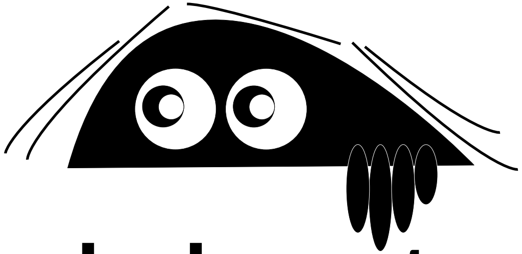


Status and prospects for dark sector searches at Belle II

Workshop on status and perspectives of physics at high intensity

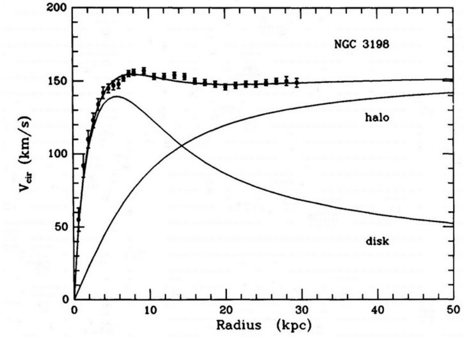
INFN – Laboratori Nazionali di Frascati, Frascati. November 09-11, 2022

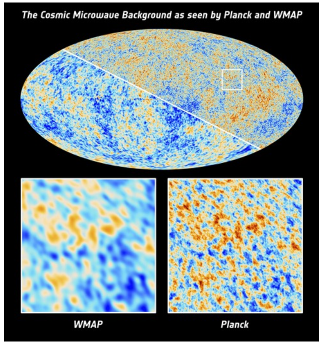
Luigi Corona - University and INFN of Pisa
on behalf of the Belle II collaboration
luigi.corona@pi.infn.it

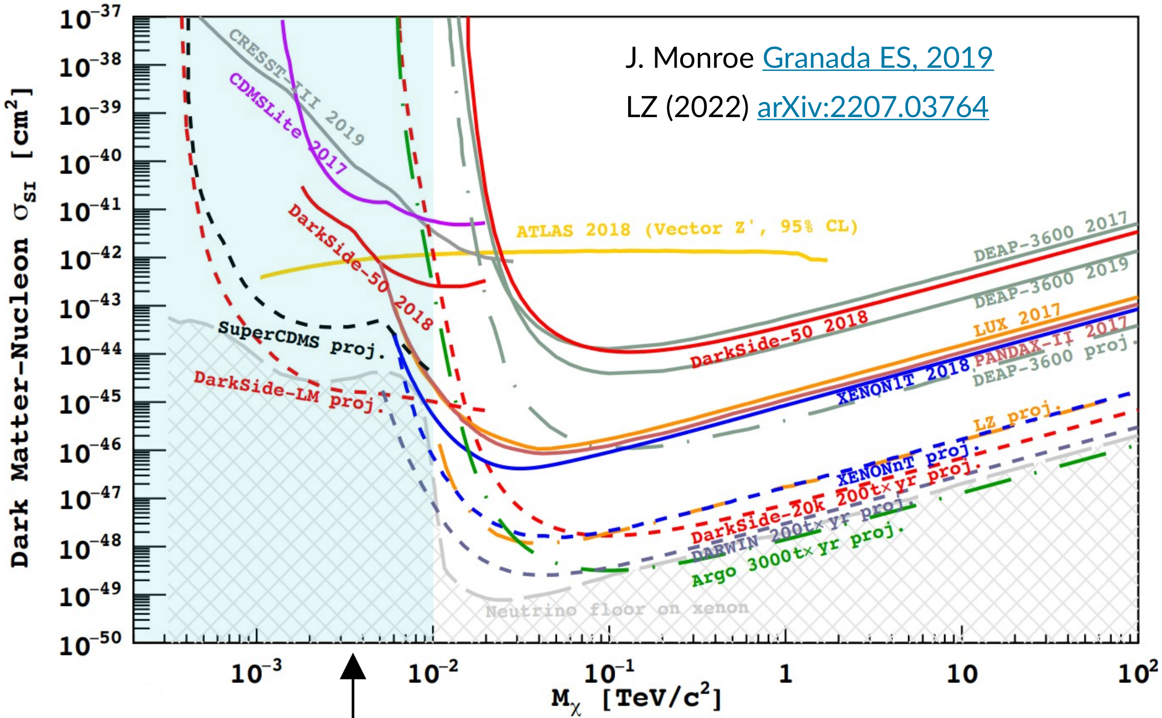
Dark matter puzzle

- DM is one of the most compelling phenomena in support for physics beyond the Standard Model

Albada et al., Astrophysical Journal (1985)



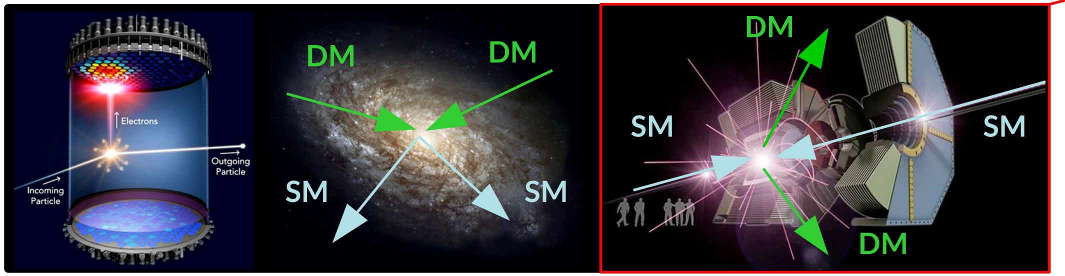




Focus on dark sector searches at Belle II

- How to search for it?

Direct **Indirect** **Colliders**



Searches at colliders

- DM weakly couples to SM particles and it can be produced in SM particles annihilation at accelerators
  - → several signatures involving light **dark sector mediators** too

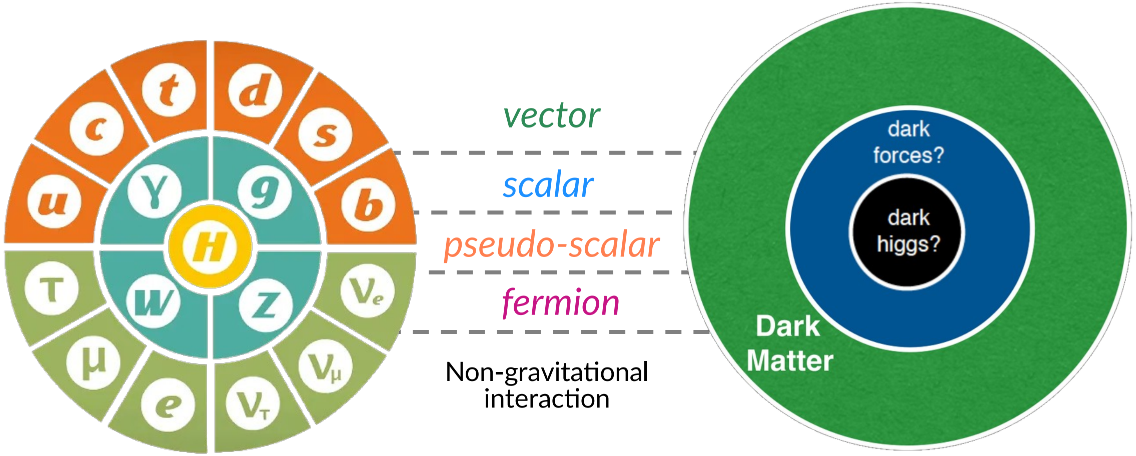
Light dark sectors

- Null dark-matter-search results at the electroweak scale by the LHC and direct detection experiments motivate the interest for models with low-mass dark matter candidates

- Theoretical scenarios introducing light dark matter with M ~ O(MeV-GeV) need light mediators too

Portals

Dark photon	$\epsilon F^{\mu\nu} A'_{\mu\nu}$
Dark Higgs	$k\|H\|^2\|S\|^2$
Neutrino	$yHLN$
Axion	$\frac{1}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} a$



- Not just solving the dark matter puzzle. Could explain:
  - some astrophysics anomalies: positron excess in cosmic rays, …, (PAMELA, Fermi, …)
  - some anomalies in *B* meson decays: R_{D^*}, R_{K^*},… (Belle, LHCb, …)
  - the $(g-2)_\mu$ anomaly, recently confirmed at Fermilab [3]

[1] Batell et al., Phys. ReV. D 80, 095024 (2009)
[2] Essig et al., arXiv:1311.0029 (2013)
[3] Abi et al., Phys. Rev. Lett. 126, 141801 (2021)

Dark sector searches at Belle II

1) Different signatures depending on the relation between mediator and dark matter mass

2) Clean environment at e^+e^- collider, high performance hermetic detector, known initial state

3) Large statistics thanks to the high luminosity provided by SuperKEKB (L_{peak} = 6.35x10^{35} $cm^{-2}s^{-1}$)

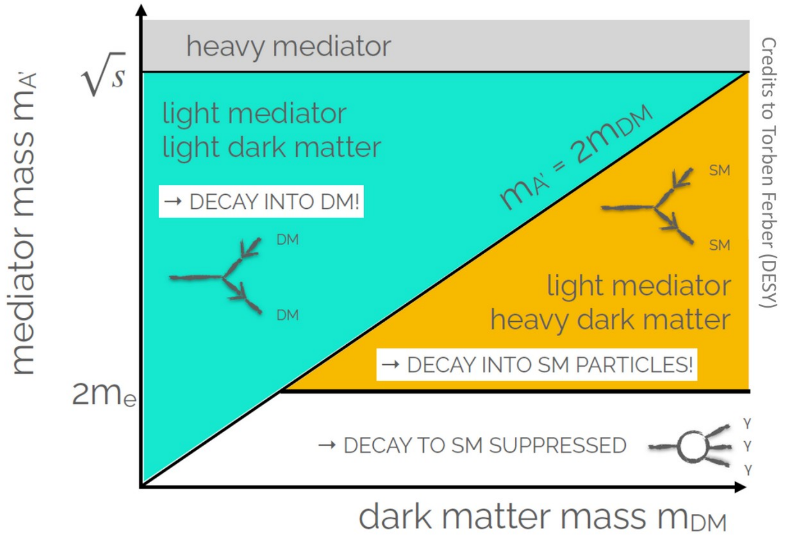
4) Dedicated low-multiplicity triggers

   - Suppress high cross section QED processes **without killing the signal**

   - It requires precise knowledge of detector acceptance and efficiencies

Excellent reconstruction capabilities for low multiplicities and missing energy signatures at B-factories

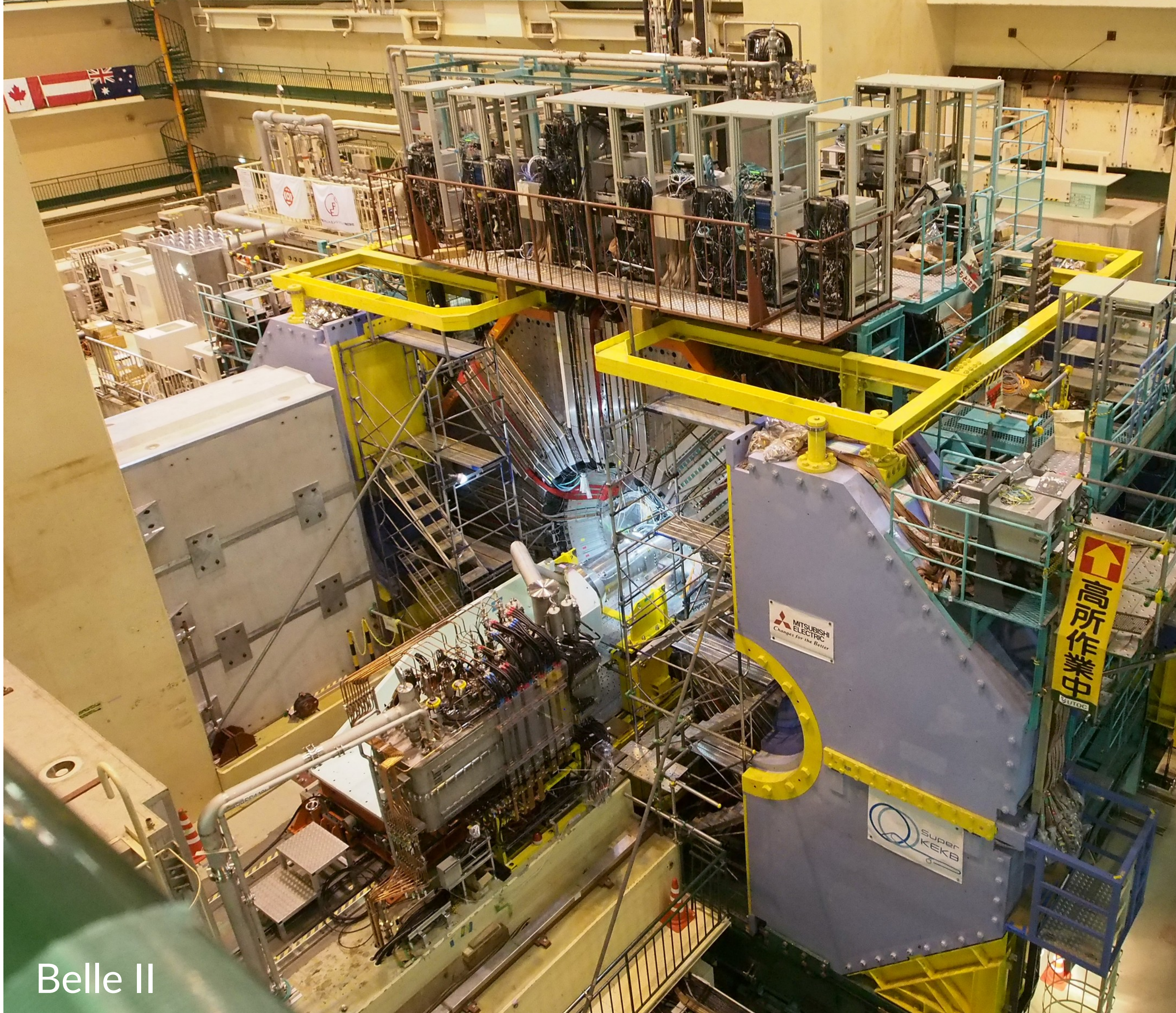
Belle II: experiment at the new generation of B-factory SuperKEKB → See Gaetano's talk!



Belle II is already providing important contributions in the search for dark sector physics with M ~ O (MeV – GeV)

- First Belle II physics publications are dark sector searches ($Z' \to inv.$, $a \to \gamma\gamma$) with commissioning dataset of ~0.5 fb^{-1} collected

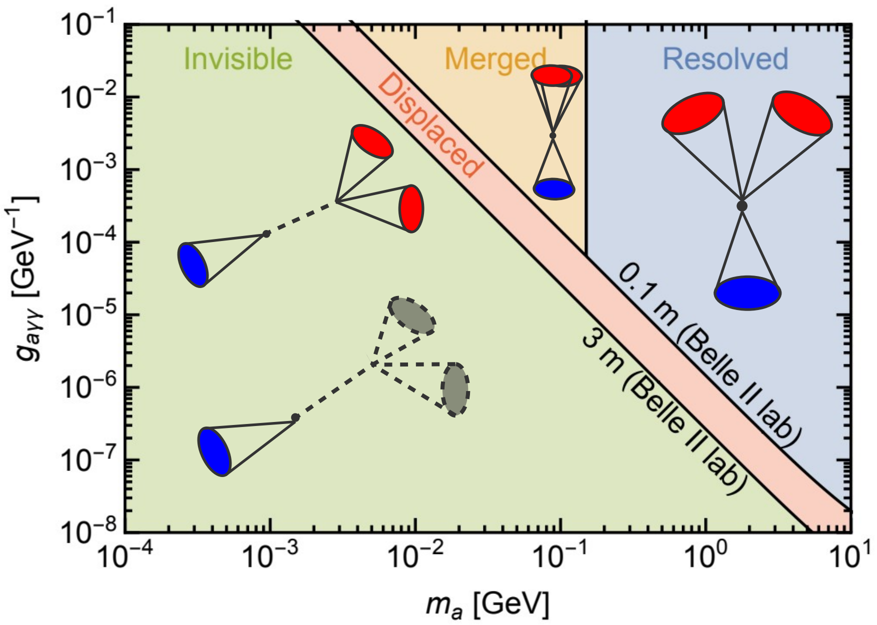
Overview on dark sector searches

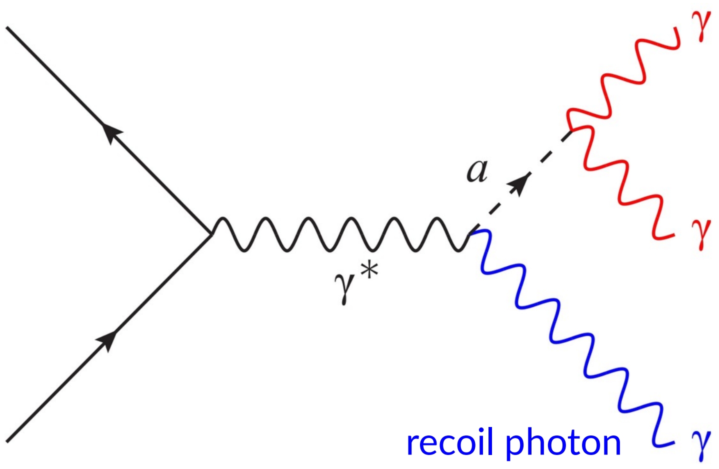


Belle II

Axion-like particles (ALPs)

- GeV-scale ALPs: pseudo-scalar portal mediator between dark sector and Standard Model
- If ALP-photon coupling ($g_{a\gamma\gamma}$) dominates, than $BR(a \to \gamma\gamma) \sim 100\%$
- Focus on mass region where ALP decay is prompt and photons can be well resolved by Belle II





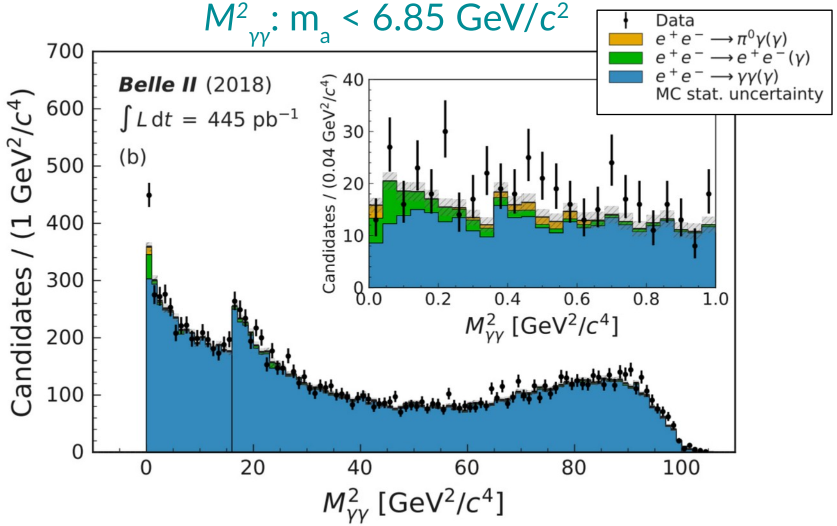
Search for an ALP at Belle II

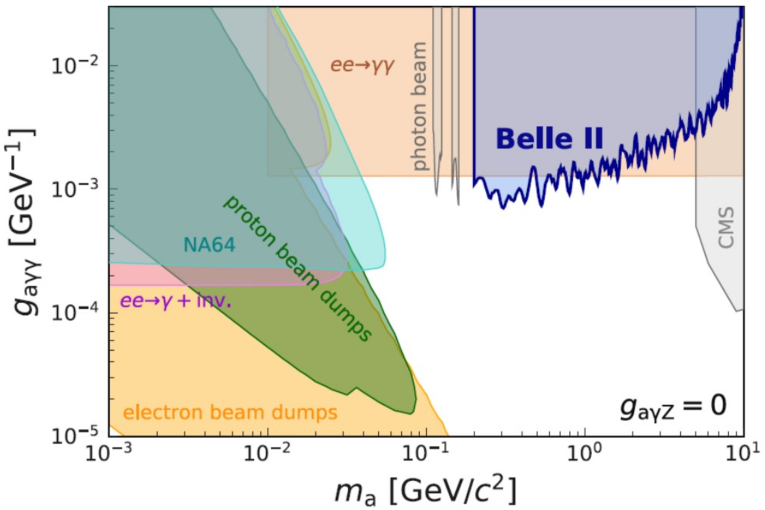
F. Abudinen et al., Phys. Rev. Lett. 125, 161806 (2020)

- Dataset: 0.445 fb^{-1}
- Event selection:
  - calorimeter trigger (e.m. calorimeter efficiency almost 100%)
  - three-γ invariant mass compatible with collision $\sqrt{s}$
- Signature: narrow peak in $M^2_{\gamma\gamma}$ or M^2_{recoil} (depending on best resolution of signal peak)
- Largest background from $e^+e^- \to \gamma\gamma(\gamma)$
- Fit scan to extract signal yield
  - ➔ No excess in data observed - 95% CL upper limits on $g_{a\gamma\gamma}$

World leading exclusion limits around m_a ~ 0.5 GeV/c^2

$M^2_{\gamma\gamma}$: m_a < 6.85 GeV/c^2





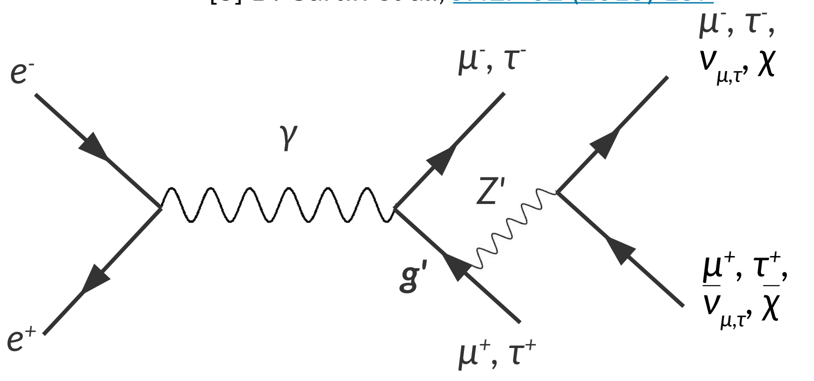
Search for a Z’ boson

[1] Shuve et al., Phys. Rev. D 89 , 113004 (2014)
[2] Altmannshofer et al., JHEP 106 (2016)
[3] D. Curtin et al., JHEP 02 (2015) 157

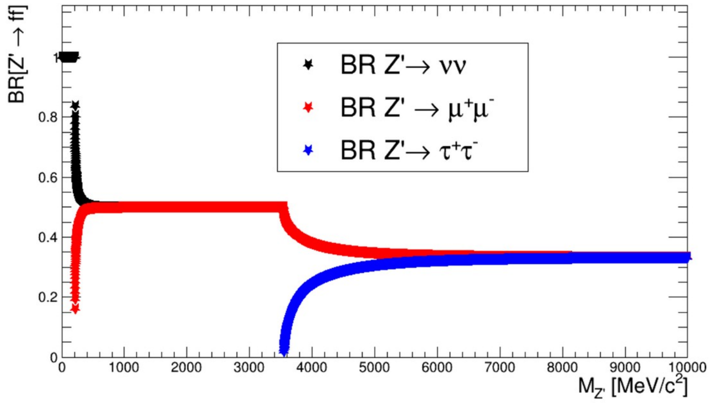
- Vector boson *Z’* with a coupling *g’* only to the 2nd and 3rd generations of leptons introduced by the $L_\mu - L_\tau$ model [1, 2, 3]

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

θ =+1 if $l = \mu$
θ =-1 if $l = \tau$

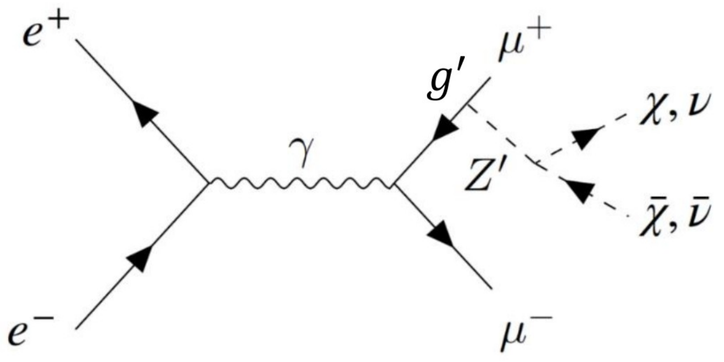


- May explain DM abundance, the $(g - 2)_\mu$ anomaly
- May solve anomalies observed in rare *B* decays, $B \to K^*\mu\mu$, $R_{K(*)}$
- Possibile decays: $Z' \to$ invisible (neutrinos or light DM), $Z' \to \tau\tau$, $Z' \to \mu\mu$
- Existing constraints from:
  - $e^+ e^- \to \mu^+ \mu^- Z'$, $Z' \to \mu^+ \mu^-$ (BaBar(2016), Belle(2022), CMS(2019)),
  - $e^+ e^- \to \mu^+ \mu^- Z'$, $Z' \to$ *invisible* (Belle II(2020))
  - neutrino-nucleus scattering processes (neutrino trident production, CCFR and CHARM-II experiments)



Z' → invisible at Belle II

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



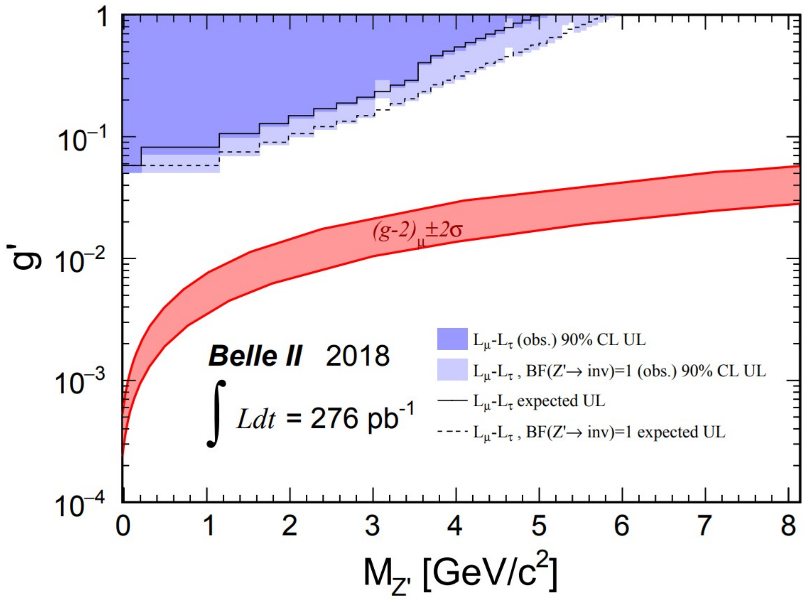
- **$e^+e^- \rightarrow \mu^+\mu^-$ + missing energy**
- Signature: a narrow peak in the recoil mass against the two muons
- First search for an invisible *Z'* has been performed at Belle II with 0.276 fb^{-1}

$e^+e^- \rightarrow \tau^+\tau^- (\gamma)$: missing energy due to neutrinos

$e^+e^- \rightarrow \mu^+\mu^- (\gamma)$: missing energy due to undetected photons

$e^+e^- \rightarrow e^+e^-\mu^+\mu$: missing energy due to undetected electrons

- No excess observed in data → 90% CL upper limits on *g'*
  >> I. Adachi et al, PhysRevLett.124.141801 (2020)



Z' → invisible at Belle II

Analysis

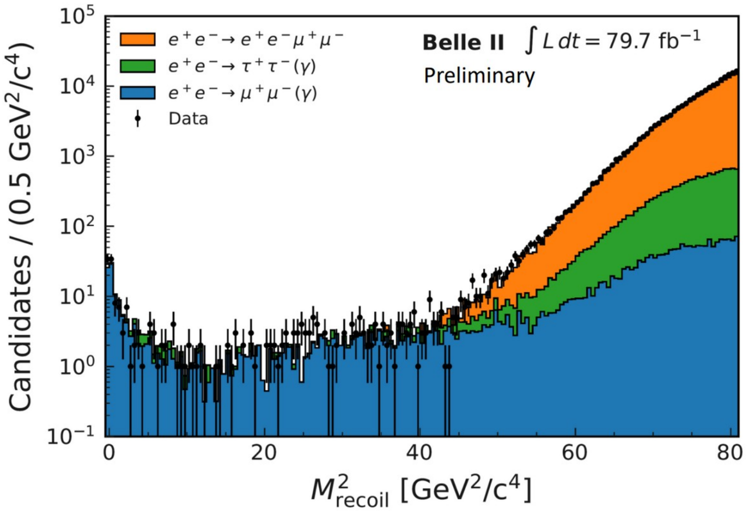
- Dataset: 79.7 fb^{-1}
- Event selection:
  - two-track trigger
  - two reconstructed muons, $p_T^\mu > 0.4$ GeV/c
  - recoil momentum no nearby photon
- Background suppression based on the different origin of the missing momentum in background and signal (FSR)
  - → neural network trained to optimize the Punzi-FOM
    >> Eur. Phys. J. C 82, 121 (2022)

$e^+e^- \rightarrow \tau^+\tau^- (\gamma)$ almost 100% suppressed

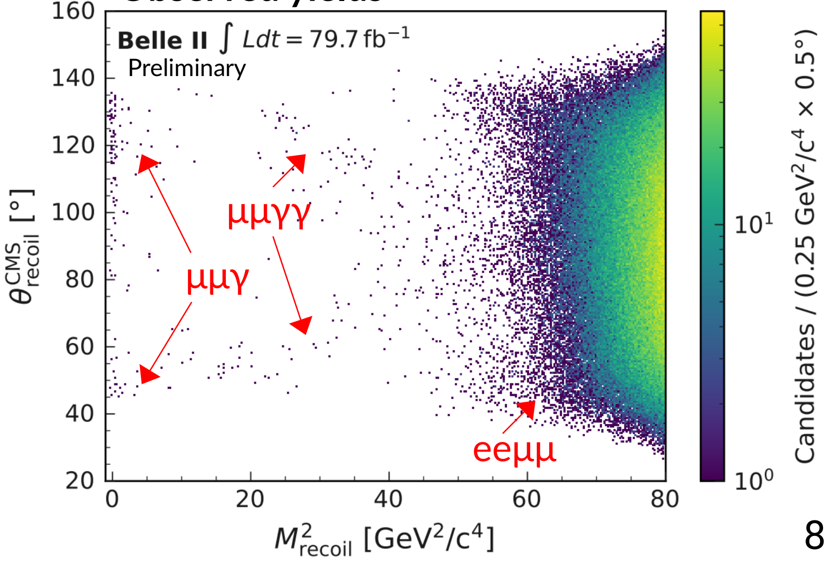
$e^+e^- \rightarrow \mu^+\mu^- (\gamma)$ bands in θ_{recoil} vs M^2_{recoil} due to γ lost in ECL gaps

$e^+e^- \rightarrow e^+e^-\mu^+\mu$

- **Search for a bump in 2D plane of θ_{recoil} vs M^2_{recoil}**



Observed yields



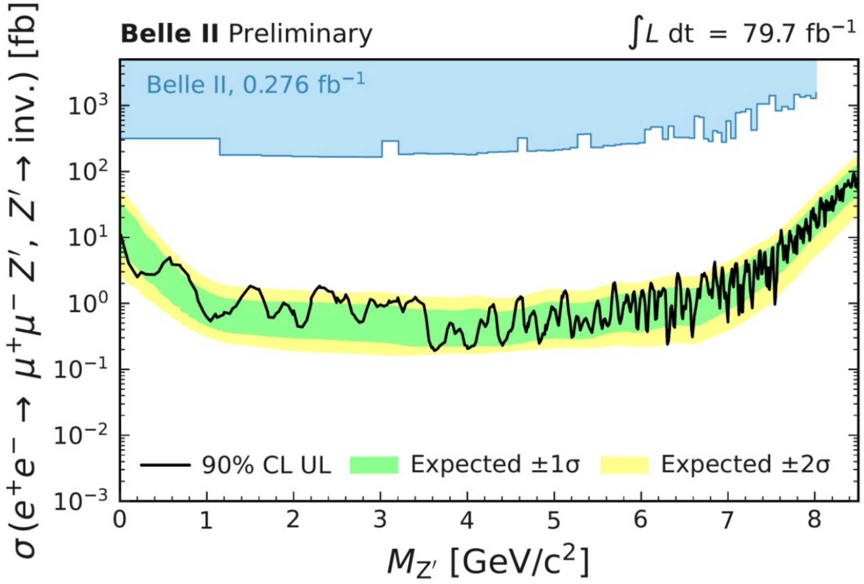
Z' → invisible at Belle II

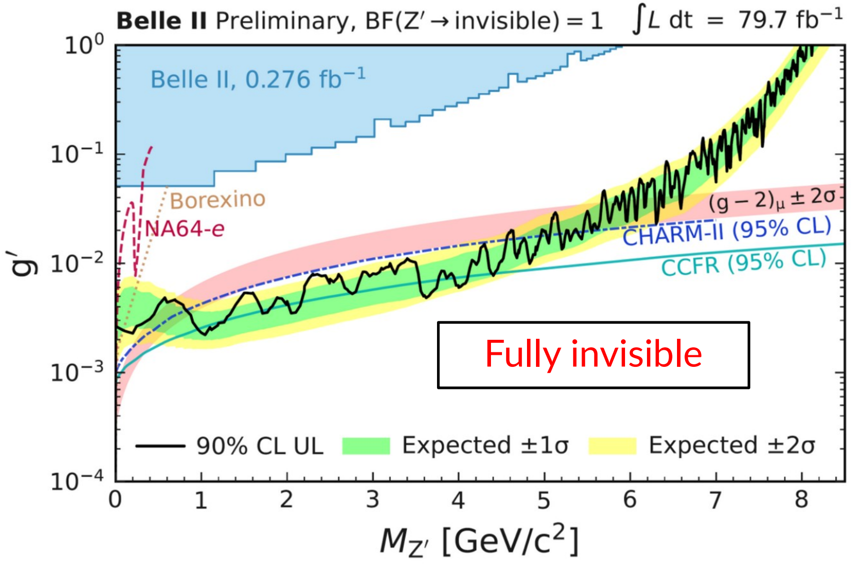
Results

★ Presented @ ICHEP 2022

- No excess found
- Set 90% CL exclusion limits on cross section and coupling
  - Standard $L_\mu - L_\tau$ model: Z' decays to Standard Model only
  - Fully invisible scenario: BR($Z' \to$ invisible) = 1 [$Z' \to \chi\bar{\chi}$]

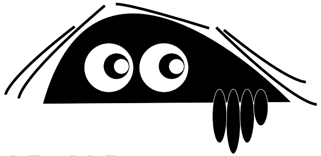
Fully invisible Z' as origin of $(g-2)_\mu$ excluded for $0.8 < M_{Z'} < 5.0$ GeV/c^2
- to be submitted for publication





Z', S, ALP → ττ at Belle II

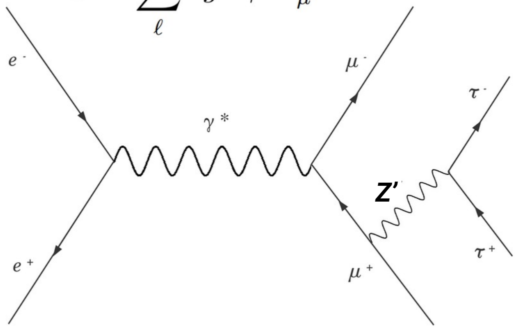
ALP ? S ? Z'?



Vector portal

$e^+ e^- \to \mu^+ \mu^- Z', Z' \to \tau^+ \tau^-$

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

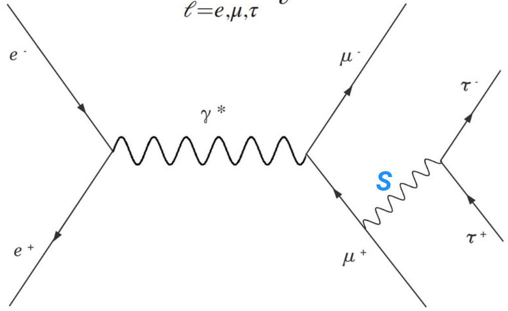


- *Z'* of the $L_\mu - L_\tau$ model
- **First search in ττ**

Scalar portal

$e^+ e^- \to \mu^+ \mu^- S, S \to \tau^+ \tau^-$

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

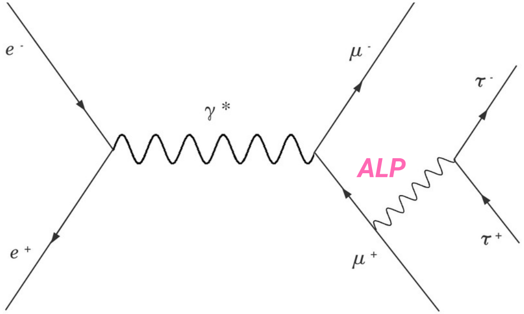


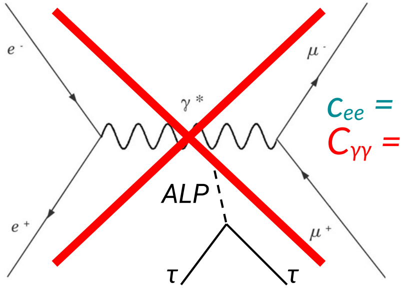
- Leptophilic dark scalar *S* model
- Constraints from $S \to ee/\mu\mu$ (BaBar(2020), Belle)
  - ➔ Model unconstrained for M_S > 6.5 GeV/c^2
- **First search in ττ**

Pseudo-scalar portal

$e^+ e^- \to \mu^+ \mu^-$ ALP, ALP $\to \tau^+ \tau^-$

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





$C_{ee} = C_{\mu\mu} = C_{\tau\tau}$

$C_{\gamma\gamma} = C_{Z\gamma} = 0$

- **First search for *ALP* → ττ**
- Yukawa-like effective coupling
- *ALP*-τ coupling unconstrained

- **ττ system difficult to reconstruct → signature unconstrained**
  - ➔ Not expected to improve existing limits on $L_\mu - L_\tau$
  - ➔ Dataset: 62.8 fb^{-1}

Z', S, ALP → ττ at Belle II

Analysis

- Signature: narrow peak in the recoil mass distribution w.r.t the $\mu^+\mu^-$ in $\mu^+\mu^-\tau^+\tau^-$ final state

- Event selection:

  - 4 tracks with M(4tracks) < 9.5 GeV/c^2
    - two tracks compatible with muon hypothesis
    - τ to 1-prong: two tracks compatible with charged stable particles (e, μ, h)

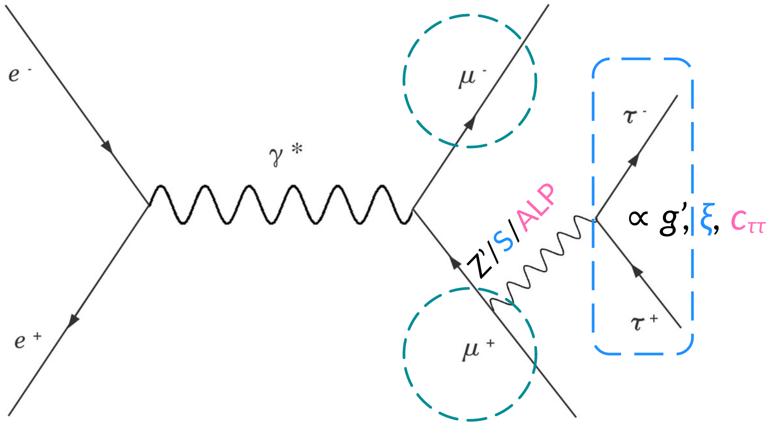
  - 3-track OR single-muon trigger

- Background suppression based on

  - 8 neural networks trained for different ranges in $M_{recoil}(\mu\mu)$ using variables
    - sensitive to the presence of a resonance produced as FSR from on the the two muons
    - sensitive to the presence of a $\tau\tau$ system in the final state

Recoil mass distribution w.r.t to the two tagging muons

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



$Z', S, ALP \to \tau\tau$ at Belle II

Analysis

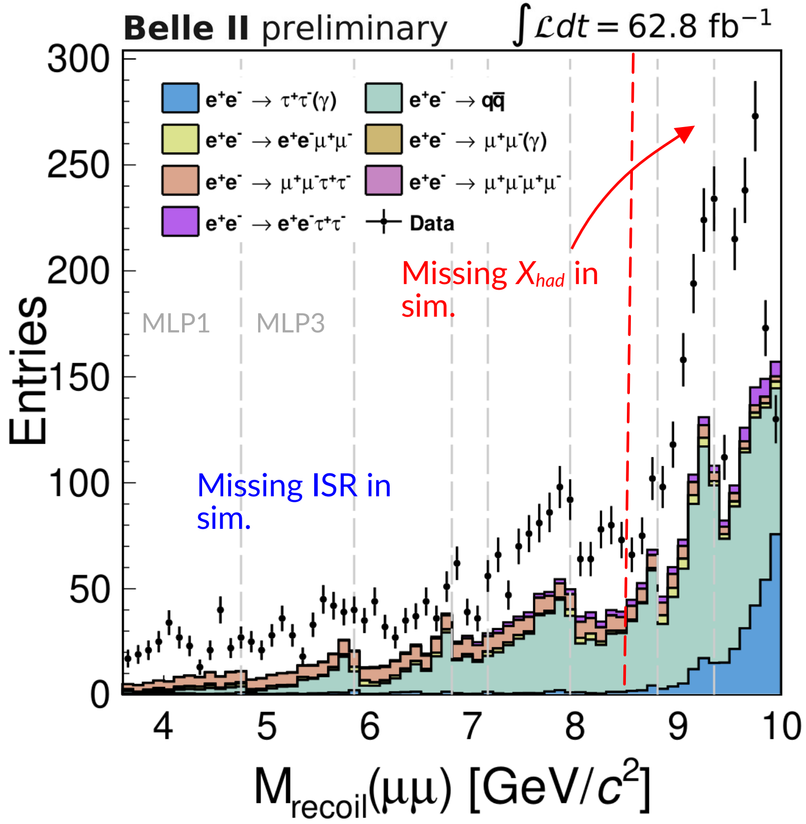
- Main background components:
  - $e^+ e^- \to \tau^+ \tau^- (\gamma)$
    $e^+ e^- \to q \bar{q}$ ($q = u, d, s, c, b$)
  - $e^+ e^- \to e^+ e^- \mu^+ \mu^-$
    $e^+ e^- \to \mu^+ \mu^- \tau^+ \tau^-$
    $e^+ e^- \to e^+ e^- \tau^+ \tau^-$
    $e^+ e^- \to \mu^+ \mu^- \mu^+ \mu^-$

    ISR **NOT** in simulation
  - $e^+ e^- \to \mu^+ \mu^- \pi^+ \pi^-$
    $e^+ e^- \to e^+ e^- X_{had}$ (two-photon processes)

    NOT in simulation

data/MC discrepancies:
No-peaking
expected and **understood**

- **Signal yield from a fit scan over M_{recoil} above floating background**
  - Expected worsening in sensitivity with respect to simulation because of the higher background in data

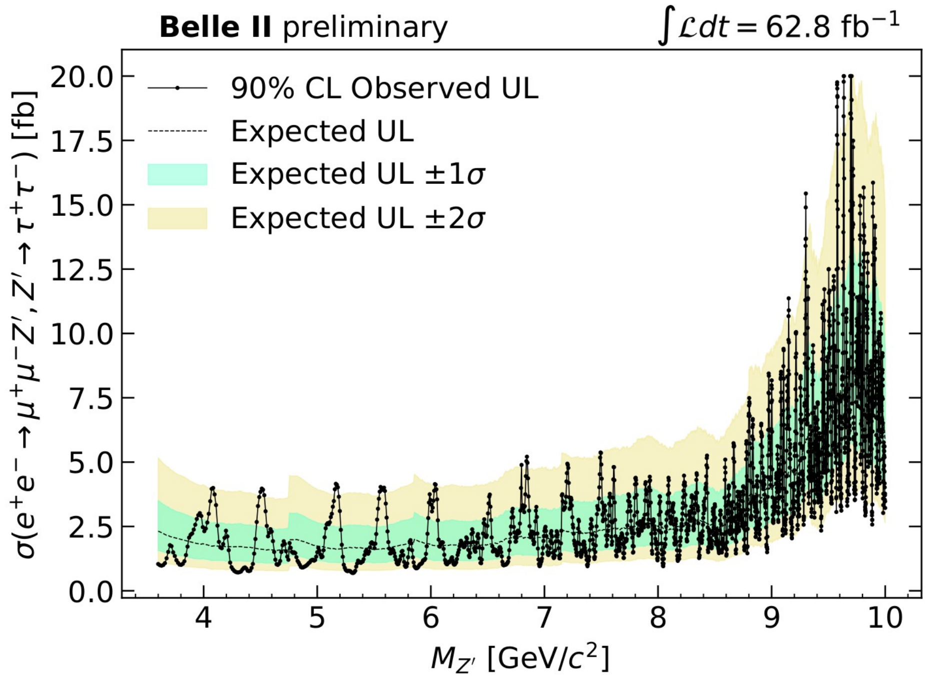


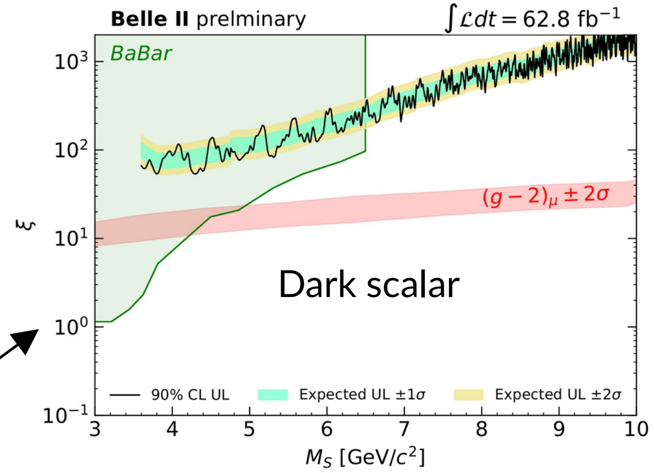
Z’, S, ALP → ττ at Belle II

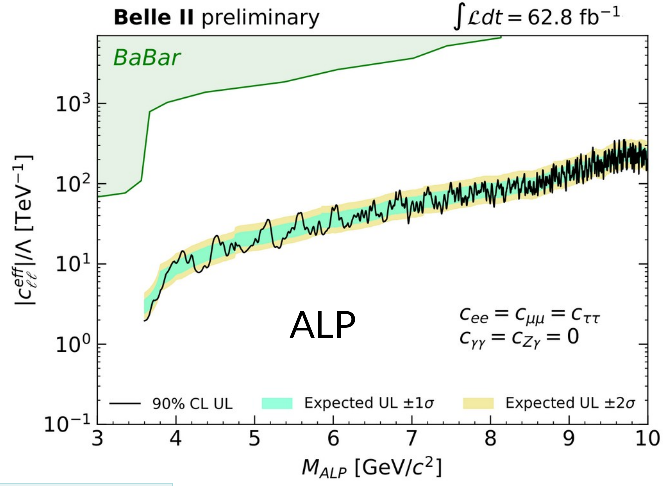
Results

- No excess compatible with signal found
  - Set 90% CL UL on cross section and couplings

★ Presented @ [ICHEP 2022]



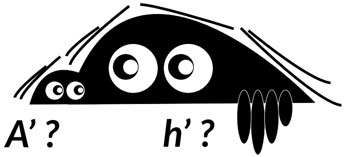




First constraints on S for M_S > 6.5 GeV/c^2 and firts direct constraints for *ALP* → ττ
- to be submitted for publication

J. P. Lees et al, PhysRevLett.125.181801 (2020)
M. Bauer et al, JHEP12(2017)044

Search for a dark Higgs (and dark photon)



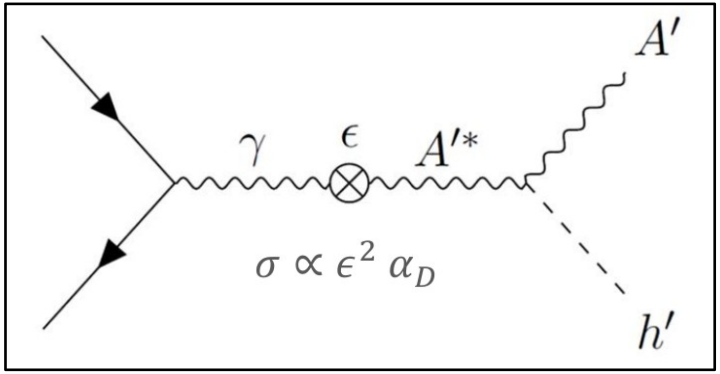
- Dark photon *A'*
  - kinetic mixing with SM photon with strength ε [1]
  - mass produced by the Higgs mechanism involving a dark Higgs boson [2]

- Dark higgs *h'*
  - couples to *A'* with α_D
  - does not mix with Standard Model Higgs

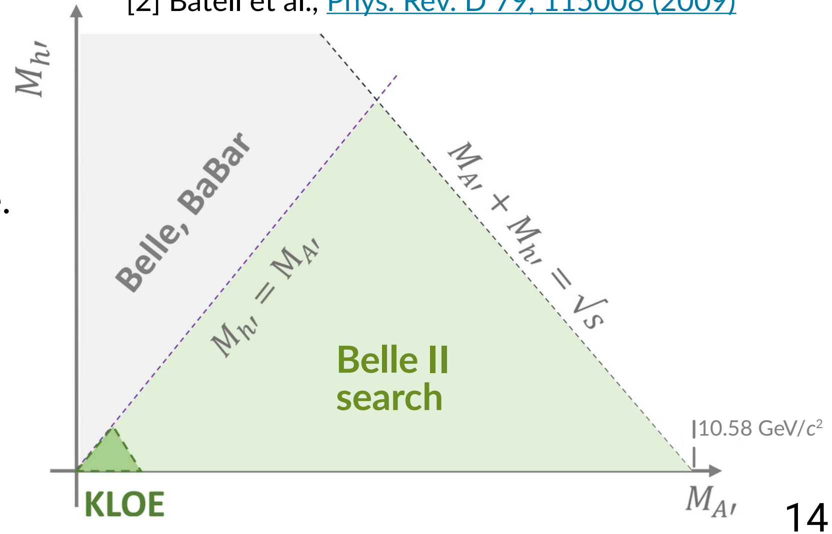
- Both *A'* and *h'* can be produced at e^+e^- colliders through the dark higgsstrahlung process
  - → $e^+e^- \to A'^* \to A' h'$

- Different signatures depending on *h'* mass
  - → $M_{h'} > M_{A'}$: prompt decay $h' \to A'A'$, up to 6 tracks in the final state. Investigated by BaBar(2012) and Belle(2015)
  - → $M_{h'} < M_{A'}$: *h'* is long-lived, thus invisible. Investigated by KLOE(2015)

- **Belle II focuses on the invisible *h'***



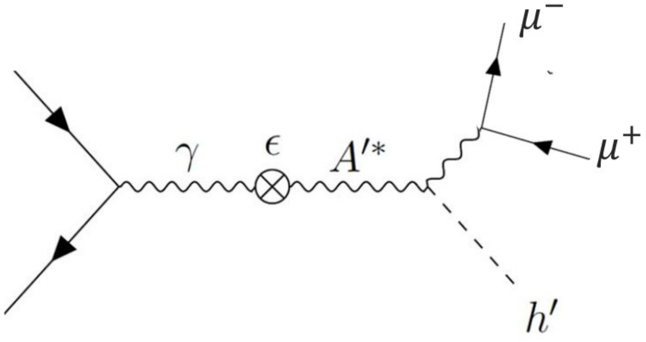
[1] P. Fayet, Nucl. Phys. B 187, 184 (1981)
[2] Batell et al., Phys. Rev. D 79, 115008 (2009)



Dark higgsstrahlung at Belle II

Analysis

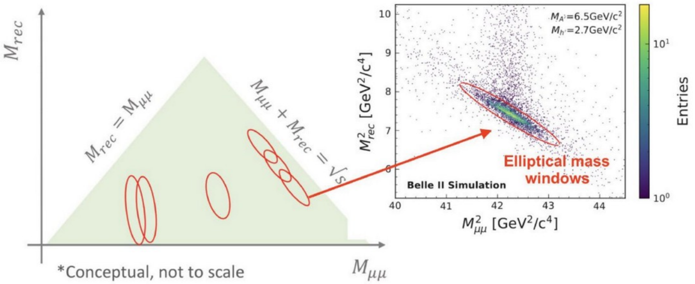
- $e^+e^- \rightarrow A'h', A' \rightarrow \mu\mu, h' \rightarrow$ **invisible**
- Same final state as for the invisible Z', similar backgrounds
- Dataset: 8.34 fb^{-1}
- Signature: 2D peak in recoil vs dimuon mass
- Event selection:
  - two reconstructed muons, $p_T^{\mu} > 0.1$ GeV/c
  - recoil momentum in the ECL barrel, no nearby photon
  - cut on dimuon helicity angle
- Signal extraction
  - scan for excess in 2D plane of M_{recoil} vs $M_{\mu\mu}$ in ~9000 elliptical mass windows

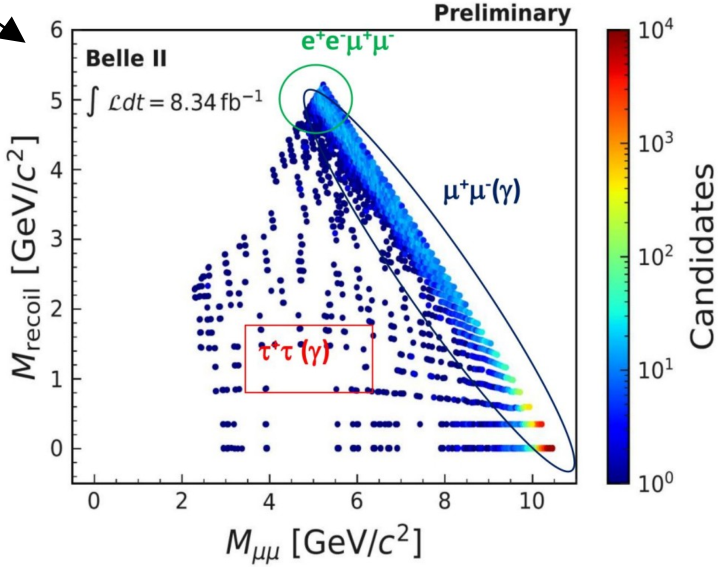


$e^+e^- \rightarrow \tau^+\tau^- (\gamma)$

$e^+e^- \rightarrow \mu^+\mu^- (\gamma)$

$e^+e^- \rightarrow e^+e^-\mu^+\mu^-$



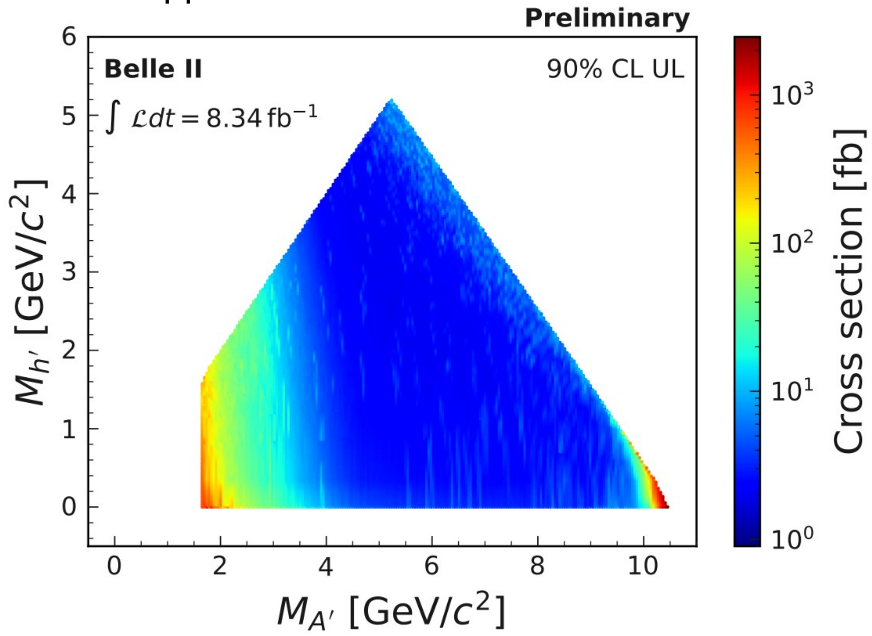


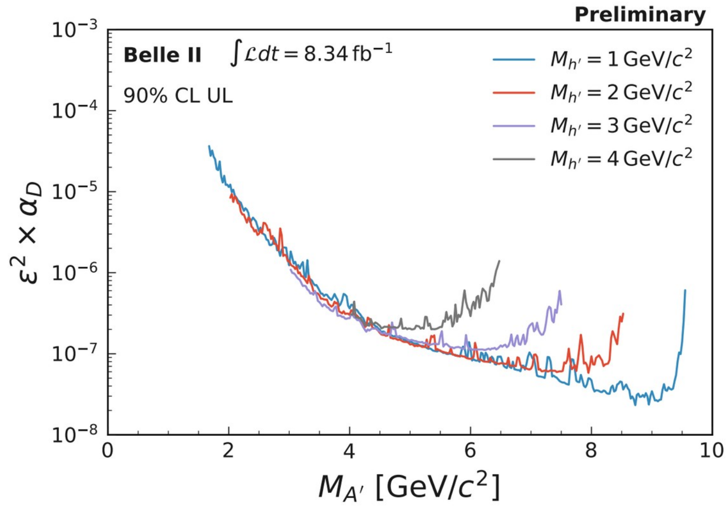
Dark higgsstrahlung at Belle II

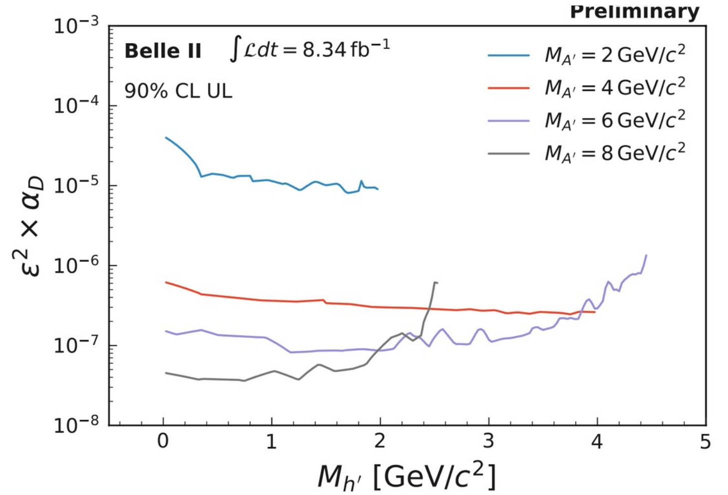
★ Presented @ Moriond 2022

Results

- No significant excess above background was observed
  - ➔ 90% CL upper limits







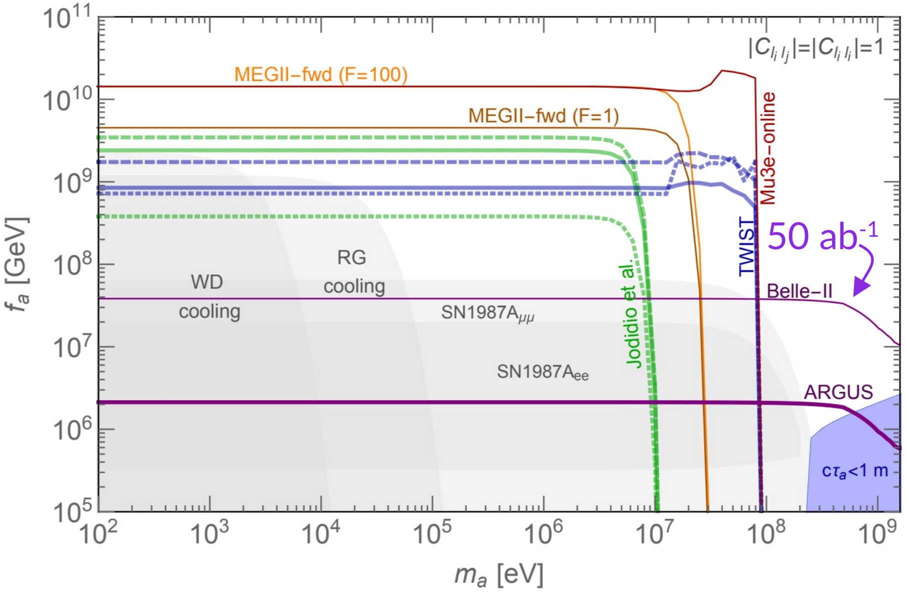
World leading limits for $1.65 < M_{A'} < 10.51$ GeV/c^2
- submitted to PRL→ arxiv.2207.00509

$\tau \to l + \alpha$ (invisible)

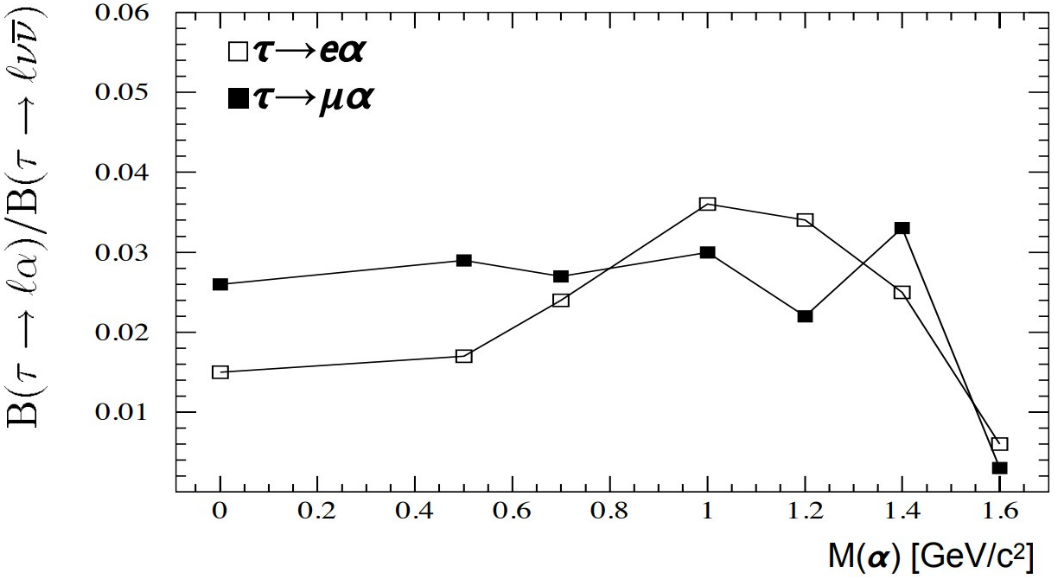
Charged Lepton Flavour Violation (LFV) is allowed in various extensions of the SM but it has never been observed

- Search for LFV two-body decay $\tau \to l + \alpha$ (invisible)
- α is an invisible gauge boson that can be predicted by several new physics models → LFV Z', **light ALP candidate**, …
- Best existing upper limits on $B(\tau \to l\alpha)/B(\tau \to l\bar{\nu}\nu)$ from ARGUS (1995, 476 pb^{-1})
- **Belle II can already set more stringent limits with current data**

L. Calibbi et al., JHEP09(2021)173



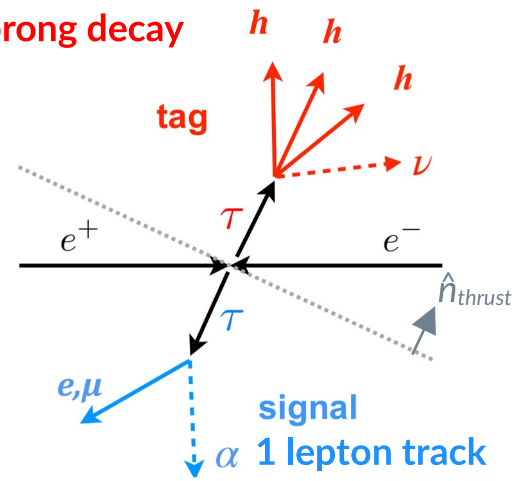
H. Albrecht et al., Z. Phys. C 68 (1995) 25



$\tau \rightarrow l + \alpha$ (invisible)

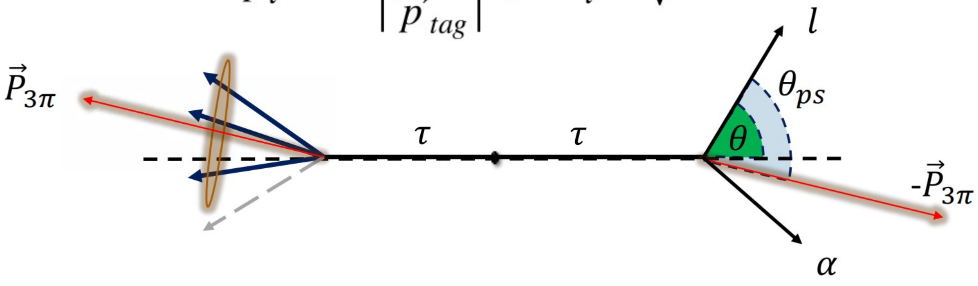
Analysis

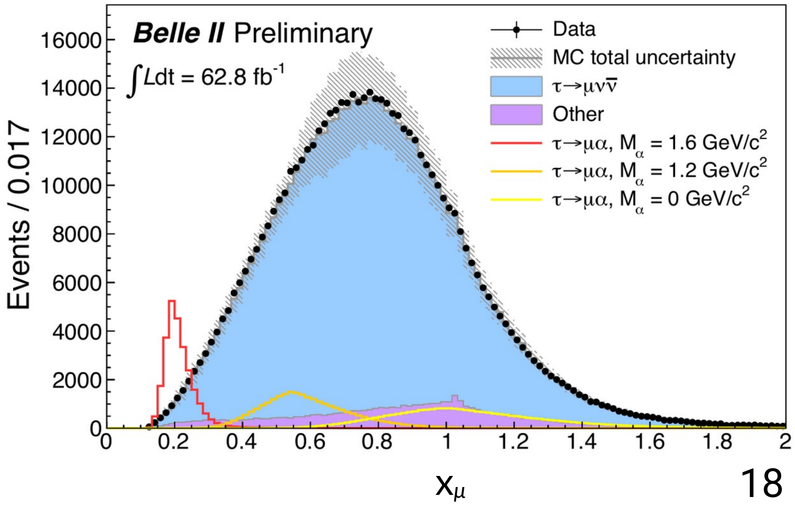
- Dataset: 62.8 fb^{-1}
- 4-track events
- γ, π^0 veto to suppress hadronic background components
- Background
  - Irreducible component: $\tau \rightarrow l\bar{\nu}\nu$ - used to optimize the selection
  - reducible components: $q\bar{q}$, l^+l^-, $l^+l^-l^+l^-$, $l^+l^-h^+h^-$ and correctly tagged $\tau^+\tau^-$ with misidentified signal (e.g. $\tau \rightarrow \pi\nu$) suppressed by cut-based selections
- Search for a peak above the expected SM spectrum
- Pseudo-rest frame



$$x_\ell \equiv E_\ell/(m_\tau/2)$$

$$\hat{p}_\tau \approx -\frac{\vec{p}_{tag}}{|\vec{p}_{tag}|}, \quad E_\tau \approx \sqrt{s}/2$$





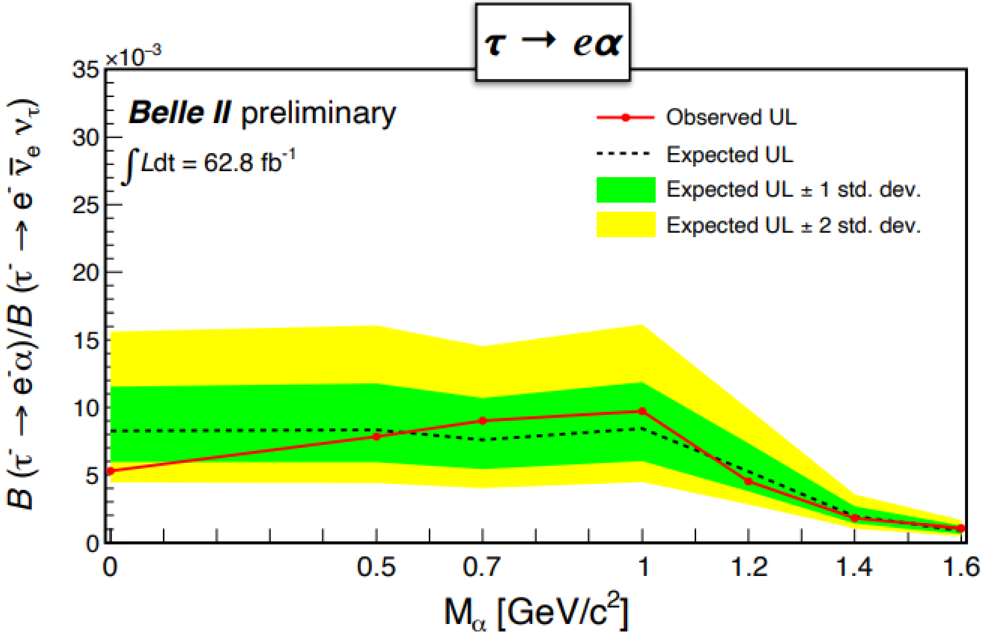
$\tau \to l + \alpha$ (invisible)

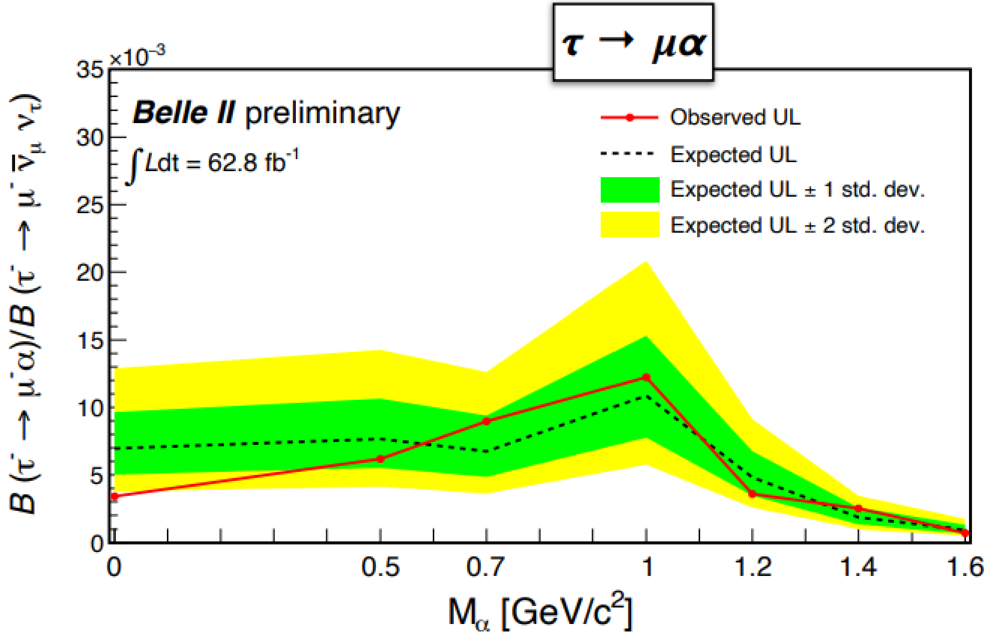
Results

★ Presented @ ICHEP 2022

- No significant excess observed
  - 95% CL upper limits on $B(\tau \to l\alpha)/B(\tau \to l\bar{\nu}\nu)$

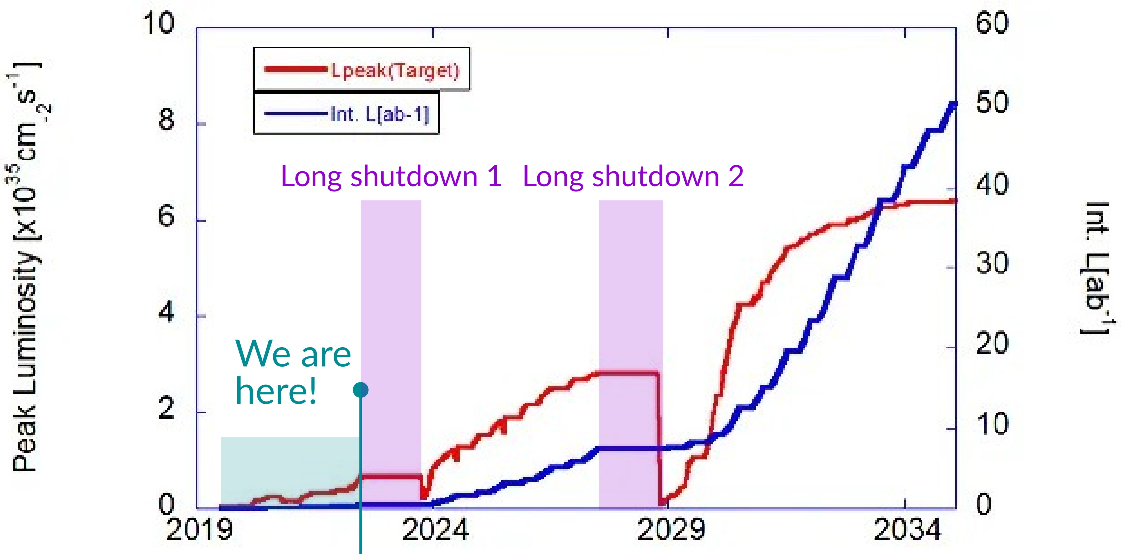
World leading limits in these channels – to be submitted for publication soon





Belle II perspectives

Luminosity projection plot (plan for the coming years)

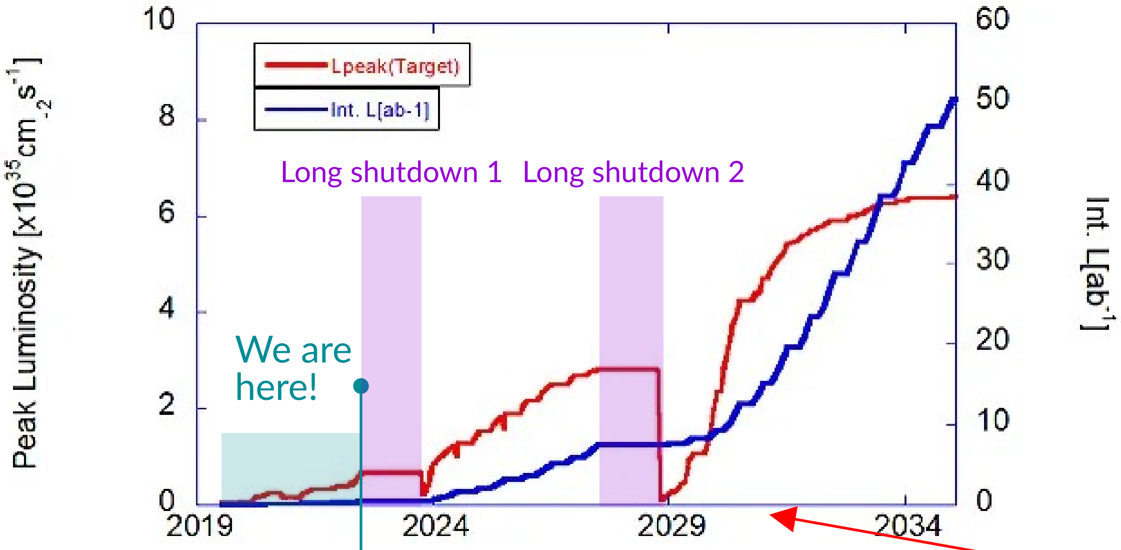


- 424 fb^{-1} collected up to now
- **Current results are strongly limited by dataset size**
  - world-leading results already published with early datasets (< 20% of the dataset collected up to now)

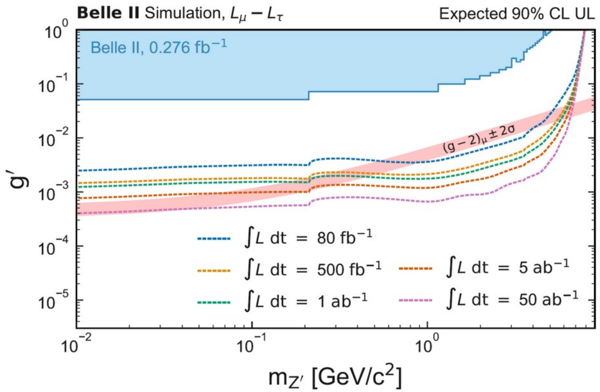
Belle II perspectives

★ Snowmass paper: [arxiv:2207.06307](https://arxiv.org/abs/2207.06307)

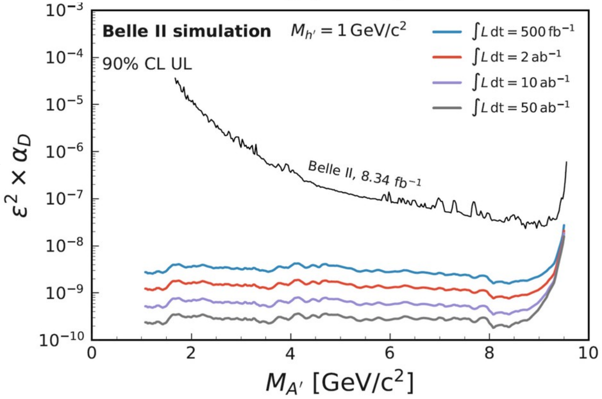
Luminosity projection plot (plan for the coming years)



$Z' \to$ invisible



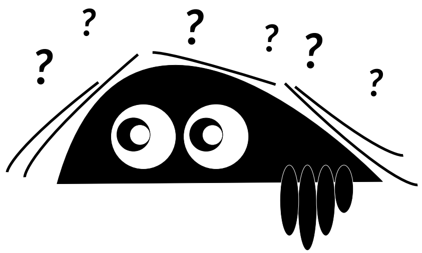
$h' \to$ invisible



- 424 fb^{-1} collected up to now
- **Current results are strongly limited by dataset size**
  - world-leading results already published with early datasets (< 20% of the dataset collected up to now)

- In next years, Belle II will collect 100x the dataset collected up to now
  - → **It will lead the exploration of dark sectors in the MeV-GeV mass range**

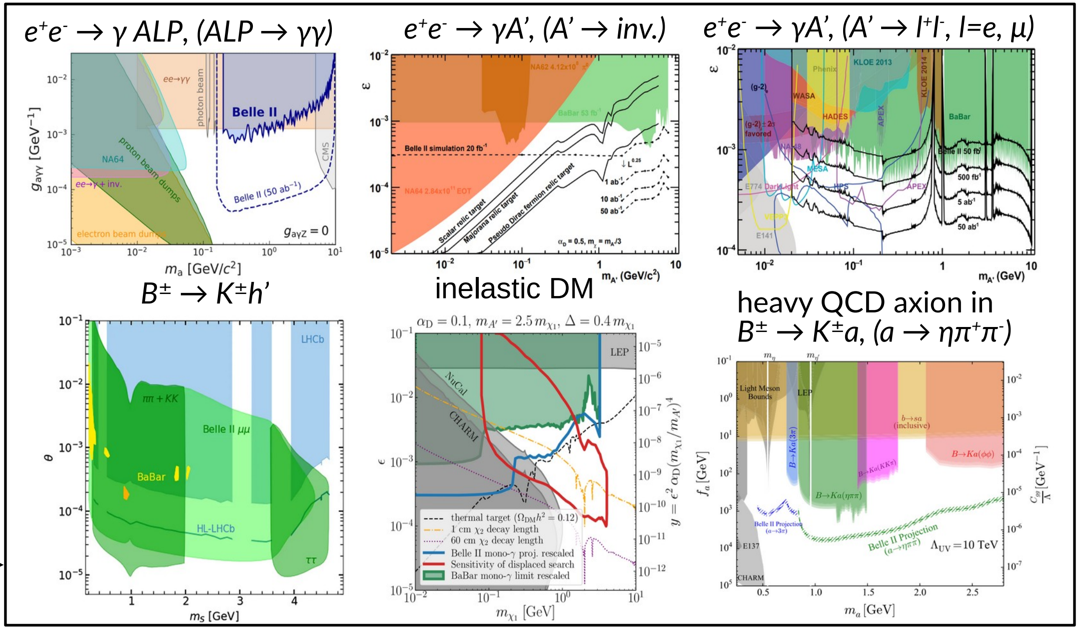
Summary and conclusions



- Belle II will progressively lead the exploration of dark sectors at the luminosity frontier

  - World-leading results with early data:
    - $a \to \gamma\gamma$: [Phys. Rev. Lett. 125, 161806 (2020)]
    - $Z' \to$ invisible: [Phys. Rev. Lett. 124 (2020) 141801]
      (**NEW** updated result to be submitted for publication)
    - Z', S, ALP $\to \tau\tau$ **NEW**
    - $h' \to$ invisible: [arxiv.2207.00509] **NEW**
    - $\tau \to l + \alpha$ (invisible) **NEW**

  - **Many other searches ongoing** →

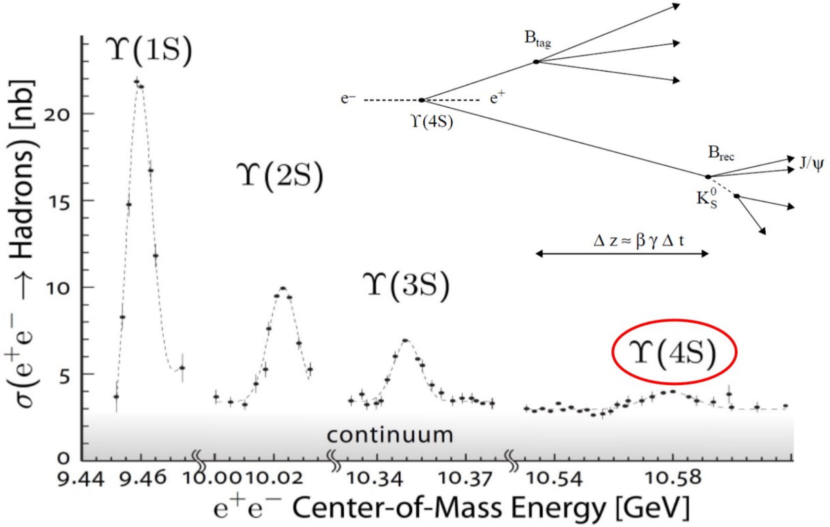


Thank you for the attention

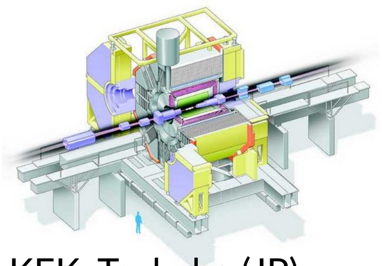
Backup slides

Experiments at B-factories

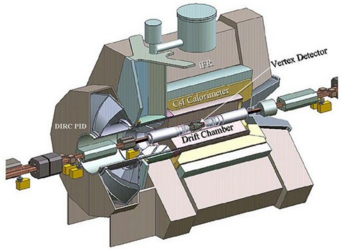
- Asymmetric e^+e^- colliders optimized for the production of *B* meson pairs, but also *D* mesons, *τ* leptons, …
- Collisions occur at Υ(nS) resonances
  - Mainly at Υ(4S): √s = 10.58 GeV
    just above the production threshold of $B\bar{B}$
    $BR(\Upsilon(4S) \to B\bar{B}) > 96\%$
- Asymmetric beam energies: boosted $B\bar{B}$ pairs, for CP-violation time-dependent measurements
- High peak luminosity $L > 10^{34}$ cm^{-2}s^{-1}



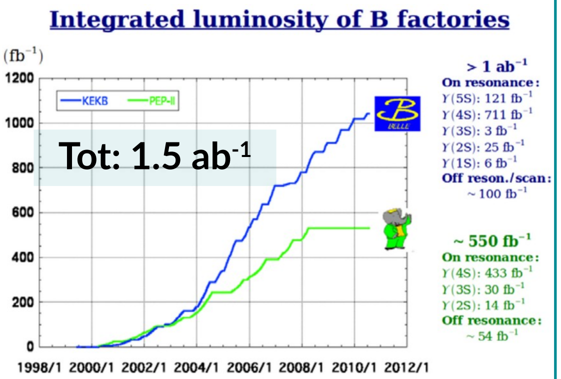
First generation of B-factories



Belle@KEKB, KEK, Tsukuba (JP)
1999–2010, $\int L\,dt$ = 1 ab^{-1}

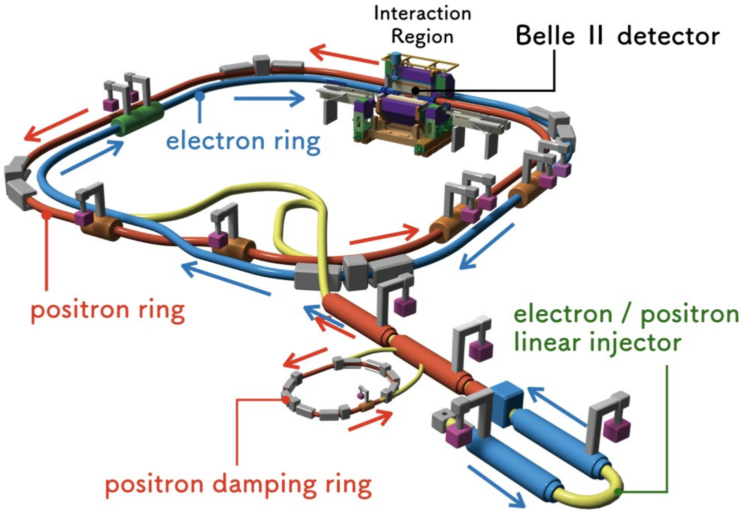


BABAR@PEP-II, SLAC (USA)
1999–2008, $\int L\,dt$ = 0.5 ab^{-1}

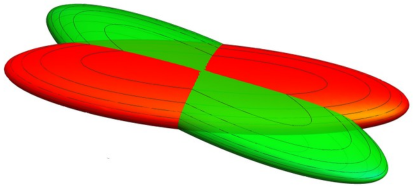


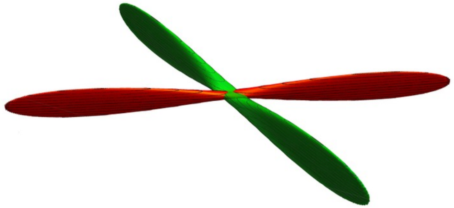
SuperKEKB

- New generation of B-factory that provides luminosity to the Belle II experiment
  - Asymmetric beam energies: e^- (7 GeV) / e^+ (4 GeV)
    Operating mainly at Υ(4S), but foreseen runs from Υ(2S) to Υ(6S)
  - Highest world peak luminosity with the nano-beam scheme



Nano-beam scheme



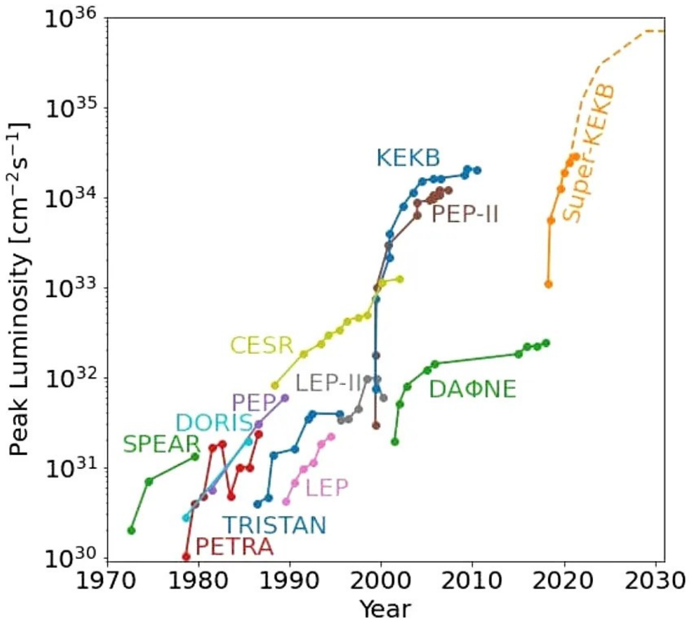


β_y^* ~ 1/20x
I ~ 1.5x

KEKB
- I(A) ~ 1.6/1.2
- β_y^*(mm) ~ 5.9/5.9

SuperKEKB
- I(A) ~ 2.9/2.0
- β_y^*(mm) ~ 0.3/0.3

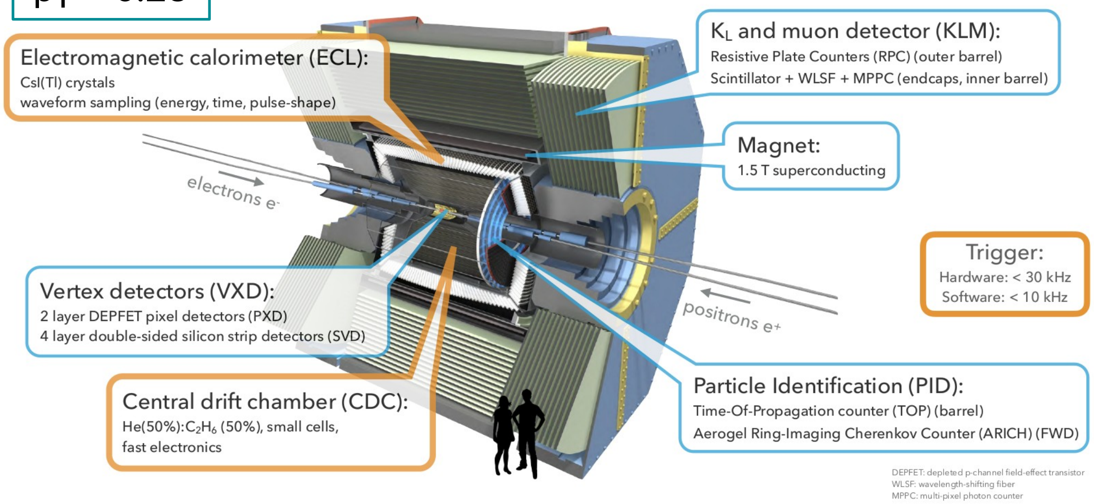
30x peak luminosity



- World record luminosity on December 2021: **3.8 x 10^{34}** $cm^{-2}s^{-1}$
- $I(e^-/e^+)$ = **820/1034** mA and β_y^* = **1** mm
- Target peak luminosity: **6.5 · 10^{35}** $cm^{-2}s^{-1}$

Belle II at SuperKEKB

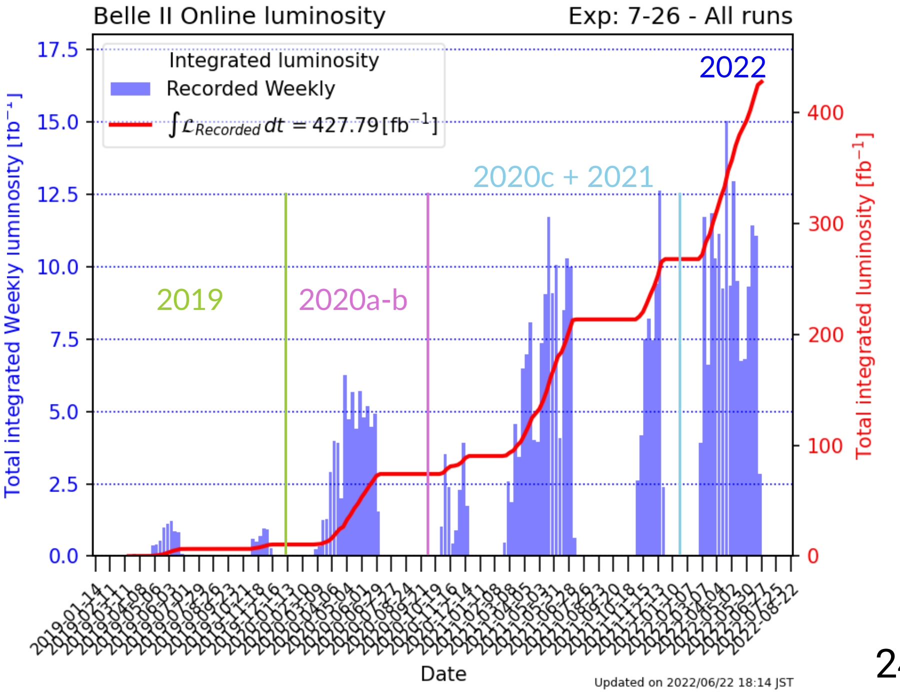
βγ = 0.28



- Major upgrade of Belle@KEKB → better resolution, PID and capability to cope with higher background

- Covers more than 90% of the total solid angle

- First collisions during commissioning run on April 26th 2018
  - 0.5 fb^{-1} collected in 2018
- First collisions with the full detector on March 2019
  - ~ 430 fb^{-1} collected in 3 years of data taking
- Target integrated luminosity of the Belle II experiment: **50 ab^{-1}** (x30 Belle + BaBar)



Dark Sector searches at B-factories

Negligible interaction probability of dark matter with the detector

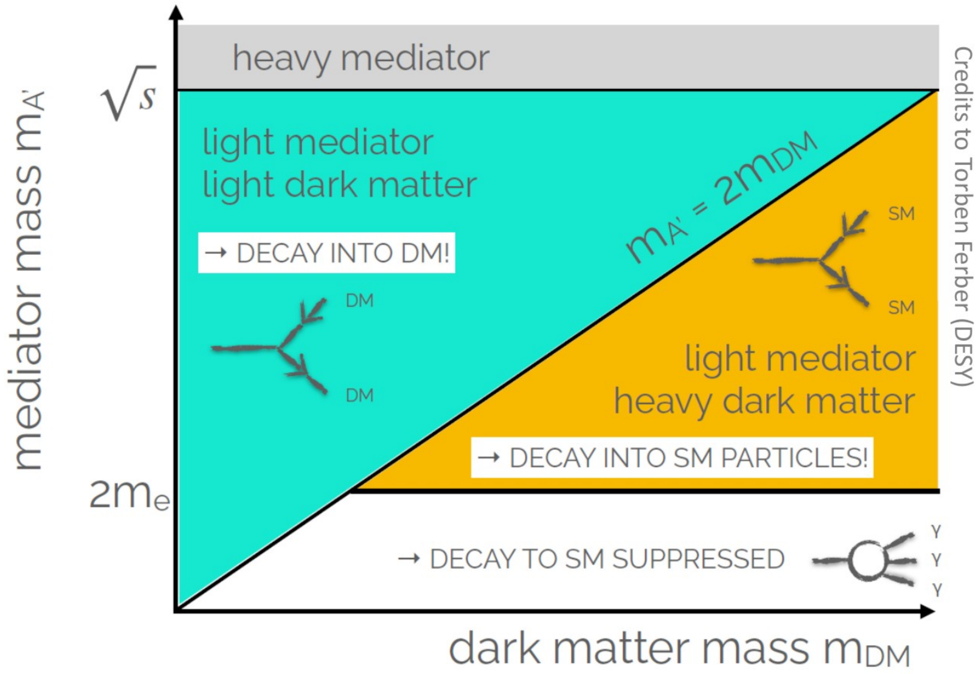
- Search for mediators (visible or invisible)
- Search for final states with missing mass
- Search for both

Advantages of B-factories

- High luminosity (L > 10^{34} $cm^{-2}s^{-1}$)
- Well known initial state
- Clean environment with low background
- Hermetic detector with good PID performance

Excellent reconstruction capabilities for low multiplicities and missing energy signatures at B-factories

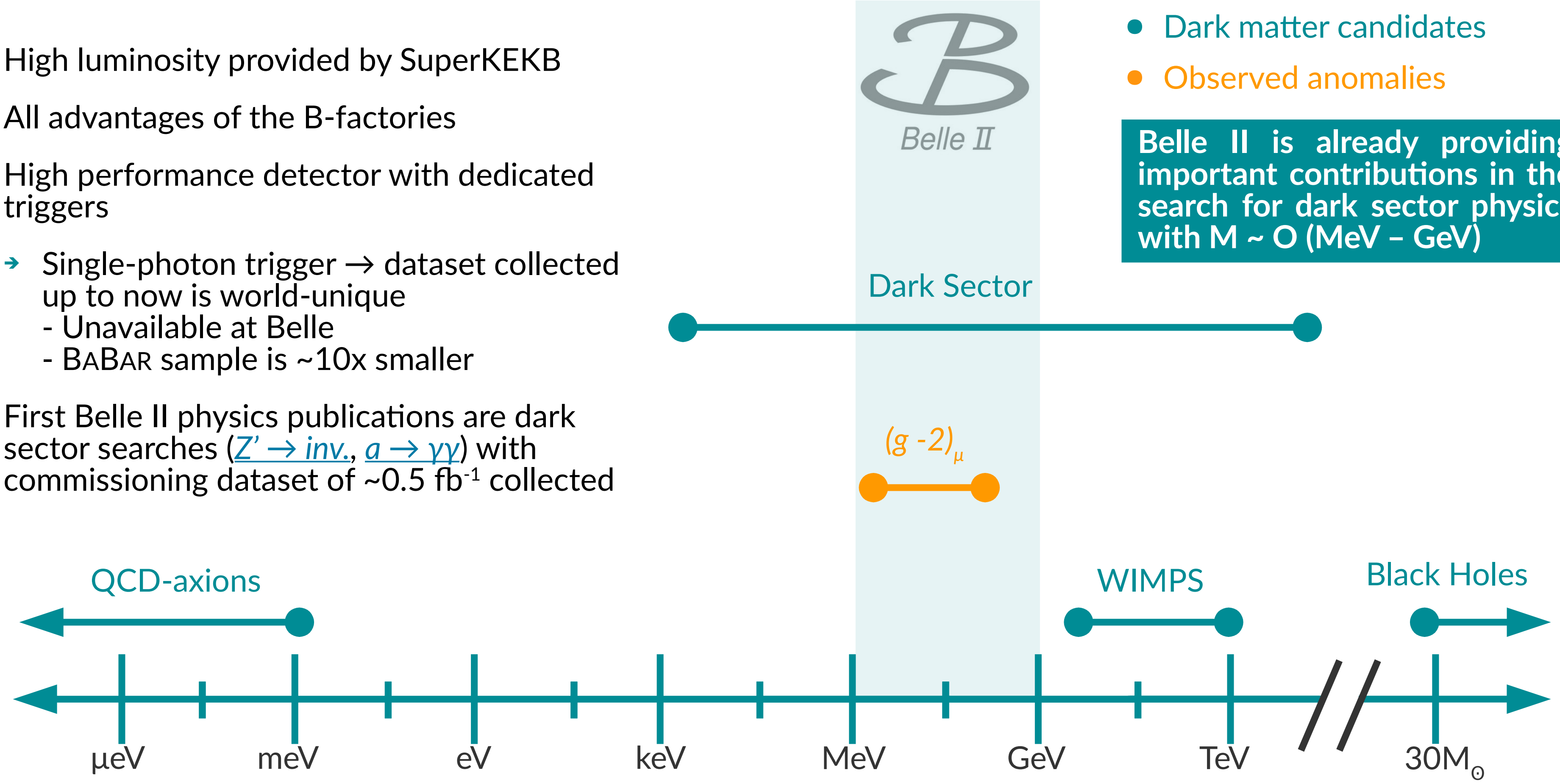
The relationship between mass of the mediators and DM candidates leads to different topologies.



Dark Sector searches at Belle II

[1] Battaglieri et al., arXiv:1707.04591

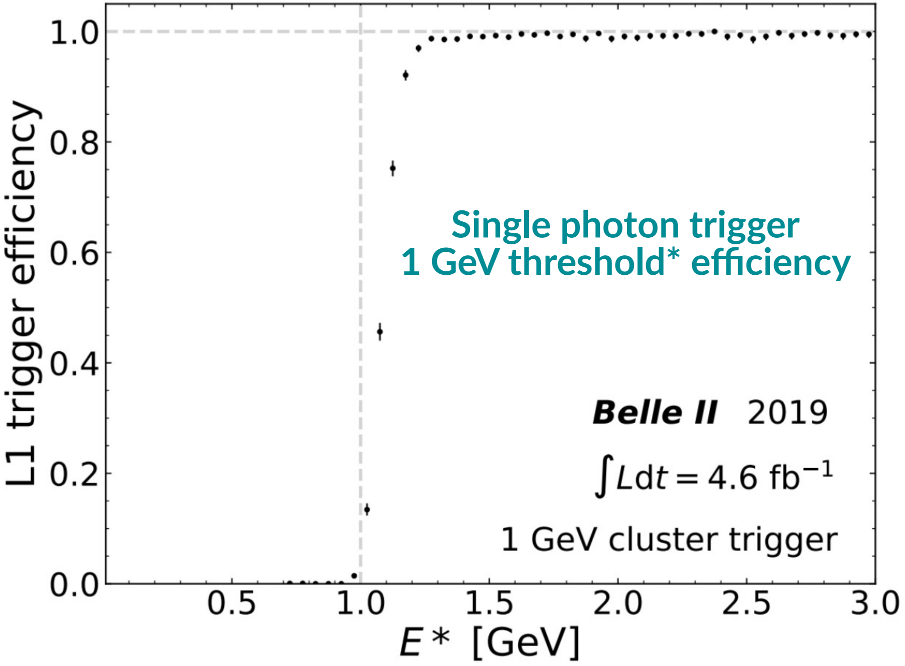
- High luminosity provided by SuperKEKB
- All advantages of the B-factories
- High performance detector with dedicated triggers
  - Single-photon trigger → dataset collected up to now is world-unique
    - Unavailable at Belle
    - BaBar sample is ~10x smaller
- First Belle II physics publications are dark sector searches (*Z' → inv.*, *a → γγ*) with commissioning dataset of ~0.5 fb^{-1} collected



Belle II is already providing important contributions in the search for dark sector physics with M ~ O (MeV – GeV)

Low-multiplicity triggers

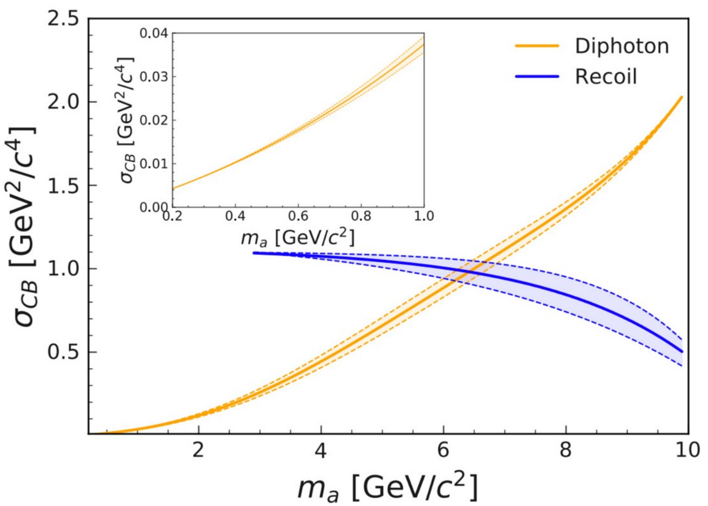
- 2-level trigger
  - ➔ Hardware-based Level1 Trigger (L1): < 30 kHz
  - ➔ Software-based High Level Trigger (HLT): < 10 kHz
- Devise specific low-multiplicity triggers
  - ➔ Suppress high-cross section QED processes but not kill the signal
  - ➔ Requires detailed knowledge of the detector efficiencies
- New dark sector and low multiplicity triggers
  - ➔ single photon trigger
  - ➔ single muon trigger
  - ➔ single track with neural network reconsruction



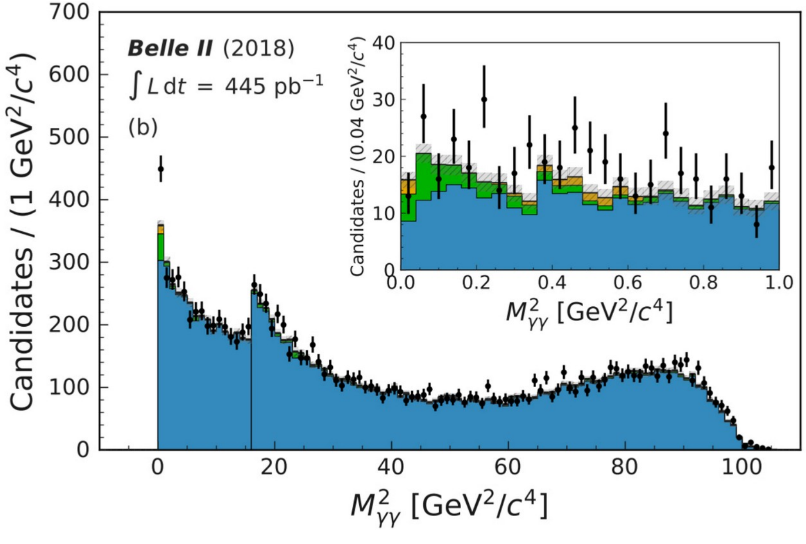
*Actually, newly designed trigger allows sensitivity down to 0.5 GeV of single photon

Search for an ALP at Belle II

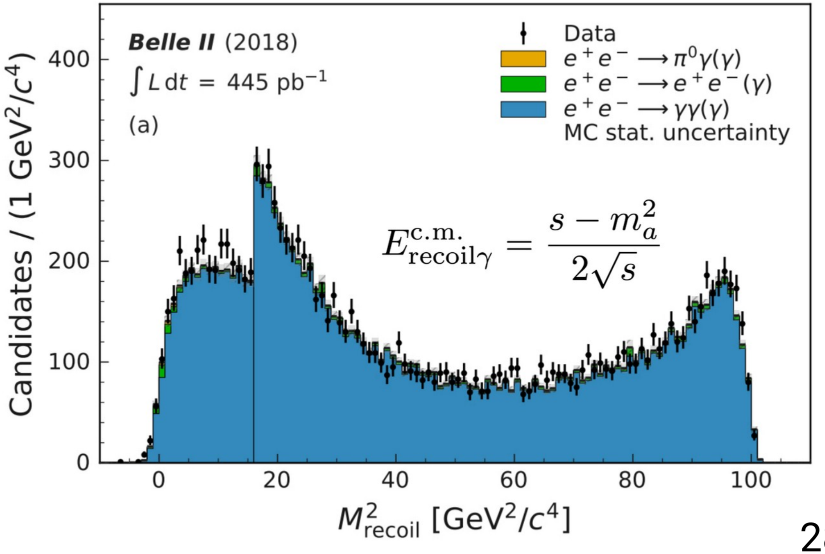
- Select events with three photon invariant mass compatible with collision √s
- Search for a narrow peak in $M^2_{\gamma\gamma}$ or M^2_{recoil}, depending on best resolution of signal peak
- Largest background from $e^+e^- \to \gamma\gamma(\gamma)$



$M^2_{\gamma\gamma}$: m_a < 6.85 GeV/c^2



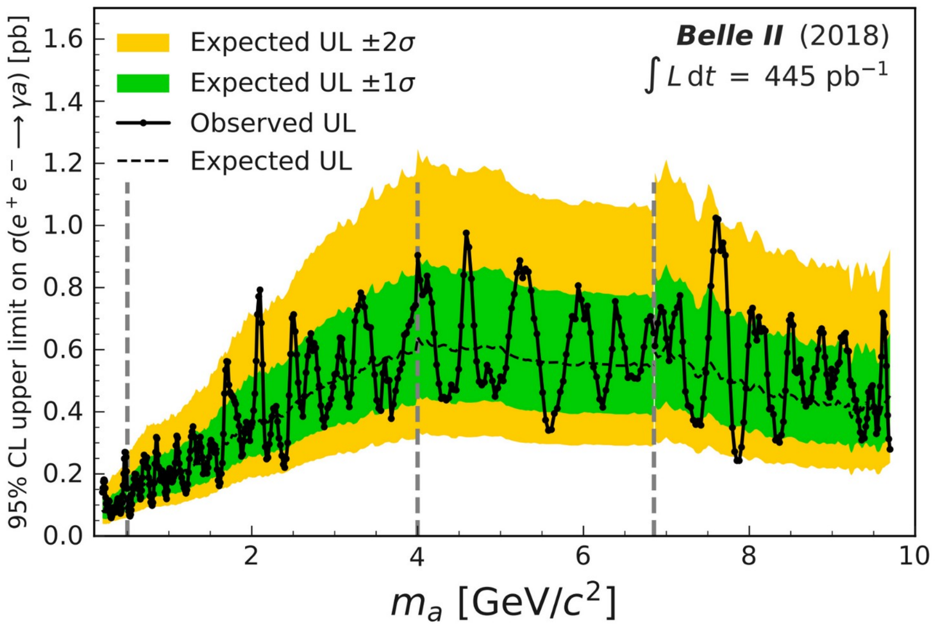
M^2_{recoil}: m_a > 6.85 GeV/c^2

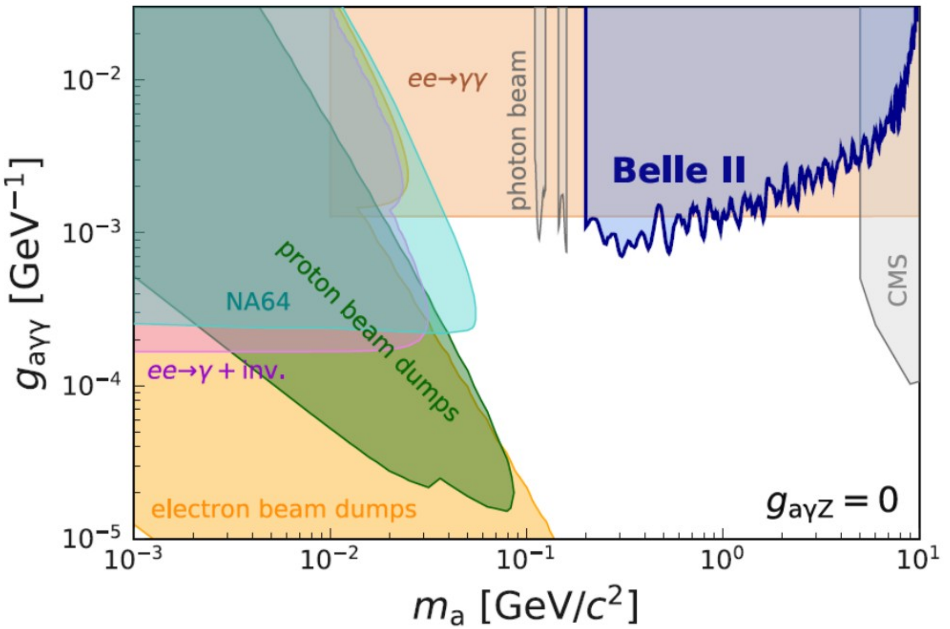


Search for an ALP at Belle II: result

- Search ranges from $0.2 < m_a < 9.7$ GeV/c^2, with the 0.445 fb^{-1} collected in 2018 with Belle II
- No excess in data observed
  - 95% CL upper limits on the cross section and coupling constant $g_{a\gamma\gamma}$

World leading exclusion limits around $m_a \sim 0.5$ GeV/c^2 → Phys. Rev. Lett. 125, 161806 (2020)





Search for a dark photon *A'*

[1] P. Fayet, Phys. Lett. B 95, 285 (1980)
[2] P. Fayet, Nucl. Phys. B 187, 184 (1981)

- U(1)' extension of the SM

- New massive vector gauge boson, *A'* , with a coupling to the Standard Model photon through the kinetic mixing mechanism, with strength ε [1,2]

Dark photon field

→ $\mathcal{L}_{int} = e\varepsilon A'_{\mu} J^{\mu}_{em}$

Interation strenght

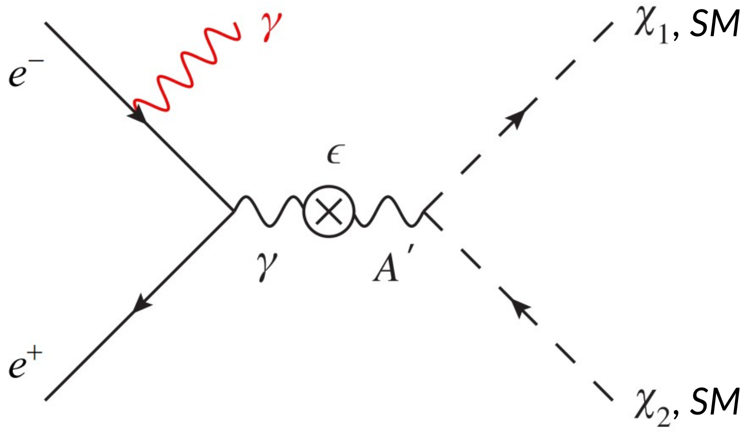
Electromagnetic current

- This gauge boson can be produced at e^+e^- colliders through different processes:
  - direct production: $e^+e^- \to \gamma_{ISR}A'$
  - meson decays: $\pi^0 \to A'\gamma$
  - dark higgsstrahlung: $e^+e^- \to A'^* \to A'h'$

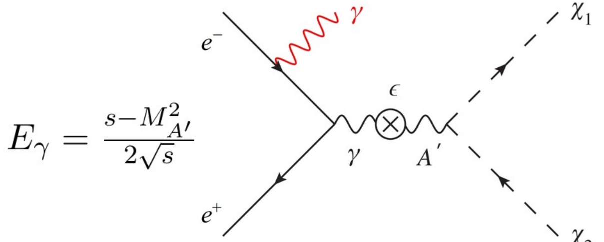
- **Direct production with ISR particularly interesting:** $e^+e^- \to \gamma_{ISR}A'$

- Two basic scenarios depending on dark photon mass:
  - → $M_{A'} > 2m_\chi$: invisible decay $A' \to \chi\bar{\chi}$
  - → $M_{A'} < 2m_\chi$: visible decay in Standard Model particles

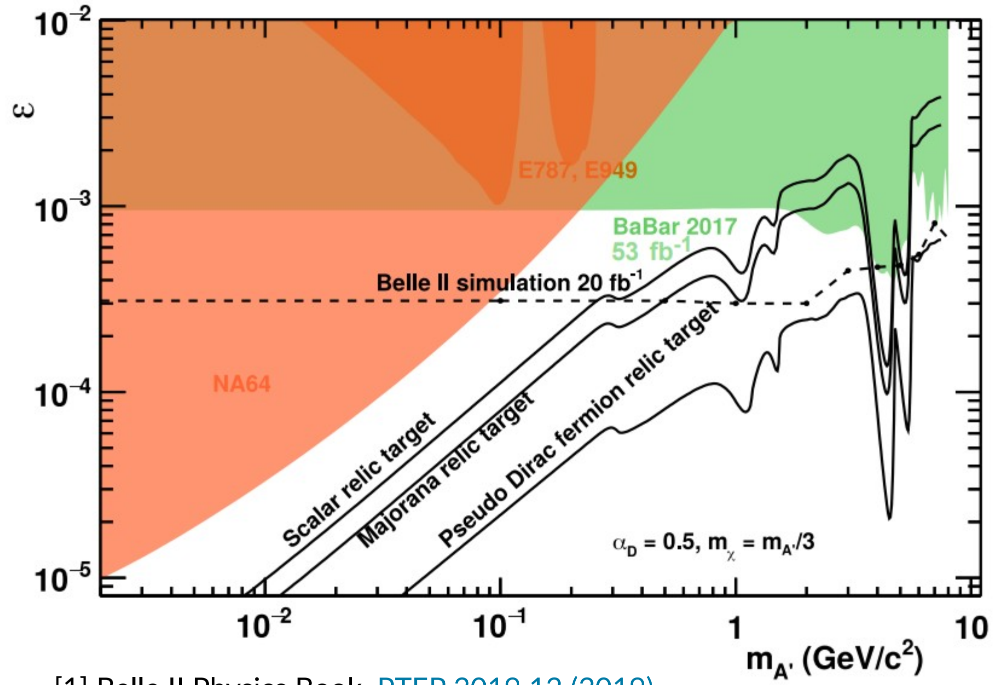
$e^+e^- \to \gamma_{ISR}A'$ $(A' \to \chi\bar{\chi}$, SM)



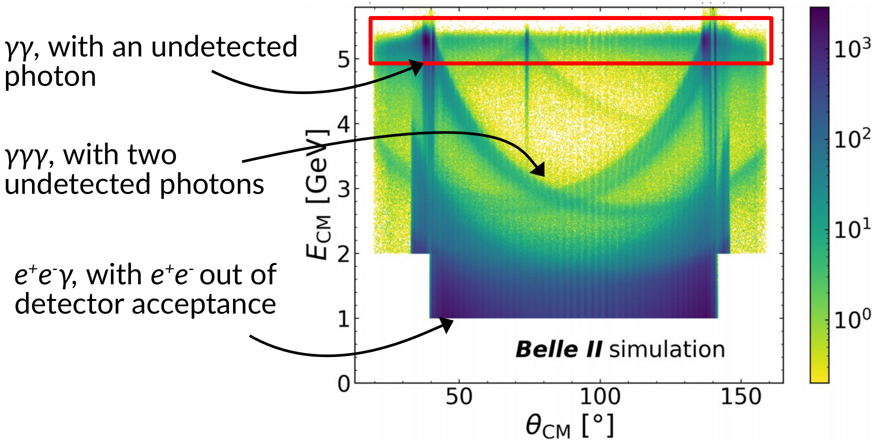
Invisible dark photon



- $e^+e^- \to \gamma_{ISR} A'$ ($A' \to$ inv.)
  - Single photon search: single photon trigger needed, present in the full Belle II dataset



Background simulation assuming 20 fb^{-1}

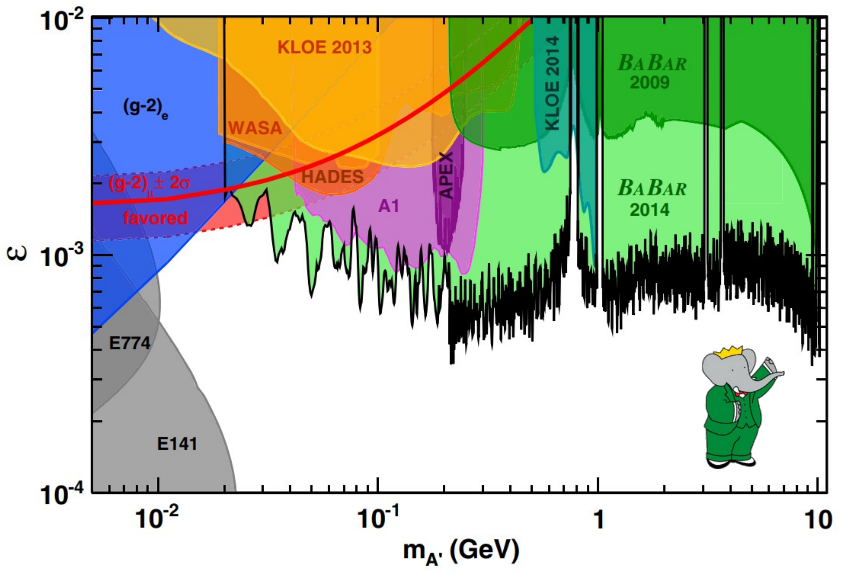


- Belle II expected to perform better than BaBar [2]:
  - smaller boost: **larger acceptance**
  - **muon detector veto**: reject events with a photon undetected in the calorimeter (efficiency currently under study)
  - **better calorimeter hermeticity**

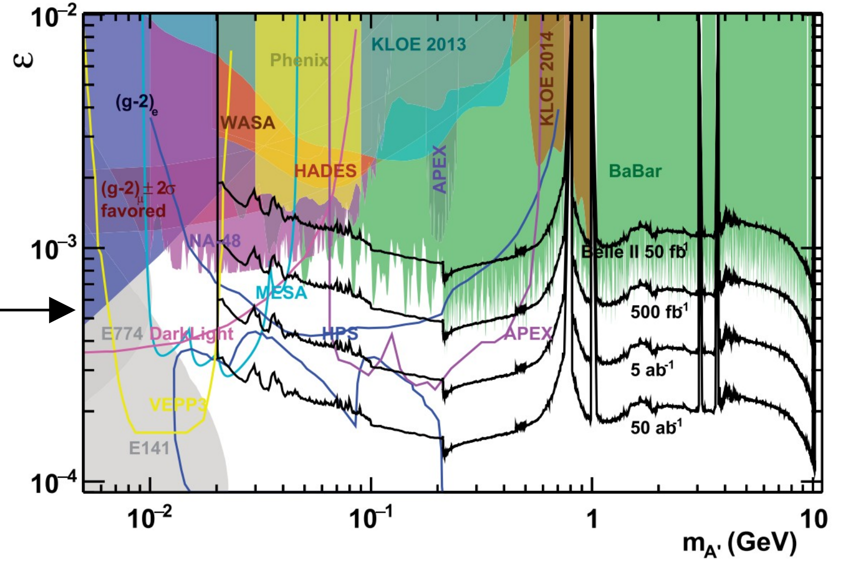
[1] Belle II Physics Book, PTEP 2019 12 (2019)
[2] Less et al, Phys. Rev. Lett. 119, 131804 (2017)

Visible dark photon

- BaBar [1]
  - Full data-set of 514 fb^{-1}
  - dark photon visible decay in e^+e^- and $\mu^+\mu^-$ final states
  - Signature: bump in the di-lepton invariant mass
  - Background: QED processes $e^+e^- \to e^+e^-(\gamma)$, $e^+e^- \to \mu^+\mu^-(\gamma)$ and resonant backgrounds from J/ψ, $\psi(2S)$ etc. (vetoed)
  - Set 90% CL upper limit on the mixing strength ε at level of O(10^{-3}):
- LHCb [2]
  - In the ~ 200 -700 MeV range best results



Belle II is expected to achieve the leading sensitivity [3] - search currently in preparation

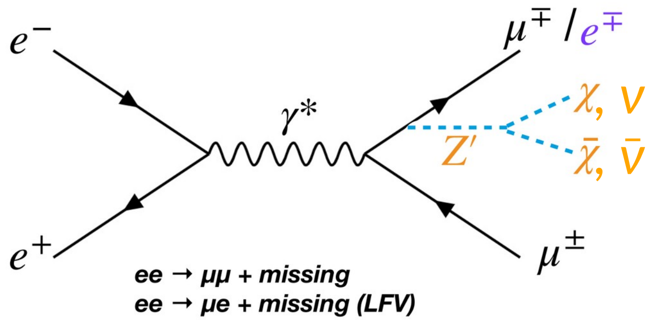


[1] J.P. Lees et al, Phys. Rev. Lett. 113, 201801 (2014)
[2] R. Aaij et al, PhysRevLett.124.041801 (2020)
[3] E. Kou et al, Prog Theor Exp Phys (2019)

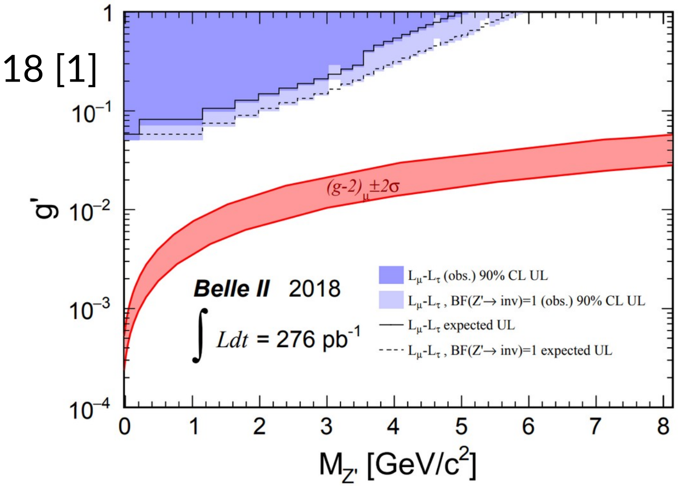
Z’ → invisible at Belle II

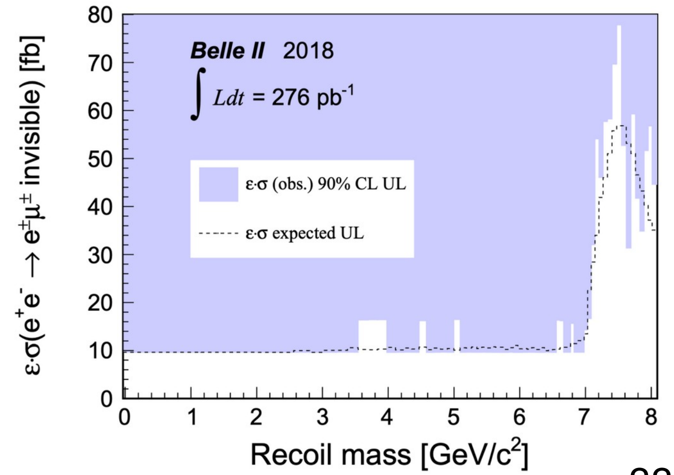
[1] I. Adachi et al, PhysRevLett.124.141801

- First time search for an invisible *Z’*, with 0.276 fb^{-1} collected by Belle II in 2018 [1]
- Hermetic Belle II detector and clean e^+e^- collisions allow precision determination of missing energy

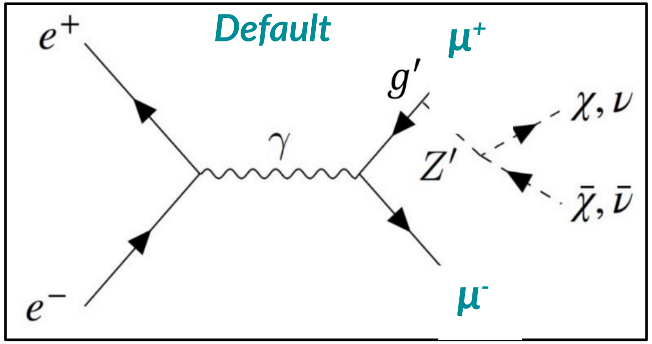


- Search for a narrow peak in the recoil mass distribution against $\mu^+\mu^-$ (LFV: $\mu^\pm e^\mp$)
- 90% CL upper limits on the coupling constant g' ~ O(5x10^{-2})
- First model independent limits on $\varepsilon \cdot \sigma(e^+e^- \to e^\pm\mu^\mp$ + invisible) down to 10 fb

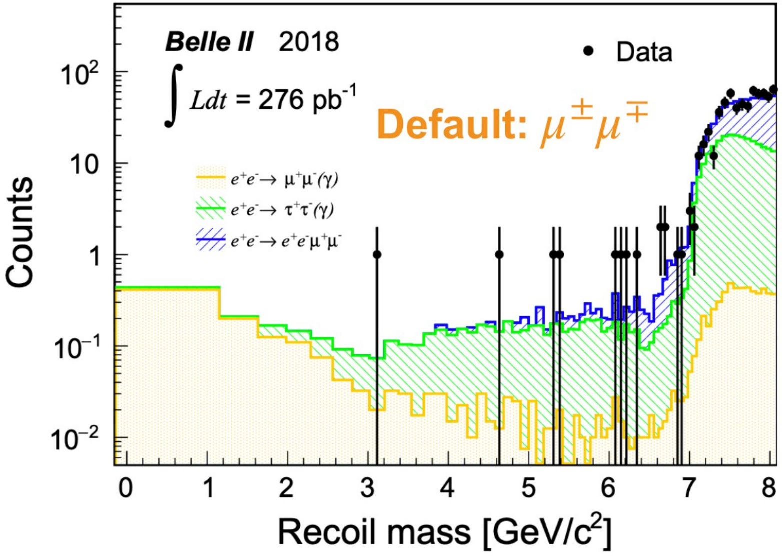


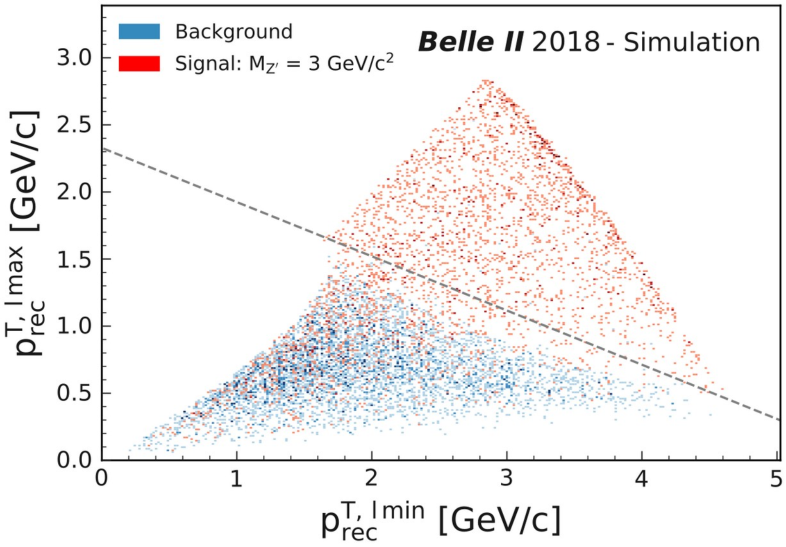


Z’ → invisible at Belle II



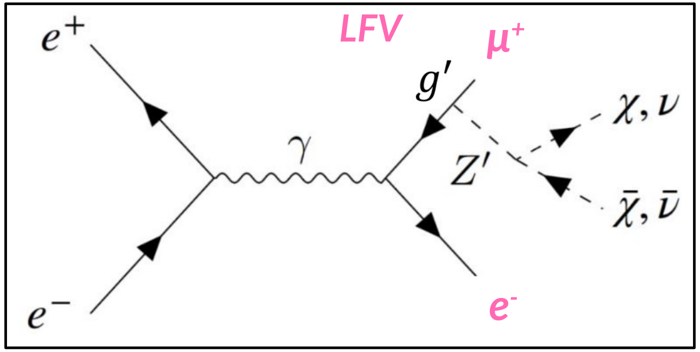
- *$e^+e^- \to \mu^+\mu^-$ + Missing Energy*
- Main background components:
  - $e^+e^- \to \tau^+\tau^-(\gamma)$: missing energy due to neutrinos
  - $e^+e^- \to \mu^+\mu^-(\gamma)$: missing energy due to undetected photons
  - $e^+e^- \to e^+e^-\mu^+\mu^-$: missing energy due to undetected electrons
- Dedicated background suppression based on the different origin of missing momentum in background (neutrinos for $\tau\tau$ and ISR for $\mu\mu(\gamma)$) and signal (FSR))
- **No significant excess observed in data**

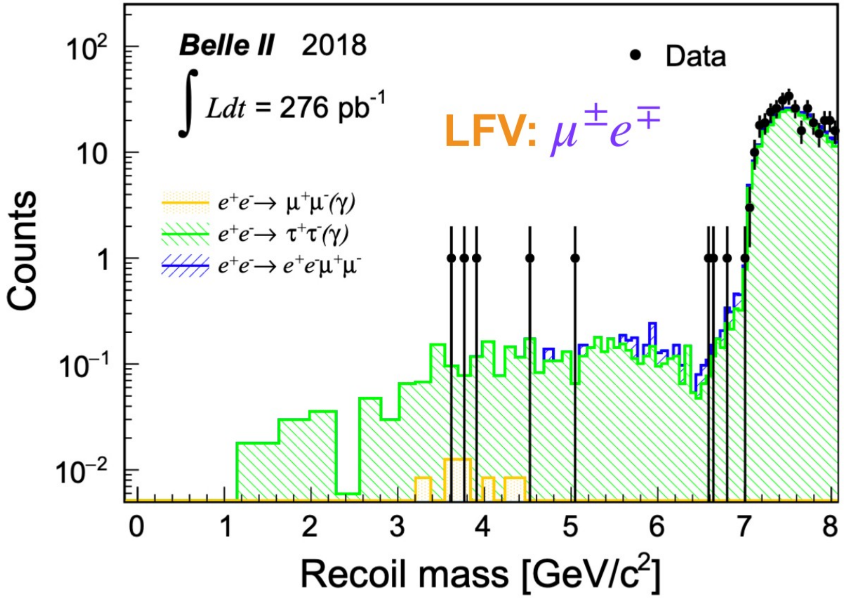


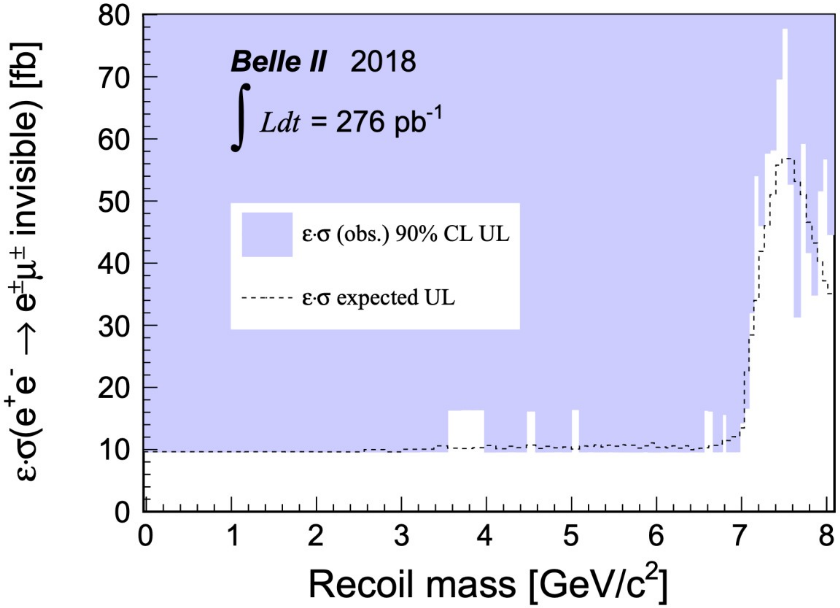


Z’ → invisible (LFV) at Belle II

- No excess observed in data
- First model independent limits on $\varepsilon \cdot \sigma(e^+e^- \to e^\pm\mu^\mp + \text{invisible})$ down to 10 fb
- First Belle II physics publication: Phys. Rev. Lett. 124 (2020) 141801





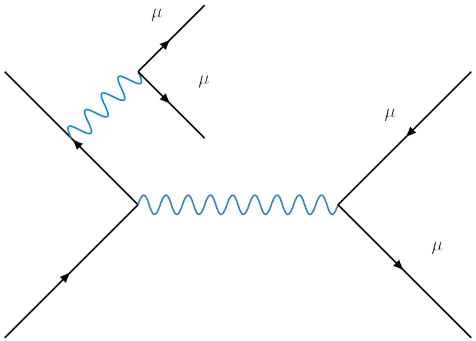


$Z' \to \mu\mu$ at Belle II

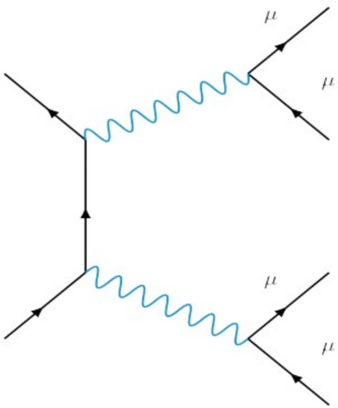
- Data set: ~ 178 fb^{-1} (2020 - 2021). Ongoing analysis, will be finalized by beginning of 2023
- Main background components from QED processes: $\mu^+\mu^-\mu^+\mu^-$, ISR, double photon conversion, combinatorial as well as peaking background
- Event selection:
  - 3-track OR single-muon trigger
  - 4 tracks (at least 3 identified as muons) with invariant mass compatible with the Υ(4S) + no energy deposit in the ECL
  - 4 neural networks trained for different ranges in dimuon invariant mass *M(μμ)*
- Signal yield from a fit scan over *M(μμ)* above floating background

Competitive with early data set (~ 178 fb^{-1}) due to aggressive background suppression!

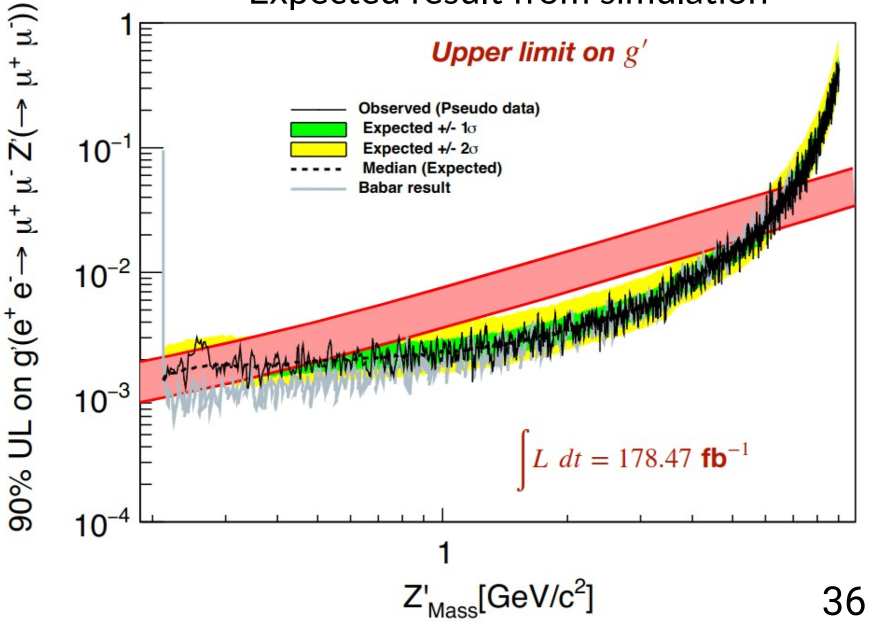
ISR



Double-photon conversion

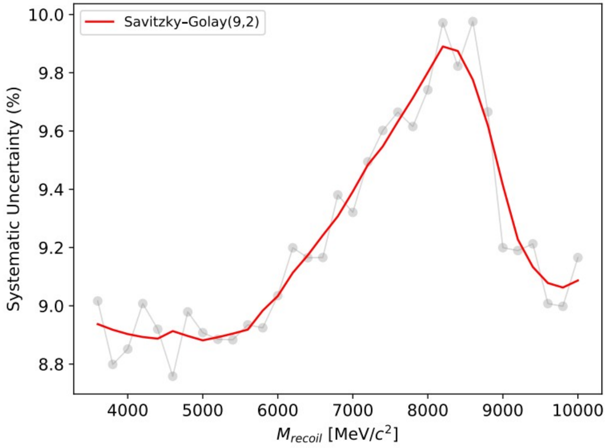


Expected result from simulation



Z', S, ALP → ττ systematics

Source	Systematic Uncertainty
MLP selection	2.8%
fff trigger efficiency	2.5%
CDCKLM trigger efficiency	1%
Mass resolution	3%
Tracking efficiency	3.6%
PID selection	(3.9 - 6.2)%
Fit (sig+bkg)	4%
Signal efficiency interpolation	2.5%
Luminosity	1%
Others (preselection, beam energy shift, momentum resolution)	1%
Total	(8.8% - 9.9%)



- **Effect of systematics on the final results is O(1%)**
- We are mainly limited by statistics

MLP from data/MC comparison using control sample

fff efficiency from signal efficiency obtained applying fff efficiency measured with different configurations

CDCKLM efficiency, PID from signal efficiency obtained varying CDCKLM efficiency and PID corrections within their systematics

Mass resolution from signal yield returned by the fit simulating the effect of momentum resolution measured on data (from Belle II internal study) on the signal peak resolution

Fit from signal yield, and its error, extracted from the fit compared with the generated one applying a bootstrap technique on MC

Signal efficiency interpolation from RMS of nominal and interpolated signal efficiencies

Tracking efficiency from internal study

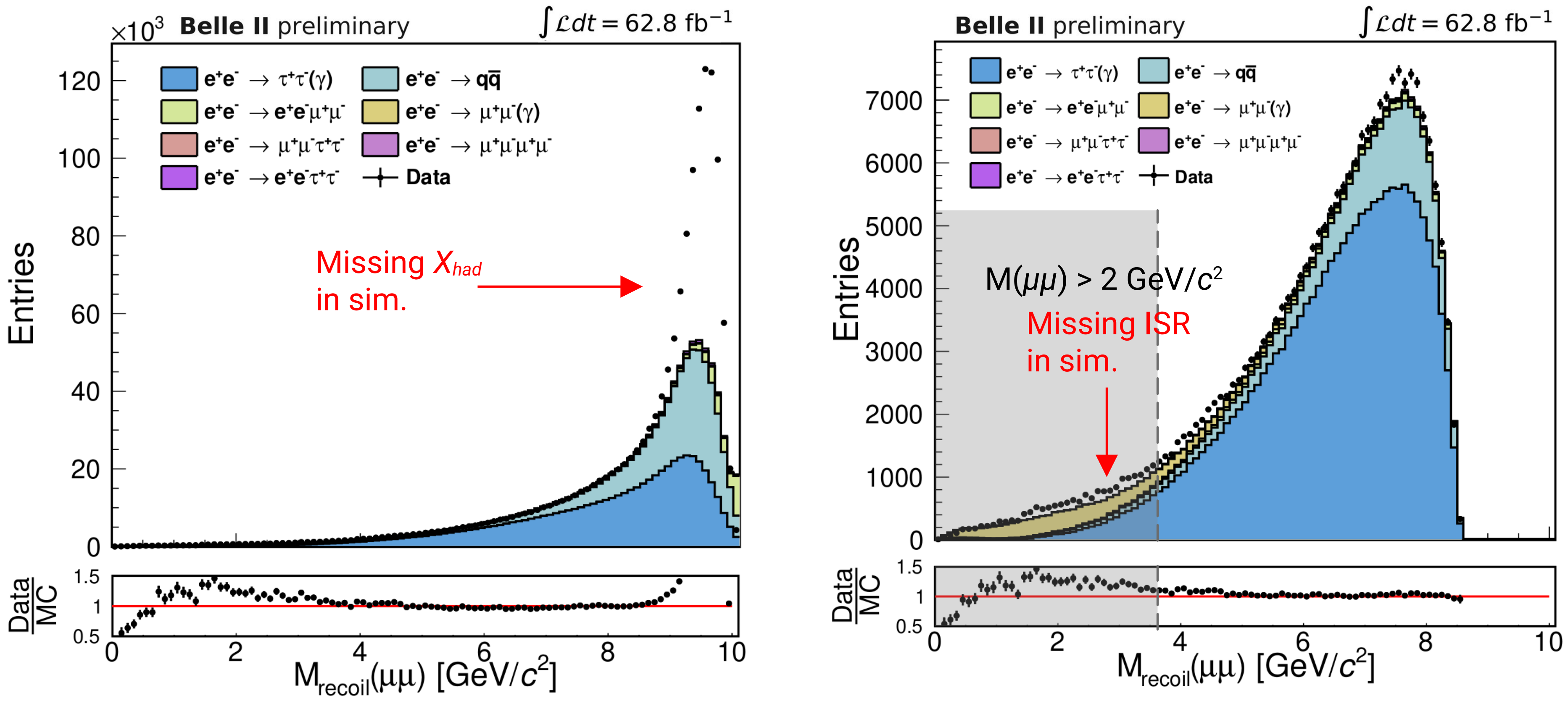
Luminosity from the difference in the measured offline luminosity on Bhabha and $\gamma\gamma$ events

Z', S, ALP → ττ at Belle II

Full data unboxing

$M(\mu\mu) > 2$ GeV/c^2 for the tagging muons

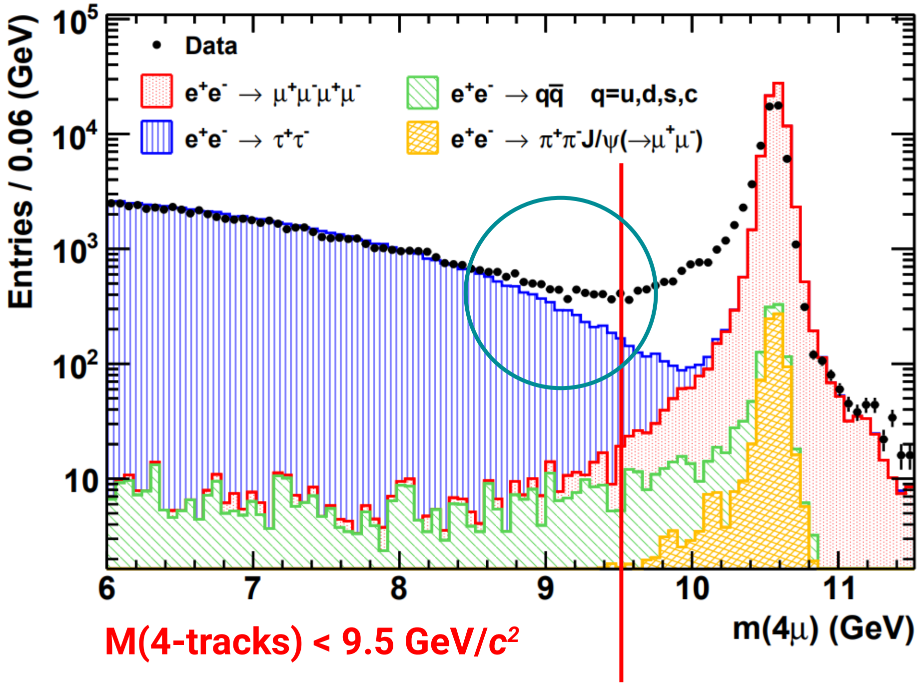
- Without applying the NN selection, the agreement is reasonable where data and MC are comparable



Z', S, $ALP \to \tau\tau$ at Belle II

Full data unboxing

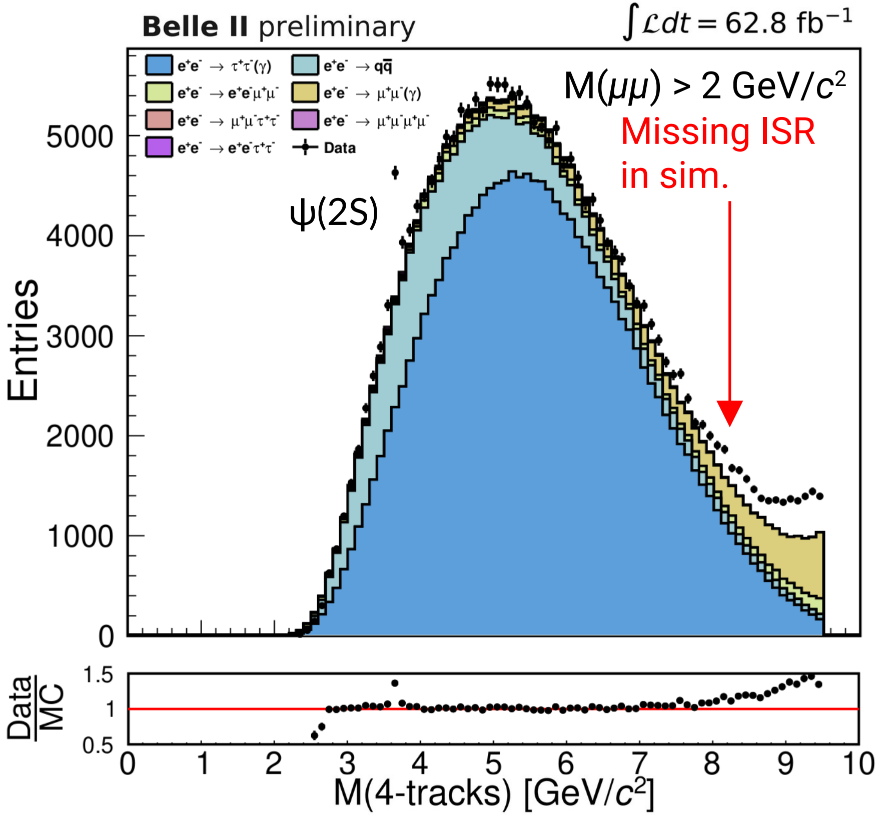
- Without applying the NN selection, the agreement is reasonable where data and MC are comparable



M(4-tracks) < 9.5 GeV/c^2

$Z' \to \mu\mu$ at BaBar
J. P. Lees et al., PhysRevD.94.011102

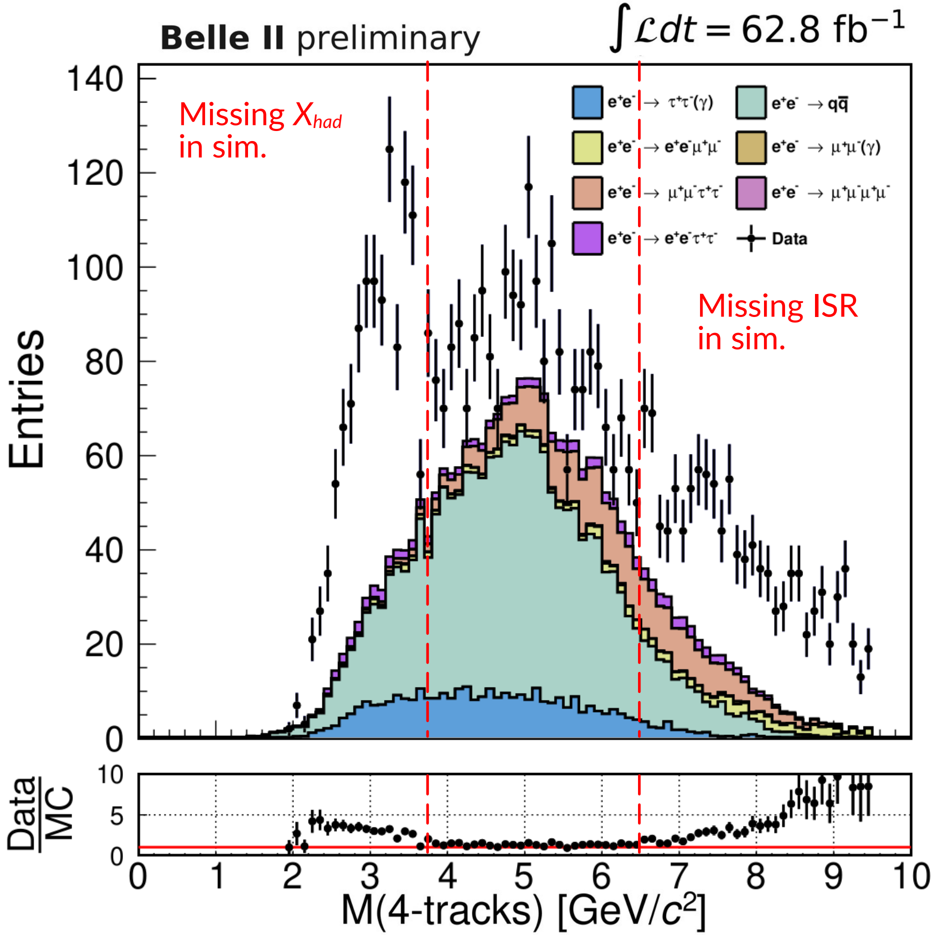
M($\mu\mu$) > 2 GeV/c^2 for the tagging muons



$Z', S, ALP \to \tau\tau$ at Belle II

Full data unboxing: after MLP selection

- In our analysis we do not select events with $M(\mu\mu) > 2$ GeV/c^2
  - missing hadronic components in MC not removed
- Fraction of no-ISR ($e^+e^- \to e^+e^-\mu^+\mu^-$, $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$, $e^+e^- \to e^+e^-\tau^+\tau^-$) components over the total from 80% to 10% in $M_{recoil}(\mu\mu)$
- In the region of M(4tracks) where the contribution from both sources of discrepancy is lower (**NOT missing**) the agreement is way better
- **Discrepancies expected**, **understood**, **non-peaking in $M_{recoil}(\mu\mu)$**
  - signal mass resolution: 1.5 - 30 MeV/c^2
- Expected worsening in sensitivity because of the higher background w.r.t simulation
  - **measured directly from data through a fit**

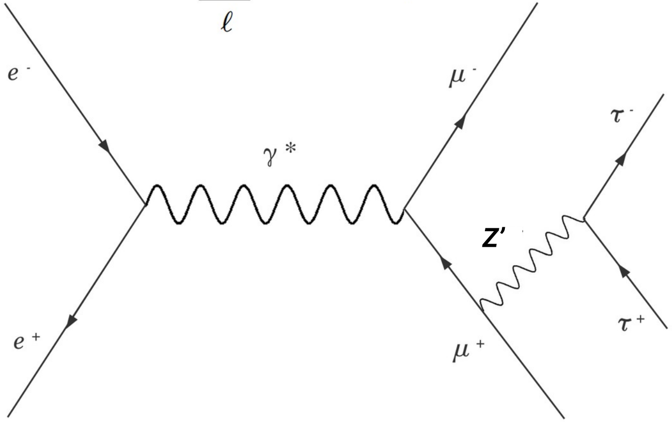


Z’ → ττ at Belle II

$L_\mu - L_\tau$ model

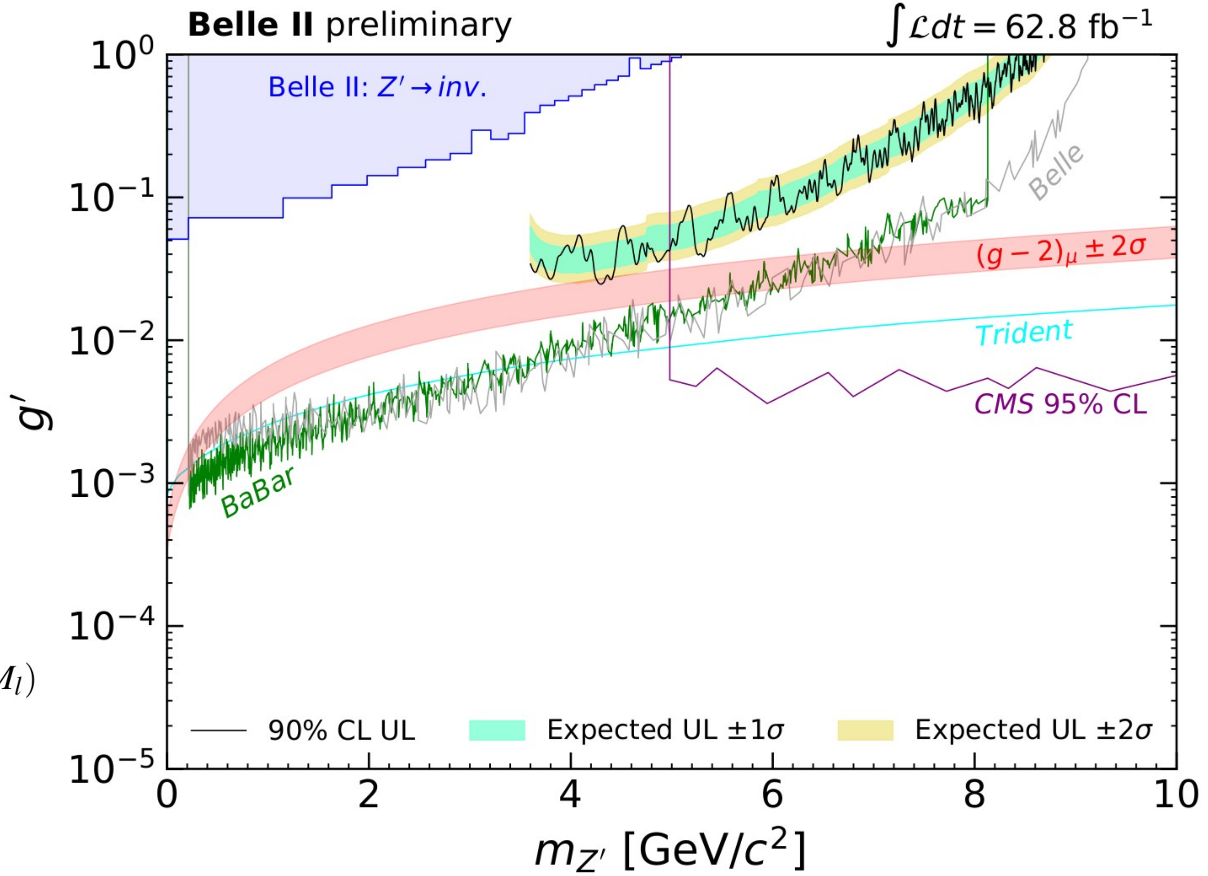
[1] Shuve et al., Phys. Rev. D 89 , 113004 (2014)
[2] Altmannshofer et al., JHEP 106 (2016)
[3] D. Curtin et al., JHEP 02 (2015) 157

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

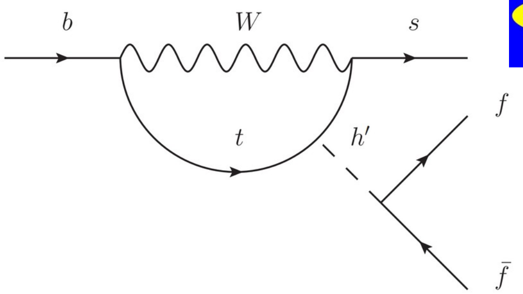


$$\Gamma_{Z' \to l^+ l^-} = \frac{(g')^2 M_{Z'}}{12\pi} \left(1 + \frac{2m_l^2}{M_{Z'}^2}\right) \sqrt{1 - \frac{4m_l^2}{M_{Z'}^2}} \theta(M_{Z'} - 2M_l)$$

$$\Gamma_{Z' \to \nu\bar{\nu}} = \frac{(g')^2 M_{Z'}}{24\pi}$$

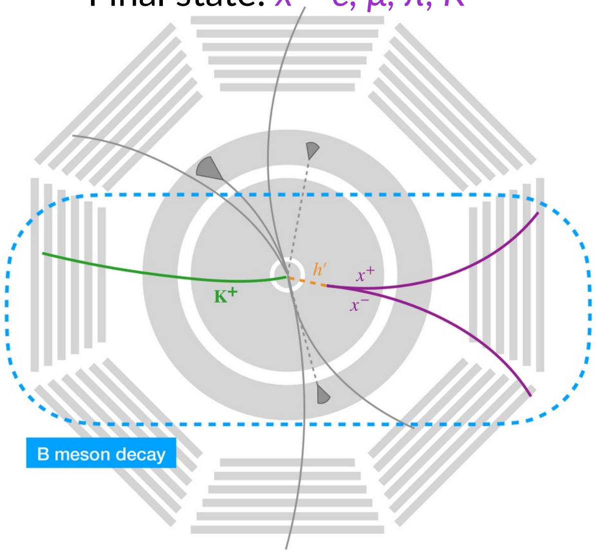


Highlights on $B \to Kh'$

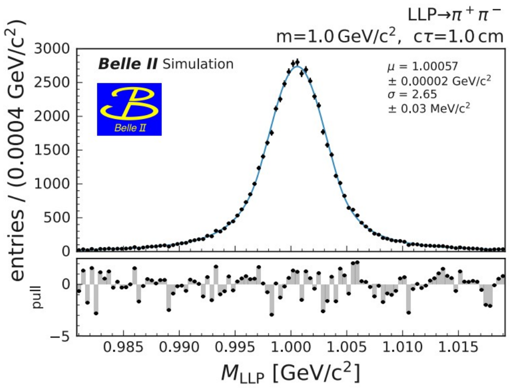


- Long-lived h' produced in $b \to s$ transition
- h' mixes with the Standard Model Higgs boson with angle θ
- Search for a bump in the invariant mass of tracks coming from a displaced vertex
- Event selection is very clean, but not quite at zero background
- LHCb and Belle II complementary

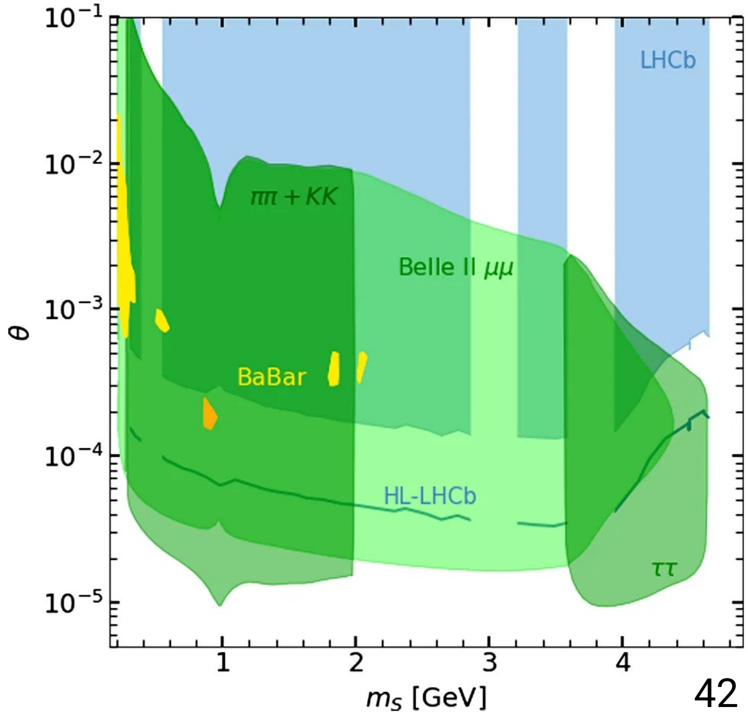
Final state: $x = e, \mu, \pi, K$



- Exclusion regions expected with 50 ab^{-1} at Belle II in green
- Analysis timescale ~ beginning of 2023



Filimonova et al., JHEP04 (2021) 39



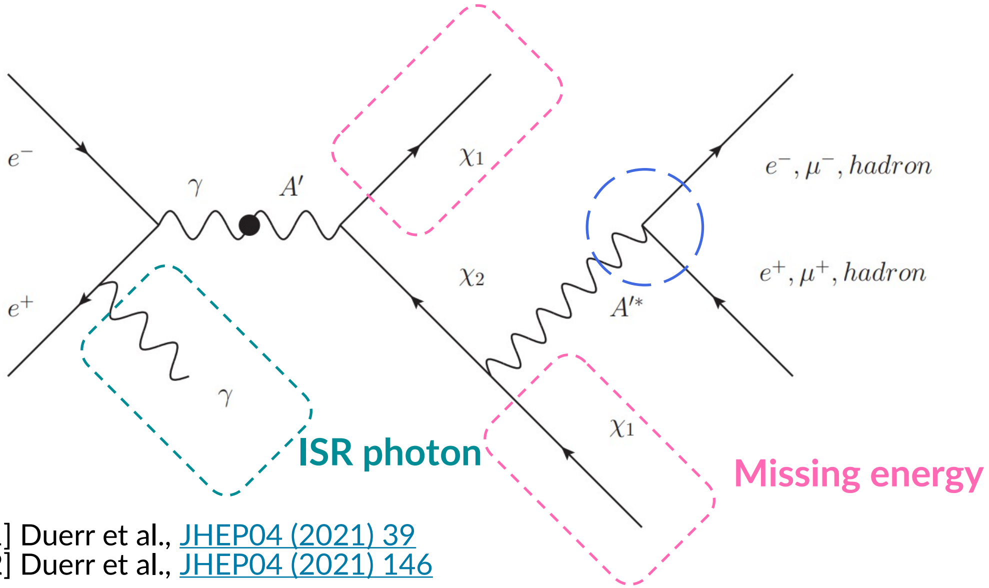
iDM at Belle II

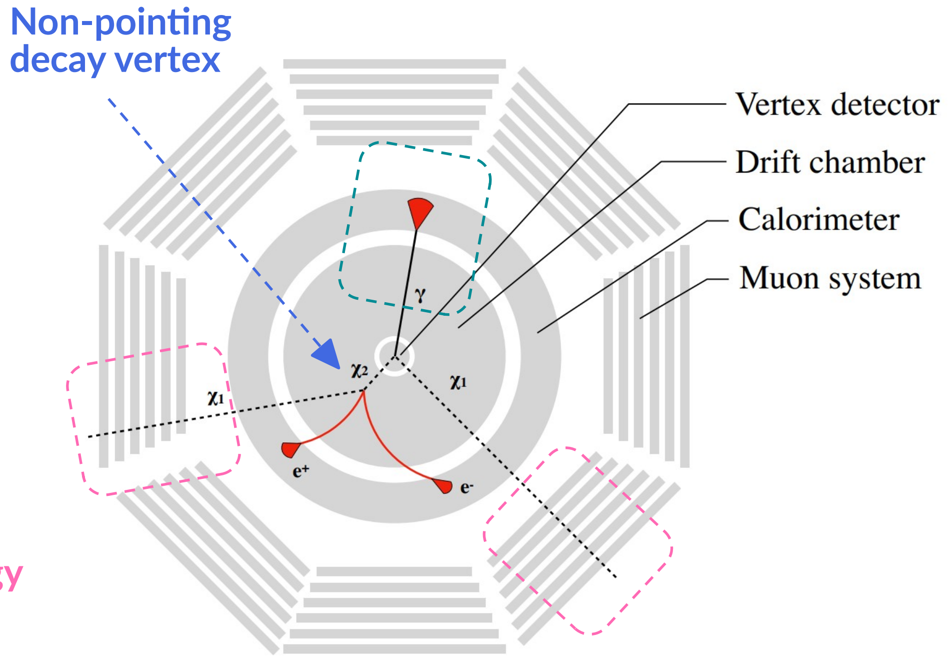
Signal = peak in $E_\gamma = \frac{s - M^2_{A'}}{2\sqrt{s}}$ + non-pointing displaced vertex + missing energy

- Expanded dark sector with two dark matter states with a small mass splitting and a dark photon
  - χ_1 is stable (relic candidate)
  - χ_2 is long-lived
- Focus on $M_{A'} > m_{\chi 1} + m_{\chi 2}$: the decay $A' \to \chi_1\chi_2$ is favored

- Mandatory to implement new trigger for displaced vertex detection

- Belle II could constrain the kinetic mixing $\varepsilon < 10^{-3} - 10^{-4}$ ~ 100 fb^{-1}

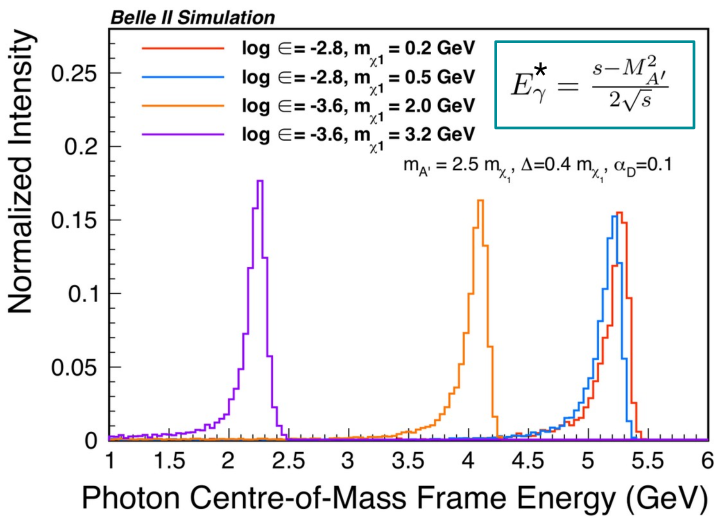




[1] Duerr et al., JHEP04 (2021) 39
[2] Duerr et al., JHEP04 (2021) 146

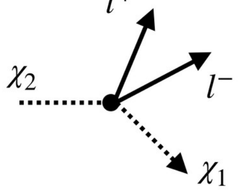
Search for iDM at Belle II

- Search for a peak in the center-of-mass frame energy of the ISR photon plus a displaced vertex V^0

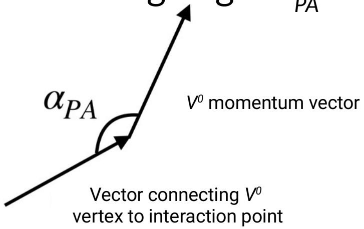


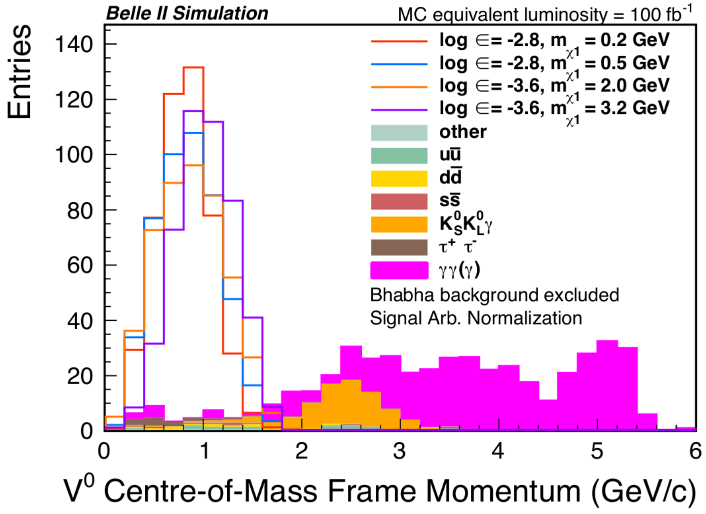
- Background:
  - photon conversion, $e^+e^- \to \gamma\gamma(\gamma)$, $\gamma \to e^+e^-$
  - meson decays, $e^+e^- \to K_S^0K_L^0(\gamma)$, K_S^0 decays

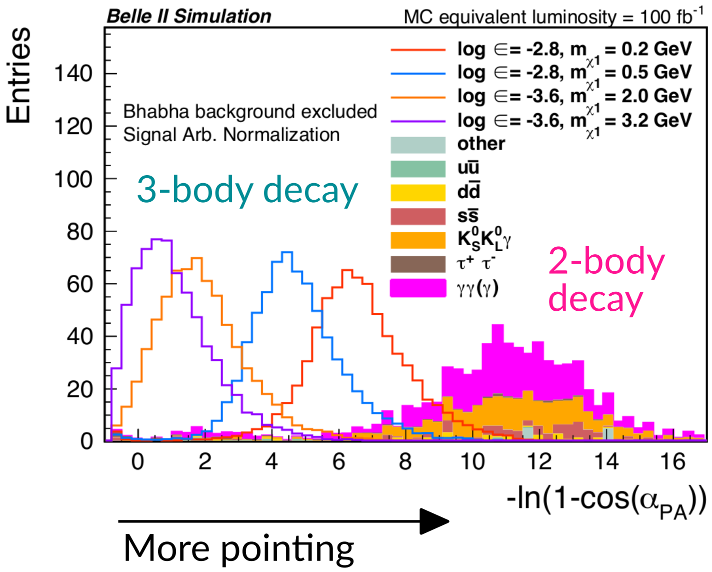
- Background suppression:
  - V^0 momentum



  - Pointing angle α_{PA}

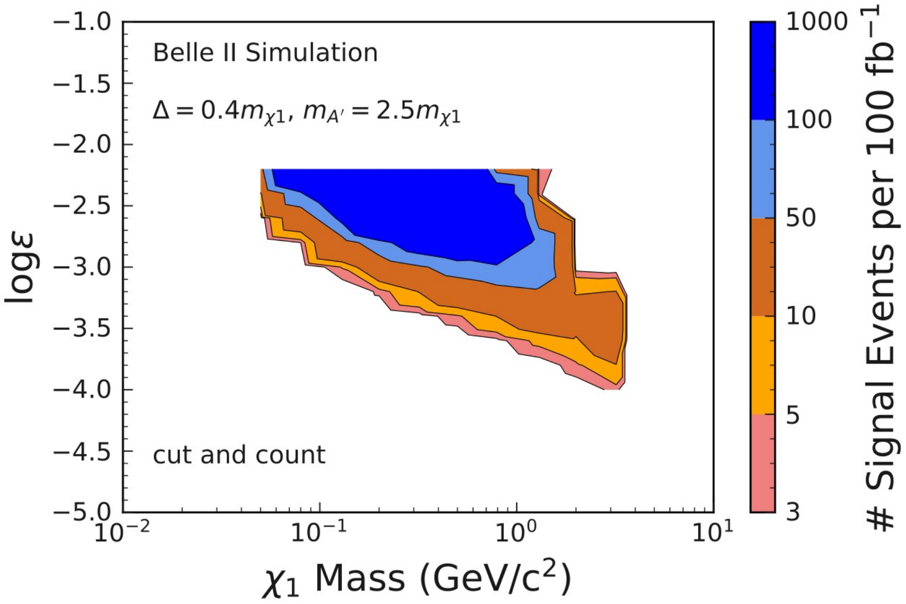




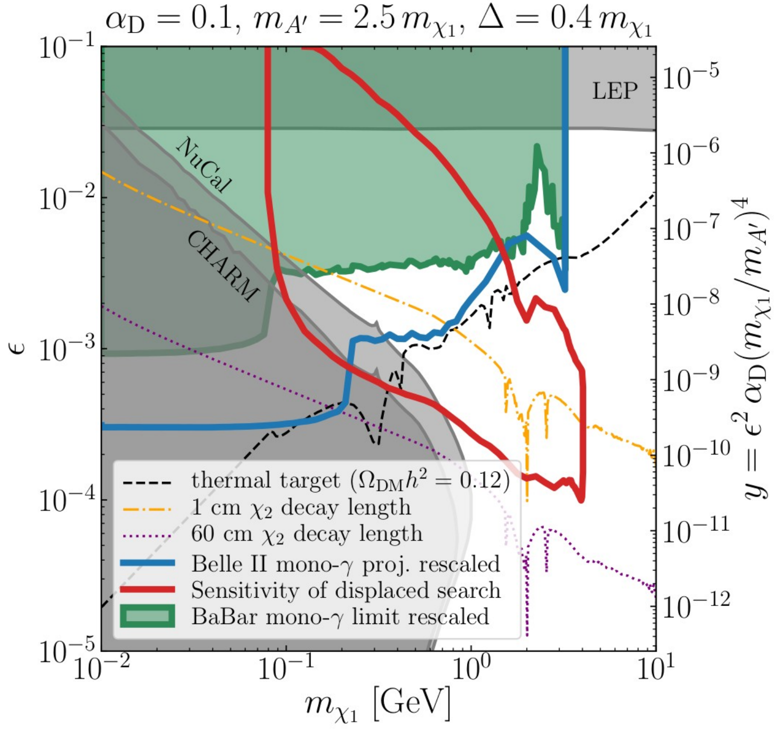


iDM prospects at Belle II

- Estimate signal yield by counting events in ISR photon energy window (final analysis will use a template fit)
- With early Belle II dataset expect to probe dark sector-Standard Model couplings down to $10^{-3} - 10^{-4}$
- Mandatory to implement new trigger for displaced vertex detection
- Analysis timescale ~ end of 2023



Duerr et al., JHEP04 (2021) 39



Heavy QCD axion: $B^+ \to K^+ a$, $a \to$ hadrons

- Chakraborty et al. (PRD 104 055036 (2021)) estimated sensitivity of heavy QCD axion using some (not DM search) experimental data
  - $a \to \eta\pi^+\pi^-$: BABAR PRL 101, 091801 (2008) (with ~400 fb^{-1})
  - $a \to \pi^0\pi^+\pi^-$: Belle PRD 90, 012002 (2014) (with ~700 fb^{-1})