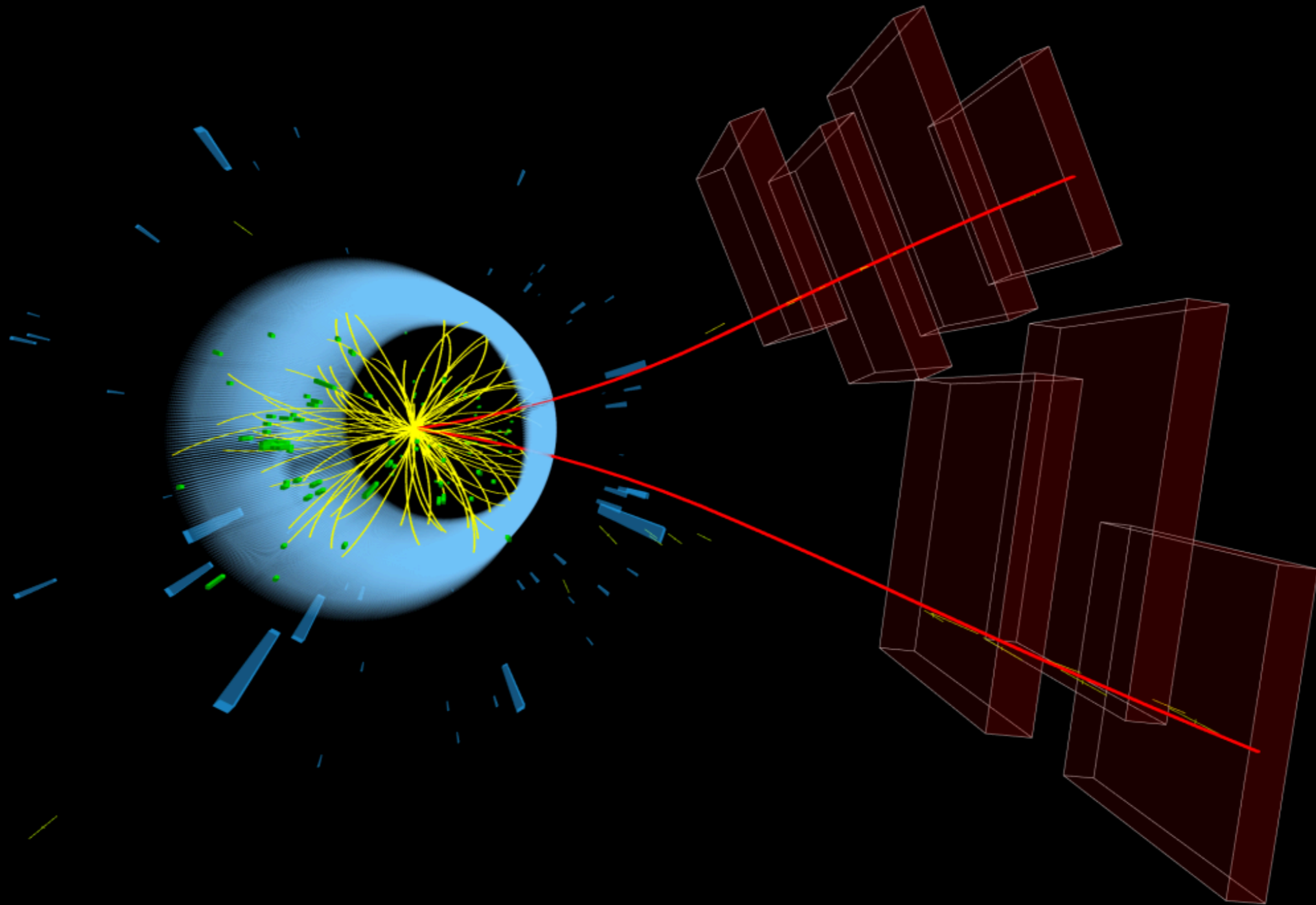


# *Dark Sectors: New ideas and how to probe them*



Simon Knapen  
CERN



# What is a “dark sector”?

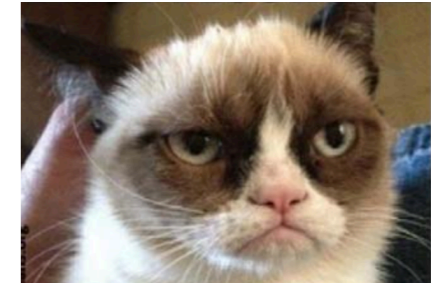
## Attempt 1: Wikipedia

### Hidden sector

---

From Wikipedia, the free encyclopedia

In [particle physics](#), the **hidden sector**, also known as the "dark sector", is the hypothetical collections of yet-unobserved [quantum fields](#) and their corresponding hypothetical [particles](#). The interactions between the hidden sector particles and the [Standard Model](#) particles are weak, indirect, and typically mediated through [gravity](#) or other new particles. Examples for the new mediating particles include [dark photon](#), [sterile neutrino](#), and [axion](#).



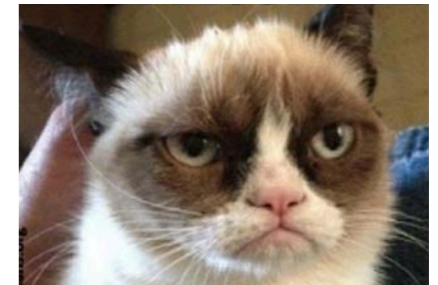
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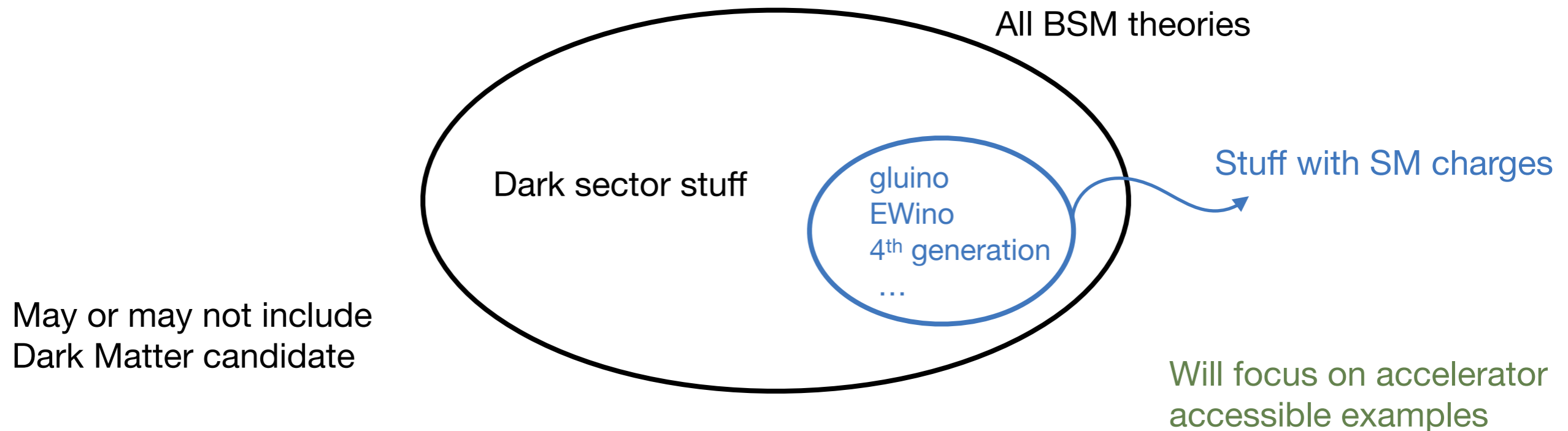
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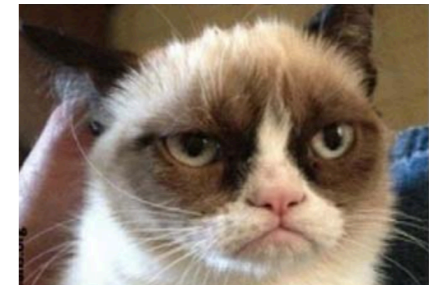
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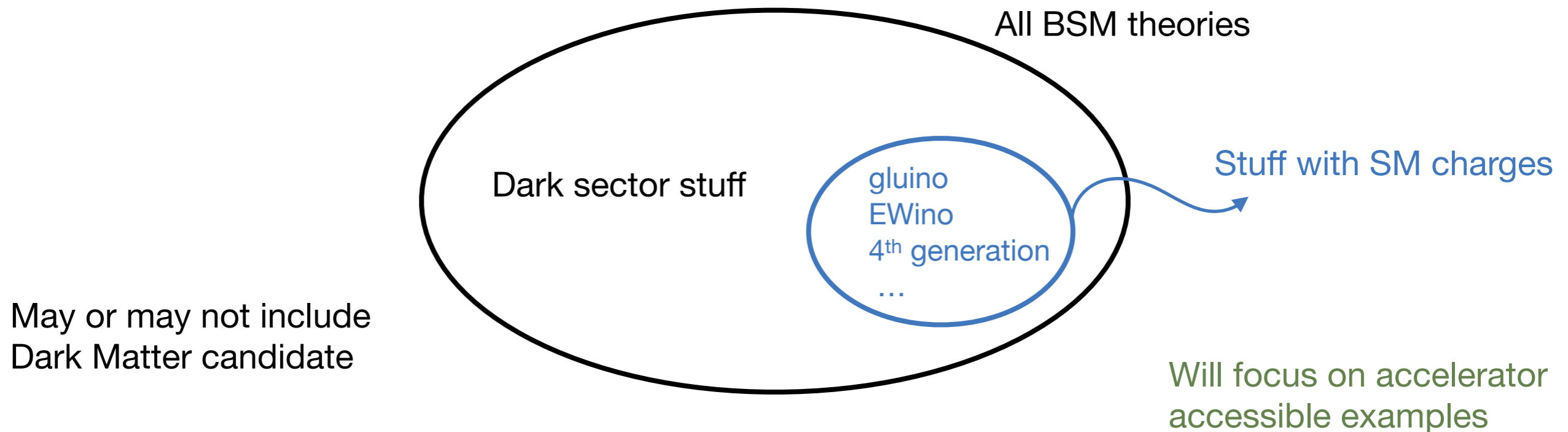
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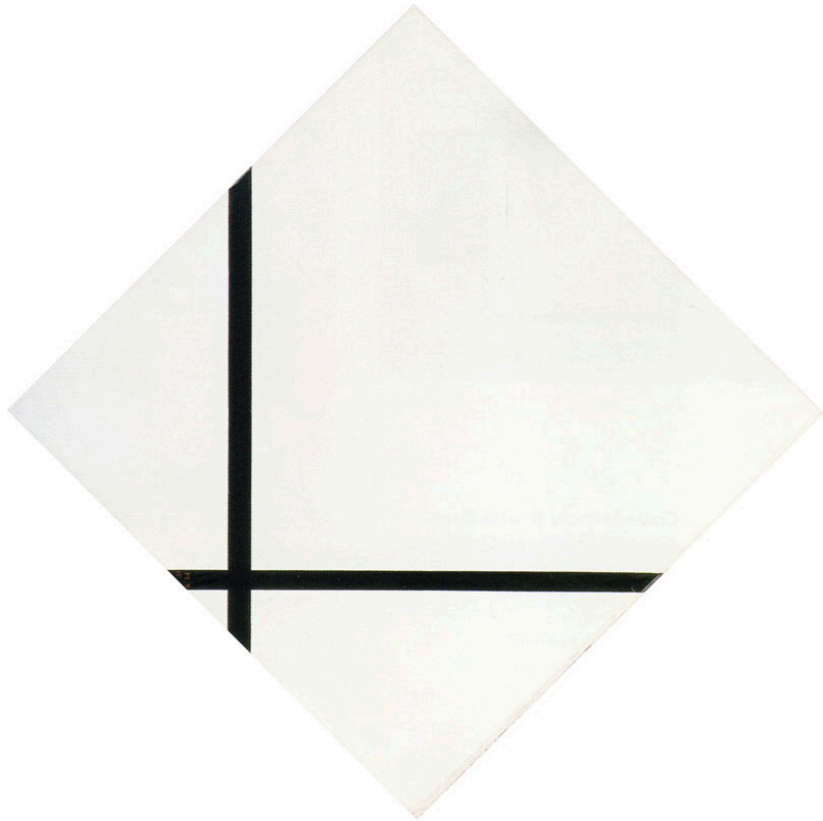
## Attempt 2: Something “dark” = not charged under SM $SU(3) \times SU(2) \times U(1)$



I will need to neglect large chunks of the literature

# Two schools

## “Minimalism”



Tries to systematically study simplest extensions of the SM

Aka “simplified models” or “portals”

## “Realism”



Tries to address problems with the SM, sometimes in great detail

e.g. hierarchy problem, Dark Matter, ...

Both are a form of theory prior

# Two schools

## “Minimalist” models

- ✓ Relatively few options
- ✓ Simple
- ✓ Great for benchmarking
- ✗ Great for benchmarking
- ✗ “Who ordered this?”

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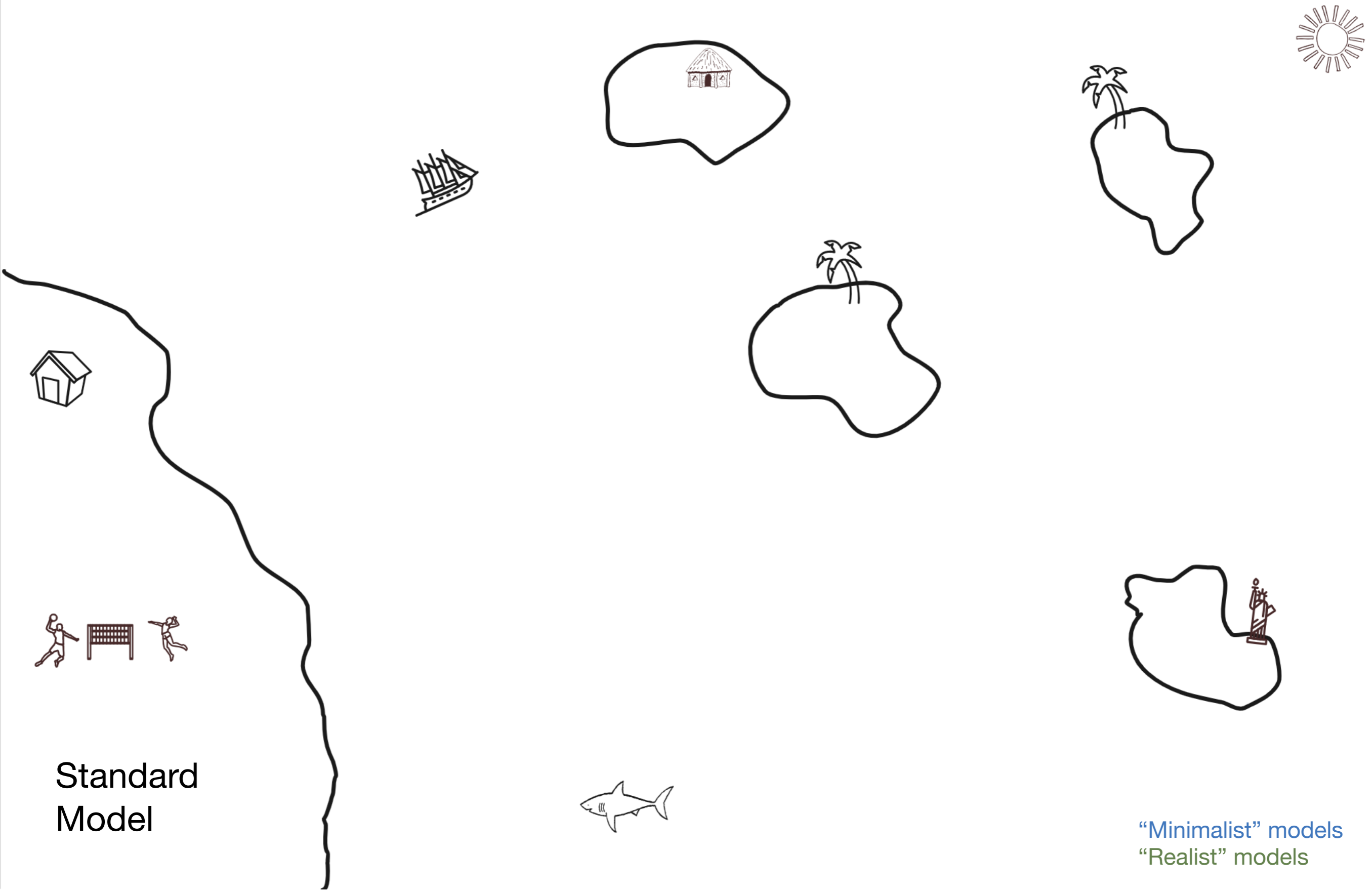
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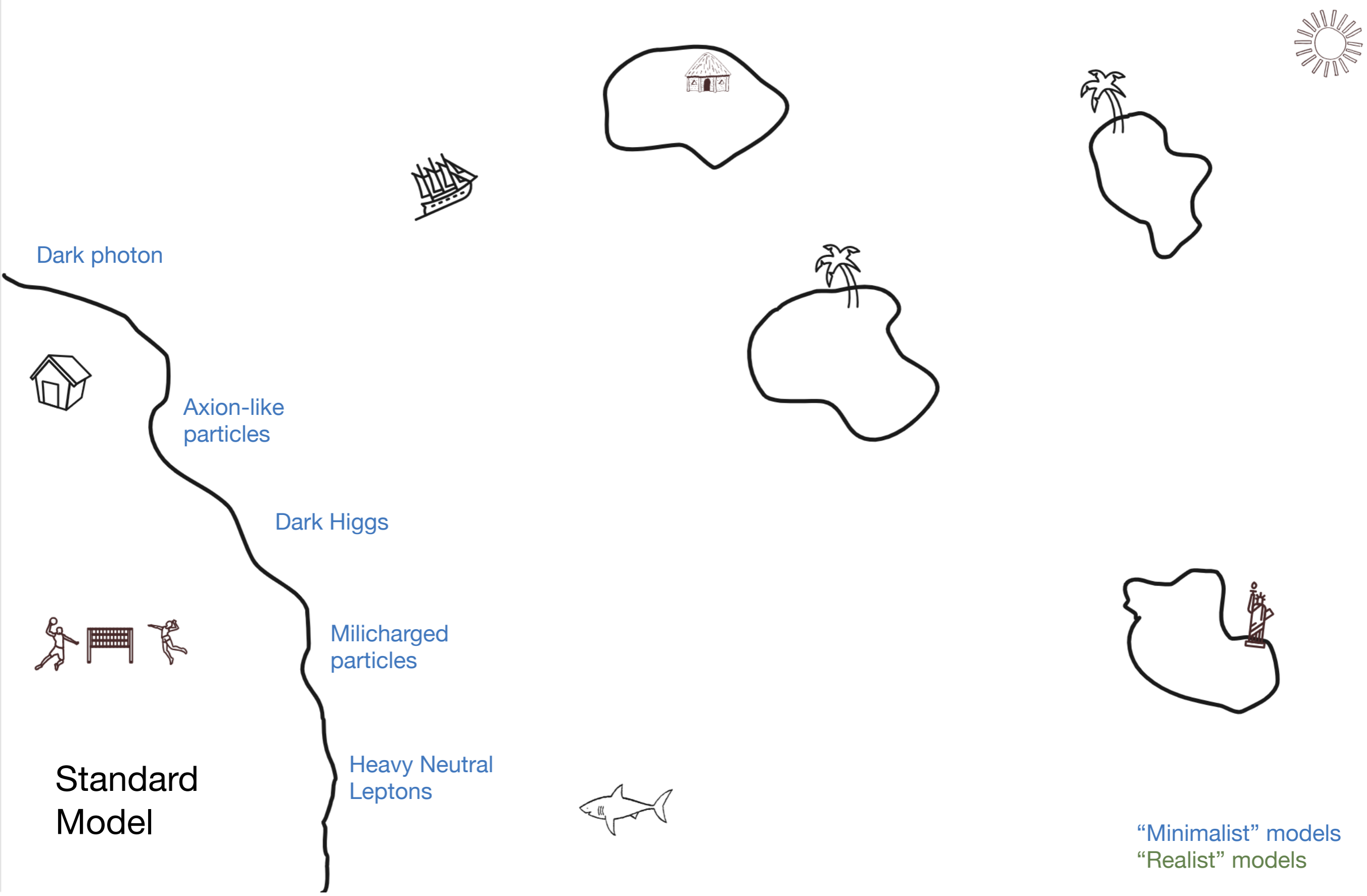
*My opinion:*

- 1. A model independent approach to dark sectors is likely not possible*
- 2. Relying too strongly one school of thought is dangerous*

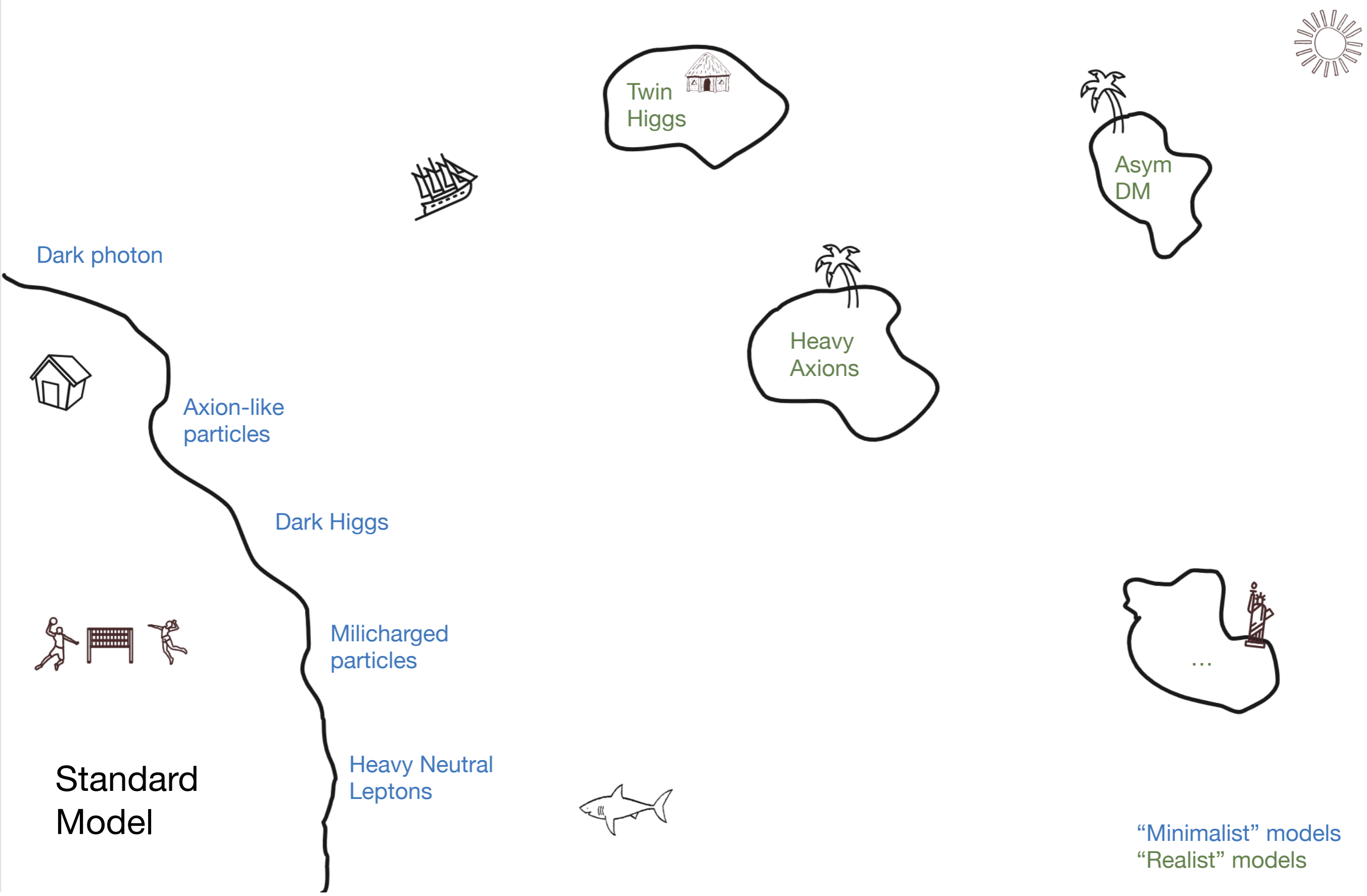
# *Journey through the dark sector*



# Journey through the dark sector

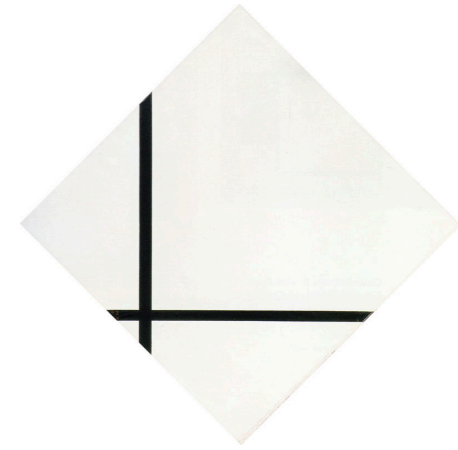
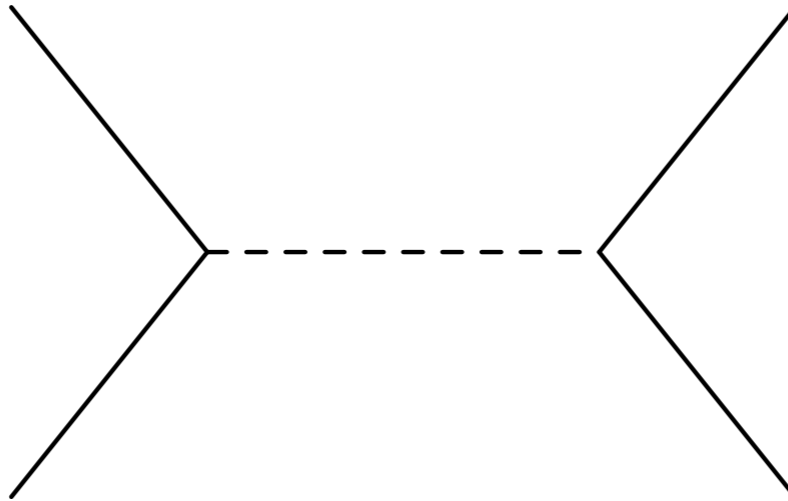


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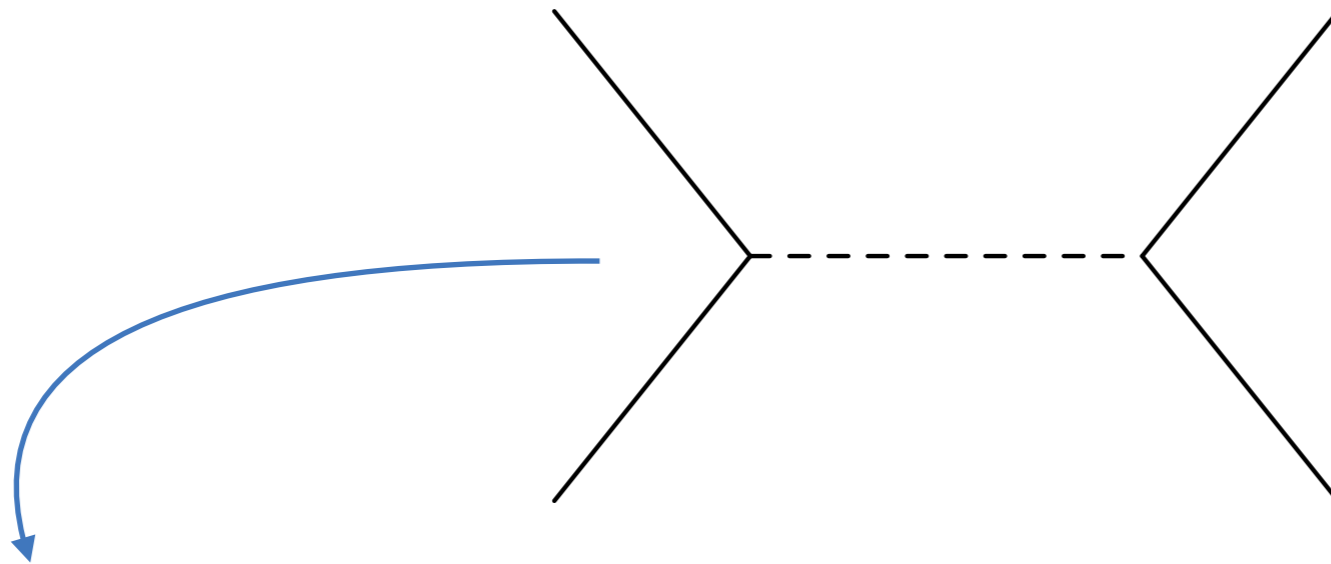
# Minimalist models

Usually only single new particle with small couplings



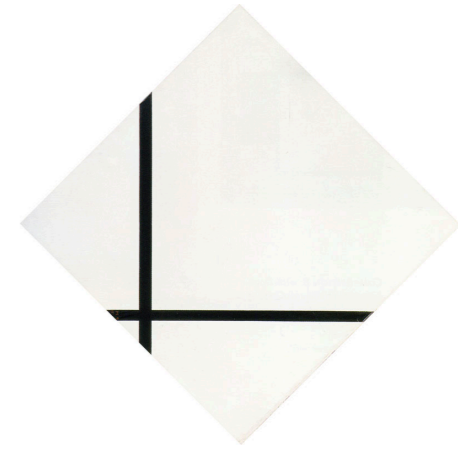
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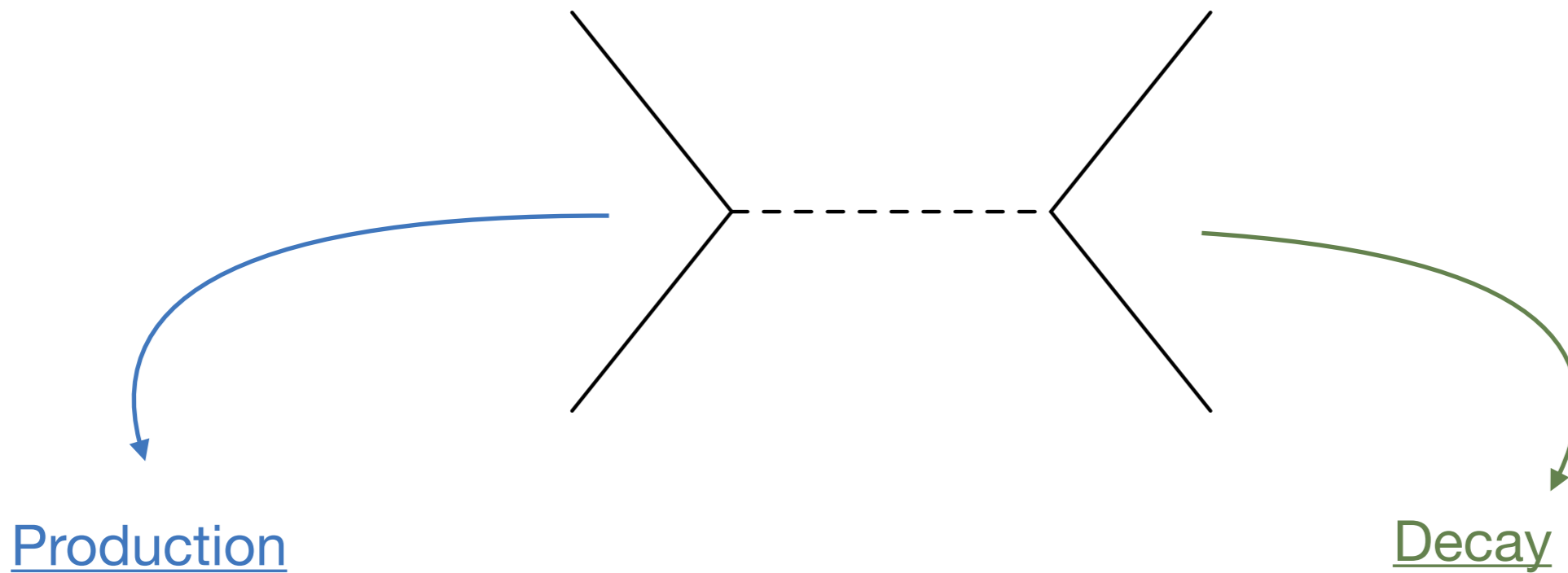
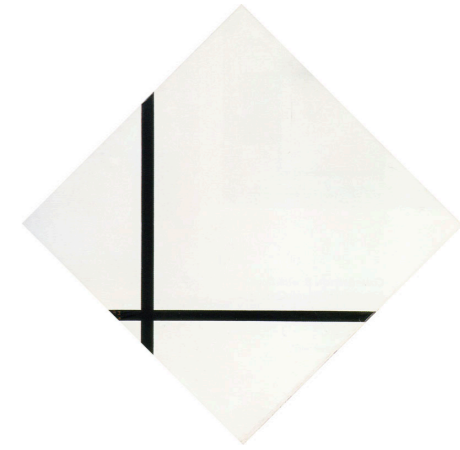
Production

- Exotic decays of narrow SM particles ( $h$ ,  $B^\pm$ ,  $K^\pm$ , etc)
- High parton luminosities



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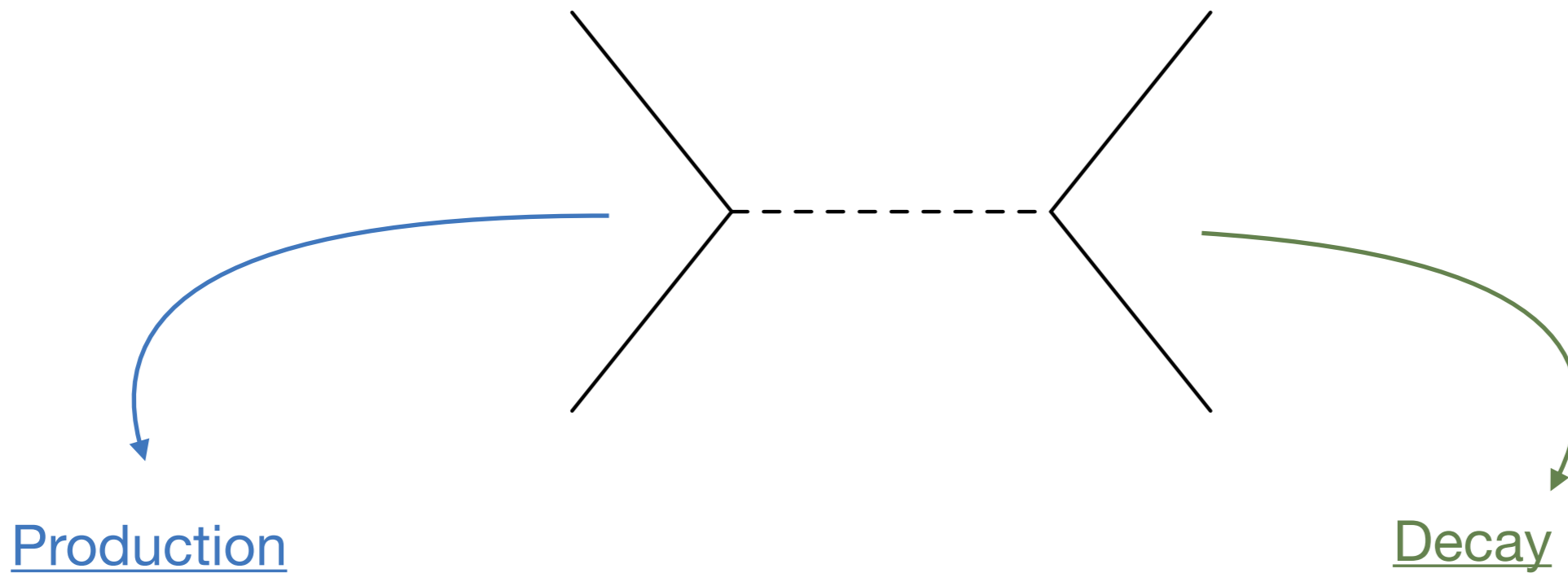
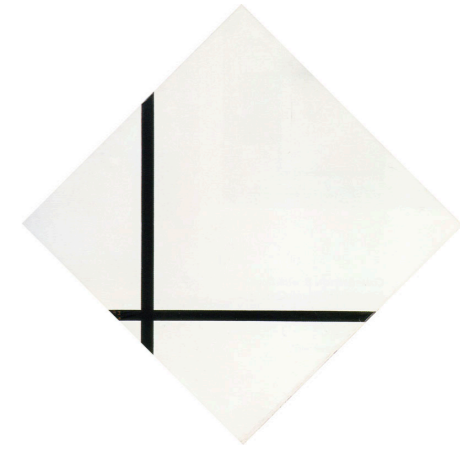
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heavy particle  
(direct searches)

For  $m \sim \text{GeV}$  macroscopic lifetimes are generic

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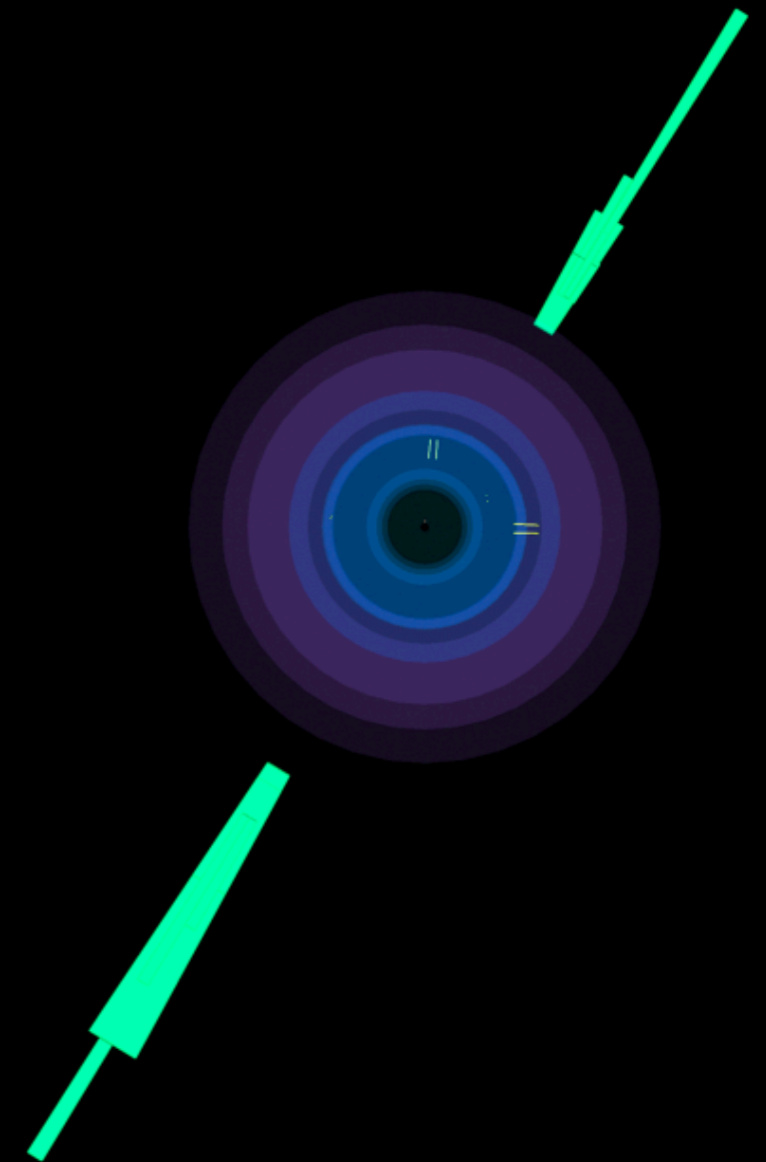
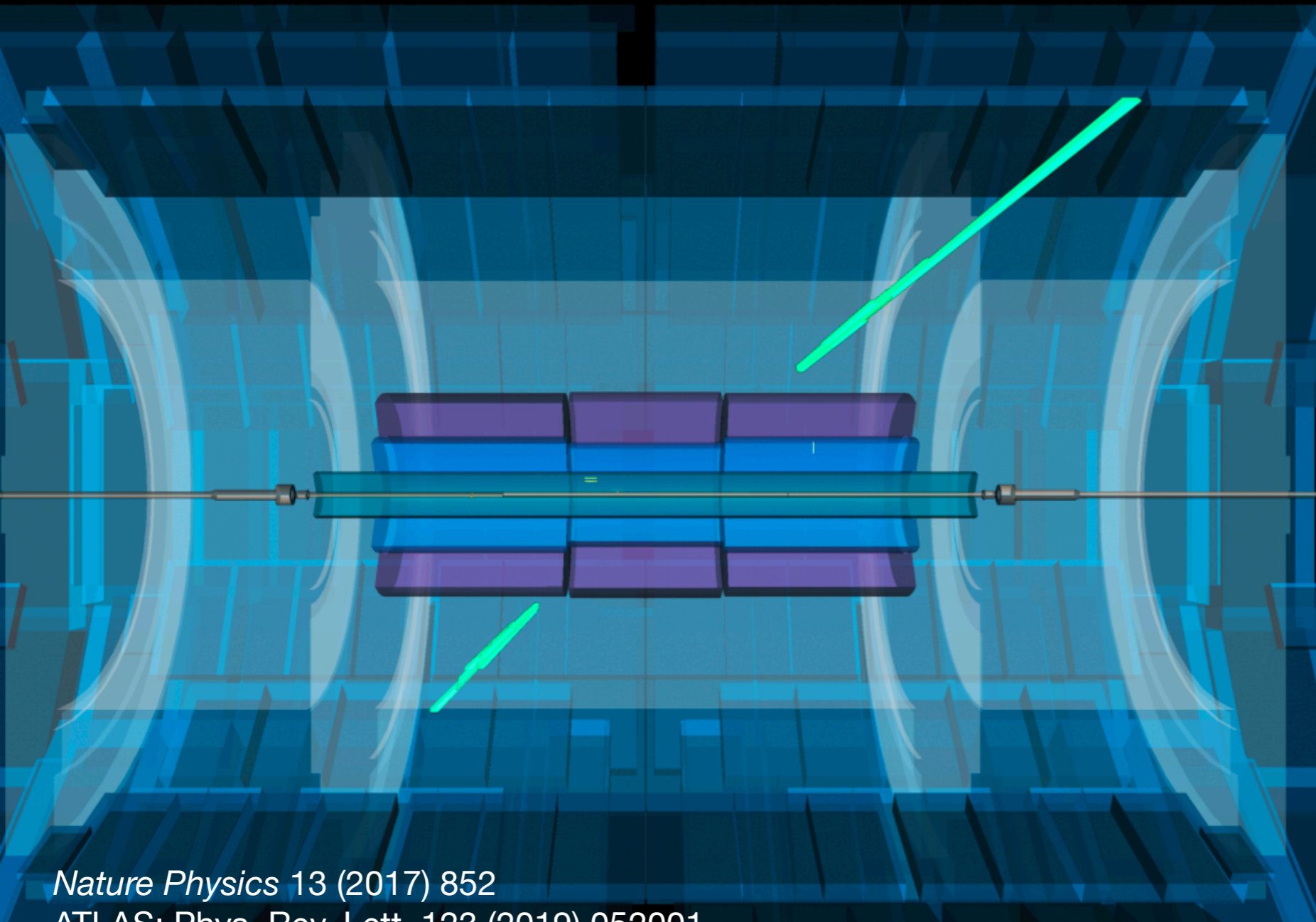
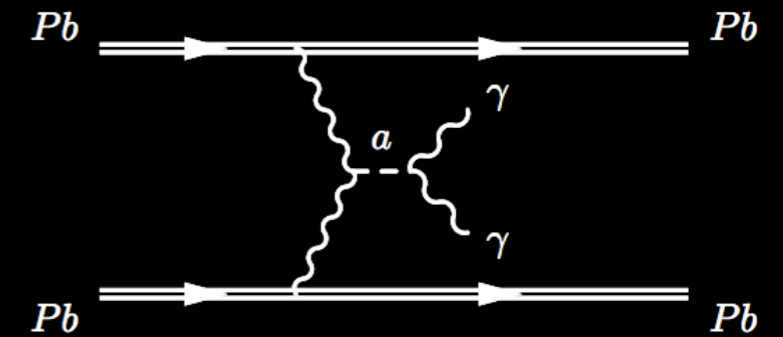
Bonus points if production and decay occur through the same vertex

# Axion-like particles in ultra-peripheral Pb-Pb collisions

7



Candidate Event:  
Light-by-Light Scattering  
Run: 366994 Event: 453765663  
2018-11-26 18:32:03 CEST



*Nature Physics* 13 (2017) 852

ATLAS: *Phys. Rev. Lett.* 123 (2019) 052001

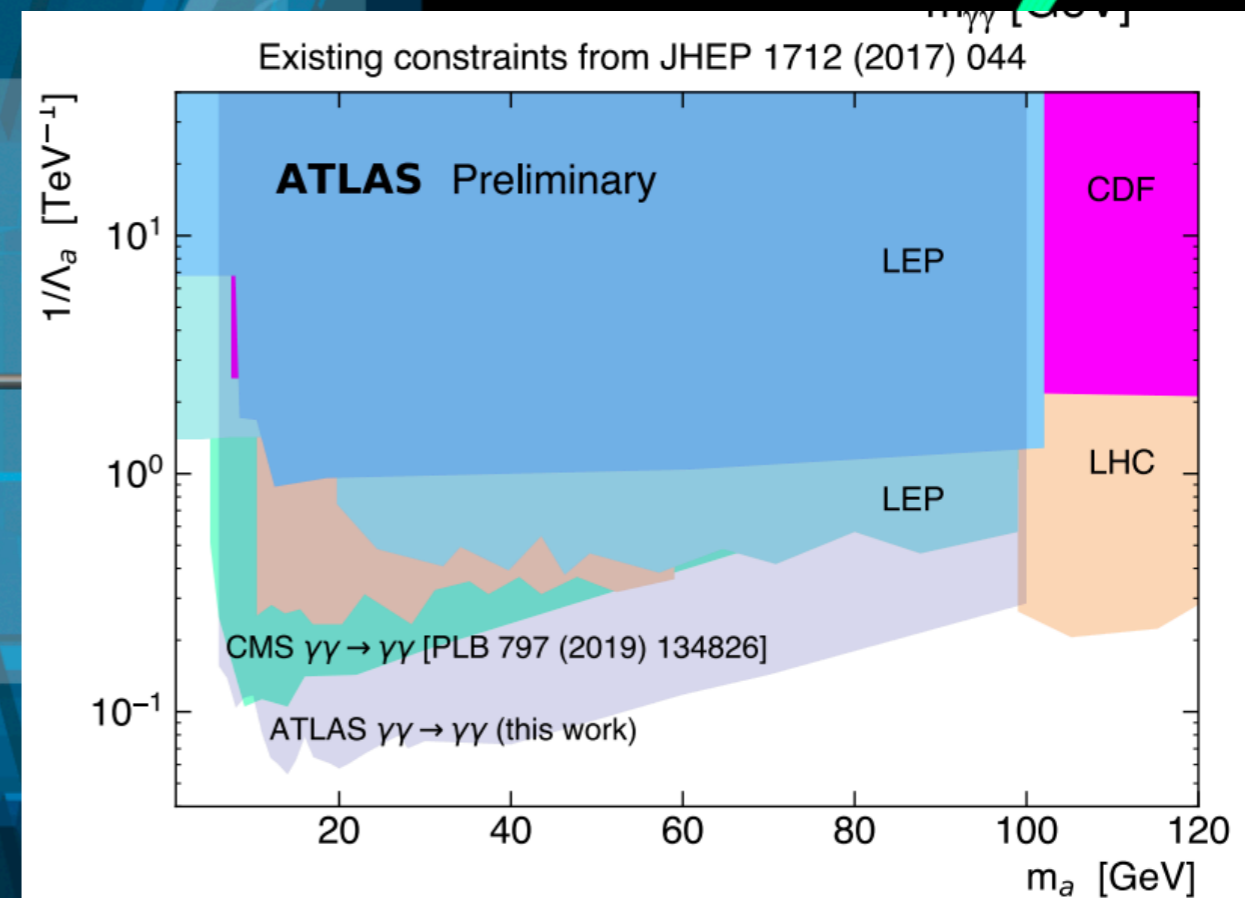
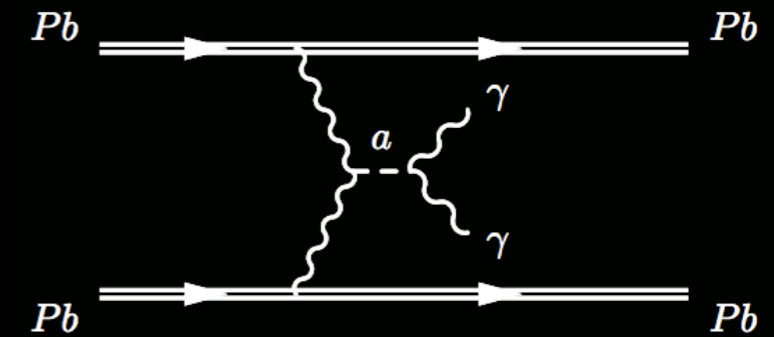
CMS: *Phys. Lett. B* 797 (2019) 134826

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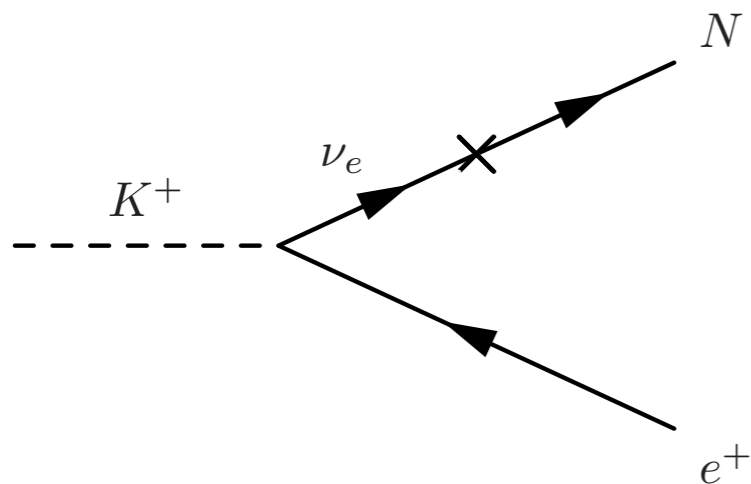
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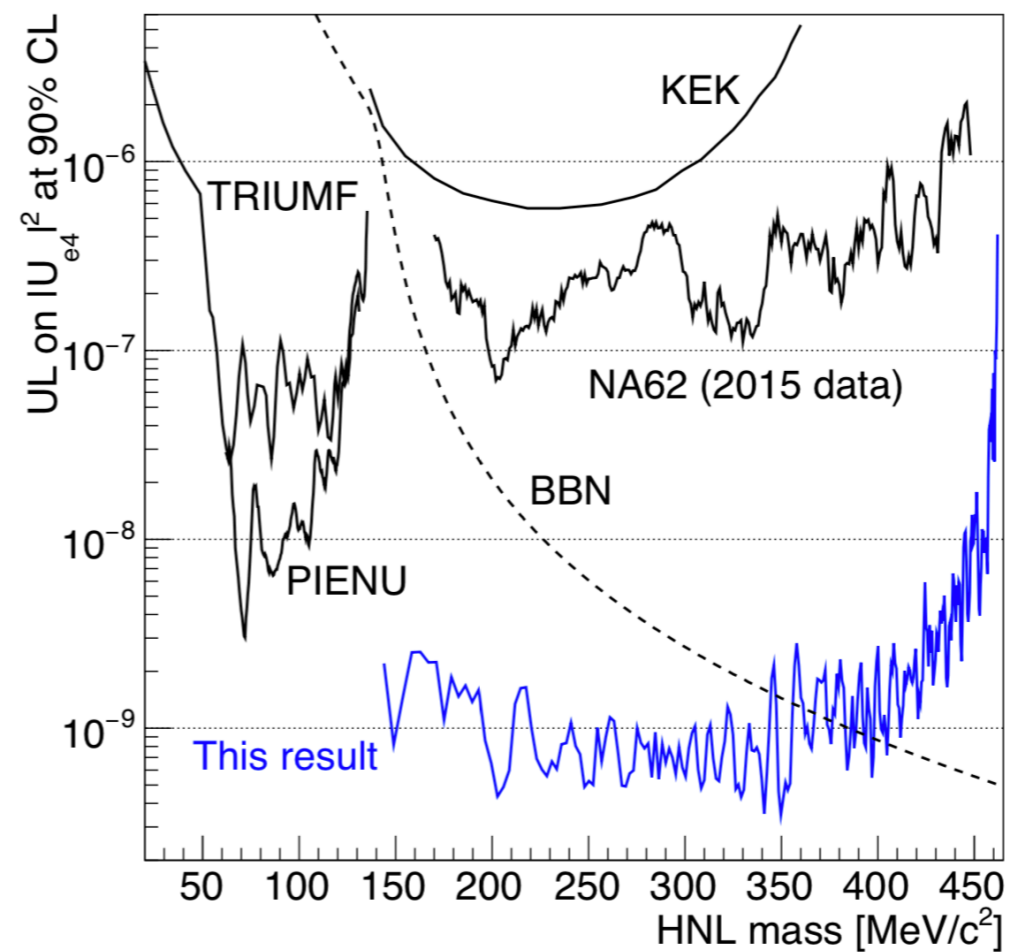
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# Production in exotic decays

Example: Heavy Neutral Lepton (HNL)



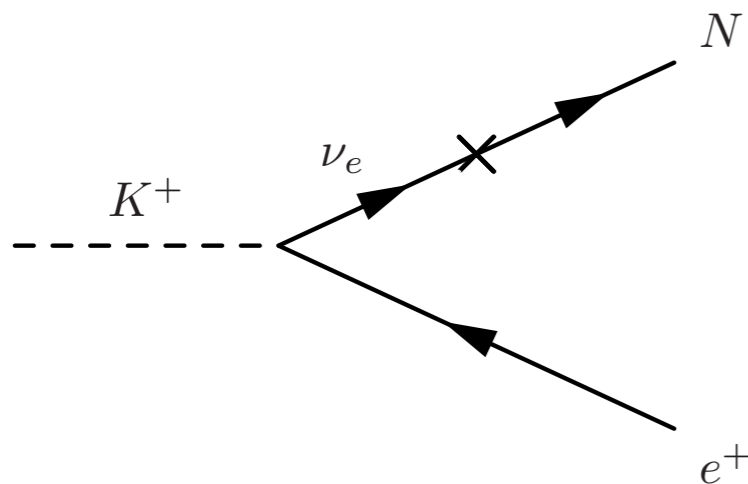
Take advantage of the extremely small width of  $K^+$



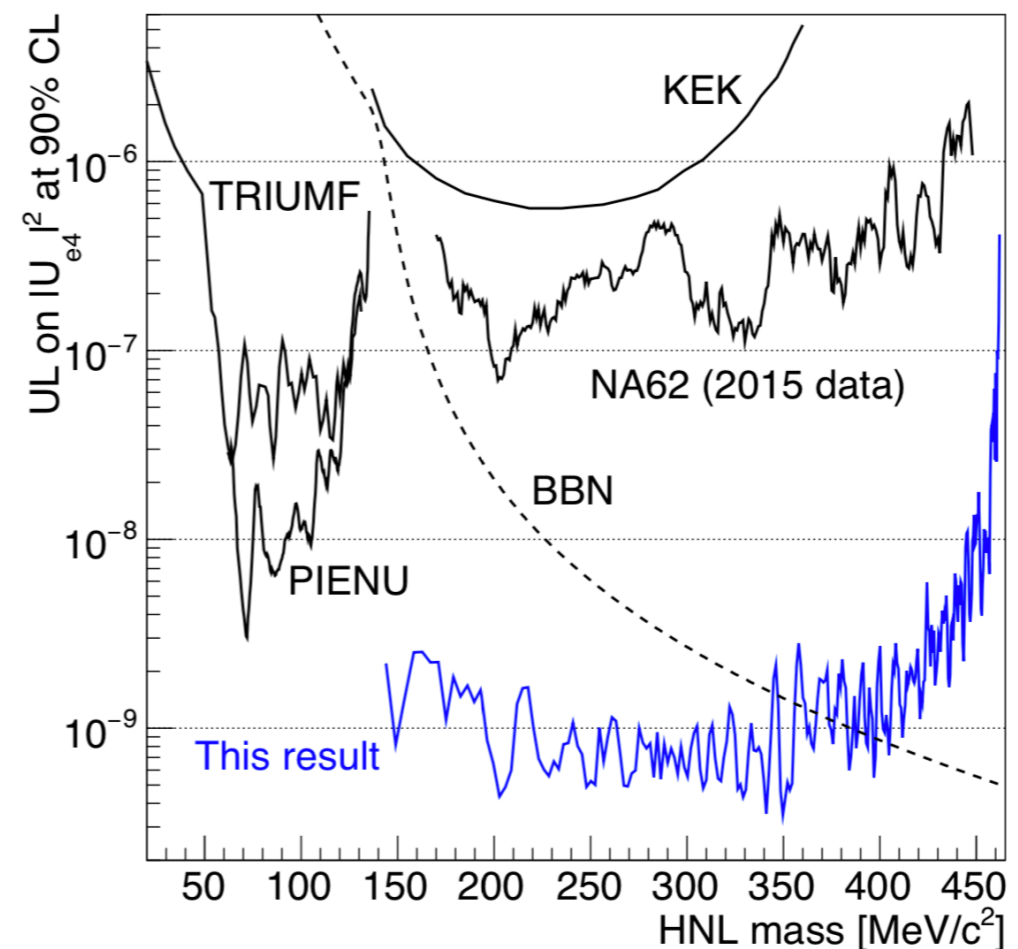
NA62: arXiv 2005.09575

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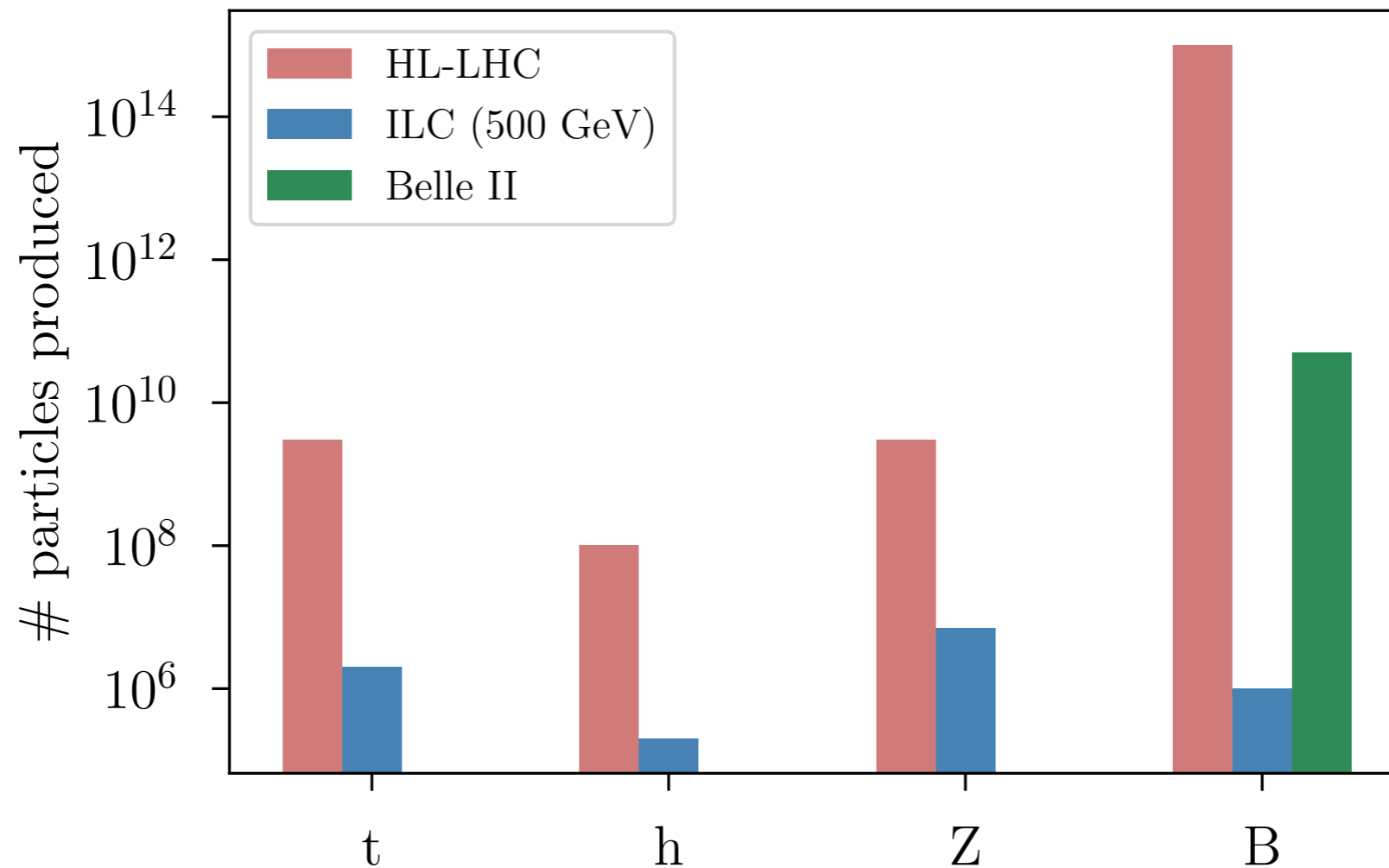
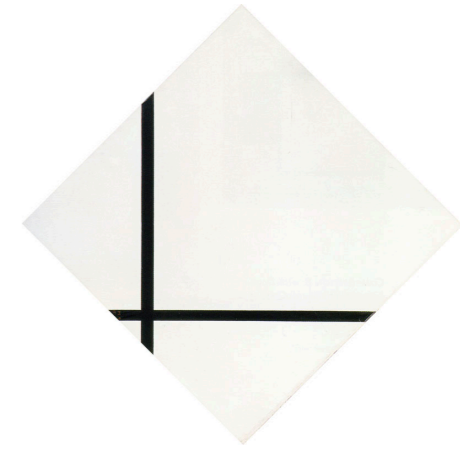
NA62: arXiv 2005.09575

For ATLAS, CMS & LHCb, B and Higgs\* decays provide the best opportunities

\* See Bhawna Gomber's talk

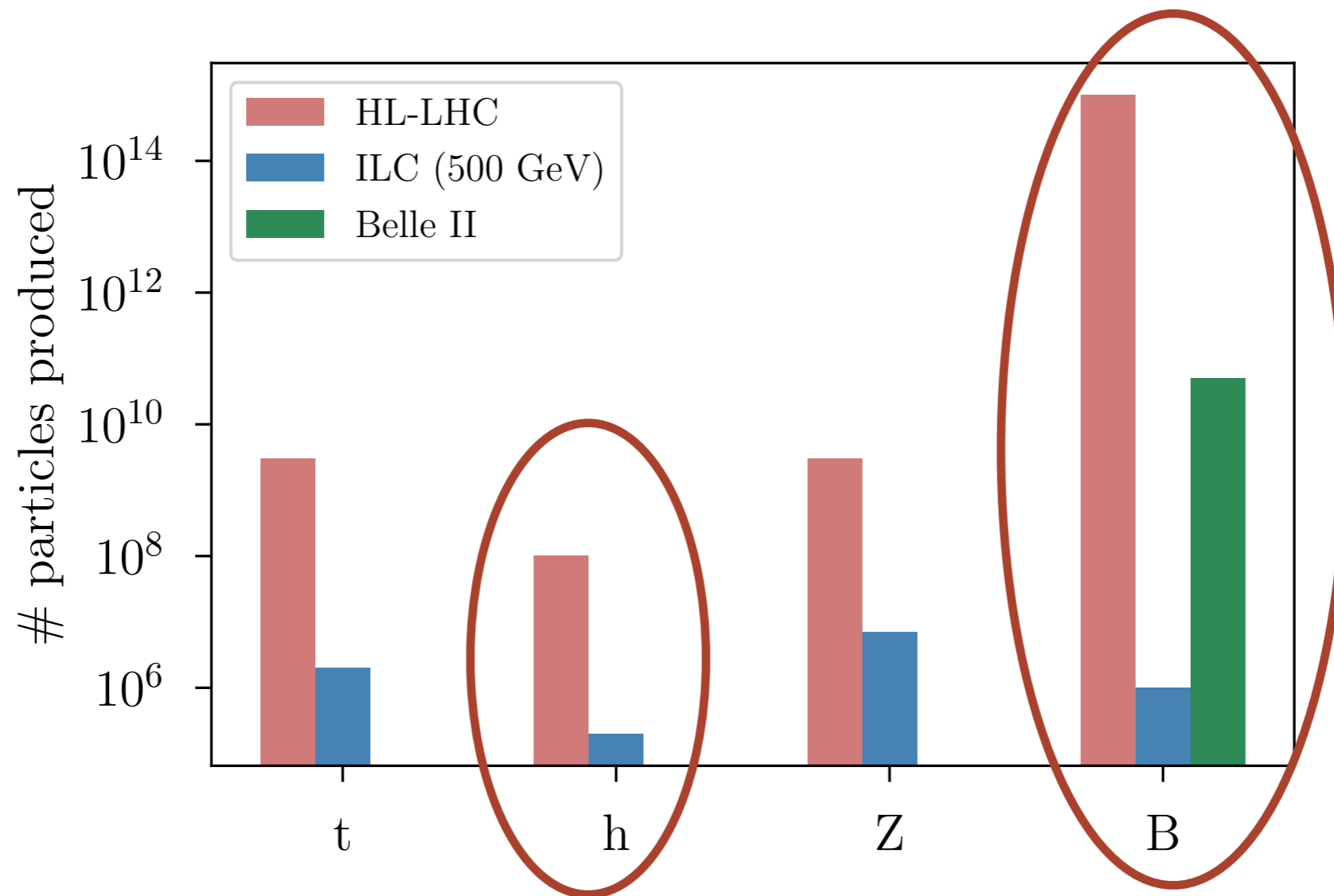
# Particle yields @ HL-LHC

Precision measurements often challenging, but huge particle yields



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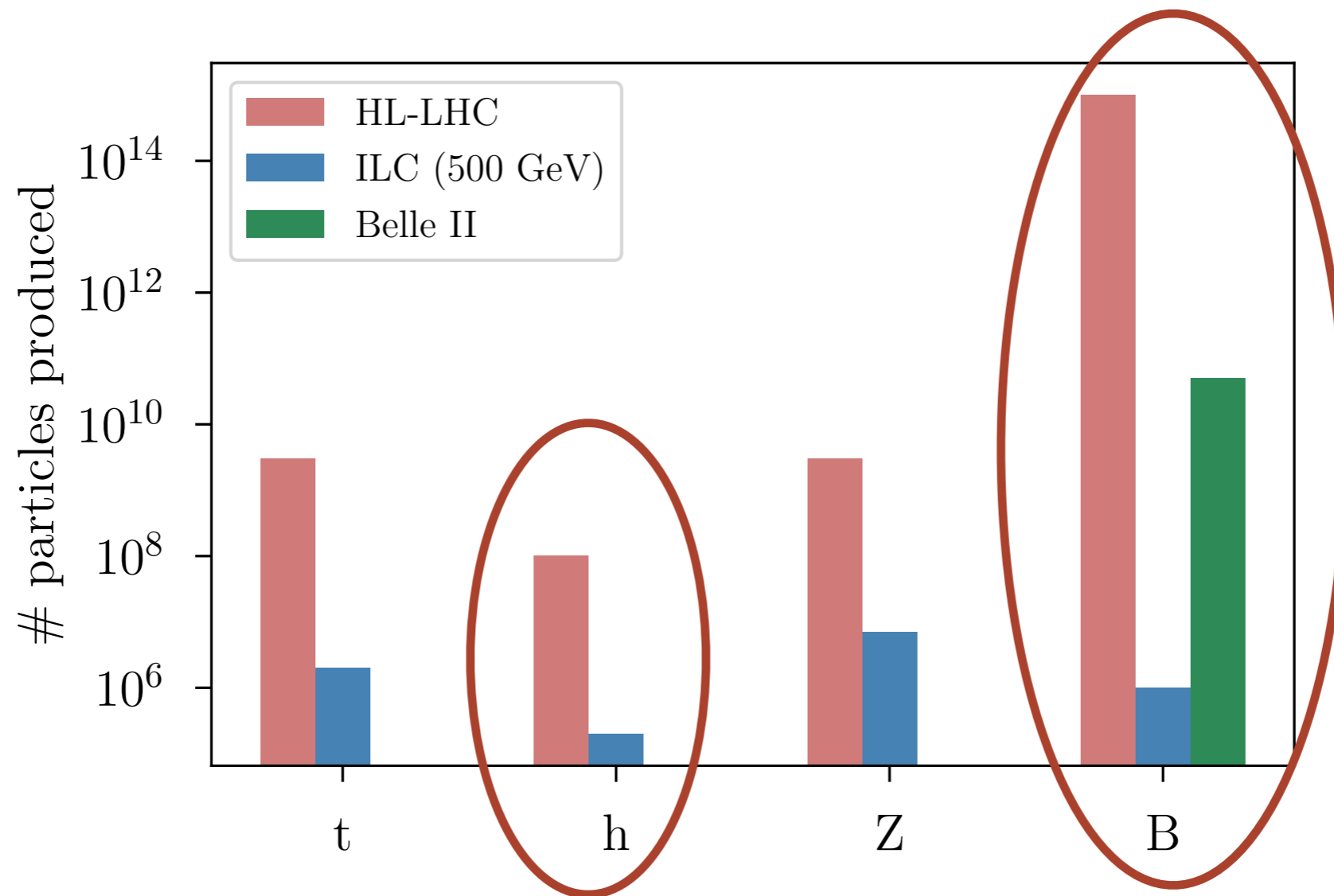
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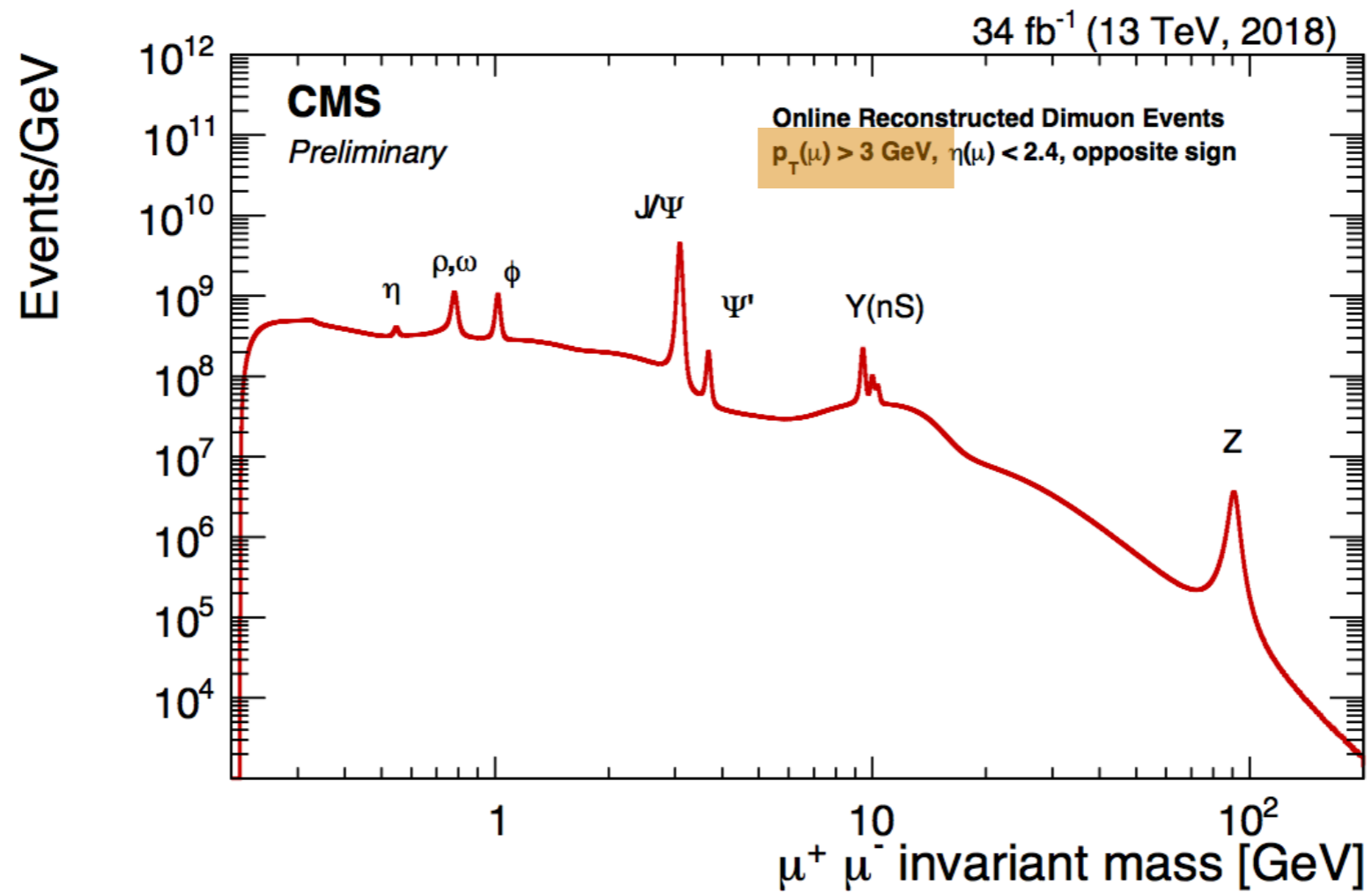


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In which cases can we overcome trigger & background challenges?

# Scouting & Parking

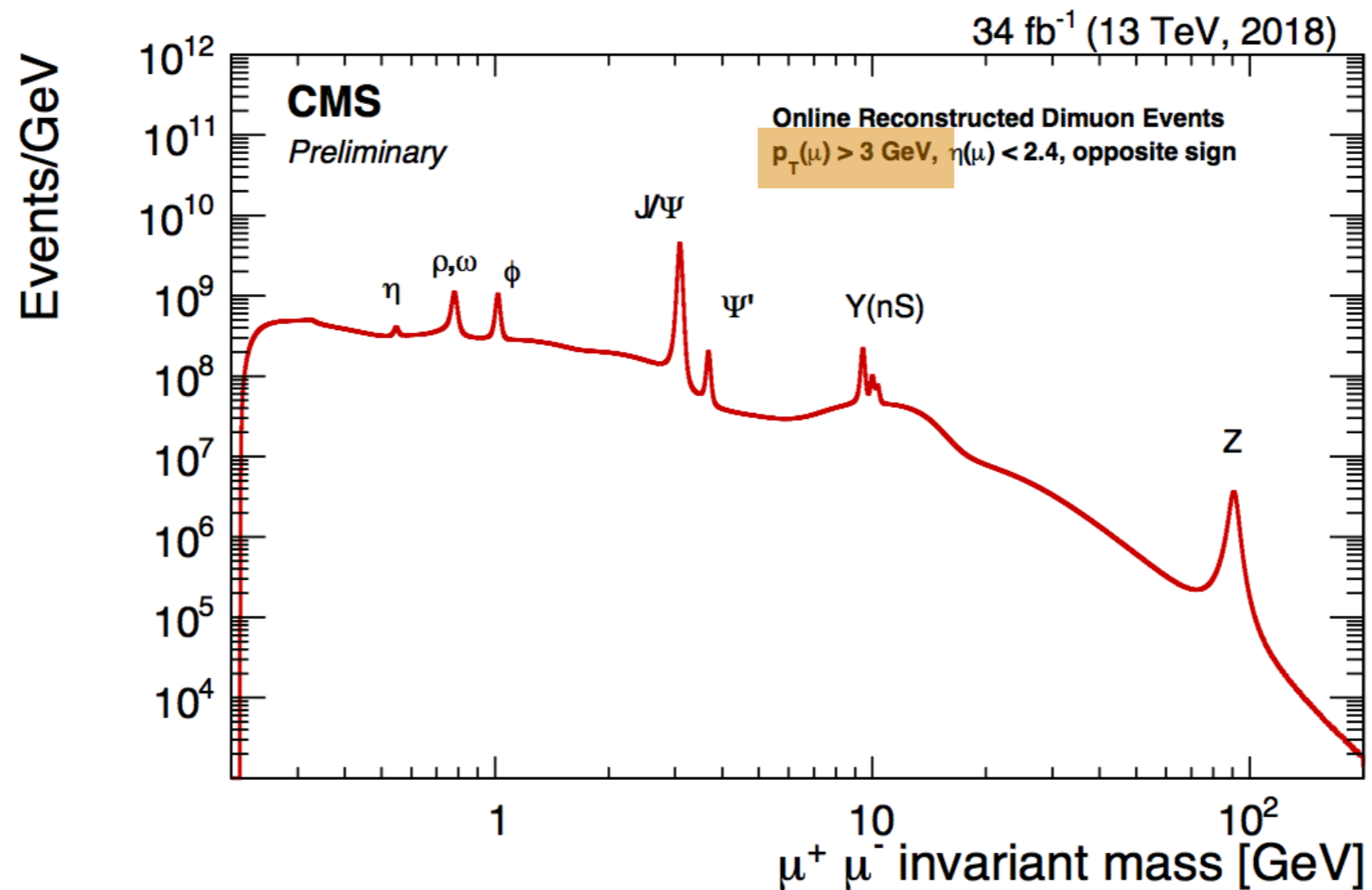
Scouting: record small fraction of the event



CMS DP-2018/055, CMS PAS EXO-19-018

# Scouting & Parking

Scouting: record small fraction of the event



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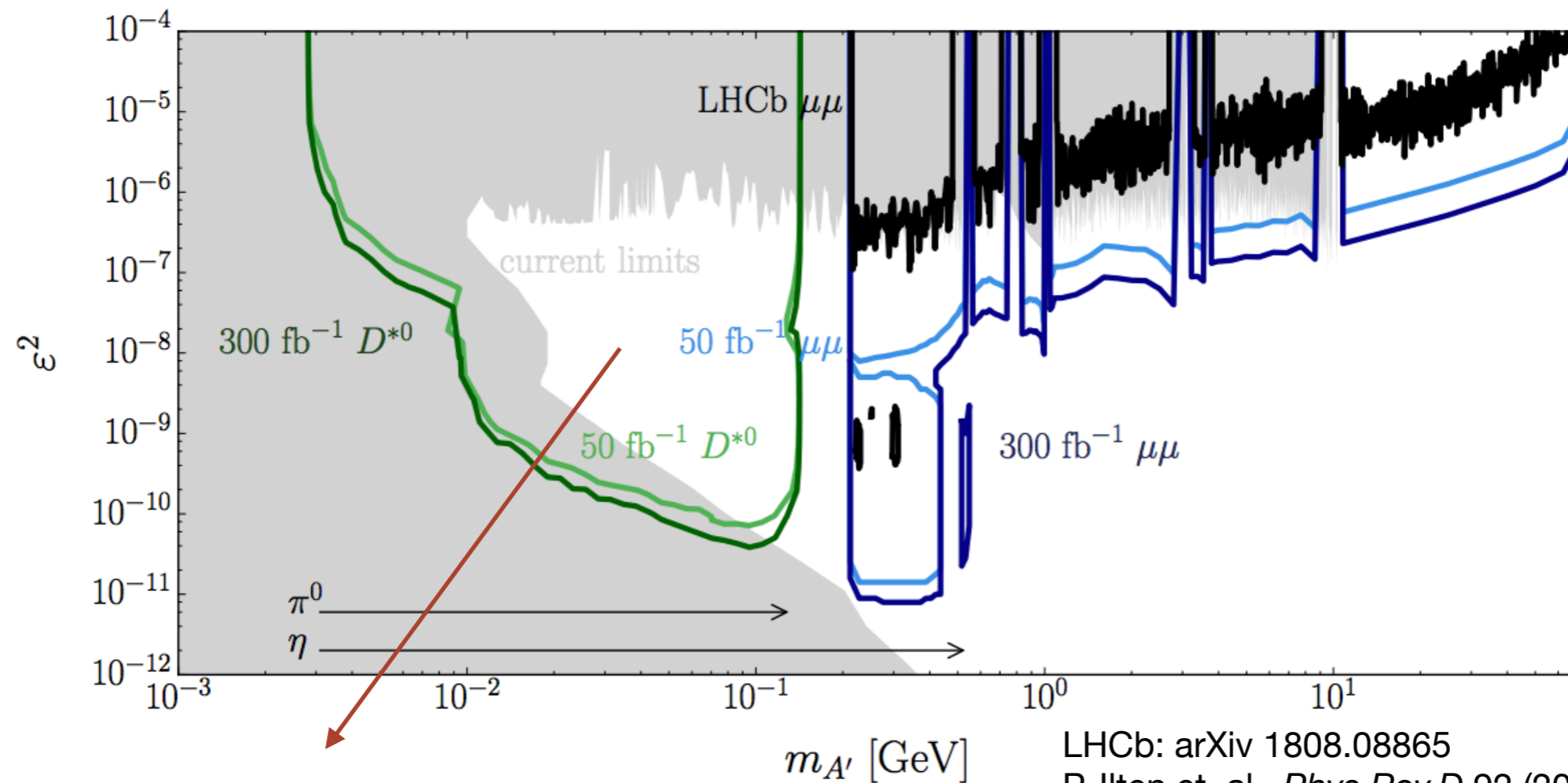
Parking: reconstruct event later  $\rightarrow 10^{10}$  B's on tape already! (CMS)

In both cases, a plan must be in place *before* data taking!

# Scouting & Parking

LHCb will take this to the next level by eliminating the L1 trigger

Example: dark photon reach



Will cover the “triangle of doom”!

LHCb: arXiv 1808.08865

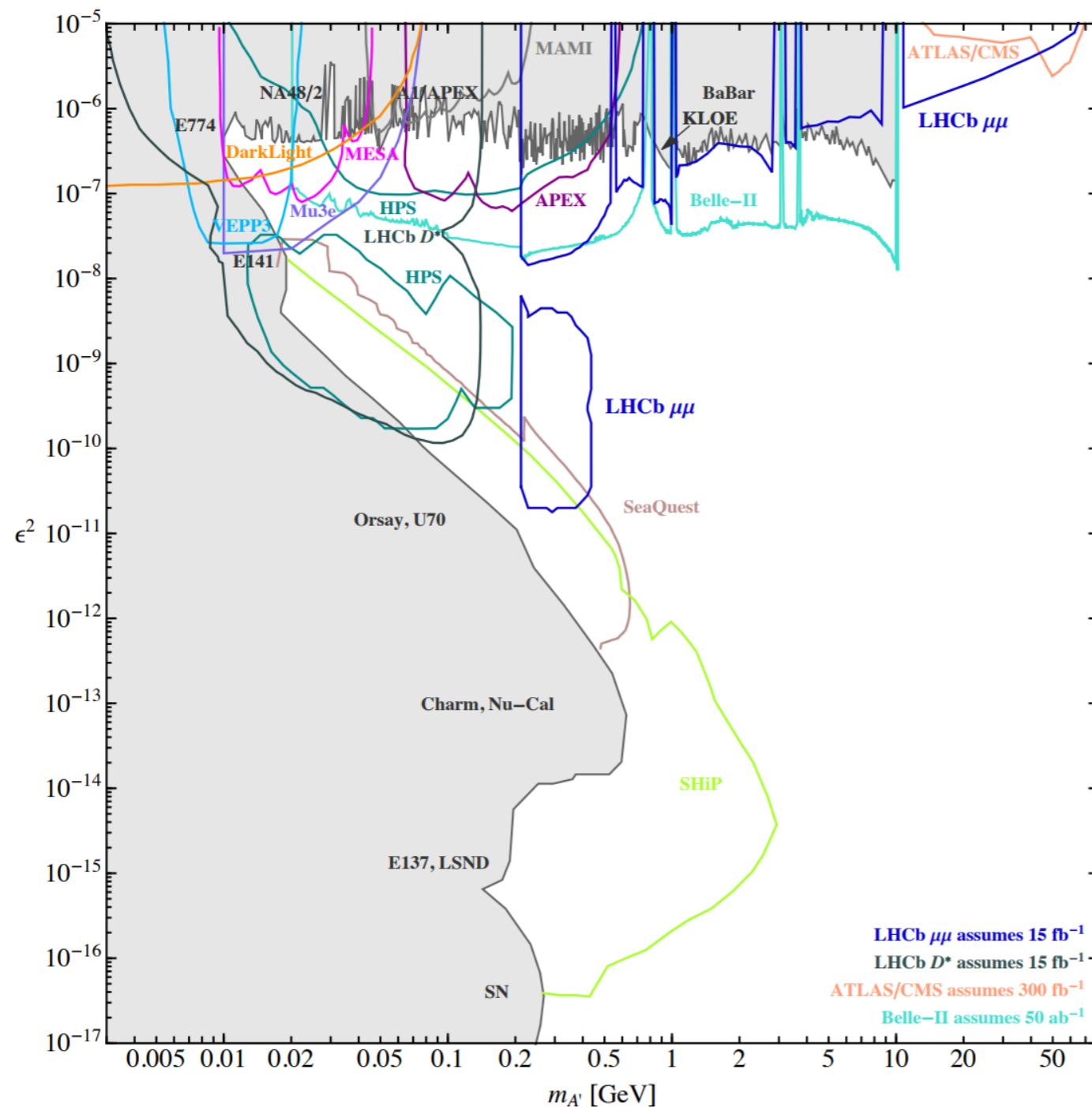
P. Ilten et. al. *Phys.Rev.D* 92 (2015) 11, 115017

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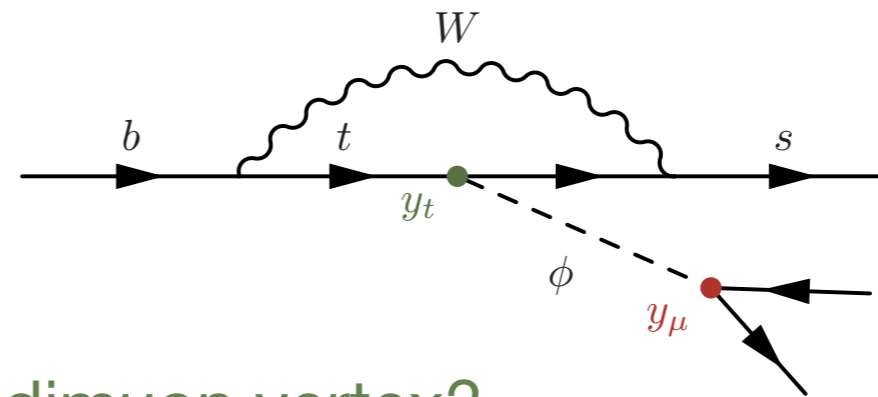
When combined with beam dump & supernova bounds, rule out\* “minimal” dark photons for  $m_{A'} \lesssim 100$  MeV

\* bounds weaken again for  $m_{A'} \ll \text{eV}$

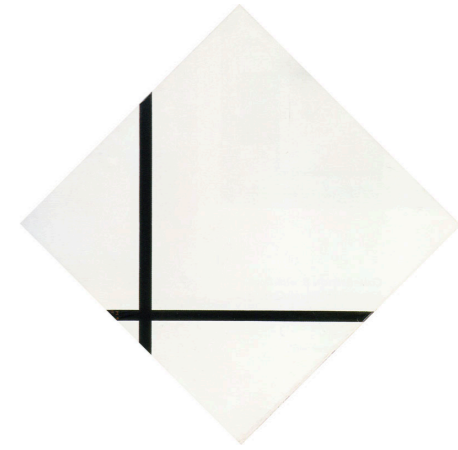
# CMS L1 track trigger

Example: dark Higgs

$$B \rightarrow X_s \phi \rightarrow \mu\mu$$



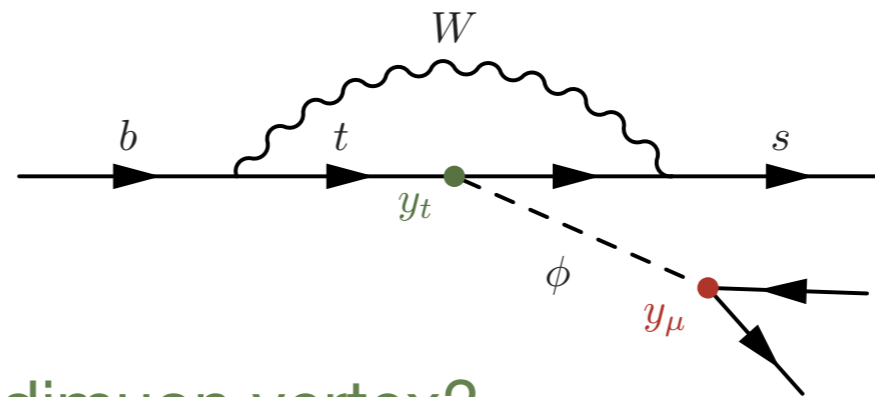
Can CMS trigger on a displaced dimuon vertex?



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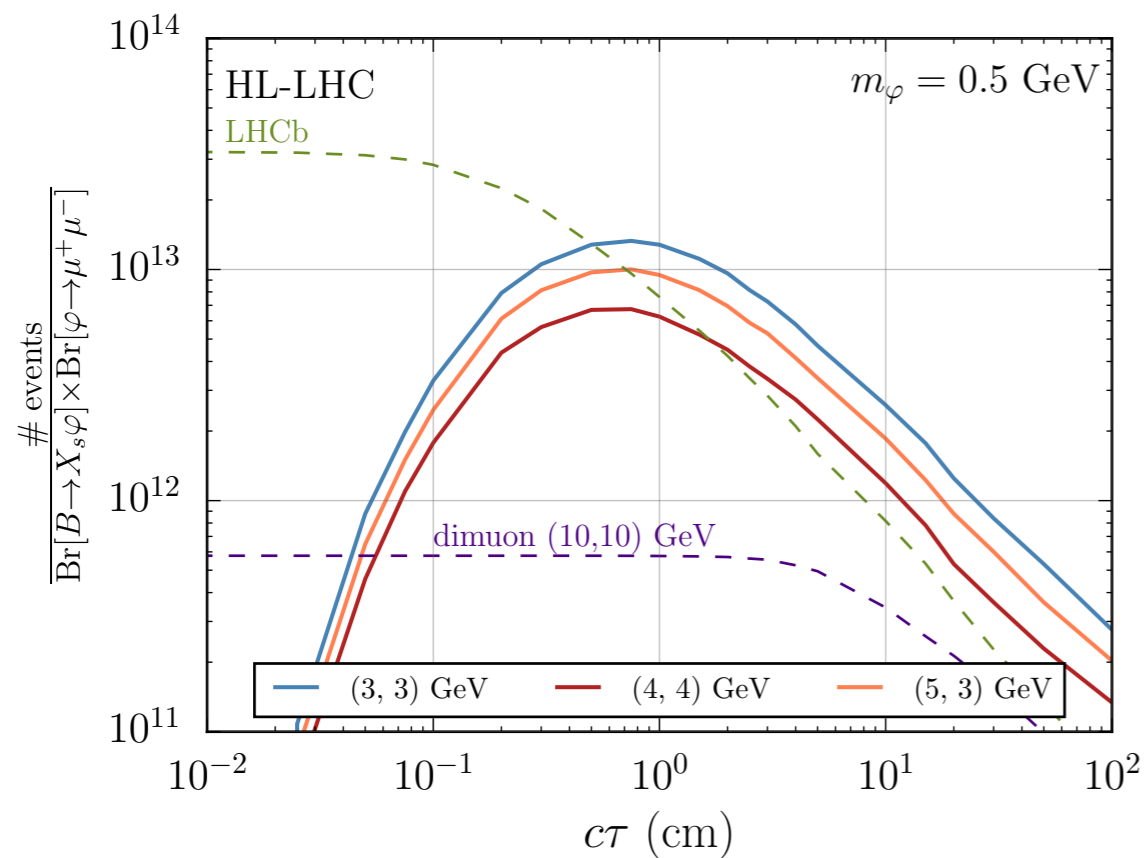
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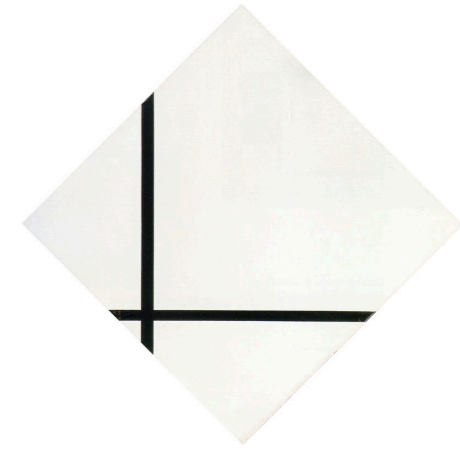
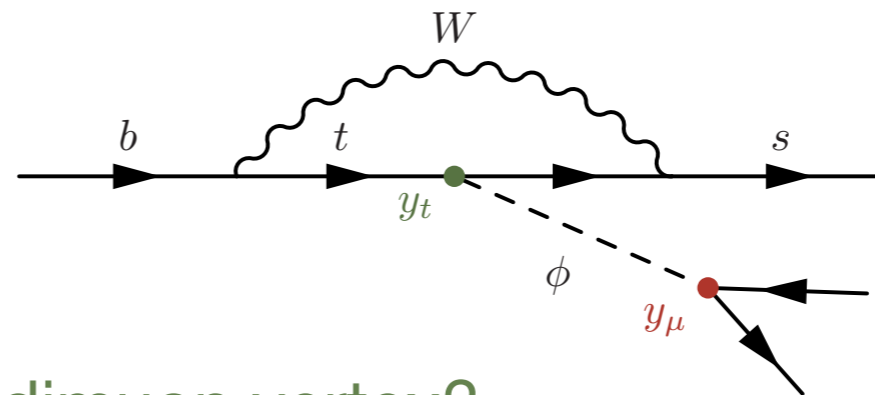
Y. Gershtein: arXiv 1705.04321

Y. Gershtein, SK: arXiv 1907.00007

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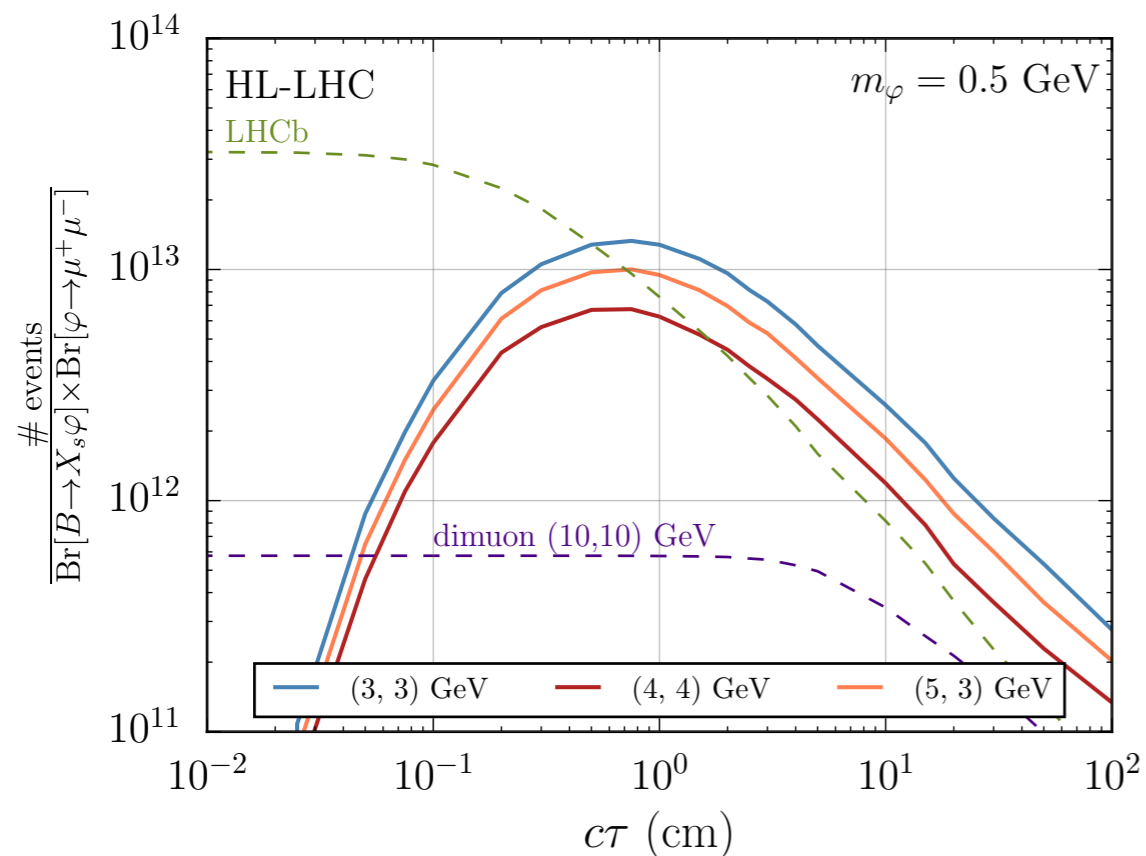
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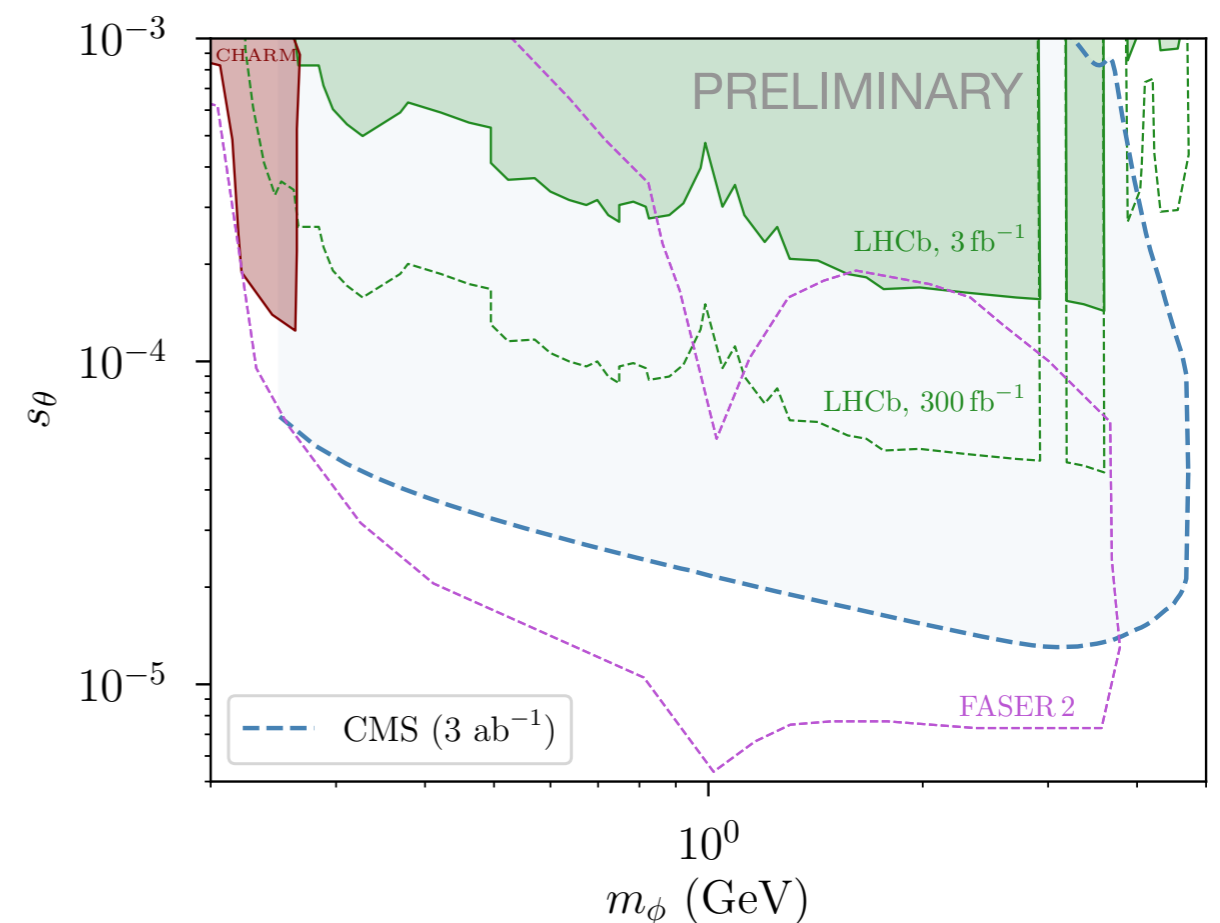


Can CMS trigger on a displaced dimuon vertex?

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Reach estimate

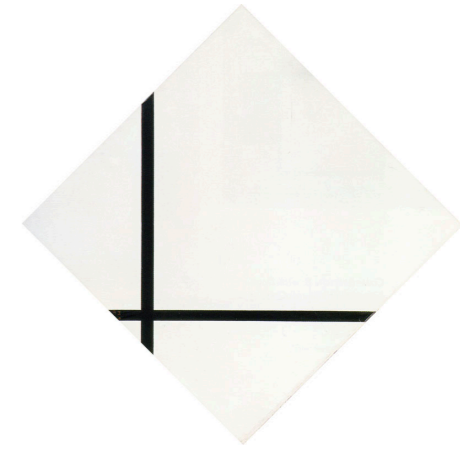


Y. Gershtein: arXiv 1705.04321

Y. Gershtein, SK: arXiv 1907.00007

J. Evans, SK: in preparation

# More about “minimalist” models



PBC: Beyond the Standard Model Working Group Report

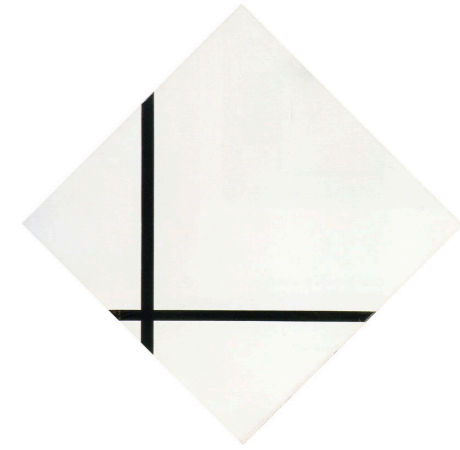


arXiv:1901.09966

(Led by G. Lanfranchi and M. Pospelov)

Caution: Fast evolving field, some details are already outdated!

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(Let by G. Lanfranchi and M. Pospelov)

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Mini virtual workshop

Physics Beyond Colliders meets theory: informal discussions about PBC selected topics

8-10 June 2020

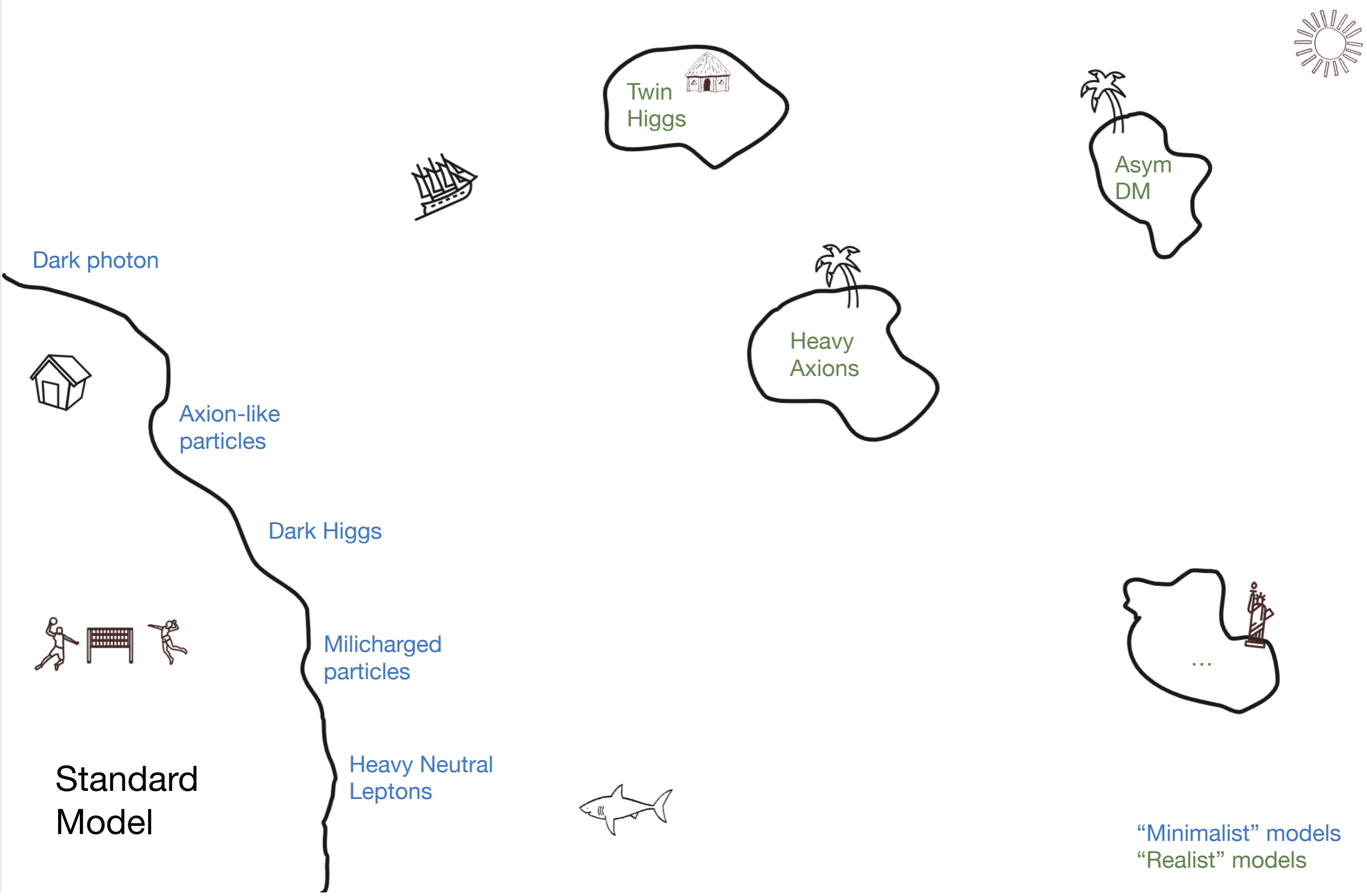
CERN

Europe/Zurich timezone

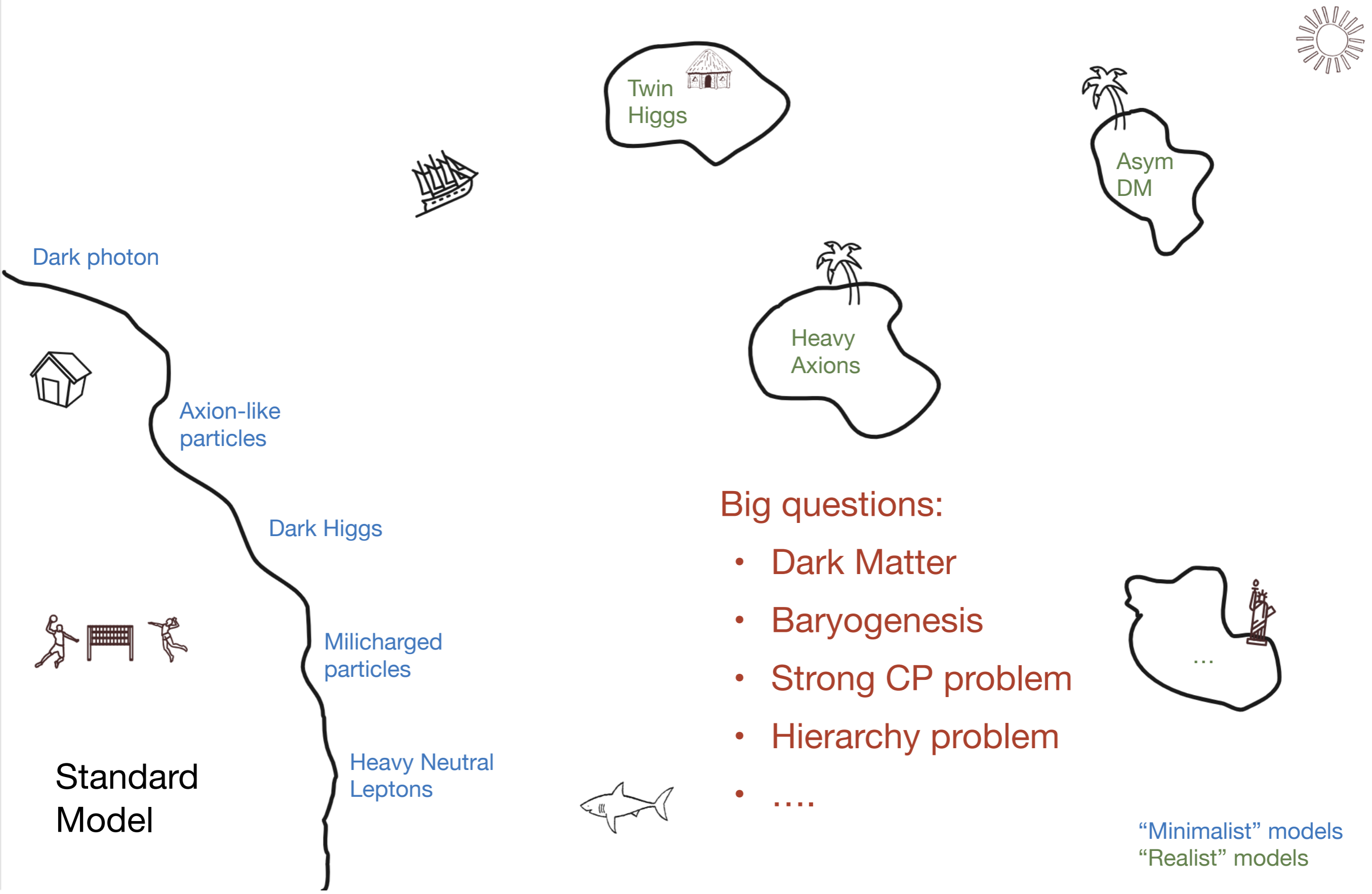


<https://indico.cern.ch/event/910753/overview>

# Journey through the dark sector



# Journey through the dark sector



# Asymmetric Dark Matter / Baryogenesis

Why is there more matter than anti-matter?



Baryogenesis needs:

- CP violation
- Out of equilibrium dynamics
- Baryon number violation

# Asymmetric Dark Matter / Baryogenesis



Why is there more matter than anti-matter?

Baryogenesis needs:

- CP violation
- Out of equilibrium dynamics
- Baryon number violation

Standard Model offers:

- CKM phase
- Electroweak phase transition
- Electroweak sphaleron processes

Unfortunately, SM phase transition and CP violation are too weak. 🥲

# Asymmetric Dark Matter / Baryogenesis

Solution: Put all your hopes and dreams in the dark sector!

Dark baryogenesis / “darkogenesis”

J. Shelton, K. Zurek: arXiv 1008.1997



# Asymmetric Dark Matter / Baryogenesis

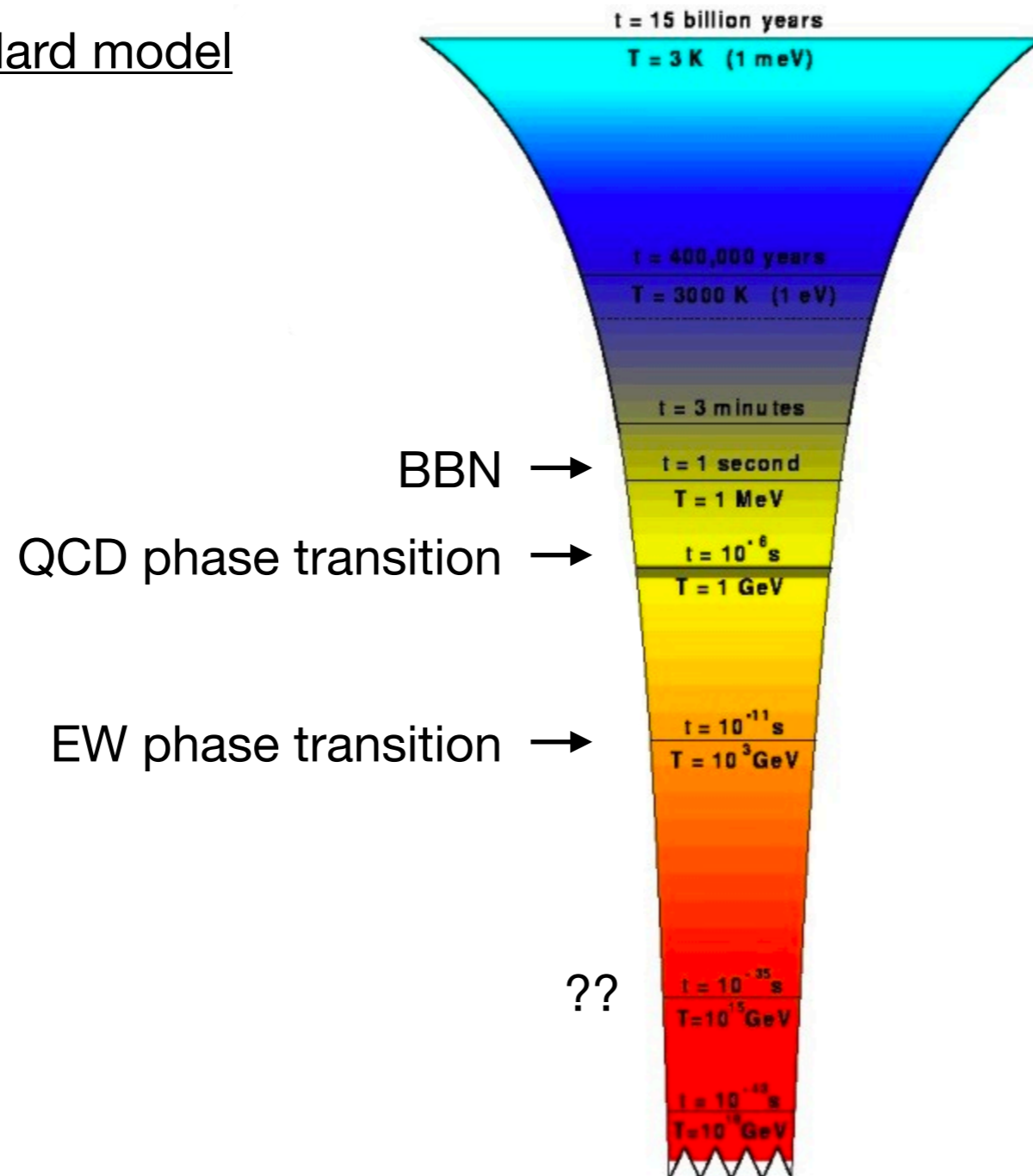
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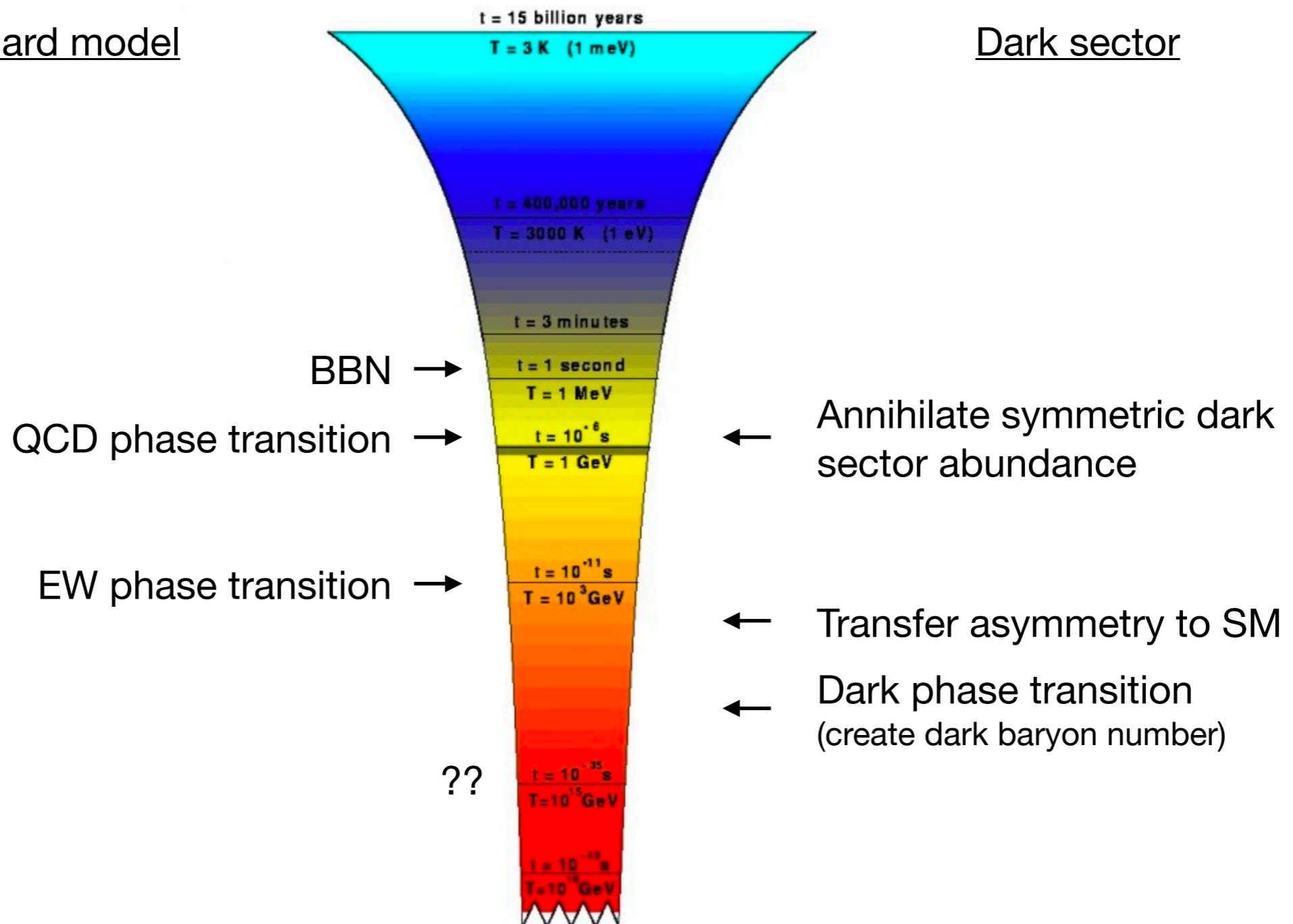
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Standard model

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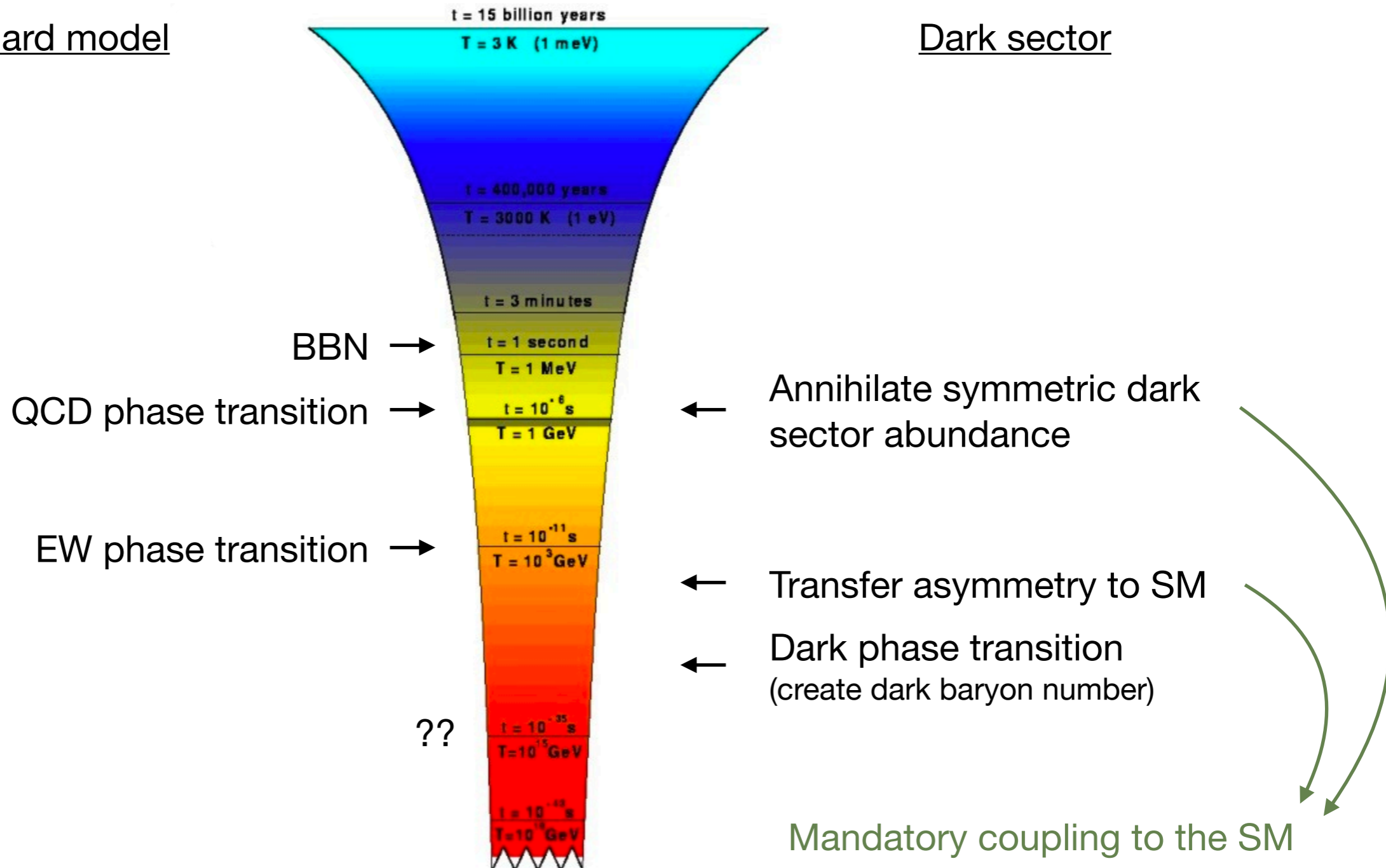
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Standard model

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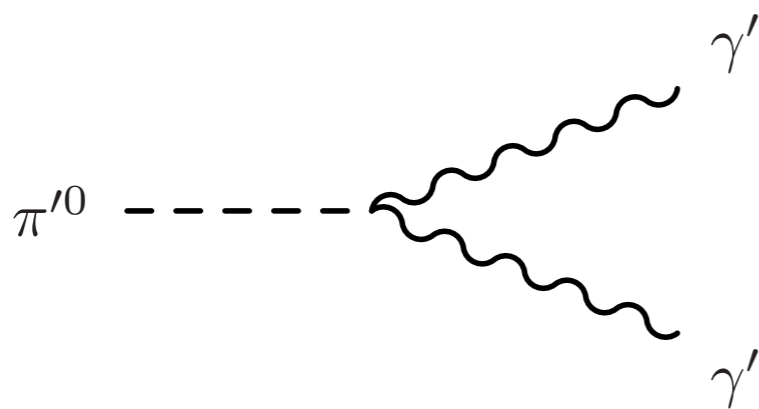
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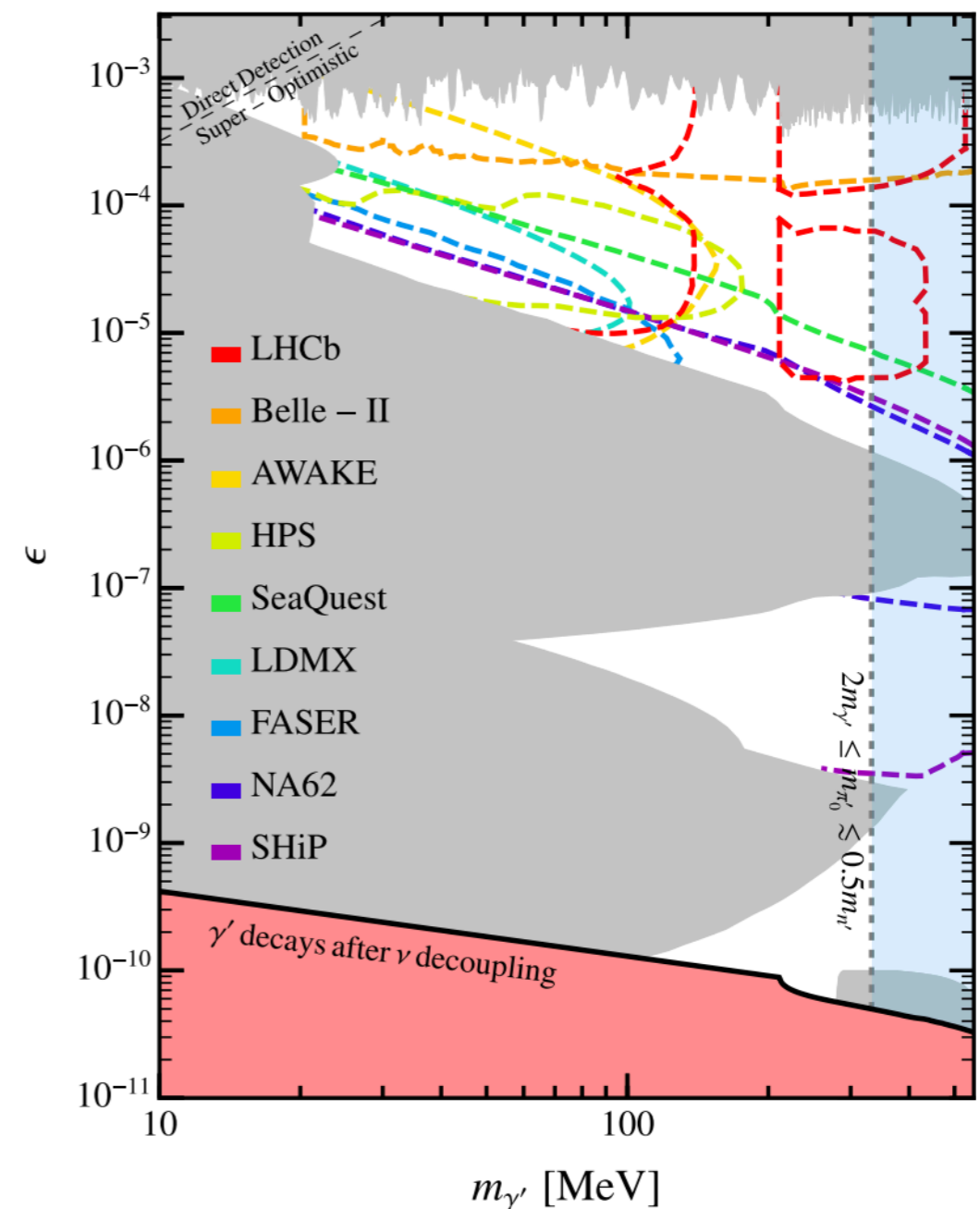
## Example

Composite dark sector with “dark neutron” as the dark matter candidate

Deplete dark pions through decay to dark photon



## Dark Neutron Dark Matter

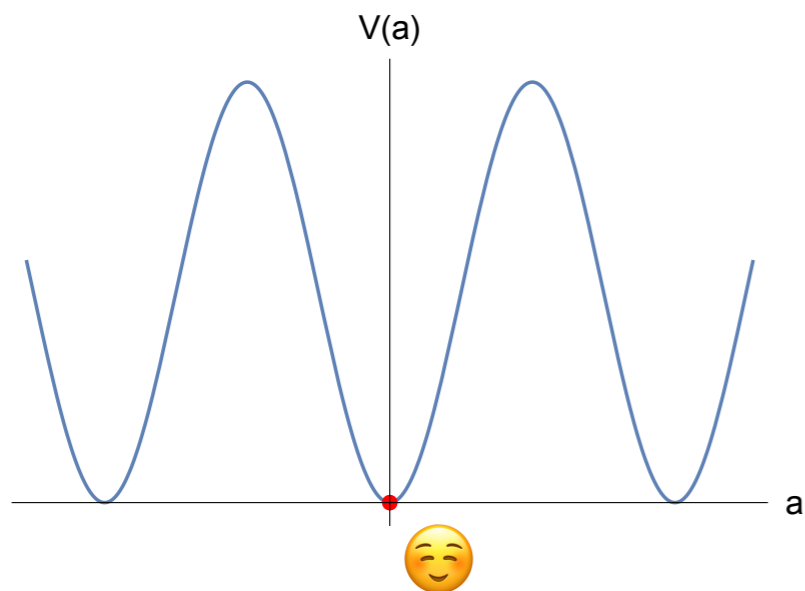


# Axion quality problem

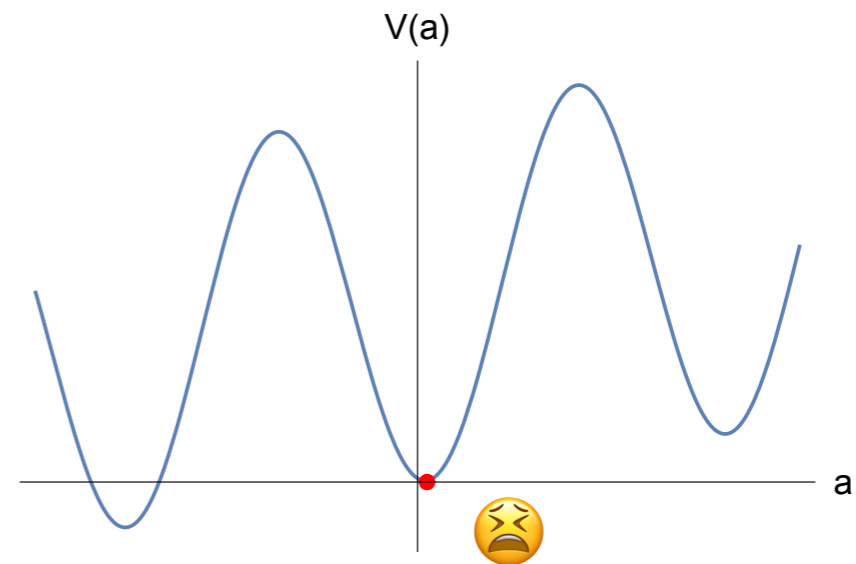
Axion solution to strong CP problem is fairly fragile:



Only QCD breaks Peccei Quin symmetry

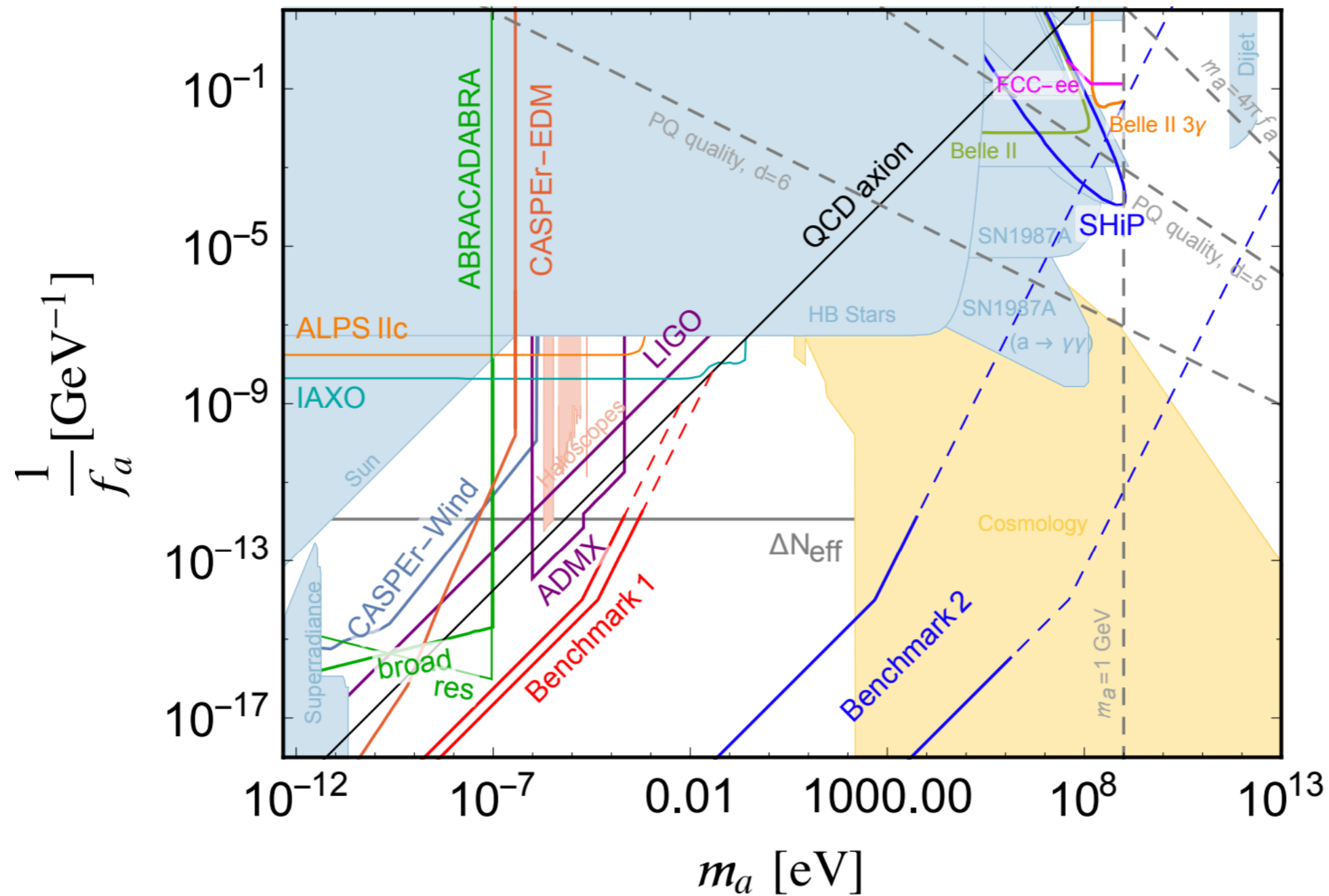


Other sources of Peccei Quin breaking (e.g. Gravity)

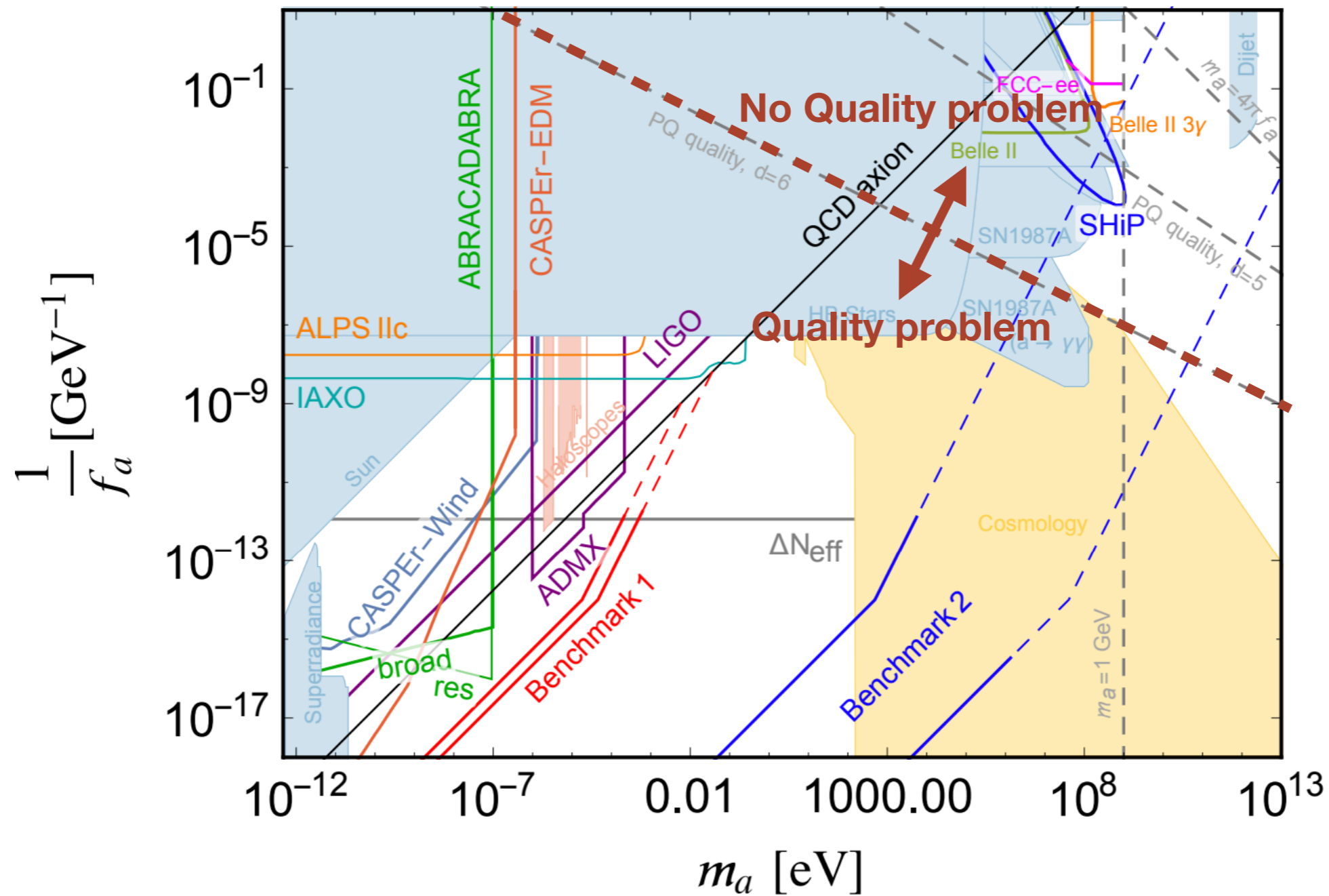


Problem most severe for low mass axions, additional UV model building is needed

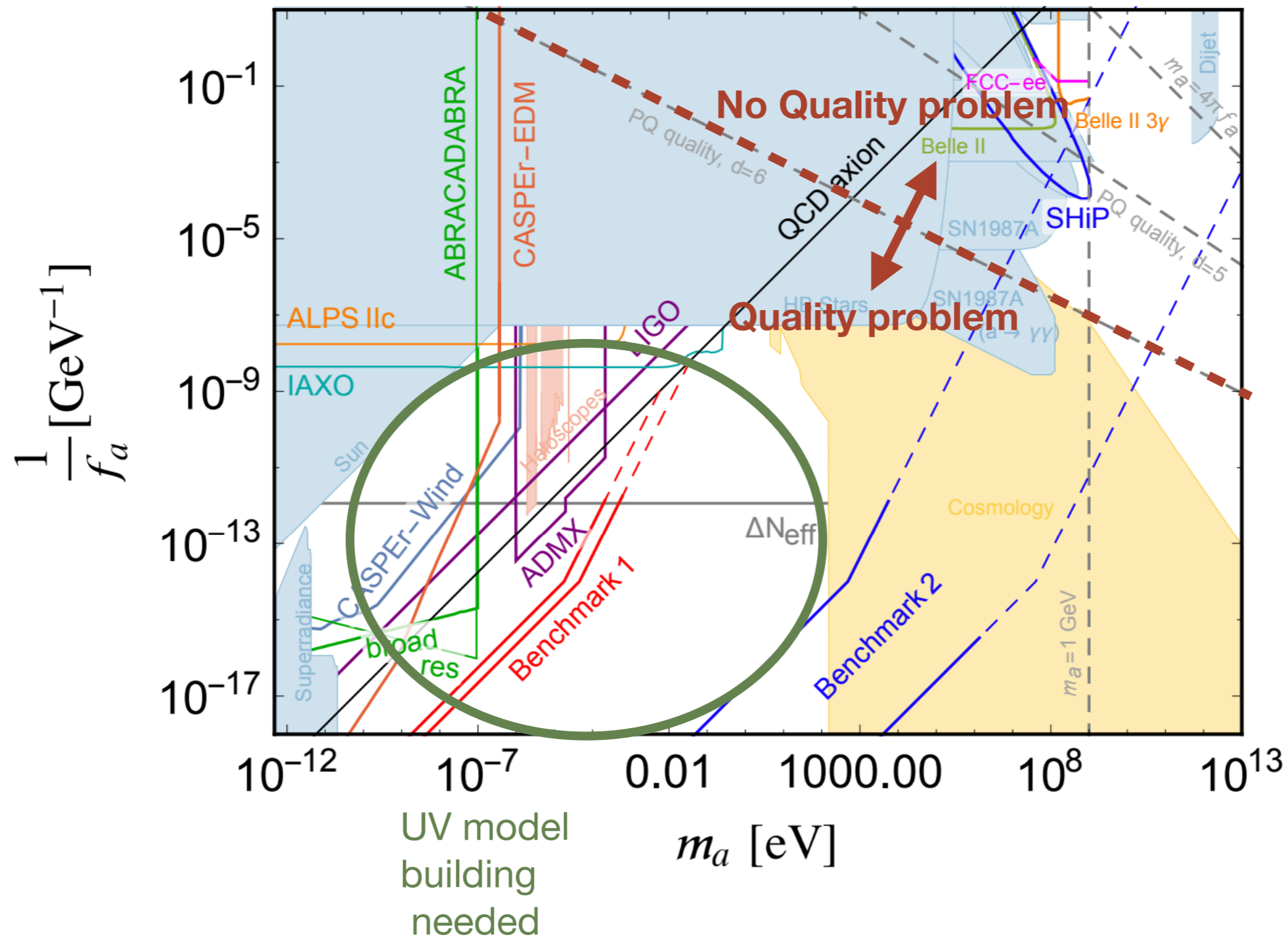
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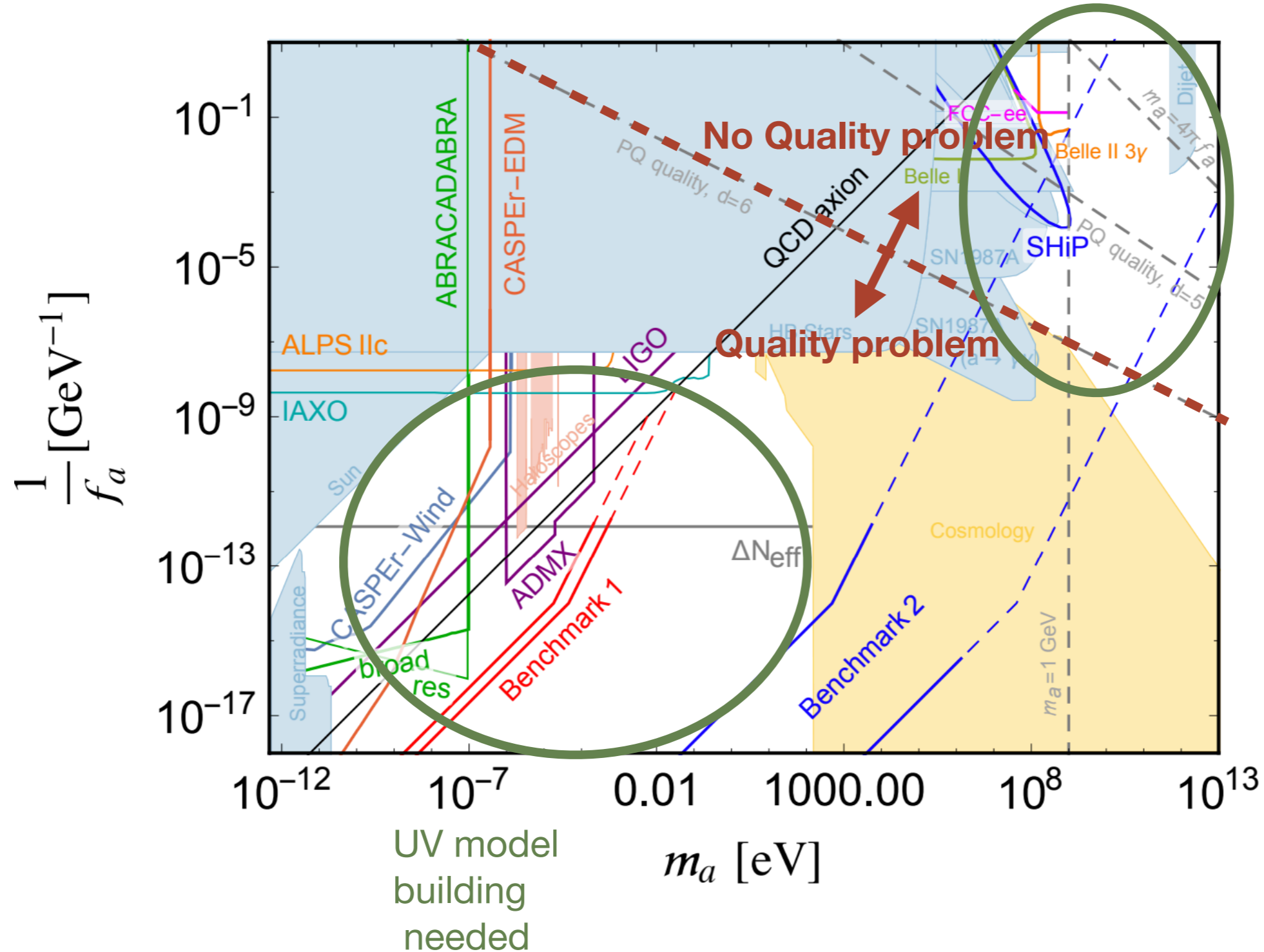
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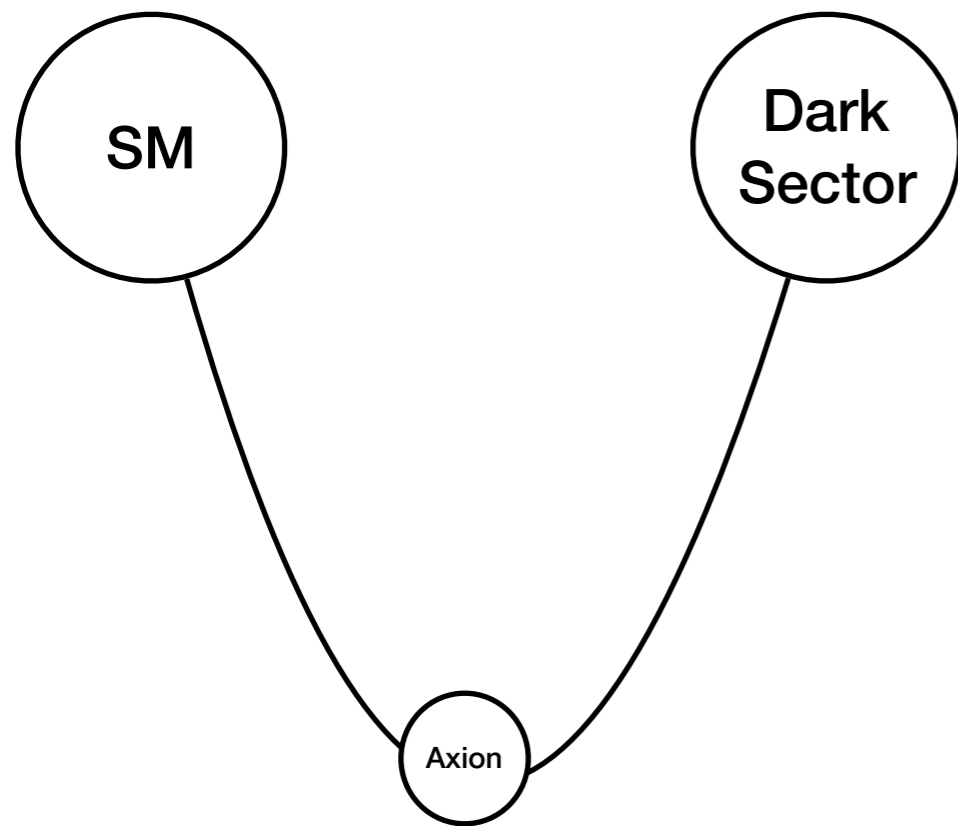
Can we make the axion heavier without spoiling the strong CP problem?



# Axion quality problem

Can we make the axion heavier without spoiling the strong CP problem?

Enter: a dark sector



V. A. Rubakov: arXiv 9703409

P. Agrawal and K. Howe: arXiv 1710.04213, 1712.05803

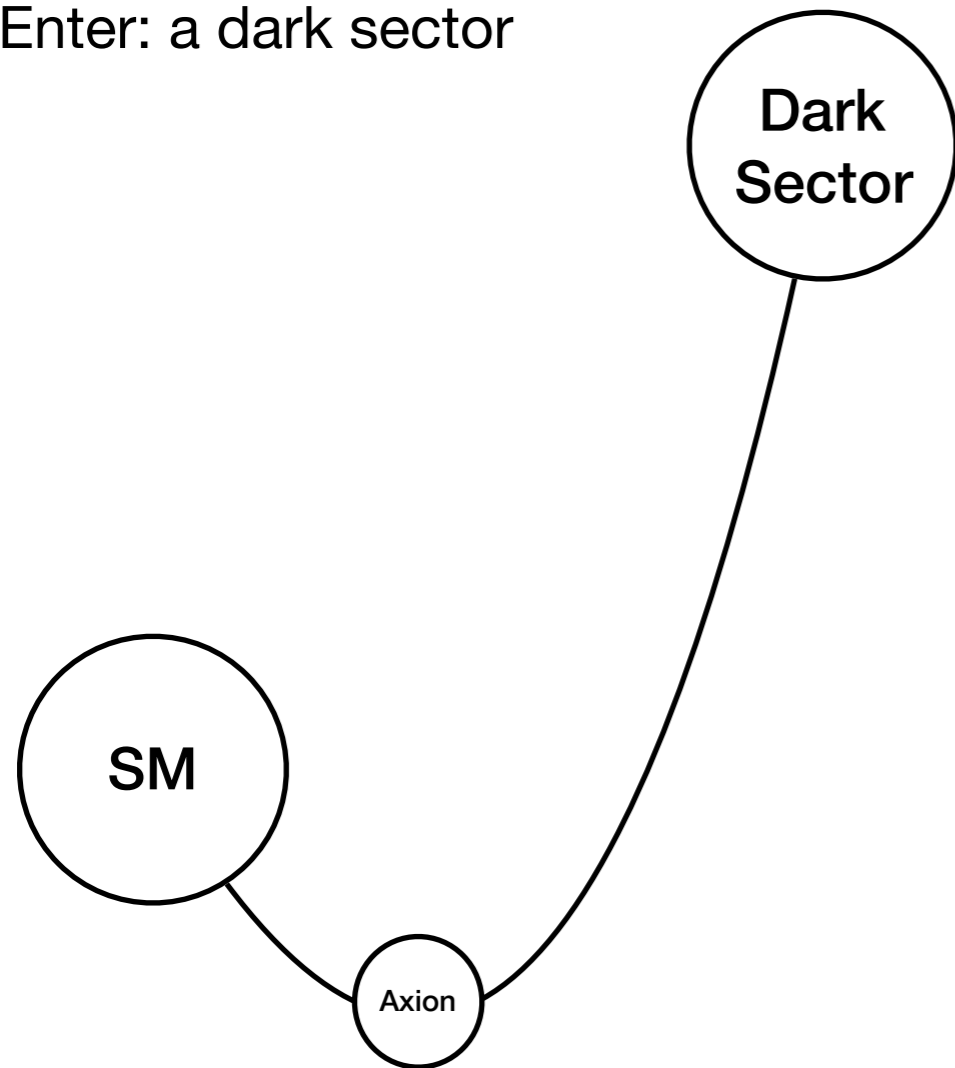
A. Hook et. al.: arXiv 1911.12364

...

# Axion quality problem

Can we make the axion heavier without spoiling the strong CP problem?

Enter: a dark sector



Some cleverness is needed to not spoil the strong CP problem

V. A. Rubakov: arXiv 9703409

P. Agrawal and K. Howe: arXiv 1710.04213, 1712.05803

A. Hook et. al.: arXiv 1911.12364

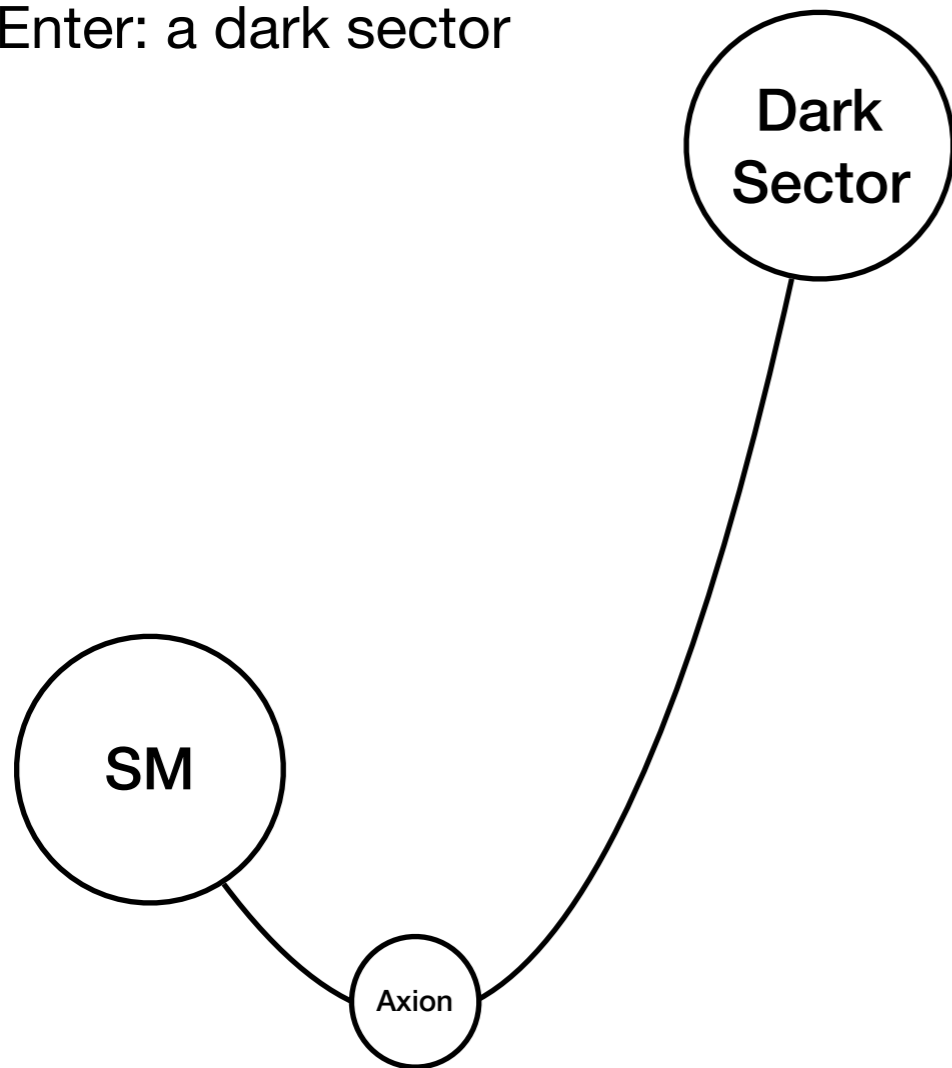
...



# Axion quality problem

Can we make the axion heavier without spoiling the strong CP problem?

Enter: a dark sector



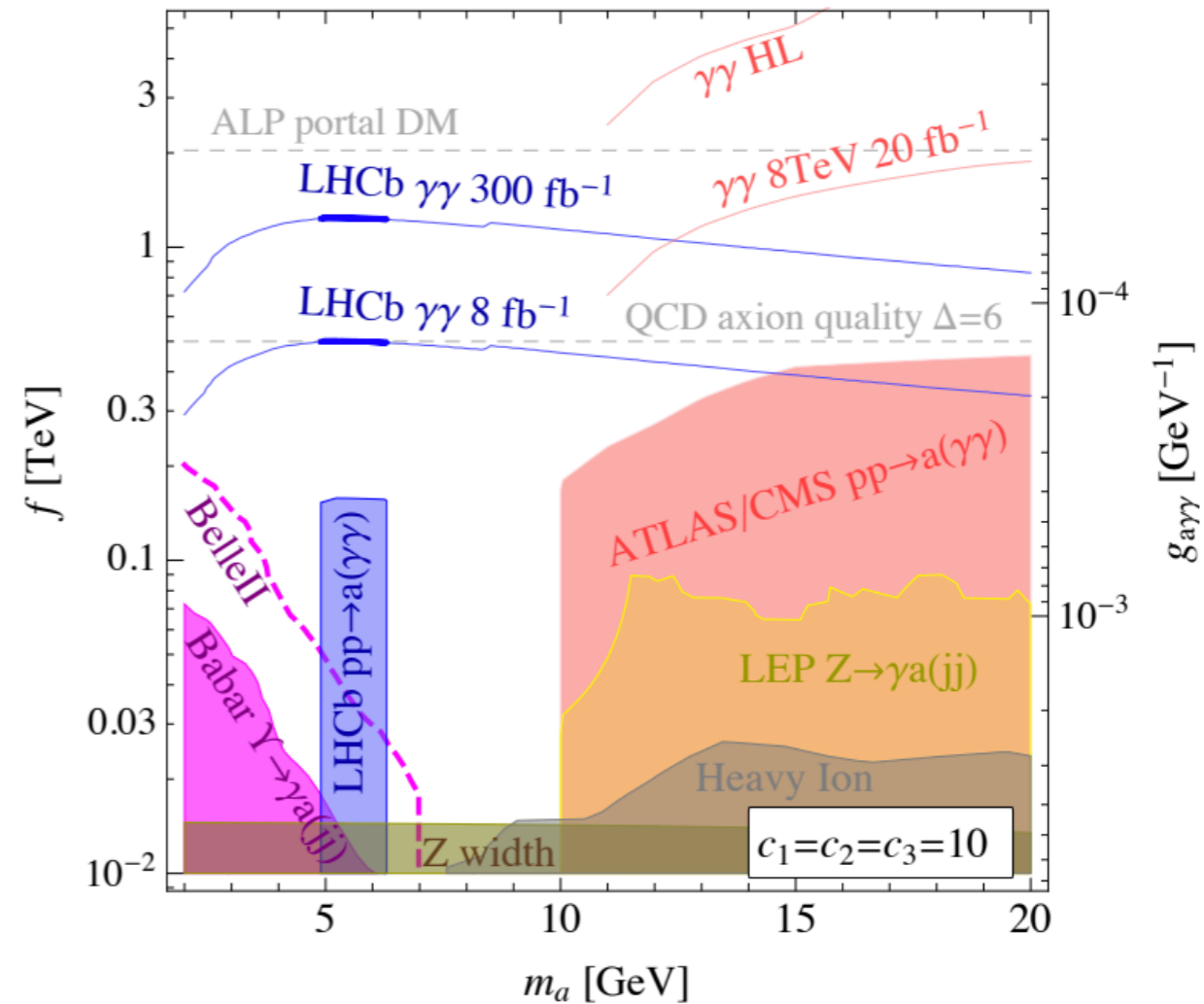
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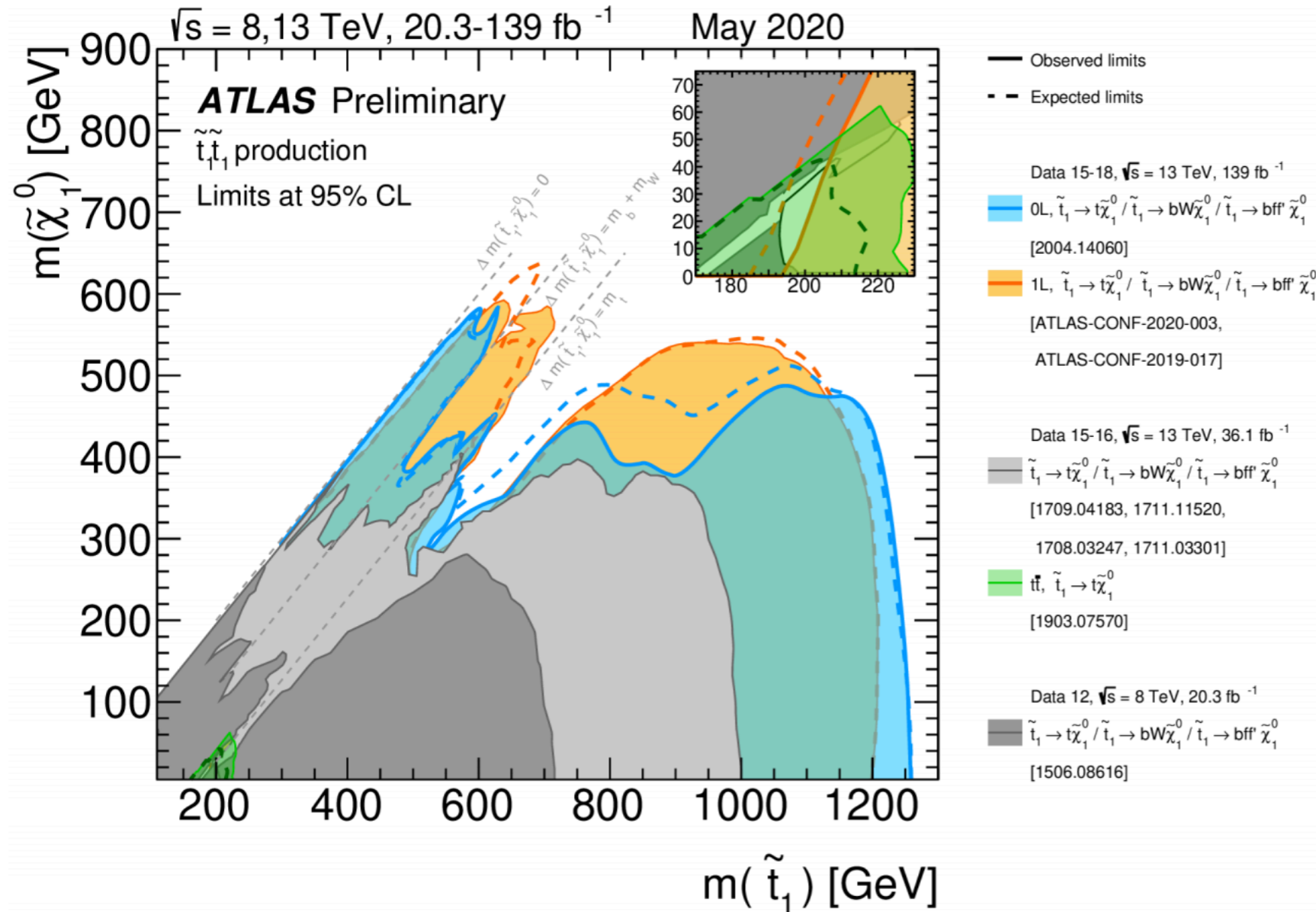
Axion **MUST** couple to gluons, and likely couples to photons (photon jets)

X. Cid Vidal et. al. : arXiv 1810.09452

See also A. Hook et. al.: arXiv 1911.12364

# Twin Higgs

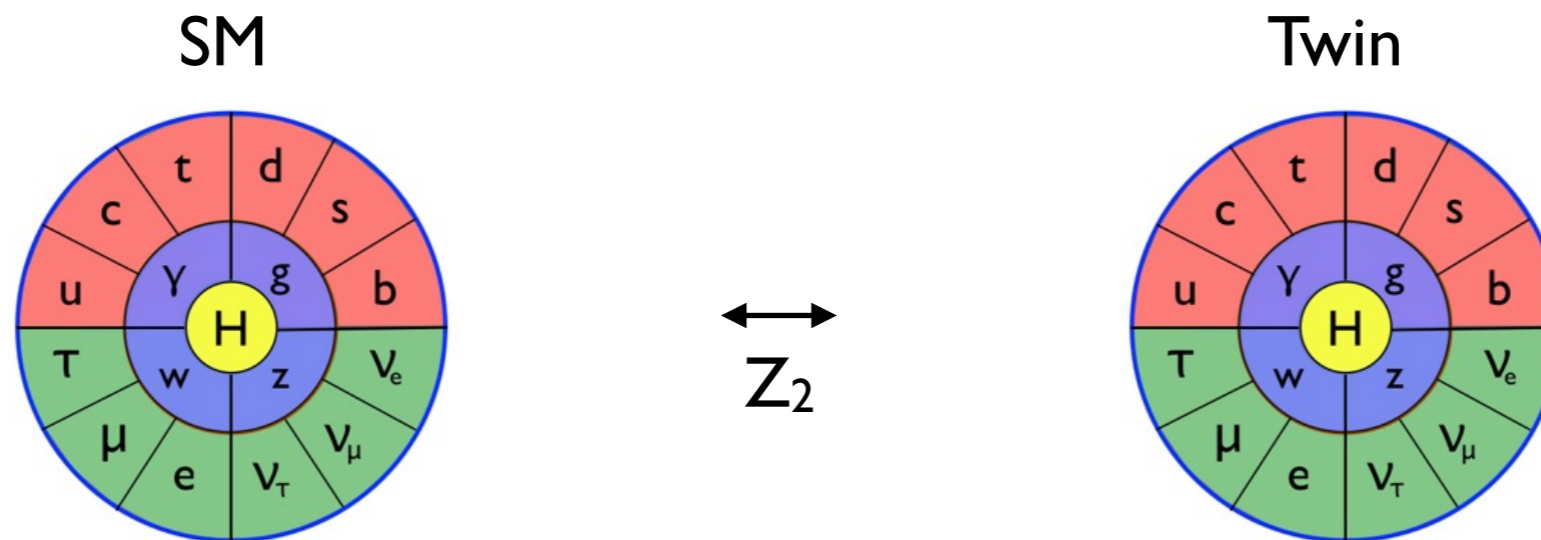
Status of “vanilla” solutions to the hierarchy problem a bit bleak



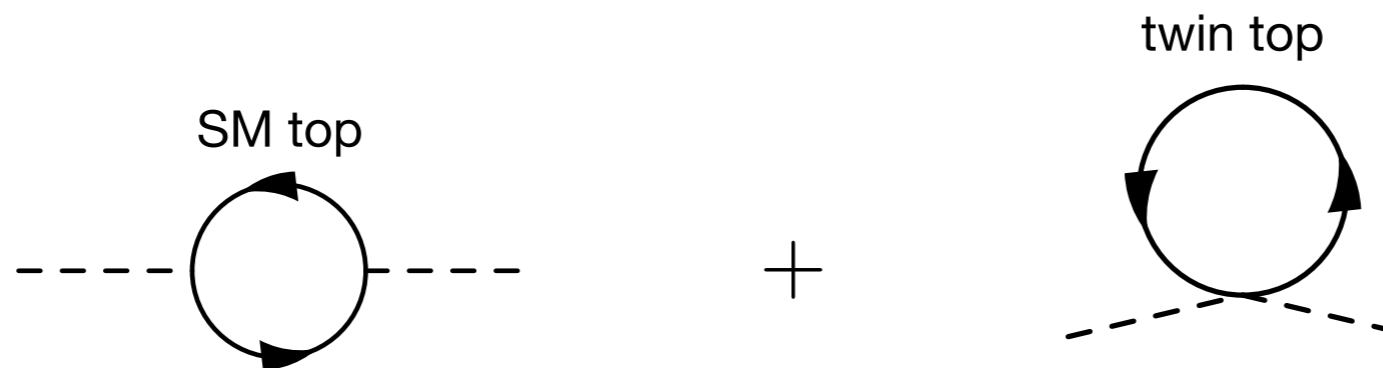
Can we still have  $< 1$  TeV top partners?

# Twin Higgs

Dark sector = (approximate) copy of the Standard Model



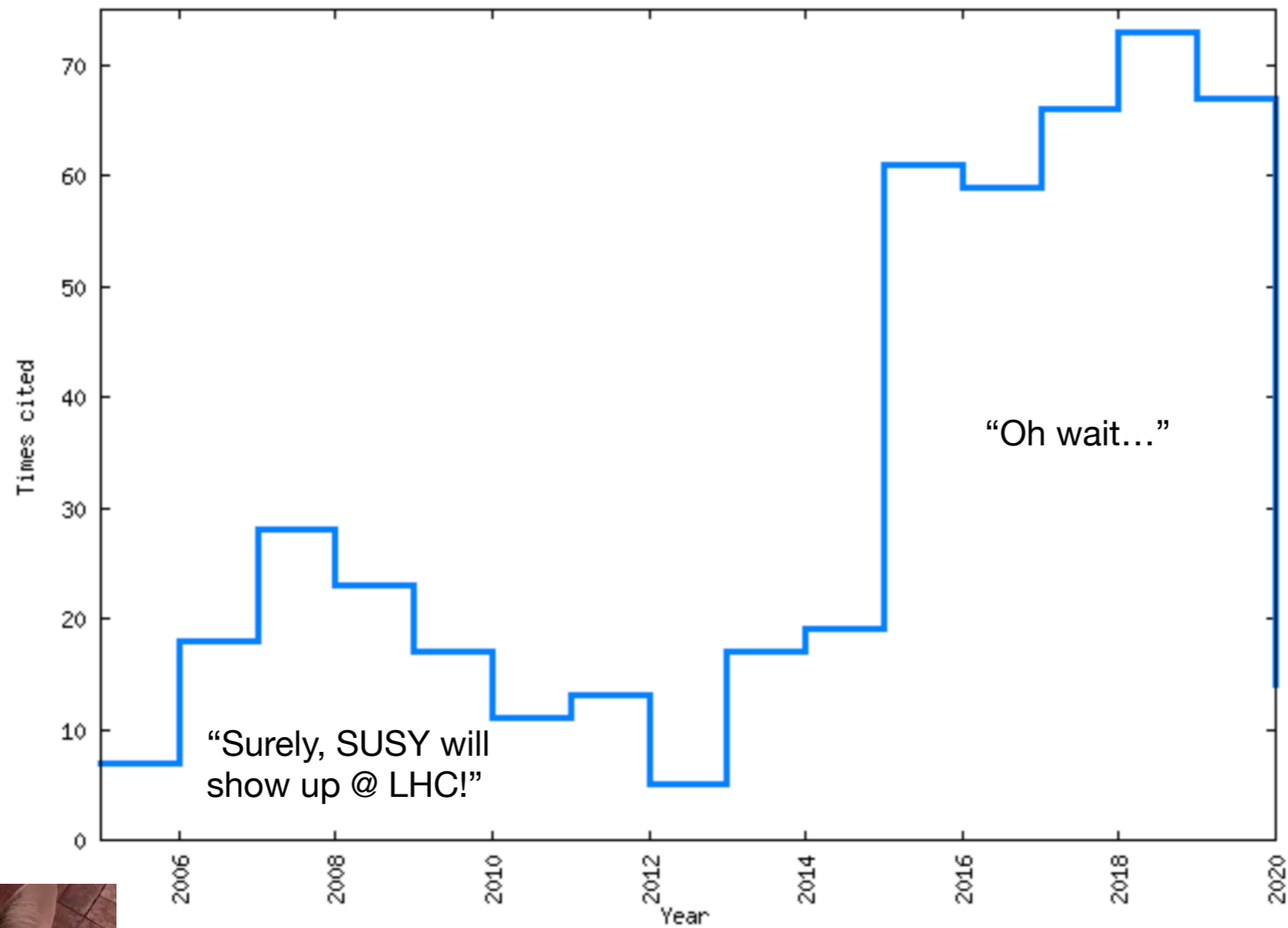
Twin top can (partially) cancel the divergent contribution from the SM top



(Of course, some cleverness required)

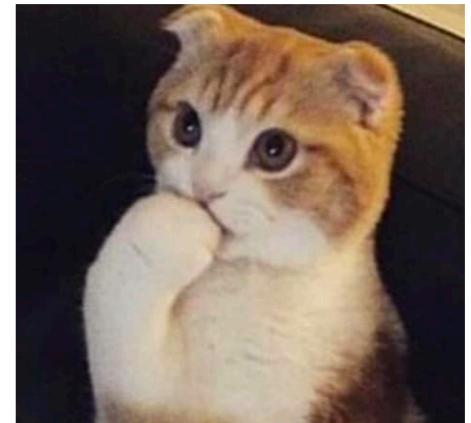
# Twin Higgs

Citation history:



“Surely, SUSY will show up @ LHC!”

“Oh wait...”



Higgs discovery

25 fb<sup>-1</sup>

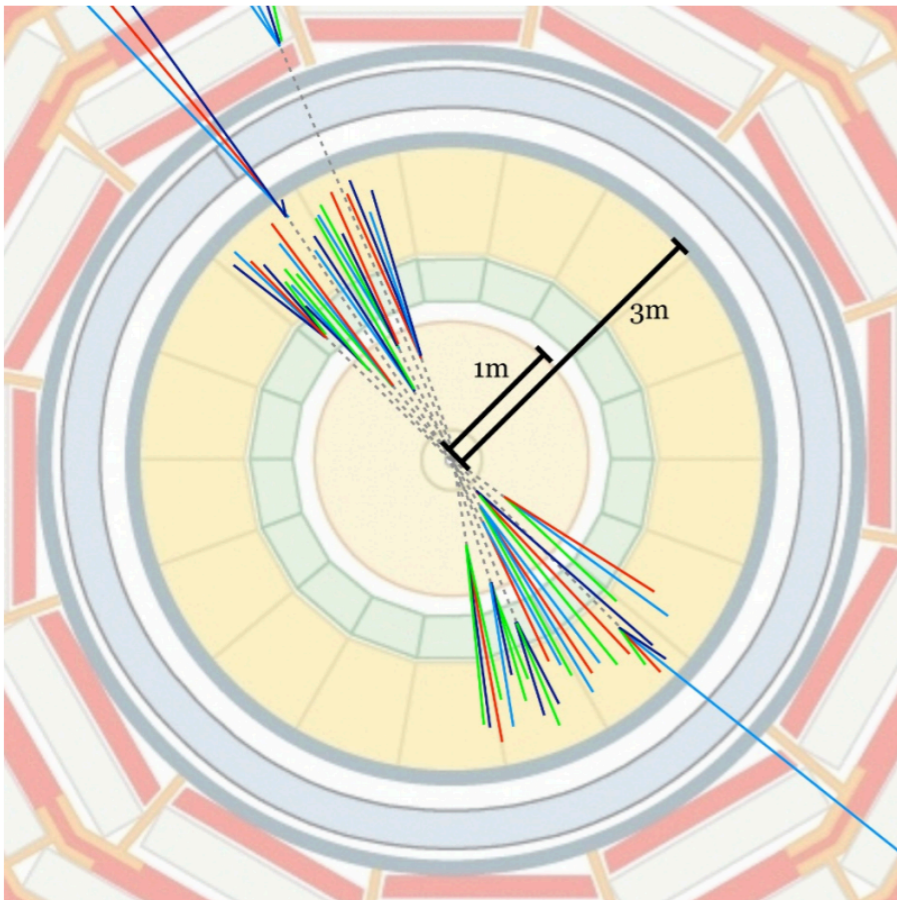
# Twin Higgs

Twin Higgs is an example of a “hidden valley”

M. Strassler, K. Zurek: arXiv 0604261



Some Twin Higgs models predict “dark shower” / “emerging jet” phenomenology:



P. Schwaller, et. al.: arXiv 1502.05409

Also check out CMS result: arXiv:1810.10069

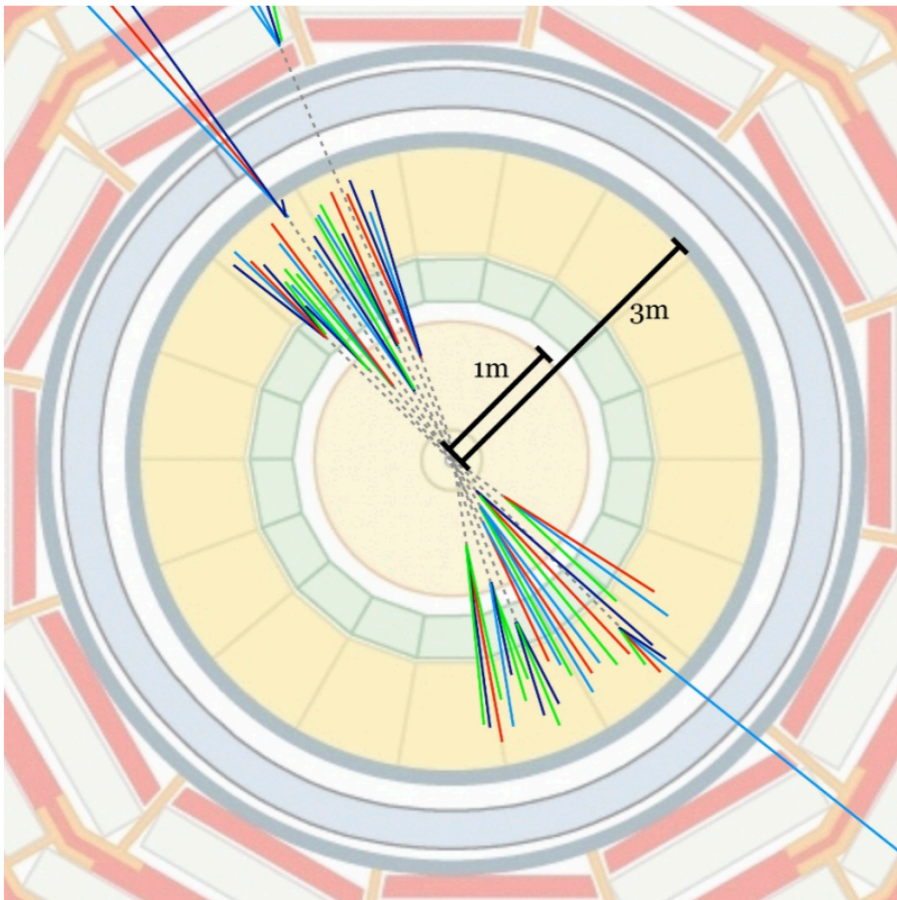
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General question:

“How do we build a suite of maximally inclusive searches?”

See “dark showers” chapter of long-lived particle community white paper: arXiv 1903.04497

- Long lived particle searches
- Jet substructure / precision QCD
- Machine learning

Much more theory work is needed / in progress.

Also check out CMS result: arXiv:1810.10069

# Conclusions

“Dark sectors” are the “Jack of all trades” of BSM model building

Lots of great ongoing work

- [ATLAS/CMS/LHCb](#): long-lived particles, MET searches, precision measurements, ML, ...
- [Intensity frontier](#): Meson factories and neutrino experiments
- [Theory](#): model building and improved calculations of production/decay rates
- [Astroparticle physics/cosmology](#)

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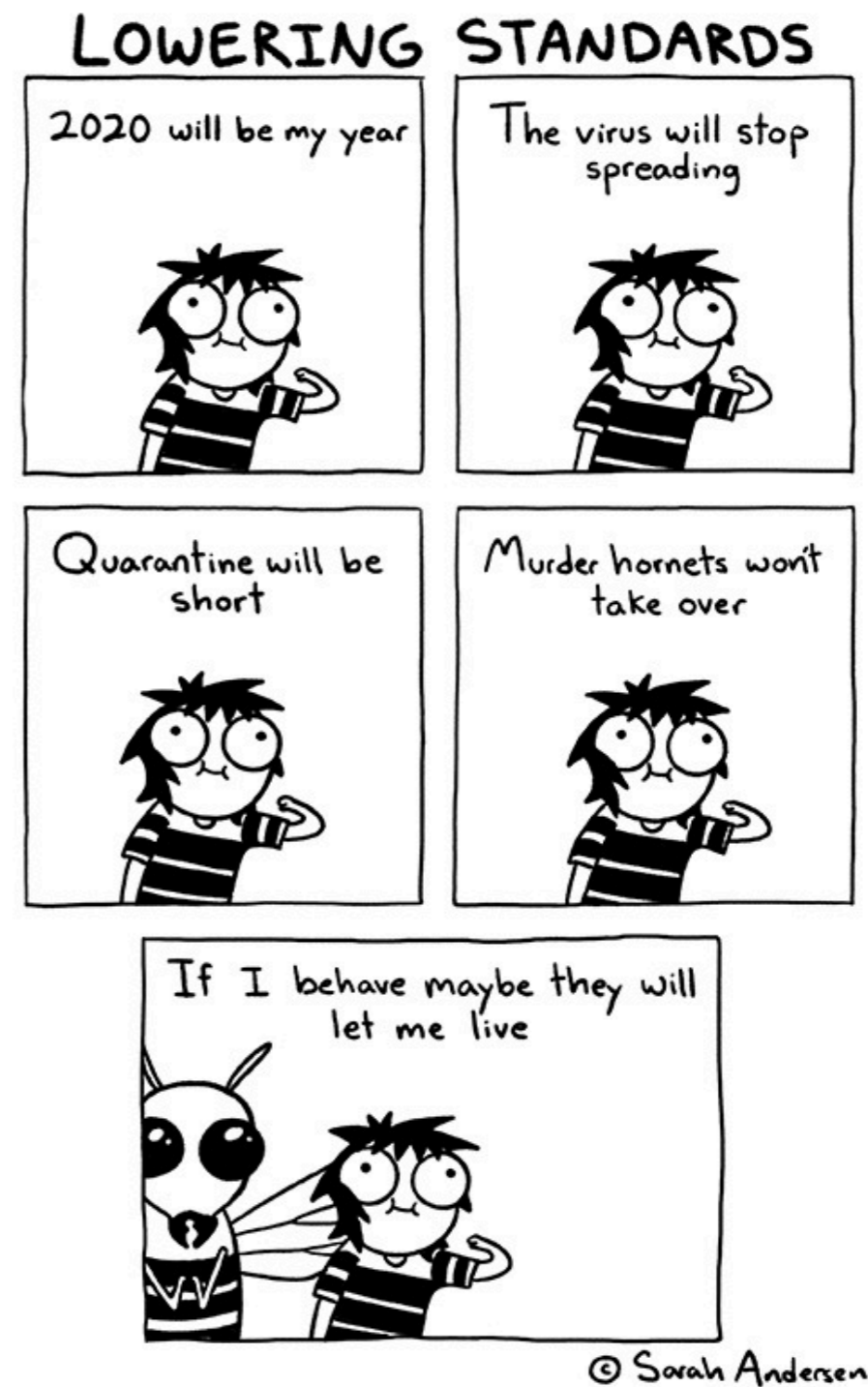
- Let's engage our experimental friends about [triggers, scouting techniques](#) etc.
- Is “[comprehensive](#)” [coverage](#) possible, and if so, what does this mean concretely?
- How do we want to go about [making predictions](#) in this complicated space?  
E.g. insist on discoverability, falsifiability, neither, ...

# Conclusions

Thanks for listening, and stay healthy!

Want to discuss more?

Zoom Meeting ID: 942 4776 4206  
Password: 2020

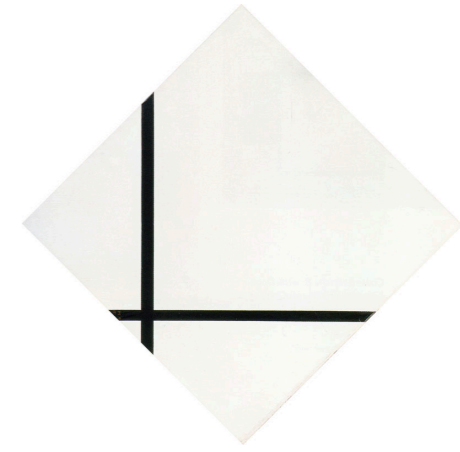


Many thanks to Diego Redigolo for useful discussions when preparing this talk

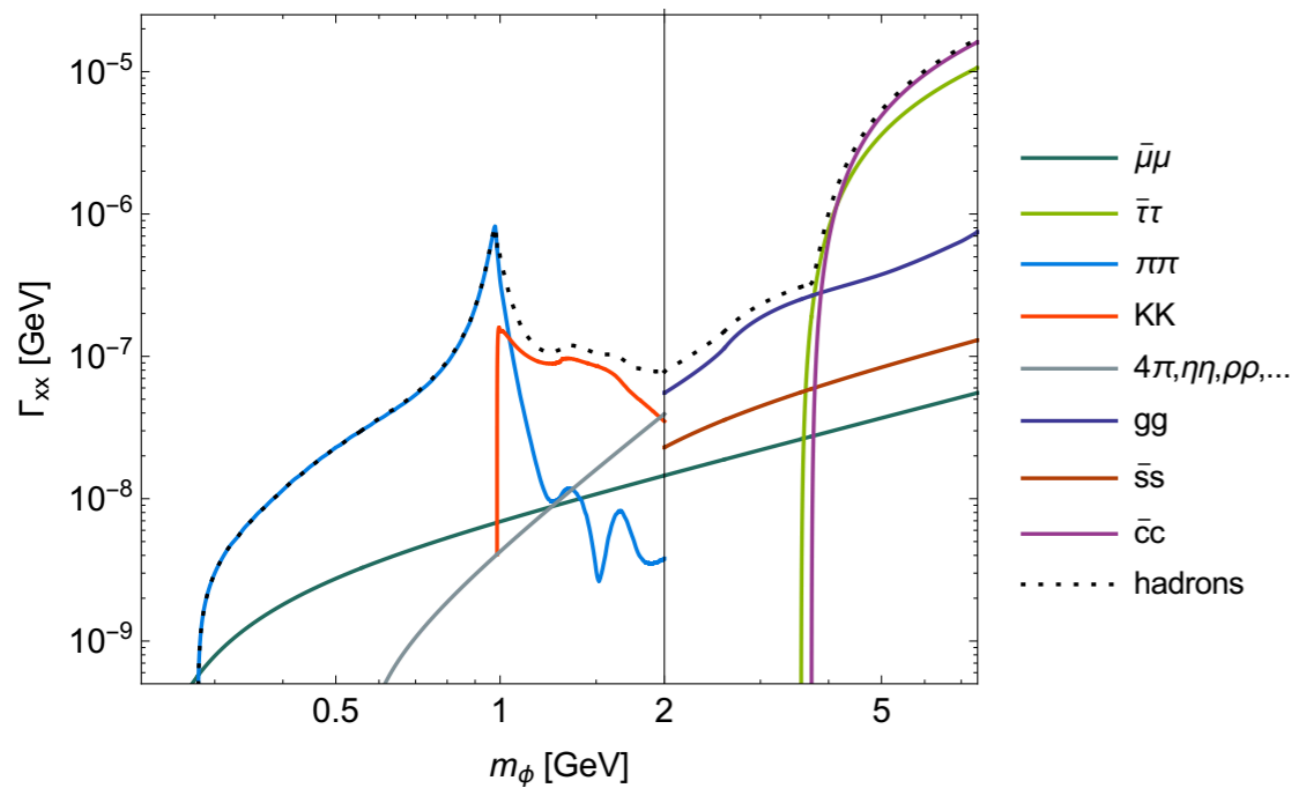
Back-up slides

# Decay modes

For mass  $\sim$  GeV, often very complicated!

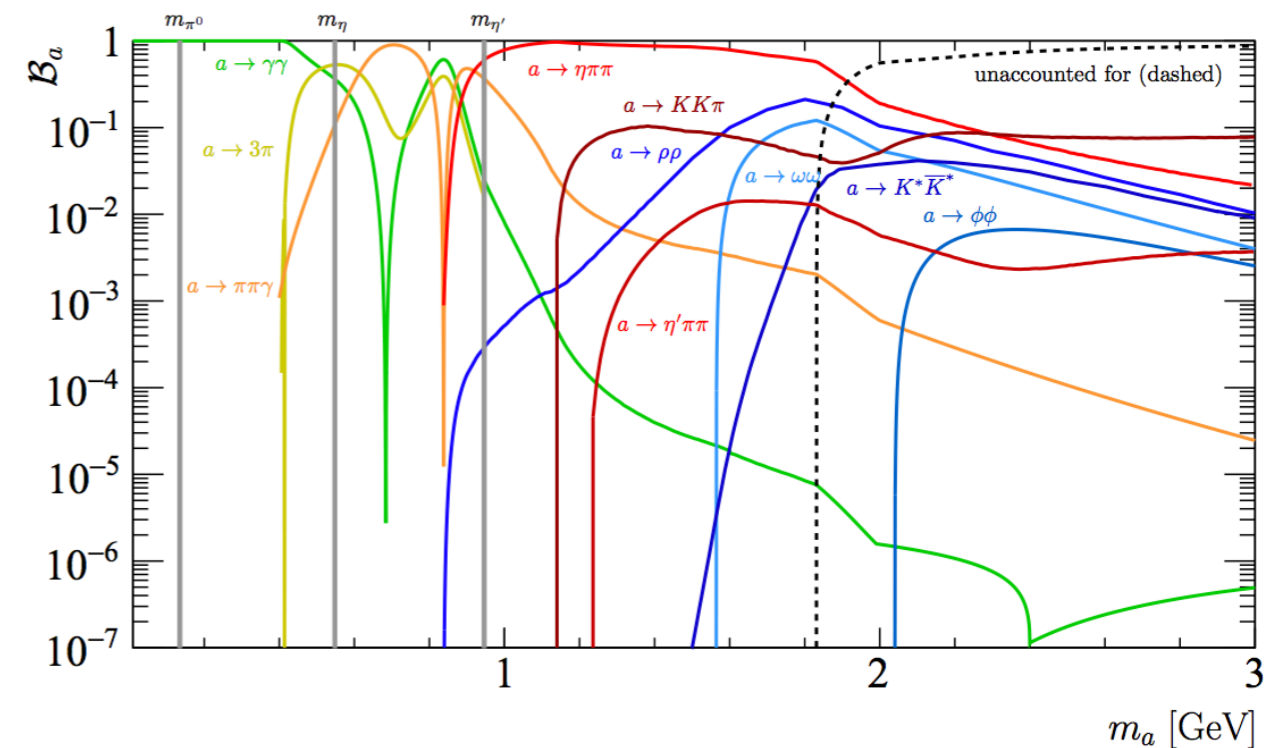


## Scalar mixing with Higgs



M. Winkler: arXiv 1809.01876

## Axion-like particle



D. Aloni, Y. Soreq, M. Williams:  
arXiv 1809.01876