Karlsruhe Institute of Technology

Dark sector searches with invisible and displaced signatures at Belle II

Giacomo De Pietro (*giacomo.pietro@kit.edu*)

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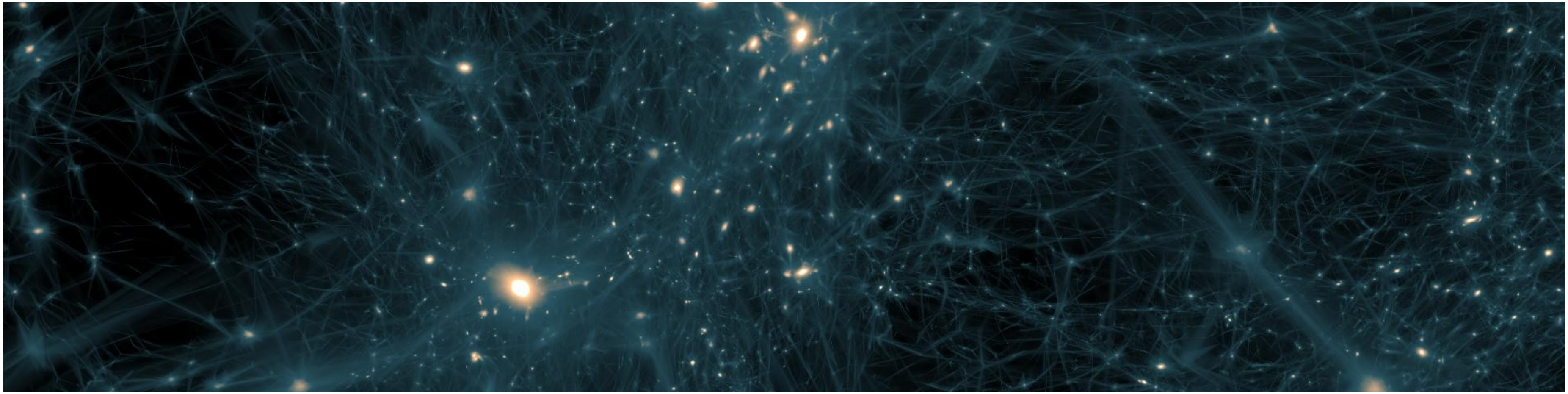

- Introduction
- Invisible signatures
  - Z' → invisible
  - Dark Higgsstrahlung
- Displaced signatures
  - Inelastic dark matter with dark Higgs

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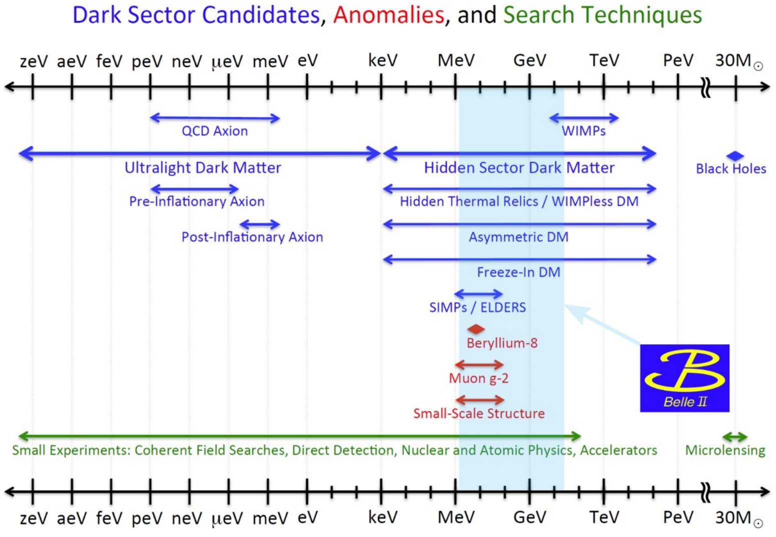
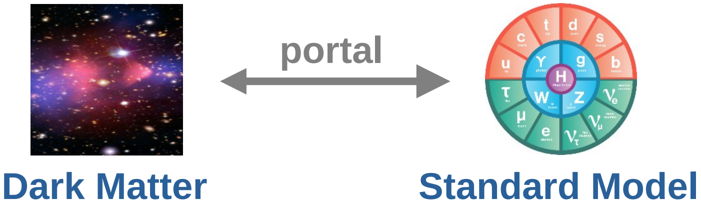
Dark sector searches

- The particle nature of dark matter (DM) is still a compelling question
- No evidence of DM at electroweak scale in experiments motivates a considerable focus on “dark sector” models [1]:
  - Light DM particles
  - New dark force carriers with feeble interactions with the SM (portals)
- B-factories can access the mass range favored by light dark sector models
  - Able to explore on-shell mediators in the MeV–GeV range in:
    - Visible and invisible decays
    - Displaced decay topologies: can reconstruct up to O(1m) decay-lengths

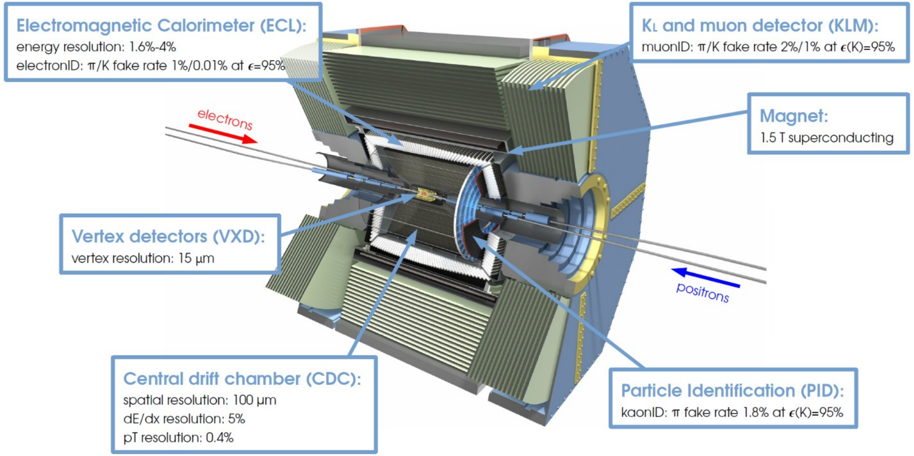


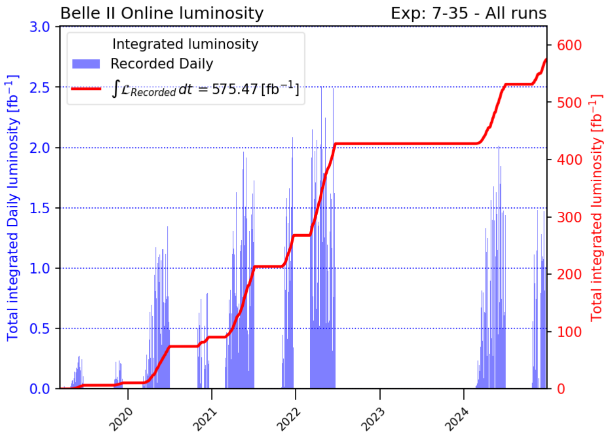


[1] Essig et al., arXiv:1311.0029 (2013)

Belle II experiment

- Belle II is the current generation of B-factories
  - Asymmetric e^+e^- colliders running mainly at the Υ(4S) resonance, $\sqrt{s} = 10.58$ GeV
- Key features:
  - Well known initial conditions
  - Hermetic detector
  - Rather clean environment
- Special triggers for dark sector physics
  - Single photon, single track and single muon triggers
- Collected ~570 fb^{-1} of data so far





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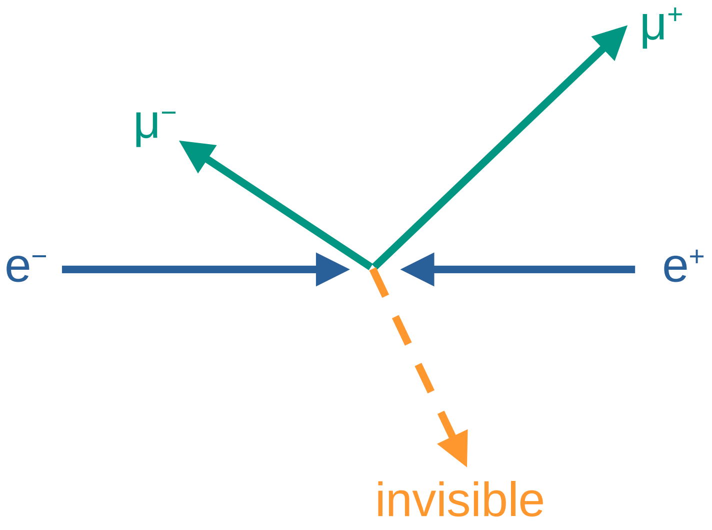
Kinematics at e^+e^- colliders

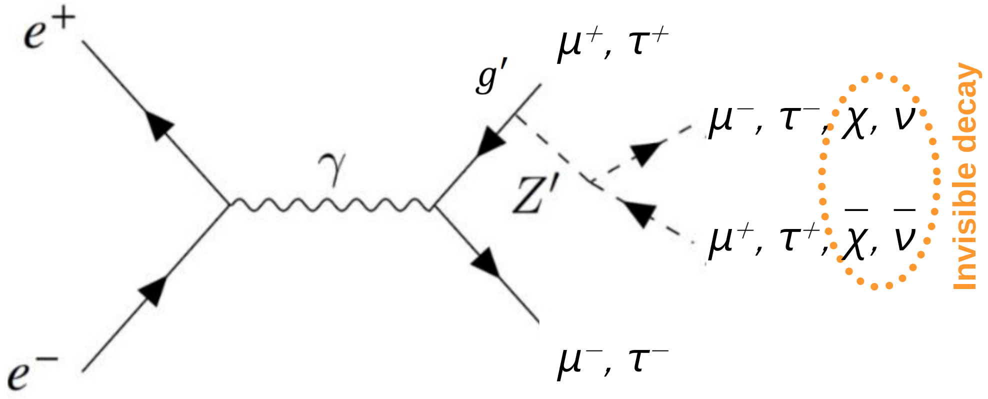
- Compared to hadron colliders, there is only up to one primary interaction per bunch crossing
- Collision of elementary particles → Initial state is perfectly known
  - Can be used for constraining the kinematics of the final state
    - E.g. searching for “invisible particles” by analyzing the system recoiling against the visible particles



$$P_{\text{invisible}} = P_{\text{recoil wrt } \mu+\mu-}$$
$$= P_{e+} + P_{e-} - P_{\mu+} - P_{\mu-}$$

Z' searches ($L_\mu - L_\tau$ model)

- Massive vector boson Z' interacting only with the 2nd and 3rd generation of leptons ($L_\mu - L_\tau$ model) via a dimensionless coupling g'
- May explain [1, 2]:
  - $(g\text{-}2)_\mu$ anomaly
  - DM phenomenology
- Experimental signatures:
  - Visible decay into
    - A pair of muons [3]
    - A pair of taus [4]
  - Invisible decay to SM neutrinos or DM
    - Focus of this talk!

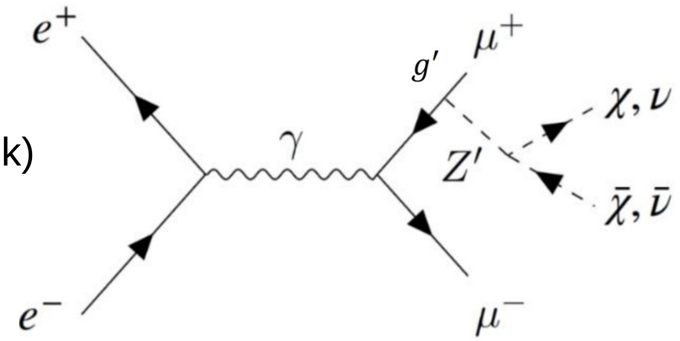


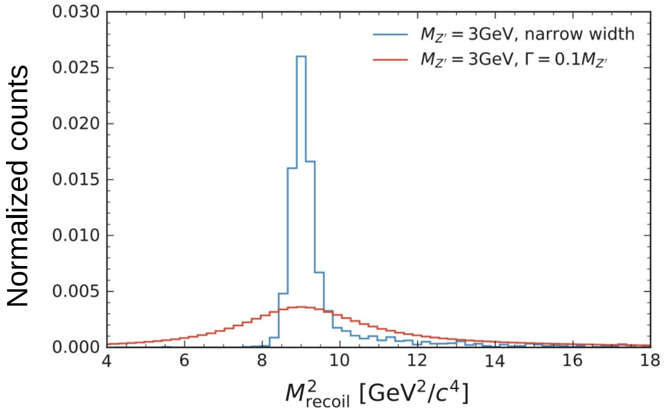
[1] Shuve et al.., Phys. Rev. D 89, 113004 (2014)
[2] Altmannshofer et al., JHEP 106 (2016)
[3] Belle II, Phys. Rev. D 109, 112015 (2024)
[4] Belle II, Phys. Rev. Lett. 131, 121802 (2023)

Invisible Z’ decay

Belle II, Phys. Rev. Lett. 130, 231801 (2023)

- Search for $e^+e^- \to \mu^+\mu^- Z'$; $Z' \to \nu\bar{\nu}/\chi\bar{\chi}$
  - First measurement with 2018 dataset: ~279 pb^{-1}
  - Updated analysis with 2019-20 dataset: ~ 79.7 fb^{-1} (this talk)
- Signature:
  - A peak in the recoil mass distribution against two muons





[1] Abudinen et al., Eur. Phys. J. C 82, 121 (2022)

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  - First measurement with 2018 dataset: ~279 pb^{-1}
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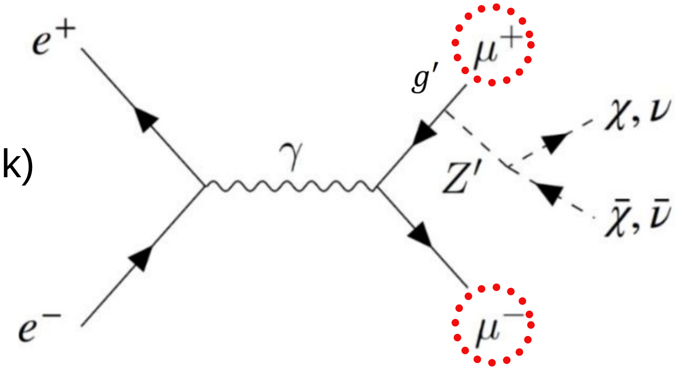
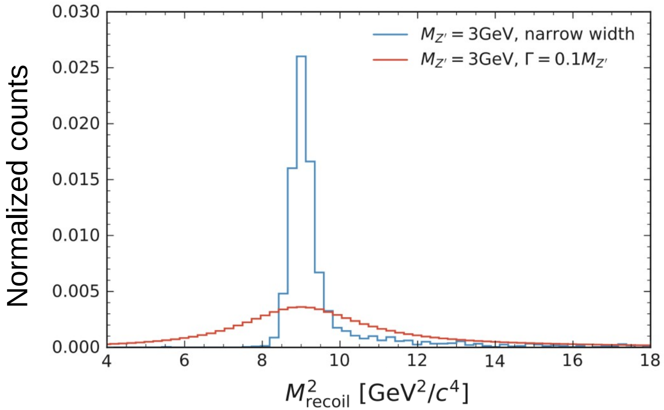
- Signature:
  - A peak in the recoil mass distribution against two muons
- Analysis selection in short:
  - Two opposite sign muon tracks
  - Recoil points to barrel calorimeter
  - Low activity in the calorimeter
  - Neural-Network exploiting "FSR" nature of Z' production [1]



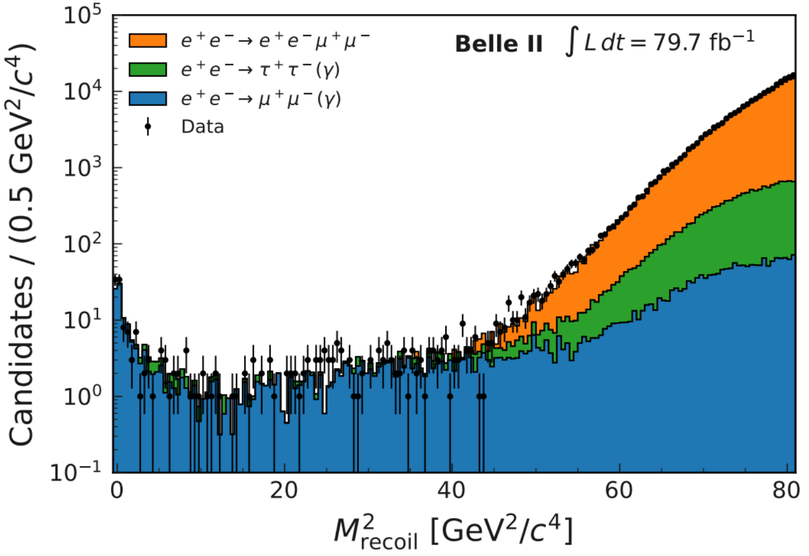


[1] Abudinen et al., Eur. Phys. J. C 82, 121 (2022)

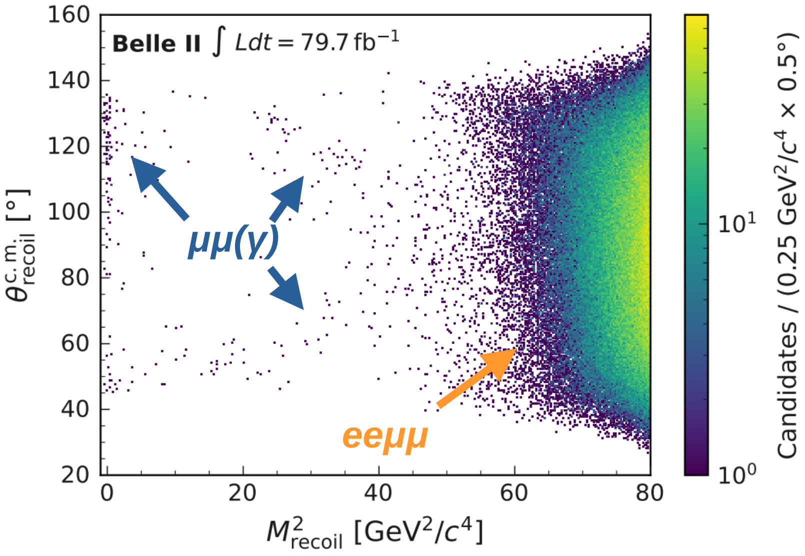
Invisible Z’ decay

Belle II, Phys. Rev. Lett. 130, 231801 (2023)

- Background composition
  - μμ(γ) dominates up to 7 GeV
  - eeμμ dominates for high masses



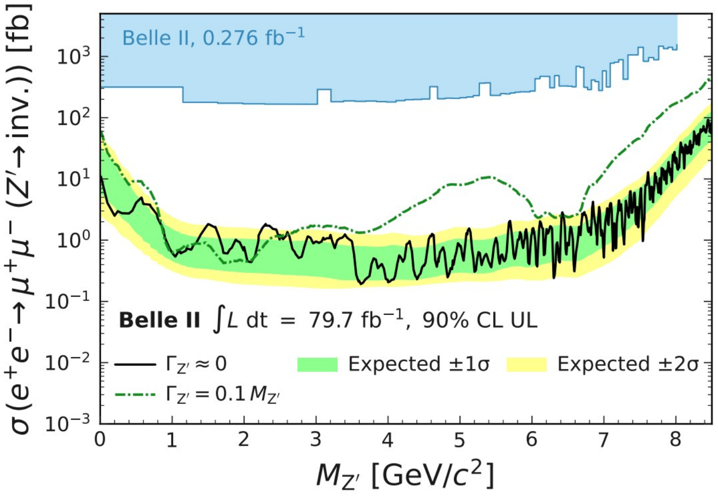
- Fitting strategy
  - Fitting over the 2D distribution θ^{CM}_{recoil} vs. M^2_{recoil}

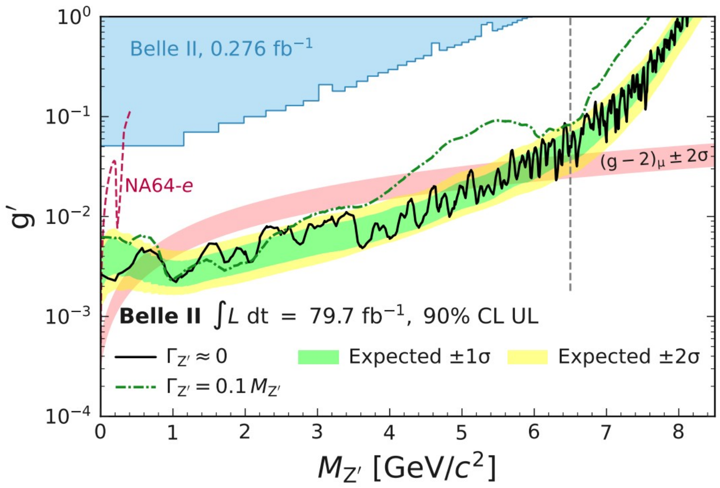


Invisible Z' decay

Belle II, Phys. Rev. Lett. 130, 231801 (2023)

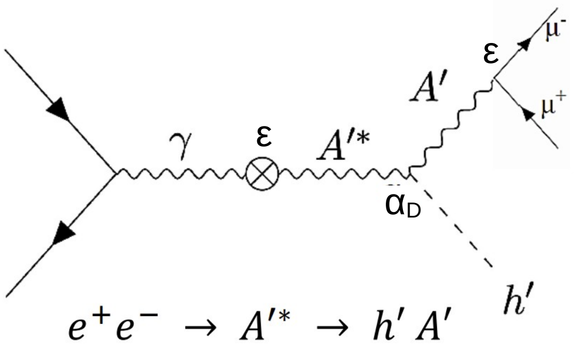
- No significant excess over the expected background
- Set 90% CL upper limits on cross section and coupling
  - World-leading UL for a fully invisible Z' (100% BR to invisible)
  - First excluding an invisible Z′ boson as an explanation of the $(g\text{-}2)_\mu$ anomaly for $0.8 < M_{Z'} < 5$ GeV

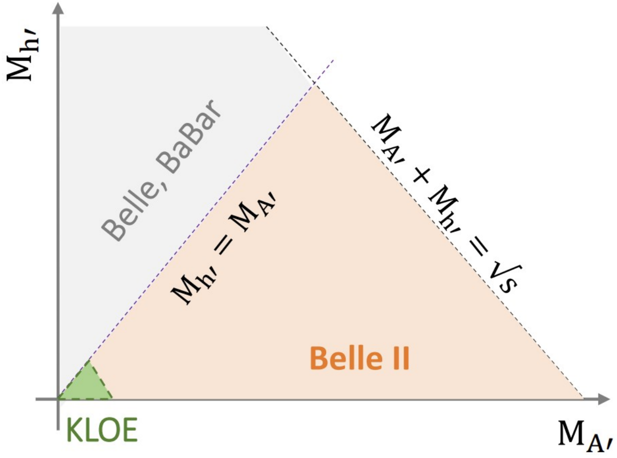




Dark Higgsstrahlung searches

- Extension of the minimal dark photon (A') model
  - A' is an additional massive spin-1 boson mixing with the SM photon via kinetic mixing ε
  - A' mass generated via spontaneous symmetry breaking by adding a dark Higgs boson h' to the model [1]
  - α_D is the coupling between A' and h'
- Both the particles A' and h' can be produced at an e^+e^- collider via the dark Higgsstrahlung process
- Mass hierarchy scenarios:
  - $M_{h'} > M_{A'}$:
    - $h' \rightarrow A'A'^{(*)}$; $A' \rightarrow$ visible
    - Possible signature: 6 charged tracks; investigated by BaBar (2012) and Belle (2015)
  - $M_{h'} < M_{A'}$:
    - h' is long-lived $\rightarrow$ invisible.
    - Possible signature: two tracks and missing energy; probed by KLOE (2015) and Belle II (2023)



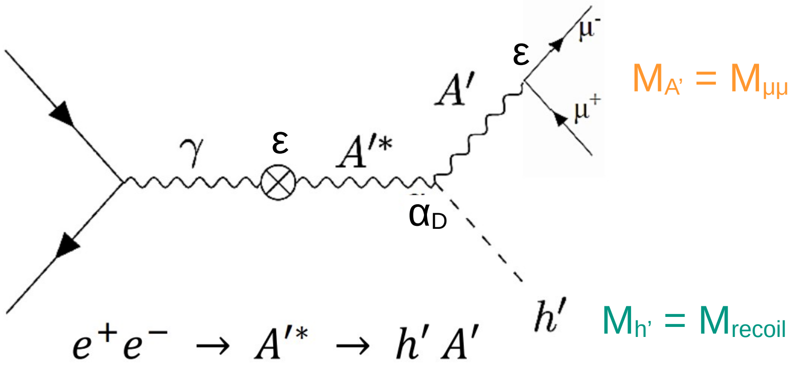


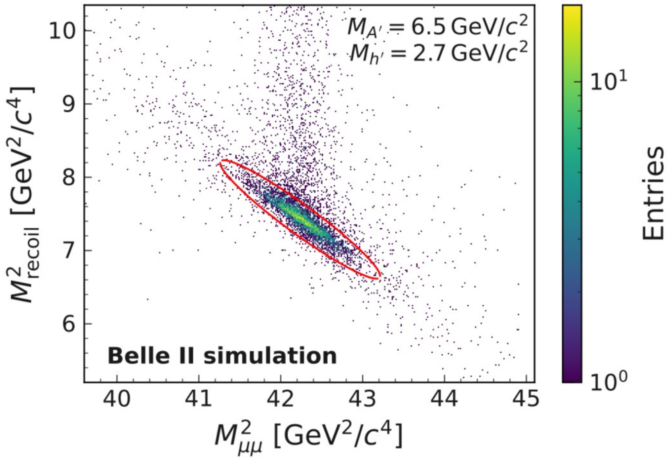
[1] Batell et al. Phys. Rev. D 79, 115008 (2009)

Dark Higgsstrahlung

Belle II, Phys. Rev. Lett. 130, 071804 (2023)

- Search performed with 2019 data → 8.34 fb^{-1}
- Signature:
  - Two opposite sign muons + missing energy
  - 2D peak in $M_{\mu\mu}$ vs. M_{recoil}:
    - Scan and count in ~9000 2D windows
- Backgrounds mainly due to μμ(γ), ττ(γ) and eeμμ
- Similar analysis strategy as for Z'
  - Cut-based suppression optimized in each 2D search window

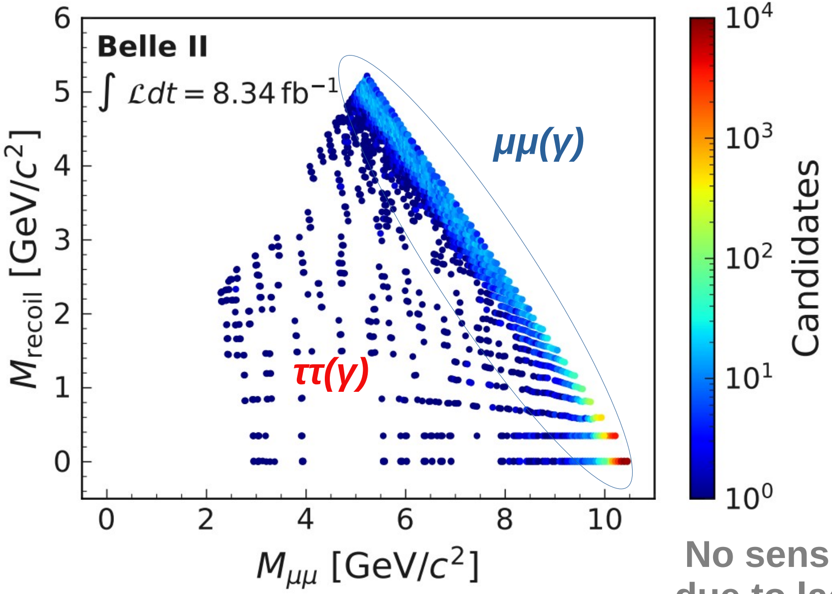


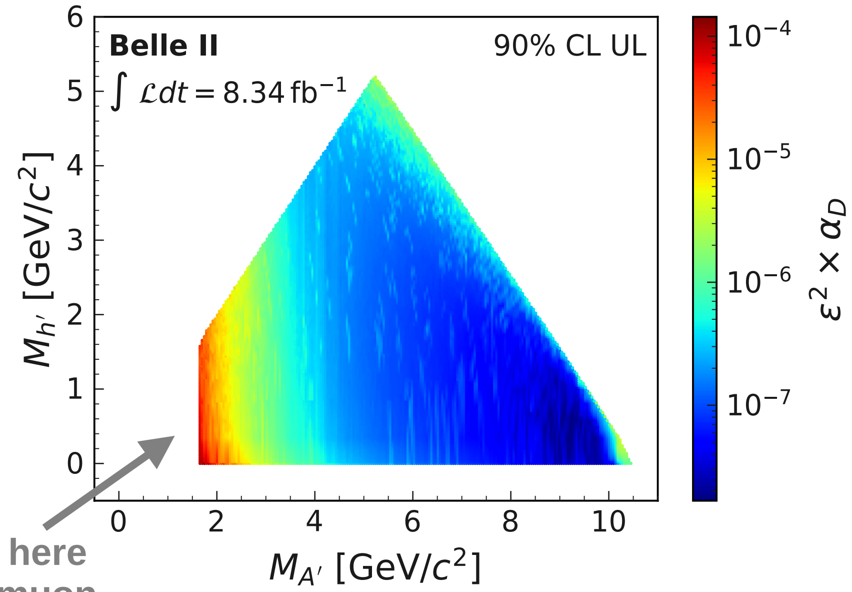


Dark Higgsstrahlung

Belle II, Phys. Rev. Lett. 130, 071804 (2023)

- No significant excess observed: 90% CL upper limits on σ and $\varepsilon^2 \times \alpha_D$
- World's first for $1.65 < M_{A'} < 10.51$ GeV and $M_{h'} < M_{A'}$
  - UL on $\varepsilon^2 \times \alpha_D$ down to 1.7×10^{-8}





No sensitivity here due to lack of muon trigger in 2019

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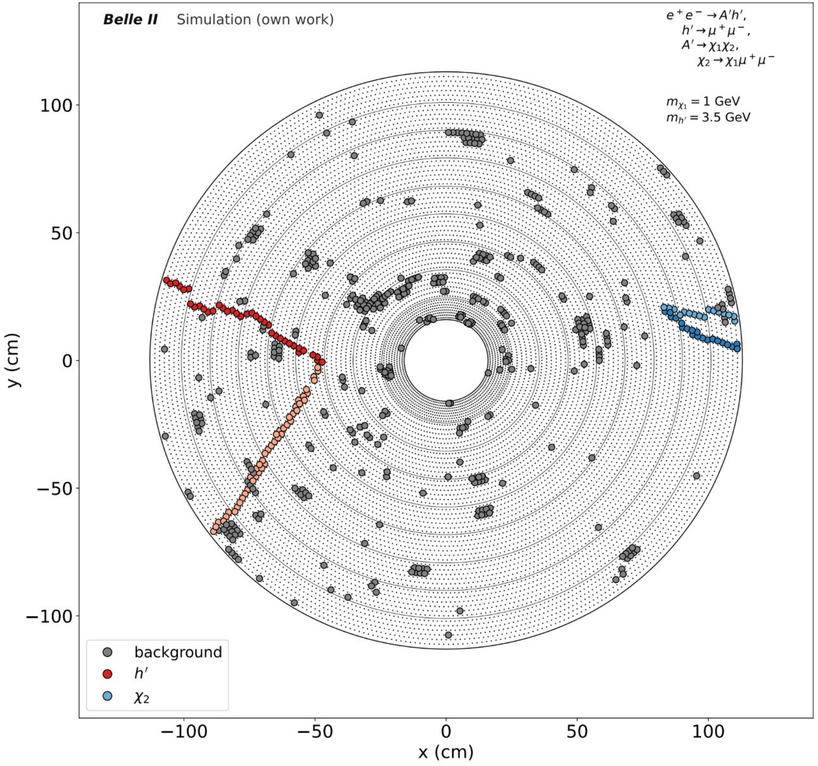
  - Inelastic dark matter with dark Higgs

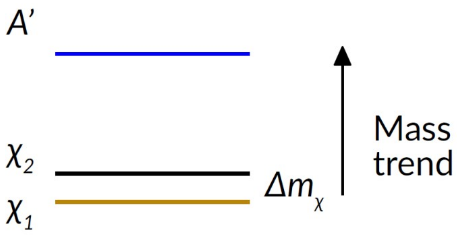
Long-lived particles

- The weaker is the (decay) coupling, the longer is the lifetime of a particle and the larger is its decay length
- The larger is the decay length of a particle, the more difficult it is to detect it
  - Tracking algorithms are usually designed to detect “prompt” particles
  - If the decay length is too large, a particle leaves the detector acceptance without being detected



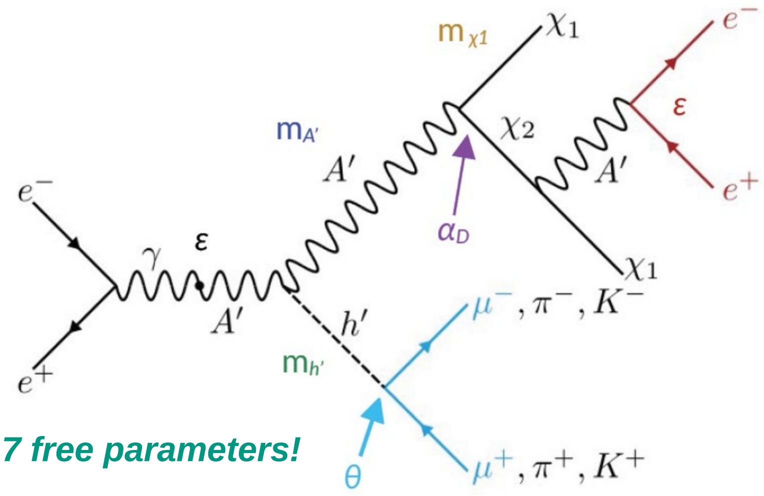
Inelastic dark matter with dark Higgs

- Non minimal dark sector with a dark photon A', a dark Higgs h' and two dark matter states with a small mass splitting [1]:
  - χ_1 is stable (relic DM candidate)
  - χ_2 is long-lived



[1] Smith et al., Phys. Rev. D 64, 043502 (2001)

- Here looking for A' and h' simultaneous production:
  - θ is the h' mixing angle with SM Higgs
  - ε is the A' kinetic mixing with SM photon
  - α_D is the coupling between A' and χ_1/χ_2
  - Focus on $M_{A'} > M_{\chi1} + M_{\chi2}$
    - the decay $A' \rightarrow \chi_1\chi_2$ is favored

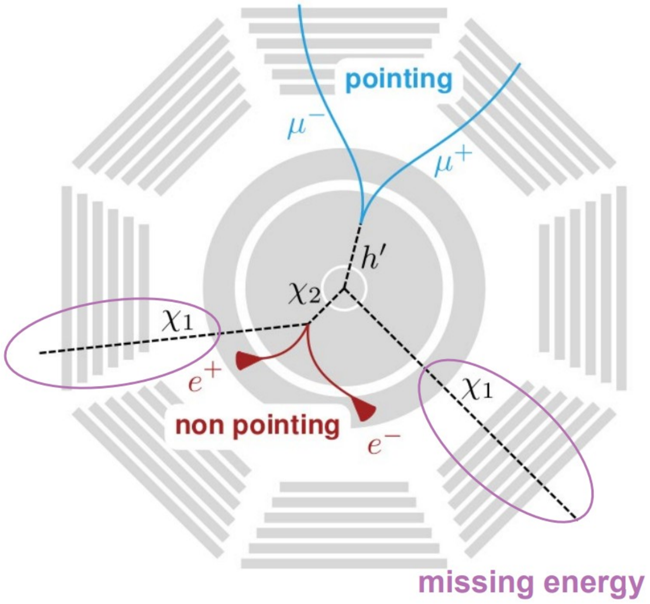


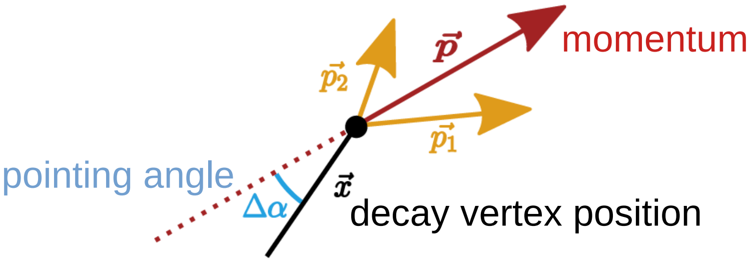
7 free parameters!

Inelastic dark matter with dark Higgs

Paper in preparation

- Used entire Run 1 dataset → 365 fb^{-1}
- Challenging analysis for tracking and trigger due to up to 2 displaced vertices:
  - χ_2 is long lived
  - h' is long lived for small mixing angle θ
- 3 channels considered:
  - $h' \to \mu^+\mu^-/\pi^+\pi^-/K^+K^-$
  - $\chi_2 \to e^+e^-$
  - Require 4 tracks in the final state:
    - 2 forming a pointing angle (h')
    - 2 forming a non-pointing angle (χ_2)
- Strategy: search for an excess in the $M_{h'}$ distribution



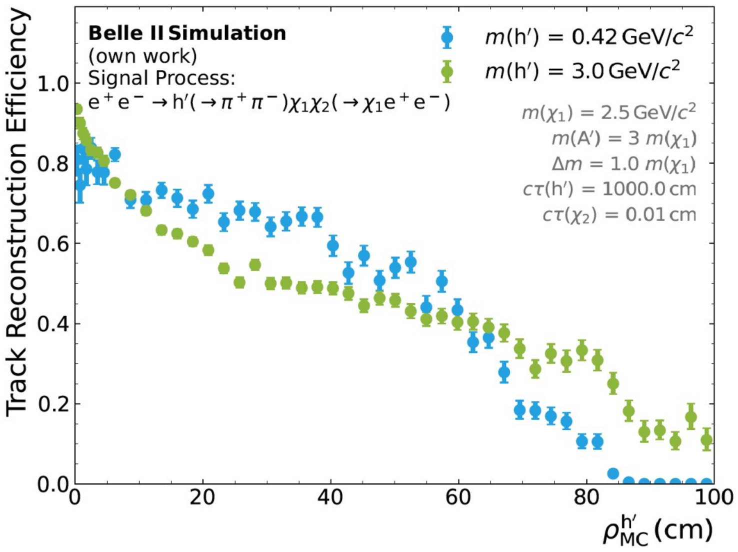


Inelastic dark matter with dark Higgs

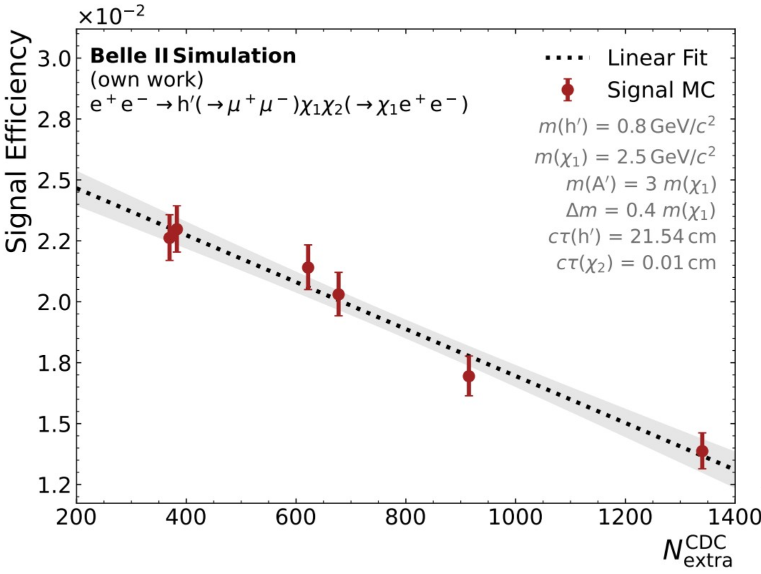
Paper in preparation

- Experimental challenges:

- Reconstruction efficiency drops with displacement of the vertices
  - Largest systematics from data/MC differences in track finding for displaced vertices



- Efficiency drops with higher beam background rates
  - Effect modeled by generating signal MC samples corresponding to different data taking conditions

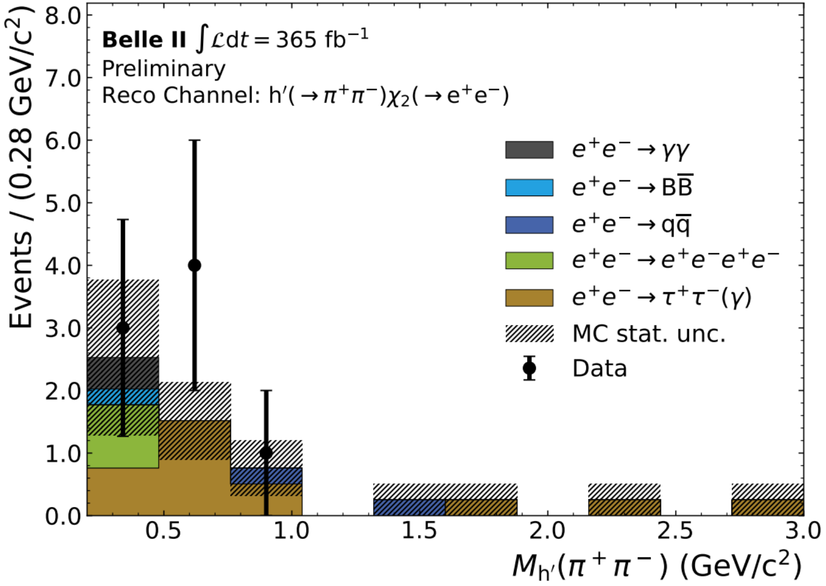


from P. Ecker

Inelastic dark matter with dark Higgs

Paper in preparation

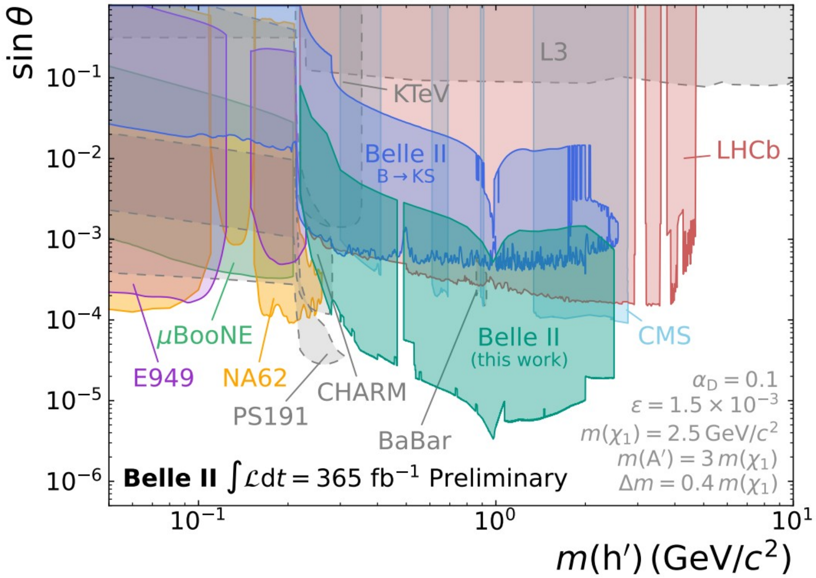
- Signal selection using requirements on pointing angles and vertex distance from the interaction point
  - Very low SM background
- Expected background estimated in data from sidebands to not rely on MC
- Counting strategy to extract signal yields
- No significant excess found in the individual final states or the combination:
  - 9 events observed (8 of 9 are $\pi^+\pi^-$) consistent with expected background.



Inelastic dark matter with dark Higgs

Paper in preparation

- World leading upper limits, but dependent on the choice of the remaining parameters
  - Provide interpretations for around 30 model parameter configurations



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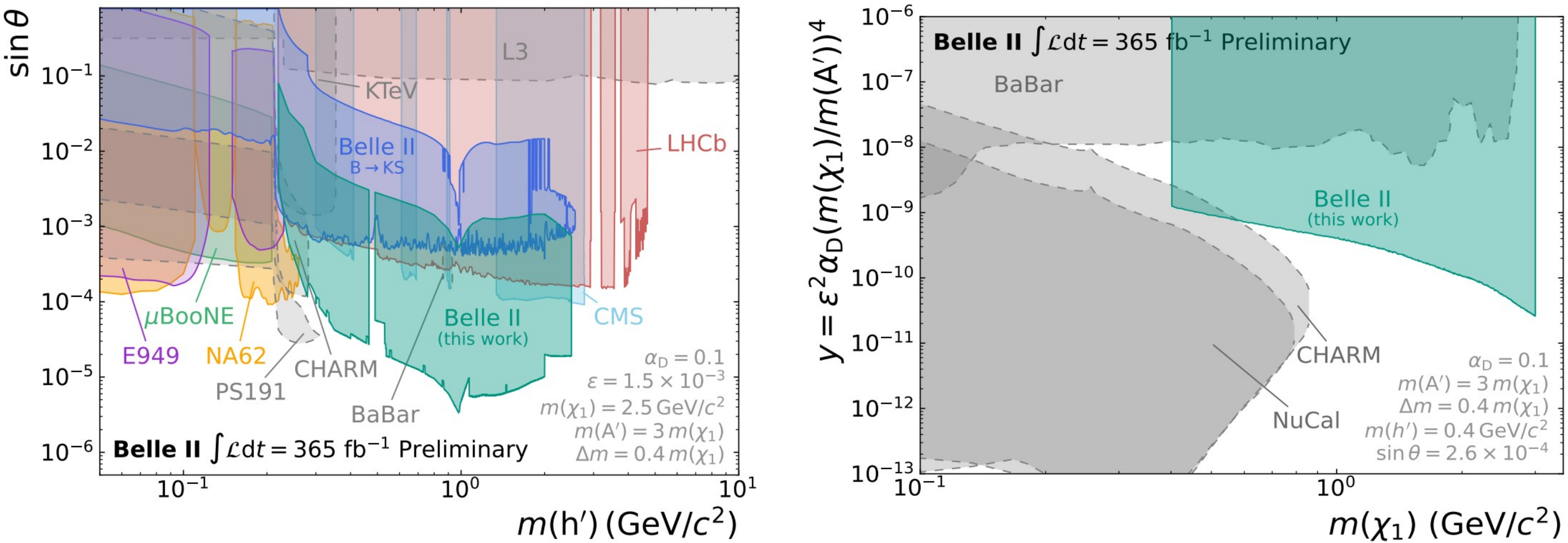
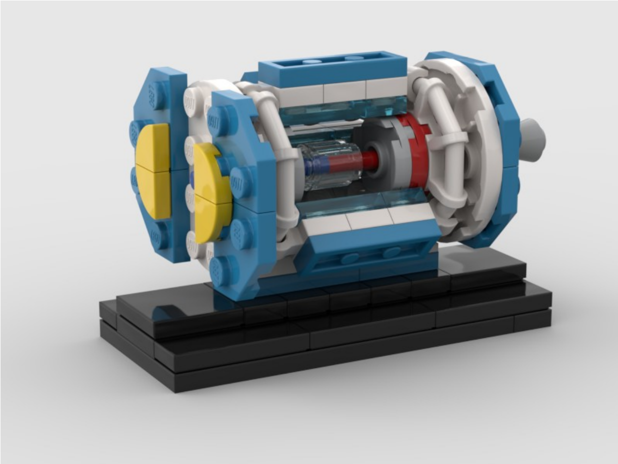


Summary

- Belle II provides a unique environment and excellent sensitivity for dark sector searches in the MeV – GeV range
- Several world leading or competitive results in the last years exploiting invisible and displaced signatures
  - Invisible Z' decay
    Belle II, Phys. Rev. Lett. 130, 231801 (2023)
  - Dark Higgsstrahlung
    Belle II, Phys. Rev. Lett. 130, 071804 (2023)
  - Inelastic dark matter with dark Higgs
    Paper in preparation



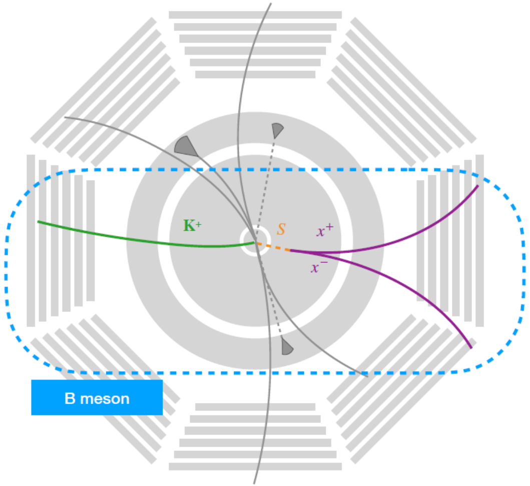
https://etpwww.etp.kit.edu/~ferber/lego.html
https://build-your-own-particle-detector.org/models/belle-2-micro-model/

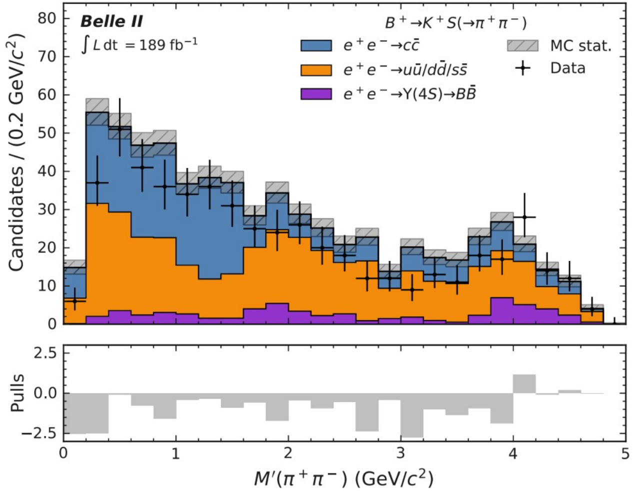
Backup

Long-lived scalar in B decays

Belle II, Phys. Rev. D 108, L111104 (2023)

- First Belle II long-lived particle search
- Search for scalar S in eight visible B channels: $B^+ \to K^+S$ and $B^0 \to K^{*0}(\to K\pi)\,S$
  - $S \to e^+e^- / \mu^+\mu^- / \pi^+\pi^- / K^+K^-$ and forming a displaced vertex
  - Probing lifetimes between $10^{-5} < c\tau < 4$ m
- Signal B-meson fully reconstructed
  - Other B non reconstructed
- Combinatorial $ee \to q\bar{q}$ reduced by requiring kinematics similar to B-meson expectations
- Bump hunt in dark scalar mass distribution using unbinned maximum likelihood fits
  - Background determined directly in data





Long-lived scalar in B decays

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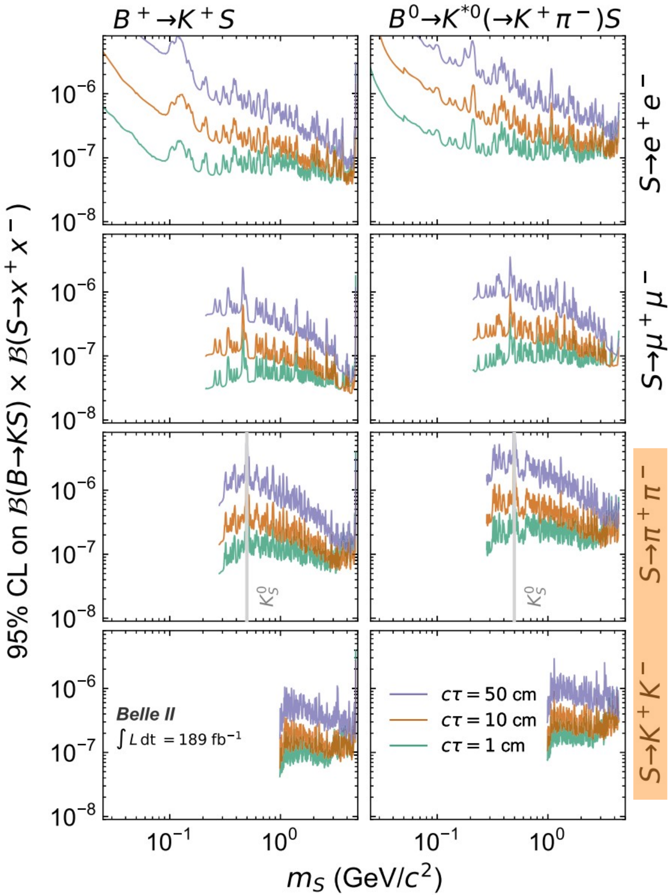

- First model-independent limits for exclusive $B^0 \to K^{(*)} S$; $S \to$ hadrons

Long-lived scalar in B decays

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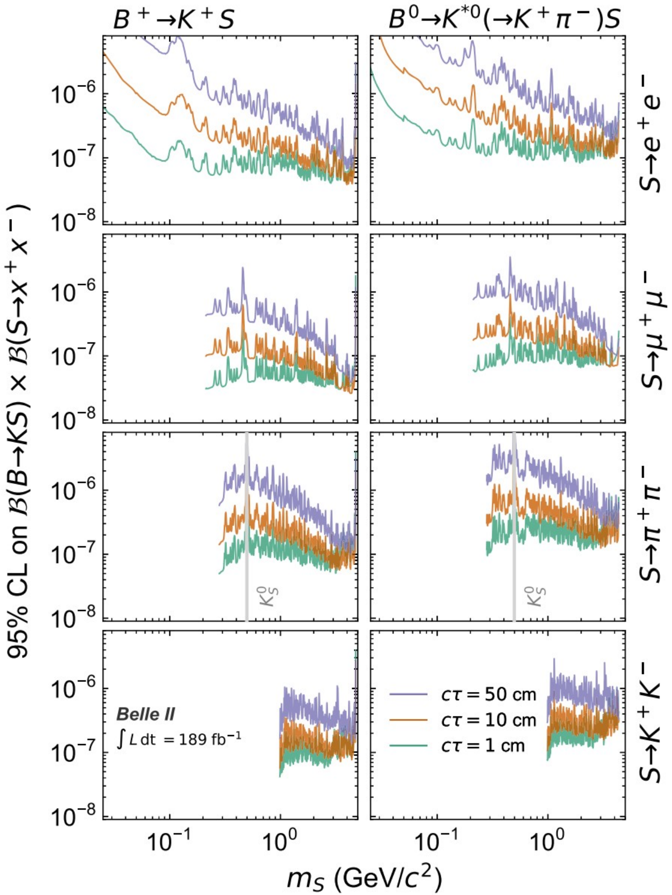
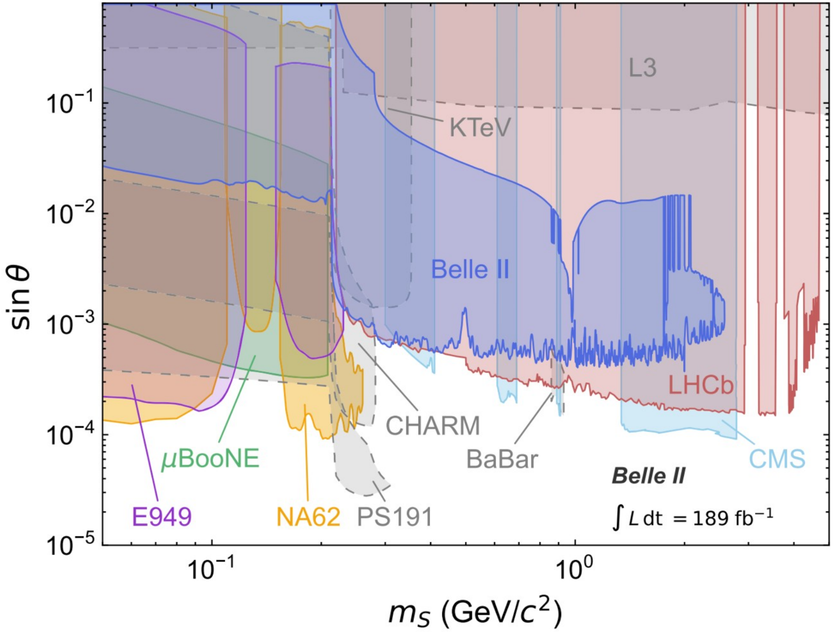


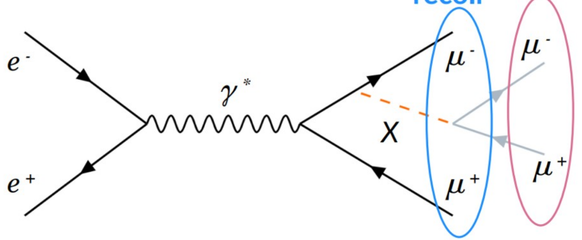
- First model-independent limits for exclusive $B^0 \to K^{(*)} S\,;\, S \to$ hadrons
- Interpretation as dark scalar with mixing angle θ with SM Higgs

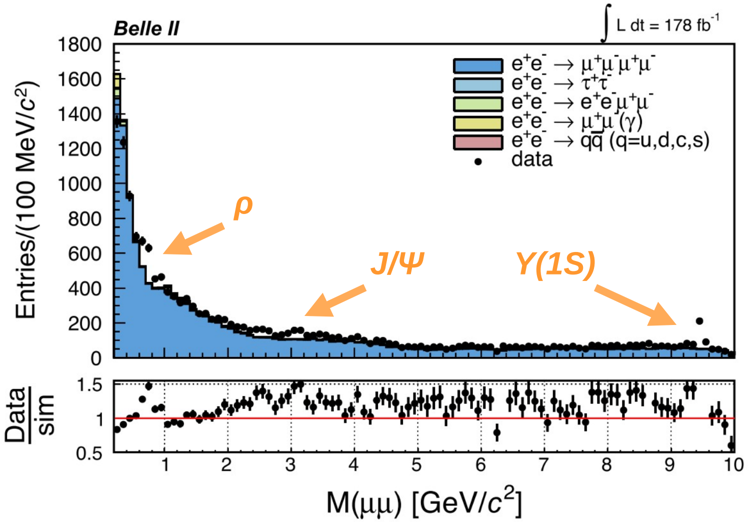


$\mu^+\mu^-$ resonance in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ @ Belle II

Belle II, Phys. Rev. D 109, 112015 (2024)

- Search for the process $e^+e^- \to \mu^+\mu^- X$ with $X \to \mu^+\mu^-$
  - Look for a narrow peak in the $\mu^+\mu^-$ mass distribution
- Probing two different models:
  - $L_\mu - L_\tau$ vector mediator (Z') [1]
  - Muonphilic dark scalar (S) [2]
- Event selection
  - 4 charged particles
    - At least 3 indentified as muons
  - M(4 tracks) ~ $\sqrt{s}$
  - No extra energy
- Aggressive background suppression based on training of NNs



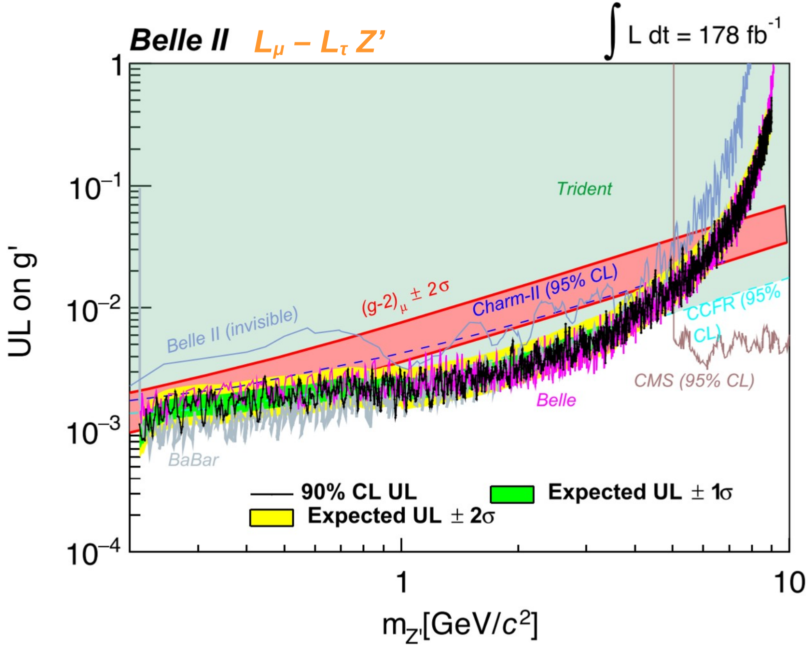


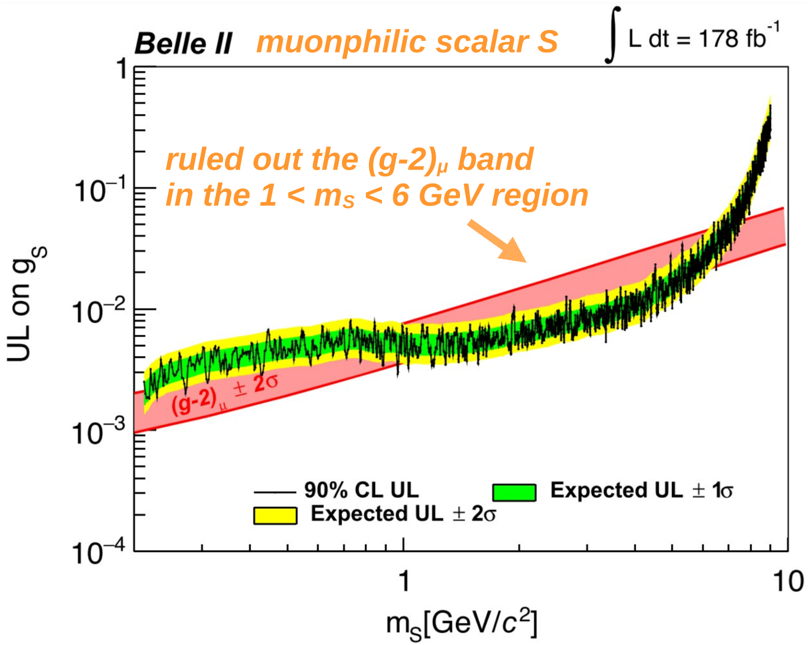
[1] W. Altmanshofer et al., J. High Energ. Phys. 2016, 106 (2016)
[2] R. Capdevilla et al., J. High Energ. Phys. 2022, 129 (2022)

$\mu^+\mu^-$ resonance in $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ @ Belle II

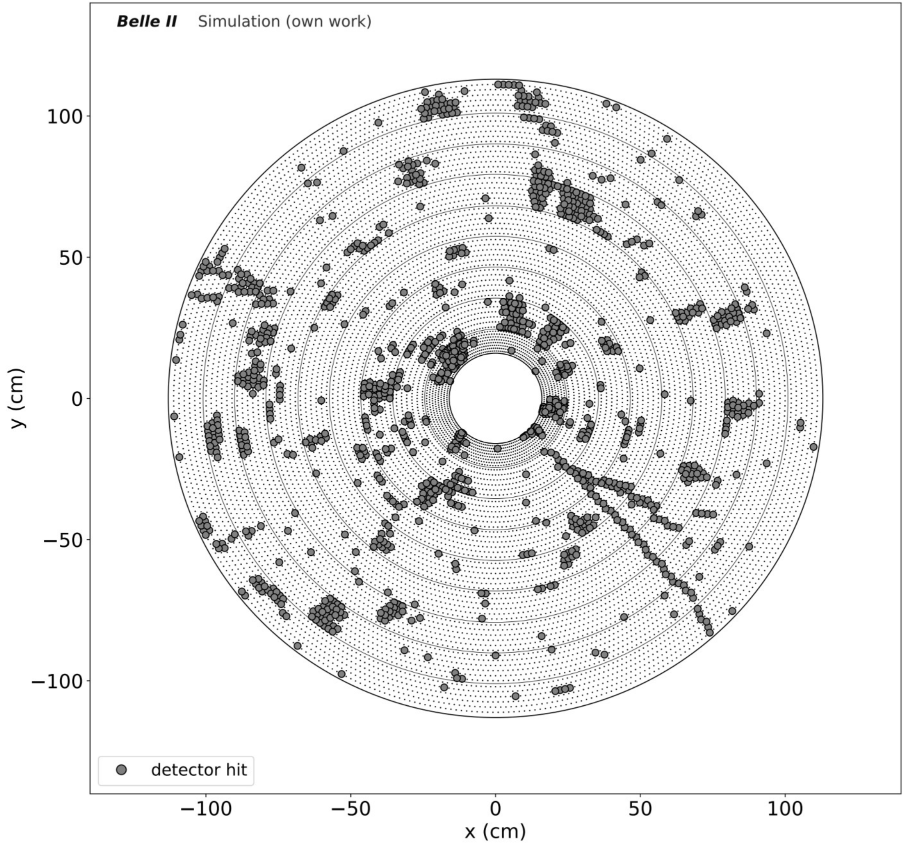
Belle II, Phys. Rev. D 109, 112015 (2024)

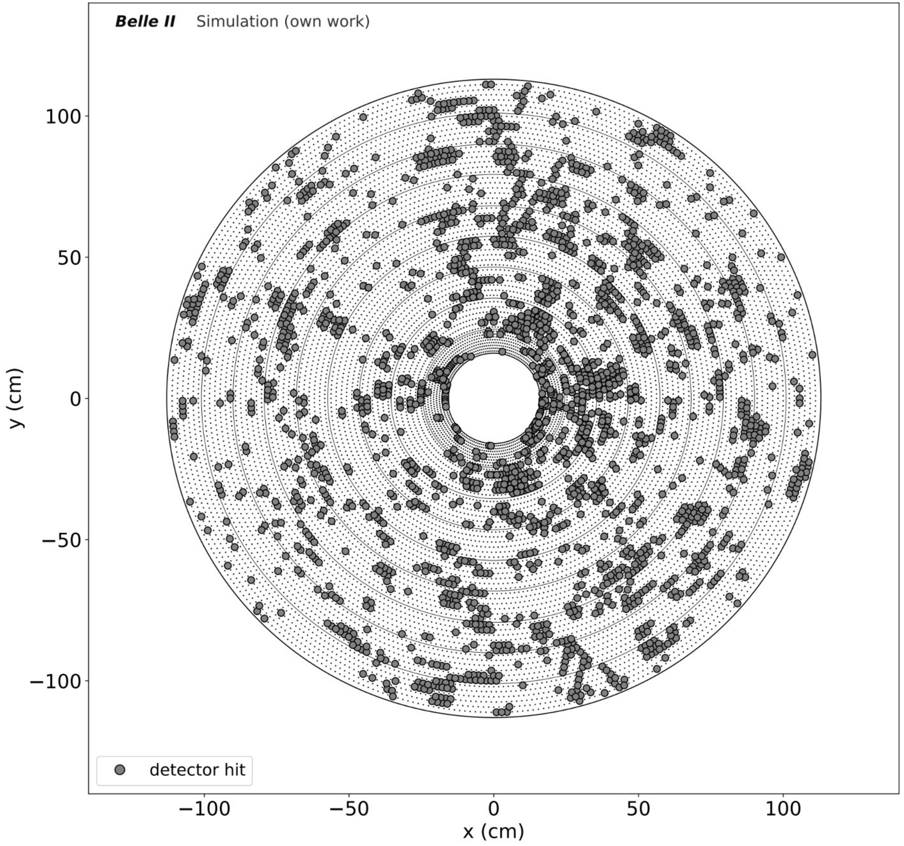
- No significant excess found in 178 fb^{-1}
  - Competitive 90% CL upper limits for g' coupling of the $L_\mu - L_\tau$ model (Z') with BaBar (> 500 fb^{-1}) and Belle (> 600 fb^{-1}) results
  - First 90% CL upper limits for the muonphilic dark scalar (S) model from a dedicated search



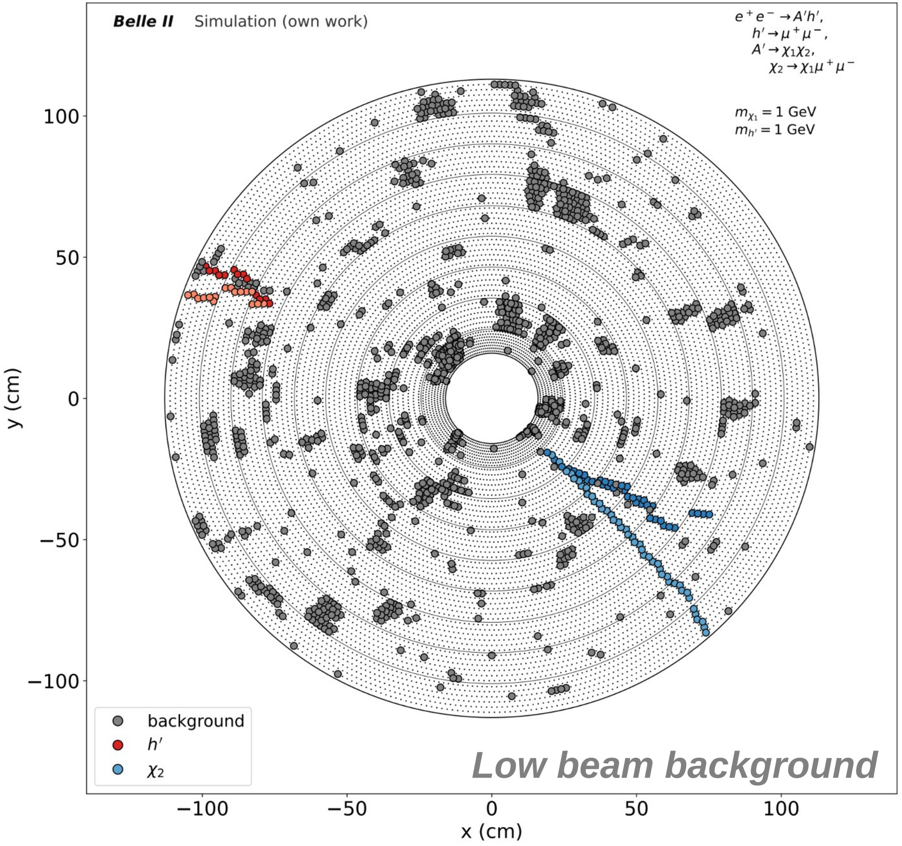


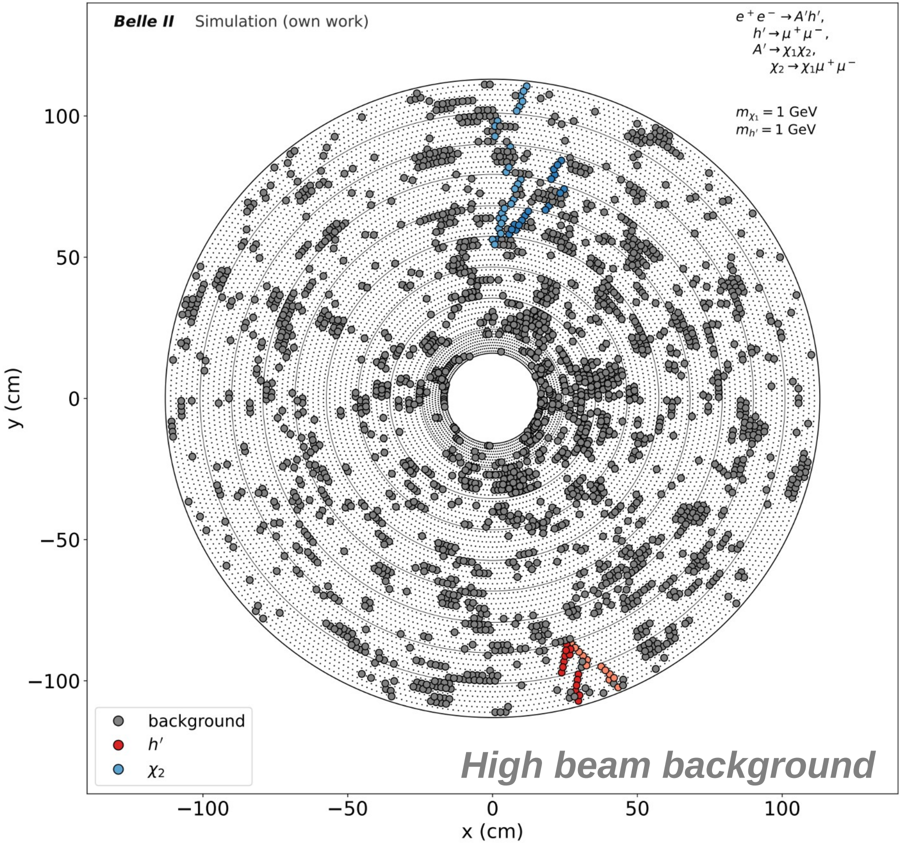
Challenging displaced vertices to find





Challenging displaced vertices to find

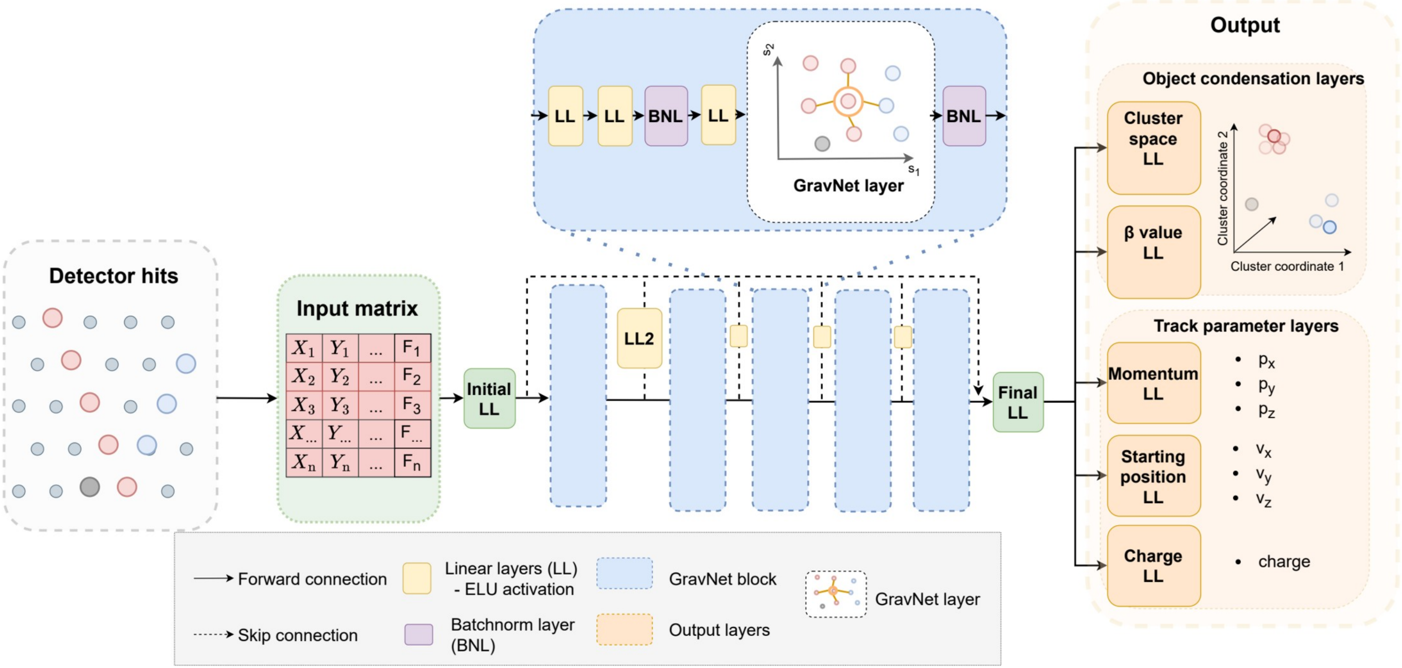




Graph neural networks for tracking

L. Reuter et al., arXiv:2411.13596, accepted for publication on Comput. Softw. Big Sci.

- Sparse inputs and irregular detector geometry → Graph Neural Networks
- Find unknown number of tracks → Object Condensation [1]

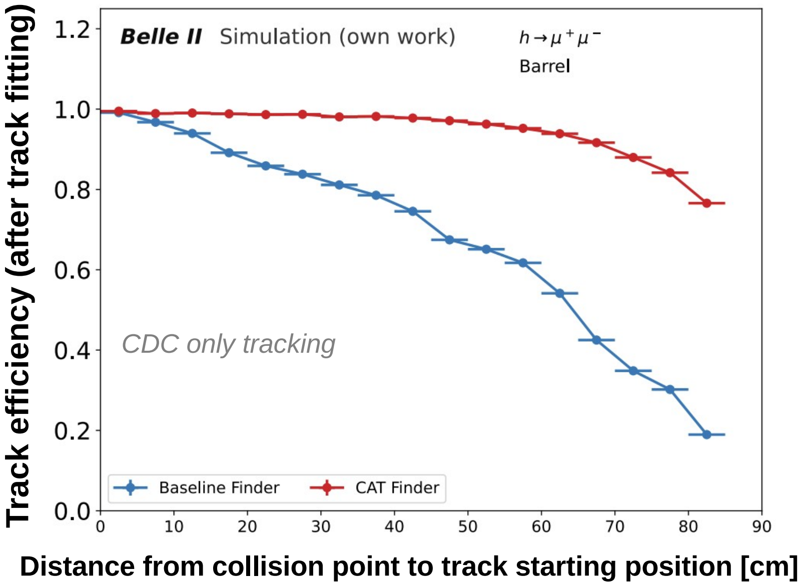


[1] Kiesler, Eur. Phys. J. C 80, 886 (2020)

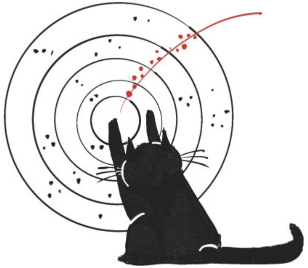
Graph neural networks for tracking

L. Reuter et al., arXiv:2411.13596, accepted for publication on Comput. Softw. Big Sci.

- Sparse inputs and irregular detector geometry → Graph Neural Networks
- Find unknown number of tracks → Object Condensation
- It outperforms the baseline algorithm used at Belle II in finding displaced tracks

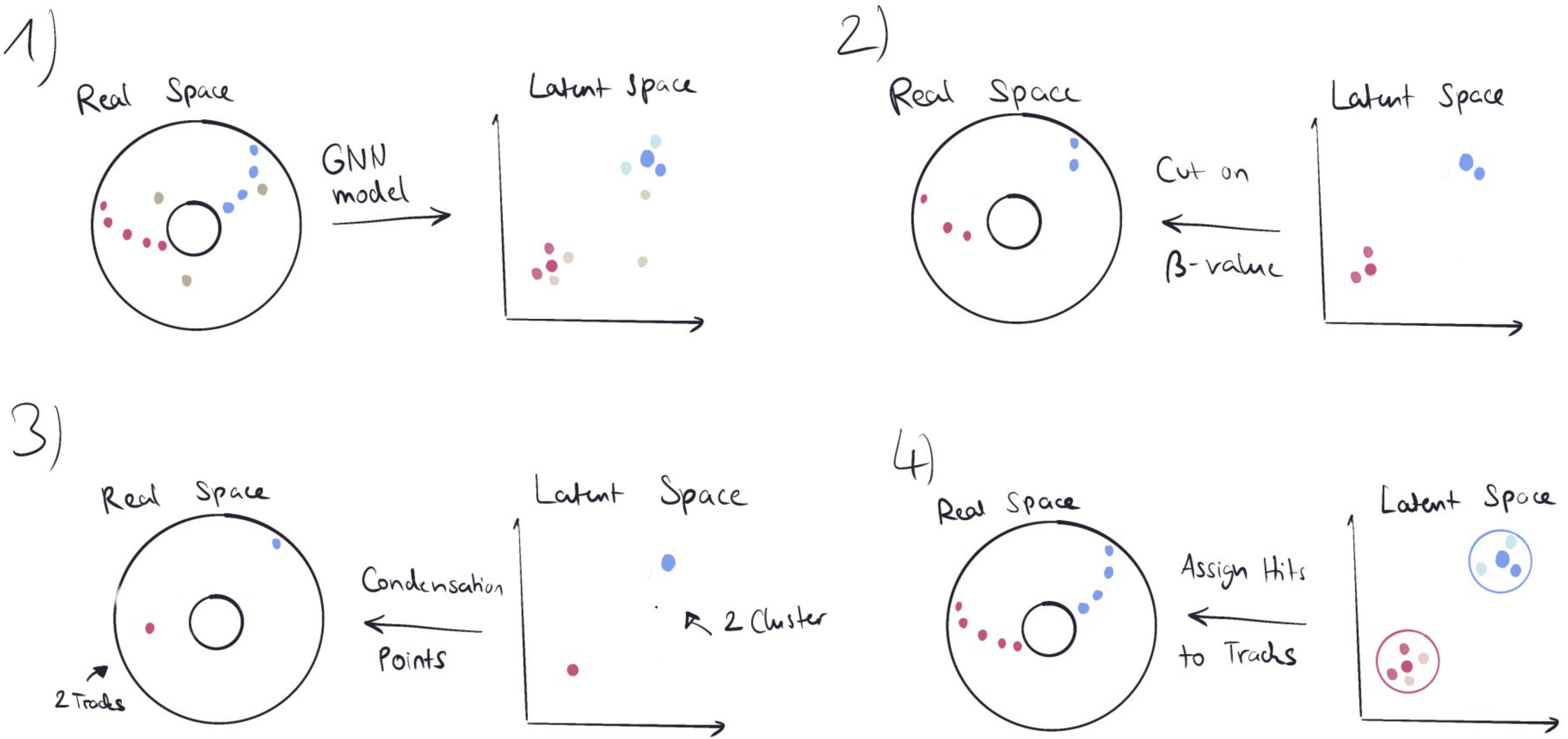


	Averaged efficiency	Averaged purity
Baseline	$0.574^{+/-0.001}$	$0.964^{+/-0.001}$
CAT Finder	$0.892^{+/-0.001}$	$0.978^{+/-0.001}$



More details in L. Reuter talk on Friday morning
T 97.2 Data, AI, Computing, Electronics IX

From object condensation to track finding



L. Reuter