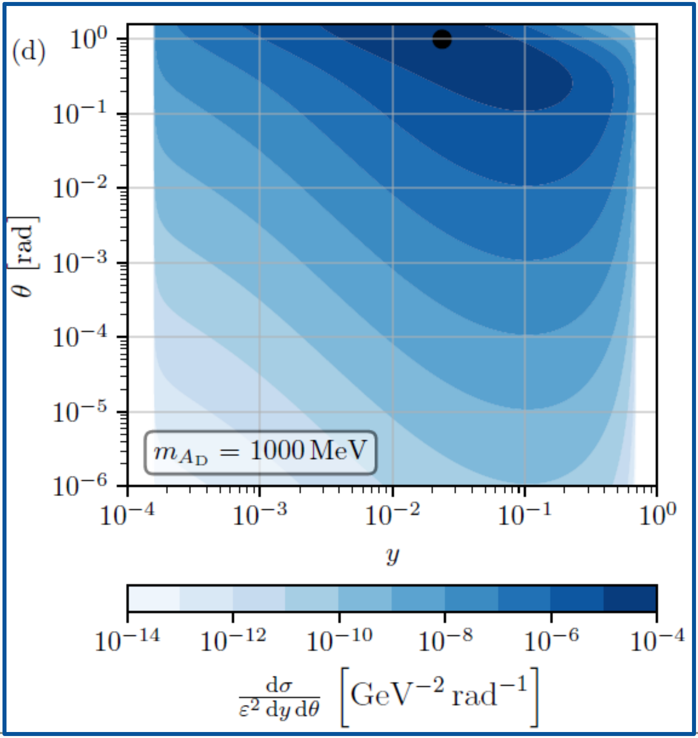
y: ratio of recoil electron energy to incident electron energy, y = E'/E

θ_e: scattering angle of electron with respect to incident beam axis

LOHENGRIN AT ELSA

- Lohengrin: a light dark matter particle search experiment at ELSA



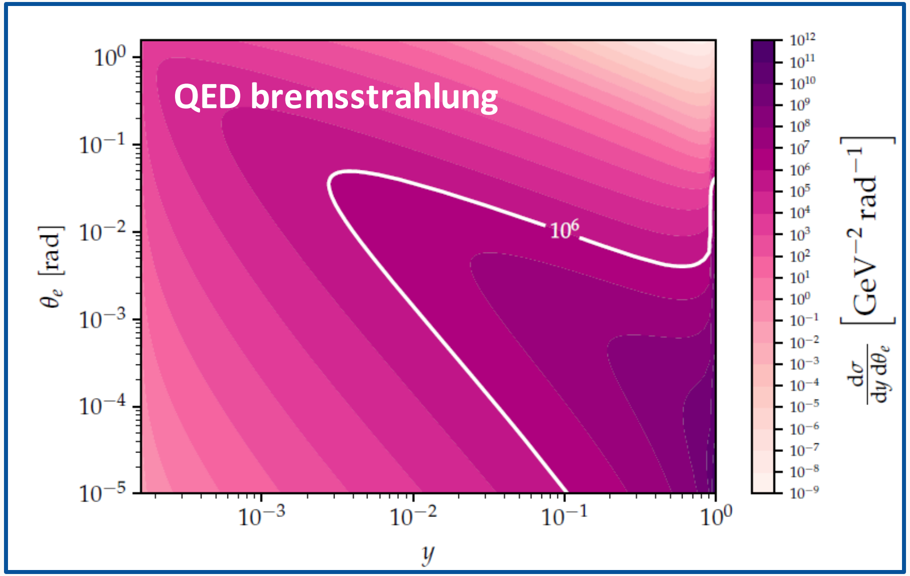


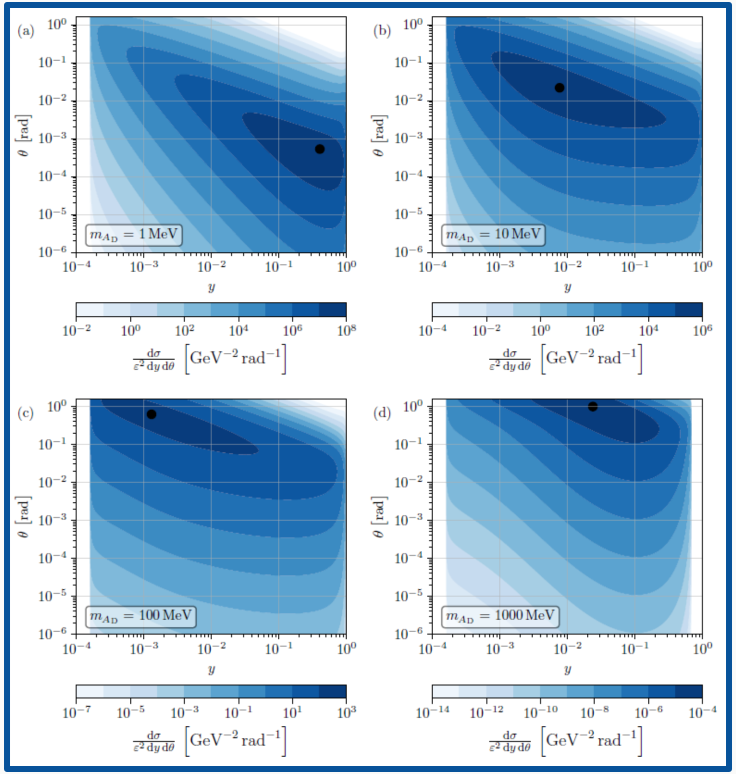
y: ratio of recoil electron energy to incident electron energy, y = E'/E

θ_e: scattering angle of electron with respect to incident beam axis

LOHENGRIN AT ELSA

- Lohengrin: a light dark matter particle search experiment at ELSA





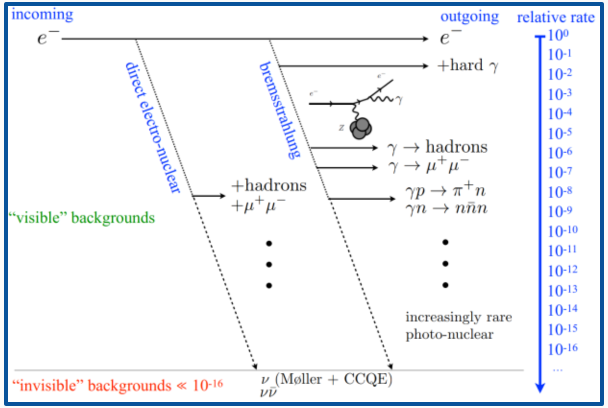
y: ratio of recoil electron energy to incident electron energy, y = E'/E

θ_e: scattering angle of electron with respect to incident beam axis

Martin Schürmann,
Jan Heinrichs

FIRST STUDIES OF BACKGROUNDS

- contamination of signal region by hadronic backgrounds
  - photo-nuclear interactions in target and/or calorimeter
  - electro-nuclear reactions
- invisible backgrounds (neutrinos)
- trying to understand requirements on HCAL for efficient background rejection

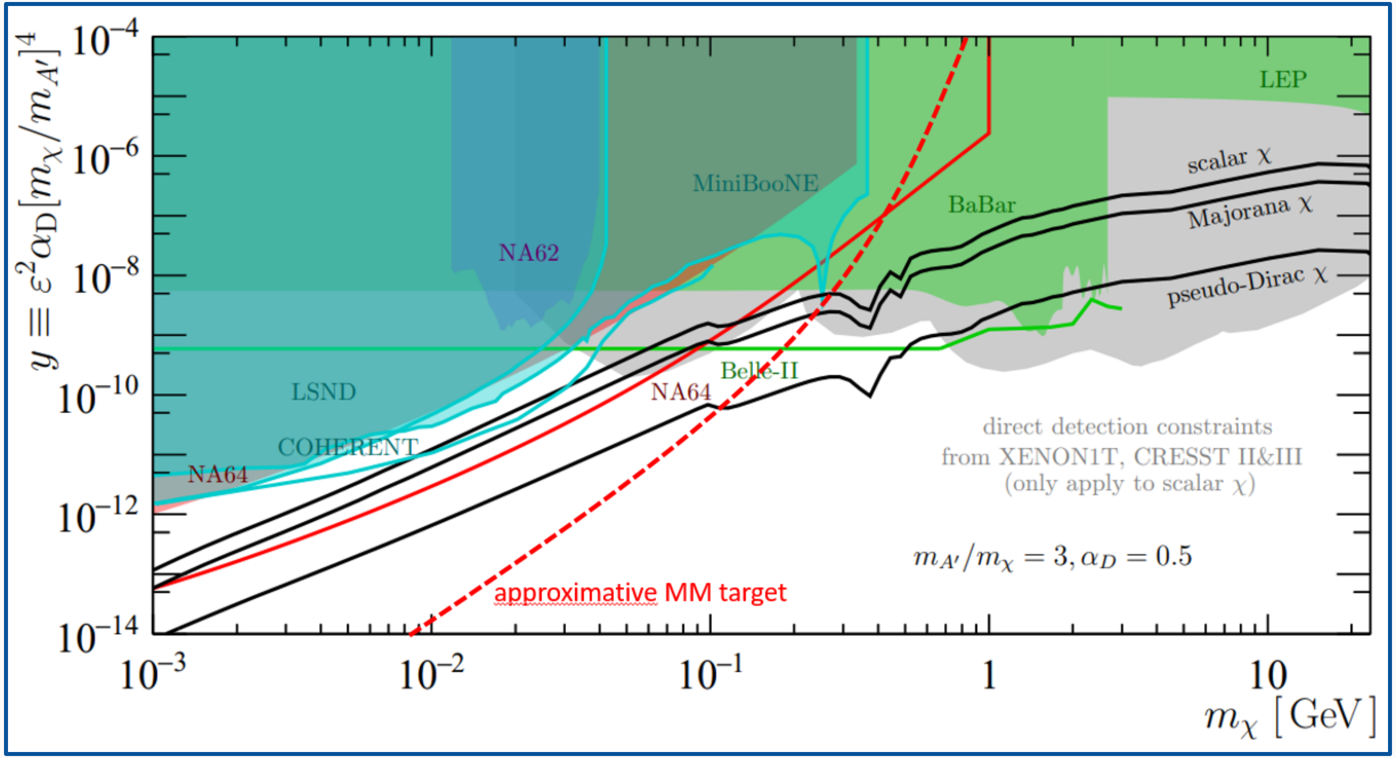


taken from: arxiv:1808.05219

Electro- and subsequent photonuclear Processes w/ psudoscalar meson and baryon octet			
$\gamma^\star N \to \mathcal{B}$	$\gamma^\star p \to p$		
	$\gamma^\star n \to n$		
$\gamma^\star N \to \phi\mathcal{B}$	$\gamma^\star p \to \pi^0\ p$	$\gamma^\star p \to \eta\ p$	$\gamma^\star p \to K^0\ \boxed{\Sigma^+}$
	$\gamma^\star p \to \pi^+\ n$		$\gamma^\star p \to \boxed{K^+}\ \Lambda/\Sigma^0$
	$\gamma^\star n \to \pi^0\ n$	$\gamma^\star n \to \eta\ n$	$\gamma^\star n \to K^0\ \Lambda/\Sigma^0$
	$\gamma^\star n \to \pi^-\ p$		$\gamma^\star n \to \boxed{K^+}\ \boxed{\Sigma^-}$
$\gamma^\star N \to \phi\phi\mathcal{B}$	$\gamma^\star p \to \pi^+\ \pi^-\ p$	$\gamma^\star p \to \boxed{K^+}\ \boxed{K^-}\ p$	$\gamma^\star p \to \pi^+\ K^0\ \Lambda/\Sigma^0$
	$\gamma^\star p \to \pi^0\ \pi^0\ p$	$\gamma^\star p \to \boxed{K^0_S}\ K^0_L\ p$	$\gamma^\star p \to \pi^0\ \boxed{K^+}\ \Lambda/\Sigma^0$
	$\gamma^\star p \to \pi^+\ \pi^0\ n$		$\gamma^\star p \to \pi^0\ K^0\ \boxed{\Sigma^+}$
	$\gamma^\star n \to \pi^+\ \pi^-\ n$	$\gamma^\star n \to \boxed{K^+}\ \boxed{K^-}\ n$	$\gamma^\star n \to \pi^0\ K^0\ \Lambda/\Sigma^0$
	$\gamma^\star n \to \pi^0\ \pi^0\ n$	$\gamma^\star n \to K^0\ \bar{K}^0\ n$	$\gamma^\star n \to \pi^-\ \boxed{K^+}\ \Lambda/\Sigma^0$
	$\gamma^\star n \to \pi^0\ \pi^-\ p$		$\gamma^\star n \to \pi^\mp\ K^0\ \boxed{\Sigma^\pm}$

- Kaons and neutrons look like the biggest challenge

LOHENGRIN AT ELSA



Searches for Dark Photons building on a measurement of the **missing momentum** in the final state have the potential to **outperform other experiments** (existing and planned) in particular for comparably **small masses** of the lightest particles in the dark sector.

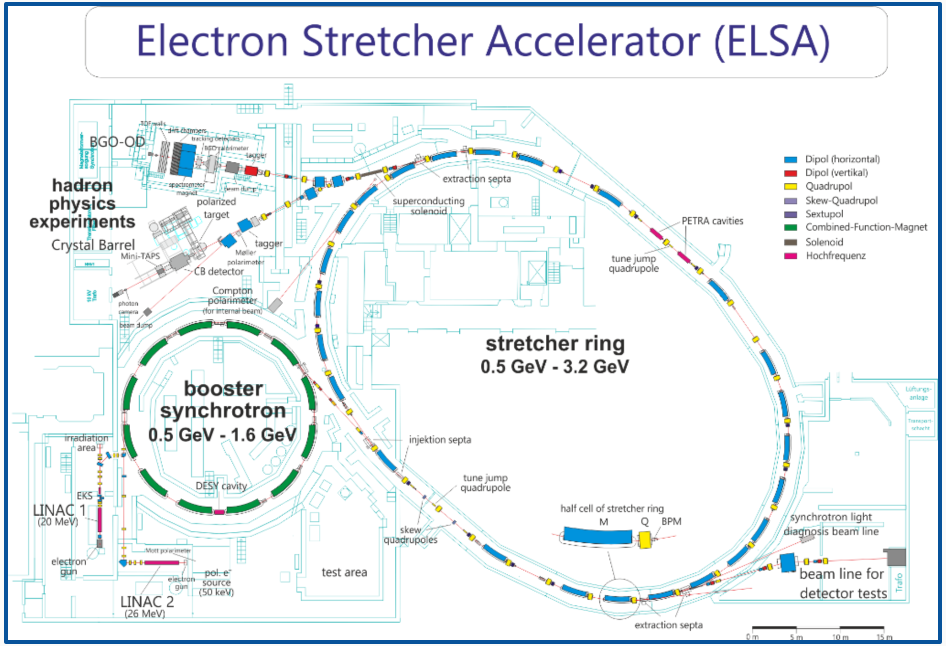
for masses in the sub-GeV regime, they can reach sensitivity to couplings as low as the targets set by the apparent relic density for a single source of dark matter

UNIVERSITÄT BONN

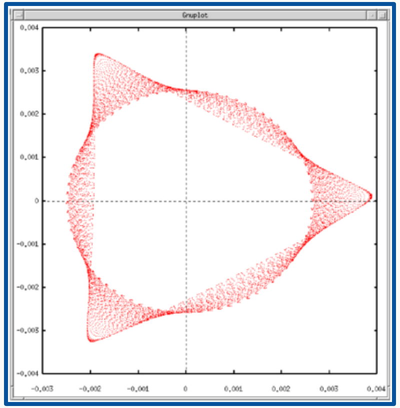
LOHENGRIN AT ELSA

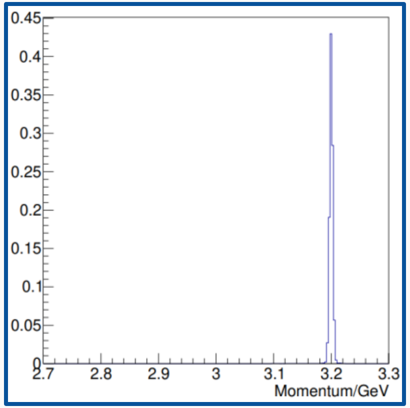
- Lohengrin: a light dark matter particle search experiment at ELSA
  - experiment strategy under study: **track trigger** to efficiently select candidate signal events
    - reduction of tracker material: **ultrathin** pixellised silicon tracking detectors (DMAPS)
    - **ultrafast** readout of the tracking detector
    - pattern recognition and track classification in **hardware** in order to **trigger** the readout of the calorimeters
  - precise **offline tracking** for electrons and possibly other charged particles
  - suitable **calorimeters**
    - **high rate** of incoming electrons and exposure to significant levels of ionizing radiation
    - sufficiently precise detection of **neutral hadrons**
  - precise reconstruction of **individual electron-target interactions**
  - good understanding of **SM backgrounds**, e.g. K_L production in photo-nuclear interactions
  - good understanding of possible signal processes in **well motivated BSM scenarios**

THE ELSA ACCELERATOR AT BONN



- 3.2 GeV electron accelerator
- extraction currently for 3 experiments
- resonance extraction: precise knowledge of initial state electron energy (0.08%)
- $\nu = 1$ electron extraction at high rates (> 100 MHz)



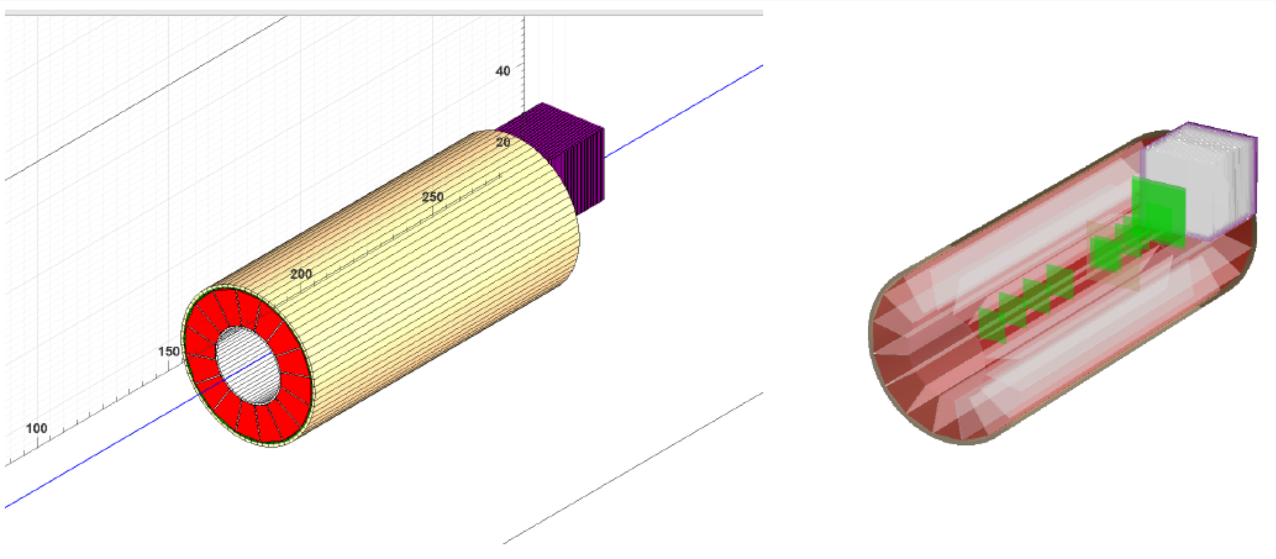


Jan Heinrichs

UNIVERSITÄT BONN

STUDIES ON DETECTOR LAYOUT

- started with implementation of simple magnet and a few thin silicon tracking planes in ExPlORA framework

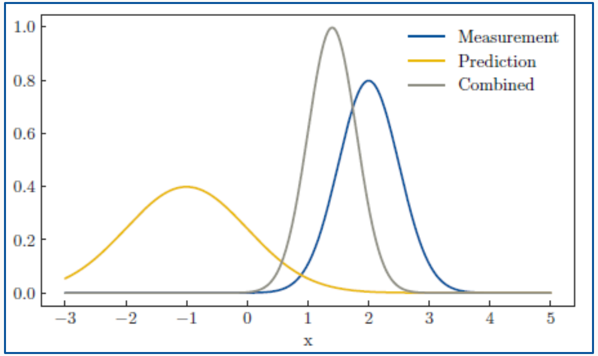


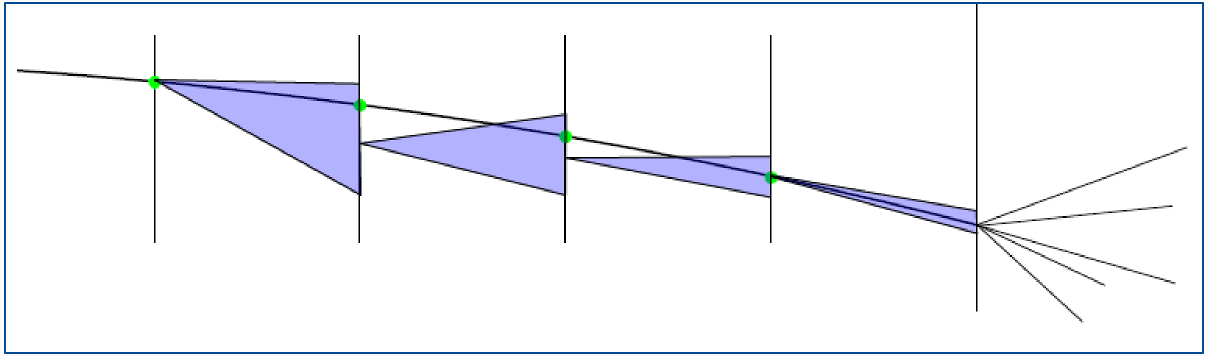
- 1 m long Halbach array, 0.5 T orthogonal to beam axis (thanks to our colleagues from the FASER collaboration)
- 6 layers of pixel tracking detector in front of target
- 6 layers of pixel tracking detector behind target
- thin tungsten target
- particle gun producing ELSA quality electrons with a momentum of 3.2 GeV

Jan Heinrichs

STUDIES ON DETECTOR LAYOUT

- started with implementation of simple magnet and a few thin silicon tracking planes in ExPlORA framework
  - electron tracking: Kalman filter with smoothing steps for tag- and recoil-tracker
  - started to look into Gaussian sum filter and higher order effects to improve tracking
  - performance so far is an excellent starting point for improvements



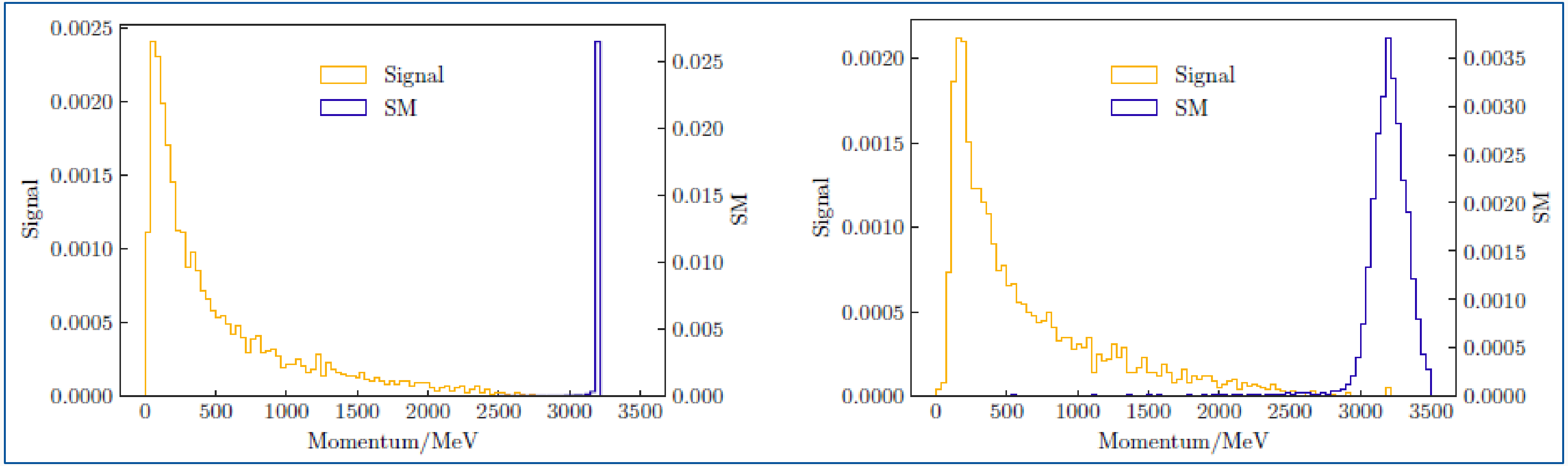


Jan Heinrichs

UNIVERSITÄT BONN

STUDIES ON DETECTOR LAYOUT

- started with implementation of simple magnet and a few thin silicon tracking planes in ExPlORA framework
  - electron tracking: Kalman filter with smoothing steps for tag- and recoil-tracker
  - started to look into Gaussian sum filter and higher order effects to improve tracking
  - performance so far is an excellent starting point for improvements

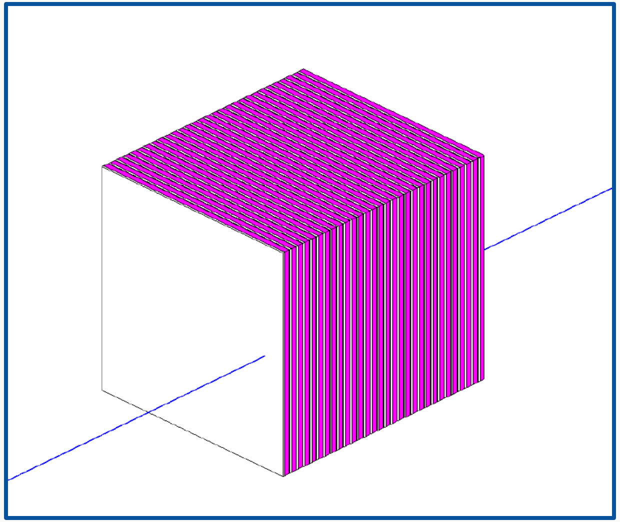


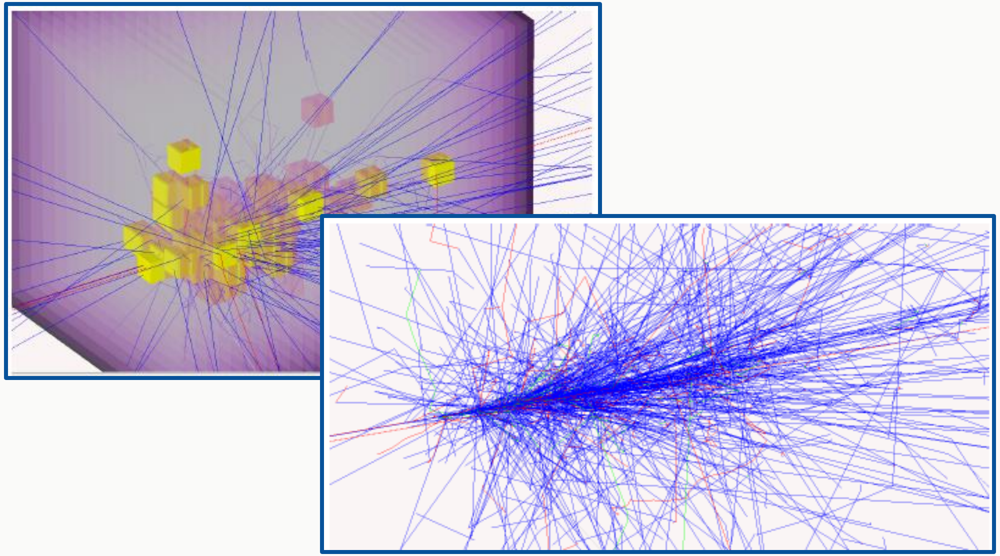
Jan Heinrichs

UNIVERSITÄT BONN

STUDIES ON DETECTOR LAYOUT

- 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

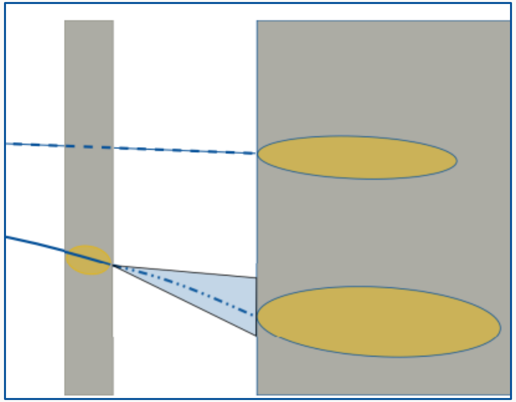


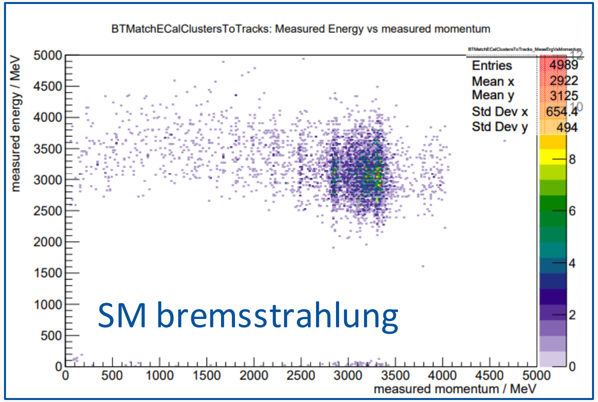


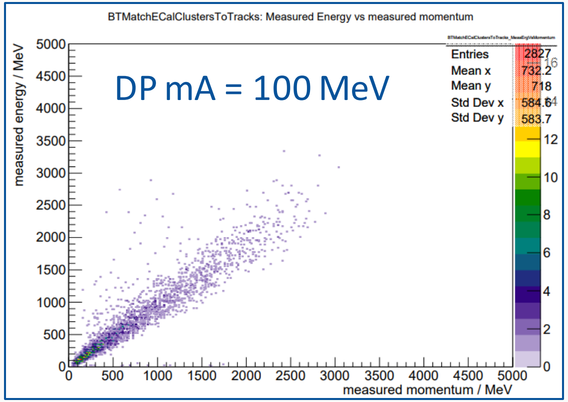
UNIVERSITÄT BONN

STUDIES ON DETECTOR LAYOUT

- electron reconstruction:
  - simple matching between calorimeter clusters and tracks
  - so far: track extension to first layer of calorimeter → match to closest cluster in ECAL
  - improvements always possible (shower shape information, development of a "particle flow" like algorithm, ...)





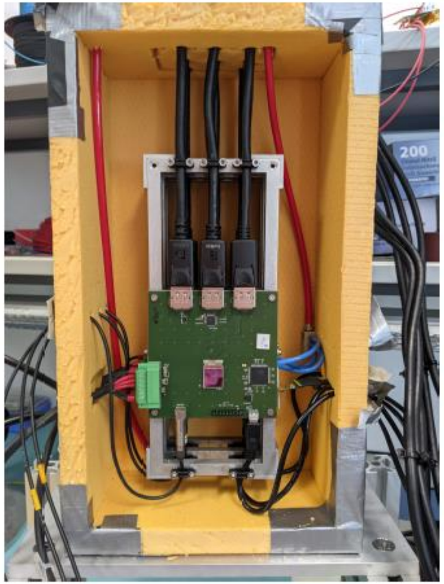


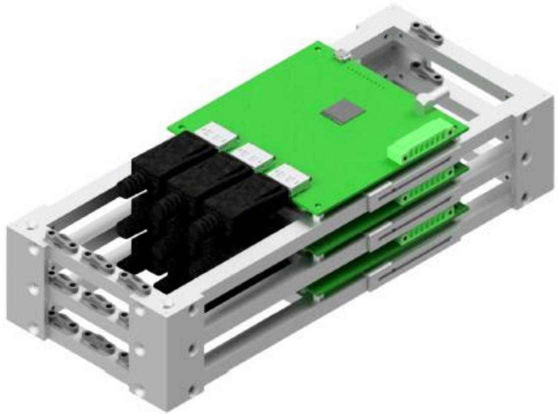
Markus Gruber,
Leonie Richarz,
Tobias Schiffer

UNIVERSITÄT BONN

STUDIES ON DETECTOR LAYOUT

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

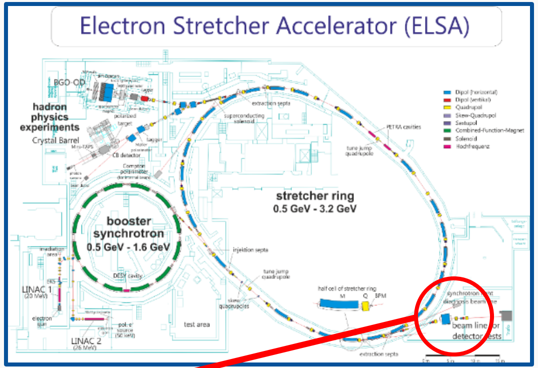




STUDIES ON DETECTOR LAYOUT

Markus Gruber,
Leonie Richarz,
Tobias Schiffer

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

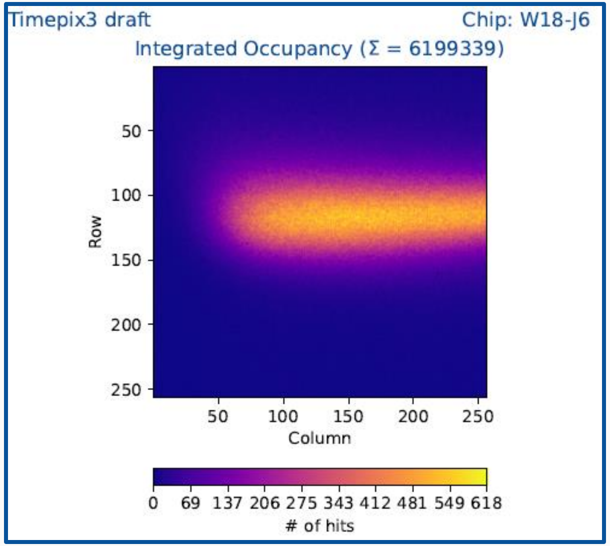


- 2 targets:
  - test rate capabilities and identify bottlenecks in DAQ system
  - study impact of multiple scattering in the tracking detector

STUDIES ON DETECTOR LAYOUT

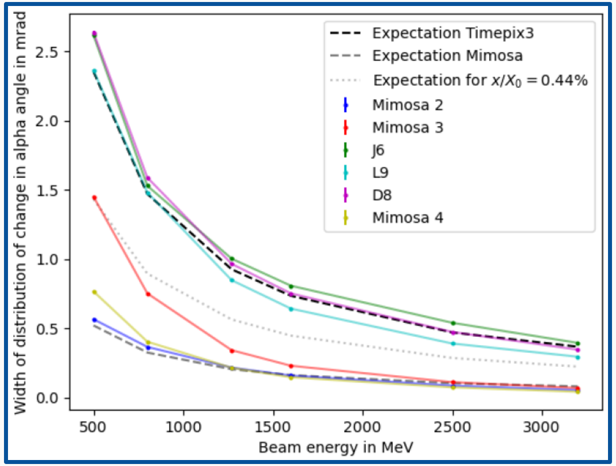
Markus Gruber,
Leonie Richarz,
Tobias Schiffer

- 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?)

CONCLUSIONS

- searches for dark matter continue to provide interesting challenges for the particle physics community
  - model with light dark matter particles that are out of reach for the large collider experiments and many existing direct and indirect detection experiments gain increasing interest
  - beam dump experiments with a precise, full reconstruction of the initial and final state allow to close an important gap in the parameter space of well motivated models

  - the Lohengrin experiment enables such a search at the electron accelerator ELSA in Bonn

- **optimization of layout**
- **development of tracker and beam test**
- **development of TDAQ strategy**
- **tests with candidate calorimeter?**

- **integration of experiment**
- **commissioning of Lohengrin at ELSA**
- **development of offline software**
- **analysis strategy finalisation**

- **data taking**
- **improvement of offline software**
- **Lohengrin upgrade?**