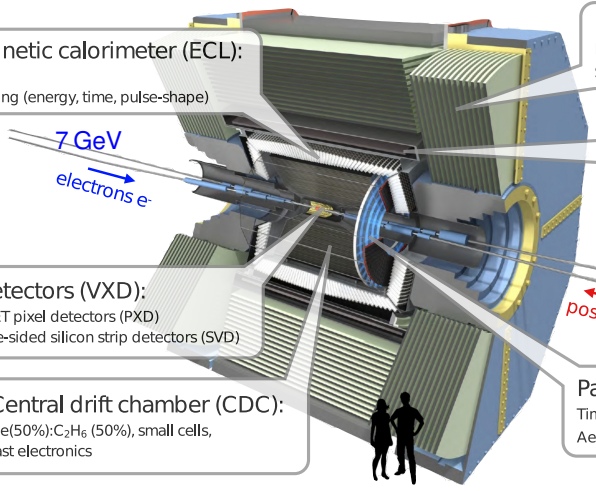
Search for Inelastic Dark Matter with a Dark Higgs at Belle II

11th KSETA Plenary Workshop, Wildberg

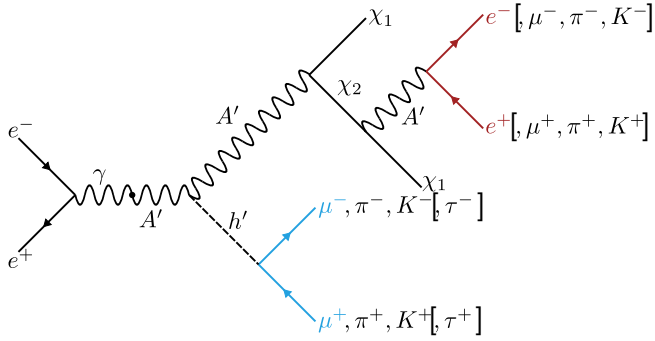
Patrick Ecker, Giacomo De Pietro, Jonas Eppelt, Torben Ferber, Pablo Goldenzweig | 15.03.2024

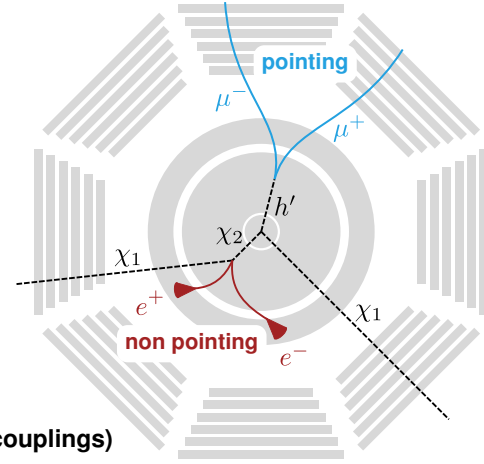
Belle II



DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

Inelastic Dark Matter with a Dark Higgs





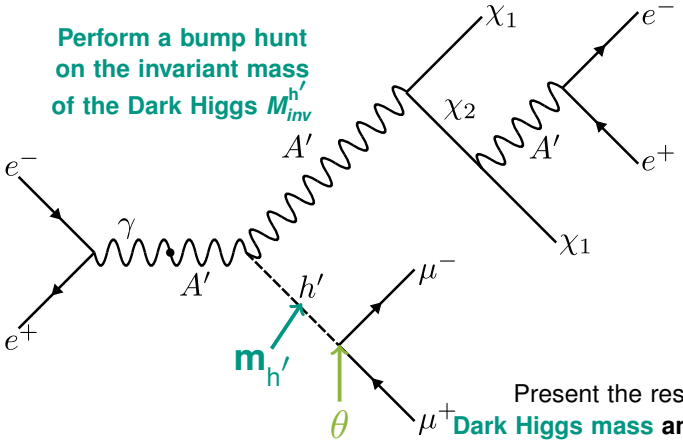
The Model

- 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

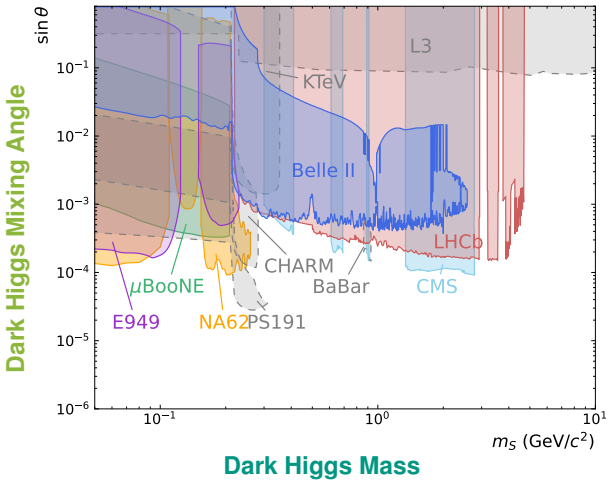
Perform a bump hunt on the invariant mass of the Dark Higgs $M_{inv}^{h'}$



- Mass of the Dark Photon
- Mass of the χ_1
- Mass of the Dark Higgs
- Mixing Angle of Dark Photon
- Mixing Angle of Dark Higgs
- Coupling of Dark Photon to DM g_χ
- Coupling of Dark Higgs to DM f

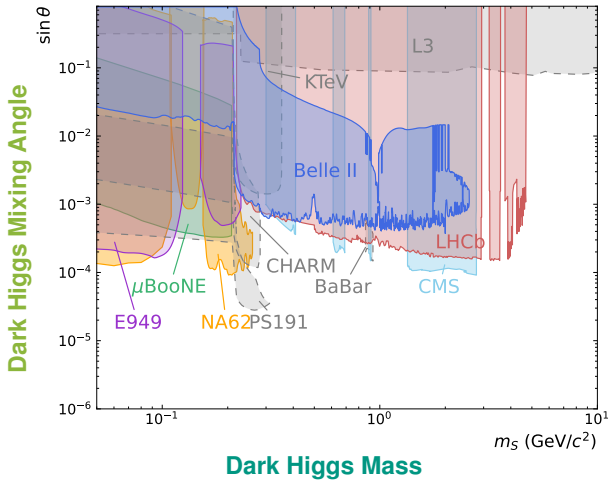
Present the results in the **plane of the Dark Higgs mass and Dark Higgs mixing angle** for a **grid of the other five parameters ($\mathcal{O}(5)$ per model parameter)**

Existing Limits

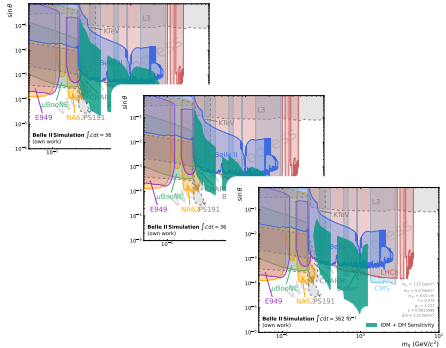


We will produce many of these plots for the variations of the other model parameters

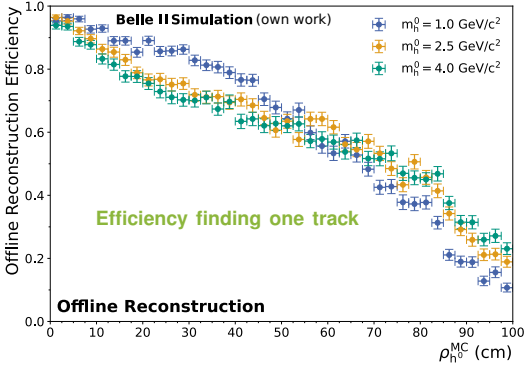
Existing Limits



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



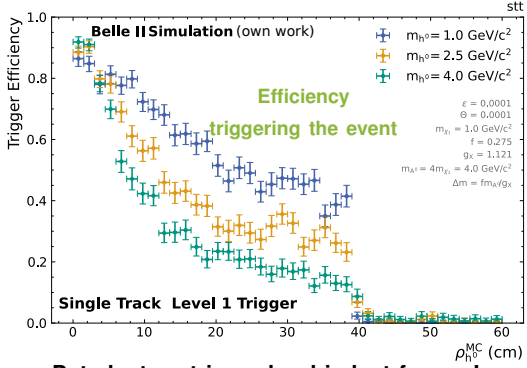
Experimental Challenges



Efficiency loss could be recovered if new track finding algorithms become available

→ Poster by Lea Reuter

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



Data lost on trigger level is lost forever!

→ Currently trigger on the electrons of the $\chi_2 \to e^+e^-$ with the ECL ($E_{sum} > 1$ GeV)!

Selection - Background Sources

SM background that consists of 4 tracks

Pair Conversions

K^0_S and Λ decays

Random combination of tracks

Selection - Background Sources

SM background that consists of 4 tracks

Require one displaced vertex

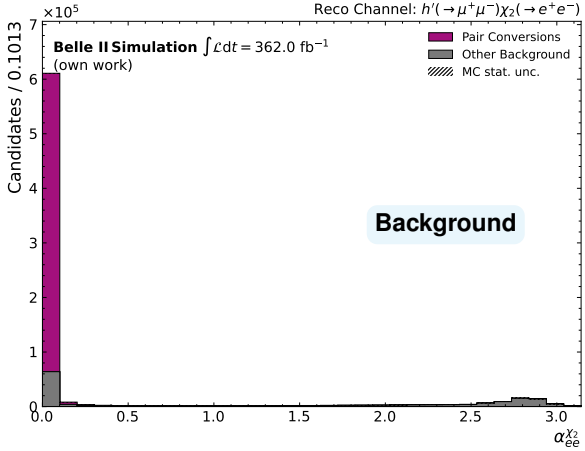
Pair Conversions

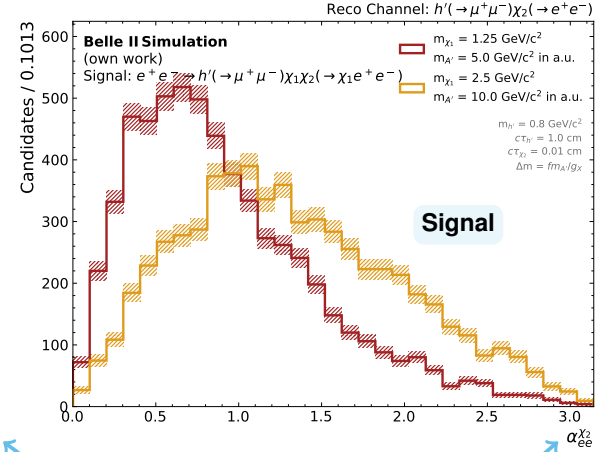
K_S^0 and Λ decays

Mass veto

Random combination of tracks

Selection - Pair Conversions





opening angle between the electron pair

Selection - Background Sources

SM background that consists of 4 tracks

Require one displaced vertex

Pair Conversions

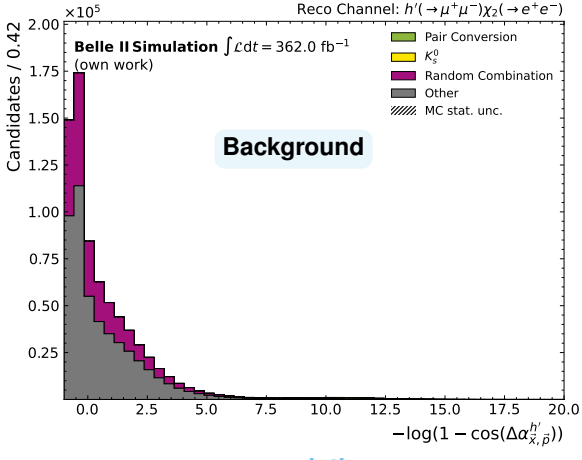
Opening angle

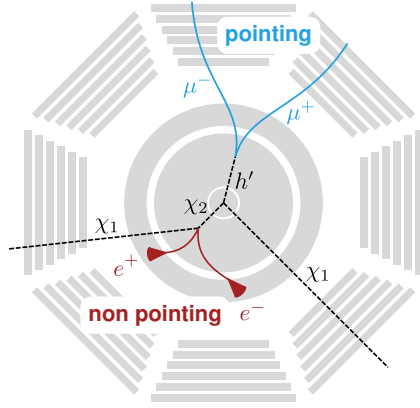
K_S^0 and Λ decays

Mass veto

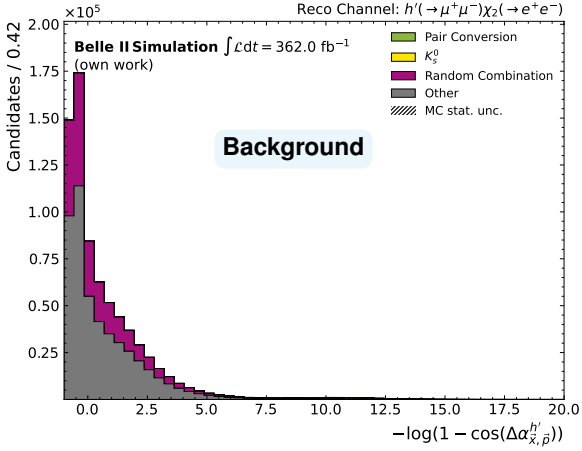
Random combination of tracks

Selection - Random Combinations

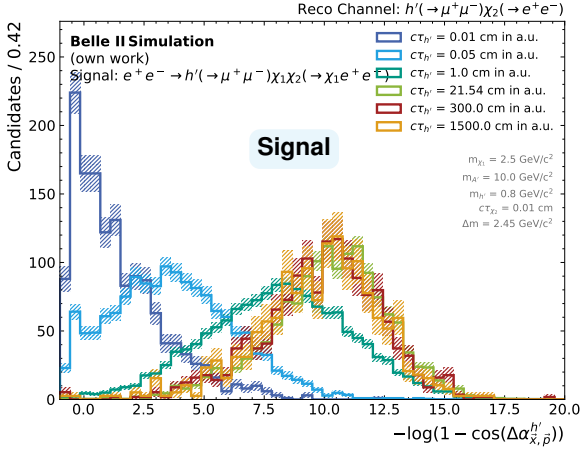




Selection - Random Combinations



more pointing



Selection - Background Sources

SM background that consists of 4 tracks

Require one displaced vertex

Pair Conversions

Opening angle

K_S^0 and Λ decays

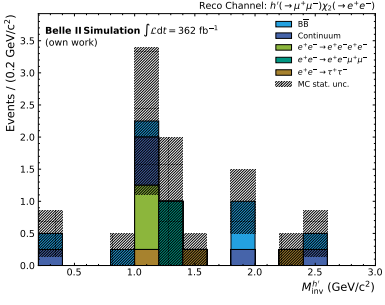
Mass veto

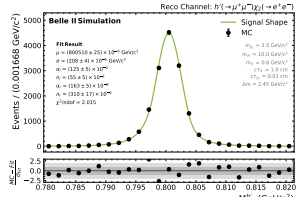
Random combination of tracks

Pointiness

Background Level after Selection

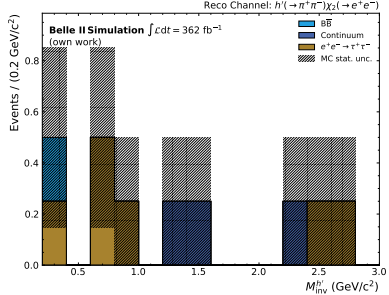
$h' \to \mu^+\mu^-$



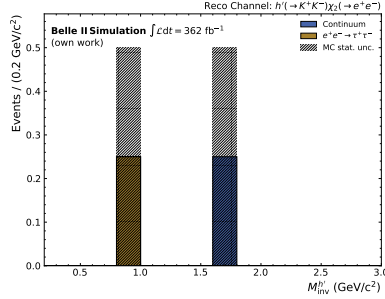


Typical signal width:
$2 - 6\,\text{MeV}/c^2$

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



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



Very low background level in all final states
→ Perform a counting experiment and a Bayesian analysis

*Each component scaled according to the available luminosity

Extracting the cross section

In total we can extract four different cross sections:

Three "model independent" ones for the different final states

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

One model dependent one for the combination

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

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

Likelihood

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

with

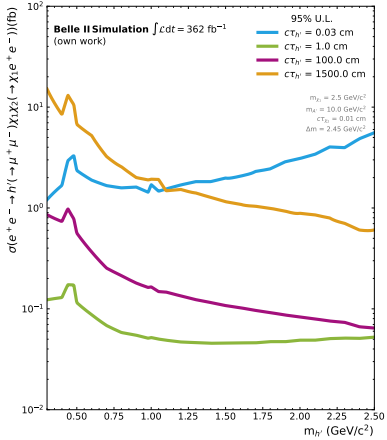
$$n_{\text{sig}} = \sigma \cdot \epsilon \cdot \int \mathcal{L} \mathrm{d}t$$

and for the combination

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

Expected Sensitivities - "Model Independent"

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



*Systematics not (yet) included

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

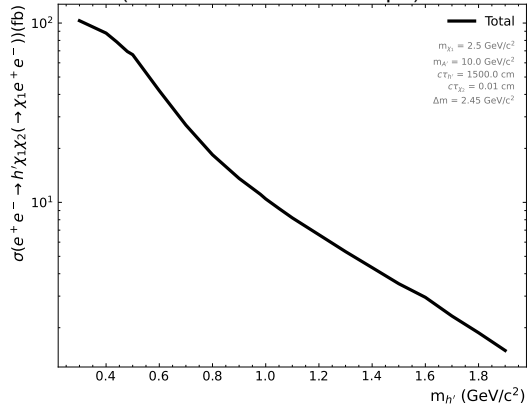
For medium lifetimes the sensitivity is pretty good since the displacement is large enough to pass the minimal displacement cut

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

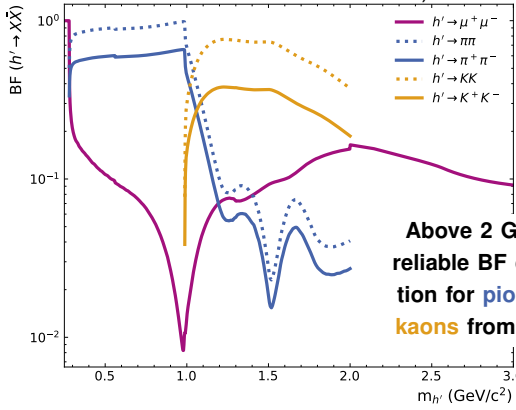
For very large lifetimes the sensitivity is low since many of the Dark Higgs bosons decay outside of the detector which leads to worse efficiency

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 no reliable BF calculation for pions and kaons from theory

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

Cross section
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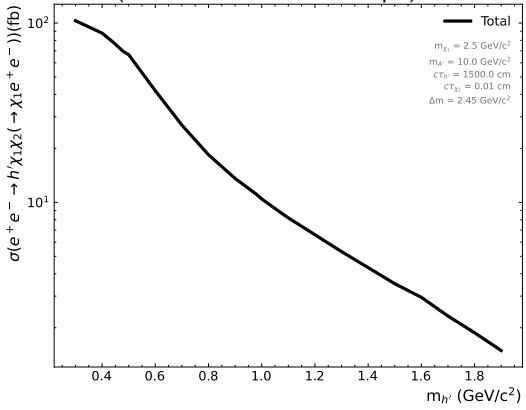

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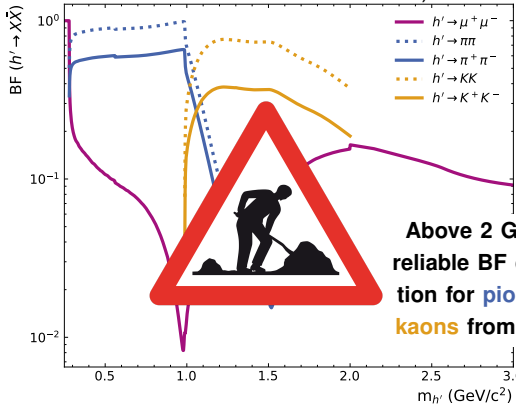

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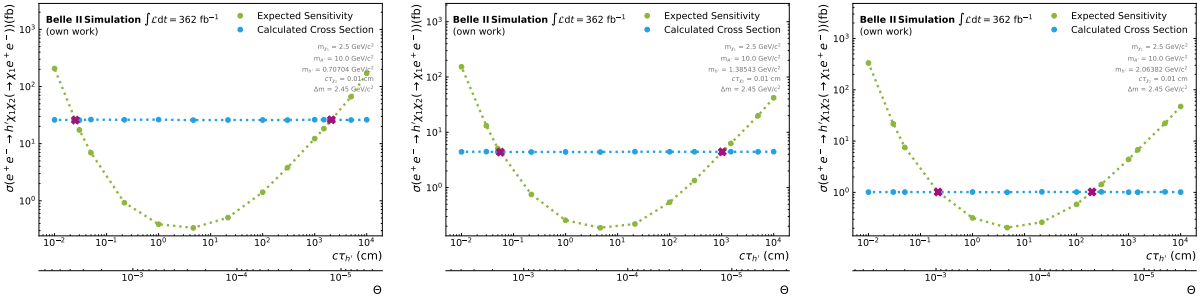
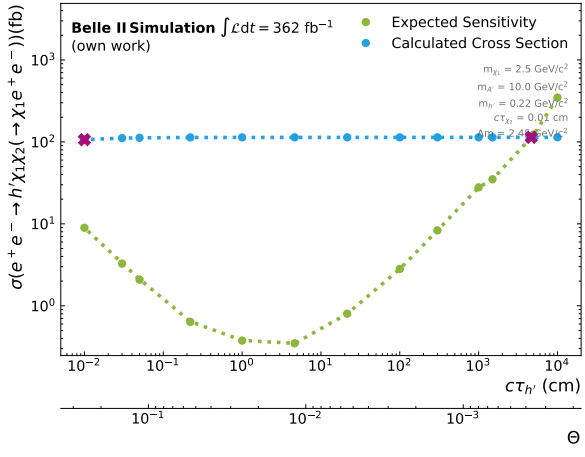
Calculated vs. Expected Cross Section

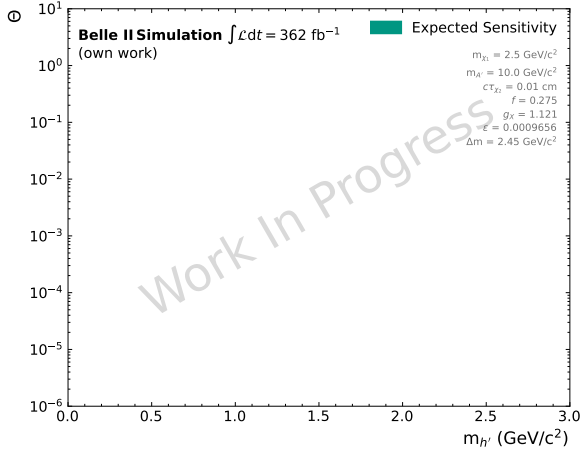
h′ mass



Can exclude everything that is below the calculated and above the expected line

How to Draw Exclusion Plots





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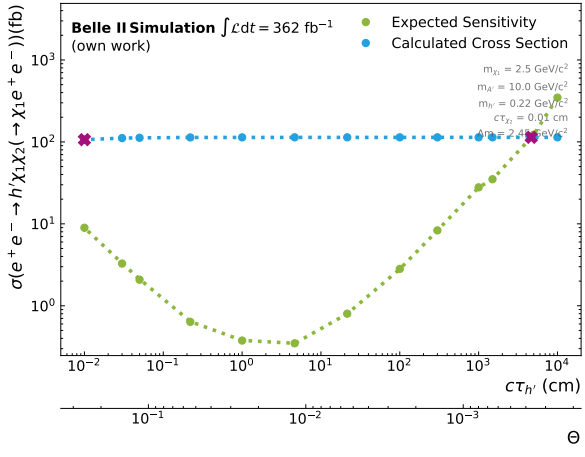

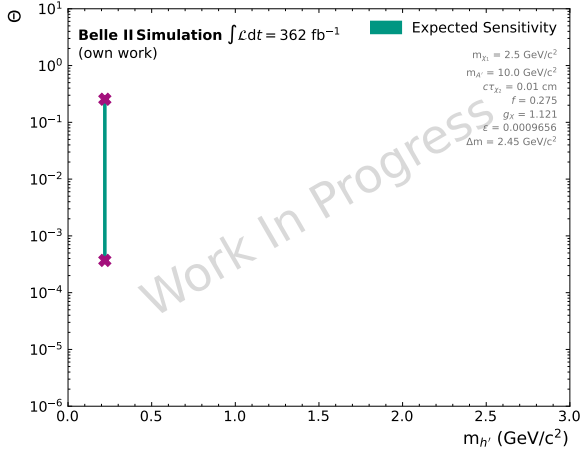

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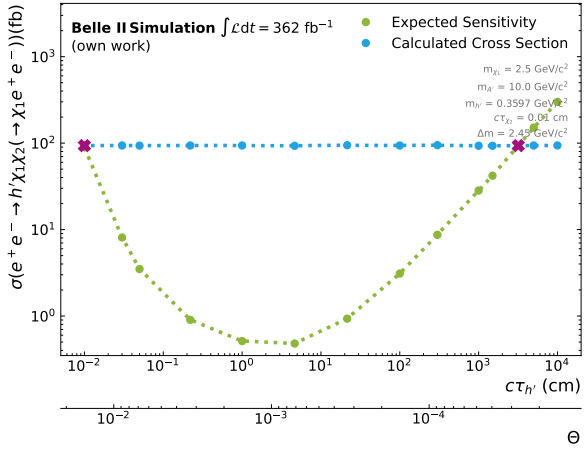

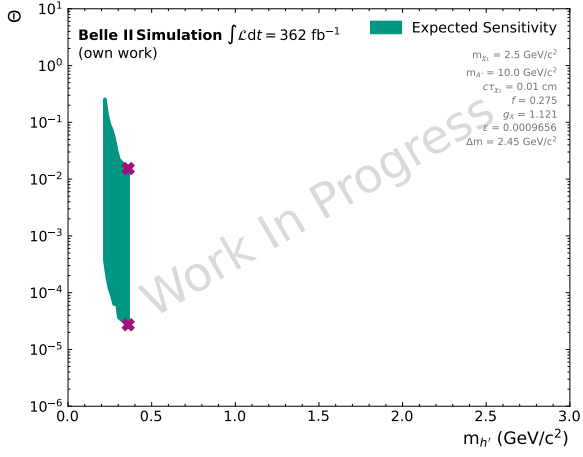

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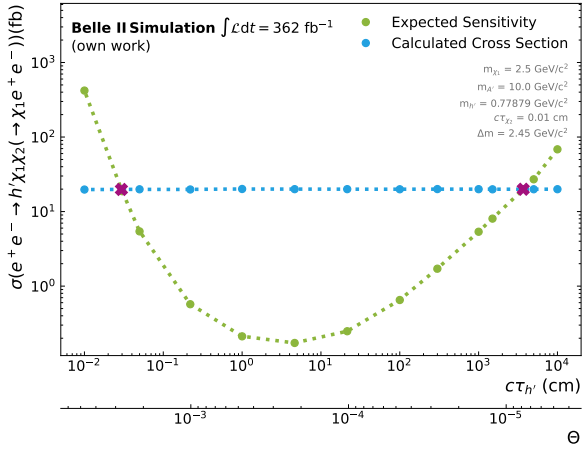

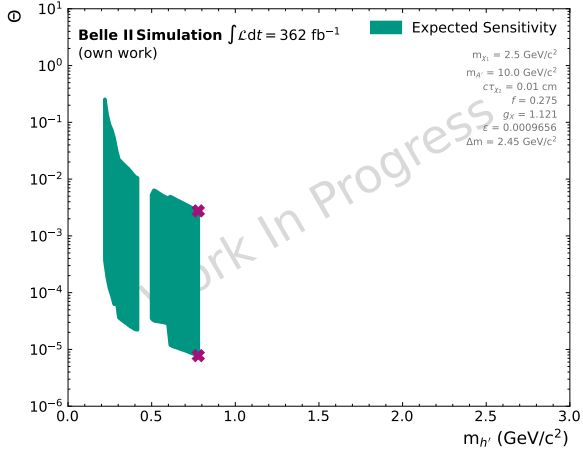

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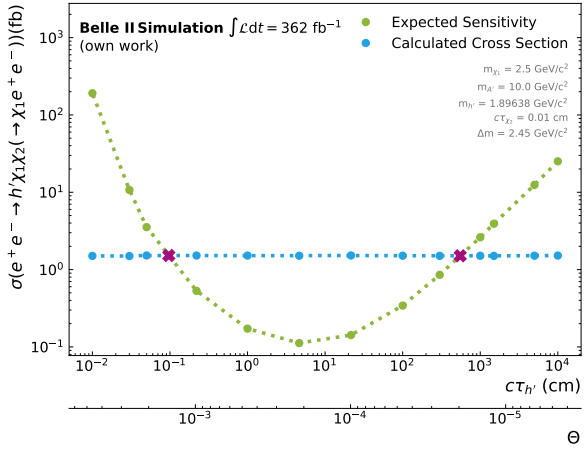
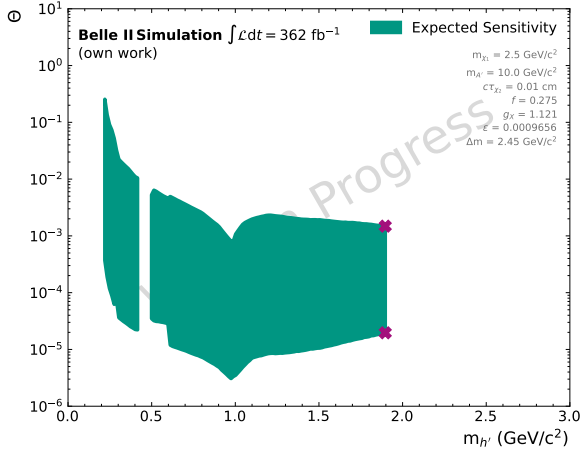
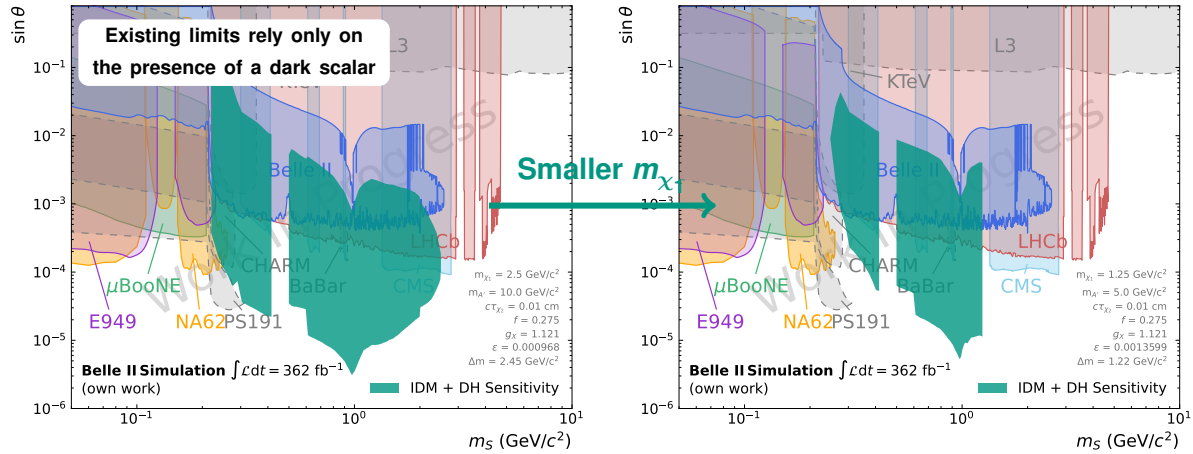




Expected Sensitivity of the Combination

These are only two out of many configurations ($\mathcal{O}(20)$)!

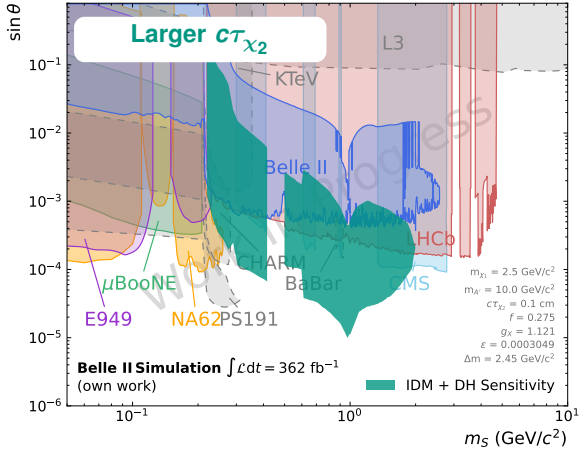


Tested parameter configurations show very competitive sensitivity!

*Systematics not (yet) included

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
- First sensitivity studies look promising to reach unexplored parameter space

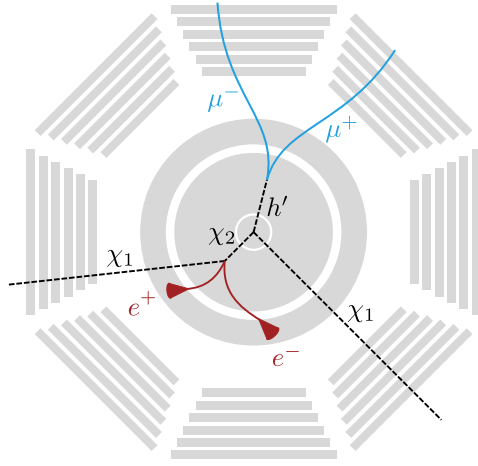


*Systematics not (yet) included

Backup

Recombination

- **Signal**
  - **Build h′ candidates:** $h' \to [\mu^+\mu^-; \pi^+\pi^-; K^+K^-]$
  - **Build χ_2 candidates:** $\chi_2 \to e^+e^-$
  - Perform **vertex fit** on both vertices
- **Build ROE**
  - Track requirements: θ in CDC acceptance, $N_{hits}^{CDC} > 20$, $dr < 0.5\,\text{cm}$, $|dz| < 2\,\text{cm}$
  - ECL requirements: θ in CDC acceptance, *clusterNHits* < 1.5, $|clusterTiming| < 200\,\text{ns}$, $E >$[80, 70, 100] MeV (FWD, Barrel, BWD)
- **Missing Energy**
  - $E_{miss} = E_{cms} - E_{\mu^+} - E_{\mu^-} - E_{e^+} - E_{e^-}$



Selection Criteria

FSP Requirements

- more than 20 tracking hits
- PID Variable score > 0.5

Model Specific Cuts

- $1\,\text{GeV} < E_{miss} < 9\,\text{GeV}$
- Dark Higgs Pointing Angle: $-\log(1 - \cos(\Delta\alpha^{h'}_{\vec{x},\vec{p}})) > 7.5$
- $M^{\chi_2}_{\ell\ell} < 2.5\ \text{GeV}/\text{c}^2$

Vertex Requirements

- $\chi^{h'}_{vertex} > 0.1$ and $\chi^{\chi_2}_{vertex} > 0.1$
- $\rho^{h'} > 0.05\,\text{cm}$ **or** $\rho^{\chi_2} > 0.05\,\text{cm}$ (in the pion final state $\rho > 0.2\,\text{cm}$)

Suppress Pair Conversions

- $\alpha^{h'}_{\ell\ell} > 0.1$
- $\alpha^{\chi_2}_{\ell\ell} > 0.1$

ROE Cuts

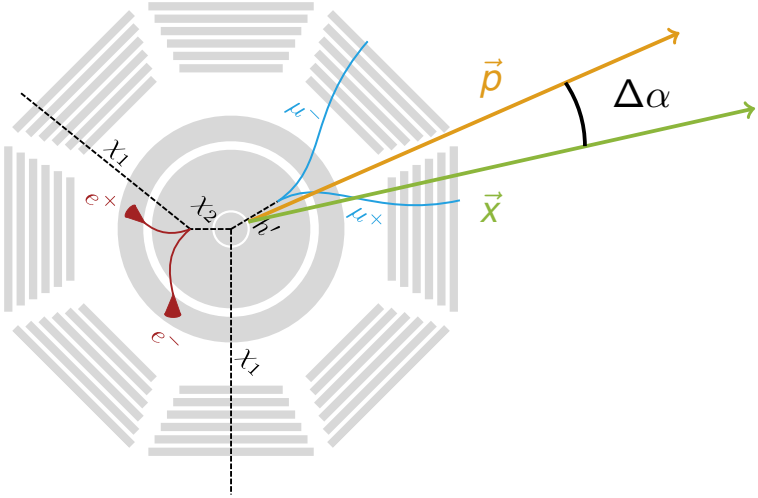
- $E^{neutral}_{extra} < 1.0\ \text{GeV}$
- No additional tracks in ROE

K^0_S-veto, ...

- $M^{h'}_{\pi\pi} < 0.489\ \text{GeV}/\text{c}^2$ or $M^{h'}_{\pi\pi} > 0.507\ \text{GeV}/\text{c}^2$
- Λ^0-veto

One selection for all model parameter configurations!

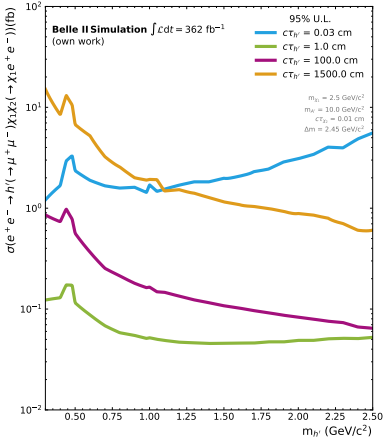
Dark Higgs Pointing Angle



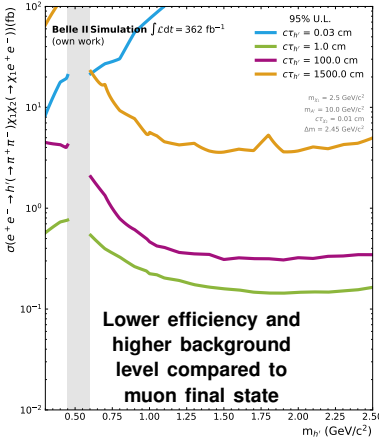
Expected Sensitivities - "Model Independent"

Karlsruhe Institute of Technology

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



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



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