Dark sector searches at Belle & Belle II

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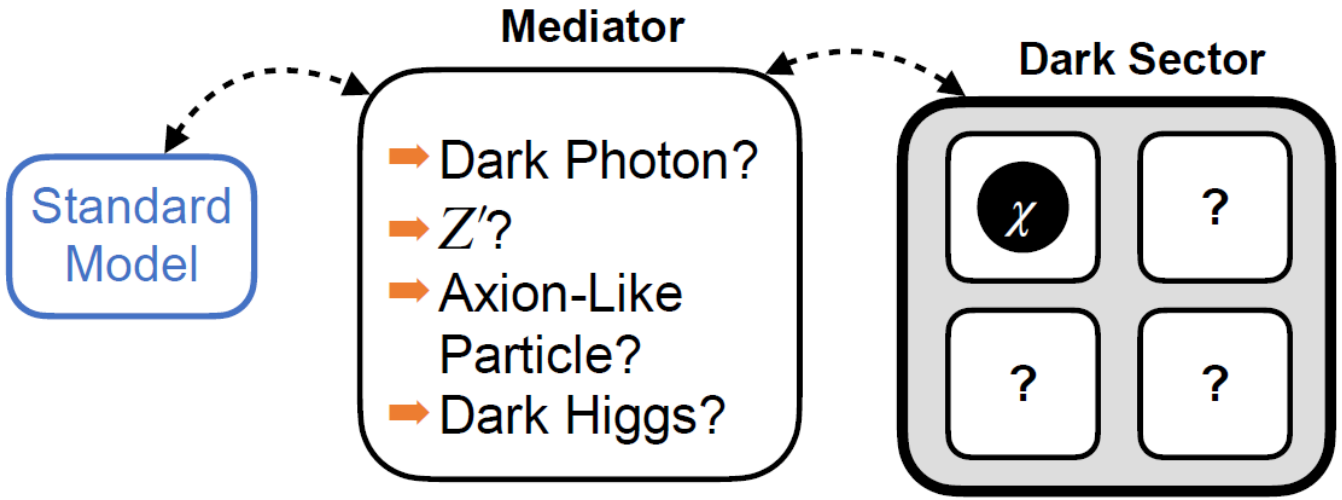
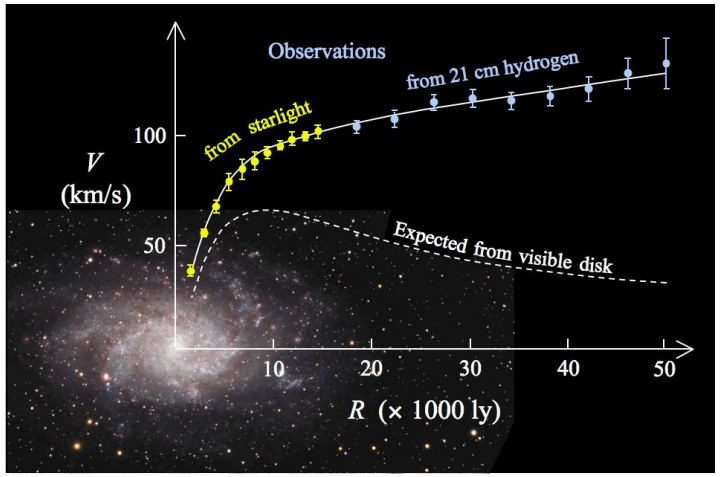
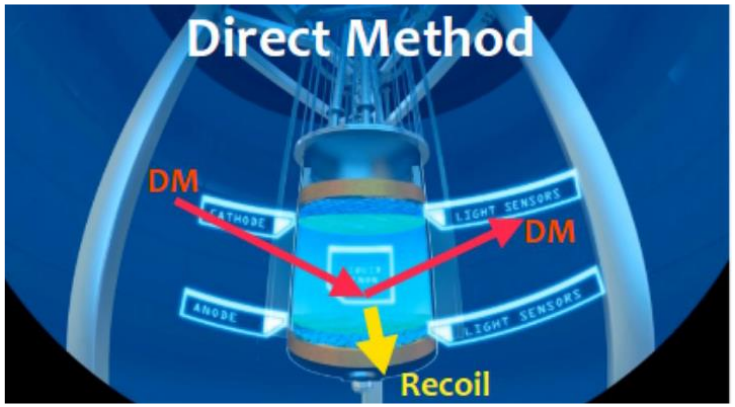


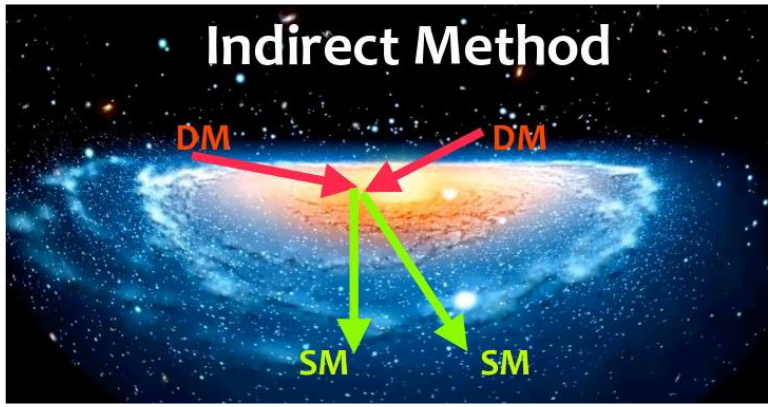
“2023年BESIII新物理研讨会”，2023.10.15，武汉

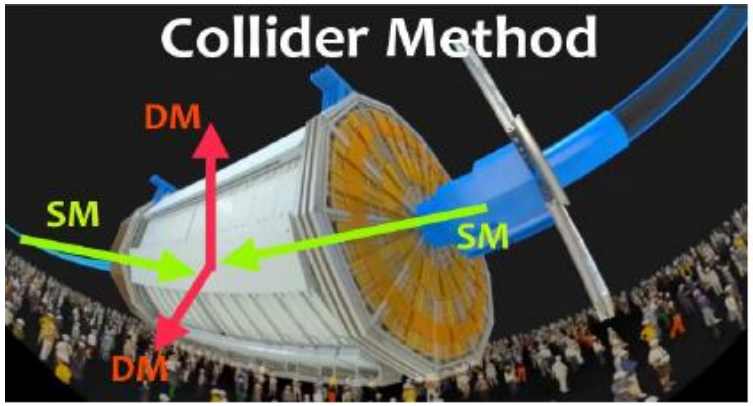
Dark sector

- Dark matter (DM): existence established in astrophysics, e.g. rotation curves of spiral galaxies
- No dark matter candidate in the SM
  - ✓ convincing indication of new physics
- How to search for DM ?
  - ✓ Detect energy of nuclear/electron recoil
  - ✓ Detect flux of visible produced by DM annihilation and decay
  - ✓ DM weakly couples SM particle, can be produced in SM-particle annihilation



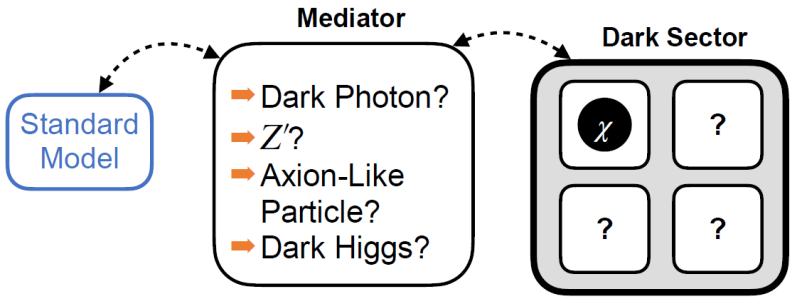


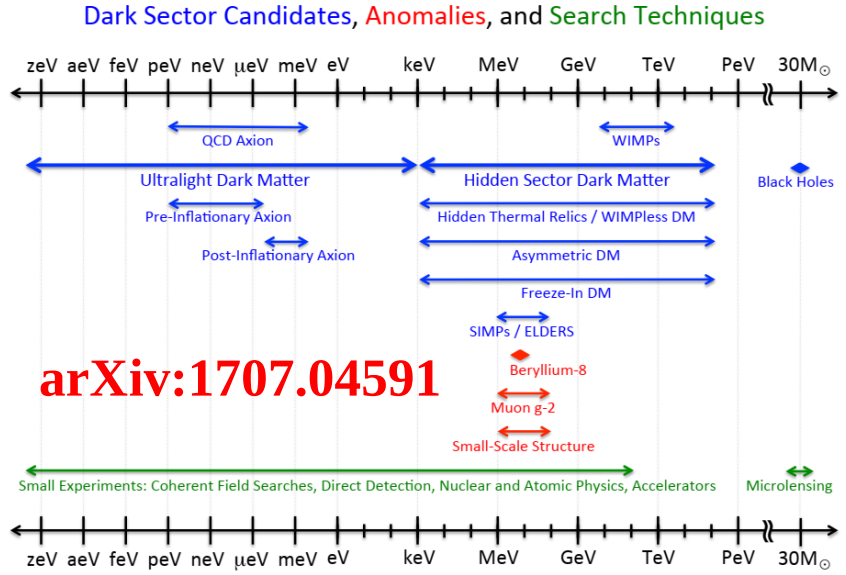




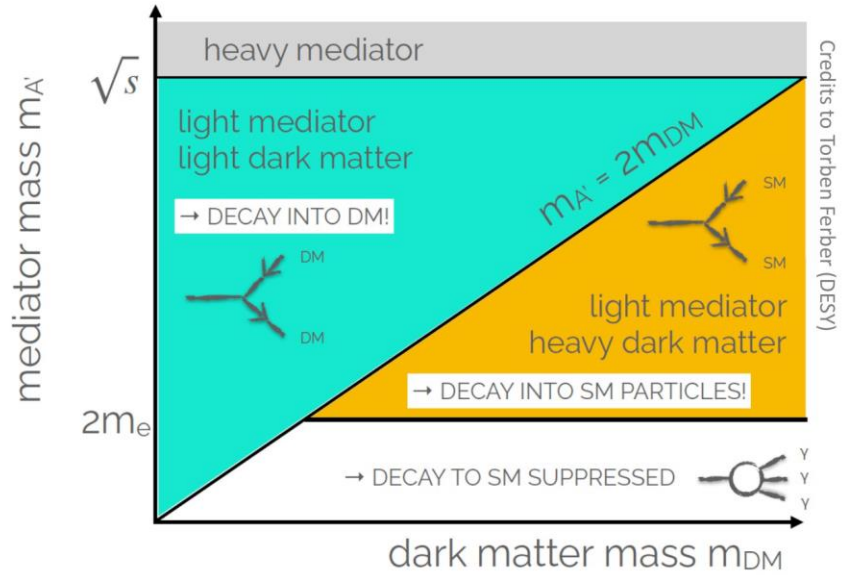
Dark sector

- **Belle II: access mass range favored by light dark sectors, ~ O(MeV-GeV)**
- **The light DM weakly interacting to SM particles though a light mediators**
- **Mediator portals**
  - ✓ **Vector: dark photon A', Z' bosons**
  - ✓ **Pseudoscalar: axion-like particles (ALPs)**
  - ✓ **Scalar: dark Higgs/scalars**
  - ✓ **Neutrino: sterile neutrinos**
- **Signatures: depend on relation between DM mass, mediator mass, and SM particles mass**

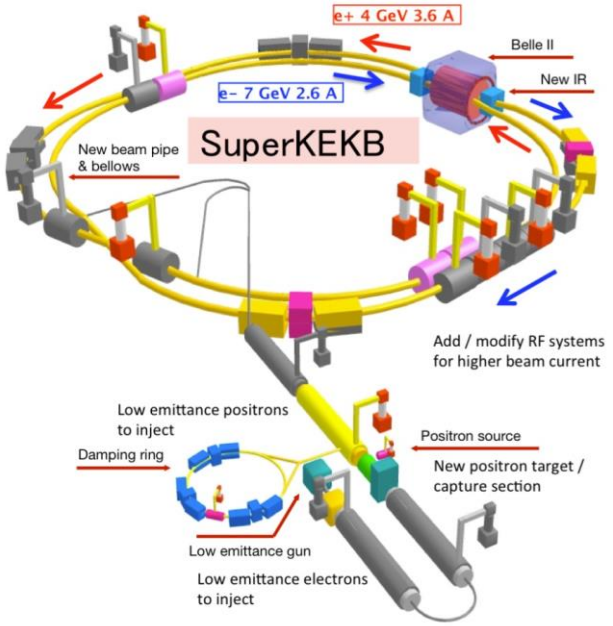


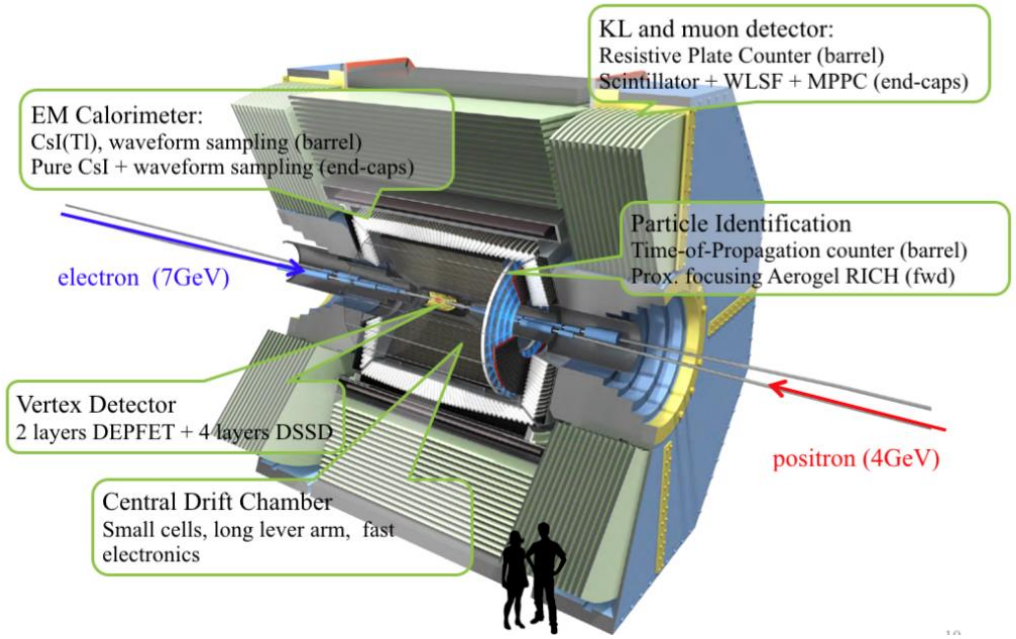


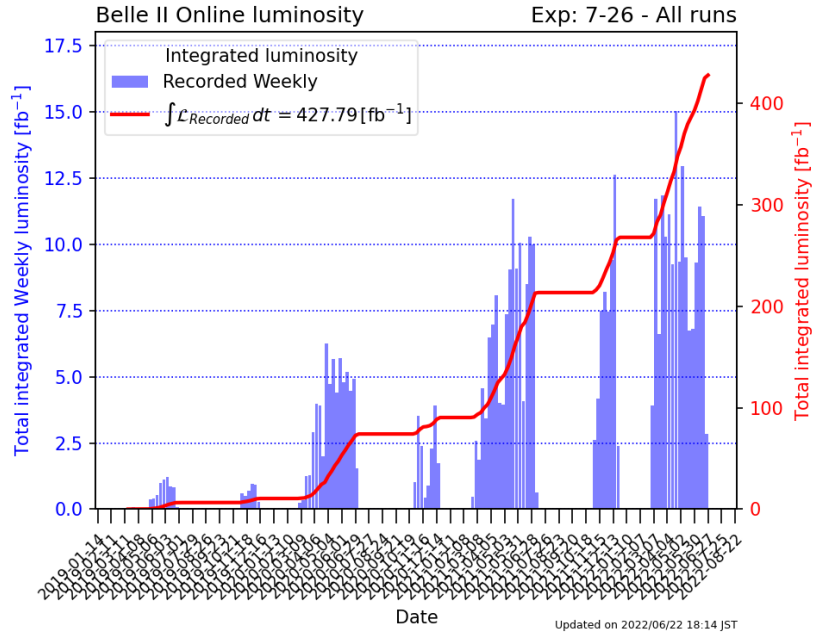
arXiv:1707.04591



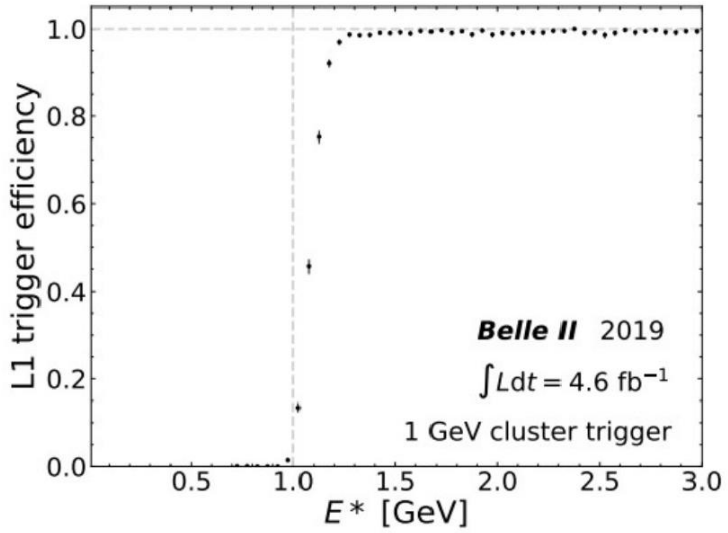
SuperKEKB & Belle II





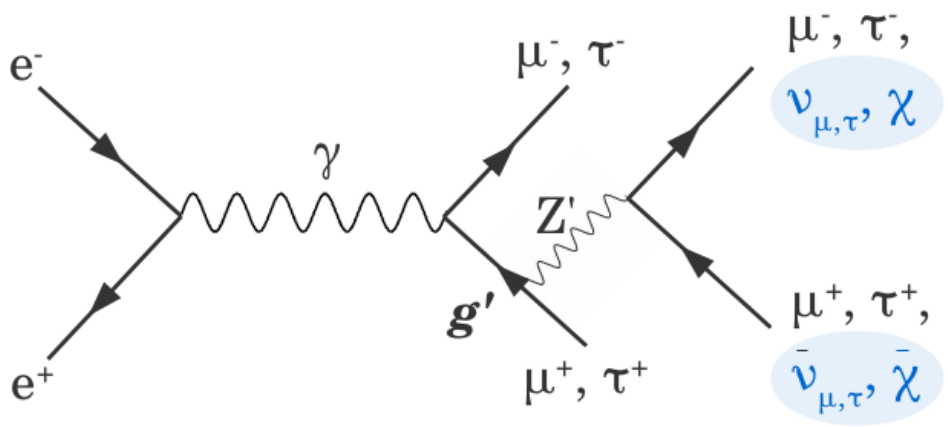


- Asymmetric e^+e^- collider @ Tsukuba, Japan
- On searching for light dark matter or mediators
  - ✓ Hermetic detector and well known initial condition
  - ✓ Low background and excellent PID
  - ✓ specialized dark sector triggers for low multiplicity events: single track/muon/photon
- Collect 428 fb^{-1} data sample: ~ BaBar; ~ half of Belle



L_μ-L_τ model & Z' decay

- Theory L_μ-L_τ model
  - ✓ JHEP 1612, 106 (2016); PRD89, 113004 (2014)
- Massive boson Z' interacting only with 2nd and 3rd generation of lepton
- This model could explain: dark matter puzzle, muon g-2 anomaly and b -> s μ^+ μ^- anomaly
- Possible Z' decay
  - ✓ Light DM χ kinematically accessible, full invisible
- Invisible Z' decay
  - ✓ e^+ e^- $\rightarrow$ μ^+ μ^- Z' and Z' invisible
  - ✓ Signal: a narrow peak in recoil mass of μ^+ μ^-



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

$$M_{Z'} < 2M_\mu \implies BF[Z' \to \text{invisible}] = 1,$$
$$2M_\mu < M_{Z'} < 2M_\tau \implies BF[Z' \to \text{invisible}] \simeq 1/2,$$
$$M_{Z'} > 2M_\tau \implies BF[Z' \to \text{invisible}] \simeq 1/3.$$

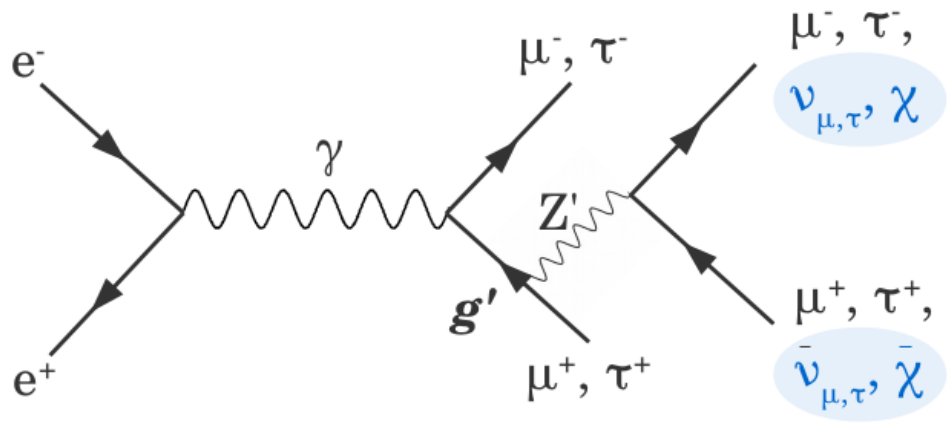
if $M_{Z'} > 2M_\chi$

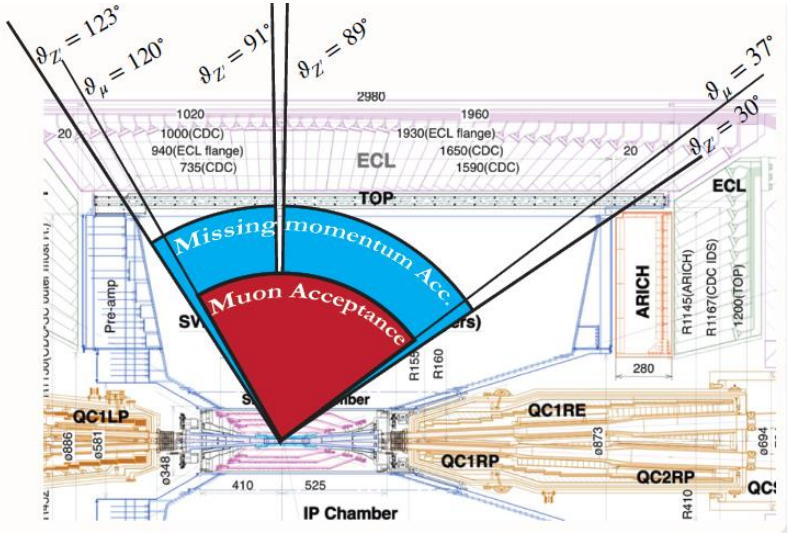
$$BF(Z' \to \chi\bar{\chi}) = 1$$

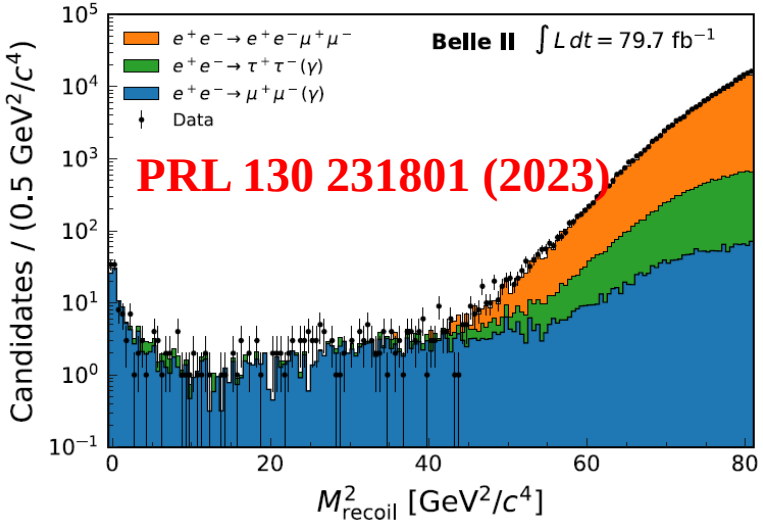
$$\mathcal{L} = \sum_\ell \theta g' \bar{\ell}\gamma^\mu Z'_\mu \ell$$

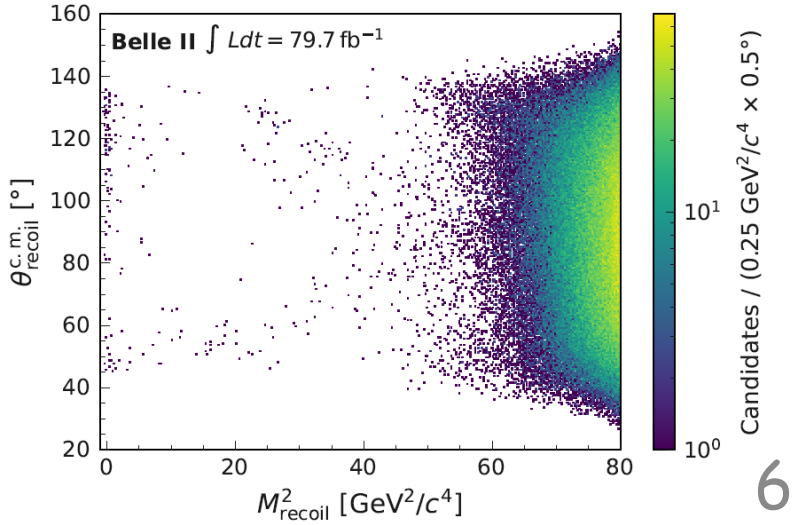
Invisible Z' decay

- **Event signature**
  - ✓ **Two oppositely charged muons**
  - ✓ **Negligible activity in calorimeter**
- **Dominant QED background sources**
  - ✓ $e^+ e^- \to e^+ e^- \mu^+ \mu^-$, **undetected** $e^+ e^-$
  - ✓ $e^+ e^- \to \mu^+ \mu^-$ **n(**γ**), undetected gammas**
  - ✓ $e^+ e^- \to \tau^+ \tau^-$ **(**γ**), leptonic** τ **decay & missing neutrinos, apply neural network**
- **No significant excess of data above expected background.**
- **Signal yield extraction: 2D fit in mass &** θ **of against a** $\mu^+ \mu^-$ **pair**

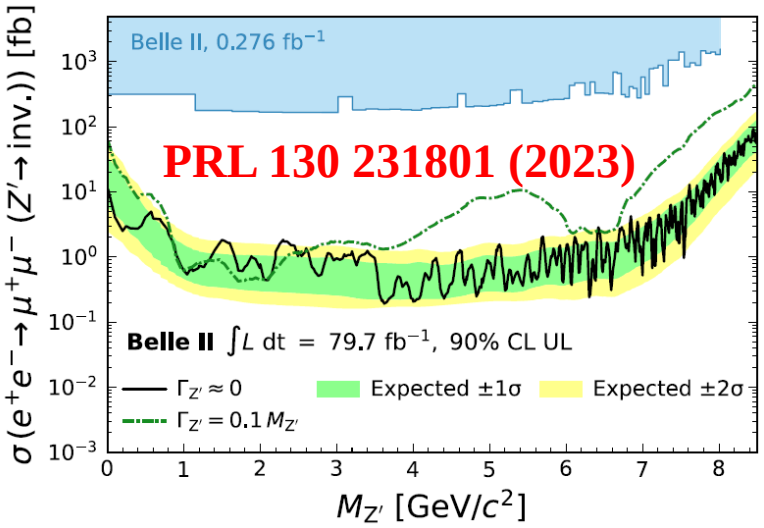


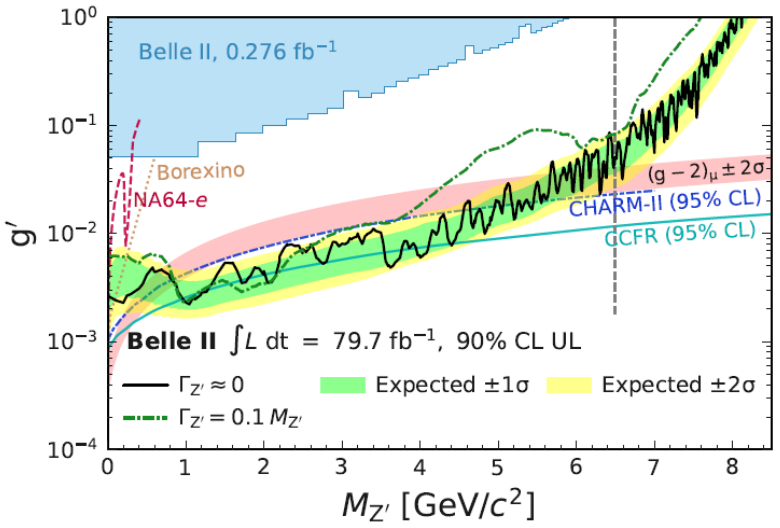


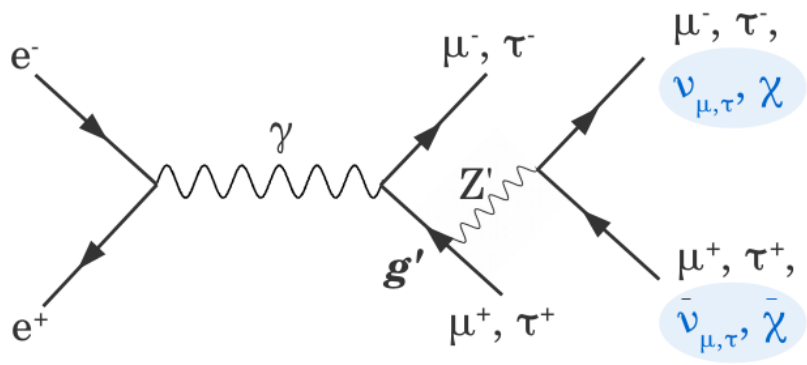




Invisible Z' decay



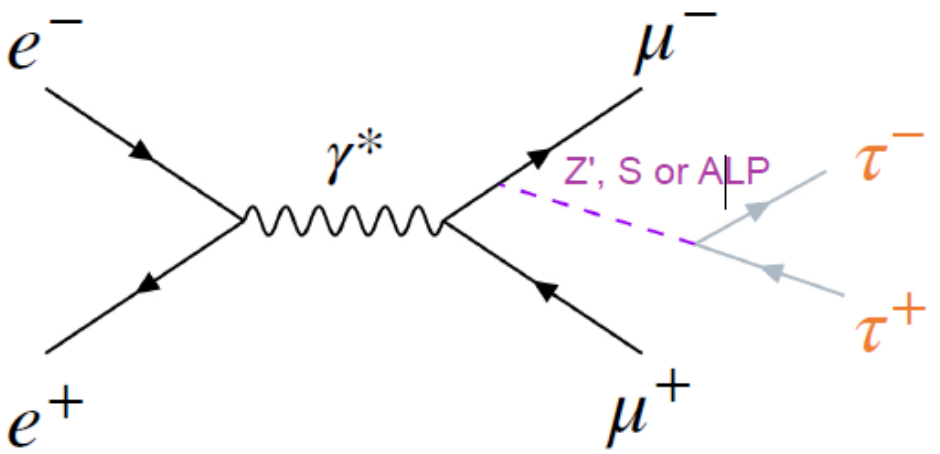


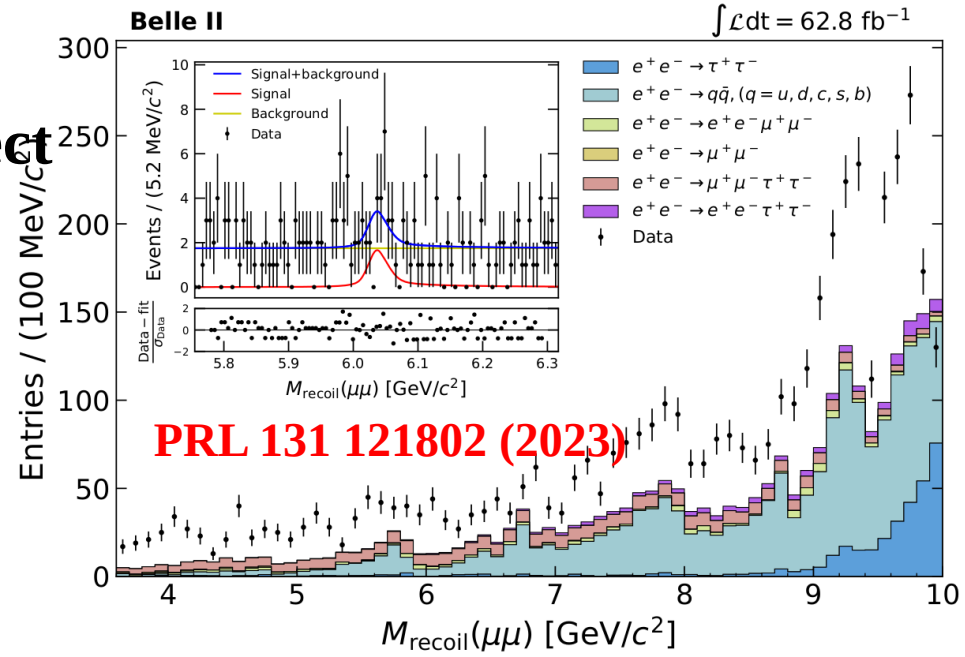


- 90% C.L. upper limits on the cross section of $e^+ e^- \to \mu^+ \mu^-$ Z' and Z' invisible
- Cross section results are translated into 90% C.L. UL on coupling g'
- Update of first Belle II analysis with 300x dataset
  - ✓ Belle II 50 ab^{-1}: about 600 x 79.7 fb^{-1}
- For fully invisible L_μ-L_τ model, Z' with negligible and non-negligible width
  - ✓ world-leading for direct searches of Z' with masses above 11.5 MeV/c^2
  - ✓ $(g\text{-}2)_\mu$ favored region excluded for 0.8 < M(Z') < 5 GeV/c^2

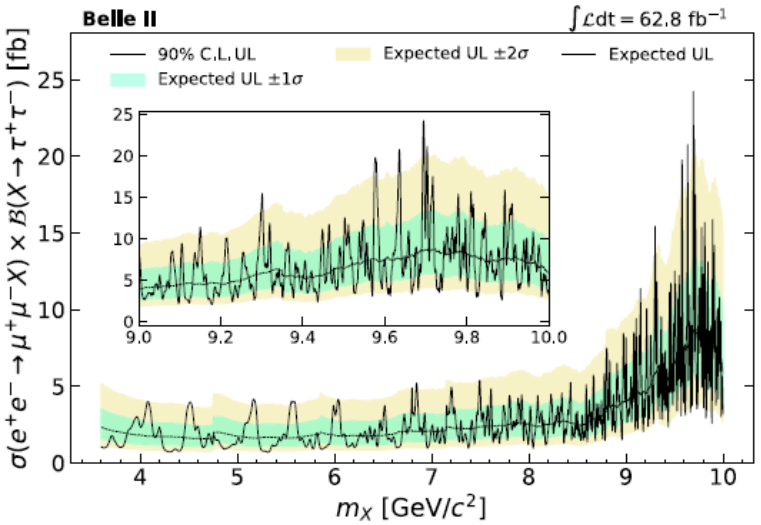
Search for $\tau^+\tau^-$ resonance in $e^+e^-\to\mu^+\mu^-\tau^+\tau^-$

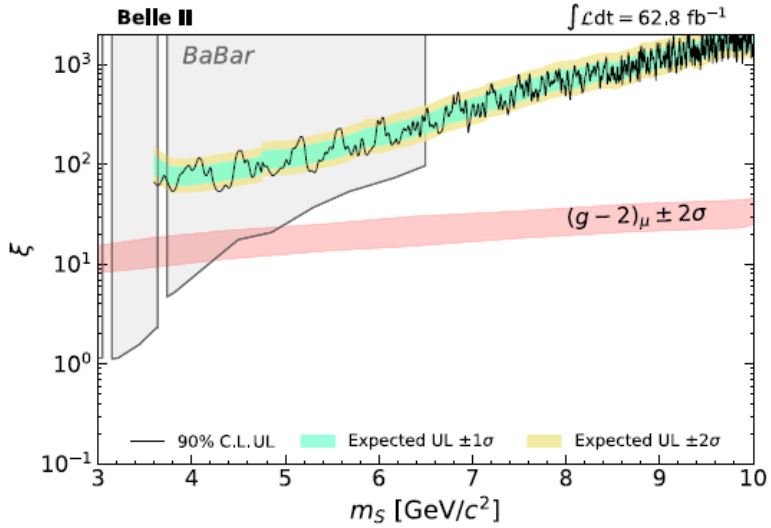
- $e^+ e^- \to \mu^+ \mu^- X$ & $X \to \tau^+ \tau^-$:
  - ✓ X = Z', ALP, leptophilic scalar
- Event signature
  - ✓ Two oppositely charged muons
  - ✓ τ decay: 1 charged particle + ≥ 0 neutral
  - ✓ Recoil mass of $\mu^+ \mu^-$ pair → search for Z', leptophilic scalar and ALP
- Challenging because of neutrinos and background
  - ✓ < 6 GeV/c^2: four lepton simulation with ISR effect
  - ✓ > 9 GeV/c^2: two-photon $e^+ e^- \to e^+ e^- h$
  - ✓ Smooth background
- Signal yield extraction: fit of recoil mass of $\mu^+ \mu^-$
  - ✓ Signal: two CB function with same mean value
  - Background: a constant
- 90% C.L. upper limits on the cross section of $e^+ e^- \to \mu^+ \mu^- \tau^+ \tau^-$

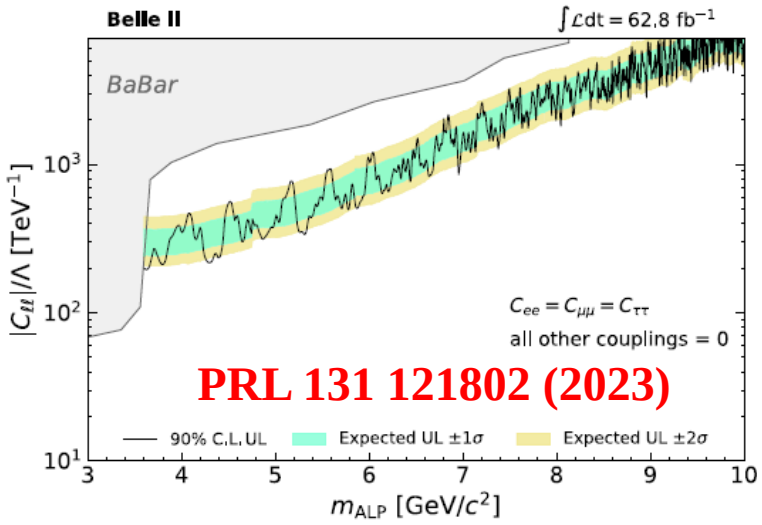




Search for $\tau^+\tau^-$ resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$







PRL 131 121802 (2023)

- **Cross section results are translated into upper limits on the coupling**
- **First limits at 90% CL for a leptophilic dark scalar S with $m_S > 6.5$ GeV/c^2**
- **First direct limits at 90% CL for axion-like particle ALP → $\tau^+\tau^-$**

ALP a

$$\Gamma(a \to \ell^+\ell^-) = \frac{m_a m_\ell^2}{8\pi f^2} c_{\ell\ell}^2(m_a) \sqrt{1 - \frac{4m_\ell^2}{m_a^2}},$$

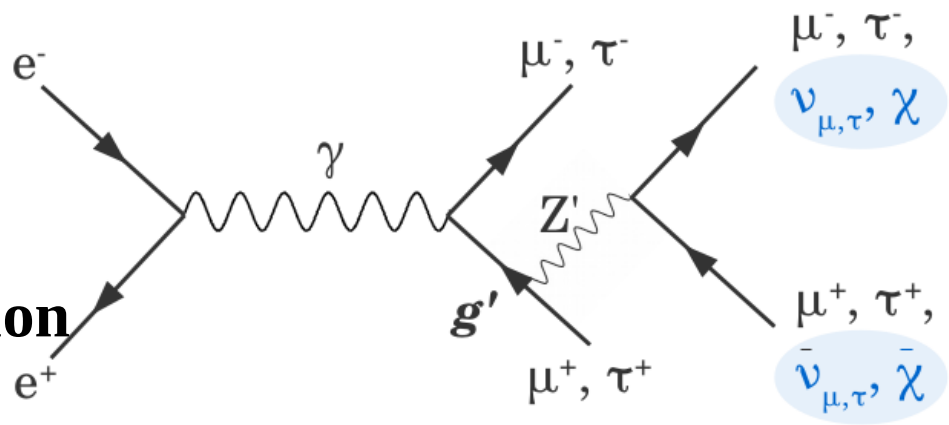
Leptophilic scalar Φ_L

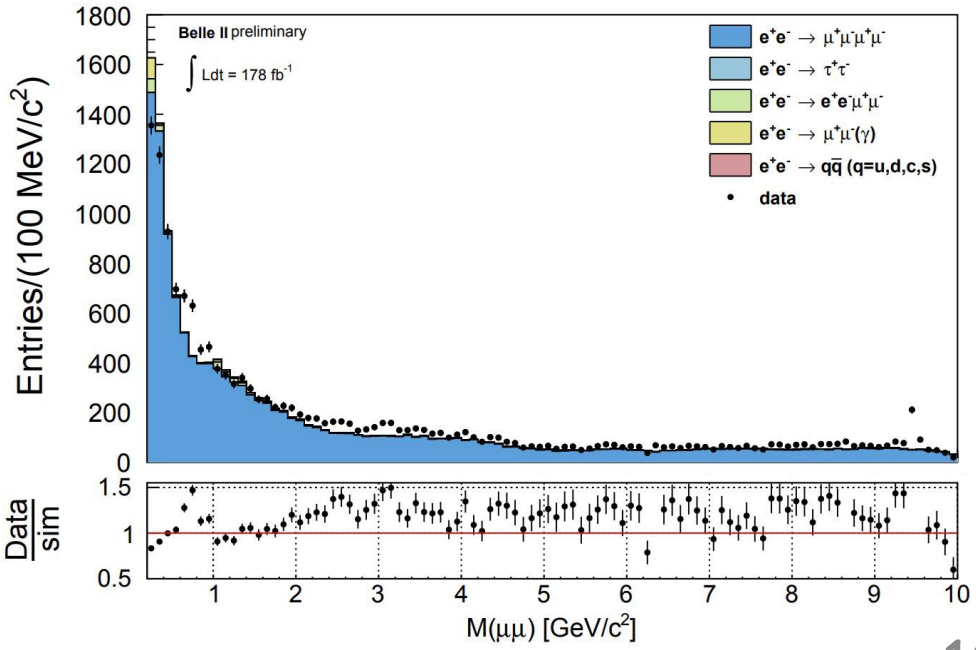
$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell}\, \phi_L \ell$$

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

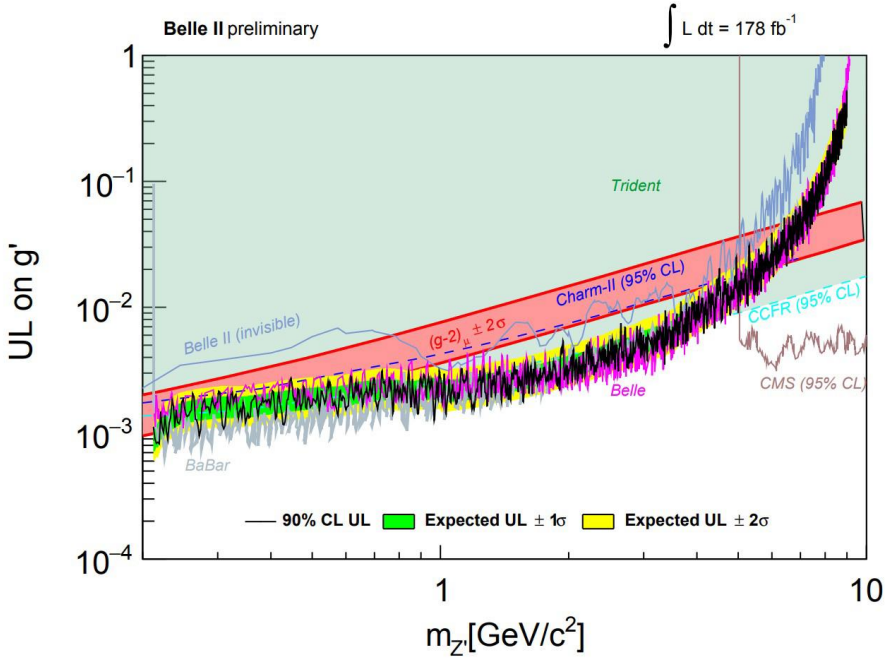
- $e^+ e^- \to \mu^+ \mu^- X$ & $X \to \mu^+ \mu^-$:
  - ✓ X = Z', muonphilic dark scalar S
  - ✓ Look for peak in in opposite charge $\mu^+ \mu^-$ mass
- Event signature
  - ✓ Four charged tracks, at least three identified muon
  - ✓ Mass(4 track) ≈ $\sqrt{s}$
  - ✓ No extra energy
- Dominant SM background $e^+ e^- \to \mu^+ \mu^- \mu^+ \mu^-$
  - ✓ Smooth background
- Signal yield: fit of invariant mass of $\mu^+ \mu^-$ of

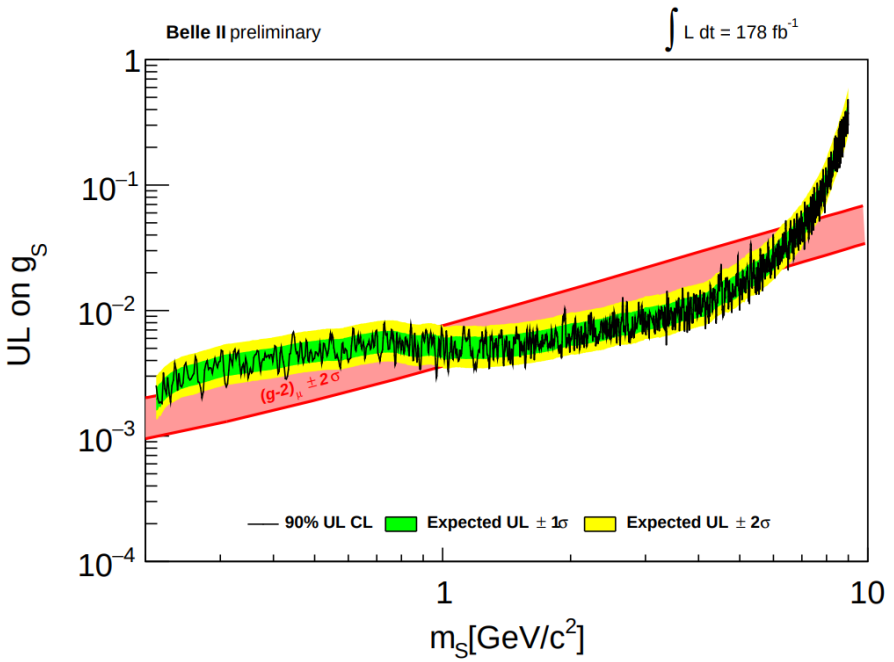
→ obtain cross section of $e^+ e^- \to \mu^+ \mu^- X$, $X \to \mu^+ \mu^-$





Search for $\mu^+\mu^-$ resonance in $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$

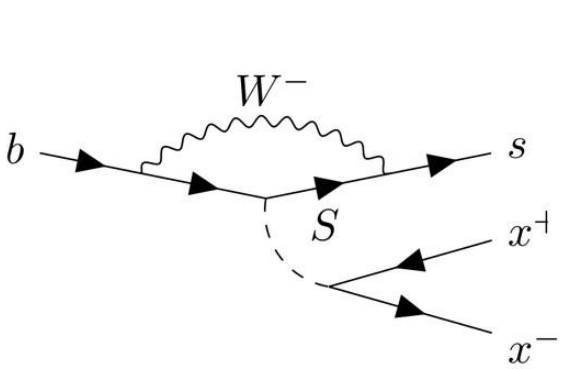


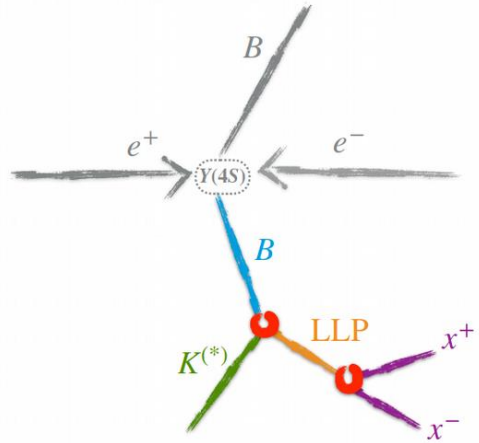


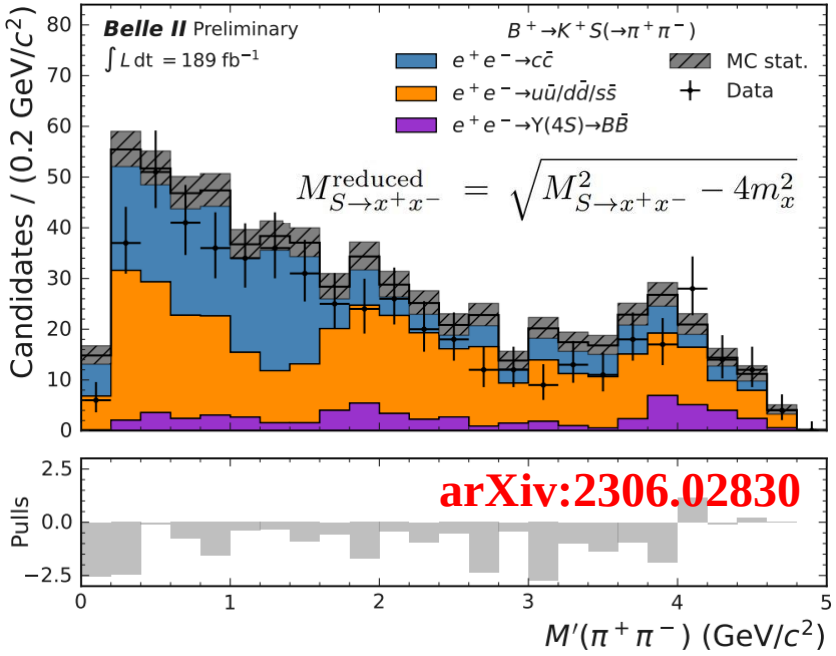
- Cross section results are translated into UL on coupling
- Competitive 90% CL upper limits on g' of Z' with BaBar (> 500 fb^{-1}) and Belle (> 600 fb^{-1})
  - ✓ aggressive background suppression
- First 90% CL upper limits for muonphilic scalar model

Search for long-lived scalar particle in b → s

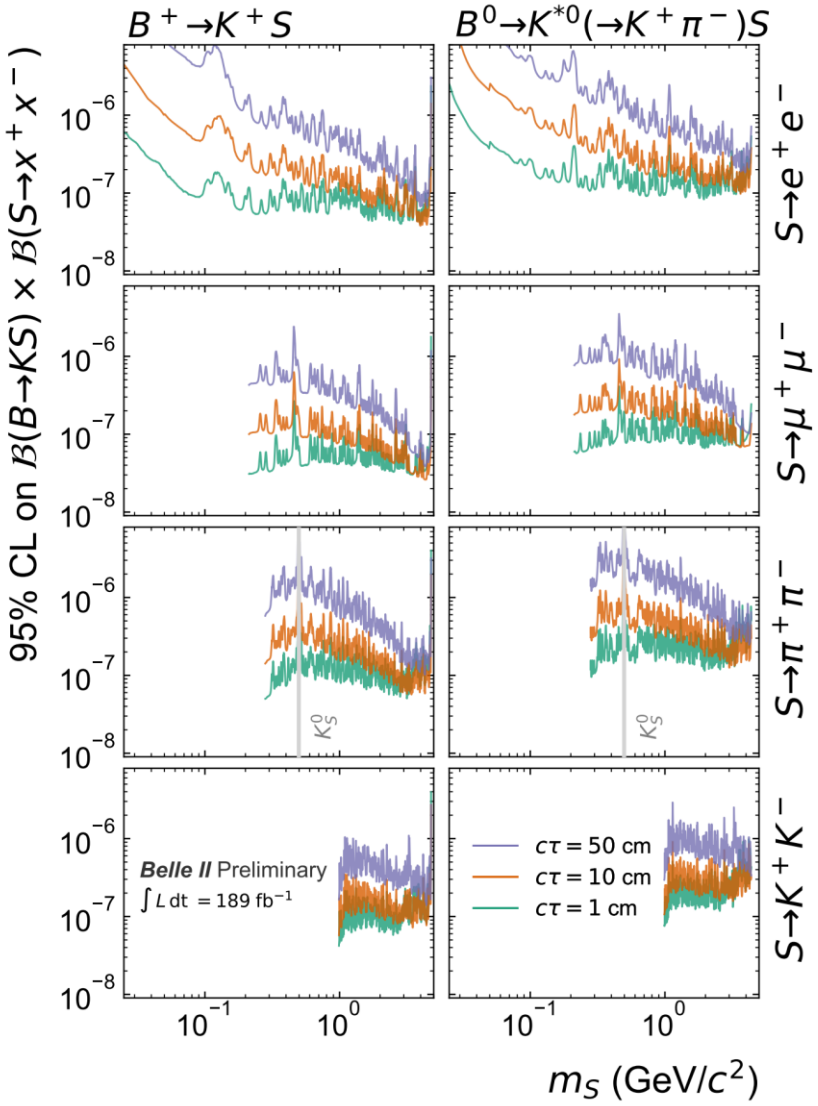
- Search for a new scalar S in b → s transitions
- scalar S can mix SM Higgs with mixing angle θ
- scalar S is long-lived particle (LLP) at small θ
  - ✓ Performance in LLP vertex reconstruction
- 8 exclusive "visible" channels
  - ✓ $B^+ \to K^+ S$ and $B^0 \to K^{*0} S \to K^+ \pi^- S$
  - ✓ $S \to e^+e^-/\mu^+\mu^-/\pi^+\pi^-/K^+K^-$
  - ✓ Explore S lifetime 0.001 cm < cτ < 100 cm
- Background
  - ✓ Combined background: reconstructed B
  - ✓ K^0_S background: mass veto
  - ✓ Large displacement requirement
- Signal extraction: fit to the LLP reduced mass, separately for each channel and lifetime



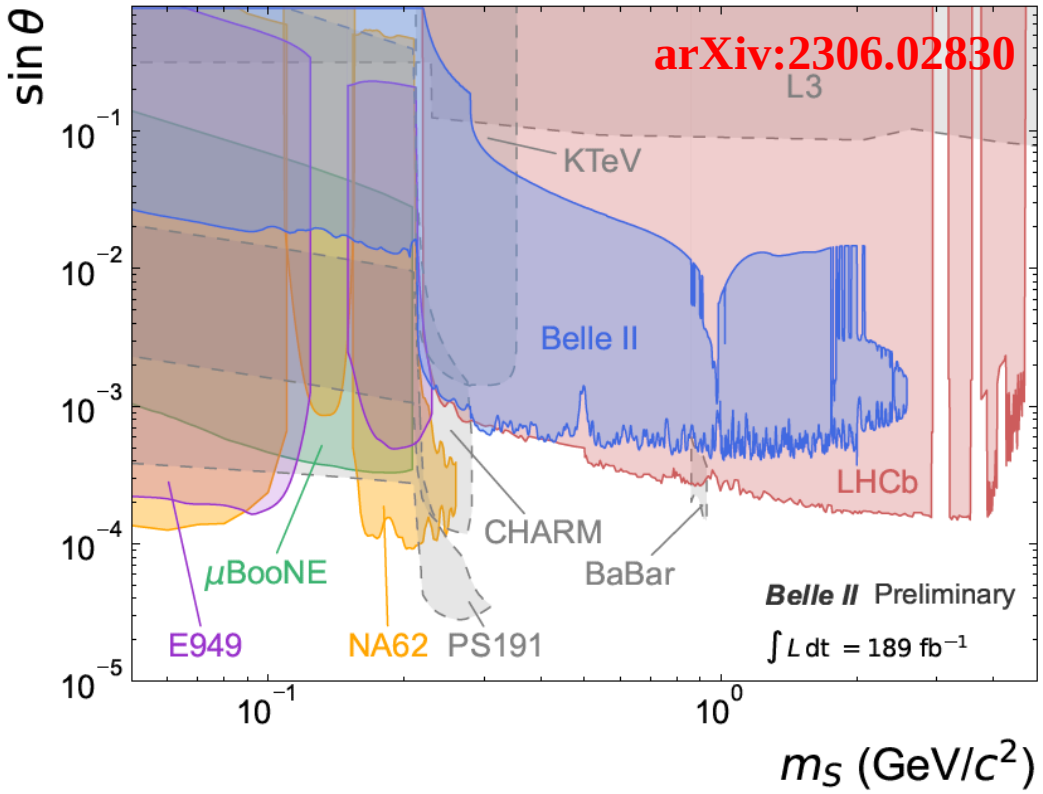




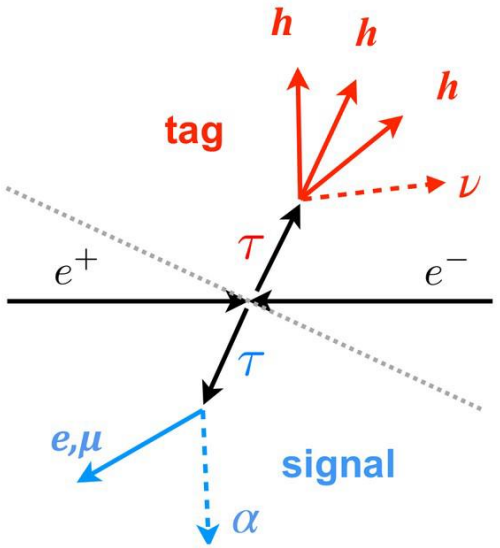
Search for long lived scalar particle in b → s

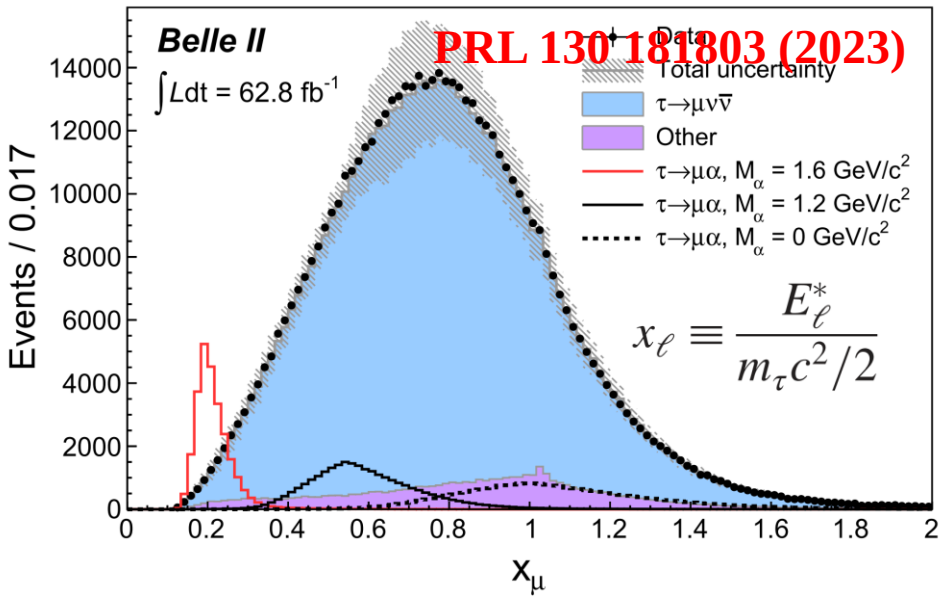


- First model independent 95% CL upper limits
- First limits for hadron ($\pi^+\pi^-$/K^+K^-)
- translate into model independent limits on sinθ vs. m_s

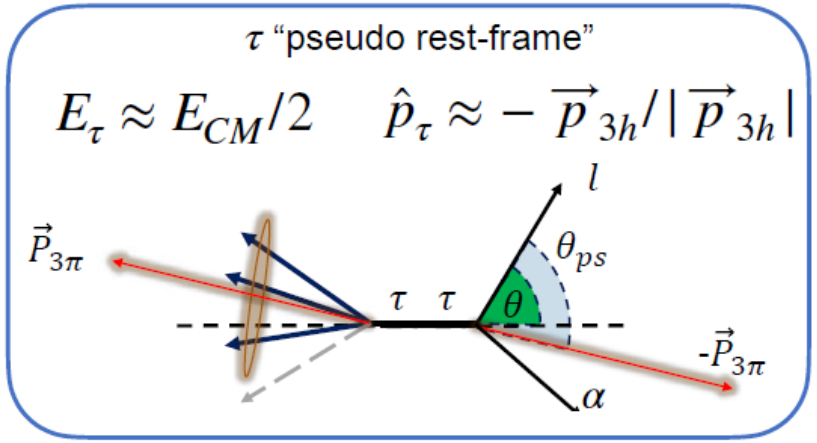


Search for inviable boson α in LFV τ decay

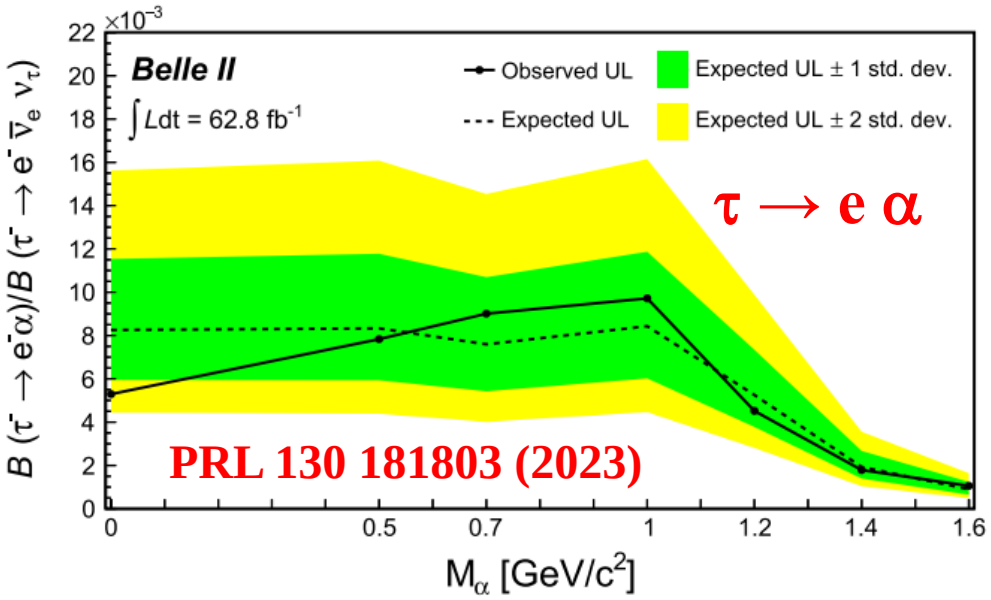


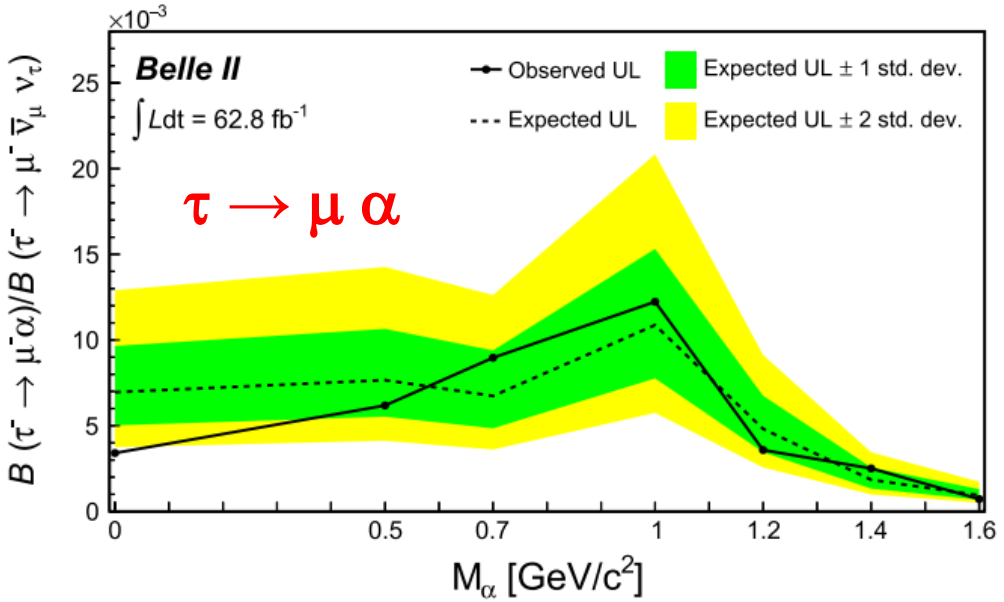


- Search for ALP particles in τ decay
- Process $e^+ e^- \to \tau^+ \tau^-$
  - ✓ Tag $\tau \to h^- h^+ h^- \nu_\tau$ (h = π, K)
  - ✓ Signal $\tau \to l\, \alpha$ (*l* = e, μ)
- Irreducible background $\tau \to l\, \nu_\tau\, \nu_l$
- Signal τ rest frame: **no** due to neutrinos
  - ✓ Pseudo-rest-frame by tagged τ
- Search for a peak in normalized lepton energy
  - ✓ No significant excess observed

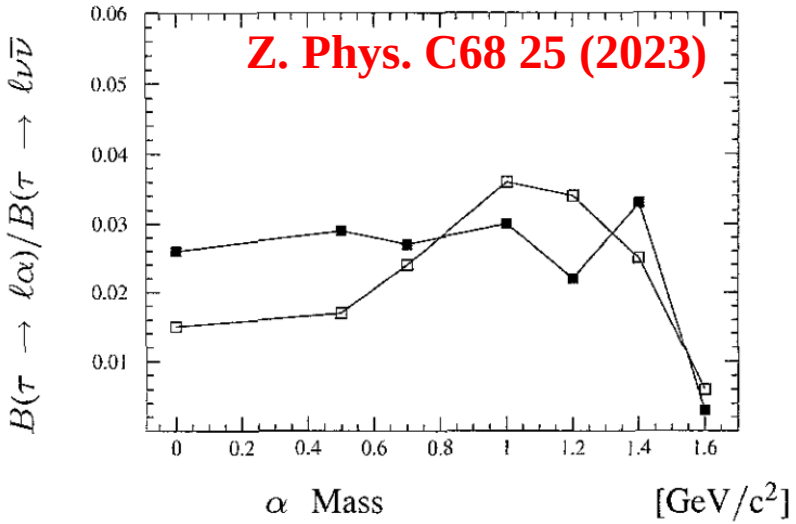


Search for inviable boson α in LFV τ decay



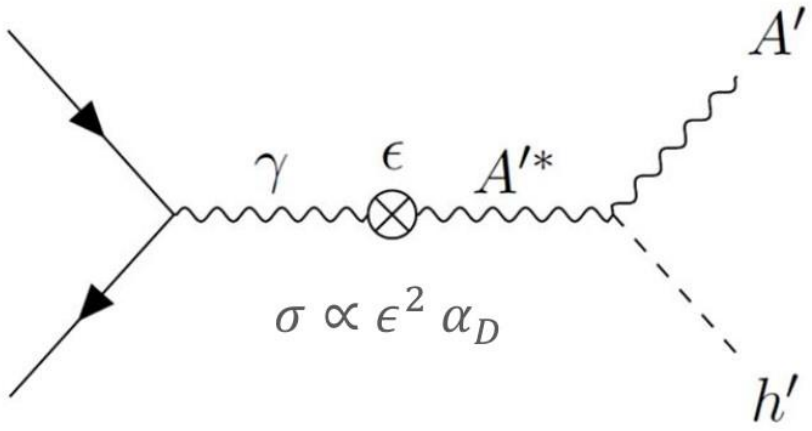


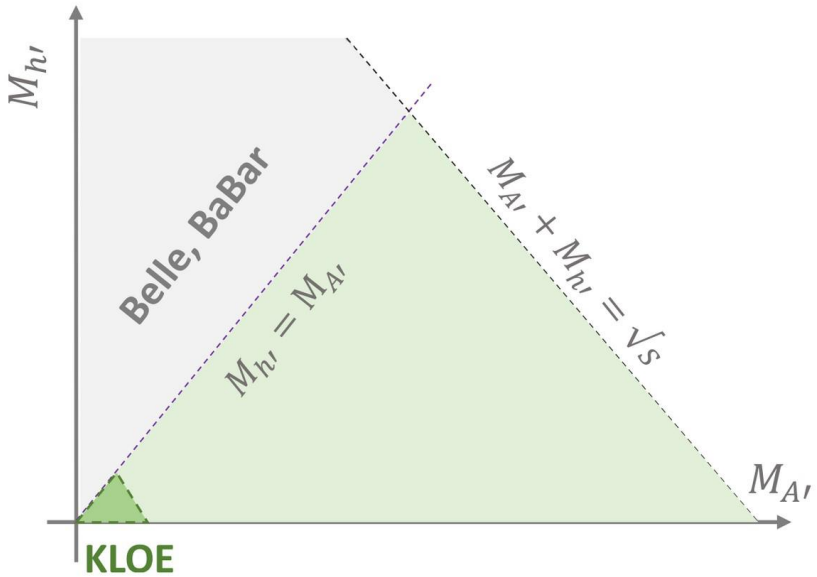
- **Upper limits at 95% C.L. on branching fraction ratios.**
- **Limits 2.2 – 14 times more stringent than best bound by ARGUS.**



Search for dark Higgs & dark photon

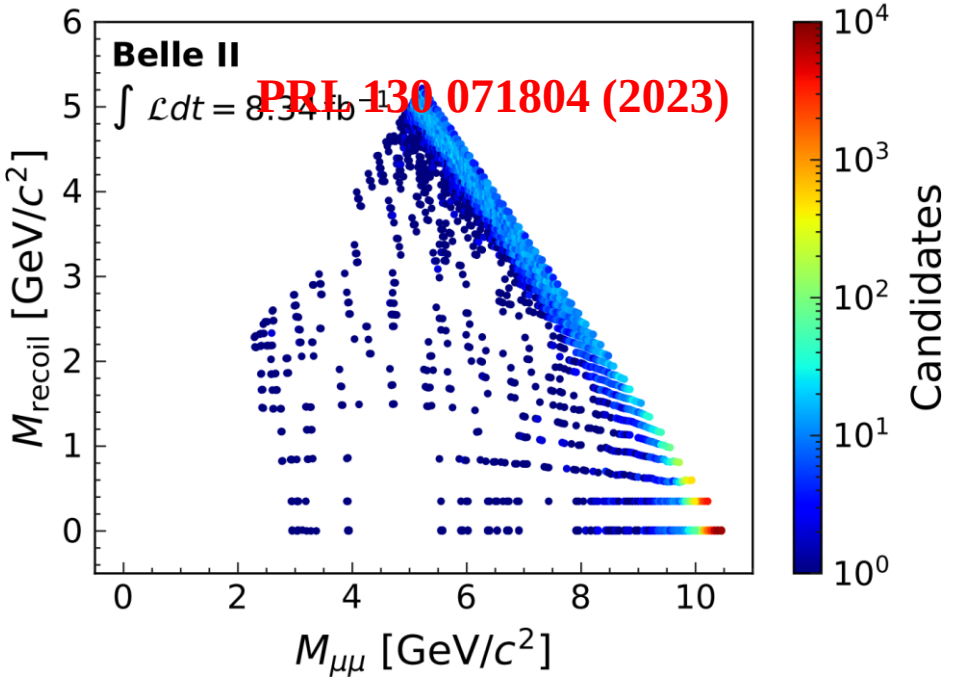
- Dark photon A'
  - ✓ Kinetic mixing with photon with strength ε
  - ✓ Mass produced by Higgs mechanism involving a dark Higgs boson
- Dark Higgs h'
  - ✓ Coupling to A' with α_DD
  - ✓ Does not mix with SM Higgs
- Dark Higgsstrahlung $e^+ e^- \rightarrow$ A'* → A' h'
- Different signatures depend on A' mass
  - ✓ $M_{h'} > M_{A'}$: h' visible, Belle & BaBar
  - ✓ $M_{h'} < M_{A'}$: h' long-lived, invisible, KLOE
- $e^+ e^- \rightarrow$ A' h'
  - ✓ A' → $\mu^+ \mu^-$ & invisible h'

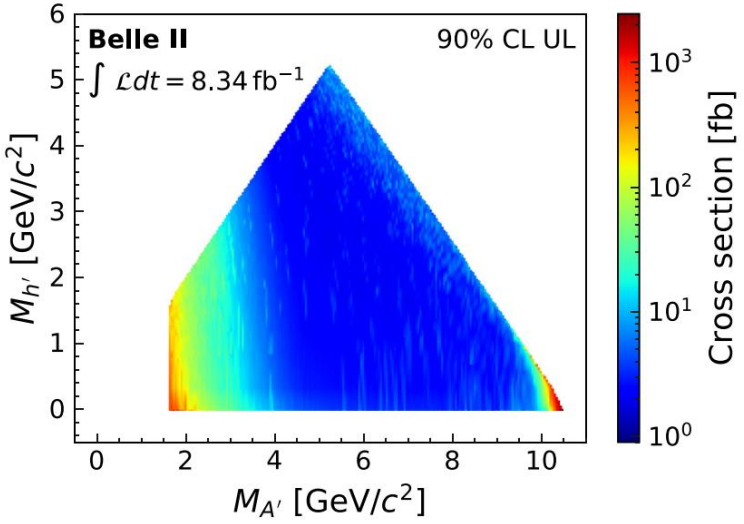


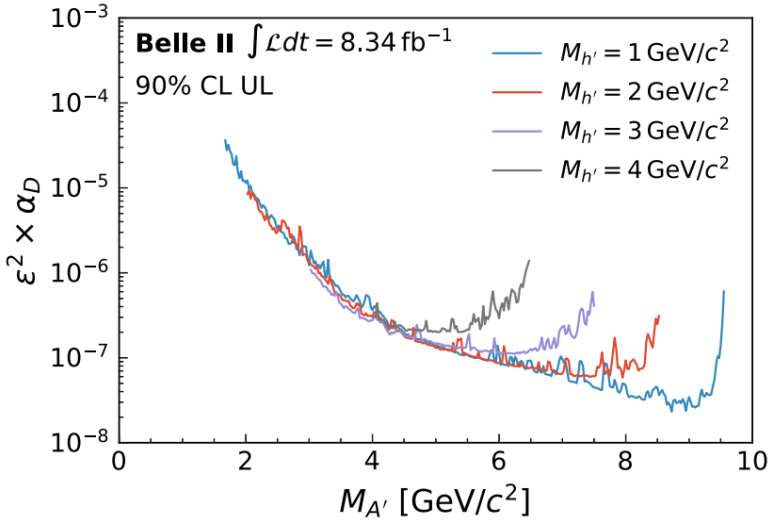


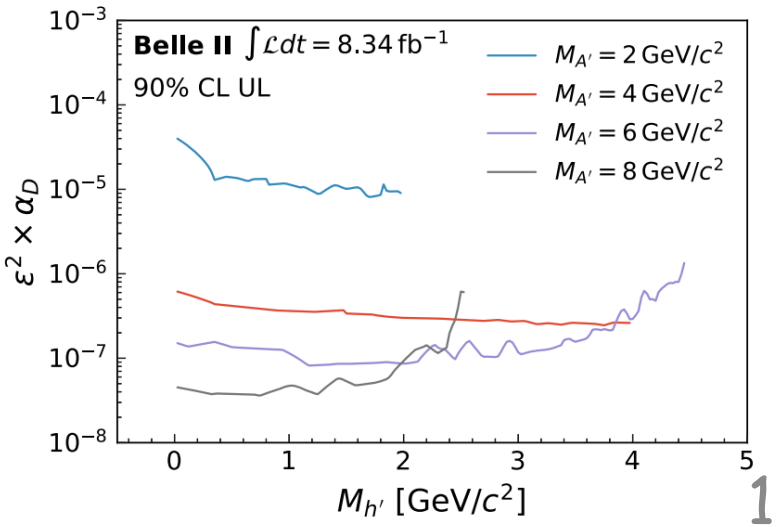
Search for dark Higgs & dark photon

- $e^+ e^- \to A' h'$: $A' \to \mu^+ \mu^-$ & invisible h'
- Experimental signature
  - ✓ $\mu^+ \mu^-$ plus missing energy
  - ✓ peak in two dimensional distribution of recoil mass and dimuon mass
- Dominant backgrounds: $(\gamma)\ \mu^+ \mu^-$, $(\gamma)\ \tau^+ \tau^-$, $e^+ e^- \mu^+ \mu^-$ and $(\gamma)\ \pi^+ \pi^-$
- 90% CL upper limit on cross section & $\varepsilon^2 \times \alpha_D$



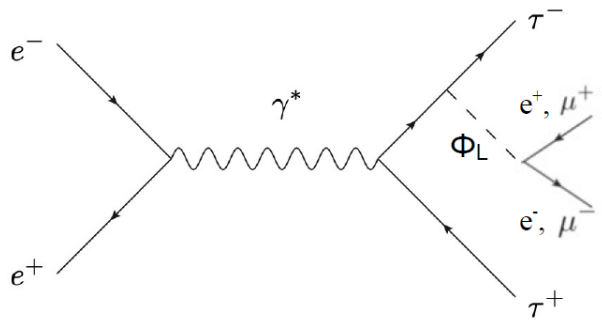


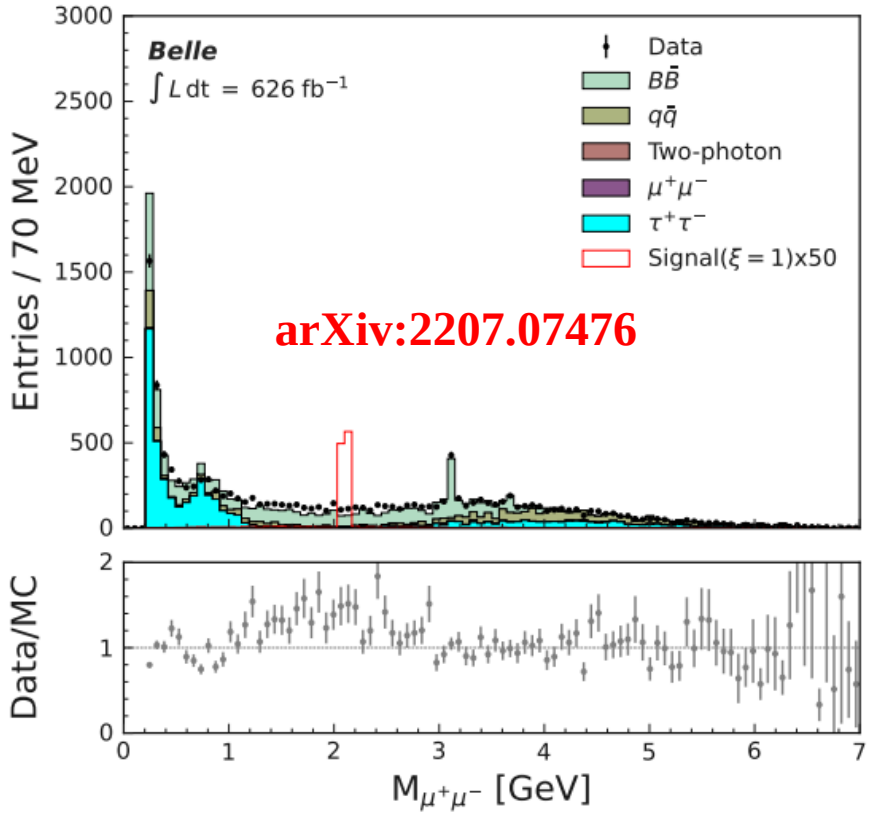




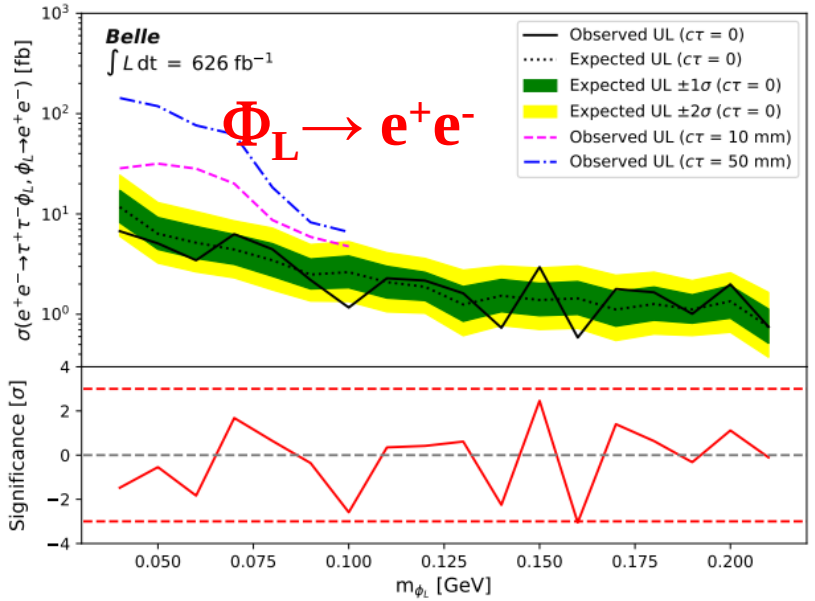
Search for leptophilic scalar in τ decay

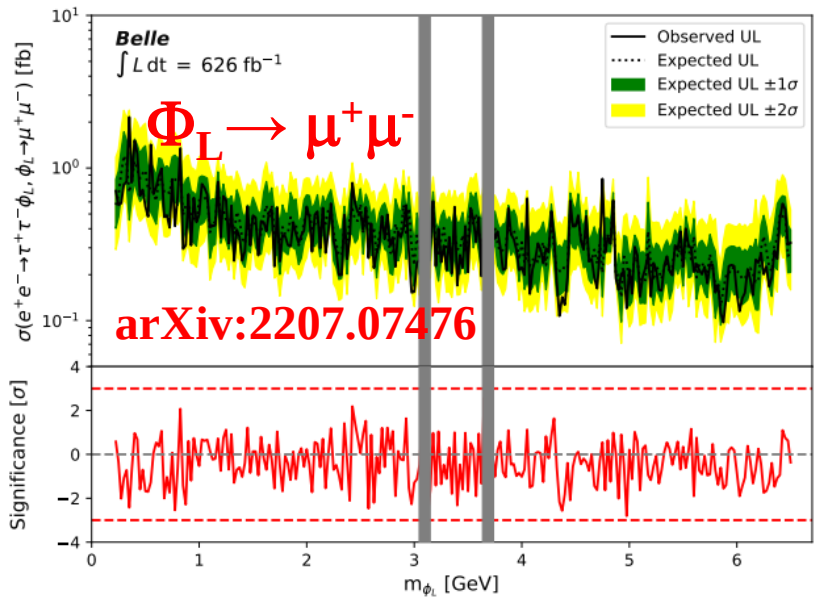
- Search for dark scalar from τ decay
- Leptophilic scalar Φ_L $e^+ e^- \to \tau^+ \tau^- \Phi_L$ & $\Phi_L \to e^+e^-/\mu^+\mu^-$
- Φ_L decay
  - ✓ $\Phi_L \to e^+e^-$ for $m(\Phi_L) < 2m_\mu$: low mass region
  - ✓ $\Phi_L \to \mu^+\mu^-$ for $m(\Phi_L) > 2m_\mu$: high mass region
- Strategy
  - ✓ Require 1-prong τ final states
  - ✓ 4 track with 0 net charge
  - ✓ peak of invariant of $m(l^+l^-)$, l = e, μ
- Define BDT score to suppress background
- Signal extraction: fit to $m(l^+l^-)$ distribution

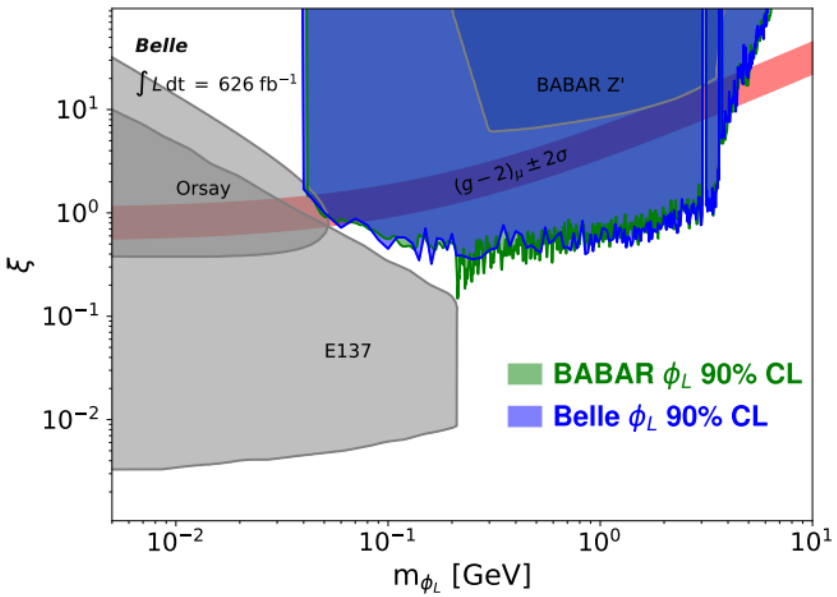




Search for leptophilic scalar in τ decay







- No significant excess obtained in low/high mass region
- 90% CL upper limits on strength ξ vs. m(Φ_L)
  - ✓ Comparable or more stringent limits than BaBar
  - ✓ Exclude wide range of parameter space of model favored by (g-2)$_\mu$

$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell}\, \phi_L \ell$$

Summary

- **The Belle & Belle II experiment are exploring light dark matter or mediators at the luminosity frontier.**
- **New dark sector triggers enable to target unique low multiplicity final states**
- **Interesting results are obtained with a subset of the full available data**
- **A lot of dark sector searches with more Belle II data are in progress.**