Theory introduction to the dark sector

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2024 Belle II Physics Week

KEK

October 14-18, 2024

Overview

Chapter 1: Introduction
Why dark sectors. Theory motivations.
Experimental targets

Chapter 2: Minimal dark sector models
dark photon,
dark scalar, sterile neutrinos

Chapter 3: Axions and axion-like particles
The effective field theory

Chapter 4: Non-minimal theories for dark sectors
Inelastic Dark matter, L_μ - L_τ

YESTERDAY

TODAY

The Higgs portal

SM + singlet scalar:

$$\mathcal{L} \supset \underbrace{-\frac{\xi}{2}|H|^2 s^2}_{\text{Higgs portal operator}} + \frac{\mu_s^2}{2}s^2 - \frac{\lambda_s}{4!}s^4 + \mu^2|H|^2 - \lambda|H|^4$$

+ couplings within the dark sector

In addition to dark matter models, new (light) scalars appear in e.g., theories that address the hierarchy problem (relaxion), or that explain the baryon-antibaryon asymmetry

The Higgs portal

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+ couplings within the dark sector

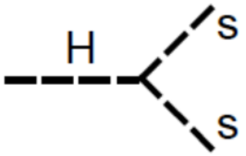
Electroweak symmetry breaking:

If the scalar, s, gets a VEV, then it will mix with the SM Higgs:

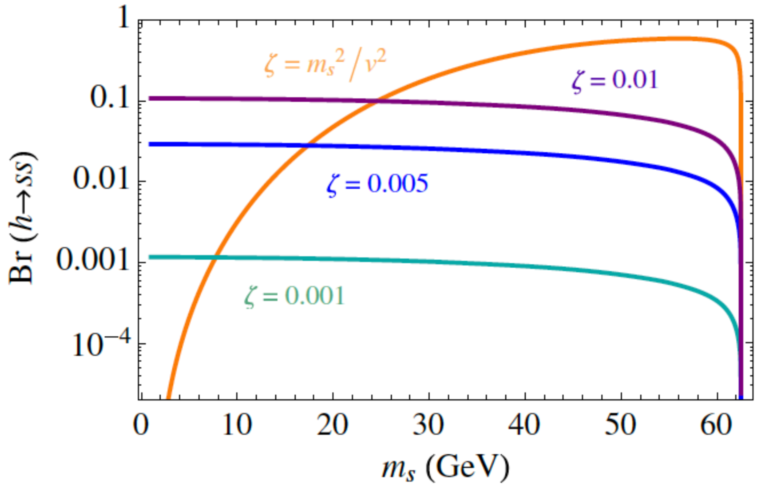
$$\tan\theta_s \sim \frac{\xi v_h v_s}{m_h^2 - m_s^2}$$

Constraints from Higgs coupling measurements since $\kappa_i \sim \cos\theta_s$

➡ The mixing cannot be too large (model independent bound)



Higgs exotic decays



Curtin et al., 1312.4992

2.

Visible decays of the dark scalar

If the scalar is heavier than ~10 GeV:

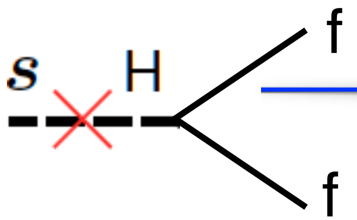
- If **θ_s=0**, s is stable
  ⇒ Scalar invisible decay
- If **$\theta_s \neq 0$**, s will decay to SM particles

$$\Gamma(s \to f\bar{f}) = \sin^2\theta_S \frac{N_c}{8\pi}\frac{m_s m_f^2}{v^2}\beta_f^3$$

Main BRs: bb, ττ, cc, ...

$\mathrm{Sin}(\theta_S) \geq O(10^{-5})$
S decays promptly

$\mathrm{Sin}(\theta_S) \leq O(10^{-5})$
S has displaced decays



As we have learnt for the dark photon, also the dark scalar will mainly decay to DM if $2m_{DM} < m_S$ **1.**

2.

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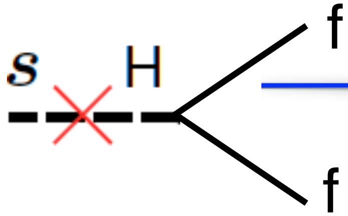
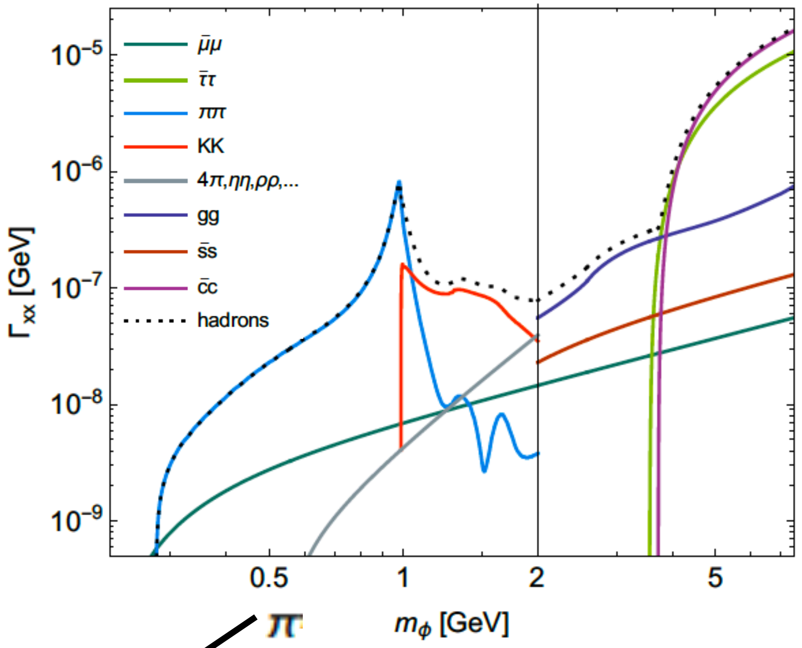


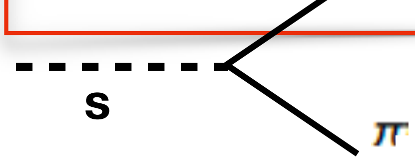
If the scalar is lighter than ~10 GeV:

The calculation of the widths has large theoretical errors

Several results in the literature show disagreement

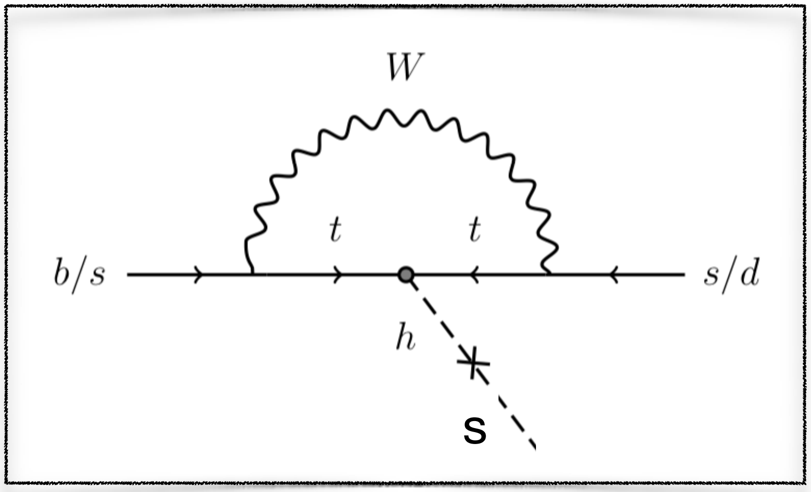
Winkler, 1809.01876





Dark scalars at fixed target experiments

At proton fixed target experiments, large production from B and K meson decays, B →K s, K → π s



particularly suited for
high energy fixed target
(SPS CERN beam)

This will produce two classes of signatures:

B →K + missing energy,
K → π + missing energy
in the case of $2m_{DM} < m_s$ **1.**

B →K + 2 leptons/tracks,
K → π + 2 leptons/tracks
in the case of $2m_{DM} > m_s$ **2.**

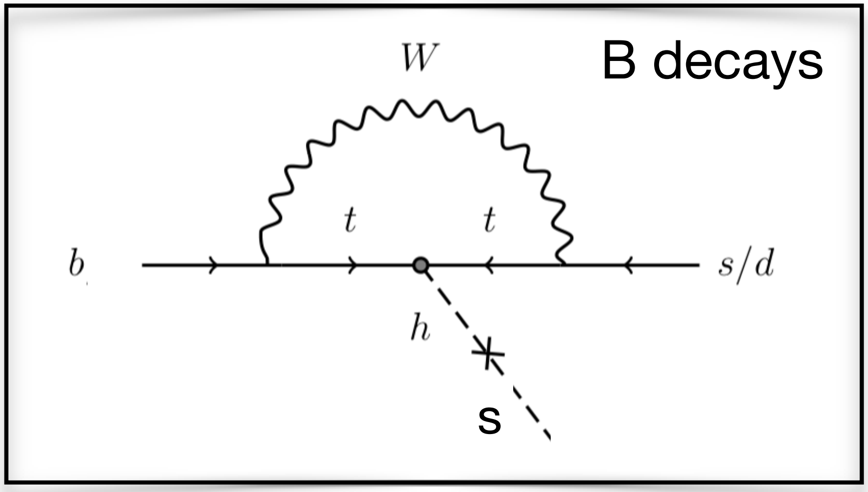
Huge meson statistics

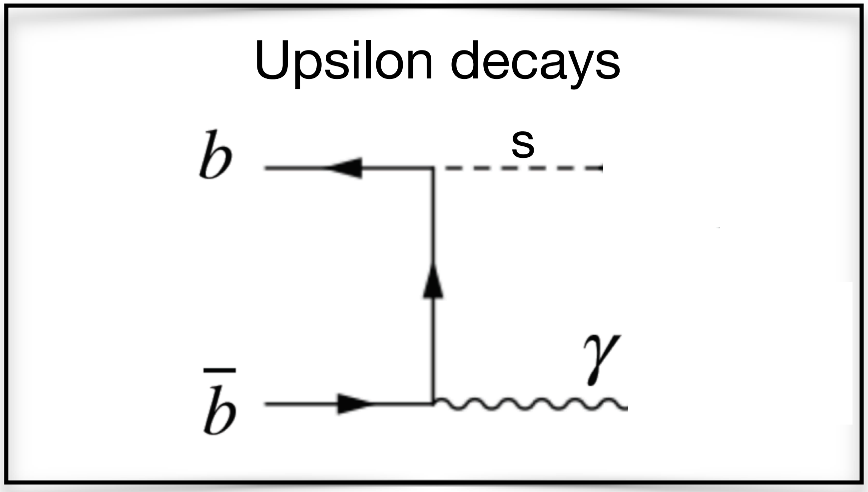
For example, at SHiP:

	SHiP (15 year run)	**Meson factory**
pions	$\sim 10^{20}$	$\sim 10^{12}$
Kaons	$\sim 10^{20}$	$\sim 10^{14}$
B-mesons	$\sim 10^{13}$	$\sim 10^{10}$

Dark scalars at B factories

2 main production mechanisms:

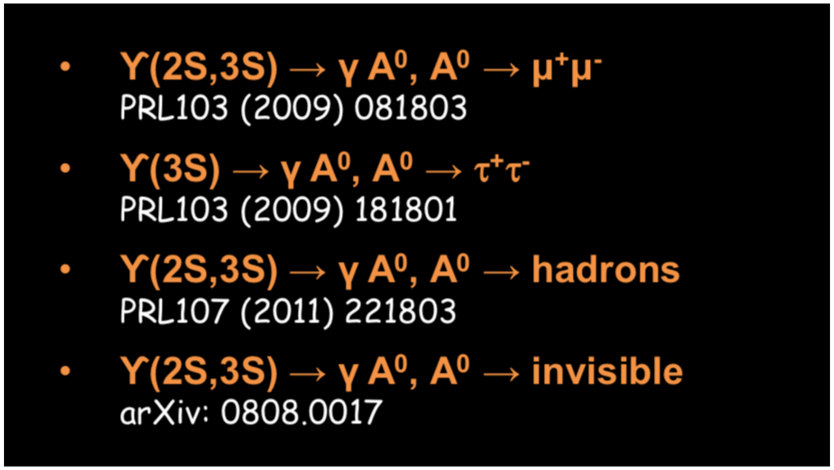




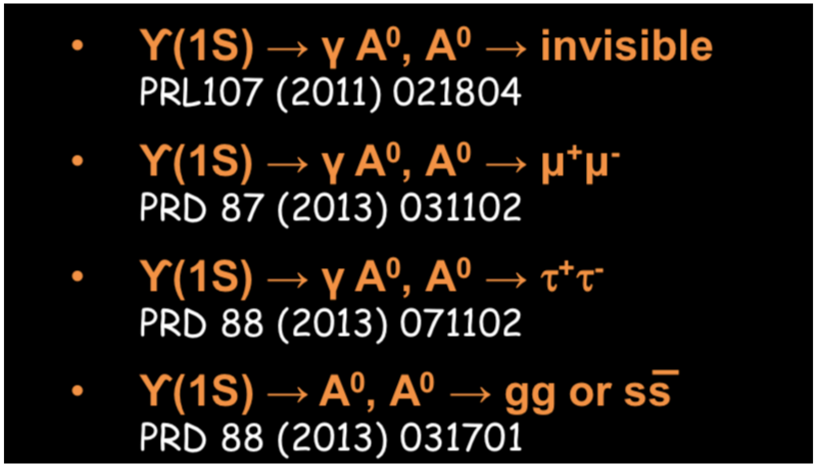
And then again either visible or invisible decays of the scalar, s

Several searches have been performed at Babar

B. Echenard



- $\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$
  PRL103 (2009) 081803
- $\Upsilon(3S) \to \gamma A^0, A^0 \to \tau^+\tau^-$
  PRL103 (2009) 181801
- $\Upsilon(2S,3S) \to \gamma A^0, A^0 \to$ hadrons
  PRL107 (2011) 221803
- $\Upsilon(2S,3S) \to \gamma A^0, A^0 \to$ invisible
  arXiv: 0808.0017



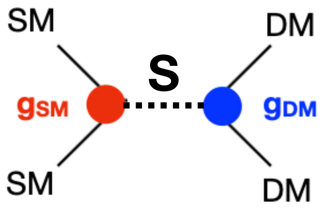
- $\Upsilon(1S) \to \gamma A^0, A^0 \to$ invisible
  PRL107 (2011) 021804
- $\Upsilon(1S) \to \gamma A^0, A^0 \to \mu^+\mu^-$
  PRD 87 (2013) 031102
- $\Upsilon(1S) \to \gamma A^0, A^0 \to \tau^+\tau^-$
  PRD 88 (2013) 071102
- $\Upsilon(1S) \to A^0, A^0 \to gg$ or $s\bar{s}$
  PRD 88 (2013) 031701

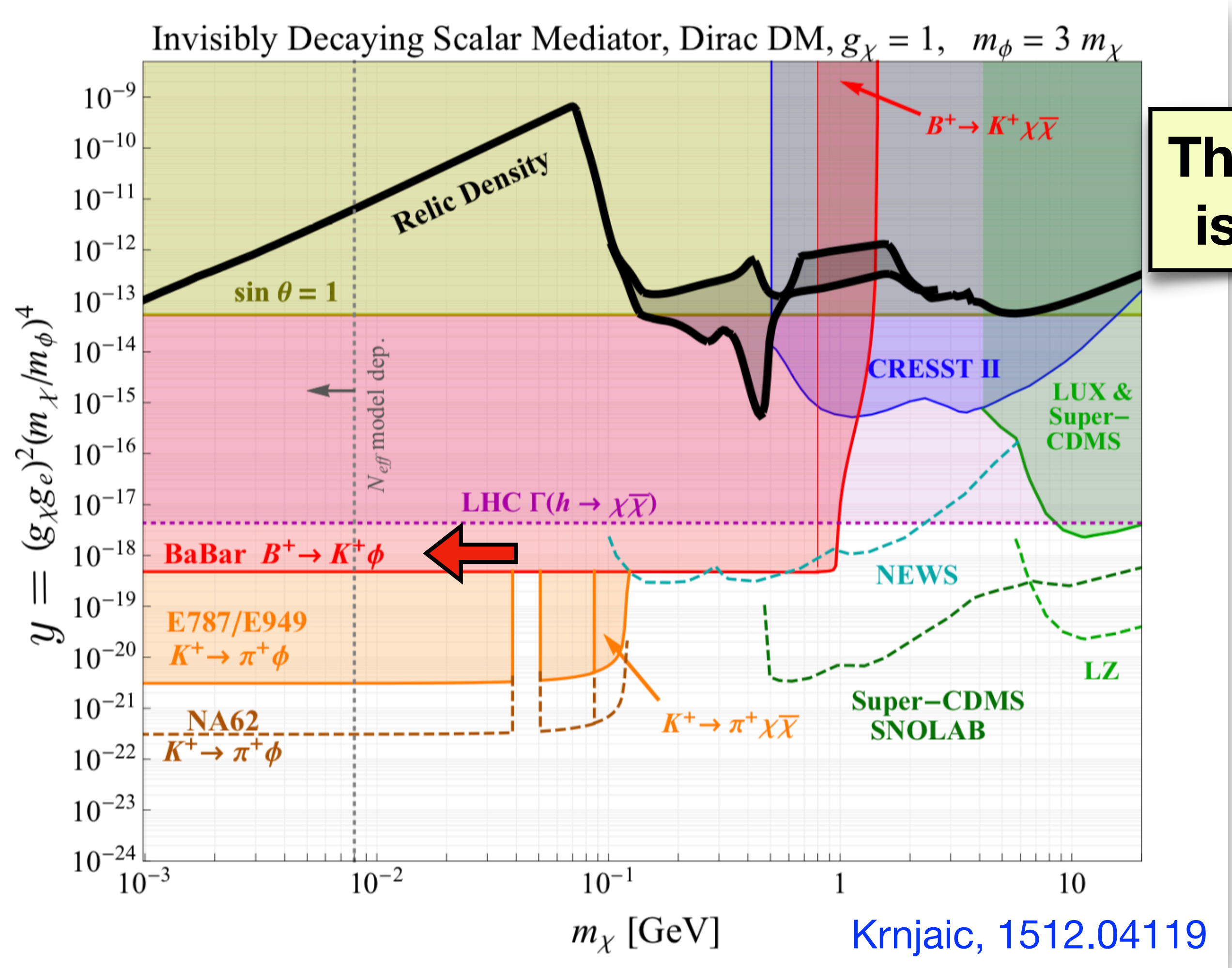
1.

Summary plot: the invisible dark scalar

$$\frac{\xi}{2}|H|^2 s^2$$

S→DM DM





Krnjaic, 1512.04119

The thermal line is fully probed!

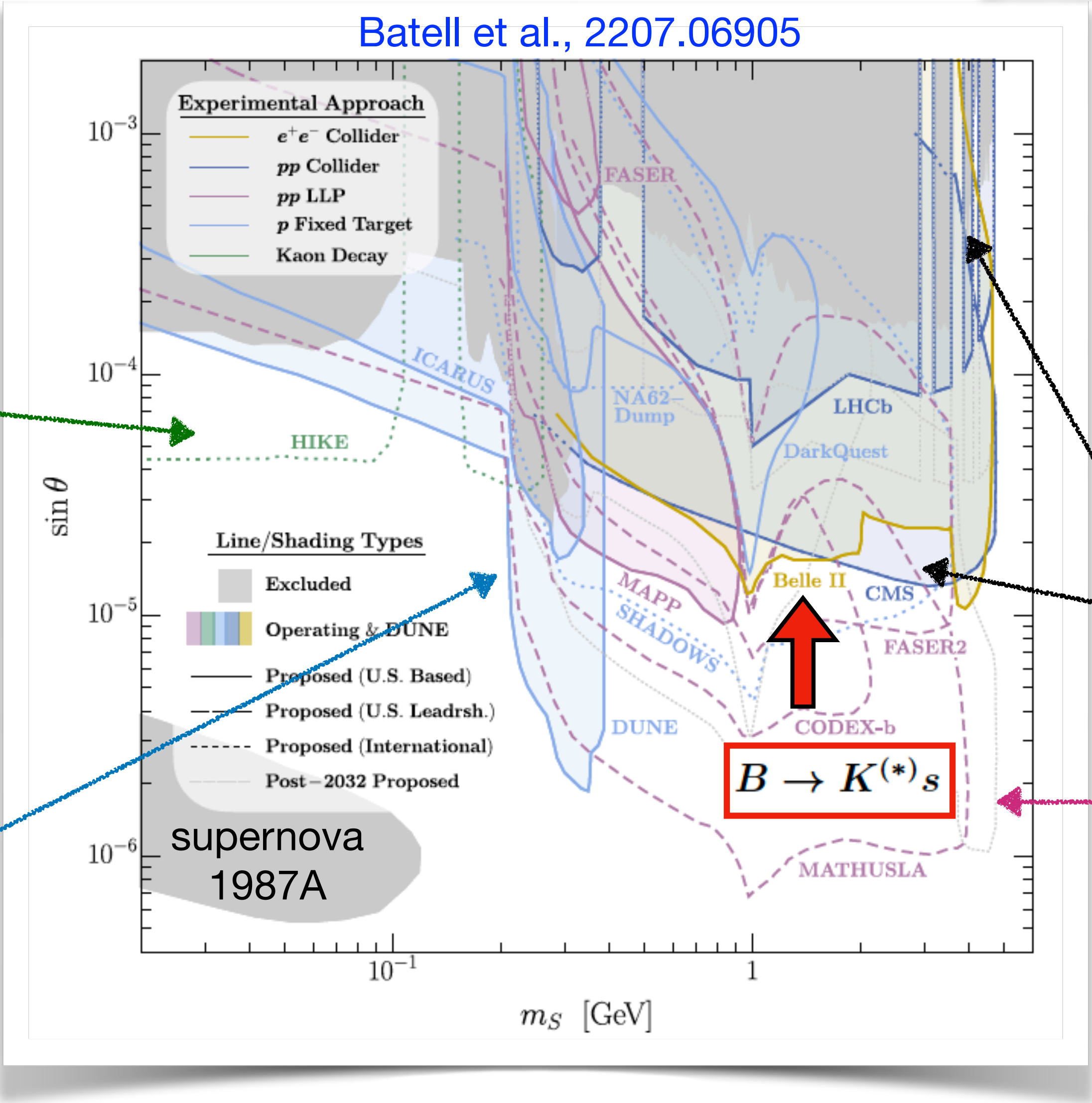
Note: here we have the assumption, $m_s = 3m_\chi$

2.

Summary plot: the visible dark scalar

Kaon factories

proton beam-dump

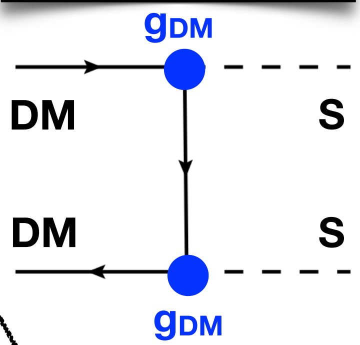


Batell et al., 2207.06905

LHC

$$\frac{\xi}{2}|H|^2 s^2$$

S→SM SM



Colliders

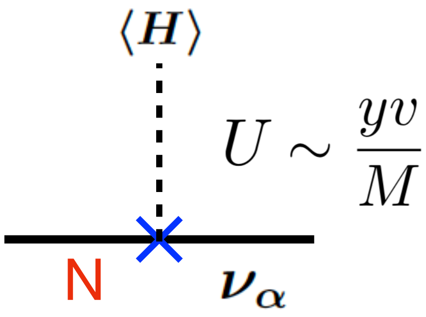
LHC auxiliary detectors

This entire parameter space predicts a **dark sector in thermal equilibrium** with the SM

The neutrino portal

$\mathcal{L} \supset yHLN + \frac{M}{2}N^2$ + interactions in the dark sector

This operator will generically induce some mixing of N with the three active SM neutrinos.



Sterile neutrinos appear in e.g., models that explain the origin of neutrino masses: seesaw mechanism. Sterile neutrinos can have a mass below the few GeV scale in inverse or linear seesaw models.

$$\boxed{m_\nu^{\mathrm{SM}} \sim \frac{y^2v^2}{M}}$$

S.Gori

The neutrino portal

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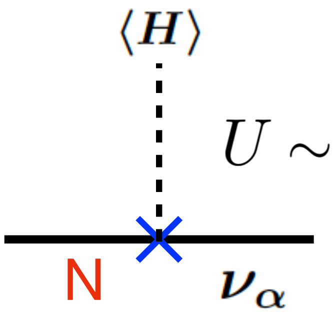


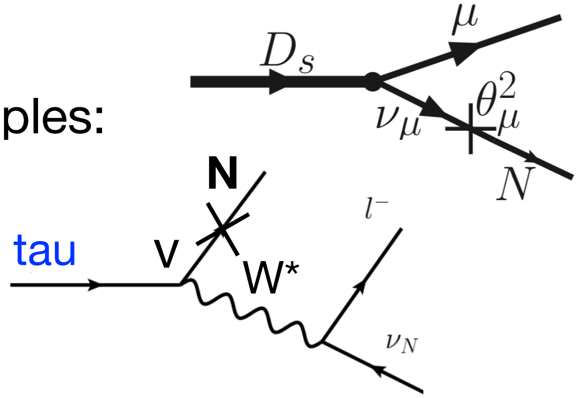
$$U \sim \frac{yv}{M}$$

This operator will generically induce some mixing of N with the three active SM neutrinos.

Production

from meson or tau decays:

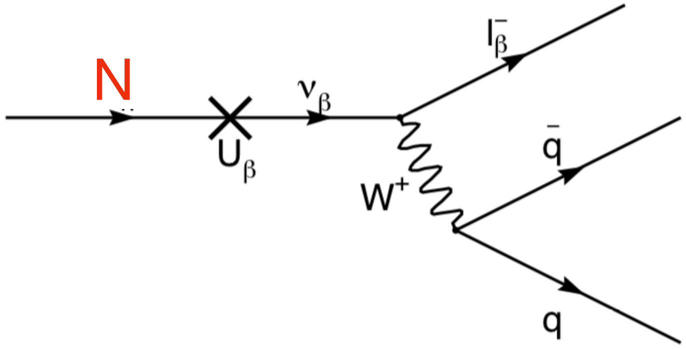
examples:



at higher energies, decays of W, Z, H

W → l N, Z/H → NN, Z/H → Nν

Decay

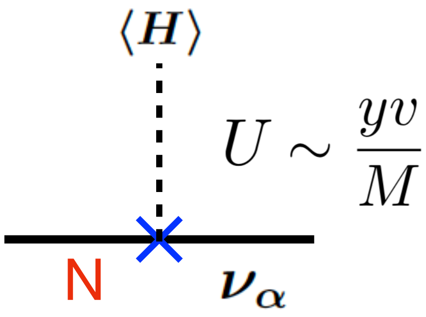


N → $Z^{(*)}\nu$, N → $W^{(*)}$ l, N → $H^{(*)}\nu$

2. If lighter than other dark sector/dark matter states

The neutrino portal

$$\mathcal{L} \supset y H L N + \frac{M}{2} N^2$$ + interactions in the dark sector



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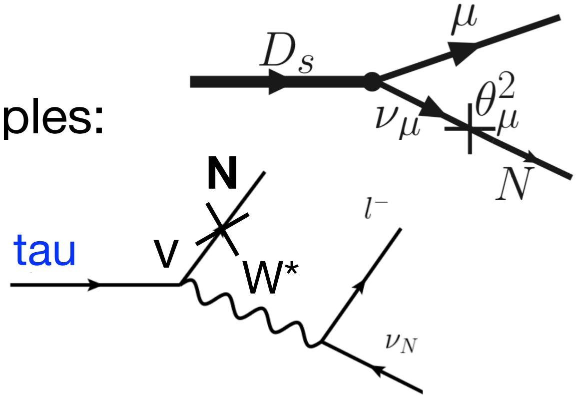
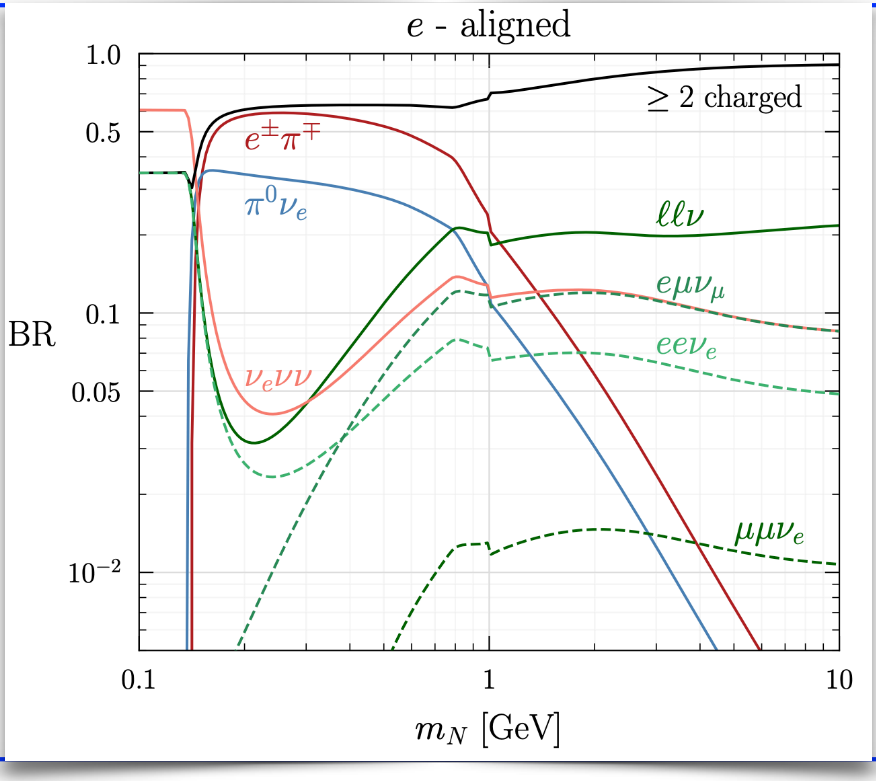


at higher energies, decays of W, Z, H

W → l N, Z/H → NN, Z/H → Nv

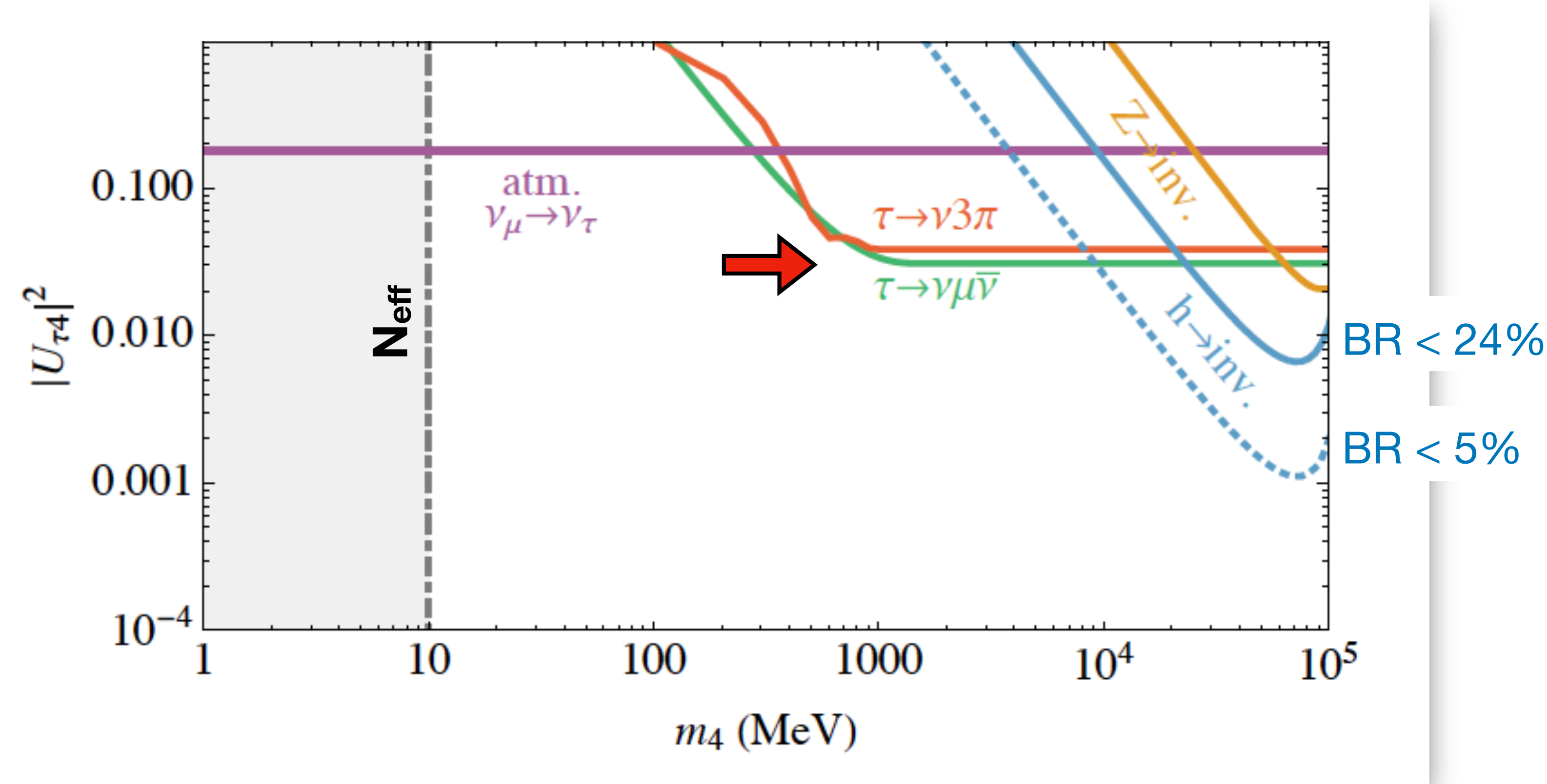


Giffin, SG, Tsai, Tuckler, 2206.13745

1.

Summary plot: the invisible sterile neutrino

Batell et al., 1709.07001



Very interesting opportunity for Belle II

Sterile neutrinos from tau decays.

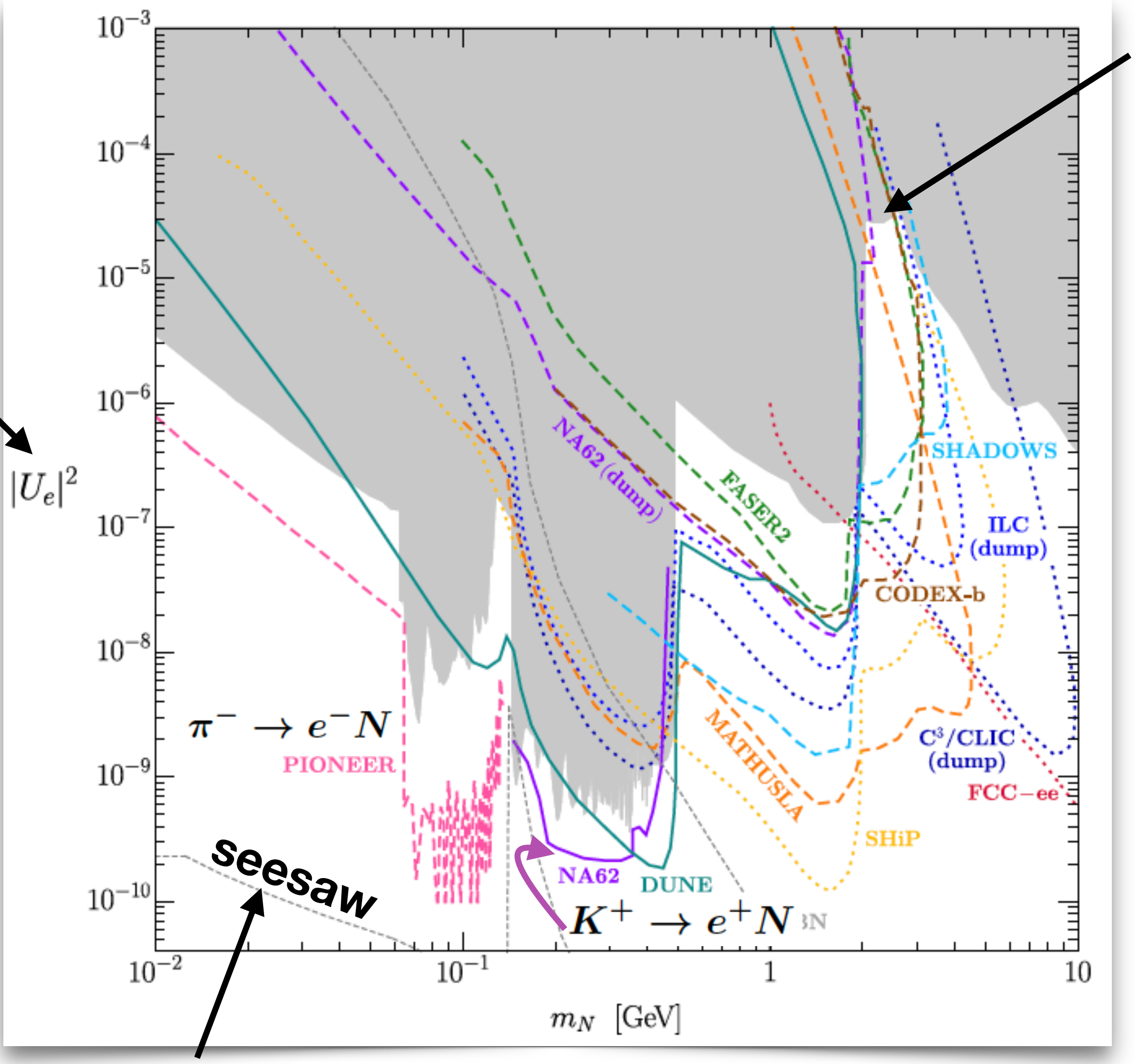
Need to measure tau decay rates and their kinematics with as much precision as possible.

2.

Summary plot: the visible sterile neutrino

Batell et al., 2207.06905

Example: mixing with the electron neutrino



Belle analysis with 711 fb^{-1}
1301.1105

B → X l N,
N → l π (l = e, μ)

“vanilla” model: $|U_e| \simeq \sqrt{\frac{m_{\nu_e}}{M_e}}$

Prospects for Belle II?

Chapter 3

Axions & axion-like particles (ALPs)

- The effective field theory
- Signatures

How do ALPs couple to the SM?

At dimension 5, the most general Lagrangian for a spin 0, CP-odd particle with an approximate shift symmetry, a → a+c:

Georgi, Kaplan, Randall 1986

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

$$g_i \propto \frac{1}{f_a}$$

For the complete one-loop analysis, see e.g.
Bonilla et al, 2107.11392
Bauer et al, 2012.12272

ALP effective field theory (EFT)

At dimension 5, also the operator $i g_{aH}(\partial_\mu a)(H^\dagger D_\mu H + \mathrm{h.c.})$ exists.

However, it can be reabsorbed in the definition of the fermion coupling.
In fact, if we redefine

Redundant operator

$$H \to e^{i g_{aH} a} H, \quad f \to e^{-i\beta_f g_{aH} a} f$$

$$\beta_u - \beta_Q = -1, \quad \beta_d - \beta_Q = 1, \quad \beta_e - \beta_L = 1, \quad 3\beta_Q + \beta_L = 0$$

the Higgs operator disappears and the fermion couplings get a shift:

$$g_{af} \to g_{af} + \beta_f\, g_{aH}\, I_{3\times 3}$$

How do ALPs couple to the SM?

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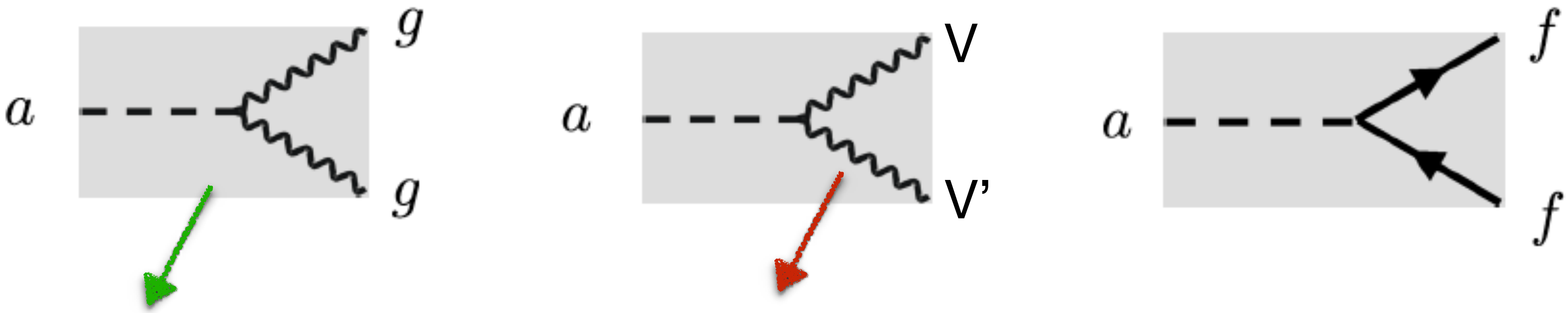


Minimal coupling expected if connection to the strong CP problem.

A ALP-photon coupling is generated in the broken phase

$$g_{aB}\cos^2\theta + g_{aW}\sin^2\theta$$

This is the main coupling that has been considered for phenomenological studies of ALPs in the sub-GeV scale.

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)

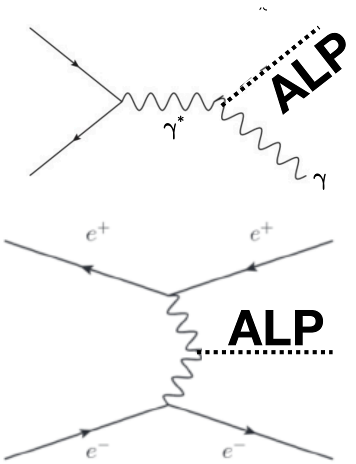
see e.g., Bauer et al, 2110.10698
Altmannshofer, Dror, SG, 2209.00665, …

Two classes of ALP production

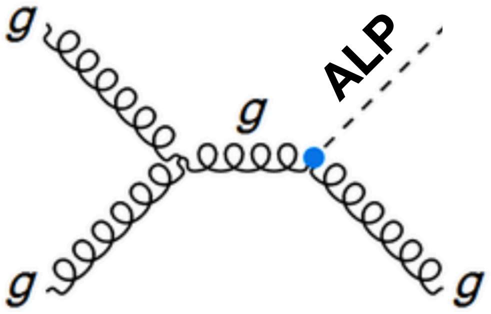
“Direct production” from beam collision

For example:

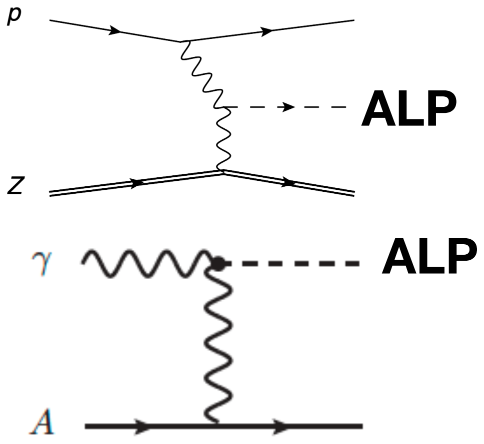
Belle II



LHC(b)



proton fixed target



Production from SM particle decays

Neutral current flavor changing transitions

K → π **ALP** (s → d **ALP**)

μ → e **ALP**

Boson decays

example: Z → γ **ALP**

Charged current transitions

example: K^+ → e^+ nu **ALP** (u → s e^+ nu **ALP**)

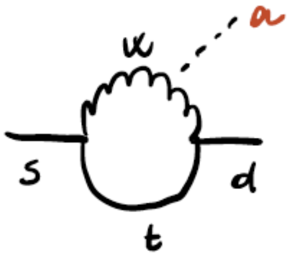
Similar transitions involving different mesons and/or leptons

Neutral & charged current meson decays to ALPs

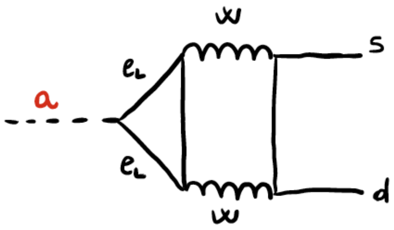
Flavor changing neutral current

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)



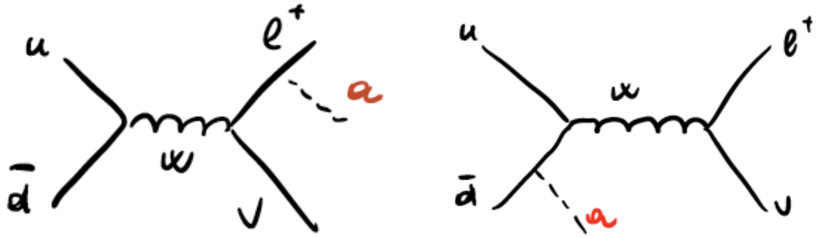
$$\begin{array}{rcl} K_L & \to & \pi^0 a \\ K^+ & \to & \pi^+ a \\ B & \to & K a \end{array}$$

- Flavor violating ALPs

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

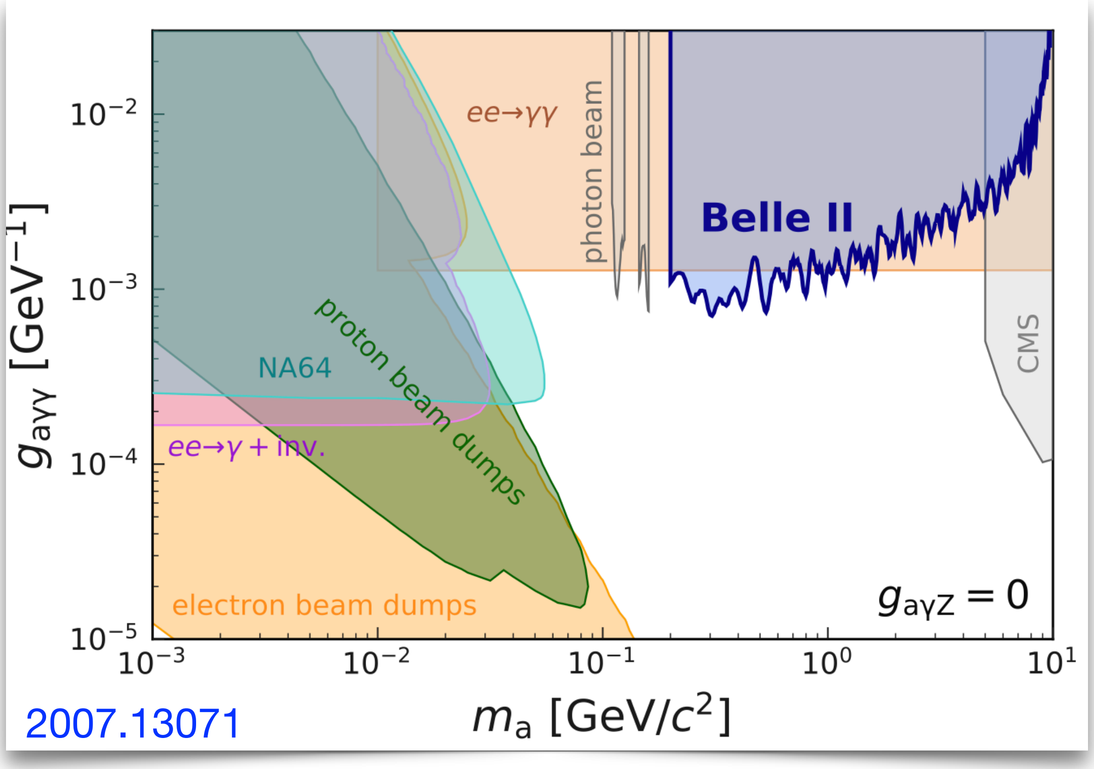


$$\begin{array}{rcl} \pi^+ & \to & a \ell^+ \nu \\ K^+ & \to & a \ell^+ \nu \\ B^+ & \to & a \ell^+ \nu \end{array}$$

S.Gori **Most studied** (both th. and exp.)

ALPs coupled to photons

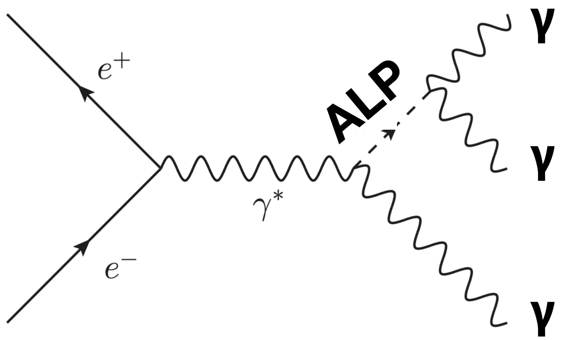
496/pb! 10^{-5} of the full data set



2007.13071

Fit of either the recoil mass or the γγ invariant mass

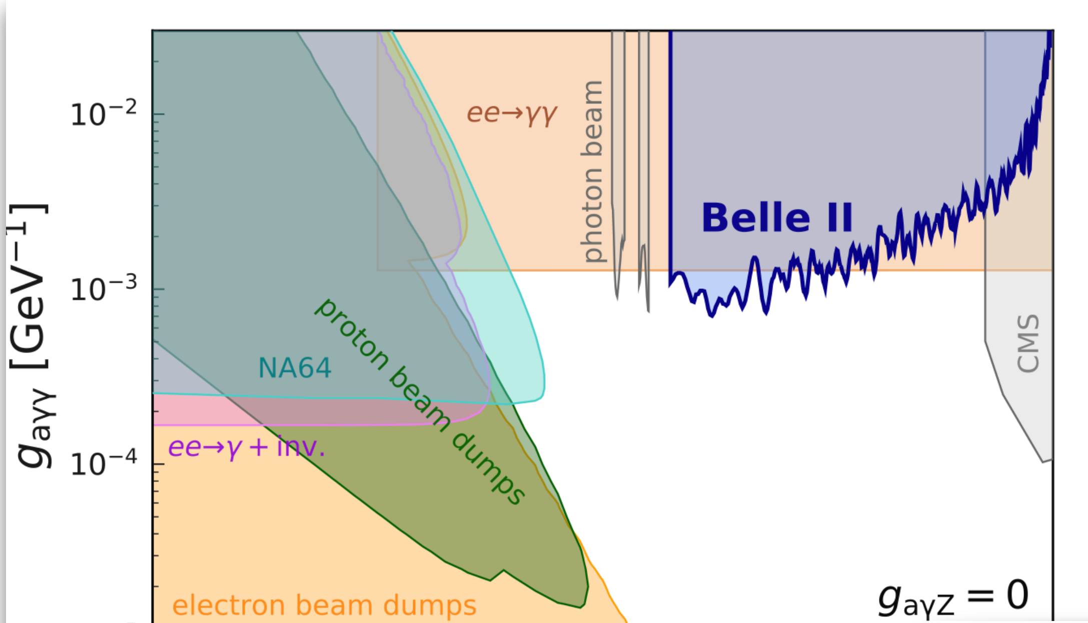
$$M^2_{\text{recoil}} = s - 2\sqrt{s}E^{\text{c.m.}}_{\text{recoil}}$$



$$\boxed{\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}}$$

ALPs coupled to photons

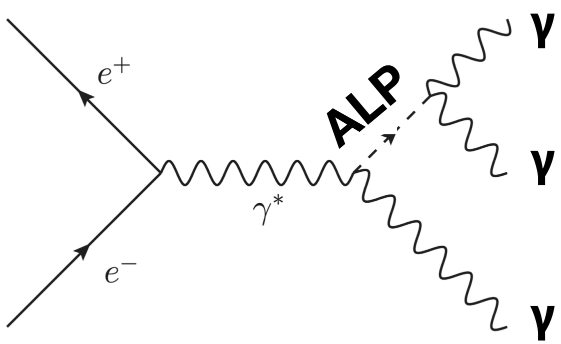
496/pb! 10^{-5} of the full data set



2007.13071

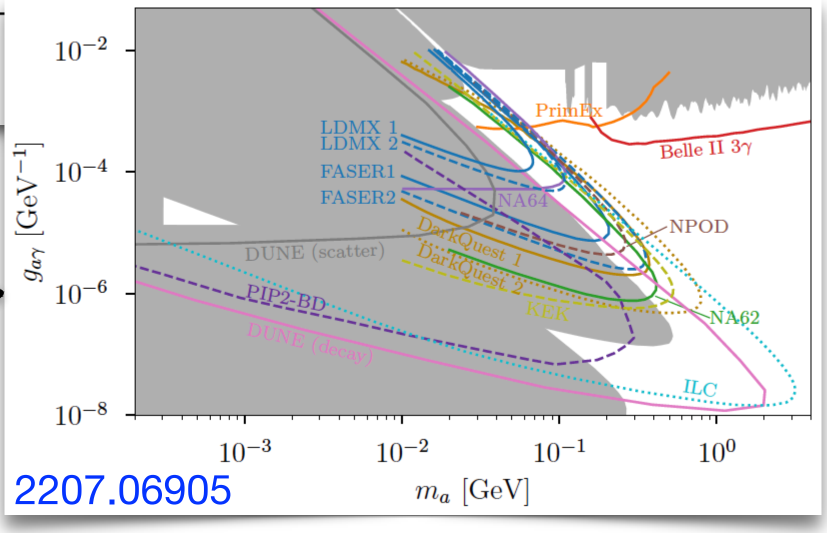
Fit of either the recoil mass or the γγ invariant mass

$$M^2_{\text{recoil}} = s - 2\sqrt{s}E^{\text{c.m.}}_{\text{recoil}}$$



$$\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

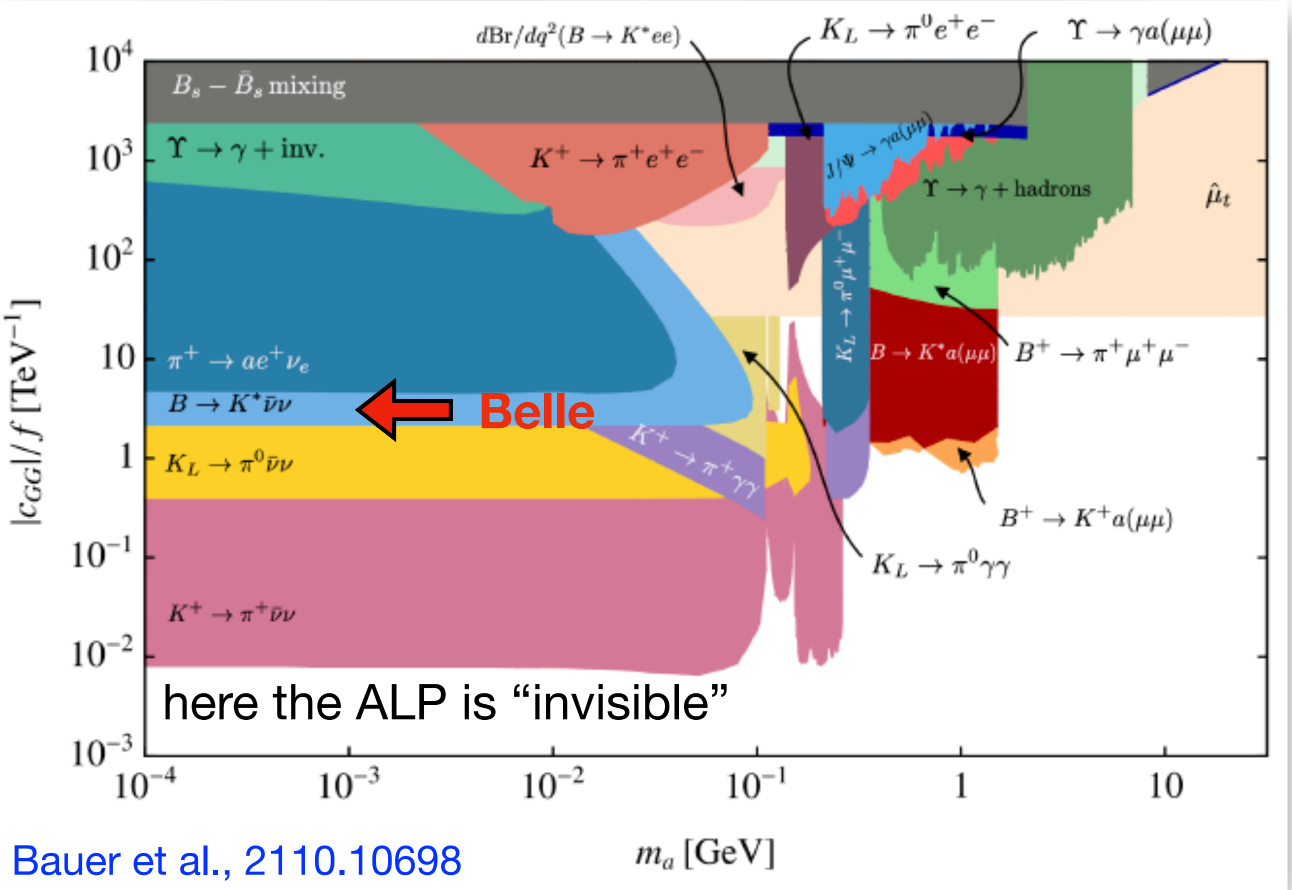
future prospects



2207.06905

with 20/fb,
Dolan et al.,
1709.00009

ALPs coupled to gluons

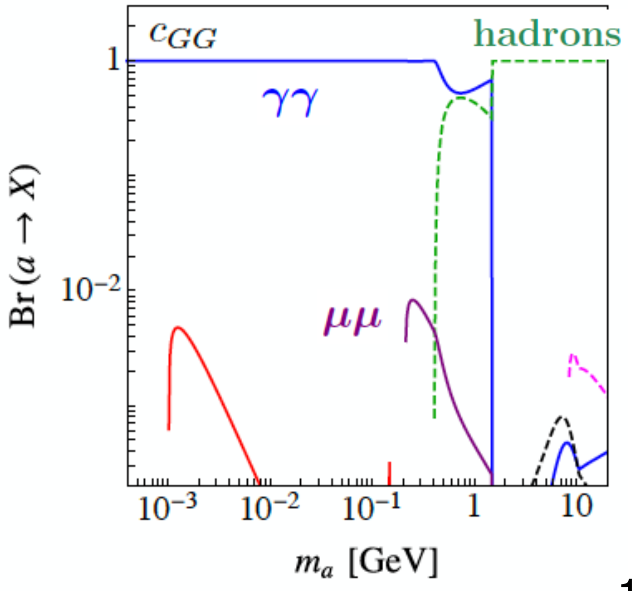


Belle

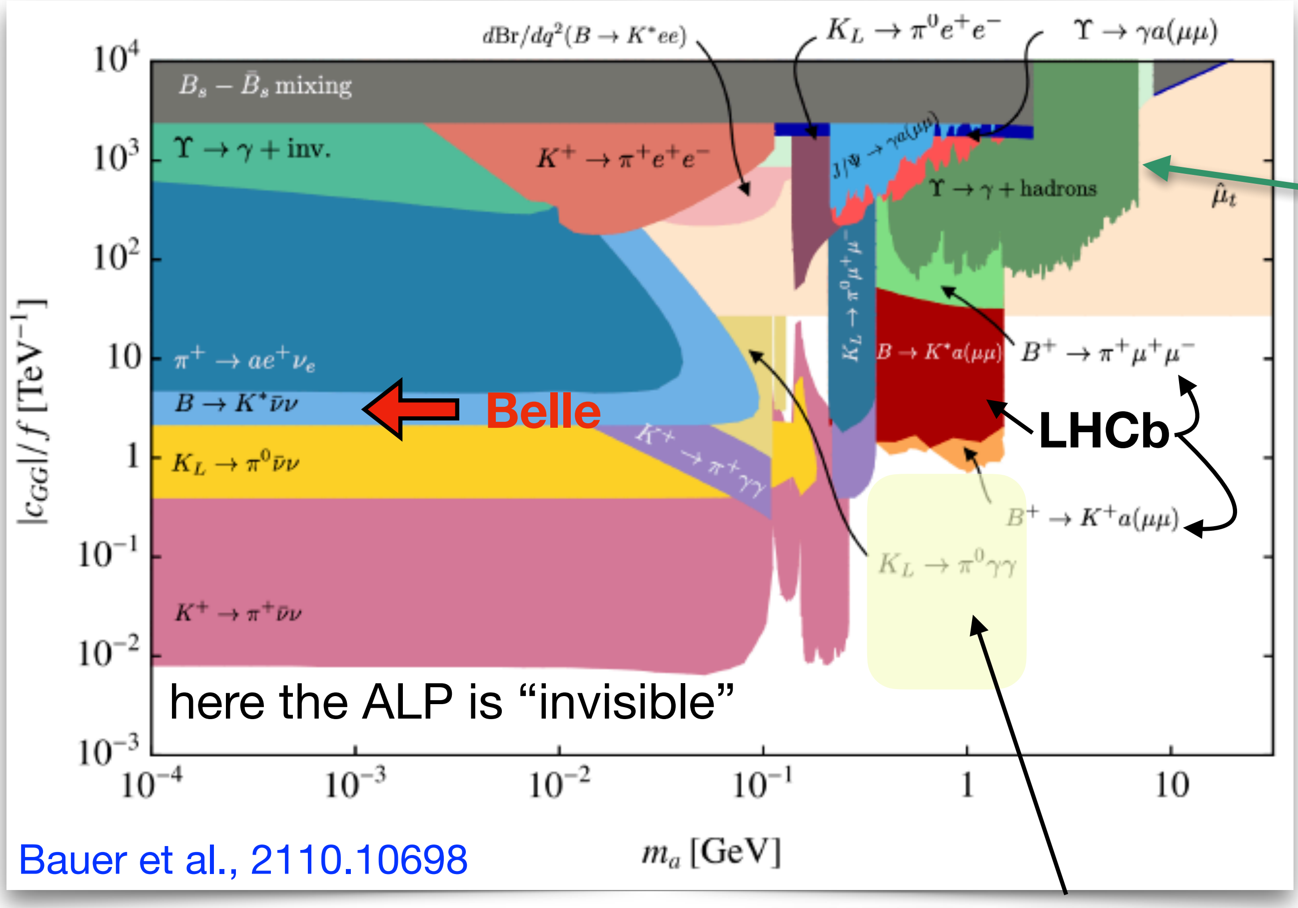
here the ALP is “invisible”

Bauer et al., 2110.10698

$$c_{GG}\frac{\alpha_S}{4\pi}\frac{a}{f}G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$$



ALPs coupled to gluons



Belle

LHCb

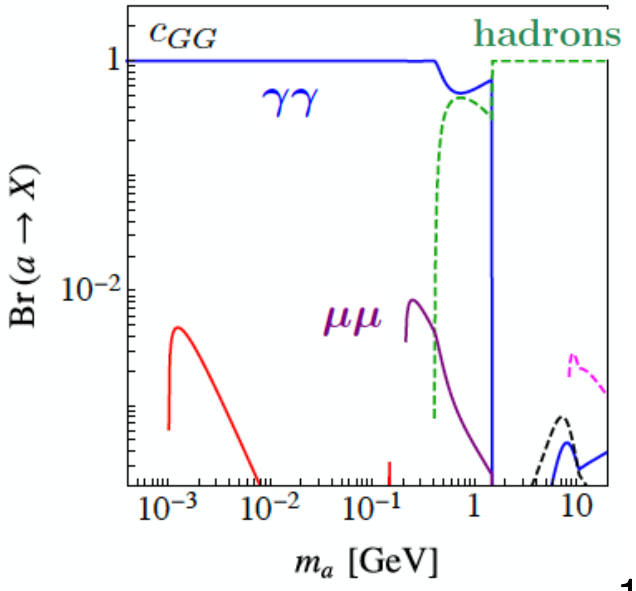
here the ALP is “invisible”

Bauer et al., 2110.10698

Babar, 1108.3549
What about Belle II?

$\Upsilon \to \gamma a, \ a \to \text{hadrons}$

What about Belle II,
B→Ka, a→γγ?



$$c_{GG} \frac{\alpha_S}{4\pi} \frac{a}{f} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}$$

Chapter 4

Non-minimal models

1. Inelastic Dark Matter (non-minimal freeze out)
2. L_μ - L_τ theories ("flavor specific" theories)

1.

Inelastic Dark Matter

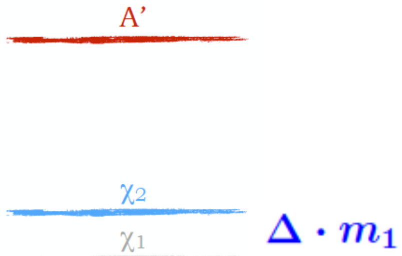
Inelastic DM (IDM) models were initially proposed to explain the DAMA anomaly, while being consistent with Dark Matter direct detection bounds from CDMS

Tucker-Smith, Weiner, 0101138

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

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

$$\begin{aligned}\chi_1 &= i(\eta-\xi)\sqrt{2}\,,\\ \chi_2 &= (\eta+\xi)\sqrt{2}\end{aligned}$$



Two states close in mass: $\Delta \equiv \frac{m_2-m_1}{m_1} \sim \frac{\delta_\xi+\delta_\eta}{m_D} \ll 1$

Easy to get it small
since it is a U(1)’
breaking effect

1.

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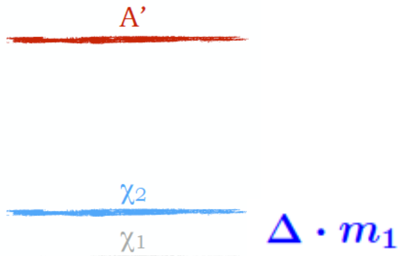
The only relevant interaction is inelastic:

$$\chi_1 = i(\eta - \xi)\sqrt{2}\,,$$
$$\chi_2 = (\eta + \xi)\sqrt{2}$$

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

The elastic piece is very small $(\delta_{\eta,\xi} \ll m_D)$:

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



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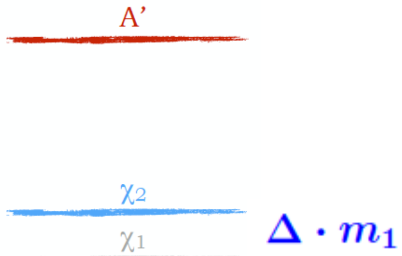

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Easy to get it small since it is a U(1)’ breaking effect

Abundance of χ_1 and χ_2 is determined by two coupled Boltzmann equations, that keep into account:

- χ_1 χ_2 co-annihilation,
- χ_2 f → χ_1 f inelastic scattering,
- $\chi_2 \to \chi_1$ + SM decays

S.Gori

Izaguirre, Krnjaic, Shuve, 1508.03050

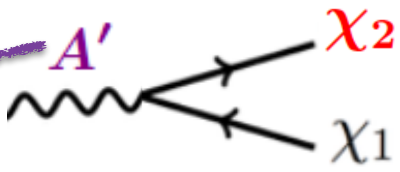
1.

IDM displaced signatures

IDMs are rather hidden to direct detection experiments
Also CMB constraints are relaxed
The prime avenue to probe IDM is at high intensity experiments

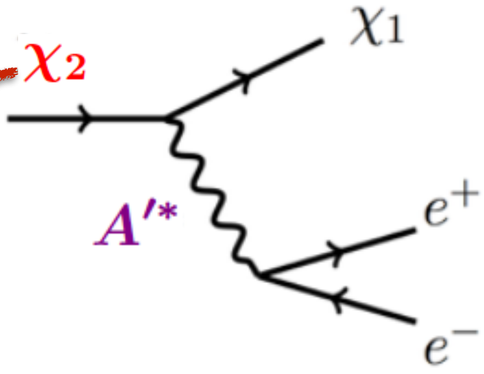
(see, however, Bramante et al., 1608.02662)

$m_\chi < m_{A'}$



Copiously produced at
high intensity experiments (see yesterday's lecture)

with



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

Non-resonant decays

1.

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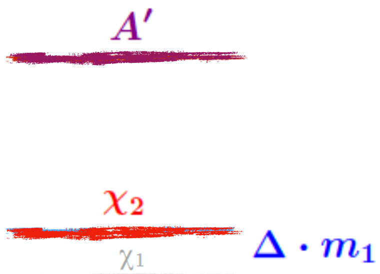

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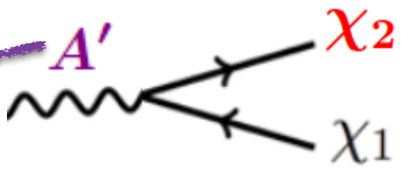

Copiously produced at high intensity experiments

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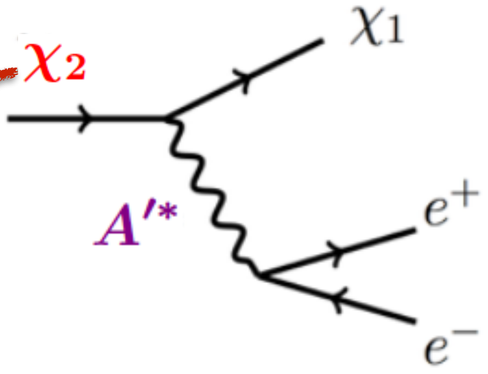

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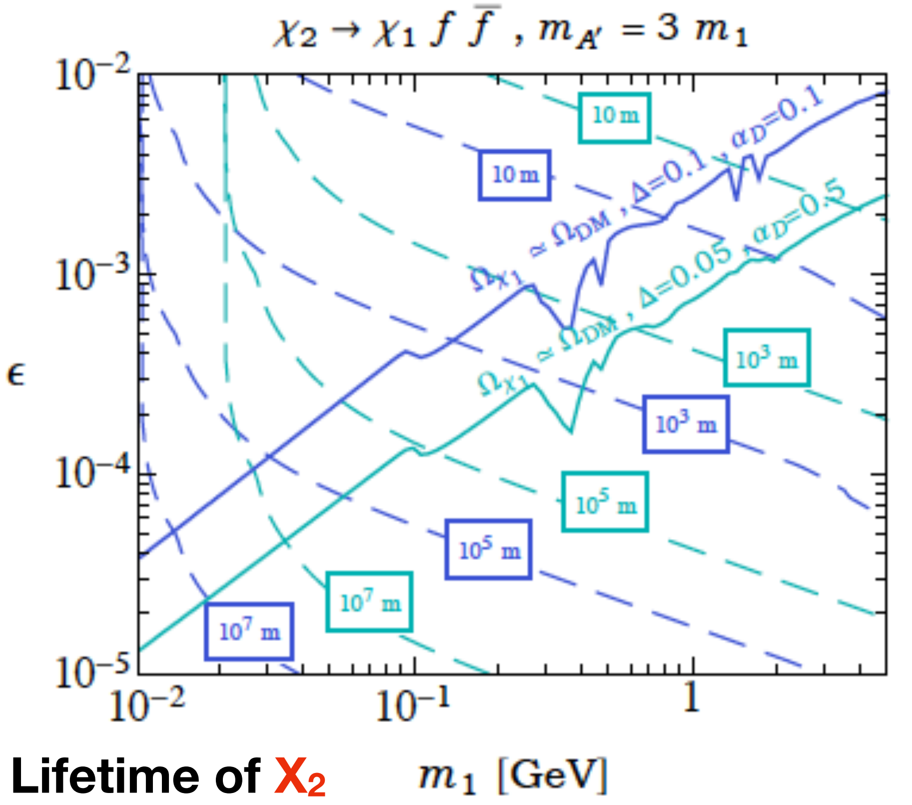
Non-resonant decays

Berlin, SG, Schuster, Toro, 1804.00661



Lifetime of X_2

Displaced decays

1.

New opportunities for B-factories

New proposed search for Belle-II:

(Photon) + displaced tracks + missing energy

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New proposed search for Belle-II:

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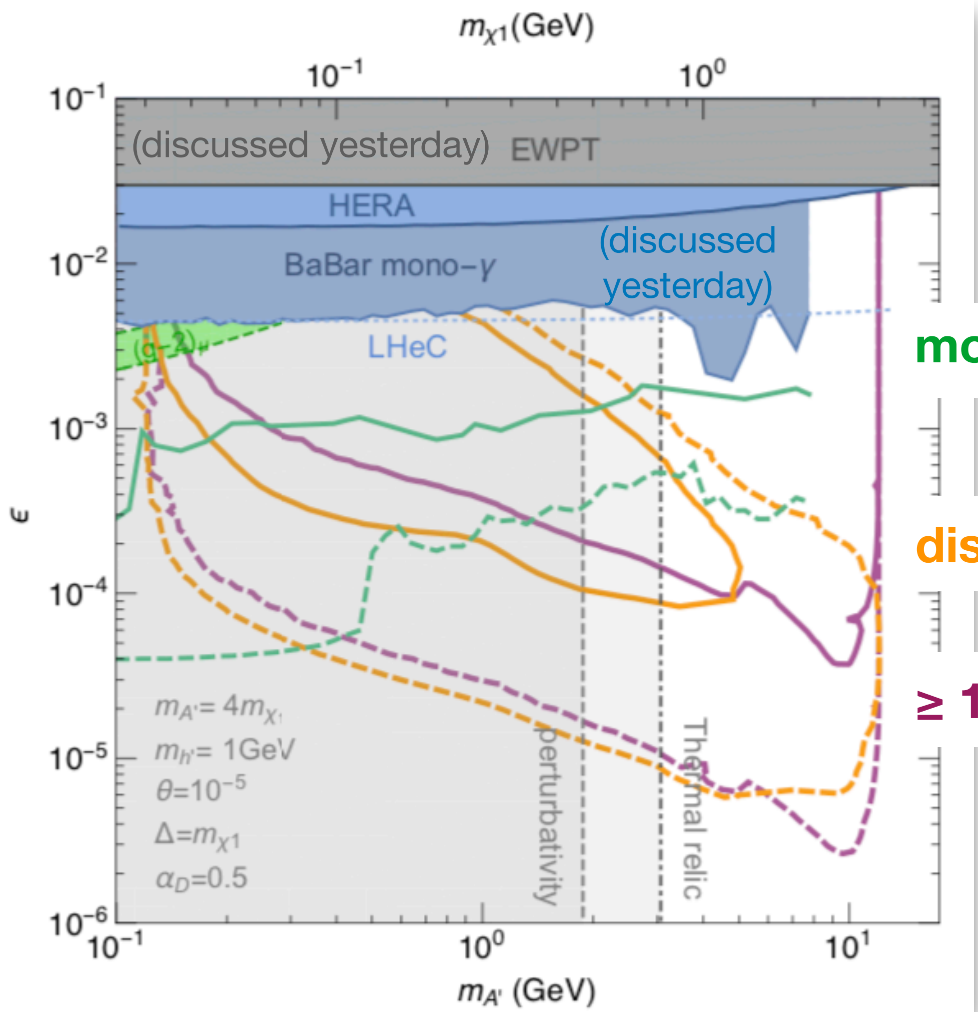


——— 100/fb

········ 50/ab

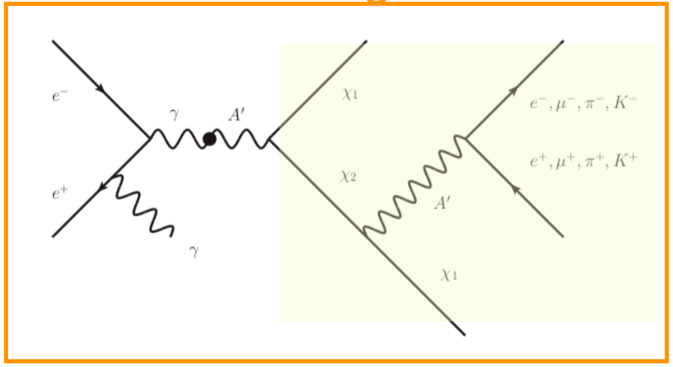
mono-photon

displaced+photon

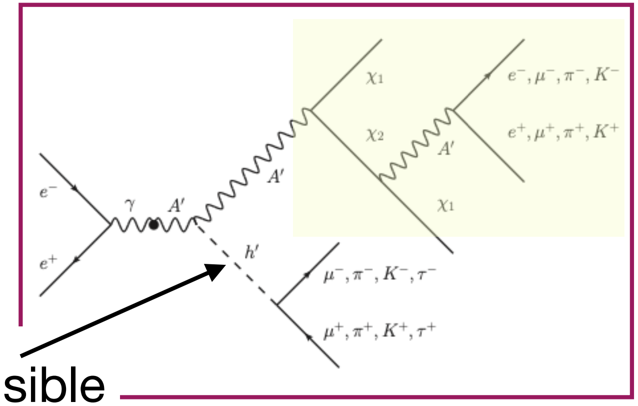
≥ 1 displaced

Duerr et al. 2012.08595

“minimal signature”



“non-minimal signature”



Higgs responsible for the A’ mass

Higgs-strahlung

Displaced vertex trigger is very important

2.

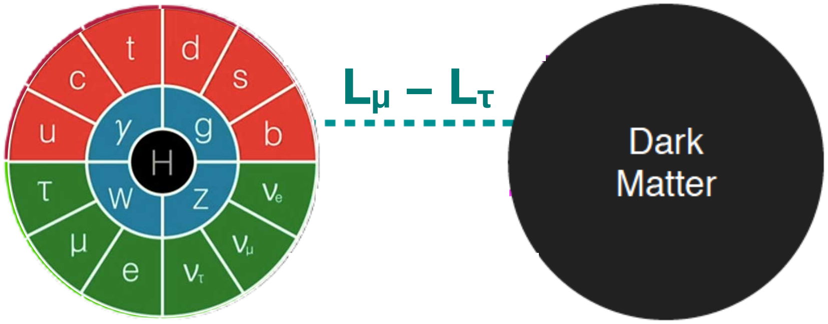
A new gauge symmetry for DM?

L_μ - L_τ

Simple example:

dark matter is a Dirac fermion charged under $L_\mu - L_\tau$, $q_\chi g' \bar{\chi} \gamma^\mu \chi Z'_\mu$

Altmannshofer, SG, Profumo, Queiroz 1609.04026
(see also Kile et al. 1411.1407; Kim et al. 1505.04620; Baek 1510.02168 ...)



This symmetry is also motivated by neutrino mass model building
+ anomalies in data (b→sll, $(g-2)_\mu$)

If $m_{Z'} < 2m_{DM}$, the Z' will decay exclusively to muons, taus, and neutrinos

2.

A new gauge symmetry for DM?

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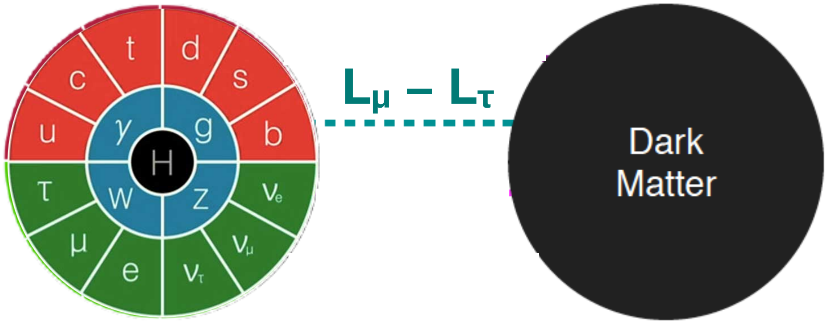
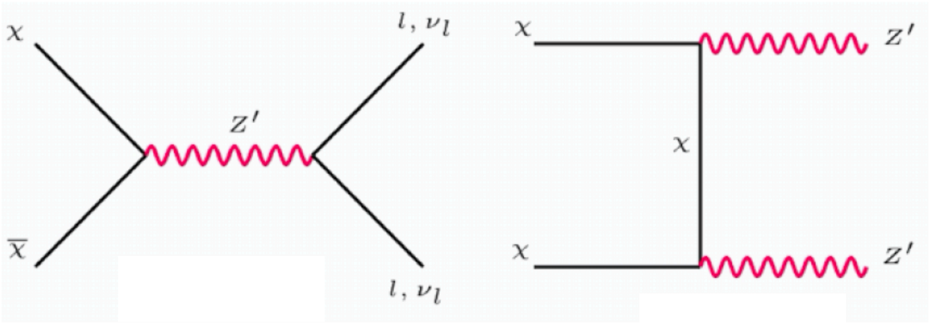


Possible signals at:

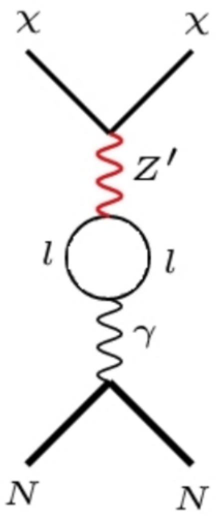
1. DM indirect detection experiments



Main constraints from CMB

If $m_{Z'} < 2m_{DM}$, the Z’ will decay exclusively to muons, taus, and neutrinos

2. DM direct detection experiments



It can be sizable, despite the loop suppression

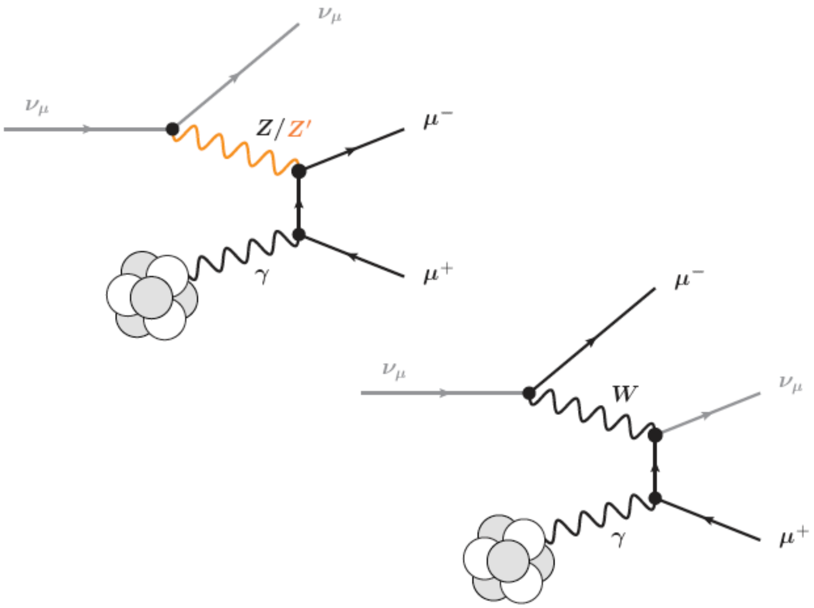
Constraints from LUX, Xenon, and PandaX

2.

Tests at neutrino experiments:

CCFR, CHARM experiments

Neutrino induced $\mu^+\mu^-$ production in the Coulomb field of a heavy nucleus: "neutrino trident production"



Altmannshofer, SG, Pospelov, Yavin, 1406.2332

Z' contribution to the cross section:

$$\frac{\sigma}{\sigma_{\mathrm{SM}}} \simeq \frac{1+\left(1+4s_W^2+\frac{2v^2(g')^2}{M_{Z'}^2}\right)^2}{1+(1+4s_W^2)^2}$$

(in the approximation of heavy Z')

Measurements in the early '90s by CCFR and CHARM:

$$\sigma/\sigma_{\mathrm{SM}} = 0.82 \pm 0.28$$

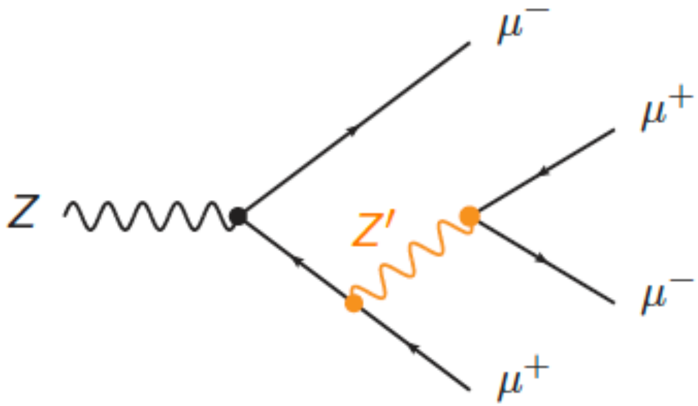
(CCFR, PRL66 (1991) 3117)

Not 100% clear how solid this measurement is

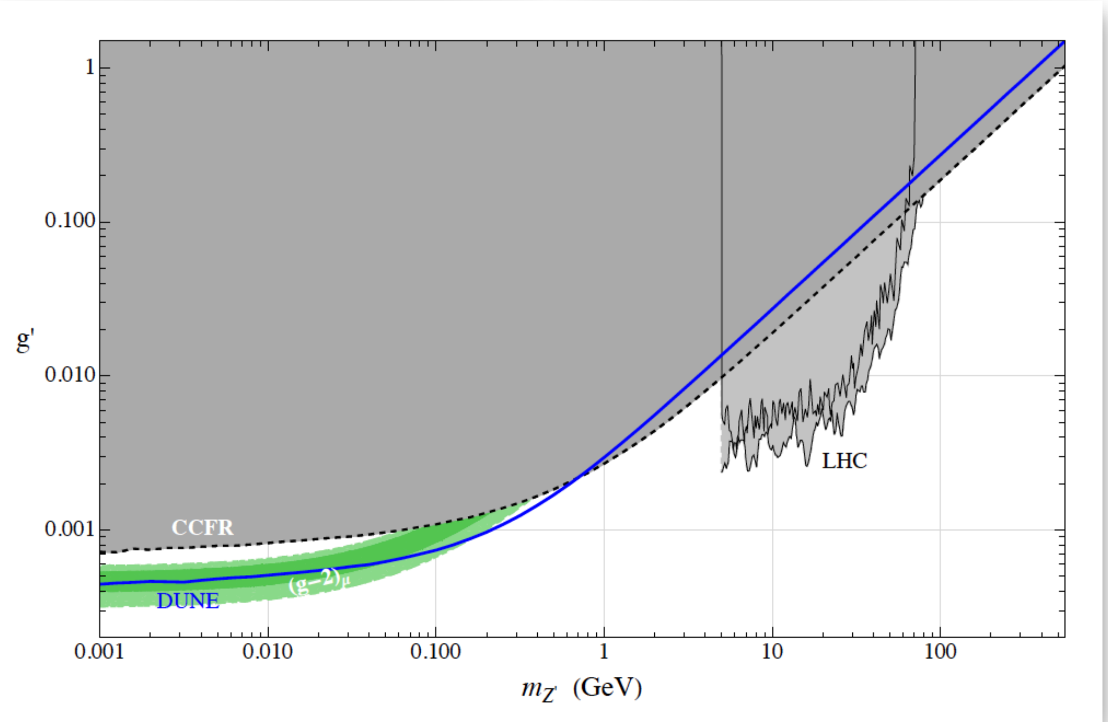
2.

Searches at the LHC

Bounds from the measured $Z \to 4\mu$ branching ratio

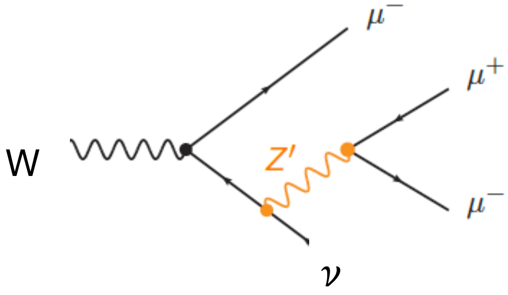


(Updated) Altmannshofer, SG, Martin-Albo, Sousa, Wallbank, 1902.06765



Recent dedicated CMS + ATLAS searches for the L_μ - L_τ gauge boson, (1808.03684, 2402.15212)

Combination with W →Z' μ ν → (μ μ) μ ν

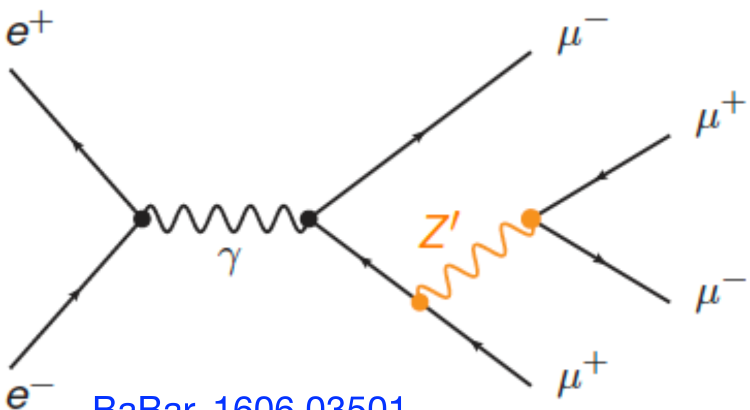


2.

Searches at B-factories

B-factories can search for the light Z’ produced with muons

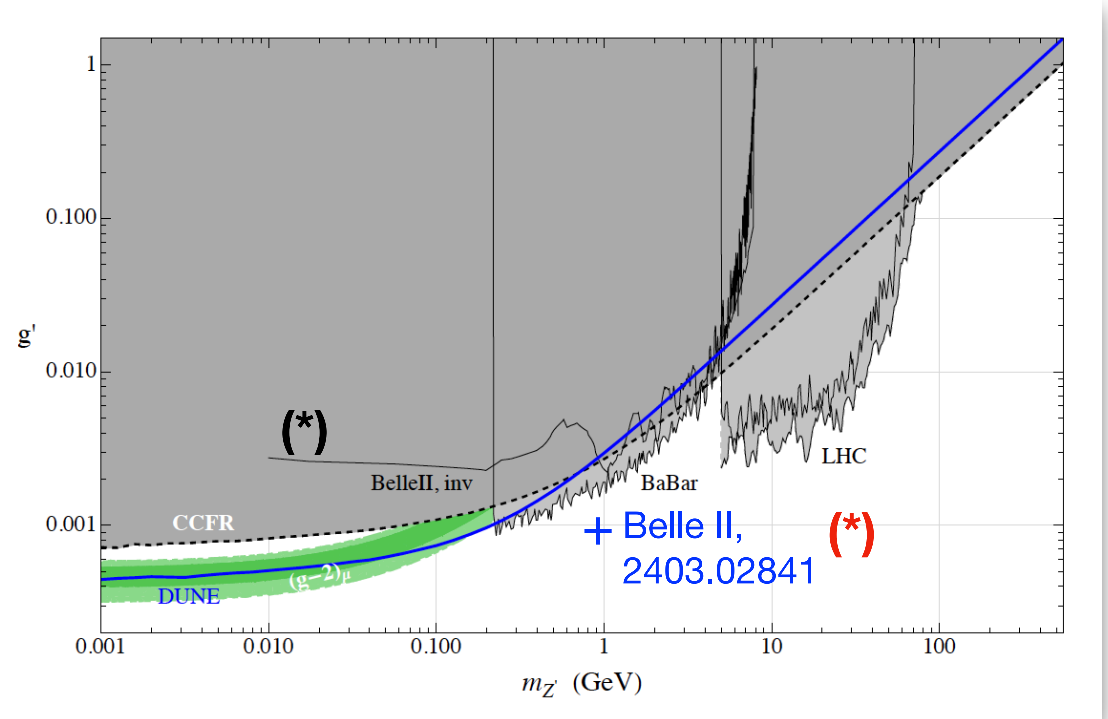
$$e^+e^- \to 2\mu Z' \to 4\mu$$



BaBar, 1606.03501
Belle II, 2403.02841 **(*)**

Additional Belle II search 2212.03066 for $e^+e^- \to \mu^+\mu^- + Z'$, $Z' \to \nu\,\nu$ **(*)** (particularly relevant for $m_{Z'} < 2m_\mu$)

(Updated) Altmannshofer, SG, Martin-Albo, Sousa, Wallbank, 1902.06765

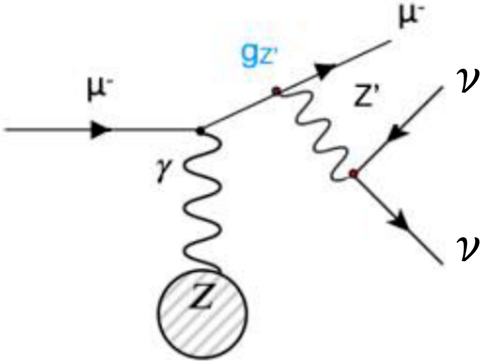


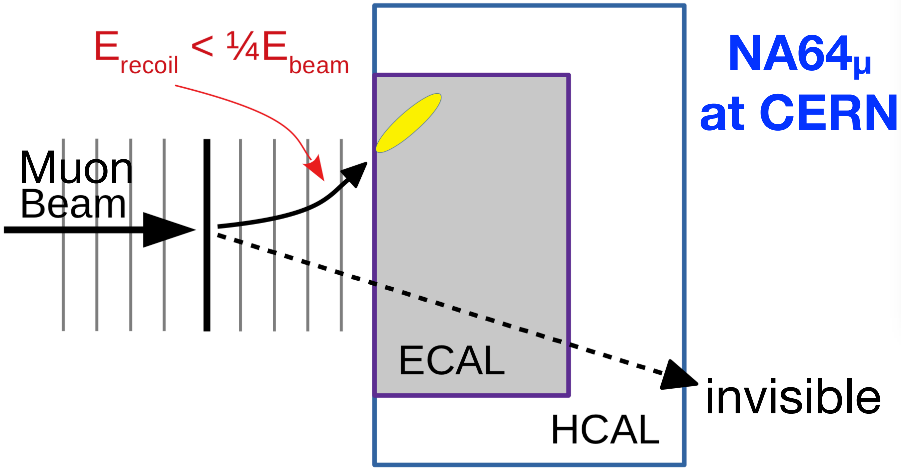
+ Belle II, 2403.02841 **(*)**

2.

Searches at fixed target experiments

High intensity fixed target experiments can produce an invisible Z’



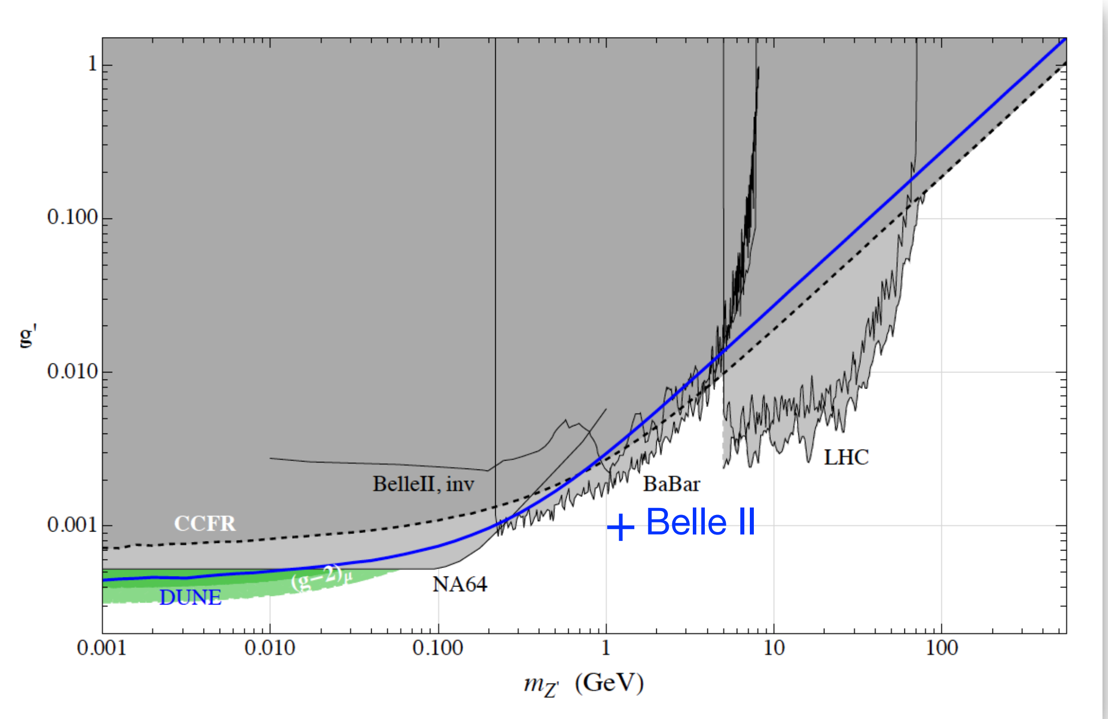


NA64$_\mu$ at CERN

missing energy-momentum search

2401.01708

(Updated) Altmannshofer, SG, Martin-Albo, Sousa, Wallbank, 1902.06765

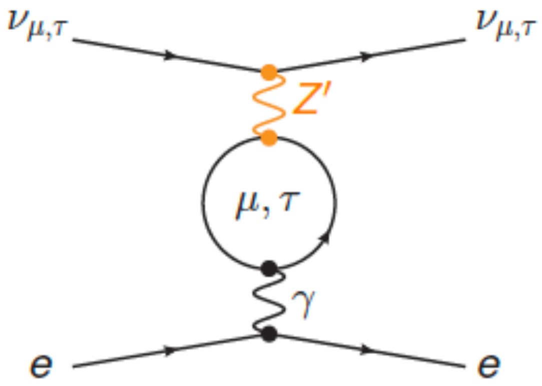


2.

Tests at neutrino experiments

Borexino

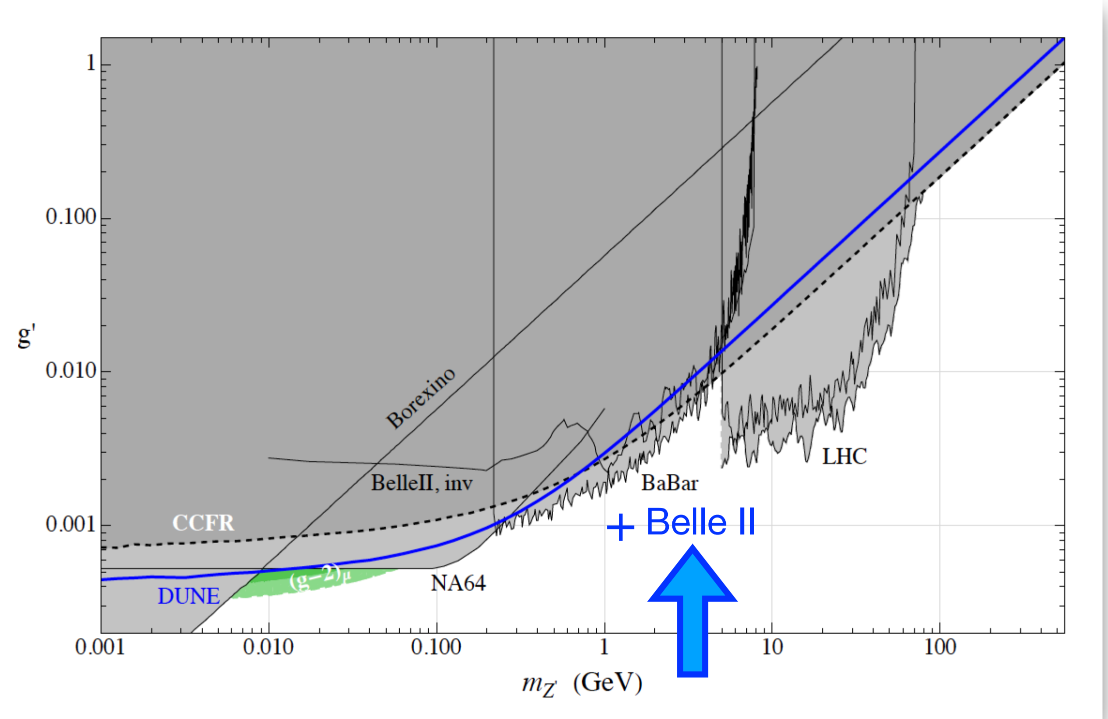
Bounds from measurements
of solar neutrino-electron scattering



tiny momentum transfer
⇒ Z’ can mix with the SM photon

relevant constraint at low masses
from the Borexino experiment

(Updated) Altmannshofer, SG, Martin-Albo, Sousa, Wallbank, 1902.06765



Belle II probes a mass range that is not probed otherwise

What we have learnt

Dark sectors are ubiquitous.

DM and the strong CP problem are two of the several motivations.
Experimental targets arise in these models (i.e. how small the couplings we should aim to probe are)

Minimal models

- dark photon
- dark scalar
- sterile neutrino

- visible
- invisible

- axion-like-particles
  (several independent couplings with the SM)

Beyond the minimal models

- Inelastic Dark Matter
- L_μ - L_τ

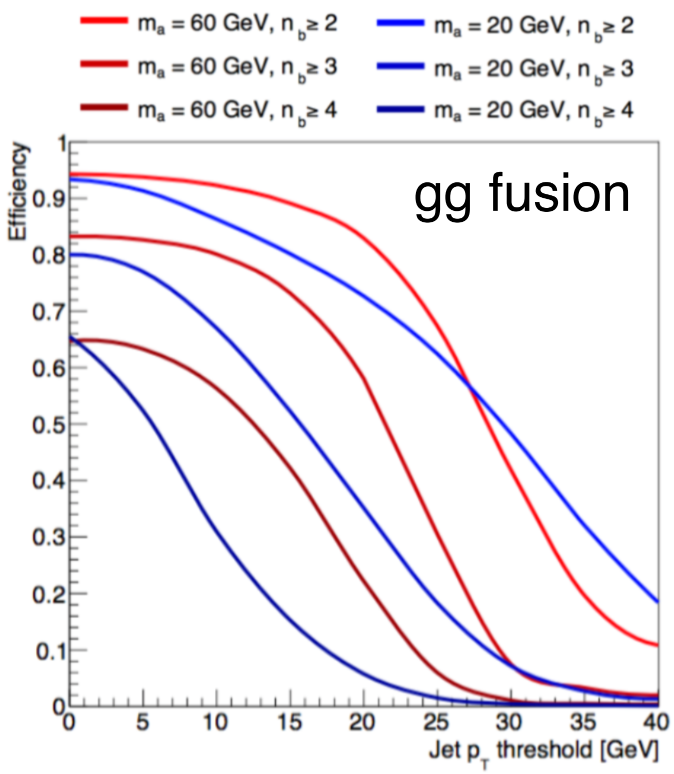
- semivisible

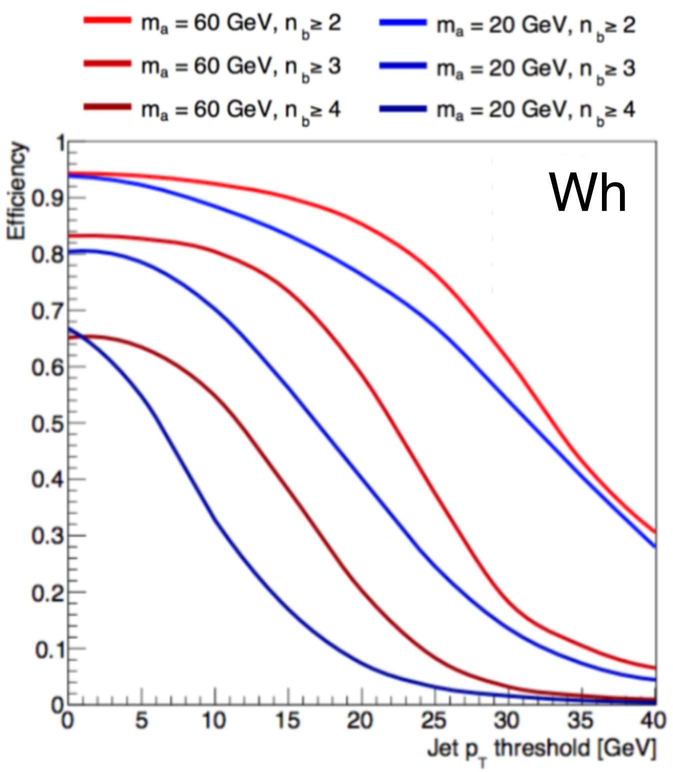
THEORY PHENOMENOLOGY

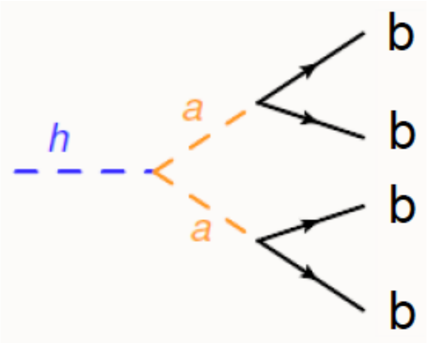
The challenge for the LHC

To be sensitive to light scalars and Higgs exotic decays, dedicated studies of trigger strategies are needed!

Let us take, for example, the challenging decay mode h → 4b







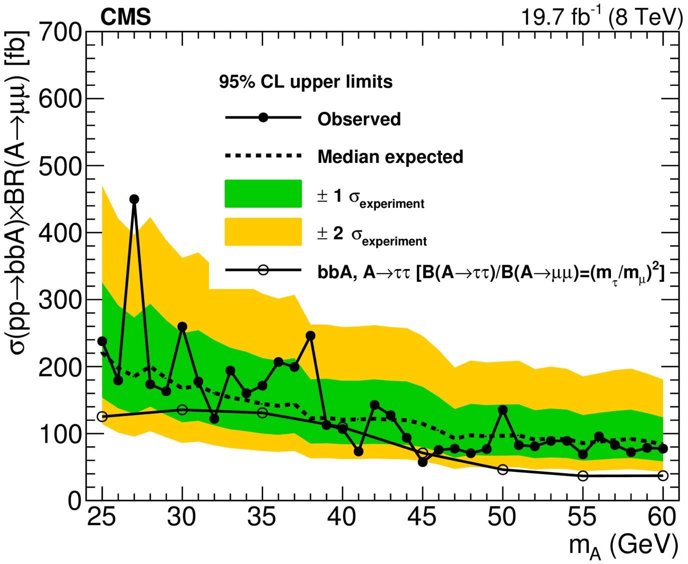
Risk of loosing the signal already at the trigger level

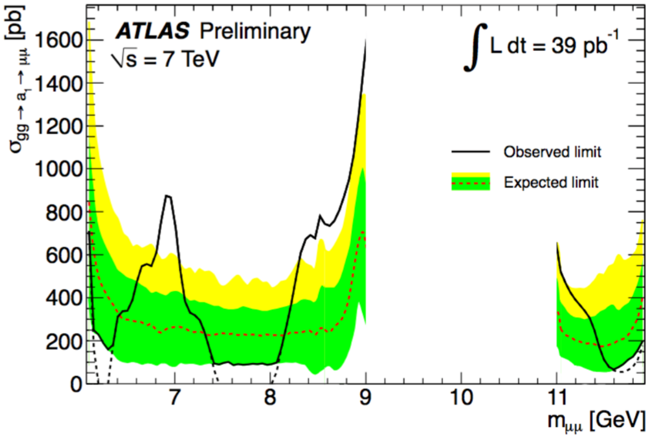
From the LHC Higgs cross section working group, Yellow report 4, 1610.07922

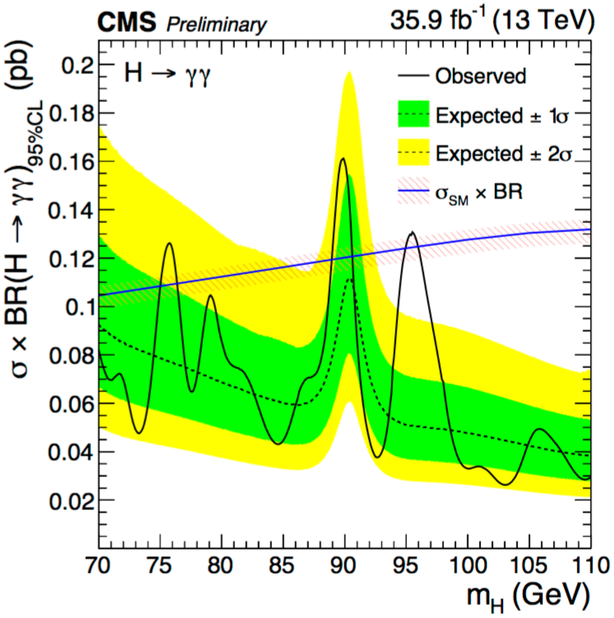
LHC production of the dark scalar

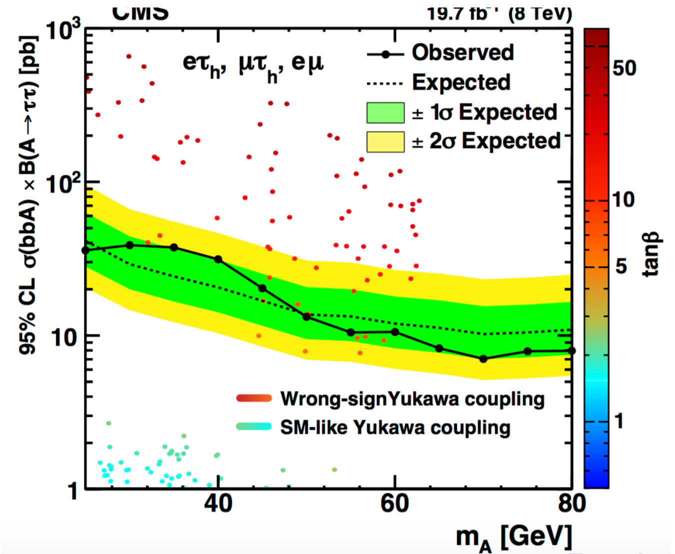
The production cross section_$_s$ = production_$_{\text{SM Higgs}}$$^*\sin^2(\theta_S)$
Same production modes as for the SM Higgs

Only a few LHC searches have been performed.
Examples are bbs, s →μμ
ggs, s →μμ,
ggs, s →γγ
bbs, s →tautau

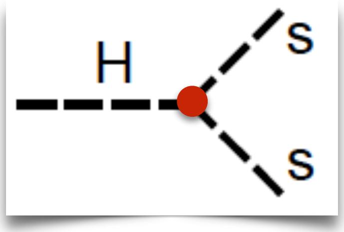




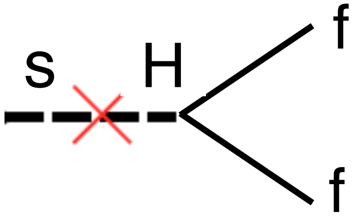


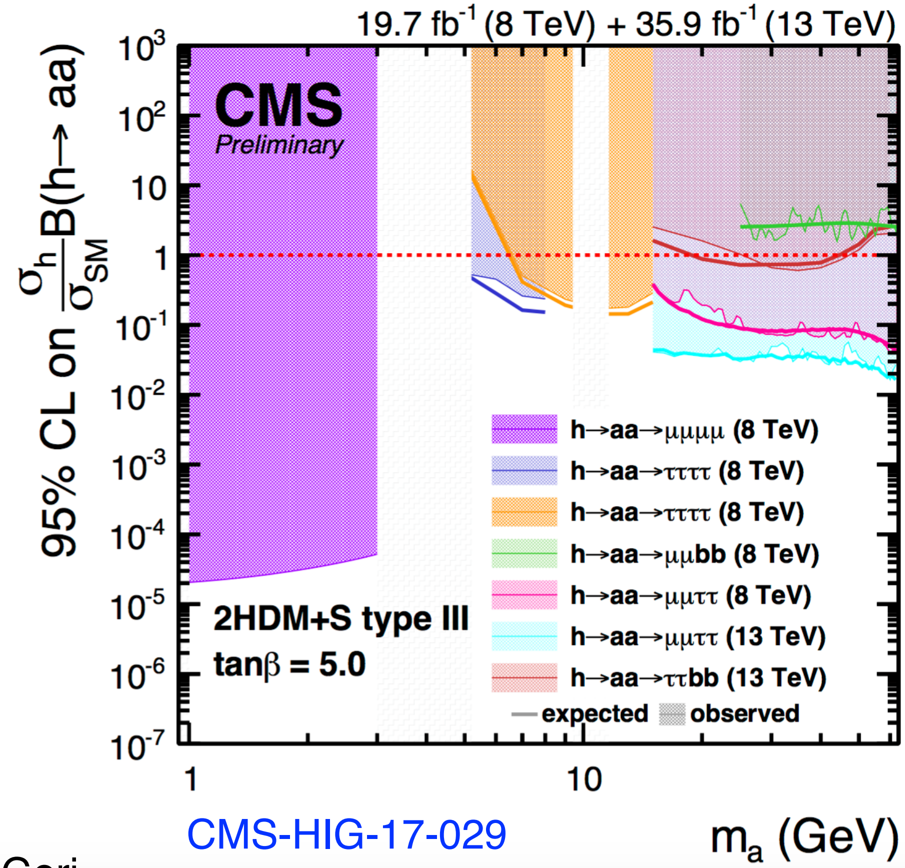


Higgs exotic decays to dark scalars



The scalar can decay thanks to its mixing with the Higgs





CMS-HIG-17-029

Many possible signatures to look for

gg → h → ss → 4b
gg → h → ss → 2b 2tau
gg → h → ss → 2b 2μ
gg → h → ss → 4tau
gg → h → ss → 4μ
gg → h → ss → 2tau 2μ
…

both **prompt** & displaced

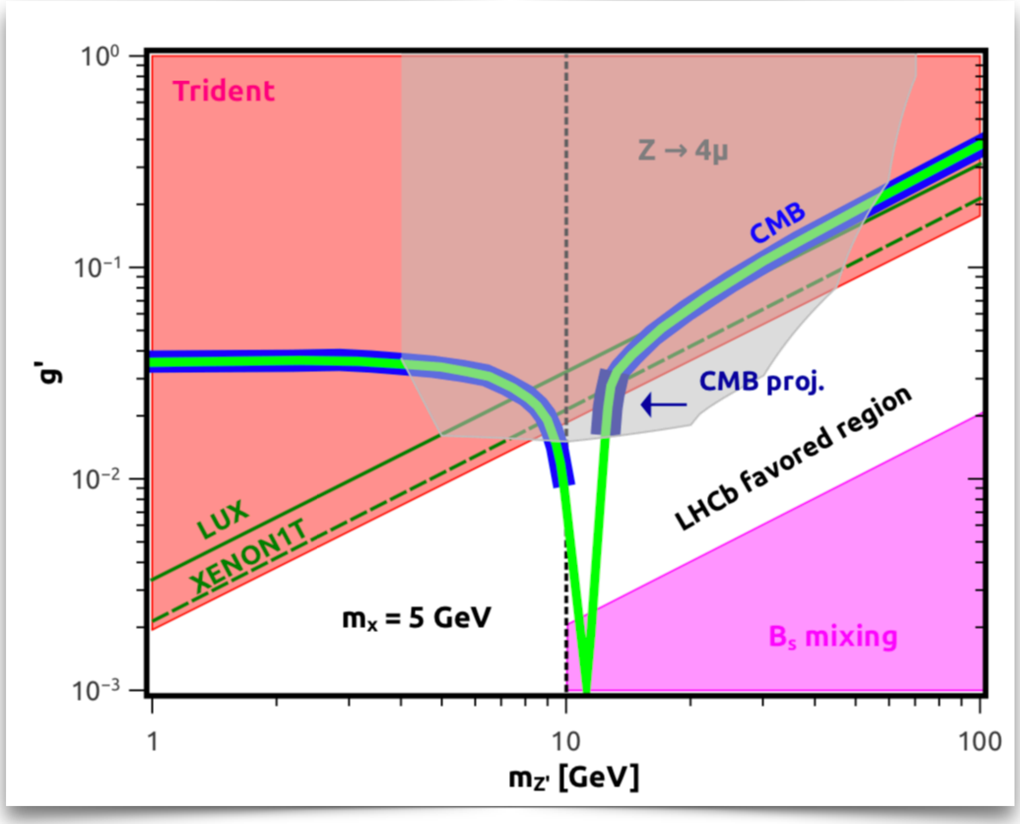
+ sub-leading production modes of the Higgs boson

e.g. qq → Zh → Z(ss) → Z(4b)
…

L_μ - L_τ and dark matter

L_μ - L_τ model + Dirac fermion DM

Altmannshofer, SG, Profumo, Queiroz, 1609.04026



Towards fully probing this model.

Only DM in ~(5-20)GeV is still viable