Dark Matter searches in e^+e^- annihilations & first results from Belle II

Next Frontiers in the Search for Dark Matter

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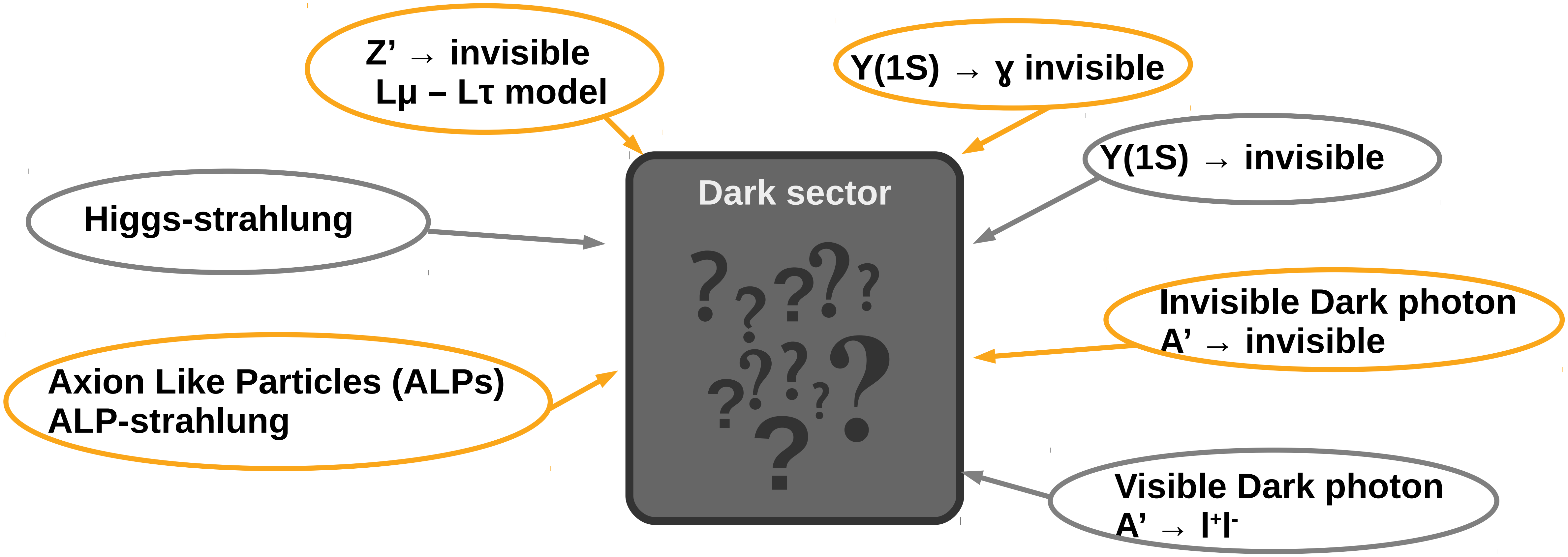
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Belle II

DESY.

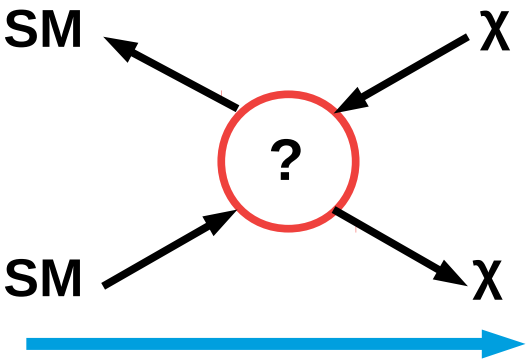
Outline

Dark Matter searches in e+e- annihilations



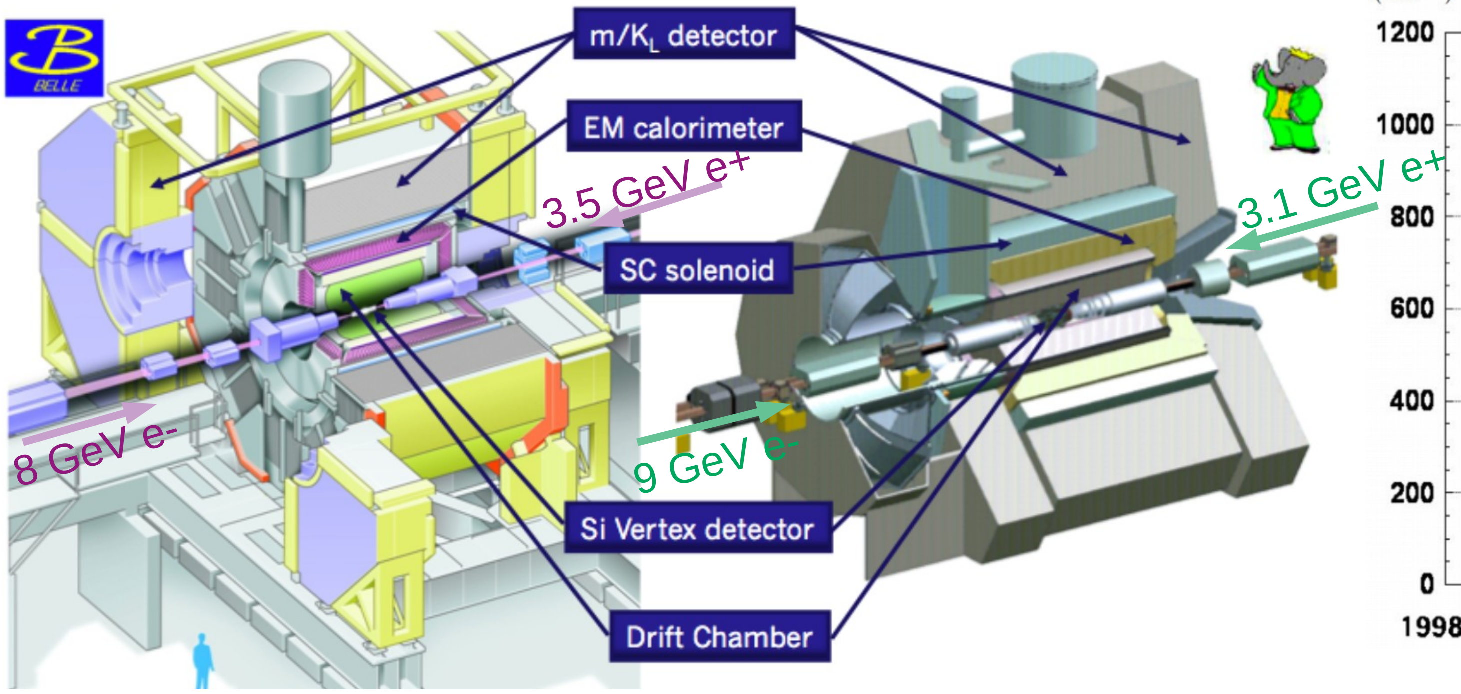
in this talk

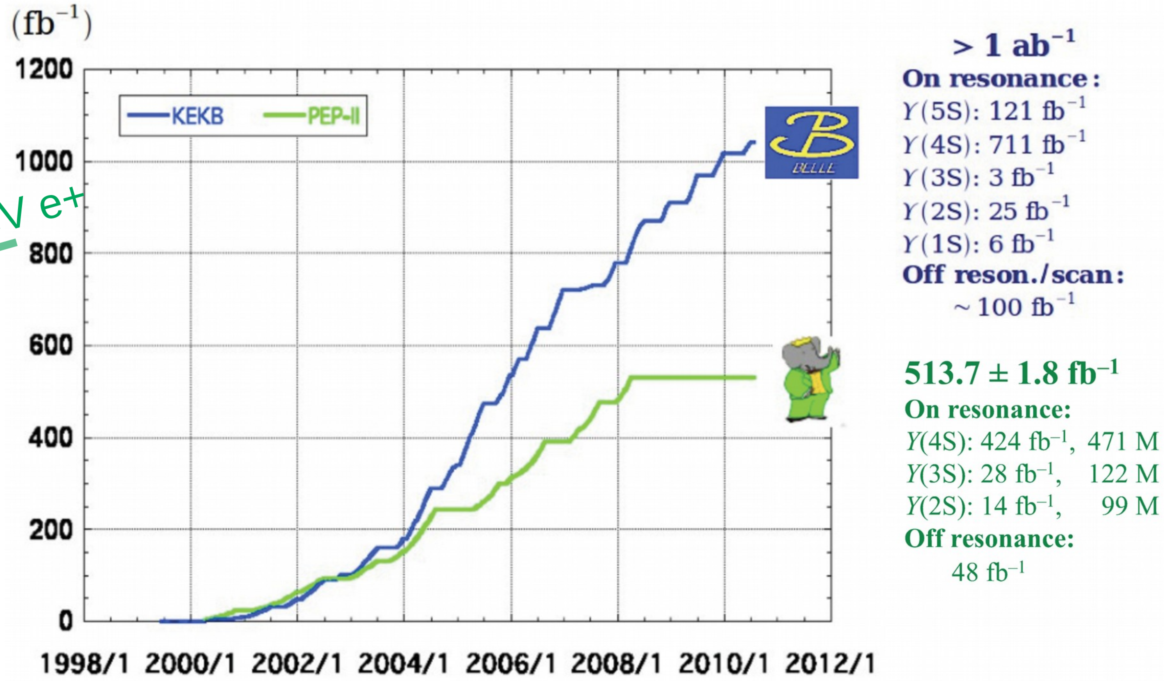
Dark Matter searches in e^+e^- annihilations



Collider Method: DM production at collider, model dependent

- Mainly operating at $\sqrt{s}$ = 10.58 GeV
- Clean environment
- Known initial energy of the system





at the KEKB collider
KEK, Japan

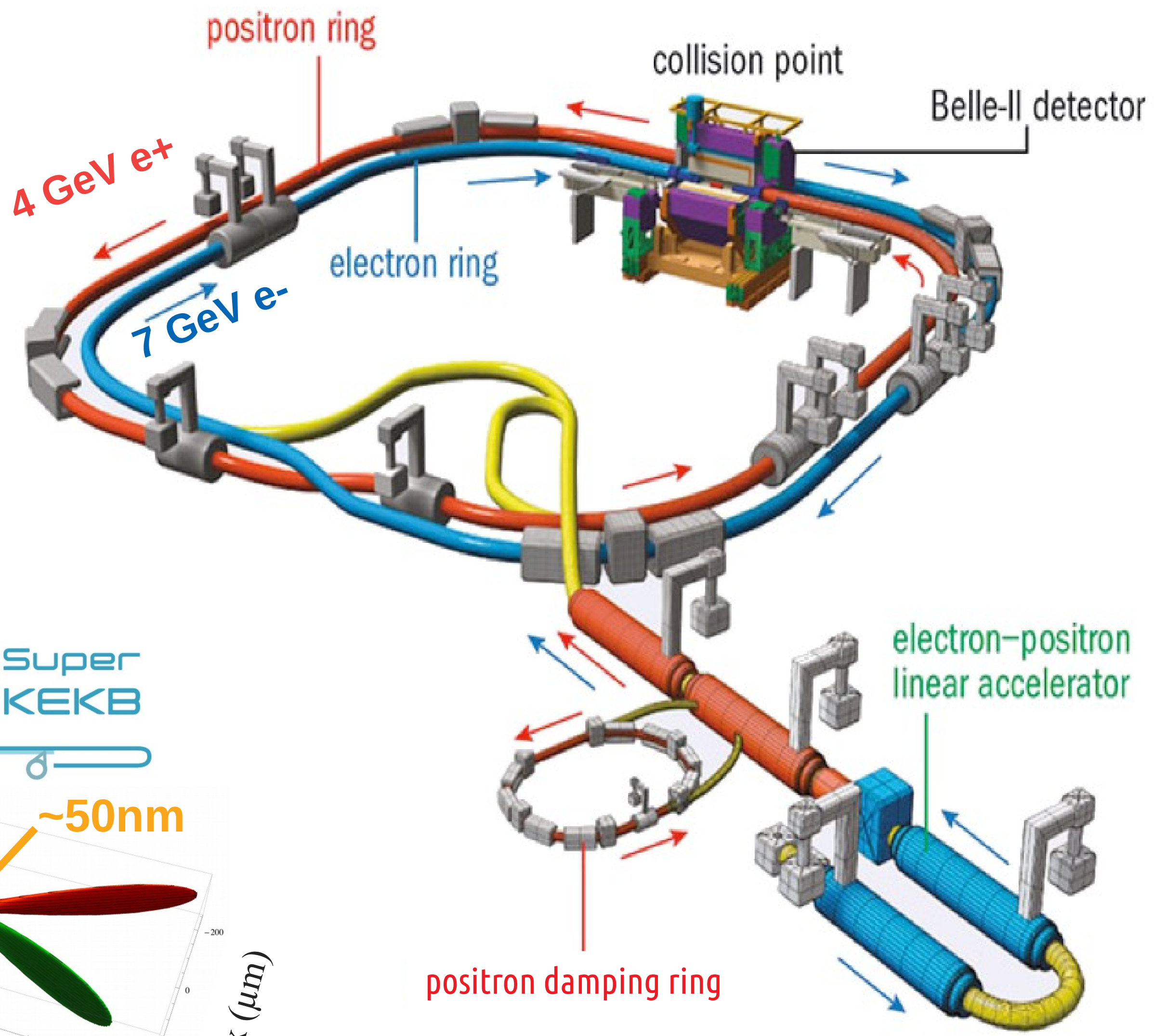
at the PEP II collider
SLAC, USA

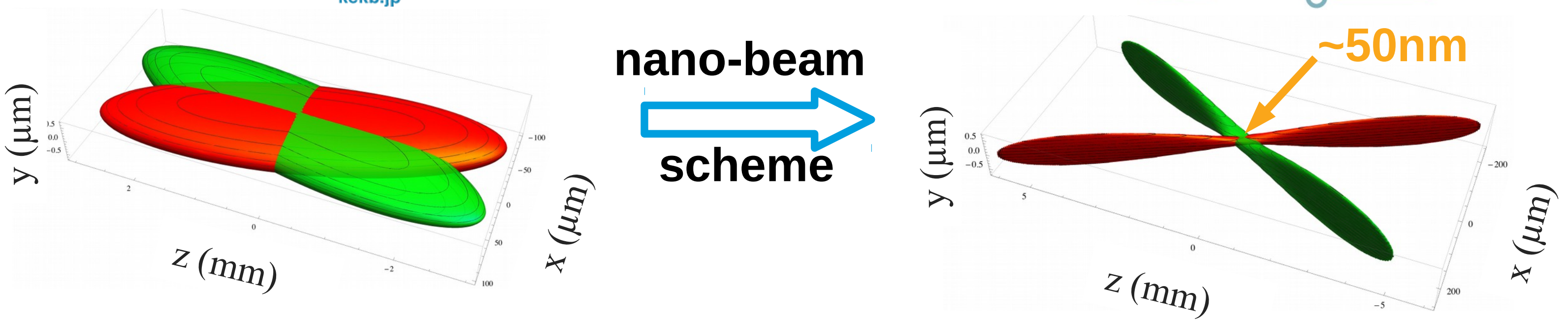
SuperKEKB

Next generation B-factory

40x KEKB integrated luminosity: **50 ab^{-1}**

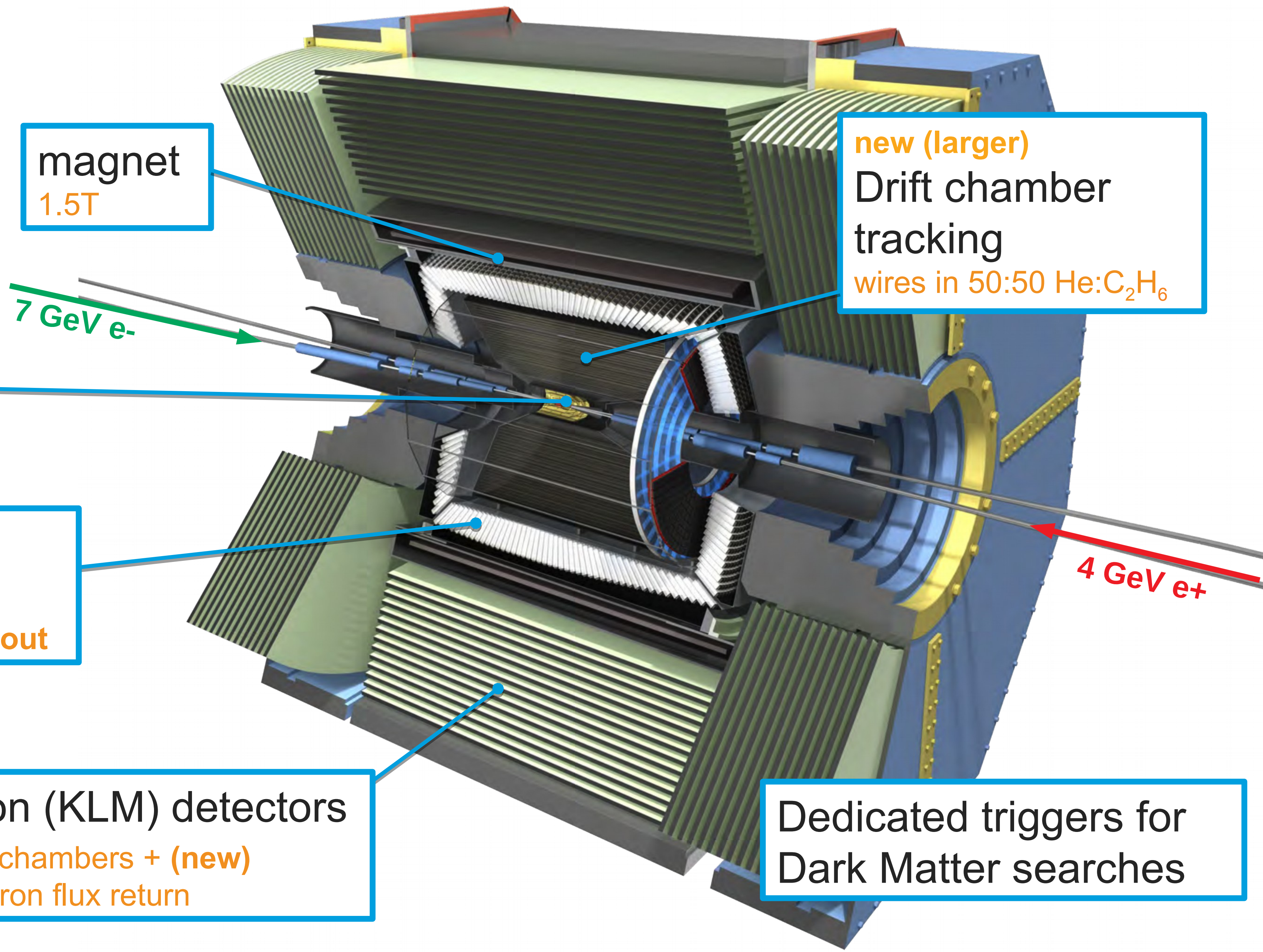
- from upgraded ring
  ×2 ↑ beam current
- from final focus magnets
  × 1/20 ↓ β* vertical beta-function at the IP
  large crossing angle (83 mrad)





Belle II

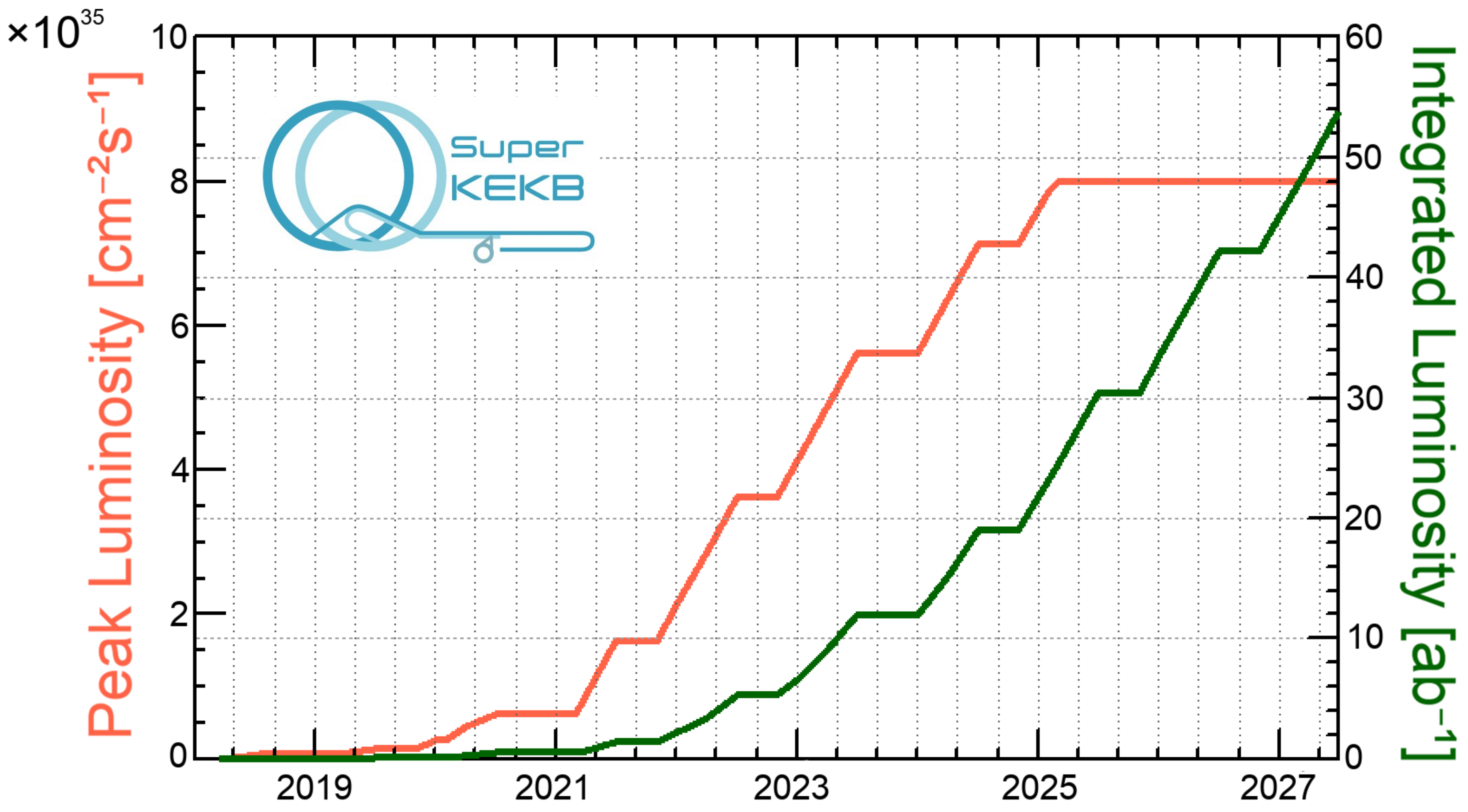
The detector



Data schedule

- 2018: 500 pb^{-1}.
  - *Commissioning* data.
- 2019: ~6.5 fb^{-1} ***delivered***.
- Expected in 2027: 50 ab^{-1}.

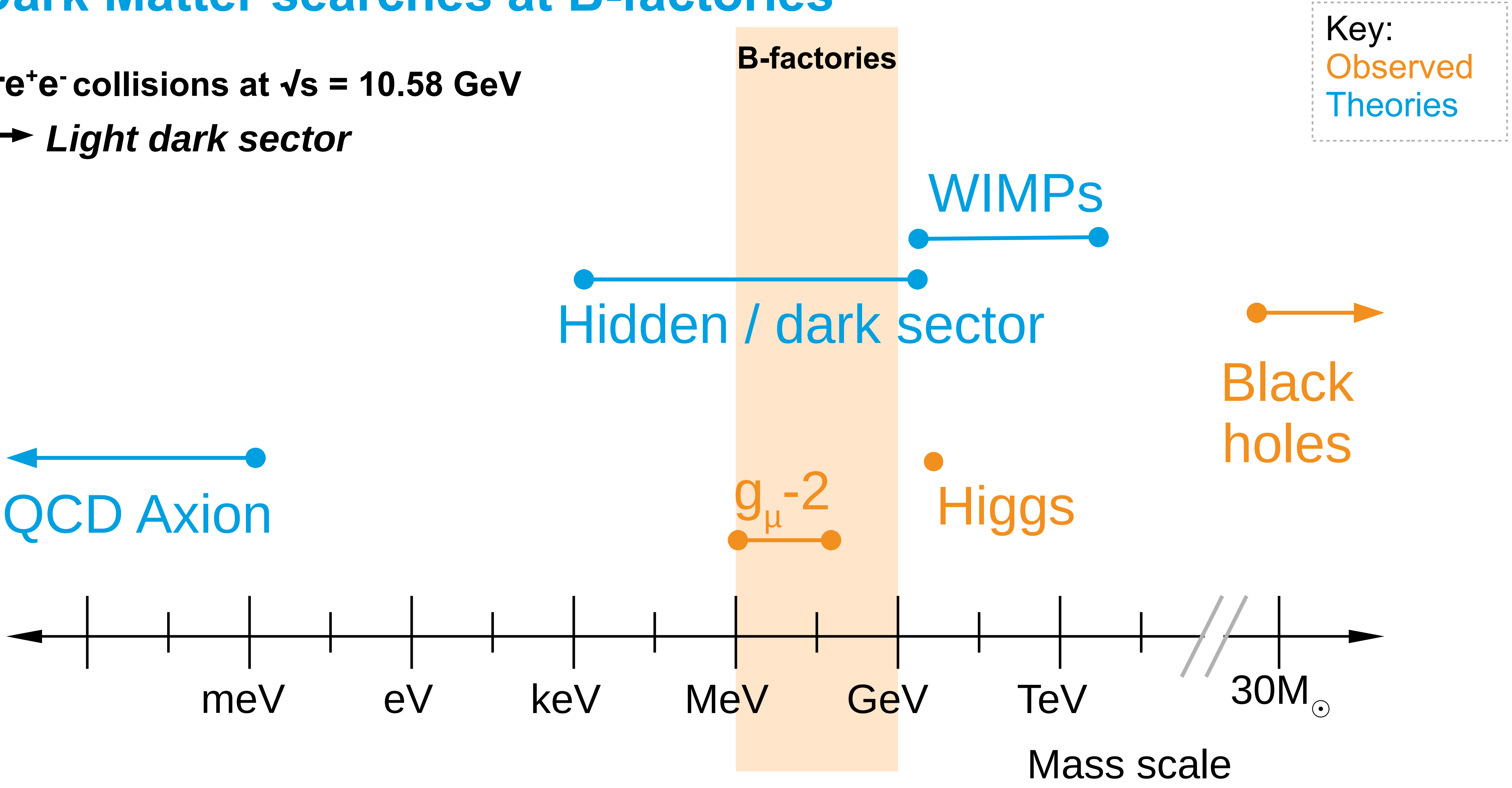
Expected data set



Dark Matter searches at B-factories

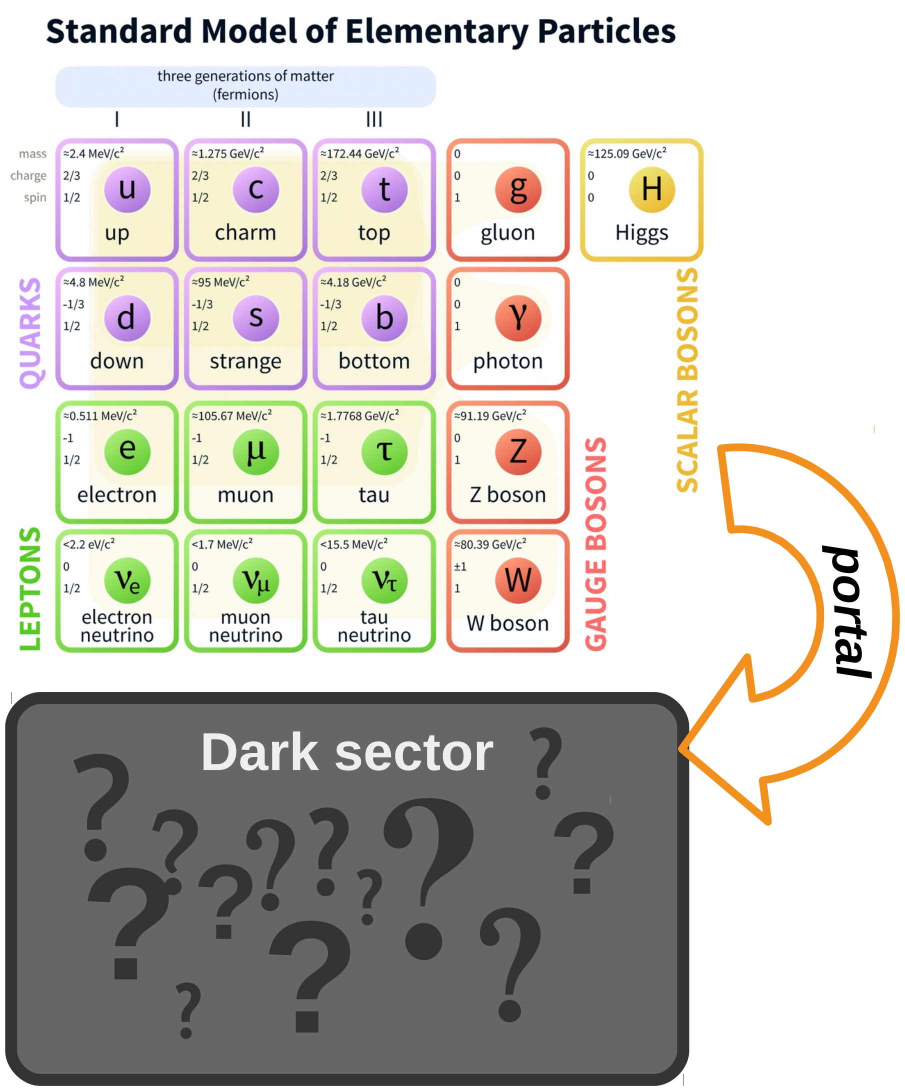
e^+e^- collisions at $\sqrt{s}$ = 10.58 GeV

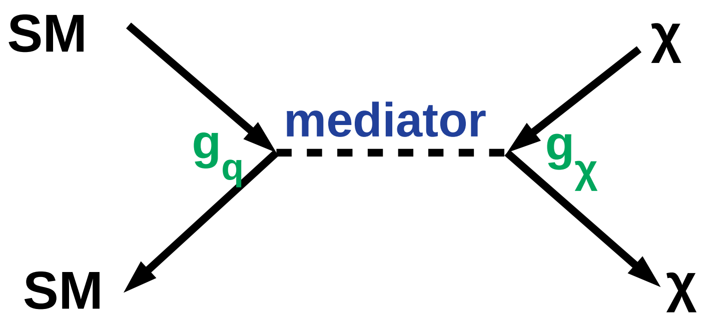
→ ***Light dark sector***



Phenomenology

Renormalizable way of Dark Matter coupling to the SM





Vector portal → *Dark photon*

$$\mathcal{L} \supset \epsilon V_\mu J^\mu_{\rm SM}$$

Scalar portal (Higgs portal) → *Dark Higgs/Scalars*

$$\mathcal{L} \supset \lambda S^2 (H^\dagger H)$$

Pseudoscalar portal → *Axion-Like Particle*

dim 5 axion portal

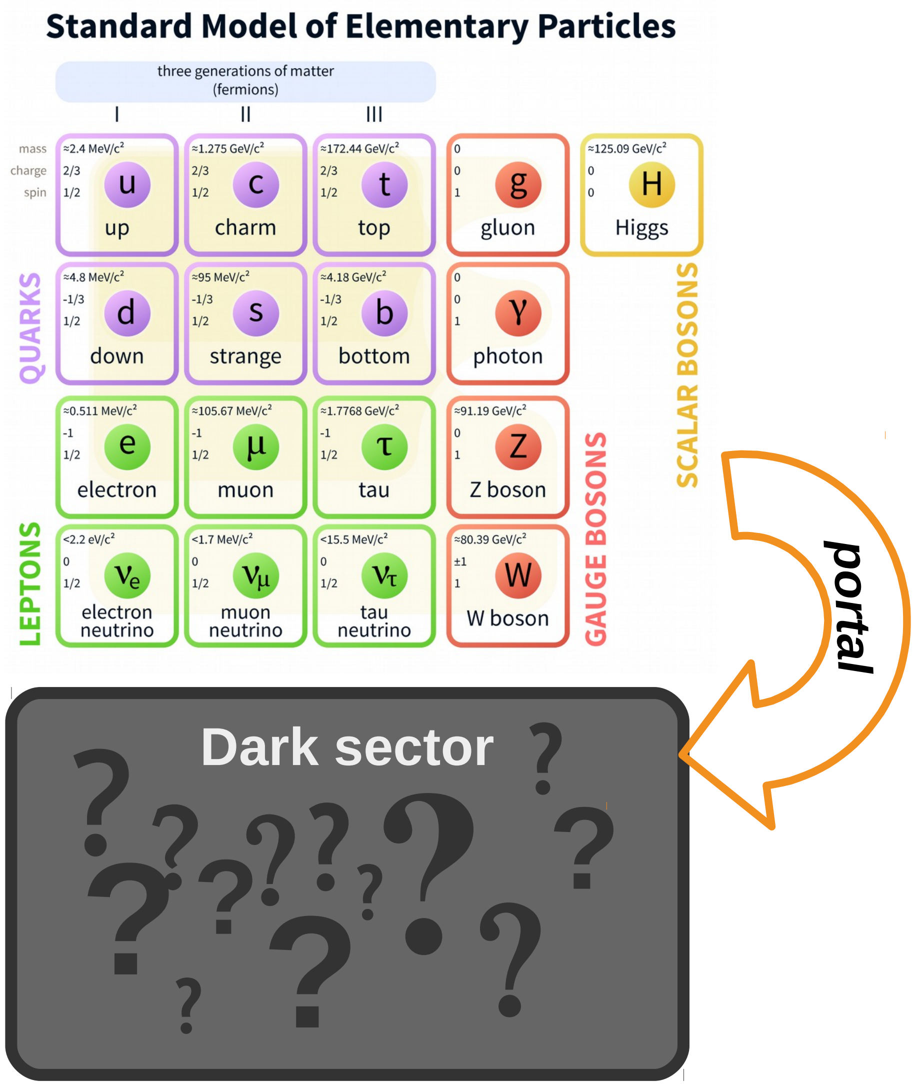
$$\mathcal{L} \supset \frac{\partial_\mu P}{f_A} \bar{f} \gamma^\mu \gamma^5 f$$

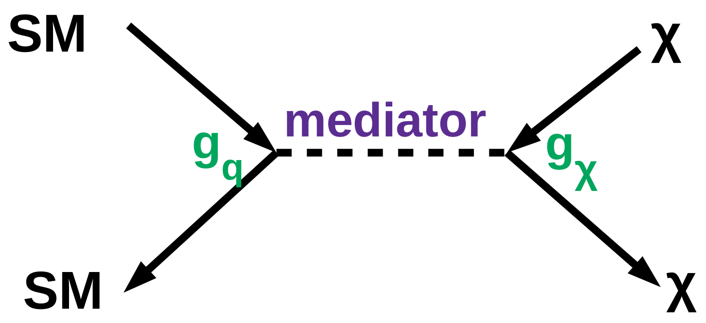
Neutrino portal → *Sterile Neutrinos*

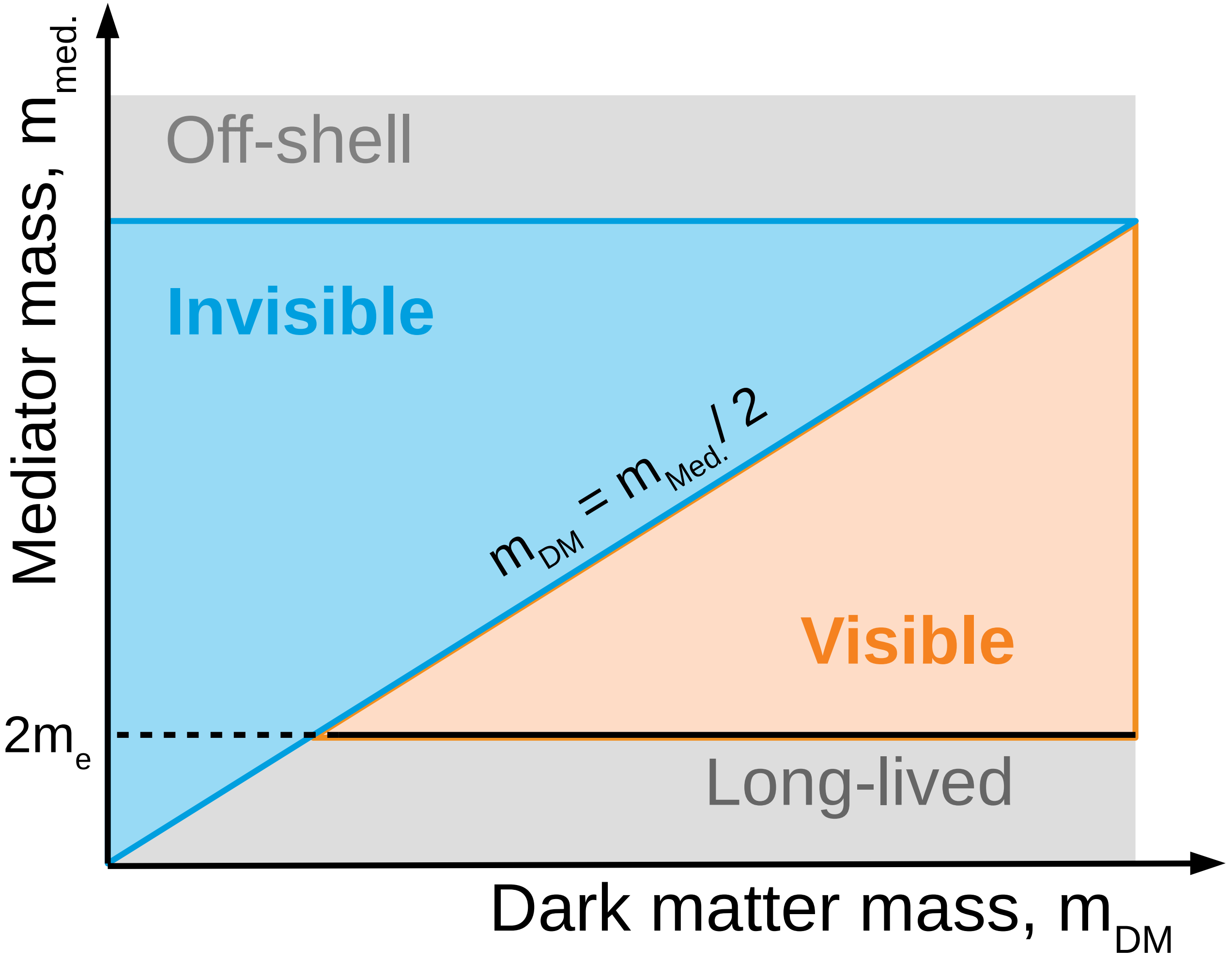
$$N(LH)$$

Phenomenology

Renormalizable way of Dark Matter coupling to the SM







Phys.Rev. D93 (2016) no.5, 054023

Υ(1S) → γ invisible

Theory

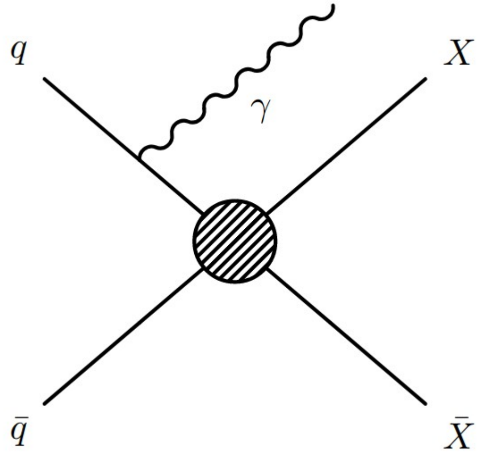
$M_{med.}$ is very large → can not be produced on-shell in B-factories
DM particle is kinematically accessible

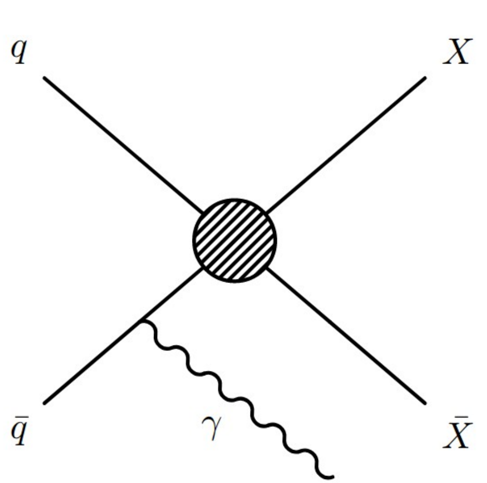
vector mediator → Υ(1S) → invisible

spin-0 mediator → Υ(1S) → γ invisible

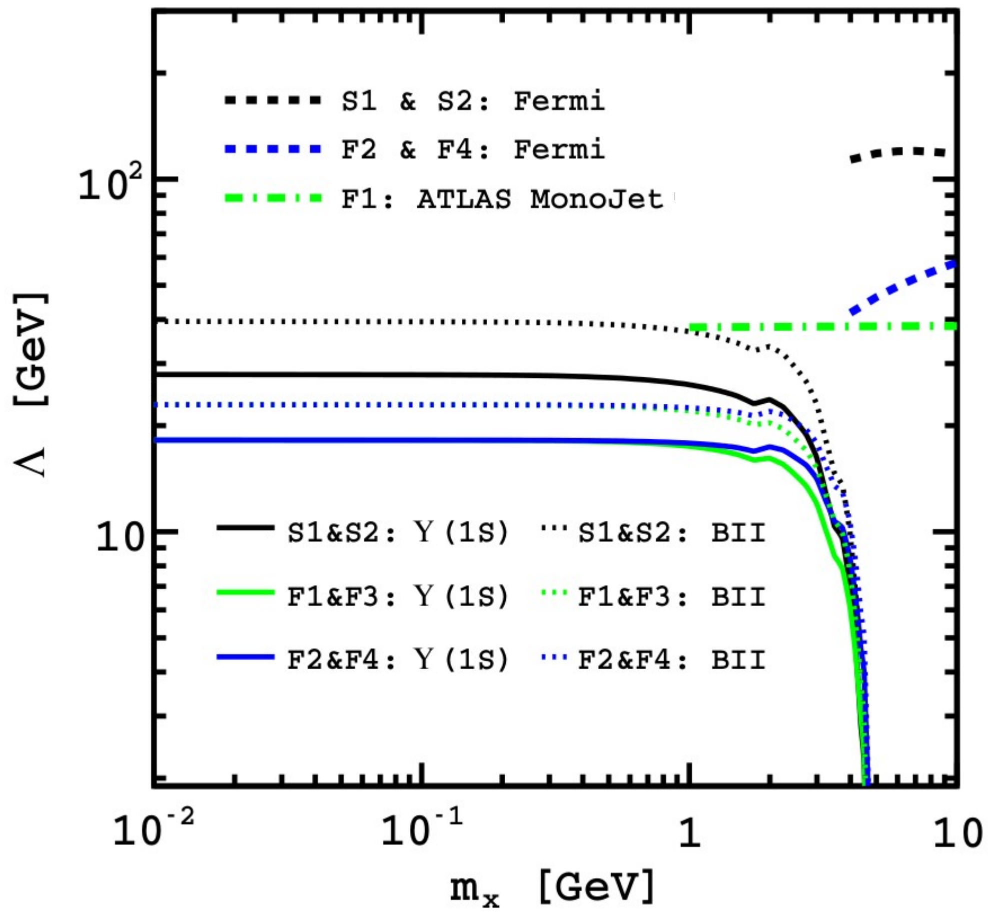
Limits on the branching fraction for Υ(1S) decays

→ **Suppression scale of the effective operator parametrizing interactions DM with quarks**





BII – expected sensitivity for Belle II



$\Upsilon(1S) \rightarrow \gamma$ invisible

PRL 103,251801 (2009)
Phys. Rev. Lett. 122, 011801 (2019)

Analysis

$\Upsilon(2S) \rightarrow \Upsilon(1S)\, \pi^+\pi^-$

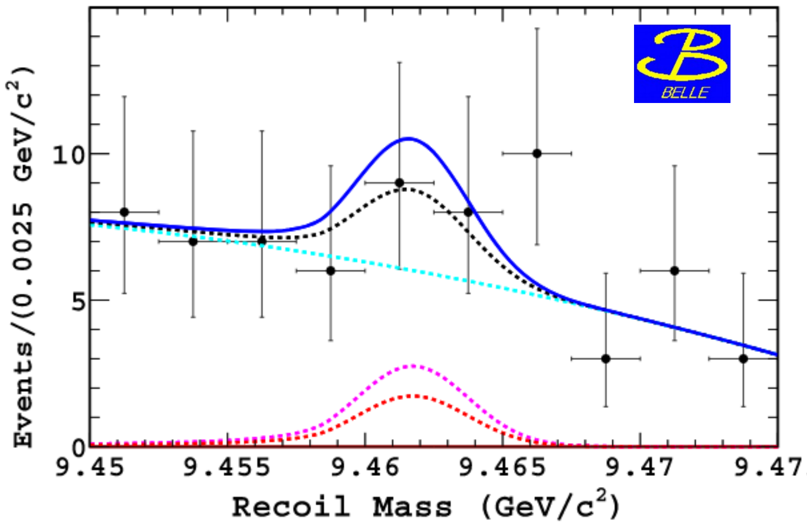
Bottonium transition with two soft pions

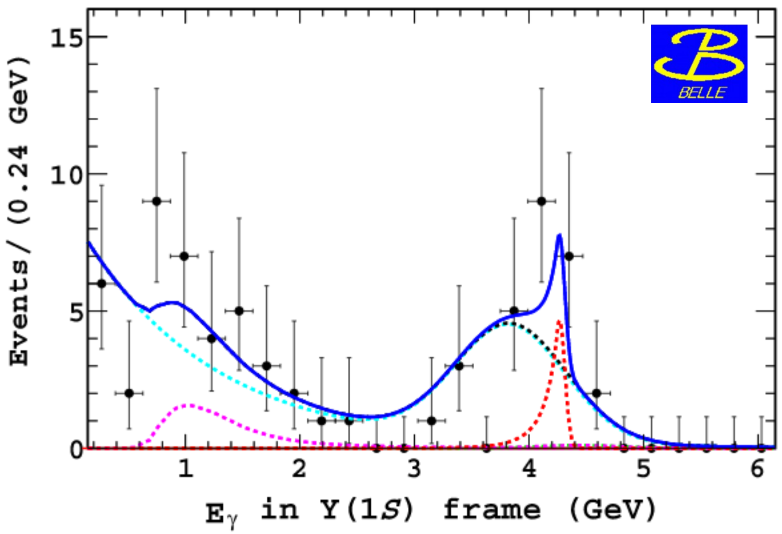
Dipion recoil mass:

$M^2_{rec} = s + M^2_{\pi\pi} - 2\sqrt{s}\, E^*_{\pi\pi}$, with

$M_{\pi\pi}$ is $[2M_{\pi}, (M_{\Upsilon(2S)} - M_{\Upsilon(1S)})]$

Mass scan point with $M_{med.} = 2.946$ Gev/c^2





Background estimation:

Continuum background

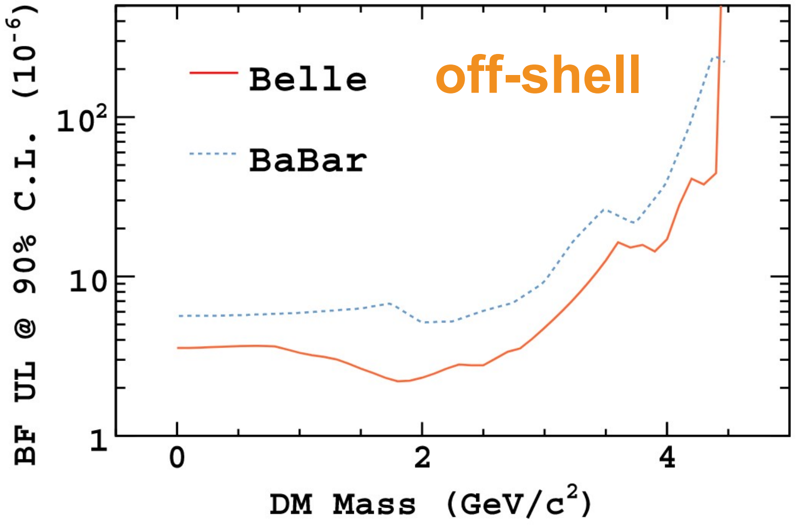
- studied with an off-resonance data set
- do not observe any significant peaking backgrounds
- $\Upsilon(2S) \rightarrow \tau\tau$ (irreducible)

$\Upsilon(1S)$ decay background (irreducible)

- $\Upsilon(1S) \rightarrow ll$ *(leptons)* do not produce a peak at $E\gamma$ but at M_{rec}
- $\Upsilon(1S) \rightarrow \gamma hh$ *(hadrons)* produce a peak at $E\gamma$ and M_{rec}

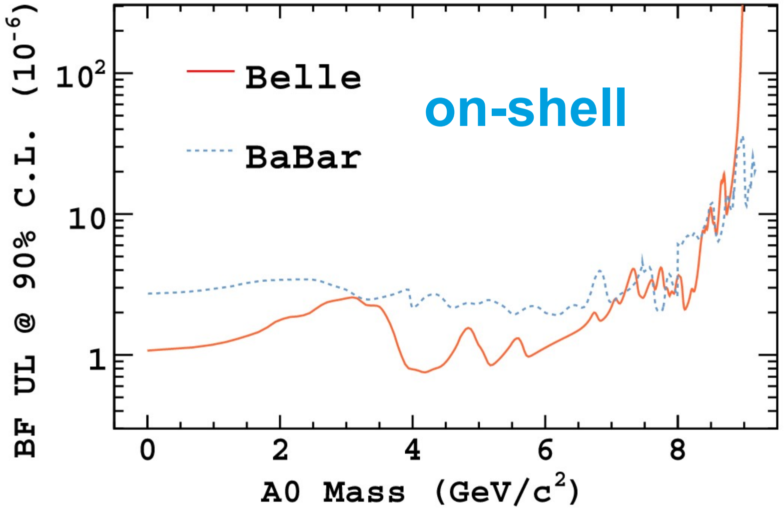
Υ(1S) → γ invisible

Physics reach

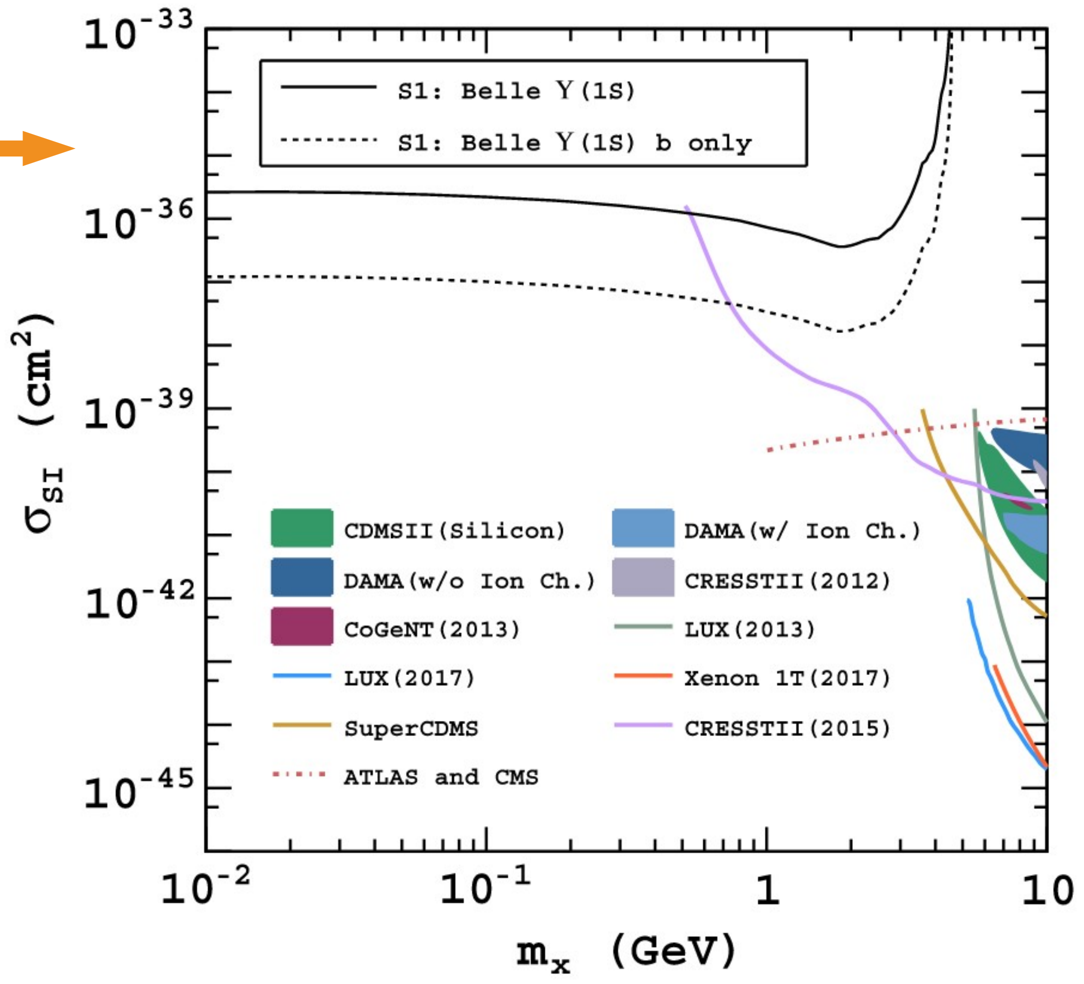


Set limits on the branching fraction

conversion into a WIMP-nucleon scattering σ limit



Used data:
Belle, **25 fb^{-1}**
BaBar, **14.4 fb^{-1}**



Dark photon

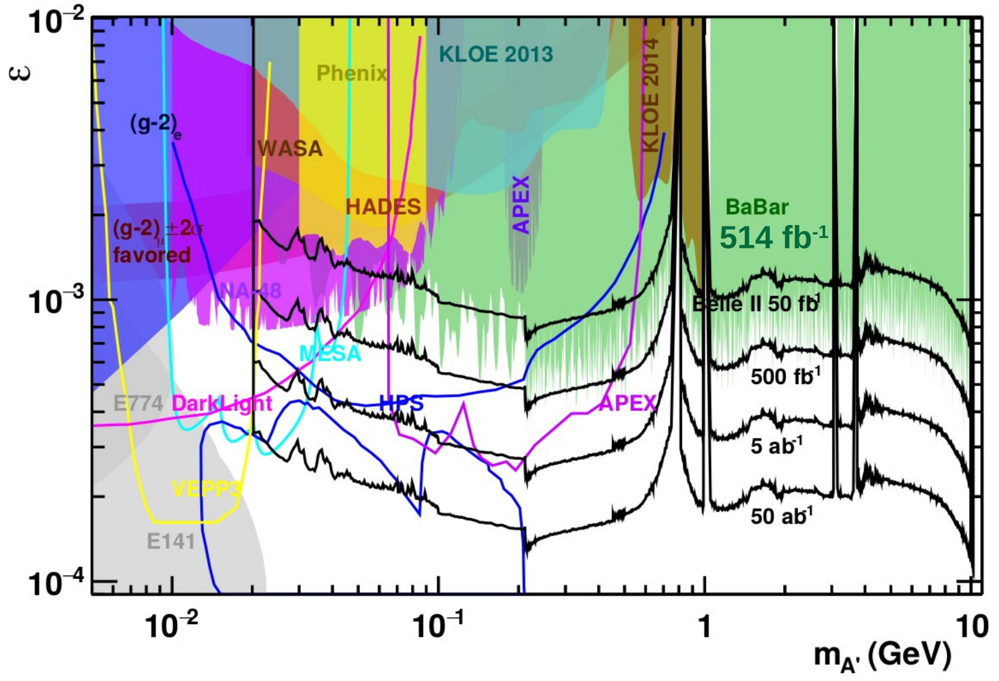
Theory

[The Belle II Physics Book](#)

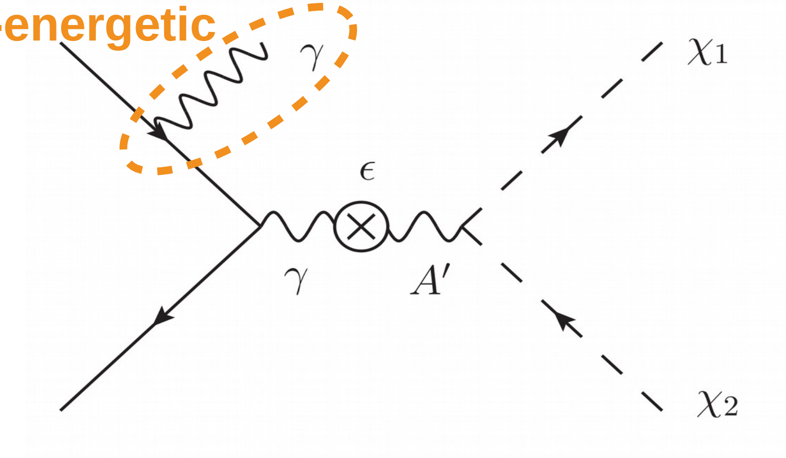
- Massive vector particle A', mixes with the SM photon:

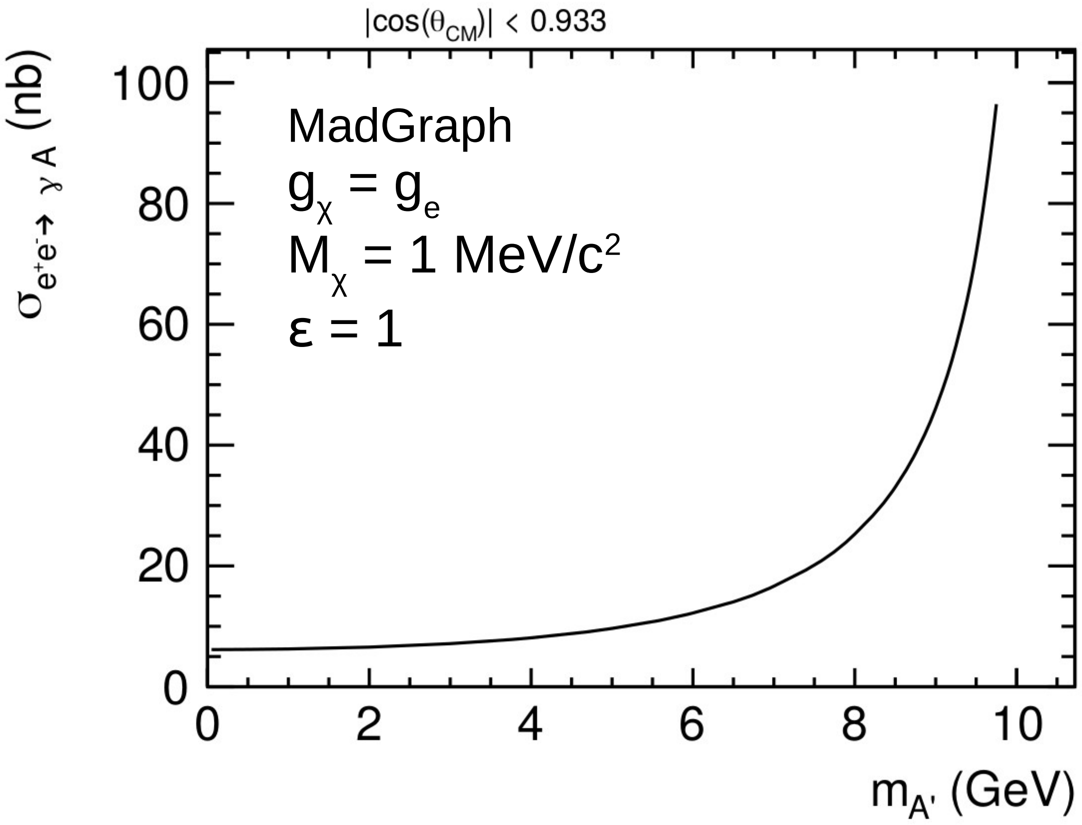
$$\mathcal{L} \supset \epsilon g_D A'_\mu J^\mu_{\mathrm{EM}}$$

- Can decay to two leptons $A' \to l^+l^-$
  Experimentally: search for a narrow peak in l^+l^- mass spectrum on top of large BG



Mono-energetic ISR γ





Dark photon

Theory

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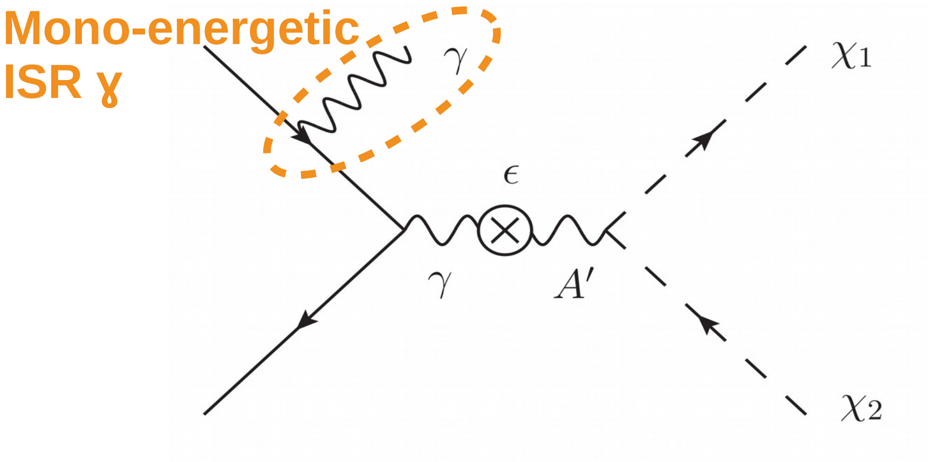
- Massive vector particle A', mixes with the SM photon:

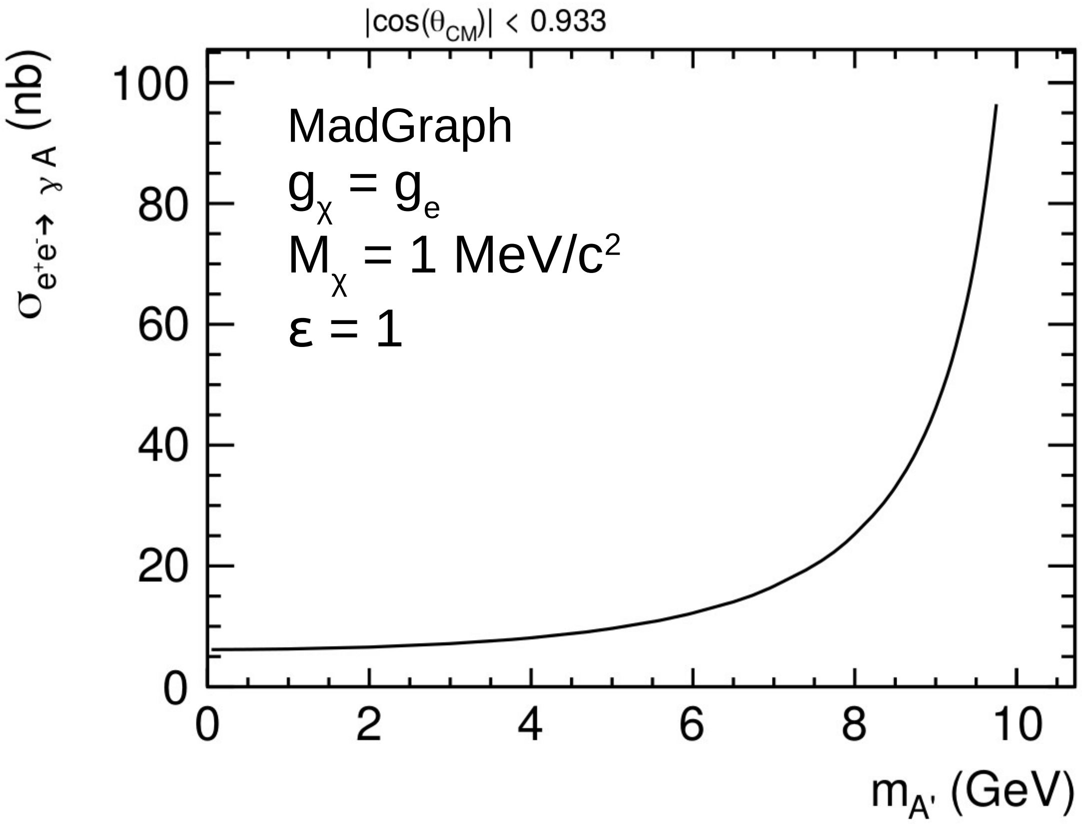
$$\mathcal{L} \supset \epsilon g_D A'_\mu J^\mu_{\mathrm{EM}}$$

- Can decay to two leptons $A' \rightarrow l^+l^-$
  Experimentally: search for a narrow peak in l^+l^- mass spectrum on top of large BG
- Can decay directly to light dark matter $A' \rightarrow \chi_1\chi_2$
  Experimentally: negligible interaction with detector
- Experimentalist's trick: require ISR photon

$$E_{\gamma_{\mathrm{ISR}}} = \frac{s - m^2_{A'}}{2\sqrt{s}}$$

Single photon trigger is required
not available at Belle, and only 10% BaBar data





Dark photon

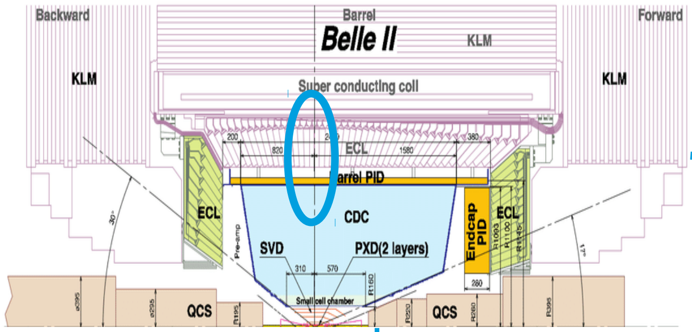
Analysis

- First analysis: **ee → γA' , A' → $\chi_1\chi_2$**

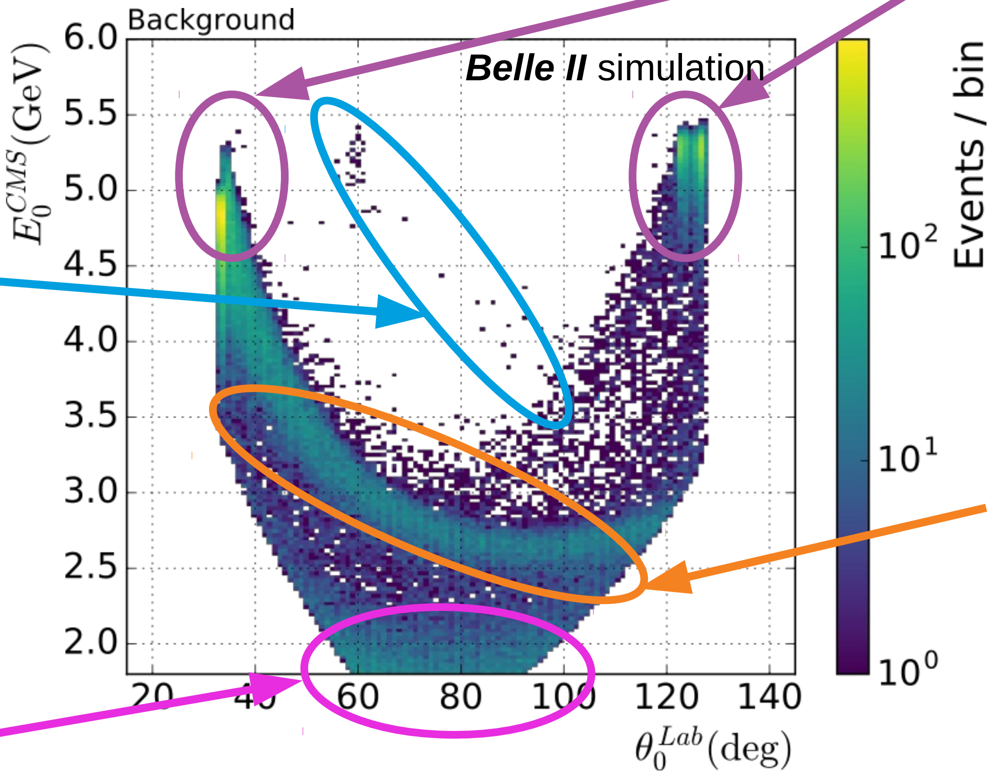
- One photon (no tracks, no other good photon clusters)
  Bump search in recoil mass spectrum

Main background sources:

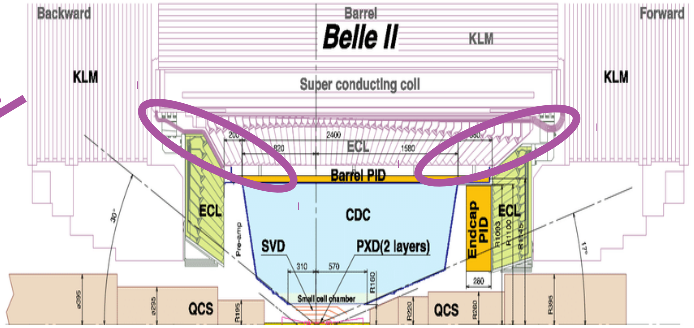
ee → eeγ(γ) and **ee → γγ(γ)**



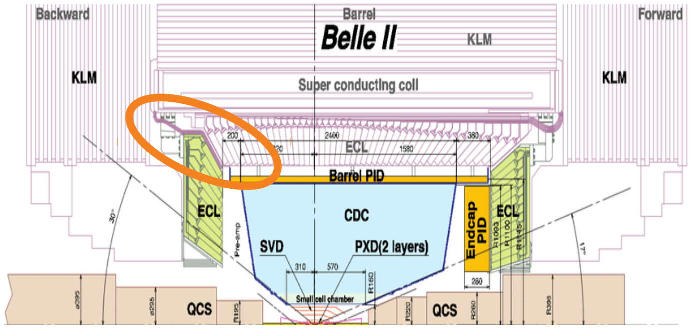
ee → γγ and **γγγ**,
1 γ in ECL 90° gap
1 γ out of ECL acc



ee → eeγ,
both leptons out
of tracking acceptance



ee → γγ,
1 γ in endcap gaps

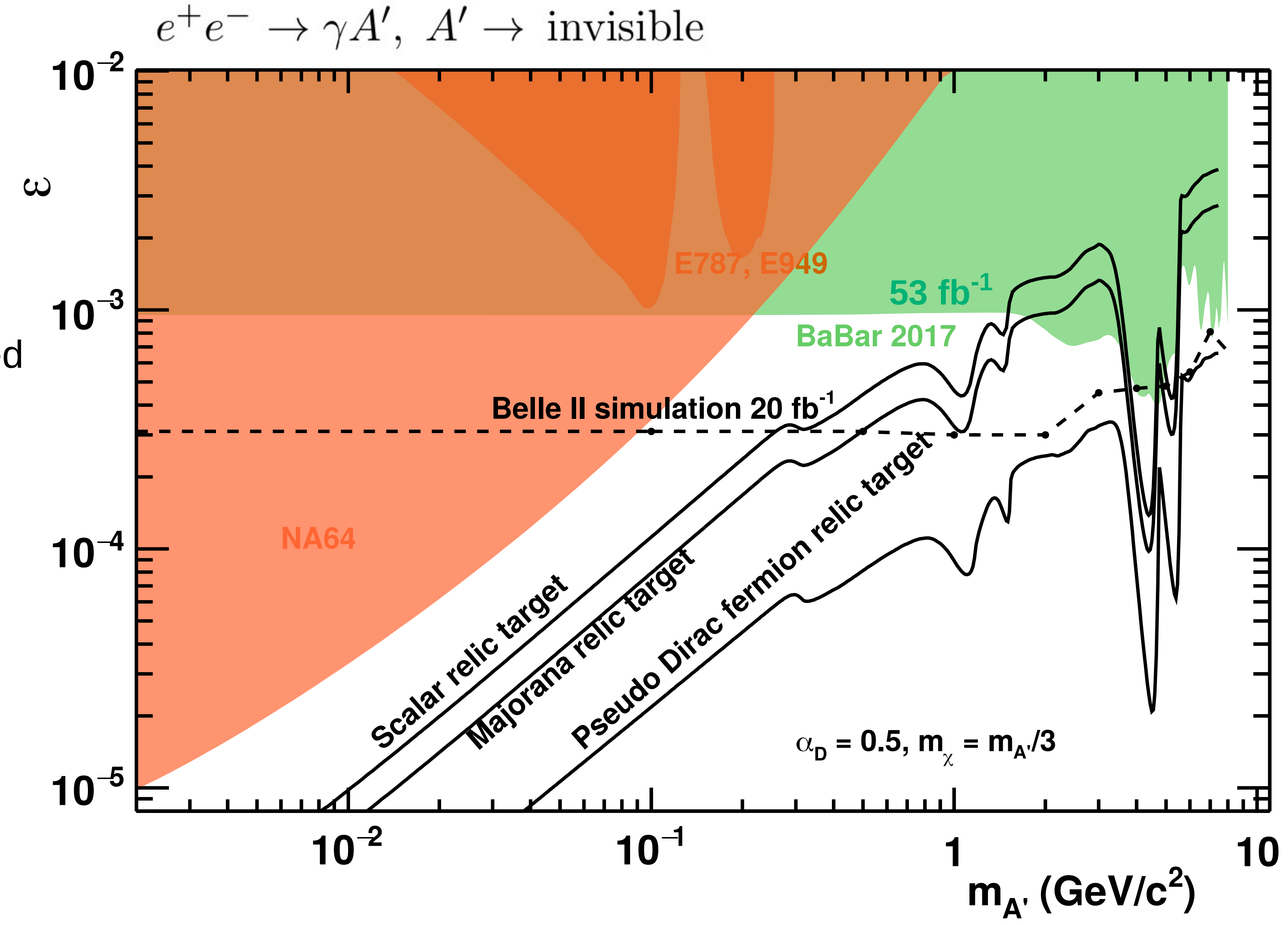


ee → γγγ,
1 γ in endcap gap
1 γ out of ECL acc.

Dark photon

Physics reach

At **Belle II** :
- single photon trigger
- use KLM to detect escaped photons

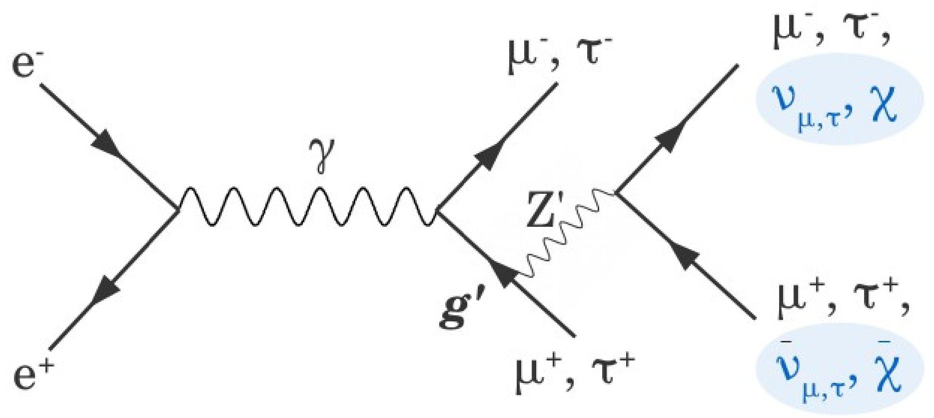


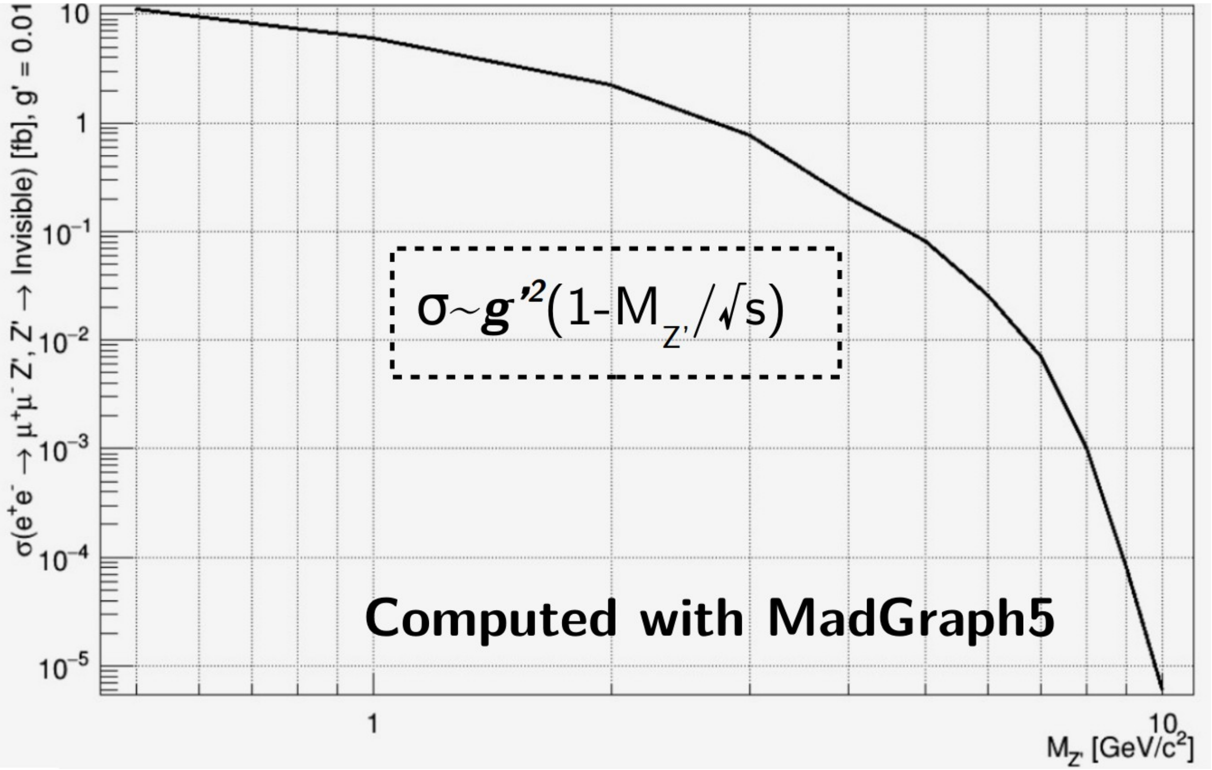
The Belle II Physics book:
arXiv:1808.10567
BaBar 53 fb^{-1} analysis:
PRL.119.131804
NA64 2019 analysis:
arXiv:1906.00176

Z’ to invisible: $L_\mu - L_\tau$ model

Theory

- “Dark photon” → Z’ if non minimal
- Search is performed in flavour violating and flavour conserving modes
- Mediator coupling to muons and taus, not electrons ($L_\mu - L_\tau$) Abelian symmetry
- Z’ → invisible: calculate a branching fraction and compare to theoretical prediction to find an indication of invisible DM





Z' to invisible: $L_\mu - L_\tau$ model

Analysis

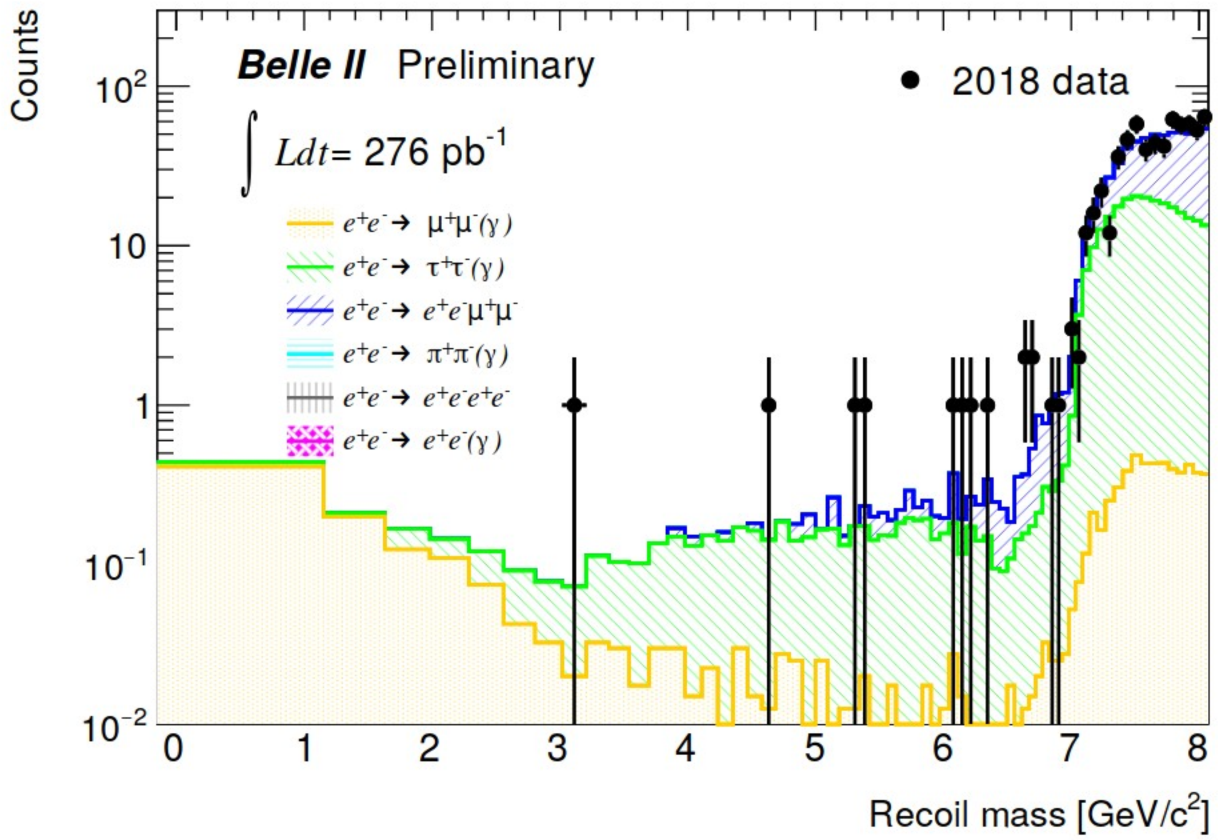
- ee → μμZ' (Z' → invisible)
- Bump hunt in recoil mass against μμ. Nothing in the rest of the event
- Kinematic fit of muons → to select events recoil energy point to the barrel (best hermiticity)
- Dimuon trigger

Main background sources:

ee→ μμ(ɣ)
ee→ ττ(ɣ)
ee→ eeμμ

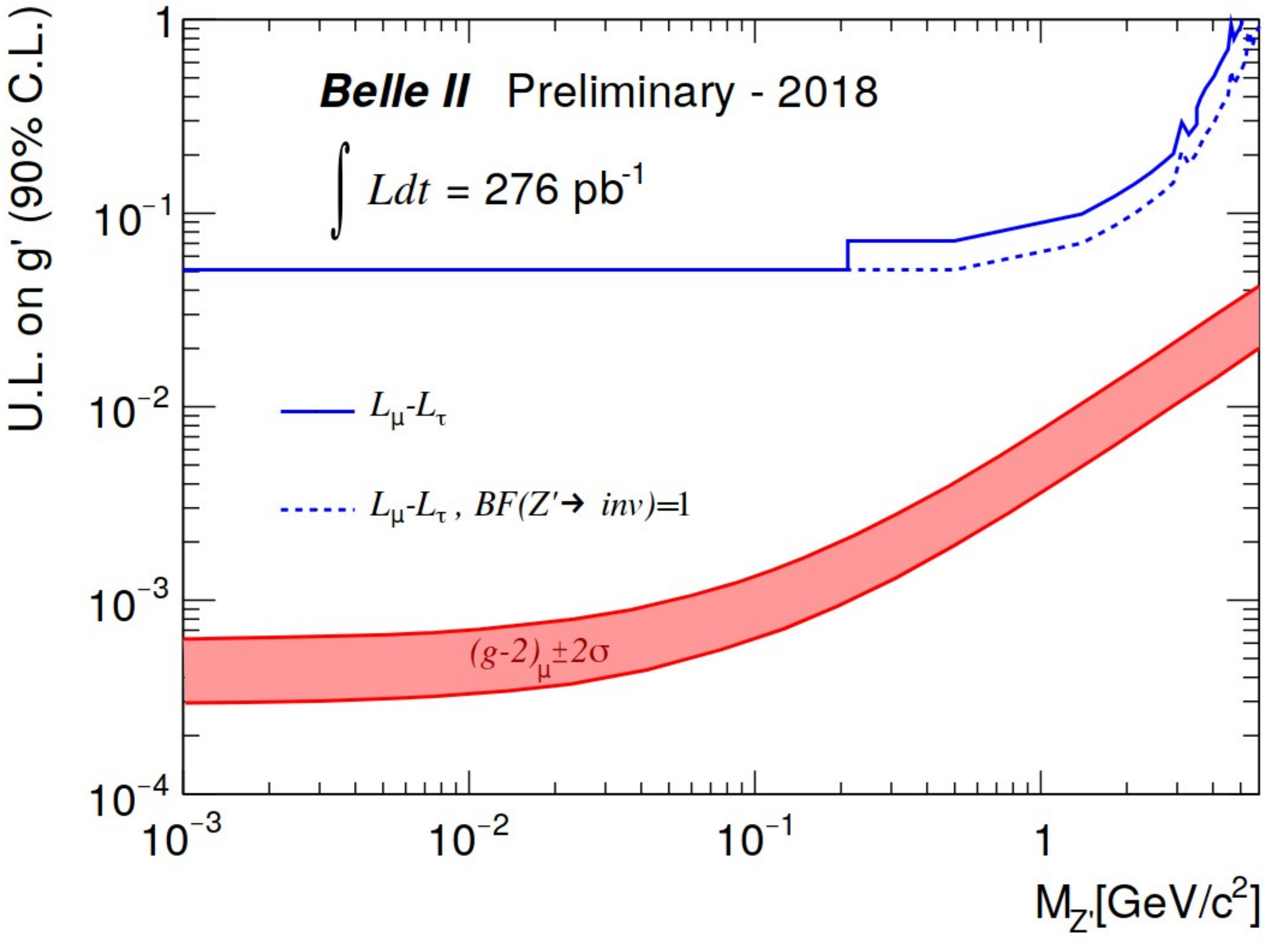
$$M_{rec} = s + M^2_{\mu\mu} - 2\sqrt{s}E^*_{\mu\mu}$$

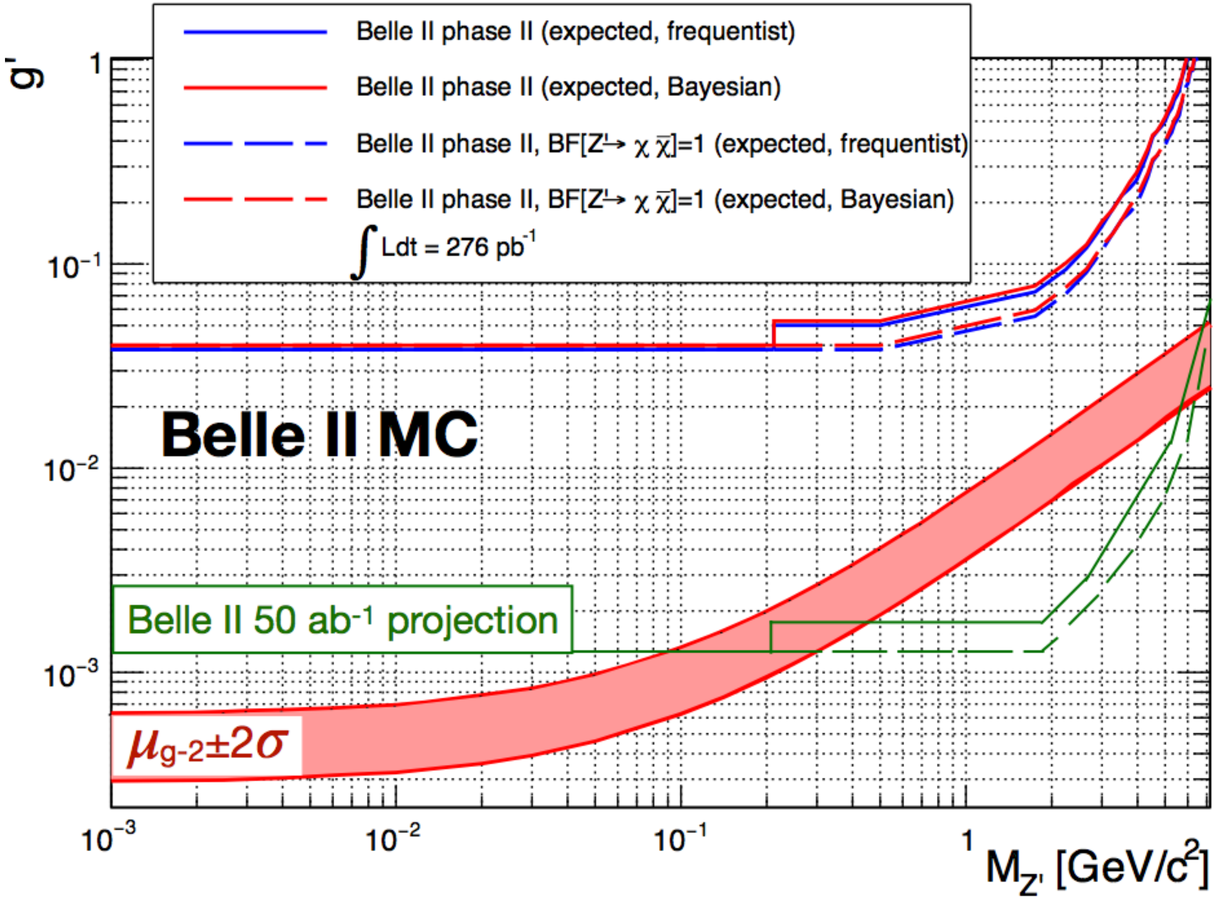
Simulated and reconstructed $M_{Z'}$ in range (0.1 – 10) GeV/c²



Z' to invisible: $L_\mu - L_\tau$ model

Physics reach





Axion Like Particles (ALPs)

JHEP 1712 (2017) 094

Theory

- Pseudo-scalar coupling to gauge bosons
- After EWSB:

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

- QED case: the coupling and the mass of the ALPs are independent
- ALPs at Belle II:

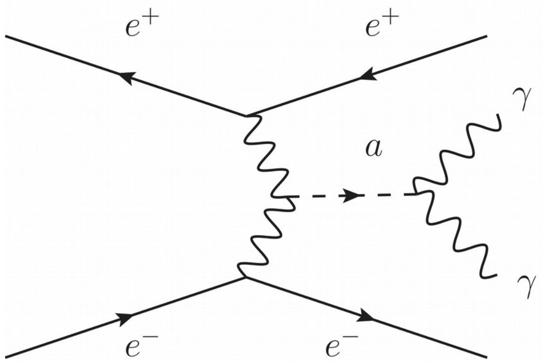
light ALPs $m_a \approx 1$ MeV/c^2,

$g_{a\gamma\gamma} \approx (10^{-5} - 10^{-6})$ GeV^{-1}

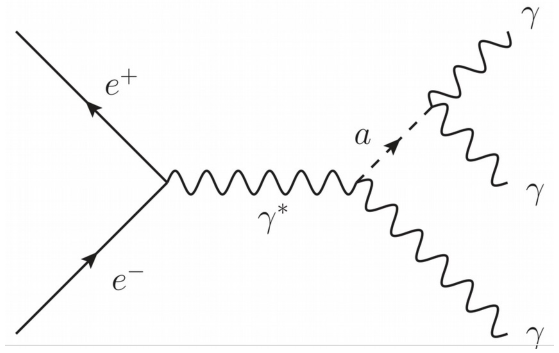
Invisible:
decays outside of the detector

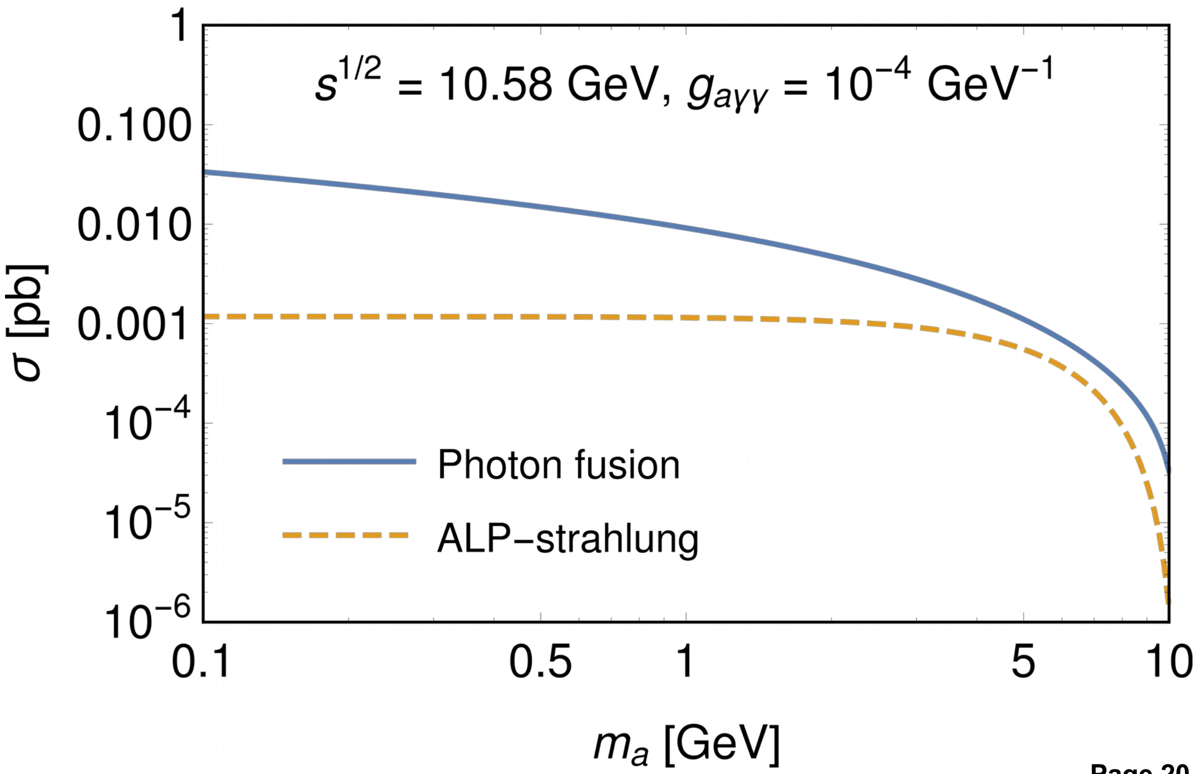
heavier ALPs $m_a \approx (0.1 - 10)$ GeV/c^2

Photon fusion



ALP-strahlung





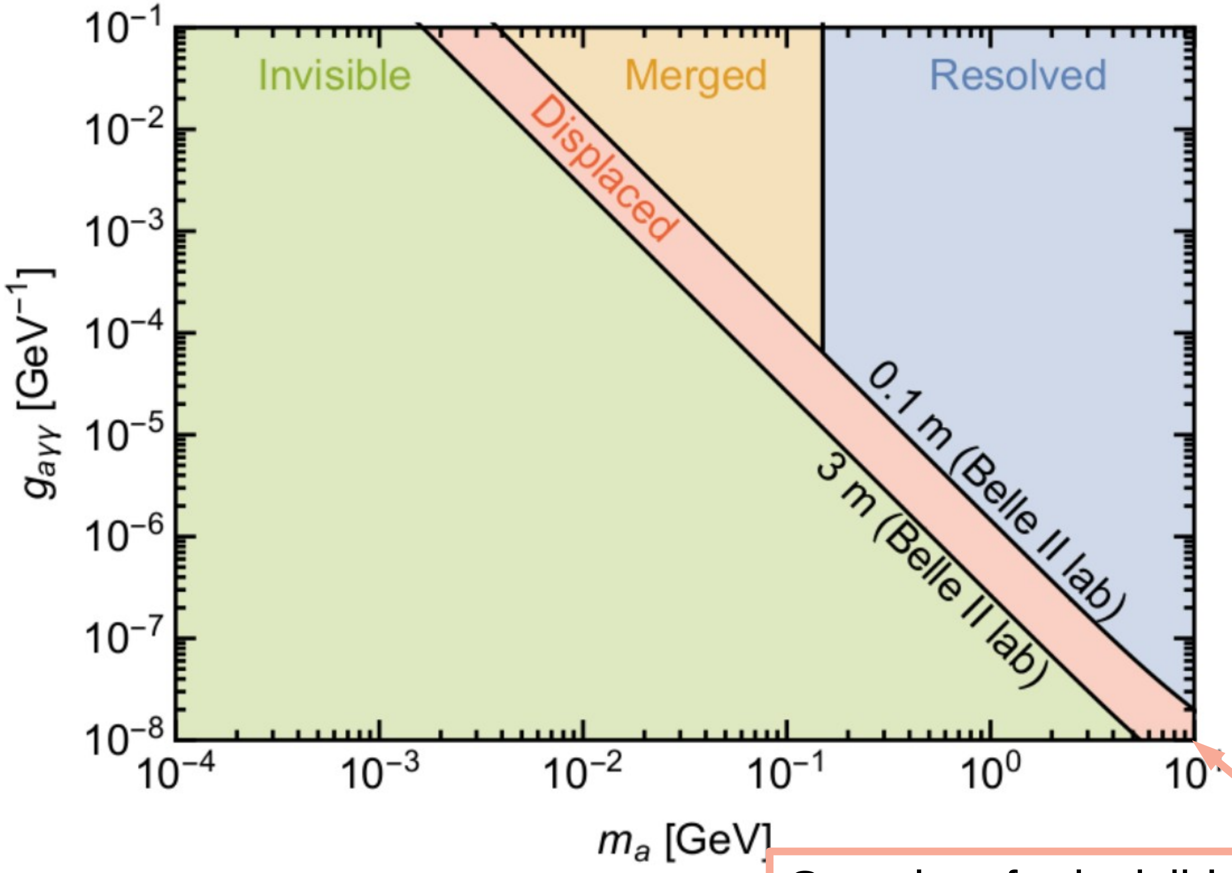
Axion Like Particles (ALPs)

Analysis

At higher masses, m_a > 200 MeV/c^2

Resolved:

- Three photons within tracking acceptance: add up to beam energy
  - Zero tracks
  - Bump on di-photon mass
- The SM background: **ee → γγ(γ)**
  - Does not peak in γγ
  - Not a 2-body system: use angles & kinematics to suppress



Searches for invisible and visible ALPs decays veto this region

At lower masses

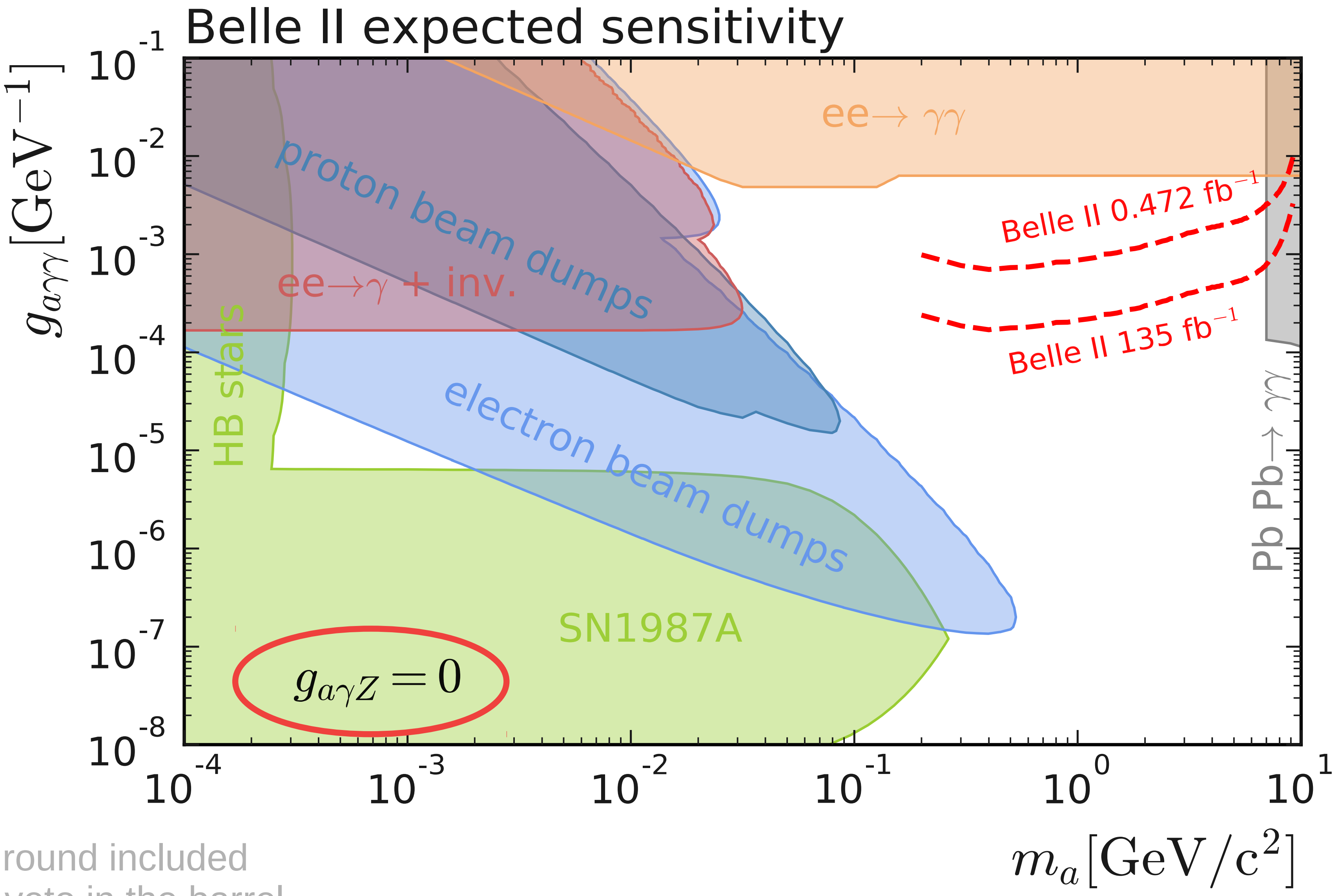
Merged:

- Two photons from ALPs are boosted: a cluster is reconstructed with one local maximum

→ **Use the same technique to reconstruct merged π^0 meson**

Axion Like Particles (ALPs)

Physics reach

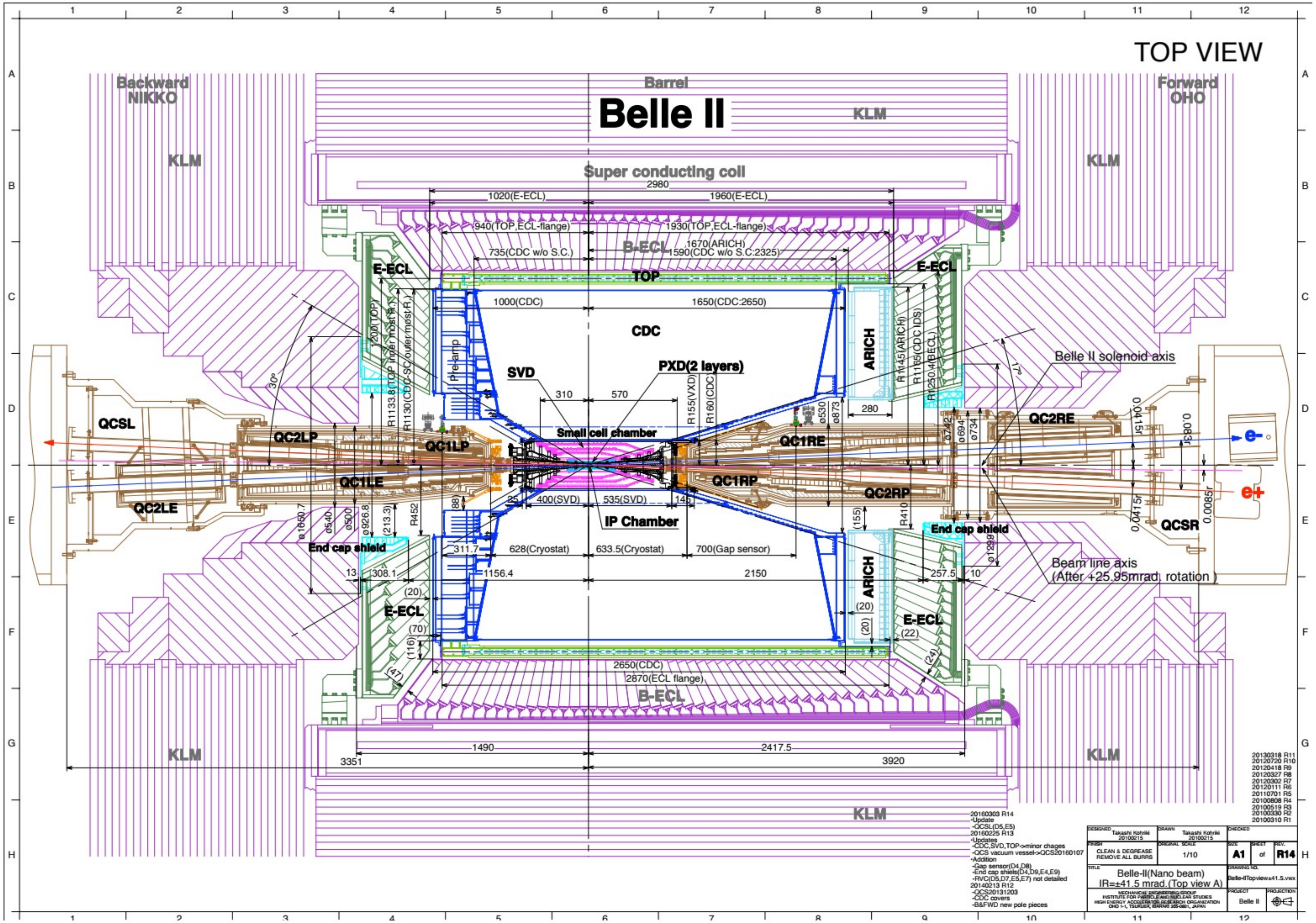


No systematics.
Only (dominant) ee→γγγ background included
135fb -1 assumes no γγ trigger veto in the barrel

Summary

- Dark sector physics at e^+e^- collider → excellent prospects even with very early data
- Only some of results are shown in this talk
- **Υ(1S) →γ invisible**: more data are needed
- **Single γ**: dark photon decaying to stable dark matter
  Can improve limits from BaBar already with 20 fb^{-1}
- **μμZ'**: L_μ - L_τ dark vector decaying to stable dark matter
  First Z' → invisible analysis with early Belle II data
- **3γ**: ALP-strahlung, experimentally clean
  Can perform analysis with *calibration* collisions data (~500 pb^{-1} 2018)
- ~ 50 ab^{-1} of Belle II data is expected to be collected ⟶ unique opportunity to study Dark Matter in the regions not covered by other experiments

Belle II



TOP VIEW
Backward NIKKO
Barrel
Belle II
Forward OHO
KLM
Super conducting coil
B-ECL
E-ECL
TOP
CDC
SVD
PXD(2 layers)
ARICH
Small cell chamber
IP Chamber
QCSL
QC2LP
QC1LP
QC1LE
QC2LE
QC2RE
QC1RE
QC1RP
QC2RP
QCSR
End cap shield
Belle II solenoid axis
Beam line axis (After +25.95mrad. rotation)
e-
e+