33rd Rencontres de Blois — May 22–27
BLOIS
EXPLORING THE DARK UNIVERSE — 2022

Probes of the Dark sector from the Belle II experiment

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On behalf of the Belle II collaboration – Château de Blois, 2022/05/25

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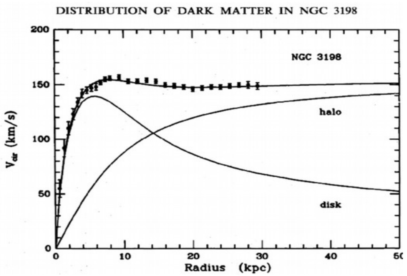
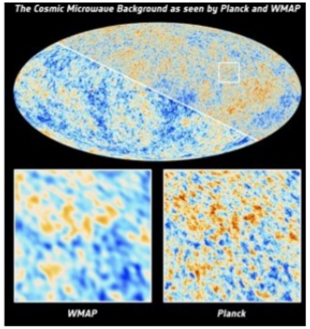
Dark matter puzzle

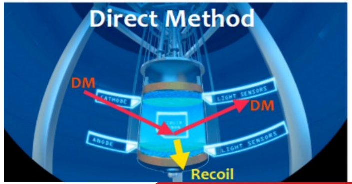
- ***Dark Matter (DM)*** is one of the most compelling reasons for NP searches

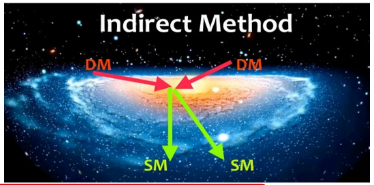


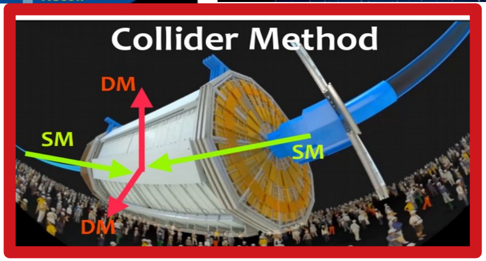


It exists...

...how to search for it?

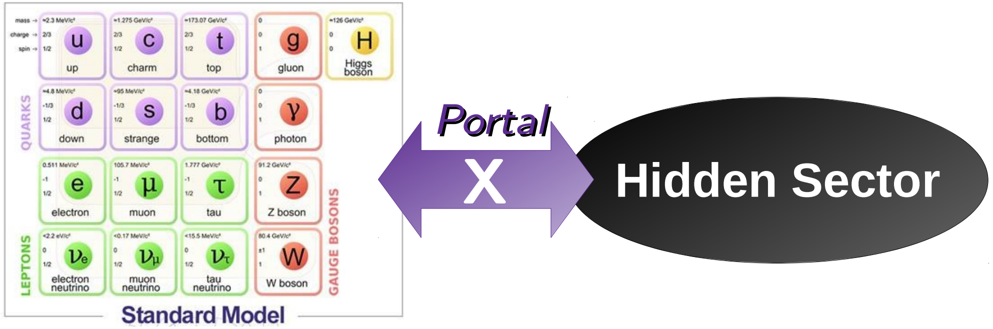






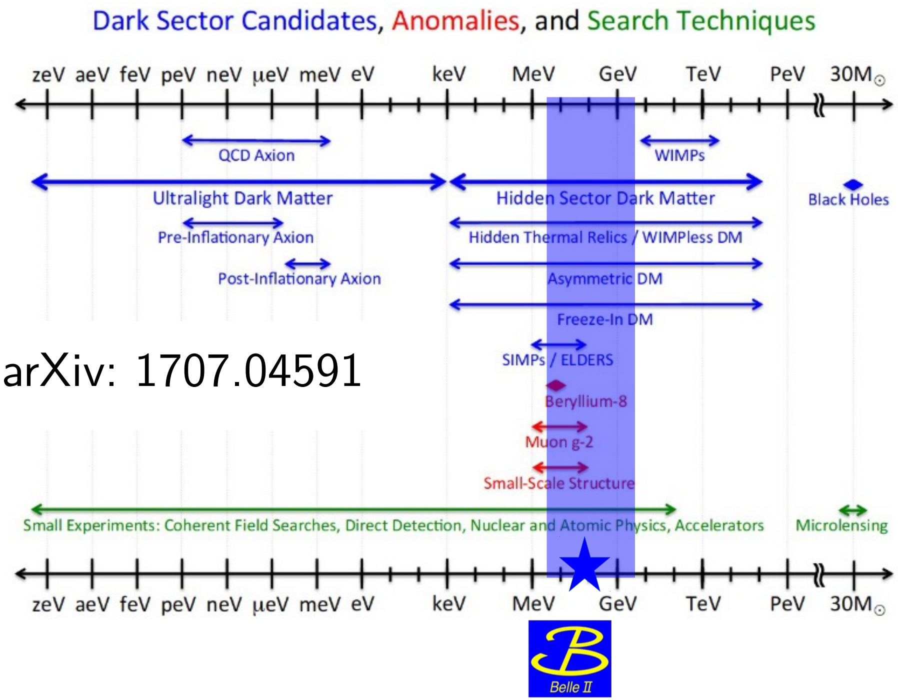
Possible sub-GeV scale DM scenario: *light dark sector* weakly coupled to SM through a light *mediator X*

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



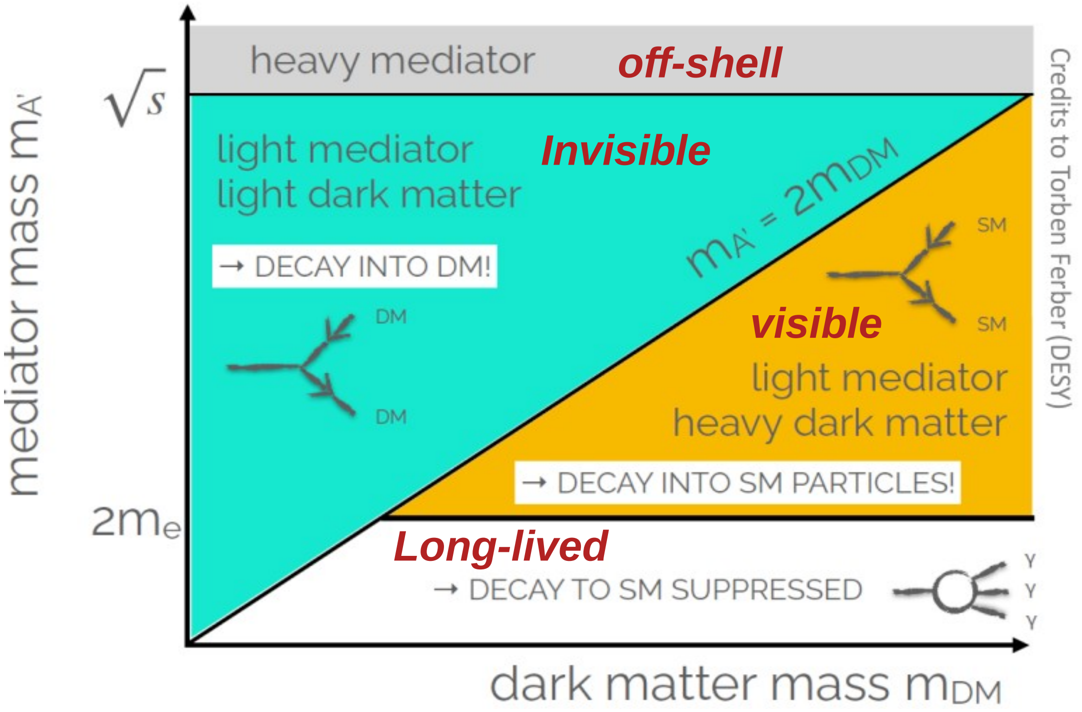
→ focus on dark sector searches at e+e- colliders

Light dark sectors



arXiv: 1707.04591

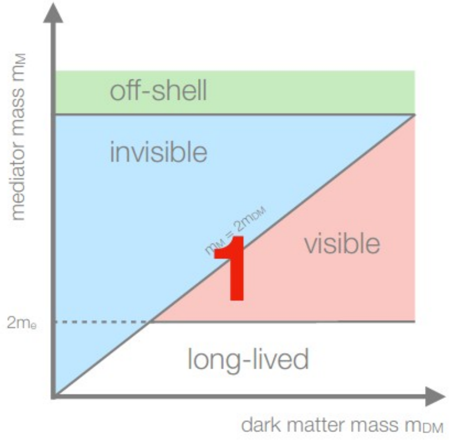
★ B-factories can access the mass range naturally favored by ***light dark sectors***

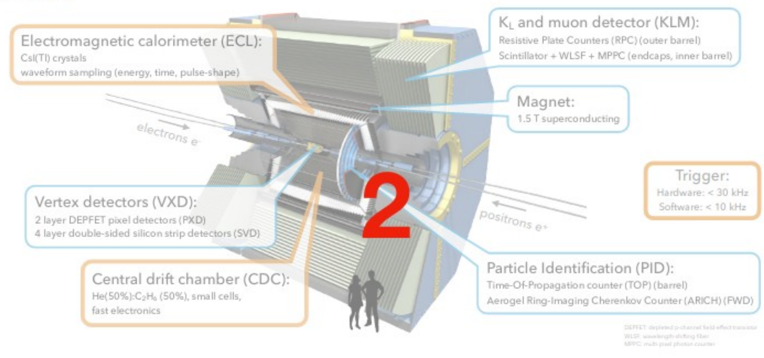


$\rightarrow$ *different topologies leading to different kinds of **DM searches***

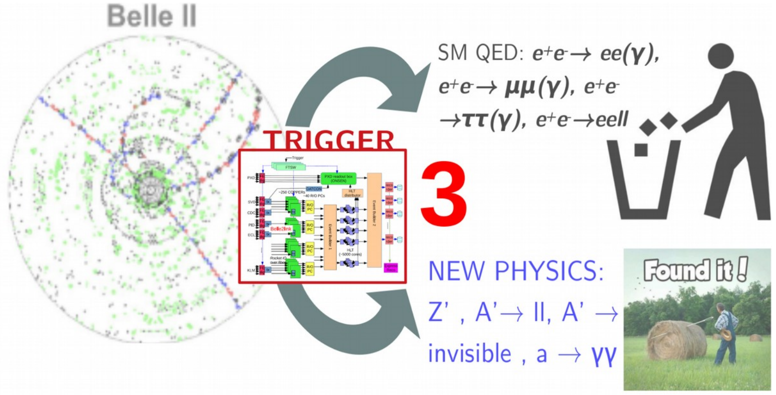
Key ingredients

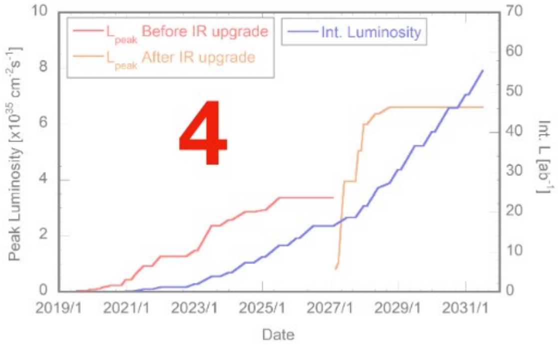
- No leading model, possibly very small couplings:
  1) Be signature-based
  2) Profit of **clean environment** at lepton colliders + **hermetic detector** $\rightarrow$ *known initial state*
  3) Devise specific ***low-multiplicity triggers***
     - $\rightarrow$ Suppress high-cross section QED processes BUT NOT KILL the signal
     - $\rightarrow$ Requires detailed knowledge of the detector efficiencies
  4) Collect largest statistics





Signature first!



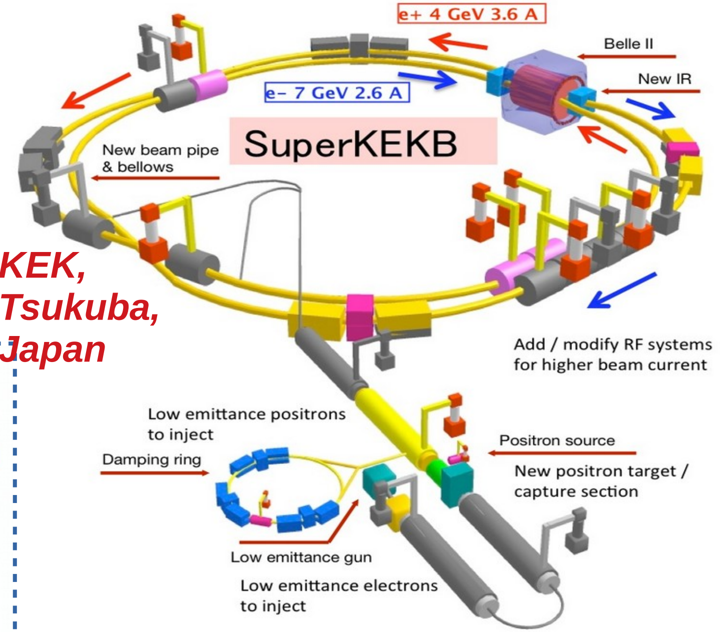


SuperKEKB accelerator

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

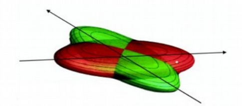
$$e^+e^- \to \Upsilon(4S)\ [10.58\ \text{GeV}] \to B\bar{B}$$

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



KEK, Tsukuba, Japan

KEKB



I (A): ~ 1.6/1.2

β^*_y (mm): ~ 5.9/5.9

X 1,5 →

x 1/20 →

SuperKEKB

I (A): ~ 3.6/2.6

β^*_y (mm): ~ 0.27/0.3

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

Lorentz factor; beam current; beam-beam parameter; geometrical reduction factors; beam aspect ratio at the IP; vertical beta-function at the IP

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

→ *Peak luminosity record* ***4.14x10^{34} cm^{-2}s^{-1}*** *on May 17th*

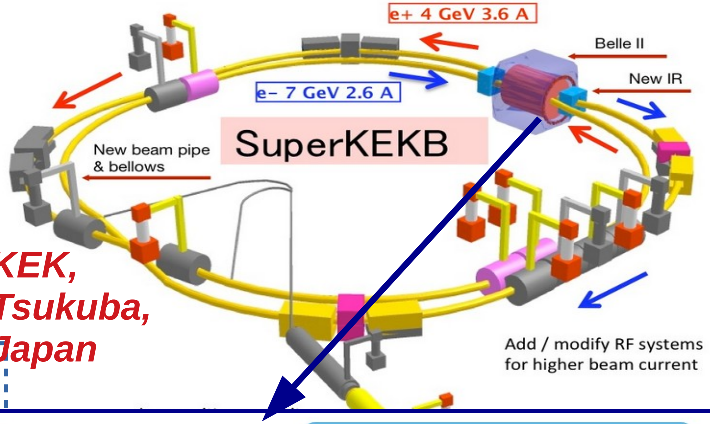
*https://arxiv.org/abs/0709.0451

SuperKEKB and BelleII

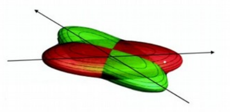
- Asymmetric-energy e^+e^- colliders + *4π detectors* → **efficient reconstruction of neutrals (π^0, η), recoiling system and missing energy**

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

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



KEKB



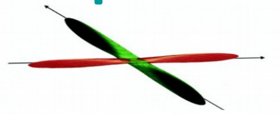
I (A): ~ 1.6/1.2

β^*_y (mm): ~ 5.9/5.9

X 1,5 →

x 1/20 →

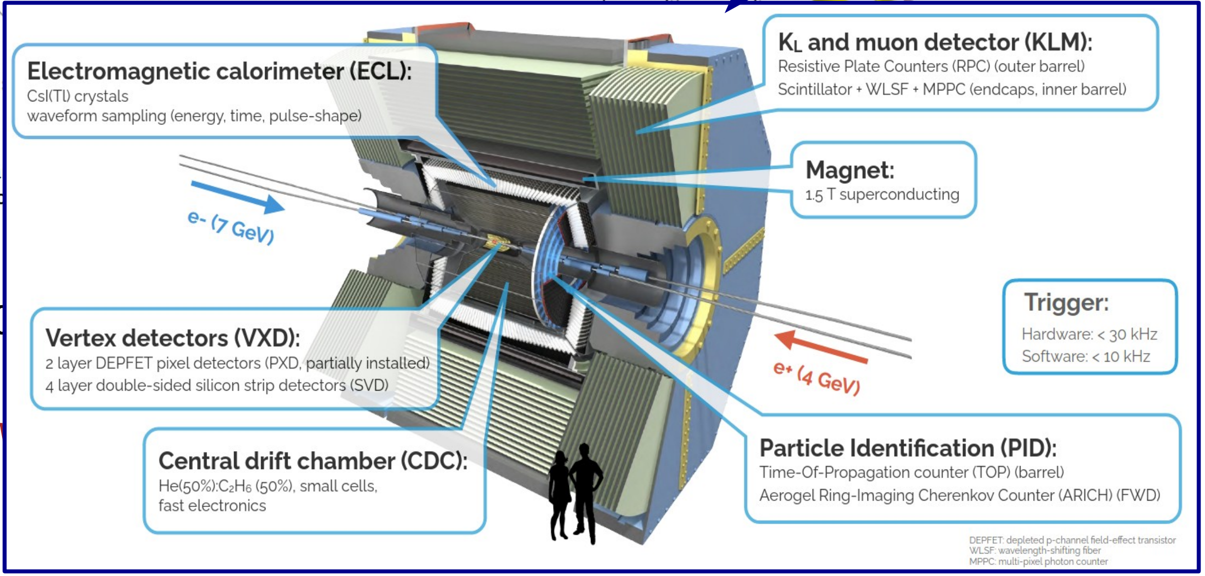
SuperKEKB



I (A): ~ 3.6/2.6

β^*_y (mm): ~ 0.27/0.3

Lorentz factor | beam current | beam-beam parameter | L | bea… ratio…



- **GOAL:** 30 x KEKB peak luminosity, $\mathcal{L} = 6 \cdot 10$… *(nano-beam scheme technique*)*

→ *Peak luminosity record* ***4.14x10³⁴ cm⁻²s⁻¹*** *on* …

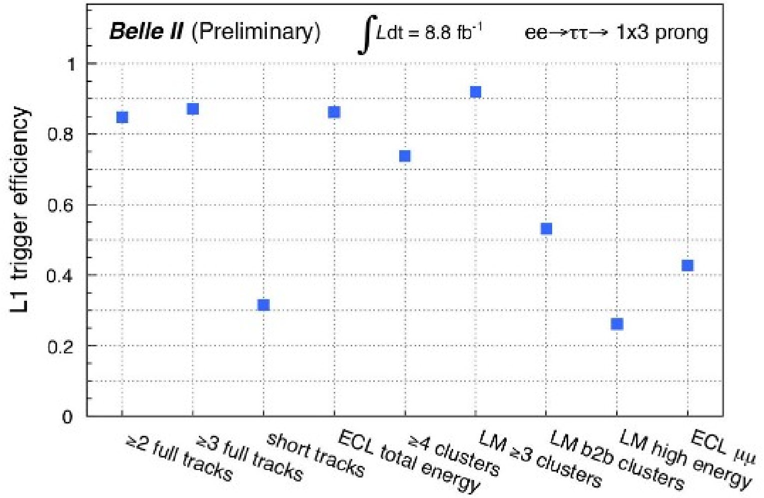
- Final target → ***50 x Belle, 50 ab⁻¹ @Belle II***

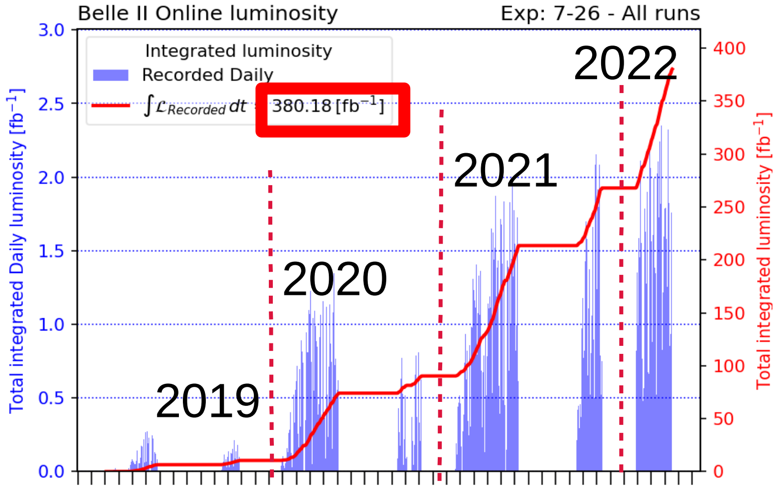
*https://arxiv.org/abs/0709.0451

Belle II triggers and data sets

- Hardware-based trigger (**L1**) combines information from several sub-detectors (*CDC, ECL, TOP* and *KLM*)
  - **Novel menu of low multiplicity triggers** unavailable at Belle (*single photon, single muon, single track with neural network reconstruction)*

*Main challenge: trigger on two-track + missing energy signal processes <**O(10 fb)** without being saturated by QED processes **O(1-300 nb)***



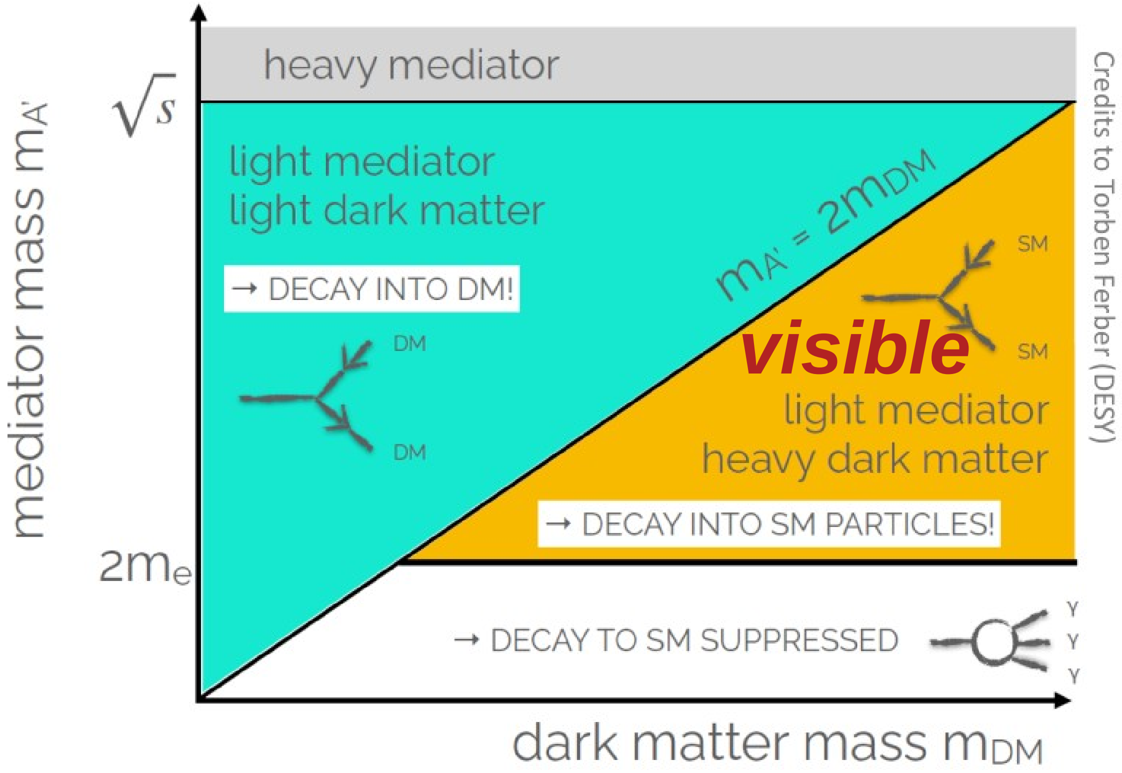


- collected **0.5 fb^{-1}** during the **2018 pilot run** (without vertex detector)**:** *Z'→invisible* ***PRL 124 (2020) 141801****, ALPs → γγ* ***PRL 125 (2020) 161806***
- On data > 2019: ***Dark Higgsstrahlung, Z' update***

talk by Huw Haigh in the parallel session

Shut-down from July 2022, resuming operation in 2023
Accumulated 0.4 ab^{-1} (40% of Belle) → *many analyses in the pipeline*

Searches for visible decays



- ALPs to photons
- Visible Z'

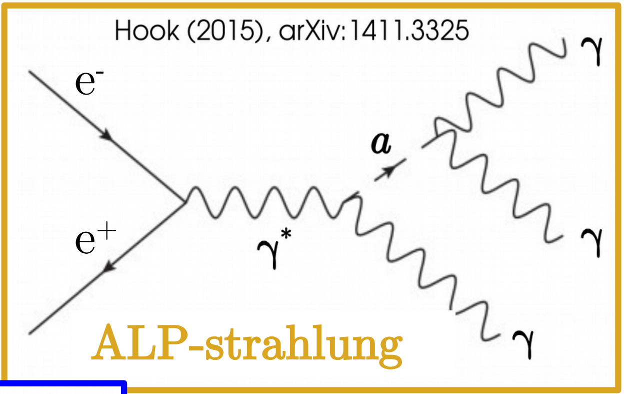
Axion-like particles

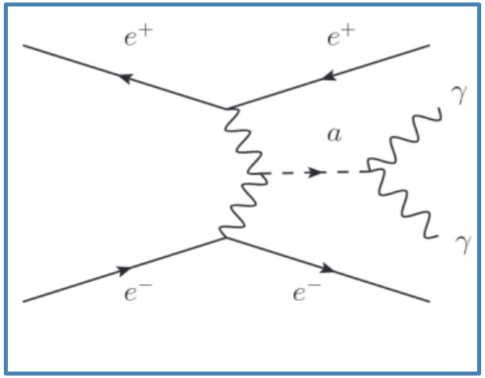
- Axion-like particles (ALPs) are pseudo-scalars coupling mainly to bosons, with non-renormalizable coupling constants $[g_{aV}] \sim 1/M$

- Explored photon coupling $g_{a\gamma\gamma}$ in *ALP-strahlung* processes

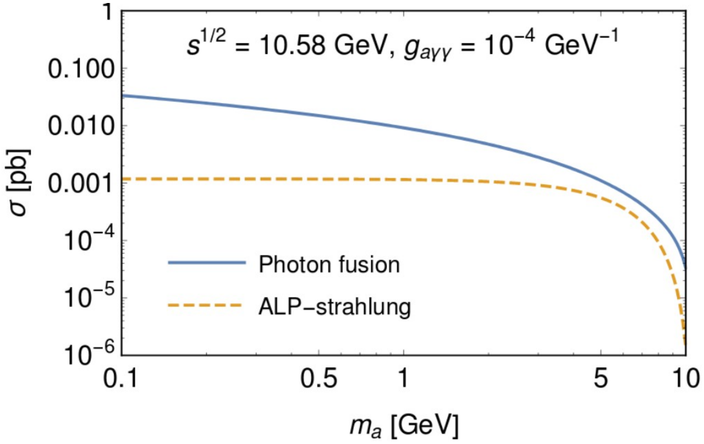
  (*photon fusion*: sensitivity under study)

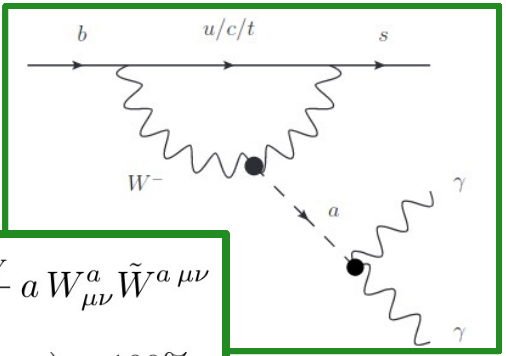
- Exploit flavor changing neutral current and rare meson decays to investigate g_{aW} coupling **ongoing studies for B→Ka**





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



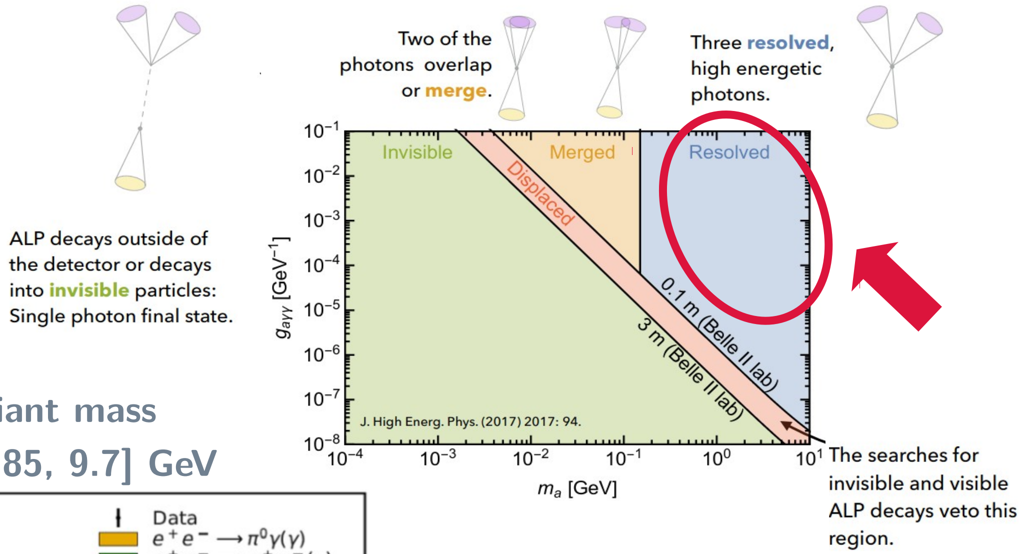


$$\mathcal{L} = -\frac{g_{aV}}{4}\, a\, W^a_{\mu\nu}\tilde{W}^{a\,\mu\nu}$$

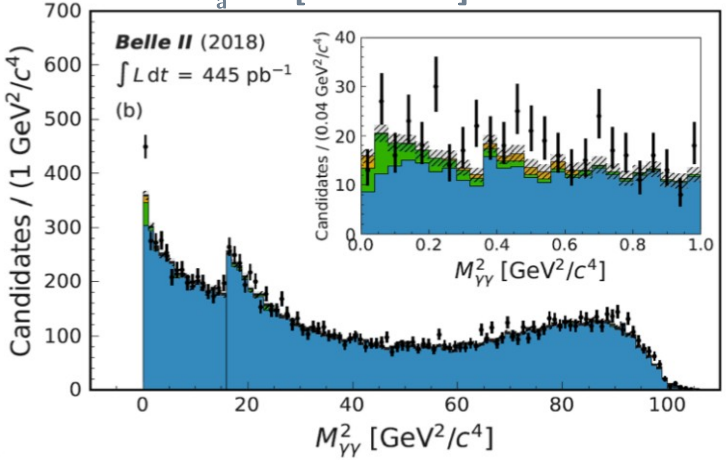
$$BF(a \to \gamma\gamma) = 100\%$$

ALPs: a → γγ

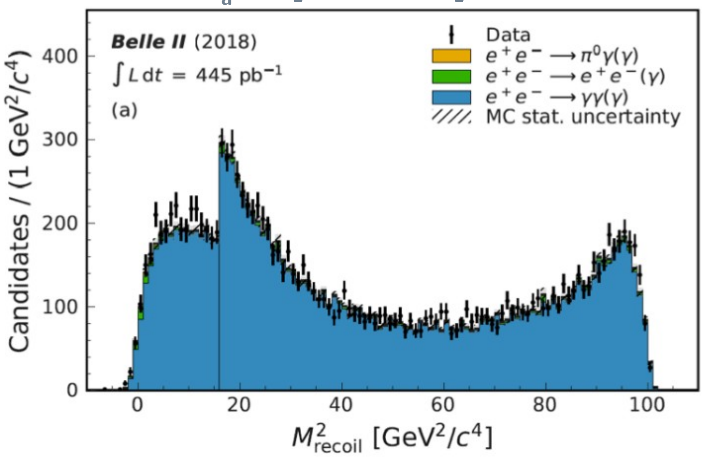
- Select fully neutral events consisting of ***3 isolated photons*** with a total invariant mass consistent with center of mass energy
  - → use calorimeter trigger (*ECL efficiency almost 100%*)
- Optimize to maximize ALP sensitivity
- Signal yield extracted with binned extended max likelihood fits in sliding ranges (half mass resolutions step) to:



Diphoton invariant mass for m_a in [0.2, 6.85] GeV



Recoil invariant mass for m_a in [6.85, 9.7] GeV



no excess found (highest local significance of 2.8σ)

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

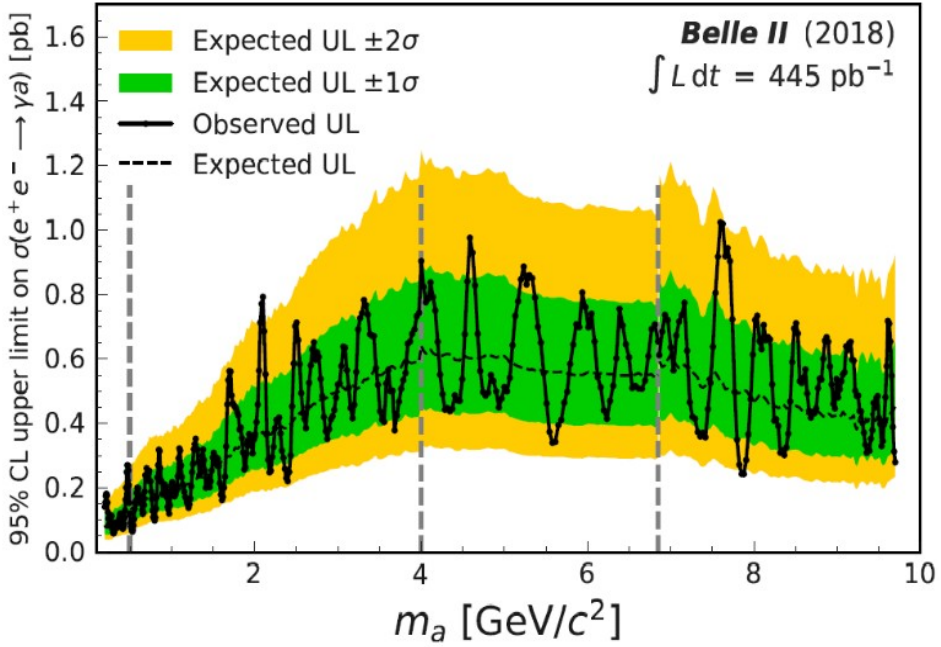
ALPs: $a \to \gamma\gamma$ results

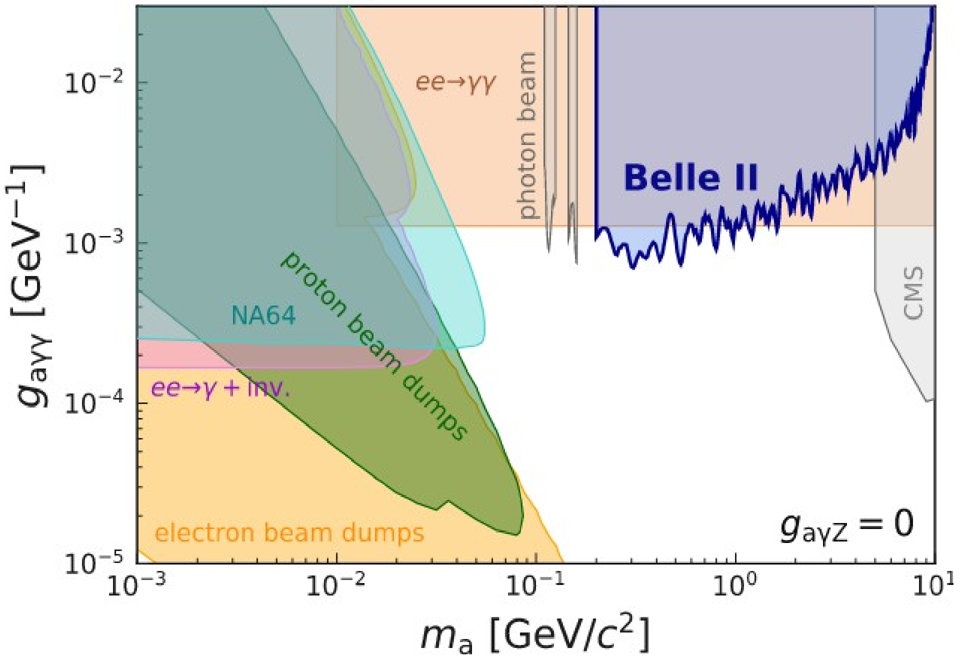
- Set 95% CL upper limits on the signal cross section and translated in $g_{a\gamma\gamma}$ limits

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

→ 1/100 000th of final target data set

→ World's best limit around 500 MeV!





PRL 125 (2020) 161806

ALPs in meson decays

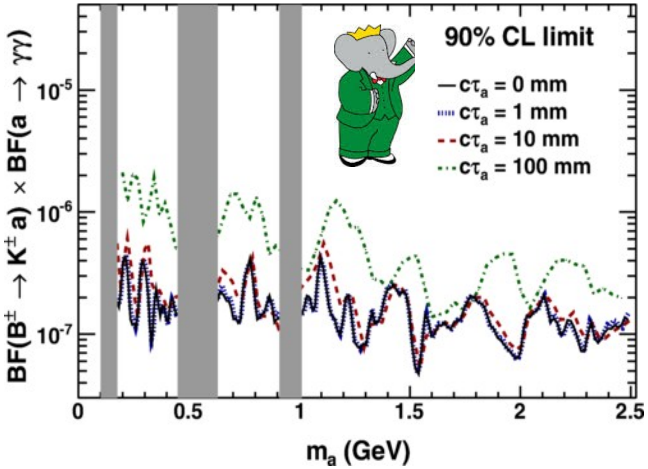
E. Izaguirre, T. Lin, B. Shuve, PRL 118 (2017)

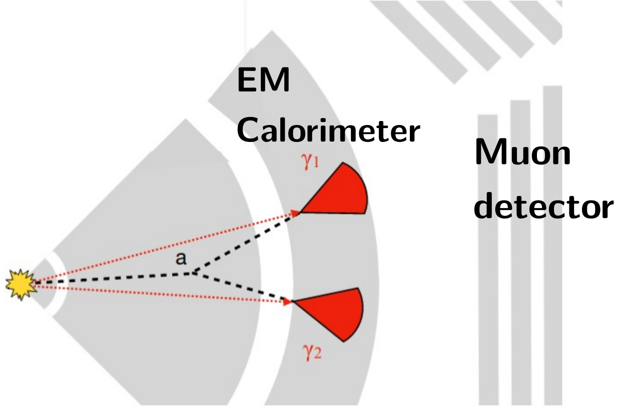
b→ sγγ is extremely rare in the SM and uniquely sensitive to very small **ALP-W coupling g_{aw}** *

- For $m_a << m_W$ naturally *long-lived* ALPs mainly decay into photons
- Search for **$B^\pm \to K^\pm a$, $a \to \gamma\gamma$** as narrow peaks in the **diphoton invariant mass** vetoing peaking background regions, both *prompt* and *long-lived* searches.

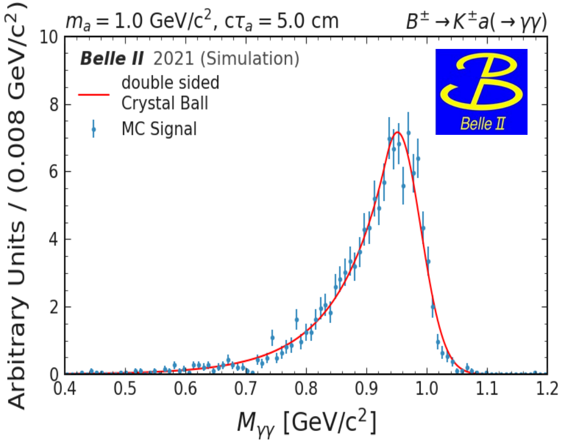
Previous results from Babar on **424/fb at Υ(4S),** $g_{aW}^{UL} < 10^{-5}$

PhysRevLett.128.131802





Belle II ongoing studies



- Belle II will extend the searched range to $m_a > 2.5$ for larger lifetimes (up to $c\tau_a \sim 40$ cm)
  → Competitive sensitivity with 100/fb

- Also studies for ***heavy QCD axion*** ongoing, search for a →ηππ, η →γγ

Z' boson: L_μ-L_τ model

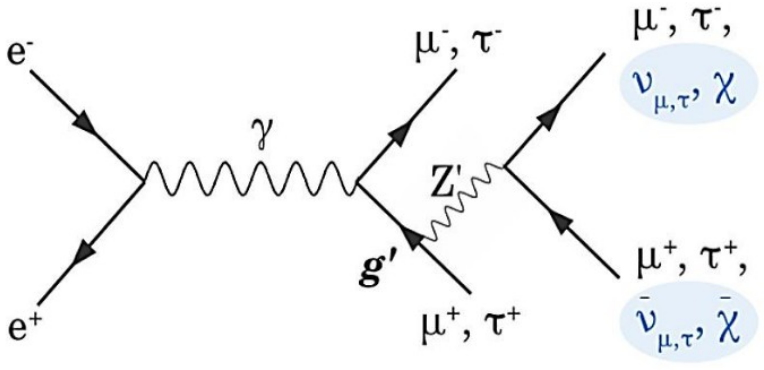
- New gauge boson Z' coupling only to the **2^{nd} and 3^{rd}** generation of leptons (L_μ-L_τ) may explain:
  - DM puzzle
  - *long-standing $(g\text{-}2)_\mu$ anomaly!*
  - Anomalies observed in rare B decays, $B\to K^*\mu\mu$, $R_{K(*)}$

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

B.Shuve and I.Yavin (2014) Phys. Rev. D 89, 113004.
Altmannshofer et al JHEP 1612 (2016) 106.

- Search for the process:

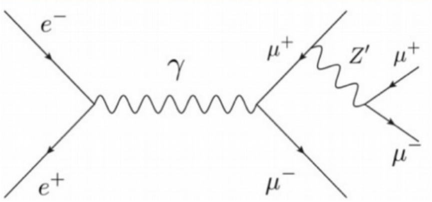
$$e^+e^- \to \mu^+\mu^- Z' \ ,\ Z' \to l, \nu, X$$



Z’ $\to$ $\mu^+\mu^-$

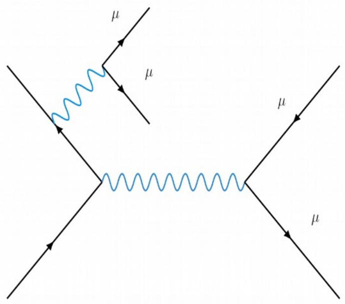
- Search for a di-muon invariant mass peak in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ events

Signal

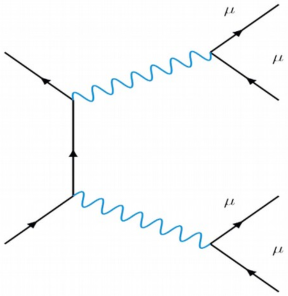


- Main backgrounds from QED processes: $\mu^+\mu^-\mu^+\mu^-$, *ISR, double photon conversion, combinatorial*

ISR

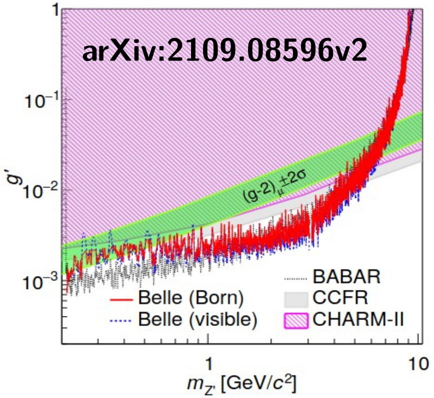


Double photon conversion

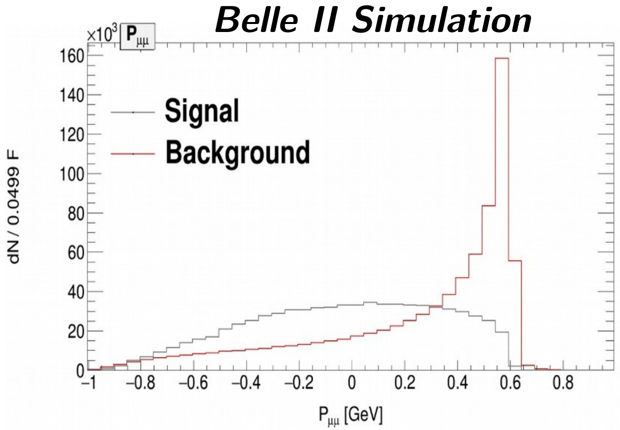


Babar: 514 fb^{-1}, PRD 94, 011102 (2016)

Belle: 643 fb^{-1}, arXiv:2109.08596v2



Competitive with early data set (~ 200 fb^{-1}) **due to aggressive background suppression!**



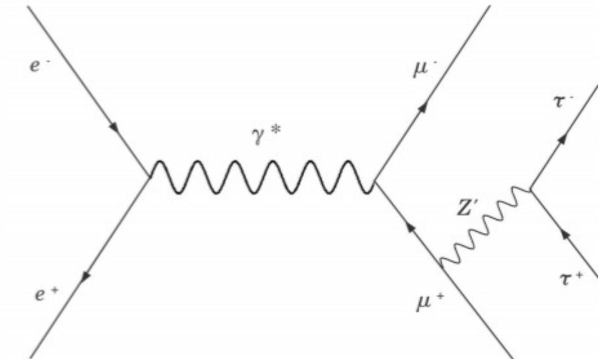
- Neural Network (*MLP, MultiLayer Perceptron*) exploiting dimuon momentum ($P_{\mu\mu}$) and other 14 discriminating variables in 4 different mass ranges to reject background $\to$ **suppression factor between 2-14 on the searched di-muon mass range**

Z’→ττ

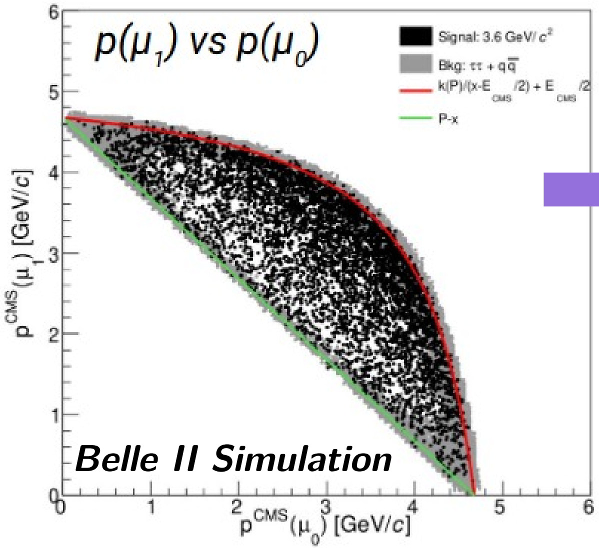
- Search for $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \tau\tau$

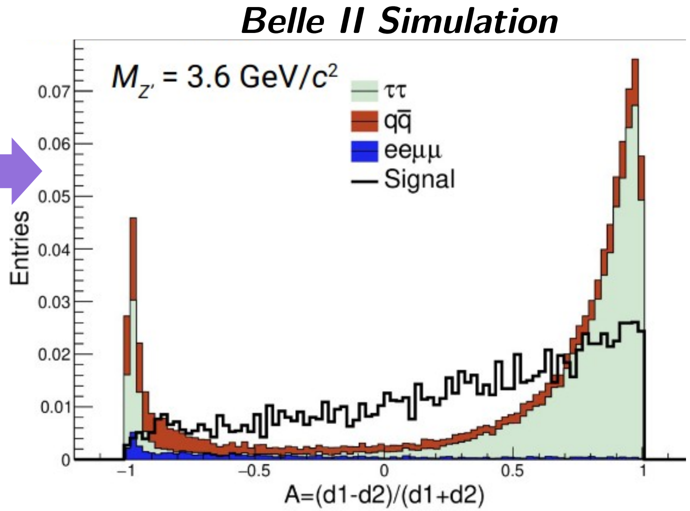
First search!

  - Almost model independent analysis
  - Selection optimized for the final state μμττ ($\tau \to l/h$, 1-prong decays)
  - Sensitive to any di-tau resonance in the searched final state



Challenging due to high background and neutrinos → MVA techniques based on *transformed variables* to optimize discriminating power

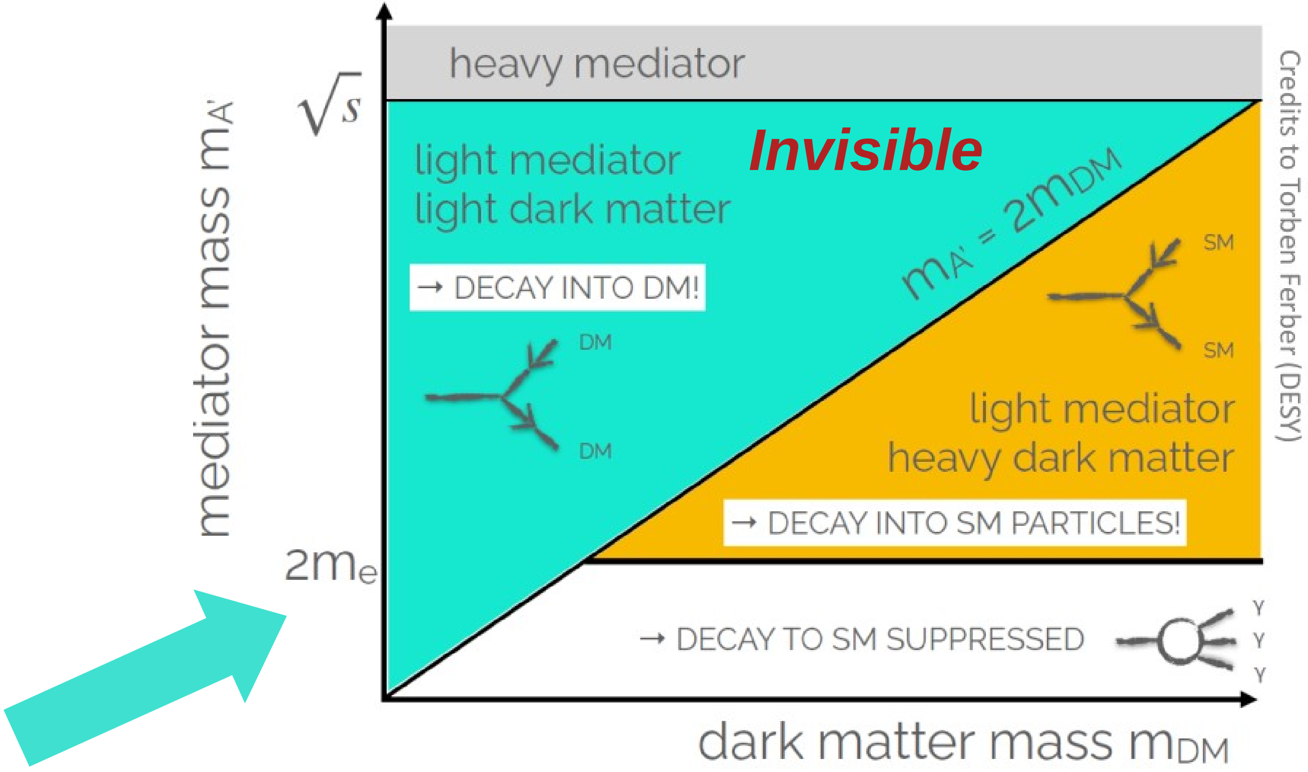




- Compute upper limits on the product $\sigma \cdot B(X \to \tau\tau)$ → ***could be re-interpreted by different models***

  → Expected sensitivity to σ ~ 1 fb from pseudo-data simulation

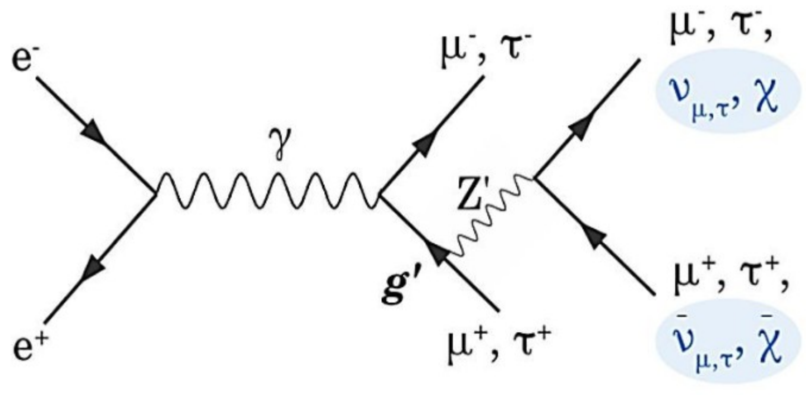
Searches for invisible decays



- $Z' \to$ invisible
- Dark higgstrahlung
- Single photon search

Search for Z' to invisible

- Search for a peak in the mass spectrum of the recoil against a $\mu^+\mu^-$ pair in events where **nothing** else is detected.
- **Only 276 pb^{-1}** of 2018 pilot run data usable due to trigger conditions.



$e^+e^- \to \mu^+\mu^- + missing\ energy$

Invisible signature investigated for the first time!

Branching ratios:

$M_{Z'} < 2M_\mu \to \Gamma(Z' \to inv.) = 1$

$2M_\mu < M_{Z'} < 2M_\tau \to \Gamma(Z' \to inv.) \sim 1/2$

$M_{Z'} > 2M_\tau \to \Gamma(Z' \to inv.) \sim 1/3$

If light DM is accessible, BR(Z'→ DM)~1

More in H. Haigh's talk

- Dominant backgrounds radiative QED processes:
  - $e^+e^- \to \mu^+\mu^-(\gamma)$
  - $e^+e^- \to \tau^+\tau^-(\gamma)$
  - $e^+e^- \to e^+e^-\mu\mu$

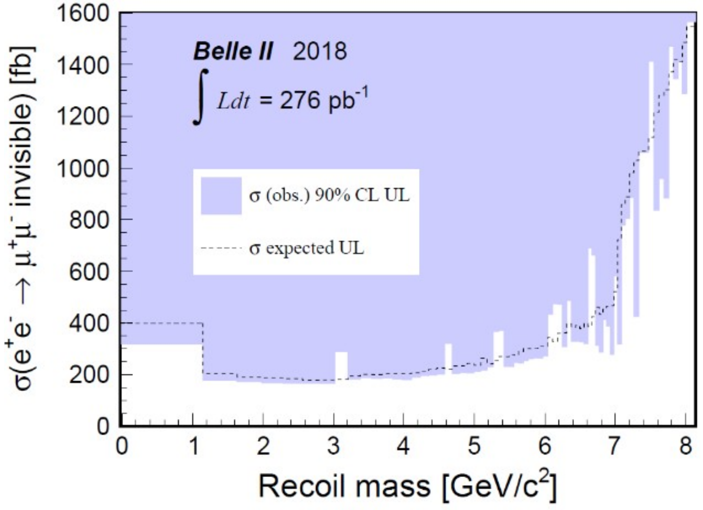
→ Rejected by exploiting pT_{rec} and FSR properties of the emitted Z' candidate

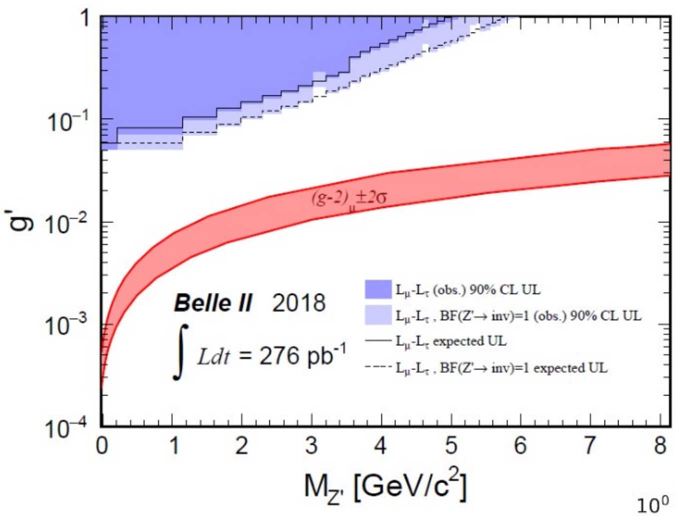
PRL 124 (2020) 141801

Search for Z' to invisible

- No significant excess found, first limits set on $m_{Z'} < 2m_{\mu}$

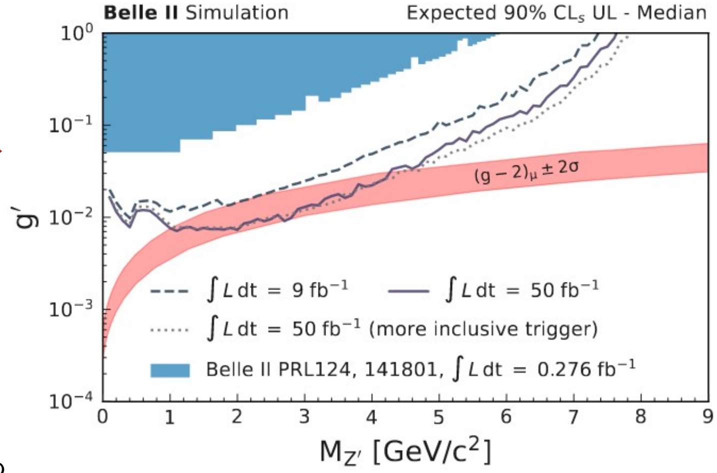
PRL 124 (2020) 141801





More in H. Haigh's talk

BELLE2-NOTE-PL-2020-012

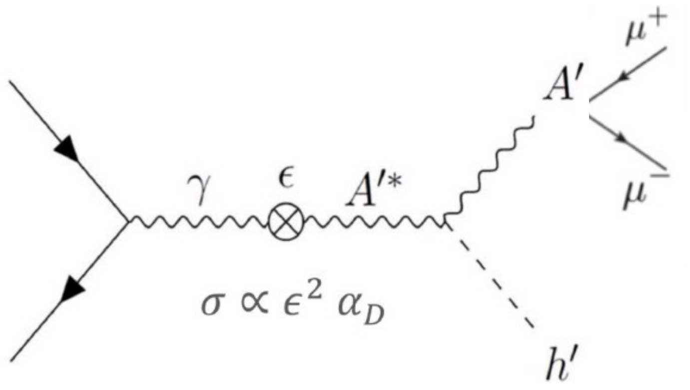


Updated results on 2019-2020 data coming soon

- ~ x 300 data set
- Analysis improvements (muon identification, MVA background suppression, new fitting strategy)
- more inclusive trigger

Dark Higgsstrahlung

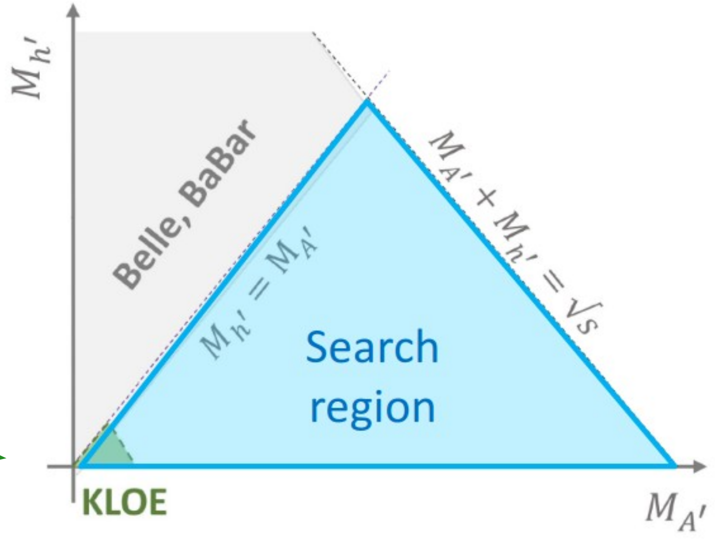
- Dark photon (A') mass can be generated via a spontaneous symmetry breaking(*) mechanism, by adding a dark Higgs boson (h'): *dark Higgsstrahlung* process, $e^+e^- \rightarrow A'^* \rightarrow h' A'$



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

More in H. Haigh's talk

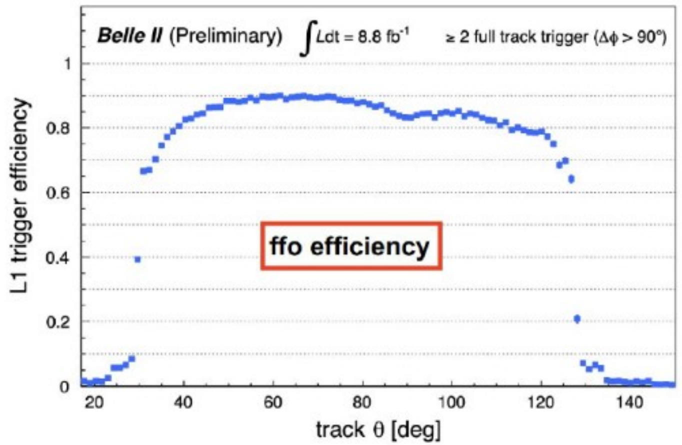
- Belle II has unique capability to probe the ***invisible h' decay*** $\boldsymbol{(m_{h'} < m_{A'})}$ with A' decaying to a muon pair
- Previously constrained only by **KLOE**(**)

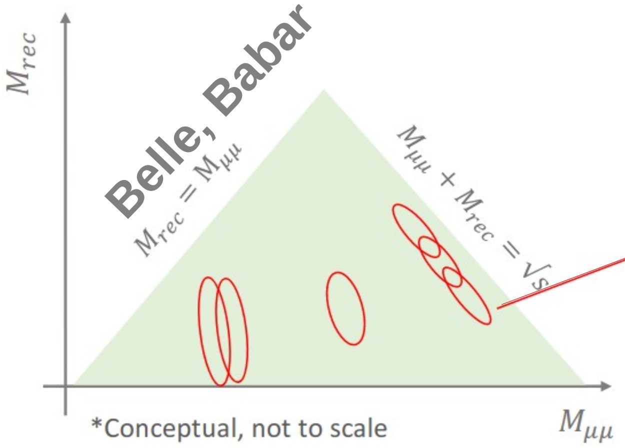


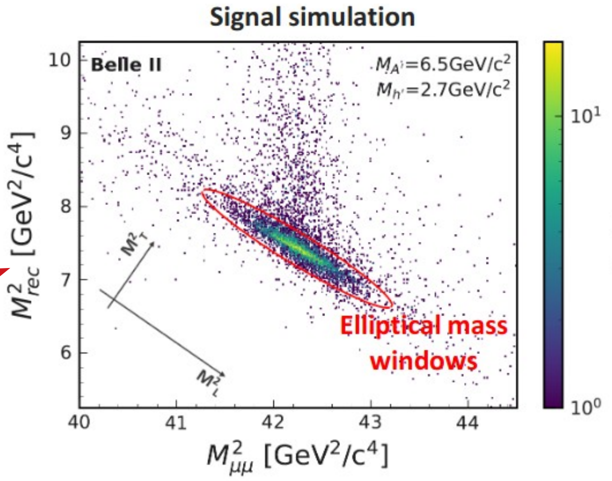
* Batell, Pospelov, Ritz, Phys. Rev. D 79, 115008 (2009)
** Babusci et al. (2015), Phys.Lett. B 747 pg. 365-372, 0370-2693

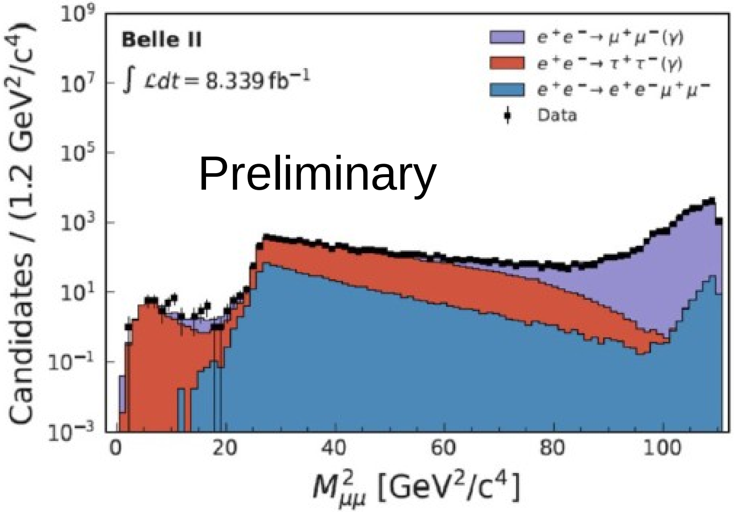
Dark Higgsstrahlung: analysis strategy

- Search in 8.34/fb data (2019)
- A' reconstructed as muon pairs, $M_{\mu\mu} > 1.65$ GeV for trigger requirements (two track+ opening angle trigger from the CDC, *ffo)*
  - $\rightarrow$ *same final state as for the invisible Z', similar backgrounds*
- Scan dimuon and recoil mass searching for peaks in 9000 sliding elliptical windows
- Apply Bayesian counting technique (challenging look-elsewhere effect)



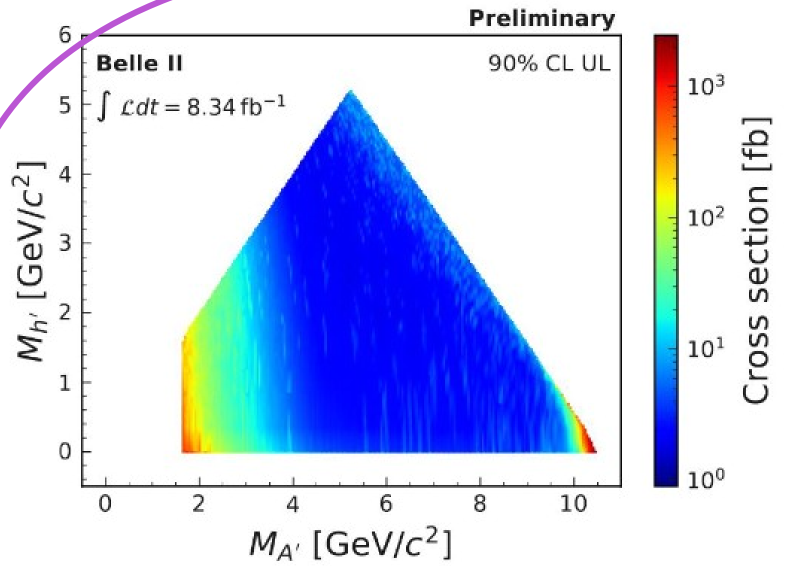


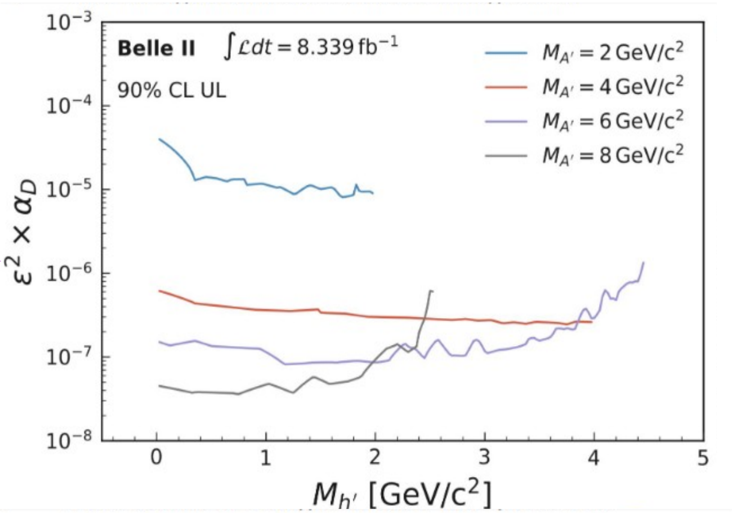


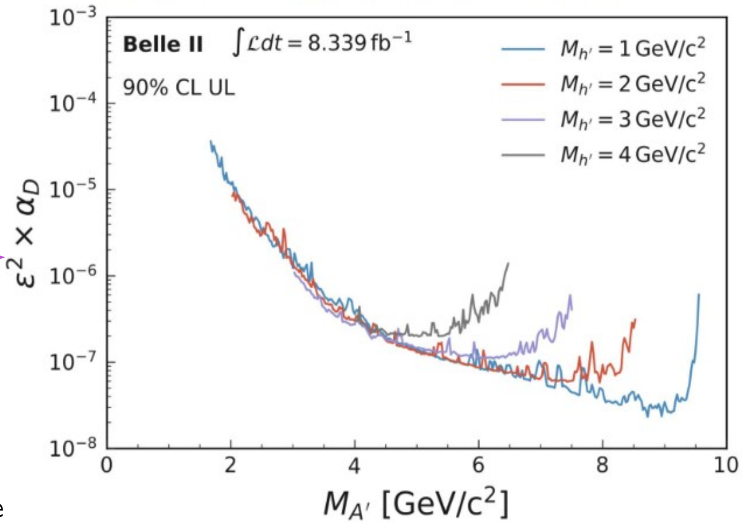


Dark Higgsstrahlung results

- With no signal excess found, Belle II provides world leading results in unexplored phase space region → **probe non-trivial $\varepsilon^2\alpha_D$ couplings**





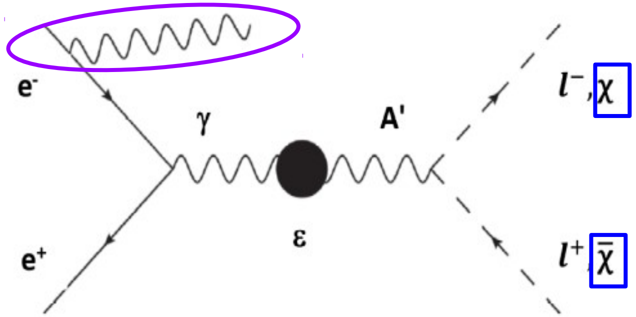


World leading results for $1.65 < M_{A'} < 10.51$ GeV/c^2

→ can be interpreted in a wider class of theoretical models (e.g., long-lived higgs mixing with h_{SM})

A’ → invisible: single photon search prospects

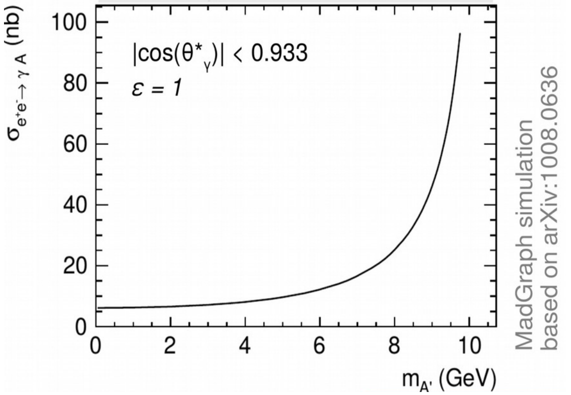
- New massive boson A’ coupling to the SM photon through the kinetic mixing with strength ε. At e^+e^- colliders investigate the ISR production $\boldsymbol{e^+e^- \to \gamma A'}$.



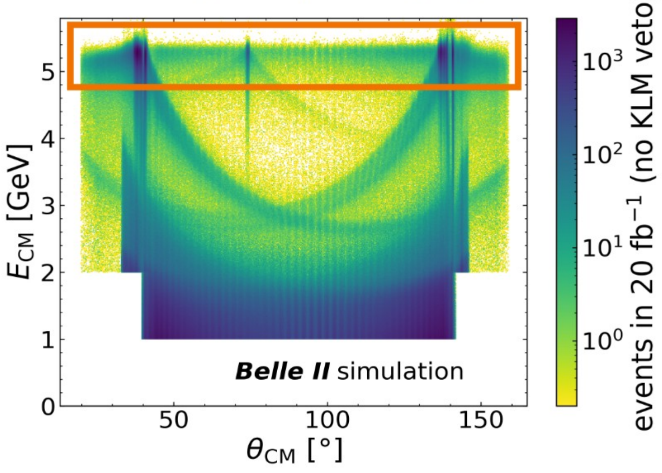
$$\mathcal{L} \supset \varepsilon A'_\mu J^\mu_{\rm SM}$$

Batell et al. (2009), arXiv:0903.0363

$m_{A'} > 2m_\chi$ → A’ decays 100% invisibly into ***DM particle***



- Select events with **nothing** but a single high energetic *ISR photon.* Look for a bump in the reconstructed photon energy $E_\gamma = (s - m^2_{A'})/2\sqrt{s}$
- **Background:** QED processes $\boldsymbol{e^+e^- \to \gamma\gamma(\gamma)}$ (*low mass* region) and radiative Bhabha $\boldsymbol{e^+e^- \to e^+e^- \gamma(\gamma)}$ (*high mass* region) + cosmics



Belle II Simulation Preliminary

A’ → invisible: single photon search prospects

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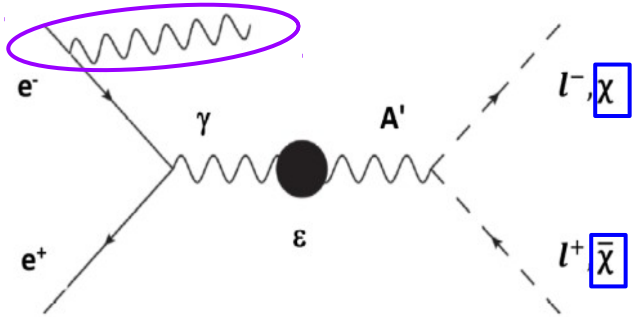

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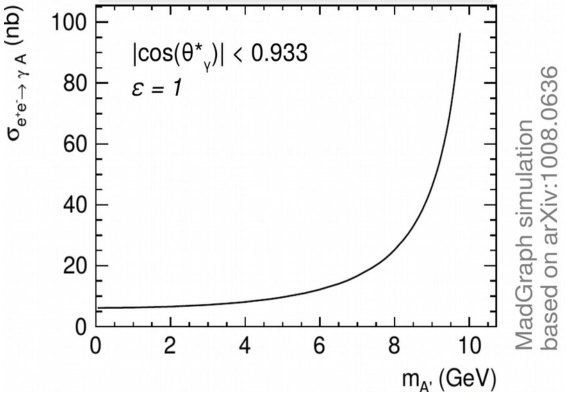

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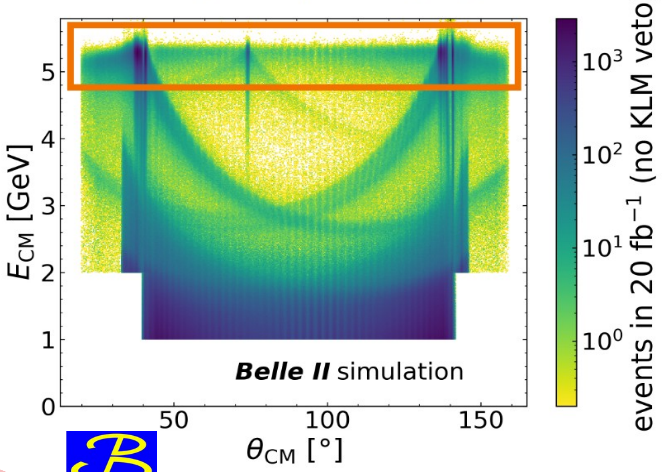
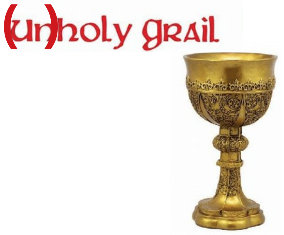
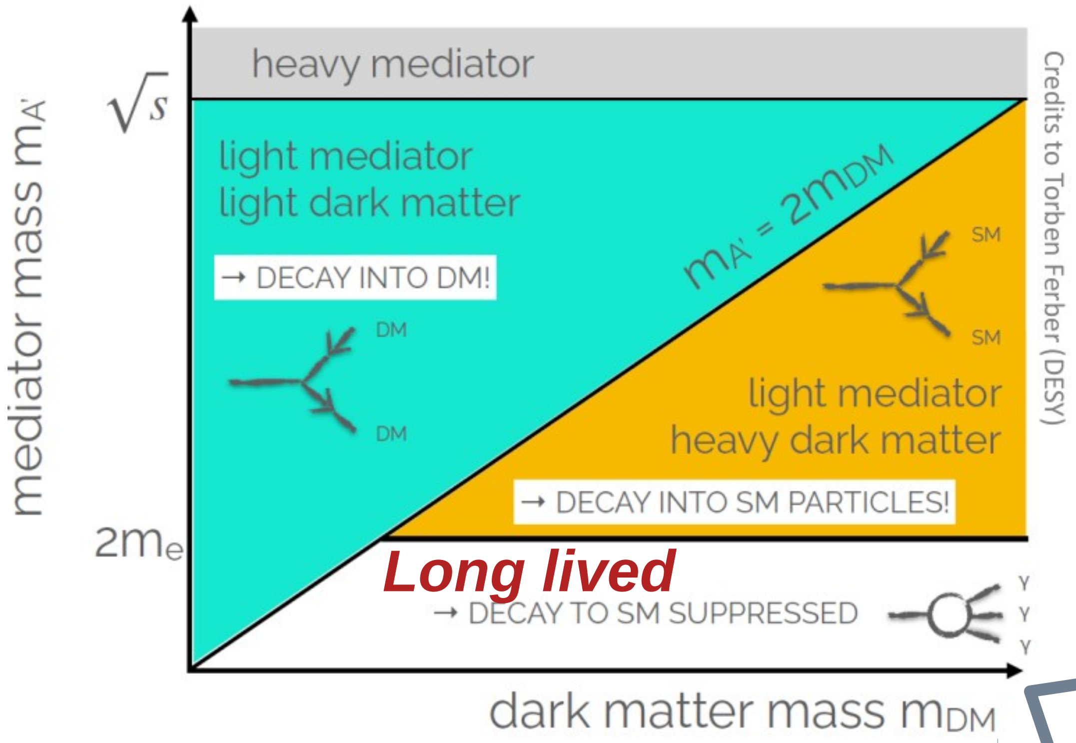


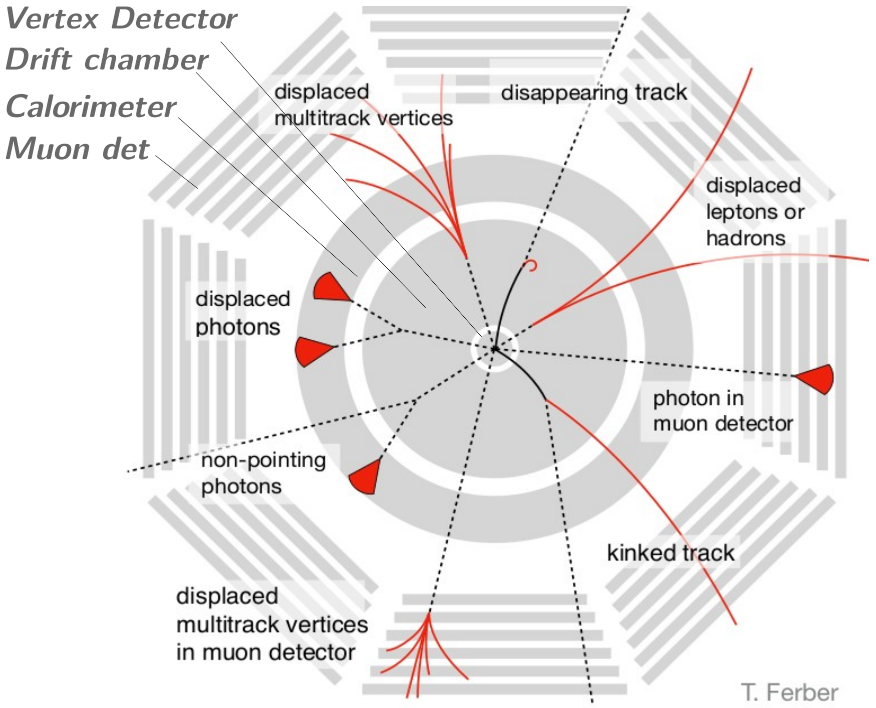


→ Dedicated **single photon trigger** (none at Belle, at Babar on 10% of the data)

Crucial for Belle II to be competitive to exploit **KLM as veto, currently missing**→ detector studies ongoing

Displaced vertices at Belle II

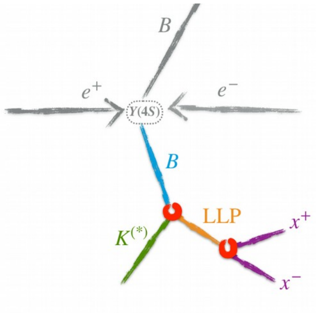


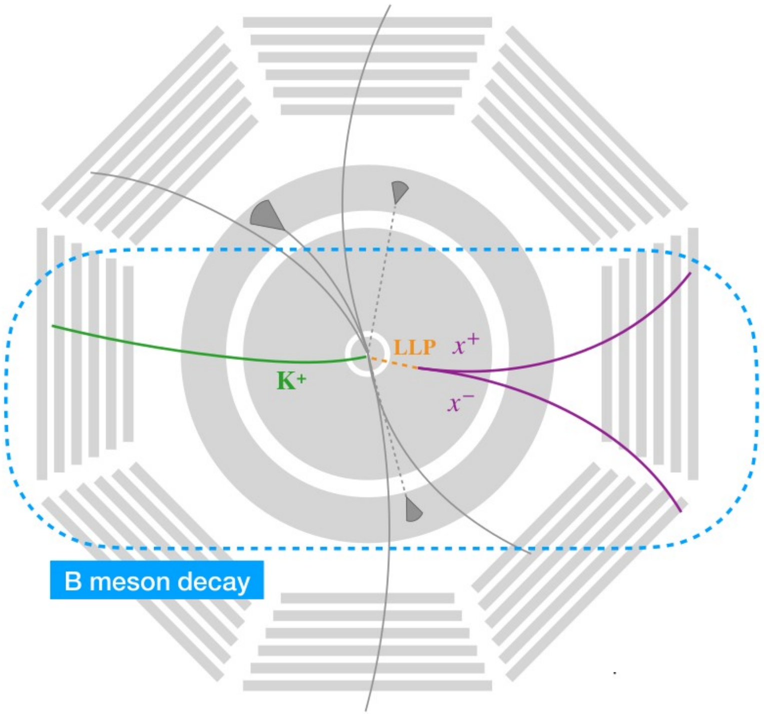


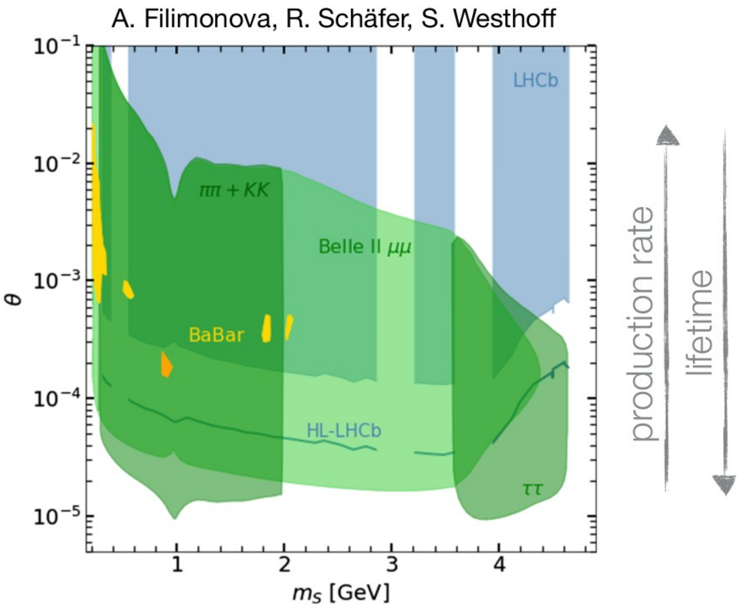
- Long-lived particles in $b \to s$ transitions:
  - displaced vertex (*scalar*, Dark Higgs)
  - displaced photons (*pseudo-scalar*, ALPs)
- Inelastic Dark Matter

Long-lived (scalar) particles at Belle II

- Reconstruct B meson decay
  - prompt Kaon + two opposite-sign tracks forming a displaced vertex (LLP)
  - Exploit B-factory closed kinematics constraint to reject background, look for a bumb in the LLP invariant mass
  - Dominant background: SM long-lived, K_S and Λ







Phys. Rev. D 101, 095006 (2020)

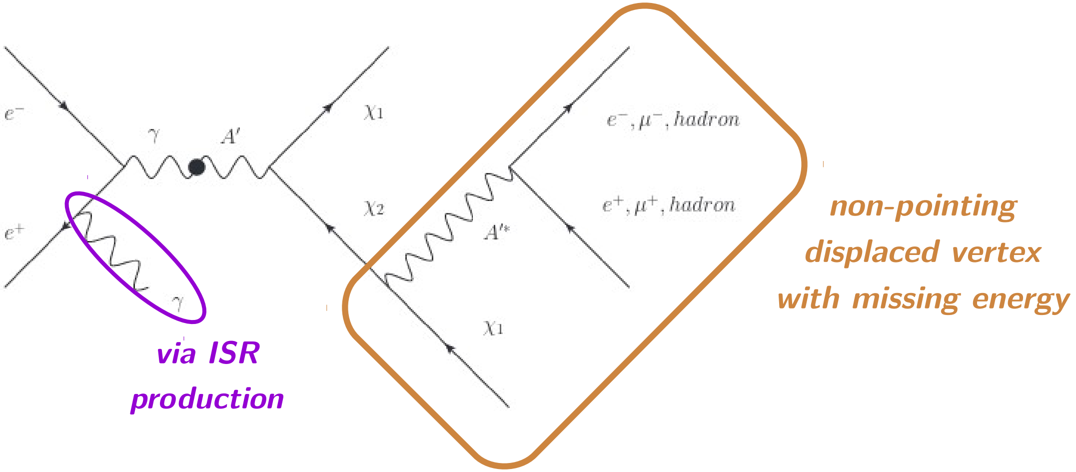
- Compute limits on cross-sections $\sigma(e^+ e^- \rightarrow \Upsilon(4S) \rightarrow [B \rightarrow K\,LLP\,]\overline{B})$ for different lifetimes and translate into model dependent limits on m_S & θ_S, where $c\tau_S = f\,(m_S\,,\,\theta_S\,)$

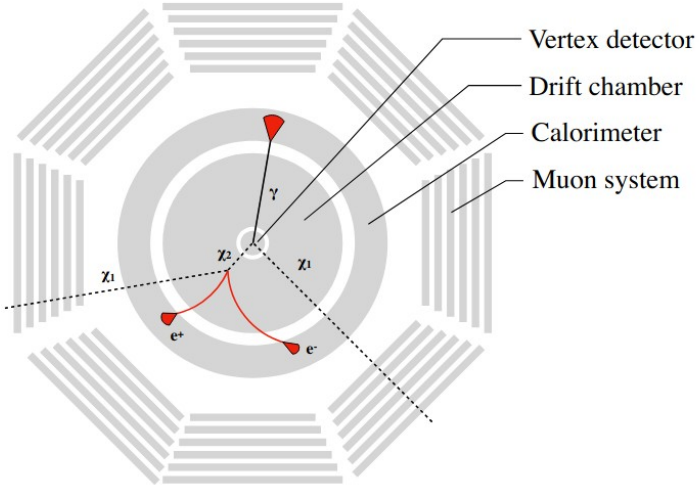
Inelastic Dark Matter

Dark photon A' and dark matter states χ1 and χ2 with a small mass splitting:

- χ1 is stable (relic)
- χ2 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





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 ~ 100/fb

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

Conclusions

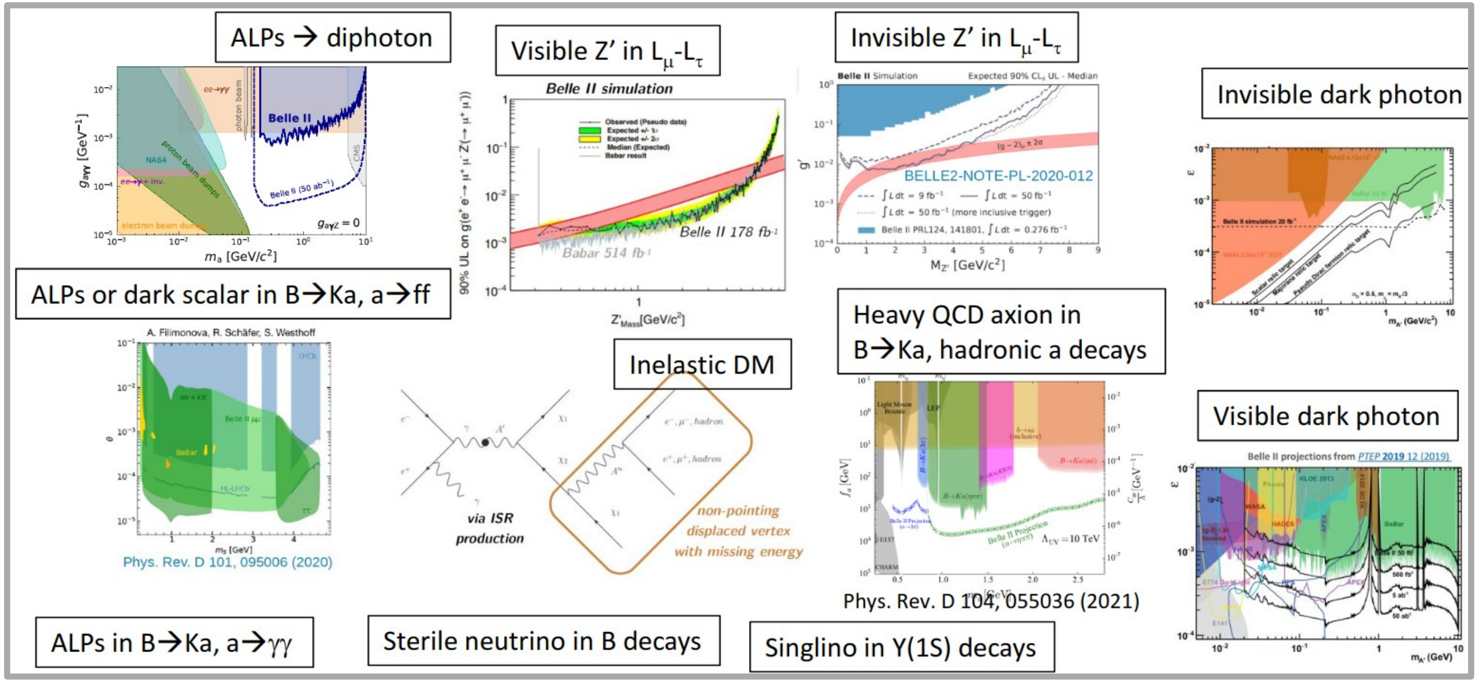
Very active and wide-ranging program of searches for dark sectors at lepton colliders → *competitive limits on several models* to probe the DM puzzle

- Belle II proved already its capability to produce ***world leading results*** even on a minimal data set
  → *with increasing luminosity, improved performance/strategies more searches to come*

Z' → inv PRL 124 (2020) 141801
a → γγ PRL 125 (2020) 161806

Dark Higgs (preliminary)
Z' update

Latest results also shown in the parallel session, H.Haigh's talk



The Belle II Physics book

Thank you!

Thanks for your attention.

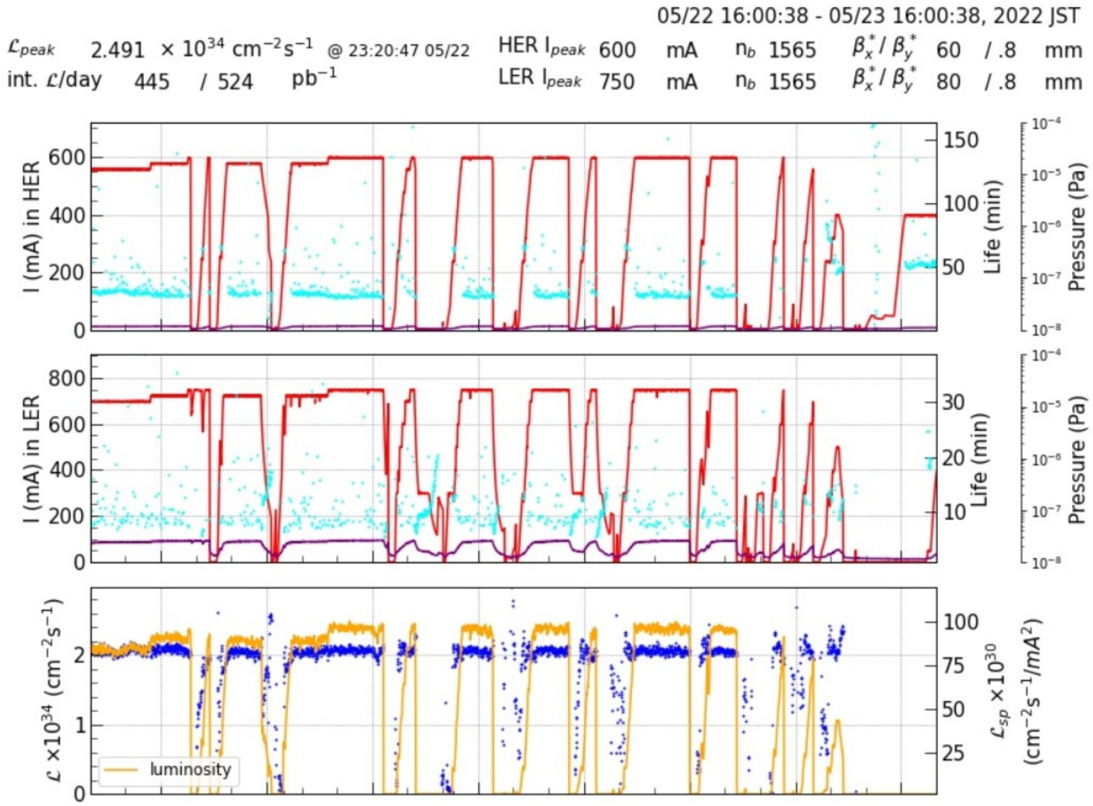
Backup

Peak luminosity record at SuperKEKB

https://www-linac.kek.jp/skekb/snapshot/dailysnap.html

SuperKEKB 24-Hour Operation Summary

New peak luminosity 4.14 x 10^34 (cm-2s-1), May 17, 2022.

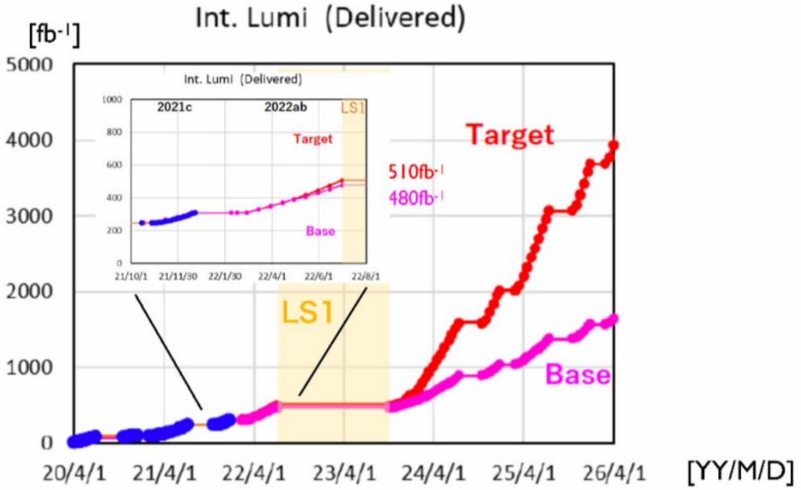


Belle II prospects

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

Cross section in e^+e^- collision at 10.58 GeV

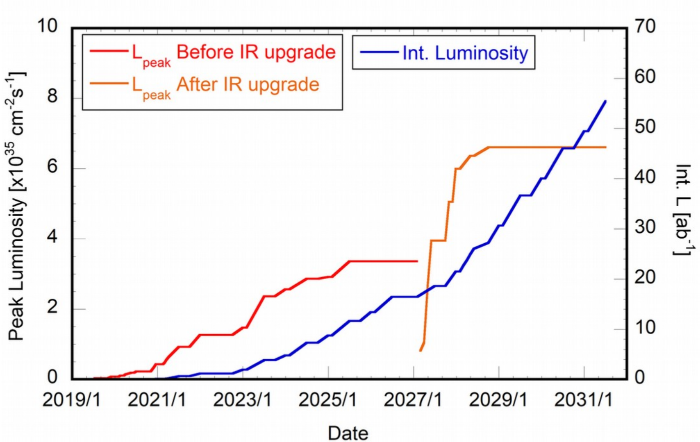
Physics process	Cross section [nb]	Selection Criteria	Reference
$\Upsilon(4S)$	1.110 ± 0.008	-	[2]
$u\bar{u}(\gamma)$	1.61	-	KKMC
$d\bar{d}(\gamma)$	0.40	-	KKMC
$s\bar{s}(\gamma)$	0.38	-	KKMC
$c\bar{c}(\gamma)$	1.30	-	KKMC
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)	$10° < \theta_e^* < 170°$, $E_e^* > 0.15\,\mathrm{GeV}$	BABAYAGA.NLO
$e^+e^-(\gamma)$	74.4	$p_e > 0.5\,\mathrm{GeV}/c$ and e in ECL	-
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10° < \theta_\gamma^* < 170°$, $E_\gamma^* > 0.15\,\mathrm{GeV}$	BABAYAGA.NLO
$\gamma\gamma(\gamma)$	3.30	$E_\gamma > 0.5\,\mathrm{GeV}$ in ECL	-
$\mu^+\mu^-(\gamma)$	1.148	-	KKMC
$\mu^+\mu^-(\gamma)$	0.831	$p_\mu > 0.5\,\mathrm{GeV}/c$ in CDC	-
$\mu^+\mu^-\gamma(\gamma)$	0.242	$p_\mu > 0.5\,\mathrm{GeV}$ in CDC, $\geq 1\ \gamma\ (E_\gamma > 0.5\,\mathrm{GeV})$ in ECL	-
$\tau^+\tau^-(\gamma)$	0.919	-	KKMC
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-	KKMC
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$	AAFH
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$	AAFH

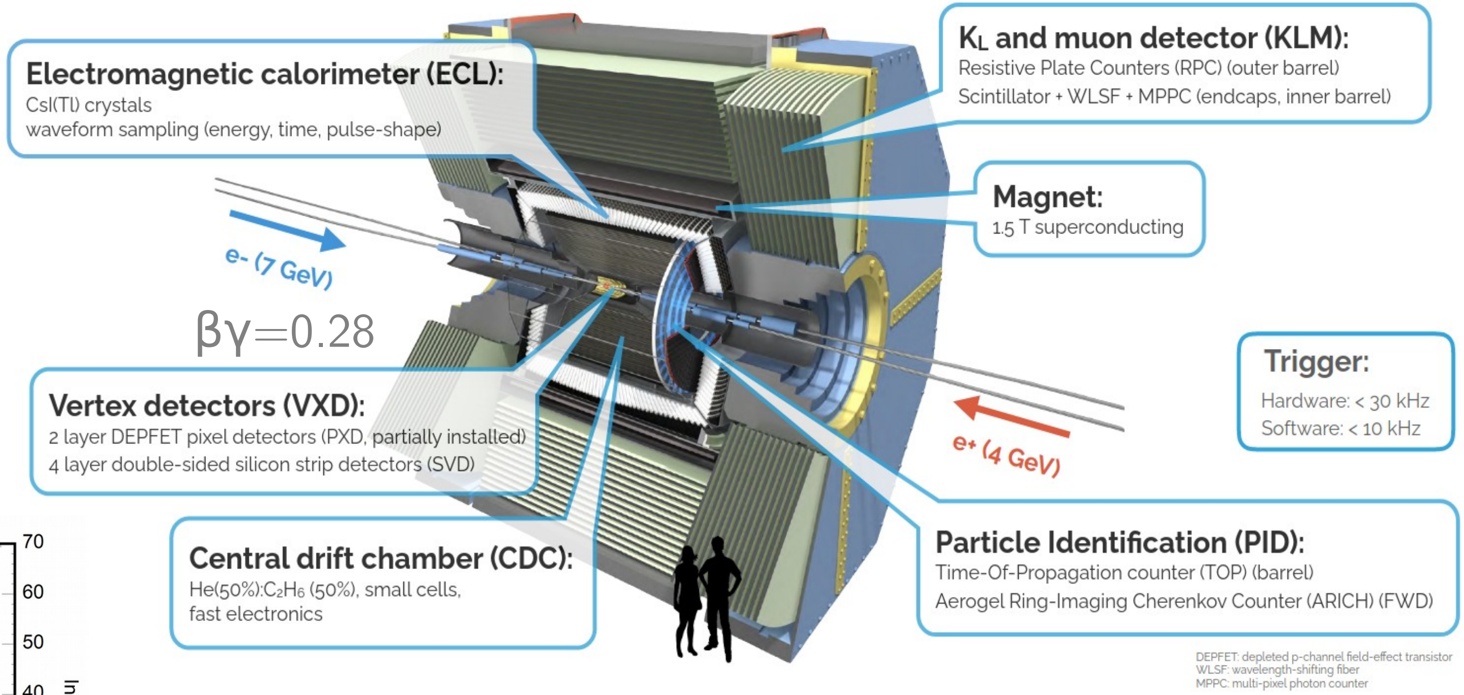
The Belle II Physics Book [arXiv:1808.10567]

- Low multiplicity event cross sections rapidly diverge compared to hadronic ones
- Selections applied at MC generator level to reduce the effective cross section (acceptance, particle momentum selections)
- W_{ll} is the minimum invariant secondary fermion pair mass

Belle II detector

- Updated detector:
  - provide comparable/better efficiencies and resolutions in a higher background
  - Improved dedicated triggers for low multiplicity and missing energy final states





$\beta\gamma=0.28$

GOAL: 50 ab^{-1}

The Belle II Physics Book, PTEP 2019 12 (2019)

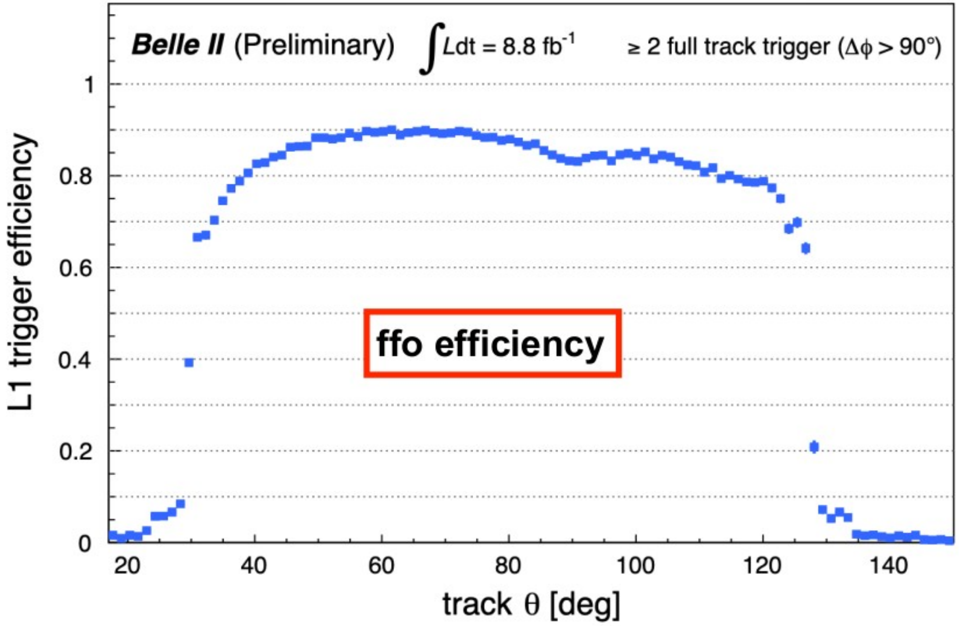
Triggers

- Belle II hardware-based (Level 1) trigger combines information from CDC, ECL, TOP and KLM.
  - Designed to reduce rate to at most 30 kHz, while delivering ~100% efficiency for $\Upsilon(4S) \rightarrow B\bar{B}$ events
  - **Novel menu of triggers unavailable in Belle enable a compelling low-multiplicity program!**

- Main trigger types for Tau & Dark Sector physics:
  - CDC number of full tracks
  - CDC number of short tracks
  - ECL total energy threshold
  - ECL number of isolated clusters
  - ECL low multiplicity
  - ECL di-muon

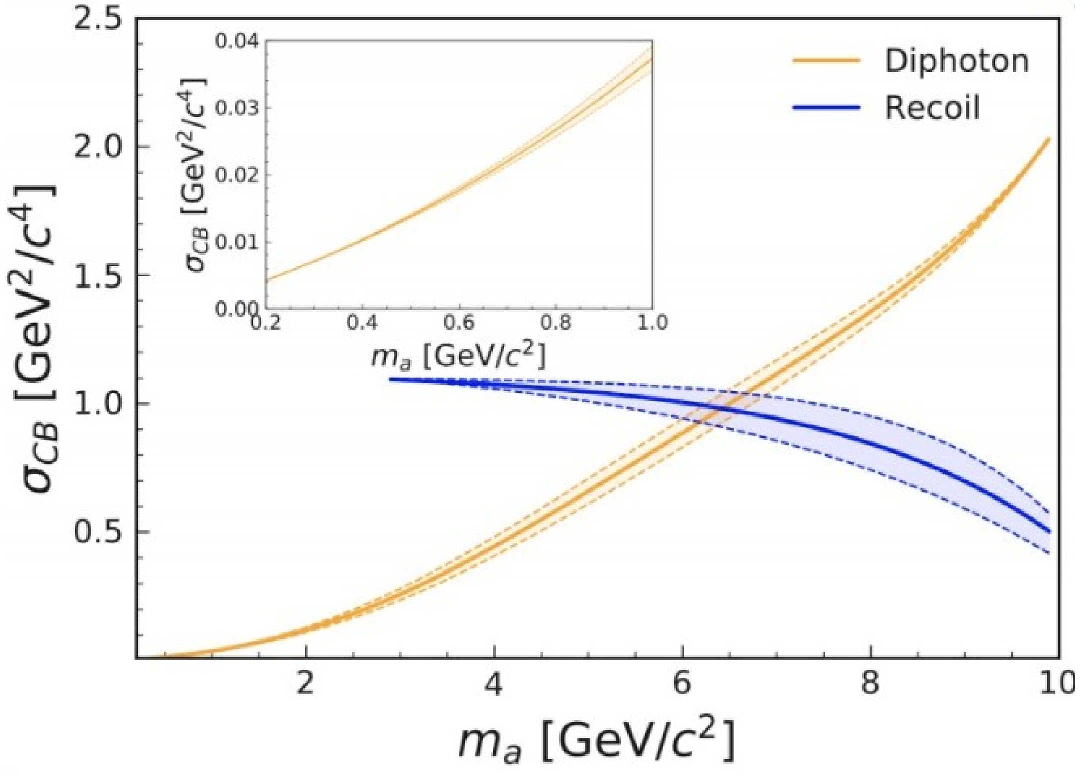
- In the **dark Higgsstrahlung** analysis events are required to fire the so-called "**ffo**" trigger:

  $\geq$ 2 full tracks, pair with $\Delta\varphi > 90°$, bhabha-veto



ALPs at Belle II: resolutions

- Signal resolutions for di-photon and recoil masses



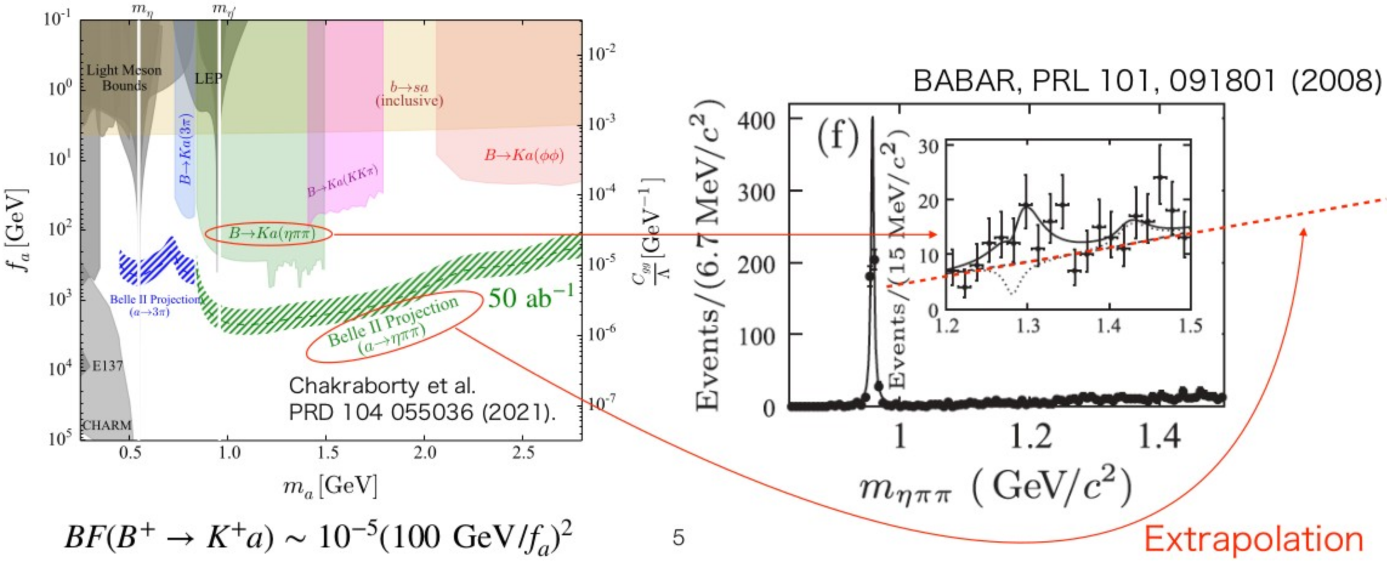
B→ Ka, a → hadrons

- Chakraborty et al. (PRD 104 055036 (2021)) estimated sensitivity of heavy QCD axion using some (not DM search) experimental data.
  - $a \to \eta\pi^+\pi^-$: BABAR, PRL 101, 091801 (2008),

    $$B^+ \to \eta_X K^+, \eta_X \to \eta\pi^+\pi^-, \ \sim 400 \text{ fb}^{-1}.$$

  - $a \to \pi^0\pi^+\pi^-$: Belle, PRD 90, 012002 (2014),

    $$B^+ \to \omega K^+, \omega \to \pi^0\pi^+\pi^-, \ \sim 700 \text{ fb}^{-1}.$$



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

5

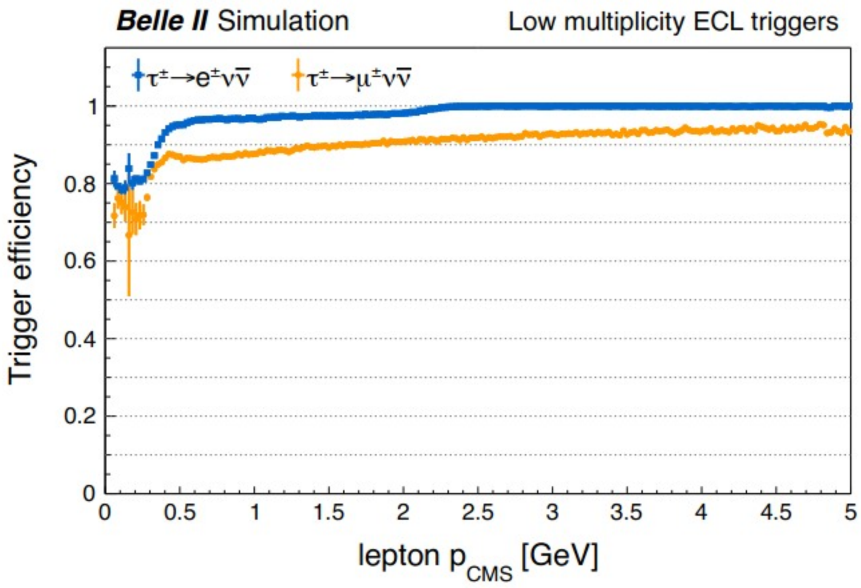
Low multiplicity triggers

- Events are required to fire the logical OR of several unprescaled low-multiplicity (**lml**) ECL triggers

- **lml0** : ≥ 3 clusters with at least one having $E^* > 300$ MeV, $1 < \theta_{ID} < 17$ (corresponding to $12.4° < \theta < 154.7°$, full ECL) and not an ECL Bhabha.
- **lml1** : exactly 1 cluster with $E^* > 2$ GeV and $4 < \theta_{ID} < 14$ ($32.2° < \theta < 124.6°$)
- **lml2** : ≥ 1 cluster with $E^* > 2$ GeV, $\theta_{ID} = 2, 3, 15$, or 16 ($18.5° < \theta < 32.2°$ or $124.6° < \theta < 139.3°$) and not an ECL Bhabha.
- **lml4** : ≥ 1 cluster with $E^* > 2$ GeV, $\theta_{ID} = 1$ or 17 ($12.4° < \theta < 154.7°$) and not an ECL Bhabha.
- **lml6** : exactly 1 cluster with $E^* > 1$ GeV, $4 < \theta_{ID} < 15$ ($32.2° < \theta < 128.7°$, full ECL barrel) and no other cluster with $E >$ 300 MeV anywhere.
- **lml7** : exactly 1 cluster with $E^* > 1$ GeV, $\theta_{ID} = 2, 3$ or 16 ($18.5° < \theta < 31.9°$ or $128.7° < \theta > 139.3°$) and no other cluster with $E >$ 300 MeV anywhere.
- **lml8** : cluster pair with $170° < \Delta\phi < 190°$, both clusters with $E^* > 250$ MeV and no 2 GeV cluster in the event.
- **lml9** : cluster pair with $170° < \Delta\phi < 190°$, one cluster with $E^* < 250$ MeV with the other having $E^* > 250$ MeV, and no 2 GeV cluster in the event.
- **lml10** : cluster pair with $160° < \Delta\phi < 200°$, $160° < \sum\theta < 200°$ and no 2 GeV cluster in the event.
- **lml12** : ≥ 3 clusters with at least one having $E^* > 500$ MeV, $2 < \theta_{ID} < 16$ (corresponding to $18.5° < \theta < 139.3°$, full ECL) and not an ECL Bhabha. (θ_{ID} values have to be double checked).

- Absolute trigger efficiency in MC (TSIM, release-05-02-00):

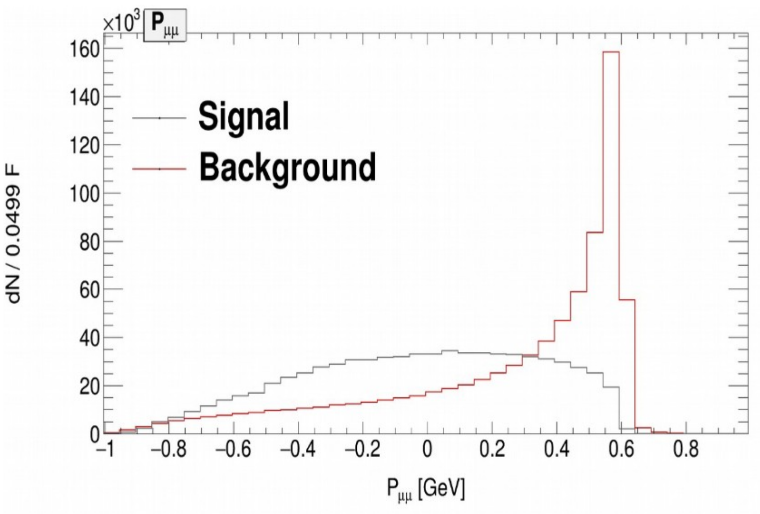
$$\epsilon_{L1} = \frac{\textbf{lml0}\ or\ \textbf{lml1}\ or\ \textbf{lml2}\ or\ \textbf{lml4}\ or\ \textbf{lml6}\ or\ \textbf{lml7}\ or\ \textbf{lml8}\ or\ \textbf{lml9}\ or\ \textbf{lml10}\ or\ \textbf{lml12}}{\text{all events}}$$

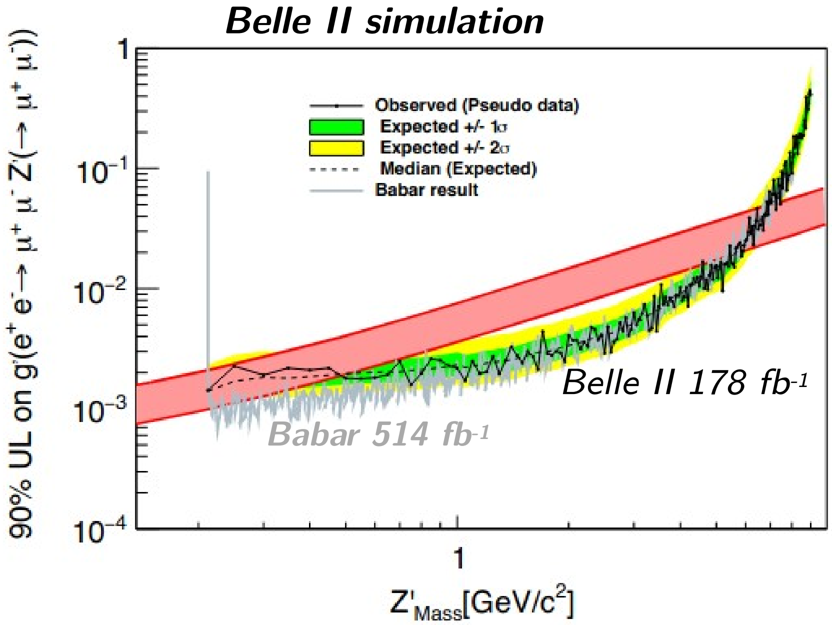


- For this trigger configuration, TSIM has been shown to reproduce data efficiency within ~1%.

Z' $\to \mu^+\mu^-$: background rejection

- Neural Network (*MLP, MultiLayer Perceptron*) exploiting dimuon momentum ($P_{\mu\mu}$) and other 14 discriminating variables in 4 different mass ranges to reject background





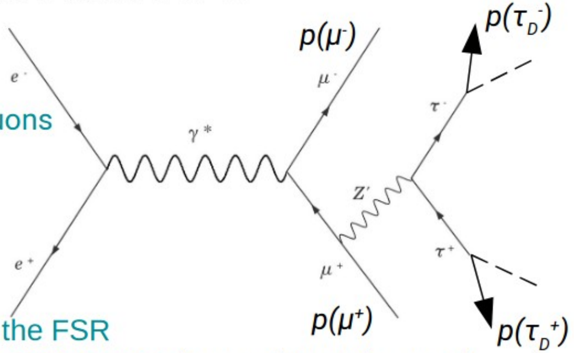
→ Background suppression factor between 2-14 on the searched di-muon mass range

Z'→ττ: background rejection (I)

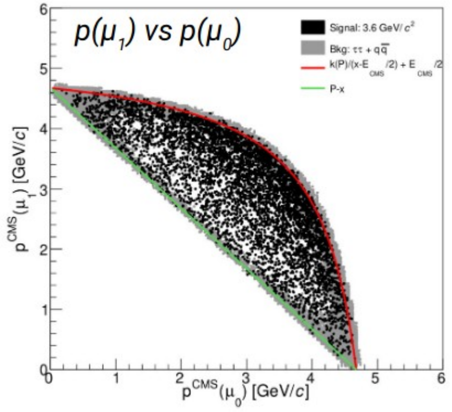
Credit to Luigi Corona

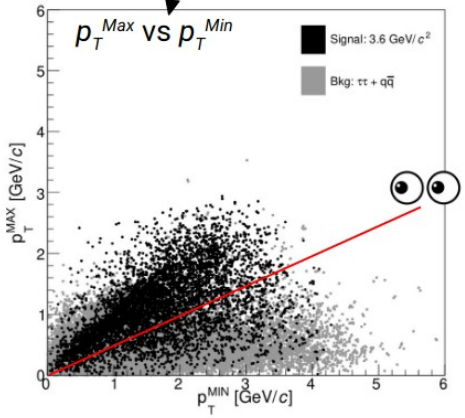
Class-1) Sensitive to a resonance

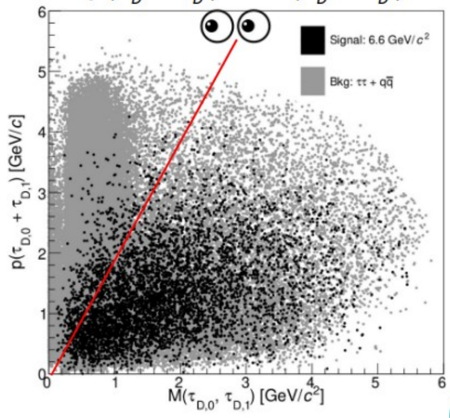
- Discriminant variables sensitive to the presence of a resonance in the recoil system
  - $p(\mu^+)$ vs $p(\mu^-)$ ← w.r.t the two tagging muons
  - p_T^{MAX} vs p_T^{MIN}: transverse component of recoil (Z' for signal) momentum along the direction of the max/min lepton momentum
  - $p(\tau_D^- + \tau_D^+)$ vs $M(\tau_D^- + \tau_D^+)$
- All momenta are expressed in the center of mass frame
- Signal and background in mass bins $M_{Z'} \pm 5\sigma_{peak}$



Also sensitive to the FSR production of the resonance







Dark Sector Meeting. $Z' \to \tau\tau$. Luigi Corona

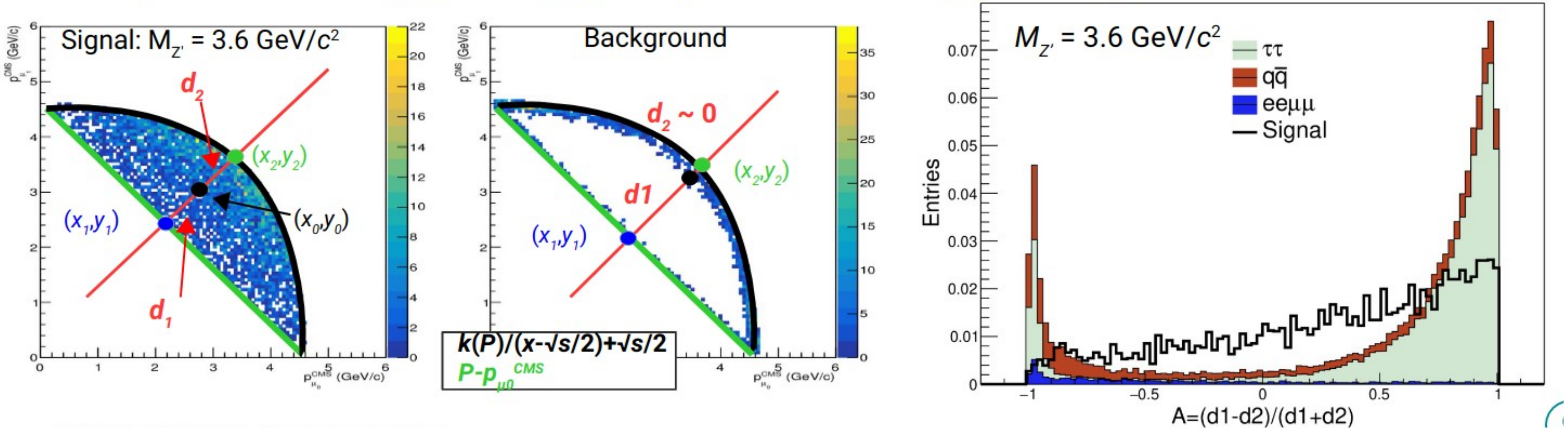
Z'→ττ: background rejection (II)

Credit to Luigi Corona

Class-1) for MVA: $p(\mu_1)$ vs $p(\mu_0)$

$$P = \frac{\sqrt{(s + M_{Z'}^2 - (2m_\mu))^2 - 4sM_{Z'}^2}}{2\sqrt{s}}$$

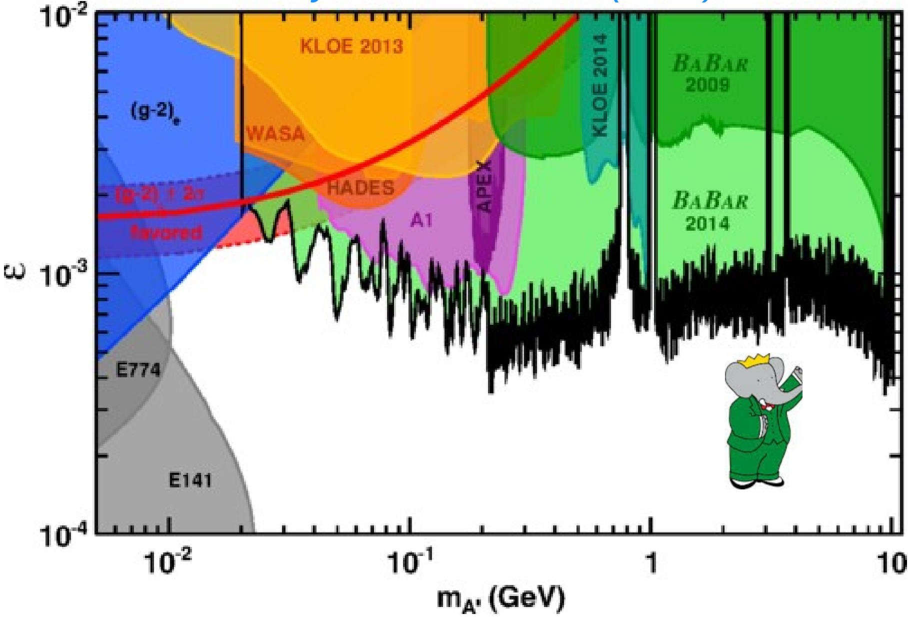
- Momentum P: the maximum Z' momentum that corresponds to a final state with a Z' and a particle of mass $2m_\mu$
- $p(\mu_1)$ vs $p(\mu_0)$ → background accumulates around a straight line (**green**) and a hyperbole (**black**), whose analytical expressions depend only on P and $\sqrt{s}/2$
- $A = (d_1 - d_2)/(d_1 + d_2)$ → considering the **red line** perpendicular to the **green line** passing for a generic point $(x0,y0)$ of the scatter plot:
  - → d_1 is the distance of (x_0,y_0) from (x_1,y_1), and d_2 is the distance of (x_0,y_0) from (x_2,y_2)



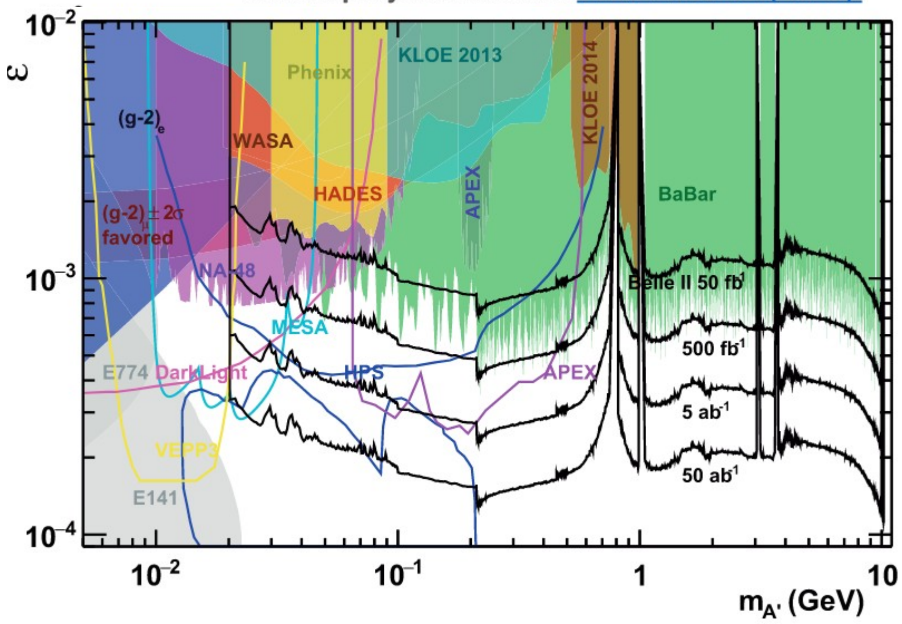
Visible dark photon

- Existing results by BaBar, currently the best limits in all the GeV range:
  - bump search in the reconstructed di-lepton spectrum from the full data set (514 fb^{-1})
- Belle II will lead the sensitivity with the final data set of 50 ab $^{-1}$

Phys. Rev. Lett. 113 (2014)



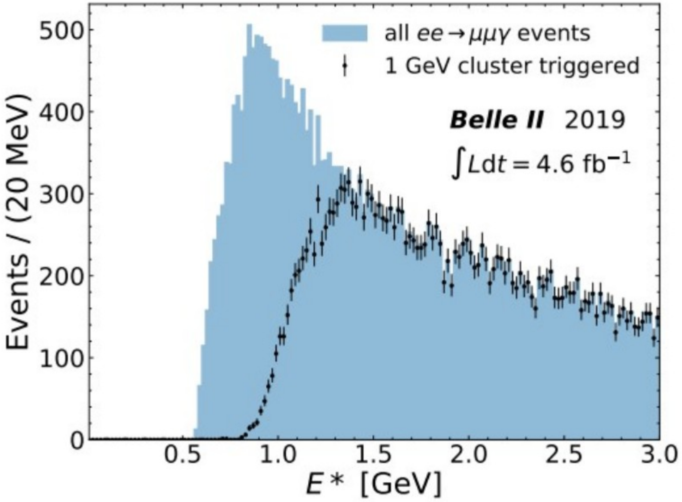
Belle II projections from PTEP 2019 12 (2019)

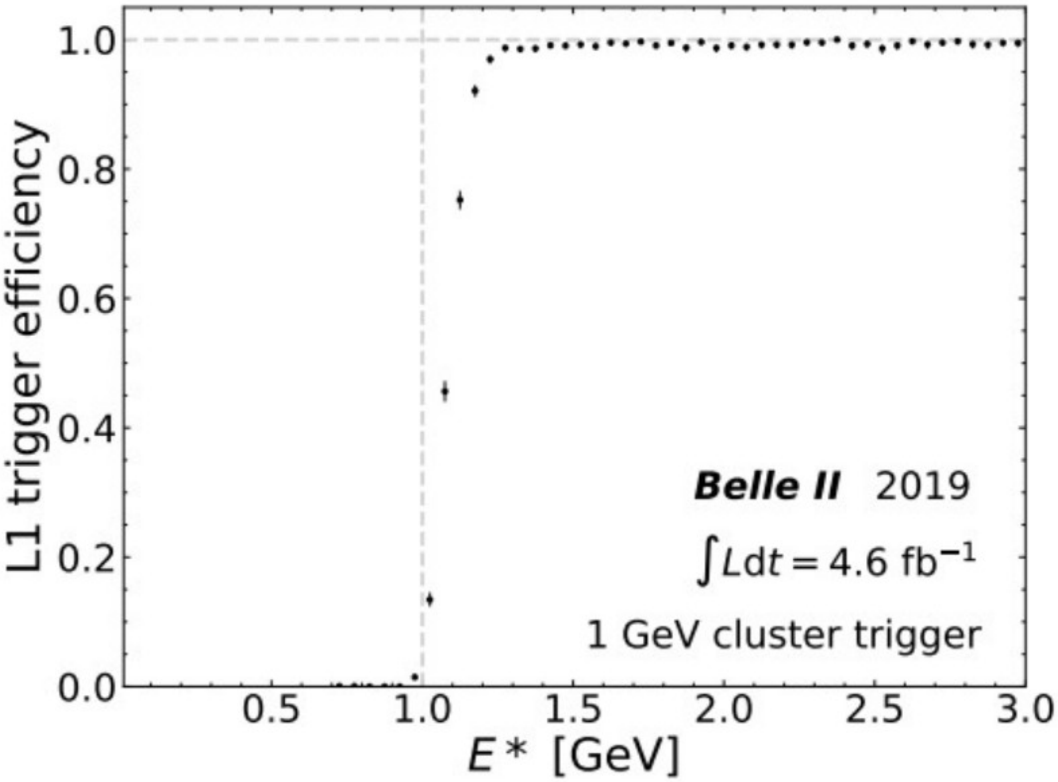


Dark photon to invisible: single photon trigger

Belle II Phase 3 (Design)

Trigger logic	L1 rate at full luminosity
E > 1 GeV (veto clusters above 300 MeV)	4 kHz (barrel) 7 kHz (endcaps)
E > 2 GeV Bhabha & γγ vetoes	5 kHz (barrel)

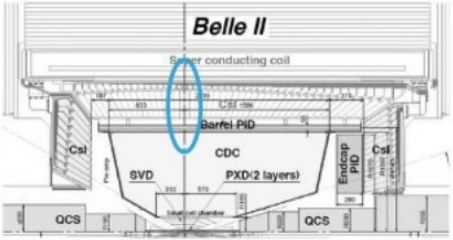




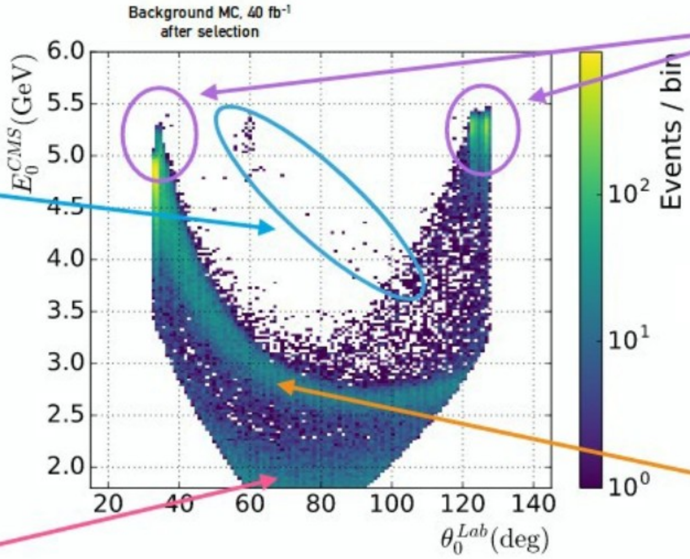
Dark photon to invisible: backgrounds

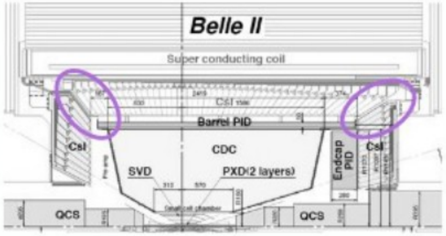
Discriminant variables:

E_{CMS} vs. polar angle of "single photon"

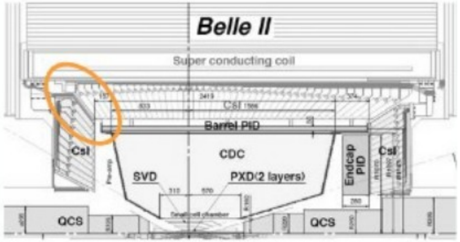


ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance





ee→2γ
1γ in ECL BWD or FWD gap

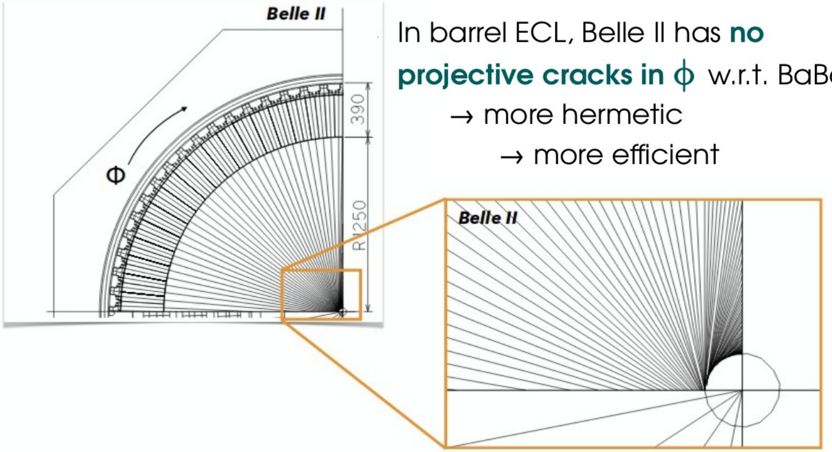


ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

ee→eeγ
both electrons
out of tracking acceptance

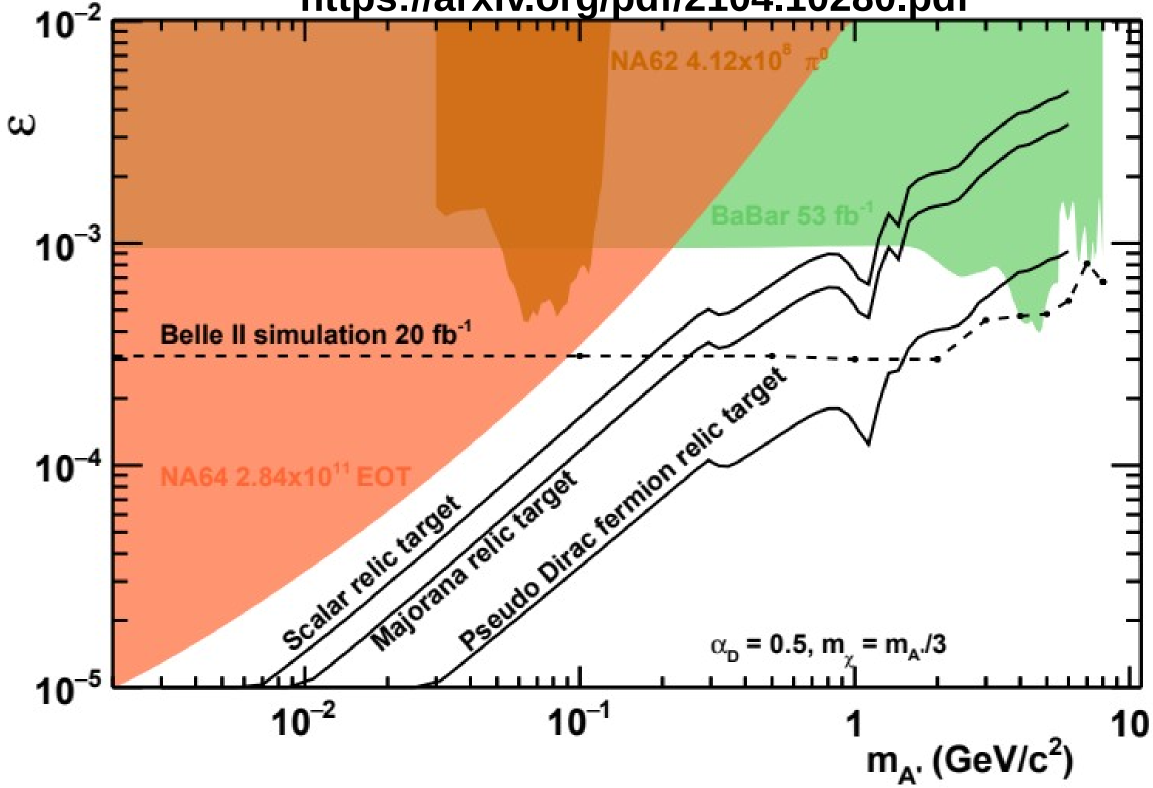
Signal signature:
peak in E_{CMS} (horizontal band)

Invisible dark photon sensitivity at Belle II



In barrel ECL, Belle II has **no projective cracks in ϕ** w.r.t. BaBar:
→ more hermetic
→ more efficient

https://arxiv.org/pdf/2104.10280.pdf

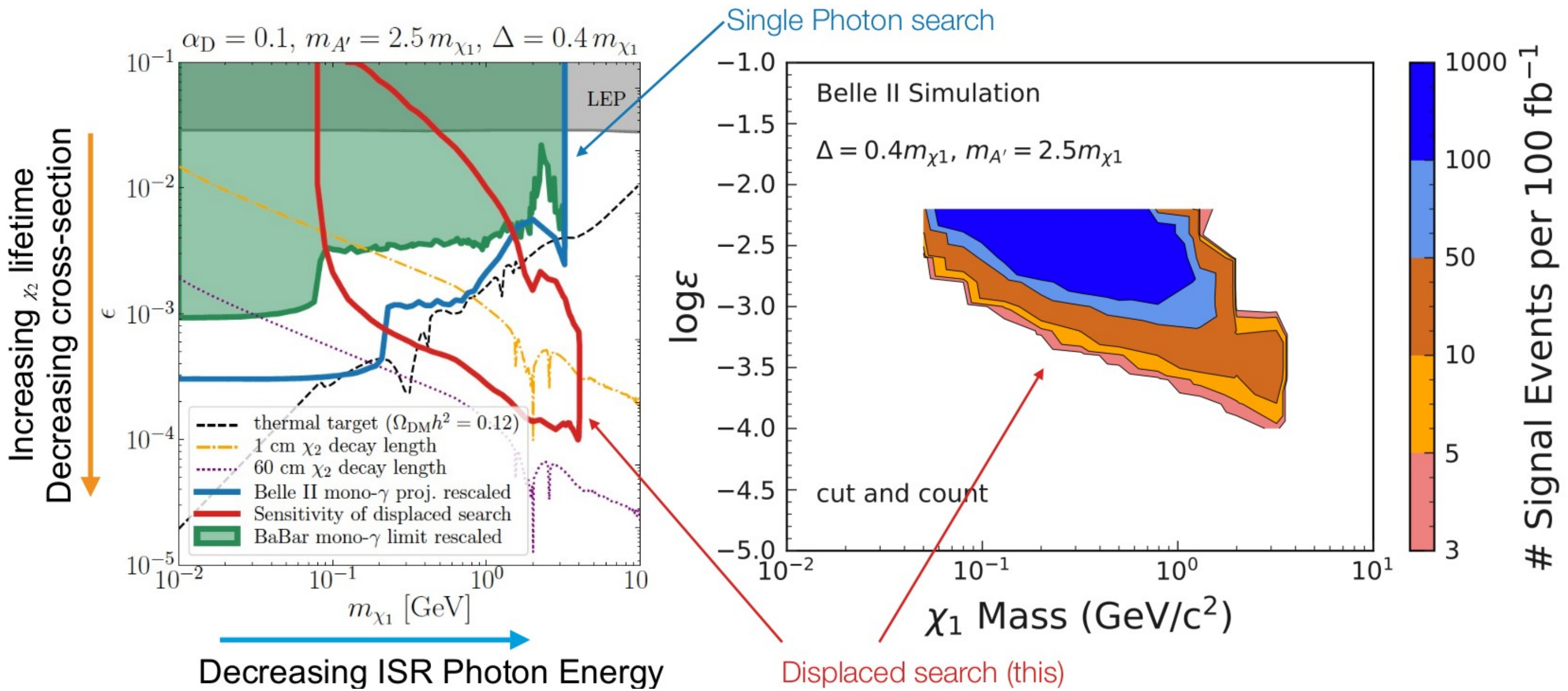


- No calorimeter cracks pointing to the interaction region and possibility to compensate for photon detection gap with ***KLM veto***
- Better hermeticity (smaller boost βγ=0.28, larger acceptance)
- Improved hardware trigger lines

→ dedicated **single photon trigger**
→ *not available at Belle, at BaBar only for ~10% data (53 fb-1)*

IDM sensitivity at Belle II

- Belle II can explore a large region of new iDM parameter space, constraining with ~ 100/fb the kinetic mixing parameter down to 10^{-4}



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