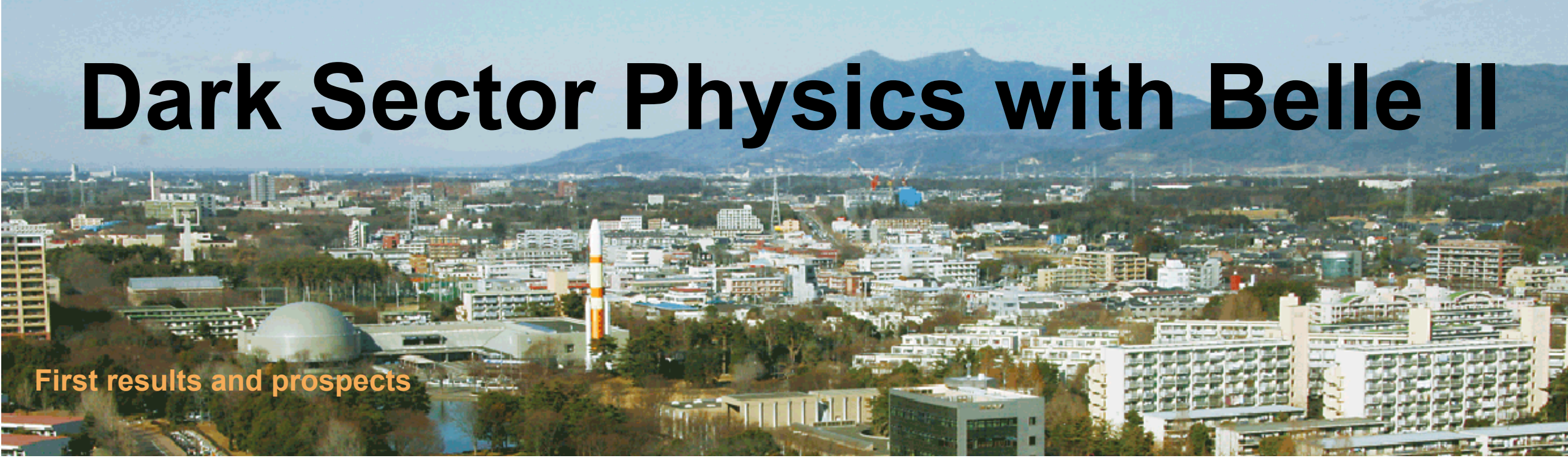
Dark Sector Physics with Belle II



First results and prospects

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8th International Conference on New Frontiers in Physics

26 Aug 2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Belle II

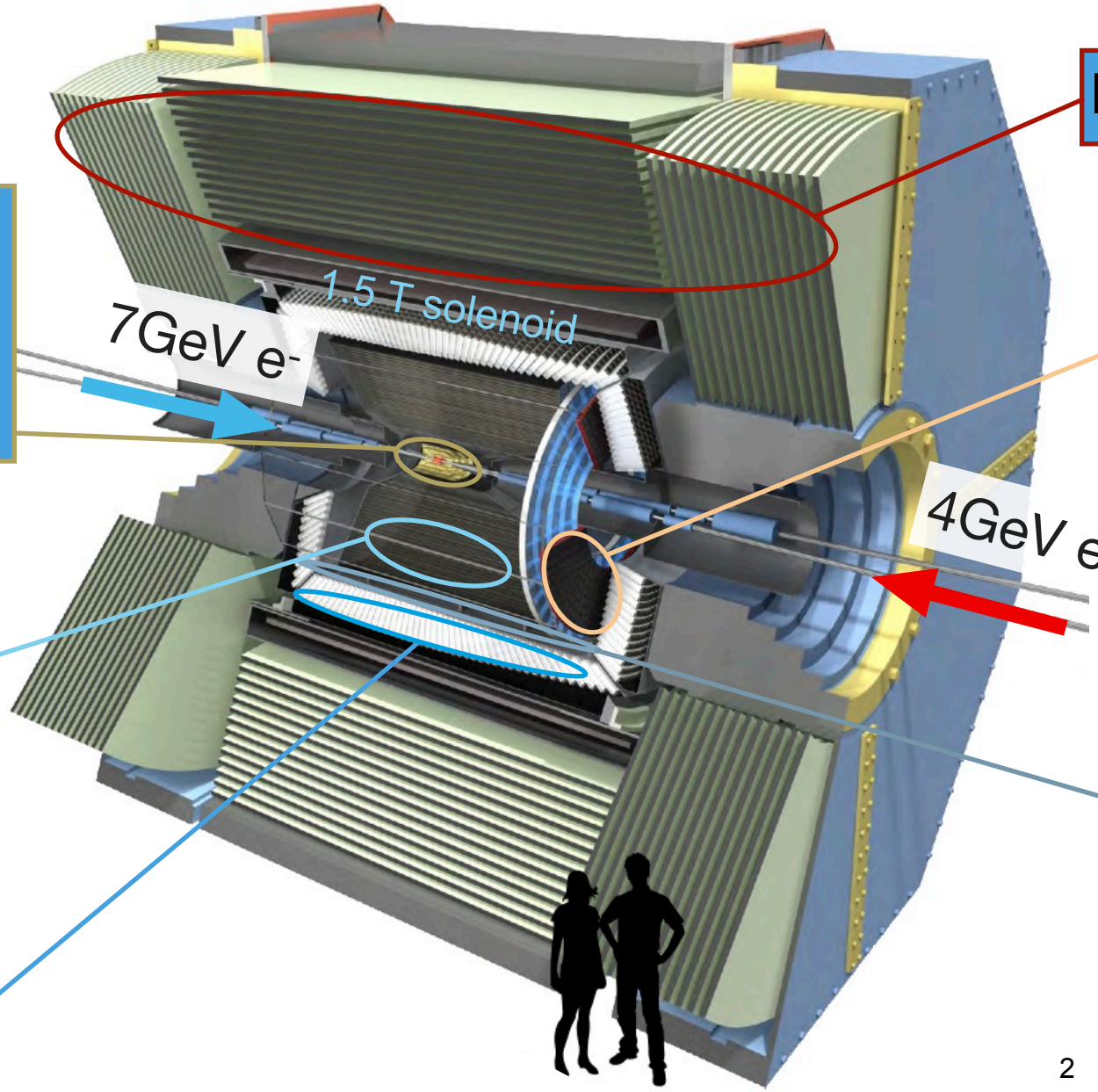
DESY.

Belle II

Vertex detector:
Pixel [PXD] and
Strip [SVD]

Drift chamber
Momentum
measurement

EM Calorimeter
Photon and
electron detection



K_L and Muon detector

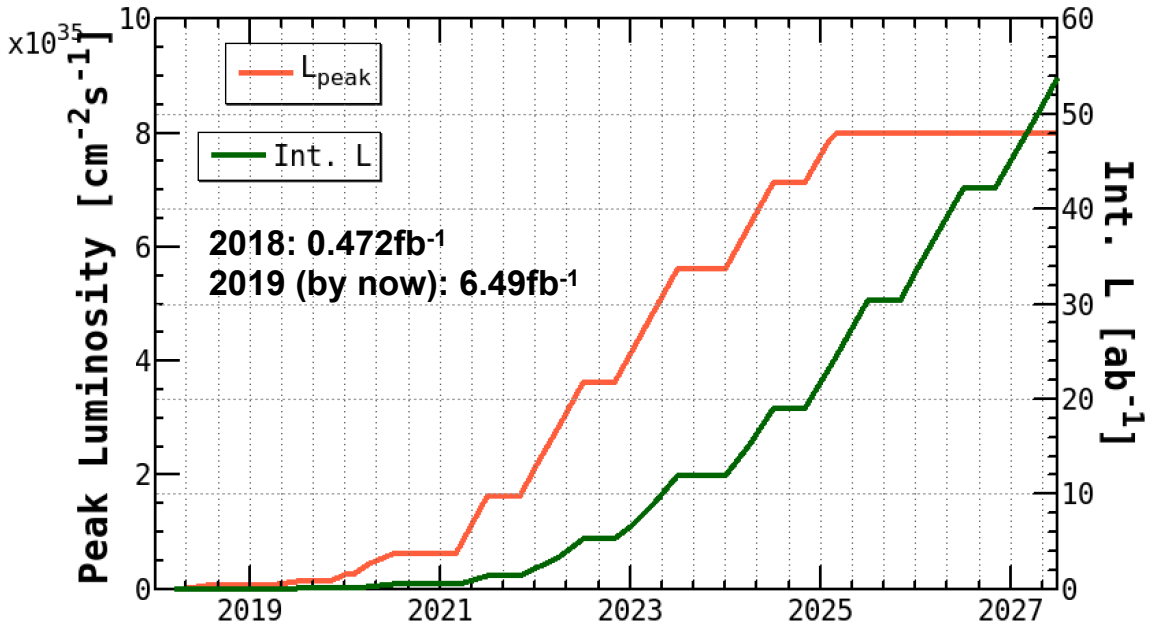
Cherenkov detector
Particle ID
(forward region)

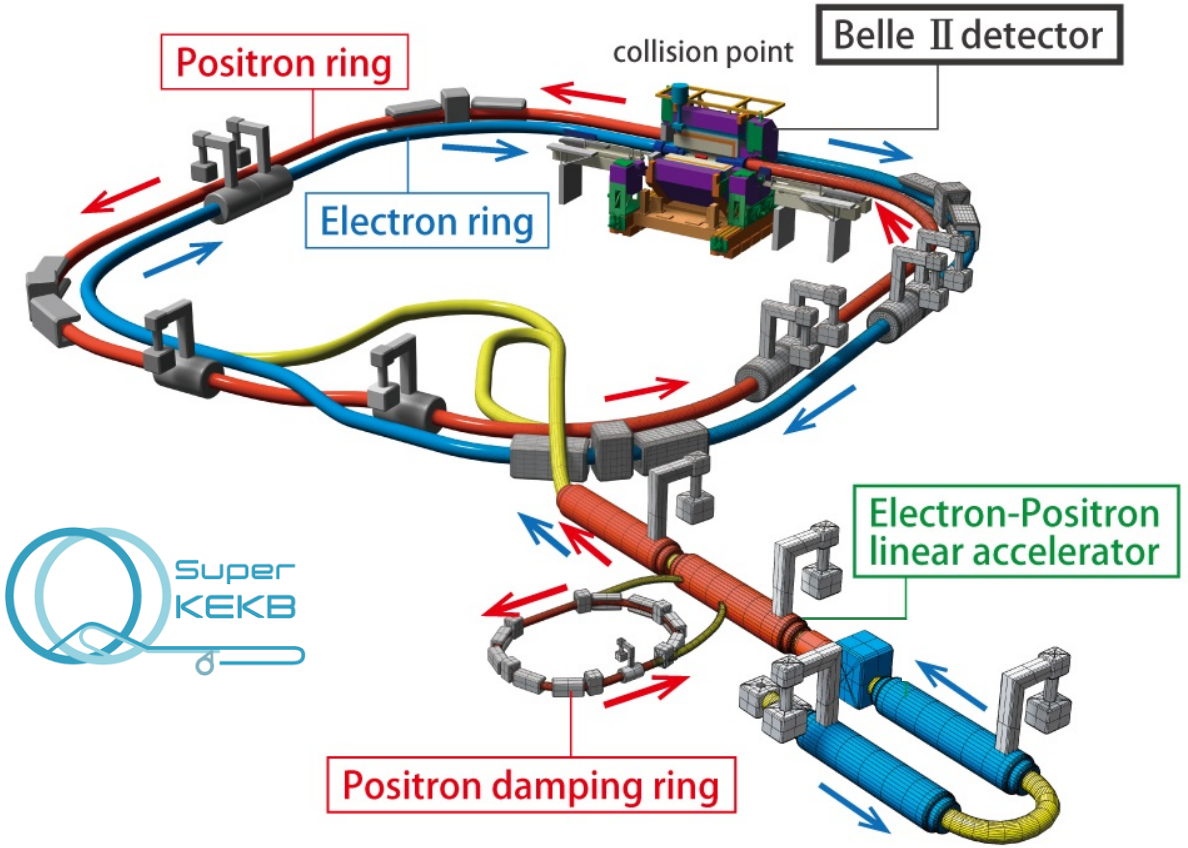
Time-Of-Propagation Counter
Particle ID
(barrel region)

SuperKEKB

e^+e^- accelerator located in Tsukuba, Japan

Built in tunnel of KEKB, but is almost entirely new machine aiming to achieve 50ab^{-1} by 2027.





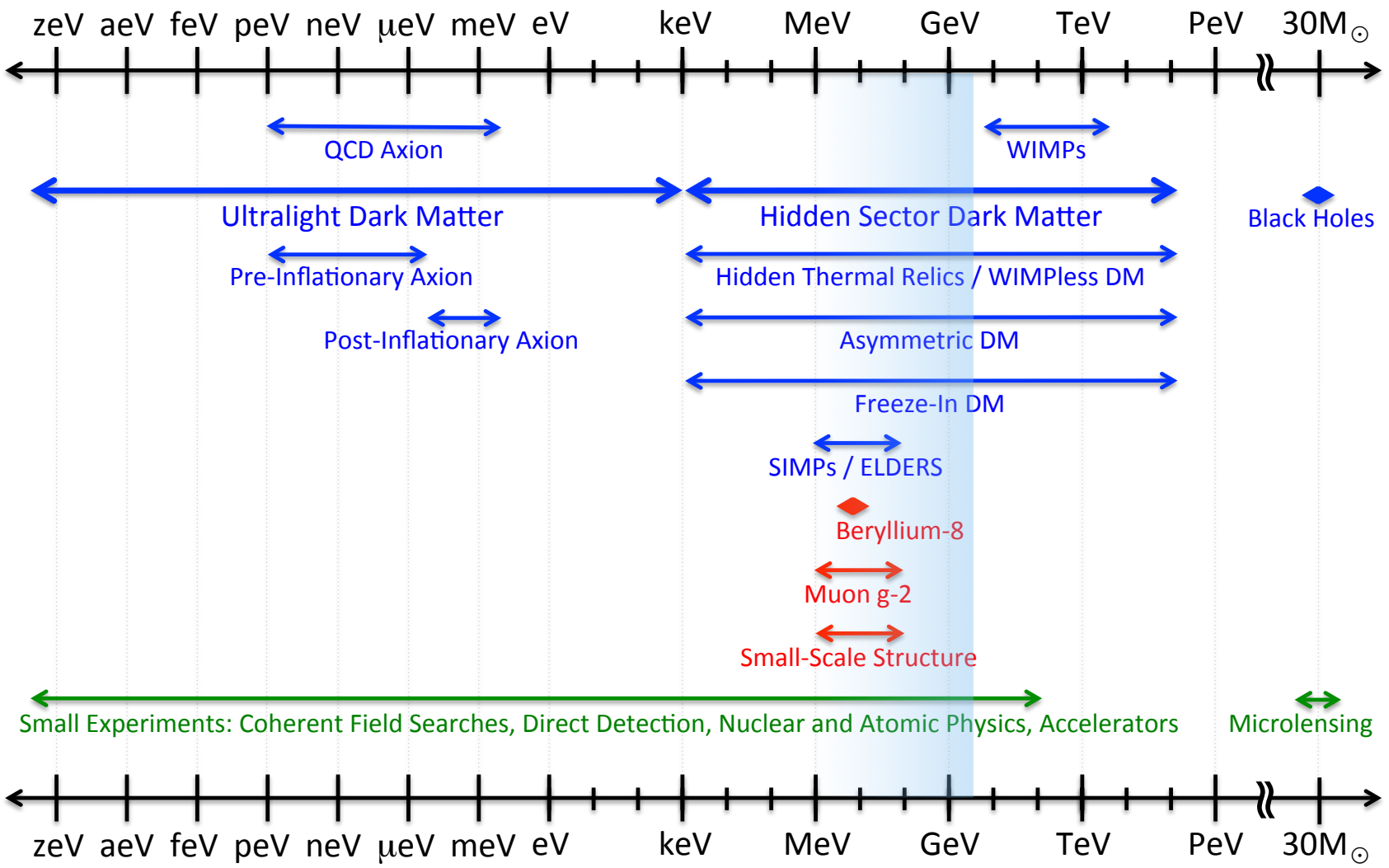
What Dark Matter?

arxiv:1707.04591

Dark Sector Candidates, Anomalies, and Search Techniques

- Belle II is sensitive up to ~10 GeV/c^2 and has mass resolution of O(10-100) MeV/c^2 *.
  *(depending on final state)

- This leave us with full hand of models *and* ***allows to cover existing anomalies***



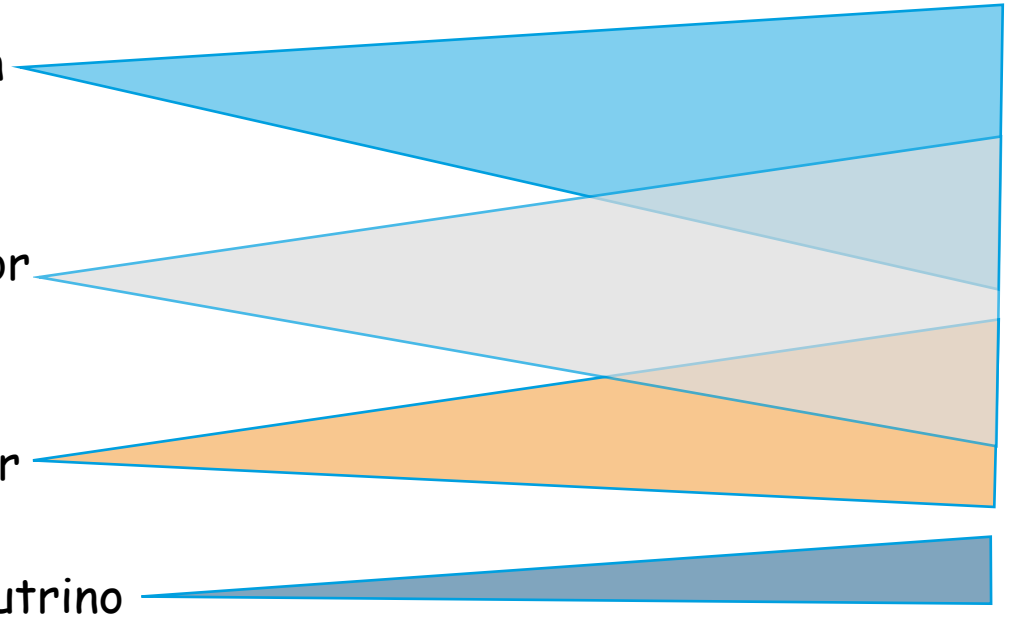
Belle II can directly test this

Make it!

Phenomenological view on DM search strategy at Belle II

Belle II is collider experiment, so we aim to detect production of the Dark Matter.
In this talk, we consider only direct DM production in e^+e^- collisions, skipping “loop production” in rare decays (These talks will become relevant in few years from now).

- From the phenomenological point of view, we can offer minimal SM extensions, that could be DM candidates by themselves or portals to dark sector:
  - New Axion
  - New Vector
  - New Scalar
  - Sterile neutrino



- Staying on purely experimental ground, we can search DM production in processes that have very distinct signatures. For example:
  - $e^+ e^- \to \gamma\gamma\gamma$
  - $e^+ e^- \to \gamma$ + Track Track (with displaced vertex)
  - $e^+ e^- \to \gamma$ + Invisible
  - $e^+ e^- \to \mu\ l(e,\mu)$ + Invisible or $\mu\ l$
  - $e^+ e^- \to \tau\ l(e,\mu,\tau)$ + Invisible or $\tau\ l$
  - $e^+ e^- \to l^+l^+l^+l^-l^-l^-$
  - $e^+ e^- \to l_1^+ l_2^-$

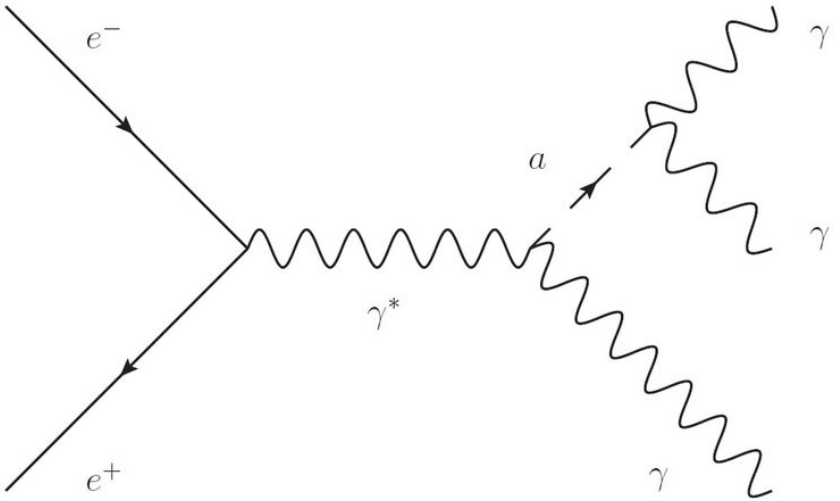
Axion-like particles

Overview

- Axion-like particles are pseudo scalars P that couple to photons*:

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

where $g_{a\gamma\gamma}$ is effective coupling



- They may also couple to fermions:

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

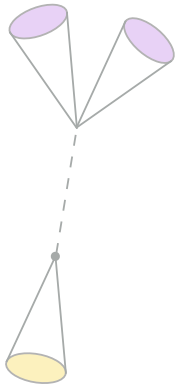
Note: no mass-coupling relation!

**They couple to other SM gauge bosons too, but we need >>1ab^{-1} to improve current limits here*

Axion-like particles

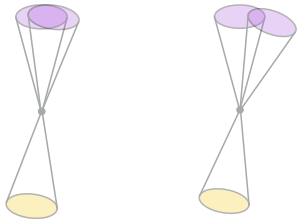
Focus of early Belle II searches

Belle II is primarily searching for ALPs coupled to photons.



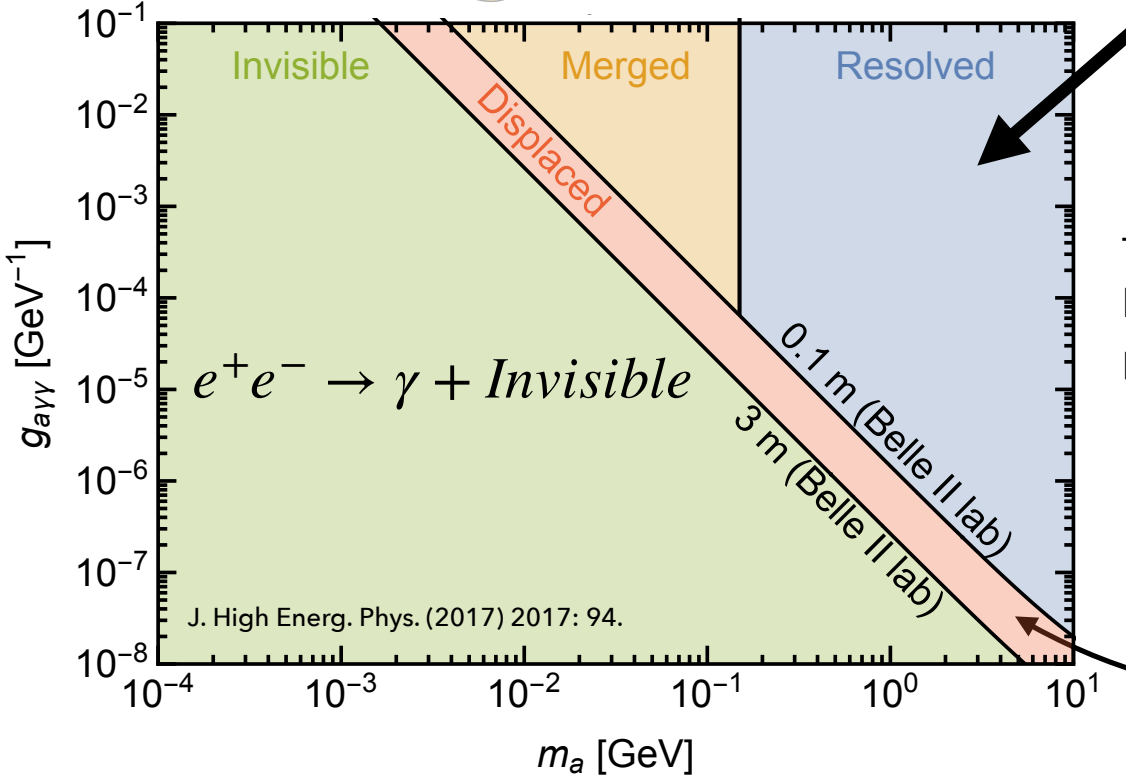
ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.

Two of the photons overlap or **merge**.

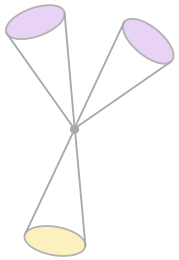


The first Belle II ALP search:

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



Three **resolved**, high energetic photons.



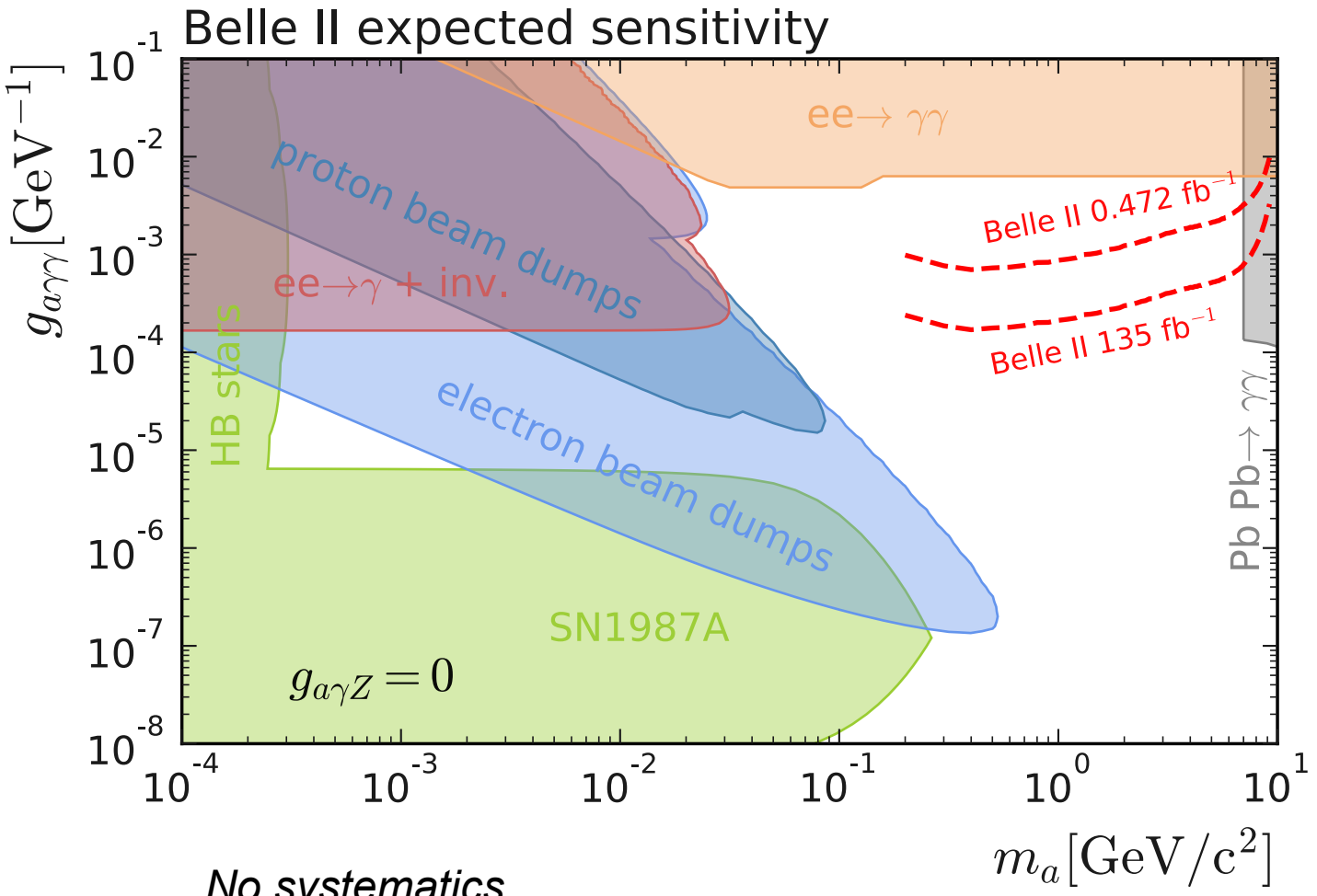
The searches for invisible and visible ALP decays veto this region.

Figure by T. Ferber

Axion-like particles

Sensitivity prospects

- Search for ALPs in $e^+ e^- \to \gamma\gamma\gamma$ is done in 0.472fb^{-1} collected last year at Belle II.
- Main analysis challenge is understanding of ECL performance.
- Analysis is under internal review.



No systematics

Only dominant ee→γγγ background included

135 fb^{-1} assumes no γγ trigger veto in the barrel

Dark photon

Overview

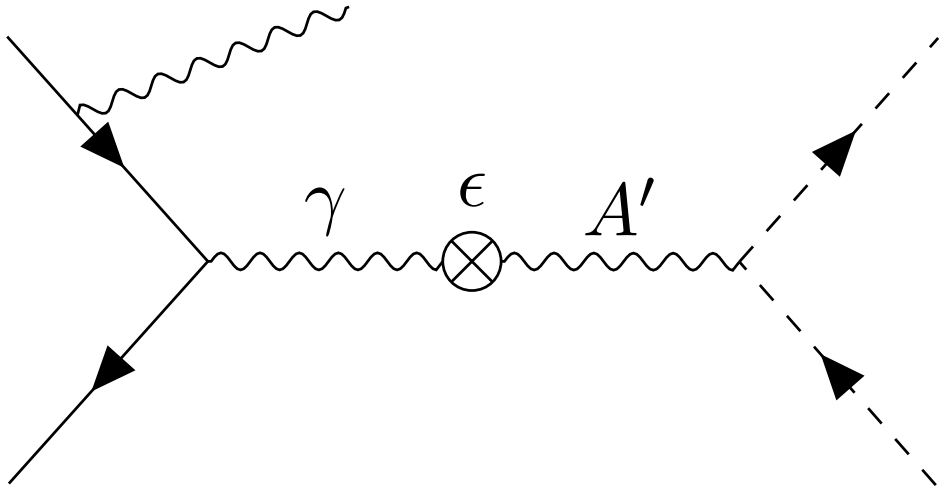
- “Dark photon" is a nickname for a new vector or pseudo-vector particle A^{μ} that couples to a SM electromagnetic current J^{μ}_{SM}:

$$\mathscr{L} \supset \epsilon A_{\mu} J^{\mu}_{\mathrm{SM}}$$

  with term “ϵ" called kinetic mixing.

- Dark photon couples to SM fermions and there are some experimental results from BaBar and Belle search is ongoing.

- Dark photon couples to DM (in some cases, A^{μ} dominantly decays to dark sector). This scenario has much looser constraints.



Dark photon

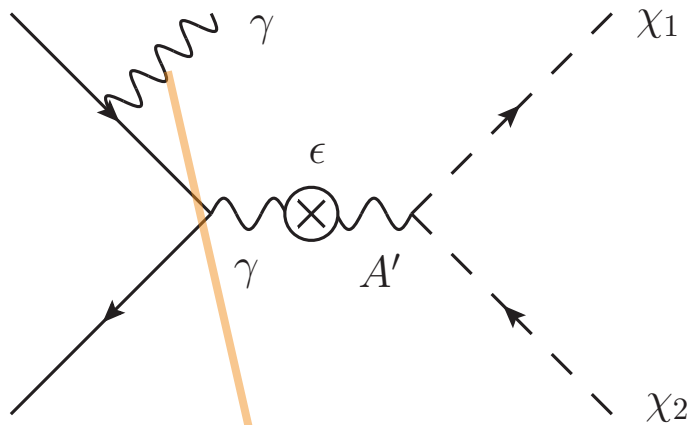
Single photon analysis

- If Dark Photon decays to DM, the signature of the process will be

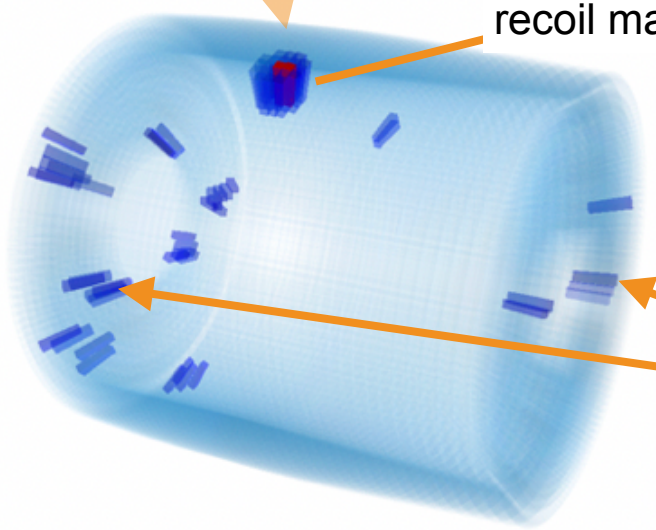
$$e^+e^- \rightarrow \gamma + Invisible$$

- Main issue in previous experiments: single photon trigger.

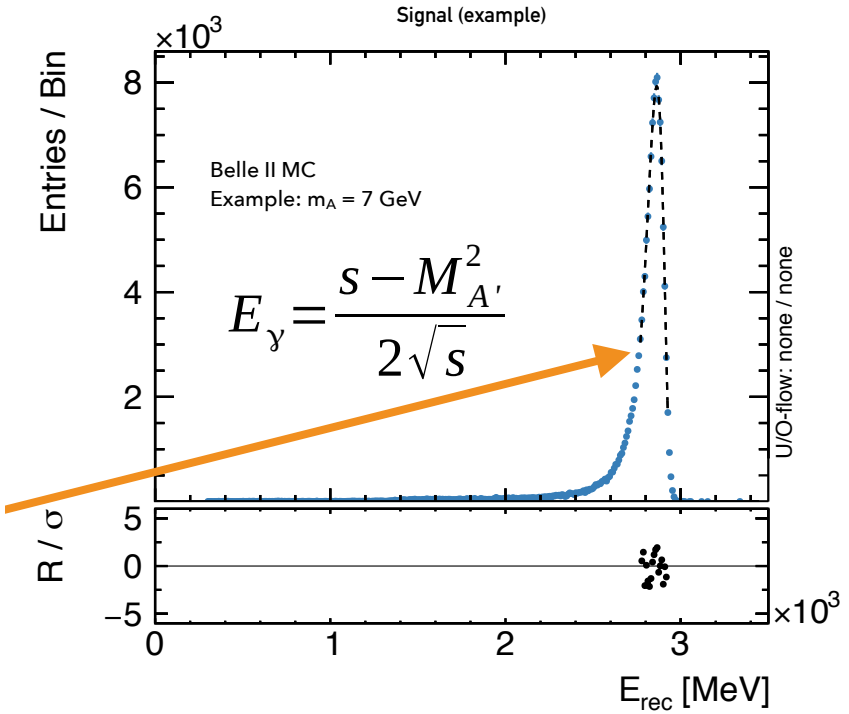
- Plenty of SM backgrounds with missing particles.



Signal photon



Peak at recoil mass

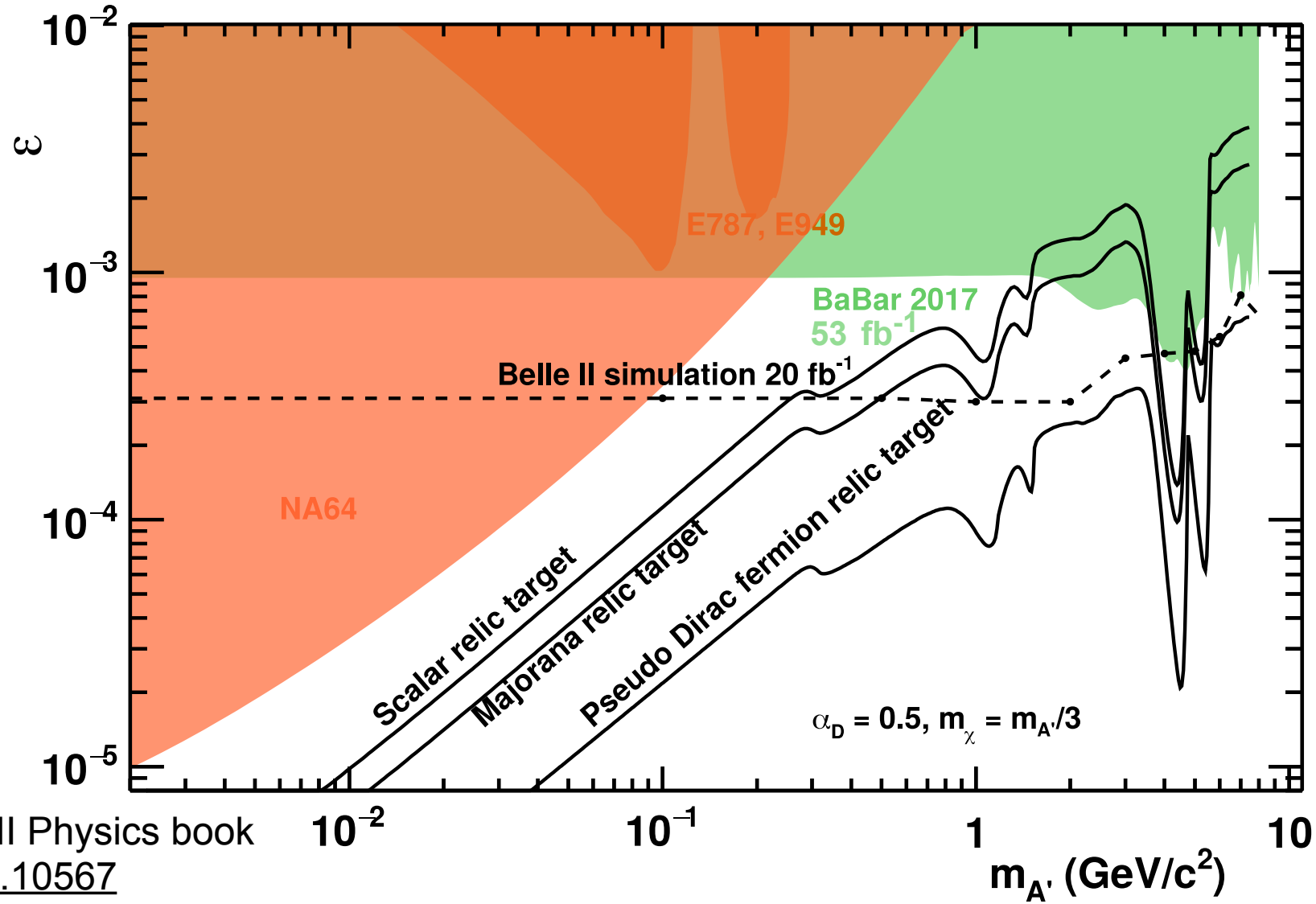


Beam background

Single photon search

Sensitivity prospects

- 2018 data are used for performance studies
- We aim to publish results with data collected this year (~20fb^{-1})
- Analysis is in progress



BaBar 2017: PRL.119.131804

NA64: arxiv:1906.00176

The Belle II Physics book arxiv:1808.10567

Vector portal

Idea

- We call Z' a new vector particle that doesn't have kinetic mixing, but couples to SM fermions:

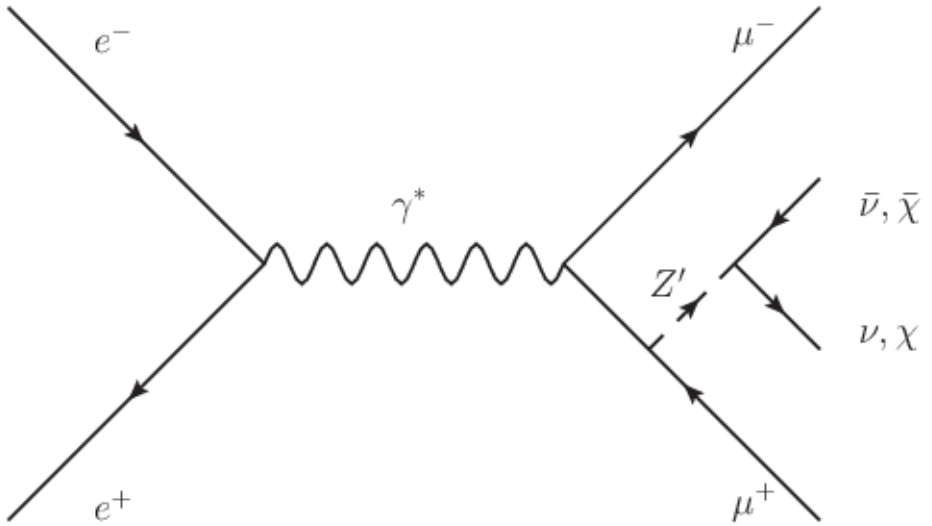
$$\mathscr{L} \supset \sum_{l} \theta g' \bar{l} \gamma^{\mu} Z'_{\mu} l$$

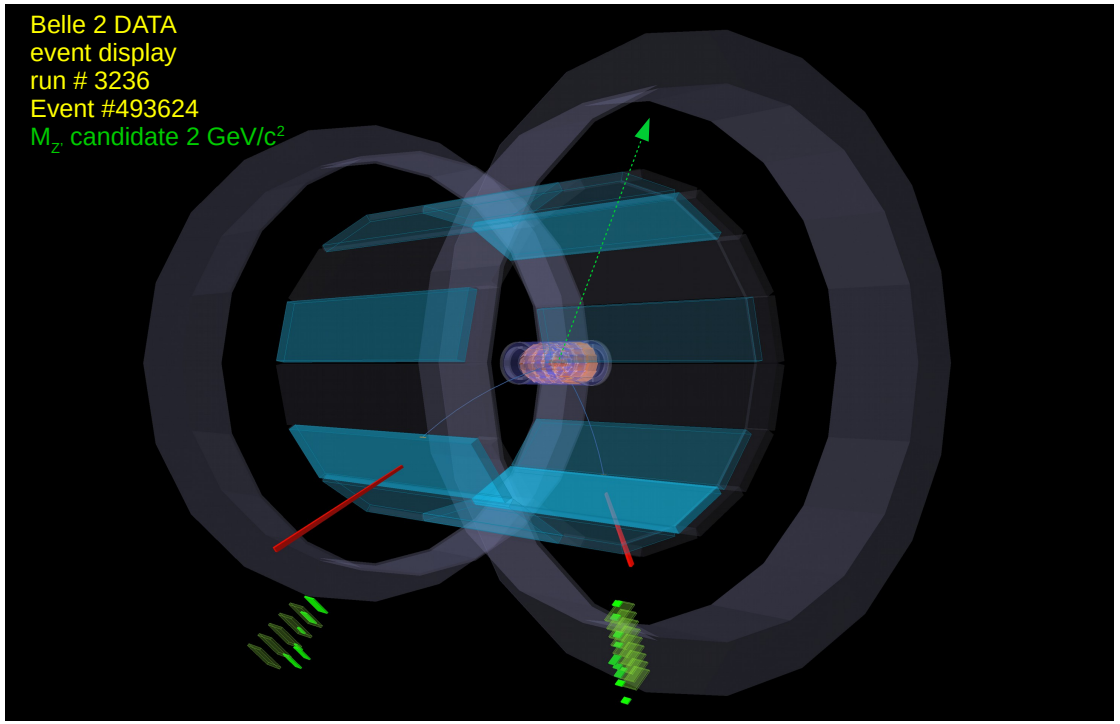
with coupling g'

- We search for Z' in

$$e^+e^- \rightarrow \mu^+\mu^- Z'(\rightarrow Invisible)$$

process.
Z' will create a bump in recoil mass of the event.

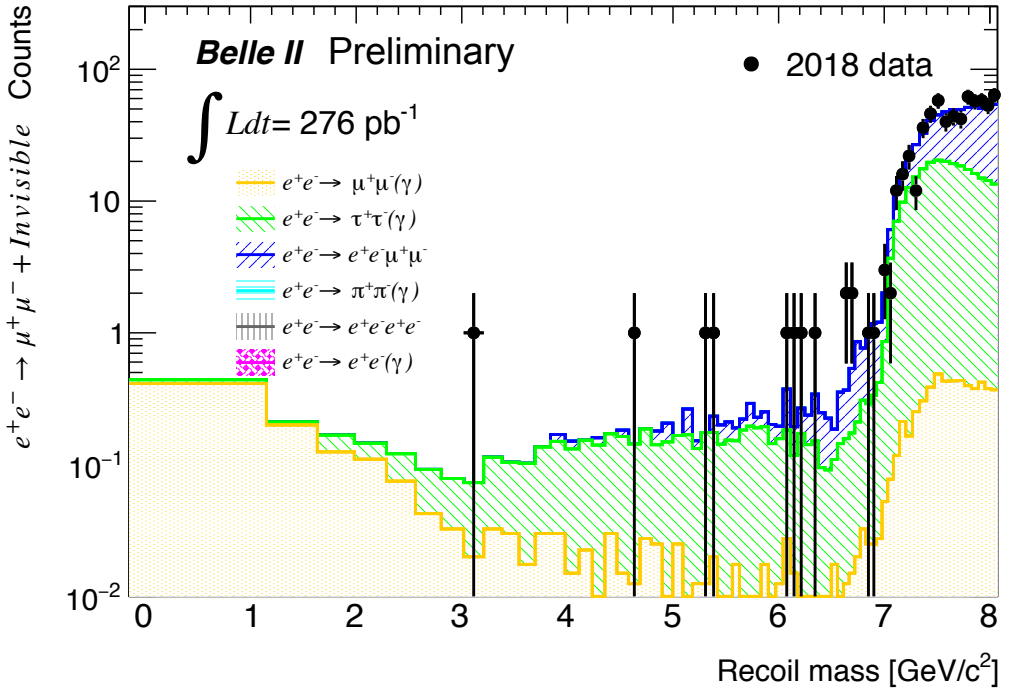




Search for Z'

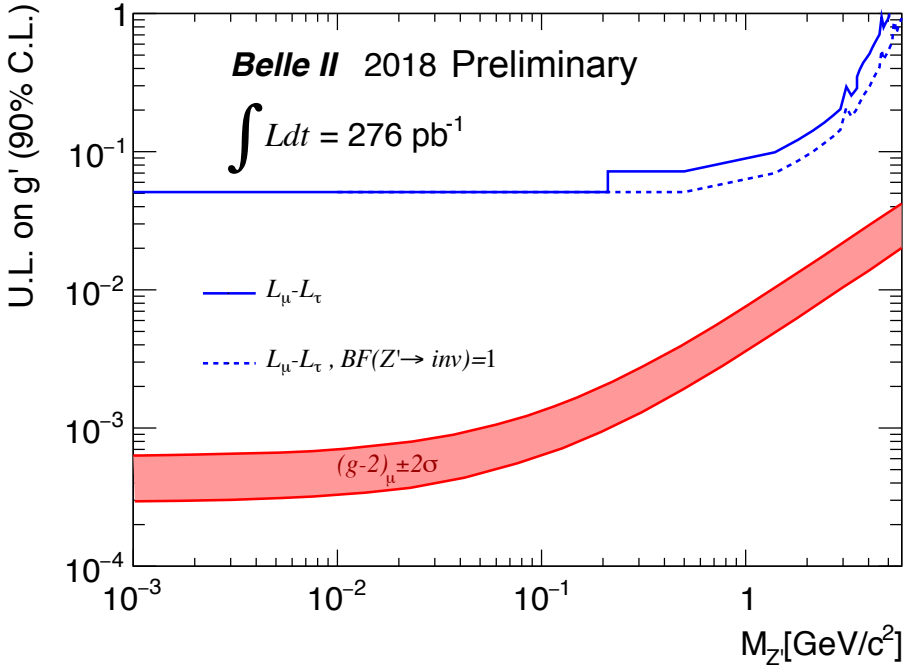
First results

- Using 2018 data, we measured cross-section of $e^+e^- \to \mu^+\mu^- Z'(\to Invisible)$ process in bins of recoil mass in the SM-suppressed region.
- We found data to be in agreement with SM and put constraints on g' in $L_\mu - L_\tau$ model.



List of systematic uncertainties

Source	$\mu\mu$
Trigger efficiency	5%
Tracking efficiency	4%
PID	4%
Luminosity	1.5%
τ suppression (background)	22%
Background before τ suppression	2%
Discrepancy in $\mu\mu$ yield (signal)	12.5%



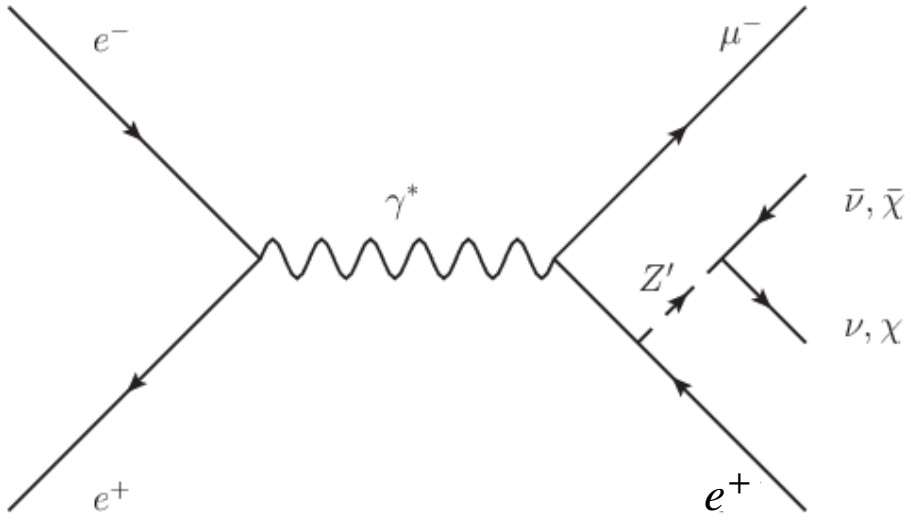
How about flavour violation?

Experiment-driven search

- If we allow for Z' to have flavour violating couplings, we can get some new signatures, that easy to check together with the "nominal" Z' search:

$$e^+e^- \rightarrow \mu^+ l^-(e,\tau)\ Z'(\rightarrow Invisible)$$

- Existing searches for LFV can only partially constrain this model (see backup).
- By now, we don't have working model for this. Theory input is needed.
- If lost energy is 0, this is cross-section measurement of $e^+e^- \rightarrow e^+ l^-(\mu,\tau)$. Could be sensitive to **sterile neutrinos** described in [*]!

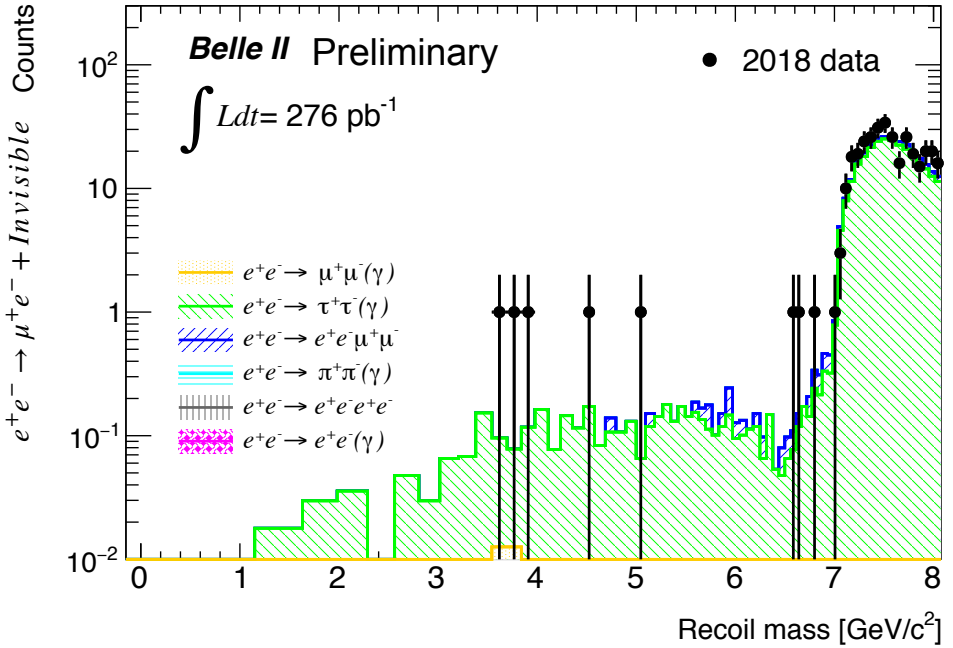


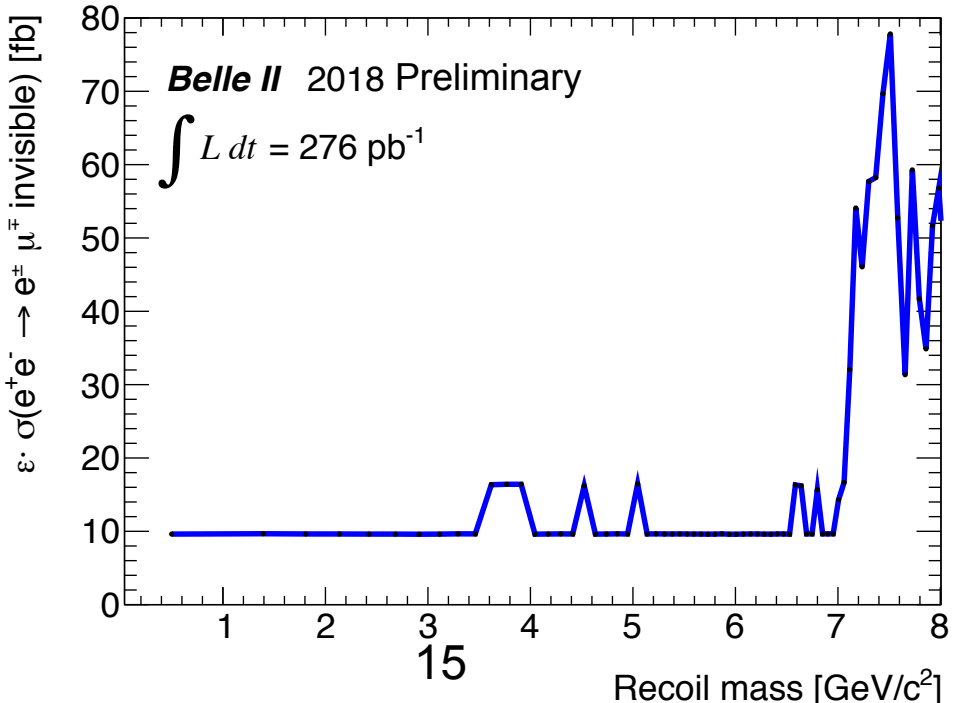
*JHEP 1504 (2015) 051; JHEP 1602 (2016) 083

LFV Z'

First results

- Using 2018 data, we measured cross-section of $e^+e^- \to e^+\mu^- Z'(\to Invisible)$ process in bins of recoil mass in the SM-suppressed region.
- Without working model to test, we sticked to model-independent approach and made an effort for our results to be valuable for theorists:
  - We used kinematic selection from flavour-conserving scenario.
  - Selection is done cutting on kinematic variables (though we used MVA to identify those that would have highest impact)
  - We studied detector performance and included its variations to the systematics.

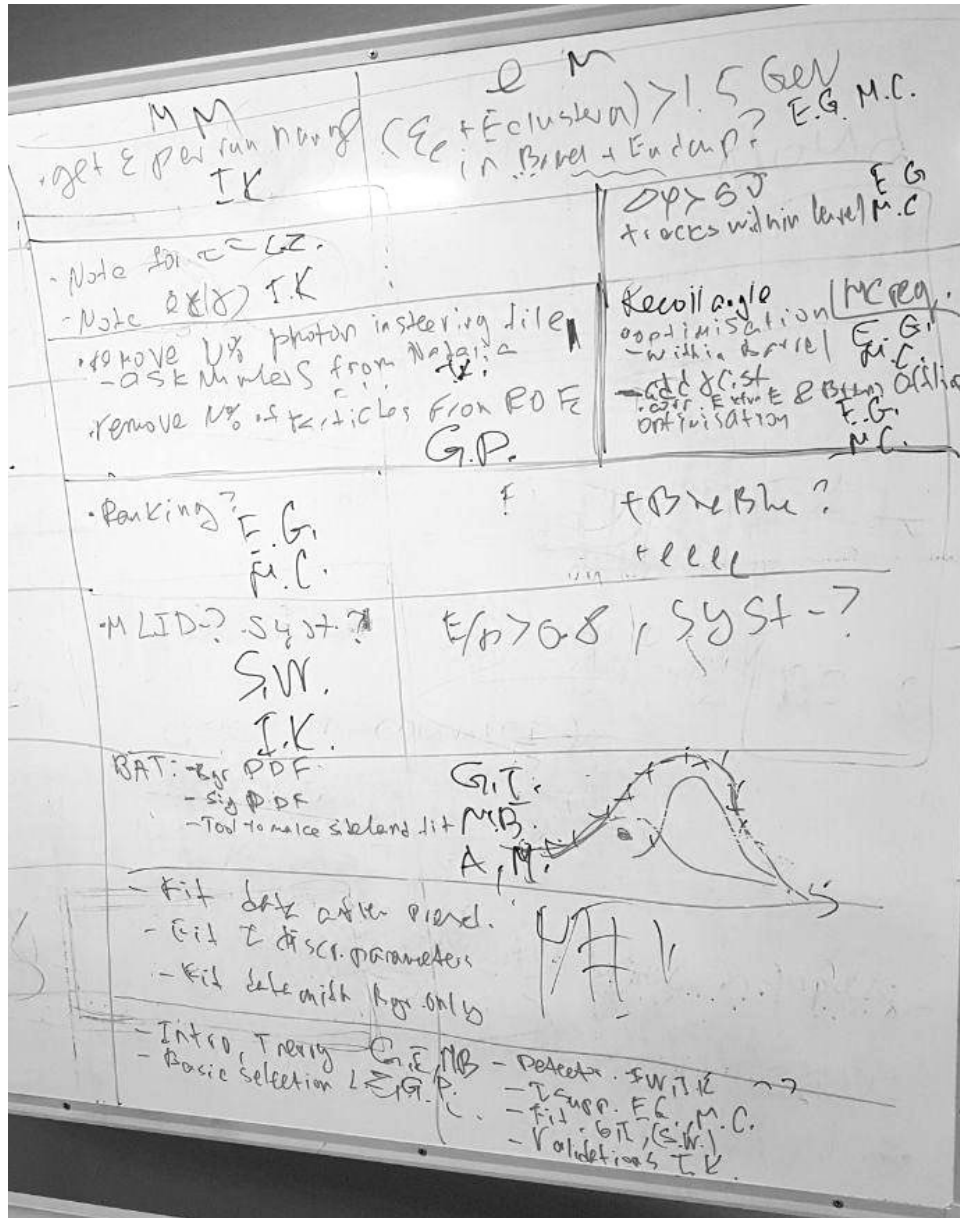




Conclusions

Shedding light to the dark sector since 2019

- Belle II started to collect data last year, and the first results are coming:
  - Search for ALPs in $e^+e^- \to \gamma\gamma\gamma$ process: publication in preparation.
  - Search for Z' (LFC and LFV modes): preliminary results are out, aiming for publication.
  - 2018 dataset was used for background studies of single photon search; physics results are expected early 2020.
- More analyses are coming with data.
- We have ideas of measurements that has never been done before. Theory/phenomenology input is welcome!

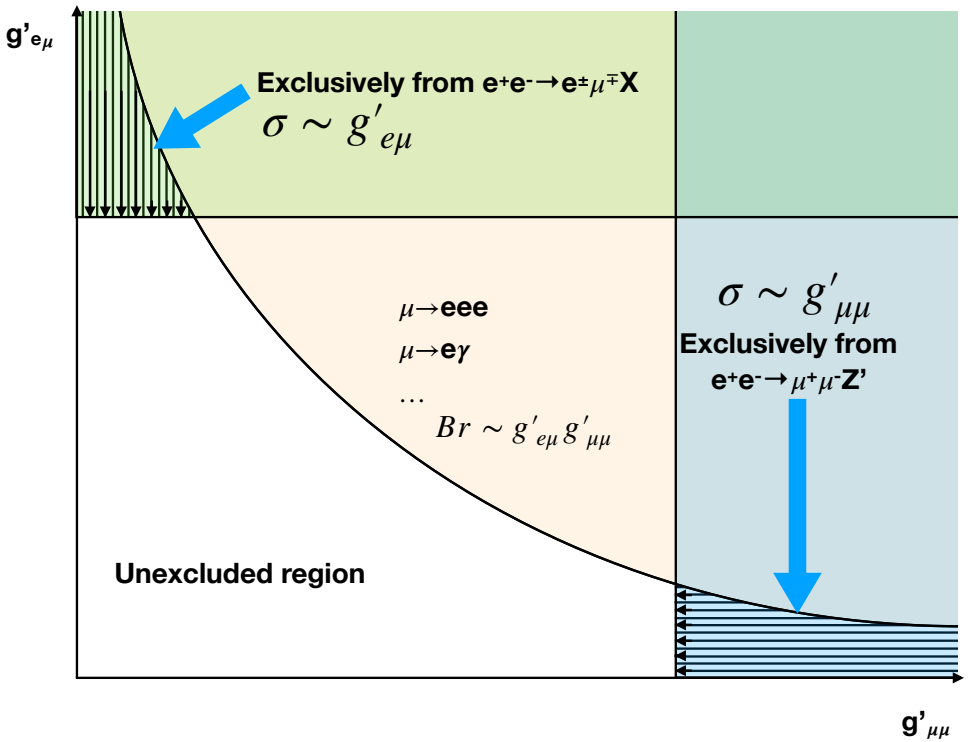


Thank you

Q: Aren't LFV modes ruled out?

A: Not really.

- LFV is currently searched in processes like $\mu \to eee$, $\mu \to e\gamma$, $\mu \to e$ conversion etc.
- If there is new LFV mediator, it would contribute there through loop diagram, i.e. branching would be proportiona to product of flavour conserving and flavour-violating couplings, eg. $g_{e\mu} \times g_{mumu}$.
- If we assume that coupling of the new particle to the dark sector is $\mathcal{O}(1)$, our cross-section will be proportional to flavour violating OR flavour conserving couplings.



Parameter space doodle indicating sensitivity regions for constraints of vector particle having $g'_{e\mu}$ and $g'_{\mu\mu}$ couplings.

Contact

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