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Long-Lived Dark Higgs and Inelastic Dark Matter at Belle II

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Long-lived Dark Higgs and inelastic Dark Matter at Belle II

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[1]

[2] [a]

[b]

Abstract:

Keywords:

Another option to circumvent these limits for s-wave DM annihilations is a resonantly enhanced cross-section at freeze-out [21].

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A different signature at Belle involving a dark Higgs boson has been studied in [29].
This implies that ψ_L and ψ_R couple to the scalar field ϕ in the same way.

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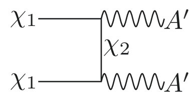
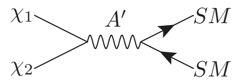
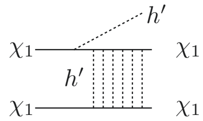
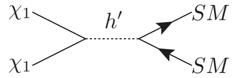
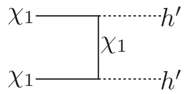
$$\int_{\iota}\ \frac{\left(\qquad\qquad\right)}{\left(\qquad\right)}$$

h

In principle rather small mixing angles of the dark Higgs can be constrained by Belle II, which are insufficient to keep up the thermal equilibrium between the dark and visible sectors until DM freeze-out. For this region in parameter space the calculation of the DM abundance is more involved [36]. For the signature we are interested in, however, a sizeable value of ϵ will always guarantee thermal equilibrium and applicability of the standard thermal freeze-out prescription.

As `micrOMEGAs` does not account for hadronisation and naively calculates the annihilation cross section into light quarks, we modify these annihilation channels by hand making use of the experimentally inferred ratio $R(s)$ as described in [26]. For most of our parameter space this turns out to be completely irrelevant however as the annihilation cross section is dominated by $\chi\ \chi\ \ \to h\ h$.

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See Ref. [19] for another production mechanism of inelastic DM leading to large couplings.

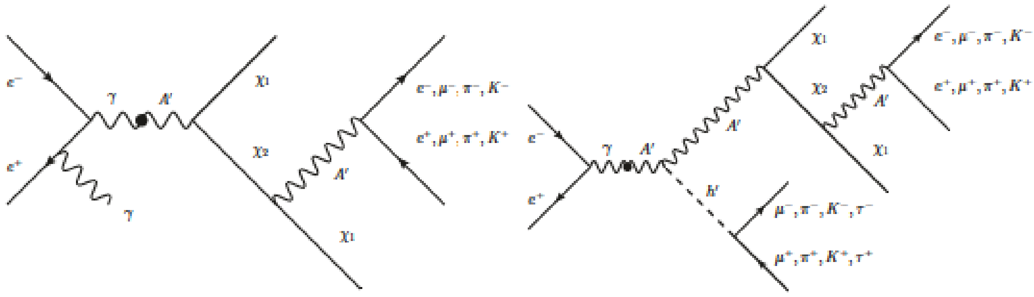


Figure 1: Feynman diagrams depicting the leading search channels for inelastic DM: A' production in association with a single photon (left) and A' production in association with a dark Higgs h' (right) with subsequent decays into both visible and dark sector states.

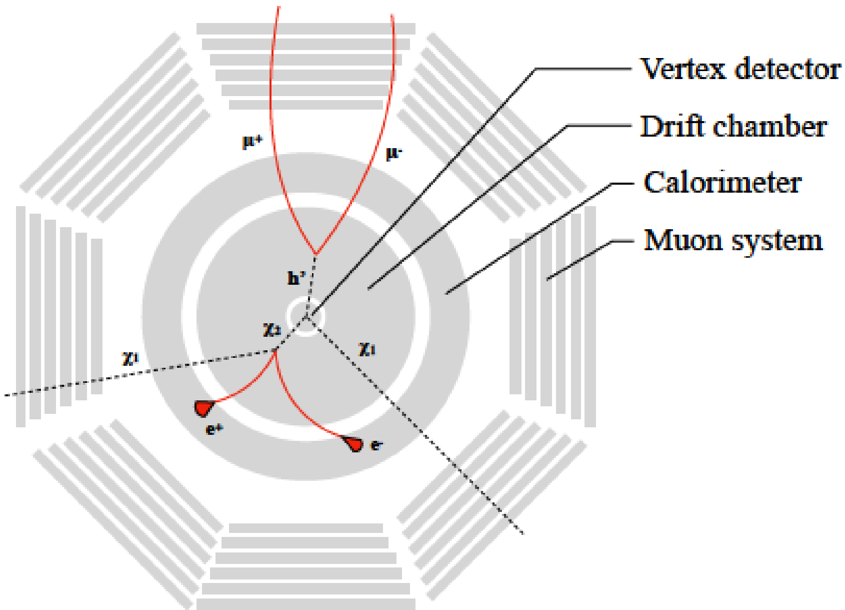


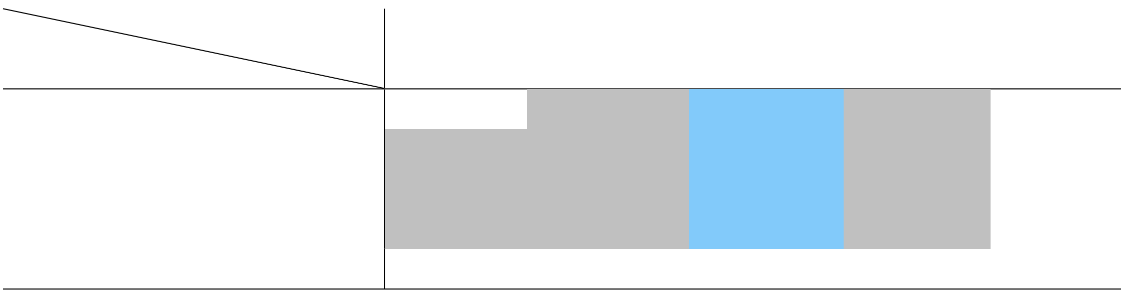
Figure 2: Schematic view of the Belle II detector (xy-plane) and example displaced signature.

3.1 The Belle II experiment

The Belle II experiment at the SuperKEKB accelerator is a next generation B-factory [54] that started physics data taking in 2019. SuperKEKB is a circular asymmetric e^+e^- collider with a nominal collision energy of $\sqrt{s} = 10.58\,\text{GeV}$ and a design instantaneous luminosity of $8 \times 10^{35}\,\text{cm}^{-2}\,\text{s}^{-1}$.

The Belle II detector is a large-solid-angle magnetic spectrometer. Particularly relevant for the searches described in this paper are the following sub-detectors: a tracking system that consists of six layers of vertex detectors (VXD), including two inner layers of silicon pixel detectors (PXD) and four outer layers of silicon vertex detectors (SVD), and a 56-layer central drift chamber (CDC) which covers a polar angle region of $(17-150)^\circ$. The

[7] In the current work we improve the description of the total χ_2 decay width as described in the appendix.



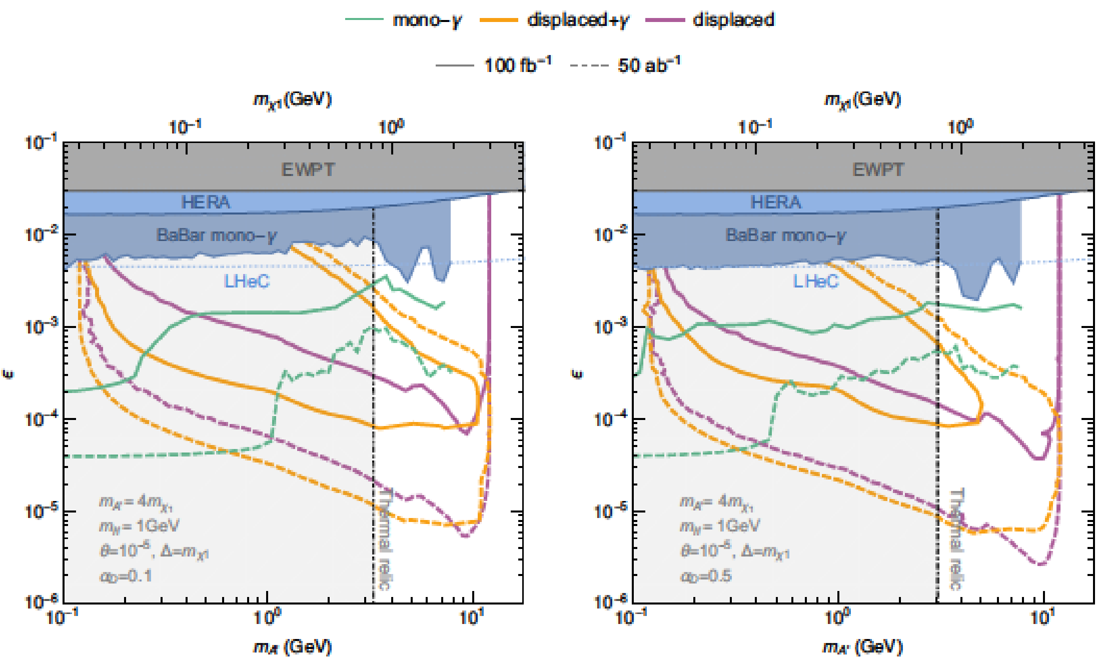


Figure 3: Expected sensitivities of the different searches at Belle II in the $\epsilon - m_{A'}$ parameter plane for integrated luminosities of 100 fb^{-1} (solid lines) and 50 ab^{-1} (dashed lines). Left plot is for $\alpha_D = 0.1$, right plot for $\alpha_D = 0.5$.

lines). The other parameters are fixed as indicated in the figures. We show 90% C.L. limits for all signatures analysed in this work, i.e. for the monophoton as well as the two displaced signatures at Belle II. Existing bounds come from electroweak precision tests (EWPT) [41] and from HERA measurements [42] as well as from the BaBar monophoton search [54]. As described in [26] we run Monte Carlo scans to take into account the fact that only a fraction of the events will pass the monophoton selection criteria, resulting in a significantly weaker bound from BaBar for the given parameters. For the rather large value of Δ and ϵ almost all χ_2 particles will decay within the detector and the remaining limit from the monophoton signature is due to the non-zero probability that the particles produced in the χ_2 decay travel in the direction of the beam pipe such that they will not be reconstructed.

The sensitivity of Belle II towards the monophoton signature (green) is significantly improved compared to BaBar due to a more hermetic calorimeter. To obtain the monophoton sensitivity for 100 fb^{-1} and 50 ab^{-1} we rescale the published sensitivity for 20 fb^{-1} using that the expected sensitivity $S(\epsilon) \propto \sqrt[4]{\mathcal{L}}$.[8] We then perform a second rescaling as above using Monte Carlo runs to account for χ_2 decays and corresponding acceptances within the detector. We observe that for small values of $m_{A'}$ the sensitivity is as good as for the usual monophoton search as basically all χ_2 particles decay outside the detector. For larger $m_{A'}$ this is no longer true and we observe a significant weakening (which is delayed for larger luminosities due to the smaller values of ϵ and therefore larger χ_2 decay lengths).

In orange we show the sensitivity due to the signature with a single photon and a

[8] The assumptions under which such a rescaling is valid are discussed in detail in [26].

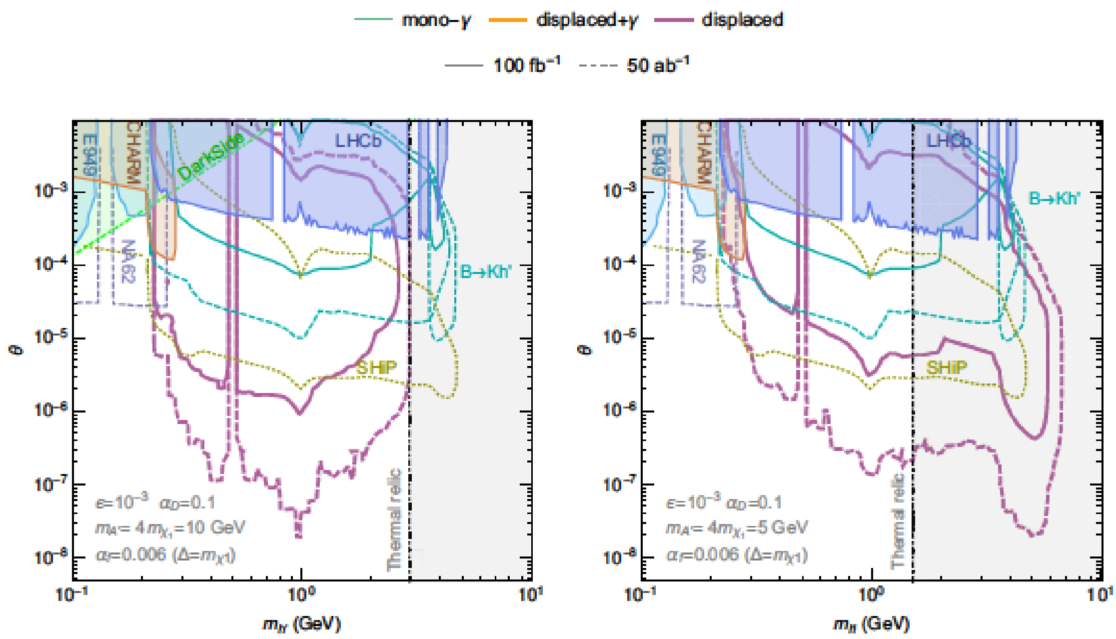


Figure 4: Expected sensitivities of the different searches at Belle II in the $\theta - m_{h'}$ parameter plane for integrated luminosities of 100 fb^{-1} (solid lines) and 50 ab^{-1} (dashed lines). We also show current limits from DarkSide [60], LHCb, CHARM and E949.

displaced pair of charged particles (denoted by 'displaced+γ' in the figure legend). We observe that there is very good sensitivity towards large dark photon masses $m_{A'}$ and rather small values of ϵ. In violet we show the corresponding sensitivity for the signature with two pairs of charged particles, where we require at least one of those to have a non-zero displacement (denoted by 'displaced' in the figure legend). While the typical sensitivity is very similar to the 'displaced+γ' signature, it extends to large values of ϵ which are not covered by any other signature. The reason is that we can allow for prompt χ_2 decay in this case as the decay products of the dark Higgs h' are basically always displaced. We further note that the constraints extend significantly into the off-shell regime with dark photon masses $m_{A'} \lesssim 12\,\text{GeV}$ for $m_{h'} = 1\,\text{GeV}$.

Because the relic density depends primarily on the process $\chi_1\chi_1 \to h'h'$, the thermal relic target does not depend on ε or θ.

In Fig. 4 we show the limits in the $\theta - m_{h'}$ parameter plane. Here general searches for dark scalars mixing with the SM Higgs boson are relevant and we show results from LHCb, CHARM and E949 as given in [43]. We also show limits from direct dark matter searches, taking into account the fact that for the regions in parameter space where χ_1 does not make up all the DM (to the left of the 'thermal relic' line), the limits have to be rescaled with a factor $\Omega_{\chi_1}h^2/0.12$.

Regarding future sensitivities we show estimates for NA62 (as given in [16]), SHiP (as given in [43]) and a possible Belle II search for the rare decay $B \to Kh'$ [17]. For the given set of parameters the monophoton as well as the 'displaced+γ' searches are not sensitive. The signature associated with the dark Higgs however is sensitive down to very small values

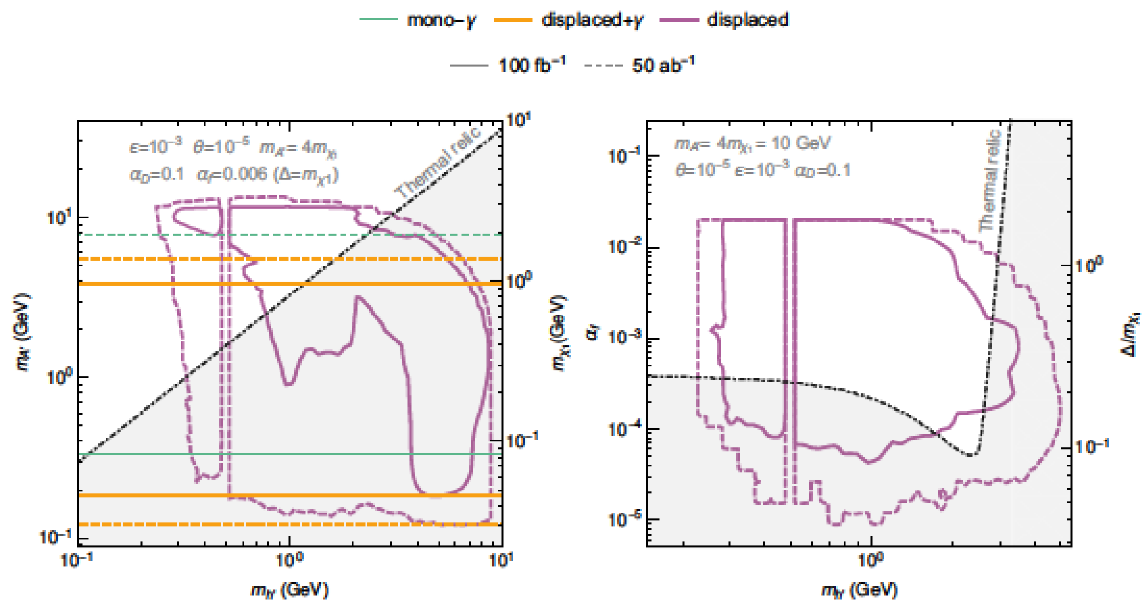


Figure 5: Expected sensitivities of the different searches at Belle II in the (left) $m_{h'} - m_{A'}$ plane and in the (right) $m_{h'} - \alpha_f$ plane for integrated luminosities of 100 fb^{-1} (solid lines) and 50 ab^{-1} (dashed lines).

of the mixing angle θ. This remarkable sensitivity can be understood from the fact that the production cross section is large and does not depend on θ. The lower boundary of the sensitivity is therefore just given by the maximal h' decay length which still allows for 2.3 events to decay within the sensitive region of the detector. The maximal decay length which Belle II can be sensitive to corresponds to more than 10^5m.

In Fig. 5 we show the sensitivities of the different Belle II searches in the $m_{h'} - m_{A'}$ plane (left) and in the $m_{h'} - \alpha_f$ plane (right). Note that we assume that in the parameter region around $m_{h'} \sim 0.5$ GeV the search does not have any sensitivity due to large K_S backgrounds (see the selection cuts in Tab 4), explaining the gap in our sensitivity. In Fig. 6 we show the same planes as in Fig. 5 but restrict ourselves to the case of 100 fb^{-1} to show more details of how the sensitivity region depends on the assumption of the presence of a displaced vertex trigger. We see that a displaced vertex trigger could significantly extend the reach in some regions of parameter space while in others there is only a mild improvement. Experimentally, a displaced vertex track trigger would be orthogonal to the calorimeter triggers and will hence provide a way to measure the trigger efficiency.

5 Conclusion

In this work we studied possible signatures at Belle II of a simple model for light thermal inelastic dark matter which is fully consistent with all cosmological probes as well as direct and indirect dark matter detection. We extend previous studies of inelastic dark matter by carefully analysing the effects of a dark Higgs boson h', which is naturally present in the low energy particle spectrum to explain the mass splitting Δ between the DM state χ_1

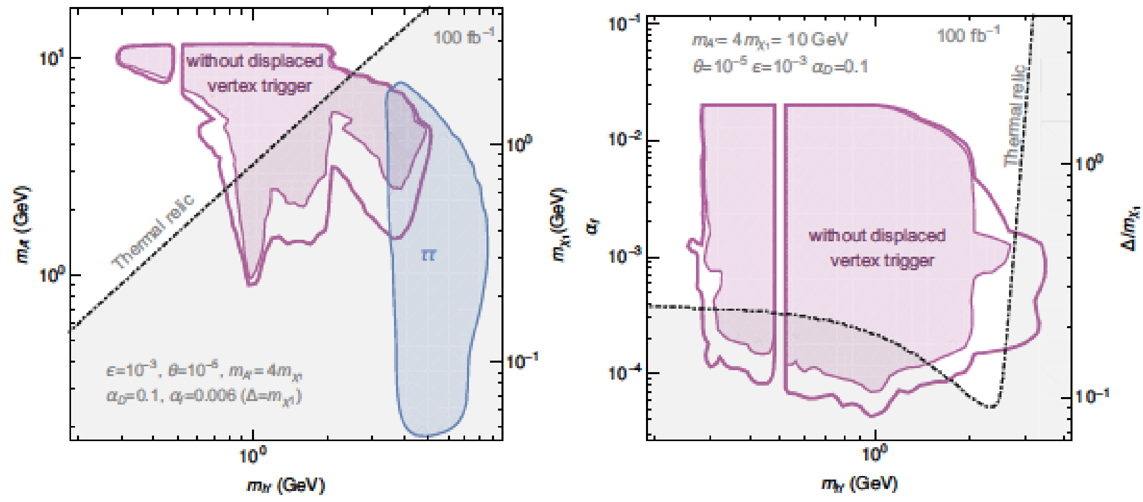


Figure 6: Expected sensitivities of the displaced search at Belle II in the $m_{h'} - m_{A'}$ plane (left) and in the $m_{h'} - \alpha_f$ plane (right) for integrated luminosity of 100 fb^{-1}. The filled regions correspond to the sensitivity without invoking a displaced vertex trigger. In addition we show the region in which the $\tau\tau$ region contributes to the overall sensitivity.

and its heavier twin χ_2 as well as the mass of the dark photon $m_{A'}$. One straightforward consequence of the presence of the dark Higgs h' is that *elastic* scattering between χ_1 and nuclei is possible even at tree-level (making the term *inelastic* DM something of a misnomer). Nevertheless, the resulting scattering cross section is still rather small due to the small couplings involved and typically not competitive with limits from colliders.

A prominent signature at Belle II which arises from dark Higgs particles h' produced in association with dark matter χ_1 consists of two pairs of (displaced) charged particles together with missing momentum. We find that the sensitivity of Belle II to the underlying model parameters is highly complementary to that from monophoton searches, while an independent signature with a single photon, one pair of charged particles and missing momentum as studied in [26] gives very similar sensitivity in large regions of parameter space. The signature involving a dark Higgs however provides sensitivity also to large values of ϵ which are not covered by any other signature. Overall it appears not unlikely that both signatures may be discovered almost simultaneously at Belle II, providing a unique signature correlation for this scenario. We also point out that some regions of parameter space will not be covered with the current experimental configuration and that a displaced vertex trigger would be highly beneficial to increase the sensitivity to this scenario.

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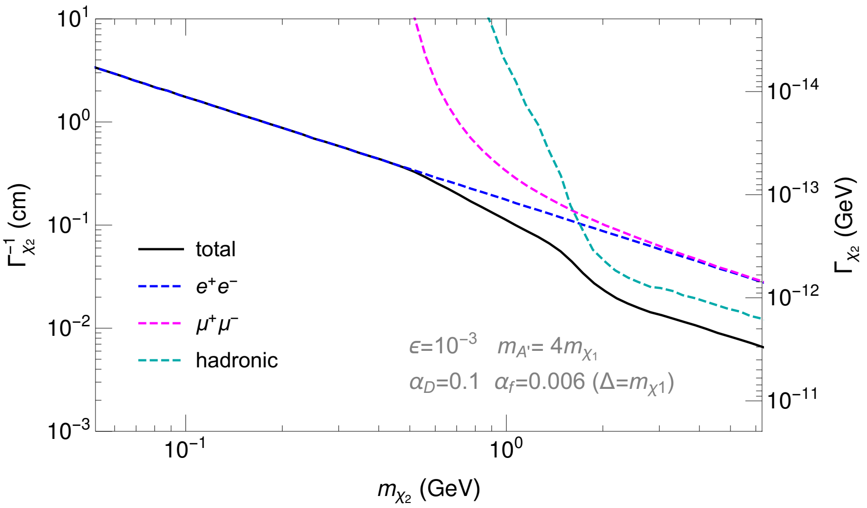
The numerical factors in Eq. (A.10) are related to spin averaging.



total
e+e−
μ+μ−
hadronic
ϵ=10−3 mA'= 4mχ1
αD=0.1 αf=0.006 (Δ=mχ1)
Γχ2−1 (cm)
Γχ2 (GeV)
mχ2 (GeV)

+ −

+ −

2

$+ \quad -$