Searches for dark Higgsstrahlung and invisible Z' at the Belle II experiment

Huw Haigh, on behalf of the Belle II Collaboration

33rd Rencontres de Blois - Dark Universe(s)

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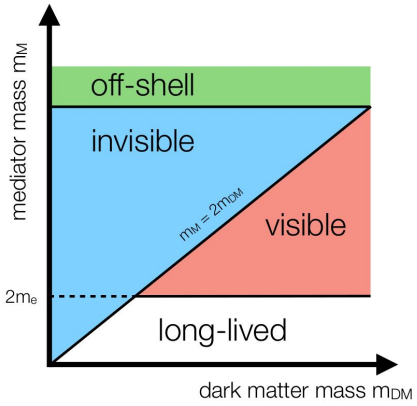
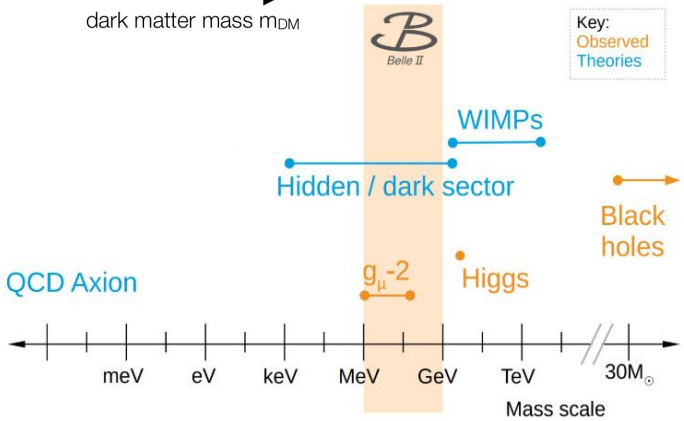
Introduction

- B-factories have a unique reach in searches for the light dark sector with low mass mediator particles on the MeV-GeV scale.

Talk by Laura Zani

- **Belle II** has great advantages in **dark sector searches**
  - Hermetic detector
  - Clean collision environment
  - Excellent PID
  - Dedicated low-multiplicity triggers



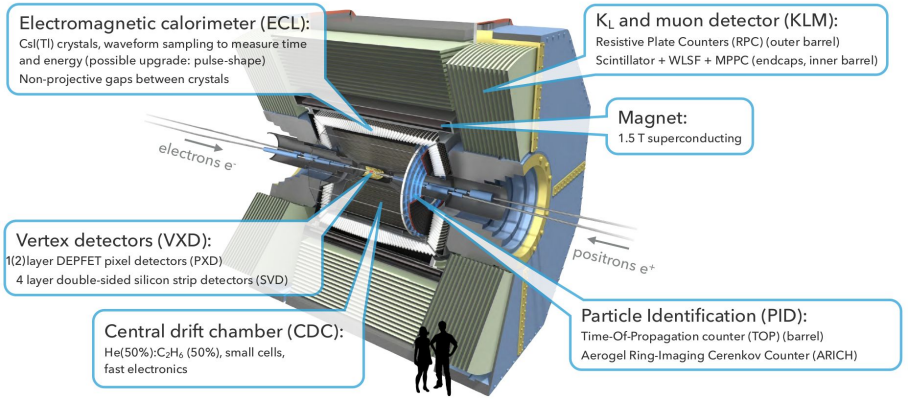


This talk focuses on two searches:

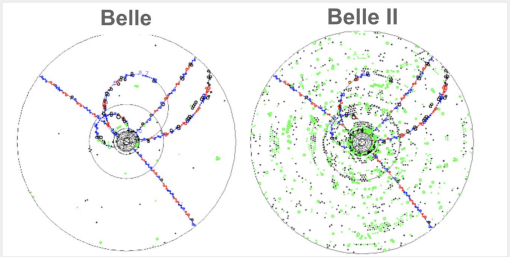
- **Dark Photon** that obtains mass through spontaneous symmetry breaking, introducing a **Dark Higgs Boson.**
- **Z' boson** that couples to 2nd and 3rd lepton generations and decays invisibly

Belle II & SuperKEKB

- **B-factory** located in Tsukuba, Japan.
- Asymmetric e^+e^- collider operating at $\mathbf{m_{\Upsilon(4S)} = 10.58\ GeV/c^2}$ (7 GeV/c^2 e^- + 4 GeV/c^2 e^+)
- Pilot run in 2018, physics runs began March 2019
- Target **x50 Belle data (≈50ab^{-1})**
- Wide-ranging and varied physics program: B and D physics, quarkonium, τ-physics, dark sector, …



- Increased beam backgrounds
  - ➔ upgraded trigger system with dedicated low multiplicity lines



- $\mathbf{B_y = 0.28}$ **(vs 0.42 @ Belle)**
  - ➔ Reduced boost requiring improved vertex reconstruction
- **Solid angle coverage > 90%**
  - ➔ High hermeticity for E_{miss} measurements.

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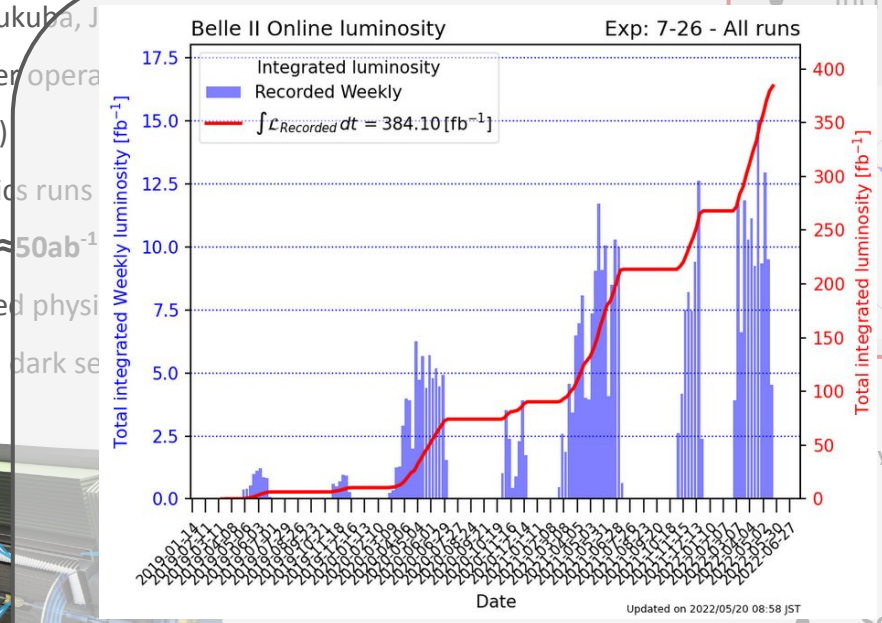
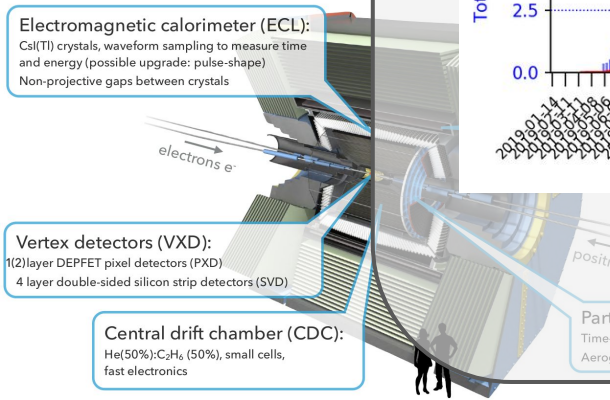


384fb^{-1} recorded integrated luminosity



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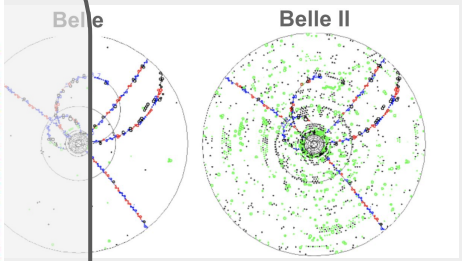
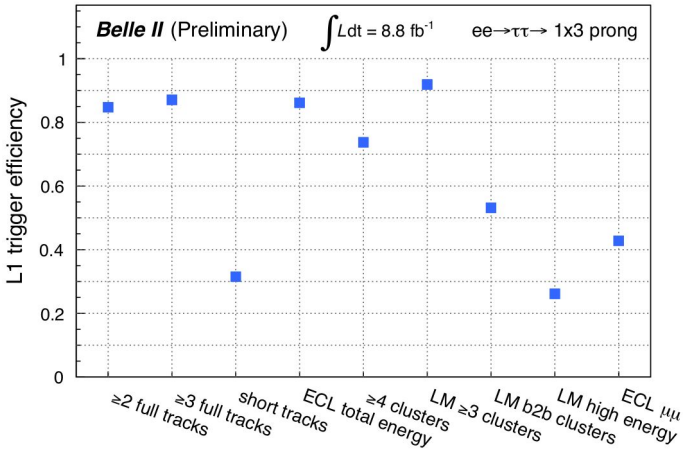


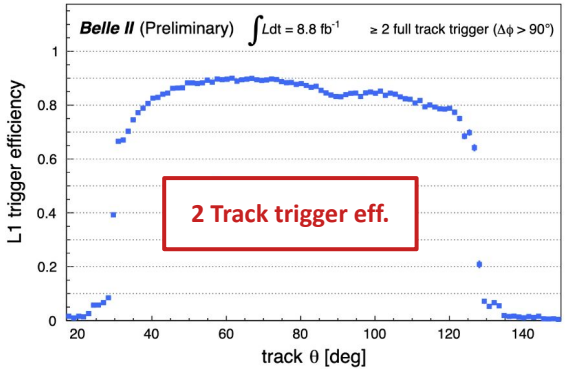
- = 0.28 (vs 0.42 @ Belle)
  Reduced boost requiring improved vertex reconstruction
- Solid angle coverage > 90%

→ High hermeticity for E_{miss} measurements.

Trigger System

- Two-tier trigger system:
  - Hardware based low level trigger (L1)
  - Software based high level trigger (HLT)
- Reduce effects from beam backgrounds (Touschek effect, beam-gas scattering, radiative Bhabha, …)
- L1 trigger
  - Max trigger rate 30KHz
  - Combines 4 sub-detector triggers; **Drift Chamber**, **Cherenkov detectors**, **Muon System**, **Electromagnetic Calorimeter**
- Dedicated trigger lines for dark sector and low-multiplicity physics (not available in Belle):
  - Single photon / track
  - Multi-track triggers
    - **2 full tracks with opening angle requirement used in dark higgsstrahlung/Z' searches**
  - 3D neural trigger

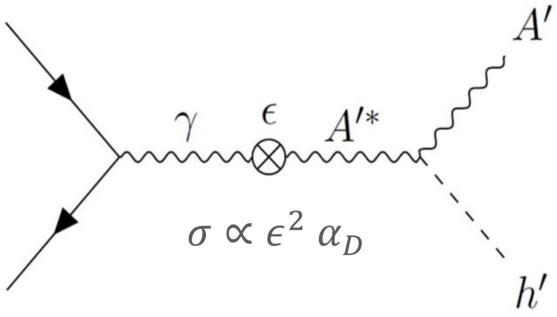




Dark Higgsstrahlung - Theory

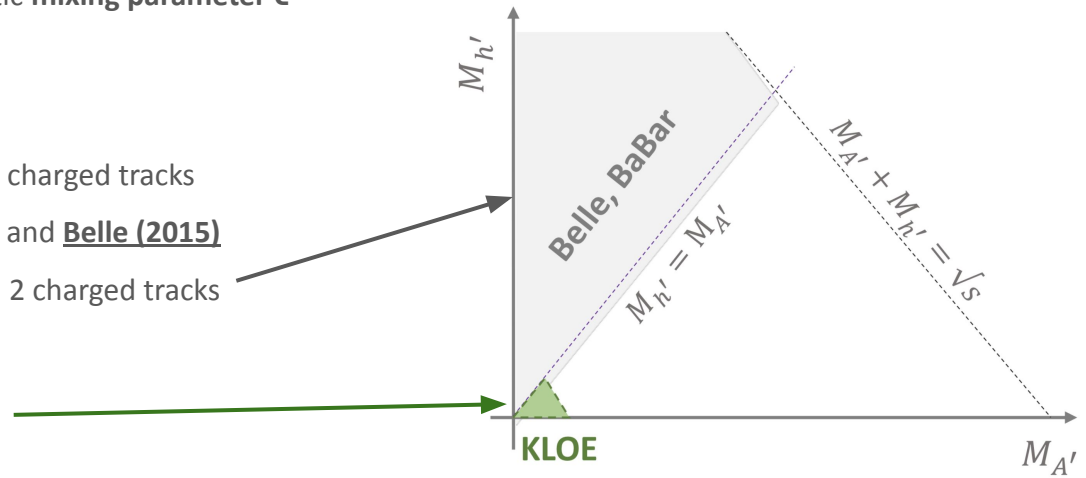
Next to minimal dark photon model

- **Dark photon**, mass generated via spontaneous symmetry breaking of **U(1)'** extension to SM, introduces dark Higgs boson. (Phys. Rev. D 79, 115008 (2009))
- Single **dark photon, A'**, and a single **dark Higgs, h'**
- Dark photon coupled to SM photon via kinetic **mixing parameter ϵ**



Mass hierarchy scenarios

- $M_{h'} > M_{A'}$ **:** h' ⟶ A' ⟶ 4l, 4had, 2l+2had ⇒ 6 charged tracks
  - Searches conducted by **BaBar (2012)** and **Belle (2015)**
- $M_{h'} < M_{A'}$ **:** h' is long-lived and so invisible ⇒ 2 charged tracks
  - Partially constrained by **KLOE (2015)**



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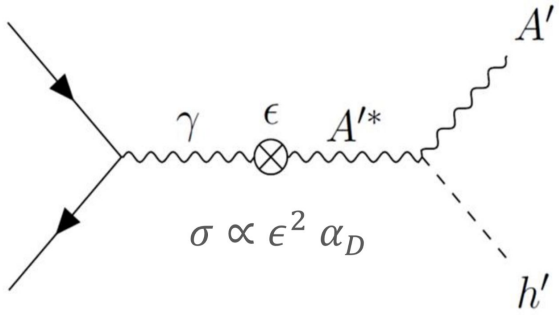

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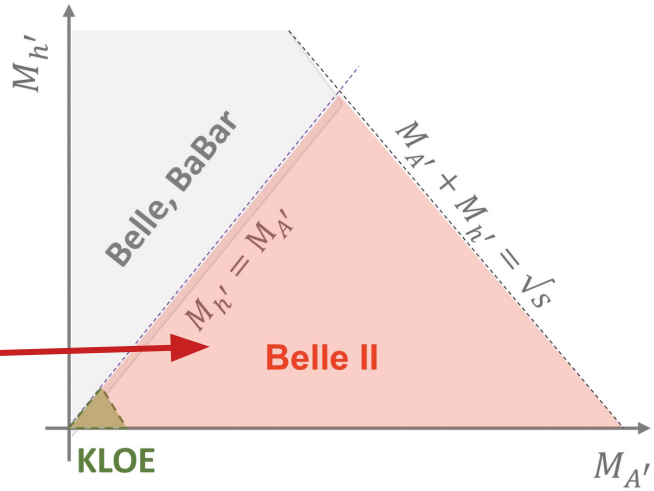
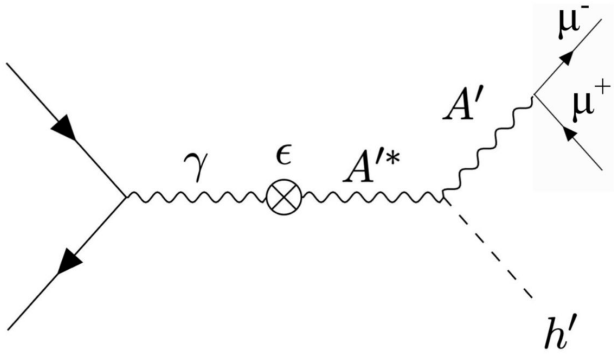


Exploring unconstrained region at Belle II

Dark Higgsstrahlung - Analysis

Data sample: 2019 dataset ⇒ 8.34fb^{-1}

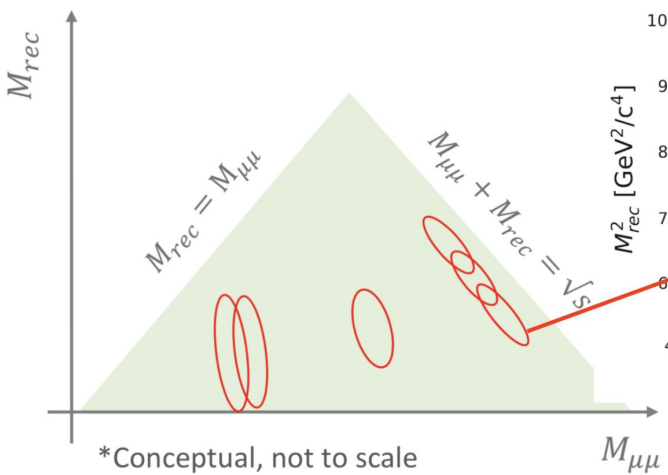


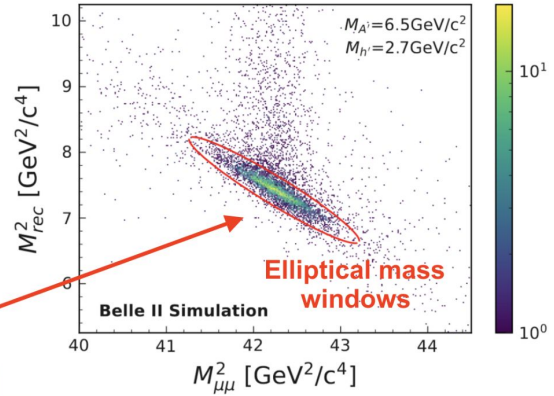
Detector signature:

- Looking for invisible h' with A' ⟶ $\mu^+\mu^-$ ⇒ $\mu^+\mu^-$ + missing energy.
- 2D peak in $M_{\mu\mu}$ vs M_{rec} (M_{rec} - invariant mass of system recoiling from $\mu^+\mu^-$)

Search strategy:

- $M_{\mu\mu}$ & M_{rec} correlated ⇒ search in tilted elliptical mass windows.
- Spacing ∝ M^2 2D resolution.
- ≈9000 overlapping windows (large look-elsewhere effect).
- Counting experiment in each window (on average, 1 event in ≈3 windows).

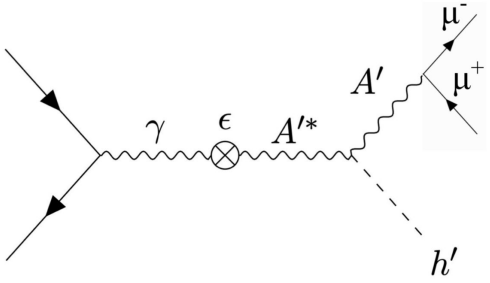




Dark Higgsstrahlung - Background suppression

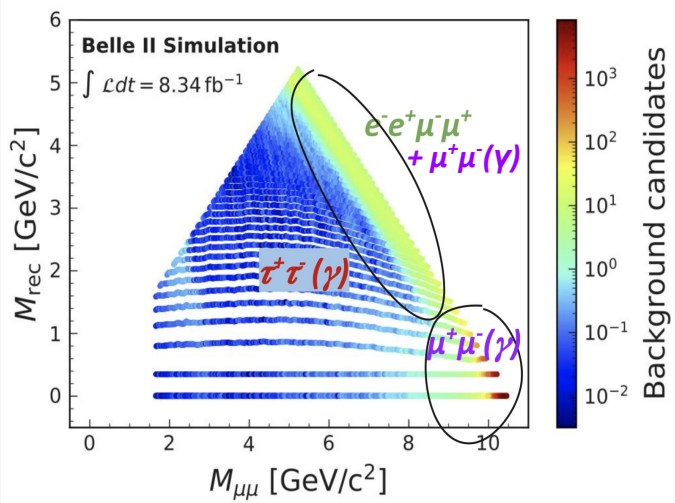
Trigger & pre-selections:

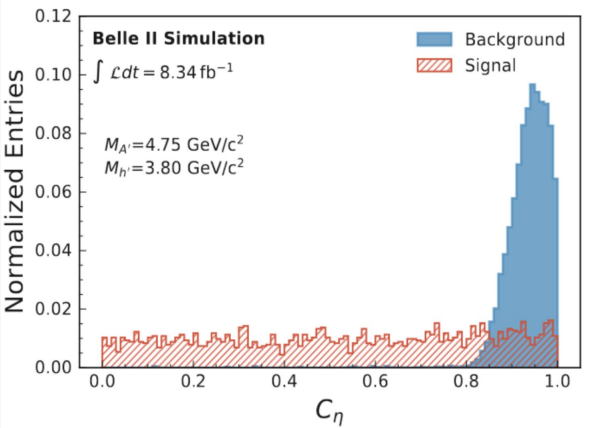
- Events fire two-track, ffo trigger
- 2 good quality tracks
- MuonID, $P_T^{\mu\mu} > 0.1 GeV/c^2$
- Recoil pointing in ECL barrel, no nearby photon
- Event extra energy < 0.4 GeV/c^2



Surviving Backgrounds:

- Main contributions
  - $\mu^+\mu^-(\gamma)$ (79%)
  - $\tau^+\tau^- \rightarrow \mu^+\mu^-$, 4ν (18%)
  - $e^+e^-\mu^+\mu^-$ (3%)
- Mostly localised near the kinematic limit, especially for $M_{\mu\mu} > 9 GeV/c^2$





Helicity angle (C_n):

- Cut on angle between flight direction of A' in CMS and μ^- in the A' rest frame (Punzi FOM optimised in each search window)
- Signal eff. 10-25% for $M_{\mu\mu} > 4 GeV/c^2$ (rapidly drops below due to trigger)

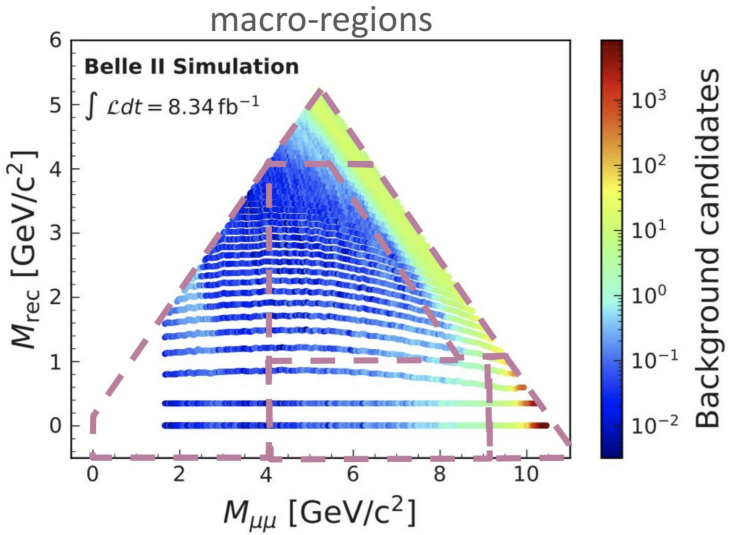
Dark Higgsstrahlung - Systematics

Data validation in control samples:

- $\mu^+\mu^-\gamma$: require energetic photon (usually vetoed)
- $\tau^+\tau^- \to e\mu$, 4ν: require electron instead of muon

- Split 2D mass plane into orthogonal macro-regions
  - Each enriched by a single source of background
  - Data vs MC: normalisation, background shape modelling, recoil mass resolution.
  - Overall good agreement observed.
  - Discrepancies assigned as systematic uncertainties.

source	uncertainty	target
Pre-selections	**2 - 9.1%**	BKG & signal
BKG shape	**9.3%** (region specific)	BKG
C_η cut	**1%**	BKG
Mass resolution	**2.4%** (on average)	signal
Eff. Inside windows	**2 - 5%**	signal
Theory (BR A')	**4%**	signal



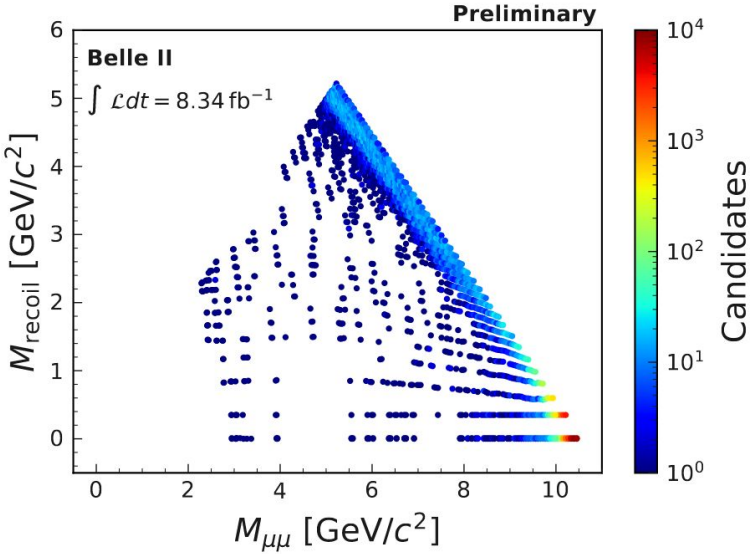
Total uncertainties	**2.2 - 12.7%**	BKG
	5.4 - 11.3%	signal

- Uncertainties in majority of search plane are dominated by sample size (impact of systematics on ULs < 1%, see next slide)
- Exception is $M_{A'} > 9\mathrm{GeV}/c^2$ (≈ 25% impact on ULs)

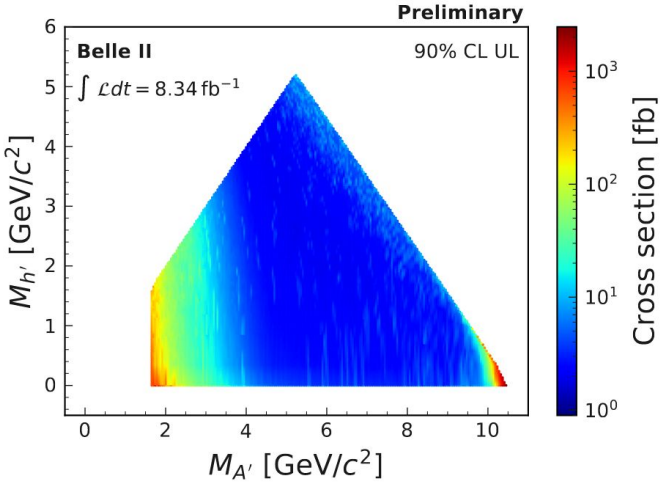
Dark Higgsstrahlung - Results

Search for excesses above expected background independently in the ≈9000 search windows.

- Event counts in a single window interpreted as:
  $N = \epsilon_{sig} \times L \times \sigma_{DH} + B$
  with systematic uncertainties taken into account.



- Find no significant excess above background.
  90% upper limits computed in a Bayesian approach on the cross section from 1.65 to 10.51 GeV/c^2 in $M_{A'}$ ($M_{h'} < M_{A'}$)



World leading ULs for $1.65 < M_{A'} < 10.51$ GeV/c^2

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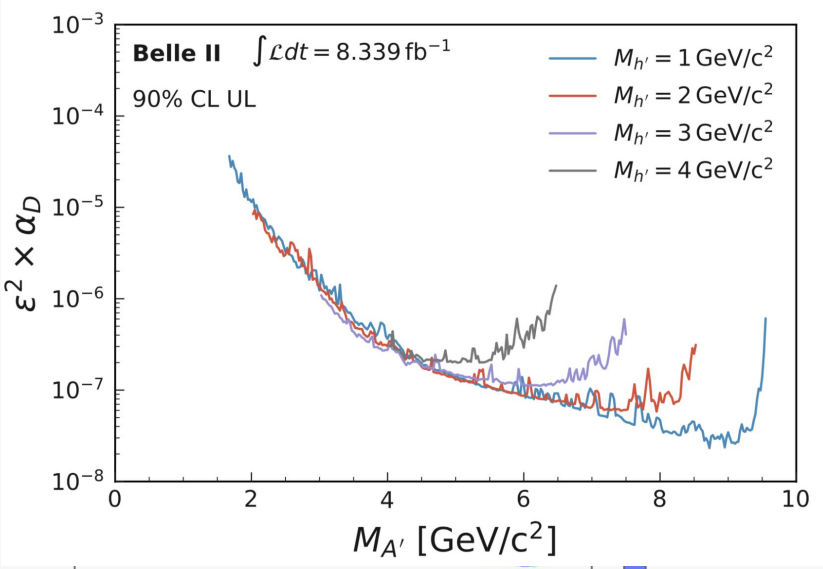

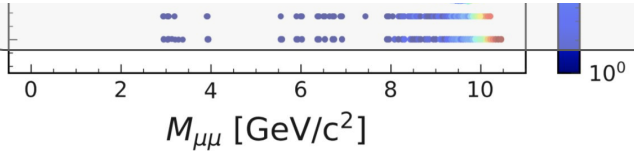

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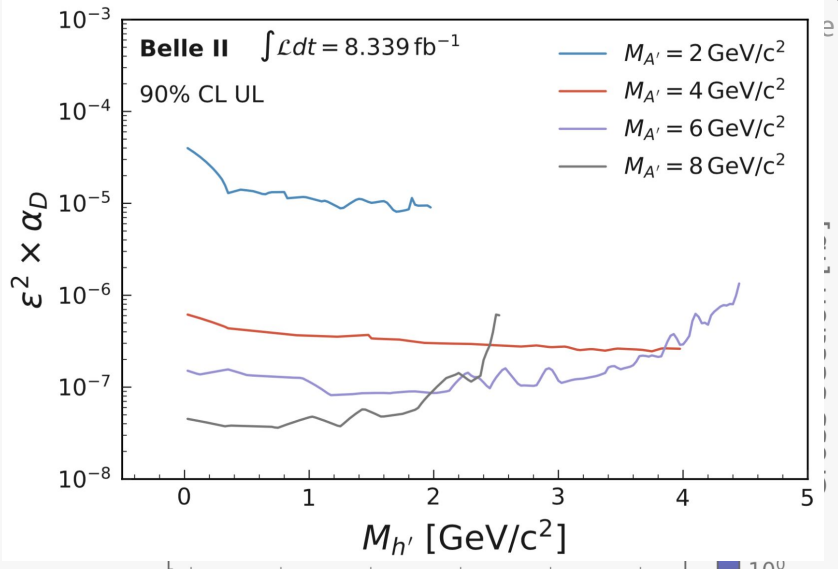
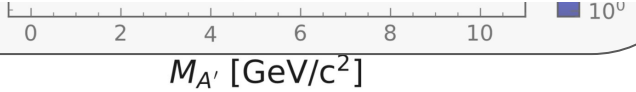




World leading ULs for $1.65 < M_{A'} < 10.51$ GeV/c^2

Invisible Z' - Theory

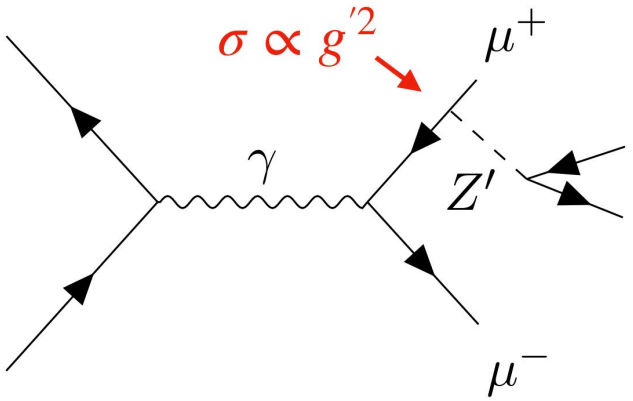
- U(1)' extension of standard model -> new massive gauge boson
- Couples to μ and τ leptons ($L_\mu - L_\tau$) via g'
- Decay to DM or neutrinos -> neither of which detectable.
- possibilities;
  - $(g-2)_\mu$
  - $B \longrightarrow s\mu\mu$
  - Mediator between SM and DS

JHEP 1612 (2016) 106
PRD 89, 113004 (2014)

$$
\begin{aligned}
M_{Z'} < 2M_\mu \quad &\Longrightarrow \quad BF[Z' \to \text{invisible}] = 1, \\
2M_\mu < M_{Z'} < 2M_\tau \quad &\Longrightarrow \quad BF[Z' \to \text{invisible}] \simeq 1/2, \\
M_{Z'} > 2M_\tau \quad &\Longrightarrow \quad BF[Z' \to \text{invisible}] \simeq 1/3.
\end{aligned}
$$

$$
\text{if } M_{Z'} > 2M_\chi \\
BF(Z' \to \chi\bar{\chi}) = 1
$$

$$
\mathcal{L} = \sum_\ell \theta g' \bar{\ell} \gamma^\mu Z'_\mu \ell
$$



Invisible Z' - Analysis

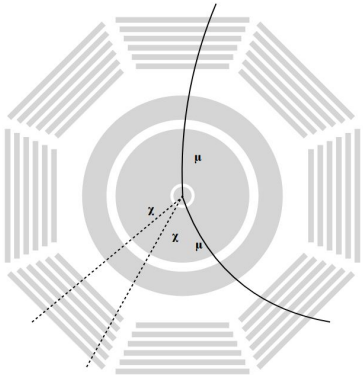
Data sample: 2018 dataset ⇒ 276pb^{-1}

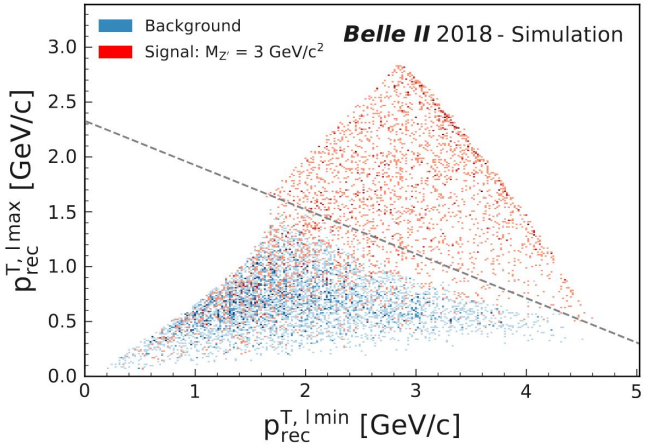
Detector signature:

- Looking for $e^+e^- \rightarrow \mu^+\mu^- Z'$ ⇒ signature $\mu^+\mu^-$ + recoil.
- Peak in the squared recoil mass distribution (M_{rec} - invariant mass of system recoiling from $\mu^+\mu^-$)

Search strategy:

- Search for peak in. M_{recoil} distribution.
- Background suppression by 2D cuts to kinematic variables.





Background Rejection:

- τ suppression - reduces $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$, $\tau \rightarrow \mu$, $\pi\tau$
- Cut applied to 2D $p_{rec}^{t,\,lmin}$ vs $p_{rec}^{t,\,lmax}$ distribution + $p^t_{\mu\mu} > p^t_{cut}$
- Selected to maximise FOM in recoil mass search windows

Invisible Z' - Result

Data sample: 2018 dataset ⇒ 276pb^{-1}

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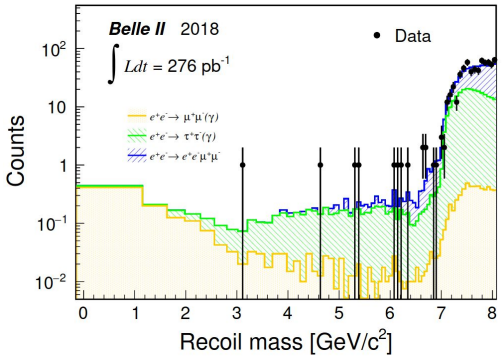
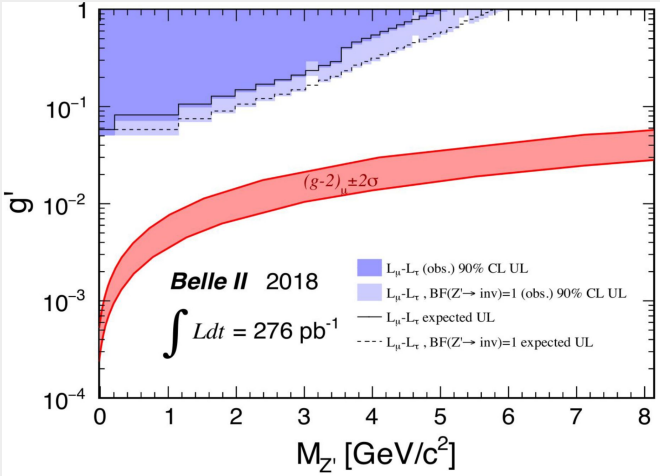


First published Belle II result - 2018 using 276pb^{-1} (pilot run data)



Phys. Rev. Lett. 124, (2020) 141801

Invisible Z' - Update

Trigger & pre-selections:

- Events fire two-track, ffo (later ff30) trigger
- 2 good quality tracks
- MuonID, $P_T^{\mu\mu} > 0.1 GeV/c^2$
- Recoil pointing in ECL barrel, no nearby photon
- Event extra energy < 0.5 GeV/c^2
- 3D opening angle < 179.5°
- $M_{recoil} < 9$ GeV

Surviving Backgrounds:

- Main contributions
  - $\tau^+\tau^- \to \mu^+\mu^-, 4\nu$
  - $e^+e^-\mu^+\mu^-$
  - $\mu^+\mu^-(\gamma)$
- Mostly localised in higher recoil mass ($M^2_{rec} > 45\ GeV^2/c^4$)

Punzi-net:

- NN trained with novel 'Punzi-loss' - designed to optimise for Punzi FOM

$$\sigma_{\min}(t) = \frac{\frac{b^2}{2} + a\sqrt{B(t)} + \frac{b}{2}\sqrt{b^2 + 4a\sqrt{B(t)} + 4B(t)}}{\varepsilon(t) \cdot L}$$

Signal Eff.

$$\varepsilon(t) \to \varepsilon(\boldsymbol{w}, \boldsymbol{b}) = \sum_x \frac{y_i \cdot \hat{y}_i(\boldsymbol{w}, \boldsymbol{b}) \cdot s_{\text{sig}}}{N_{\text{gen}}} \quad \text{and}$$

$$B(t) \to B(\boldsymbol{w}, \boldsymbol{b}) = \sum_x (1 - y_i) \cdot \hat{y}_i(\boldsymbol{w}, \boldsymbol{b}) \cdot s^i_{\text{bkg}}$$

No. Surviving bkgs

- Single cut to output of Punzi-net provides optimum FOM across search space.

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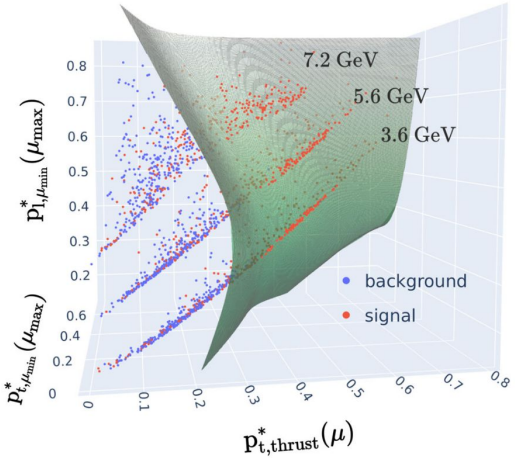


Update expected soon!

Invisible Z' - Update

Trigger & pre-selections:

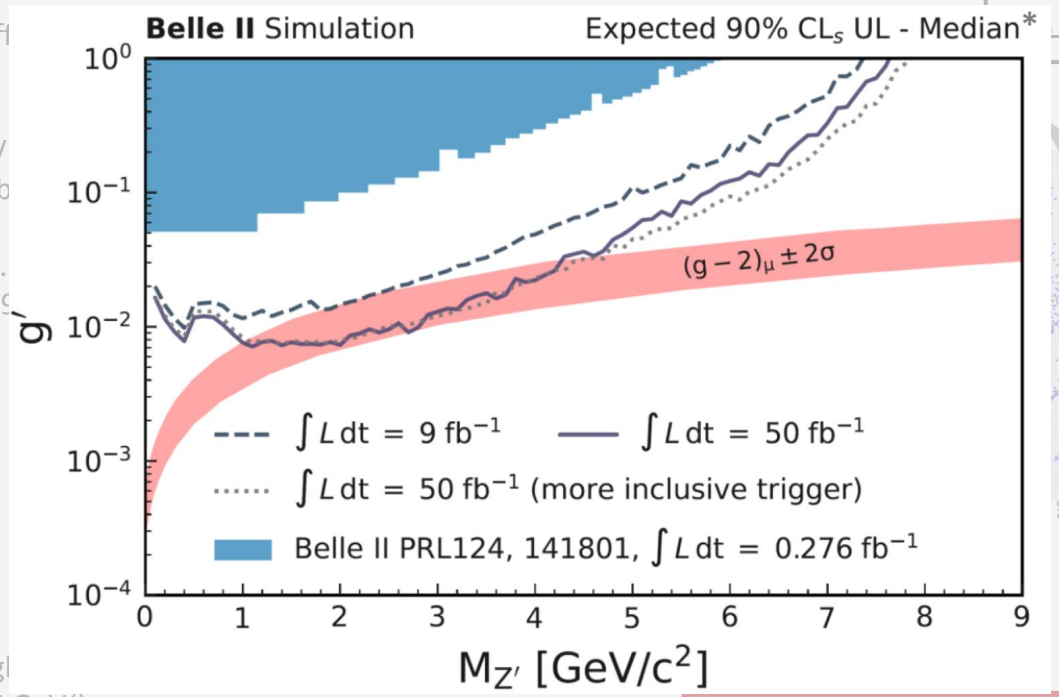
- Events fire two-track, ff ff30) trigger
- 2 good quality tracks
- MuonID, $P_T^{\mu\mu} > 0.1$GeV
- Recoil pointing in ECL b nearby photon
- Event extra energy < 0.
- 3D opening angle < 17
- $M_{recoil} < 9$ GeV

Surviving Backgrounds:

- Main contributions
  - $\tau^+\tau^- \to \mu^+\mu^-, 4\nu$
  - $e^+e^-\mu^+\mu^-$
  - $\mu^+\mu^-(\gamma)$
- Mostly localised in high recoil mass ($M^2_{rec} > 45$ GeV^2)

Punzi-net:

*preliminary (conservative) systematics



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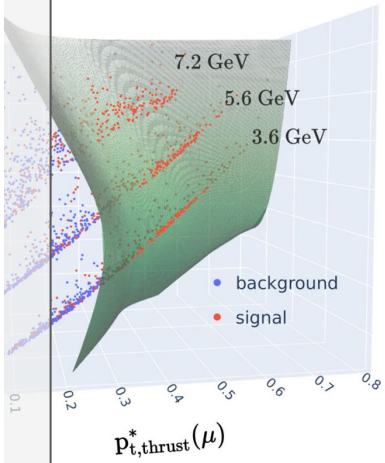
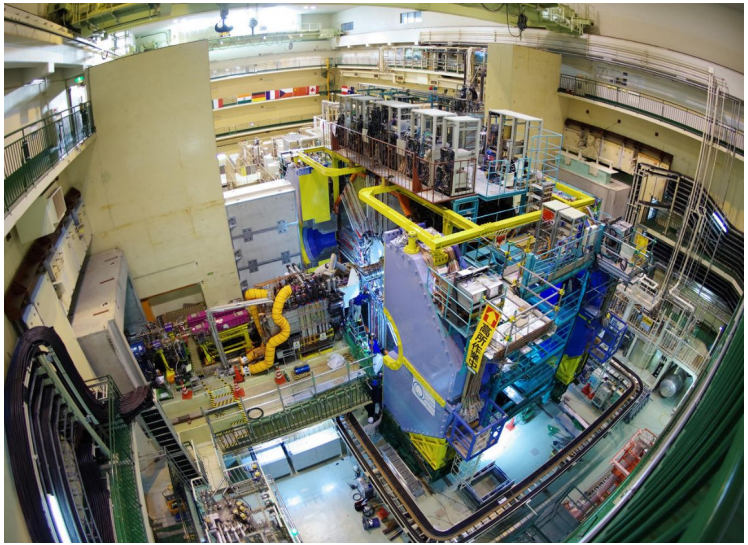


Update expected soon!

Conclusion

- Belle II has collected 384fb^{-1} thus far -> will collect ≈50ab^{-1} in the next decade.

- Advantages in dark sector searches;
  - Hermetic detector
  - Clean collision environment
  - Excellent PID
  - Dedicated low-multiplicity triggers



- **Dark Higgsstrahlung search**
  - Search for invisible h' with A' $\rightarrow \mu^+\mu^-$ $\Rightarrow$ $\mu^+\mu^-$ + missing energy. $\Rightarrow$ 2D peak in $M_{\mu\mu}$ vs M_{rec}
  - No significant excess above bkg, 90% upper limits computed for 1.65 - 10.51 GeV/ in $M_{A'}$ ($M_{h'} < M_{A'}$)
  - **World leading ULs for 1.65 < $M_{A'}$ < 10.51 GeV/c^2**

- **Z' to invisible search**
  - First Belle II physics paper with 276pb^{-1} - world leading result.
  - Update with much more data, inclusive trigger, optimised selection on the way very soon $\Rightarrow$ will probe g' coupling associated with muon g-2