Dark Sector searches at the Belle II experiment

M.C. for the Belle II Napoli group

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Dark Sector searches

Motivations & Models

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

So far, no evidences for Dark Matter at direct detection experiments or TeV New Physics at LHC.

Maybe we were just looking in the wrong direction…
Accessible sector of new physics could be **light** and **feebly interacting with SM**.

Dark Sector: a natural framework for physics beyond SM

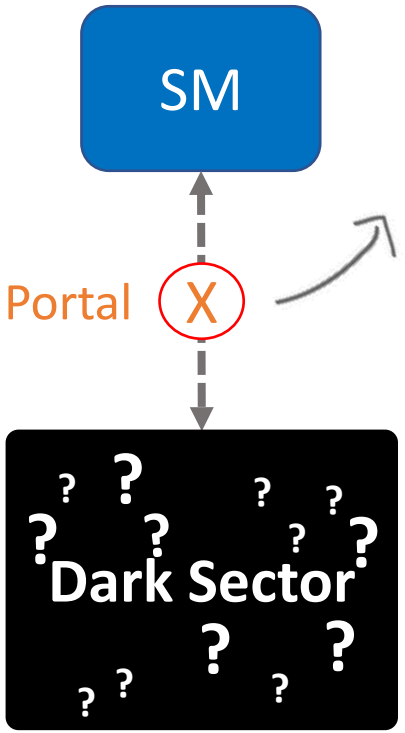
- Made of particles neutral under SM gauge interactions
- Stable dark particles are good candidates for DM
- New hidden symmetries and particles accessible through portals
- Only a small number of possible portal interactions between DS and SM (e.g. [1]);

$$\mathcal{L}_{\text{portals}} = -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \cdots$$

Vector portal | Higgs portal | Neutrino portal + Psuedoscalar portal

Not just solving the DM puzzle. Dark Sector could explain:

- some astrophysics anomalies (positron excess, 3.5 keV line, …)
- the $(g\text{-}2)_\mu$ anomaly
- some flavour anomalies: $R_{D(*)}$



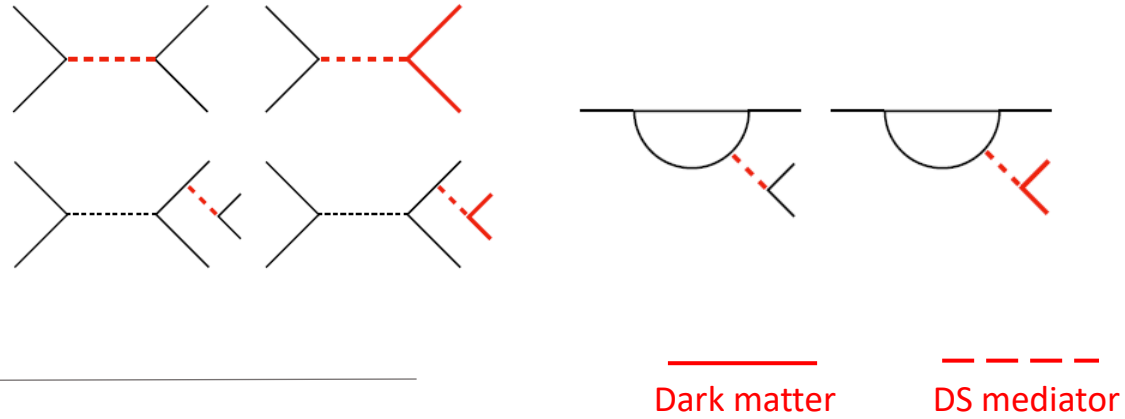
Dark Sector searches

Strategies at colliders

Looking for DS particles production @ Belle II

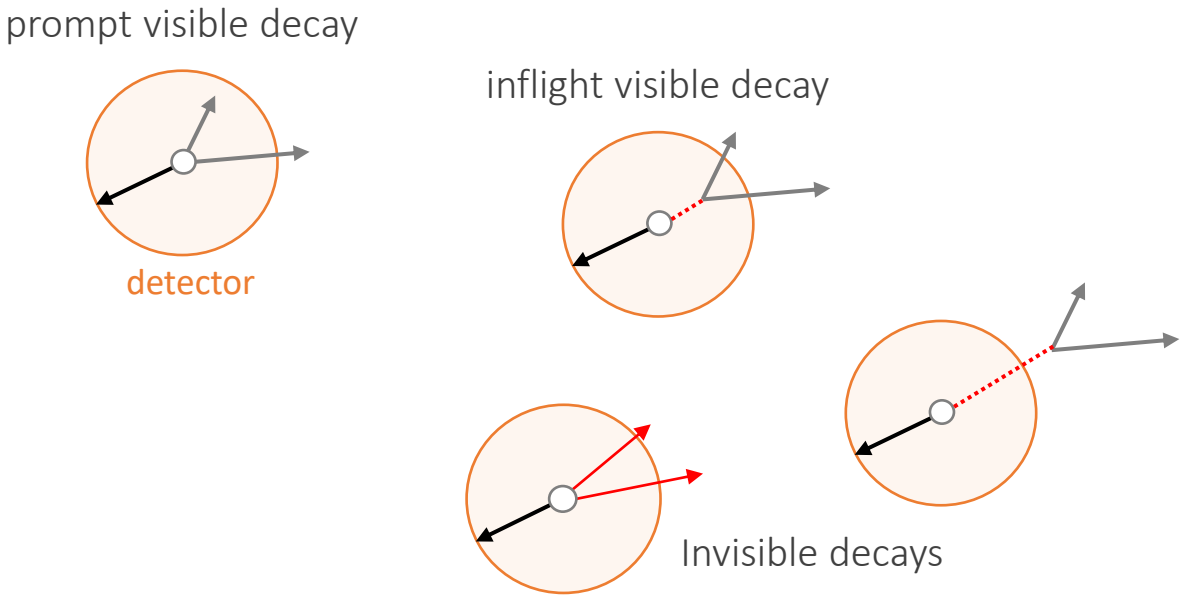
Directly produced in SM particle collisions or in mesons (*D, B, Y* or other) decay

- probe mediator masses up to $\sqrt{s}$ or up to respective meson mass



Different signatures depending on DS particles **mass** hypotheses and mediator **life-time** (decay length):

- Prompt decay to SM -> invariant mass bump
- Long lived:
  - decay-length < O(1)m -> displaced vertex
  - decay-length > O(1)m -> missing momentum
- Decay to DM particle -> missing momentum
- Mixed cases



Dark Sector searches

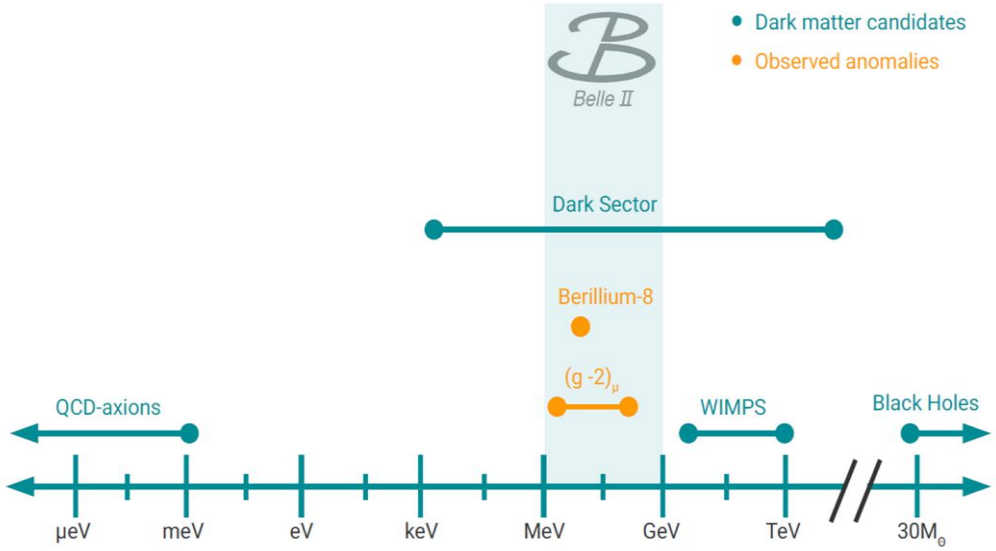
Strengths of Belle II

Belle II, not just a B-factory…
a very good environment for dark sector searches

- Very high luminosity
- Well defined initial state, closed kinematics
- Clean environment and low background
- Hermetic detector
- Excellent PID capability
- Low multiplicity triggers (non trivial)

efficient reconstruction of neutrals, recoiling system and **missing energy final state;**

able to access the mass range naturally favored by **light DS** and very small couplings



Dark Higgsstrahlung search

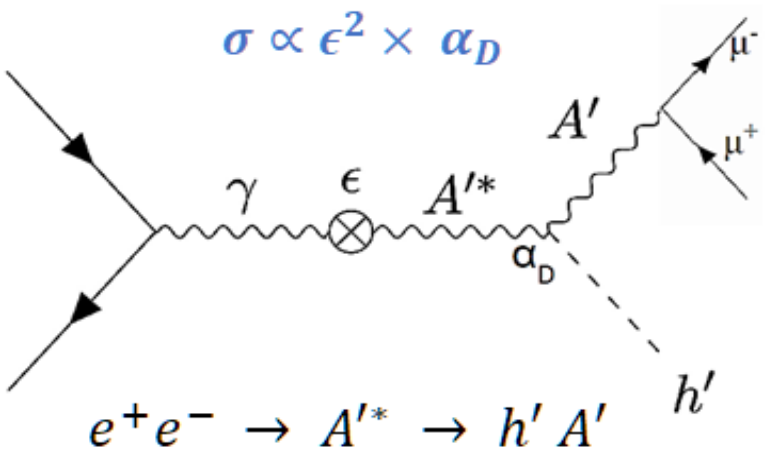
Introduction

[1] P. Fayet, *Phys. Lett. B* **95**, 285 (1980),
[2] P. Fayet, *Nucl. Phys. B* **187**, 184 (1981)
[3] B. Batell, et al., *Phys. Rev. D* **79**, 115008 (2009)

Hypothetical new massive gauge boson **A'**, called **dark photon,** coupling to the SM photons through kinetic mixing with strength ε [1,2].

A' mass can be generated via a spontaneous symmetry breaking mechanism, by adding a **dark Higgs boson** *h*' to the theory [3].

Both particles ($\boldsymbol{A'}$ $\boldsymbol{h'}$) can be produced via the **dark Higgsstrahlung process**.



Different signature depending on the masses relationship:

- $\boldsymbol{m_{h'} > m_{A'}}$:
  - $h' \rightarrow A'A' \rightarrow 4l, 4had, 2l + 2had.$
  - Investigated by BaBar (2012) and Belle (2015)
- $\boldsymbol{m_{h'} < m_{A'}}$:
  - h' is long-lived -> thus invisible.
  - Constrained by KLOE (2015) below 1 GeV/c2
  - Brand new results by Belle II

Experimental signature:
Two opposite sign muons + missing energy
a peak in $M^2_{\mu\mu}$ vs M^2_{recoil}

Dark Higgsstrahlung search

Analysis strategy

Analysis selection in short:

- Two opposite sign muons, $p_T^{\mu\mu} > 0.1$ GeV/c
- Recoil points to barrel calorimeter
- Low activity in the calorimeter
- Final suppression exploiting helicity angle
  - $C_\eta = |\cos(\vartheta_{helicity})|$ flat for signal, peak at 1 for BKG

Backgrounds:

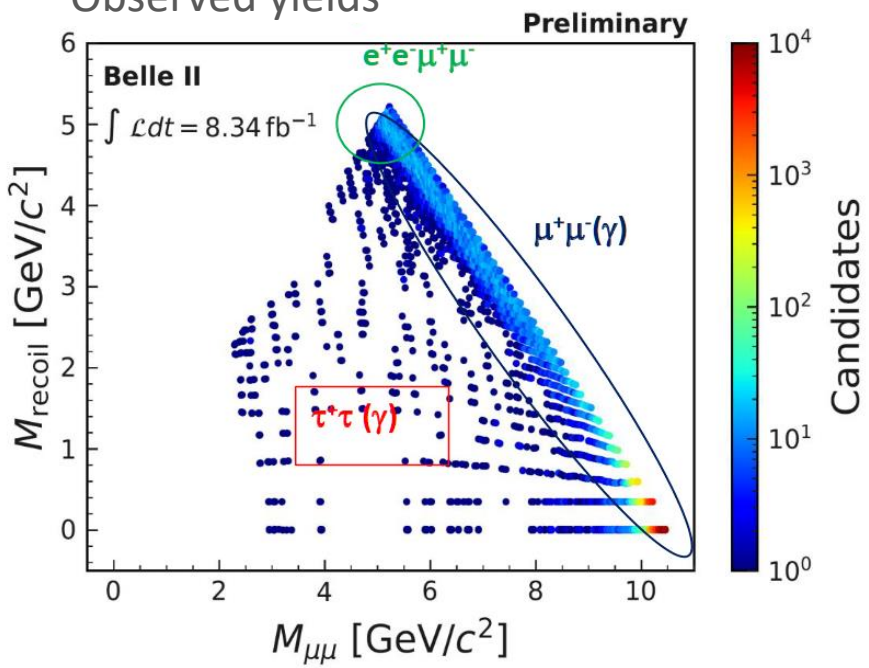
SM processes with 2 particles identified as muons and missing momentum.

Mainly due to $\boldsymbol{\mu\mu(\gamma)}$, $\boldsymbol{\tau\tau}$, $\boldsymbol{ee\mu\mu}$

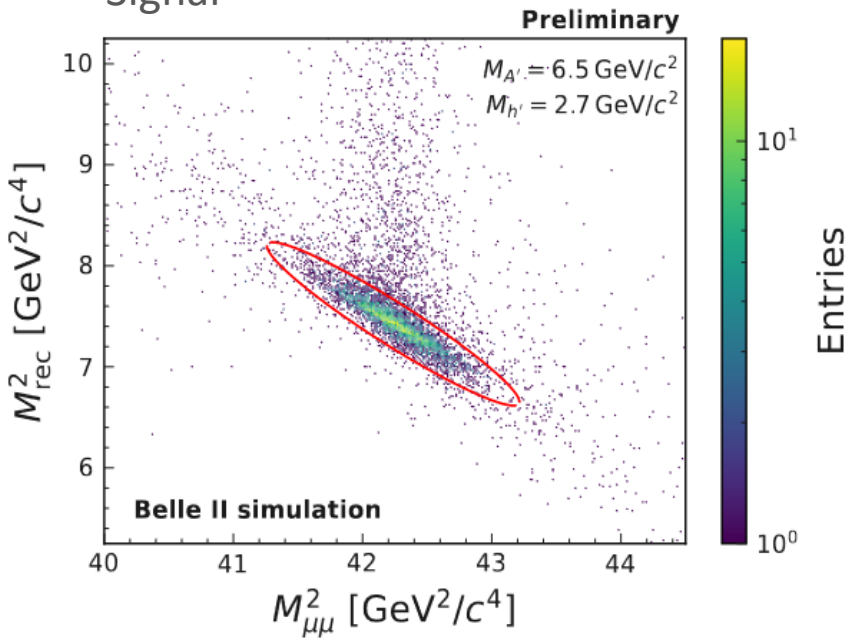
Search strategy: masses scan and count in search windows

- ~9000 2D elliptical windows;

Observed yields



Signal



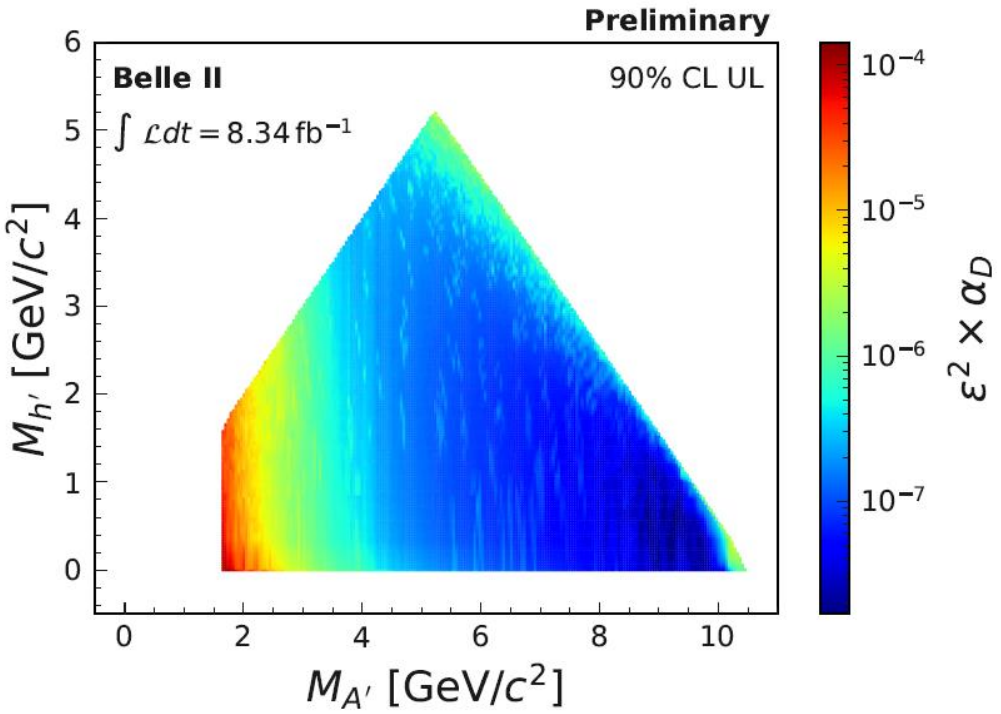
Dark Higgsstrahlung search

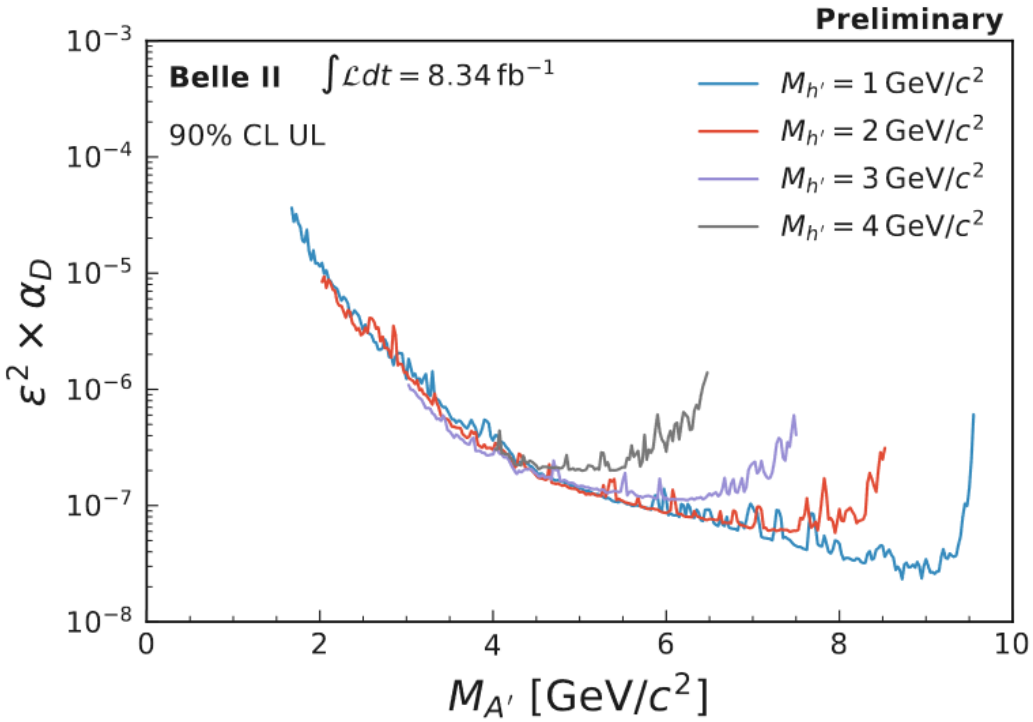
Results

Search performed with 2019 data -> 8.34 fb^{-1} arXiv:2207.00509 (Accepted by PRL)

No significant excess over the expected background. Set 90% CL exclusion limits on cross section and coupling:

- World's first for $1.65 < M_{A'} < 10.51$ GeV and $M_{h'} < M_{A'}$
- UL on $\epsilon^2 \times \alpha_D$ down to 1.7×10^{-8} in the most sensitive regions





Search for a Z' invisible decay

Introduction

[1] Shuve et al., *Phys. Rev. D* **89** (2014)
[2] Altmannshofer et al., *JHEP* **106** (2016)

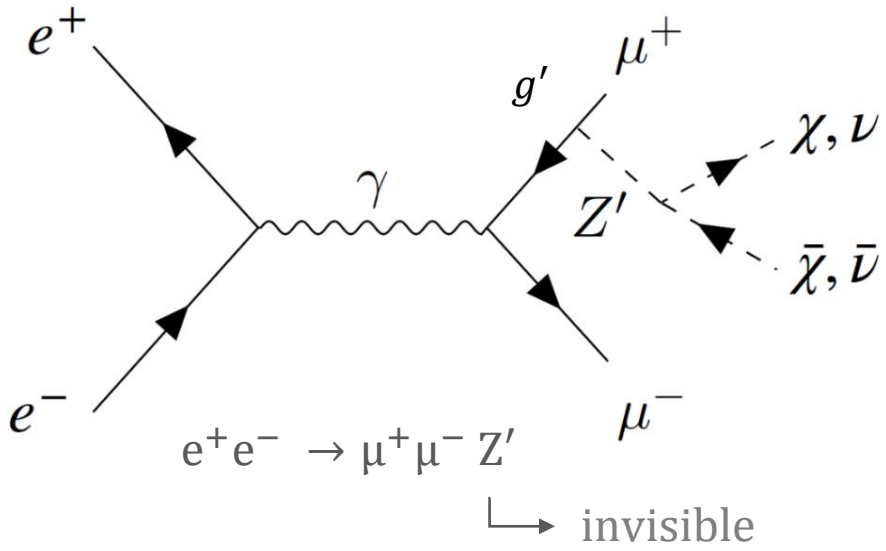
Hypothetical massive gauge boson **Z'** coupling only to the 2nd and 3rd generation of leptons in the framework of $\boldsymbol{L_\mu - L_\tau}$ **model** [1,2].

Seek to explain:

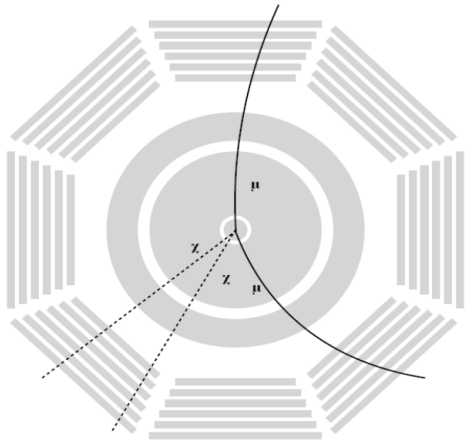
- $(g\text{-}2)_\mu$ anomaly;
- anomalies in B decays to leptons;
- the Dark Matter puzzle;

State of the art:

- Existing limits from BaBar, CMS and Belle for a Z' visible decay into a couple of muons and from NA64-e for a Z' invisibly decaying;
- **Brand new searches Belle II for a Z' invisible decay;**



Experimental signature:
Two opposite sign muons + missing energy
a peak in the recoil mass distribution against two muons



Search for a Z’ invisible decay

Analysis strategy

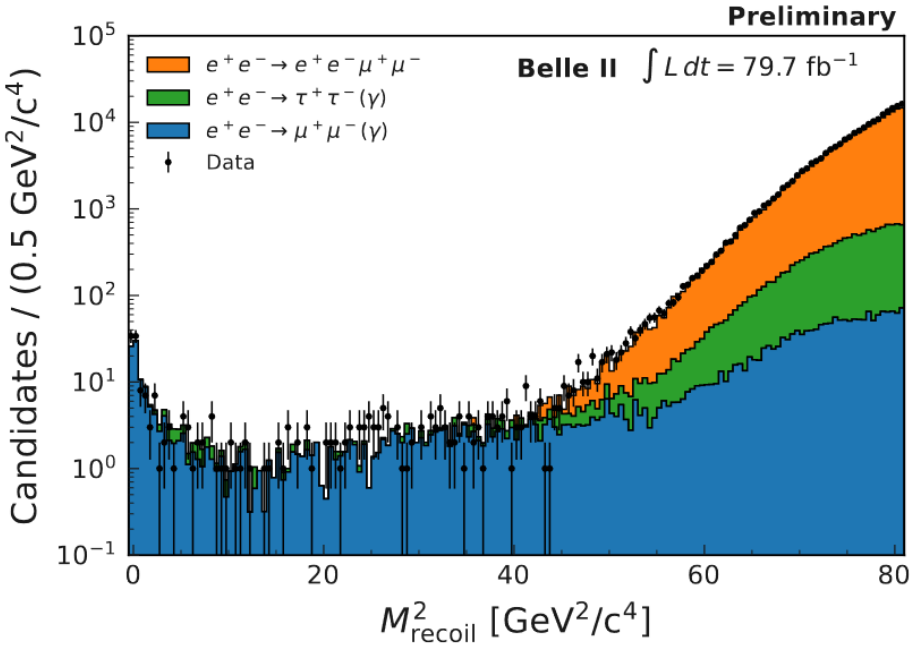
Analysis selection in short:

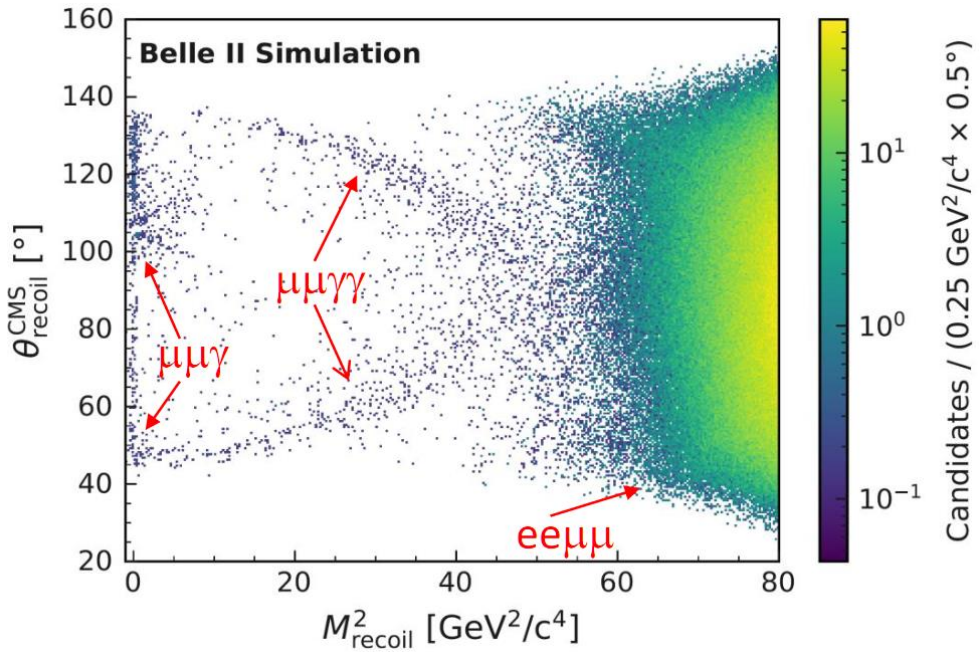
- Two opposite sign muon tracks; $p_T^{\mu\mu} > 0.1$ GeV/c
- Recoil points to barrel calorimeter ($M_{\text{recoil}} < 2$ GeV)
- Low activity in the calorimeter and γ veto
- Neural-Network exploiting FSR nature of Z’ production
  >> Eur.Phys.J.C 82 (2022) 2, 121 (M. Campajola *et al.*)

Backgrounds:
SM processes with 2 particles identified as muons and missing momentum.
Mainly due to $\boldsymbol{\mu\mu(\gamma)}$, $\boldsymbol{\tau\tau}$, $\boldsymbol{ee\mu\mu}$

Search strategy: mass scan with a fitting technique

- Fitting over the 2d distribution θ_{recoil} vs. M^2_{recoil}





Search for a Z' invisible decay

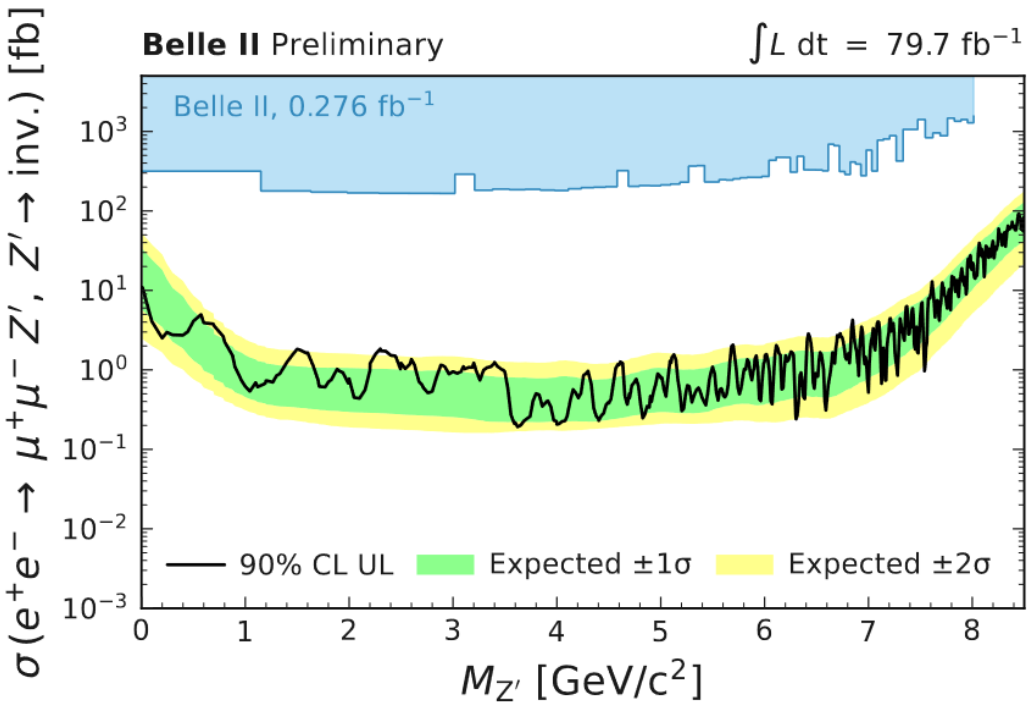
Results

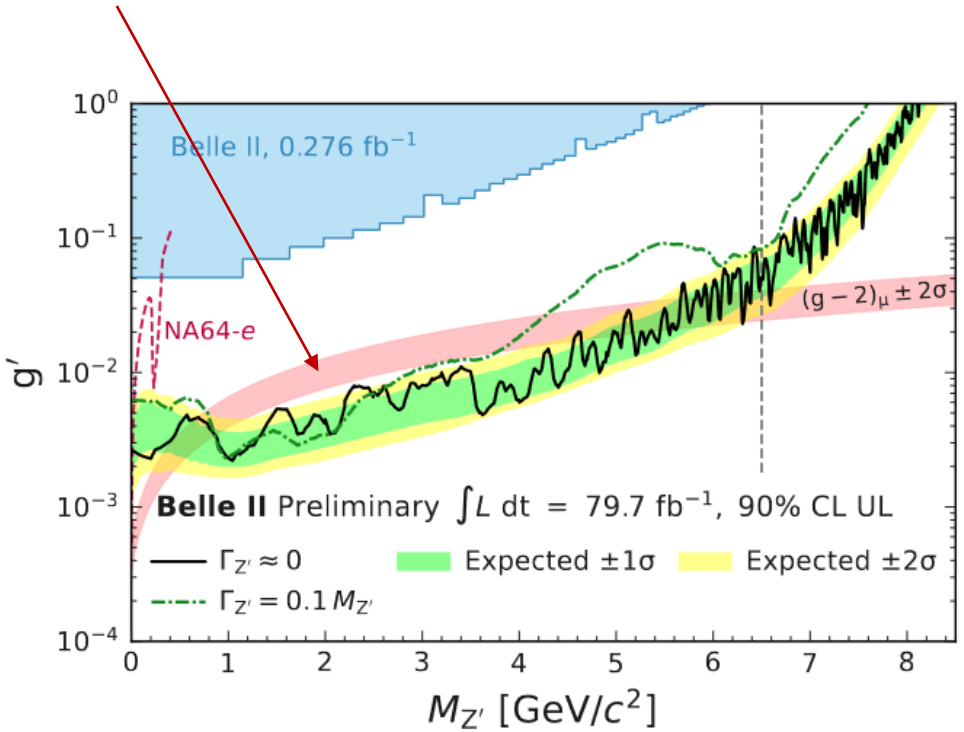
First measurement with 2018 dataset: ~279 pb^{-1} PRL 124, 141801

New analysis with 2019-20 dataset: ~ 79.7 fb^{-1} arXiv: 2212.03066 (Submitted to PRL)

No significant excess over the expected background. Set 90% CL exclusion limits on cross section and coupling:

- **World-leading UL for a fully invisible Z' (100% BR to invisible) above 11 MeV/c^2**
- **First excluding a fully invisible Z' boson as an explanation of the $(g-2)_\mu$ anomaly for *0.8 < $M_{Z'}$ < 5 GeV/c^2***





Conclusions

Belle II is exploring Dark Sectors at the luminosity frontier

First (world-leading) results with the early dataset:

- Z' -> invisible:
  - 2018 data PRL 124, 141801 (**NA**, RM3, PI, DESY, HEPHY)
  - Update: arXiv: 2212.03066 (Submitted to PRL) (**NA**, RM3, HEPHY, CPPM)
- Dark Higgsstrahlung arXiv:2207.00509 (Accepted by PRL) (**NA**, RM3, HEPHY)

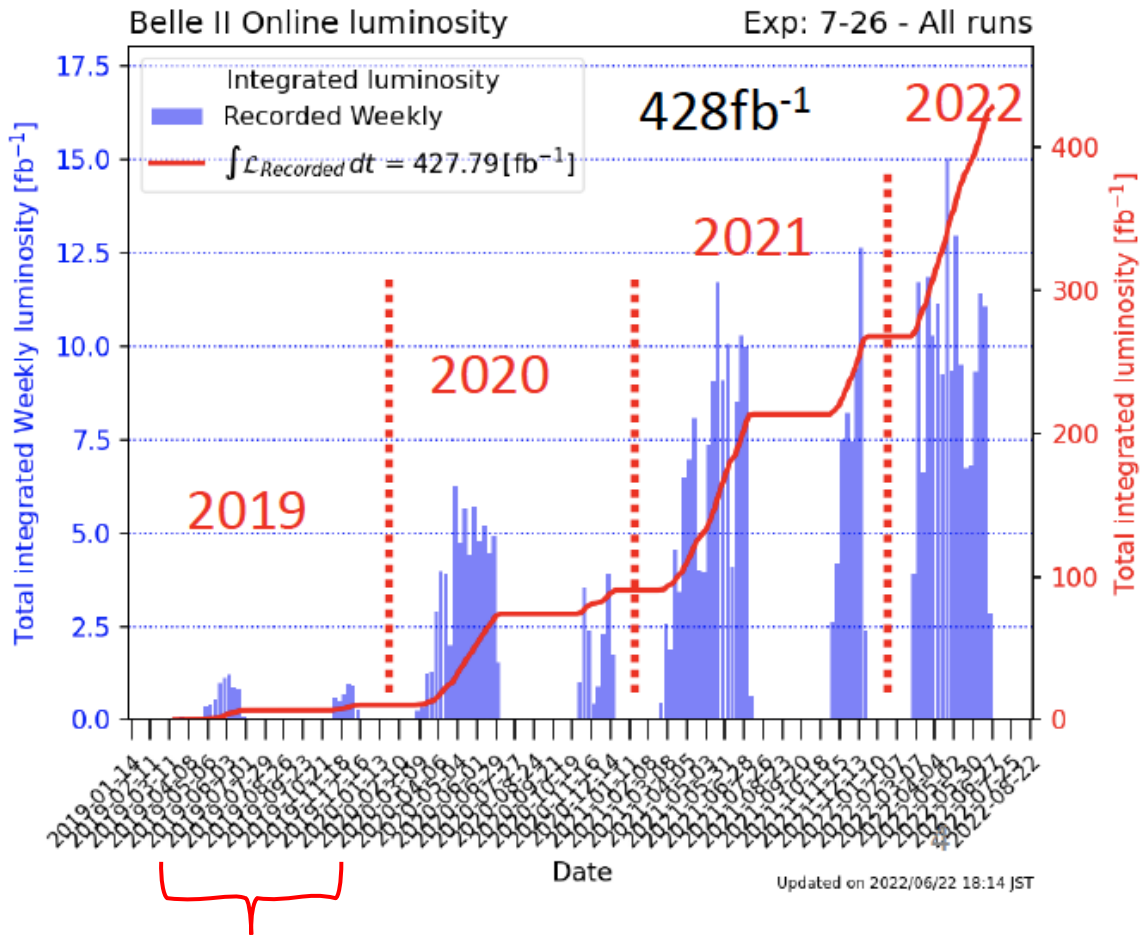
and many other searches performed/ongoing:

- ALPs -> $\gamma\gamma$ Phys Rev Lett **125**, 161806
- visible and invisible dark photon;
- visible Z';
- long-lived dark particles;
- Inelastic dark matter;

Stay tuned…
Belle II is expected to lead in the MeV-GeV mass range in the coming years

What's next?

Invisible Z' search



Dark Higgsstrahlung search

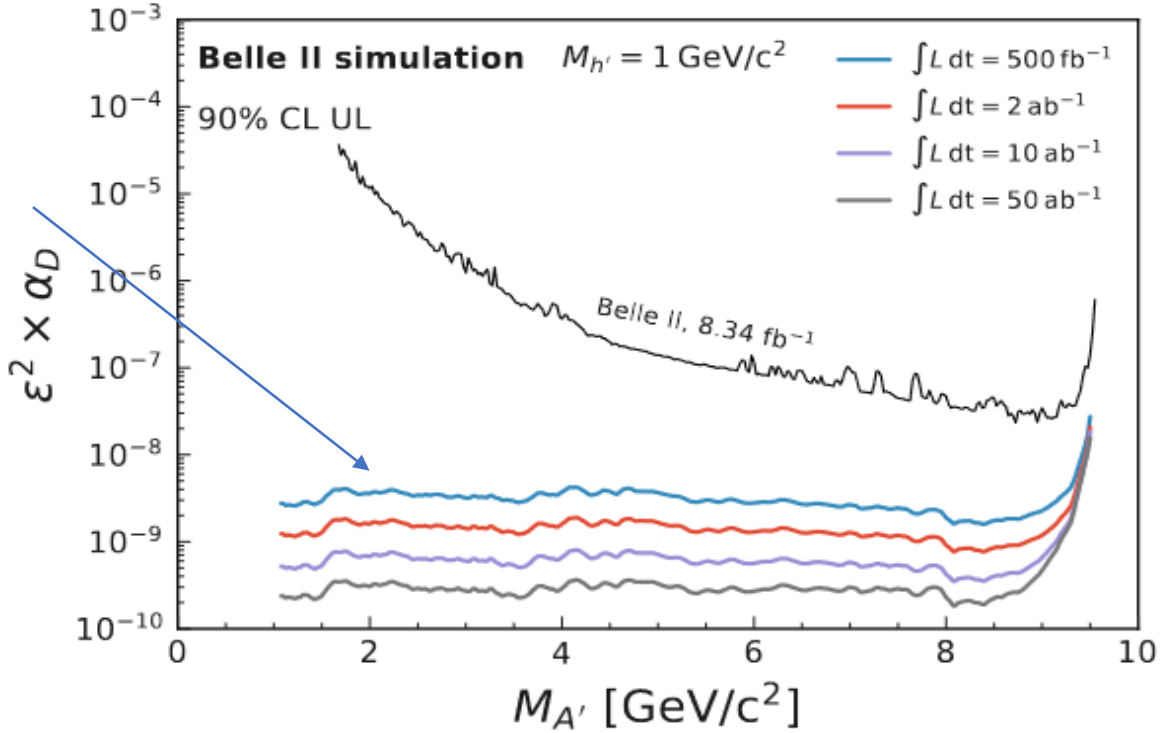
What's next?

Dark Higgsstrahlung search

~450 fb^{-1}

Large room for improvements the full pre LS1 dataset:

- x50 in the dataset
- more inclusive triggers (fy30, cdcklm#) allow probing low mA' region
- μμγ background suppression using KLM as veto for undetected gammas
- extending results to models with h' - SM h mixing



What's next?

Invisible Z'

~450 fb^{-1}

Still room for improving results with the full pre LS1 dataset:

- x5 in the dataset
- more inclusive trigger (cdcklm#) improve sensitivity at high $m_{Z'}$
- μμγ background suppression using KLM as veto for undetected gammas especially in the low-middle mass region;