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DMLAB MEETING 16.-17.10.2025

LOHENGRIN
THEORY PREDICTIONS

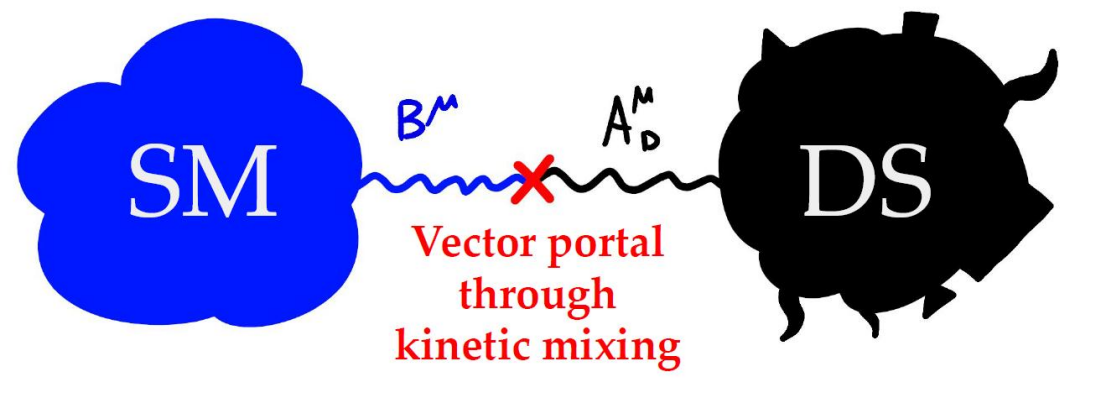
Martin Schürmann, University of Bonn

Lohengrin Study Group:

Philip Bechtle[1], Christian Bespin[1], Dominique Breton[2], Cedric Breuning[1], Carlos Orero Canet[4], Klaus Desch[1], Herbi Dreiner[1], Oliver Freyermuth[1], Rhorry Gauld[1,3], Markus Gruber[1], Cesar Blanch Gutierrey[4], Hayem Hajjar[1], Matthias Hamer[1], Jan-Eric Heinrichs[1], Adrian Irles[4], Jochen Kaminski[1], Laney Klipphahn[1], Hans Krüger[1], Michael Lupberger[1], Jihane Maalmi[2], Roman Pöschl[2], Dennis Proft[1], Leonie Richarz[1,6], Tobias Schiffer[1], Patrick Schwäbig[1], Martin Schürmann[1], Dirk Zerwas[5]

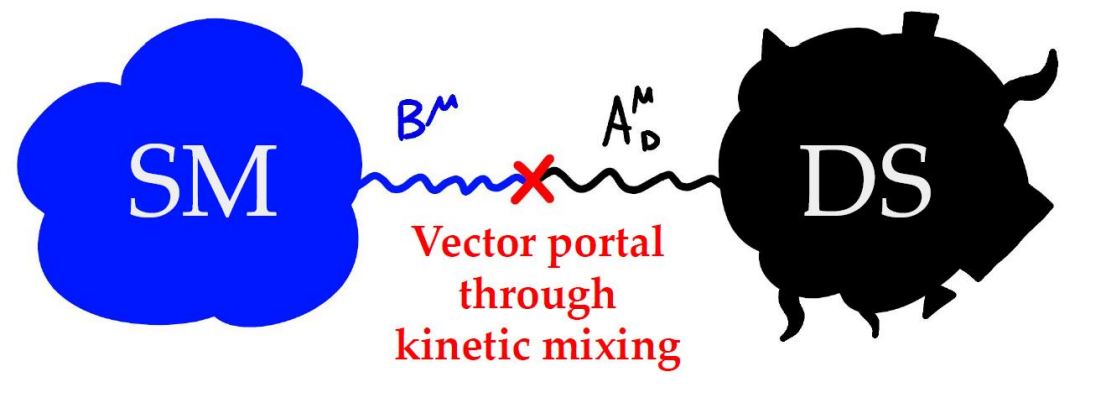
1 Physikalisches Institut, University of Bonn | 2 IJCLab Orsay | 3 Werner-Heisenberg-Institute, MPP Garching | 4 IFIC, Valencia | 5 DMLab, DESY/IN2P3/CNRS | 6 NTNU Norway

LOHENGRIN IN A NUTSHELL



$$\mathcal{L} \supset -\frac{1}{4} F_{\mathrm{D}\mu\nu} F_{\mathrm{D}}^{\mu\nu} + \frac{1}{2} m_{A_{\mathrm{D}}}^2 A_{\mathrm{D}\mu} A_{\mathrm{D}}^{\mu} - \frac{\sin \varepsilon_Y}{2} F_{\mathrm{D}}^{\mu\nu} B_{\mu\nu} - g_{\mathrm{D}} A_{\mathrm{D}\mu} J_{\mathrm{D}}^{\mu}$$

LOHENGRIN IN A NUTSHELL



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- interaction terms for mass eigenstate:

$$\mathcal{L}_{\mathrm{int}} = -A'_\mu \left(\sum_f g_f^{A'} \, \bar{f} \gamma^\mu f + g_{\mathrm{D}}^{A'} \, J_{\mathrm{D}}^{\mu} \right)$$

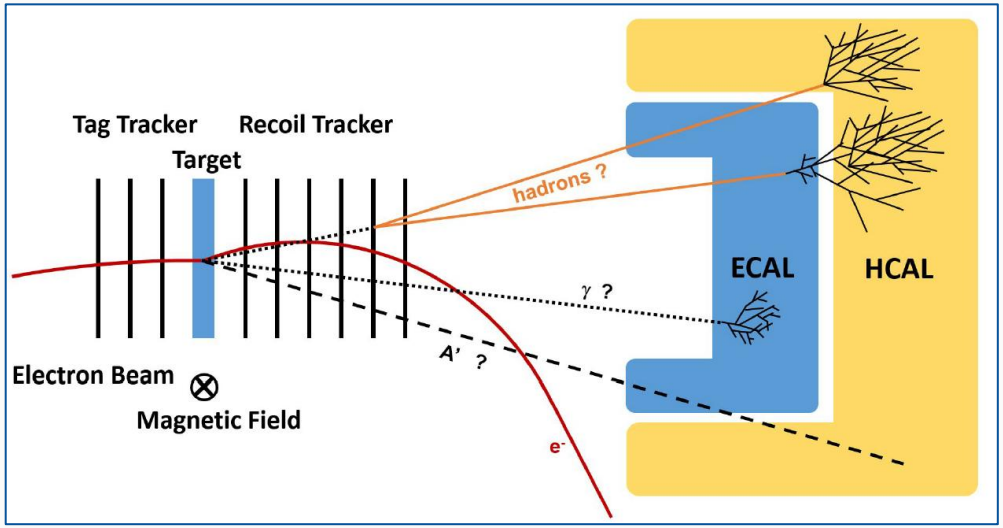
- with couplings

$$g_{\ell_L}^{A'} = \frac{e\varepsilon_Y}{2\cos\theta_W} \frac{2m_Z^2 \cos^2\theta_W - m_{A_{\mathrm{D}}}^2}{m_Z^2 - m_{A_{\mathrm{D}}}^2}$$

$$g_{\ell_R}^{A'} = \frac{e\varepsilon_Y}{\cos\theta_W} \left(1 - \frac{m_Z^2 \sin^2\theta_W}{m_Z^2 - m_{A_{\mathrm{D}}}^2} \right)$$

LOHENGRIN IN A NUTSHELL

- experiment overview just given by Cedric



- dominant process(es):

$$e^- \mathcal{H} \rightarrow e^- \mathcal{H} \gamma$$

- subsequent photo- and electro-nuclear interactions with the detector possible

- occasional production of dark photon:

$$e^- \mathcal{H} \rightarrow e^- \mathcal{H} A'$$

- cross-section dominated by ε and $m_{A'}$

Signal Signature: low energy recoiling electron, no significant energy deposits in ECAL or HCAL

similar experiments: LDMX, DarkSHINE, NA64

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BACKGROUNDS

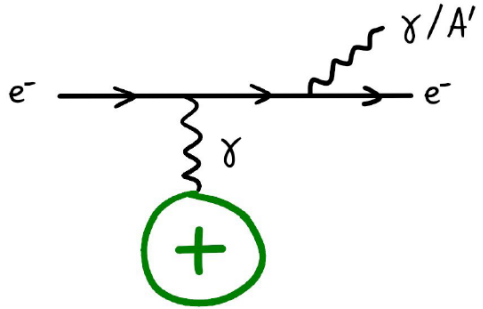
- important backgrounds
  - SM QED bremsstrahlung where the photon misses the ECAL
  - SM QED bremsstrahlung where the photon interacts with a second nucleus in the target or the detector to produce hadrons
  - electron-nuclear processes in which the recoil electron interacts with a nucleus in the target or the detector to produce hadrons

  - important to understand all possible contributions to the SM cross-sections as well as the signal cross-sections to adequately dimension and instrument the detector

THEORY PREDICTIONS AT O($\alpha^3\varepsilon^2$)

Bethe-Heitler scattering off nuclear charge distribution with one photon exchange:

$$i\mathcal{M}_{\text{coh}}(e^- \Phi^+ \xrightarrow{\gamma} e^- \Phi^+ R) = L^{\mu}_{\text{BH}}[R] \frac{-ig_{\mu\nu}}{q^2_{\text{BH}}} H^{\nu}_{\text{BH, coh}} \qquad \text{where} \qquad R = \gamma, A'$$

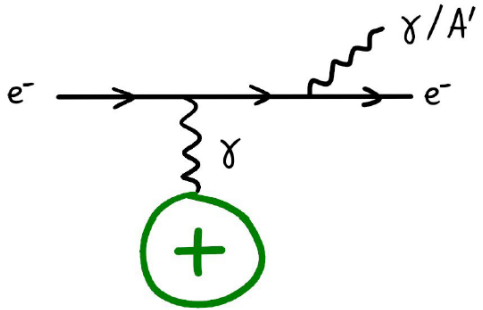


"coherent": $\mathcal{H} = \Phi^+$

THEORY PREDICTIONS AT O($\alpha^3\varepsilon^2$)

Bethe-Heitler scattering off **general hadronic current** with one photon exchange:

$$i\mathcal{M}_{\mathrm{R}}(e^- \mathcal{H} \xrightarrow{\gamma} e^- \mathcal{H} R) = L^{\mu}_{\mathrm{BH}}[R] \frac{-ig_{\mu\nu}}{q^2_{\mathrm{BH}}} H^{\nu}_{\mathrm{BH,\,R}}$$



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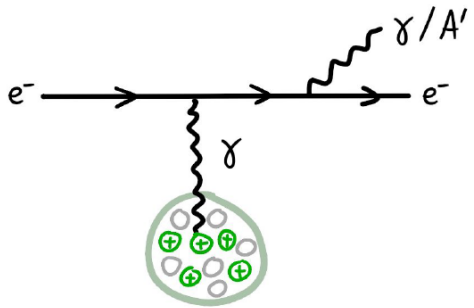


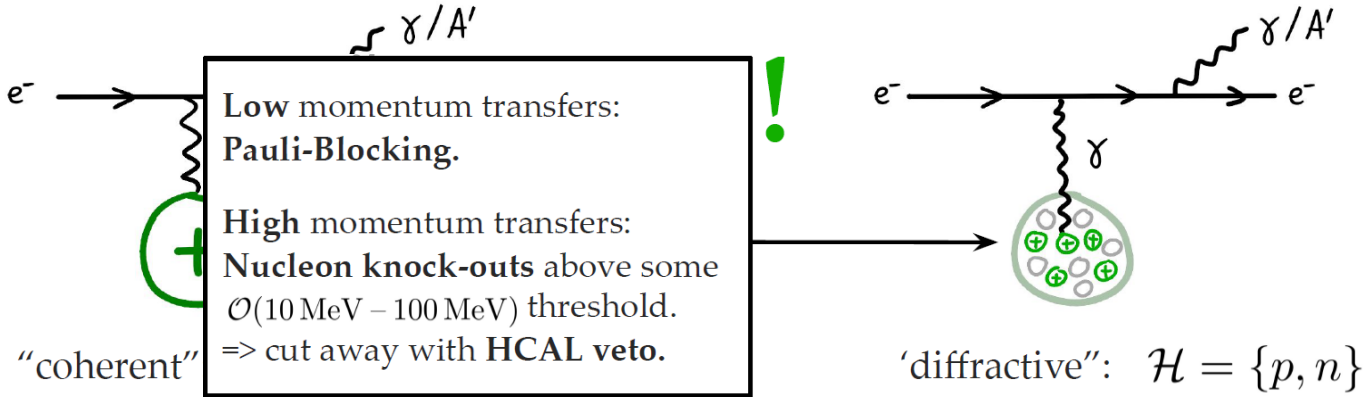
"diffractive": $\mathcal{H} = \{p, n\}$

=> $\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{coh}} + \mathrm{d}\sigma_{\mathrm{dif}}$. $H^{\nu}_{\mathrm{BH,\,R}}$ comes in different shapes and with different form factors [bal18].

THEORY PREDICTIONS AT $O(\alpha^3\varepsilon^2)$

Bethe-Heitler scattering off **general hadronic current** with one photon exchange:

$$i\mathcal{M}_{\mathrm{R}}(e^- \mathcal{H} \xrightarrow{\gamma} e^- \mathcal{H} R) = L^{\mu}_{\mathrm{BH}}[R] \frac{-ig_{\mu\nu}}{q^2_{\mathrm{BH}}} H^{\nu}_{\mathrm{BH,\,R}}$$



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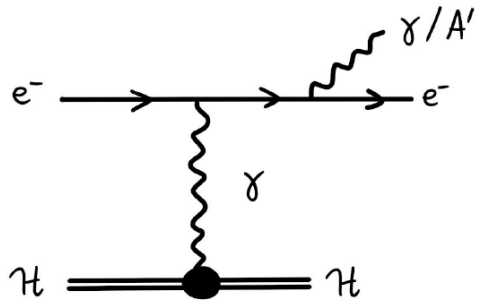
$$i\mathcal{M}_{\mathrm{R}}(e^- \mathcal{H} \xrightarrow{\gamma} e^- \mathcal{H}\, R) = L^{\mu}_{\mathrm{BH}}[R]\, \frac{-ig_{\mu\nu}}{q^2_{\mathrm{BH}}}\, H^{\nu}_{\mathrm{BH,\,R}}$$

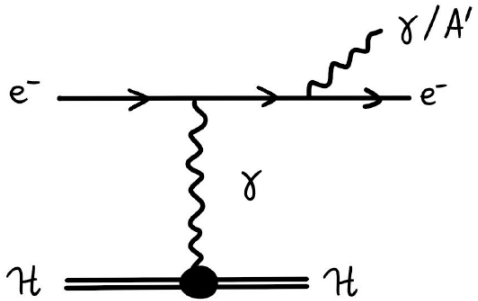


Bethe-Heitler (BH) scattering

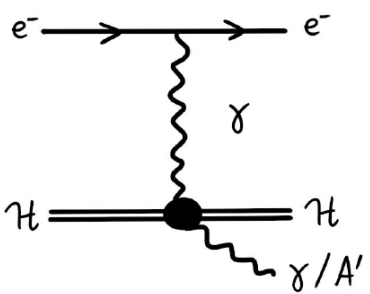
THEORY PREDICTIONS AT $O(\alpha^3\varepsilon^2)$

BH and VC scattering off **general hadronic current** with one photon exchange:

$$i\mathcal{M}_{\mathrm{R}}(e^- \mathcal{H} \xrightarrow{\gamma} e^- \mathcal{H} R) = L^{\mu}_{\mathrm{BH}}[R] \frac{-ig_{\mu\nu}}{q^2_{\mathrm{BH}}} H^{\nu}_{\mathrm{BH,\,R}} + L^{\mu}_{\mathrm{VCS}} \frac{-ig_{\mu\nu}}{q^2_{\mathrm{VCS}}} H^{\nu}_{\mathrm{VCS,\,R}}[R]$$



Bethe-Heitler (BH) scattering



Virtual Compton (VC) scattering

THEORY PREDICTIONS AT O($\alpha^3\varepsilon^2$)

BH and VC scattering off **general hadronic current** with one photon exchange:

$$i\mathcal{M}_{\mathrm{R}}(e^- \mathcal{H} \xrightarrow{\gamma} e^- \mathcal{H} R) = L^{\mu}_{\mathrm{BH}}[R]\,\frac{-ig_{\mu\nu}}{q^2_{\mathrm{BH}}}\,H^{\nu}_{\mathrm{BH,\,R}} + L^{\mu}_{\mathrm{VCS}}\,\frac{-ig_{\mu\nu}}{q^2_{\mathrm{VCS}}}\,H^{\nu}_{\mathrm{VCS,\,R}}[R]$$

VCS terms are known and determined by low energy theorems (LET).
Add to **diffractive** scattering, but stay **below resonance** region, i.e.

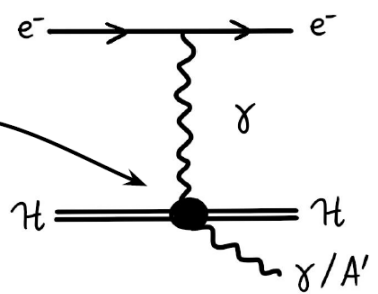
$$\sqrt{(p_R + p_N)^2} < m_\Delta$$

Compton tensor has the form [van00, dju08]:

$$C^{\mu\nu}_{\mathrm{Born}} = \overline{u}_N(P')\left[\Gamma^{\nu}_N(q)\frac{\not{P} - \not{k} + m_N}{(P-k)^2 - m_N^2}\Gamma^{\mu}_N(k) + \Gamma^{\mu}_N(k)\frac{\not{P} - \not{q} + m_N}{(P-q)^2 - m_N^2}\Gamma^{\nu}_N(q)\right]u_N(P)$$

with appropriate $-\varepsilon$ rescaling for A' emission.

!

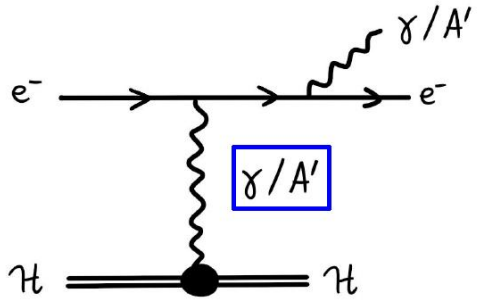


Virtual Compton (VC) scattering

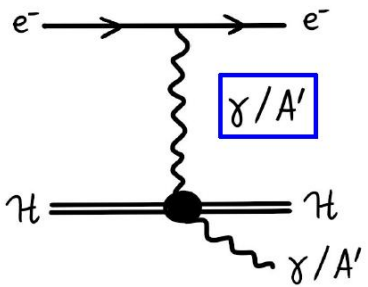
THEORY PREDICTIONS AT $O(\alpha^3\varepsilon^2)$

BH and VC scattering off **general hadronic current** with **one (dark) photon** exchange:

$$i\mathcal{M}_{\mathrm{R}}(e^-\,\mathcal{H} \xrightarrow{V=\gamma,A'} e^-\,\mathcal{H}\,R) = L^{\mu}_{\mathrm{BH}}[R,V]\; i\Pi_{\mu\nu}[V](q_{\mathrm{BH}})\; H^{\nu}_{\mathrm{BH,\,R}}[V] + L^{\mu}_{\mathrm{VCS}}[V]\; i\Pi_{\mu\nu}[V](q_{\mathrm{VCS}})\; H^{\nu}_{\mathrm{VCS,\,R}}[R,V]$$



Bethe-Heitler (BH) scattering



Virtual Compton (VC) scattering

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THEORY PREDICTIONS AT $O(\alpha^3\varepsilon^2)$

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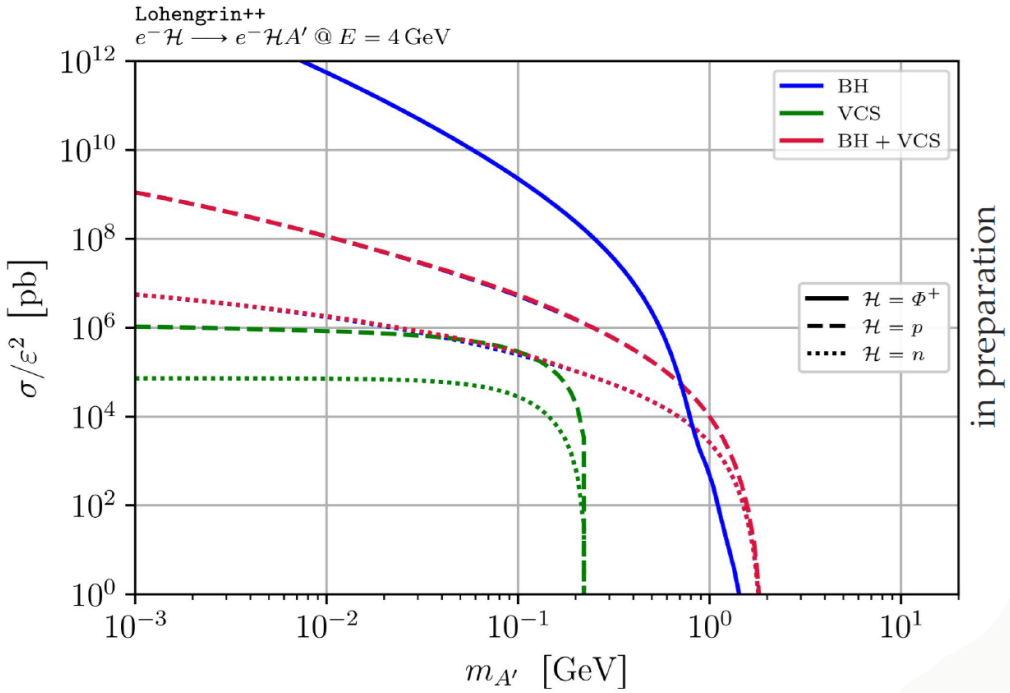
=> **Everything implemented in dedicated Monte-Carlo code `Lohengrin++` to study signal and (irreducible) QED background.**

- Written in `C++`
- Amplitudes (squared): `FeynRules` [chr08, all13], `FeynArts` [hah00] and `FeynCalc` [mer90, sht16, sht20]
- Phase space integration: `Vegas` algorithm from `Cuba` library [hah04]
- Corresponding publication in preparation

DARK PHOTON REAL EMISSION AT O($\alpha^3\varepsilon^2$)

- Inclusive A' production cross section (at 4 GeV)
- Diffractive scattering important for heavy A'
- VCS terms are negligibly small



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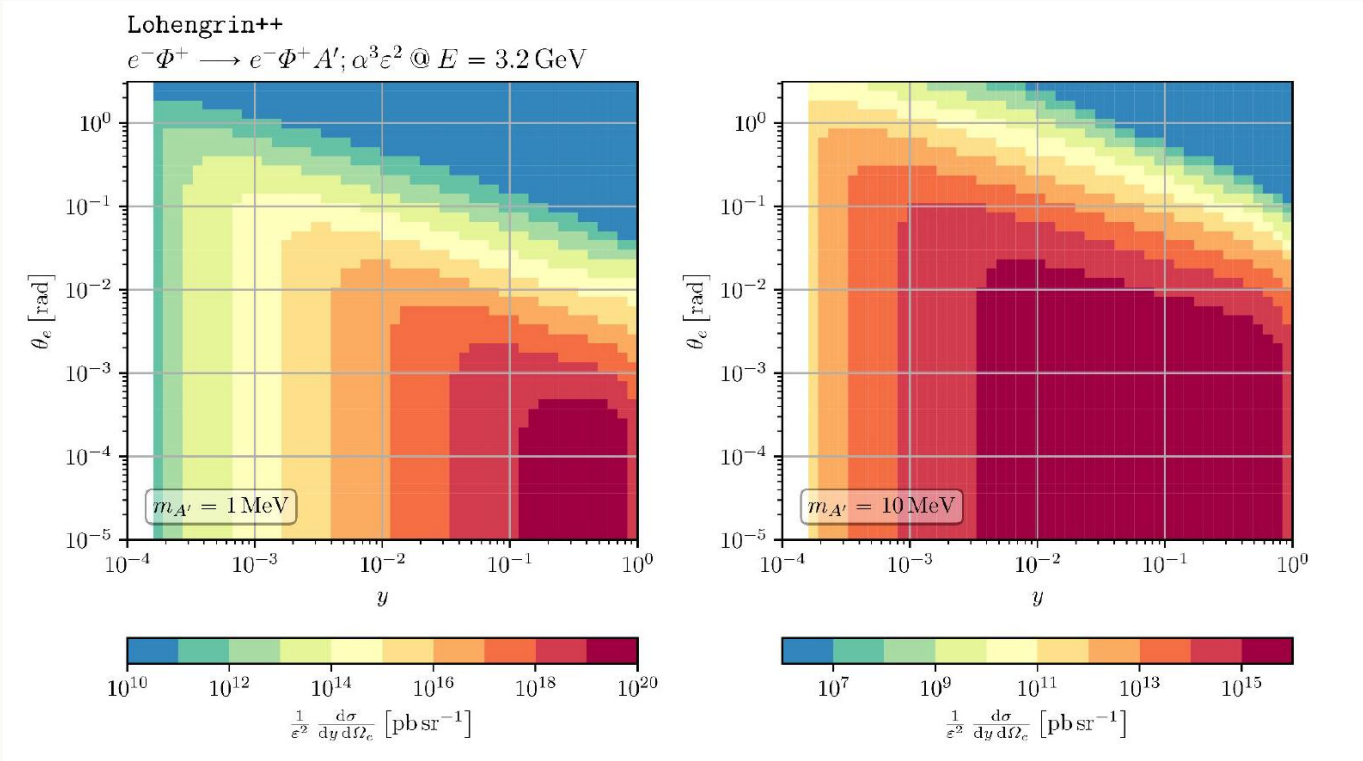
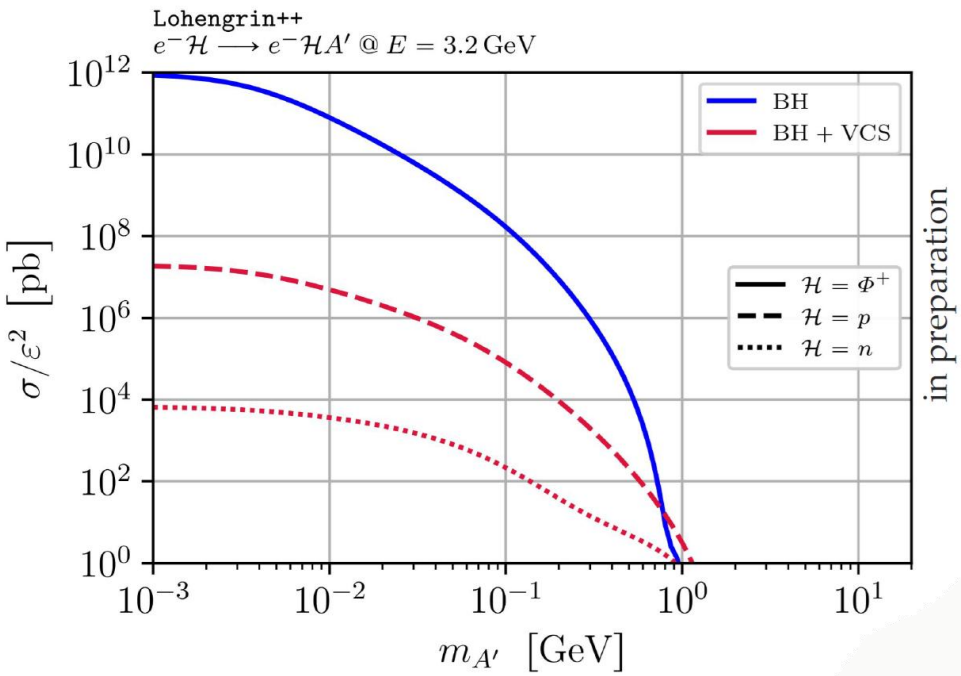
DARK PHOTON REAL EMISSION AT O($\alpha^3\varepsilon^2$)



DARK PHOTON REAL EMISSION AT O($\alpha^3\varepsilon^2$)

- LOHENGRIN **signal region SR1** optimized for coherent BH scattering
  - 25 MeV ≤ $|p_e|$ ≤ 75 MeV
  - $\theta_e < 0.25$ rad
  - **Baseline** HCAL veto for knock-outs

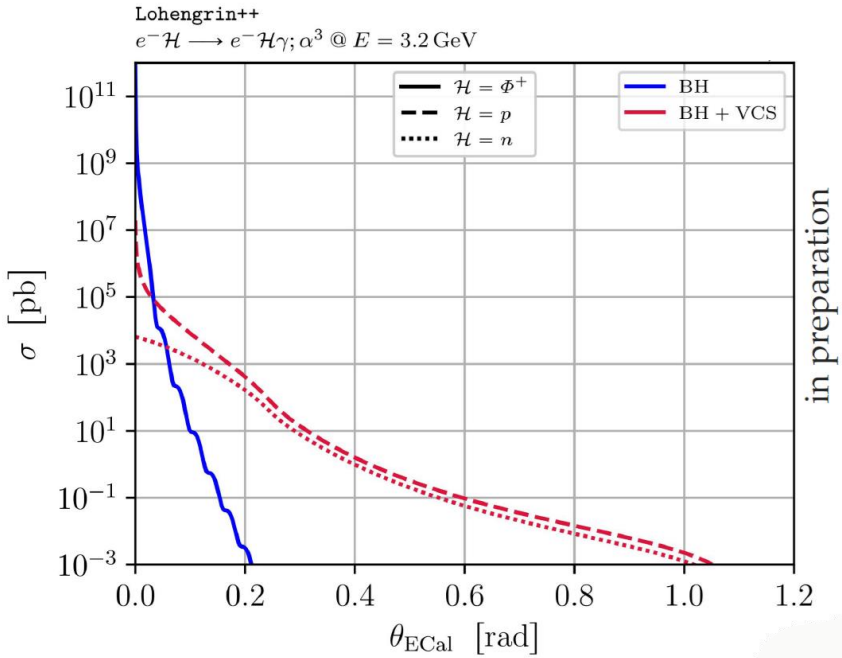


QED PHOTON REAL EMISSION AT O(α^3)

- LOHENGRIN **signal region SR1** optimized for coherent BH scattering
  - 25 MeV ≤ $|p_e|$ ≤ 75 MeV
  - $\theta_e < 0.25$ rad
  - **Baseline** HCAL veto for knock-outs
  - ECAL veto: Treat $\boldsymbol{\theta}_{\mathbf{ECAL}}$ as free parameter

=> Dominant missing energy background cross section

=> Roughly estimated nucleon knock-outs (and FLUKA simulations) suggest spatial extension of HCAL.



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SUMMARY

- feasibility study for Lohengrin published based on available estimates

- significant effort ongoing in improving the estimates
  - signal cross-section
  - higher order and highly suppressed processes may become relevant due to the high required background suppression O(10^{-12}-10^{-14})

- theory paper for Lohengrin and similar experiments is in preparation

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REFERENCES

- **[bat17]**: Battaglieri, M., Belloni, A., Chou, A., Cushman, P., Echenard, B., Essig, R., Estrada, J., Feng, J. L., Flaugher, B., Fox, P. J., Graham, P., Hall, C., Harnik, R., Hewett, J., Incandela, J., Izaguirre, E., McKinsey, D., Pyle, M., Roe, N., … Zhong, Y.-M. (2017). US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report (Version 1). arXiv. https://doi.org/10.48550/ARXIV.1707.04591
- **[ldm18]**: Åkesson, T., Berlin, A., Blinov, N., Colegrove, O., Collura, G., Dutta, V., Echenard, B., Hiltbrand, J., Hitlin, D. G., Incandela, J., Jaros, J., Johnson, R., Krnjaic, G., Mans, J., Maruyama, T., McCormick, J., Moreno, O., Nelson, T., Niendorf, G., … Whitbeck, A. (2018). Light Dark Matter eXperiment (LDMX) (Version 1). arXiv. https://doi.org/10.48550/ARXIV.1808.05219
- **[wal25]**: Wallin, E. (2025). The Light Dark Matter eXperiment at 8 GeV. In Proceedings of 42nd International Conference on High Energy Physics — PoS(ICHEP2024) (p. 748). 42nd International Conference on High Energy Physics. Sissa Medialab. https://doi.org/10.22323/1.476.0748
- **[dar22]**: Chen, J., Chen, J.-Y., Chen, J.-F., Chen, X., Fu, C.-B., Guo, J., He, L., He, Z.-T., Khaw, K. S., Li, J.-L., Li, L., Li, S., Lv, M., Liu, D.-N., Liu, H.-Q., Liu, K., Liu, Q.-B., Liu, Y., Lu, Z.-J., … Zhu, Y.-F. (2022). Prospective study of light dark matter search with a newly proposed DarkSHINE experiment. Science China Physics, Mechanics & Astronomy, 66(1). https://doi.org/10.1007/s11433-022-1983-8
- **[ban19]**: Banerjee, D., Burtsev, V. E., Chumakov, A. G., Cooke, D., Crivelli, P., Depero, E., Dermenev, A. V., Donskov, S. V., Dusaev, R. R., Enik, T., Charitonidis, N., Feshchenko, A., Frolov, V. N., Gardikiotis, A., Gerassimov, S. G., Gninenko, S. N., Hösgen, M., Jeckel, M., … Karneyeu, A. E. (2019). Dark Matter Search in Missing Energy Events with NA64. Physical Review Letters, 123(12). https://doi.org/10.1103/physrevlett.123.121801

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MORE REFERENCES

- **[pos22]**: Pöschl, R. (2022). The CALICE SiW ECAL Technological Prototype—Status and Outlook. Instruments, 6(4), 75. https://doi.org/10.3390/instruments6040075
- **[flu24]**: Ballarini, F., Batkov, K., Battistoni, G., Bisogni, M. G., Böhlen, T. T., Campanella, M., Carante, M. P., Chen, D., De Gregorio, A., Degtiarenko, P. V., De la Torre Luque, P., dos Santos Augusto, R., Engel, R., Fassò, A., Fedynitch, A., Ferrari, A., Ferrari, A., Franciosini, G., … Zana, L. (2024). The FLUKA code: Overview and new developments. EPJ Nuclear Sciences & Technologies, 10, 16. https://doi.org/10.1051/epjn/2024015
- **[bal18]**: Ballett, P., Hostert, M., Pascoli, S., Perez-Gonzalez, Y. F., Tabrizi, Z., & Funchal, R. Z. (2019). Neutrino trident scattering at near detectors. Journal of High Energy Physics, 2019(1). https://doi.org/10.1007/jhep01(2019)119
- **[van00]**: Vanderhaeghen, M., Friedrich, J. M., Lhuillier, D., Marchand, D., Van Hoorebeke, L., & Van de Wiele, J. (2000). QED radiative corrections to virtual Compton scattering. Physical Review C, 62(2). https://doi.org/10.1103/physrevc.62.025501
- **[dju08]**: D. Djukanovic, Ph.D. thesis, Mainz U. (2008)

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EVEN MORE REFERENCES

- **[chr08]**: Christensen, N. D., & Duhr, C. (2009). FeynRules – Feynman rules made easy. Computer Physics Communications, 180(9), 1614–1641. https://doi.org/10.1016/j.cpc.2009.02.018
- **[all13]**: Alloul, A., Christensen, N. D., Degrande, C., Duhr, C., & Fuks, B. (2014). FeynRules 2.0 — A complete toolbox for tree-level phenomenology. Computer Physics Communications, 185(8), 2250–2300. https://doi.org/10.1016/j.cpc.2014.04.012
- **[hah00]**: Hahn, T. (2001). Generating Feynman diagrams and amplitudes with FeynArts 3. Computer Physics Communications, 140(3), 418–431. https://doi.org/10.1016/s0010-4655(01)00290-9
- **[mer90]**: Mertig, R., Böhm, M., & Denner, A. (1991). Feyn Calc - Computer-algebraic calculation of Feynman amplitudes. Computer Physics Communications, 64(3), 345–359. https://doi.org/10.1016/0010-4655(91)90130-d
- **[sht16]**: Shtabovenko, V., Mertig, R., & Orellana, F. (2016). New developments in FeynCalc 9.0. Computer Physics Communications, 207, 432–444. https://doi.org/10.1016/j.cpc.2016.06.008
- **[sht20]**: Shtabovenko, V., Mertig, R., & Orellana, F. (2020). FeynCalc 9.3: New features and improvements. Computer Physics Communications, 256, 107478. https://doi.org/10.1016/j.cpc.2020.107478
- **[hah04]**: Hahn, T. (2005). Cuba—a library for multidimensional numerical integration. Computer Physics Communications, 168(2), 78–95. https://doi.org/10.1016/j.cpc.2005.01.010