Anomalies and Precision in the Belle II Era - Workshop

6-8 September 2021

Europe/Vienna timezone

Dark Sector searches at Belle II

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On behalf of the Belle II collaboration

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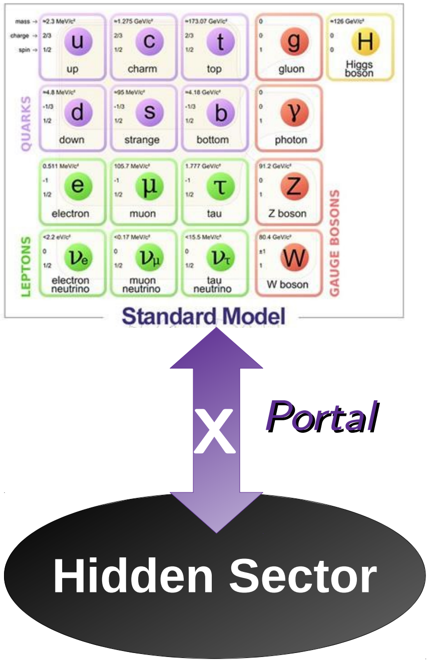
EU grant n.822070

Light dark sectors

- Possible sub-GeV scale Dark Matter (DM) scenario: *light dark sector* weakly coupled to SM through a light ***mediator X***
  - Vector portal $\rightarrow$ Dark Photons (A'), Z' bosons
  - Pseudo-scalar portal $\rightarrow$ Axion Like Particles (ALPs)
  - Scalar portal $\rightarrow$ Dark Higgsstrahlung/Scalars
  - Neutrino portal $\rightarrow$ Sterile Neutrinos



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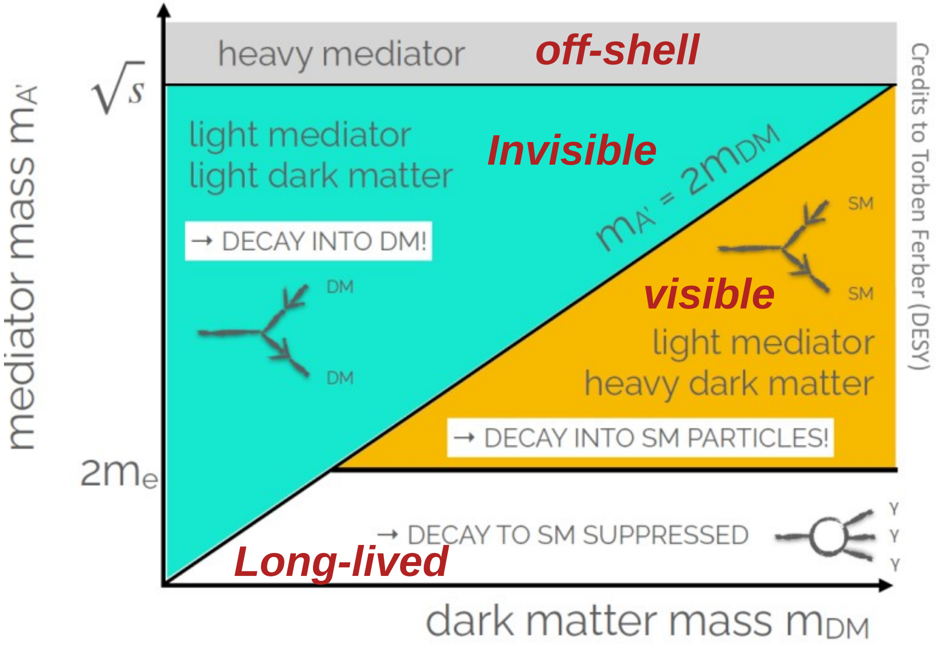


$\rightarrow$ *The masses of the mediator/DM candidates produce different topologies leading to different kinds of* ***DM searches***

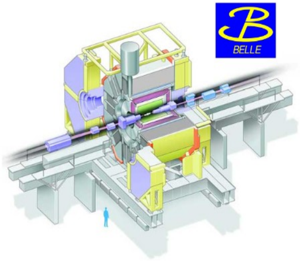
Experiments at B-factories

- **Clean environment and hermetic detectors** $\rightarrow$ efficient reconstruction of **neutrals** (π^0, η), recoiling system and ***missing energy*** final states

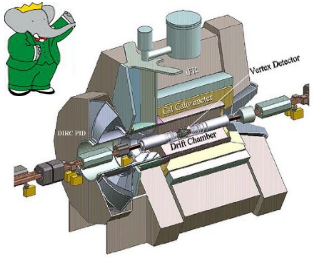
$e^+e^- \rightarrow \Upsilon(4S)$* [10.58 GeV] *$\rightarrow B\overline{B}$

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

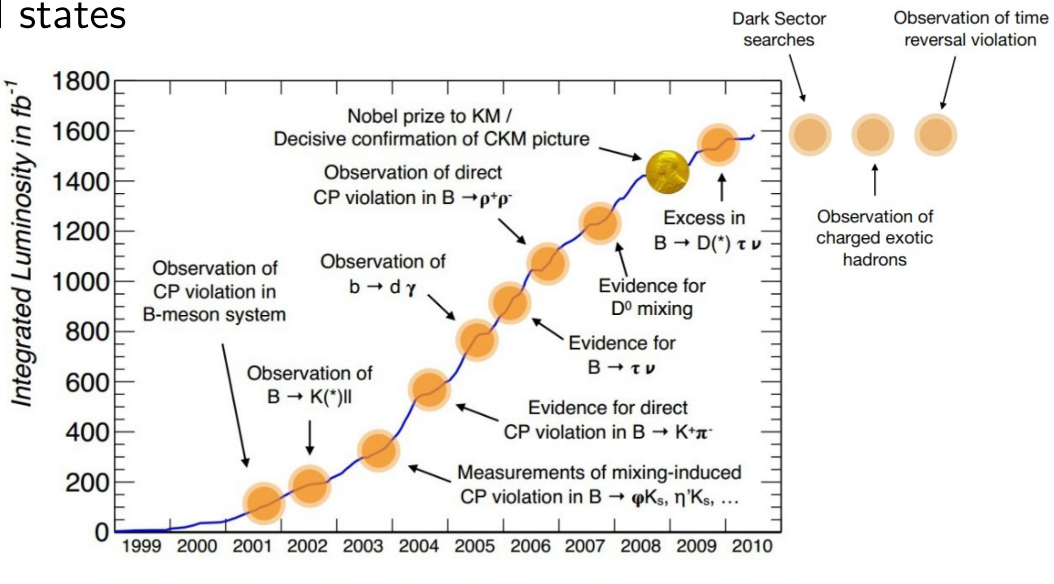
First generation of B-factories



at the KEKB collider (KEK, Japan)



at the PEP II collider (SLAC, California)



BaBar: PEP-II e^+e^- collider, SLAC, USA, 1999–2008
Belle: KEKB e+e− collider, KEK, Tsukuba, Japan, 1999–2010

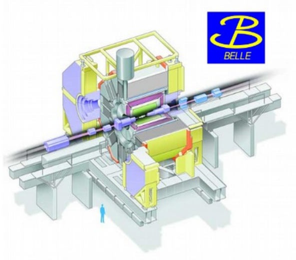
Experiments at B-factories: second generation

- **Clean environment and hermetic detectors** → efficient reconstruction of **neutrals** (π^0, η), recoiling system and ***missing energy*** final states

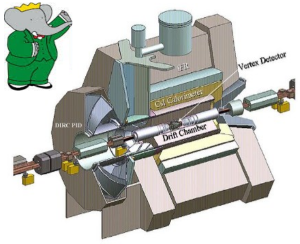
$e^+e^- \rightarrow \Upsilon(4S)$ **[10.58 GeV]** $\rightarrow B\bar{B}$

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

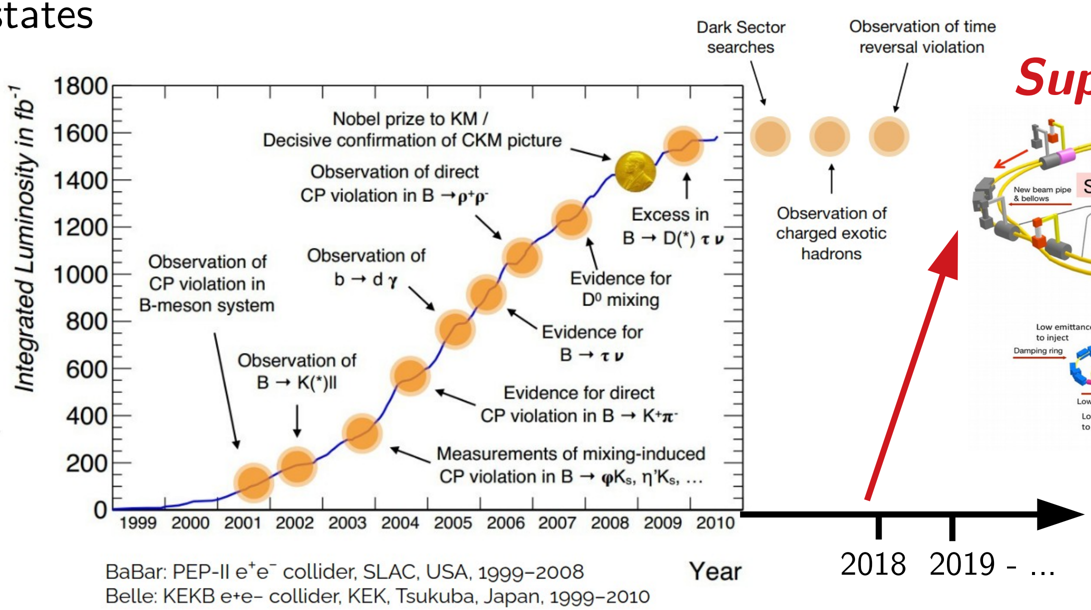
First generation of B-factories



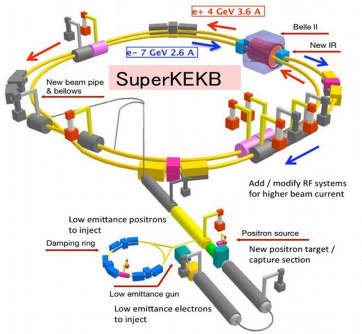
at the KEKB collider (KEK, Japan)

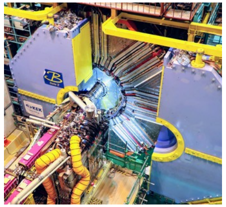


at the PEP II collider (SLAC, California)



SuperKEKB





Belle II

- 30 x KEKB peak luminosity (*nano-beam* scheme*, *1.5 x beam currents*): ***L = 6 · 10^{35} cm^{-2} s^{-1}***
- Final target: ***50 ab^{-1}***

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

Dark sectors at Belle II

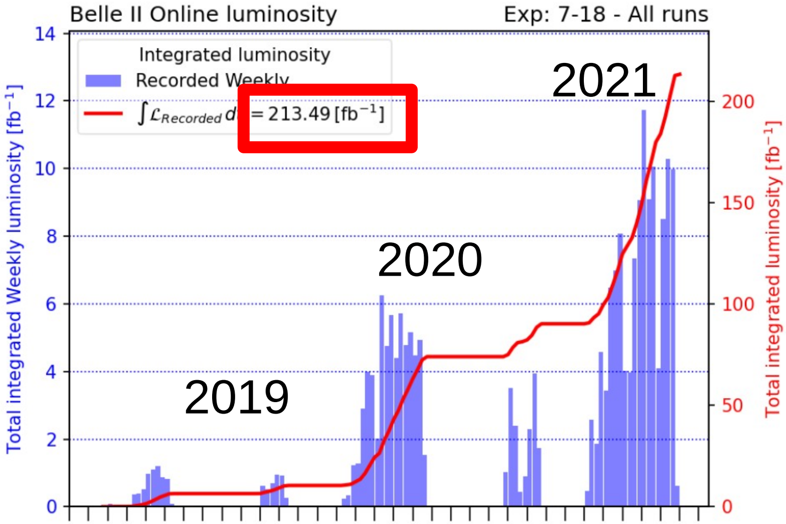
First collisions on 2018 April 26th

- B-factories can access the GeV range naturally favored by light dark sectors
  - **Special low multiplicity triggers**: single photon trigger, single muon trigger, 3D track reconstruction at hardware trigger using Neural Network

  More in previous talks (Tau Physics at Belle II)

- collected **0.5 fb^{-1}** during the **pilot run April-July 2018** → **published two searches on this data set**
  - *Z' → invisible (Michel's talk)*
  - *ALPs → γγ*
- Since March 2019 collected > **213 fb^{-1}** and hit the **3.1x10^{34} cm^{-2}s^{-1}** instantaneous luminosity → *many analyses in the pipeline*
  - *B → Ka*
  - *Visible Z': Muonic dark force Z' → μμ , Z'→ ττ*
  - *Single photon*

Highlights from this talk



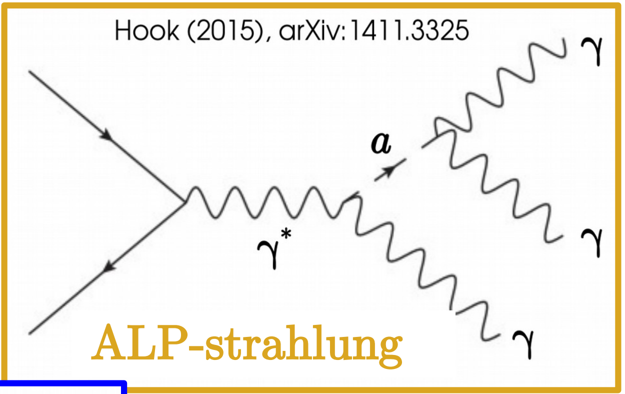
Axion Like Particles (ALPs)

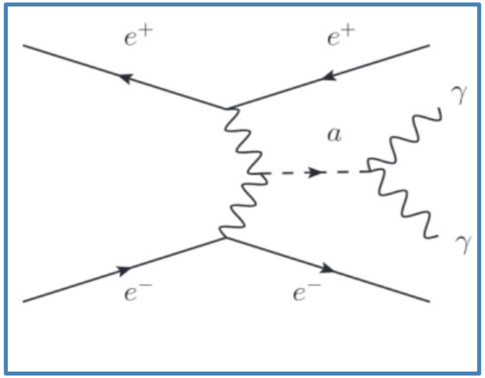
- Axion Like Particles are pseudo-scalars coupling mainly to bosons, with non-renormalizable coupling constants $[g_{aV}] \sim 1/M$

- Explored photon coupling $g_{a\gamma\gamma}$ in *ALP-strahlung* processes → **second Belle II physics paper**

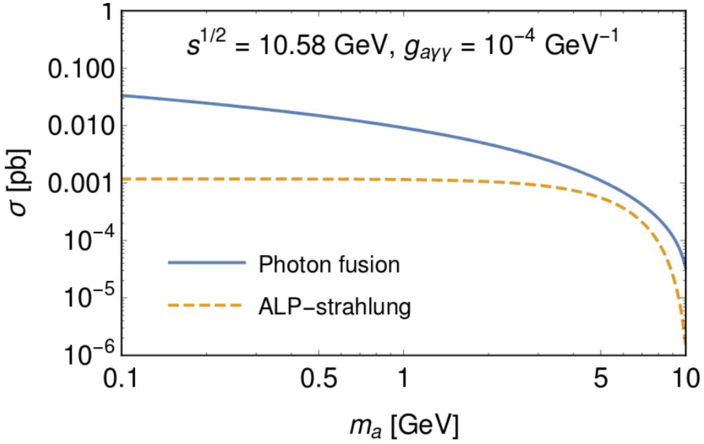
  (*photon fusion*: sensitivity under study)

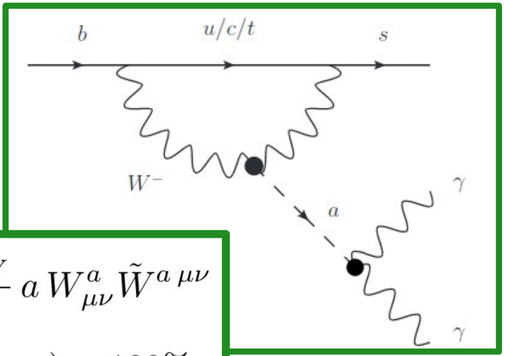
- Exploit *Flavor Changing Neutral Current* (FCNC) and rare meson decays to investigate g_{aW} coupling
  ongoing studies for B→Ka





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





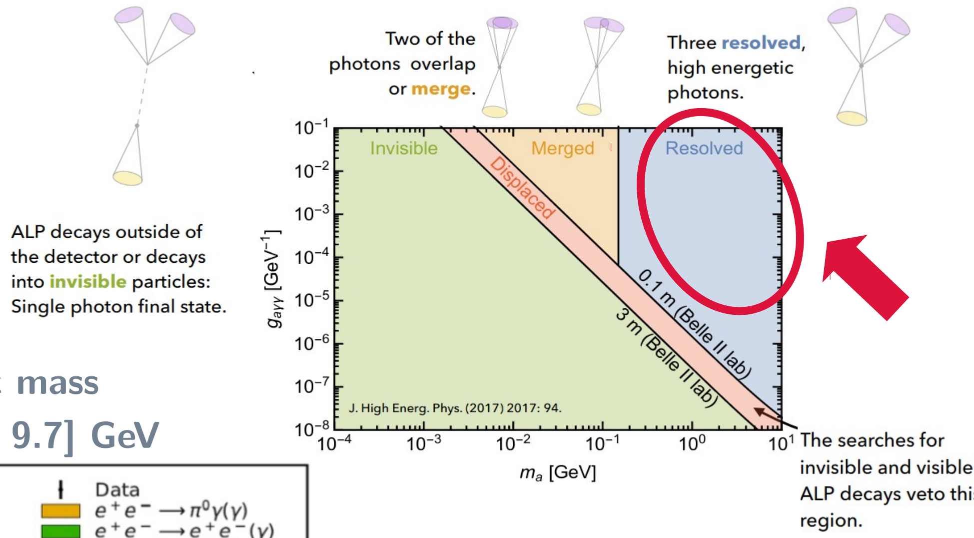
$$\mathcal{L} = -\frac{g_{aV}}{4} a W^{a}_{\mu\nu} \tilde{W}^{a\,\mu\nu}$$

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

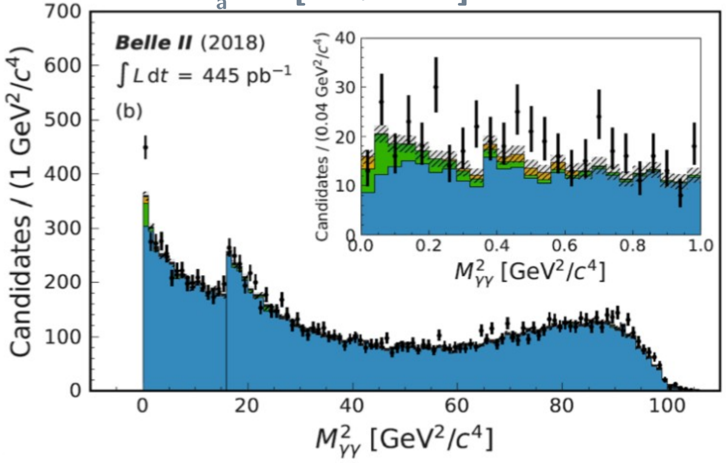
ALPs: a → γγ at Belle II

PRL 125 (2020) 161806

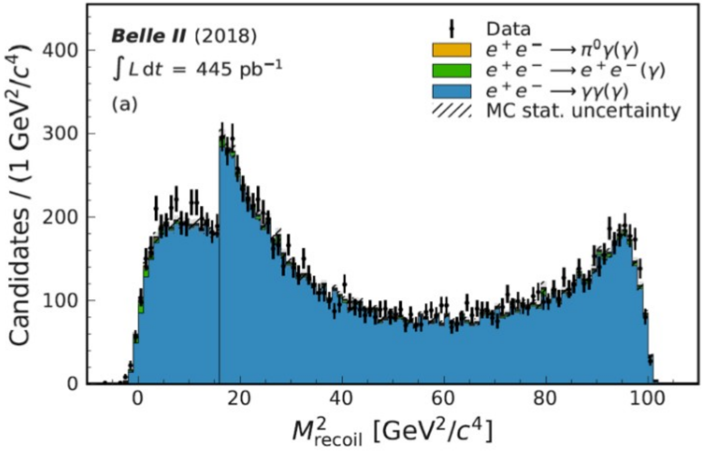
- Select fully neutral events consisting of 3 isolated photons with a total invariant mass consistent with center of mass energy → optimize to maximize ALP sensitivity
- Signal yield extracted with binned extended max likelihood fits in sliding ranges (half mass resolutions step) to:



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

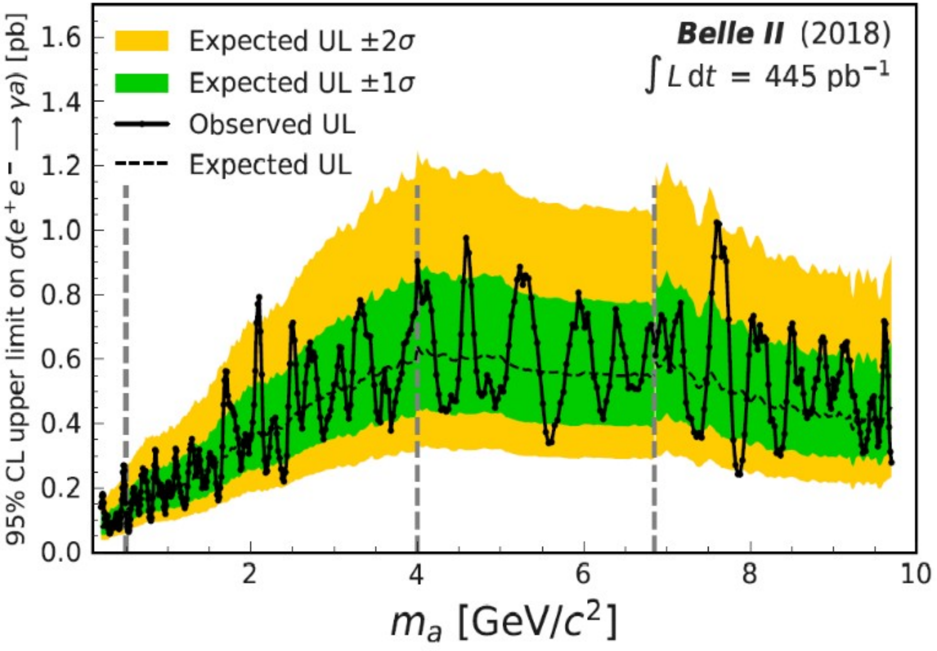
ALPs: a → γγ results

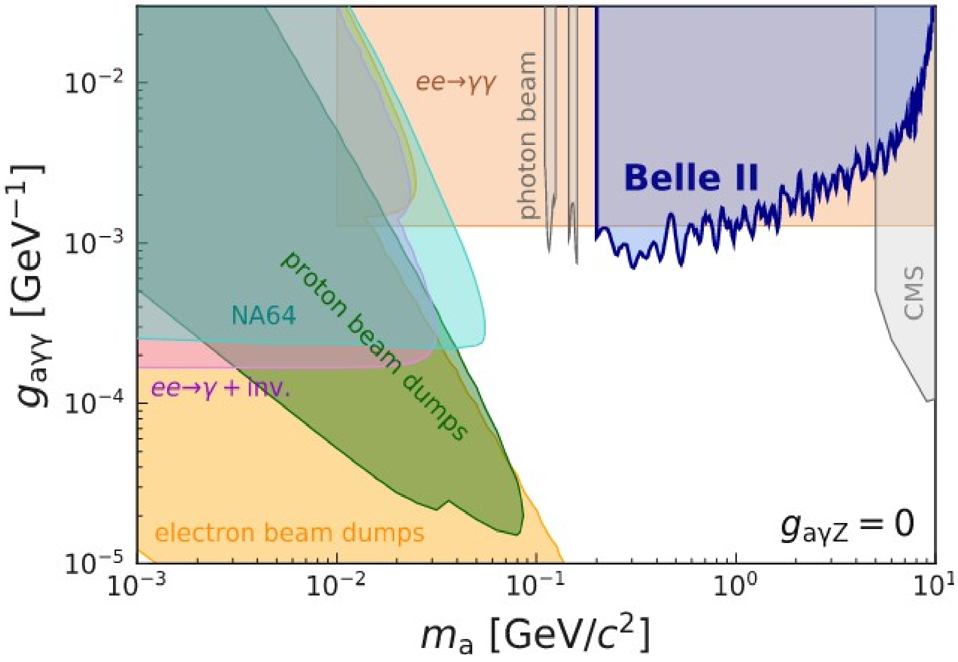
PRL 125 (2020) 161806

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

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

→ With only 1/100 000th of final target data set



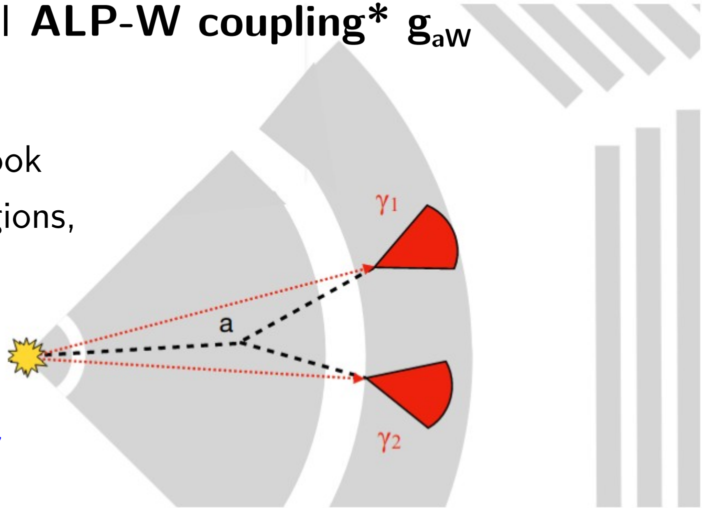


ALPs in meson decays

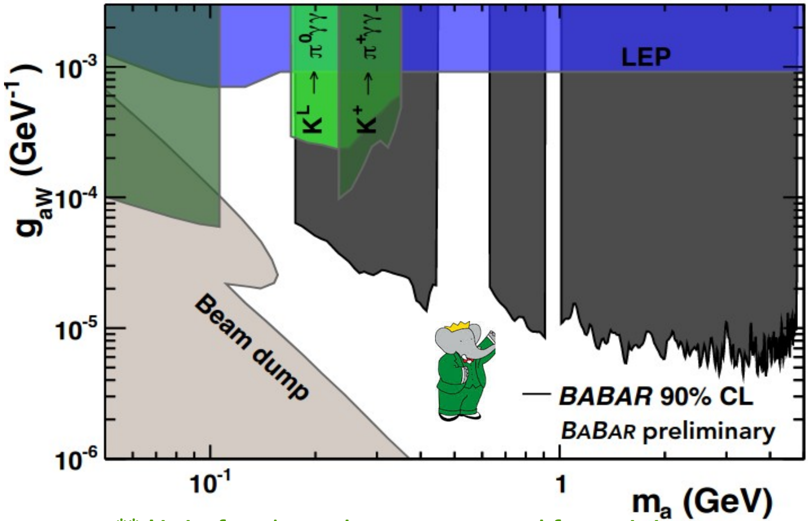
**E. Izaguirre, T. Lin, B. Shuve, PRL 118 (2017)*

b$\rightarrow$ s$\gamma\gamma$ is extremely rare in the SM and uniquely sensitive to very small **ALP-W coupling*** $\mathbf{g_{aW}}$

- For $m_a << m_W$ naturally *long-lived* ALPs mainly decay into photons
- Preliminary results for the searched process $\mathbf{B^\pm \rightarrow K^\pm a,\ a \rightarrow \gamma\gamma}$ from BaBar: look at narrow peaks in the **diphoton invariant mass** vetoing peaking background regions, both *prompt* and *displaced* vertex signatures.

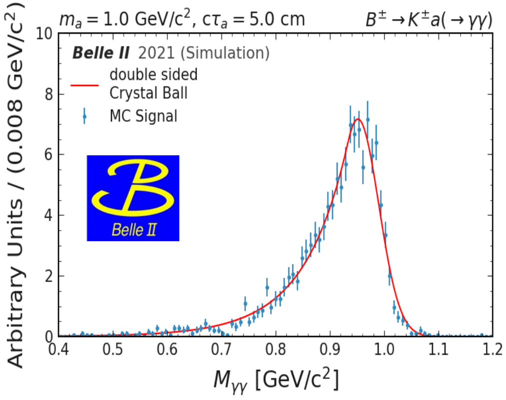


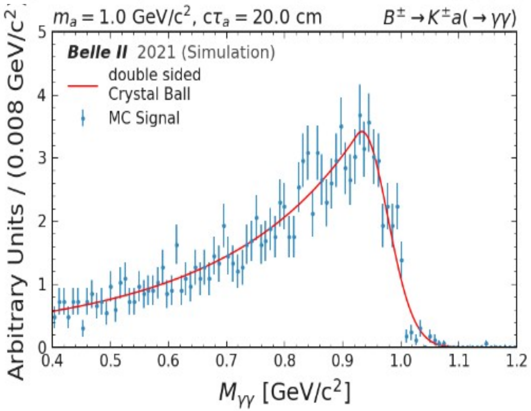
From B.Shuve's talk at ICHEP2020



** Limits from kaons decays are extracted from existing measurements presented in: Phys.Rev.Lett. 118 (2017) 11, 111802

Belle II ongoing studies





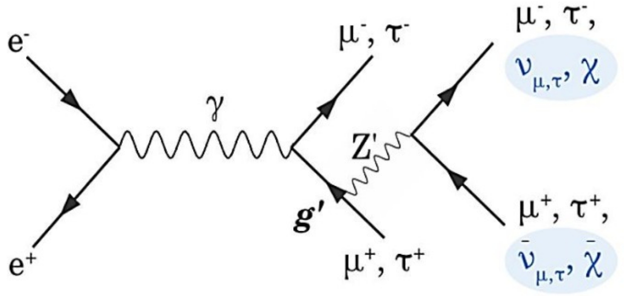
Muonic dark forces: L_μ-L_τ model

→ New gauge boson Z' coupling only to the **2nd and 3rd** generation of leptons (L_μ-L_τ) may explain:

- DM puzzle
- $(g\text{-}2)_\mu$ anomaly
- Anomalies observed in rare B decays, B→ K*μμ, $R_{K(*)}$

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

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



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

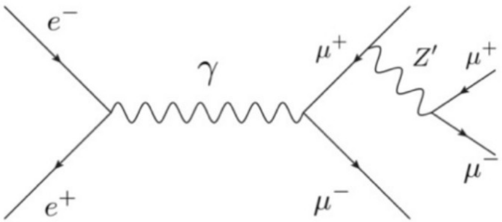
- Search for the process:

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

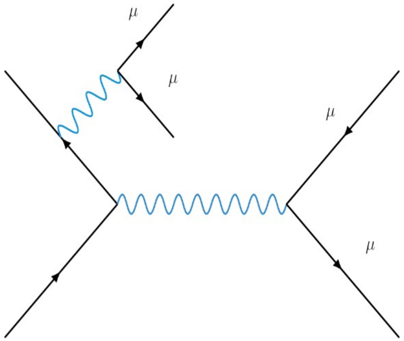
- Existing limits on the Z' coupling (g'):
  - searches for **visible decays** $Z' \rightarrow \mu^+\mu^-$ (BaBar **PRD 94, 011102 (2016)**, CMS **arXiv:1808.03684**) and neutrino-nucleus scattering processes (*neutrino trident production*, CCFR experiment at Fermilab)
  - search for **Z' → invisible:** Belle II first physics result, **PRL 124 (2020) 141801** → ***see Michel's talk***

$Z' \to \mu^+\mu^-$

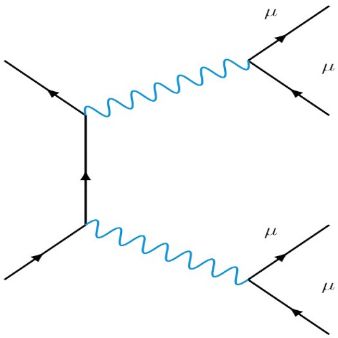
Signal



ISR



Double photon conversion

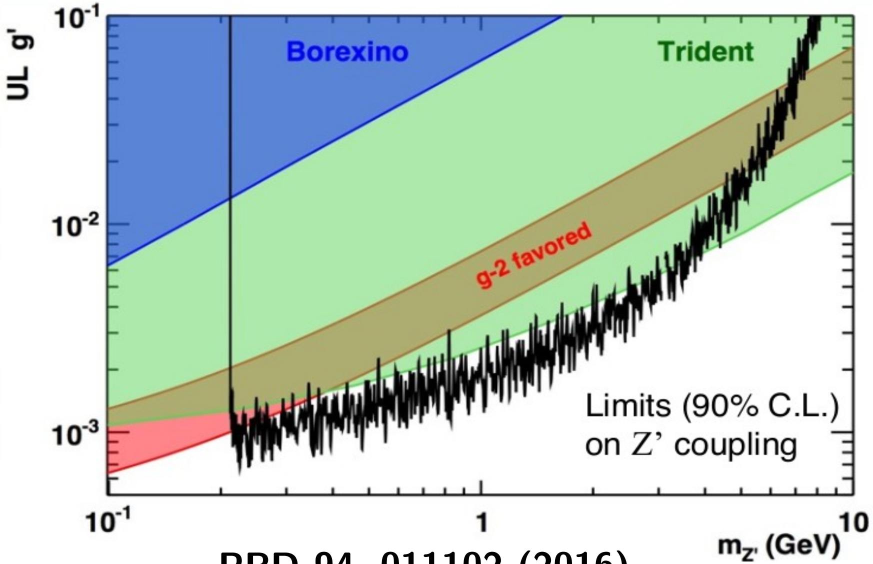


Main backgrounds from SM QED processes:

$\mu^+\mu^-\mu^+\mu^-$, ISR, double photon conversion, combinatorial

Competitive with early data set ($\sim$ 100 fb^{-1}) **due to aggressive background suppression!**

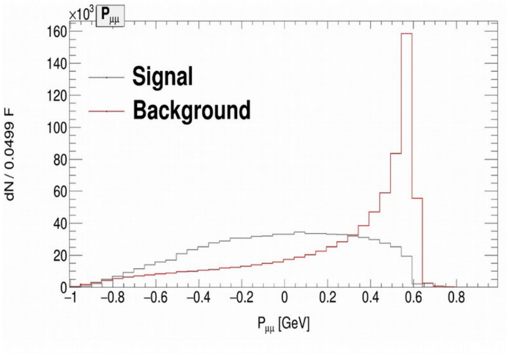
Search for a di-muon invariant mass peak in $\boldsymbol{e^+e^- \to \mu^+\mu^-\mu^+\mu^-}$ events in the final data set 514 fb^{-1}

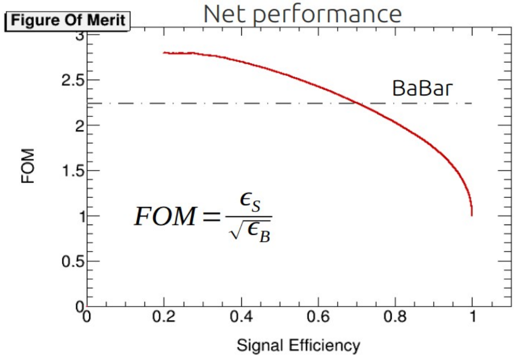


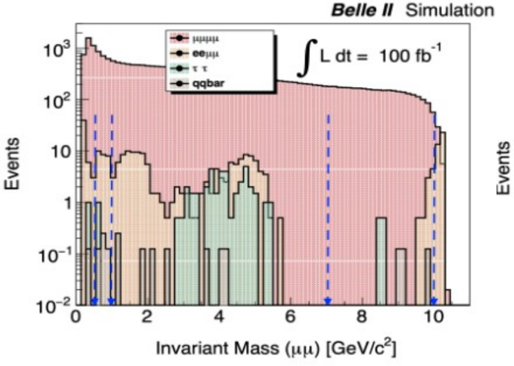
PRD 94, 011102 (2016)

Z’ → $\mu^+\mu^-$: background rejection

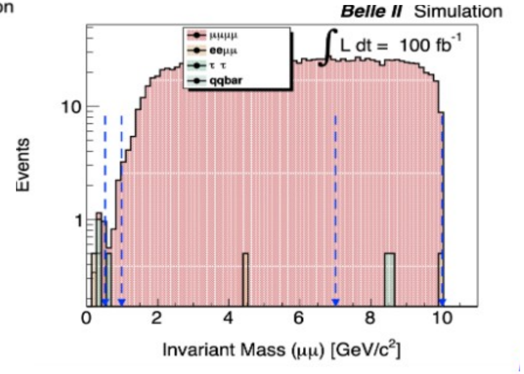
- Neural Network (*MLP, MultiLayer Perceptron*) exploiting dimuon momentum ($P_{\mu\mu}$) and other 14 discriminating variables in 4 different mass ranges to reject background





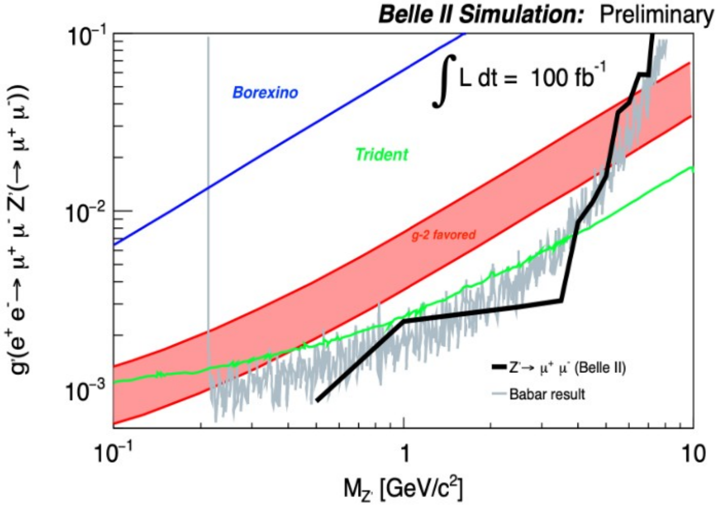


Before MLP



After MLP

→ Background suppressed by 2 orders of magnitude over the whole sensitive range



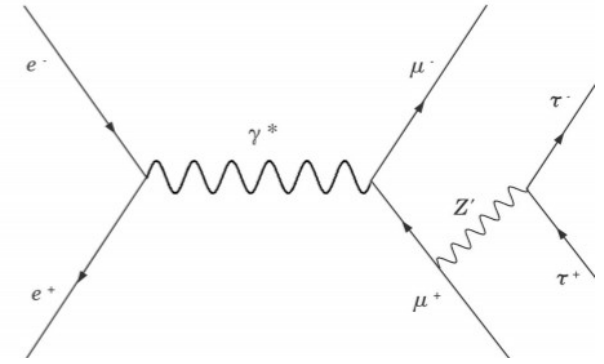
- Sensitivity computation ongoing: preliminary results from fitting technique (90% CL upper limits), no systematic effects included

$Z' \to \tau\tau$

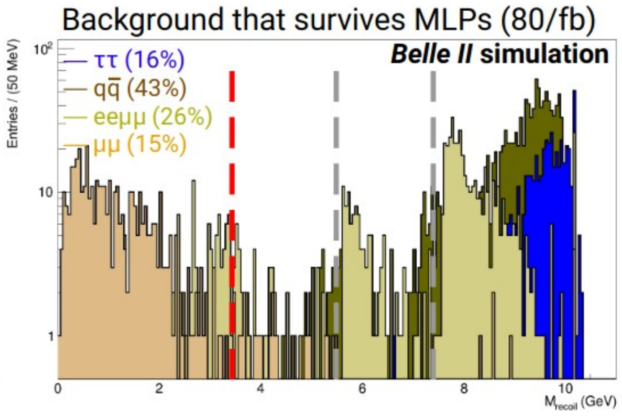
- Also ongoing studies on:

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

First time search!

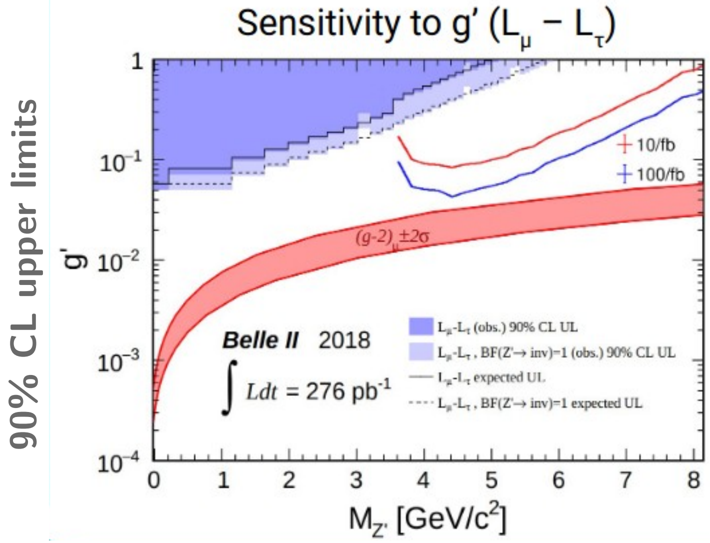


  - Almost model independent analysis
  - Selection optimized for the final state $\mu\mu\tau\tau$ ($\tau \to l/h$, 1-prong decays)
  - **Compute upper limits on the product $\boldsymbol{\sigma \cdot B(X \to \tau\tau)} \to$ could be re-interpreted by any models**



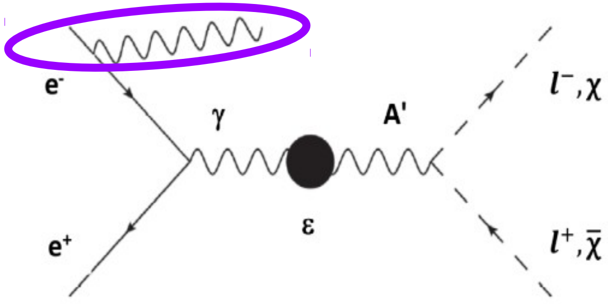
Challenging due to high background and neutrinos

→ profit of B-factory clean environment and MVA techniques



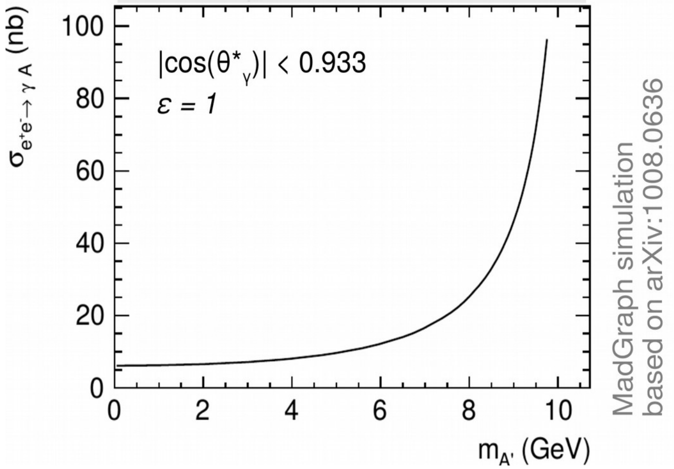
Dark photons

- A possible U(1) extension of the SM includes a new massive vector gauge boson A' coupling to the SM photon through the kinetic mixing with strength ε → the ***dark photon***
- At e^+e^- colliders investigate the ISR production $e^+e^- \to \gamma\, A'$.



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

Batell et al. (2009), arXiv:0903.0363



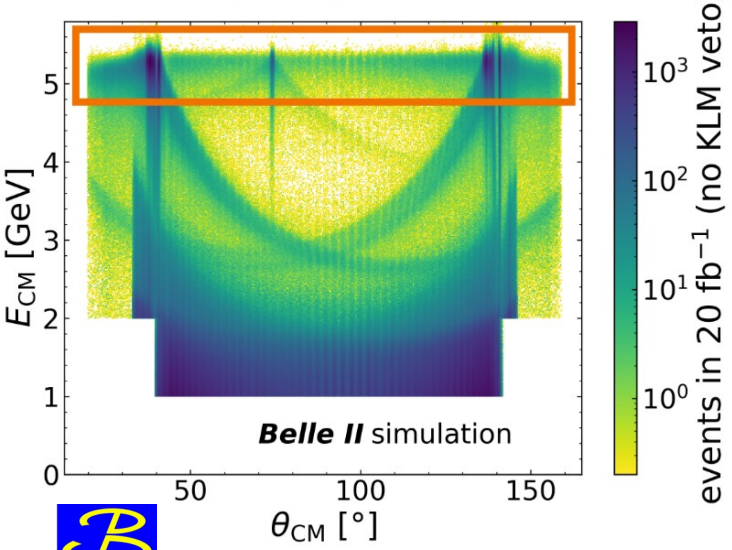
- $m_{A'} > 2m_\chi$ → A' decays 100% invisibly into DM particle (*single photon search*)
- $m_{A'} < 2m_\chi$ → A' decays visibly to SM particle (leptons)

Dark photon to invisible

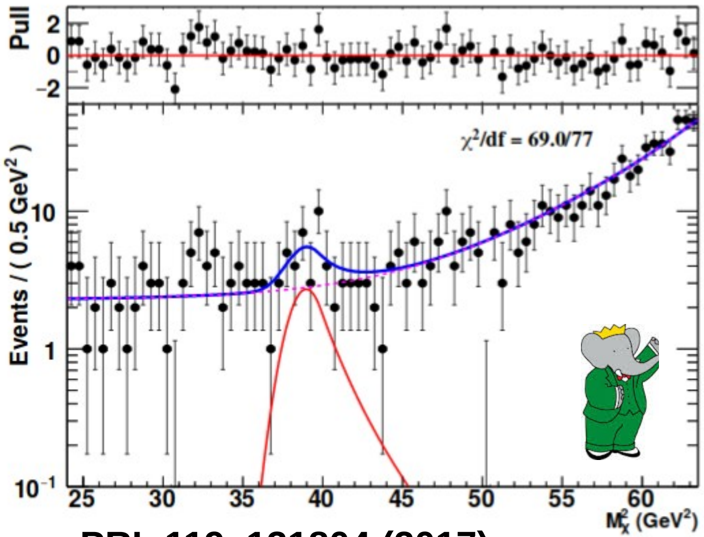
- Select events with **nothing** but a single high energetic *ISR photon.* Look for a bump in the reconstructed photon energy $E_\gamma = (s - m^2_{A'})/2\sqrt{s}$
- **Background:** QED processes $e^+e^- \to \gamma\gamma(\gamma)$ (*low mass* region) and radiative Bhabha $e^+e^- \to e^+e^- \gamma(\gamma)$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

→ only one photon in the detector requires a dedicated **single photon trigger**

→ *at Belle was not available, at BaBar was available only on ~10% data (53 fb^{-1})*

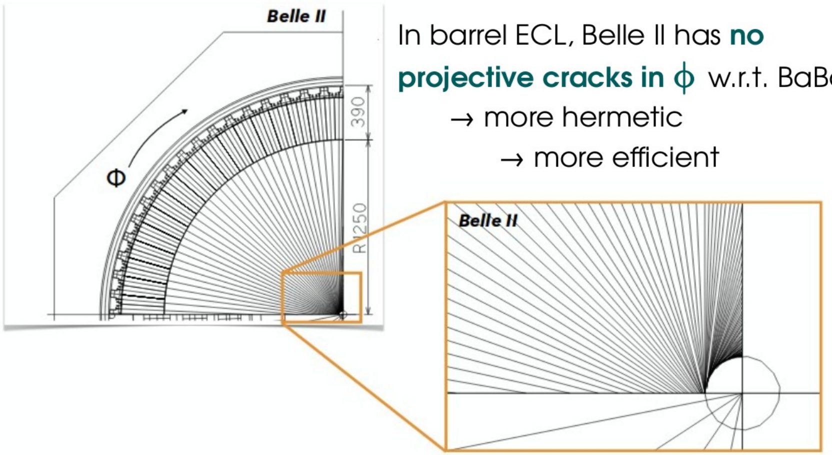


Belle II Simulation Preliminary



PRL 119, 131804 (2017)

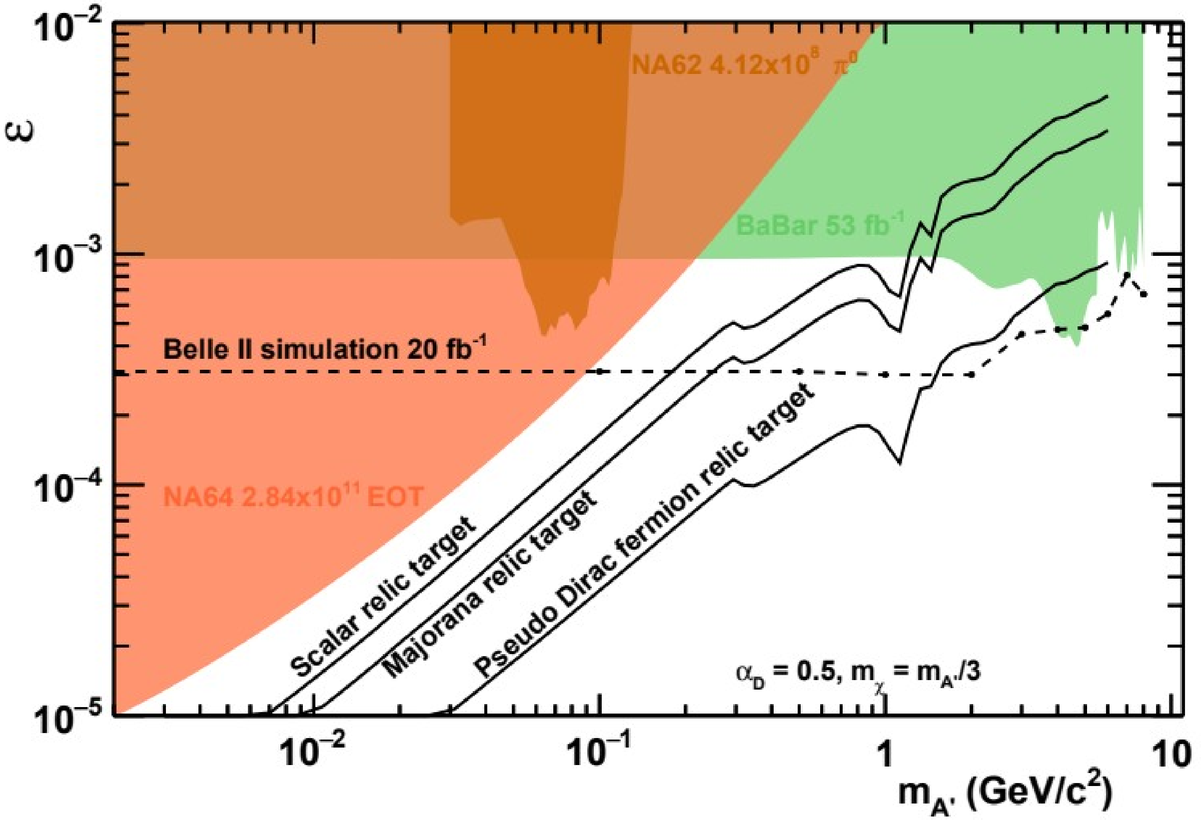
Invisible dark photon sensitivity at Belle II



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

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

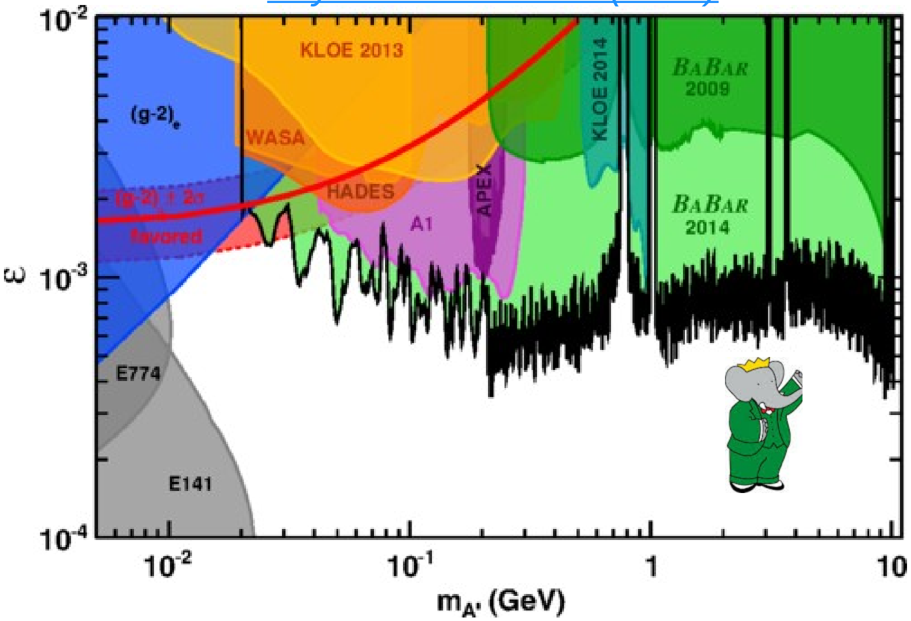
https://arxiv.org/pdf/2104.10280.pdf



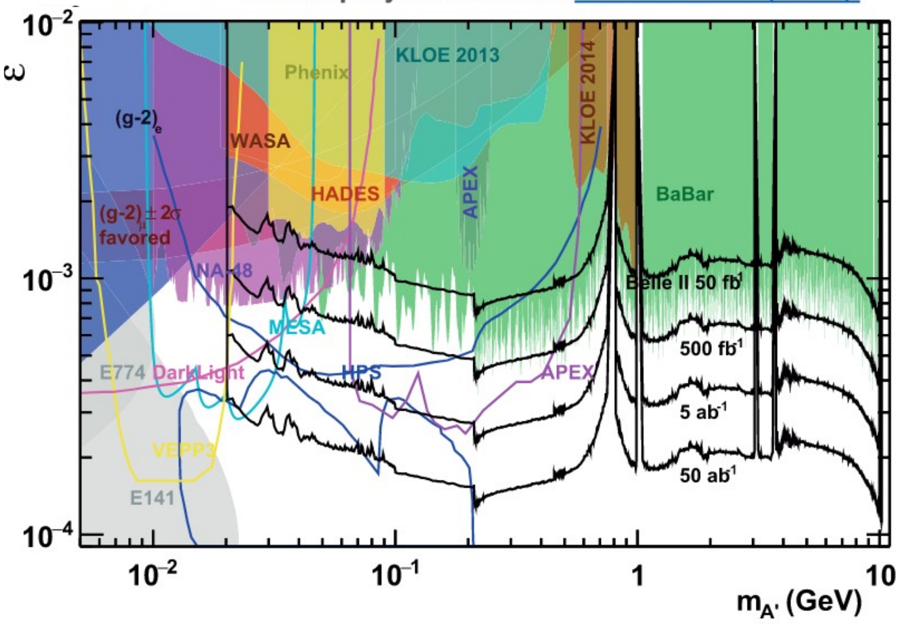
Visible Dark Photon

- 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)



Conclusions

Very active and wide-ranging program of searches for dark sectors at Belle II: interesting to probe not only the DM puzzle, but also many anomalies in flavor.

Belle II proved already its capability to produce ***world leading results*** even on a minimal data set (1/100 000th of the final target one)

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

- Ongoing studies show we'll be competitive in almost all of the light dark sector searches areas:
  - ***Displaced vertex signatures, missing energy final state searches (in Michel's talk)***, *visible SM decays of light mediator*
- Increased luminosity, upgraded detector and better analysis strategies will improve existing limits and provide soon new results.

...more to come: magnetic monopoles, dark shower, visible A', ALPs to hadron, etc.

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

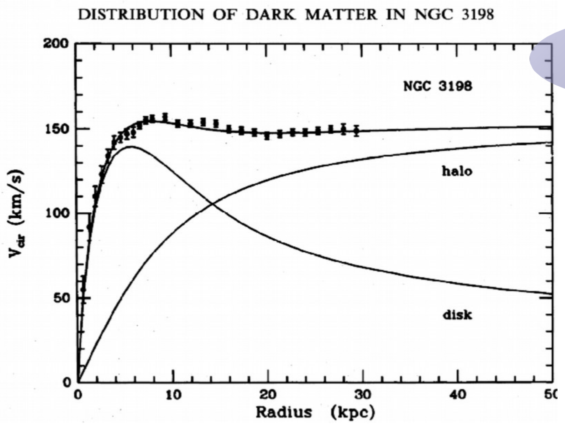
LUMINOSITY
IS
COMING

Thanks for your attention.

Backup

Dark matter puzzle

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

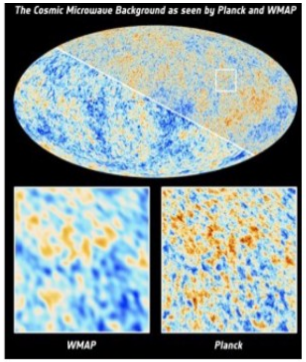


It exists...

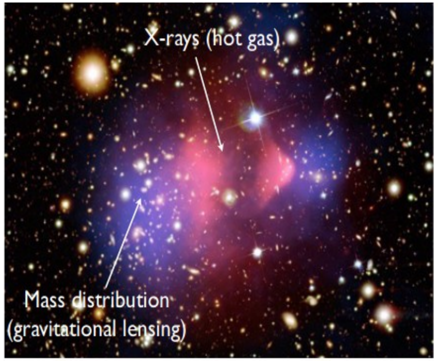
Flat rotational curves

$v(r)=\sqrt{M(r)/r}$

CMB fluctuations

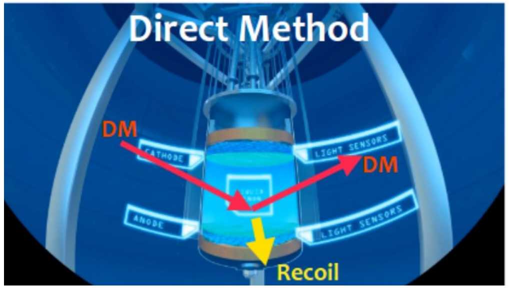


Gravitational lensing

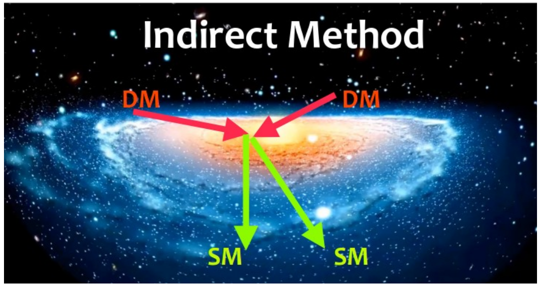


...how to search for it?

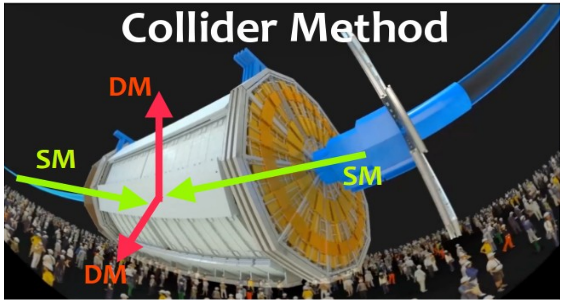
1) Detect the energy of *nuclear(electron) recoil*



2) Detect the *flux of visible particles* produced by *DM annihilation* and decay

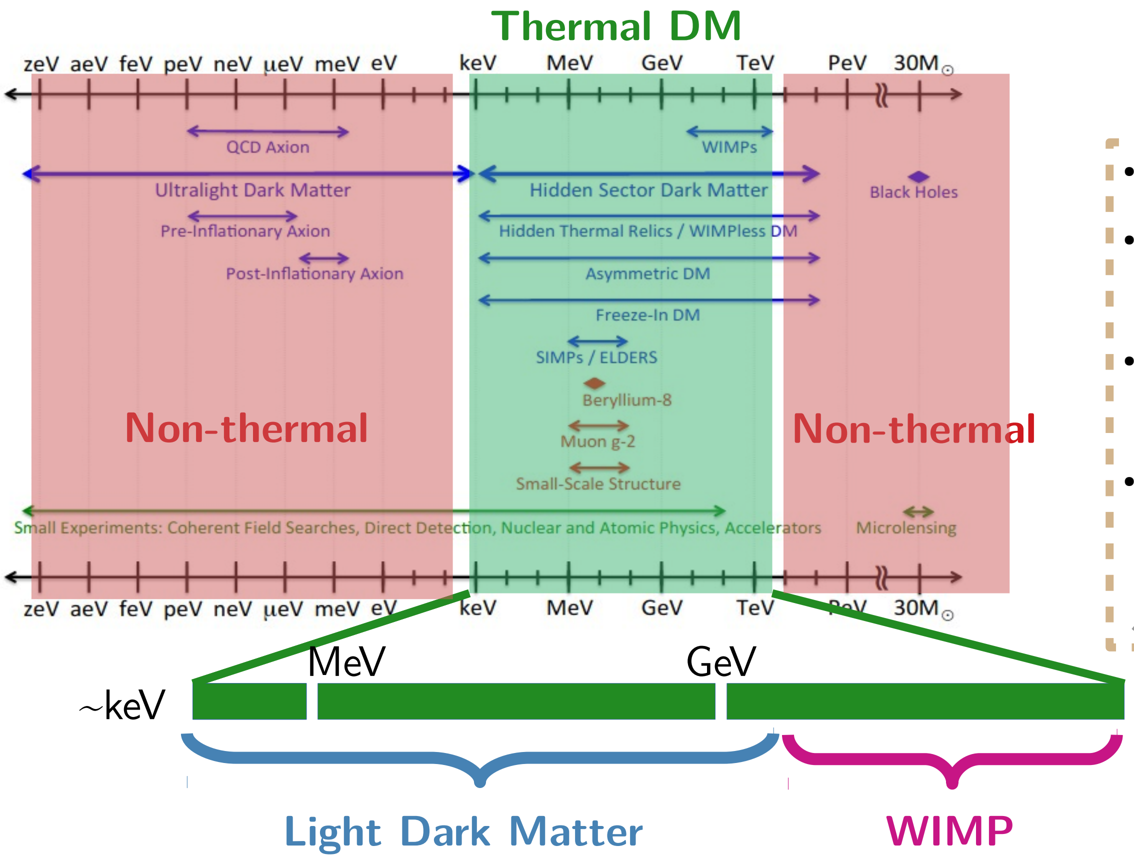


3) DM weakly couples to SM particles and it can be produced in *SM-particles annihilation* at ***accelerators***



Dark matter candidates

- DM is an unsolved puzzle → Unknown origin and nature!



→ Modified Newtonian Gravity...
→ Non-particle candidates: MACHOs

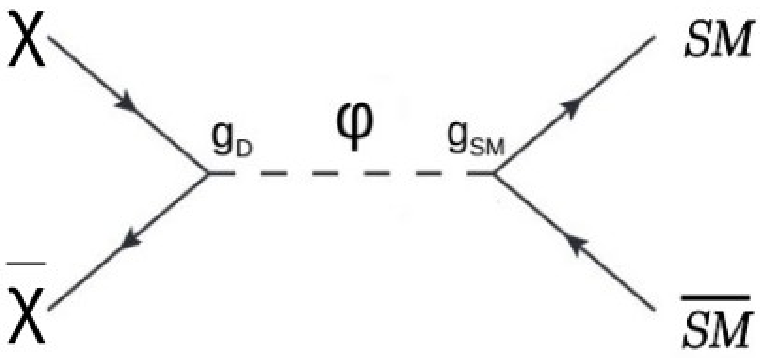
→ Particle candidates

- **Neutrinos** ✗ hot, relativistic candidates
- **QCD Axions** ✗ constrained by stellar cooling processes and supernovae dynamics, disfavoring thermal production
- **Sterile Neutrinos** ✓ observed DM abundance ✓ neutrino masses
- Weakly Interacting Massive Particles (**WIMPs**) ✓ match supersymmetric candidates (neutralino, *WIMP miracle*)

✗ null results from direct searches

Light dark matter scenarios

- No evidences for WIMP favor light DM hypotheses
- Possibility of *light dark sectors* motivates the search for a ***DM mediator (φ):***



Measured from cosmological observations

<1

$$\langle \sigma v \rangle_{relic} \sim \frac{g_D g_{SM} m_\chi^2}{m_\phi^4}$$

→ Experimentally constrained by current searches

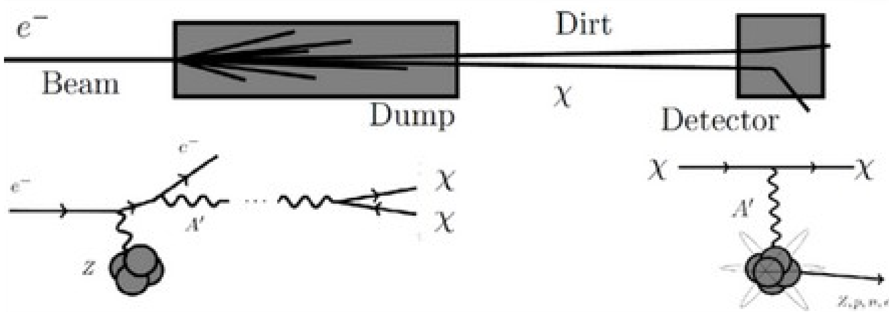
$$m_\phi^4 \leq \frac{m_\chi^2}{< \sigma v >} \text{ since g} < O(1)$$

May be too small to be consistent with the mass of any known SM mediator

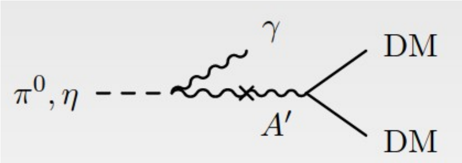
→ NEW PORTALS

Dark matter production at accelerators

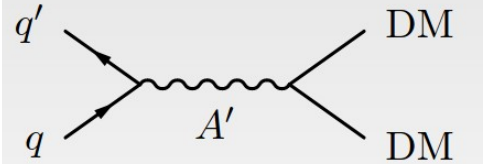
- Fixed-target experiment
  - Electron beam dump



  - Proton beam dump (DM at neutrino facilities)



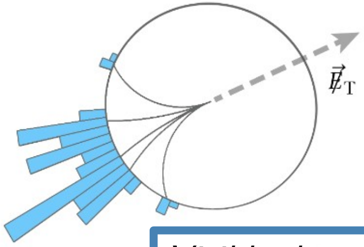
Via meson production

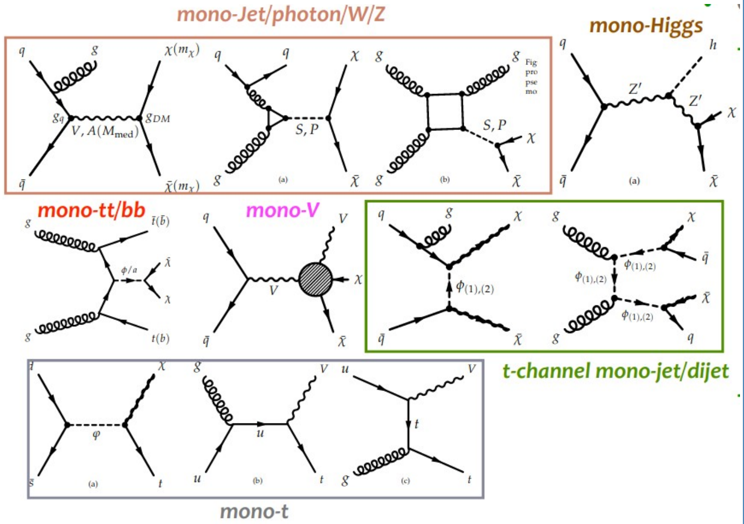


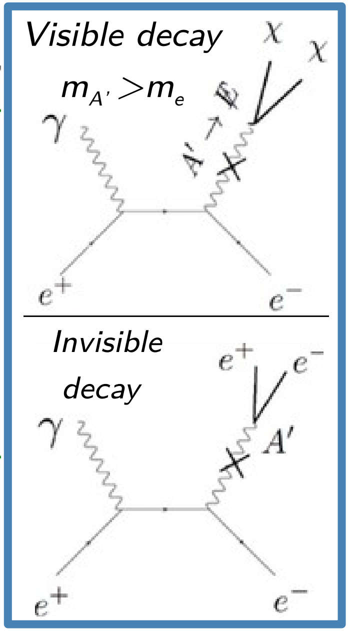
Direct production

- Colliders

Mono-X searches: detect a well-reconstructed SM object (ISR photon, jets..) + missing energy

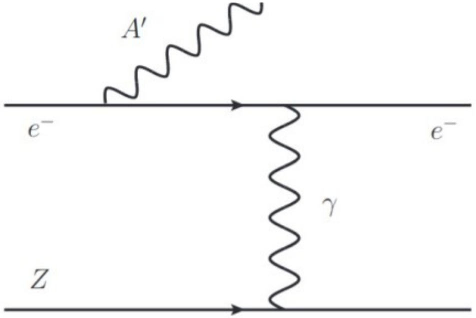






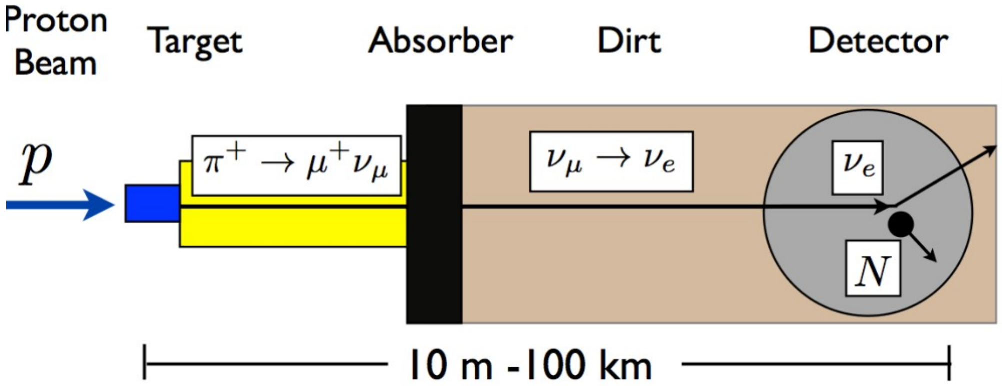
Dark matter searches at fixed-target

- Electron beam dump



- Suitable to investigate *vector* portals for mediator masses $2m_e < m_{A'} < \text{GeV}$
- Larger luminosity
- Scattering cross section enhanced by nuclear charge coherence
- Compact special-purpose detectors (dual-arms spectrometer @JLAB, MAMI, forward vertexing spectrometer @HPS)

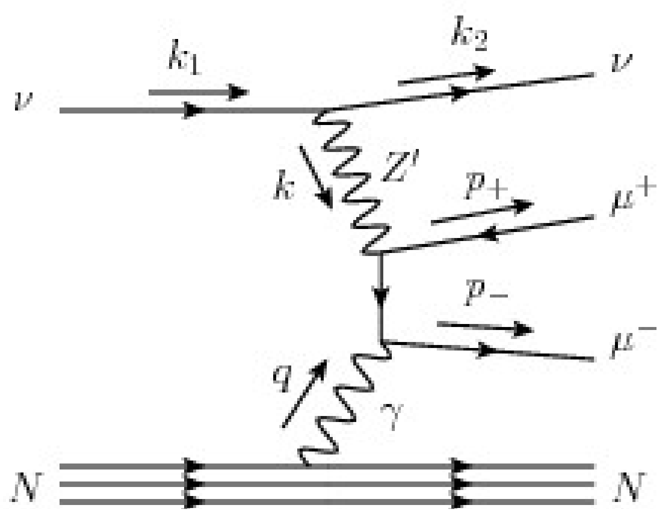
- Proton beam dump: exploiting neutrino facilities

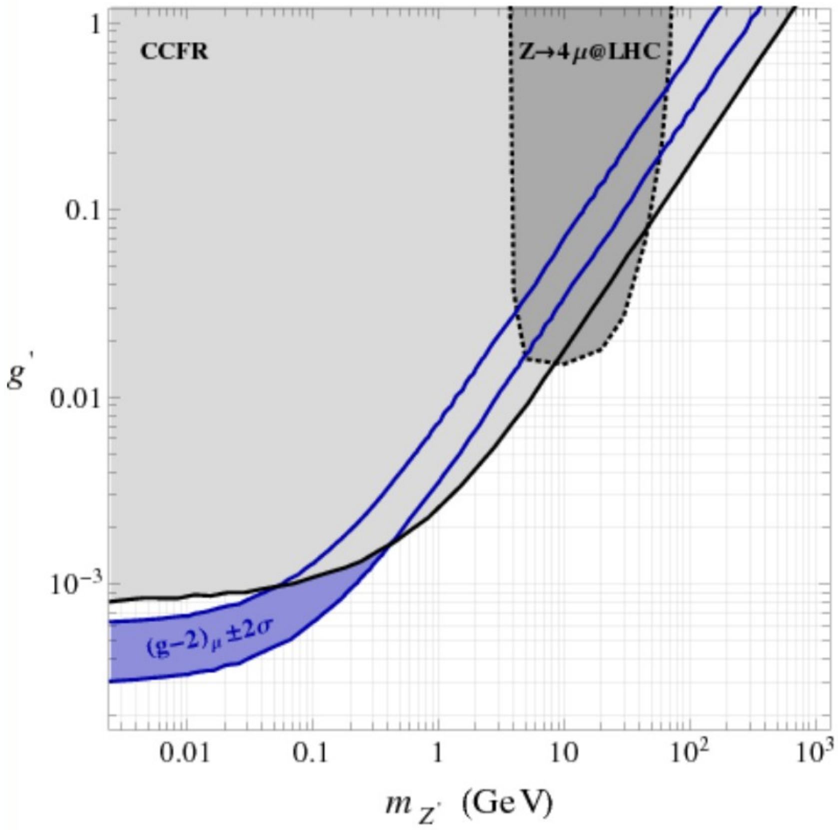


- Exploit existing neutrino facilities
- Look for neutral pion conversions to photons that may kinetically mix with the dark photon
- Signal signature: dilepton resonances, long-lived particle, missing energy

Neutrino trident production

- Neutrino trident production with a Z' boson





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.)	$10^\circ < \theta_e^* < 170^\circ$, $E_e^* > 0.15\,\mathrm{GeV}$	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.)	$10^\circ < \theta_\gamma^* < 170^\circ$, $E_\gamma^* > 0.15\,\mathrm{GeV}$	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

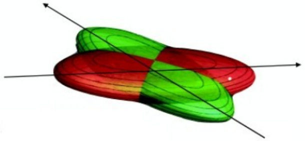
The Belle II Physics Book [arXiv:1808.10567]

- 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

SuperKEKB accelerator

- **World highest luminosity,** applying the large crossing angle (83 mrad) *nano-beam scheme* [arXiv:0709.0451].

KEKB



SuperKEKB

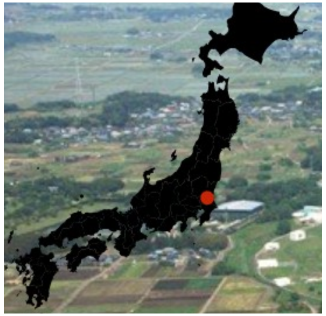
I (A): ~ 1.6/1.2 —— **X 1,5** ——→ I (A): ~ 3.6/2.6

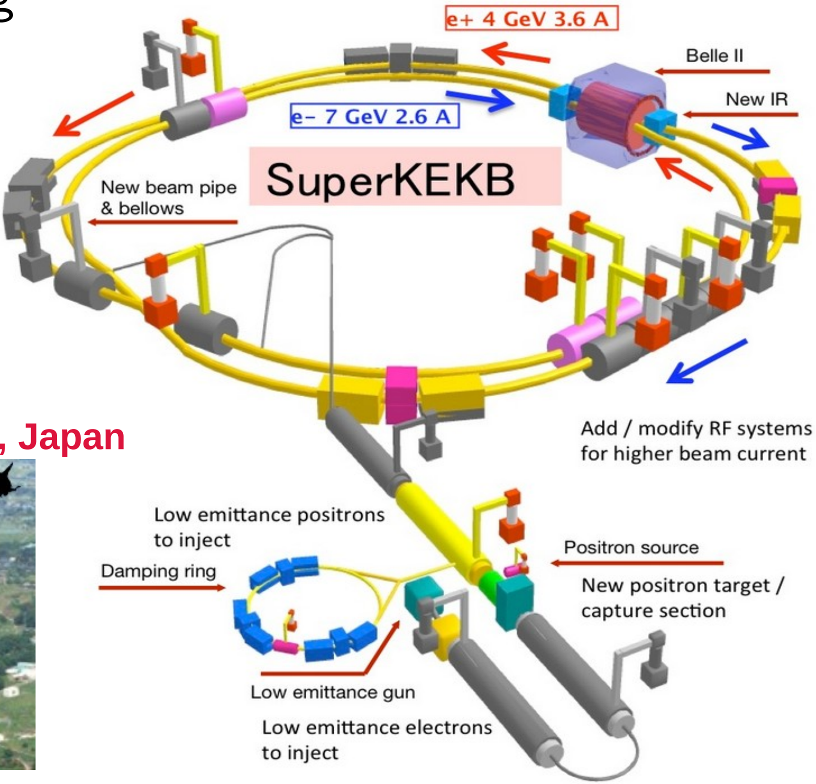
β^*_y (mm): ~ 5.9/5.9 —— **x 1/20** ——→ β^*_y (mm): ~ 0.27/0.3

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

- Lorentz factor: $\gamma_\pm$
- beam current: $I_\pm$
- beam-beam parameter: $\xi_{y\pm}$
- beam aspect ratio at the IP: σ_y^*/σ_x^*
- vertical beta-function at the IP: $\beta_{y\pm}^*$
- geometrical reduction factors: R_L/R_{ξ_y}

KEK
Tsukuba, Japan

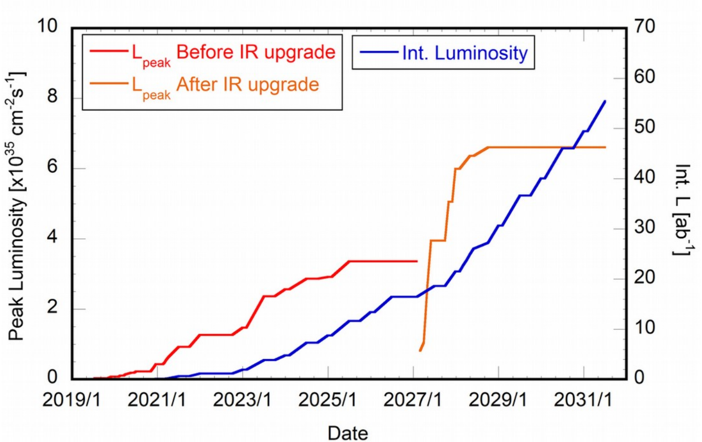


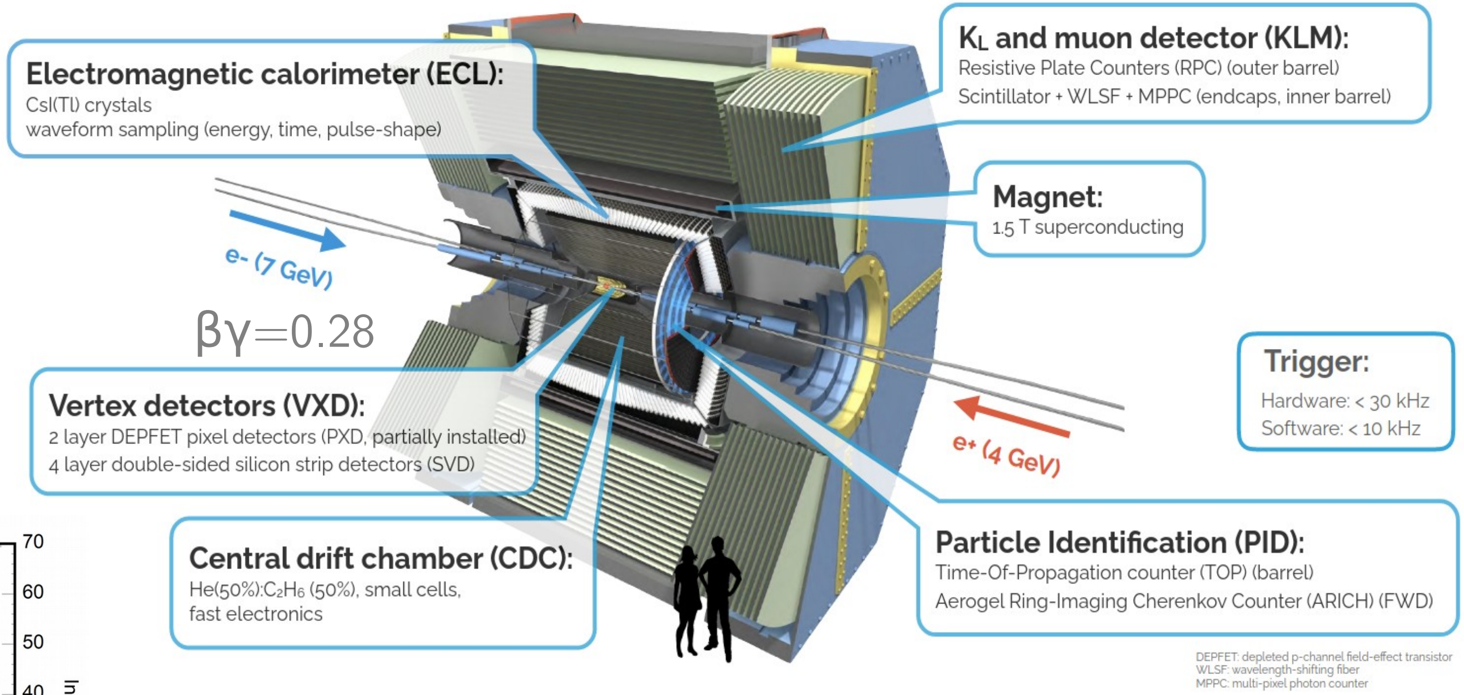


30x KEKB peak luminosity: $\mathcal{L} = 6 \cdot 10^{35}$ cm^{-2} s^{-1}

Belle II at SuperKEKB

- Updated detector:
  - provide comparable/better efficiencies and resolutions in a higher background
  - Improved dedicated triggers for low multiplicity and missing energy final states → *see more in previous session talks*

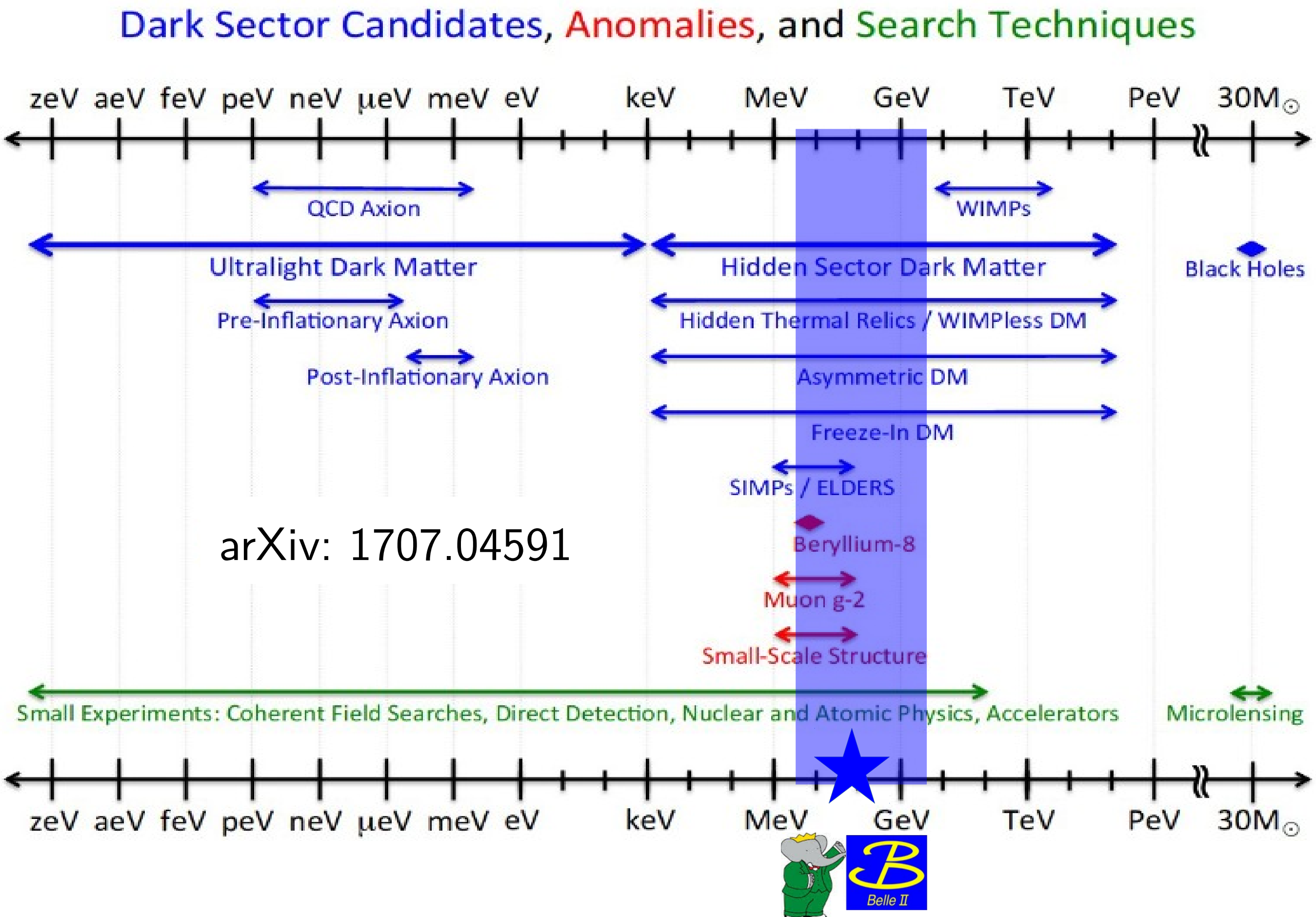




GOAL: 50 ab^{-1}

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

Overview of dark sector searches

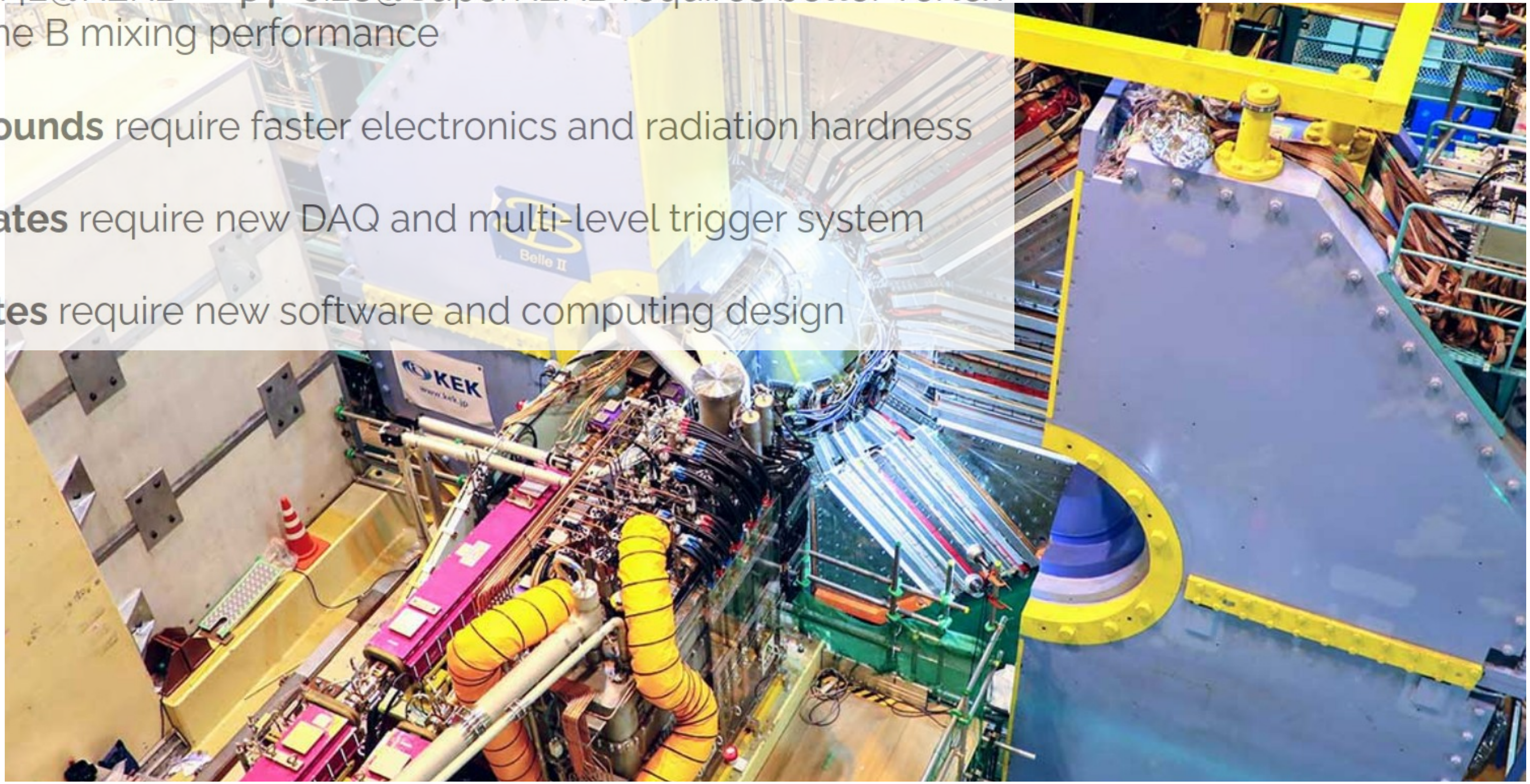


arXiv: 1707.04591

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

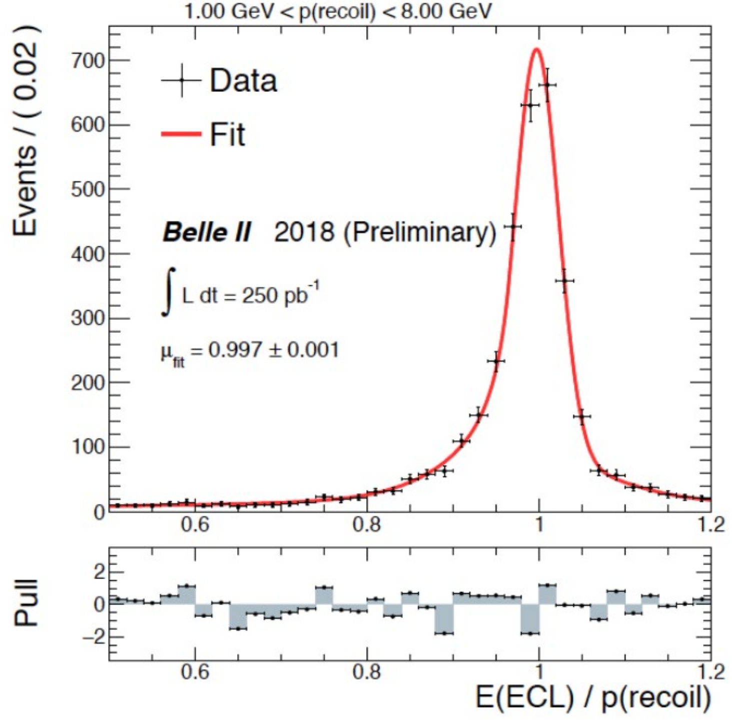
Belle II Challenges

- **Reduced boost** $\beta\gamma$=0.42@KEKB → $\beta\gamma$=0.28@SuperKEKB requires better vertex resolution for the same B mixing performance
- Much **higher backgrounds** require faster electronics and radiation hardness
- Much **higher event rates** require new DAQ and multi-level trigger system
- Much **higher data rates** require new software and computing design

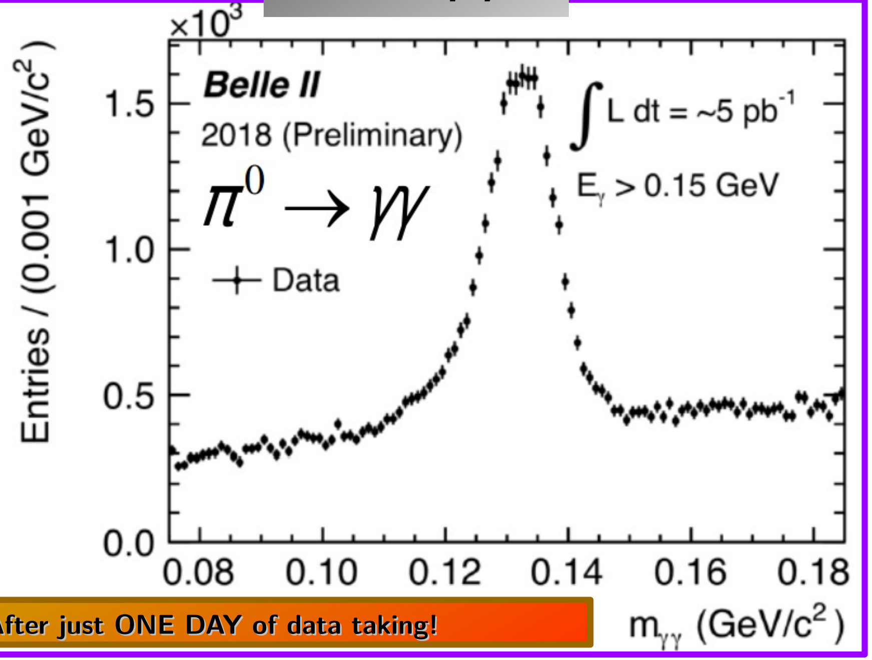


Belle II Performances in Phase 2: photon reconstruction

$e^+e^- \to \mu\mu\gamma$



$\pi^0 \to \gamma\gamma$

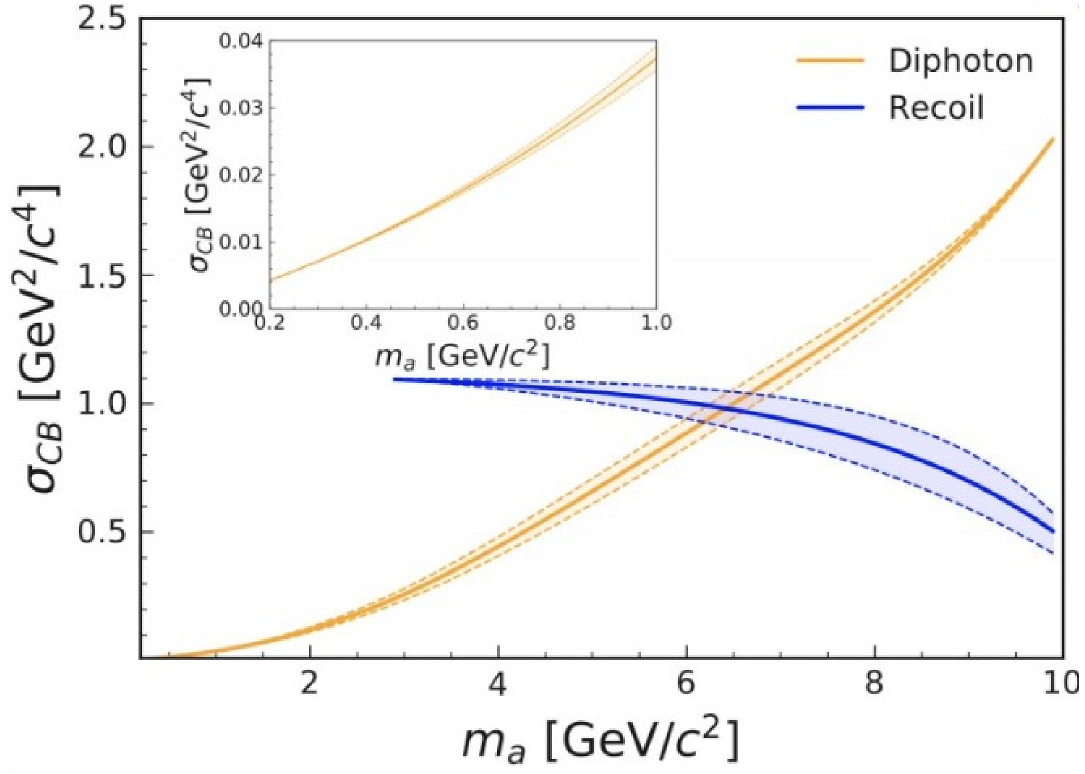


After just ONE DAY of data taking!

$e^+e^- \to \gamma\ X$, $e^+e^- \to \gamma\ ALPS \to \gamma(\gamma\gamma)$

ALPs at Belle II: resolutions

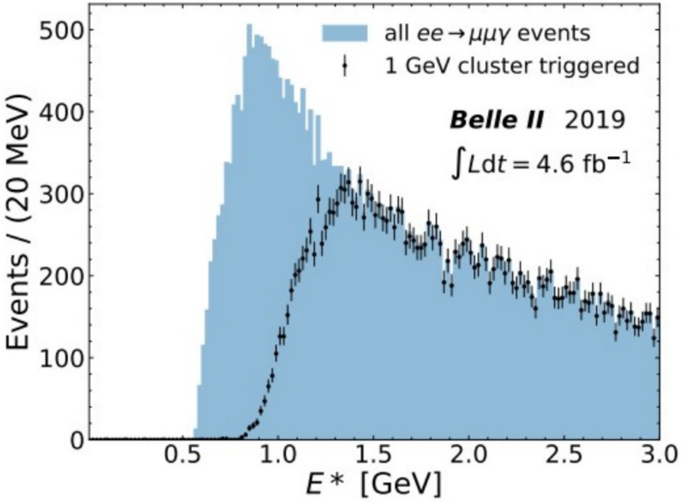
- Signal resolutions for di-photon and recoil masses

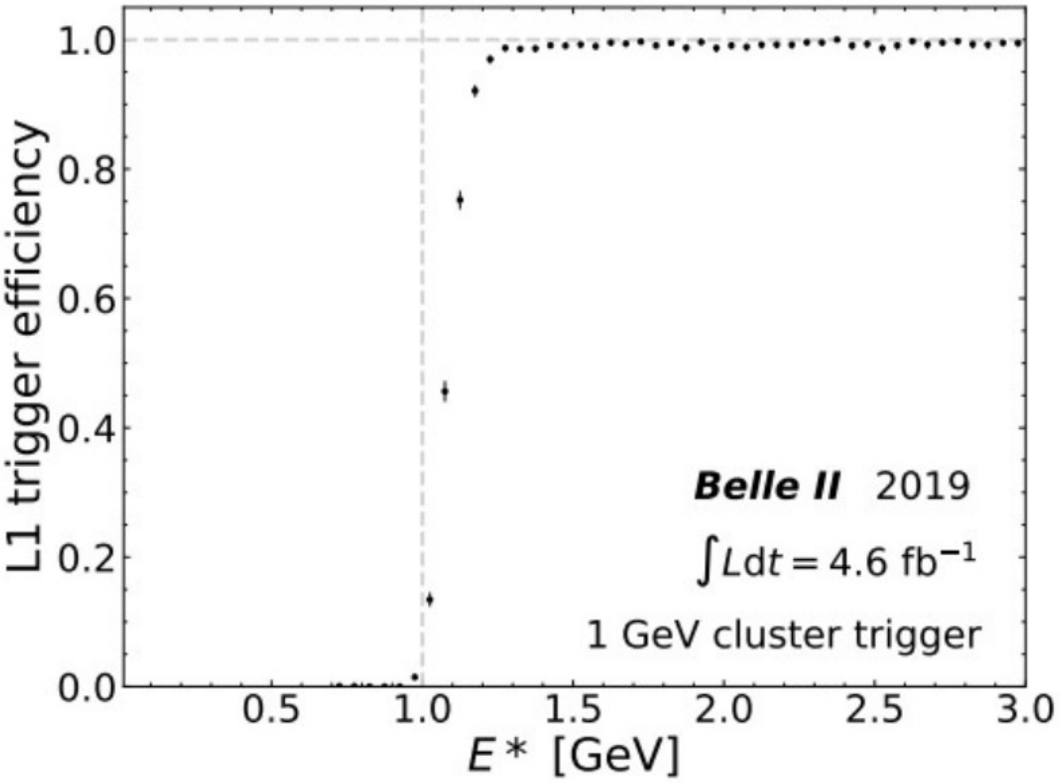


Dark photon to invisible: single photon trigger

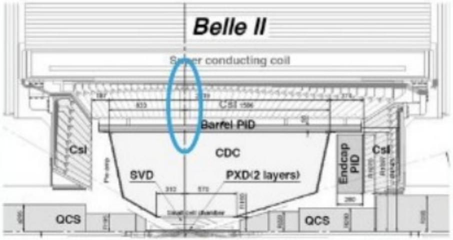
Belle II Phase 3 (Design)

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)





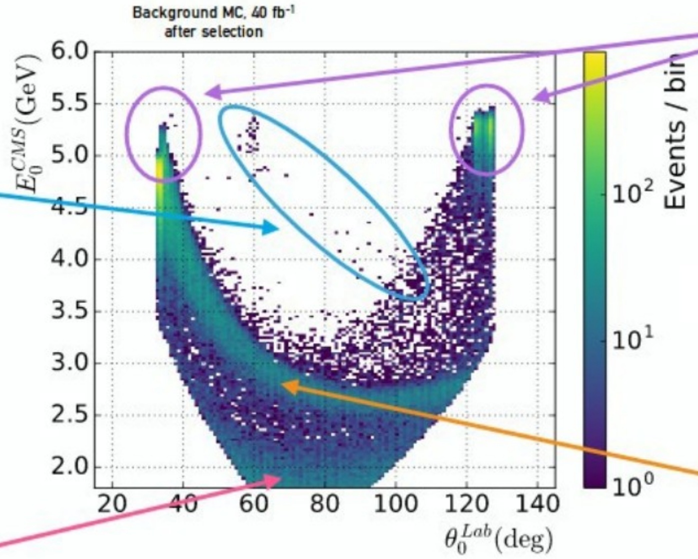
Dark photon to invisible: backgrounds



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

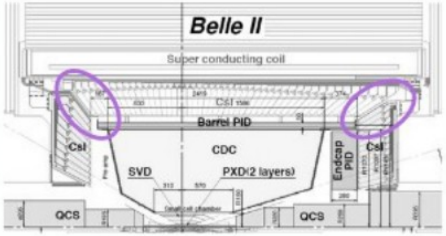
Discriminant variables:

E_{CMS} vs. polar angle of “single photon”

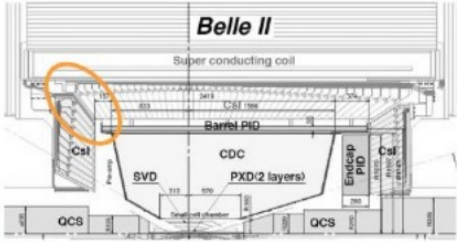


Signal signature:
peak in E_{CMS} (horizontal band)

ee→eeγ
both electrons
out of tracking acceptance



ee→2γ
1γ in ECL BWD or FWD gap



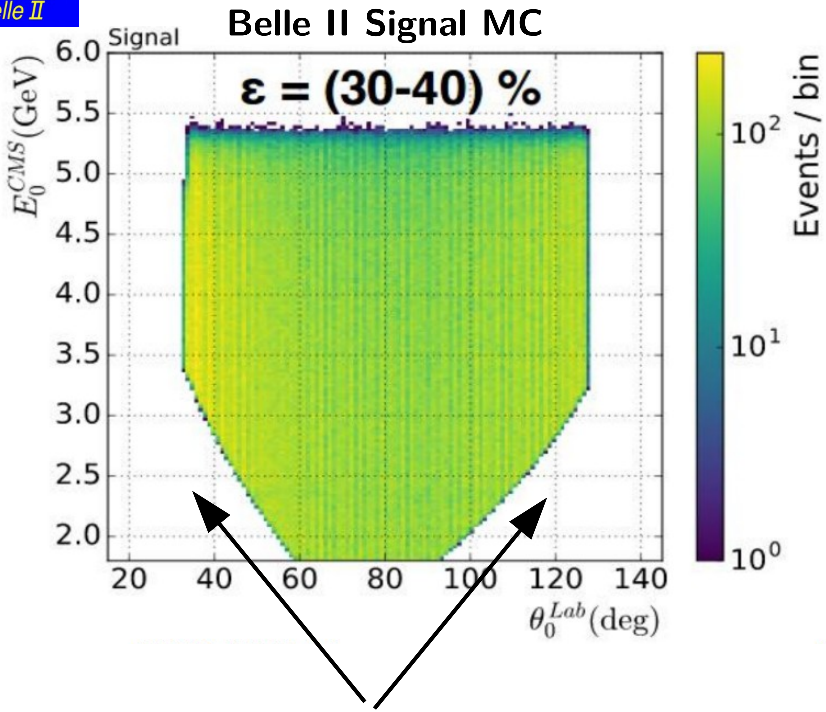
ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

Dark photon to invisible: discriminant variables

Optimize the analysis separately in the Low Mass region, $M_x^2 < 36$ GeV^2, and High Mass region, $24 < M_x^2 < 69$ GeV^2.

- *BDT discriminant* trained on 12 variables (signal cluster shape, cluster properties, additional energy deposited in the calorimeter, etc)
- Optimize analysis in model independent approach
- Interpret results for dark photon decay (ε, $M_{A'}$)

Discriminant variables: E^*_γ, θ_γ



Effect of selection on E*(θ) for background rejection