# Belle II dark-sector physics: status and future plans.

Sam Cunliffe
Belle II DE, 14.09.2020

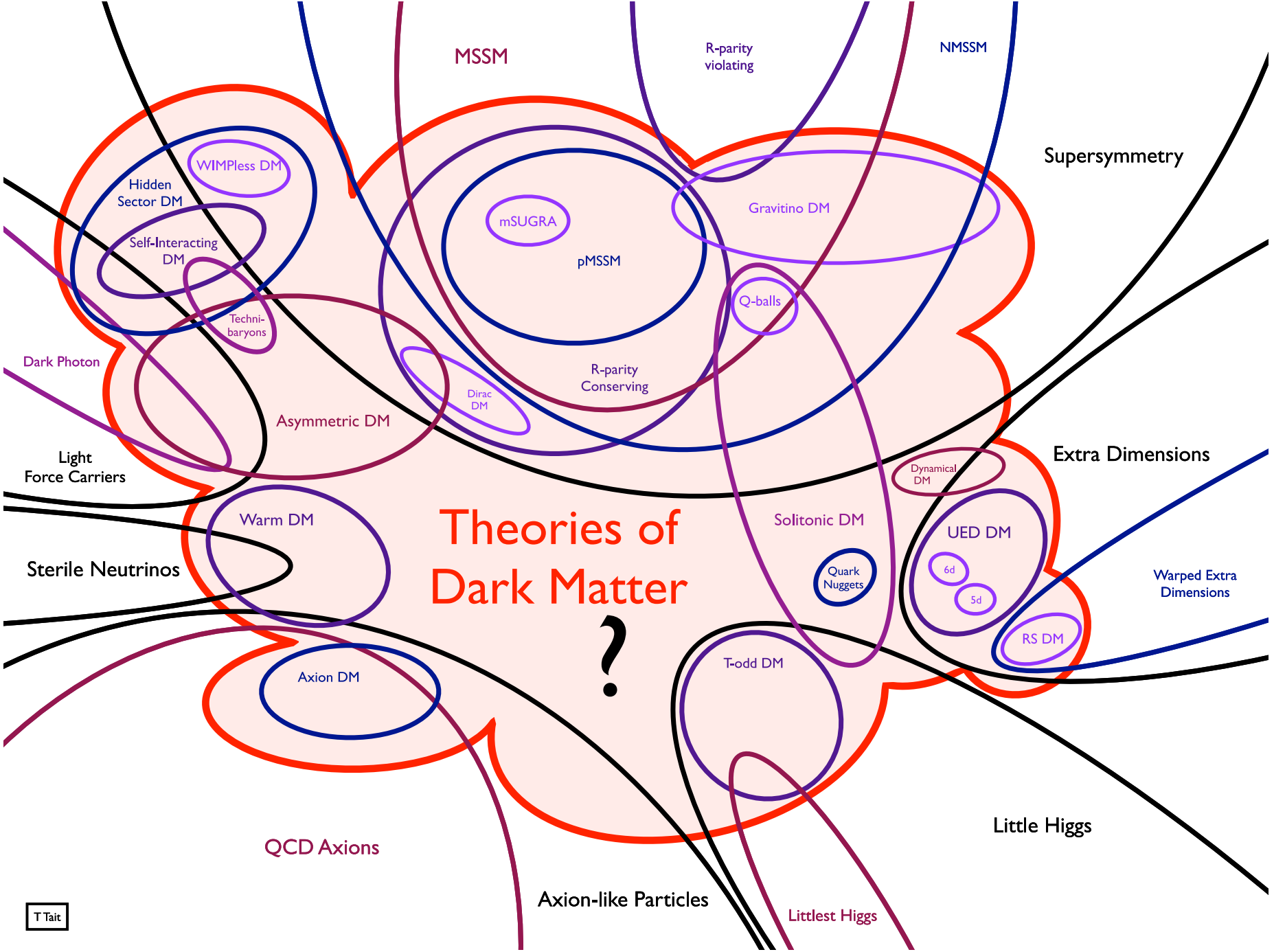
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

# The problem of dark matter

- It’s dark.
- It exists.

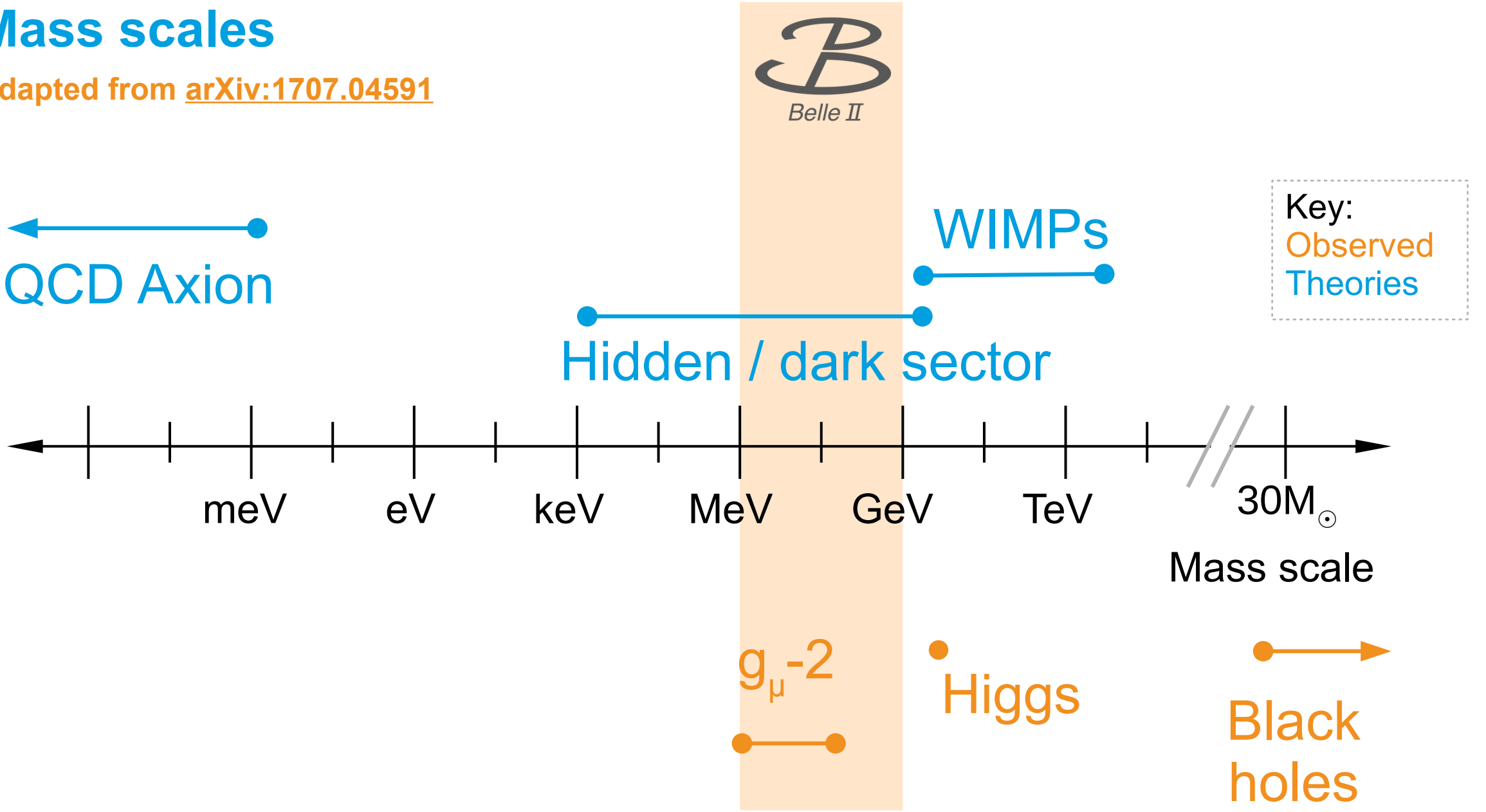
# Plenty of ideas

Feng, et al.
arXiv:1401.6085

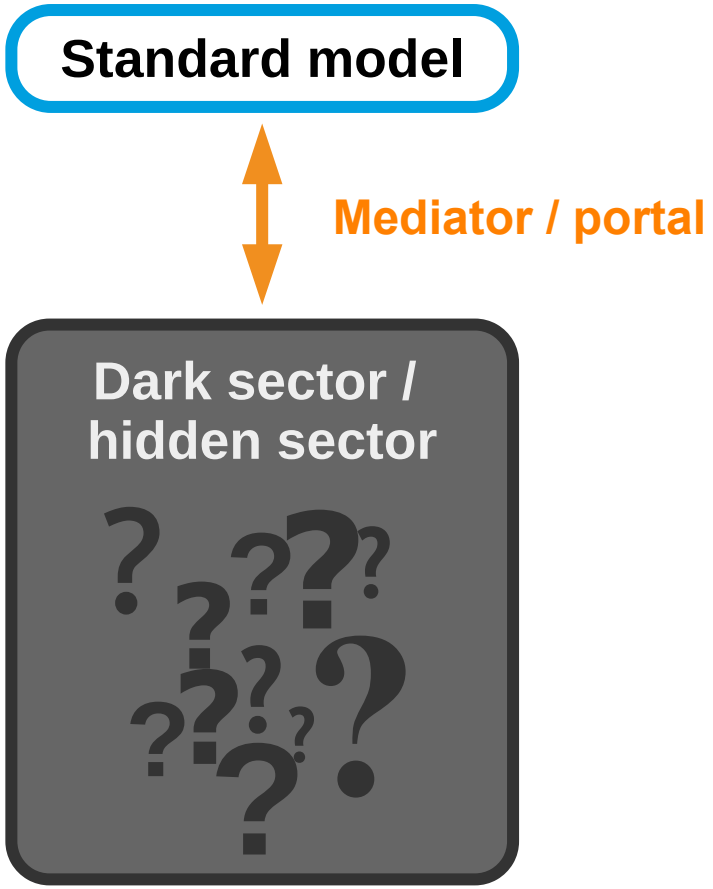


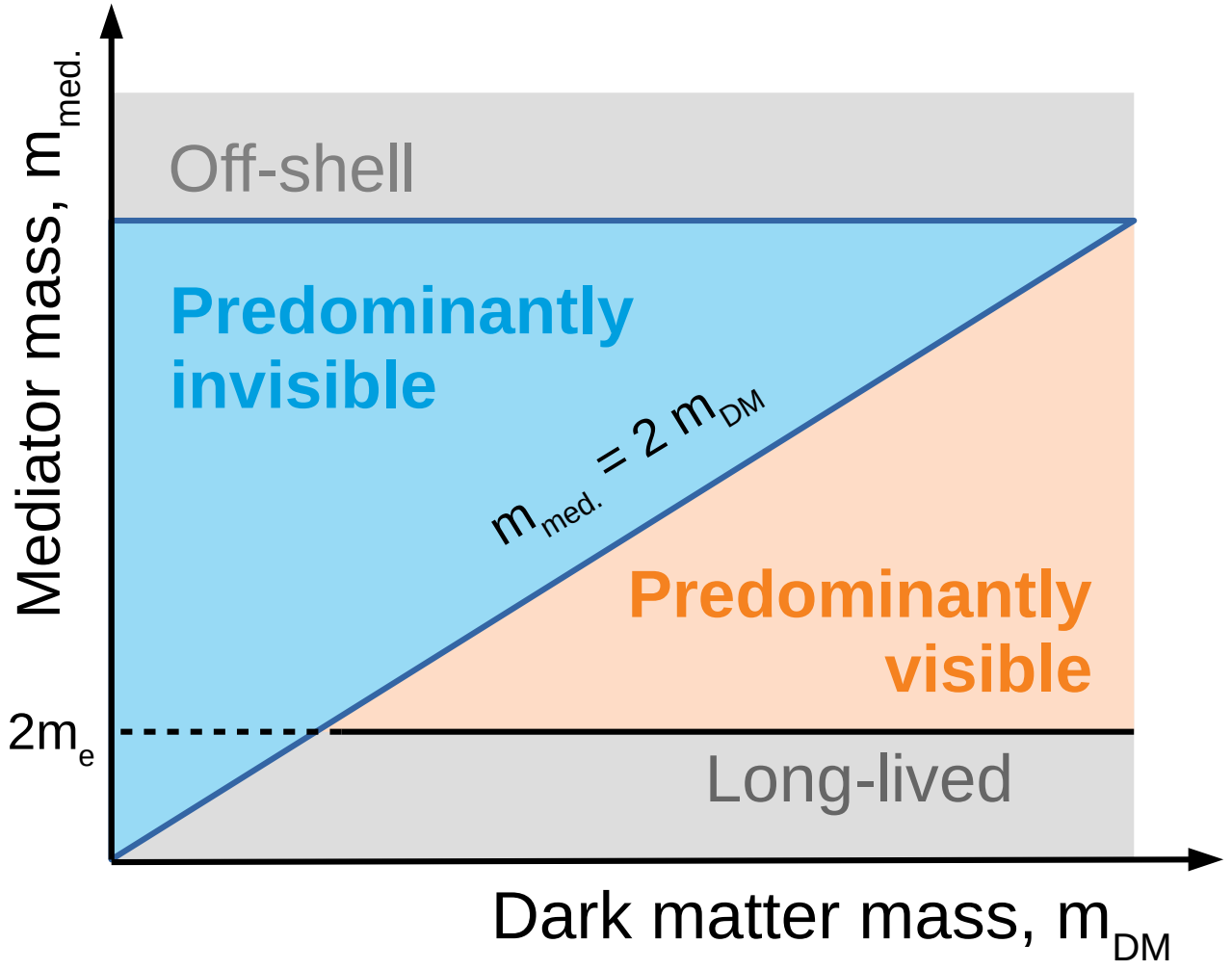
# Mass scales

**Adapted from arXiv:1707.04591**



# What is the dark sector?



# tl;dr

## Three bullets summary

- What if dark matter isn't WIMPs?
- Maybe: ***dark sector*** which doesn't interact directly but via a ***mediator***.
  - So (typically) add two new particles: dark matter, and mediator.
  - ...and (minimally) a 2D mass-coupling-space where we search.
- We could have a richer dark sector…

# Dark-sector working group @ Belle II

## What?

- Historically joined with “low-multiplicity” physics group, ∴ “dark low-multiplicity” channels form our core.
  - Triggers and skims are **important**. Unlike for B physics.
- Of course, B and ϒ decays with DM / invisible final states will come .

## Who?

- We have a strong  European participation.





- Some nomads from other groups: Nagoya, Virginia Tech, Melbourne, …
- Currently distinct and separate from the equivalent Belle 1 group.

# We have a lot of things planned

## Don’t worry, we don’t need to discuss *all* of these

- ee → μμ Z’; { Z’ → inv. | Z’ → ℓℓ | Z’ → 4μ }
- ee → μe Z’; { Z’ → inv. | Z’ → ℓℓ }
- ee → γ A’; { A’ → inv. | A’ → ℓℓ }
- ee → { γ a | ee a };  a → γγ
- ee → h’ A’; A’ → ℓℓ
- b → s { h’ | a }
- b → s inv. (interpretation of a b-physics golden channel B → $K^{(*)}$νν).
- Υ(1S) → { inv. | γ + inv. }
- ee → γ + DM; DM → A + inv.; A’ → { ee | μμ | ππ }; “Inelastic dark matter”.
- Dark QCD final states.
- Long lived ( & very ) long lived particles: generic displaced vertices.
- ee → $e^{\pm}e^{\pm}\mu^{\mp}\mu^{\mp}$
- ee → τℓ
- ee → { μe | μτ } + missing

# We have a lot of things planned

## 6 ± 1 select topics for today

Key.
**Bold**: mentioned in this talk.
Green: in Torben's talk

- **ee → μμ Z'**; { **Z' → inv.** | Z' → ℓℓ | Z' → 4μ }
- **ee → μe Z'**; { **Z' → inv.** | Z' → ℓℓ }
- **ee → γ A'**; { **A' → inv.** | A' → ℓℓ }
- **ee →** { **γ a** | ee a }; **a → γγ**
- **ee → h' A'; A' → ℓℓ**
- **b → s { h' | a }**
- b → s inv. (interpretation of a b-physics golden channel B → $K^{(*)}$νν).
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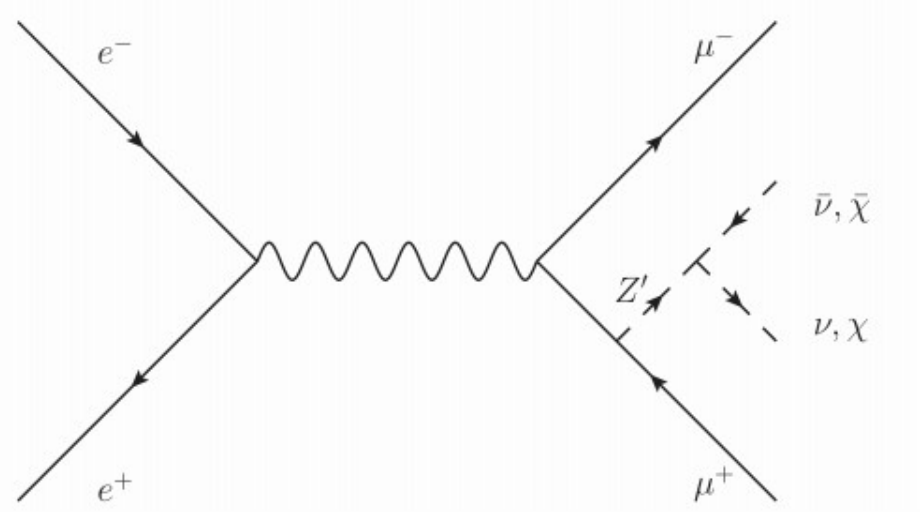
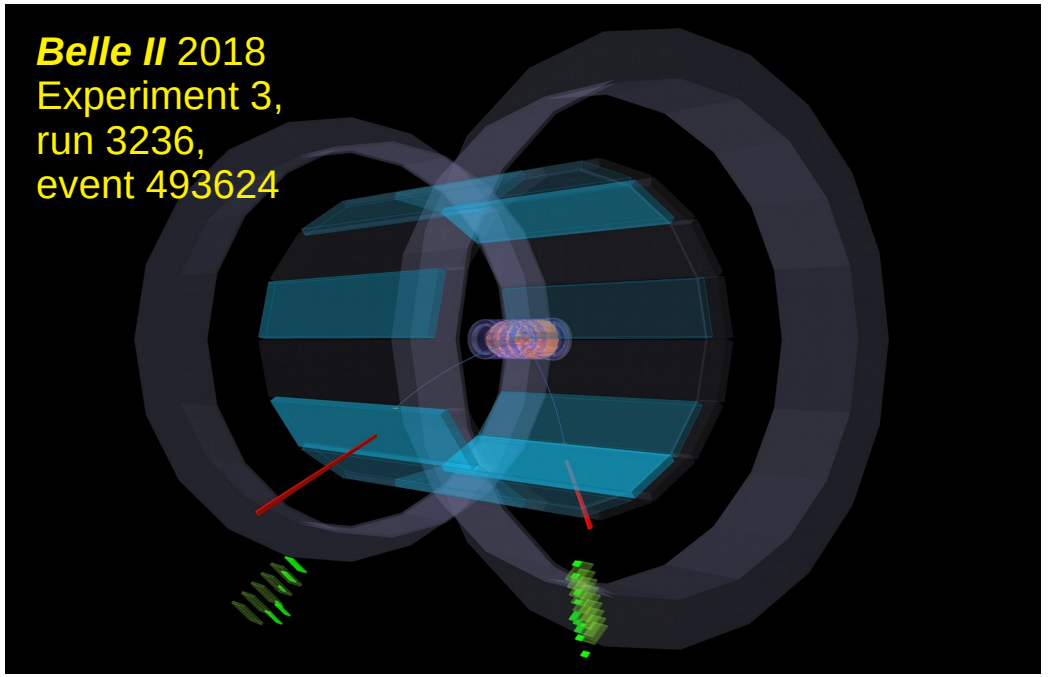
# Status

# ee → μμZ’ and ee → μeZ’

PhysRevLett.124.141801



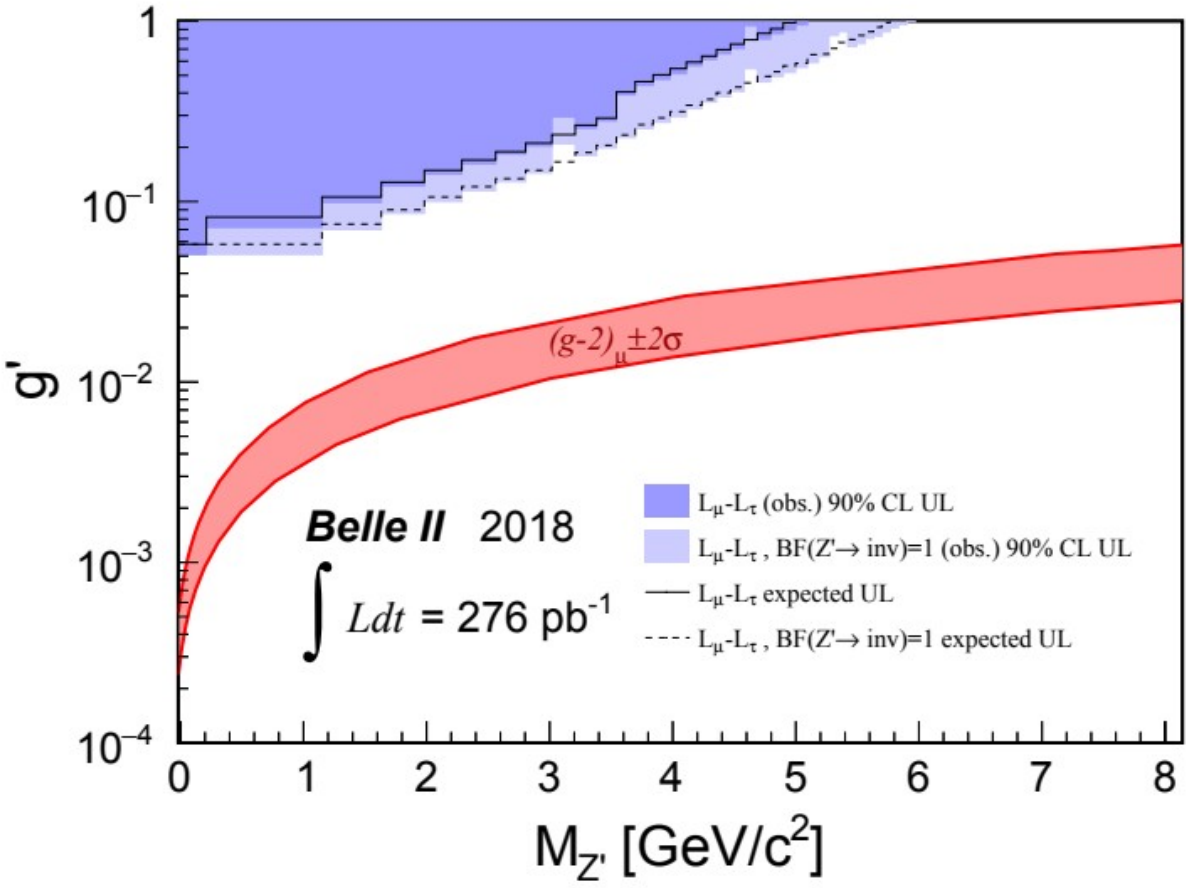

- First “real” published physics paper.
- World-leading search for $L_\mu$-$L_\tau$ and LFV Z’.
- Analysis:
  - Search for 2 tracks with e/μ -like calorimeter clusters + missing energy.
  - Nothing else in event (above beam background).
  - Bump hunt in recoil mass.



# Z' results

PhysRevLett.124.141801

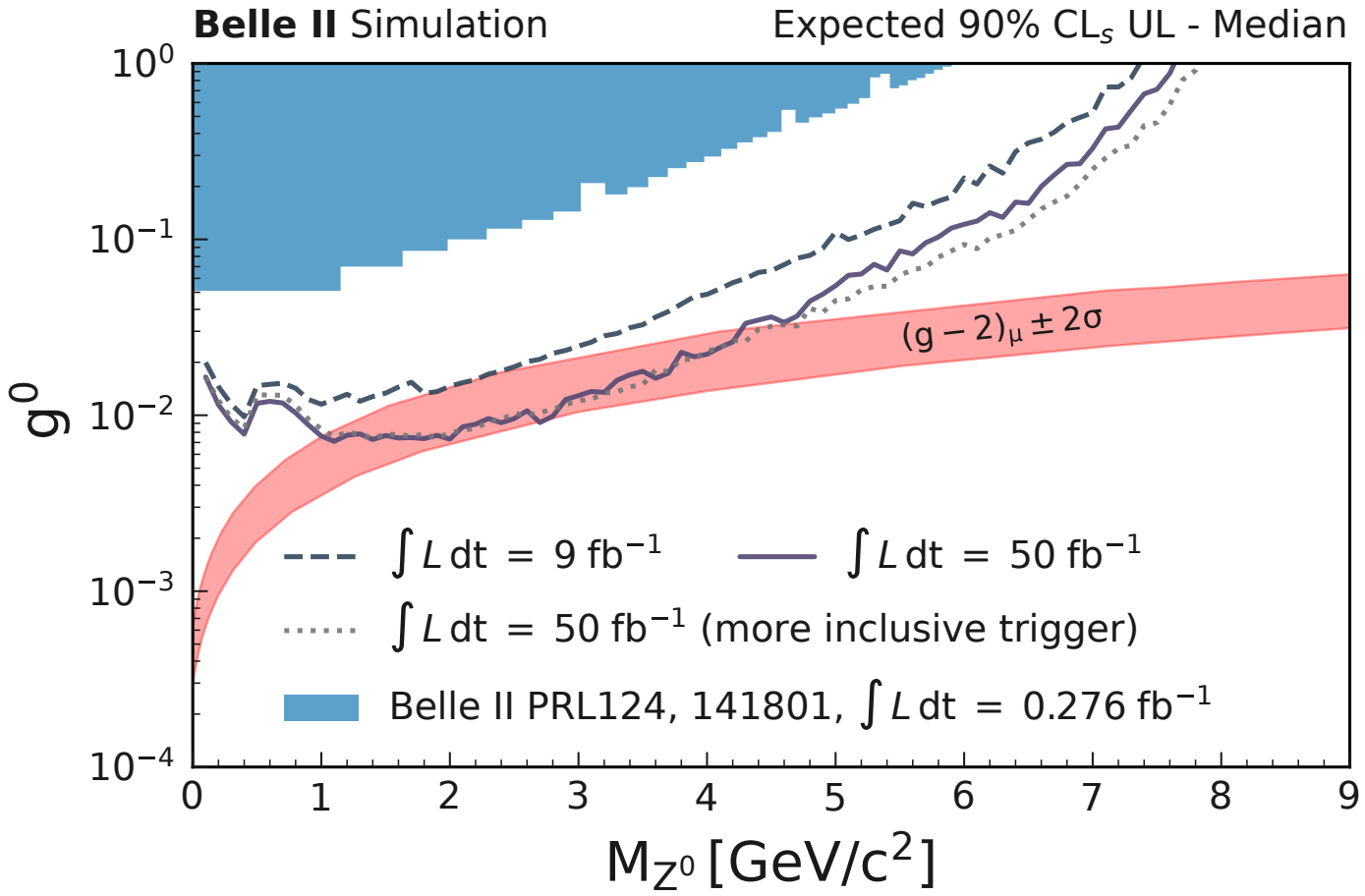
- Set limits in Z' coupling vs. Z' mass.
- For LFV mode: simply set limits on product of efficiency and cross section: ϵ×σ (no theory model at time of publication).
- Update underway with 2019+20 data.
  - ~300 $pb^{-1}$ → ~50 $fb^{-1}$.



# Z' prospects

**We now have more data!**

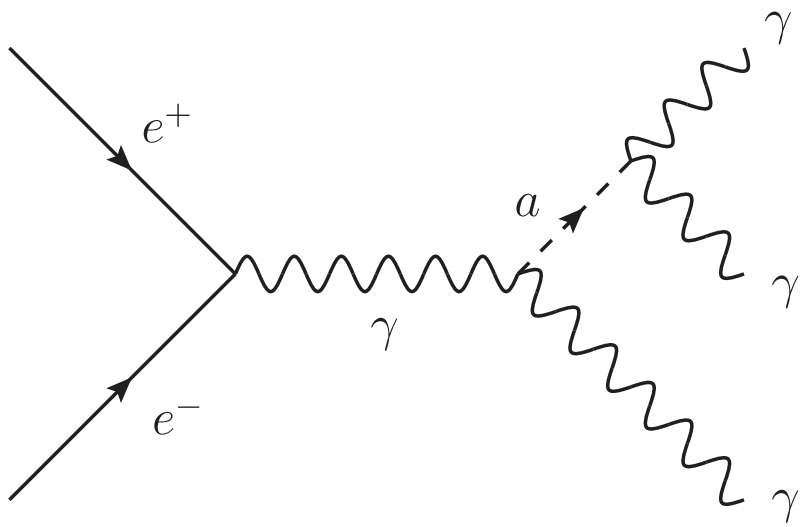
**BELLE2-NOTE-PL-2020-012**

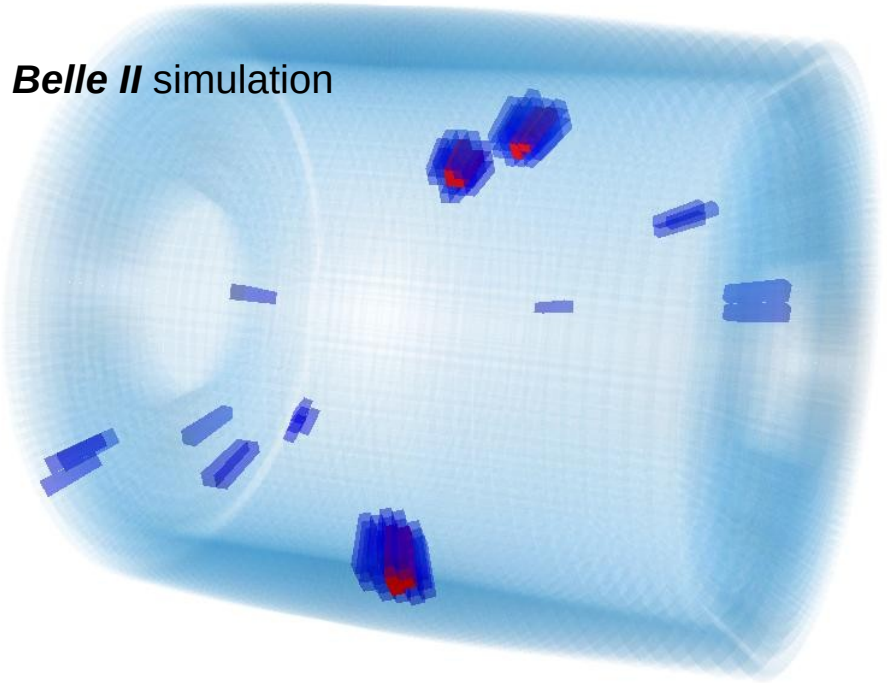


# Axion-like particle

arXiv:2007.13071 *submitted to PRL*

- Second “real” physics paper.
- World-leading direct search an ALP, a → γγ
- Analysis:
  - Search for ALPsstrahlung production process (ee → γa → 3γ final state).
  - Nothing else in event (above beam background).
  - Bump-hunt in γγ/recoil mass.



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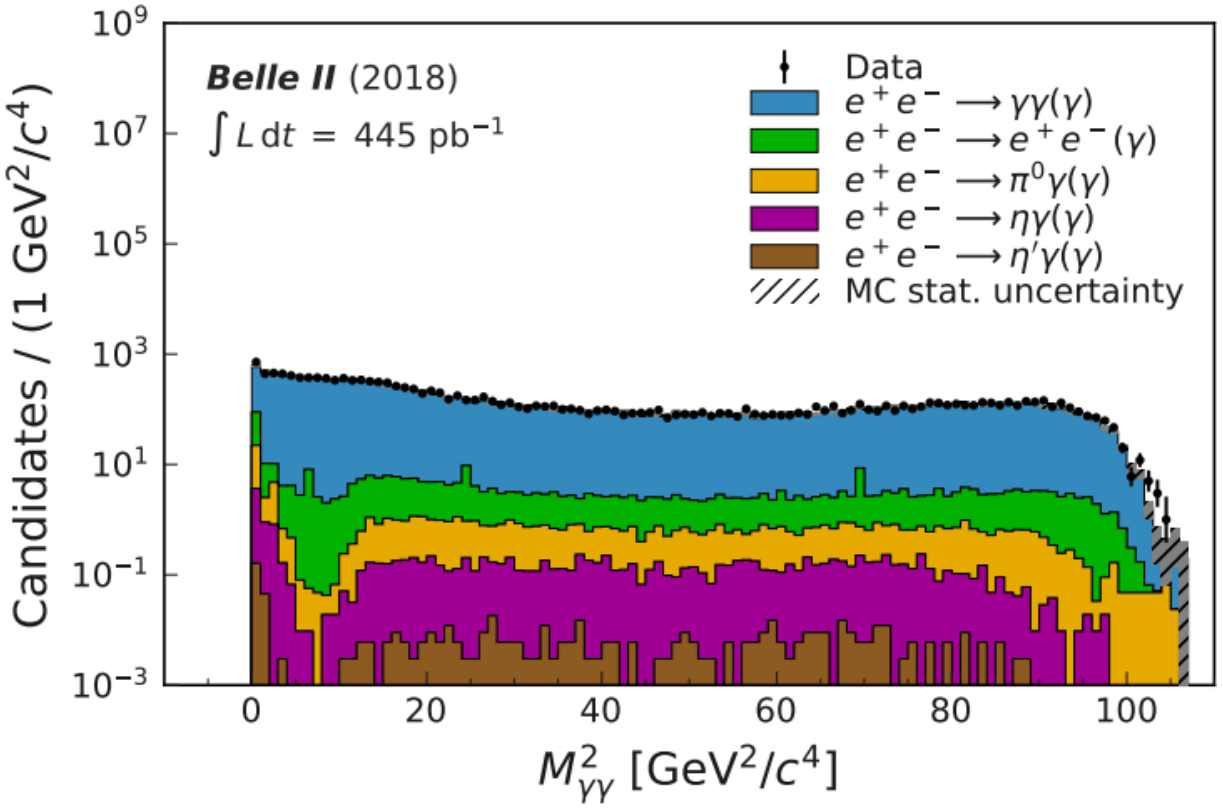


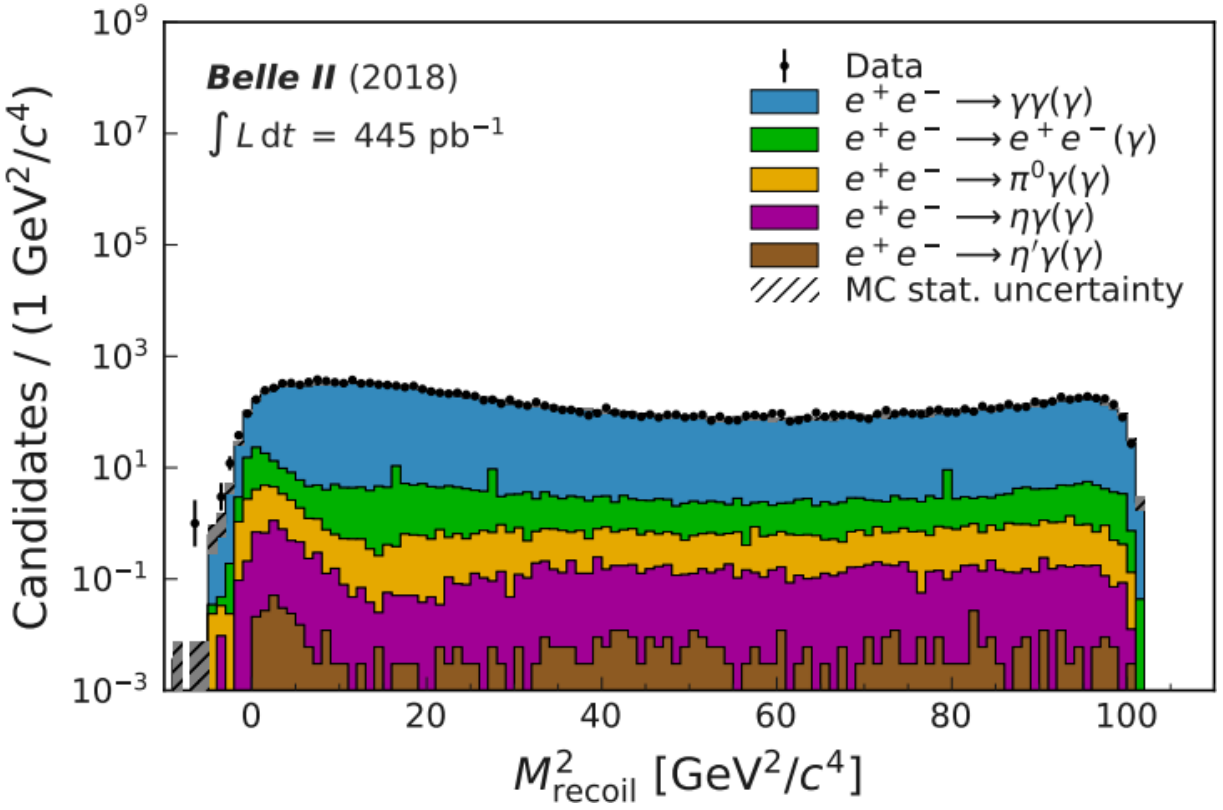

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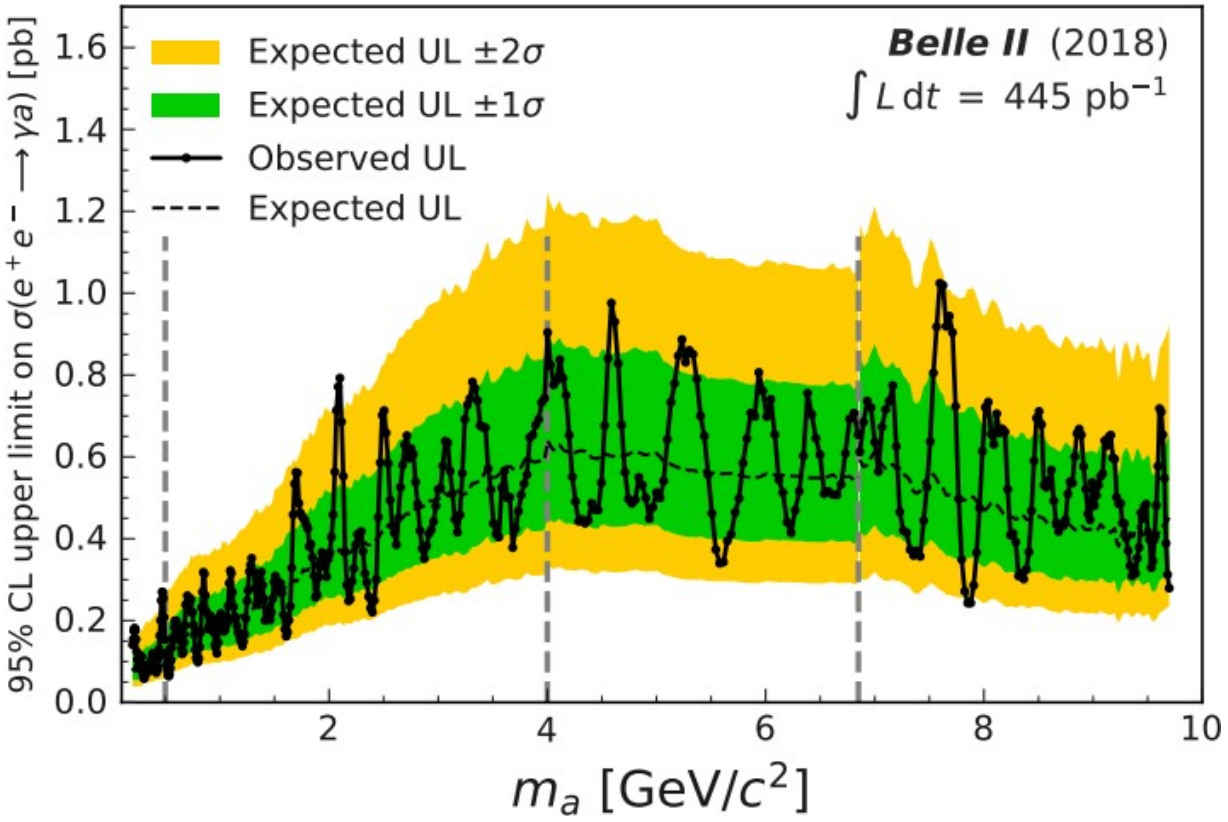
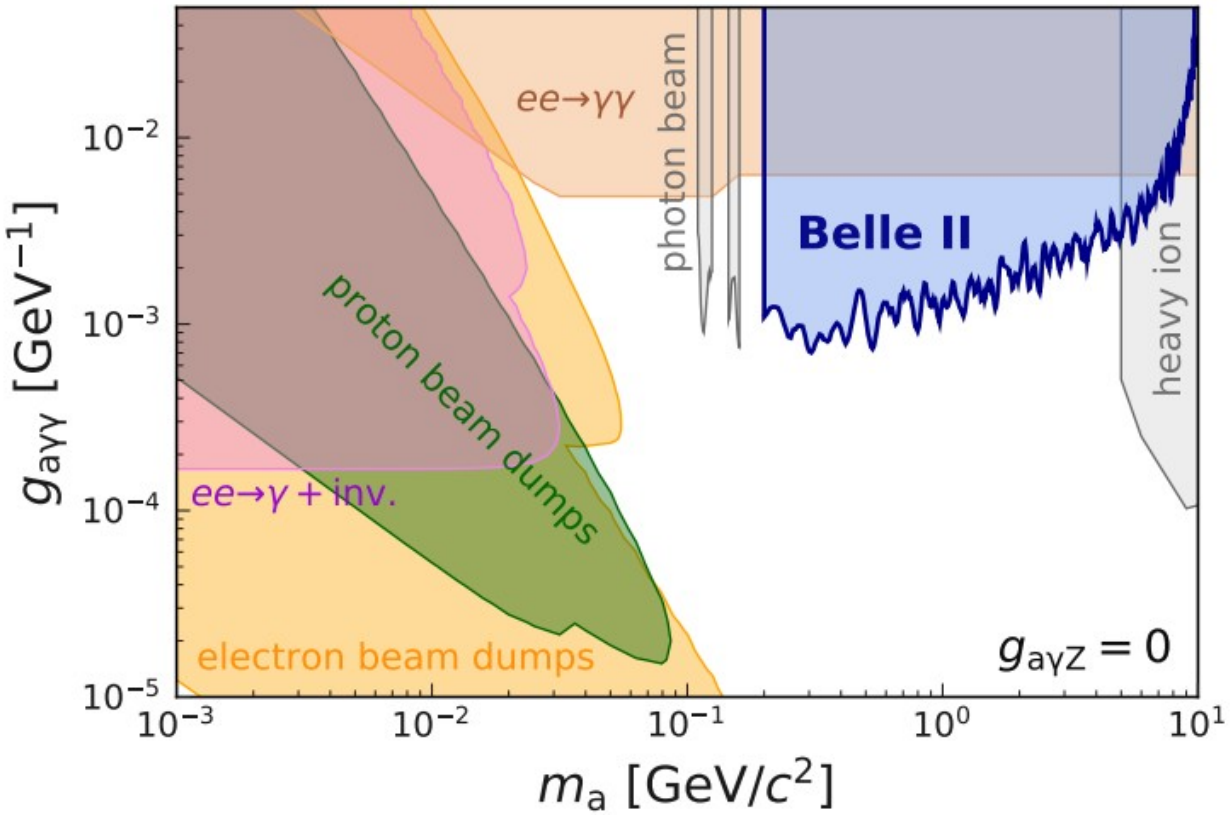
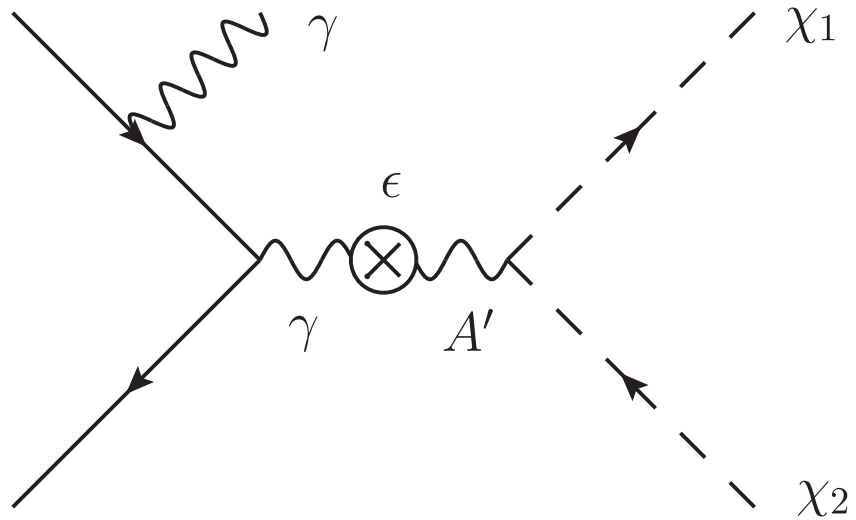


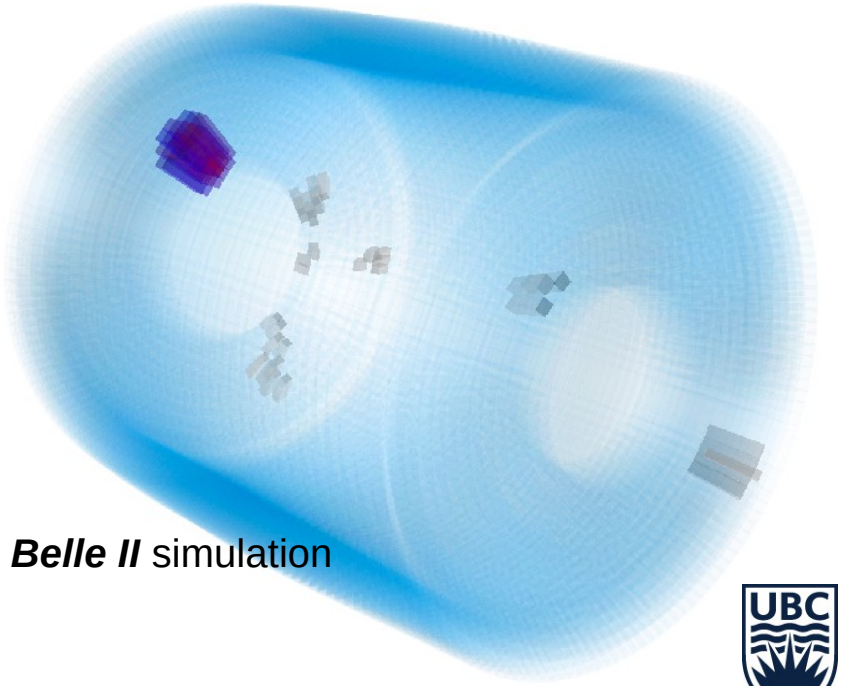



# Single photon search

## Ongoing

- Benchmark model: a dark photon decay invisibly to DM.
  - ee → γ A’; A’ → inv.
  - Could also be long lived decay of ALP.
  - ...and other models.
- Analysis:
  - Single photon cluster.
  - Nothing else in event (above beam background)… Hope that the KLM is turned on and working efficiently.
  - Bump-hunt in recoil mass.



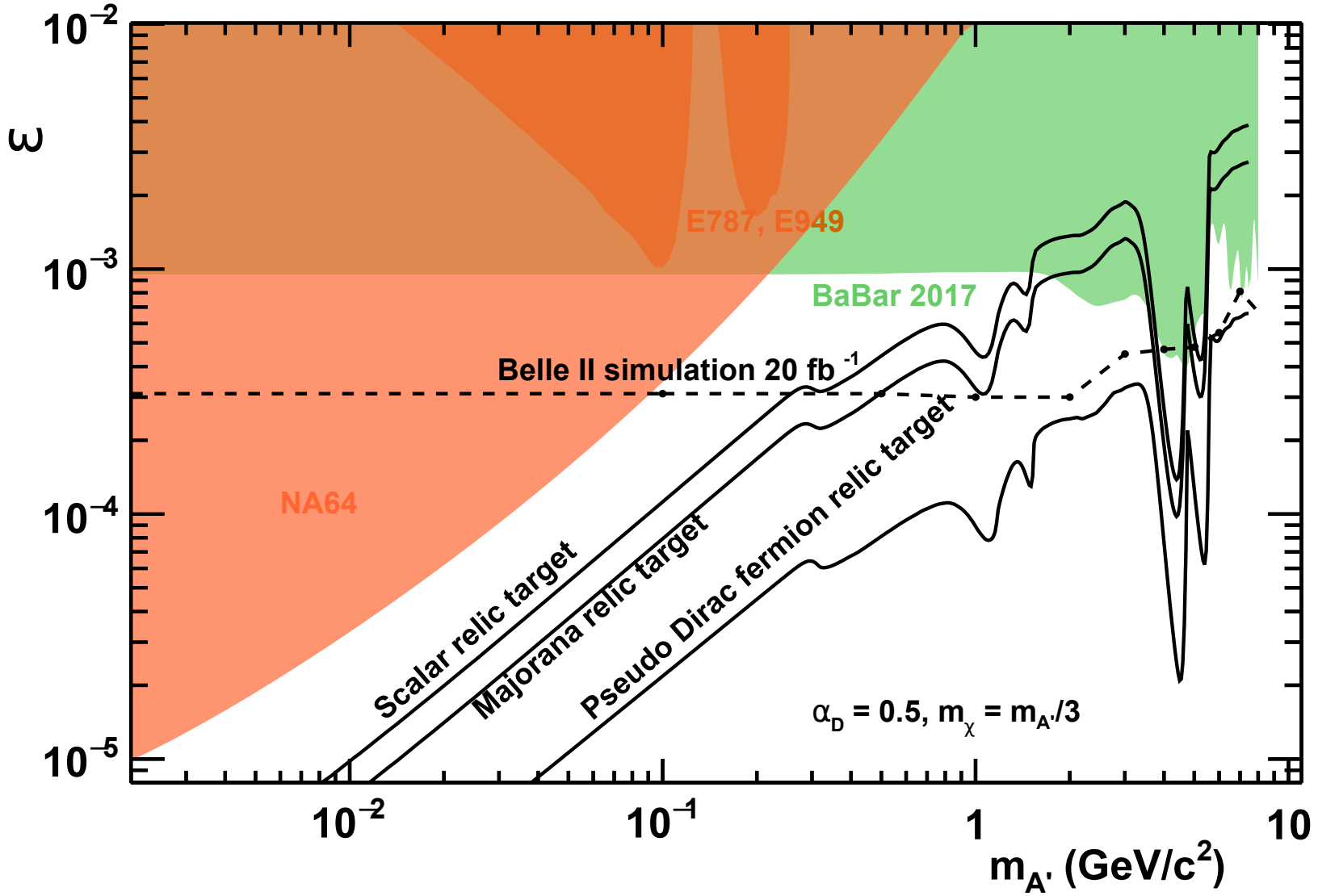



***Belle II*** simulation

# Single photon search

PTEP(2019)12

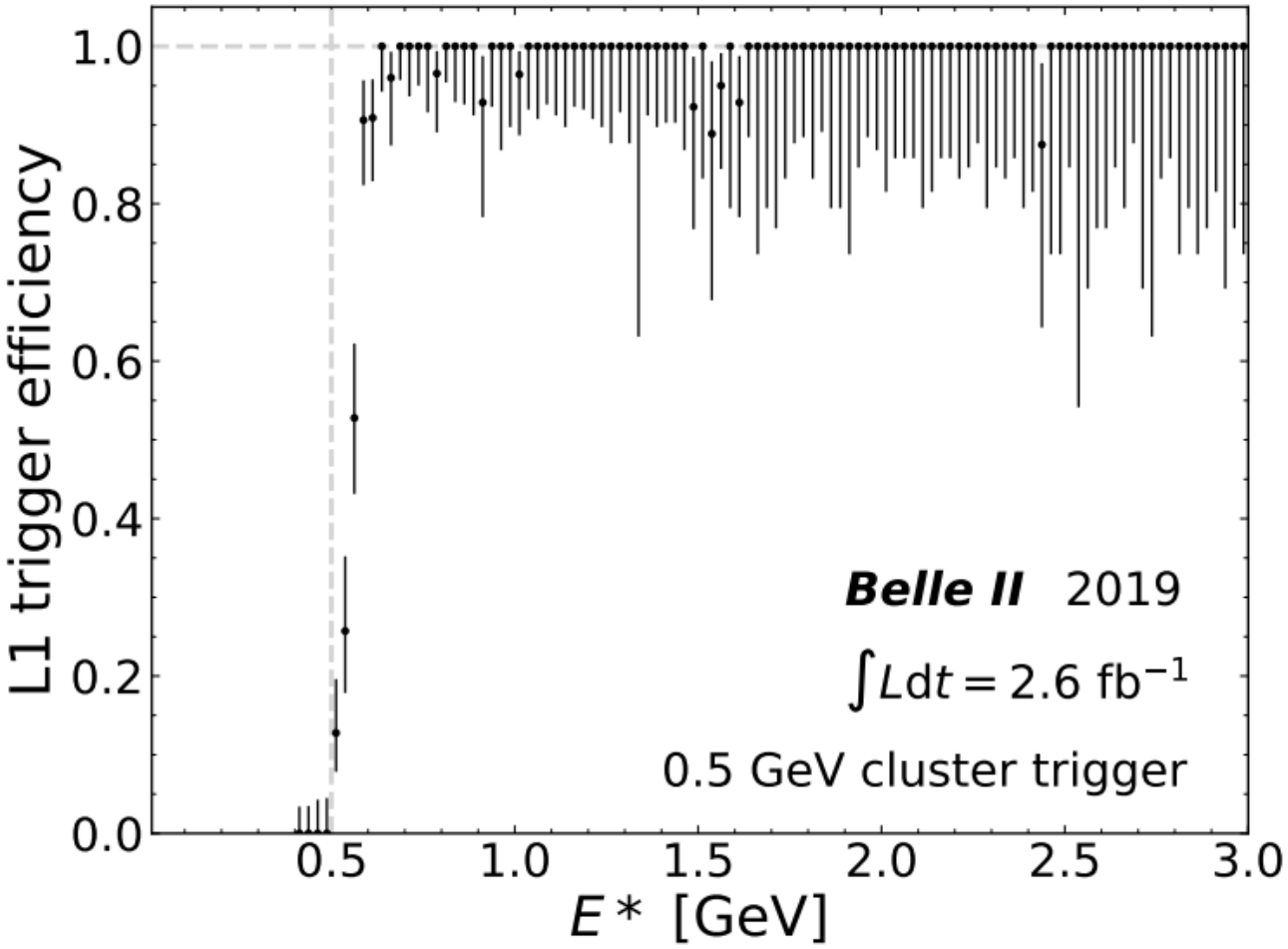
- Nominally exclude dark-photon mass vs. kinematic mixing parameter, ε.
- World-leading sensitivity expected with the data we have now.



# Single photon search

## Can you really trigger that low?

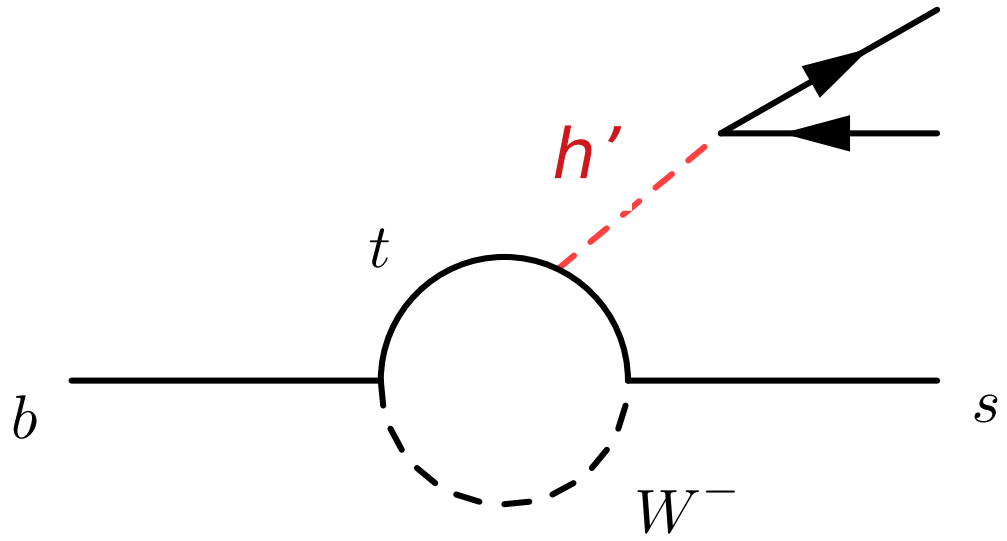
- Trigger on **isolated** calorimeter cluster.
- Check efficiency w/ ee → μμγ events.
- Common Q from LHC people: “can you really go that low?”
  - A: **Yes**, for the moment.

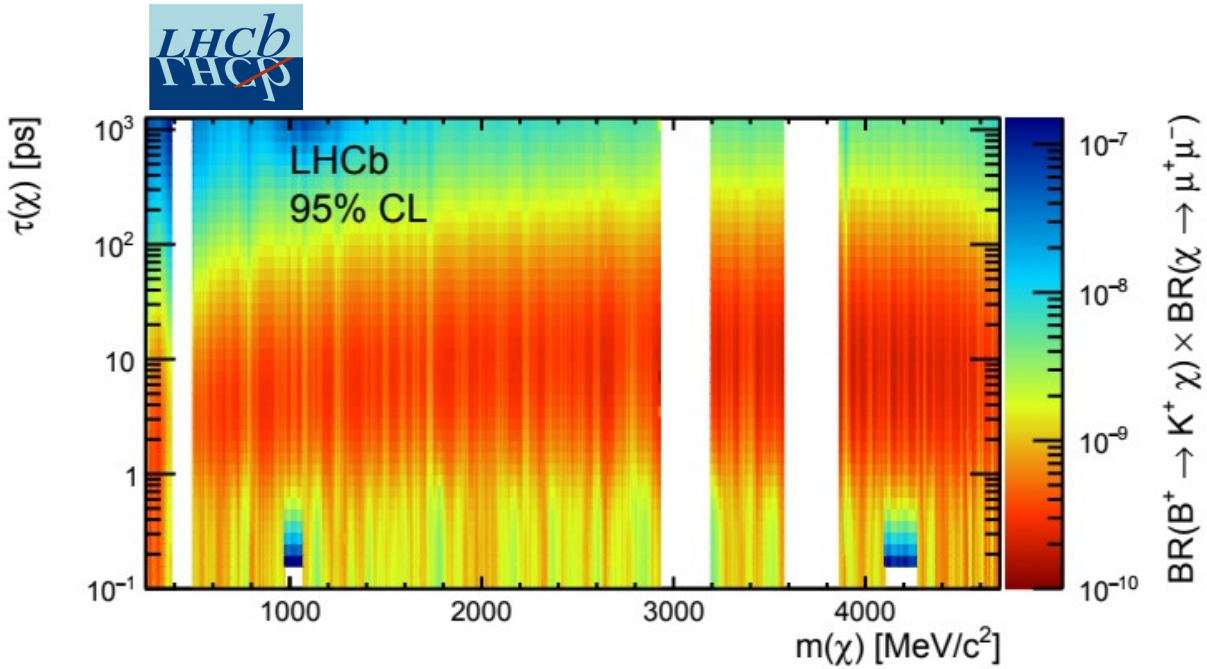


# $B \to K^{(*)}h'$

## h', S, χ, a

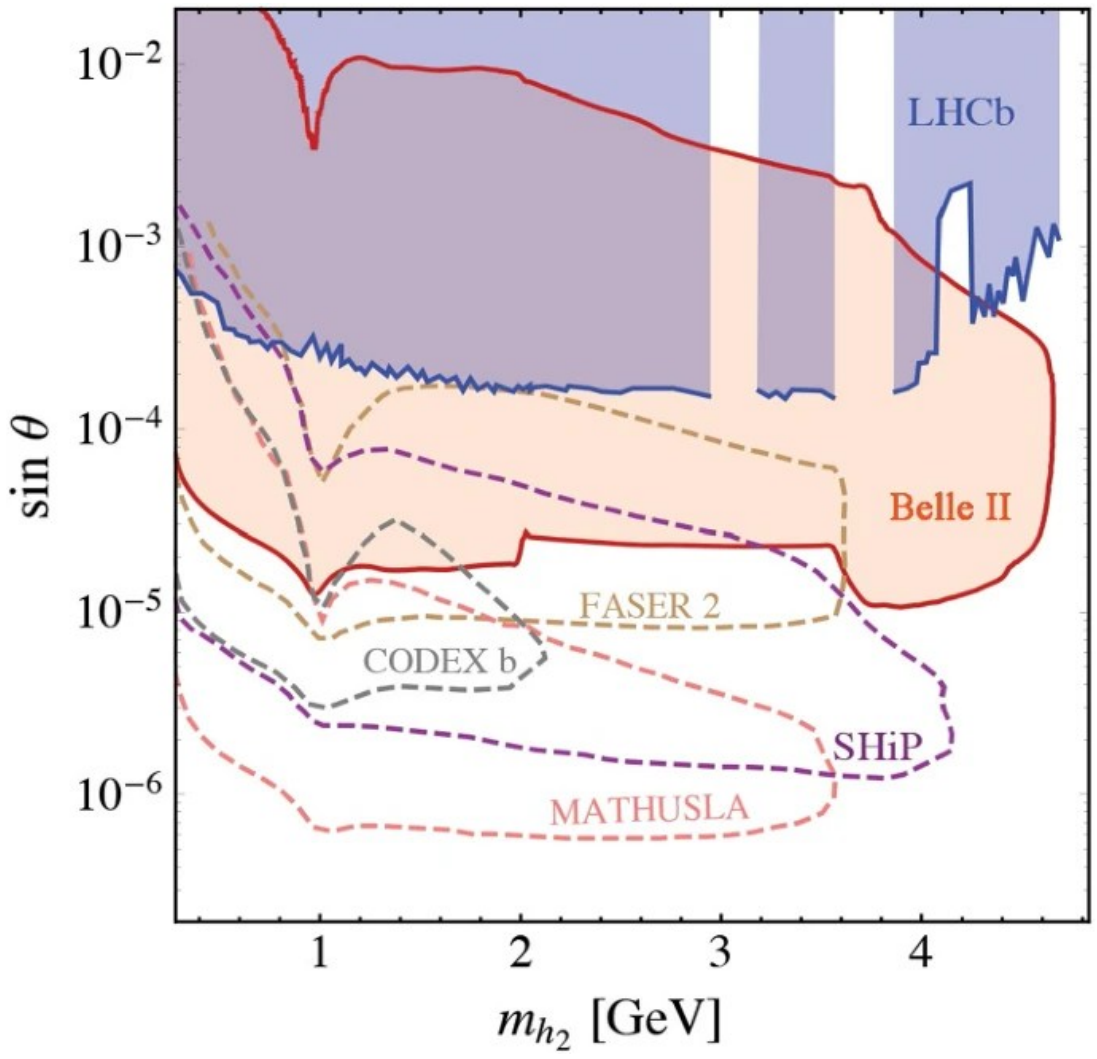
- Scalar, long-lived particle (Higgs like) that couples to the b → s penguin.
- A somewhat prompt version performed by LHCb [PhysRevD.95.071101].
- Analysis @ Belle II:
  - Relatively "standard" b-physics. Displaced vertex + kaon track. $M_{bc}$ vs. ΔE window.
  - Displaced vertex resolution is key.

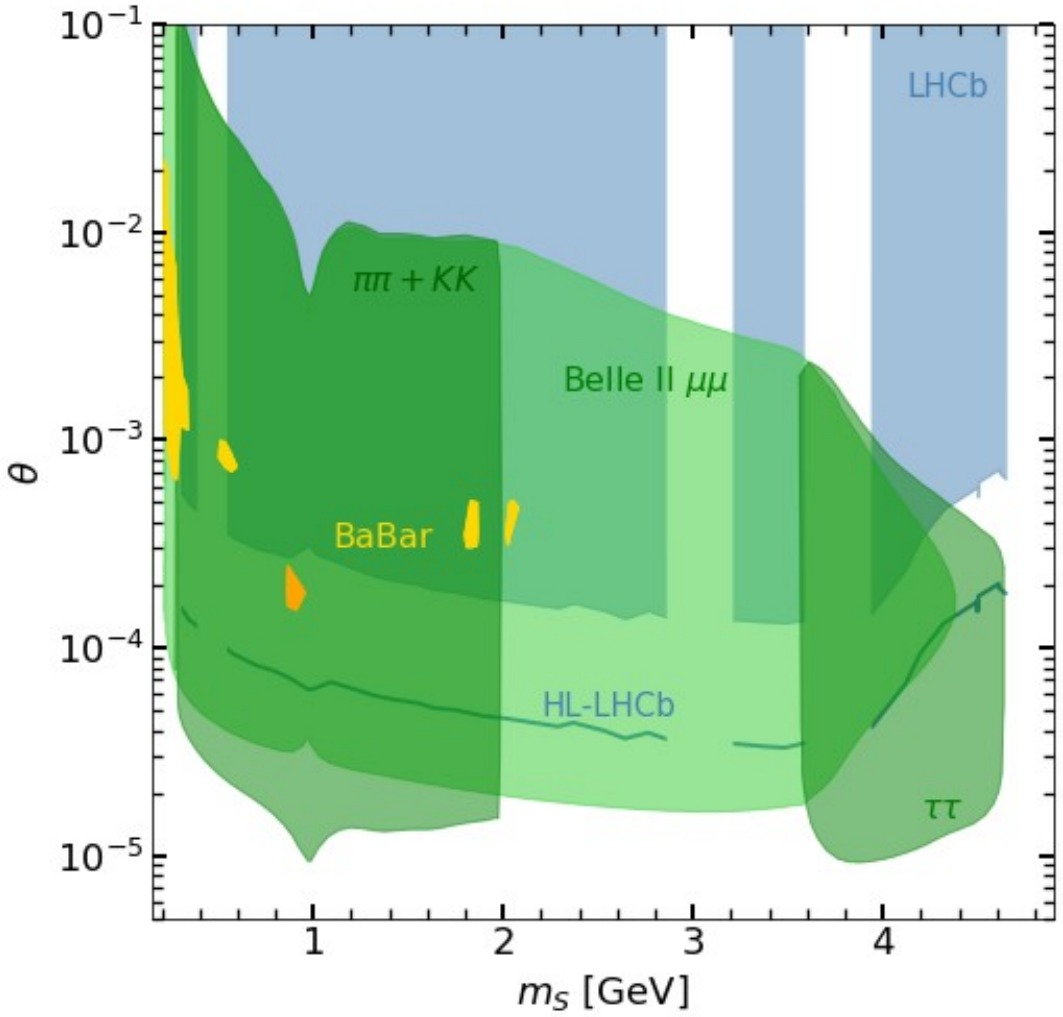


# $B \to K^{(*)}h'$

**Filimonova, et al. PhysRevD.101.095006 ; Kachanovich, et al. Eur. Phys. J. C 80, 669 (2020)**

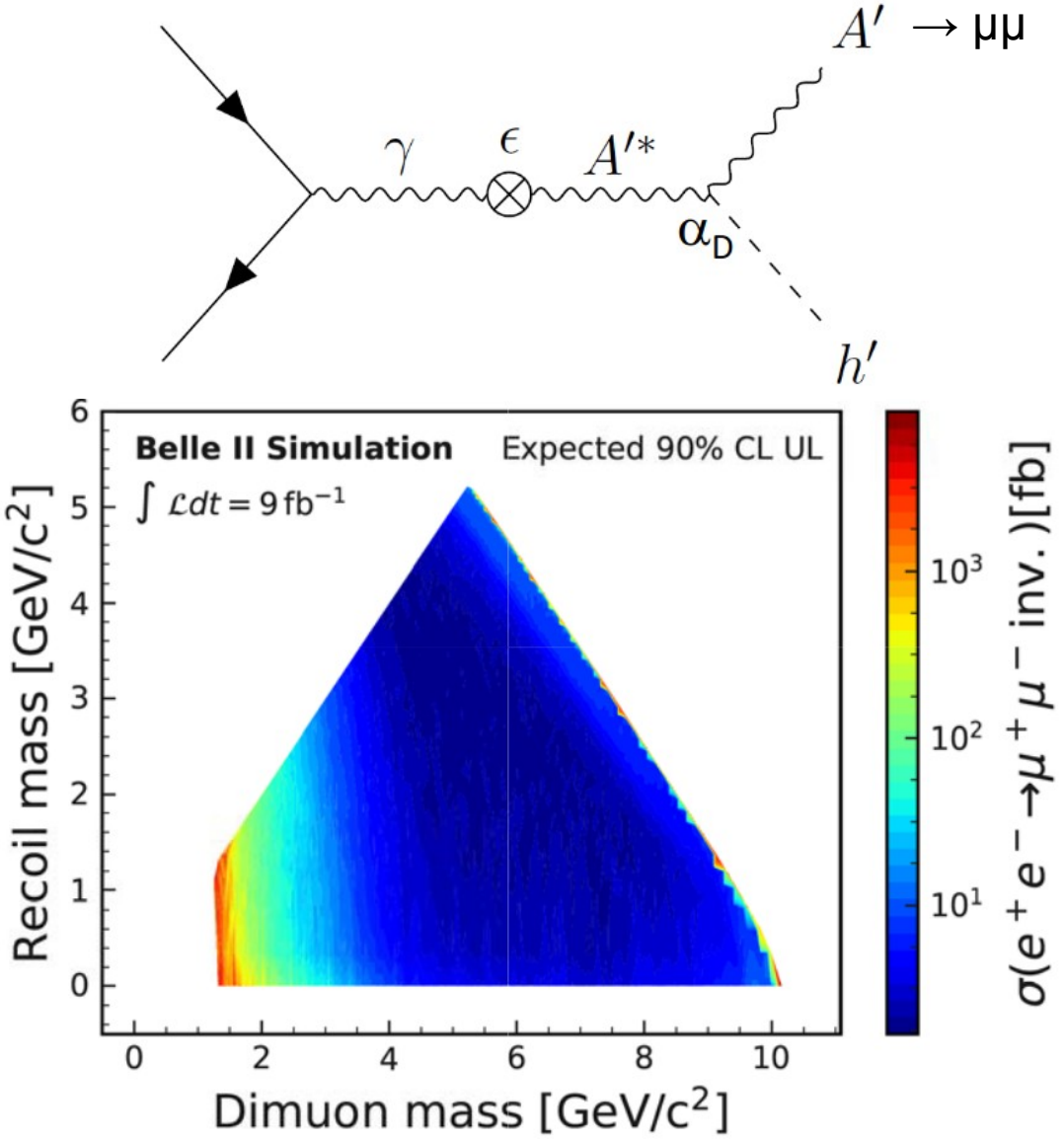


# Dark Higgsstrahlung

**Planned on 2019 data – paper soon.**
**BELLE2-NOTE-PL-2020-013**

- Same final state as published Z' search.
- Different model interpretation.
- Analysis:
  - Search for 2 tracks with μ-like PID + missing energy.
  - Nothing else in event (above beam background).
  - **Search in recoil vs. invariant mass plane**.



# Future plans

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## Talk done?

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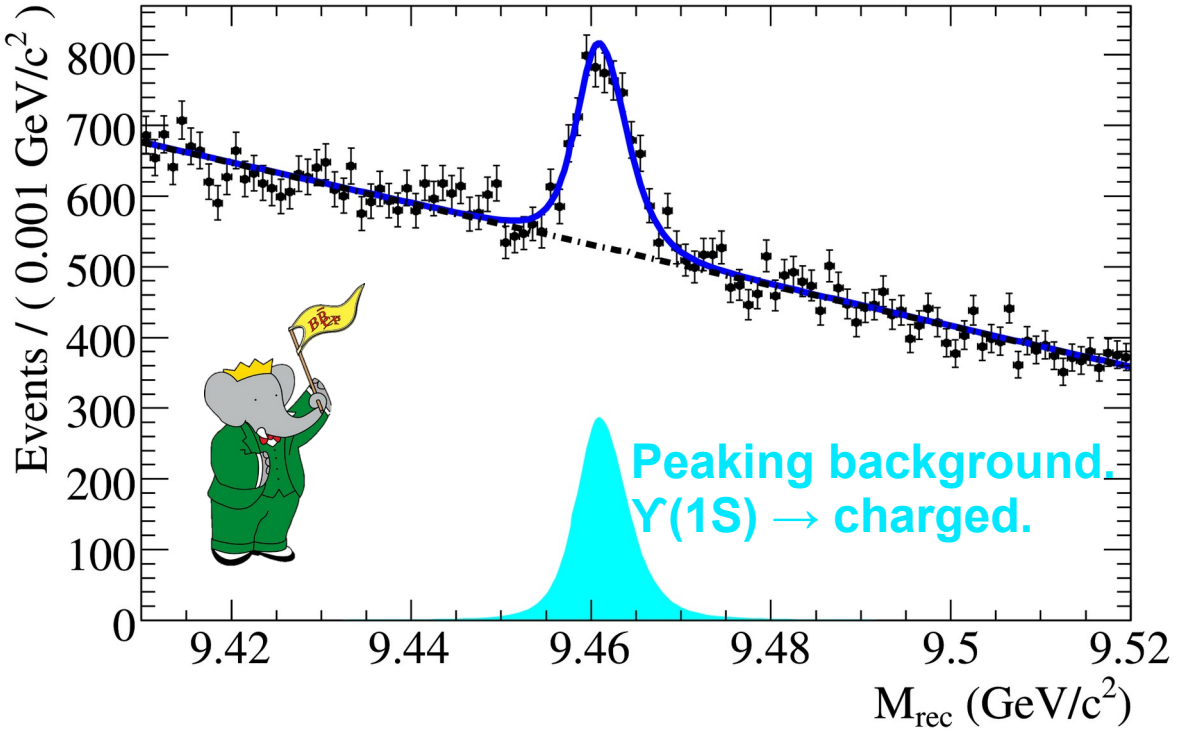
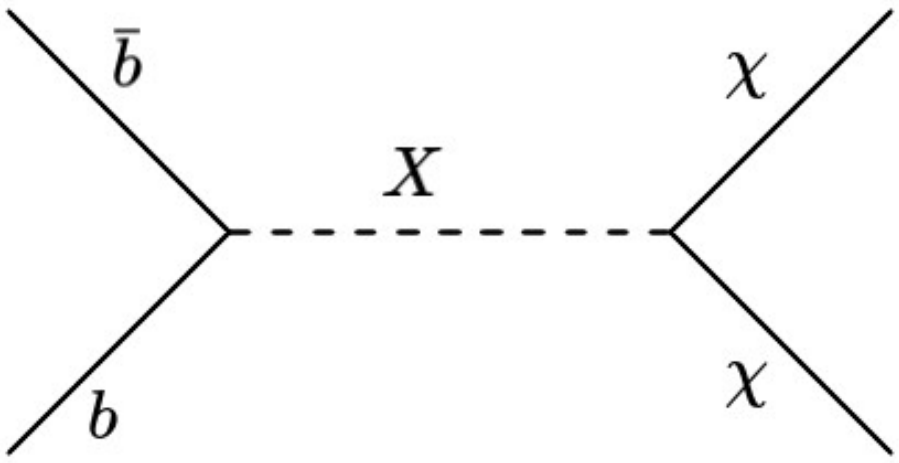
Let me mention
something a bit different.

# Υ(1S) → invisible

**Non-4S searches are cool too!**

- Step 0: convince SuperKEKB to change beam energy.
- Make use of clean dipion "tagging" in cascade decays of Υ.
  - ee → Υ(3S) → **ππ** Υ(1S)
- SM branching fraction prediction for Υ(1S) → νν ~ $10^{-5}$ and Υ(1S) → ννγ ~ $10^{-9}$.
- Light dark matter enhancement up to $10^{-4}$ ! [Phys.Rev.D72(2005)103508] [arXiv:0712.0016
- BaBar sets best limit < $3\times10^{-4}$ [Phys.Rev.Lett.103(2009)251801].

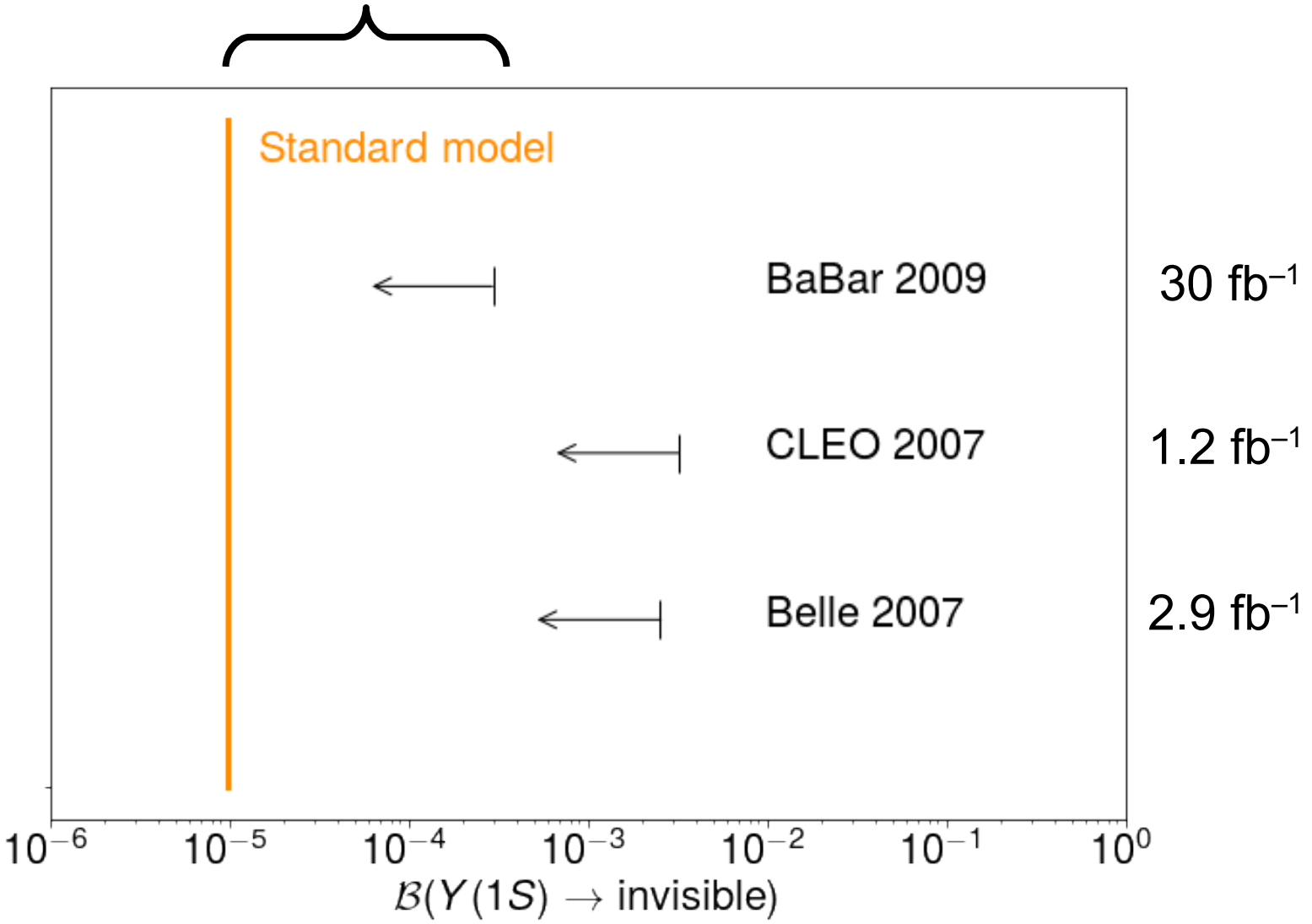


# Υ(1S) → invisible

U. Tamponi

Room for new physics in here!
[Phys.Rev.D93(2016)5,054023]



# Conclusions

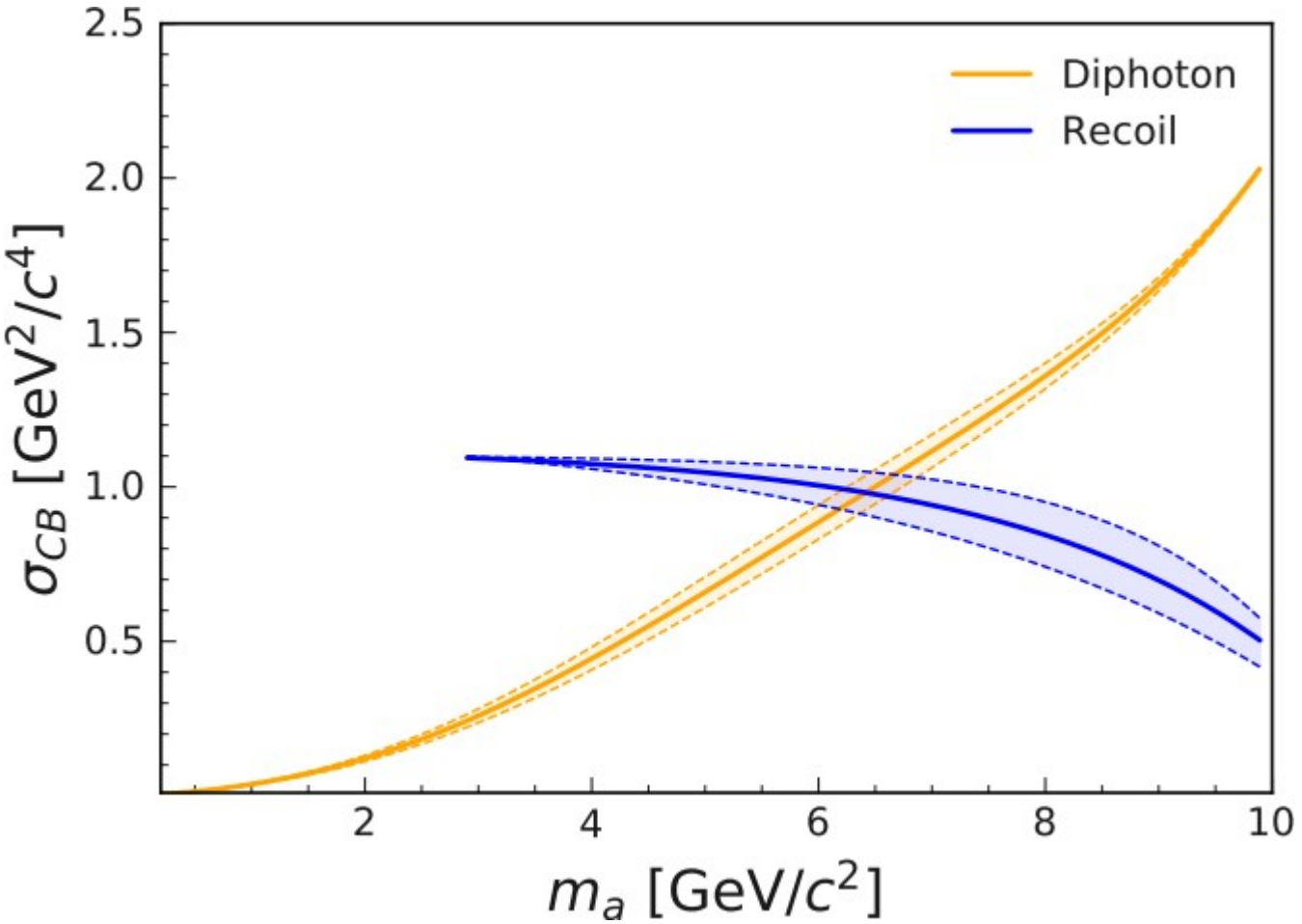
- Dark-sector physics is strong in Belle II.
  - So far the only world-leading measurements.
- Germany is strong in the dark-sector group.
  - One of the leading groups (friends from IT, AT, CA, … ).
- Belle II will be leading the field of light dark matter in the coming years.
  - Some overlap from NA64, LHCb, ...

# Extra slides

# Axion-like particle

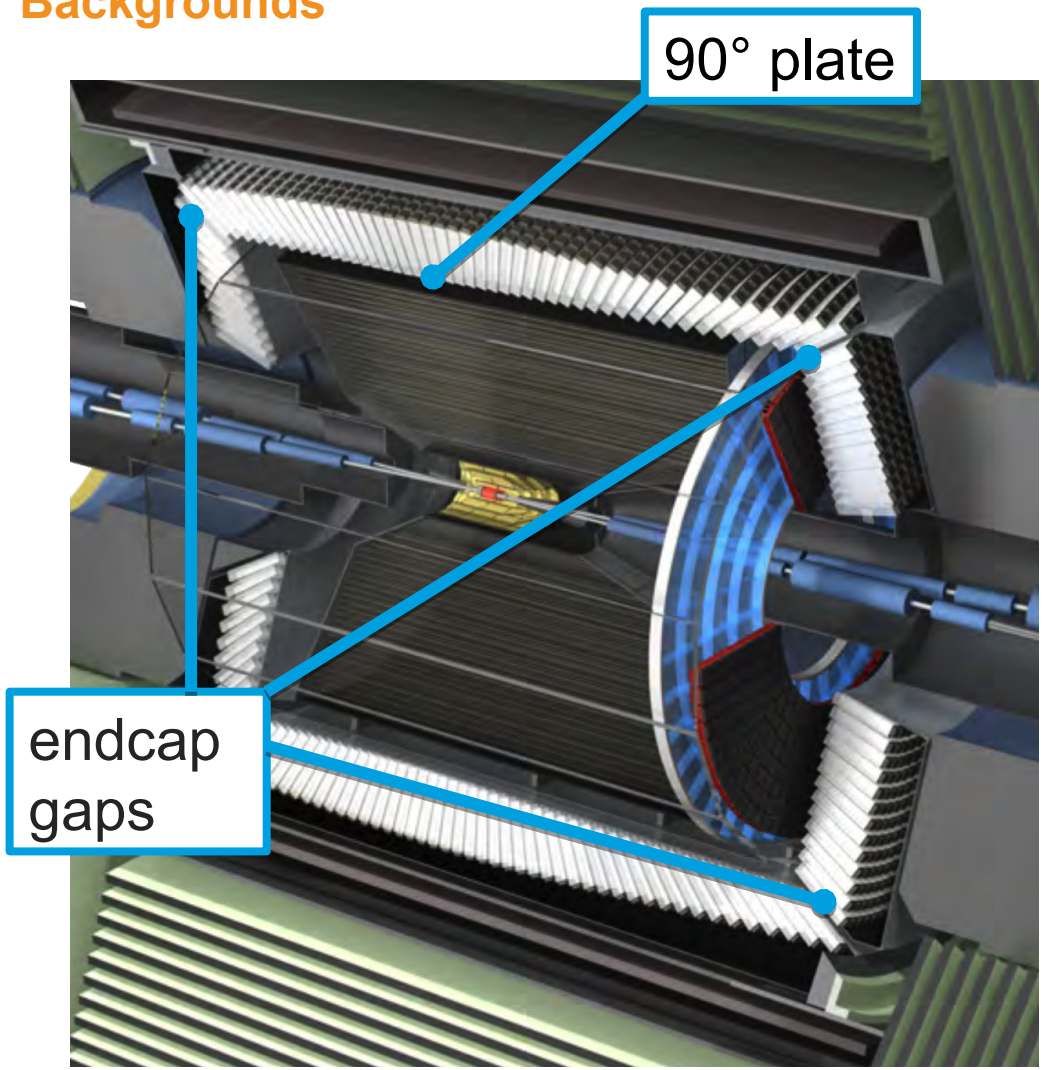
arXiv:2007.13071 *submitted to PRL*

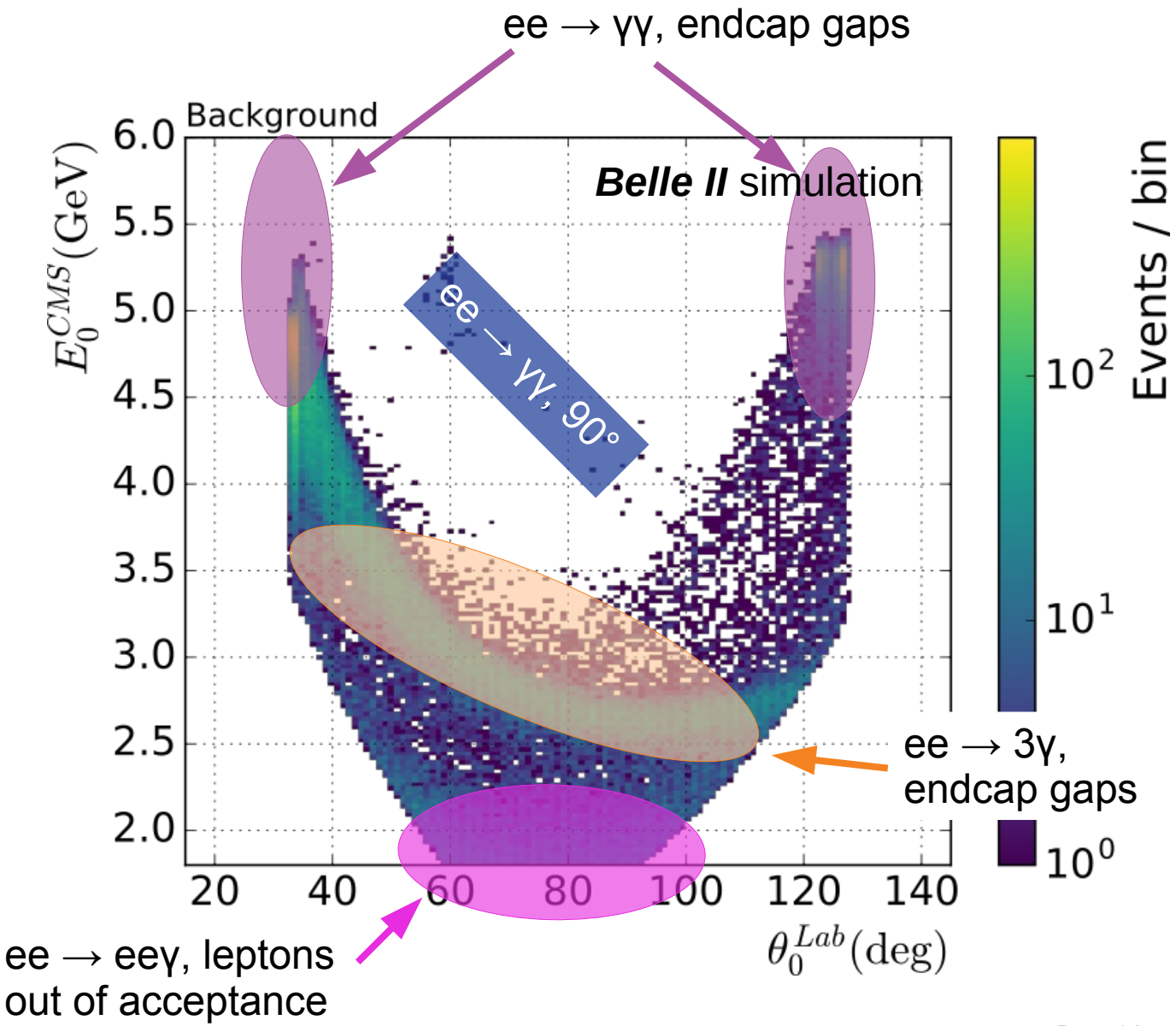
- Why do you use two masses for the bump hunt?



# Single photon search

## Backgrounds



## Contact

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