Gr1 Napoli meeting. 21-12-2021

Dark sector searches at Belle II

- Focus on activities @Napoli:
  - Search for an *invisible Z'*;
  - Search for the *dark Higgsstrahlung* process;

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Dark sector searches

Motivations

[1] Batel et al., *Phys. ReV. D* **80** (2009)
[2] Essig et al. arXiv:1311.0029 (2013)

The absence of dark matter discoveries at the electroweak scale by the LHC or direct detection experiments motivates the interest in models with low-mass dark matter candidates.

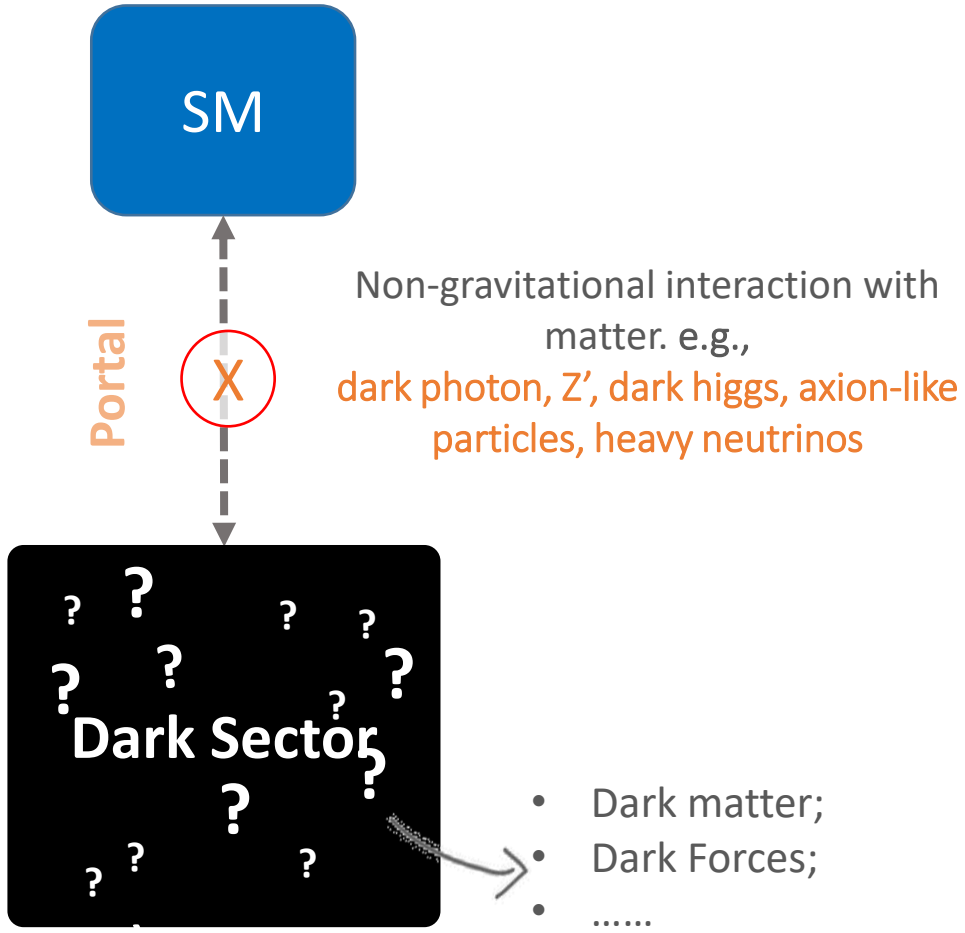
- **Theoretical scenarios introducing light dark matter with O(MeV-GeV) mass need light mediators too, e.g. [1, 2].**

Not just solving the DM puzzle. Could explain:

- some astrophysics anomalies (positron excess, 3.5 keV line, …);
- the $(g\text{-}2)_\mu$ anomaly;
- some flavour anomalies (LHCB, Belle, …).

Dark Sector searches @ colliders. Typically looking for:

- Mediators decaying to SM particles;
- Missing energy/momentum signatures;
- both;



Belle II @ SuperKEKB

Not just a B factory

An intensity frontier machine:

- Will provide the world highest luminosity (L = 6.5x10^{35} $cm^{-2}s^{-1}$).
- To date ~250/fb collected.
- Final goal: 50/ab.

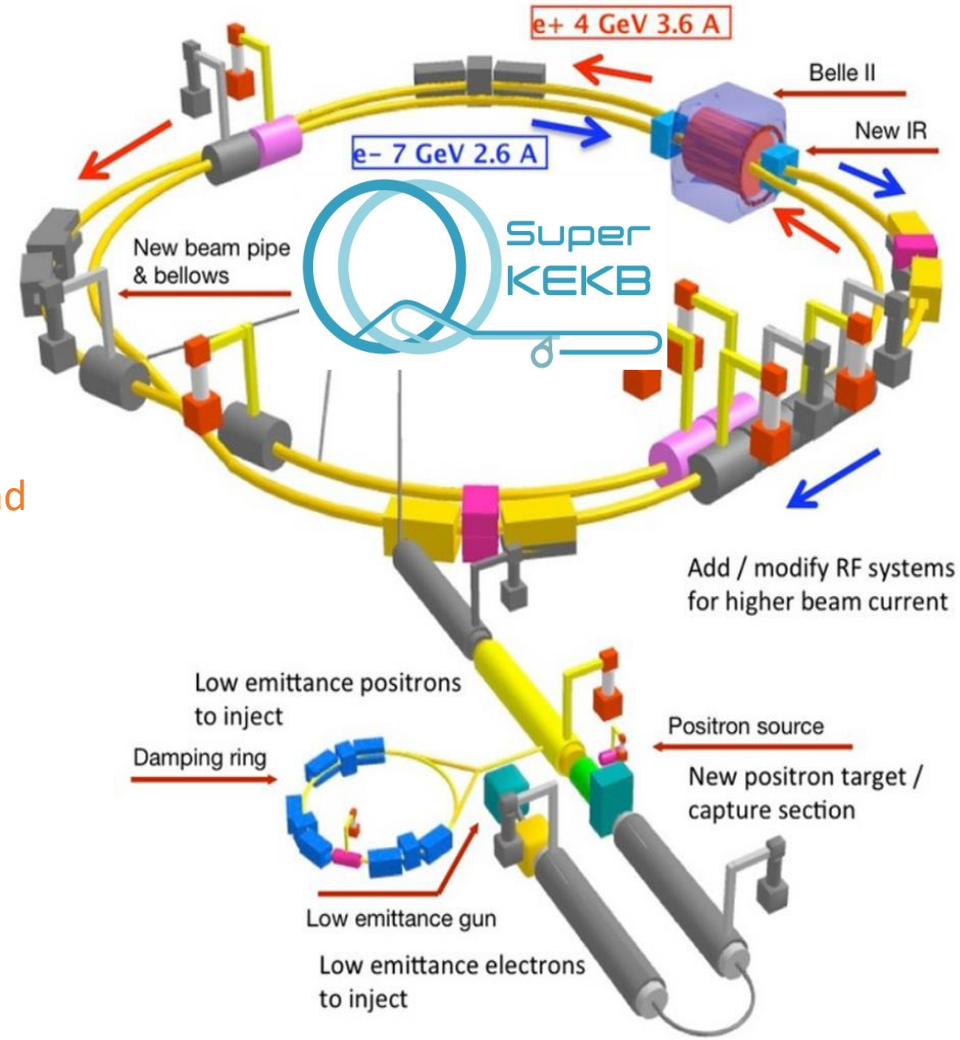
A wide physics program:

- B-physics, charm, tau and ….

Ideal environment for dark sector searches:

- High luminosity;
- Closeness to the light region;
- Well defined initial state, closed kinematics;
- Clean environment and low background;
- Hermetic detector;
- Excellent PID capability;
- Low multiplicity triggers (non trivial);

Many DS searches ongoing and first results for already out



Invisible Z’ search

Introduction

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

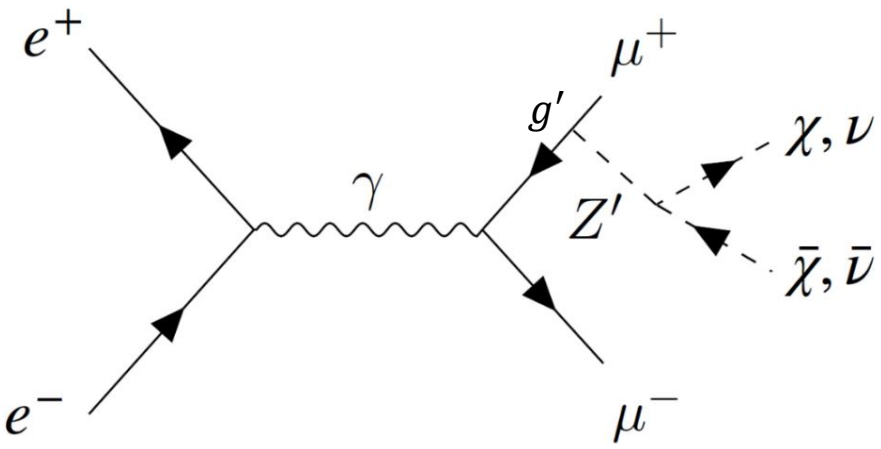
A massive gauge boson Z’ coupling only to the 2nd and 3rd generation of leptons [1,2].

This model may explain:

- DM puzzle;
- $(g\text{-}2)^{\mu}$ anomaly;
- B-physics anomalies: e.g., R_K, R_{K^*} ;

Experimental signatures:

- **Visible decay** into a muon (tau) pair.
  Constrained by BaBar(2016) and CMS(2019) and neutrino-nucleus scattering experiments;
- **Invisible decay** in SM neutrinos or DM if kinematically accessible.
  First physics result from Belle II (2020);



$e^+e^- \rightarrow \mu^+\mu^- Z'$

$\hookrightarrow$ *invisible*

➡ Here, looking for an invisibly decaying Z’ produced with a pair of muons.

Invisible Z' search

Analysis in short

Signal signature: a peak in the mass distribution of the recoiling system against $\mu\mu$ pair;

Background: everything with 2 particles identified as muons and missing momentum: $\mu\mu(\gamma), \tau\tau(\gamma), ee\mu\mu$;

Selection:

- Just two tracks and low activity in the calorimeter;
- Tau suppression based on kinematics;

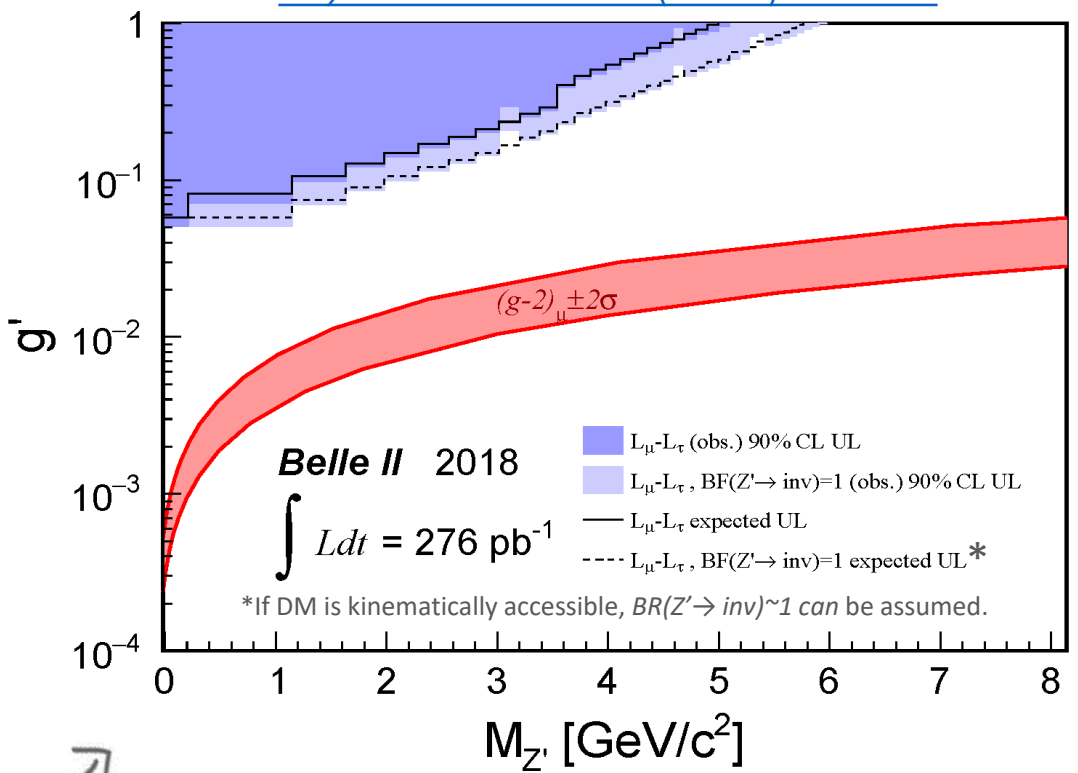
Mass scan plus Bayesian counting technique adopted.

Measurement performed with 2018 pilot run data (~276/pb):

- No hints for signal;
- UL on cross section and the coupling constant;

<u>First results ever for the *Z'* to invisible decay.</u>
<u>First physics paper by Belle II</u>

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



Z' phase space that could explain the $(g-2)_\mu$ anomaly. Based on old experimental value [BNL(2006)]

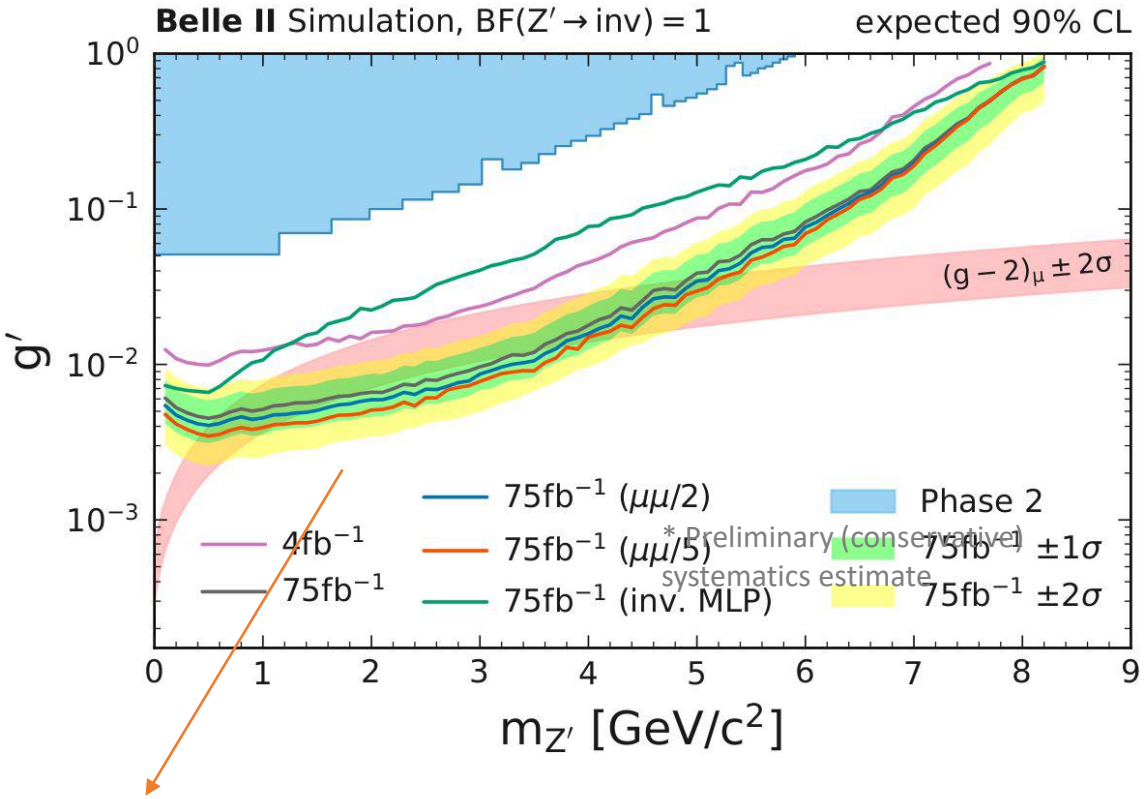
Invisible Z’ search

What’s next

Working at the analysis update with 2019 + 2020 data (~80 fb-1)

Major improvement wrt Phase2 results:

- ~ x285 data used in Phase2 analysis.
- Better detector and analysis tools (for example MuonID);
- More inclusive trigger lines;
- Improved background suppression:
  - Better understanding of $\mu\mu\gamma$;
  - Neural network based cut;
- Fitting procedure wrt counting technique;



Starting to probe the (g-2)$_\mu$ band.

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)

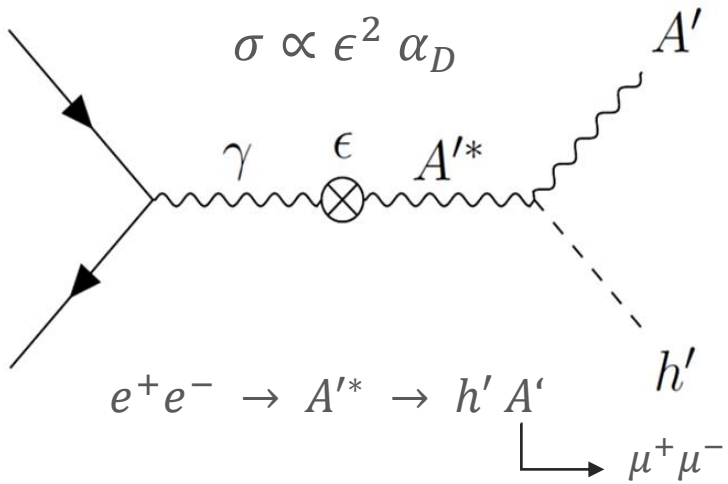
New massive gauge boson A' of coupling to the SM photons through the kinetic mixing with strength ε, called **dark photon** [1,2].

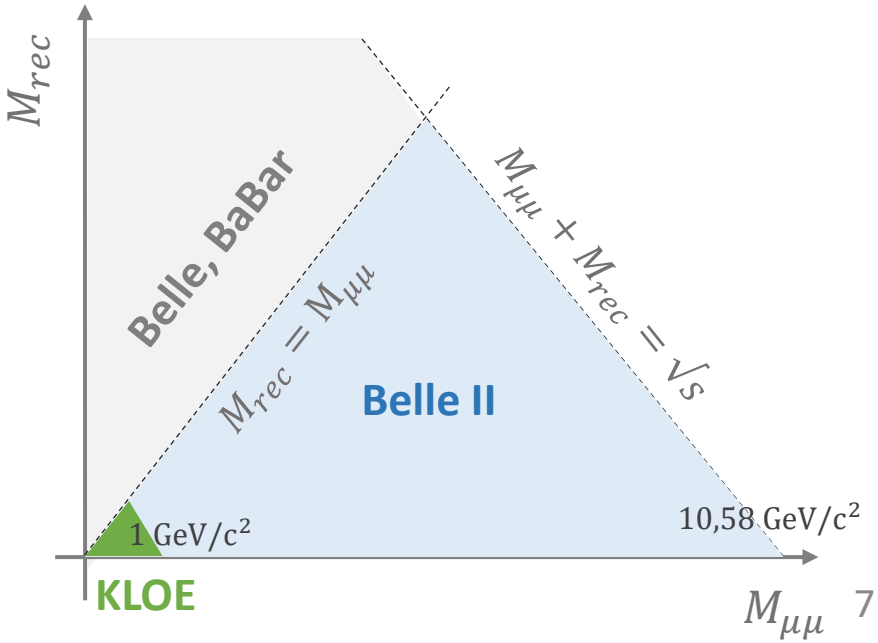
A' mass can be generated via a spontaneous symmetry breaking mechanism, adding a **dark Higgs boson** *h*' to the theory [3].

Both particles (A' h') can be produced via the **dark Higgsstrahlung process**. Different signature depending on the masses relationship:

- $\boldsymbol{m_{h'} > m_{A'}}$: $h' \to A'A' \to 4l, 4had, 2l + 2had.$
  Investigated by BaBar (2012) and Belle (2015)
- $\boldsymbol{m_{h'} < m_{A'}}$: h' is long-lived, thus invisible.
  Constrained by KLOE (2015).

➡ **Here, investigating the invisible dark higgs case with a dark photon decay to muons**





Dark Higgsstrahlung search

Analysis in short

Signal signature: a 2d peak in the dimuon versus recoil mass distribution;

Background: everything with 2 particles identified as muons and missing momentum: $\mu\mu(\gamma), \tau\tau(\gamma), ee\mu\mu;$

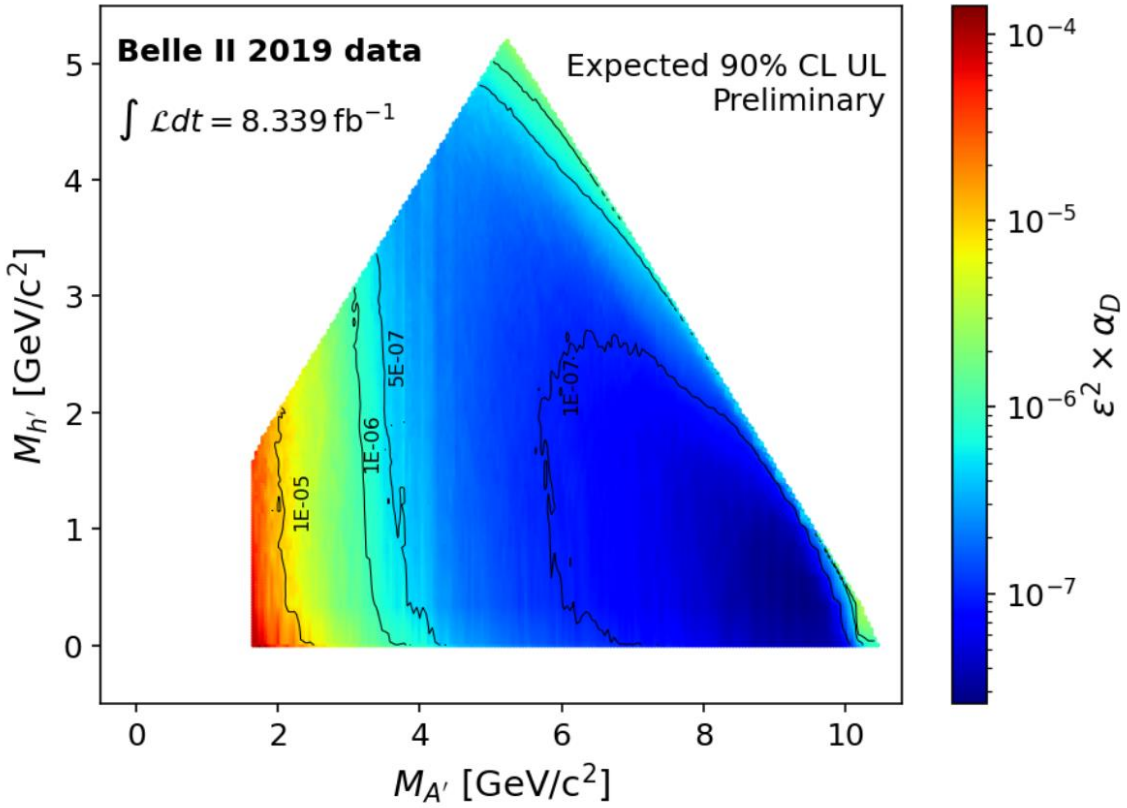
Selection:

- Just two tracks and low activity in the calorimeter;
- Kinematics behavior, helicity angle;

2D mass scan plus Bayesian counting technique adopted.

Analysis completed with 2019 dataset (~8.34/fb);

Under collaboration internal review



Conclusion

Belle II is exploring Dark Sectors at the luminosity frontier:

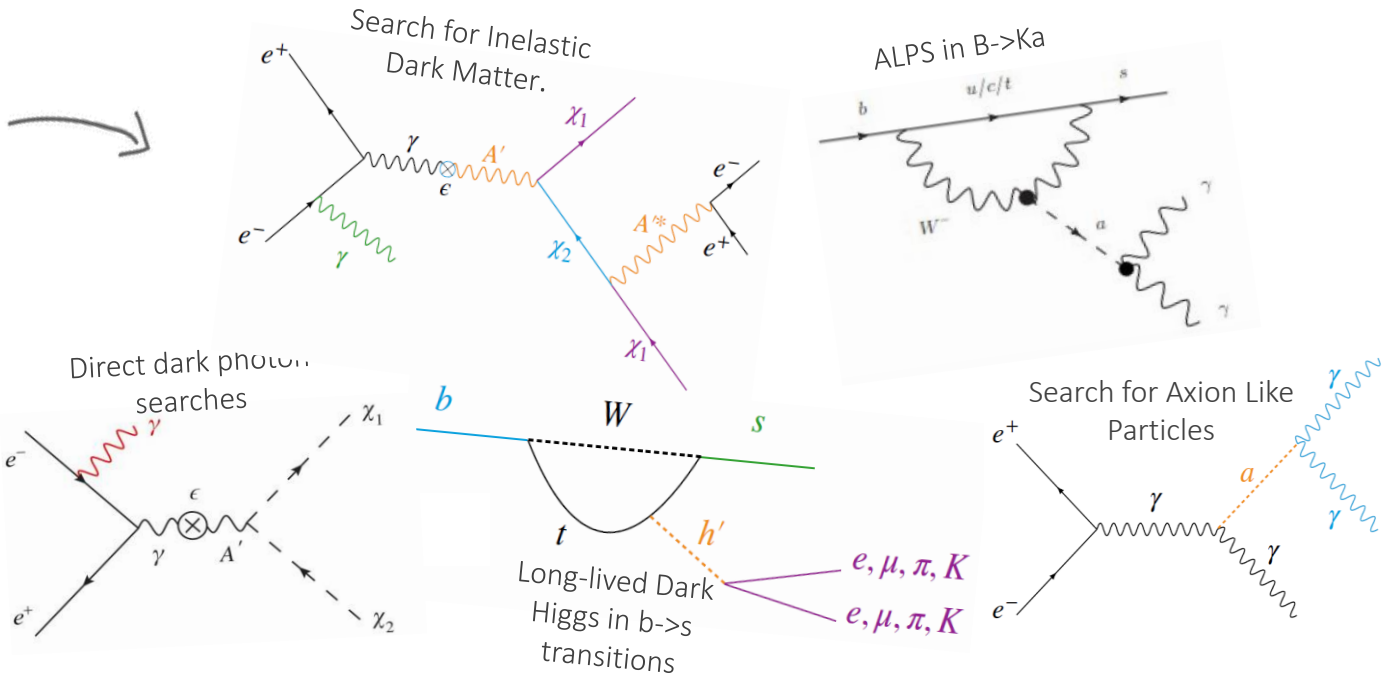
World-leading results with early data:

- Z' -> invisible;
- ALPs -> $\gamma\gamma$;
- Dark Higgsstrahlung in a short term;

Many other searches ongoing:

- dark Higgs, dark photon, visible Z', Long-lived dark particles

Will lead in the MeV-GeV mass range in the coming years



Stay tuned… new results are coming.