Dark Matter Studies in Accelerator Physics
3rd DMNet international symposium
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Palazzo Moroni, Padua, Italy

Search for (pseudo-)scalar and long-lived particles at Belle II

Laura Zani*
on behalf of the Belle II collaboration

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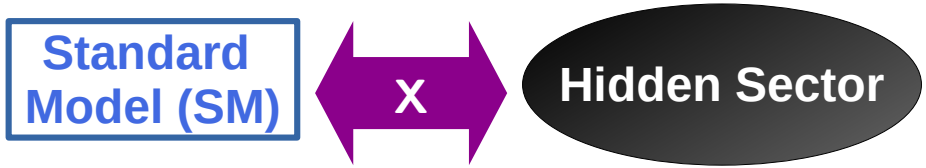
*laura.zani@roma3.infn.it

Outline

- Long-lived pseudo-scalar particles
- Invisible boson in τ decays
- Axion-like Particles
- Dark higgsstrahlung
- Outlook



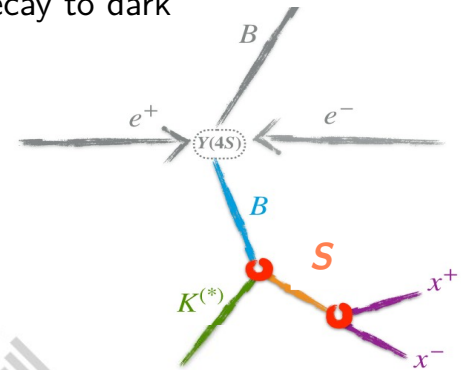
light mediator X:

- Pseudo-scalar portal $\rightarrow$ **Axion Like Particles (ALPs)**
- Scalar portal $\rightarrow$ **Dark higgs/Scalars**
- Vector portal $\rightarrow$ Dark Photons, Z' bosons
- Neutrino portal $\rightarrow$ Sterile Neutrinos

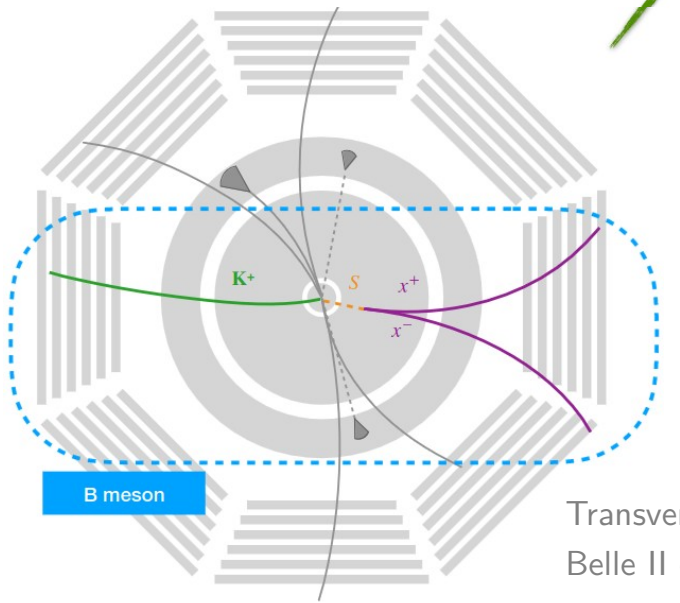
M.Laurenza's talk this afternoon!

Search for long-lived (pseudo)scalar in b→s transitions

- **First model-independent** search for dark scalar particles S from B decays in rare $b \to s$ transition
- S could mix with SM Higgs with mixing angle θ_s (naturally long-lived for $\theta_s << 1$). For $M_S < M_B$ decay to dark matter kinematically forbidden by relic density constraint



- Look for S decays into SM final states in **8 exclusive channels:**
  - $B^+ \to K^+ S$ and $B^0 \to K^{*0} (\to K^+\pi^-) S$, with $S \to ee/\mu\mu/\pi\pi/KK$
- B-meson kinematics to reject combinatorial $ee \to q\bar{q}$ background
- SM long-lived $\mathbf{K^0_S}$ **mass region vetoed** → excellent control sample in data to evaluate **LLP performance** (efficiencies, shapes)
- Further peaking backgrounds suppressed by tighter displacement selection



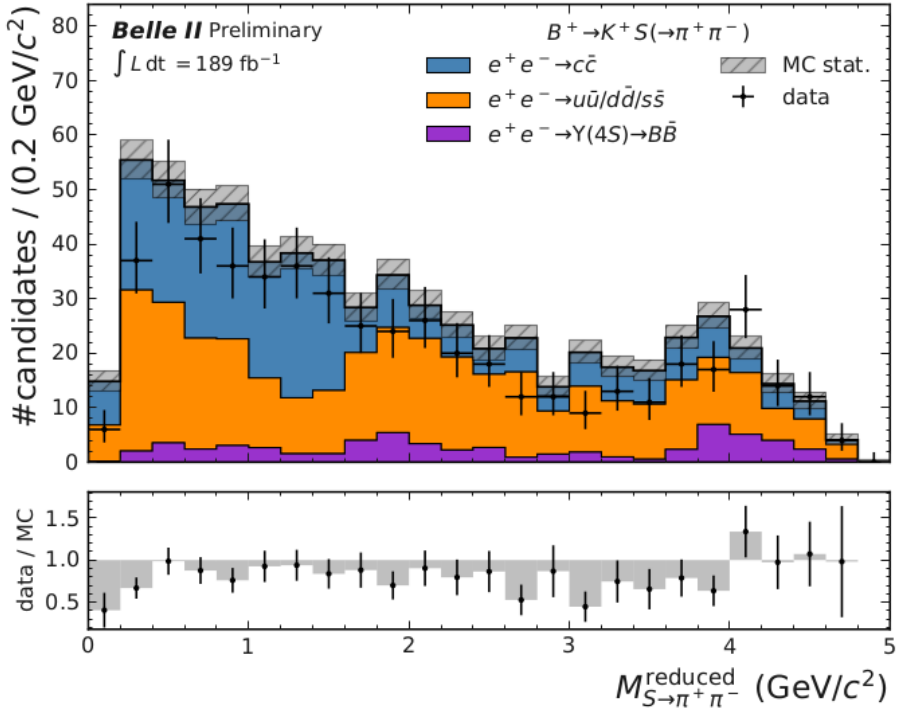
Transverse view of the Belle II detector

Search for LLP: signal extraction

- Bump hunt in the LLP mass with unbinned maximum likelihood fits to
  - using the **reduced mass spectrum** easier to model at threshold, separately for each channel and lifetime

$$M^{\text{reduced}}_{S\to x^+x^-} = \sqrt{M^2_{S\to x^+x^-} - 4m_x^2}$$

- Background determined directly in data (robust against un-modelled non-peaking background)



First model independent results for LLP

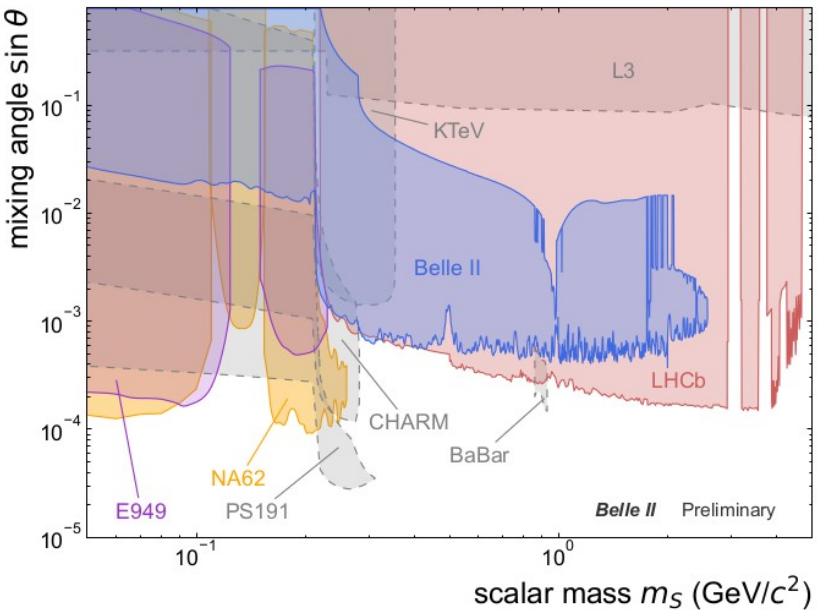
- No significant excess found in **189 fb^{-1}** → **first model-independent** 95% CL upper limits on BF(B→K*S)×BF(S→x$^+$x$^-$) and BF(B→ K$^+$S)×BF(S→x$^+$x$^-$)

  First limits on exclusive hadronic final states

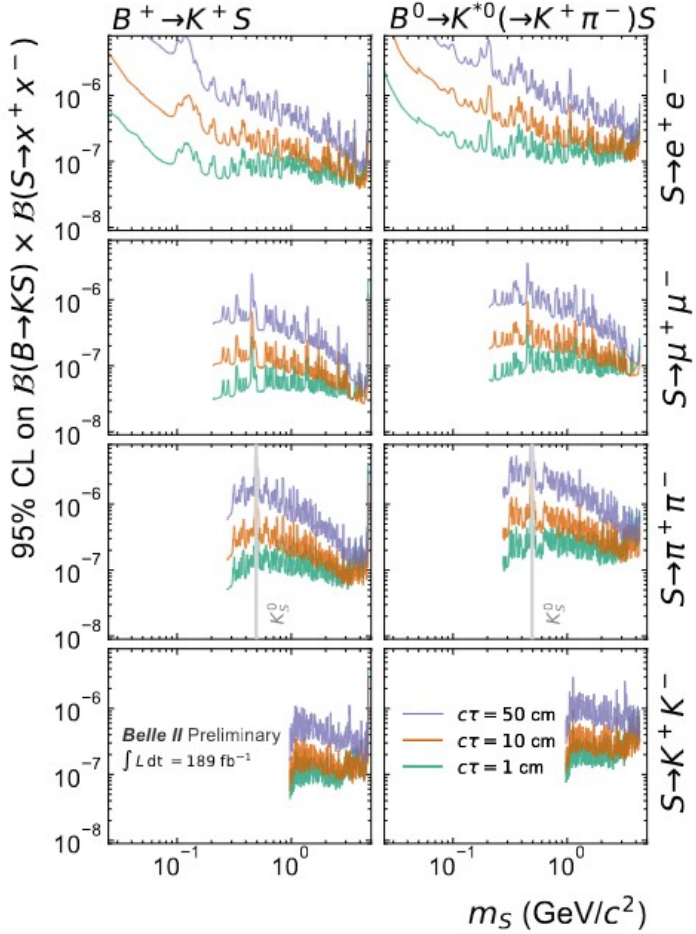
  → best sensitivity for direct search for K*e$^+$e$^-$ final state

- Translate into model dependent limits on m_S vs sinθ_S, with $c\tau_S = f(m_S, \theta_S)$

Combined scalar and ALP model fit [1]



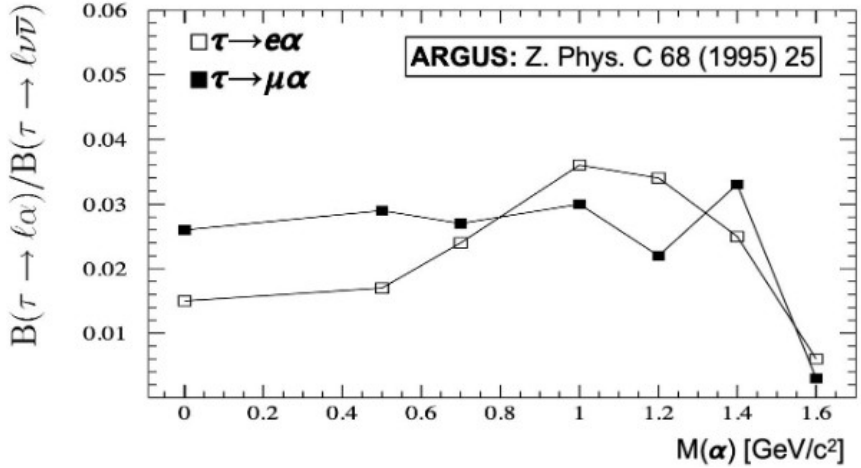
Submitted to PRL, arxiv:2306.02830



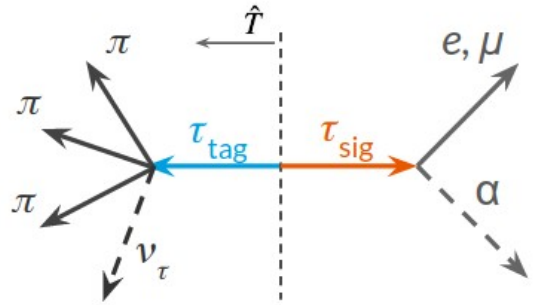
[1]: Phys. Rev. D 101 095006 (2020)

Invisible boson in lepton-flavor violating τ decays

- τ decays to new LFV bosons decaying invisibly predicted in many models, possible **ALPs candidates**[1]
- Previously at **ARGUS** [2](~ 0.5 fb^{-1}) → Belle II analysis relies on **120 x luminosity**
- Search for the process $e^+e^- \rightarrow \tau_{sig}(\rightarrow \ell\alpha)\,\tau_{tag}(\rightarrow 3\pi\nu)$, with ℓ=e or ℓ=μ



- Split event in two hemispheres based on the ***thrust axis:***
  - three tracks on the tag side, one track on the signal side
  - exploit the **shape differences**: *2-body* decay of signal (peaking in some kinematics features) over *3-body* decay of irreducible background from $\tau_{SM} \rightarrow \ell\nu\nu$

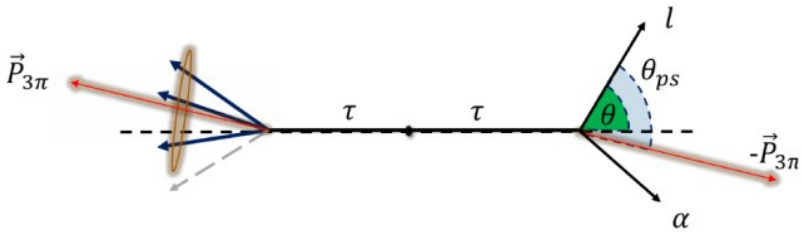


$$\vec{T} = max\left(\sum_i \frac{\vec{p_i}\cdot\hat{T}}{|p_i|}\right)$$

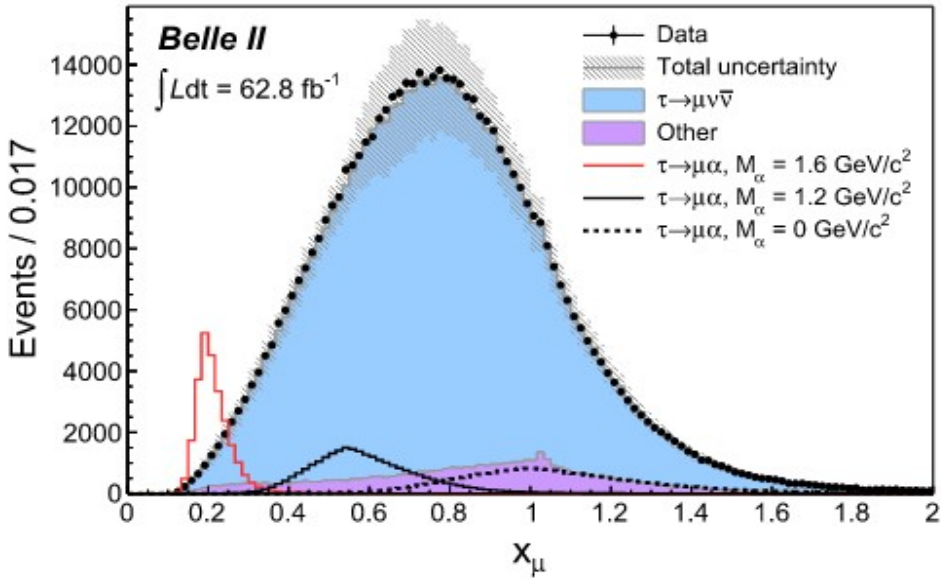
[1] M. Bauer, et al. Phys. Rev. Lett. 124, 211803 (2020)
[2] ARGUS Collaboration, Z. Phys. C 68, 25 (1995)

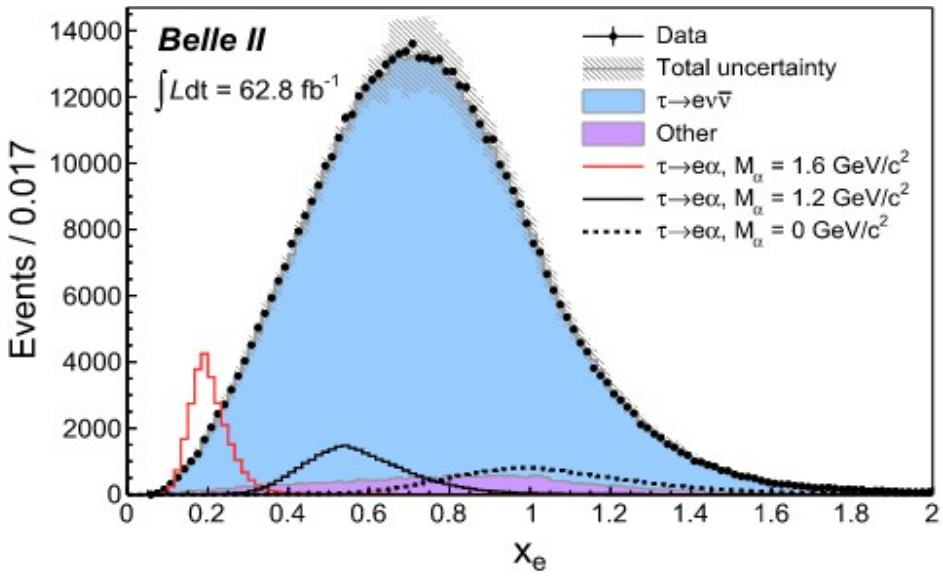
τ pseudo-rest frame

- Shape differences more prominent in the rest frame: approximate τ_{sig} pseudo-rest frame as $E_{sig} \sim \sqrt{s}/2$ and $\hat{p}_{sig} \approx -\vec{p}_{\tau_{tag}}/|\vec{p}_{\tau_{tag}}|$
- Discriminating variable: **normalized lepton energy** x_ℓ
- Bump hunt above broad spectrum from $\tau_{SM} \to \ell\nu\nu$



$$x_\ell \equiv \frac{E^*_\ell}{m_\tau c^2/2},$$

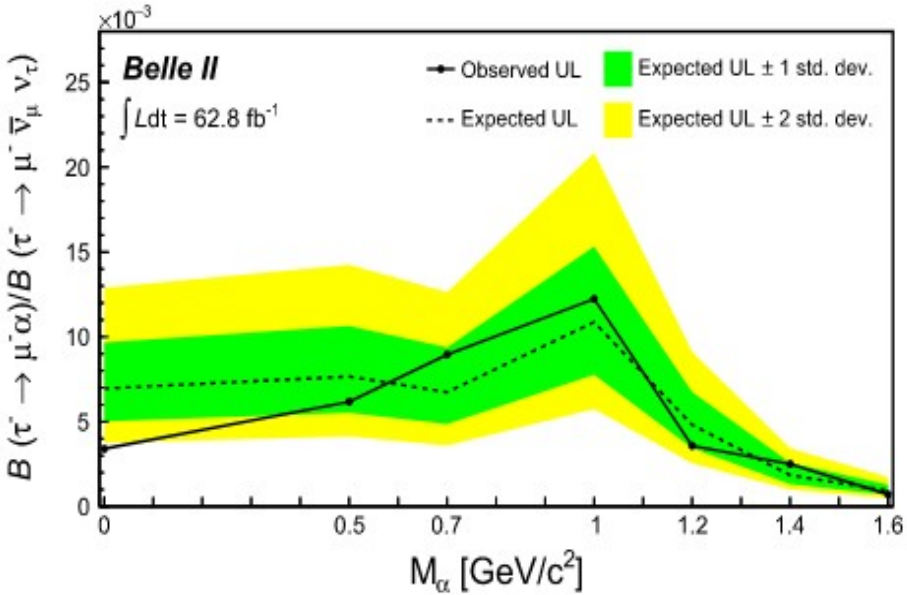


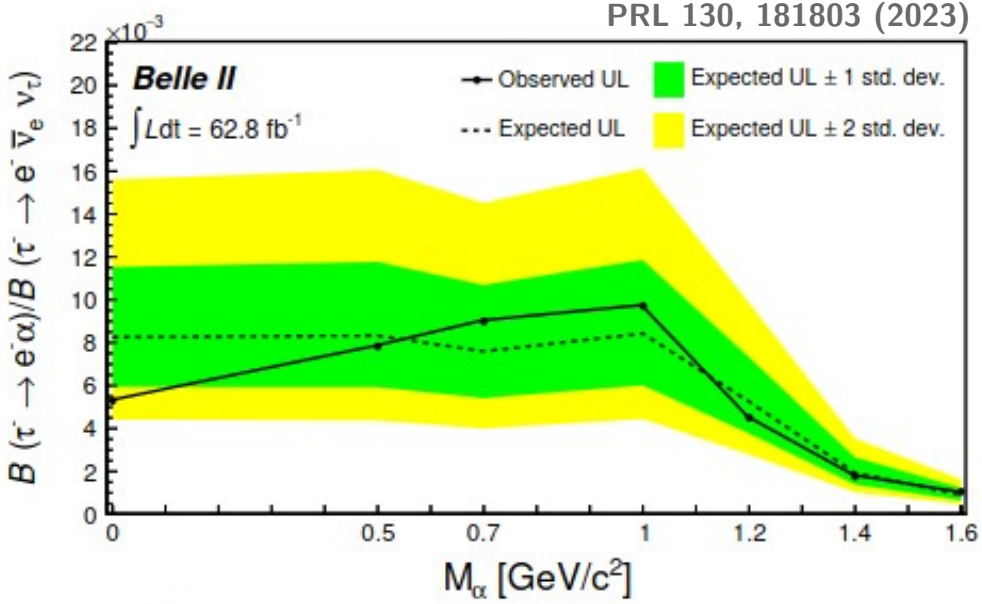


Invisible boson in LFV τ decays: results

- No significant excess found in **62.8 fb^{-1}**
- Set 95% CL upper limits on BF ratios of **BF($\tau_{sig} \to \ell\alpha$)** normalized to BF($\tau_{SM} \to \ell\nu\nu$)

PRL 130, 181803 (2023)

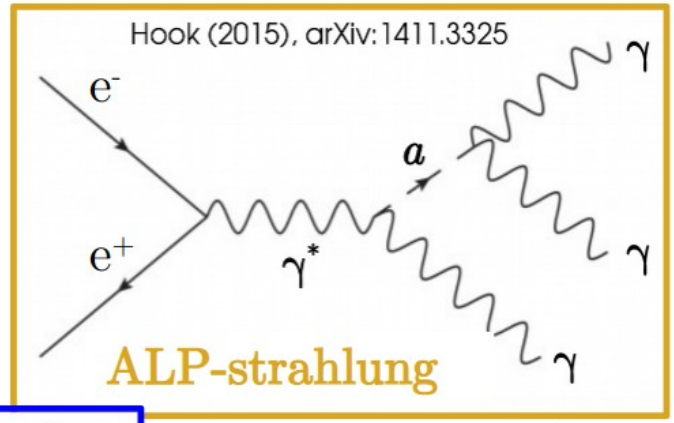


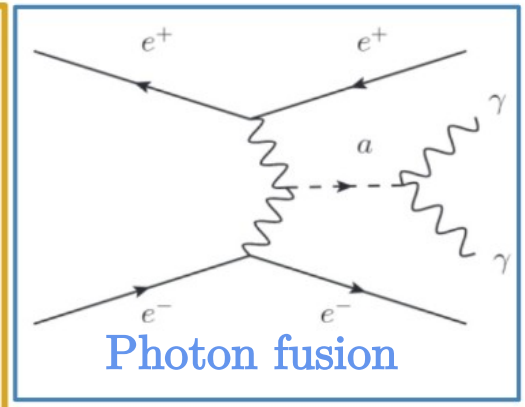


Between 2-14 times more stringent than previous limits

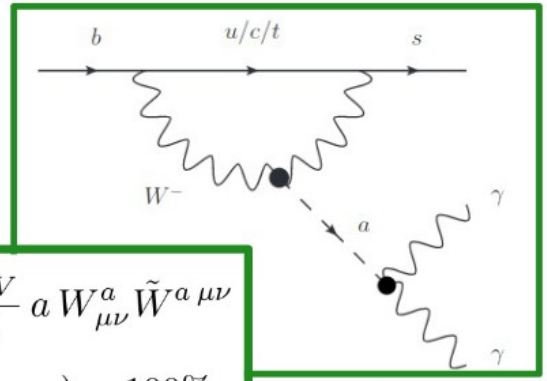
Axion-like particle

- Axion-like particles (ALPs) are pseudo-scalars coupling to bosons
- Unlike QCD axions, no relation between the coupling and the mass
- Explored photon coupling $g_{a\gamma\gamma}$ in *ALP-strahlung* processes (*photon fusion:* sensitivity under study)
- Exploit flavor changing neutral current and rare meson decays to investigate g_{aW} coupling ongoing studies for B→Ka



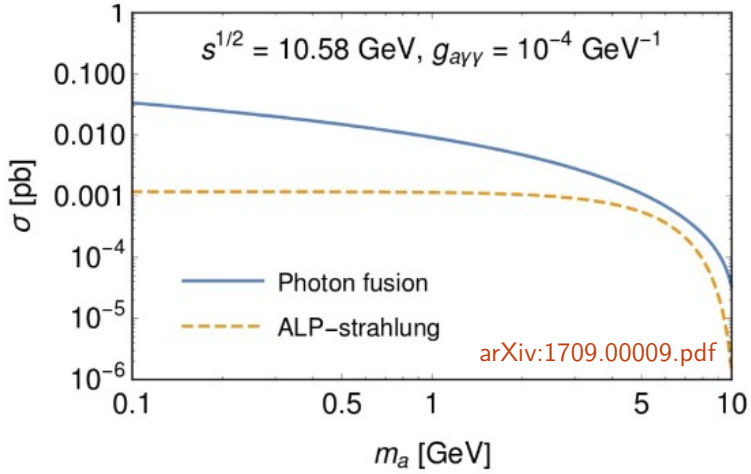


$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

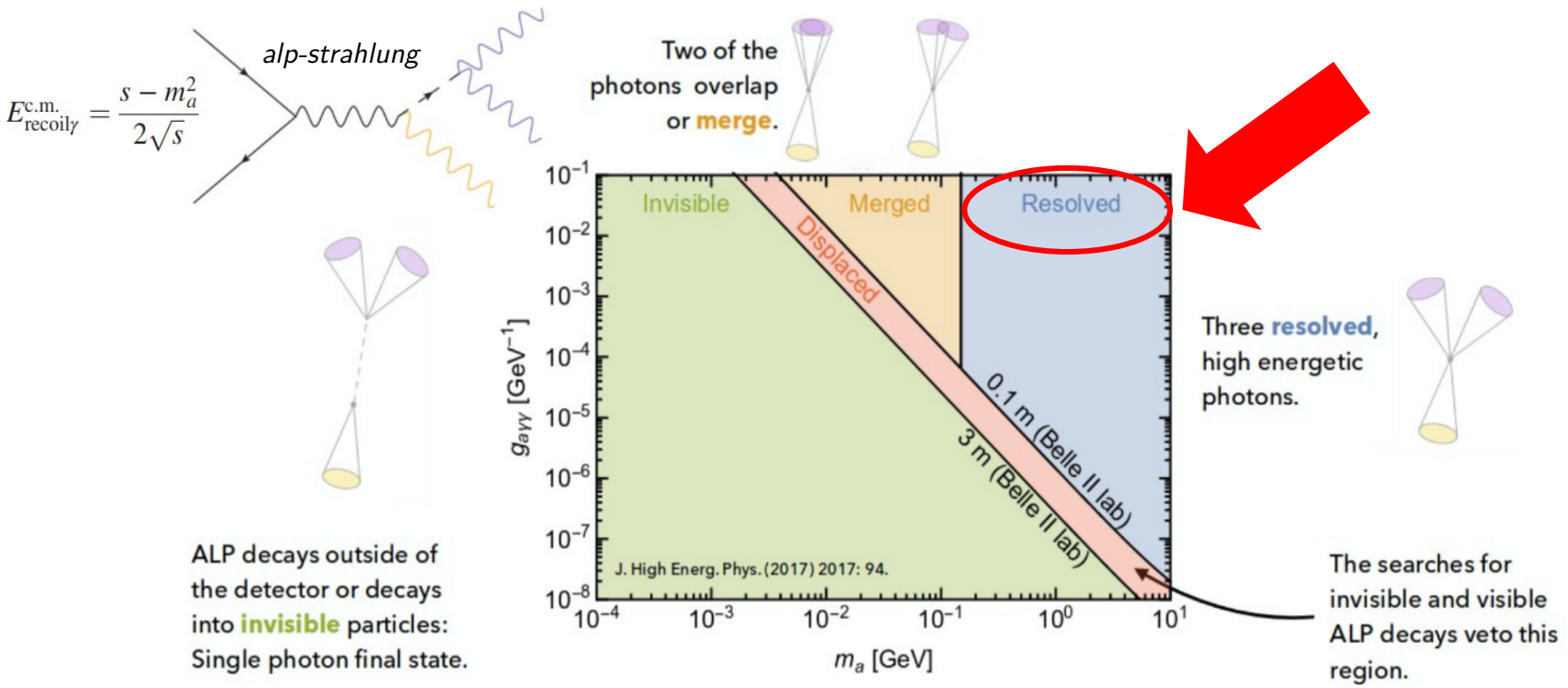


$$\mathcal{L} = -\frac{g_{aV}}{4}\, a\, W^{a}_{\mu\nu}\tilde{W}^{a\,\mu\nu}$$

$$BF(a \to \gamma\gamma) = 100\%$$



Search for a $\rightarrow \gamma\gamma$: analysis strategy

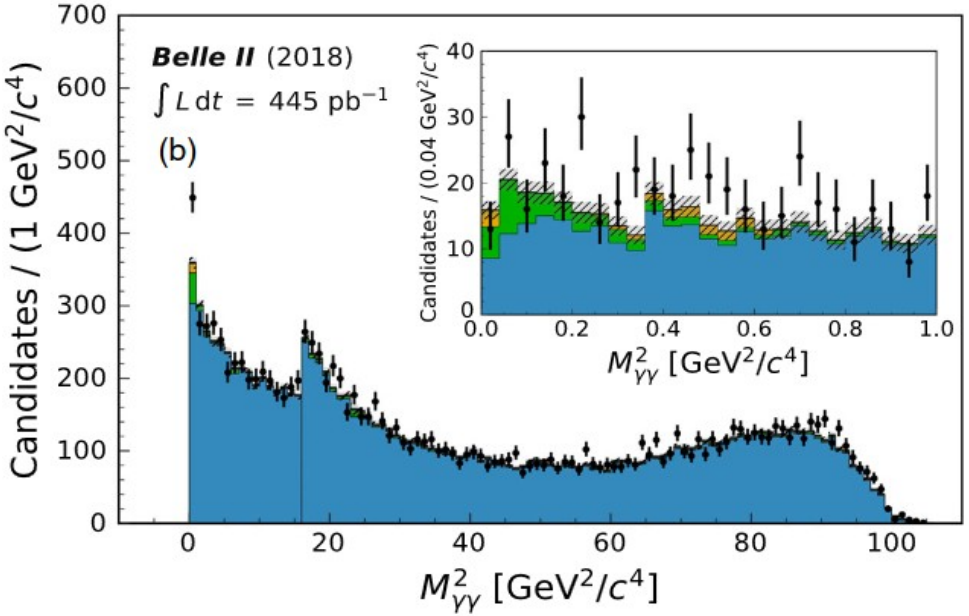


- Select fully **neutral events** consisting of **three isolated photons** with a total invariant mass consistent with center of mass energy $\rightarrow$ optimize to maximize ALP sensitivity
- Use calorimeter trigger (ECL efficiency almost 100%)

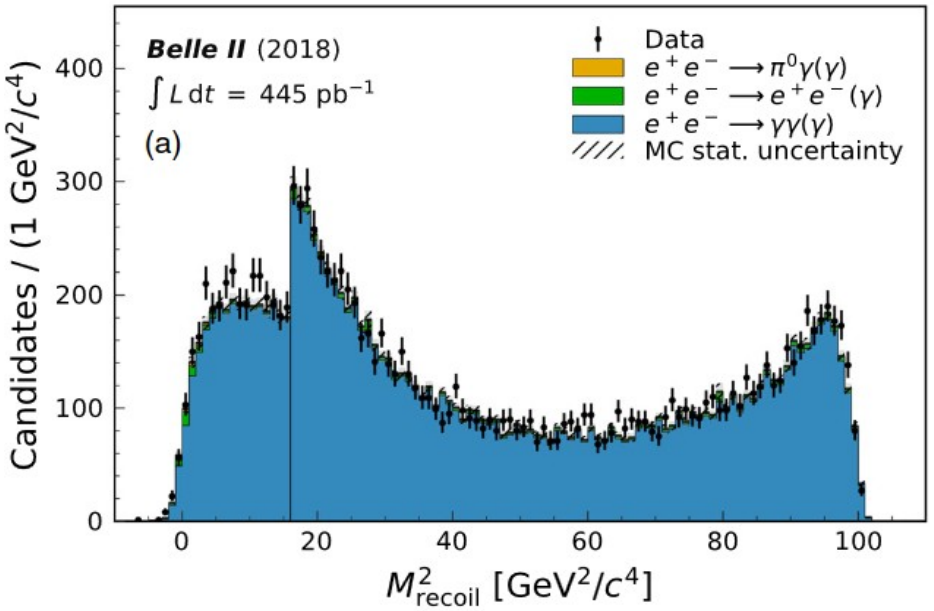
Search for a $\rightarrow \gamma\gamma$: signal extraction

- Signal yield extracted with binned maximum likelihood fits in sliding ranges (half mass resolutions step) to:

Diphoton invariant mass
for m_a in [0.2, 6.85] GeV/c^2



Recoil invariant mass
for m_a in [6.85, 9.7] GeV/c^2



$\rightarrow$ no excess found (highest local significance of 2.8σ)

Data set: **445 pb^{-1}** from 2018 pilot run

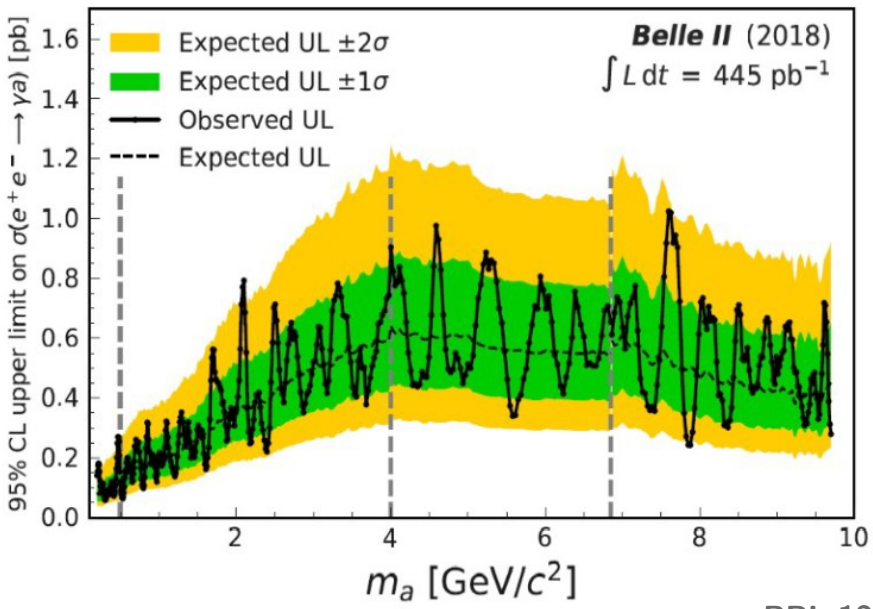
PRL 125 (2020) 161806

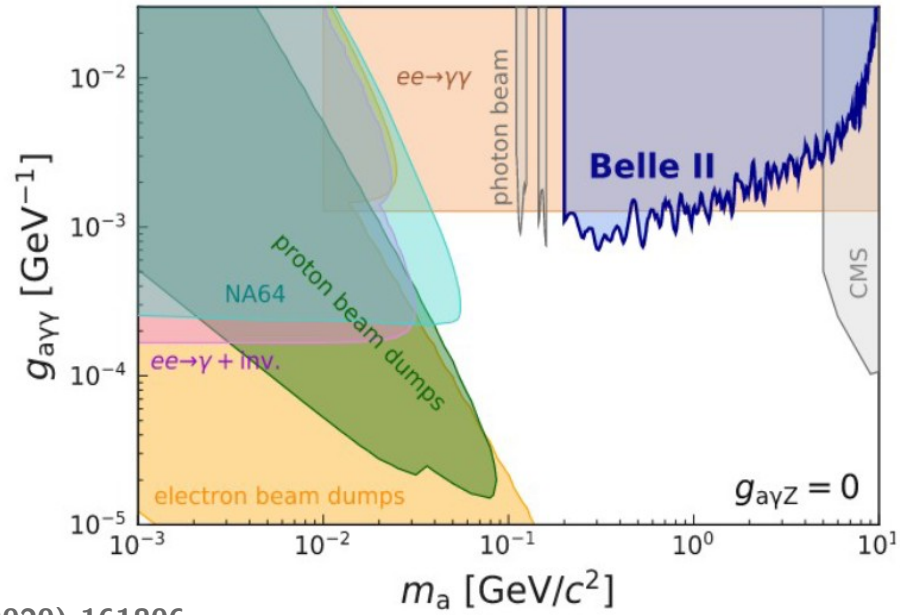
Search for a → γγ: results

- Set 95% CL upper limits on the signal cross section and $g_{a\gamma\gamma}$ coupling

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

→ World's best limit around 500 MeV

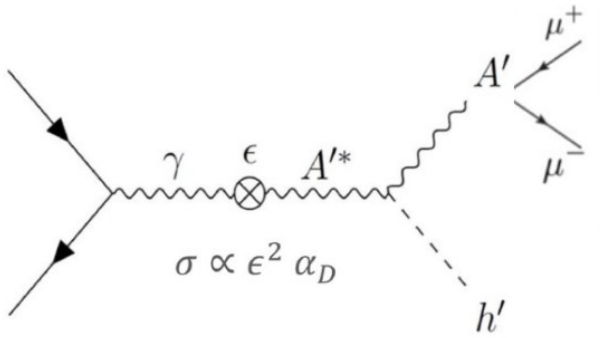




PRL 125 (2020) 161806

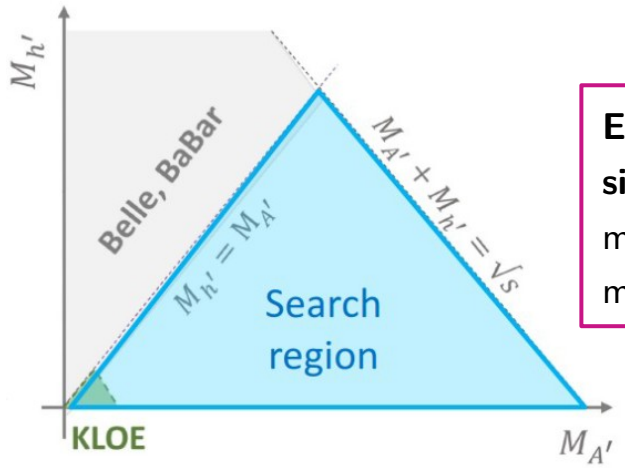
Dark higgsstrahlung

- Dark photon (A') mass can be generated via a spontaneous symmetry breaking(*) mechanism, by adding a dark Higgs boson (h'): dark Higgsstrahlung process, $e^+e^- \rightarrow A' \rightarrow h\ A'$



- 4 parameters (no mixing with SM Higgs assumed): $m_{h'}$, $m_{A'}$, ε, α_D
- $M_{h'} > M_{A'}$: *visible dark higgs, already searched by Belle, Babar*
- $M_{h'} < M_{A'}$: *invisible decays of h'*

- Belle II has unique capability to probe the **invisible h'** decay ($m_{h'} < m_{A'}$) with A' decaying to a **muon pair**
- Previously constrained only by KLOE(**)



Experimental signature: two muons + missing mass

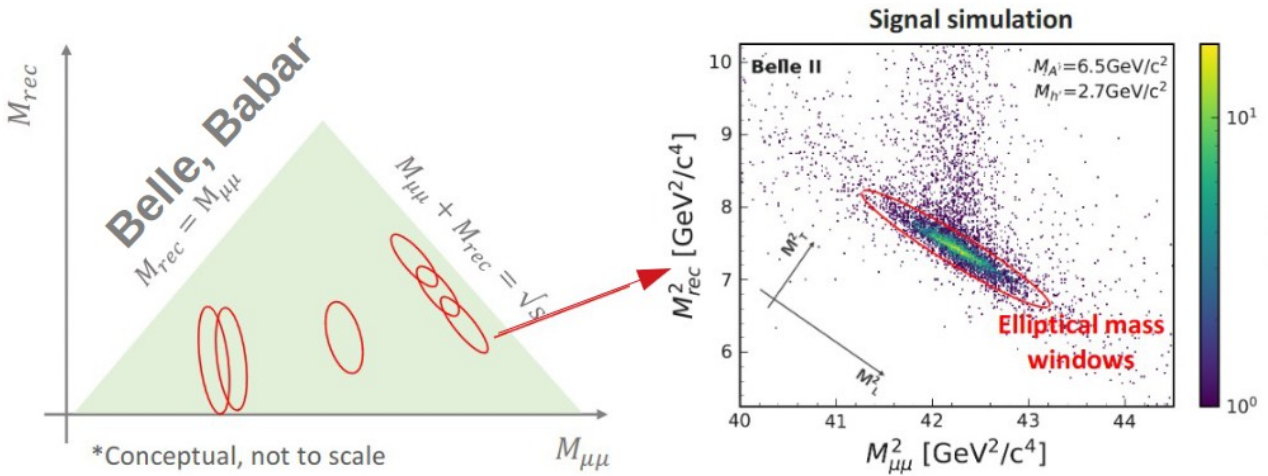
* Batell, Pospelov, Ritz, Phys. Rev. D 79, 115008 (2009)
** Babusci et al. (2015), Phys.Lett. B 747 pg. 365-372, 0370-2693

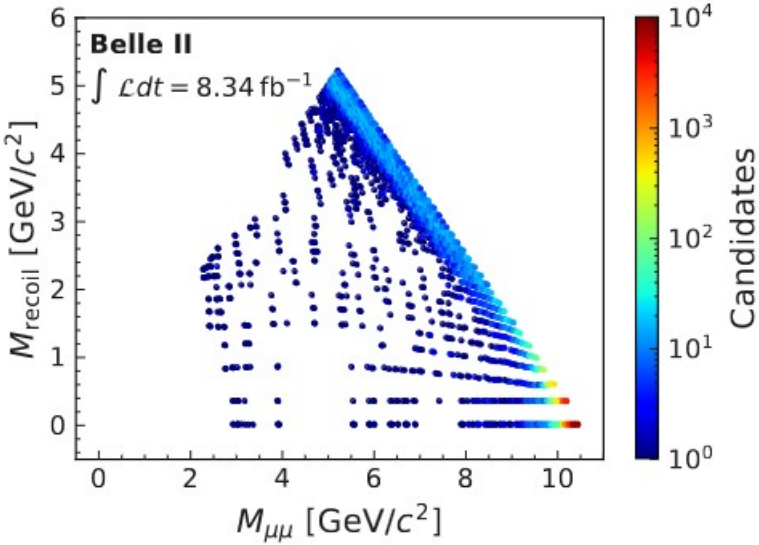
Dark higgsstrahlung: analysis strategy

- A' reconstructed as muon pairs, $M_{\mu\mu} > 1.65$ GeV for trigger requirements (two-track trigger)
- Background from **radiative QED processes**

  → same final state as for the invisible Z' search **M.Laurenza's talk**
- Scan dimuon and recoil mass **searching for peaks** in 9000 overlapping elliptical windows
- Apply Bayesian counting technique (challenging look-elsewhere effect)

→ observed yields in 8.34 fb^{-1} data (2019)

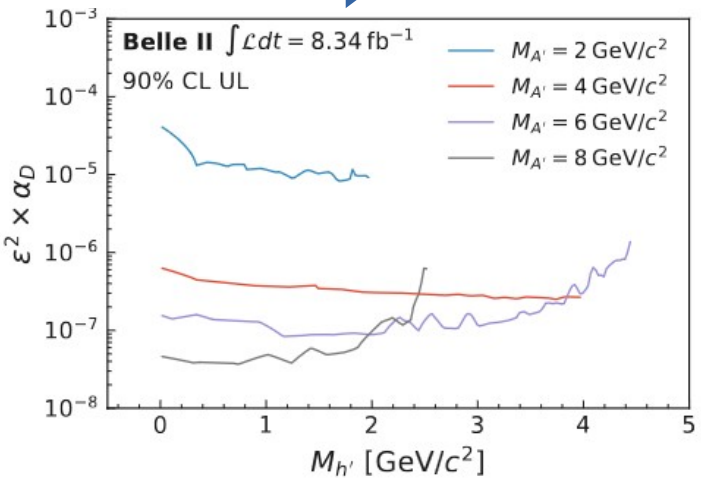


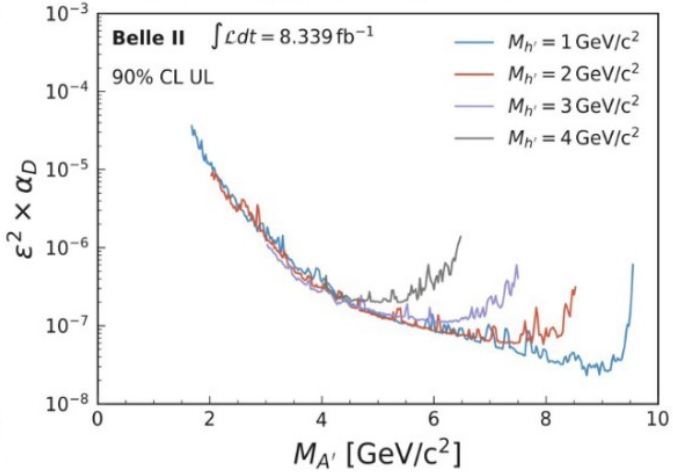


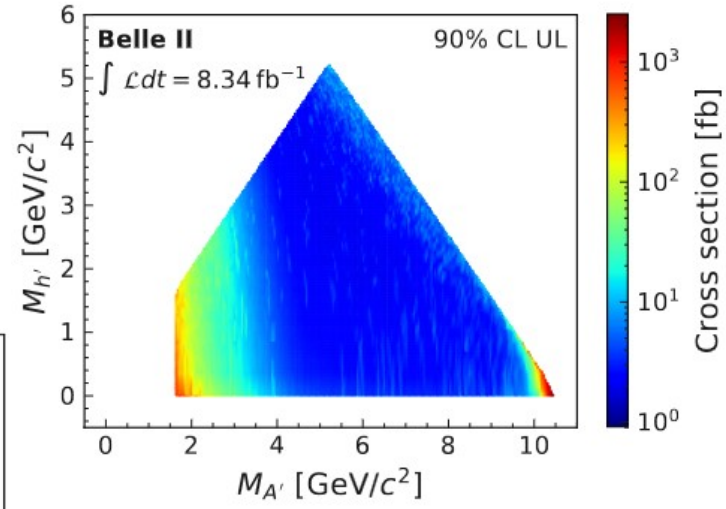
No signal excess found

Dark higgsstrahlung: results

- World leading results in unexplored phase space region
  - probe non-trivial $\varepsilon^2 \times \alpha_D$ couplings





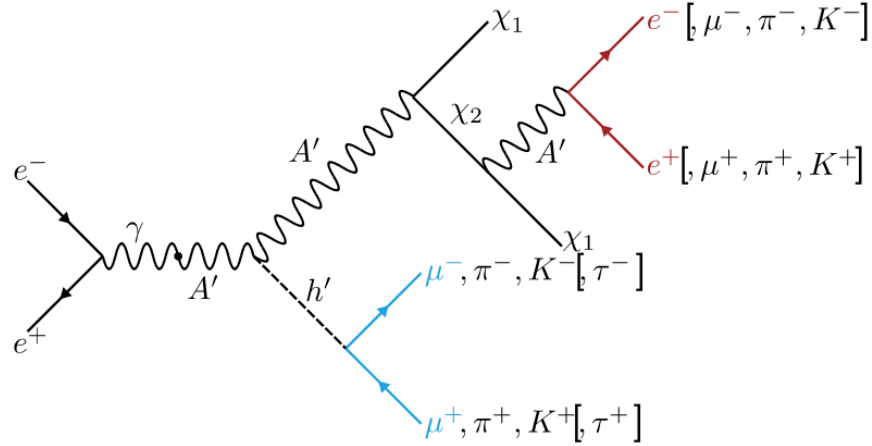


PRL 130, 071804 (2023)

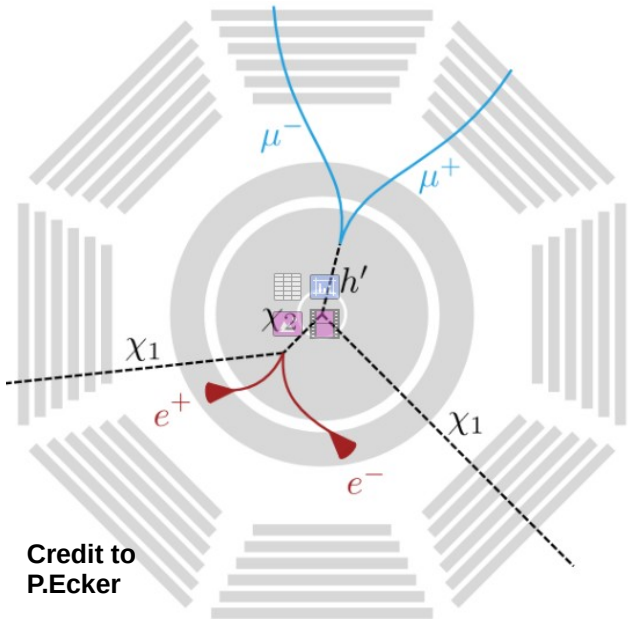
World leading results for $1.65 < M_{A'} < 10.51$ GeV/c^2 → can be interpreted in a wider class of theoretical models (e.g., long-lived higgs mixing with h_{SM})

Inelastic dark matter with dark higgs

- Dark photon A' and dark higgs h'
- Dark matter states χ_1 and χ_2 with a small mass splitting:
  - χ_1 is stable (contributes to relic density)
  - χ_2 is long-lived at small values of kinetic-mixing coupling (ε)



JHEP 04 (2021), arXiv:2012.08595



Credit to P.Ecker

Transverse view of the Belle II detector

Experimental signature: up to two displaced vertices + missing energy

→ unconstrained by direct detection experiments, both inelastic and elastic scattering suppressed

Inelastic DM with dark higgs: analysis strategy

- Perform a bump hunt on the invariant mass of the dark higgs $M_{h'}$
- Set limits on dark higgs mixing angle **θ** as function of dark higgs mass **$M_{h'}$** as varying the other five parameters

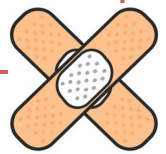
Model Parameters [JHEP 04 (2021), arXiv:2012.08595]

1) Mass of the Dark Photon, ($M_{A'}$)
2) Mass of the χ1, ($m_{\chi 1}$)
3) **Mass of the Dark Higgs ($M_{h'}$)**
4) Mixing Angle of Dark Photon and SM (ε)
5) **Mixing Angle between dark higgs and SM Higgs (θ)**
6) Coupling of Dark Photon to DM (g_X)
7) Coupling of Dark Higgs to DM (f)

- **Experimental challenges:**

  1) dropping of reconstruction and trigger efficiencies with displacement of the vertices

- **New algorithms** could recover reconstruction losses at reprocessing level
- **Trigger losses** are NOT recoverable, devise dedicated line, exploit calorimeter information



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7) Coupling of Dark Higgs to DM (f)

- **Experimental challenges:**

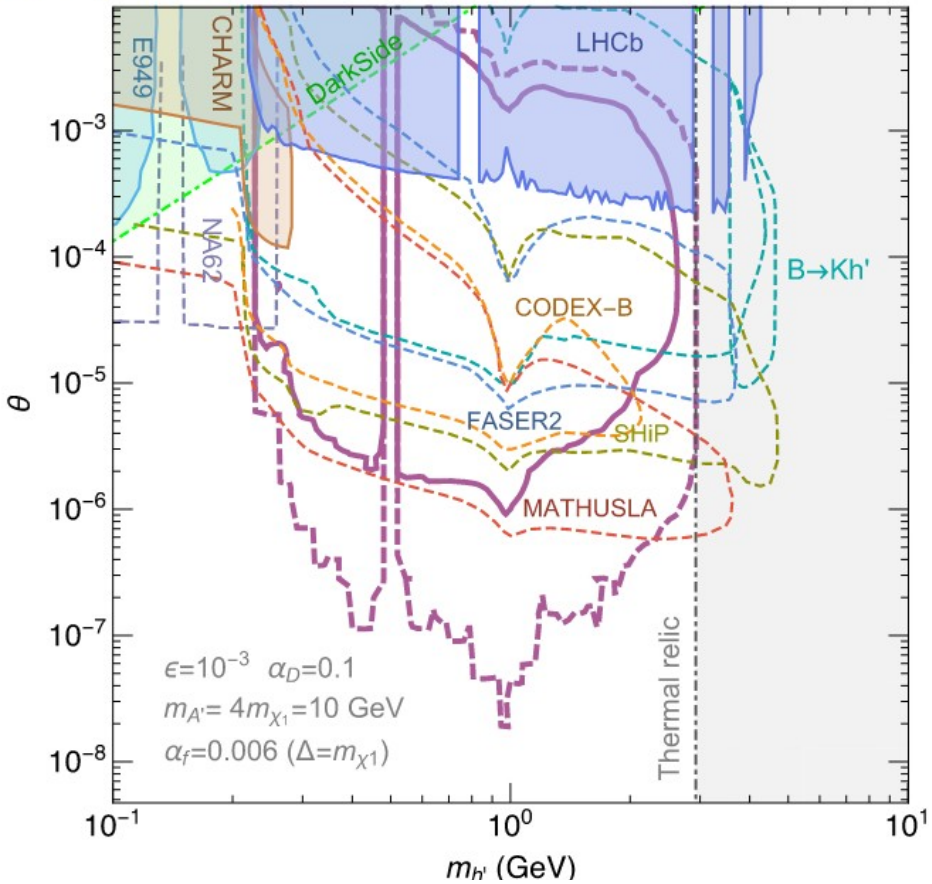
  1) dropping of reconstruction and trigger efficiencies with displacement of the vertices

  2) efficiency depends on the beam background conditions

- Effects can be studied and modeled

Inelastic DM with dark higgs: sensitivity

[JHEP 04 (2021), arXiv:2012.08595]



- **Belle II expected sensitivity for 100 fb^{-1} (solid) and 50 ab^{-1} (dashed)**
- Preliminary studies show lower efficiencies → one order of magnitude less sensitive
- Mandatory to implement **new trigger for displaced vertex detection**

Outlook and conclusion

Belle II has **unique sensitivity** for light dark sectors searches, **complementary** to beam-dump experiments and high-energy colliders

Excellent performance with **displaced vertices** and **missing energy** allows **world's leading** results on several models to probe DM puzzle

→ Search for a long-lived (pseudo-)scalar in b → s transitions, arXiv:2306.02830

→ Search for dark-Higgs particles Phys. Rev. Lett. 130, 071804 (2023)

→ Search for an invisible boson in LFV tau decays, Phys. Rev. Lett. 130, 181803 (2023)

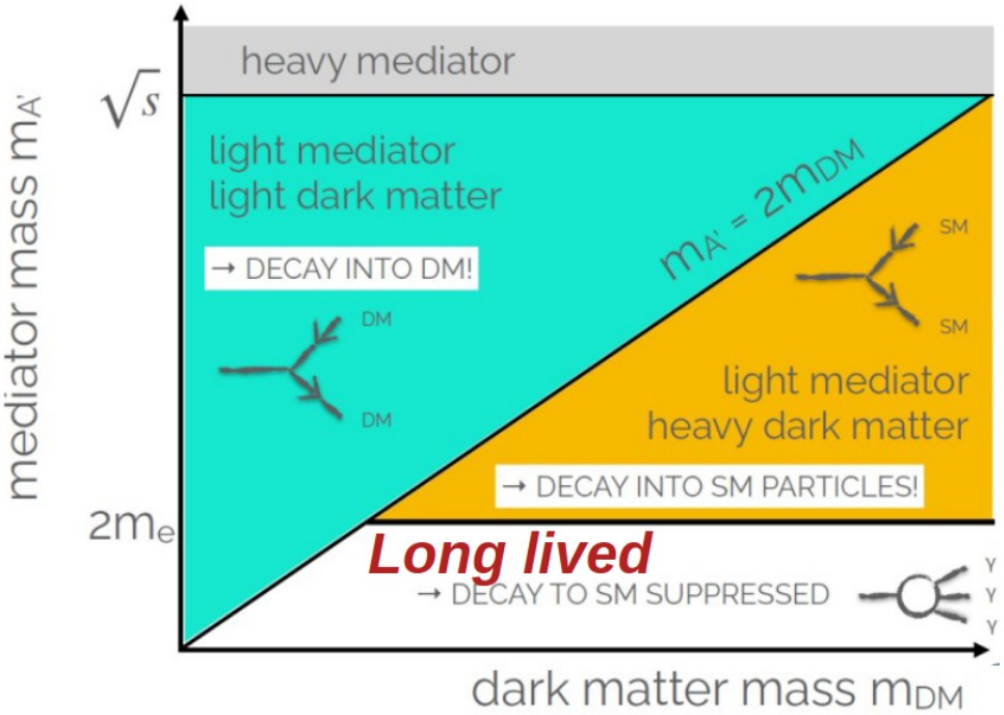
→ Search for axion-like particles Phys. Rev. Lett. 125, 161806 (2020)

→ Sensitivity at Belle II for Inelastic DM searches, JHEP 04 (2021), arXiv:2012.08595

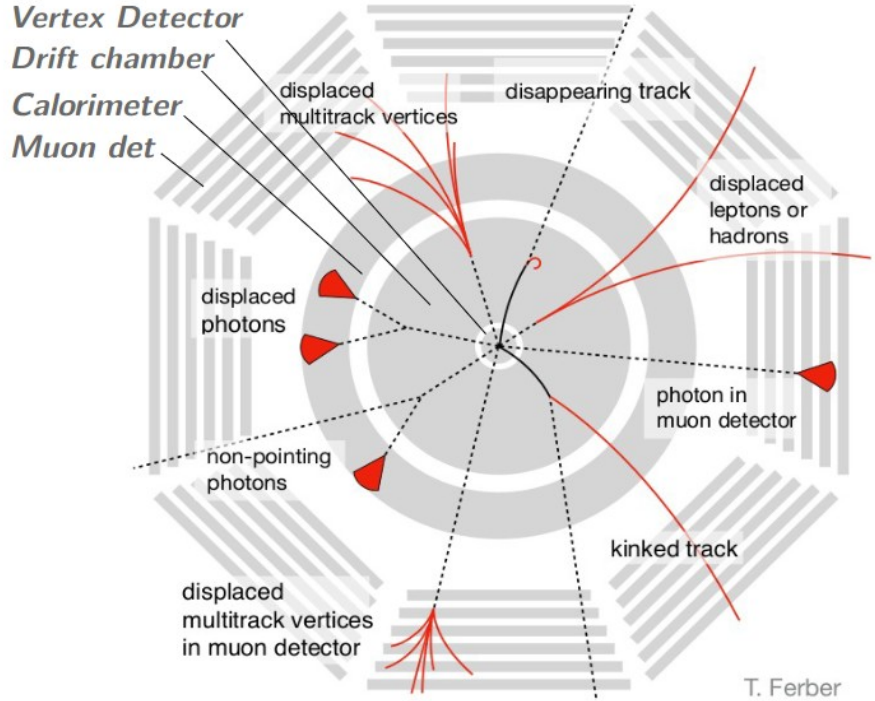
Thanks for your attention!

backup

Long-lived particle searches at Belle II



Transverse view of the Belle II detector

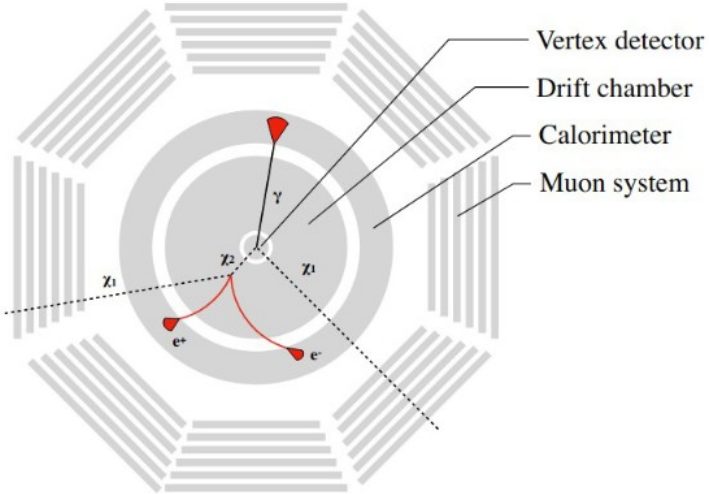


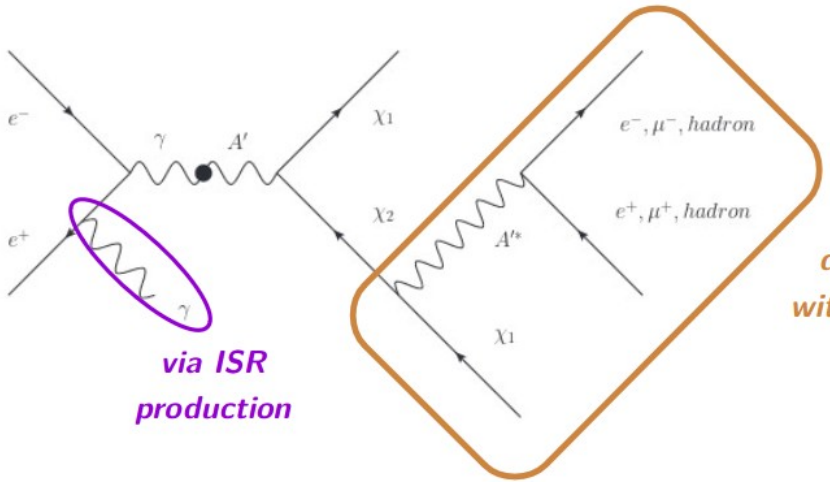
Inelastic dark matter

Dark photon A' and dark matter states $\chi 1$ and $\chi 2$ with a small mass splitting:

- $\chi 1$ is stable (relic)
- $\chi 2$ is long-lived at small values of kinetic-mixing coupling (ε)

- unconstrained by direct detection experiments, both inelastic and elastic scattering suppressed
- focus on $m_{A'} > m_{\chi 1} + m_{\chi 2}$, such that $A' \rightarrow \chi 1\ \chi 2$ is dominant decay





via ISR production

non-pointing displaced vertex with missing energy

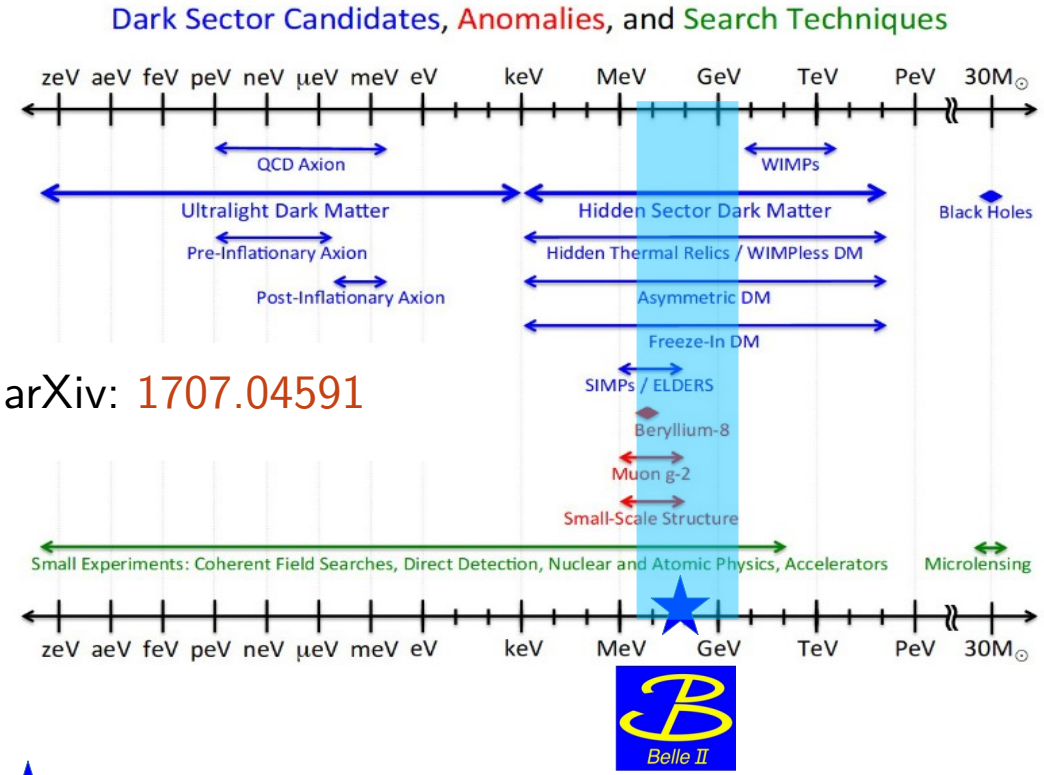
5 parameter model:
$m_{A'}$ (fixed relative to $m_{\chi 1}$)
$m_{\chi 1}$ (scan)
mass difference $\Delta = m_{\chi 2} - m_{\chi 1}$ (categorical)
dark coupling α_D (fixed to benchmarks)
kinetic mixing parameter ε (limit)

- ***Mandatory to implement new trigger for displaced vertex detection***
- Belle II could constrain the kinetic mixing $\varepsilon < 10^{-4}$ with $\sim 100/\text{fb}$

Journal of High Energy Physics volume 2020, Article number: 39 (2020)

Dark matter and light dark sectors

- ***Dark matter*** is one of the most compelling reasons for new physics

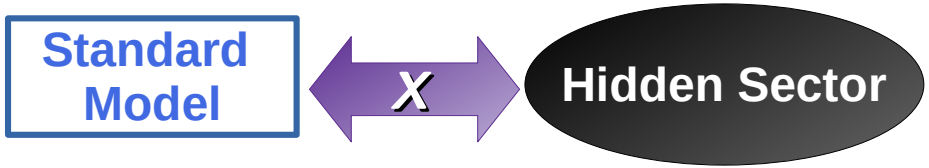


arXiv: 1707.04591

★ **B-factories at e^+e^- collider** can access the mass range favored by **light dark sectors**

Possible sub-GeV scale scenario: *light dark sector* weakly coupled to SM through a light *mediator X*

- Vector portal → **Dark Photons, Z' bosons**
- Pseudo-scalar portal → **Axion Like Particles (ALPs)**
- Scalar portal → **Dark higgs/Scalars**
- Neutrino portal → Sterile Neutrinos



Dark sectors searches at Belle II

- Many models proposed, possibly very small couplings:

  1) Be signature-based

  2) Profit from **clean environment** at lepton colliders + **hermetic detector: Belle II** at **SuperKEKB** asymmetric-energy e^+e^- collider

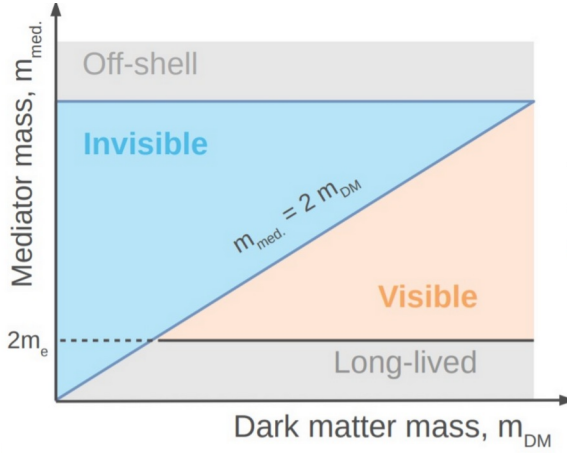
  → running mainly at $\sqrt{s} = 10.58$ GeV: B & **τ factory** ($\sigma_{bb} \sim \sigma_{\tau\tau} \sim 1$ nb), known initial state

  → efficient reconstruction of **neutrals** (π^0, η), **recoiling system** and **missing energy**

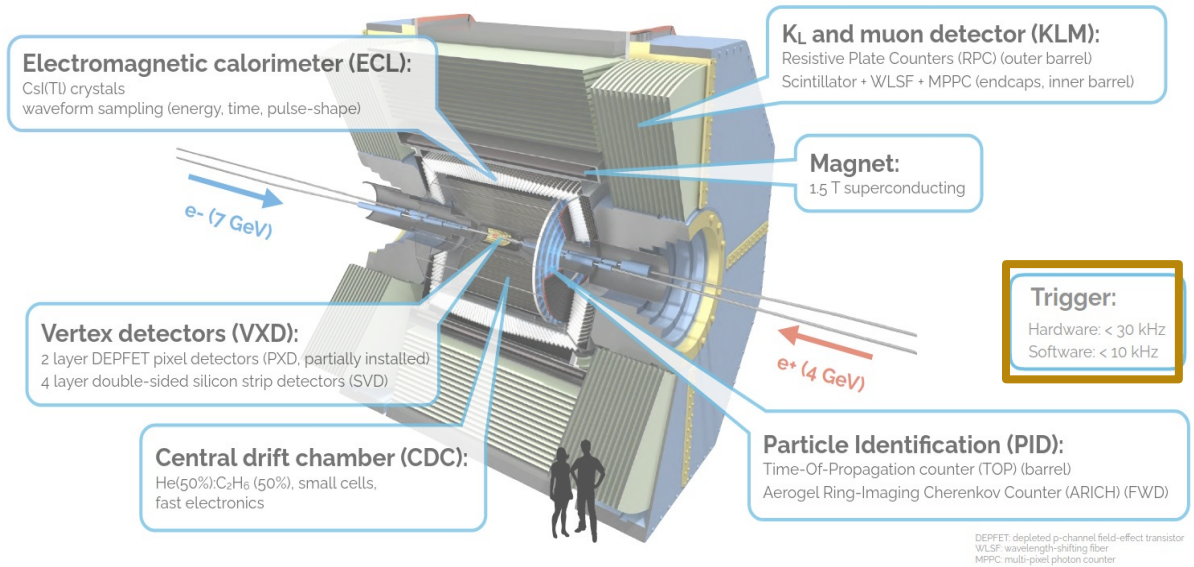
  → specific **low-multiplicity triggers:** single track/muon/photon (previously not available at Belle)

  GOAL: suppress high-cross section QED processes O(1-300 nb), without killing the signal < O(10 fb)

- Currently on first shutdown since July 2022
- **Accumulated 424 fb^{-1}** (~ Babar, ~ half of Belle) and unique energy scan samples



Unprecedented luminosity, 4.7×10^{34} cm^{-2}s^{-1} world record



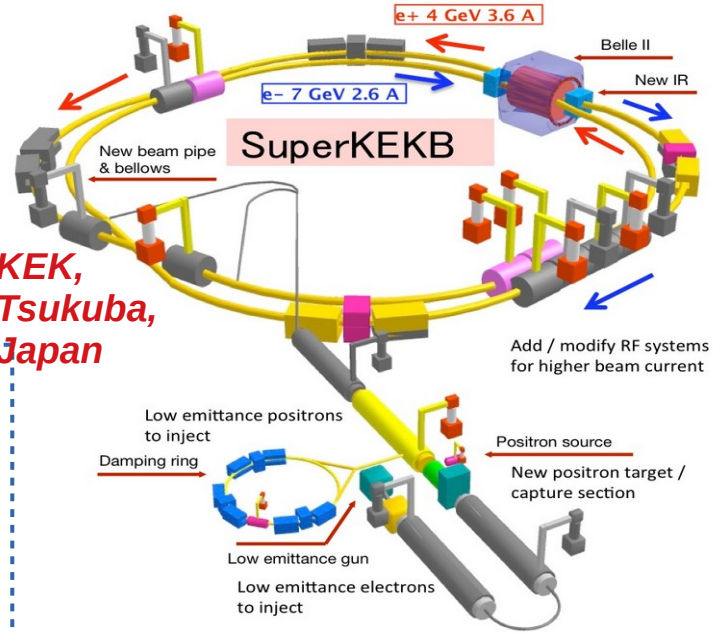
SuperKEKB accelerator

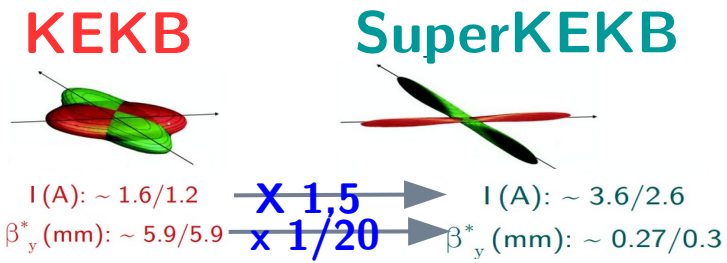
- Asymmetric-energy e^+e^- colliders + *4π detectors* → **efficient reconstruction of neutrals (π^0, η), recoiling system and missing energy**

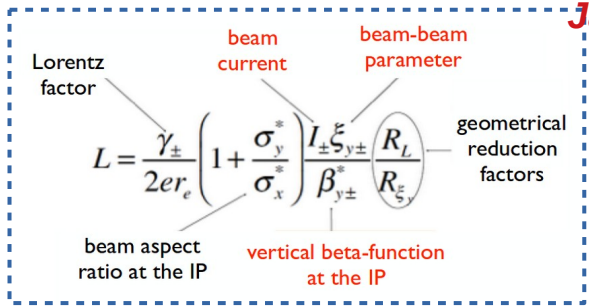
$$e^+e^- \rightarrow \Upsilon(4S)\ [10.58\ \text{GeV}] \rightarrow B\bar{B}$$

- B & **τ factory** ($\sigma_{bb} \sim \sigma_{\tau\tau} \sim 1$ nb) + **light dark sectors**

KEK, Tsukuba, Japan







$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

- **GOAL:** 30 x KEKB peak luminosity, $\mathcal{L} = 6 \cdot 10^{35}\text{cm}^{-2}\text{s}^{-1}$ *(nano-beam scheme technique*)*

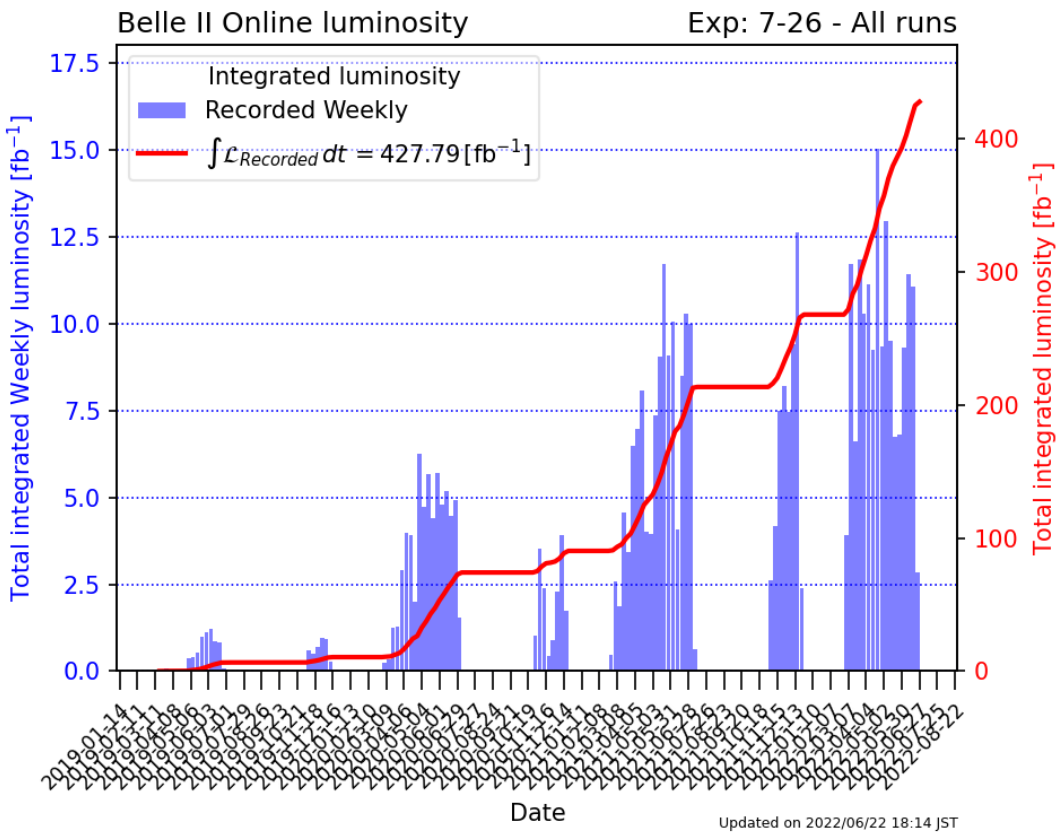
→ *unprecedented luminosity, wolrd record* $4.7 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$

*https://arxiv.org/abs/0709.0451

Belle II Luminosity

Total Integrated luminosity for *good* runs:

- Total integrated luminosity: **424 fb^{-1}**
- Total integrated luminosity at the Y(4S) resonance: **363 fb^{-1}**
- Total integrated luminosity below Y(4S) resonance: **42 fb^{-1}**
- Total integrated luminosity above Y(4S) resonance: **19 fb^{-1}**



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
- complete transition to new DAQ boards (PCIe40)
- replacement of aging components
- additional shielding and increased resilience against beam backgrounds

Currently working on pixel detector installation:
- > shipping to KEK in mid March
- > final test at KEK scheduled in April

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