Searches for invisible new particles at Belle II

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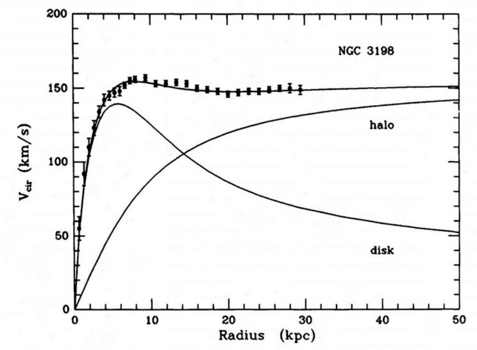
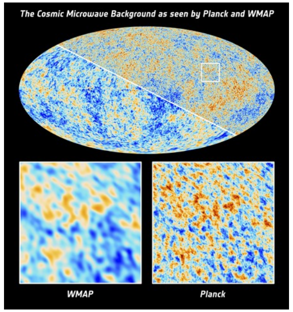
Dark matter searches

Dark Matter (DM)

- It is one of the most compelling phenomena in support for physics beyond the Standard Model (SM)
  - ➔ It exists, awaiting for discovery

Albada et al., Astrophysical Journal (1985)

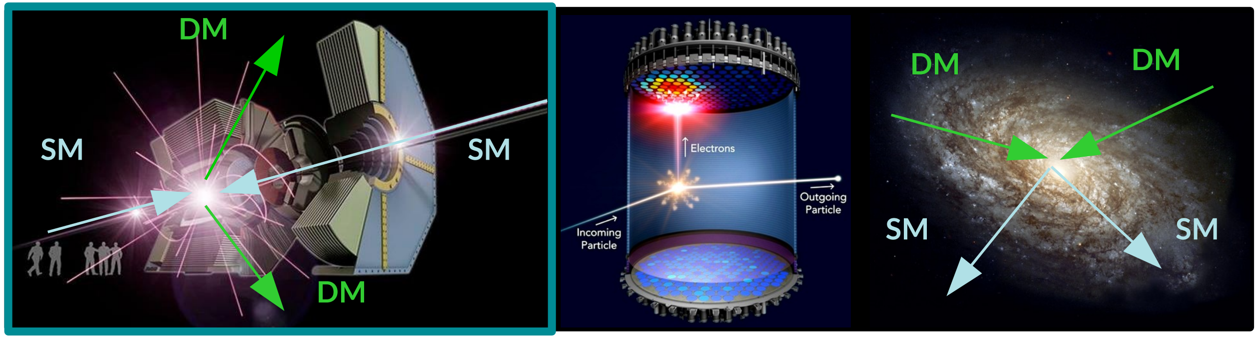




How to search for DM?

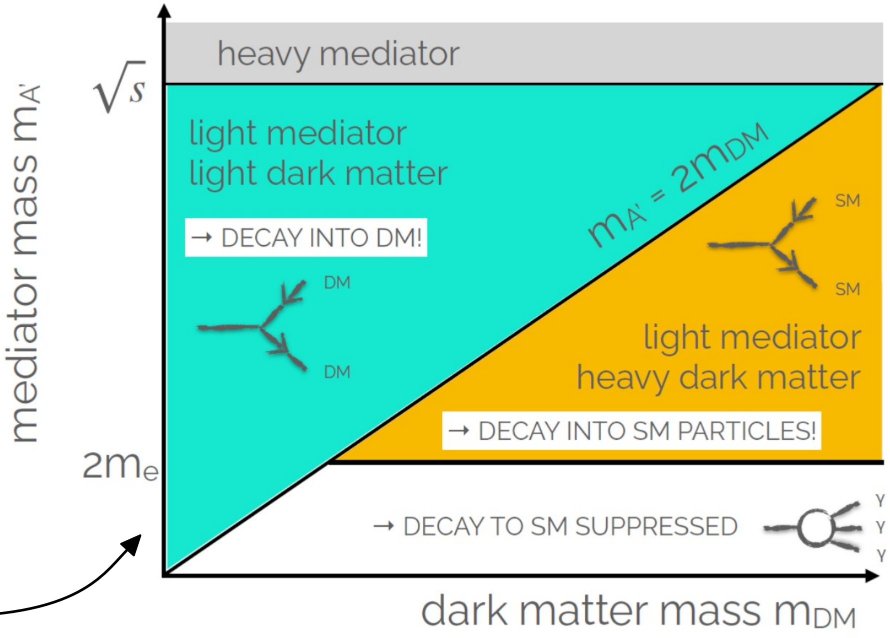
- Focus on searches at collider experiment (Belle II)
  - ➔ DM weakly couples to SM particles, it can be produced in SM particle annihilations at accelerators
  - ➔ Involve light dark sector mediators too

Colliders | Direct | Indirect



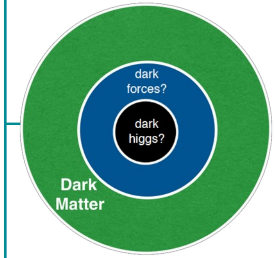
Light dark sector

- No evidence of DM at electro-weak scale in experiments
- Light DM with mass of ***M* ~ *O*(MeV-GeV)** theoretically well motivated
- **Light dark mediators** involved in the interaction with SM and DM
  - → several signatures depending on the relation between the mediator mass and the DM mass
- Theoretical description through interaction "**portals**"
- They may solve "DM puzzle" and explain observed anomalies [1, 2, 3] like the $(g-2)_\mu$



Portals

Vector	$\epsilon F^{\mu\nu} A'_{\mu\nu}$
Scalar	$k\lvert H\rvert^2 \lvert S\rvert^2$
Fermion	$yHLN$
Pseudo-scalar	$\frac{1}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} a$

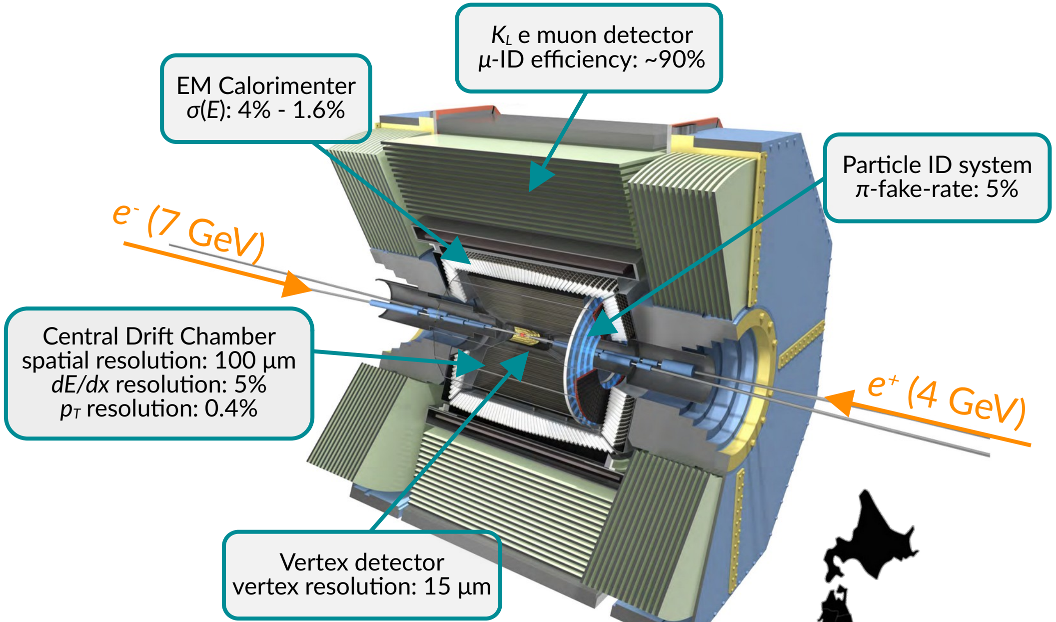


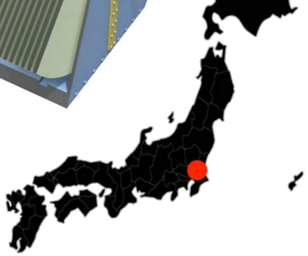
[1] Abi et al., Phys. Rev. Lett. 126, 141801 (2021)
[2] G. Caria et al. Phys. Rev. Lett.124, 161803 (2020)
[3] R. Aaij et al. Nature Physics 18, 277 (2022)

The Belle II experiment @ SuperKEKB

See Pavel Pakhlov's talk for details!

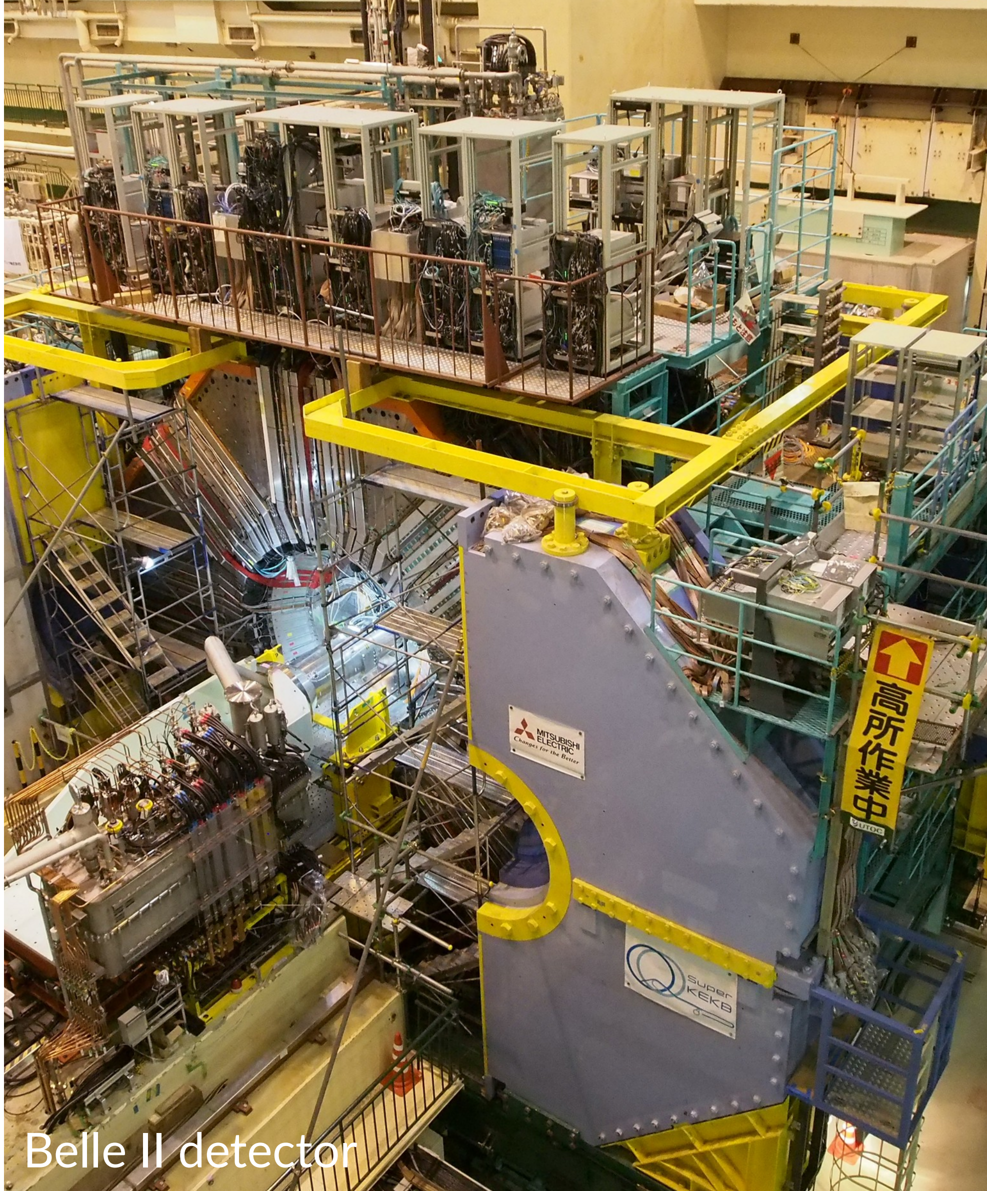
- **SuperKEKB** is a new generation *B*-factory → asymmetric e^+/e^- collider, mainly operated at √s = 10.58 GeV [Υ(4S)]
- **Belle II** is the upgrade of Belle @ KEKB
  → Hermetic detector with high performances
- **424 fb^{-1} collected**, currently not in data taking
- Well known initial-state condition and clean environment (Low/no pile-up)
- **Dedicated low-multiplicity triggers**
  - Suppress high-cross-section QED processes **without "killing" the signal**
  - **Precise knowledge of acceptance and efficiencies of the detector required**
  - Example: single-photon trigger in the full collected data set → makes Belle II dataset world-unique
- **Excellent reconstruction capabilities for low multiplicities and missing energy signatures**





Belle II Physics Book, PTEP 2019 12 (2019)

Recent dark sector results at Belle II



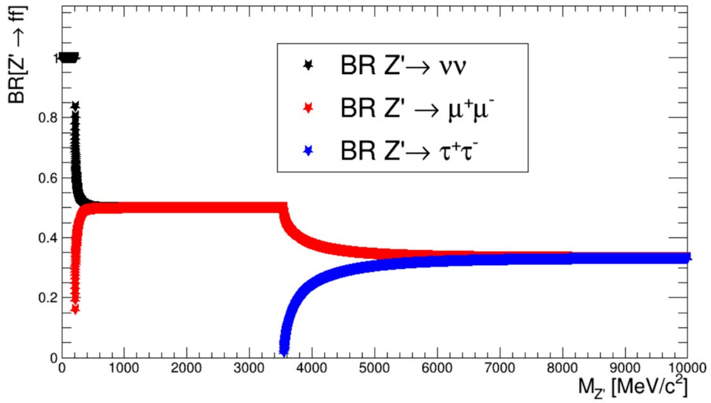
Belle II detector

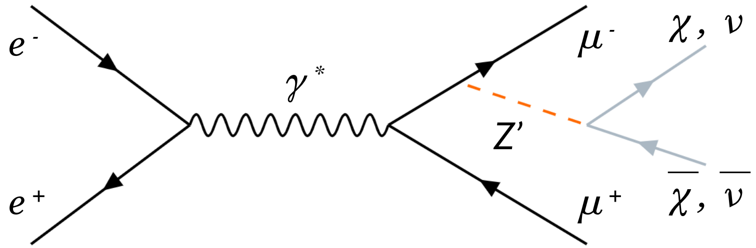
Search for an invisible *Z'* boson

[1] Shuve et al., Phys. Rev. D 89 , 113004 (2014)
[2] D. Curtin et al., JHEP 02 (2015) 157
[3] Altmannshofer et al., JHEP 106 (2016)

- Massive *Z'* boson with a coupling *g'* only to leptons with μ- and τ-lepton numbers ($L_\mu - L_\tau$ extension of the SM) [1,2,3]
  - ➔ It may explain $(g-2)_\mu$ anomaly and DM abundance
- Possible decays:
  - ➔ $Z' \to$ invisible ($\nu\bar{\nu}$ or $\chi\bar{\chi}$), $Z' \to \mu\mu$, $Z' \to \tau\tau$
- ***Z'* → invisible ($Z' \to \nu\bar{\nu}/\chi\bar{\chi}$)**
  - ➔ If light DM χ kinematically accessible exists, *BR*($Z' \to$ invisible) = 100%
  - ➔ Profit from the excellent Belle II capabilities for missing energy signatures
  - ➔ Searched for through the process $e^+ e^- \to \mu^+ \mu^- Z'$, $Z' \to$ **inv.**
  - ➔ Signal signature is a narrow peak in the recoil mass of the two final-state muons

$L_\mu - L_\tau$ model *Z'* branching ratios in leptons



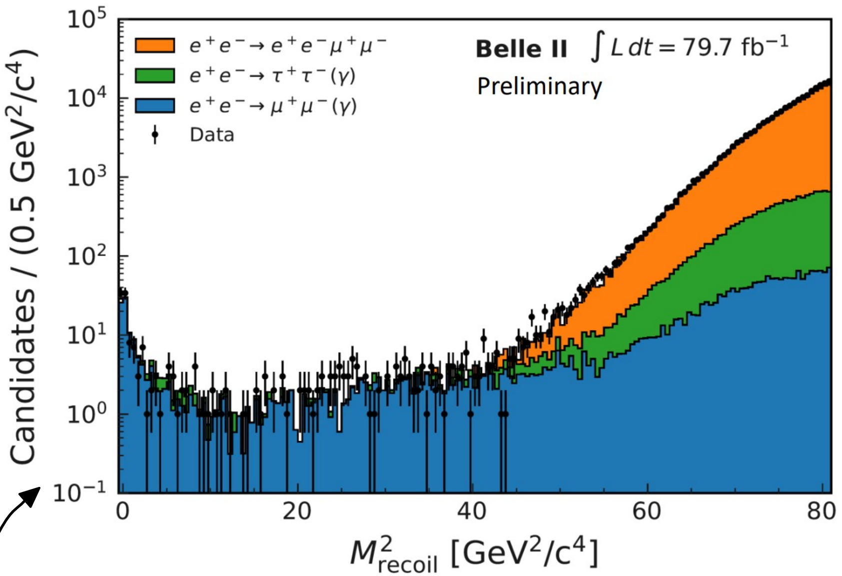


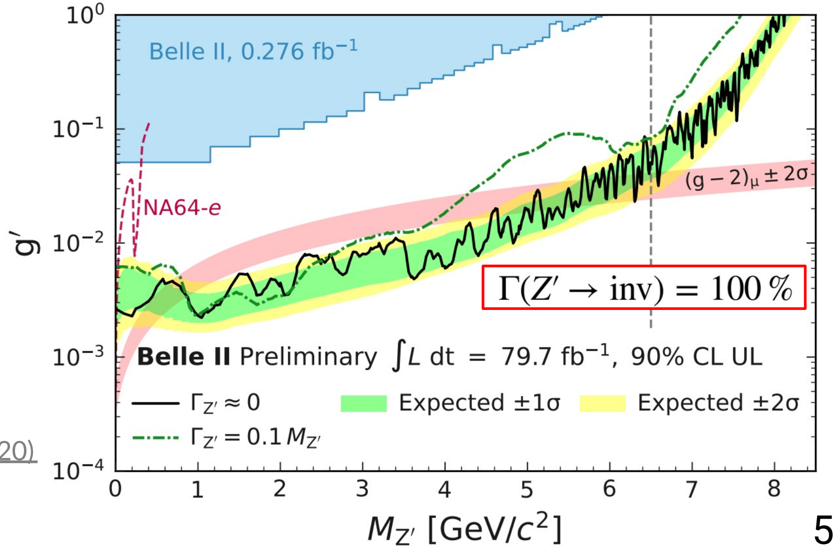
$$M^2_{recoil}(\mu\mu) = s + M(\mu\mu)^2 - 2\sqrt{s}(E^{CMS}_{\mu^+} + E^{CMS}_{\mu^-})$$

Search for Z' → invisibile

I. Adachi et al., Phys. Rev. Lett. 130, 231801 (2023)

- Searched for through the process **$e^+ e^- \to \mu^+ \mu^- Z', Z' \to$ inv.**
- Challenging **$e^+e^- \to \tau^+\tau^-$ (γ)** suppression tackled with **neural network** trained simultaneously on all *Z'* mass hypotheses [2]
  - Based on *Z'* property to be emitted as final state radiation (FSR) from one of the two muons in the final state
    - Different origin of missing energy with respect to main background components
- Remaining background from $e^+e^- \to \mu^+ \mu^-$ (γ) and $e^+e^- \to e^+ e^- \mu^+ \mu^-$ (γ)
- From 2D fit, **no significant excess found in 79.7 fb^{-1}**
  - $(g - 2)_\mu$ region escluded for $M_{Z'} \in (0.8, 5.0)$ GeV/c^2 for Γ(Z' → inv.) = 100%



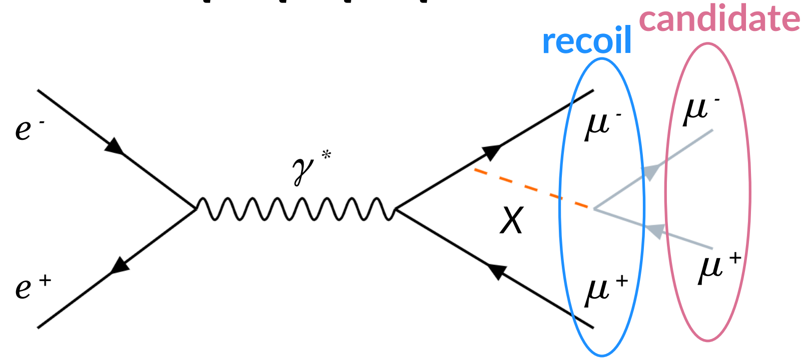


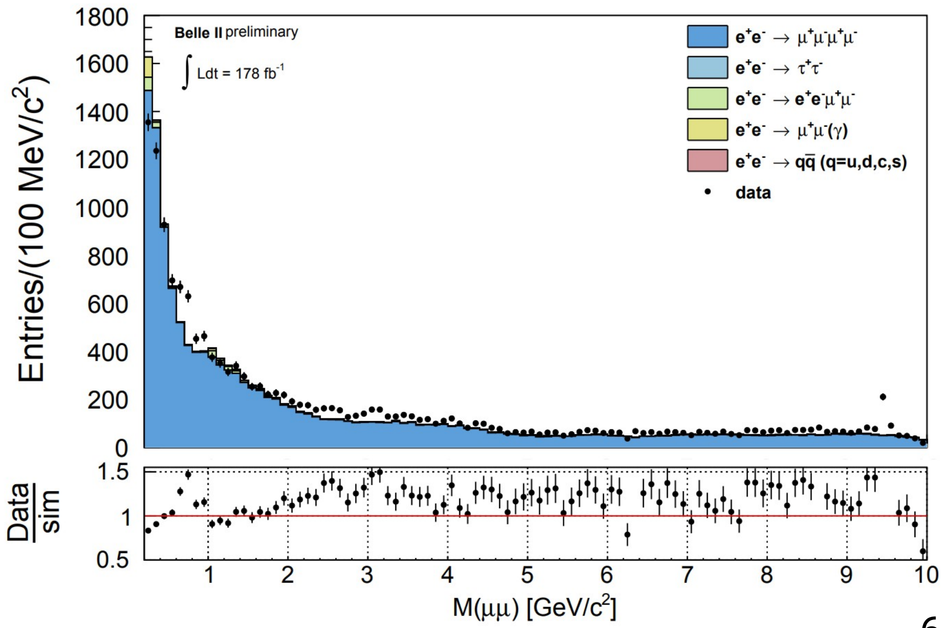
[1] I. Adachi et al., Phys. Rev. Lett. 124, 141801 (2020)
[2] F. Abudinén et al., Eur. Phys. J. C 82, 121 (2022)

Search for a $\mu\mu$-resonance in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$

New for EPS-HEP2023

- Four-track final state with at least **three identified as muons**
  - Four-track invariant mass compatible with collision $\sqrt{s}$
  - No extra energy
- Signal signature is a **narrow peak in the opposite-charge di-muon mass $M(\mu\mu)$**
- Challenging aggressive suppression of main **SM background $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$**
  - based on classifiers trained exploting the features of kinematic distributions in signal events
    - **Presence of a resonance in both candidate and recoil muon pairs**
- Signal extracted through **fits to $M(\mu\mu)$**



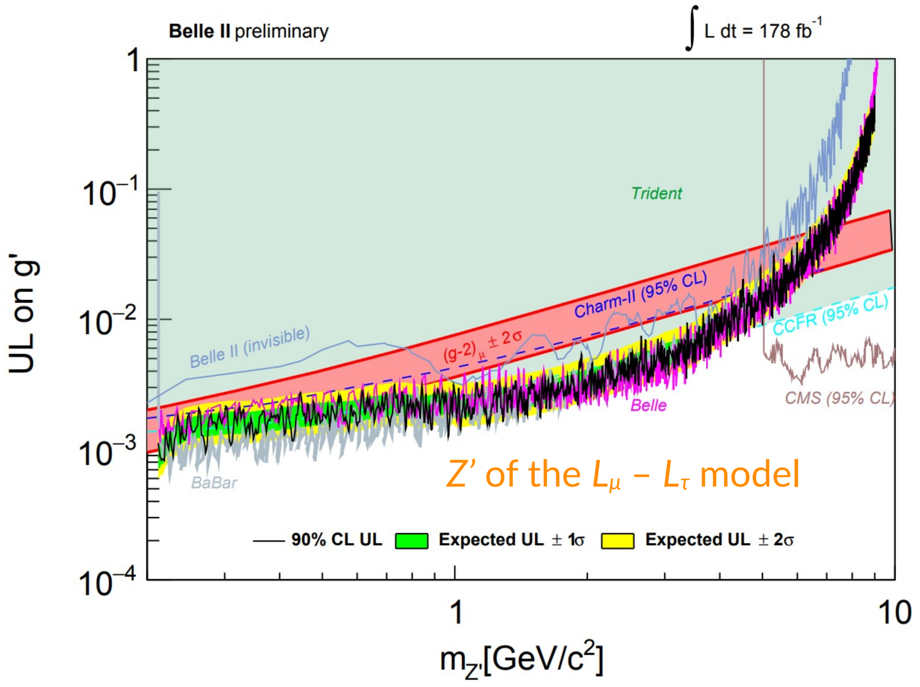


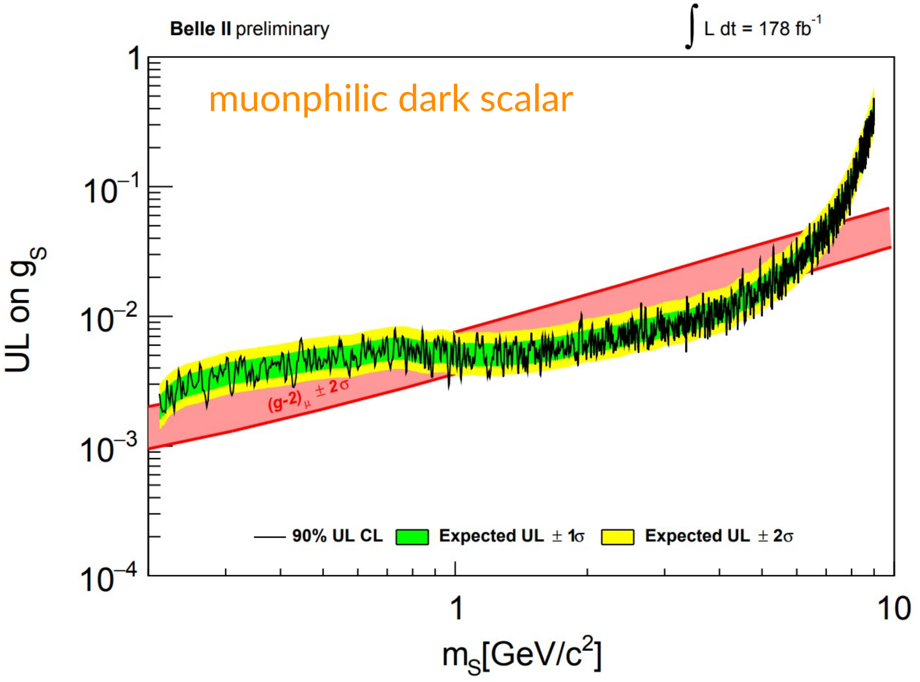
Search for a $\mu\mu$-resonance in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$: results

New for EPS-HEP2023

[1] P. Harris et al., arxiv-2207.08990 (2022)
[2] S. Gori et al., arxiv-2209.04671 (2022)

- **No significant excess found in 178 fb^{-1}**
  - Competitive 90% CL upper limits on the g' coupling of the $L_\mu - L_\tau$ model (Z') with *BaBar* (> 500 fb^{-1}) and Belle (> 600 fb^{-1}) results
  - First 90% CL upper limits for the muonphilic scalar model from a dedicated search [1, 2]

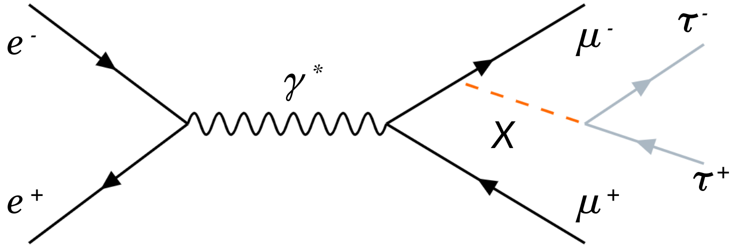


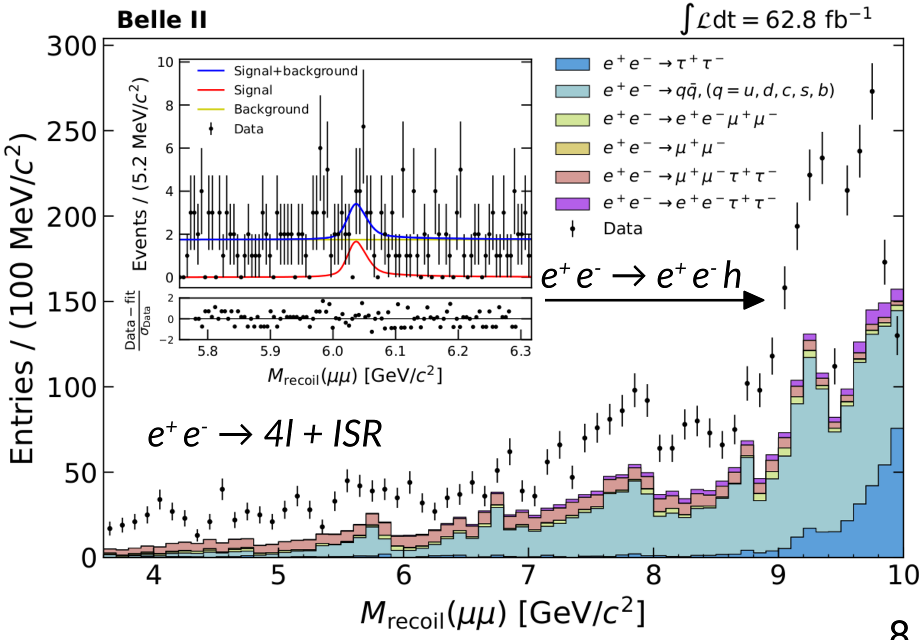


Search for a $\tau\tau$-resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$

I. Adachi et al., arXiv:2306.12294 (2023) - accepted by PRL

- Four-track final state: τ decay in $\tau \to l\nu\bar{\nu}$, $\tau \to h\nu\bar{\nu}$
- Signal peaks in the **recoil mass of $\mu^+\mu^-$ $M_{recoil}(\mu\mu)$**
- Challenging **background rejection to reduce event contamination with missing energy not associated with signal signature**
  - Eight classifiers trained on different regions of recoil mass
    - Based on resonance X properties (FSR) and $\tau\tau$ system
- **Signal extracted through fit to $M_{recoil}(\mu\mu)$** distribution
  - **Background measured directly on data** to minimize impact of not correctly simulated backgrounds
  - **Smooth background** $\to$ not problematic



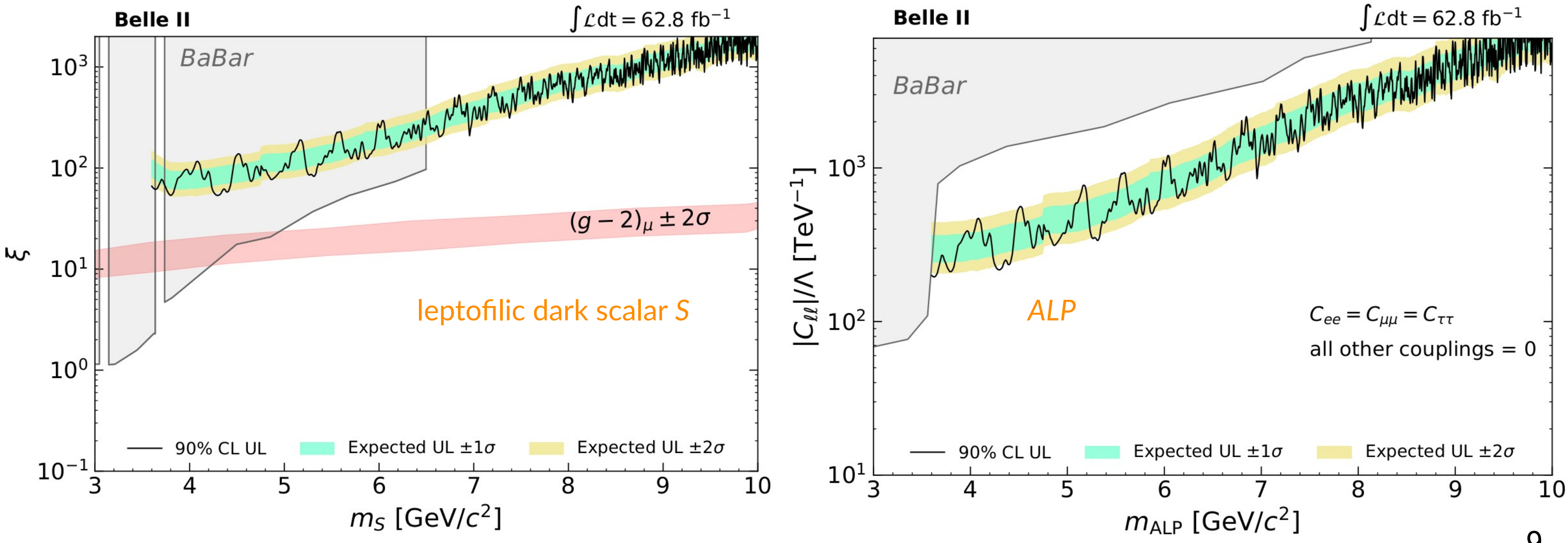


Search for a $\tau\tau$-resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$: results

I. Adachi et al., arXiv:2306.12294 (2023) - accepted by PRL

[1] J. P. Lees et al., PhysRevLett.125.181801 (2020)
[2] M. Bauer et al., JHEP09-056 (2022)

- **No significant excess found in 62.8 fb^{-1}**
  - First limits at 90% CL for a leptophilic dark scalar *S* model with m_S > 6.5 GeV/c^2 [1]
  - First direct limits at 90% CL for axion-like particle $ALP \to \tau\tau$ [2]

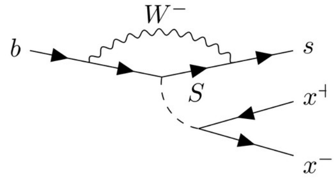


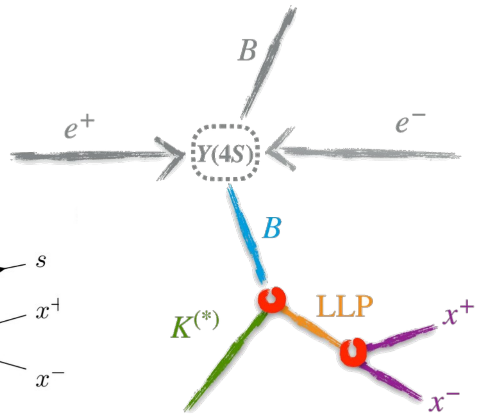
Long-lived spin-0 boson in $b \to s$ transitions

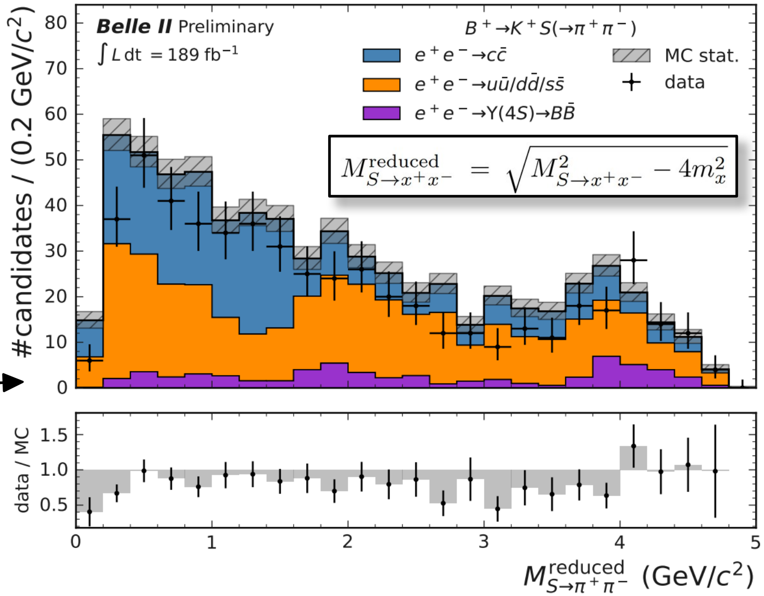
I. Adachi et al., arXiv:2306.02830 (2023)

- Search for a **new scalar** *S* in *B* meson decays in $b \to s$ transitions
  - *S* can mix with SM Higgs boson with mixing angle θ_s → natural long-lived particle (*LLP*) for small θ_s
  - **High performance in *LLP* vertex reconstruction are necessary**
- *B* meson decays
  - Eight exclusive "visible" channels reconstructed
  - Prompt decay of *K* or *K** + opposite-charged tracks that make a **displaced vertex**
  - Backgrounds: combinatory $e^+e^- \to q\bar{q}$, K_S vetoed in $M_{\pi\pi}$ mass, additional peaking backgrounds suppressed with tighter selections on displaced vertices
- Signal extracted through **fit to the *LLP* reduced mass, separately for each channel and lifetime**

$B^+ \to K^+ S$
$B^0 \to [K^{*0} \to K^+\pi^-] S$
$S \to ee/\mu\mu/\pi\pi/KK$



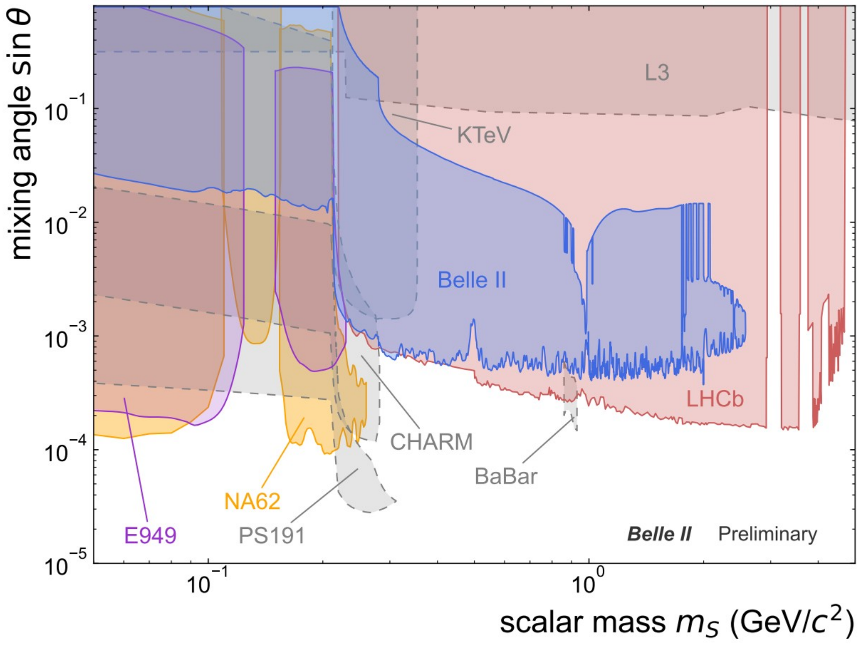




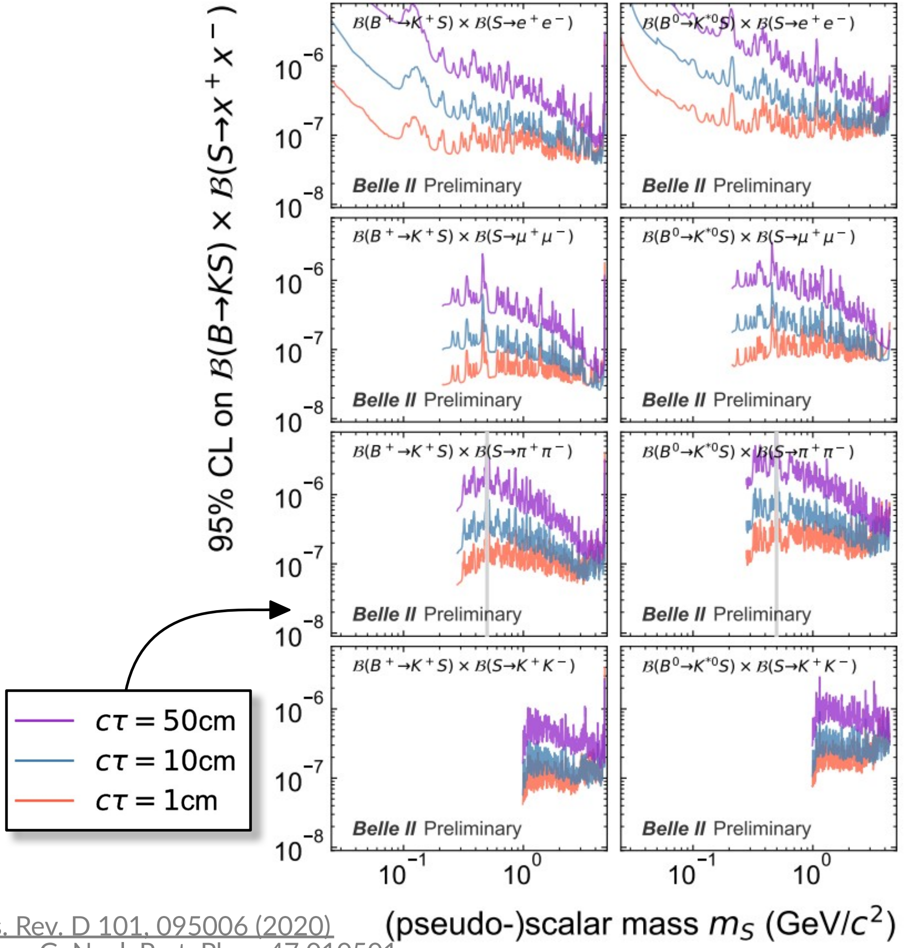
Long-lived spin-0 boson in $b \to s$ transitions: results

I. Adachi et al., arXiv:2306.02830 (2023)

- **No significant excess observed in 189 fb^{-1}**
  - First model-independent limits at 95% CL on $BR(B \to K_S) \cdot BR(S \to x^+x^-)$
  - First limits on decays to hadrons
- Interpretation as dark scalar S [1, 2]



Limits for each channel and lifetime



[1] Phys. Rev. D 101, 095006 (2020)
[2] J. Phys. G: Nucl. Part. Phys. 47 010501

$\tau \to l\, \alpha$ (invisible) decay

I. Adachi et al., Phys. Rev. Lett. 130, 181803 (2023)

- Charged-Lepton Flavour Violation (**LFV**) is allowed in various SM extensions → it has never been observed

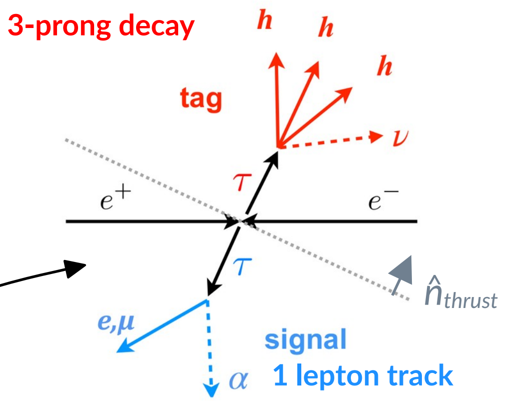
- τ-decays in new α bosons that **mediate LFV processes** are predicted in different theoretical models [1]

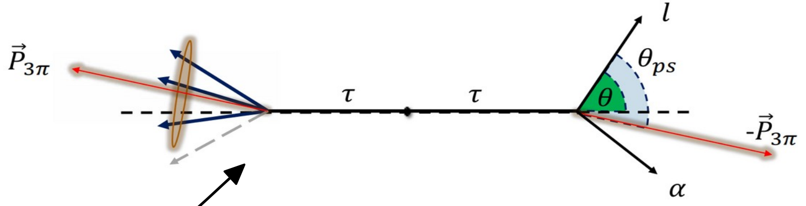
- Search for $e^+ e^- \to \tau_{sig}\, \tau_{tag}$, $\tau_{tag} \to 3\pi\, \nu$

- The **presence of neutrinos** does not allow to define the reference frame in which τ_{sig} is at rest

  → **Introduce the approximate τ_{sig} reference frame**

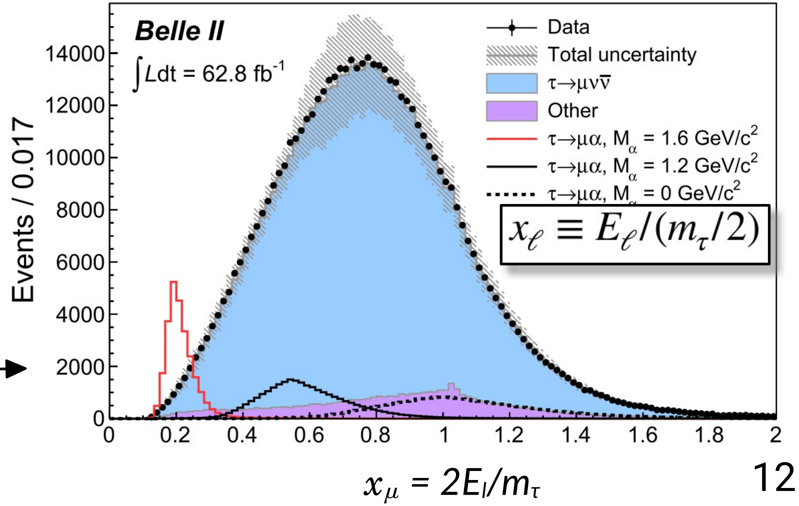
- **Search for a peak** in the normalized energy spectrum of the lepton x_l (in the approximate τ_{sig} reference frame) **over the irriducible SM $\tau \to l\, \bar{\nu}\, \nu$ background**





$$\hat{p}_\tau \approx -\frac{\vec{p}_{tag}}{|\vec{p}_{tag}|}$$

$$E_\tau \approx \sqrt{s}/2$$



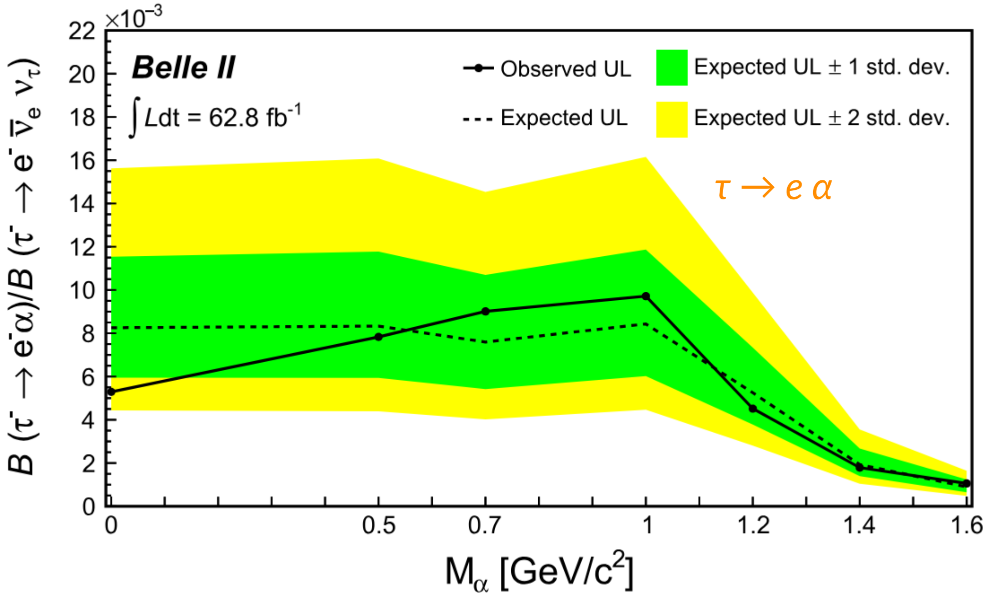
[1] M. Bauer, et al. Phys. Rev. Lett. 124, 211803 (2020)

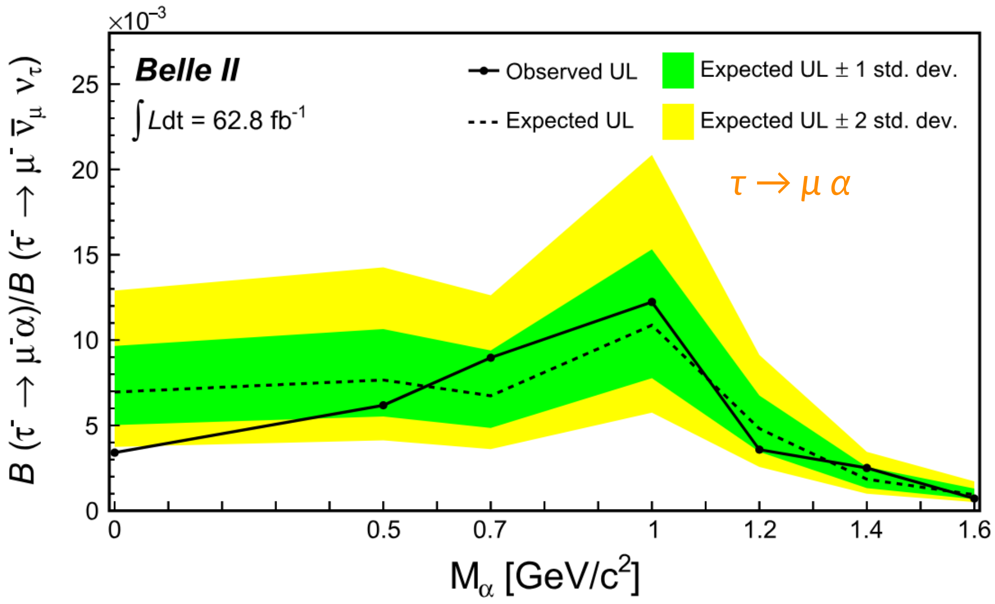
$\tau \to l\ \alpha$ (invisible) decay: results

I. Adachi et al., Phys. Rev. Lett. 130, 181803 (2023)

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

- **No excess observed in 62.8 fb^{-1}**
  - Limits from 2.2 to 14 times more stringent with respect to the previous existing limits set by ARGUS [1]

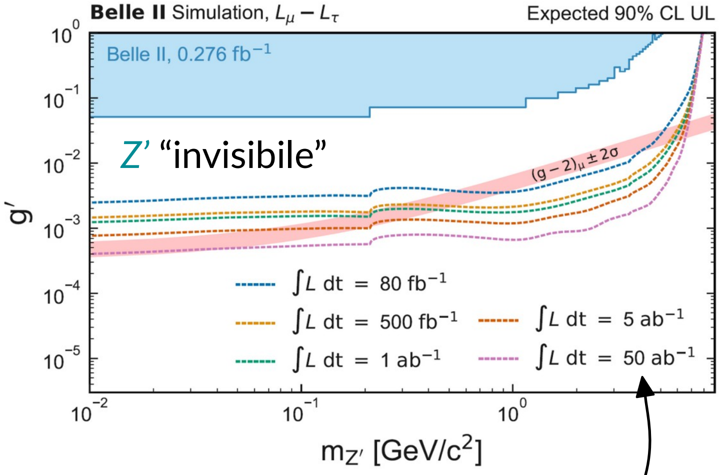




Summary and conclusions

- Belle II has a **unique sensitivity** to light dark sector and progressively will lead its exploration at luminosity frontier
  - Complementary results to higher energy colliders and beam-dump experiments

Snowmass paper arxiv:2207.06307



Belle II target integrated luminosity is 50 ab^{-1}

- Search for an invisible Z' in $ee \to \mu\mu Z'$ Phys. Rev. Lett. 130, 231801 (2023)
- Search for a resonance decaying to $\mu\mu$ in $ee \to \mu\mu\mu\mu$ events New for EPS-HEP2023
- Search for a resonance decaying to $\tau\tau$ in $ee \to \mu\mu\tau\tau$ events arXiv:2306.12294 (2023)
- Search for a long-lived spin-0 boson in $b \to s$ transitions arXiv:2306.02830 (2023)
- Search for the LFV $\tau \to l\,\alpha$ (invisible) decay Phys. Rev. Lett. 130, 181803 (2023)

Thank you!

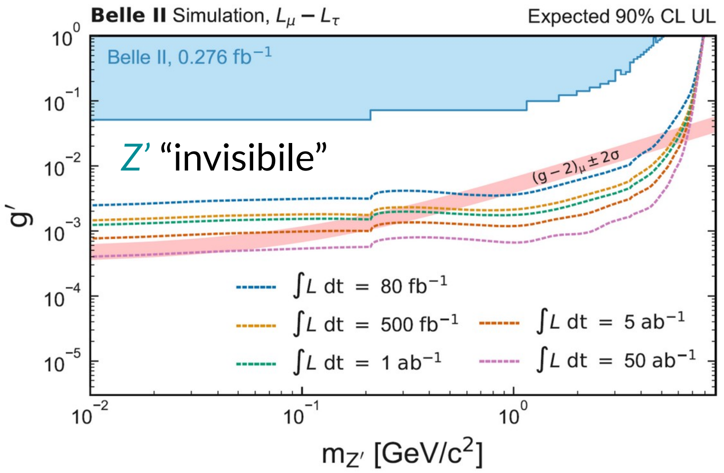
Backup slides

Belle II perspectives

- Target integrated luninosity: 50 ab^{-1}
- Target peak luminosity: 6×10^{35} cm^{-2} s^{-1}

Luminosity projection (plan for next years)

Snowmass paper arxiv:2207.06307

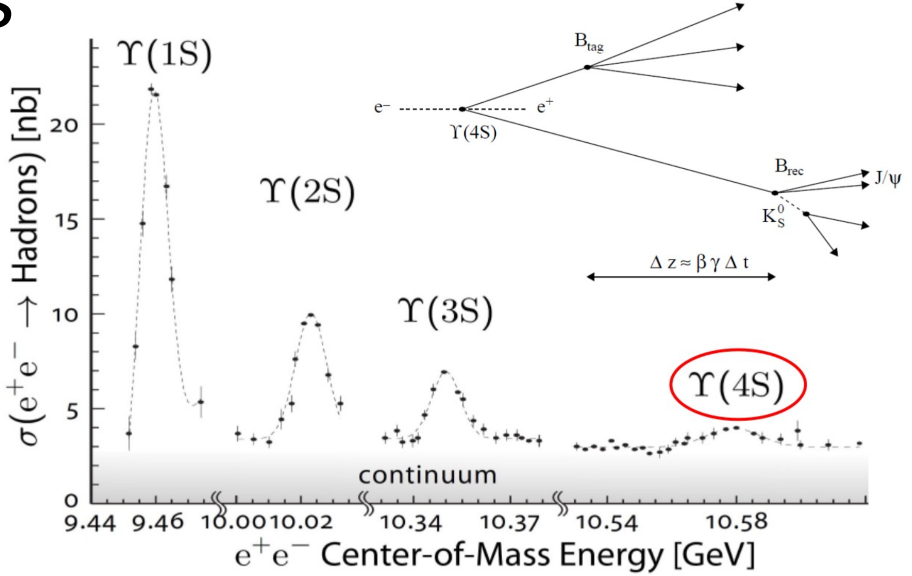


- 424 fb^{-1} collected
- **Obtained results are strongly limited by statistics**
  - World-leading results already published with early datasets (< 20% of the collected dataset of 424 fb^{-1})

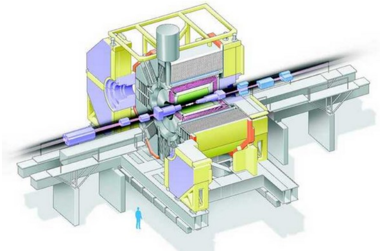
- In next years, Belle II will collect 100-times the dataset collected up to now
  - ➔ **The best is yet to come!**

Experiments at B-factories

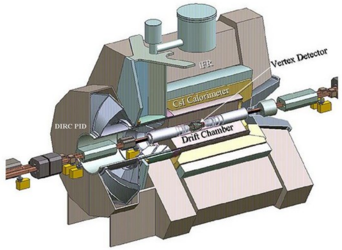
- Asymmetric e^+e^- colliders optimized for the production of *B* meson pairs, but also *D* mesons, τ leptons, …
- Collisions occur at Υ(nS) resonances
  - ➔ Mainly at Υ(4S): $\sqrt{s}$ = 10.58 GeV
    just above the production threshold of $B\overline{B}$
    $BR(\Upsilon(4S) \to B\overline{B}) > 96\%$
- Asymmetric beam energies: boosted $B\overline{B}$ pairs, for CP-violation time-dependent measurements
- High peak luminosity $L > 10^{34}$ cm^{-2}s^{-1}



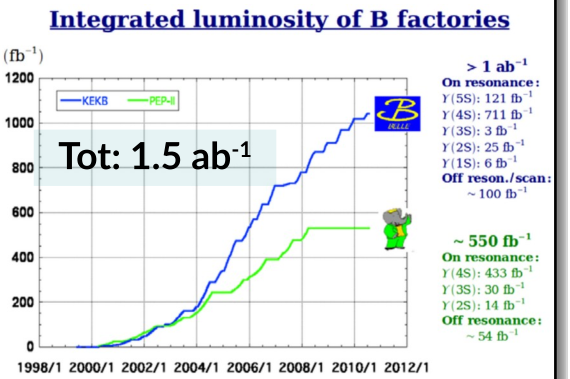
First generation of *B*-factories



Belle@KEKB, KEK, Tsukuba (JP)
1999–2010, $\int L\,dt$ = 1 ab^{-1}

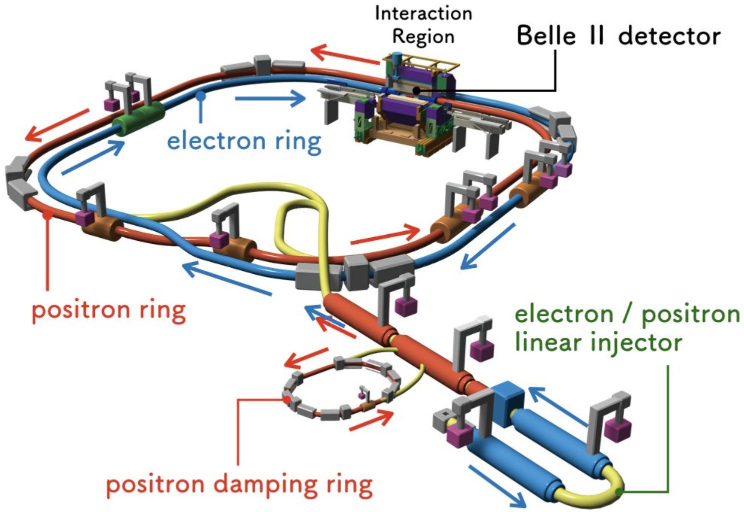


BABAR@PEP-II, SLAC (USA)
1999–2008, $\int L\,dt$ = 0.5 ab^{-1}

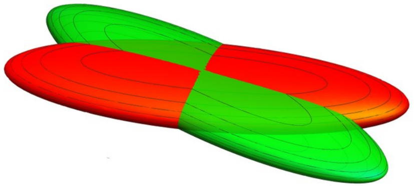


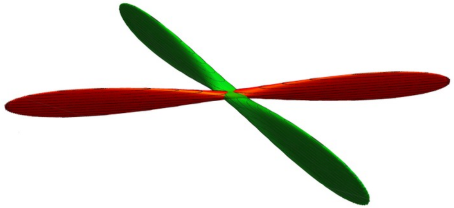
SuperKEKB

- New generation of B-factory that provides luminosity to the Belle II experiment
  - Asymmetric beam energies: e^- (7 GeV) / e^+ (4 GeV)
    Operating mainly at Y(4S), but foreseen runs from Y(2S) to Y(6S)
  - Designed to reach the world highest peak luminosity with the nano-beam scheme



Nano-beam scheme



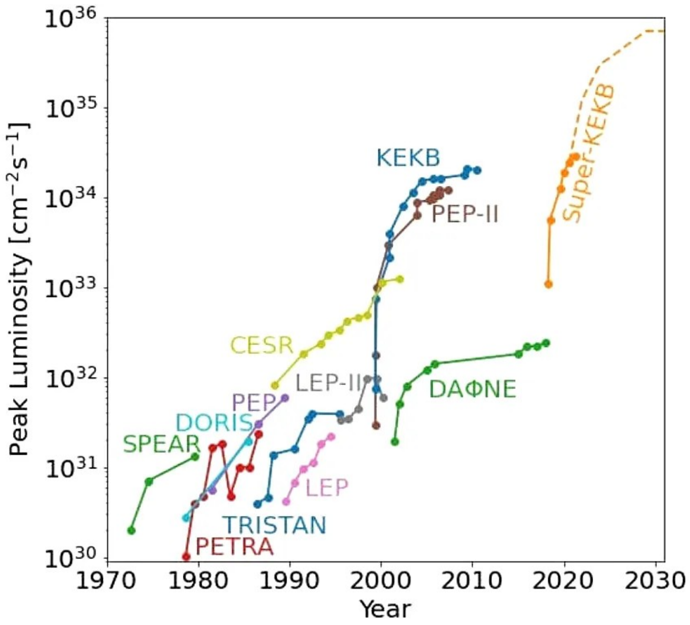


β_y^* ~ 1/20x
I ~ 1.5x

KEKB
- I(A) ~ 1.6/1.2
- β_y^*(mm) ~ 5.9/5.9

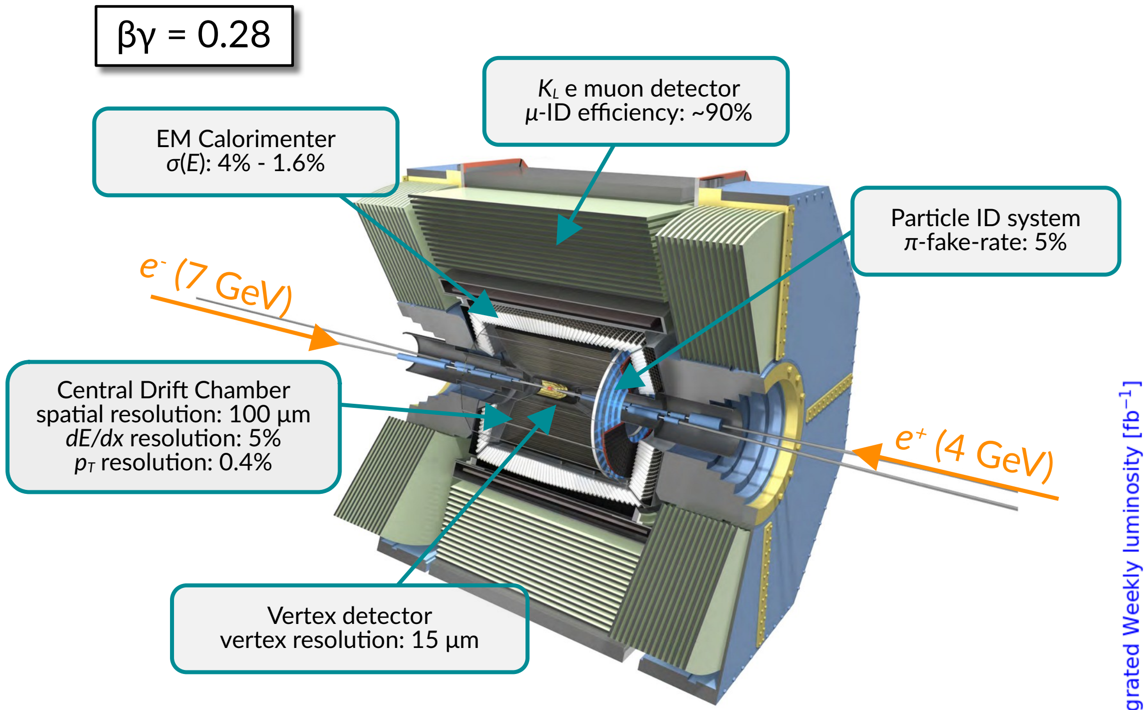
30x peak luminosity

SuperKEKB
- I(A) ~ 2.9/2.0
- β_y^*(mm) ~ 0.3/0.3



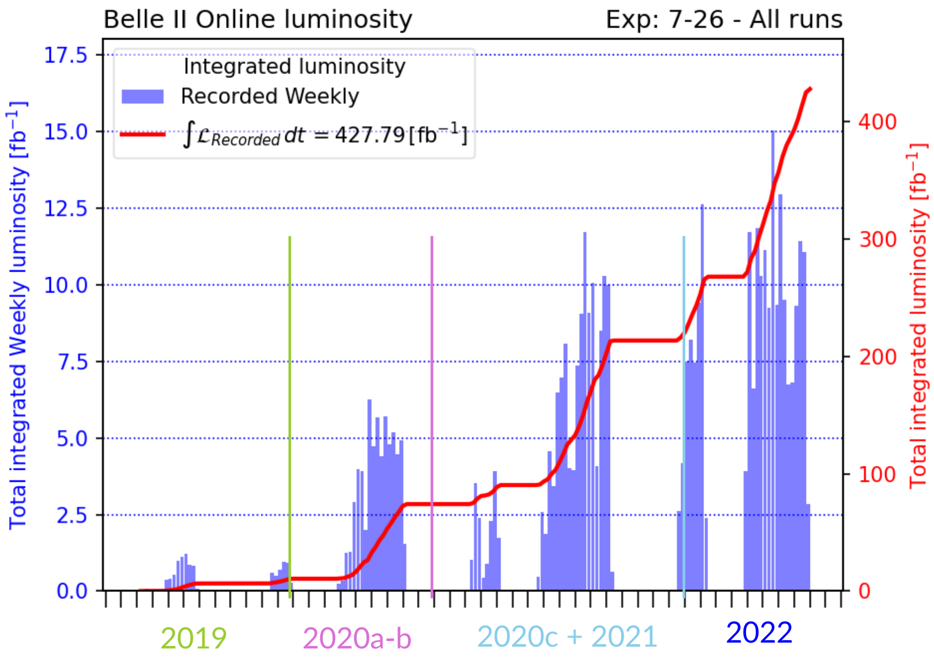
- World record luminosity on December 2021: **3.8×10^{34}** $cm^{-2}s^{-1}$
- $I(e^-/e^+)$ = **820/1034** mA and β_y^* = **1** mm
- Target peak luminosity: **$6.5 \cdot 10^{35}$** $cm^{-2}s^{-1}$

Belle II at SuperKEKB



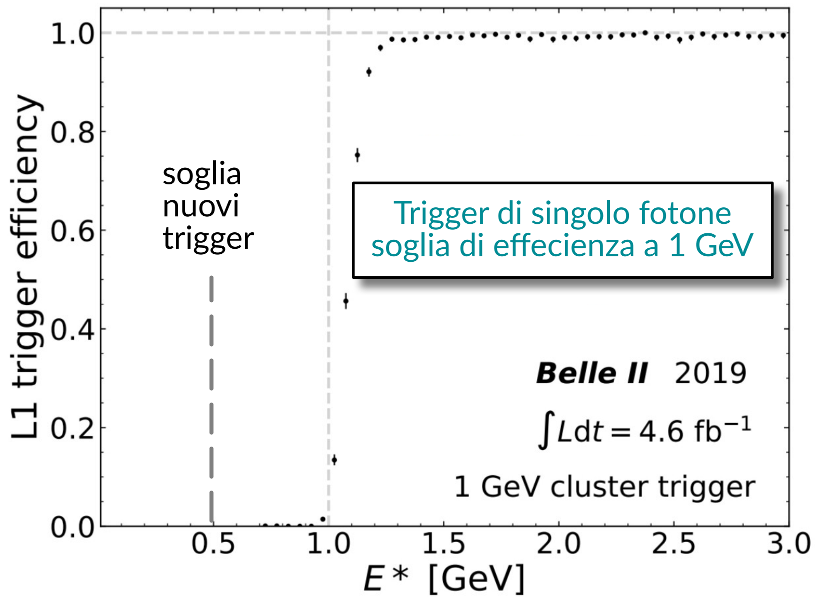
- Major upgrade of Belle@KEKB → better resolution, particle identification (PID) and capability to cope with higher background
- Covers more than 90% of the total solid angle

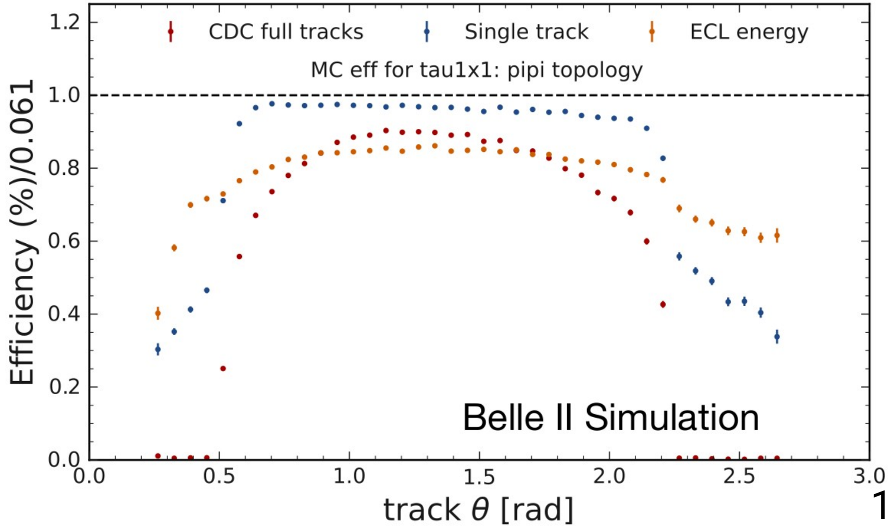
- First collisions during commissioning run on April 26th 2018
  - 0.5 fb^{-1} collected in 2018
- First collisions with the full detector on March 2019
  - ~ 430 fb^{-1} collected in 3 years of data taking
- Target integrated luminosity of the Belle II experiment: **50 ab^{-1}** (x30 Belle + BaBar)



Low-multiplicity triggers

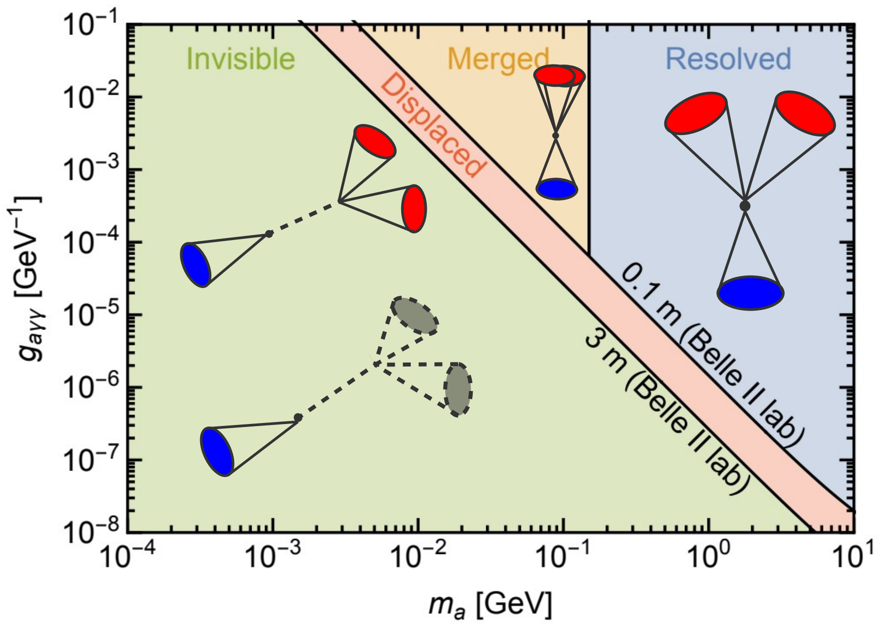
- Two-level trigger
  - Hardware-based Level 1 Trigger (L1): < 30 kHz
  - Software-based High Level Trigger (HLT): < 10 kHz
- Devised specific low-multiplicity trigger lines
  - Suppress high-cross-section QED processes **without “killing” the signal**
  - **Precise knowledge of acceptance and efficiencies of the detector required**
- Examples
  - Single-photon trigger
  - Single-muon trigger
  - Single-track trigger

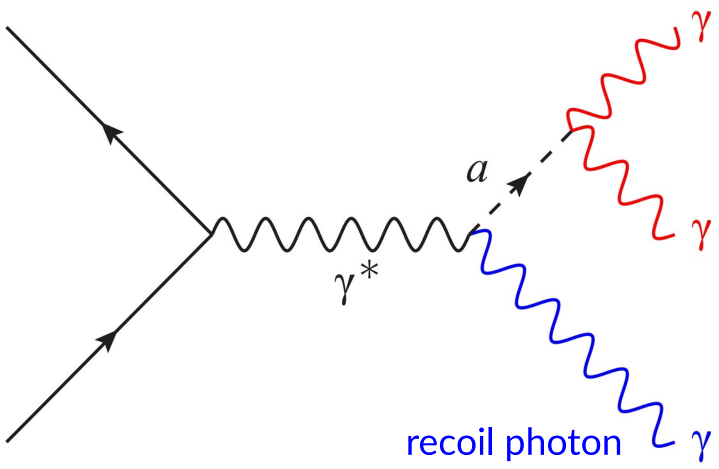




Axion-like particles (ALPs)

- GeV-scale ALPs: pseudo-scalar portal mediator between dark sector and Standard Model
- If ALP-photon coupling ($g_{a\gamma\gamma}$) dominates, than $BR(a \to \gamma\gamma)$ ~ 100%
- Focus on mass region where ALP decay is prompt and photons can be well resolved by Belle II



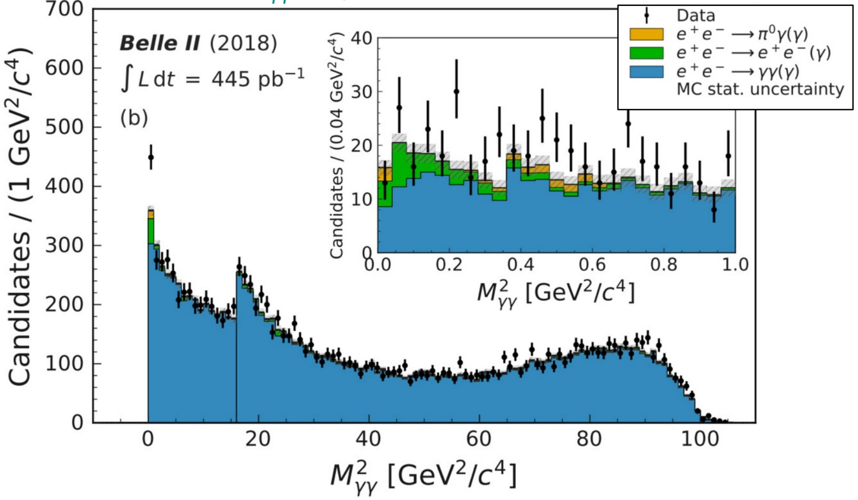


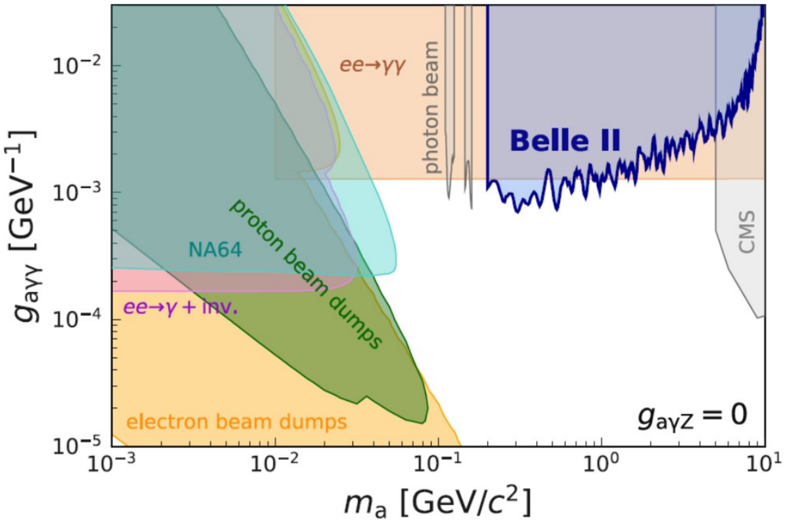
Search for an ALP at Belle II

F. Abudinén et al., Phys. Rev. Lett. 125, 161806 (2020)

- Event selection:
  - electromagnetic calorimeter trigger (efficiency ~100%)
  - three-γ invariant mass compatible with collision $\sqrt{s}$
- Signal signature is a **narrow peak in $M^2_{\gamma\gamma}$ or M^2_{recoil}** (depending on best resolution of signal peak)
- Largest background from $e^+e^- \rightarrow \gamma\gamma(\gamma)$
- Segnal extracted through fit
  - **No excess observed in 0.445 fb^{-1}**
  - Upper limits at 95% CL on $g_{a\gamma\gamma}$
  - World-leading limits for m_a ~ 0.5 GeV/c^2

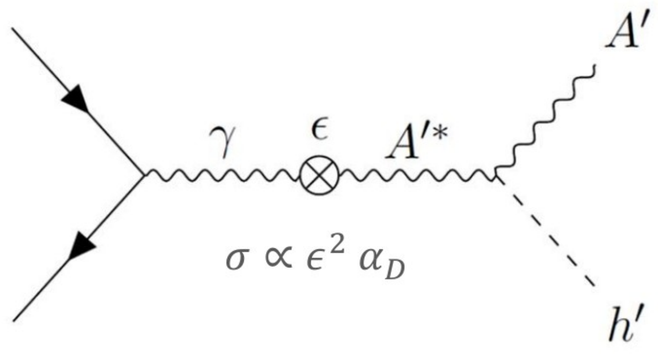
$M^2_{\gamma\gamma}$: m_a < 6.85 GeV/c^2



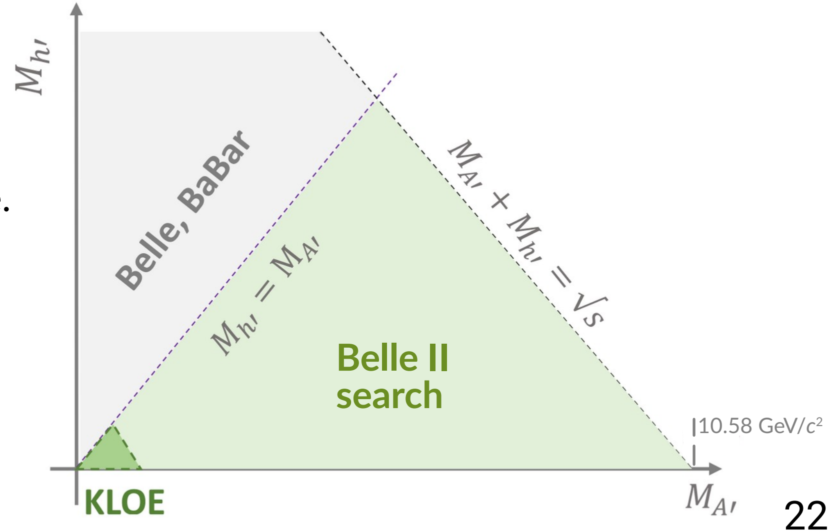


Search for a dark Higgs (and dark photon)

- Dark photon *A'*
  - kinetic mixing with SM photon with strength ε [1]
  - mass produced by the Higgs mechanism involving a dark Higgs boson [2]
- Dark higgs *h'*
  - couples to *A'* with α_D
  - does not mix with SM Higgs
- Both *A'* and *h'* can be produced at e^+e^- colliders through the dark higgsstrahlung process
  - → $e^+e^- \rightarrow A'^* \rightarrow A' h'$
- Different signatures depending on *h'* mass
  - → $M_{h'} > M_{A'}$: prompt decay $h' \rightarrow A'A'$, up to 6 tracks in the final state. Investigated by BaBar(2012) and Belle(2015)
  - → $M_{h'} < M_{A'}$: *h'* is long-lived, thus invisible. Investigated by KLOE(2015)
- **Belle II focuses on the invisible *h'***

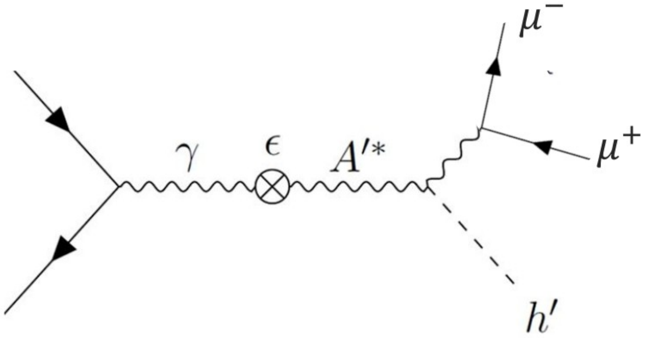


[1] P. Fayet, Nucl. Phys. B 187, 184 (1981)
[2] Batell et al., Phys. Rev. D 79, 115008 (2009)



Dark higgsstrahlung at Belle II

F. Abudinén et al., Phys. Rev. Lett. 130, 071804 (2023)



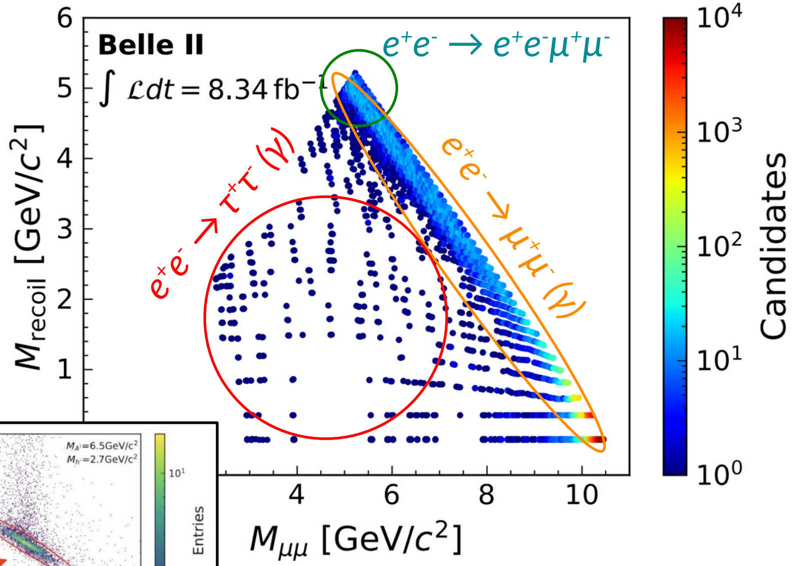
- ***$e^+e^- \to A'h', A' \to \mu\mu, h' \to$* invisible**

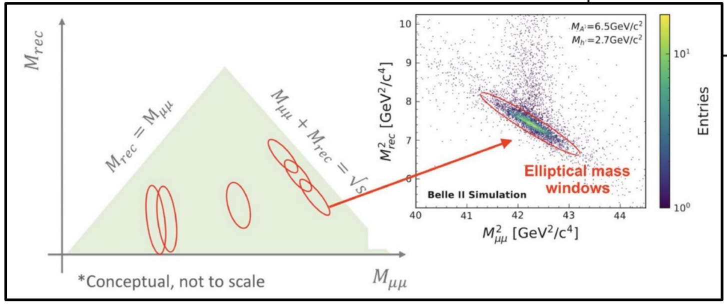
- Same final state as for the invisible *Z'*, similar backgrounds:
  $e^+e^- \to \tau^+\tau^-$ (γ), $e^+e^- \to \mu^+\mu^-$ (γ), $e^+e^- \to e^+e^-\mu^+\mu^-$

- Signal signature is a 2D peak in the recoil mass vs the dimuon mass

- Event selection
  - Two reconstructed muons, p_T^μ > 0.1 GeV/c
  - Recoil momentum in the ECL barrel, no nearby photon
  - Cut on dimuon helicity angle
    → efficiently suppress background

- Signal extraction through 2D fit in M_{recoil} vs $M_{\mu\mu}$ plane in elliptical windows

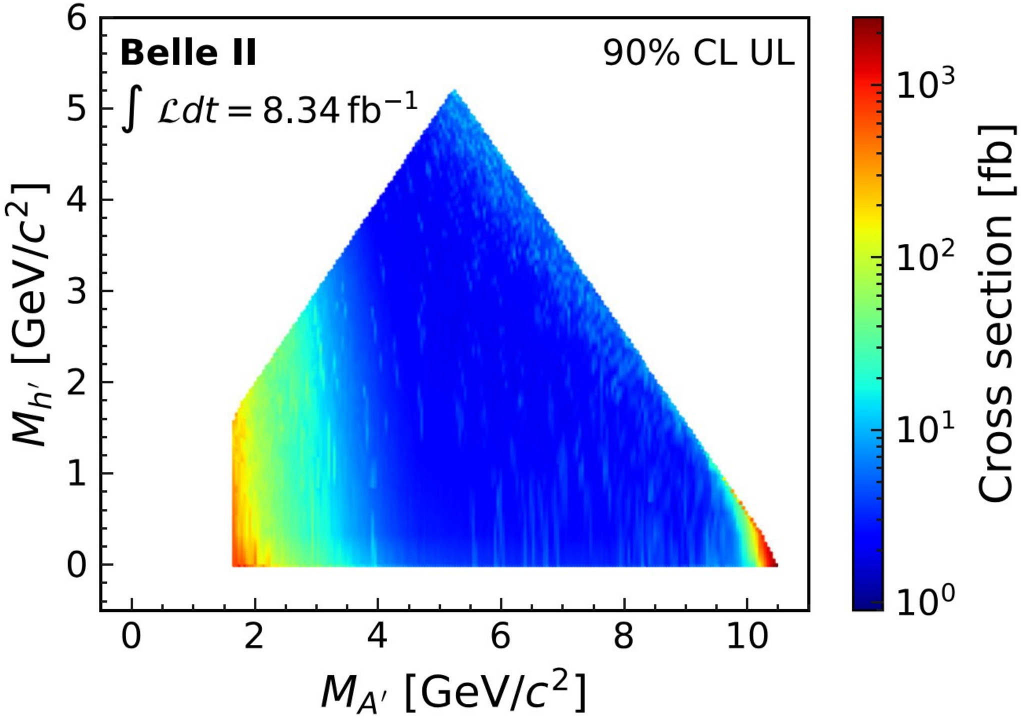


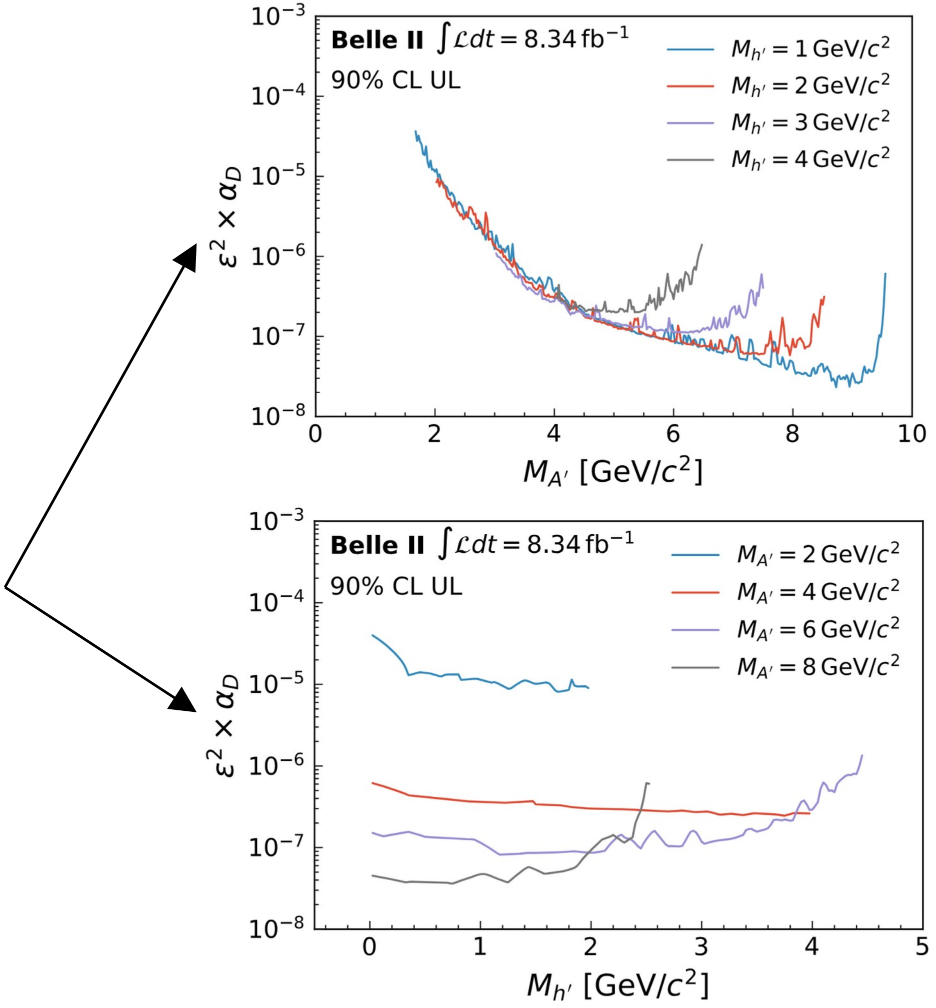


Dark higgsstrahlung at Belle II: results

F. Abudinén et al., Phys. Rev. Lett. 130, 071804 (2023)

- **No significant excess in 8.34 fb^{-1}**
  - 90% CL upper limits and world leading limits for $1.65 < M_{A'} < 10.51$ GeV/c^2





Search for dark photon *A'*

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

- U(1) extension of the SM
- New massive vector gauge boson, *A'* , with a coupling to the Standard Model photon through the kinetic mixing mechanism, with strength ε [1,2]

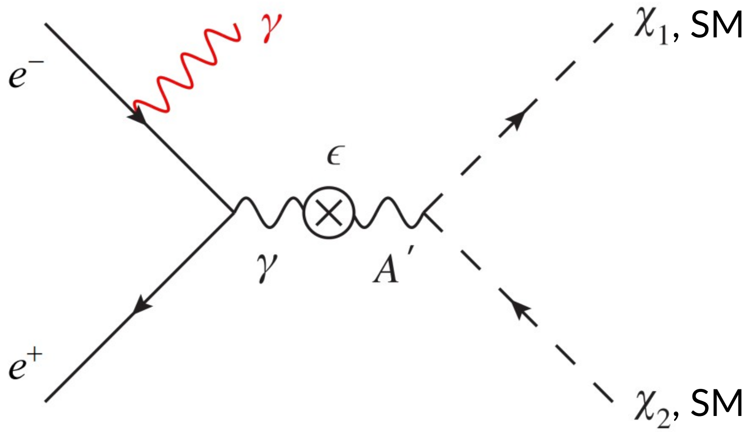
Dark photon field

$$\mathcal{L}_{int} = e\varepsilon A'_{\mu} J^{\mu}_{em}$$

Interation strenght — Electromagnetic current

- This gauge boson can be produced at e^+e^- colliders through different processes:
  - direct production: $e^+e^- \rightarrow \gamma_{ISR}A'$
  - meson decays: $\pi^0 \rightarrow A'\gamma$
  - dark higgsstrahlung: $e^+e^- \rightarrow A'^* \rightarrow A'h'$
- **Direct production with ISR particularly interesting:** $e^+e^- \rightarrow \gamma_{ISR}A'$
- Two basic scenarios depending on dark photon mass:
  - ➔ $M_{A'} > 2m_\chi$: invisible decay $A' \rightarrow \chi\bar{\chi}$
  - ➔ $M_{A'} < 2m_\chi$: visible decay in Standard Model particles

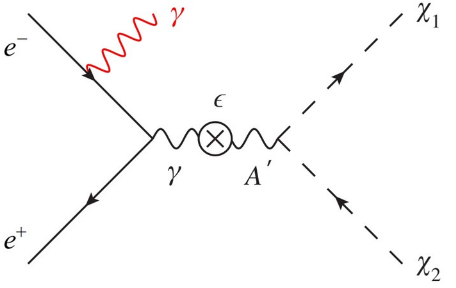
$e^+e^- \rightarrow \gamma_{ISR}A'$ $(A' \rightarrow \chi\bar{\chi}$, SM)

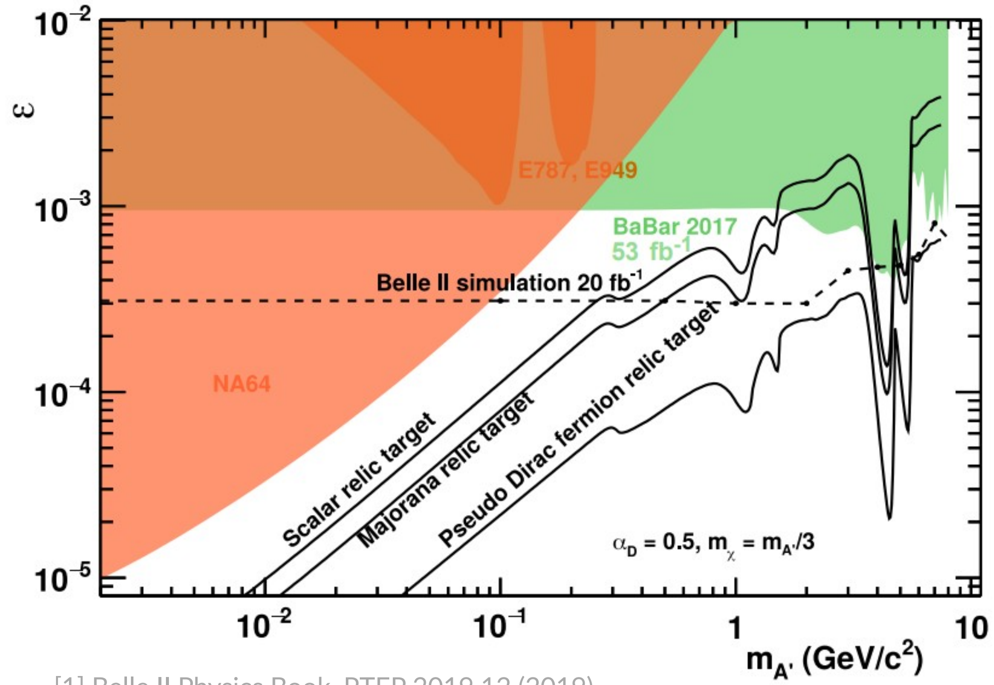


Invisible dark photon

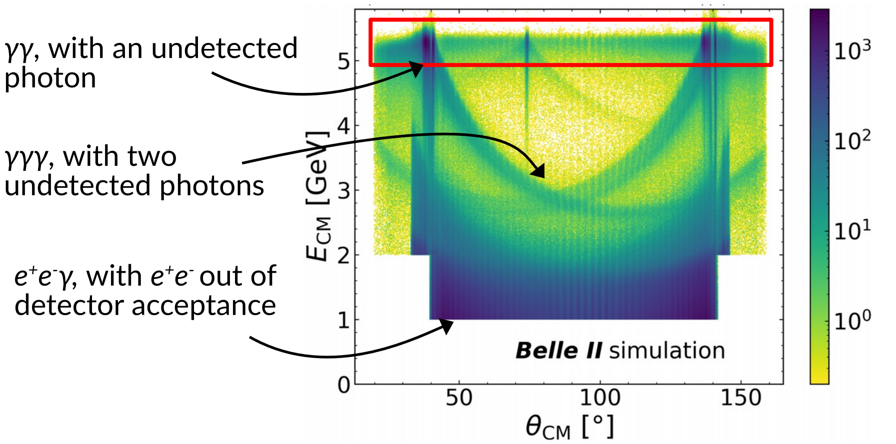
- *$e^+e^- \rightarrow \gamma_{ISR} A'$ ($A' \rightarrow$ inv.)*
  - Single photon search: single photon trigger needed, present in the full Belle II dataset

$$E_\gamma = \frac{s - M^2_{A'}}{2\sqrt{s}}$$





Background simulation assuming 20 fb^{-1}

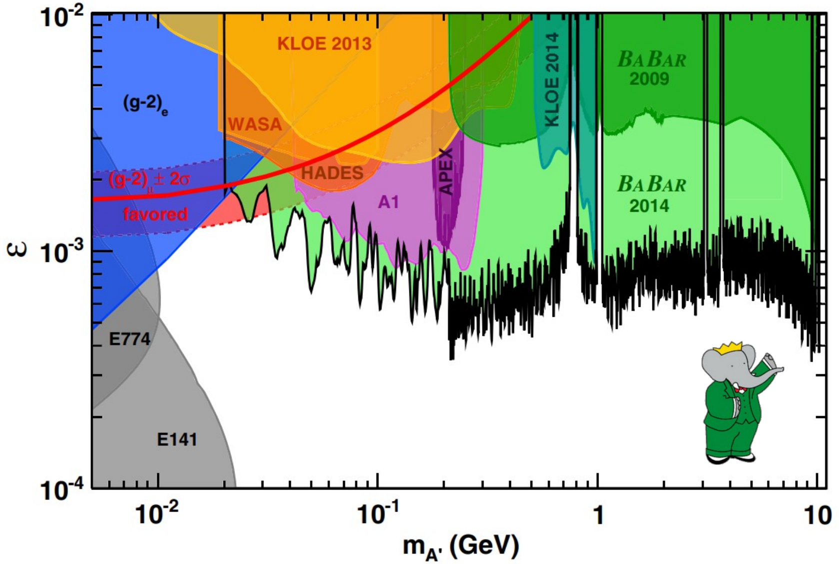


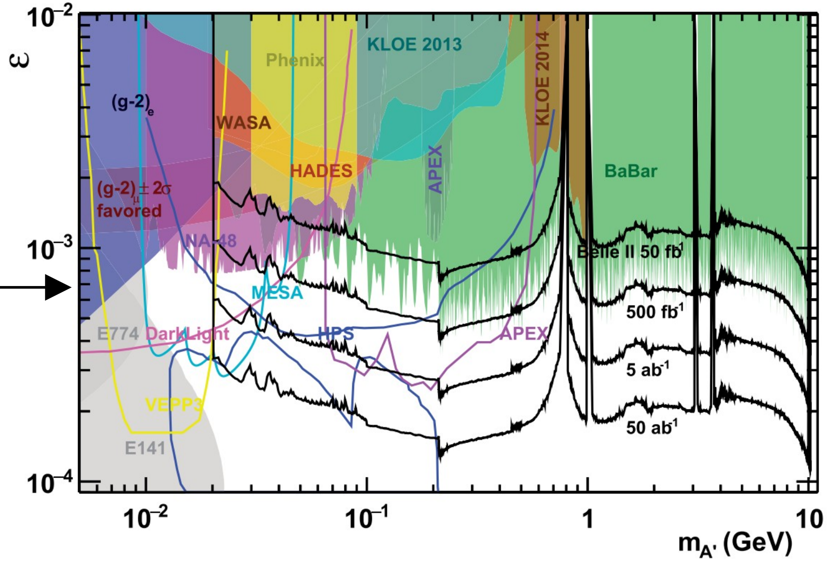
- Belle II expected to perform better than BABAR [2]:
  - smaller boost: **larger acceptance**
  - **muon detector veto**: reject events with a photon undetected in the calorimeter (efficiency currently under study)
  - **better calorimeter hermeticity**

[1] Belle II Physics Book, PTEP 2019 12 (2019)
[2] Less et al, Phys. Rev. Lett. 119, 131804 (2017)

Visible dark photon

- *BaBar* [1]
  - Full dataset of 514 fb^{-1}
  - Dark photon visible decay in e^+e^- and $\mu^+\mu^-$ final states
  - Signal signature, bump in the dilepton invariant mass
  - Background: QED processes $e^+e^- \rightarrow e^+e^-(\gamma)$, $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ and resonant backgrounds from J/ψ, $\psi(2S)$ etc. (vetoed)
  - Upper limits at 90% CL kinetic mixing strength ε at level of O(10^{-3}):
- LHCb [2]
  - Best limits in the mass range 200 -700 MeV
- Belle II is expected to achieve the leading sensitivity [3]
  - Search in preparation





[1] J.P. Lees et al, Phys. Rev. Lett. 113, 201801 (2014)
[2] R. Aaij et al, PhysRevLett.124.041801 (2020)
[3] E. Kou et al, Prog Theor Exp Phys (2019)

Search for a $\tau\tau$-resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$: Z'

- **No significant excess found in 62.8 fb^{-1}**
  - 90% CL upper limits on the g' coupling of the $L_\mu - L_\tau$ model (Z')