High-intensity probes of dark sector particles

Stefania Gori
UC Santa Cruz
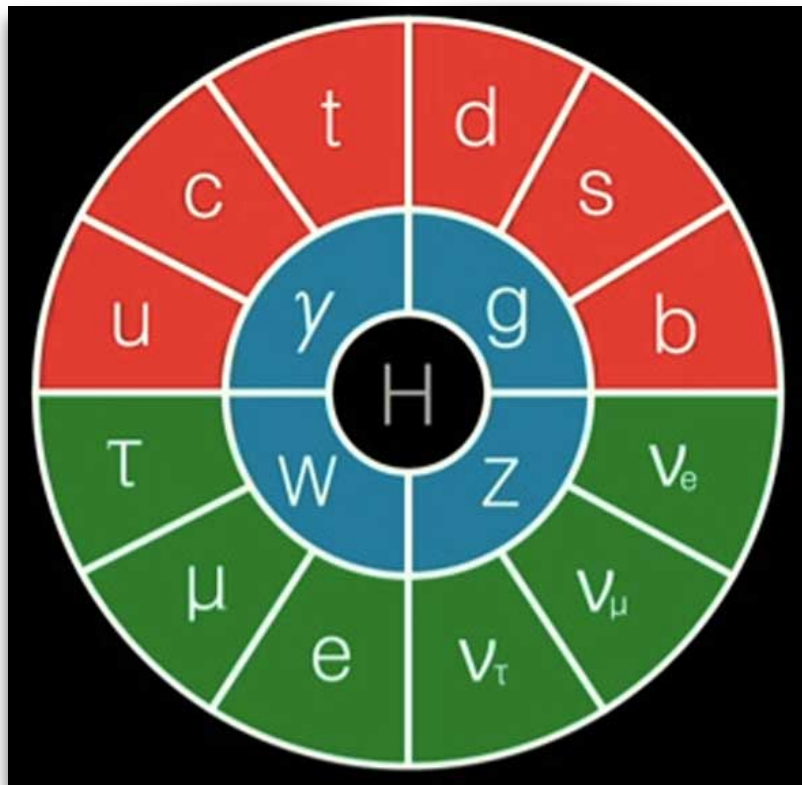
DESY Virtual Theory Forum, 2020

September 23, 2020
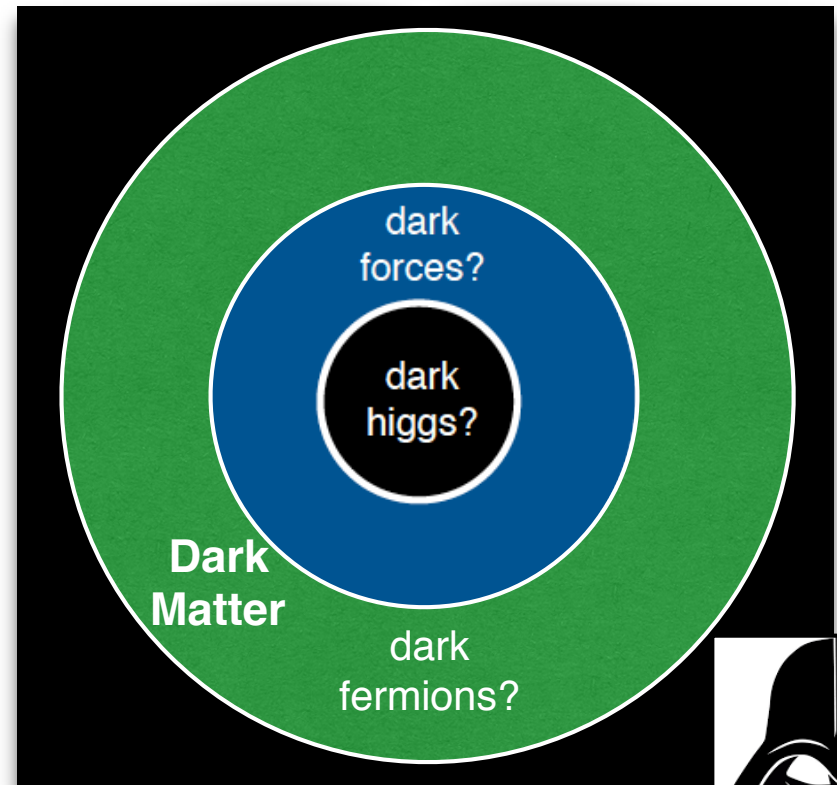
What is a dark sector particle?

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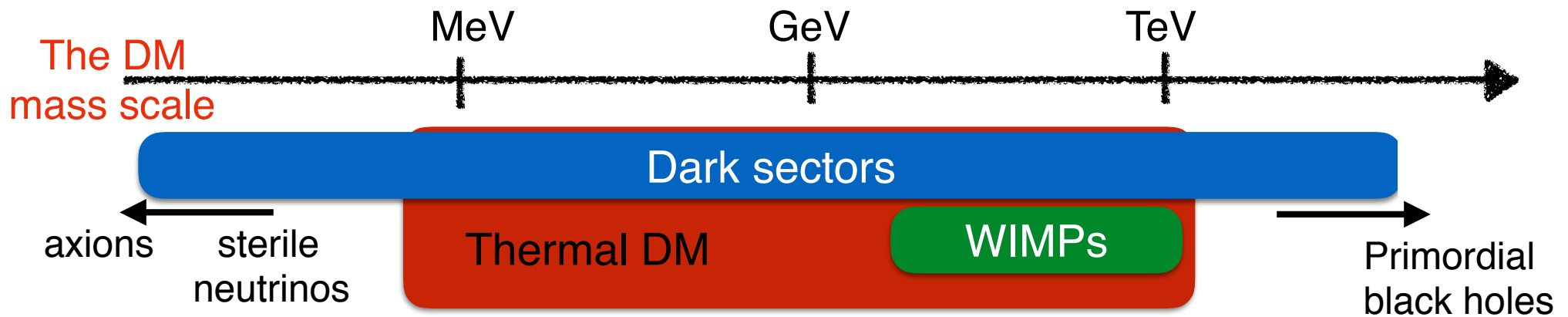
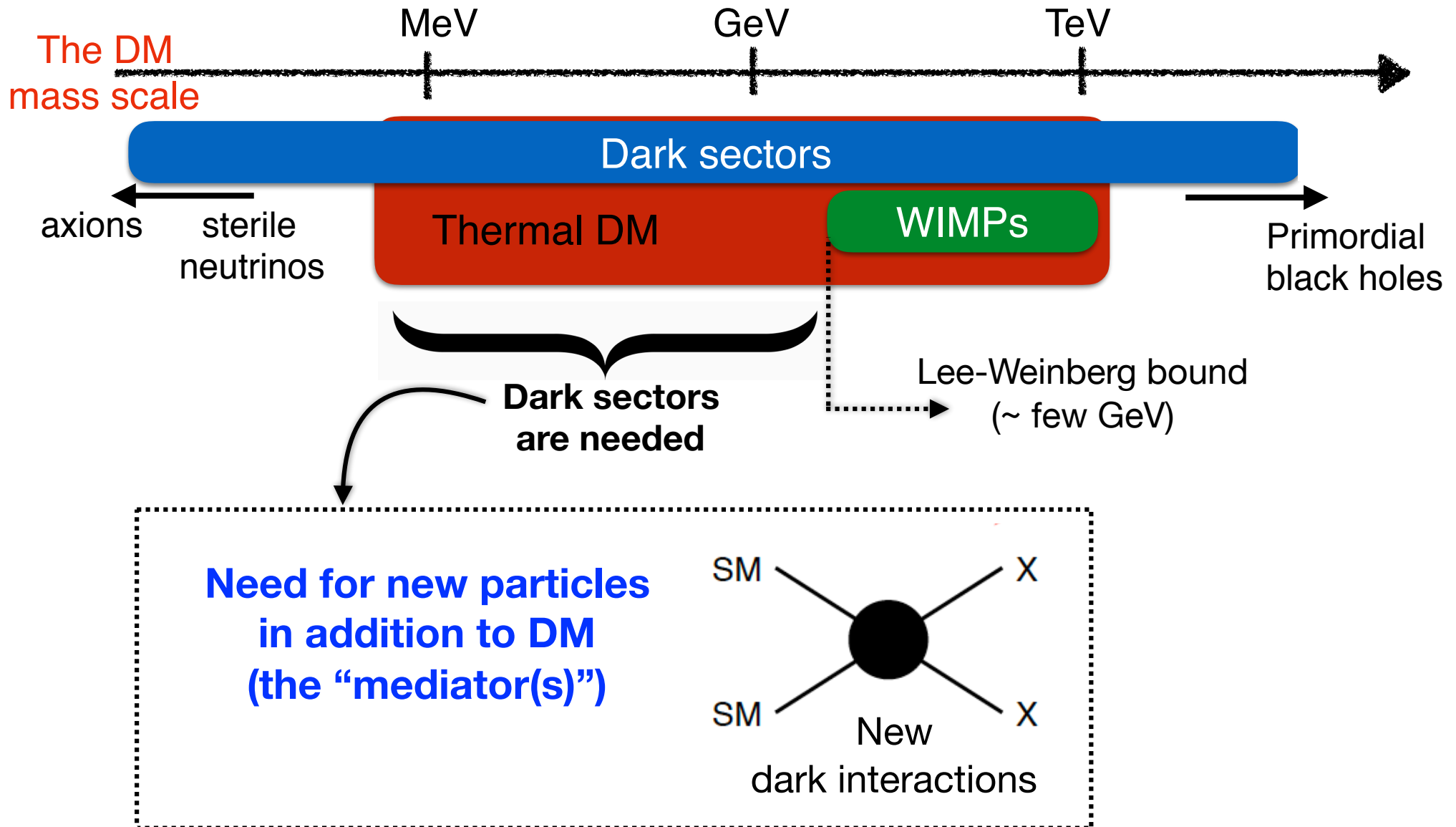Our visible universe

The dark universe

Why a dark sector? (DM)

Why a dark sector? (DM)

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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?
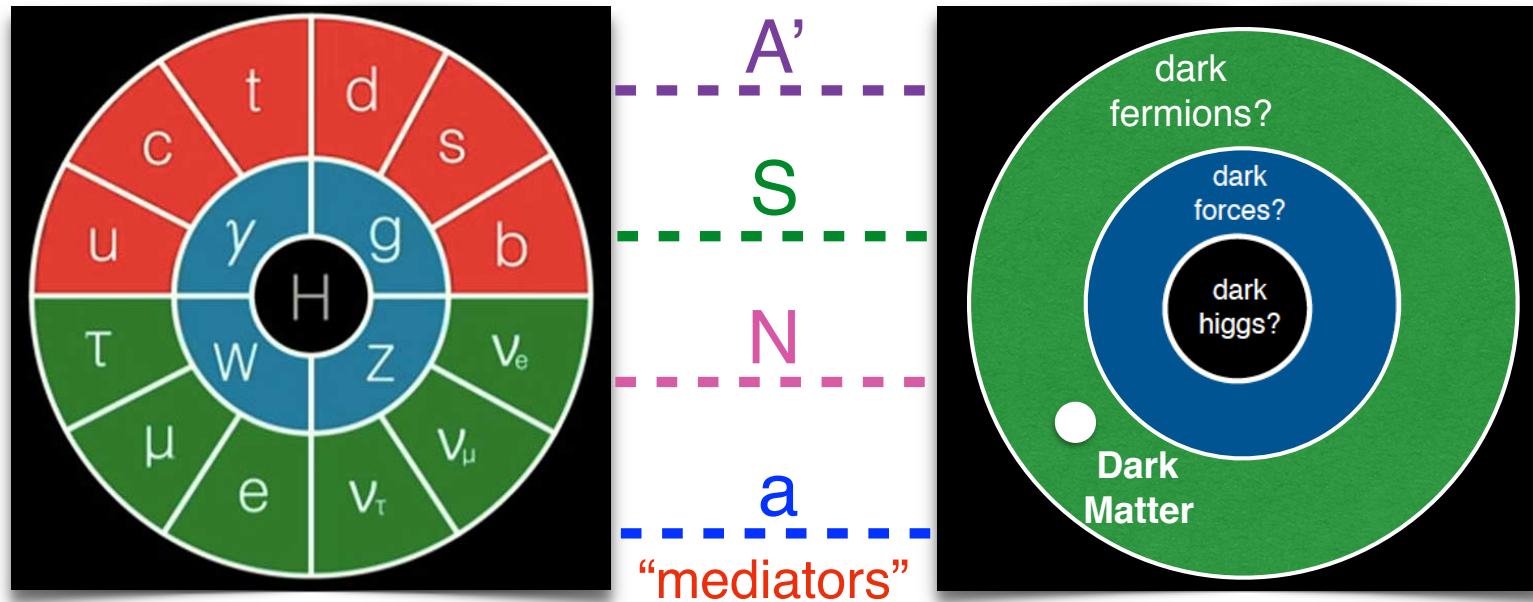
A'

S

N

a

"mediators"

"mediators"   "portal interactions"

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

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	$g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$

How to gain access to the dark sector?
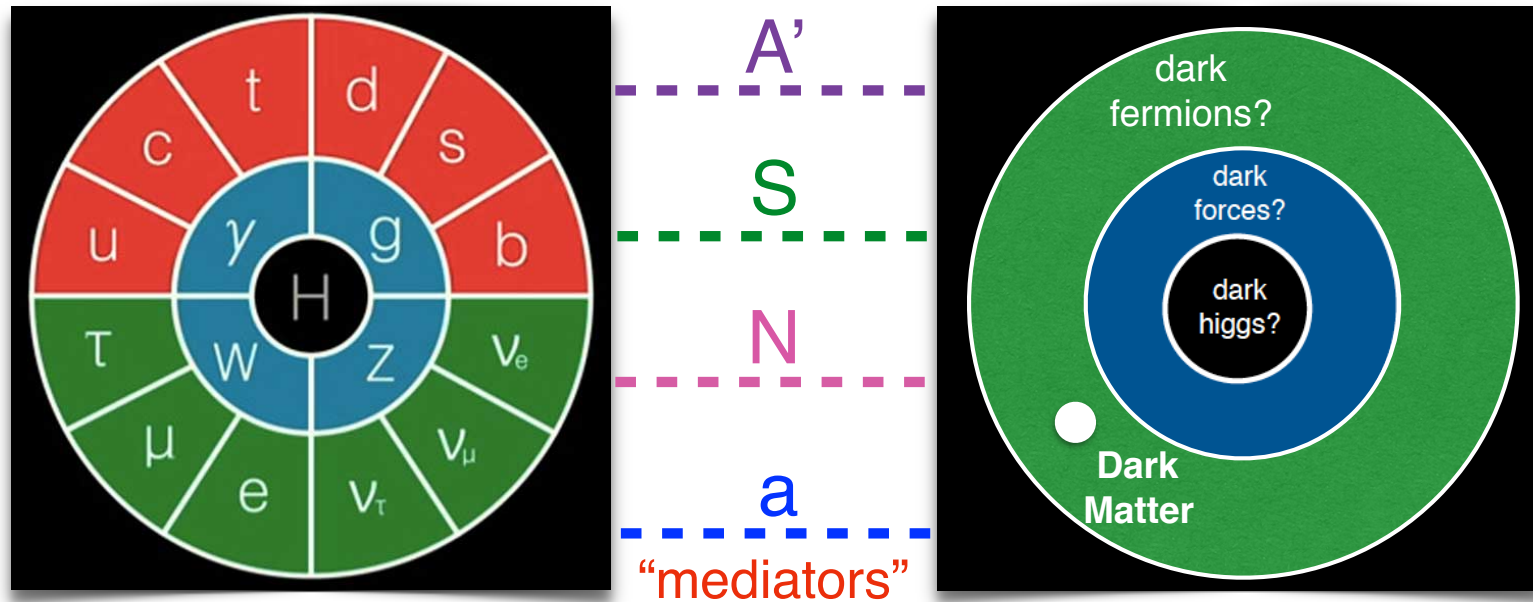
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+ possible new dark gauge bosons obtained gauging e.g. B-L, L_μ-L_τ, …

A broad program of searches

Vigorous effort of the community proposing new experiments & measurements

1. **The LHC**

dark particle

p   p
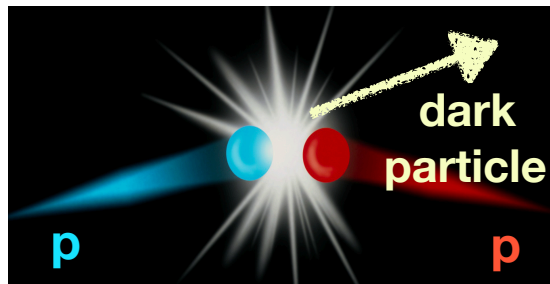
Novel search strategies are needed!

Flavor-factories **2.**

Belle II
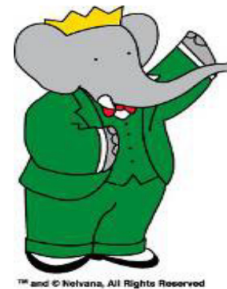
Unique access to dark sectors!

3. **Fixed target / neutrino experiments**

e/p

DM/dark sectors

Beam
(high intensity)   **Dump/shield**   **Decay volume**   **Detector**
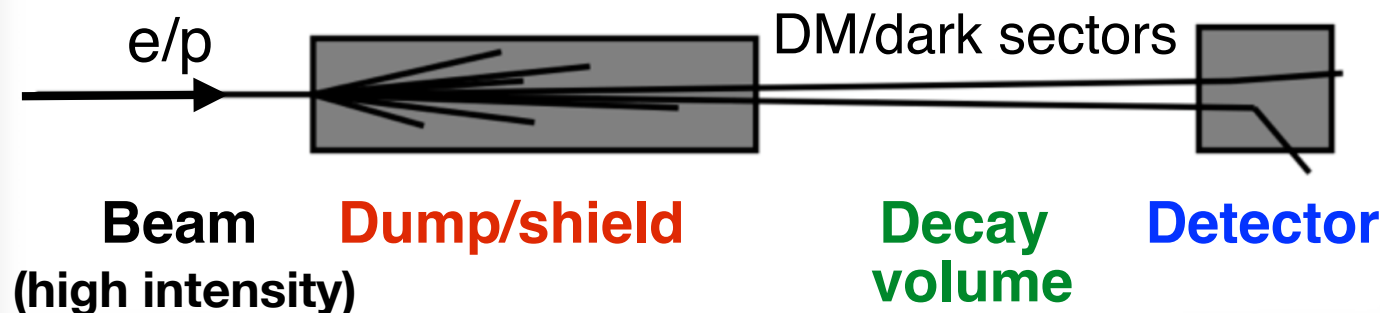
Complementarity with direct and indirect DM detection experiments

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Final states to look for

Invisible, non-SM

Dark Matter production

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

SM mediator X
SM X

Visible, SM

Production of portal-mediators that decay to SM particles

Systematically exploring the portal coupling to SM particles

SM mediator SM
SM SM

Mixed visible-invisible

Production of "rich" dark sectors

Testing the structure of the dark sector

Final states to look for

Invisible, non-SM	Visible, SM	Mixed visible-invisible

Invisible, non-SM

Dark Matter production

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

SM · mediator · **X**
SM · **X**

Non-secluded DM models

X · mediator · **SM**
X · **SM**

Visible, SM

Production of <u>portal-mediators</u> that decay to SM particles

Systematically exploring the portal coupling to SM particles

SM · mediator · **SM**
SM · **SM**

Secluded DM models

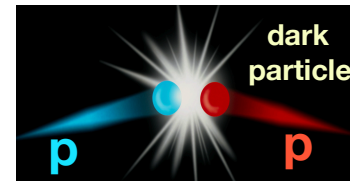**X** —— mediator
X —— mediator

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, ...

dark
particle

p   p

Direct production

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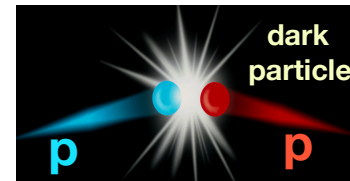since they mix

$B_{\mu\nu}F'_{\mu\nu}$ 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

+ proposed additional detectors: MATHUSLA, FASER, CODEX-b, …

dark
particle

p   p

Direct production

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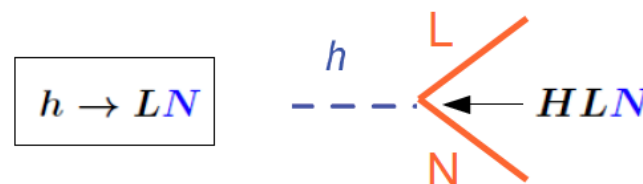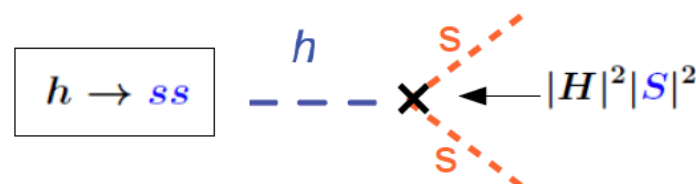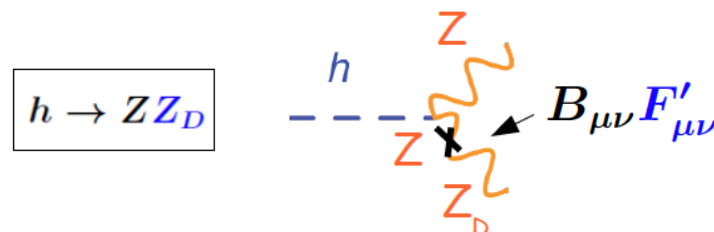
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$|H|^2|S|^2$ Mixing of the dark Higgs and the SM Higgs

HLN Mixing of the dark neutrino and the SM neutrinos

LHCb covers an important role if the dark particle is light

Higgs exotic decays
(if light)

$h \to ZZ_D$ h --- Z Z_D $B_{\mu\nu}F'_{\mu\nu}$ Z

$h \to ss$ h --- s s $|H|^2|S|^2$

$h \to LN$ h --- L N HLN

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

Huge statistics still to come:

$$N_{\text{Higgs}}^{\text{now}} \sim 8\text{M}$$
$$N_{\text{Higgs}}^{\text{HL-LHC}} \sim 170\text{M}$$

+ proposed additional detectors: MATHUSLA, FASER, CODEX-b, ...

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An example: Twin Higgs models

$\boxed{\textbf{SM}_A \textbf{ x } \textbf{SM}_B \textbf{ x } \textbf{Z}_2}$
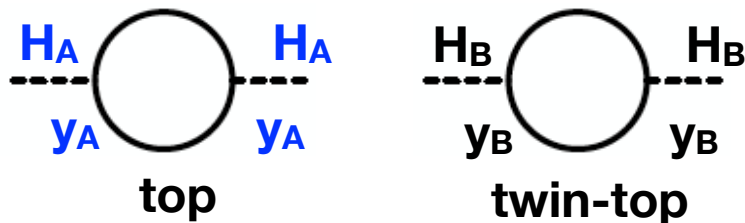
Global symmetry of the scalar potential (e.g. SU(4))

➡️ The SM Higgs is a (massless) Nambu-Goldstone boson

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

~SM Higgs doublet

Twin Higgs doublet

$$V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

Loop corrections to the Higgs mass:

$$\frac{3}{8\pi^2} \Lambda^2 (y_A^2 H_A^\dagger H_A + y_B^2 H_B^\dagger H_B)$$

top   twin-top

$$\boxed{Z_2 \Rightarrow y_A = y_B}$$

Loop corrections to mass are SU(4) symmetric

➡️ no quadratically divergent corrections!

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An example: Twin Higgs models

SM$_A$ x SM$_B$ x Z$_2$

Global symmetry of the scalar potential (e.g. SU(4))
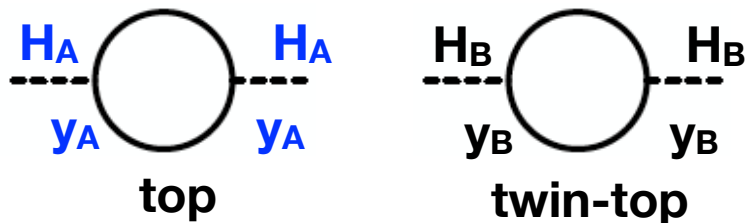
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H$_A$ ⬤ H$_A$ H$_B$ ⬤ H$_B$
y$_A$ y$_A$ y$_B$ y$_B$
top   **twin-top**

$$Z_2 \Rightarrow y_A = y_B$$

Loop corrections to mass are SU(4) symmetric

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Higgs portal

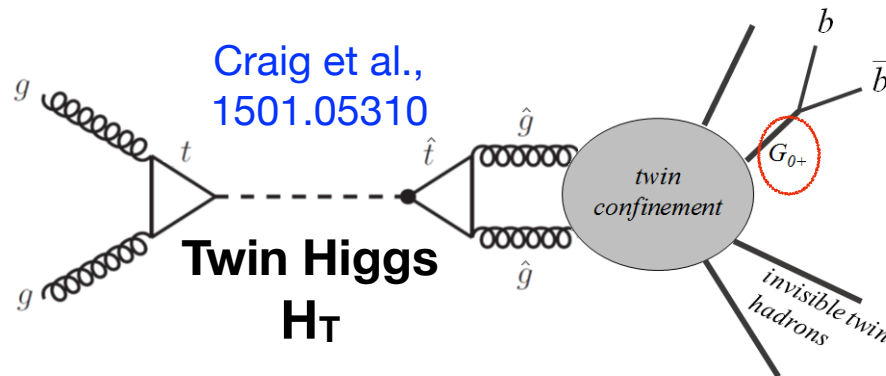**1.** SU(4) and Z$_2$ are (softly) broken:

$$v_A \neq v_B \qquad \boxed{|H_A|^2 |H_B|^2}$$

$$(f^2 \equiv v_A^2 + v_B^2 \gg 246 \text{ GeV})$$

$$\sin\theta \sim \frac{v}{f}$$ Mixing between the SM and the **twin Higgs**

2. Glue-balls can mix with the SM Higgs, H$_A$

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Long-lived signatures from twin Higgs decays

Craig et al.,
1501.05310

**Twin Higgs
H_T**

Glue-ball.

O++ mixes with the 125 GeV Higgs and decays typically displaced.

$$\frac{\alpha_s^{\mathrm{B}}}{3\pi} \left[\frac{y^2}{M^2} \right] |H|^2\, G_{\mu\nu}^{(\mathrm{B})} G^{(\mathrm{B})\mu\nu}$$

Signature: H_T → >= 2 displaced

Long-lived signatures from twin Higgs decays
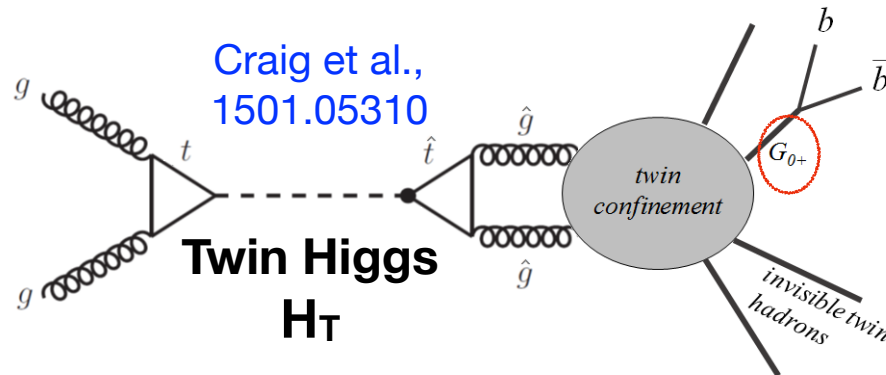

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125 GeV Higgs coupling
measurements

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

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Long-lived signatures from twin Higgs decays
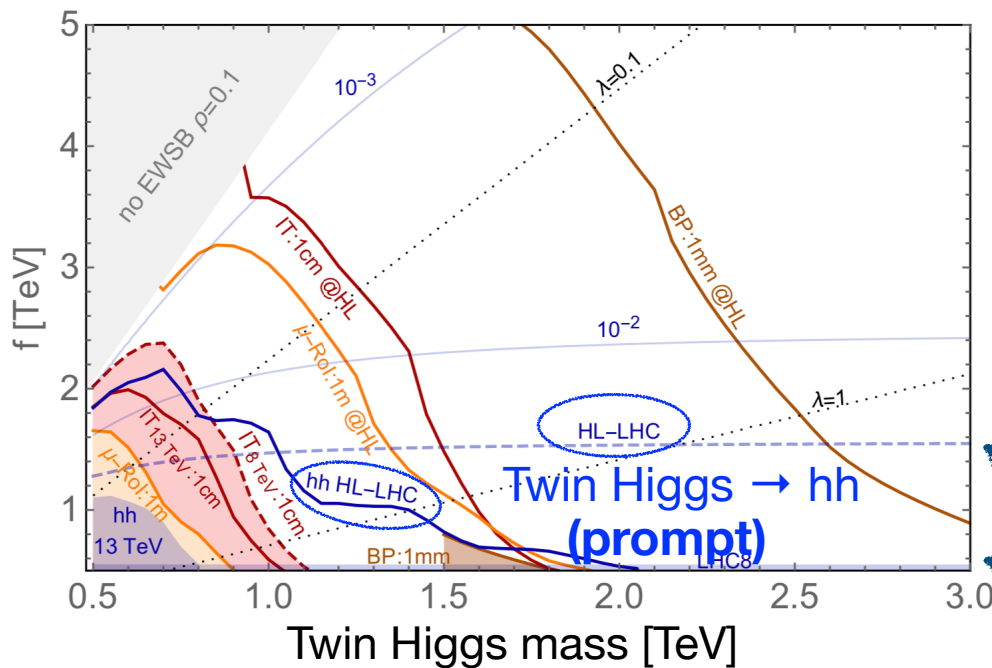
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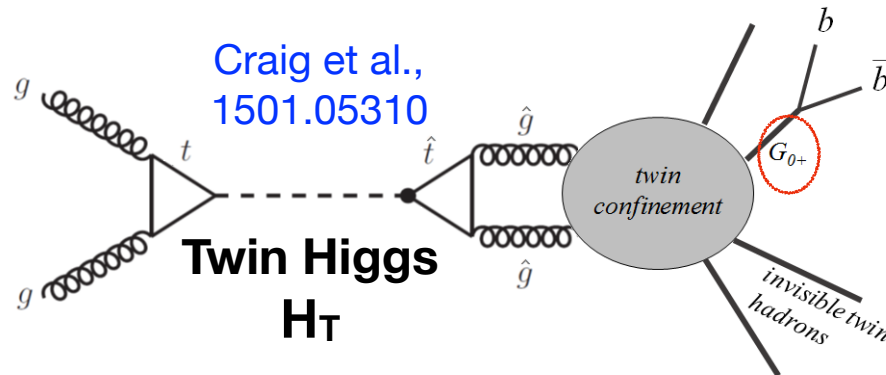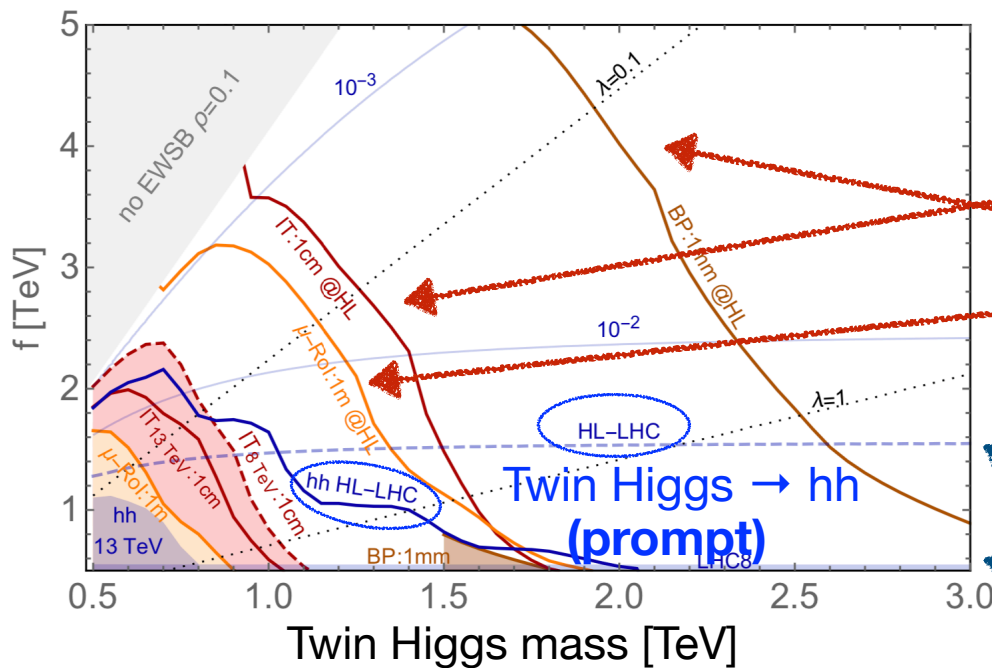$$\frac{\alpha_s^B}{3\pi}\left[\frac{y^2}{M^2}\right]|H|^2\,G_{\mu\nu}^{(B)}G^{(B)\mu\nu}$$

Signature: $H_T \rightarrow\ \text{>= 2 displaced}$

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

Twin Higgs → glue-balls:
(long lived)

CMS inner tracker analysis;
CMS beam pipe analysis;
ATLAS muon spectrometer analysis

The relative strength depends on other parameters of the theory

125 GeV Higgs coupling measurements

+ 125 GeV Higgs exotic decays to glue-balls

A big jump in luminosity is expected in the coming years

Past/Present   **Future**

B-factories

**Kaon-
factories**

**Pion-
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)

?

Plenty of dark particles can be produced from meson decays

A big jump in luminosity is expected in the coming years

	Past/Present	**Future**
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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
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Plenty of dark particles can be produced from meson decays

Kaon rare decays: K → π ν ν

SM $\quad \mathcal{H}_{\mathrm{SM}} = g_{\mathrm{SM}}^2 \sum_{\ell=e,\mu,\tau} \left[V_{cs}^* V_{cd} X(x_c) + V_{ts}^* V_{td} X(x_t) \right] \underbrace{(\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_\ell \gamma^\mu \nu_\ell)}$
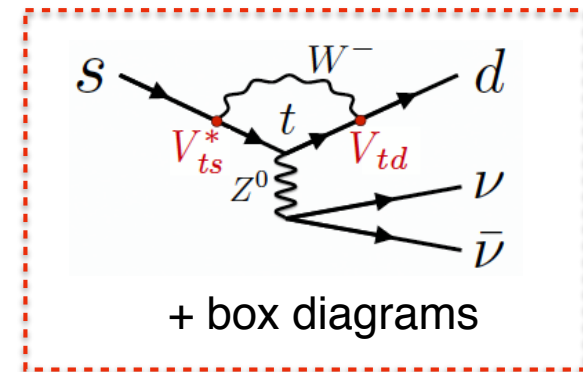
Only operator in the SM

$$\mathrm{BR}(K^+ \to \pi^+ \bar{\nu}\nu) = (9.11 \pm 0.72) \times 10^{-11}$$
$$\mathrm{BR}(K_L \to \pi^0 \bar{\nu}\nu) = (3.4 \pm 0.6) \times 10^{-11}$$

Very rare!
→ Access to NP

Brod, Gorbahn, Stamou 1009.0947;
Buras, Buttazzo, Girbach-Noe, Knegjens, 1503.02693

+ box diagrams

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Kaon rare decays: K → π ν ν

SM

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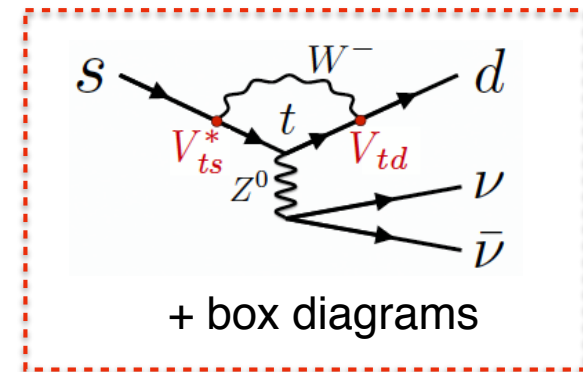
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Buras, Buttazzo, Girbach-Noe, Knegjens, 1503.02693

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Exp. ✳ <u>NA62</u>: Analysis of the <u>2018 data</u>

20 events observed in total   Marchevski talk
@ ICHEP

$$\mathrm{BR}(K^+ \to \pi^+ \bar{\nu}\nu) = (11.0^{+4.0}_{-3.5}\,_{\mathrm{stat.}} \pm 0.3_{\mathrm{syst.}}) \times 10^{-11}$$ **3.5σ evidence**

✳ <u>KOTO</u>: Analysis of the <u>2016-2018 data</u>

3 events in the signal region $K_L \to \pi^0 \nu\bar{\nu}$

Expected number of events:
0.05±0.02 → 1.05±0.28   talk by Shimizu
(pre → post-ICHEP)   @ ICHEP

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Testing axion-like-particles at NA62 & KOTO

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

ALP mixing with SM mesons (pions, etas)

$$\mathcal{L}_{eff} = \frac{iF_\pi^2}{4}\frac{\partial_\mu a}{F_a}\mathrm{Tr}[\tilde{\kappa}_q(\Sigma^\dagger D^\mu\Sigma - \Sigma D^\mu\Sigma^\dagger)] + \frac{F_\pi^2}{2}B_0\mathrm{Tr}[\Sigma m^\dagger + m^\dagger\Sigma^\dagger],$$

The ALP-pion and ALP-eta mixing will induce

∗ an effective K-π-ALP coupling   (K → aπ)
∗ an ALP coupling to photons   (a → γγ)

We can search for

$$K^+ \to \pi^+ a \to \pi^+ \gamma\gamma \quad (\mathrm{NA62})$$
$$K_L \to \pi^0 a \to \pi^0 \gamma\gamma \quad (\mathrm{KOTO})$$

Testing axion-like-particles at NA62 & KOTO

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SG, G. Perez, K. Tobioka, 2005.05170

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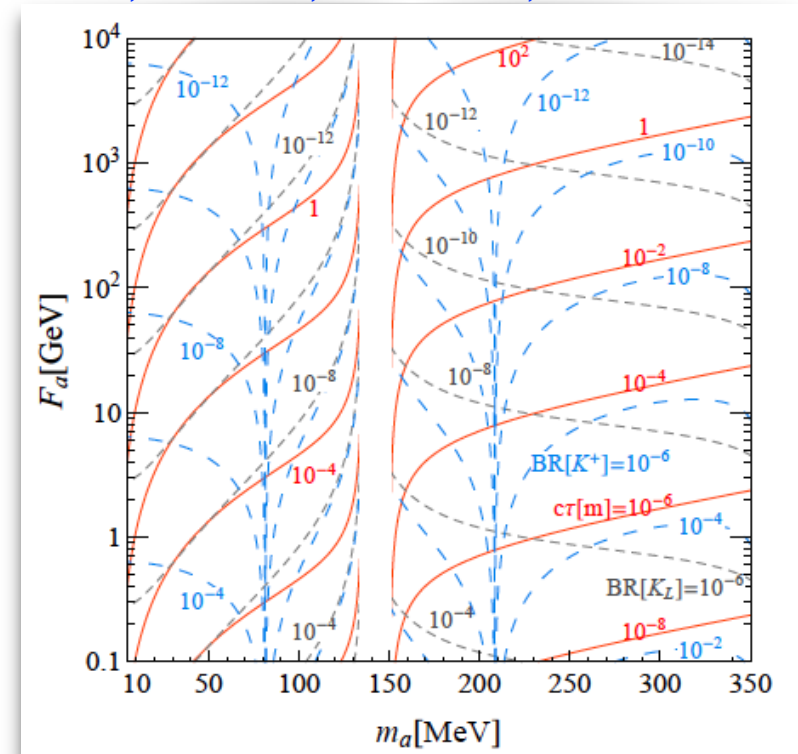* an effective K-π-ALP coupling $(K \to a\pi)$
* an ALP coupling to photons $(a \to \gamma\gamma)$

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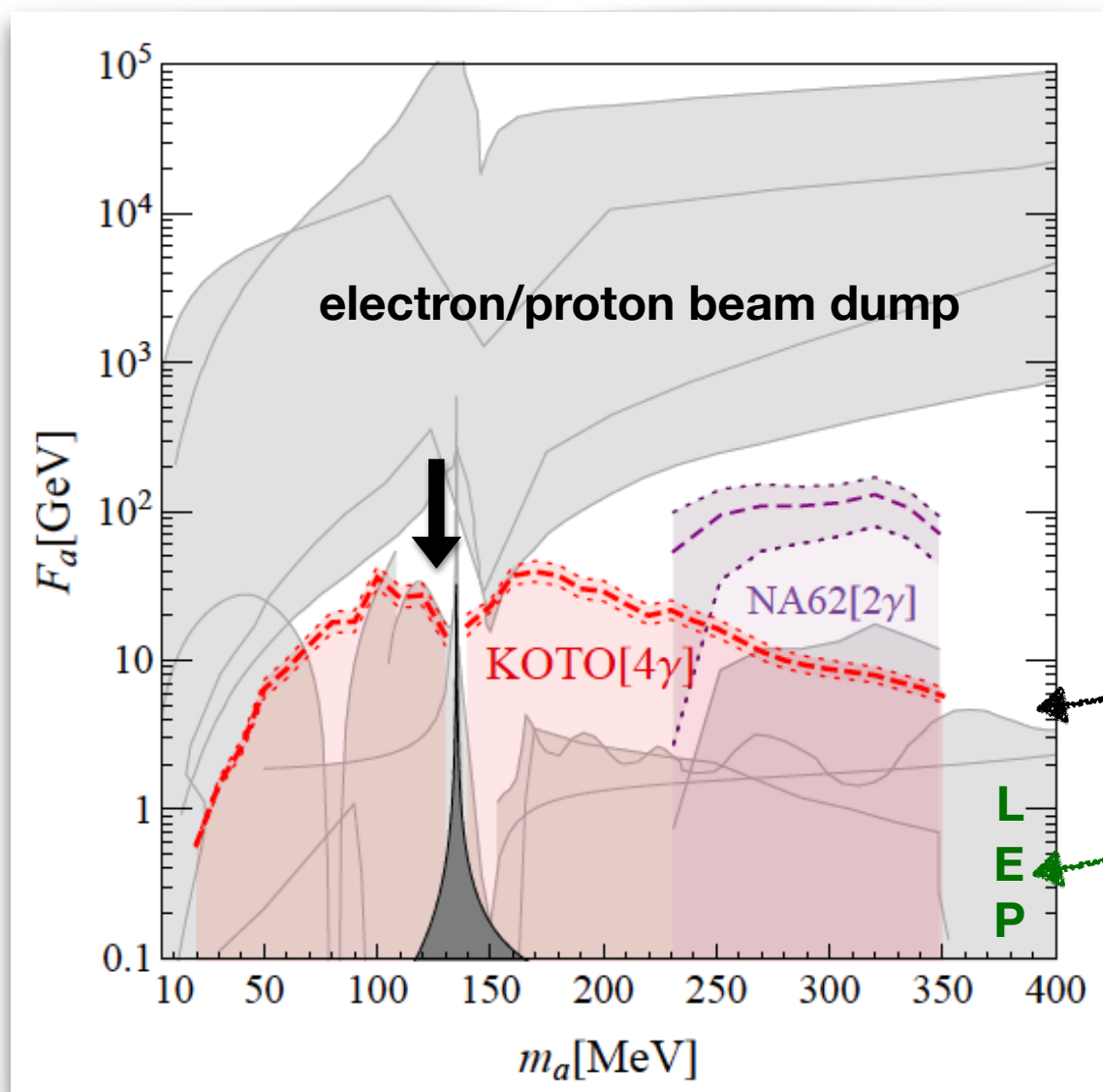
$$K^+ \to \pi^+ a \to \pi^+ \gamma\gamma \quad (\text{NA62})$$
$$K_L \to \pi^0 a \to \pi^0 \gamma\gamma \quad (\text{KOTO})$$

ALP lifetime (in meters), BR($K_L \to \pi\, a$), BR($K^+ \to \pi^+ a$)

The reach on the ALP parameter space

In gray,
we show all present constraints

➡ **This bound comes from precision pion experiments**

(new interpretation of existing PIBETA data for $\pi^+ \to \pi^0 (\to \gamma\gamma) e^+ \nu$)
W. Altmannshofer, SG, D. Robinson, 1909.00005

GlueX,
Aloni et al., 1903.03586

$e^+ e^- \to \gamma\, a,\ a \to \gamma\gamma$
(collimated)

SG, G. Perez, K. Tobioka, 2005.05170

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3. Fixed-target experiments

Several running/proposed experiments to search for prompt or long lived dark sector particles.
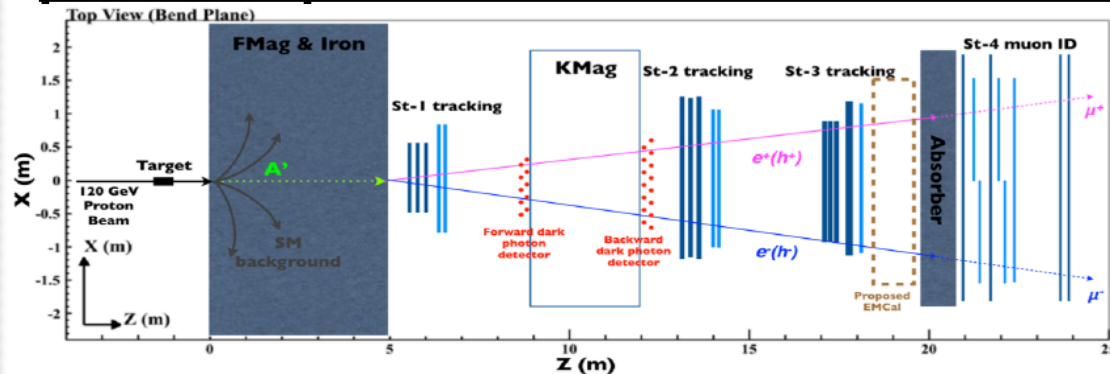
Let's mention a few of them.
<u>Disclaimer:</u> this is not an exhaustive list.

3. Fixed-target experiments

Visible final states

Excellent for detecting low-mass displaced visible dark particles

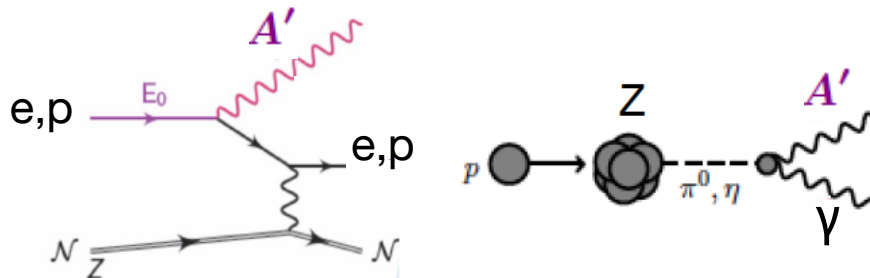**Near forward detectors.** Examples:

p-beam: SpinQuest/DarkQuest @ Fermilab

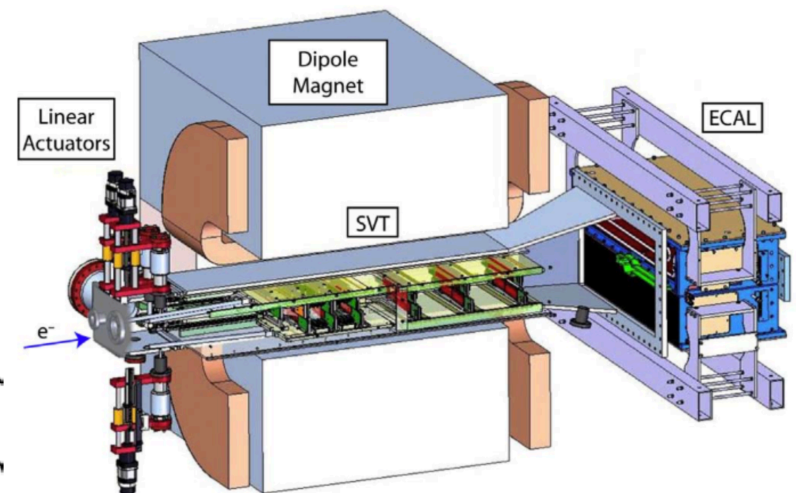Berlin, SG, Schuster, Toro, 1804.00661

See also LongQuest proposal:
Tsai, De Niverville, Liu, 1908.07525

e.g. dark photon production:

e-beam: HPS @ JLAB, MAGIX @ MESA

3. Fixed-target experiments

Invisible final states
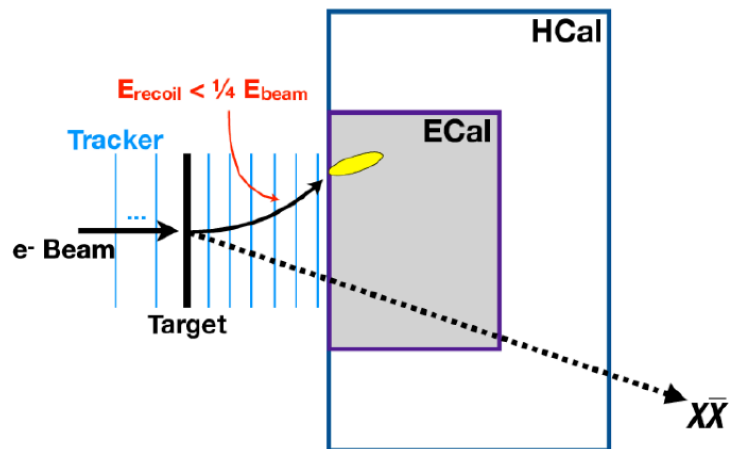
Excellent for detecting low-mass invisible dark particles

Examples:

Missing momentum or energy

NA64, LDMX, M3

electron and muon beams

Unique capability to "image" individual beam particles

DM beam dump

BDX, DarkMESA

Izaguirre, Krnjaic, Schuster, Toro, 1307.6554
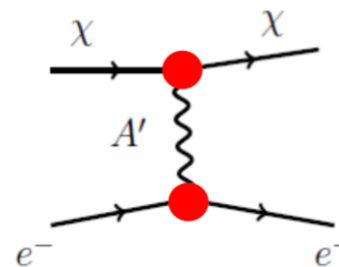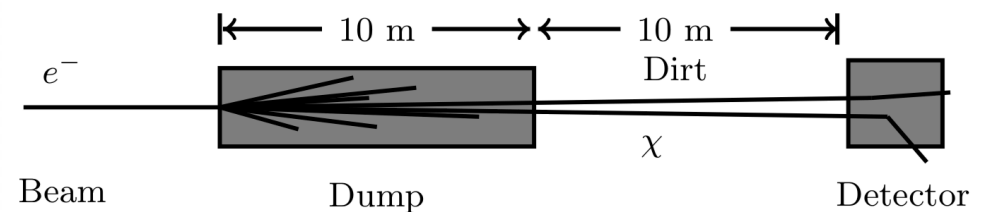
DM-detector scattering

The reach on visible & invisible dark sectors

$$\epsilon B^{\mu\nu} A'_{\mu\nu}$$

Visible

Berlin, SG, Schuster, Toro, 1804.00661

LHCb, Babar

FASER (2035)

FASER (2023)

NA62++ (2023)

SHiP (2032)

DarkQuest (2023)

DarkQuest (2026+)
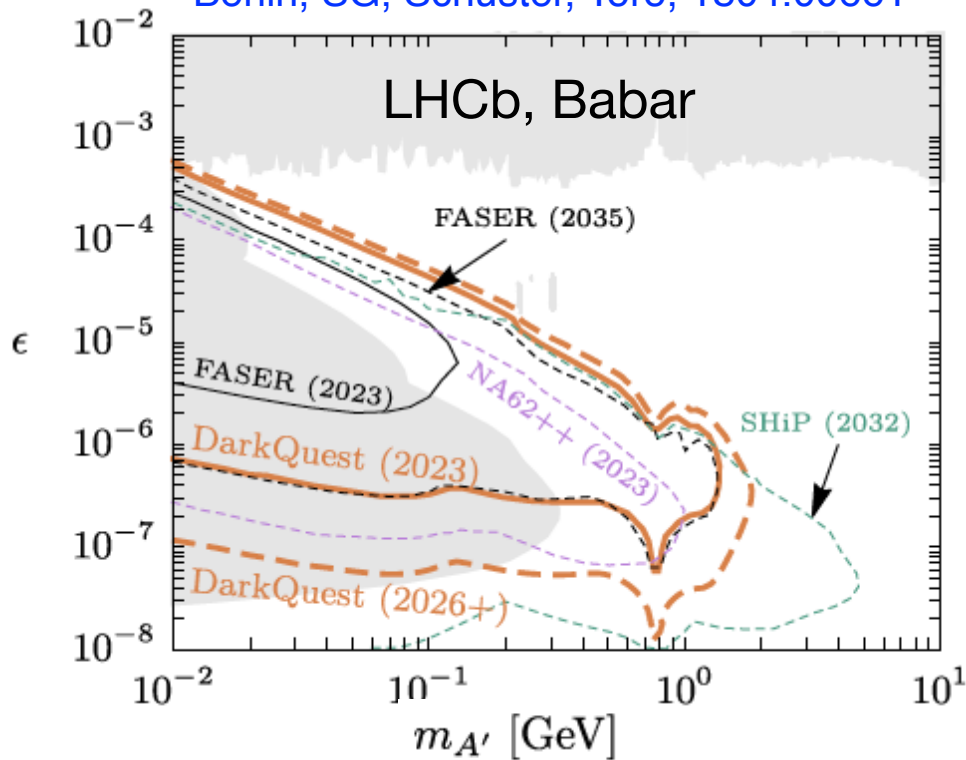
$$pp \rightarrow A' \rightarrow e^+ e^-$$

Invisible

The Belle-II physics book, 1808.10567

LEP

BaBar

NA64

E137

LSND

Scalar Relic Target

Pseudo-Dirac Fermion Relic Target

Belle II (Phase 2)
Belle II (Phase 3)

LDMX1@4GeV
LDMX2@8GeV
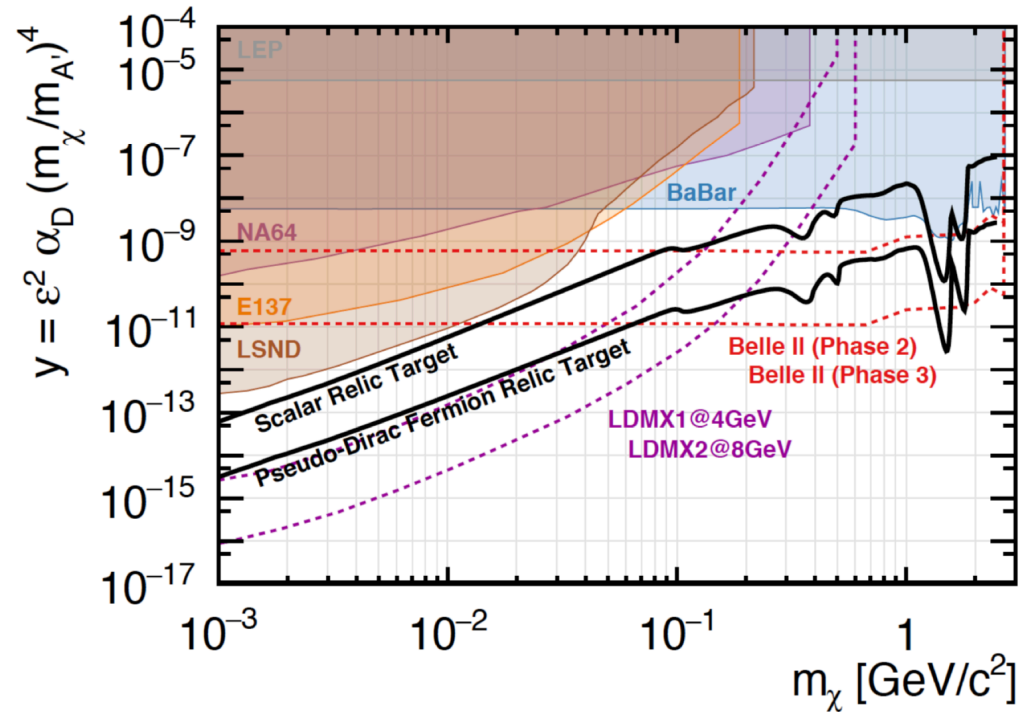
$$e^+ e^- \rightarrow A' \rightarrow \chi\chi$$

Conclusions & Outlook

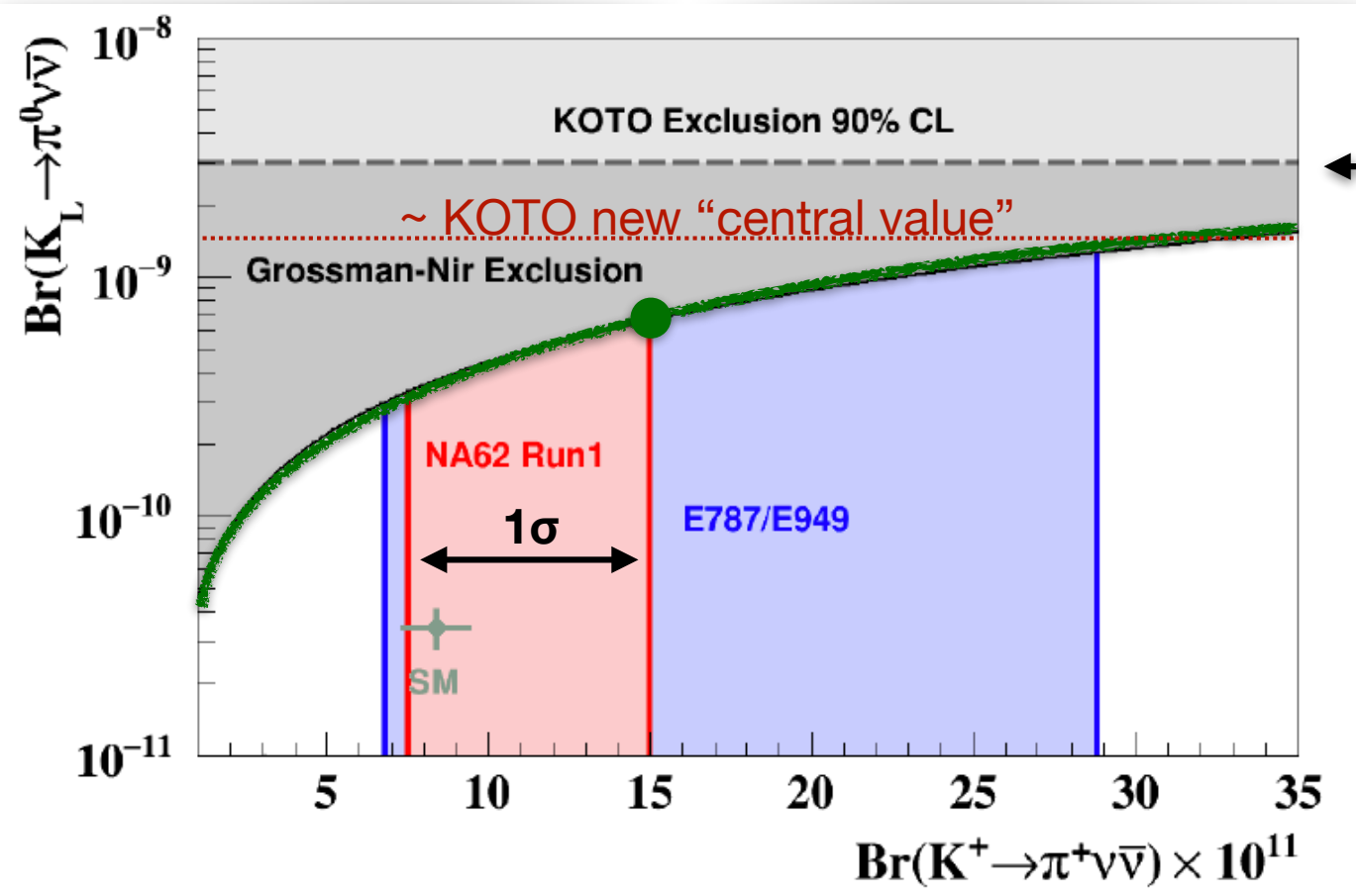**Dark sector particles arise in a large variety of beyond the Standard Model theories.**

Unique opportunity to probe dark sectors at <u>high-intensity experiments</u>:

✳ **LHC as a high-intensity machine**
✳ **Flavor factories**
✳ **Fixed target experiments**

Complementarity with direct detection & astrophysical probes

How do the NA62 & KOTO results compare?

Marchevski talk @ ICHEP

2015 run

$$\frac{\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})}{\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})} < 4.3$$

Light ($< m_K$) new physics would be required if this will turn out to be a "real" anomaly

It cannot be described by an EFT

2. GG-coupled ALP simplified model

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

ALP interactions with SM mesons

$$\mathcal{L}_{eff} = \frac{iF_\pi^2}{4}\frac{\partial_\mu a}{F_a}\text{Tr}[\tilde{\kappa}_q(\Sigma^\dagger D^\mu\Sigma - \Sigma D^\mu\Sigma^\dagger)] + \frac{F_\pi^2}{2}B_0\text{Tr}[\Sigma m^\dagger + m^\dagger\Sigma^\dagger]$$

Kinetic mixing   Mass mixing

$$m = \exp\left(i\kappa_q\frac{a}{2F_a}\gamma_5\right)\cdot m_q \cdot \exp\left(i\kappa_q\frac{a}{2F_a}\gamma_5\right) \quad \tilde{\kappa}_q = \text{diag}(\kappa_q), \quad \kappa_q = \frac{1}{m_q}\Big/\sum_{q'}\left(\frac{1}{m_{q'}}\right)$$

$$\begin{cases} \theta_{\pi a} \simeq \dfrac{F_\pi}{2F_a}(\kappa_u - \kappa_d)\dfrac{m_a^2}{m_a^2 - m_{\pi^0}^2} & \quad\text{Kinetic mixing with the \textbf{pion} of the SM} \\[3mm] \theta_{\eta a} \simeq \dfrac{F_\pi}{F_a}\dfrac{\sqrt{2}m_a^2[\kappa_u + \kappa_d - 2\kappa_s]\cos\theta_{\eta\eta'} - 2\left(m_a^2[\kappa_u + \kappa_d + \kappa_s] - 6\Delta m_{\pi^0}^2\right)\sin\theta_{\eta\eta'}}{2\sqrt{6}(m_a^2 - m_\eta^2)} \end{cases}$$

Kinetic mixing and mass mixing with the **eta** of the SM

(mass mixing is due to the eta-eta' mixing, θ$_{\eta\eta'}$)

S.Gori   Christ et al., 1002.2999   Backup
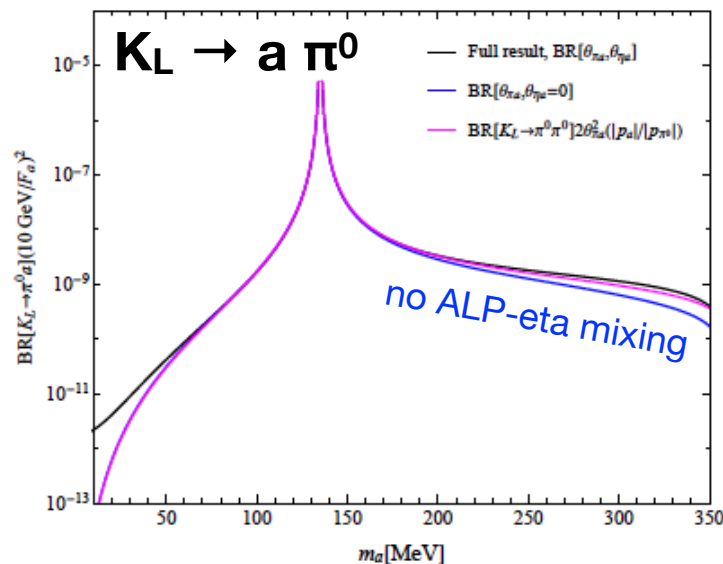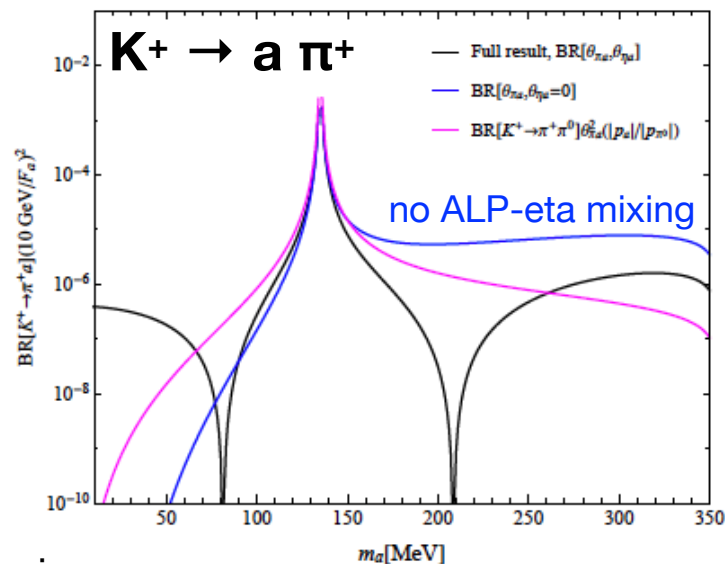
Theory prediction for K → π a

The ALP-pion and ALP-eta mixing will induce

* an effective K-π-ALP coupling   (K → aπ)
* an ALP coupling to photons   (a → γγ)

At low energy, the two operators responsible for s → d transitions are

$$\mathcal{L}_{\Delta S=1} = G_8 F_\pi^4 \mathrm{Tr}[\lambda_{sd} D^\mu \Sigma^\dagger D_\mu \Sigma] + G_{27} F_\pi^4 \left(L_{\mu 23} L_{11}^\mu + \frac{2}{3} L_{\mu 21} L_{13}^\mu \right) + h.c.$$

$$\pi^0 \rightarrow \pi_{\mathrm{phy}}^0 + \theta_{\pi a} a_{\mathrm{phy}}$$
$$\eta \rightarrow \eta_{\mathrm{phy}} + \theta_{\eta a} a_{\mathrm{phy}}$$

$$L_\mu \equiv i \Sigma^\dagger D_\mu \Sigma, \quad \lambda_{sd} \equiv \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$$

K+ → a π+

- Full result, BR[$\theta_{\pi a}, \theta_{\eta a}$]
- BR[$\theta_{\pi a}, \theta_{\eta a}=0$]
- BR[$K^+ \to \pi^+ \pi^0$]$\theta_{\pi a}^2$(|p_a|/|p_{π^0}|)

no ALP-eta mixing

K_L → a π0

- Full result, BR[$\theta_{\pi a}, \theta_{\eta a}$]
- BR[$\theta_{\pi a}, \theta_{\eta a}=0$]
- BR[$K_L \to \pi^0 \pi^0$]2$\theta_{\pi a}^2$(|p_a|/|p_{π^0}|)

no ALP-eta mixing

Note:
possible additional
UV contributions

S.Gori