



Recent Dark Sector Results from Belle II

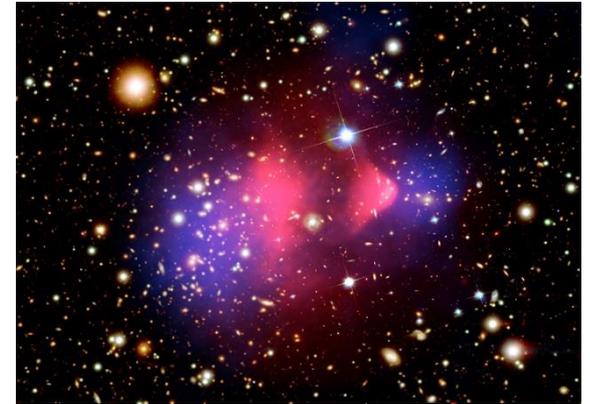
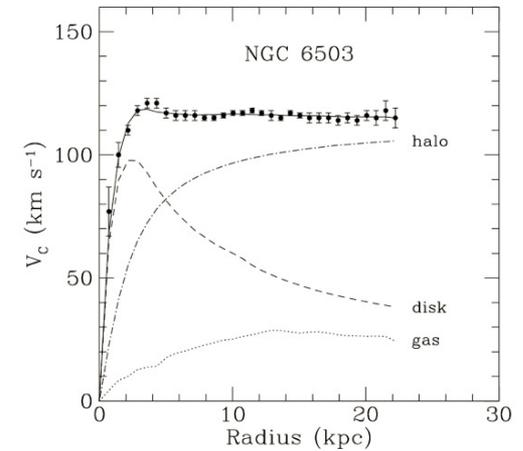
Akimasa Ishikawa
(KEK)



International Conference on Physics of Two Infinities@Kyoto

Dark Matter

- Existence of dark matter (DM : χ) had been established in astrophysics.
 - Rotation curve of a disk galaxy
 - Spatial distributions of **luminous baryonic matter** (with X-ray) and **total matter** (with gravitational lens) in a collision of galaxy clusters
 - CMB
 - And more
- We know the DM density in the Universe
 - $\Omega h^2 = 0.1188 \pm 0.0010$
 - **27%** of total energy
- However there is no DM candidate in the standard model (SM) of particle physics
- Search for DM is a central issue in elementary particle physics



NASA



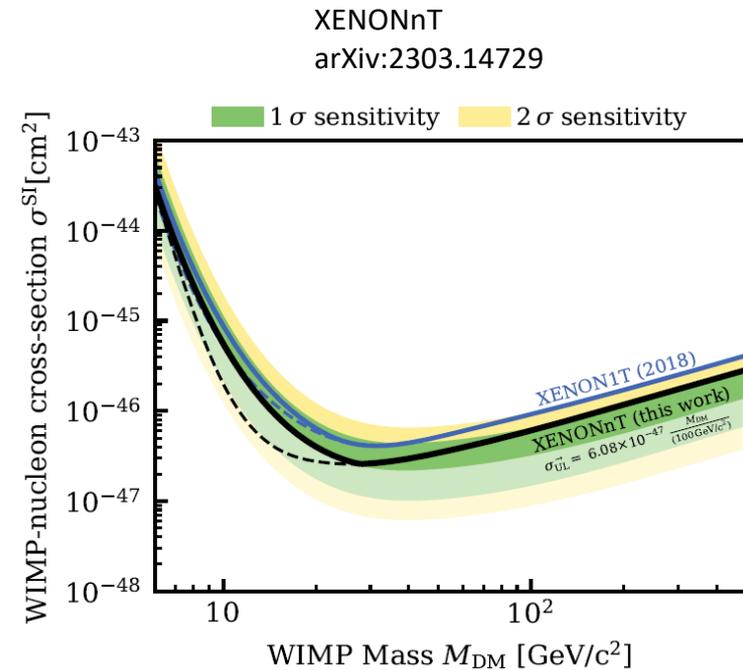
WIMP Miracle and...

- Assuming the thermal relic, **WIMP** with mass around $O(100)$ GeV can explain the relic density.
- WIMP miracle !!**

$$\Omega h^2 \simeq 0.1 \left(\frac{\langle \sigma v \rangle}{10^{-26} \text{ cm}^3/\text{s}} \right)^{-1}$$

$$10^{-26} \text{ cm}^3/\text{s} \simeq 10^{-9} \text{ GeV}^{-2} \sim \frac{g_2^4}{4\pi} \frac{1}{m_{\text{DM}}^2}$$

- However, WIMP has not been observed yet at the energy frontier collider, direct and indirect experiments.
- So wide variety of DM scenarios** got attention recently.
- Dark sector (DS)** is one of the important DM scenarios.



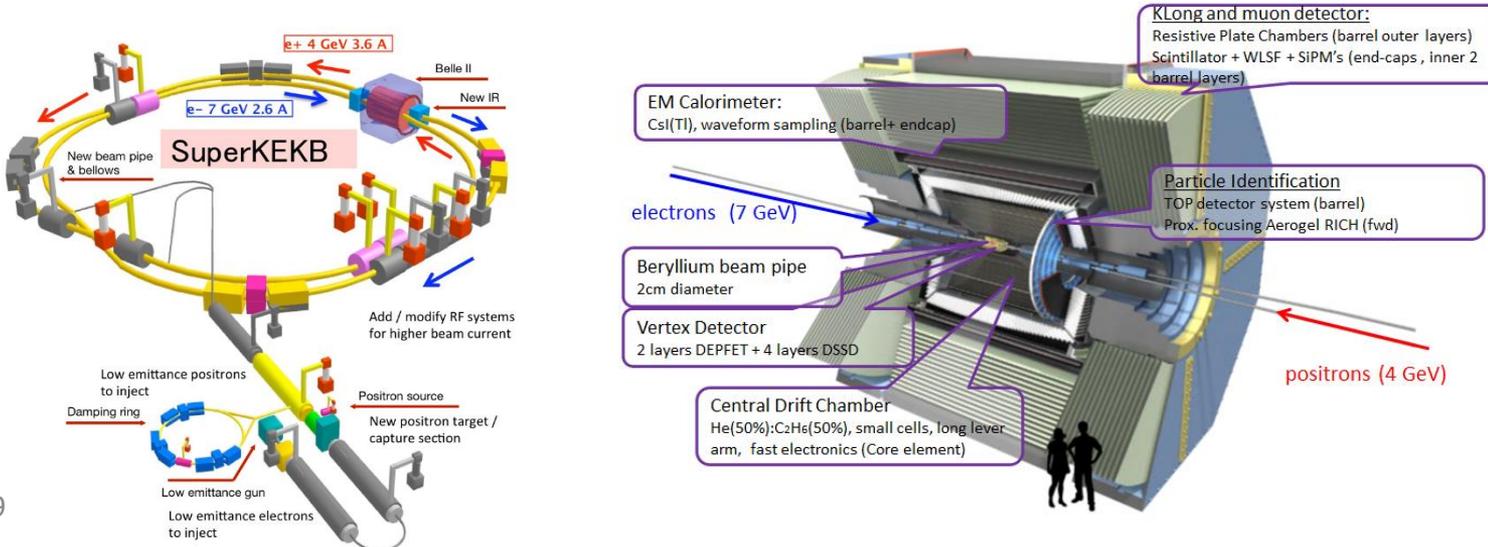
Dark Sector Models

- Particles in the **dark sector** are SM gauge singlet
- **Dark sector** and **SM sector** weakly couple with **mediators (portal particles)**
- (At least) four types of **mediators**
 - Scalar portal : Dark Higgs S
 - Pseudo scalar portal : Axion like particles (ALPs) a
 - Vector portal : Dark photon A', Z' in L_μ - L_τ model
 - Fermion portal : Sterile neutrinos ν_h
 - (Tensor portal??)
- The mediators could have mass around **MeV-GeV**
- Parameter space which can explain **thermal relic** exists
 - heavy sterile neutrinos in GeV scale could also explain leptogenesis



SuperKEK and Belle II

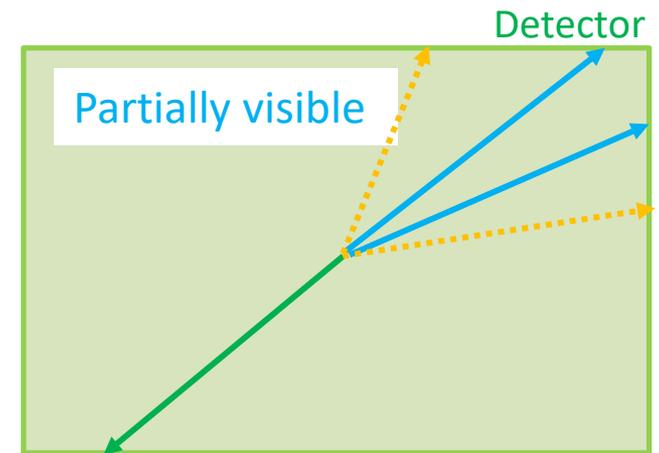
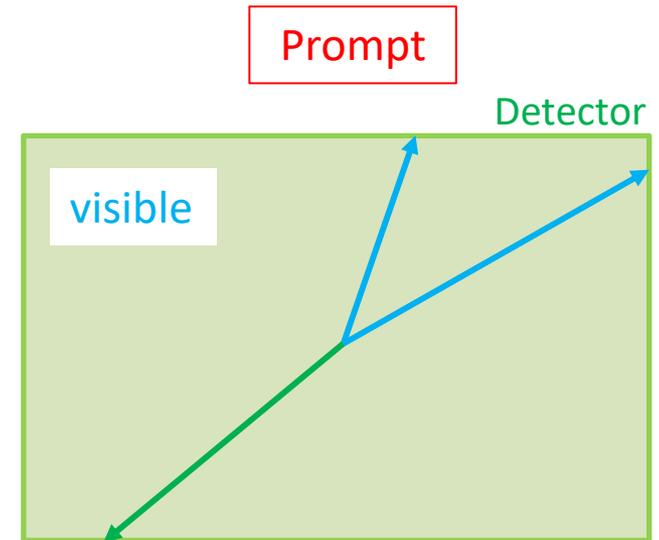
- Belle II@SuperKEKB is a good playground to search for these **mediators and DM around MeV-GeV scale**
 - Electron positron collider with $E_{CM} \sim 10\text{GeV}$
 - **Highest luminosity** in the world : $4.7 \times 10^{34} / \text{cm}^2/\text{s}$ (Target $6 \times 10^{35} / \text{cm}^2/\text{s}$)
 - Collected : 428fb^{-1} , target : 50ab^{-1} around 2034
 - $4\pi \times 94\%$ detector \rightarrow **4momentum conservation** usable
 - In additions to the usual DS searches with leptons and photons, DS searches with heavy flavor **b, τ and c** decays possible.
 - $e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$, $e^+e^- \rightarrow \tau\tau$, $e^+e^- \rightarrow cc$
 - **Single photon/track trigger** enable us to search for dark sector with missing energy



Signatures at e^+e^- Collider

- Mediator can decay to
 - SM particles : **visible**
 - SM+DS final states : **partially visible**
 - DS particles : **invisible**
 - No Decays : **invisible**
- Decay length
 - **Prompt** ($c\tau\beta\gamma \ll 1\text{mm}$)
 - Same as SM physics
 - Bump hunting (**visible**)
 - Recoil or endpoint (**partially visible**)
 - **Long lived (Decay-in-flight)** ($O(1)\text{mm} < c\tau\beta\gamma < O(1)\text{m}$)
 - BG is small thanks to displaced vertex reconstruction
 - except for photon conversions, K_S and Λ
 - Pointing to IP (**visible**)
 - No pointing to IP (**partially visible**)
 - **Very Long lived (Missing)** ($c\tau\beta\gamma \gg O(1)\text{m}$)
 - Or **invisible** decays
 - Missing mass from 4-momentum conservation
 - ν and misreconstructed events (inefficiency) are the BG sources

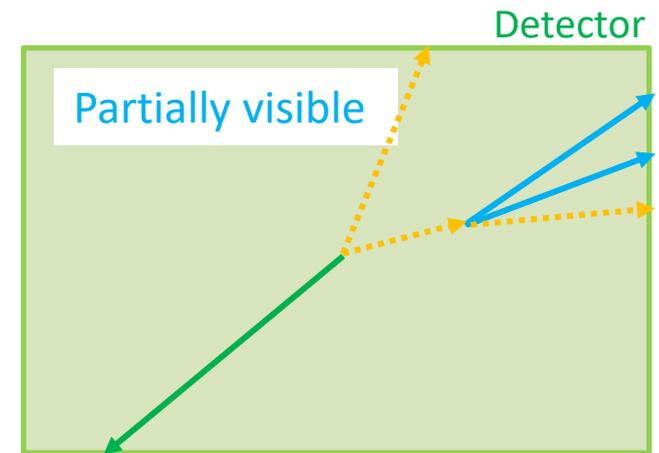
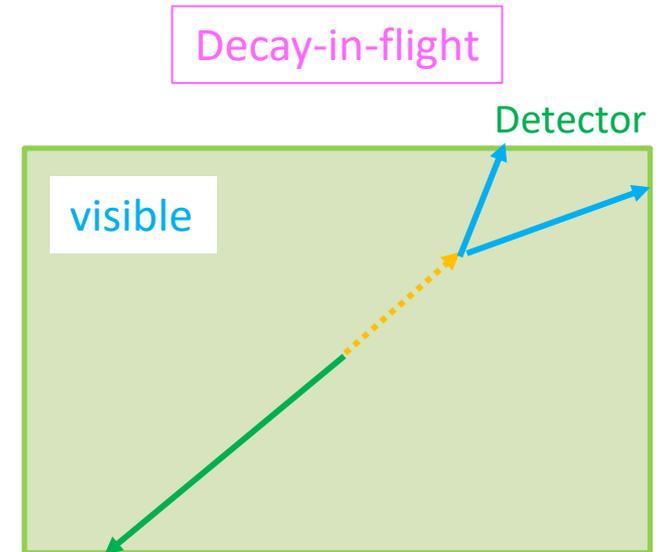
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- ← SM particle from mediator decay
- ←···· Mediator or DS particle



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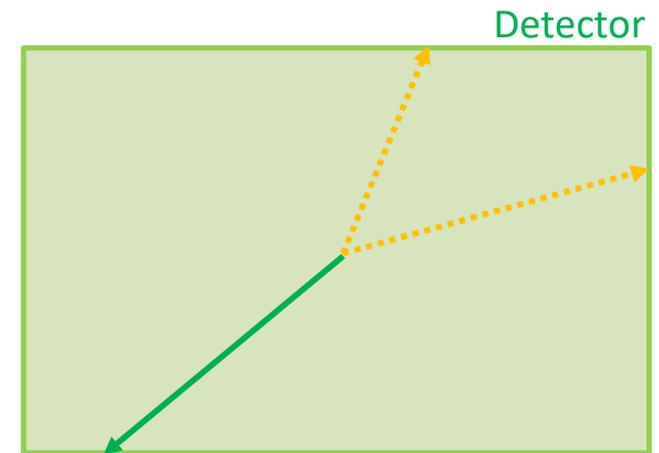
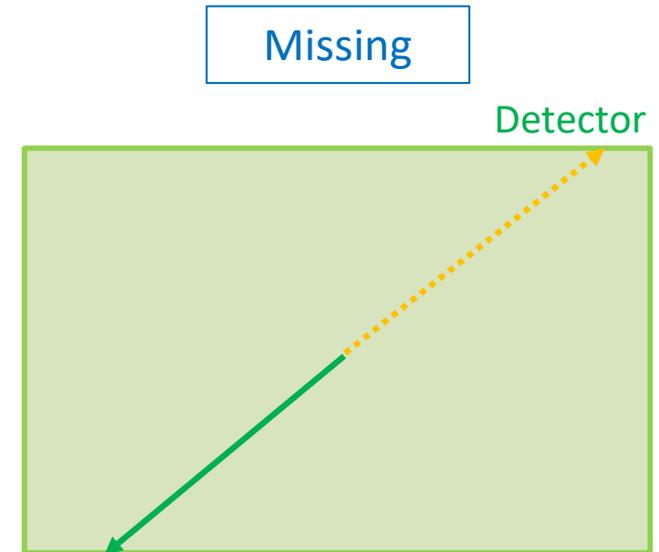
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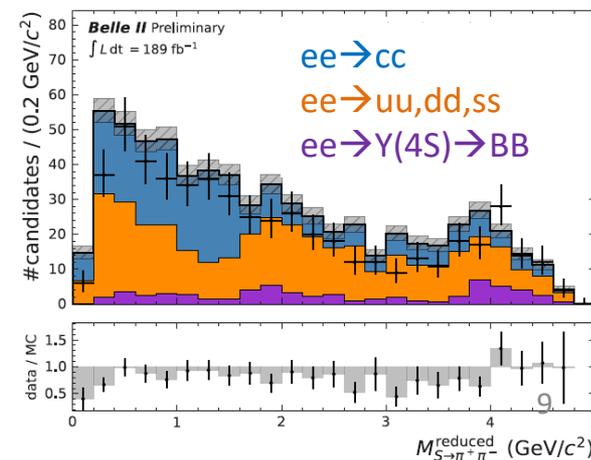
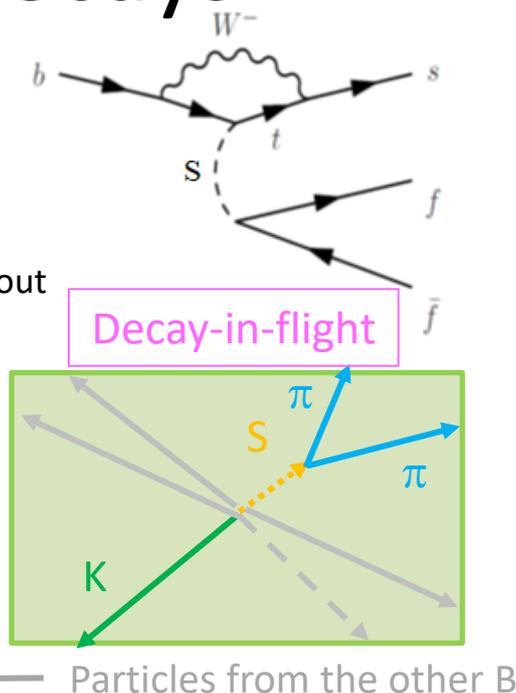
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New !!

Long-lived Dark Scalar in B Decays

- Dark scalar particles S
 - $M_S < 2M_\chi$
 - region where $S \rightarrow \chi\chi$ could explain the relic density already ruled out
 - Can mix with SM Higgs with the mixing angle θ
 - Yukawa coupling larger for heavier fermion
 - long-lived if θ is small
- $B \rightarrow K^+ S$ and $B \rightarrow K^{*0} S$ decays
 - S is radiated off from internal top quark in $b \rightarrow s$ decays
 - $S \rightarrow ee, \mu\mu, \pi\pi, KK$
 - $K^{*0} \rightarrow K^+\pi^-$
 - In total, **8 decay modes**
- Search for B decaying to long-lived S
 - Clean displaced vertex signature
 - Dominant backgrounds are combinatorial
 - $ee \rightarrow cc, ee \rightarrow uu, dd, ss, ee \rightarrow Y(4S) \rightarrow BB$
 - Long-lived K_S^0 is a good control sample

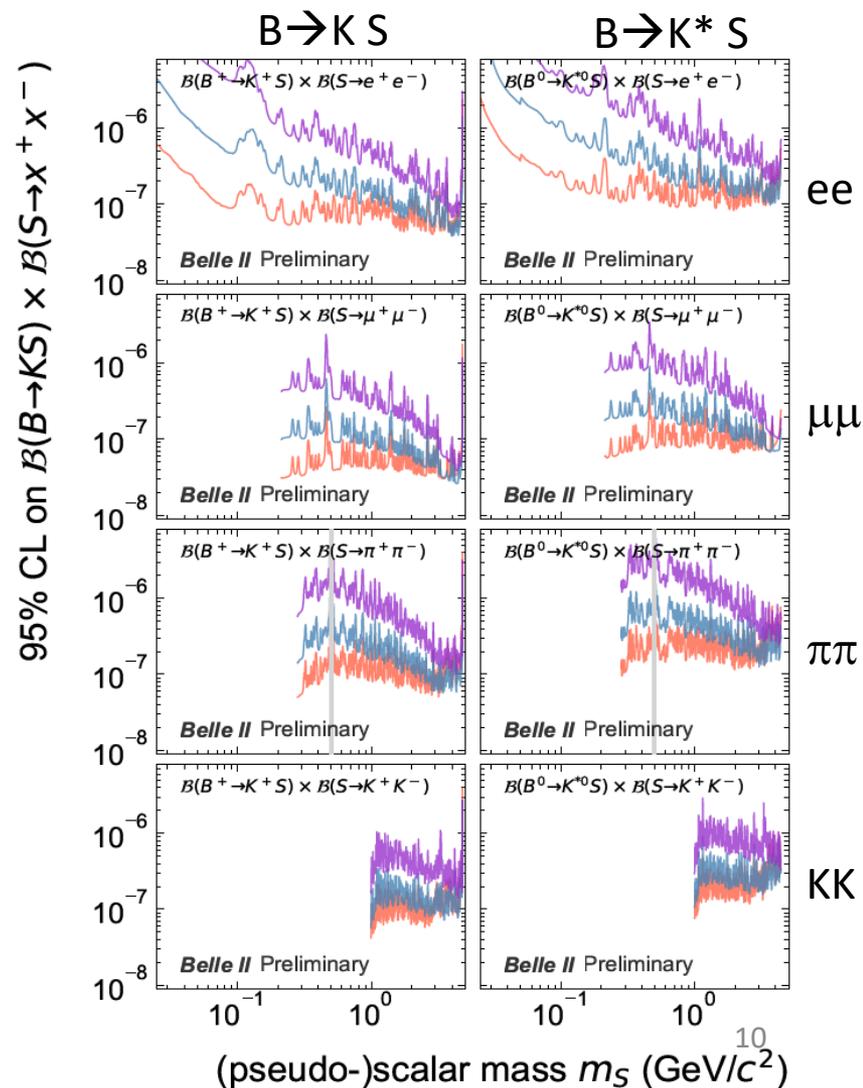


New !!

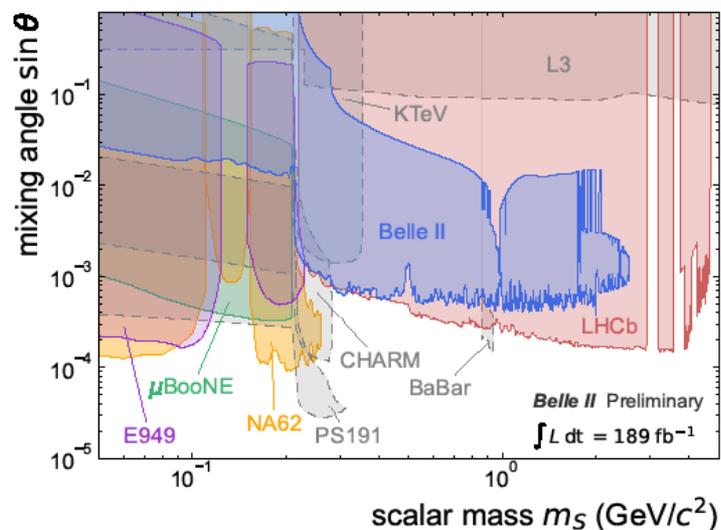
Limit on $B \rightarrow K^{(*)} S$

- Model independent limit on BF
 - As functions of $c\tau$ and mass. $c\tau = 100\text{cm}$
 - For 8 decay modes $c\tau = 10\text{cm}$
 - First limit on S decaying to hadrons $c\tau = 1\text{cm}$
- Model dependent limit on m_S vs. $\sin\theta$
 - Dark Higgs mixing with the SM Higgs
Filimonova, Schäfer, Westhoff, Phys. Rev. D 101, 095006

Model independent



Model dependent

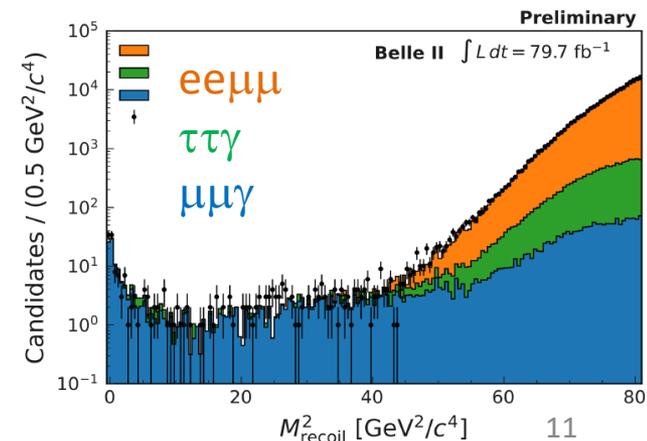
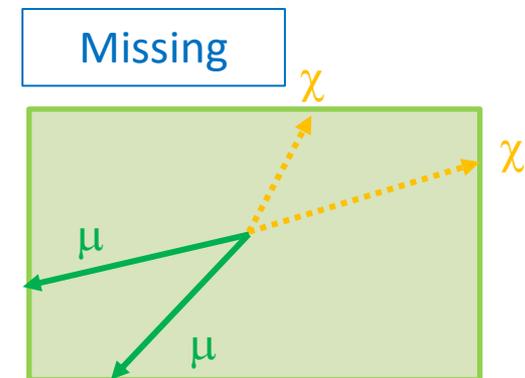
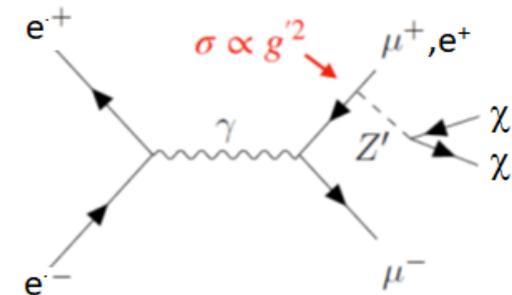


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publication in preparation

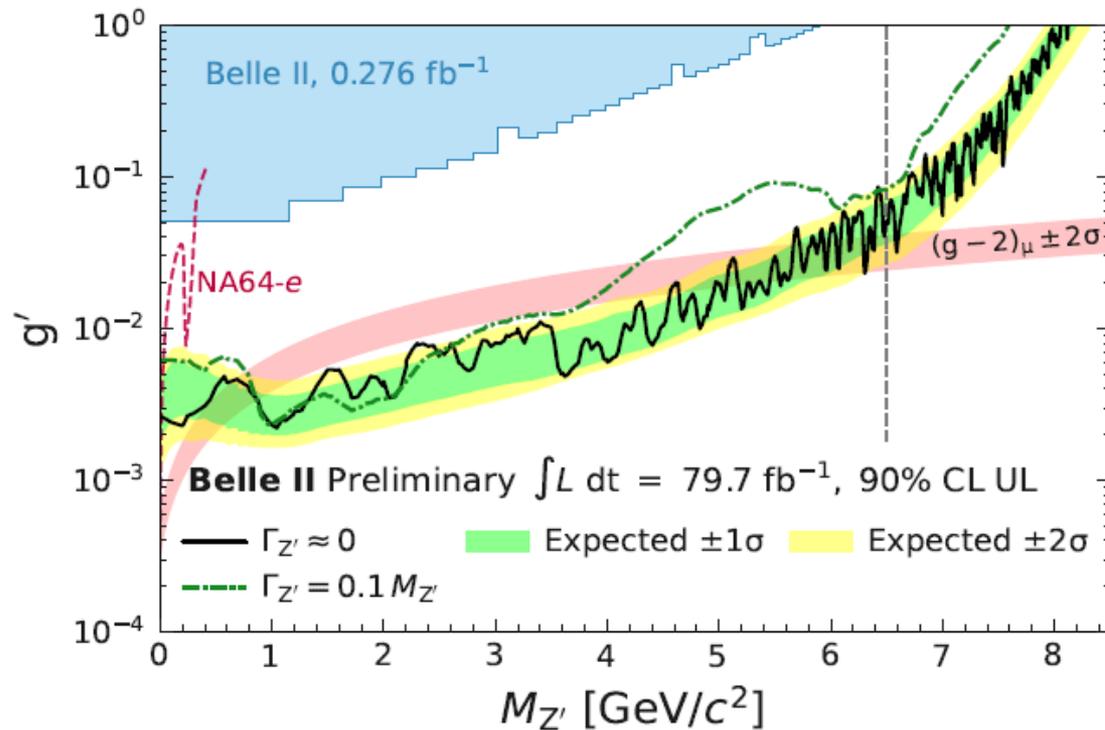
Invisible Z' in L_μ-L_τ model

- Z' only couples to particles with 2nd and 3rd lepton family numbers : μ, τ, ν_μ, and ν_τ
 - Two parameters : m_{Z'} and g'
 - If DM χ carries the 2nd or 3rd lepton family numbers, invisible BF is almost 1 if kinematically allowed.
 - Can access to m_{Z'} < 2m_μ
- Can explain the muon g-2 anomaly
- Signature at Belle II
 - e⁺e⁻ → μ⁺μ⁻Z' → μ⁺μ⁻χχ
- Search
 - Dominant backgrounds
 - ee → eeμμ, ττγ, μμγ
 - Recoil mass and θ_{Recoil} to identify the signal



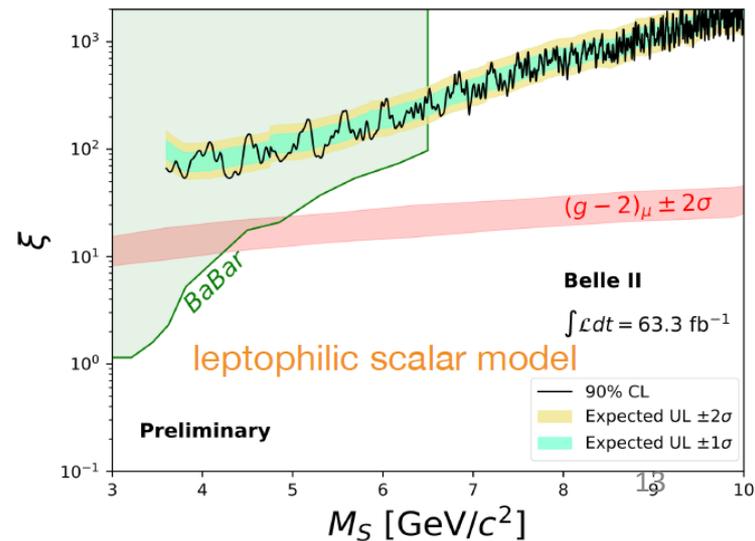
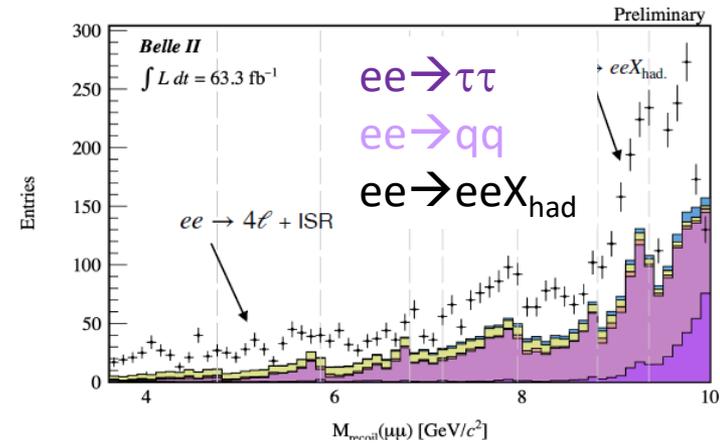
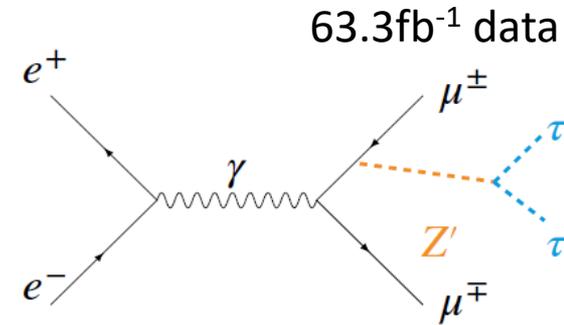
Limit on invisible Z'

- Excluding parameter space explaining **muon g-2 anomaly**
 - $0.8 < M_{Z'} < 4.5\text{GeV}$



$\tau\tau$ Resonance

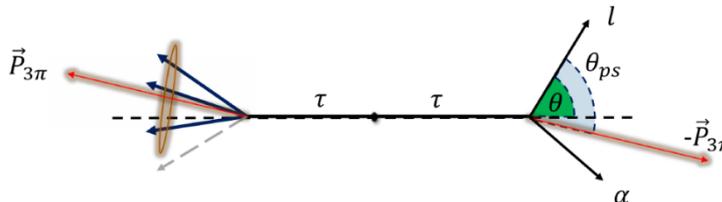
- Signature based searches
 - $ee \rightarrow \mu\mu\tau\tau$
 - τ decays to one-prong and neutrals \rightarrow 4 charged final states
- Search
 - Loose muon ID
 - $M_{4\text{track}} < 9.5\text{GeV}$
 - Multi layer perception to suppress backgrounds
 - Recoil mass against dimuons
 - Dominant backgrounds
 - $ee \rightarrow \tau\tau$
 - Continuum $ee \rightarrow qq$
 - Two photon $ee \rightarrow eeX_{\text{had}}$
- Interpretation
 - Z' in L_μ - L_τ model, leptophilic S , ALP a
 - Best sensitivity for $M_S > 6.5\text{GeV}$



Invisible Boson in Lepton Flavor Violating τ Decays

Signature

- $ee \rightarrow \tau_{\text{sig}} \tau_{\text{tag}}$
- $\tau_{\text{sig}} \rightarrow \mu\alpha, e\alpha$: α is the invisible boson
- $\tau_{\text{tag}} \rightarrow 3\pi\nu$



Long-lived ALPs, etc contribute the decays.

Reconstruction

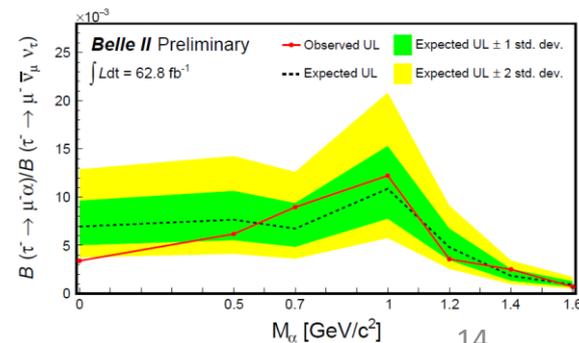
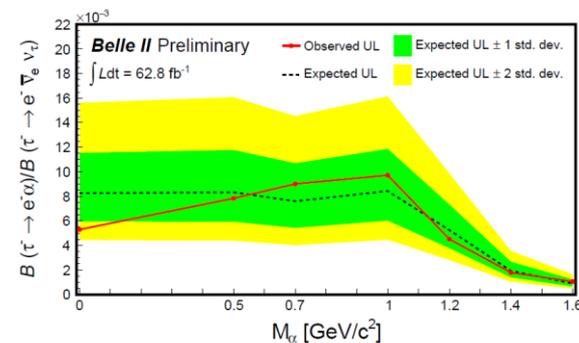
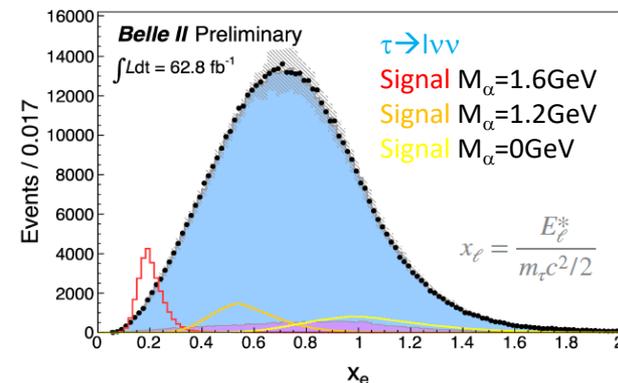
- τ_{tag} momentum direction from 3π
- Pseudo rest frame of τ_{sig}
- **Normalized lepton energy** $x_\ell \equiv \frac{E_\ell^*}{m_\tau c^2/2}$

Dominant background

- Michel decays $\tau \rightarrow l\nu\nu$

Limit on BF ratio as a function of M_α

- New since ARGUS results in 1995.
- The improvement is from **2-fold to 14-fold** dependent on the mass of α



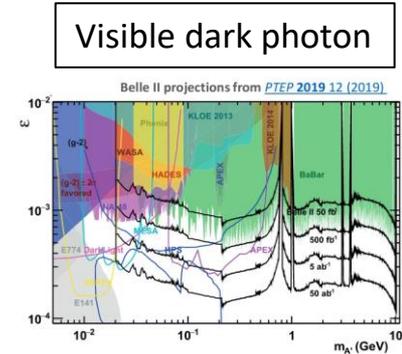
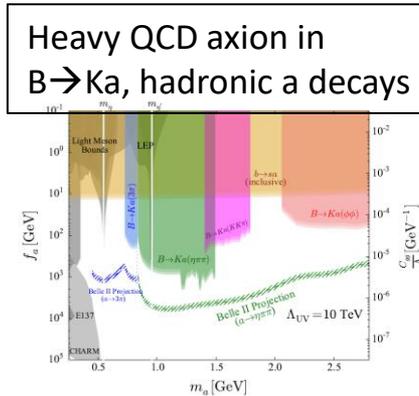
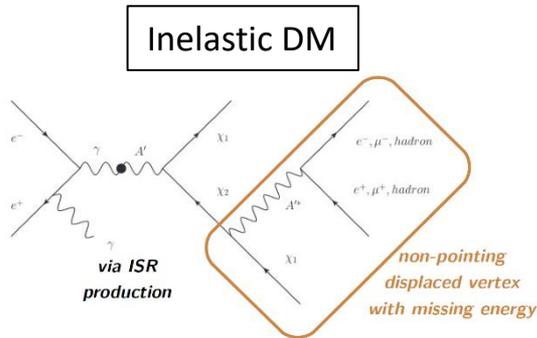
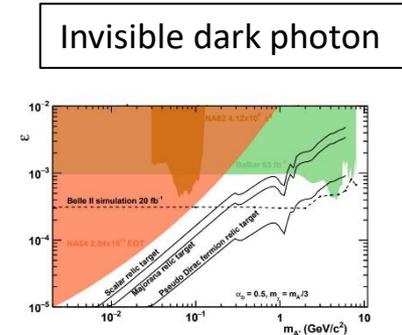
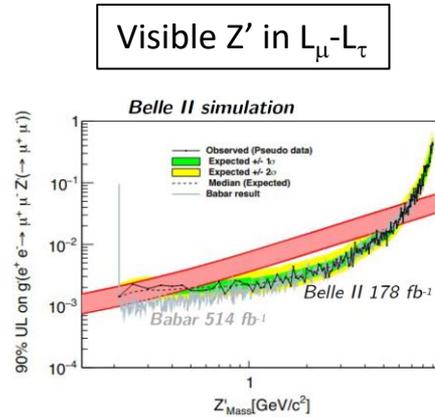
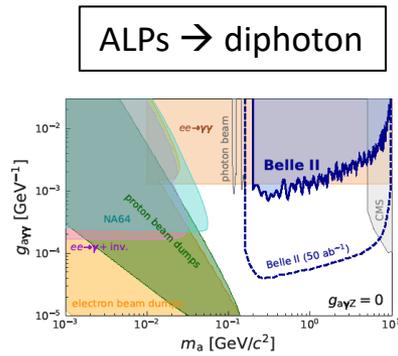
Summary

- Dark sector scenarios are very interesting
- Belle II is a good playground for dark sector searches
- Several searches has been performed with limited statistics
 - Dark Scalar in B decays
 - Invisible Z'
 - $\tau\tau$ resonance
 - Dark boson in τ decays
- World best limits has been obtained.
- Many searches are possible at Belle II and are in pipeline with more data
 - If found, calculate relic density together with theorists
- Stay tuned

backup

Other Dark Sector Searches

- Many searches are possible at Belle II and are in pipeline with more data



ALPs in $B \rightarrow Ka$, $a \rightarrow \gamma\gamma$

Sterile neutrino in B decays

Singlino in $Y(1S)$ decays

ATOMKI dark photon

20230329 Sterile neutrino in τ decays

Dark Higgs in $Y(1S)$ decays

Dark shower

Displaced jets