Exploring the frontier: Theoretical insights into the physics of dark sectors

Stefania Gori
UC Santa Cruz

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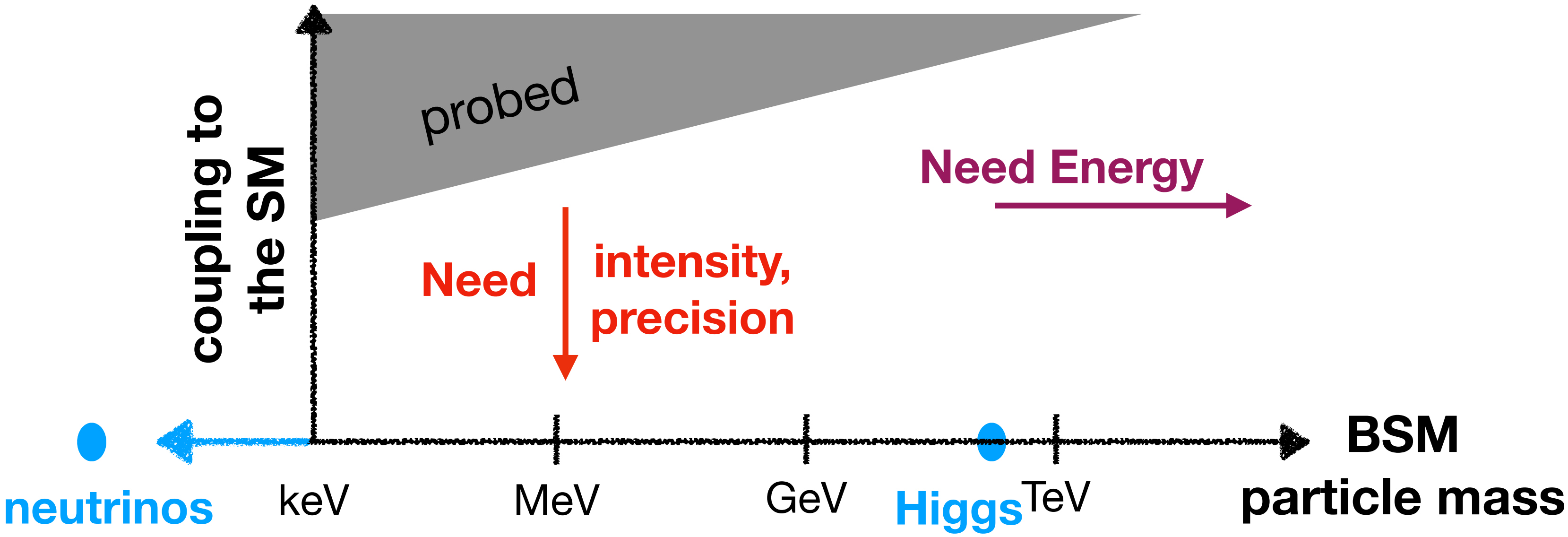
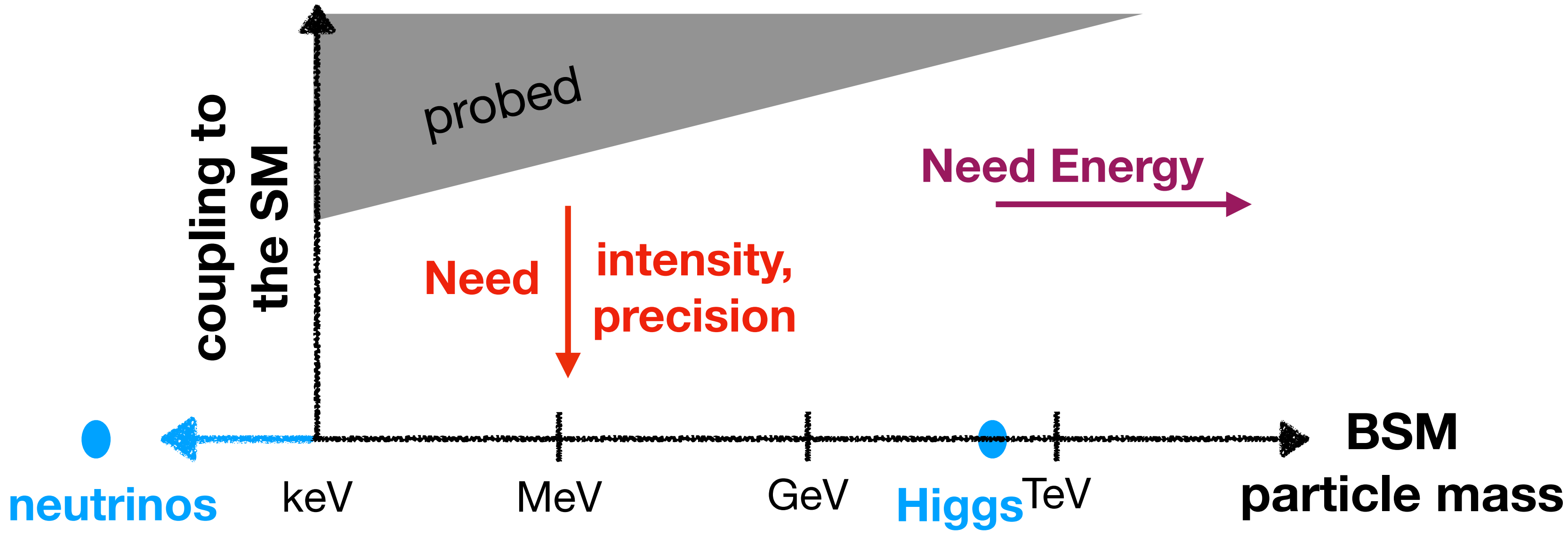
July 23, 2024

The quest for new physics



We do not know what will be the next New Physics (NP) scale.

The quest for new physics



We do not know what will be the next New Physics (NP) scale.

➡ **Search as broadly as possible.**

Accelerator experiments have access to NP scales in the range of few TeV and below.
Enormous progress in the exploration has been made in the past several years. Numerous gaps still to cover.

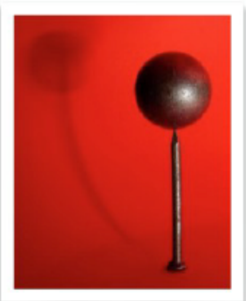
The most hidden particles are “dark sector particles”, i.e. those particles that are not charged under the Standard Model (SM) gauge symmetries.

“Portals”:

Dark photon	$\epsilon Z^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H \rvert^2 \lvert S \rvert^2$
Neutrino	$y H L N$
Axion	$\frac{1}{f_s} F_{\mu\nu} \tilde{F}_{\mu\nu} a$

Theoretical guidance

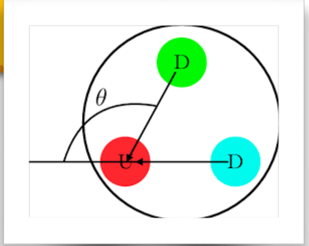
No guaranteed discovery but…



Naturalness problem

dark scalars
(twin Higgs, SUSY)

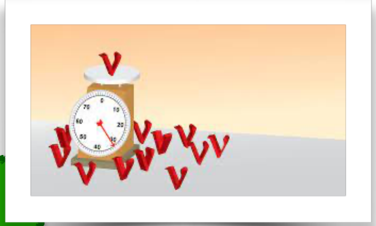
Strong CP problem



axions

dark photons

Nature of Dark Matter



Neutrino masses

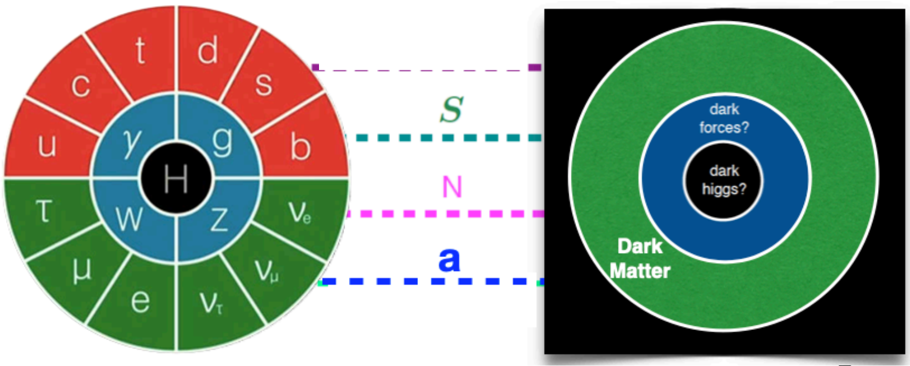
sterile neutrinos

Baryon anti-baryon asymmetry

dark scalars

As we will discuss in this talk, **new dark particles could address each of these problems.**

Experiments and experimental techniques



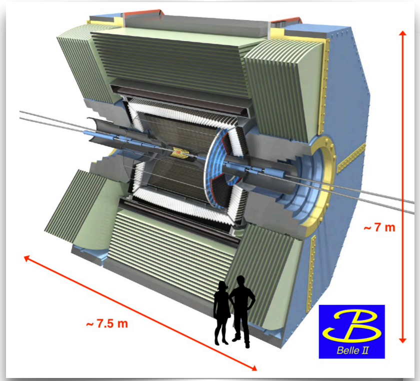
For this talk:

dark sector theories
& experimental strategies
(focus on search gaps)

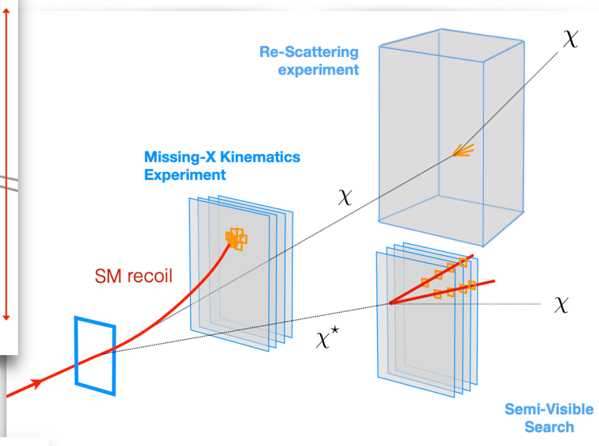
Chapter 1
New electroweak scale dark particles

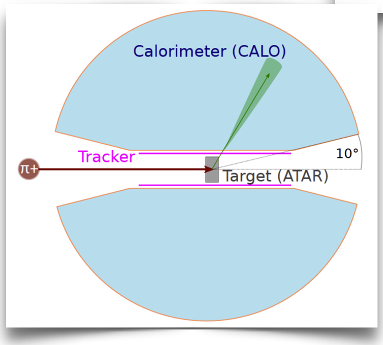
Chapter 2
New light sub-GeV scale dark particles

(2) Low energy colliders



(2) Fixed target experiments

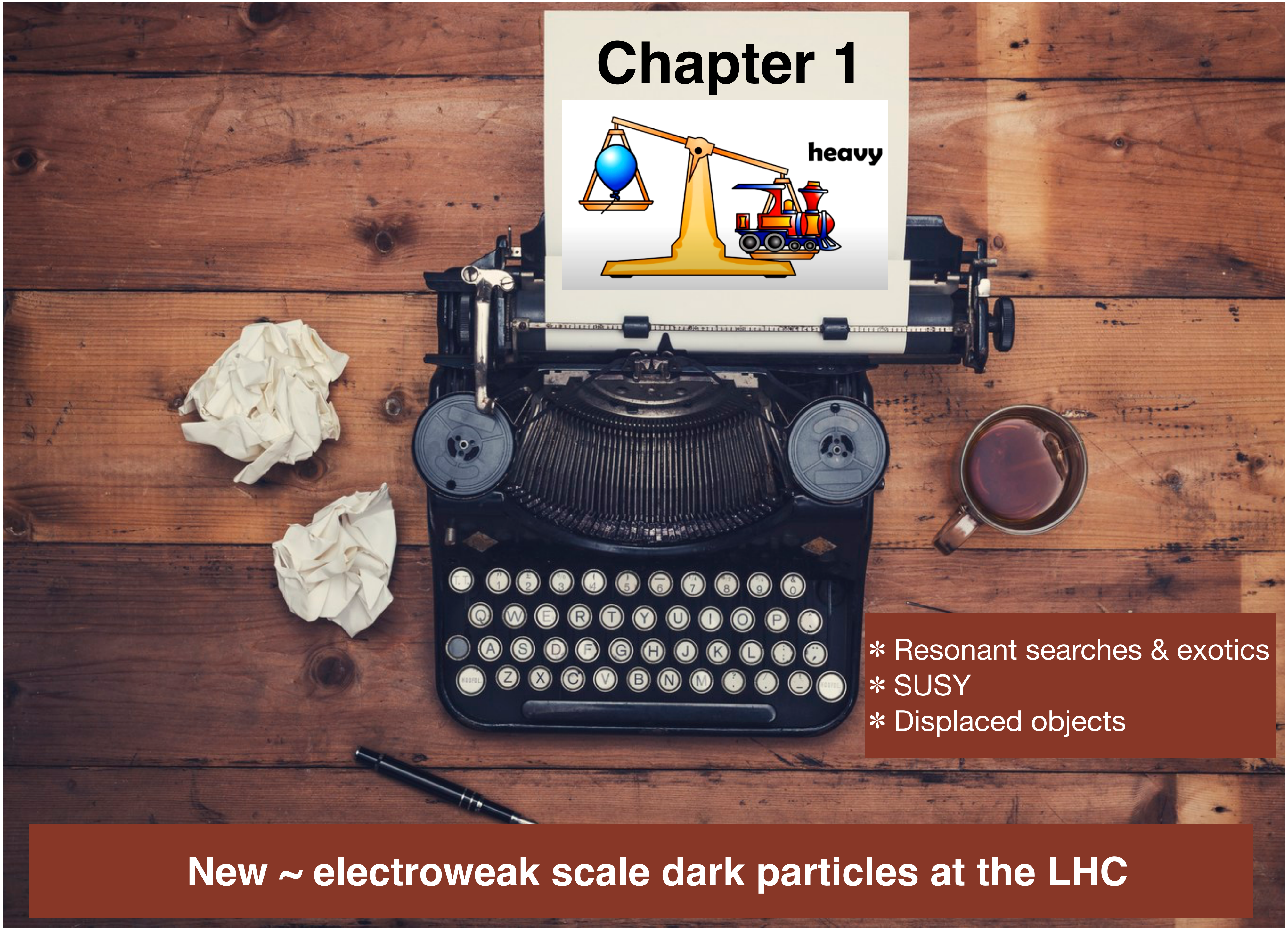




(2) Light meson factories

(1) LHC

Chapter 1

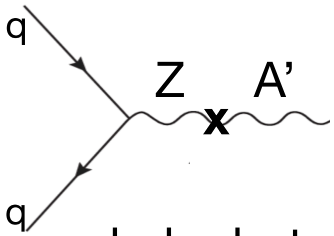


- ✻ Resonant searches & exotics
- ✻ SUSY
- ✻ Displaced objects

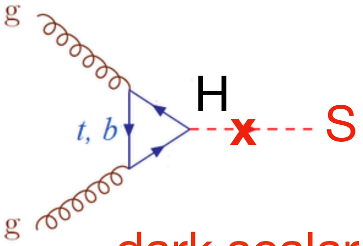
New ~ electroweak scale dark particles at the LHC

Resonances & exotic searches at the LHC

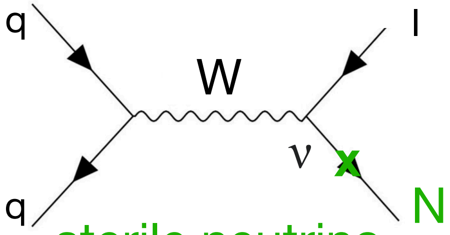
Dark sector particles can be produced because they generically mix with SM particles



dark photon



dark scalar



sterile neutrino

Resonances & exotic searches at the LHC

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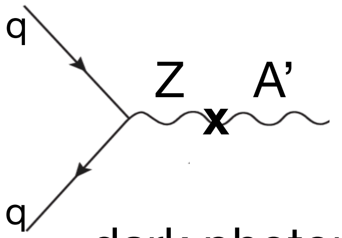
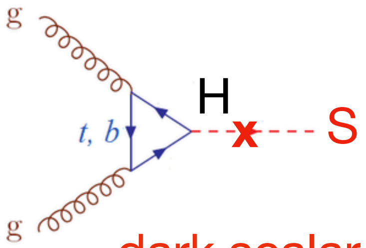
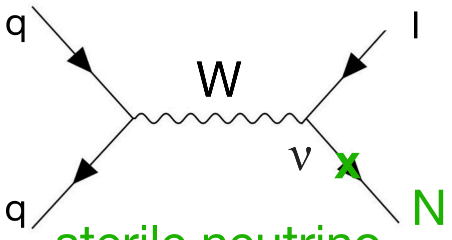


dark photon

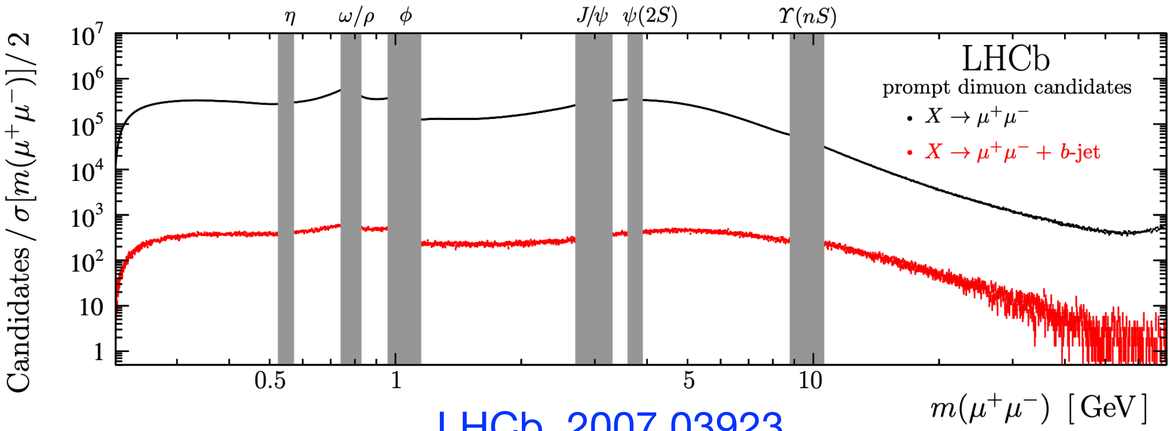


dark scalar



sterile neutrino

Importance of resonance searches in a **range of masses as broad as possible**
(data scouting, data parking, LHCb searches at low mass, ISR, …)



LHCb, 2007.03923

see also CMS PAS EXO-21-005

Often times dark particles lead to exotic signatures:

- collimated objects, e.g., photon-jets, …
- exotic jet structure in dark QCD models, e.g., semi-visible jets, large R-jets with high track multiplicity, soft unclustered energy patterns, …

ATLAS, 2403.09292
CMS, 2405.13778

Creativity is important!

New SUSY searches to dark sectors

SUSY searches are also affected by the presence of a dark sector.

For example, the **NMSSM** has a singlet chiral super field in addition to the particle content of the MSSM.

Because of the additional dark scalar, pseudo-scalar, and neutralino (singlino), the NSSM has a richer phenomenology. New signatures can arise.

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For example: Singlino-Higgsino coannihilation regime ($m_{\chi_1^\pm} \simeq m_{\chi_3^0} \simeq m_{\chi_2^0} \simeq m_{\chi_1^0}$)

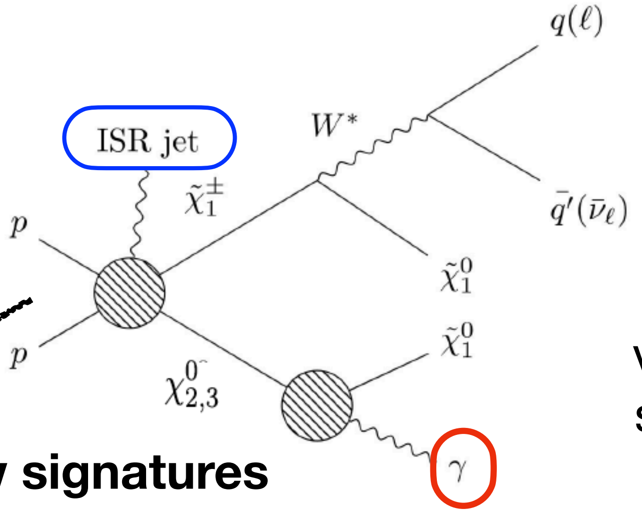
Most searched decay modes are suppressed because of the **squeezed** spectrum:

$$pp \to \chi_1^\pm \chi_2^0 \to (W^{(*)}\chi_1^0)(Z^{(*)}\chi_1^0) \to 3\ell + \text{MET}$$

$$\Gamma(\chi_2^0 \to \chi_1^0\, f\bar{f}) \;\propto\; \left(\frac{m_{\chi_2^0}}{m_{\chi_1^0}} - 1\right)^5$$

main decay mode

$$\Gamma(\chi_2^0 \to \chi_1^0 \gamma) \;\propto\; \left(\frac{m_{\chi_2^0}}{m_{\chi_1^0}} - 1\right)^3$$



New signatures for the LHC

soft visible states

Singlino-Bino coannihilation regime: cascade decays containing multiple photons

e.g., $pp \to \chi_1^\pm \chi_{3,4}^0 \to (\chi_2^0 W^\pm)(\chi_2^0 h) \to (\chi_1^0\gamma)(\chi_1^0\gamma)W^\pm h$

S.Gori

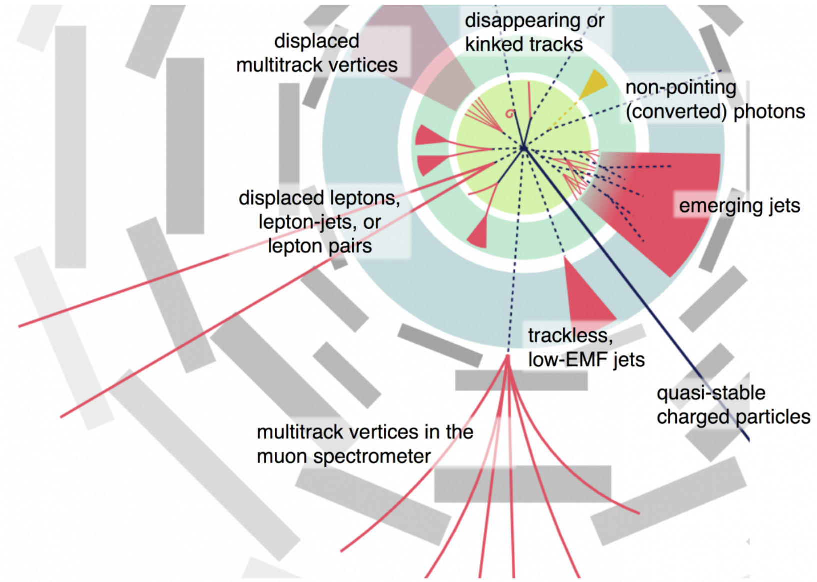
Roy, Wagner, 2401.08917

Long-lived-particles (LLPs)

Long-lived-particles generically arise in dark sector models.

NP particles can have a width that is suppressed by

- small mass splitting
- multi-body final states
- symmetry
- high NP scale
- small coupling



H. Russell

Examples

Models to explain the origin of the EW scale

SUSY: pure wino states

$$\delta m_\chi = M_{\chi^\pm} - M_{\chi^0} \simeq 166\text{MeV}$$

$$\tau_{\chi^\pm}^{-1} \propto \frac{G_F^2}{\pi} f_\pi^2\, \delta m_\chi^3 \sim \frac{1}{6\text{ cm}}$$

Twin Higgs: glueballs

Models to explain the origin of neutrino masses

Sterile neutrinos

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Appreciable gaps

- Singly produced LLPs **(*)**
- Low-mass (< 20 GeV)
- LLPs from Higgs decays **(*)**
- High multiplicities
- displaced taus
- small displacements
- …

Examples

Models to explain the origin of the EW scale

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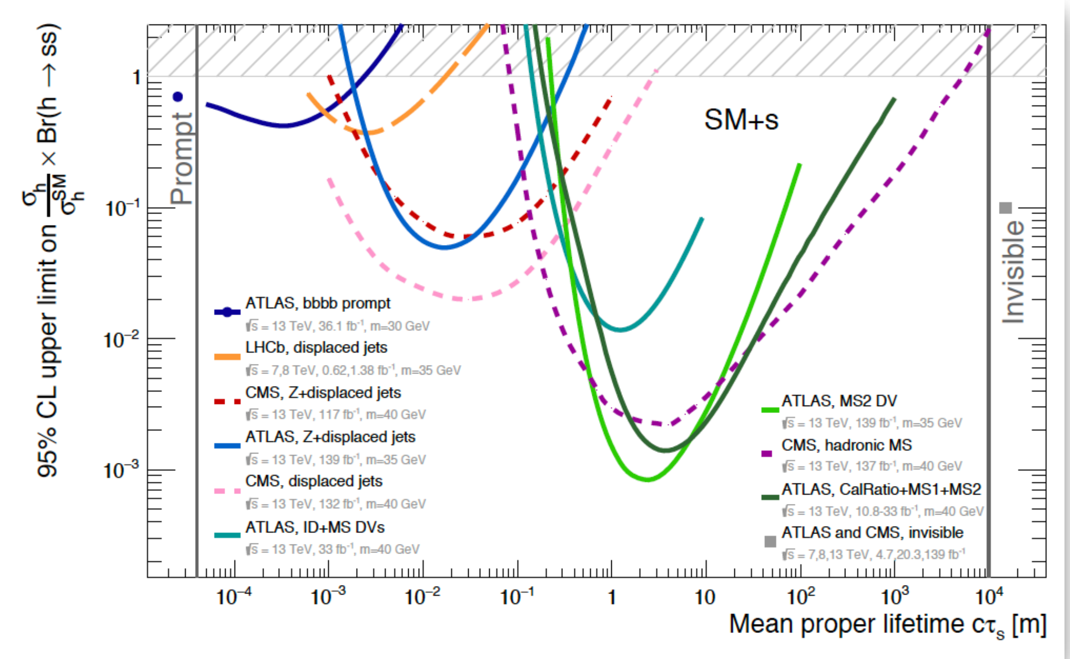
Twin Higgs: glueballs

Models to explain the origin of neutrino masses

Sterile neutrinos

Higgs exotic decays to LLPs

- Some searches will greatly benefit from the increase in luminosity (case of low/negligible backgrounds)



Cepeda, SG, Martinez-Outschoorn, Shelton, 2111.12751

h → SS
S = long-lived

- Significant improvements in sensitivity of many searches could be possible in the future with potential improvements in

- timing (Liu, Liu, Wang, 1805.05957, …);
- triggers (Gershtein, 1705.04321, Gershtein et al., 2012.07864…);
- analysis strategies (e.g. Csaki et al, 1508.01522, …).

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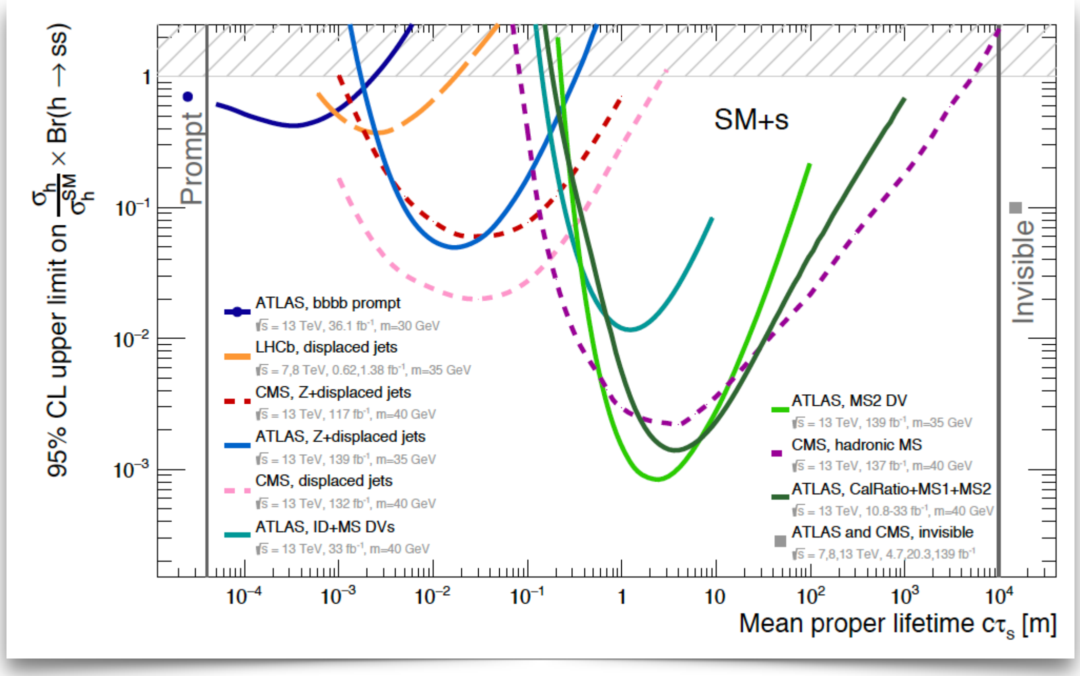

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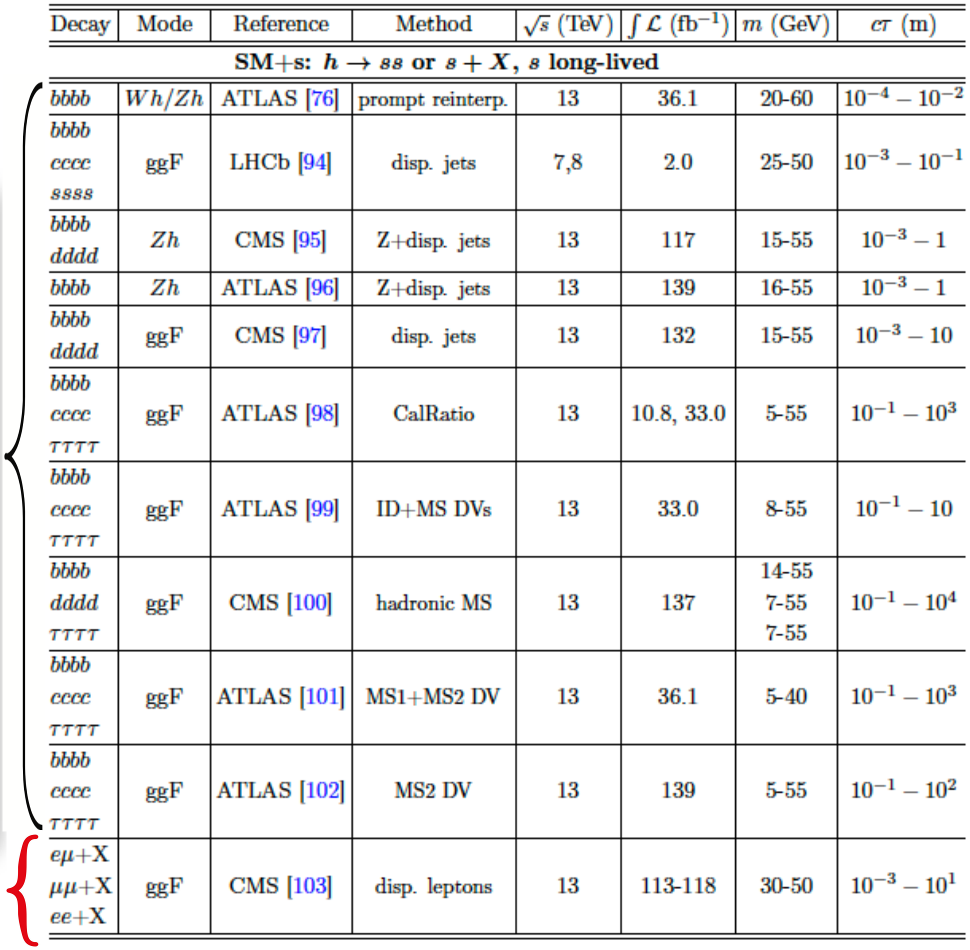


Decay	Mode	Reference	Method	$\sqrt{s}$ (TeV)	$\int \mathcal{L}$ (fb^{-1})	m (GeV)	$c\tau$ (m)
SM+s: $h \to ss$ or $s + X$, s long-lived							
$bbbb$	Wh/Zh	ATLAS [76]	prompt reinterp.	13	36.1	20-60	$10^{-4} - 10^{-2}$
$bbbb$ $cccc$ $ssss$	ggF	LHCb [94]	disp. jets	7,8	2.0	25-50	$10^{-3} - 10^{-1}$
$bbbb$ $dddd$	Zh	CMS [95]	Z+disp. jets	13	117	15-55	$10^{-3} - 1$
$bbbb$	Zh	ATLAS [96]	Z+disp. jets	13	139	16-55	$10^{-3} - 1$
$bbbb$ $dddd$	ggF	CMS [97]	disp. jets	13	132	15-55	$10^{-3} - 10$
$bbbb$ $cccc$ $\tau\tau\tau\tau$	ggF	ATLAS [98]	CalRatio	13	10.8, 33.0	5-55	$10^{-1} - 10^{3}$
$bbbb$ $cccc$ $\tau\tau\tau\tau$	ggF	ATLAS [99]	ID+MS DVs	13	33.0	8-55	$10^{-1} - 10$
$bbbb$ $dddd$ $\tau\tau\tau\tau$	ggF	CMS [100]	hadronic MS	13	137	14-55 7-55 7-55	$10^{-1} - 10^{4}$
$bbbb$ $cccc$ $\tau\tau\tau\tau$	ggF	ATLAS [101]	MS1+MS2 DV	13	36.1	5-40	$10^{-1} - 10^{3}$
$bbbb$ $cccc$ $\tau\tau\tau\tau$	ggF	ATLAS [102]	MS2 DV	13	139	5-55	$10^{-1} - 10^{2}$
$e\mu$+X $\mu\mu$+X ee+X	ggF	CMS [103]	disp. leptons	13	113-118	30-50	$10^{-3} - 10^{1}$

$h \to SS$
S = long-lived

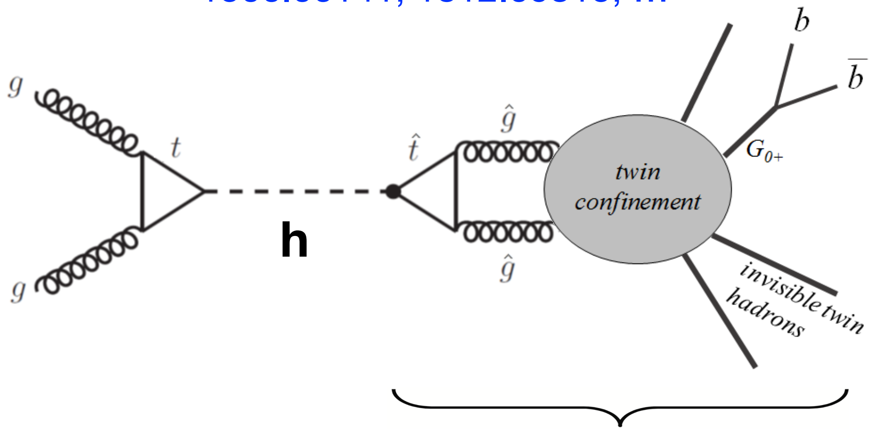
Most searches are done requiring ≥1 displaced particles.

$h \to S_1S_2$

Many new opportunities for 1 displaced particle + E_T or visible.

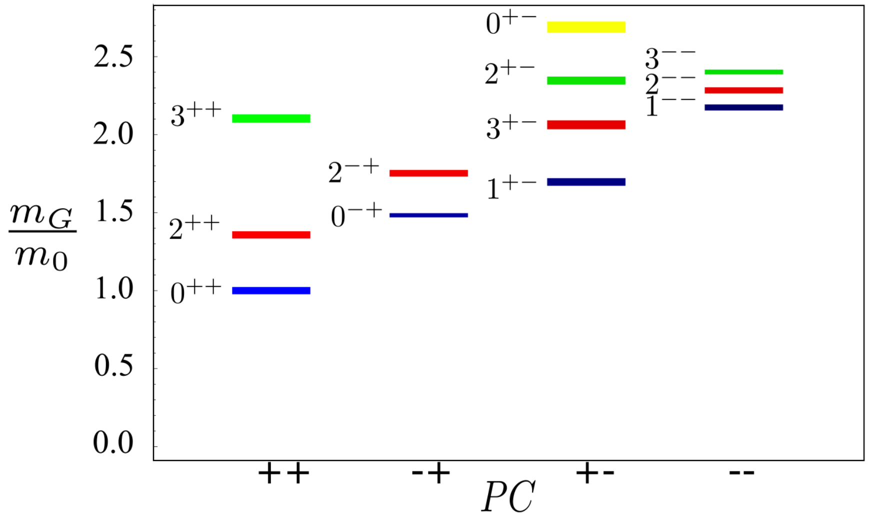
An example scenario: twin Higgs models

1506.06141, 1812.09315, …



decays of the Higgs into the twin sector

Juknevich, 0911.5616



Spectrum of glueballs in a pure glue SU(3) theory

Several studies for **h → 0^{++} 0^{++},** with 0^{++} decaying to two displaced SM fermions (0^{++} mixes with the Higgs).

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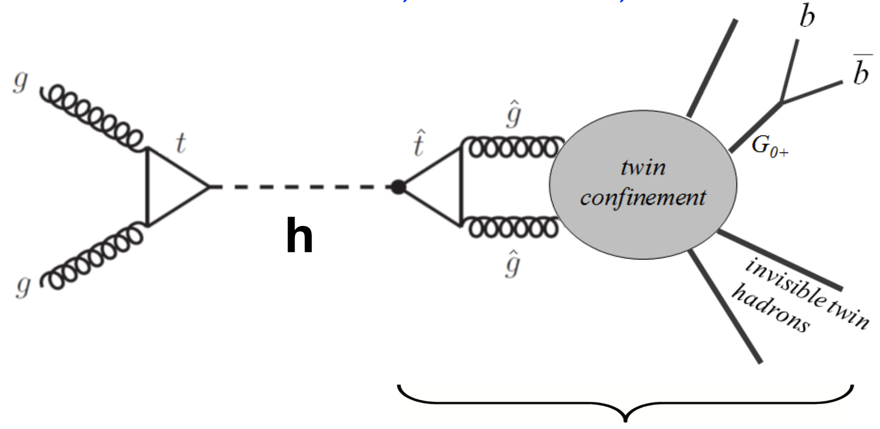
1506.06141, 1812.09315, …



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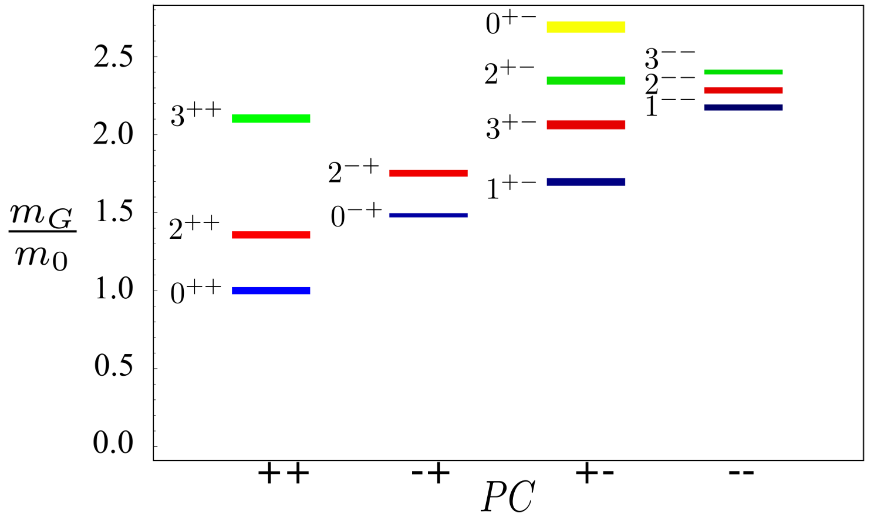


Spectrum of glueballs in a pure glue SU(3) theory

Several studies for **h** → $\mathbf{0^{++}\,0^{++}}$, with 0^{++} decaying to two displaced SM fermions (0^{++} mixes with the Higgs).

What about decays containing heavier glueballs? e.g. **h** → $\mathbf{0^{++}\,2^{++}}$.
Typically, heavier glueballs have a much longer life time ➡ invisible to LHC detectors.

Tools have been developed for parton shower and hadronization in dark QCD theories:
Curtin, Gemmell, Verhaaren, 2202.12899; Batz, Cohen, Curtin, Gemmell, Kribs, 2310.13731, …

Chapter 2

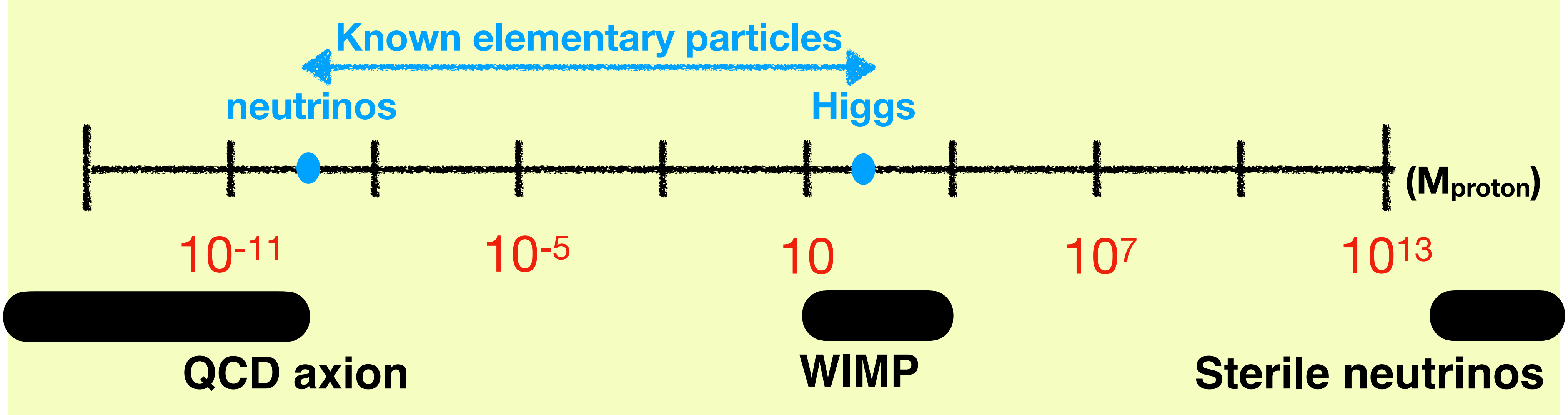
- ✻ Sterile neutrinos
- ✻ Axions and axion-like-particles

Focus on meson factories

New light (sub-GeV) dark particles

S.Gori

Why sub-GeV New Physics?



Known elementary particles

neutrinos

Higgs

(M_{proton})

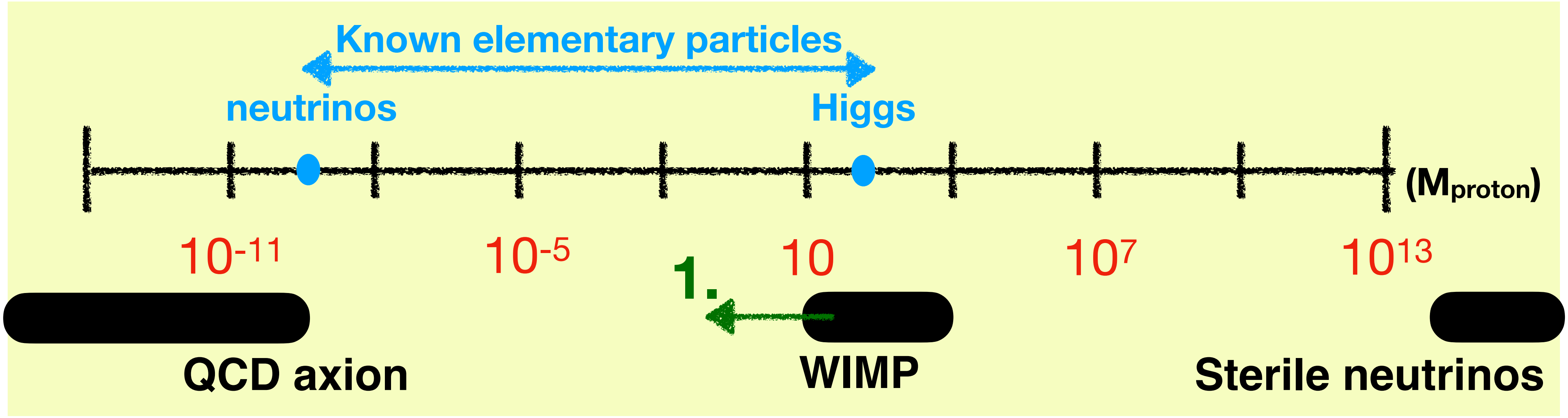
10^{-11} 10^{-5} 10 10^{7} 10^{13}

QCD axion

WIMP

Sterile neutrinos

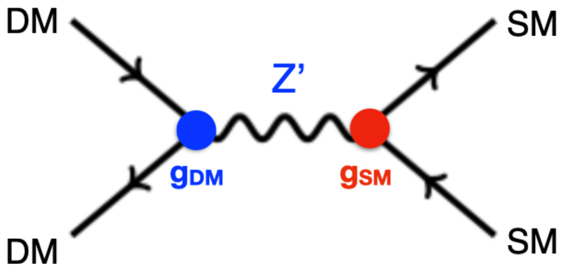
Why sub-GeV New Physics?



1. WIMP is a beautiful and predictive framework.

Can we extend it to lower masses?

YES!



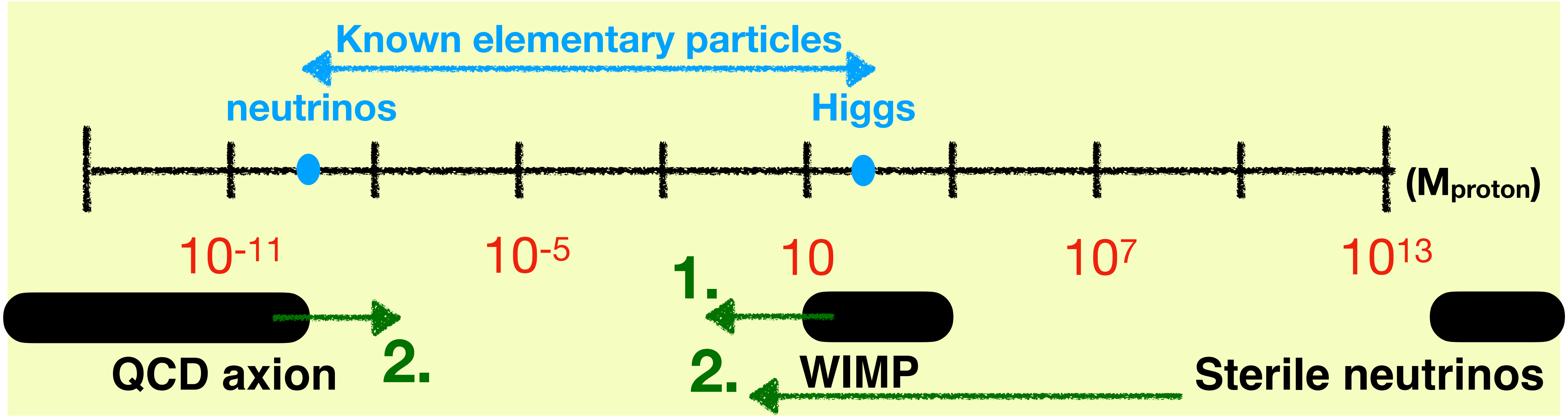
for the measured relic abundance

$$\langle\sigma v\rangle \sim 1\text{pb}\times\left(\frac{g_{\rm DM}}{0.5}\right)^2\left(\frac{g_{\rm SM}}{0.001}\right)^2\left(\frac{m_{\rm DM}}{100\ \text{MeV}}\right)^2\left(\frac{1\ \text{GeV}}{m_{Z'}}\right)^4 \sim 1\text{pb}$$

Lee Weinberg bound: $m_{\rm DM} \geq O(1\ \text{GeV})$,

or **existence of a “Dark Sector”**

Why sub-GeV New Physics?



2. Can the strong CP problem be addressed by **heavier axions** (or axion-like-particles)?

YES!

Extended QCD sectors can do that. (Easier to address the axion quality problem with heavier axions and lower f_a.)

(e.g., Agrawal, Howe, 1710.04213;
Foster, Kumar, Safdi, Soreq, 2208.10504, …)

Can SM neutrino masses be generated in theories with **lighter sterile neutrinos**?

YES!

Inverse or linear seesaw models can do that (lepton number is an approximate symmetry)

(e.g., Mohapatra, Valle, ’86,
Akhmedov, et al, 9507275, …)

Advances in meson factories

A big jump in luminosity is expected in the coming years

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A big jump in luminosity is expected in the coming years

	Past/Present	Future
Pion-factories	**PIENU experiment** at TRIUMF: $\sim 10^{11}$ pi^{+}	**PIONEER experiment** at PSI (phase 1 approved. Data in ~2028(?)): $\sim 10^{12}$ pi^{+}
Kaon-factories	**E949** at BNL: $\sim 10^{12}$ K^{+} **E391** at KEK: $\sim 10^{12}$ K_L	**NA62** at CERN: $\sim 10^{13}$ K^{+} **KOTO** at JPARC: $\sim 10^{14}$ K_L
B-factories	**LHCb:** more than ~ $5*10^{12}$ b quarks produced so far; **Belle** (running until 2010): $\sim 10^{9}$ BB-pairs were produced.	**LHCb:** ~30 times more b quarks will be produced by the end of the LHC; **Belle-II:** ~50 times more BB-pairs will be produced.

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Kaon-factories	**E949** at BNL: ~10^{12} K^+ **E391** at KEK: ~10^{12} K_L	**NA62** at CERN: ~10^{13} K^+ **KOTO** at JPARC: ~10^{14} K_L **Proton fixed target:** 10^{17}; 10^{20} K^+, K_L
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+ LHC, future colliders!

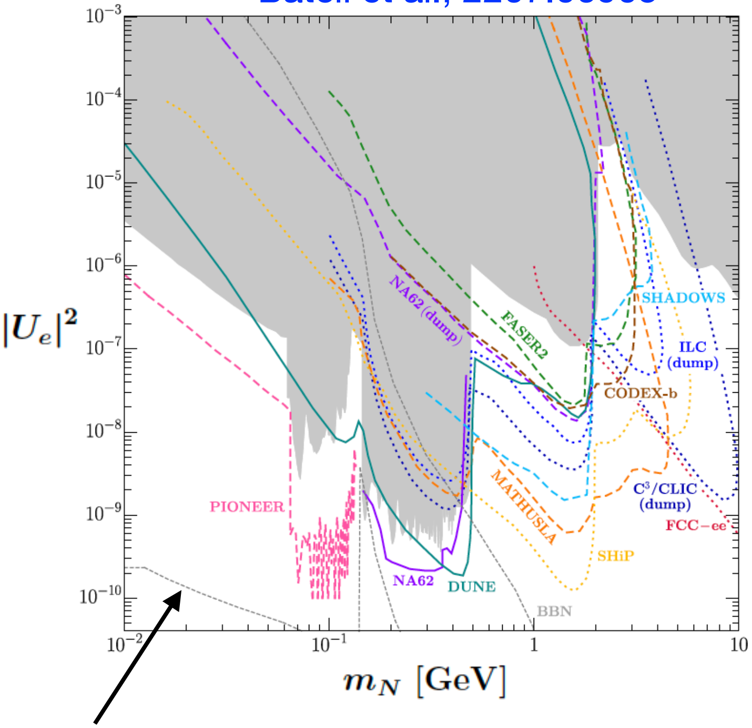
Proton fixed target experiments also produce a huge statistics of mesons.

E.g., DarkQuest (120 GeV protons, $2*10^{18}$ POT); SHiP (400 GeV protons, $2*10^{20}$ POT)

Sterile neutrinos at meson factories

Several meson decays can lead to a sizable production of sterile neutrinos.
E.g., B → X l N, π → l N, D_s → μ N, …

Batell et al., 2207.06905



“vanilla” seesaw

$$|U_e| \simeq \sqrt{\frac{m_{\nu_e}}{M_e}}$$

visibly decaying sterile neutrinos

Less attention has been dedicated to invisible sterile neutrinos. ➡ New searches can be performed.

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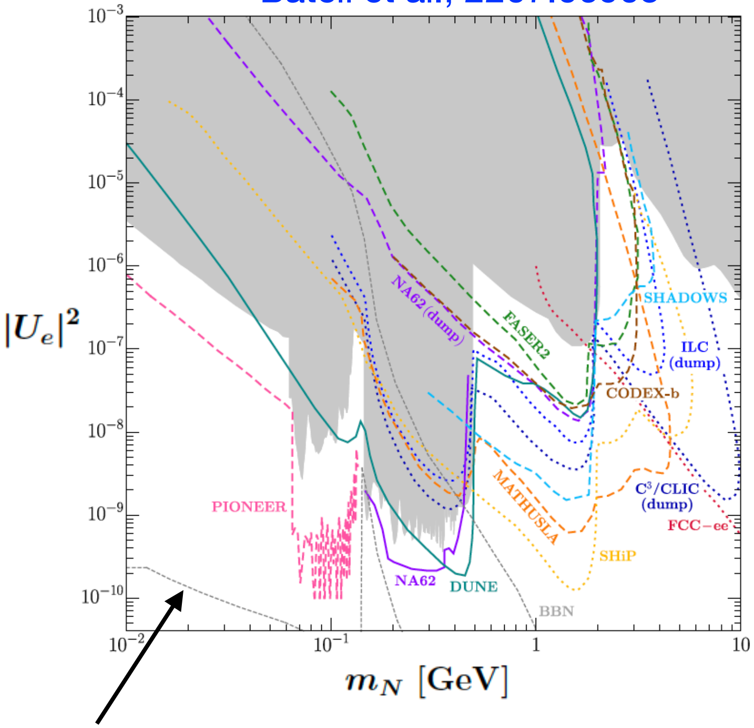

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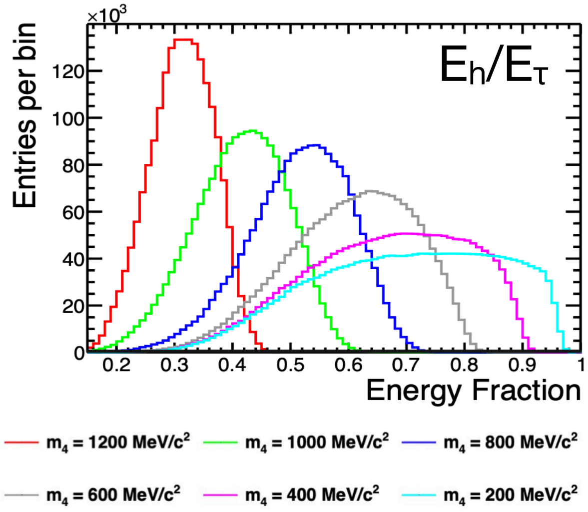
Opportunity to set a <u>model independent bound</u> on invisible sterile neutrinos that mix with the tau neutrino:

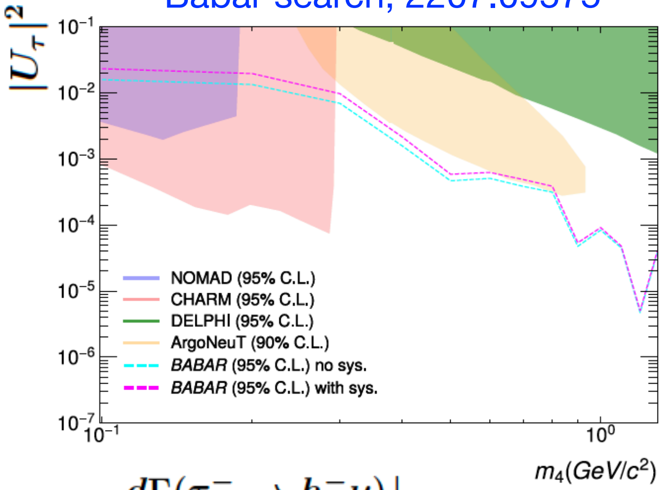
B factories: $\tau^- \to h^- + \nu/N$ 3-prong hadronic final state

Search proposed by Kobach, Hobbs, 1412.4785



What about Belle-II?

Babar search, 2207.09575



$$\frac{d\Gamma(\tau^- \to h^-\nu)}{dm_h dE_h} = |U_\tau|^2 \left.\frac{d\Gamma(\tau^- \to h^-\nu)}{dm_h dE_h}\right|_{\rm HNL} + (1-|U_\tau|^2) \left.\frac{d\Gamma(\tau^- \to h^-\nu)}{dm_h dE_h}\right|_{\rm SM}$$

ALP EFTs at high intensity/energy experiments

see e.g. Brivio et al, 1701.05379
Bauer et al, 1708.00443, 1808.10323, …

High energy colliders
(LHC, Tevatron, LEP, future colliders)

see e.g. Calibbi et al, 2006.04795
Panci et al, 2209.03371, …

Low energy flavor experiments
(Mu3e, MEG-II, …)

$$\mathcal{L} \supset -\frac{g_{ag}}{4}\, a\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - \frac{g_{aW}}{4}\, a\, W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - \frac{g_{aB}}{4}\, a\, B_{\mu\nu}\tilde{B}^{\mu\nu} + i g_{af}(\partial_\mu a)(\bar{f}\gamma^\mu\gamma_5 f)$$

Fixed target (beam dump)
experiments
(proton, electron, photons)

see e.g., Dobrich et al, 1512.03069
Harland-Lang et al, 1902.04878, …

Meson factories
(pion, Kaon, and B-mesons)

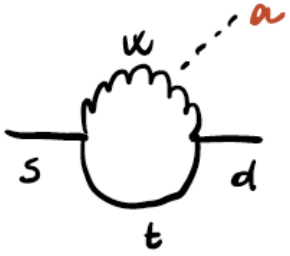
see e.g., Bauer et al, 2110.10698
Altmannshofer, Dror, SG, 2209.00665, …

Neutral & charged current meson decays to ALPs

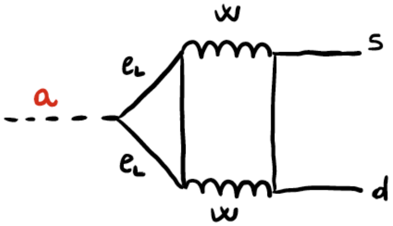
Flavor changing neutral current

They arise in models with

- ✱ ALPs mixed with SM neutral pions (e.g. $K^+ \to \pi^+ \pi^0 \;\Rightarrow\; K^+ \to \pi^+ a$)
- ✱ ALPs coupling to W or tops



- ✱ ALPs coupling to leptons (higher loop)



$$\begin{array}{rcl} K_L & \to & \pi^0 a \\ K^+ & \to & \pi^+ a \\ B & \to & K a \end{array}$$

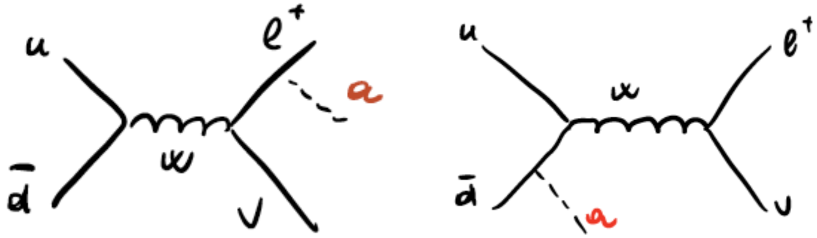
- ✱ Flavor violating ALPs

Most studied (both th. and exp.)

Charged current

They arise in models with

- ALPs mixed with SM neutral pions (e.g. $\pi^+ \to \ell^+ \nu \pi^0 \;\Rightarrow\; \pi^+ \to \ell^+ \nu a$)
- ALP coupling to leptons or quarks



$$\begin{array}{rcl} \pi^+ & \to & a \ell^+ \nu \\ K^+ & \to & a \ell^+ \nu \\ B^+ & \to & a \ell^+ \nu \end{array}$$

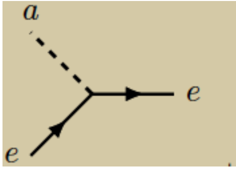
Example scenario: Lepton-coupled ALPs

$$\boxed{\frac{(\partial_\mu a)}{m_e}\left[\bar{e}\gamma^\mu\left(\bar{g}_{ee}+g_{ee}\gamma_5\right)e+g_\nu\bar{\nu}\gamma^\mu P_L\nu\right]}$$

$$\mathcal{L}=-a\partial_\mu j^\mu_{PQ}$$

$$\partial_\mu j^\mu_{\mathrm{PQ}}=g_{\ell\ell}(\bar{\ell}i\gamma_5\ell)$$

“Standard” vertex



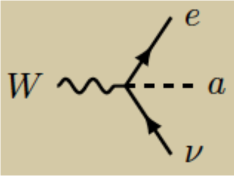
$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}-g_{\ell\ell}+g_{\nu_\ell}}{4s_W^2}W^+_{\mu\nu}\tilde{W}^{-,\mu\nu}$$

$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}-g_{\ell\ell}(1-4s_W^2)}{2c_W s_W}F_{\mu\nu}\tilde{Z}^{\mu\nu}-g_{\ell\ell}F_{\mu\nu}\tilde{F}^{\mu\nu}+$$

$$+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}(1-4s_W^2)-g_{\ell\ell}(1-4s_W^2+8s_W^4)+g_\nu}{8s_W^2c_W^2}Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

$$+\frac{ig}{2\sqrt{2}m_\ell}(g_{\ell\ell}-\bar{g}_{\ell\ell}+g_{\nu_\ell})(\bar{\ell}\gamma^\mu P_L\nu)W^-_\mu$$

Weak vertex



(only present for
SU(2) weak-violating models)

$$\bar{g}_{ee}-g_{ee}-g_\nu\neq 0$$

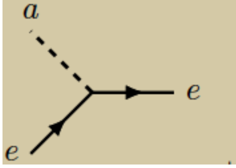
Example scenario: Lepton-coupled ALPs

$$\frac{(\partial_\mu a)}{m_e}\left[\bar{e}\gamma^\mu\left(\bar{g}_{ee}+g_{ee}\gamma_5\right)e+g_\nu\bar{\nu}\gamma^\mu P_L\nu\right]$$

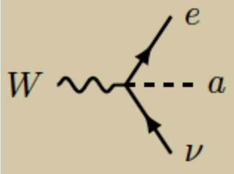
$$\mathcal{L}=-a\partial_\mu j^\mu_{PQ}$$

$$\begin{aligned}\partial_\mu j^\mu_{\rm PQ} &= g_{\ell\ell}(\bar{\ell}i\gamma_5\ell)\\ &+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}-g_{\ell\ell}+g_{\nu_\ell}}{4s_W^2}W^+_{\mu\nu}\tilde{W}^{-,\mu\nu}\\ &+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}-g_{\ell\ell}(1-4s_W^2)}{2c_W s_W}F_{\mu\nu}\tilde{Z}^{\mu\nu}-g_{\ell\ell}F_{\mu\nu}\tilde{F}^{\mu\nu}+\\ &+\frac{e^2}{16\pi^2 m_\ell}\frac{\bar{g}_{\ell\ell}(1-4s_W^2)-g_{\ell\ell}(1-4s_W^2+8s_W^4)+g_\nu}{8s_W^2c_W^2}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\\ &+\frac{ig}{2\sqrt{2}m_\ell}(g_{\ell\ell}-\bar{g}_{\ell\ell}+g_{\nu_\ell})(\bar{\ell}\gamma^\mu P_L\nu)W^-_\mu\end{aligned}$$

“Standard” vertex



Weak vertex



(only present for **SU(2) weak-violating** models)

$$\bar{g}_{ee}-g_{ee}-g_\nu\neq 0$$

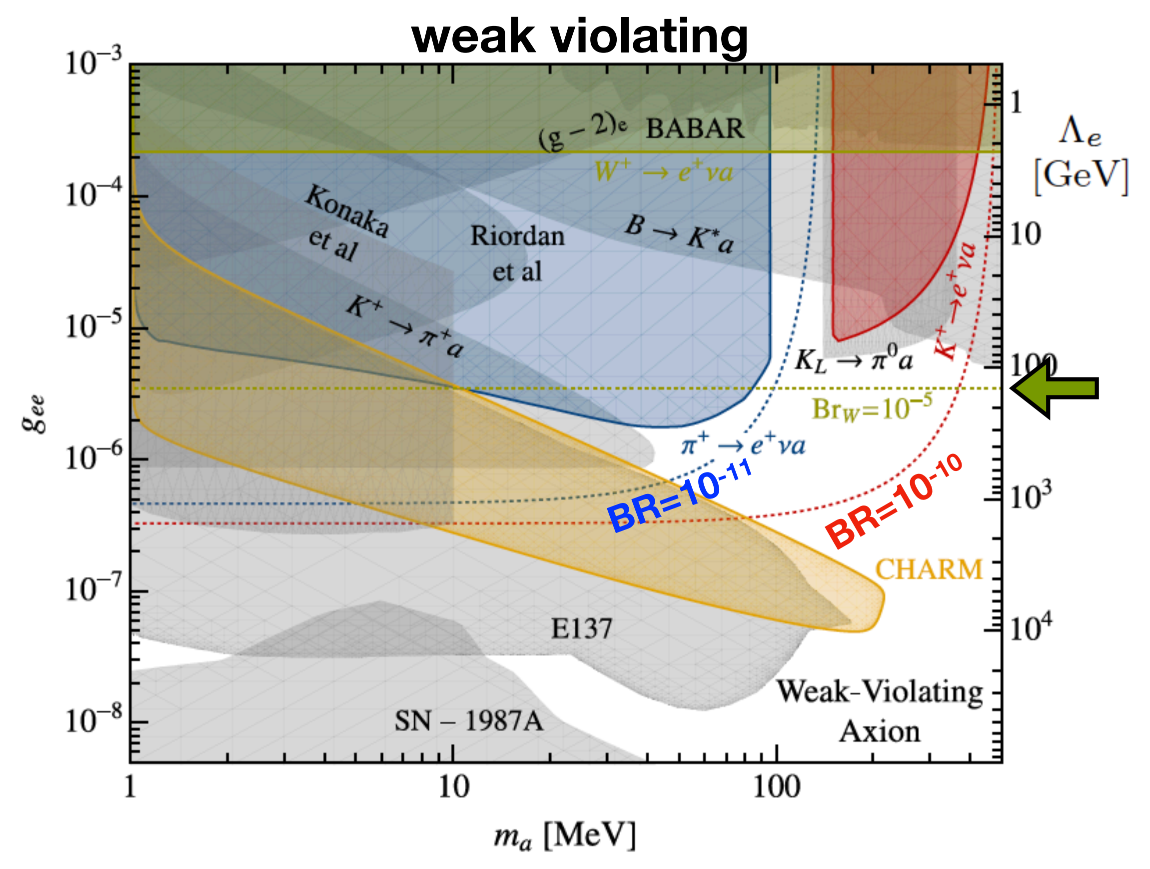
Enhancement of the charged-current decays:

$$\Gamma_{\pi^+\to e^+\nu a}\propto g_{ee}^2\frac{m_\pi^3 f_\pi^2}{m_W^4}$$ “standard” vertex

$$\Gamma_{\pi^+\to e^+\nu a}\propto \frac{m_\pi^2}{m_e^2}g_{ee}^2\frac{m_\pi^3 f_\pi^2}{m_W^4}$$ weak vertex

Altmannshofer, Dror, SG, 2209.00665

Example scenario: Lepton-coupled ALPs



Altmannshofer, Dror, SG, 2209.00665

Gray: neutral current decays K→π **a**, B→K **a**

Blue: π→eν**a**→eν(ee), interpretation from SINDRUM search, ‘80s

Red: K → eν**a**→eν(ee), interpretation from E865, ’00s

Green: W→ eν**a**→eν(ee) **exotic W boson decay**

No targeted searches yet!

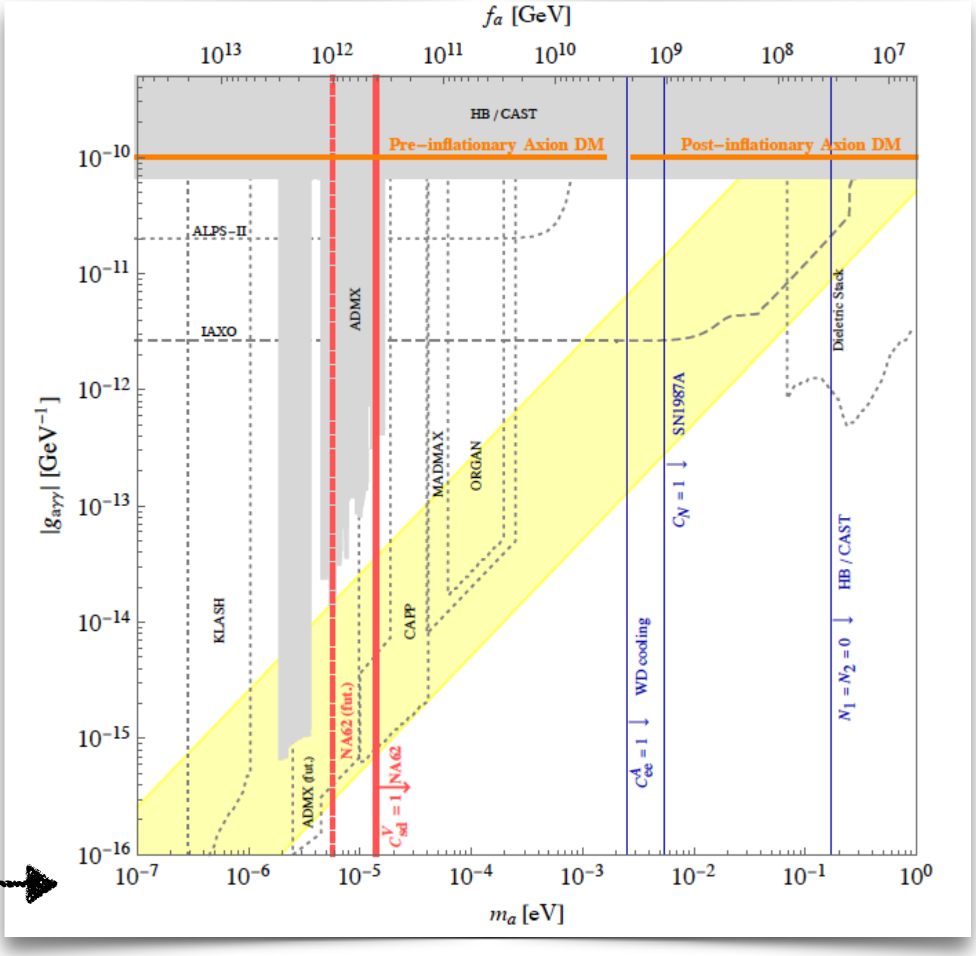
Flavor violating QCD axion

Kaon factories **can probe the QCD axion**, in the case of additional flavor violating couplings:

$$\mathcal{L} \supset \frac{\partial_\mu a}{2 f_a} C^V_{sd} (\bar{s}\gamma^\mu d)$$

access to **very low masses** (sub-eV):

Goudzovski, et al., 2201.07805

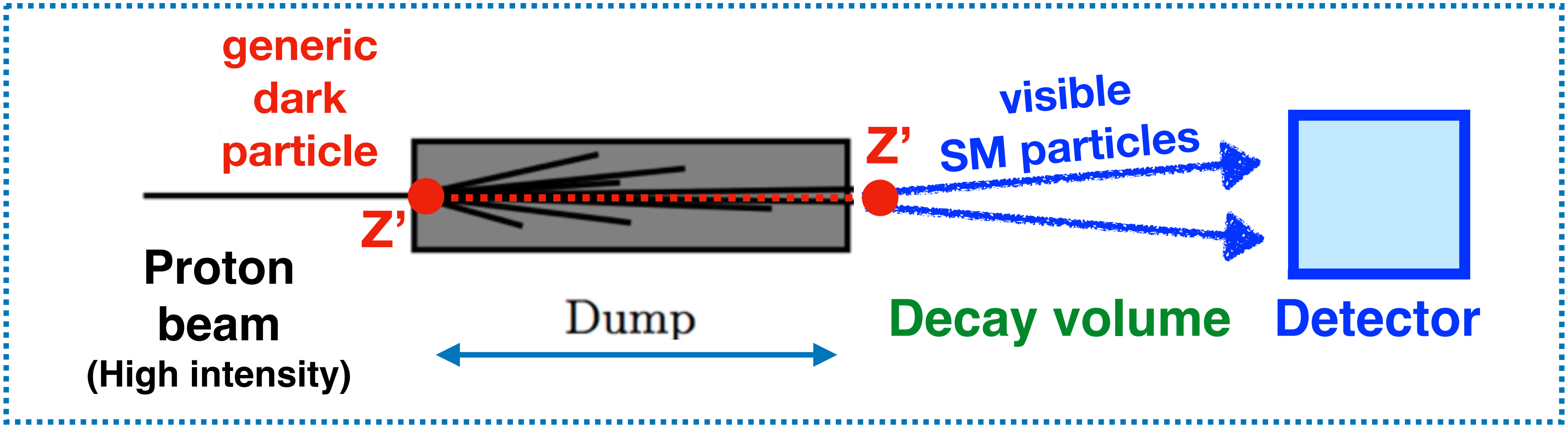


now

future

$K^+ \to \pi^+ + \text{inv.}$ at NA62

Dark particles at proton beam dump experiments

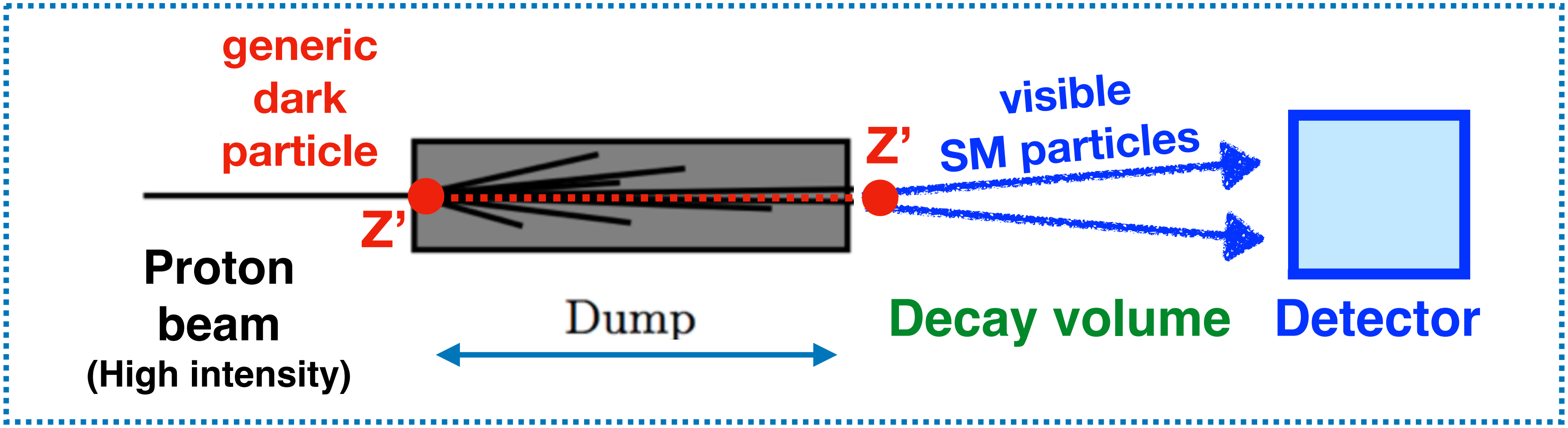


Two main examples: **DarkQuest** @ Fermilab; **SHiP** @ CERN

Dark particles can be produced from **meson decays or radiated** from the high intensity (primary or secondary) beam.

Many searches can be performed in the coming years…

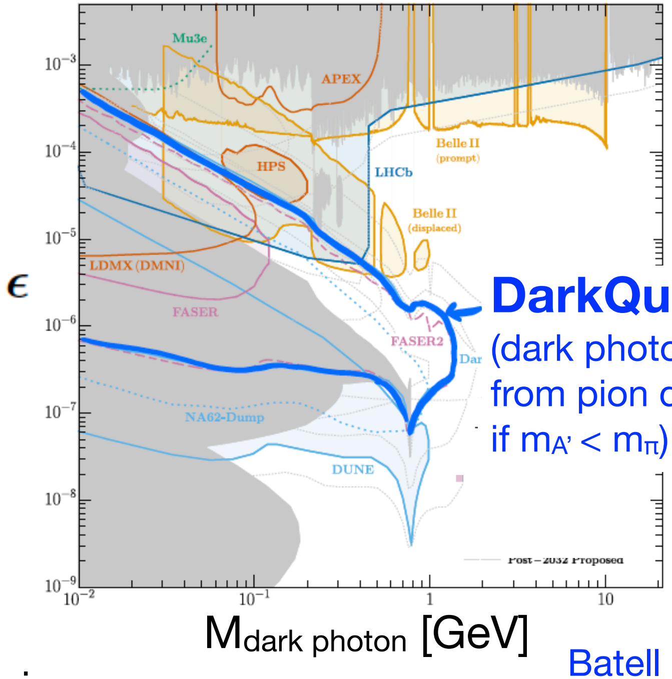
Dark particles at proton beam dump experiments



Two main examples: **DarkQuest** @ Fermilab; **SHiP** @ CERN

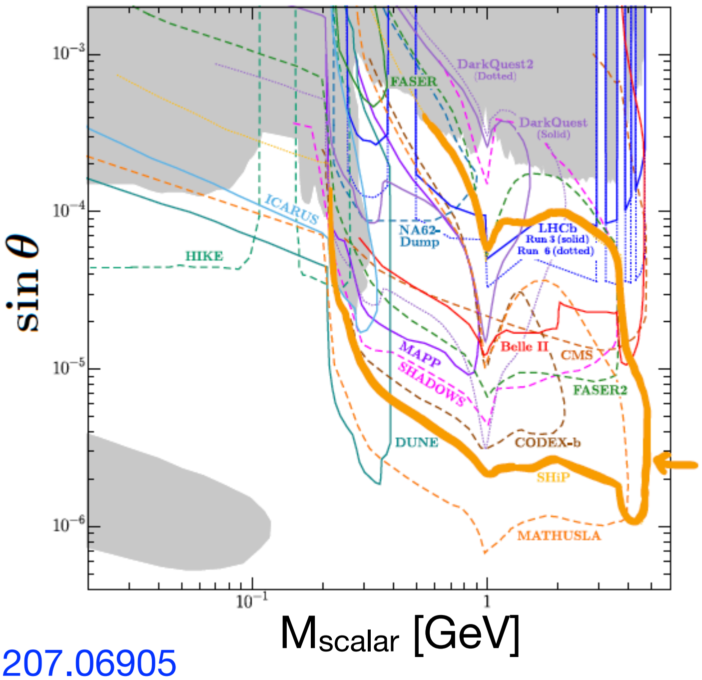
For example,

dark photon



DarkQuest
(dark photon from pion decays if $m_{A'} < m_{\pi}$)

dark scalar



Batell et al., 2207.06905

Complementarity with LHC auxiliary detectors + neutrino experiments

SHiP
(scalar from meson decays)
(to be updated, see CERN-SPSC-2022-032

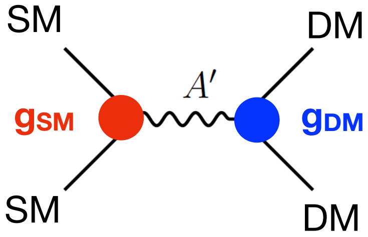
Take home messages

Dark sectors - i.e. new particles not charged under the SM gauge symmetries - very often arise in well-motivated beyond the SM theories.

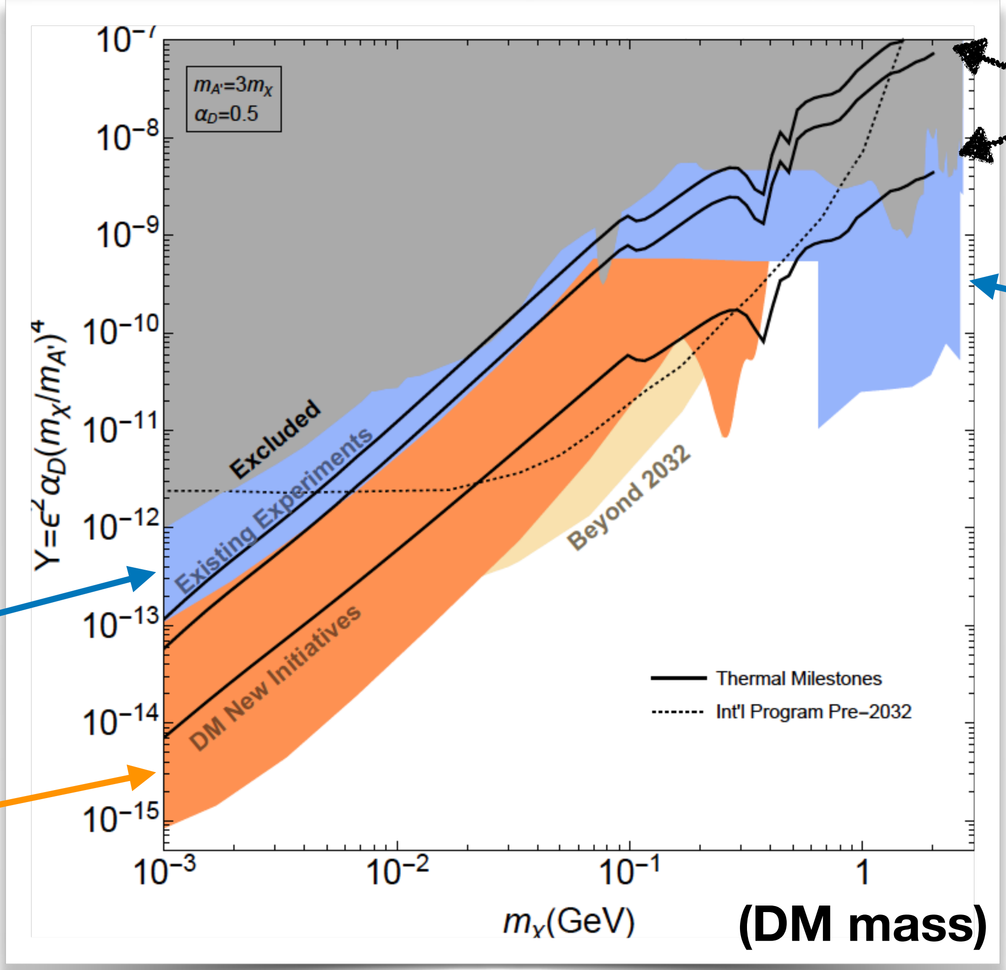
They can address open problems in particle physics (origin of Dark matter, the hierarchy problem, the strong CP problem, the origin of neutrino masses, …)

- There are numerous gaps in the experimental exploration of dark sectors, both at the electroweak-TeV scale and at the sub-GeV scale.
- The LHC will have many opportunities to test these theories in the coming years, looking for exotics, soft objects, displaced particles, new SUSY signatures, …
- Meson factories and fixed target experiments will be able to probe new scenarios with sub-GeV dark particles.

Testing the thermal DM framework



Let's put all these experiments together and see how far we get in testing the **thermal freeze-out mechanism**



(DM mass)

benchmarks for thermal DM

Belle-II

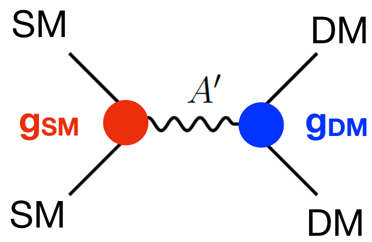
neutrino experiments (DUNE, PIP2-BD, Coherent, …)

LDMX

Krnjaic, Toro et al, 2207.00597

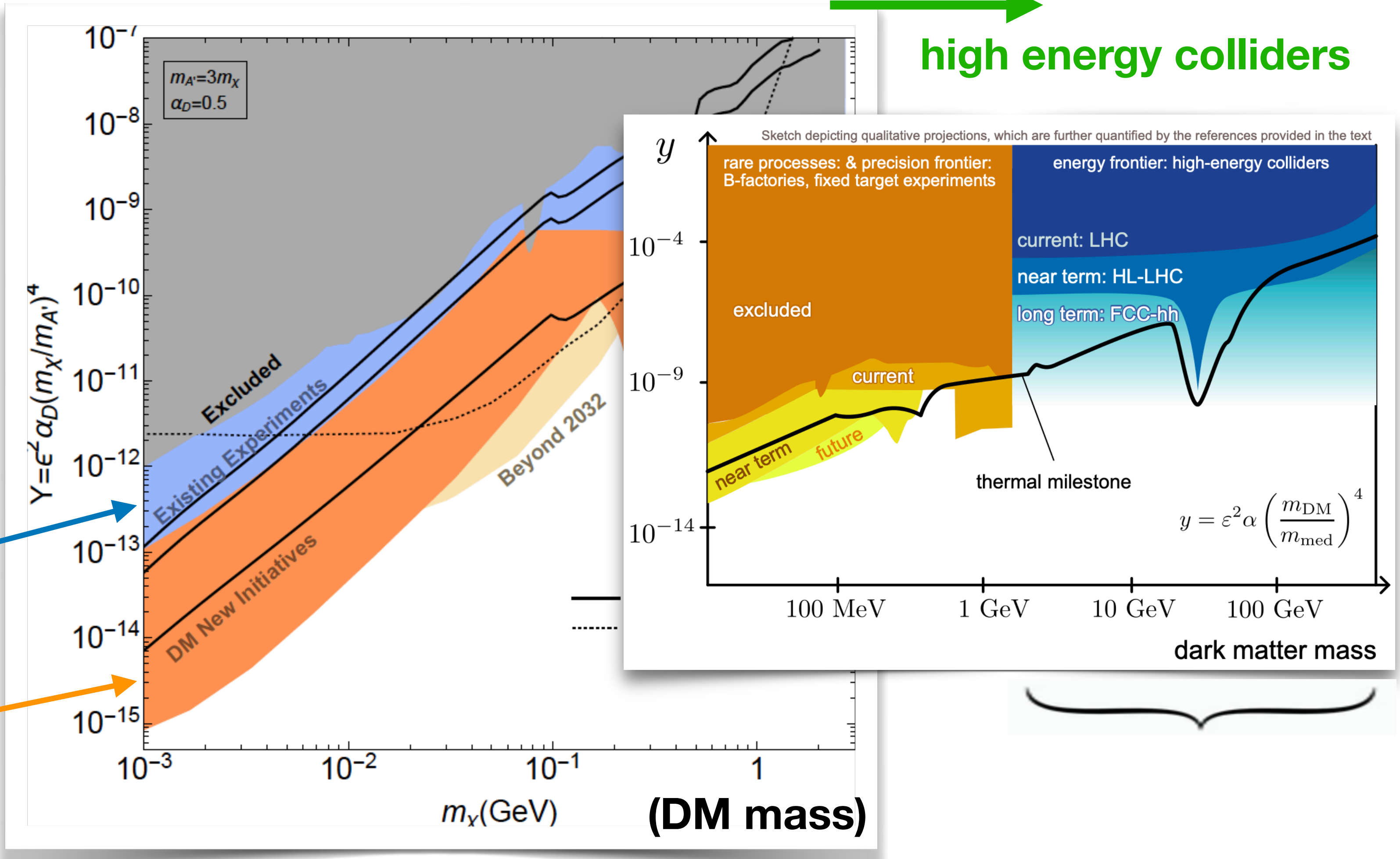
A combination of running & proposed experiments will be able to solidly probe (minimal) thermal freeze-out scenarios

Testing the thermal DM framework



Let's put all these experiments together and see how far we get in testing the **thermal freeze-out mechanism**

high energy colliders



(DM mass)

neutrino experiments
(DUNE, PIP2-BD, Coherent, …)

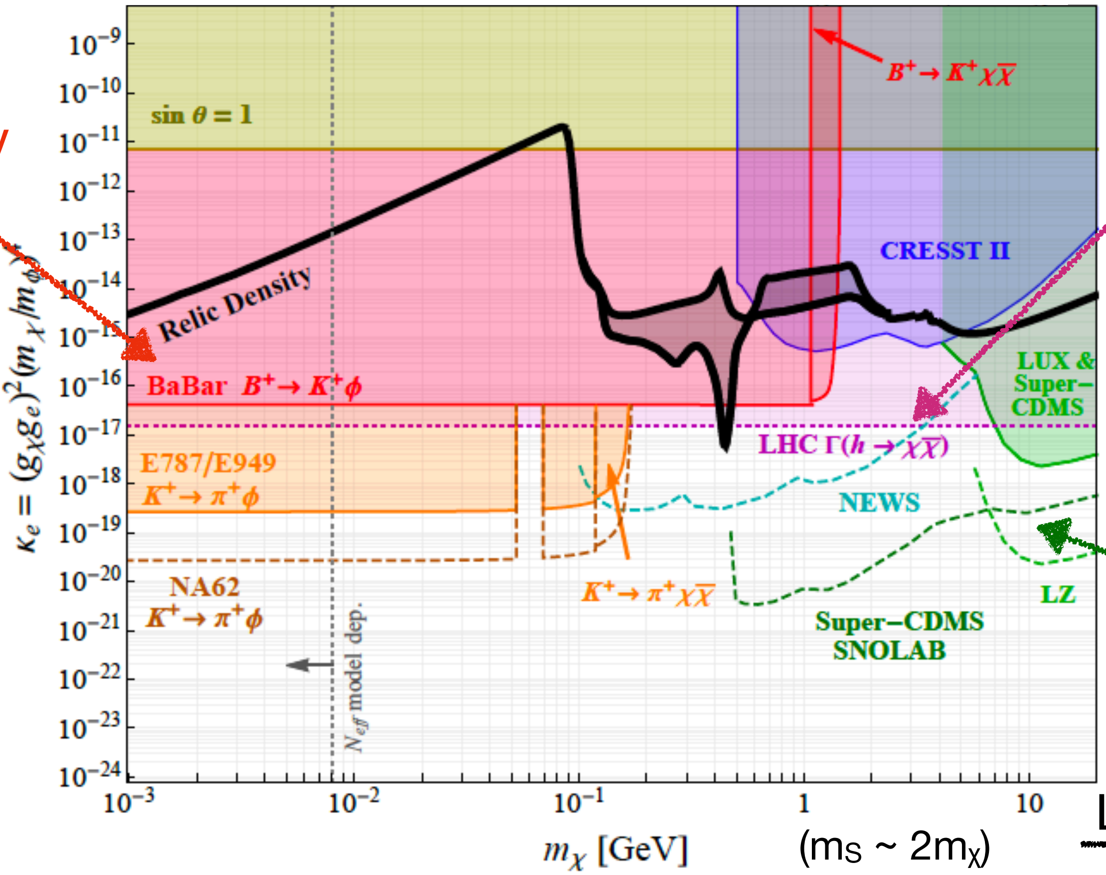
LDMX

Krnjaic, Toro et al, 2207.00597

Invisible dark sectors at B-factories

The dark Higgs, S, can decay (invisibly) to dark matter particles, χ, and then…

Krnjaic, 1512.04119



(Past) B-factory BaBar

LHC search for Higgs **exotic decay** (to invisible)

Direct detection experiments

($m_S \sim 2m_\chi$)

LHC →

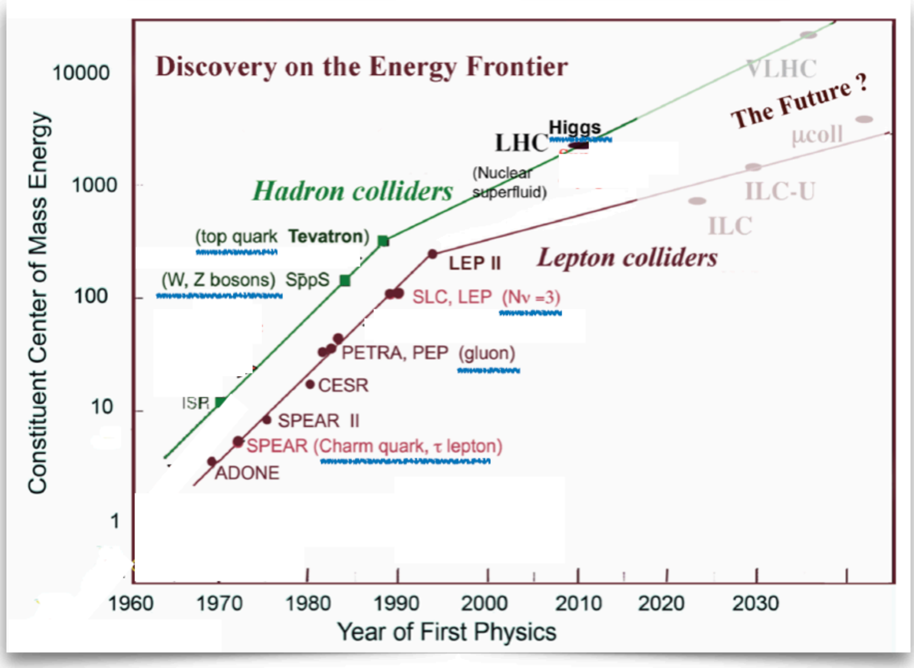
Belle II will record ~ O(100) more data than Babar

What regions will Belle-II be able to probe?

What about the other dark particles? axions, dark photons, dark neutrinos, …

Historical note: Discoveries of new particles at fixed target experiments

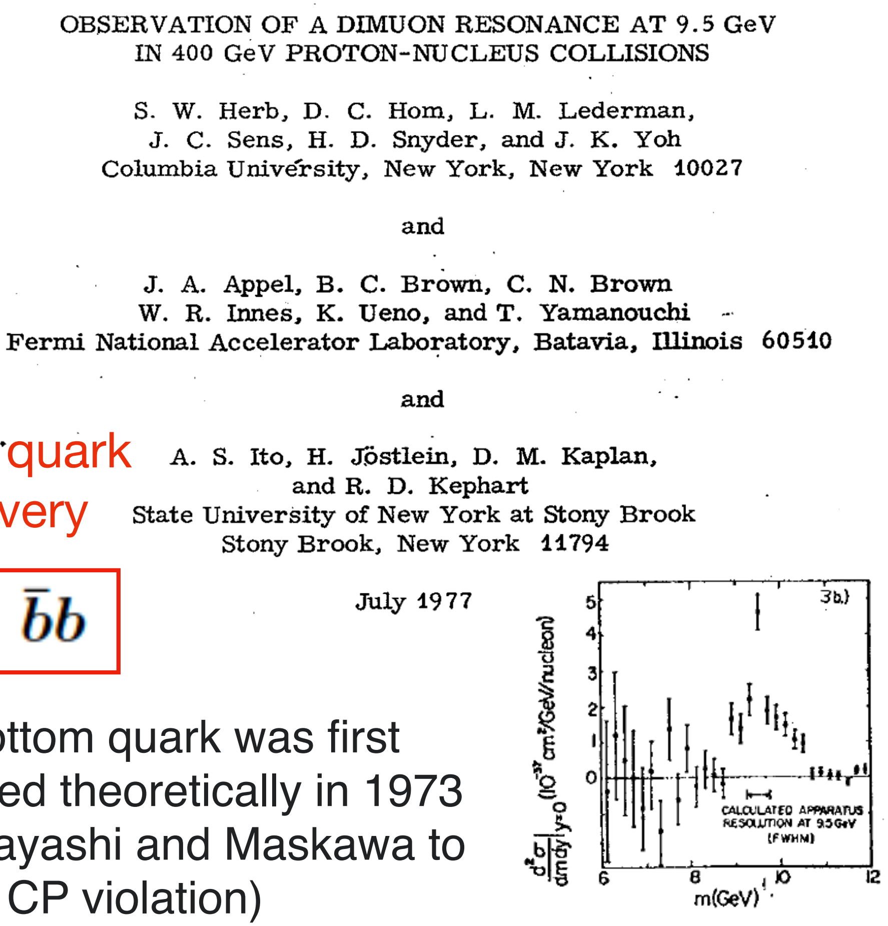
History of incredibly successful **colliding beam experiments**



Adapted from 1401.6114
(also shown by Zhen Liu last week)

New particle discoveries were done at **fixed target experiments**, as well!

E288 Collaboration:



OBSERVATION OF A DIMUON RESONANCE AT 9.5 GeV
IN 400 GeV PROTON-NUCLEUS COLLISIONS

S. W. Herb, D. C. Hom, L. M. Lederman,
J. C. Sens, H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

and

J. A. Appel, B. C. Brown, C. N. Brown
W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

A. S. Ito, H. Jöstlein, D. M. Kaplan,
and R. D. Kephart
State University of New York at Stony Brook
Stony Brook, New York 11794

July 1977

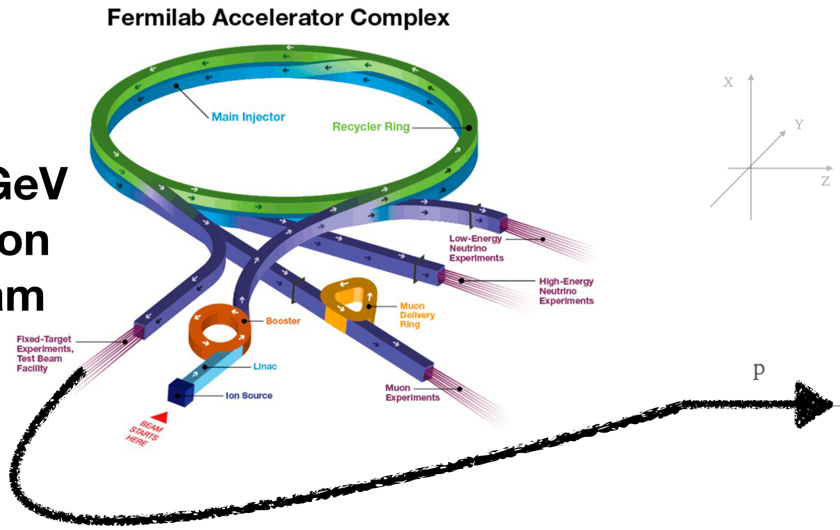
bottom quark discovery

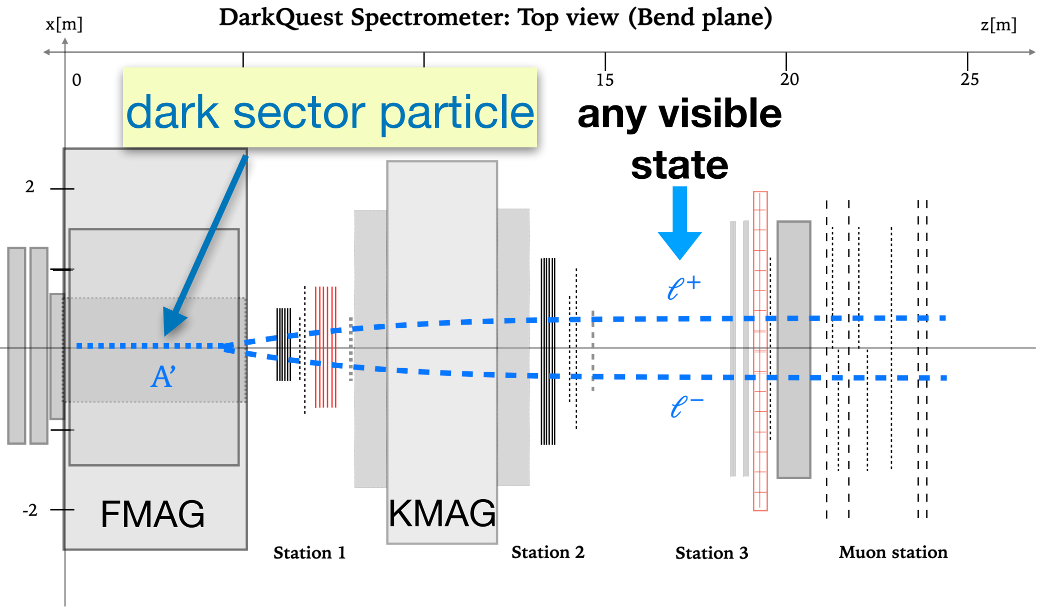
$\boxed{\Upsilon = \bar{b}b}$

(The bottom quark was first described theoretically in 1973 by Kobayashi and Maskawa to explain CP violation)

A new proposal for Fermilab: the DarkQuest experiment

120 GeV proton beam





SpinQuest → DarkQuest

proposed upgrade
(calorimeter +
more tracking layers +
hodoscope for triggering)

Nuclear physics: Measuring the Drell-Yan muon process for studies of the proton structure

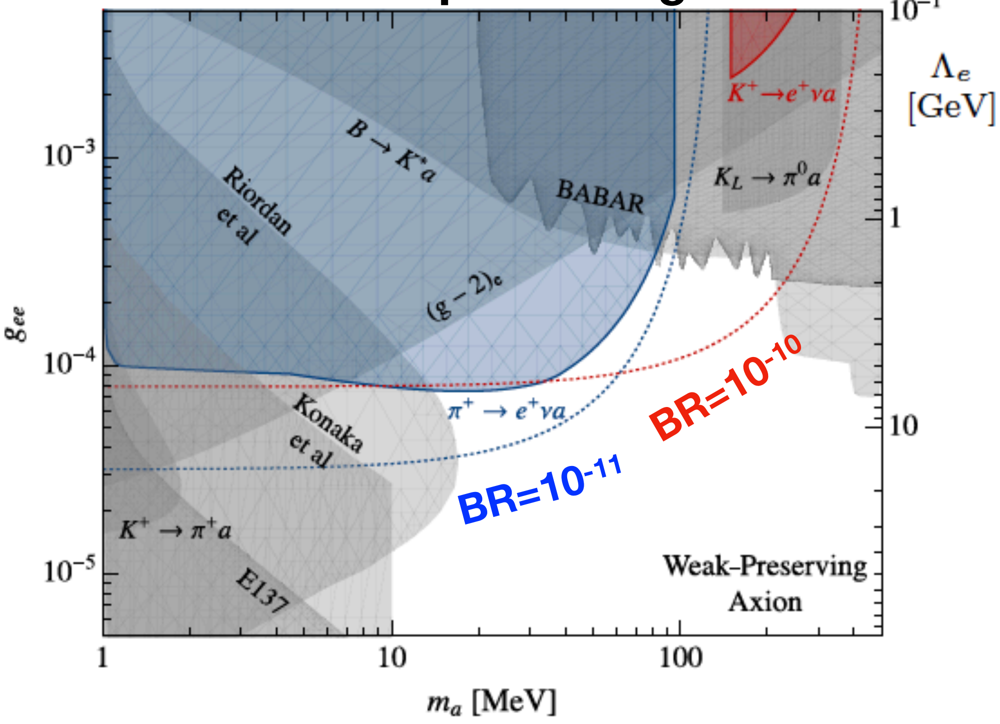
Particle Physics: Visible dark sector searches (any visible)

Initial proposal:
Berlin, SG, Schuster, Toro, 1804.00661

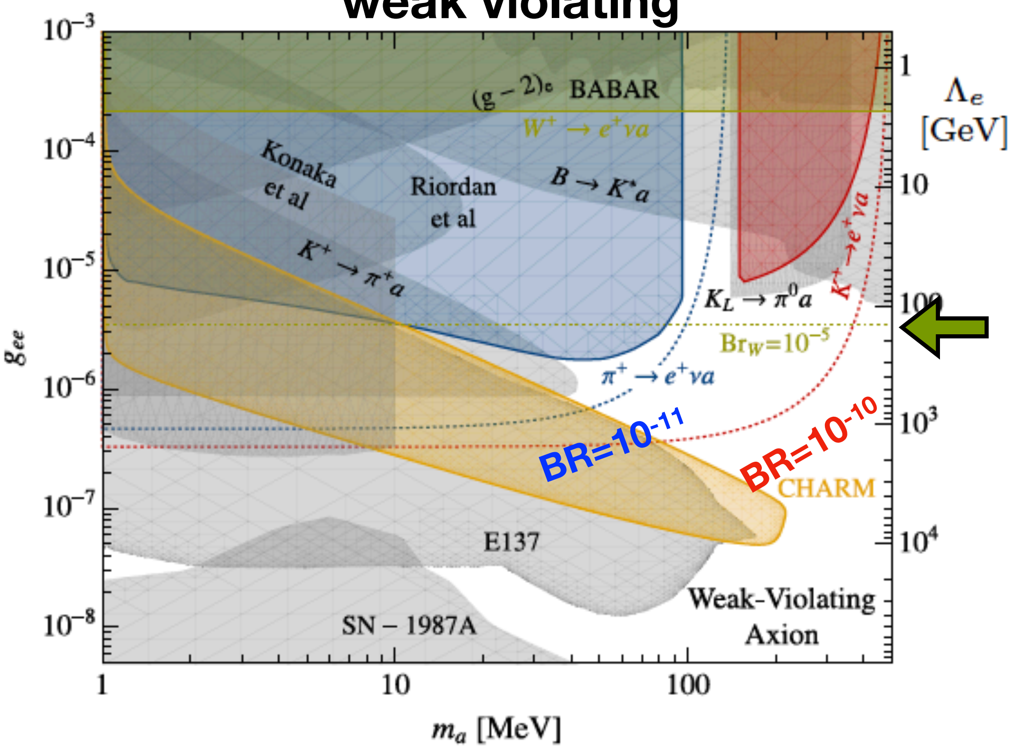
Example scenario: Lepton-coupled ALPs

$$\frac{(\partial_\mu a)}{m_e}\left[\bar{e}\gamma^\mu\left(\bar{g}_{ee}+g_{ee}\gamma_5\right)e+g_\nu\bar{\nu}\gamma^\mu P_L\nu\right]$$

weak preserving



weak violating



Gray: neutral current decays K→π **a**

Blue: π→eν**a**→eν(ee), interpretation from SINDRUM search, ‘80s

Red: K → eν**a**→eν(ee), interpretation from E865, ’00s

➡ Green: W→ eν**a**→eν(ee) **exotic W boson decay**

No targeted searches yet!

S.Gori

Backup

The strong CP problem & the QCD axion

The strong interactions have a puzzling problem, which became particularly clear with the development of QCD in the 70s.

A problem of small numbers

Why in QCD is the CP symmetry not very badly broken?

$$\mathcal{L}_{\rm QCD} \supset \bar{\theta}\frac{g^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Strong experimental bound on the neutron electric dipole moment implies a very small parameter: $|d_n| \leq 10^{-26} e\ \mathrm{cm}$ ⇒ $\bar{\theta} \leq 10^{-10}$

Peccei-Quinn solution (Phys.Rev.Lett. 38 (1977) 1440-1443):
the Lagrangian of SM is augmented by axion interactions $\mathcal{L} \supset \frac{a}{f_a}\frac{1}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}$

At the minimum of the axion potential $\bar{\theta} = 0$ ✓

Additional interesting property: the QCD axion can be a **DM candidate**!

(1) Inelastic DM and singly produced LLP

Tucker-Smith, Weiner, 0101138

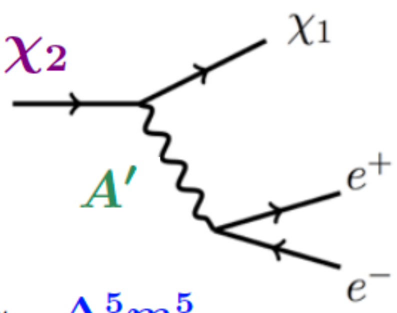
Inelastic Dark Matter (IDM) models:

$$-\mathcal{L} \supset m_D \eta\xi + \frac{1}{2}\delta_\eta \eta^2 + \frac{1}{2}\delta_\xi \xi^2 + \text{h.c.}$$

2-component Weyl spinors
with opposite charge under U(1)’

$$\mathcal{L} \supset \frac{i e_D m_D}{\sqrt{m_D^2 + (\delta_\xi - \delta_\eta)^2/4}} \underbrace{A'_\mu}_{\text{dark photon}} (\bar{\chi}_1 \gamma^\mu \chi_2 - \bar{\chi}_2 \gamma^\mu \chi_1)$$

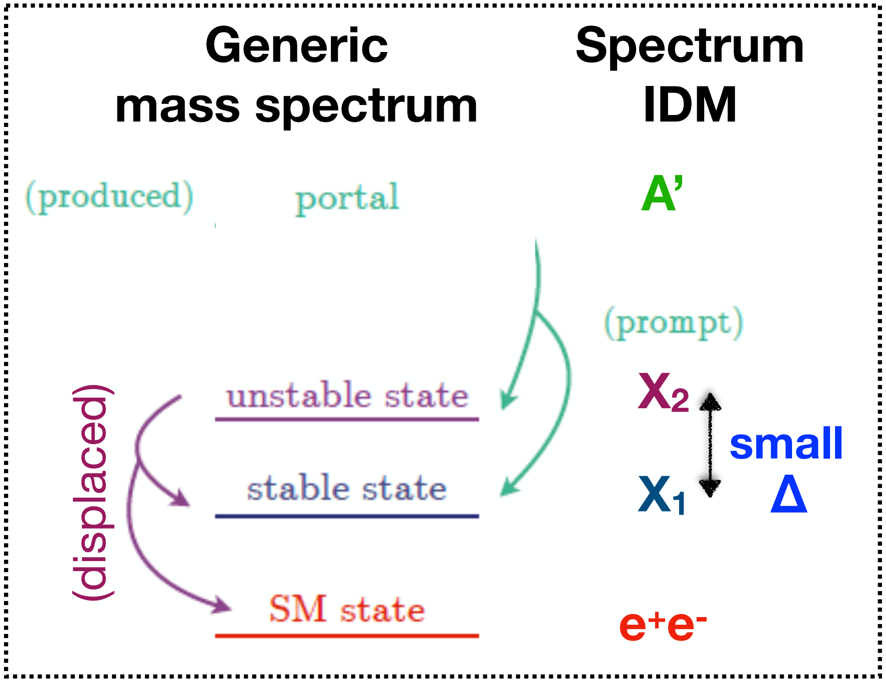
- ✱ <u>Freeze-out:</u> X$_1$ X$_2$ → SM
- ✱ <u>Signatures</u> in our labs:



$$\Gamma(\boxed{\chi_2} \rightarrow \chi_1 e^+ e^-) = \frac{4\epsilon^2 \alpha_{\text{em}}\, \alpha_D\, \Delta^5 m_1^5}{15\pi m_{A'}^4}$$

generically long-lived (because of the small mass splitting, Δ)

$$\boxed{pp \rightarrow A' \rightarrow \chi_2 \chi_1,\ \chi_2 \rightarrow e^+ e^- \chi_1}$$



Generic mass spectrum

Spectrum IDM

A’

X$_2$

small Δ

X$_1$

e$^+$e$^-$

$$\Delta \equiv \frac{m_2 - m_1}{m_1}$$

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Tucker-Smith, Weiner, 0101138

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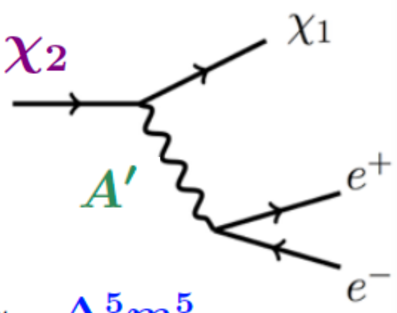
dark
photon

- Freeze-out: X_1 X_2 → SM



- Signatures in our labs:

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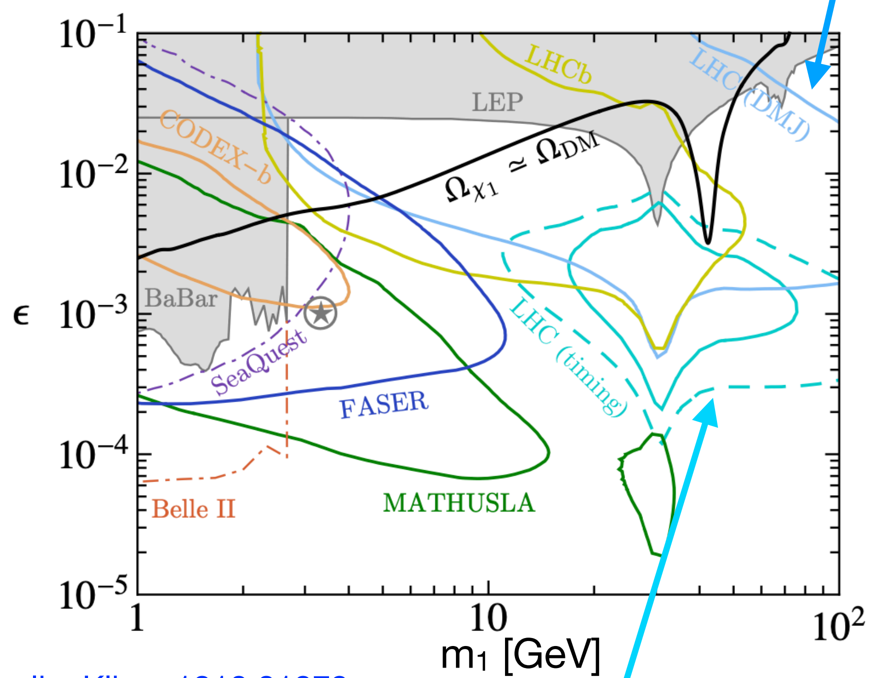
generically
long-lived (because of the small mass splitting, Δ)

$$\boxed{pp \to A' \to \chi_2\chi_1,\ \ \chi_2 \to e^+e^-\chi_1}$$

Recent: first di-muon jet search,
CMS, 2305.11649



Berlin, Kling, 1810.01879

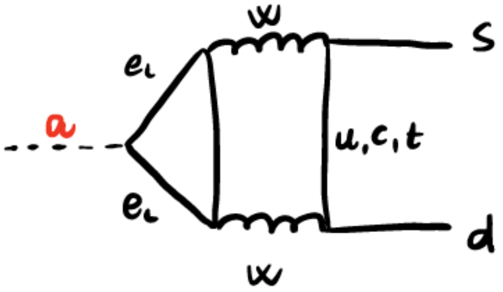
new opportunity
trigger based on timing
Liu, Liu, Wang, 1805.05957

Complementarity with <u>neutral current</u> decays

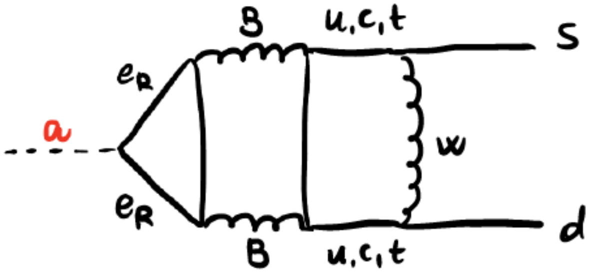
Neutral current meson decays are also generated at the 2 or 3-loop level (suppressed by CKM elements as well)

$\boxed{K \to \pi a}$

1. ALP with LH coupling



2. ALP with RH coupling



Similar diagrams for $B \to K^{(*)} a$

Main bounds: reinterpreting past data

NA62, 2103.15389: $K^+ \to \pi^+ + (a \to \text{ invisible})$

KTeV, 0309072: $K_L \to \pi^0(a \to e^+e^-)$

m_{ee} in (140, 363) MeV

777 @ BNL, Phys. Rev. Lett. 59 (1987) 2832–2835:

$K^+ \to \pi^+(a \to e^+e^-)$ m_a < 100 MeV

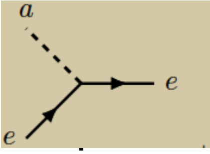
see also Alves, Weiner, 1710.03764

LHCb, 1501.03038: $B^0 \to K^{(*)0}(a \to e^+e^-)$

Complementarity with neutral current decays

Neutral current meson decays are also generated at the 2 or 3-loop level (suppressed by CKM elements as well)

$K \to \pi a$



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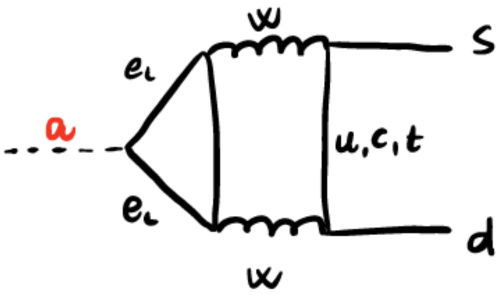
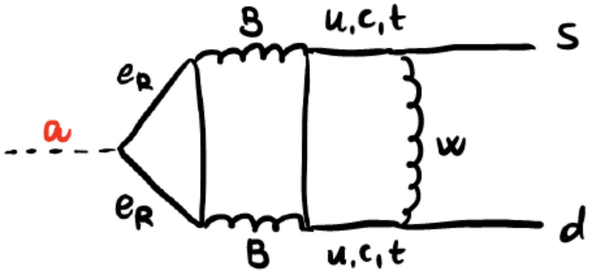
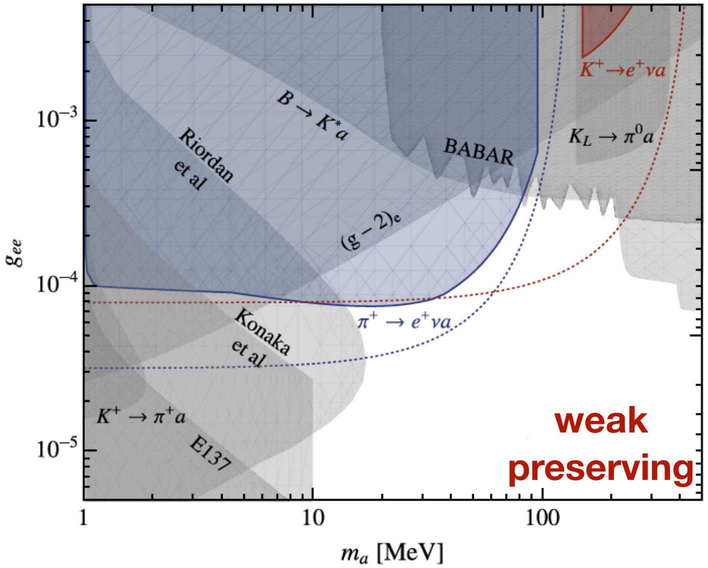


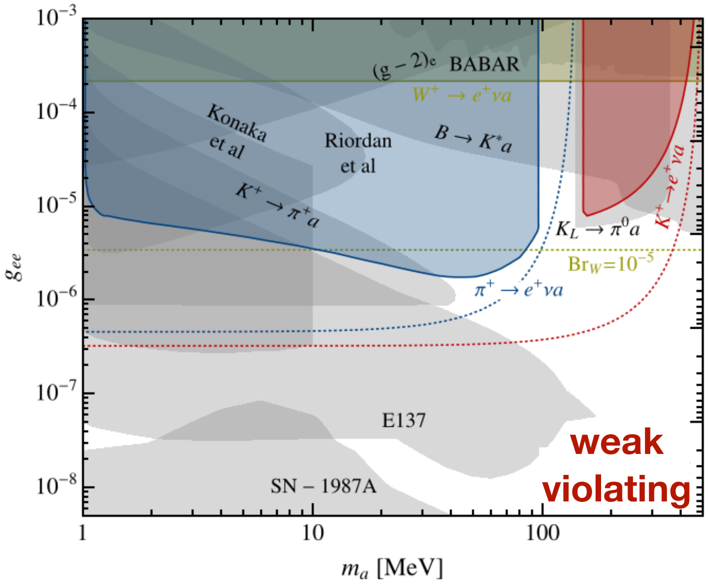
2. ALP with RH coupling



Similar diagrams for $B \to K^{(*)} a$



weak preserving



weak violating

S.Gori

Backup