Dark Sectors

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UC Santa Cruz

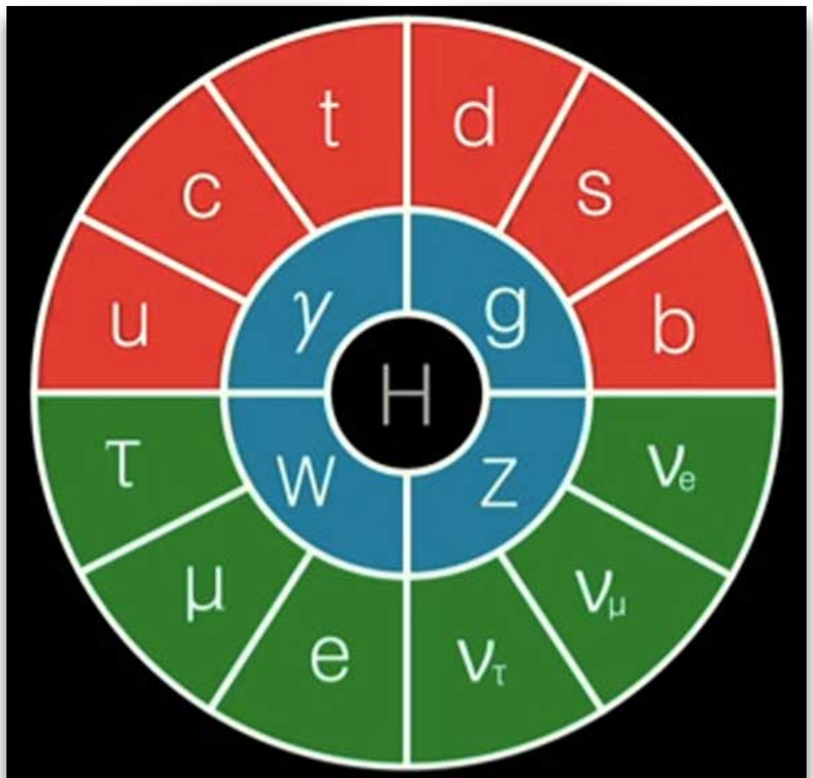
PPC 2021: XIV International workshop on interconnections between Particle Physics and Cosmology

May 17, 2021

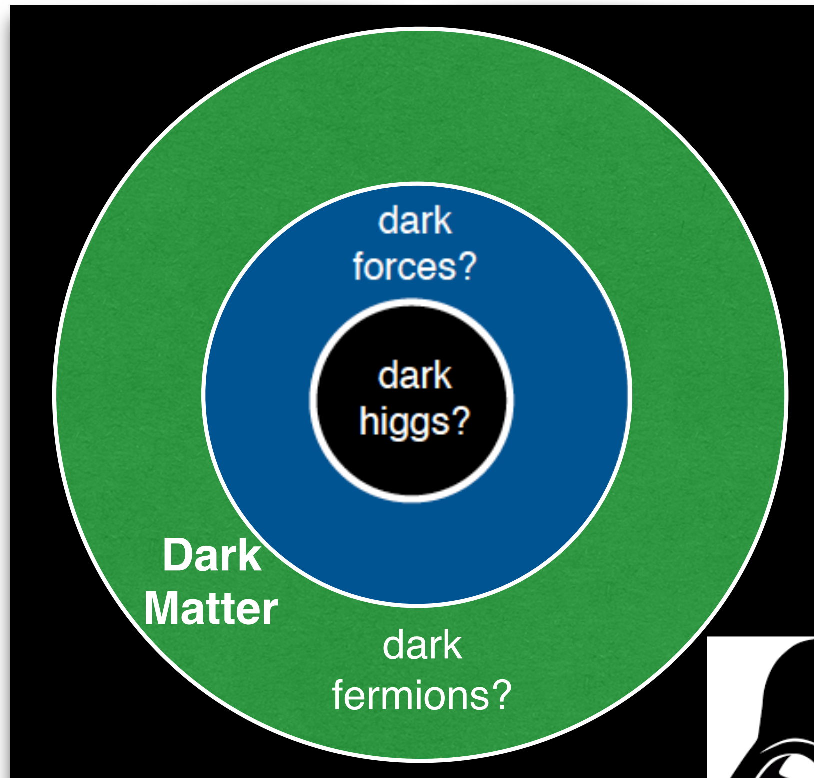
What is a dark sector particle?

Any particle that does not interact through the Standard Model (SM) forces.

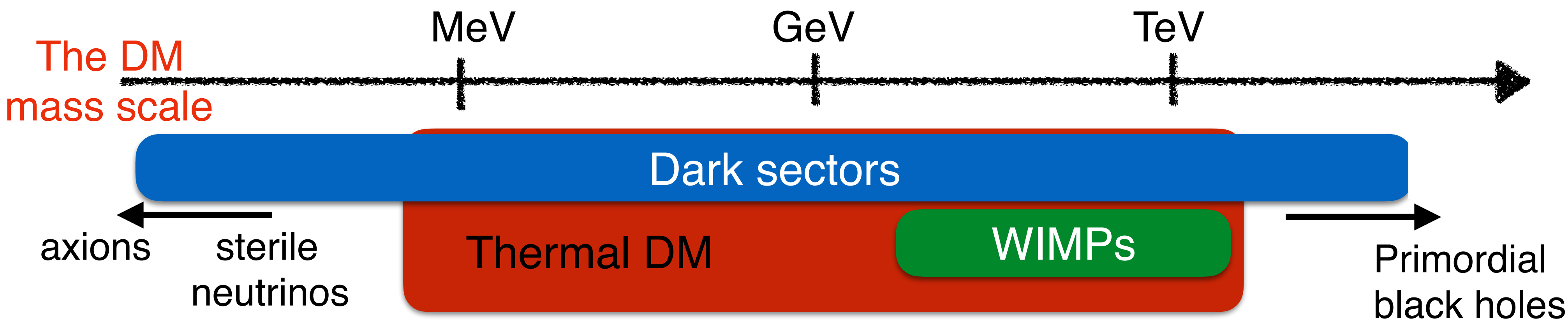
Our visible universe



The dark universe



Why a dark sector? (DM)



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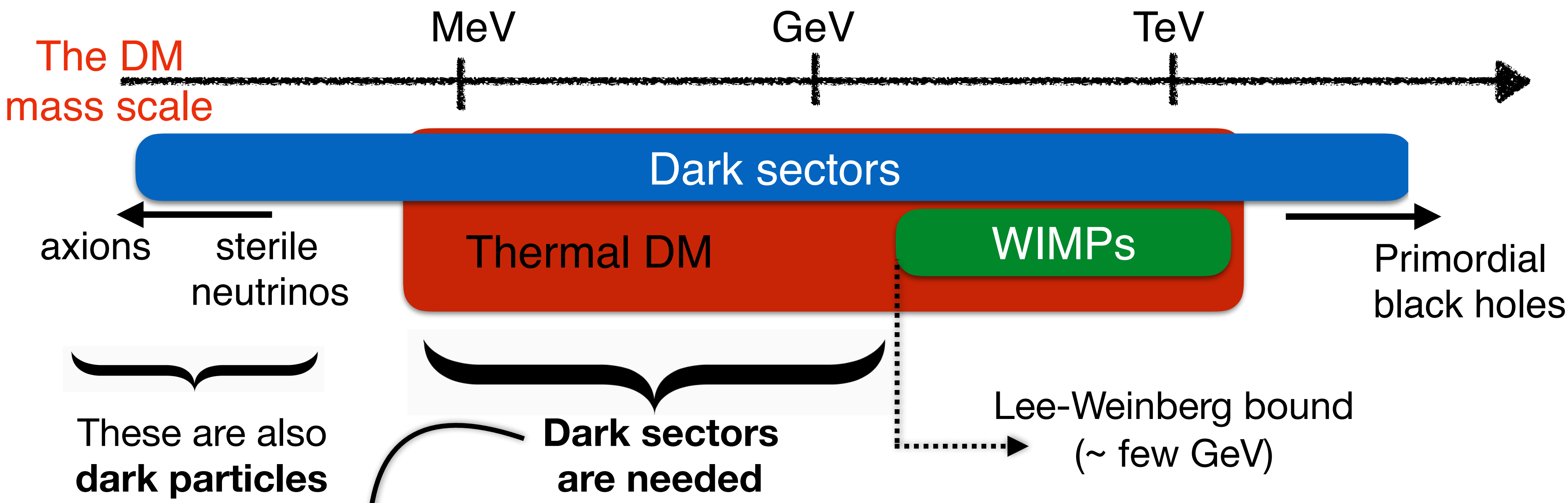
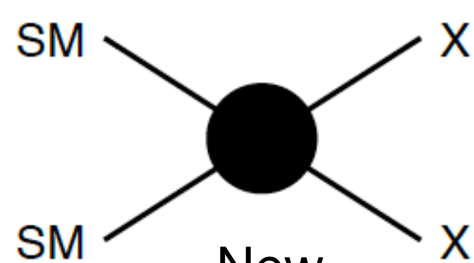


Need for new particles in addition to DM (the “mediator(s)”)



New
dark interactions

Why a dark sector? (beyond DM)

Beyond the DM motivation, many other open problems in particle physics let us think about dark particles.

Why a dark sector? (beyond DM)

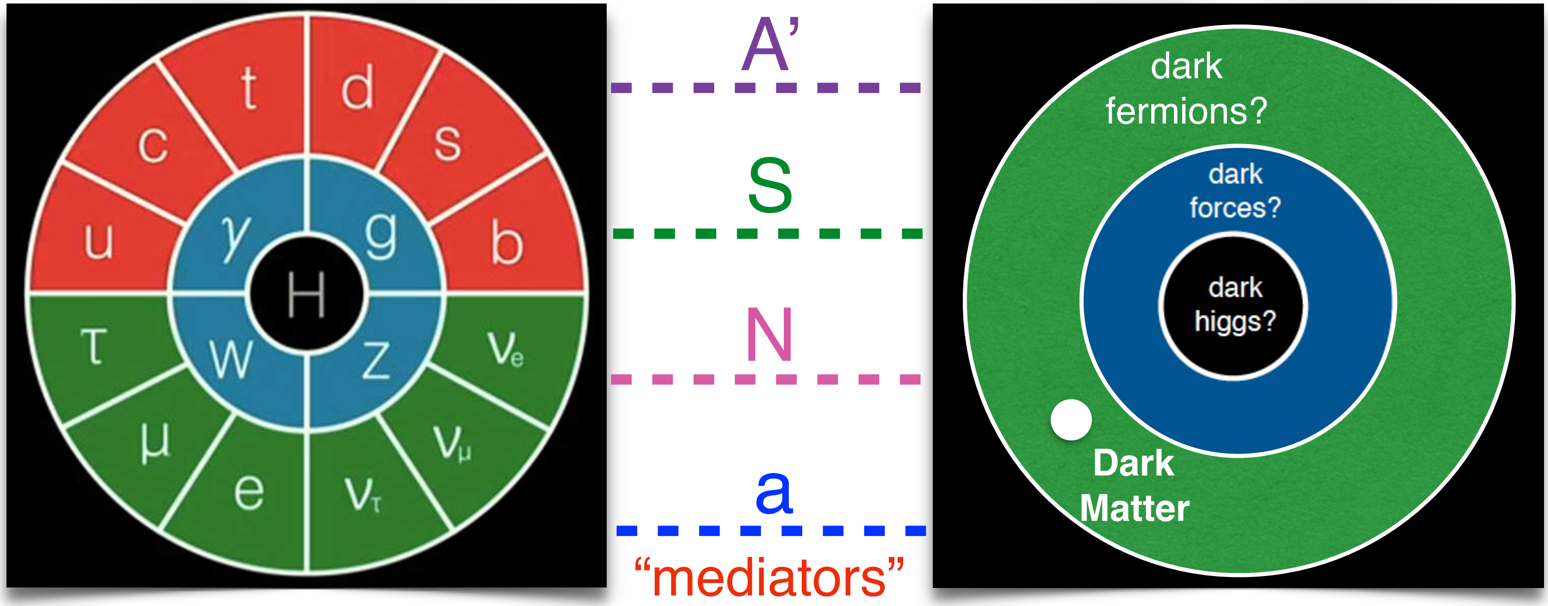
Beyond the DM motivation, many other open problems in particle physics let us think about dark particles.

- Models to address the strong CP problem. Axions and axion-like particles;
- Models to address the gauge hierarchy problem (relaxion);
- SUSY extended models (Next-to-Minimal-Supersymmetric-Standard-Model);
- Models for baryogengesis;
- Models for neutrino mass generation;
- Models addressing anomalies in data

($(g-2)_\mu$, galactic center excess for Dark Matter, Xenon1T anomaly, B-physics anomalies, KOTO anomaly, …).

Some of these particles are naturally light thanks to approximate global symmetries.

How to gain access to the dark sector?



Only a few interactions exist that are allowed by Standard Model symmetries:

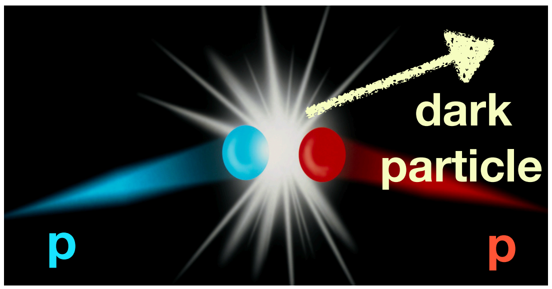
+ possible new dark gauge bosons obtained gauging e.g. B-L, L_μ-L_τ, …

"mediators"	"portal interactions"
Dark photon	$\epsilon B^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$y H L N$
Axion	$g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$

A broad program of searches

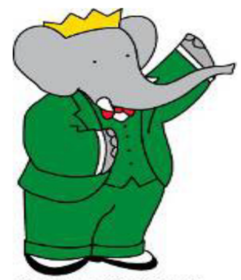
Vigorous effort of the community proposing new experiments & measurements

1. **The LHC**

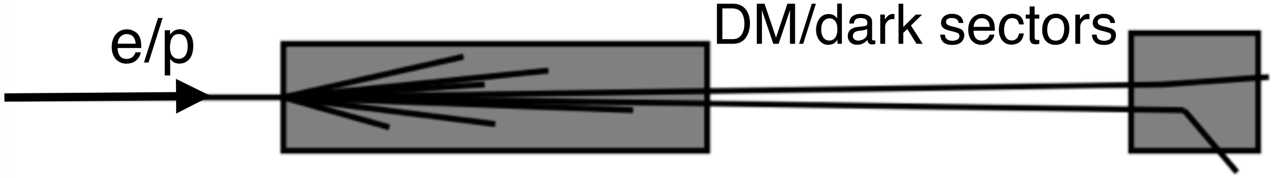


+ future colliders (hadron + lepton)

Flavor-factories **2.**



3. **Fixed target / neutrino experiments**



Beam **(high intensity)** **Dump/shield** **Decay volume** **Detector**

Complementarity with direct and indirect DM detection experiments

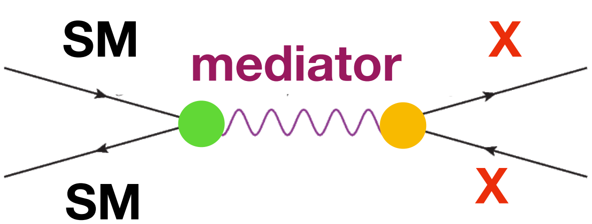
FOCUS OF THIS TALK: accelerator probes of dark sectors

Final states to look for

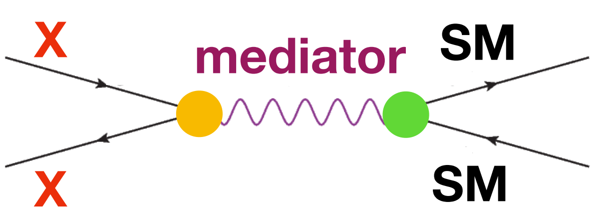
Invisible, non-SM

Dark Matter production

Producing stable particles that could be (all or part of) Dark Matter



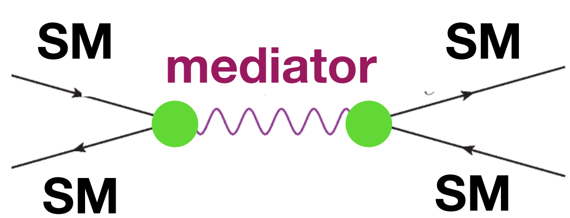
Non-secluded DM models



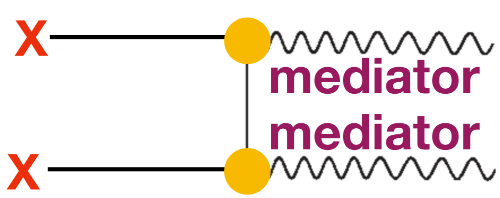
Visible, SM

Production of portal-mediators that decay to SM particles

Systematically exploring the portal coupling to SM particles



Secluded DM models



Mixed visible-invisible

Production of "rich" dark sectors

Testing the structure of the dark sector

Examples of DM models:

Inelastic DM models

Strongly interacting DM models,

…

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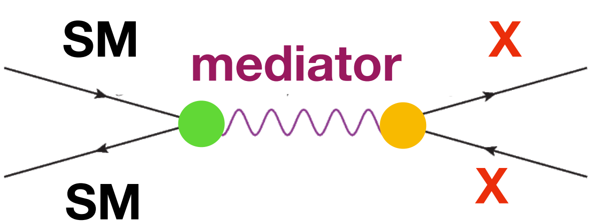

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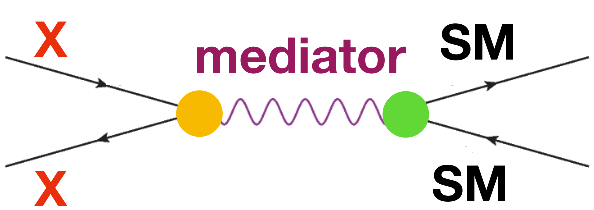

Focus of A. Whitbeck talk on Thursday

Visible, SM

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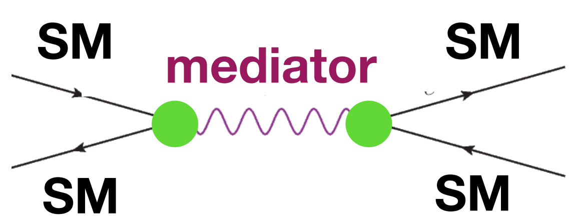

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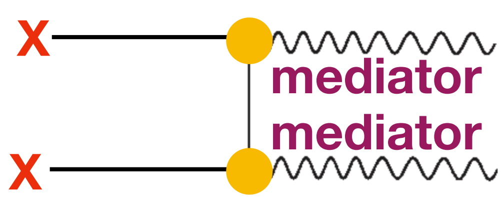

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Examples of DM models:

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Focus of this talk

Long lived particles (LLPs)

A generic feature of dark sector models:
appearance of particles with a long life time

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A generic feature of dark sector models:
appearance of particles with a long life time

Possible reasons:

- squeezed spectra (decay width suppressed by kinematics)

examples:

* inelastic Dark Matter models $\Gamma(\chi_2 \to \chi_1 \ell^+ \ell^-) \propto \Delta^5 m_{\mathrm{DM}}$

* SUSY models with light winos and all the other sparticles very heavy

(SM example: the neutron) $\Gamma(\chi^+ \to \chi^0 \pi^+) \propto \Delta^3 \frac{f_\pi^2}{v^4} m_{\tilde{W}}^3$

- Small couplings

examples:

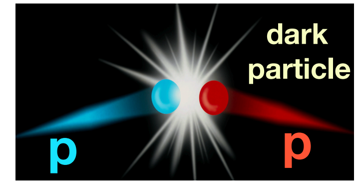
* freeze-in Dark Matter models

* seesaw models

* neutral naturalness models

(SM example: the muons)

1. Light dark particles at the LHC



Direct production

Dark particles can be produced in the same way as SM particles since they mix

$B_{\mu\nu}F'_{\mu\nu}$ Mixing of the dark photon with the SM photon/Z boson

$|H|^2|S|^2$ Mixing of the dark Higgs with the SM Higgs

HLN Mixing of the dark neutrino with the SM neutrinos

LHCb covers an important role if the dark particle is light

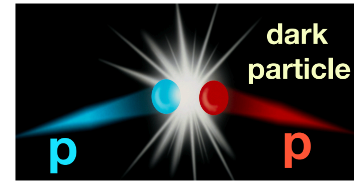
Only <u>few searches</u> have been done for masses below the electroweak scale.

Importance of looking for light resonances!

Searches performed:

bbS, S $\to \mu\mu$
ggS, S $\to \mu\mu$, (also searched for by LHCb)
ggS, S $\to \gamma\gamma$
bbS, S $\to$ tautau
jS, S $\to$ bb ($m_S >$ 50 GeV)

jZ', Z' $\to$ jj ($m_{Z'} >$ 10 GeV)



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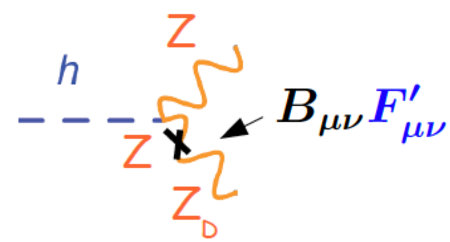
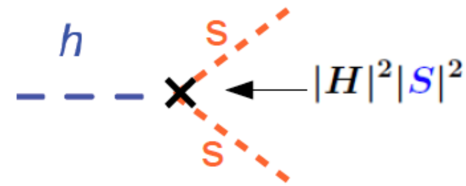
Higgs exotic decays

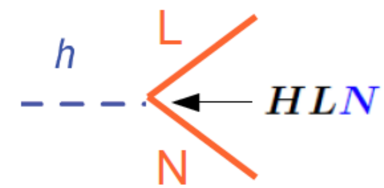
$h \to ZZ_D$



$h \to ss$



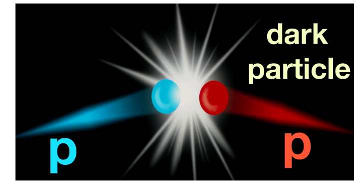
$h \to LN$



Easy to obtain sizable branching ratios (SM Higgs width is tiny!)

Huge statistics still to come:

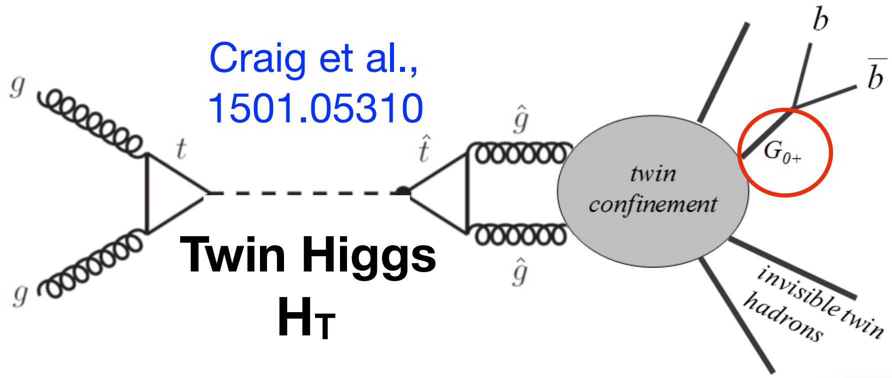
$$\boxed{\begin{array}{l} N^{\text{now}}_{\text{Higgs}} \sim 8\text{M} \\ N^{\text{HL-LHC}}_{\text{Higgs}} \sim 170\text{M} \end{array}}$$



1. Heavy dark LLPs at the LHC

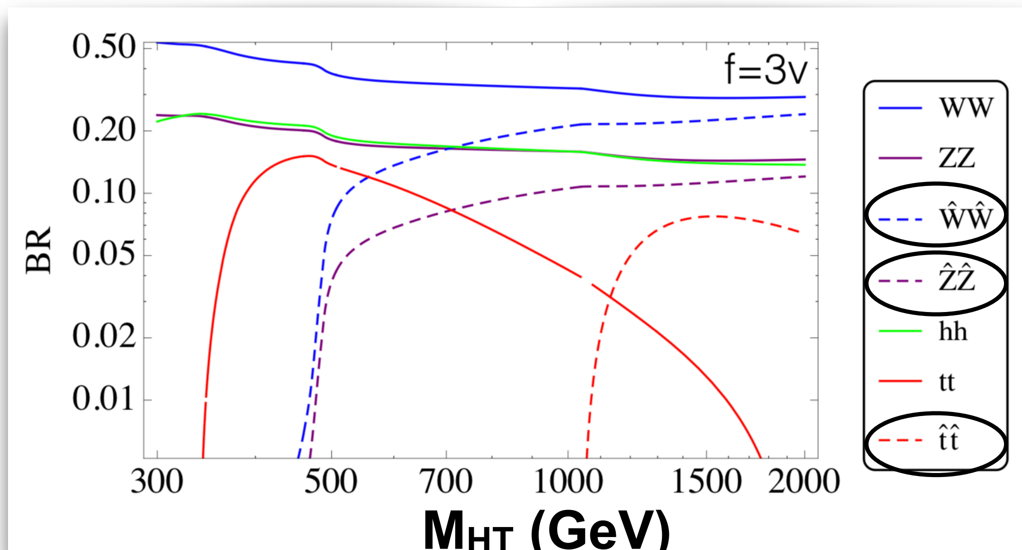
“Heavy” dark sectors at the TeV scale are well motivated.

Classic example: <u>neutral naturalness theories</u>

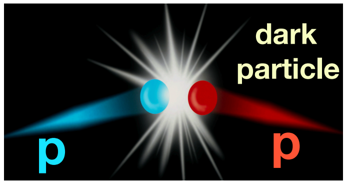


Glue-ball.
O^{++} mixes with the 125 GeV Higgs and decays typically displaced.

Signature: H$_T$ → >= 2 displaced



subleading decay to the dark sector, but …



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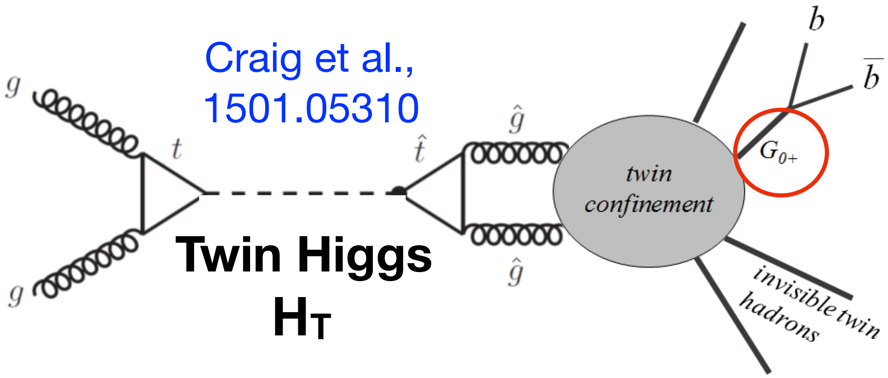

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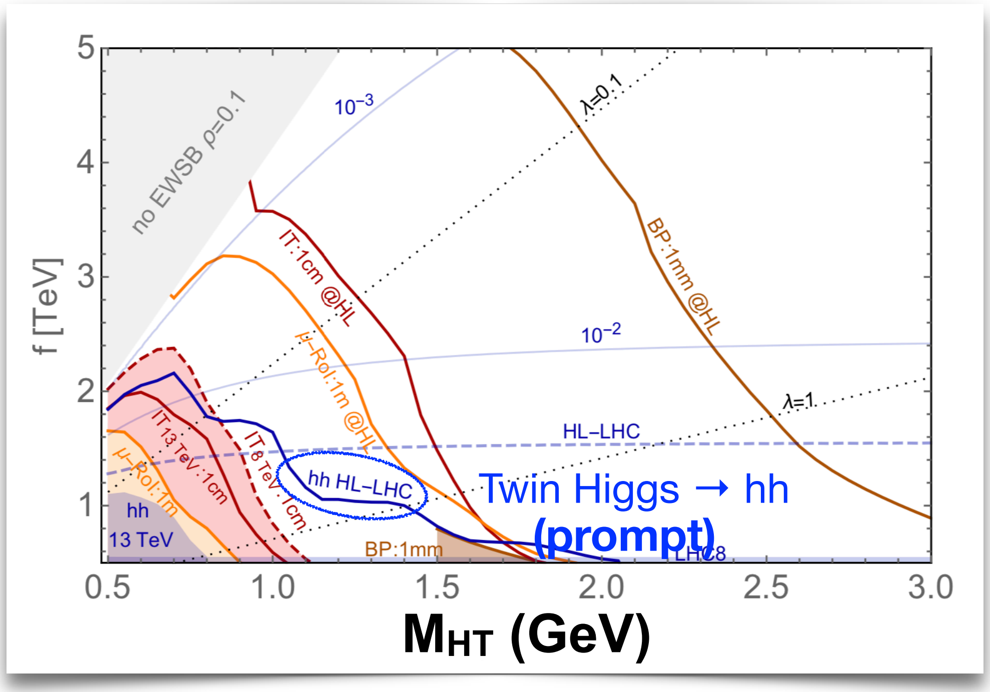


…Direct searches of the twin Higgs decaying to long lived glueballs can test large regions of parameter space

Alipour-Fard, Craig, SG, Koren, Redigolo, 1812.09315

2. The precision frontier @ flavor factories

A big jump in luminosity is expected in the coming years

	Past/Present	Future
B-factories		
Kaon-factories		
Pion-factories		

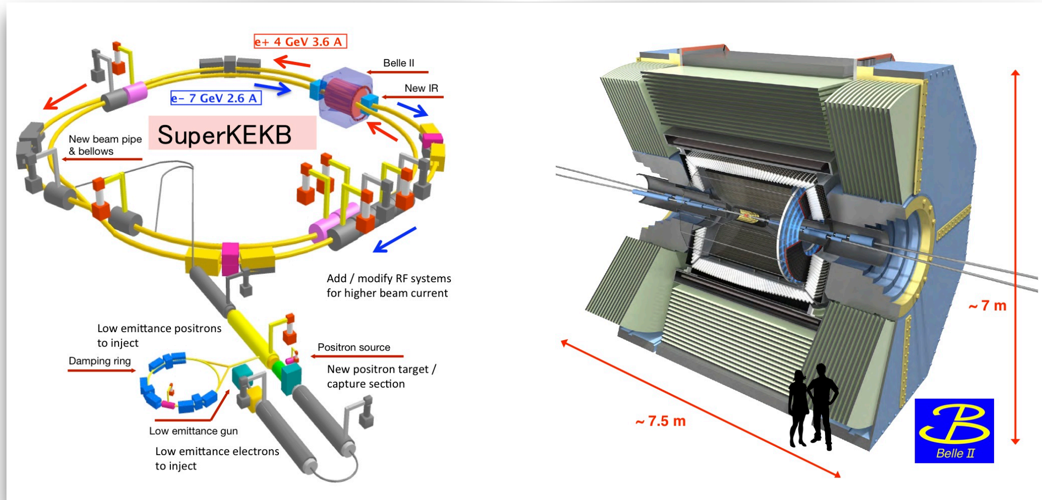
2. The precision frontier @ flavor factories

A big jump in luminosity is expected in the coming years

	Past/Present	Future
B-factories	**LHCb:** more than ~ 10^{12} b quarks produced so far; **Belle** (running until 2010): ~10^9 BB-pairs were produced.	~40 times more b quarks will be produced by the end of the LHC; ~50 times more BB-pairs will be produced by **Belle-II**.
Kaon-factories	**E949** at BNL: ~10^{12} K^+ (decay at rest experiment); **E391** at KEK: ~10^{12} K_L	**NA62** at CERN: ~10^{13} K^+ by the end of its run (decay in flight experiment); **KOTO** at JPARC: ~10^{13} K_L by the end of its run
Pion-factories	**PIENU experiment** at TRIUMF: ~10^{11} pi^+ (still analyzing data)	**PIENUX experiment** at TRIUMF: new proposal. > 1 order of magnitude more pions

Plenty of dark particles can be produced from meson decays

2. Dark sectors at b-factories (Belle II)



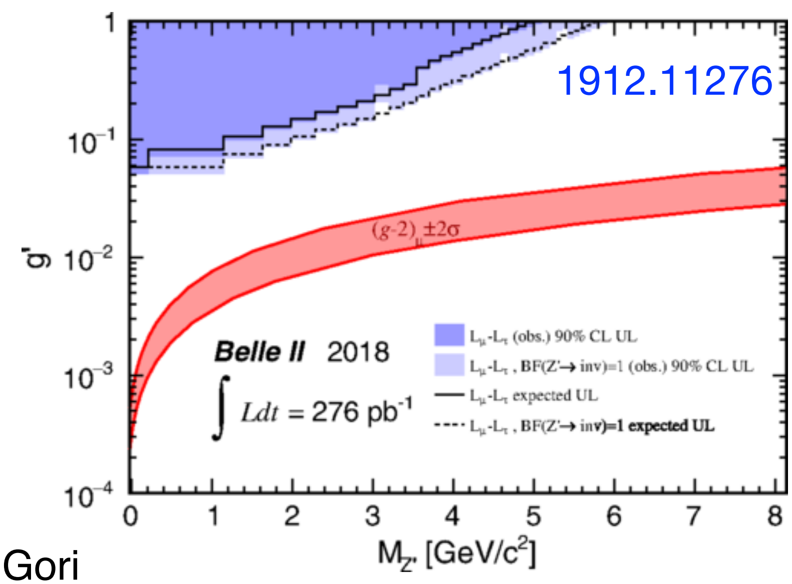
Belle II started collecting data in 2018

So far ~70/fb have been collected/analyzed.

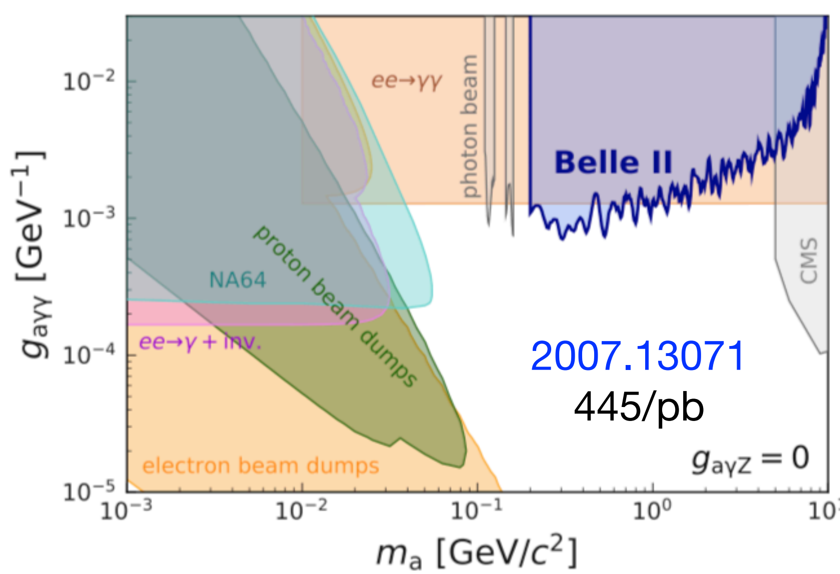
Goal: 50/ab

The first two publications cover interesting dark sector models:

$$e^+e^- \to \mu^+\mu^- Z',\ Z' \to \text{inv}$$



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

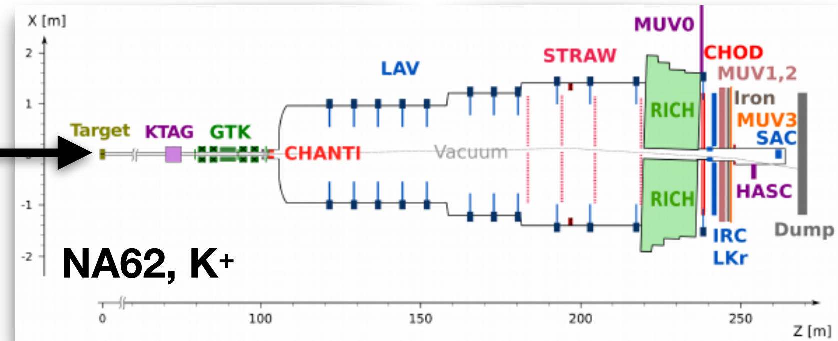


2. Dark sectors at Kaon experiments

Production of dark particles through

1. Kaon decays
2. proton beam-target scattering
3. Decays of secondary particles
   (e.g. pion decays)

p beam



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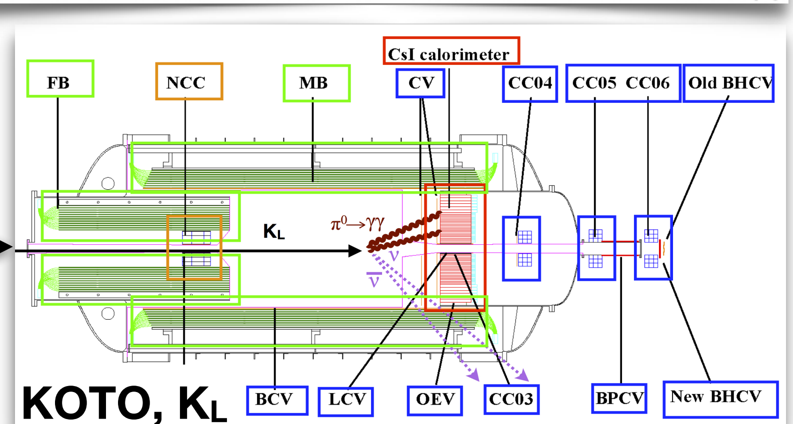

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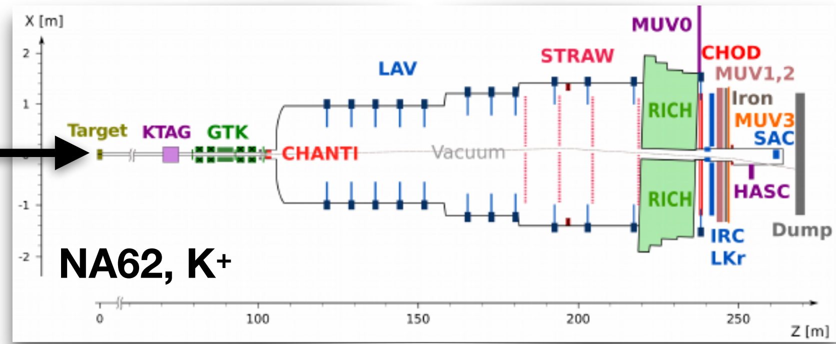
K^+ and K_L have a small decay width.
➡ It is easy to obtain sizable BRs into dark particles

p beam



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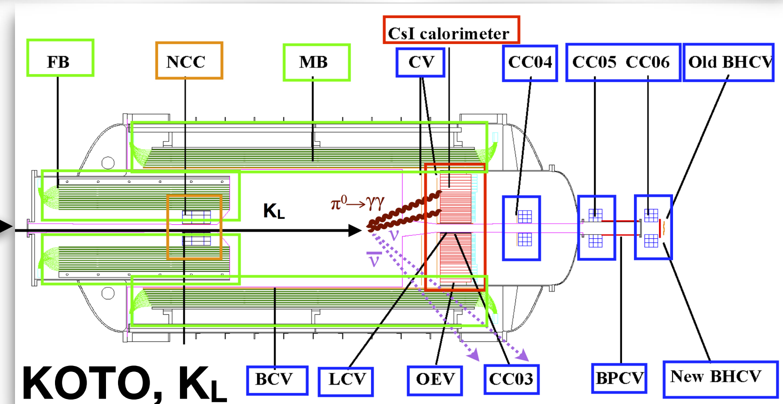

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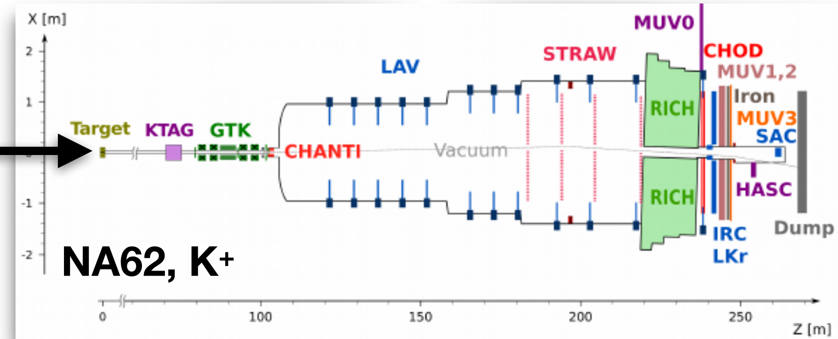

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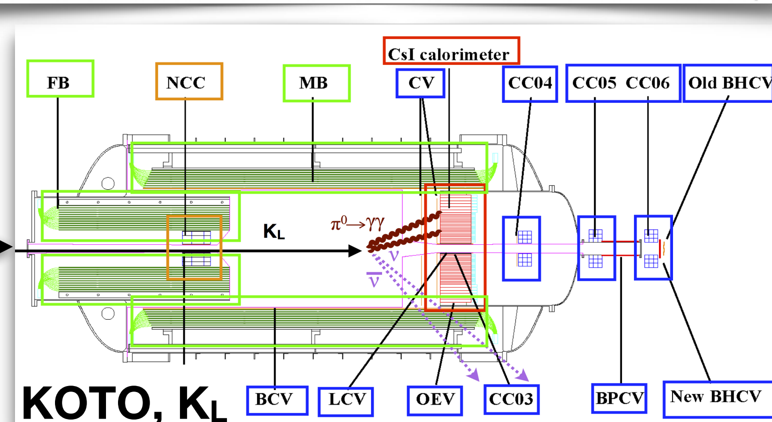

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Recent developments in the calculation of axion-like-particle production from Kaon decays: **$K \to \pi\, a$**

Introduction of

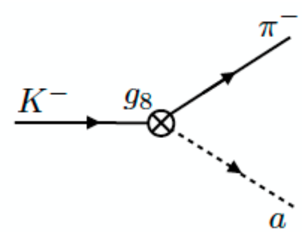
- ALP-eta mixing
- both G8 and G27 operators

SG, Perez, Tobioka, 2005.05170

- weak-interaction vertex

$$G_8 F_\pi^4 \mathrm{Tr}[\lambda_{sd} D^\mu \Sigma^\dagger D_\mu \Sigma] + G_{27} F_\pi^4 \left(L_{\mu 23} L_{11}^\mu + \frac{2}{3} L_{\mu 21} L_{13}^\mu \right)$$

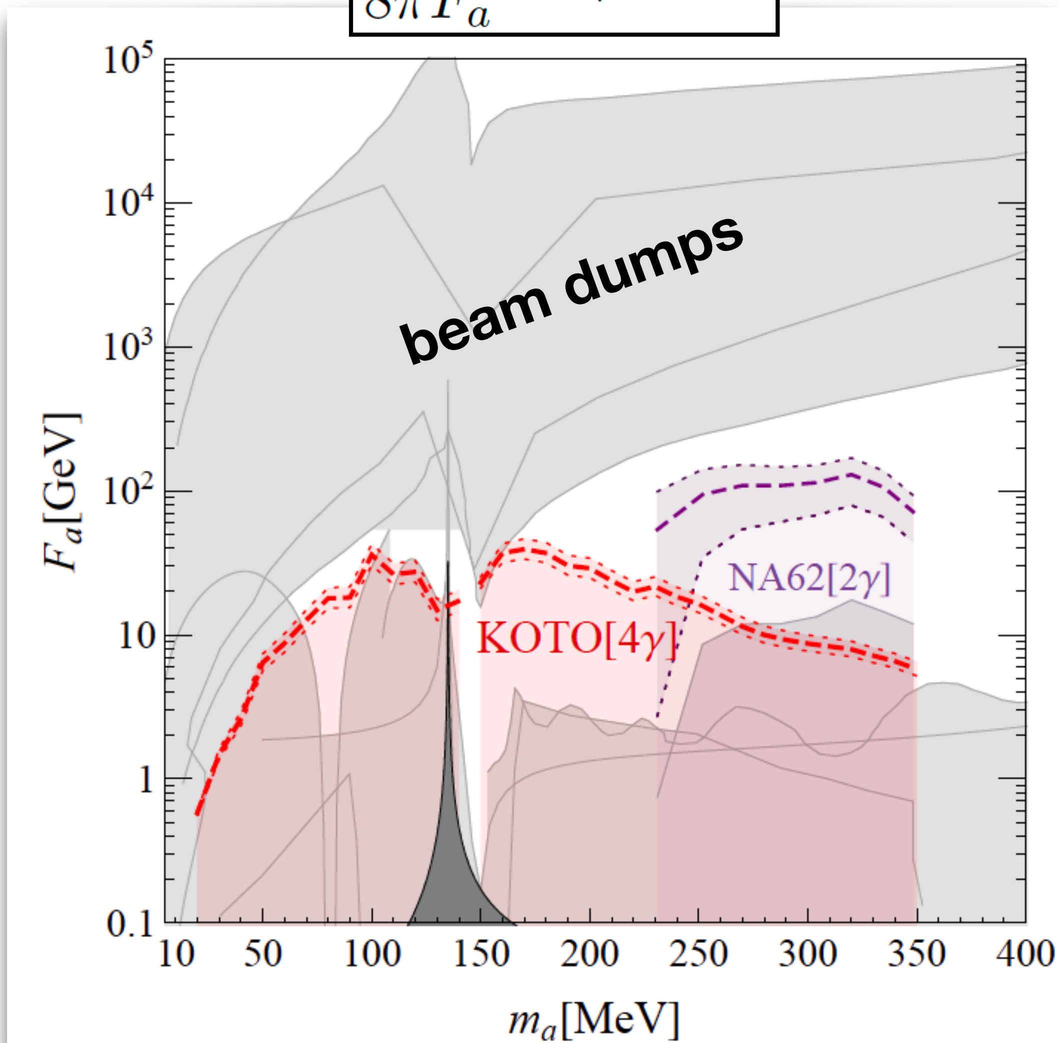
$$L_\mu \equiv i \Sigma^\dagger D_\mu \Sigma$$



Bauer et al., 2102.13112

2. ALP reach at Kaon experiments

$$\frac{\alpha_s}{8\pi F_a}\, a\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$



SG, Perez, Tobioka, 2005.05170

Two proposed searches:

NA62: $K^+ \to \pi^+ a$, $a \to \gamma\gamma$

(reach obtained via rescaling the NA62/48 bound)

KOTO: $K_L \to \pi^0 a \to 4\gamma$

(reach obtained via a new collider study)

2. Dark sectors at pion experiments

In the past, several pion-decay-at-rest experiments looked for rare decays of charged pions.

PIENU @ TRIUMF:	$\pi^+ \to e^+ \nu$	$BR_{SM} \sim 10^{-4}$	measurement of the positron energy
PIBETA @ PSI:	$\pi^+ \to \pi^0 e^+ \nu$	$BR_{SM} \sim 10^{-8}$	measurement of the photon opening angle

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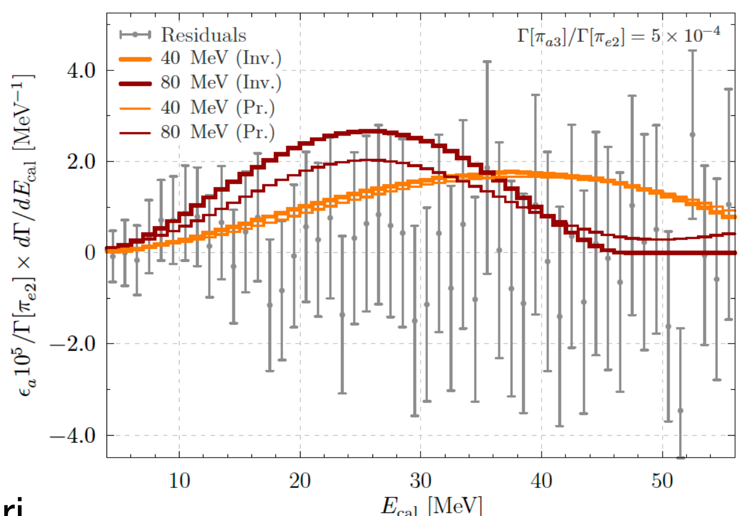
Idea: we can use this data to set bounds on ALPs mixing with pions

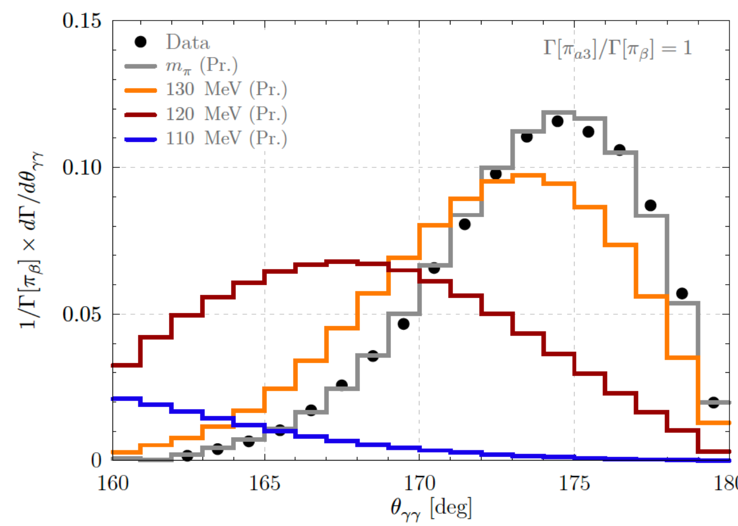
W. Altmannshofer, SG, D. Robinson, 1909.00005

$$\boxed{\pi^+ \to a e^+ \nu}$$

@PIENU: the positron spectrum will be affected

@PIBETA: the photon angle will be affected





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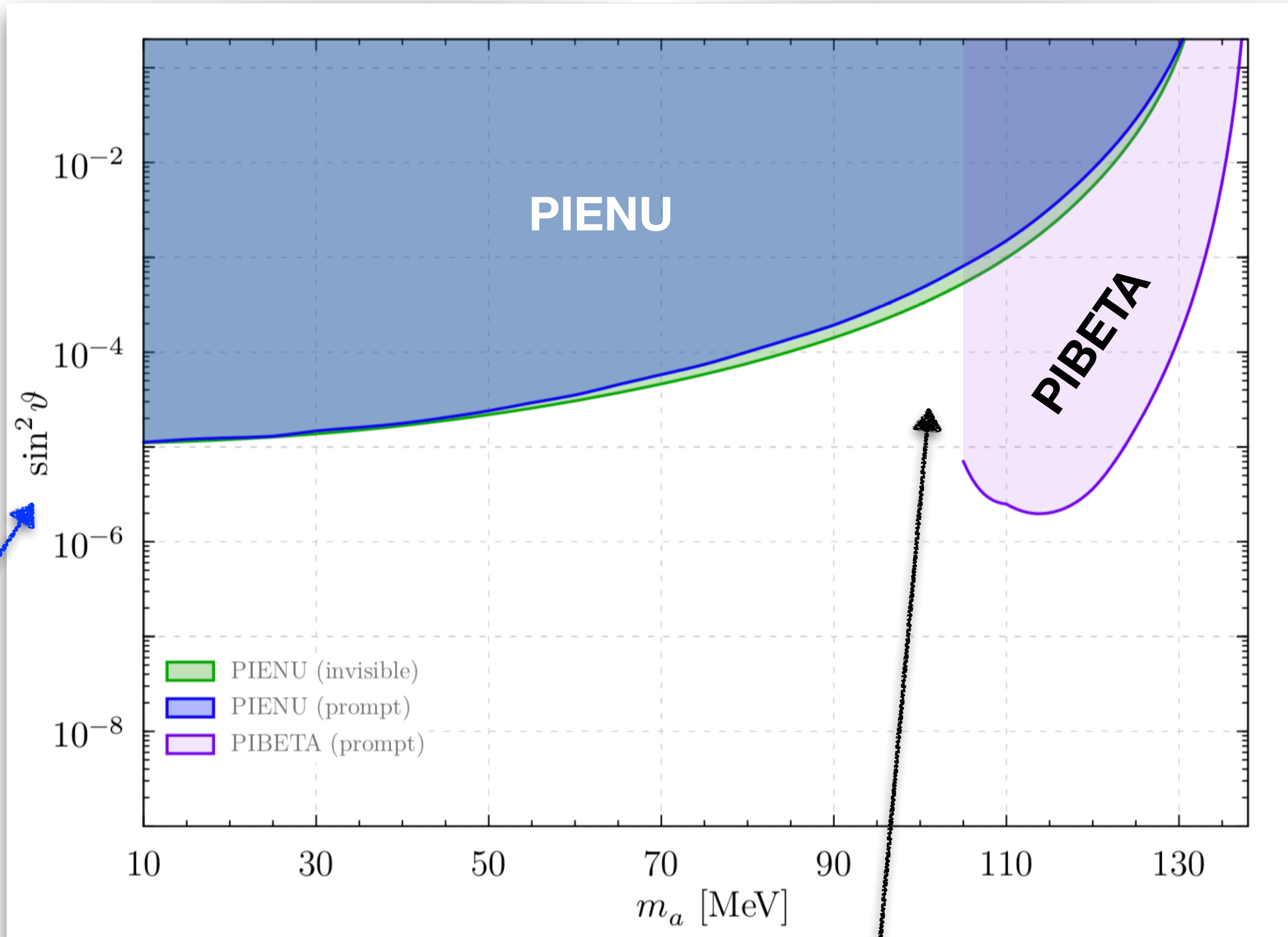
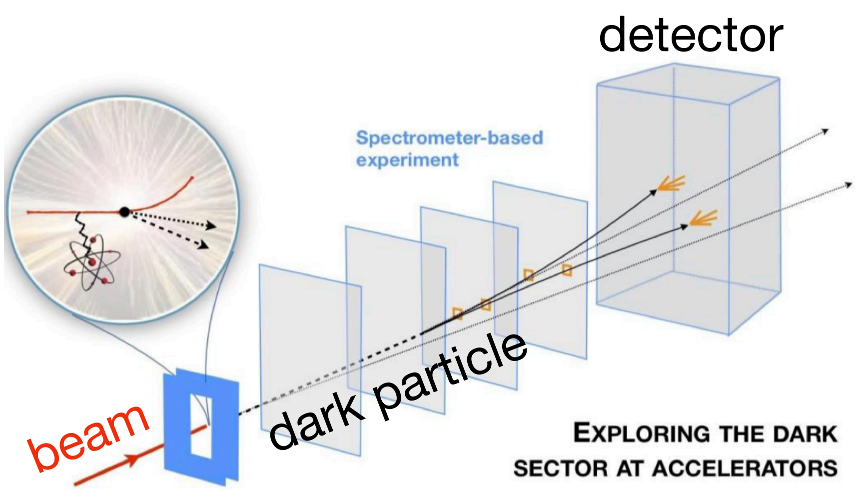


pion-ALP mixing

W. Altmannshofer, SG, D. Robinson, 1909.00005

Possibility to go to lower masses at future experiments (data at smaller angles!)

3. Dark sectors @ fixed target/beam dumps



Dark Matter New Initiatives BRN report

For example, for proton beams:

	Experiment	Proton energy	POT	Dump	Decay volume
	SeaQuest	120GeV	10^{18}	5 m	10 m
past	CHARM	400GeV	2.4×10^{18}	480 m	35 m
past	LSND	800MeV	10^{22}	30 m	10 m
	NA62	400 GeV	10^{18}	100 m	250 m
	SHiP	400 GeV	10^{20}	65 m	125 m

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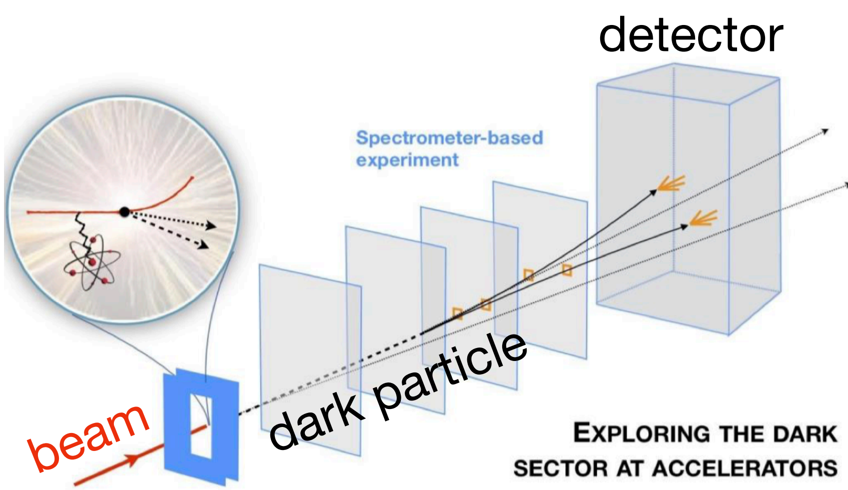

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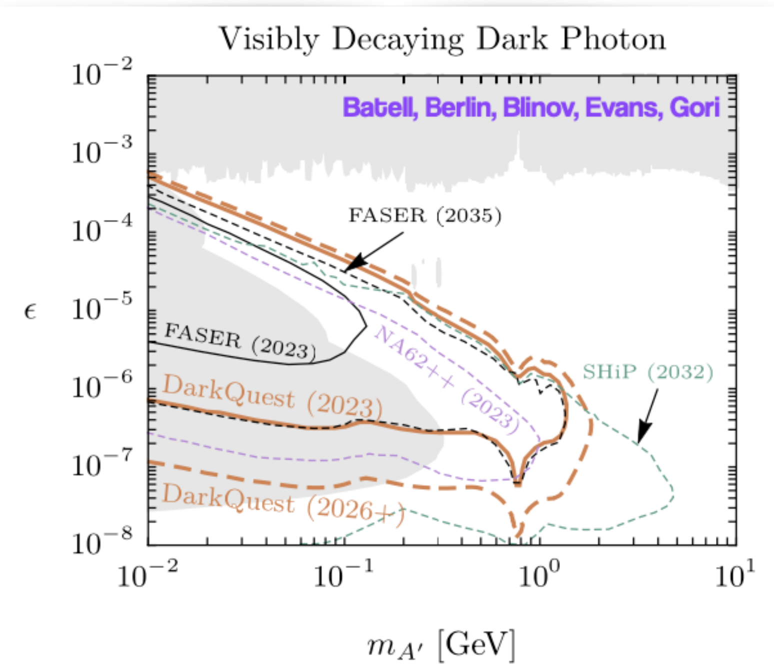
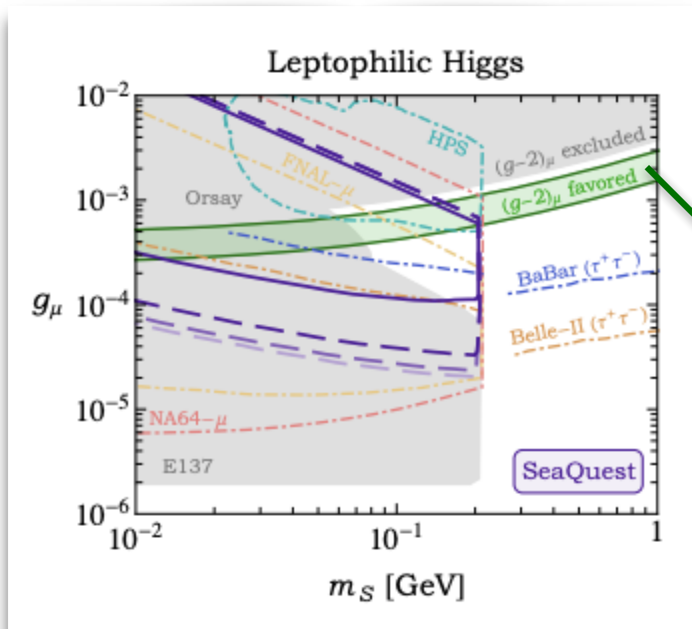
past





Berlin, SG, Schuster, Toro, 1804.00661

see talk by Y.Feng on Thursday (DM parallel session)

One of the few available light dark sector models for $(g-2)_\mu$

Dark sectors at Snowmass (RF6)

RF6 group, Dark Sector Studies at High Intensities
https://snowmass21.org/rare/dark, conveners: SG, Mike Williams.

RF6 has identified 3 "big questions" to organize our studies.

- Organization around science goals/questions.
- Arrange the breadth of RF6 science so that all the main techniques have a chance to shine.

1. Detect dark matter particle production (production reaction or through subsequent DM scattering), with a focus on exploring sensitivity to thermal DM interaction strengths.

2. Explore the structure of the dark sector by producing and detecting unstable dark particles: Minimal Portal Interactions.

3. New Flavors and Rich Structures in Dark Sectors.

3 white papers around these 3 big ideas + white paper on experiments/facilities/tools

Echoes BRN framing but with more breadth within each "thrust"
(https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf)

Conclusions & Outlook

Dark sector particles arise in a large variety of beyond the Standard Model theories.

Unique opportunity to probe dark sectors at accelerator experiments:

- **LHC**
- **Flavor factories**
- **Fixed target experiments**

Complementarity with direct detection & astrophysical probes

More details on the "big questions"

Big Idea 1: Detect dark matter particle production (production reaction or through subsequent DM scattering), with a focus on exploring sensitivity to thermal DM interaction strengths.

- Dark matter production through the vector portal
- Millicharged particles
- Neutrino-portal DM production
- What are the basic concepts for searches, their capabilities, challenges, and complementarity
- Targets can include theory, anomalies in data, …

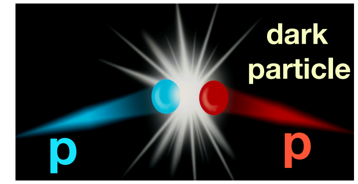
Key goals beyond current capabilities

Big Idea 2: Explore the structure of the dark sector by producing and detecting unstable dark particles: *Minimal Portal Interactions*.

- Scalar portal searches
- Pseudo-Scalar portal searches
- Visible signals in vector portal (minimal and non-minimal (SIMP, IDMs, ..))
- Fermion Portals
- What are the basic concepts for searches, their capabilities, challenges, and complementarity
- Targets can include theory, anomalies in data, …

Big Idea 3: New Flavors and Rich Structures in Dark Sectors

- Exploring flavor structure in more detail for standard portals and their marginal generalizations
- Higher-dimension portals (e.g. magnetic photon/dark photon coupling, neutron oscillations)
- What are the basic concepts for searches, their capabilities, challenges, and complementarity
- Targets can include theory, anomalies in data, …
- Perhaps also include non-minimal structures w/in dark sector, not already covered above – e.g non-Abelian – and missing- mass searches



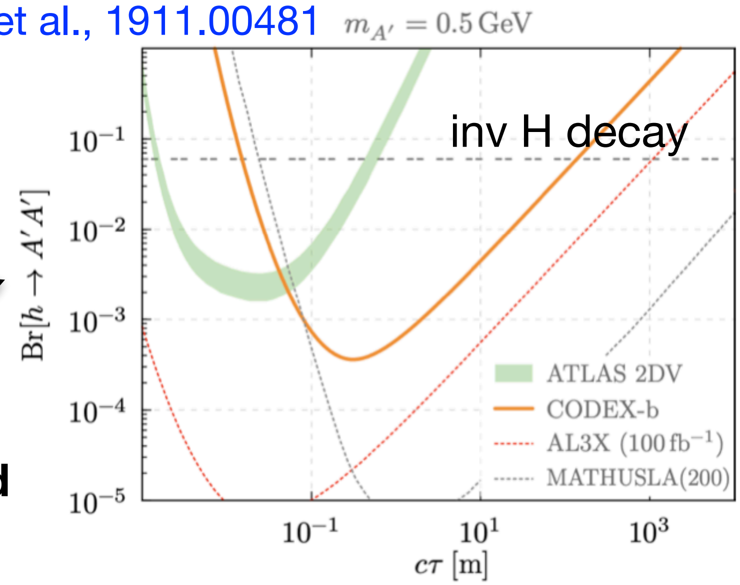
1. New detectors at high energy colliders

Several proposals for **new detectors** to add to the **LHC** to search for long lived dark particles:

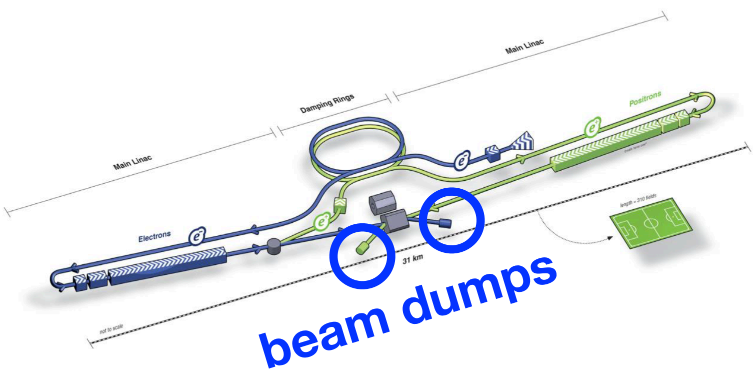
AL3x, Codex-b, Faser, Mathusla

H exo decay to 2 long lived dark photons

Aielli et al., 1911.00481



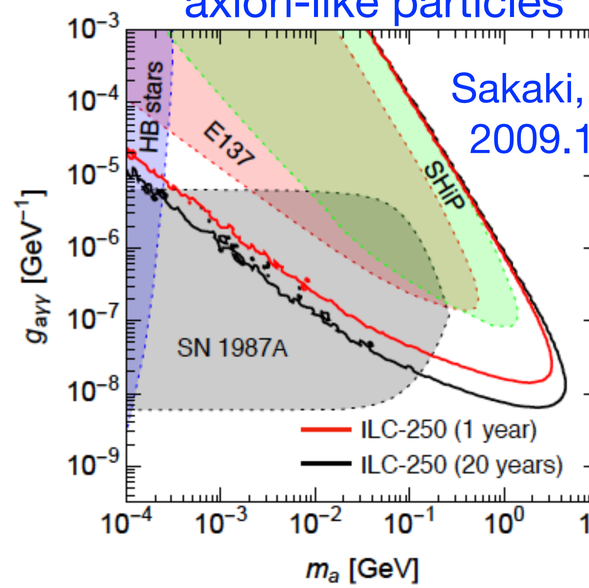
Novel ideas for **future colliders**.
Example: a **beam dump** experiment for the **ILC**



ILC Fixed Target/ Dark Sectors study group (M. Perelstein, SG) join us!

Kanemura, Moroi, Tanabe, 1507.02809

axion-like particles



Sakaki, Ueda, 2009.13790