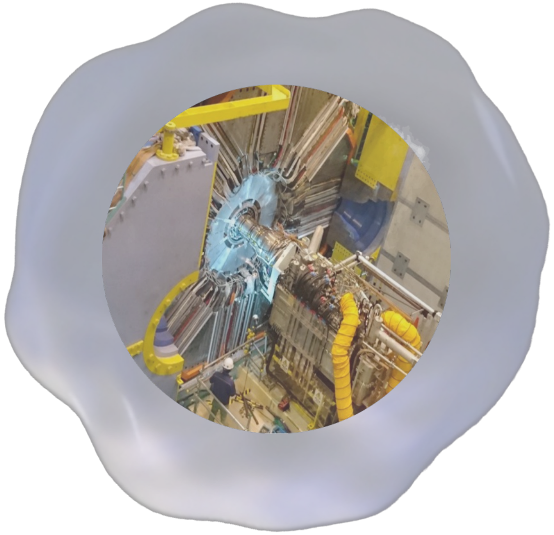
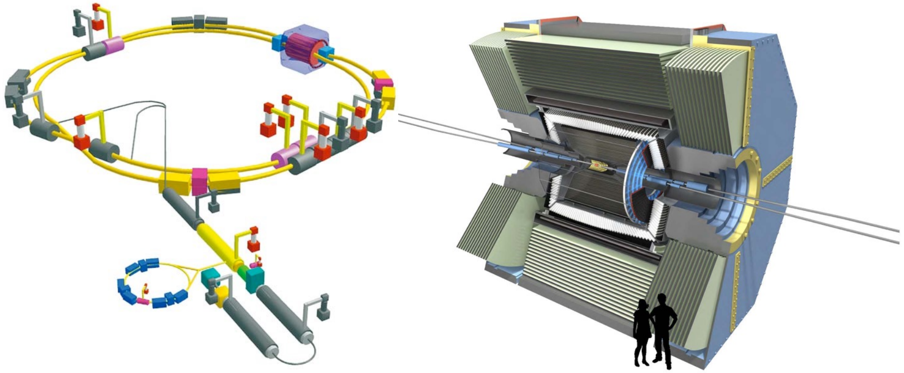
Dark-sector physics at Belle II



Ezio Torassa INFN Padova
on behalf of the Belle II Collaboration

Outlook



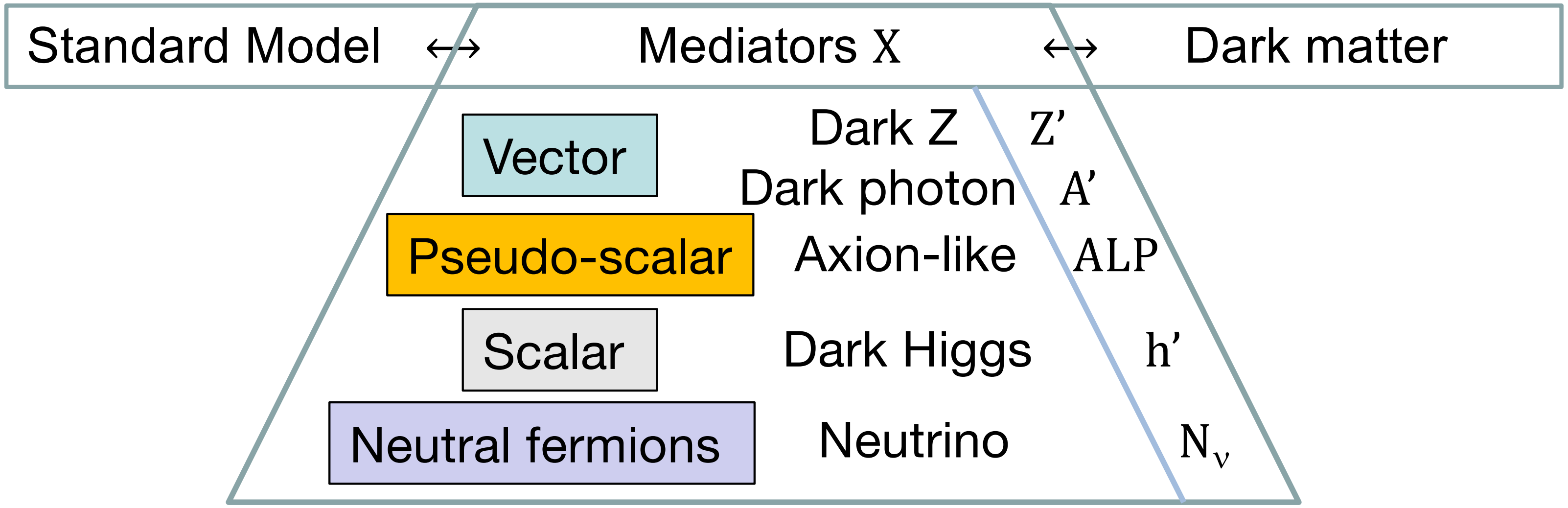
- Introduction

- SuperKEKB collider
- Belle II Detector

- Z' → invisible
- Dark Higgsstrahlung
- Z', S → $\tau^+\tau^-$
- Long-lived scalar in $b \to s$

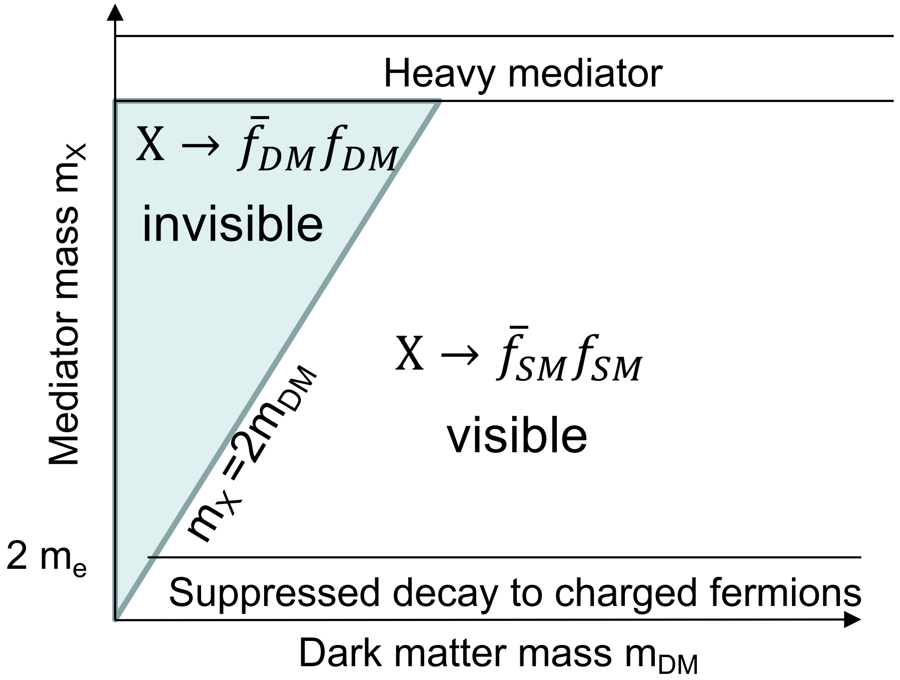
- Summary

Introduction: SM-DM mediators



Standard Model ↔ Mediators X ↔ Dark matter

Vector	Dark Z Dark photon	Z’ A’
Pseudo-scalar	Axion-like	ALP
Scalar	Dark Higgs	h’
Neutral fermions	Neutrino	N_ν



Introduction: dark gauge bosons

Vector

New U(1) gauge symmetry: dark Z and dark photon

Gauge symmetry: $SU(2)_L \otimes U(1)_Y \otimes U'(1)$

Z' dark force carrier

g' (or ϵ) coupling with SM particles

α_D coupling with new DM particles

For SM couplings both e.m. and weak components can be present:

$$\mathcal{L} = -\left[\epsilon e J^{\mu}_{em} + \epsilon_Z \left(\frac{g}{2\cos\theta_W}\right) J^{\mu}_{NC}\right] Z'_{\mu}$$

$$J^{\mu}_{em} = \bar{\Psi}\gamma^{\mu}\Psi$$

$$J^{\mu}_{NC} = \bar{\Psi}\gamma^{\mu}(c_v - \gamma^5 c_a)\Psi$$

Dark Z (Z')

$$\mathcal{L} = -\left[\cancel{\epsilon e J^{\mu}_{em}}^{(*)} + \epsilon_Z \left(\frac{g}{2\cos\theta_W}\right) J^{\mu}_{NC}\right] Z'_{\mu}$$

Dark photon (A')

$$\mathcal{L} = -\left[\epsilon e J^{\mu}_{em}\right] A'_{\mu}$$

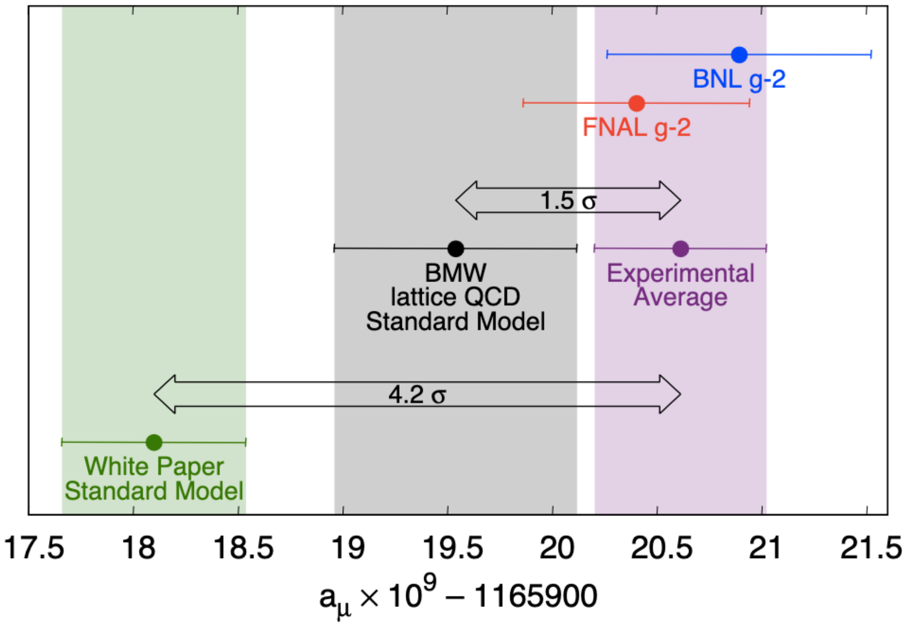
We will see: $Z' \rightarrow \tau^+\tau^-$ $Z' \rightarrow \text{inv.}$ $A'^* \rightarrow h'A'$

$(*)$ Z' decay to invisible (ν or DM)

Introduction: $L_\mu - L_\tau$ model

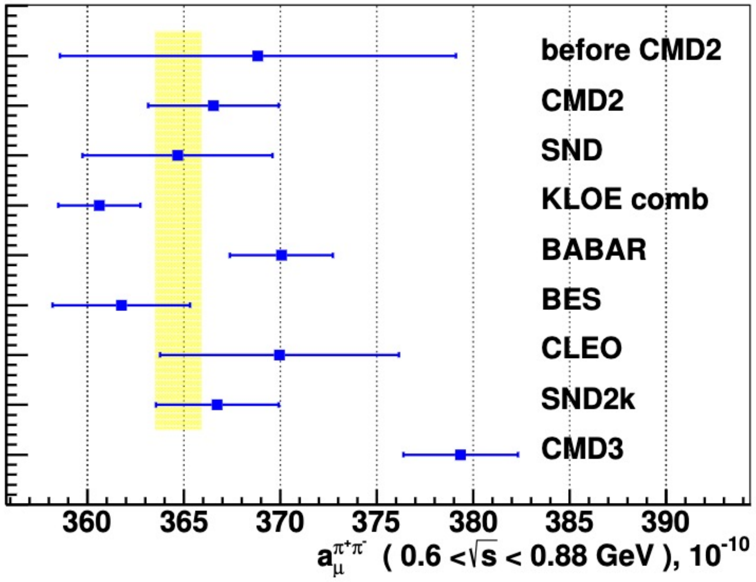
The vector DM portal extension of standard model can add $U(1)_{L_{l1}-L_{l2}}$ gauges without introducing gauge anomaly. The $L_\mu - L_\tau$ model:

- introducing a new Z' coupling only to the 2nd or 3rd generation leptons, could explain at the same time the dark matter and the g-2 anomaly.
- The last measurement of the of the anomalous magnetic moment of muon by the FNAL g-2 experiment confirmed the discrepancy with respect to the SM expectation although the BMW collaboration considering corrections from lattice QCD estimates a smaller discrepancy



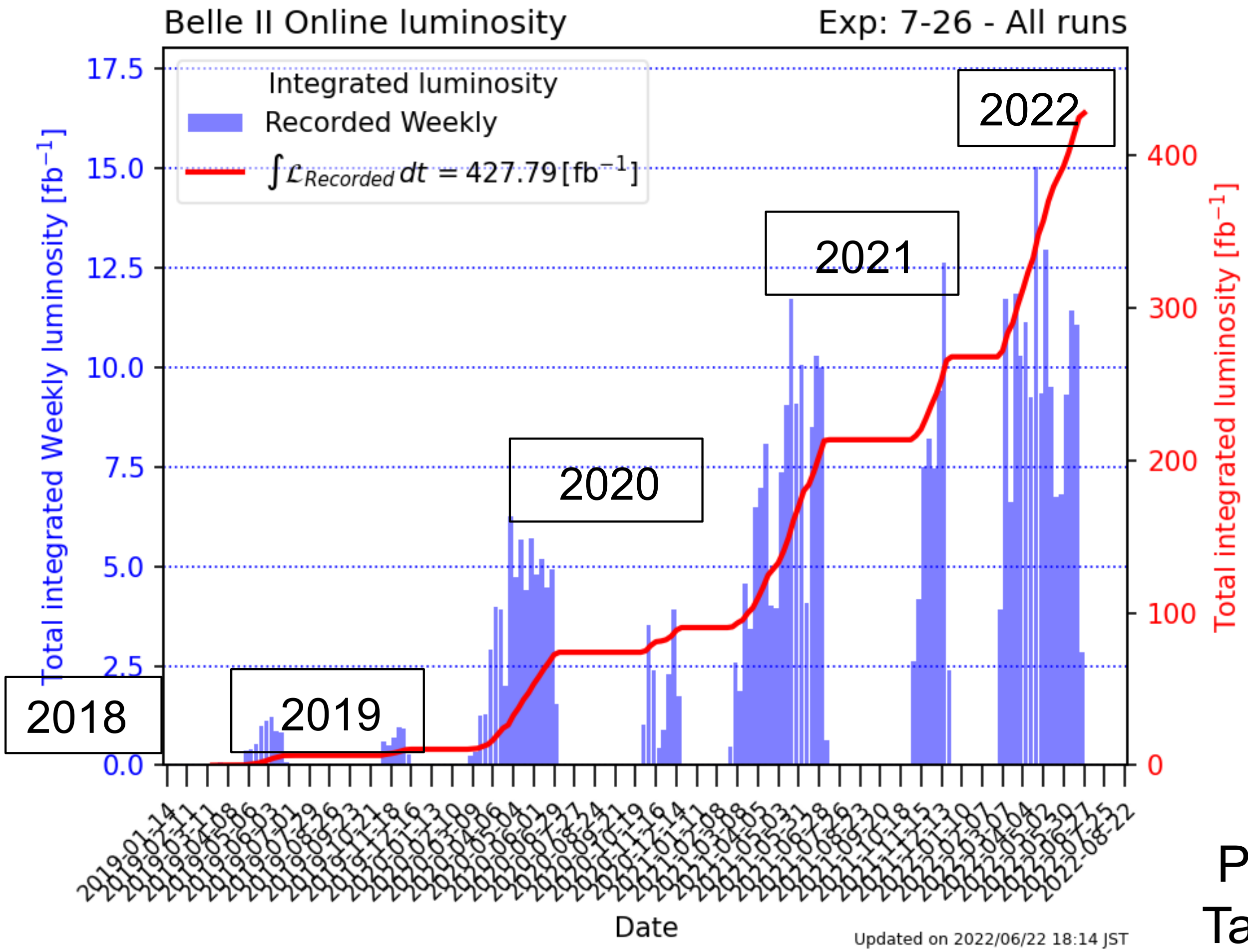
FNAL g-2 PRL126, 141801 (2021)

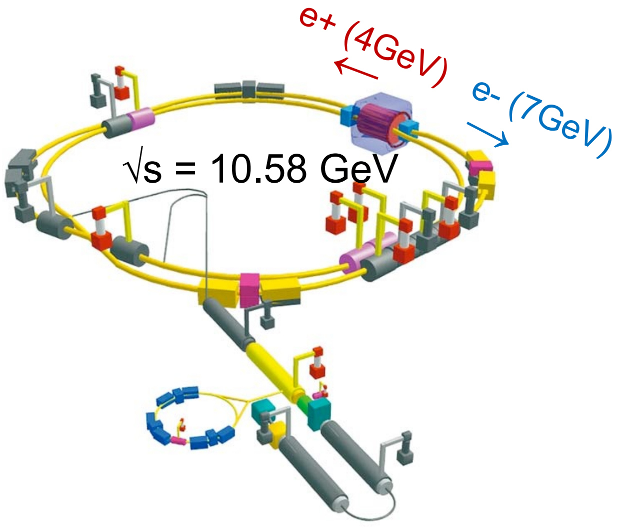
$a_\mu^{\pi^+\pi^-}$ contribution to $a_\mu^{had,LO}$ from σ($e^+e^-\to\pi^+\pi^-$)



CMD-3 arXiv:2302.08834

SuperKEKB collider





Total $\int \mathcal{L}_{Physics}$: 424 fb^{-1}

Target $\int \mathcal{L}$: 50 ab^{-1}

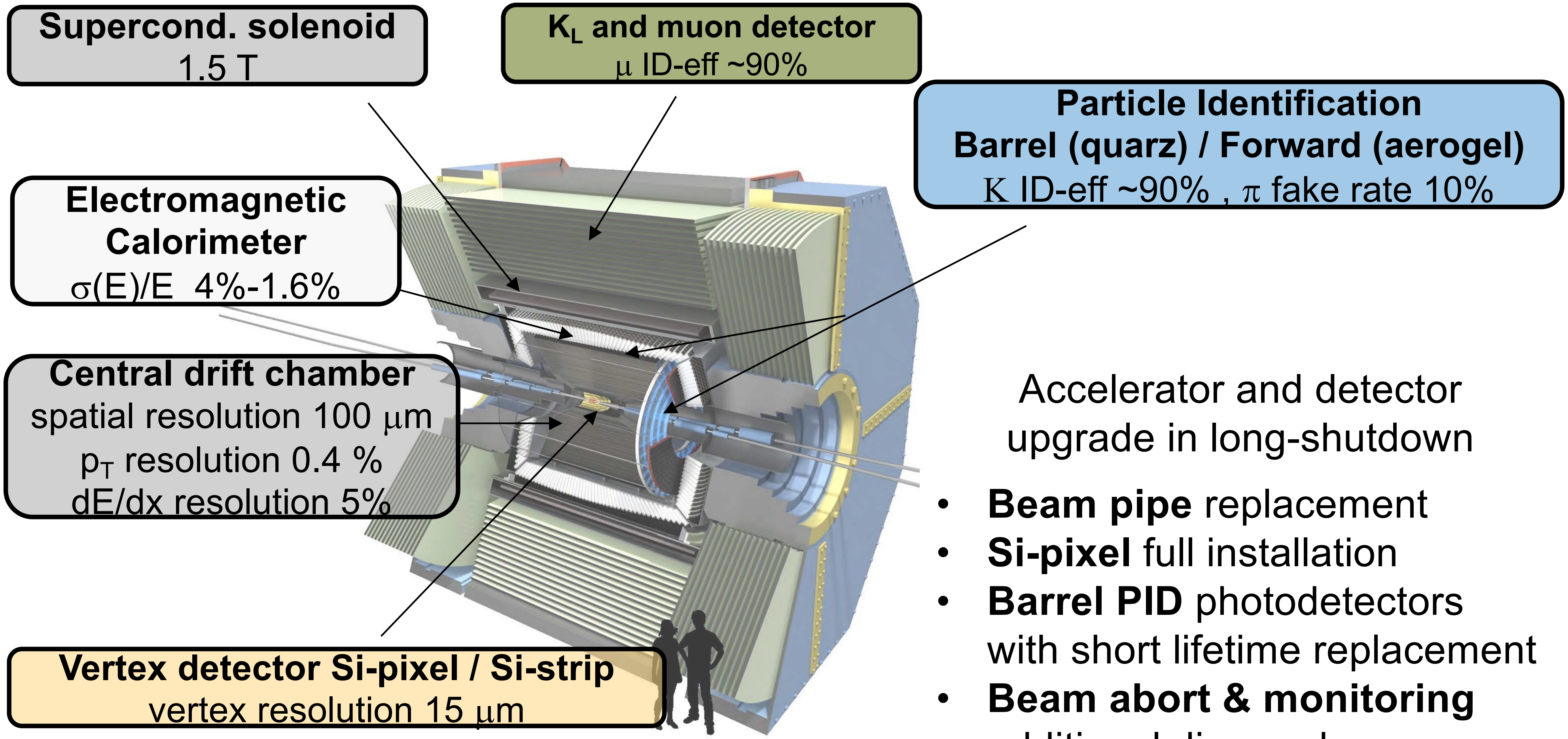
Peak inst. $\mathcal{L}^{*}$: 4.65 x 10^{34} $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Target inst. $\mathcal{L}$: 6 x 10^{35} $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

(* June 8, 2022)

We are now in long-shutdown for accelerator and detector upgrade

Belle II detector



Supercond. solenoid
1.5 T

K_L and muon detector
μ ID-eff ~90%

Particle Identification
Barrel (quarz) / Forward (aerogel)
K ID-eff ~90% , π fake rate 10%

Electromagnetic Calorimeter
$\sigma(E)/E$ 4%-1.6%

Central drift chamber
spatial resolution 100 μm
p_T resolution 0.4 %
dE/dx resolution 5%

Vertex detector Si-pixel / Si-strip
vertex resolution 15 μm

Accelerator and detector upgrade in long-shutdown

- **Beam pipe** replacement
- **Si-pixel** full installation
- **Barrel PID** photodetectors with short lifetime replacement
- **Beam abort & monitoring** additional diamonds
- **ALL** repair not working electronics channels

Belle II detector: trigger & efficiencies

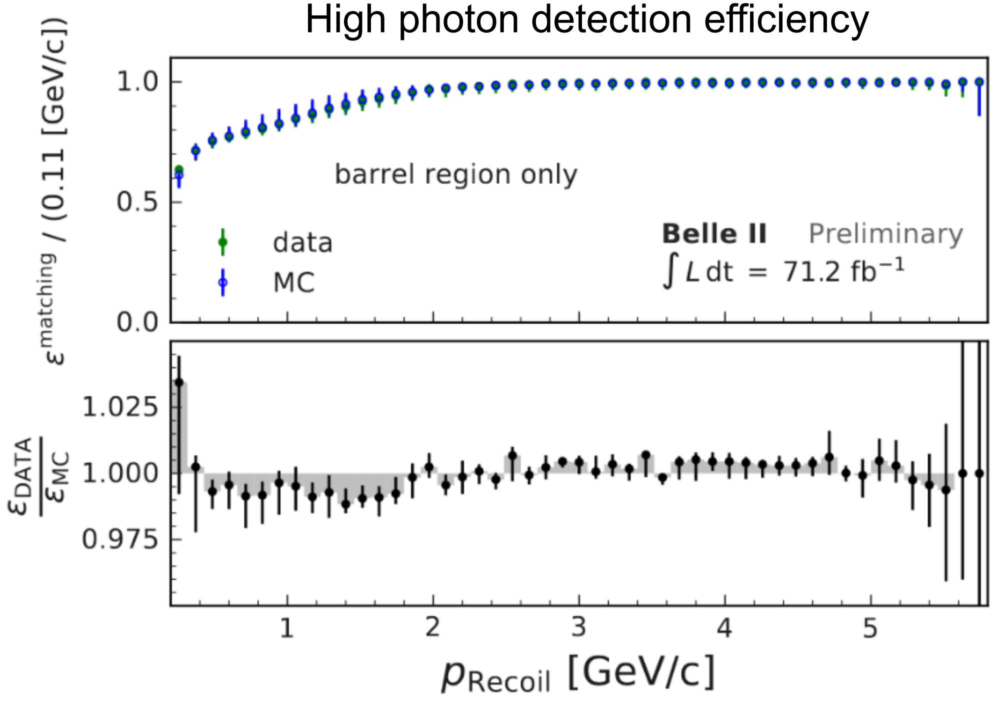
Strengths of Light Dark-Sectors at Belle II

- well known initial condition
- special trigger for low multiplicity
- trigger and tracking efficiencies
- particle identification efficiencies

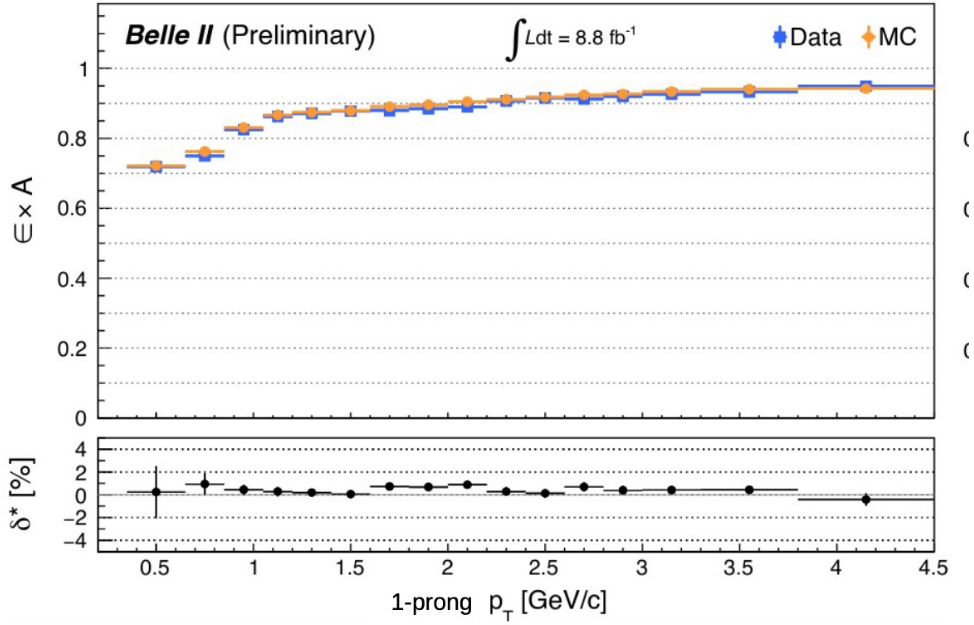
single photon trigger (not available at Belle)
single muon trigger
single track trigger using NN

Particle Identification using Neural Networks

High photon detection efficiency



Tracking efficiency (accept.* reconstr.) for $\tau\tau$ events



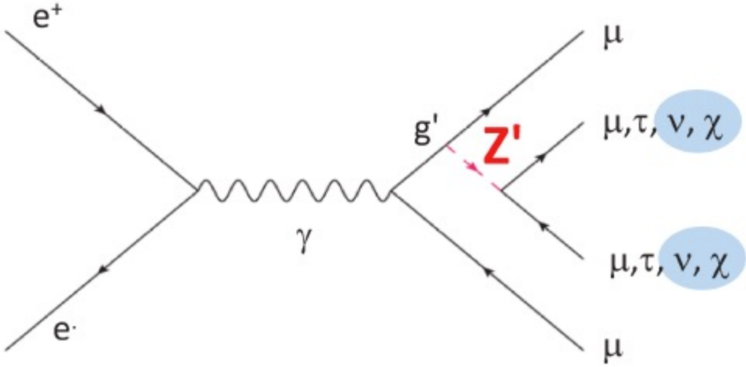
Z’ → invisible

arXiv:2212.03066
Submitted to PRL
Belle II data 2019-2020

Updated Z’ analysis 276 pb^{-1} → 79.7 fb^{-1}

Higher statistics, improved selection

Search for the Z′ in the process $e^+e^- \to \mu^+\mu^- Z'$ with Z′ → invisible



Events with 2 opposite charge muons
Search for signal in Z’ recoil mass

Two alternative $L_\mu - L_\tau$ models:

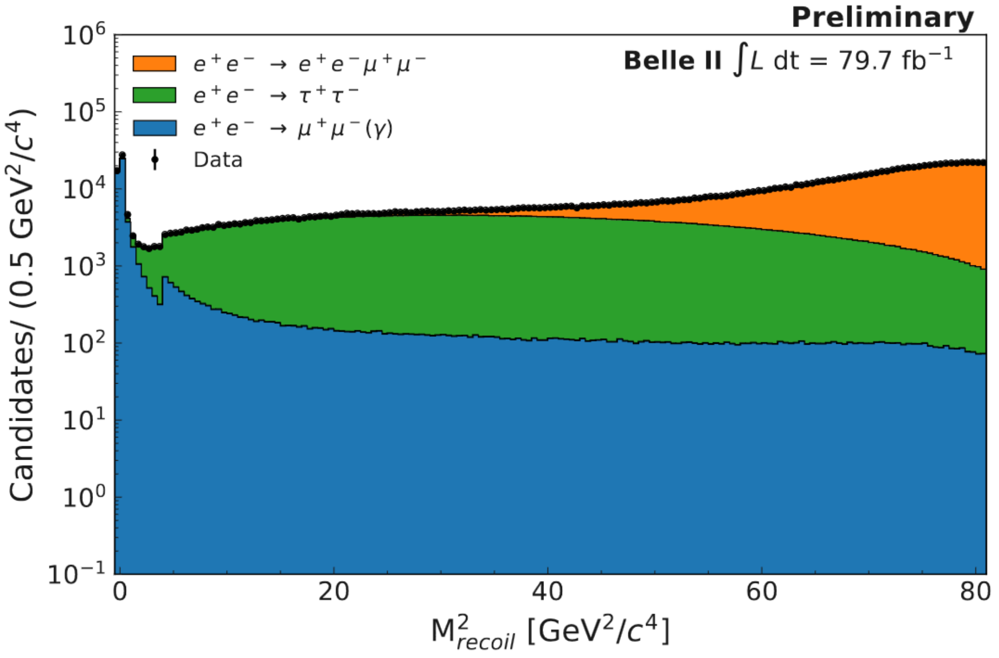
- “vanilla model” Z’ coupling only to SM, predicted BF Z’ → νν (33%-100%, $f(M_{Z'})$)
- Fully invisible model Z’ coupling also with χχ we expect $g'_D \gg g'$, BF=1

Z’ → invisible

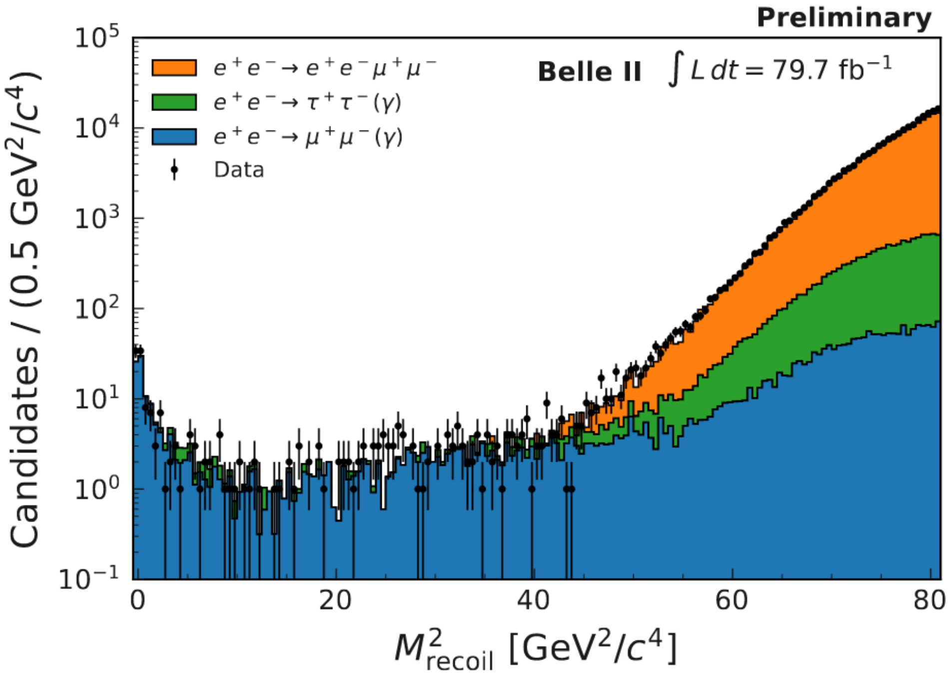
Selection:

- two muons, $p_T > 0.4$ GeV/c
- trigger veto to suppress Bhabha scattering
- opening angles between muons in c.m. frame < 179° to suppress $\mu^+\mu^-(\gamma)$
- the final selection uses an artificial neural network, denoted as Punzi-net, specifically designed to optimize a figure of merit for all Z′ mass hypotheses simultaneously. [Eur. Phys. J. C 82, 121 (2022)]

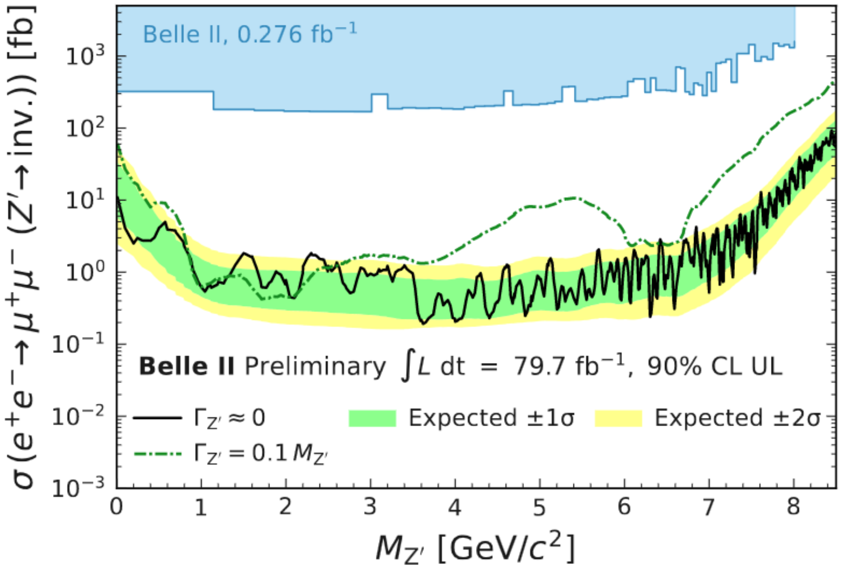
recoil mass before the Punzi-net selection



recoil mass after the Punzi-net selection



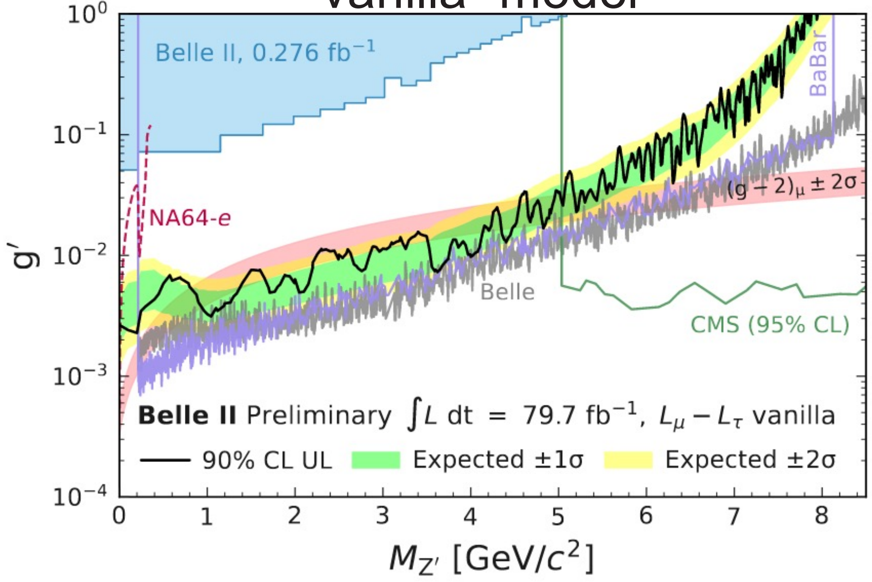
Z’ → invisible



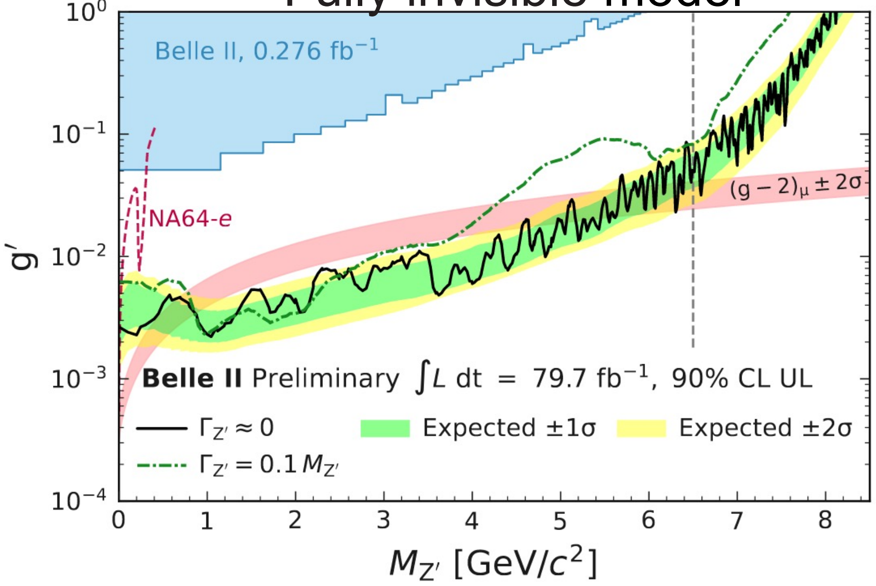
90% CL upper limits on the cross section

Invisible Z’ as origin of (g-2)
excluded for 0.8 < $M_{Z'}$ < 5.0 GeV/c2

“vanilla” model



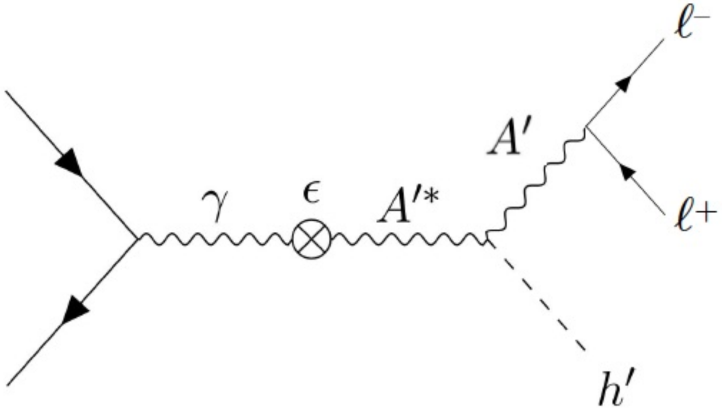
Fully invisible model



Dark Higgsstrahlung

PRL 130(2023)071804
arxiv:2207.00509
Belle II data 2019

Higgsstralhung from dark photon A'

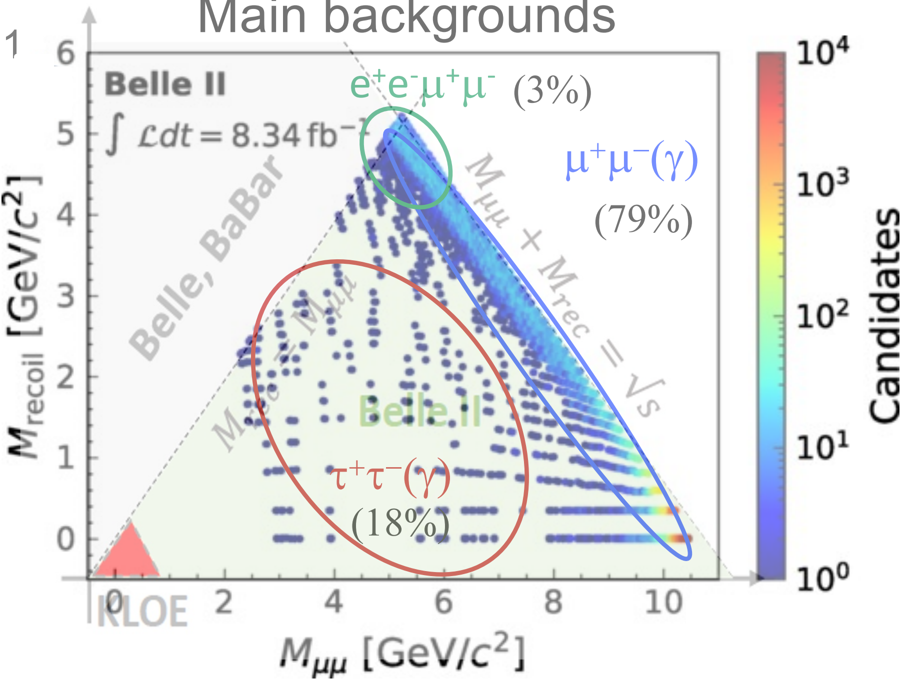


1. Dark Higgs h' gives mass to A' through SSB
2. No mixing of h' with SM Higgs
3. Coupling α_D in the dark sector, $\epsilon^2\alpha_D$ overall

- $M_{h'} > M_{A'}$ $h' \rightarrow A'A'^{(*)}$ Belle PRL 114(2015)211801
  BaBar PRL 108(2012)211801
- $M_{h'} < M_{A'}$ this publication
  - ✧ $h' \rightarrow$ invisible, $e^+e^- \rightarrow h'A' \rightarrow \mu^+\mu^- + E_{miss}$
  - ✧ probed by KLOE for low $M_{A'}$ PLB747(2015)p365

Selection	Suppression
$E_\gamma^{TOT} < 0.4\ GeV$	radiative μ pairs
$p_T{}^{c.m.}_{\mu\mu} > 0.1\ GeV$	$\mu^+\mu^-(\gamma)$, $e^+e^-\mu^+\mu^-$
Recoil points ECL_{barrel}	lost γ
$\lvert\cos(\text{helicity } \eta)\rvert \lesssim 0.9$	$\tau^+\tau^-(\gamma)$

Main backgrounds

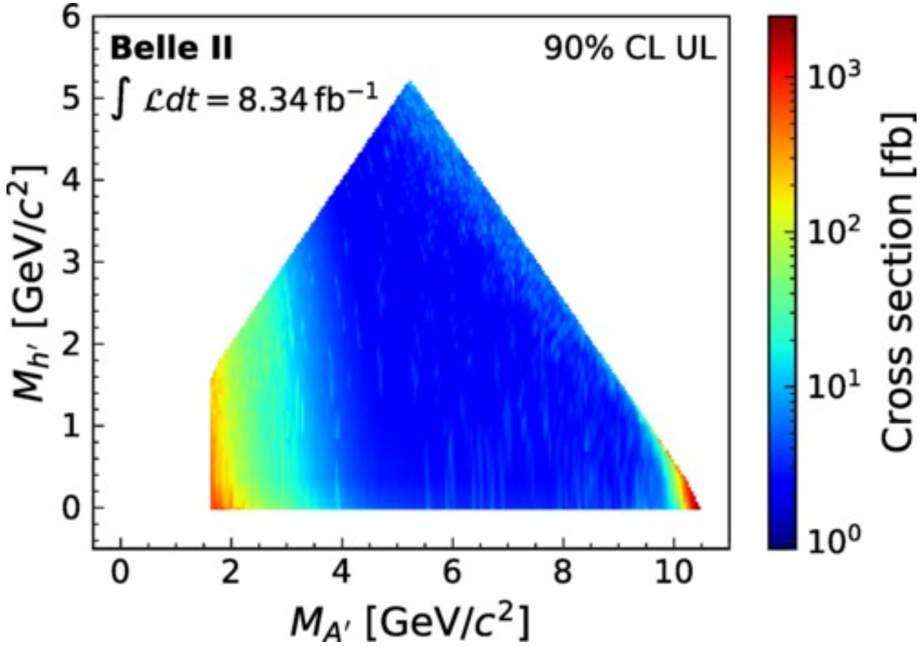


Dark Higgsstrahlung

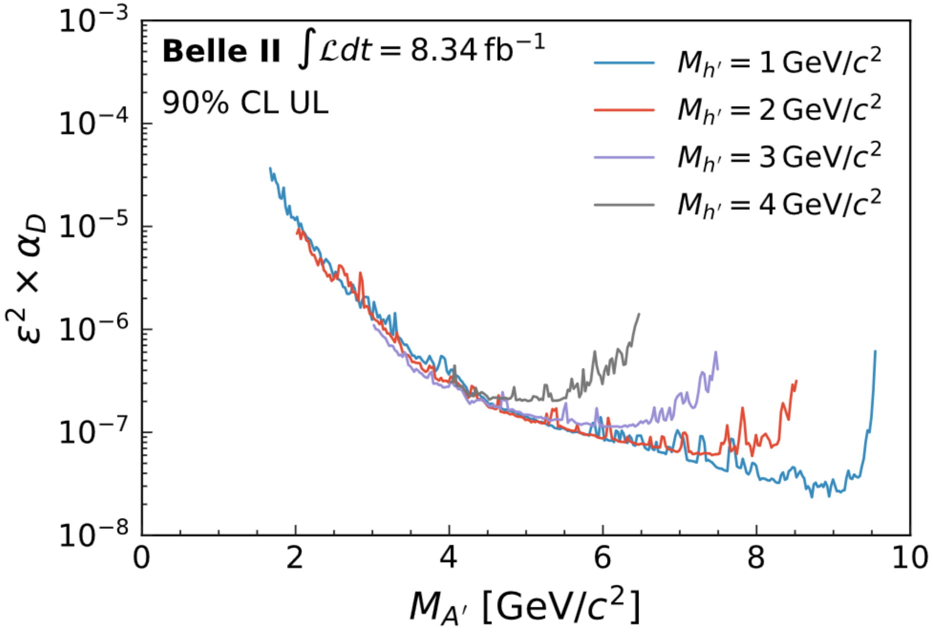
No excess of events was found

Observed 90% CL upper limits

cross section of $e^+e^- \to A'h'$ in $(M_{A'}, M_{h'})$



$\epsilon^2 \times \alpha_D$ as a function of $M_{A'}$

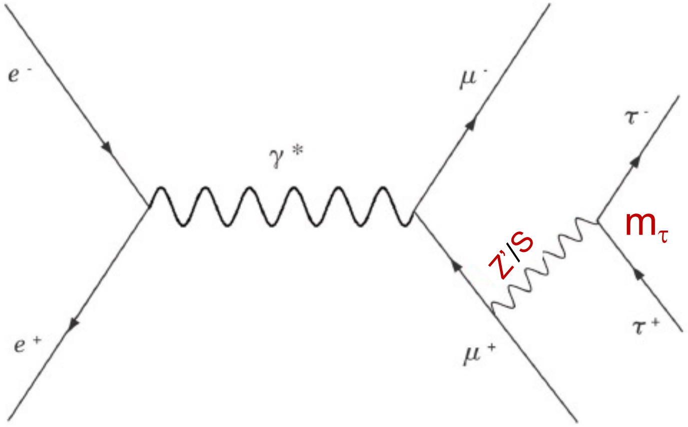


Most sensitive region: $4 < M_{A'} < 9.7$ GeV/c^2

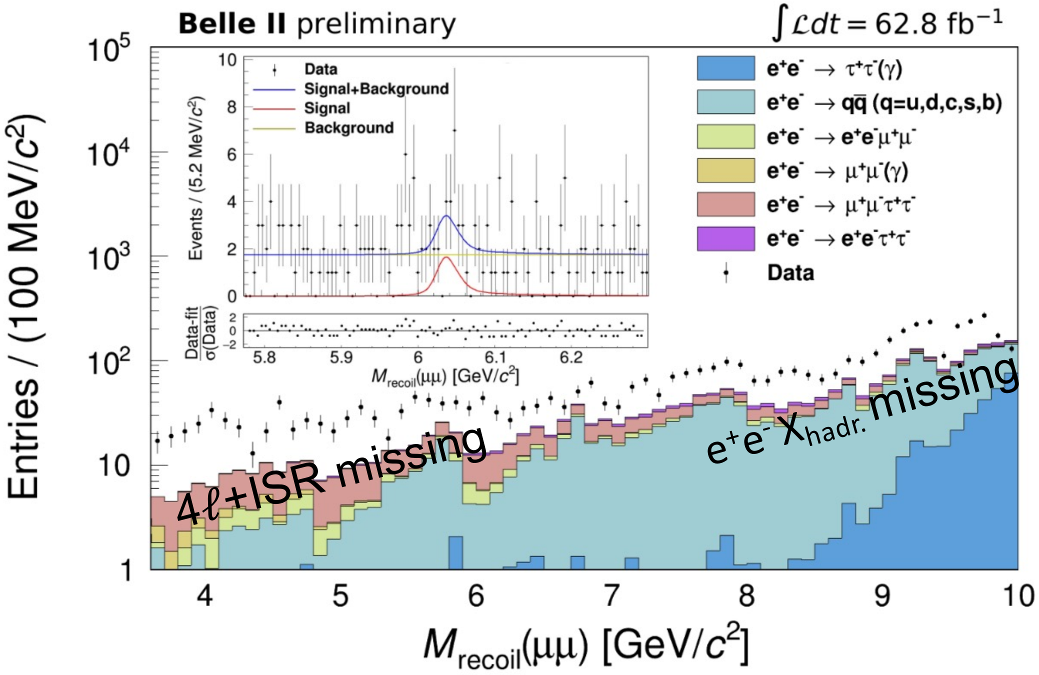
First world limit for $1.65 < M_{A'} < 10.51$ GeV/c^2

Search for $\tau^+\tau^-$ resonance in $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$

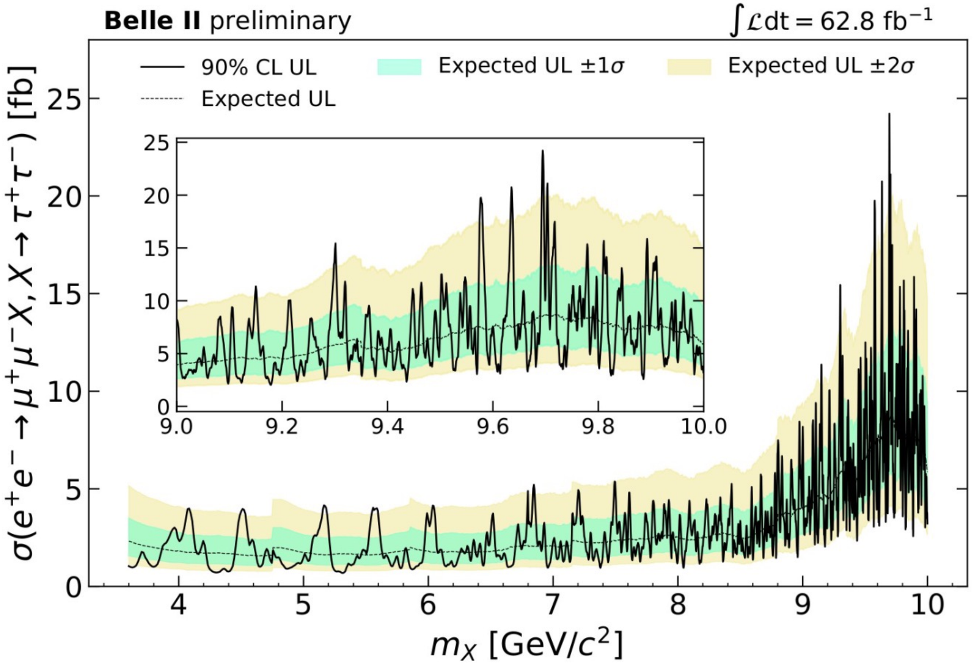
- Search new resonance in X → $\tau^+\tau^-$ decay
- Two different models:
  - Z' vector particle coupling only to heavy lepton
  - S leptophilic dark scalar
- Selection: M (4tracks) < 9.5 GeV and & NN



M_{recoil} against 2μ



90% CL upper limits

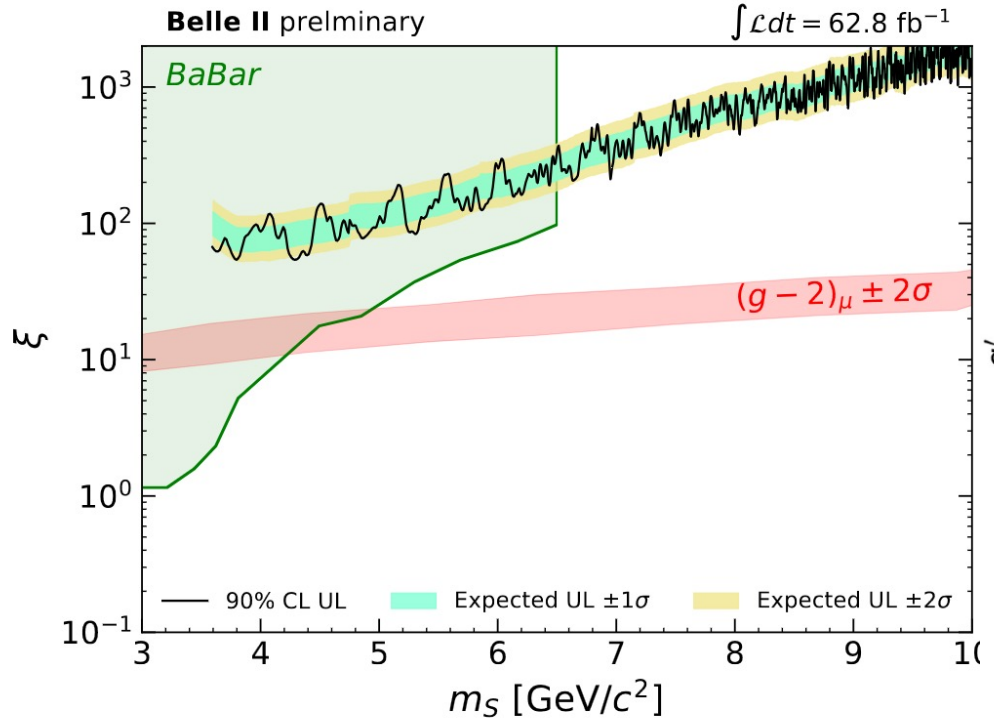


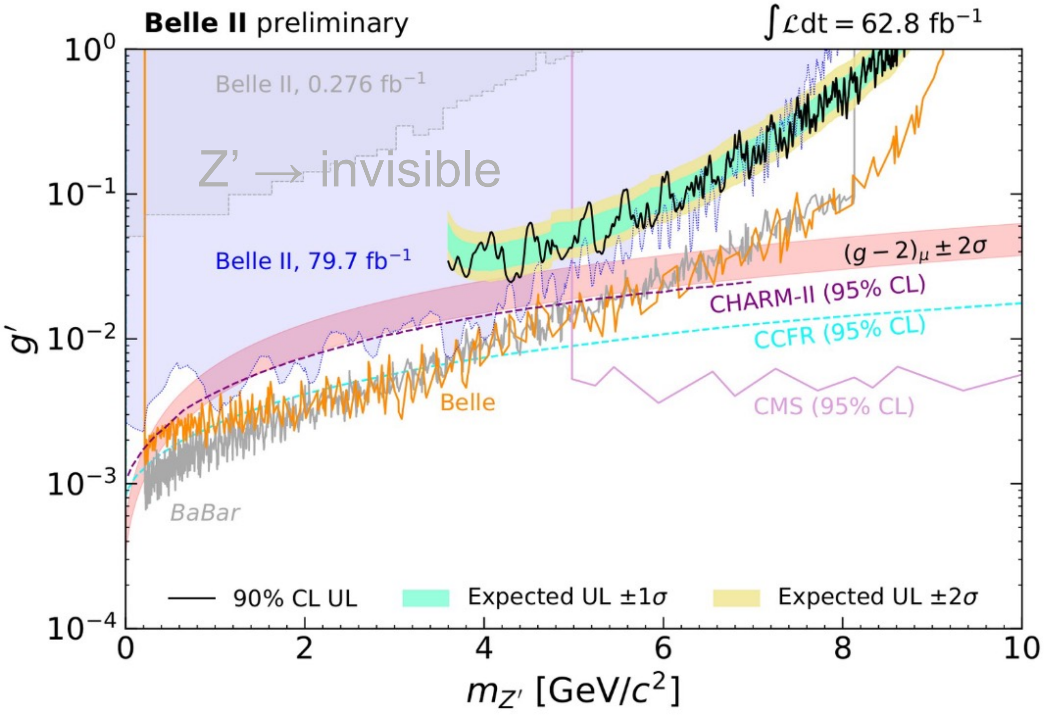
Search for $\tau^+\tau^-$ resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$

Reinterpretation of limits for different models:

$$UL(g')_{90\%\ CL} = \sqrt{\frac{g'_{ref}\cdot UL(\sigma)_{90\%\ CL}}{\sigma_{ref}}}$$

σ_{ref} = Theoretical cross section for the reference coupling g'_{ref} implemented in the MC generator





World-leading limits over 6.5 GeV

Improved Z' → invis. limits over 7 GeV

Search for a long-lived scalar in $b \to s$

Minimal SM extention with light scalar **S** that mixes with the SM Higgs boson:

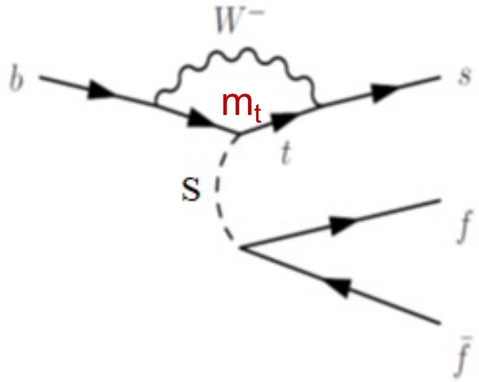
$$\mathcal{L} = \mathcal{L}_{S,H} + \mathcal{L}_{S,DM} + \mathcal{L}_{S,SM}$$

- New scalar field S: $\mathcal{L}_{S,H} = (\mu\, S + \lambda\, S^2)H^\dagger H$
- Dirac fermion DM candidate: $\mathcal{L}_{S,DM} = S(g_\chi \bar{\chi}\chi \; + g'_\chi \bar{\chi}\gamma^5\chi)$
- S can mix with the scalar component of H (the Higss boson) with mixing angle θ, it acquires a coupling to SM particles:

$$\mathcal{L}_{S,SM} = S\, sin\theta \sum_f \frac{m_f}{v} \bar{f} f$$

First LLP search from Belle II

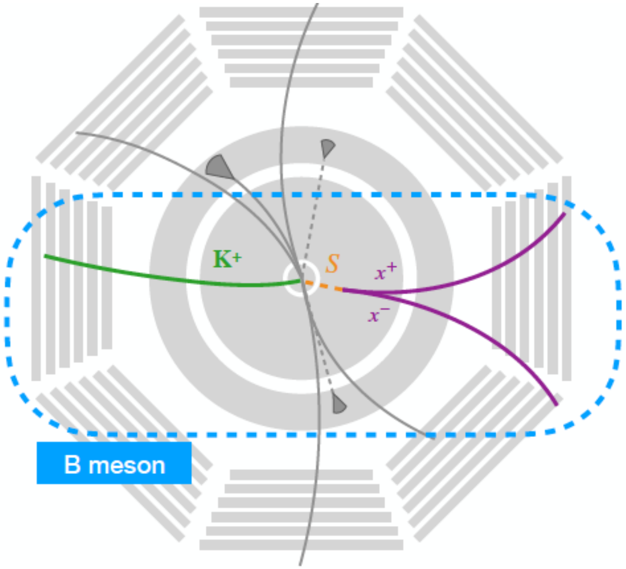
- Search a long-lived S in:
  (1) B → K^+ **S**
  (2) B → K^{*0} **S** ($K^{*0} \to K^+\pi^-$)
- **S** → e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$, K^+K^- total 8 decay channels



Search for a long-lived scalar in $b \to s$

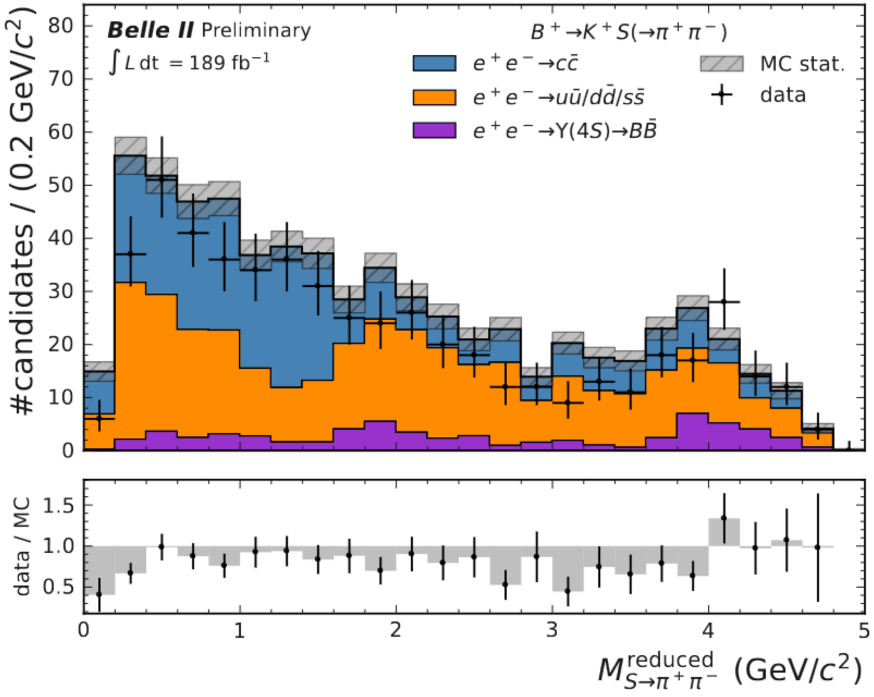
- Search for the signal as a narrow enhancement in the invariant mass M_S
- Displaced tracks for S vertex with $d_v > 0.05$ cm
- M_{inv} selections to reject peaking backgrounds (D^0, J/ψ, $\psi(2S)$, ϕ, …) from B decays
- For the signal extraction we use the reduced mass: $M^{reduced}_{S\to x^+x^-} = \sqrt{M^2_{S\to x^+x^-} - (2m_x)^2}$

  ✧ to simplify the modeling of the signal width where the scalar mass approaches twice the rest mass of the final state particles.



Inv. mass distribution

$S \to \pi^+\pi^-$

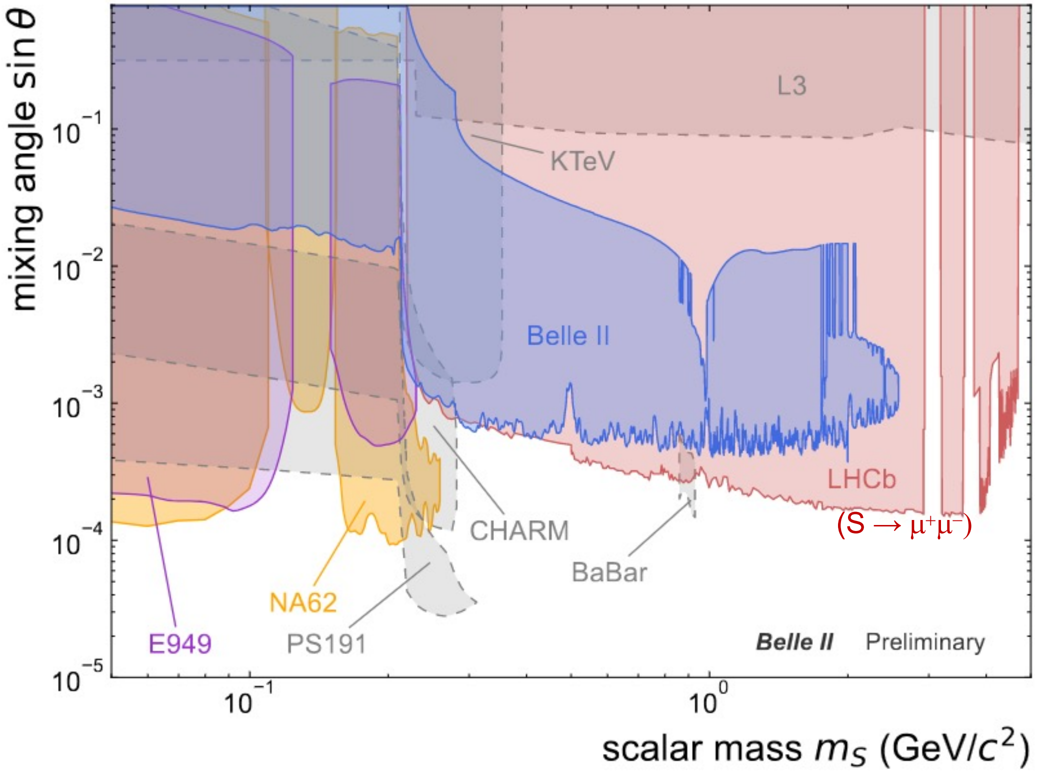


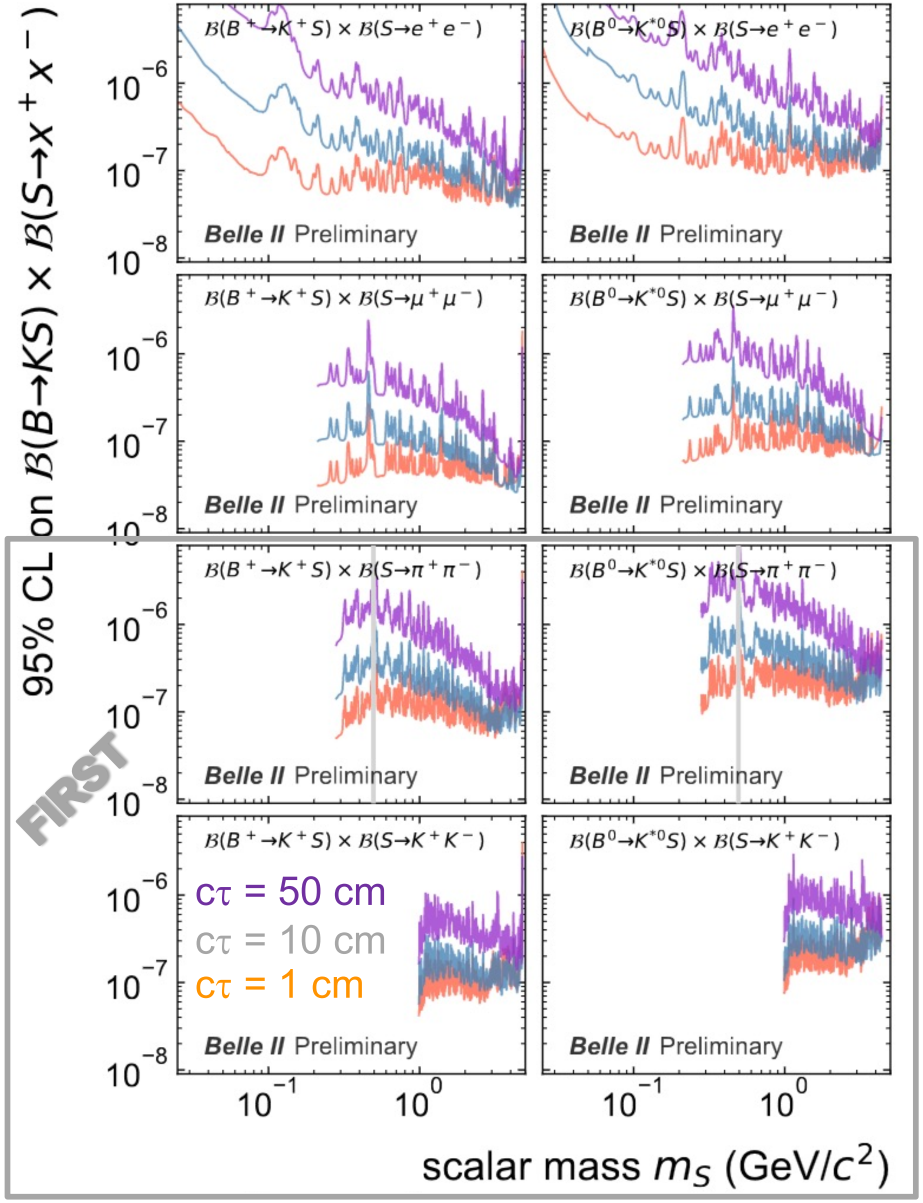
Search for a long-lived scalar in $b \to s$

Model independent 95% CL limits on scalar LLP branching fraction

Dark Higgs-like scalar model interpretation:

95 % CL limits on the mixing angle θ as function of scalar mass m_S. First limits for hadronic final states and strongest limits e^+e^-





Summary

- The Belle II experiment at SuperKEKB collected the integrated luminosity of 424 fb^{-1} up to June 2022 with a world record of peak instantaneous luminosity of 4.65 x 10^{34} cm^{-2} s^{-1}.
- We are now in long-shutdown for accelerator and detector upgrade.
- Several analysis have been completed in the Dark Sector, others are close to be submitted for publication.

Published

ALP $\to \gamma\gamma$	0.445 fb^{-1}
$Z' \to$ invisible	0.276 fb^{-1}
Dark Higgsstrahlung	8.34 fb^{-1}

Submitted to PRL

$Z' \to$ invisible	79.7 fb^{-1}
$\tau \to \ell\ a$ (invis. scalar)	62.8 fb^{-1}

(Michael Roney Talk 31/3)

Close to submission

Z', S $\to \tau^+\tau^-$	63.3 fb^{-1}
NEW Long-lived scalar in $b \to s$	189 fb^{-1}

Backup

Long-shutdown activity and plans

Belle II stopped taking data in Summer 2022 for a long shutdown

- replacement of beam-pipe
- replacement of photomultipliers of the central PID detector (TOP)
- installation of 2-layered pixel vertex detector
- improved data-quality monitoring and alarm system
- completed transition to new DAQ boards (PCIe40)
- accelerator improvements: injection, non-linear collimators, monitoring
- replacement of aging components
- additional shielding and increased resilience against beam background

Currently working on pixel detector installation:

==> arrived at KEK on March 16
==> final tests at KEK scheduled in April

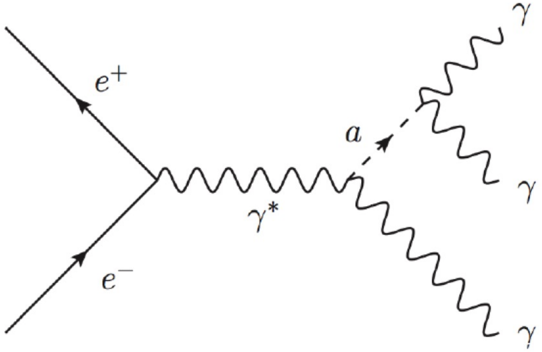
On track to resume data taking next winter with new pixel detector

Axion-like → γγ

PRL 125(2020)161806
(Belle II data 2018 w/o SVD)

ALP: gauge-singlet neutral pseudoscalar ($J^P=0^-$) with independent mass and coupling

APL 2γ decay and 3γ final state



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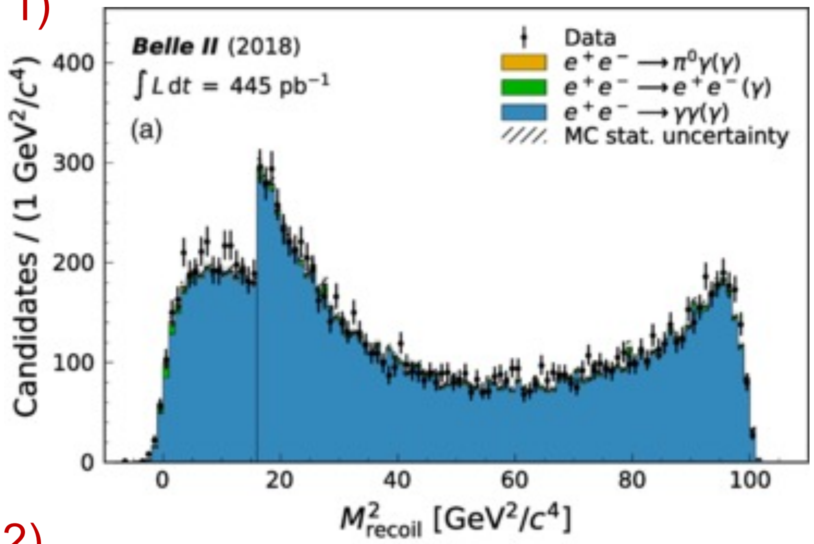

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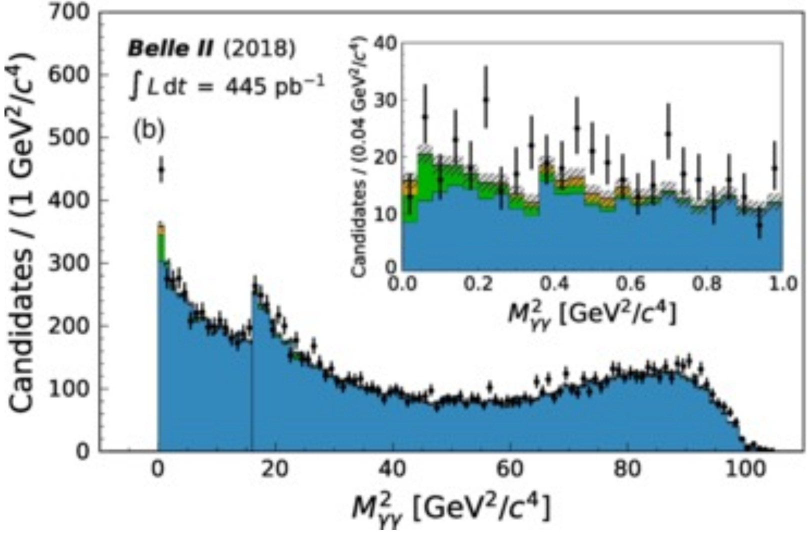


Main backgrounds are γγ(γ) and e^+e^-(γ)

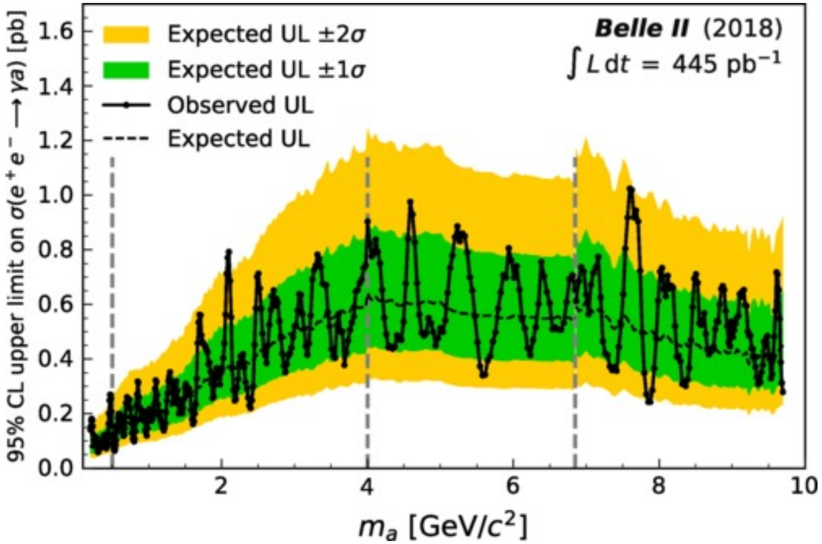
Events selected with at least 3γ (Eγ≳1GeV)
99.8% of events have 3γ for the others the three most energetic are selected.

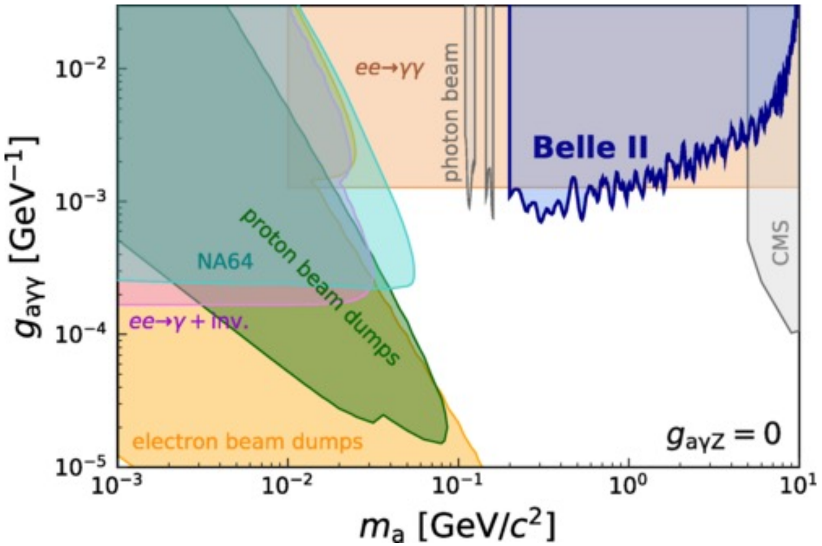
Signal can be identified by a peak in
1) recoil mass (better resolution if m_a > 6.5 GeV)
2) $M^2_{\gamma\gamma}$ (better resolution if m_a < 6.5 GeV)

Axion-like $\longrightarrow \gamma\gamma$

PRL 125(2020)161806
(Belle II data 2018 w/o SVD)

Extension of the exclusion region in the ($g_{a\gamma\gamma}$,m_a) param. space already with ~0.5 fb^{-1}

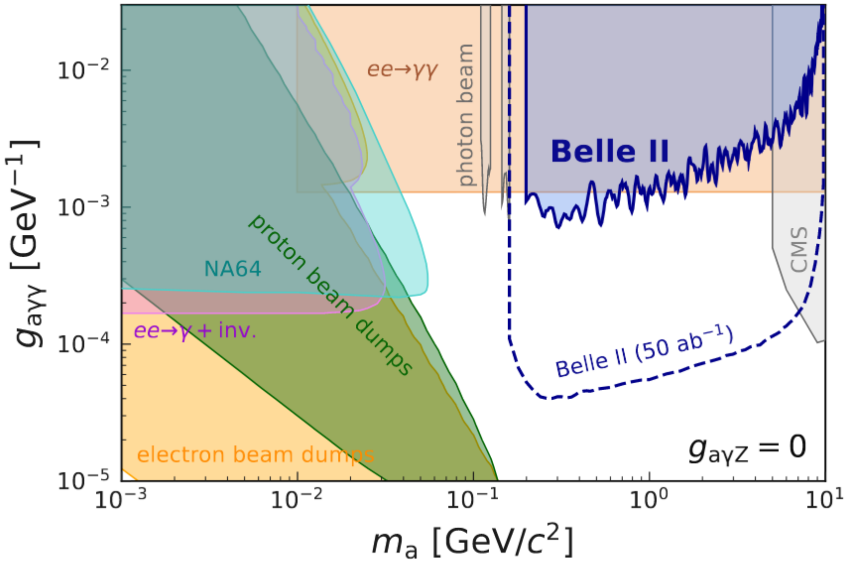




Expected Belle II sensitivity for ALPs with a three photons signature for $\int \mathcal{L} = 50$ ab^{-1}

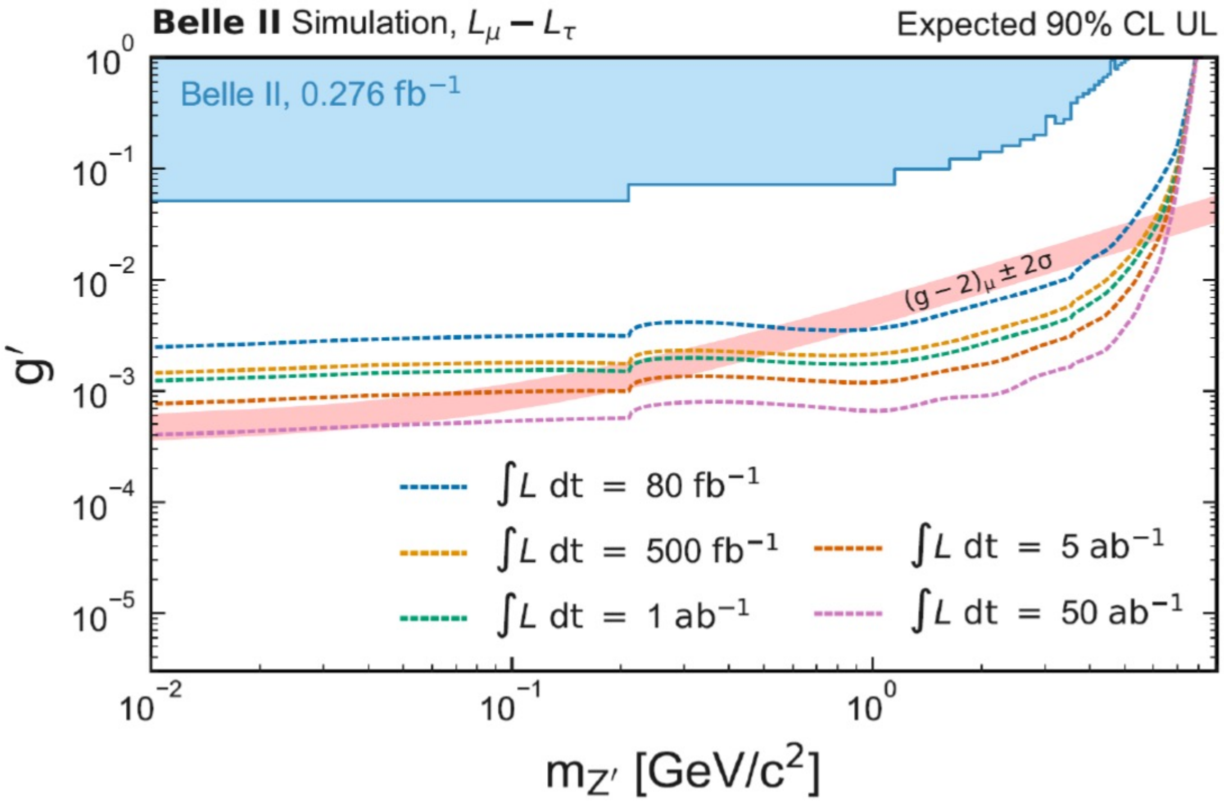
Belle II can reach unique sensitivity in parameter-space regions inaccessible to beam-dump experiments

[arxiv:2207.06307]

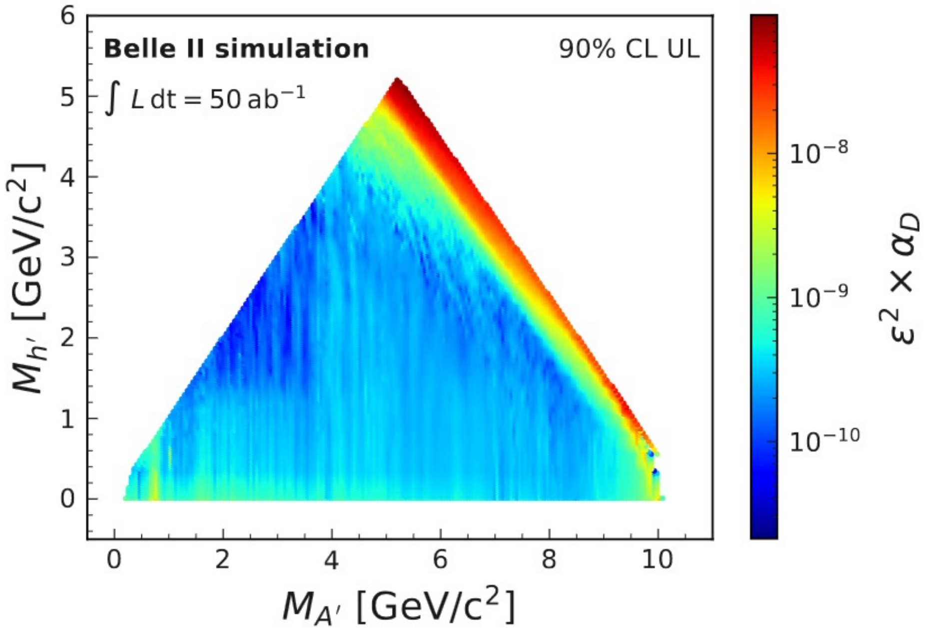


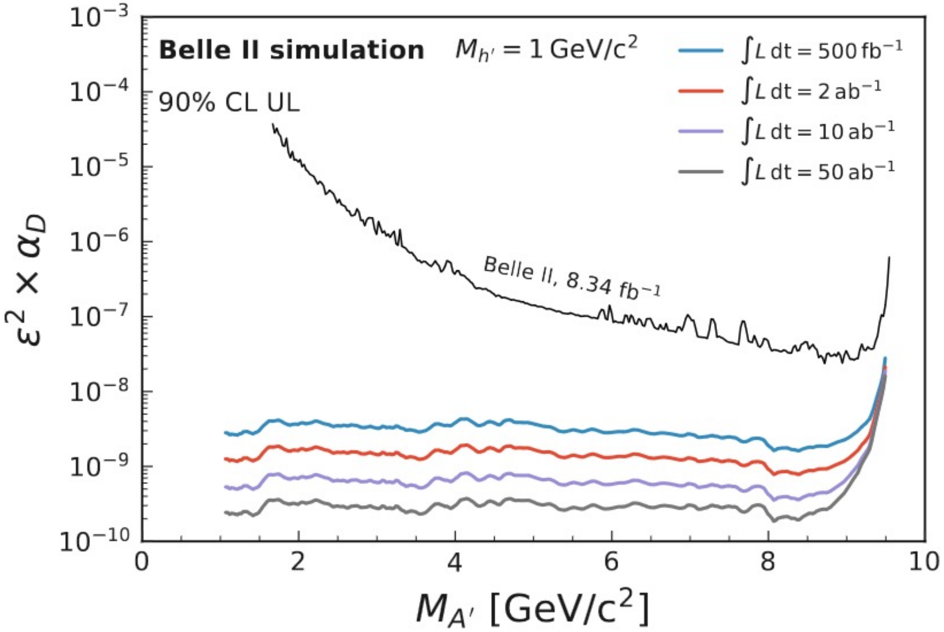
Z’ → invisible luminosity projections

Expected limits for luminosities up to 50 ab^{-1} [arxiv:2207.06307]



Dark Higgsstrahlung: luminosity projections





Systematic uncertainties are assumed to be at the same present level of 2% both for signal and background.

Limits on coupling will be still dominated by statistics also at the highest projected luminosities. Improvements of limits will be ~2 order of magnitude for $M_{A}' \gtrsim 8$ GeV and several orders of magnitude for lower masses

[arxiv:2207.06307]