Identification of Dark Matter IDM2022

Vienna - July 18-22, 2022

# Searches for dark sector particles in LHCb/Belle II

On behalf of the LHCb and Belle II collaborations

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Belle II

# Dark Sector searches

Motivations & Models

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

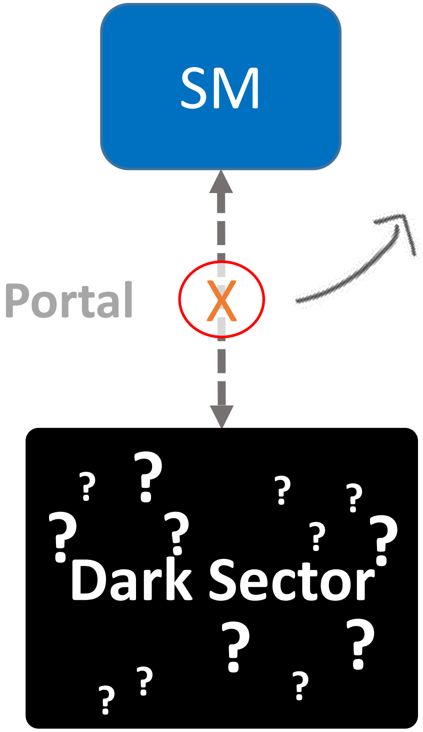
The absence of DM discoveries by LHC or direct detection experiments motivate the strong interest for models with **low-mass dark matter** candidates or mediators.

**A possible MeV - GeV theoretical scenarios:**

- DM not charged directly under the SM;
- DM may interact with SM through several "**portal**" interactions (e.g. [1, 2]).

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

Vector portal  Higgs portal  Neutrino portal + Psuedoscalar portal




Non-gravitational interaction with matter

- Dark matter;
- Dark Forces;
- ......

**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: $R_K$, $R_{K*}$ .... (LHCb, Belle, ..).

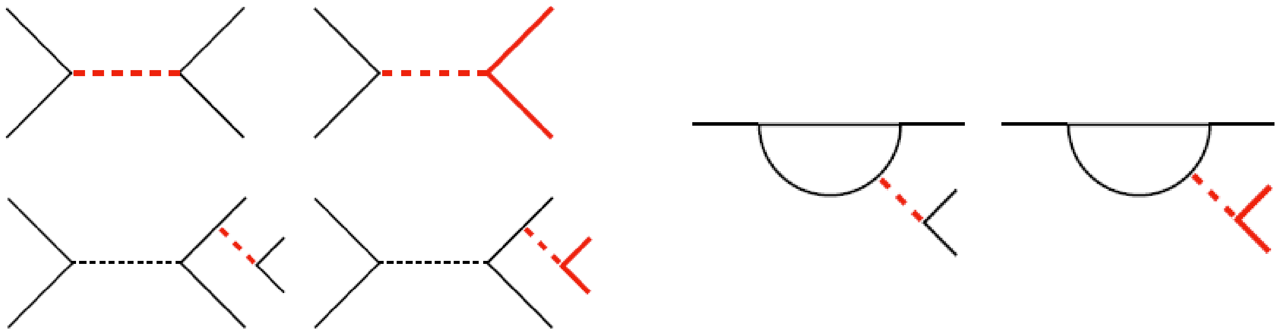
# Dark Sector searches

## Collider strategies

Searches at collider usually focused on mediators rather than DM itself.

**Two strategies:**

### Direct production



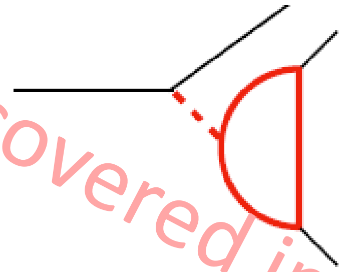
Directly produced in SM particle collisions;

- probe mediator masses up to $\sqrt{s}$

Produced in mesons (*D, B, Y* or other) decay;

- probe mediator masses up to respective meson mass

### Precision physics



not covered in this talk

loop induced effects

- probe very high mediator masses

# Dark Sector searches

Signatures

In most of the models life-time is proportional to some inverse power of the coupling and of the mediator mass

**Different possible signature depending on:**

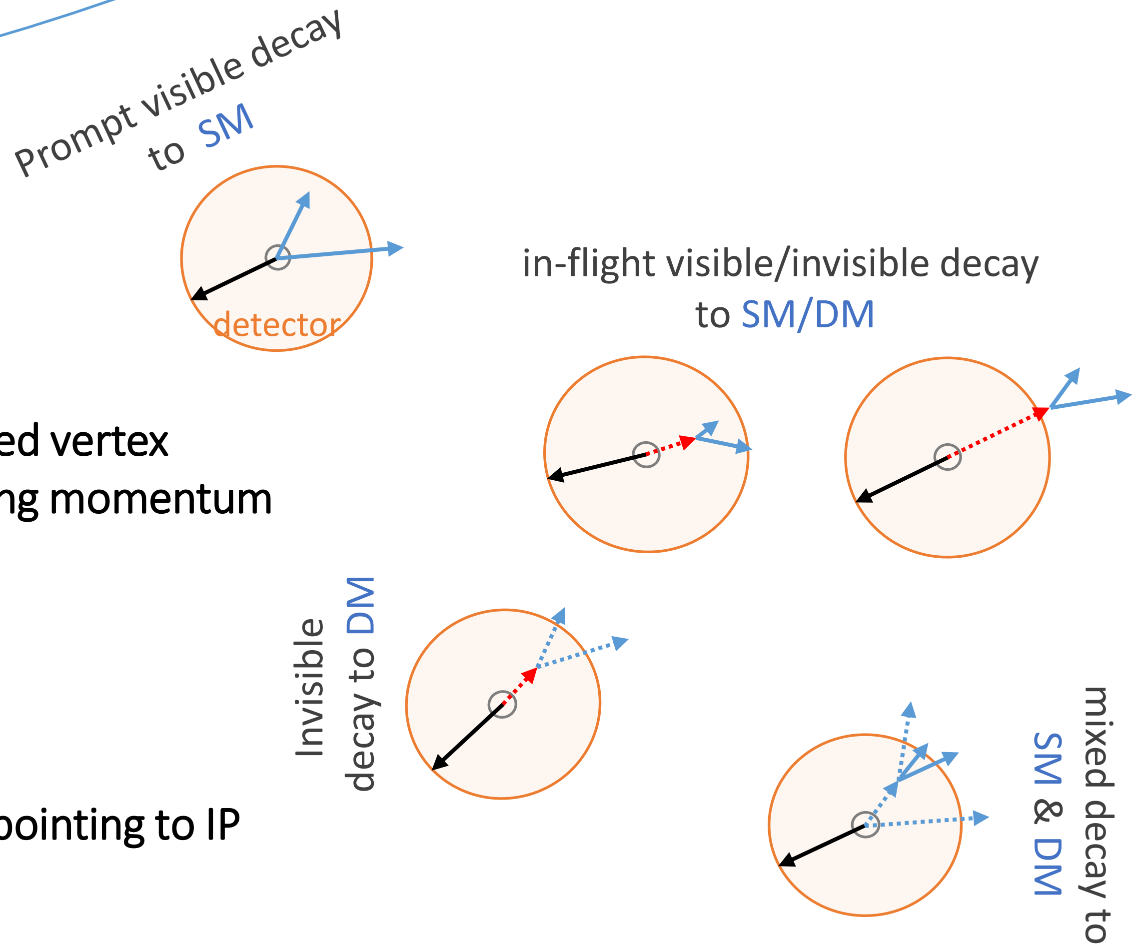
- mediator and DM mass hypothesis
- mediator life-time -> decay length

**Prompt decay to SM:**
- visible signature -> **invariant mass bump**;

**Long lived:**
- decay-length < O(1)m: visible signature -> **displaced vertex**
- decay-length > O(1)m: invisible signature -> **missing momentum**

**Decay to DM particle:**
- invisible signature -> **missing momentum**

**Decay to SM + DM particles:**
- partially visible signature -> **displaced vertex non pointing to IP**



# LHCb and Belle II experiments

# LHCb

## Experiment overview

**LHCb is a single-arm forward spectrometer (along the beamline) at LHC collider**

- pp collisions at $\sqrt{s}$ = 7; 8; 13 TeV
- Luminosity 4 x $10^{32}cm^{-2}s^{-1}$ (1/20 – 1/8 of ATLAS/CMS)
- Cover the region 2 < η < 5 (~ 1 - 15°);
  - Large $b\bar{b}$ quark pairs produced correlated in the forward region;

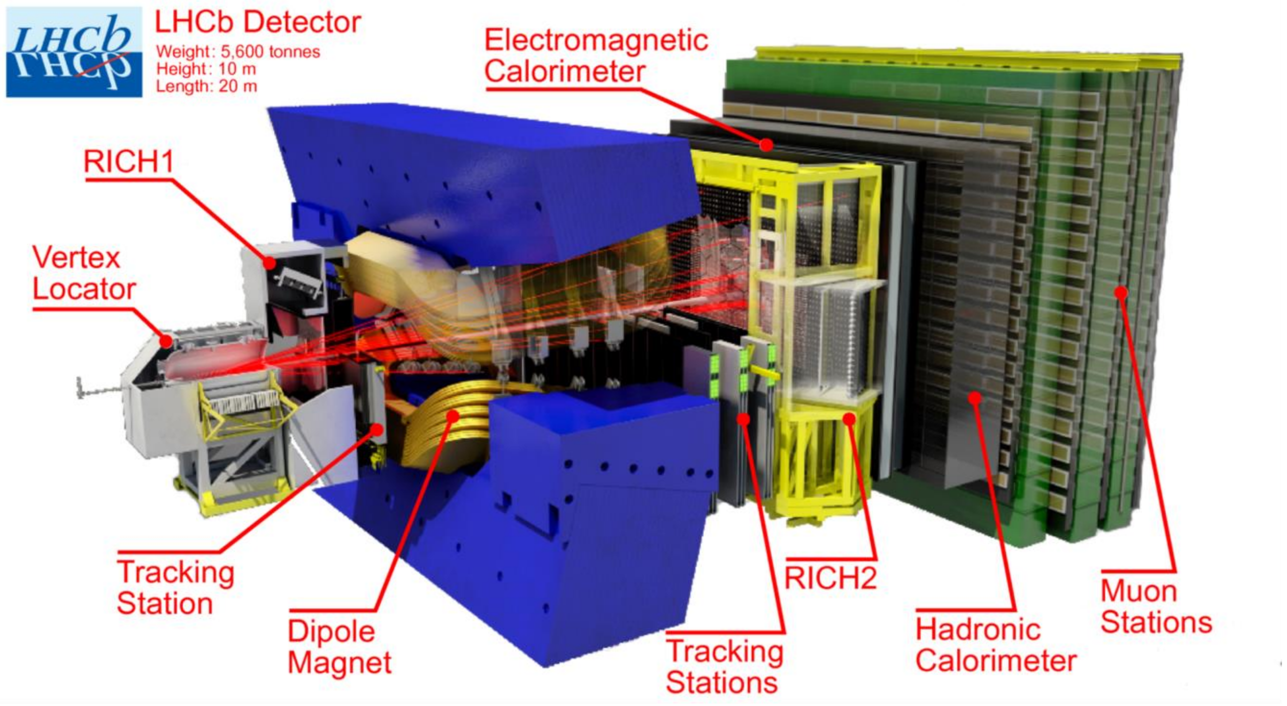
**Data taking:**

- 9 $fb^{-1}$ collected to date;
- Target: 50 $fb^{-1}$ by 2030;

**Key factors for dark sector physics:**

- Excellent vertex
- Excellent momentum and mass resolution
- Good PID capabilities;
- Triggers with low $p^t$ thresholds (ex: $p_{\mu}^{T}$ > 1.5 GeV)

vertex resolution: $10\mu m$




Trak momentum resolution: 0.5% to 1%
Mass resolution: ~ 7-20 MeV

Particle ID (μID: 97% with a [π->μ]mis-ID of 1--3%)

Int.J.Mod.Phys. A 30, 1530022 (2015

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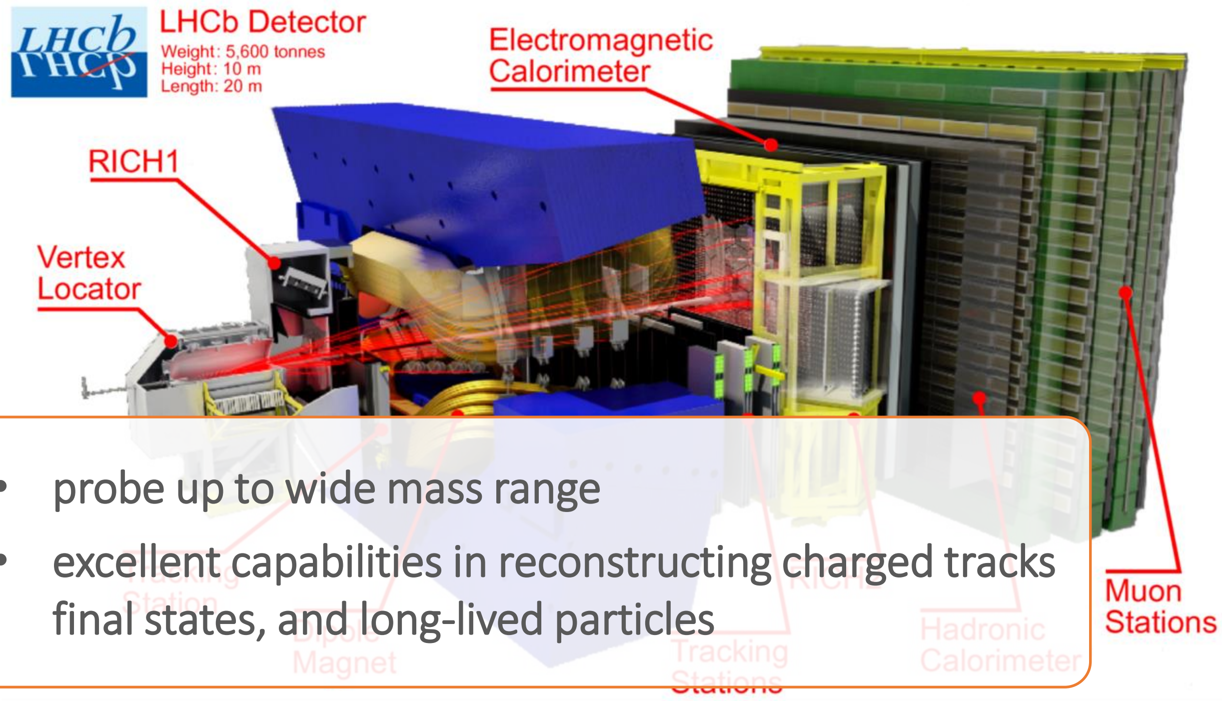


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- Excellent vertex
- Excellent momentum and mass resolution
- Good PID capabilities;
- Triggers with low $p^t$ thresholds (ex: $p_\mu^T$ > 1.5 GeV)

- probe up to wide mass range
- excellent capabilities in reconstructing charged tracks final states, and long-lived particles

Trak momentum resolution: 0.5% to 1%

Mass resolution: ~ 7-20 MeV

Int.J.Mod.Phys. A 30, 1530022 (2015

# Belle II

Experiment overview

**Belle II is a ~$4\pi$ detector @ SuperKEKB collider (Tsukuba, JP):**

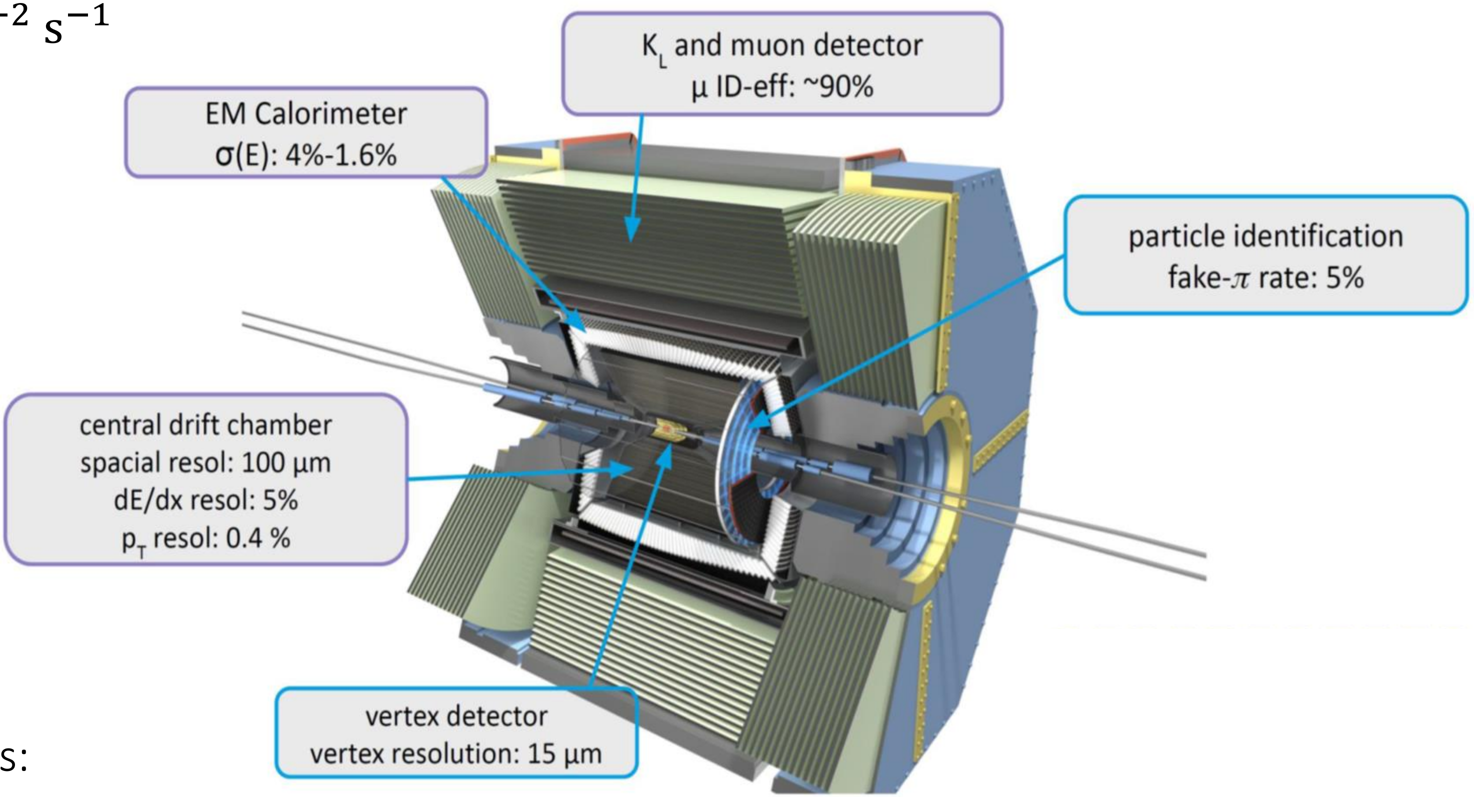
- $e^+e^-$ collision at the $\sqrt{s} = 10.58$ GeV ($= m_{\Upsilon(4s)}$);
- Asymmetric beam energies: Boosted BB;
- Large luminosity: world record $4{,}7 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
    - Final goal is $6 \times 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$;

**Data taking:**

- First collisions in 2018 (Commissioning);
- ~ 430 $\mathrm{fb}^{-1}$ collected to date;
- Target: 50 $\mathrm{ab}^{-1}$ in the next 10 years;

**Key factors for dark sector physics:**

- High luminosity;
- Well defined initial state, clean environment;
- Hermetic detector, excellent PID;
- Dedicated trigger to low multiplicity final states:
    - E.g., single photon, single muon;



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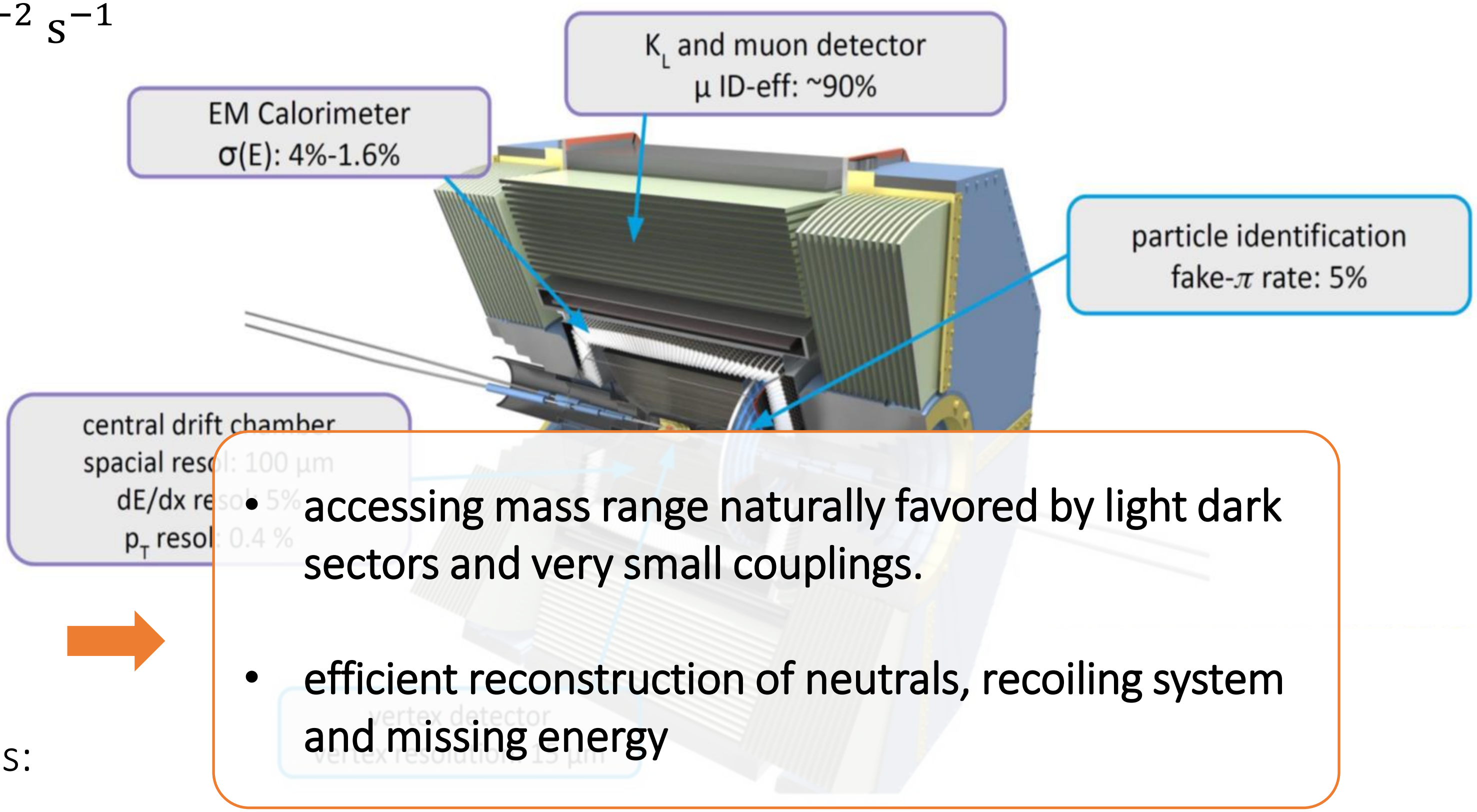



- accessing mass range naturally favored by light dark sectors and very small couplings.
- efficient reconstruction of neutrals, recoiling system and missing energy

# Dark sector searches results

**Disclaimer:**
non exhaustive talk, personal selection of some recent results

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

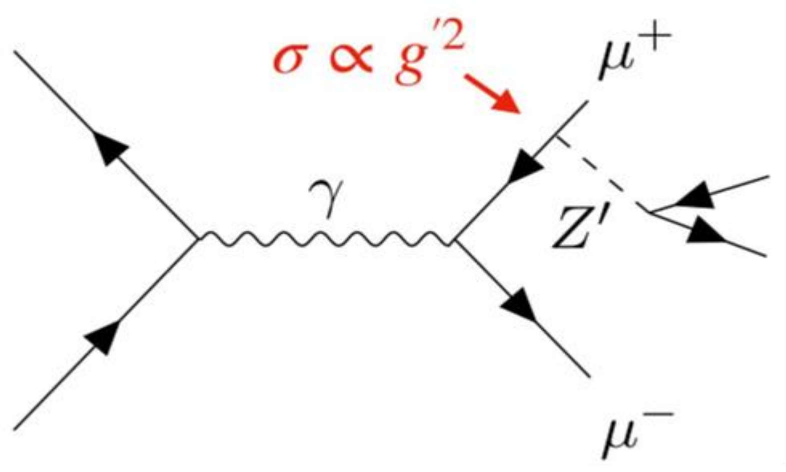
Phenomenology

Vector portal

New massive vector boson Z' coupling only to the 2nd and 3rd generation of leptons ($L_\mu - L_\tau$ model);

May explain [1], [2]:

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




Experimental signatures:

- Visible decay into a muon or tau pair
  - Previous constraints from BaBar(2016), CMS(2019), Belle(2022) and neutrino-nucleus scattering experiments (CCFR and CHARM);
- Invisible decay to SM neutrinos or DM
  - Previous results from Belle II (2020), NA64-e(2022);

brand new @ Belle II


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

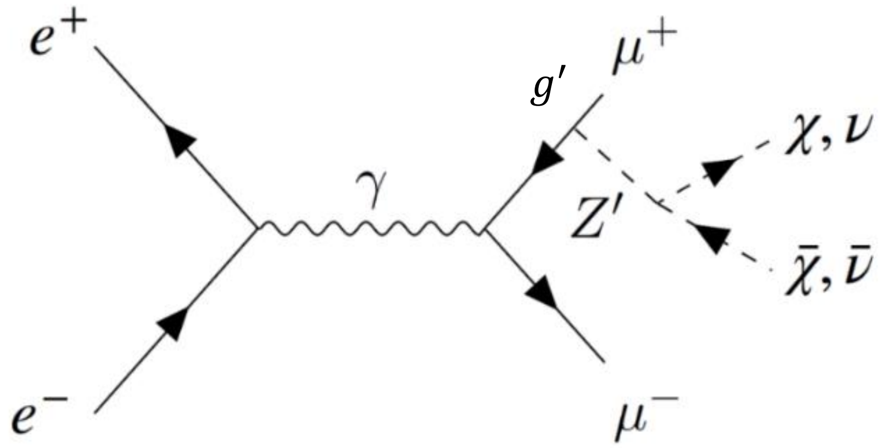
# Invisible Z’ @ Belle II

Strategy

**Search for $e^+e^- \to \mu^+\mu^- Z',\ Z' \to \textbf{invisible}$**

- First measurement with 2018 dataset: ~279 pb$^{-1}$ ;
- New analysis with 2019-20 dataset: ~ 79.7 fb$^{-1}$

Much higher luminosity;
Analysis strategy improved;
New triggers.




**Signature:**

- A peak in the recoil mass distribution against two muons

**Background**:

- SM processes with 2 particles identified as muons and missing momentum
  - mainly due to $\mu\mu\gamma, \tau\tau, ee\mu\mu$

**Analysis selection in short:**

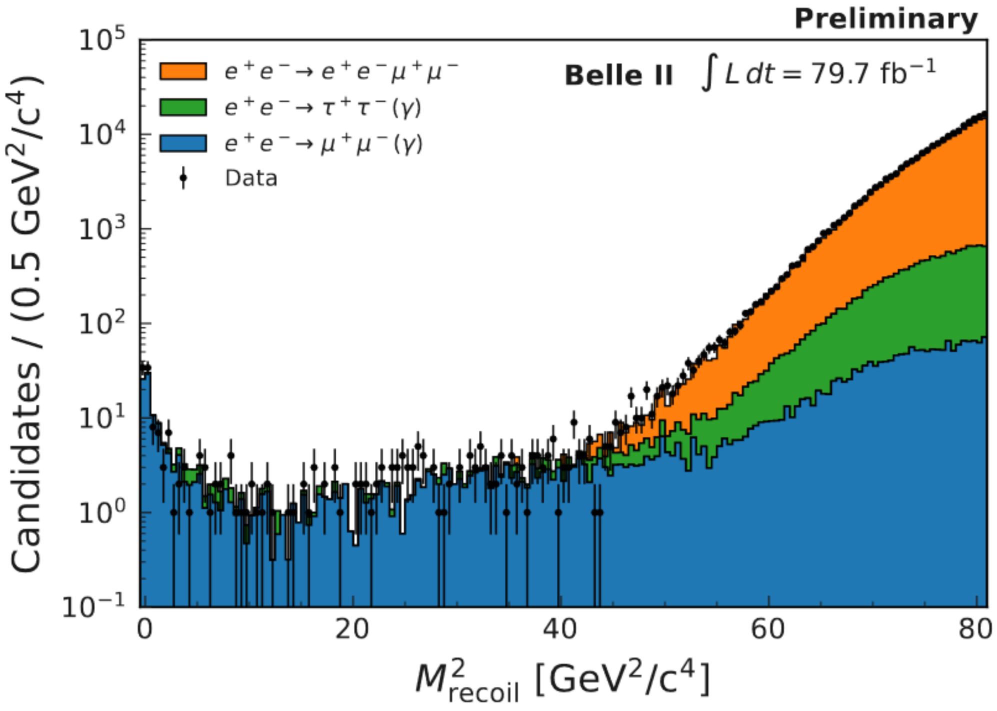
- Two OS muon tracks; $p_T^{\mu\mu} > 0.1$ GeV/c
- Recoil points to barrel calorimeter ($M_{\text{recoil}} < 2$ GeV)
- Low activity in the calorimeter; $\gamma$ veto;
- Neural-Network exploiting FSR nature of Z’ production Eur.Phys.J.C 82 (2022) 2, 121

# Invisible Z' @ Belle II

Results

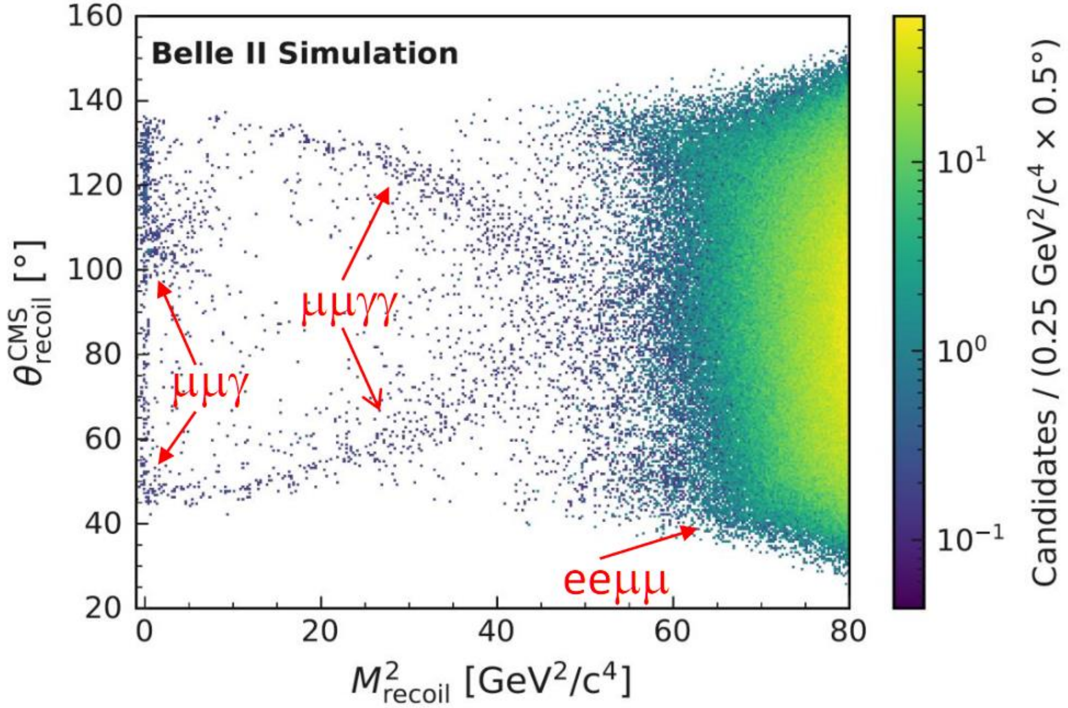
**Background composition**:

- $\mu\mu(\gamma)$ dominates up to 7 GeV$^2$/c$^4$;
- $ee\mu\mu$ dominates for high masses;
- $\tau\tau$ almost 100% up to ~7 GeV$^2$/c$^4$;




**Search strategy**:

- Fitting over the 2d distribution $\theta_{\text{recoil}}$ vs. $M^2_{\text{recoil}}$



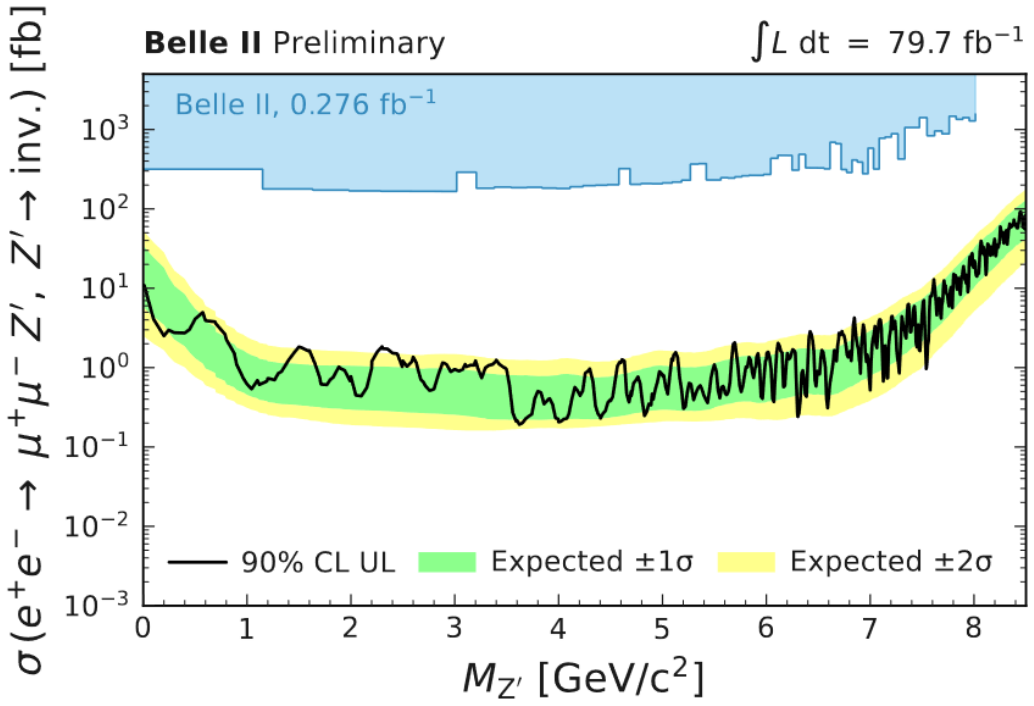
# Invisible Z’ @ Belle II

Results

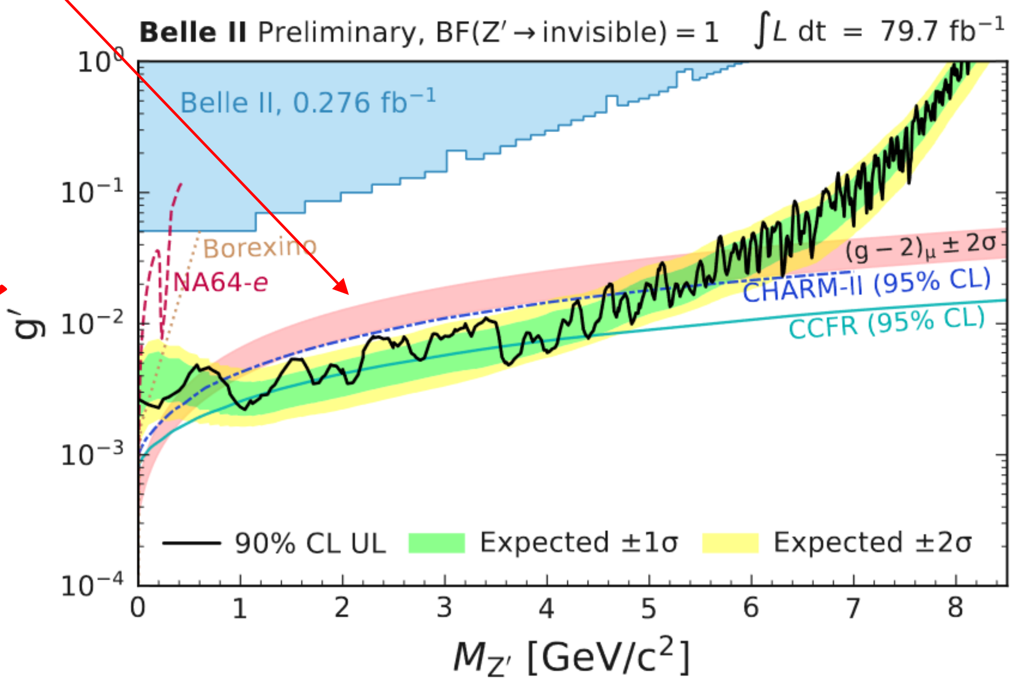
No significant excess over the expected background

Set 90%CL exclusion limits on cross section and coupling

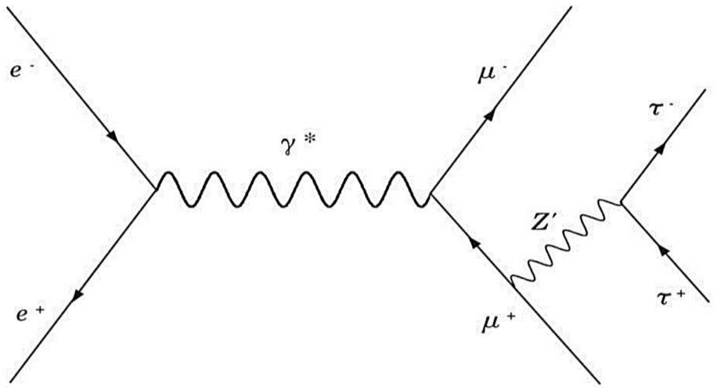
- World-leading UL for a fully invisible Z’ (100% BR to invisible)
  - First excluding a fully invisible Z′ boson as an explanation of the $(\mathbf{g}-\mathbf{2})_{\boldsymbol{\mu}}$ anomaly for 0.8 < $M_{Z'}$ < 5 GeV/c$^2$




new



# Search for a $\tau^+\tau^-$ resonance in $\mu^+\mu^-\tau^+\tau^-$ @ Belle II




$e^+e^- \rightarrow \mu^+\mu^- Z'$, $Z' \rightarrow \tau^+\tau^-$: first time search.

- Performed with 2019 + 2020 data (63.3 $fb^{-1}$)

More in yesterday talk by G. De Pietro

Signature:

- A peak in the recoil mass distribution against two muons

Z' model as benchmark. Results re-casted for:

- Leptophilic scalar S;
- Axion-like-particle;

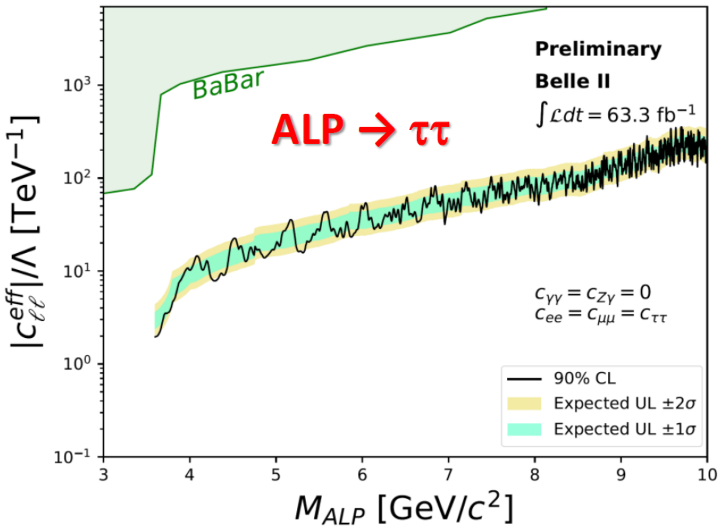
Scalar and pseudo-scalar portals

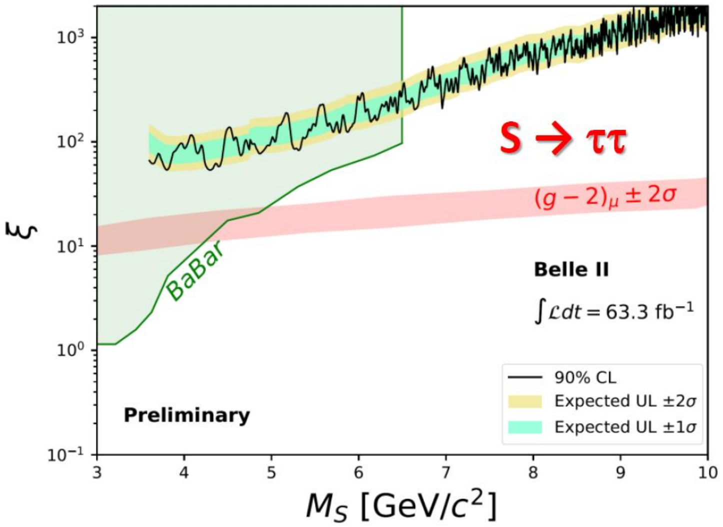
new

No excess found

Set 90% CL UL on $\sigma$ and couplings:

- First constraints on S for $M_S > 6.5$ GeV/$c^2$;
- First direct constraints for ALP → $\tau\tau$;



# Dark Photon

## Phenomenology

[1] P. Fayet, *Phys. Lett. B* **95**, 285 (1980),
[2] P. Fayet, *Nucl. Phys. B* **187**, 184 (1981)

Hypothetical massive gauge boson A’ of spin = 1 coupling to the SM hypercharge through the kinetic mixing with strength ε [1,2].

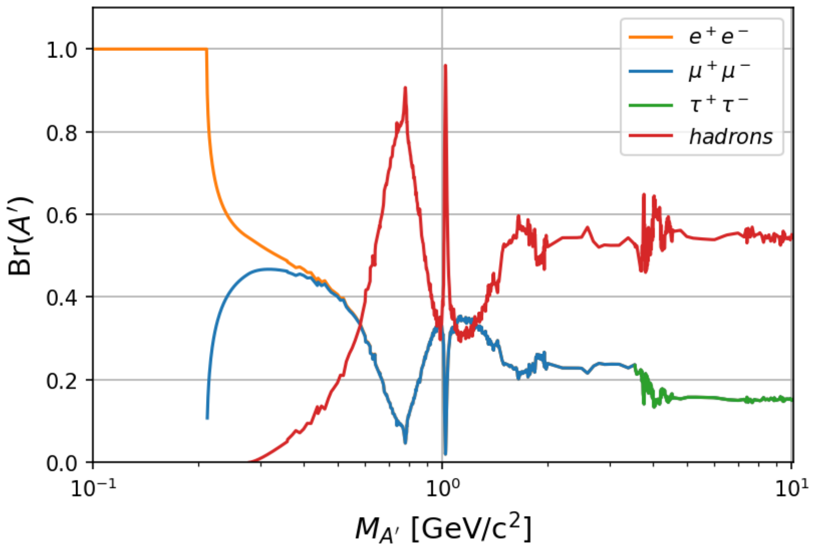
Vector portal


Several possible production mechanisms:

- ISR, Drell-Yan, meson decay, dark Higgsstrahlung.

Two basic scenarios depending on A’ vs DM masses relationship:

- $m_\chi > \frac{1}{2}\mathrm{m}_{A'}$, → A’ visible decays to SM particles;
- $m_\chi < \frac{1}{2}m_{A'}$, → A’ invisible decays to LDM;




**Dark photon lifetime proportional to $1/(\epsilon^2 m'_A)$**

# Dark Photon @LHCb

Visible decay

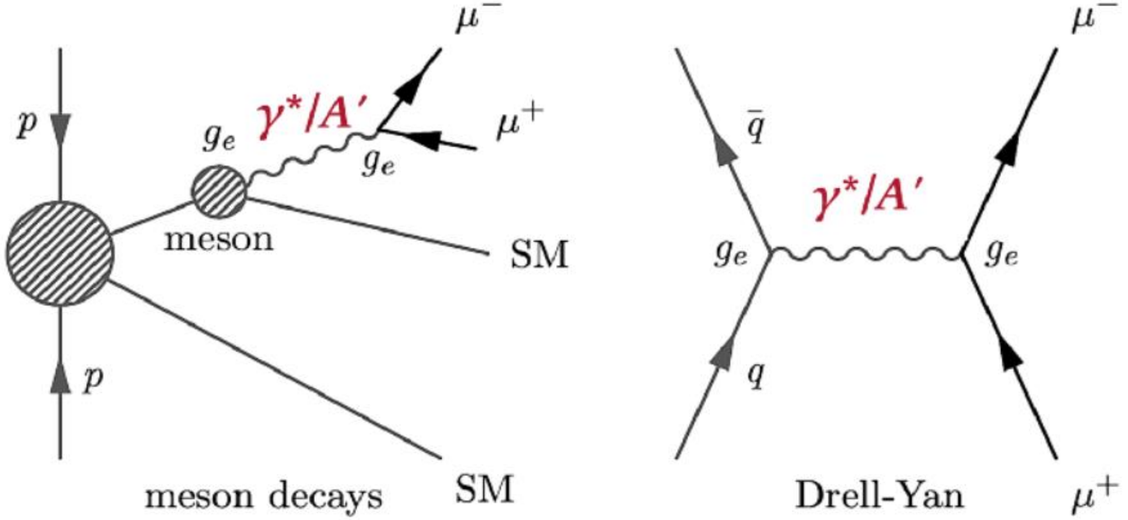
**Search for $A' \rightarrow \mu^+\mu^-$:**

- First results with 2016 data (1.6 $fb^{-1}$): PRL 120 (2018)
- Analysis update with full run2 data: 5.5 $fb^{-1}$: PRL 124 (2020)

+ improved software trigger

**Main production:**

- Kinetic mixing oh the dark photon with off-sell $\gamma$:
  - m(A)<1 GeV: Meson decays;
  - m(A)>1 GeV: Drell-Yan




**General strategy: bump hunt search**

- Prompt-like search (up to 70 GeV/c2)
- displaced search (214-350 MeV/c2)

A′ inherits the production mode mechanisms from γ∗

- **A' expected yield can be normalized to off-shell photon**
- Prompt search: no need for efficiency from simulation
  - **Fully data-driven analysis**

$$n^{A'}_{\mathrm{ex}}[m(A'),\varepsilon^2] = \varepsilon^2 \left[\frac{n^{A'}_{\mathrm{ob}}[m(A')]}{2\Delta m}\right] \mathcal{F}[m(A')]\epsilon^{A'}_{\gamma^*}[m(A'),\tau(A')]$$

**Phase space**

**Off-shell photon**

**Efficiency ratio $A'/\gamma^*$**

**$\epsilon = 1$ for prompt decays**

Need to separate non $\gamma^*$ background

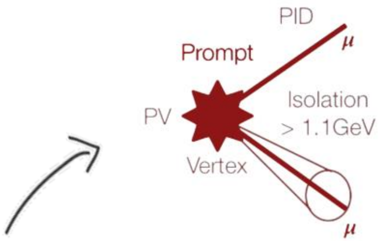
Non-trivial in displaced case due to $\gamma$ conversion veto

# Dark Photon @LHCb

Prompt decay results

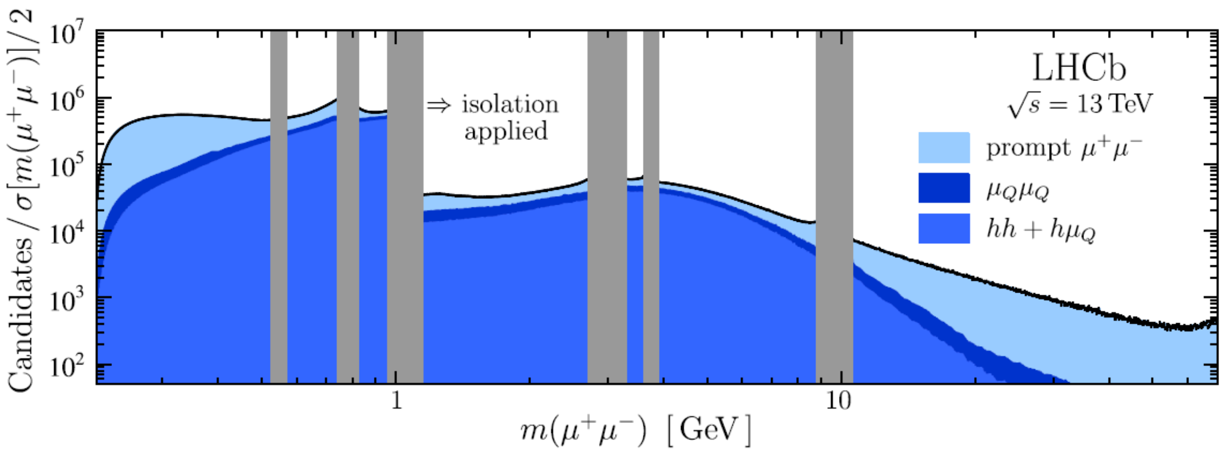
PRL 120 (2018) 061801

PRL 124 (2020) 041801




**Strategy:**

- Scan the spectrum in steps of $\sigma[m(\mu^+\mu^-)]/2$ and fit for the signal over a large background
- Regions with known resonances are removed
- isolation cut applied only above 1 GeV/c$^2$




**Background is estimated mostly with data-driven techniques:**

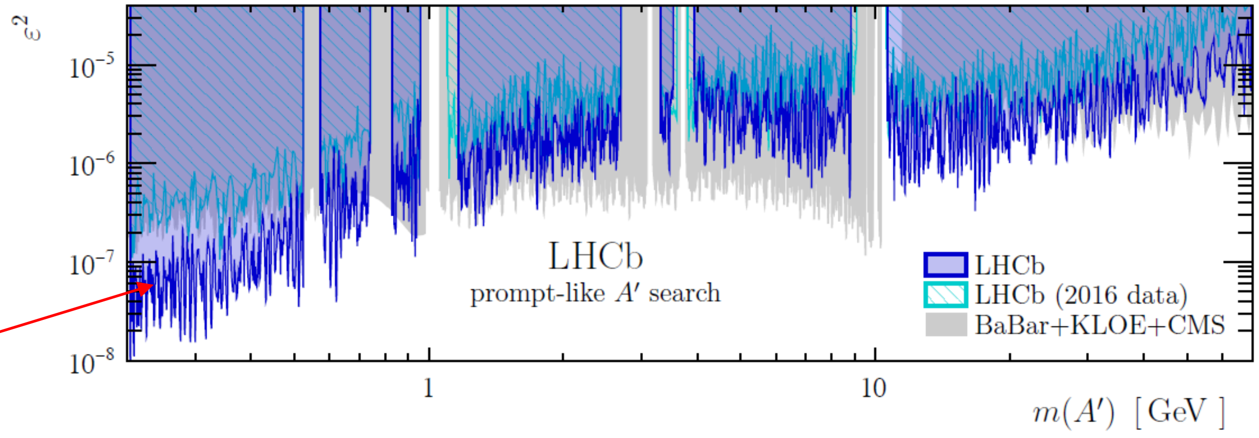
- prompt $\mu\mu$ → from $m(J/\psi)$ and $m(Z)$*
- $\mu_Q\mu_Q$ → from simulation
- $hh + h\mu_Q$ → from same-sign dimuons

*validated on $m(\phi)$ and $m(\Upsilon(1S))$

**No significant excess found**

**90% CL UL on $\epsilon^2$**

- Most stringent limits for 214 < mA'< 740 MeV and 10.6 < mA' < 30 GeV



# Dark Photon @LHCb

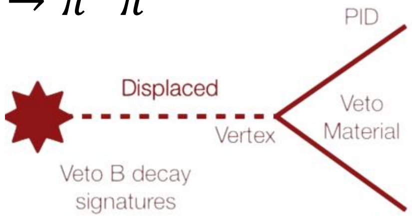
Displaced decay results

PRL 120 (2018) 061801
PRL 124 (2020) 041801

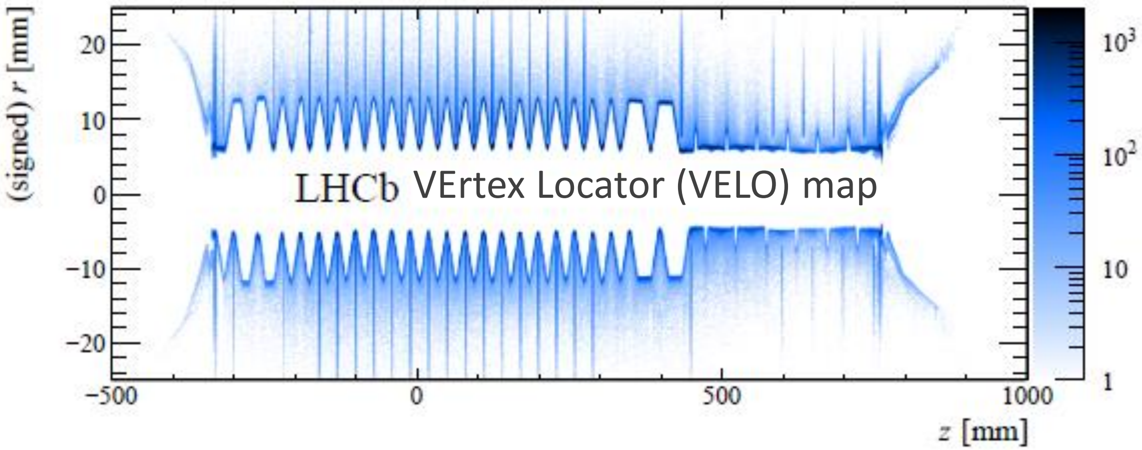
Currently only within the VELO: max displacement < 20 cm

Main background:

- $\gamma$ conversion in the VELO
  - Precise knowledge material location needed to reduce it
- B-hadron decays with $2\mu$ and misID $K_S^0 \to \pi^+\pi^-$




Special beam-gas runs: high-precision material map to veto



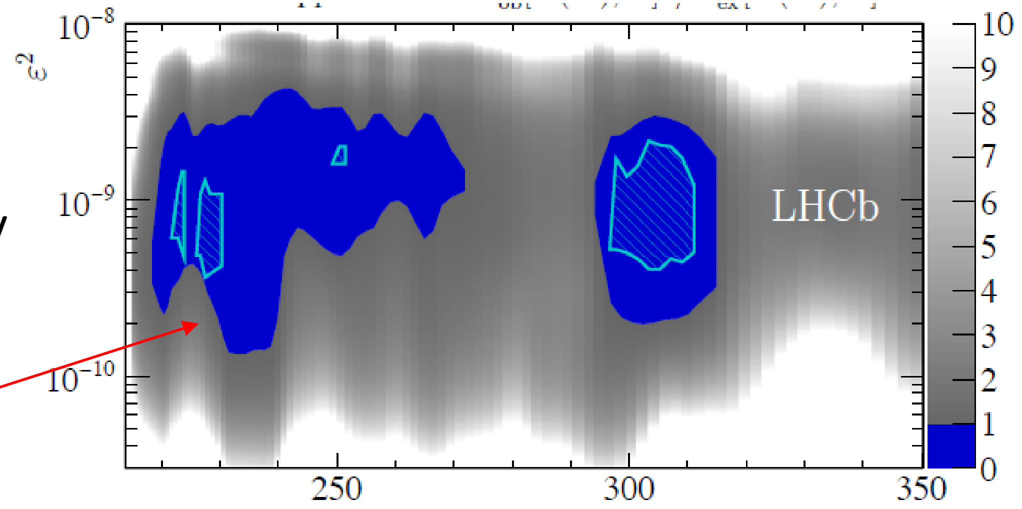

Use simulation to find relative A′/γ∗ decay-time inefficiency

Fit in bins of mass and lifetime and use of consistency of decay topology

No significant excess found

90% CL UL on $\epsilon^2$

- First non-fixed-target constraint from displaced signature search




Regions less than unity are excluded.

# Inclusive $X \to \mu^+\mu^-$ search @LHCb

.

**Probe additional dark sectors in di-muon resonance:**

- 2016-2018 data set: 5.1 fb-1
- Explored $2m_\mu < m(X) < 60$ GeV

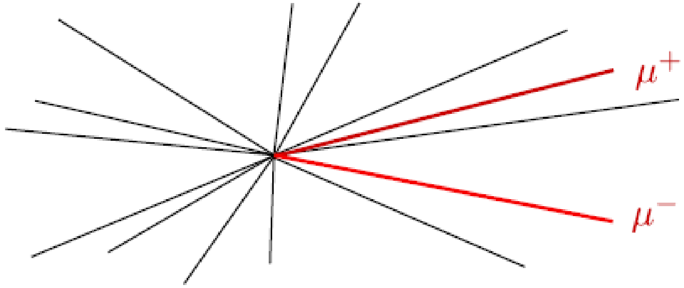
**Topologies investigated:**

- Inclusive prompt;
- Prompt +b-jet;
- Displaced pointing;
- Displaced non pointing;

**Strategy:**

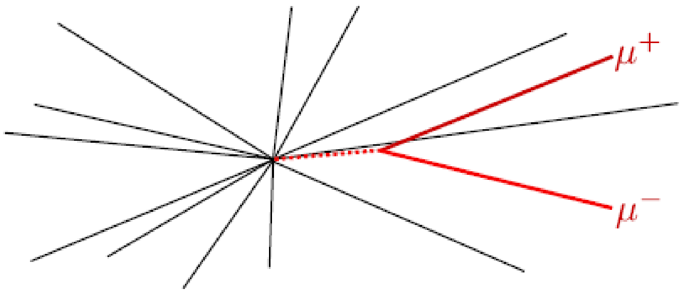
- Minimize assumptions on production;
    - **drop kinetic mixing assumption with γ***
- Obtain results in bins of mass and $p^T$

Prompt, inclusive

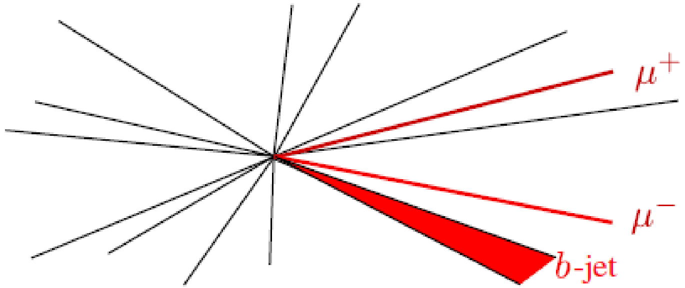



- No isolation requirements
- Non-zero width considered

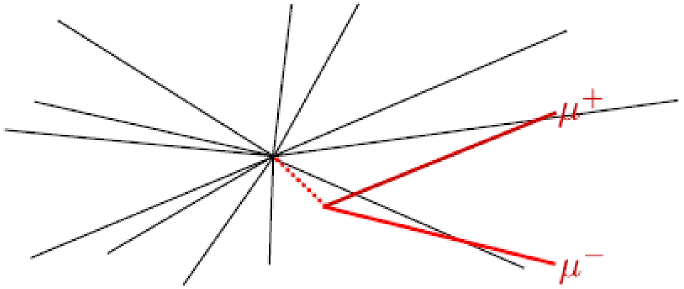
Displaced (prompt source)




Prompt + $b$—jet




Displaced (non-prompt source)



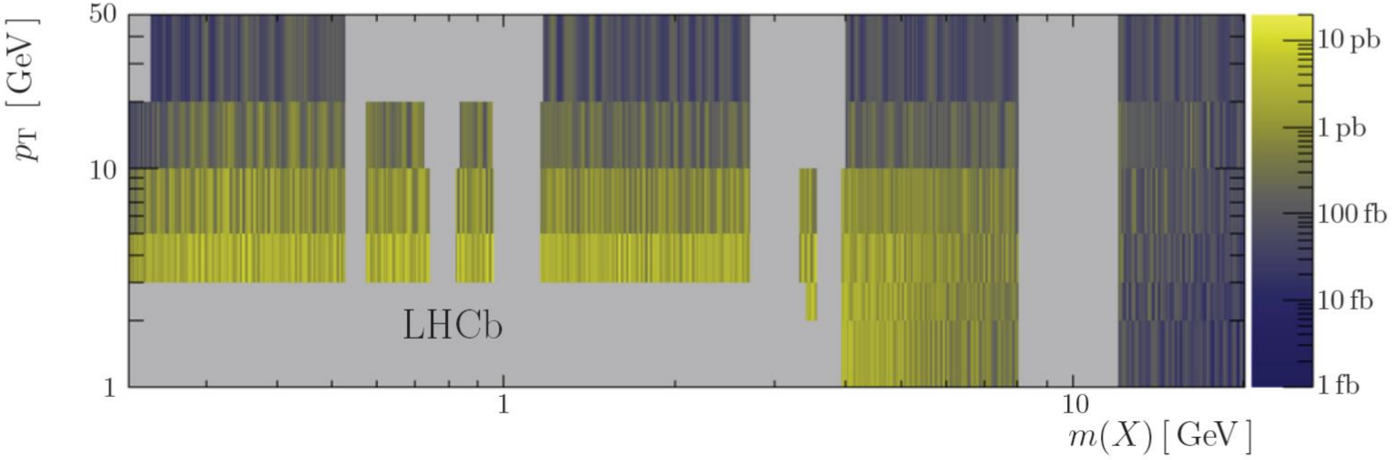
# Inclusive $X \to \mu^+\mu^-$ search @LHCb

Results

JHEP 10 (2020) 156

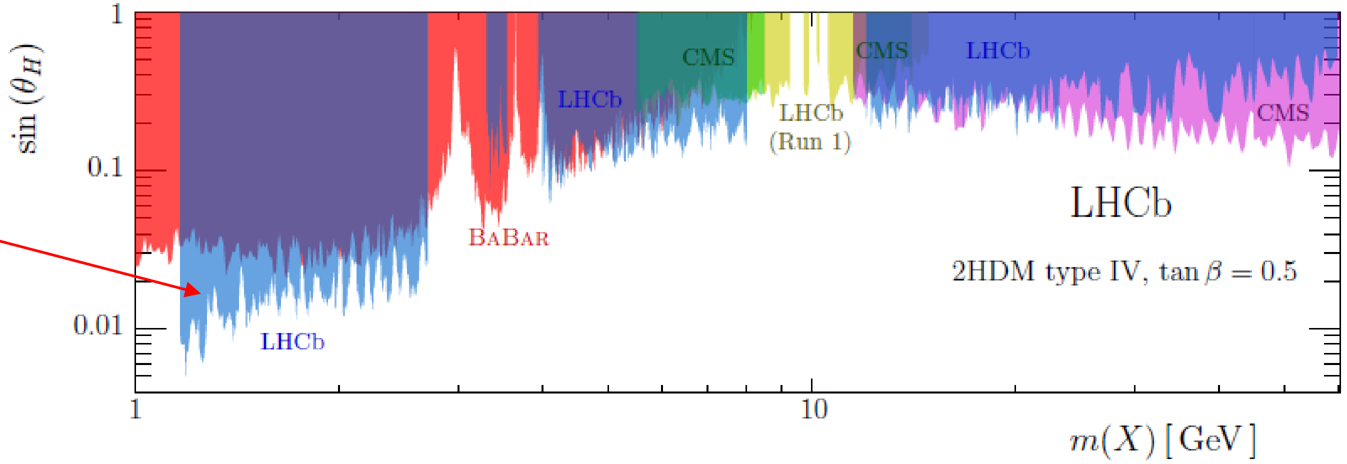
No excess found

Model independent UL on cross section in bins of mass and $p^T$




**Prompt search results to constraint 2HDM + complex scalar singlet X** (model from: [PRD 93, 055047 (2016)](PRD 93, 055047 (2016)))

- world-best upper limit on X mixing angle with SM Higgs $\theta_H$



# Dark Higgsstrahlung searches

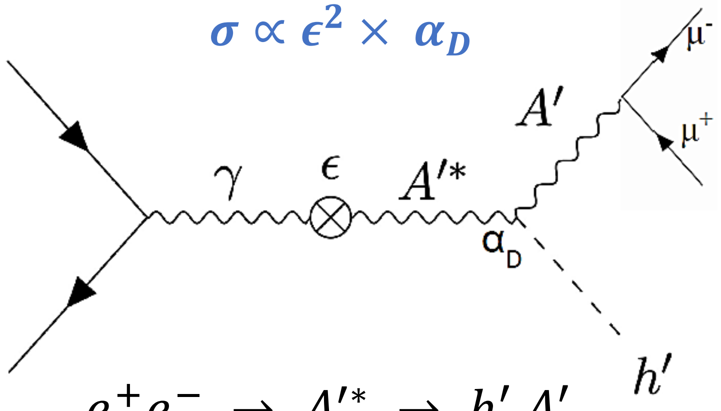
Intro

Vector portal

**Next to minimal dark photon model.**

- A' mass generated via spontaneous symmetry breaking, by adding **a dark Higgs boson $h'$** to the theory [1]:

Both the particles (A', h') can be produced at an $e^+ e^-$ collider via the **dark Higgsstrahlung** process.

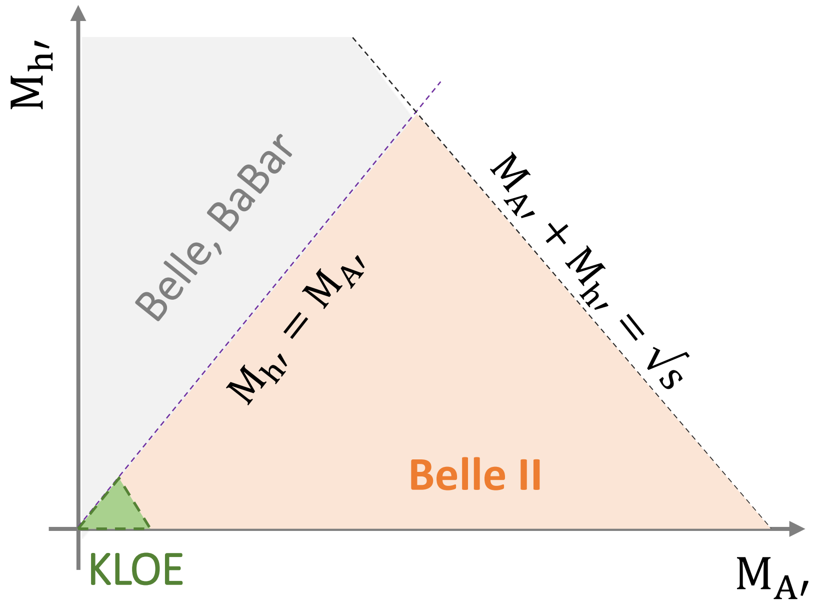



$$e^+e^- \rightarrow A'^* \rightarrow h' A'$$

**Mass hierarchy scenarios:**

- $M_{h'} > M_{A'}$:
  - $\mathrm{h}' \rightarrow \mathrm{A}'\mathrm{A}'$
  - Signature: 6 charged tracks;
  - Investigated by BaBar(2012) and Belle(2015)
- $M_{h'} < M_{A'}$:
  - $\mathrm{h}'$ is long-lived -> invisible.
  - Signature: two OS tracks and missing energy
  - Probed by KLOE(2015).

Investigated by Belle II




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

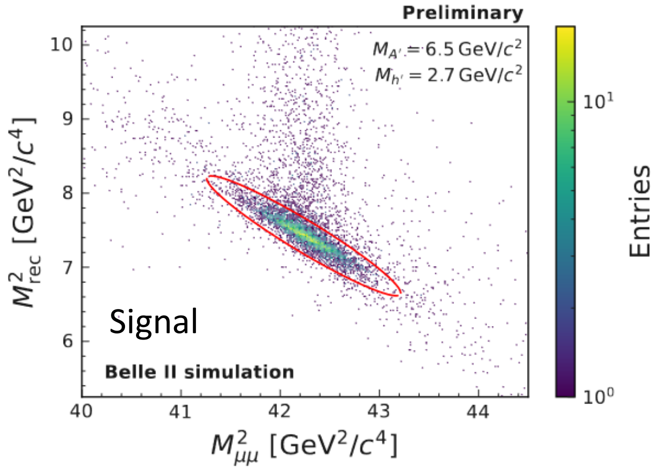
# Dark Higgsstrahlung @ Belle II

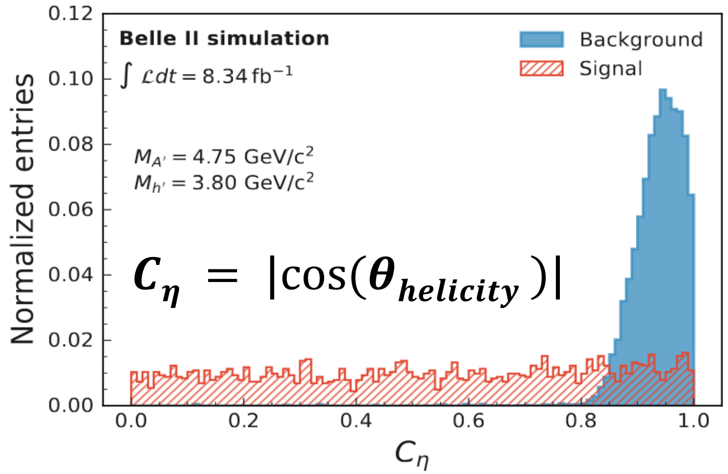
Strategy

Search performed with 2019 data -> 8.34 $fb^{-1}$

Signature:

- Two OS muons and missing energy
- 2D peak in $M^2_{\mu\mu}$ vs $M^2_{recoil}$:
  - scan and count in search windows
  - ~9000 2D elliptical windows



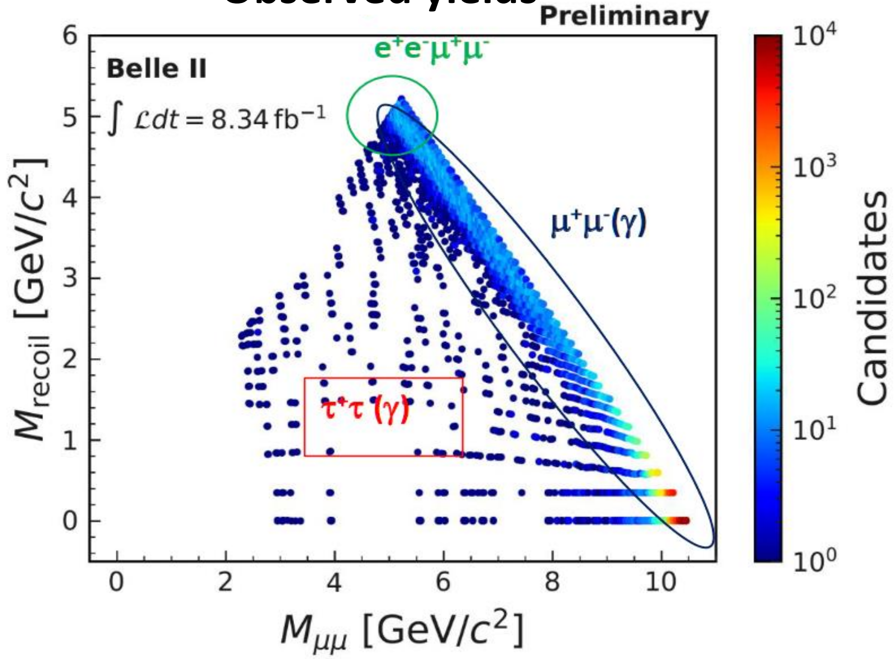




Backgrounds mainly due to $\mu\mu\gamma, \tau\tau, ee\mu\mu$

Analysis in short:

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

**Observed yields**



# Dark Higgsstrahlung @ Belle II

Results

Submitted to PRL
ArXiv: 2207.00509

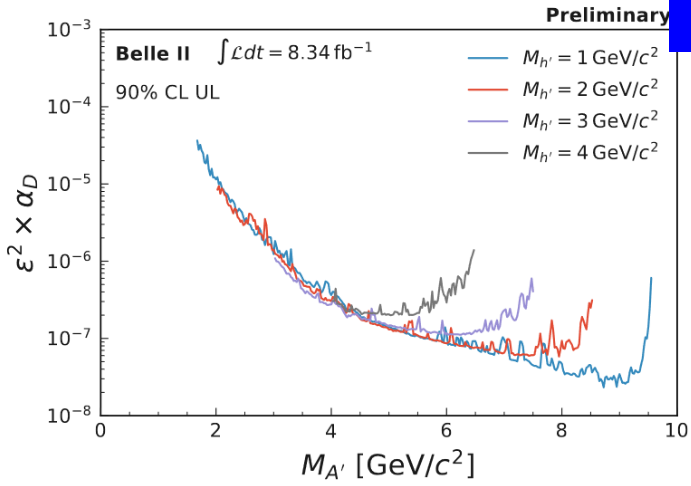
No significant excess observed
90% CL UL on σ and $\epsilon^2 \times \alpha_D$

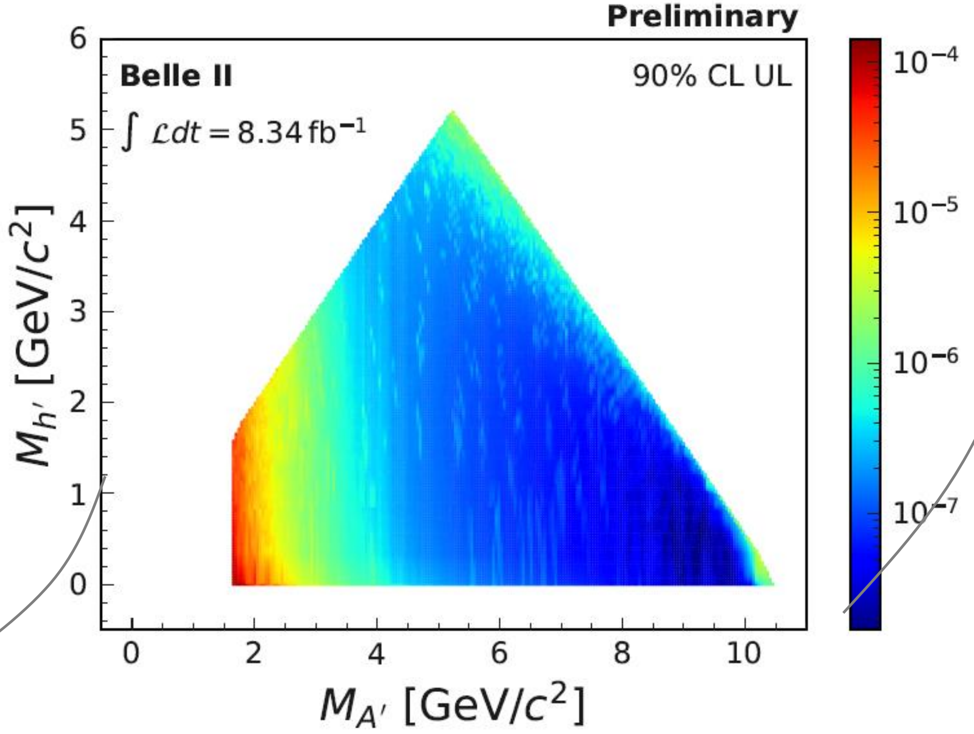
World first for $1.65 < M_{A'} < 10.51$ GeV and $M_{h'} < M_{A'}$

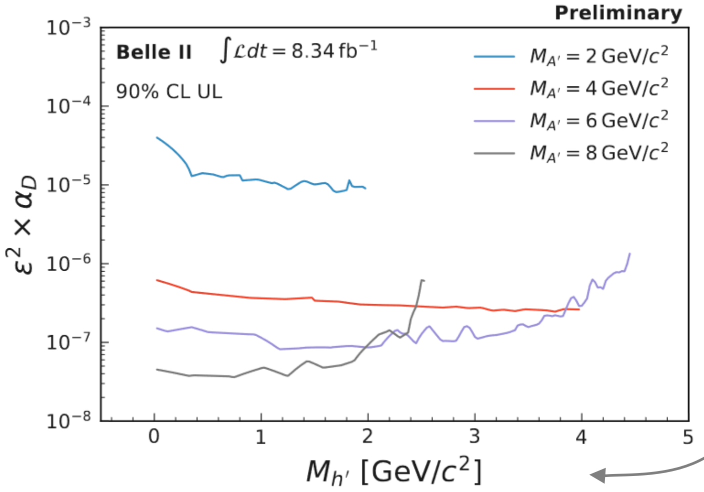
- UL on $\epsilon^2 \times \alpha_D$ down to $1.7 \times 10^{-8}$ in the most sensitive regions

Low sensitivity for:

- $M_{A'} < 4$ GeV: due to low trigger efficiency;
- $M_{A'} > 9$ GeV: large dimuon background



# Dark bosons in b → s @LHCb

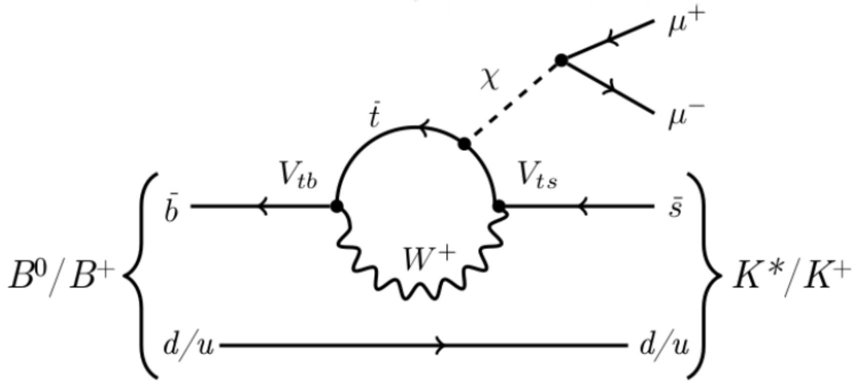
Strategy

Scalar portal

Flavour-changing neutral currents to search for new physics

Run1 dataset (3 fb$^{-1}$) used to reach for:

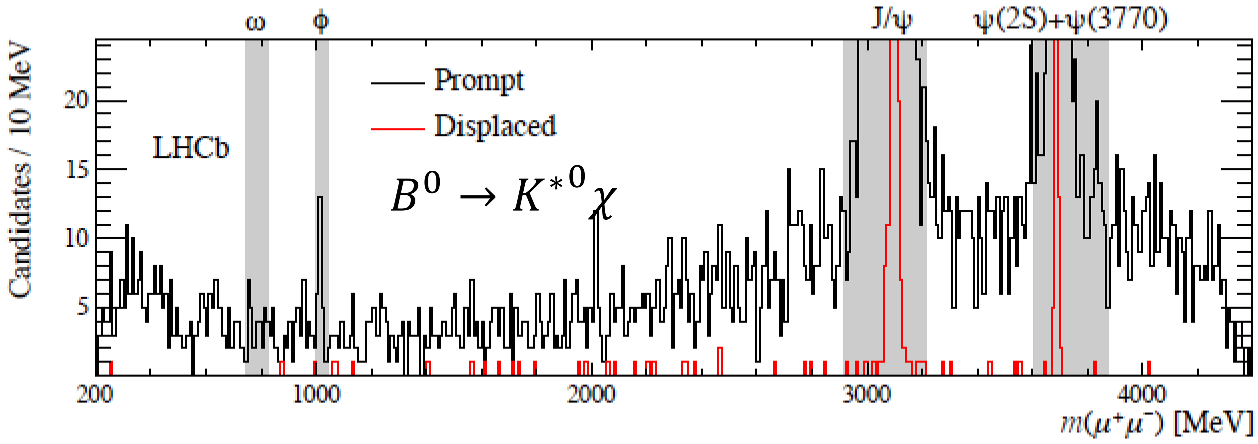
- $B^0 \to K^{*0}\chi$ [PRL 115 (2015) 161802]
- $B^+ \to K^+\chi$ [PRD 95 (2017) 071101 (R)]



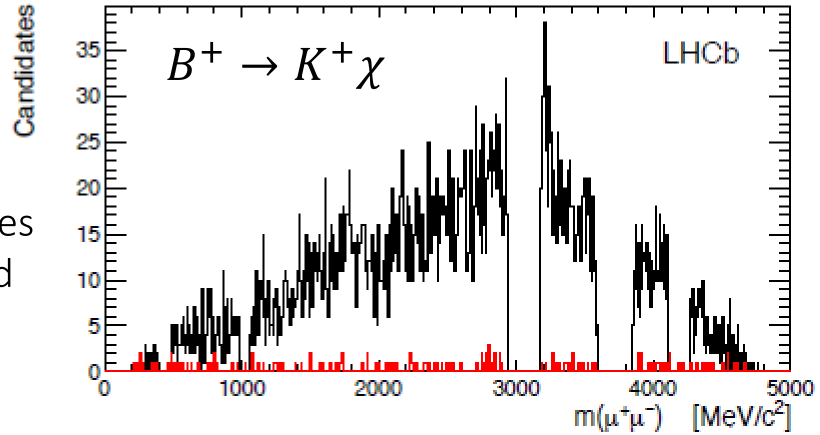

Scalar (Higgs) portal ($\chi$ as inflaton) [JHEP 05 (2010) 10]

- Rate and lifetime controlled $\theta$ mixing angle with SM Higgs $\tau \propto 1/\theta^2$ $\mathcal{B}(B^+ \to K^+\chi) \propto \theta^2$

Allow for prompt and detached di-muon candidates up to 1000 ps (~30 cm).
Look for a narrow di-muon peak (mass resolution between 2 and 9 MeV/c2).




Known resonances removed



# Dark bosons in $b \to s$ @LHCb

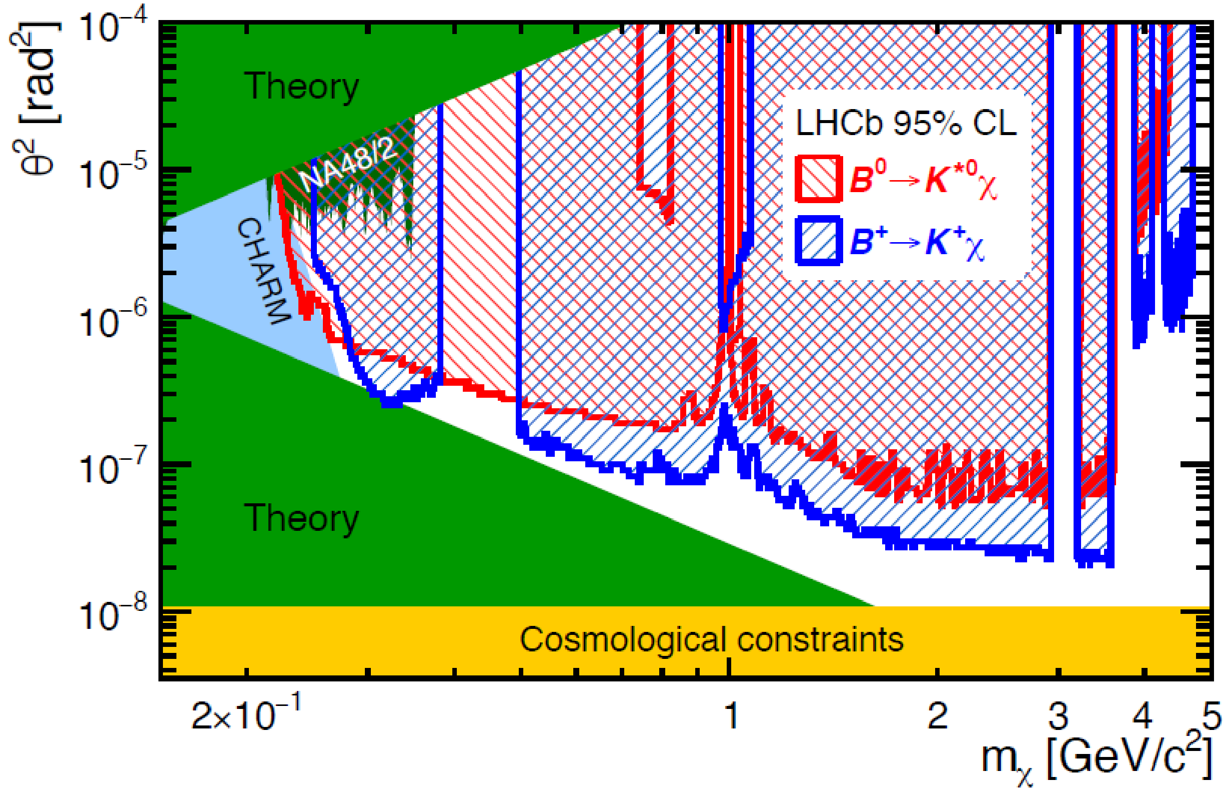
Strategy

[PRL 115 (2015) 161802]
[PRD 95 (2017) 071101 (R)]

No evidence for signal

Constraints on mixing angle $\theta^2$ between the Higgs and $\chi$ in the infaton model

- Large fraction of allowed inflaton parameter space ruled out.



# Future prospects

some highlights

# Visible Dark Photon searches

Prospects @Belle II and @LHCb

@Belle II: leading sensitivity for masses ~ 400 MeV < $M_{A'}$ < 10 GeV

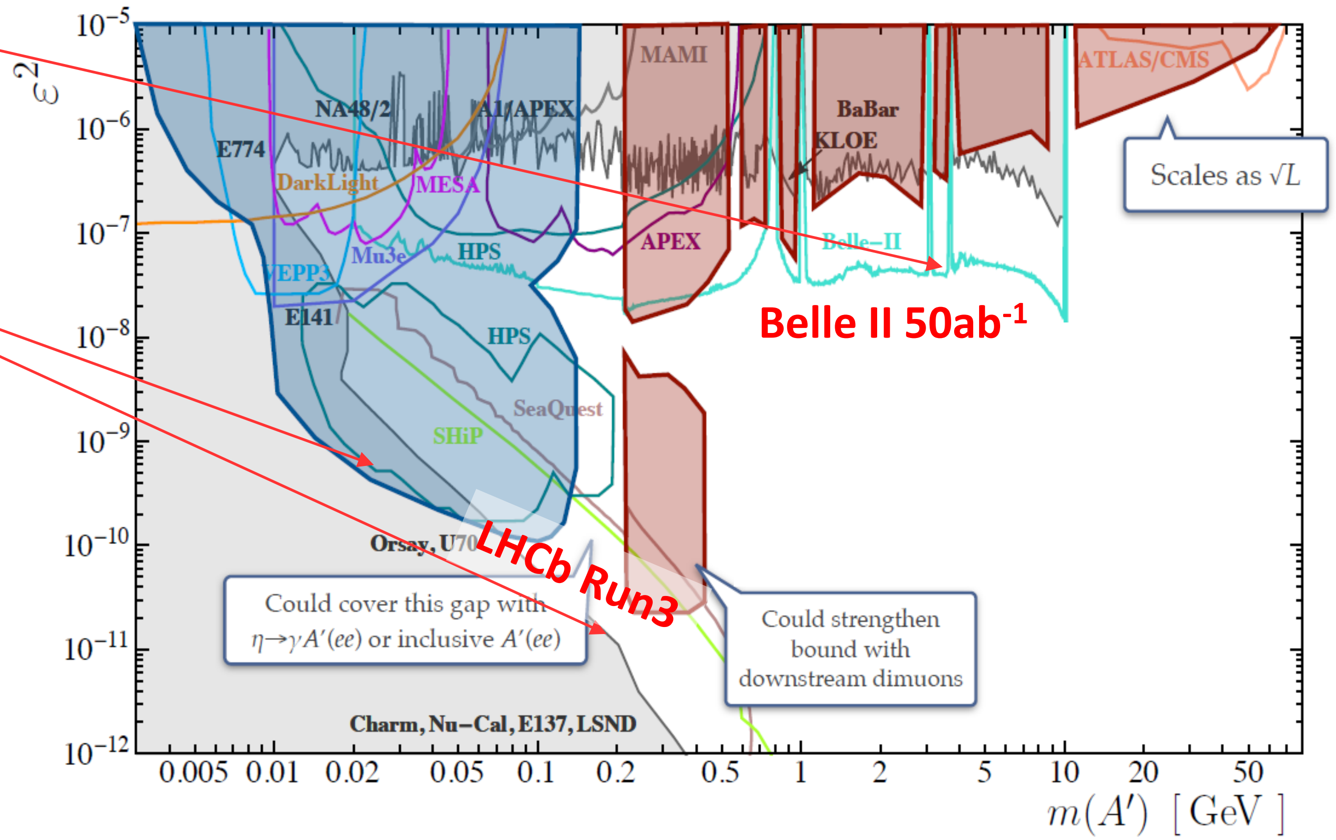
- Needs to collect much more statistics

@LHCb: updates for both displaced and prompt searches in upcoming datataking

- cover region below 2mμ using charm decays $D_0^* \rightarrow D_0 A'(ee)$.
- Requires upgraded trigger to select efficiently soft final state

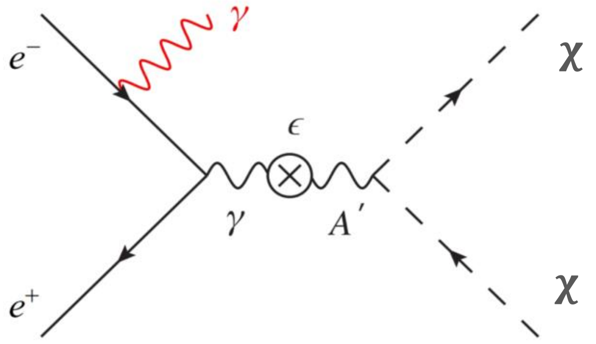
Inclusive $A' \to \mu\mu$ at LHCb
Ilten, Soreq, Thaler, Williams, Xue [1603.08926]

Radiative $D$ Decays at LHCb
Ilten, Thaler, Williams, Xue [1509.06765]



# Invisible Dark Photon searches @ Belle II

Prospects




In case of DM kinematically accessible we can expect $BR(A' \to \chi\chi) = 1$

- Invisible searches of fundamental importance

**Signature:**

- **Only one mono-chromatic high-E photon $\boldsymbol{\gamma_{ISR}}$;**
- Bump in the photon energy:

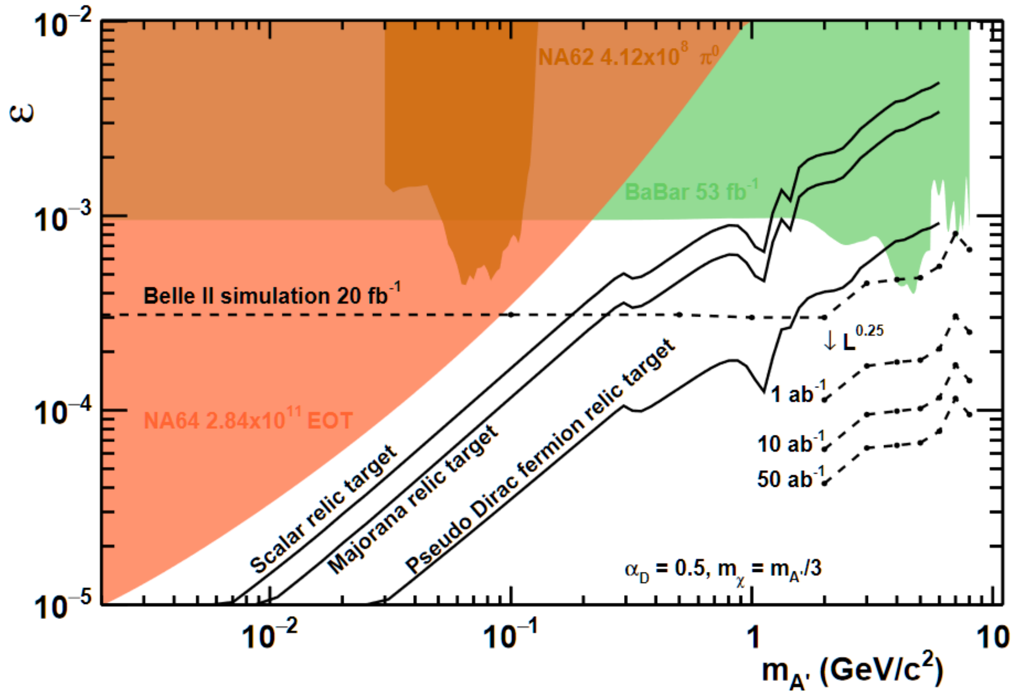
**SM backgrounds:** $ee \to \gamma\gamma(\gamma)$, $ee \to$ee$(\gamma)$, Cosmics;

**Requires a single photon trigger:**

- Bottleneck for previous B-factories;

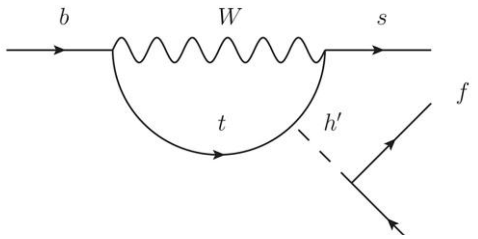
**Expected to perform better than BaBar due to:**

- no ECL cracks pointing to the interaction regions;
- Trigger threshold lower than in BaBar;
- KLM veto;
- Smaller boost;



# Light scalars in b → s transitions @ Belle II

Prospects




**Long-lived h’ produced in b → s transition**

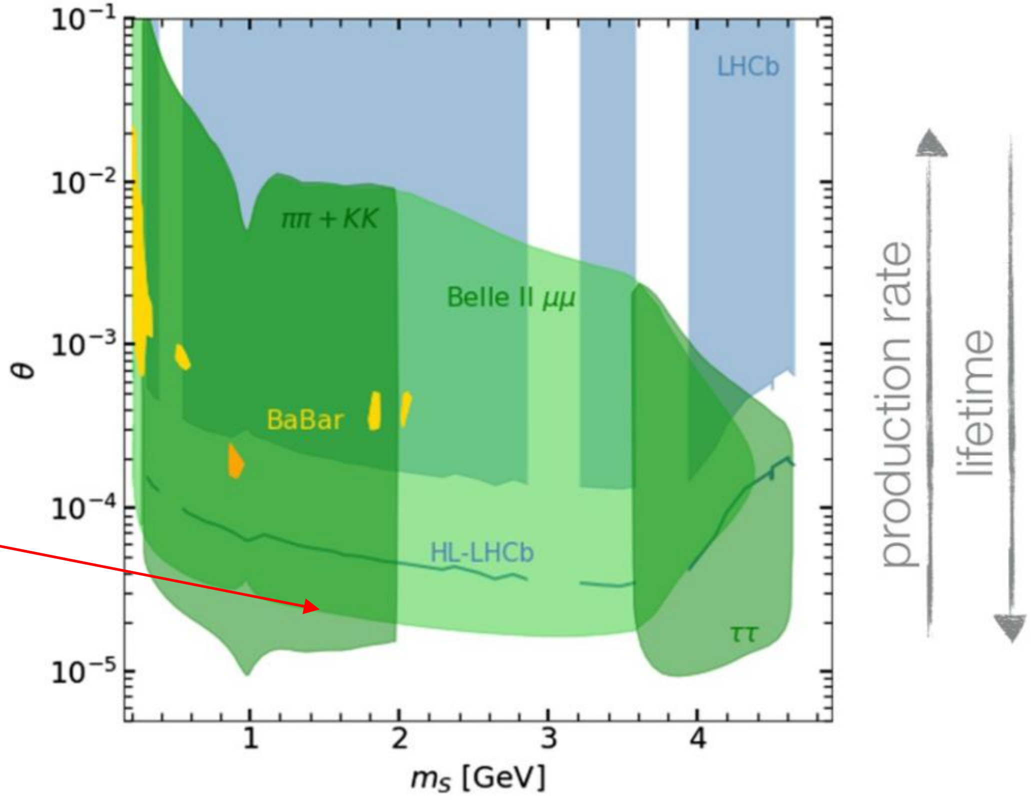
- h’ mixes with the Standard Model Higgs boson with angle θ
- prompt K + two opposite signed tracks from a displaced vertex
  - Separately for different exclusive final states: $\mu\mu, \pi\pi, KK, \tau\tau$

**Strategy:** Search for a bump in the invariant mass of tracks coming from a displaced vertex

Belle II could have a better reach wrt LHCb thanks to the lower boost: longer mediator life-times -> smaller couplings;

**Exclusion regions expected with 50/ab at Belle II**

Filimonova et al., [JHEP04 (2021) 39]




Belle II can an also perform:
- B → K + invisible
- B → Ka (a → $\gamma\gamma$)

# Conclusions

**LHCb and Belle II have an extensive program of searches in the Dark Sector and provided complementary competitive limits on several models**

**Shown results on :**

- Prompt and displaced visible dark photon search;
- Inclusive dimuon resonance search;
- Dark scalar in $b \to s$ transition search;

- Invisible Z' search;
- $\tau^+\tau^-$ resonance search;
- Dark higgstrahlung;

new

Increased luminosity, upgraded detectors and better analysis strategies will improve existing limits and provide soon new results.

**Details on future strategies:**

- Rep. Prog. Phys. 85 (2022) 024201
- Prog. Theo. Exp. Phys. 12 (2019)