Dark sector at the B-factories

1. Introduction: Dark matter and B-factories
2. A selection of recent Dark Sector analyses at BaBar, Belle & Belle II

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Introduction

Standard Model: open questions

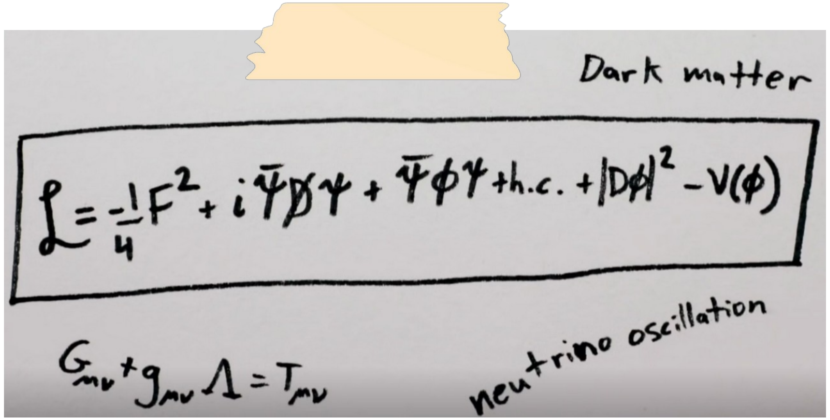
- The Standard Model (SM) is the best tested theory of nature at fundamental level describing particles and their interactions

- there are still open questions coming from observations unexplained by the SM

  - no explanation of the observed matter-antimatter asymmetry

  - no dark matter candidate or dark energy explanation

  - no explanation of mass hierarchy, …



- and tensions between measurements and SM predictions that need to be interpreted (see $(g\text{-}2)_\mu$ for example)

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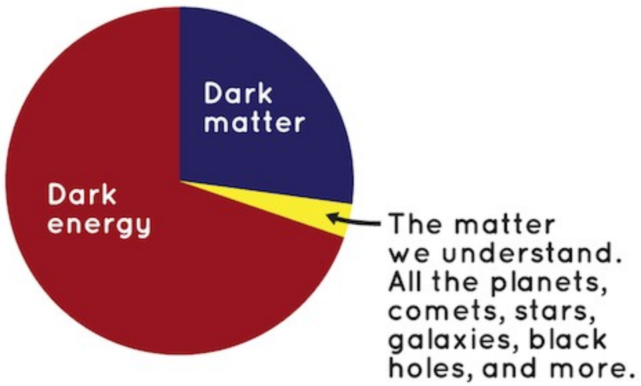

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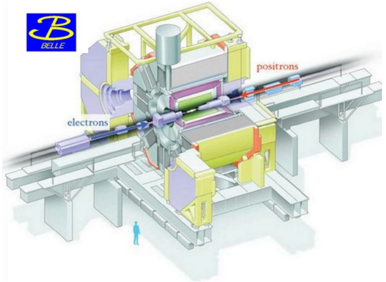
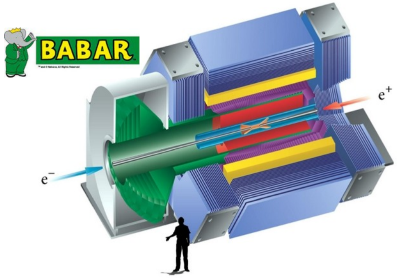
B-factories: first generation

Dedicated experiment at e^+e^- asymmetric-energy colliders for the production of a $B\bar{B}$ pairs.

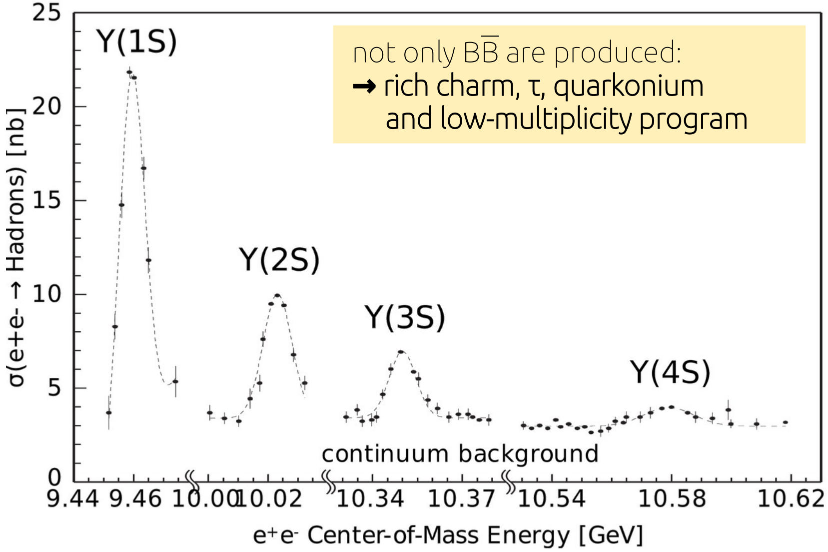
- Main process: $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$



@KEKB collider (KEK, Japan)



@PEP II collider (SLAC, California)



not only $B\bar{B}$ are produced:
→ rich charm, τ, quarkonium and low-multiplicity program

- **Belle** and **BaBar** have collected together 1.5 ab^{-1}
  → the majority of existing measurements are limited by statistical uncertainties

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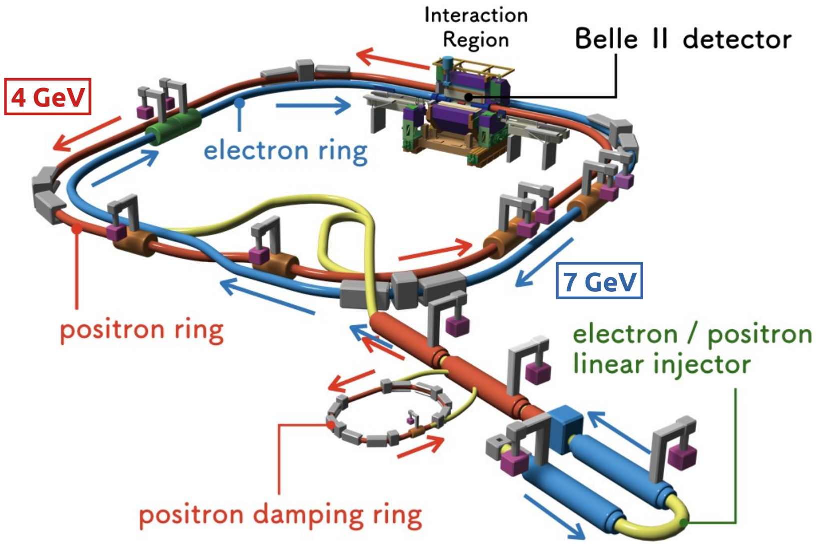
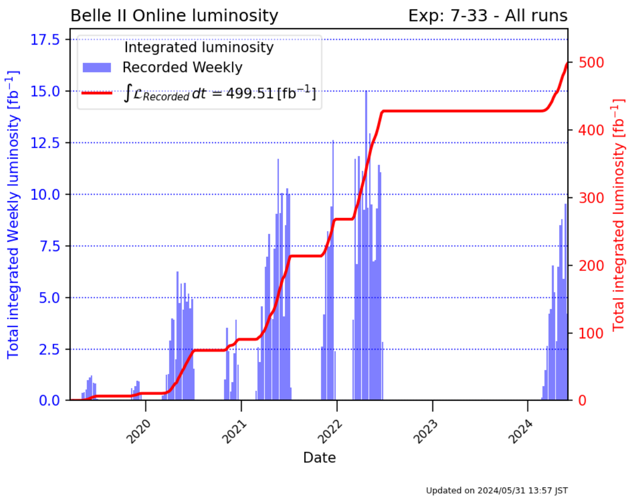
SuperKEKB: a second generation B-factory

- SuperKEKB is a 2nd generation asymmetric e^+e^- collider at the $\Upsilon(4S)$ energy located at **Tsukuba, Japan**
- target instantaneous luminosity is 6×10^{35} $cm^{-2}s^{-1}$ (x30 KEKB/Belle)



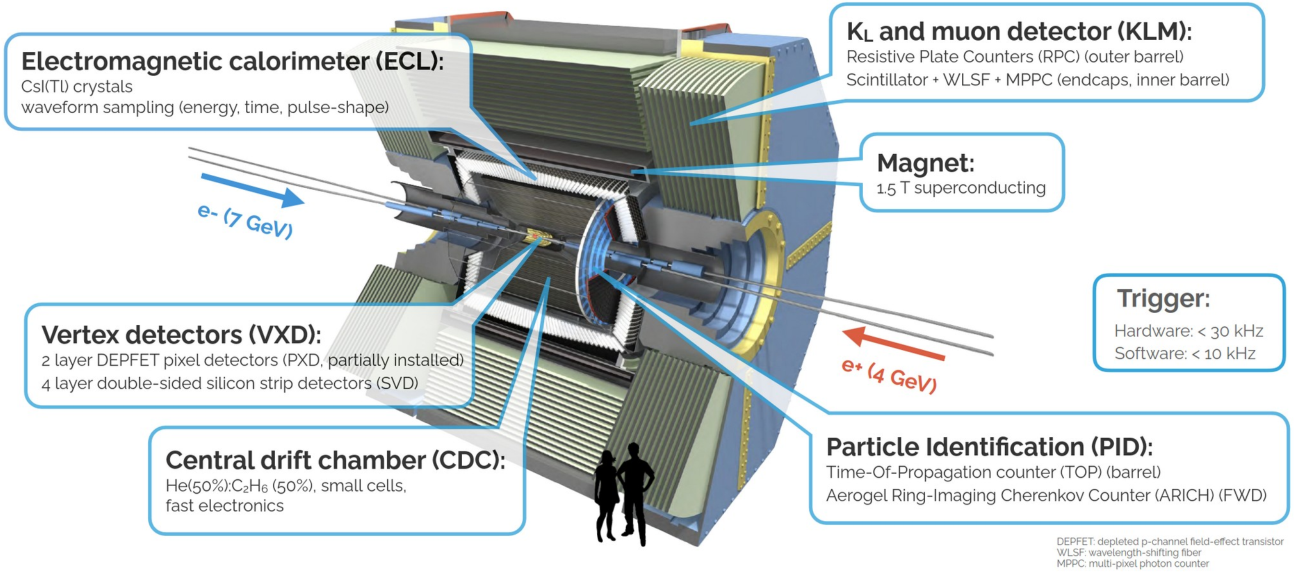


unprecedented instantaneous luminosity: 4.7 x 10^{34} cm^{-2} s^{-1}

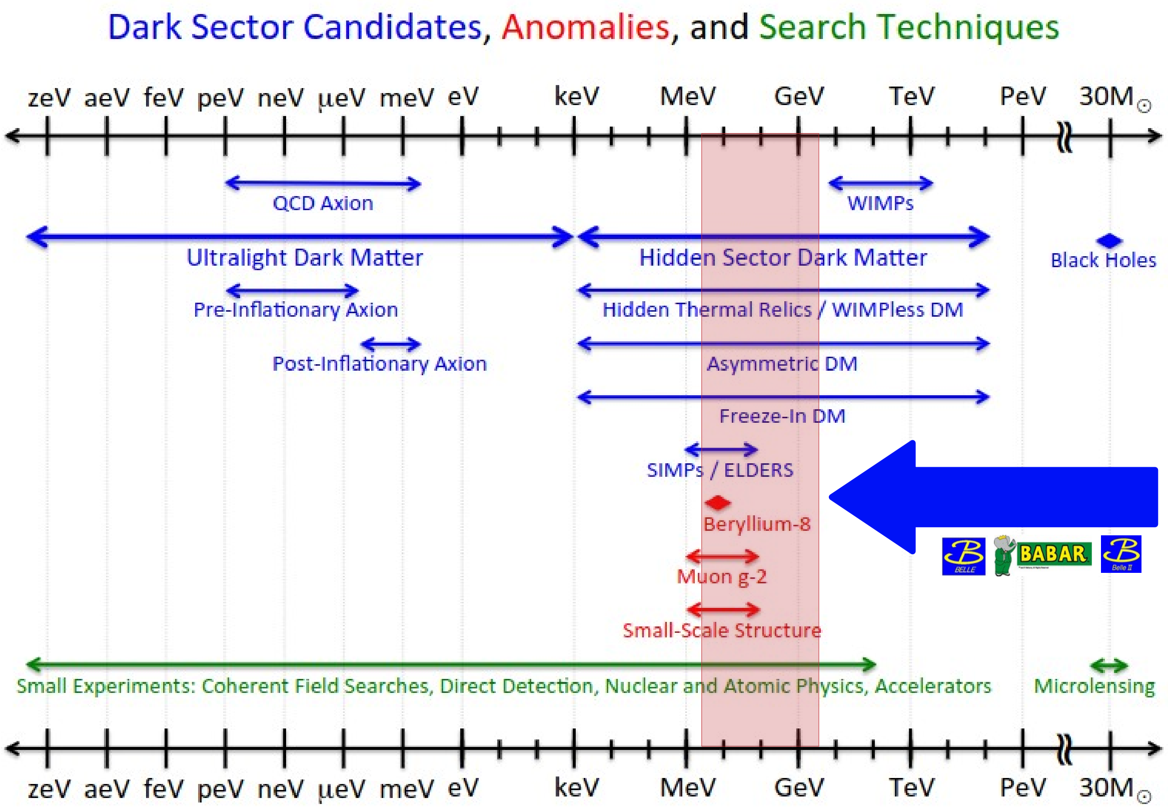
data taking recently resumed after long shutdown

Dark Matter at B-factories: Why

- efficient reconstruction of **neutrals (γ, π^0, η, η'...)**
- **high trigger efficiency** (including some specific trigger for low-multiplicity events)
- excellent **particle identification** capabilities
- very good **vertexing**



Light Dark Matter at B-factories



ArXiv:1707.04591

B-factories at e^+e^- collider can access the mass range favored by light dark sector

→ possible sub-GeV scenario: DM weakly coupled to SM through a light mediator:

- Vector portal (Dark Photons, Z' bosons)
- Pseudo-scalar portal (ALPs)
- Scalar portal (Dark higgs/Scalars)
- Neutrino portal (Sterile Neutrinos)

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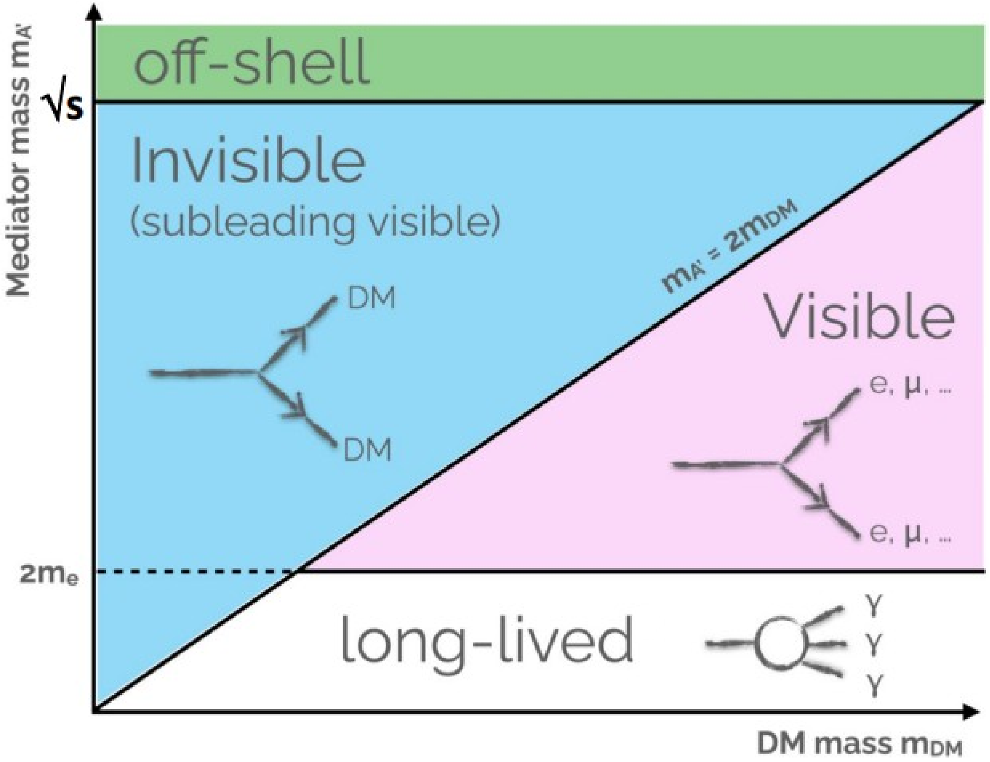
Light Dark Matter at B-factories: possible signatures



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Recent Dark Sector Analyses Results

BELLE BABAR Belle II

I. Z'
II. (Pseudo-)Scalars
III. B-Mesogenesis

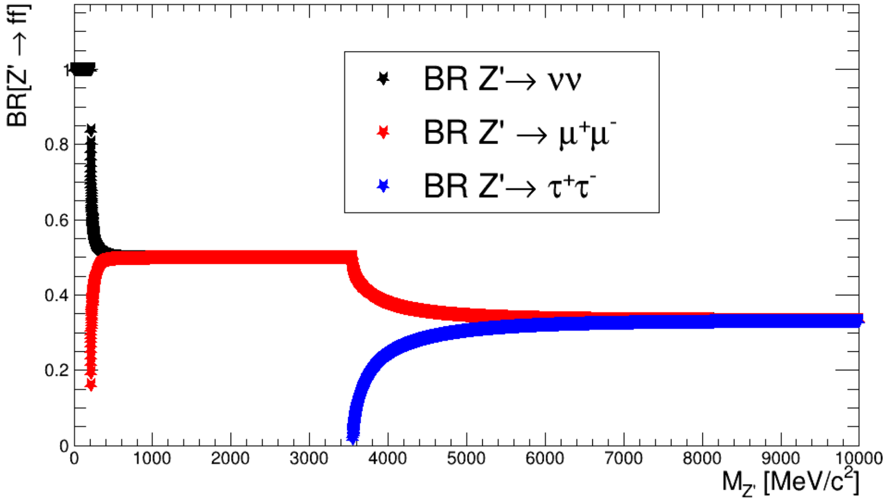
Z’

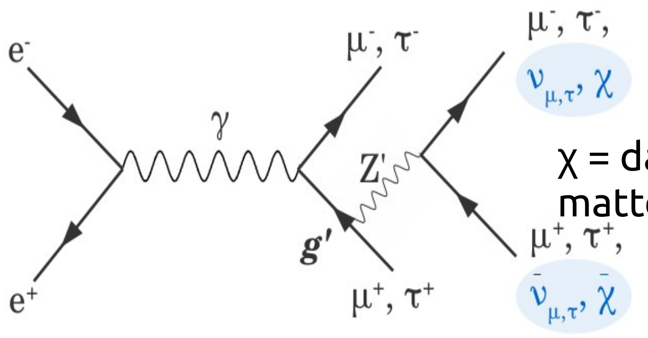
The $L_\mu - L_\tau$ model

[1] B.Shuve and I.Yavin (2014) Phys. Rev. D 89, 113004; Altmannshofer et al JHEP 1612 (2016) 106

New gauge boson Z' coupling only to the 2nd and 3rd generation of leptons (L_μ-L_τ)[1] may explain:

- long-standing $(g-2)_\mu$ anomaly
- dark matter abundance





χ = dark matter

- Searches at B-factories: $e^+e^- \rightarrow \mu^+\mu^- Z'$
  - invisible
  - μμ
  - ττ

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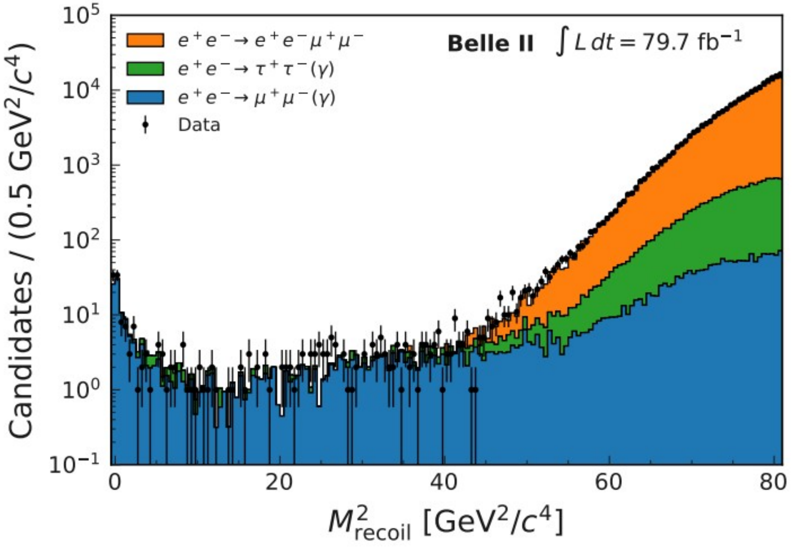
Search for an invisible Z'

- Search for the process: **$e^+e^- \rightarrow \mu^+\mu^- Z' \rightarrow$ inv.**
  → Two possible interpretations:
  1) Vanilla, BF($Z' \rightarrow \nu\bar{\nu}$) ~ 33-100%
  2) Full invisible BF($Z' \rightarrow \chi\bar{\chi}$) ~ 100%

- Look for a narrow peak **in the recoil mass against a $\mu^+\mu^-$ pair** in events where nothing else is detected

- Dominant background radiative QED processes

- Final State Radiation properties of the emitted Z' fed in a **neural network** trained for all Z' masses simultaneously



I. Adachi et al. (Belle II Collaboration) Phys. Rev. Lett. 130, 231801

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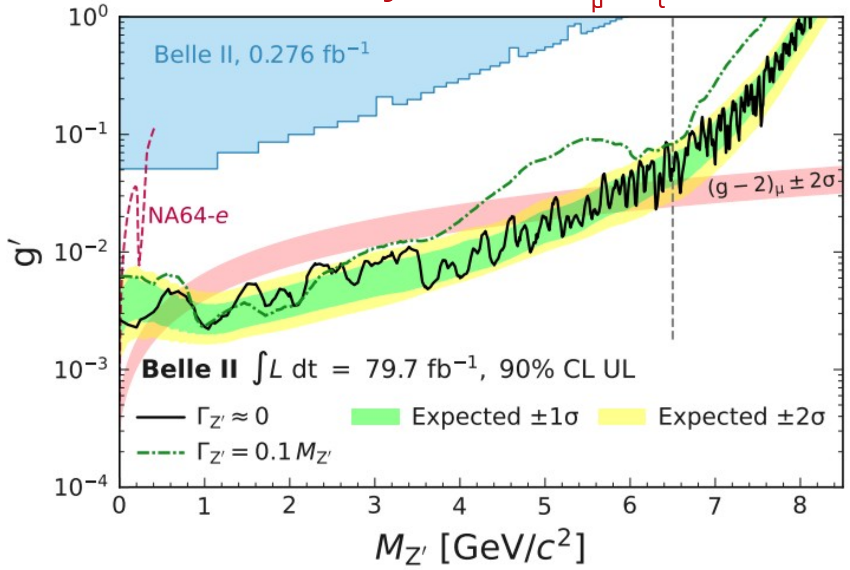
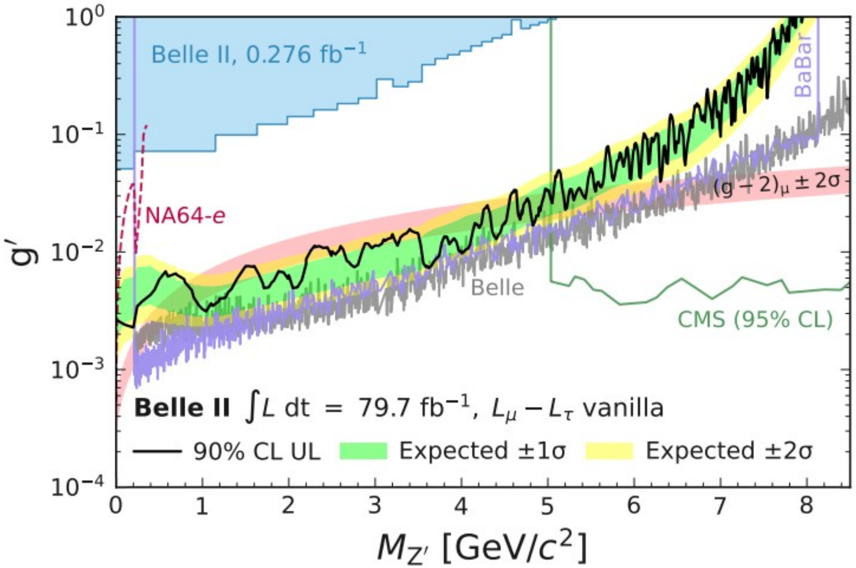
Search for an invisible Z'

- No excess found in 79.7 fb^{-1}
  → 90% CL upper limits on $\sigma(e^+e^- \to \mu^+\mu^- Z', Z' \to \text{inv.})$ and on g'
  → $(g-2)_\mu$ favored region excluded for $0.8 < M(Z') < 5$ GeV/c^2

Fully invisible L_μ - L_τ



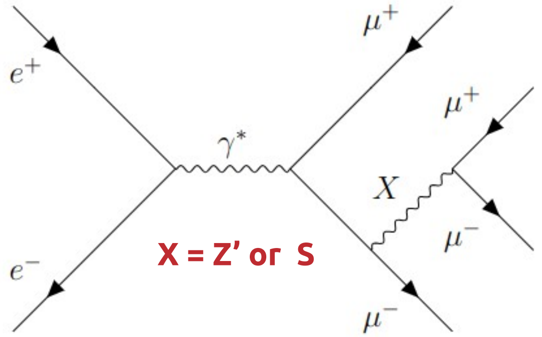
Vanilla



I. Adachi et al. (Belle II Collaboration) Phys. Rev. Lett. 130, 231801

Search for a μμ resonance in ee ➞ μμμμ

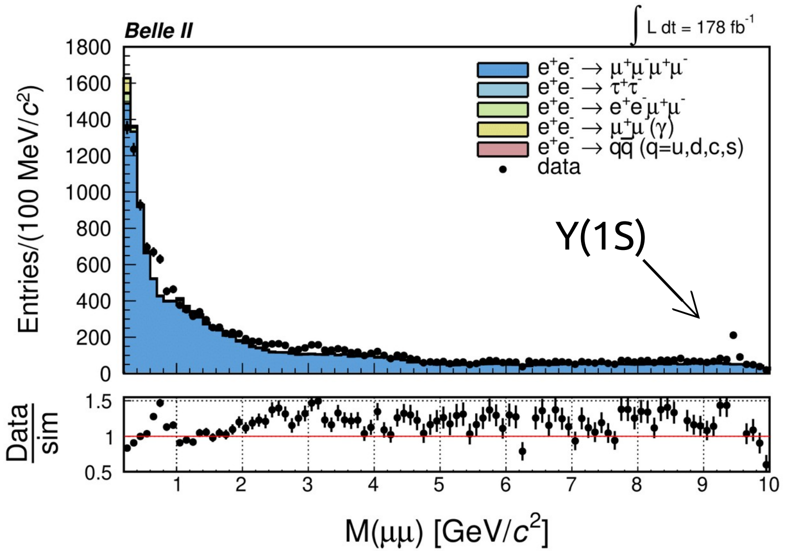
- Search for the process $e^+e^- \to \mu^+\mu^- (X \to \mu^+\mu^-)$, X = Z', S
  → Look for a peak in the opposite charge di-muon mass distribution in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ events



- $(L_\mu - L_\tau)$ **model** used as benchmark and then performance is checked for the scalar case [5]

- Events selected have **4 charged particles:**
  - zero charge
  - at least **three identified as muons**
  - M(4tracks) ~ $\sqrt{s}$
  - no extra energy

- **Multi-Layer Perceptron (MLP)-based background suppression**



arXiv:2403.02841

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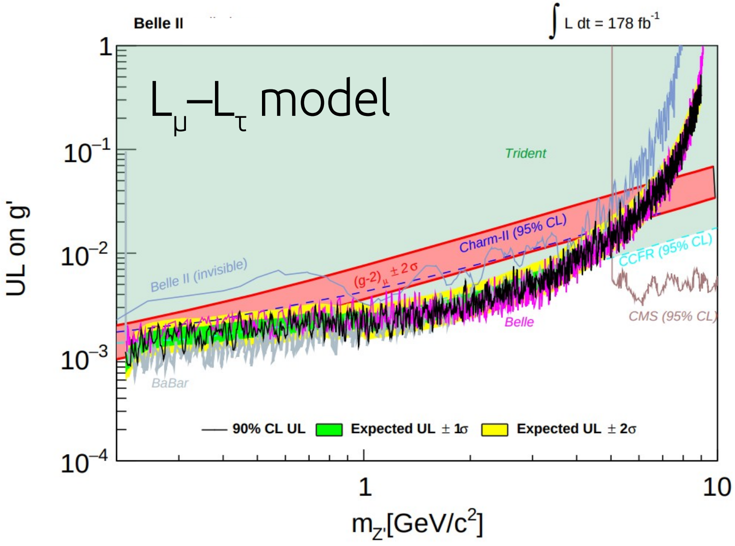
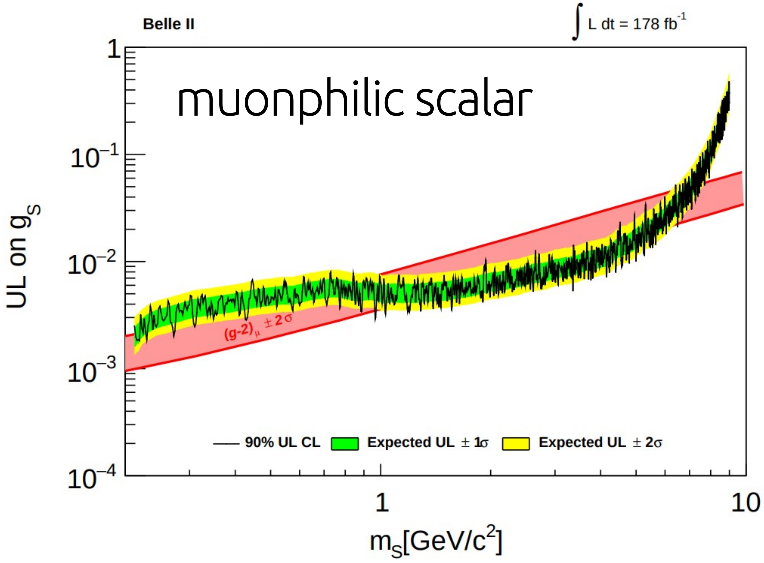
Search for a μμ resonance in ee ➞ μμμμ

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

- No significant excess observed in 178 fb^{-1}
  - ➞ 90% CL upper limits on the process cross-section $\sigma(e^+e^- \to X\,\mu^+\mu^-) \times B(X \to \mu^+\mu^-)$, with X = Z', *S*
  - ➞ cross section limits are translated into upper limits on the g' coupling constant for the $L_\mu\!-\!L_\tau$ model and on the g_S coupling constant for the muonphilic dark scalar *S* [5]





arXiv:2403.02841

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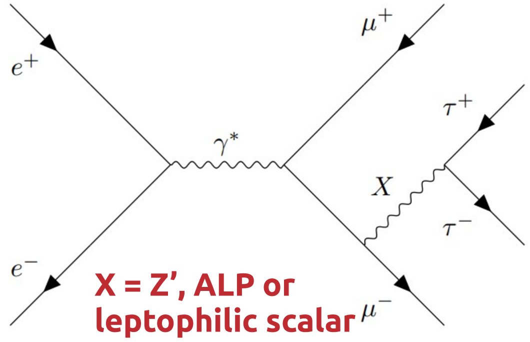
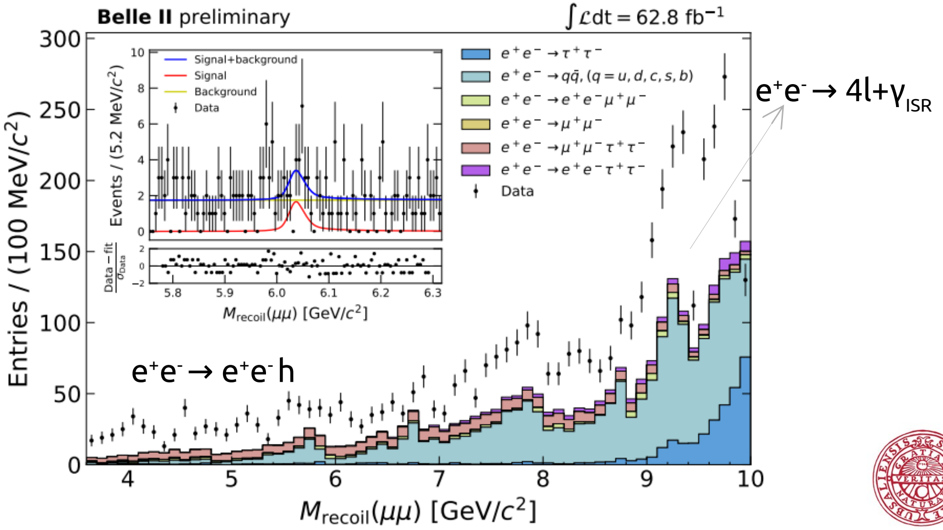
Search for a ττ resonance in ee ➞ μμττ

- Search for a **di-tau resonance in e^+e^-➞ $\mu^+\mu^-\tau^+\tau^-$** as a peak in the recoil against two muons

- Reconstruct **τ decays to one-charged particle**
  → select **four-track events** with at least two tracks identified as muons
  → **M(4tracks) < 9.5 GeV/c²** to suppress the four-lepton backgrounds that peak at the c.m. energy

- **Background suppression exploits features of kinematic variables in the signal**





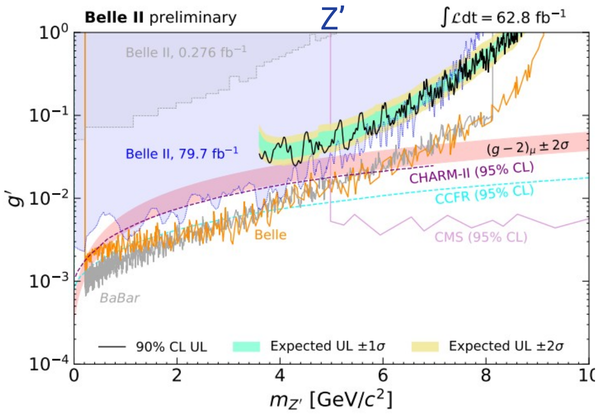
I. Adachi et al. (Belle II Collaboration) Phys. Rev. Lett. 131, 121802

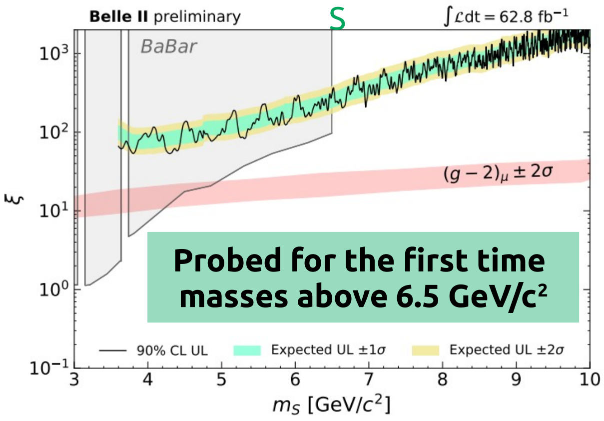
Search for a ττ resonance in ee → μμττ

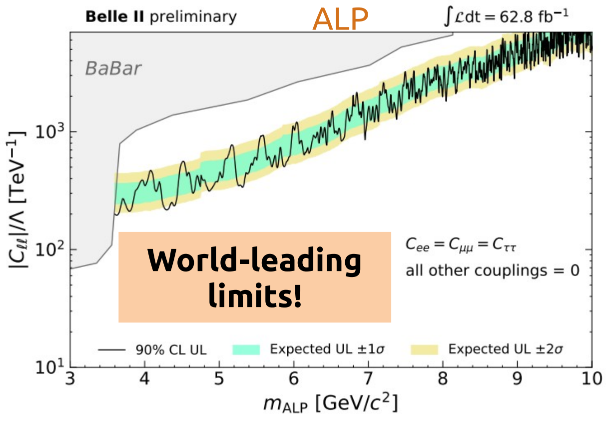
[2] W. Altmannshofer et. al. JHEP 12 (2016) 106
[3] B. Batell, N. Lange, D. McKeen, M. Pospelov, and A. Ritz, Phys. Rev. D 95, 075003 (2017)
[4] M. Bauer, M. Neubert, and A. Thamm, J. High Energy Phys. 2017, 44 (2017)

- No significant excess observed in 62.8 fb^{-1}
  → 90% CL upper limits on the process 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'

- Exclusion limits on the couplings for three different models (Z'[2], leptophilic scalar (S)[3], and ALP[4]) are derived:







I. Adachi et al. (Belle II Collaboration) Phys. Rev. Lett. 131, 121802

(Pesudo-)Scalars

Search for a dark leptophilic scalar in τ decays

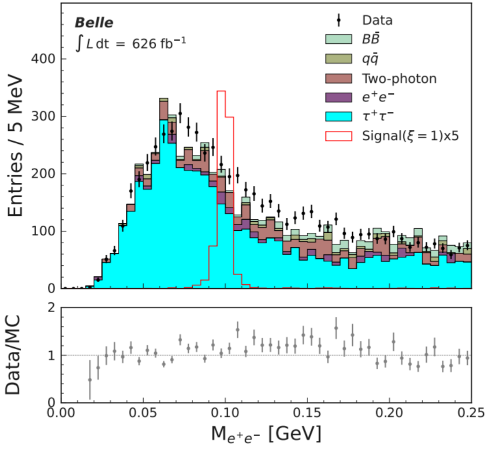
[6] P. J. Fox and E. Poppitz, Phys. Rev. D 79, 083528 (2009)

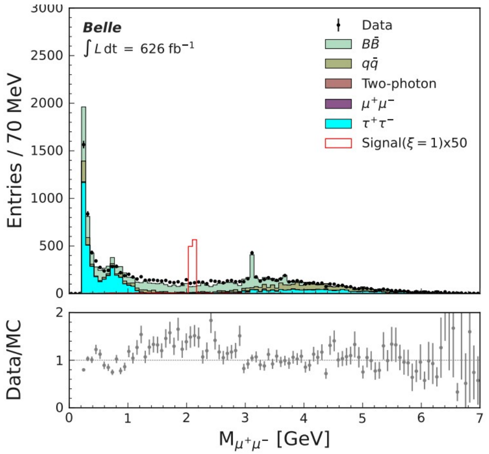
Mass range probed in this analysis: **40 MeV < $m(\Phi_l)$ < 6.5 GeV**
- $\Phi_l \rightarrow e^+e^-$ for $m(\Phi_l) < 2m(\mu)$ → low mass region
- $\Phi_l \rightarrow \mu^+\mu^-$ for $m(\Phi_l) > 2m(\mu)$ → high mass region

- **Strategy:** search for a narrow peak in m_{ll} distribution
  - $e^+e^- \rightarrow \tau^+\tau^-\Phi_l$ require 1-prong decay
  - 4 tracks with 0 net charge

- **Background:** $e^+e^- \rightarrow \tau^+\tau^-$, $e^+e^-/\mu^+\mu^-$, $q\bar{q}$, $B\bar{B}$
  → define five BDT score to suppress backgrounds

- Maximum Likelihood fit to m_{ll} distribution
  → evaluate sensitivities to each mass point





D. Biswas et al. (Belle Collaboration) Phys. Rev. D 109, 032002

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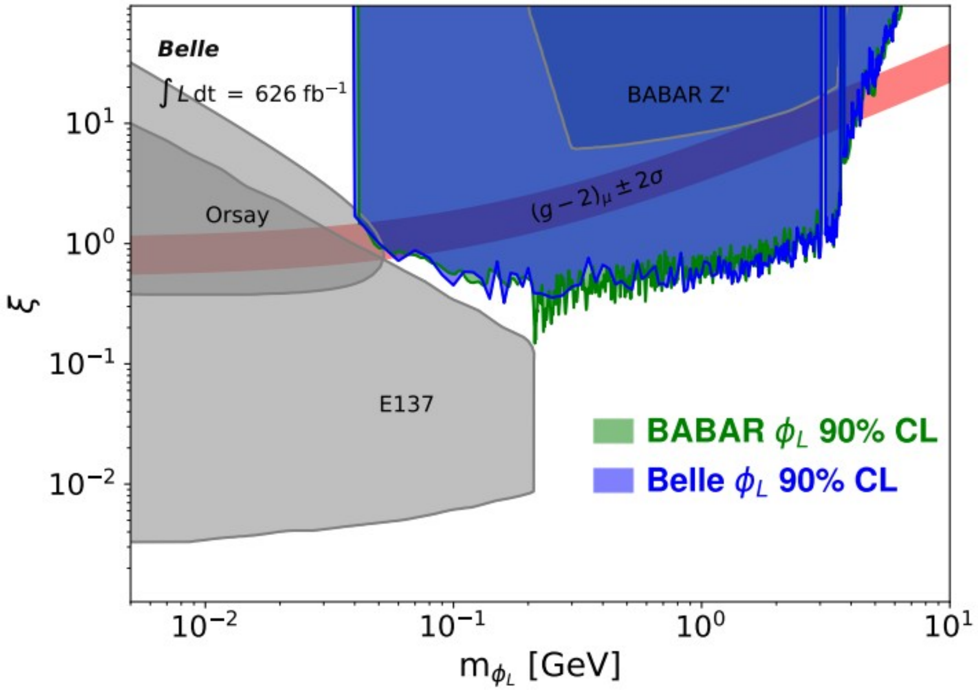
Search for a dark leptophilic scalar in τ decays

[7] Phys. Rev. Lett. 125, 181801Phys. Rev. Lett. 125, 181801

- No significant excess observed in 626 fb^{-1}
  ➞ 90 % CL UL on ξ vs $m(\Phi_l)$



→ comparable or more stringent limits than [7]BaBar (514 fb^{-1})

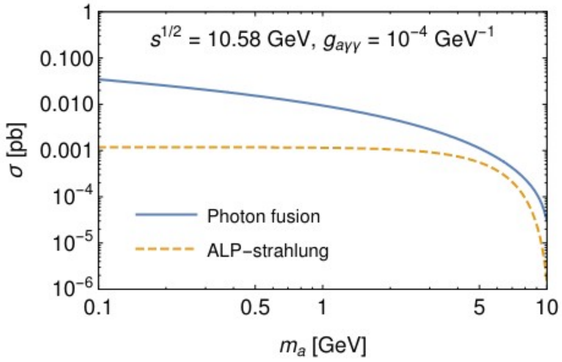
→ exclude a wide range of parameter space of the model favored by $(g-2)_\mu$

D. Biswas et al. (Belle Collaboration) Phys. Rev. D 109, 032002

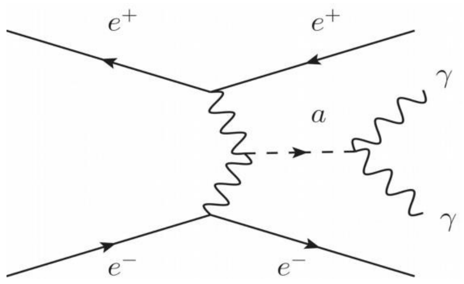
Search for ALPs

[8] Annual Review of Nuclear and Particle Science
[9] F. Abudinén et al. (Belle II Collaboration) Phys. Rev. Lett. 125, 161806

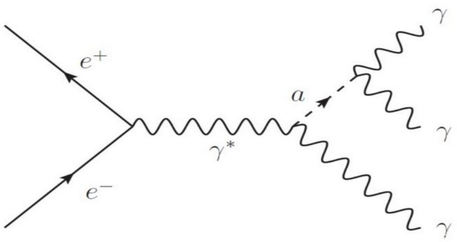
- ALPs are **pseudo-scalars** particles coupling with bosons
- Difference to QCD axions: **no relation between the coupling and the mass**
- **Three possible scenarios:**



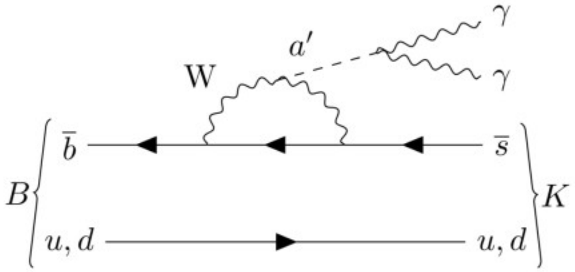
Photon-fusion



[9]ALP-strahlung



B-meson decay



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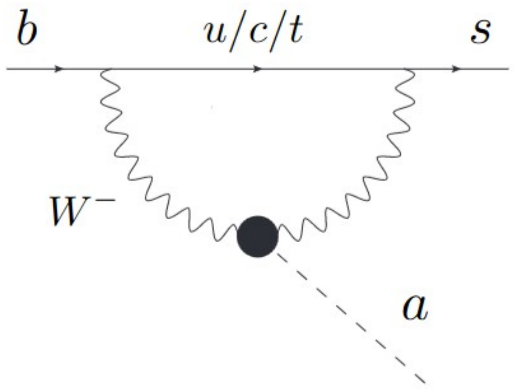
Search for ALP in B Meson decays

- Search for ALPs that predominantly couple to electroweak gauge bosons
  → can be emitted in flavour-changing B Meson decays

- Strategy:
  - signal $B^{\pm}$ reconstructed combining a pair of photons with a track identified as a kaon
  - total energy and invariant mass constrained to the nominal B mass and measured c.m. beam energy
  - two BDTs used to separate the signal from each background

- Search targeting prompt ALPs. However, **ALPs can be long-lived for small mass and coupling**



$$\Gamma(a \to \gamma\gamma) = \frac{g_{aW}^2 \sin^4\theta_W M_a^3}{64\pi}$$

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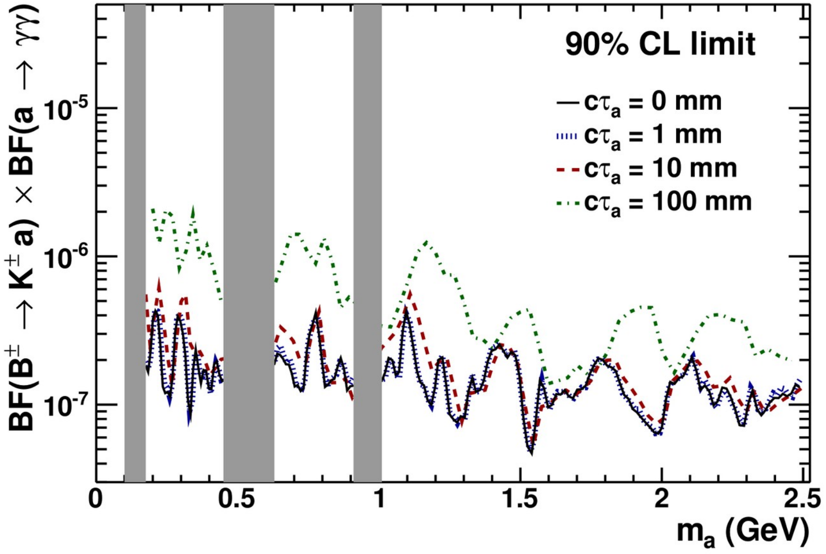
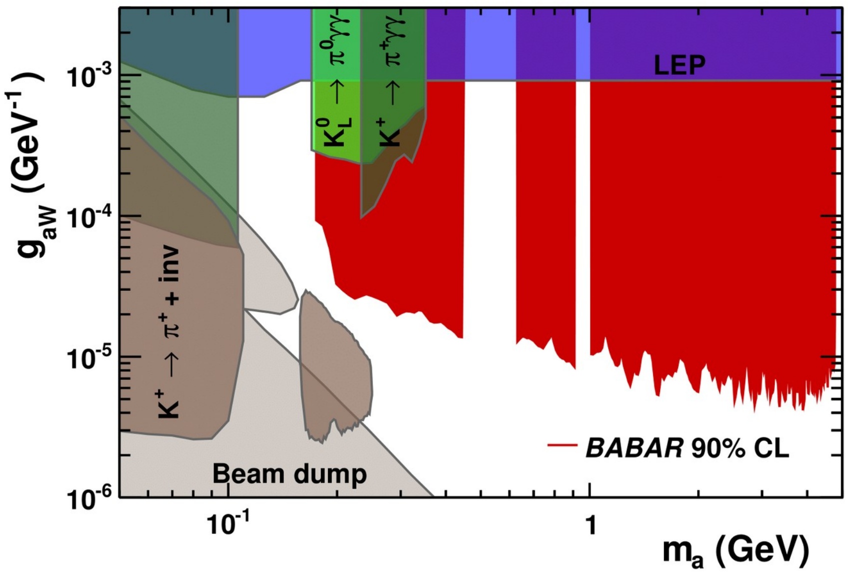
Search for ALP in B Meson decays

- No signal in **424 fb^{-1} of data**
  → 90% C.L. upper limits set on the **g_{aW} coupling constant**
  → BR measured for **different lifetimes**

- <u>Limits improved of several order of magnitudes</u>





J. P. Lees et al. (BABAR Collaboration) Phys. Rev. Lett. 128, 131802

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Search for a long-lived (pseudo-)scalar particle in $b \to s$

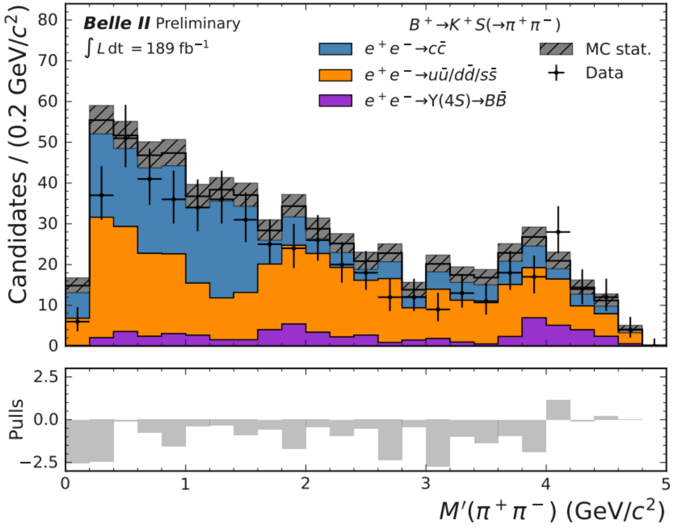
- Search for **dark scalar** particles S from B decays in **rare b→s transitions**
  - S could mix with SM Higgs with mixing angle θ_s (naturally long-lived for $\theta_S << 1$)
  - $M_S < M_B$, decays of S into dark matter particles must be kinematically forbidden to provide the correct relic density

- Look for S decays into SM final states in **8 exclusive channels**

$B^+ \to K^+ S$
$B^0 \to K^{*0} (\to K^+\pi^-) S$
→ **S → ee/μμ/ππ/KK**

- **B-meson candidates** are reconstructed from prompt and displaced charged tracks

- **S candidates** are reconstructed from displaced oppositely-charged tracks pairs



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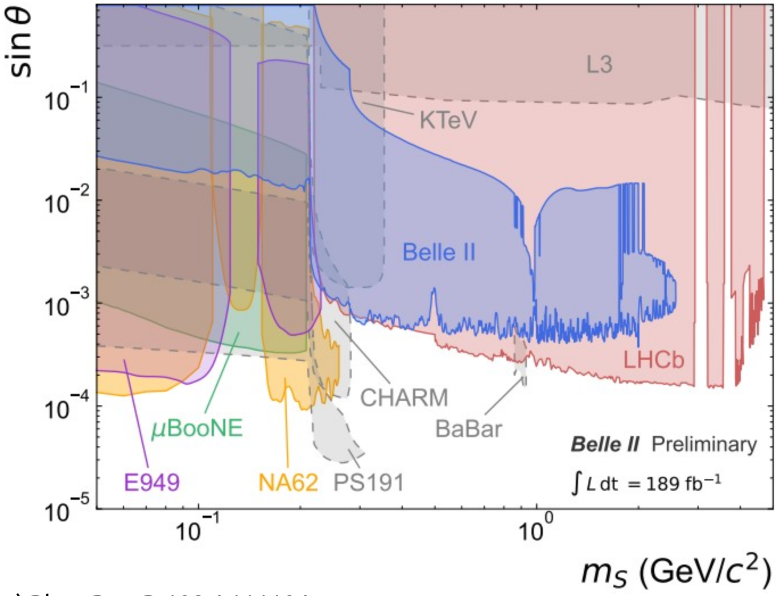
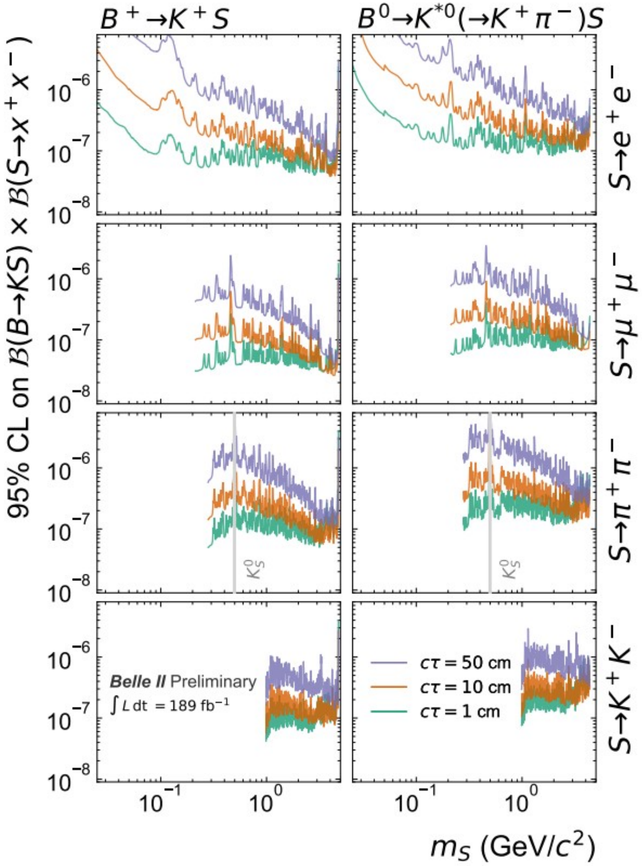
Search for a long-lived (pseudo-)scalar particle in $b \to s$

- No significant excess found in 189 fb^{-1}
  - first model-independent 95% CL upper limits on $BF(B \to KS) \times BF(S \to x^+x^-)$
  - translate into model independent limits on $\sin\theta_s$ vs. m_s

First limits on decay to hadrons

Results are also available for the pseudo-scalar (ALP) model





I. Adachi et al. (Belle II Collaboration) Phys. Rev. D 108, L111104

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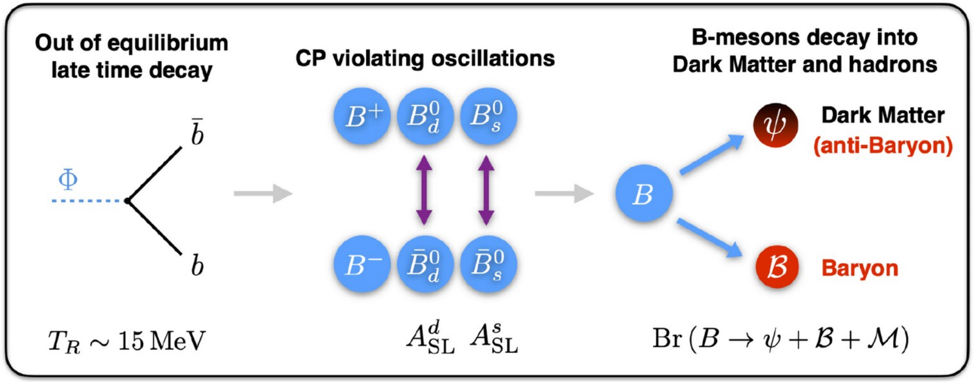
B mesogenesis

B-Mesogenesis

[10]Gonzalo Alonso-Álvarez, Gilly Elor, and Miguel Escudero Phys. Rev. D 104, 035028
[11]Gilly Elor, Miguel Escudero, and Ann E. Nelson Phys. Rev. D 99, 035031

- **Baryogenesis** is required in order to produce an initial excess of baryons over anti-baryons consistent with observations

- **B-Mesogenesis paradigm**[10,11] explains baryonic + dark matter of the Universe
  → baryo- and dark matter genesis from B-Meson give rise to **distinctive signals at collider experiments**



- A new dark anti-baryon is proposed ψ_D which can also explain the Baryon Asymmetry of the Universe (BAU)

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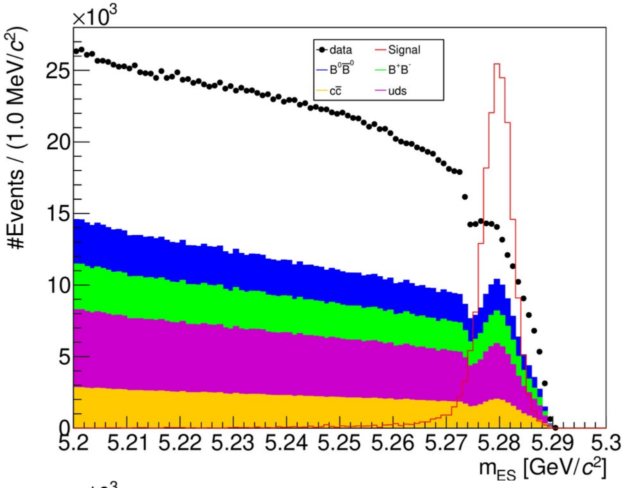
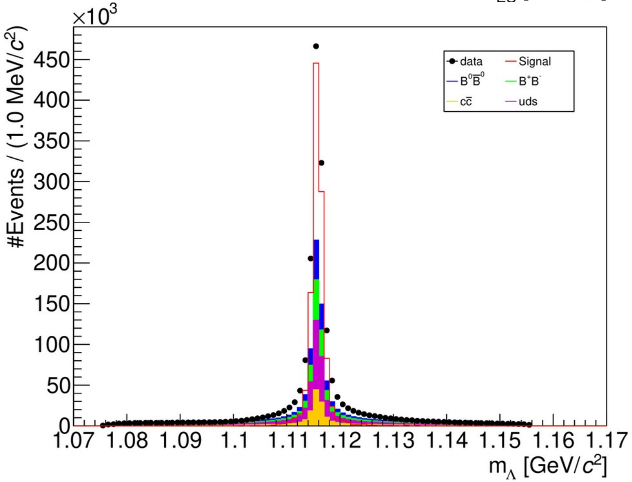
B-Mesogenesis: Search for $B^+ \to \Lambda\, \psi_D$

- BaBar analysis on 398.5 fb^{-1} of data:
  - signal B meson tagged by fully reconstructing the non-signal B meson (B_{tag})
    - → B_{tag} candidate is reconstructed via the decays $B \to SX$
    - → selection based on:

$$\Delta E = E_{beam} - E_{tag} \qquad m_{ES} = \sqrt{E_{beam}^2 - p_{tag}^2}$$

  - remaining particles are associated to B_{sig} ($B \to \Lambda\, \psi_D$):
    - → required presence of only one Λ baryon, reconstructed from p-π couple
    - → ψ_D identified as the system recoiling against the B_{tag} and Λ candidates
  - signal purity increased via a Multi Variate Analysis

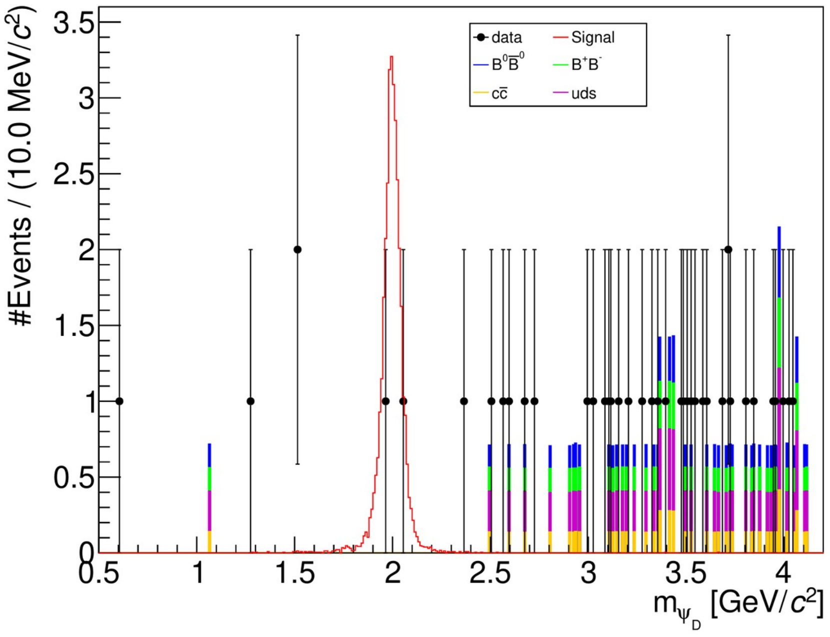


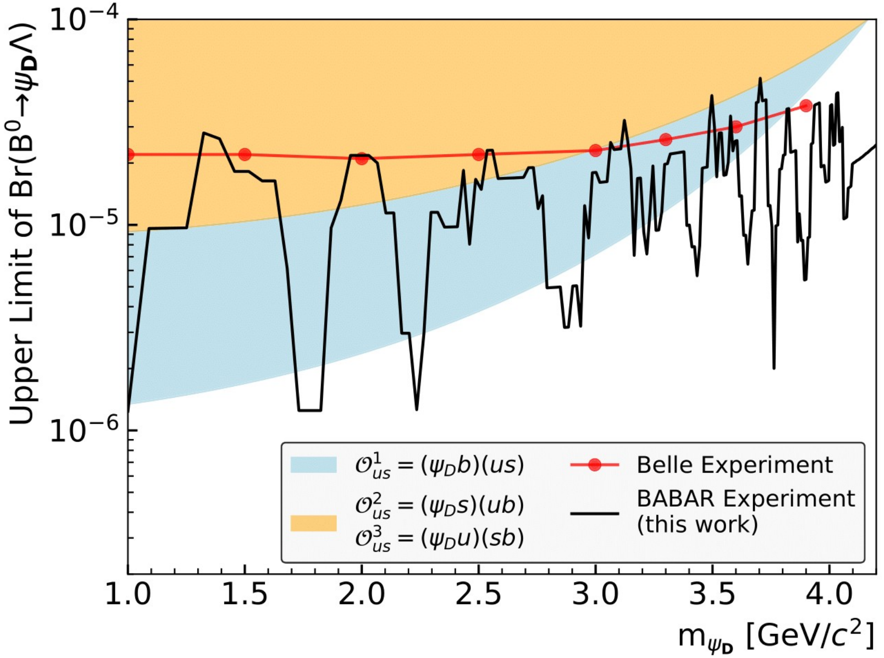


J. P. Lees et al. (The BaBar Collaboration) Phys. Rev. D 107, 092001

B-Mesogenesis: Search for $B^+ \to \Lambda\, \psi_D$

- No significant signal is observed
  → upper limits on the branching fraction are set
  → a large fraction of the parameter space allowed by B-Mesogenesis is excluded





J. P. Lees et al. (The BaBar Collaboration) Phys. Rev. D 107, 092001

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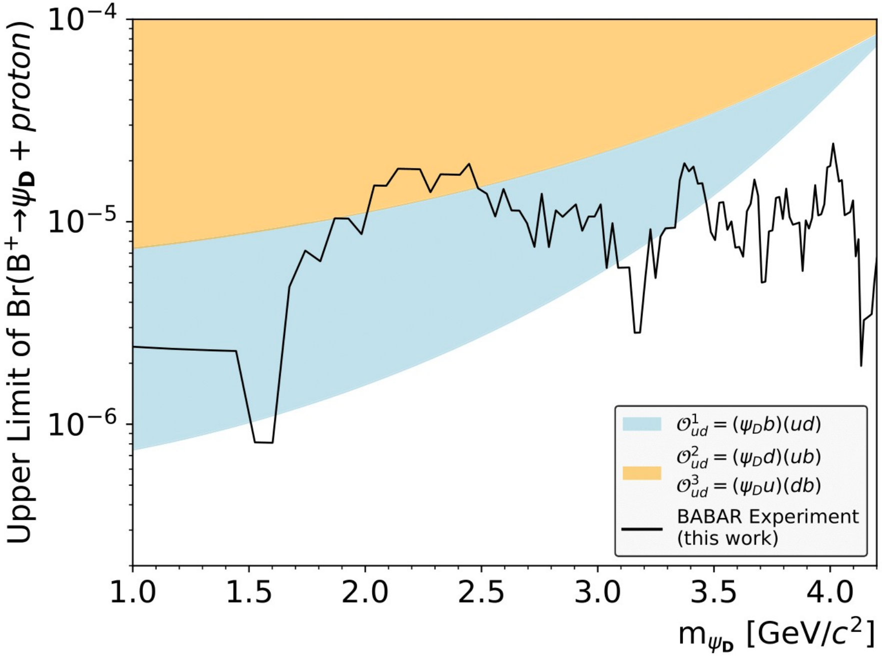
B-Mesogenesis: Search for $B^+ \to \psi_D + p$

- No significant signal is observed in 398.5 fb^{-1} of data
  → upper limits on the branching fraction are set

$$m_{\rm miss}c^2 = \sqrt{(E^*_{B_{\rm sig}} - E^*_{\rm p})^2 - |\vec{p}^{\,*}_{B_{\rm sig}} - \vec{p}^{\,*}_{\rm p}|^2 c^2}$$



arXiv:2306.08490

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Summary

- $e^+ e^-$ B-factories provide unique opportunities to study light dark matter and mediators
`

- BaBar and Belle collected 1.5 ab^{-1} of data
  - still producing dark sector physics with world's unique or leading results

- Belle II is a super B-factory with excellent sensitivity for dark sector searches
  - competitive or better limits with a subset of the available data
  - recorded 424 fb^{-1} to date, more results with higher statistics and improved analyses will be produced

- This is a very exciting time to look for new physics beyond the Standard Model, especially in the Dark Sector

...Thanks for your attention!

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Backup

Summary

1. Search for an Invisible Z’ in a Final State with Two Muons and Missing Energy at Belle II
2. Search for a $\mu^+\mu^-$ resonance in four-muon final states at Belle II
3. Search for a $\tau^+\tau^-$ Resonance in $e^+e^-\to\mu^+\mu^-\tau^+\tau^-$ Events with the Belle II Experiment
4. Search for a dark leptophilic scalar produced in association with $\tau+\tau-$ pair in $e+e-$ annihilation at center-of-mass energies near 10.58 GeV
5. Search for an Axionlike Particle in B Meson Decays
6. Search for a long-lived spin-0 mediator in $b\to s$ transitions at the Belle II experiment
7. Search for B Mesogenesis at BABAR
8. Search for Evidence of Baryogenesis and Dark Matter in $B^+\to\psi_D+p$ Decays at BABAR

...and the best is yet to come!

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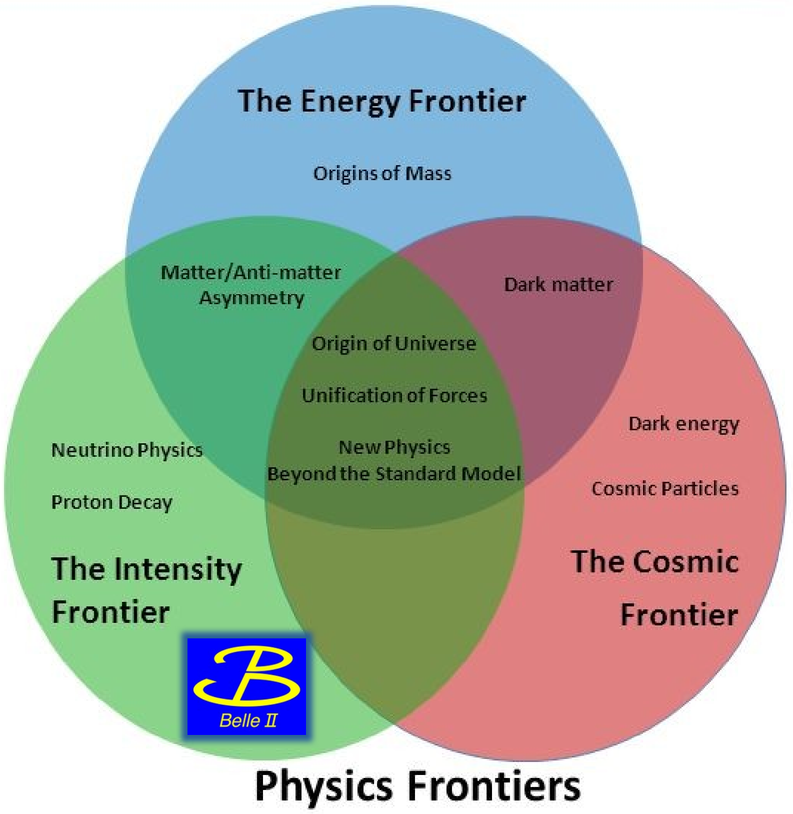
Moving beyond the Standard Model

- at energy frontier experiments are able to discover new particles
  → mass reach for new particle $O(1\ \mathrm{TeV}/c^2)$

- at rare/precision frontier, observable signatures of new particles or processes can be obtained through measurements of flavor physics reactions at lower energies
  → an observed discrepancy can be interpreted in terms of (New Physics) NP models
  - unprecedented sensitivity to the effect of NP
  - probes NP mass scale higher than the one accessed at the energy frontier



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Belle II: the physics program

Belle II Physics Book   Snowmass White Paper

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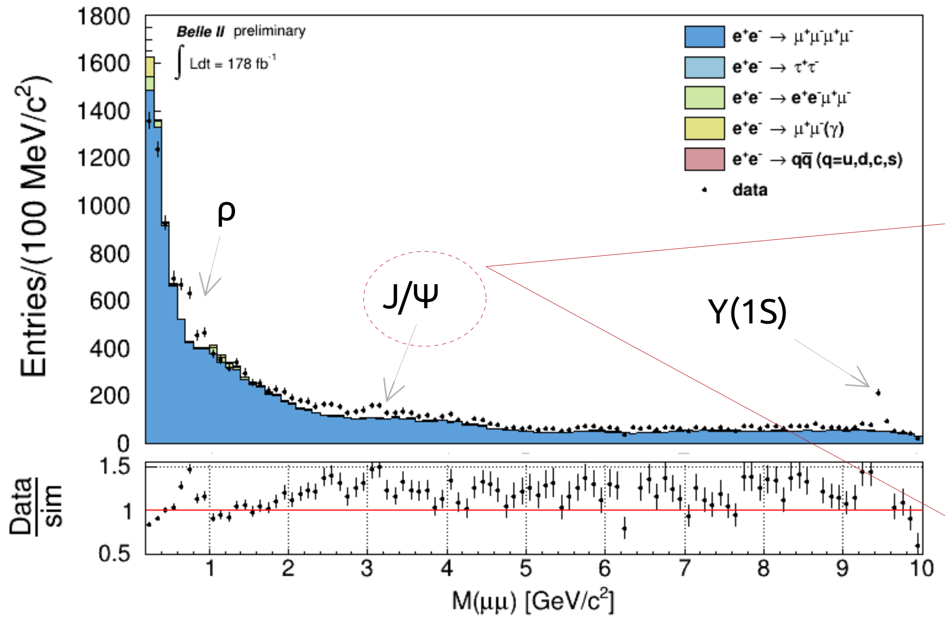
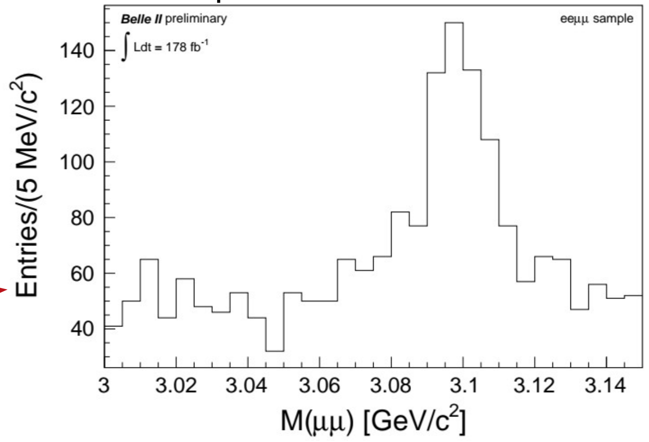
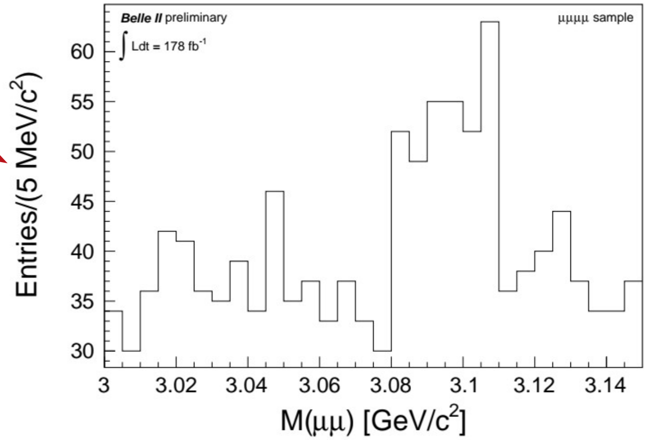
Search for a μμ resonance in ee → μμμμ: J/Ψ



Closeup around J/Ψ nominal mass





- data/MC ratio is over 1 (but for very low masses)
- Modulations due to the different MLP ranges
- Visible features: **ρ, J/Ψ, Υ(1S)**

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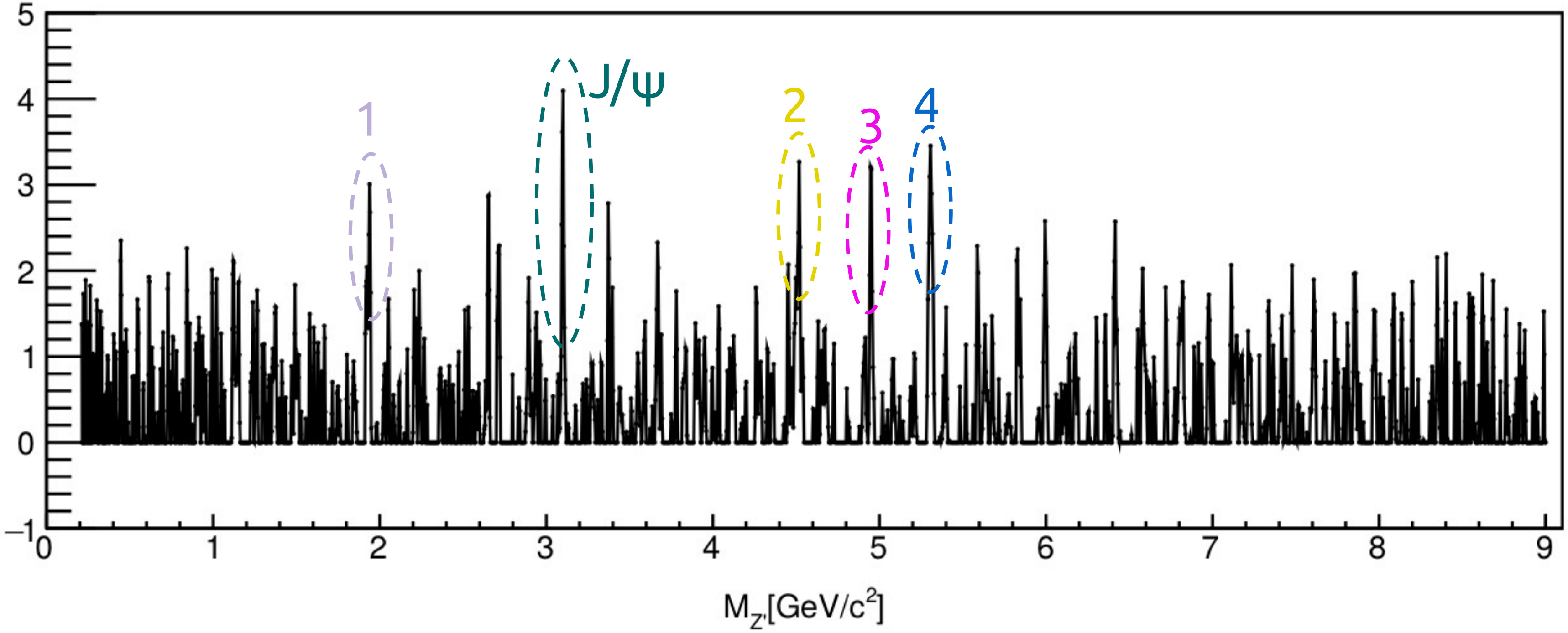
Search for a μμ resonance in ee → μμμμ



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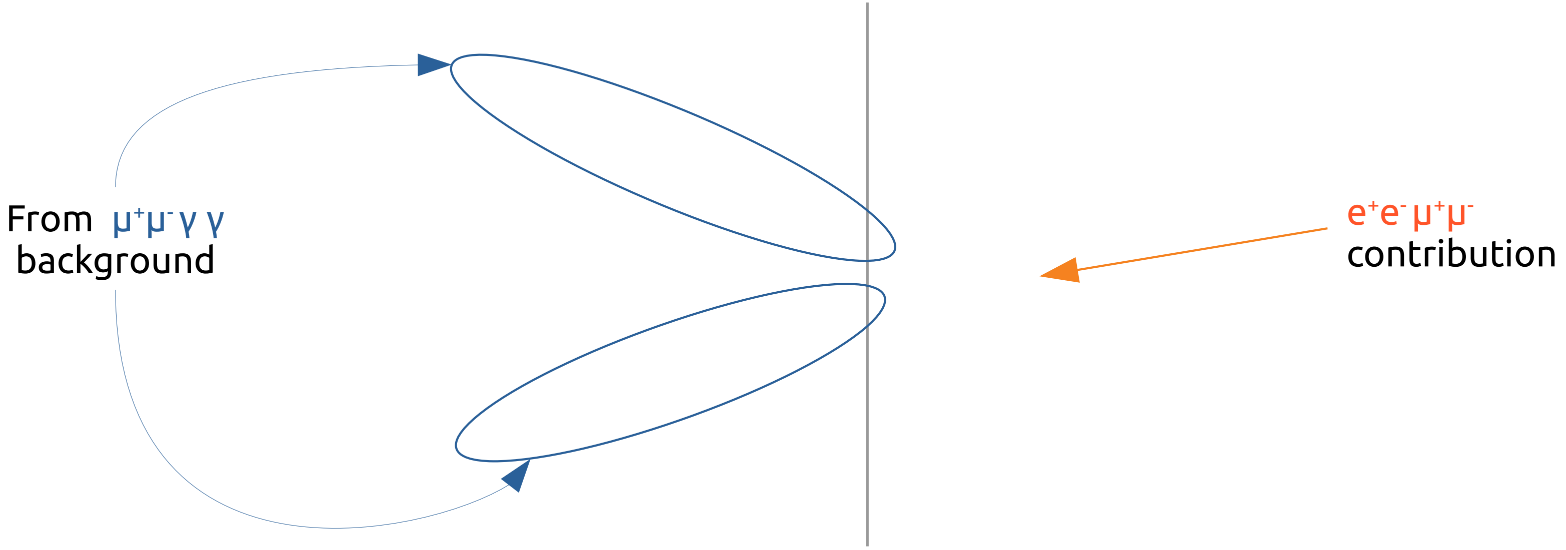
Search for an invisible Z'

- The signal yield extraction is performed through a **two-dimensional fit**
  → exploit of the features in the M^2_{recoil} vs. θ_{recoil} distribution
  → double the sensitivity with respect to the one-dimensional fit



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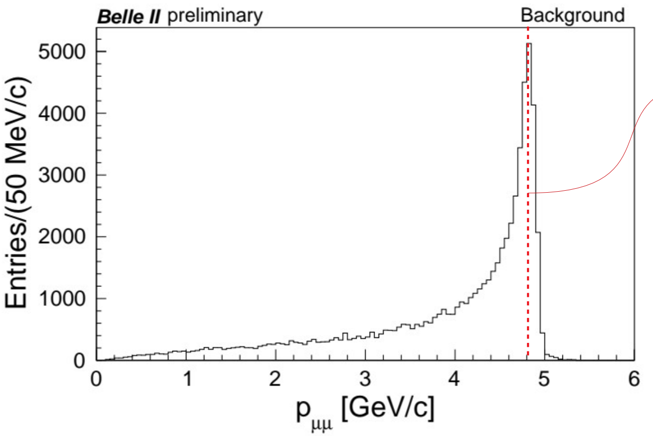
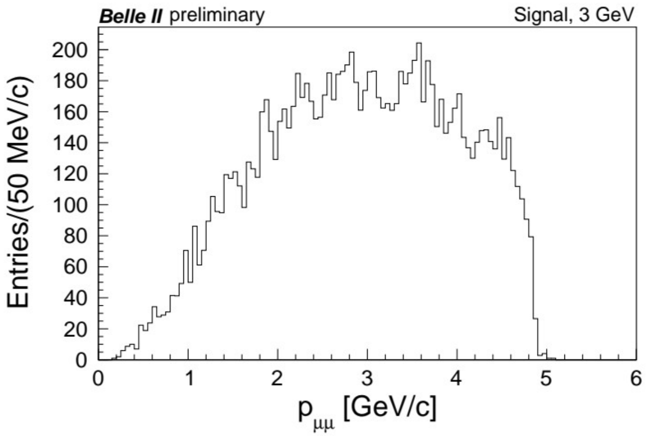
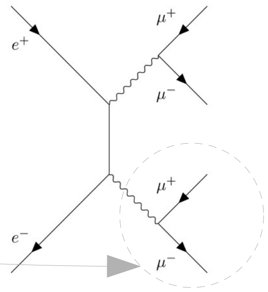
Search for a μμ resonance in ee → μμμμ





Peak corresponding to the **maximum muon pair momentum**



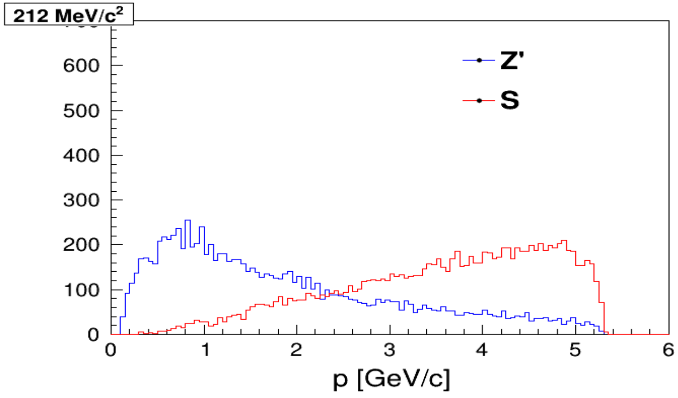
→ transformed variables fed into MLP in order to reduce their change with the Z' mass

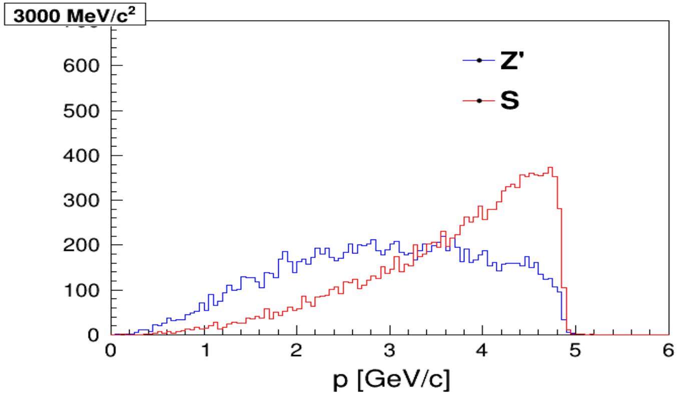
→ five separate MLPs in different M(μμ) intervals

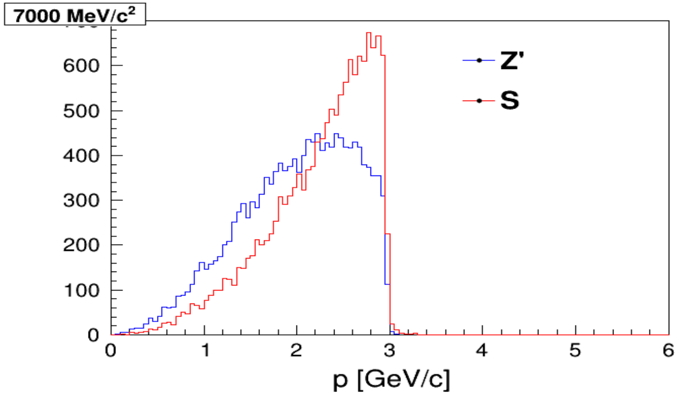
→ selection optimized in each interval with a figure of merit

→ **background rejection factor from 2 to 14**
→ **signal efficiency from 20% to 35%**

Search for a μμ resonance in ee → μμμμ: muonphilic dark-scalar







Difference: Z' is softly produced at low masses, S have a hard momentum spectrum also in the low mass region.

In $e^+e^- \rightarrow \mu^+\mu^- X$ interactions X can be:

- A vector: production occurs through a s-wave process
- A scalar: production occurs through a p-wave process

At low *S* masses the p-wave suppression makes the scalar process grow slowly with the energy, while there is no suppression for vector processes.

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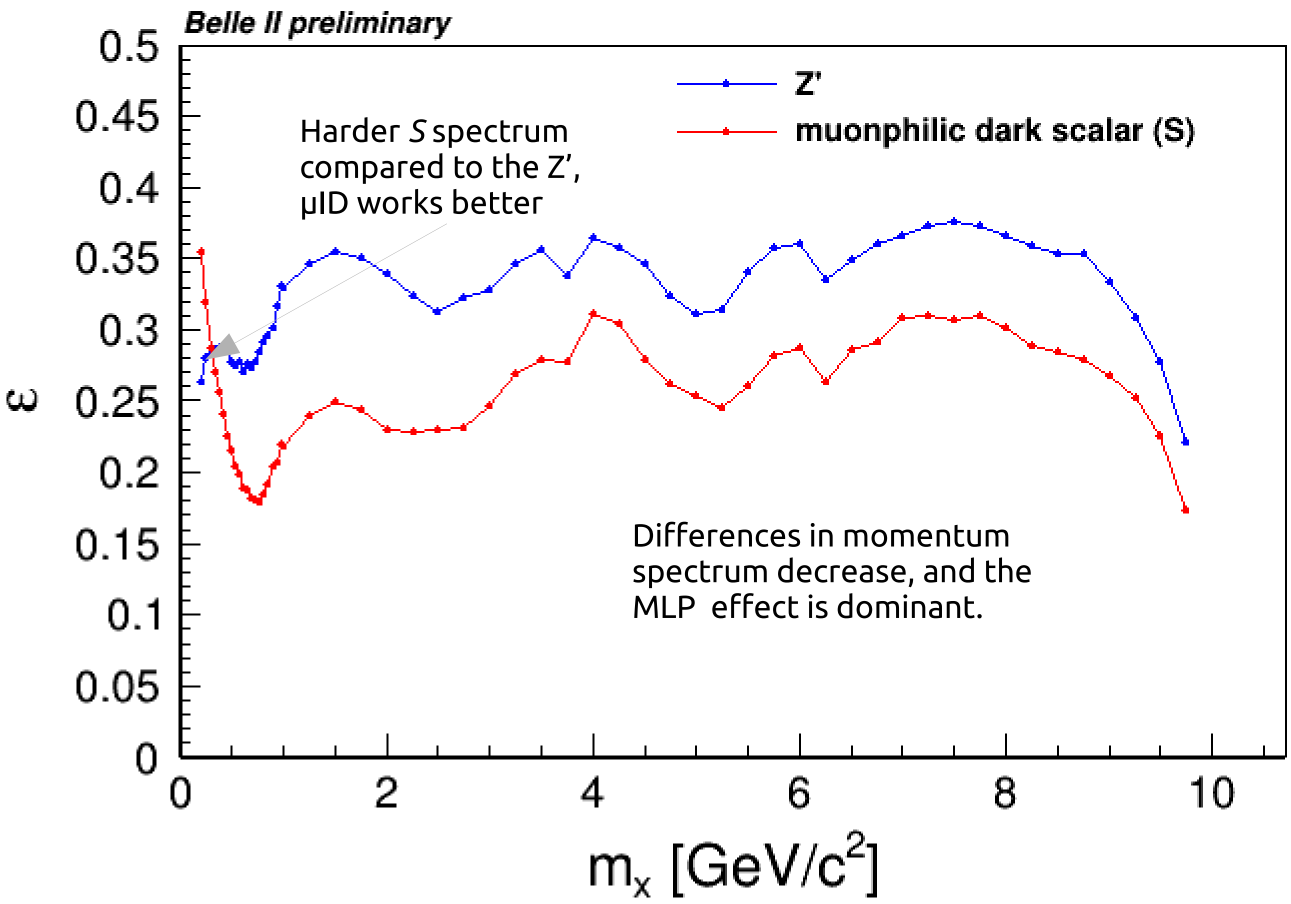
Search for a μμ resonance in ee → μμμμ: muonphilic dark-scalar



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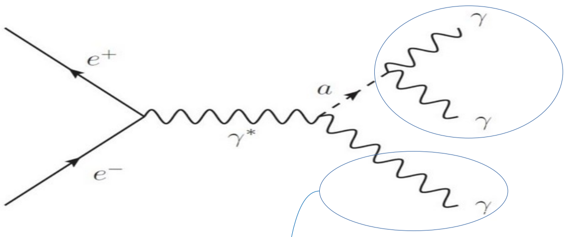
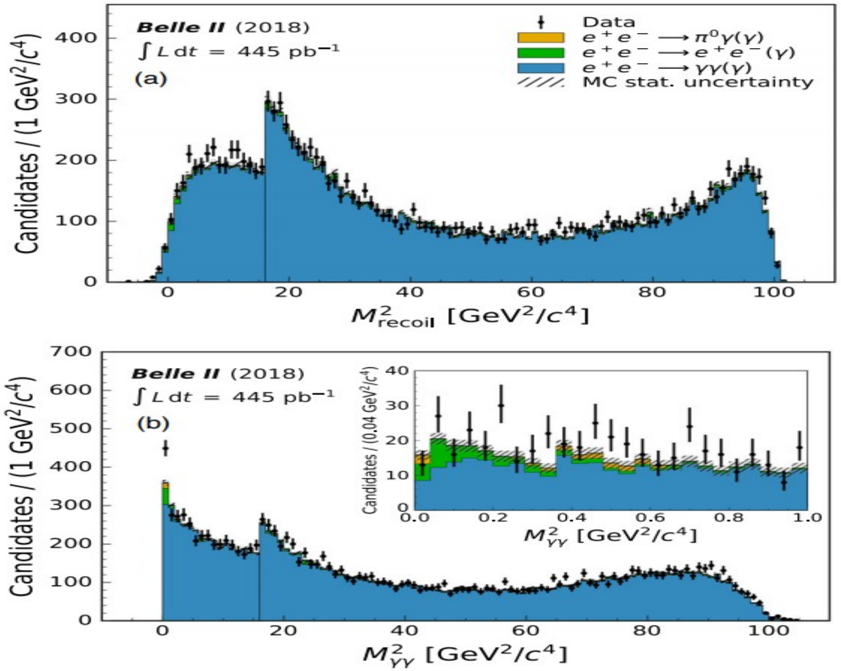
Axion-Like Particles

Experimental signature



Looking for:

- three photons summing up to beam energy and no other particles;
- No tracks;
- Search for a bump into di-photon and recoil mass.



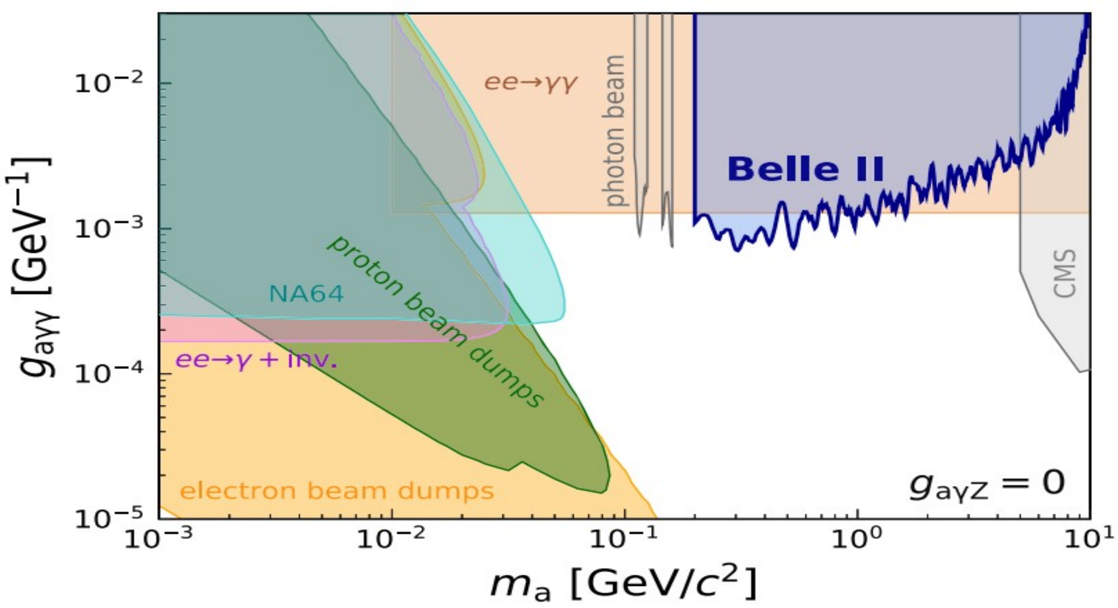
Backgrounds:

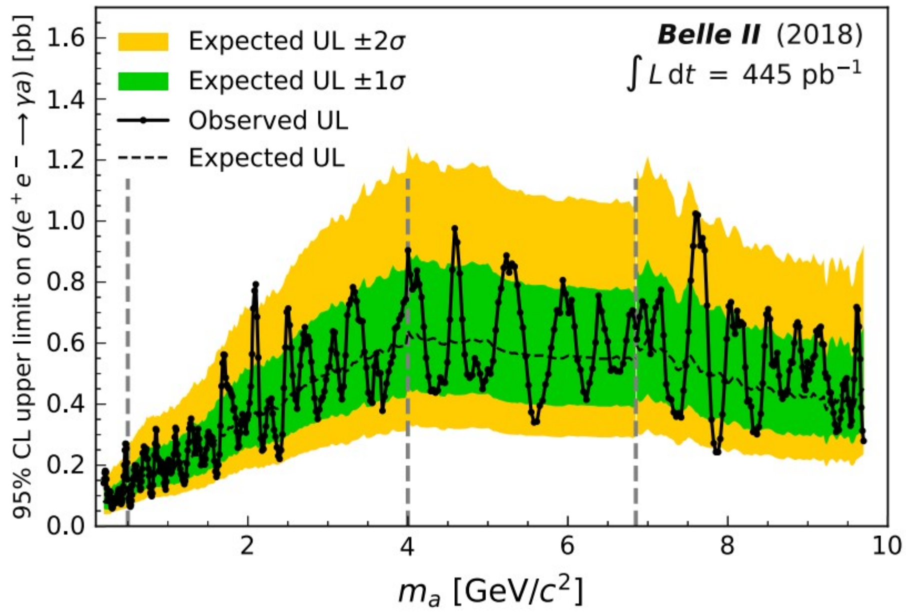
1. $e^+e^- \rightarrow \gamma\gamma(\gamma)$;
2. $e^+e^- \rightarrow e^+e^-(\gamma)$;
3. $e^+e^- \rightarrow P\gamma\gamma$, $P = \pi^0, \eta, \eta'$.

Second Belle II physics paper:
Abudinén et al. (Belle II Collaboration)
Phys. Rev. Lett. 125, 161806

Axion-Like Particles

$g_{a\gamma\gamma}$ and cross-section upper limit





$$\sigma_a = \frac{g^2_{a\gamma\gamma}\alpha_{QED}}{24}\left(1-\frac{m_a^2}{s}\right)^3$$

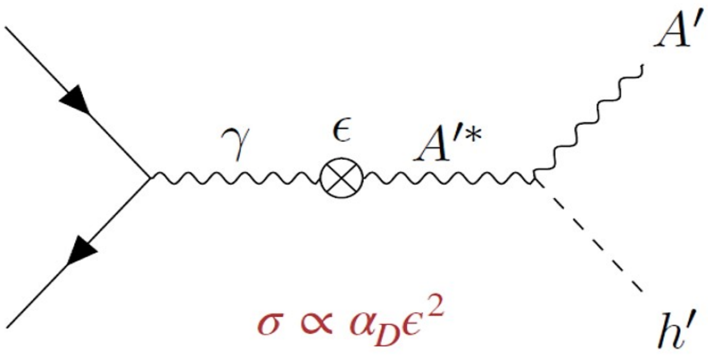
Measurement performed with 445 pb^{-1}

- These limits are the first obtained for the fully reconstructed three-photon final state;
- They are more restrictive than previous limits.

Dark Higgsstrahlung

Theory*

*Batell, Pospelov, Ritz, Phys. Rev. D 79, 115008 (2009)



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

The dark photon mass could be generated via a spontaneous symmetry breaking mechanism, adding a dark Higgs boson h' to the theory.

In a minimal scenario: a single dark photon A' and a single dark Higgs boson h'.

The h' could be produced in the Higgsstrahlung process, which is also sensitive to the dark sector coupling constant α_D.

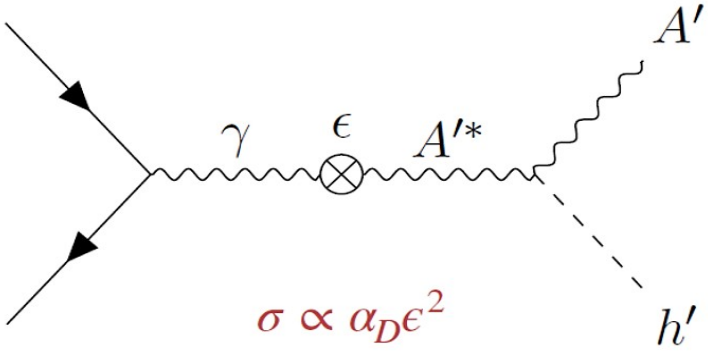
Different scenarios depending on the mass hypothesis.

We focus on the case: $m_{h'} < m_{A'}$ with invisible h', up to now only investigated by KLOE.

(Phys.Lett.B 747 (2015) 365-372)

Dark Higgsstrahlung

Experimental signature

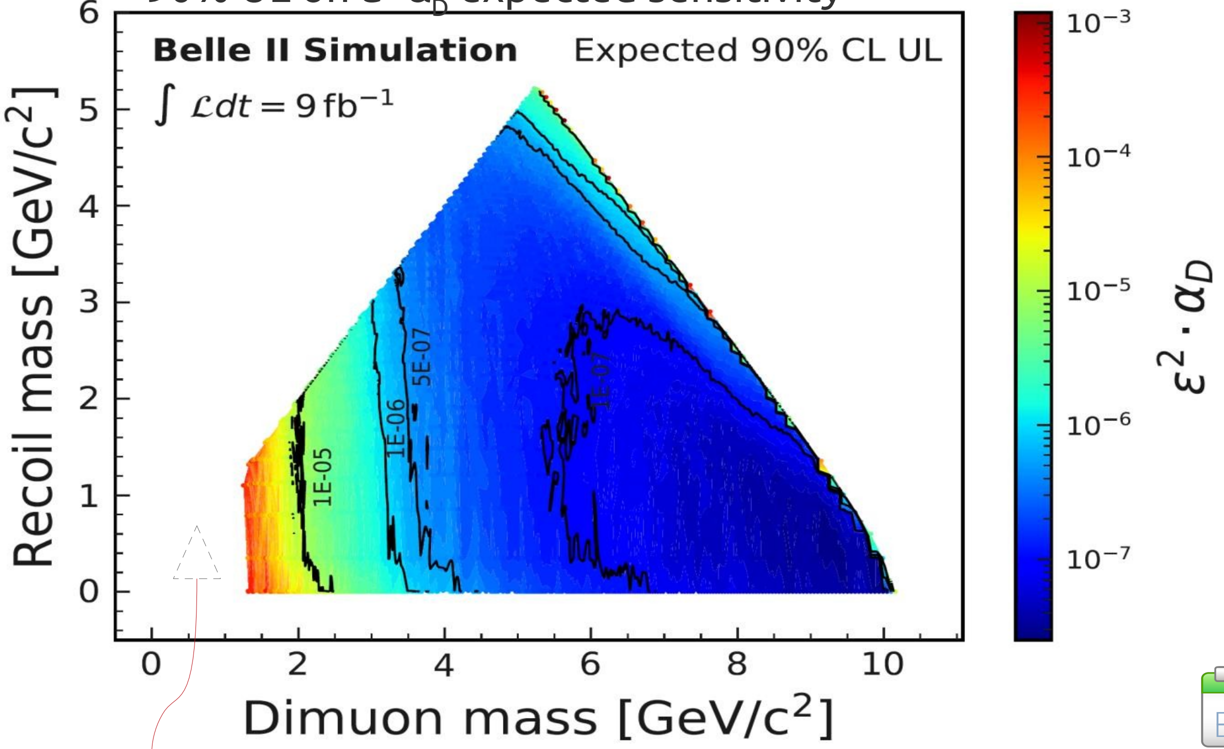


$e^+e^- \rightarrow A'^* \rightarrow h'A',\ A' \rightarrow \mu^+\mu^-$

Dark Higgsstrahlung

Expected sensitivity

90% UL on ε^2 α_D expected sensitivity



KLOE
(Phys.Lett.B 747 (2015) 365-372)

Very promising results even with 9 fb^{-1}.

- Accessing unconstrained regions, well beyond KLOE coverage;
- Probing non-trivial $\varepsilon^2\alpha_D$ couplings.

Analysis to be finalized shortly (by end 2021).

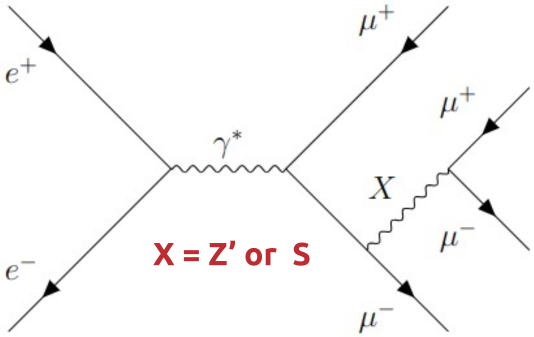
Dark Higgstrahlung

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

Search for a μμ resonance in ee → μμμμ

- Search for the process $\mathbf{e^+e^- \to \mu^+\mu^- X}$, with $\mathbf{X \to \mu^+\mu^-}$ **(X = Z', S)**
  → Look for a peak in the opposite charge di-muon mass distribution in $\mathbf{e^+e^- \to \mu^+\mu^-\mu^+\mu^-}$ events

- $\mathbf{(L_\mu - L_\tau)}$ **model** used as benchmark and then performances are checked for the **scalar case** [5]



Scalar particle coupling to muons through Yukawa-like interaction

Mainly proposed as a way to solve the muon $(g\text{-}2)_\mu$ anomaly

$$\mathcal{L} \supset g_S S \bar{\mu}\mu$$

Coupling constant:
induces a shift in
$\Delta a_\mu = a_\mu^{exp} - a_\mu^{theory}$

If $m_S > 2m_\mu$ the only tree-level decay channel is $S \to \mu\mu$
($S \to \nu\bar{\nu}$, $\gamma\gamma$ also are possible at one loop level, but highly suppressed)

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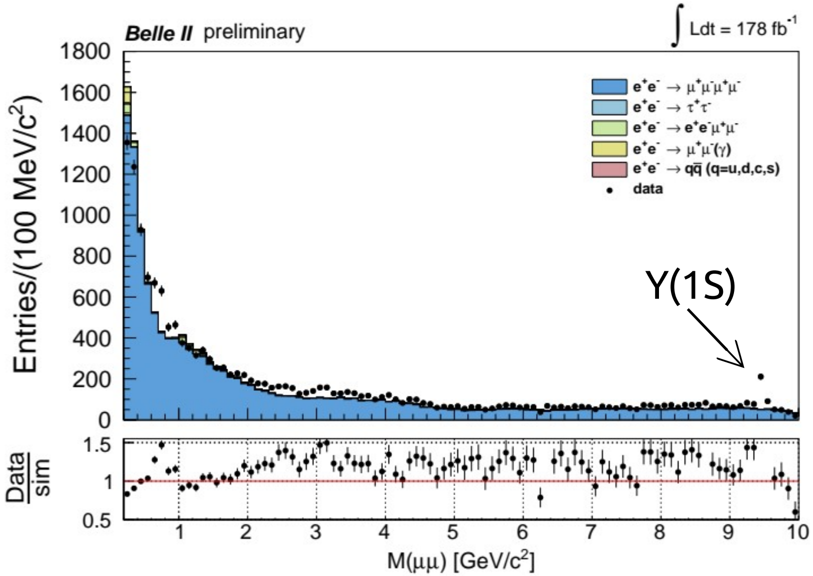
Search for a μμ resonance in ee → μμμμ

- Events selected have **4 charged particles:**
  - zero charge
  - at least **three identified as muons**
  - M(4tracks) ~ $\sqrt{s}/c^2$
  - no extra energy

- Main SM background contributions:
  1) $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$
  2) $e^+e^- \to e^+e^-\mu^+\mu^-$
  3) $e^+e^- \to \mu^+\mu^-(\gamma)$



→ **Multi-Layer Perceptron (MLP)-based background suppression**
Signal over background discrimination relying on a few variables sensitive the signal features:

(a) Presence of a μμ resonance
(b) Production mechanism

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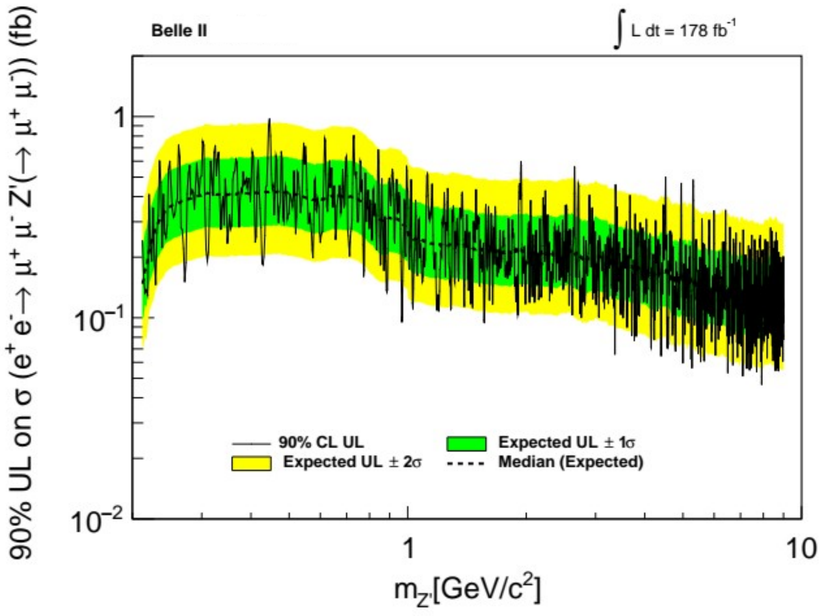
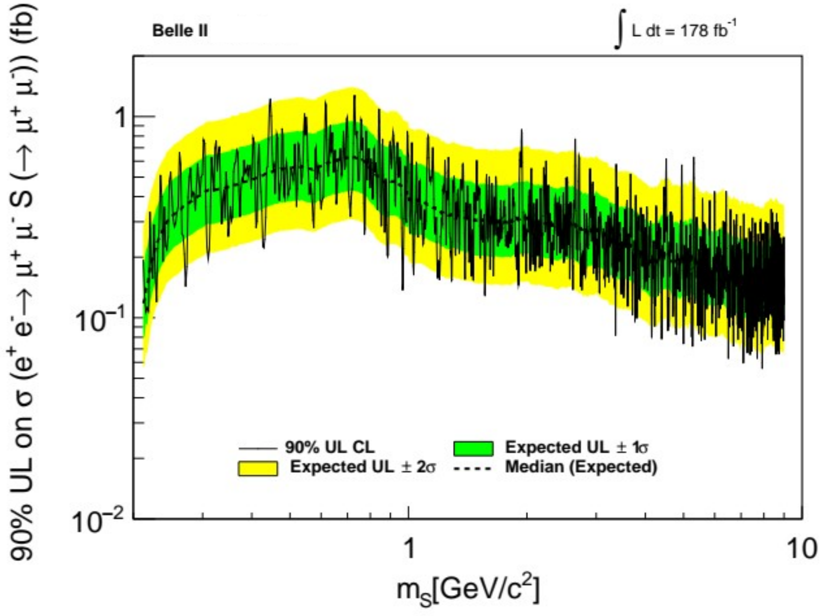
Search for a μμ resonance in ee → μμμμ

- **No significant excess observed in 178 fb^{-1}**
  → 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*





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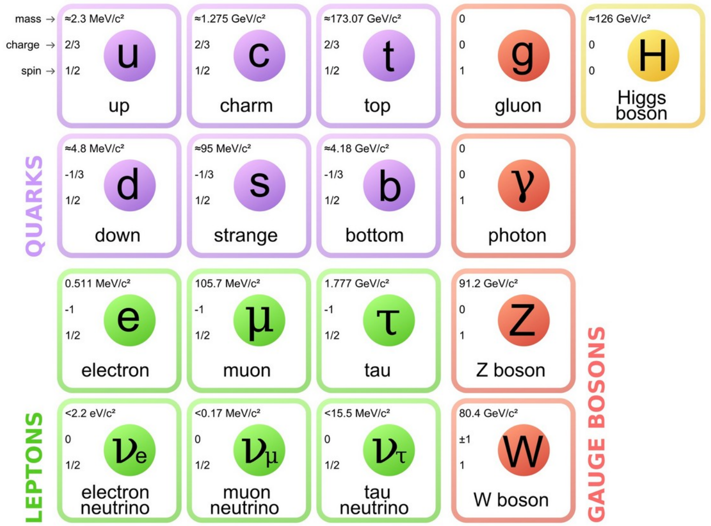
Standard Model: a successful theory

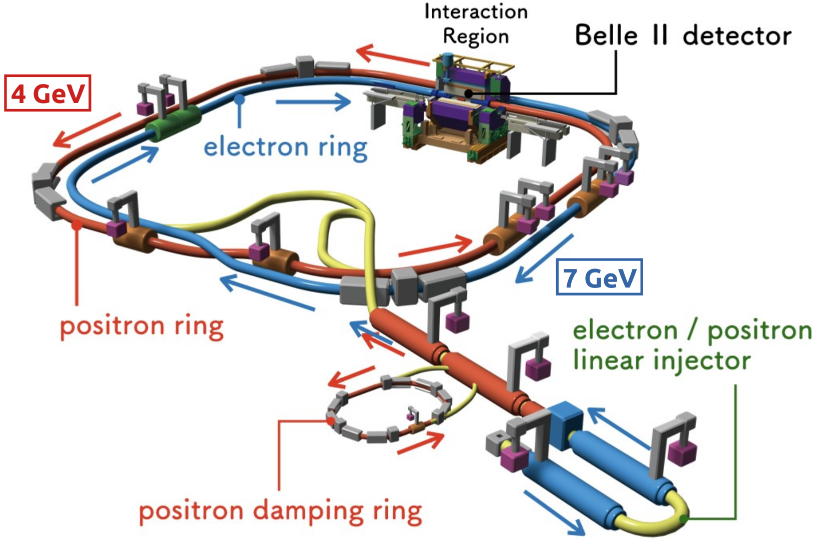
- the Standard Model (SM) is the best tested theory of nature at fundamental level describing particles ad their interactions:
  - the elementary **fermions and bosons** have been observed and their properties measured
  - the **quark model** predicts the vast majority of observed bound states, mesons and baryons



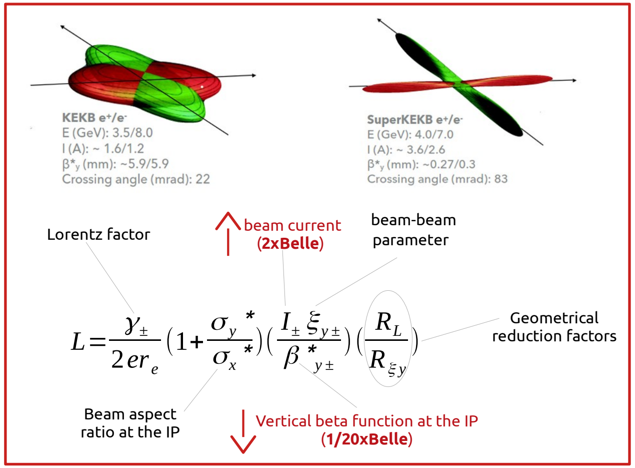
  - **interactions** between mesons, baryons and lepton are predicted with a precision of $\mathcal{O}(1\%)$
  - hundreds of **observables** (branching ratios, CP violation parameters, asymmetries, …) are measured to be consistent with the theory predictions

SuperKEKB: a second generation B-factory

- SuperKEKB is a 2nd generation asymmetric e^+e^- collider at the Υ(4S) energy located at **Tsukuba, Japan**
- **target instantaneous luminosity is 6×10^{35} $cm^{-2}s^{-1}$ (x30 KEKB/Belle)**



nano-beam scheme

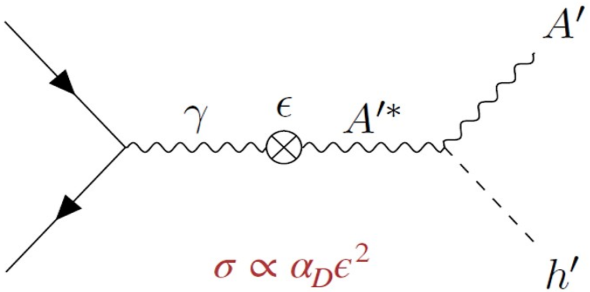


$$L=\frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\xi_{y\pm}}{\beta_{y\pm}^*}\right)\left(\frac{R_L}{R_{\xi y}}\right)$$

Dark Higgstrahlung

- The dark photon mass could be generated via a spontaneous symmetry breaking mechanism, adding a dark Higgs boson h' to the theory.

- The h' could be produced in the Higgsstrahlung process, which is also sensitive to the dark sector coupling constant α_D.



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

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Dark Matter

What do we know about dark matter:

1. It exists
2. It is dark

Existence of dark matter had been established in astrophysics:

- Rotation curve of a disk galaxy
- Spatial distributions of luminous baryonic total matter in a collision of galaxy clusters
- CMB

Dark Matter

What do we know about dark matter:

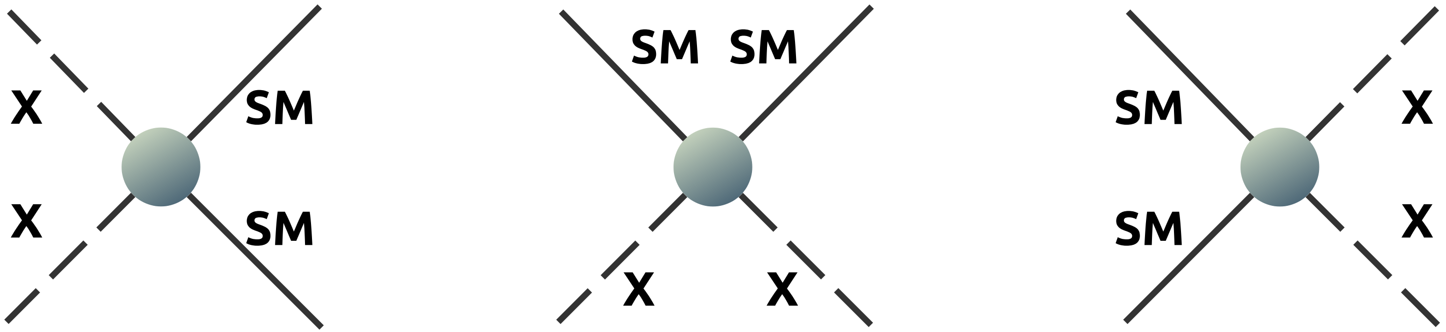
1. It exists
2. It is dark

Dark matter does not interact with the electromagnetic force:

- No absorption
- No reflection
- No emission

Dark matter is one of the most compelling reasons for new physics

Dark Matter: three ways of detecting it

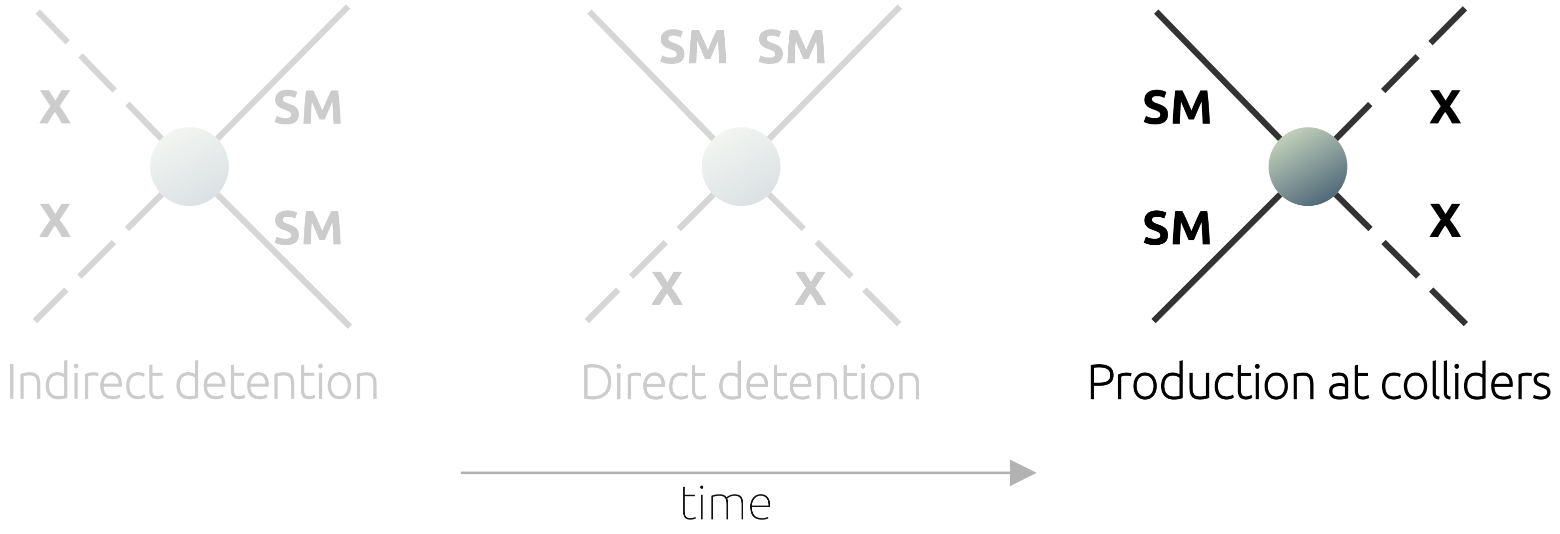


Indirect detention

Direct detention

Production at colliders

Dark Matter: three ways of detecting it



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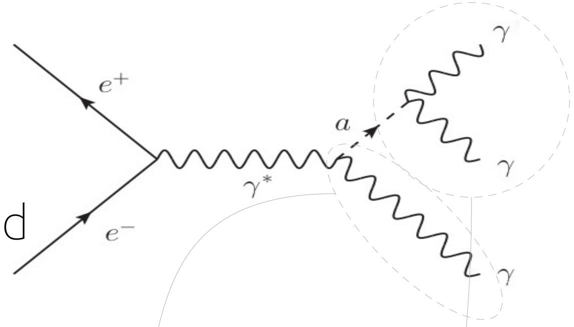
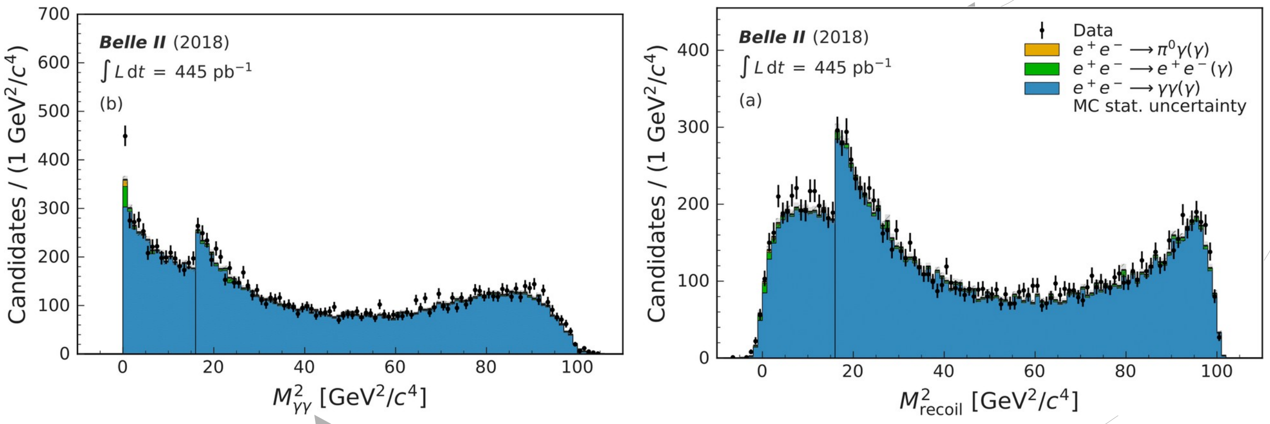
Search for ALP in $e^+e^- \rightarrow \gamma\gamma\gamma$

[7] Annual Review of Nuclear and Particle Science

- ALPs[7] predominantly **coupling to photons ($g_{a\gamma\gamma}$)** with $B(a \rightarrow \gamma\gamma) \approx 100\%$
- Events with at least three photon candidates are selected
  → photon candidates reconstructed from ECL clusters
  → looking for an excess in the diphoton or in the recoil squared invariant mass distribution





F. Abudinén et al. (Belle II Collaboration) Phys. Rev. Lett. 125, 161806

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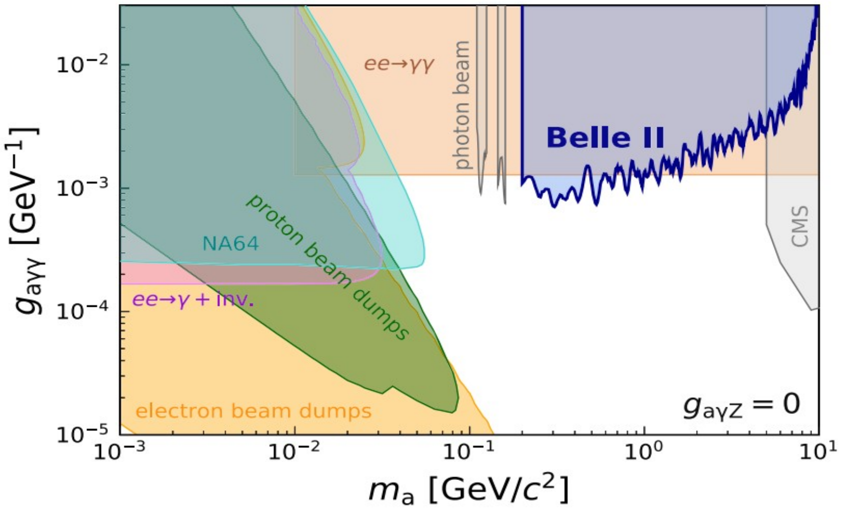
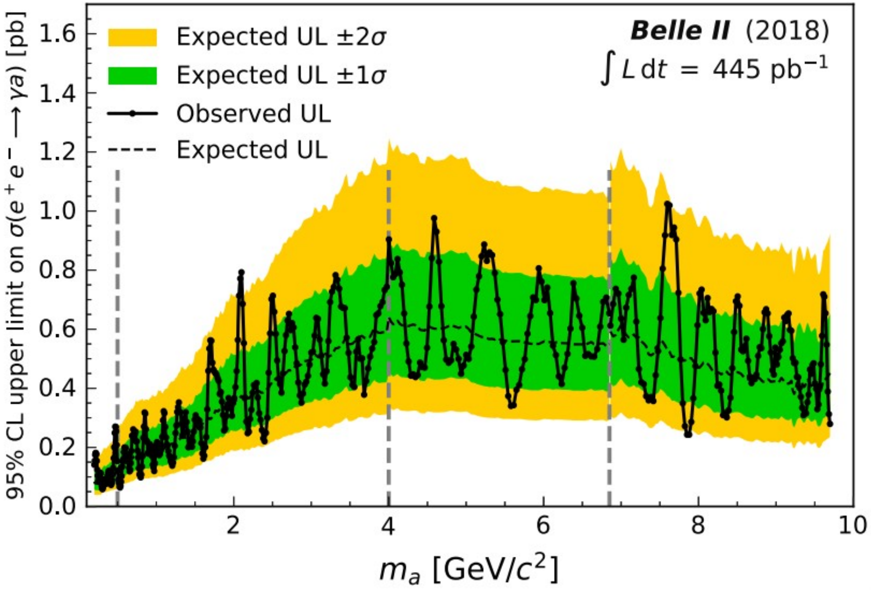
Search for ALP in $e^+e^- \rightarrow \gamma\gamma\gamma$

- No signal found in **445 pb⁻¹** of data
- First limits on $g_{a\gamma\gamma}$ set using the <u>fully reconstructed three-photon final state</u>

$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{QED}}{24} \left(1 - \frac{m_a^2}{s}\right)^3$$





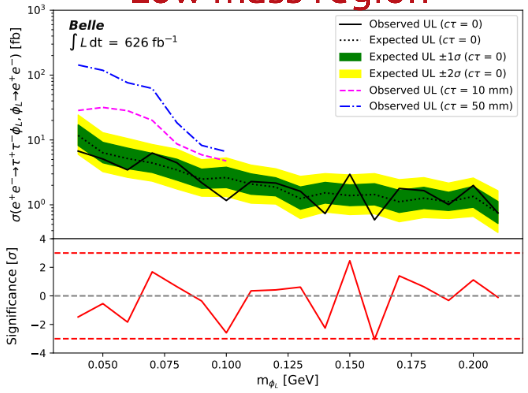
F. Abudinén et al. (Belle II Collaboration) Phys. Rev. Lett. 125, 161806

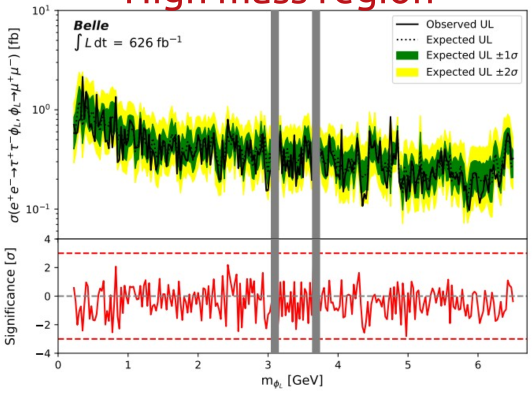
Search for a dark leptophilic scalar in τ decays

- No significant excess observed in 626 fb^{-1} in all mass region

Low mass region

High mass region

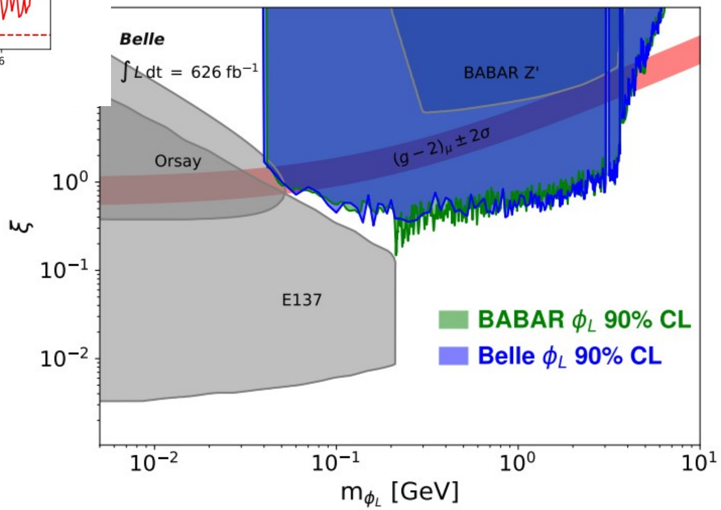




- 90 % CL UL on ξ vs m(Φ_l)

→ comparable or more stringent limits than BaBar (Phys. Rev. Lett. 125, 181801, 514 fb^{-1})

→ exclude a wide range of parameter space of the model favored by $(g-2)_\mu$



D. Biswas et al. (Belle Collaboration) Phys. Rev. D 109, 032002

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