# Search for a dark photon and a visible long-lived dark higgs boson at the Belle II experiment

La Thuile 2025 - Les Rencontres de Physique de la Vallée d'Aoste, *9-15 March 2025*

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- Introduction
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  - Analysis overview
- Preliminary studies
  - Signal generation
  - Background suppression
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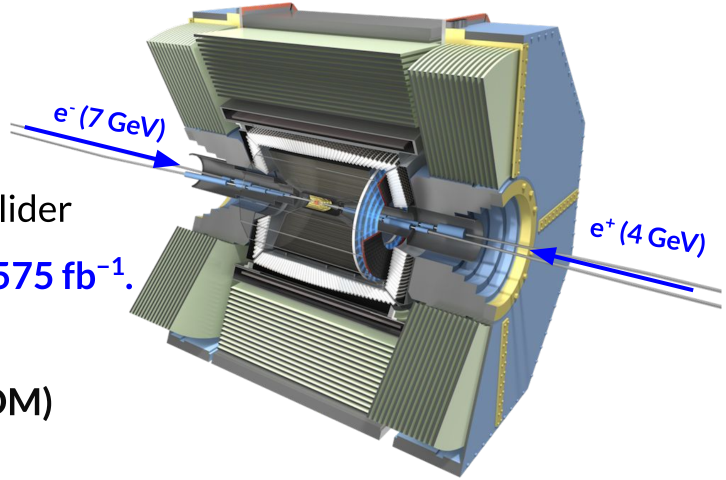
# Introduction

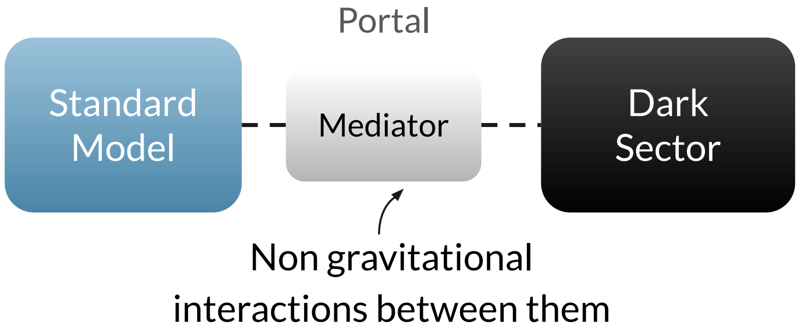
# The Dark Sector at Belle II




- **Intensity frontier experiment**
  - Operating at the SuperKEKB accelerator in Japan, an $e^+e^-$ asymmetric energy collider
  - Current data taking status: Recorded a total integrated luminosity of more than **575 fb$^{-1}$.**

➢ **Provides a unique opportunity to search for new physics such as dark matter (DM)**

DM could be part of a larger hidden/dark sector, interacting with Standard Model (SM) matter **very weakly via subtle mixing** through ***portals***.




➢ ***High sensitivity to dark sectors :*** Can access the mass range naturally favored by light dark sectors at **$M_{\text{Dark matter}}$ ~ O (MeV – GeV)**

➢ ***Large potential for dark matter discoveries***

High luminosity, dedicated triggers and excellent reconstruction capabilities for low multiplicity final states and missing energy signatures

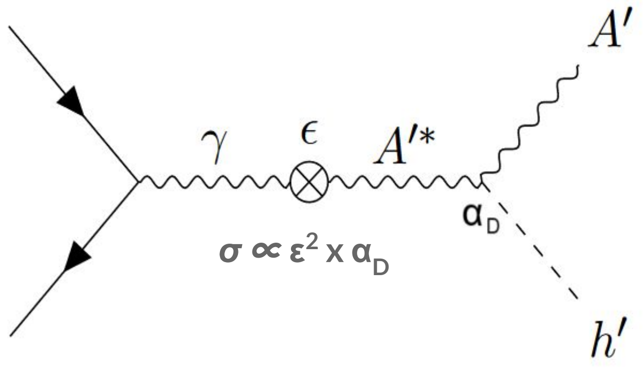
See talks by M.Veronesi and M.Campajola for more information on Belle II searches

# The Dark Higgsstrahlung process

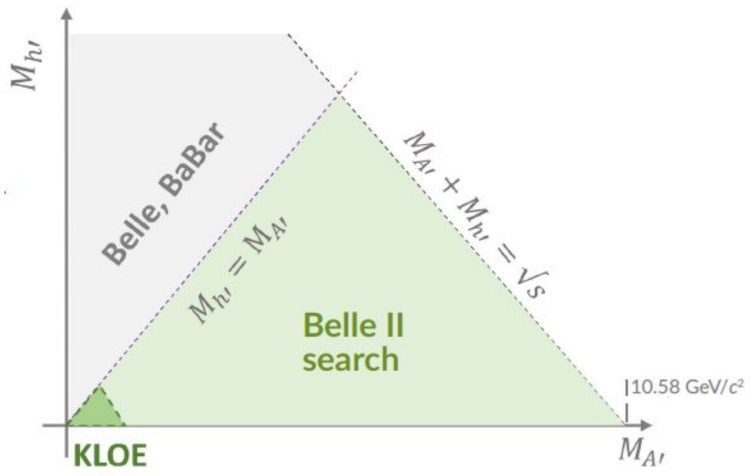
- Exploring two dark sector particles: the **dark photon $A'$** and the **dark Higgs boson $h'$**

  The mass of the $A'$ can arise, in close analogy with the SM, via a spontaneous symmetry breaking mechanism
  → Introduces a new scalar particle: a dark Higgs boson $h'$

  - The $A'$ interacts with the SM photon through a kinetic mixing mechanism with strength **ε** while $h'$ couples to $A'$ with $\alpha_D$




- Different scenarios depending on the mass hierarchy
  - $m_{h'} > m_{A'}$: $h' \rightarrow A'A'$ with up to 6 tracks in the final state
    Investigated by BaBar (2012) and Belle (2015)
  - $m_{h'} < m_{A'}$: $h'$ decays outside the detector resulting invisible
    Constrained by KLOE (2015) and Belle II (2023)



# Analysis overview

- Focusing on the light dark higgs $h'$ scenario ($m_{h'} < m_{A'}$)

**Considered model:** $h'$ is naturally the lightest dark sector state and decays into SM particles via interacting with the SM Higgs at **a mixing angle *θ***

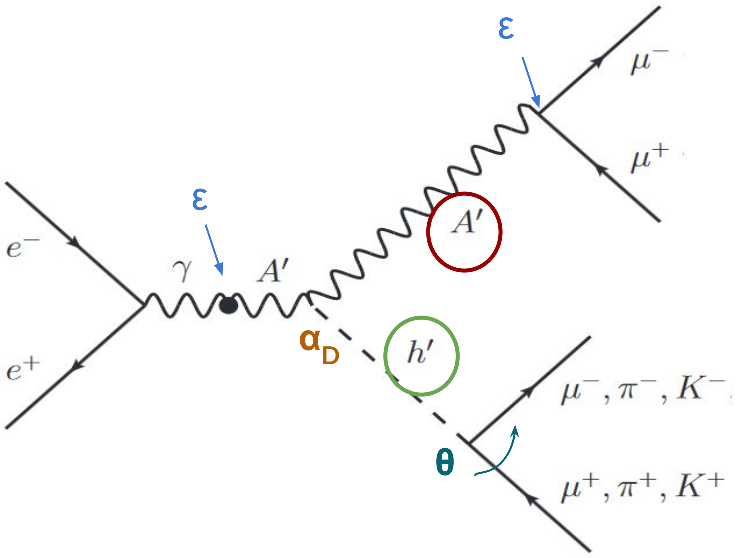
- Search for a dark photon $A'$ and a visible long lived dark Higgs boson $h'$ via the ***dark Higgsstrahlung process:***

$$e^+e^- \to A'(\to \mu^+\mu^-)h'(\to \mu^+\mu^-/h^+h^-) \text{ where } h = \pi, K$$

- **Motivation to search for a long-lived dark higgs boson**

- θ affects the lifetime of the dark Higgs : $\tau_{h'} \propto 1/\sin^2(\theta)$
  Renders it naturally a **long-lived particle** for small values of θ

➔ **Search:** $h'$ decaying **inside** the Belle II detector




***Key model parameters***

- Mass of the dark photon $m_{A'}$
- Mass of the dark higgs $m_{h'}$
- Kinetic mixing with strength **ε** of the $A'$ with SM
- Mixing angle **θ** of the $h'$ with the SM higgs
- $\alpha_D$ the coupling between the $h'$ and the $A'$

[Duerr M. et al, J. High Energ. Phys. 2021, 146 (2021)]

# Analysis overview

- Focusing on the light dark higgs $h'$ scenario ($m_{h'} < m_{A'}$)

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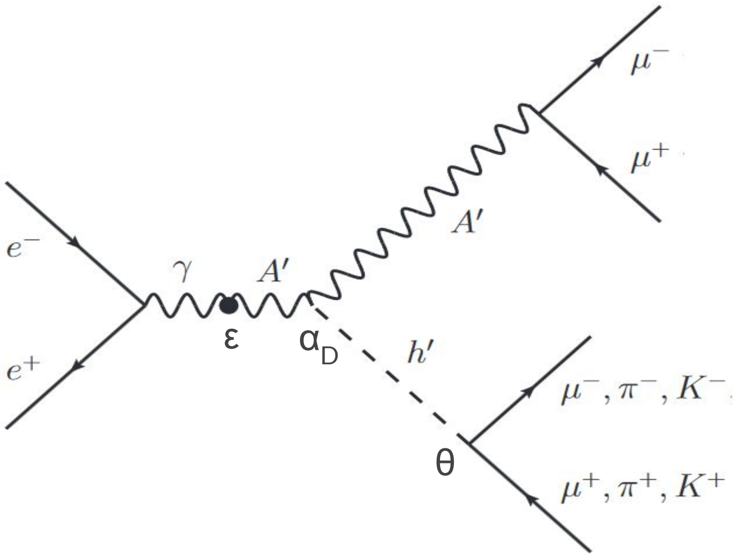


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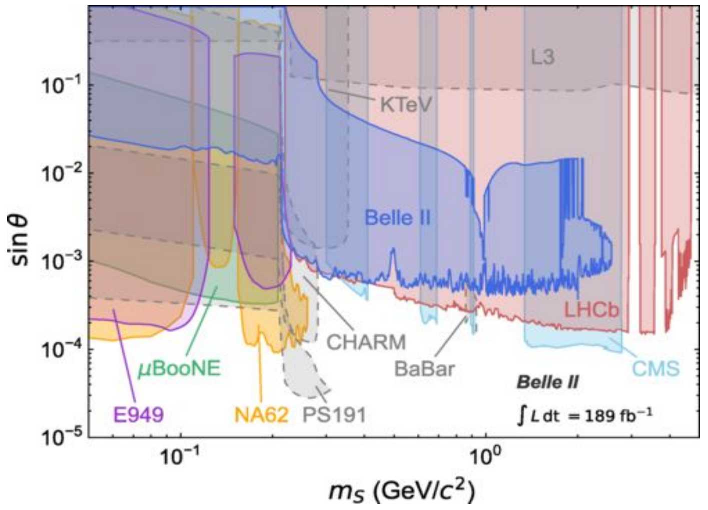
$$e^+e^- \to A'(\to \mu^+\mu^-)h'(\to \mu^+\mu^-/h^+h^-) \text{ where } h = \pi, K$$

***Existing limits to my model from other dark scalar searches***




I. Adachi et al. (Belle II Collaboration), Phys. Rev. D 108 (2023)

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- θ affects the lifetime of the dark Higgs : $\tau_{h'} \propto 1/\sin^2(\theta)$
  Renders it naturally a **long-lived particle** for small values of θ

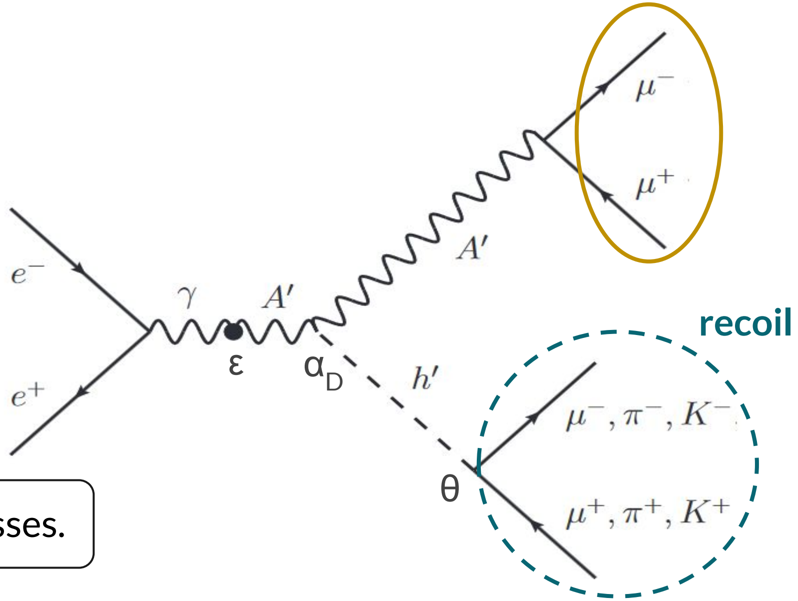
➔ **Search:** $h'$ decaying **inside** the Belle II detector

# Preliminary studies

# Signal signature and reconstruction

- Simultaneous search of a dark photon $A'$ and a dark higgs $h'$ in **four-track** events and final states with **no missing energy E$_{miss}$**
- 2 prompt tracks, associated with the $A'$ decaying into a pair of muons
  + 2 tracks forming a displaced vertex (LLP $h'$ decay)

**Signal signature** is **two narrow peaks**, at different invariant masses.

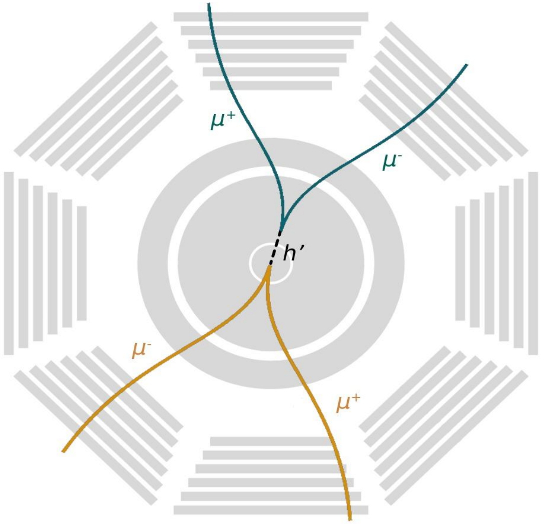



- ***Current focus on*** $h' \rightarrow \mu^+\mu^-$ :
- Signal generation using MadGraph5 aMC@NLO with Initial State Radiation (ISR) effects included.
- The $h'$ production vertex is displaced according to the lifetime in **cτ** [cm].

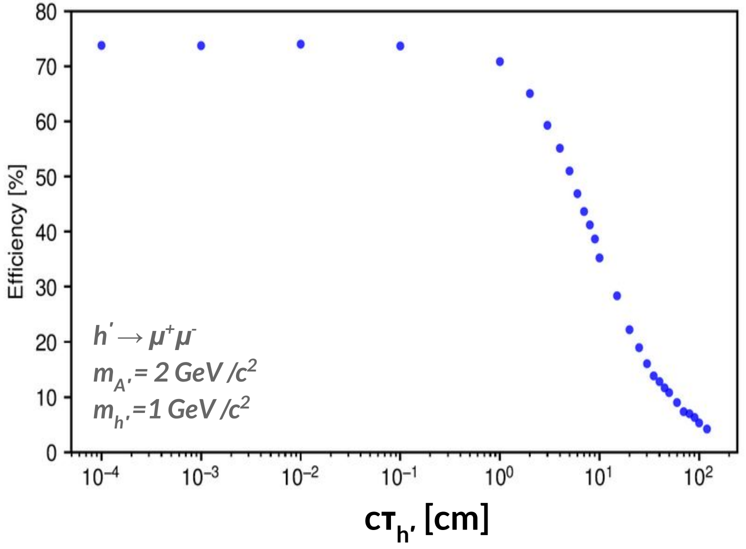
Event pre-selections

→ **Maximum 6 tracks** in the final state coming from the interaction point (IP), with **two tracks** identified as **muons**

→ **No missing energy** with $m_{Recoil}$ < 6.5 GeV/c$^2$



# Signal efficiency and resolutions



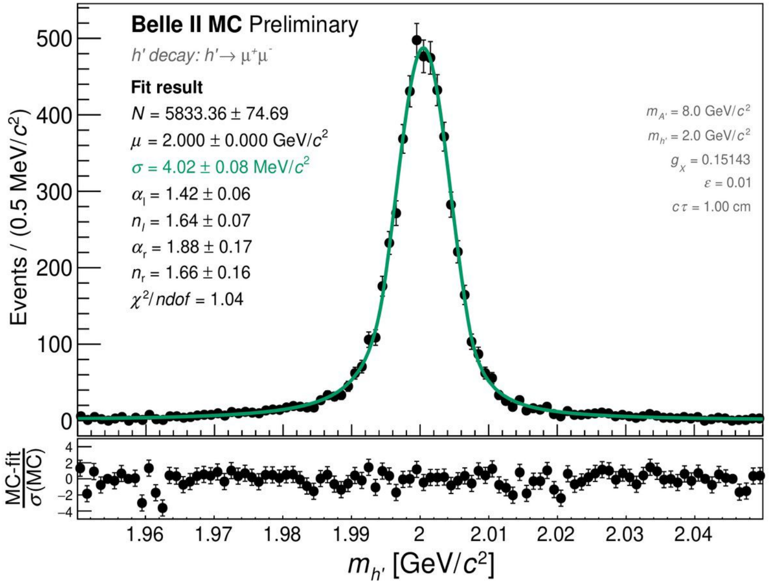

**Reconstruction efficiency as a function of the dark Higgs lifetime**

**Sensitivity to long-lived particles** with notable $\epsilon_{reco}$ even at extended lifetimes

- To estimate the resolutions, we fit the signal shape with a Double Sided Crystal Ball function with the following characteristics:
  - **Gaussian core** and **exponential tails** on each side
  - **Fixed mean** according to the respective invariant mass.

- We extract the width of the signal peaks and obtain the resolutions:

➔ **σ increases** as a function of the invariant masses but **remains small** at $\sigma_{A'}$= 4 − 40 MeV/$c^2$ and $\sigma_{h'}$ = 1 − 14 MeV/$c^2$.




- **Defining the signal mass windows :** Window size is set ±5 **σ** around the nominal value of the corresponding $h'$ and $A'$ mass.

# Background studies

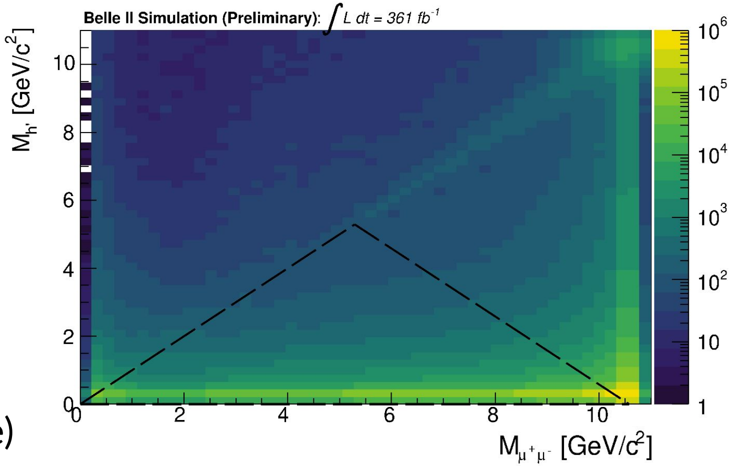
## Characterization and suppression

Main SM background contributions from combinatorial $e^+e^- \to q\bar{q}$ events, **two** and **four lepton** events such as $e^+e^- \to \mu^+\mu^-(\gamma)$.

- ***Applying preselections*** leads to **96.1 %** **background suppression** (no mass selections here)

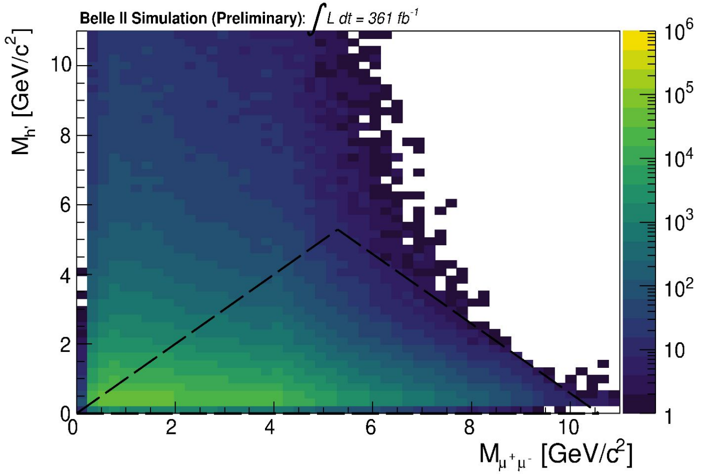
- Using run dependent samples, each rescaled to the target dataset size of this analysis:
  $$\int \mathcal{L}\, dt = 361 fb^{-1}$$

$e^+e^- \to \mu^+\mu^-(\gamma)$

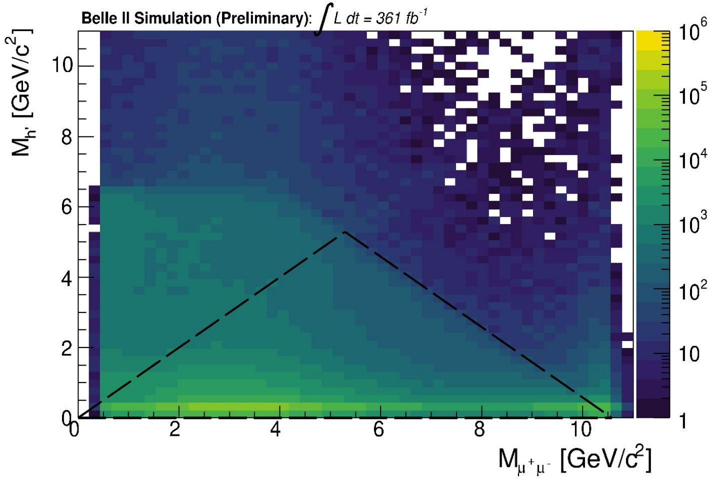



Accessible search region has **a triangle shape** corresponding to the mass plane $m_{h'} - m_{A'}$ in signal events.

$e^+e^- \to q\bar{q}$



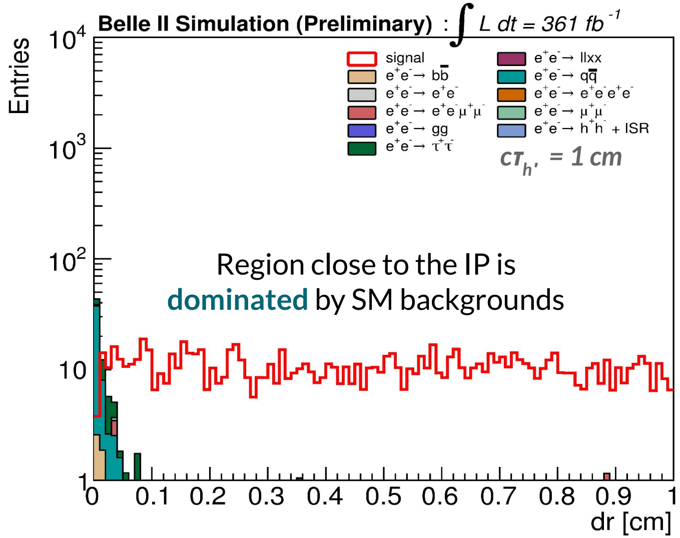

$e^+e^- \to e^+e^-\mu^+\mu^-(\gamma)$



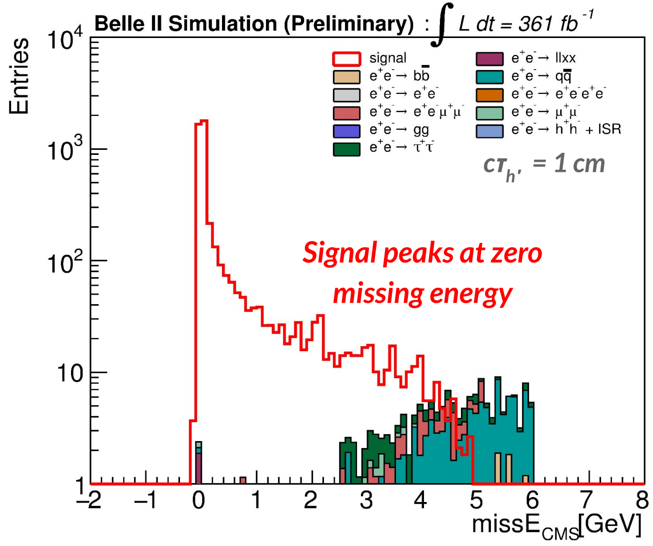
# Background suppression

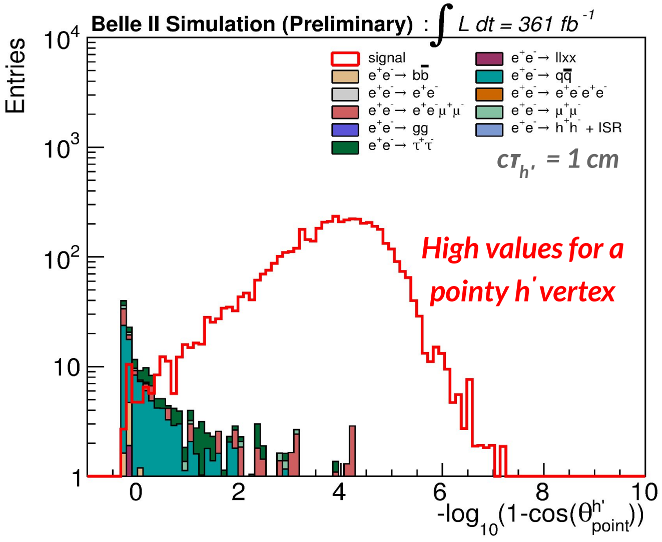
Utilizing a collection of **discriminating variables**, motivated by signal kinematics:

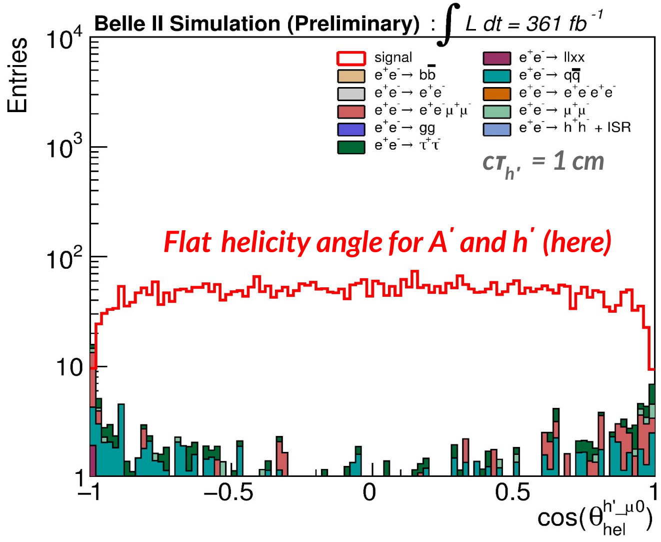
- **dr :** Transverse distance of the $h'$ decay vertex with respect to the IP [cm]
- **missing_E$_{CMS}$:** Total missing energy of the four reconstructed tracks
- **$\theta^{h'}_{point}$:** Pointing angle of the dark higgs $h'$
- **$\theta_{helicity}$:** Helicity angle of the dark photon $A'$ and the dark higgs $h'$




***Here:*** Mass selections are applied, both for signal and background, at **±5 $m_{inv}$**



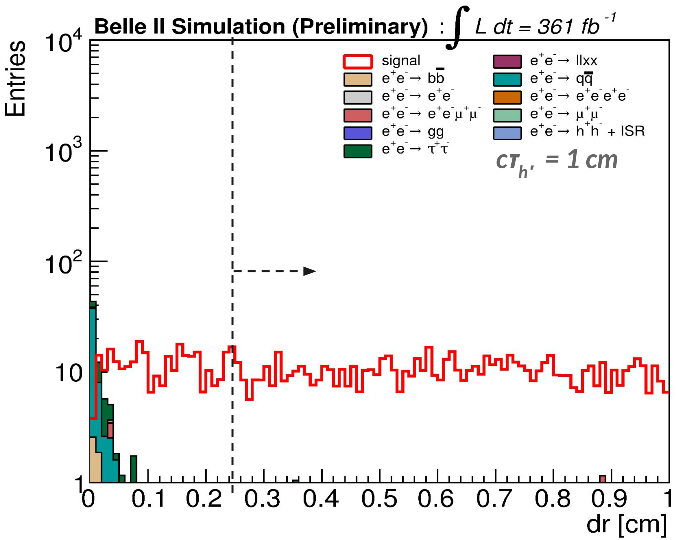



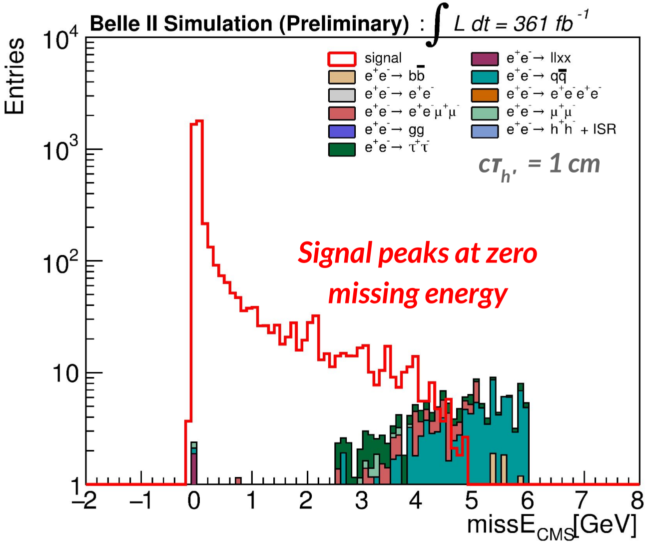
# Background suppression

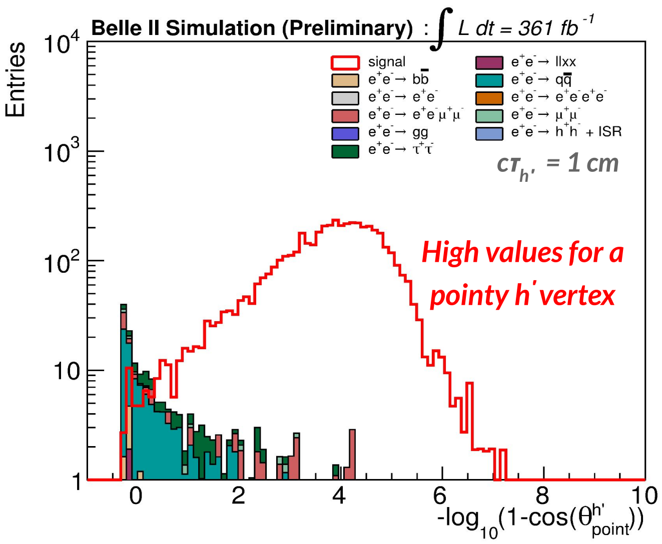
Utilizing a collection of **discriminating variables**, motivated by signal kinematics:

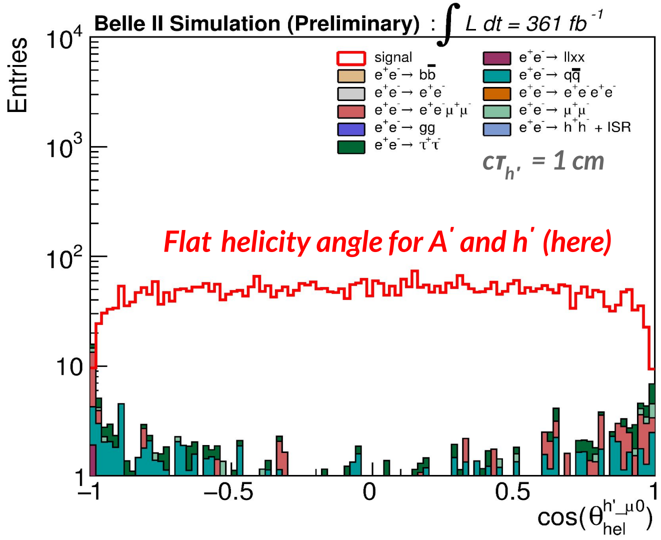
- **dr :** Transverse distance of the $h'$ decay vertex with respect to the IP [cm]

***Sufficient displacement of h′ - LLP analysis :***
Common cut on across the mass plane at ***0.2 < dr < 110 cm***



# Background accumulation

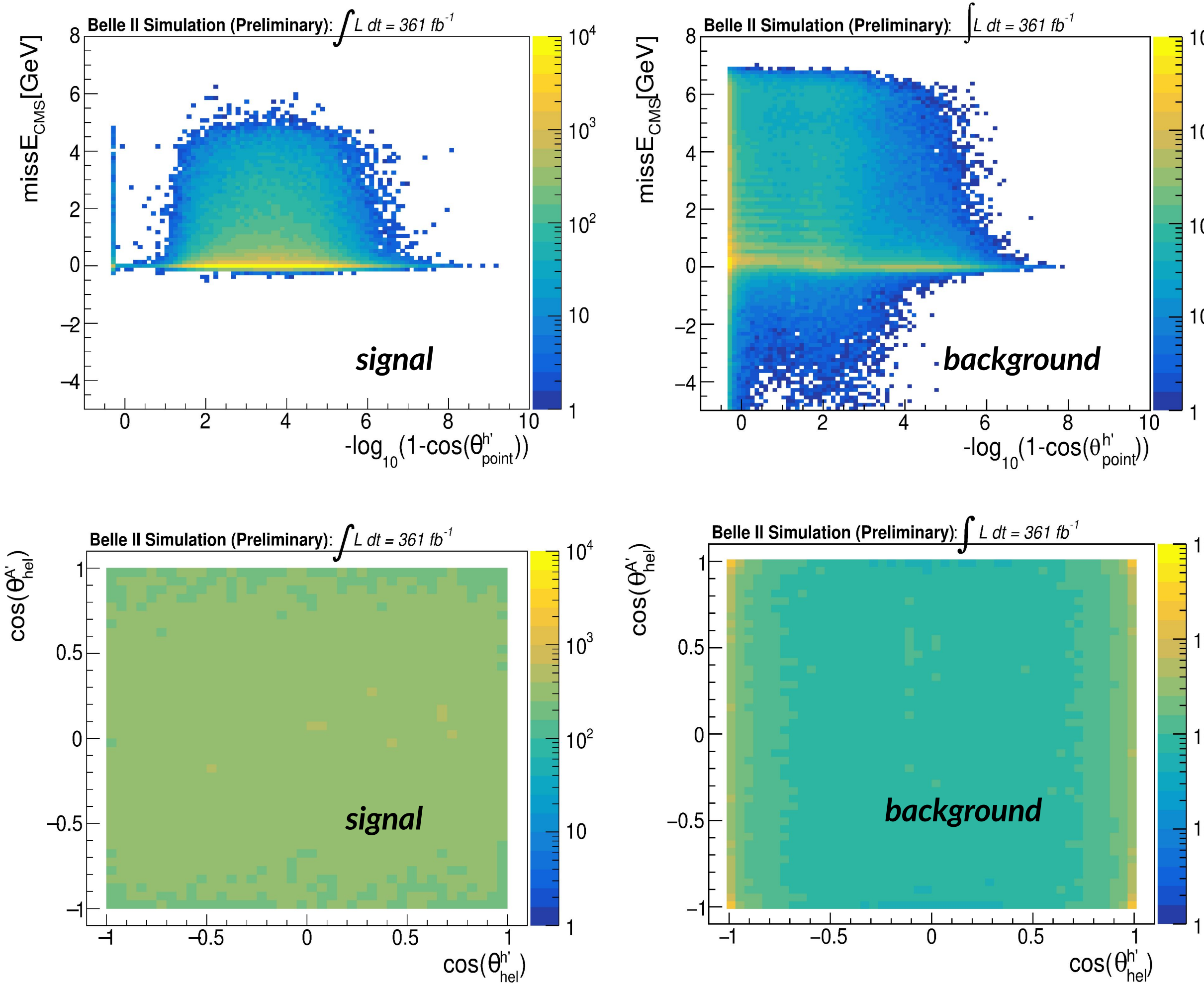
Studied via the correlation of the discriminant variables

- **missing_E$_{CMS}$ vs $\theta^{h'}_{point}$:**

Background peaks for **high values** of the missing energy and for **non pointing** *h'* vertices

- **$\theta^{A'}_{helicity}$ vs $\theta^{h'}_{helicity}$:**

Background distribution peaks at **± 1** as muons do not originate from a common source



# Background accumulation

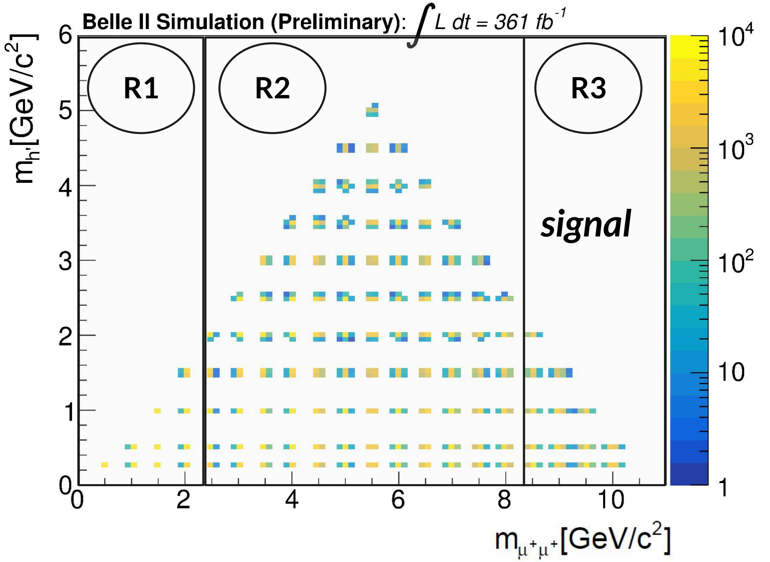
Across the mass plane, we observe:

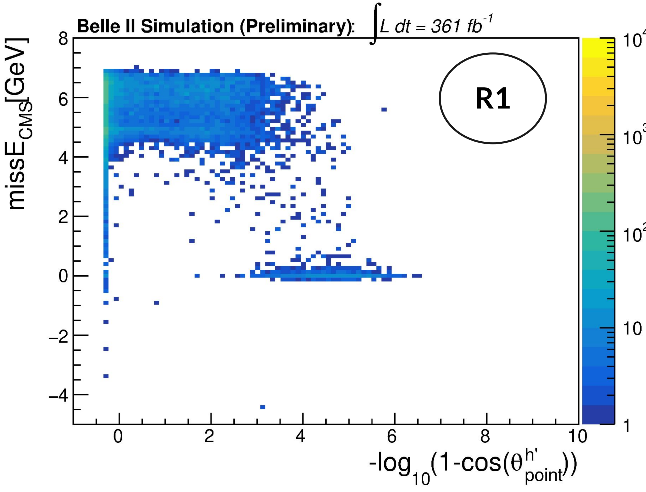
❖ **Different background contributions per region**

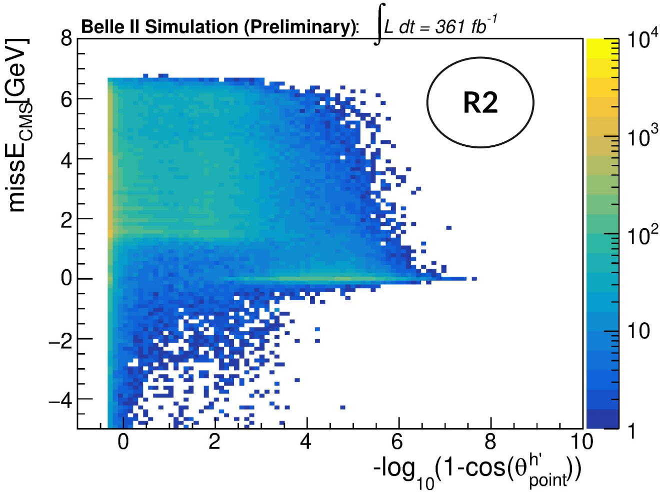
$\tau^+\tau^-$ and $q\bar{q}$ events populate mainly **R2**

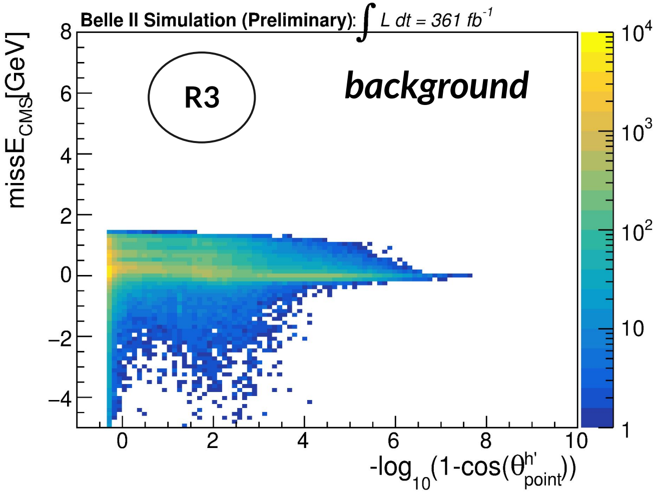
❖ **Uneven background distributions**

Mostly in **R3** where $N_{bkg}(\mu^+\mu^-)$ is 79.6% of the total events.



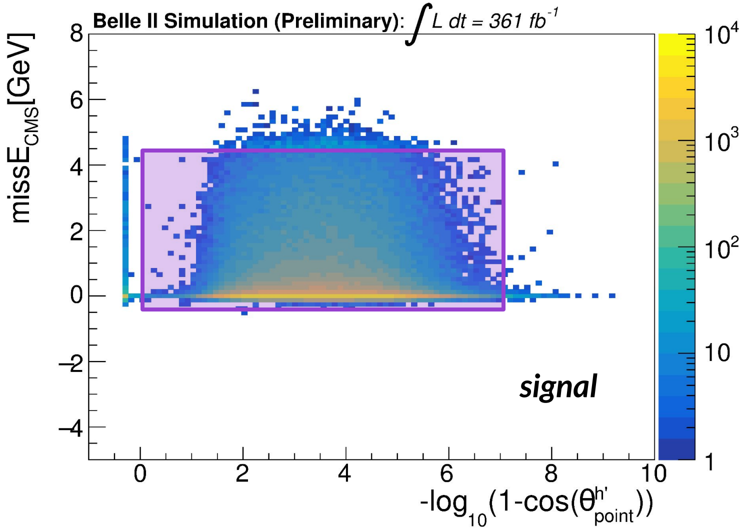



# Event selection strategy

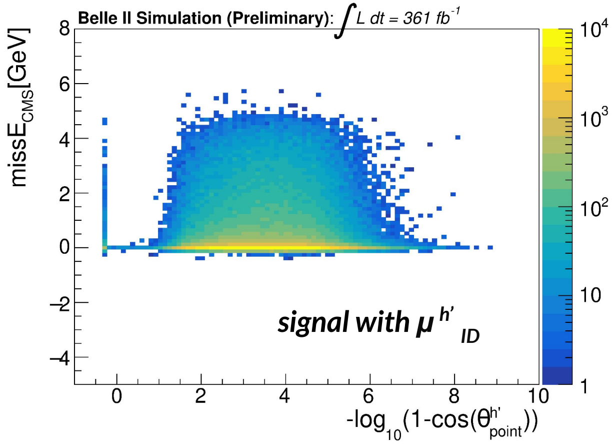
- Utilizing the **signal distribution shape**
- We apply a **box shaped cut** and perform a 2D **missing_$E_{CMS}$ vs $\theta^{h'}_{point}$** scan , followed by a scan on $\theta^{h'}_{helicity}$

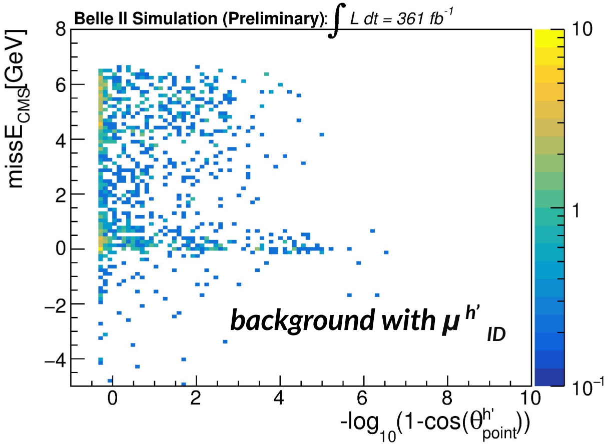



➢ Selections are optimized in each region separately using the Punzi$_{FOM}$ : $\frac{\epsilon_{sig}(t)}{\frac{a}{2}+\sqrt{N_{bkg}}}$

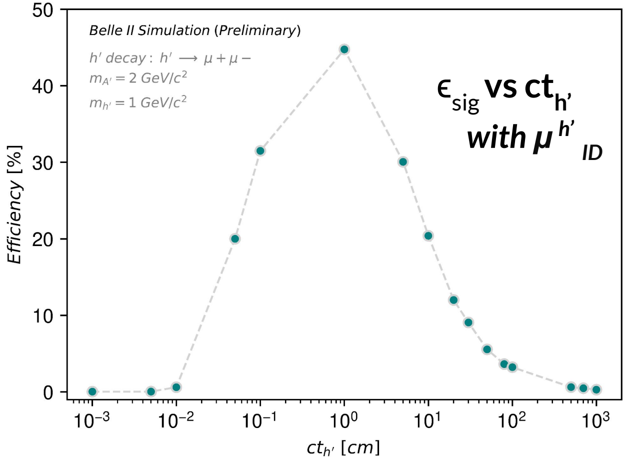
➢ **Strong suppression** achieved using particle identification also on the ***h'* muons**

- Negligible effect on the signal efficiency $\epsilon_{sig}$
- Significant reduction for background



# Signal efficiency and background




## Combining all discriminant variables

Signal efficiency remains high across the whole mass plane with

**$\epsilon_{sig}$ = 32.5 %** and, after applying $\mu^{h'}_{ID}$ , **$\epsilon_{sig}$ = 28.5 %**

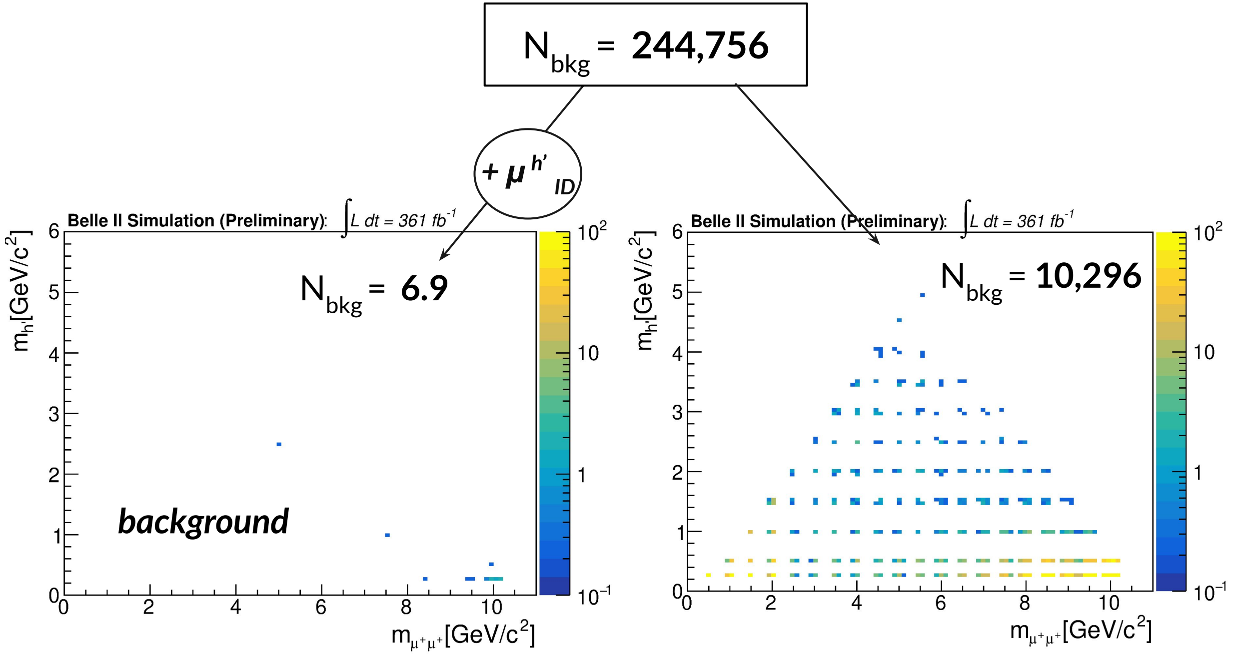
- **$\epsilon_{sig}$ ~ 3%** even at extended lifetimes such as $c\tau_{h'}$ = 100 cm

## Expecting minimum background levels:

Selections result in high background rejection power

Remaining background, inside each signal window, can be very low and varies across the mass plane

**Plan for signal yield extraction:**
Cut and count technique



# Summary

- Search for a dark photon $A'$ and a visible long lived dark Higgs $h'$ boson at the Belle II experiment via the ***dark Higgsstrahlung process***:

$$e^+e^- \to A'(\to \mu^+\mu^-)h'(\to \mu^+\mu^-/h^+h^-) \text{ where } h = \pi, K$$

- ***Dark higgs could interact with the SM higgs at a mixing angle θ***

  For a **LLP $h'$ decay scenario,** we can search $h'$ decaying inside the Belle II detector

- Preliminary studies on $h' \to \mu^+\mu^-$ show:
  - Significant background suppression utilizing various discriminating analysis variables
  - Signal efficiency > **28%** across the mass plane

➢ ***Ongoing:*** **Estimate the Belle II's sensitivity to the signal cross section for $h' \to \mu^+\mu^-$**

➢ ***Next steps:***
- Include $h = \pi, K$ final states
- Trigger and control data studies
- Calculate and assign the systematic uncertainties

***Thank you for your attention***

# Backup

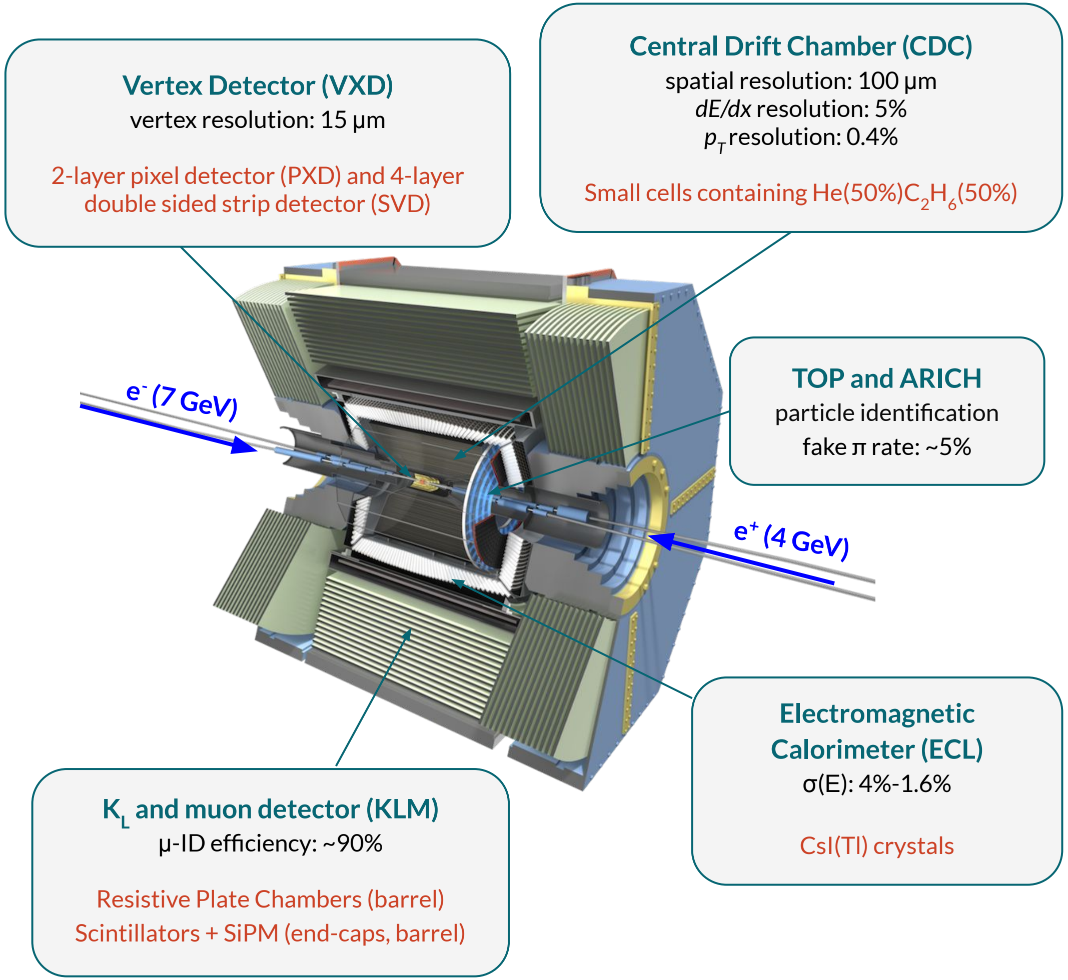
# The Belle II experiment

## Overview

- Operating at the SuperKEKB accelerator (Tsukuba, JP), an $e^+e^-$ asymmetric energy collider
- Optimized for the production of B meson pairs, but also D mesons and τ leptons.
- Collisions occur mainly at **√s = 10.58 GeV**, corresponding to the $m_{inv}$ = Υ(4S)

## Data taking status

- Run I (2019-2022) + Run II (February 2024-Now): Recorded a total luminosity of more than **575 fb$^{-1}$.**
- SuperKEKB reached world's highest instantaneous luminosity at $\mathcal{L} = 5.1 \times 10^{34} cm^{-2} s^{-1}$ .
- Target: $\int \mathcal{L}\ dt = 50\ ab^{-1}$(***50 x Belle dataset!***)



# Phases of the Experiment

- Belle II's data taking timeline is separated into three phases.

❖ **Phase** (2016) + **Phase II** (April - July 2018) :
Dedicated to commissioning both the machine and the detector.

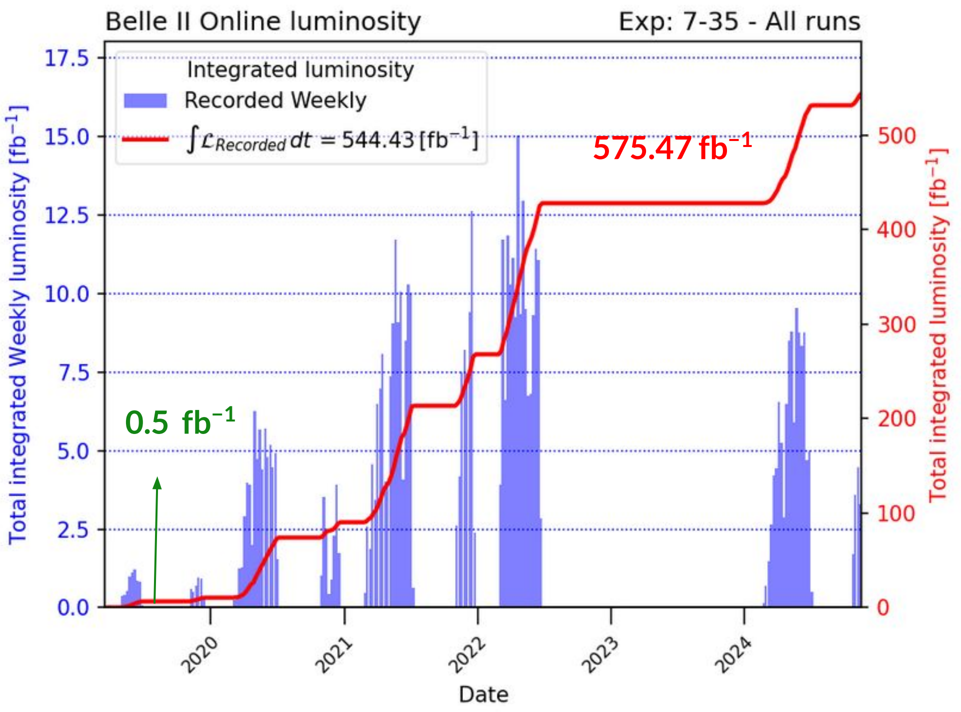
Collected 0.5 $fb^{-1}$ of data with an incomplete vertex detector (VXD).

❖ **Phase III** (March 25, 2019 - Now) : Beginning of a full-scale data collection

- **Run I** (2019-2022): Recorded a total of **427 $fb^{-1}$**
- **Run II** (January 2024-Now)

The total luminosity collected by the experiment for

Run I and Run II amounts to 575.47 $fb^{-1}$



# Signal studies

## Branching fractions

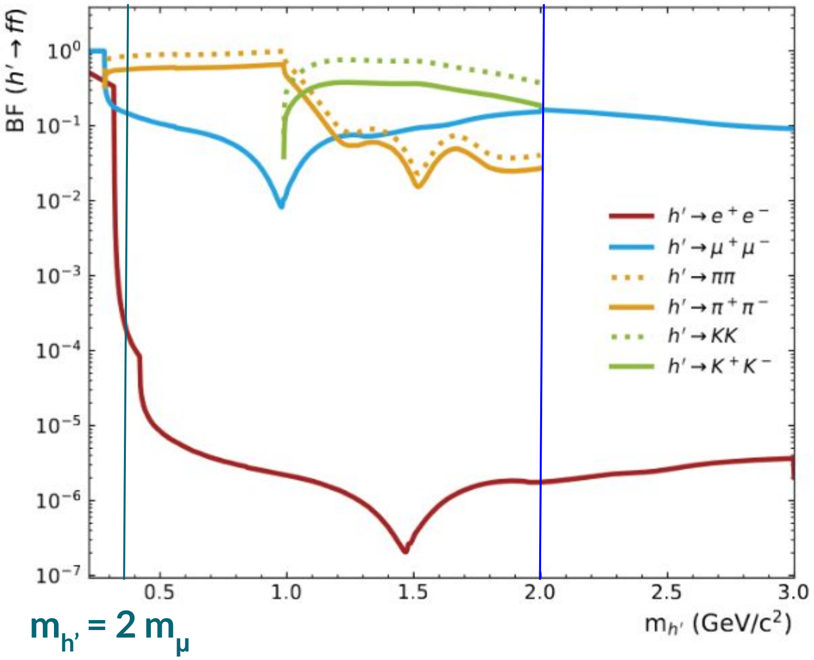
- Search can be performed in various final states, depending on the **decay of the dark Higgs $h'$**

- **Limited in mass for hadrons**
  For pions and Kaons, current theoretical calculations provide predictions up to $m_{h'} = 2\ \mathrm{GeV}/c^2$ .

- **Other decays of the dark Higgs (not considered)**

I. **Electron decay**
Existing limits bellow the **di-muon threshold** are quite strong, while above it, the $e^-$ decay is heavily suppressed.

II. Tau decay (not depicted)
Introduces complications in the reconstruction of the final state due to its neutrino decay and the no missing energy requirement we impose.




BR of the dark Higgs decaying into four different final states as a function of its mass.

# Signal studies

## Expected cross section

- Cross section of the process $e^+e^- \rightarrow A'(\rightarrow \mu^+\mu^-)\, h'(\rightarrow \mu^+\mu^-)$ evaluated by MadGraph at generator level

- **Dependency on the boson masses:**
  Accessible search region has **triangle shape** that corresponds to the mass plane $m_{h'} - m_{A'}$ in signal events.
  - $\sigma \sim 10^{-2} - 10^{-1}$ fb for $m_{h'} > 4$ GeV $/c^2$
  - $\sigma \sim 10^2$ fb for $m_{h'} < 0.5$ GeV $/c^2$

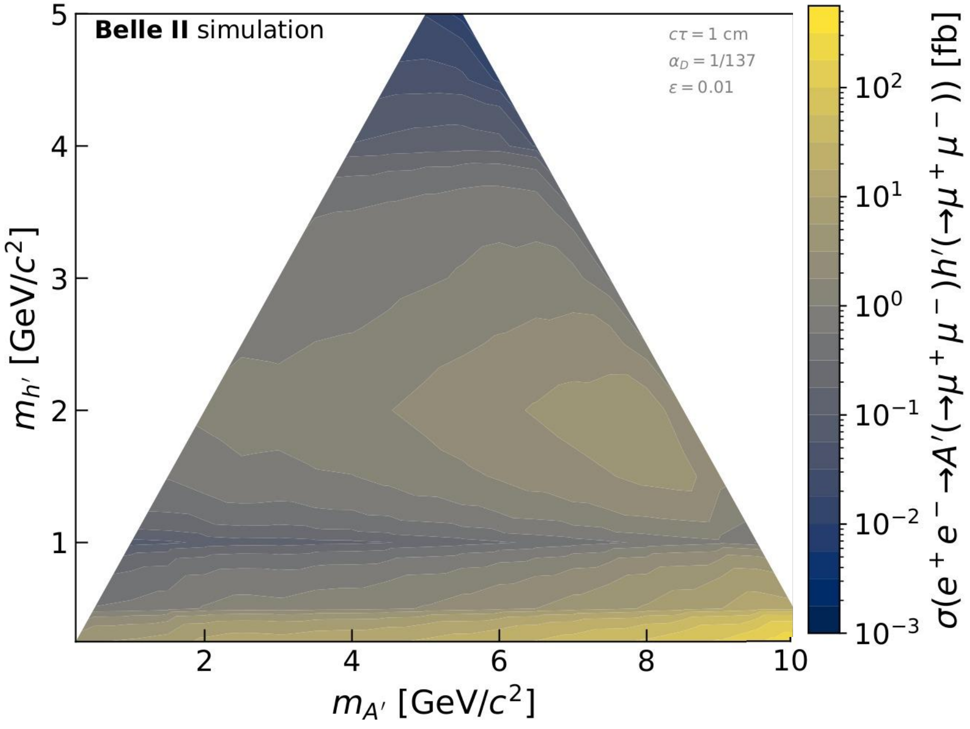
- **Dependency on other parameters**
  The mixing angle and lifetime of the dark higgs are **related** via

$$\tau_{h'} \propto 1/\sin^2(\theta)$$

- $\sigma$ is **stable** up to $\theta = 0.1$ rad, with noticeable effects appearing at higher values.

- $\sigma$ shows **negligible** variation in relation to the $h'$ lifetime.

**BR ($h' \rightarrow \mu^+\mu^-$)**




For comparison: $\sigma(B\overline{B}) = 1.1\ nb$

# Signal studies

## Reconstruction efficiency

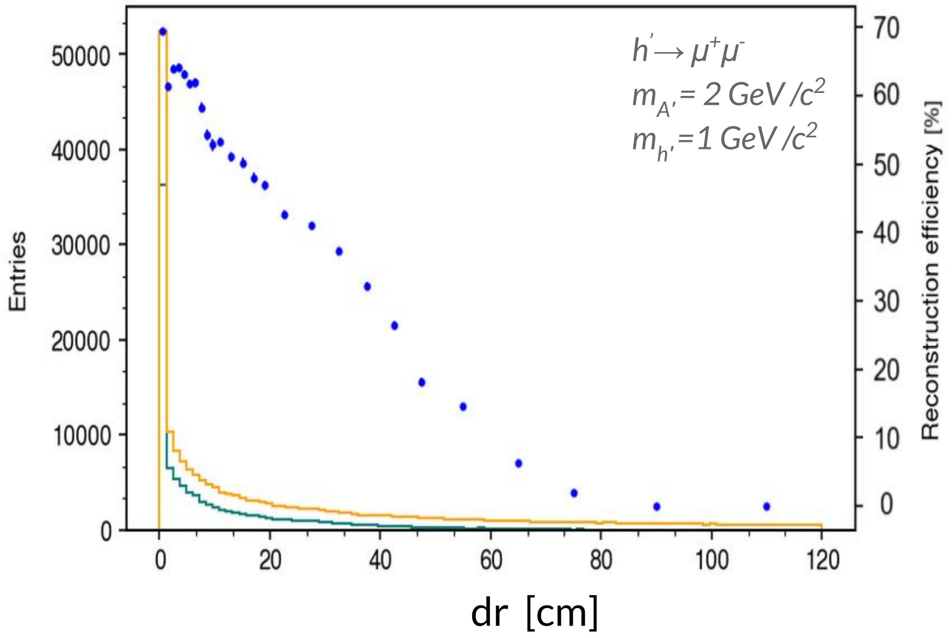
- **Efficiency = #Correctly reconstructed events / #All generated events**

  as a function of the true transverse distance of the reconstructed $h'$ decay vertex ***dr*** with respect to the IP

$$\epsilon_{reco} = \frac{h'_{reconstructed}}{h'_{generated}}$$

- Efficiency decreases as the distance of the *h'* decay vertex increases

- $\epsilon_{reco}$ greater for prompt $h'$ decays, maintaining values above **40%** for decay distances up to *dr* = 25 cm.



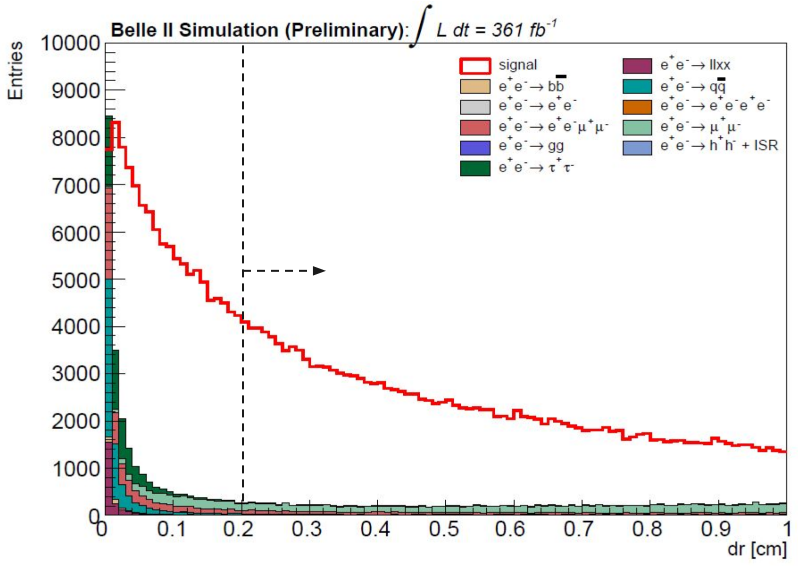

Using MC truth matching for selecting signal events

# Discriminating variables (1)

## Transverse distance of the $h'$ decay vertex dr

- Region close to the IP is expected to be dominated by SM backgrounds

→ Requiring that the $h'$ decays with sufficient displacement at **0.2 < dr < 110 cm** (upper limit is set by the location of the CDC tracking detector at Belle II)

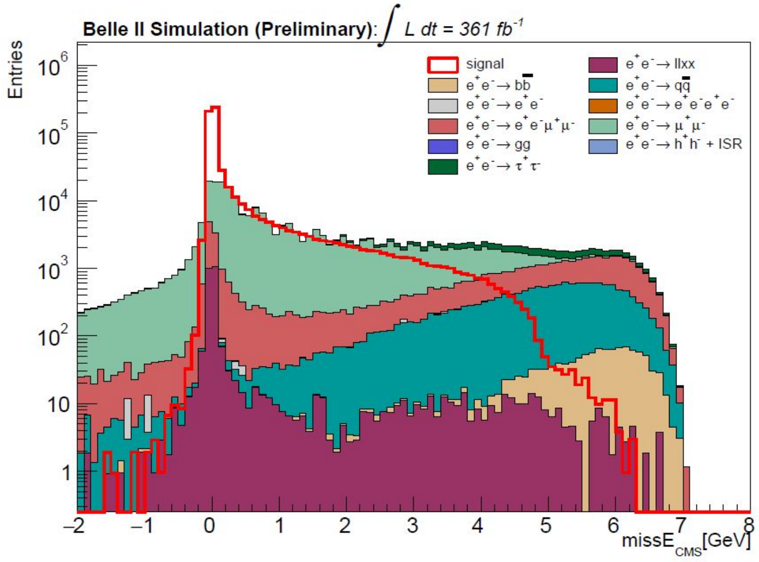



## Total missing energy of the four reconstructed tracks

- The **signal** should peak at values close to **zero**

  Deviations could derive from the ISR, misreconstruction or resolution effects.

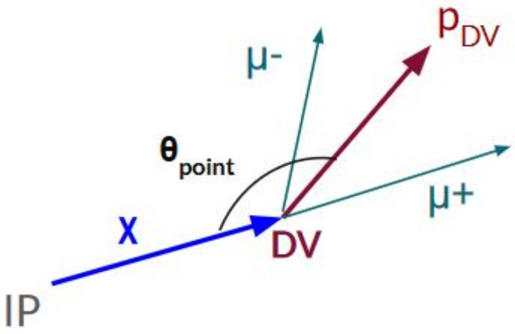
- Background peaks at larger values.



# Discriminating variables (2)

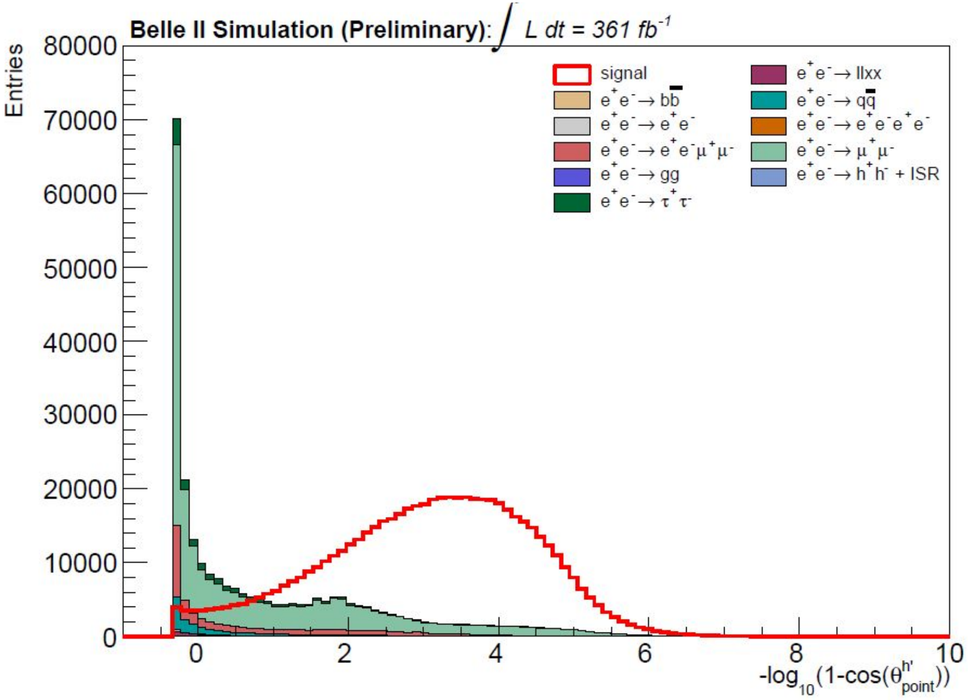
- **Pointing angle of the dark higgs $h'$**

The angle between the **vector** connecting the reconstructed displaced vertex (DV) to the IP and the momentum vector $\mathbf{p_{DV}}$ of the dimuon system for $h'$ decay in signal events.




Depicted in $-log_{10}(1 - cos(\theta^{h'}_{point}))$

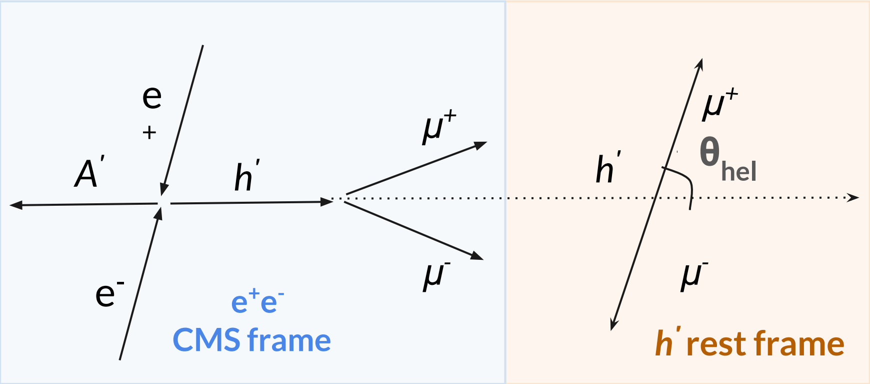
- Expecting high values for signal since $h'$ vertices are pointing back to the IP
- **Background** candidates are made up from random track combinations and peak at **low values**



# Discriminating variables (3)

- **Helicity angle of the dark photon *A'* and the dark higgs *h'***

  The angle between the flight direction of the $h'$ in the CMS system and the $\mu^+$ in the $h'$ rest frame ( same for the $A'$)




- Signal is a resonance decaying into two fermion particles

  → Observing an **almost flat** distribution of $\cos(\theta_{hel})$ for $A'$ and $h'$

- No direct physical meaning for the background:

  muons do not originate from a common resonance

  and the distribution peaks at **± 1**