Z' analyses at Belle II

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for the Belle II experiment

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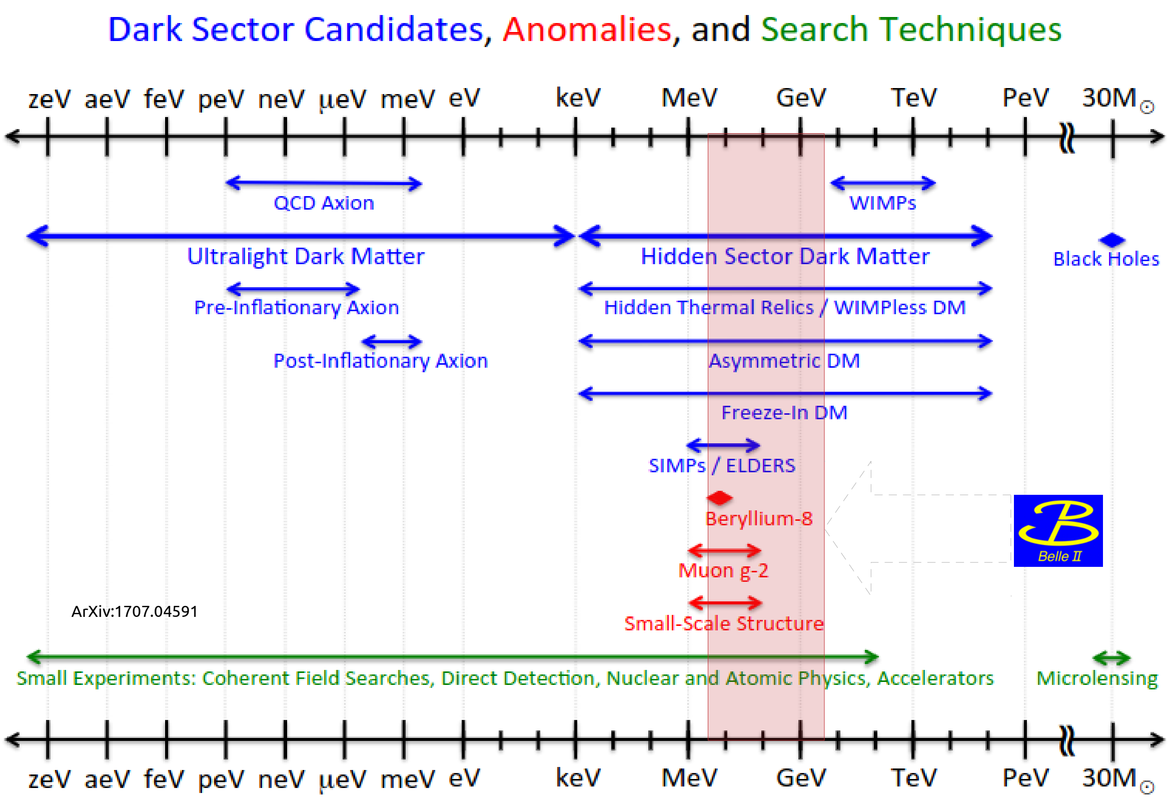
Introduction

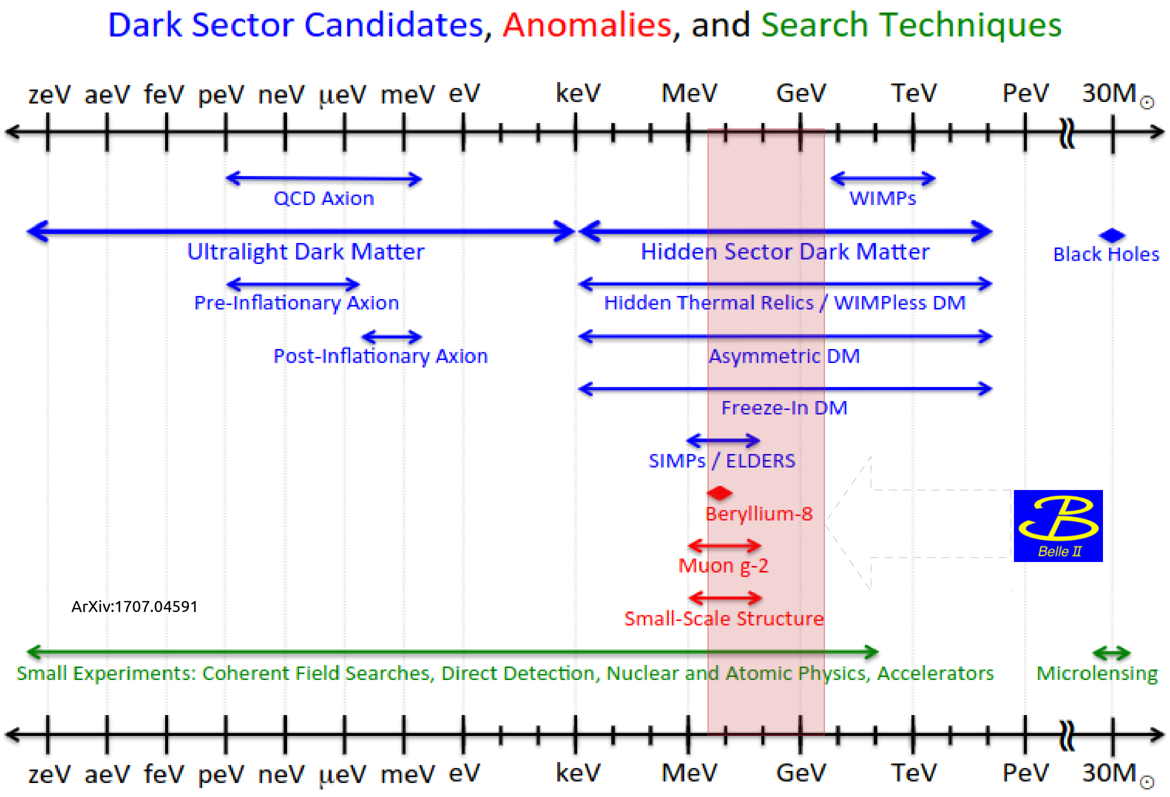
Light Dark Matter at B-factories



- **Dark Matter** is one of the most compelling reasons for **New Physics**
- 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 X**:

1. Vector portal
   Dark Photons, Z' bosons
2. Pseudo-scalar portal
   Axion Like Particles (ALPs)
3. Scalar portal
   Dark higgs/Scalars
4. Neutrino portal
   Sterile Neutrinos

Light Dark Matter at B-factories



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See L. Zani presentation

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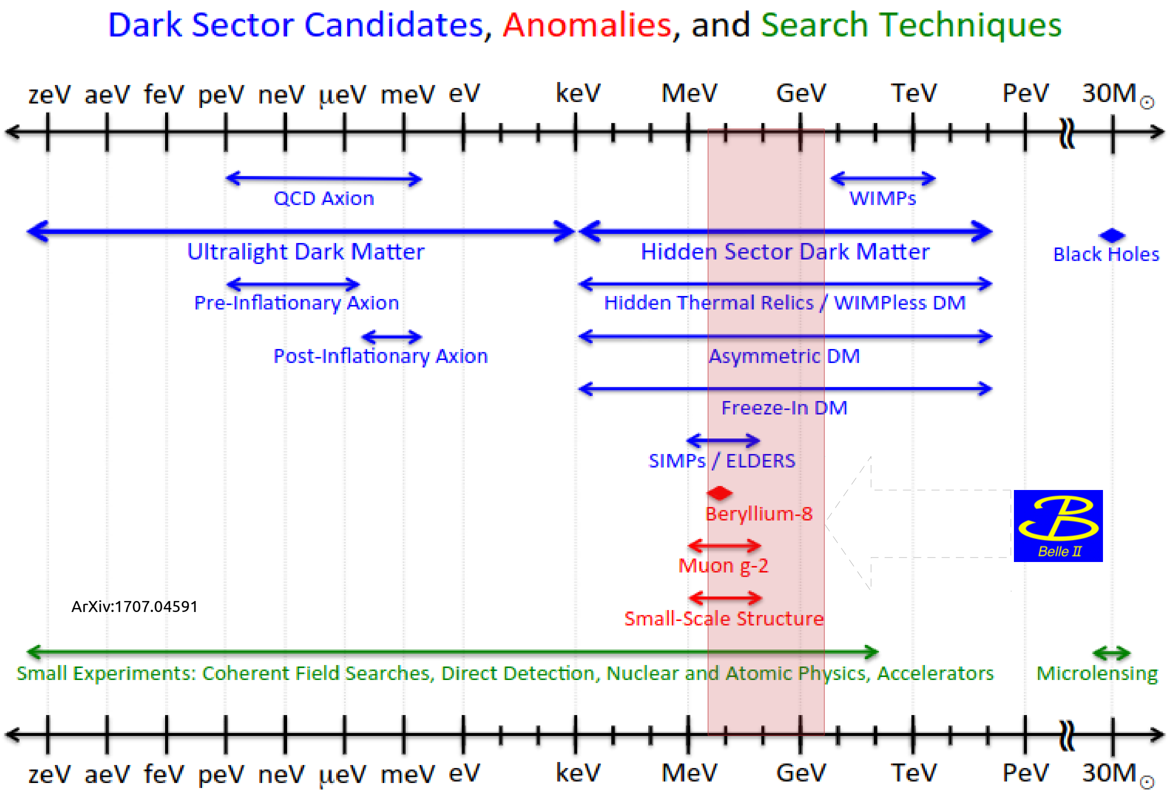
Light Dark Matter at B-factories



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This presentation

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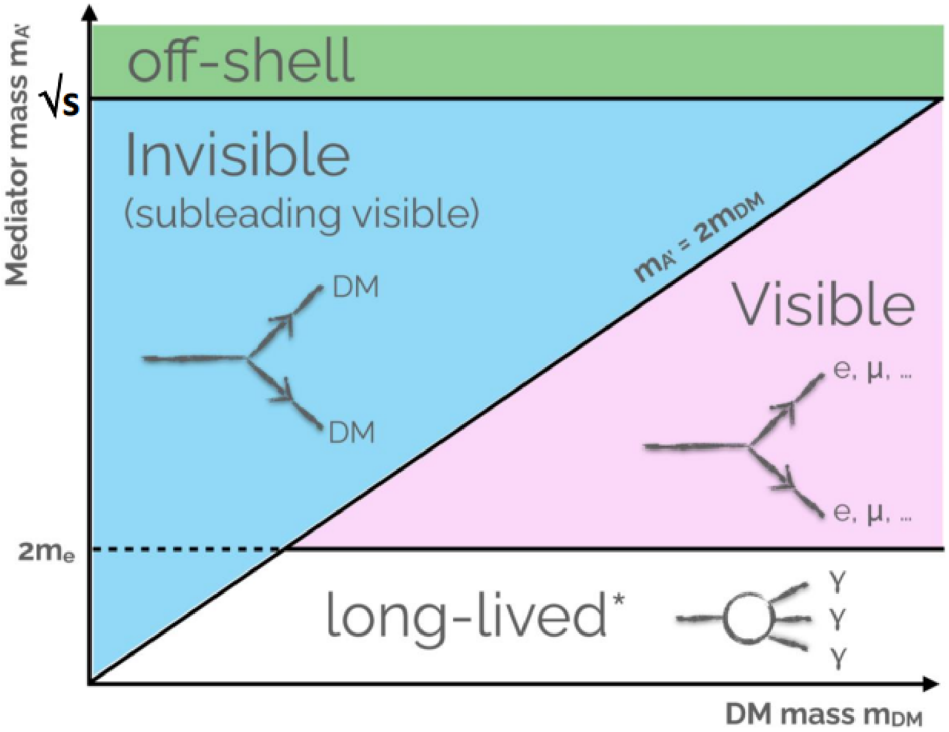
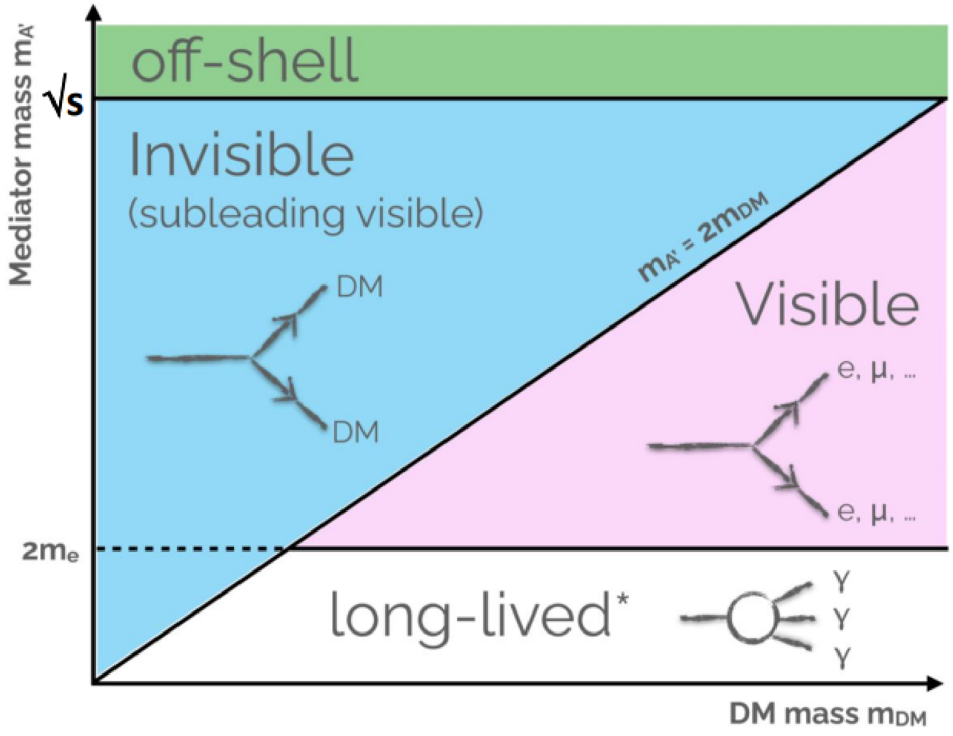
Light Dark Matter possible signatures



- Once produced, the mediator can have three different types of decays:
  1. Invisible decays
  2. Leptonic decays
  3. Hadronic decays

Light Dark Matter possible signatures



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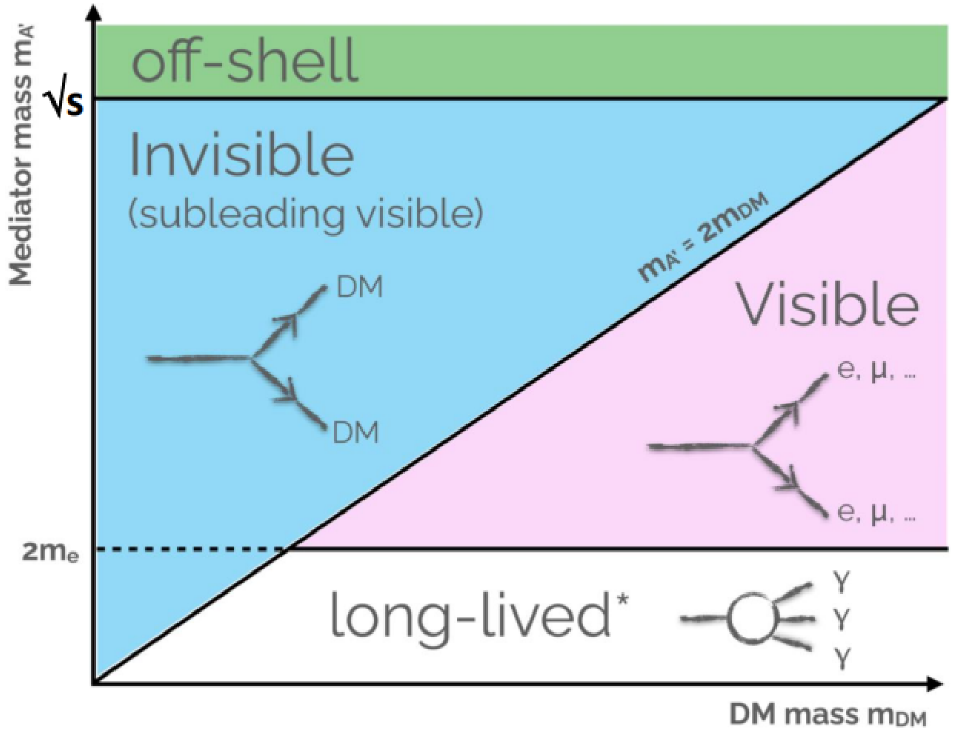
Light Dark Matter possible signatures



- In this presentation:
  - Once produced, the mediator can have three different types of decays:
    1. Invisible decays: **Z' → inv.**
    2. Leptonic decays: **Z' → μμ**
    3. Hadronic decays **Z' → ττ**

+ some reinterpretations

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Dark Sector @ Belle II

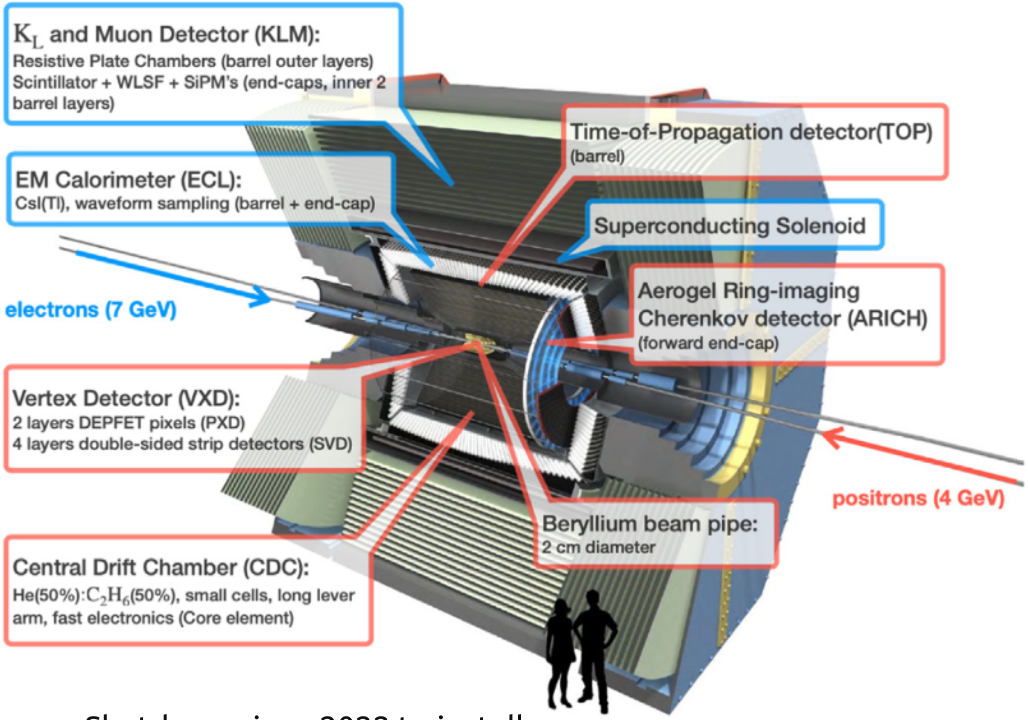
* Dedicated talk from E. Graziani

- Signature-based

- Advantages from the **low particle multiplicty** at lepton colliders + **hermetic detector**:
  → Belle II at SuperKEKB asymmetric e^+e^- collider

  - running at 10.58 GeV, well-known **initial condition**
  - efficient reconstruction of **neutrals**
  - specific low-multiplicity **triggers (not present at Belle)**
  - excellent particle identification system

Unprecedented luminosity
4.7×10^{34} cm^{-2} s^{-1}



- Shutdown since 2022 to install two-layer pixel detector
- 424 fb^{-1} collected to date
- Data taking resume by end of 2023

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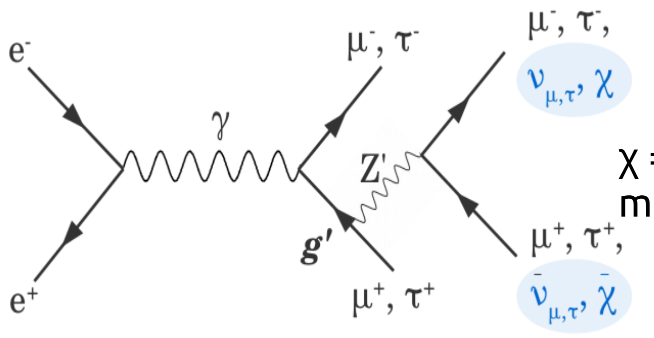
Z’ analyses at Belle II

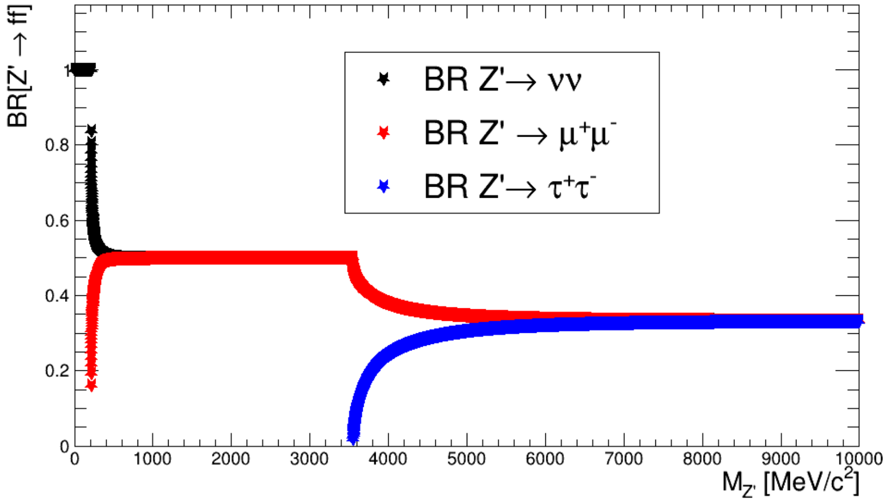
The $L_\mu - L_\tau$ model

[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



- In Belle II we search for the processes:
  $e^+e^- \to \mu^+\mu^- Z'$
  - invisible
  - μμ
  - ττ

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Search for an invisible Z'

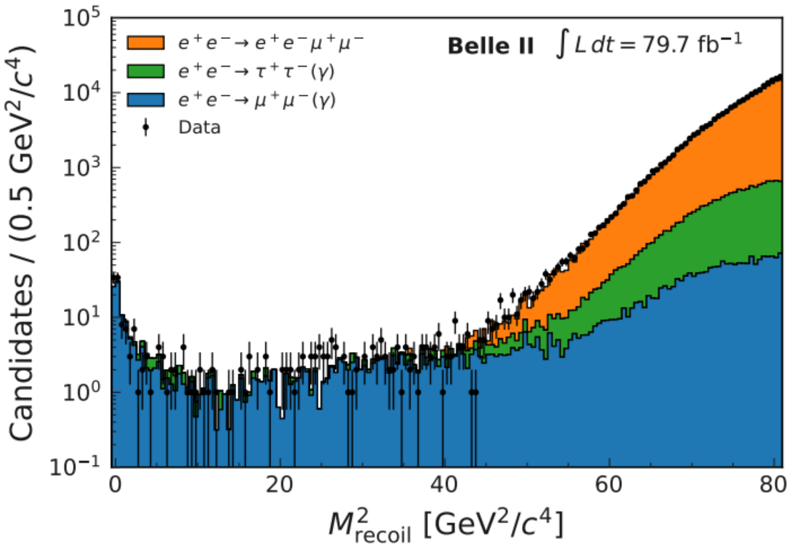
PRL 130, 231801

- Search for the process: **$e^+e^- \to \mu^+\mu^- Z' \to$ invisible**
  → Two possible interpretations:
  1) Vanilla, BF($Z' \to \nu\bar{\nu}$) ~ 33-100%
  2) Full invisible, BF($Z' \to \chi\bar{\chi}$) ~ 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:
  1) $e^+e^- \to e^+e^-\mu^+\mu^-$
  2) $e^+e^- \to \tau^+\tau^-(\gamma)$ (especially with both $\tau \to \mu$)
  3) $e^+e^- \to \mu^+\mu^-(\gamma)$

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



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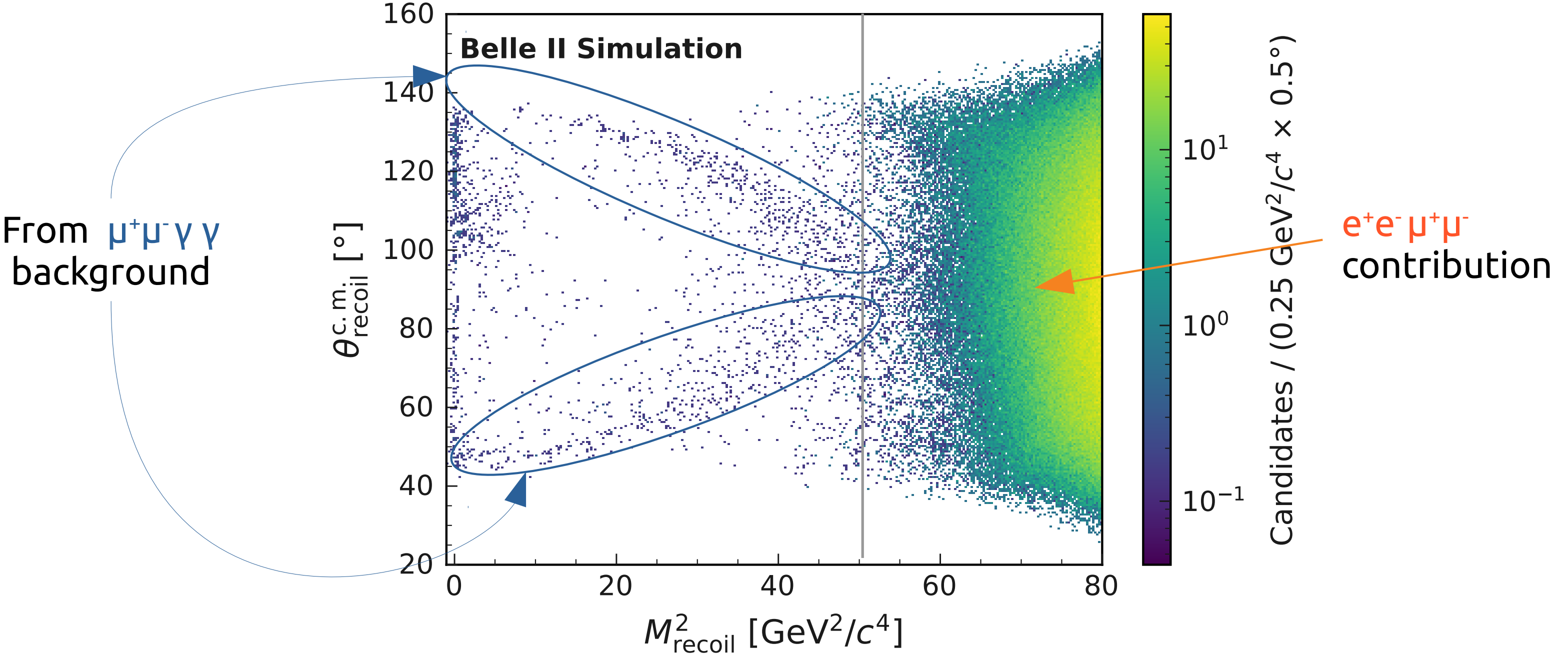
Search for an invisible Z'

- 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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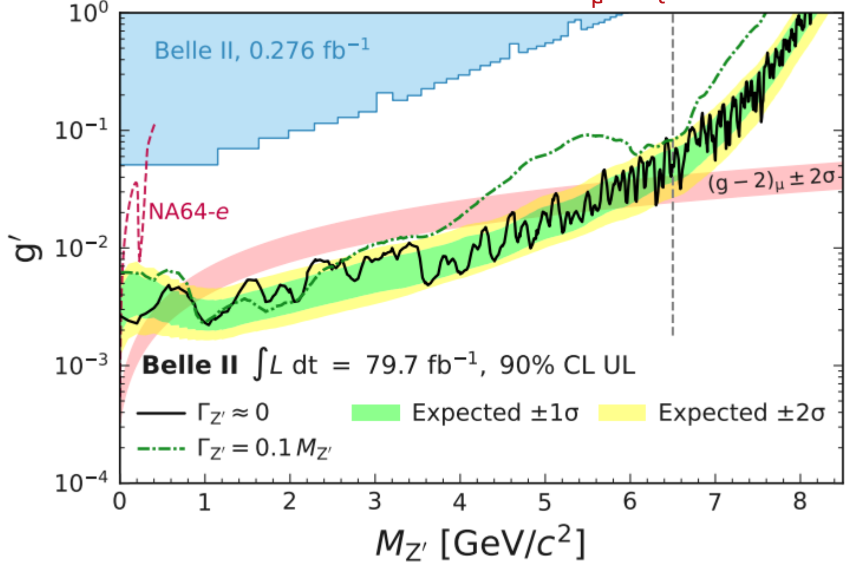
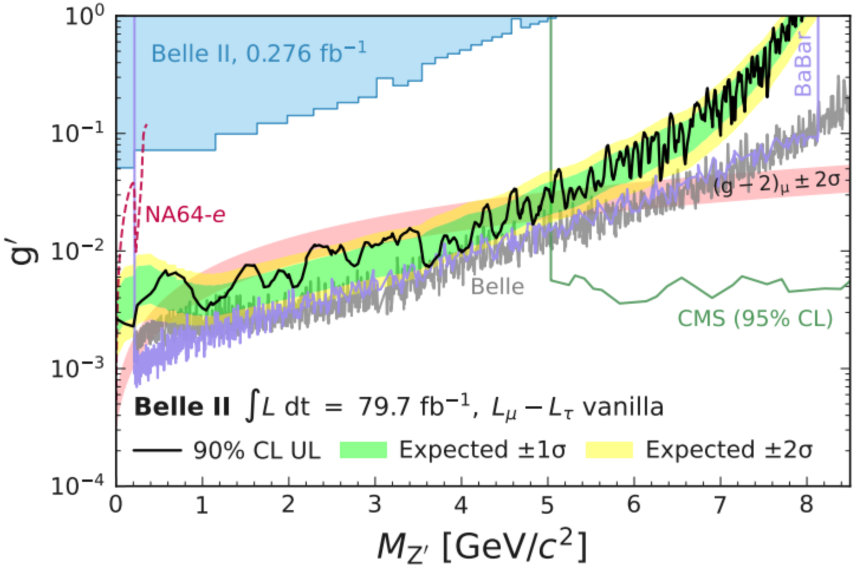
Search for an invisible Z’

- **No excess found in 79.7 fb^{-1}**
  → 90% CL upper limits on **$\sigma(e^+e^- \to \mu^+\mu^- Z', Z' \to$ invisible)** 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



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Search for a ττ resonance in ee → μμττ

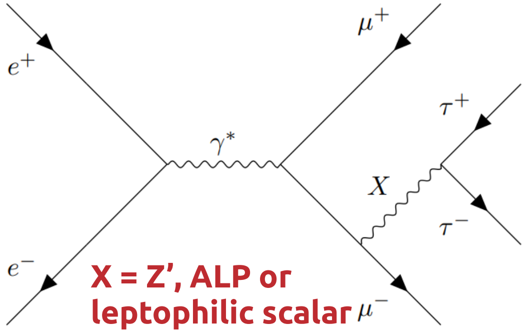
PRL 131, 121802 (2023)

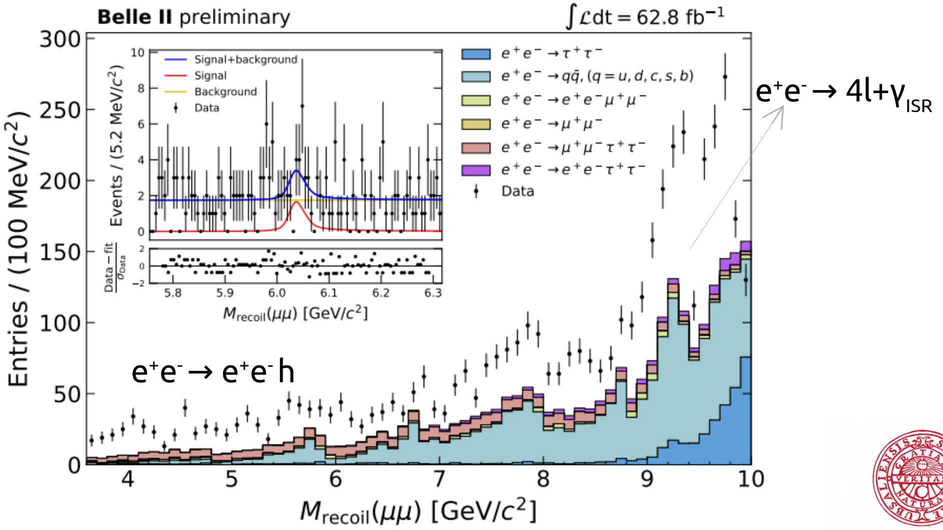
- Search for a **di-tau resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$** as a peak in the recoil against two muons

- Reconstruct **τ decays to one-charged particle** (+nh⁰)
  → 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 them c.m. energy

- **Background suppression exploits features of kinematic variables in the signal**
  (*X* arising from a final state radiation, system recoiling against the 2 muons is a tau pair)

- Discrepancies between data and simulation due to contributions from non-simulated/unmodeled processes





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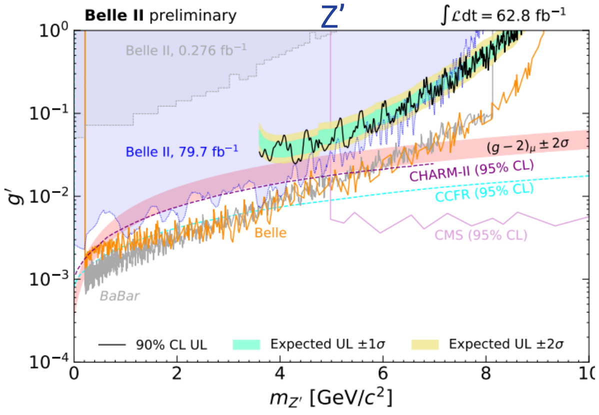
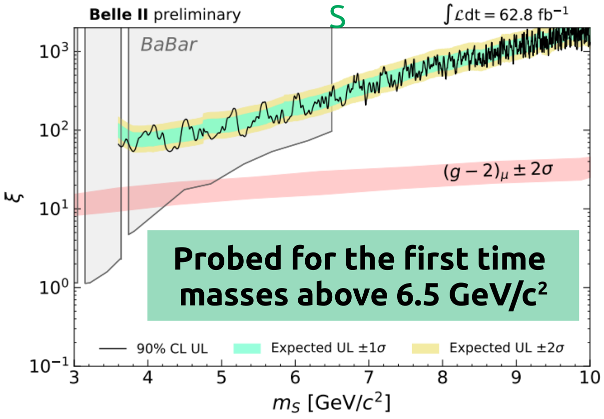
[2] W. Altmannshofer et. al. JHEP 12 (2016) 106
[3] B. Batell, N. Lange, D. McKeen, M. Pospelov, and A. Ritz, Phys. Rev. D 95, 075003 (2017)
[4] M. Bauer, M. Neubert, and A. Thamm, J. High Energy Phys. 2017, 44 (2017)

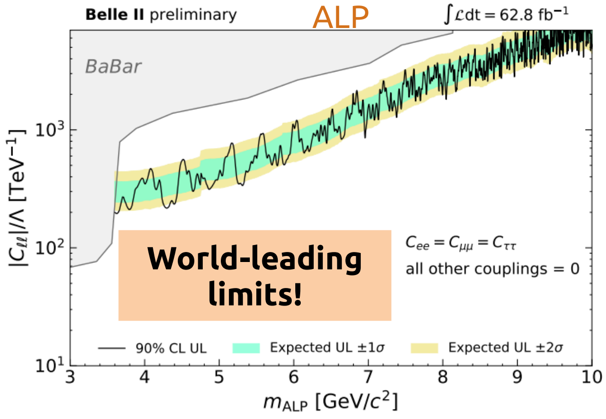
Search for a ττ resonance in ee → μμττ

- **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:





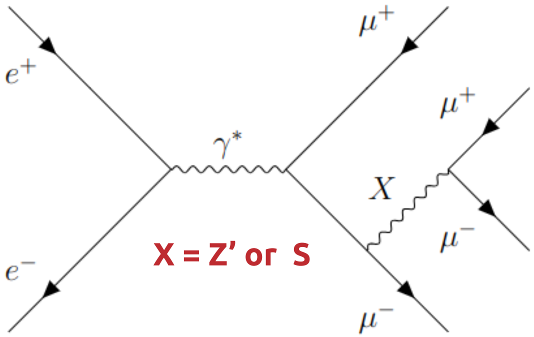


[5] P. Harris, P. Schuster, and J. Zupan, arXiv:2207.08990 [hep-ph];
R. Capdevilla, D. Curtin, Y. Kahn, and G. Krnjaic, J. High Energy Phys. 04 (2022) 129

Search for a μμ resonance in ee → μμμμ

- Search for the process **$e^+e^- \to \mu^+\mu^- X$**, with **$X \to \mu^+\mu^-$ (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_μ - L_τ) 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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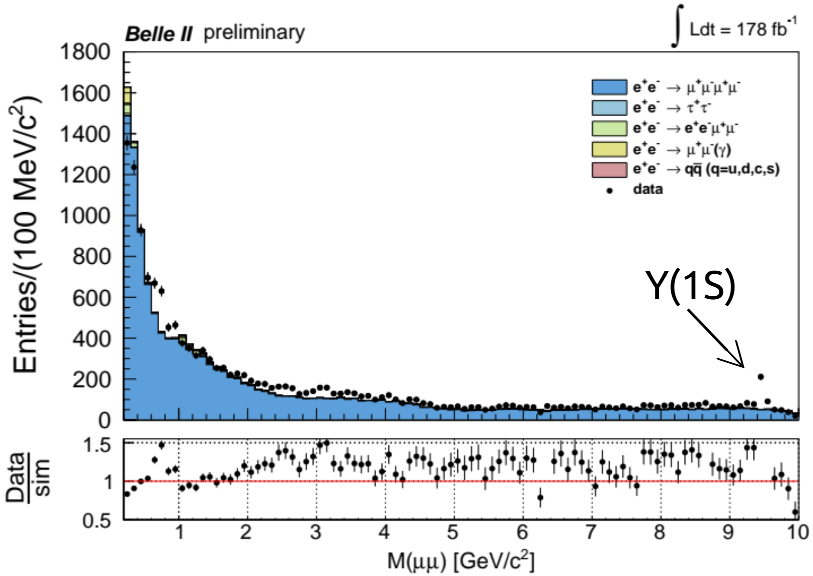
Search for a μμ resonance in ee → μμμμ

- 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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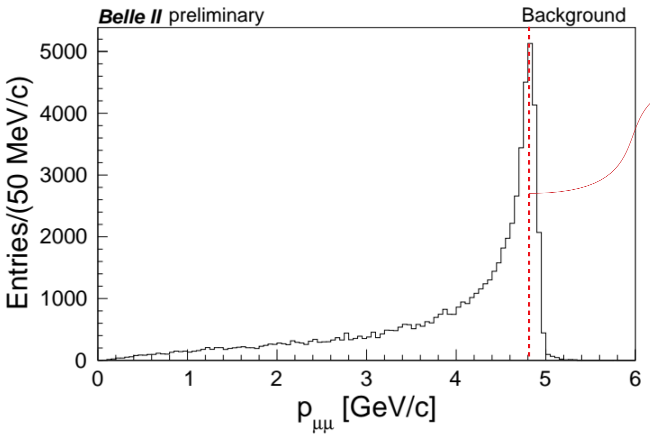
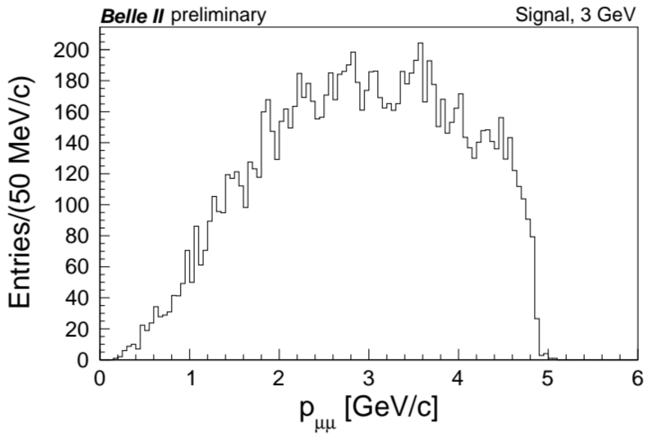
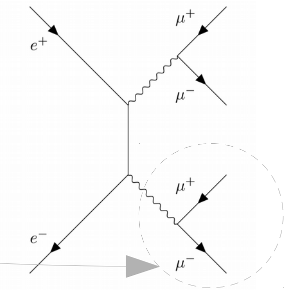
Search for a μμ resonance in ee → μμμμ





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%**

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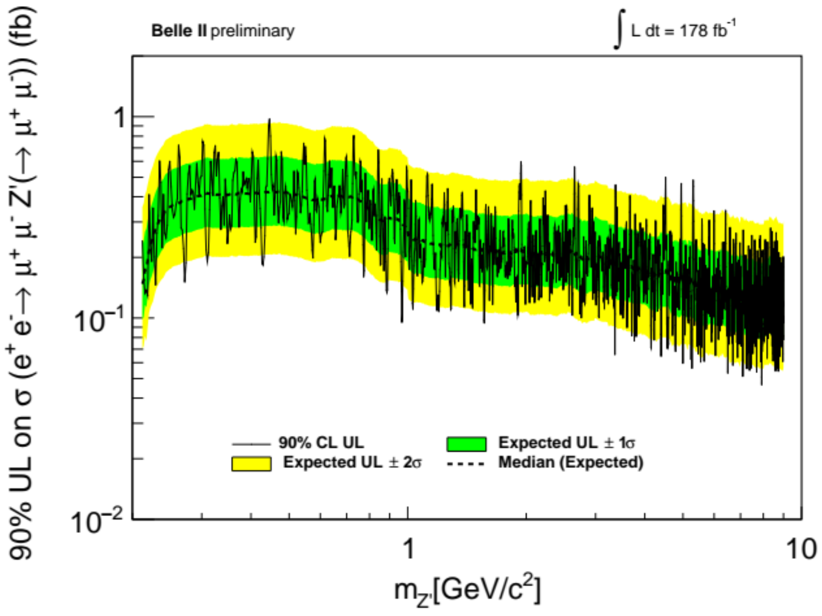
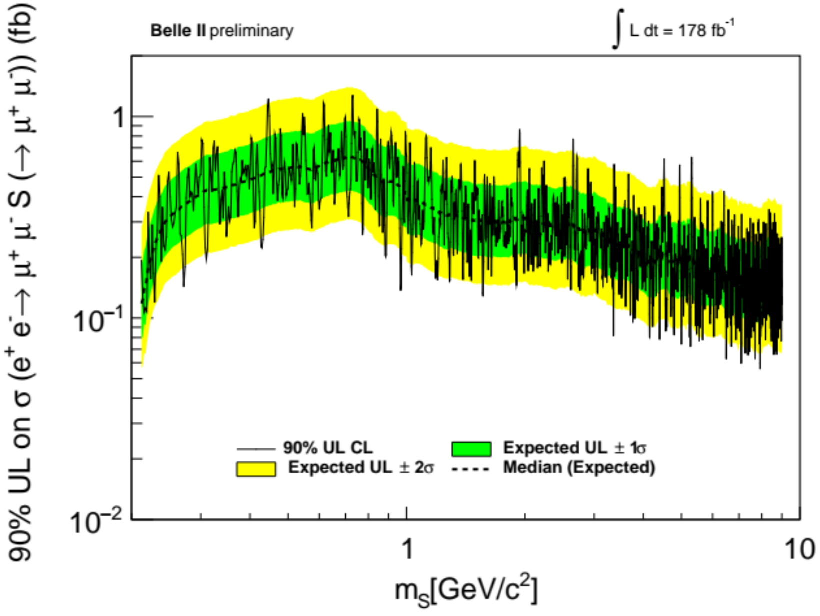
Search for a μμ resonance in ee → μμμμ

- **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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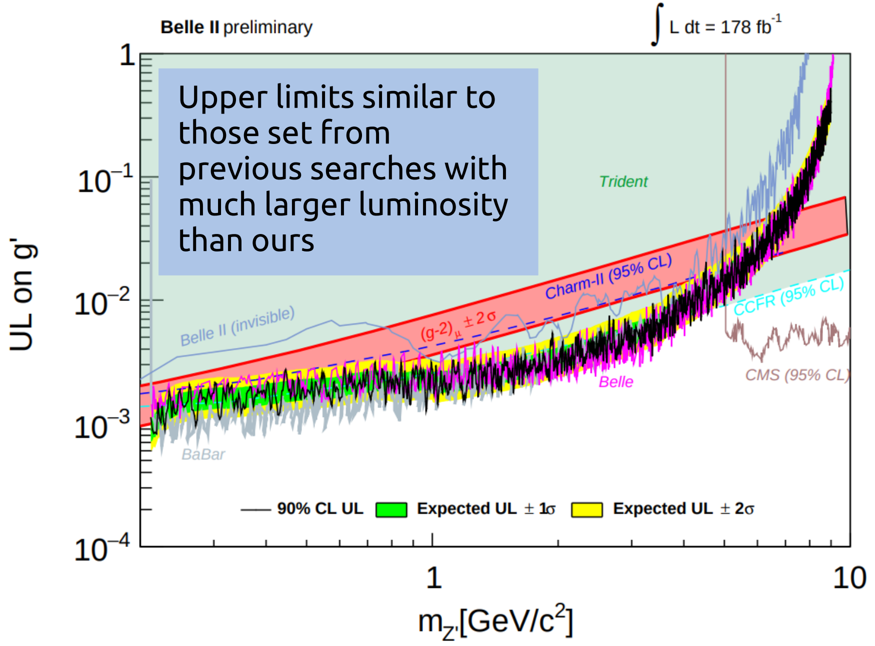
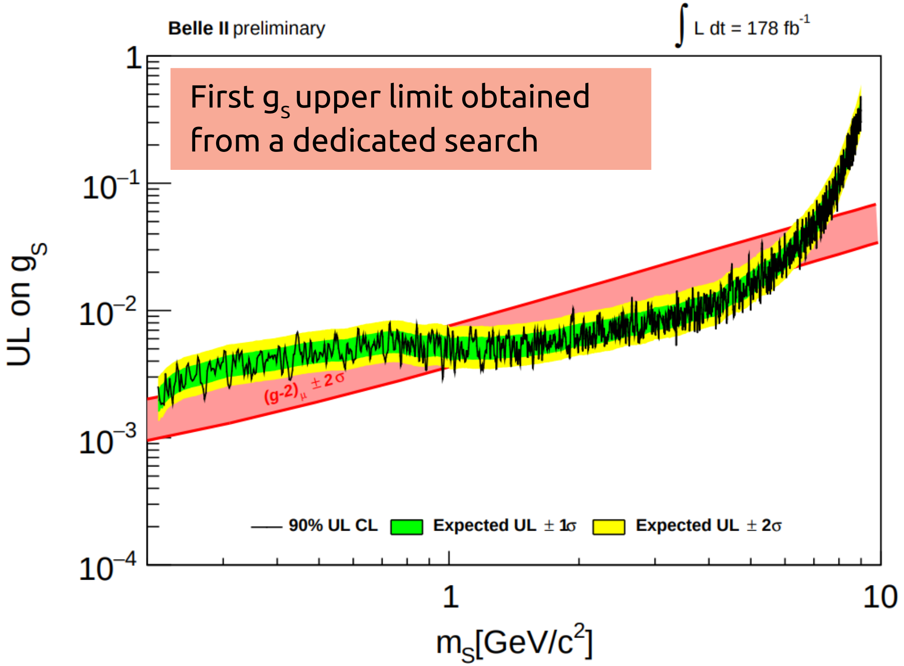
Search for a μμ resonance in ee → μμμμ

- **No significant excess observed in 178 fb^{-1}**
  → 90% CL upper limits on the process cross-section **σ(e^+e^- → X $\mu^+\mu^-$)** x **B(X → $\mu^+\mu^-$)**, 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]





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Conclusion

- Belle II/SuperKEKB is a **unique environment** to search for **light dark matter or mediators**

- **Excellent sensitivity** for dark sector searches

- **World's leading results** are obtained with a subset of the full available data

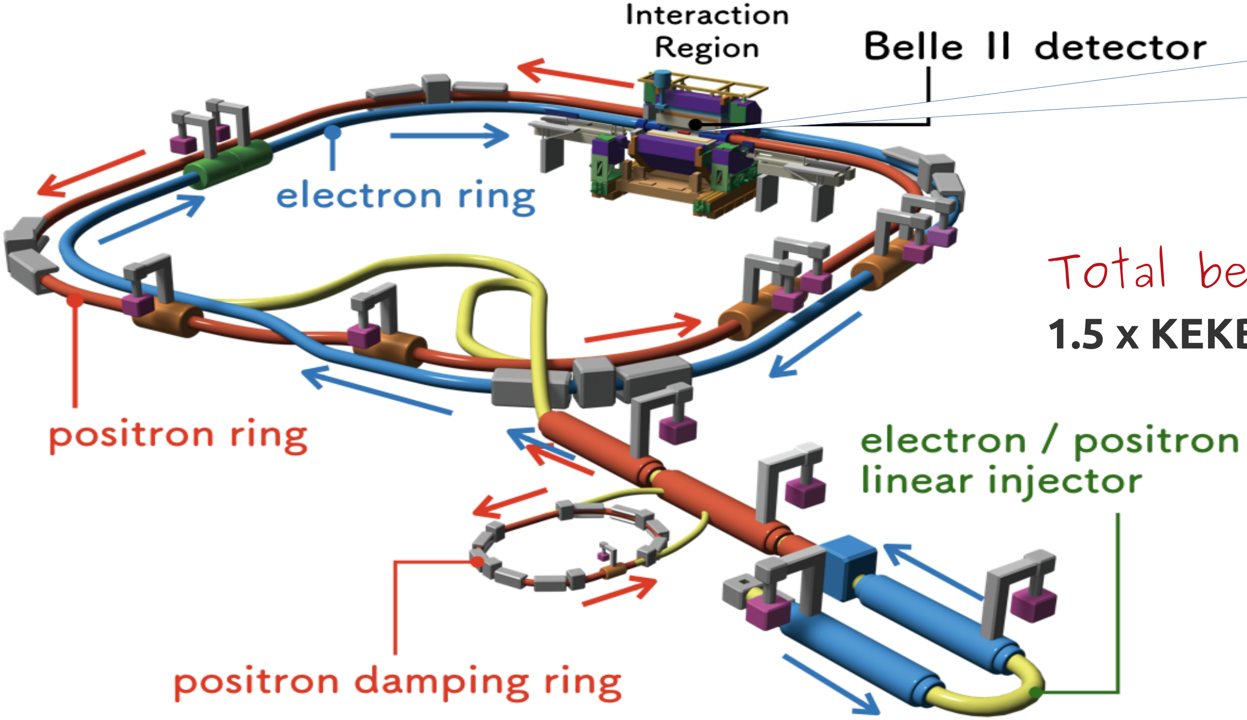
→ Search for invisible Z'
→ Search for visible Z' to muons (+ muonphilic scalar)
→ Search for visible Z' to taus (+ leptophilic scalar and ALP)

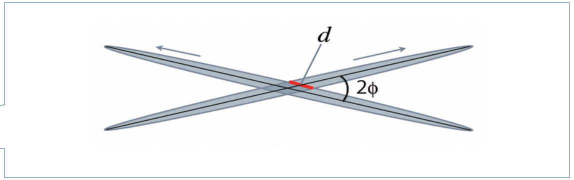
- 424 fb^{-1} recorded to date, **more results with higher statistics and improved analyses will be produced**

Thank you!

Backup

SuperKEKB





Vertical beam-beam parameter

Total beam current

1.5 x KEKB current

$$L = \frac{\gamma_{\pm}}{2 e r_e} \left(\frac{I_{\pm} \xi_{y\pm}}{\beta^*_{y\pm}} \right) \left(\frac{R_L}{R_{\xi y}} \right)$$

Beta function at the IP

20 times smaller than KEKB

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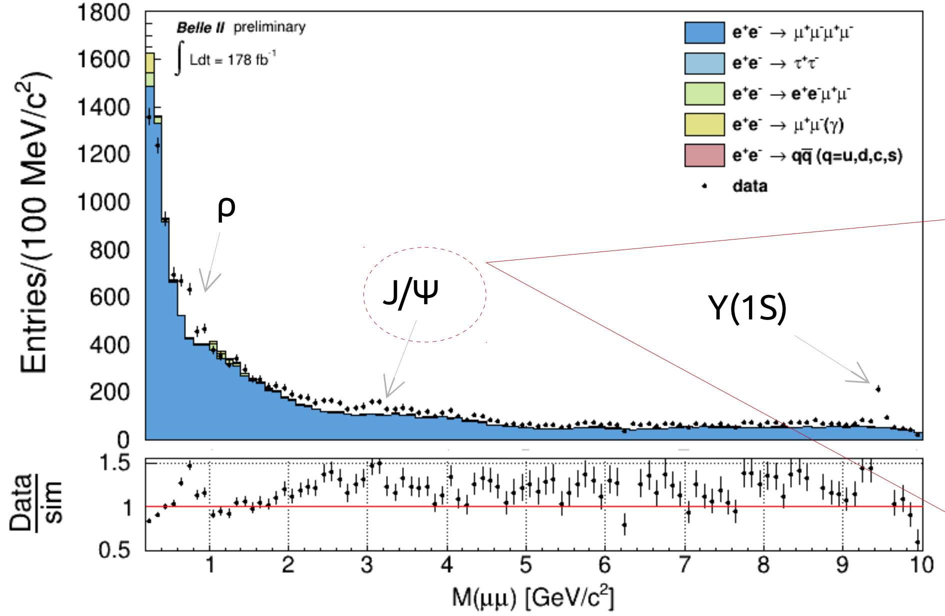
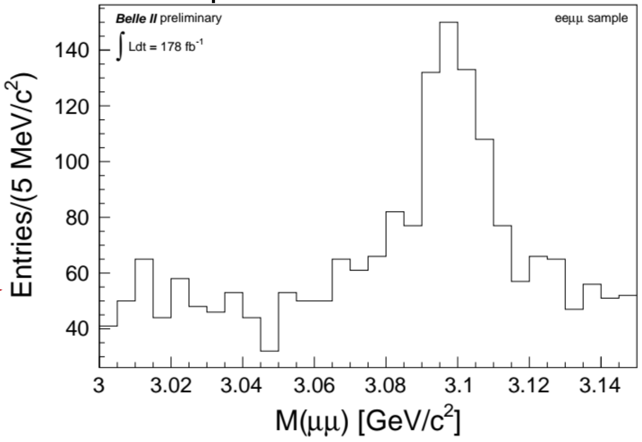
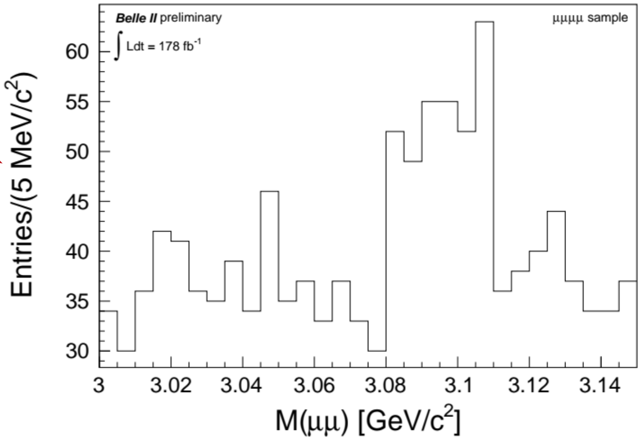
Search for a μμ resonance in ee → μμμμ: J/Ψ



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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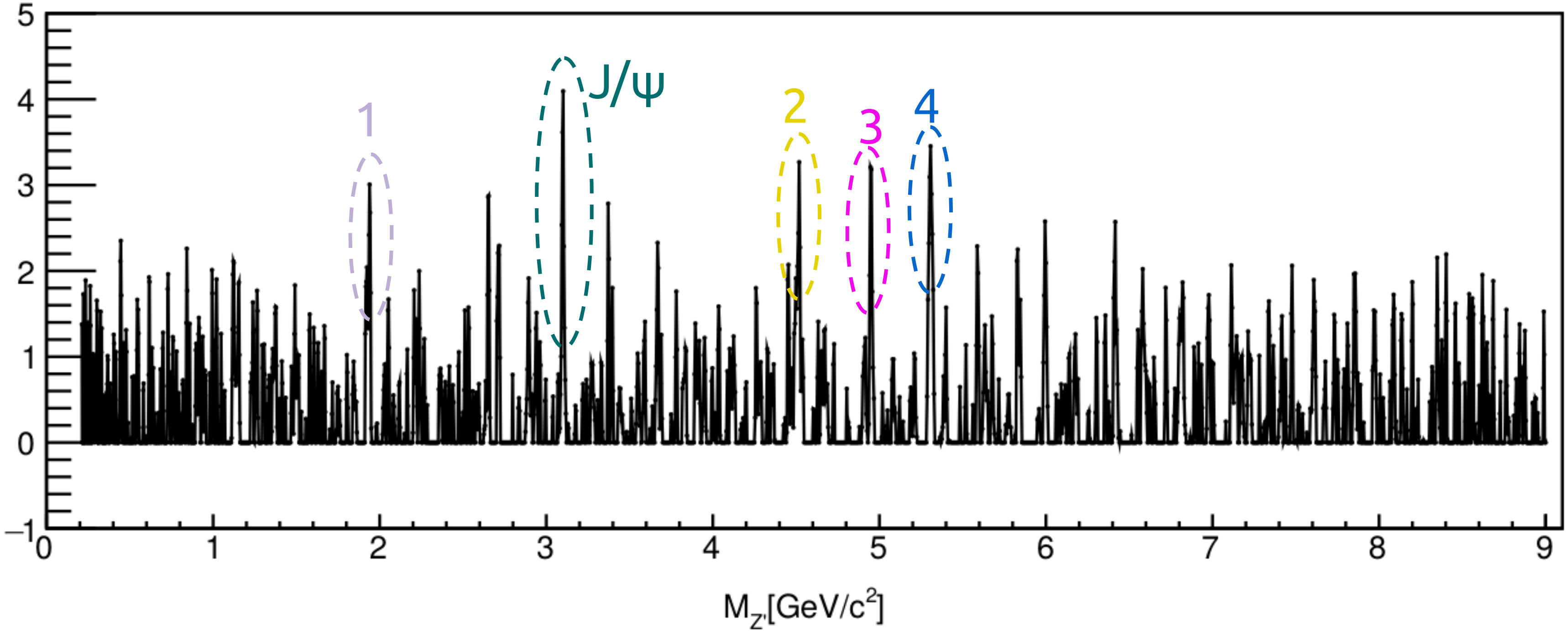
Search for a μμ resonance in ee → μμμμ



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

We extended the Z' search to the case of a muophilic dark scalar, *S*

- Scalar particle coupling through Yukawa-like interaction, only
- Mainly proposed as a way to solve the muon $(g\text{-}2)_\mu$ anomaly

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

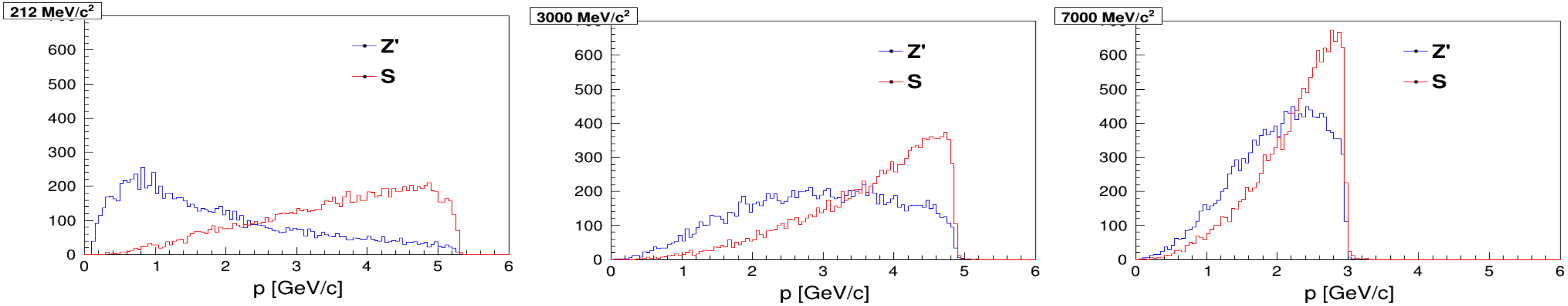
Coupling constant: induces a shift in $\Delta a_\mu = a_\mu^{exp} - a_\mu^{theory}$

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

We reinterpreted our result in terms of the dark scalar *S*, keeping all the steps of the analysis completely unaltered

1) *P. Harris, P. Schuster, J.Zupan, Snowmass White Paper: New flavors and rich structures in dark sectors*
2) *S. Gori, M. Williams, et al., Dark Sector Physics at High-Intensity Experiments*
3) *D. Forbes, C. HerwigNew Searches for Muonphilic Particles at Proton Beam Dump Spectrometers*
4) *R. Capdevilla, D. Curtin et al., Systematically testing singlet models for (g − 2)μ*

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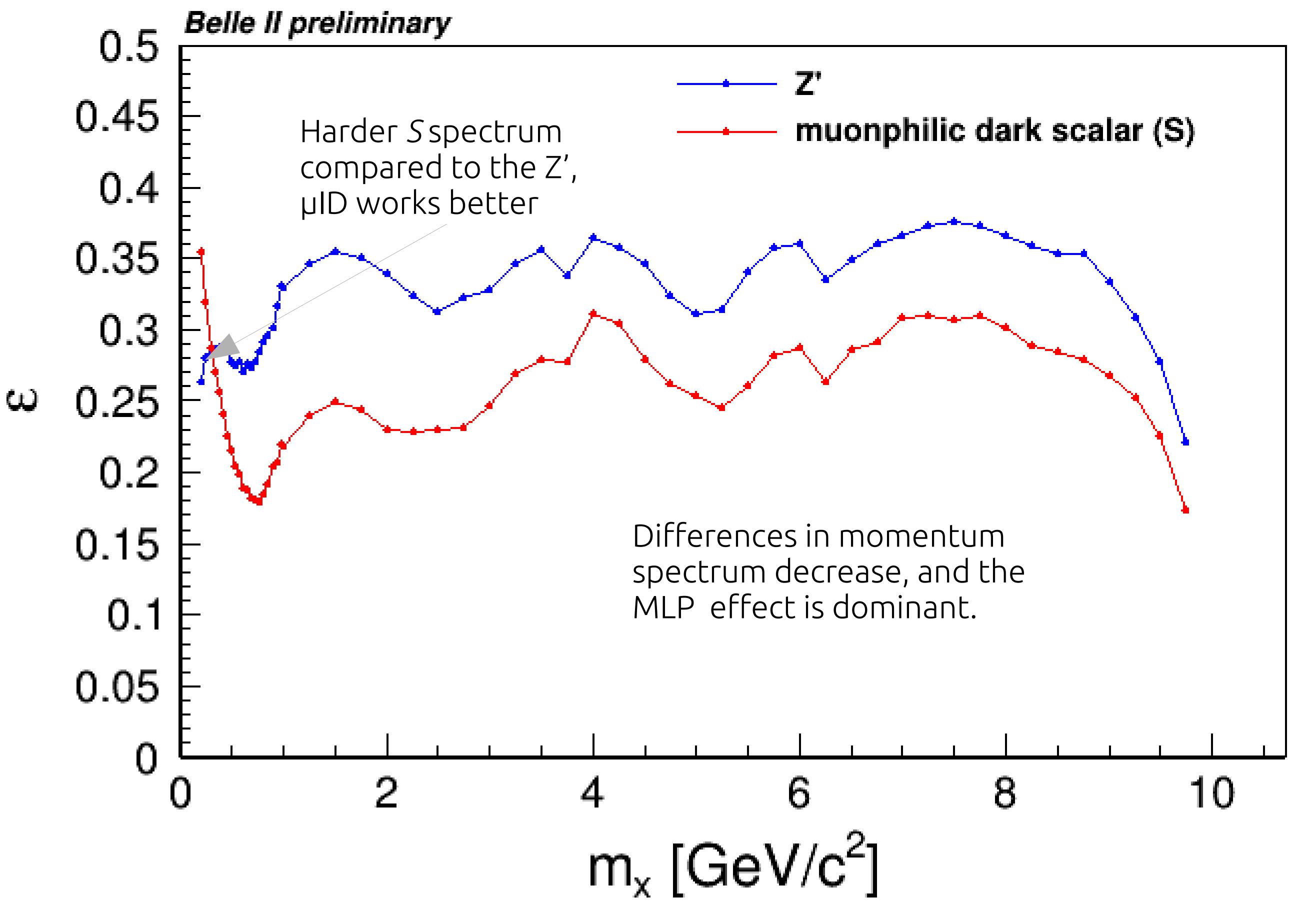
Search for a μμ resonance in ee → μμμμ: muonphilic dark-scalar



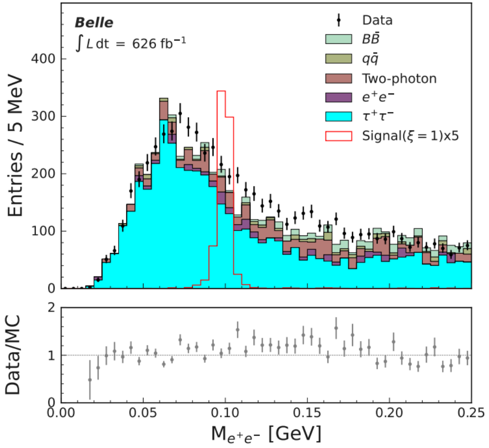
Search for a dark leptophilic scalar in τ decays at Belle

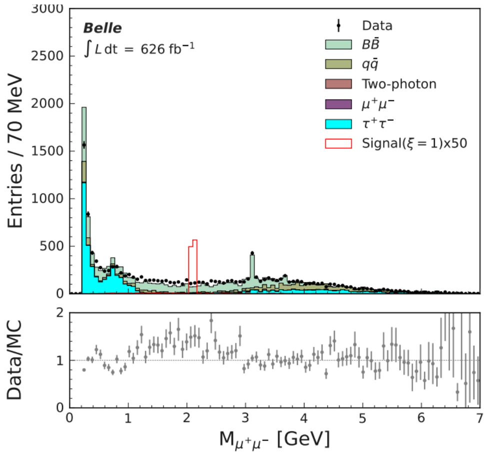
- Search for a narrow peak in m_{ll} distribution
- Mass range probed in this analysis:
  40 MeV < m(Φ_l) < 6.5 GeV
  – $\Phi_l \rightarrow e^+e^-$ for m(Φ_l) < 2m(μ) → low mass region
  – $\Phi_l \rightarrow \mu^+\mu^-$ for m(Φ_l) > 2m(μ) → high mass region

- **Strategy:**
  → $e^+e^- \rightarrow \tau^+\tau^-\Phi_l$ 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





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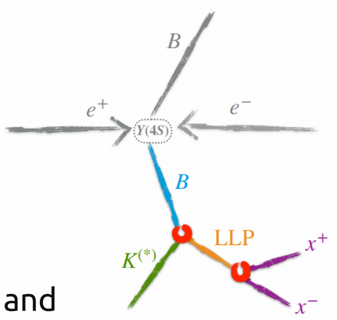
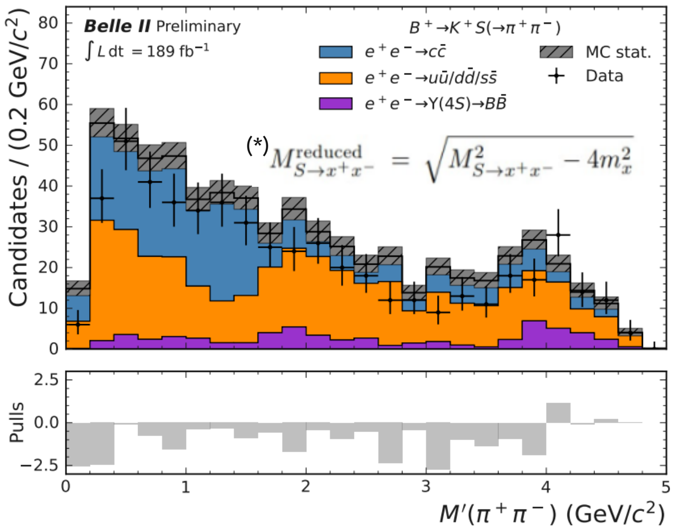
Search for a long-lived (pseudo-)scalar particle in $b \to s$

- 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
- B-meson kinematics to reject combinatorial background
- **Signature**: bump hunt with extended max likelihood unbinned fits to the (*)reduced mass spectrum, separately for each channel and lifetime



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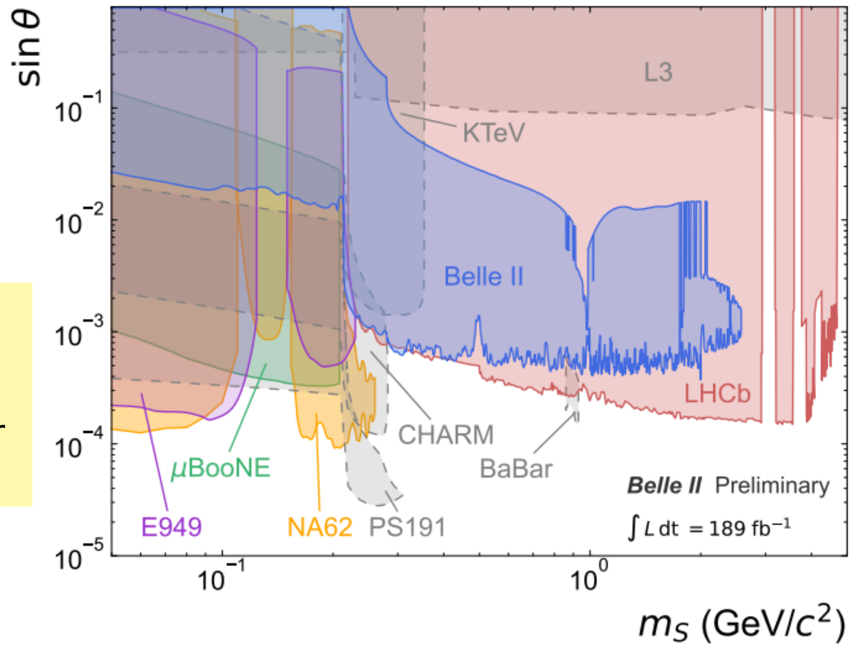
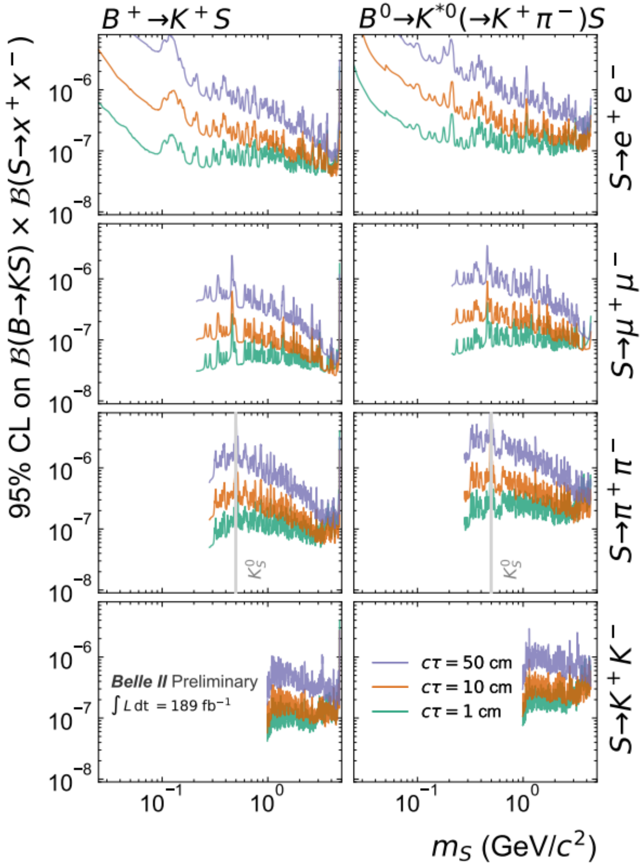
Search for a long-lived (pseudo-)scalar particle in $b \to s$

- **No significant excess found in 189 fb^{-1}**
  - first model-independent 95% CL upper limits on **BF(B→KS)×BF(S→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



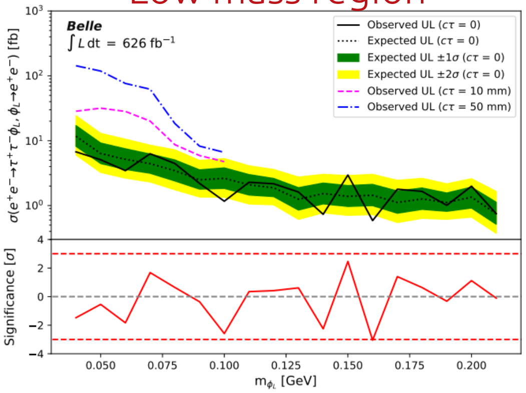


Submitted to PRL: https://arxiv.org/abs/2306.02830

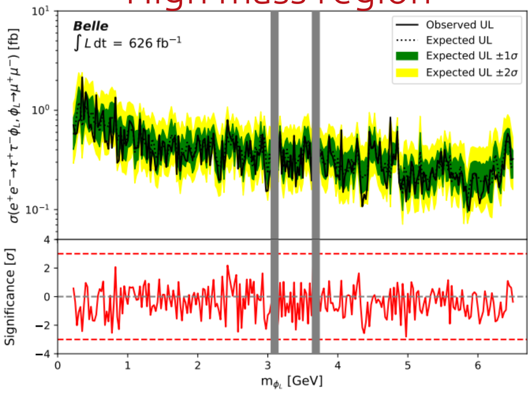
Search for a dark leptophilic scalar in τ decays at Belle

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

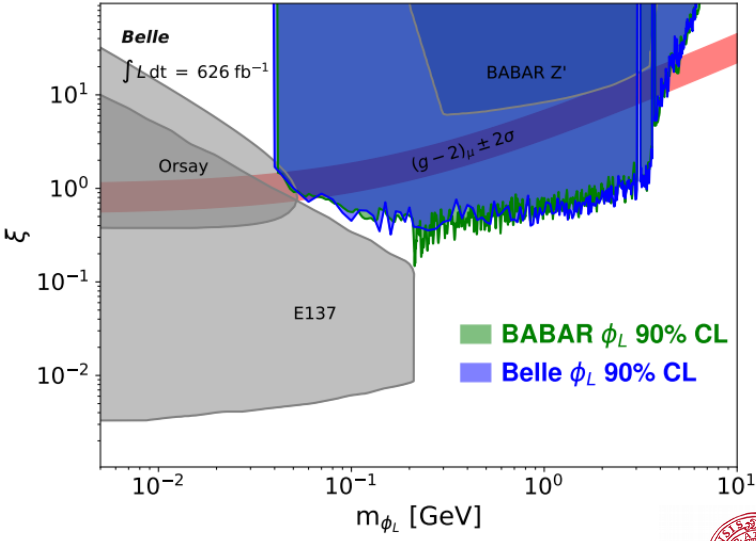
Low mass region



High mass region



Submitted to PRL: arXiv:2207.07476



- **90 % CL UL on ξ vs m(Φ_l)**
  - → Comparable or more stringent limits than BaBar (Phys. Rev. Lett. 125, 181801)
  - → Exclude a wide range of parameter space of the model favored by $(g\text{-}2)_\mu$

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