Dark matter searches in Belle II

Belle II Summer School

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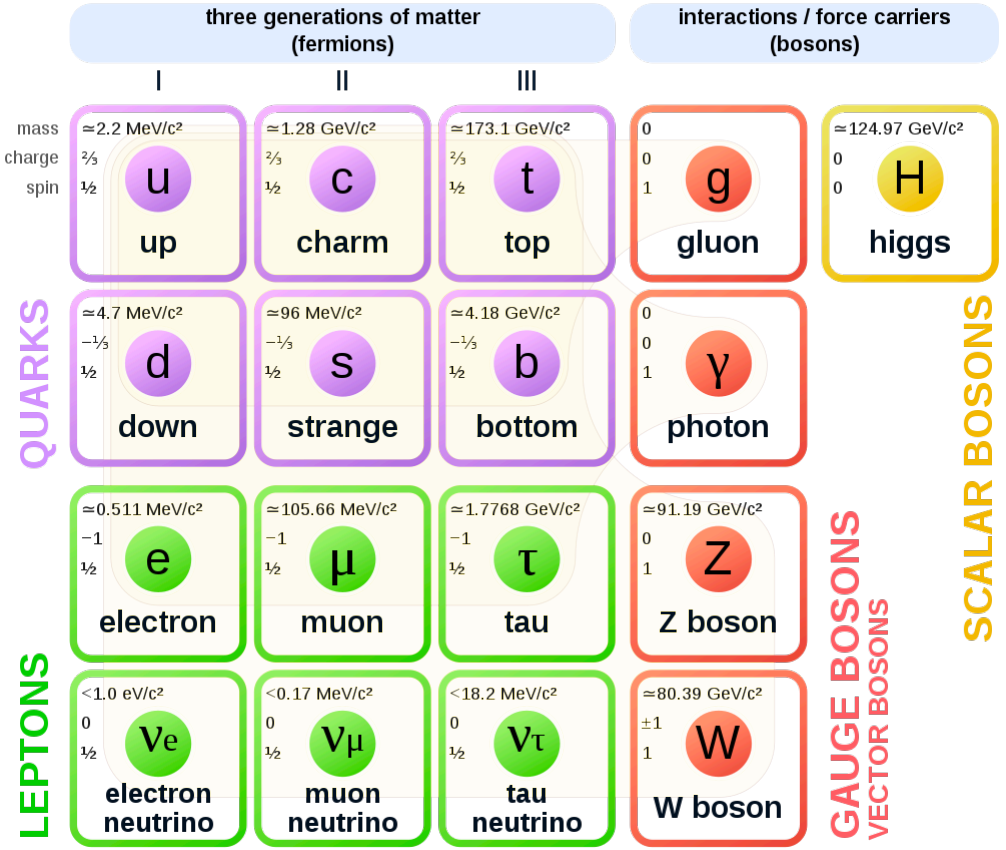
Gaps in the Standard Model

- Several open questions point to physics that is beyond the Standard Model
- Dark sectors often are proposed to address multiple open questions

  - Dark Matter
  - Baryon Asymmetry of the Universe
  - Muon g-2 Anomaly
  - Neutrino mass
  - Strong CP problem
  - Dark Energy
  - Gravitation



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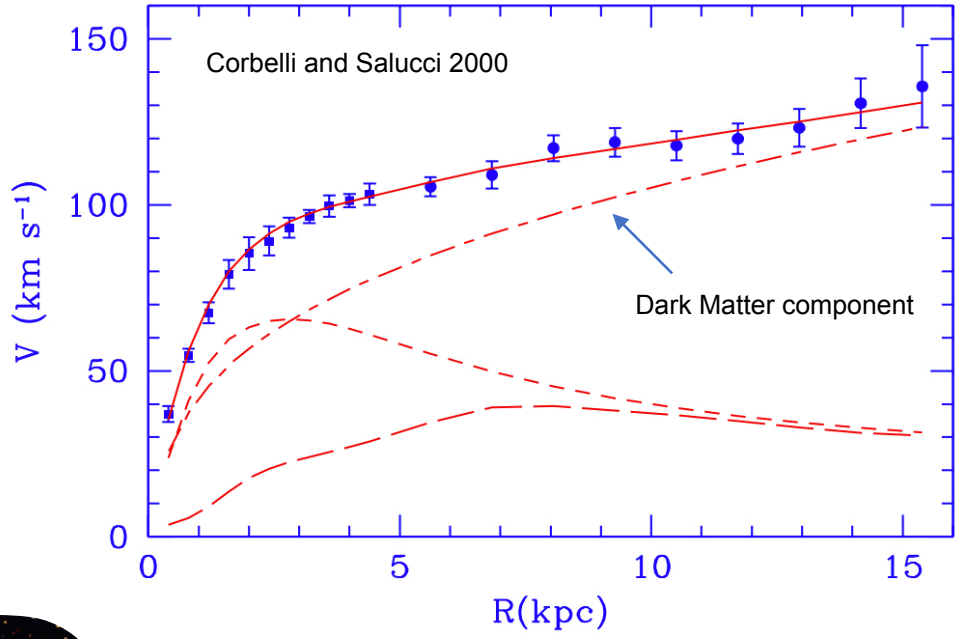
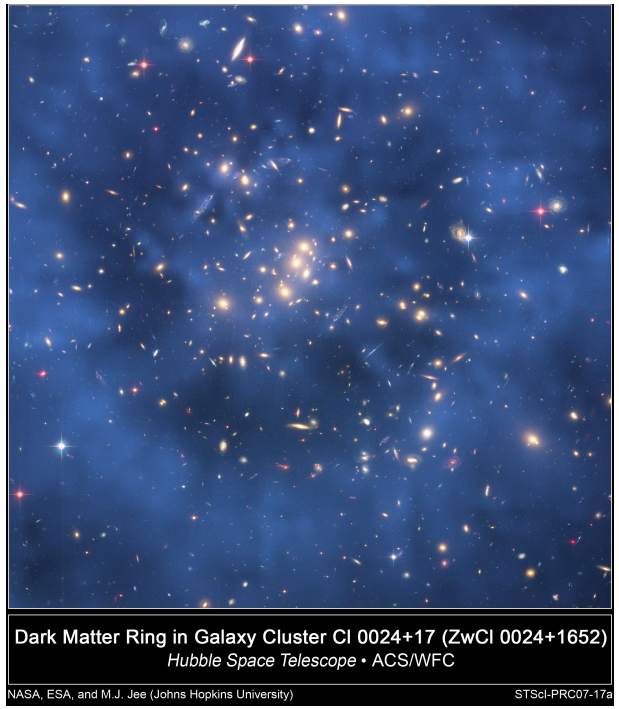
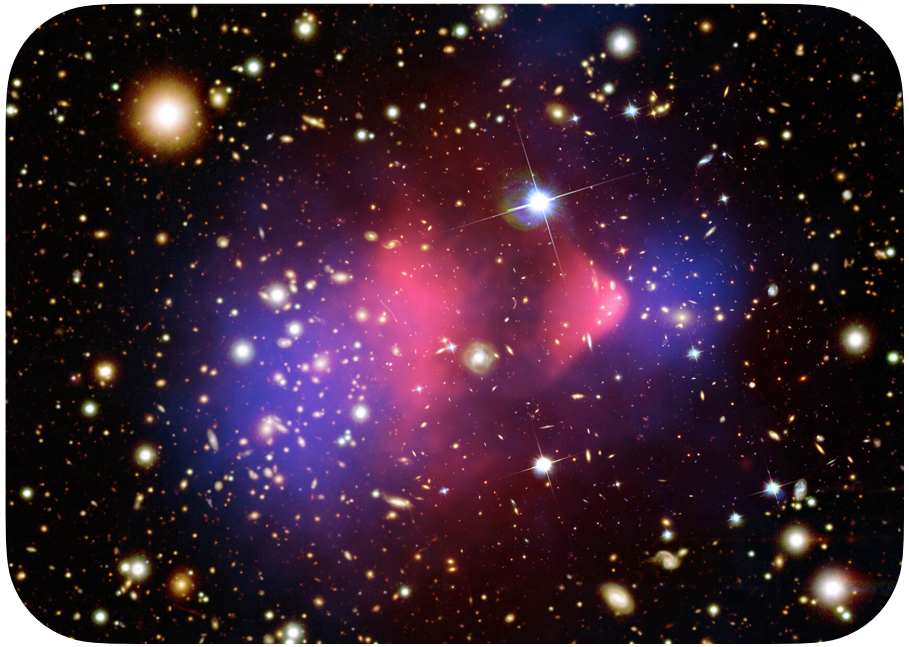
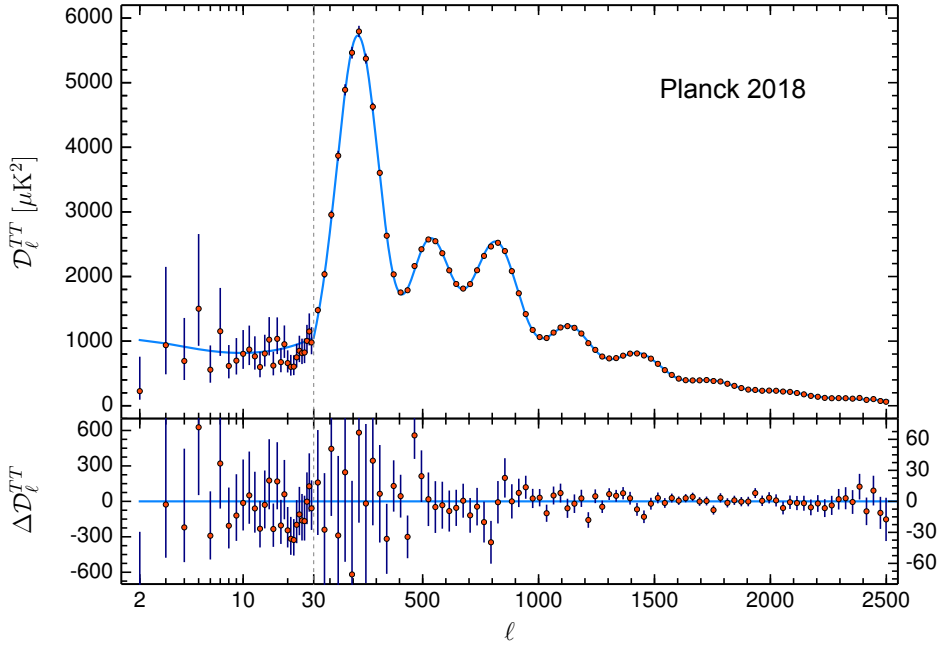
Dark Matter

- Astronomical and cosmological observations show 84% of universe's matter content is Dark Matter
- What we know:
  - ➡It's stable, interacts Gravitationally with the known particles and it is very abundant
- Cannot be explained by any of the particles in the Standard Model









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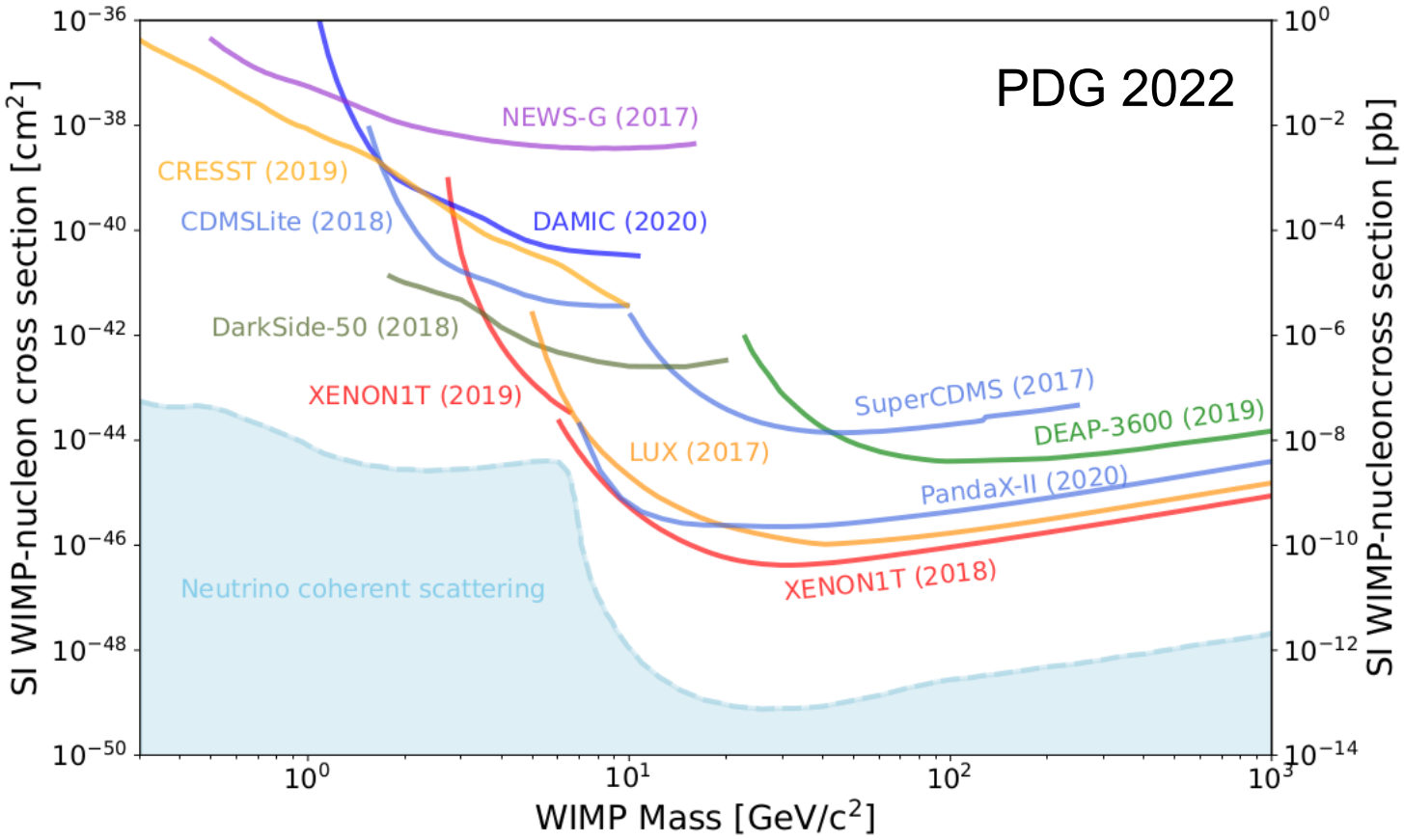
Weakly Interacting Massive Particles (WIMPS)

- Stable particle with GeV-TeV mass
- Interaction cross section with Standard Model near weak scale
- Dark Matter candidate



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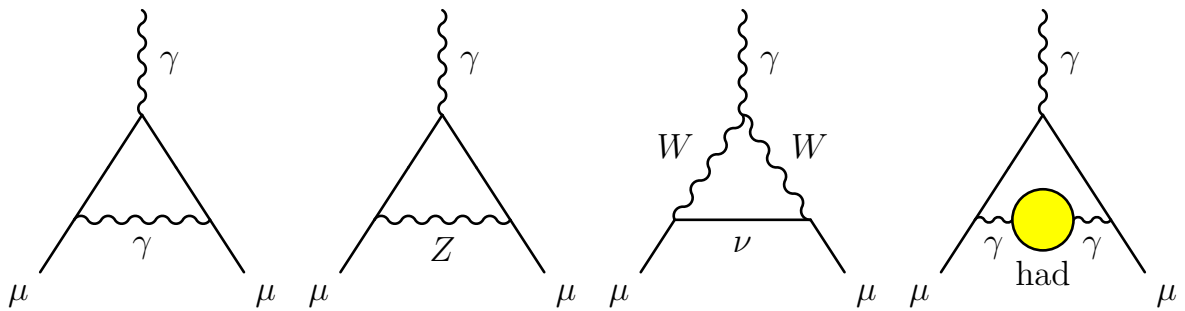
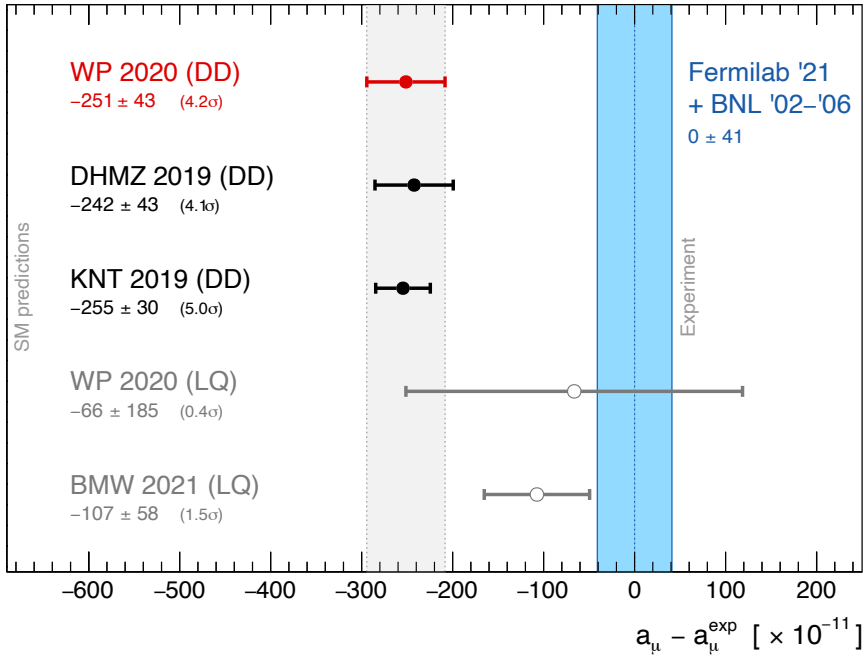
Muon Anomalous Magnetic Moment

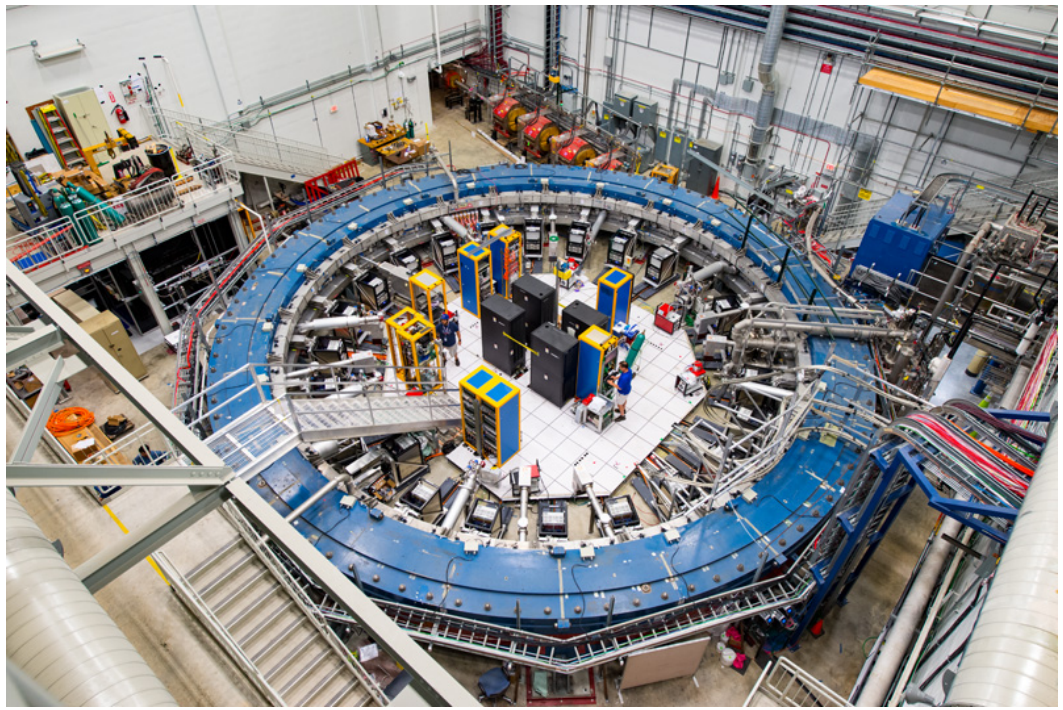
$$\vec{M} = g_\mu \frac{e}{2m_\mu} \vec{S}$$

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Had}}$$







T. Aoyama, N. Asmussen, M. Benayoun et al. Physics Reports 887 (2020) 1–166
B. Abi et al. (Muon g−2 Collaboration) Phys. Rev. Lett. 126, 141801 (2021)

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https://news.fnal.gov/2021/04/first-results-from-fermilabs-muon-g-2-experiment-strengthen-evidence-of-new-physics/

Dark Sectors

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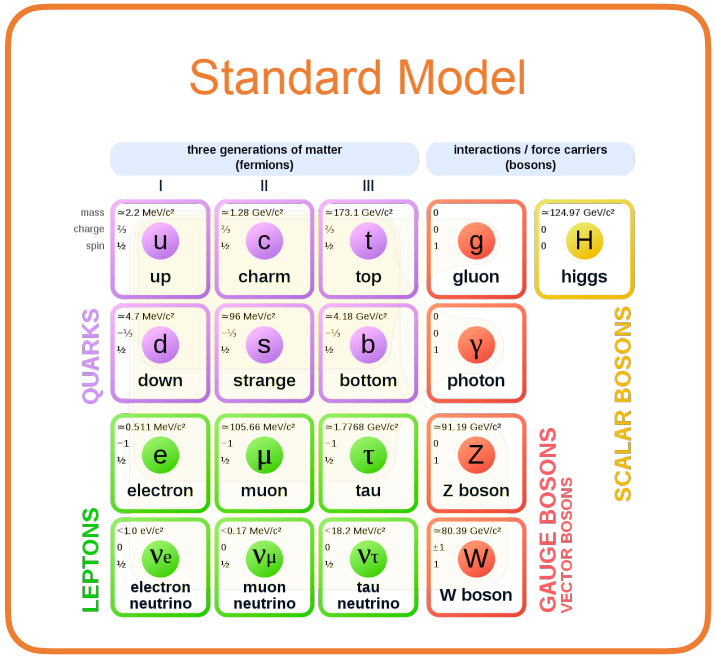
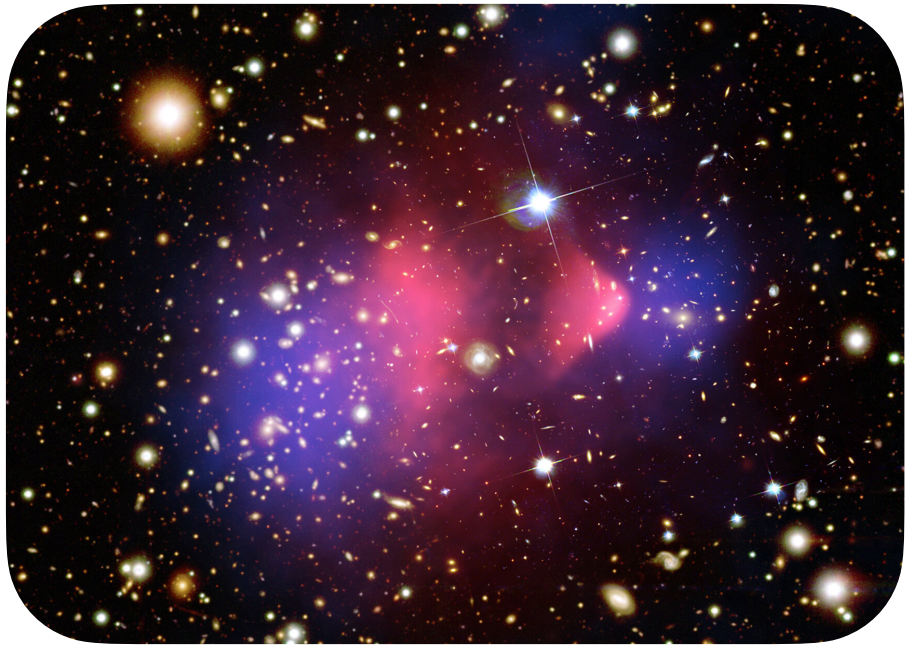
Dark Sectors





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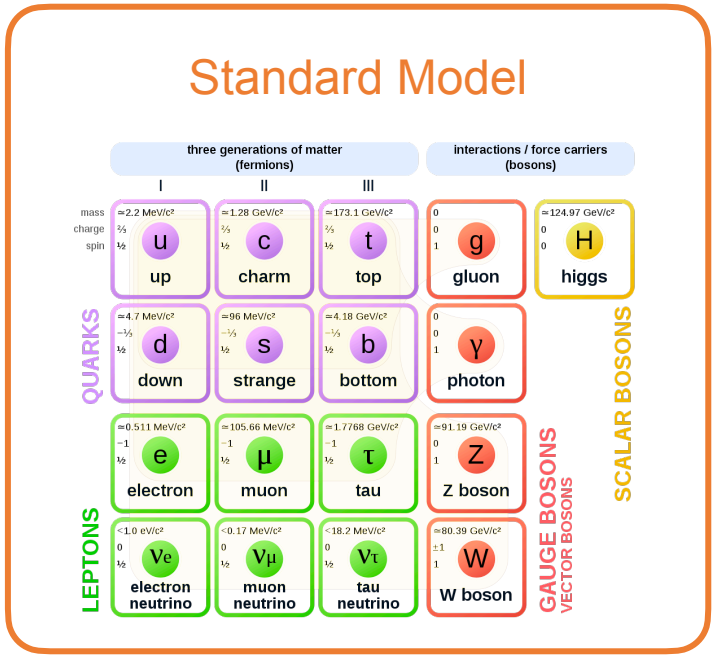
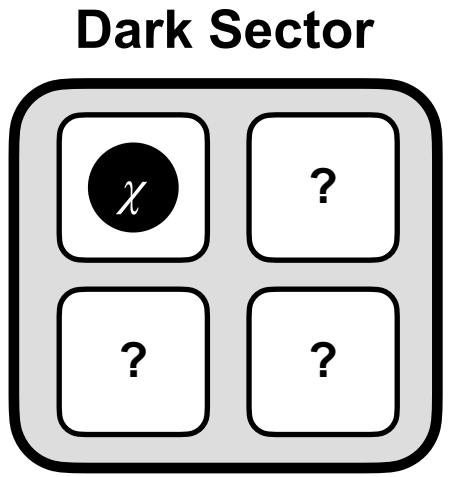
Dark Sectors





Collection of particles with no direct coupling to Standard Model

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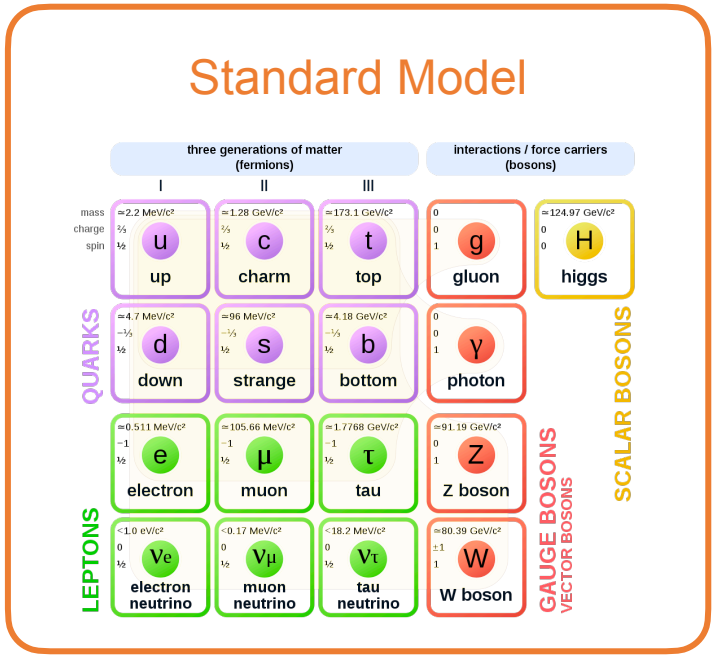
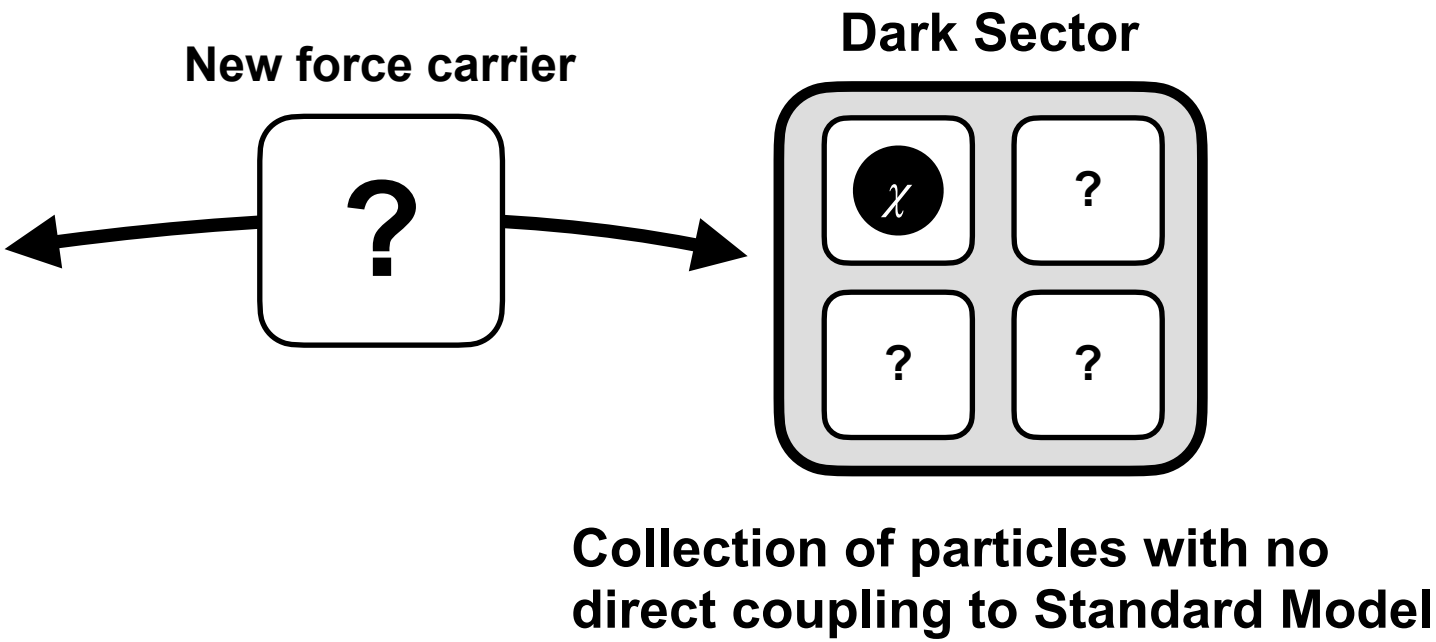
Dark Sectors





Collection of particles with no direct coupling to Standard Model

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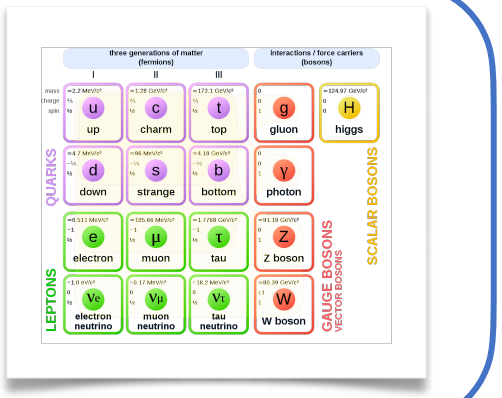
New mediator is a portal to couple dark sector to SM



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A' **Dark Photon** → New **photon-like** interactions
spin $= 1$, parity $= -1$

h' **Dark Higgs** → New **Higgs-like** interactions
spin $= 0$, parity $= +1$

a **Axion-Like Particles** → New gauge boson interactions
spin $= 0$, parity $= -1$

… Many possibilities!

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Dark Photons

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Dark Photon

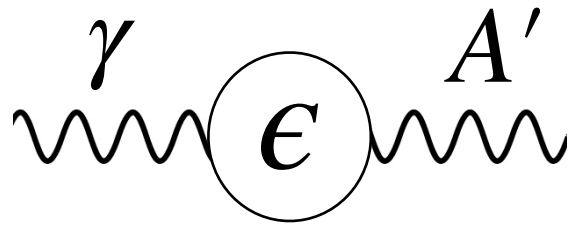
- Massive vector boson arising from broken $U(1)$ gauge symmetry in dark sector
- Couples to Standard Model via kinetic mixing with photon

$m_{A'}$ - Dark Photon Mass

ϵ - Coupling strength to SM

$\Gamma_{A' \to \chi\chi}$ - Branching fractions to decay to DM

$$\varepsilon\, e\, A'_\mu J^\mu_{\mathrm{EM}} + \mathcal{L}_{A'\chi\chi}$$



- Detector signature classified as **invisible** or **visible**

If $m_{A'} > 2m_\chi$

~100% of A' decays are to dark matter

$$A' \to \chi\bar{\chi}$$

"**Invisible**" Detector Signature

If $m_{A'} < 2m_\chi$

$A' \to \chi\bar{\chi}$ is forbidden.

Must decay to Standard Model!

$$A' \to e^+e^-, \mu^+\mu^-, \ldots$$

"**Visible**" Detector Signature

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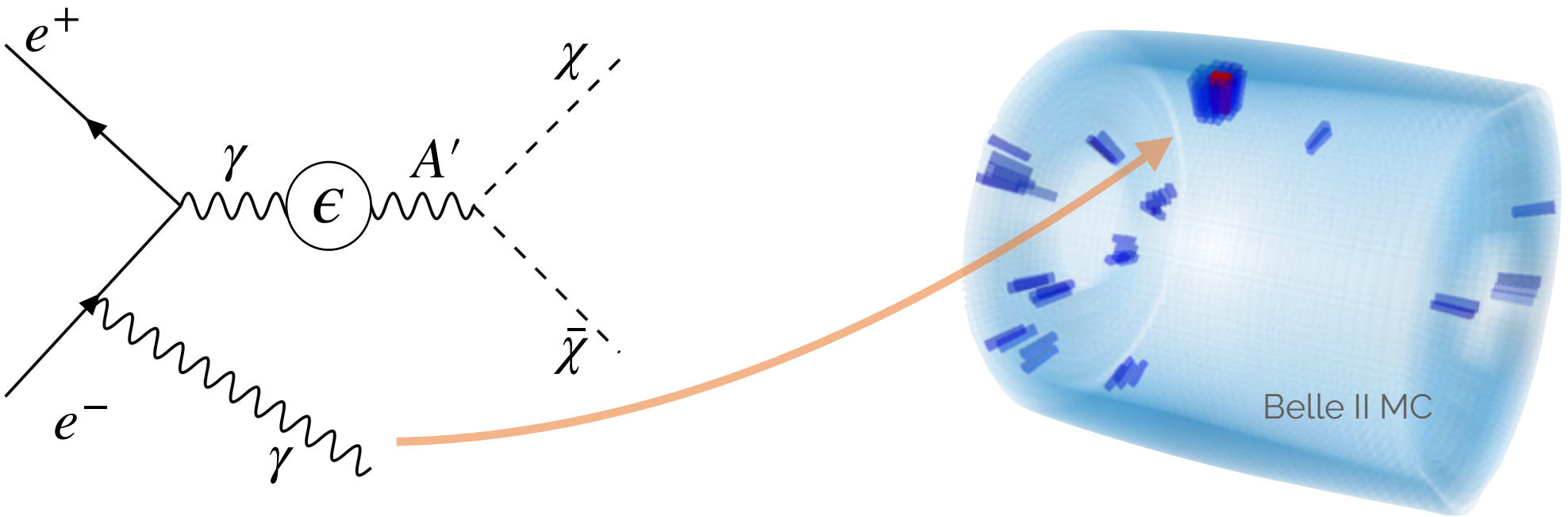
M. Graham, C. Hearty, and M. Williams, Annu. Rev. Nucl. Sci. 71 (2021)

Invisible Dark Photons

- Initial State Radiation photon recoils against Dark Photon
- “Single Photon Search”
- Specialized Single Photon Trigger” is essential (was not present at Belle)

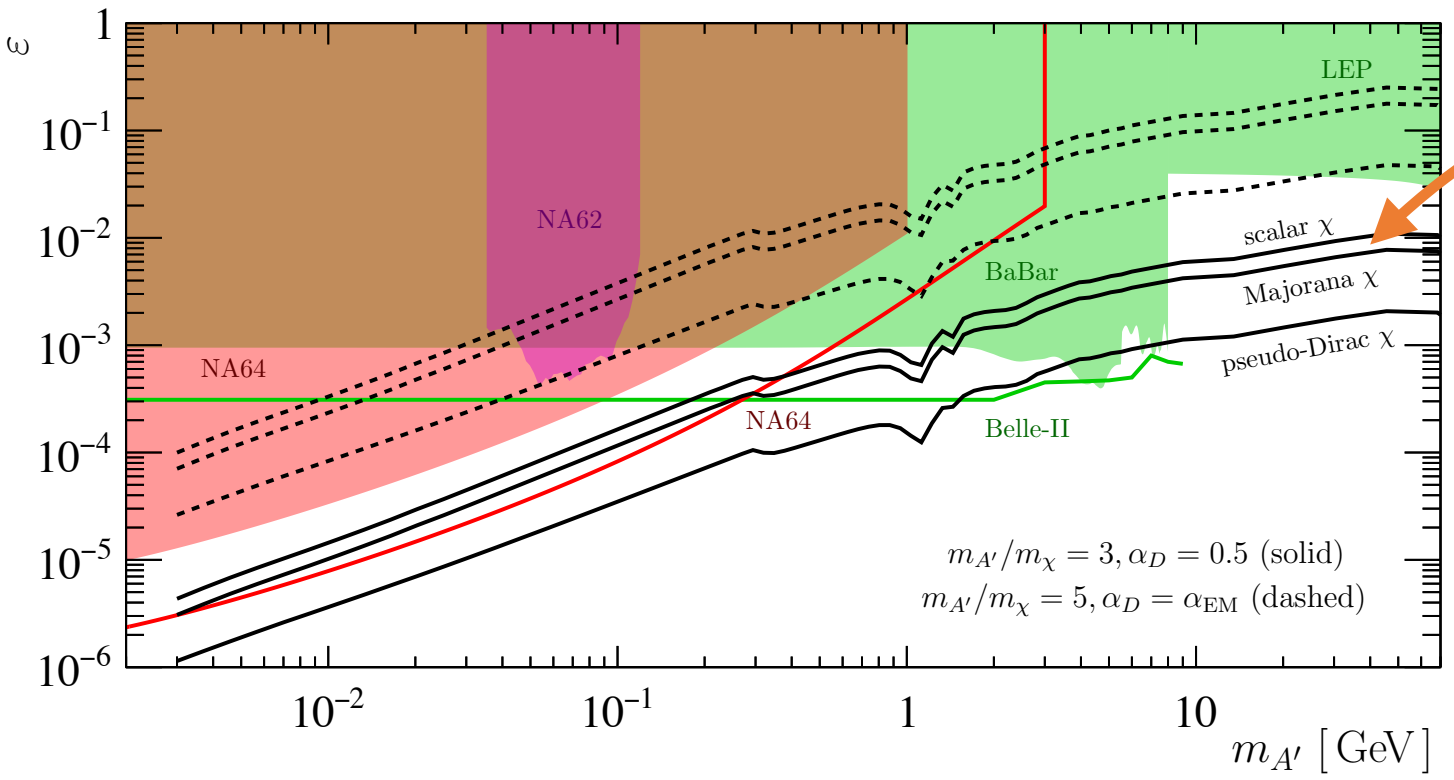


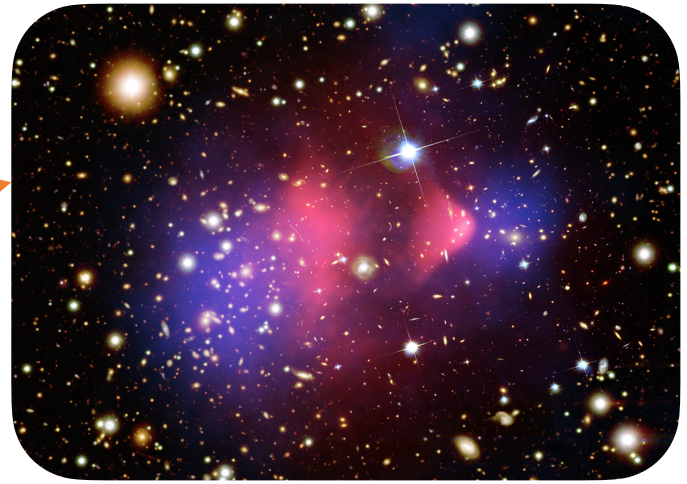
Single Photon Triggers at Belle II:

- At least one photon with E_{CMS} > 2 GeV
- One E_{CMS} > 1 GeV photon in barrel + no other energetic photons
- One E_{CMS} > 0.5 GeV photon in central barrel + no other energetic photons

Invisible Dark Photons

- Belle II analysis (in progress) will explore parameter space that is consistent with universes dark matter abundance





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Invisible Dark Photons

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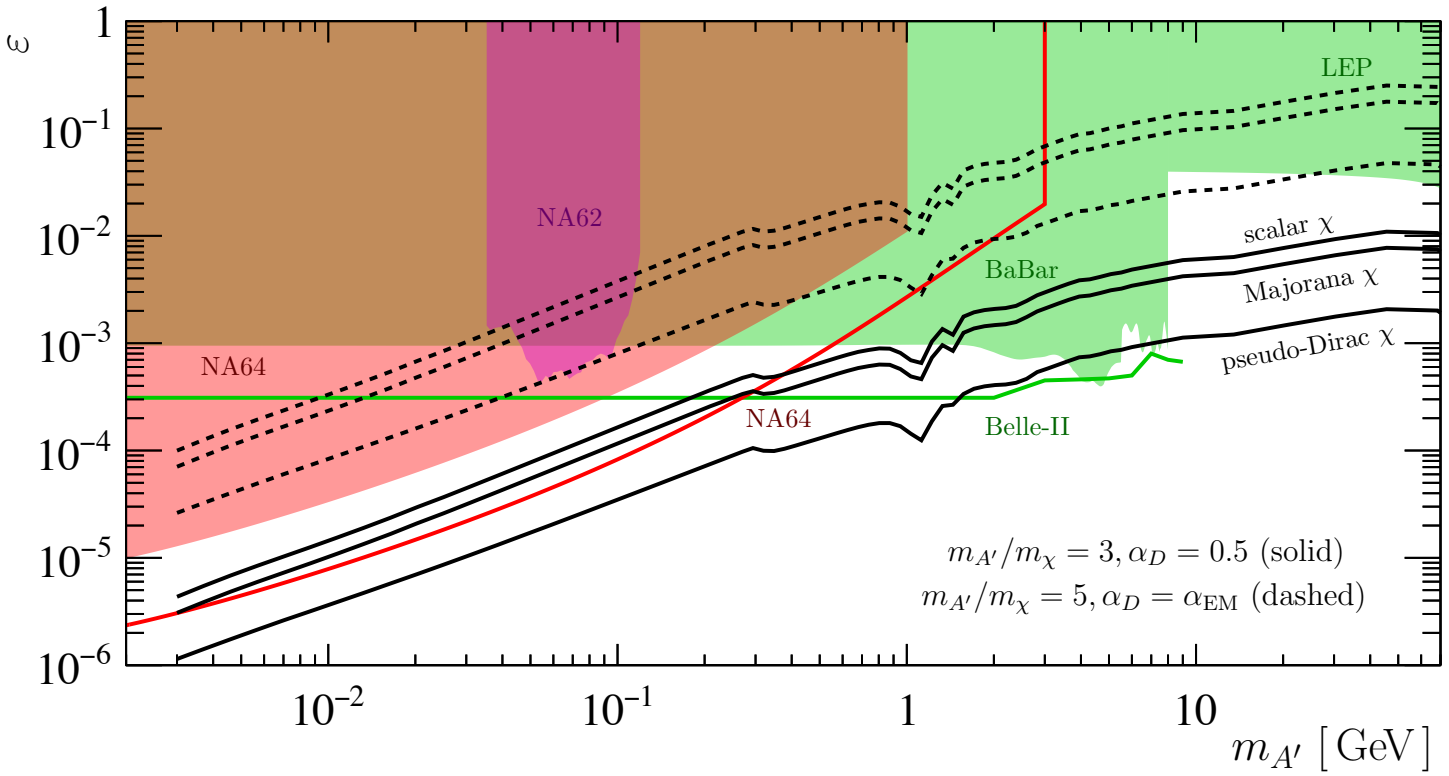

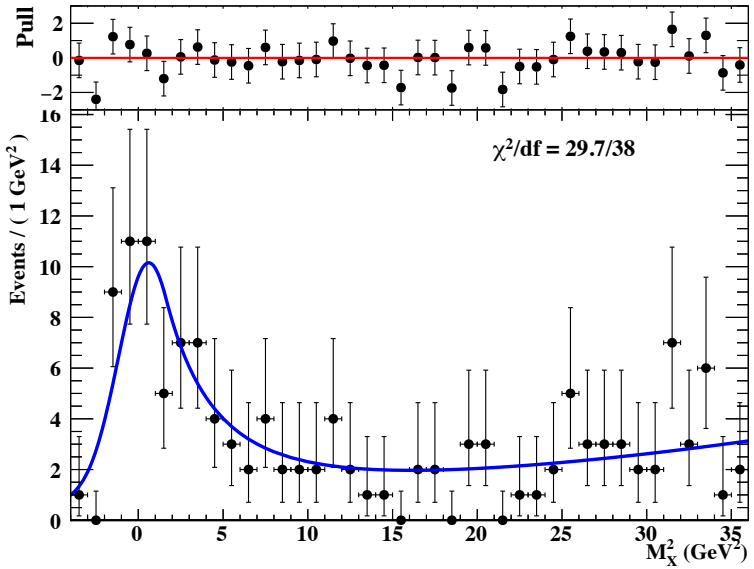

J.P. Lees et al (BaBar Collaboration) Phys. Rev. Lett. 119, 131804 (2017)

- Calorimeter coverage critical to suppress $e^+e^- \to \gamma\gamma(\gamma)$ background
- Belle II benefits from non-projective gaps in ECL geometry. Photons cannot escape between crystal boundaries.
- KLM Veto also essential

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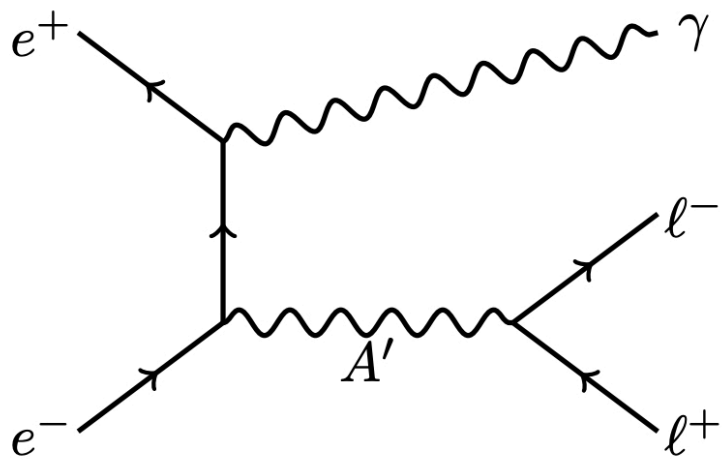
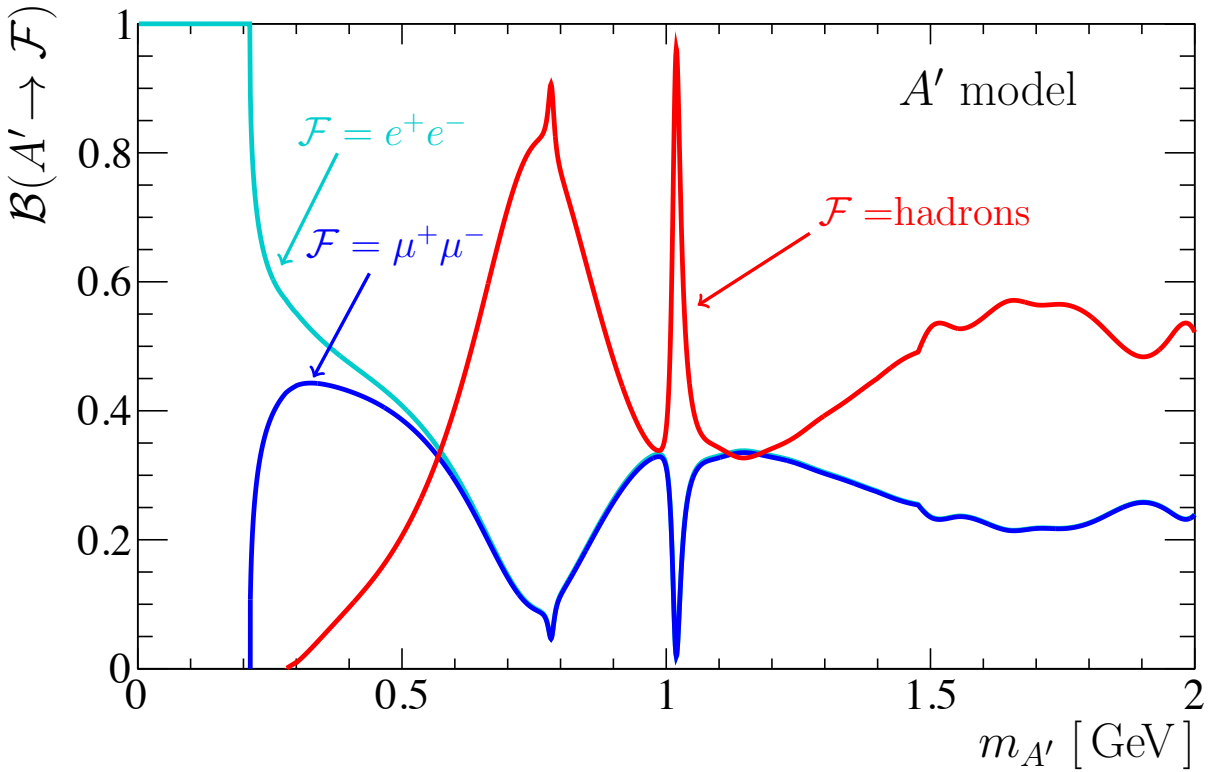
M. Graham, C. Hearty, and M. Williams, Annu. Rev. Nucl. Sci. 71 (2021)

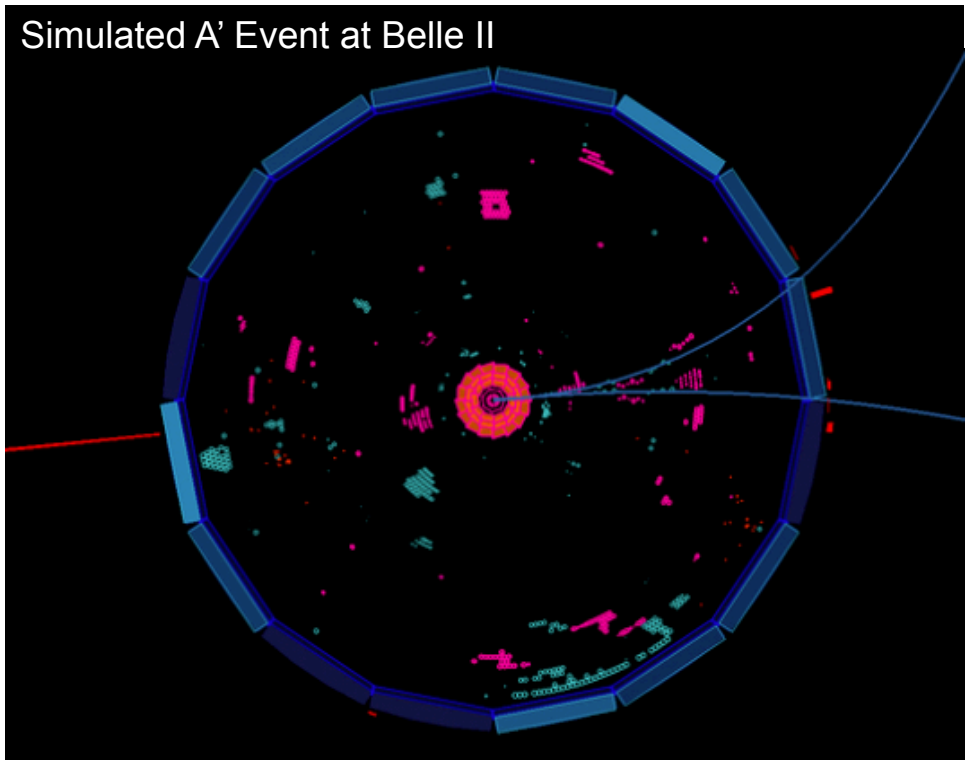
Visible Dark Photons

If $A' \to \chi\bar{\chi}$ is forbidden.

Must decay to Standard Model!







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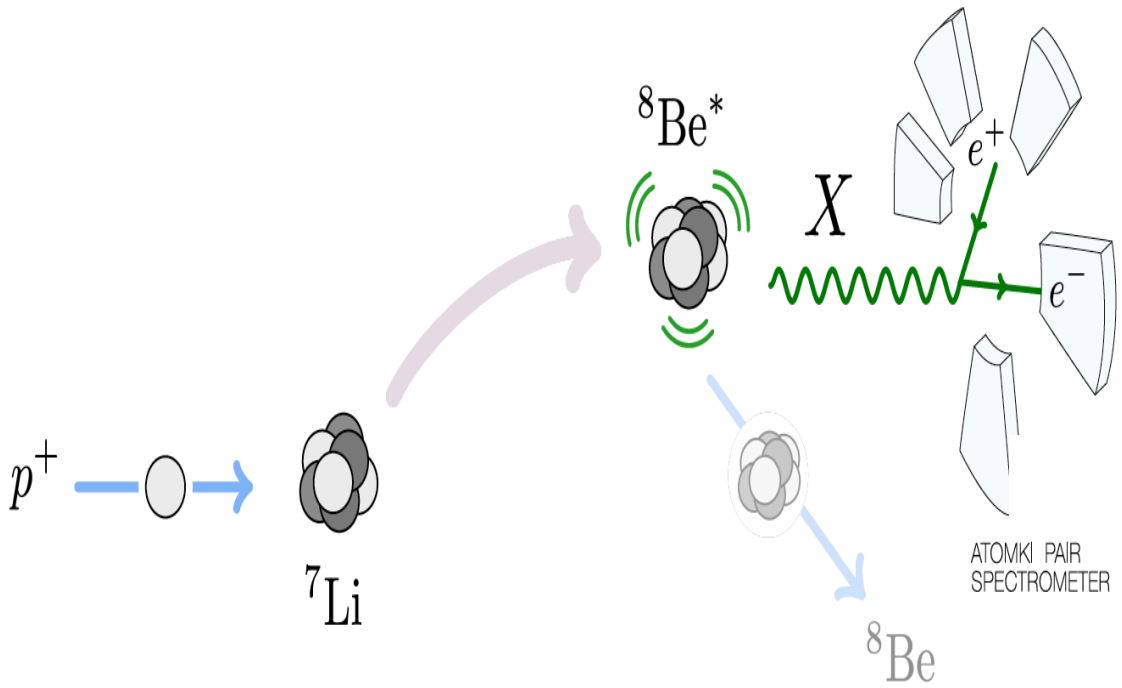
M. Graham, C. Hearty, and M. Williams, Annu. Rev. Nucl. Sci. 71 (2021)

ATOMKI ANOMOLY: A 17 MeV Dark Photon?



- ^{8}Be nuclei excited to 17.6 and 18.15 MeV to 1^+ states
- Standard Model predicts de-excitation via internal-pair-conversion, emitting e^+e^- pair
- De-excitation can also occur through via dark photon. **Would give peak in e^+e^- angular distribution**

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A. J. Krasznahorkay, et al. Phys. Rev. Lett. 116, 042501
A. J. Krasznahorkay, et al. Phys. Rev. C 104, 044003

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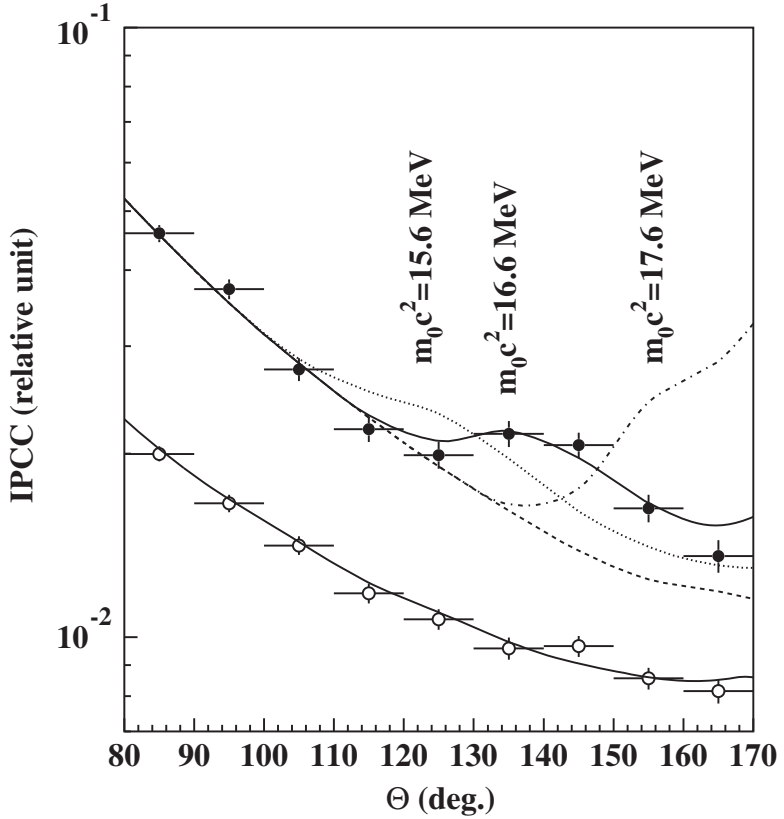

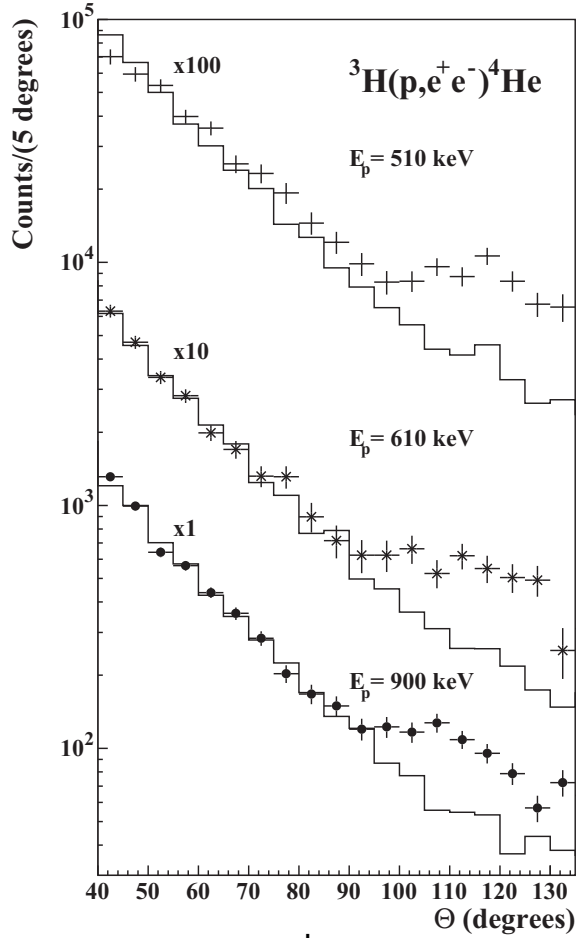

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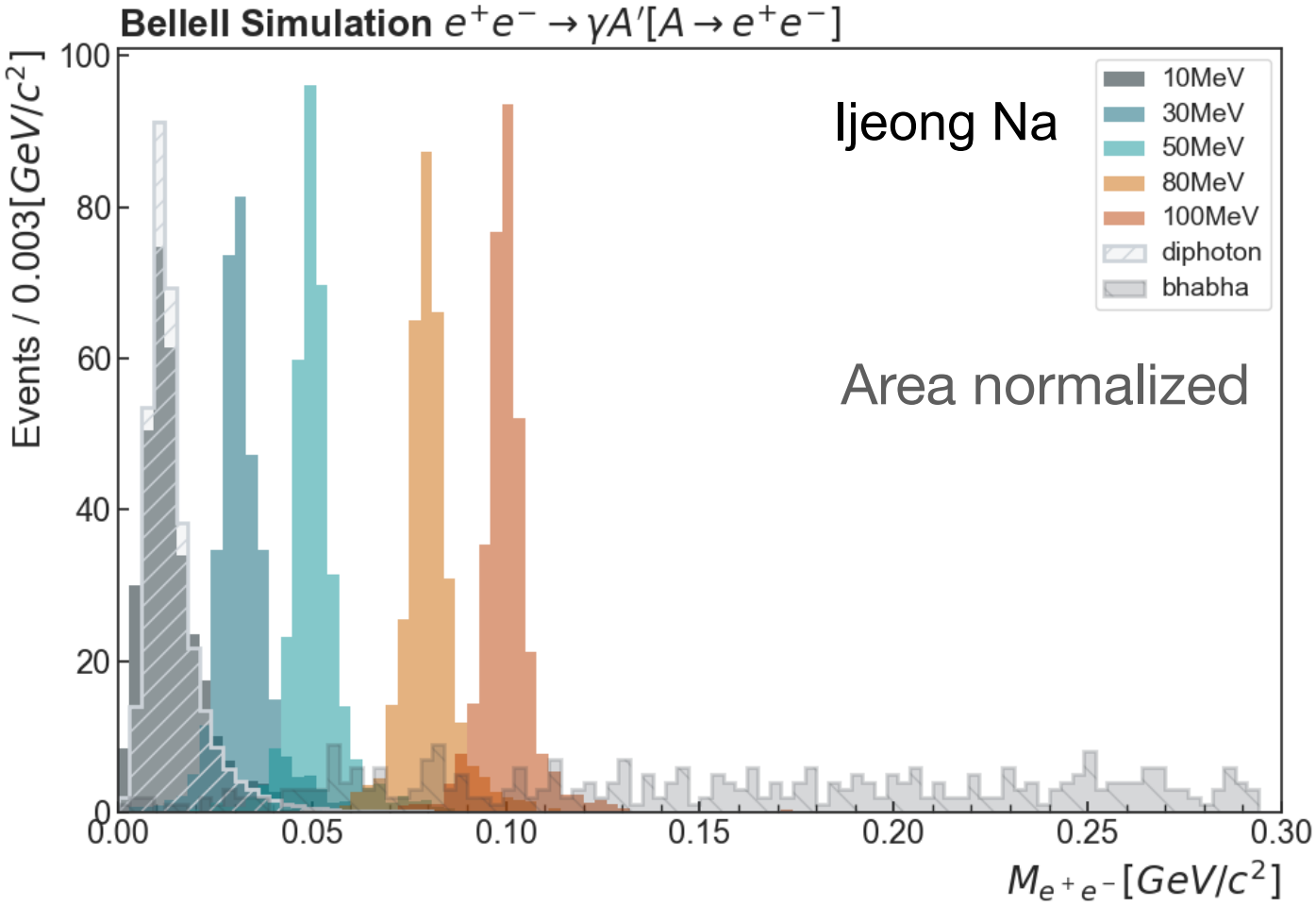
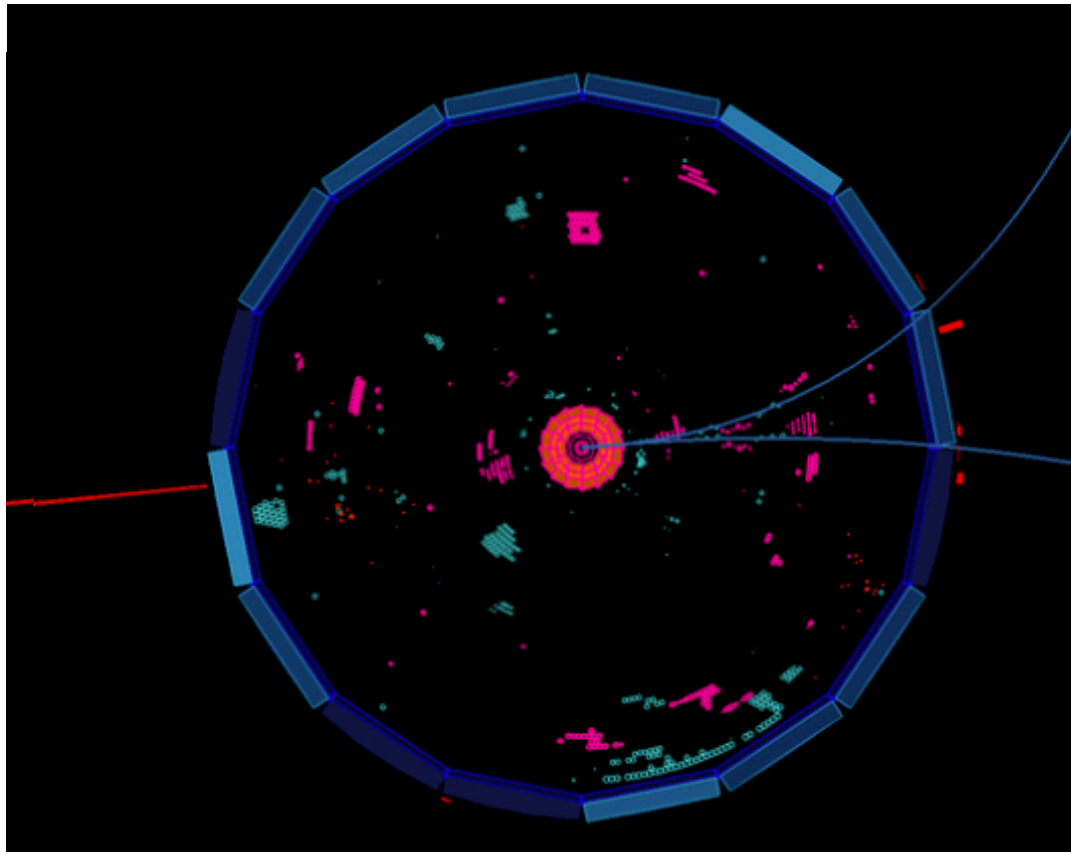
X17 Search at Belle II (In Progress)

Main background sources :

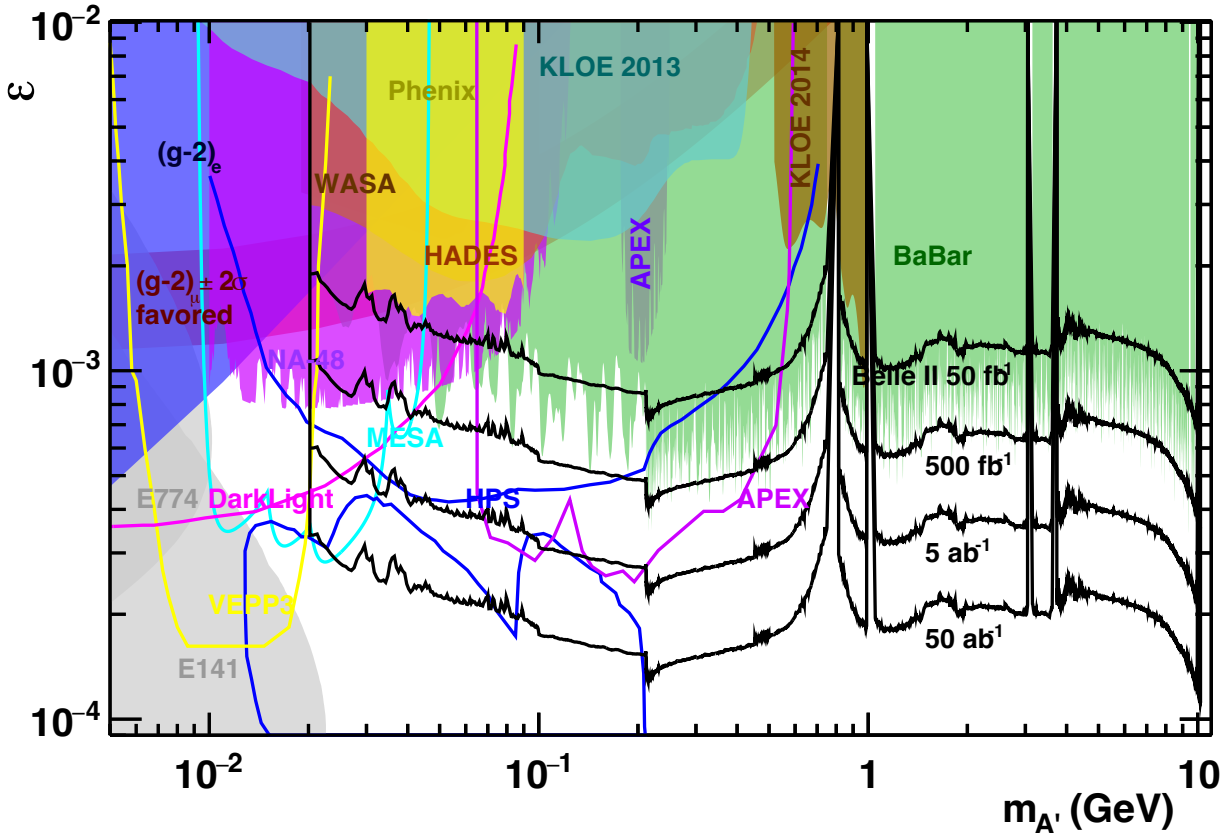
- $e^+e^- \to e^+e^-\gamma$
  $e^+e^- \to \gamma\gamma \quad (\ \gamma \to e^+e^-\ )$

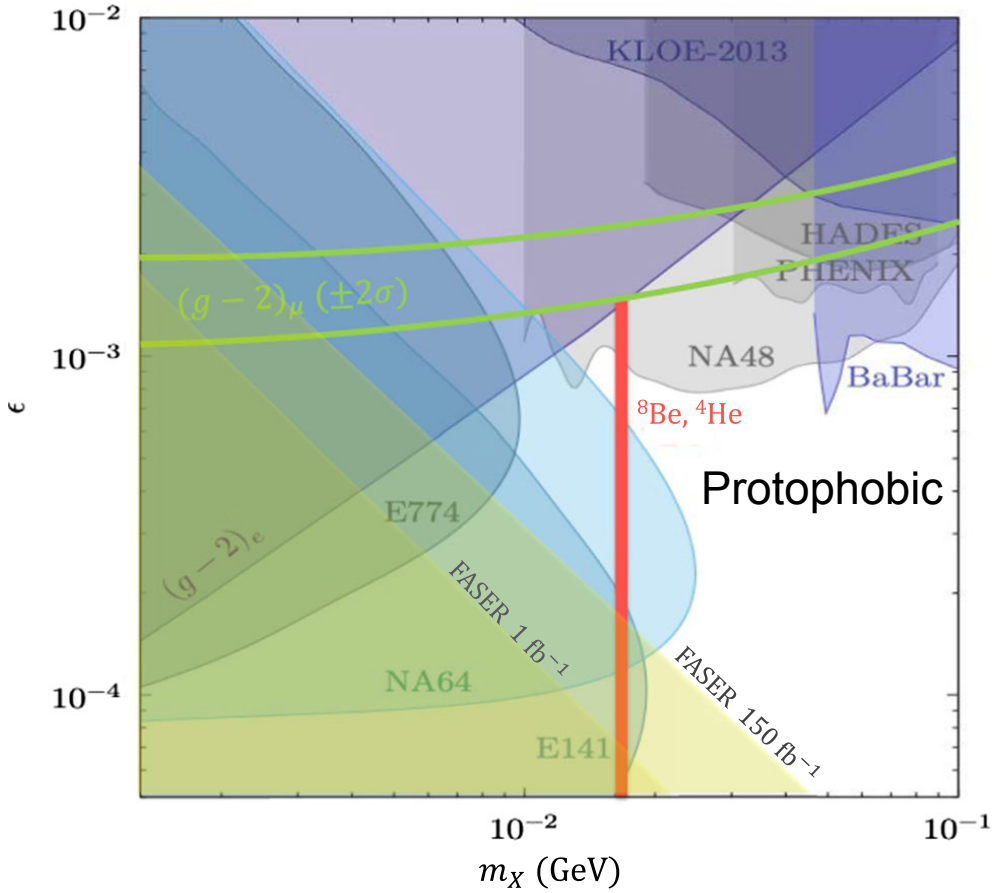




Visible Dark Photons

- Belle II search bypasses nuclear physics uncertainties
- Current Belle II dataset can search remaining parameter space for protophobic X17 ($2\epsilon_u + \epsilon_d \lesssim 0.1\epsilon_u$)





E. Kou et al. Prog Theor Exp Phys (2019)
Feng et al, Phys. Rev. Lett. 117, 071803
D. Alves et al. Eur. Phys. J. C (2023) 83:230

Muonic Dark Force: $L_\mu - L_\tau$ Model

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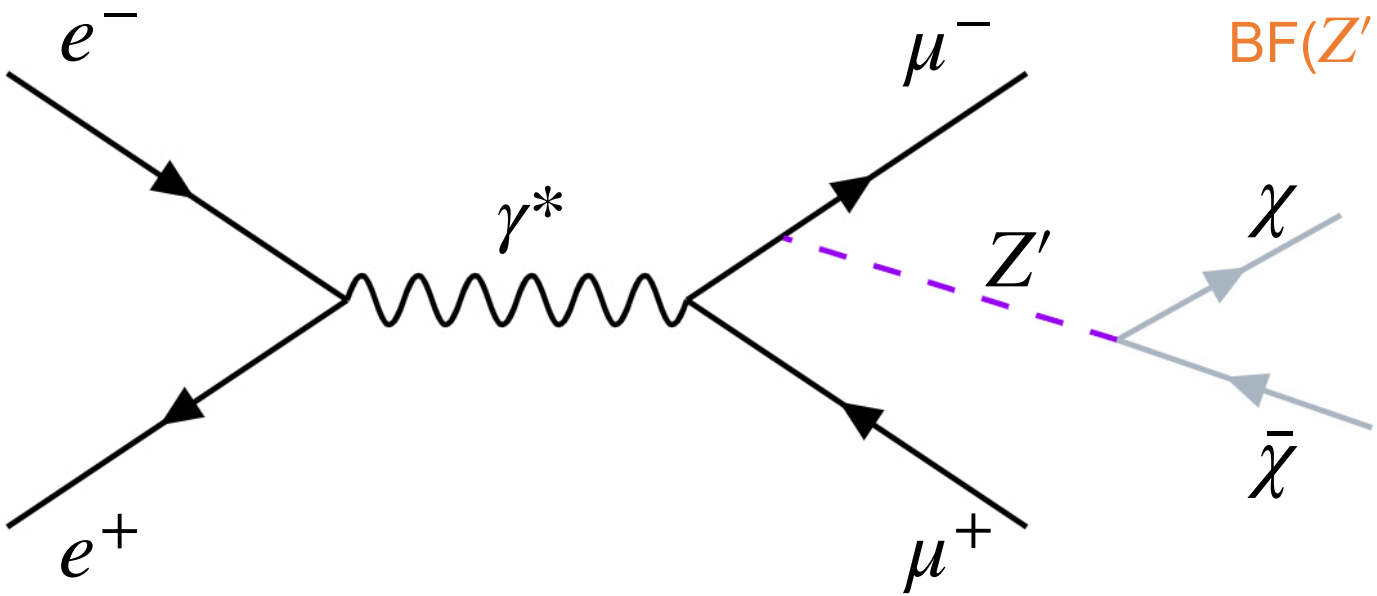
Dark Z' Boson and $L_\mu - L_\tau$ Model

- Massive dark vector boson (similar to Dark Photon)
- $L_\mu - L_\tau$ model: Z' couples only to second and third generation leptons

  ➡muon g-2, dark matter
- Invisible and visible signatures at Belle II depending on how Z' decays



BF($Z' \to \nu\bar{\nu}$) ~ 33 - 100%

BF($Z' \to \chi\bar{\chi}$) ~ 100% if kinematically allowed

Detected muons used to compute recoil mass that peaks for Z' signal

B. Shuve and I. Yavin, PRD 89, 113004 (2014)
W. Altmannshofer, S. Gori, M. Pospelov, and I. Yavin, PRL 113, 091801 (2014)
W. Altmannshofer, S. Gori, S. Profumo, and F. S. Queiroz, JHEP 12 (2016) 106
P. Harris, P. Schuster, and J. Zupan (2022), arXiv:2207.08990
N. Tran, and A. Whitbeck, PRD 107, 116026 (2023)

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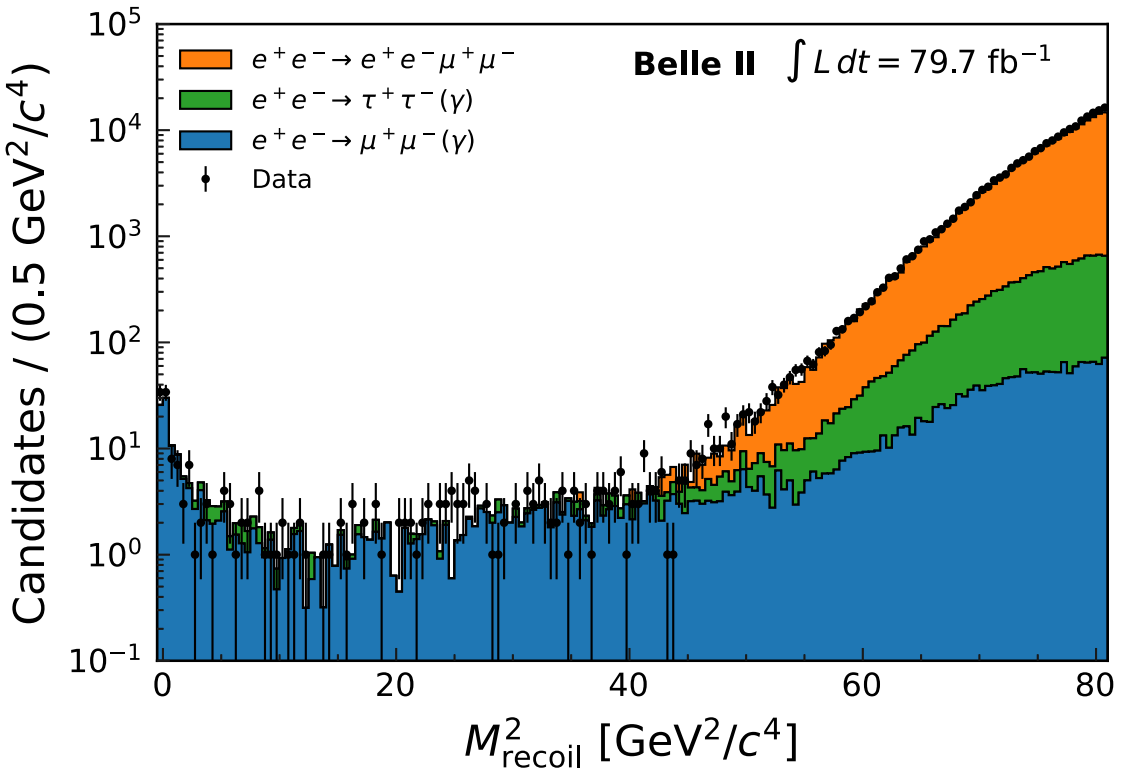
Search for Invisible Z'

- Backgrounds arise from:

$e^+e^- \to \mu^+\mu^-(\gamma)$ where photon is not reconstructed

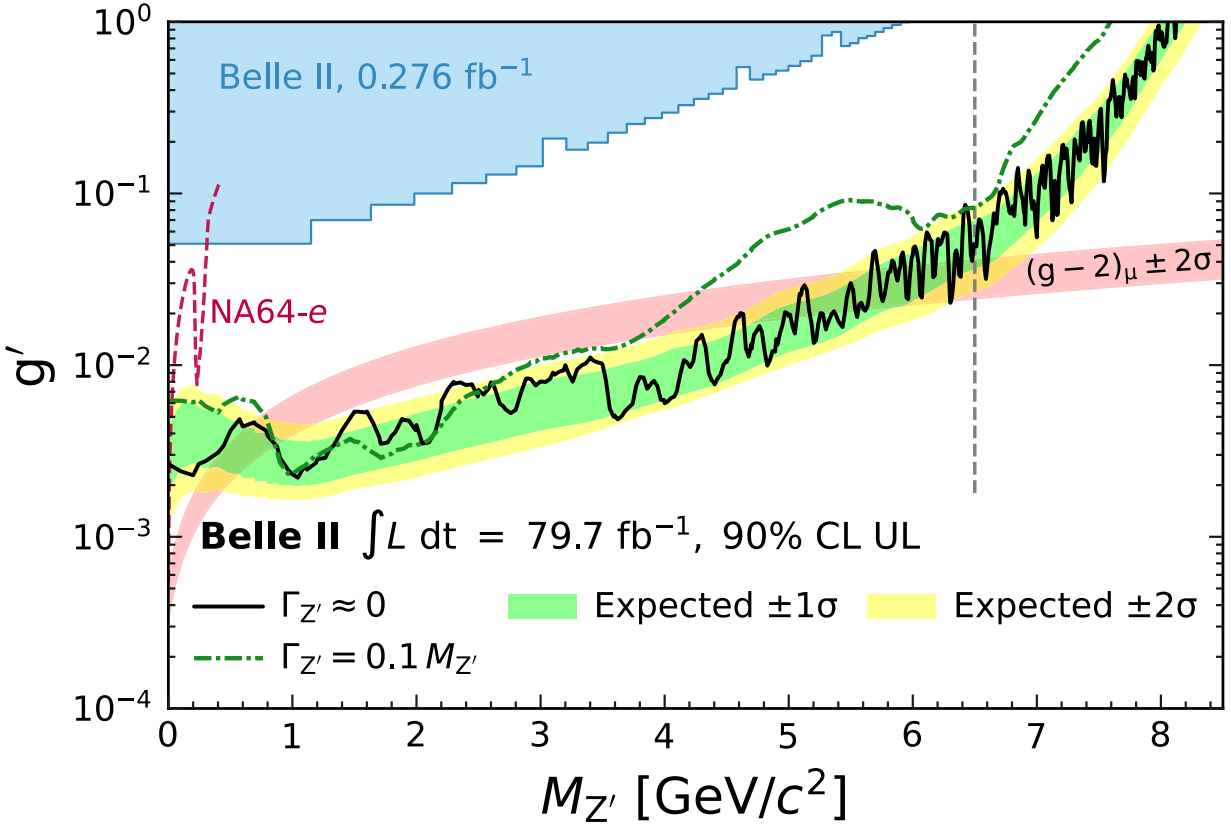
$e^+e^- \to \tau^+\tau^-(\gamma)$ neutrinos escape detector

$e^+e^- \to e^+e^-\mu^+\mu^-$ with e^+e^- not in acceptance



- No significant excess observed in 79.7 fb^{-1}
- Excluded part of Z' parameter space, which could explain muon $g-2$ tension

Case: BF($Z' \to \chi\bar{\chi}$) ~ 100%



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Belle II Collaboration Phys. Rev. Lett. 130, 231801 (2023)

Search for Invisible Z'

- Backgrounds arise from:

$e^+e^- \rightarrow$

e^+e^- —

e^+e^- —

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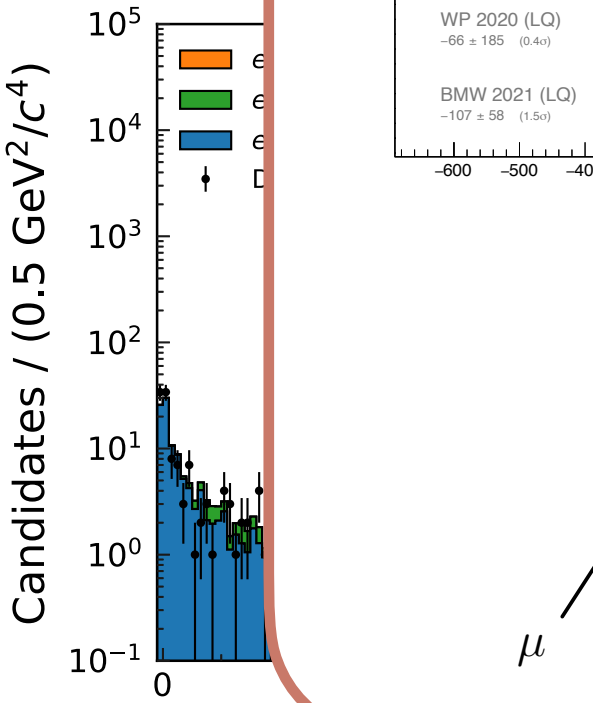

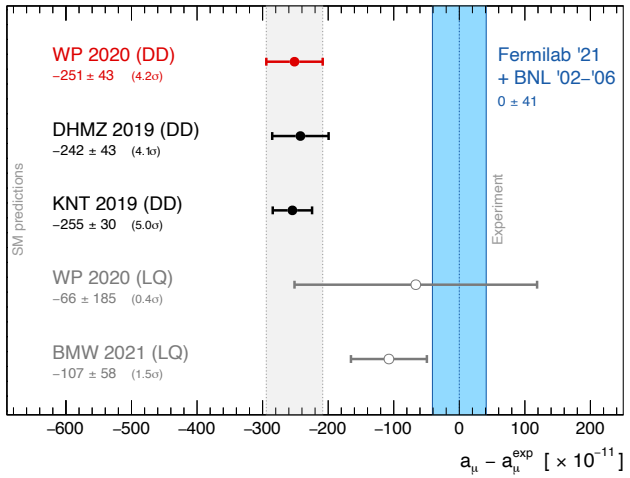

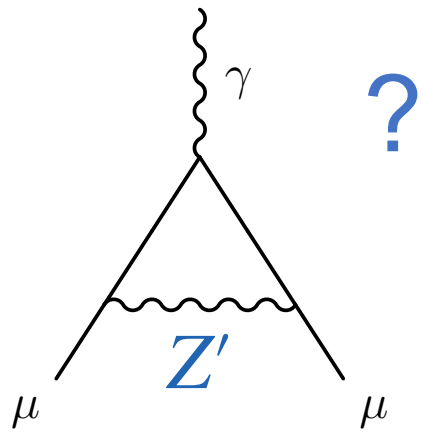

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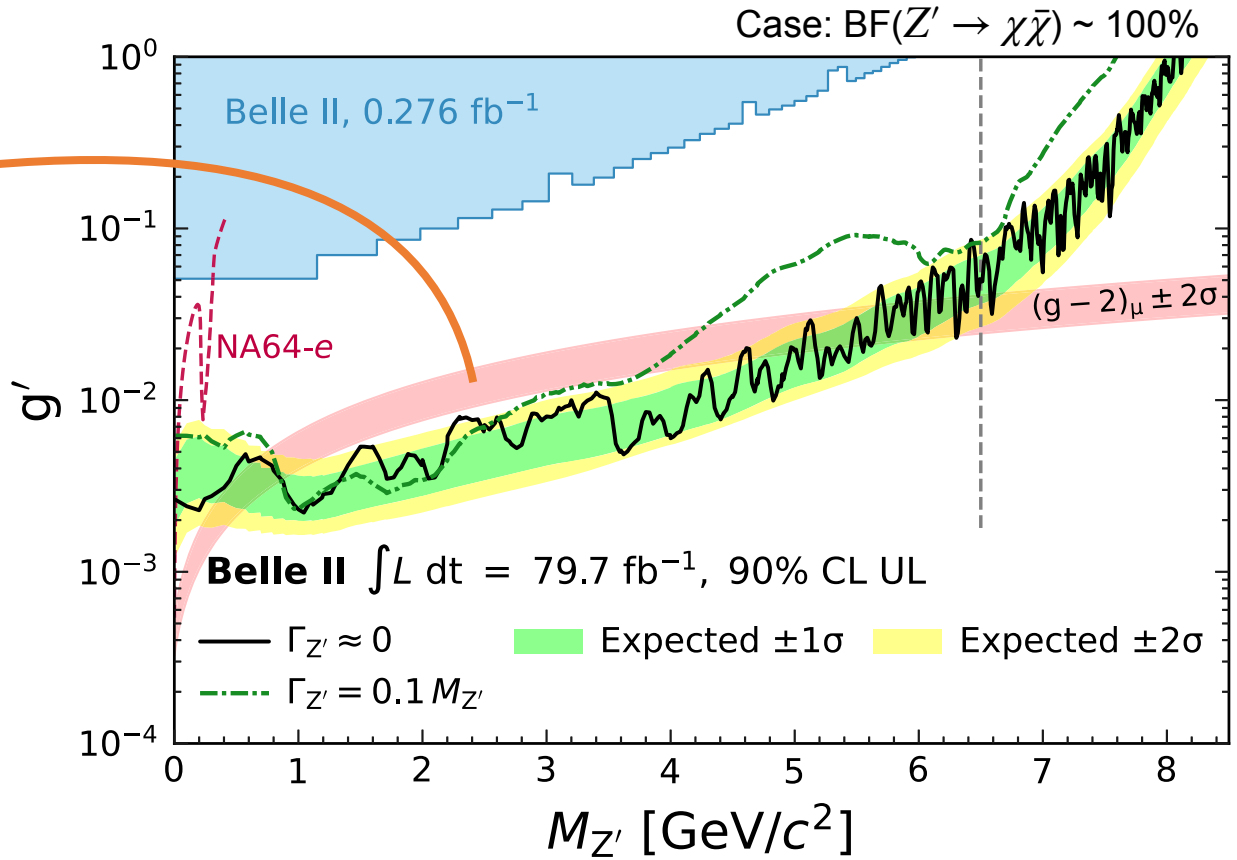
M_{recoil} [GeV/c^2]

- No significant excess observed in 79.7 fb^{-1}
- Excluded part of Z' parameter space, which could explain muon $g-2$ tension



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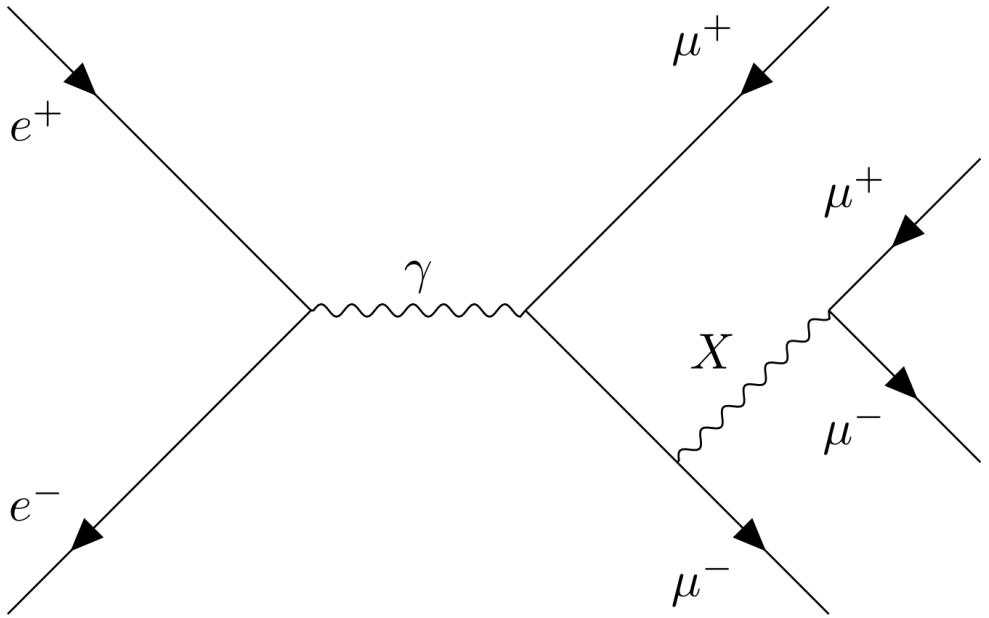
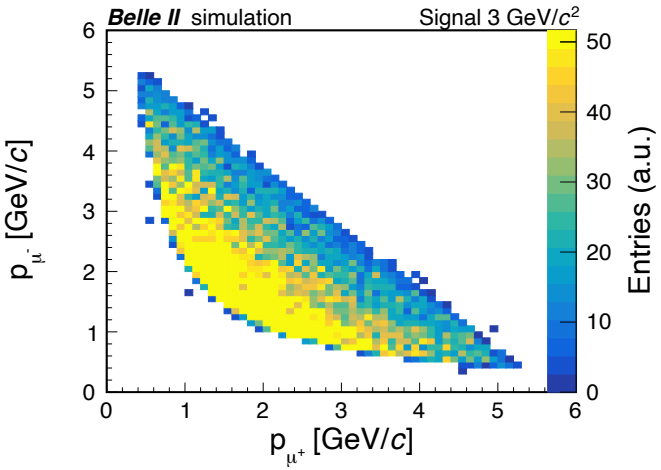
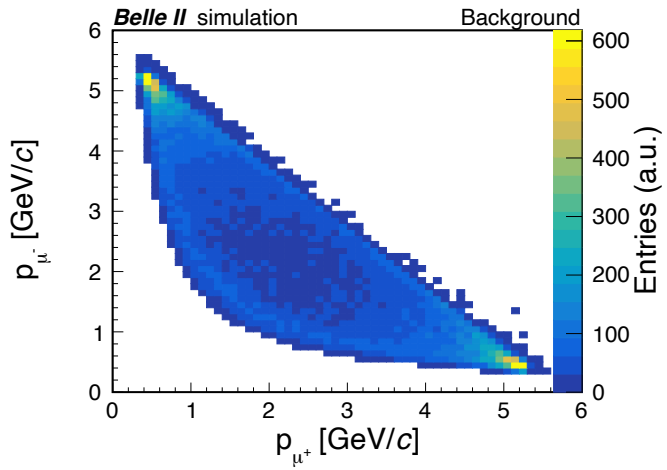
Belle II Collaboration Phys. Rev. Lett. 130, 231801 (2023)

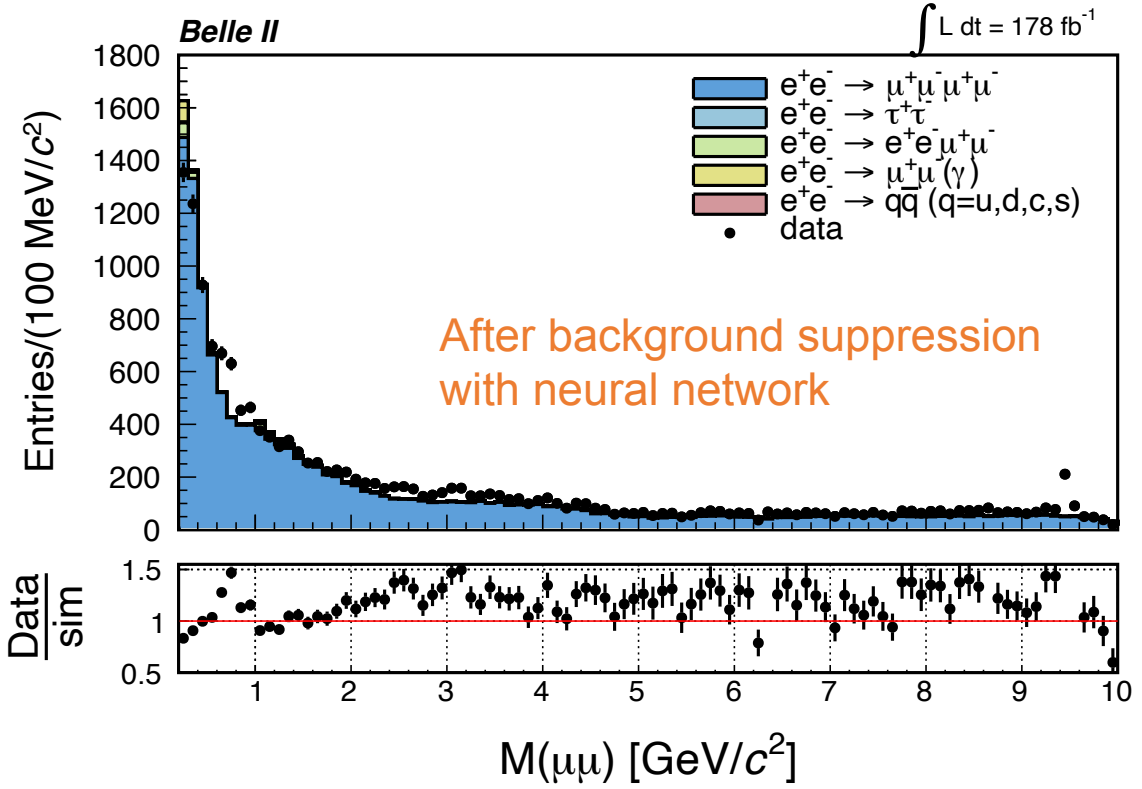
Search for Visible Z'

- Search in channel $e^+e^- \to \mu^+\mu^- X, \quad X \to \mu^+\mu^-$
- Select events with four muons with total centre-of-mass energy consistent with $\sqrt{s}$
- Main background $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ has distinct kinematics from signal
- Neural network for background suppression









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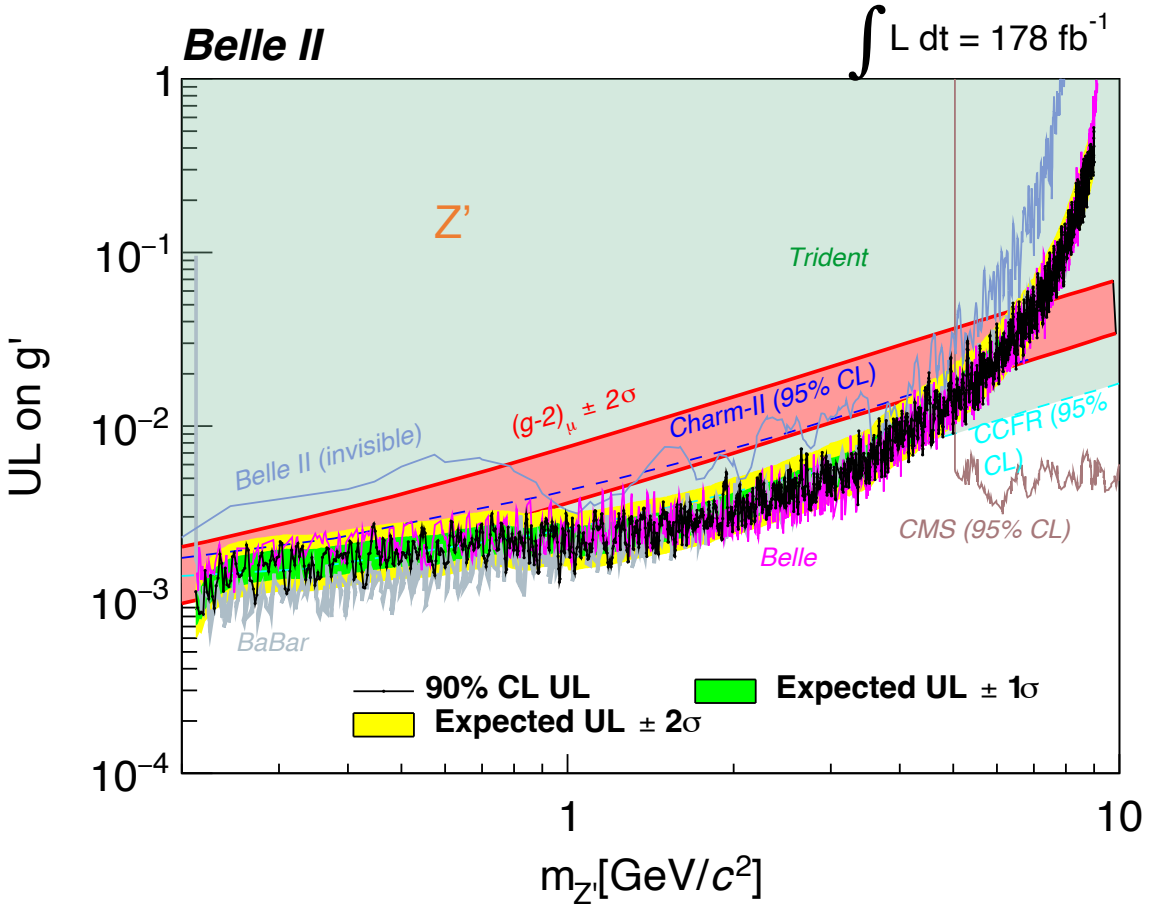
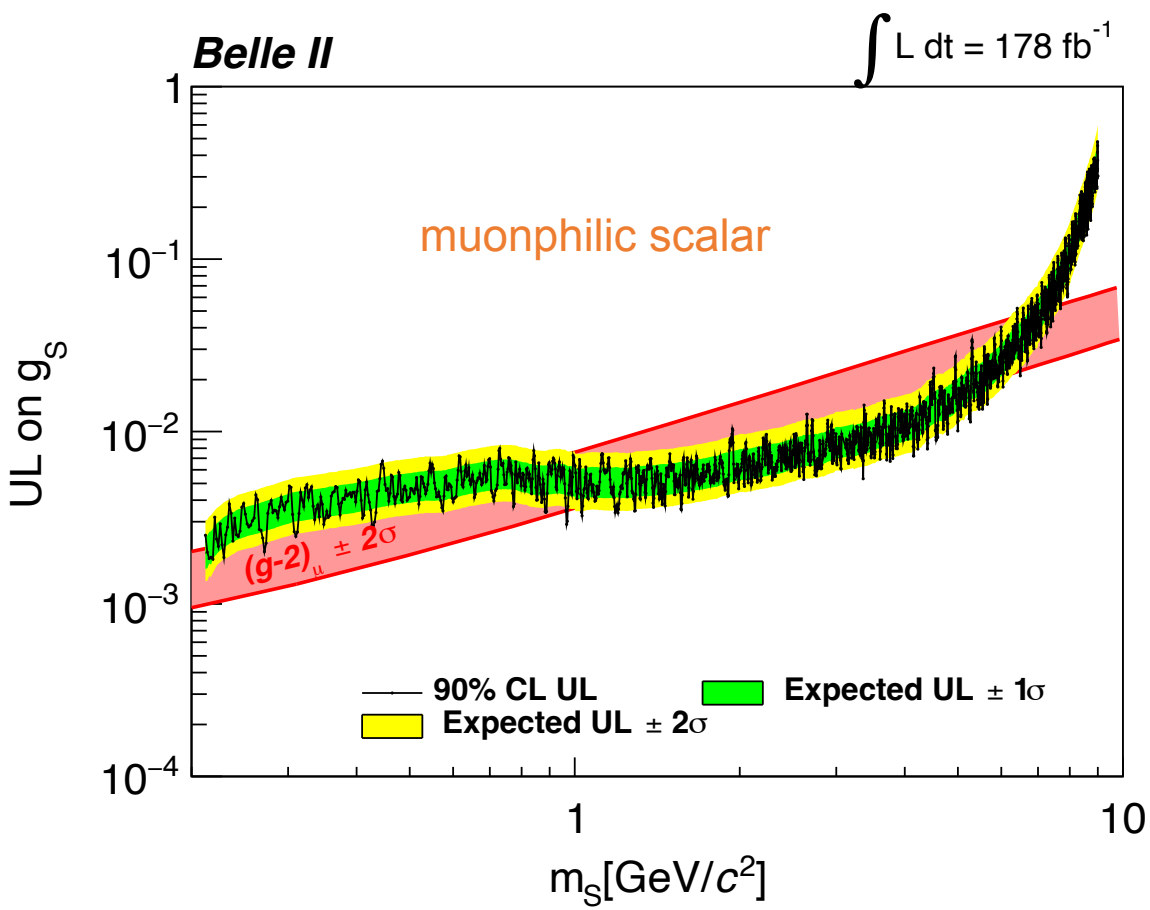
Belle II Collaboration, Accepted to PRD arXiv:2403.02841

Search for Visible Z'

- No significant excess observed in 178 fb^{-1}
- Limits also set on Z' interpretation
- Set first limits on muonphilic scalar, which constrain explanation for muon g-2 anomaly





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Belle II Collaboration, Accepted to PRD arXiv:2403.02841

Dark Scalar/Dark Higgs Boson

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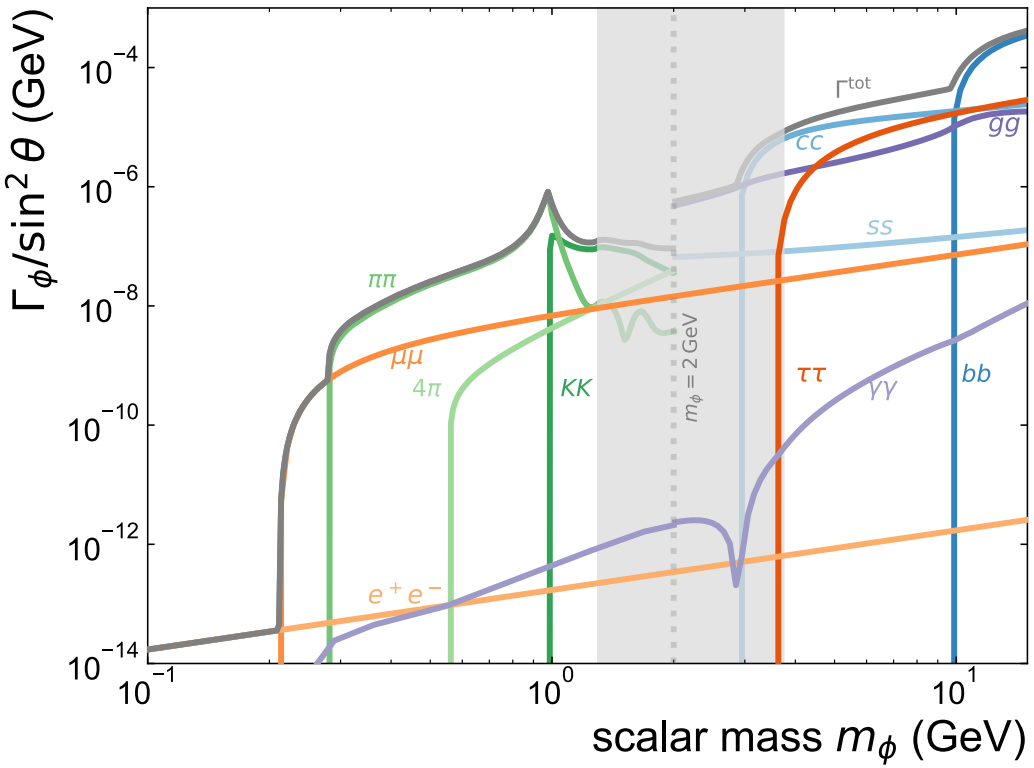
Dark Higgs Boson

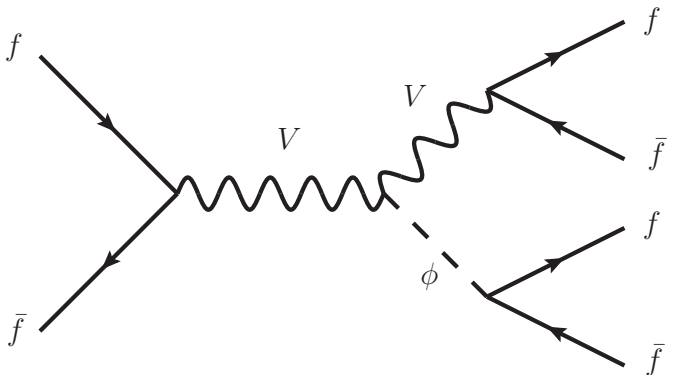
- Light spin-0 scalar ϕ that mixes with Higgs boson (mixing angle θ)
- Motivated by dark matter mass generation

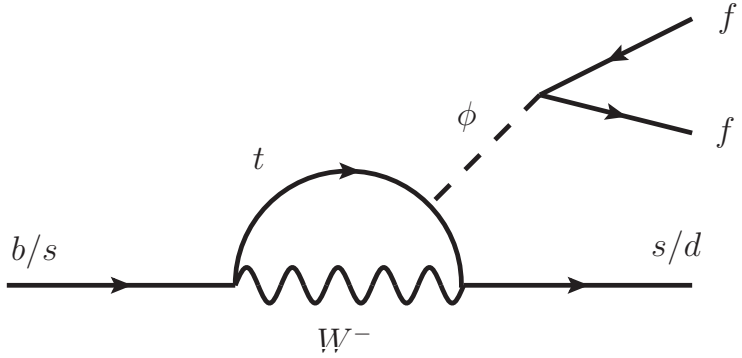
$$\mathcal{L} \supset \lambda S^2 (H^\dagger H)$$

Fermion couplings after SSB: $\sin\theta\, y_q\, \bar{q} q\, S$

Several possible production channels at Belle II







- Same decays as an SM Higgs boson with suppression of $\sin^2\theta$
- Lifetime increases as $\sin^2\theta$ decreases → Long Lived Particle at small mixing angles

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E. Kou et al. Prog Theor Exp Phys (2019)
T. Ferber, A. Grohsjean F. Kahlhoefer Prog. Part. Nucl. Phys. Vol 136 104105 (2024)

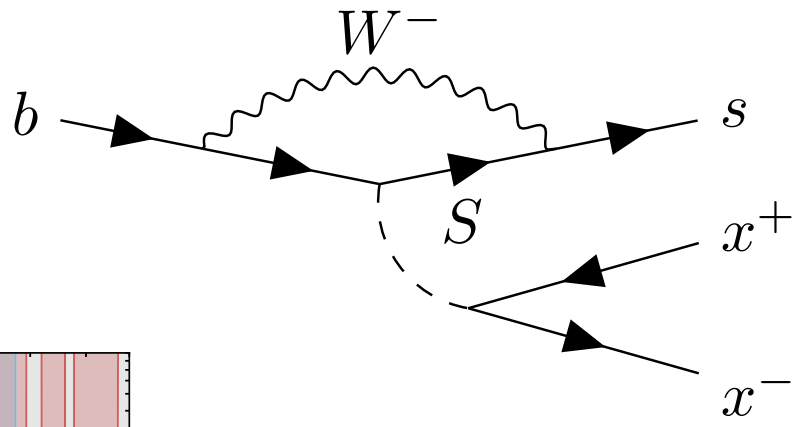
Belle II Search for Dark Higgs (S)

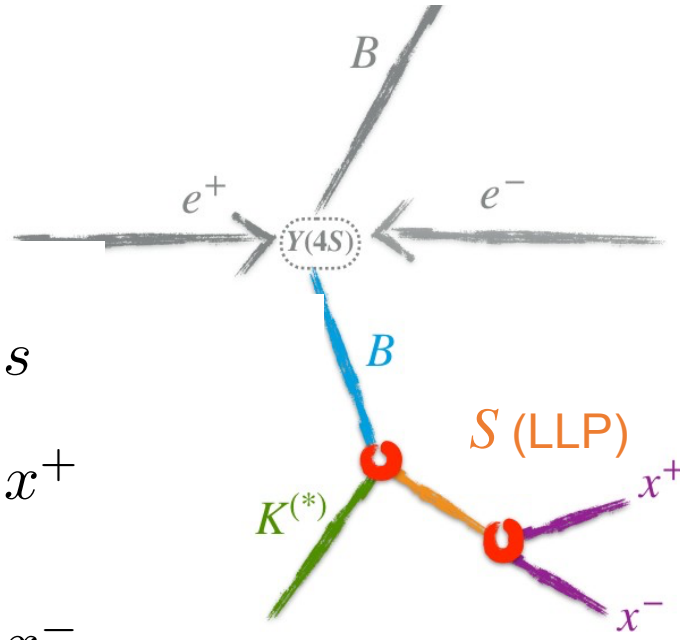
- Searched S lifetime range from 0.001 < $c\tau$ < 100 cm

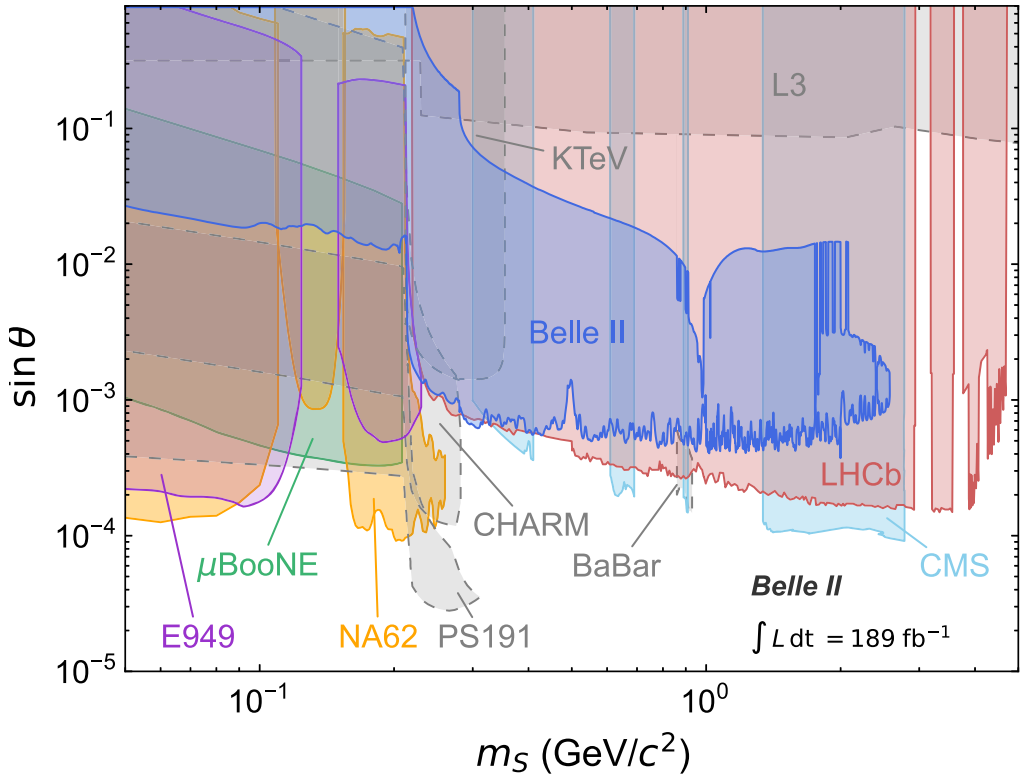
$$B^+ \to K^+ S$$

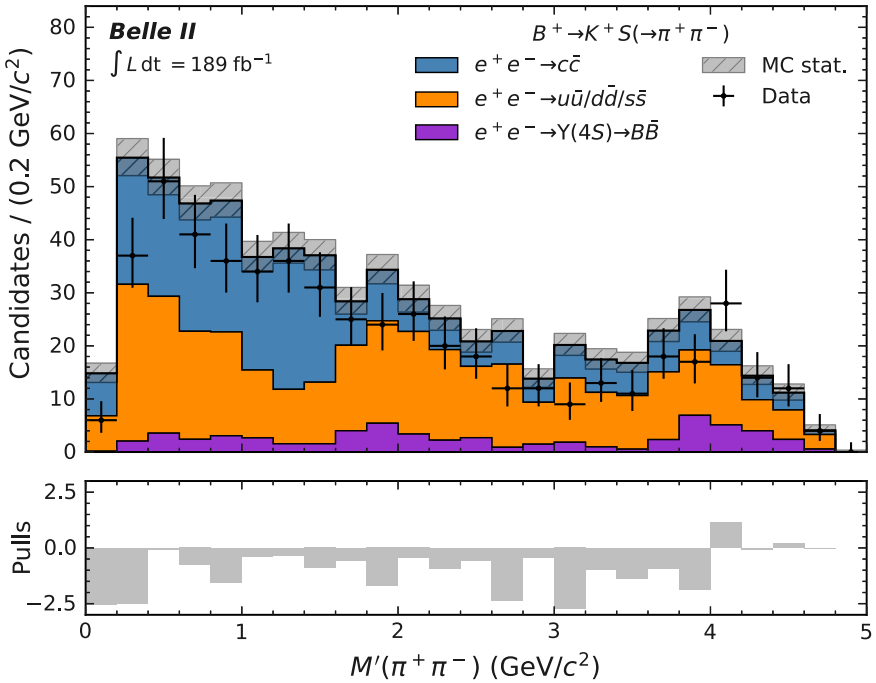
$$B^0 \to K^{*0}(\to K^+\pi^-)S$$

$$S \to x^+x^-, x = e, \mu, \pi, K$$









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I. Adachi et al. (Belle II Collaboration) Phys. Rev. D 108, L111104 (2023)

Axion-Like Particles

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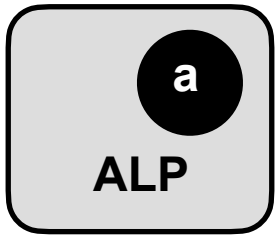
Axion-Like Particles (ALPs)

- Axions originally proposed to solve strong Charge-Parity problem
- Axion-like particles (a) are a generalization of the axion
- Searches focus on ALP interactions with gauge bosons

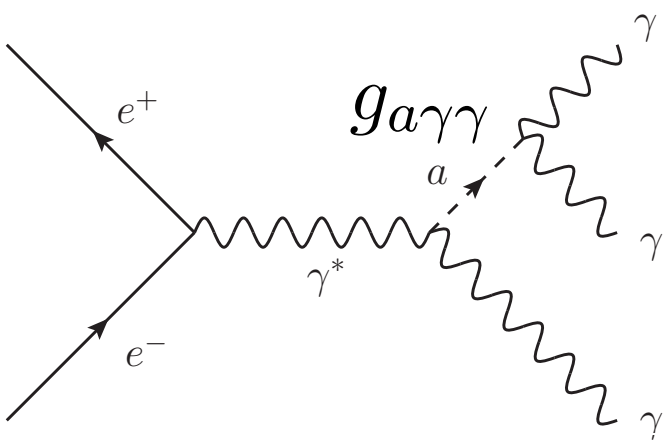


Pseudo-scalar with mass m_a

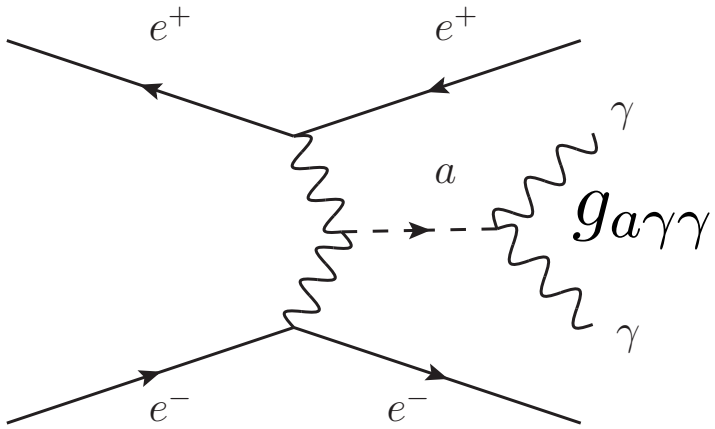
$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{a\gamma Z}}{4} a F_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aZZ}}{4} a Z_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4} a W_{\mu\nu}\tilde{W}^{\mu\nu}$$

- ALPs could be directly produced at Belle II through variety of channels

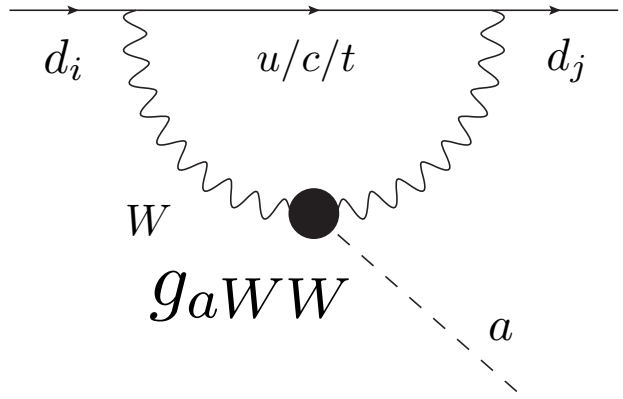
$e^+e^- \to \gamma a,\ a \to \gamma\gamma$



$e^+e^- \to e^+e^- a,\ a \to \gamma\gamma$



$B \to Ka,\ a \to \gamma\gamma$



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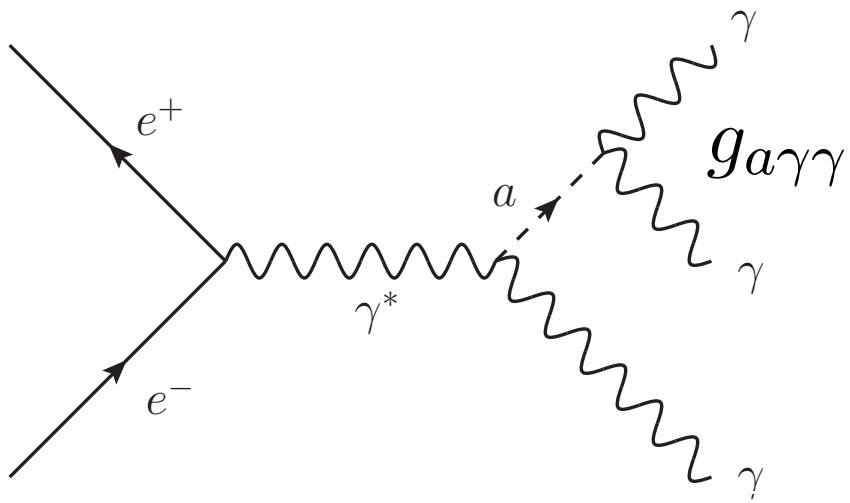
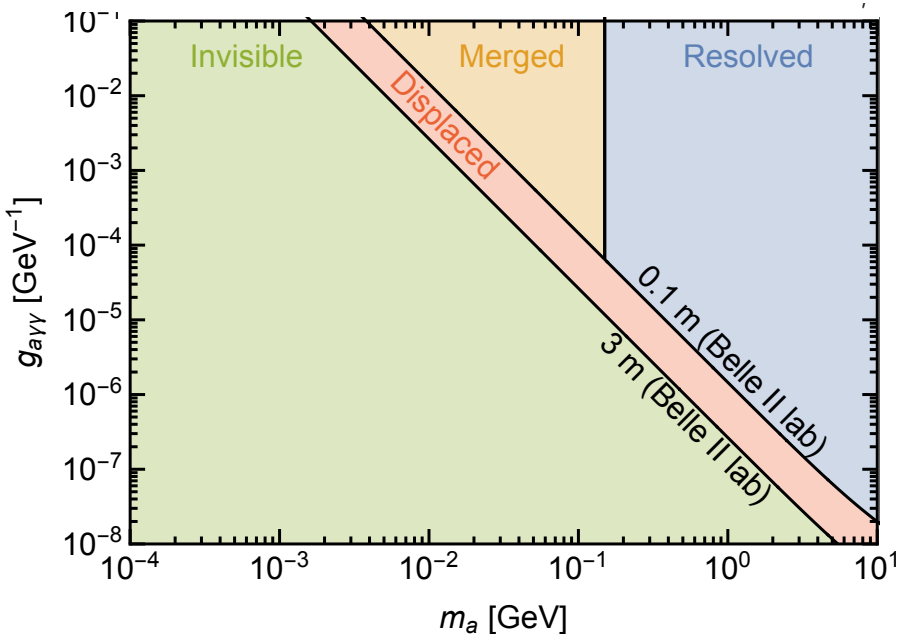
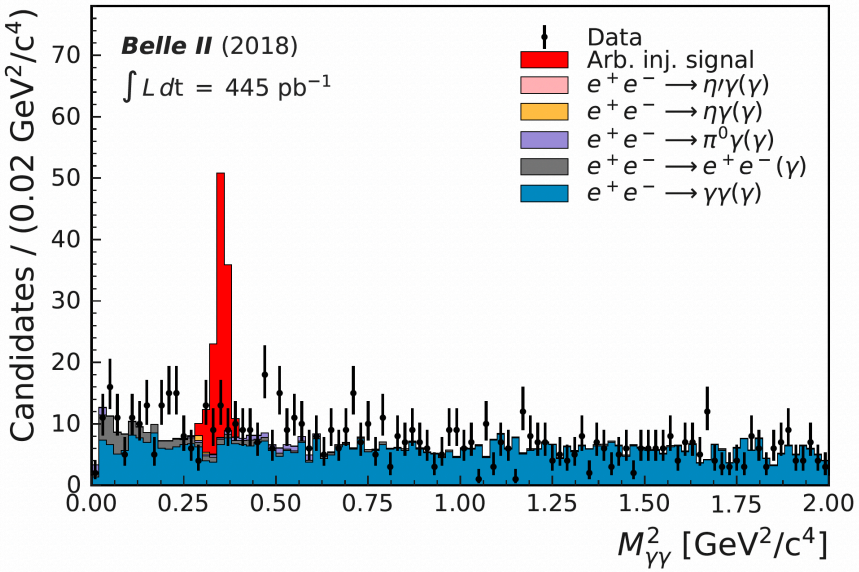
M. Dolan, T. Ferber, C. Hearty, F. Kahlhoefer & K. Schmidt-Hoberg, JHEP 12, 094 (2017)
E. Izaguirre, T. Lin, and B. Shuve Phys. Rev. Lett. 118, 111802 (2017)

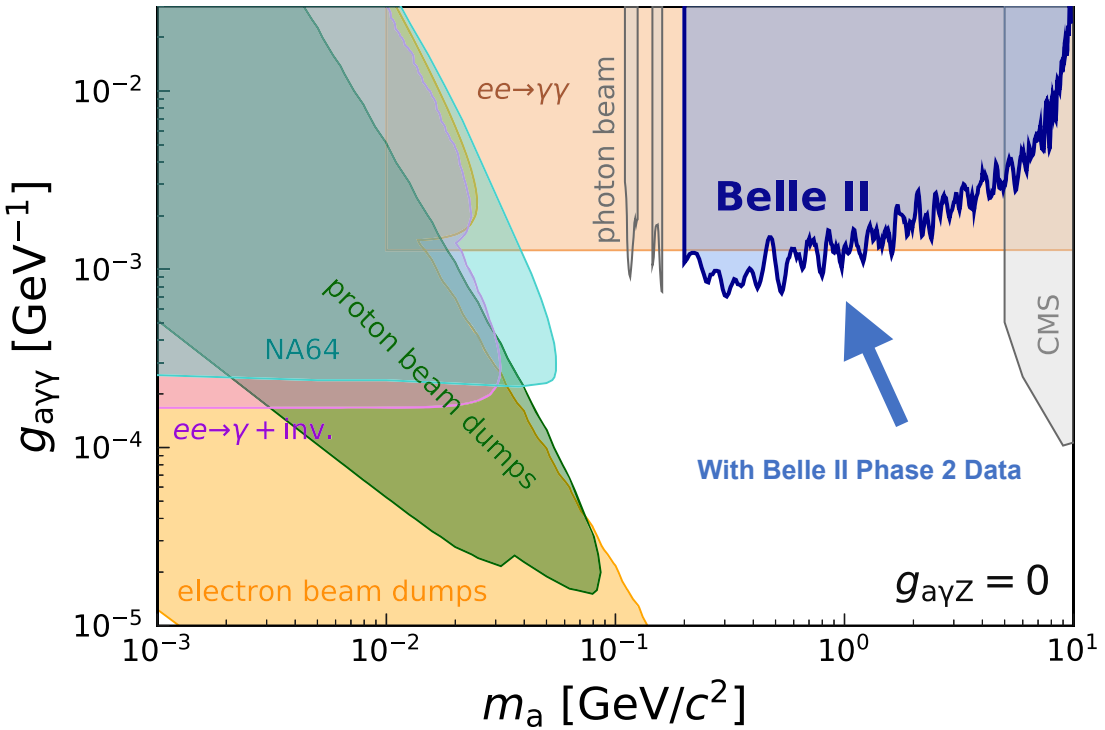
ALPs at Belle II

- Analysis focuses on ALP-Photon coupling









F. Abudinén *et al.* (Belle II Collaboration) Phys. Rev. Lett. 125, 161806 (2020)

M. Nuccio. *Search for Axion-Like Particles produced in e^+e^- collisions and photon energy resolution studies at Belle II.* [PhD Dissertation] University of Hamburg (2021

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Search for $\tau\tau$ resonance

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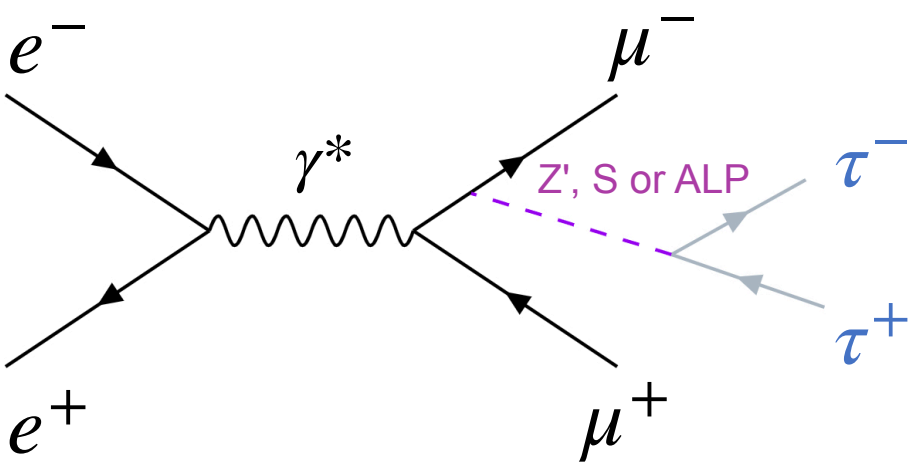
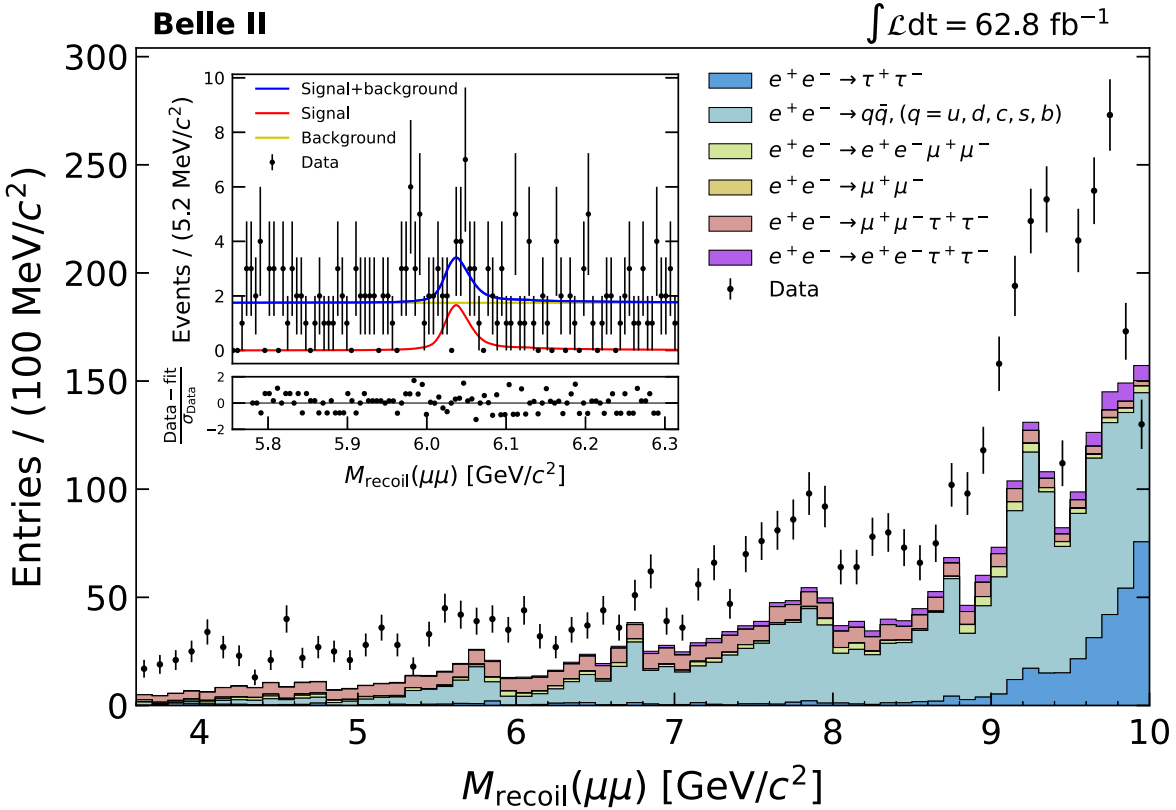
Search for $\tau\tau$ resonance

- $\tau\tau$ resonance in $e^+e^- \to \mu\mu\tau\tau$ arise in many dark sector models:
  - ➡ Spin-1 particle coupling only to the heavier lepton families
  - ➡ Higgs-like spin-0 particle that couples preferentially to charged leptons (leptophilic scalar)
  - ➡ Axion-like particles

B. Shuve and I. Yavin, PRD 89, 113004 (2014)
W. Altmannshofer et al, JHEP 12, 106 (2016)
B. Batell et al, PRD 95, 075003 (2017)
M. Bauer et al, JHEP. 2022, 1 (2022)



Require $\tau^\pm$ decay as
$\tau^- \to \ell^-\nu\nu$ or $\tau^- \to \pi^-\nu n\pi^0$



- Event signature is four tracks with missing energy
- Muons used to compute $M_{\text{recoil}}(\mu\mu)$, which peaks for signal
- Background suppression via neural network
- $e^+e^+ \to e^+e^-X_{\text{had}}$ and $e^+e^+ \to 4\ell(\gamma)$ backgrounds not included in simulation

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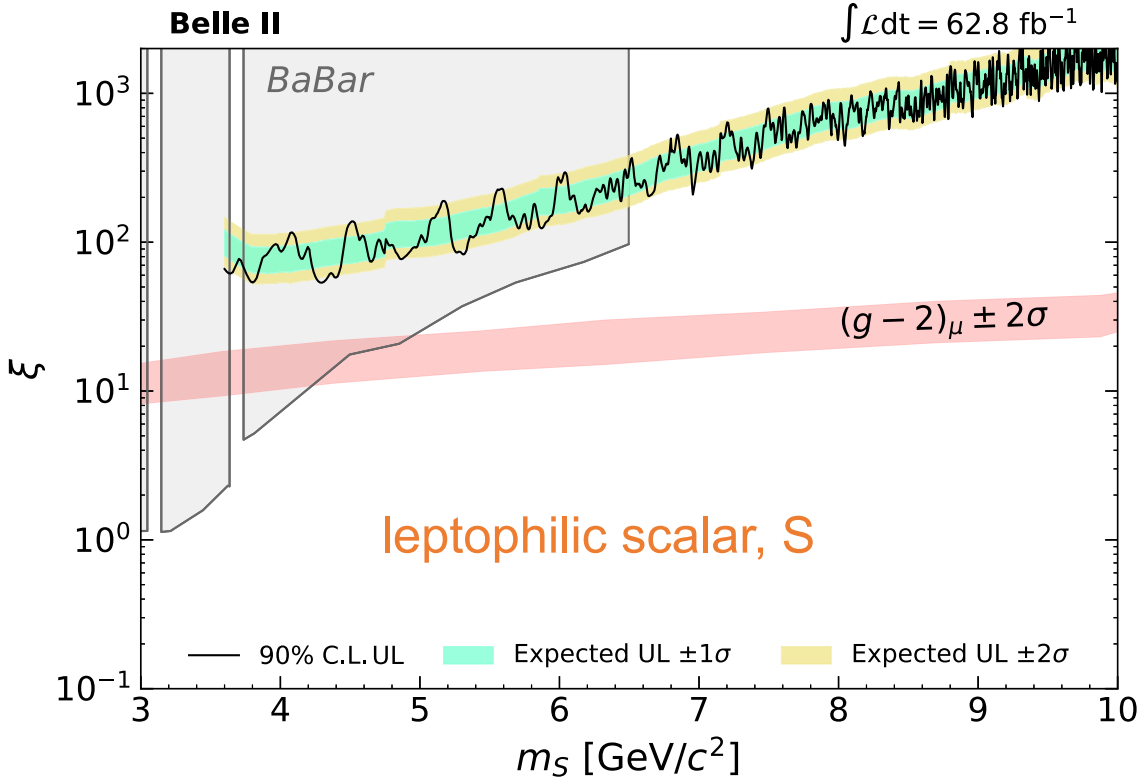
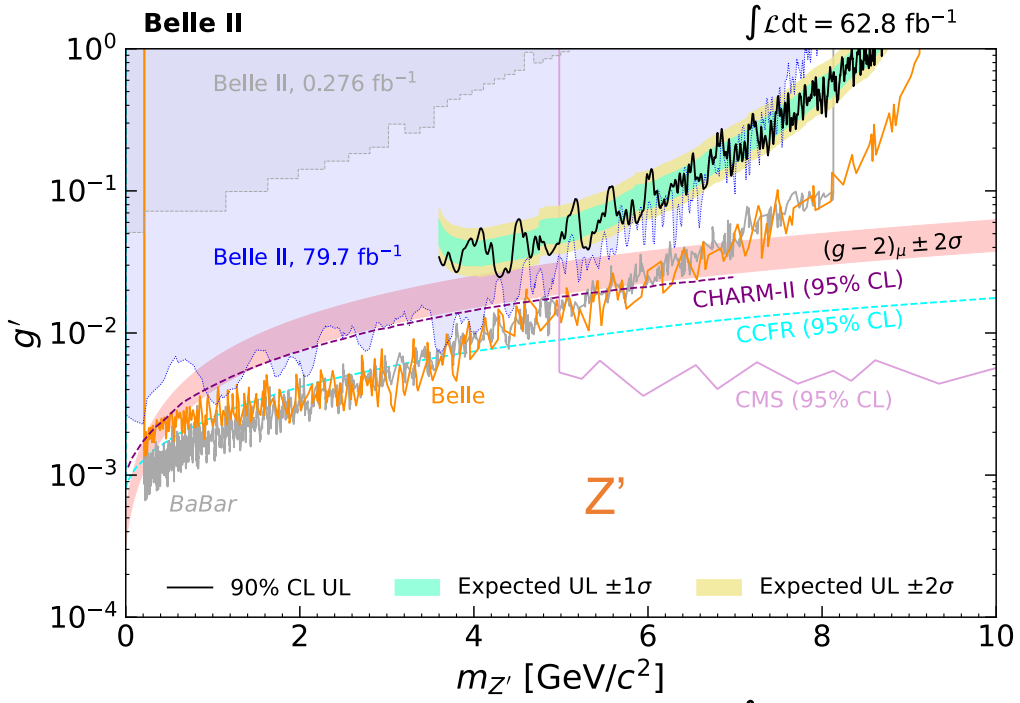
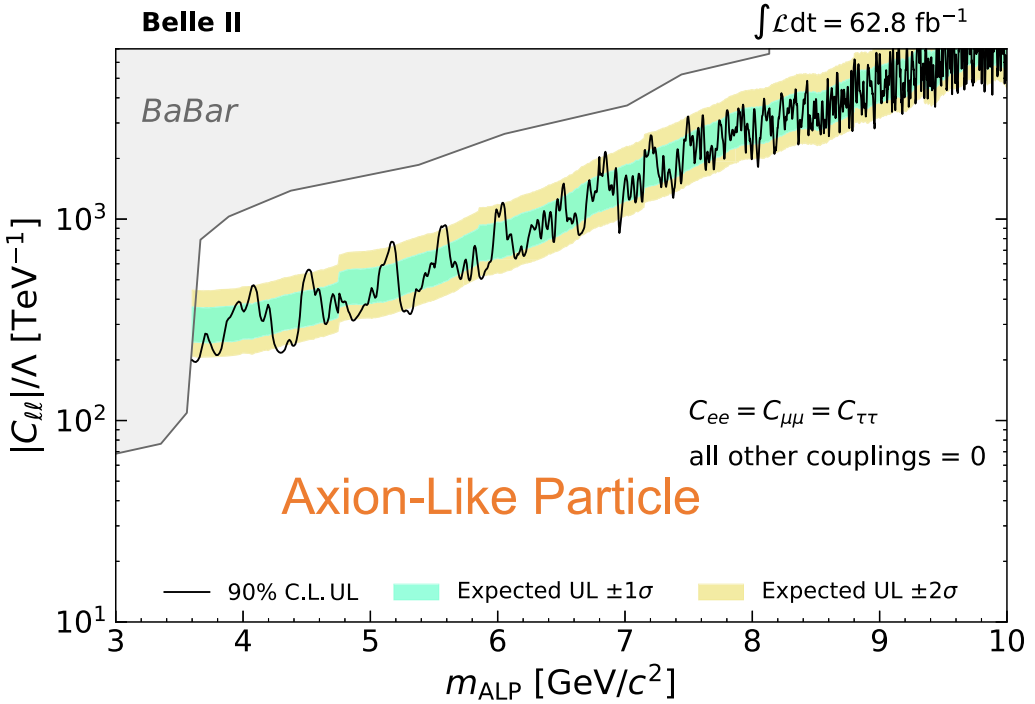
Search for $\tau\tau$ resonance

- No significant excess observed in 62.8 fb^{-1}
- Limits on $e^+e^- \to X(\to \tau^+\tau^-)\mu^+\mu^-$ cross section translated to limits on leptophilic scalar, Z', and ALP mediator interpretations

I. Adachi et al. (Belle II Collaboration) Phys. Rev. Lett. 131, 121802 (2023)







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Getting Involved with Dark Sector Physics at Belle II

- Many opportunities to get involved with ongoing and new Dark Sector Physics analyses at Belle II!
- Only small selection of analyses was covered in this talk

- Mailing-list:

physics-dark-low-multiplicity@belle2.org

- Weekly Meetings (alternates timezones):

https://indico.belle2.org/event/12405/