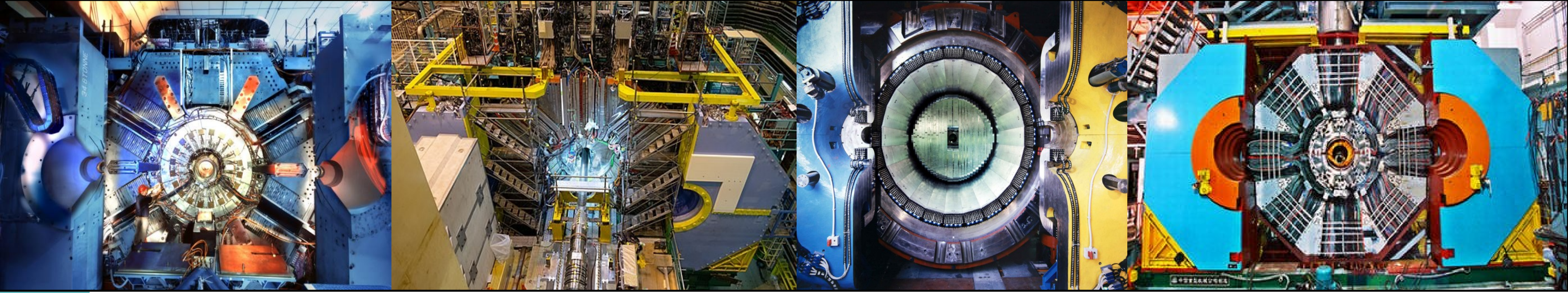


Dark sector searches at Belle II and other experiments at e^+e^- colliders

IPA2022: Interplay between Particle and Astroparticle physics 2022

Technische Universität (TU), Wien. September 05-09, 2022

Luigi Corona - University and INFN of Pisa

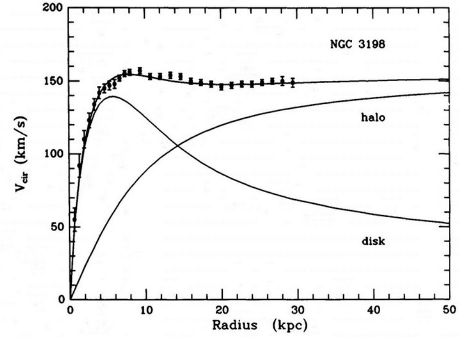
on behalf of the Belle II collaboration and including material by the KLOE, BaBar, Belle and BES III collaborations

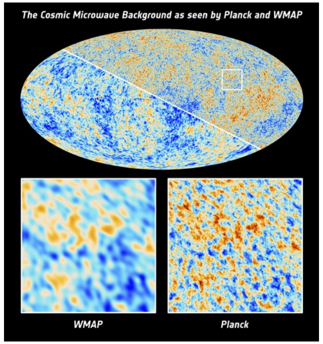
luigi.corona@pi.infn.it

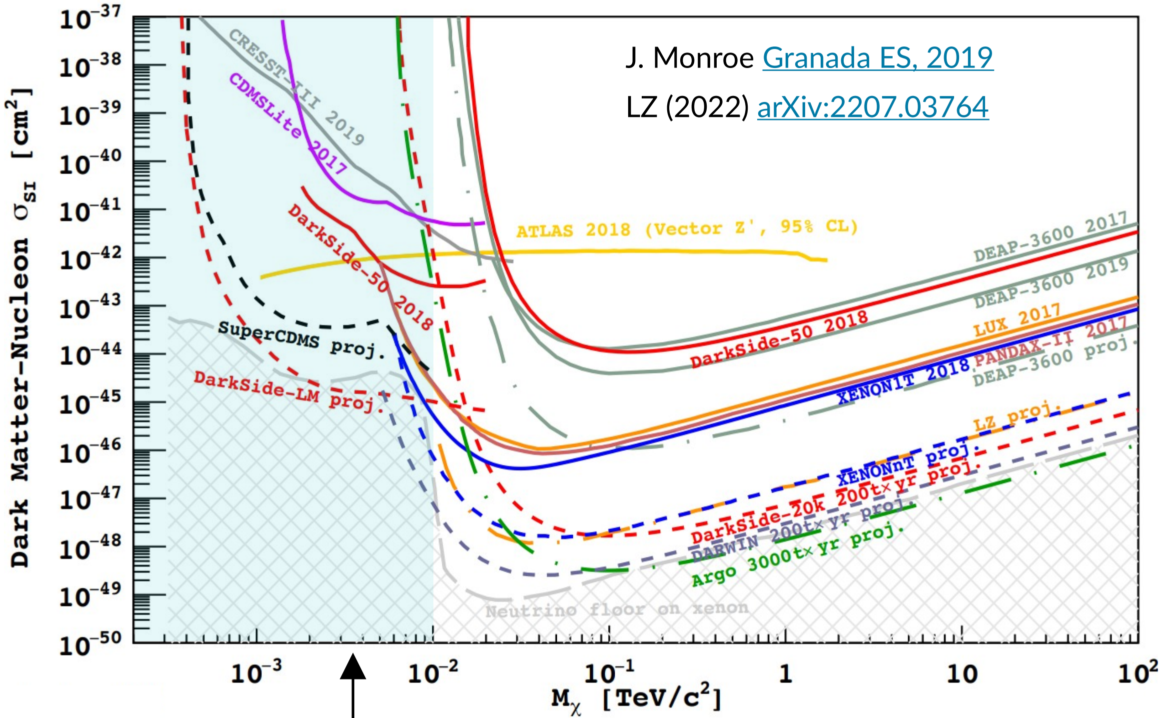
Dark matter puzzle

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

Albada et al., [Astrophysical Journal (1985)]







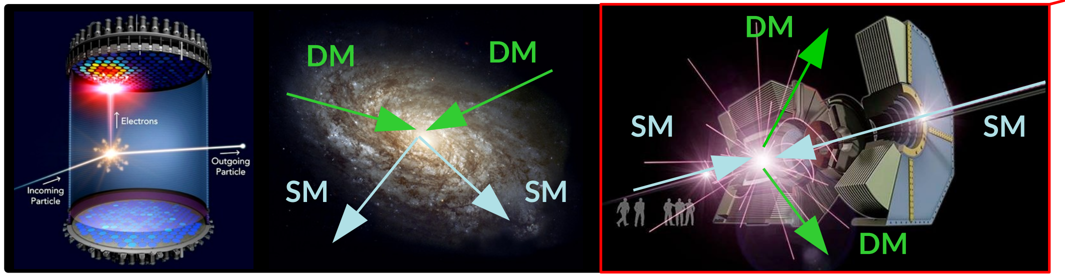
J. Monroe [Granada ES, 2019]

LZ (2022) [arXiv:2207.03764]

Focus on dark sector searches at e^+e^- colliders

- How to search for it?

Direct Indirect Colliders



Searches at colliders

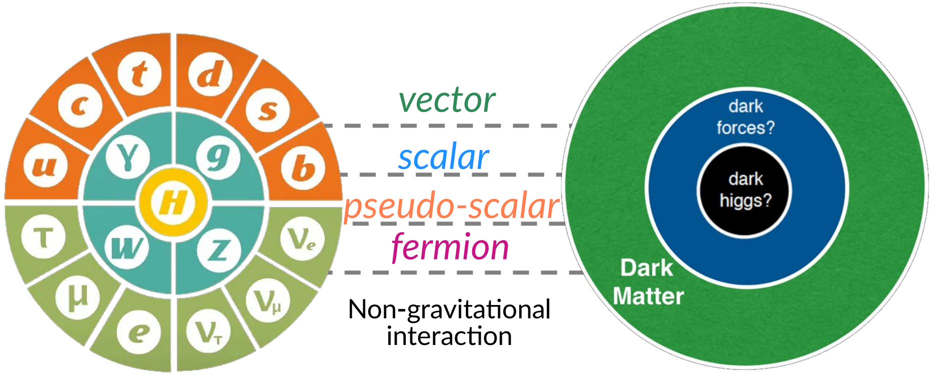
- DM weakly couples to SM particles and it can be produced in SM particles annihilation at accelerators
  - → several signatures involving light **dark sector mediators** too

Light dark sectors

- Null dark-matter-search results at the electroweak scale by the LHC and direct detection experiments motivates 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

- Dark matter does not interact directly with the Standard Model



- Dark matter may interact with Standard Model through several "**portal**" interactions [1, 2]:
  - vector portal (dark photon (*A'*), Z',...)
  - scalar portal (dark scalar (*S*), dark Higgs,...)
  - pseudo-scalar portal (axions, axion-like particles (*ALP*)),
  - neutrino portal (heavy neutrinos (*N*))

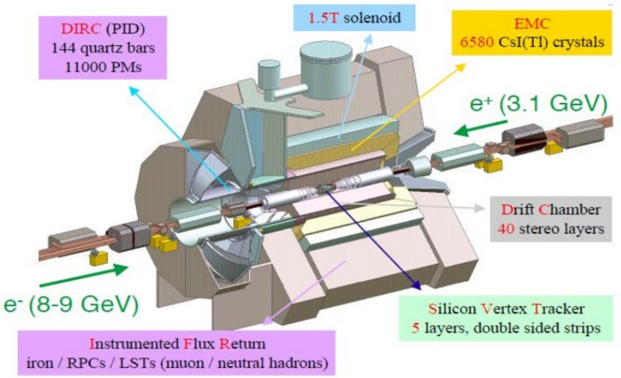
- Not just solving the dark matter puzzle. Could explain:
  - some astrophysics anomalies: positron excess in cosmic rays, ..., (PAMELA, Fermi, ...)
  - some anomalies in *B* meson decays: R_{D^*}, R_{K^*},... (Belle, LHCb, ...)
  - the $(g-2)_\mu$ anomaly, recently confirmed at Fermilab [3]

[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)

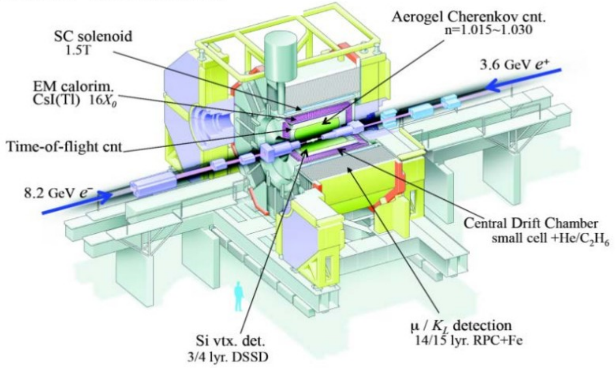
Experiments at e^+e^- colliders

- Many experiments at e^+e^- colliders have been providing important contribution to dark sector searches

BABAR detector



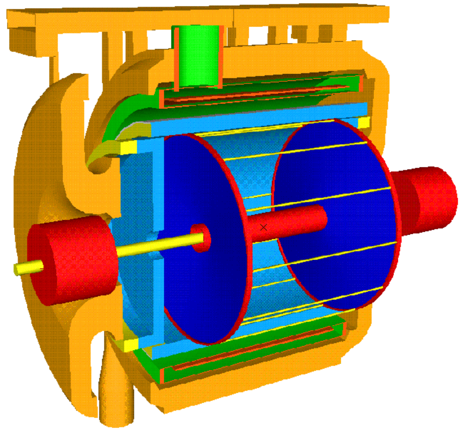
Belle detector



- Experiments at B-factories
  - BABAR @ PEP-II (2000-2008)
  - Belle @ KEKB (1999 - 2010)
  - **Belle II @ SuperKEKB (2018 -)**
  - ➔ $\sqrt{s}$ = 10.58 GeV (Υ(4S))

This talk: **the focus mostly on B-factories**

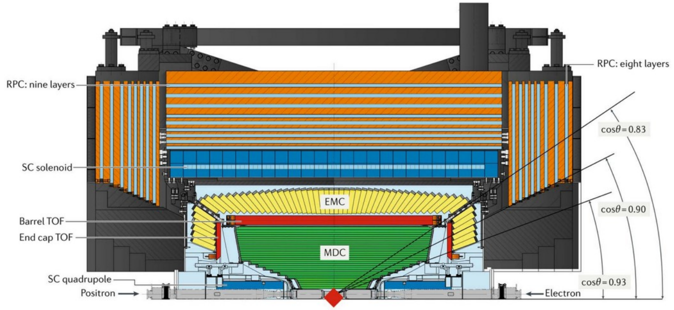
KLOE detector



- KLOE (2001 – 2006) and KLOE-2 (2014 – 2018) @ DAΦNE
  - ➔ $\sqrt{s}$ = 1.019 GeV (Φ meson)

- BES III (2009 -) @ BEPC II
  - ➔ $\sqrt{s}$ = 2 - 4.95 GeV

BESIII detector   See Gianluigi's talk!



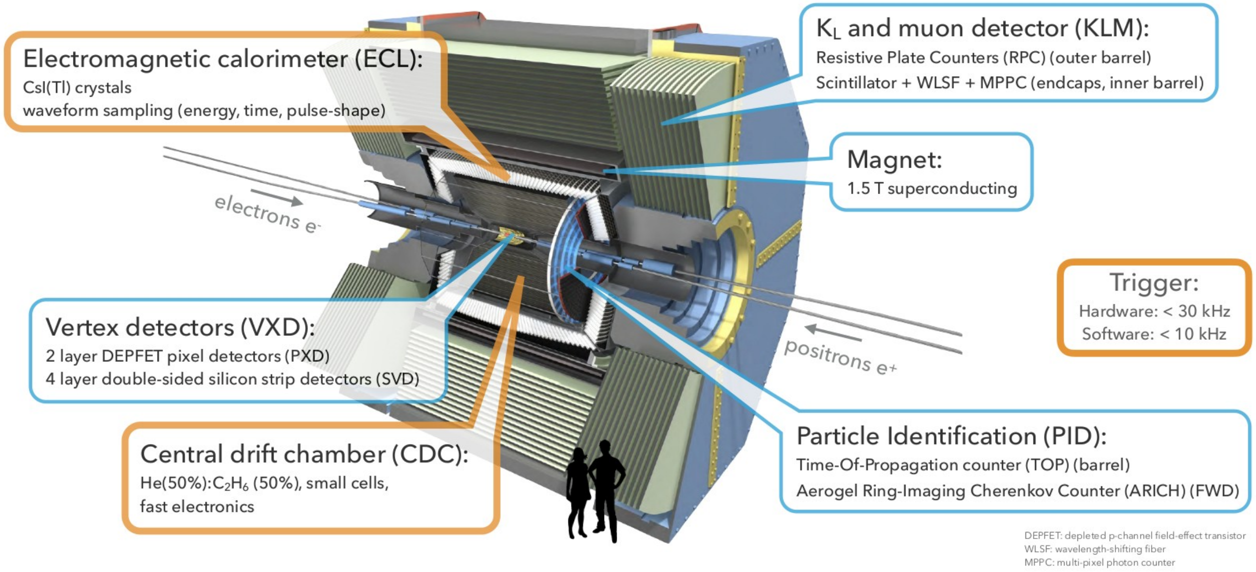
Experiments at B-factories

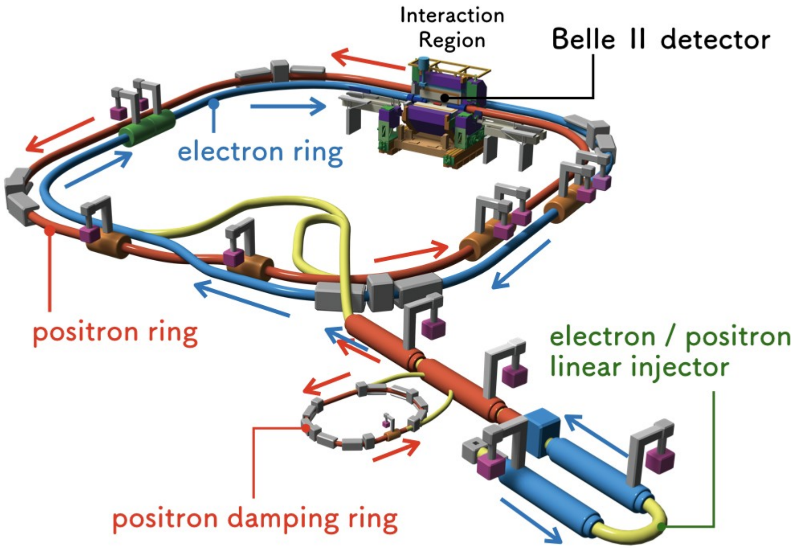
See Alan's talk on Belle II!

Belle II Physics Book, PTEP 2019 12 (2019)

- Asymmetric e^+e^- colliders optimized for the production of B meson pairs, but also D mesons, τ leptons, ...
- High peak luminosity $L > 10^{34}$ cm^{-2}s^{-1}
- BaBar and Belle collected ~ 1.5 ab^{-1}

- SuperKEKB
  - New generation of B-factories
  - target peak luminosity: $6.5 \cdot 10^{35}$ cm^{-2}s^{-1}
- Belle II target integrated luminosity: 50 ab^{-1}
  - Belle II collected 424 fb^{-1} in 3 years of data taking





Dark Sector searches at B-factories

Negligible interaction probability of dark matter with the detector

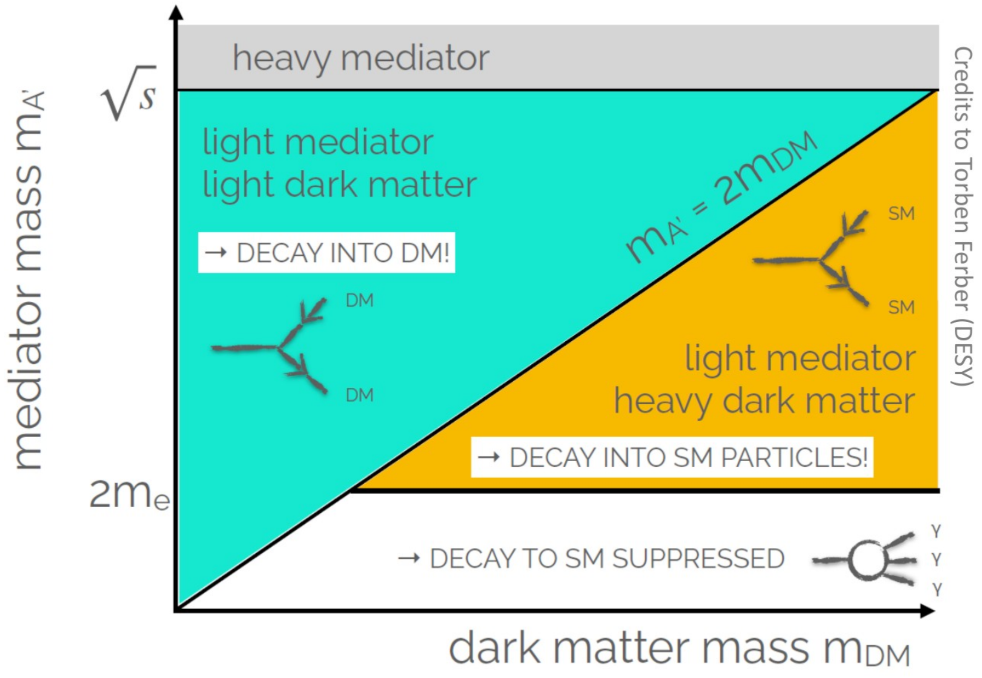
- Search for mediators (visible or invisible)
- Search for final states with missing mass
- Search for both

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.

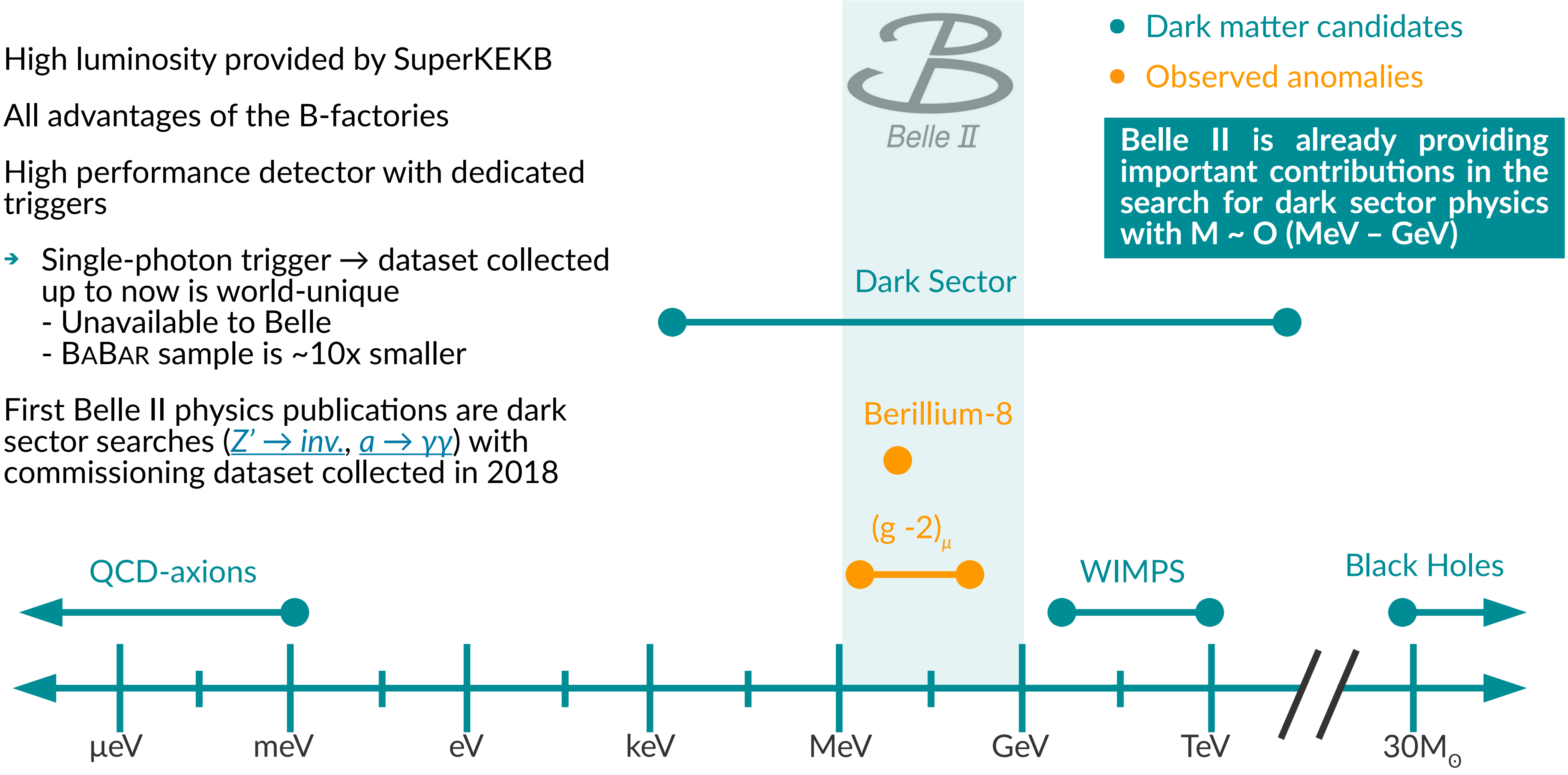


Dark Sector searches at Belle II

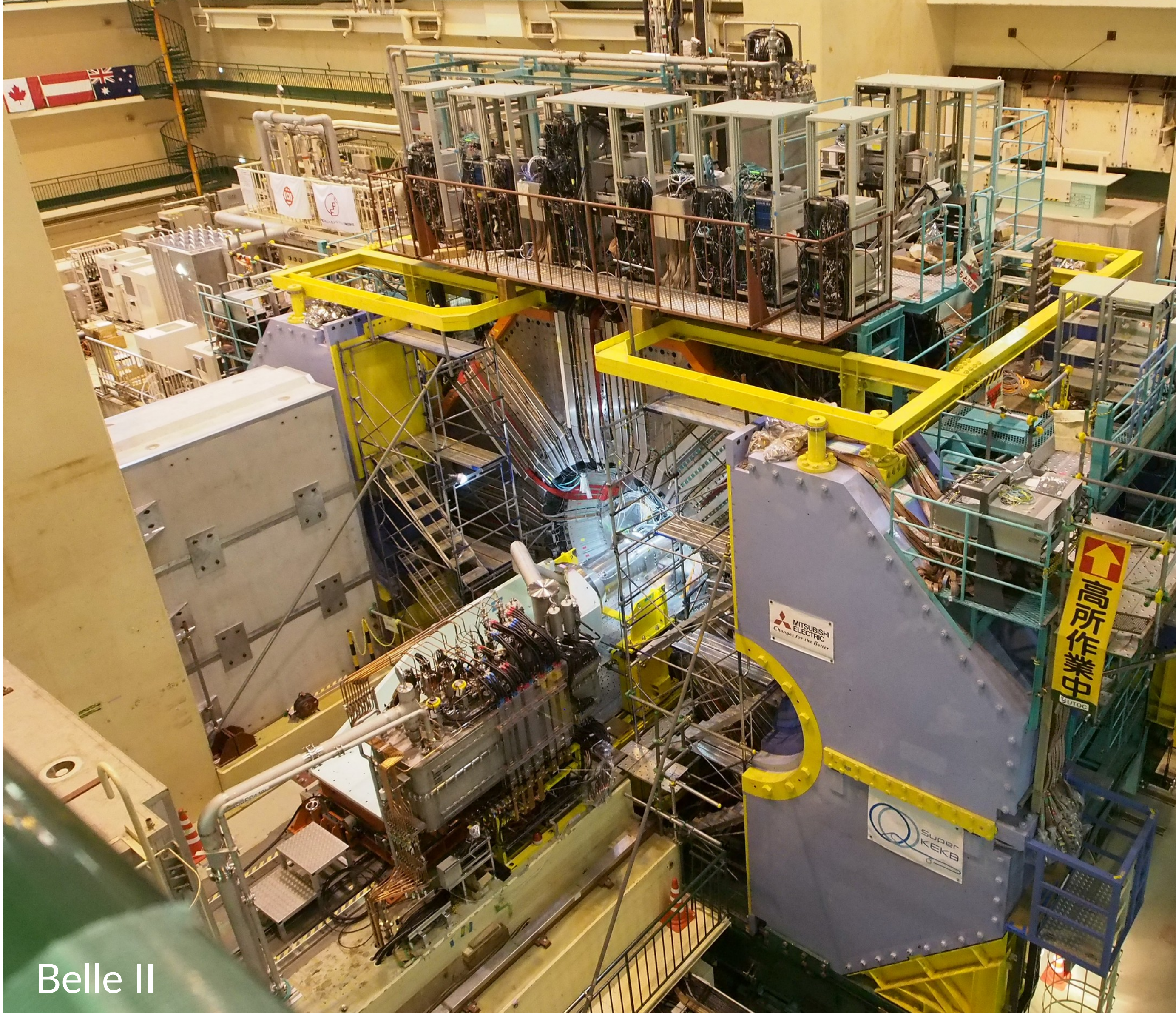
[1] Battaglieri et al., arXiv:1707.04591

- 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 to Belle
    - BaBar sample is ~10x smaller
- First Belle II physics publications are dark sector searches (*Z' → inv.*, *a → γγ*) with commissioning dataset collected in 2018

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



Overview on dark sector searches: *Z’ boson*



Belle II

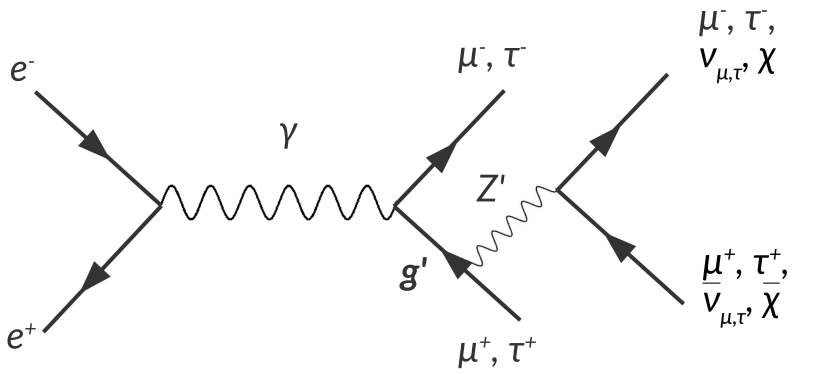
Search for a Z' boson

[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

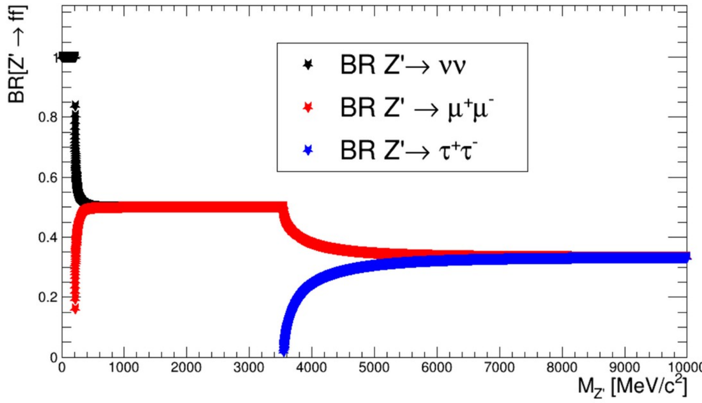
- Vector boson Z' with a coupling g' only to the 2nd and 3rd generations of leptons introduced by the $L_\mu - L_\tau$ model [1, 2, 3]

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

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

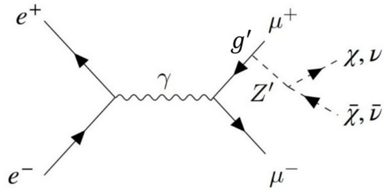


- May explain DM abundance, the $(g-2)_\mu$ anomaly
- May solve anomalies observed in rare B decays, $B \to K^*\mu\mu$, $R_{K(*)}$
- If lighter accessible DM exists, Z' could decay to DM
- Possibile decays: $Z' \to$ invisible (neutrinos or light DM), $Z' \to \tau\tau$, $Z' \to \mu\mu$
- Existing constraints 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

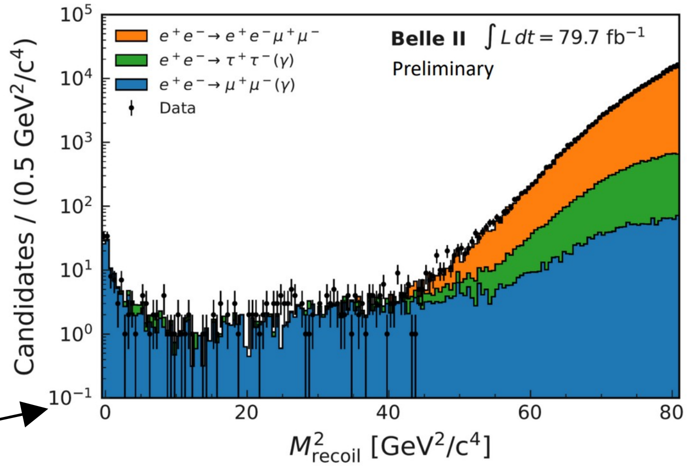
Analysis

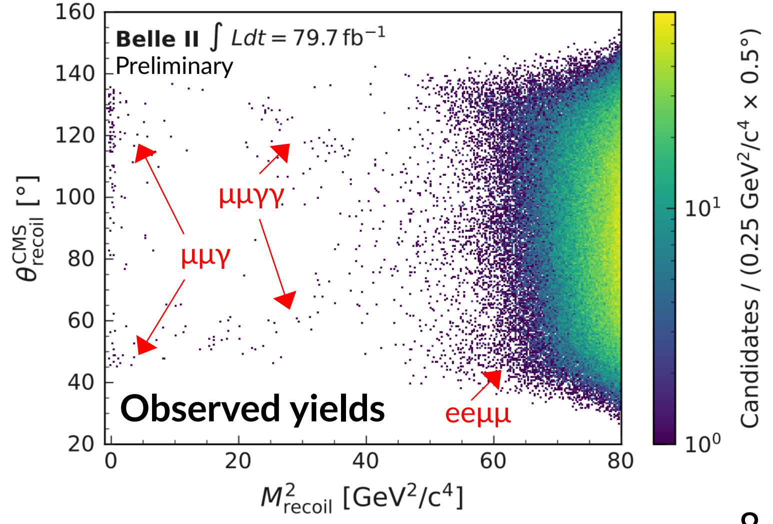


$$M^2_{recoil}(\mu\mu) = s + M(\mu\mu)^2 - 2\sqrt{s}(E^{CMS}_{\mu^+} + E^{CMS}_{\mu^-})$$

- ***$e^+e^- \to \mu^+\mu^-$* + missing energy**
- Update of the search for an invisible Z', with 0.276 fb^{-1} collected by Belle II in 2018 (commissioning run)
  - first search for $Z' \to$ invisible >> I. Adachi et al, [PhysRevLett.124.141801 (2020)]
- Dataset: 79.7 fb^{-1} (2019-2020)
- Event selection:
  - two-track trigger
  - two reconstructed muons, p_T^μ > 0.4 GeV/c
  - no nearby photon
  - Background suppression: different origin of missing momentum
    - background: neutrinos for $\tau\tau$ and ISR for $\mu\mu(\gamma)$
    - signal: FSR
- Neural network trained to optimize [Punzi-FOM] >> [Eur. Phys. J. C 82, 121 (2022)]
- Signature: bump in 2D plane of θ_{recoil} recoil vs M^2_{recoil}

Backgrounds
$e^+e^- \to \tau^+\tau^- (\gamma)$: ~ 100% suppressed
$e^+e^- \to \mu^+\mu^- (\gamma)$: up to 7 GeV
$e^+e^- \to e^+e^-\mu^+\mu^-$: above 7 GeV





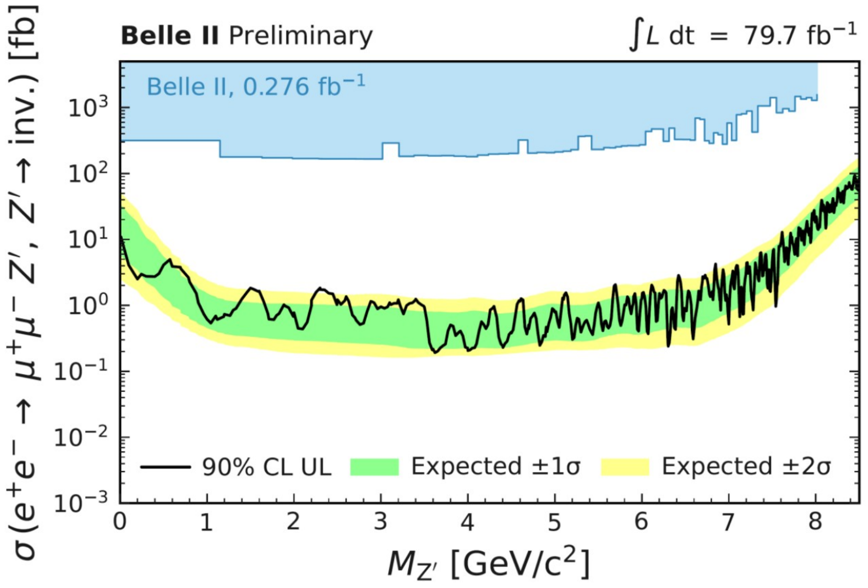
$Z' \to$ invisible at Belle II

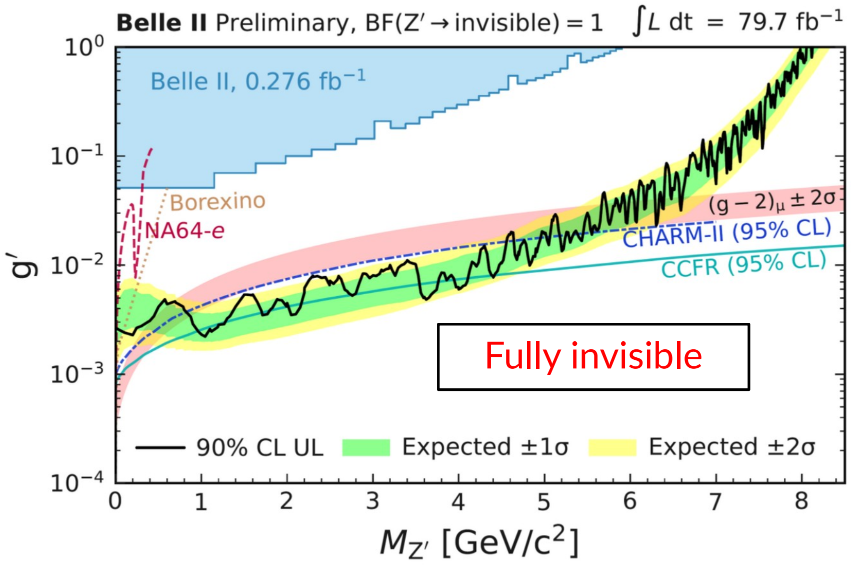
Results

★ 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 $(g\text{-}2)_\mu$ excluded for $0.8 < M_{Z'} < 5.0$ GeV/c^2
- to be submitted for publication

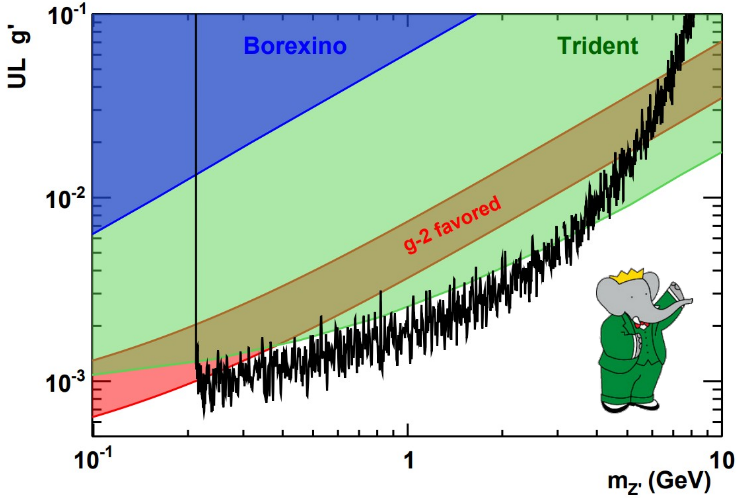


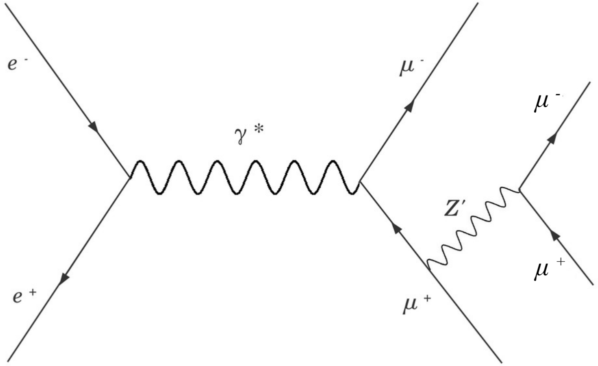


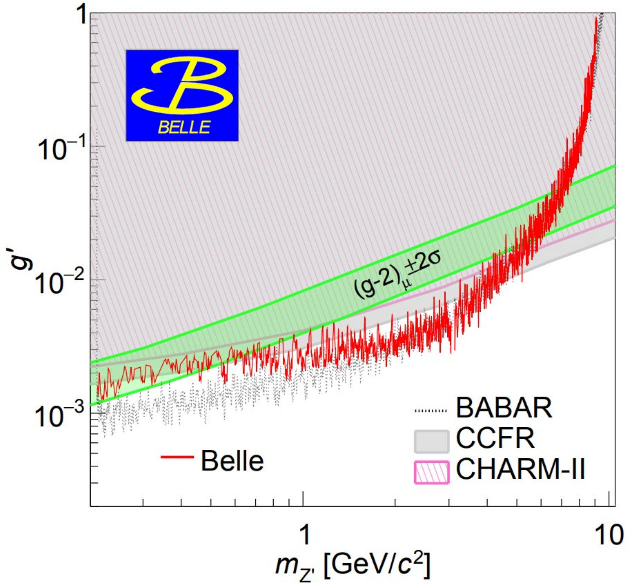
Fully invisible

$Z' \to \mu\mu$ at BaBar and Belle

- $e^+e^- \to \mu^+\mu^- Z', Z' \to \mu^+\mu^-$
- Search for a di-muon invariant mass peak in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ events
  - Background: mainly from QED $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ process, as well as peaking backgrounds from $e^+e^- \to \pi^+\pi^- J/\psi$ and ρ
- BaBar [1]
  - Dataset: 514 fb^{-1}
  - 90% CL upper limits on g' at the level of $O(10^{-3})$
  - a large part of the $(g-2)_\mu$ band excluded
- Belle [2]
  - Dataset 643 fb^{-1}
  - Improvement in the upper limits to g' for 2 GeV/c^2 < $m_{Z'}$ < 8.4 GeV/c^2







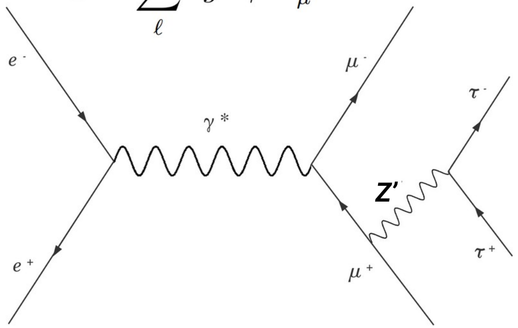
[1] J. P. Lees et al, PhysRevD.94.011102 (2016)
[2] T. Czank et al, PhysRevD.106.012003 (2022)

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

Vector portal

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

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

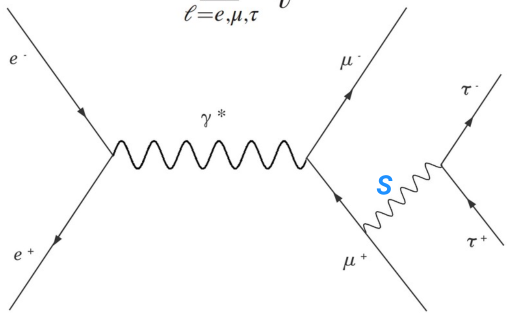


- Z' of the $L_\mu - L_\tau$ model
- **First search in ττ**

Scalar portal

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

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

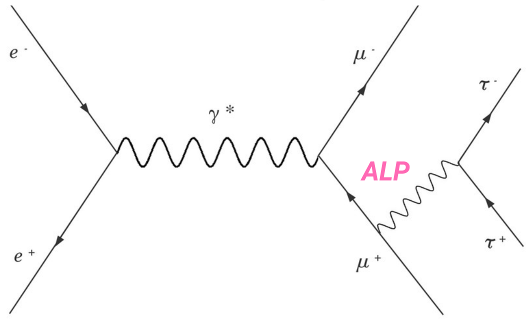


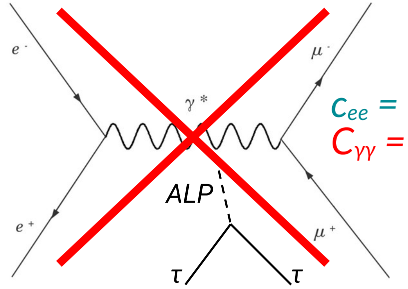
- Leptophilic dark scalar S model
- Constraints from $S \to ee/\mu\mu$ (BaBar(2020), Belle)
  - Model unconstrained for $M_S > 6.5$ GeV/c^2
  - See Swagato's talk
- **First search in ττ**

Pseudo-scalar portal

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

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





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

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

- **First search for $ALP \to \tau\tau$**
- 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: ~63 fb^{-1} (2019+first half of 2020)

Z', S, ALP → ττ at Belle II

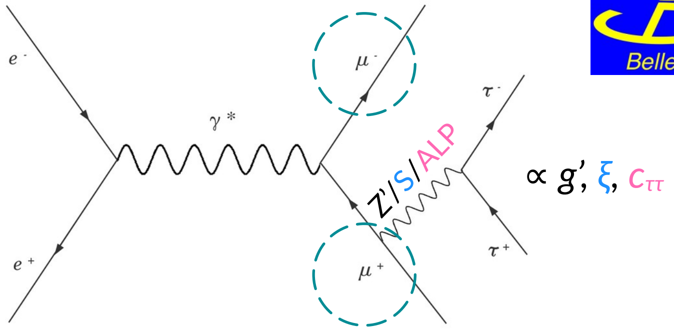
Analysis

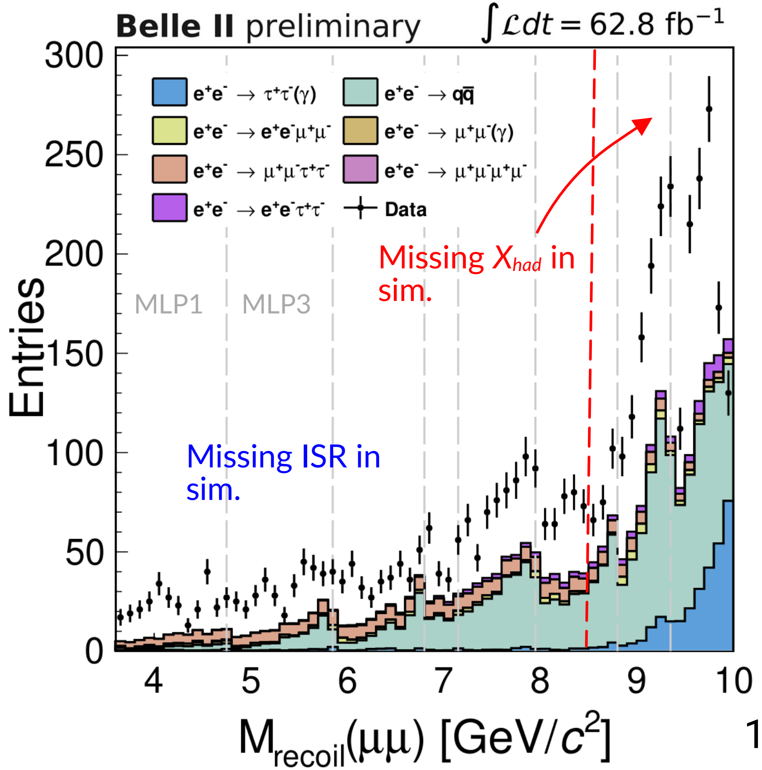
- Signature: narrow peak in the recoil mass distribution w.r.t the $\mu^+\mu^-$ in $\mu^+\mu^-\tau^+\tau^-$ final state
- Event selection:
  - 3-track OR single-muon trigger
  - 1-prong τ decays (+ neutrals)
    2μ + 2 additional tracks (e, μ, π) with M(4tracks) < 9.5 GeV/c^2
  - 8 neural networks trained for different ranges in $M_{recoil}(\mu\mu)$
- Main background components:
  - $e^+ e^- \to \tau^+ \tau^- (\gamma)$
    $e^+ e^- \to q \bar{q}$ ($q = u, d, s, c, b$)
  - 4-lepton final states
  - $e^+ e^- \to \mu^+ \mu^- \pi^+ \pi^-$
    $e^+ e^- \to e^+ e^- X_{had}$ (two-photon processes)
- **Signal yield from a fit scan over M_{recoil} above floating background**

ISR **NOT** in simulation

NOT in simulation

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



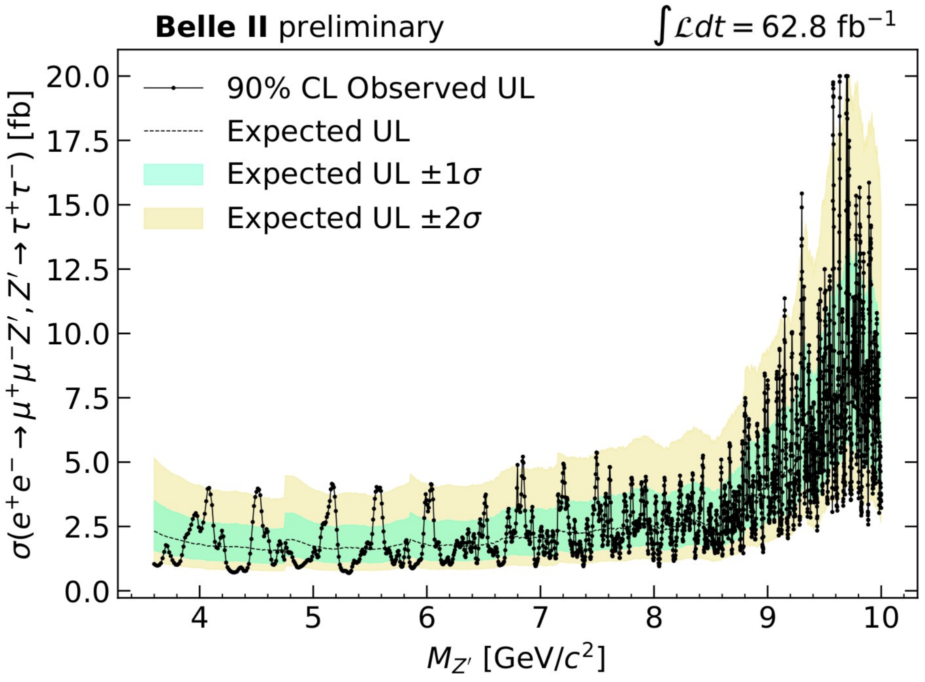


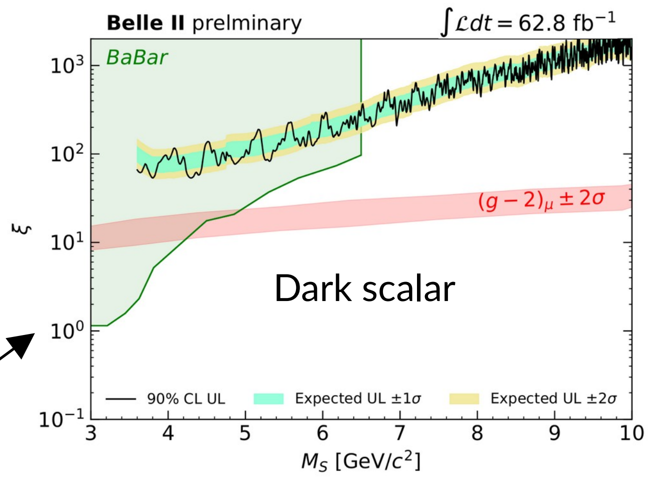
Z', S, ALP → ττ at Belle II

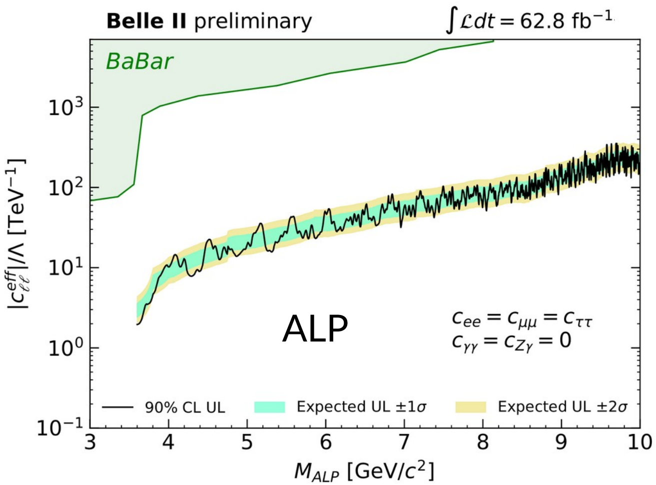
Results

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

★ Presented @ ICHEP 2022



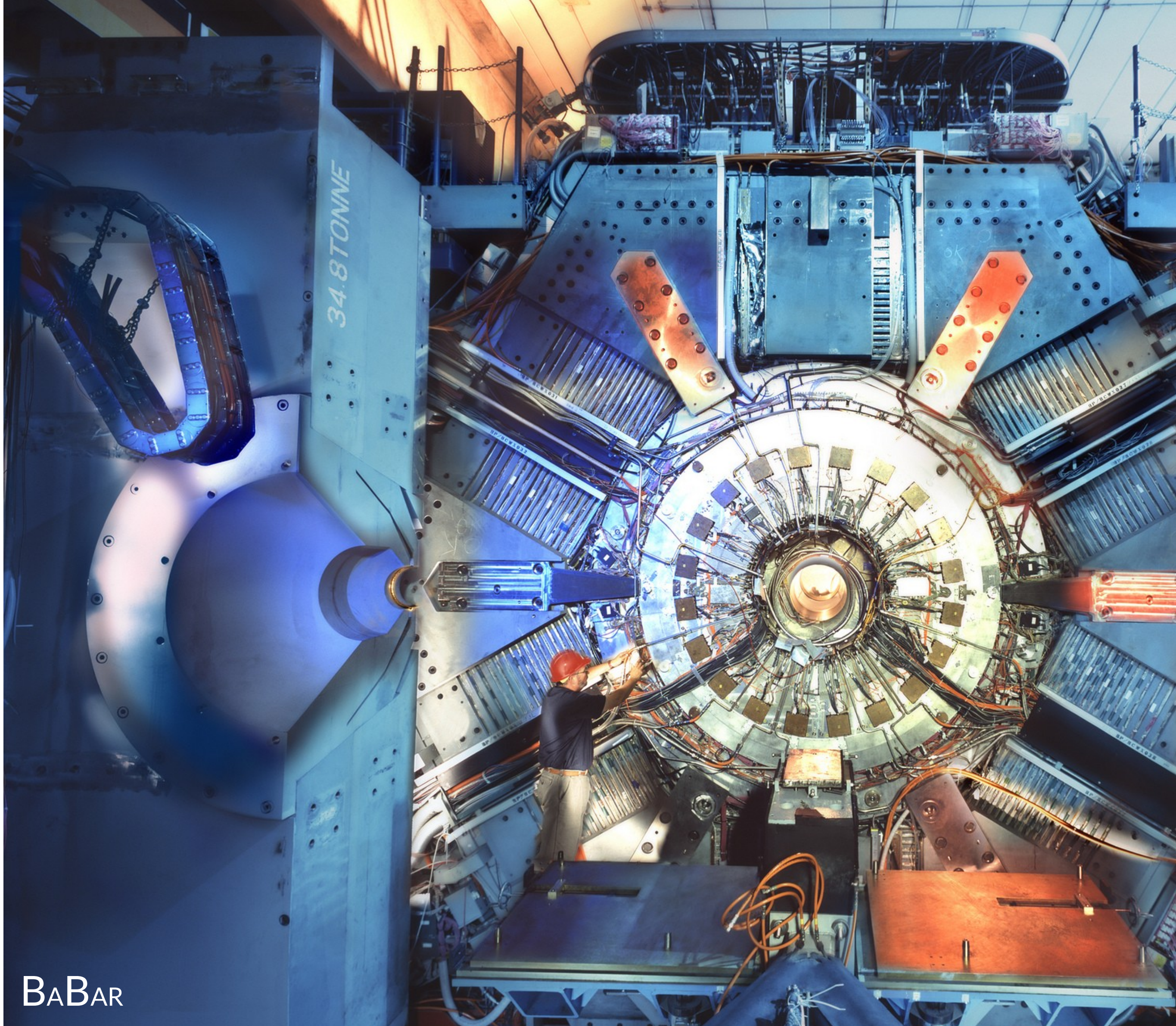




First constraints on S for M_S > 6.5 GeV/c^2 and firts direct constraints for $ALP \to \tau\tau$ - to be submitted for publication

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

Overview on dark sector searches: ***dark photon***



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]

  → $$\mathcal{L}_{int} = \underbrace{e\varepsilon}_{\text{Interation strenght}} \underbrace{A'_\mu}_{\text{Dark photon field}} \underbrace{J^\mu_{em}}_{\text{Electromagnetic current}}$$

- 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: $e^+e^- \to A'^* \to A'h'$

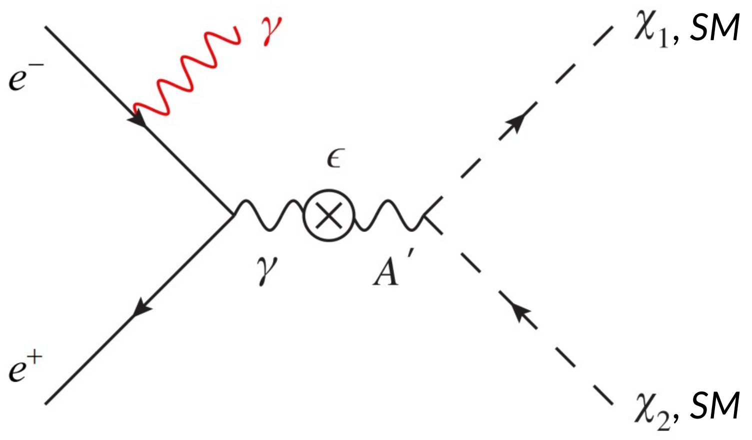
- **Direct production with ISR particularly interesting:** $e^+e^- \to \gamma_{ISR}A'$

- Two basic scenarios depending on dark photon mass:

  → $M_{A'} > 2m_\chi$: invisible decay $A' \to \chi\bar{\chi}$

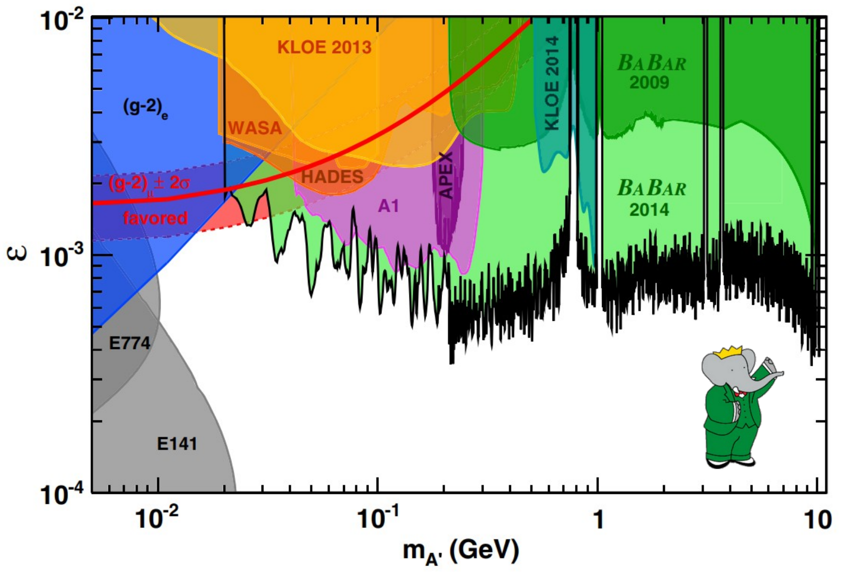
  → $M_{A'} < 2m_\chi$: visible decay in Standard Model particles

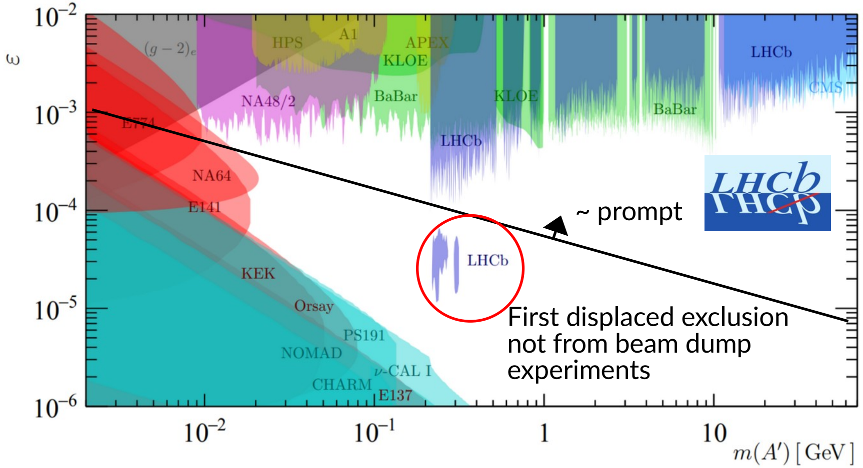
$e^+e^- \to \gamma_{ISR}A'$ $(A' \to \chi\bar{\chi}, SM)$



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 better results

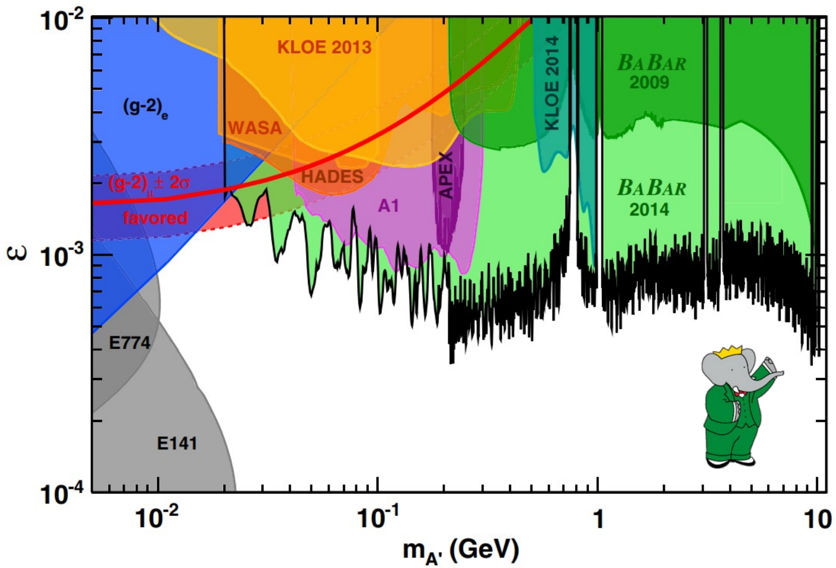




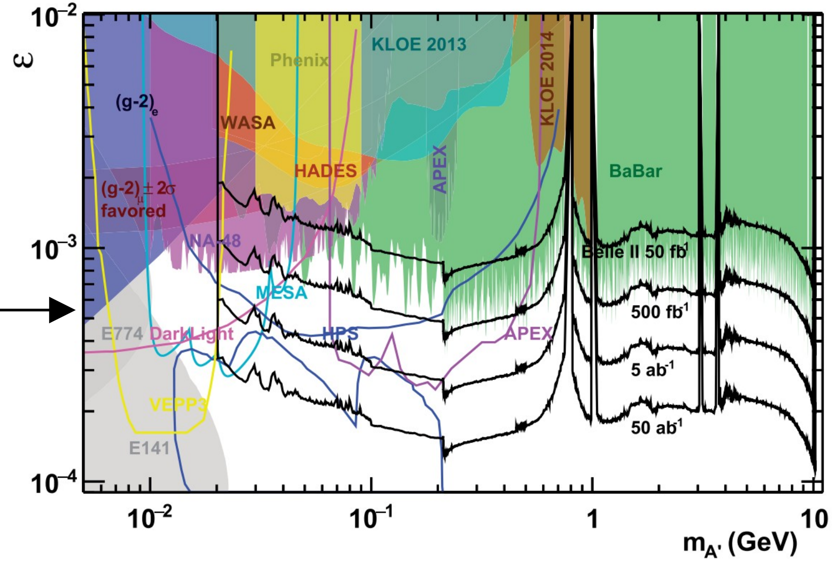
[1] J.P. Lees et al, Phys. Rev. Lett. 113, 201801 (2014)
[2] R. Aaij et al, PhysRevLett.124.041801 (2020)

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 better results



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



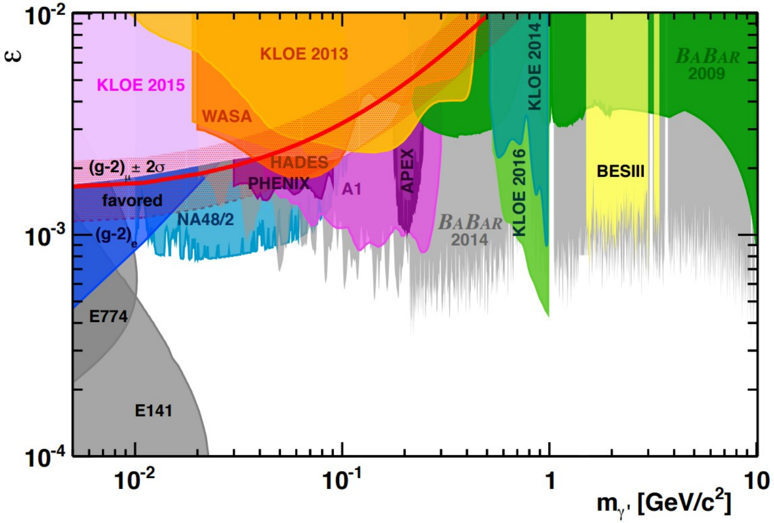
[1] J.P. Lees et al, Phys. Rev. Lett. 113, 201801 (2014)
[2] R. Aaij et al, PhysRevLett.124.041801 (2020)
[3] E. Kou et al, Prog Theor Exp Phys (2019)

Visible dark photon at BESIII

$e^+e^- \to \gamma_{ISR} A', A' \to l^+l^-$ ($l = e, \mu$)

- $2.93\ \text{fb}^{-1}$ @ $\sqrt{s} = 3.773$ GeV
- Untagged photon method to increase statistics
- Search for a narrow peak in m_{l+l-} spectrum
- 90% CL UL on $\varepsilon \sim O(10^{-4} - 10^{-3})$
  $1.5 < m_{A'} < 3.4\ \text{GeV}/c^2$

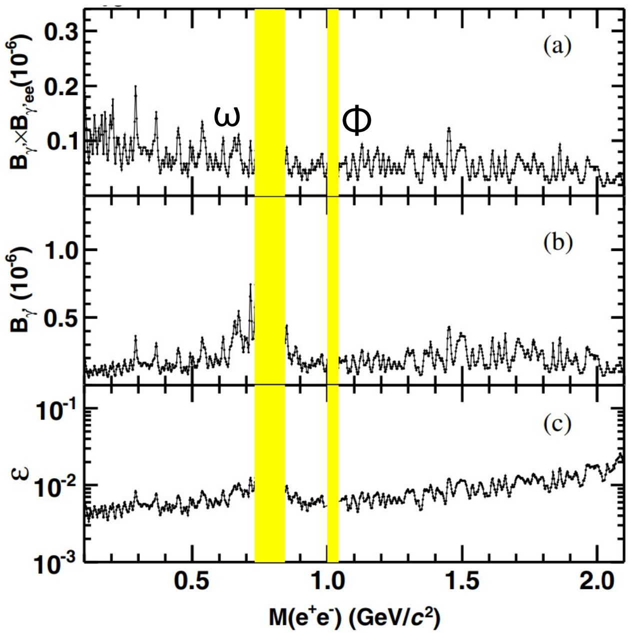
M. Ablikim et al, Physics Letters B 774, 252 (2017)



$J/\psi \to A' \eta/\eta', A' \to e^+e^-$ [1,2]

- First search for dark photon via electromagnetic Dalitz decays with 1.3 billion J/ψ
- 90% CL UL on $\varepsilon \sim O(10^{-3} - 10^{-2})$ for $0.1 < m_{A'} < 2.\ \text{GeV}/c^2$

[1] M. Ablikim et al, PRD.99.012006 (2019)
[2] M. Ablikim et al, PRD.99.012013 (2019)



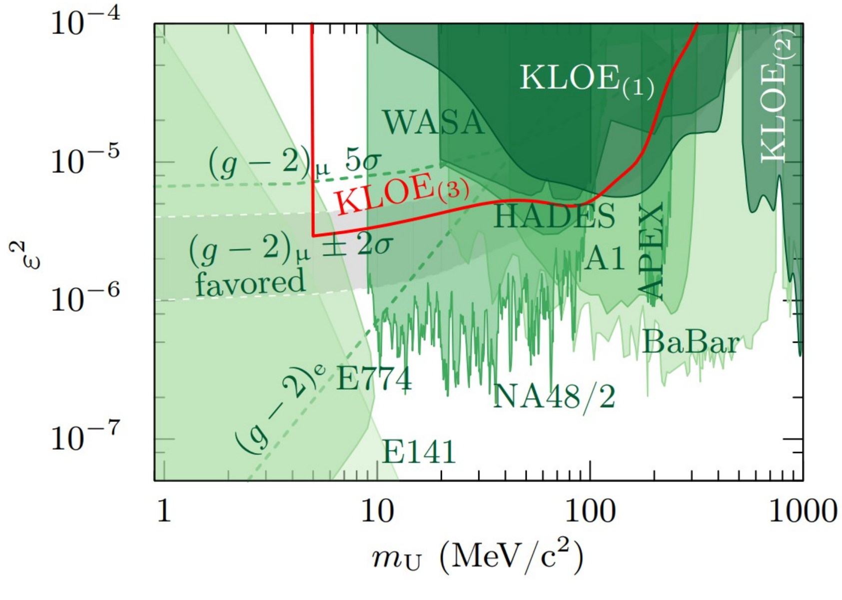
$J/\psi \to \gamma' \eta', \gamma' \to e^+e^-$

Visible dark photon at KLOE/KLOE-2

$e^+e^- \to \gamma_{ISR} A', A' \to e^+e^-$

- 1.54 fb^{-1} @ $\sqrt{s}$ = 1.019 GeV
- Search for a narrow peak in m_{e+e-} spectrum
- 90% CL UL on ε^2 ~ O(10^{-6} – 10^{-4}) in the mass range 5 – 520 MeV/c^2

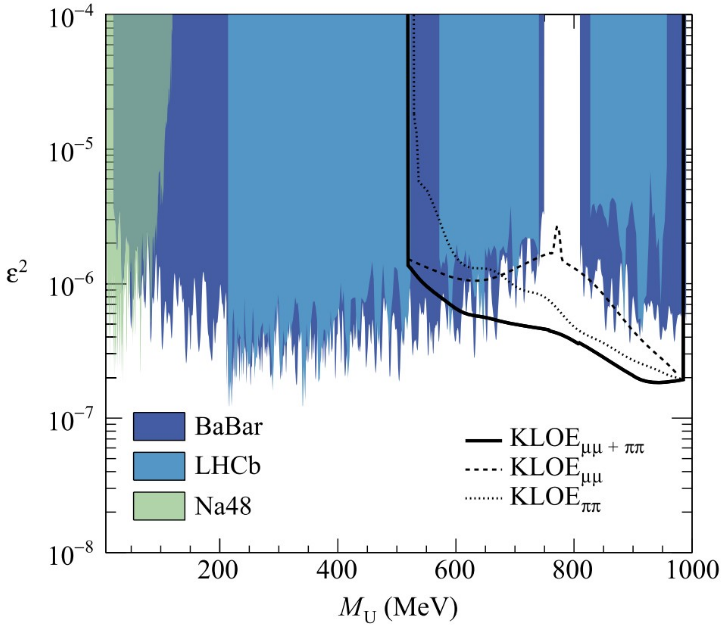
A. Anastasi et al, [Phys. Lett. B 750 (2015) 633-637]



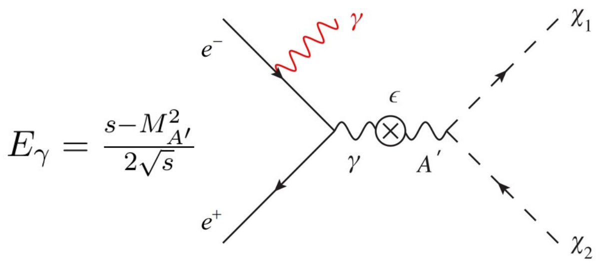
$e^+e^- \to \gamma_{ISR} A', A' \to \mu^+\mu^-/\pi^+\pi^-$

- 1.93 fb^{-1} @ $\sqrt{s}$ = 1.019 GeV
- Search for a narrow peak in $m_{\mu+\mu-/\pi+\pi-}$ spectrum
- 90% CL UL on ε^2 ~ O(10^{-7}) in the mass range 519–987 MeV/c^2

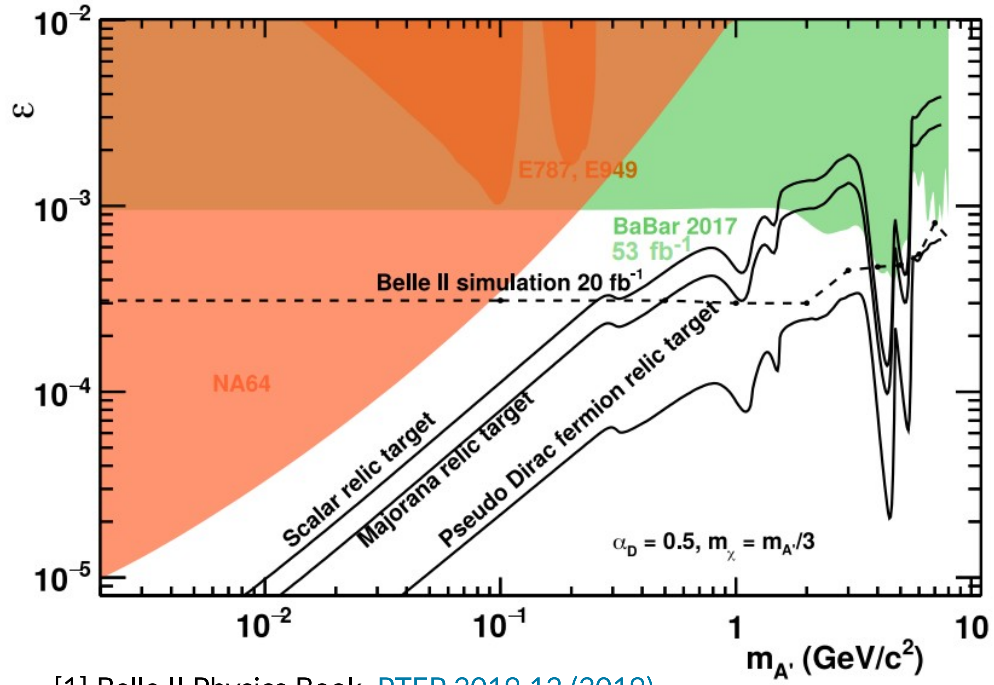
A. Anastasi et al, [Phys. Lett. B 784 (2018) 336-341]



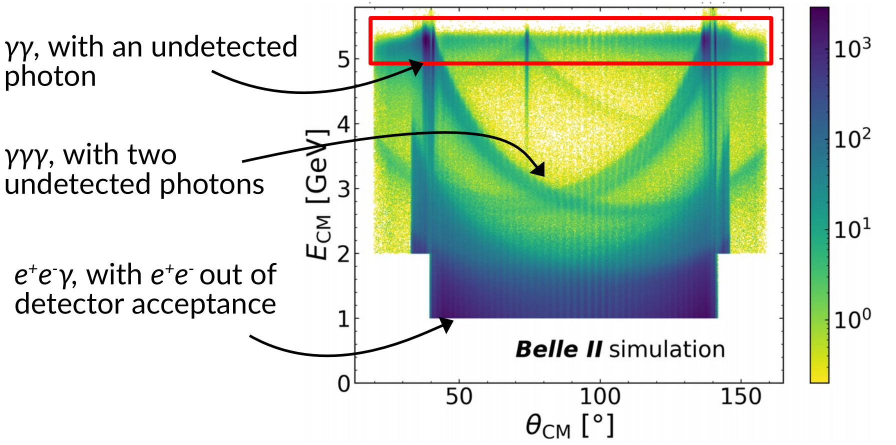
Invisible dark photon



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



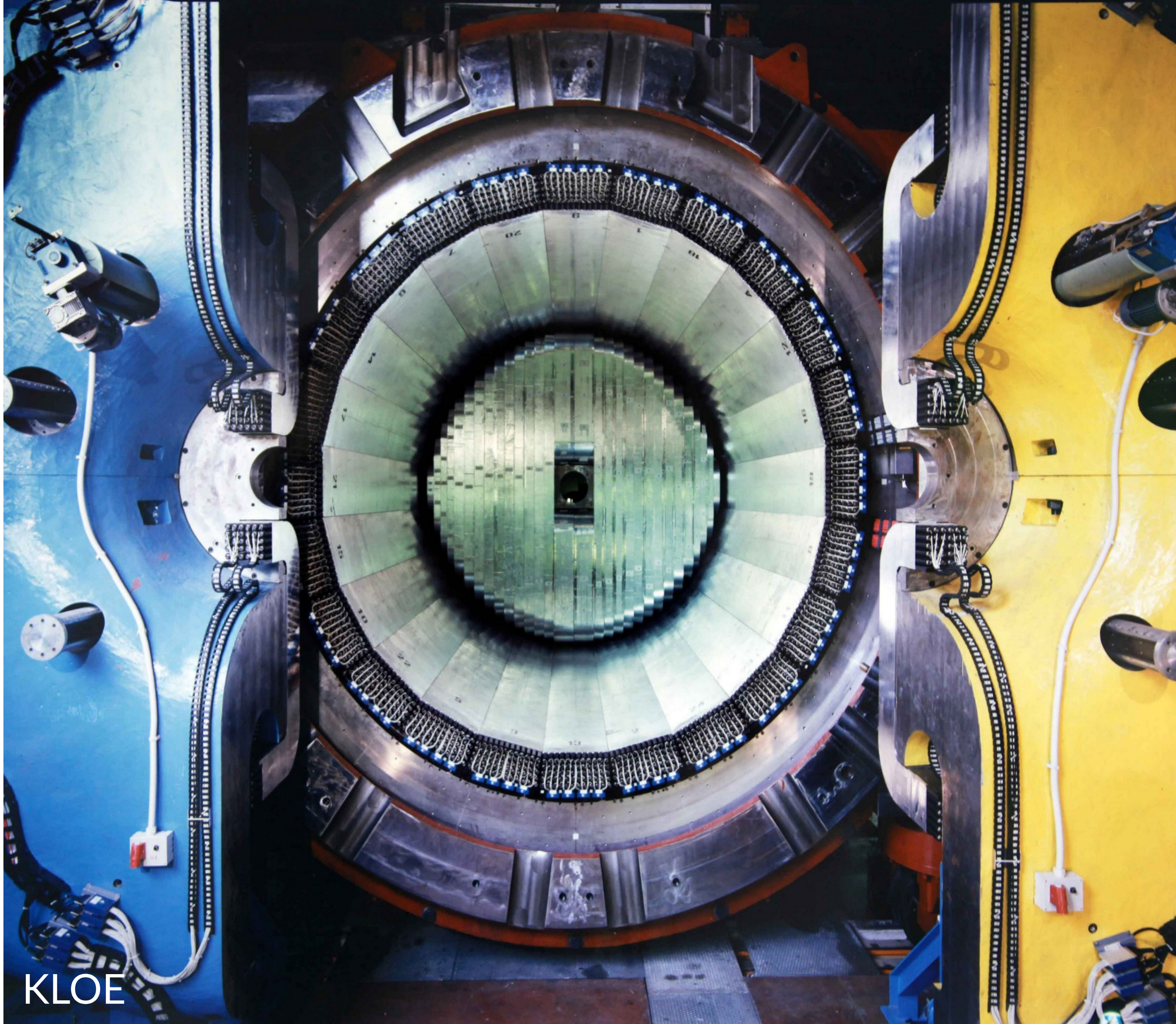
Background simulation assuming 20 fb^{-1}



- 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**

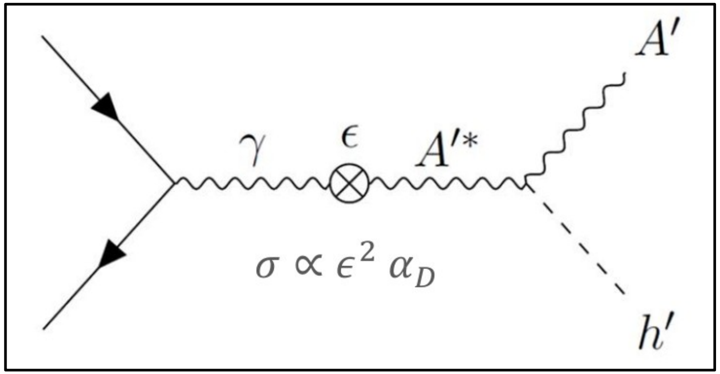
[1] Belle II Physics Book, PTEP 2019 12 (2019)
[2] Less et al, Phys. Rev. Lett. 119, 131804 (2017)

Overview on dark sector searches: ***dark Higgs***

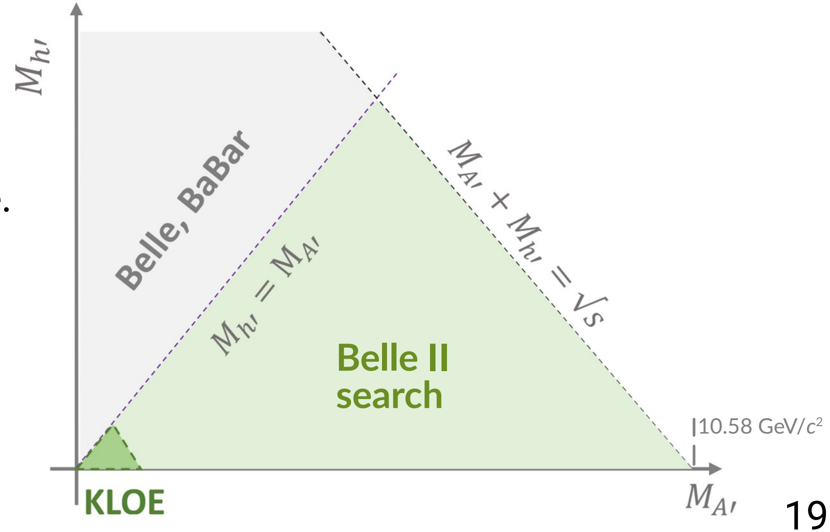


Search for a dark Higgs (and dark photon)

[1] Batell et al., Phys. Rev. D 79, 115008 (2009)



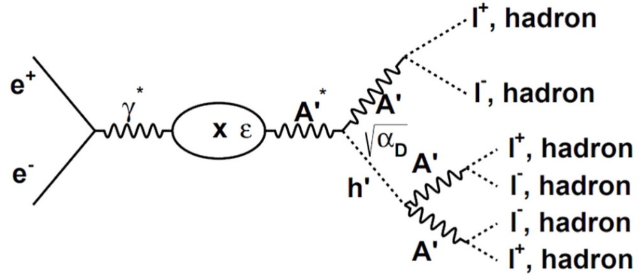
- Dark photon *A'*
  - mass produced by the Higgs mechanism involving a dark Higgs boson [1]
- Dark higgs *h'*
  - couples to *A'* with α_D
  - does not mix with Standard Model Higgs
- Both *A'* and *h'* can be produced at e^+e^- colliders through the dark higgsstrahlung process
  - $e^+e^- \to A'^* \to A' h'$
- 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'***



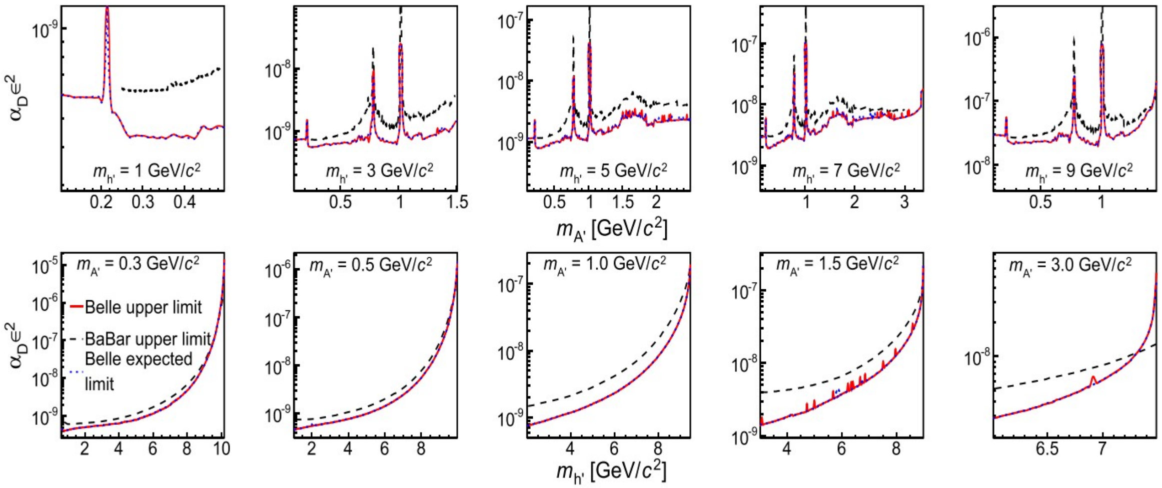
Search for a dark Higgs at BABAR and Belle

[1] J. P. Lees et al PhysRevLett.108.211801 (2012)
[2] I. Jaegle et al, PhysRevLett.114.211801 (2015)

- BABAR [1] and Belle [2] searched for the visible *h*'
  - Signal: three pairs of tracks (*ee*, *μμ*, *ππ*) at the same mass and no missing energy
  - Background: almost background free
- Full data-sets from both experiments (BABAR: 516 fb^{-1}, Belle: 977 fb^{-1})
- 90% CL upper limits on $\varepsilon^2 \cdot \alpha_D$ at the level of $O(10^{-8} - 10^{-10})$:
  - Belle limits improve upon and explore slightly wider mass ranges than BABAR

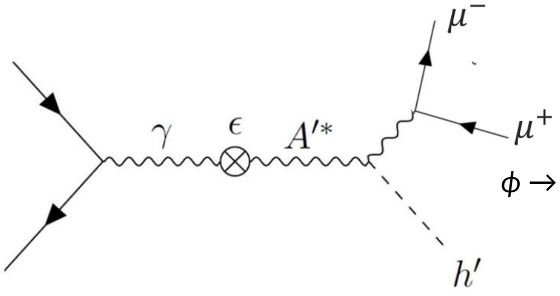


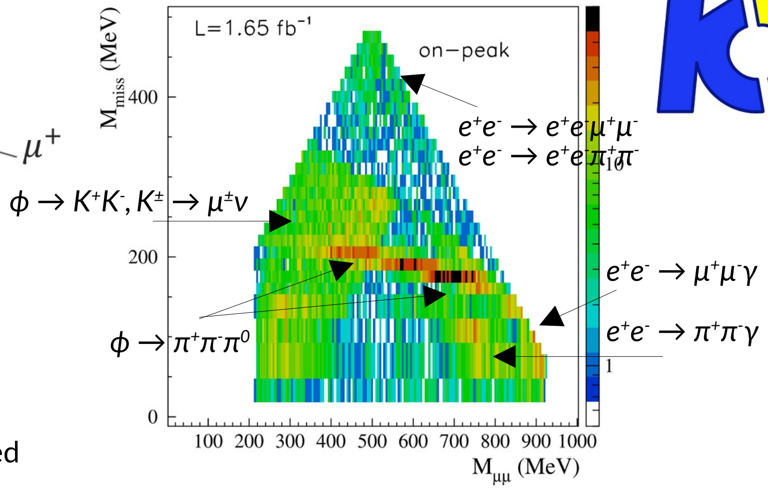
Upper limits at 90% CL on $\varepsilon^2 \cdot \alpha_D$



Search for a dark Higgs at KLOE/KLOE-2

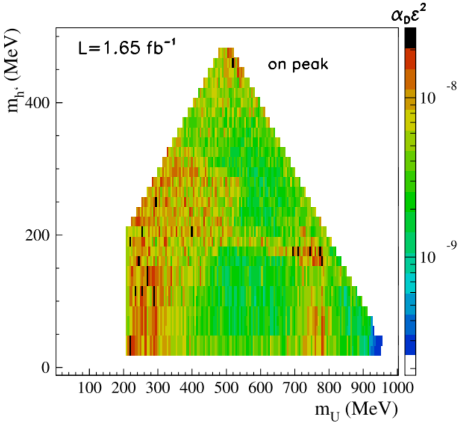
- $e^+e^- \rightarrow A'h', A' \rightarrow \mu\mu, h' \rightarrow$ **invisible**
- Signature: 2D peak in recoil vs dimuon mass
- Data:
  - 1.65 fb^{-1} at the ϕ resonance
  - 0.21 fb^{-1} off-peak
- Limits on $\varepsilon^2 \cdot \alpha_D$ range from 10^{-9} – 10^{-8}
- Assuming $\alpha_D = \alpha_{em} \rightarrow \varepsilon \sim O(10^{-4} – 10^{-3})$
- First limits for $M_{h'} < M_{A'}$

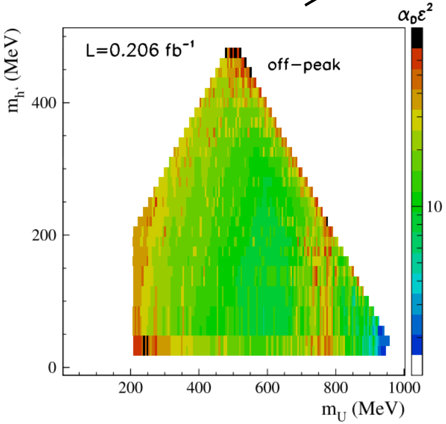




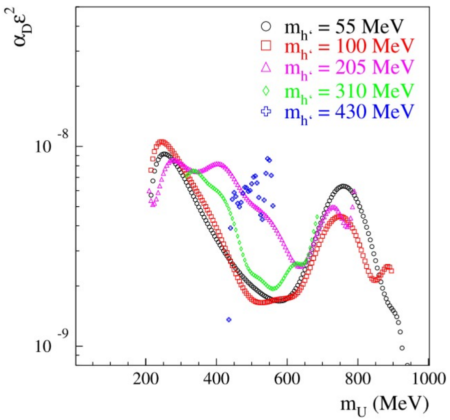
A. Anastasi et al, Phys. Lett. B 747 (2015) 365-372

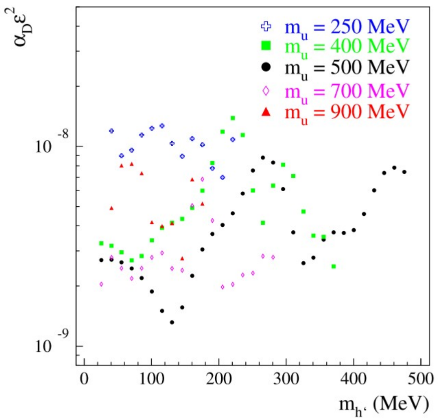
90% CL upper limits in $\varepsilon^2 \cdot \alpha_D$





on-peak and off-peak combined

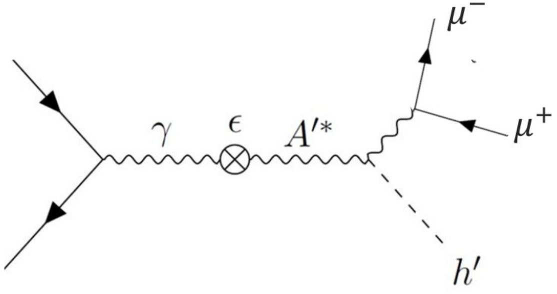


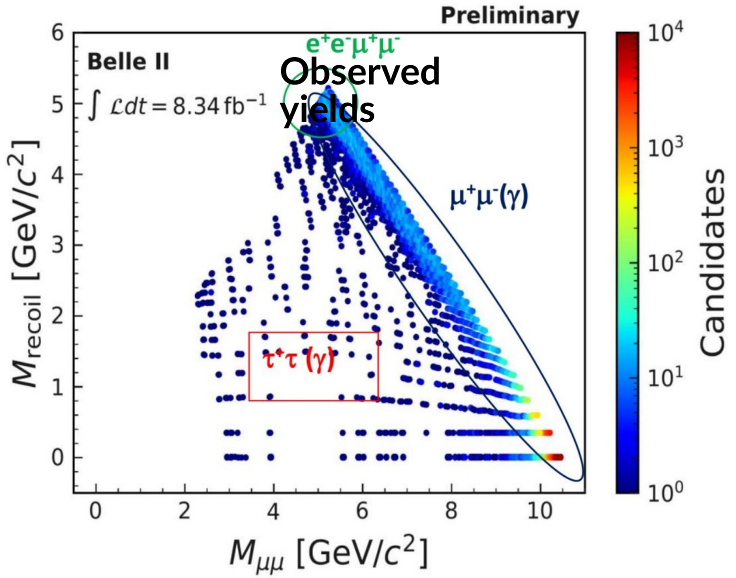


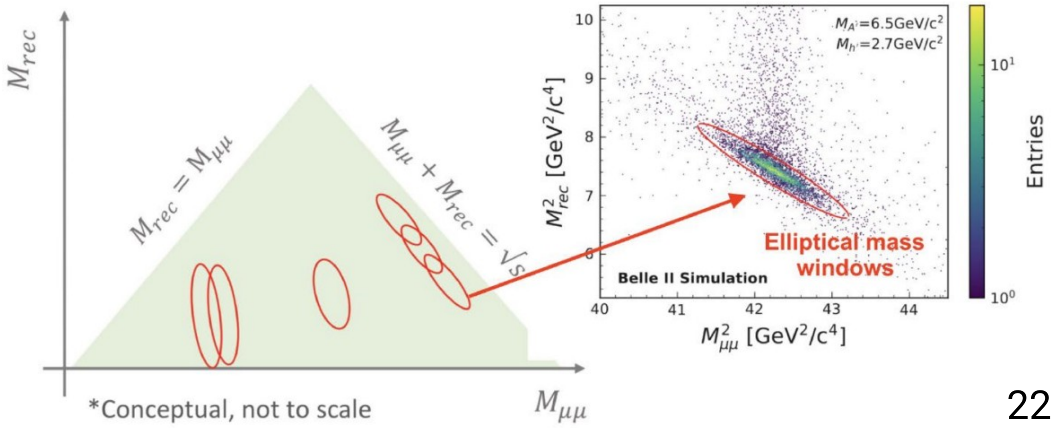
Dark higgsstrahlung at Belle II

Analysis

- $e^+e^- \to A'h', A' \to \mu\mu, h' \to$ invisible
  - Dataset: 8.34 fb^{-1} (2019)
  - Signature: 2D peak in recoil vs dimuon mass
  - Background from QED:
    - $e^+e^- \to \mu^+\mu^-(\gamma)$ (79%)
    - $e^+e^- \to \tau^+\tau^-(\gamma)$ (18%)
    - $e^+e^- \to e^+e^-\mu^+\mu^-$ (3%)
- 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
- Analysis strategy:
  - scan for excess in 2D plane of M_{recoil} vs $M_{\mu\mu}$ in ~9000 elliptical mass windows





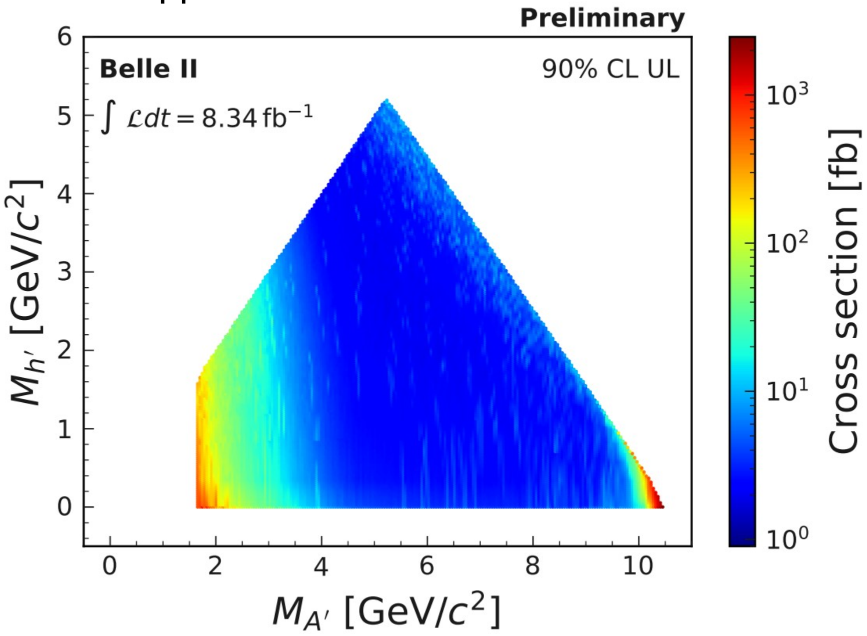


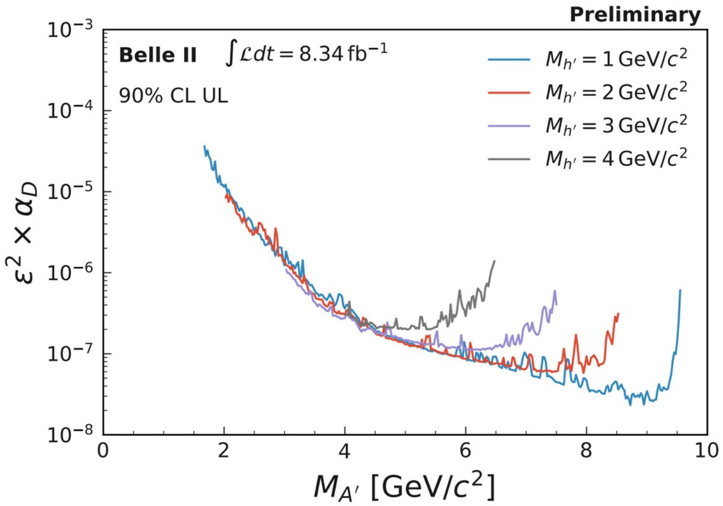
Dark higgsstrahlung at Belle II

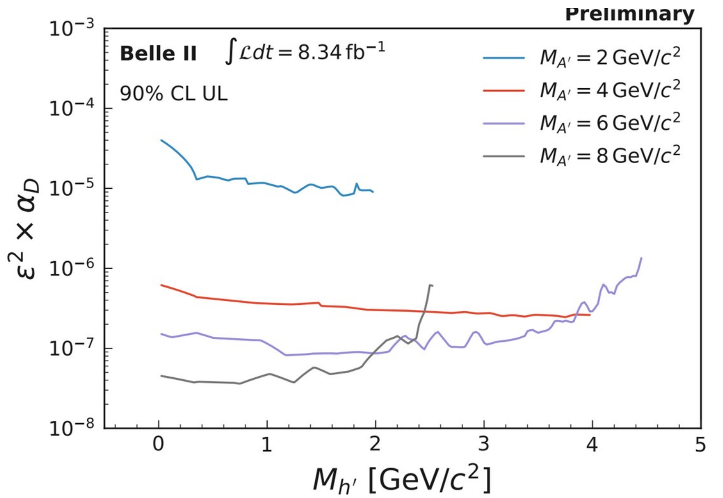
★ Presented @ [Moriond 2022]

Results

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



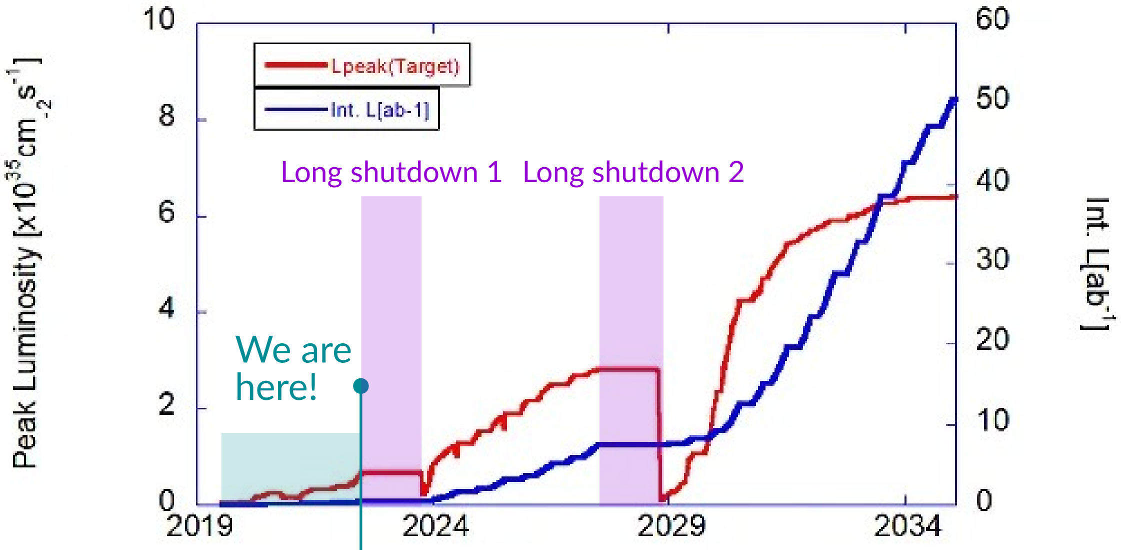




World leading limits for $1.65 < M_{A'} < 10.51$ GeV/c^2
- submitted to PRL→ [arxiv.2207.00509]

Belle II perspectives

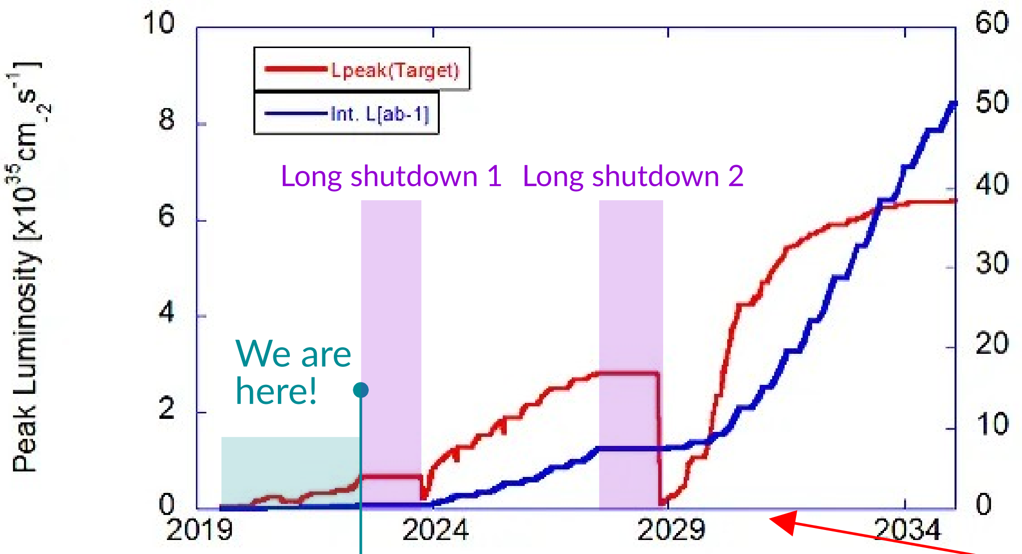
Luminosity projection plot (plan for the coming years)

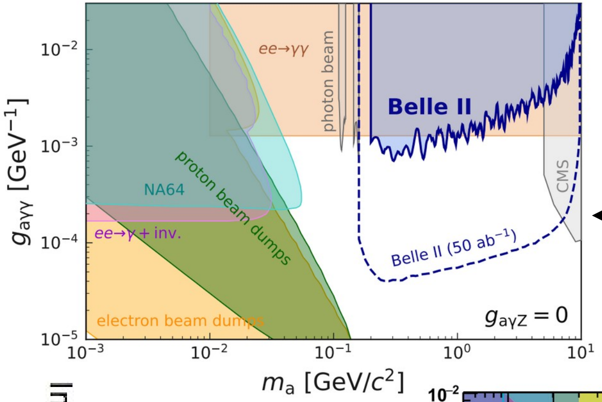


- 424 fb^{-1} collected up to now
- **Current results are still strongly limited by dataset size**
  - world-leading results already published with early datasets

Belle II perspectives

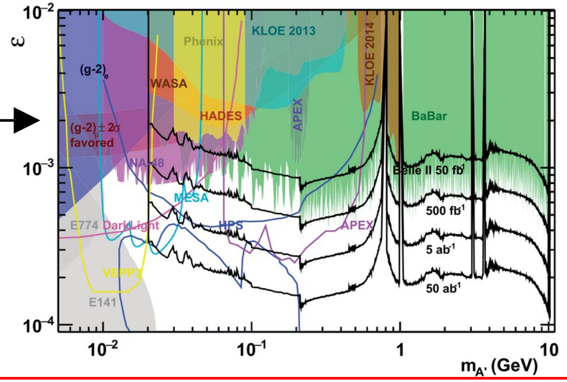
Luminosity projection plot (plan for the coming years)





ALPs: in [Alan's talk]()

Visible dark photon



★ Snowmass paper: [arxiv:2207.06307]()

- 424 fb^{-1} collected up to now
- **Current results are still strongly limited by dataset size**
  - ➔ world-leading results already published with early datasets

- 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

- Experiments at e^+e^- colliders offer excellent opportunities to probe dark sector models
  - sensitive to regions of parameters that can solve the dark matter puzzle and explain Standard Model anomalies

  - Belle, BaBar, BESIII and KLOE excluded many dark sector models
    - in this talk: a subset of results

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

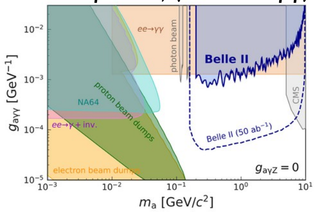
    - World-leading results with early data:
      - Z' → invisible: [Phys. Rev. Lett. 124 (2020) 141801](#) (**NEW** updated result to be submitted for publication)
      - $a \to \gamma\gamma$: [Phys. Rev. Lett. 125, 161806 (2020)](#)
      - h' → invisible: [arxiv.2207.00509](#) **NEW**
      - Z', S,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

    - Will lead in the MeV-GeV mass range in the coming years

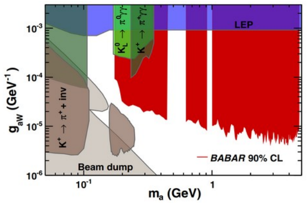
Latest results also shown in [Alan's talk](#), [Swagato's talk](#) and [Alberto's talk](#)

Many other searches

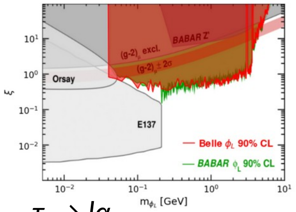
$e^+e^- \to \gamma$ ALP, (ALP $\to \gamma\gamma$)



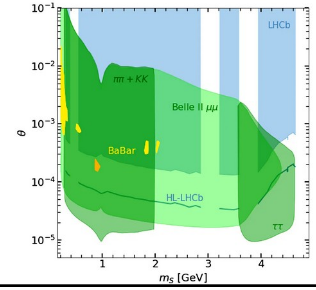
$B^\pm \to K^\pm$ALP, (ALP $\to \gamma\gamma$)



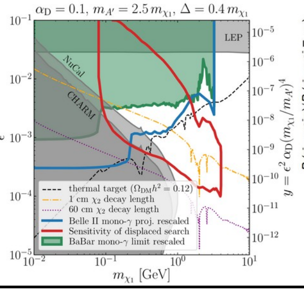
$e^+e^- \to \tau^+\tau^- S$, ($S \to l^+l^-$, $l=e, \mu$)



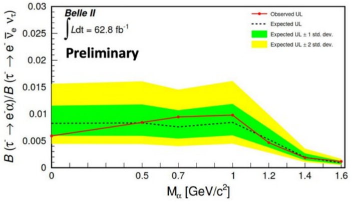
$B^\pm \to K^\pm h'$



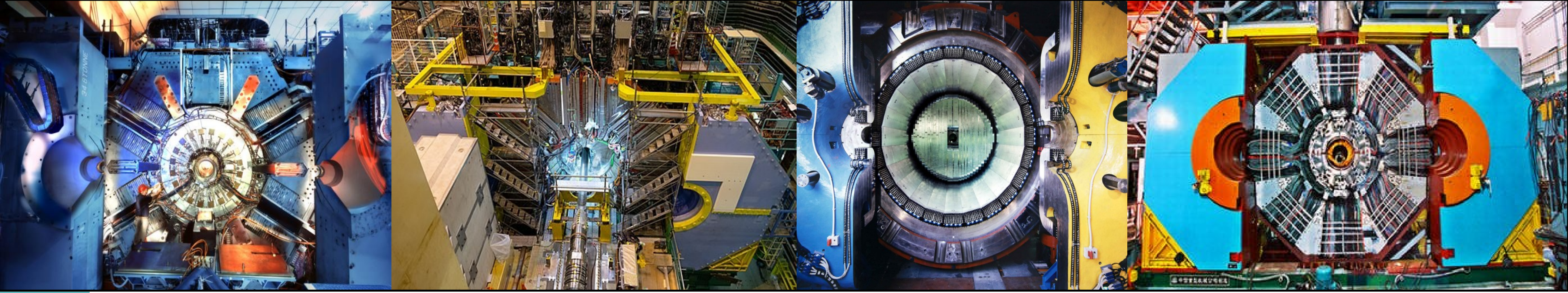
inelastic DM



$\tau \to l\alpha$



heavy QCD axion in $B^\pm \to K^\pm a$, ($a \to \eta\pi^+\pi^-$)



Thank you for the attention

Luigi Corona - University and INFN of Pisa
on behalf of the Belle II collaboration and including material by the KLOE, BaBar, Belle and BES III collaborations
luigi.corona@pi.infn.it

Backup slides

Topics presented in this talk

Z' boson

- $e^+e^- \to \mu^+\mu^- Z', (Z' \to invisible);$ >> I. Adachi et al, PhysRevLett.124.141801 >> **NEW**: update @ Belle II ICHEP 2022
- $e^+e^- \to \mu^+\mu^- Z', (Z' \to \mu^+\mu^-);$ >> J. P. Lees et al, PhysRevD.94.011102 (2016) >> T. Czank et al, PhysRevD.106.012003 (2022)
- $e^+e^- \to \mu^+\mu^- Z', S, ALP, (Z', S, ALP \to \tau^+\tau^-);$ >> **NEW** @ Belle II ICHEP 2022

dark photon A'

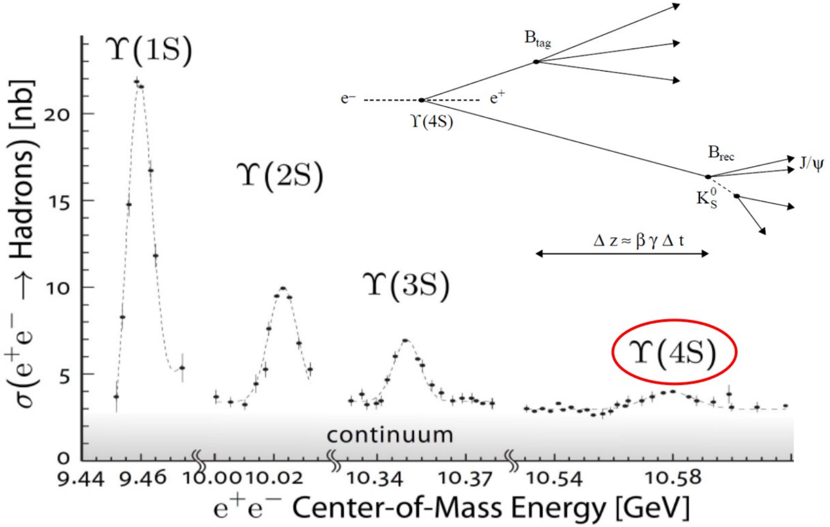
- $e^+e^- \to \gamma A', (A' \to l^+l^-/\pi^+\pi^-, l=e, \mu);$ >> J.P. Lees et al, Phys. Rev. Lett. 113, 201801 (2014) >> M. Ablikim et al, Physics Letters B 774, 252 (2017) >> A. Anastasi et al, Phys. Lett. B 750 (2015) 633-637 >> A. Anastasi et al, Phys. Lett. B 784 (2018) 336-341
- $J/\psi \to A'\,\eta/\eta', A' \to e^+e^-;$ >> M. Ablikim et al, PRD.99.012006 (2019) >> M. Ablikim et al, PRD.99.012013 (2019)
- $e^+e^- \to \gamma A', (A' \to invisible);$ >> Less et al, Phys. Rev. Lett. 119, 131804 (2017)

dark Higgs h'

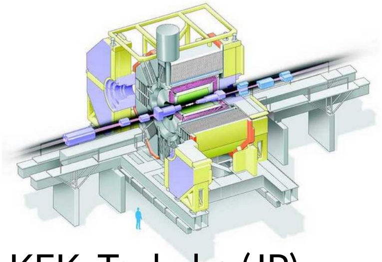
- $e^+e^- \to (A' \to l/\pi^+ l/\pi^-)\,(h' \to A'A'\,(A' \to l/\pi^+ l/\pi^-)), l=e, \mu;$ >> J. P. Lees et al PhysRevLett.108.211801 (2012) >> I. Jaegle et al, PhysRevLett.114.211801 (2015)
- $e^+e^- \to A'h', A' \to \mu^+\mu^-, h' \to invisible;$ >> A. Anastasi et al, Phys. Lett. B 747 (2015) 365-372 >> Belle II, arxiv.2207.00509

Experiments at B-factories

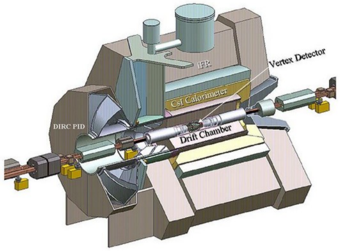
- Asymmetric e^+e^- colliders optimized for the production of B meson pairs, but also D mesons, τ leptons, …
- Collisions occur at Υ(nS) resonances
  - Mainly at Υ(4S): $\sqrt{s}$ = 10.58 GeV
    just above the production threshold of $B\bar{B}$
    $BR(\Upsilon(4S) \to B\bar{B}) > 96\%$
- Asymmetric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



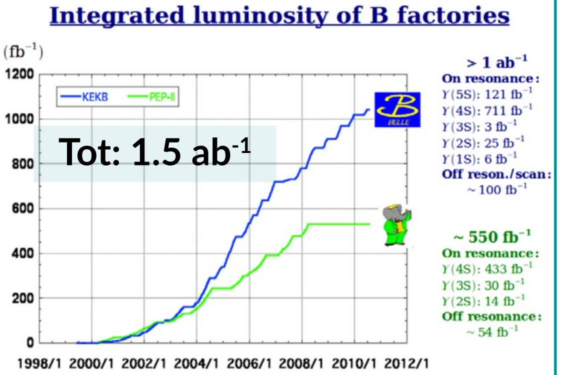
First generation of B-factories



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

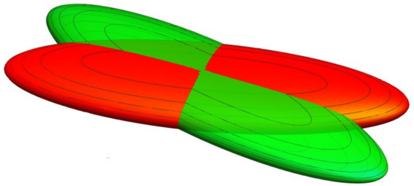


BABAR@PEP-II, SLAC (USA)
1999–2008, $\int L\,dt$ = 0.5 ab^{-1}

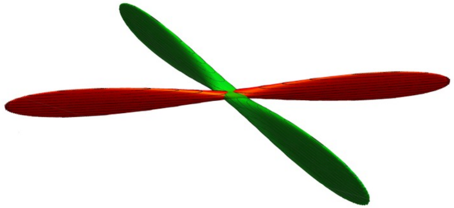


SuperKEKB

- 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



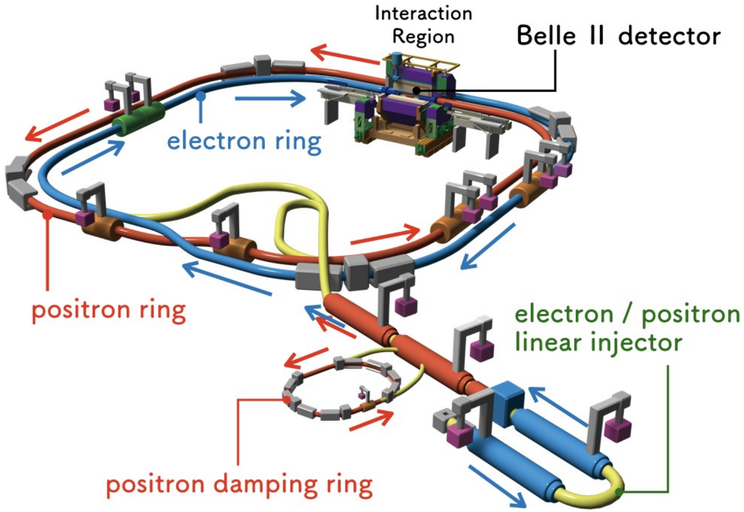
β_y^* ~ 1/20x
I ~ 1.5x

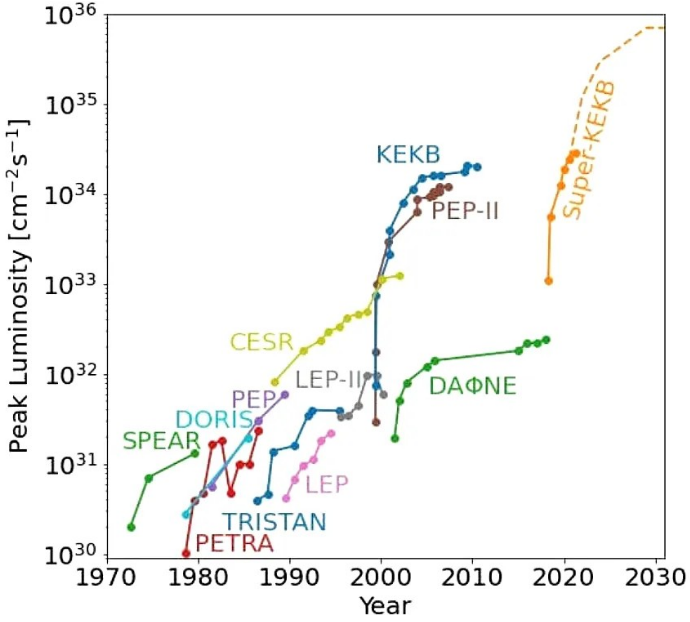
KEKB
- I(A) ~ 1.6/1.2
- β_y^*(mm) ~ 5.9/5.9

30x peak luminosity

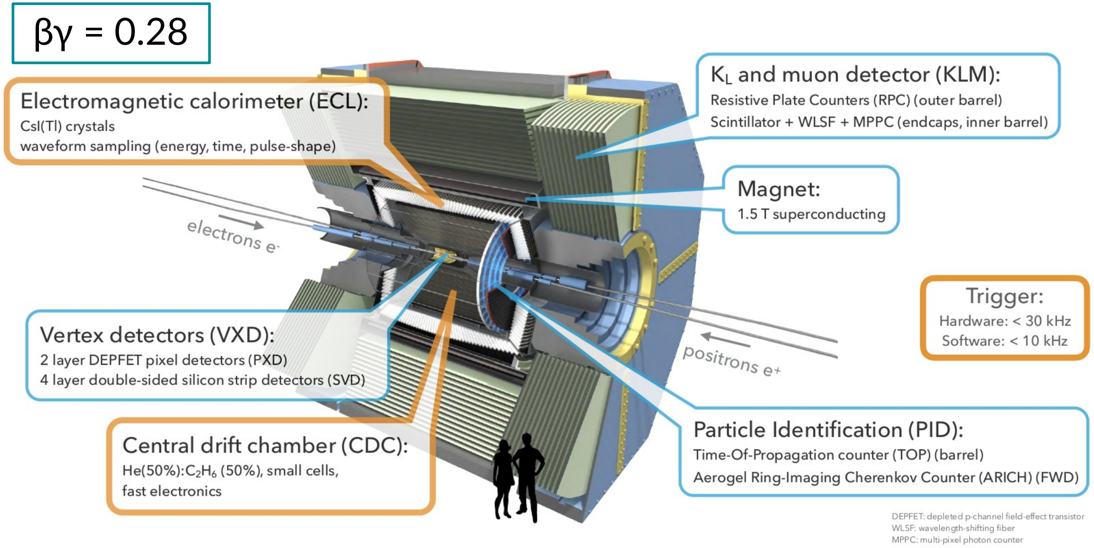
SuperKEKB
- I(A) ~ 2.9/2.0
- β_y^*(mm) ~ 0.3/0.3

- 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}



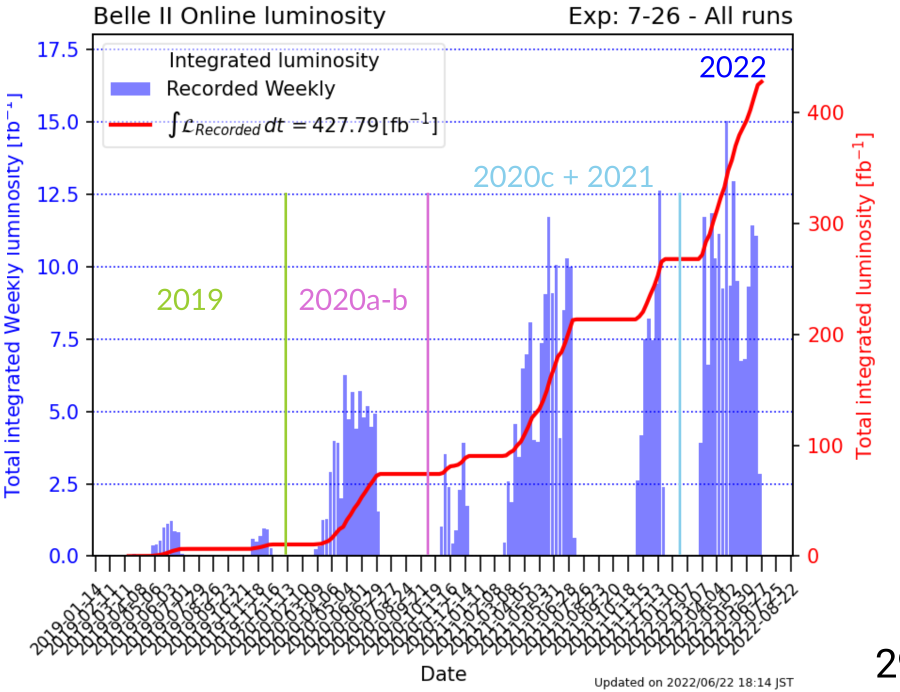


Belle II at SuperKEKB



- Major upgrade of Belle@KEKB → better resolution, PID and capability to cope with higher background
- Covers more than 90% of the total solid angle

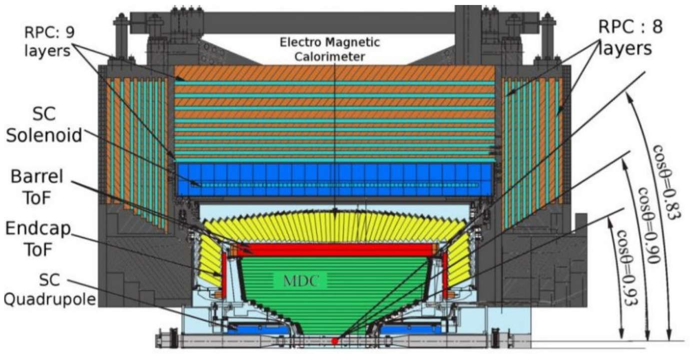
- First collisions during commissioning run on April 26th 2018
  - 0.5 fb^{-1} collected in 2018
- First collisions with the full detector on March 2019
  - ~ 430 fb^{-1} collected in 3 years of data taking
- Target integrated luminosity of the Belle II experiment: **50 ab^{-1}** (x30 Belle + BaBar)



BESIII and KLOE experiments

- Experiments at symmetric e^+e^- colliders running at tau-charm and ϕ(1019) mass regions, respectively
- **Physics objectives**: study the light hadron spectroscopy and search for new physics phenomena [1,2]

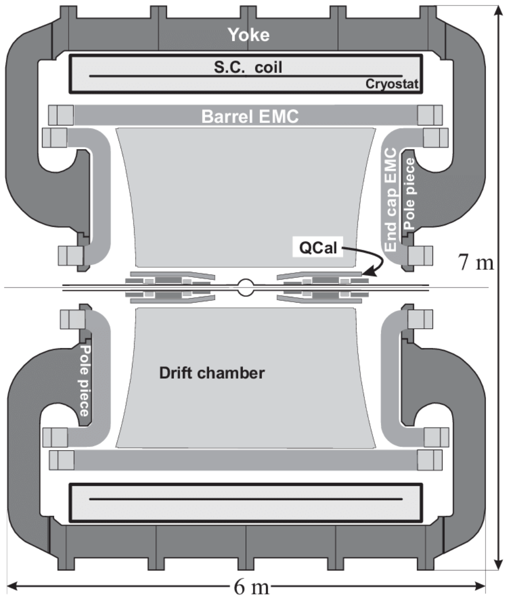
***BESIII* experiment** See Gianluigi's talk!



- BESIII (from 2009)
  - Dataset:
    - collected large data samples at several energy points between 2 – 4.95 GeV

***KLOE* experiment**

- KLOE (2001 – 2006)
  - Dataset:
    - 2.5 fb^{-1} data at ϕ peak
    - 250 pb^{-1} off-peak
- KLOE-2 (2014 – 2018)
  - detector upgrade
  - extension of the KLOE physics program
  - Dataset:
    - 5.5 fb^{-1} data at ϕ peak

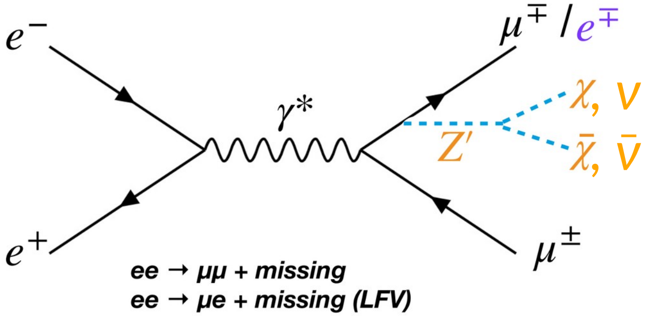


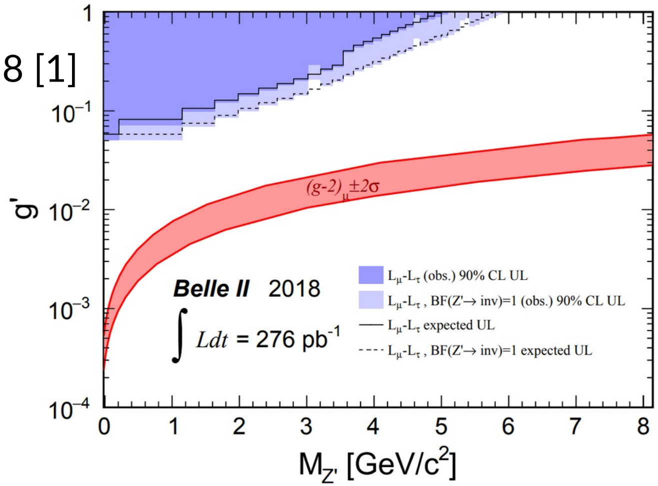
[1] CZ. Yuan et al, Nat Rev Phys 1, 480–494 (2019)
[2] G. Amelino-Camelia et al, Eur. Phys. J. C 68, 619–681 (2010)

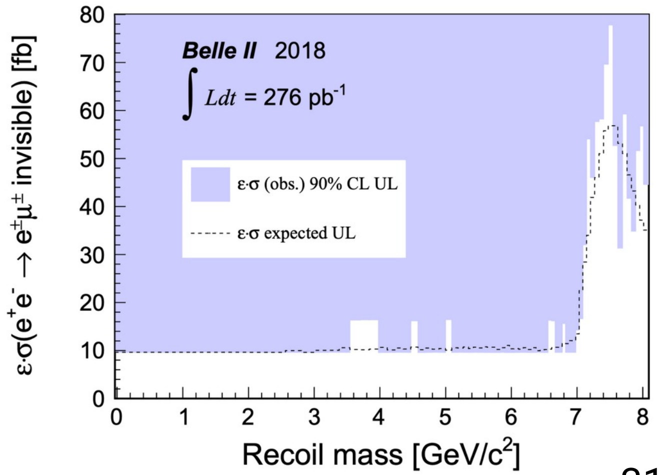
Z’ → invisible at Belle II

[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

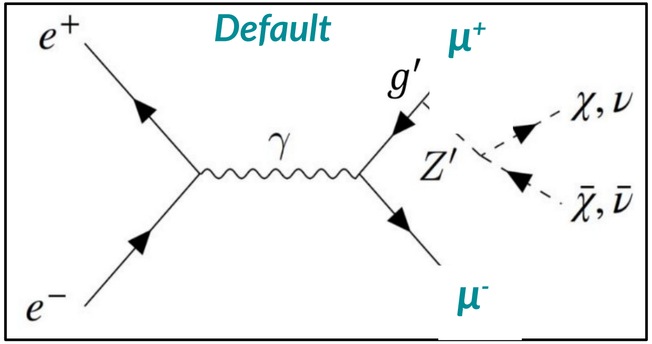




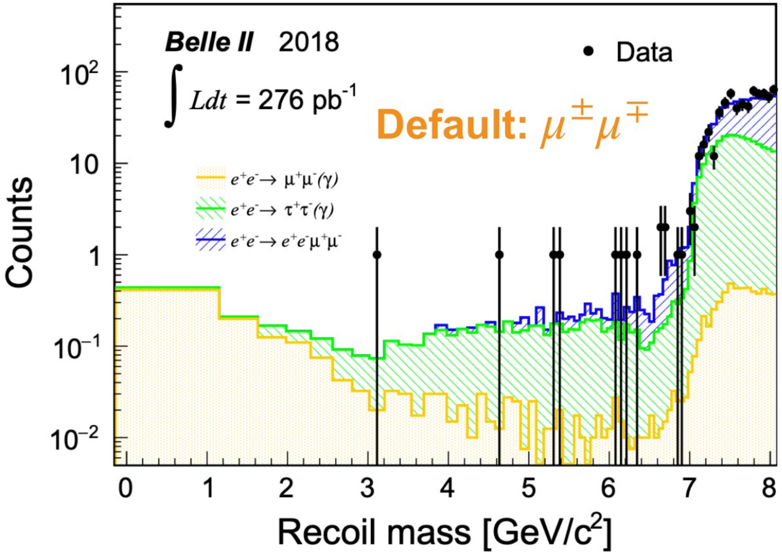


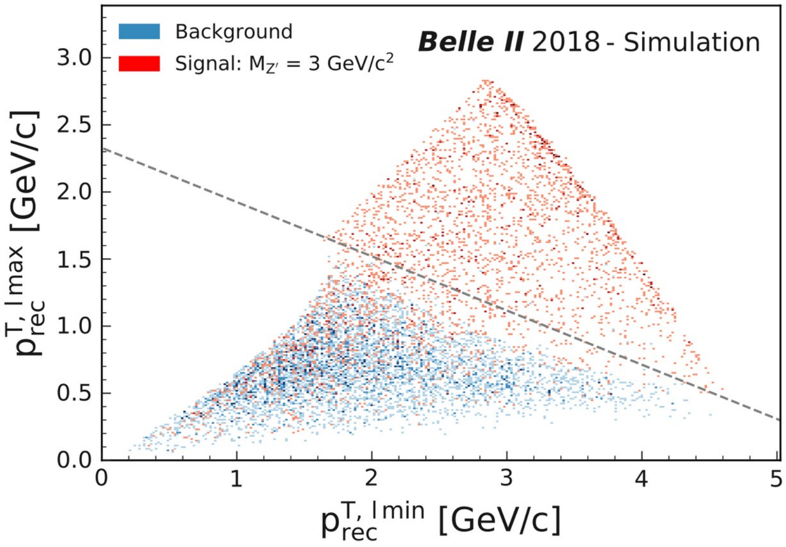
- Search for a narrow peak in the recoil mass distribution against $\mu^+\mu^-$ (LFV: $\mu^\pm e^\mp$)
- 90% CL upper limits on the coupling constant g' ~ O(5x10^{-2})
- First model independent limits on $\varepsilon \cdot \sigma(e^+e^- \to e^\pm\mu^\mp$ + invisible) down to 10 fb

$Z' \rightarrow$ invisible at Belle II



- *$e^+e^- \rightarrow \mu^+\mu^-$ + Missing Energy*
- Main background components:
  - $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$: 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
- 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**

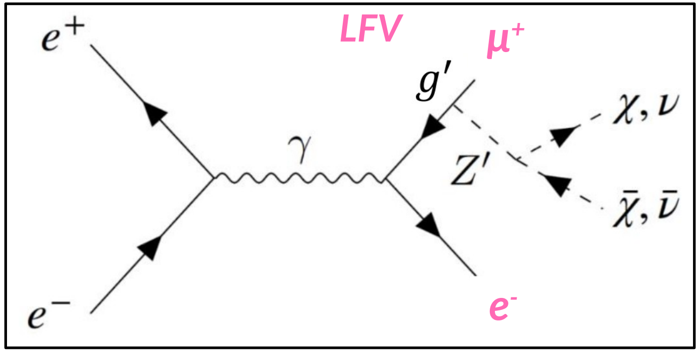


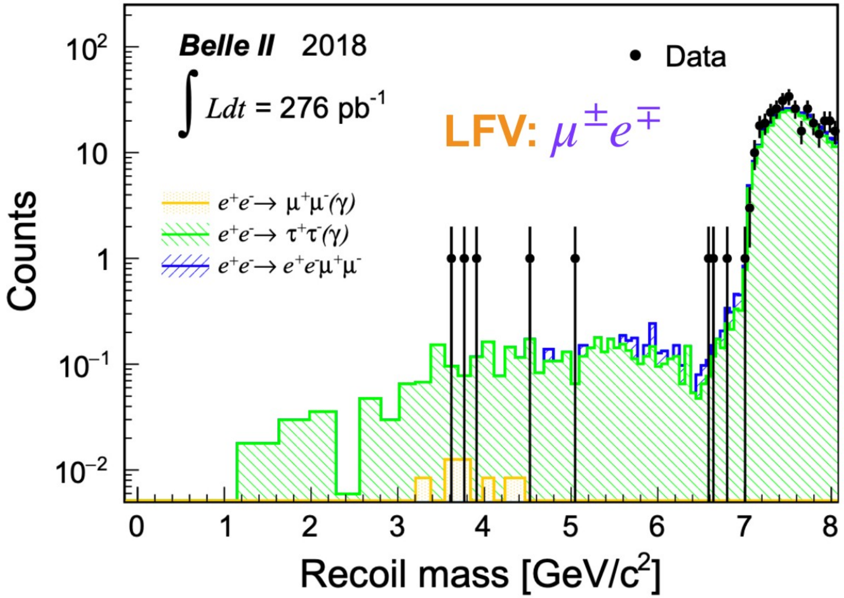


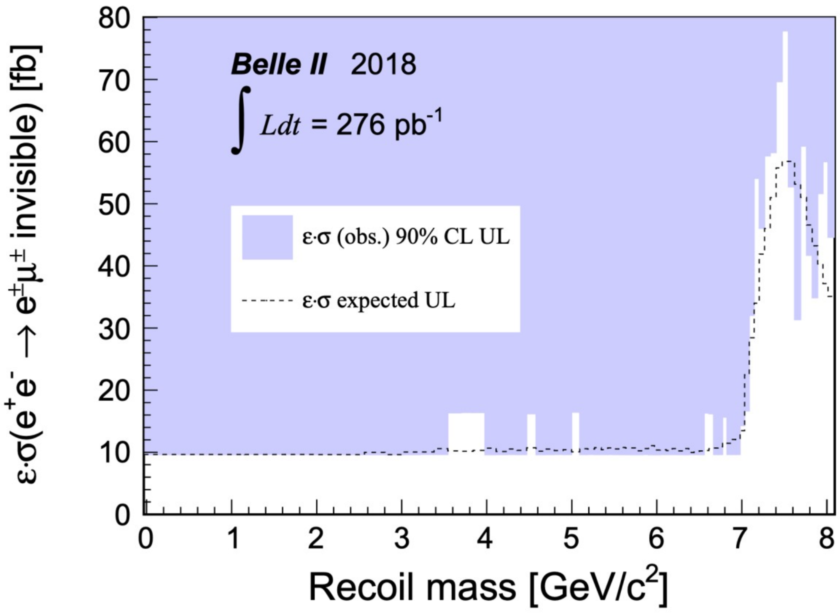
[Dark sector searches at Belle II and other e+e- colliders](). IPA2022, Vienna.

Z’ → invisible (LFV) at Belle II

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





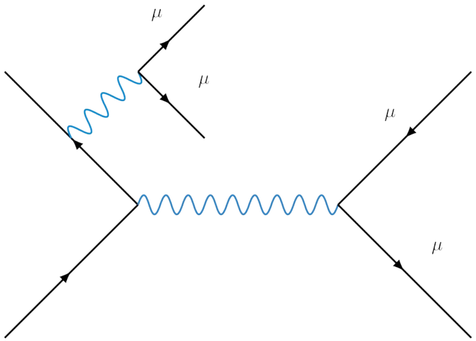


$Z' \to \mu\mu$ at Belle II

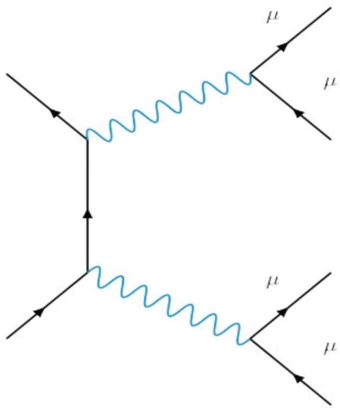
- Data set: ~ 178 fb^{-1} (2020 - 2021). Ongoing analysis, will be finalized by beginning of 2023
- Main background components from QED processes: $\mu^+\mu^-\mu^+\mu^-$, ISR, double photon conversion, combinatorial as well as peaking background
- Event selection:
  - 3-track OR single-muon trigger
  - 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 $M(\mu\mu)$
- Signal yield from a fit scan over $M(\mu\mu)$ above floating background

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

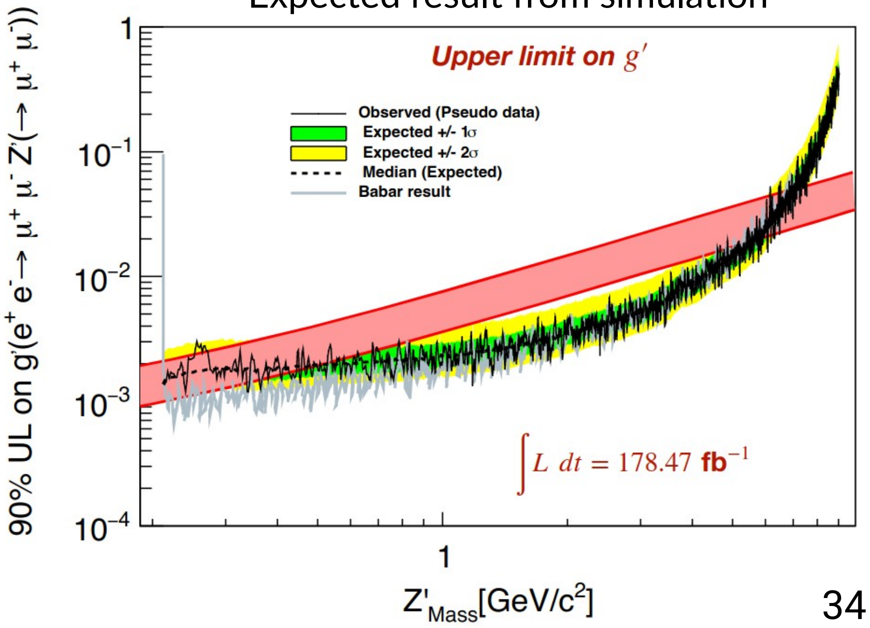
ISR



Double-photon conversion



Expected result from simulation



Z’, S, ALP → ττ at Belle II

Data validation

- Control sample: “$\pi^+\pi^-\tau^+\tau^-$” (2 identified **pion tracks** (tagging pions, rather than 2 muons) + 2 additional tracks (e, μ, h))
  - no sensitivity to signal
  - data/MC comparison for a wide region of the recoil mass distribution

M($\pi\pi$) > 2 GeV/c^2 **NOT** applied

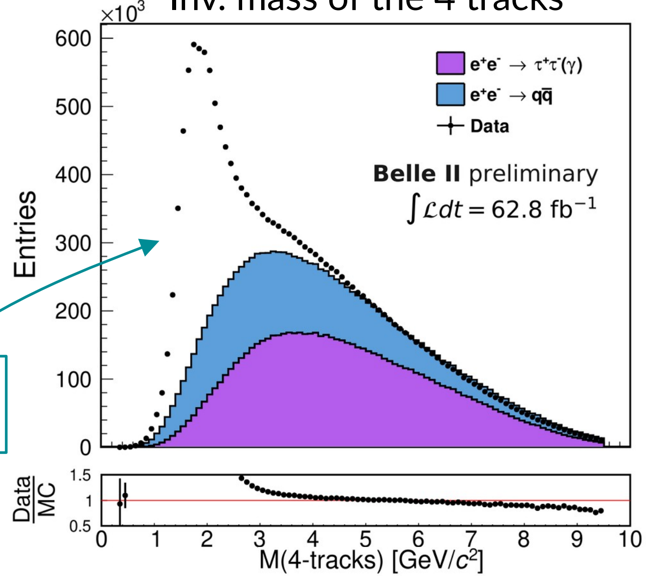
- Main contribution from $e^+ e^- \to \tau^+ \tau^- (\gamma)$ and $e^+ e^- \to q \bar{q}$ (both generated with ISR)

- M($\pi\pi$) > 2 GeV/c^2 (for tagging pions) to remove the part of the mass spectrum where there are missing components in MC, like hadron components at low invariant mass of 4-tracks
  - two-photon $e^+ e^- \to e^+ e^- X_{had}$, with hadronic X_{had} up to 4 tracks
  - already observed at Belle II

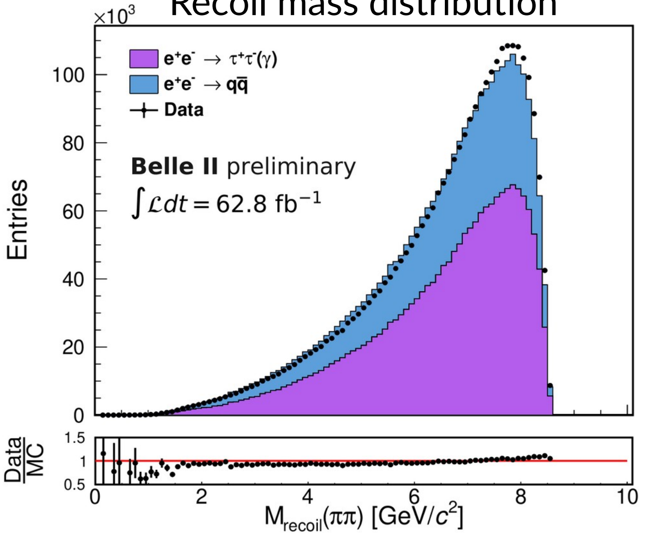
  → Mass dependent data/MC ratio discrepancy ~15%

- **The background is measured directly from data by fitting.** Data/MC comparison is useful to better understand data

Inv. mass of the 4 tracks



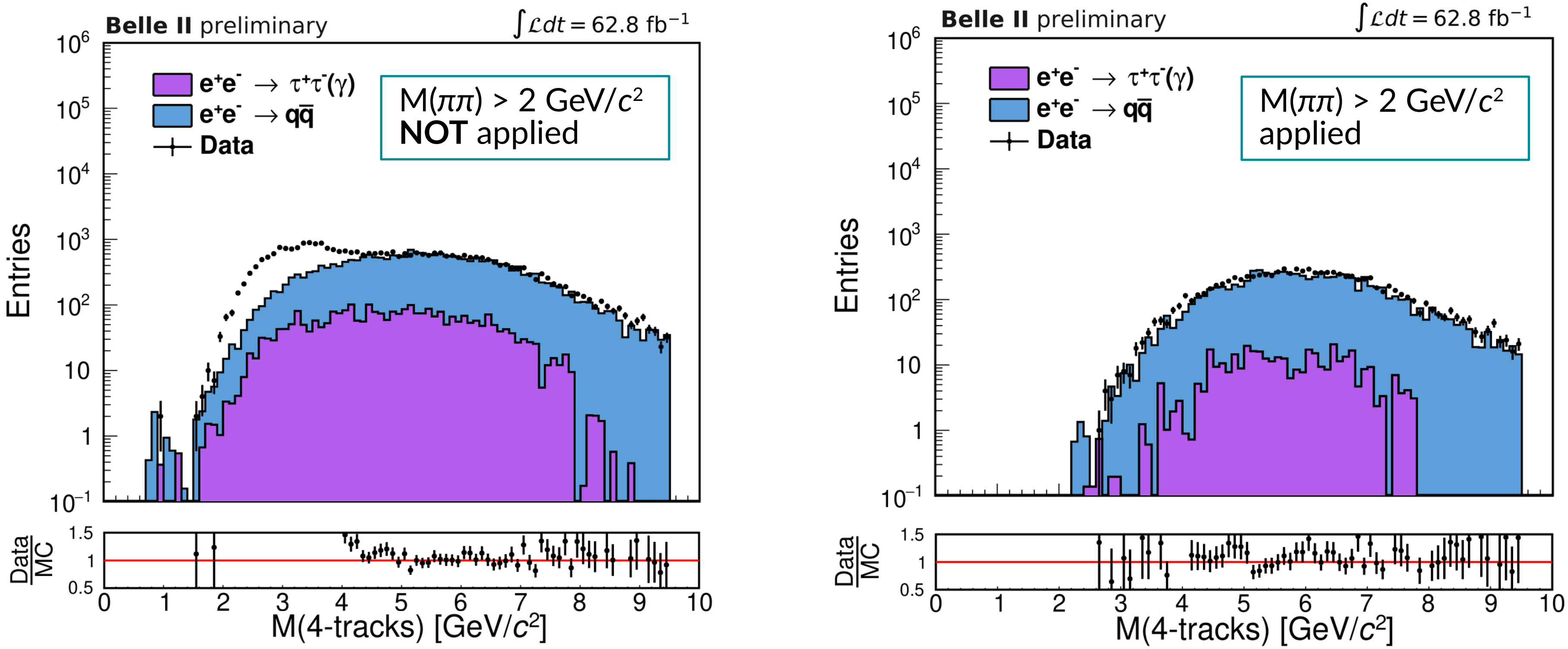
Recoil mass distribution



Z’, S, ALP → ττ at Belle II

Data validation: after MLP selection

- Control sample: “$\pi^+\pi^-\tau^+\tau^-$”: M(4-tracks) distribution (invariant mass of the 4 tracks)
- Two photon hadronic processes not fully removed by MLP selection → source of discrepancy
  - removing it with $M(\pi\pi) > 2$ GeV/c^2 data/MC agreement is reasonable



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

Data validation: MLP efficiency

- Comparison data/MC of the MLP background efficiency with control sample control sample when $M(\pi\pi) > 2$ GeV/c^2 - check that MLP selection is reliable

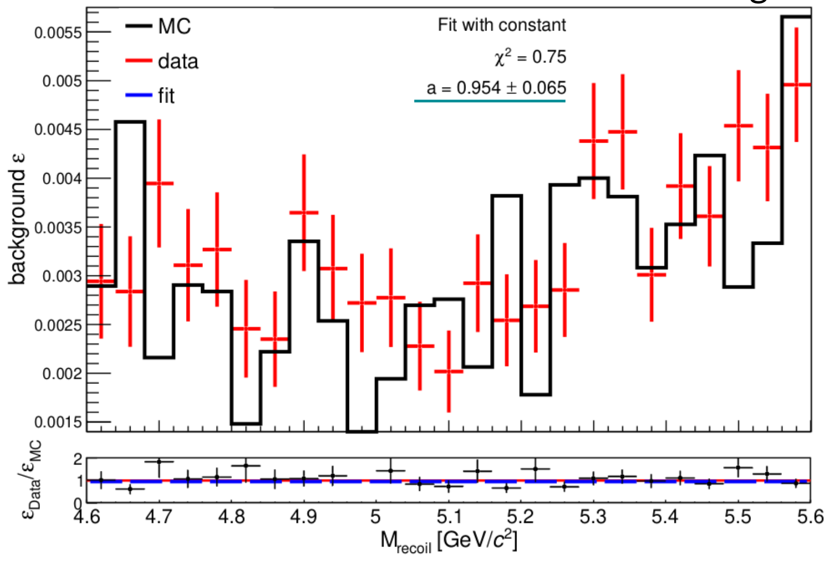
- With these comparisons we study the data/MC agreement of the **signal-like background component**, to evaluate the signal systematics

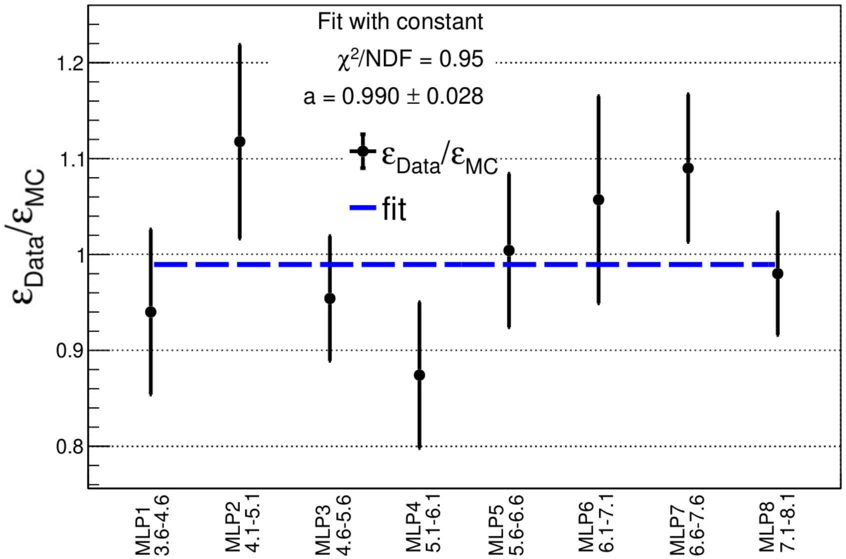
- Systematic of 2.8%

MLP efficiency:

- fraction of surviving events after applying the MLP selection
- more reliable than the number of events surviving the MLP selection

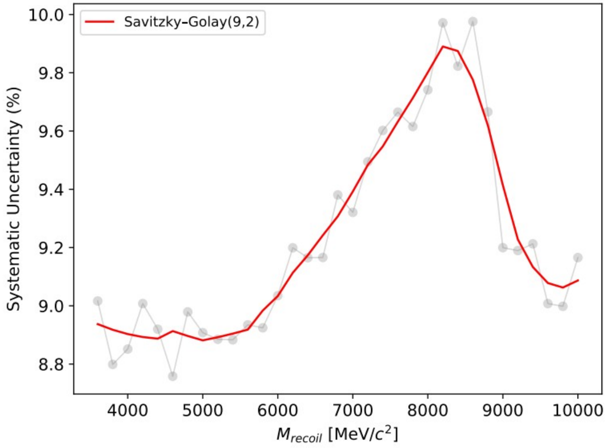
MLP-range3





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

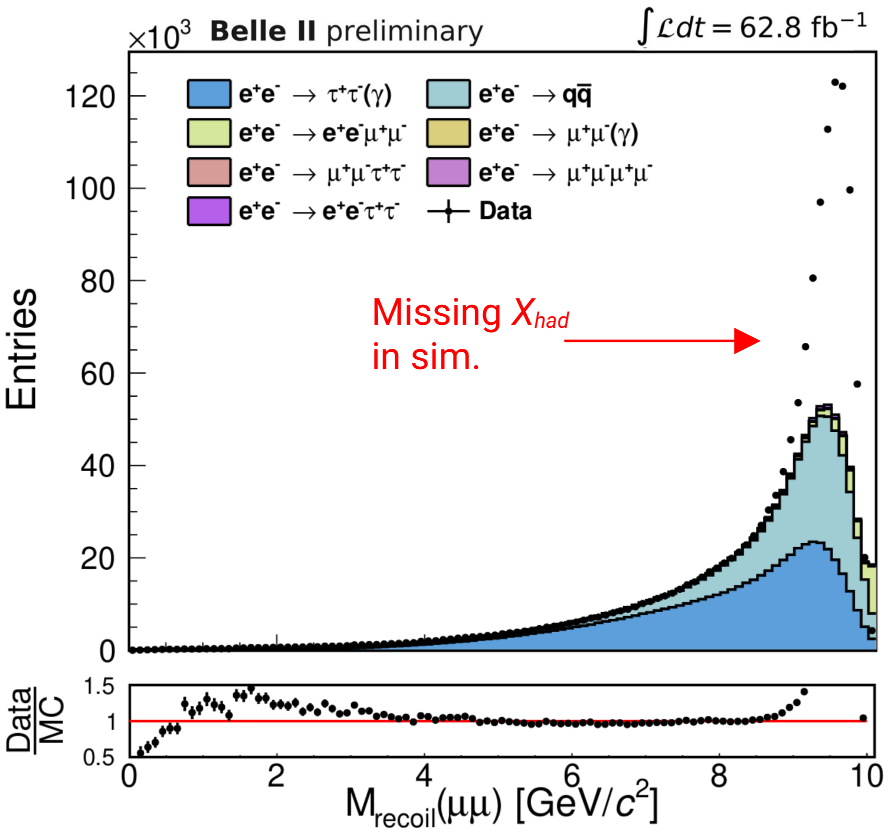
Luminosity from the difference in the measured offline luminosity on Bhabha and γγ events

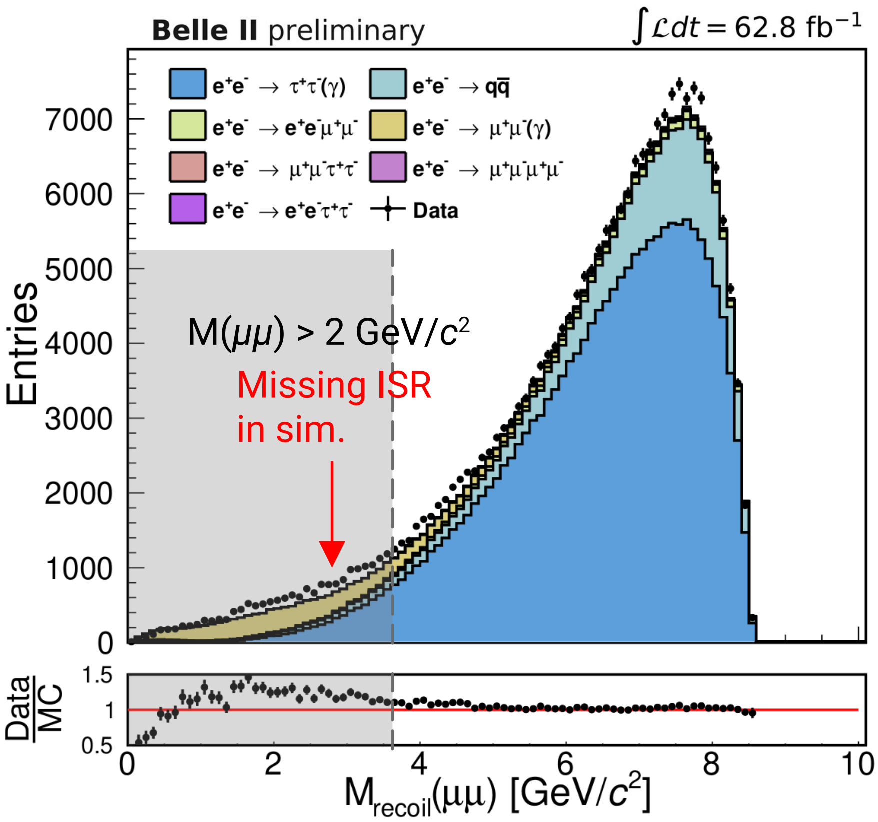
Z', S, $ALP \to \tau\tau$ at Belle II

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



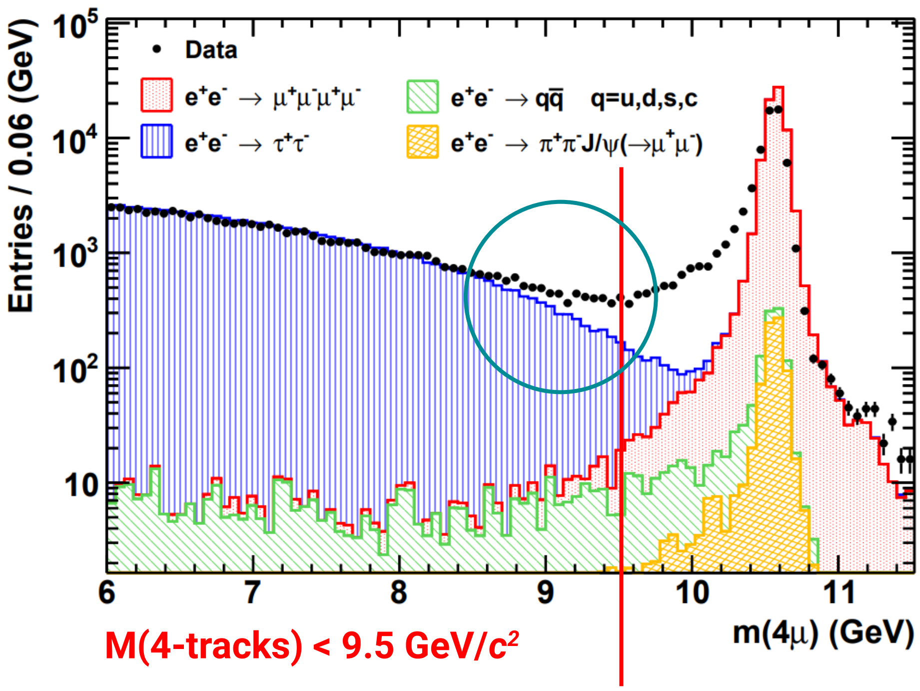


Z', S, ALP → *ττ* at Belle II

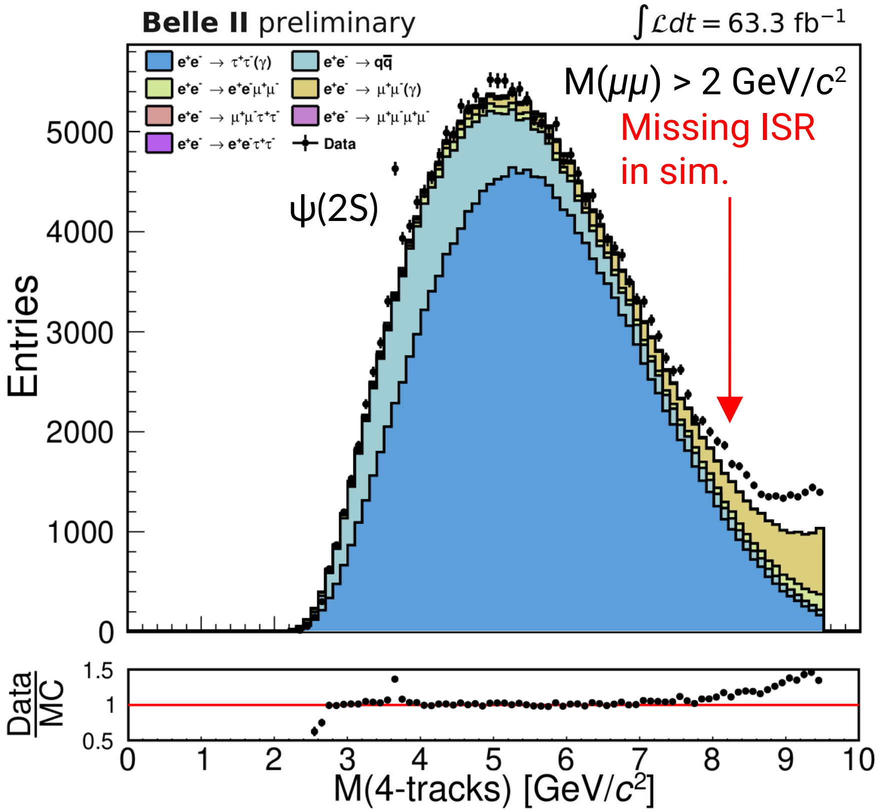
Full data unboxing

M(*μμ*) > 2 GeV/*c*² for the tagging muons

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



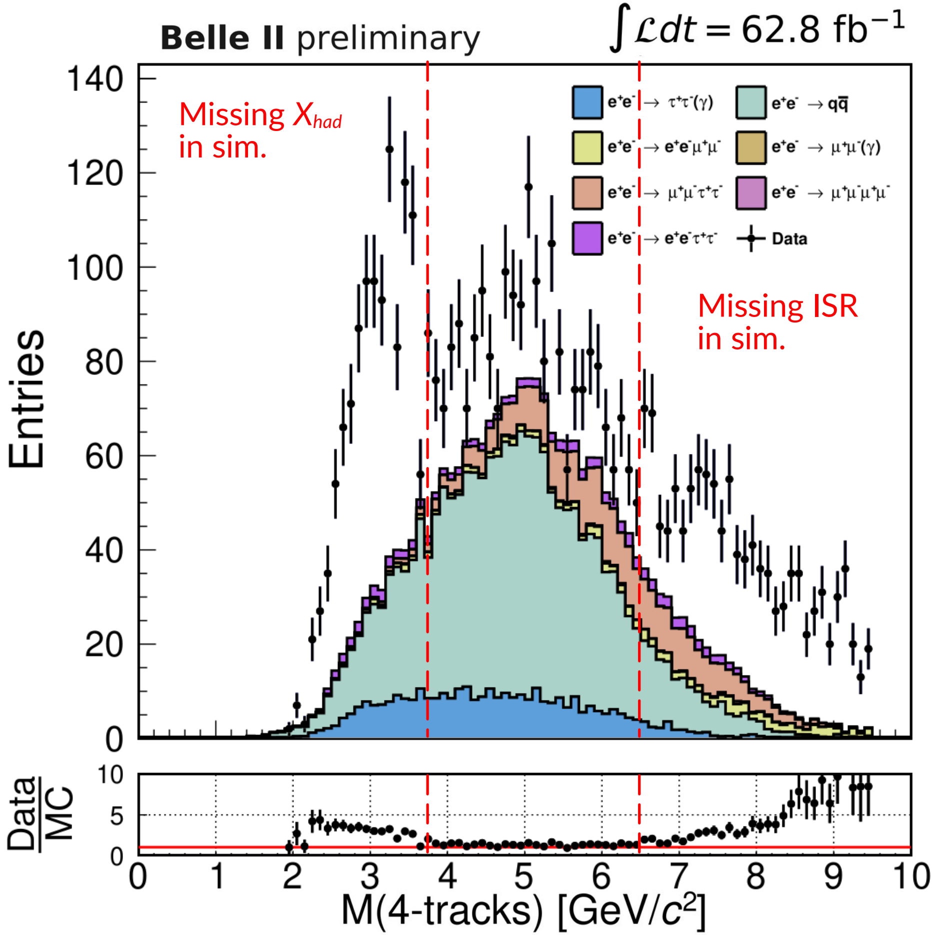
Z' → *μμ* at BaBar
J. P. Lees et al., [PhysRevD.94.011102]



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**

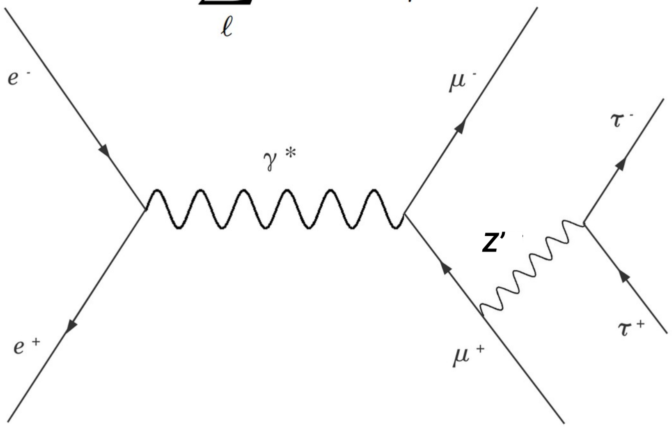


Z' → ττ at Belle II

$L_\mu - L_\tau$ model

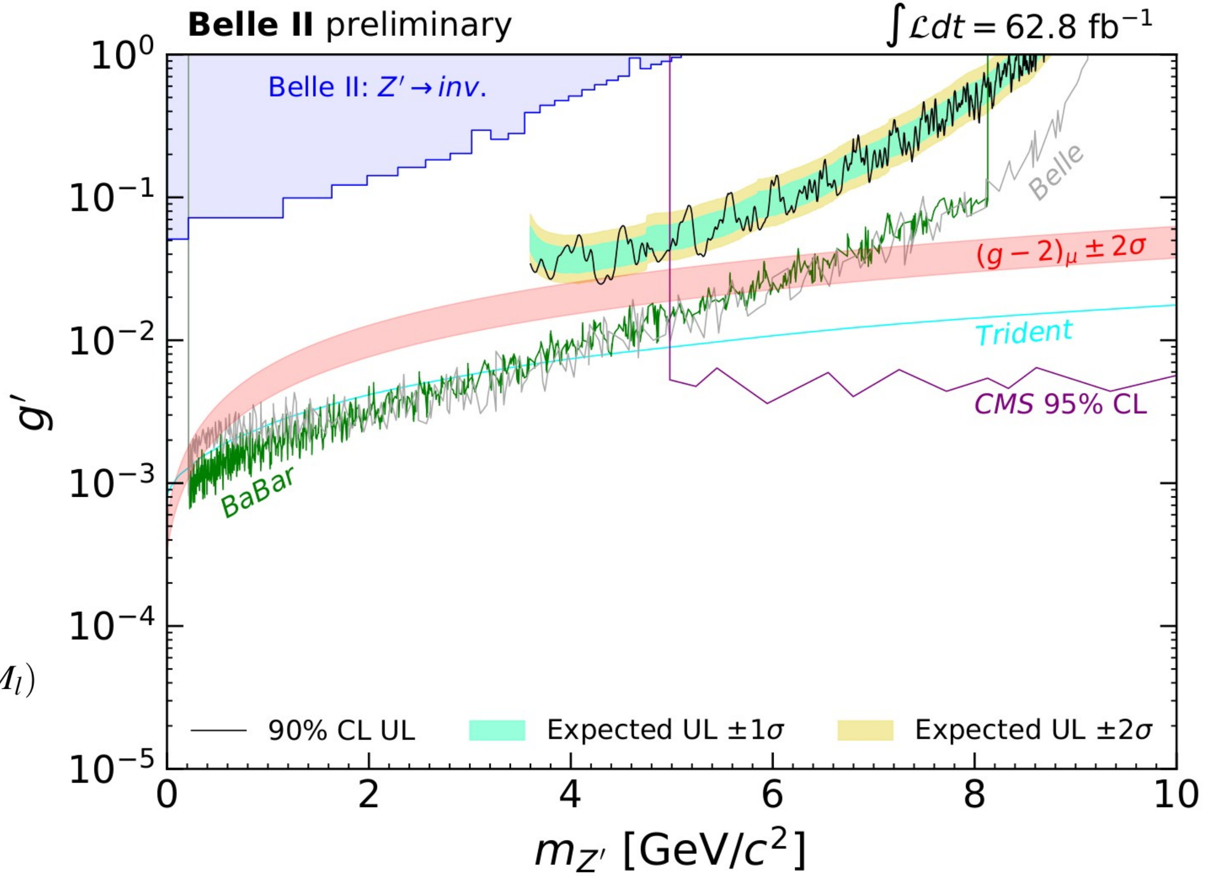
[1] Shuve et al., Phys. Rev. D 89 , 113004 (2014)
[2] Altmannshofer et al., JHEP 106 (2016)
[3] D. Curtin et al., JHEP 02 (2015) 157

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



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

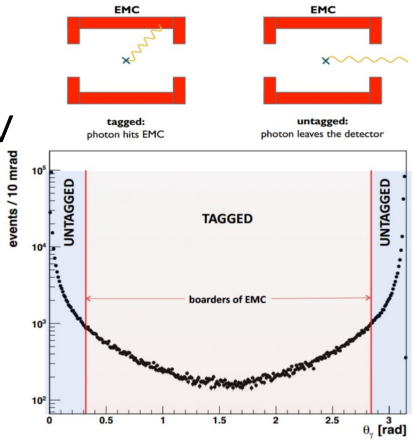
$$\Gamma_{Z'\to\nu\bar{\nu}} = \frac{(g')^2 M_{Z'}}{24\pi}$$



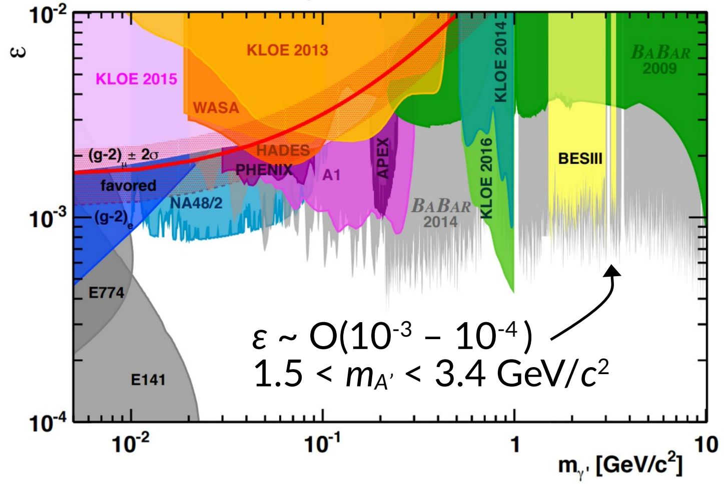
Visible dark photon at BESIII

$e^+e^- \to \gamma_{ISR} A', A' \to l^+l^-$ ($l = e, \mu$)

- 2.93 fb^{-1} @ $\sqrt{s}$ = 3.773 GeV
- Untagged photon method to increase statistics
- Search for a narrow peak in m_{l+l-} spectrum
- 90% CL UL on ε

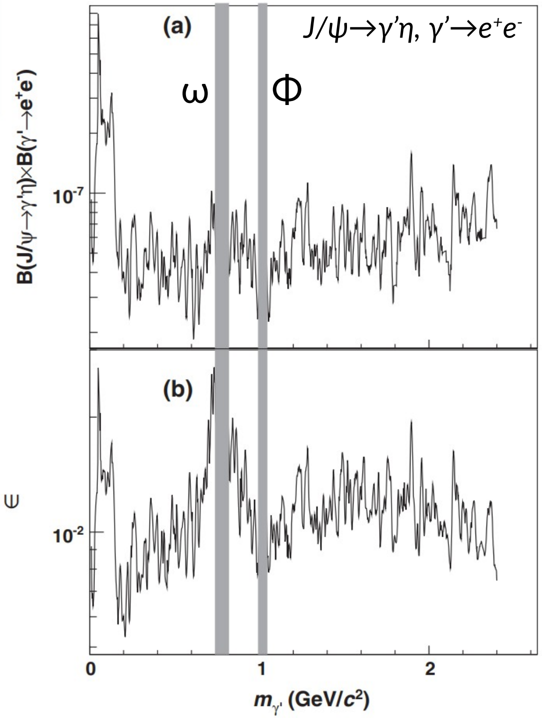


M. Ablikim et al, Physics Letters B 774, 252 (2017)

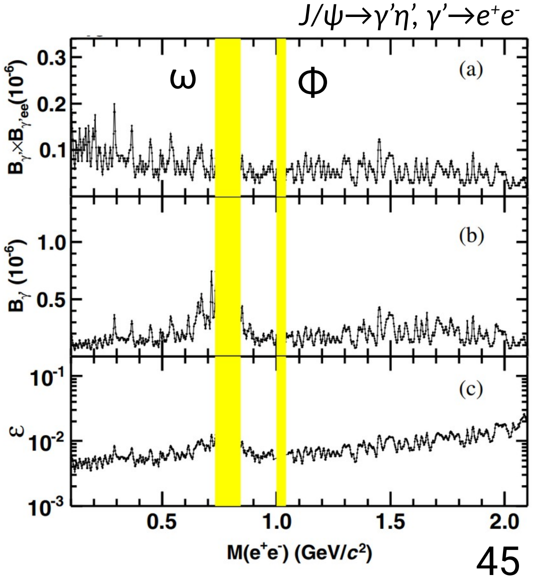


$J/\psi \to A'\,\eta/\eta', A' \to e^+e^-$ [1,2]

- First search for dark photon via electromagnetic Dalitz decays with 1.3 billion J/ψ
- 90% CL UL on $\varepsilon \sim O(10^{-3} - 10^{-2})$ for $0.1 < m_{\gamma'} < 2.1$ GeV/c^2



[1] M. Ablikim et al, PRD.99.012006 (2019)
[2] M. Ablikim et al, PRD.99.012013 (2019)

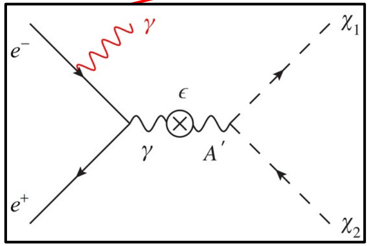


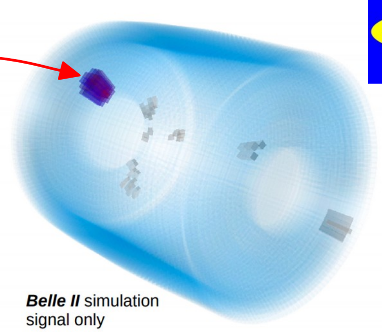
Invisible dark photon

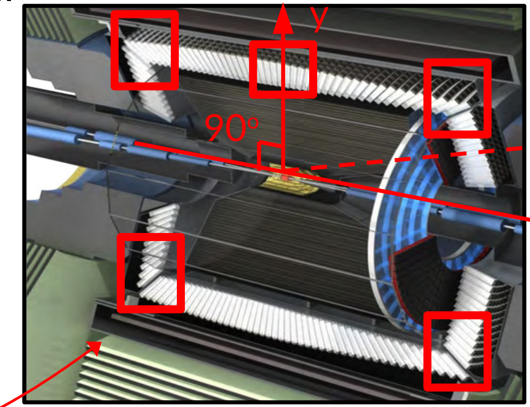
- Single photon search
- Single photon in the final state needs a single photon trigger, present in the full Belle II dataset
- Signature: peak in the energy of the photon depending on the $M_{A'}$

  → $$E_\gamma = \frac{s - M^2_{A'}}{2\sqrt{s}}$$

- Main background components:
  - $e^+e^- \to e^+e^-(\gamma)$: electrons out of acceptance
  - $e^+e^- \to \gamma\gamma(\gamma)$: photons lost in e.m. calorimeter inefficient regions (gaps)
  - cosmic rays
- Event selection criteria based on E_γ vs θ_γ distribution







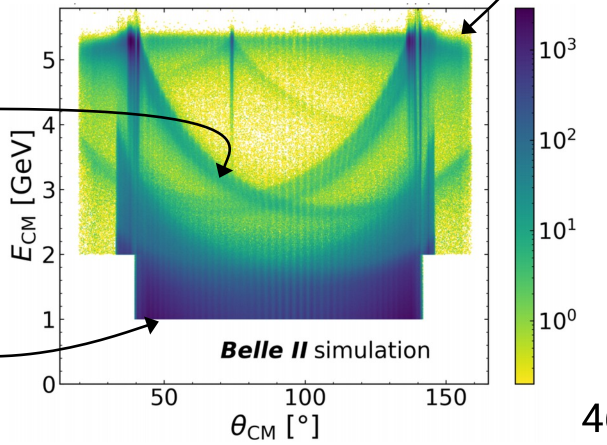
θ Boost direction

γγ, with an undetected photon

Background simulation assuming 20/fb

γγγ, with two undetected photons

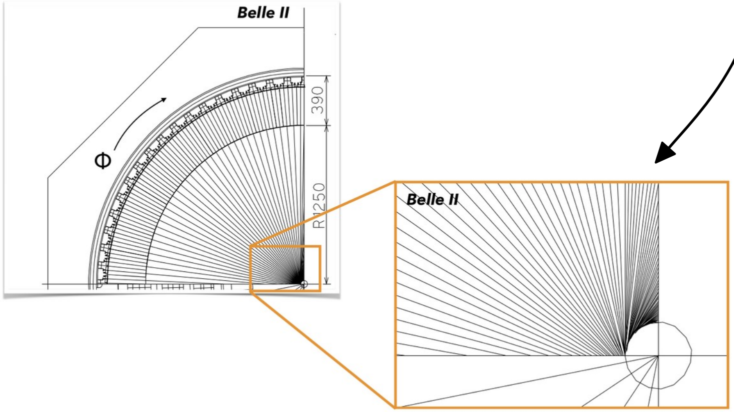
$e^+e^-\gamma$, with both e^+e^- out of detector acceptance

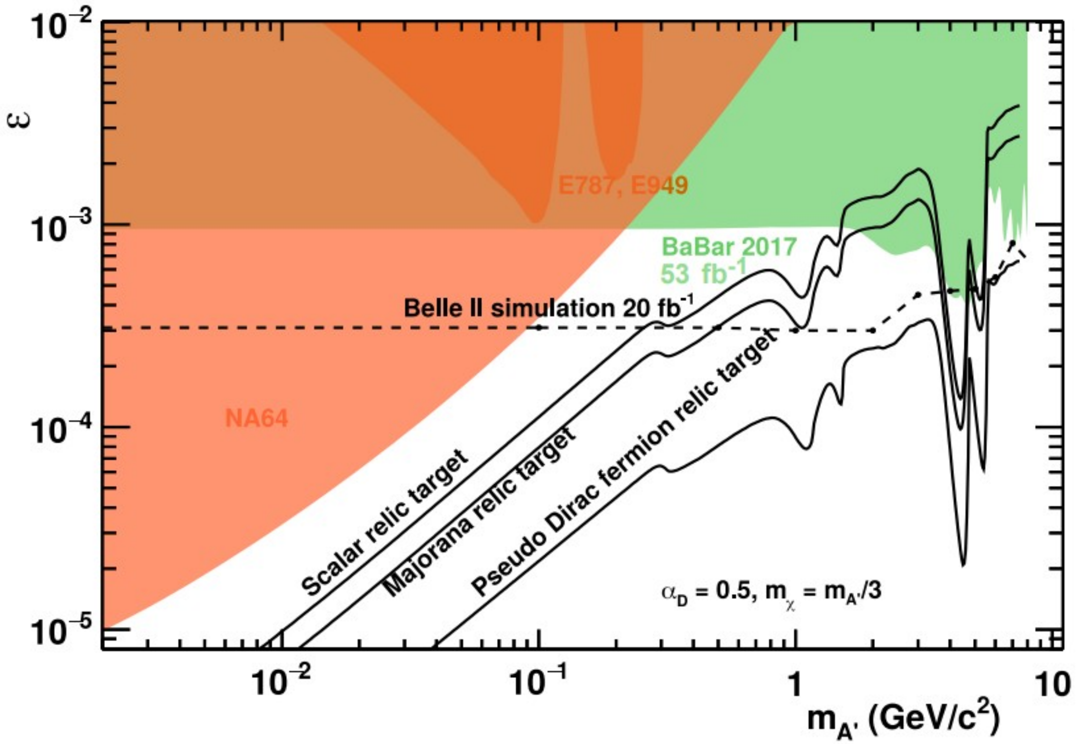


Expected 90% CL exclusion on ε

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

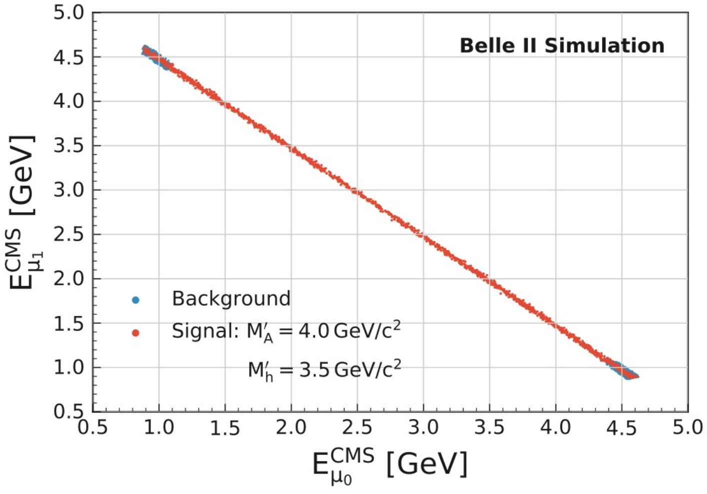
- ***$e^+e^- \to \gamma_{ISR}A'$ ($A' \to$ inv.)***: very promising @ Belle II, even with low statistics [1]
- Expected to perform better than BaBar [2]:
  - smaller boost:
    larger acceptance
  - **muon detector veto**:
    reject events with a photon undetected in the calorimeter (efficiency currently under study)
  - no e.m calorimeter cracks in pointing to the interaction region: **better calorimeter hermeticity**

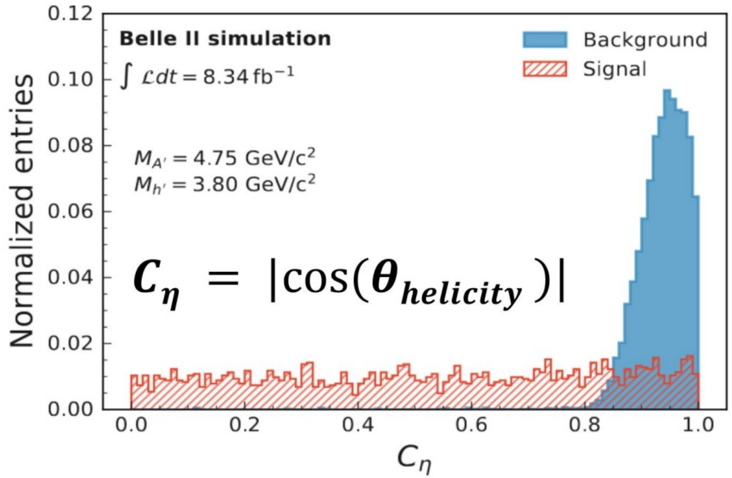




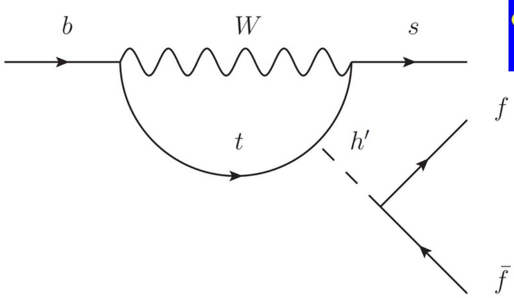
Dark higgstrahlung at Belle II

- *$e^+e^- \rightarrow A'h', A' \rightarrow \mu\mu, h' \rightarrow$ invisible*
  - Signature: 2D peak in recoil vs dimuon mass
- Analysis strategy:
  - scan+count in elliptical mass windows
    (9k overlapping ellipses)
- Background from QED:
  - $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$
  - $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$
  - $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$
- Background suppression based on helicity angle
  (muon energy asymmetry)



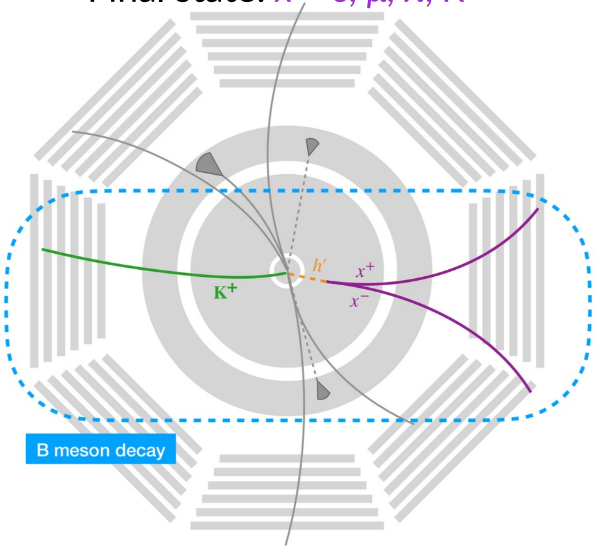


Highlights on $B \to Kh'$

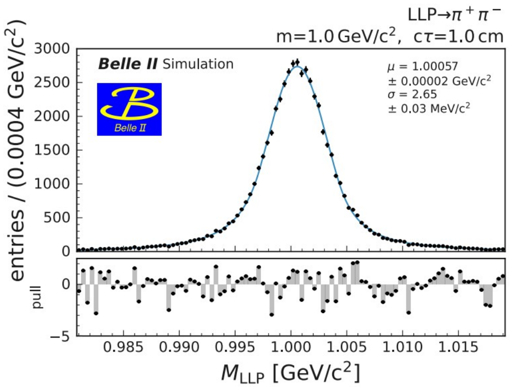


- Long-lived h' produced in $b \to s$ transition
- h' mixes with the Standard Model Higgs boson with angle θ
- Search for a bump in the invariant mass of tracks coming from a displaced vertex
- Event selection is very clean, but not quite at zero background
- LHCb and Belle II complementary

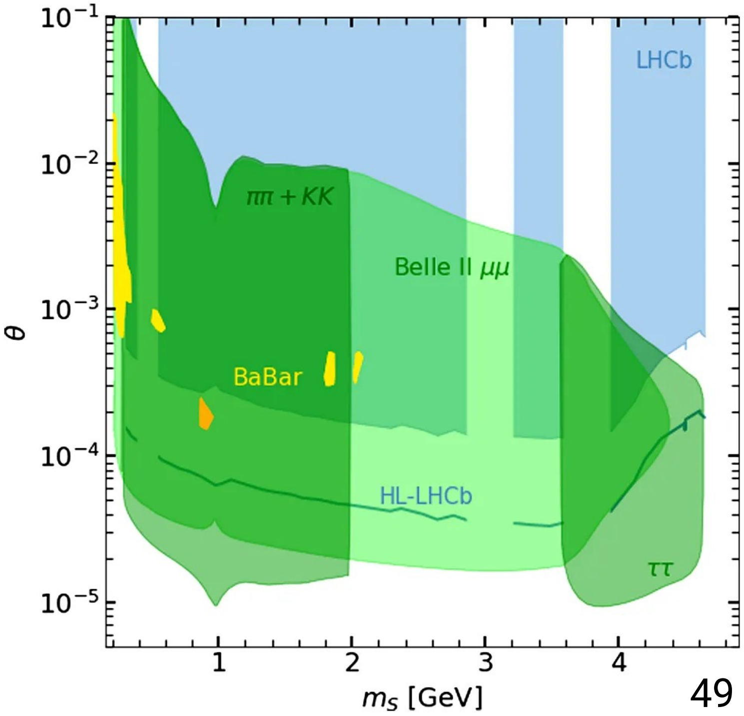
Final state: $x = e, \mu, \pi, K$



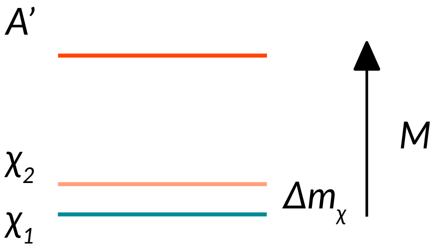
- Exclusion regions expected with 50 ab^{-1} at Belle II in green
- Analysis timescale ~ beginning of 2023



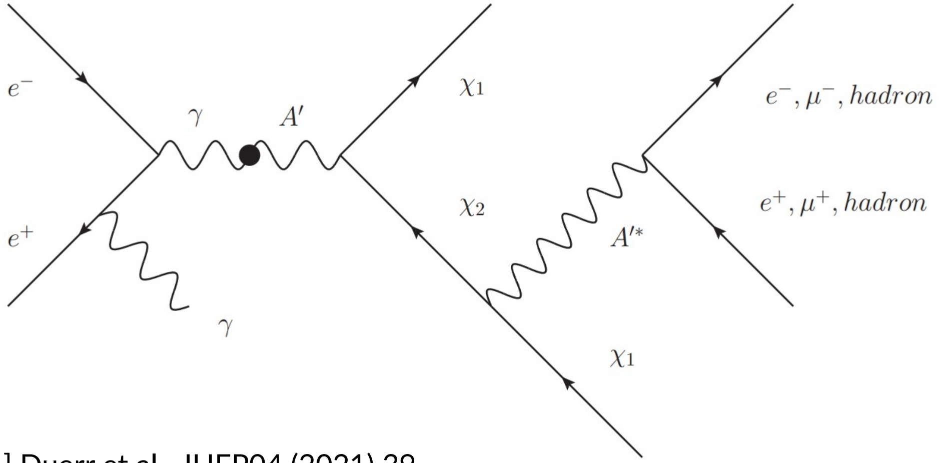
Filimonova et al., [JHEP04 (2021) 39]

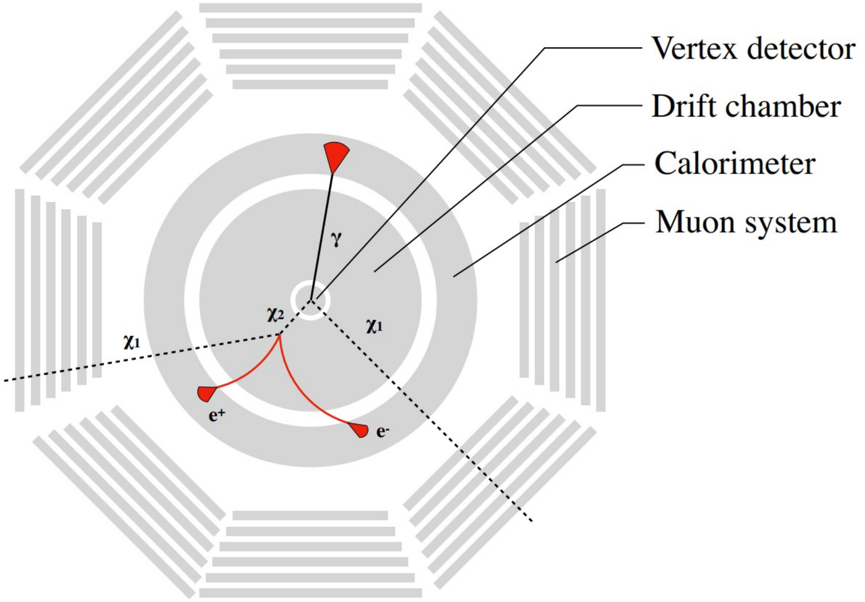


Inelastic dark matter (iDM) at Belle II



- 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





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

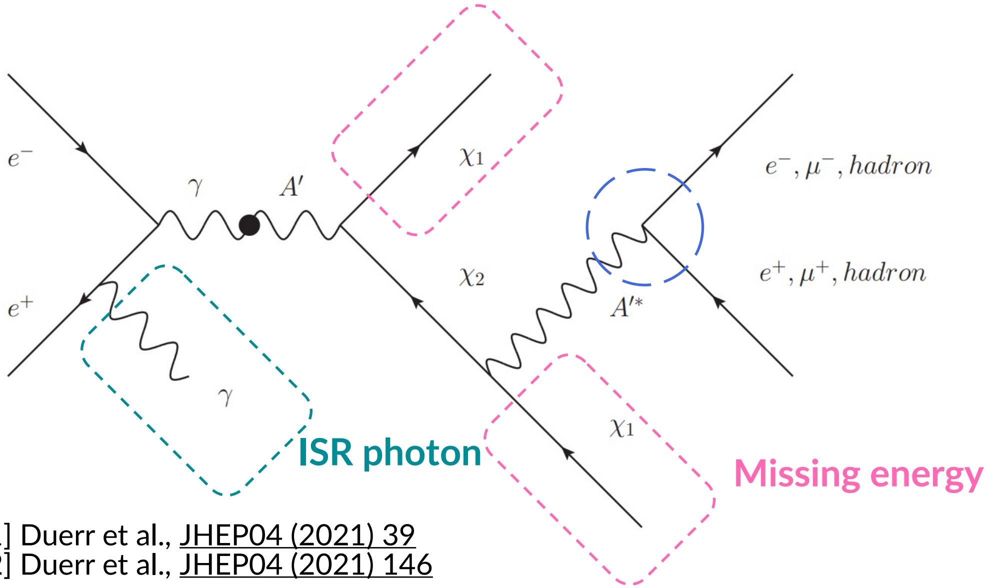
iDM at Belle II

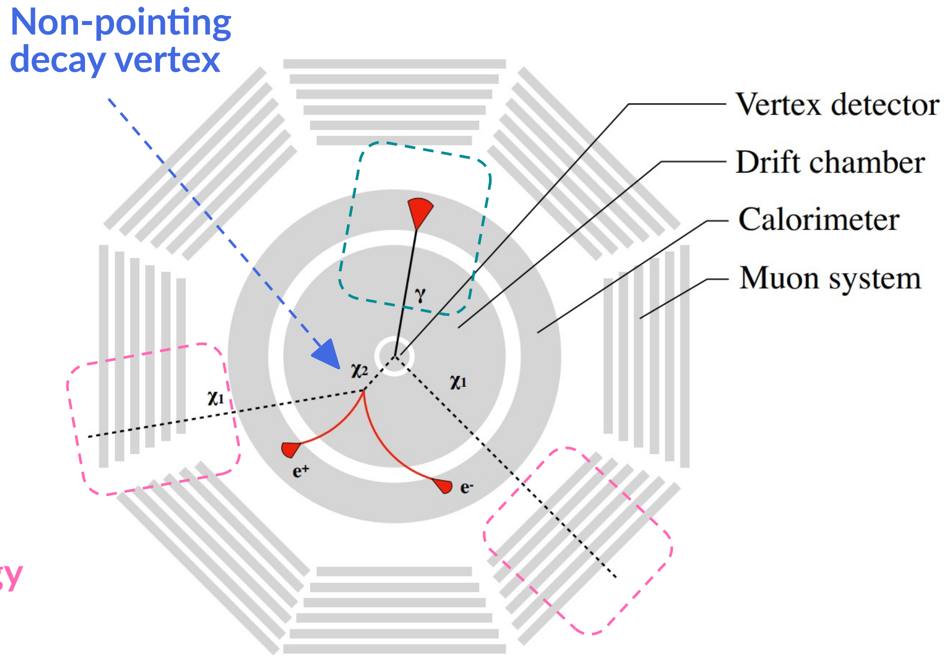
Signal = peak in $\boxed{E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}}$ + non-pointing displaced vertex + missing energy

- 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 $A' \rightarrow \chi_1 \chi_2$ is favored

- Mandatory to implement new trigger for displaced vertex detection

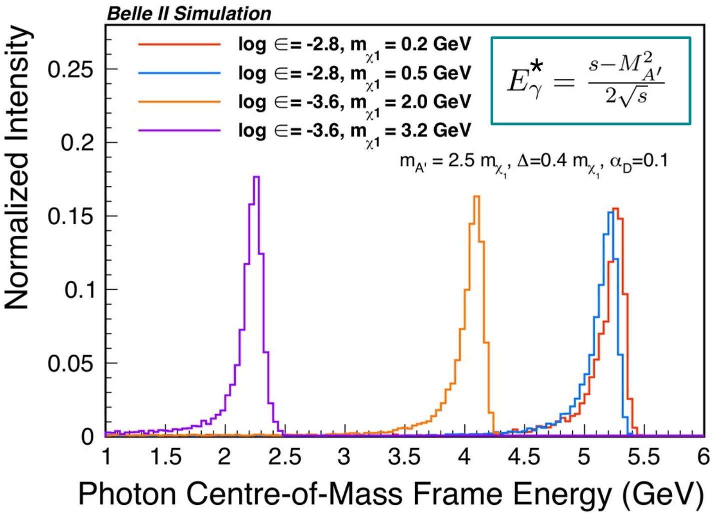
- Belle II could constrain the kinetic mixing $\varepsilon < 10^{-3} - 10^{-4} \sim 100\ \text{fb}^{-1}$





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

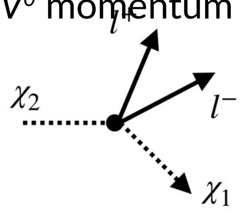
Search for iDM at Belle II



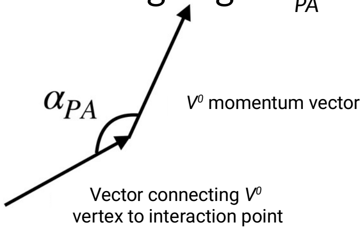
- Search for a peak in the center-of-mass frame energy of the ISR photon plus a displaced vertex V^0

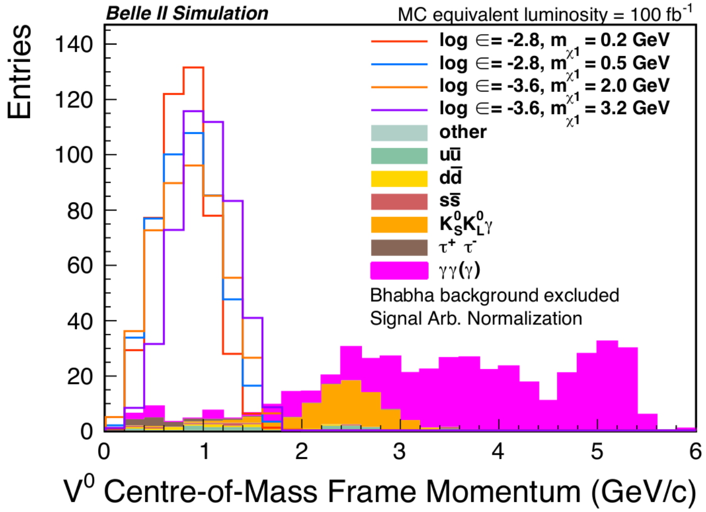
- Background:
  - photon conversion, $e^+e^- \to \gamma\gamma(\gamma)$, $\gamma \to e^+e^-$
  - meson decays, $e^+e^- \to K_S^0 K_L^0(\gamma)$, K_S^0 decays

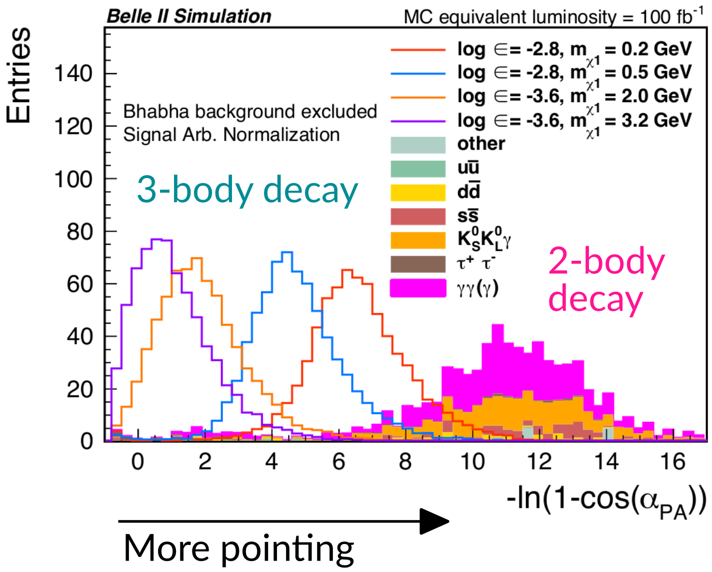
- Background suppression:
  - V^0 momentum



  - Pointing angle α_{PA}

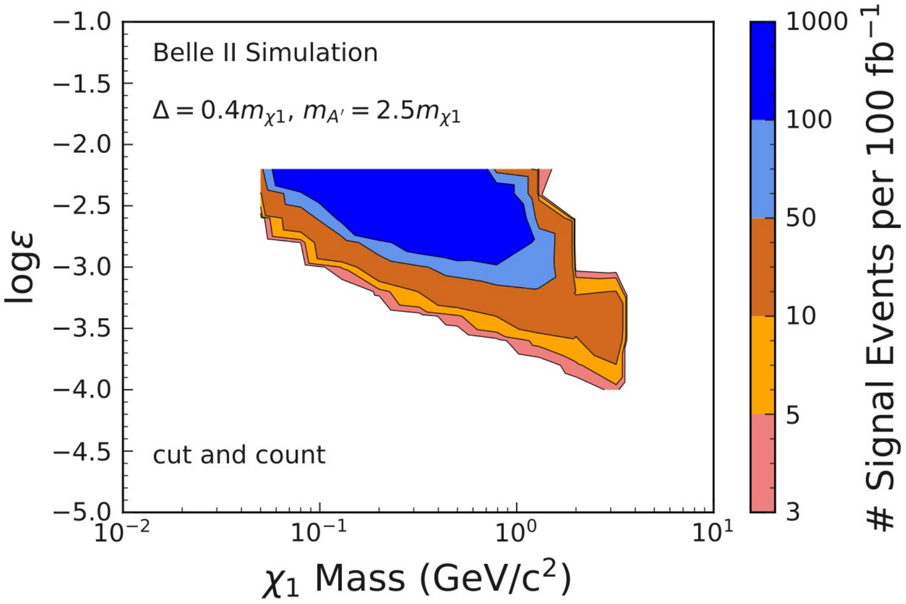




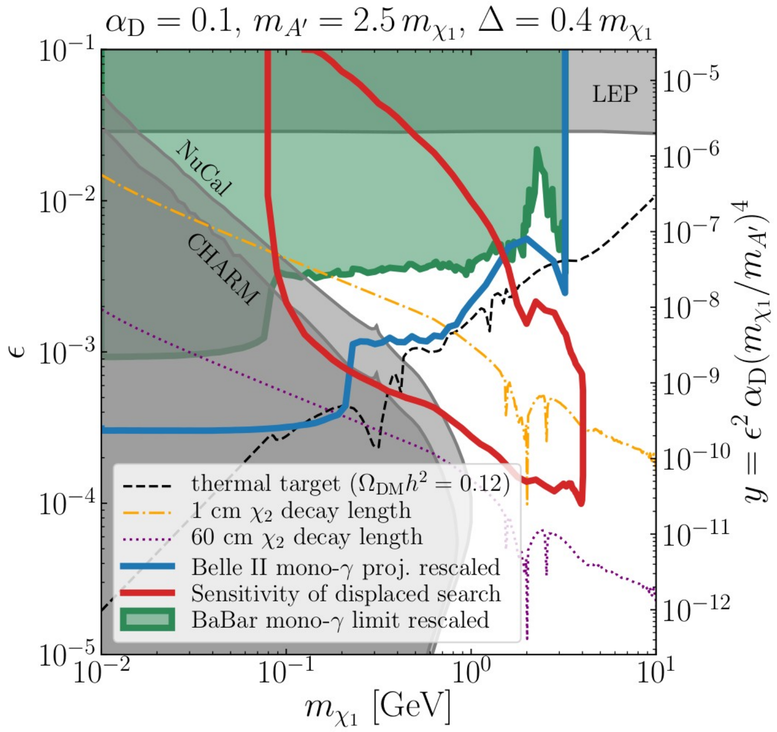


iDM prospects at Belle II

- 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

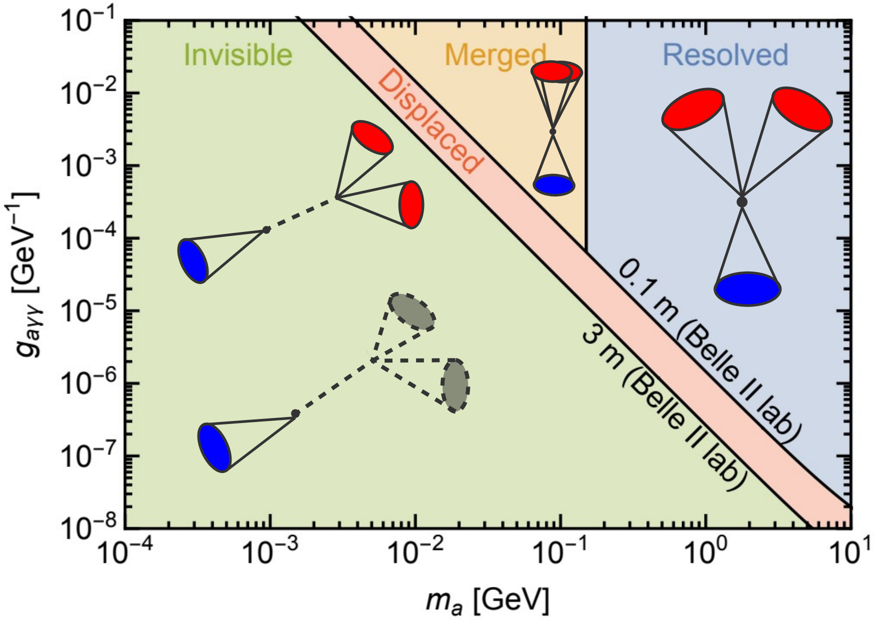


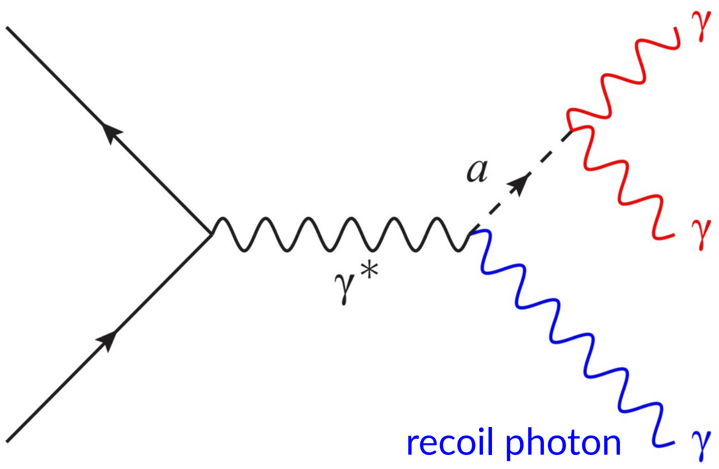
Axion-like particles (ALP) at Belle II

Belle II

Analysis on data, published on PRL

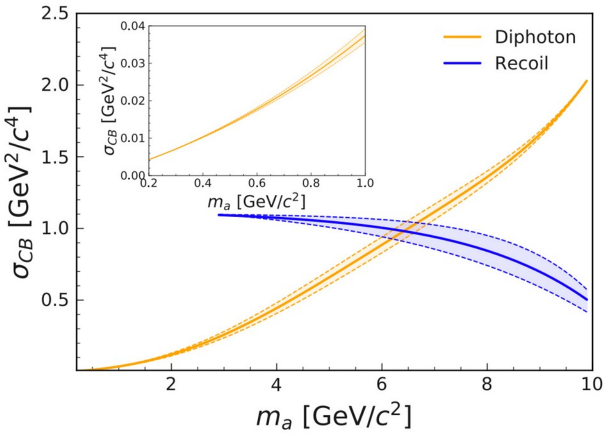
- GeV-scale ALPs: pseudo-scalar portal mediator between dark sector and Standard Model
- If ALP-photon coupling ($g_{a\gamma\gamma}$) dominates, than $BR(a \to \gamma\gamma)$ ~ 100%
- Different topologies depending on model parameters (m_a, $g_{a\gamma\gamma}$): focus on mass region where ALP decay is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



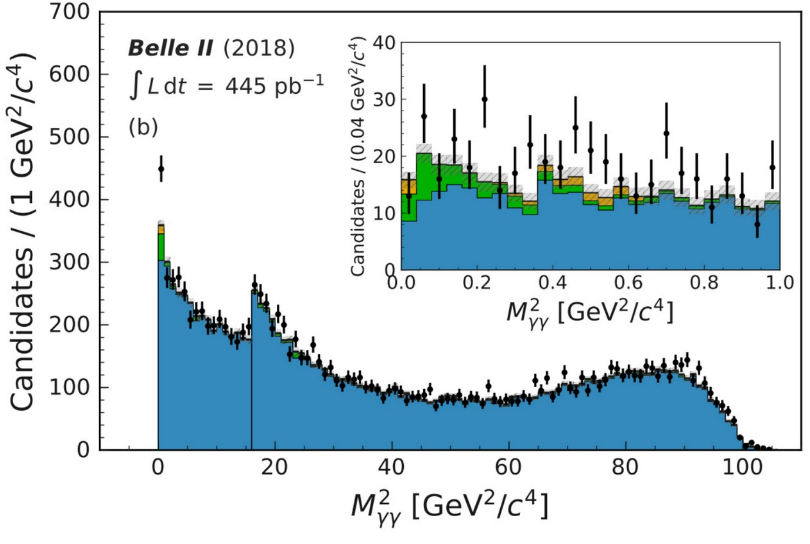


Search for an ALP at Belle II

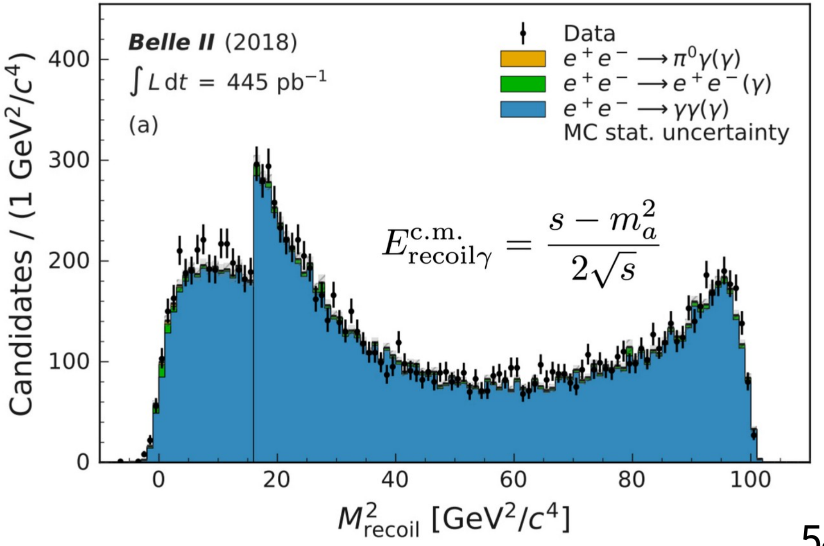
- Select events with three photon invariant mass compatible with collision √s
- Search for a narrow peak in $M^2_{\gamma\gamma}$ or M^2_{recoil}, depending on best resolution of signal peak
- Largest background from $e^+e^- \rightarrow \gamma\gamma(\gamma)$



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

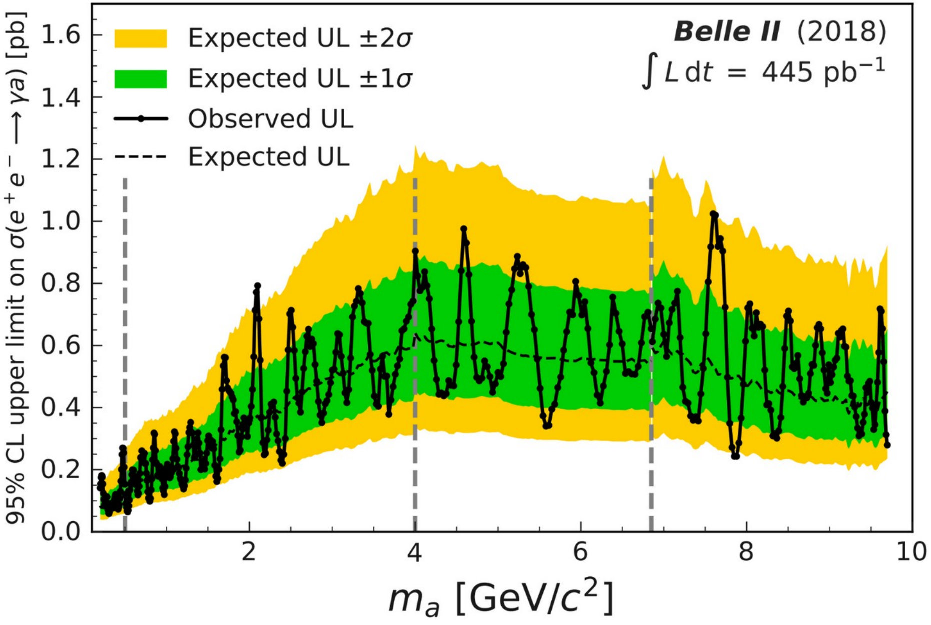


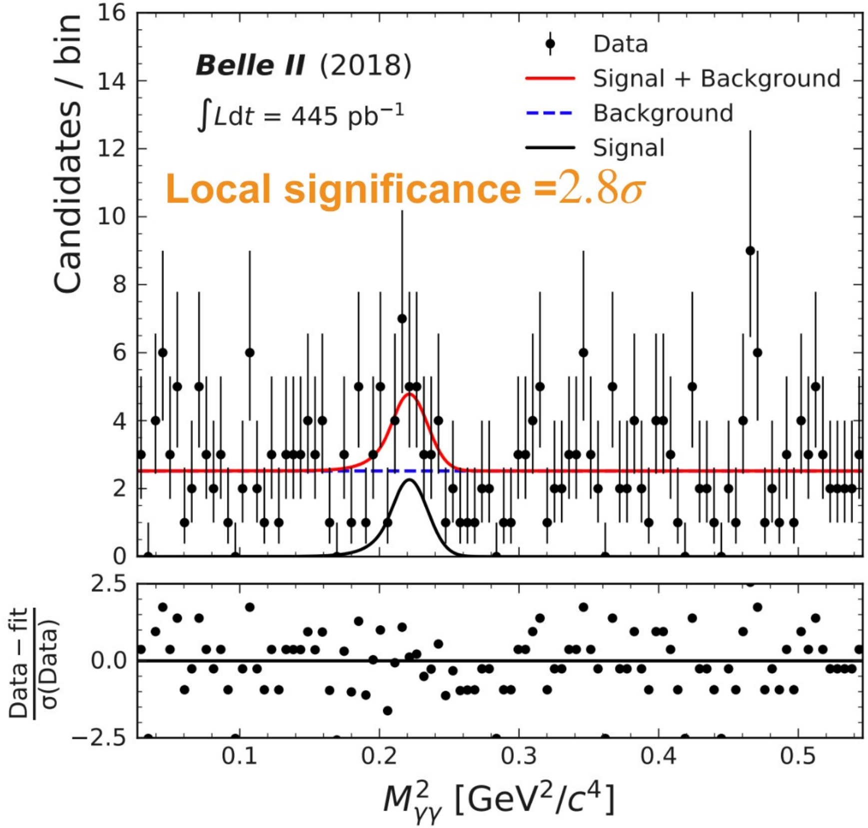
M^2_{recoil}: m_a > 6.85 GeV/c^2



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 collected in 2018 with *Belle II*
  - 500 fits with steps of half mass resolution
- No excess in data observed
  - Highest local significance 2.8σ, observed at $m_a = 0.477$ GeV/c^2

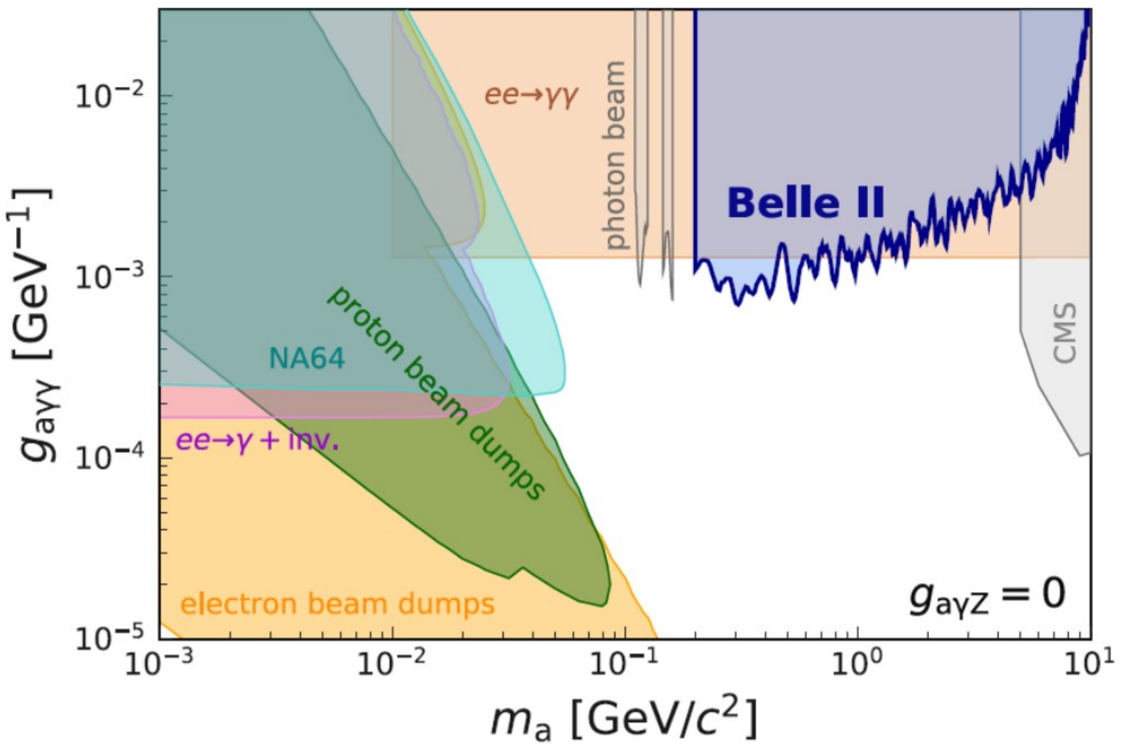




Exclusion of $g_{a\gamma\gamma}$

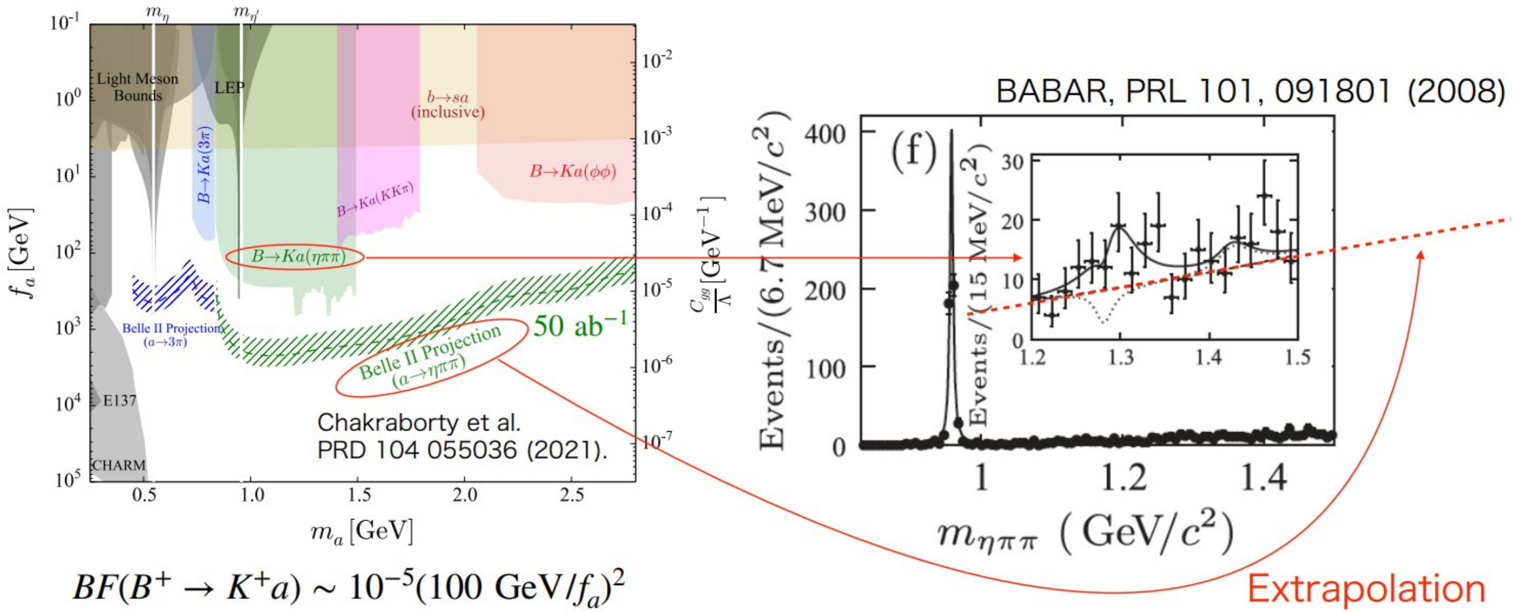
$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{\mathrm{QED}}}{24}\left(1 - \frac{m_a^2}{s}\right)^3$$

- 95% CL upper limits on the coupling constant $g_{a\gamma\gamma}$
  - $g_{a\gamma\gamma}$ below 10^{-3}
- Limits improve over recast from $e^+e^- \to \gamma\gamma$ analysis by LEP-II
- First result for ALP at *B*-factories and second physics publication of *Belle II*
  Phys. Rev. Lett. 125, 161806 (2020)



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 → $\eta\pi^+\pi^-$: BaBar PRL 101, 091801 (2008) (with ~400 fb^{-1})
  - a → $\pi^0\pi^+\pi^-$: Belle PRD 90, 012002 (2014) (with ~700 fb^{-1})



$$BF(B^+ \to K^+a) \sim 10^{-5}(100\ \text{GeV}/f_a)^2$$