Karlsruhe Institute of Technology

Institute of Experimental Particle Physics

Belle II

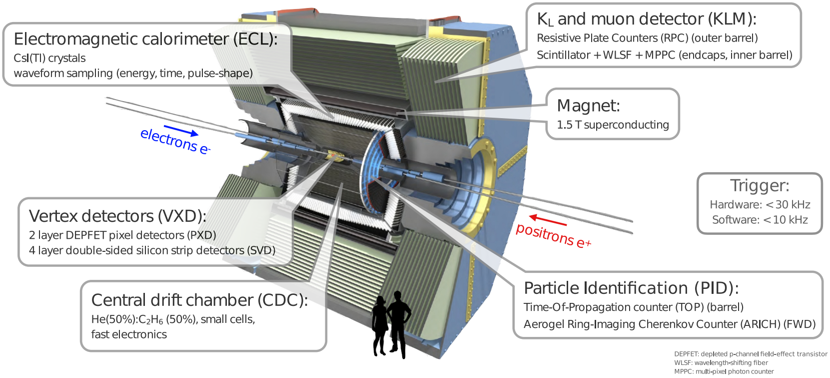
Search for inelastic dark matter in association with a dark Higgs boson at Belle II

Roadmap of Dark Matter models for Run 3, CERN

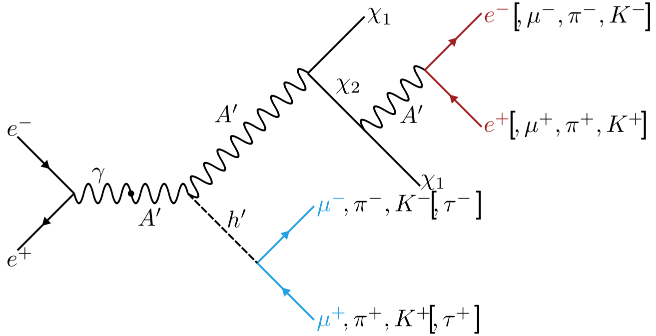
Patrick Ecker on behalf of the Belle II Collaboration | 16.05.2024

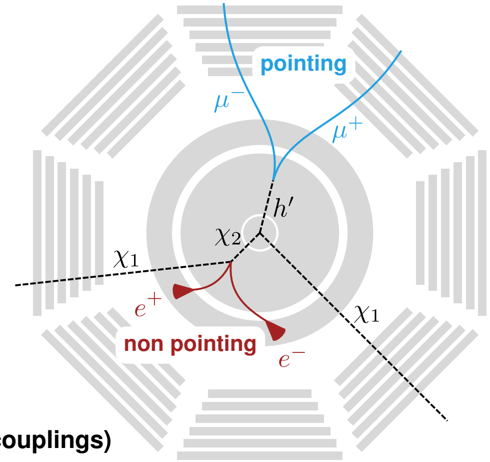
Belle II

- **Asymmetric e^+e^- collider SuperKEKB in Japan**
  - Running at the $\Upsilon(4S)$
  - Electrons: 7 GeV, Positrons: 4 GeV
- **Collected** 428 fb^{-1} **of data in Run 1**
- **Run 2 started a few months ago**
- **Well known initial conditions**
- **Little/no pile-up - clean environment**



Inelastic Dark Matter with a Dark Higgs





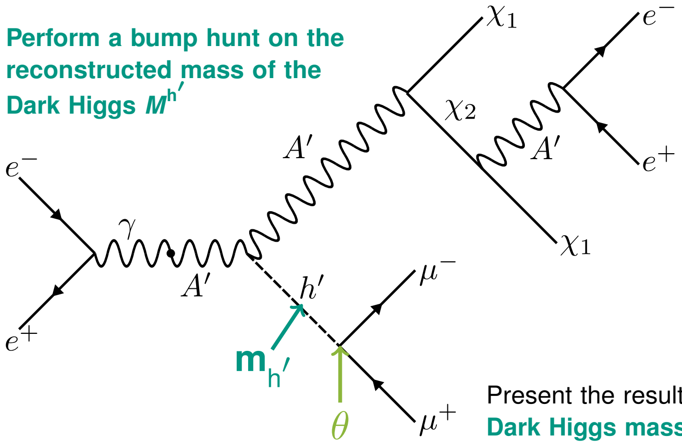
The Model

- 4 Dark Sector particles: χ_1, χ_2, h′, A′
- **7 free model parameters (3 masses, 2 mixing angles, 2 couplings)**
- **up to two displaced vertices + missing energy**

[Duerr, Ferber, Garcia-Cely, Hearty, Schmidt-Hoberg(JHEP 04 (2021), 2012.08595)]

Strategy

Perform a bump hunt on the reconstructed mass of the Dark Higgs $M^{h'}$

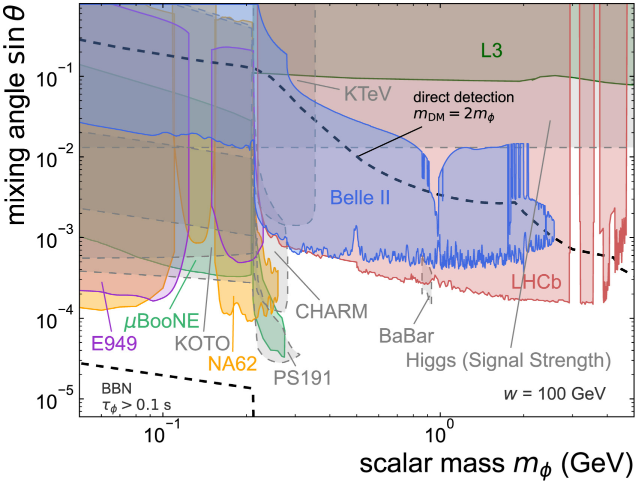


Model Parameters

- Mass of the Dark Photon $m_{A'}$
- Mass of the χ_1
- Mass of the Dark Higgs $m_{h'}$
- Mixing of the Dark Photon ϵ
- Mixing Angle of the Dark Higgs θ
- Coupling of Dark Photon to DM g_X
- Coupling of Dark Higgs to DM f

Present the results in the **plane of the Dark Higgs mass and Dark Higgs mixing angle** for a **variations of the other five parameters (around 5 per model parameter)**

Existing Limits



E949: $K^+ \to \pi^+ \phi(\to \mathrm{inv.})$
Phys. Rev. D 79 (2009) 092004

KOTO: $K_L^0 \to \pi^0 \phi(\to \mathrm{inv.})$
Phys. Rev. Lett. 126 (12) (2021) 121801

μBooNE: $K^+ \to \pi^+ \phi(\to e^+e^-, \mu^+\mu^-)$
Phys. Rev. Lett. 127 (15) (2021) 151803, Phys. Rev. D 106, 092006 (2022)

NA62: $K^+ \to \pi^+ \phi(\to \mathrm{inv.})$
JHEP 02 (2021) 201, JHEP 06 (2021) 093

PS191: $K^\pm \to \pi^\pm \phi(\to e^+e^-, \mu^+\mu^-)$
Phys. Lett. B 203(1988) 332–334, Phys. Lett. B 820 (2021) 136524

CHARM: $K^\pm \to \pi^\pm \phi(\to e^+e^-, \mu^+\mu^-)$
Phys. Lett. B 203(1988) 332–334, Phys. Lett. B 820 (2021) 136524

Belle II: $B \to K^{(*)} \phi(\to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-)$
arXiv:2306.02830 [hep-ex] 2023

KTeV: $K_L^0 \to \pi^0 \phi(\to \mu^+\mu^-)$
Phys. Rev. Lett. 84(2000) 5279–5282, Phys. Rev. D 99 (1) (2019) 015018

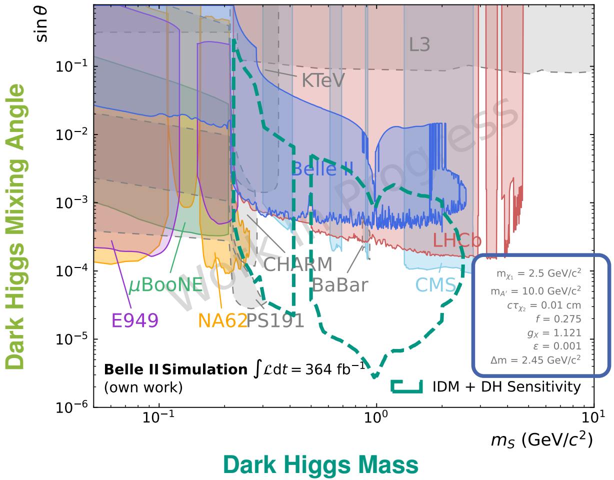
BaBar: $B \to X_S \phi(\to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-)$
Phys. Rev.Lett. 114 (17) (2015) 171801, Phys. Rev. D 99 (1) (2019) 015018

L3: $e^+e^- \to Z^* \phi$
Phys. Lett. B 385 (1996) 454–470

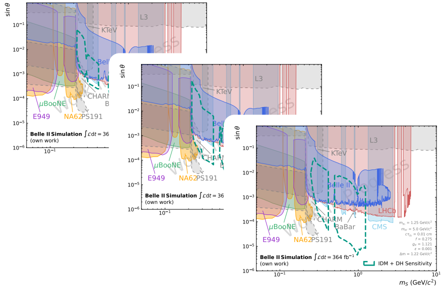
LHCb: $B \to K^{(*)} \phi(\to \mu^+\mu^-)$
Phys. Rev.Lett. 115 (16) (2015) 161802, Phys. Rev. D 95 (7) (2017) 071101,
Phys. Rev. D 99 (1) (2019) 015018

[Ferber, Grohsjean, Kahlhoefer]

Existing Limits



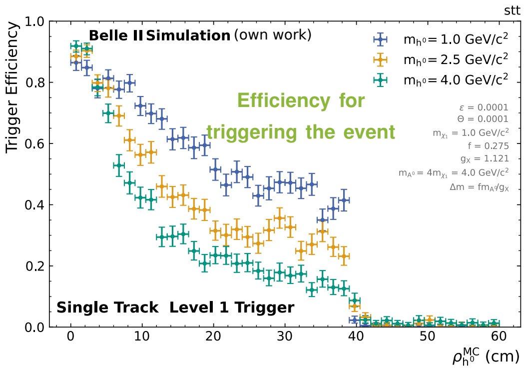
We will produce many of these very model dependent plots for the variations of the other model parameters

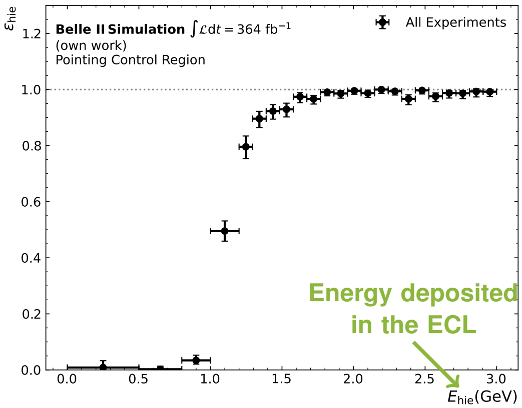


Will produce similar plots in the $m_{A'} - \epsilon$ plane, as well!

Experimental Challenges

Both the reconstruction efficiency and the track trigger efficiency drop with displacement of the vertices!



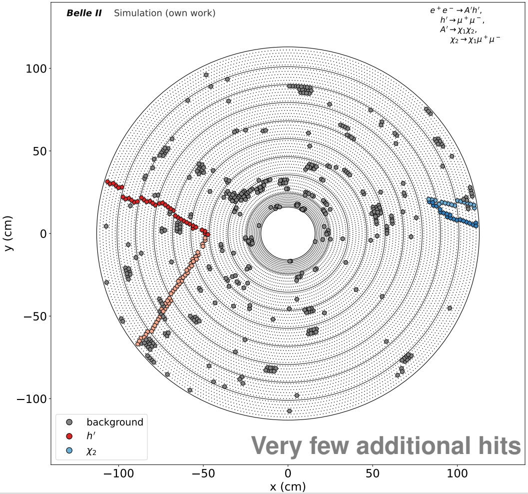


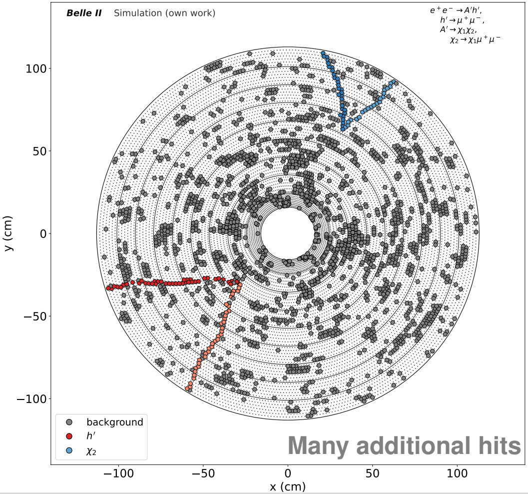
If the electrons of the $\chi_2 \rightarrow \chi_1 e^+ e^-$ carry enough energy we can trigger on them using the ECL

Experimental Challenges

The beam background conditions depend on the data taking period

Low beam background, $\mathcal{L} = 3 * 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$





High beam background, $\mathcal{L} = 6 * 10^{35} \mathrm{cm}^{-2} \mathrm{s}^{-1}$

Experimental Challenges

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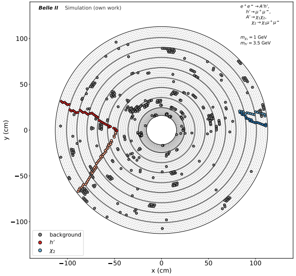
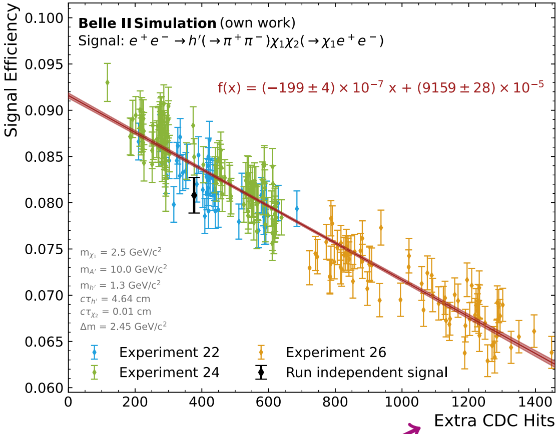
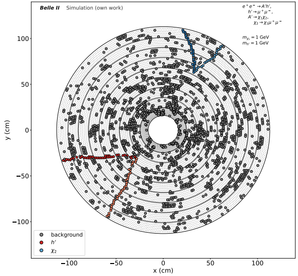
Efficiency for displaced vertices depends on the beam back-ground conditions!



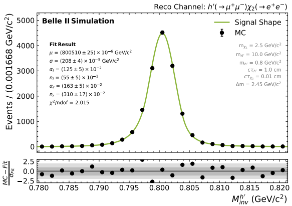


Effect can be modelled!



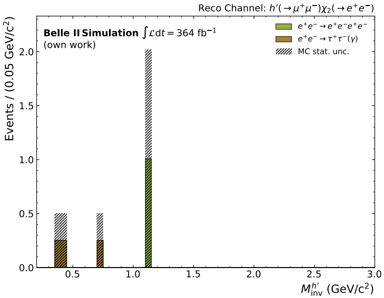
Proportional to the beam background conditions

Expected Backgrounds after Selection

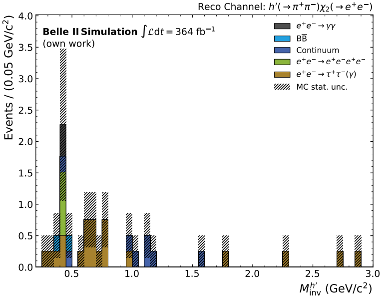


Typical signal width: $2 - 6\,\mathrm{MeV/c^2}$

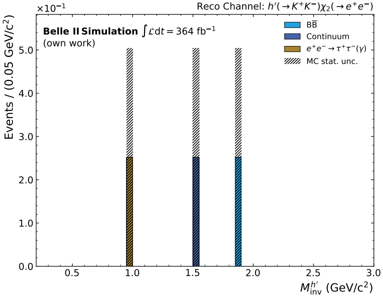
$\mathrm{h}' \to \mu^+\mu^-$



$\mathrm{h}' \to \pi^+\pi^-$



$\mathrm{h}' \to \mathrm{K}^+\mathrm{K}^-$



Very low background level in all final states

$\longrightarrow$ Perform a counting experiment, calculate semi-Bayesian p-values and derive Bayesian upper limits

*Each component scaled according to the available luminosity

Extracting the cross section

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In total we can extract four different cross sections:

Three "model independent" ones for the different final states

- $e^+e^- \rightarrow \chi_1\chi_2(\rightarrow \chi_1 e^+e^-)h'(\rightarrow \mu^+\mu^-)$
- $e^+e^- \rightarrow \chi_1\chi_2(\rightarrow \chi_1 e^+e^-)h'(\rightarrow \pi^+\pi^-)$
- $e^+e^- \rightarrow \chi_1\chi_2(\rightarrow \chi_1 e^+e^-)h'(\rightarrow K^+K^-)$

One model dependent one for the combination

- $e^+e^- \rightarrow \chi_1\chi_2(\rightarrow \chi_1 e^+e^-)h'$

In case no signal is observed, set 95% CL upper limits on the cross sections

Likelihood

$$\mathcal{L} = \frac{(\mu_{\text{sig}} + \mu_{\text{bkg}})^{N_{\text{obs}}}}{N_{\text{obs}}!} e^{-(\mu_{\text{sig}}+\mu_{\text{bkg}})}$$

with

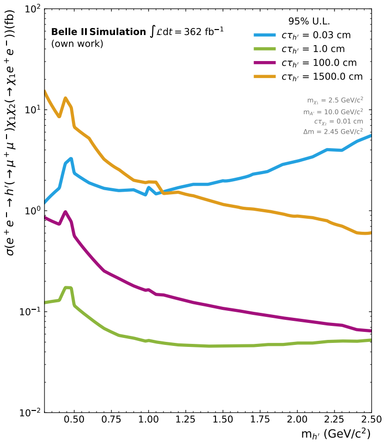
$$\mu_{\text{sig}} = \sigma \cdot \epsilon \cdot \int \mathcal{L} \mathrm{d}t$$

and for the combination

$$\mathcal{L}_{\text{total}} = \prod_{f=\mu,\pi,K} BF_f \cdot \mathcal{L}_f$$

Expected Sensitivities - "Model Independent"

$h' \to \mu^+\mu^-$



For short h′ lifetimes the sensitivity is lower since the efficiency is low due to the minimal displacement cut

For medium h′ lifetimes the sensitivity is pretty good since the displacement is large enough to pass the minimal displacement cut

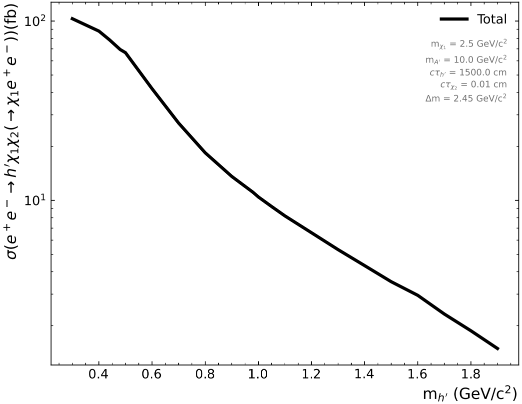
For larger h′ lifetimes the sensitivity starts to drop since the finding efficiency for displaced tracks drops with the displacement

For very large h′ lifetimes the sensitivity is low since many of the Dark Higgs bosons decay outside of the detector which leads to worse efficiency

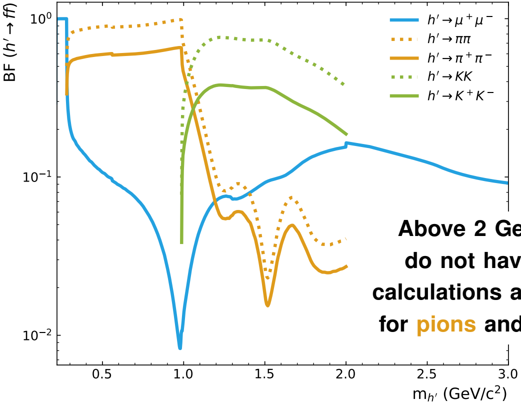
*Systematics not (yet) included, but we are statistically limited

Becoming Model Dependent

Cross section
(calculated with MadGraph)



h′ branching fraction
(Current Physics Beyond Colliders benchmark, state of the art BF values from 2305.16169)



Above 2 GeV we do not have BF calculations available for pions and kaons

Need to compare the calculated cross section with the expected sensitivity from the limit to exclude certain parts of the parameter space

Becoming Model Dependent

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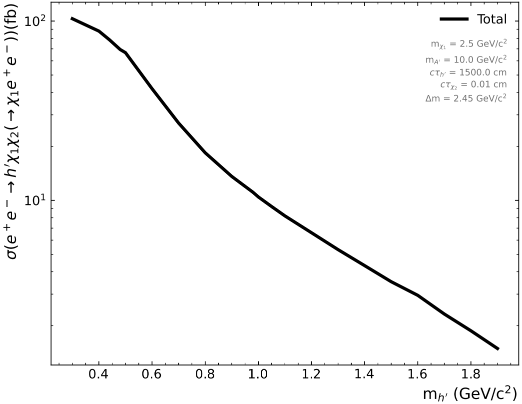

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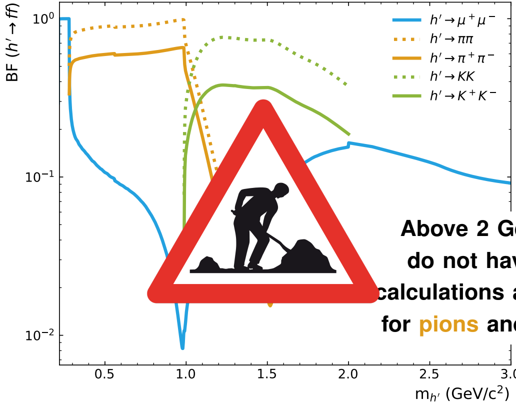

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Expected Sensitivity of the Combination

These are only two out of many configurations!

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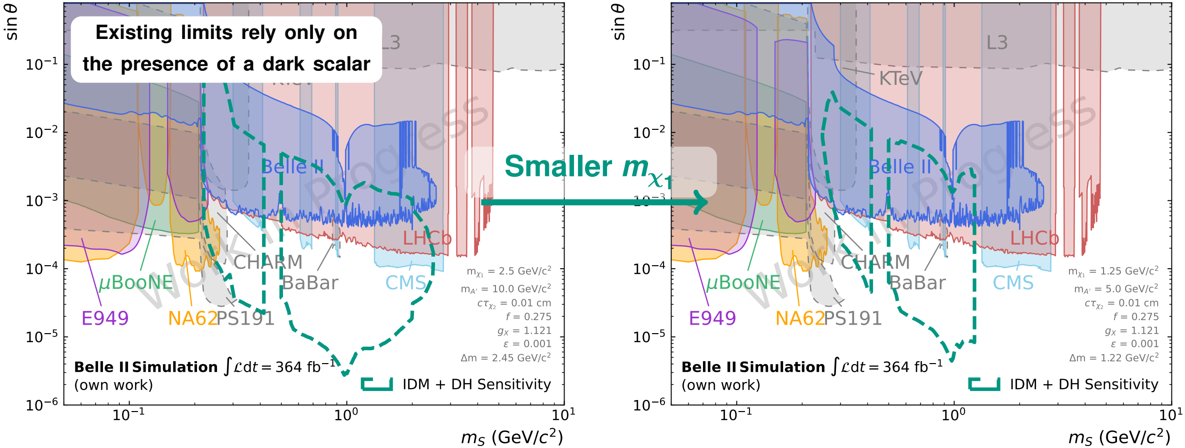

Tested parameter configurations show very competitive sensitivity!

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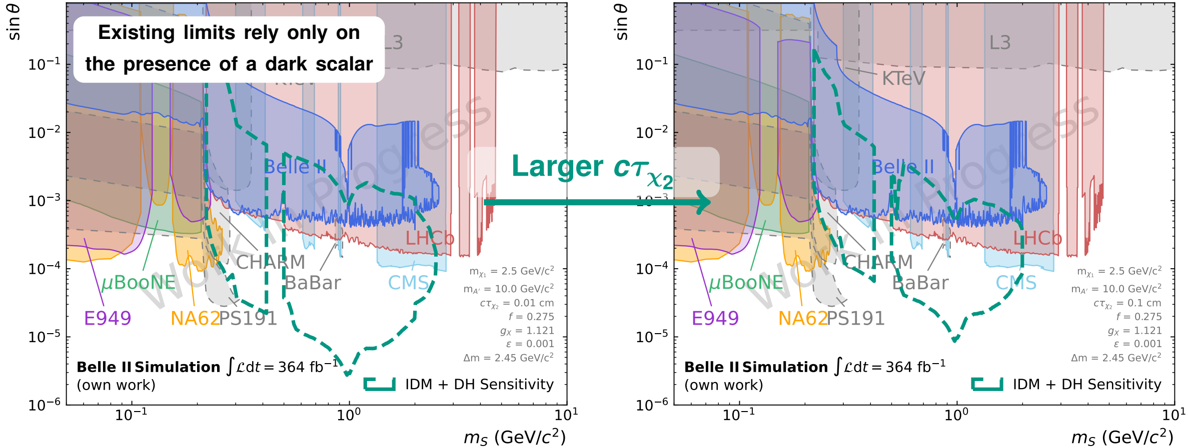

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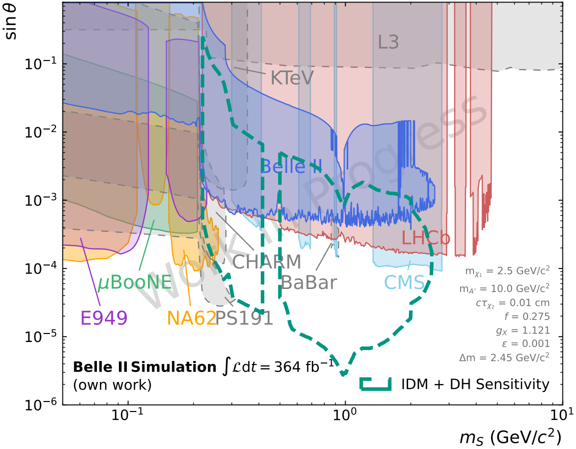
Summary

- **Showed a strategy for a search for inelastic Dark Matter with a Dark Higgs boson in a seven dimensional parameter space**
- **Expect very low background: perform a counting experiment and a Bayesian analysis**
- **Can derive both model independent and model dependent limits on the signal cross section**
- **Sensitivity studies look promising to reach unexplored parameter space**



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Backup