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

Marcello Campajola
INFN Napoli – Belle II
marcello.campajola@na.infn.it

Istituto Nazionale di Fisica Nucleare

Dark Sector searches

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

Motivations & Models

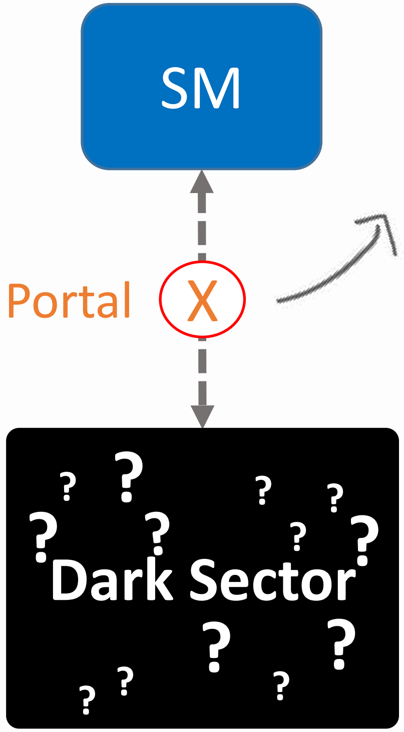
The absence of DM discoveries at LHC or direct detection experiments motivate the strong interest for models with **low-mass dark matter** candidates or mediators.

A possible MeV - GeV theoretical scenarios:

- Light DM feebly interacting with SM through a new light mediator (‘**portal**’)
- There is a small number of possible portal interactions between Dark Sector 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



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

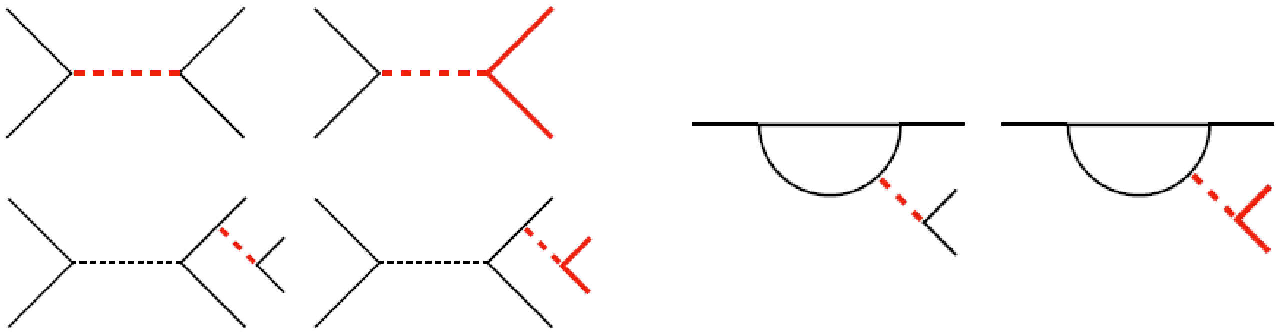
Dark Sector searches

Collider strategies

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

Two strategies:

Direct production



Directly produced in SM particle collisions

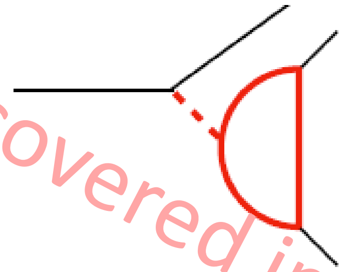
- probe mediator masses up to $\sqrt{s}$

Produced in mesons (*D, B, Υ* 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 signatures depending on:

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

Prompt decay to SM:

- visible signature -> **invariant mass bump**

Long lived:

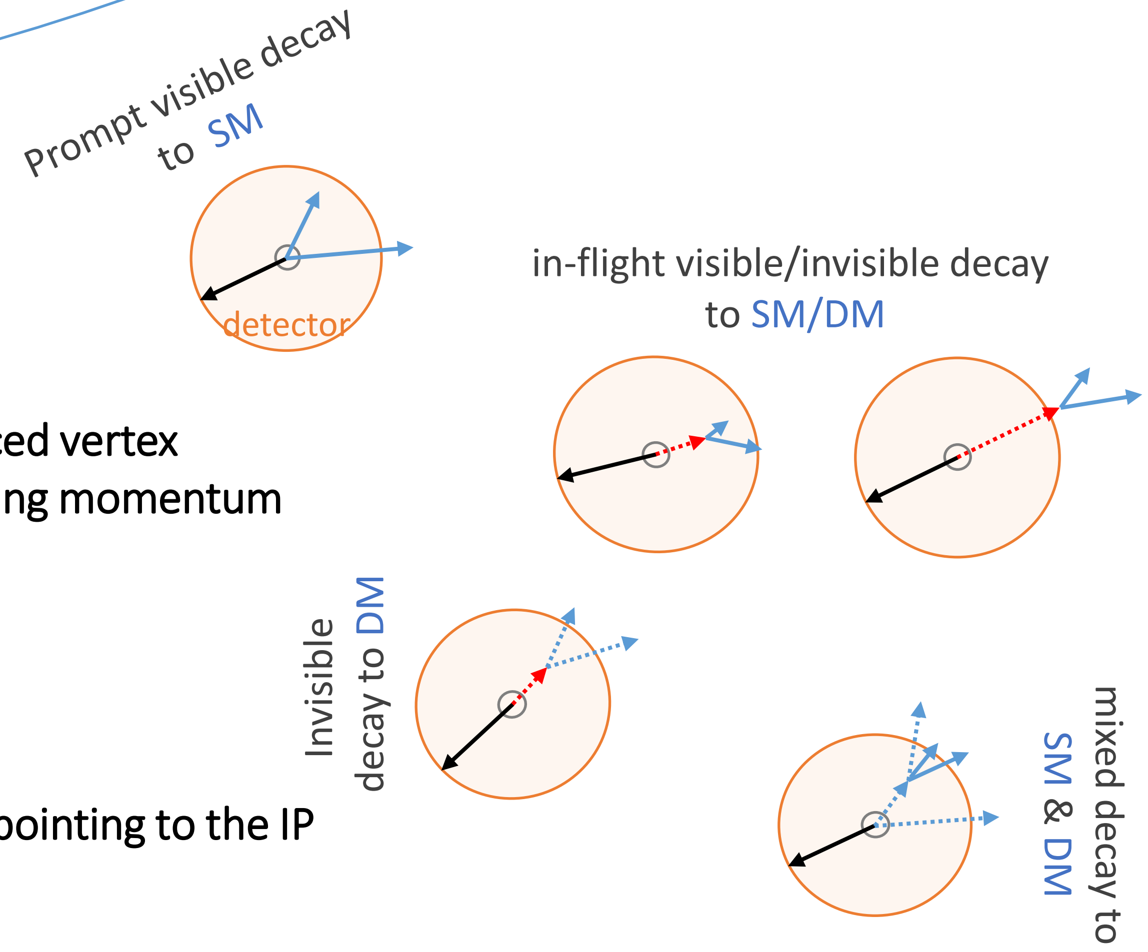
- decay-length < O(1)m: visible signature -> **displaced vertex**
- decay-length > O(1)m: invisible signature -> **missing momentum**

Decay to DM particle:

- invisible signature -> **missing momentum**

Decay to SM + DM particles:

- partially visible signature -> **displaced vertex not pointing to the IP**



LHCb and Belle II experiments

LHCb

Experiment overview

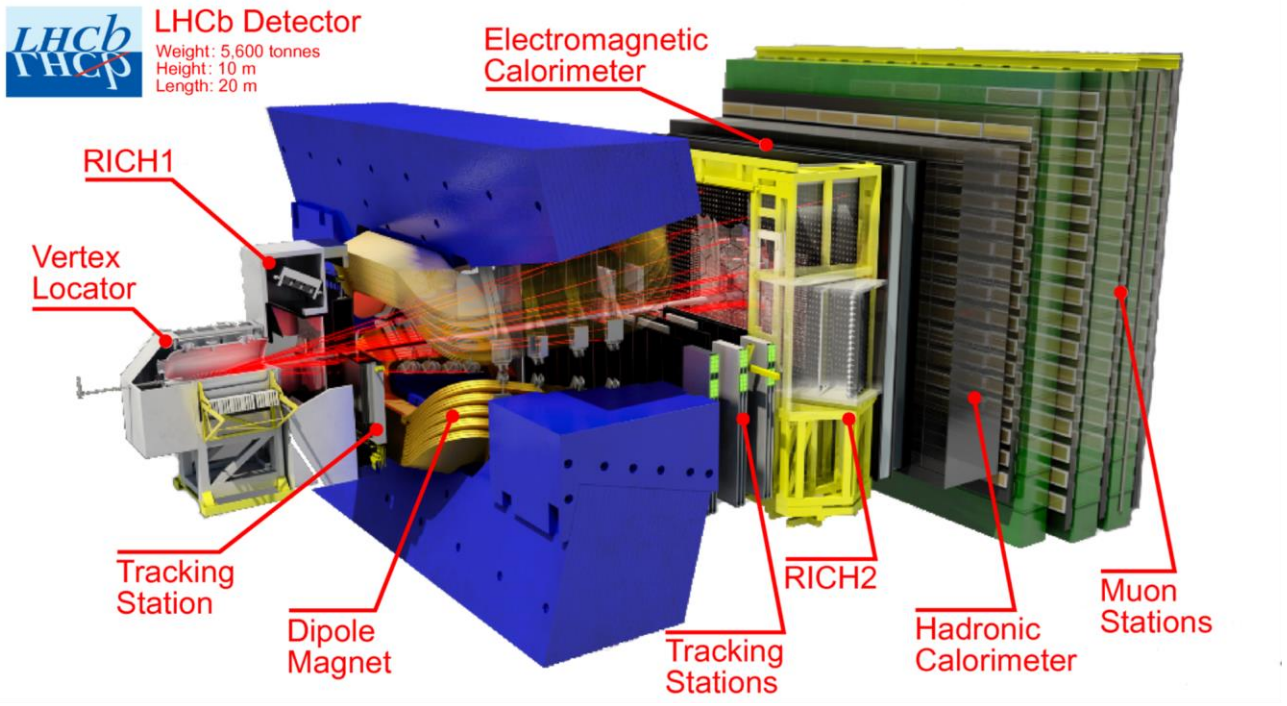
LHCb is a single-arm forward spectrometer (along the beamline) at the LHC collider:

- 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 in the forward region

Data taking:

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

vertex resolution: $10\mu m$



Track 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

Key factors for dark sector physics:

- Excellent vertexing
- Excellent momentum and mass resolution
- Good PID capabilities
- Triggers with low p^t thresholds (ex: p_μ^T > 1.5 GeV)

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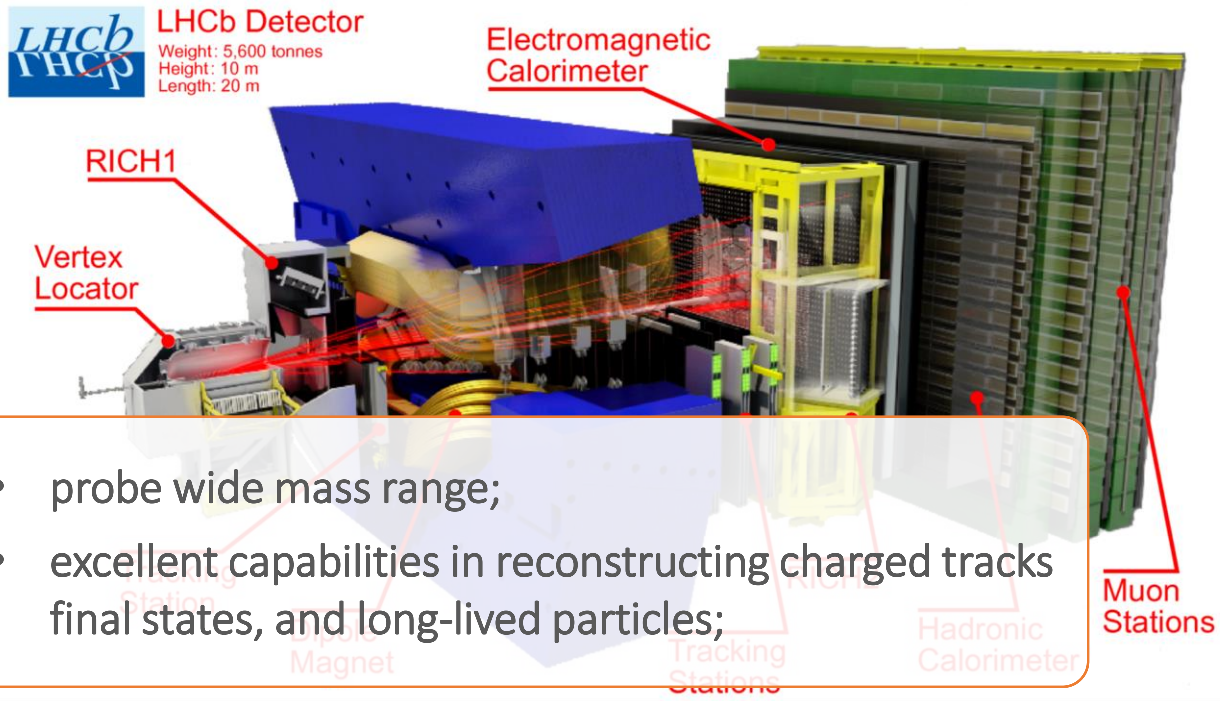

- probe wide mass range;
- excellent capabilities in reconstructing charged tracks final states, and long-lived particles;

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Belle II

Experiment overview

Belle II is a ~4π detector @ SuperKEKB collider (Tsukuba, JP):

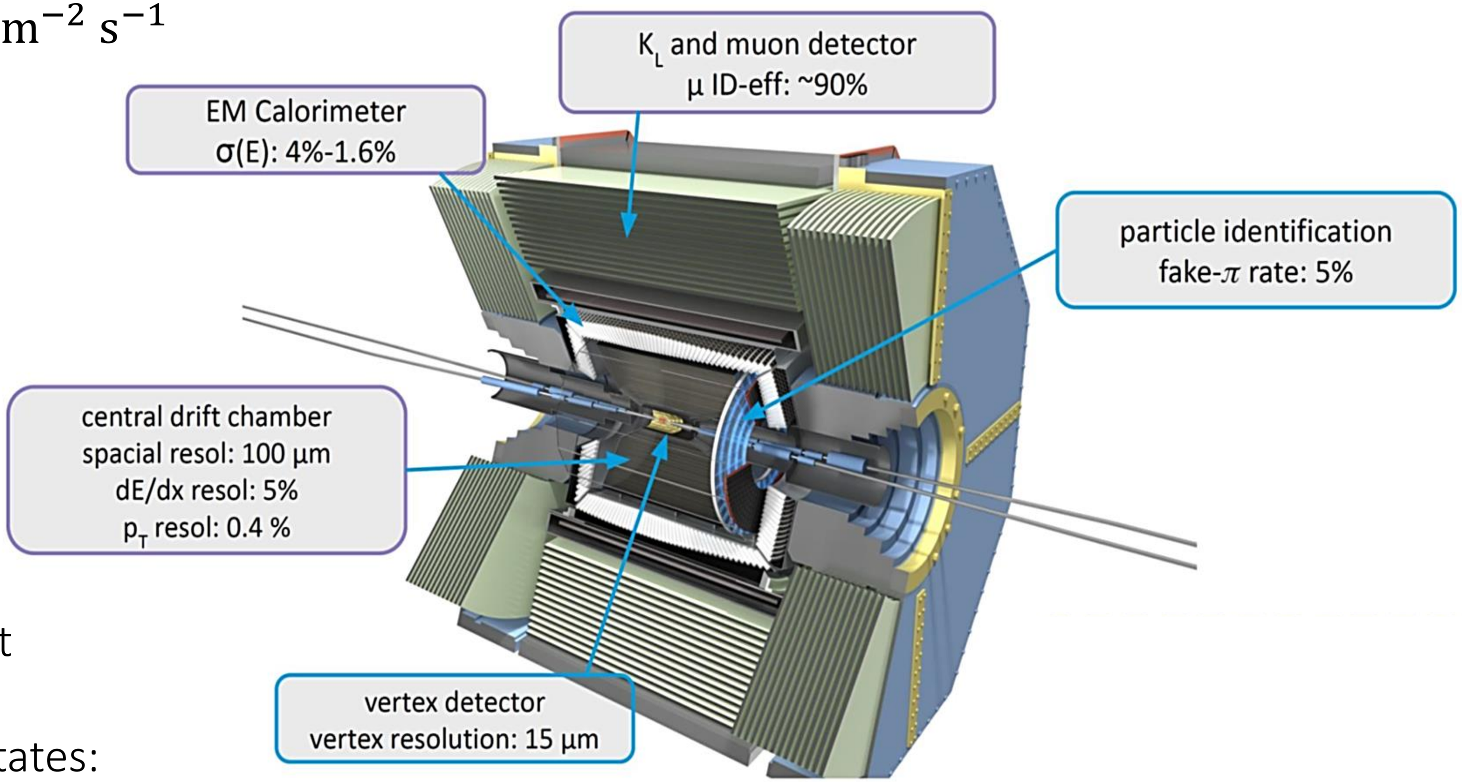
- e^+e^- collision at the $\sqrt{s} = 10.58$ GeV $(= m_{\Upsilon(4s)})$
- Asymmetric beam energies: Boosted $B\bar{B}$
- Large luminosity: world record $4.7 \times 10^{34}\ \mathrm{cm^{-2}\ s^{-1}}$
  - Final goal is ~$6 \times 10^{35}\ \mathrm{cm^{-2}\ s^{-1}}$

Data taking:

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

Key factors for dark sector physics:

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



Prog. Theo. Exp. Phys. 12 (2019)

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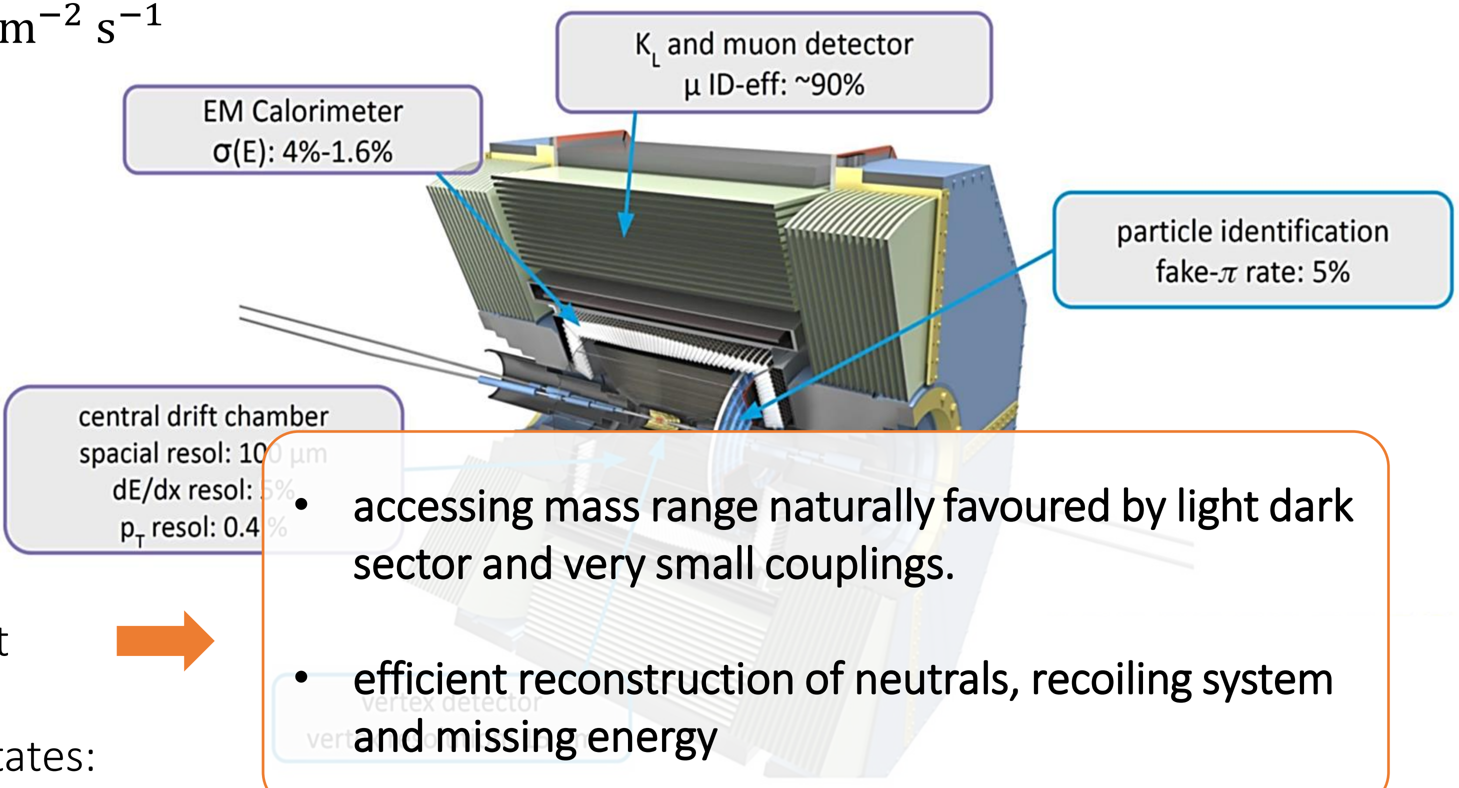


- accessing mass range naturally favoured by light dark sector and very small couplings.
- efficient reconstruction of neutrals, recoiling system and missing energy

Prog. Theo. Exp. Phys. 12 (2019)

Dark sector searches results

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

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

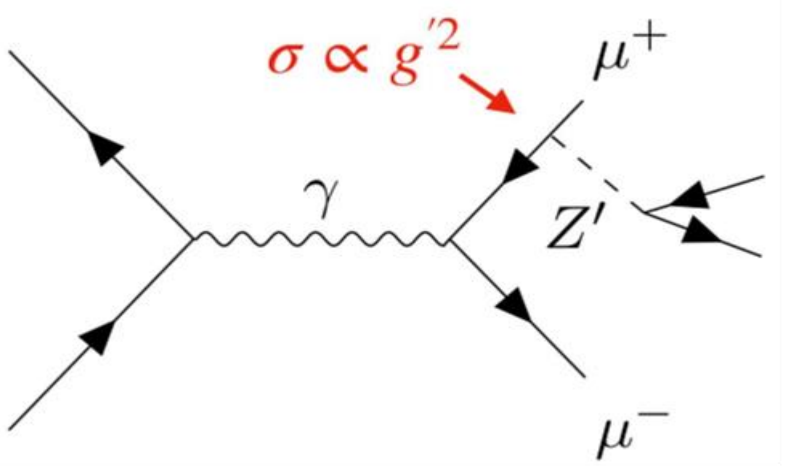
Phenomenology

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)

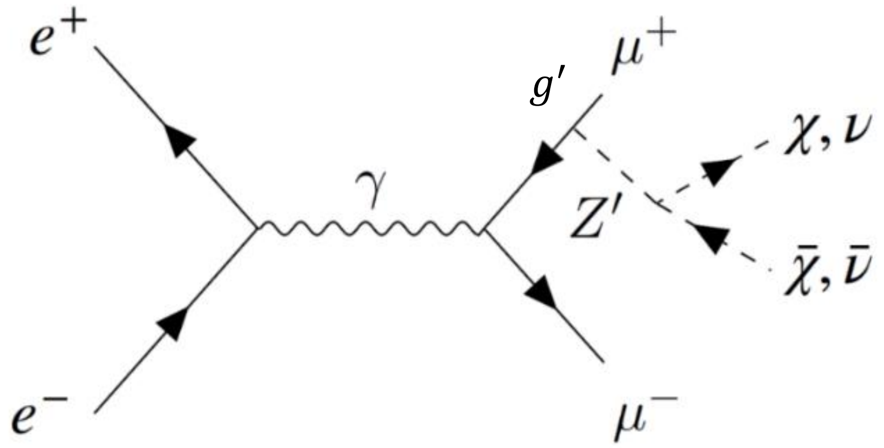
Invisible Z’ @ Belle II

Strategy

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

- 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 $\boldsymbol{\mu\mu(\gamma), \tau\tau, ee\mu\mu}$

Analysis selection in short:

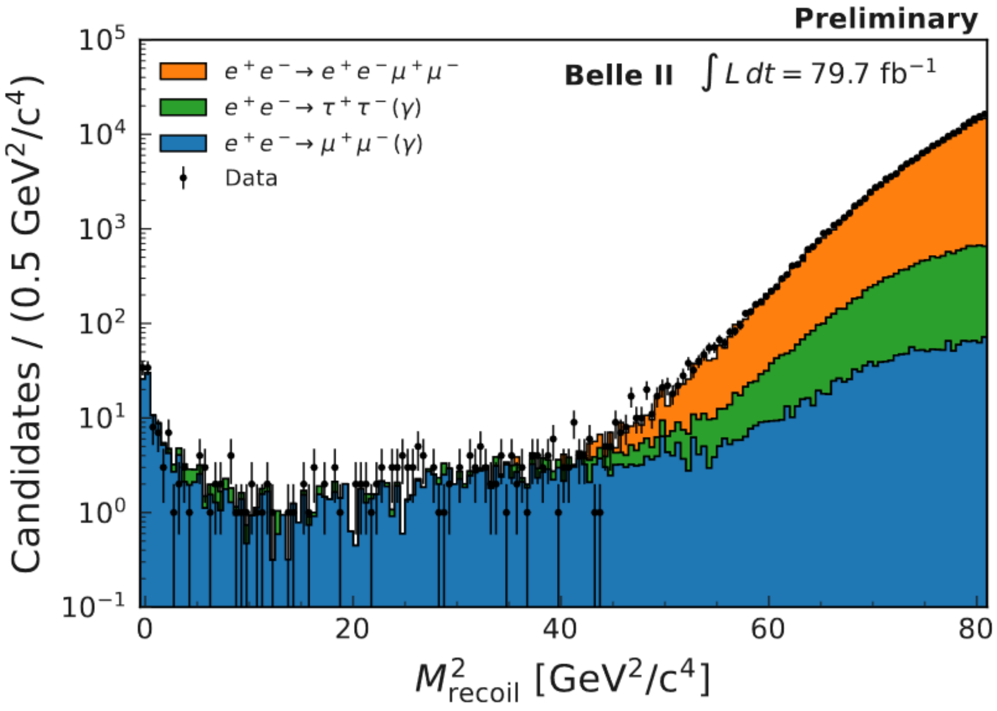
- Two opposite sign muon tracks; $p_T^{\mu\mu} > 0.1$ GeV/c
- Recoil points to barrel calorimeter ($M_{\text{recoil}} < 2$ GeV)
- Low activity in the calorimeter; γ veto
- Neural-Network exploiting FSR nature of Z’ production Eur.Phys.J.C 82 (2022) 2, 121

Invisible Z' @ Belle II

Results

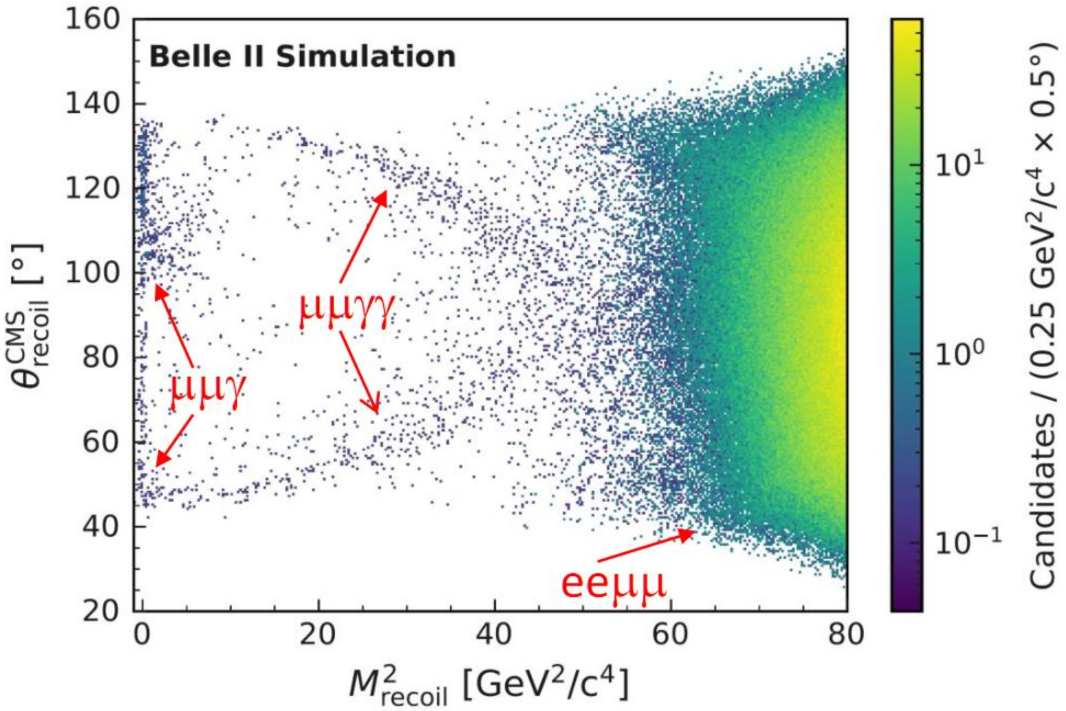
Background composition:

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



Search strategy:

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



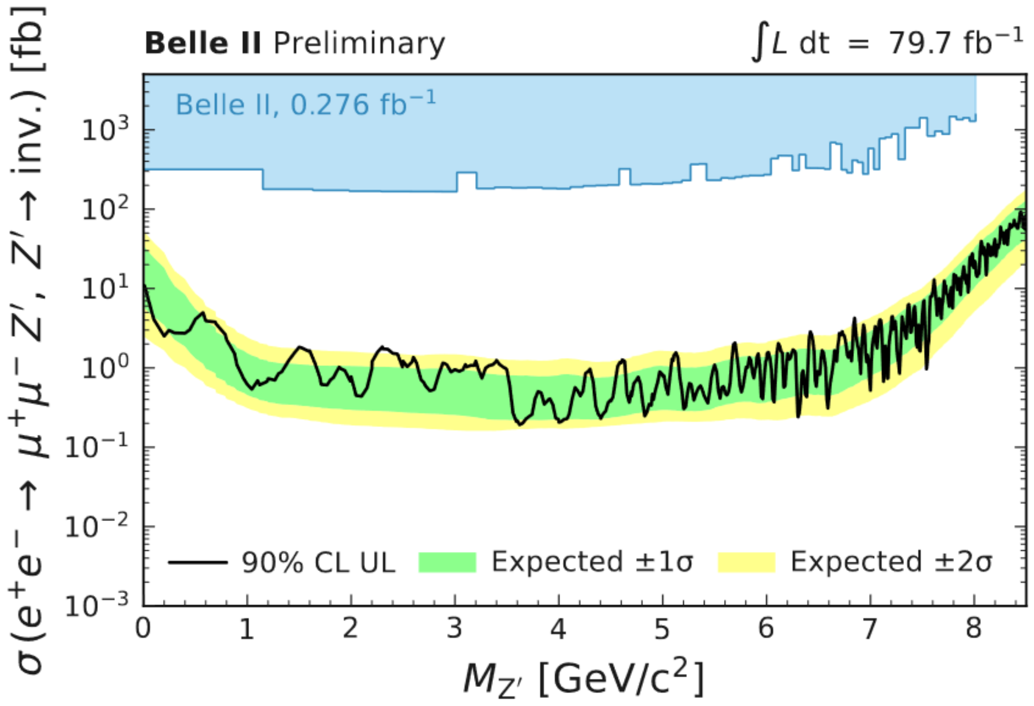
Invisible Z’ @ Belle II

Results

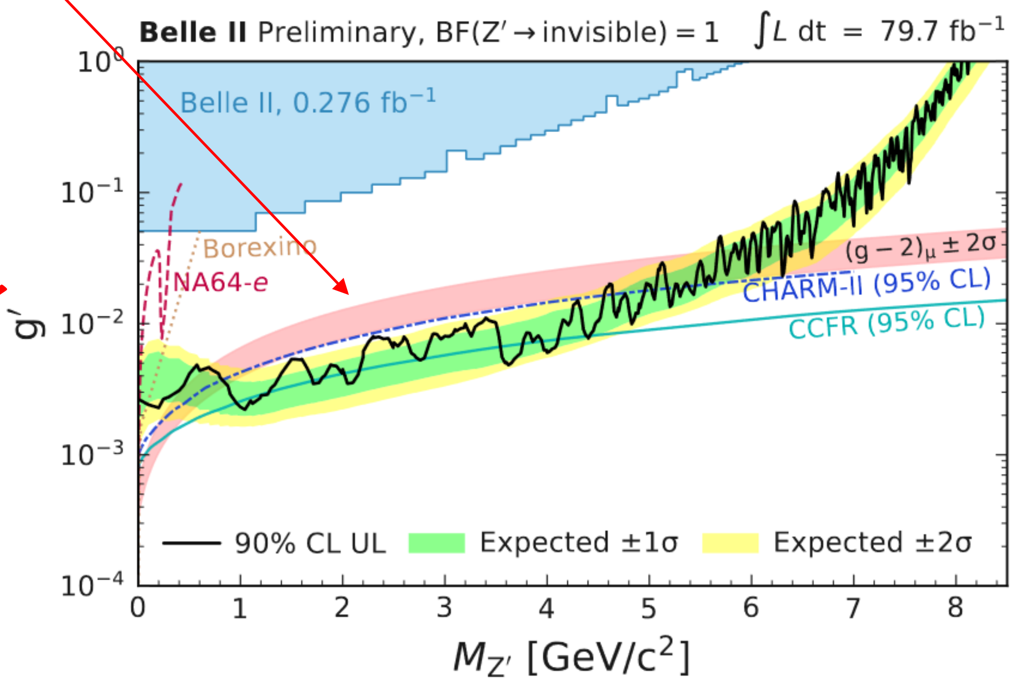
No significant excess over the expected background

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 $(\mathbf{g}-\mathbf{2})_{\mu}$ anomaly for $0.8 < M_{Z'} < 5$ GeV/c^2



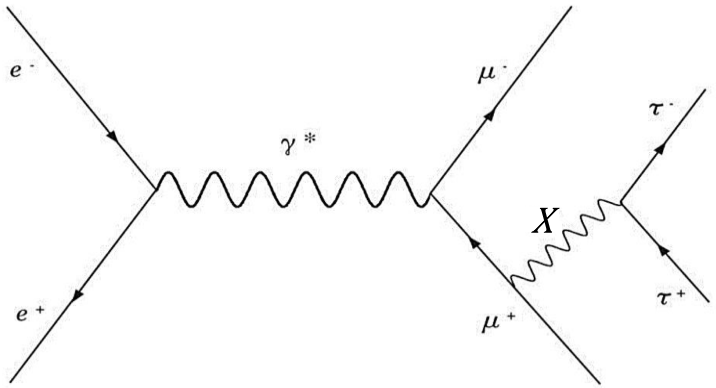
new



Search for $X \to \tau^+\tau^-$ in $\mu^+\mu^-\tau^+\tau^-$ events @ Belle II

$e^+e^- \to \mu^+\mu^- X,\ \ X \to \tau^+\tau^-$: first time search.

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



More details in the talk by G. De Pietro

Signature:

- A peak in the recoil mass distribution against two muons

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

- Leptophilic scalar S
- Axion-like-particle

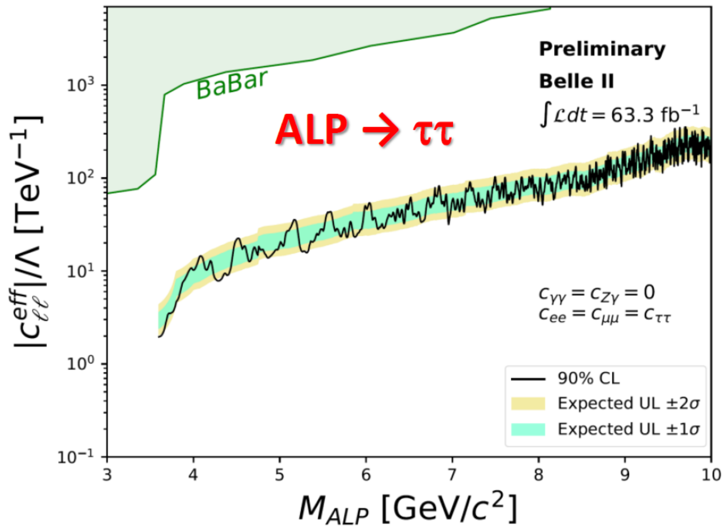
Scalar and pseudo-scalar portals

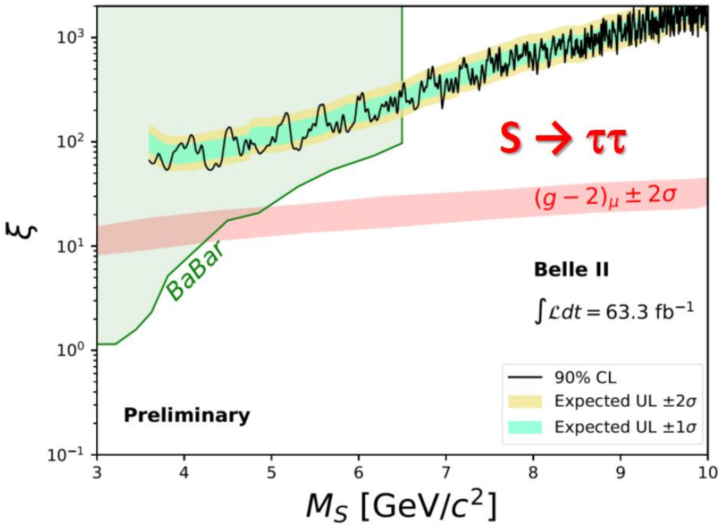
new

No excess found

Set 90% CL UL on σ and couplings:

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





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]

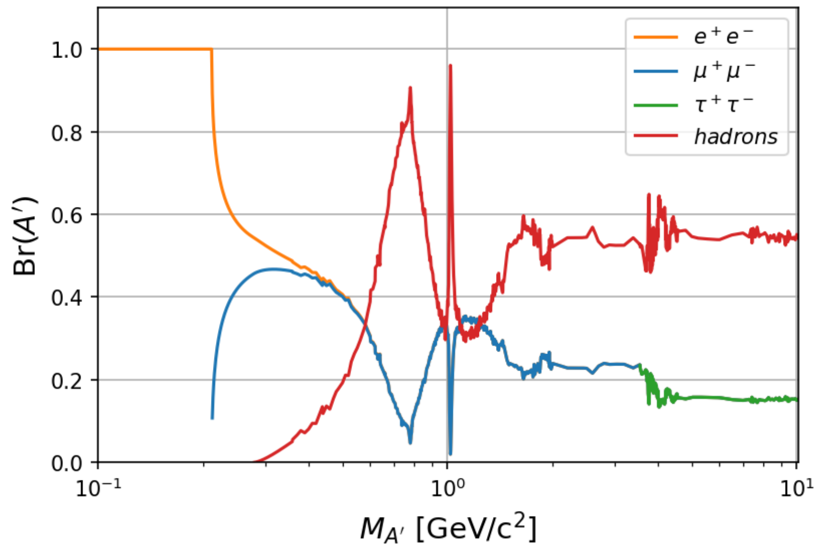
Vector portal

Several possible production mechanisms:

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

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

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



Dark photon lifetime proportional to $1/(\epsilon^2 m_A')$

Dark Photon @LHCb

Visible decay

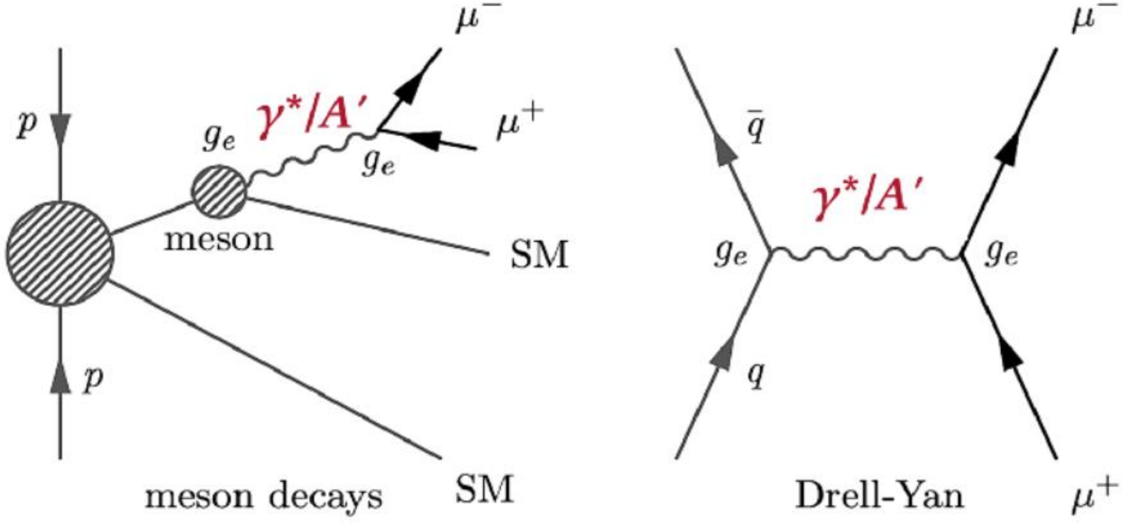
Search for $A' \to \mu^+\mu^-$:

- 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 γ:
  - m(A')<1 GeV: Meson decays
  - m(A')>1 GeV: Drell-Yan



General strategy: bump hunt search on di-muon mass

- Prompt-like search (up to 70 GeV/c^2)
- displaced search (214-350 MeV/c^2)

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**

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

Off-shell photon

Need to separate non γ^* background

Phase space

Efficiency ratio A'/γ^*

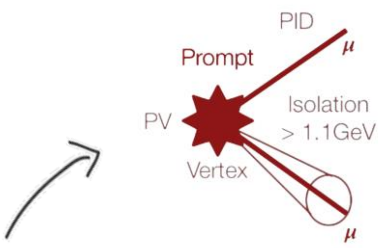
$\epsilon = 1$ **for prompt decays**

Non-trivial in displaced case due to γ conversion veto

Dark Photon @LHCb

Prompt decay results

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



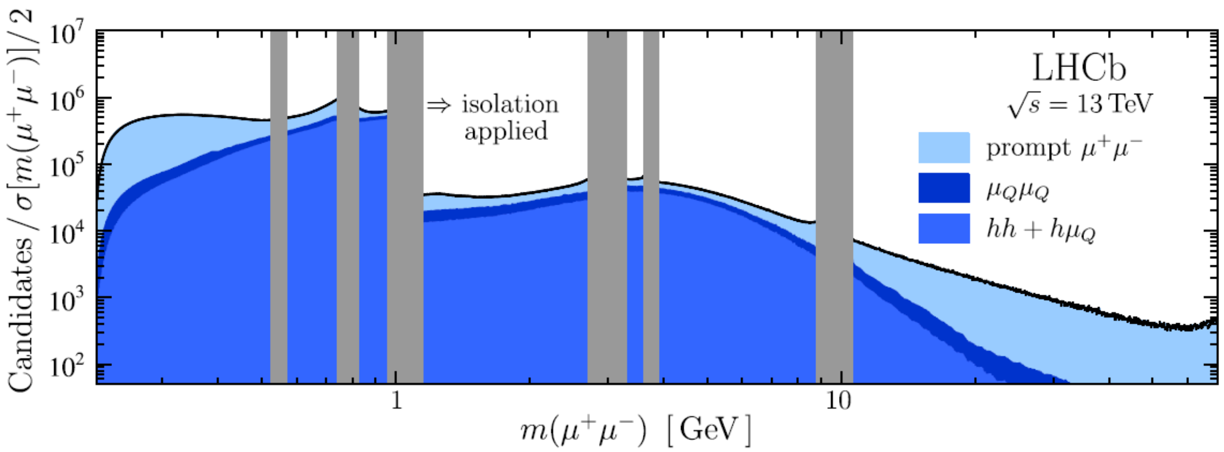
Strategy:

- 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

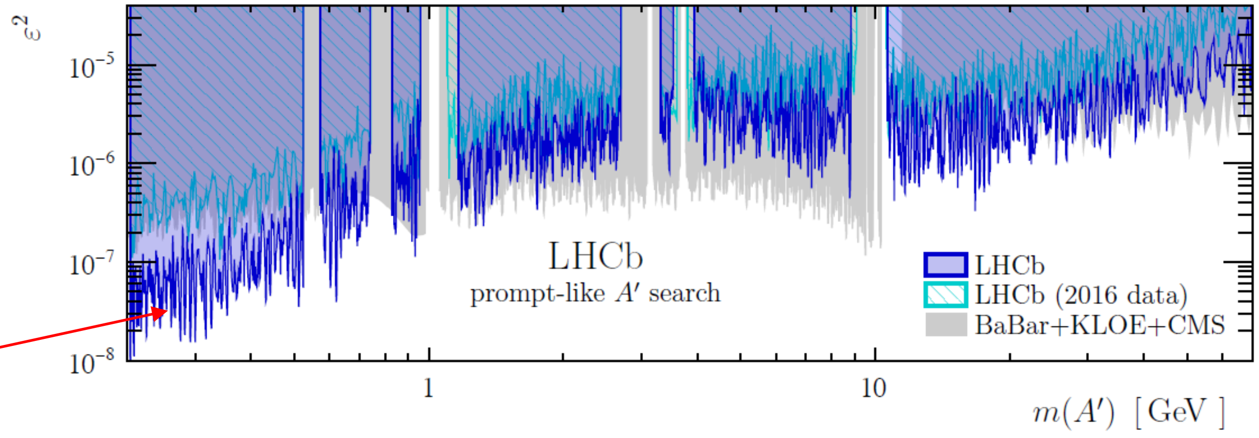
*validated on $m(\phi)$ and $m(\Upsilon(1S))$



No significant excess found

90% CL UL on ϵ^2

- Most stringent limits for $214 < m_{A'} < 740$ MeV/c^2 and $10.6 < m_{A'} < 30$ GeV/c^2



Dark Photon @LHCb

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

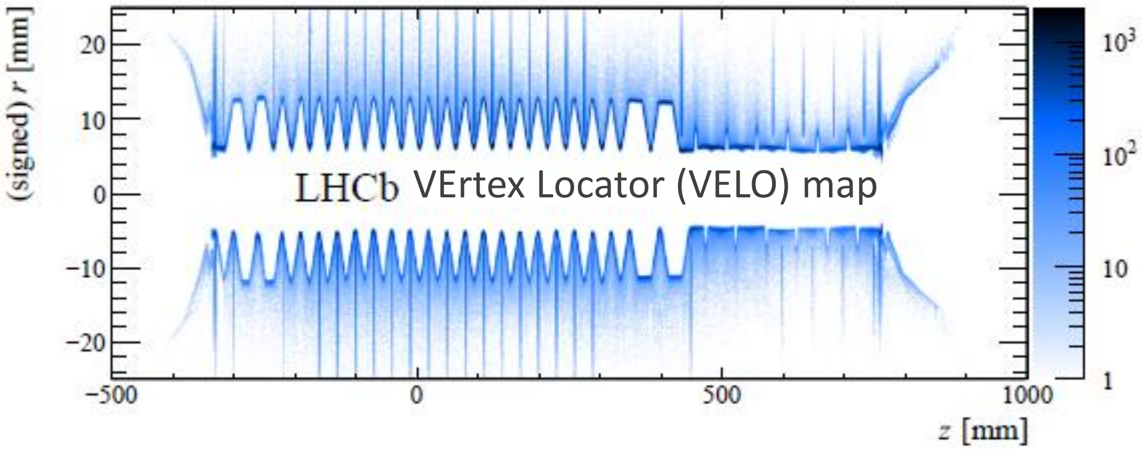
Displaced decay results

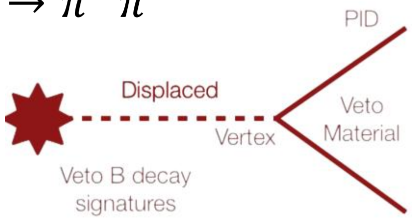
Currently only within the VELO: max displacement < 20 cm

Main background:

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

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





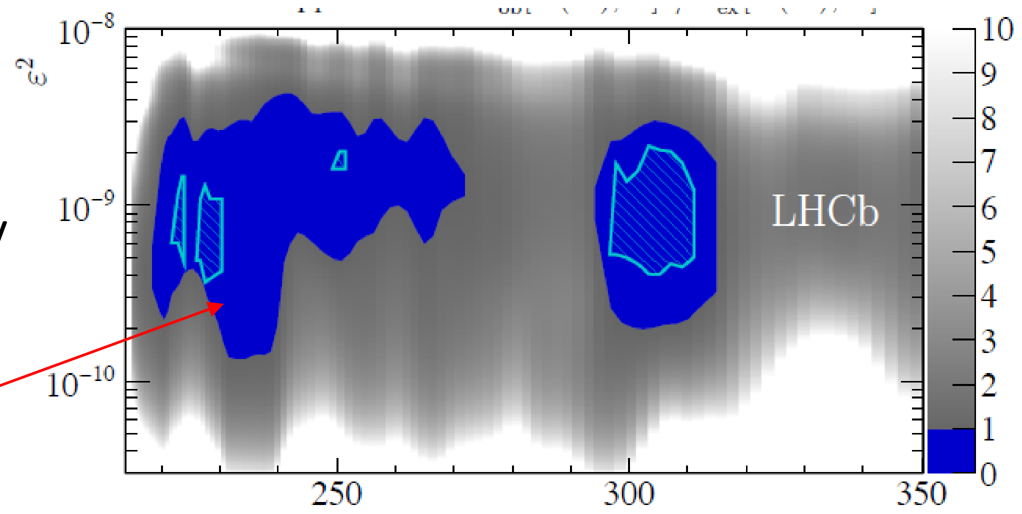
Use simulation to find relative A′/γ∗ decay-time inefficiency

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

No significant excess found

90% CL UL on ϵ^2

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



Regions less than unity are excluded.

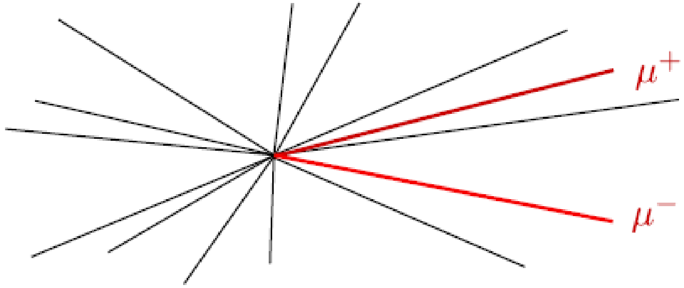
Inclusive $X \to \mu^+\mu^-$ search @LHCb

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

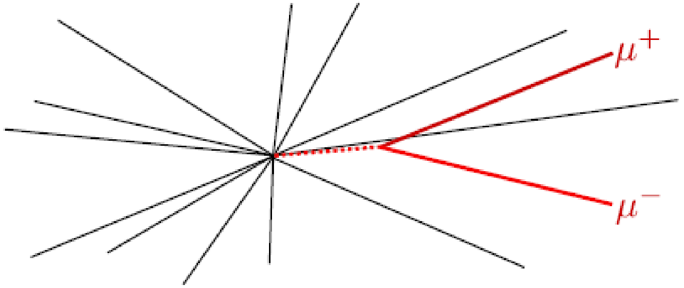
Strategy:
- Minimize assumptions on production;
  - **drop kinetic mixing assumption with γ***
- Obtain results in bins of mass and p^T

Prompt, inclusive

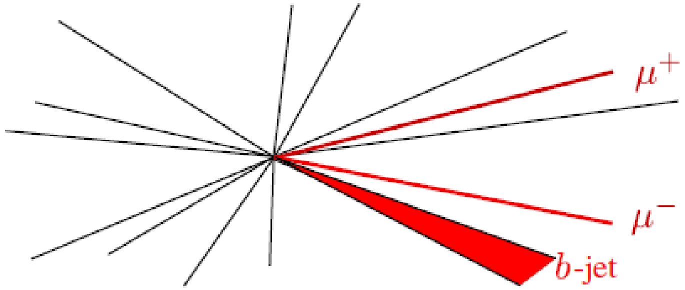


- No isolation requirements
- Non-zero width considered

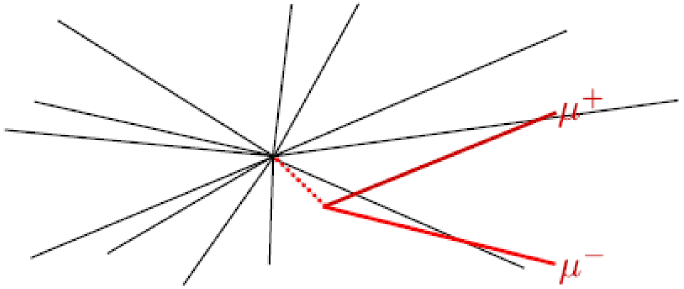
Displaced (prompt source)



Prompt + b—jet



Displaced (non-prompt source)



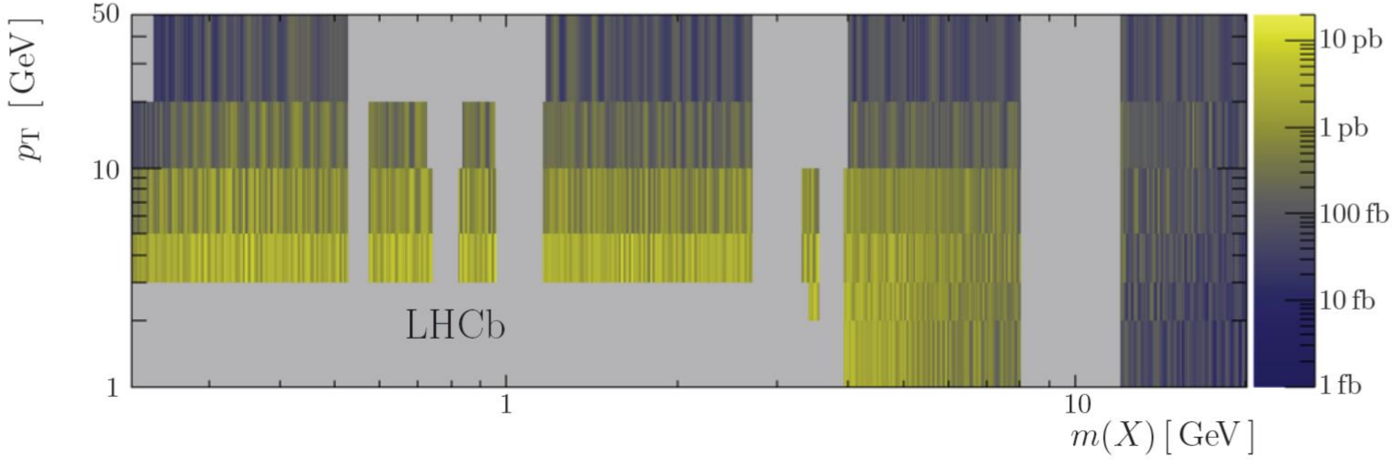
Inclusive $X \to \mu^+\mu^-$ search @LHCb

Results

JHEP 10 (2020) 156

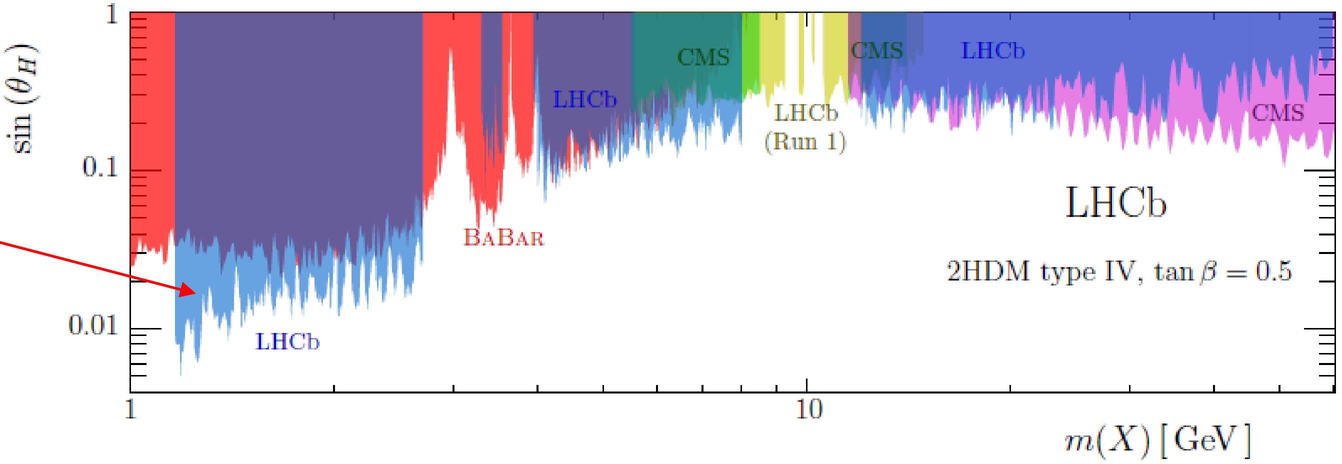
No excess found

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))

- world-best upper limit on X mixing angle with SM Higgs θ_H



Dark Higgsstrahlung searches

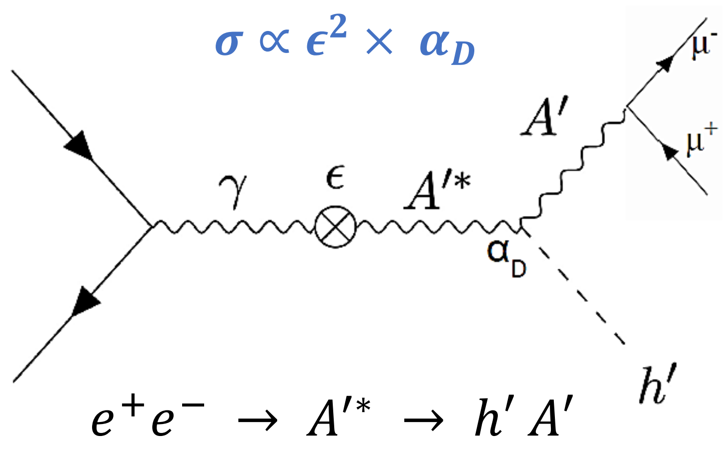
Introduction

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]:

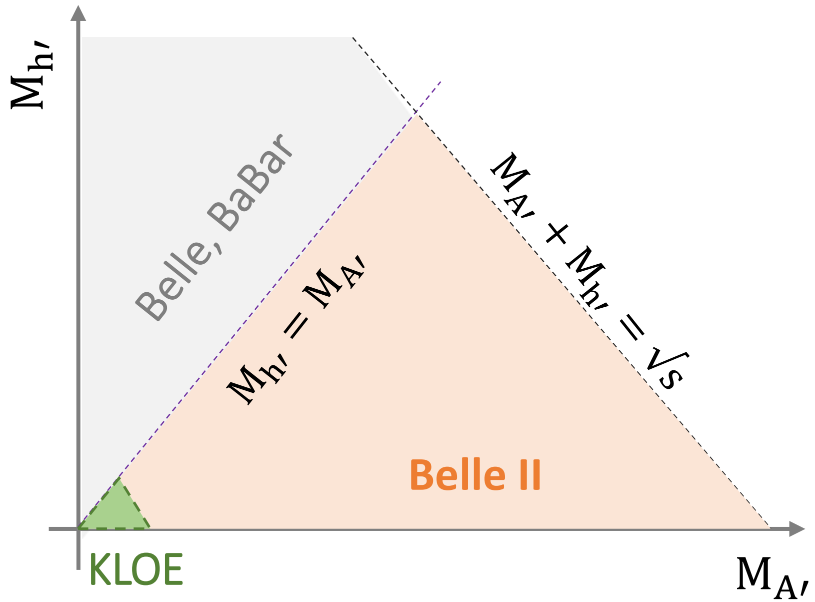
Both the particles (A', h') can be produced at an $e^+ e^-$ collider via the **dark Higgsstrahlung** process.



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)
- $M_{h'} < M_{A'}$:
  - h' is long-lived -> invisible.
  - Signature: two tracks and missing energy
  - Probed by KLOE(2015).

Investigated by Belle II



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

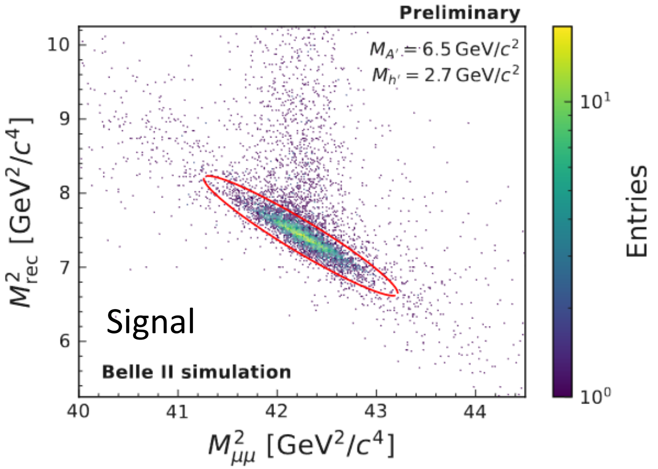
Dark Higgsstrahlung @ Belle II

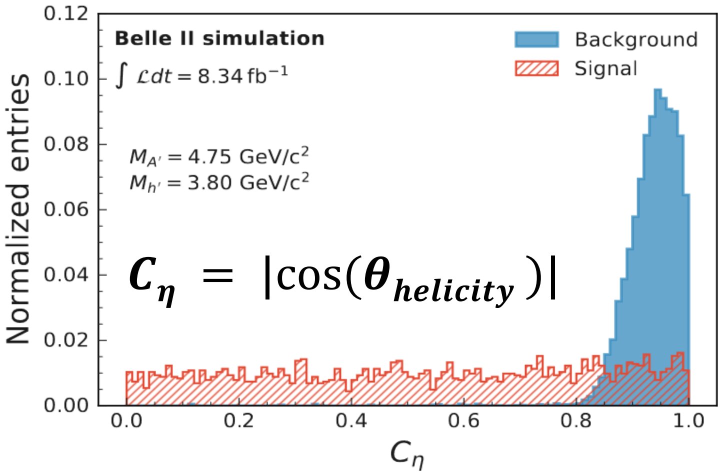
Strategy

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

Signature:

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



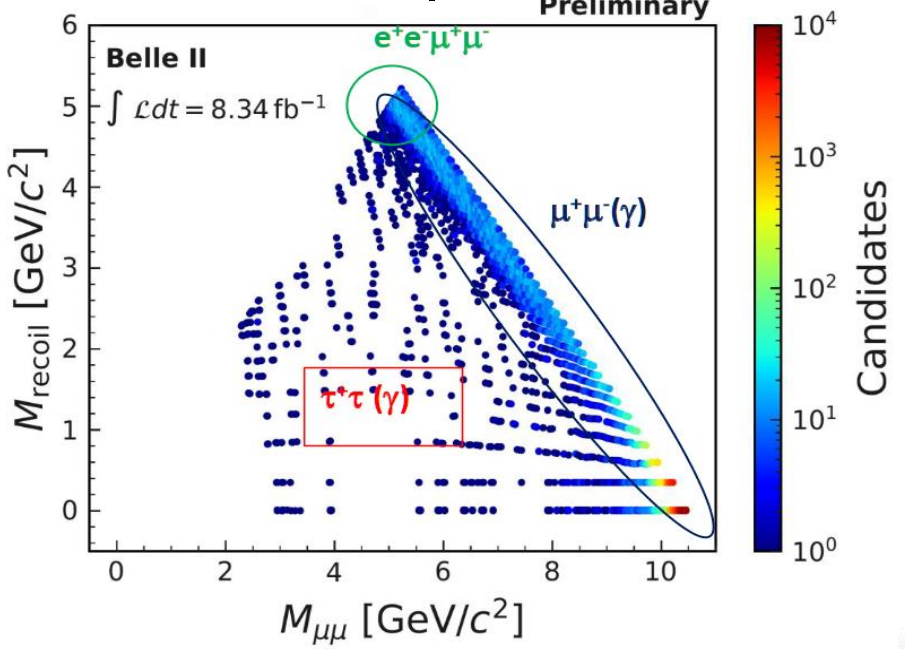


Backgrounds mainly due to $\mu\mu(\gamma), \tau\tau, ee\mu\mu$

Analysis in short:

- Two 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
  - $C_\eta = |\cos(\theta_{helicity})|$ flat for signal, peak at 1 for bkg

Observed yields



Dark Higgsstrahlung @ Belle II

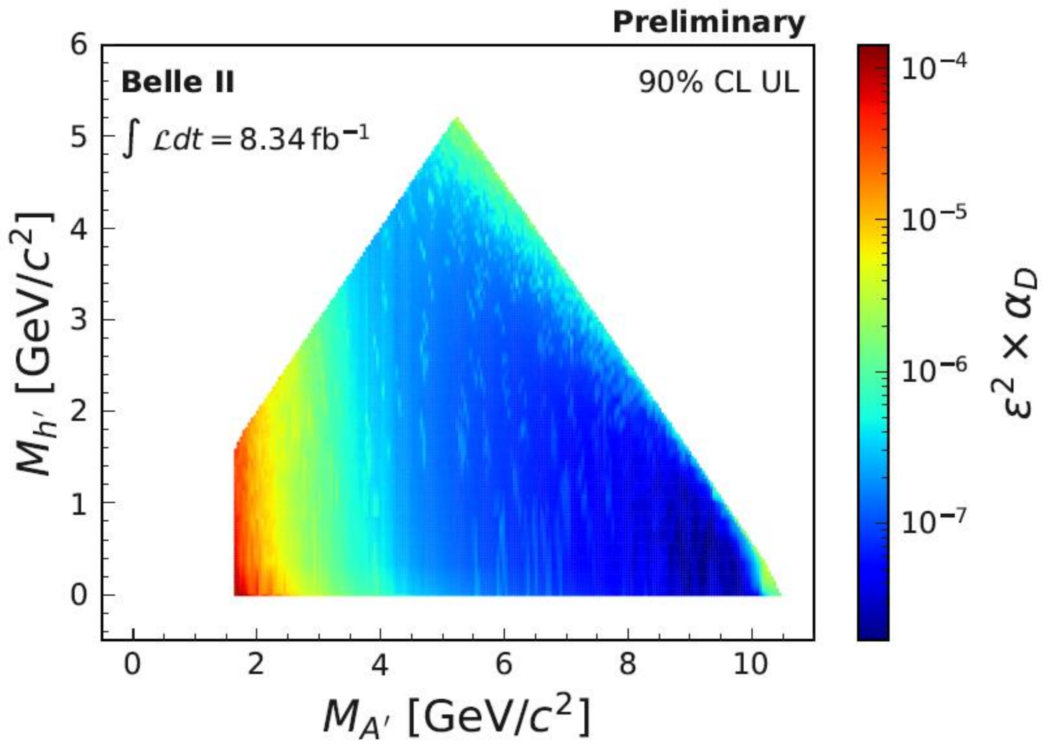
Results

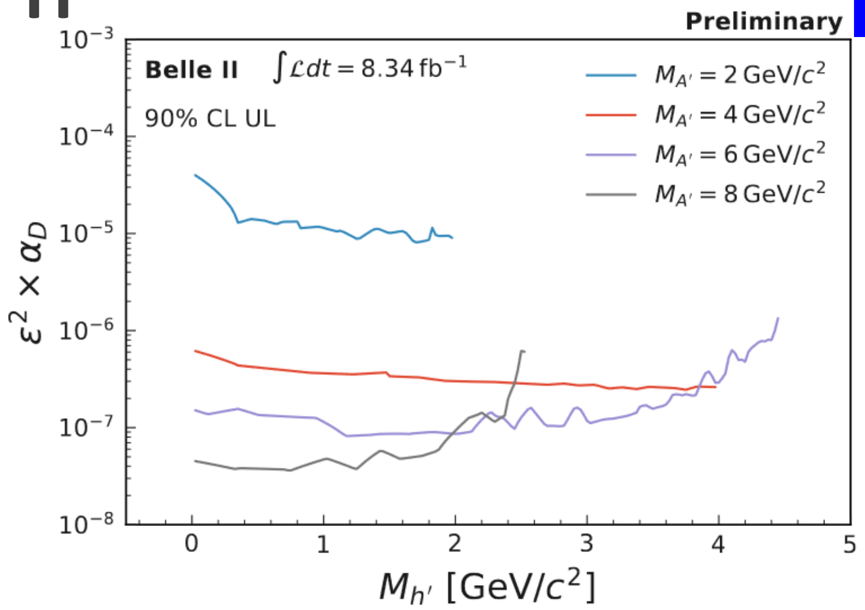
Submitted to PRL
ArXiv: [2207.00509](https://arxiv.org/abs/2207.00509)

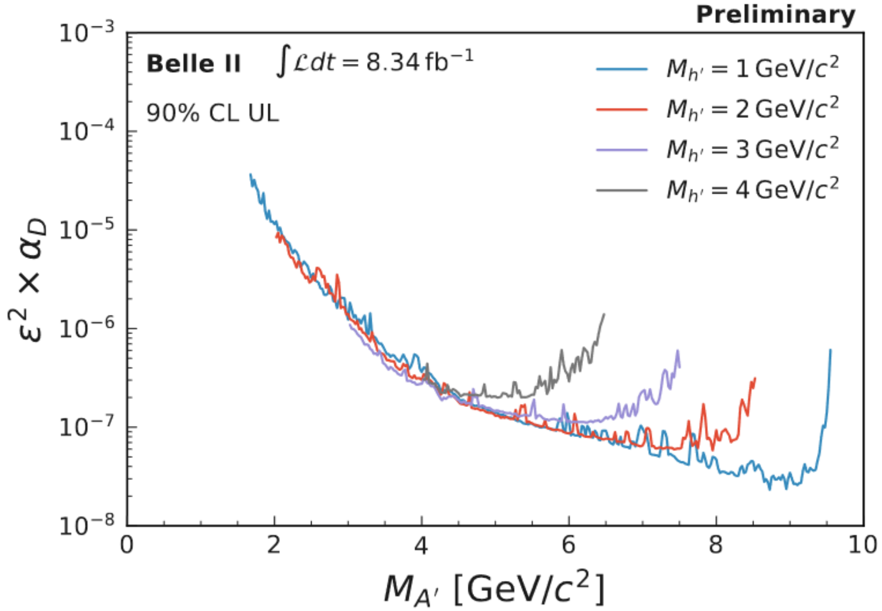
No significant excess observed
90% CL UL on σ and $\epsilon^2 \times \alpha_D$

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







Dark bosons in b → s @LHCb

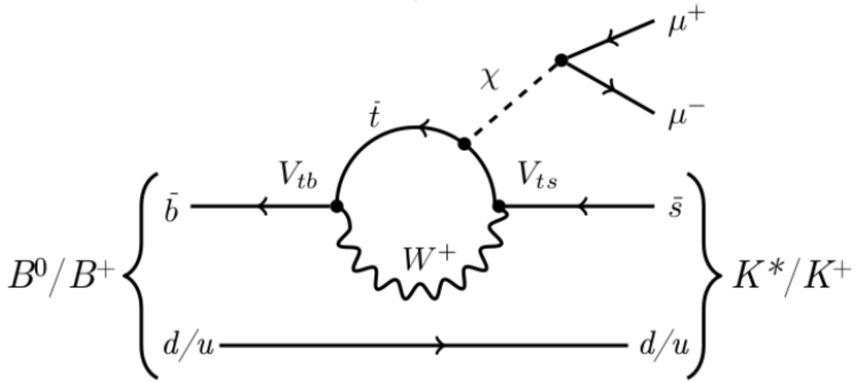
Strategy

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)]

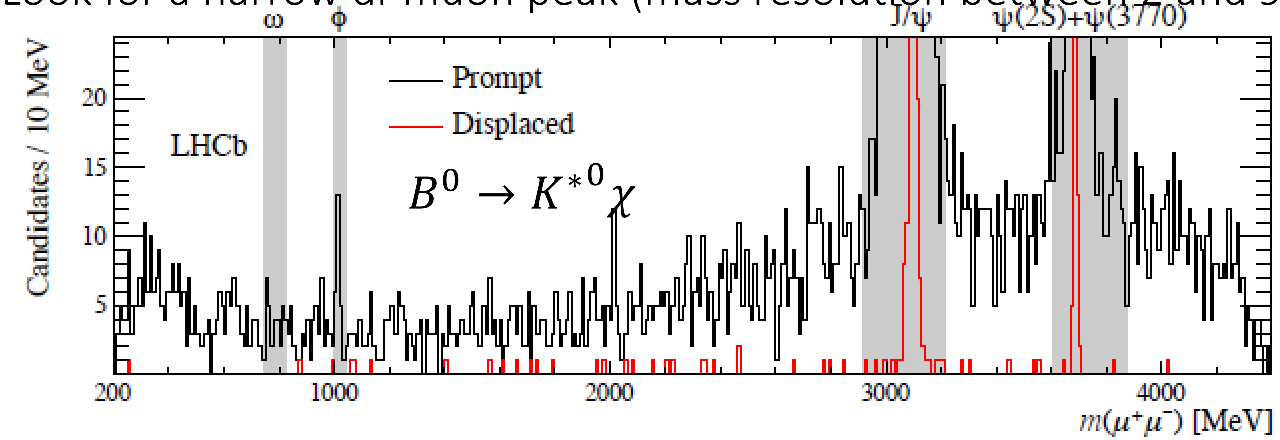


Scalar (Higgs) portal (χ as inflaton)
https://doi.org/10.1007/JHEP05%282010%29010

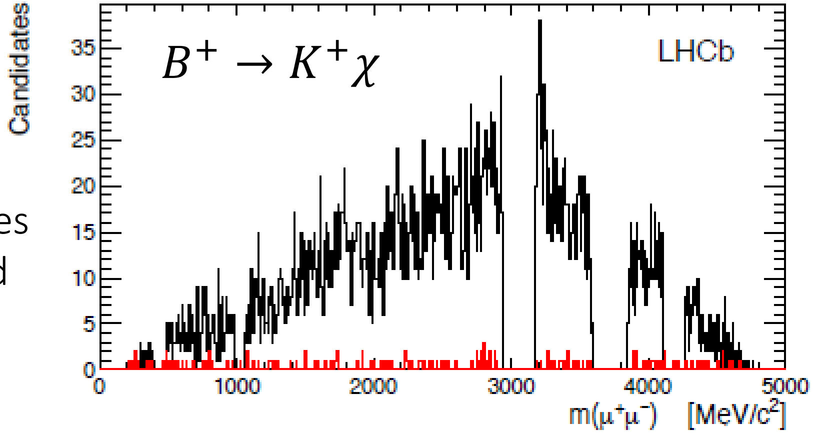
- Rate and lifetime controlled θ mixing angle with SM Higgs

$\tau \propto 1/\theta^2$ $\quad \mathcal{B}(B^+ \to K^+\chi) \propto \theta^2$

Allow for prompt and detached di-muon candidates
Look for a narrow di-muon peak (mass resolution between 2 and 9 MeV/c^2).



Known resonances removed



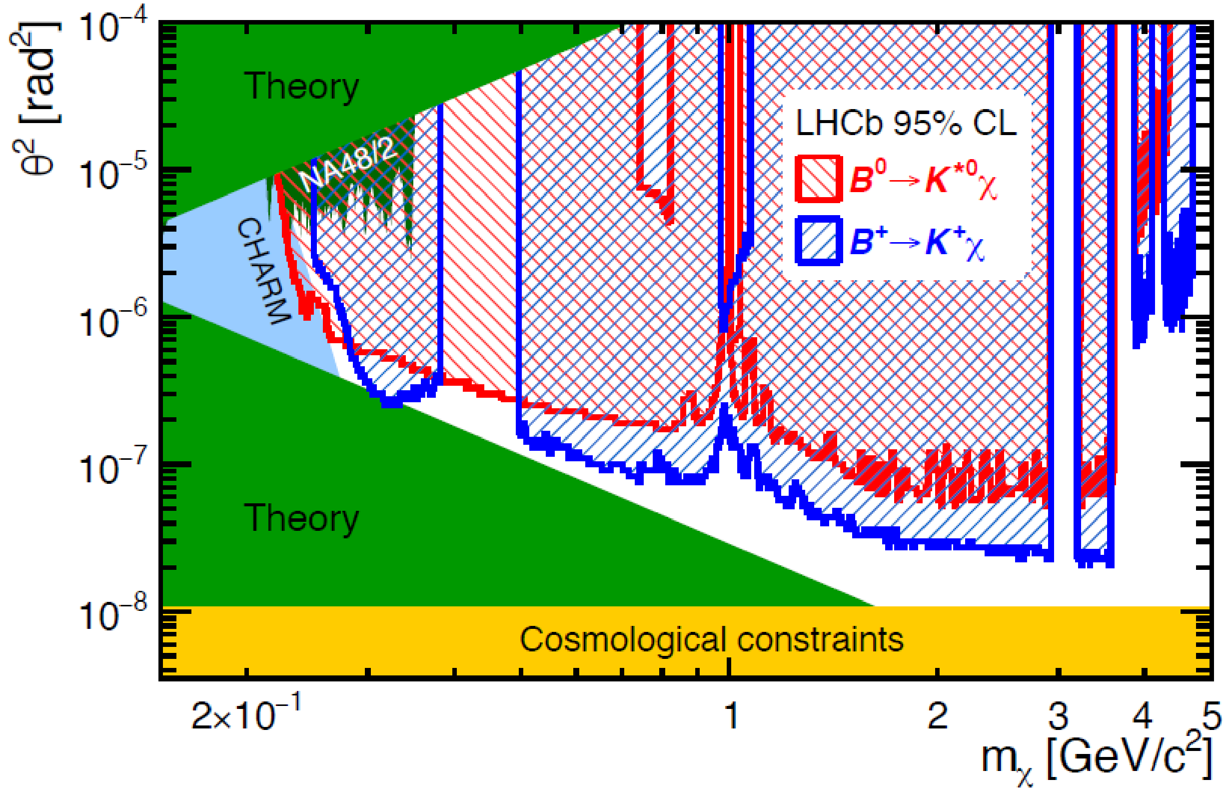
Dark bosons in b → s @LHCb

Strategy

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

No evidence for a signal
Constraints on mixing angle θ^2 between the Higgs and χ in the inflaton model

- Large fraction of allowed inflaton parameter space ruled out.



Future prospects

some highlights

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

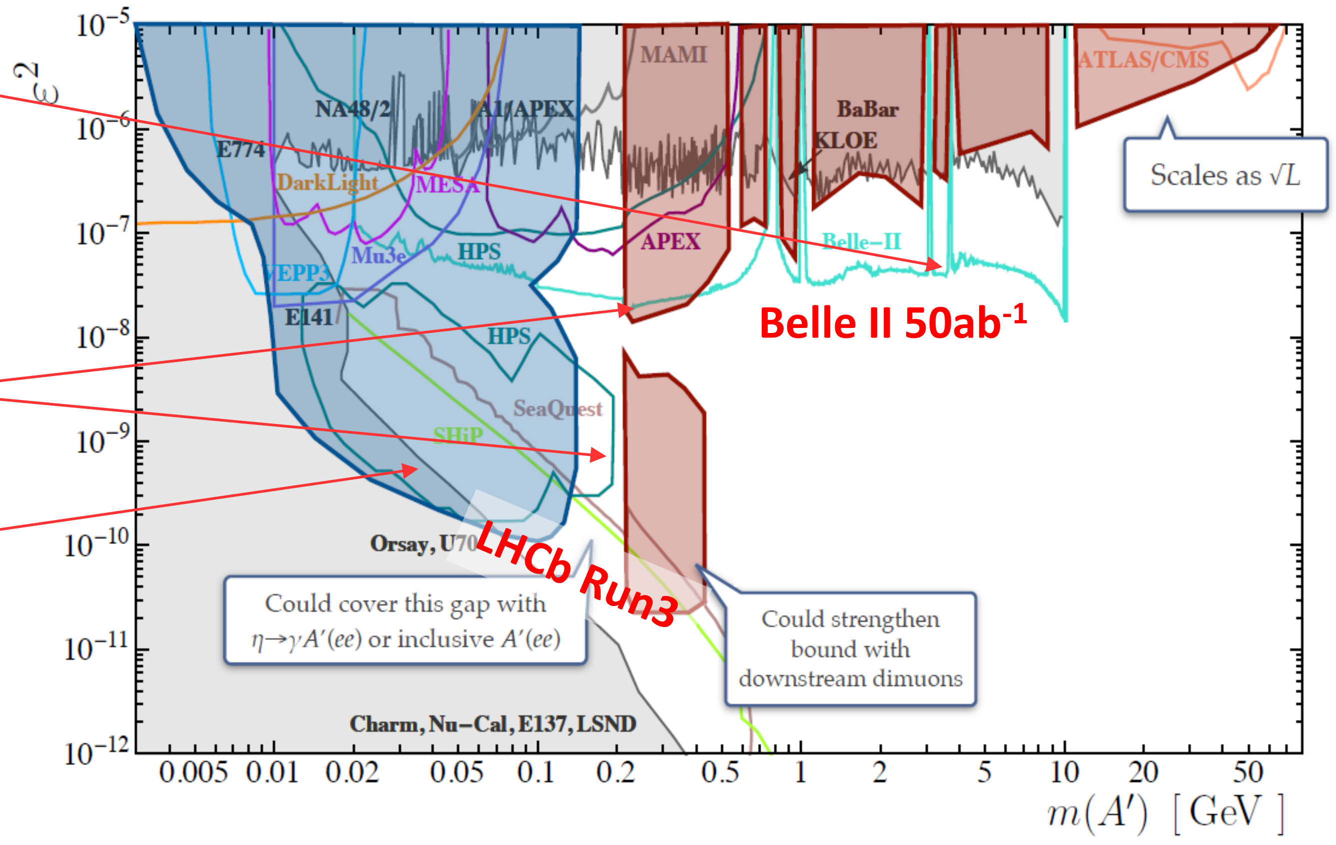
+

@Belle II: invisible dark photon search

- Expected competitive results in the short term

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

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

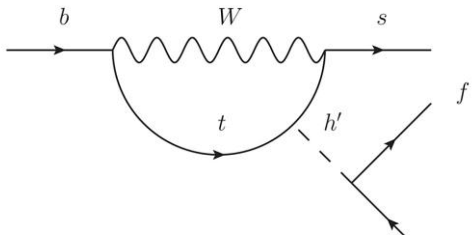


Inclusive $A' \to \mu\mu$ at LHCb
Ilten, Soreq, Thaler, Williams, Xue [1603.08926]

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

Light scalars in b → s transitions @ Belle II

Prospects



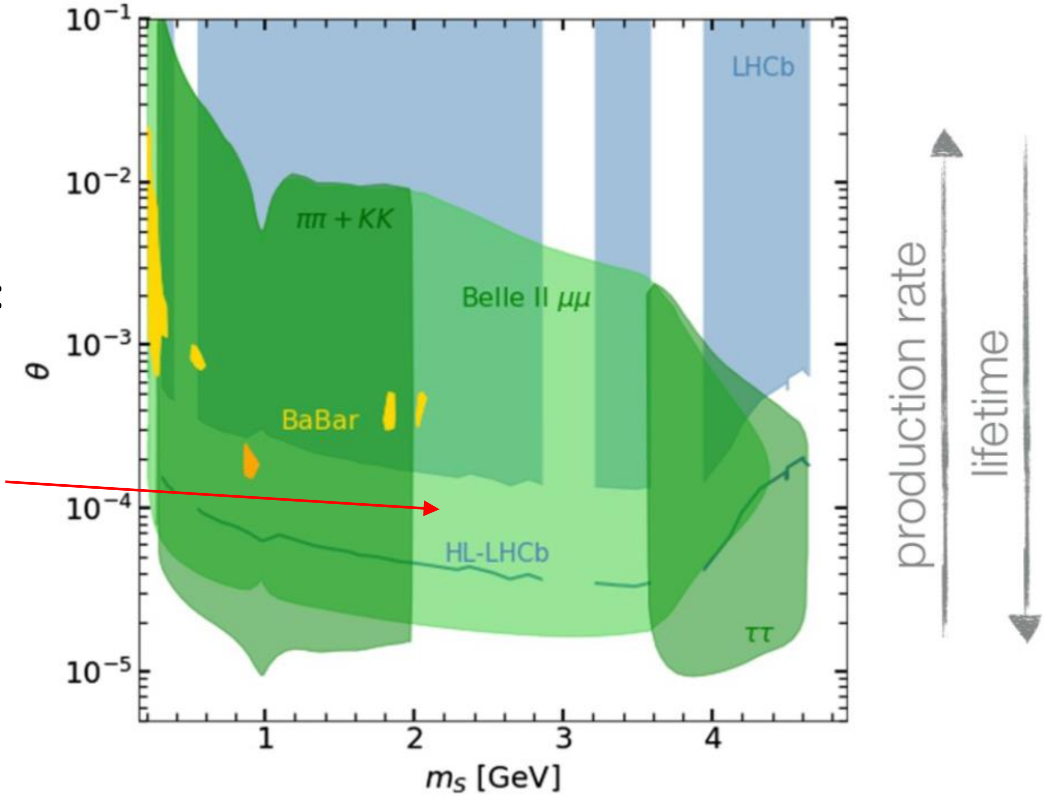
Long-lived h' produced in b → s transition

- 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

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



Exclusion regions expected with 50/ab at Belle II

Belle II can an also perform:

- B → K + invisible
- B → Ka ($a \to \gamma\gamma$)
  - Both prompt and displaced ALP decay

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 Higgsstrahlung

new

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

Highlights on future strategies:

- for LHCb
- for Belle II

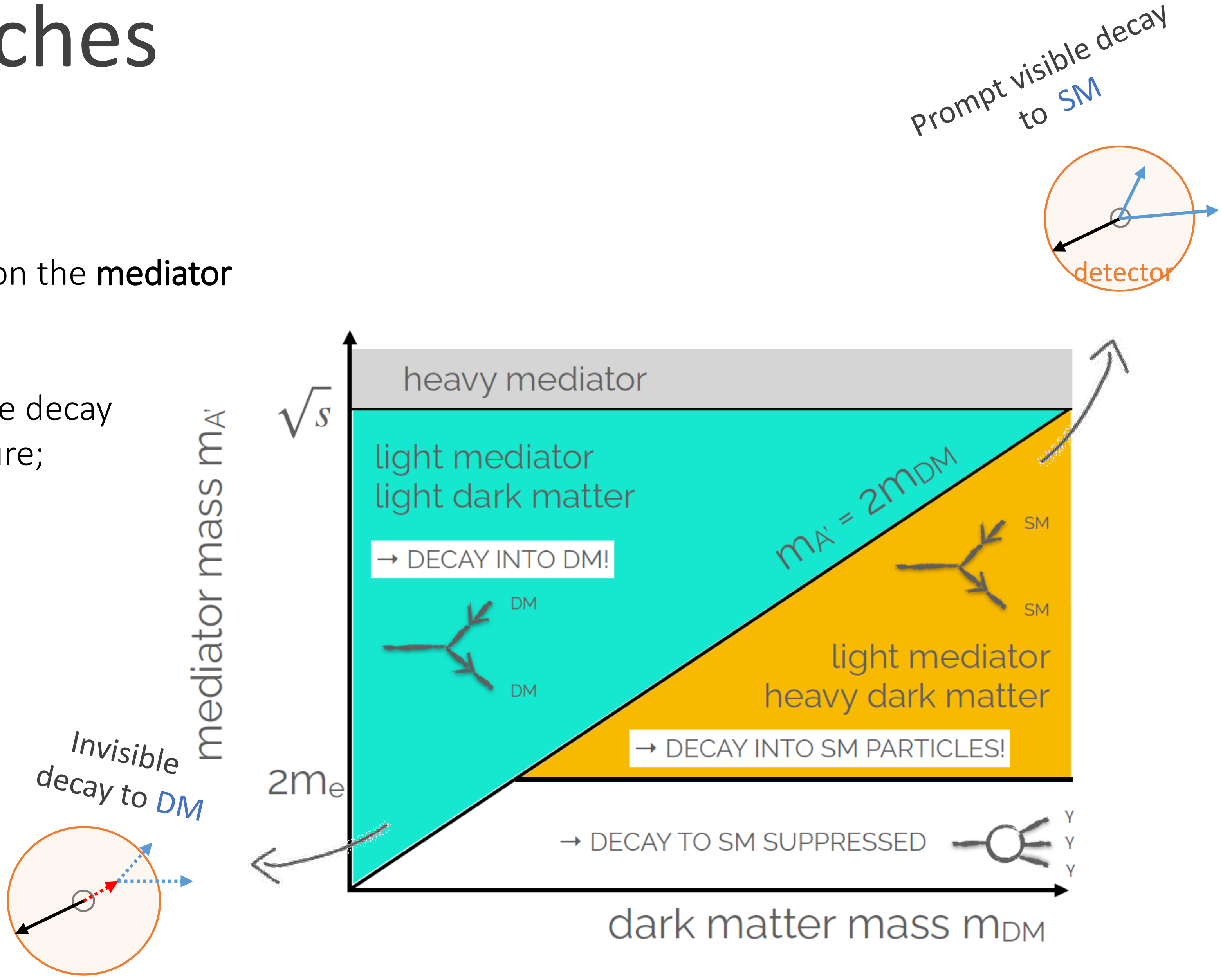
Spares

Dark Sector searches

Signatures @ colliders

Different possible topologies depending on the **mediator** and **DM candidate mass** hypothesis:

- If DM kinematically accessible: invisible decay
  - search for missing energy signature;
- If decay to SM: visible decay
  - bump hunt search;



Dark Sector searches

Signatures @ colliders

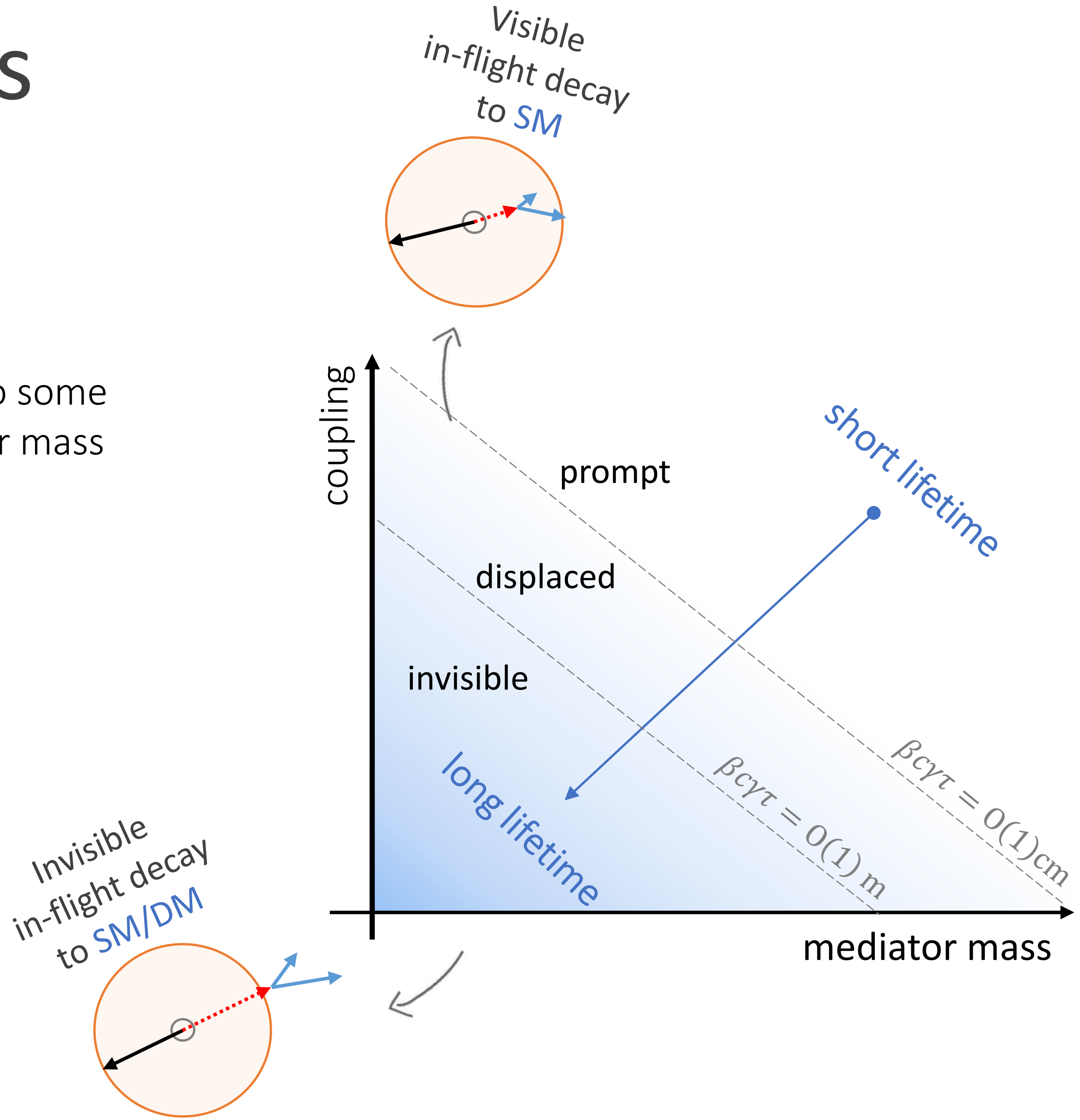
An additional player: **mediator lifetime.**

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

lifetime ⟷ decay length

If decay to SM:

- Short lifetime: prompt decay;
- Long lifetime:
  - Displaced decay vertices;
  - Decay outside the detector (invisible)

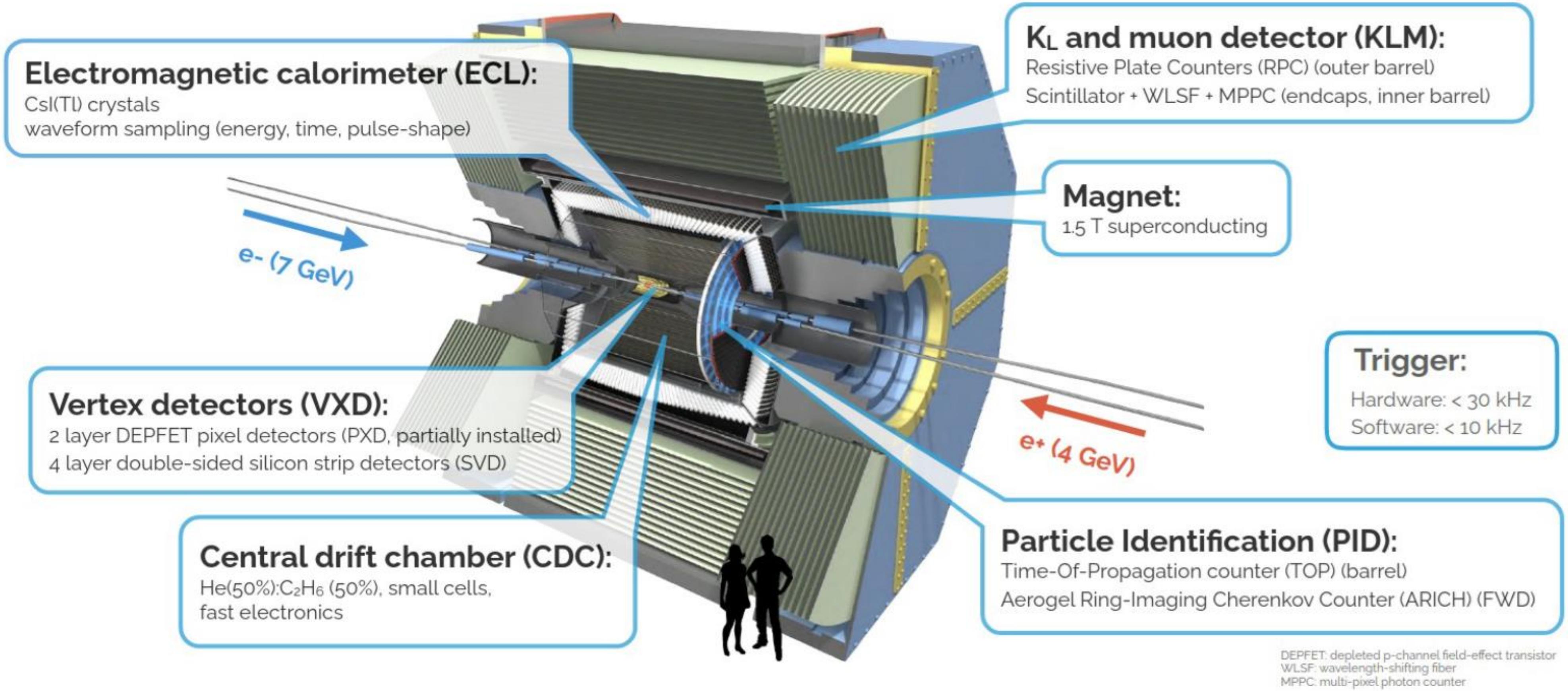


Competition and Complementarity

Caveat: generic statements, impact is analysis dependent

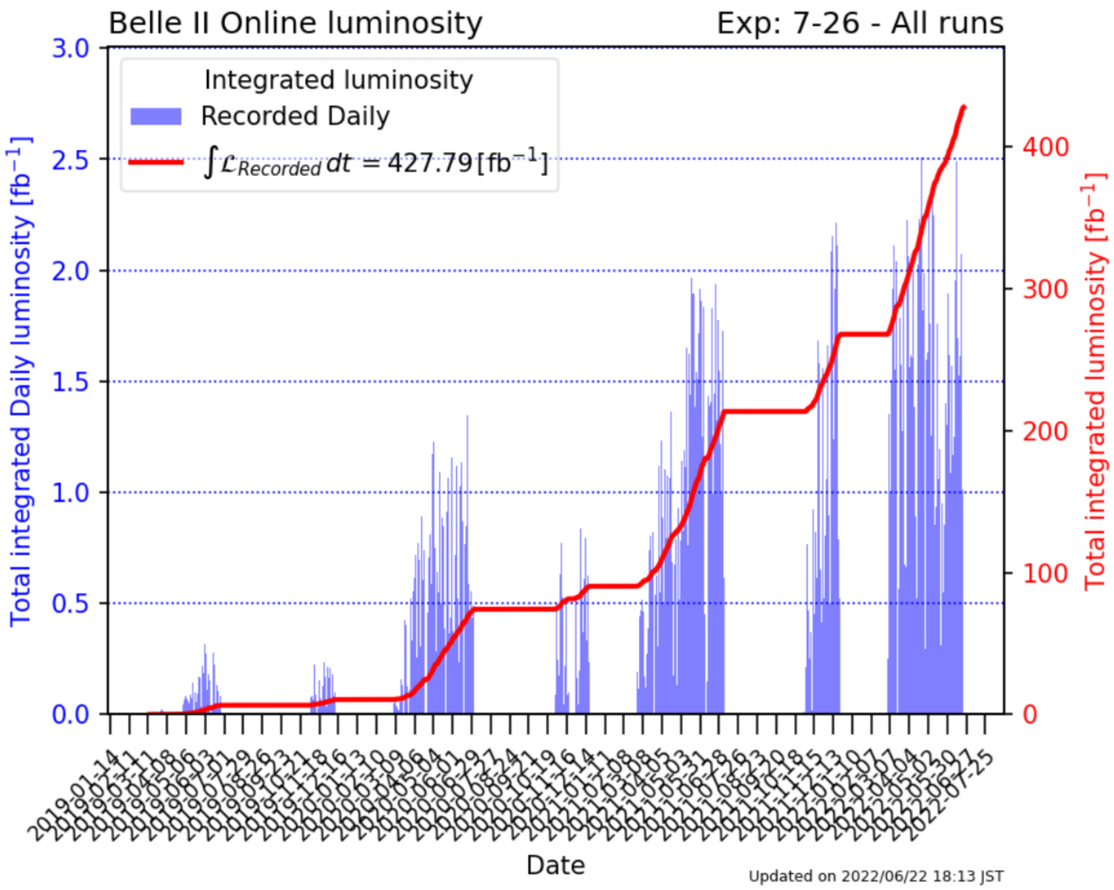
Property	LHCb	Belle II
$\sigma_{b\bar{b}}$ (nb)	~150,000	~1
$\int L\,dt$ (fb^{-1}) by ~2027	~25	~50,000
Background level	High	Low
Typical efficiency	Low	High
Initial state	Not well known	Well known
Decay-time resolution	Excellent	Very good
Collision spot size	Large ($10\times10\times 10^5 \mu m^3$)	Tiny ($6\times0.06\times 10^2\ \mu m^3$)
LLP-sensitive Size	Large	Small
Typical boost of LLP	Large	Small
Mass reach	High	Low
τ physics capability	Limited	Excellent

Belle II detector

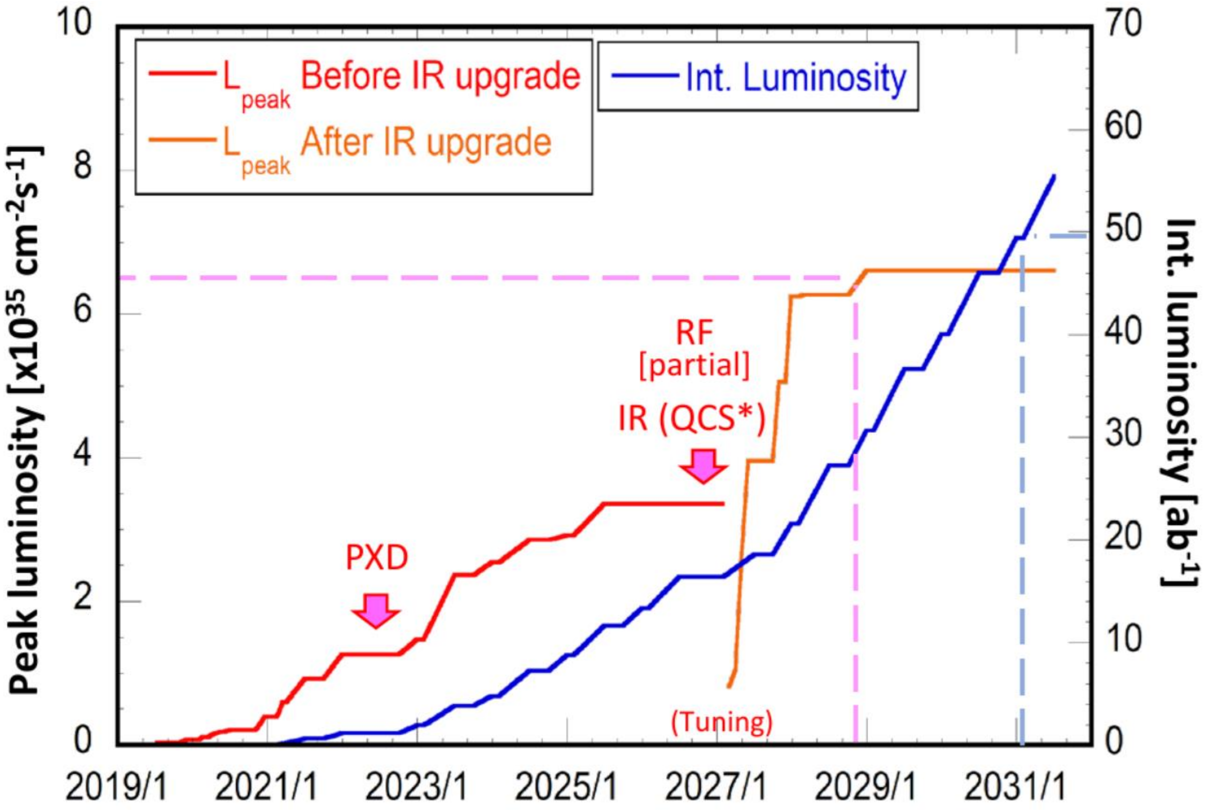


SuperKEKB luminosity

Collected luminosity up to now



Luminosity schedule



Belle II trigger

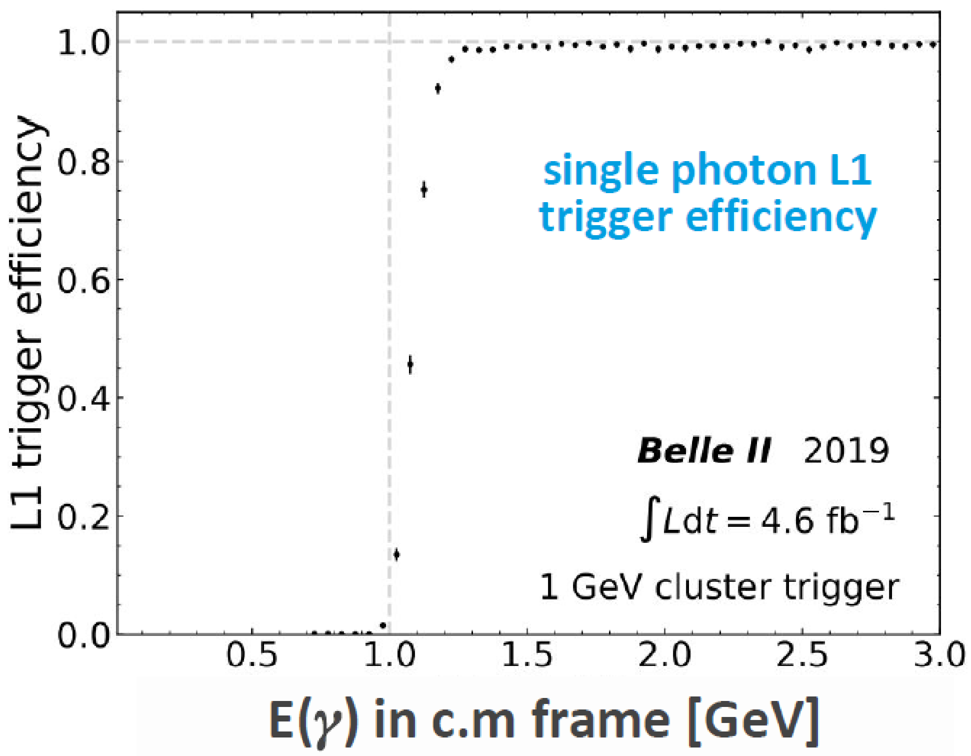
Performances

essential for dark-sector and tau physics

- typical signatures include low-multiplicity of tracks, and energy deposits in EM calorimeter
- large background from radiative Bhabha and two-photon processes

some of the dedicated low-multiplicity triggers:

- single muon
  - combine drift chamber and muon detector information
- single track:
  - neural-net based hardware trigger
- single photon:
  - high efficiency for E(γ) > 1 GeV



LHCb Upgrade I

Major upgrade of all subdetectors, target $L_{peak} = 2x10^{33}\ cm^{-2}\ s^{-1}$,

← 9 fb^{-1} → | **Upgrade I** | ← **Goal: 50 fb^{-1}** →

Run 1			LS1		Run 2				LS2				Run 3			LS3			Run 4			
2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032

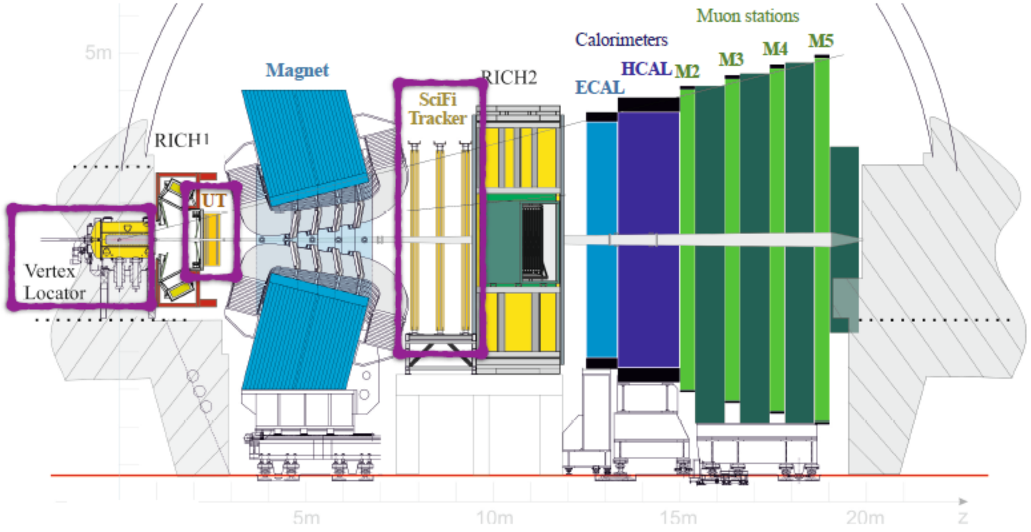
Runs 1 and 2

Upgrade I (being installed)

All electronics upgraded to send every hit to
flexible software trigger (GPUs + CPUs)

CERN-LHCC-2012-007

Increase granularity and longevity of **3 new trackers**



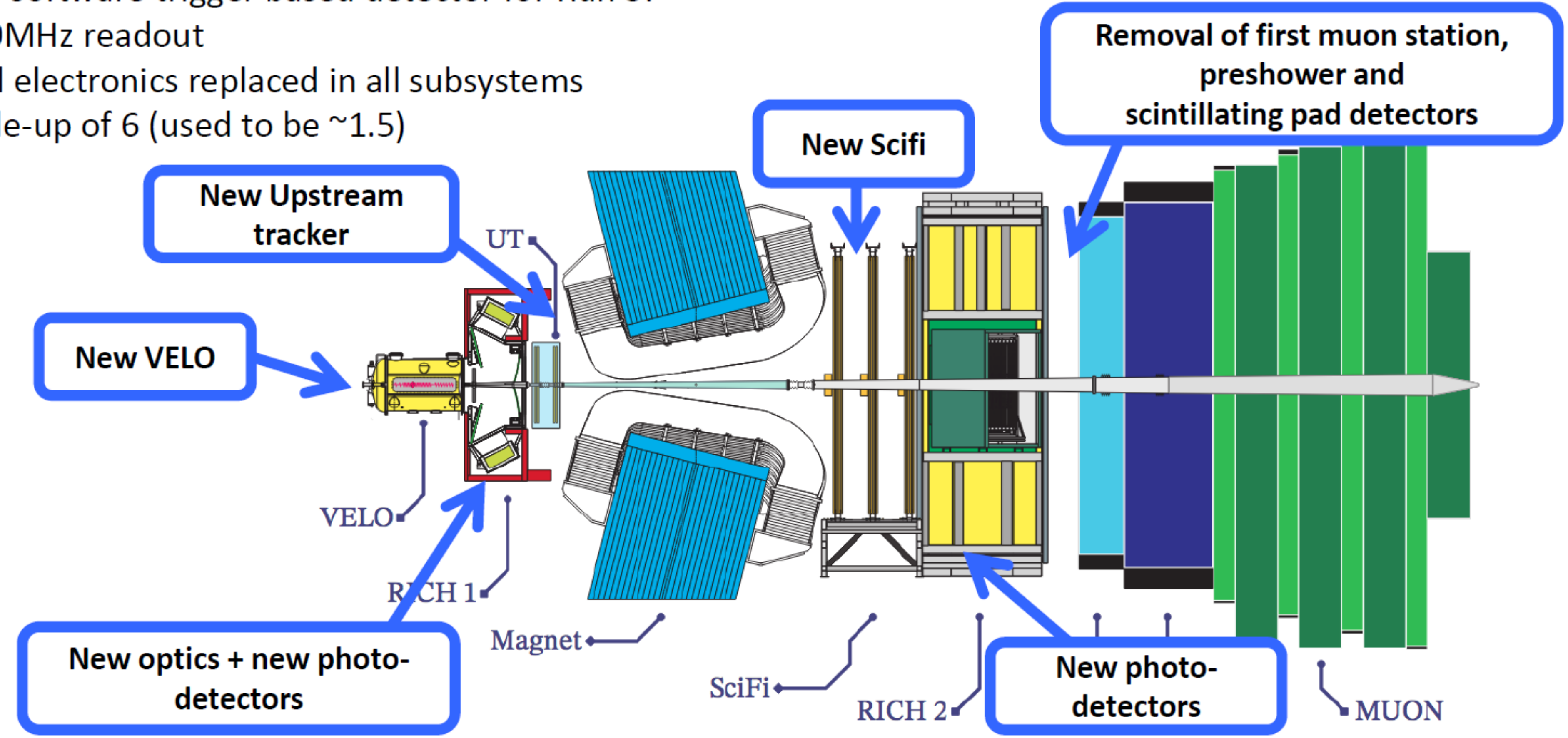
5x higher inst. lumi. to $2 \times 10^{33}\ cm^{-2} s^{-1}$,
5 visible interactions/crossing

LHCb Upgrade I

Major upgrade of all subdetectors, target $L_{peak} = 2x10^{33}\ cm^{-2}\ s^{-1}$,

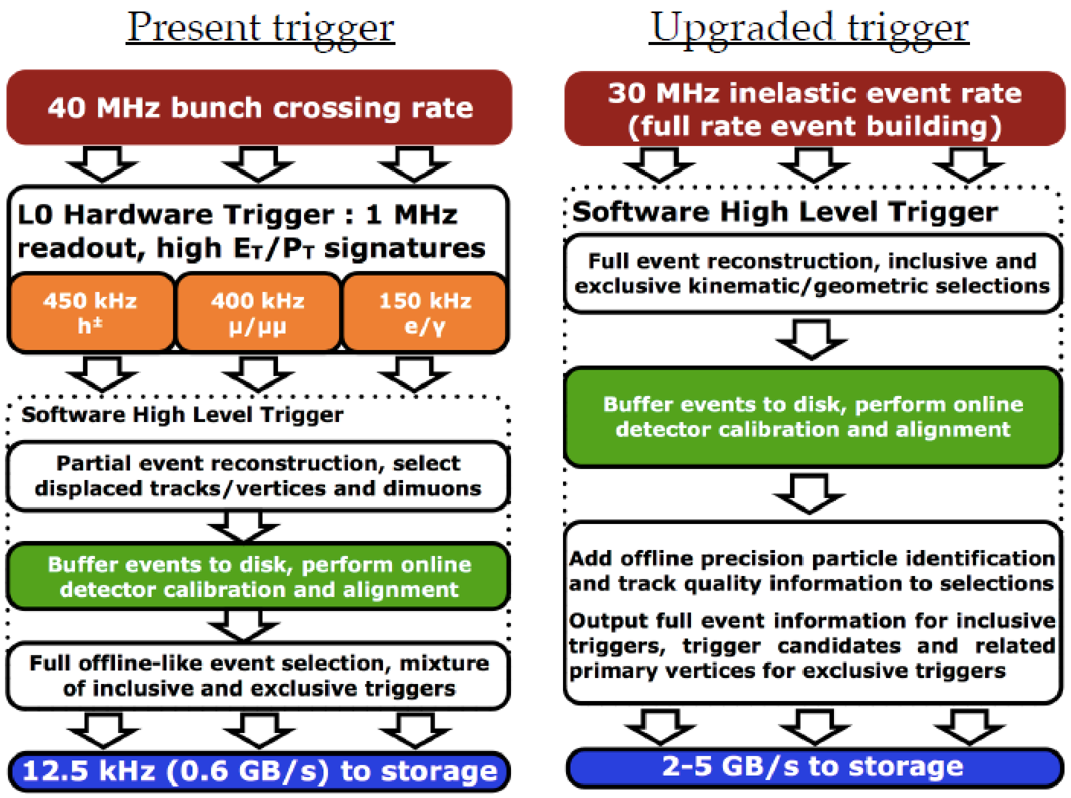
New software trigger based detector for Run 3:

- 40MHz readout
- All electronics replaced in all subsystems
- Pile-up of 6 (used to be ~1.5)



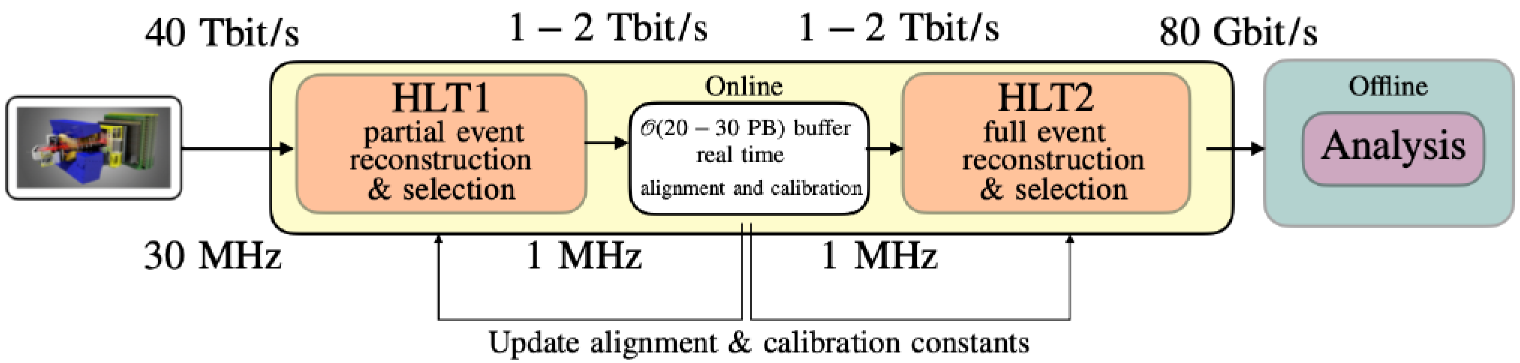
LHCb trigger

- Lower luminosity (and low pile-up)
  - **~1/8** of ATLAS/CMS in **Run 1**
  - **~1/20** of ATLAS/CMS in **Run 2**
- **Real-time reconstruction** for all charged particles with pT > 0.5 GeV
- Real-time calibration & alignment
- **Full real-time** reconstruction for all particles available to select events
- We go from 1 TB/s (post zero suppression) to 0.7 GB/s (mix of full + partial events)
- LHCb will move to a **trigger-less readout system** for LHC Run 3 (2021-2023), and process
  5 TB/s in real time on the CPU farm



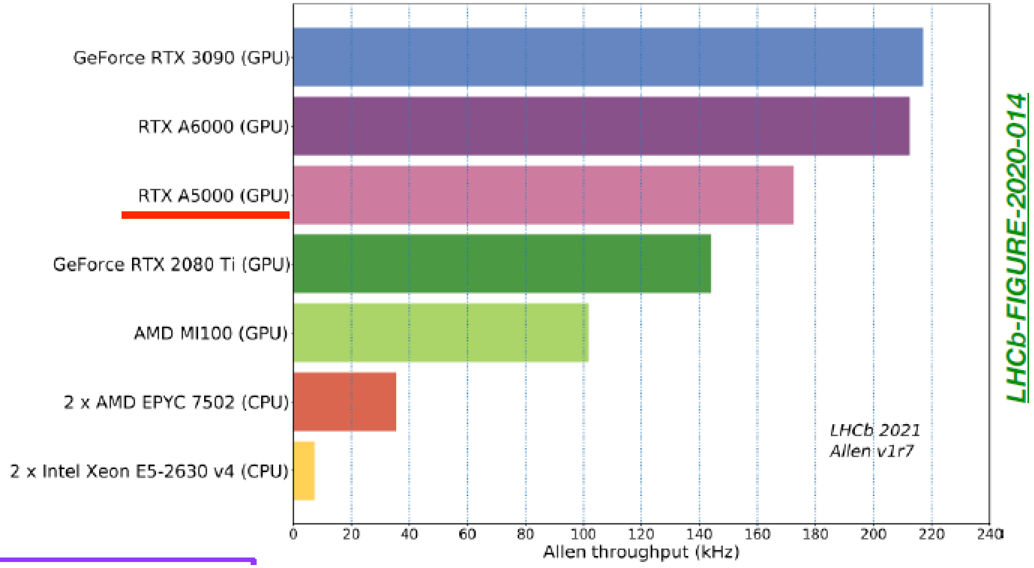
LHCb Upgrade I

L0 hardware has been removed, a full software trigger will process 30 MHz of inelastic collisions → factor of ~10 expected in hadronic yields at Run 3

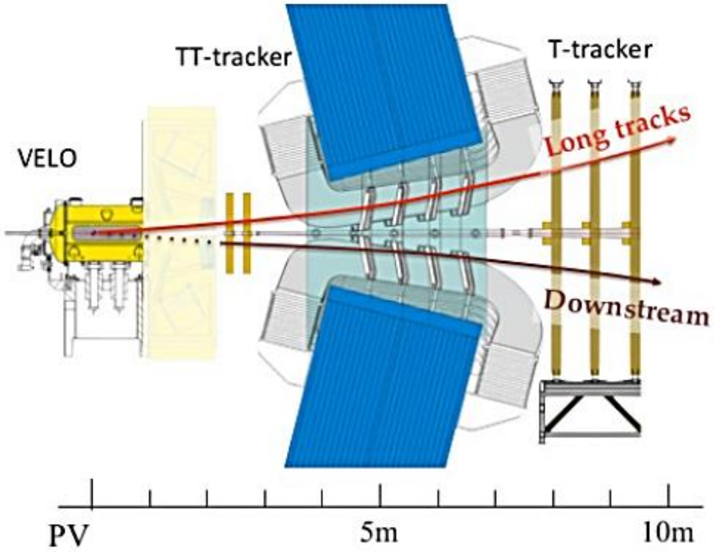


30 MHz of inelastic collisions will be reduced to ~1MHz by the HLT1 (tracking/vertexing and muon ID) running on GPUs

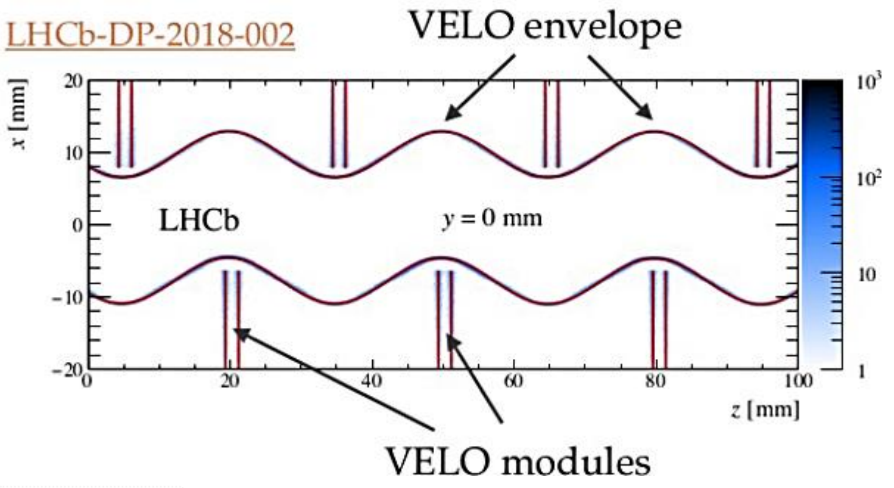
- *achieved with ~200 cards*
- *room to expand to ~500 cards when porting more reco/selection functionalities into HLT1*



Displaced vertex at LHCb.

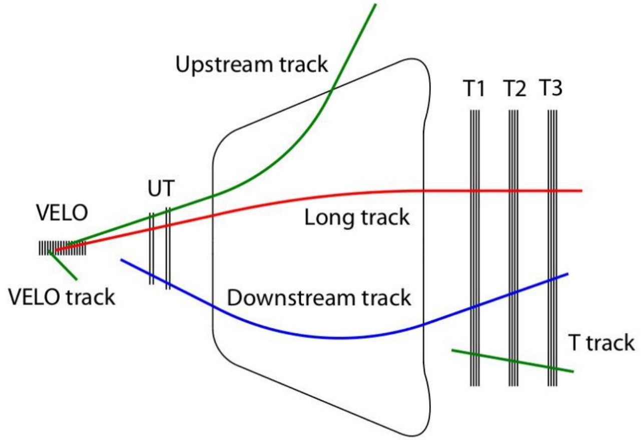


LHCb-DP-2018-002



- Currently only **within VELO**
  - Displacement < 20 cm (but with boost)
- Could extend to ***downstream tracks***
  - Displacement < 200 cm
  - Worse vertex and p resolution ($m(\pi\pi)$ resolution 2× larger)
  - Being optimised in the trigger

[LHCb-PUB-2017-005]



Backgrounds in VELO

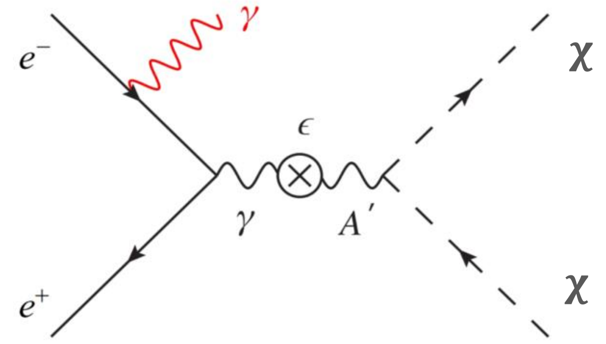
- Heavy Flavour displaced decays
  - $\tau(B)$~1.5 ps, $\beta\gamma$~10 ⇒ few mm
- Thin VELO envelope (RF foil)
  - **< 5 mm**: background mainly from heavy-flavour background
  - **> 5 mm**: background mainly from material interaction

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 γ_{ISR};**
- Bump in the photon energy:

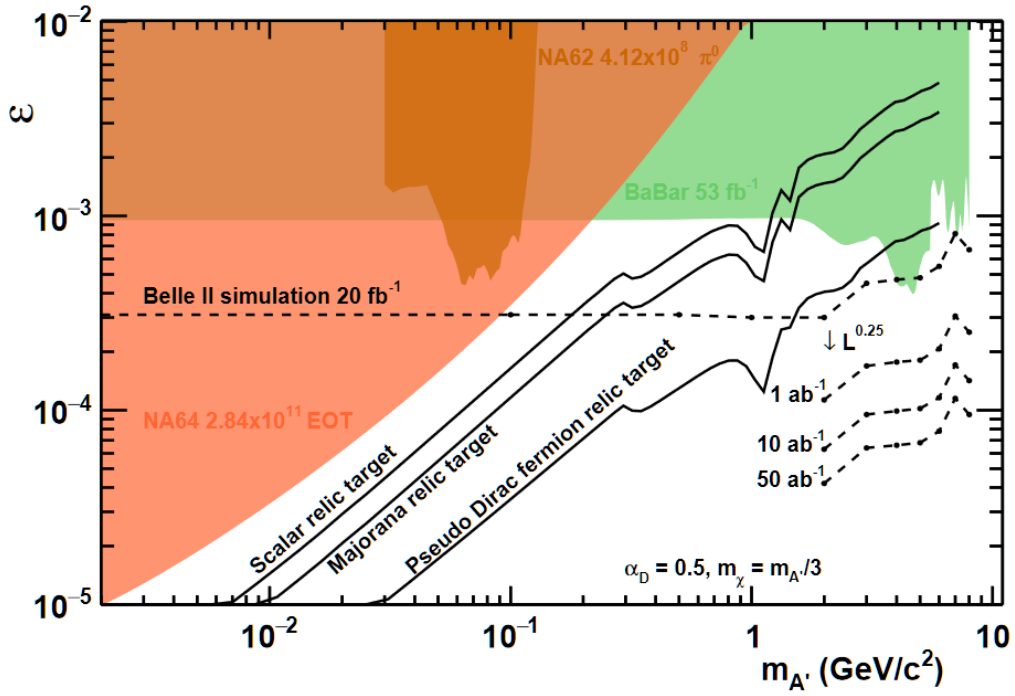
SM backgrounds: $ee \to \gamma\gamma(\gamma)$, $ee \to ee(\gamma)$, Cosmics;

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;



Dark Photon @LHCb

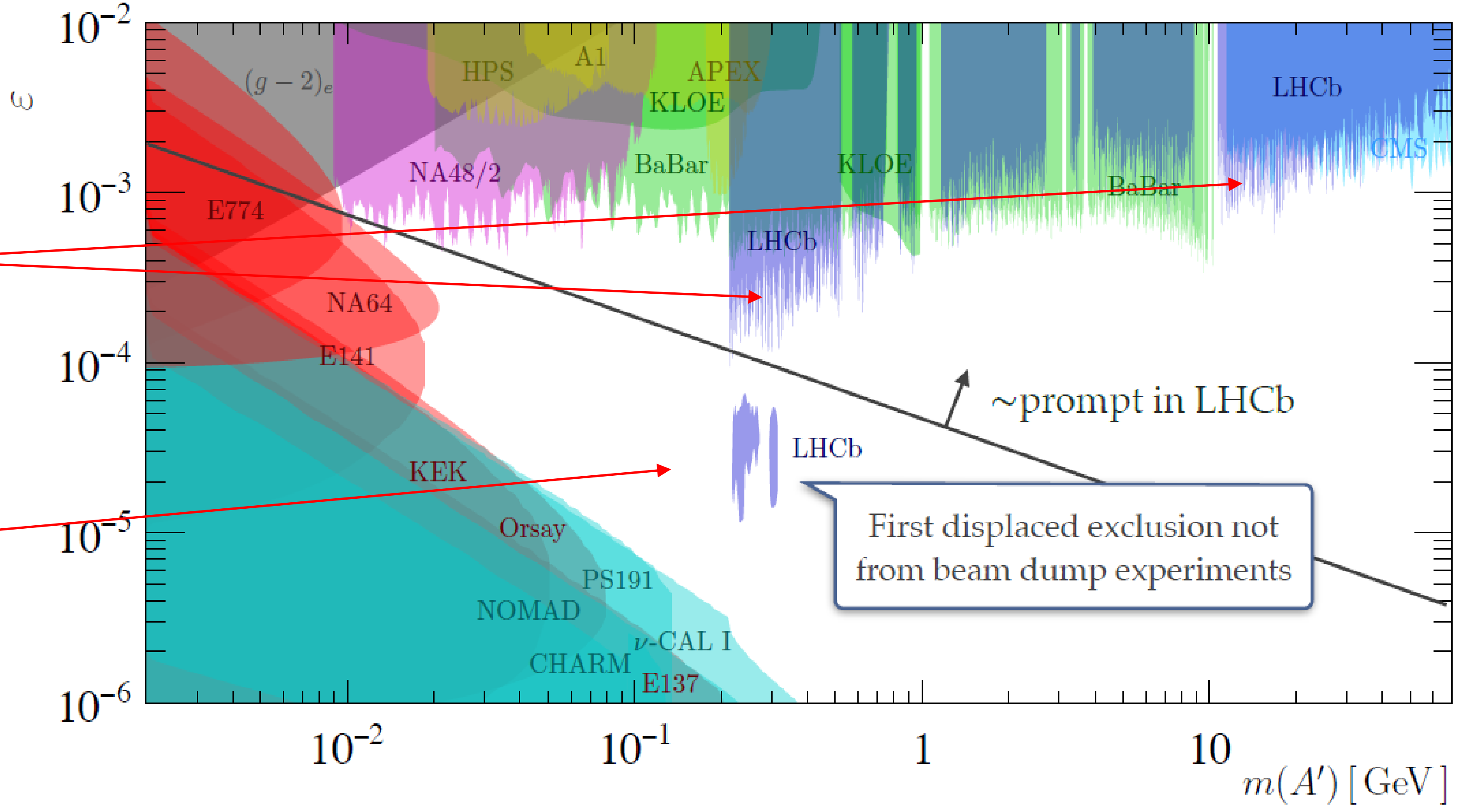
Results

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

Exclusion regions at 90% C.L.

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

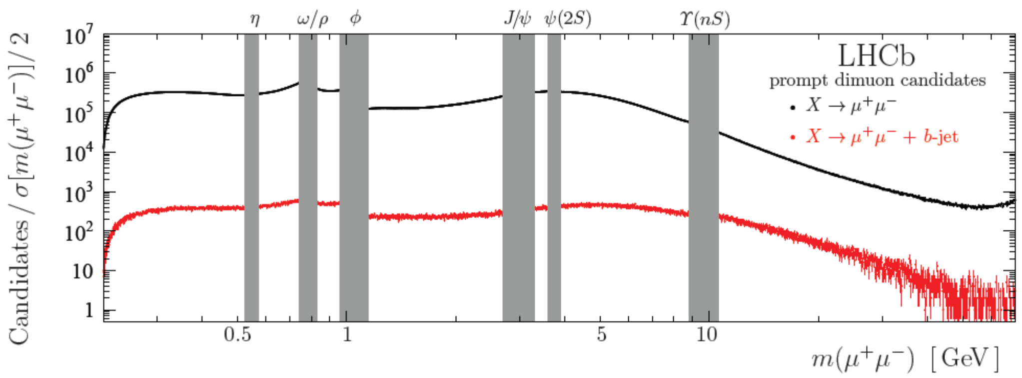
First non-fixed-target constraint from displaced signature search

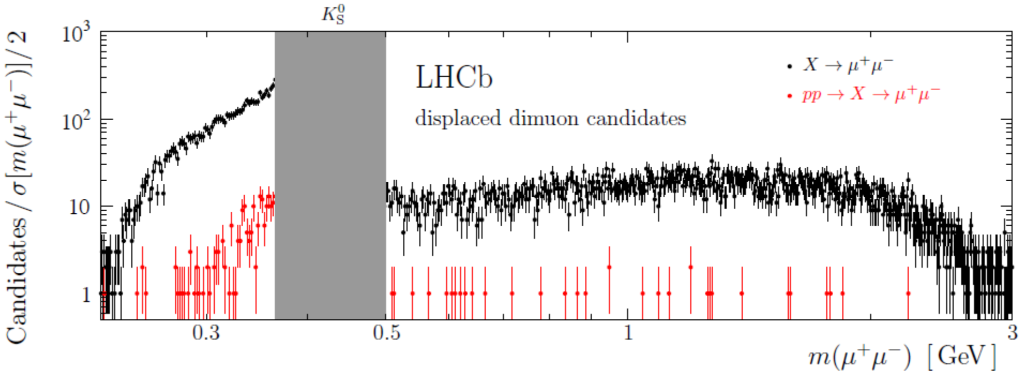


Inclusive $X \to \mu^+\mu^-$ search @LHCb

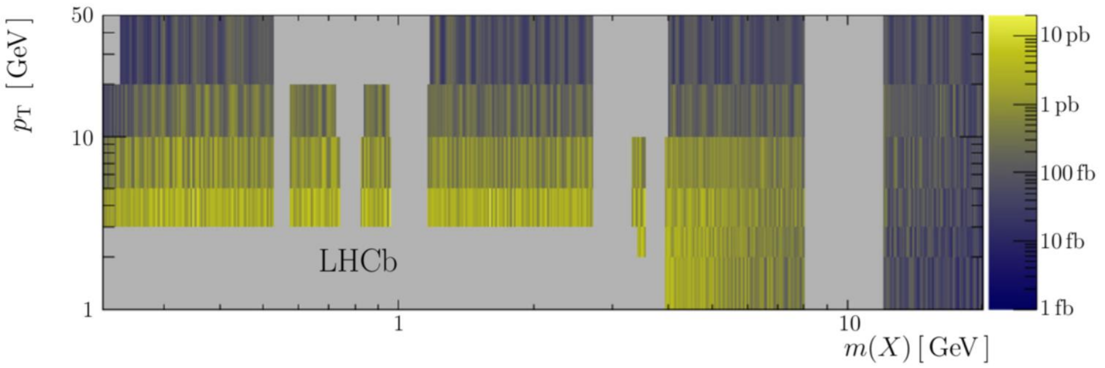
Results

m(μμ) for the four signature:

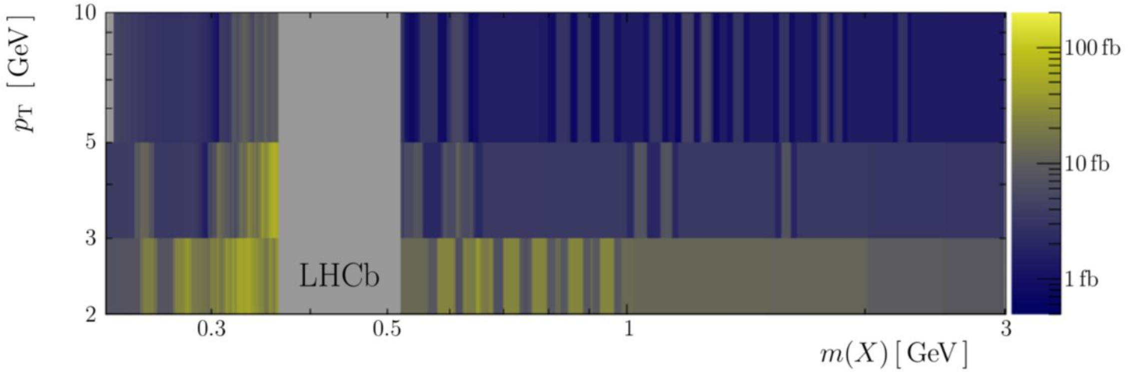




Model independent upper limits at 90% CL on σ(X → μμ)



Prompt Inclusive



Displaced prompt source

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

Table 1: Fiducial regions of the searches for prompt and displaced $X \to \mu^+\mu^-$ decays.

All searches	$p_T(\mu) > 0.5$ GeV $10 < p(\mu) < 1000$ GeV $2 < \eta(\mu) < 4.5$ $\sqrt{p_T(\mu^+)p_T(\mu^-)} > 1$ GeV $5 \leq n_{\text{charged}}(2 < \eta < 4.5, p > 5\text{ GeV}) < 100$ (from same PV as X)
Prompt $X \to \mu^+\mu^-$ decays	$1 < p_T(X) < 50$ GeV X decay time < 0.1 ps $\alpha(\mu^+\mu^-) > 1$ mrad $20 < p_T(b\text{-jet}) < 100$ GeV, $2.2 < \eta(b\text{-jet}) < 4.2$ ($X + b$ only)
Displaced $X \to \mu^+\mu^-$ decays	$2 < p_T(X) < 10$ GeV $2 < \eta(X) < 4.5$ $\alpha(\mu^+\mu^-) > 3$ mrad $12 < \rho_T(X) < 30$ mm X produced in pp collision (promptly produced X only)

systematics

Source	Relative uncertainty
Signal model	5%
Background model	data driven, see Sec. 4
Trigger, reconstruction, selection	2–5% (bin dependent)
Charged-particle multiplicity	5%
X kinematics	10–30% (bin dependent)
b-jet selection	11% ($X + b$ only)
SV selection	5% (SV-based only)
X SV distribution	10% (SV-based only)
Luminosity	6%
Total	11–30% (bin dependent)

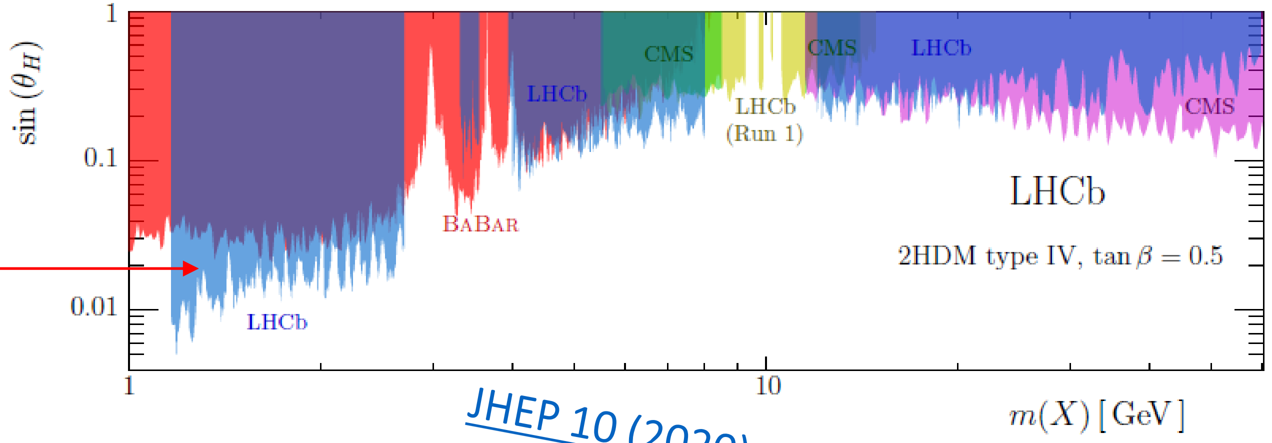
Inclusive $X \to \mu^+\mu^-$ search @LHCb

Results

No excess found and model independent UL on cross section

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

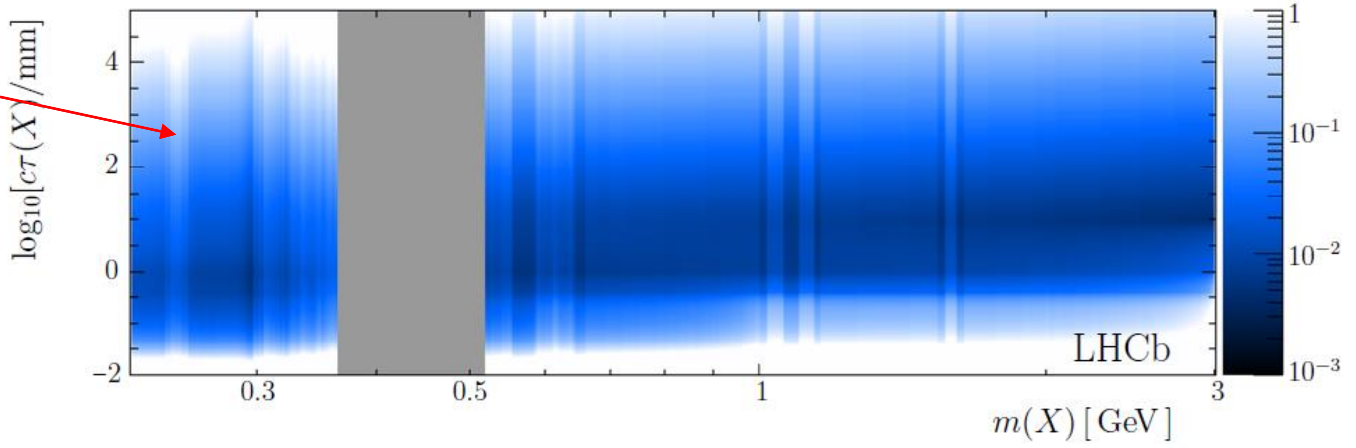
- world-best upper limit on mixing angle with SM Higgs θ_H



[JHEP 10 (2020) 156]

Displaced results interpreted onto limits on **Hidden Valley** model with dark showers of light **hidden hadrons** (model from [PRD 97 (2018) 095033])

- **90% CL UL on kinetic mixing between γ and Z_{HV}**
- **World-first constraints with minimal model dependence**



Result depends on hidden hadron multiplicity (NHV ~10)

Dark photon search @LHCb

·

Prompt Backgrounds

1. $\gamma^* \to \mu^+\mu^-$ production [Irreducible]
2. Resonant decays to $\mu^+\mu^-$ [Veto these regions]
3. Various types of misreconstruction:

Muons from heavy-flavor quark decays misreconstructed as prompt [Fits]

Double misidentification of prompt hadrons as muons [$\mu^\pm\mu^\pm$ sample]

A mix of these two [$\mu^\pm\mu^\pm$ sample]

Above $m'_A > 1.1\ GeV$ misreconstruction still dominates. [Isolation]

Displaced Backgrounds

1. B-hadron decay chains that produce two muons

[Require decay topology to be consistent with a 2-body long-lived particle decay that originated at a PV ;
Rejected if selected by inclusive heavy-flavor software trigger
+ BDT classifiers]

2. $K_S^0 \to \pi^+\pi^-$ tail

[This limits the mass range for the displaced search.
Subtracted by extrapolation]

3. Photon conversions to μ+μ− in the silicon-strip vertex detector

[Rejected by material veto tool]

Dark photon search @LHCb

.

Compare to bump hunt

What we fit for normalisation

Efficiency Ratio = 1 for $\tau'_A \ll$resolution

$$n_{\text{ex}}^{A'}[m(A'),\varepsilon^2] = \varepsilon^2 \left[\frac{n_{\text{ob}}^{\gamma^*}[m(A')]}{2\Delta m}\right] \mathcal{F}[m(A')]\,\epsilon_{\gamma^*}^{A'}[m(A'),\tau(A')],$$

What we set limits on

Known factors

Dark photon search @LHCb

Prompt normalization

Determine observed off-shell photon yield:

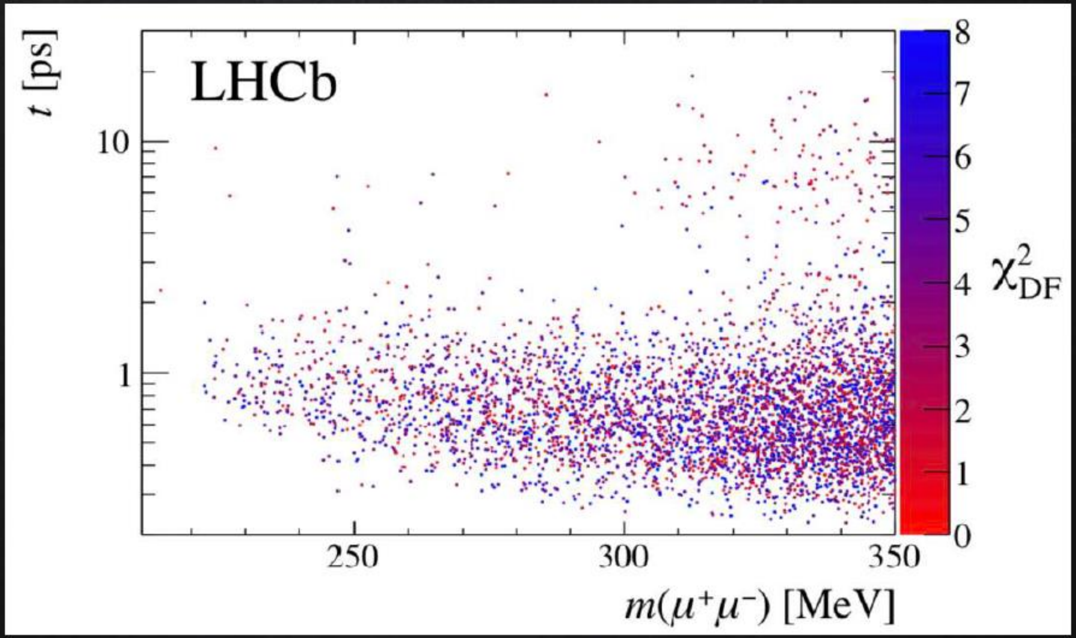
1. Estimate misID background by subtracting $\mu^{\pm}\mu^{\pm}$ yields
2. Estimate heavy flavor background by performing binned extended maximum likelihood fits to the $\min[\chi^2 IP(\mu^{\pm})]$ distributions

$\chi^2_{\rm IP}(\mu^{\pm})$: difference in the vertex-fit χ^2 when the PV is reconstructed with and without the muon

Dark photon search @LHCb

Displaced Fits

3D binned extended maximum likelihood fits
Templates are derived from control samples.
Conversions are extrapolated from candidates rejected by cut.



For visible decays $\tau(A') \propto \frac{1}{m(A')\epsilon^2}$: $n^{A'}[m(A'), \tau(A')]$ -> $n^{A'}[m(A'), \epsilon^2]$

Invisible Z’ @ Belle II

Systematics

3 control samples:

- $\mu\mu\gamma$: check selections @ low masses
- $e\mu$: check selections @ high masses;
- ee: γ-veto studies;

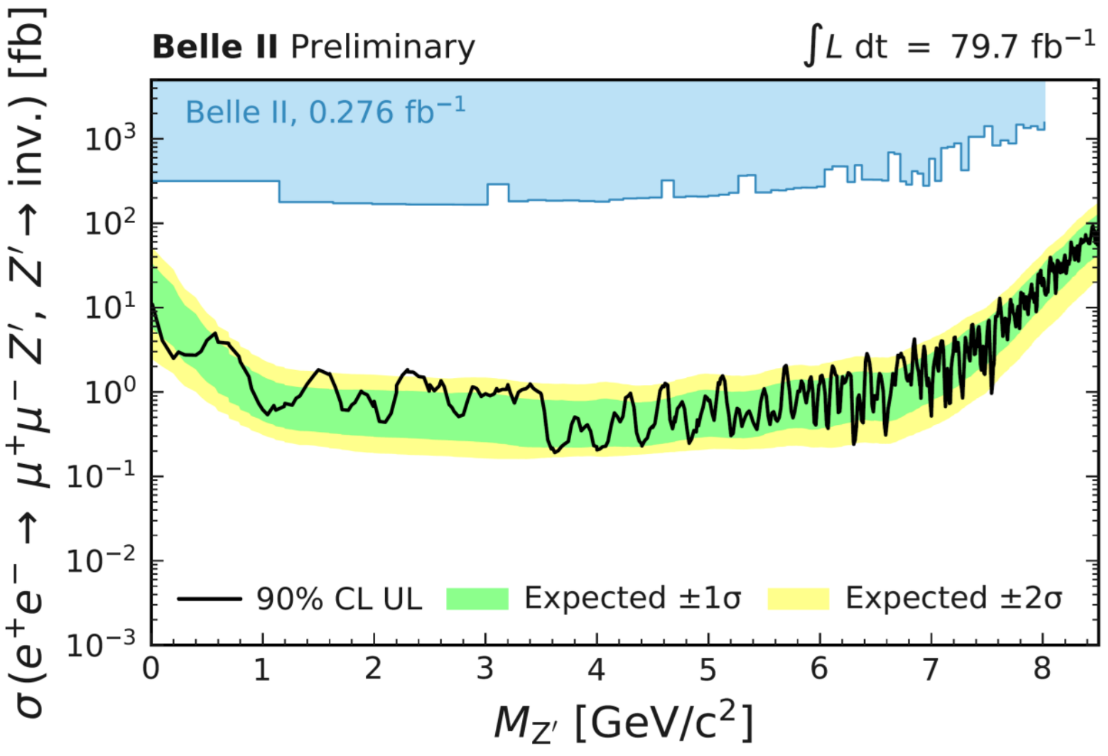
Table of systematics:

Source	Low mass	Medium mass	High mass
selections	2.7%	6.5%	8.3%
Mass resolution	10%	10%	10%
Background shapes	3.2%	8.6%	25%
Photon veto	34%	5%	5%
luminosity	1%	1%	1%

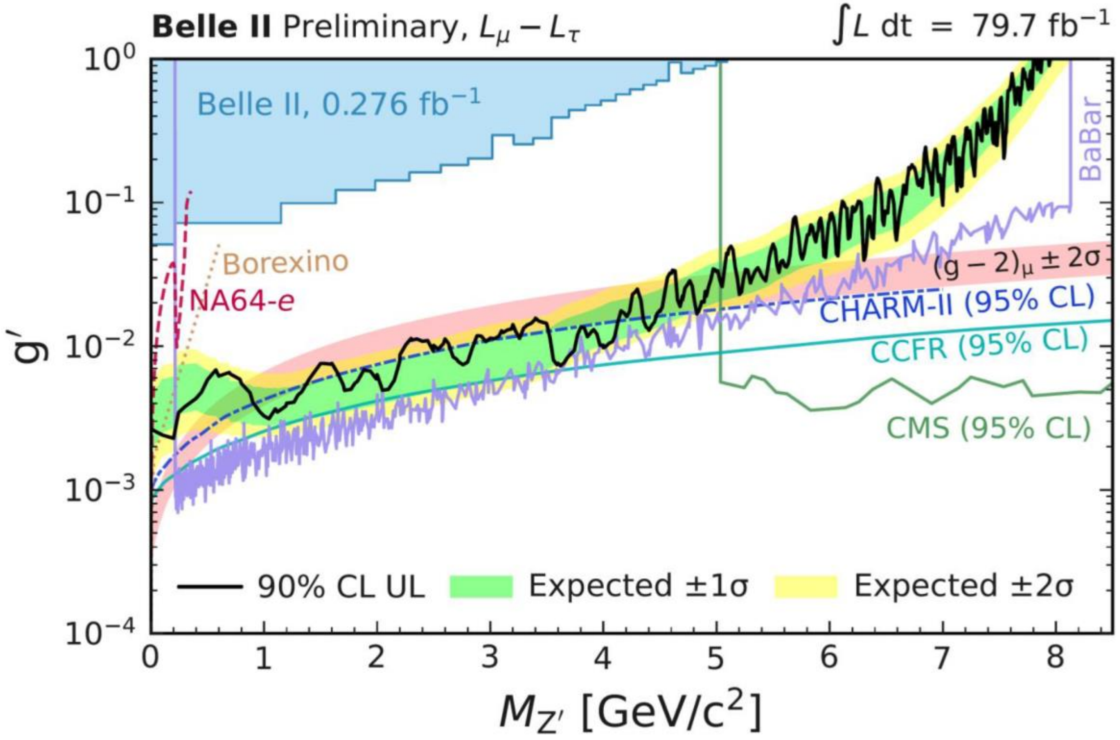
Invisible Z’ @ Belle II

Results

Cross section UL



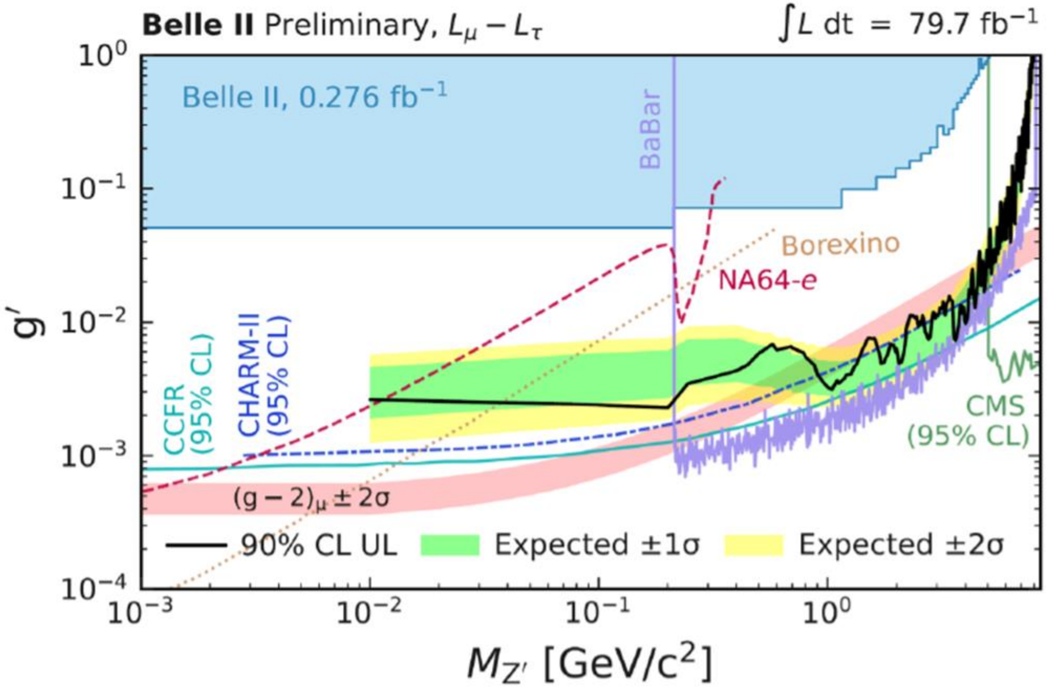
g’ Uls in vanilla model Z’



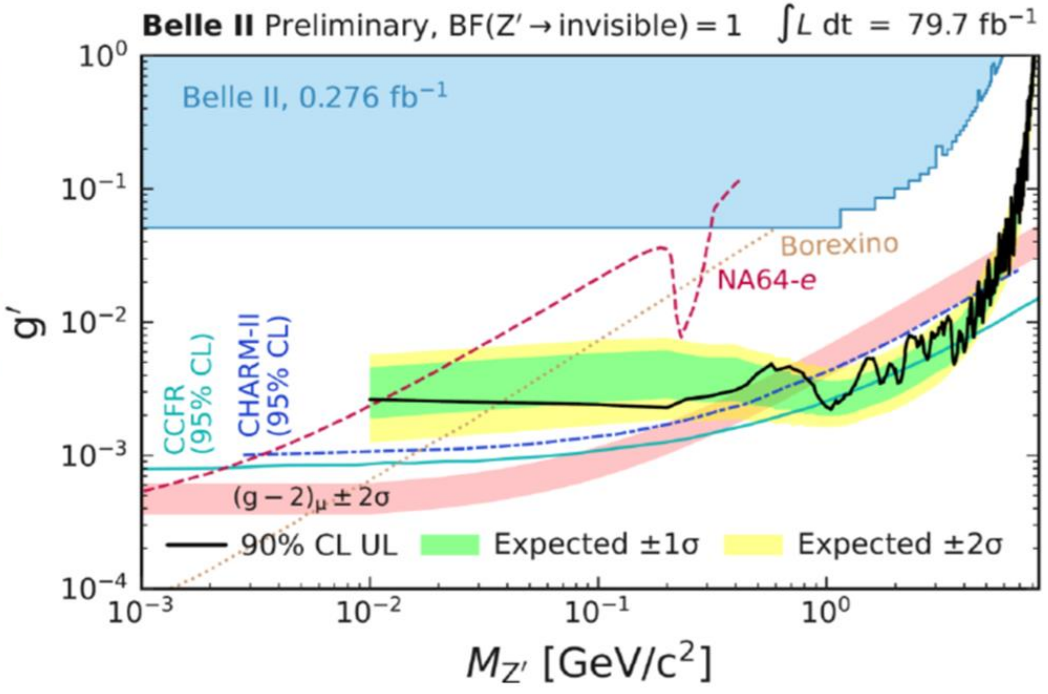
Invisible Z’ @ Belle II

Results

Vanilla model Z’



Fully invisible Z’

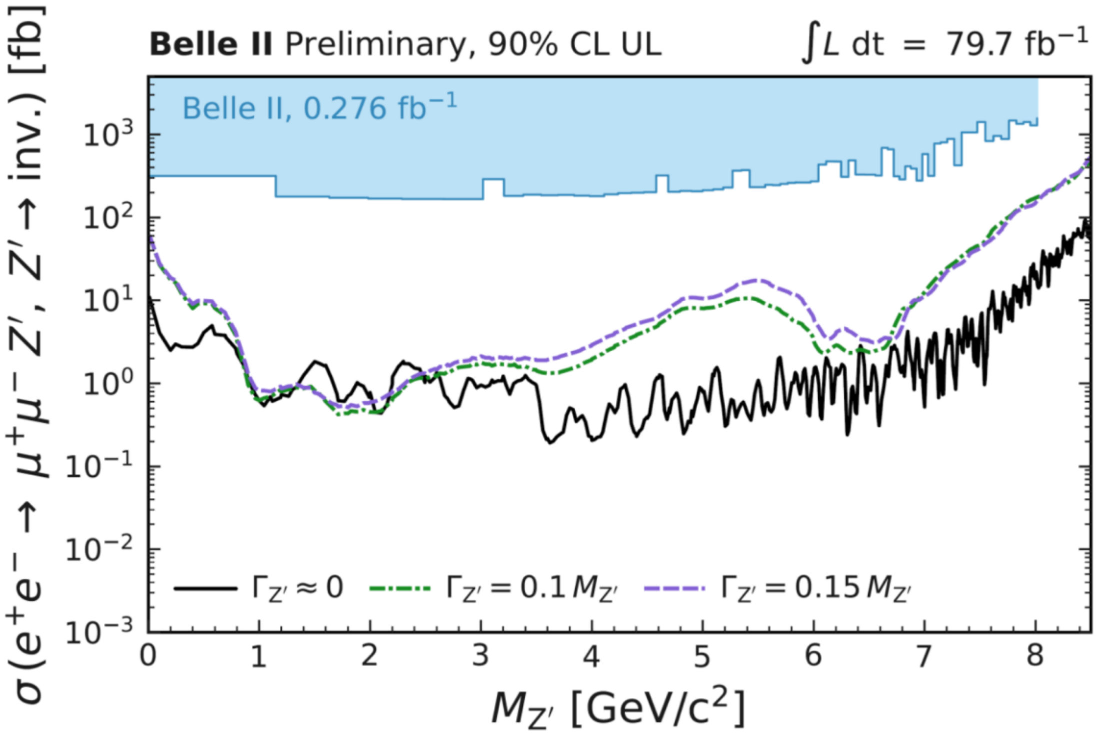


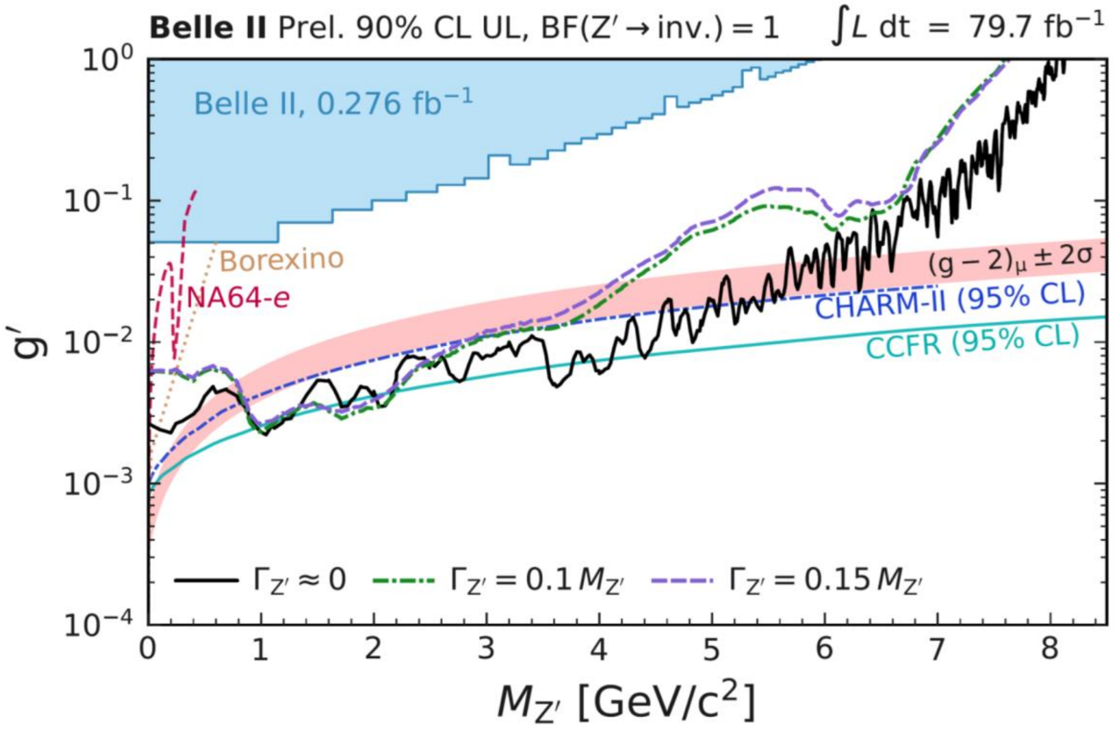
Invisible Z’ @ Belle II

Results

Invisible Z’ with non negligible intrinsic width:

- $\Gamma_{Z'} = 0.1\, M_{Z'}\,, 0.15\, M_{Z'}$





Dark Higgsstrahlung @ Belle II

Systematics

2 control samples:

- $\mu\mu\gamma$: largely dominated by $\mu\mu(\gamma)$ background;
- $e\mu$: largely dominated by $\tau\tau$ background;

→

Split mass plane into orthogonal macro-regions

- Each dominated by a single background source
- Data/MC normalization+ shape

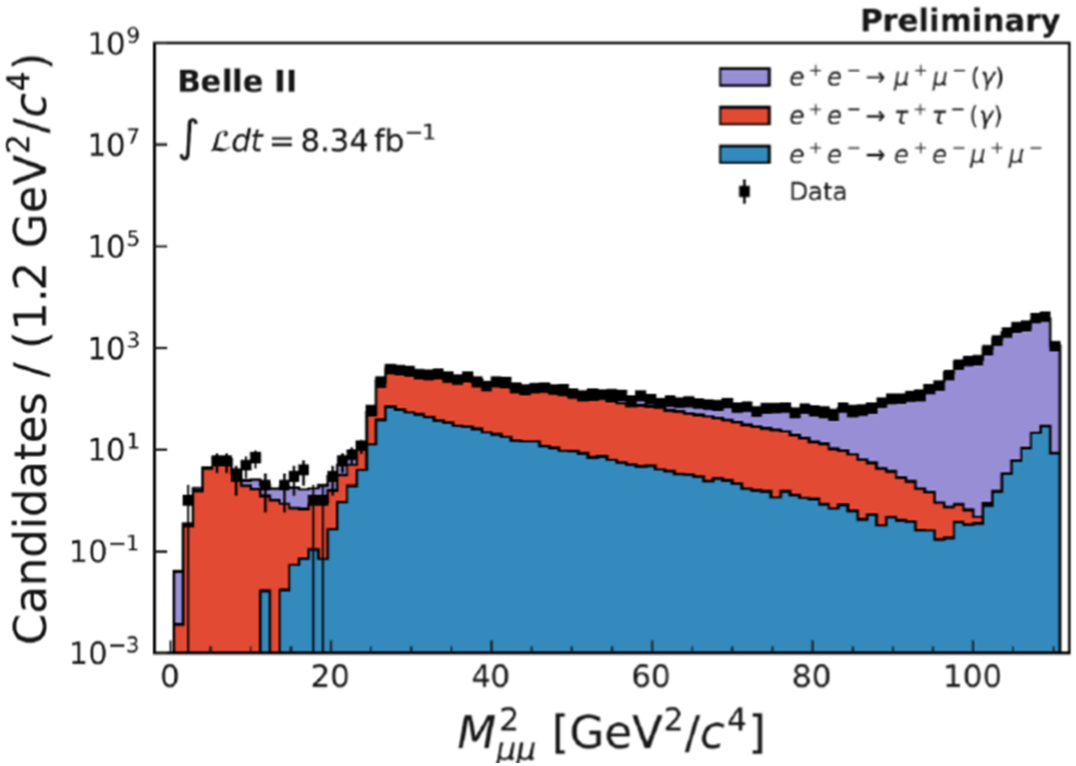
Table of systematics:

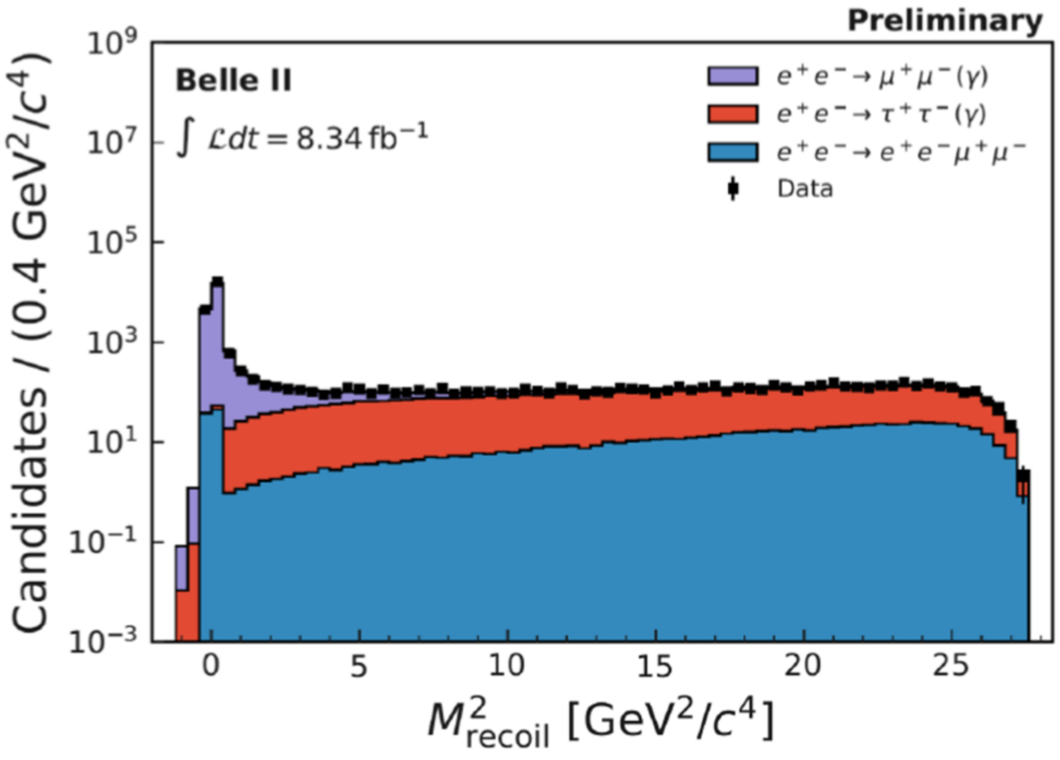
source	uncertainty	target
Pre-selections	**2 - 9.1%**	BKG & signal
BKG shape	**9.3%** (region specific)	BKG
C_η cut	**1%**	BKG
Mass resolution	**2.4%** (on average)	signal
Eff. Inside windows	**2 - 5%**	signal
Theory (BR A')	**4%**	signal

Negligible effect on Uls (~1%)
Exception is $M_{A'} > 9$ GeV/c^2 (~25%)

Dark Higgsstrahlung @ Belle II

Data/MC



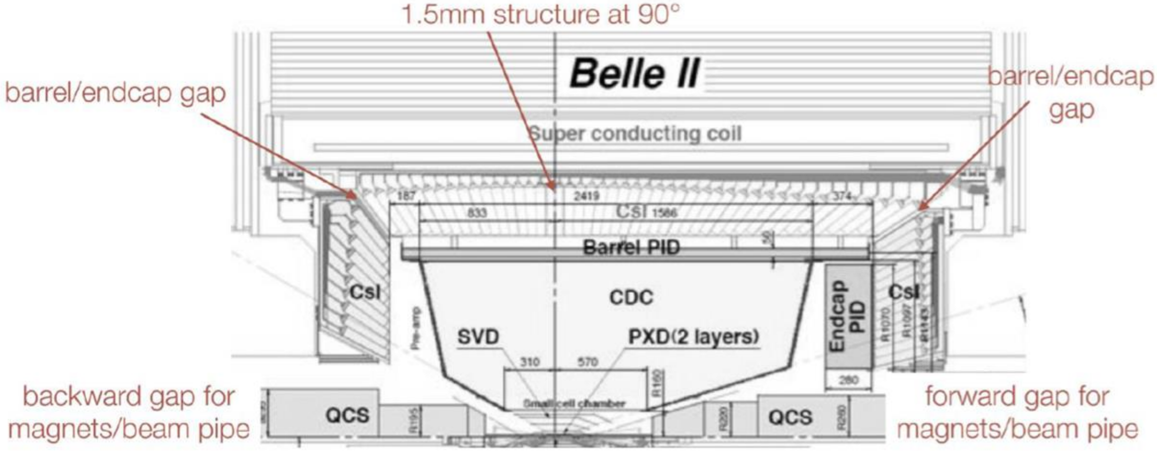


Invisible dark photon @ Belle II

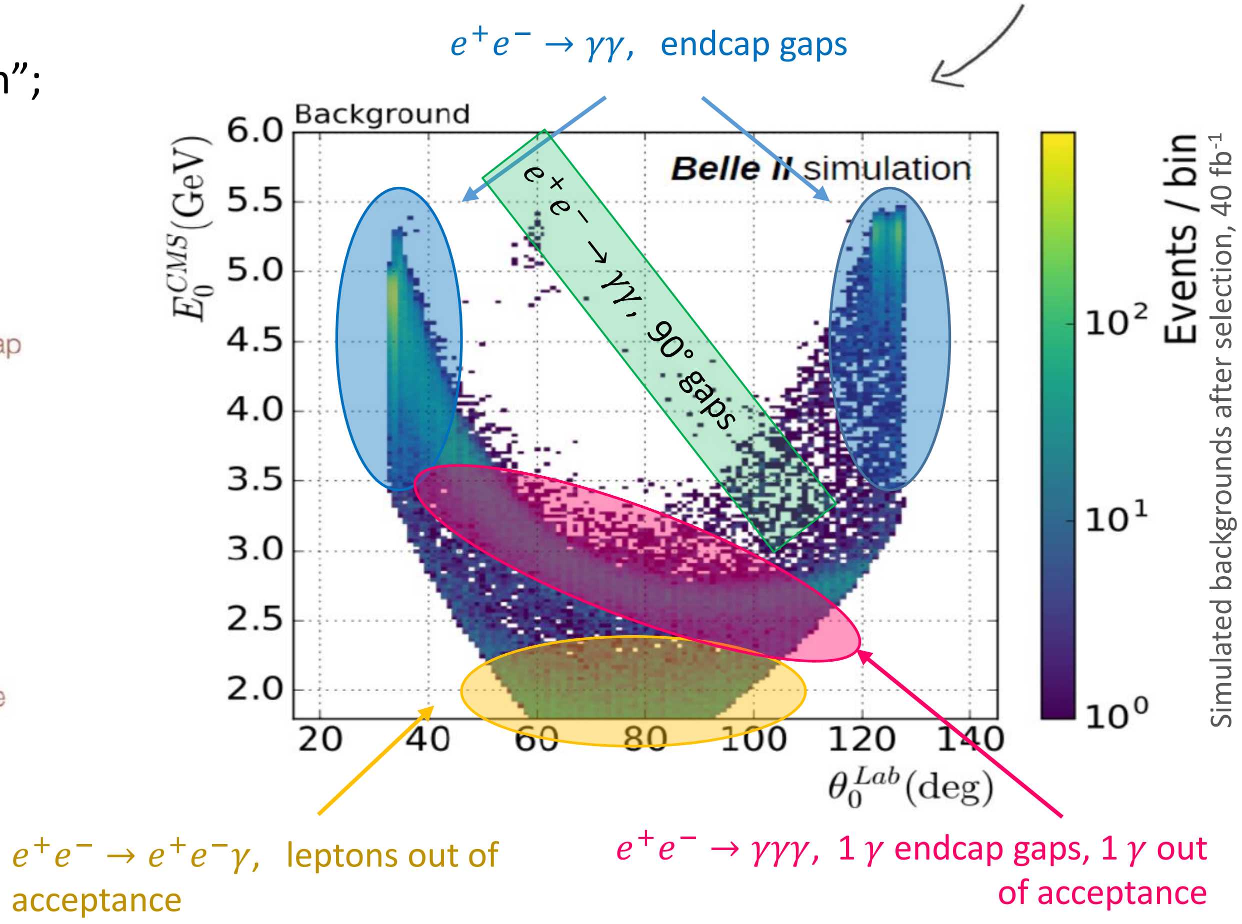
Results

Background suppression:

- Discriminant variables: E_{CMS} vs. polar angle of "single photon";



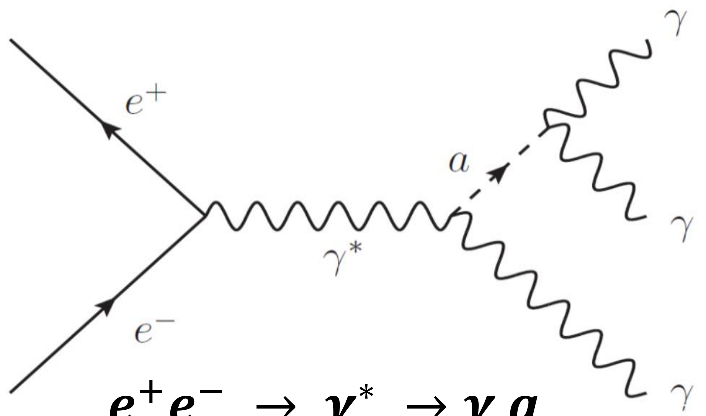
SM backgrounds:



ALPs @ Belle II

Results

[Phys. Rev. Lett. **125**, 161806 (2020)]



$$e^+e^- \rightarrow \gamma^* \rightarrow \gamma\, a,$$
$$a \rightarrow \gamma\gamma$$

Axion Like Particles (ALPs): pseudo-scalars particles (a) that couple to fermions or boson.

Search for ALP-strahlung in the 3γ resolved final state

- Used first data from 2018 commissioning run (0.455 fb^{-1});

Signature:

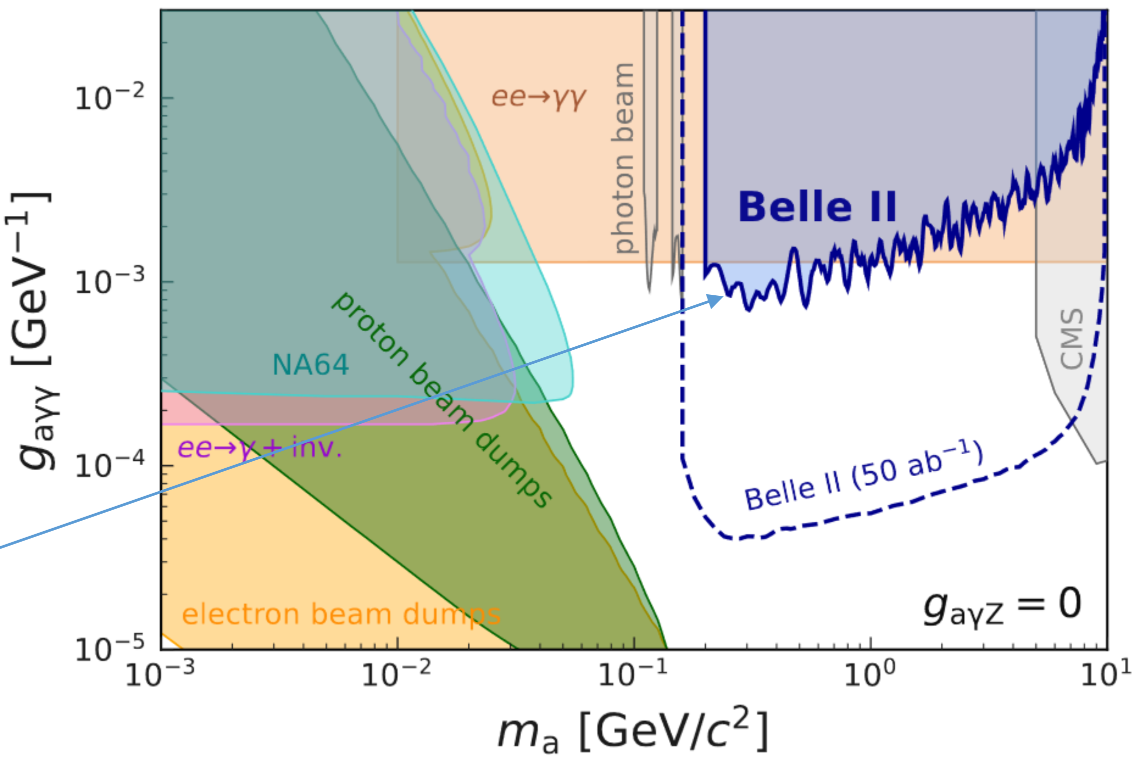
- 3γ that add up to the beam energy;
- bump on di-photon mass;

Background:

- $\gamma\gamma(\gamma)$; $e^+e^-(\gamma)$; $P\,\gamma(\gamma)$ with $P = \pi^0, \eta, \eta'$;

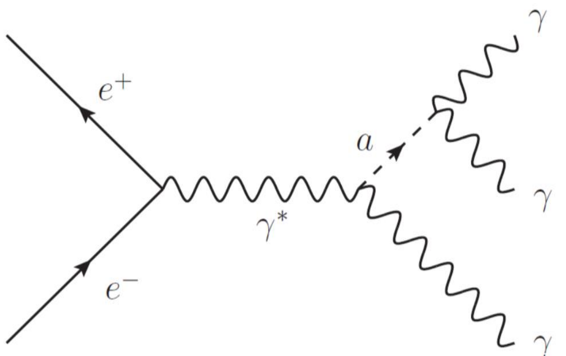
No excess observed and 90% CL UL on $g_{a\gamma\gamma}$ down to $O(10^{-3})$.

First results ever for ALPs @ B-factories



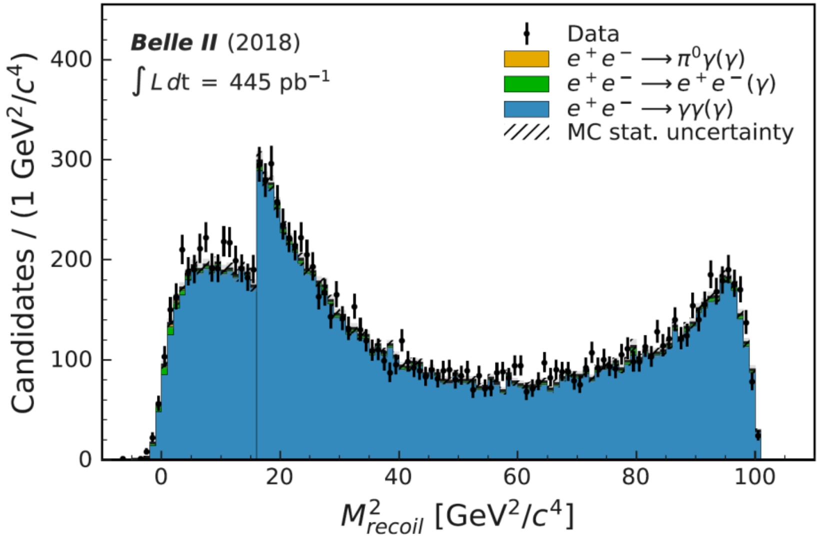
ALPs @ Belle II

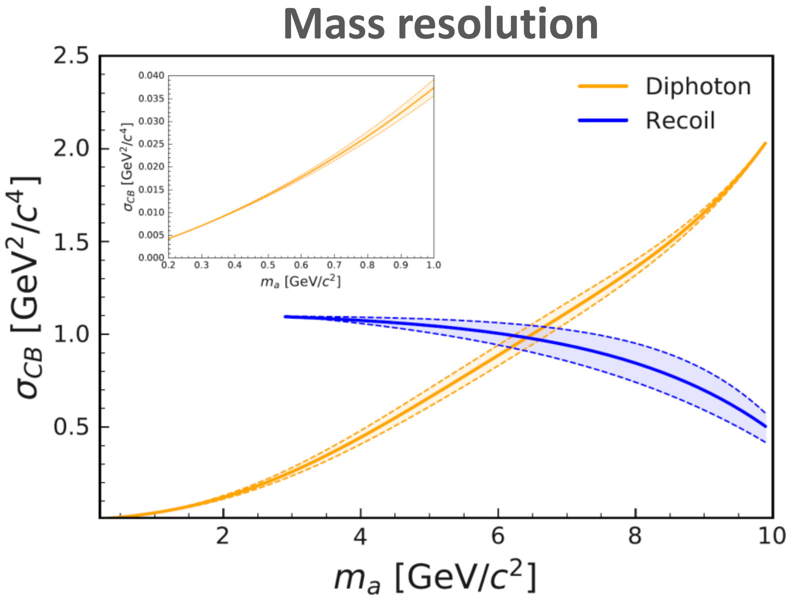
Results

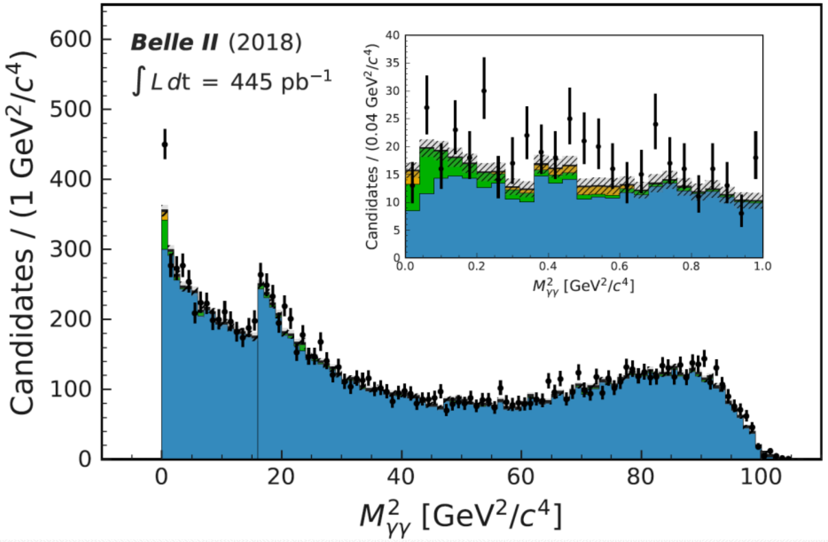


Belle II searched for ALP-strahlung in the 3γ resolved final state;

- Search for a peak either in the recoil invariant mass (high m_a) or in the dilepton mass (low m_a)







Dark Sector searches

Models, searches and signatures

Model dependency:

- Most of the searches at Belle II and LHCb are performed for some “benchmark” models;
- However, recasting limits to account for different models (*e.g.*, A’ vs. ALPs) is usually rather straight forward;

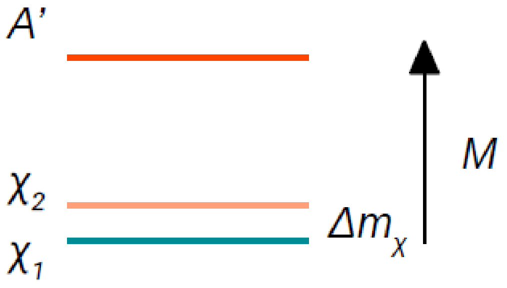
Searches strongly depends on signatures:

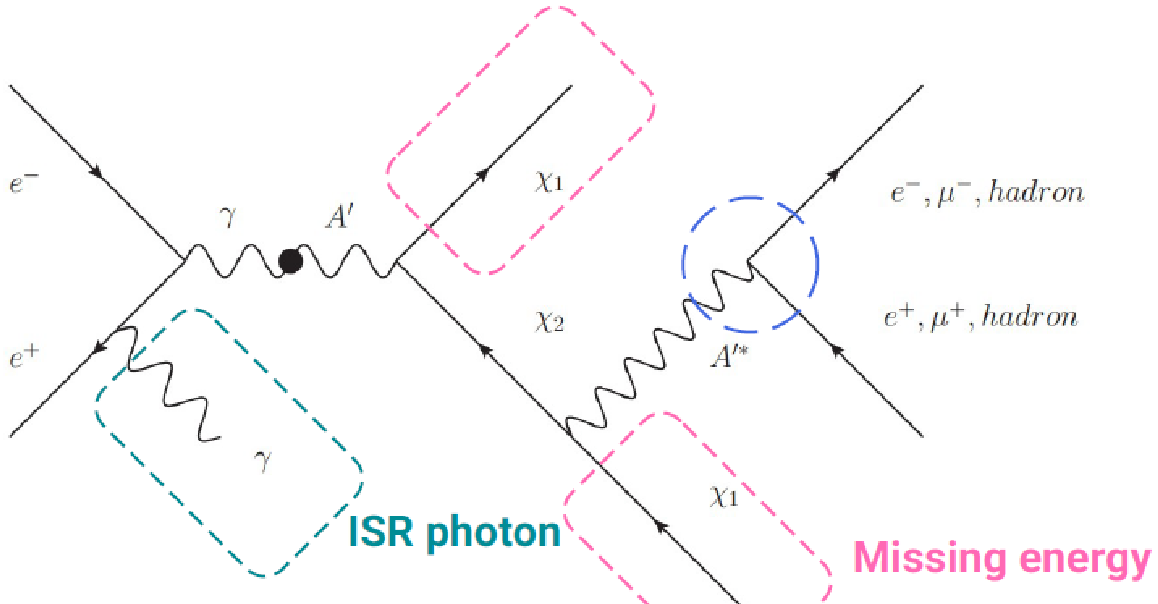
- Trigger and selections for low multiplicity final states are very sensitive to the presence or absence of additional particles;

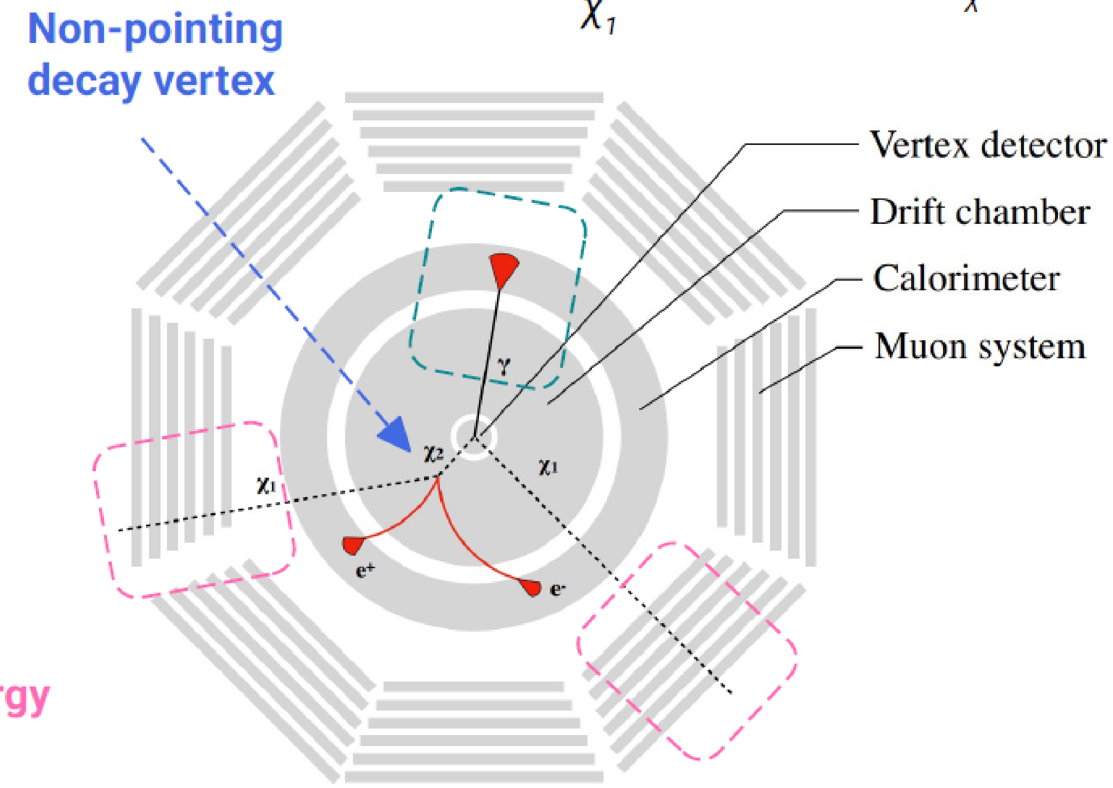
Inelastic Dark Matter (iDM) @ Belle II

Prospects

- Expanded dark sector with two dark matter states with a small mass splitting and a dark photon
  - ➔ χ_1 is stable (relic dark matter)
  - ➔ χ_2 is long-lived
- Focus on $M_{A'} > m_{\chi 1} + m_{\chi 2}$: the decay $A' \rightarrow \chi_1\chi_2$ is favored





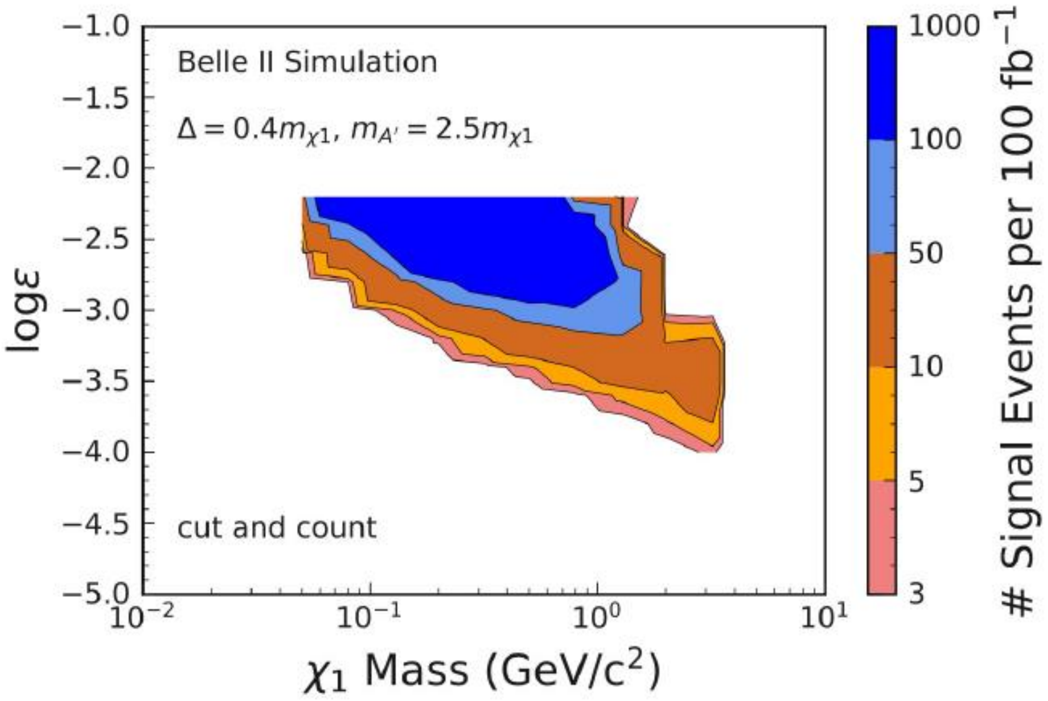


[1] Duerr et al., JHEP04 (2021) 39
[2] Duerr et al., JHEP04 (2021) 146

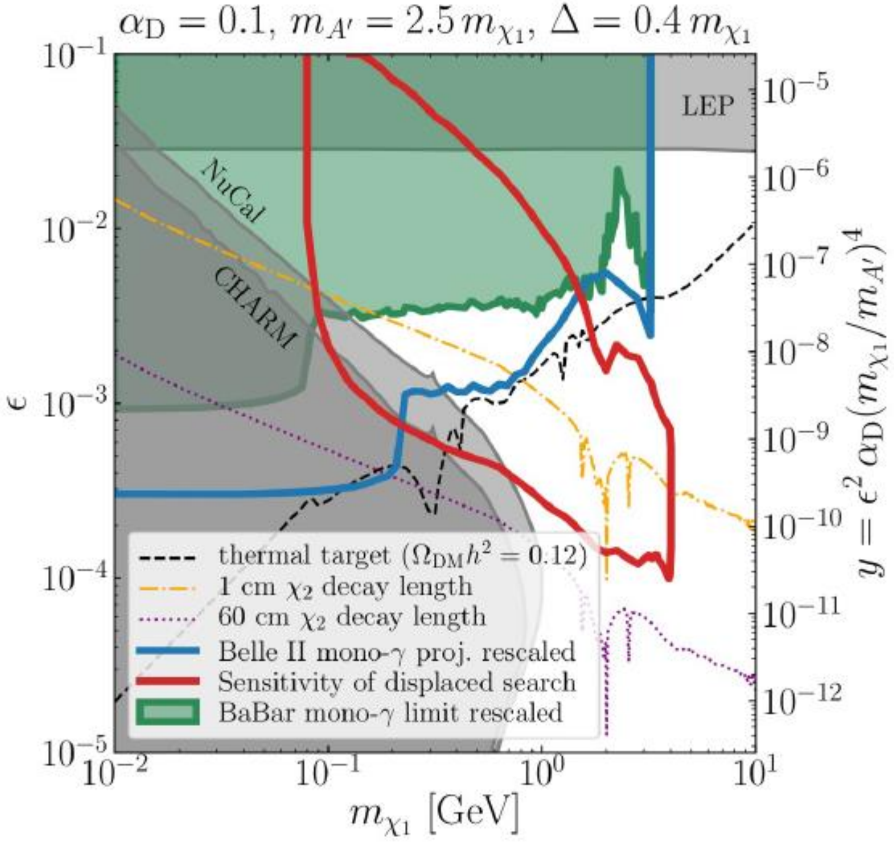
Inelastic Dark Matter (iDM) @ Belle II

Prospects

- Estimate signal yield by counting events in ISR photon energy window (final analysis will use a template fit)
- With early *Belle II* dataset expect to probe dark sector-Standard Model couplings down to 10^{-3} – 10^{-4}
- New displaced vertex trigger under consideration



Duerr et al., JHEP04 (2021) 39



State of the art @ B-factories

A lot of DM searches @ B-factories excluded Dark Sector parameters down to:

	Belle	BaBar	Belle II
$ee \to \gamma A', A' \to ll$	-	$\epsilon < 5 \times 10^{-4}$ (514 fb^{-1}) [1]	-
$ee \to \gamma A', A' \to$ invisible	-	$\epsilon < 10^{-3}$ (53 fb^{-1}) [2]	-
$B^0 \to A'A'$	BF $< 10^{-7}$ (711 fb^{-1}) [3]	-	-
$ee \to \gamma \Upsilon_D$ (DM bound state)	-	$\epsilon < 10^{-3}$ (514 fb^{-1}) [*]	-
$ee \to A'h', h' \to A'A'$	$\alpha_D \epsilon < 10^{-9}$ (977 fb^{-1}) [4]	$\alpha_D \epsilon < 10^{-9}$ (514 fb^{-1}) [5]	-
$ee \to \mu\mu Z', Z' \to ll$	$g' < 10^{-3}$ (643 fb^{-1}) [*]	$g' < 10^{-3}$ (514 fb^{-1}) [1]	-
$ee \to \mu\mu Z', Z' \to$ invisible	-	-	$g' < 5 \times 10^{-2}$ (0.27 fb^{-1}) [6]
$\eta \to \gamma A'_q, A'_q \to \pi\pi$	$\alpha_q < 5 \times 10^{-3}$ (976 fb^{-1}) [7]	-	
$ee \to \tau\tau\phi_\tau, \phi_\tau \to ll$	-	$\eta < 5 \times 10^{-1}$ (514 fb^{-1}) [8]	
$ee \to \gamma a, a \to \gamma\gamma$	-	-	$g_{a\gamma\gamma} < 10^{-3}\,\text{GeV}^{-1}$ (0.45 fb^{-1}) [9]
$B^\pm \to K^\pm a, a \to \gamma\gamma$	-	$g_{aWW} < 10^{-5}\,\text{GeV}^{-1}$ (424 fb^{-1}) [*]	-
$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \mu\mu$	-	(99, 122 $\times 10^6 \Upsilon(2S,3S)$) [10]	-
$\Upsilon(3S) \to \gamma A^0, A^0 \to \tau\tau$	-	BF $< 10^{-5}(122 \times 10^6 \Upsilon(3S))$ [11]	-
$\Upsilon(2S) \to \Upsilon(1S)\pi\pi, \Upsilon(1S) \to \gamma A^0, A^0 \to$ invisible	BF $< 10^{-6}(157 \times 10^6 \Upsilon(2S))$ [12]	BF $< 10^{-6}(98 \times 10^6 \Upsilon(2S))$ [13]	-
$\Upsilon(2S,3S) \to \pi\pi\Upsilon(1S), \Upsilon(1S) \to \gamma A^0, A^0 \to \mu\mu$	-	BF $< 10^{-6}(93, 117 \times 10^6 \Upsilon(2S,3S))$ [14]	-

State of the art @ LHCb

- Search for long-lived scalar particles in $B^+ \to K^+\chi(\mu^+\mu^-)$ decays arXiv:1612.07818 - Submitted to PRL
- Search for massive long-lived particles decaying semileptonically in the LHCb detector arXiv:1612.00945 - Submitted to EPJC
- Search for hidden-sector bosons in $B_d^0 \to K^*\mu^+\mu^-$ decays Phys. Rev. Lett. 115, 161802 (2015)
- Search for Majorana neutrinos in $B^- \to \pi^+\mu^-\mu^-$ decays Phys. Rev. Lett. 112, 131802 (2014)
- Search for long-lived particles decaying to jet pairs Eur. Phys. J. C75 (2015) 152
- Evidence for the rare decay $\Sigma^+ \to p\mu^+\mu^-$ LHCb-CONF-2016-013
- Search for Higgs-like bosons decaying into long-lived exotic particles Eur. Phys. J. C (2016) 76: 664
- Search for long-lived heavy charged particles using a ring imaging Cherenkov technique at LHCb Eur. Phys. J. C 75 (2015) 595
- Searches for Majorana neutrinos in B decays Phys. Rev. D 85, 112004 (2012)

Form F. Dettori