WIFAI 2023

Roma 09/11/2023

Dark sector particles searches at Belle II

Marcello Campajola
on behalf of the Belle II Collaboration

Marcello Campajola
Università di Napoli 'Federico II' and INFN Napoli
marcello.campajola@na.infn.it

Dark Sector searches

Motivations & Models

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

Possible light dark matter (LDM) theoretical scenarios foresee:

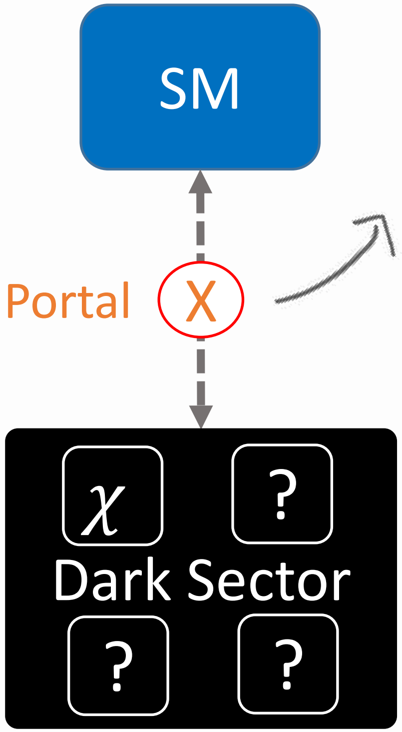
- LDM part of a hidden or dark sector, feebly interacting with SM via a new light mediator (referred as **‘portal’**):

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

Vector portal | Higgs portal | Neutrino portal

only a small number of possible portal interactions between Dark Sector and SM (e.g. [1]);

Not just solving the DM puzzle. Often offer solution to SM anomalies.



Non-gravitational interaction with matter

- Dark matter;
- Dark Forces;
- ……

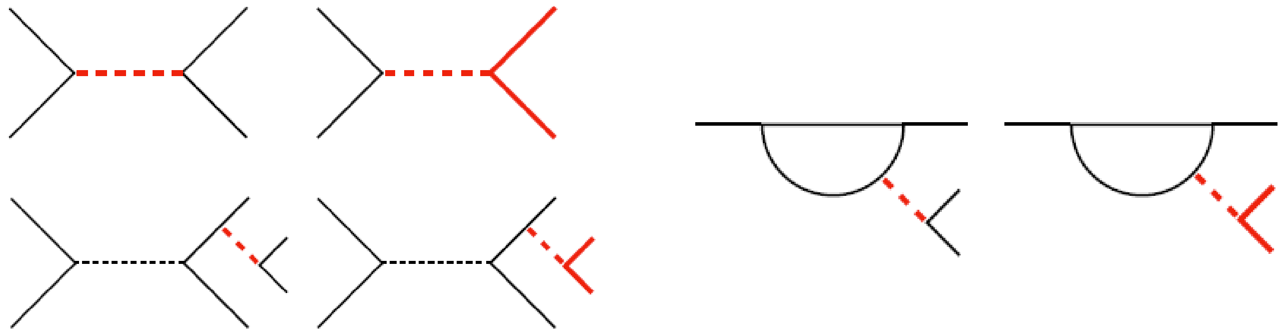
Dark Sector searches

Collider strategies

Probability of interaction of LDM with the detectors is negligible.
↳ Searches at collider usually focuses on mediators rather than DM itself.

Two general strategies:

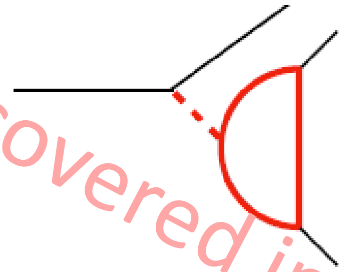
Direct production



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



loop induced effects
- probe very high mediator masses

not covered in this talk

The Belle II detector

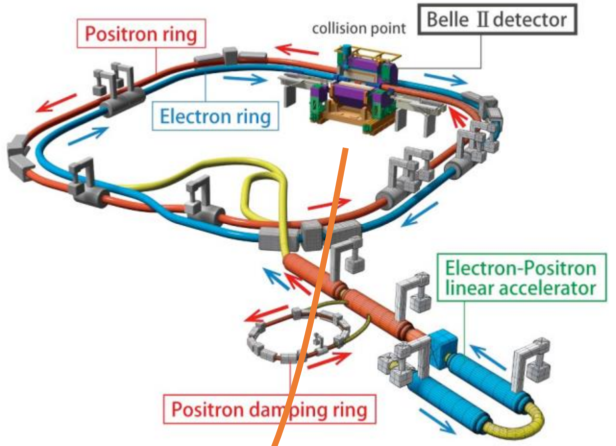
Experiment overview

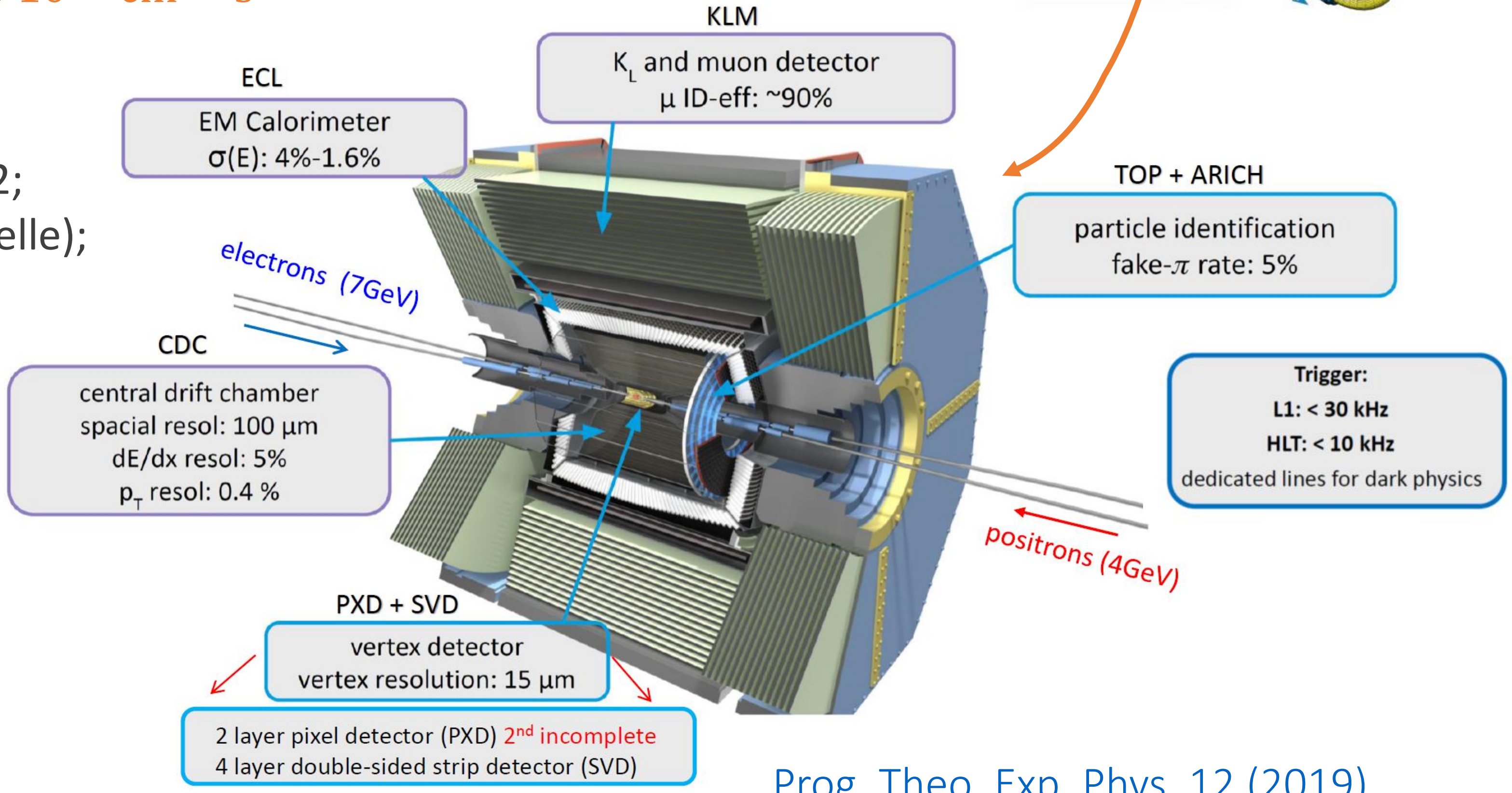
Belle II is a ~4π detector @ SuperKEKB collider (Tsukuba, JP):

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

Data taking:

- Currently on first shutdown since July 2022;
- ~ 430 fb^{-1} collected to date (~ Babar, ~ ½ Belle);
- Run 2 starts coming winter;
- Target: 50 ab^{-1} in the next decade





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

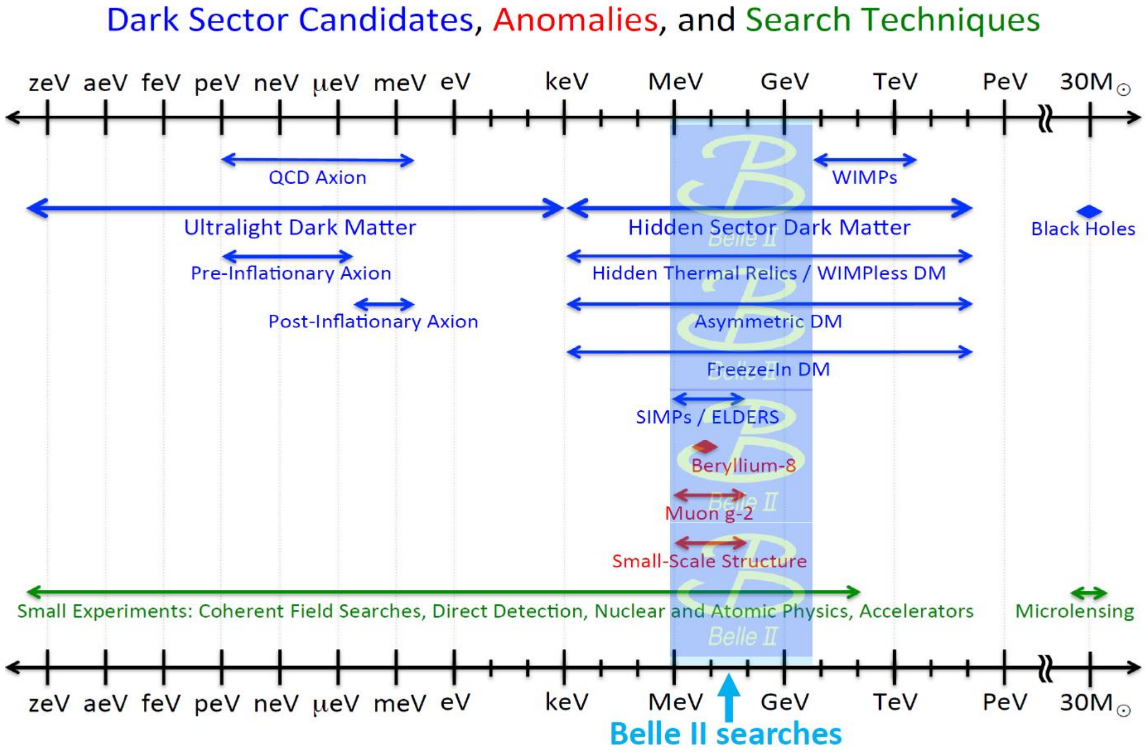
The Belle II detector

Key factors for dark sector physics

Belle II able to investigate the mass range naturally favored by light dark sector

DS searches @ Belle II benefit of:

- High luminosity;
- Clean environment, low background;
- Well defined initial state;
- Hermetic detector;
- Excellent PID;
- Dedicated trigger for low multiplicity final states:
  - single photon, single muon, single track, displaced-vertex in preparation;



- Low multiplicity signatures possible;
- Efficient reconstruction of missing energy and recoiling system <-> signature of invisible particle;
- Full event interpretation for DS searches in B and τ decays available;

Dark Sector searches

Signatures @ colliders

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

- If DM kinematically accessible -> invisible decay:
  - Missing energy or momentum signature;
- If decay to SM -> visible decay:
  - bump hunt search;

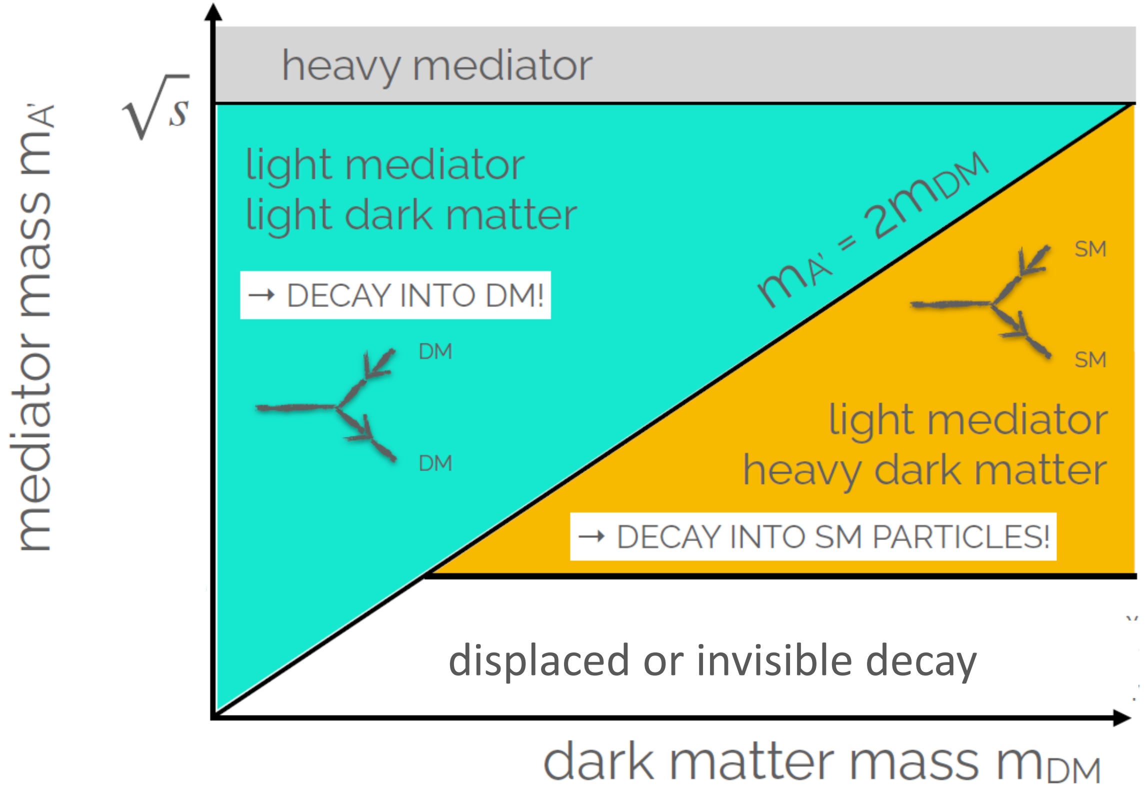
An additional player: **mediator lifetime.**

- Usually life-time is proportional to some power of the coupling and of the mediator mass

lifetime ⟺ **decay length**

- Long lifetime:
  - decay-length < O(1)m: displaced decay vertices;
  - decay-length > O(1)m: decay outside the detector;

~ drift chamber radius



The Z’ search saga

Phenomenology

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

Gauging $L_\mu - L_\tau$, the difference of leptonic μ and τ numbers:

- new gauge boson which couples only to the 2nd and 3rd lepton family;
- anomaly free (by construction);

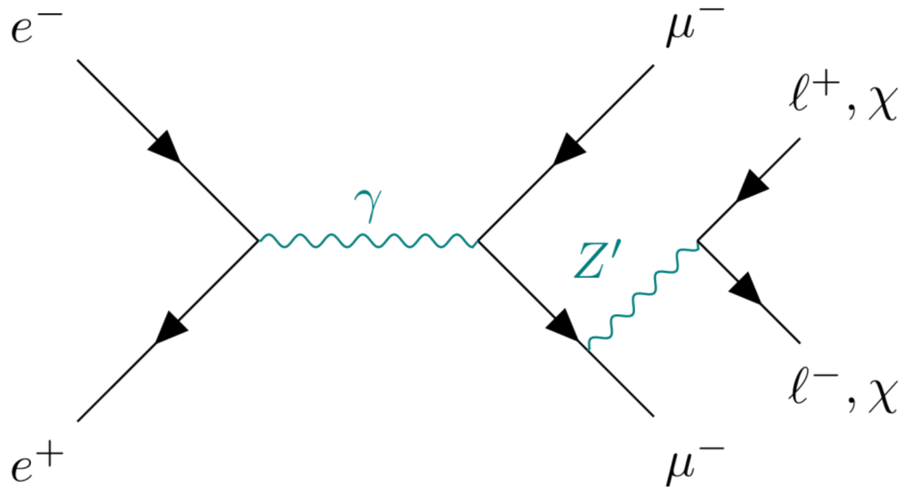
Could explain [1], [2] **:**

- $(g\text{-}2)_\mu$ anomaly;
- DM phenomenology; → Sterile neutrinos; Light dirac fermions;
- ~~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 constraints from Belle II (2020), NA64-e(2022)

brand new @ Belle II



@ Belle II search for:

$$e^+e^- \to \mu^+\mu^- Z'$$
$$Z' \to invisible;\ \mu\mu;\ \tau\tau;$$

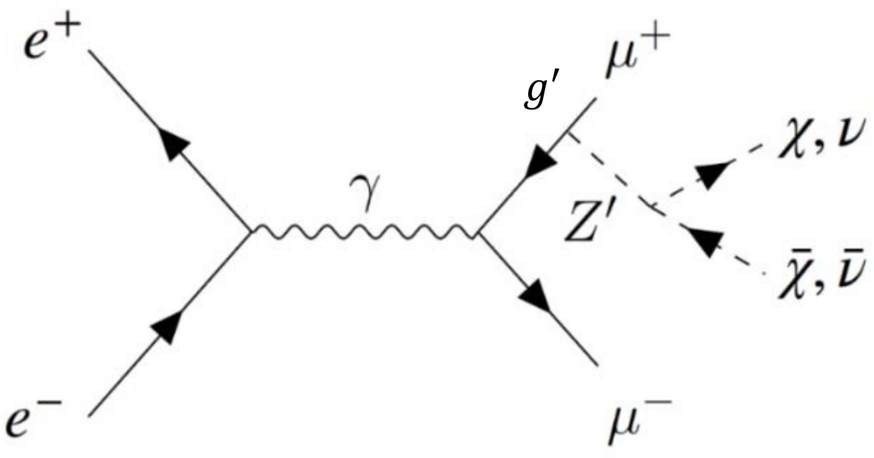
Search for an invisible Z’

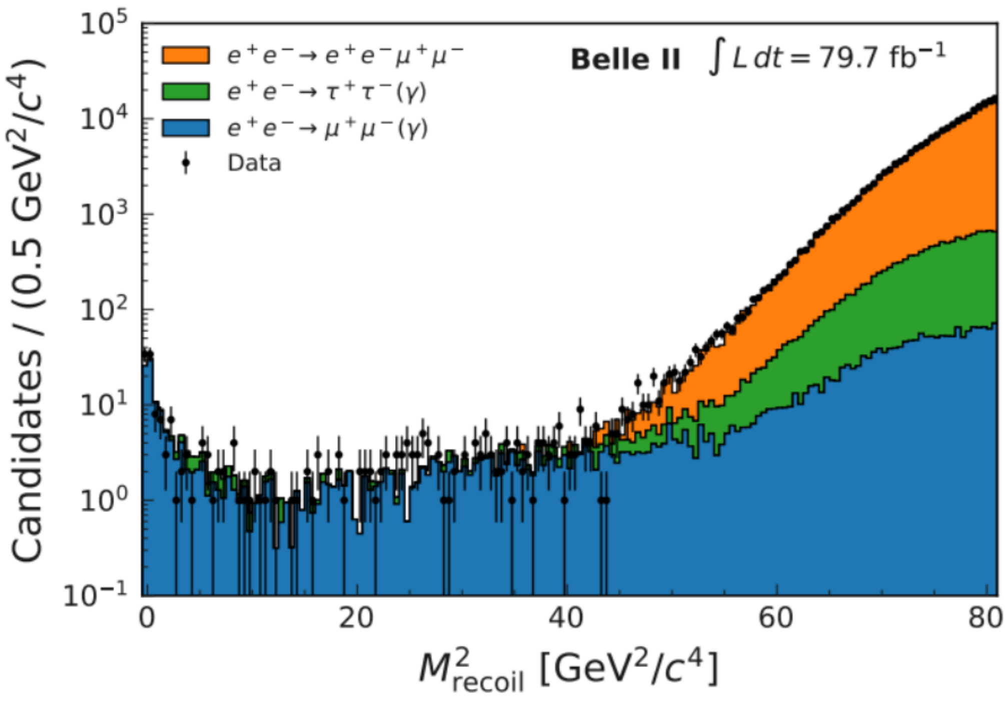
Strategy

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

Analysis in short:

- muons used to reconstruct recoil mass (peaking for Z’ signal);
- Background from QED processes with 2 particles identified as muons and missing momentum. Mainly due to $\mu\mu(\gamma), \tau\tau, ee\mu\mu$;
- Analysis selections:
  - Two opposite sign muon tracks; $p_T^{\mu\mu} > 0.1$ GeV/c
  - Recoil points to barrel calorimeter ($M_{\text{recoil}} < 2\ \text{GeV/c}^2$);
  - Low activity in the calorimeter; γ veto;
  - Neural-Network exploiting FSR nature of Z’ production;
- Signal extraction by fitting over the 2d distribution θ_{recoil} vs. M^2_{recoil};





First measurement with 2018 dataset: ~279 pb^{-1};

New analysis with 2019-20 dataset: ~ 79.7 fb^{-1}

- higher luminosity; analysis strategy improved; new triggers.

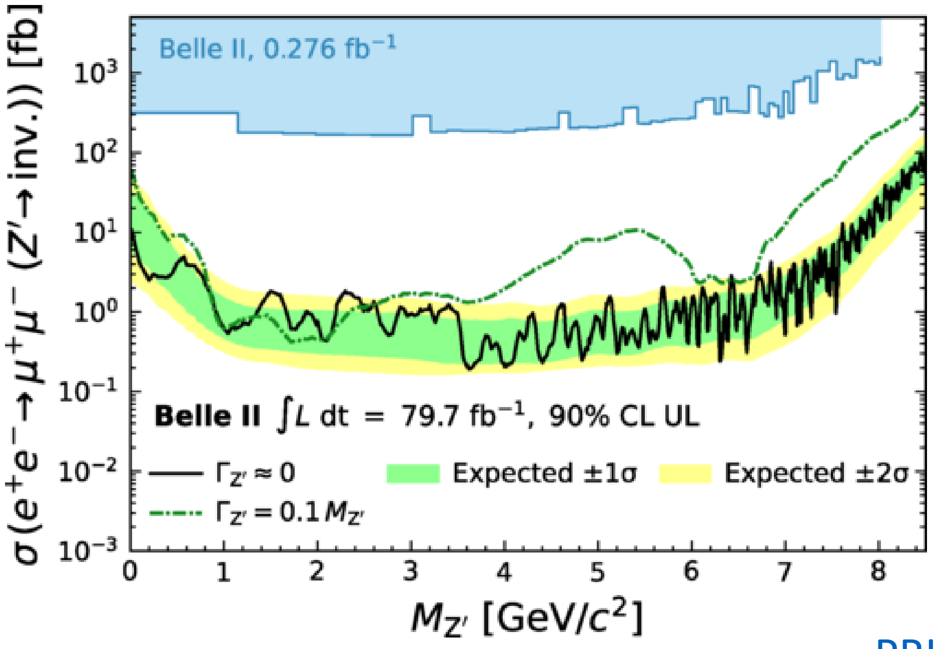
Search for an invisible Z'

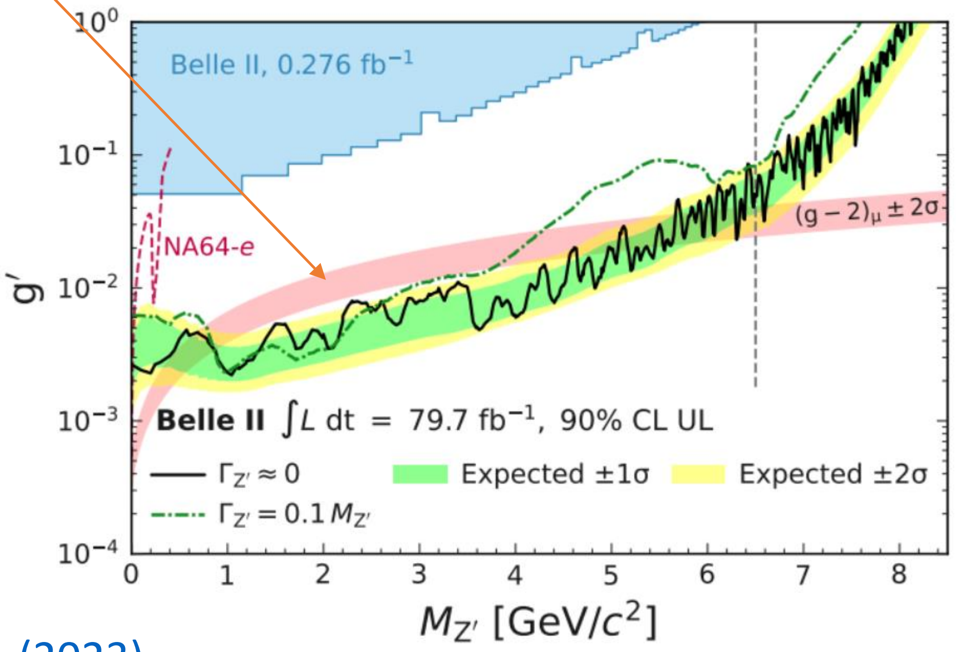
Results

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 exclusion of a fully invisible Z' boson as an explanation of the $(g-2)_\mu$ anomaly for 0.8 < $M_{Z'}$ < 5 GeV/c^2;**

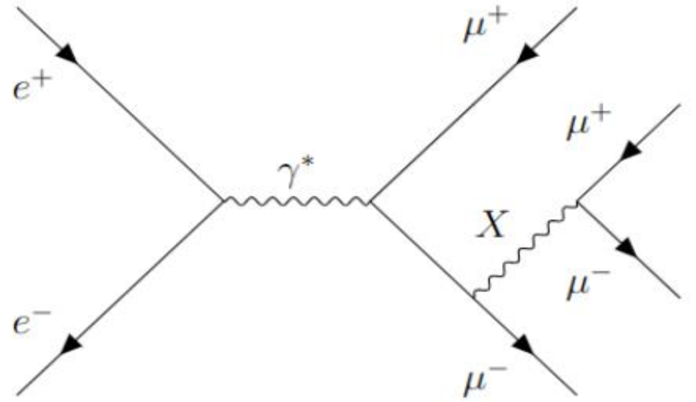




PRL 130, 231801 (2023)

Search for Z' decay in $\mu\mu$

Strategy



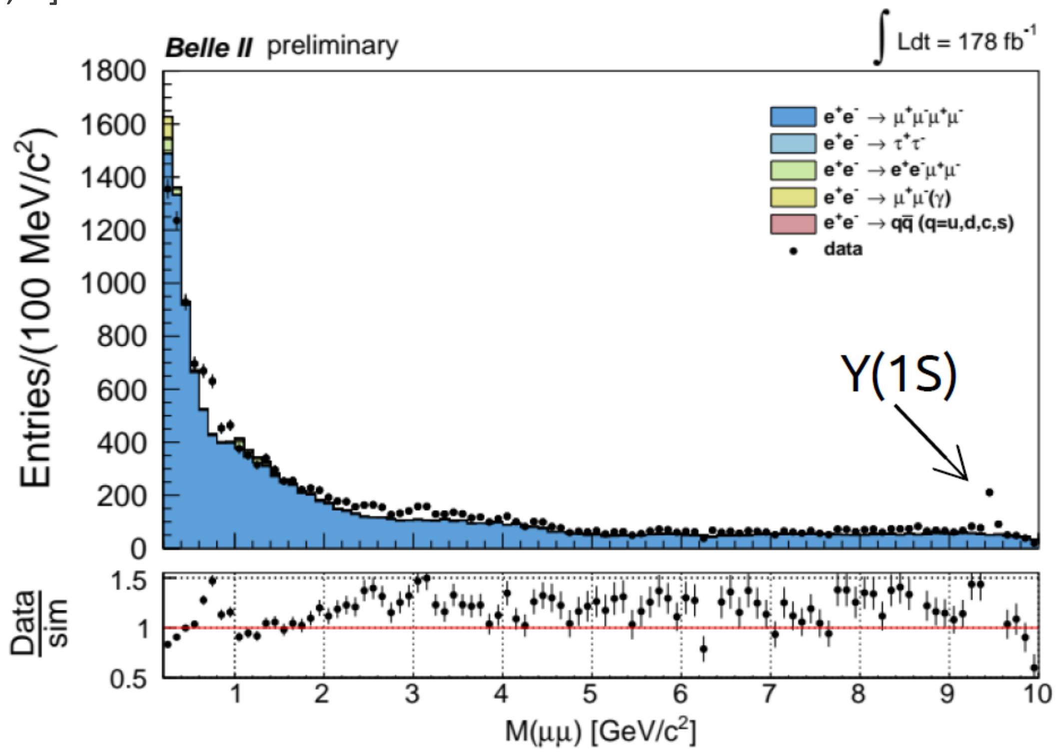
Search for di-muon resonance in 4 muon events with 178 fb^{-1}

- Z' model as benchmark;
- Reinterpreted also as muonphilic dark scalar S;

may explain: $(g-2)_\mu$ [1, 2]

Selections in brief:
- At least three muons identified;
- Total charge zero;
- M(4 tracks) ~ beam energy;
- No extra energy;
- Multi-layer Perceptron (MLP) based background suppression;

Analysis strategy:
- Fit on the dimuon reduced mass spectrum;



[1] P. Harris, P. Schuster, and J. Zupan, arXiv:2207.08990 [hep-ph];
[2] R. Capdevilla, D. Curtin, Y. Kahn, and G. Krnjaic,J. High Energy Phys. 04 (2022) 129

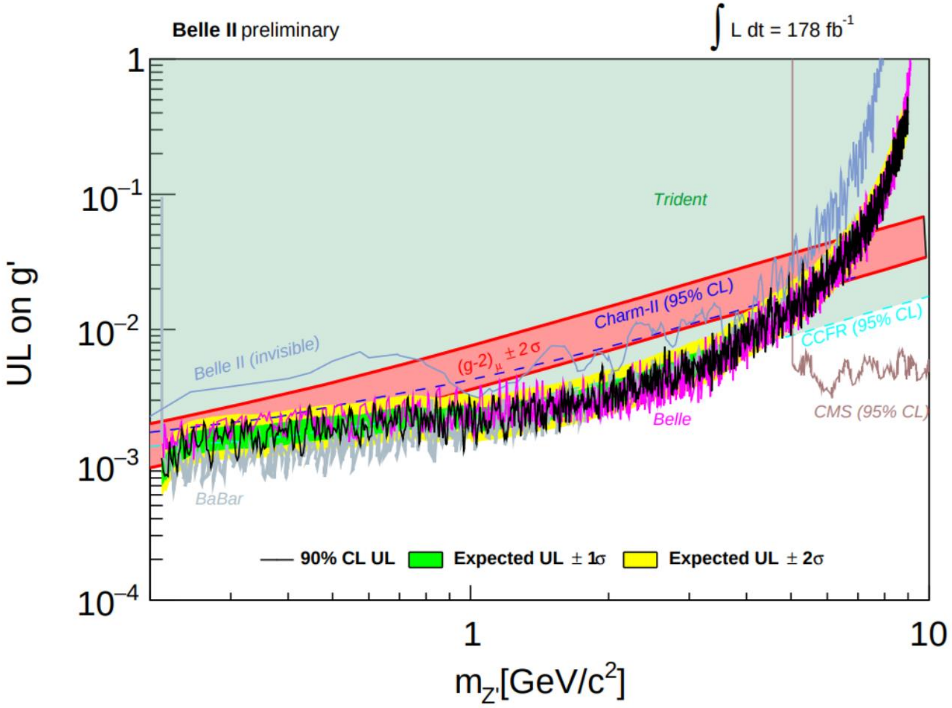
Search for Z’ decay in $\mu\mu$

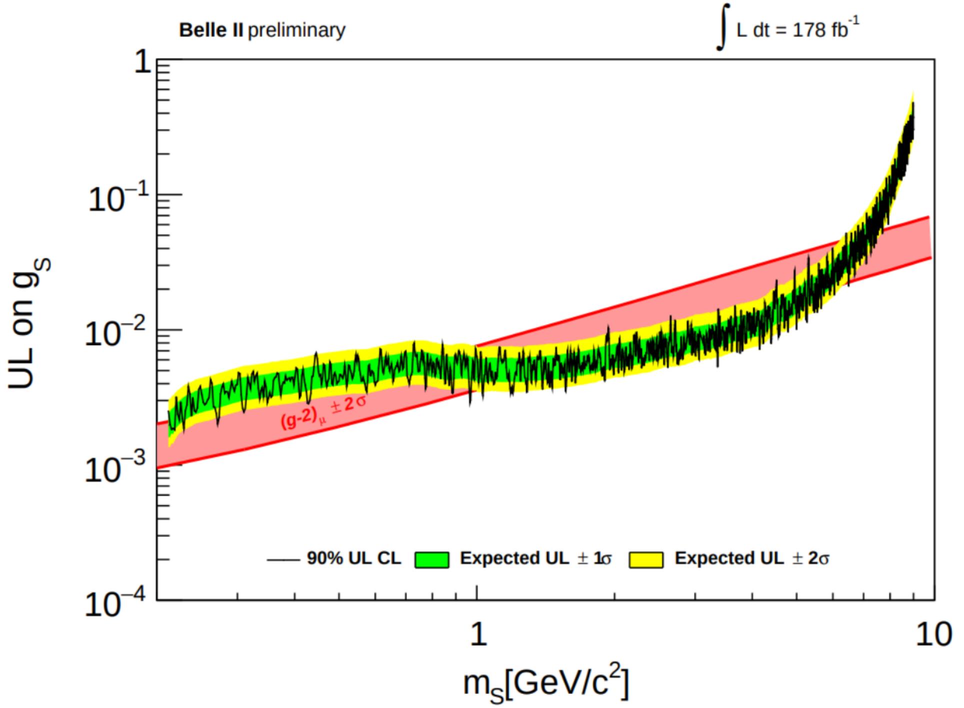
Results

No excess found -> 90% CL upper limits on the process cross-section: **$\sigma(e^+e^- \to X\ \mu^+\mu^-)$** x **$B(X \to \mu^+\mu^-)$**, with X = Z’, *S*

Results translated into upper limits on the coupling constant:

- g' for the $L_\mu - L_\tau$ model (results comparable to Babar and Belle results with much less luminosity);
- g_s for the muonphilic dark scalar S → first limits on S with a dedicated search;





To be submitted to PRD

Search for $\tau^+\tau^-$ resonance in $\mu\mu\tau\tau$ events

Strategy

[1] B. Batell, N. Lange, D. McKeen, M. Pospelov, and A. Ritz, Phys. Rev. D 95, 075003 (2017)
[2] M. Bauer, M. Neubert, and A. Thamm, J. High Energy Phys. 2017, 44 (2017)

Search for a di-tau resonance with 63.3 fb^{-1} :

$$e^+e^- \to \mu^+\mu^- X, \quad X \to \tau^+\tau^-$$

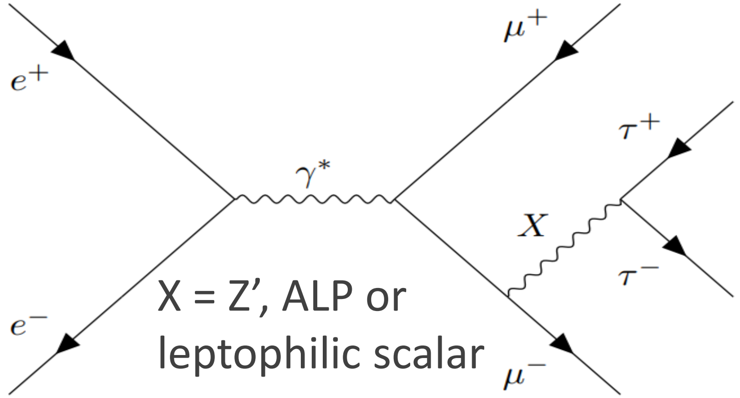
(first time search)

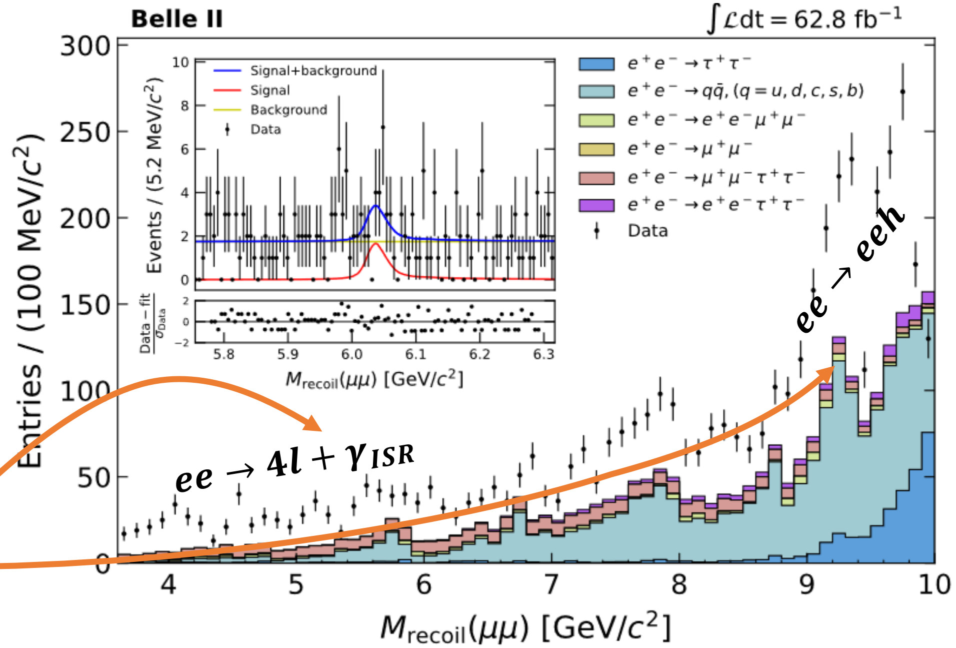
Z' model as benchmark. Results re-cast for:

- Leptophilic scalar **S** [1];
- **Axion-like-particle** with tau couplings [2];

Analysis in brief:

- Select taus decays to one-charged particle (+nh^0)
- Event signature is four tracks (2 μ) with missing energy;
- Muons used to compute recoil mass (peaking for signal);
- Dominant background from 4 leptons suppressed by M(4tracks) < 9.5 GeV/c^2;
- MLP exploiting the FSR nature of the signal and that the system recoiling against the 2 muons is a tau pair.





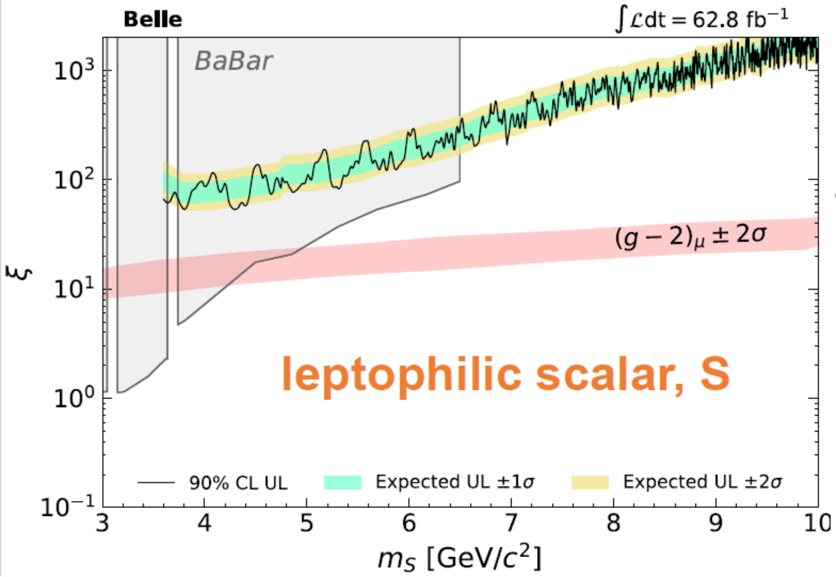
Data/simulation discrepancy from non-simulated/unmodeled processes
Background determined directly in data

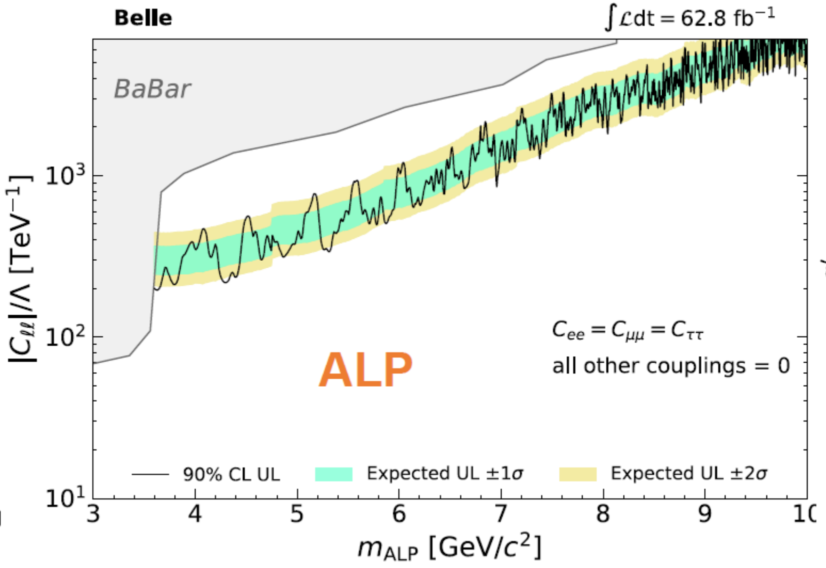
Search for $\tau^+\tau^-$ resonance in $\mu\mu\tau\tau$ events

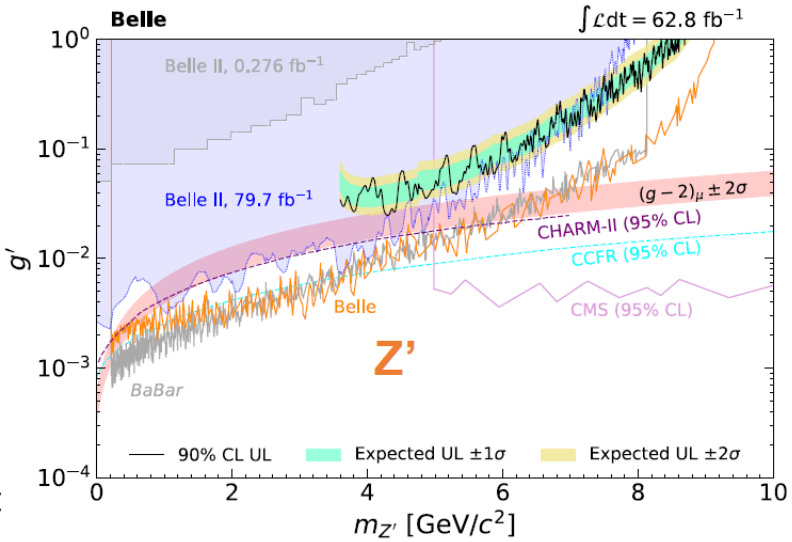
Results

No excess found. -> 90% CL upper limits on the cross section: **$\sigma(e^+e^- \to (X \to \tau^+\tau^-)\,\mu^+\mu^-) = \sigma(e^+e^- \to X\,\mu^+\mu^-)B(X \to \tau^+\tau^-)$**, with X = S, ALP, Z'

- Results translated to limits on leptophilic scalar, ALP and Z' mediator couplings:
  - **First constraints on S for M_S > 6.5 GeV/c^2 ;**
  - **First direct constraints for ALP → $\tau\tau$;**







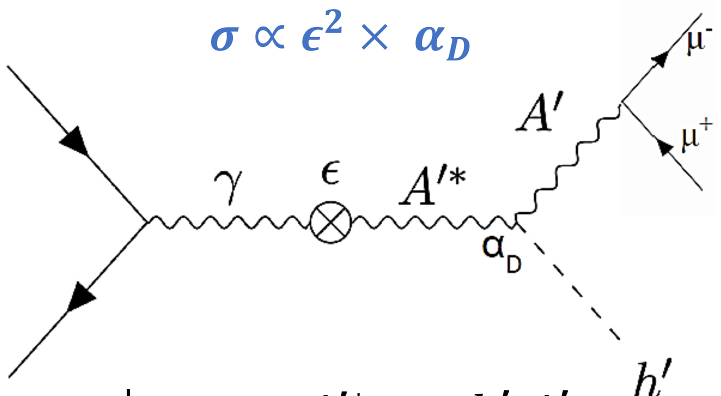
PRL 131, 121801 (2023)

Dark Higgsstrahlung search

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

Strategy

$\sigma \propto \epsilon^2 \times \alpha_D$



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

Massive (spin=1) gauge boson A' coupling to the SM hypercharge through the kinetic mixing with strength ε:

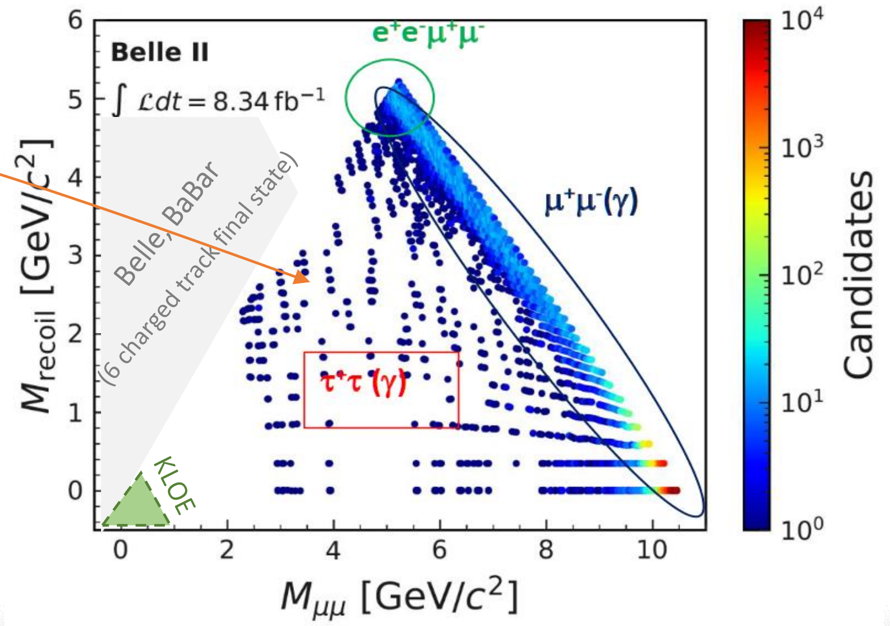
- A' mass generated by adding a dark Higgs boson h' to the theory [1];

Searching for A', h' production in a **dark Higgsstrahlung** process, with the hypothesis of $M_{h'} < M_{A'}$: h' is long-lived -> invisible.

Analysis in brief:

- two tracks + missing energy and a 2D peak in $M^2_{\mu\mu}$ vs M^2_{recoil}:
  - scan and count in search windows;
- Backgrounds mainly due to $\mu\mu(\gamma), \tau\tau, ee\mu\mu$;
- Analysis selections:
  - 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



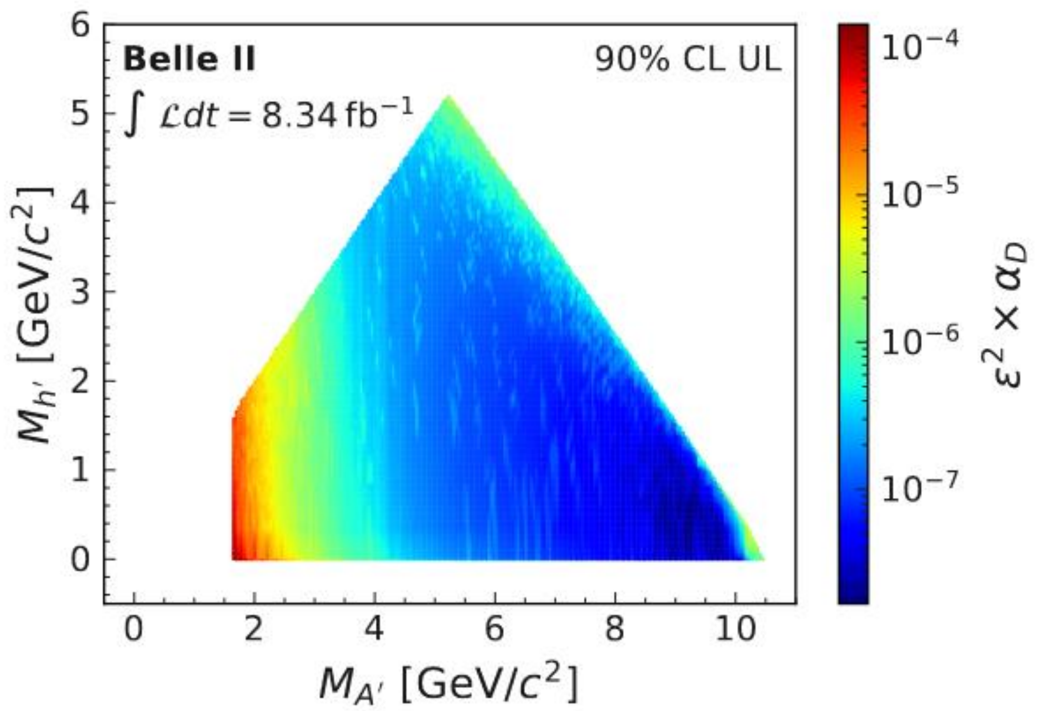
Dark Higgsstrahlung

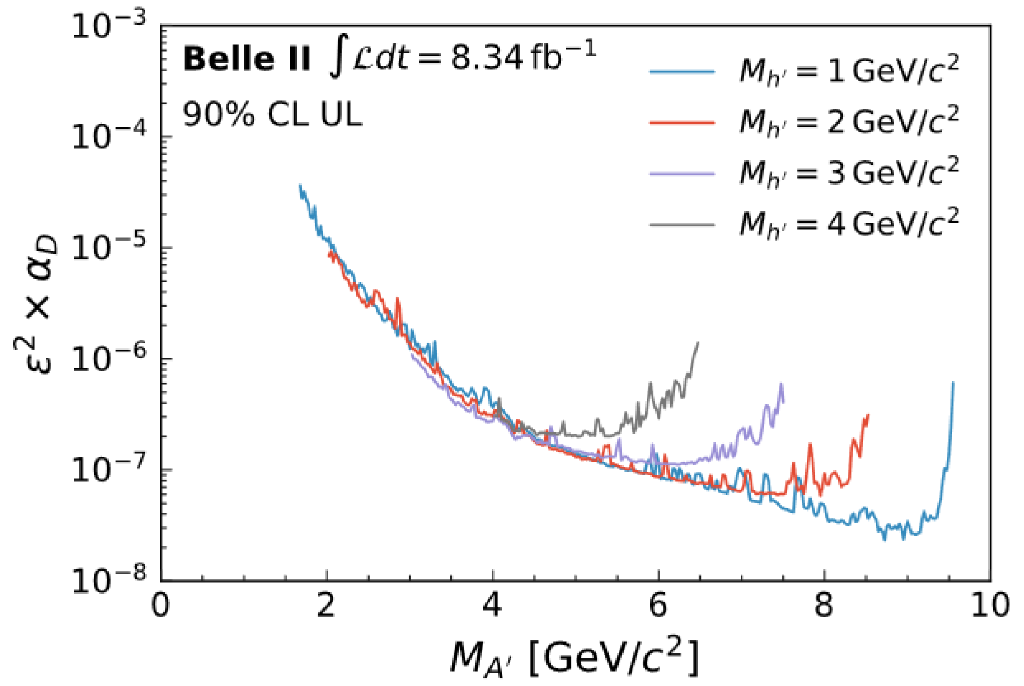
Results

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

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

- **World's first results for 1.65 < $M_{A'}$ < 10.51 GeV and $M_{h'}$ < $M_{A'}$**





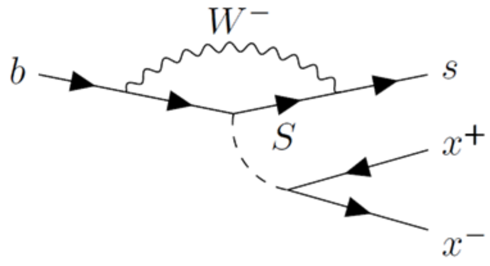
PRL 130, 071804 (2023)

Light (pseudo)scalars in B-meson decays

Strategy

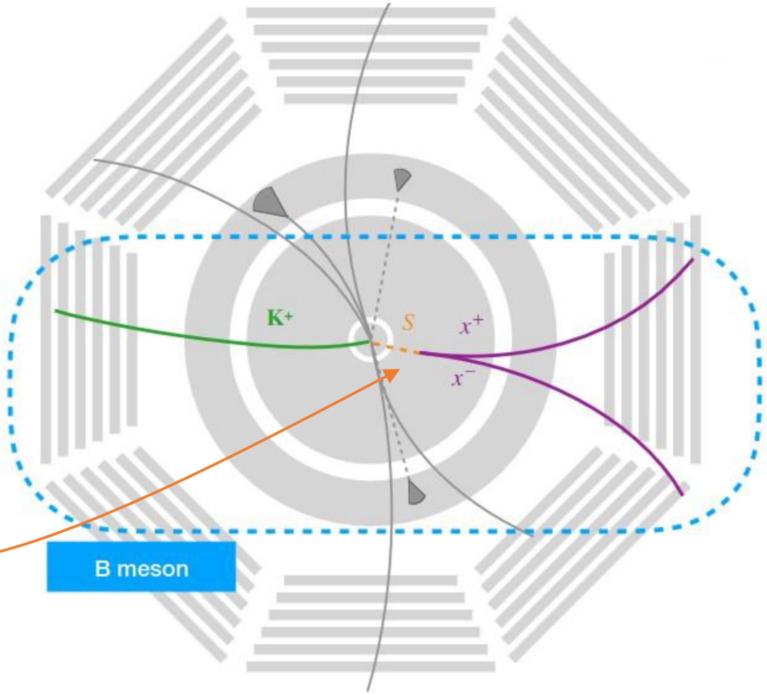
Extensions of SM predict **dark matter mass generation via light scalar S** that can mix with the SM Higgs boson with angle θ

S could be produced in b to s transitions:
- $B^+ \to K^+ S$;
- $B^0 \to K^{*0}(\to K^+\pi^-)S$;



At small angles S is **long lived**:
- prompt K + two opposite signed tracks from a **displaced vertex;**

Transverse view of the Belle II detector



Probe lifetimes between $10^{-5} < c\tau < 4\,\mathrm{m}$

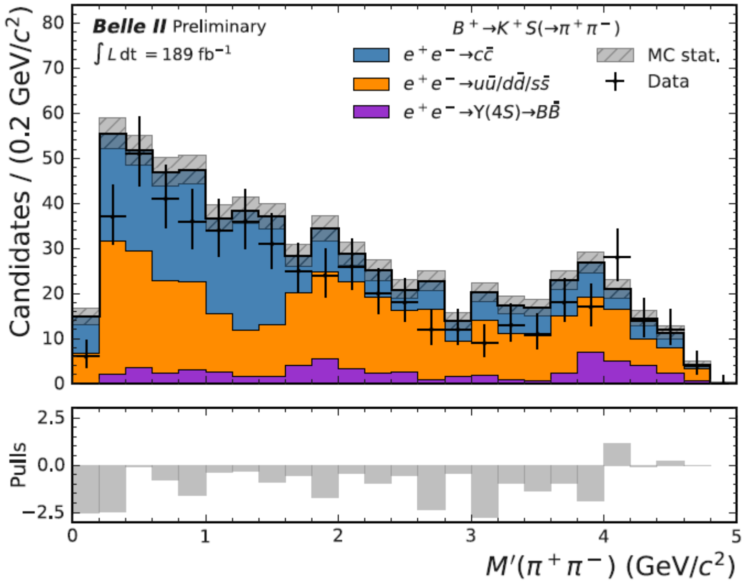
Strategy:
- Look for S decays into $ee, \mu\mu, \pi\pi, KK$;
- Search for a bump in the reduced invariant mass of tracks coming from a displaced vertex: $M'(x^+x^-) = \sqrt{M^2_{S\to x^+x^-} - 4m_x^2}$
- Require signal B to be fully reconstructed for background rejection ($ee \to q\bar{q}$);
- SM long-lived K_S^0 mass region vetoed;
  - excellent control sample in data to evaluate LLP performance (efficiencies, shapes);

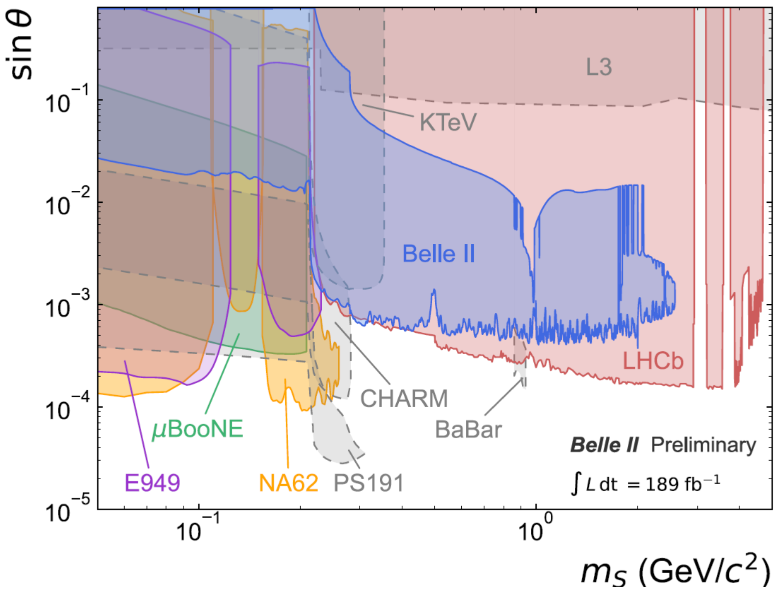
Light (pseudo)scalars in B-meson decays

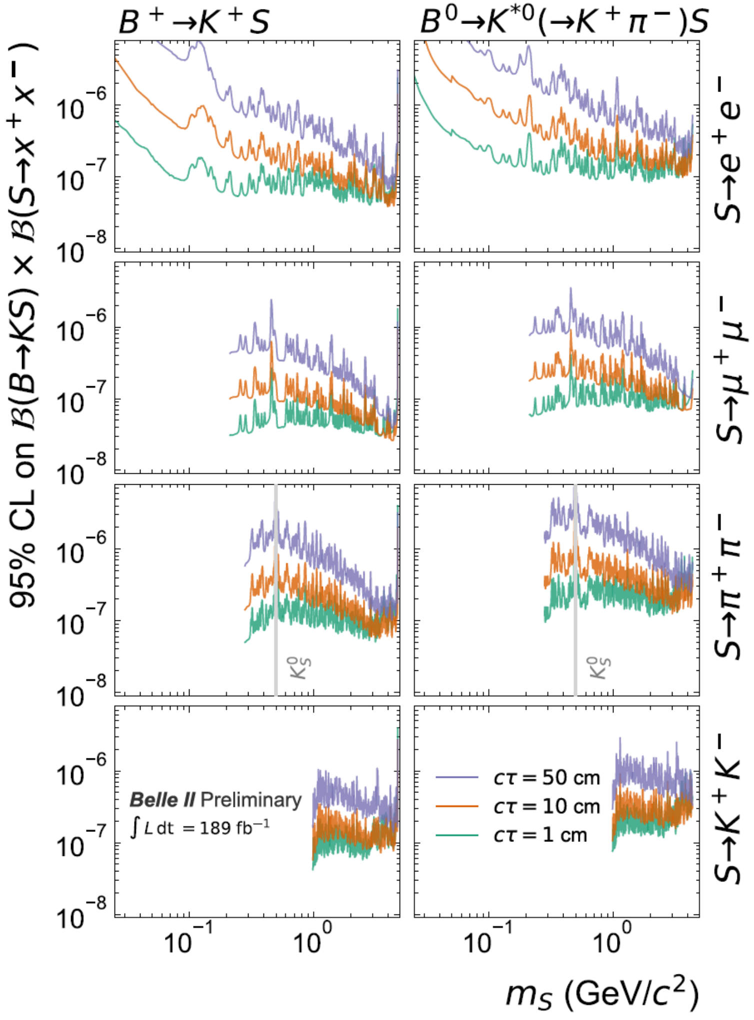
Results

No significant excess observed in 189 fb^{-1}.

- First limits on exclusive hadronic final states;
- Best sensitivity for direct search for $K^* e^+ e^-$ final state;
- Dark Higgs-like scalar interpretation ;
- Pseudo-scalar (ALP) interpretation;







Submitted to PRL, arXiv:2306.02830

Invisible boson in lepton-flavor violating τ decays

Strategy

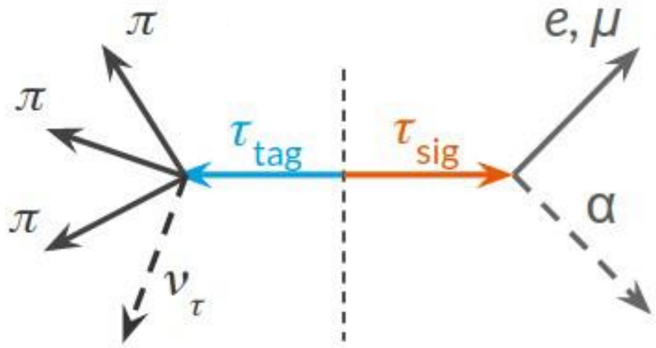
[1] M. Bauer, et al. Phys. Rev. Lett. 124, 211803 (2020)

Look for an invisible α boson produced in a LFV tau decay

τ→ℓα

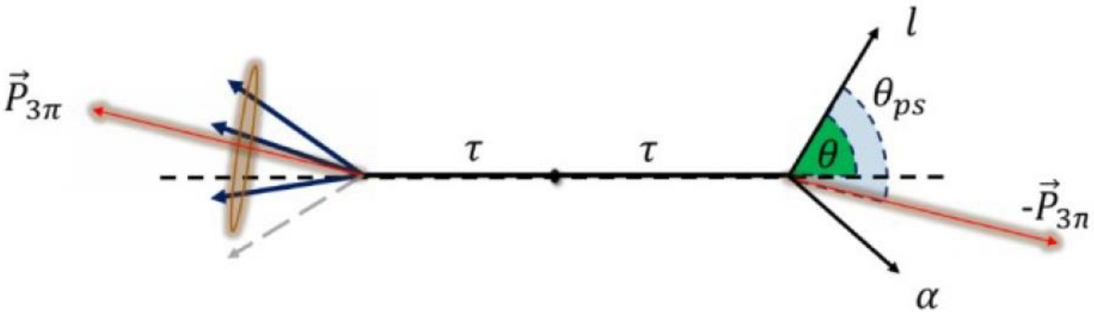
α→invisible

α can be an ALP candidate [1].

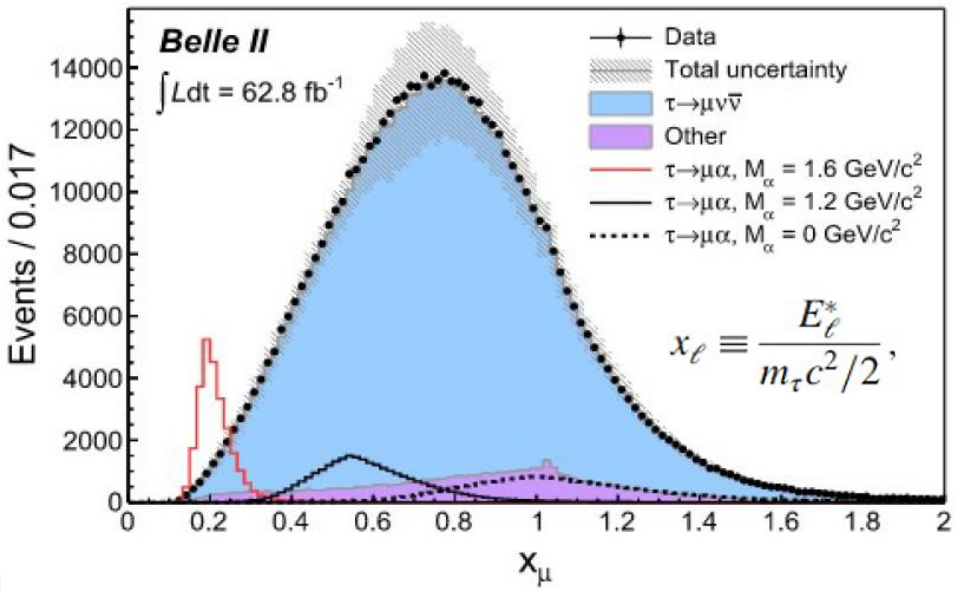


Analysis in brief:

- three tracks on the **tag** side, one track on the **signal** side (ℓ=e or ℓ=μ);
- background from **τ_{SM}→ℓνν**
- exploit the **shape differences**: *2-body* decay for signal (peaking in the normalized lepton energy x_l in the **τ_{sig}** pseudo-rest frame) over *3-body* decay of irreducible background;



approximate **τ_{sig}** pseudo-rest frame as $E_{sig} \sim \sqrt{s}/2$ and $\hat{p}_{sig} \approx -\vec{p}_{\tau_{tag}}/|\vec{p}_{\tau_{tag}}|$



Invisible boson in lepton-flavor violating τ decays

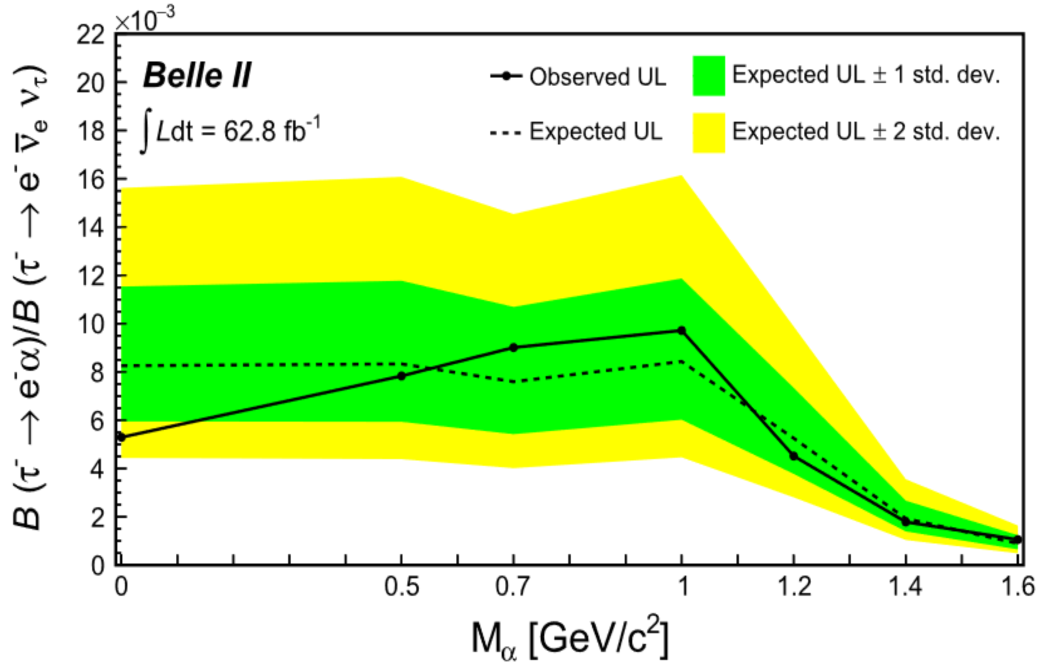
Results

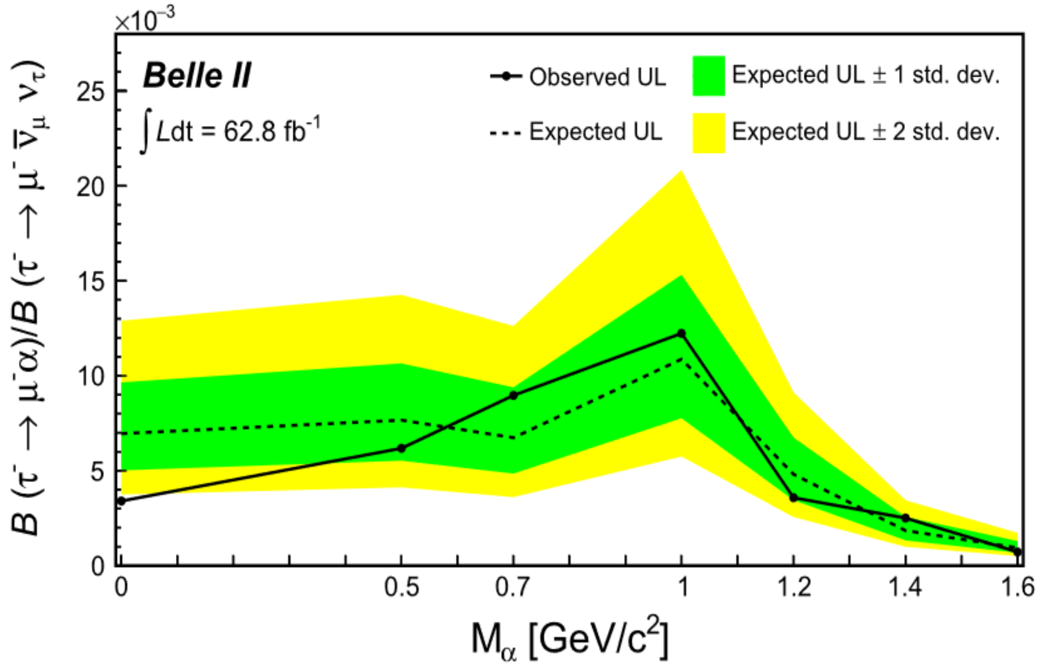
[1] ARGUS Collaboration, Z. Phys. C 68, 25 (1995)

No significant excess in 62.8 fb^{-1}.

95% CL upper limits on BF ratios of **BF(τ_{sig} →ℓα)** normalized to BF(τ_{SM}→ ℓνν);

- 2-14 tighter limits on the previous Argus results [1];



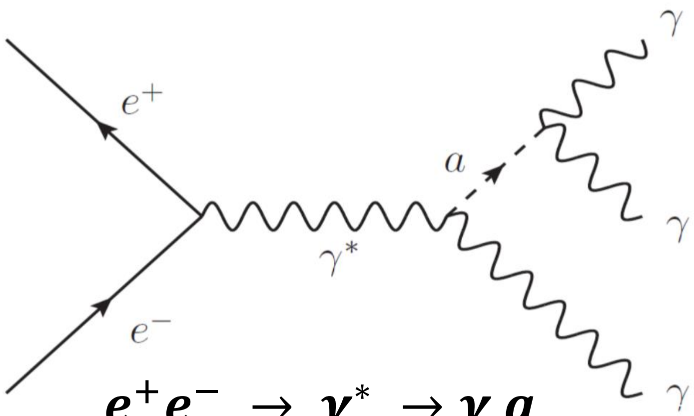


PRL 130, 181803 (2023)

Search for the ALP-strahlung

Results

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



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

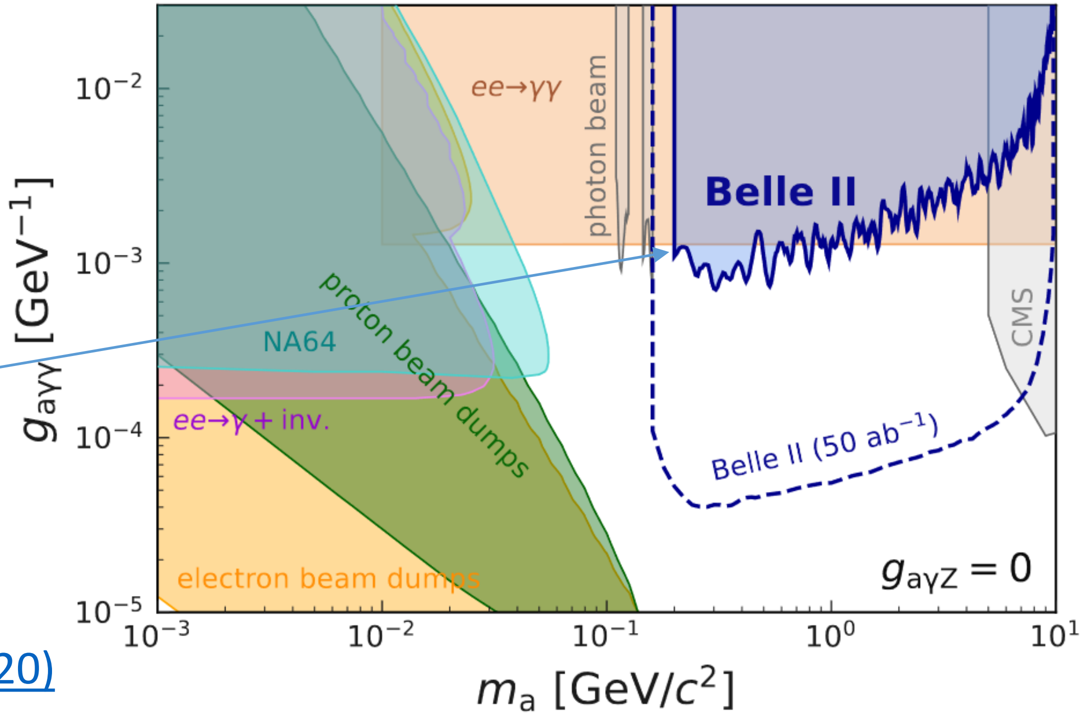
Analysis in brief:

- 3γ that add up to the beam energy;
- Search for a peak either in the recoil invariant mass (high ma) or in the diphoton mass (low ma);
- Background from $\gamma\gamma(\gamma)$; $e^+ e^- (\gamma)$; $P\,\gamma(\gamma)$ $with\ P = \pi^0, \eta, \eta'$;

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

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

- First results ever for ALPs @ B-factories



PRL **125**, 161806 (2020)

Conclusions

It's a great time to explore physics beyond SM…

- many new theoretical possibilities opened, expecially in the dark sector.

e^+e^- B-factories provide unique opportunities to explore dark sector;

- **Belle II has an intensive DS physics program and already provided competitive limits on several models.**

Results shown today on :

- Z' searches: $Z' \to \mu\mu$; $Z' \to \tau\tau$; $Z' \to$ invisible;
- $\mathrm{ALP} \to \gamma\gamma$;
- Dark Higgsstrahlung: $A'h'$ $A' \to \mu\mu, h' \to$ invisible;
- Invisible α in LFV tau decay;
- LLP dark scalar in B decays;

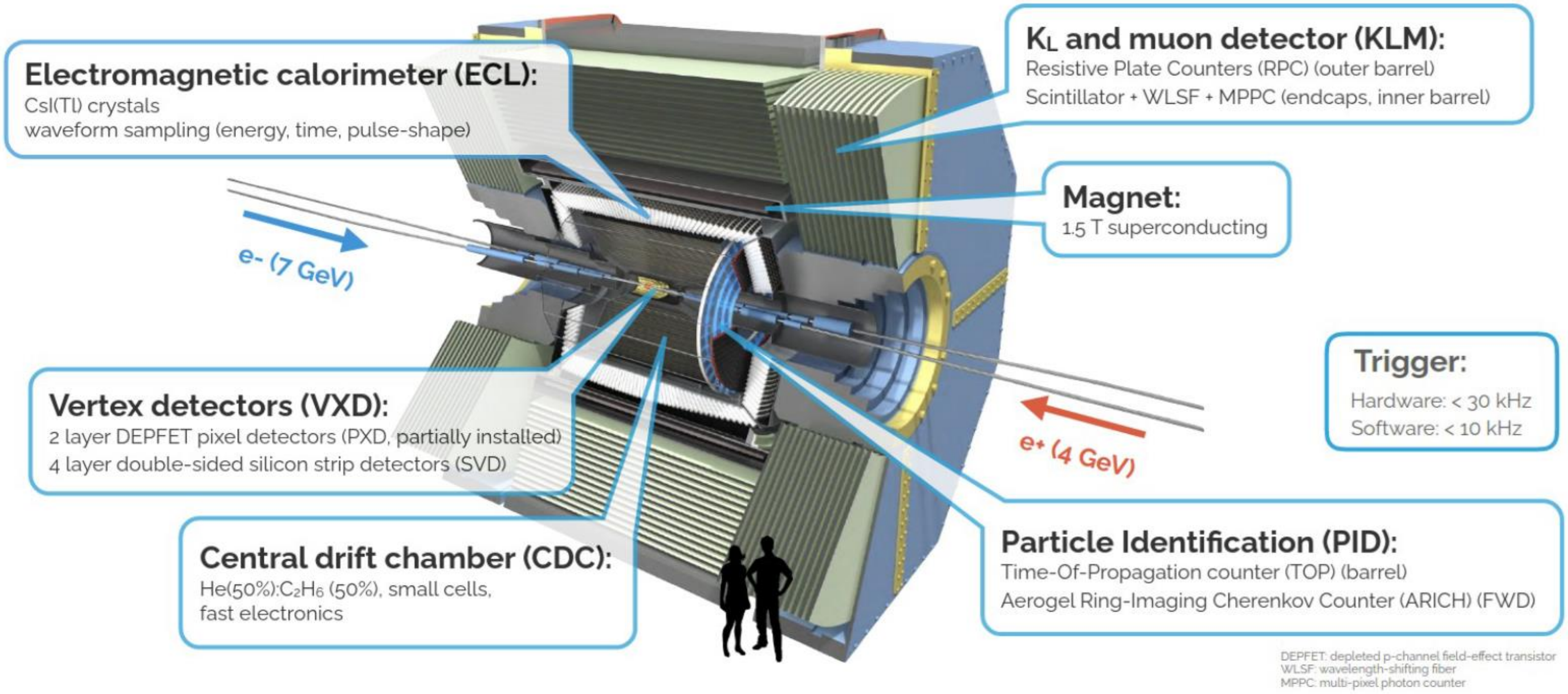
Future prospects:

- Increased luminosity and improved strategies:
  - 2nd generation analyses with new best sensitivities;
- Will enter into the dark photon business: both visible and (especially) invisible;
- LLP searches will have a considerable weight in the next years;

More on future searches @ Belle II in the Snowmass report (arXiv:2207.06307)

Spares

Belle II detector



Belle II trigger

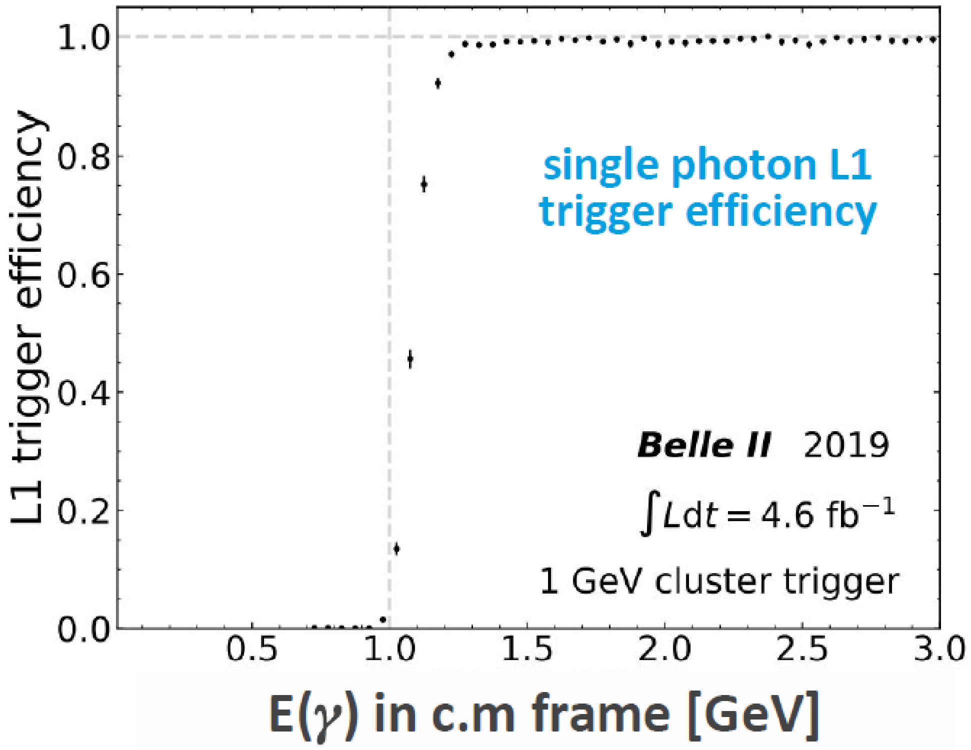
Performances

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



Dark Sector searches

Signatures @ colliders

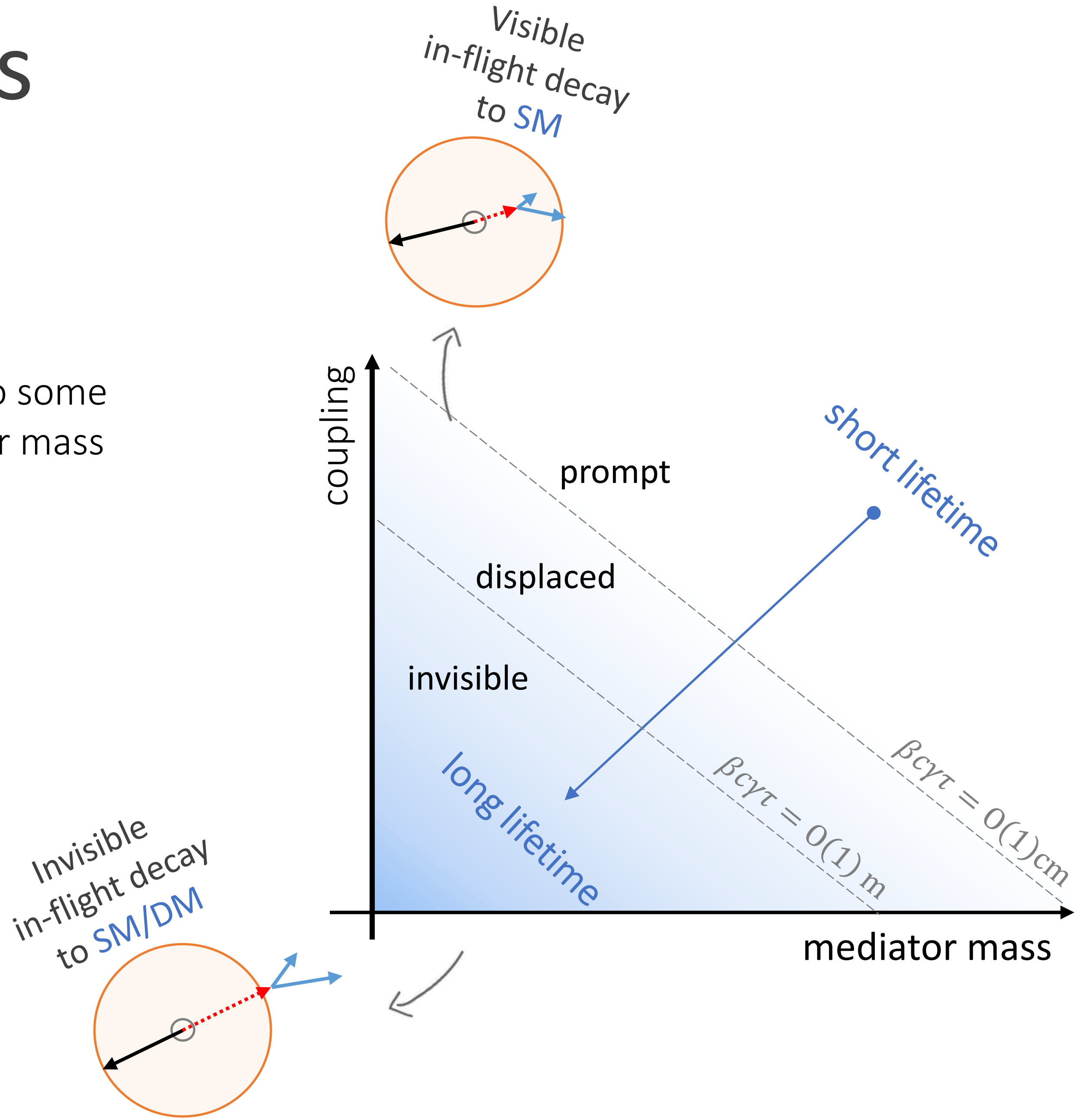
An additional player: **mediator lifetime.**

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)



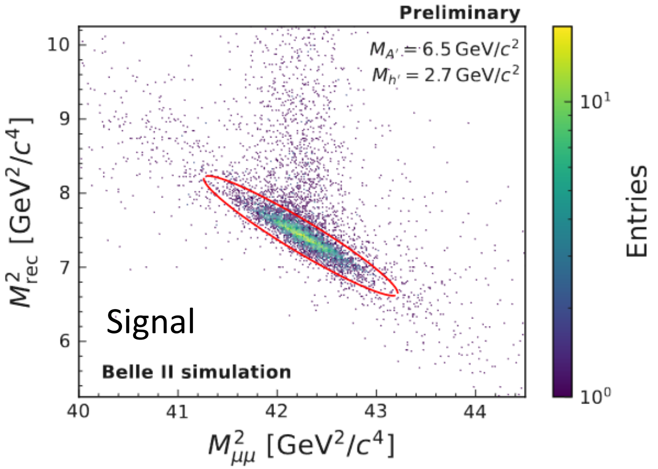
Dark Higgsstrahlung

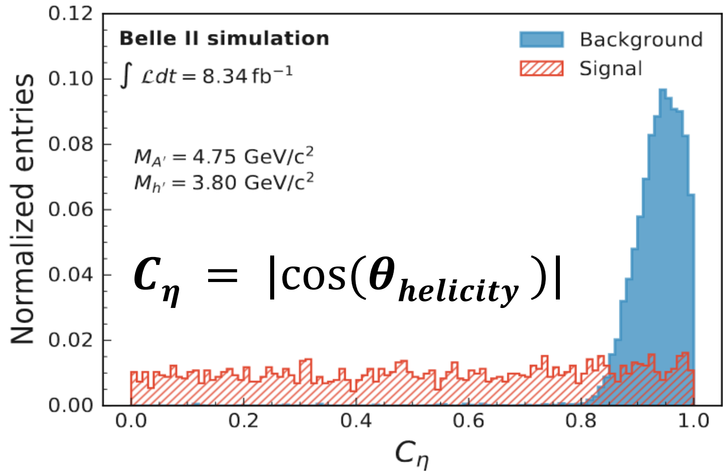
Strategy

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

Signature:

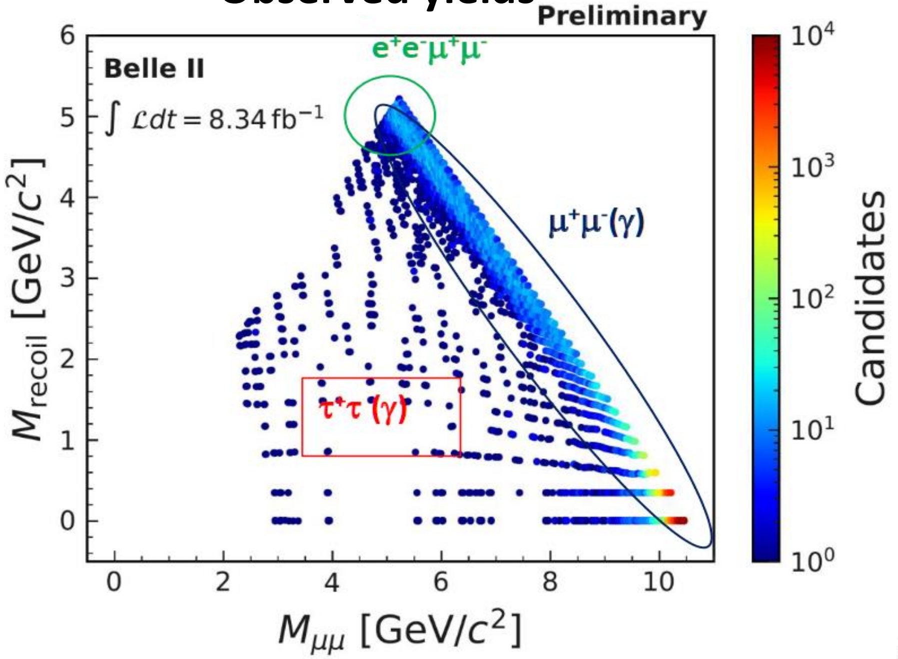
- Two opposite sign muons + missing energy
- 2D peak in $M^2_{\mu\mu}$ vs M^2_{recoil}:
  - scan and count in search windows
  - ~9000 2D elliptical windows





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

Observed yields

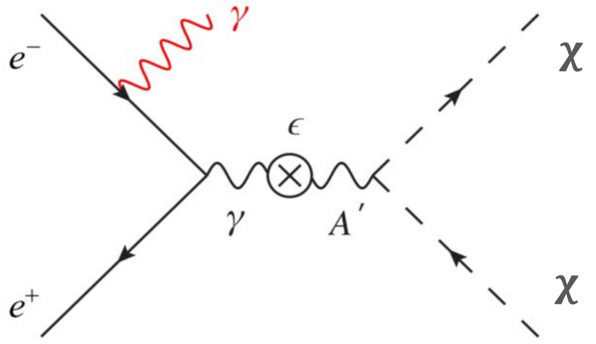


Analysis in short:

- 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

Invisible Dark Photon search

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:

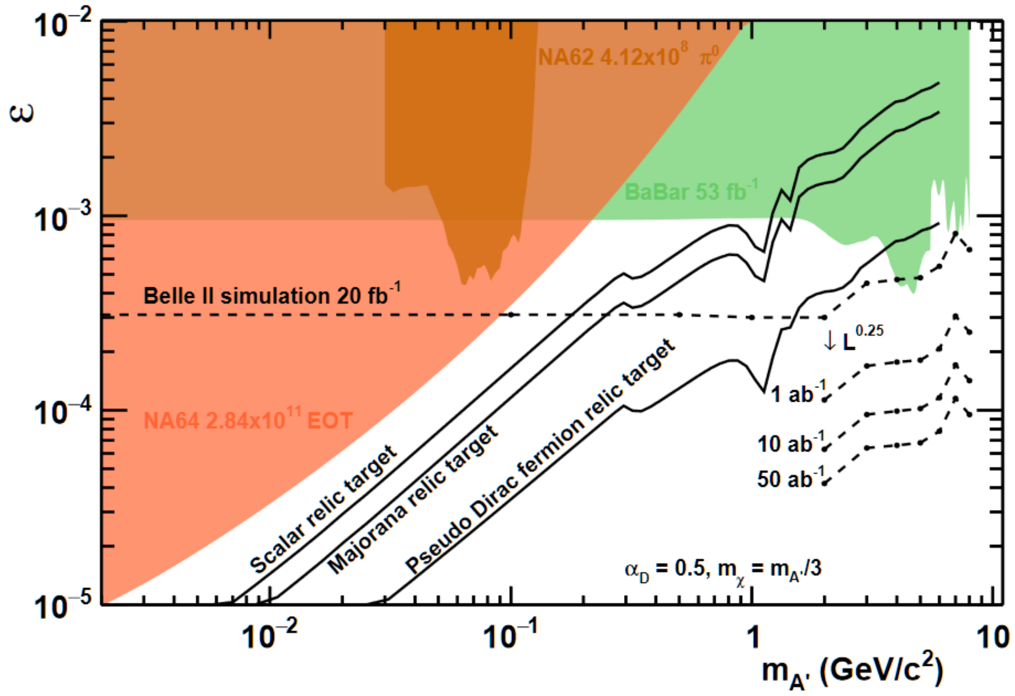
SM backgrounds: $ee \to \gamma\gamma(\gamma)$, $ee \to$ee(γ), Cosmics;

Requires a single photon trigger:

- Bottleneck for previous B-factories;

Expected to perform better than BaBar due to:

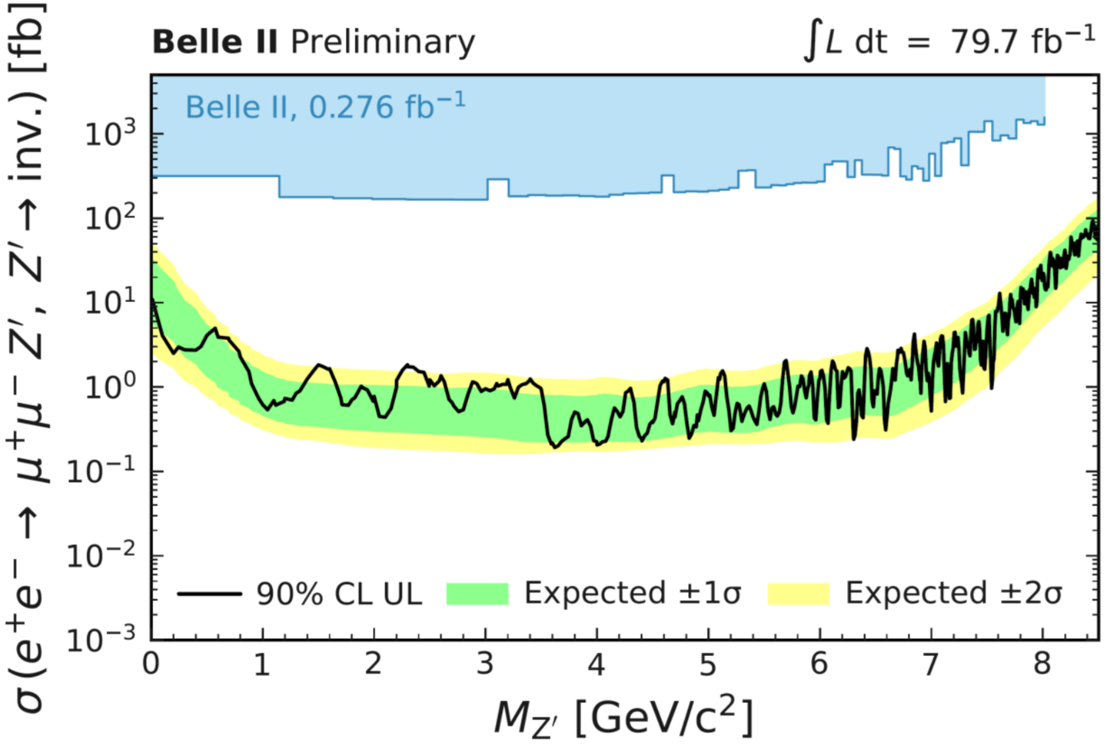
- no ECL cracks pointing to the interaction regions;
- Trigger threshold lower than in BaBar;
- KLM veto;
- Smaller boost;



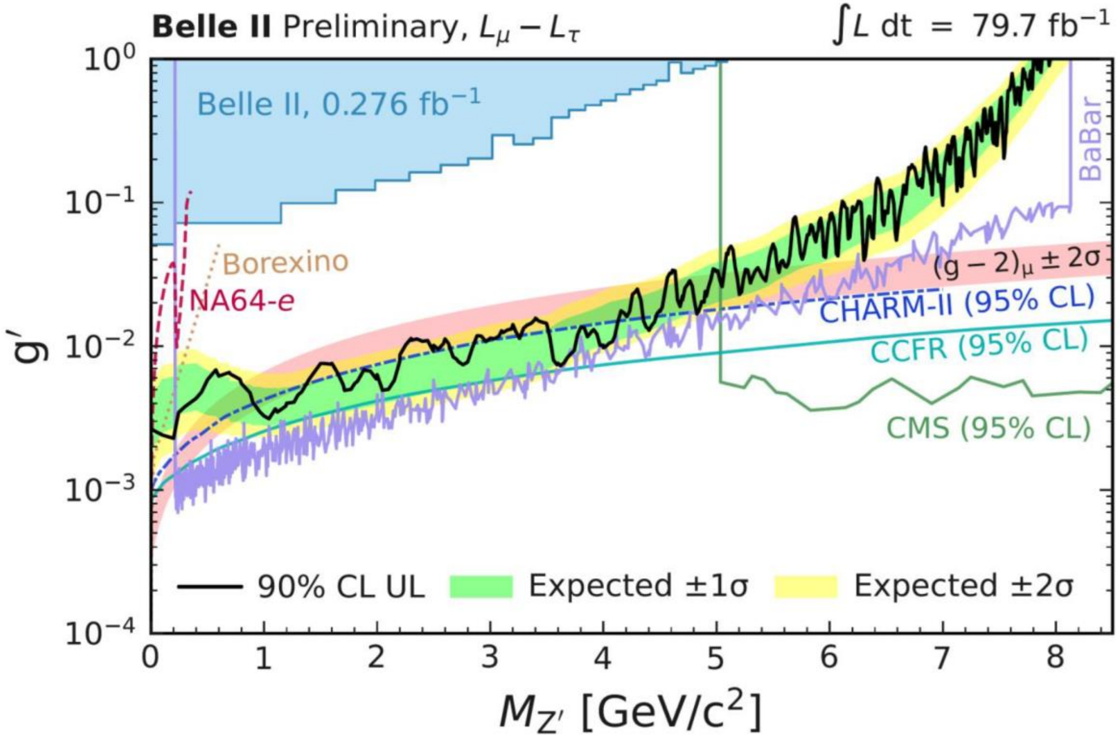
Invisible Z'

Results

Cross section UL



g' Uls in vanilla model Z'

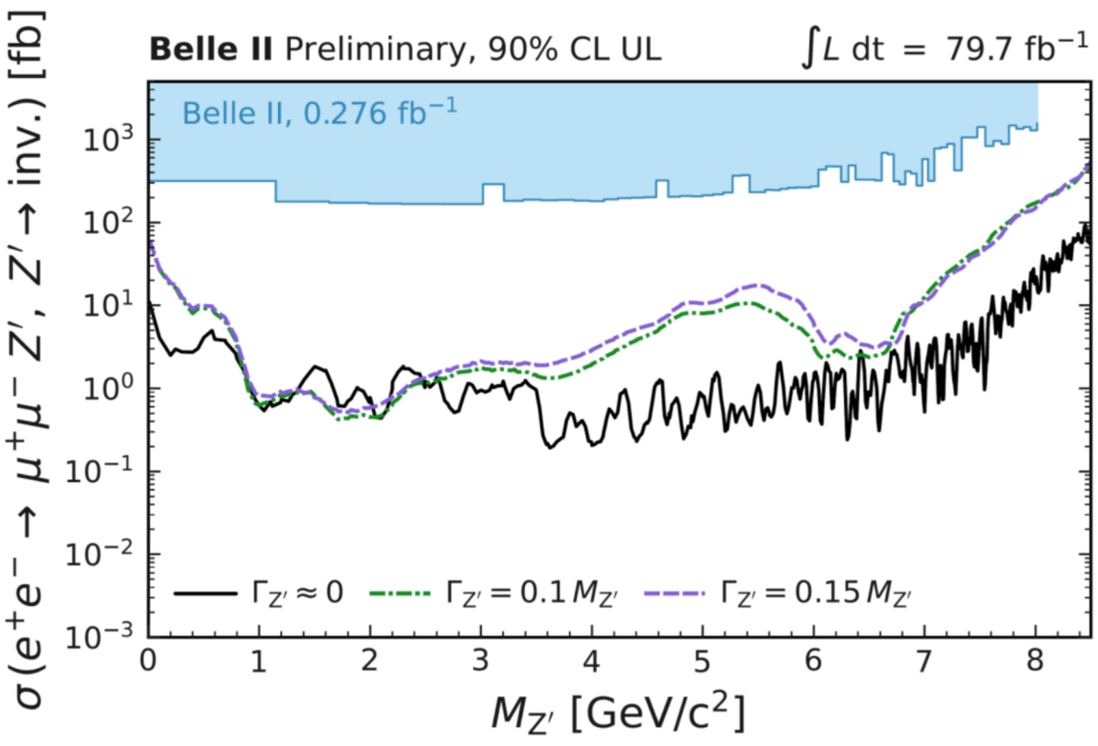


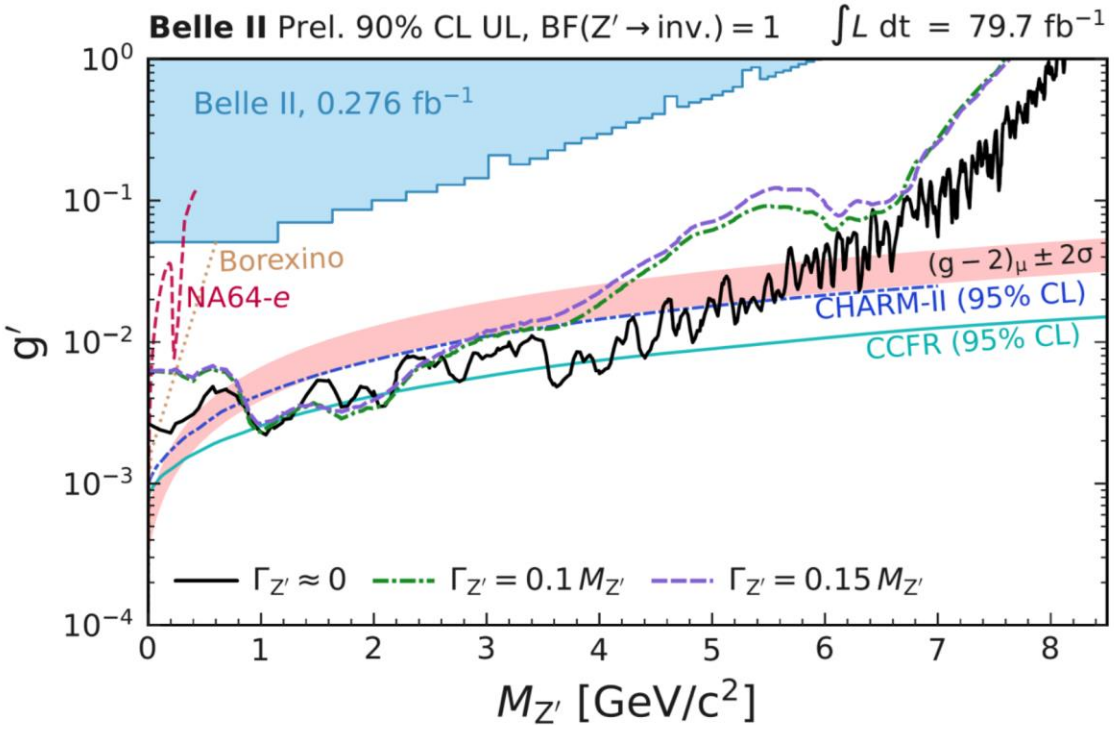
Invisible Z’

Results

Invisible Z’ with non negligible intrinsic width:

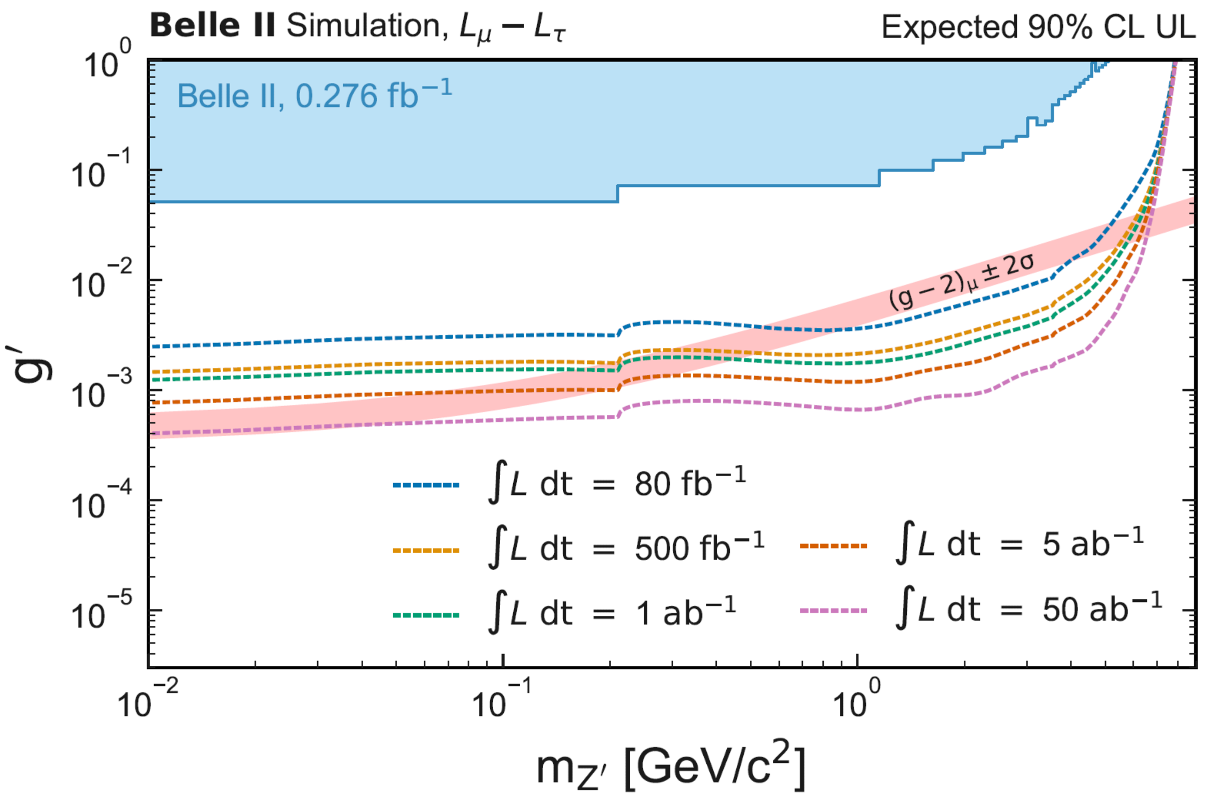
- $\Gamma_{Z\prime} = 0.1\ M_{Z\prime}\ , 0.15\ M_{Z\prime}$





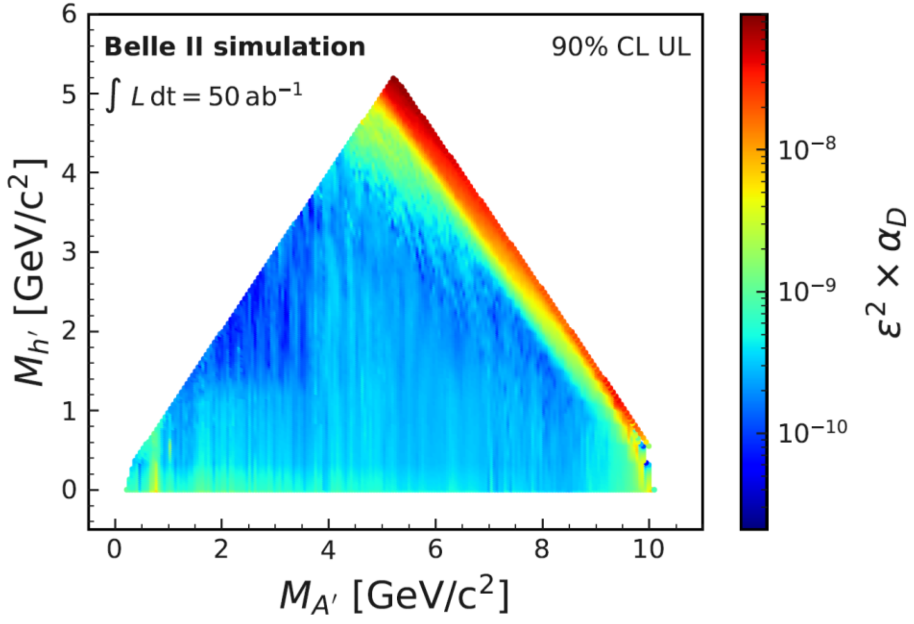
Invisible Z'

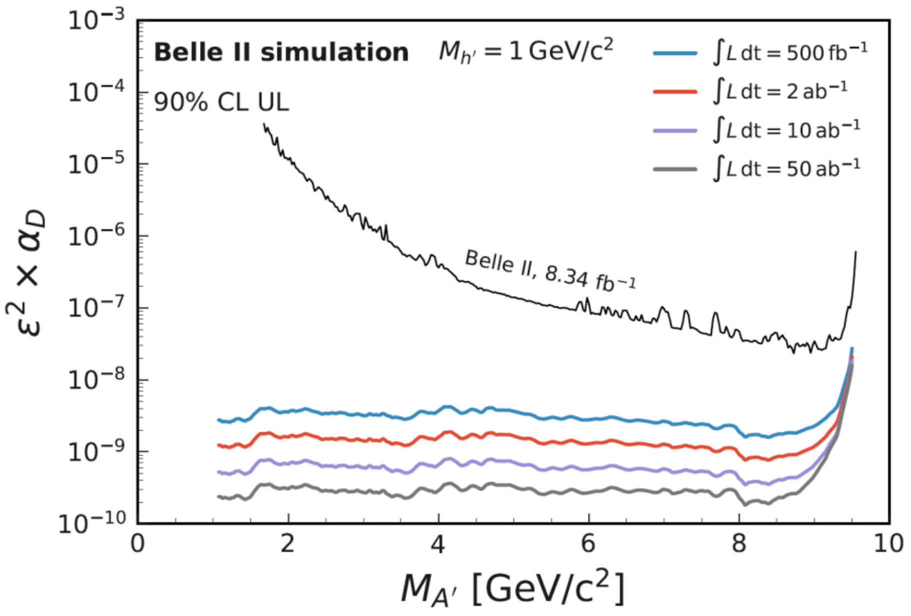
prospects



Dark Higgsstrahlung

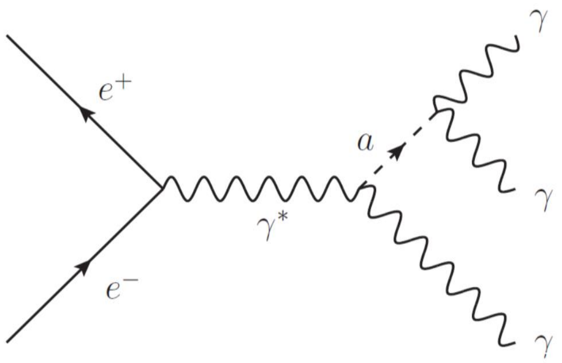
prospects





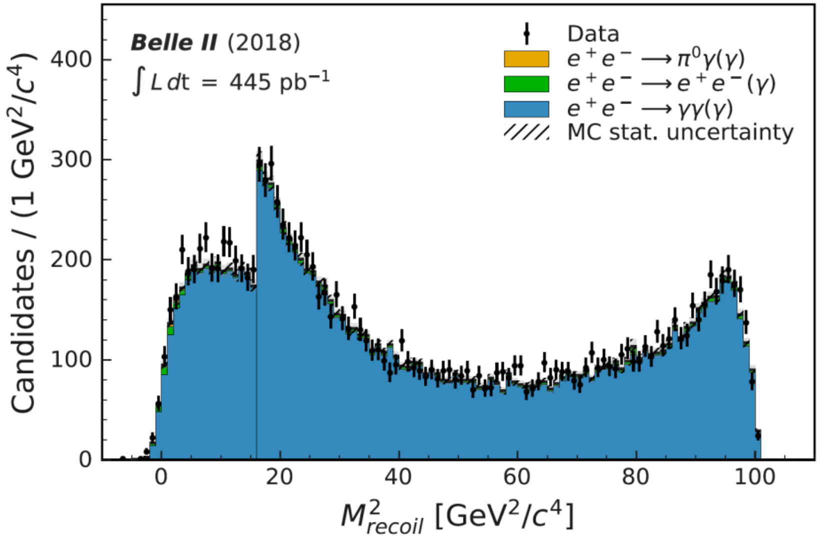
ALPsstrahlung

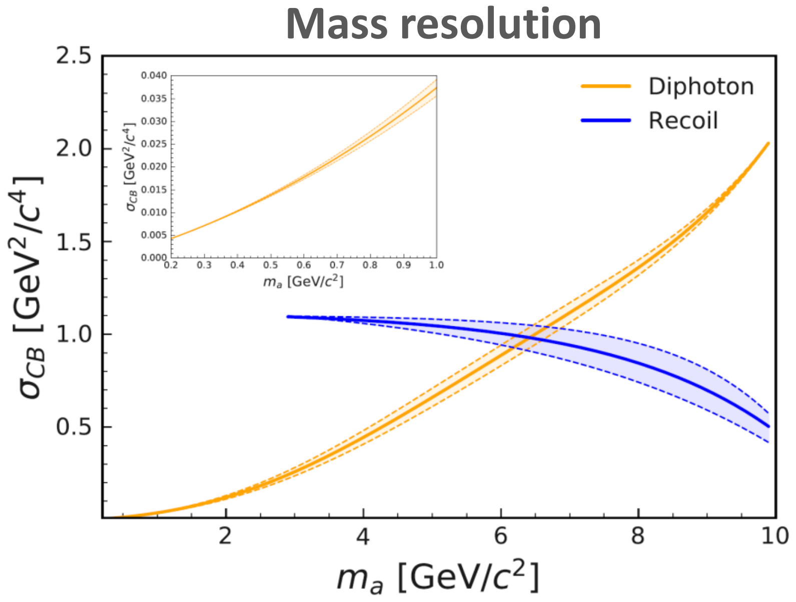
Results

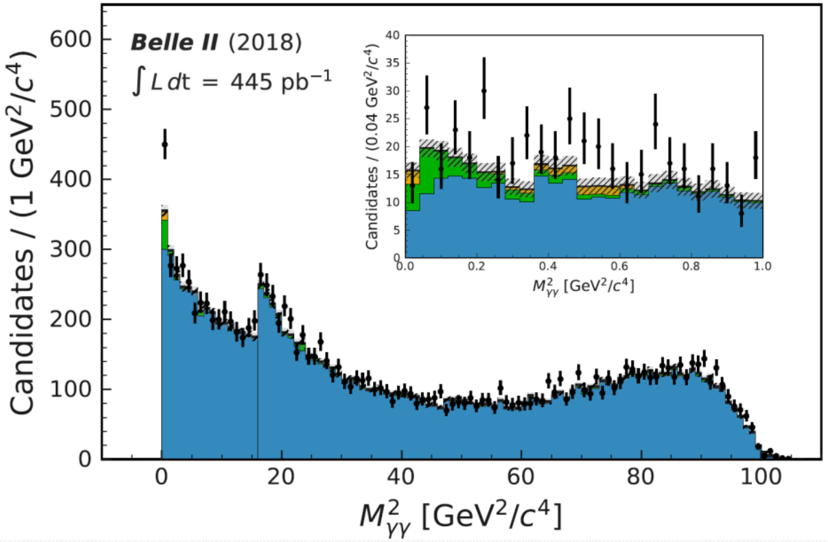


Belle II searched for ALP-strahlung in the 3γ resolved final state;

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



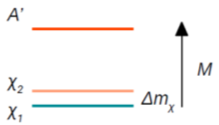


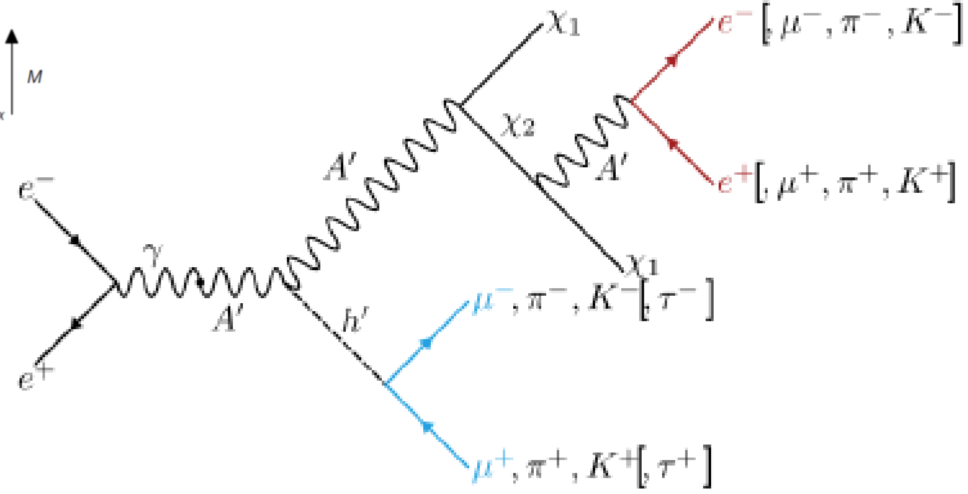


Inelastic Dark Matter and dark higgs

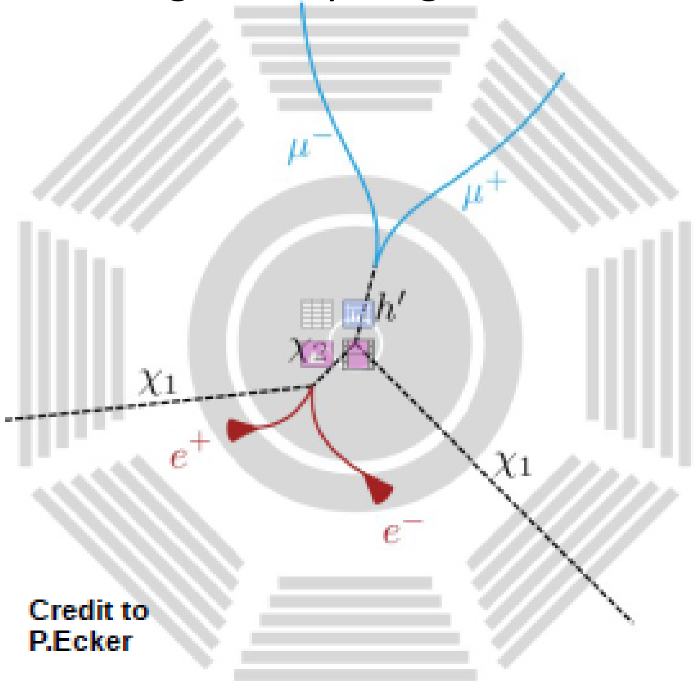
Prospects

- Dark photon A' and dark higgs h'
- Dark matter states χ_1 and χ_2 with a small mass splitting:
  - χ_1 is stable (contributes to relic density)
  - χ_2 is long-lived at small values of kinetic-mixing coupling (ε)
  - h’ is generally long lived and mixes with the SM higgs





JHEP 04 (2021), arXiv:2012.08595



Transverse view of the Belle II detector

Experimental signature: up to two displaced vertices + missing energy

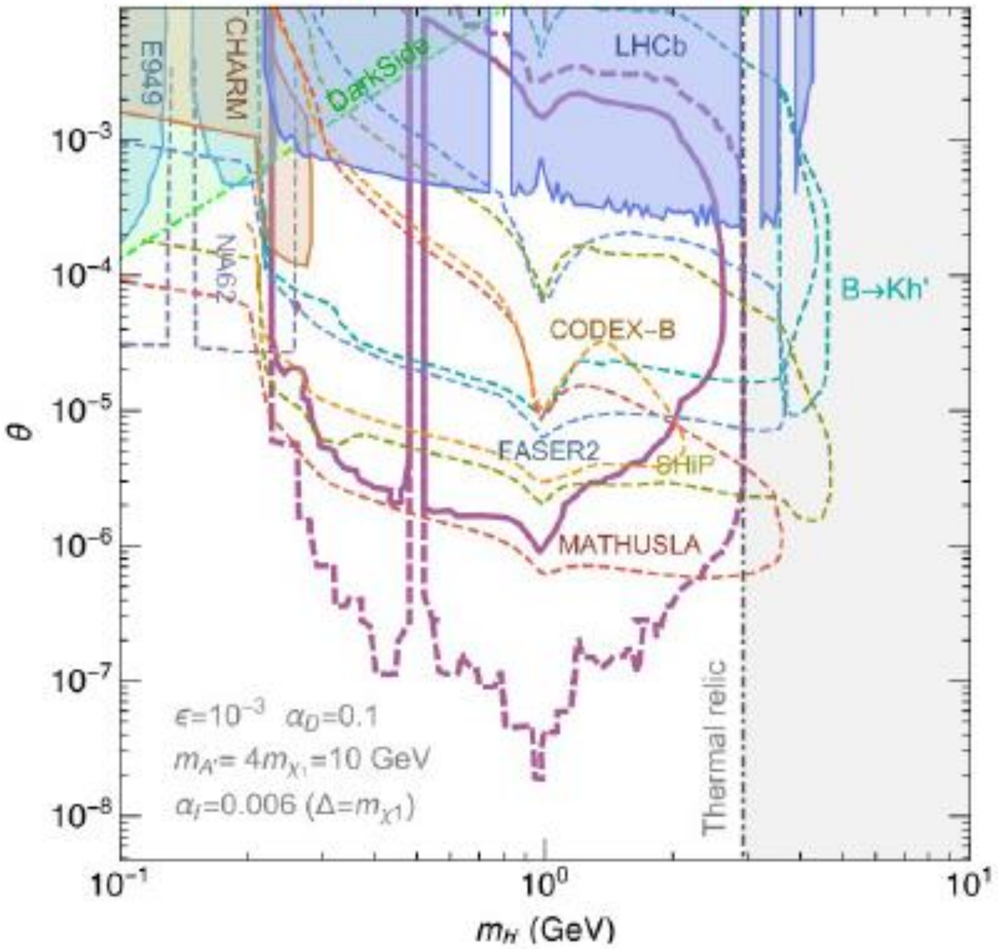
Perform a bump hunt on the invariant mass of the dark higgs $M_{h'}$

$\rightarrow$ unconstrained by direct detection experiments, both inelastic and elastic scattering suppressed

Inelastic Dark Matter and dark higgs

Prospects

[JHEP 04 (2021), arXiv:2012.08595]



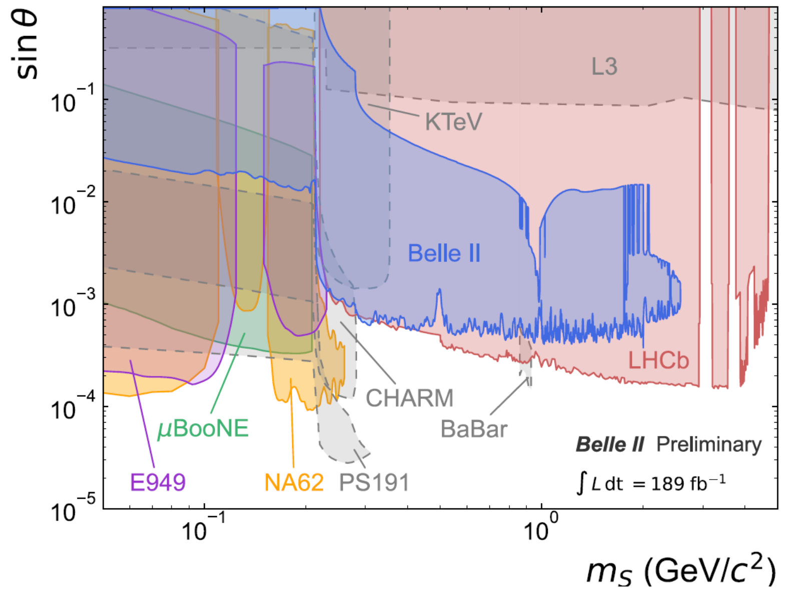
- **Belle II expected sensitivity for 100 fb^{-1} (solid) and 50 ab^{-1} (dashed)**
- Preliminary studies show lower efficiencies → one order of magnitude less sensitive
- Mandatory to implement **new trigger for displaced vertex detection**

Belle II 100 fb^{-1}

Belle II 50 ab^{-1}

Light (pseudo)scalars in B-meson decays

prospects



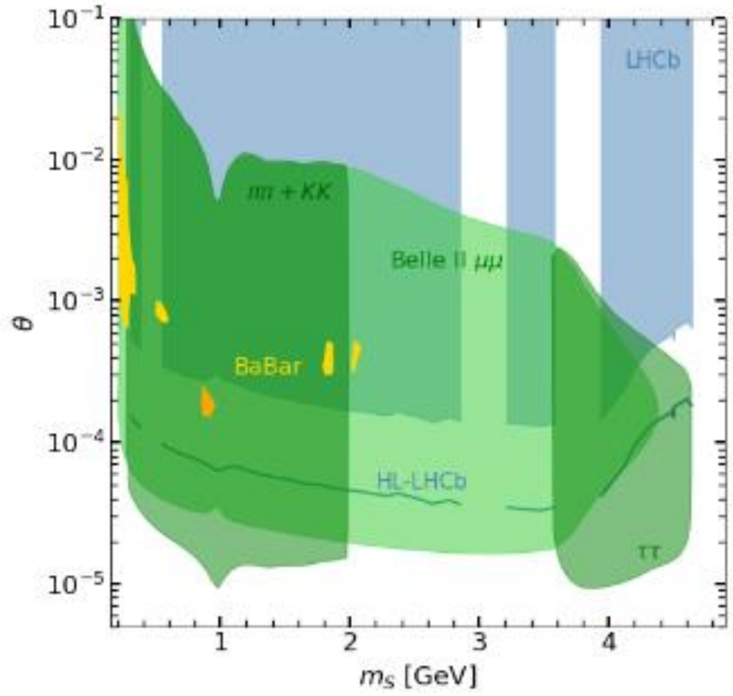


Figure 15: Projected $B \to KS$ sensitivity in terms of θ as a function of visible S mass for 50 ab^{-1}.