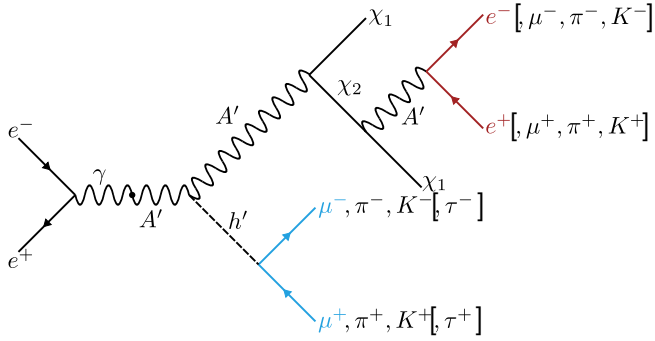
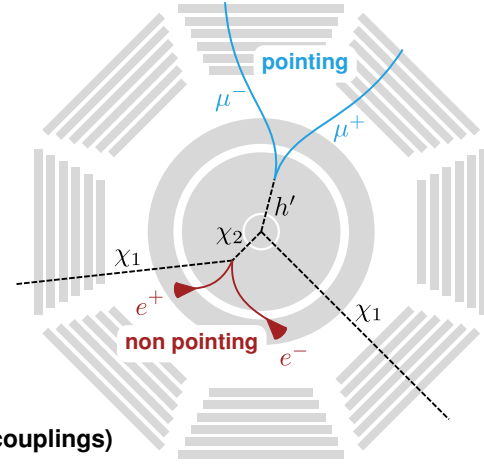
Search for Inelastic Dark Matter with a Dark Higgs at Belle II

Light Dark World 2023, Karlsruhe

Patrick Ecker on behalf of the Belle II collaboration | 19.09.2023

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)]

Presentation of the Limits for this 7D Parameter Space

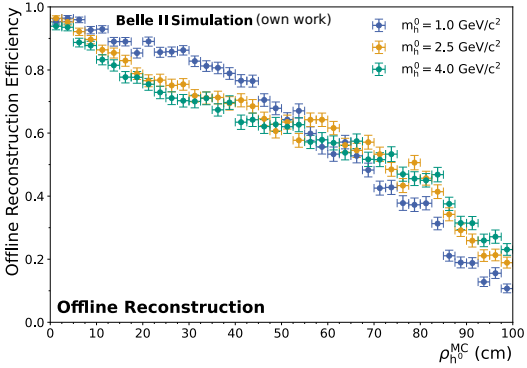
- **Perform a bump hunt on the invariant mass of the Dark Higgs $M_{inv}^{h'}$**
- Present the results in the **plane of the Dark Higgs mass and Dark Higgs mixing angle** for a **grid of the other five parameters ($\mathcal{O}(5)$ per model parameter)**

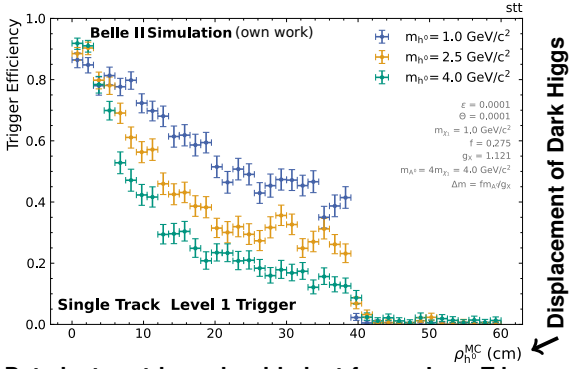
Model Parameters

- **Mass of the Dark Photon**
- **Mass of the χ_1**
- **Mass of the Dark Higgs**
- **Mixing Angle of Dark Photon with the SM photon**
- **Mixing Angle of Dark Higgs with the SM Higgs boson**
- **Coupling of Dark Photon to DM g_χ**
- **Coupling of Dark Higgs to DM f**

Experimental Challenges

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



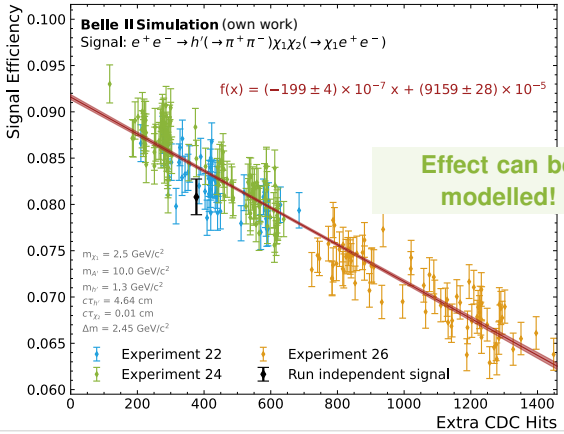


Efficiency loss can be recovered when reprocessing with new algorithms

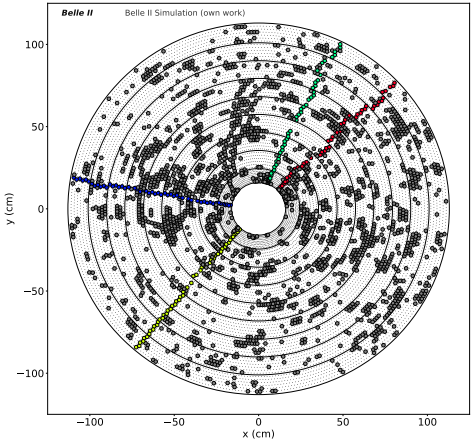
Data lost on trigger level is lost forever! → Trigger on the electrons of the χ_2 → e^+e^- with the electromagnetic calorimeter ($E_{sum} > 1$ GeV)!

Experimental Challenges

Efficiency depends on the beam background conditions!



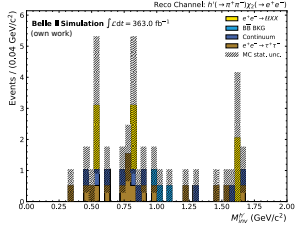
Effect can be modelled!

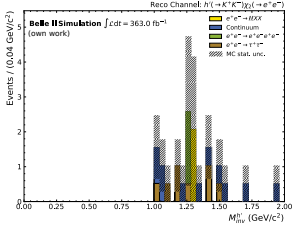


CDC hits with high beam background level

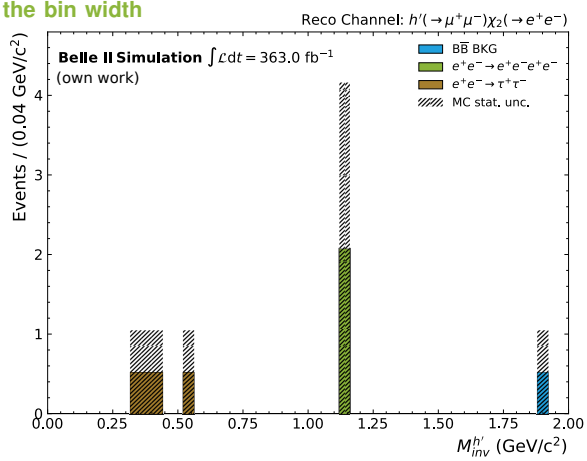
Background Distributions

- **One selection for all model parameter configurations:** Requiring at least one displaced to get rid of most SM background, suppress pair conversions and K^0_S's, etc.
- Our current selection delivers a **nearly background free** scenario **in all final states** in the signal window

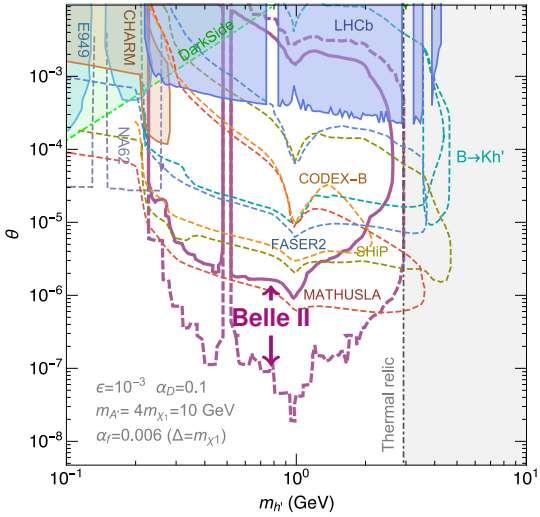




signal width is approximately 10 times smaller than the bin width



Projections

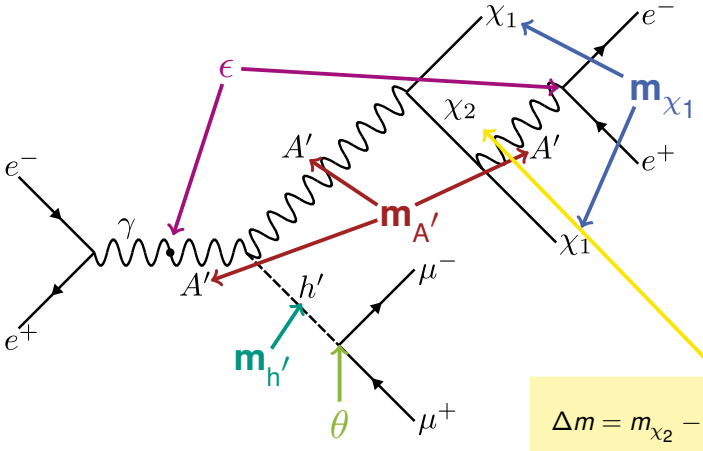


Expected Belle II sensitivity from the pheno paper 100 fb^{-1} **(solid) and** 50 ab^{-1} **(dashed)** [Duerr, Ferber, Garcia-Cely, Hearty, Schmidt-Hoberg (JHEP 04 (2021), 2012.08595)]

- **Analysis ongoing with current Belle II dataset of** 363 fb^{-1}
- **Our efficiency is lower than in JHEP 04 (2021), 0-25% depending on model parameters and final state → Expect around one order of magnitude less sensitivity**
- **Expect to cover a huge unexplored region of parameter space**
- **Interesting Field**
  - Belle II dark scalar search [2306.02830]
  - iDM pheno paper [Duerr, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, Tunney (JHEP 02 (2020) 039, 1911.03176)]
  - iDM seach at CMS [2305.11649]

Backup

Model Parameters



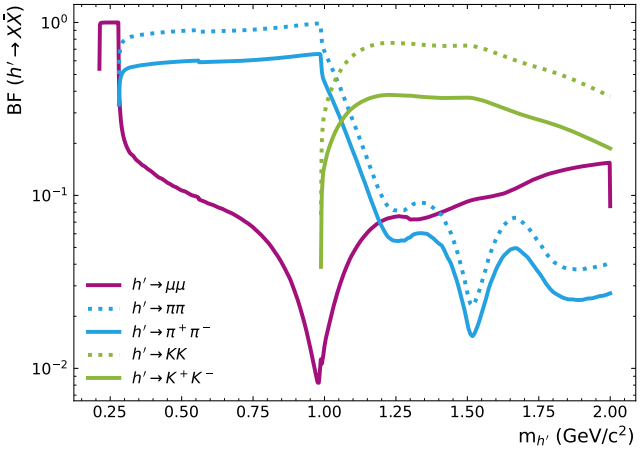
- Mass of the Dark Photon
- Mass of the χ_1
- Mass of the Dark Higgs
- Mixing Angle of Dark Photon
- Mixing Angle of Dark Higgs
- Coupling of Dark Photon to DM g_χ
- Coupling of Dark Higgs to DM f

$$\Delta m = m_{\chi_2} - m_{\chi_1} \approx \frac{f}{g_\chi} \cdot \mathrm{m}_{A'}$$

7 free parameters

Dark Higgs Branching Fractions

- Until now only looked into the $h' \to \mu^+\mu^-$ final state
- In most of the Dark Higgs mass region the **decay into pions/kaons dominates**
- **Include also these final states** in the analysis
- Still only consider $\chi_2 \to e^+e^-$ to use hie trigger line
- $\mathrm{BF}(h' \to \pi^+\pi^-) = \frac{2}{3}\mathrm{BF}(h' \to \pi\pi)$
- $\mathrm{BF}(h' \to K^+K^-) = \frac{2}{4}\mathrm{BF}(h' \to KK)$



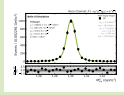
Analysis Strategy

Generating Signal MC using MadGraph5

Simulate and reconstruct the generated events

Recombination and loose pre-selection

Estimate the **signal window** (SW) via fitting the $M_{inv}^{h'}$ signal shape



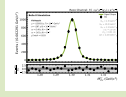
Optimize the selection in the SW

Study the **trigger performance** (L1 and HLT) on the selection

Bump hunt in $M_{inv}^{h'}$

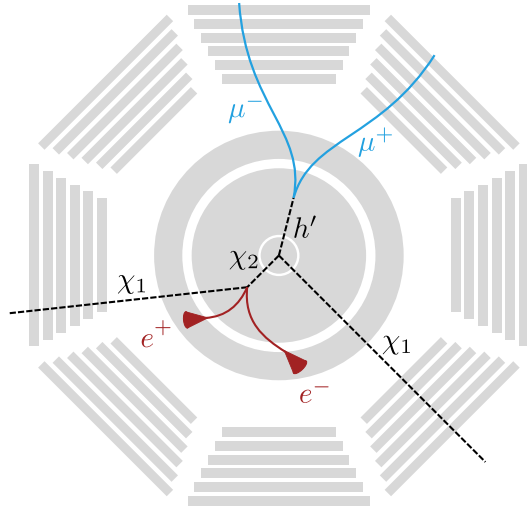
Study the sensitivity and **limit setting**

Fit the signal (and background) **shape** in $M_{inv}^{h'}$



Recombination

- **Used Versions**
  - MC15 run-independent Background MC
  - Private signal MC produced with release-06-00-08
  - light-2210-devonrex
- **Signal**
  - **Build h′ candidates:** $h' \to \mu^+\mu^-$
  - **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, $E > 50\,\text{MeV}$
- **Missing Energy**
  - $E_{miss} = E_{cms} - E_{\mu^+} - E_{\mu^-} - E_{e^+} - E_{e^-}$



Selection Criteria

FSP Requirements

more than 20 tracking hits

ChargedPIDMVA score > 0.5

Model Parameter Dependent Cuts

$X < E_{miss} < Y$

Dark Higgs Pointing Angle:
$-\log(1 - \cos(\Delta\alpha_{\vec{x},\vec{p}}^{h'})) > X$

$M_{\ell\ell}^{\chi_2} < 2.5\ \mathrm{GeV/c^2}$

Vertex Requirements

$\chi_{vertex}^{h'} > 0.001$ and $\chi_{vertex}^{\chi_2} > 0.001$

$\chi_{vertex}^{h'} > 0.1$ **or** $\chi_{vertex}^{\chi_2} > 0.1$

$\rho^{h'} > 0.05\,\mathrm{cm}$ **or** $\rho^{\chi_2} > 0.05\,\mathrm{cm}$
for pions > 0.2 cm

Suppress Pair Conversions

$\alpha_{\ell\ell}^{h'} > f\left(p, m_{h'}\right)$

$\alpha_{\ell\ell}^{\chi 2} > 0.1$

ROE Cuts

$nE_{extra} < 1.0\ \mathrm{GeV}$

No additional tracks in ROE

K_S^0-veto, ...

$M_{\pi\pi}^{h'} < 0.489\ \mathrm{GeV/c^2}$
or
$M_{\pi\pi}^{h'} > 0.507\ \mathrm{GeV/c^2}$

Λ^0-veto

Signal Shape Fits

- Fitting the signal shape using a **Double Sided Crystal Ball** function
- **Fixing the n_l and n_r parameters** to $n_{l/r} = 3$ to get a more stable fit
- All other paramters are kept floating
- Fix the shape parameters in the final fit

Double Sided Crystal Ball

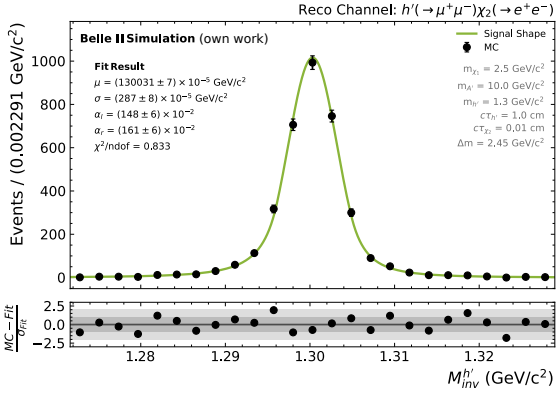
$$\vec{\Theta} = (\mu, \sigma, \alpha_l, \alpha_r, n_l, n_r)$$

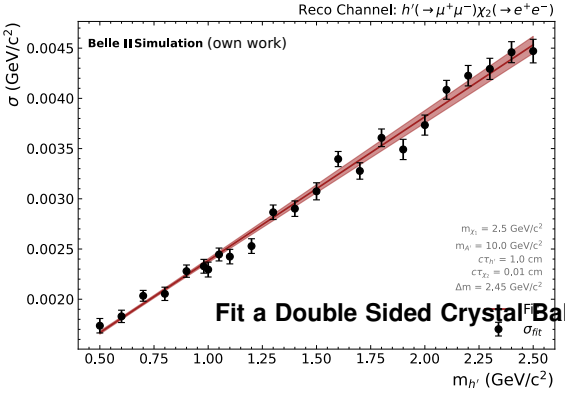
$$f\left(x; \vec{\Theta}\right) = \begin{cases} A_l \left(B_l - \frac{x-\mu}{\sigma}\right)^{-n_l} & \text{for } \frac{x-\mu}{\sigma} < \alpha_l, \\ \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) & \text{for } \alpha_l \leq \frac{x-\mu}{\sigma} \leq \alpha_r, \\ A_r \left(B_r - \frac{x-\mu}{\sigma}\right)^{-n_r} & \text{for } \frac{x-\mu}{\sigma} > \alpha_r, \end{cases}$$

$$A_{l/r} = \left(\frac{n_{l/r}}{|\alpha_{l/r}|}\right)^{n_{l/r}} \exp\left(-\frac{|\alpha_{l/r}|^2}{2}\right)$$

$$B_{l/r} = \frac{n_{l/r}}{|\alpha_{l/r}|} - |\alpha_{l/r}|$$

Signal Shape





Fit a Double Sided Crystal Ball on th

- **Signal width of $\mathcal{O}(2-6\,\mathrm{MeV})$** (given by detector resolution)
- **The width varies with the Dark Higgs mass $m_{h'}$ and the Dark Higgs lifetime**