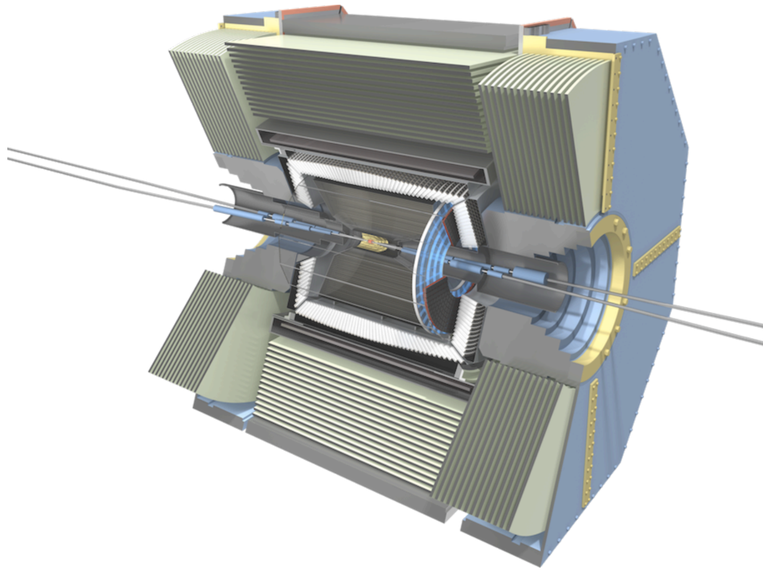


Searches for light dark sectors at BaBar, Belle, and Belle II

2022 November 07th, DISCRETE22

Michael De Nuccio [they/them]
(michael.denuccio@ubc.ca)

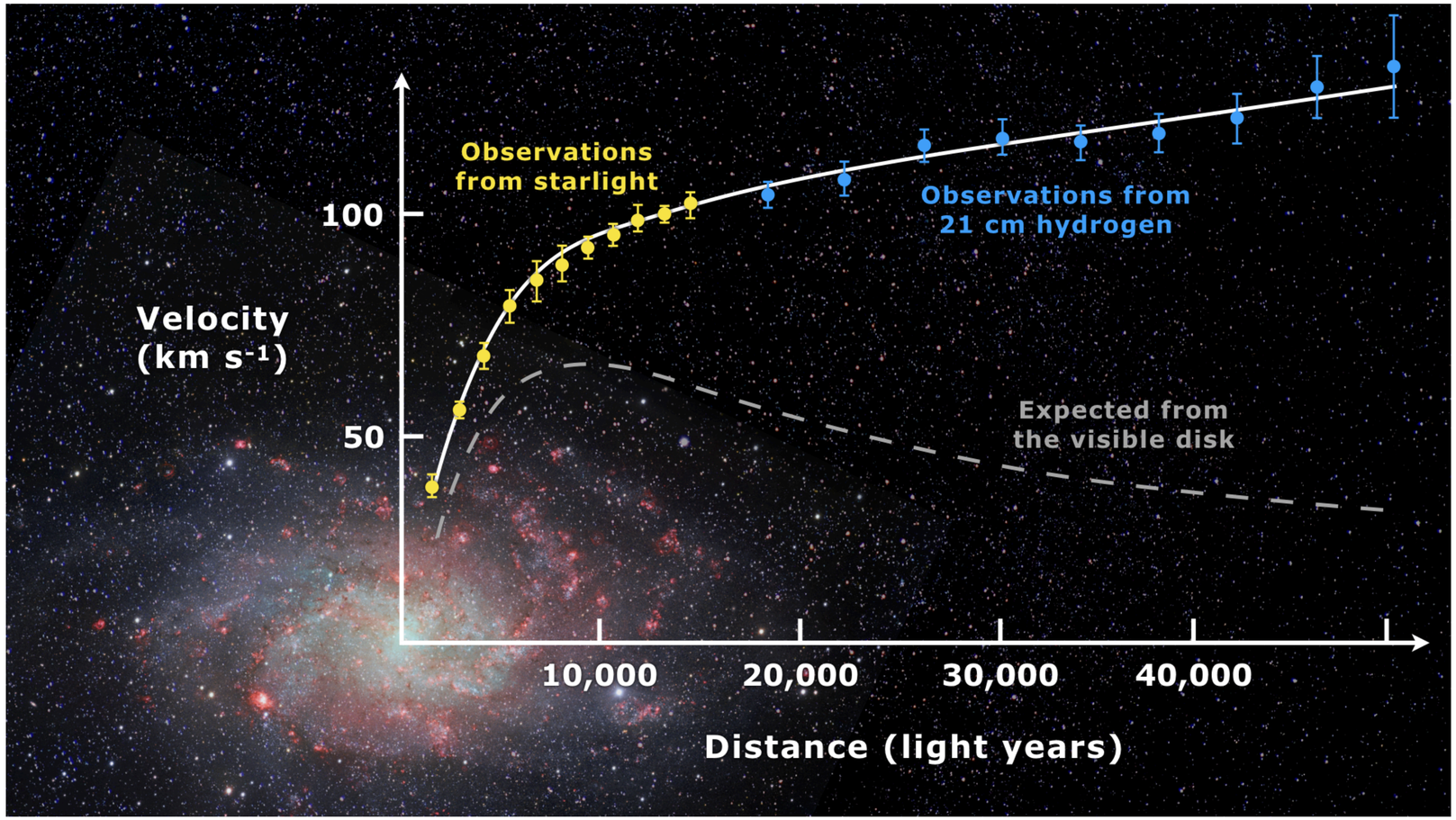
Overview

- Dark Sector @ **B factories**
- **Dark analyses in the last ~1 year**
  - BaBar
  - Belle
  - Belle II

Introduction

Compulsory picture about Dark Matter

- Modified gravity and/or **new particles** ⟹ **Dark Matter (DM)**

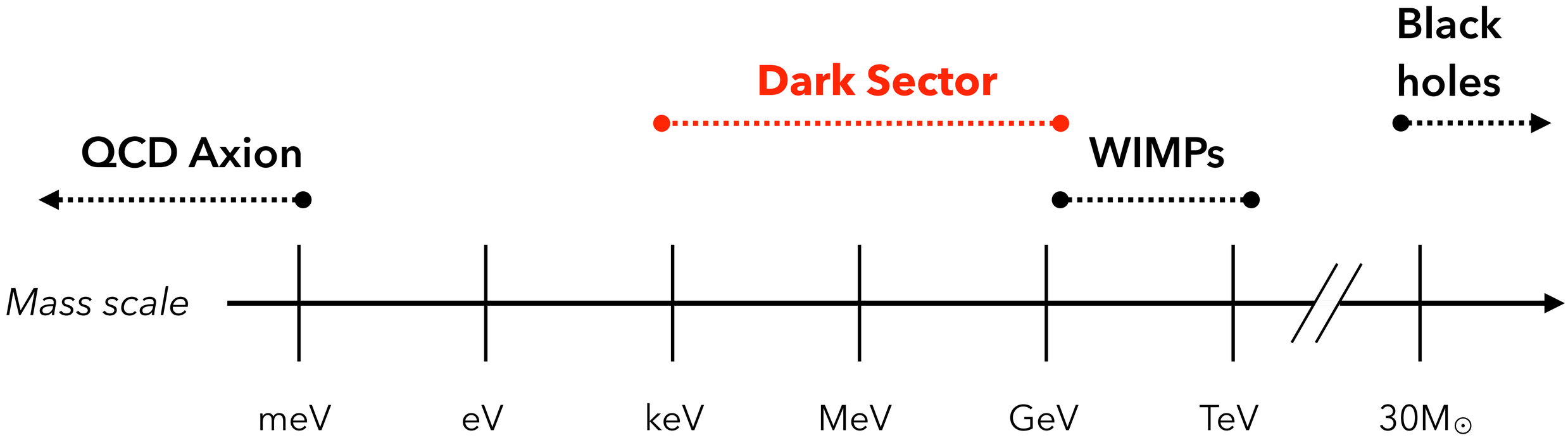


Mario De Leo (Wikipedia)

Dark Sector

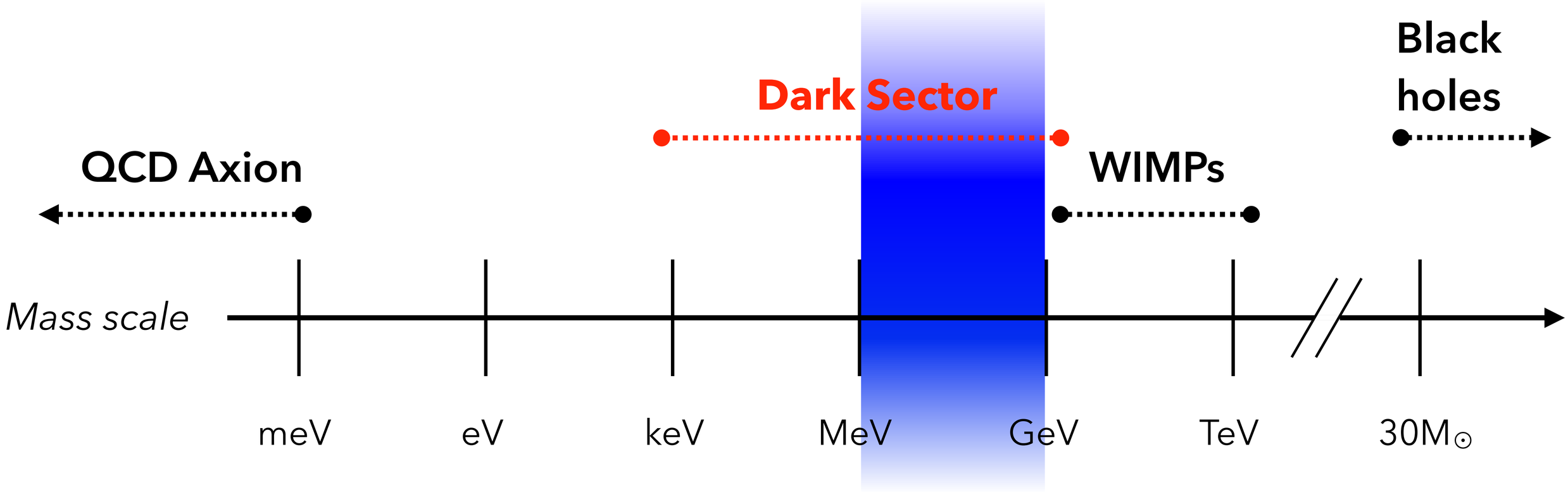
- DM and Standard Model (SM) matter in thermal equilibrium in early universe: $\chi\bar{\chi} \leftrightarrow M\bar{M}$
- Cool down $\Longrightarrow$ DM production & annihilation stop (freeze-out) $\Longrightarrow$ **relic density**
- Low-mass DM, new feeble interaction: **Dark Sector**
  - SM and DM coupled via a **dark mediator**

Dark Sector


Black holes
Dark Sector
QCD Axion
WIMPs
Mass scale
meV
eV
keV
MeV
GeV
TeV
30M⊙

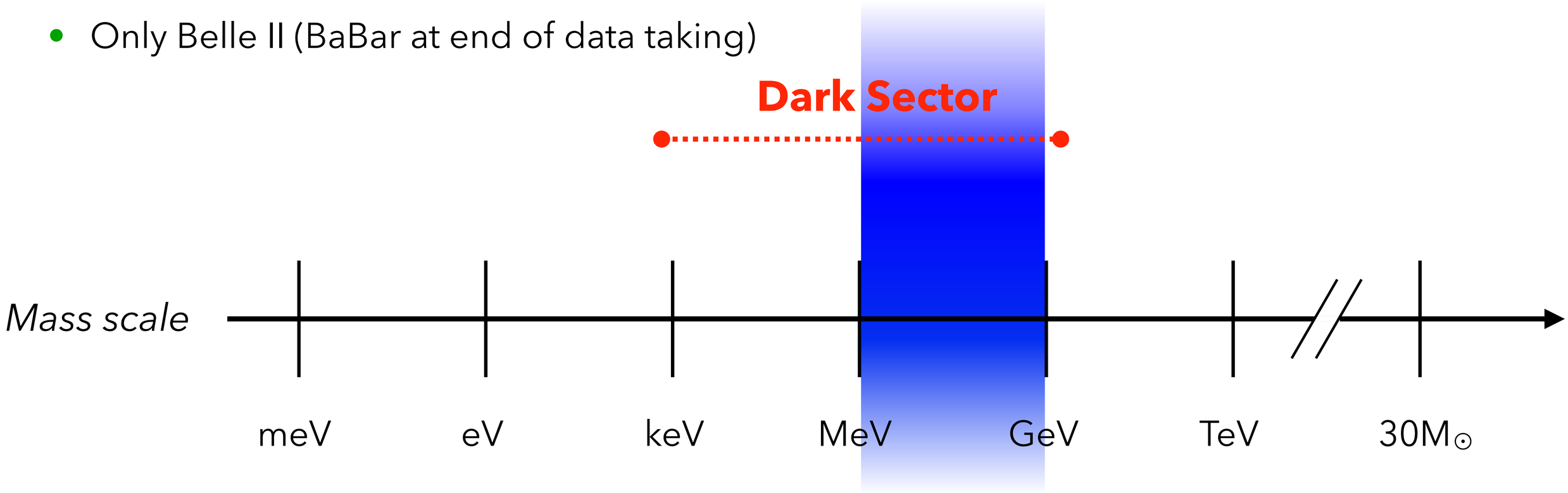
B factories can explore the Dark Sector

- Running energy = $M(\Upsilon(4S)) \approx$ **10.5 GeV**



B factories are good at exploring the Dark Sector

- **Hermetic detector** (90% of solid angle)
- **Clean environment** (e^+e^- collider)
  - Known initial state
  - Low-multiplicity events
- **Dedicated triggers for low-multiplicity** events
  - Only Belle II (BaBar at end of data taking)



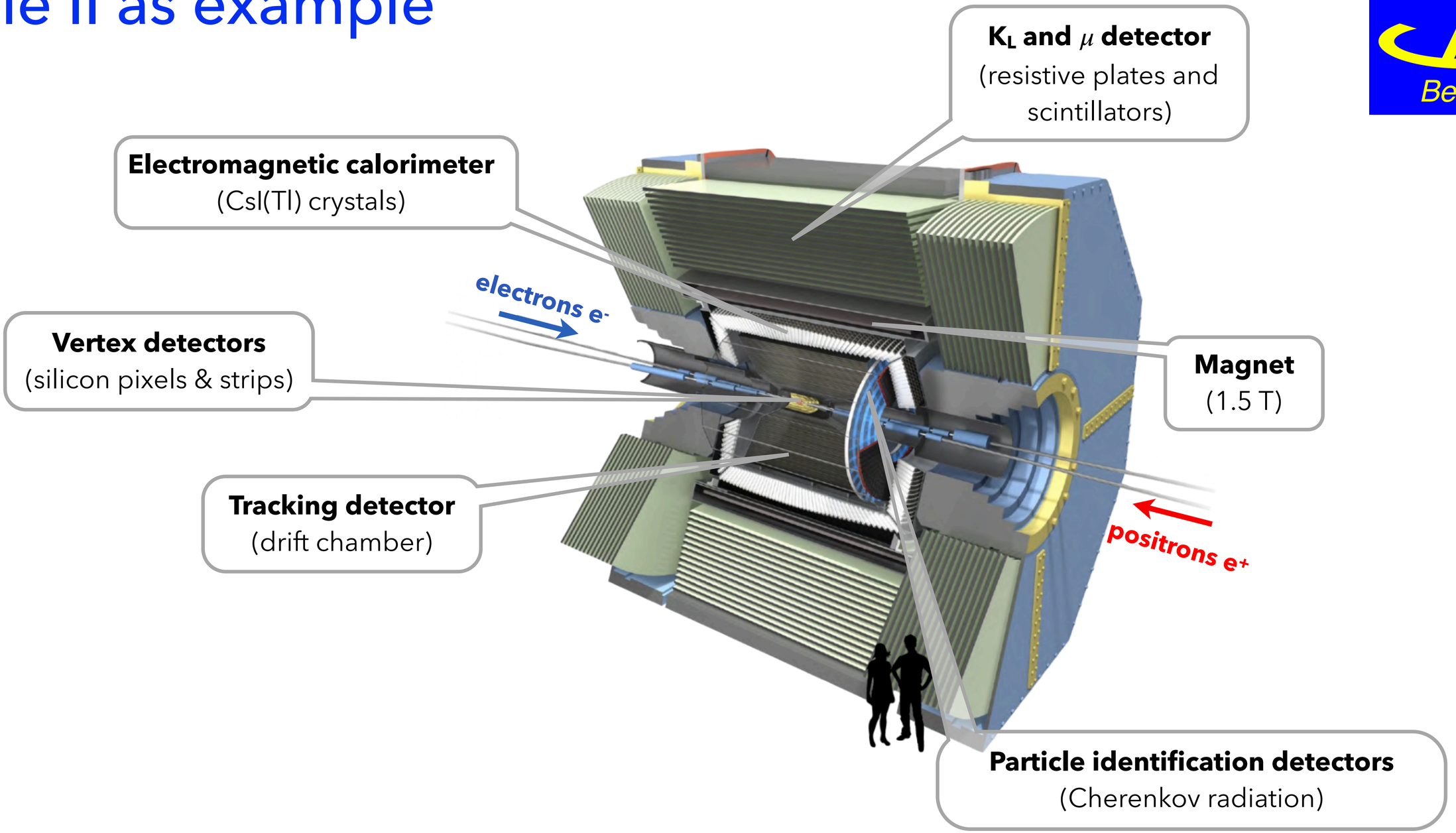
B factories

- **BaBar:** @SLAC, on PEP-II, 1999-2008

- **Belle:** @KEK, on KEKB, 1999-2010

- **Belle II:** @KEK, on SuperKEKB, 2018-onward

Belle II as example



[Belle II official website]

SPOILER!!!

None of the following searches found any evidence for dark sector! :(

All set **upper limits** (ULs) with a 90-95% Confidence Level (CL)


BABAR
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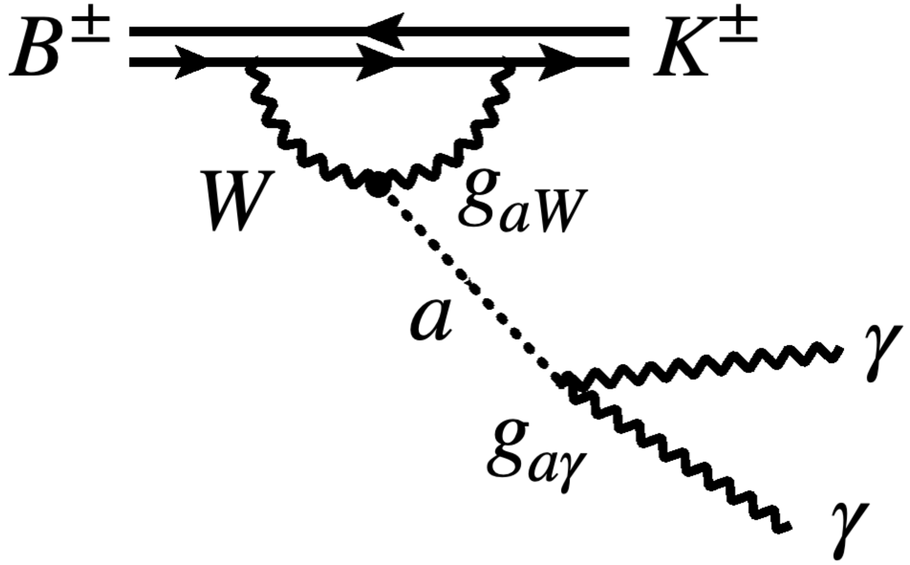
Axion-Like Particles in B decays:

$$B \to Ka, a \to \gamma\gamma$$

ALPs in B decays: $\mathbf{B \to Ka, a \to \gamma\gamma}$

- **Axion-Like Particles (ALPs)**: ~ axion; massive, neutral, pseudoscalar; dark mediators
  - Often: investigated their coupling to gluon and γ
  - Here: **coupling to** $W^{\pm}$
- $B^{\pm} \to K^{\pm}a, a \to \gamma\gamma$
- Also study non-prompt decay, i.e. lifetime $c\tau \neq 0$
- **First** search for visibly decaying ALPs coming from Bs
- $\mathscr{L}$ = 424 fb^{-1}
  - On $\Upsilon(4S)$ resonance
  - 8% used to optimize search strategy, then excluded

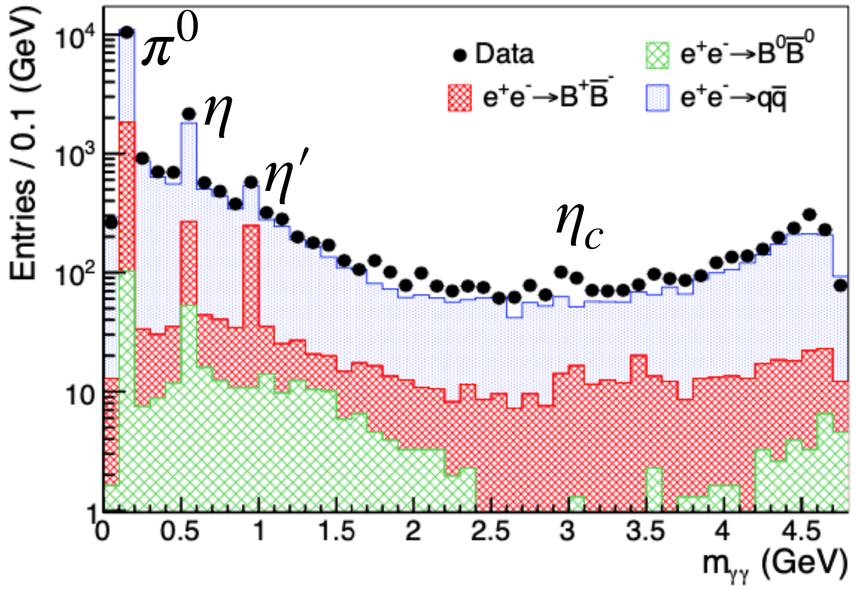


(I worked on this during my master!)

[Phys. Rev. Lett. 128, 131802 (2022)]

ALPs in B decays: $\mathbf{B \to Ka}, \mathbf{a \to \gamma\gamma}$

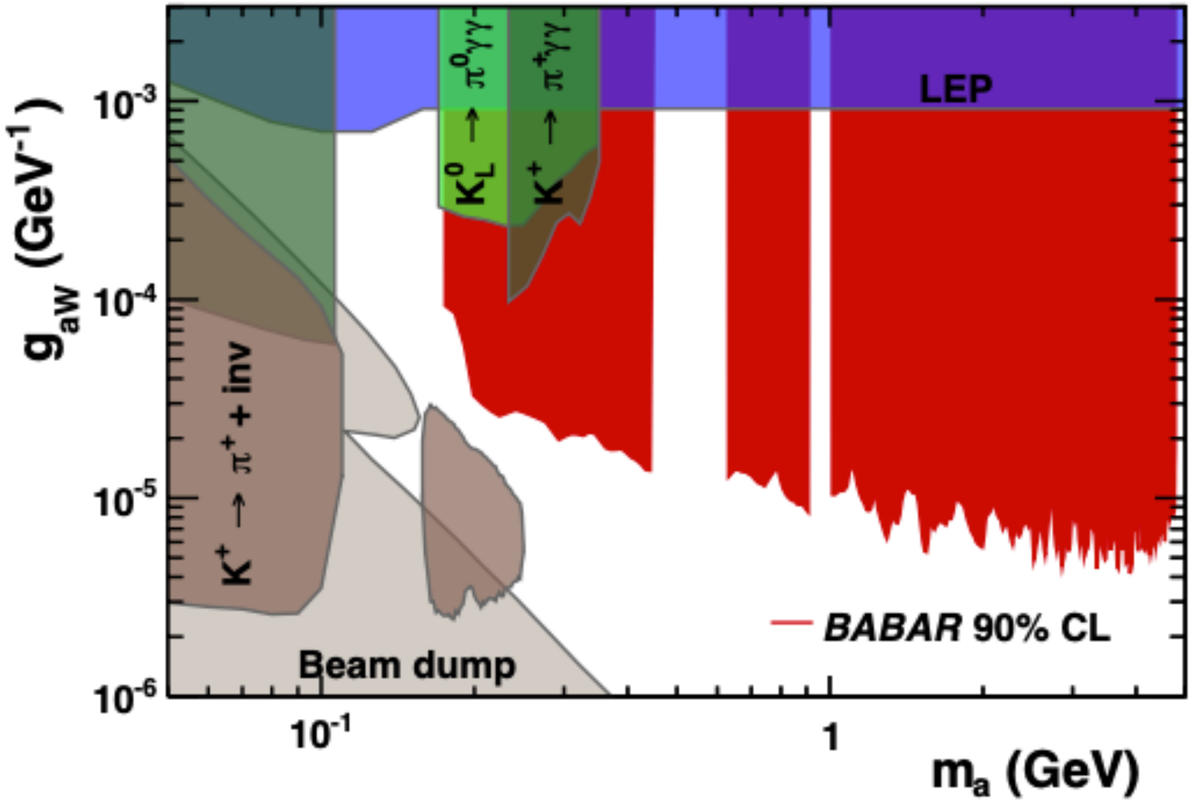
- **Signal:**
  - 1 track + 2 γ summing to $m(B)$
- **Backgrounds:**
  - $e^+e^- \to q\bar{q}$ $(q = u, d, c, s)$: **continuum**
    - Dominant background
  - $e^+e^- \to B\bar{B}$
    - Peaking, vetoed: $B^\pm \to K^\pm h^0$, $h^0 \to \gamma\gamma$ $(h^0 = \pi^0, \eta, \eta')$
    - Peaking, small, not modeled: $B^\pm \to K^\pm \eta_c$, $\eta_c \to \gamma\gamma$
- **2 BDTs**: vs continuum and vs $B\bar{B}$



Phys. Rev. Lett. 128, 131802 (2022)

ALPs in B decays: $\mathbf{B \to Ka, a \to \gamma\gamma}$

- **Peak hunt: 1D fit on $\mathbf{m}(\gamma\gamma)$** of peaking signal over background
- **Re-performed** the upper limit extraction for **non-zero lifetimes**
  - $c\tau$ = 1, 10, 100 mm
- 90% CL UL on $\mathbf{g_{aW}}$**: improving previous constraints** by 2 orders of magnitude

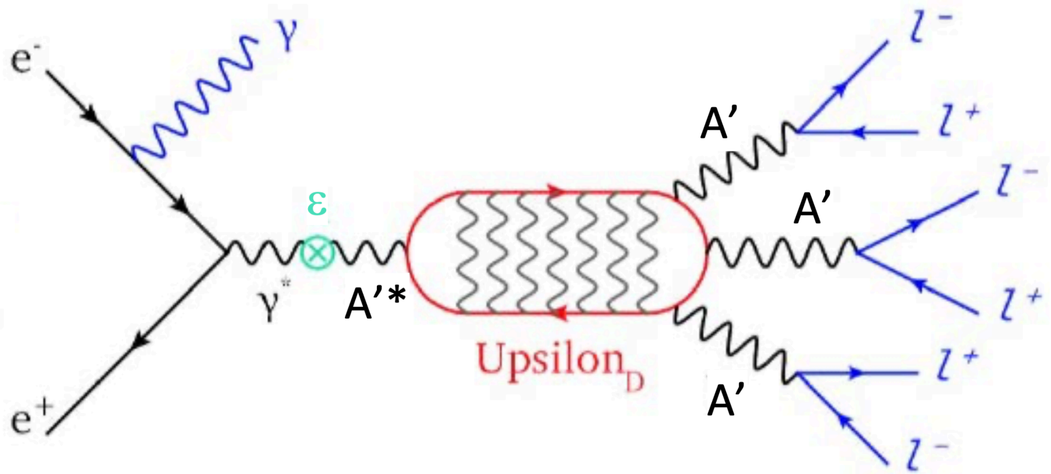


Phys. Rev. Lett. 128, 131802 (2022)

Darkonium: dark bound state

Darkonium: dark bound state

- **Darkonium Υ_D:** bound dark matter, i.e. self-interacting DM
- $e^+e^- \to \gamma_{ISR}\Upsilon_D, \Upsilon_D \to A'A'A', A' \to x\bar{x}\ (x = \mu, e, \pi)$
  - ISR = Initial State Radiation
- Bounds on **kinetic mixing** ε vs **coupling constant** $g_D \propto \sqrt{\alpha_D}$
- First search for bound dark state into 3 dark photons
- $\mathscr{L}$ = 514 fb^{-1}
  - $\Upsilon(4S), \Upsilon(3S), \Upsilon(2S)$ resonances and vicinities

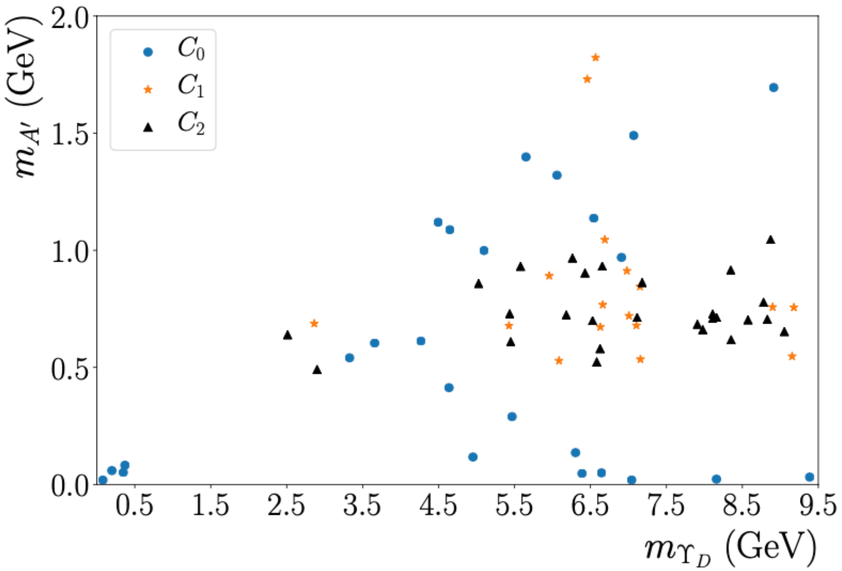


Phys. Rev. Lett. 128, 021802 (2022)

Darkonium: dark bound state

- **Signal:**
  - 3 pairs of oppositely charged tracks (μ, e, π), similar masses
  - If recoil momentum within calorimeter: require compatible γ (ISR)
- **Backgrounds:**
  - Too complex to be properly simulated
  - 5% of data to optimize selection criteria, then discarded
- Scan $\mathbf{m(A')} - \mathbf{m(\Upsilon_D)}$ plane: signal is a point there

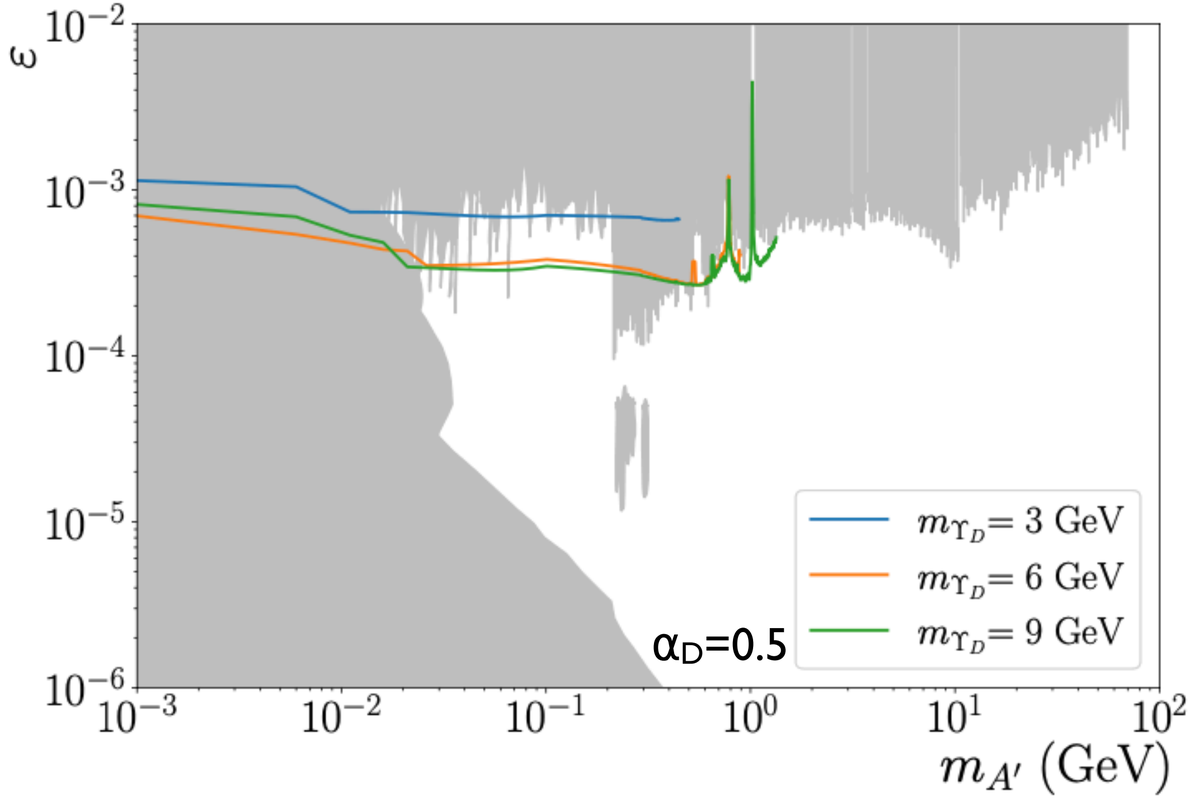
Events passing the selection
Cn: NN trained for n π pairs

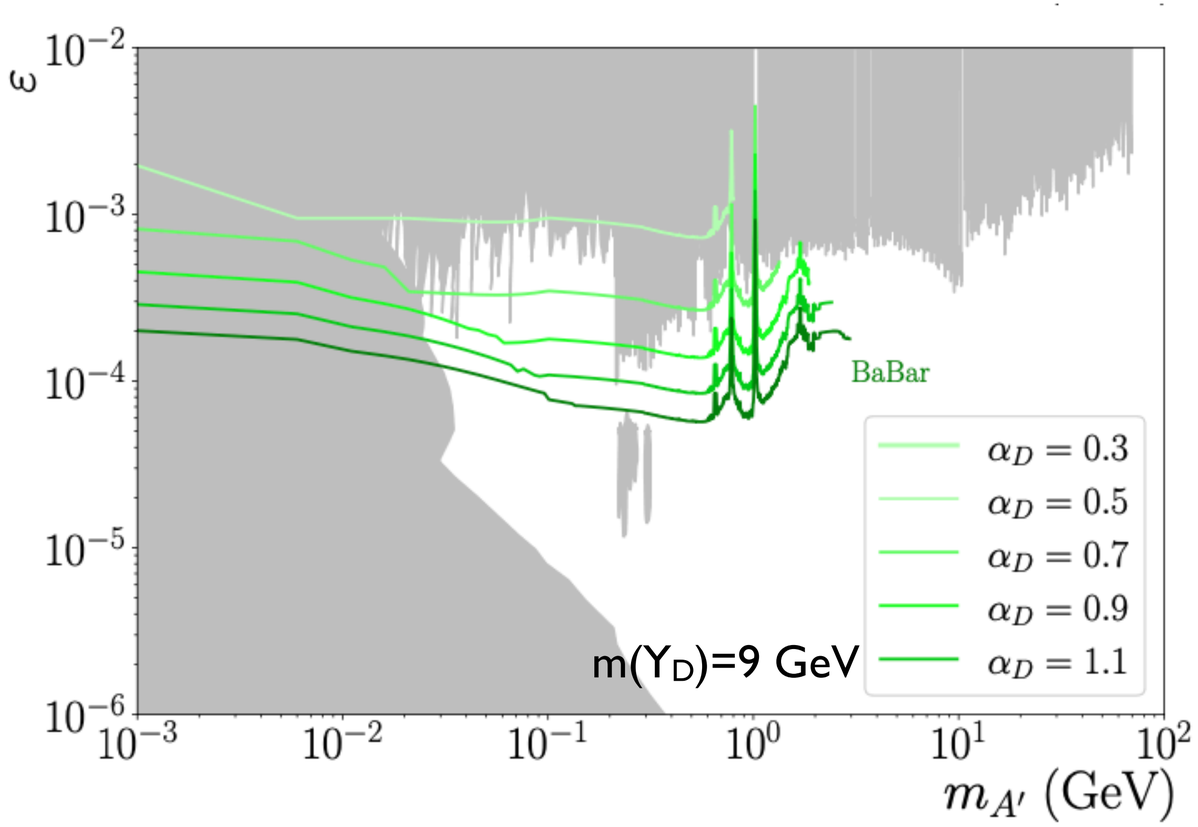


Phys. Rev. Lett. 128, 021802 (2022)

Darkonium: dark bound state

- **90% CL UL on kinetic mixing ε**
  - depends on the values of $\alpha_D \propto g_D^2$ and $m(\Upsilon_D)$
- **Improve constraints for large dark coupling and Υ_D masses**





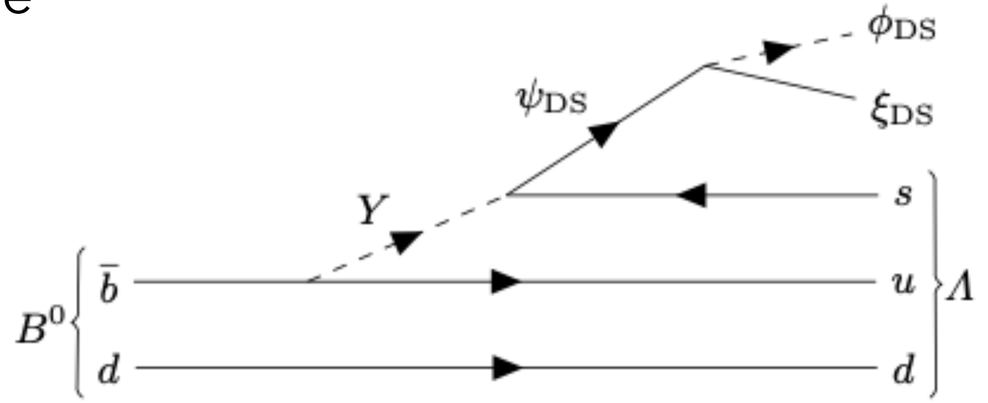
Phys. Rev. Lett. 128, 021802 (2022)


BELLE

$B^0 \to \Lambda$ + dark baryon

$B^0 \to \Lambda$ + dark baryon

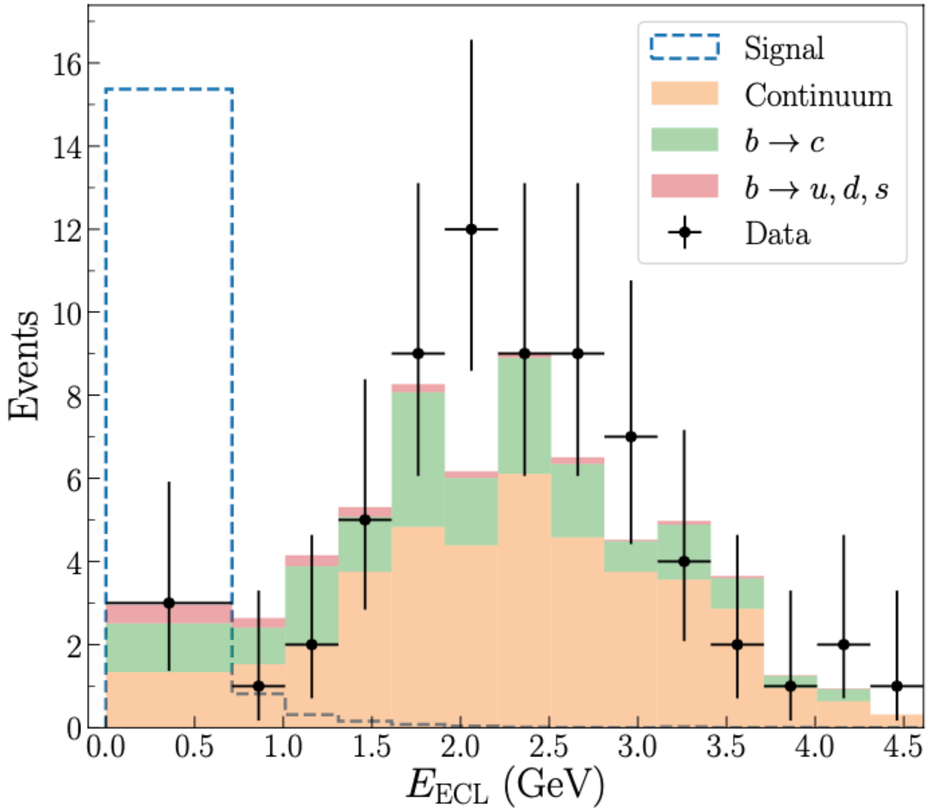
- **B-mesogenesis mechanism**: address DM & baryon asymmetry via CP-violating oscillation
- Prediction of $B^0 \to \Lambda$ + missing E + any light mesons (BF~10^{-4})
  - Mediator Y
  - Ψ_{DS} → dark
- $\mathbf{B^0 \to \Lambda}$ **+ missing E,** $\mathbf{\Lambda \to p^+\pi^-}$
- Other B (tag side): fully reconstructed with hadronic channels
  - **Full-Event Interpretation (FEI)** from **Belle II** software
    Comput.Softw.Big Sci. 3 (2019) 1, 6
- $\mathscr{L}$ = 711 fb^{-1} on-resonance + 89 fb^{-1} off-resonance



Phys. Rev. D 105, L051101 (2022)

$B^0 \to \Lambda$ + dark baryon

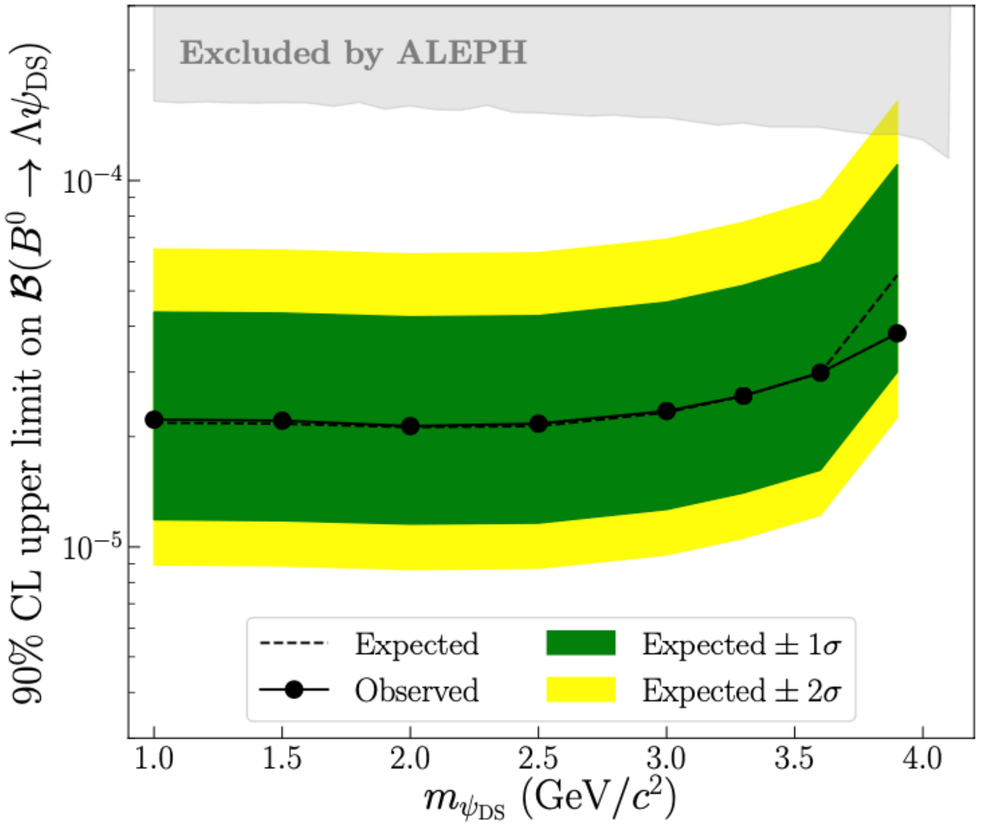
- **Signal**:
  - B_{tag}: fully reconstructed hadronically with FEI
  - B_{signal}: proton + π^- + missing E
- **Backgrounds**:
  - $e^+e^- \to B\bar{B}$
  - $e^+e^- \to q\bar{q}$ $(q = u, d, c, s)$ (*continuum*)
- **Residual energy in the calorimeter E_{ECL}**
- **Count event** in signal region



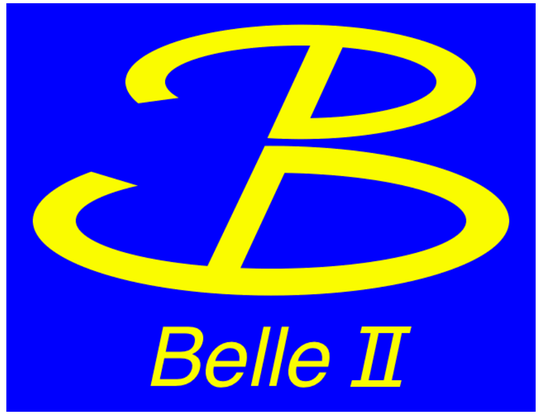
Phys. Rev. D 105, L051101 (2022)

$B^0 \to \Lambda$ + dark baryon

- **90% CL UL** on branching ratio
- Partially exclude B-mesogenesis mechanism
- **Improve on previous results**, and further improvable at Belle II



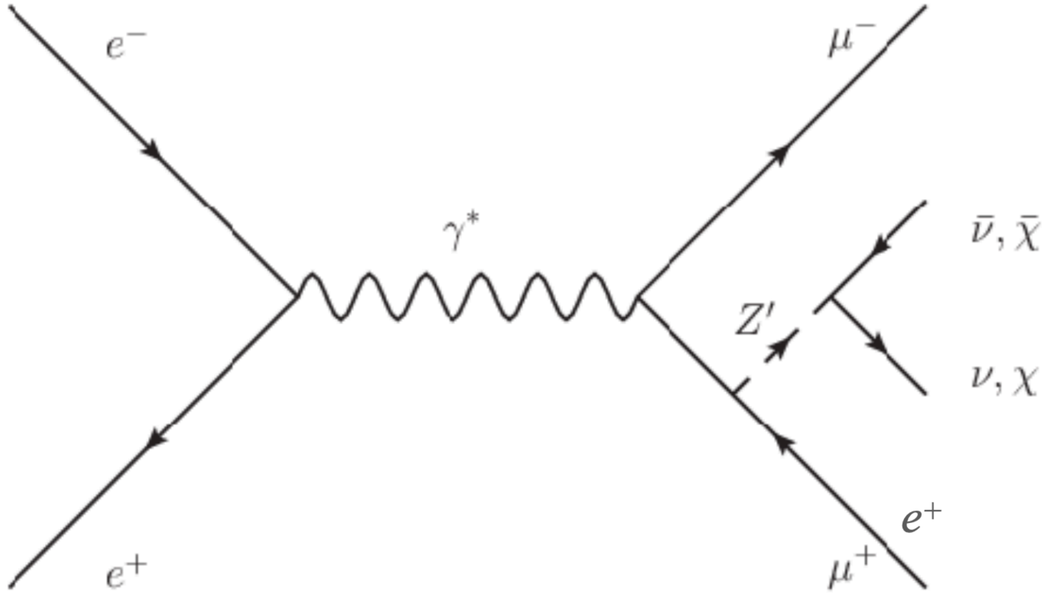
[Phys. Rev. D 105, L051101 (2022)]


Belle II

$L_\mu - L_\tau$ extension:
Z' to invisible

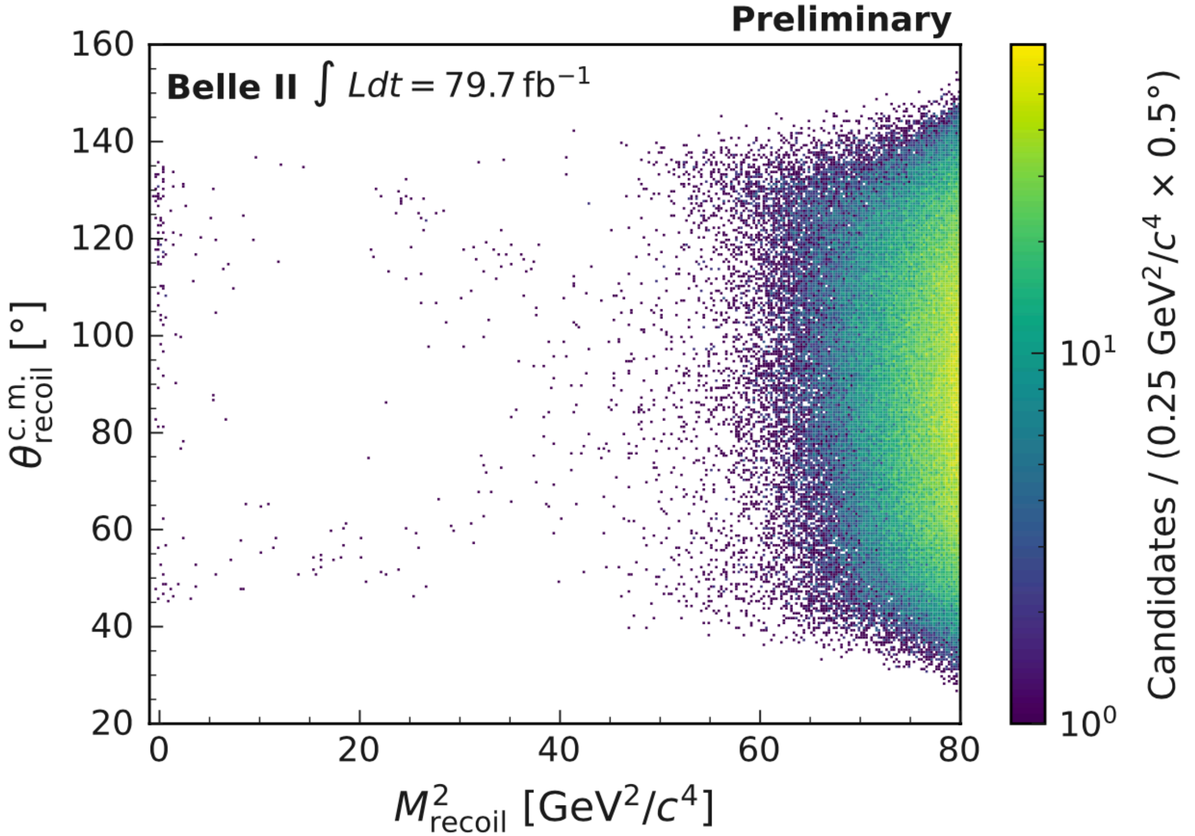
$L_\mu - L_\tau$ extension: Z' to invisible

- $L_\mu - L_\tau$ extension: new Z' particle couples only to 2nd & 3rd generation leptons
- Could solve Dark Matter & $(g-2)_\mu$ & B decay anomalies
- $e^+e^- \to \mu\mu Z'$, $Z' \to$ **invisible**
  - Assumed decay to neutrinos or dark matter
  - If coupling only to SM: different limits
- $\mathscr{L}$ = 80 fb^{-1}



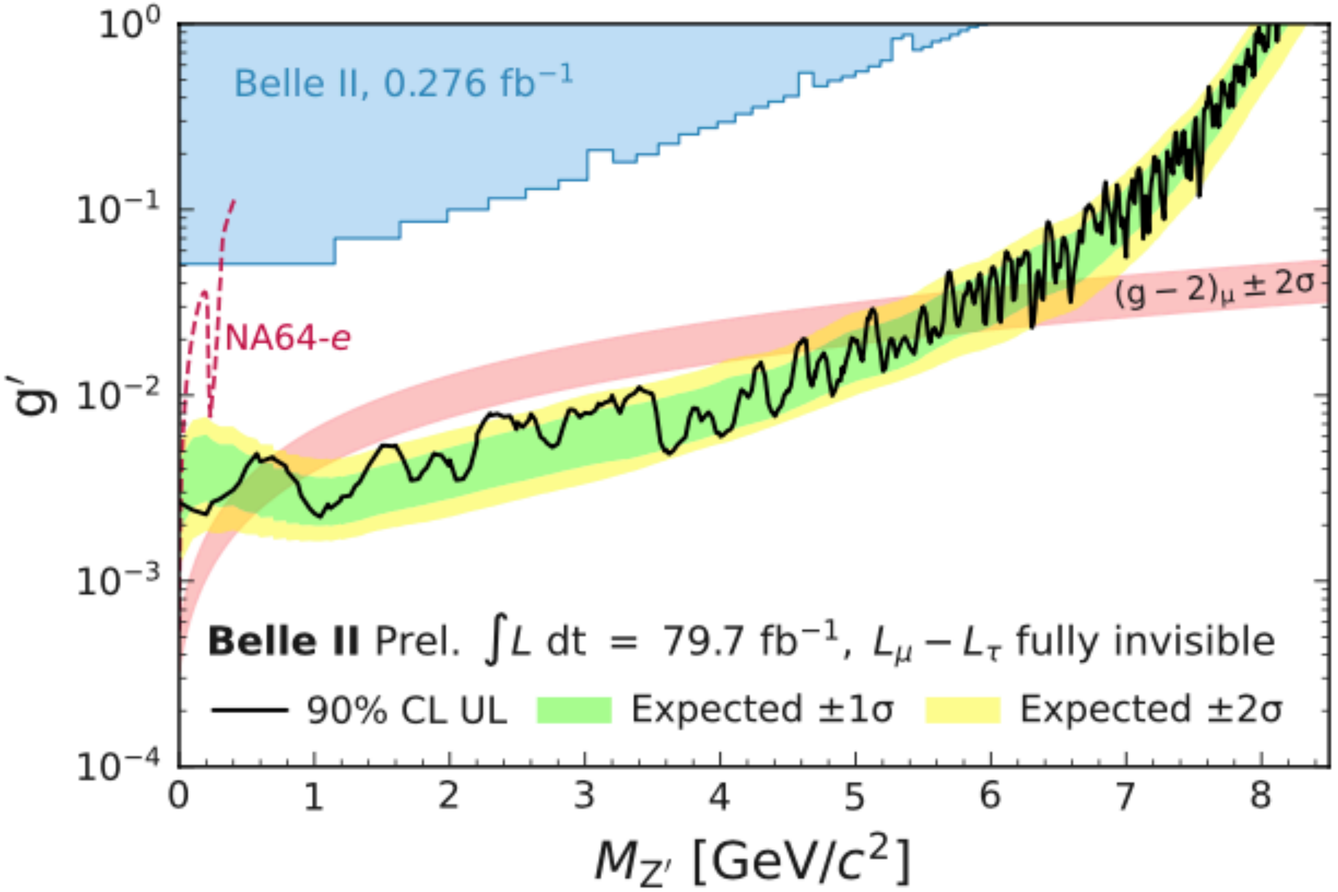
$L_\mu - L_\tau$ extension: Z' to invisible

- **Signal:**
  - 2 μ + missing E
- **Backgrounds:**
  - $e^+e^- \to \mu\mu(\gamma)$
  - $e^+e^- \to \tau\tau(\gamma)$
  - $e^+e^- \to ee\mu\mu$
- 2D fit to **recoil mass** ~ $m(Z')$ vs θ^*_{recoil}



$L_\mu - L_\tau$ extension: Z' to invisible

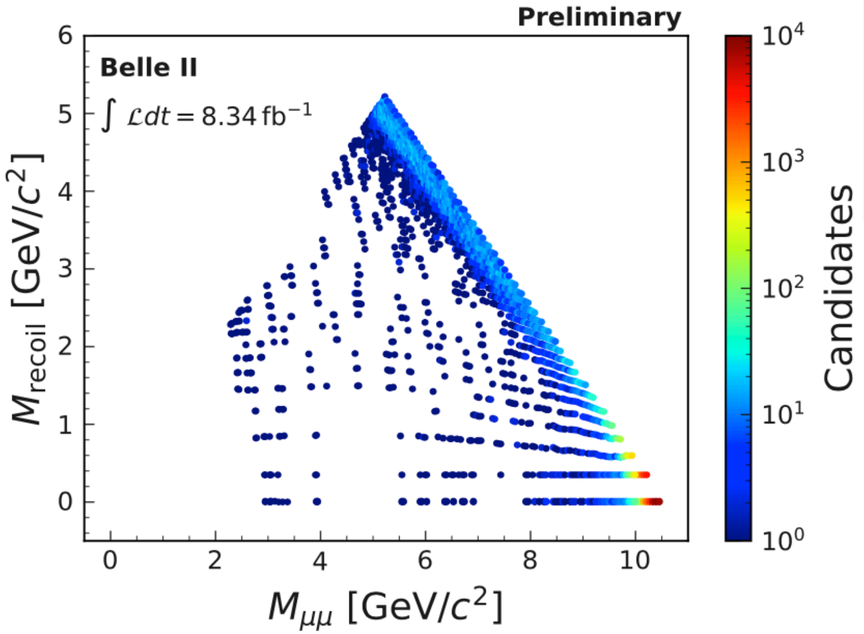
- **90% CL UL** on g' (coupling of Z' to muons)
- Exclude $(g-2)_\mu$ parameter space for $0.8 < m(Z') < 5.0$ GeV
- World-leader above 11 MeV

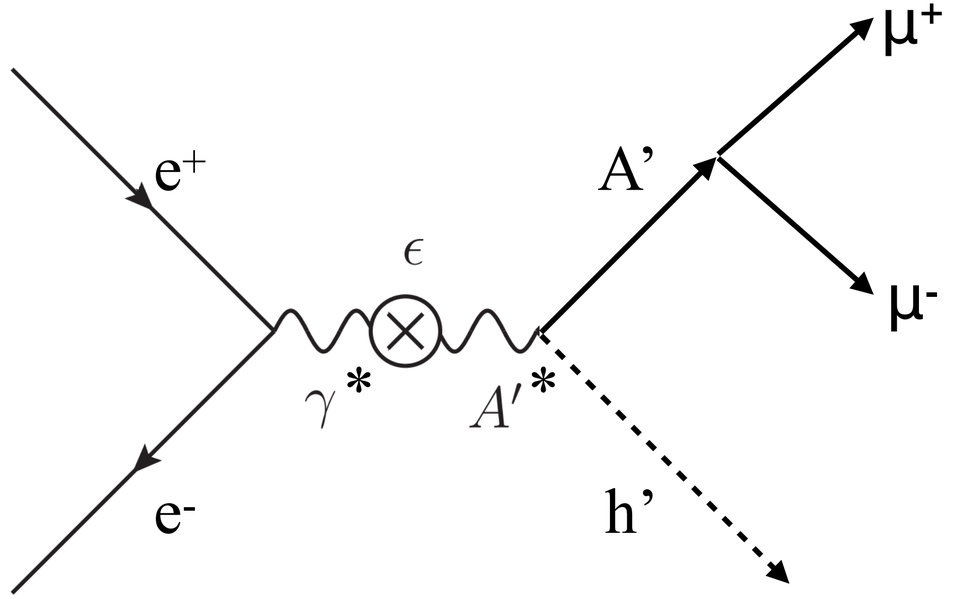


Dark photon + dark Higgs

Dark photon + dark Higgs

- $\mathbf{e^+e^- \to A'h',\ A' \to \mu\mu,\ h' \to}$ **invisible**
  - Assume $m(h') < m(A') \Longrightarrow h'$ stable/invisible
- Same final state as Z' to invisible
  - Same backgrounds
  - Recoil mass ~ $m(h') \Longrightarrow$ extra mass constraint $\Longrightarrow$ **2D fit** of $\mathbf{m_{recoil}}$~$m(h')$ vs $\mathbf{m}(\mu\mu)$~$m(A')$
- $\mathscr{L}$ = 8 fb^{-1}

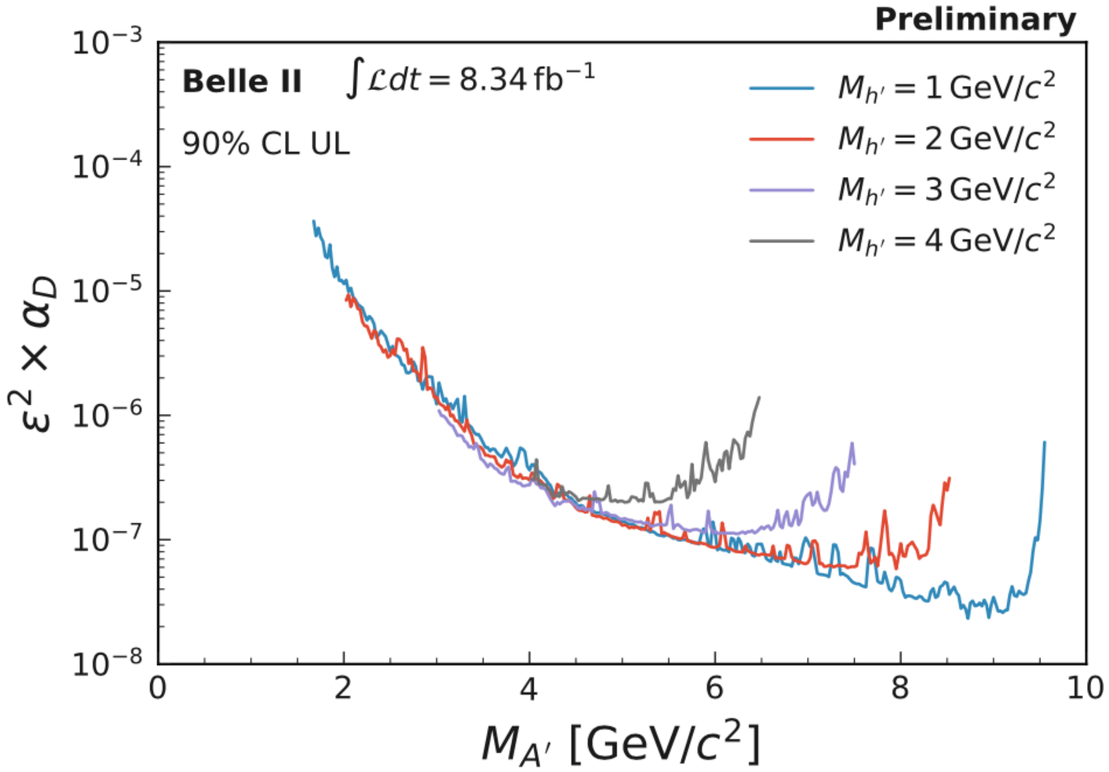


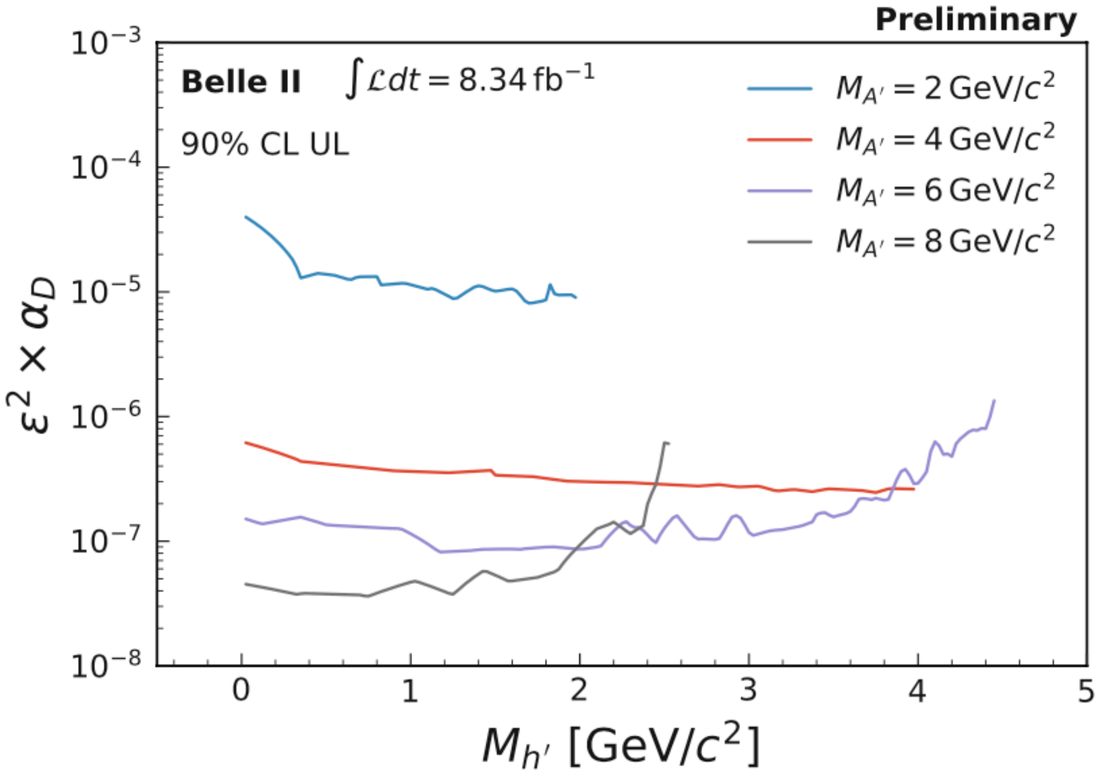


https://arxiv.org/abs/2207.00509

Dark photon + dark Higgs

- **90% CL UL** on $\epsilon^2\alpha_D$ as function of $m(h')$ & $m(A')$
  - ϵ=kinetic mix γ to A', α_D=coupling A' to h'
- Next iteration: (much) more data & improved triggers
- **First limits for these ranges**



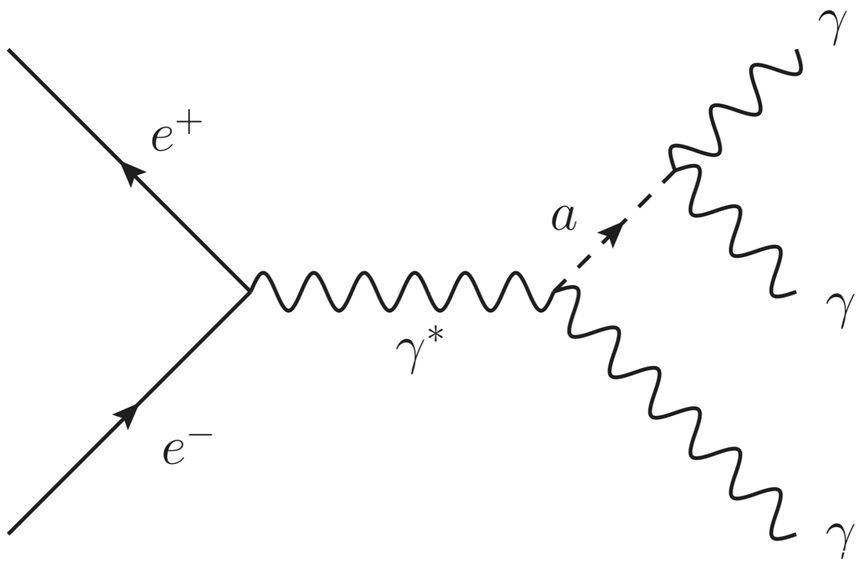


https://arxiv.org/abs/2207.00509

ALPs in ee collisions: $ee \to \gamma a,\ a \to \gamma\gamma$

ALPs in ee collisions: $\mathbf{ee \to \gamma a,\ a \to \gamma\gamma}$

- **ALPs**: cousins of axion; massive, neutral, pseudoscalar; dark mediators
- $\mathbf{e^+e^- \to \gamma a,\ a \to \gamma\gamma}$
- Parameters: mass $\mathbf{m}_a$ and coupling $\mathbf{g}_{a\gamma\gamma}$
- Pushing to **low masses is difficult**
  - $\gamma\gamma$ from ALP merge & π^0 peak
  - Can be address in second iteration
- $\mathscr{L}$ = 0.445 fb^{-1}

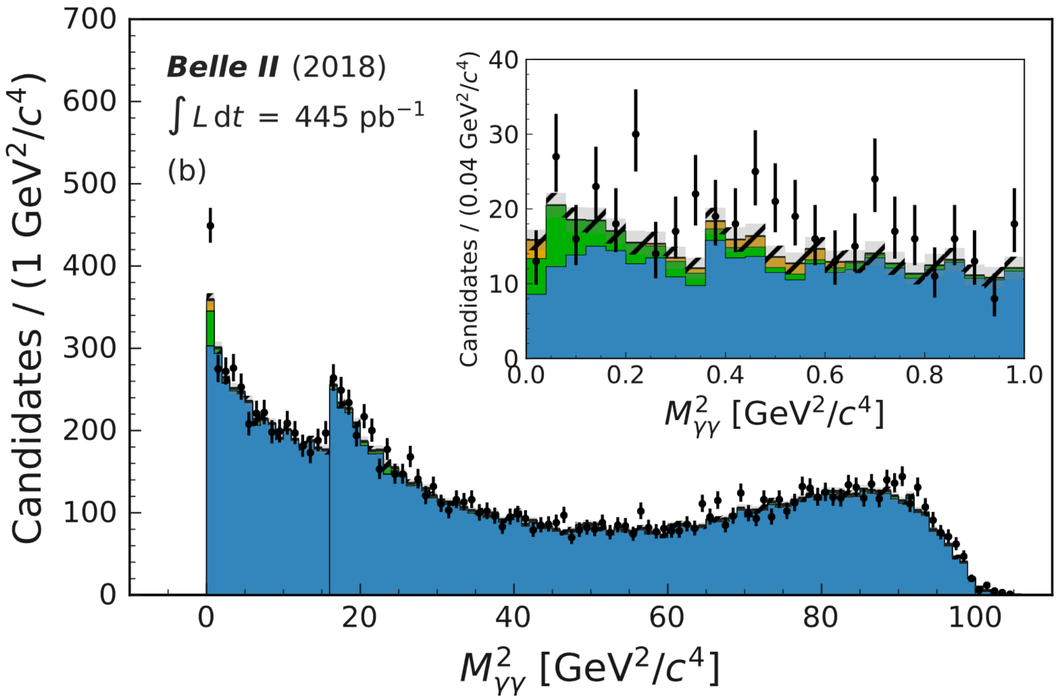


(this was my PhD research topic!)

Phys. Rev. Lett. 125, 161806 (2020)

ALPs in ee collisions: $ee \to \gamma a,\ a \to \gamma\gamma$

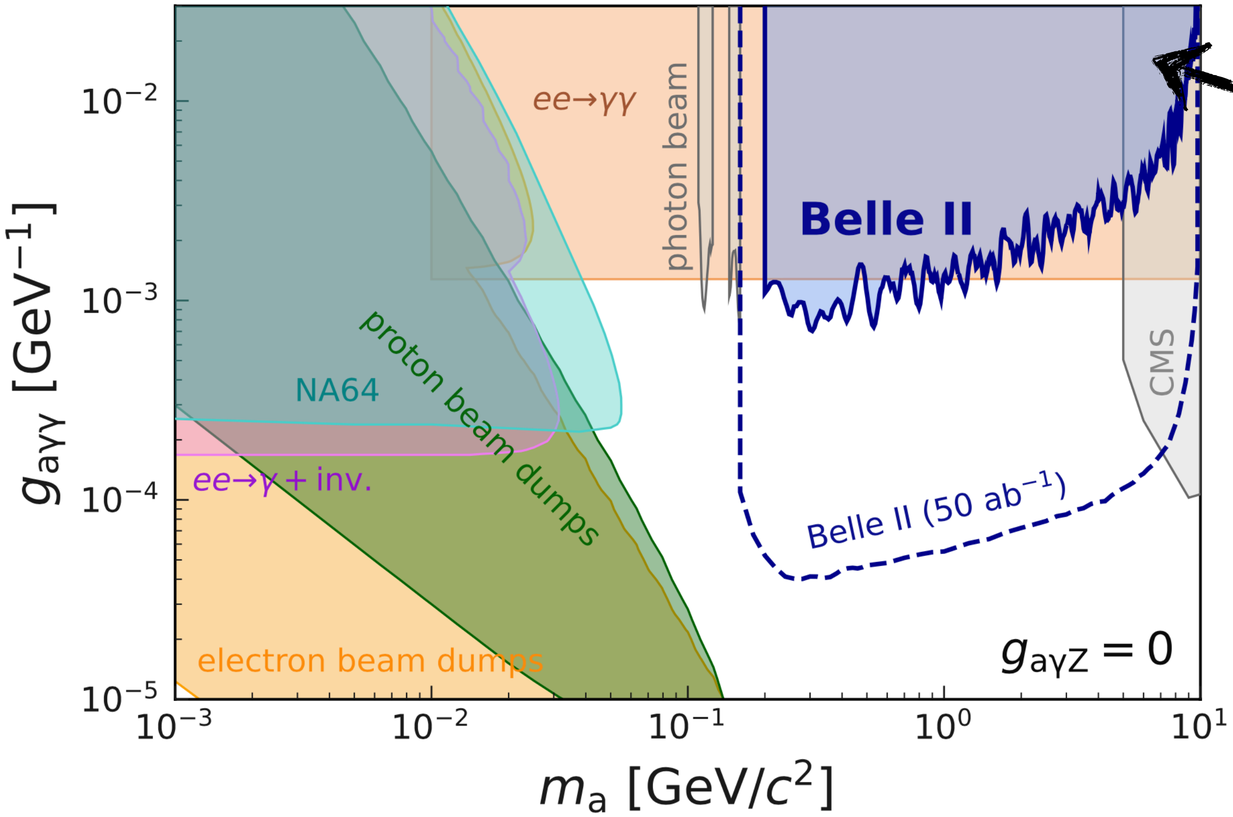
- **Signal**:
  - 3-photon final state, no missing E
- **Backgrounds**:
  - $e^+e^- \to \gamma\gamma(\gamma)$
  - $e^+e^- \to ee(\gamma)$
  - $e^+e^- \to h^0\gamma,\ h^0 \to \gamma\gamma\ (h^0 = \pi^0, \eta, \eta')$
- **Selection**: multi-dimensional **rectangular cut(s)**
  - **Future** possibility: **Neural Network** particularly for low mass
- 1D peak hunt over $m^2(\gamma\gamma)$ (or m^2_{recoil})



Phys. Rev. Lett. 125, 161806 (2020)

ALPs in ee collisions: $ee \to \gamma a,\ a \to \gamma\gamma$

- **95% CL UL** on $g_{a\gamma\gamma}$
- Already competitive with preliminary data
- Belle II has a **unique area of sensitivity**



Phys. Rev. Lett. 125, 161806 (2020)

Summary

Summary

- **Dark Sector** is cool
- Quite a few (recent!) **dark searches** @ BaBar, Belle, & Belle II
  - **Here**: Axion-like particles, Darkonium, B-mesogenesis, Dark photons, Dark Higgs, Z′, …
  - **Also** (links to backup or papers, ask me if you're interested!):
    - Heavy neutrinos using taus
    - Light Higgs from Υ(1S)
    - Dark leptophilic scalar feat tau pairs
    - ττ resonances in ee→μμττ
    - Z′ at , $B0 \to A'A'$, $A' \to x\bar{x}$ (x=μ,e,π) at , ...
- They all have **unique sensitivity** complementary to higher-E experiments

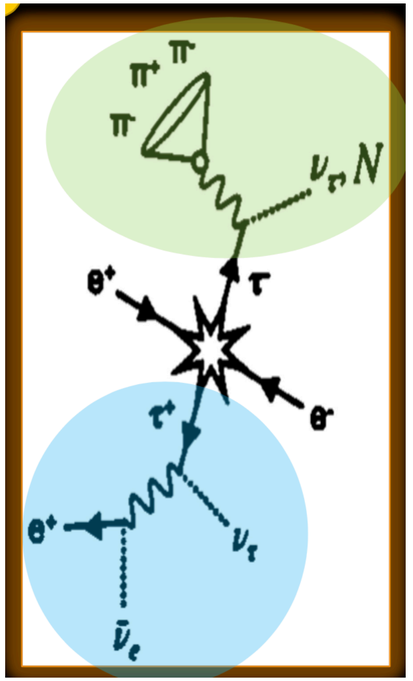
Backup

Extra analyses

Heavy Neutrinos using taus

Heavy Neutrinos using taus

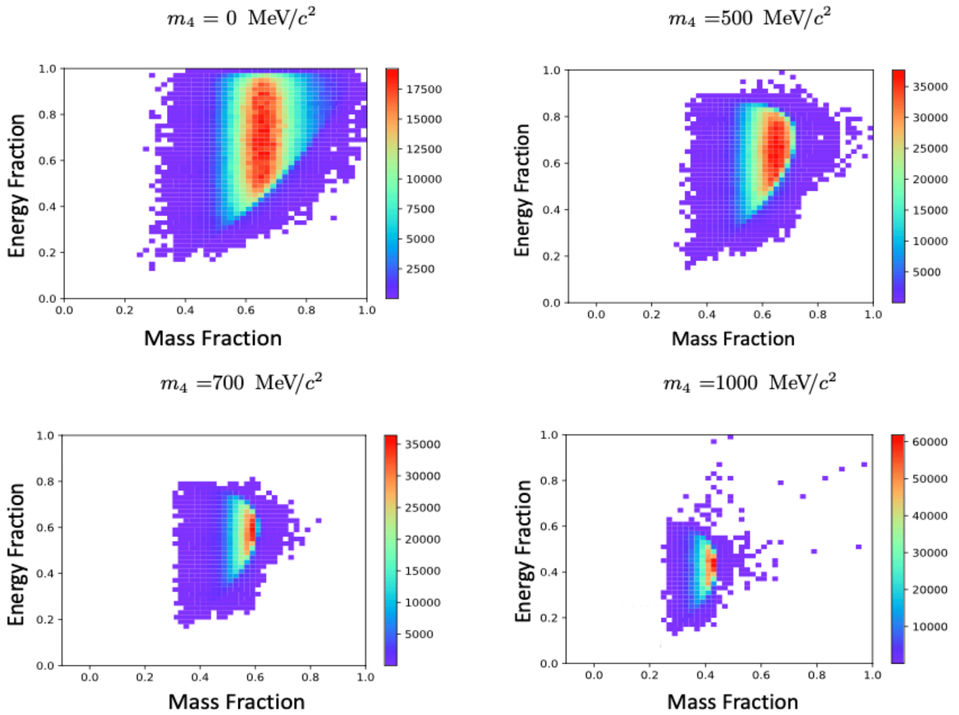
- **Heavy Neutrinos** aka **Heavy Neutral Leptons (HNLs)** aka **sterile** neutrinos
  - Can give mass to SM neutrinos
  - Possible DM candidates
- Search mixing with taus (less constrained): $\mathbf{|U_{\tau 4}|}$
- $\boldsymbol{\tau^- \to \pi^+\pi^-\pi^-\nu_\tau}$
- Signal:
  - 3 π + missing E
  - tag side 1-prong: only 1 track, e or μ
- Backgrounds:
  - $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$ with outgoing ν
  - τ and non-τ decays mis-identified as 3-prong
- $\mathscr{L}$ = 424 fb^{-1}

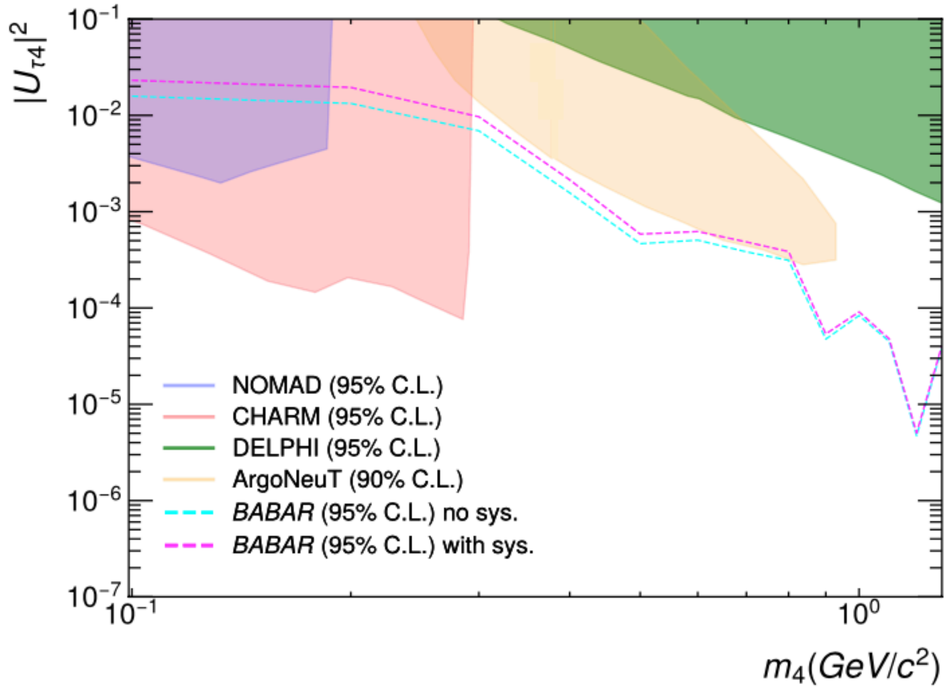


Accepted for Physical Review D

Heavy Neutrinos using taus

- If HNL exists and mixes with ν_T: **modifies kinematics** of decays involving ν_T
- Search for **alteration of distribution of E, m of the 3π system**
  - Depends on **m(HNL)=m_4**
- **95% CL UL** on **$|U_{T4}|$** for HNLs mixing with taus in range $100<m_4<1300$ MeV/c^2





[Accepted for Physical Review D]

Light Higgs boson from Y(1S)

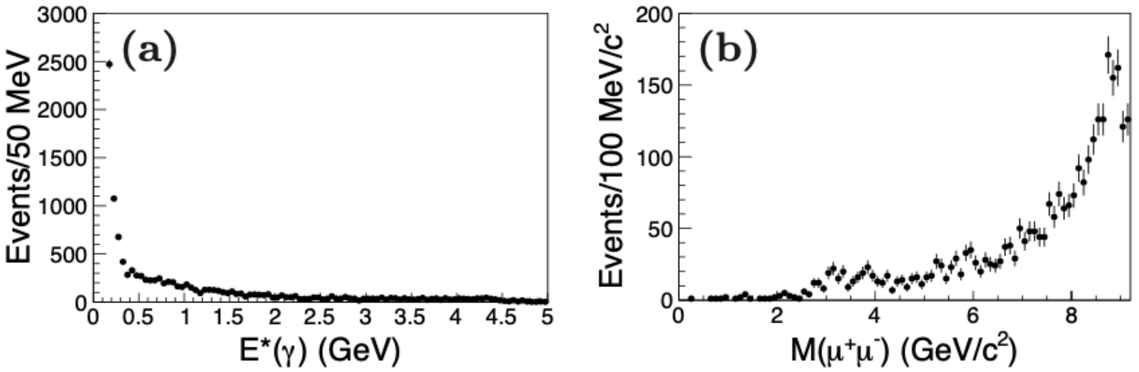
Light Higgs boson from Y(1S)

- **Light Higgs boson:** from radiative decays of Y(1S)
- $\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \to \gamma A^0$, $A0 \to l\bar{l}$, $l = \mu, \tau$
  - Above ττ threshold: ττ; below: μμ
  - Two **modes** → two selections
- History of similar searches from CLEO, BaBar, Belle
- $\mathscr{L} = 25\ fb^{-1}$

Phys. Rev. Lett. 128, 081804 (2022)

Light Higgs boson from Y(1S)

- **Signal:**
  - 2 π, 1 γ, 2 leptons, missing E
- **Backgrounds:**
  - $\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \to l\bar{l}$, l=e,μ,τ + any γ
- Protection from γ from FSR or π^0
- 4C kinematic fit for muonic mode
- $m_{cand}(A^0)$ = m(μμ) or $m_{recoil}(\gamma)$
- Y(1S) tagged with $m_{recoil}(\pi^+\pi^-)$
- **2D fit to $m_{cand}(A^0)$ vs $m_{recoil}(\pi^+\pi^-)$**

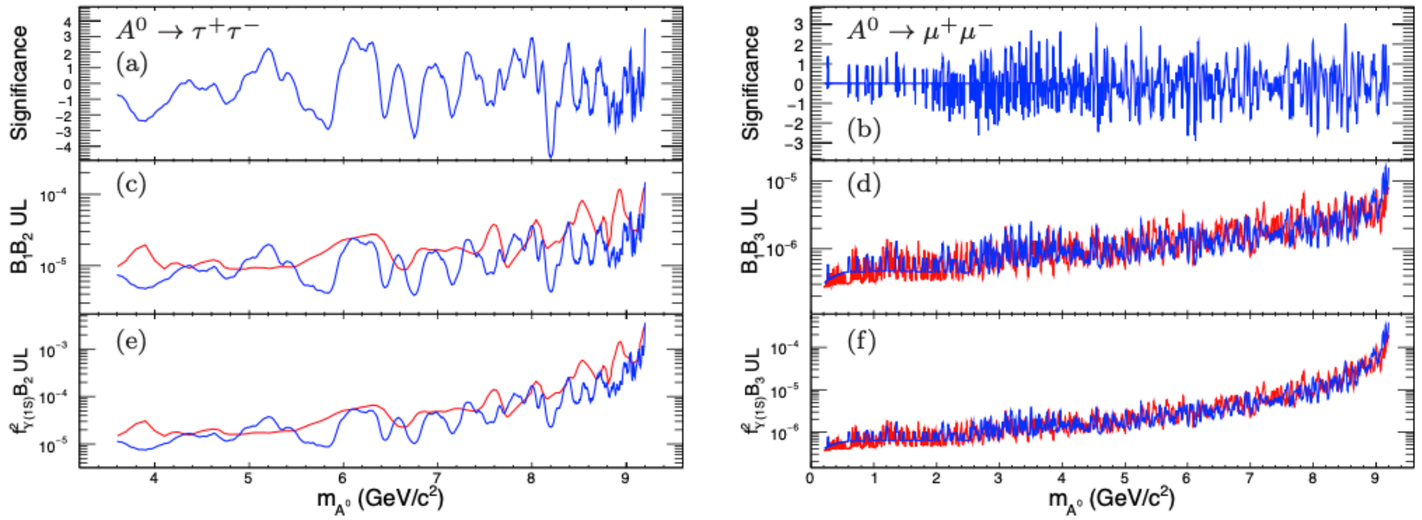


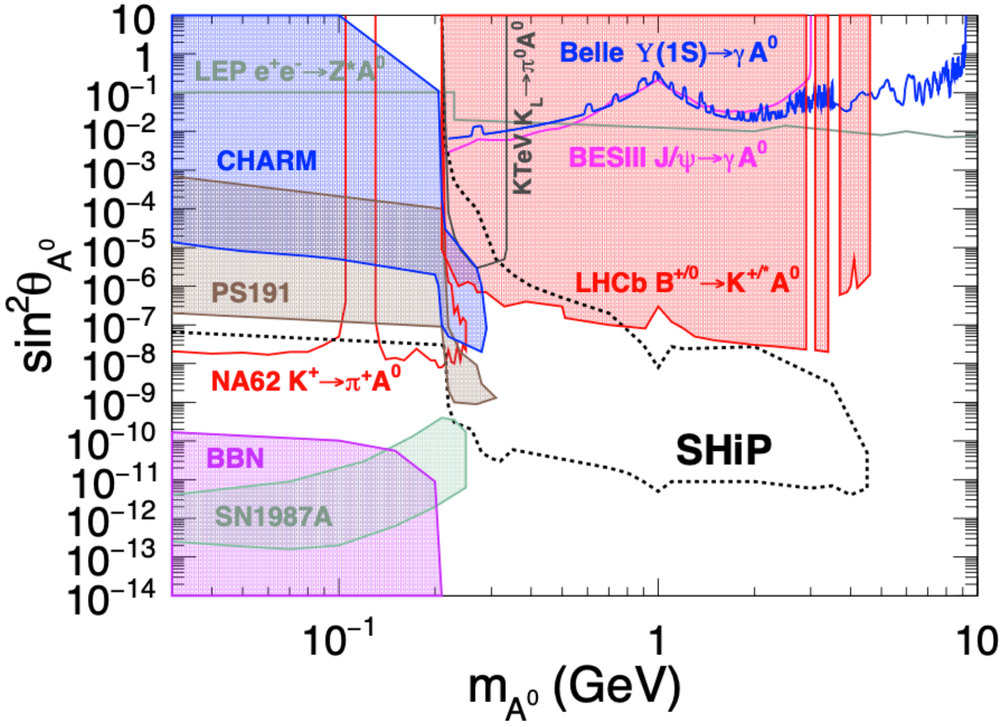
The (a) $E^*(\gamma)$ and (b) $M(\mu^+\mu^-)$ distributions from the $\Upsilon(2S)$ data sample.

Phys. Rev. Lett. 128, 081804 (2022)

Light Higgs boson from Y(1S)

- **90% CL UL** on product Branching Ratio (BR)
- Same results as BaBar
- Converted to Yukawa coupling and mixing angle sin(θ(A⁰))



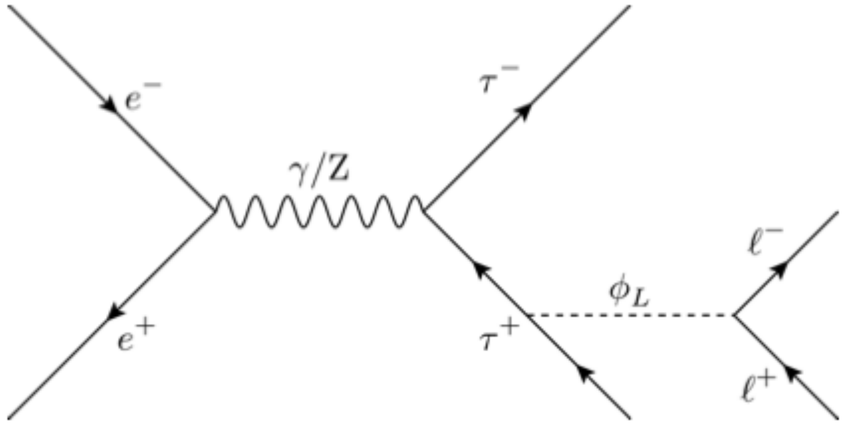


Phys. Rev. Lett. 128, 081804 (2022)

Dark leptophilic scalar
Feat: tau pair

Dark leptophilic scalar, feat tau pair

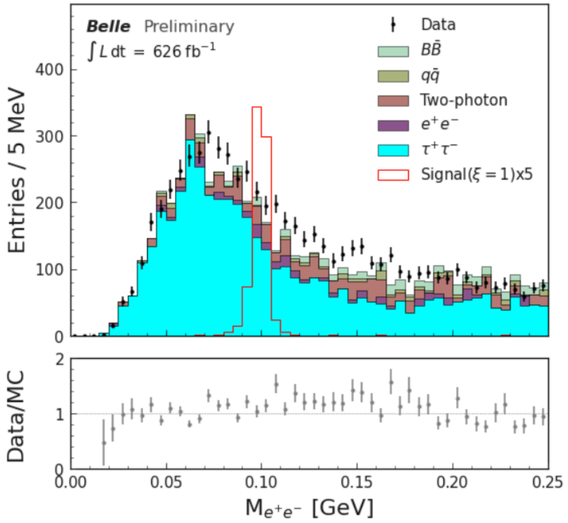
- **Dark leptophilic scalar φ_L:** couples only to leptons, not quarks
- Could explain $(g-2)_\mu$, Lepton Flavor Universality Violation (LFUV)
- **$e^+e^- \to \tau^+\tau^-\varphi_L$, $\varphi_L \to l\bar{l}$ (l=e,μ)**
  - Electronic and muonic **modes**
- Mixing between φ_L and Higgs: coupling ∝ m(l)
- Little constraints in MeV-GeV range
  - 0.04 GeV < m(φ_L) < 6.5 GeV
- **Background modeling** using MC samples + data in control regions for normalization
- $\mathscr{L}$ = 626 fb^{-1}

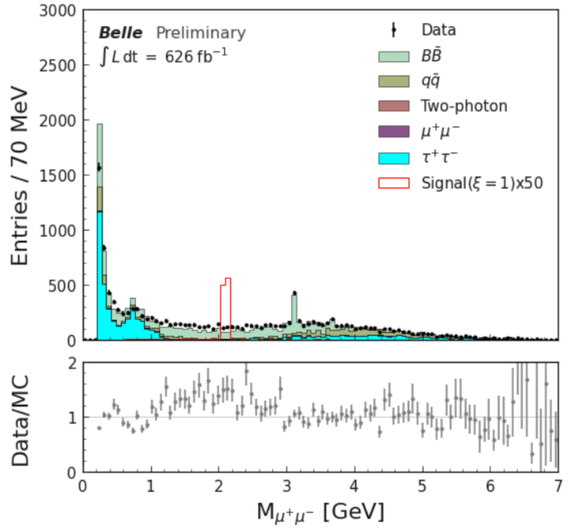


https://arxiv.org/abs/2207.07476

Dark leptophilic scalar, feat tau pair

- **Signal:**
  - τ: 1-prong decay (1 track)
  - 4 tracks + missing E
- **Backgrounds:**
  - $e^+e^- \to \tau^+\tau^-$: big
  - $e^+e^- \to e^+e^-$ / $\mu^+\mu^-$
  - $e^+e^- \to q\bar{q}$: big for muonic mode for high masses
  - $e^+e^- \to B\bar{B}$
- **5 BDTs**: 4 for the backgrounds, 1 for signal
- **Control region** (BDT signal score < 0.5) to study background normalizations

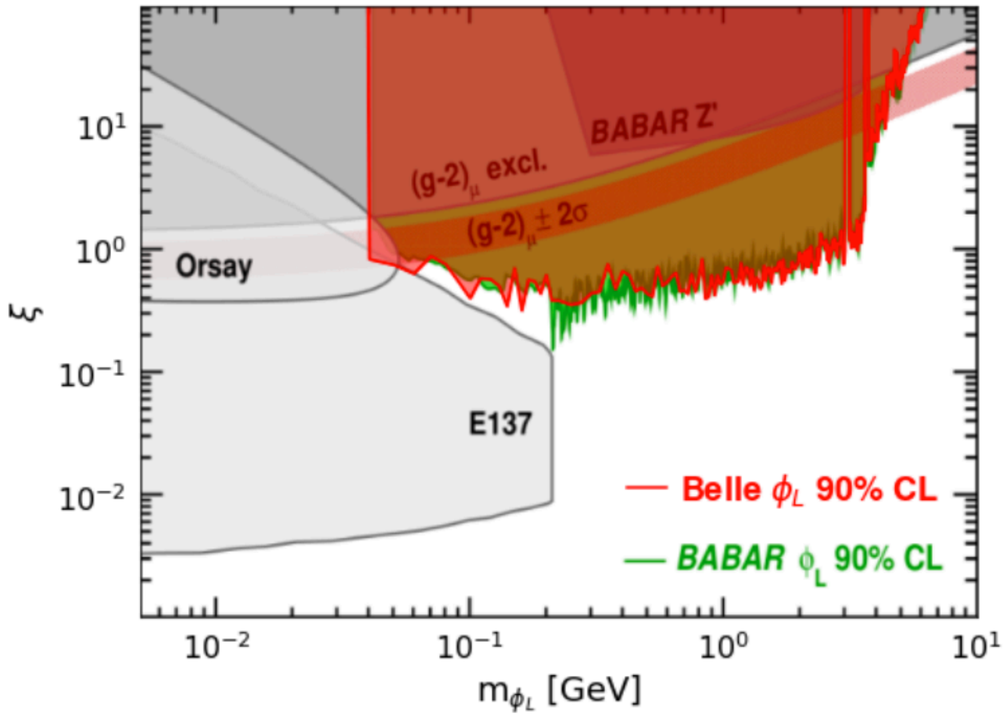




https://arxiv.org/abs/2207.07476

Dark leptophilic scalar, feat tau pair

- **Peak hunt** in m(ee) / m(μμ) distribution
  - Skip around J/Ψ and Ψ(2S)
- Additional uniform background component to account for un-modeled processes
- **90% CL UL**
  - Excluded parameter space with **$0.04<m(\varphi_L)<4$ GeV as $(g-2)_\mu$** explanation

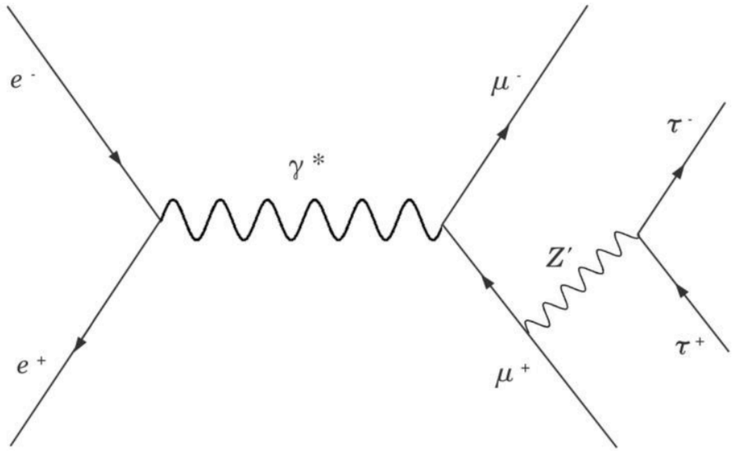


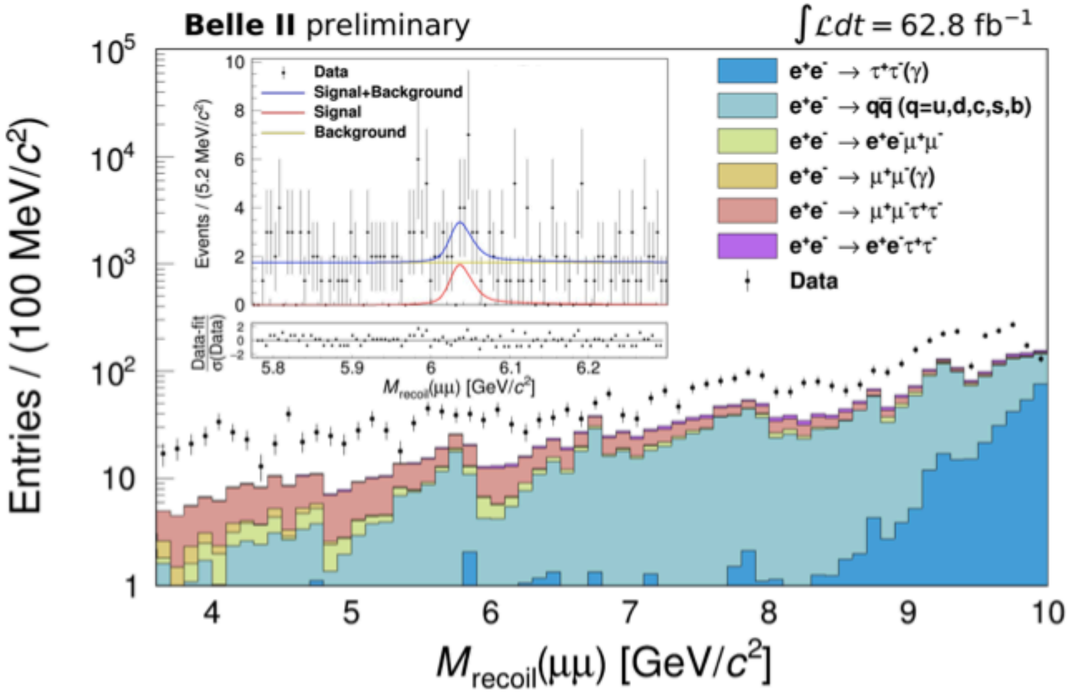
https://arxiv.org/abs/2207.07476

ττ resonances in ee→μμττ

ττ resonances in ee→μμττ

- **Z′/ALP/leptophilic scalar into visible**: ee→μμX′, X′→ττ
- 4 tracks, ≥2 muons, missing E
- **Backgrounds:**
  - Continuum & 4-lepton processes
  - **Un-modeled**: ee→μμ$\pi\pi$ & ee→ee$X_{hadrons}$
    - Normalization discrepancy
  - No ISR in 4-lepton generator
    - New (Wizard) being looked into
- $\mathscr{L}$ = 63 fb^{-1}

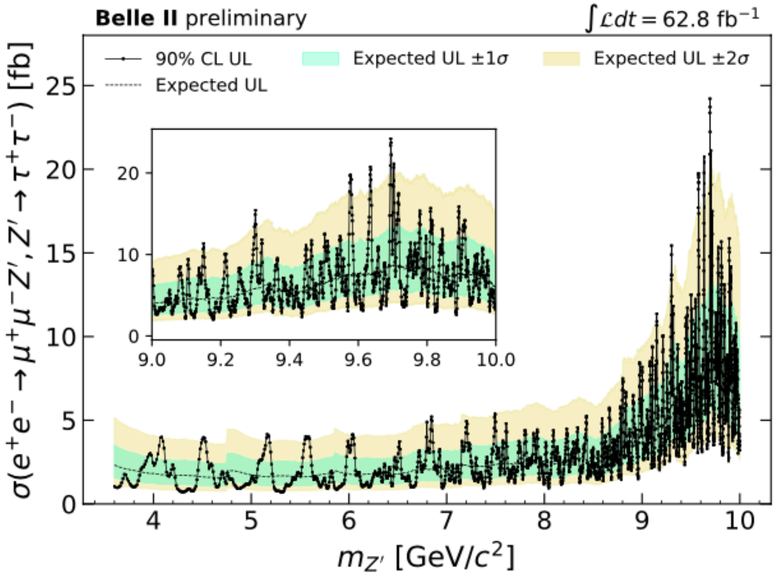




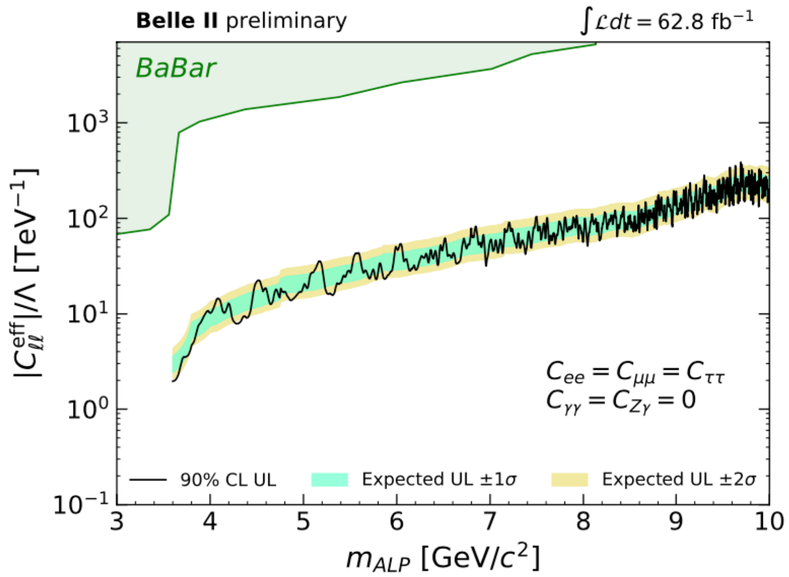
ττ resonances in ee→μμττ

- **90% CL UL** interpreted for **Z' / ALP / leptophilic scalar**
- **ALP:** world-leading for ALPs into leptons
- **Leptophilic scalar**: first limits above 6.5 GeV

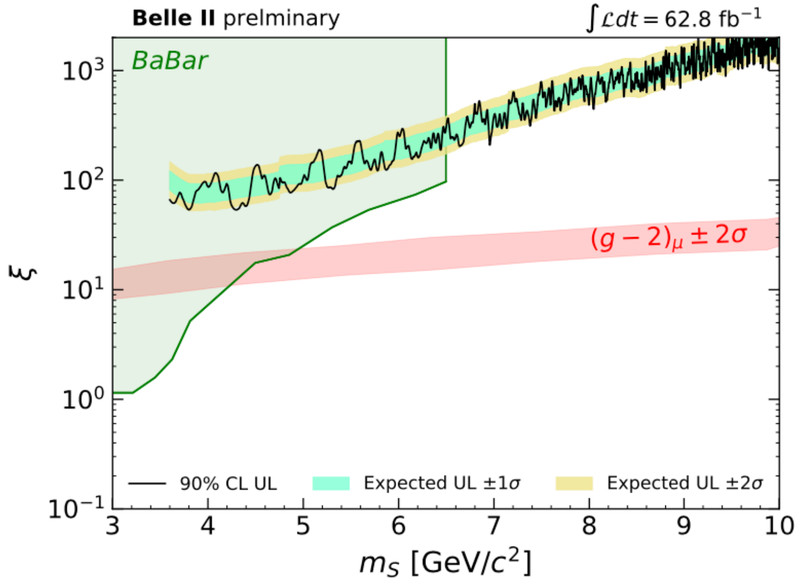
Z'



ALP



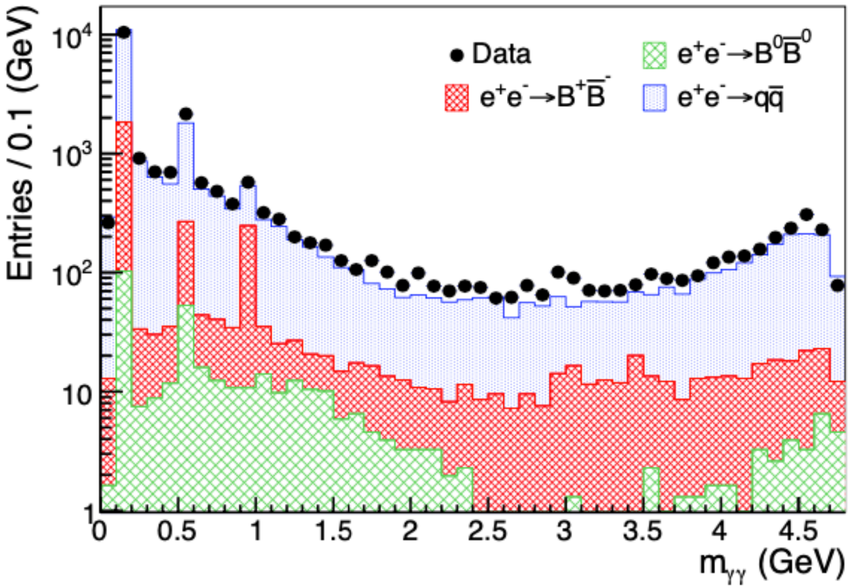
Leptophilic scalar



Extra details on main-body analyses

ALP in B decays: B→Ka, a→γγ

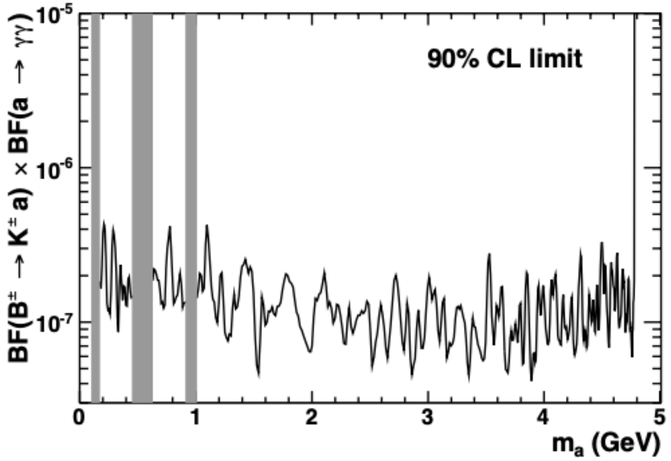
- **Signal:**
  - 1 track + 2 γ summing to m(B)
- **Backgrounds:**
  - $e^+e^- \to l^+l^- (\gamma)$ (l=e,μ,τ)
  - $e^+e^- \to q\bar{q}$ (q=u,d,s,c): **continuum**
    - Dominant background
  - $e^+e^- \to B\bar{B}$
    - Peaking, vetoed: $B^\pm \to K^\pm h^0$, $h^0 \to \gamma\gamma$ ($h^0=\pi^0,\eta,\eta'$)
    - Peaking, small, not modeled: $B^\pm \to K^\pm \eta_c$, $\eta_c \to \gamma\gamma$
- **2 BDTs**: vs continuum and vs $B\bar{B}$

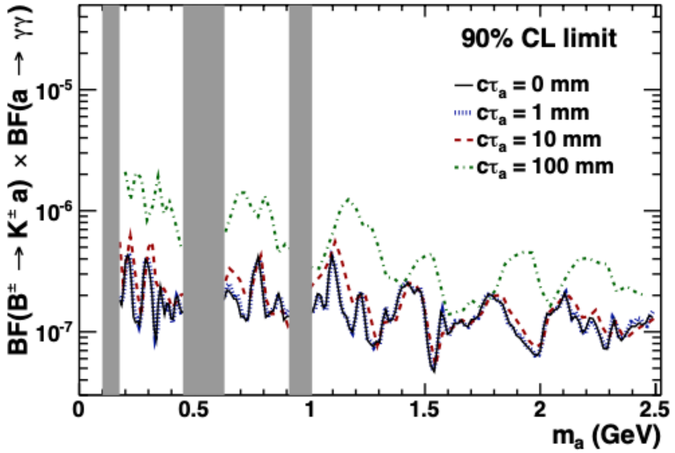


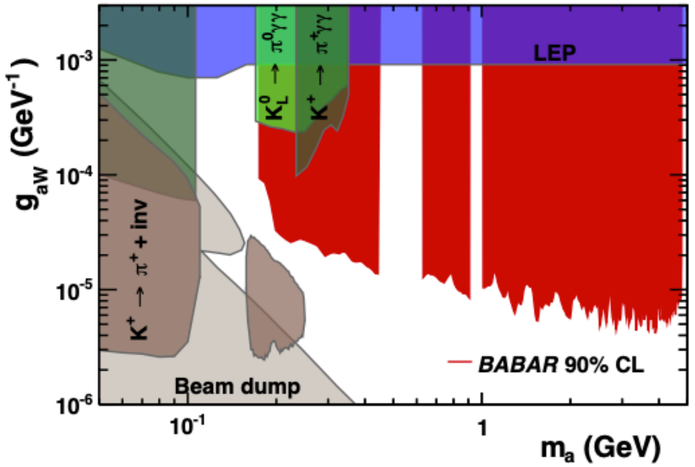
https://arxiv.org/abs/2111.01800

ALP in B decays: B→Ka, a→γγ

- **Peak hunt: 1D fit on m(γγ)** of peaking signal over background
  - Signal = KDE (Kernel Density Estimator)
  - Background = 1st-order polynomial (+ template) & resonance peaks
- **Re-performed** the upper limit extraction for **non-zero lifetimes**
  - Small mass and coupling
  - cτ = 1, 10, 100 mm
- 90% CL UL on **g_{aW}: improving previous constraints** by >O(100)



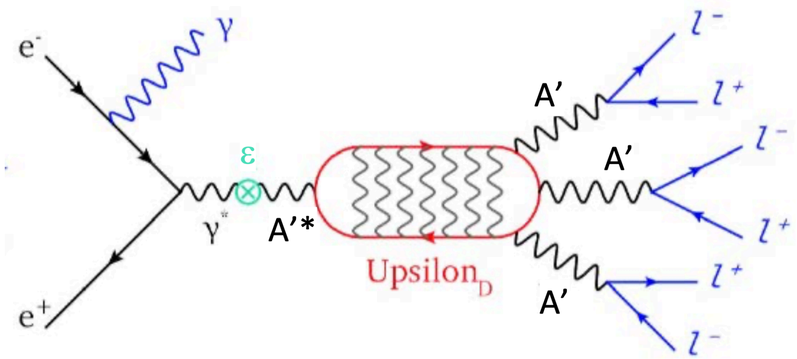




https://arxiv.org/abs/2111.01800

Darkonium: dark bound state

- **Darkonium:** bound dark matter, i.e. self-interacting DM
- $J^{PC}=1^{--}$ state Y_D
- **$e^+e^- \to \gamma_{ISR} Y_D$, $Y_D \to A'A'A'$, $A' \to x\bar{x}$ ($x=\mu, e, \pi$)**
  - ISR = Initial State Radiation
- Bounds on **kinetic mixing ε** vs **coupling constant $g_D \propto \alpha_D^{0.5}$**
- $0.001 < m(A') < 3.16$ GeV & $0.05 < m(Y_D) < 9.5$ GeV
- Lifetime of A′ does not depend on g_D, only on ε and m(A′)
  - Long for small mass and mixing
- $\mathscr{L} = 514$ fb^{-1}
  - Y(4S), Y(3S), Y(2S) resonances and vicinities

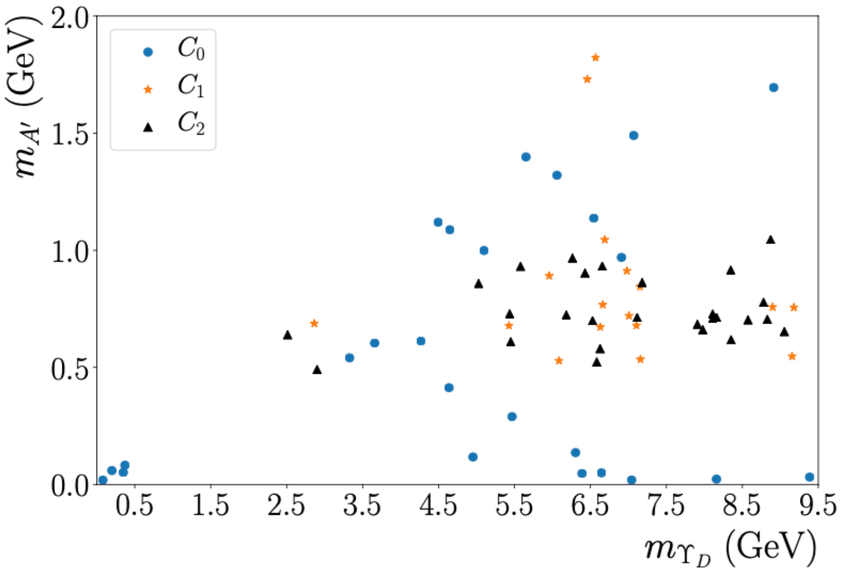


https://arxiv.org/abs/2106.08529

Darkonium: dark bound state

- **Signal:**
  - 3 pairs of oppositely charged tracks (μ,e,π), similar masses
  - If recoil momentum within calorimeter: require compatible ɣ (ISR)
- **Backgrounds:**
  - Too complex to be properly simulated
  - 5% of data to optimize selection criteria, then discarded
- **3 Neural Networks (NNs)** depending on # π pairs
- Scan **m(A')-m(Υ_D)** plane: signal is a point there

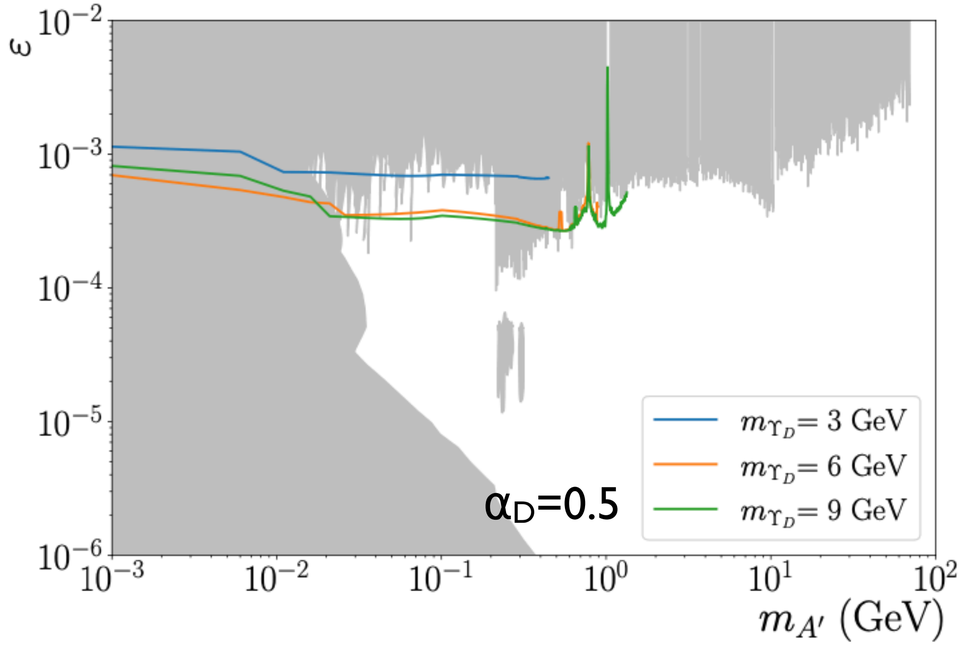
Events passing the selection
Cn: NN trained for n π pairs

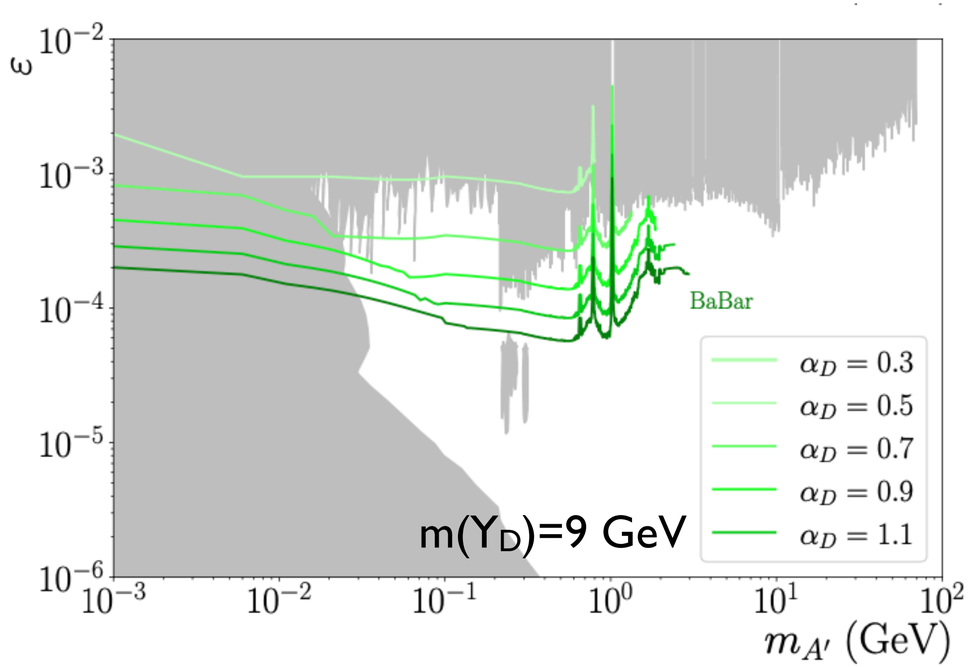


https://arxiv.org/abs/2106.08529

Darkonium: dark bound state

- Considered **different lifetimes**
- **Limits on kinetic mixing** ε depend on assumptions on $\alpha_D \propto g_D^2$ and **m(Y_D)**
- 90% CL UL on ε for different values of α_D and **m(Y_D)**
- First search for bound dark state into 3 dark photons
- **Improve constraints for large dark coupling and Y_D masses**

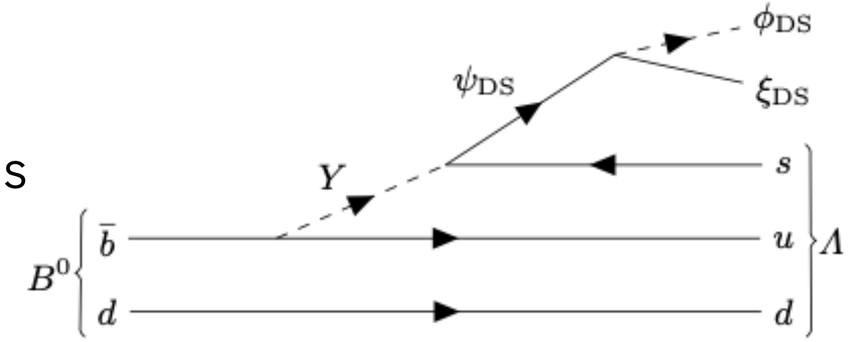




https://arxiv.org/abs/2106.08529

$B^0 \to \Lambda$ + dark baryon Ψ_{DS}

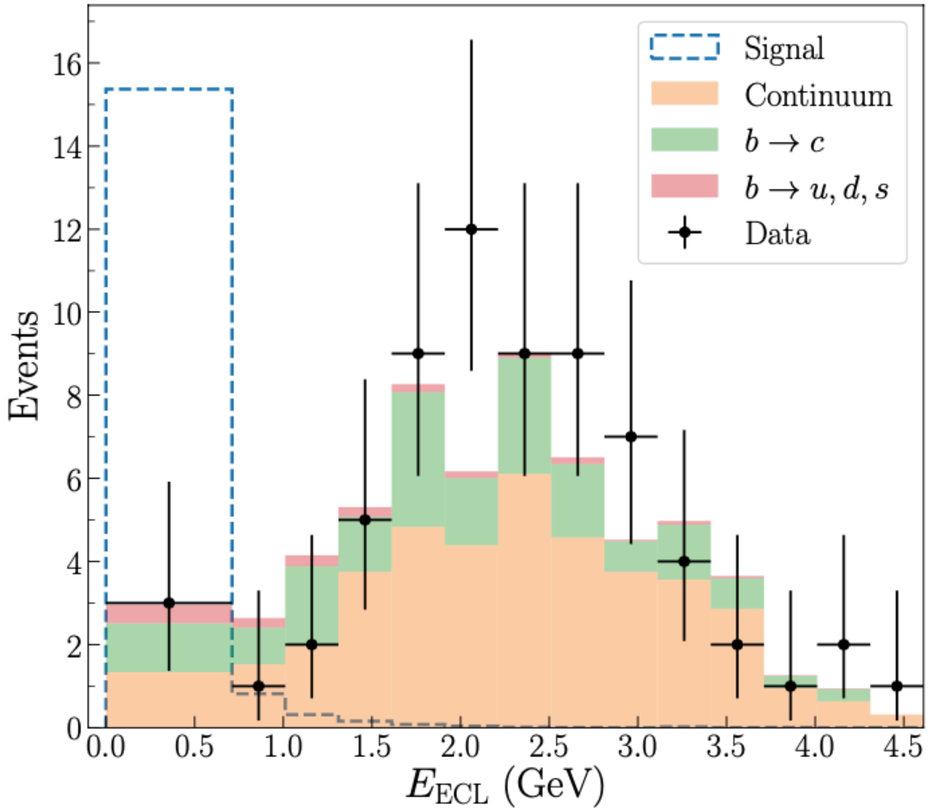
- **B-Mesogenesis mechanism**: address DM & baryon asymmetry via CP-violating oscillation
- Prediction of $B^0 \to \Lambda$ + missing E + any light mesons (BF~10^{-4})
  - Mediator Y
  - Ψ_{DS} → dark
- **$B^0 \to \Lambda$ + missing E, $\Lambda \to p^+\pi^-$**
- Other B (tag side): fully reconstructed with hadronic channels
  - **Full-Event Interpretation (FEI)** from **Belle II** software
  - 6-step process, including:
    - BDTs to identify particles
    - Default combinations into intermediate daughters/mothers
- $\mathscr{L}$ = 622 on +89 off fb^{-1}



https://arxiv.org/abs/2110.14086

$B^0 \rightarrow \Lambda$ + dark baryon Ψ_{DS}

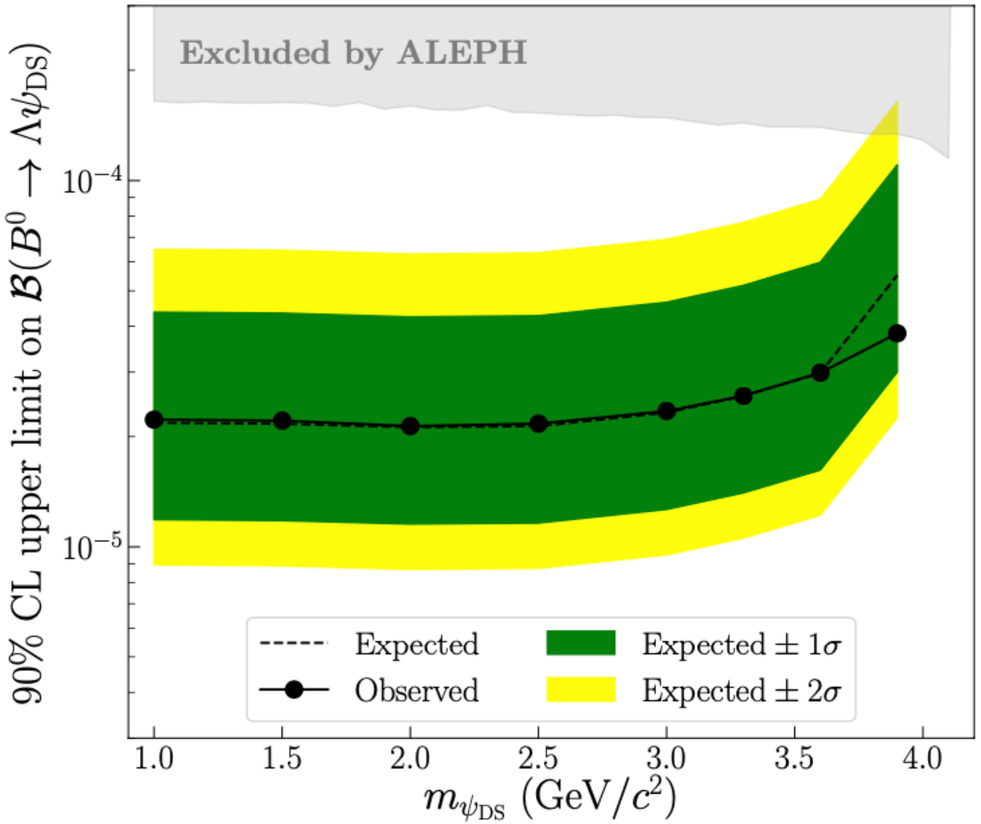
- **Signal**:
  - B_{tag}: fully reconstructed hadronically with FEI
  - B_{signal}: proton + π^- + missing E
- **Backgrounds**:
  - $e^+e^- \rightarrow B\bar{B}$
  - $e^+e^- \rightarrow q\bar{q}$, q=u,d,s,c (*continuum*)
- **Residual energy in the calorimeter E_{ECL}**
- **Count event** in signal region



https://arxiv.org/abs/2110.14086

$B^0 \to \Lambda$ + dark baryon Ψ_{DS}

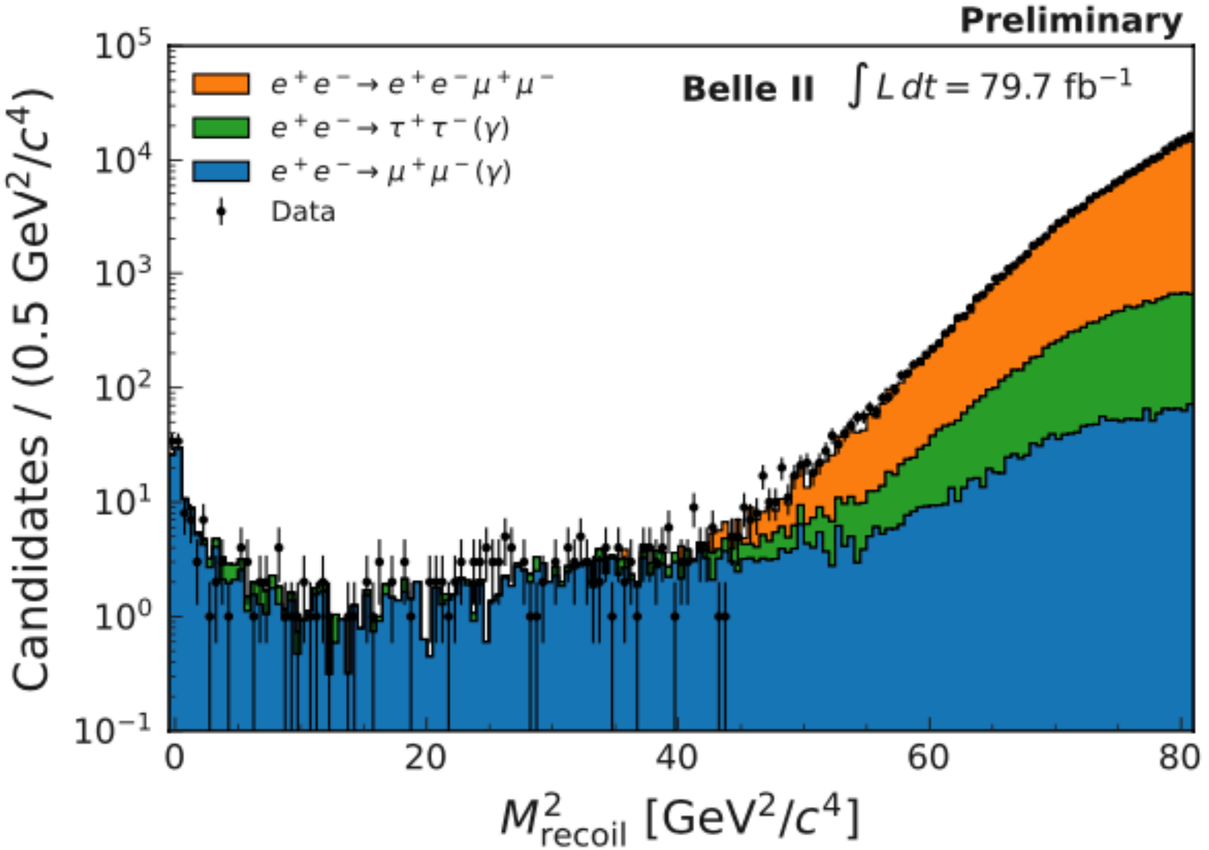
- **90% CL UL** on branching ratio
- Partially exclude B-mesogenesis mechanism
- **Improve on previous results**, and further improvable at Belle II



https://arxiv.org/abs/2110.14086

L_μ-L_τ extension: Z' to invisible

- **Signal:**
  - 2 μ + missing E
- **Backgrounds:**
  - ee→μμ(ɣ)
  - ee→ττ(ɣ)
  - ee→eeμμ
- 2D fit to **recoil mass** ~ m(Z') vs θ^*_{recoil}



L_μ-L_T extension: Z′ to invisible

- **Vanilla mode**: coupling to SM

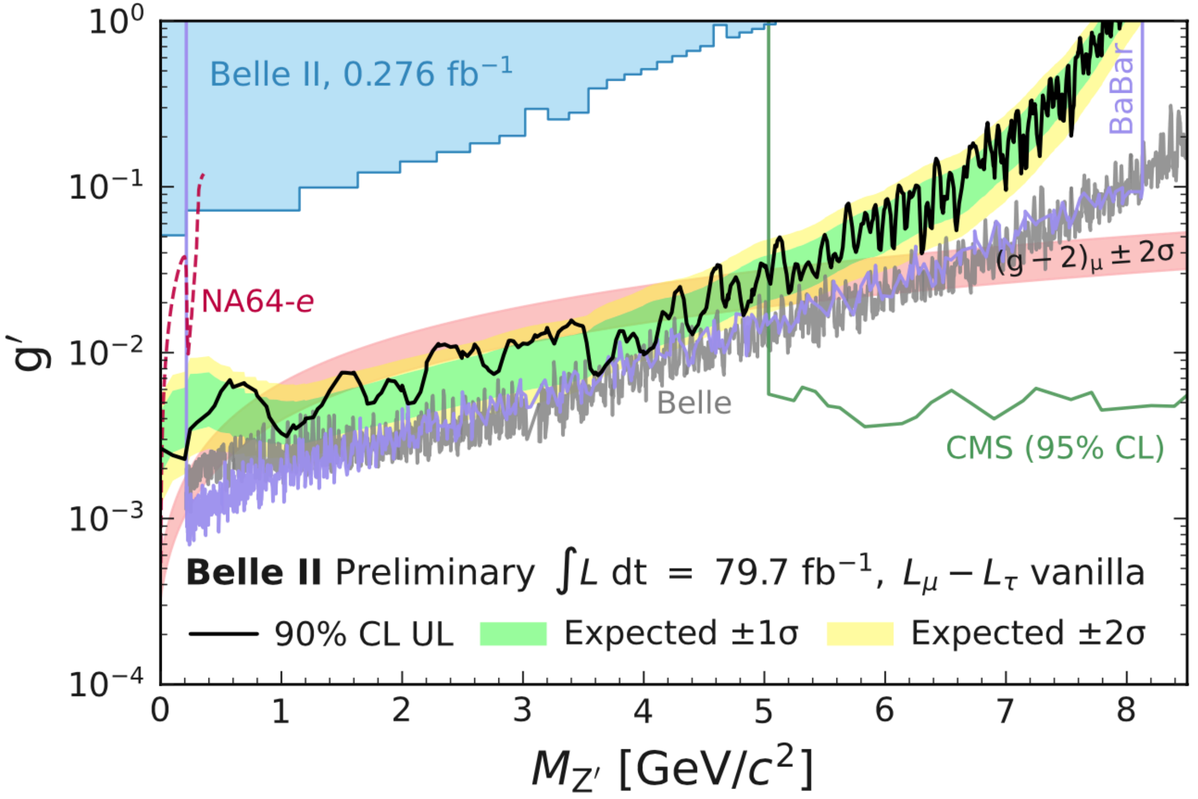
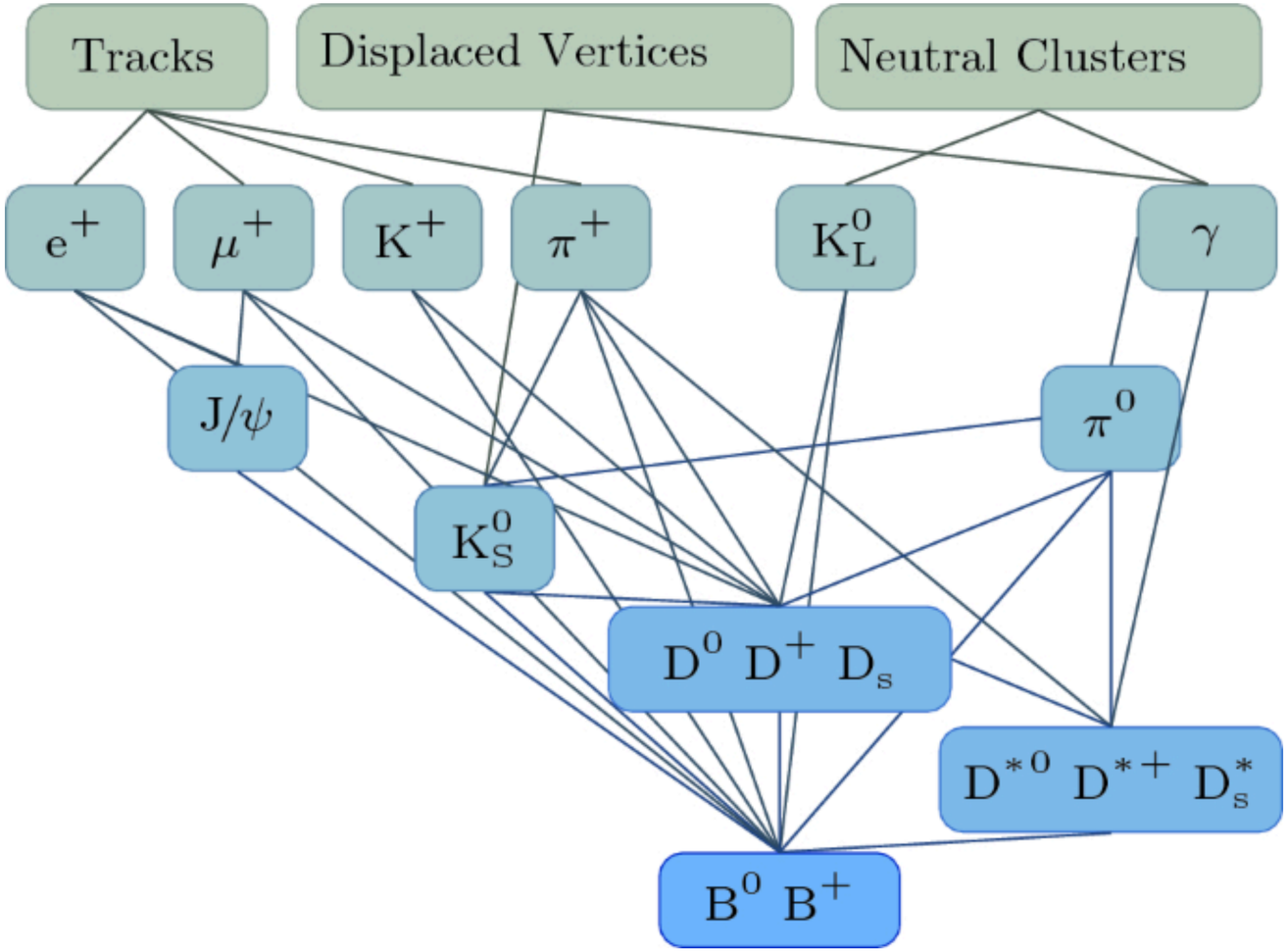


Figure 4: Observed 90% CL upper limits on the coupling constant g' for the $L_\mu - L_\tau$ vanilla model as a function of the Z' mass. Also shown are previous limits from Belle II [19] and NA64-e [18] searches for invisible Z' decays, and from Belle [16], BaBar [15] and CMS [17] (95% CL) searches for Z' decays to muons. The red band shows the region that could explain the muon anomalous magnetic moment $(g-2)_\mu \pm 2\sigma$ [2].

Extra

Full-Event Interpretation

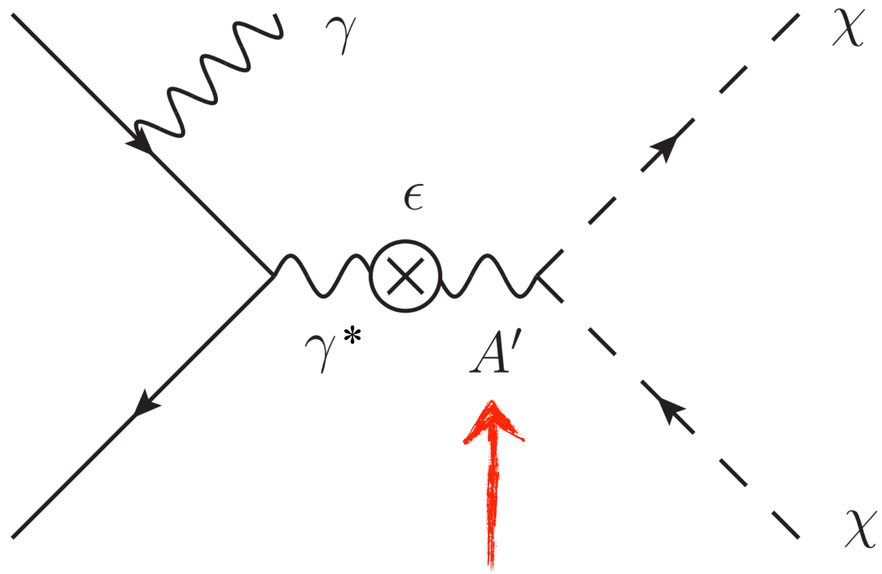


[Comput.Softw.Big Sci. 3 (2019) 1, 6]

Dark photon

My current analysis

- Dark mediator (mixes with SM photons and with DM)
- **$e^+e^- \to \gamma A'$, $A' \to \chi\chi$**
- **Search for 1 single γ and missing E**
  - Works also for long-lived particles
- Parameters: mass $\mathbf{m_{A'}}$ and coupling ε
- **Backgrounds:**
  - $e^+e^- \to \gamma\gamma(\gamma)$ with **missed** photons
  - Cosmics
- Detector inefficiencies: what if we **miss a γ**?
  - Measure and correct **photon inefficiencies** in data & MC



Dark photon

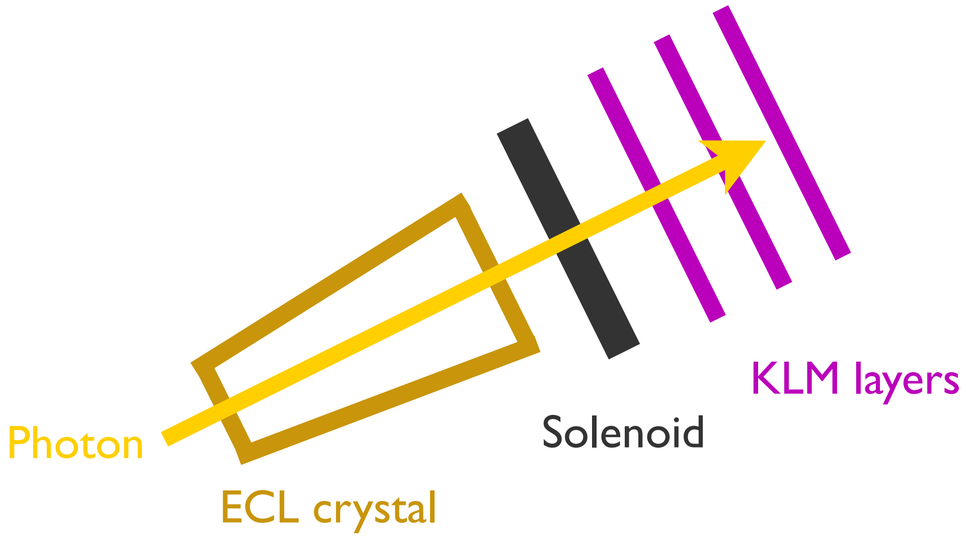
Selection:

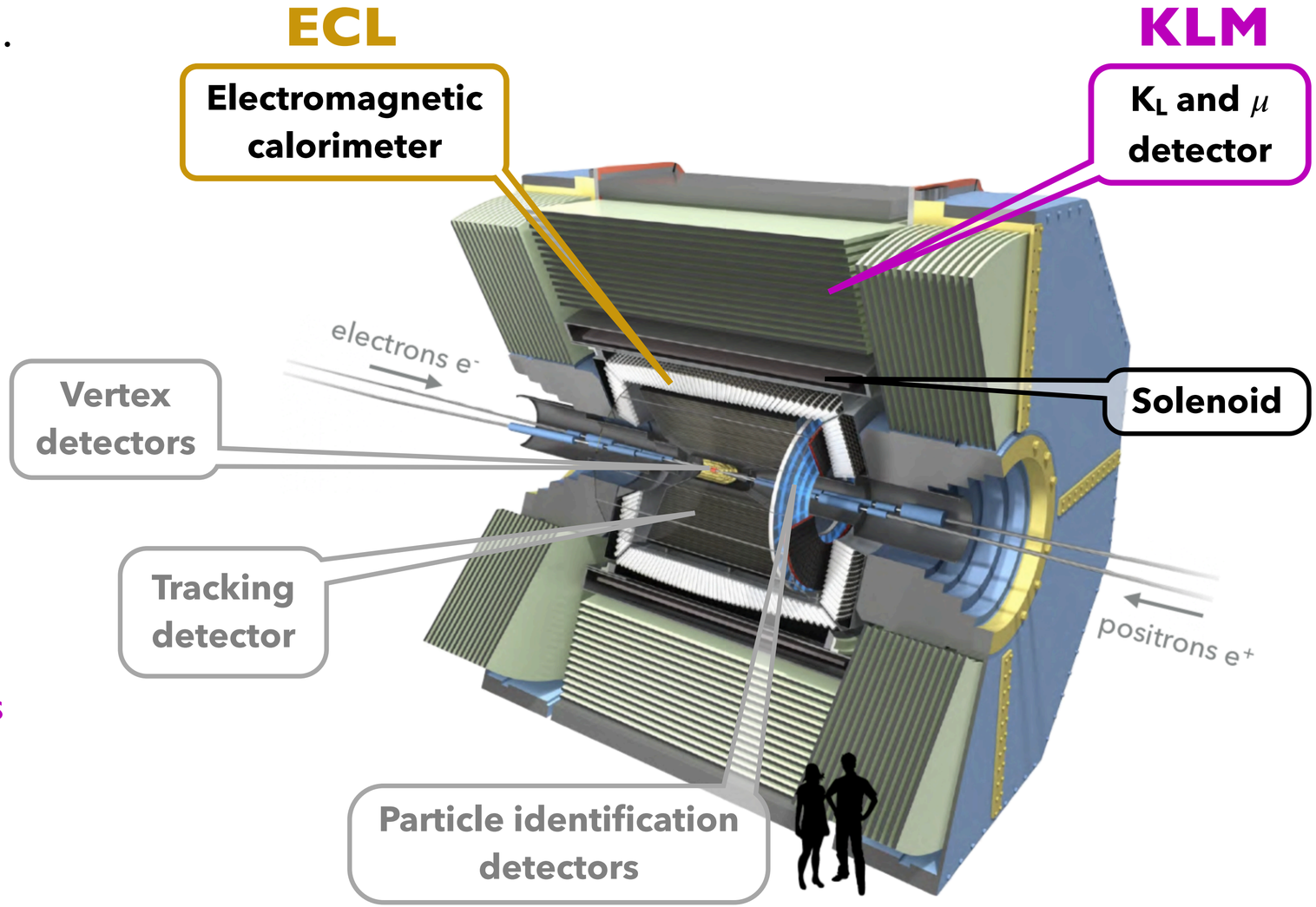
- **Define what photon we accept**
  - E, θ, t, shower shape variables, ...
- **Define what we reject**
  - Other photons
  - **KLM clusters**
  - Tracks

Dark photon

Selection:

- **Define what photon we accept**
  - E, θ, t, shower shape variables, ...
- **Define what we reject**
  - Other photons
  - **KLM clusters**
  - Tracks



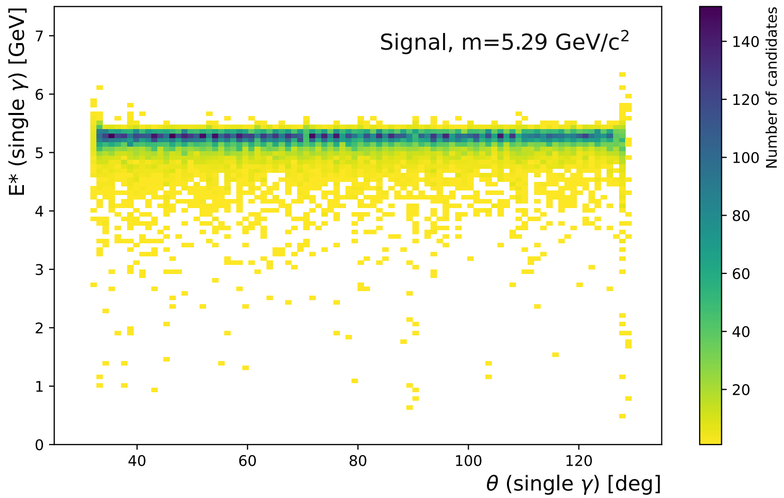


Dark photon

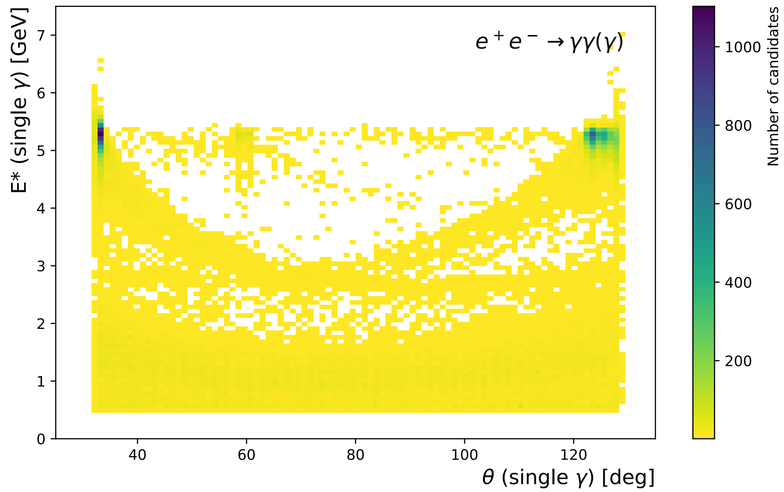
Brutally preliminary!

- Signal vs background
  - E*(ɣ) vs θ(ɣ)
  - Signal: **horizontal strips**
  - Background (ee→ɣɣ(ɣ), cosmics): **blobs**

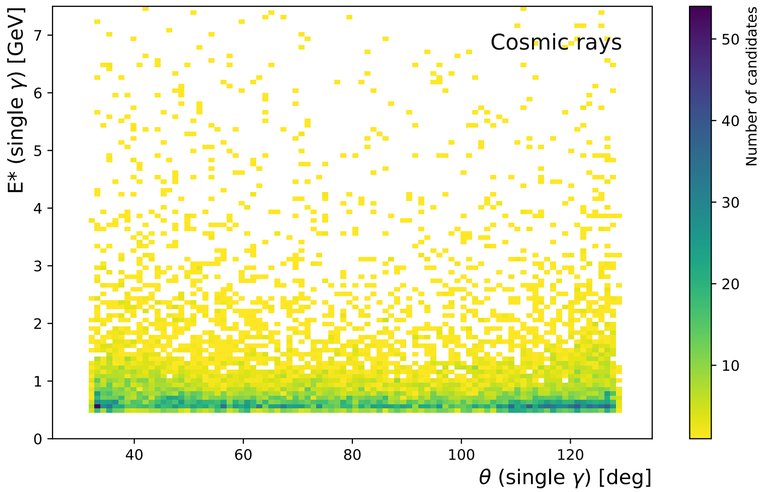
Signal



ee→ɣɣ(ɣ)

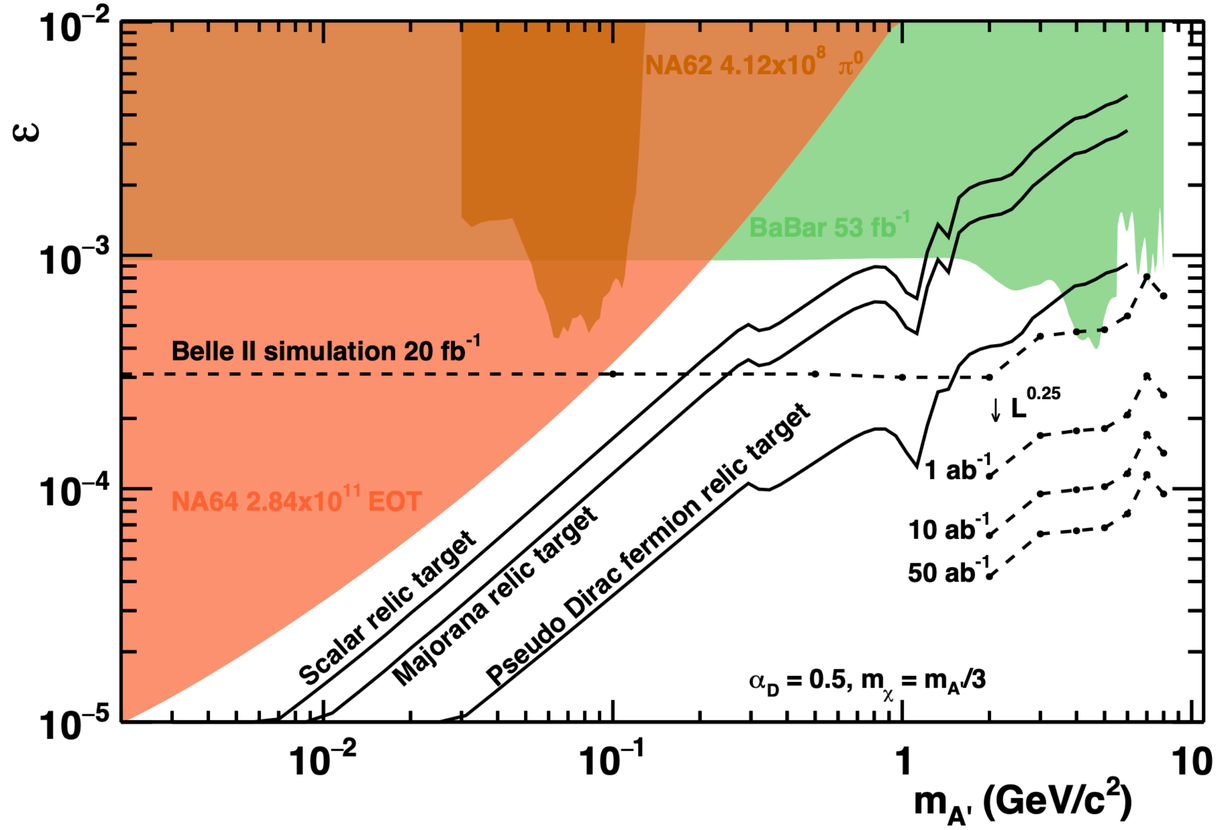


Cosmics



Dark photon

- Belle II has **unique reach**
- Sensitivity to see a signal where it could explain relic Dark Matter



Other dark searches

- Z′ to (in)visible
- Dark photon + dark Higgs

} $\mu\bar{\mu}$+ **missing E**

- Inelastic dark matter
- Dark scalar

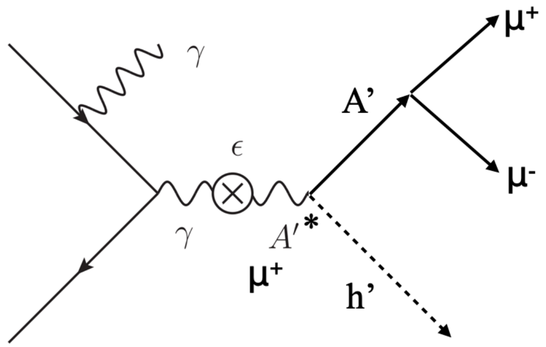
} **Displaced** vertexes

} **Known initial state** &
low multiplicity
very important for these analyses

Belle II excels
Unique sensitivities

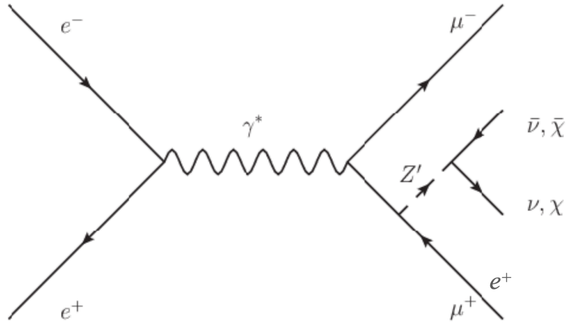
Other dark searches

Dark photon + dark Higgs



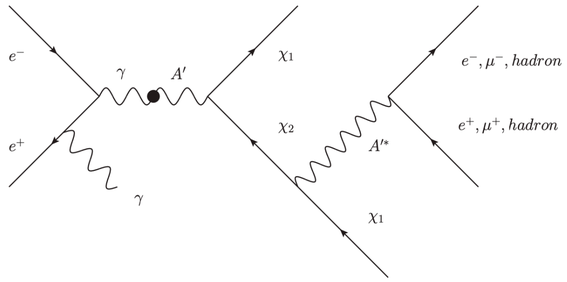
- μμ̄ + missing E
- Unique sensitivity

Z' to (in)visible



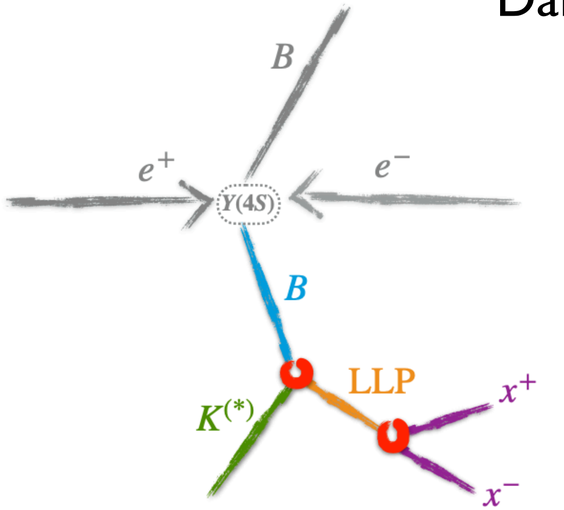
- Addresses g-2 anomaly
- μμ̄ + missing E
- Probe g-2 with 50 ab^{-1}

Inelastic dark matter



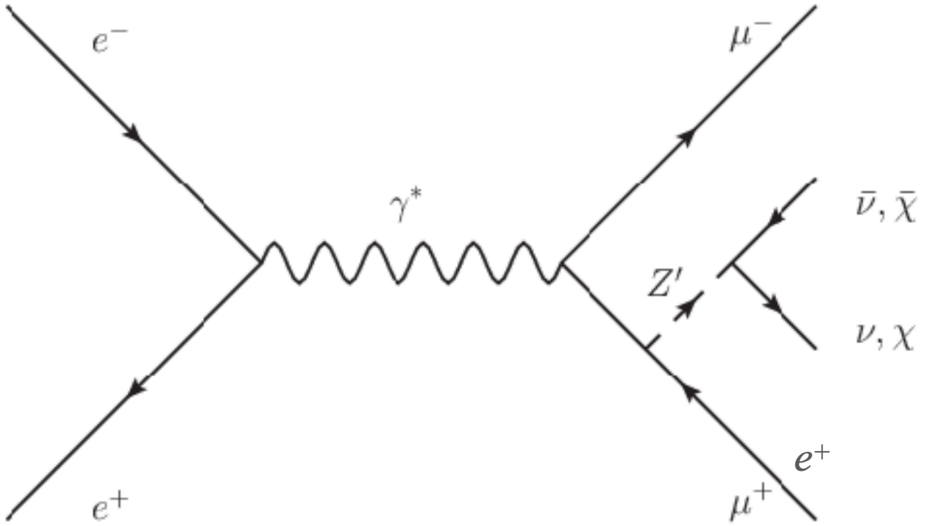
- 3 new particles: χ_1, χ_2, A
- ɣ + displaced eē/μμ̄/hh̄ + missing E
- Bkg: K_S^0, Λ^0, continuum
- Displaced vertexing

Dark scalar



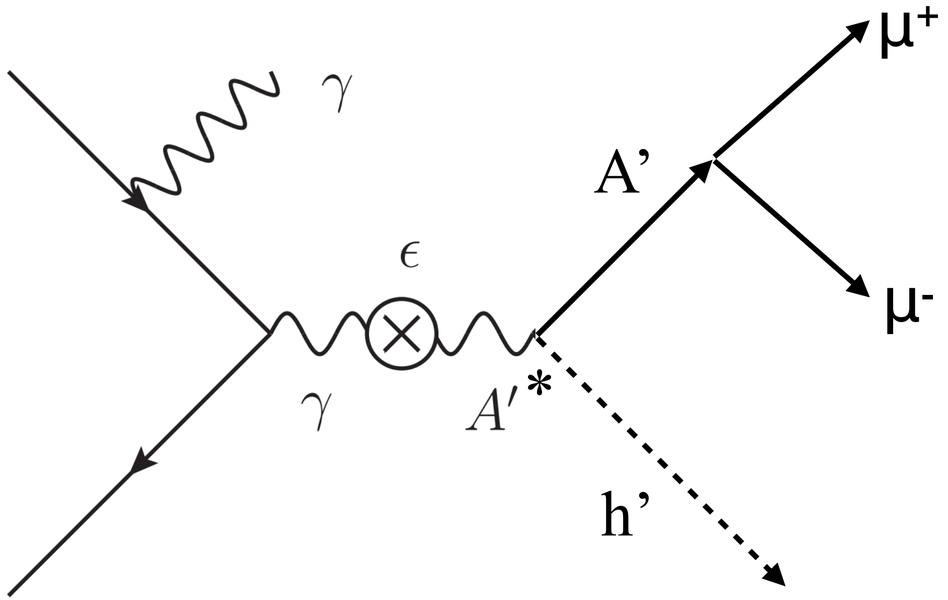
- K + displaced xx̄
- Bkg: K_S^0, Λ^0, continuum
- Displaced vertexing, multiple channels, multiple lifetimes

(In)visible Z’



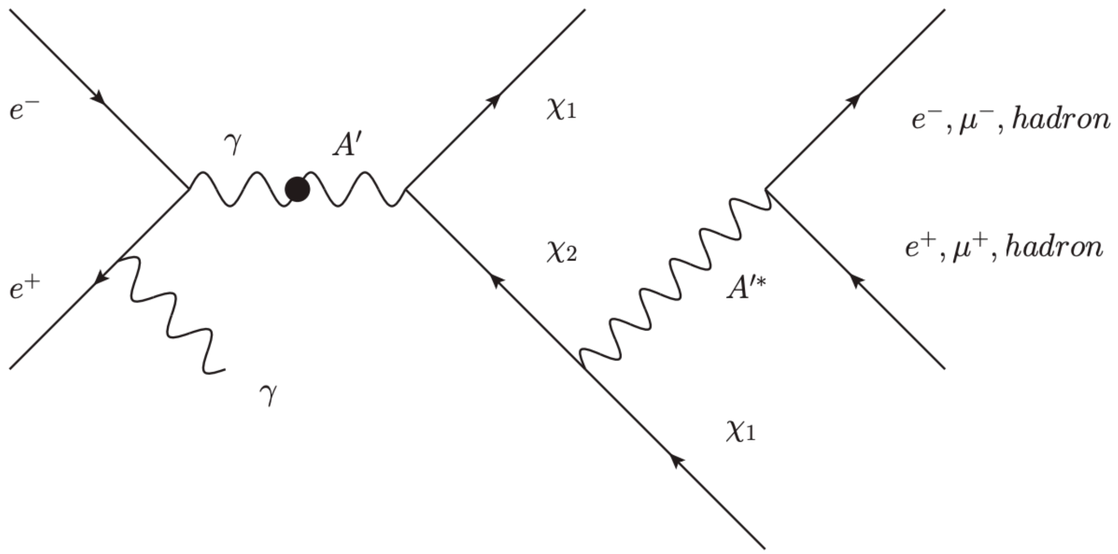
- Z’ interacts only with mu and taus
- ee -> mu mu Z’, Z’ undetected so missing energy
- Could explain the g-2 anomaly
- Z’ -> mumu are relevant if m(Z’)>2m(mu) (another analysis)

Dark photon + dark Higgs



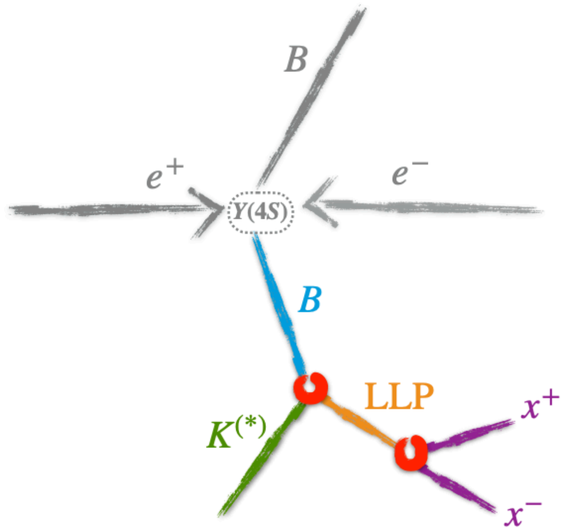
- Looks exactly like (in)visible Z′, mu mu
- ee -> gamma* -(epsilon)-> A′* -> A′ h′, A′->mumu
- Final state: mu mu + missing energy (from the undetected h′)

Inelastic dark matter



- 5 parameters, 3 new DM particles, off-shell DM->DM decay
- satisfies relics density with thermal freeze-out and
  is compatible with constraints from direct detection experiments
- ee -> gamma A’ -> gamma X1 X2, X2 -> X1ee
- Displaced vertex
- Bkg-free even with 50 ab-1, so sensitivity scales w lumi and not lumi^1/2

Dark scalar



- Dark scalar S and dark fermion x (chi)
- If m(S)>2m(x): invisible decay of S
- If m(S)<2m(x): S->ff, S long lived if small mixing angle
- Search both