Recent results on the dark sector from Belle II

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PASCOS - 27th International Symposium on Particles, Strings and Cosmology

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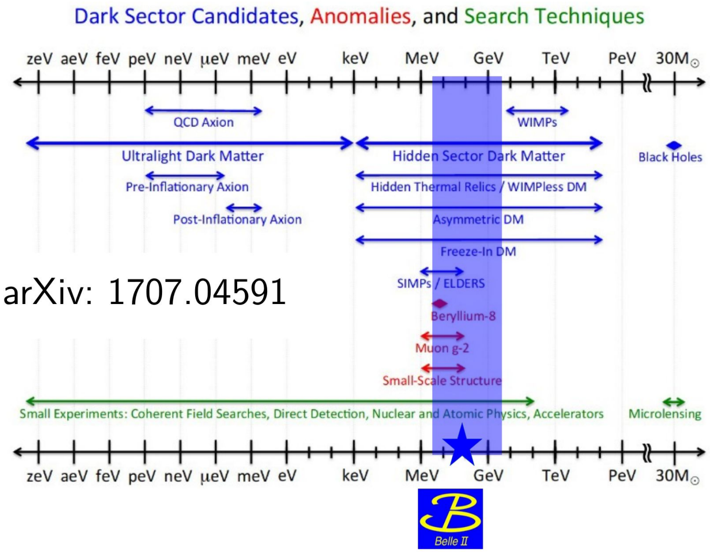
Introduction

- B-factories have unique reach in direkt searches for the light dark sector
  - low mass mediator particles on the MeV-GeV scale

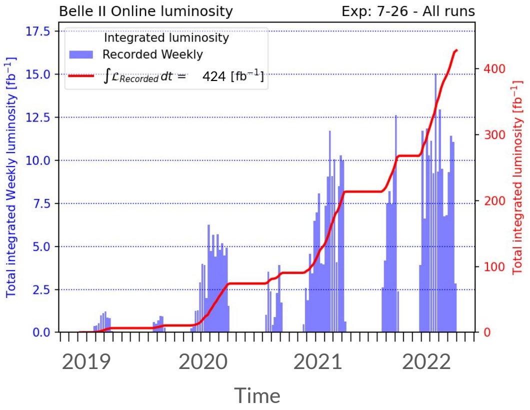
- Recent results from Belle II:
  - Dark Higgsstrahlung
  - Z’ → invisible
  - ττ resonance
    - Z’ → ττ
    - S → ττ
    - ALP → ττ



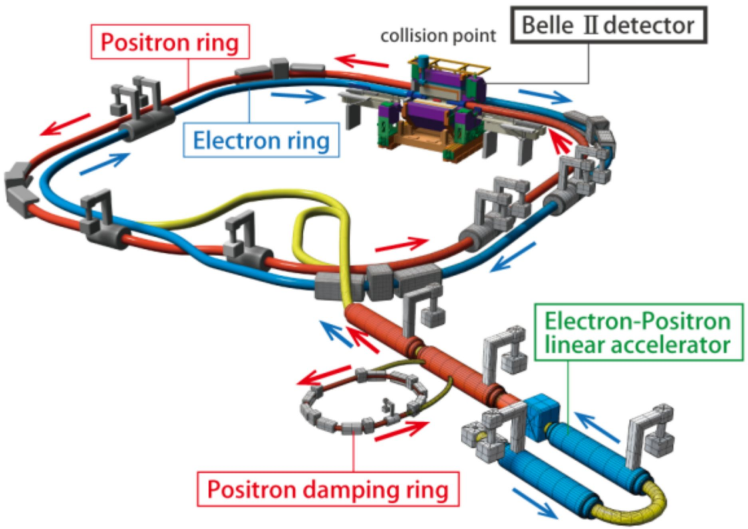
arXiv: 1707.04591

Belle II and SuperKEKB

- B-factory located in Tsukuba, Japan
- colliding electrons and positrons at $m_{\Upsilon(4S)}$=10.58 GeV/c^2
- collected luminosity from 2019-2022: **424 fb^{-1}**
- peak luminosity world record: **4.7 x 10^{34} cm^{-2} s^{-1}**
- target x50 Belle data (≈**50ab^{-1}**)



SuperKEKB accelerator

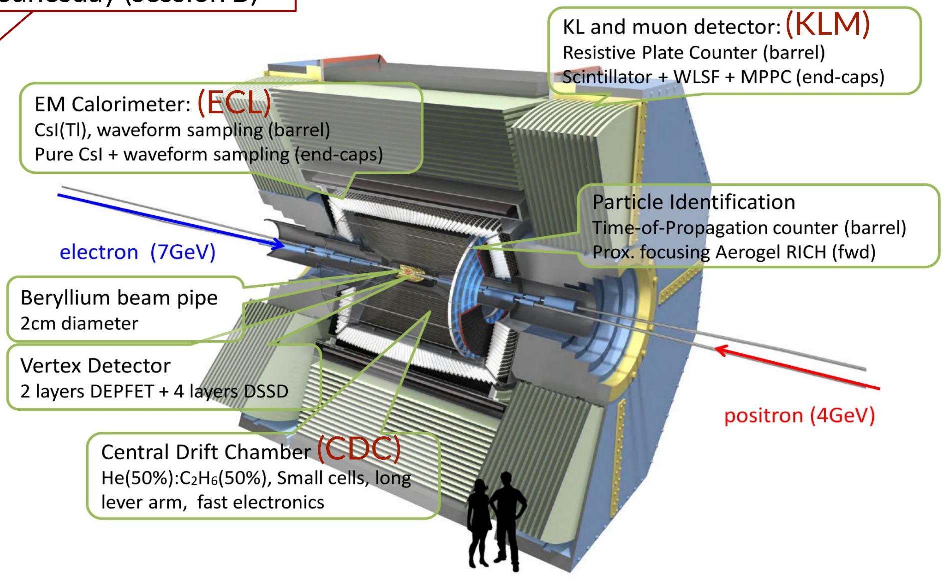


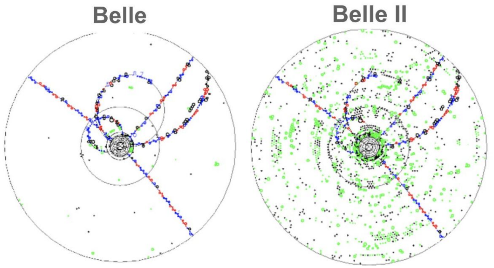
Belle II and SuperKEKB

see talk by Doris Kim on wednesday (session B)

- general purpose detector: B and D physics, quarkonium, τ-physics, dark sector, …
- large solid angle coverage (> 90%)
  - well known missing mass and energy
- clean collision environment
- excellent PID
- dedicated low-multiplicity triggers
  - two-track trigger (+ opening angle)
  - three-track trigger
  - E_{ECL}>1 GeV trigger

Belle II detector

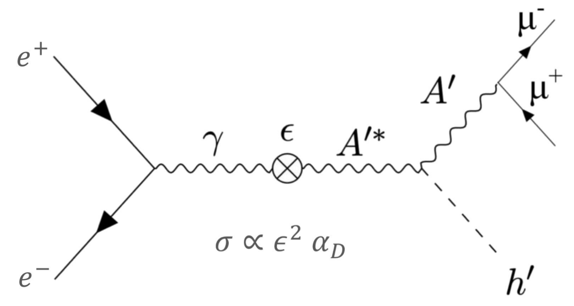




challenge: increased beam backgrounds

Dark Higgsstrahlung: $e^+e^- \to A' h'$

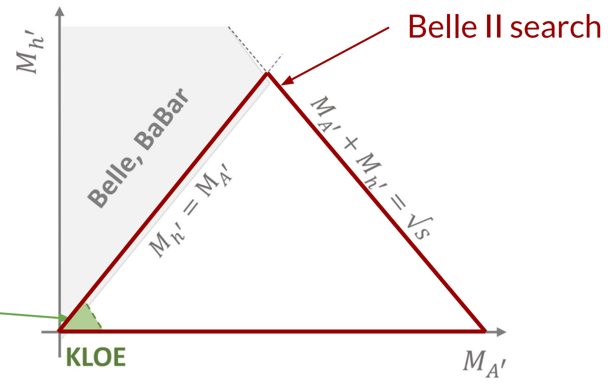
- U(1)' extension to SM » [Phys. Rev. D 79, 115008 (2009)]
  - Dark photon A'
    - coupled to SM photon via kinetic mixing parameter ε
    - mass generated via spontaneous symmetry breaking
  - Dark Higgs h'
    - couples with α_D to A'



- $M_{h'} < M_{A'}$: h' is long-lived (invisible) ⇒ 2 charged tracks

  $M_{A'} \Leftrightarrow M_{\mu\mu}$ and **$M_{h'} \Leftrightarrow M_{recoil}$**

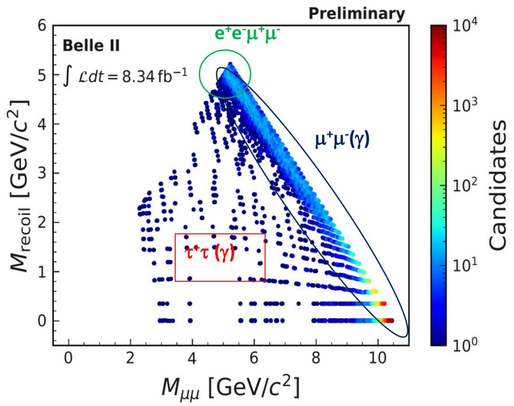
  partially constrained by [KLOE (2015)]



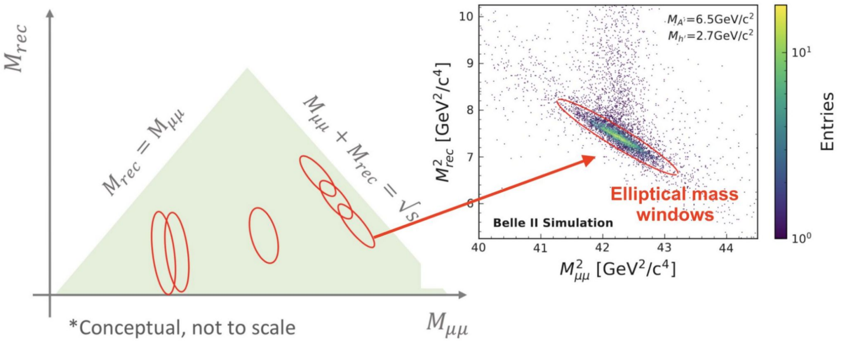
Dark Higgsstrahlung - Analysis

- data
  - 8.34 fb^{-1} (2019)
- backgrounds
  - $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ 79%
  - $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$ 18%
  - $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ 3%

observed yields →



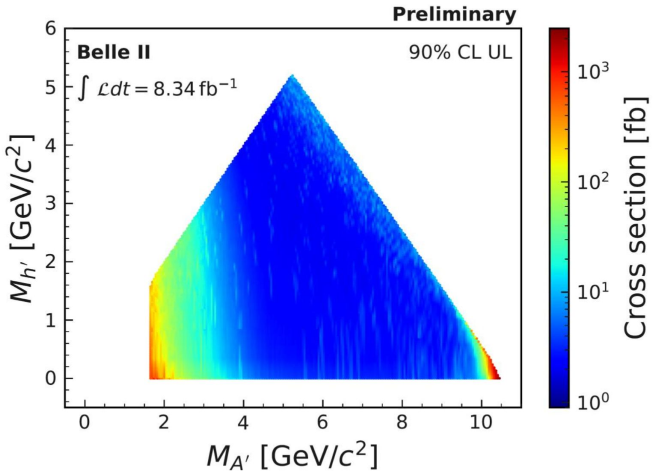
- selection
  - two reconstructed muons, $p_T^{\mu\mu} > 0.1$ GeV/c
  - recoil momentum in the ECL barrel, no nearby photon
  - cut on helicity angle
- strategy
  - scan for excess in 2D plane of M_{recoil} vs $M_{\mu\mu}$
  - ~9000 rotated elliptical mass windows to test signal hypotheses

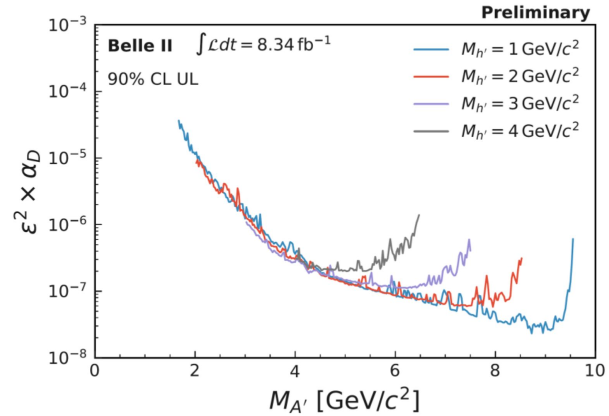


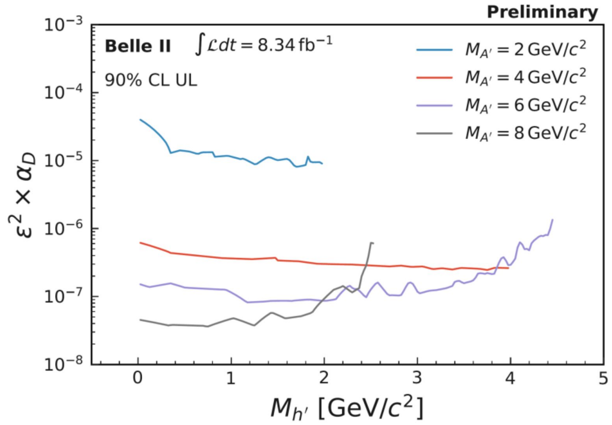
submitted to PRL
» ArXiv: 2207.00509

Dark Higgsstrahlung - Results

- no significant excess above background was observed → 90% CL upper limits

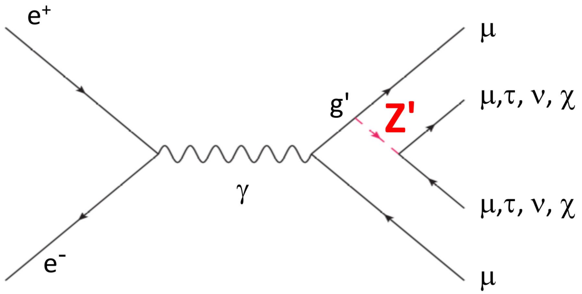






world leading limits for $1.65 < M_{A'} < 10.51$ GeV/c^2

Z': the L_μ-L_τ model



- extension of standard model with a U(1)' group
- gauging L_μ-L_τ, the difference of leptonic μ and τ number
- Z' is resulting new massive gauge boson that couples only to μ and τ leptons

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

- can provide solution for
  - dark matter puzzle (Z' as mediator between SM and DS)
  - $(g-2)_\mu$
  - $b \to s\mu\mu$, R_K , R_{K^*} anomalies

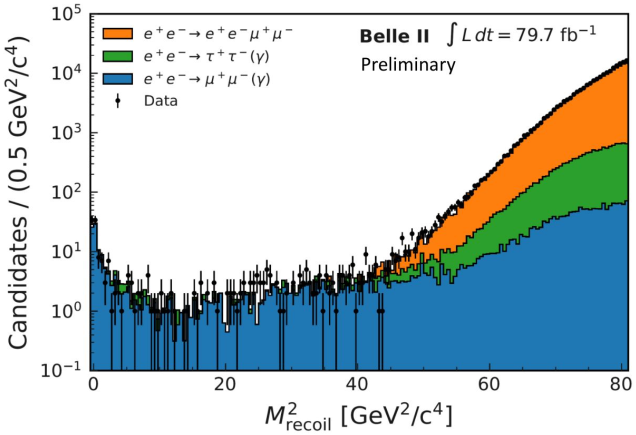
» Altmannshofer et al. JHEP 1612 (2016) 106
» Shuve et al. PRD 89, 113004 (2014)

- Belle II search for Z' in $\mu^+\mu^-$ final state with
  - Z' → invisible (neutrinos / dark matter)
  - Z' → ττ

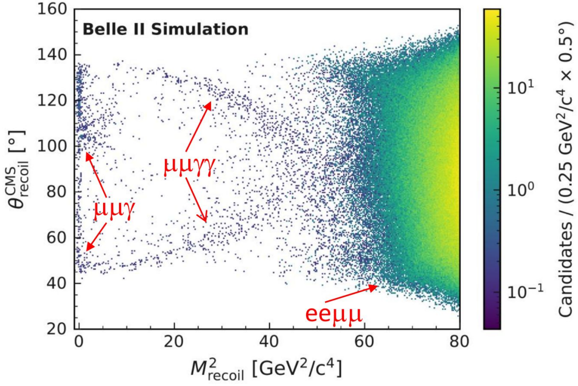
→ final states with missing energy, $M_{Z'} \Leftrightarrow M_{recoil}$

Z' → invisible - Analysis

- data
  - 79.7 fb^{-1} (2019-2020)
- backgrounds
  - $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$
  - $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$
  - $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$

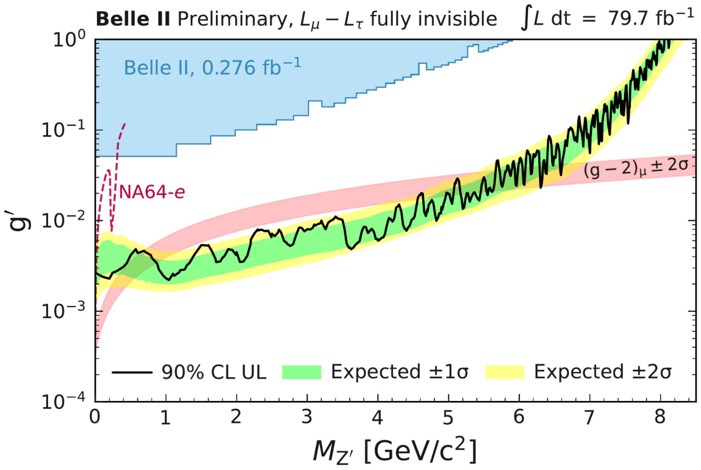


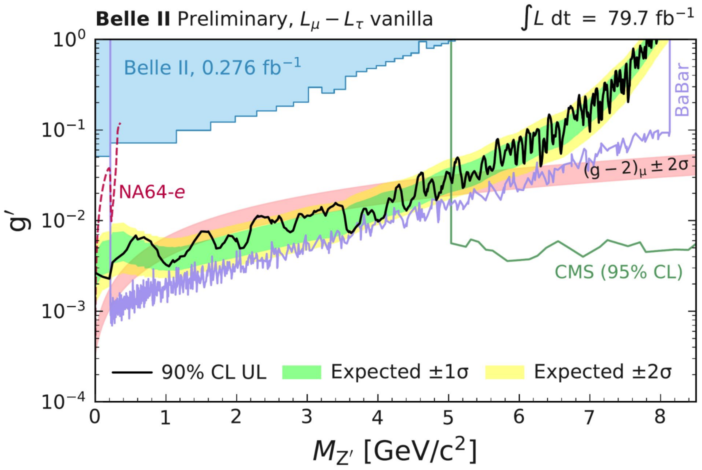
- selection
  - two reconstructed muons, $p_T^{\mu\mu} > 0.4$ GeV/c
  - recoil momentum in the ECL barrel, no nearby photon
  - neural network trained to optimize Punzi FOM
    - » Eur. Phys. J. C 82, 121 (2022)
- strategy
  - template fit in 2D plane of θ_{recoil} vs M^2_{recoil}



Z' → invisible - Results

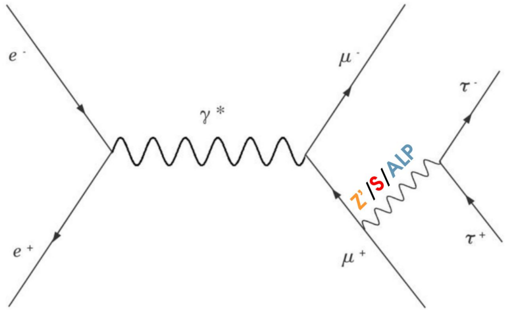
- no significant excess above background was observed → 90% CL upper limits





excluded fully invisible Z' as explanation for $(g\text{-}2)_\mu$ for $0.8 < M_{Z'} < 5.0$ GeV/c^2

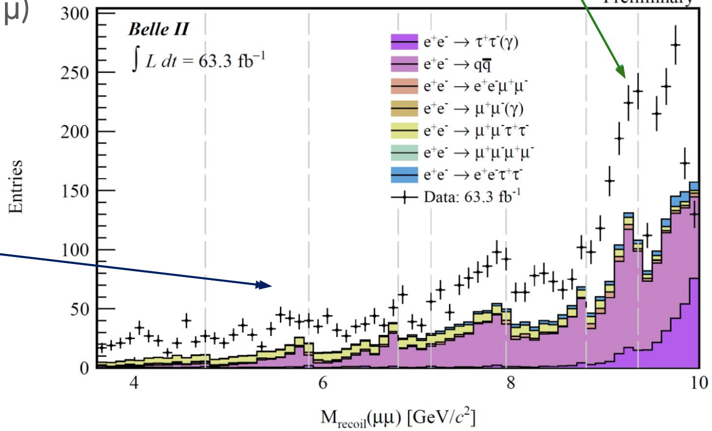
Z', S, ALP $\rightarrow \tau\tau$ - Analysis



- search for a $\tau\tau$ resonance in $\mu^+\mu^-\tau^+\tau^-$ final states
- data
  - 63.3 fb^{-1} (2019-2020)
- selection
  - 4 tracks: 2μ + 2 e/μ/π (1-prong τ decay)
  - M(4-track) < 9.5 GeV/c^2
  - 8 neural networks - trained for different ranges in $M_{recoil}(\mu\mu)$
- backgrounds
  - $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$ (1x3 prong)
  - $e^+e^- \rightarrow qq$ (q=u,d,s,c)
  - $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$
  - $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$ ← no ISR in simulation
  - $e^+e^- \rightarrow e^+e^-\tau^+\tau^-$
  - $e^+e^- \rightarrow \mu^+\mu^-\pi^+\pi^-$, $e^+e^- \rightarrow e^+e^-X_{hadronic}$ ← not simulated
- strategy
  - fit for a signal in M_{recoil} above floating background

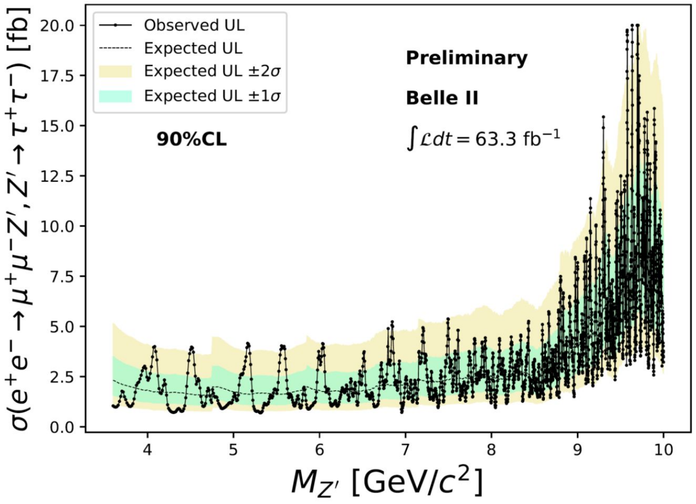
$e^+e^- \rightarrow e^+e^-X_{hadronic}$

signal mass resolution: 1.5 – 30 MeV/c^2

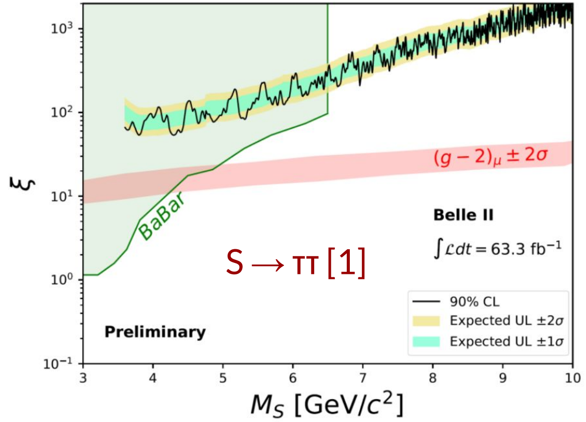


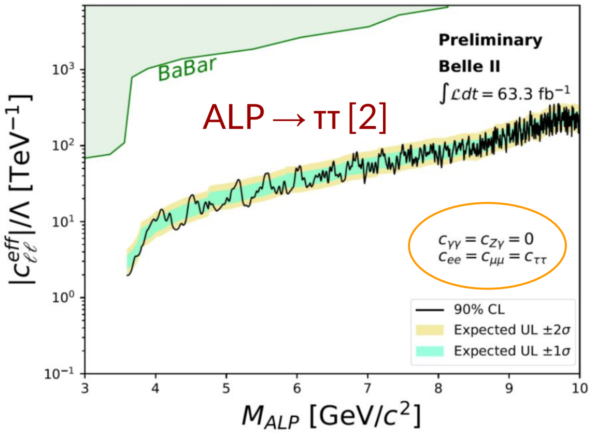
Z', S, ALP → ττ - Results

- no significant excess above background was observed → 90% CL upper limits



leptophilic scalar S



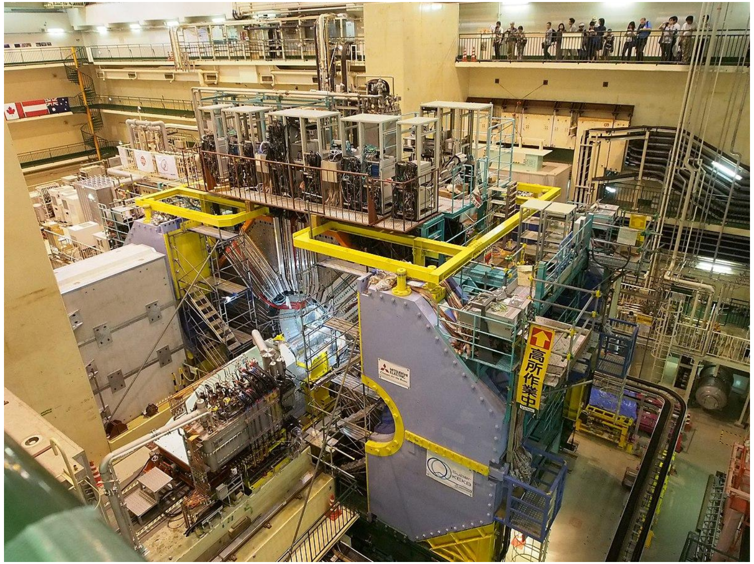


first constraints on S for $M_S > 6.5$ GeV/c² + first direct constraints for ALP→ττ

» [1] PRD 95 (2017) 075003
» [2] arXiv:2110.10698

Summary

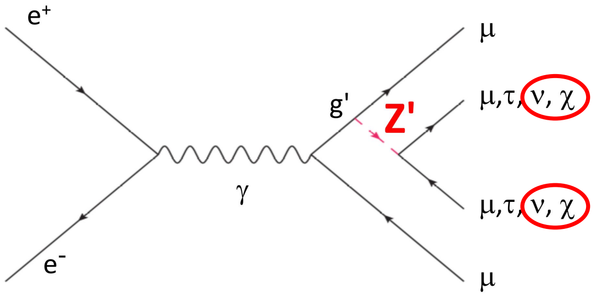
- Belle II recorded 424 fb^{-1} so far → plan to collect $50ab^{-1}$ in the next decade
- suitable for light dark sector searches
  - hermetic detector
  - clean collision environment
  - excelled particle identification
  - dedicated low multiplicity triggers
- new results for
  - Dark Higgsstrahlung search
  - Z' → invisible search
  - Z', S, ALP → $\tau\tau$ search
- more to come in the future



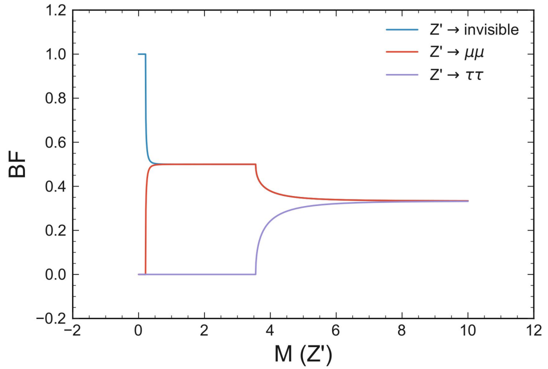
Thank you!

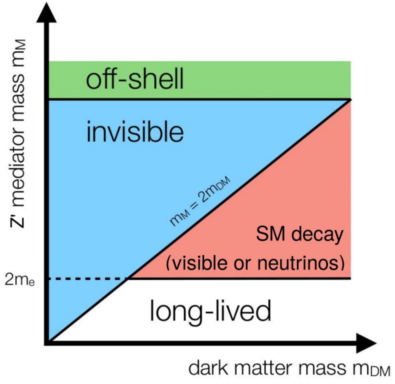
backup slides ⤵

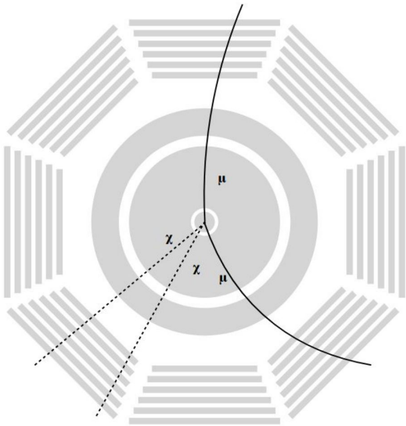
Z' → invisible



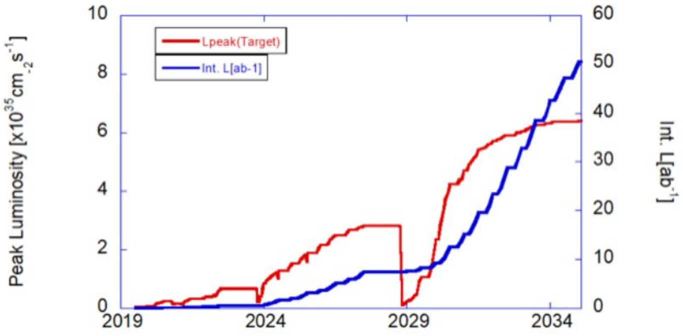
- within the L_μ-L_τ model the Z' can decay invisibly only via neutrinos
- if we allow a hypothetical decay of the Z' to dark matter, the BF(Z'→invisible) can be enhanced
- we consider both cases in our search







From KEKB to SuperKEKB

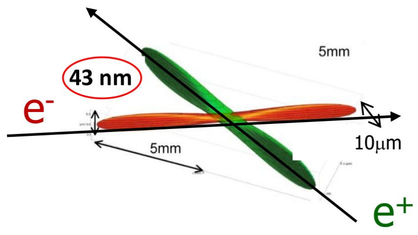


Belle + KEKB (1999-2010)

- peak luminosity: $2.1 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
- collected almost 1 ab^{-1} at different resonances and off-resonances

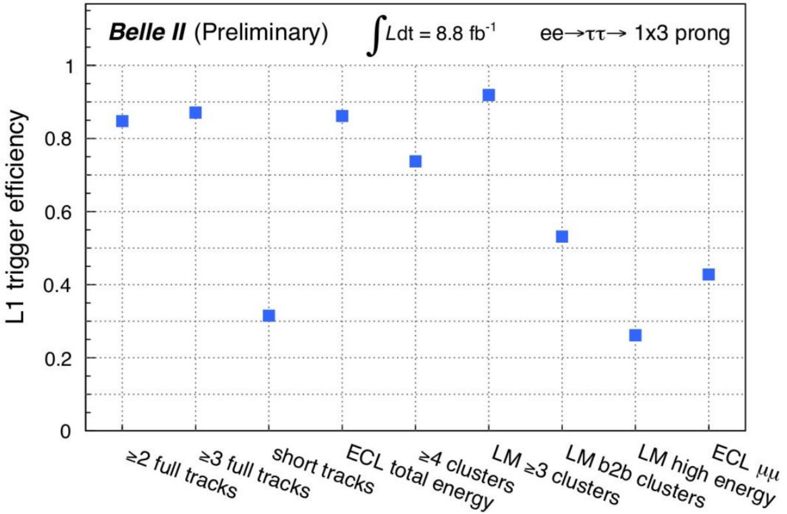
Belle II + SuperKEKB (first collisions in 2019)

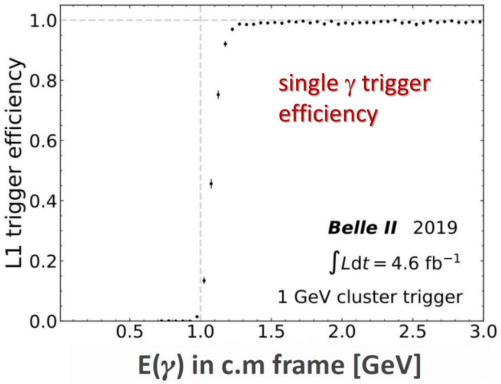
- nanobeam scheme + increased beam current
  → goal is 30 times higher luminosity
- luminosity world record ($2.9 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$)
- goal: collect 50 ab^{-1} during lifetime (now: 213 fb^{-1})
- challenges: dealing with higher machine backgrounds and trigger rates

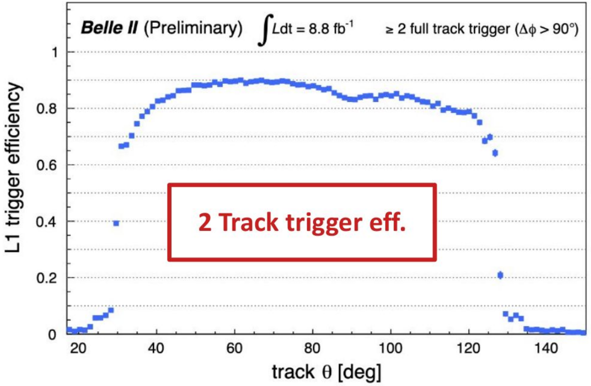


(LER/HER)	E (GeV)	β_y^* (mm)	β_x^* (cm)	φ (mrad)	I (A)	L ($\text{cm}^{-2}\text{s}^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	60×10^{34}

Trigger



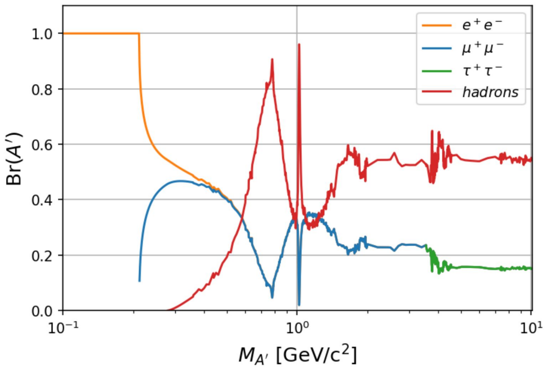


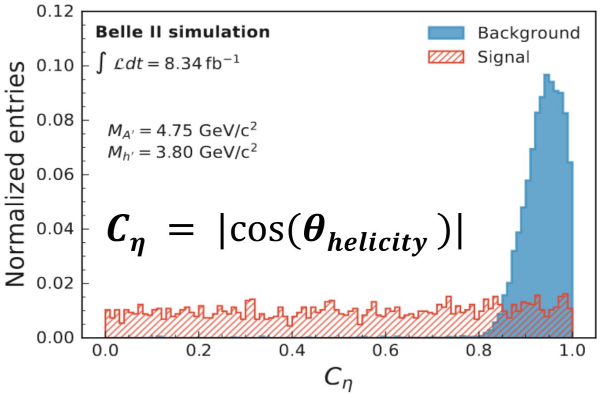


- + single muon trigger (drift chamber + muon detector)

Dark Higgsstrahlung

- $M_{h'} > M_{A'}$: $h' \to A'A' \Rightarrow$ 6 charged tracks searches by BaBar (2012) and Belle (2015)
- 2-track trigger
- control samples
  - μμγ μμ(γ) background
  - eμ ττ background

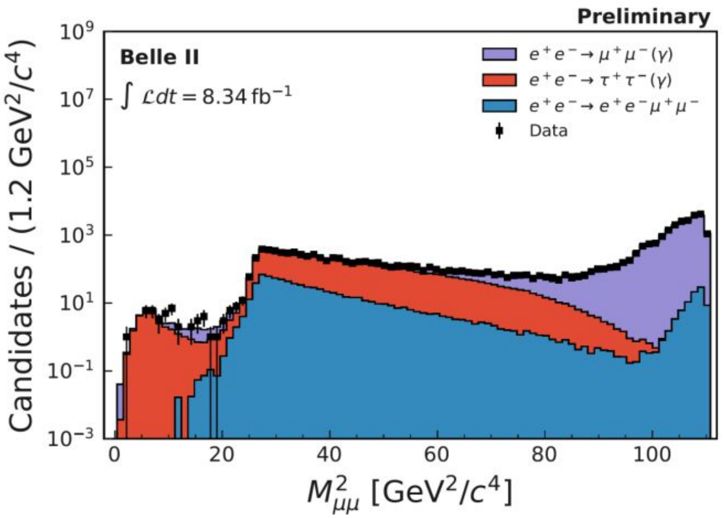


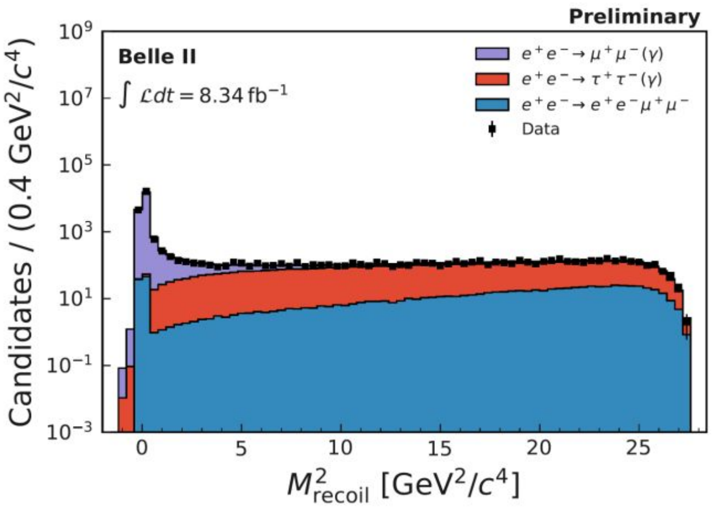


systematics

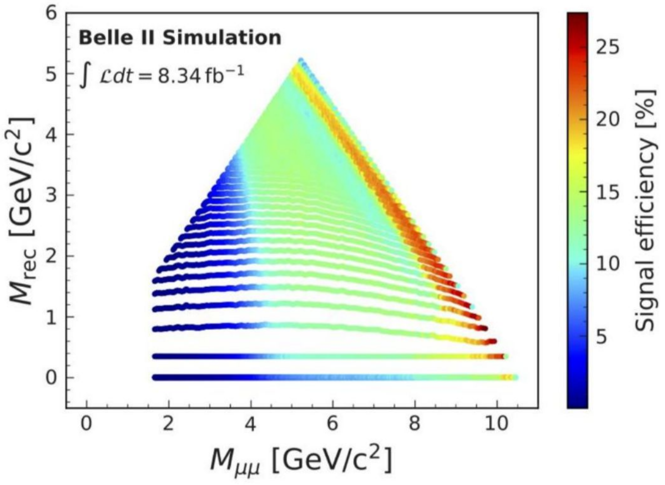
source	uncertainty	target
Pre-selections	**2 - 9.1%**	BKG & signal
BKG shape	**9.3%** (region specific)	BKG
C_η cut	**1%**	BKG
Mass resolution	**2.4%** (on average)	signal
Eff. Inside windows	**2 - 5%**	signal
Theory (BR A')	**4%**	signal

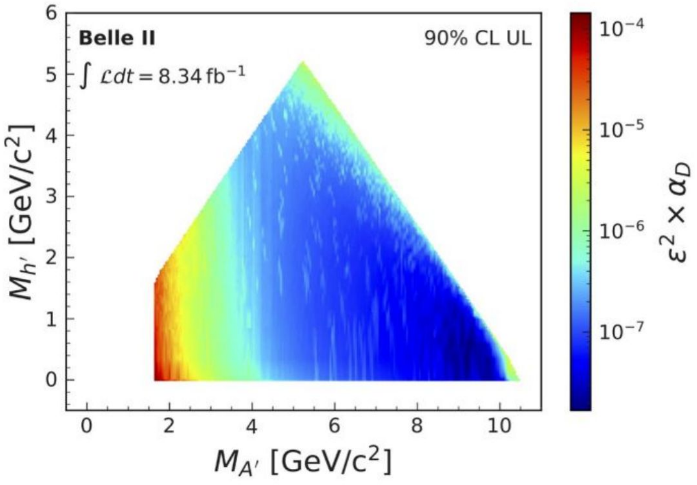
Dark Higgsstrahlung





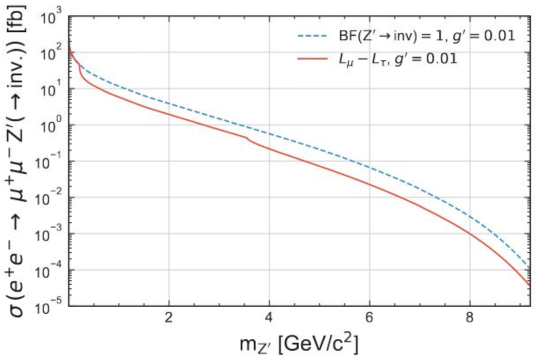
Dark Higgsstrahlung





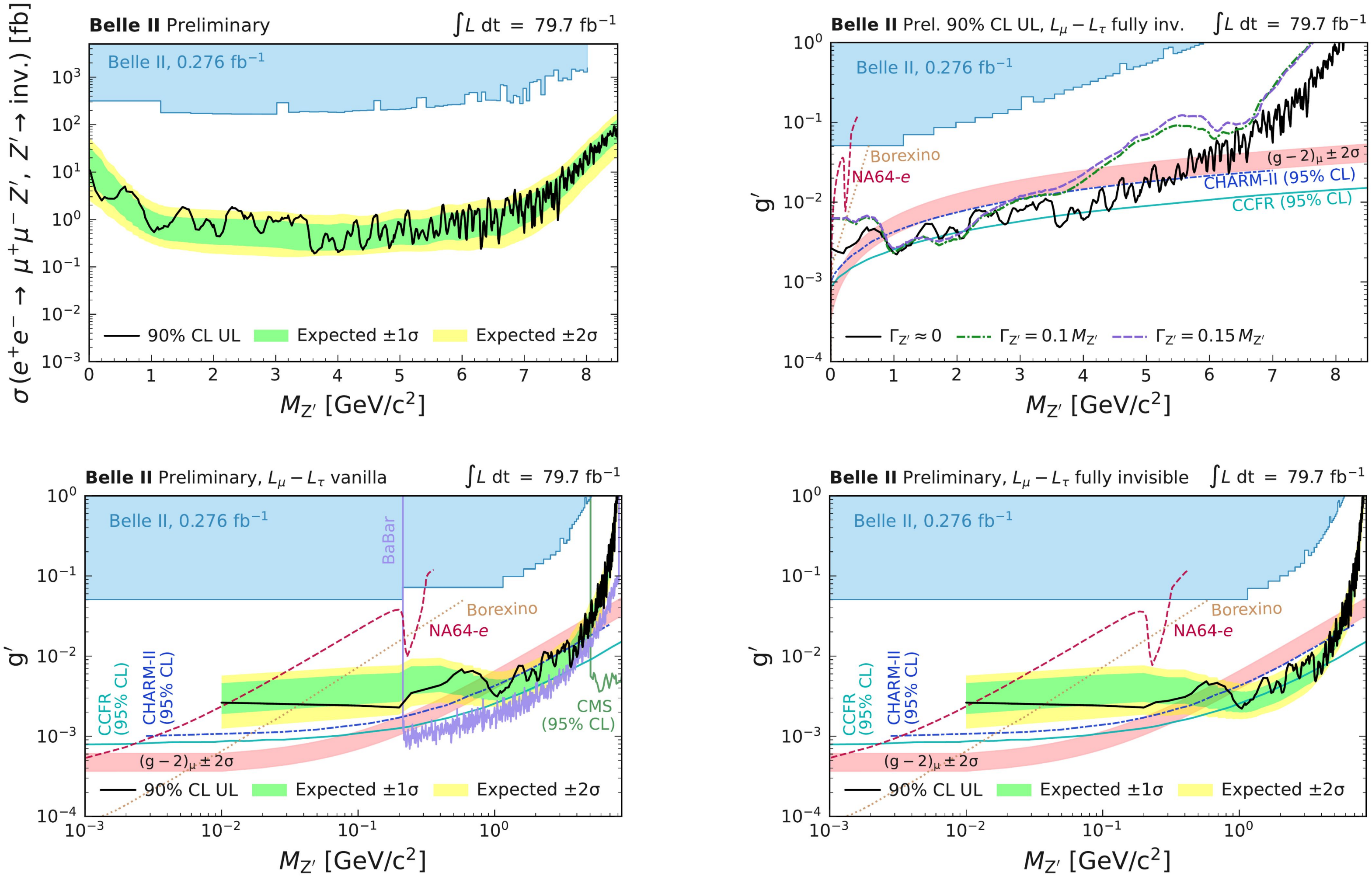
Z' → invisible

- previous searches for Z' → $\mu^+\mu^-$ by BaBar, Belle, CMS
- 2-track trigger
- control samples
  - μμγ selection+NN studies (low mass)
  - eμ selection+NN studies (medium + high mass)
  - ee(γ) γ veto studies



systematics

Source	Low mass	Medium mass	High mass
selections	2.7%	6.5%	8.3%
Mass resolution	10%	10%	10%
Background shapes	3.2%	8.6%	25%
Photon veto	34%	5%	5%
luminosity	1%	1%	1%



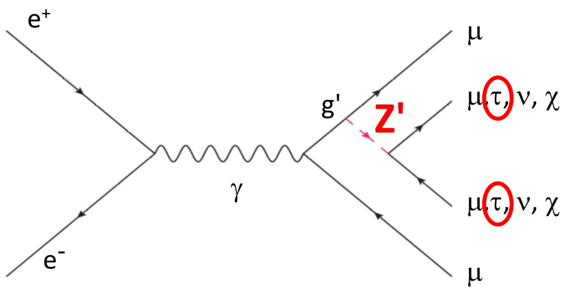
Belle II Preliminary
∫L dt = 79.7 fb⁻¹
Belle II, 0.276 fb⁻¹
90% CL UL
Expected ±1σ
Expected ±2σ
σ(e⁺e⁻ → μ⁺μ⁻ Z′, Z′ → inv.) [fb]
M_Z′ [GeV/c²]
Belle II Prel. 90% CL UL, L_μ − L_τ fully inv.
∫L dt = 79.7 fb⁻¹
Belle II, 0.276 fb⁻¹
Borexino
NA64-e
(g − 2)_μ ± 2σ
CHARM-II (95% CL)
CCFR (95% CL)
Γ_Z′ ≈ 0
Γ_Z′ = 0.1 M_Z′
Γ_Z′ = 0.15 M_Z′
g′
M_Z′ [GeV/c²]
Belle II Preliminary, L_μ − L_τ vanilla
∫L dt = 79.7 fb⁻¹
Belle II, 0.276 fb⁻¹
BaBar
Borexino
NA64-e
CCFR (95% CL)
CHARM-II (95% CL)
CMS (95% CL)
(g − 2)_μ ± 2σ
90% CL UL
Expected ±1σ
Expected ±2σ
g′
M_Z′ [GeV/c²]
Belle II Preliminary, L_μ − L_τ fully invisible
∫L dt = 79.7 fb⁻¹
Belle II, 0.276 fb⁻¹
Borexino
NA64-e
CCFR (95% CL)
CHARM-II (95% CL)
(g − 2)_μ ± 2σ
90% CL UL
Expected ±1σ
Expected ±2σ
g′
M_Z′ [GeV/c²]

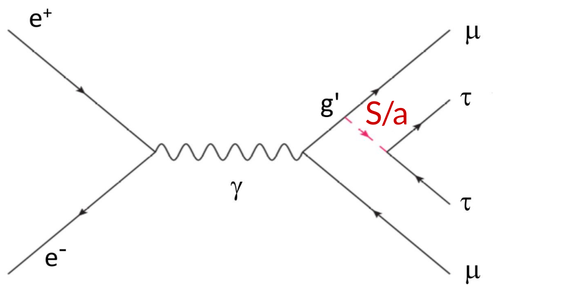
Z', S, ALP $\rightarrow \tau\tau$

- L_μ-L_τ: Z'
  - first search in ττ final state

- leptophilic scalar: S
  - partially constraint by BaBar in $S \rightarrow \mu\mu$
  - first search in ττ final state

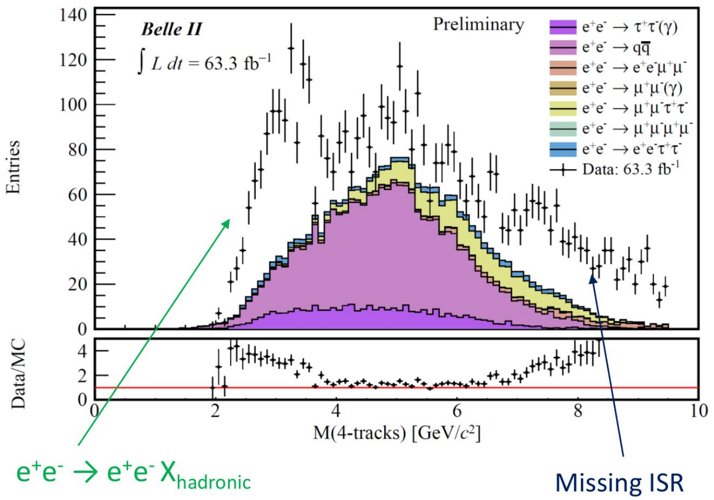
- ALP: a
  - assume $\mathbf{C_{ee}=C_{\mu\mu}=C_{\tau\tau}}$ and $\mathbf{C_{\gamma\gamma}=C_{Z\gamma}=0}$
  - ALP-τ coupling unconstrained





Z', S, ALP → ττ

- control sample
  - 2 π + 2 e/μ/π
- 3-track or single muon trigger



systematics

source	Uncertainty (%)
trigger	2.7
Particle ID	3.9-6.2
Tracking	3.6
Fit bias	4
MLP selection	2.8
Mass resolution	3
Efficiency interpolation	2.5
Luminosity	1
other	1
Total	**8.8-9.9**

Punzi-Net

» Eur. Phys. J. C 82, 121 (2022)

Min. detectable cross-section at Luminosity L

$$\sigma_{\min}(t) = \frac{\frac{b^2}{2} + a\sqrt{B(t)} + \frac{b}{2}\sqrt{b^2 + 4a\sqrt{B(t)} + 4B(t)}}{\varepsilon(t)\cdot L}$$

Signal efficiency

N surviving background events

True label

NN output

$$\varepsilon(t) \rightarrow \varepsilon(\boldsymbol{w},\boldsymbol{b}) = \sum_{\boldsymbol{x}} \frac{y_i \cdot \hat{y}_i(\boldsymbol{w},\boldsymbol{b})\cdot s_{\mathrm{sig}}}{N_{\mathrm{gen}}}$$

Scaling factor

N generated MC signal events

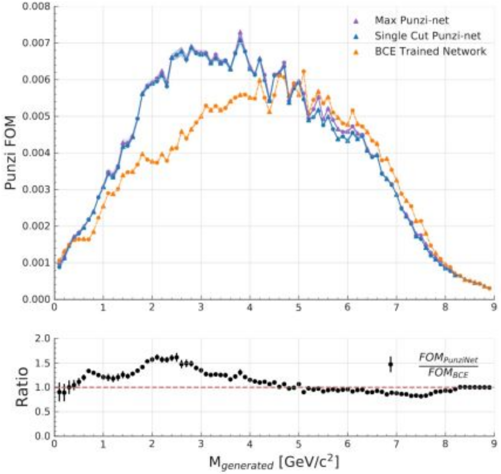
The constants a and b are the number of sigmas corresponding to one-sided Gaussian tests at some predefined significance level, α and β . Here α is the probability of rejecting H_B when it is true (type I error), and β is the probability of not rejecting H_B when instead H_{S+B} is true (type II error).

NN output

$$B(t) \rightarrow B(\boldsymbol{w},\boldsymbol{b}) = \sum_{\boldsymbol{x}} (1-y_i)\cdot \hat{y}_i(\boldsymbol{w},\boldsymbol{b})\cdot s^i_{\mathrm{bkg}}$$

True Label

Scaling factor



Trained on 4 kinematic variables:

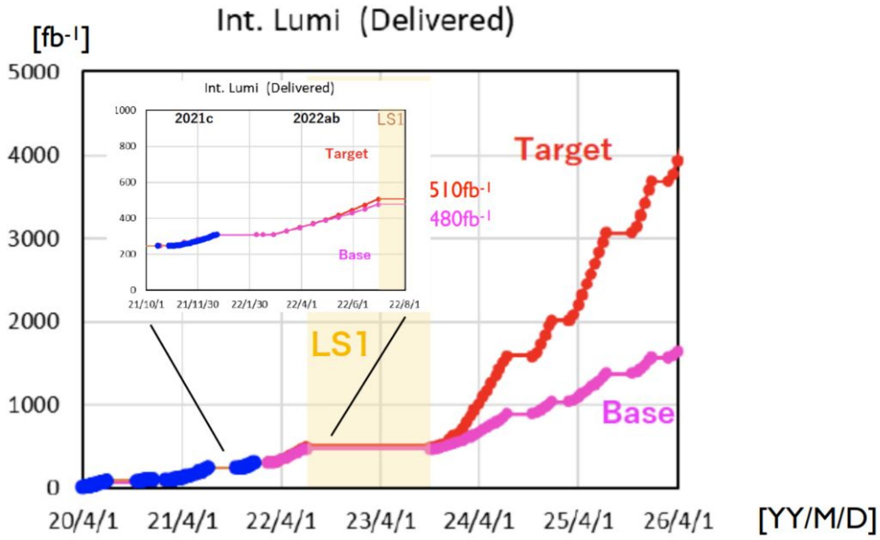
variable	description
$p^*_{t,\mathrm{thrust}}(\mu)$	The transverse momentum component of the muons with respect to the thrust axis.
$p^*_{t,\mu_{\min}}(\mu_{\max})$	The transverse momentum component of the higher energetic muon with respect to the lower energetic muon.
$p^*_{l,\mu_{\min}}(\mu_{\max})$	The longitudinal momentum component of the higher energetic muon with respect to the lower energetic muon.
$p^*_t(\mu^+\mu^-)$	The transverse momentum of the dimuon system.

» G. Punzi, Sensitivity of searches for new signals and its optimization

Projection of integrated luminosity delivered by SuperKEKB to Belle II

Target scenario: extrapolation from 2021 run including expected improvements.

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run



- We start long shutdown 1 (LS1) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement works of machine and detector.
- We resume physics running from Fall 2023.
- A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.
- An LS2 for machine improvements could happen on the time frame of 2026-2027