Dark Sector Searches at Belle II

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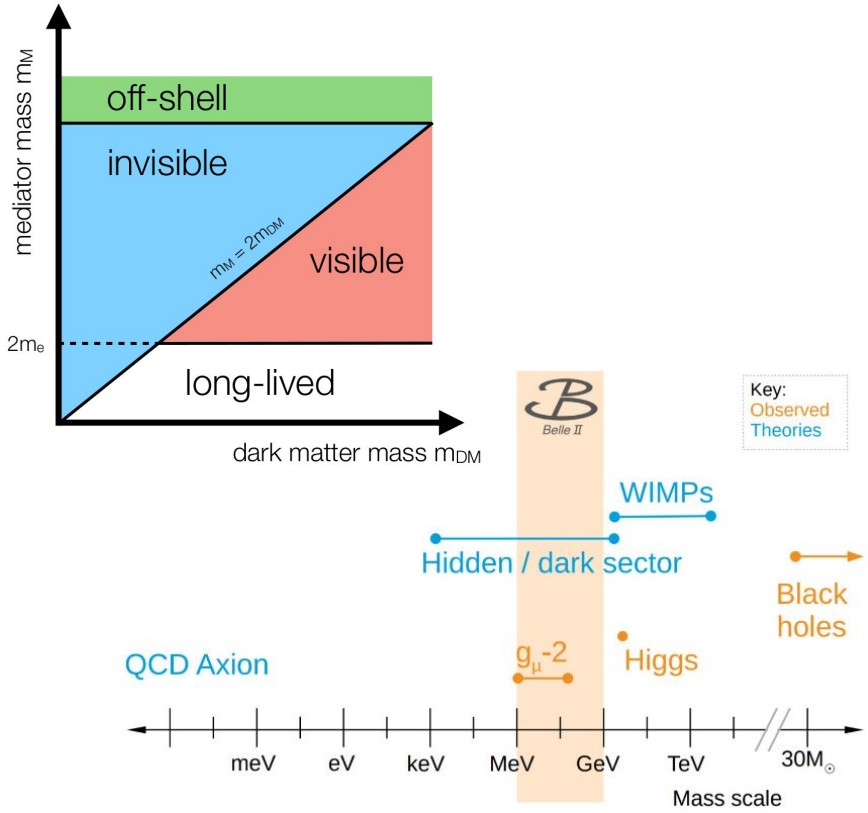
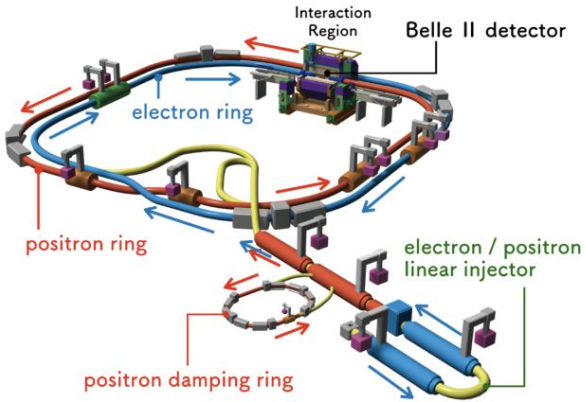
Dark Sector Searches

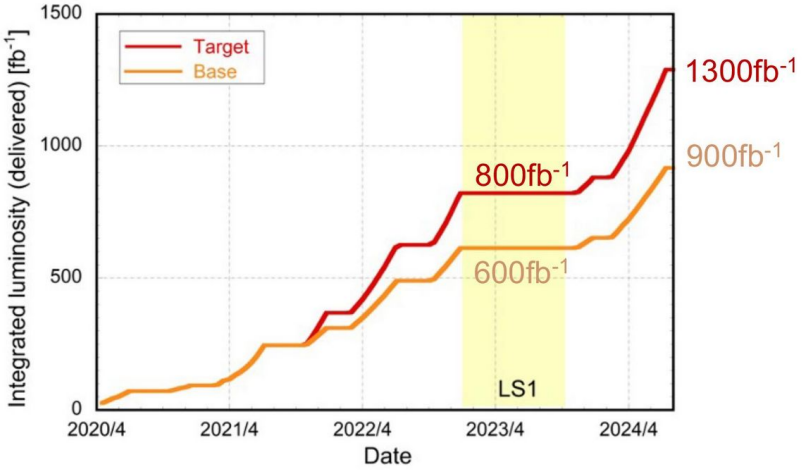
- Probe light dark sectors with low mass mediators O(GeV)
- Possible portals between SM and DS include:
  - Vector portal (Dark photon, Z')
  - Pseudo-scalar portal (Axion-like particle)
  - Scalar portal
  - Neutrino portal
- Belle II advantages:
  - Hermetic detector
  - Clean collision environment
  - Excellent PID
  - Dedicated low-multiplicity triggers



SuperKEKB

- **B-factory** located in Tsukuba, Japan.
- Asymmetric e^+e^- collider operating at $\mathbf{m_{\Upsilon(4S)}}$ **= 10.58 GeV** (7 GeV e^- + 4 GeV e^+)
- x30 instantaneous luminosity increase over KEKB
- Regular operations commenced March 2019



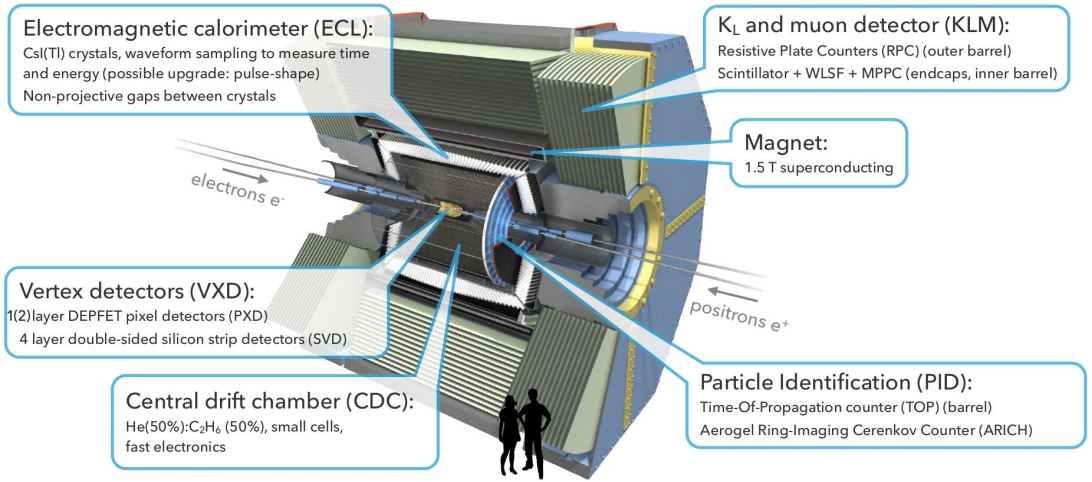


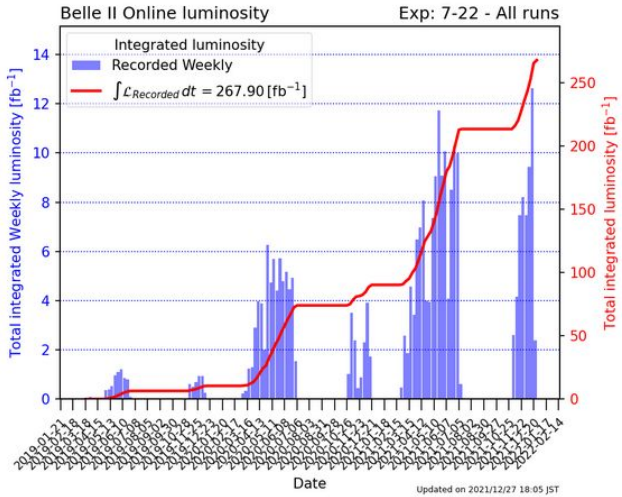
WORLD RECORD INSTANTANEOUS LUMINOSITY!

3.81×10^{34} $cm^{-2}s^{-1}$

Belle II

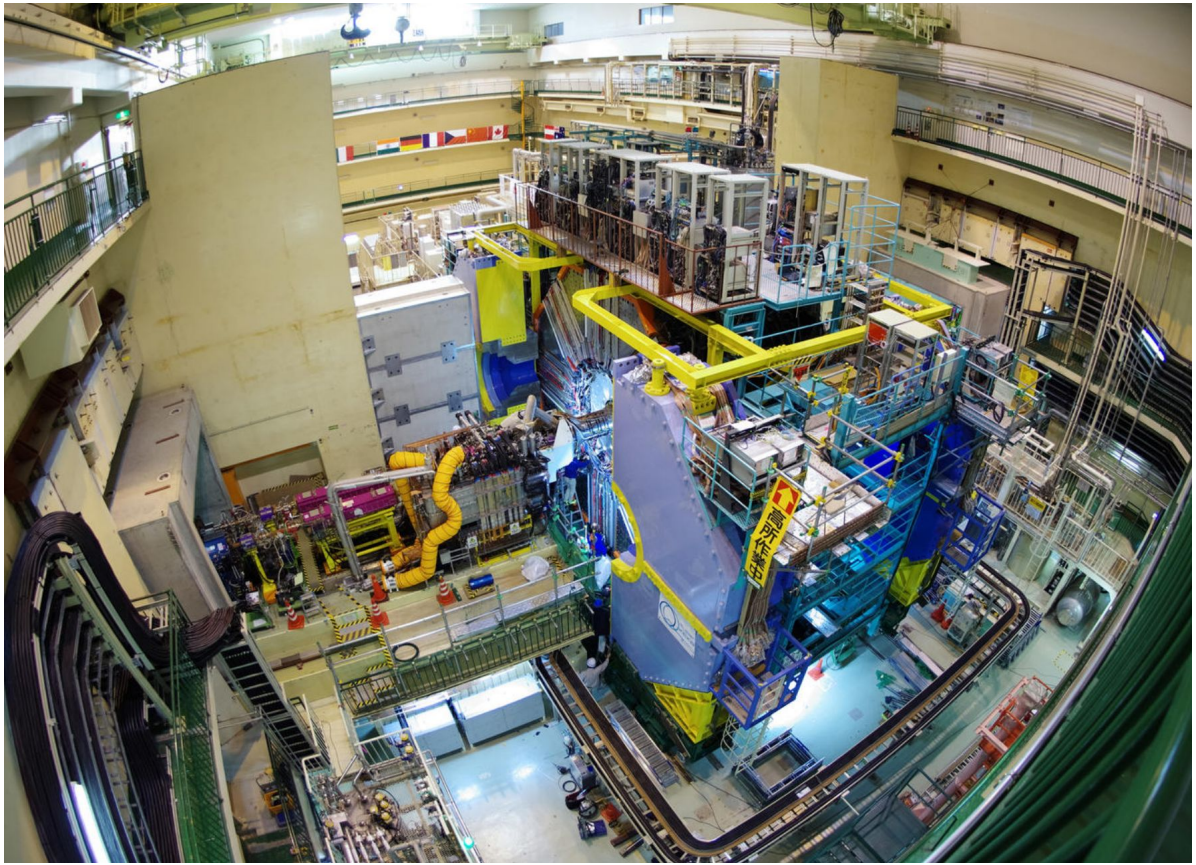
- 1102 members from 123 institutes across the globe
- Pilot run in 2018, physics runs began March 2019
- Target **x50 Belle data (≈50ab^{-1})**
- Wide-ranging and varied physics program: B and D physics, quarkonium, τ-physics, dark sector, …





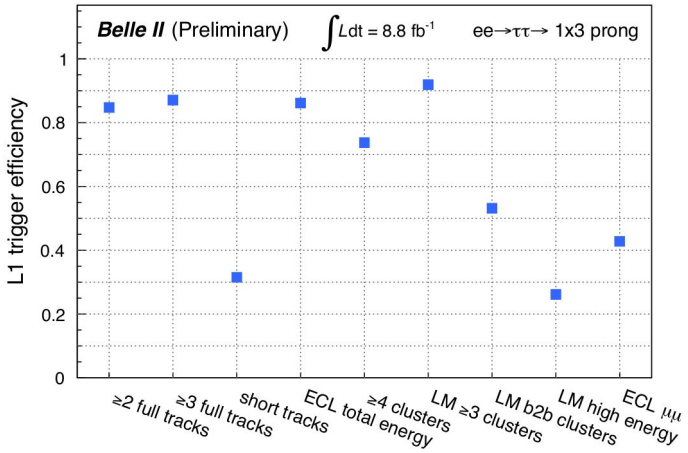
267fb^{-1} recorded integrated luminosity

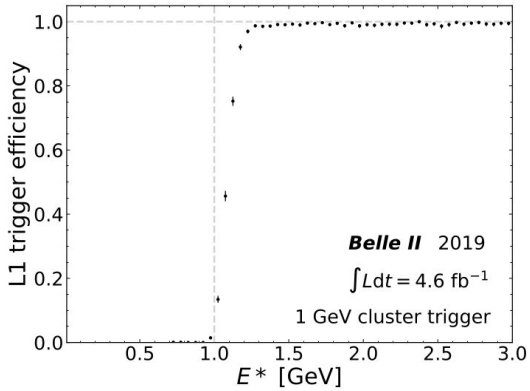
Belle II



Trigger System

- Two-tier trigger system:
  - Hardware based low level trigger (L1)
  - Software based high level trigger (HLT)
- Reduce effects from beam backgrounds (Touschek effect, beam-gas scattering, radiative Bhabha, …)
- L1 trigger (not available in Belle)
  - Max trigger rate 30KHz
  - Combines 4 sub-detector triggers; CDC, TOP, KLM, ECL
- Dedicated trigger lines for dark sector and low-multiplicity physics:
  - Single photon
  - Single track
  - Multi-track triggers
  - ECL cluster triggers
  - 3D neural trigger

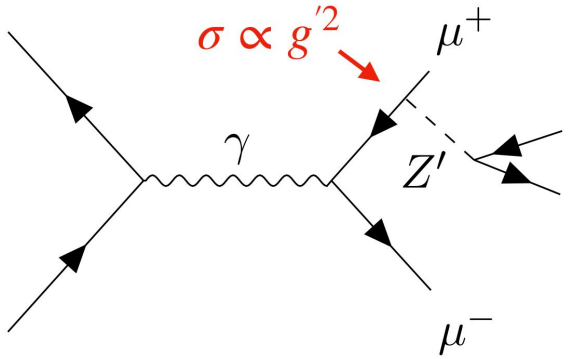




Invisible Z’

Invisible Z' I

- U(1)' extension of standard model -> new massive gauge boson
- Couples to μ and τ leptons ($L_\mu - L_\tau$) via g'
- possibilities;
  - $(g\text{-}2)_\mu$
  - $B \longrightarrow s\mu\mu$
  - Mediator between SM and DS

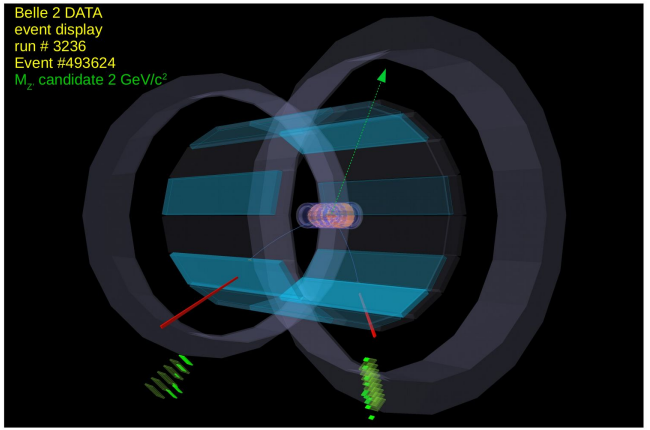


JHEP 1612 (2016) 106
PRD 89, 113004 (2014)

$$
\begin{aligned}
M_{Z'} < 2M_\mu \quad &\Longrightarrow \quad BF[Z' \to \text{invisible}] = 1, \\
2M_\mu < M_{Z'} < 2M_\tau \quad &\Longrightarrow \quad BF[Z' \to \text{invisible}] \simeq 1/2, \\
M_{Z'} > 2M_\tau \quad &\Longrightarrow \quad BF[Z' \to \text{invisible}] \simeq 1/3.
\end{aligned}
$$

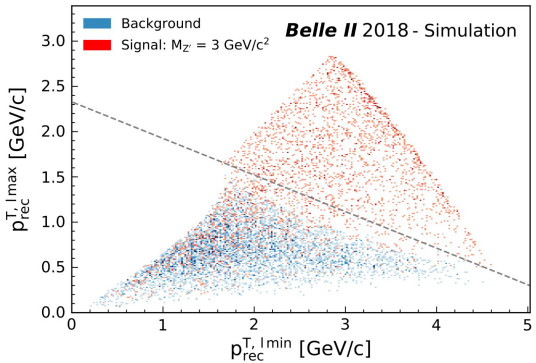
$$
\text{if } M_{Z'} > 2M_\chi \\
BF(Z' \to \chi\bar{\chi}) = 1
$$

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

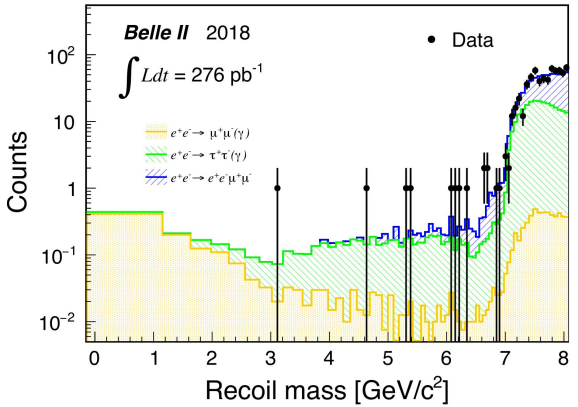


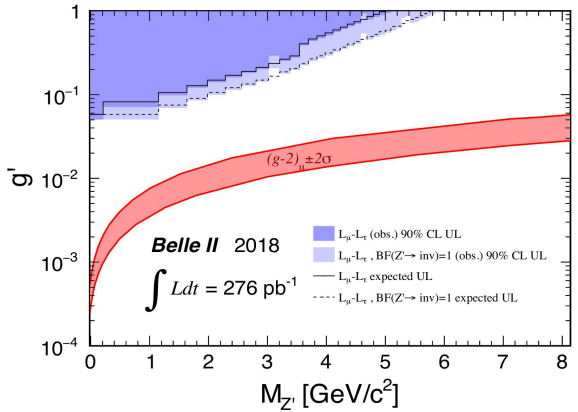
Invisible Z' II

- First published Belle II result - 2018 using **276pb^{-1}** (2018 pilot run data)
- Event reconstruction - recoil mass from $\mu^+\mu^-$-pair with photon veto.
- Main challenge: reduction of $\mu^+\mu^-\gamma$ background.
- Bump hunt of recoil mass distribution.
- Main backgrounds from QED processes;
  - $\mu^+\mu^-\gamma$
  - $\mu^+\mu^-e^+e^-$
  - $\tau^+\tau^-\gamma$

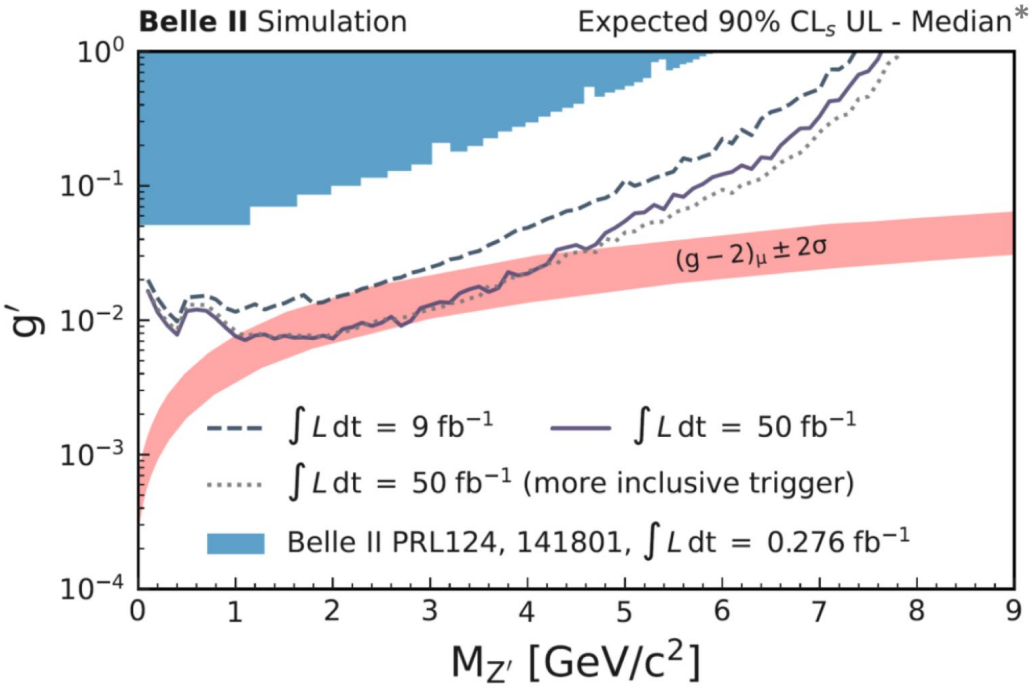


PRL 124, 141801 (2020)





Invisible Z' II

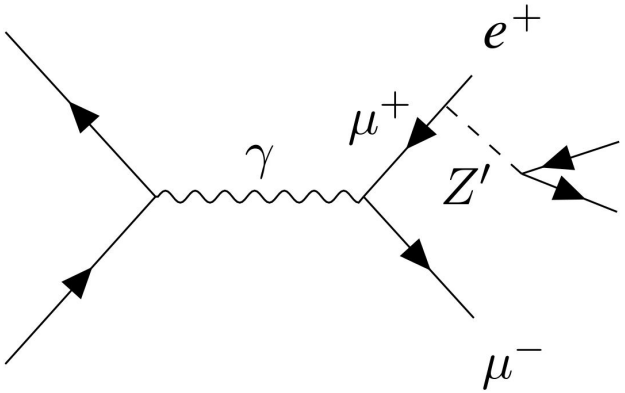


Updated result expected soon!

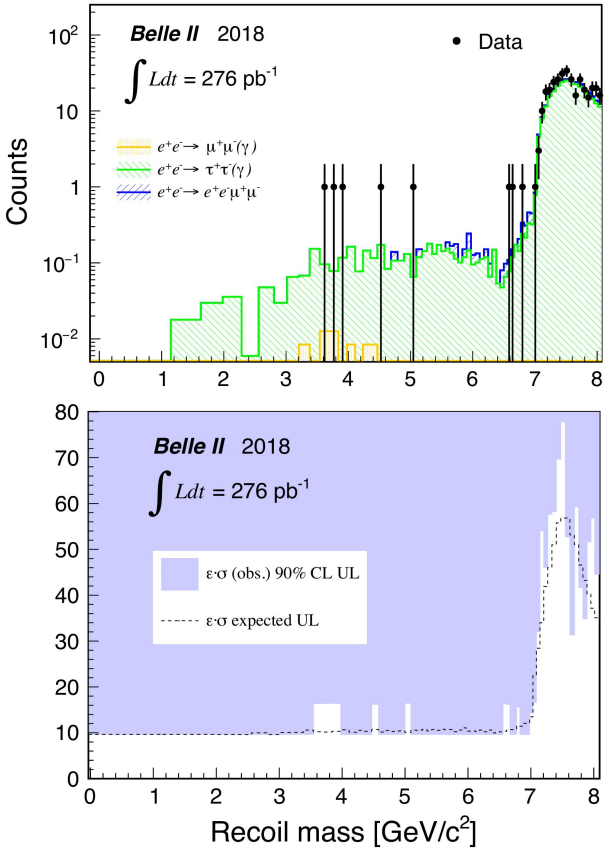
*preliminary (conservative) systematics

Invisible Z’ III - LFV

- Event reconstruction - recoil mass from eμ-pair with photon veto.
- Included in same publication
- Model independent search with the same criteria.



PRL 124, 141801 (2020)

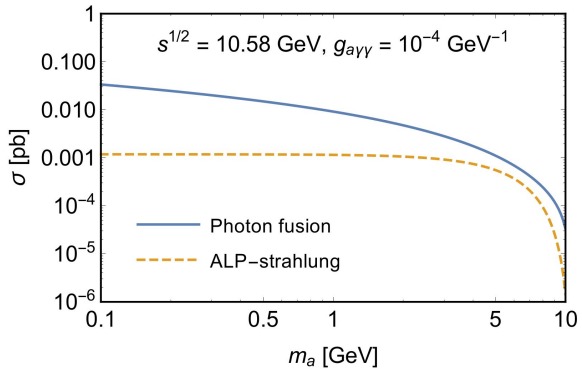


Axion-like Particles

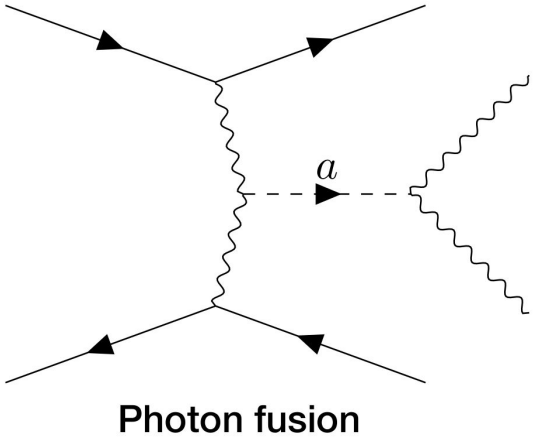
Axion-like Particles I

- Pseudoscalar particles that couple to bosons
- Unlike QCD axions, coupling and mass of ALPs are taken to be independent
- Search conducted via two photon coupling;
  - Photon fusion (high QED background)
  - **ALP-strahlung** (more promising)

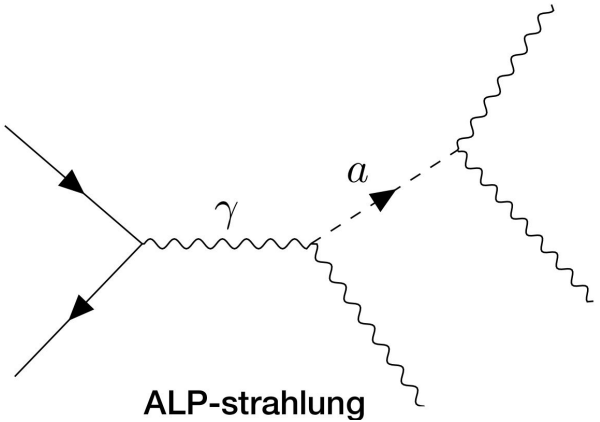
$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \tau_a \sim 1/g_{a\gamma\gamma}^2 m_a^3$$



First search at B-factory



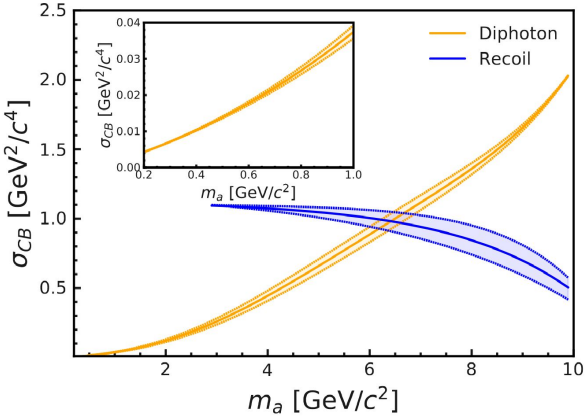
Photon fusion

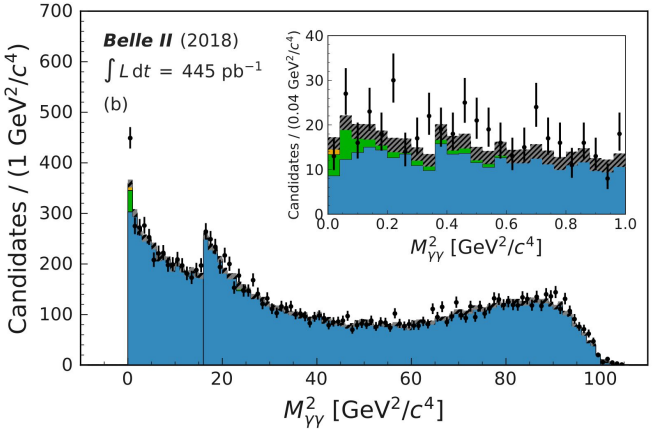


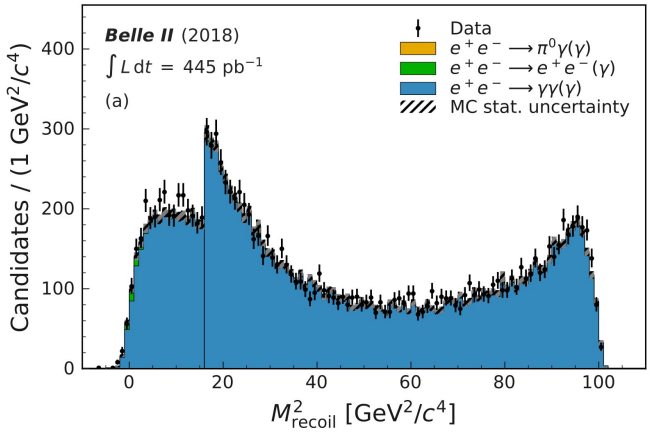
ALP-strahlung

Axion-like Particles II

- Search for events containing 3 photons which sum to beam energy [Υ(4S)], no tracks.
- Main challenge: signal signature, three photons often difficult to resolve
- Bump hunt in diphoton mass and squared recoil mass.
  - Low ALP mass -> squared diphoton mass
  - High ALP mass -> squared recoil mass
- Main backgrounds:
  - $e^+e^- \rightarrow \gamma\gamma(\gamma)$
  - $e^+e^- \rightarrow e^+e^-\gamma$
  - $e^+e^- \rightarrow P\gamma\gamma$, $P=\pi^0, \eta, \eta'$



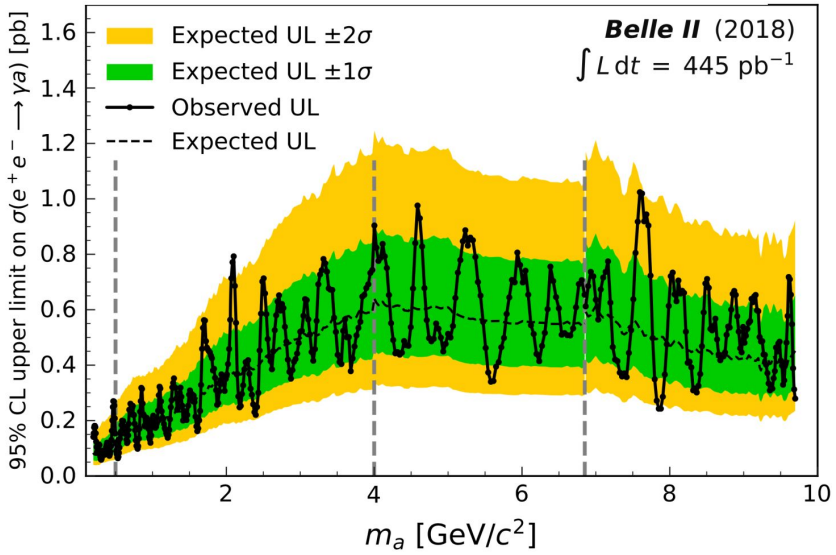


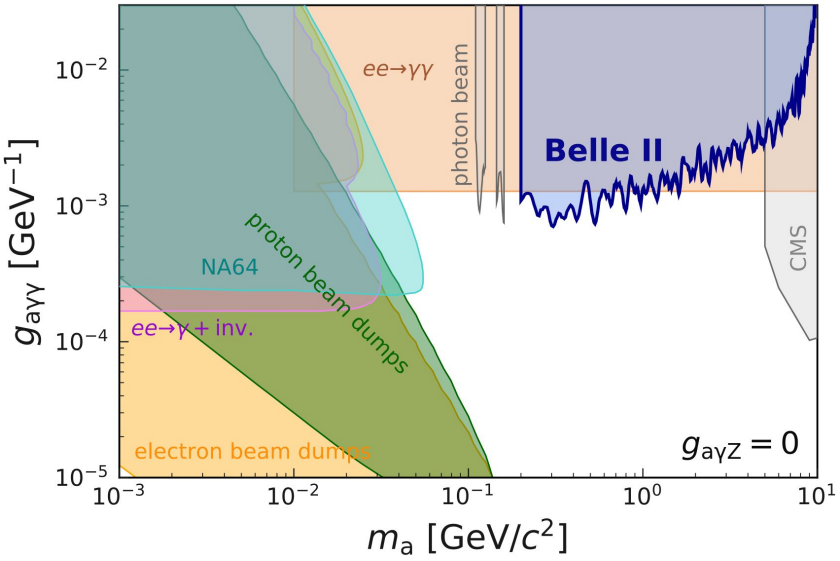


Axion-like Particles III

- Search conducted with 445pb^{-1} of 2018 pilot run data.
- 500 fits in sliding ranges with steps of half mass resolution.
- No excess observed (largest local sig. - 2.8σ)

PRL 125, 161806 (2020)

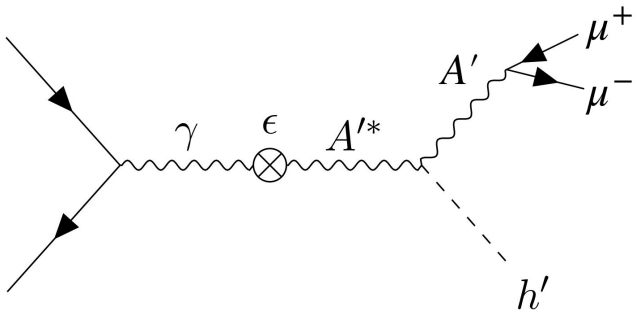




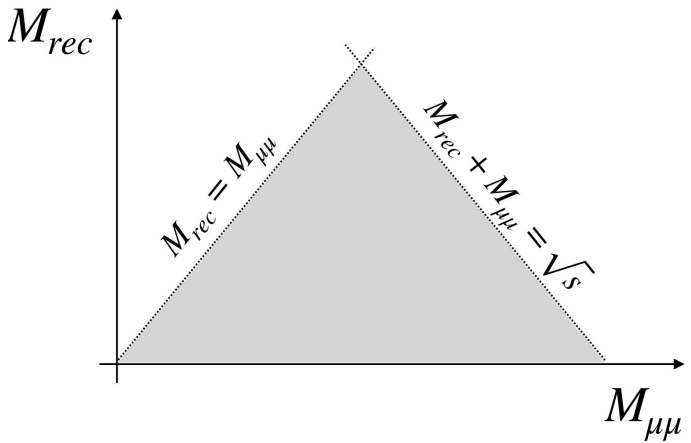
Dark Higgsstrahlung

Dark Higgsstrahlung I

- Dark photon mass generated via spontaneous symmetry breaking of **U(1)'** extension to SM, introduces dark Higgs boson
- In minimal scenario: a single **dark photon, A'**, and a single **dark Higgs, h'**
- $e^+e^- \rightarrow A'h'$ (higgsstrahlung)
  - Focus on $m_{h'} < m_{A'}$ => h' has long lifetime, escapes detection
  - Search for $\mu^+\mu^-$ + missing energy
  - Peak in 2D recoil mass vs. dimuon mass distribution

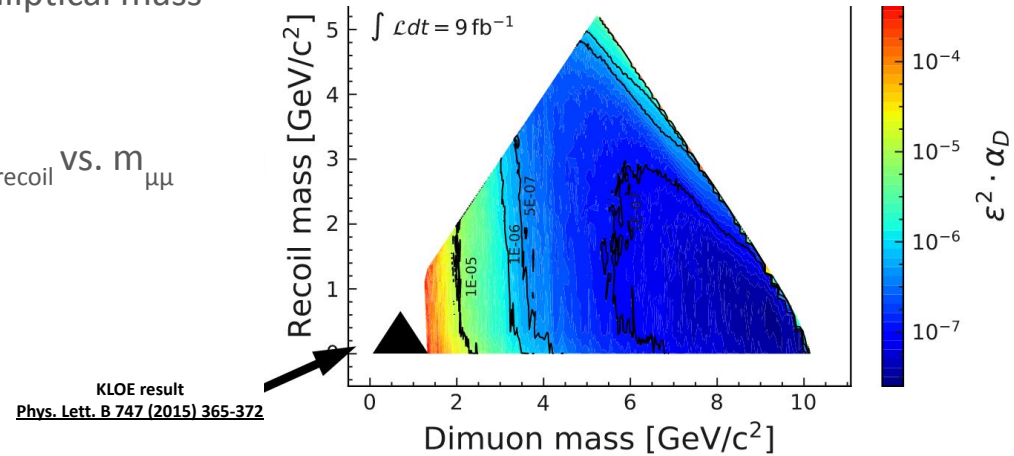


$$\sigma \propto \epsilon^2 \times \alpha_D$$



Dark Higgsstrahlung II

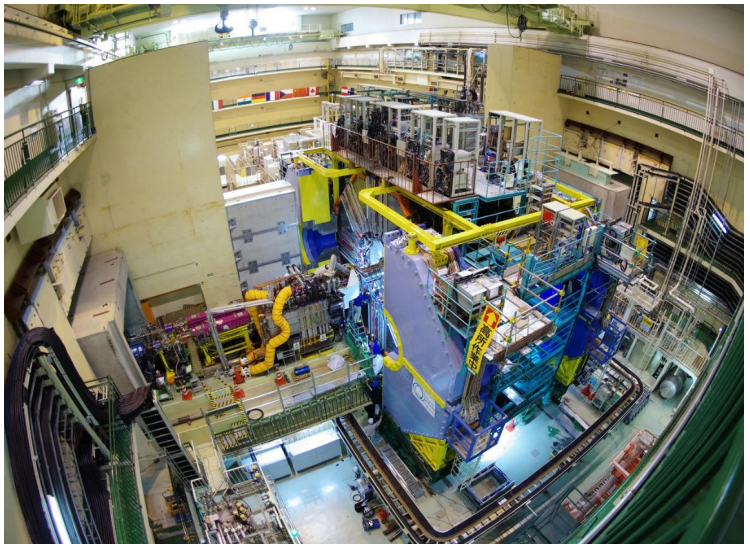
- Background suppression based on kinematic features
- Main challenge: measurement strategy, looking for two particles while scanning and counting 9000 elliptical mass windows.
- Improvements w.r.t KLOE result;
  - Probing unconstrained regions in 2D m_{recoil} vs. $m_{\mu\mu}$ plane.
  - Probing non-trivial regions of $\varepsilon^2\alpha_D$
- Backgrounds:
  - $\mu^+\mu^-\gamma$
  - $\mu^+\mu^-e^+e^-$
  - $\tau^+\tau^-\gamma$



Results very soon

Conclusion

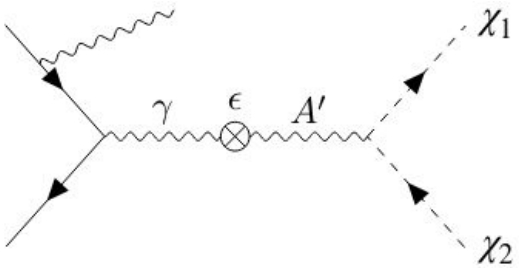
- Broad and varied dark sector searches at Belle II => set to lead the field in the MeV - GeV mass range in the coming years
- Belle II has collected 267fb^{-1} thus far -> will collect ≈50ab^{-1} in the next decade.
- First results published (using 2018 pilot run data):
  - Z’ ⟶ invisible (with LFV Z’) (PRL 124, 141801 (2020))
  - ALP ⟶ γγ (PRL 125, 161806 (2020))
- Further results in the pipeline with data collected since 2019:
  - A’ ⟶ invisible search
  - Dark higgsstrahlung
  - Z’ ⟶ invisible update
  - B decays
  - Much more!

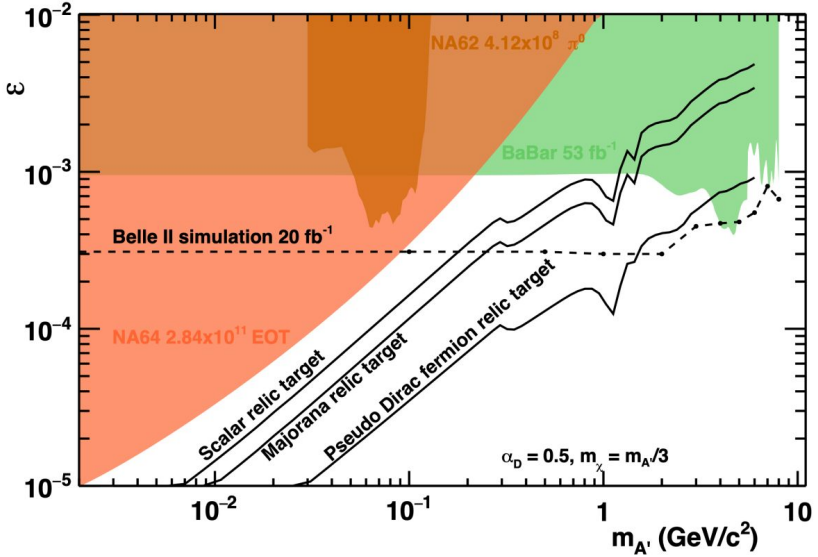


Backup

Dark Photon

- U(1)' extension to SM introduces new massive gauge boson A' of spin 1.
- Coupled to SM photon by kinetic mixing parameter ε
- $m_{DM} < 0.5m_{A'}$ => A' decays into an invisible state
- Search for single high energy photon (ISR)
- Backgrounds;
  - $e^+e^- \longrightarrow \gamma\gamma(\gamma)$
  - $e^+e^- \longrightarrow e^+e^-\gamma$
  - Cosmics



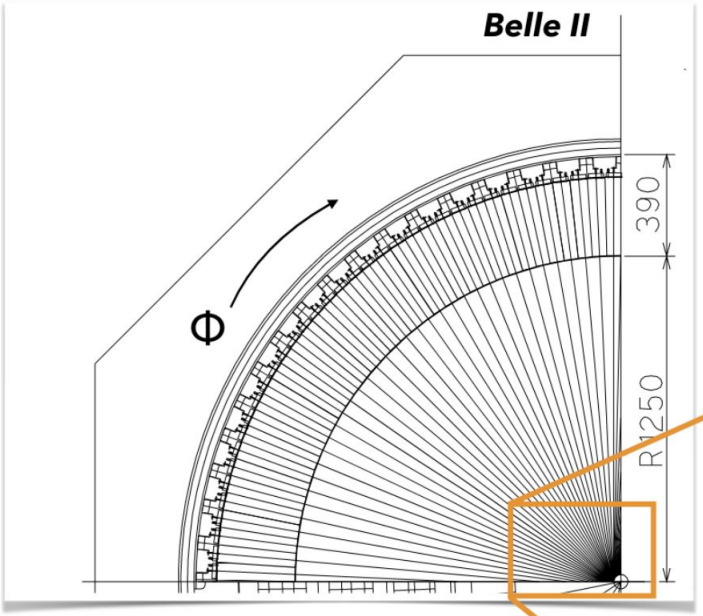


- Improvements over BaBar;
  - No projective cracks in ECL
  - KLM veto
  - More hermetic calorimeter

Other Searches

- Dark photon
- Dark scalar; $e^+e^- \rightarrow \tau^+\tau^- S(\rightarrow l^+l^-)$
- Dark matter from B decays:
  - $B^+ \rightarrow K^+ S(\rightarrow l^+l^-)$
  - $B^+ \rightarrow K^+ a(\rightarrow \gamma\gamma)$
- Inelastic dark matter (LLP)
- Other Z' decays:
  - $e^+e^- \rightarrow \mu^+\mu^- Z'(\rightarrow \mu^+\mu^-)$
  - $e^+e^- \rightarrow \mu^+\mu^- Z'(\rightarrow \tau^+\tau^-)$
- Magnetic monopoles
- AND MORE!

Electromagnetic Calorimeter (ECL)



- No projective cracks in ϕ in ECL barrel
- More hermetic => more efficient