Probing Dark Sectors with Flavor Physics

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IJCLab (Orsay)

Belle II Physics Week, October, 2024

Prelude

The goals of this lecture are to:

- Review the **motivation** and **phenomenology** of **minimal dark sectors**.
- Discuss their potential **impact** on **flavor-physics** measurements *(with emphasis on B-physics experiments).*

Our **focus** will be the possible **experimental signatures/opportunities** (*and not the details of specific DM models — there are many possibilities*).

For a discussion of Dark Matter phenomenology, see the lectures by S. Gori.

Outline

I. Introduction (recap)

II. Dark sector portals

III. Dark sectors in flavor experiments

IV. Examples (@ Belle-II):

   i. Dark photons

   ii. Axionlike-particles

   iii. Sterile neutrinos

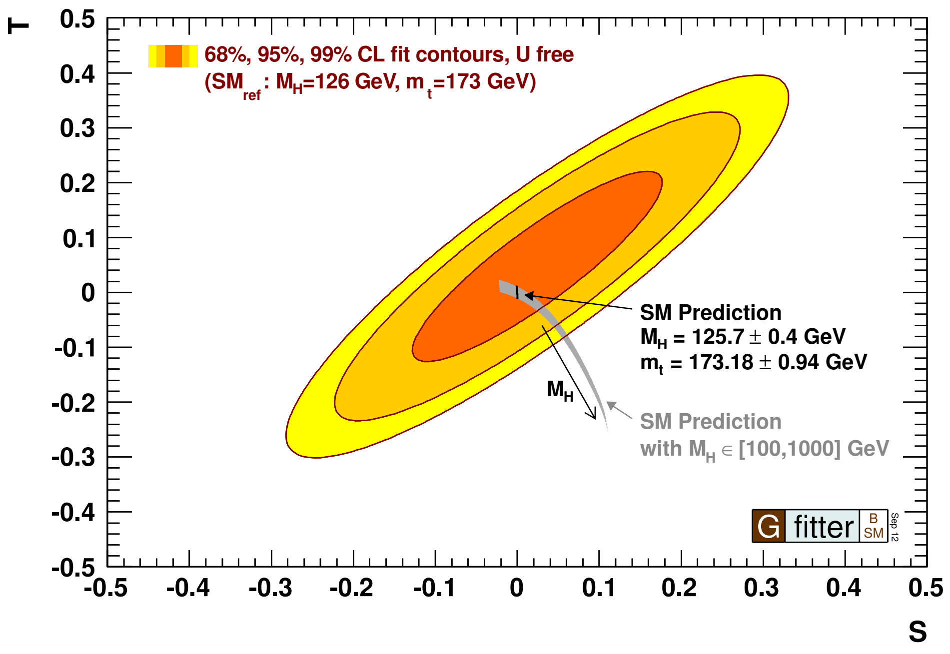
V. Summary/Outlook

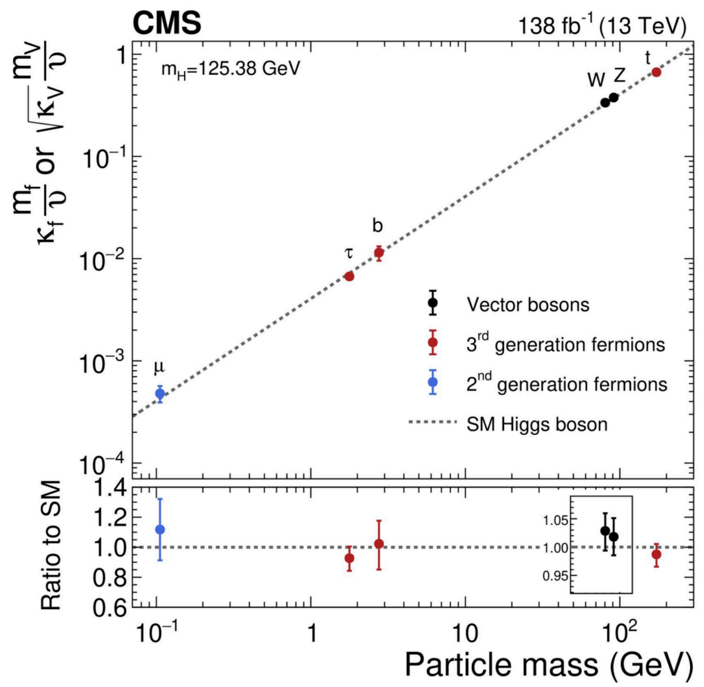
→ **Emphasis on the possible connection to flavor physics!**

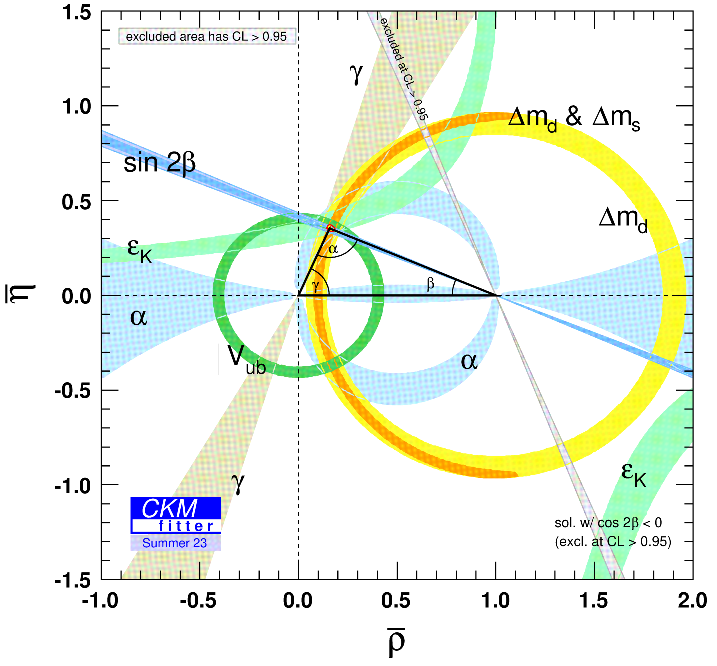
Introduction

The Standard Model

$$\mathscr{L}_{\text{SM}} = \mathscr{L}_{\text{Gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yukawa}}$$





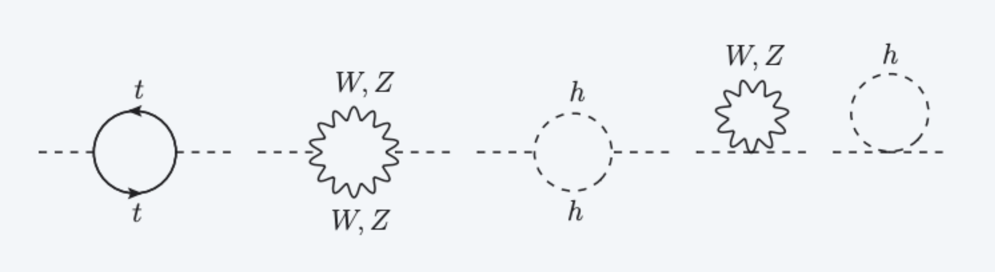


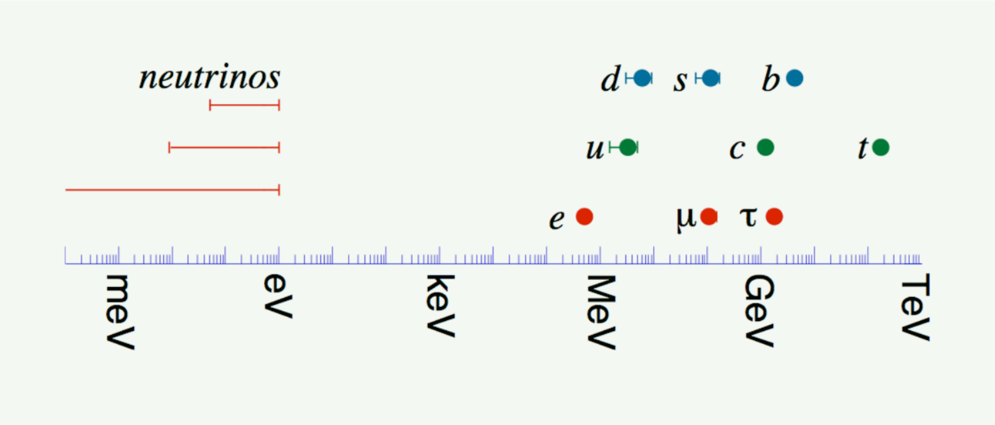
- The SM is *extremely successful* in describing exp. data — *"modelo standardissimo"*.
- No evidence of new (heavy) resonances at the LHC so far...
- Yet, many questions remain unanswered!

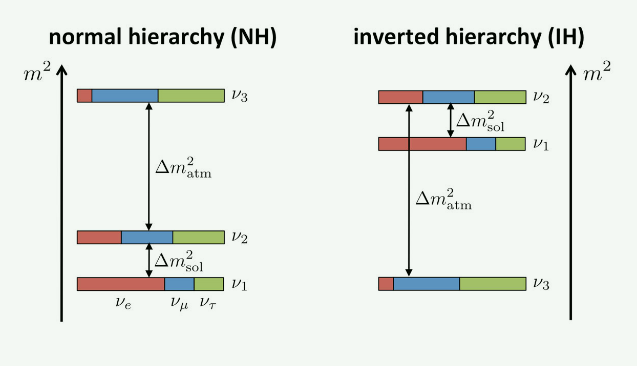
Beyond the Standard Model

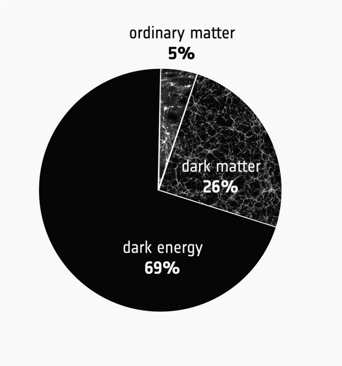
Several questions remain unanswered by the SM:

- The hierarchy problem
- The flavor problem
- Neutrino masses
- Strong CP problem
- Dark matter
- Baryon asymmetry of the Universe
- ...









⇒ The **SM** should be an **effective theory** of a more fundamental theory (*yet unknown*).

⇒ Quest for physics beyond the SM! ***But... where is it?***

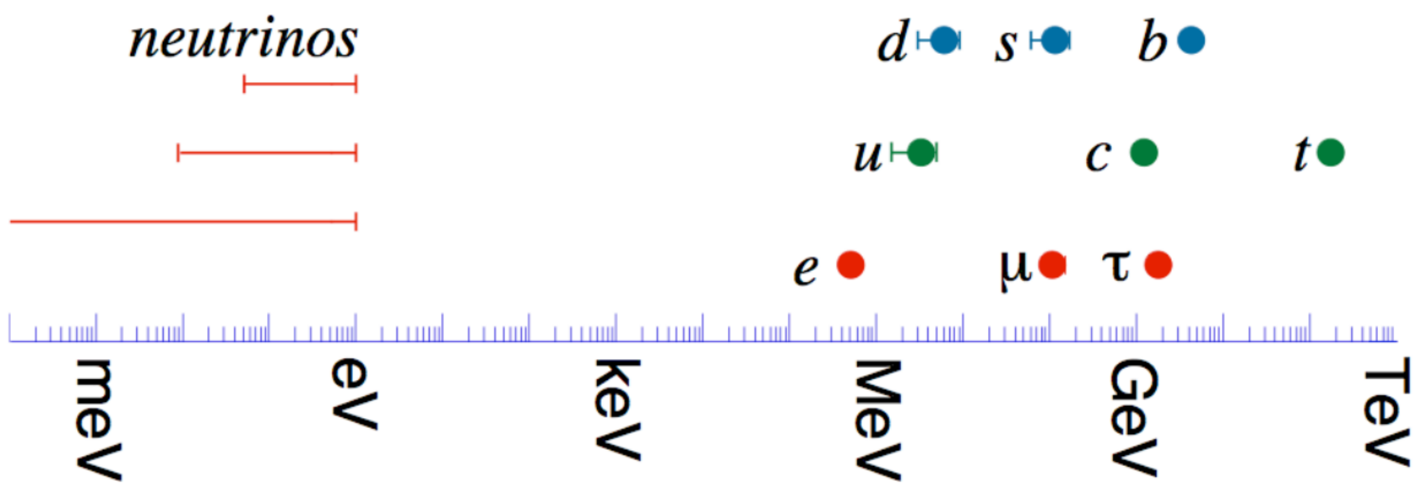
Flavor in the SM

- The SM **flavor sector** is **loose**:

⇒ 13 free parameters (masses and quark mixing) — *fixed by data.*

$$\mathcal{L}_{\rm Yuk} = -Y_d^{ij}\,\overline{Q}_i d_{Rj}\,H - Y_u^{ij}\,\overline{Q}_i u_{Rj}\,\widetilde{H} - Y_\ell^{ij}\,\overline{L}_i e_{Rj}\,H + \text{h.c.}$$

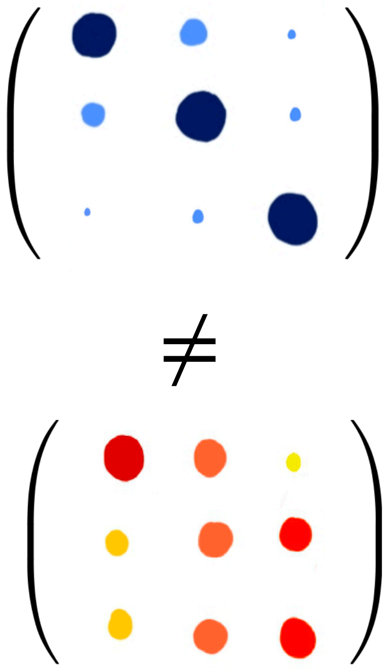
⇒ These (many) parameters exhibit a hierarchical structure which we do not understand.



$V_{\rm CKM} =$

$\neq$

$V_{\rm PMNS} =$



How to **explain the observed patterns** in terms of **less** and **more fundamental parameters**?

Steve Weinberg interview (The Guardian, ’13)

"After experiments started to show the electroweak theory was right... **it was obvious to anyone that the theory has a lot of arbitrary features.** It contains the electron and another particle called the muon, **which is to all appearances identical to the electron but its mass is 210 times larger. We have no idea why this ratio of masses is what it is. We have no idea why there even is a muon.”**

"One summer I sat down and said: **'This is the summer when I'm not going to do anything but solve that problem.' This was 40 years ago and I haven't solved it**. No one has. I thought it would be a simple matter of extending the kind of symmetry principles I used in the electroweak theory to have some kind of symmetry that involved electrons turning into muons and I could never make it work. **That's been a frustration now for 40 years.”**

For Weinberg we are at a dangerous point in the history of physics. Both cosmology and particle physics have "standard models" that contain mysteries, **like his electron/ muon problem or the existence of dark matter and dark energy**, the unexpected extra mass of galaxies and the accelerating expansion of the cosmos, accounting for 95% of the mass and energy of the universe.

Weinberg does not see how we can solve these problems without new data – which means pushing the boundaries.

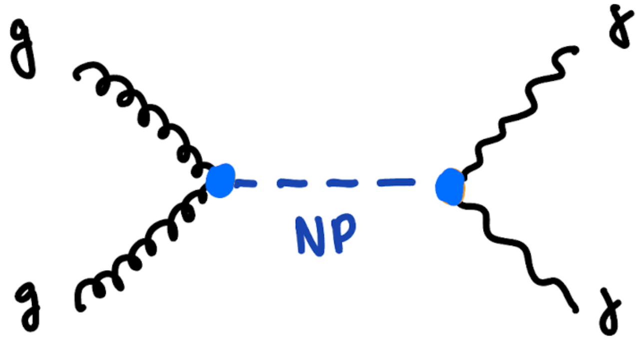
Looking for New Physics

The usual complementary strategies to seek New Physics:

Energy Frontier

Searches for **new heavy resonances** that can be produced **on-shell** at **high energies**:

e.g.,



⇒ *Sensitive to strongly interacting particles.*

⇒ Limited by the collider energy-reach.

CMS

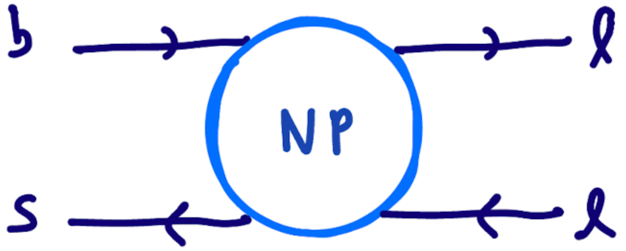
ATLAS EXPERIMENT

Precision Frontier

Searches for **deviations** w.r.t. **SM** in **rare/ forbidden processes**:

$$\mathcal{O}_{exp} = \mathcal{O}_{SM} + \# \frac{g_{NP}^2}{m_{NP}^2} + \dots$$

e.g.,



⇒ *Stringent constraints on $g_{\mathrm{NP}}/m_{\mathrm{NP}}$ (in the EFT limit).*

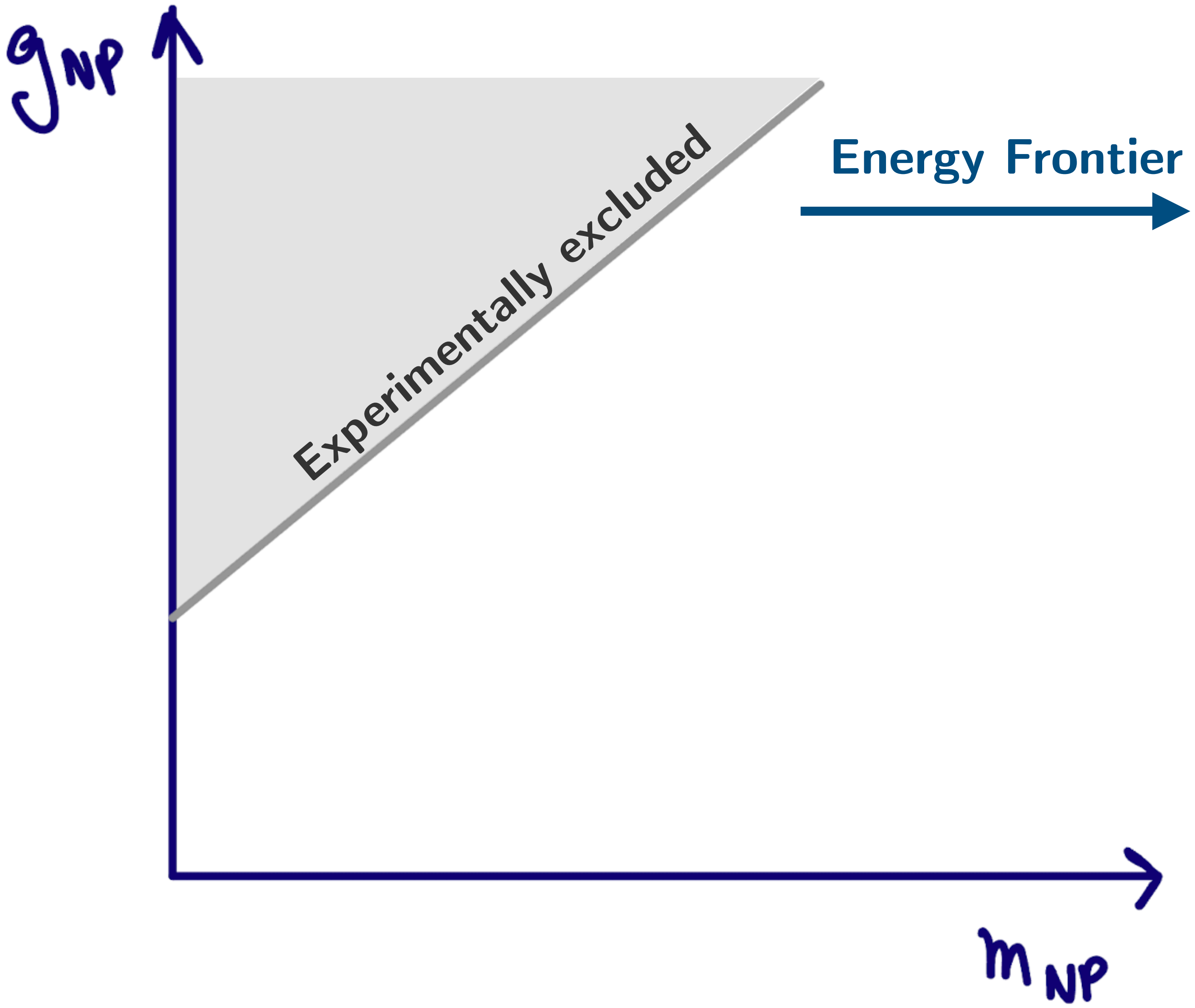
⇒ *Challenge: control hadronic uncertainties...*

Belle II LHCb BESIII

KOTO NA62 ...

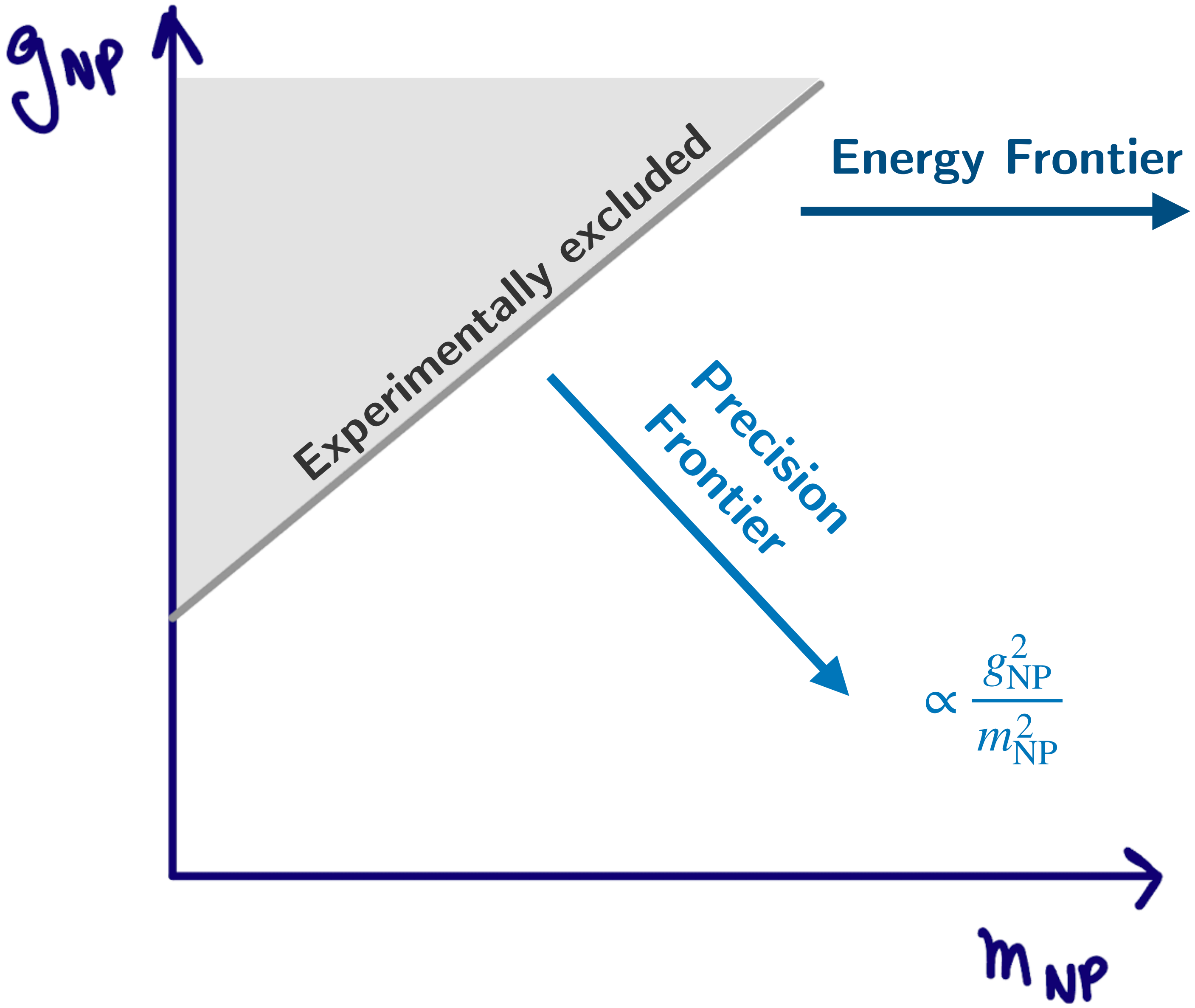
The New Physics Landscape

Usual strategies



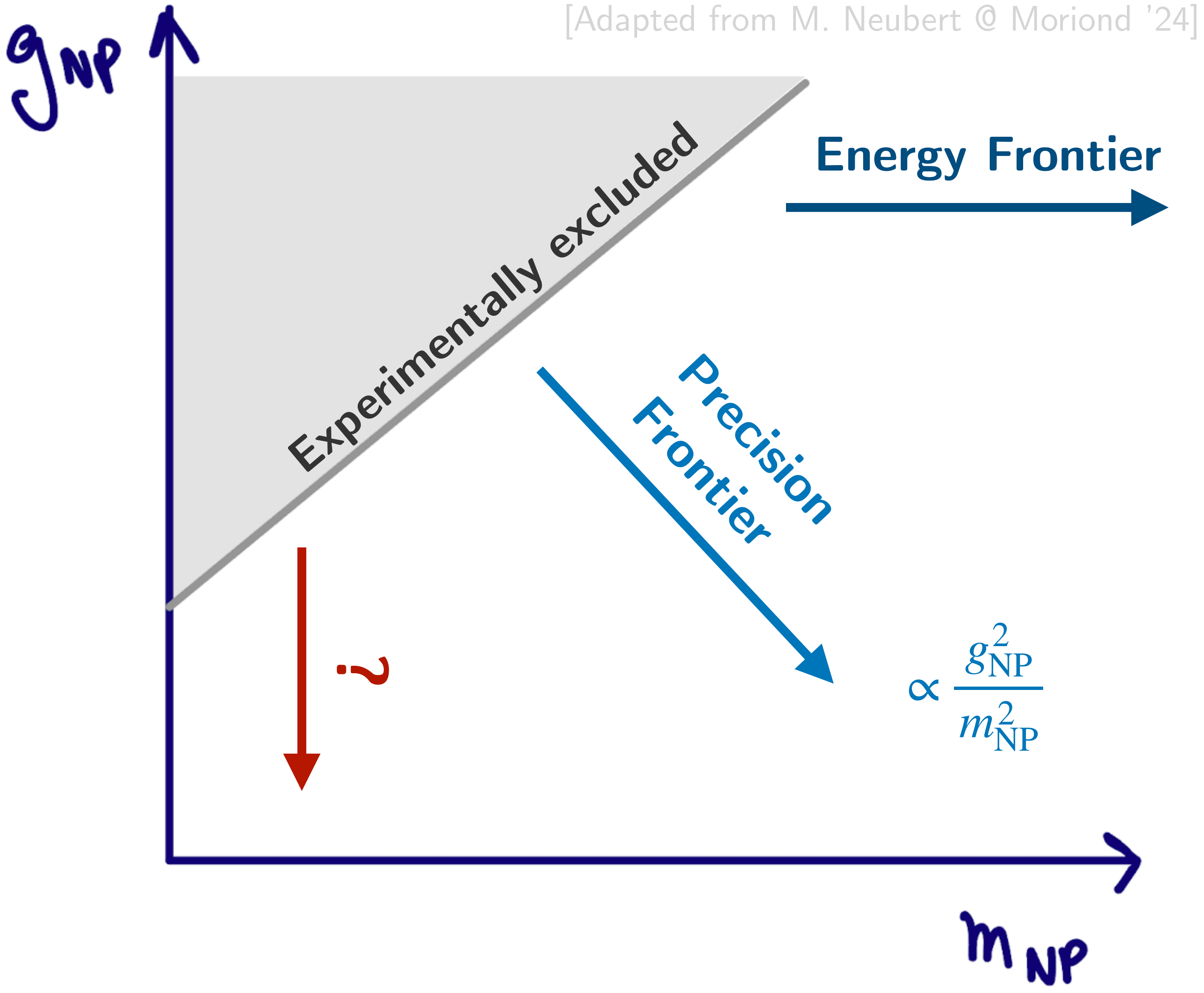
The New Physics Landscape

Usual strategies



The New Physics Landscape

Another possibility...



- **Light** and **weakly-interacting particles** are also **theoretically motivated** in certain cases *(e.g., in connection to dark matter and the strong CP-problem, cf. lectures by S. Gori).*
- They can lead to **new experimental signatures**, including **flavor experiments** — *"leave no stone unturned"...*

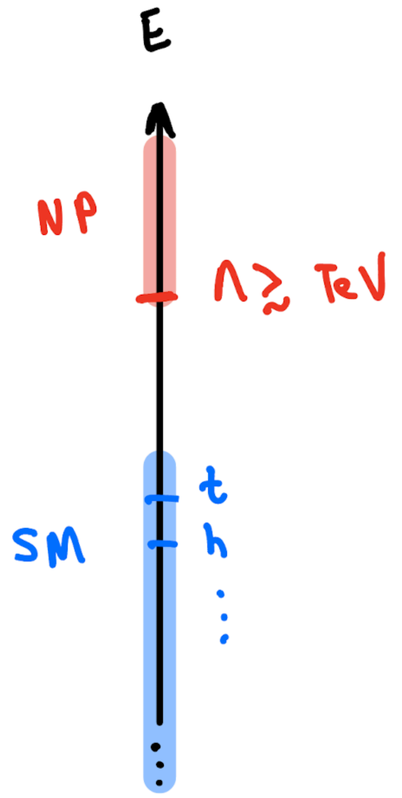
[Reminder] Effective Field Theories

Effective Field Theories (EFTs) are **QFTs** that describe the **low-energy limit** of an underlying ultraviolet theory in terms of only the light degrees of freedom.

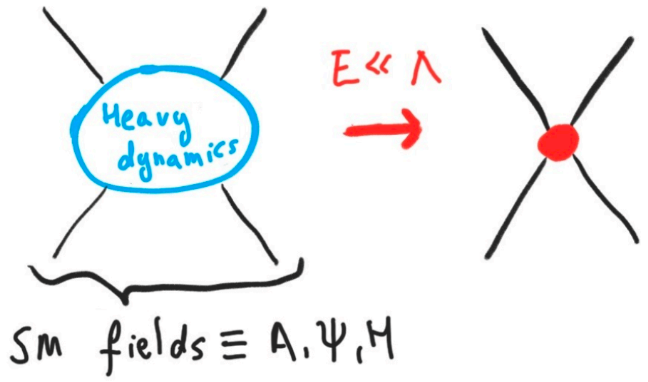
The SM is an EFT at low energies of a more fundamental theory that is still unknown:

$$\mathcal{L}_{\rm eff} = \overbrace{\mathcal{L}_{\rm gauge}(A,\Psi) + \mathcal{L}_{\rm Higgs}(A,\Psi,H)}^{\mathcal{L}_{\rm SM}\ \text{(renormalizable)}} + \underbrace{\sum_{d\geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}}\, \mathcal{O}_n^{(d)}(A,\Psi,H)}_{\text{Operators of dim} \geq 5 \text{ made of SM fields}}\,,$$

Assumption: $E \ll \Lambda$

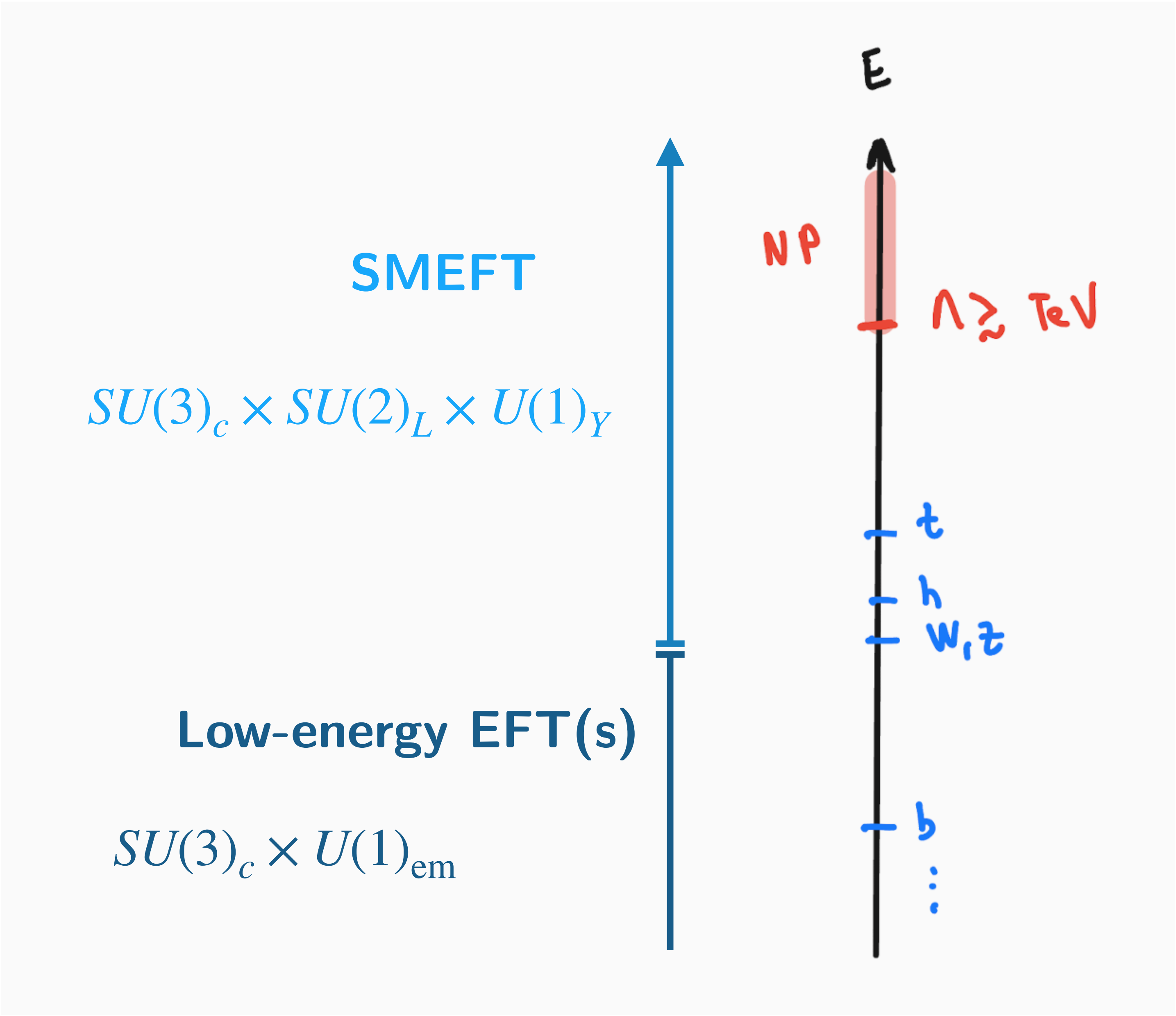


Most general description of new physics as long as there is not enough energy to produce the new degrees of freedom.



[Reminder] The SM as an EFT

- **New Physics effects** can be described by a **tower of EFTs** at different energy scales.
- **Wilson coefficients** encapsulate the effects of **short-distance** physics.
- **Effective operators** are built using the **available degrees of freedom**, respecting the relevant **symmetries**.



SMEFT

$SU(3)_c \times SU(2)_L \times U(1)_Y$

Low-energy EFT(s)

$SU(3)_c \times U(1)_{\text{em}}$

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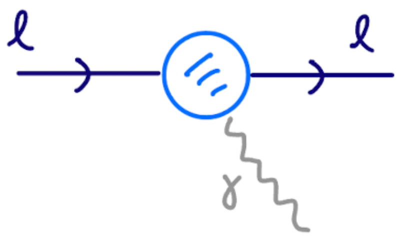
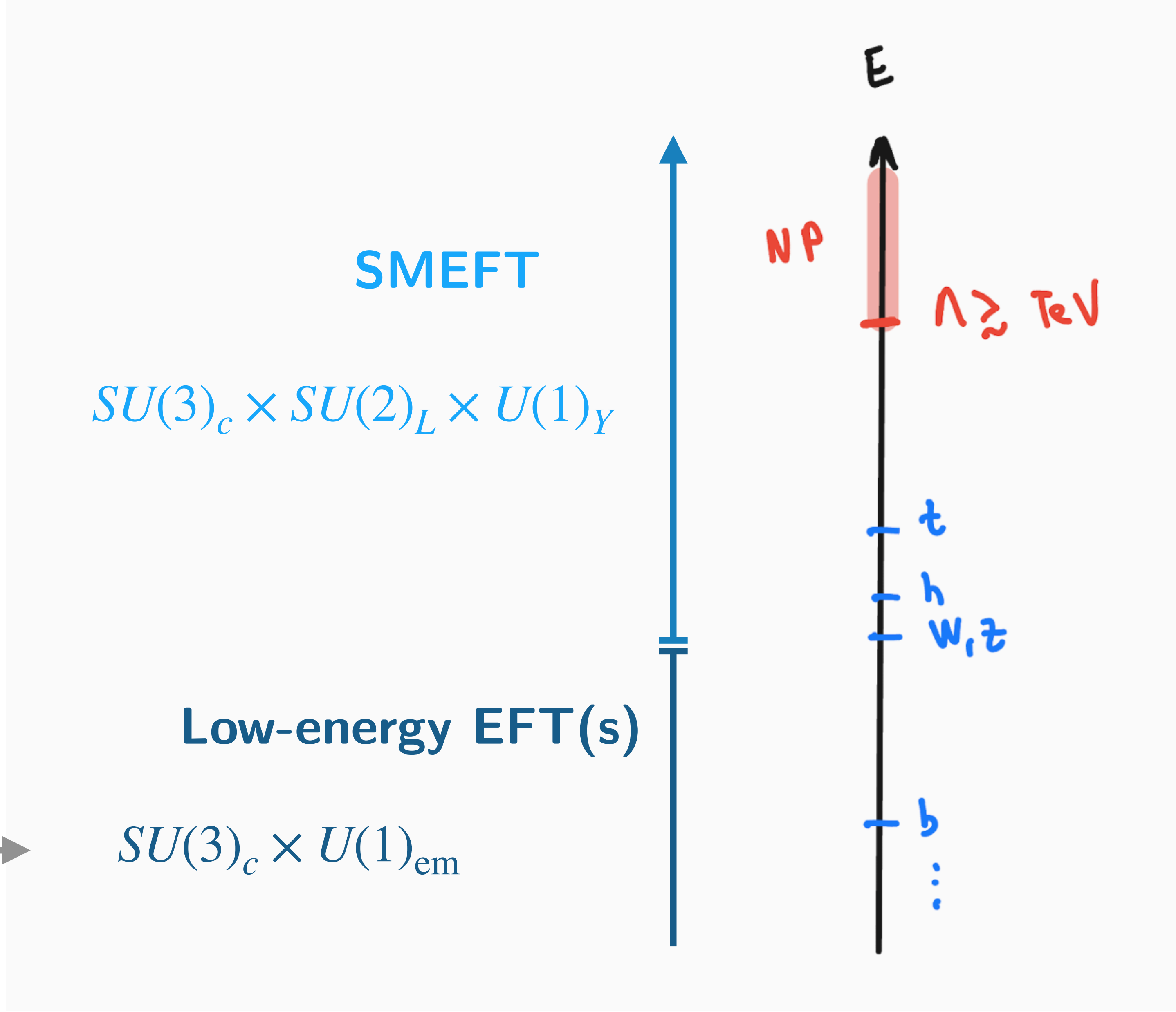
Example: lepton g-2

$$\mathcal{O}_{\text{dip}} = m_\ell \, (\bar{\ell}\sigma_{\mu\nu}\ell)\, F^{\mu\nu}$$





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with $C_{\text{dip}} \propto \cos\theta_W \, C_{eB} - \sin\theta_W \, C_{eW}$

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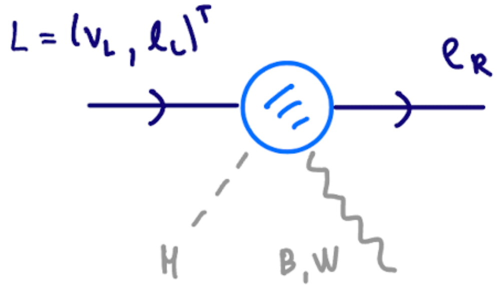
$$\mathcal{O}_{eB} = (\bar{L}\sigma_{\mu\nu}e_R)\,H\,B^{\mu\nu}$$

$$\mathcal{O}_{eW} = (\bar{L}\tau^I\sigma_{\mu\nu}e_R)\,H\,W_I^{\mu\nu}$$



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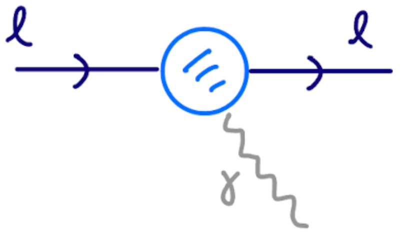

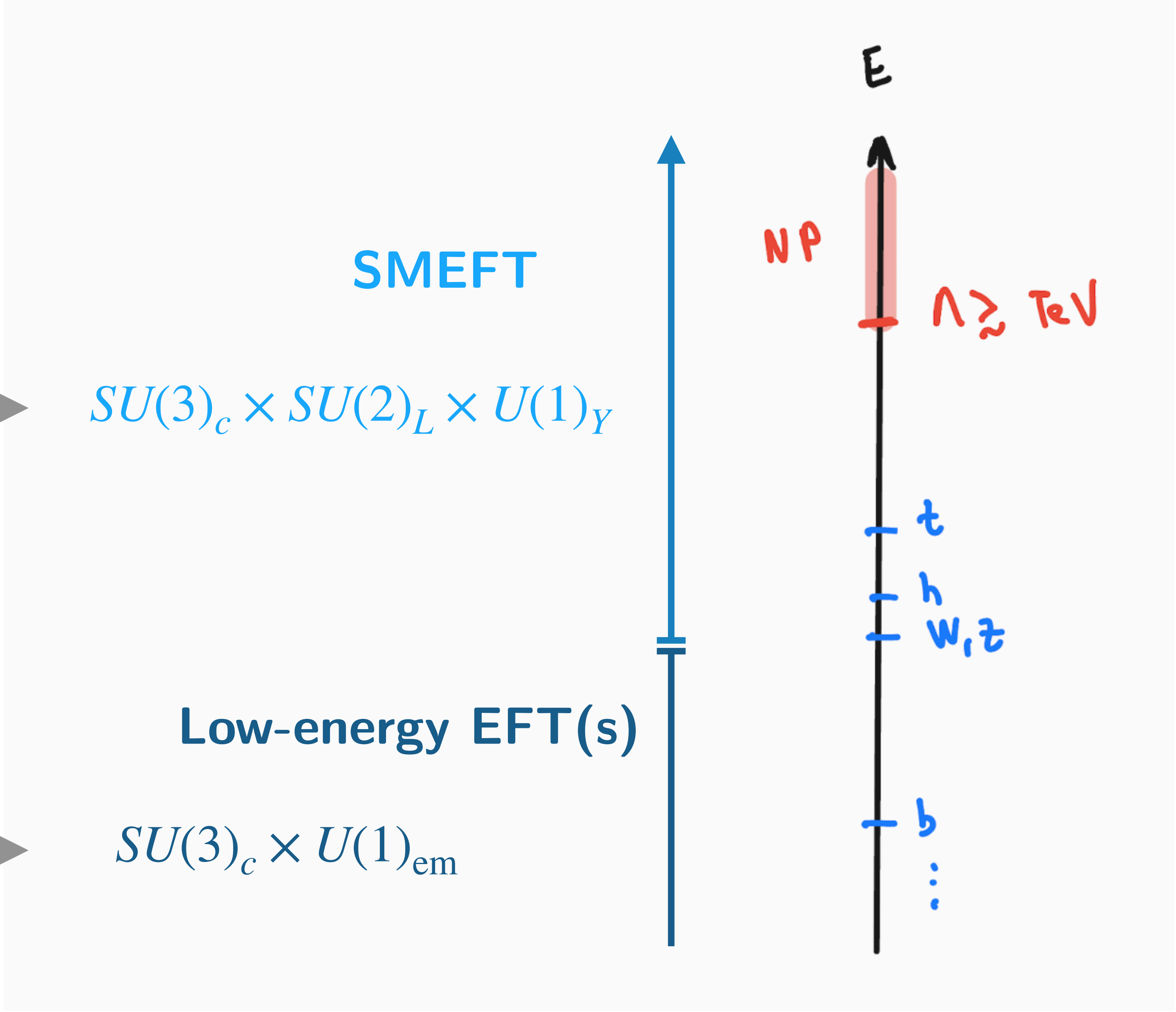

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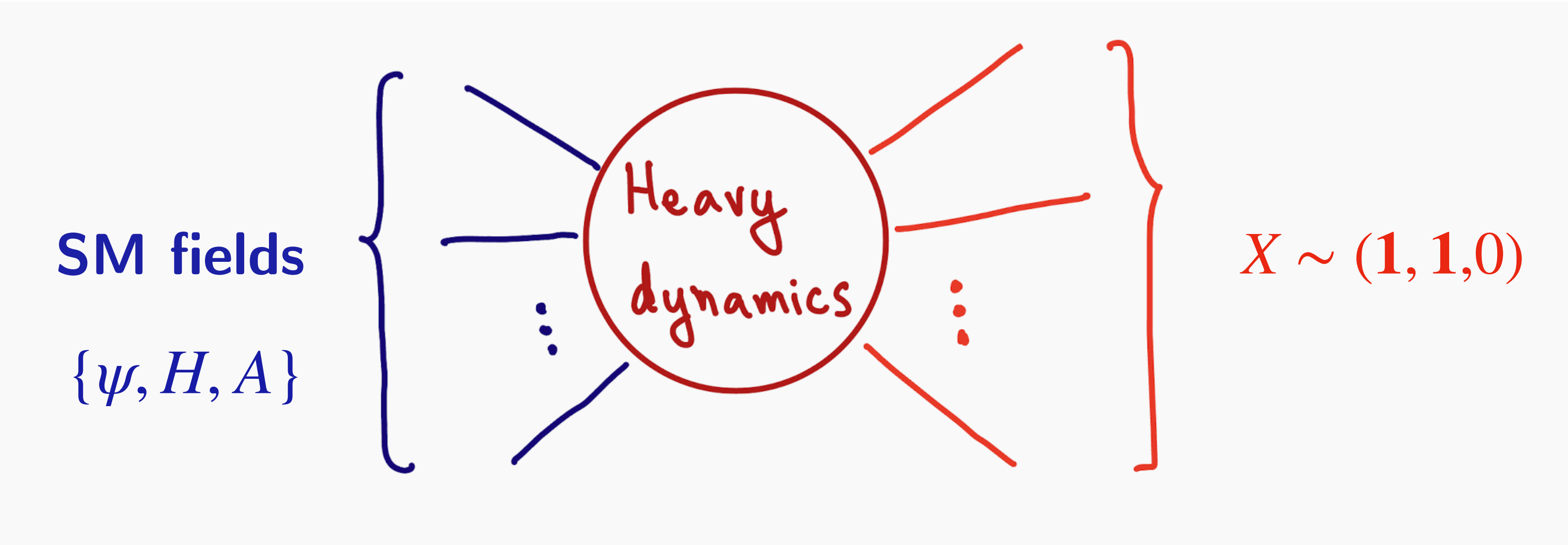
Dark Sectors

Not charged under $(SU(3)_c \times SU(2)_L \times U(1)_Y)$

<u>Assumption</u>: There exist **light particles** $X \sim (\mathbf{1},\mathbf{1},0)$ *(below the electroweak scale)* that interact **weakly** with the SM.

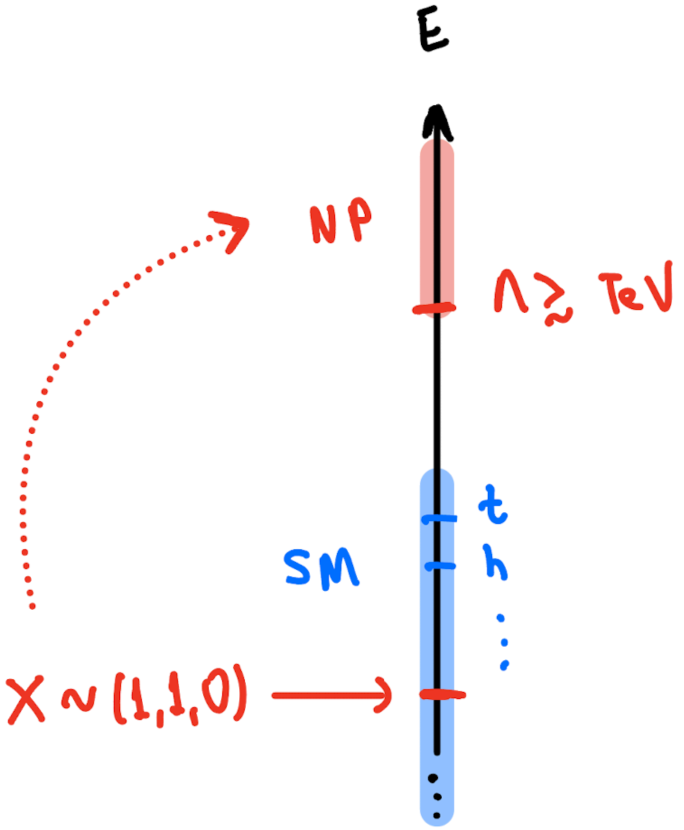
They can interact with the SM via *renormalizable interactions*. **<u>More generally</u>**, there will be $\mathrm{SM} + X$ interactions described by **higher-dimensional** *operators (suppressed by $1/\Lambda$)*:



SM fields

$\{\psi, H, A\}$

$X \sim (\mathbf{1},\mathbf{1},0)$



e.g., light pseudoscalar coupled via $\mathscr{L}_{\mathrm{portal}} \supset \dfrac{\partial_\mu a}{\Lambda}\bar{\psi}\gamma^\mu\psi$

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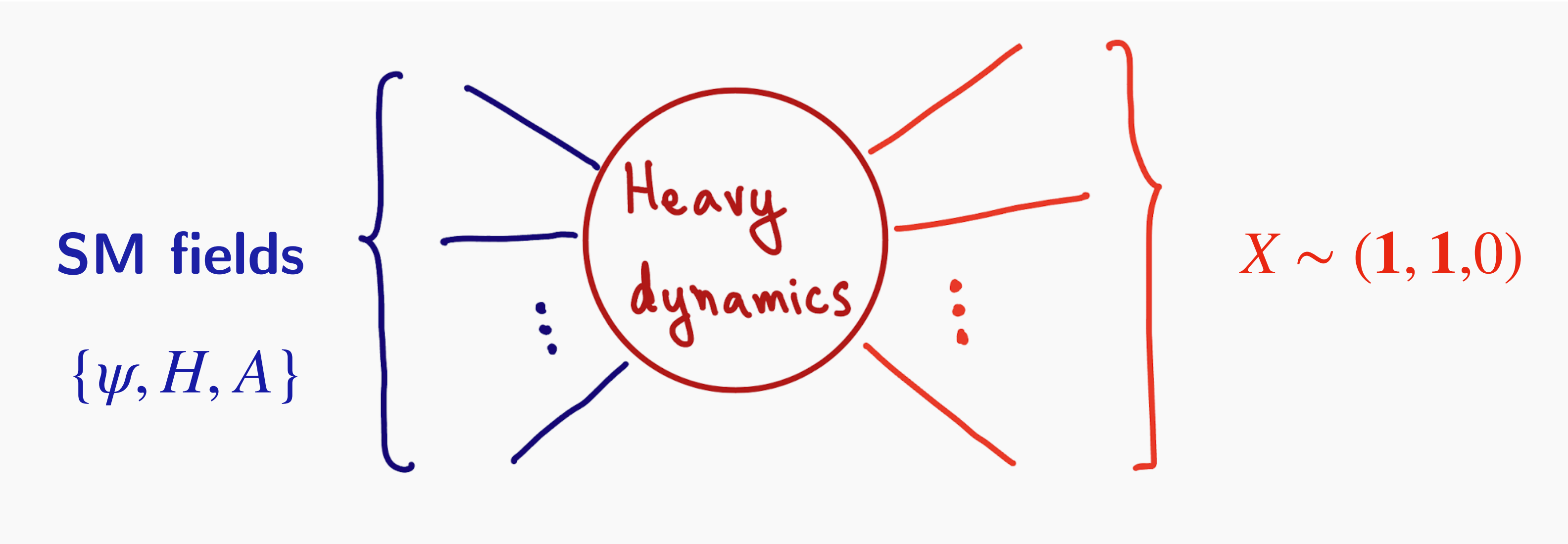

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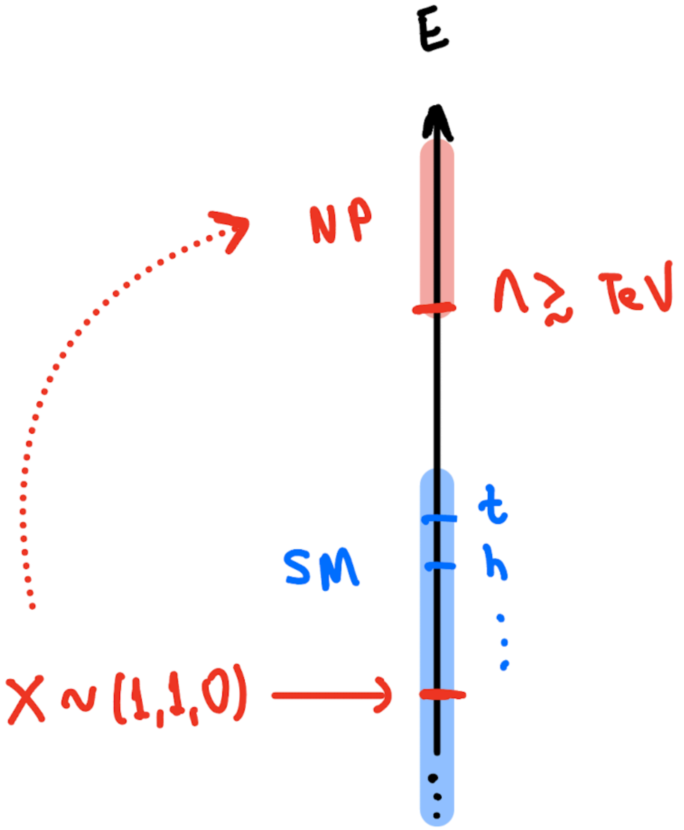


- The SM singlet X can be a **window to UV dynamics** *(e.g., pNGB* of a spontaneously broken symmetry*).*

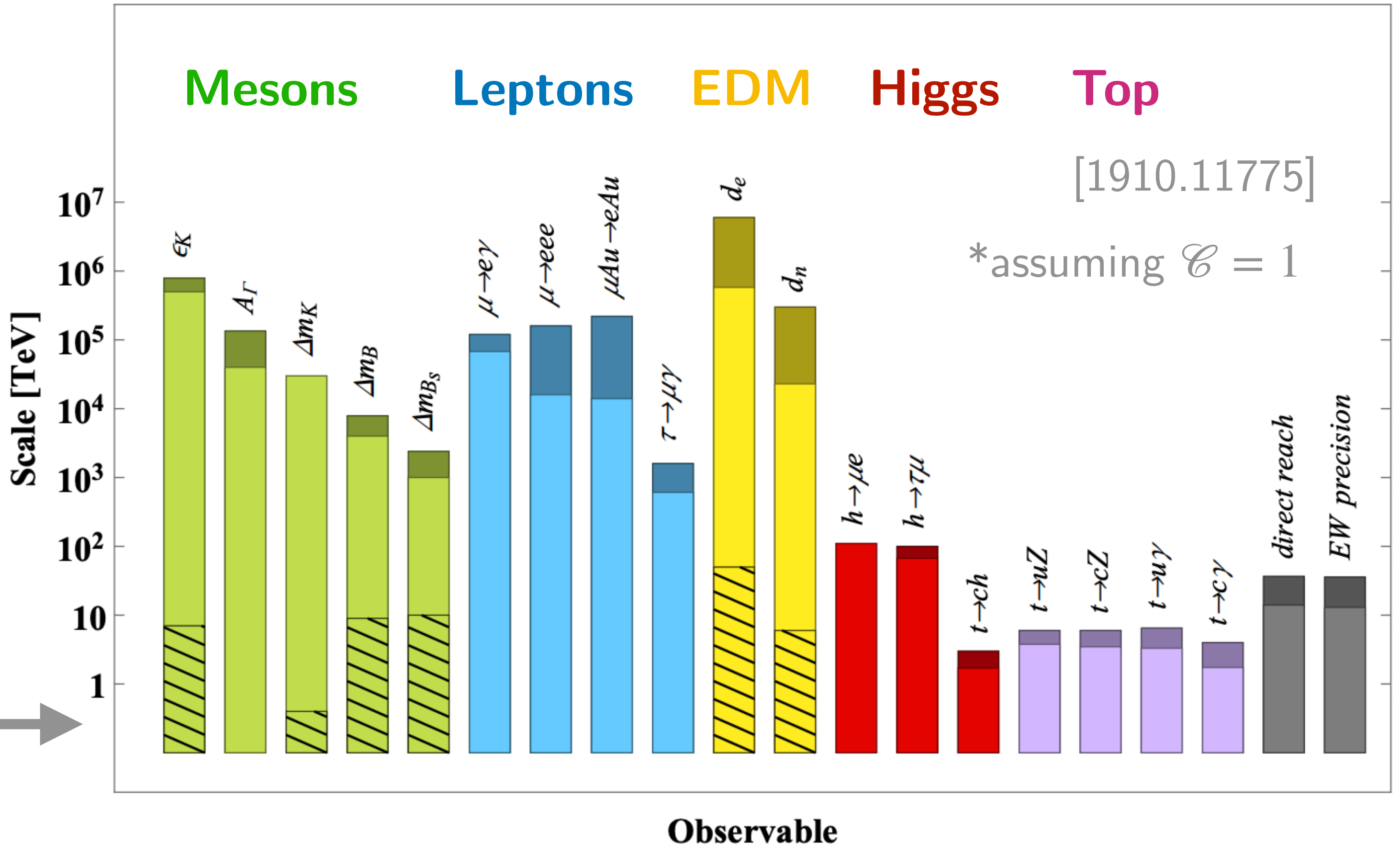
- **Theory inputs needed**: *which particle X? (which ansatz for flavor couplings?)*

The New Physics flavor problem

Flavor experiments are **sensitive probes** of very heavy **New Physics** through the study of **rare/forbidden** processes:

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{d\geq 5} \sum_{i} \frac{\mathscr{C}_i^{(d)}}{\Lambda^{d-4}} \mathscr{O}^{(d)}$$

Hatched: **MFV**

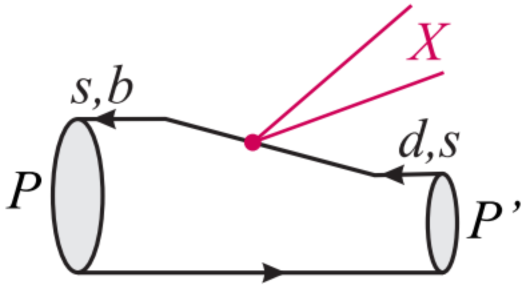


- **Flavor violation** must be **protected** in the SMEFT to suppress these rare processes — *e.g., via Minimal Flavor Violation or flavor symmetries.* [D'Ambrosio et al. '02],[Barbieri et al. '11]...

- The **same conclusion** holds for **"portal operators"** with SM singlets *(i.e., SMEFT+X)*!

FCNCs portals to the Dark Sector

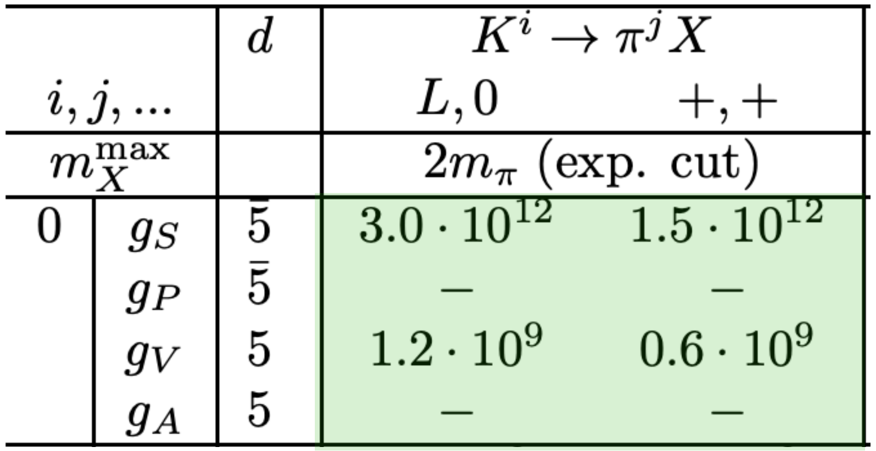
[Kamenik, Smith. '11]



$$\mathcal{H}_{eff}(q^I \to q^J X) = \frac{c^{IJ}}{\Lambda^n} \bar{q}^I q^J \times X$$

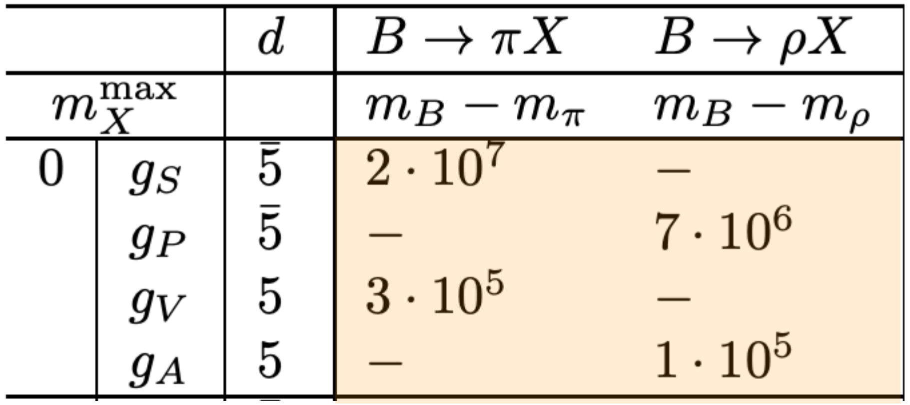
"Dark EFT"

Energy scales (in TeV) accessible with **kaon** decays →



		d	$K^i \to \pi^j X$	
$i, j, \ldots$			$L, 0$	$+, +$
$m_X^{\max}$			$2m_\pi$ (exp. cut)	
0	g_S	$\bar{5}$	$3.0 \cdot 10^{12}$	$1.5 \cdot 10^{12}$
	g_P	$\bar{5}$	–	–
	g_V	5	$1.2 \cdot 10^{9}$	$0.6 \cdot 10^{9}$
	g_A	5	–	–

Energy scales (in TeV) accessible with B-**meson** decays →



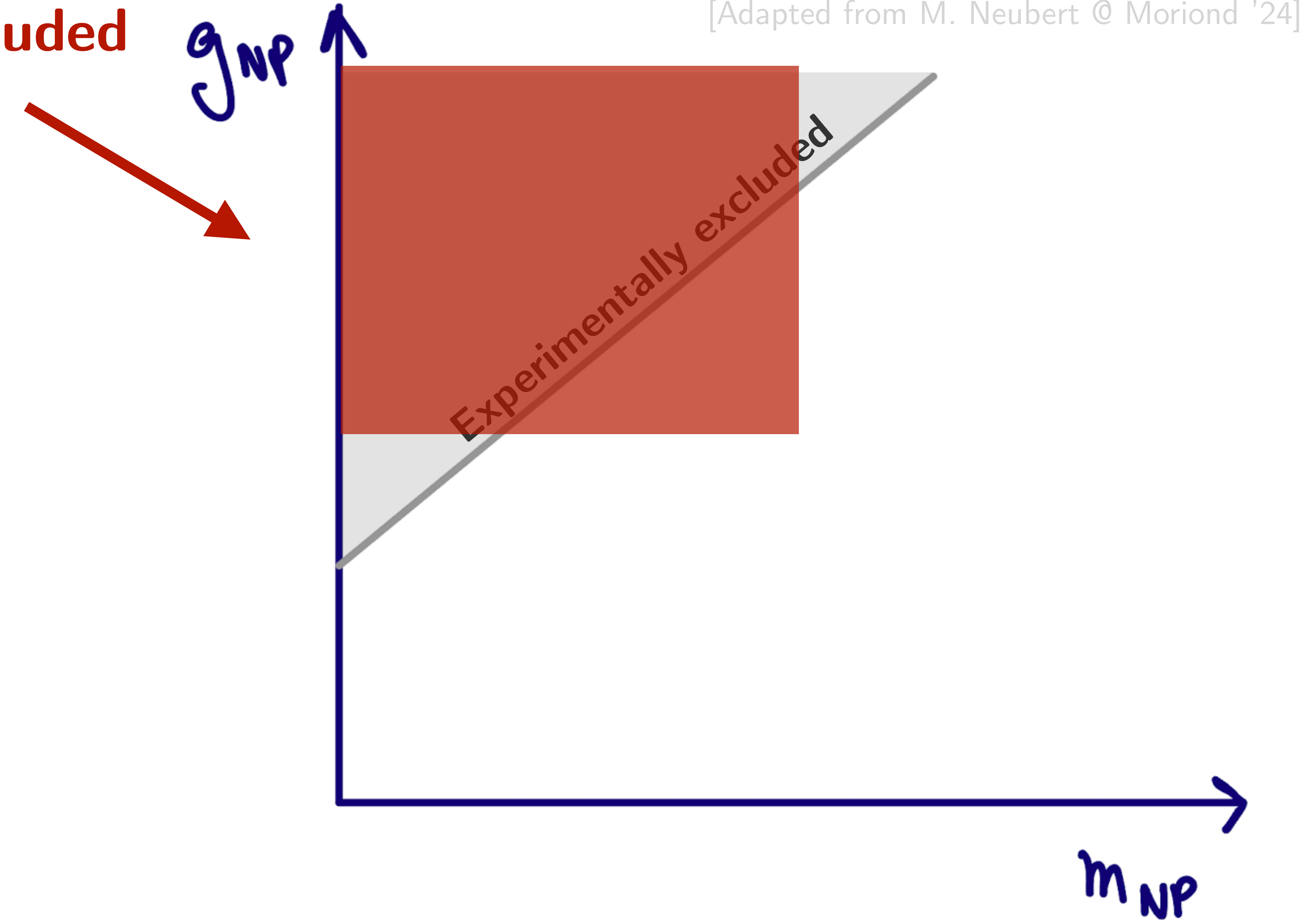
		d	$B \to \pi X$	$B \to \rho X$
$m_X^{\max}$			$m_B - m_\pi$	$m_B - m_\rho$
0	g_S	$\bar{5}$	$2 \cdot 10^{7}$	–
	g_P	$\bar{5}$	–	$7 \cdot 10^{6}$
	g_V	5	$3 \cdot 10^{5}$	–
	g_A	5	–	$1 \cdot 10^{5}$

NB. For a light scalar produced on-shell

The **suppression of FCNCs** is **needed** to lower the cutoff Λ — *NP cannot be blind to flavor...*

[Summary] The NP landscape

Already excluded



[Adapted from M. Neubert @ Moriond '24]

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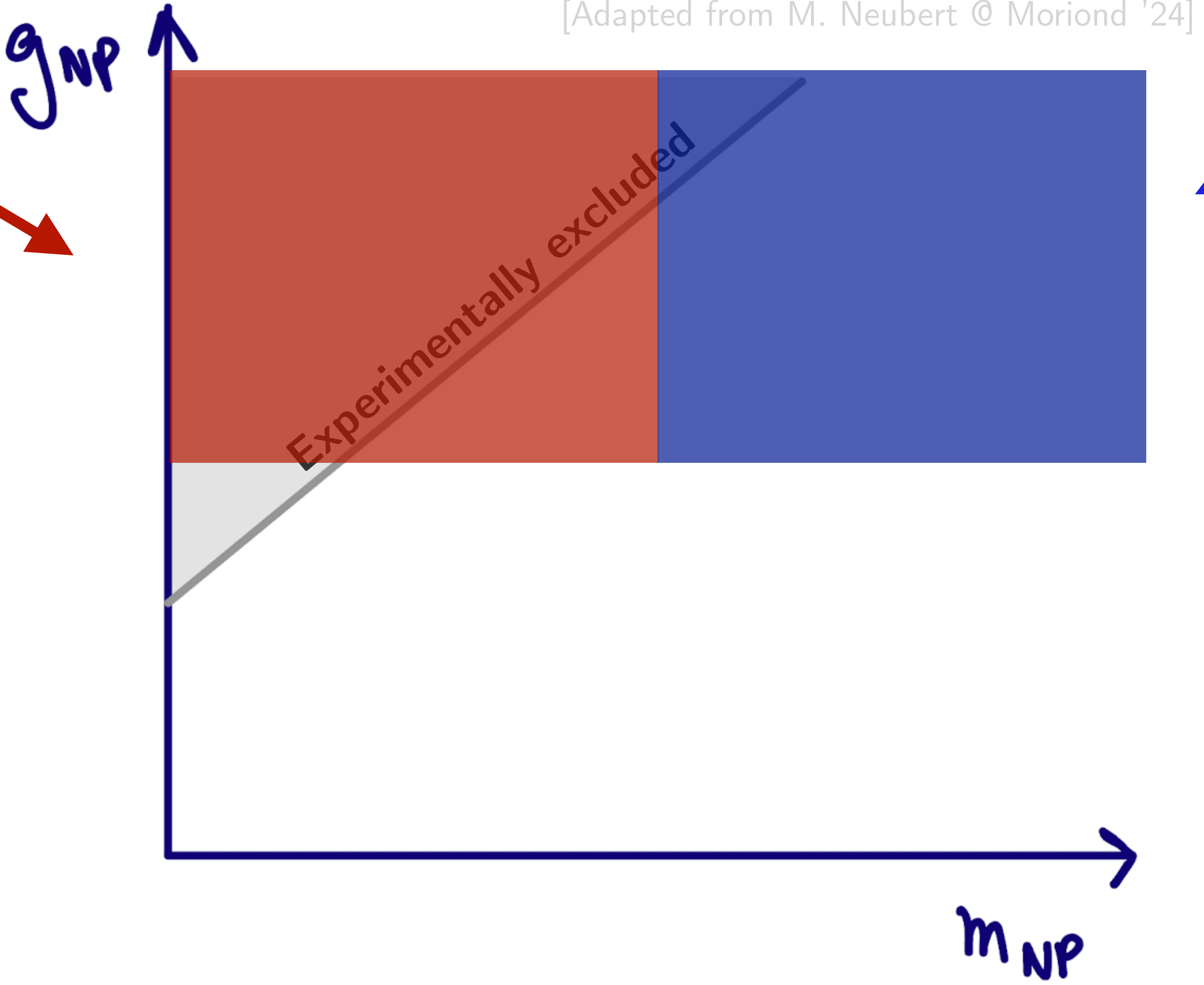

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SMEFT

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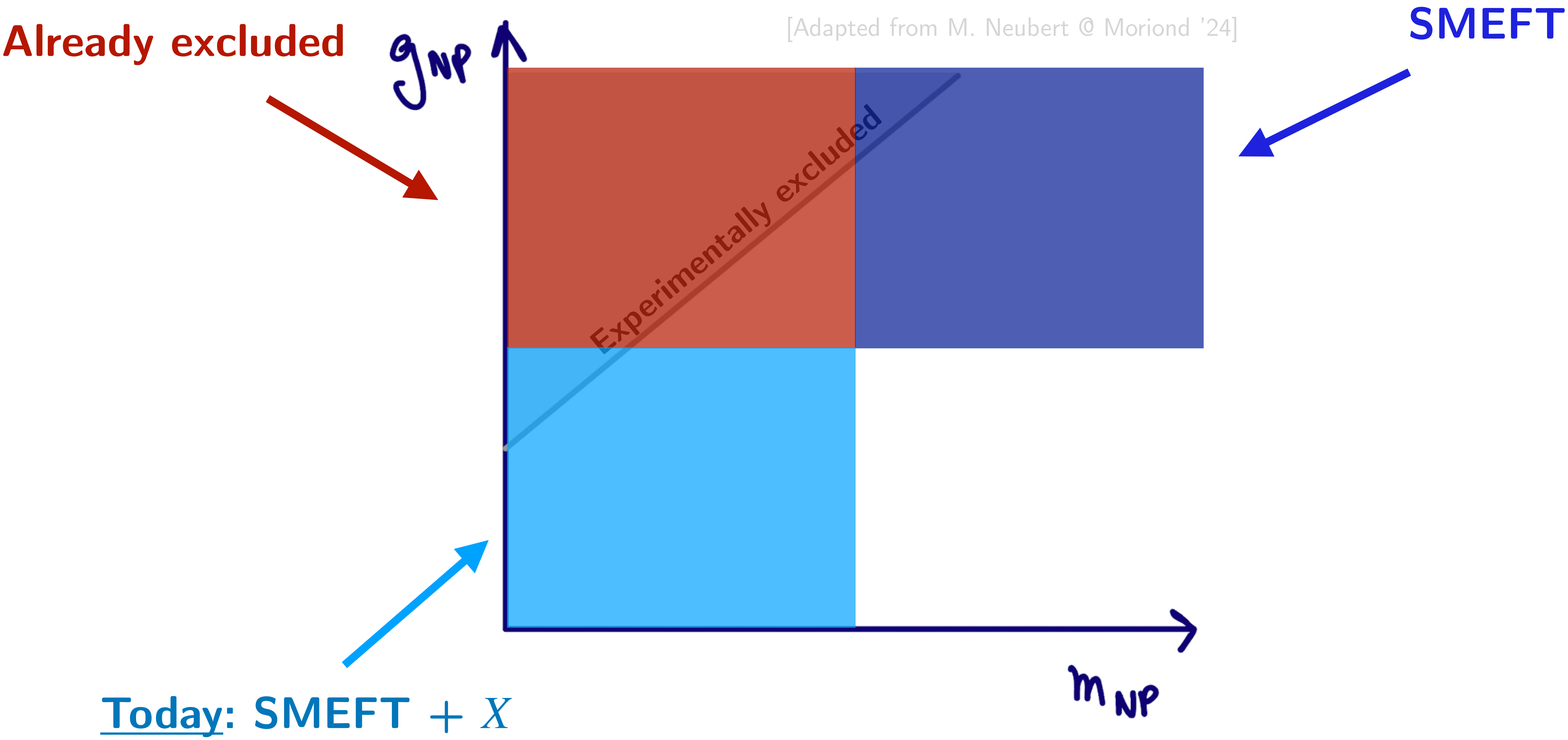

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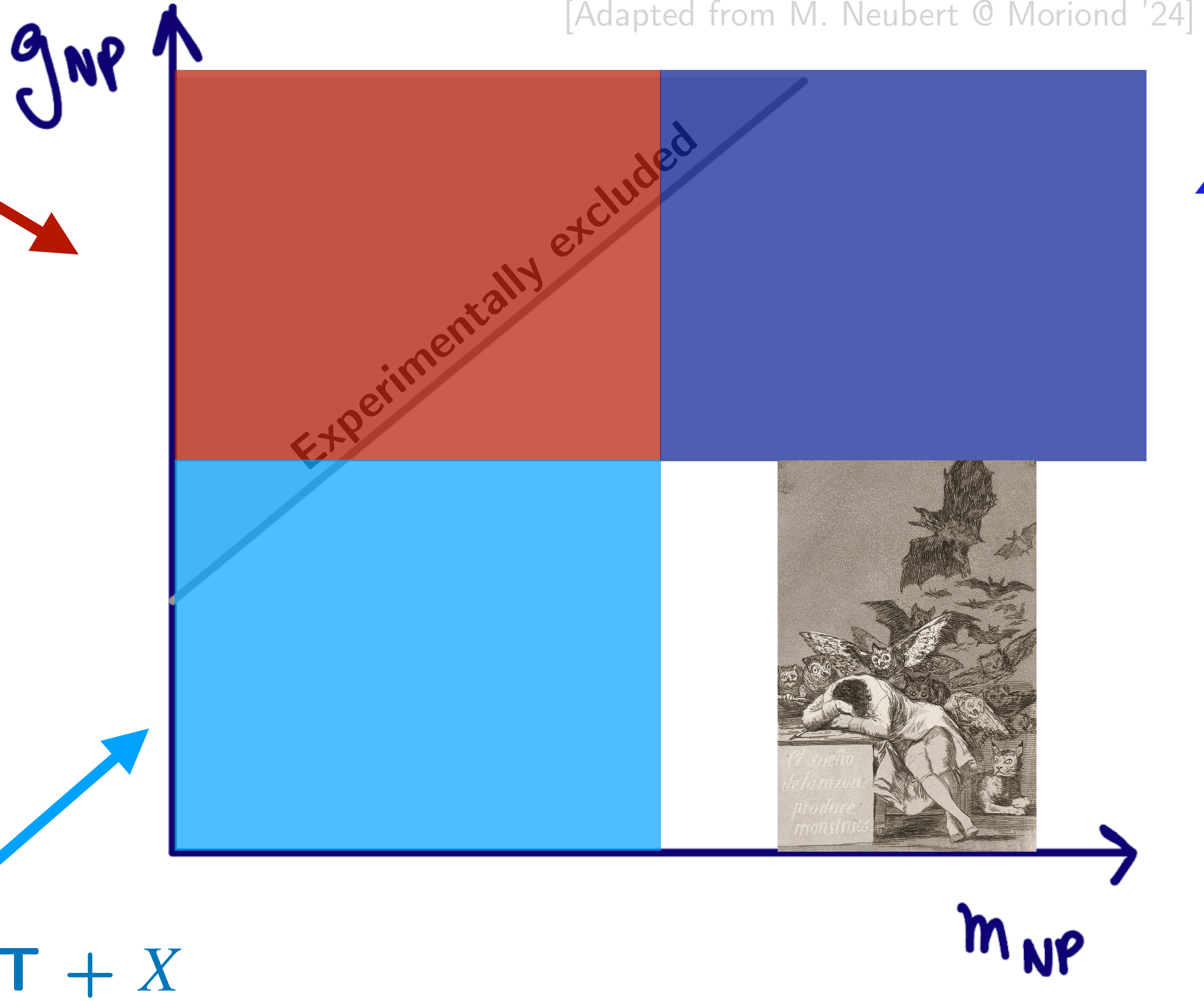

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Today: SMEFT $+ X$

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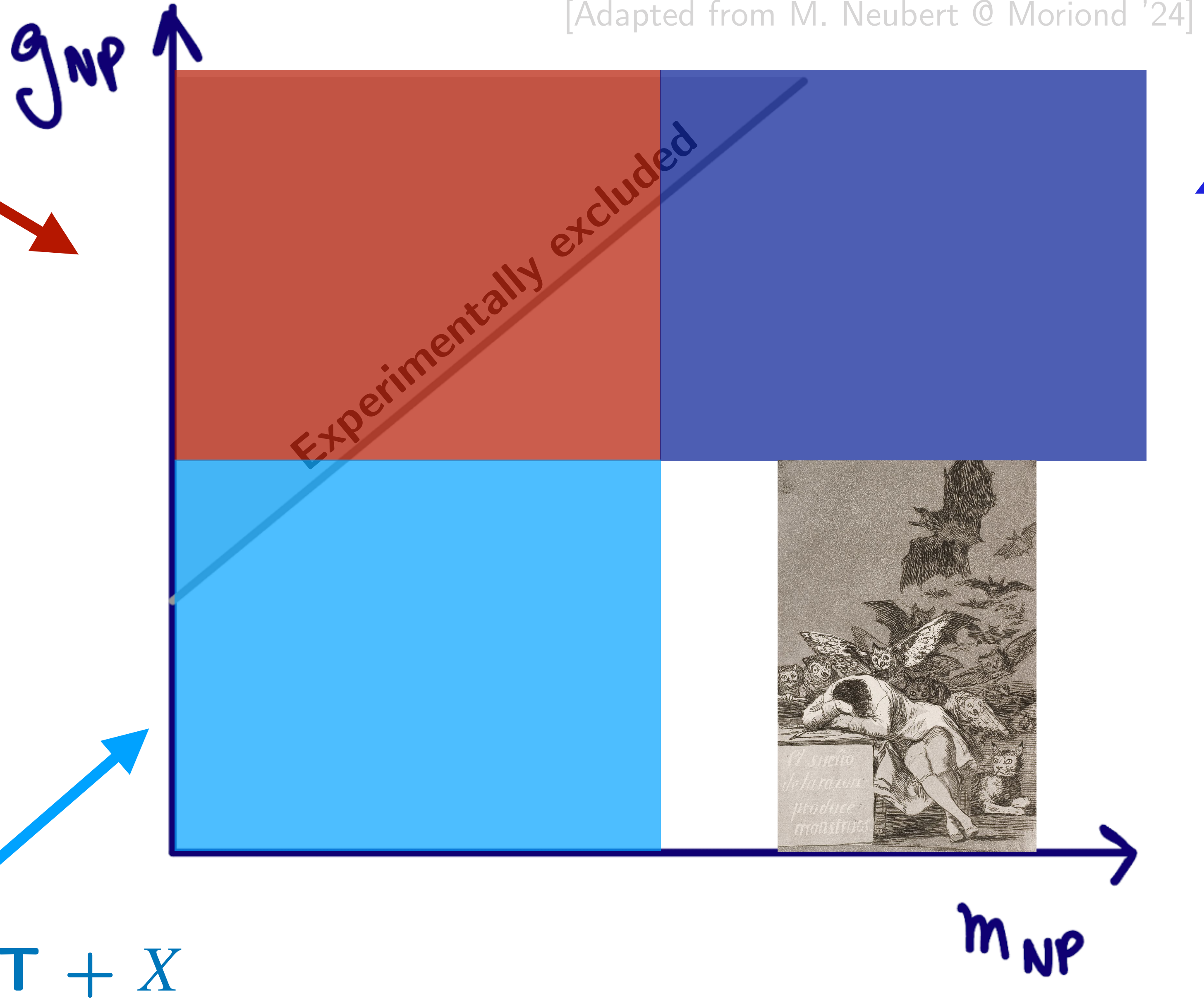


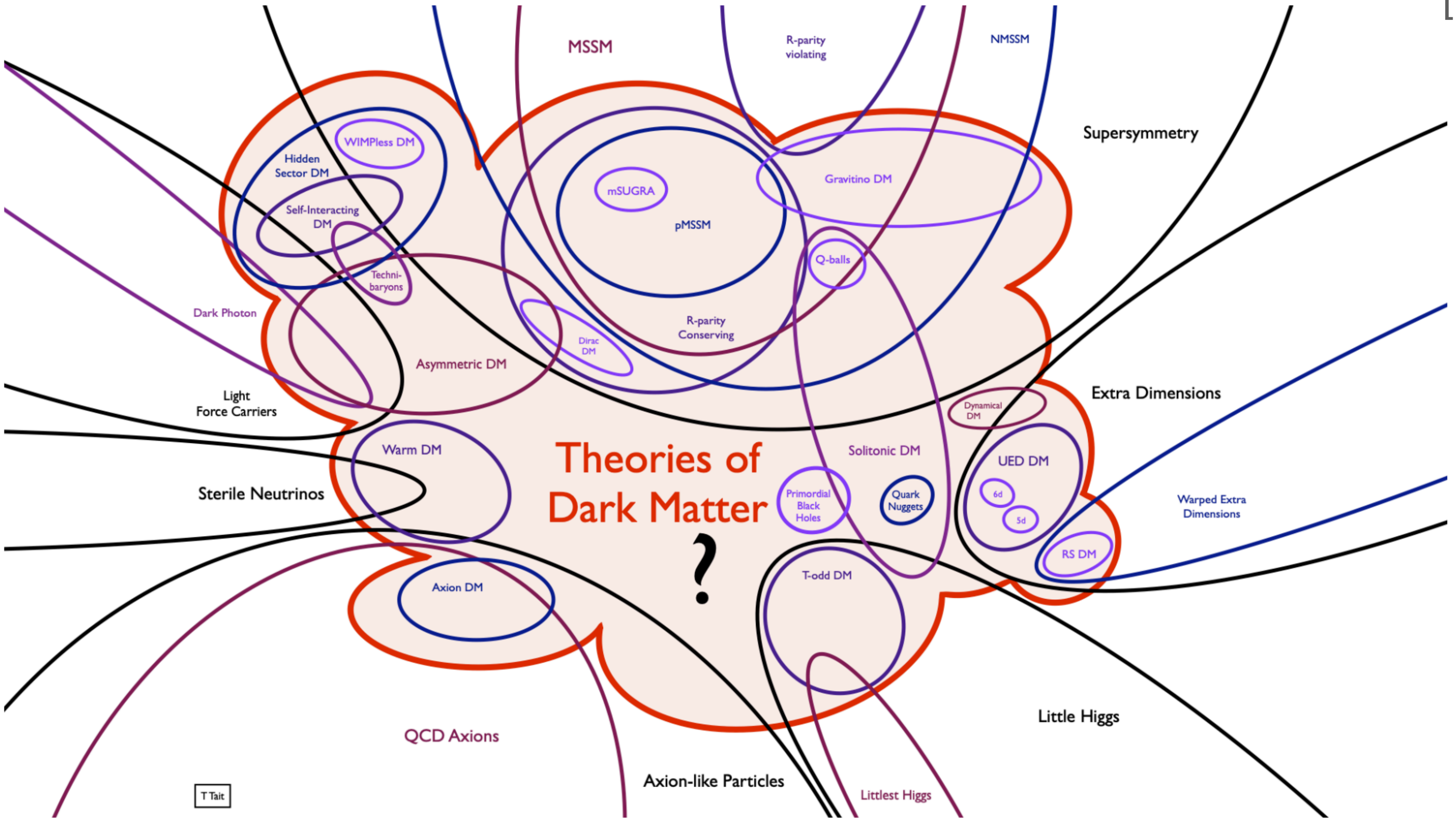
Today: SMEFT $+ X$

How can **flavor experiments** such as Belle-II help us to **probe light and weakly interacting particles** *(through invisible/semi-visible signatures)*?

Portals to the Dark Sector

What is Dark Matter?

[2211.09978]



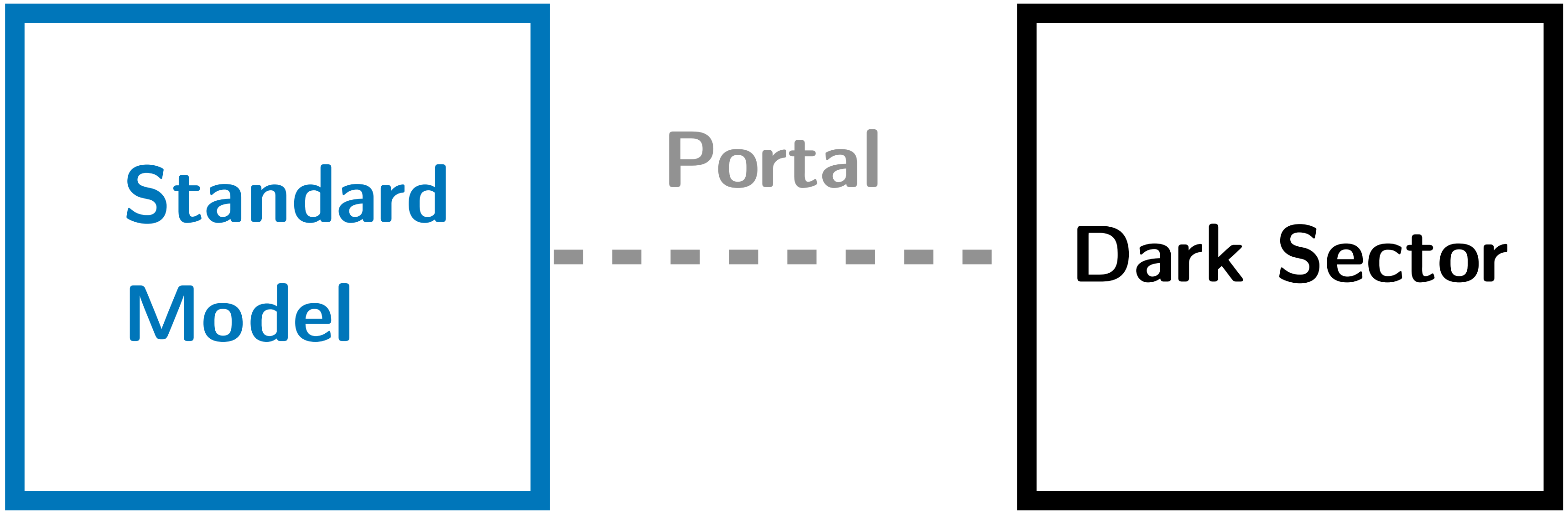
- There are **many possibilities** *(at very different energy scales...)* to explain the DM relic abundance — *experiments must be our guide.*

See lectures by S. Gori

- In these lectures, we will use **general notions** such as **Dark Sectors** and tools such as **Effective Field Theories** (*when it is possible*).

Dark/Hidden Sectors

[Adapted from B. Batel @ Invisibles '17]



Broad notion:

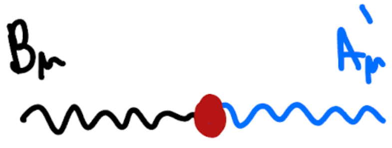
- **SM gauge singlets** — i.e., not charged under $SU(3)_c \times SU(2)_L \times U(1)_Y$.
- **Possibly light** — i.e., below $\mu_{\text{ew}} \simeq 100$ GeV.
- *Dark matter, right-handed neutrinos* etc could be part of the Dark Sector.
- The dark and visible sectors **might be connected** by a **portal/mediator.**

⇒ **Opportunity** for experiments in the **intensity frontier** (including flavor).

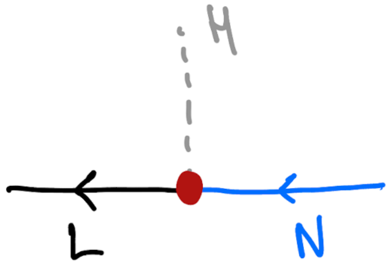
[Reminder] Minimal portals to the Dark Sector

There are three types of **gauge-invariant renormalizable** portals:

- **Vector**: $$\mathscr{L}^{(4)} \supset \frac{\varepsilon}{2c_w} F'_{\mu\nu} B^{\mu\nu}$$

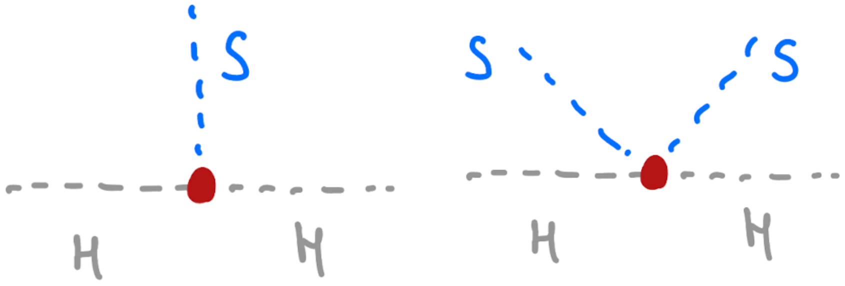


- **Neutrino**: $$\mathscr{L}^{(4)} \supset y \bar{L} N \tilde{H} + \mathrm{h.c.}$$



- **Scalar**: $$\mathscr{L}^{(4)} \supset (\lambda' S + \lambda'' S^2) H^\dagger H$$

cf. back-up



- They could be *viable DM candidates* in specific regions of parameter space.
- *More generally*, DM could be a *different particle* living in the Dark Sector interacting with the portal.
- Useful **benchmark scenarios**, with distinct experimental signatures.

cf. lectures by S. Gori

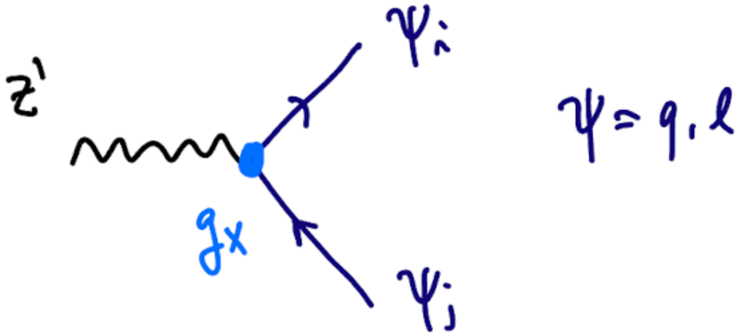
(Next-to-)minimal portals to the Dark Sector

Vector portals

- The new vector boson (Z') could be the gauge boson of an **accidental symmetry** of the SM if it is **anomaly-free**.

  ⇒ These scenarios have direct (model-dependent) couplings to specific quark/lepton flavors.

$$\mathscr{L}_{\text{gauge}} \supset g_X \, J_X^\mu \, Z'_\mu$$



⇒ Example: $U(1)_{L_\mu - L_\tau}$ leads to $J_X^\mu = \bar{\mu}_R \gamma^\mu \mu_R - \bar{\tau}_R \gamma^\mu \tau_R + \bar{L}_2 \gamma^\mu L_2 - \bar{L}_3 \gamma^\mu L_3$ $\qquad L_i = (\nu_{Li} \; \ell_{Li})^T$

⇒ **Opportunities** for **flavor experiments** such as Belle-II. see e.g. [Heeck et al. '11, Altmannshofer et al. '14]

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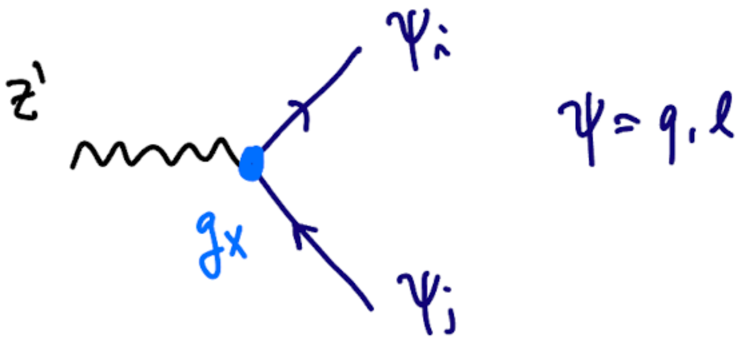

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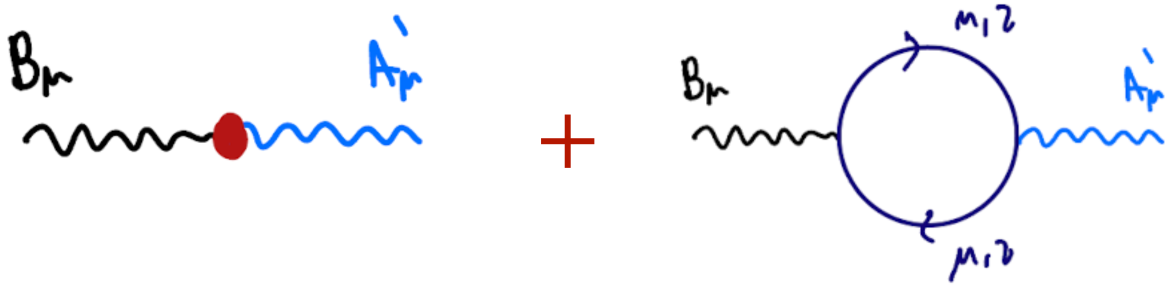
NB. Loop-level contributions to kinetic mixing are unavoidable at one-loop as the SM fermions talk to both $U(1)_Y$ and $U(1)_{L_\mu - L_\tau}$.



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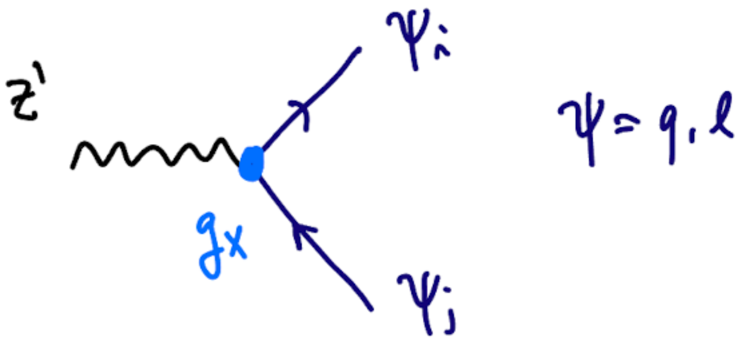

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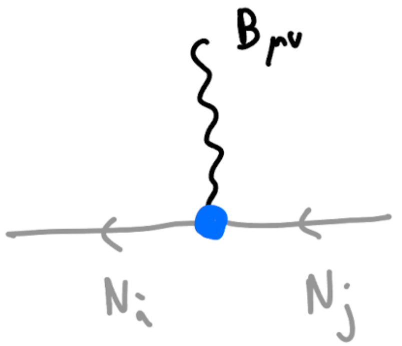
NB'. These models have been used in the past to explain the discrepancy in $(g-2)_\mu$ — disfavored after recent LQCD determinations of HVP *(cf. BMW Lattice and window observables)*.

Non-renormalizable portals

- The SM can also couple to the **portal mediator** through **higher-dimensional operators**.

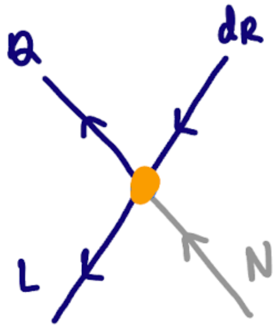
- Example: right-handed neutrinos.

$$\overline{N}_i^C \sigma_{\mu\nu} N_j B^{\mu\nu}$$



$(i \neq j)$

$$(\bar{L}N)\,\varepsilon(\bar{Q}d_R)$$



$H \sim (\mathbf{1}, \mathbf{2}, 1/2)$

$Q \sim (\mathbf{3}, \mathbf{2}, 1/6)$

$L \sim (\mathbf{1}, \mathbf{2}, -1/2)$

$u_R \sim (\mathbf{3}, \mathbf{1}, 2/3)$

$d_R \sim (\mathbf{3}, \mathbf{1}, -1/3)$

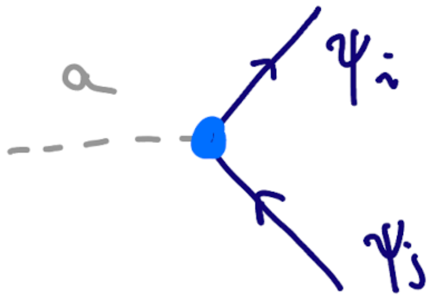
$e_R \sim (\mathbf{1}, \mathbf{1}, -1)$

$(SU(3)_c, SU(2)_L, U(1)_Y)$

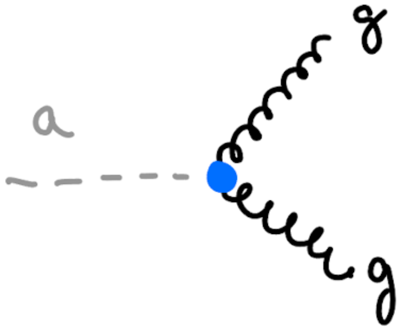
$Q = Y + T_3$

- Example: light pseudoscalar bosons — *a.k.a. axionlike particles.*

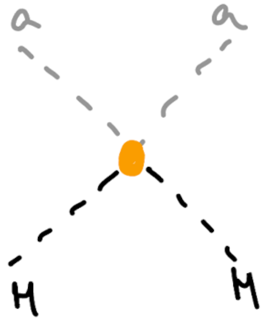
$$\partial_\mu a\,(\bar{\psi}\gamma^\mu \psi)$$



$$a\,G_{\mu\nu}\tilde{G}_{\mu\nu}$$



$$(\partial_\mu a\,\partial^\mu a)\,H^\dagger H$$



Question: Which are the dimensions of these operators?

[Reminder] Dimensional Analysis

$c = \hbar = 1$

$[M] = [E] = -[L] = 1$

- Canonical mass dimension:

$$[S] = 0 \xrightarrow{S = \int \mathrm{d}^4x\, \mathscr{L}} [\mathscr{L}] = 4$$

- Scalar field: $\mathscr{L}_\phi = (\partial^\mu \phi)(\partial_\mu \phi) + \dots \longrightarrow \boxed{[\phi] = 1}$

- Spin-1/2 field: $\mathscr{L}_\psi = \bar{\psi} i \gamma^\mu \partial_\mu \psi + \dots \longrightarrow \boxed{[\psi] = 3/2}$

- Spin-1 field: $\mathscr{L}_A = F^{\mu\nu} F_{\mu\nu} + \dots \longrightarrow \boxed{[A] = 1}$

with $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + \dots$

Non-renormalizable portals

- The SM can also couple to the **portal mediator** through **higher-dimensional operators**.

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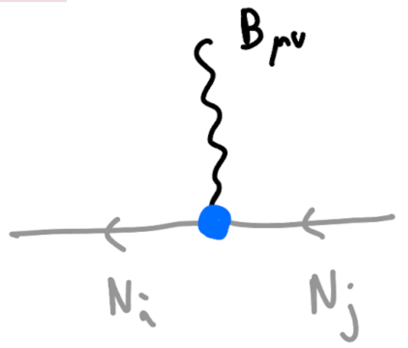
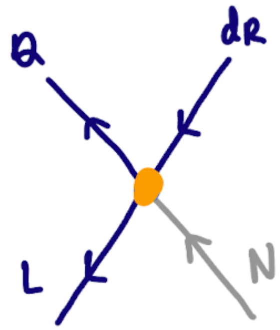
$$\frac{1}{\Lambda}\,\overline{N}_i^C \sigma_{\mu\nu} N_j\, B^{\mu\nu}$$



$(i \neq j)$

$$\frac{1}{\Lambda^2}\,(\overline{L}N)\,\varepsilon(\bar{Q}d_R)$$



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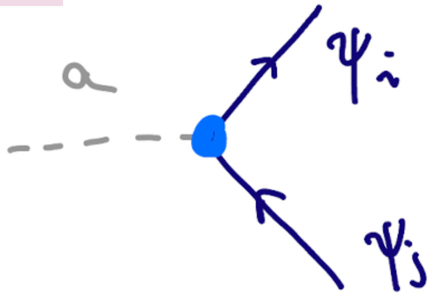
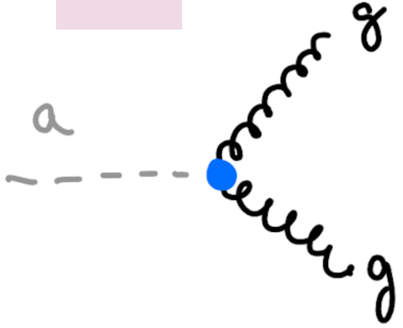
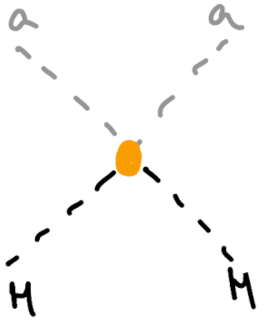


$$\frac{1}{\Lambda}\,a\,G_{\mu\nu}\tilde{G}_{\mu\nu}$$



$$\frac{1}{\Lambda^2}\,(\partial_\mu a\,\partial^\mu a)\,H^\dagger H$$

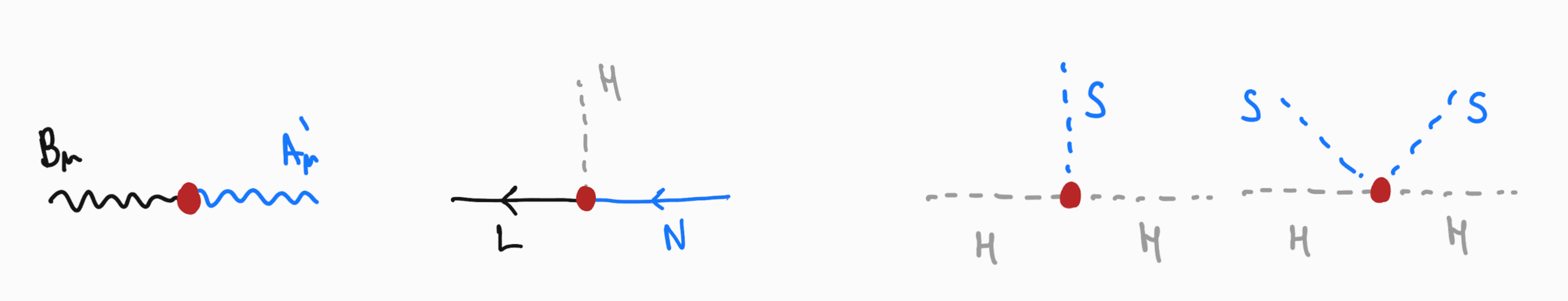


The **leading operators** appear at **lower dimensions** (*observable dependent*).

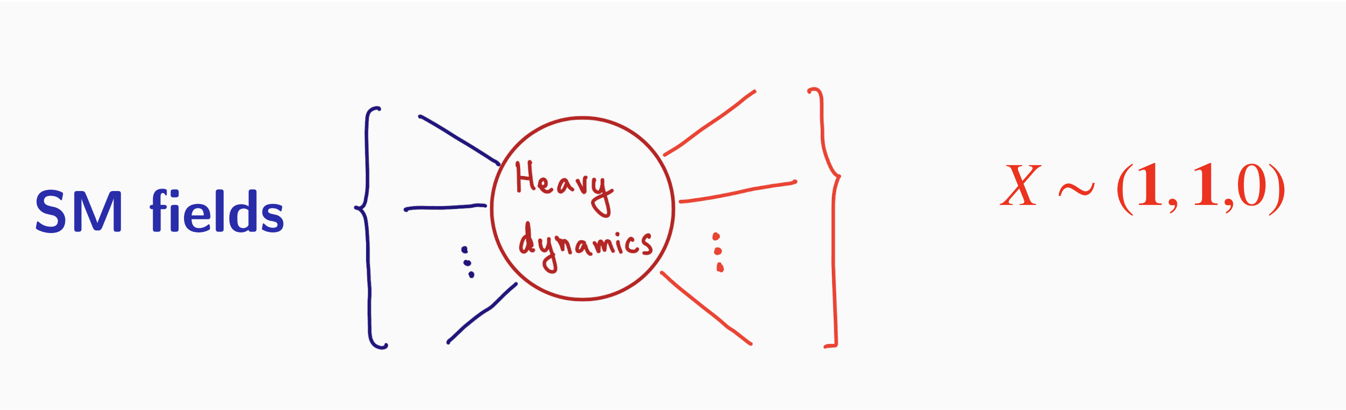
Summary

- We have reviewed the **minimal portal mediators** $X \sim (\mathbf{1}, \mathbf{1}, 0)$ that **connect** the **SM** with a **general Dark Sector** (... *which could include dark matter particles*).

- The simplest possibilities are the **renormalizable portals** (vector, neutrino and scalar):



- Besides renormalizable interactions, there could also be **higher-dimensional operators** connecting the mediator and the SM (*suppressed by the EFT cutoff*):



- In models such as **ALPs**, the **interactions** with the SM start already **at** $d \geq 5$

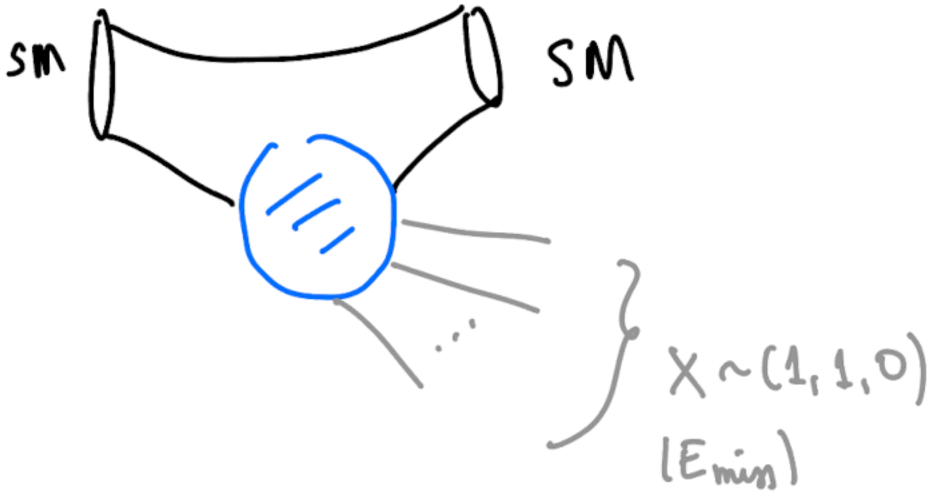
Next: We will explore how flavor experiments can probe these minimal models.

Flavor probes of Dark Sectors

How to test dark sectors in flavor experiments?

I. **Virtual corrections** to processes with SM particles:

II. **Contributions** to processes mimicking the SM (with E_{miss}):



III. **New signatures**:

- *Displaced vertices/missing energy* in *processes* or *kinematical configurations* that are *not expected in the SM.*

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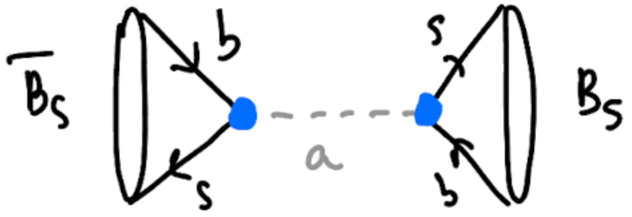
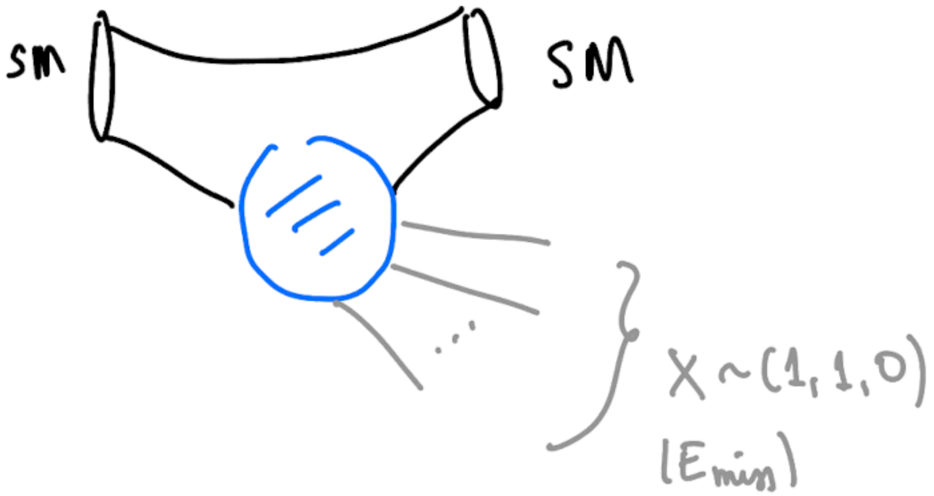
I. **Virtual corrections** to processes with SM particles:

Example: ALP (decaying invisibly)

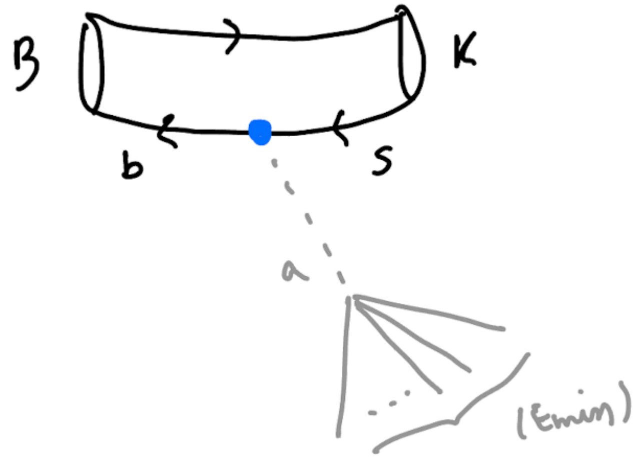
$B_s - \overline{B}_s$ mixing



II. **Contributions** to processes mimicking the SM (with $E_{\rm miss}$):



$B \to K + \text{inv}$



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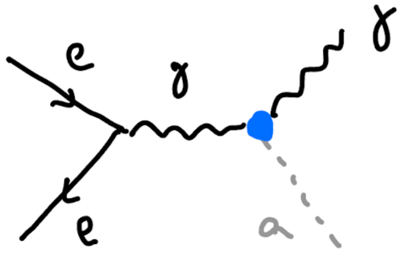
- *Displaced vertices/missing energy* in *processes* or *kinematical configurations* that are *not expected in the SM.*

$e^+e^- \to \gamma a(\to \ldots)$



Concrete examples

- Vector Portals
- ALPs
- Sterile neutrinos

I. Dark photon

- Simplest possibility: A' gauge boson of $U(1)_X$ with a dark Higgs Φ'

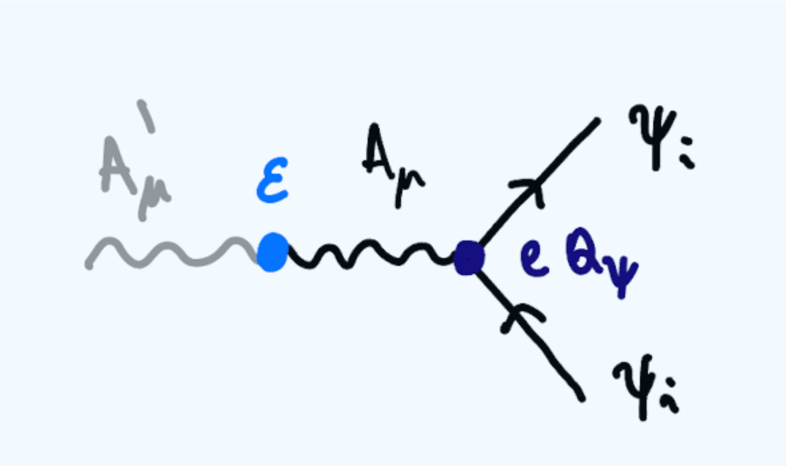
$$\mathscr{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \sum_{\psi} \bar{\psi} i D^{\mu}\gamma_{\mu}\psi - \frac{\varepsilon}{2c_W}F'_{\mu\nu}B^{\mu\nu} + |D_\mu \Phi'|^2 + V(\Phi')$$

$$\Big\downarrow \; \langle \Phi' \rangle = (v_d + \phi')/\sqrt{2}$$

$$\frac{1}{2}(\partial_\mu \phi')^2 - \frac{1}{2}m_{\phi'}^2 \phi'^2 + \frac{1}{2} m_{A'}^2 A'^2_\mu + \dots$$

  - Field redefinitions allow us to write after EW symmetry breaking:

$$\mathscr{L} \supset \varepsilon \sum_f Q_f \, e \, A'_\mu (\bar{f}\gamma^\mu f) + \mathcal{O}(\varepsilon^2)$$



$\Rightarrow$ **Good benchmark:** *in principle*, only two relevant parameters $(\varepsilon, m_{A'})$

Flavor blind!

NB. The *"dark Higgs"* in the spectrum could also lead to other interesting signatures.

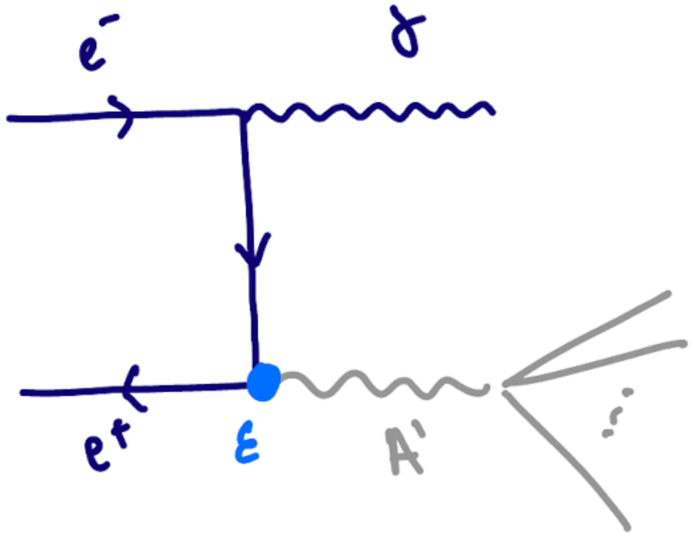
cf. [Batell et al.'09]

I. Dark photons @ Belle-II

Invisible channel

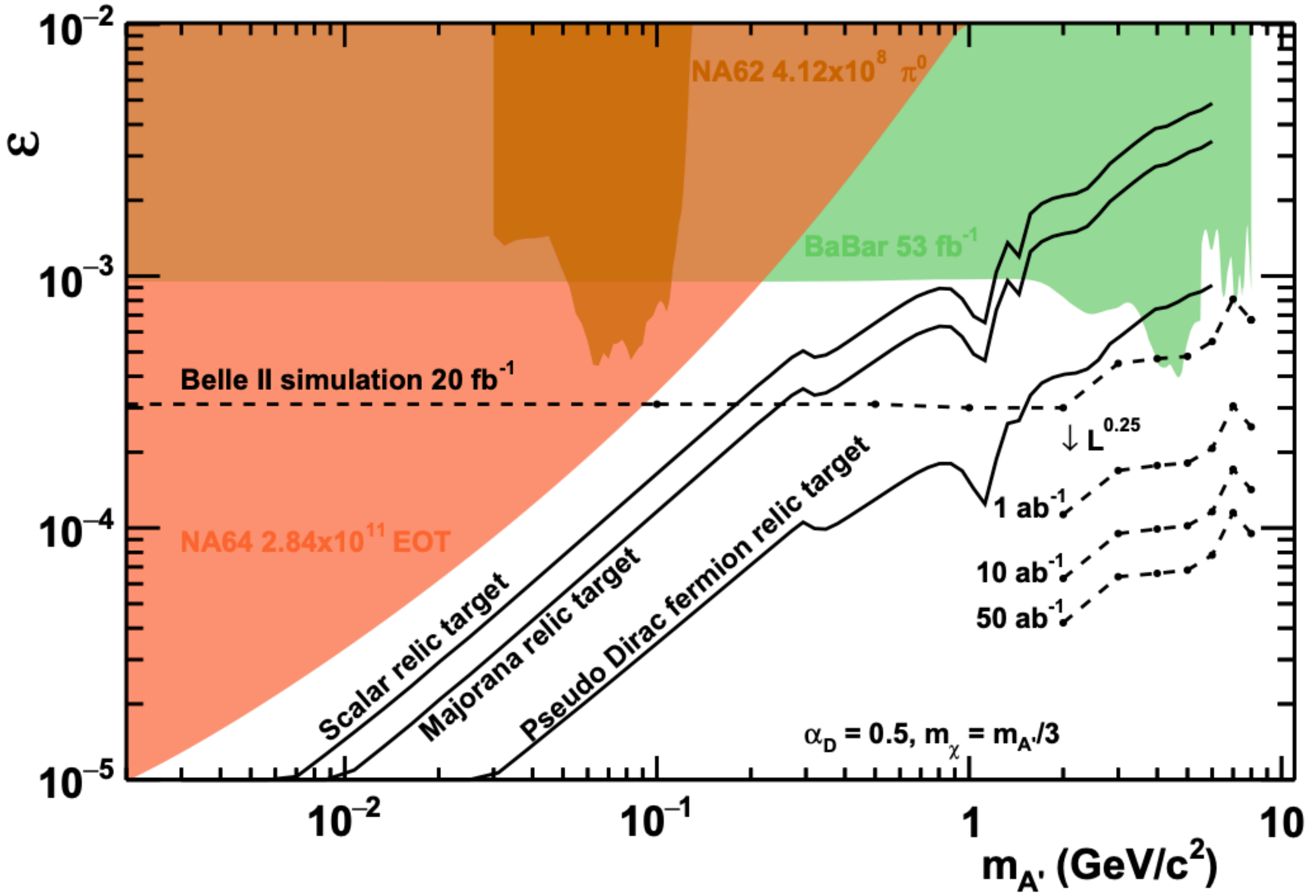
Assumption: the dark photon will decay into invisible particles (*dark matter...*)

- $e^+e^- \to \gamma + A'(\to \text{inv})$ [Essig et al.'09]



Prediction: peak in the single-photon energy distribution

$$E_\gamma = \frac{s - m_{A'}^2}{2\sqrt{s}}$$



[Belle-II projections, Aggarwal et al. '2207.06307]

See lectures by S. Gori for DM pheno in these models

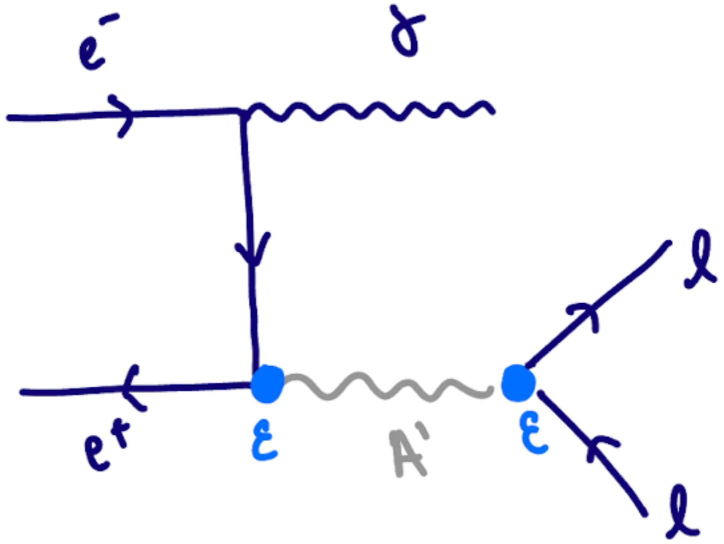
I. Dark photons @ Belle-II

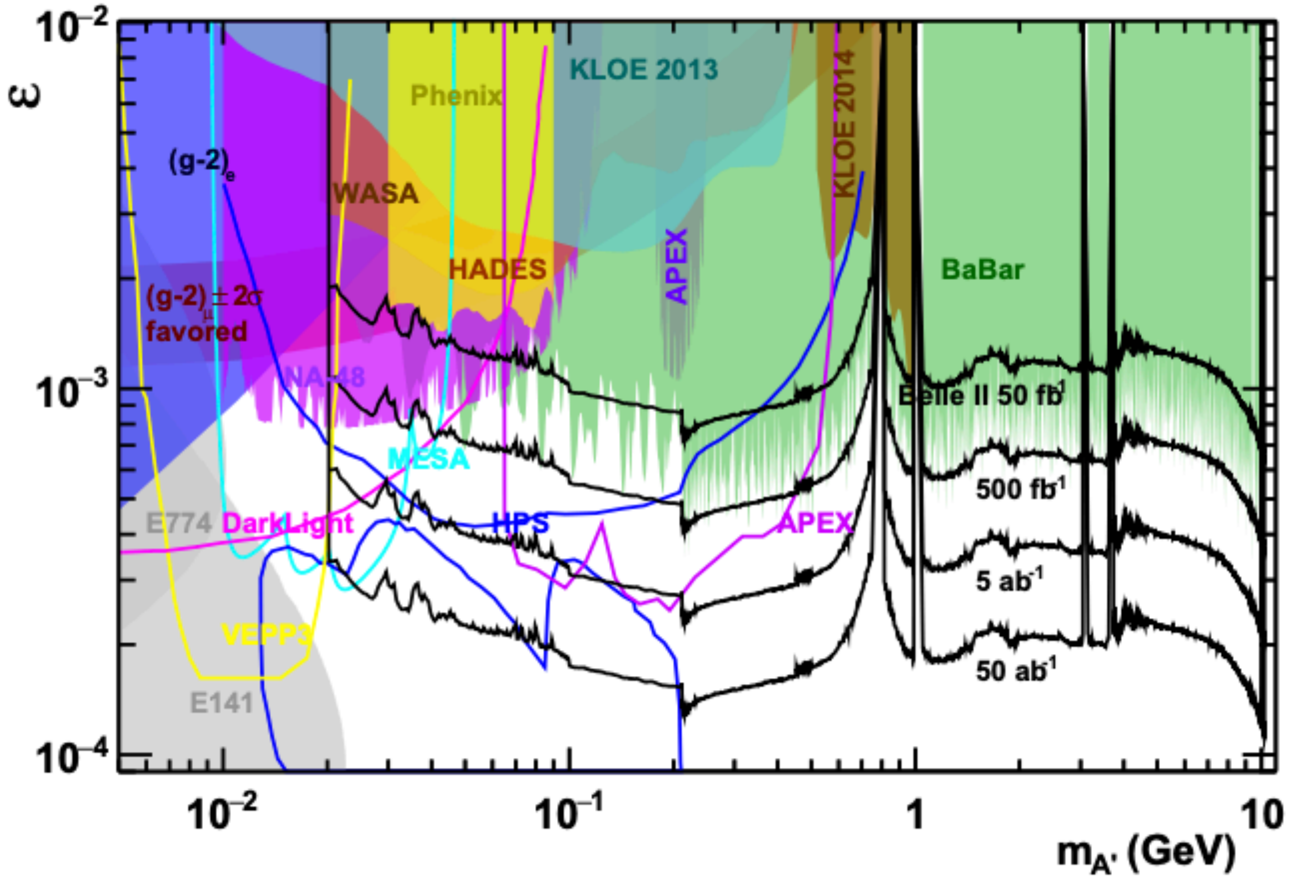
Visible channel

Assumption: the dark photon coupling to invisible particles is small.

- $e^+e^- \to \gamma + A'(\to \ell\ell, \text{had})$

e.g.,





[Belle-II projections, Aggarwal et al. '2207.06307]

Possible final states:

- Leptonic: ee, $\mu\mu$ and $\tau\tau$.
- Hadronic: $\pi\pi$, KK ...

Non-perturbative input needed!
cf. e.g. [Ilten et al. '18]

II. Z' portal

Example: $L_\mu - L_\tau$

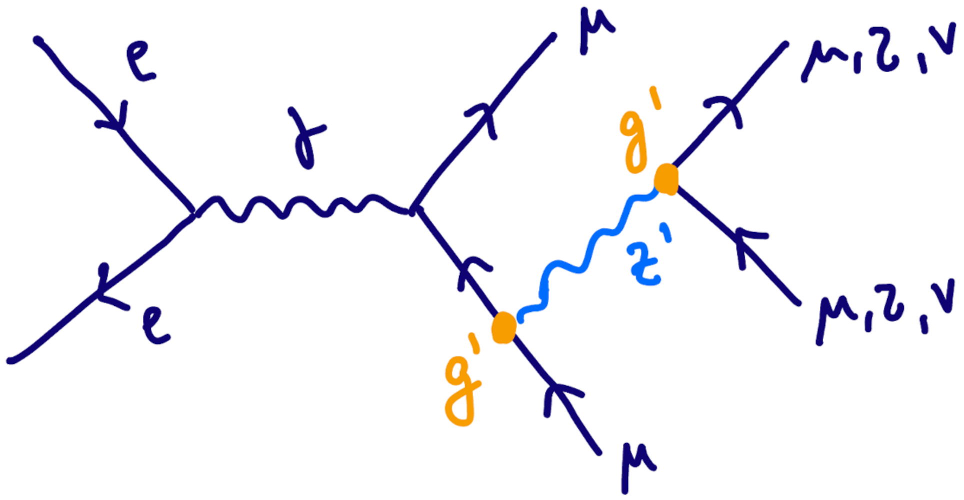
- The **new vector boson** could also **couple directly** to **SM fermions** (*model dependent*).

- **Example:** $U(1)_{L_\mu - L_\tau}$

$$\mathscr{L}_{Z'} \supset \ldots - \frac{\varepsilon}{2c_W} B_{\mu\nu} F'^{\mu\nu} + g' Z'_\mu J^\mu \,, \qquad J^\mu = \bar{\mu}\gamma^\mu \mu - \bar{\tau}\gamma^\mu \tau + \bar{\nu}_\mu \gamma^\mu P_L \nu_\mu - \bar{\nu}_\tau \gamma^\mu P_L \nu_\tau$$

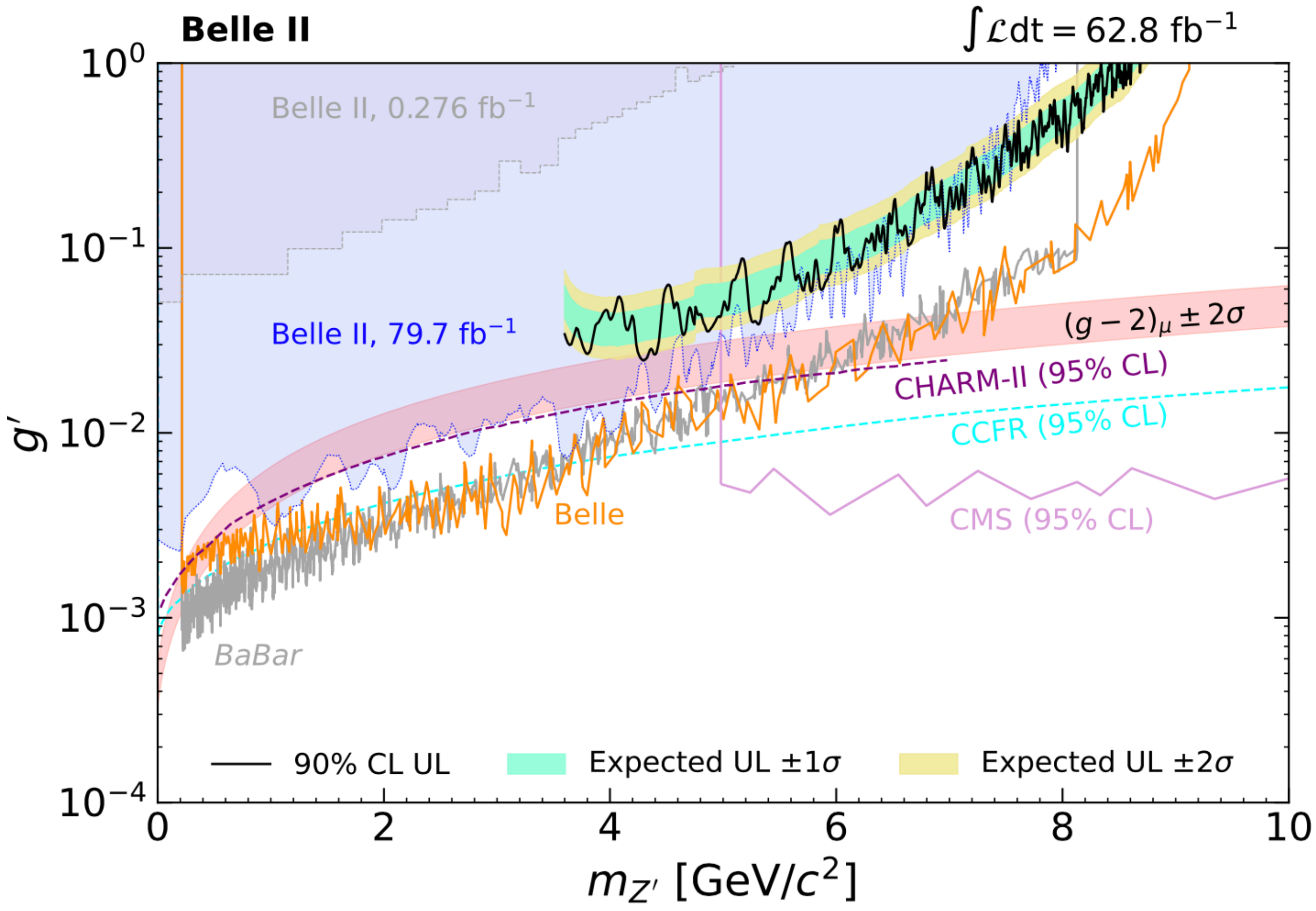
- **New exp. signatures at Belle-II** (in addition to kinetic mixing):

$$e^+e^- \to \mu\mu + Z'(\to \mu\mu, \tau\tau)$$



$\Rightarrow$ Several searches performed at Belle-II.

[2212.03066, 2306.122942, 2403.02841]



(Neglecting kinetic mixing)

Concrete examples

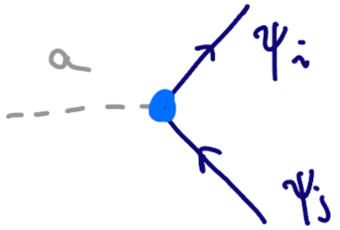
- Vector Portals
- ALPs
- Sterile neutrinos

III. ALPs

- **Theoretically well-motivated** — light pseudoscalars can arise as pNGB of spontaneously broken global $U(1)$ symmetries.

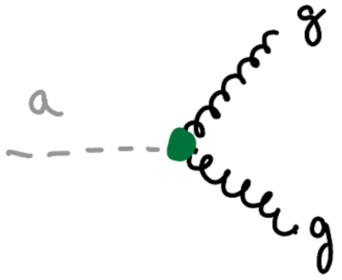
- Most general **effective Lagrangian** for a light pseudoscalar, with a classical shift-symmetry explicitly broken by a mass term:

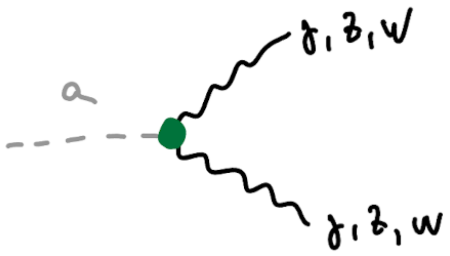
[Georgi et al. '86]



$$\mathscr{L}_{\text{eff}}^{d\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a}\sum_\psi c_\psi^{ij}(\bar\psi_i\gamma^\mu\psi_j) + c_H\frac{\partial_\mu a}{f_a}(H^\dagger i\overleftrightarrow{D}^\mu H)$$
$$+ c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f_a}G^a_{\mu\nu}\tilde G^{\mu\nu,a} + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f_a}W^A_{\mu\nu}\tilde W^{\mu\nu,A} + c_{BB}\frac{\alpha_1}{4\pi}\frac{a}{f_a}B^A_{\mu\nu}\tilde B^{\mu\nu,A} + \mathcal{O}(f_a^{-2})$$

$\psi \in \{u_R, d_R, e_R, L, Q\}$





⇒ Operators **suppressed** by **inverse powers** of f_a — *power counting*.

⇒ The **ALP couplings to fermions** can be **flavor violating** — ***which flavor ansatz?***

[Bauer et al. '21]

III. ALPs

- **Equations of motions** can be useful:

$\psi = \ell, d, u$

$$\mathscr{L}_{\text{eff}} \supset \frac{\partial_\mu a}{f_a} c^{ij}_{\psi_R} \bar{\psi}_{Ri} \gamma^\mu \psi_{Rj} + \frac{\partial_\mu a}{f_a} c^{ij}_{\psi_L} \bar{\psi}_{Li} \gamma^\mu \psi_{Lj}$$

$$\to -i \frac{a}{2f_a} \Big[(c^{ij}_{\psi_R} + c^{ij}_{\psi_L}) (m_{\psi_i} - m_{\psi_j}) \bar{\psi}_i \psi_j + (c^{ij}_{\psi_R} - c^{ij}_{\psi_L}) (m_{\psi_i} + m_{\psi_j}) \bar{\psi}_i \gamma_5 \psi_j \Big]$$

Scalar couplings can only be off-diagonal

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Scalar couplings can only be off-diagonal

- There are also **redundancies** that can be **removed** via field redefinitions:

see e.g. [Brivio et al. '17]

e.g.,

$$H \to \exp\left(i x_H \frac{a}{f_a} \right) H$$

$$\psi \to \exp\left(i y_\psi x_H \frac{a}{2f_a} \right) \psi$$

$$\mathscr{L}_{\text{SM}} \longrightarrow \mathscr{L}_{\text{SM}} - x_H \frac{\partial_\mu a}{f_a} (H^\dagger i \overleftrightarrow{D}^\mu H) + \mathcal{O}(f_a^{-2})$$

We can choose x_H to remove the ALP operator with the Higgs from the basis

Exercise (if you are motivated!): Derive the above expression.

cf. [Bauer et al. 2110.10698]

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In total, there are $4+5\times 9-5=$ **44 ALP couplings** at $d=5$ — *flavor assumption needed...*

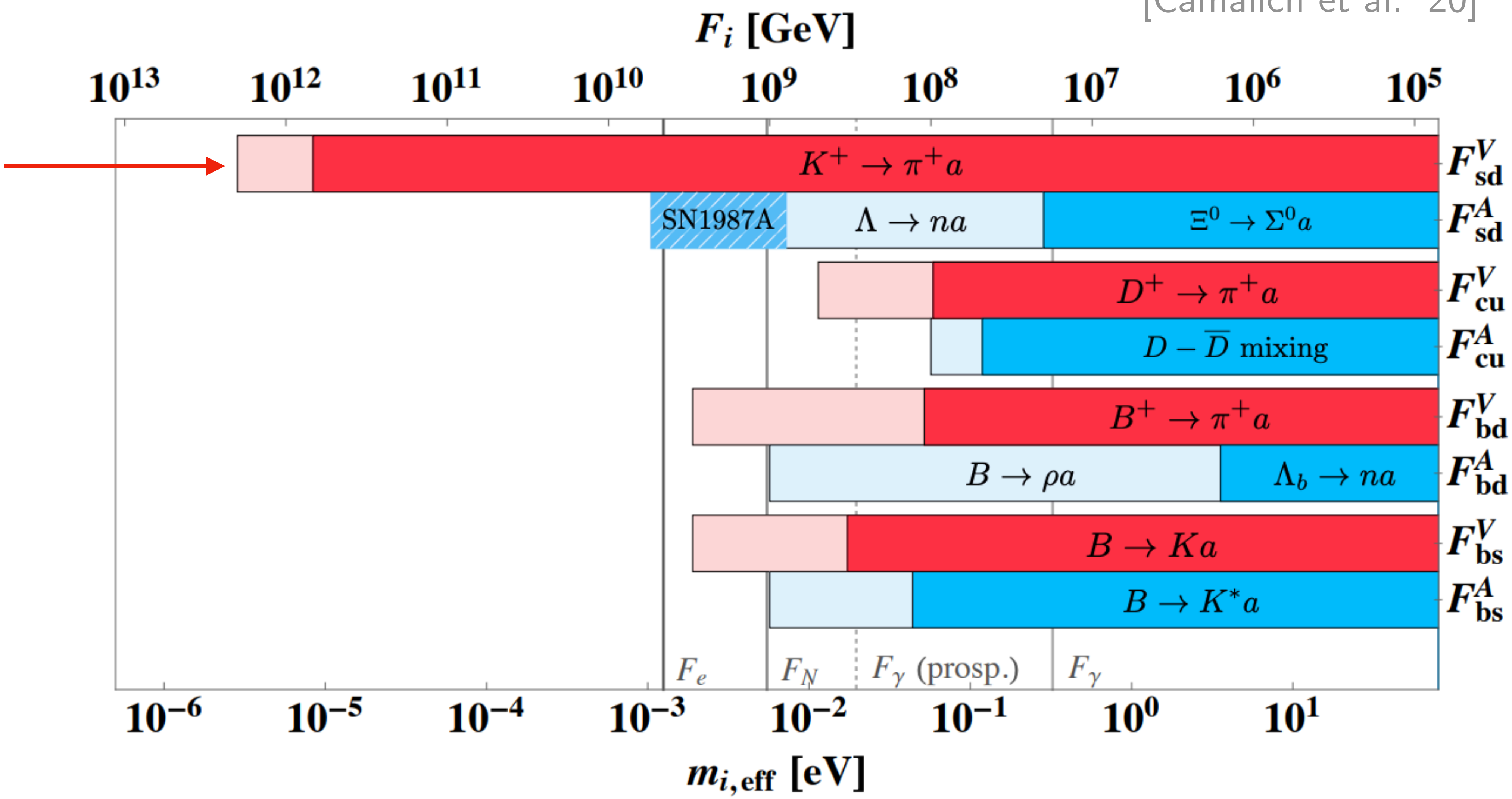
III. ALPs

The **most stringent constraints** on ALPs arise from **flavor-violating** decays $K \to \pi a$ if they are kinematically allowed:

[Camalich et al. '20]

$$F_{ij}^V \equiv \frac{f_a}{c_{\psi_R}^{ij} + c_{\psi_L}^{ij}}$$

$$F_{ij}^A \equiv \frac{f_a}{c_{\psi_R}^{ij} - c_{\psi_L}^{ij}}$$



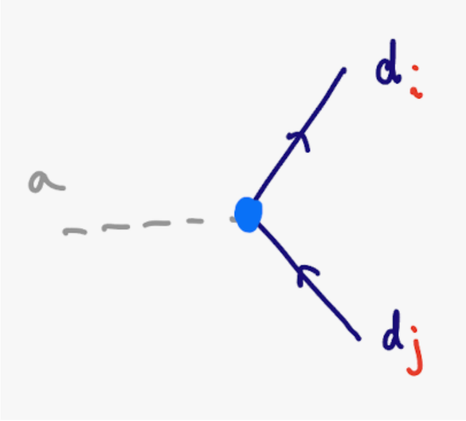
⇒ The **lower limits** on f_a depend importantly on the **flavor inputs** for c_{ff}^{ij} .

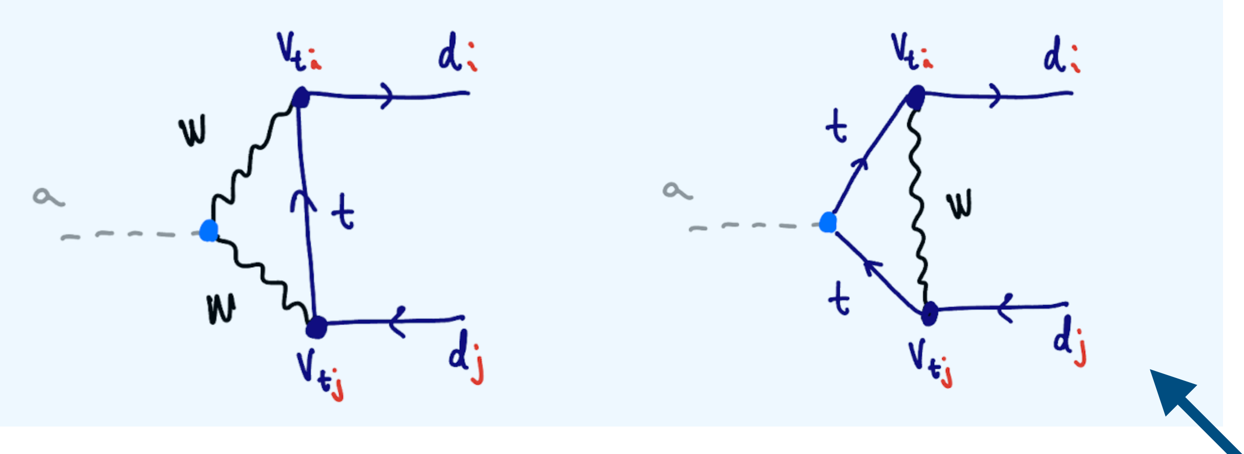
III. Flavor and ALPs

Even if **flavor-violating** couplings are forbidden in the UV, they are still unavoidably **generated** through **renormalization-group effects** *(via the flavor violation from the CKM matrix)*.

- Examples: c_{WW} or c_{tt} in the UV

[Izaguirre et al. '16], [Gavela et al **(OS)**. '19], [Bauer et al. '21]





$$c_{d_L}^{ij} \propto \frac{y_t^2\, V_{ti}^{*} V_{tj}}{16\pi^2}$$

Top-quark loops are the dominant effects!

⇒ Same **CKM suppression** of **FCNC processes** in the SM!

⇒ In such scenarios, the limits on the EFT cutoff from kaon decays are weaker — *opportunities for searches with B-mesons?*

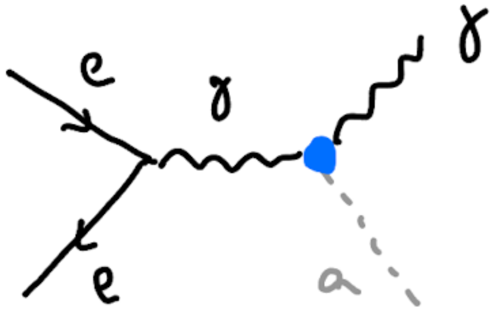
III. Looking for ALPs @ Belle-II

Direct production

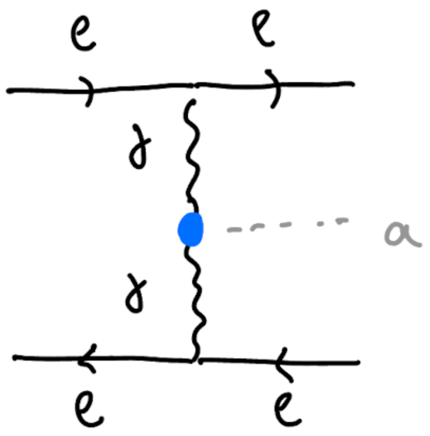
- ALPs can be *directly* produced in e^+e^- collisions:

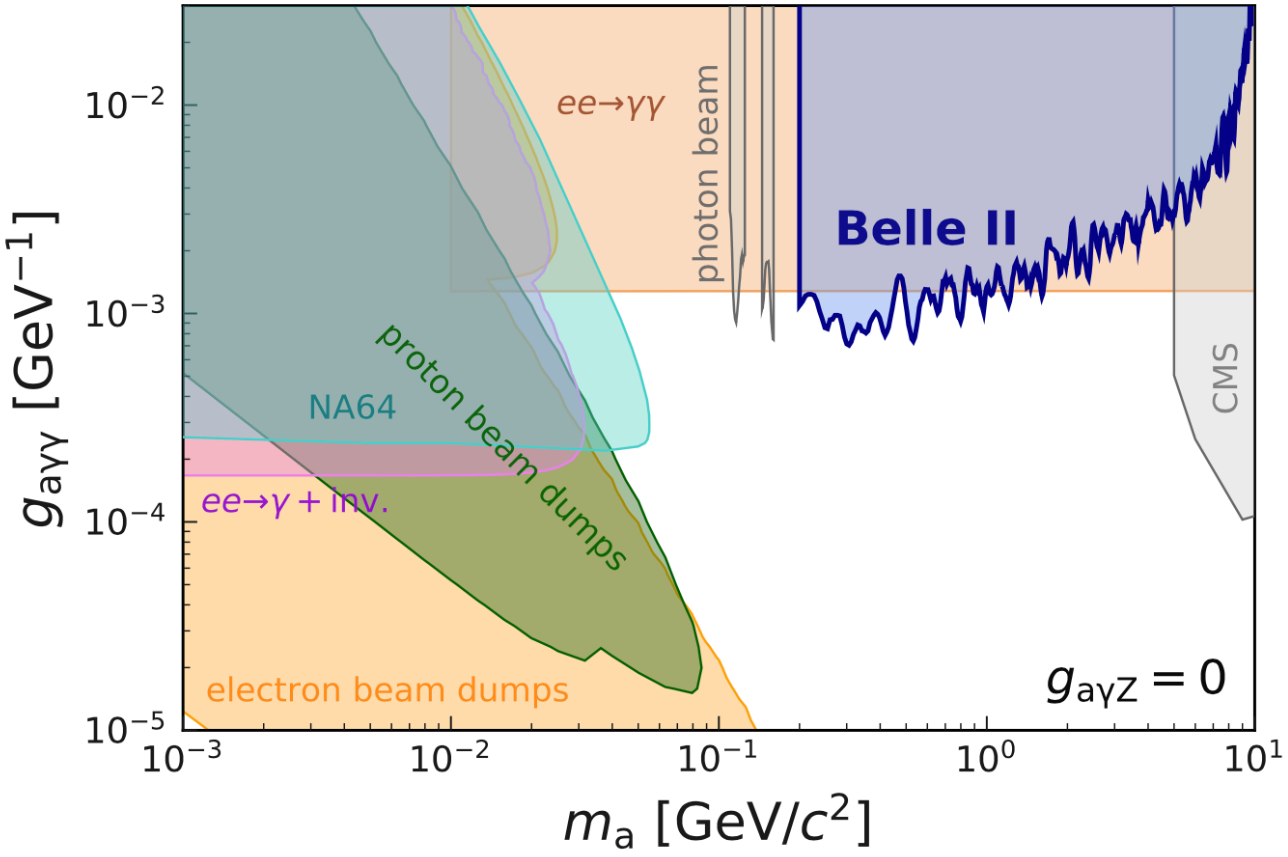
[Belle-II, 2207.06307]

"ALP-stralung"



"Photon fusion"





⇒ First channel is easier to detect as the ALP will be more energetic. [Dolan et al. '16]

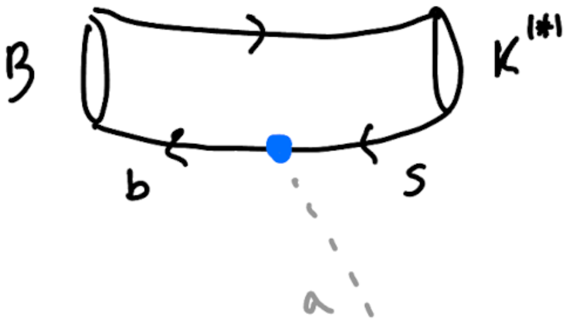
$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 - \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

III. Looking for ALPs @ Belle-II

Production in B-decays

[Izaguirre et al. '16], [Dobrich et al. '18], [Gavela et al **(OS)**. '19], [Bauer et al. '21]

- ALPs can also be **indirectly produced** in the decays of B-mesons:



$$\mathscr{B}(B \to Ka) \propto |c_V^{sb}|^2$$

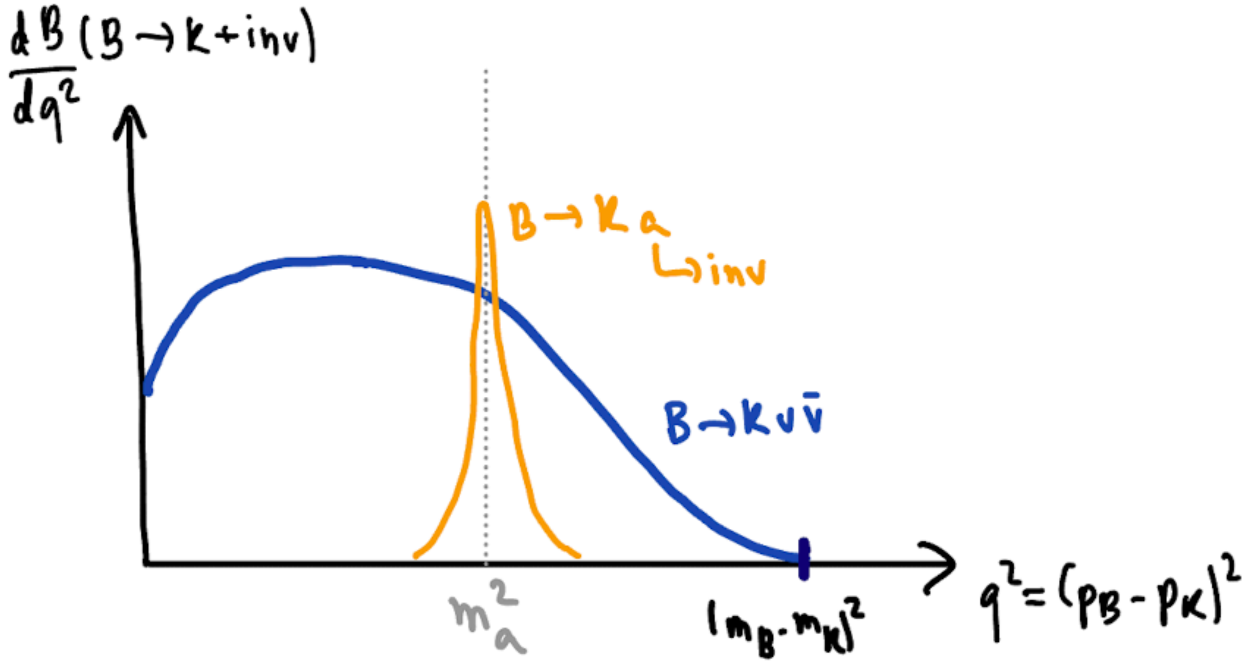
$$\mathscr{B}(B \to K^*a) \propto |c_A^{sb}|^2$$

- **Different kinematics** compared to SM processes: *two vs three-body decay*

e.g., for the invisible ALP

Assumption:

$$\mathscr{B}(a \to \text{inv}) = 1$$



NB. The flavor-conserving couplings can be probed in decays of quarkonia such as $\Upsilon(nS) \to a\gamma$ — weaker constraint, but complementary as it probes different couplings.

[Dolan et al. '16], [Merlo et al. **(OS)** '19]

[Intermezzo: $B \to K\nu\bar{\nu}$ at Belle-II]

- The first determination of $\mathscr{B}(B \to K + \mathrm{inv})$ by Belle-II shows a mild excess ($\approx 3\sigma$) w.r.t. the SM predictions:

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})^{\mathrm{SM}} = (4.4 \pm 0.3) \times 10^{-6}$$

[Becirevic, Piazza, **OS**. '23]

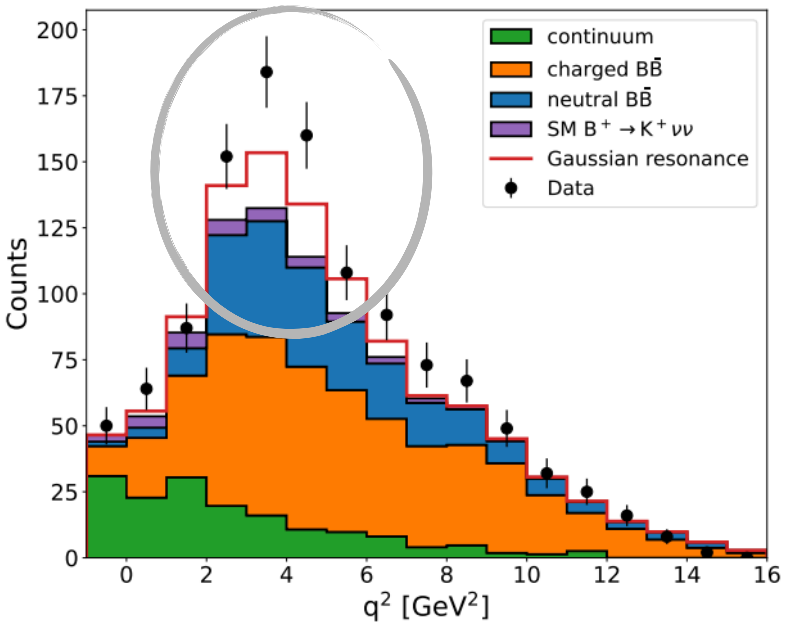
*using FNAL & HPQCD FFs

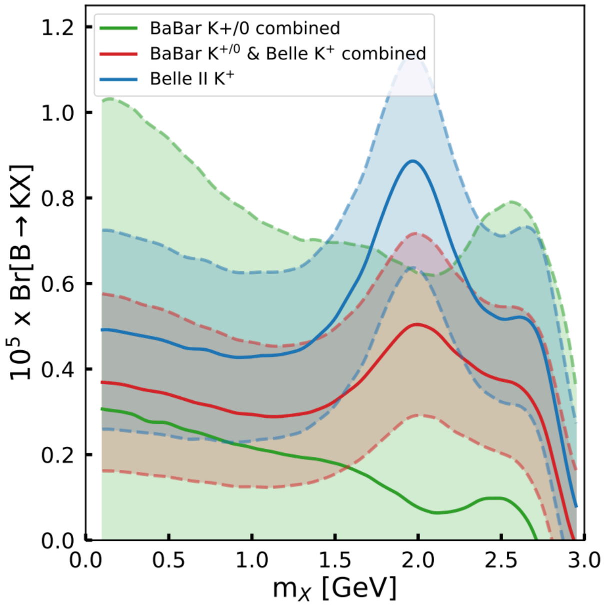
$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})^{\mathrm{exp}} = \left[2.4 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})\right] \times 10^{-5}$$

[Belle-II, 2311.14647]

- If the excess is due to $B \to KX(\to \mathrm{inv})$, where $X \sim (\mathbf{1},\mathbf{1},0)$ is a mediator produced on-shell *(i.e., with $m_X < m_B$),* the main difference would be a **peak** at $q^2 \simeq m_X^2$.

- **Good fit** to Belle-II data since the excess is mostly localised (**within large uncertainties**), but there is a **small tension** with previous searches for light mediators by **BaBar**:





Best fit (2.8σ): $m_X \approx 2$ GeV

$$\mathcal{B}(B \to KX) = (5.1 \pm 2.1) \times 10^{-6}$$

[Altmannshofer et al. '23]

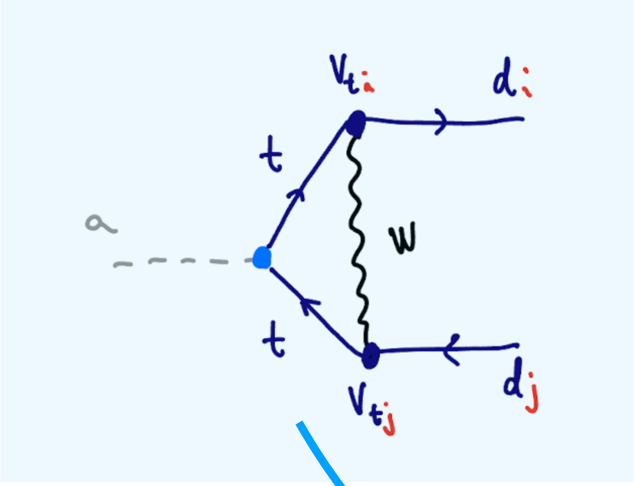
⇒ To be checked by **dedicated searches** at **Belle-II**!

III. Looking for invisible ALPs @ Belle-II

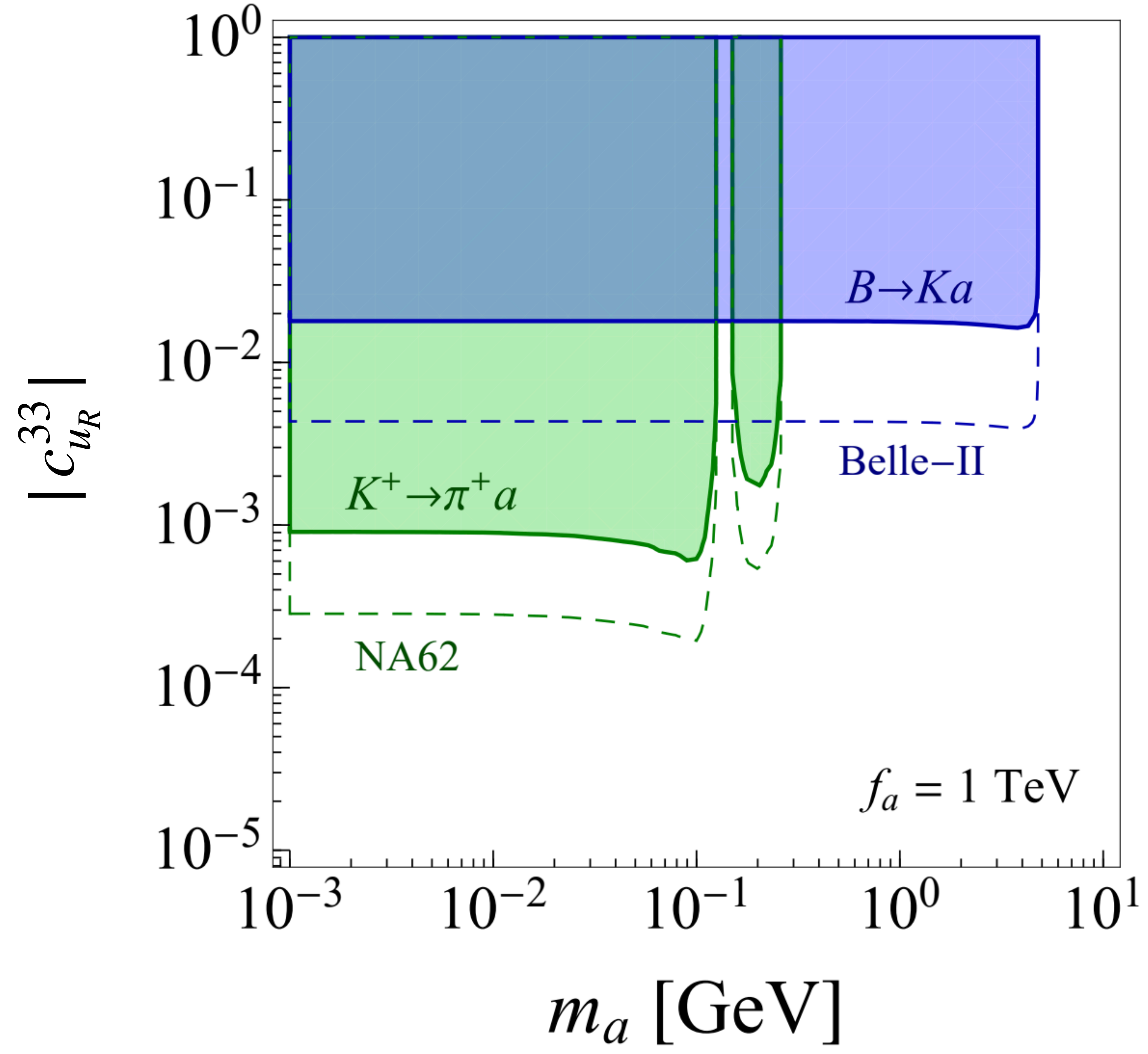
$c_{u_R}^{ij} = c_{u_R}\delta^{ij}$

Example: universal coupling to up-quarks in the UV

adapted from [Gavela et al **(OS)**. '19]



$$\propto \frac{y_t^2}{16\pi^2} V_{ti} V_{tj}^*$$



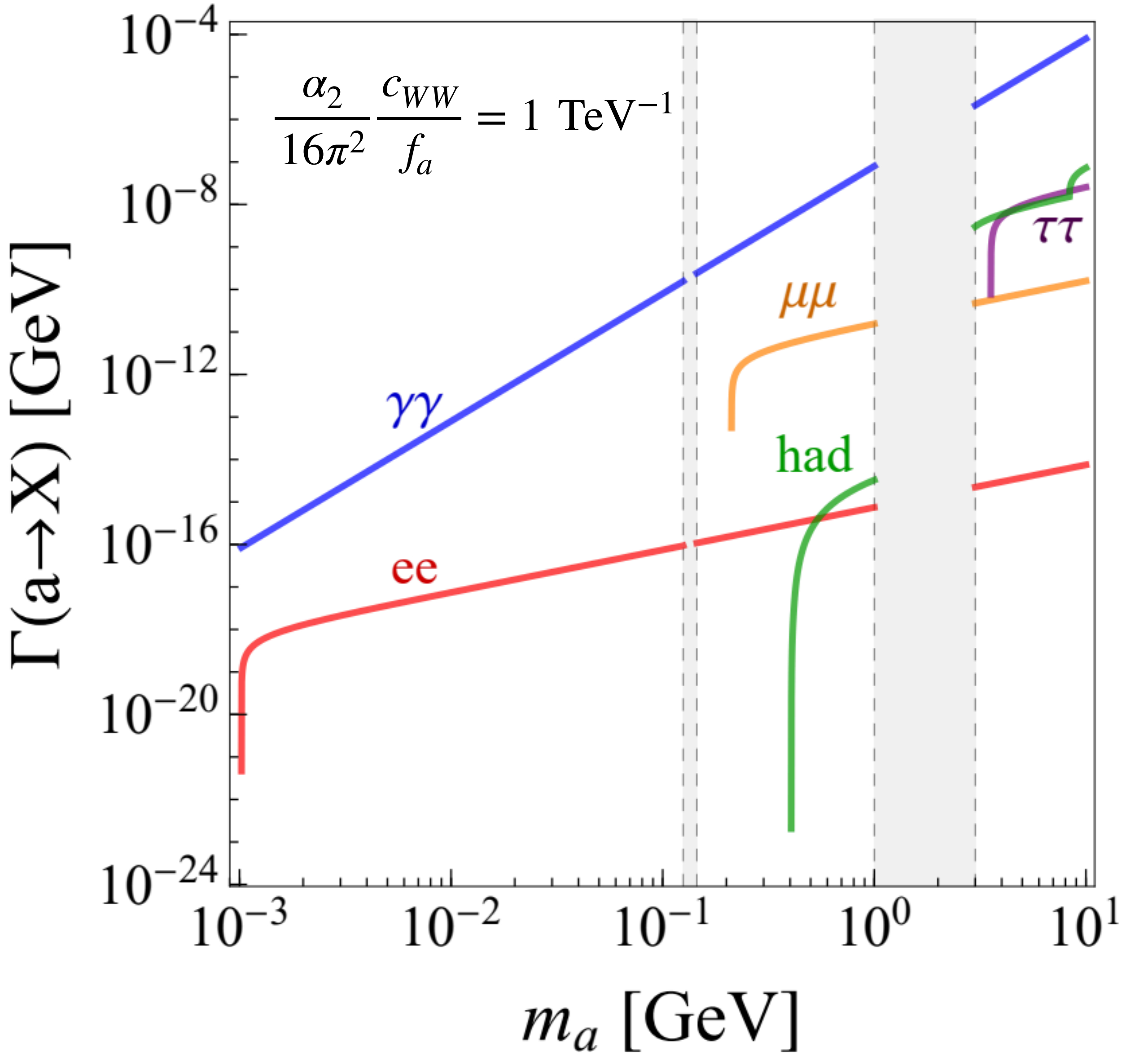
**assuming that the ALP decays into invisibles particles (from the dark sector)*

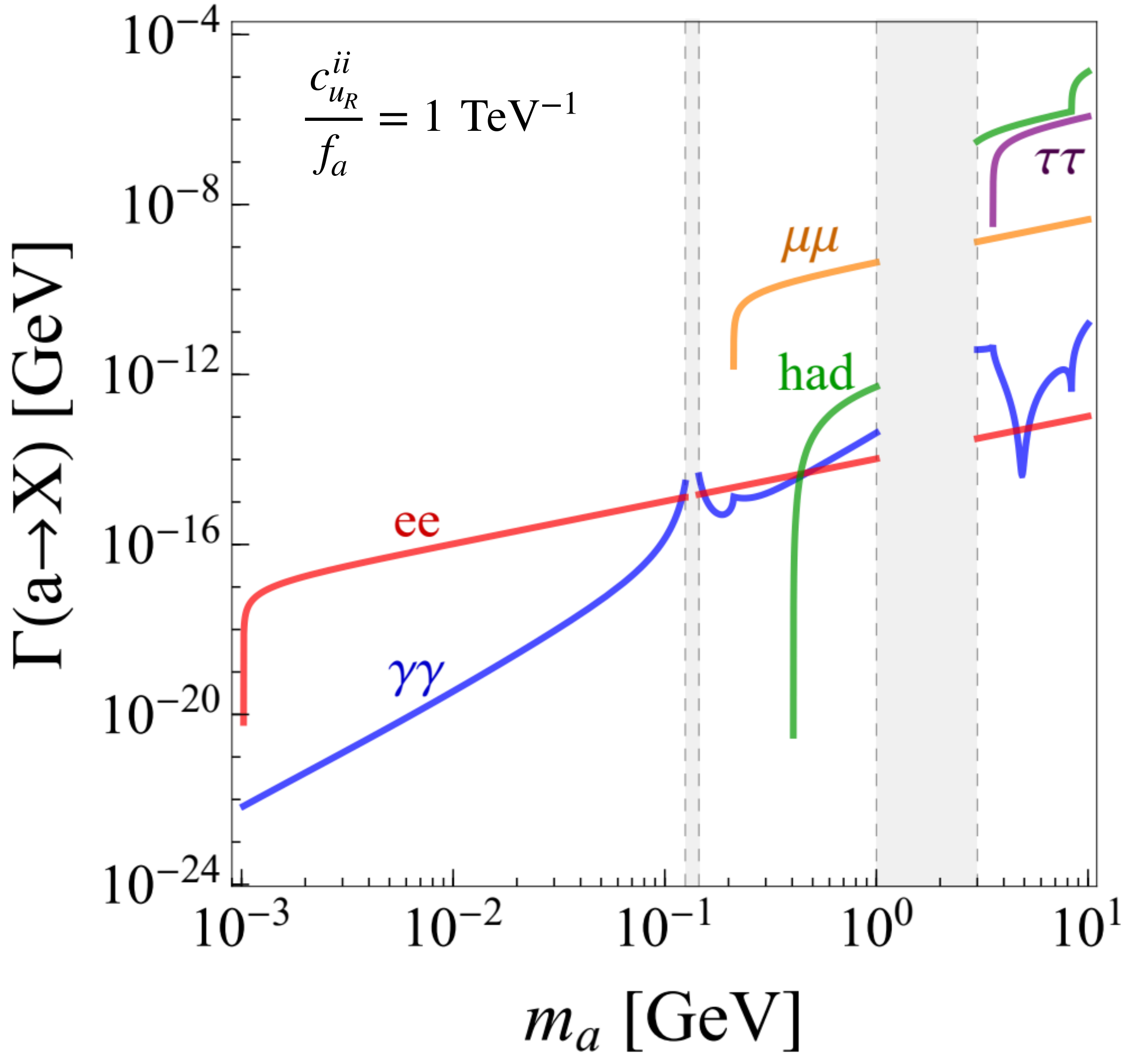
III. Looking for visible ALPs @ Belle-II

ALP decay channels

- **Model-dependent input:**

[Gavela et al. **(OS)** '19]





Even if an ALP coupling is set to zero, it will be generated through loops.

[Bauer et al. '17, '20, '21]

III. Looking for visible ALPs @ Belle-II

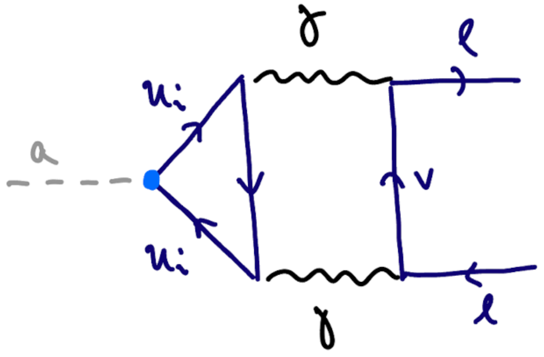
$c_{u_R}^{ij} = \delta^{ij}$

Benchmark: universal coupling to up-quarks in the UV

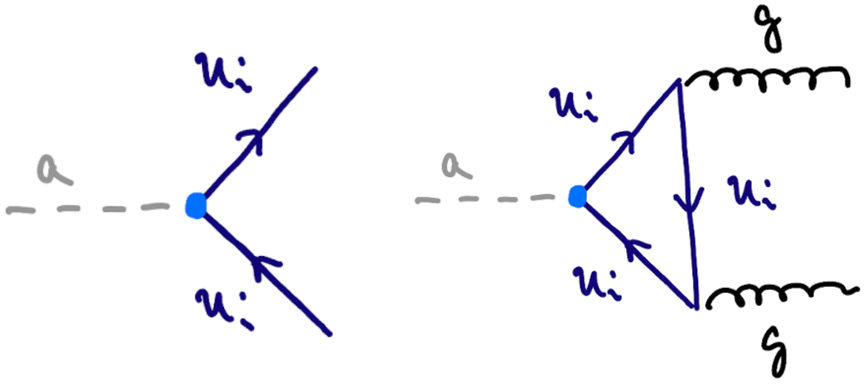
- **ALP production:**

Dominant production through **FCNC** processes

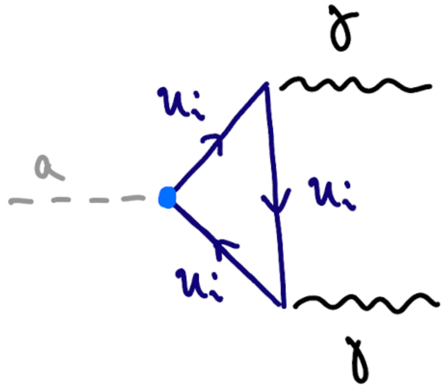
- **ALP decays:**



Leptons



Hadrons



Photons

ALP production and decays are induced by the same couplings

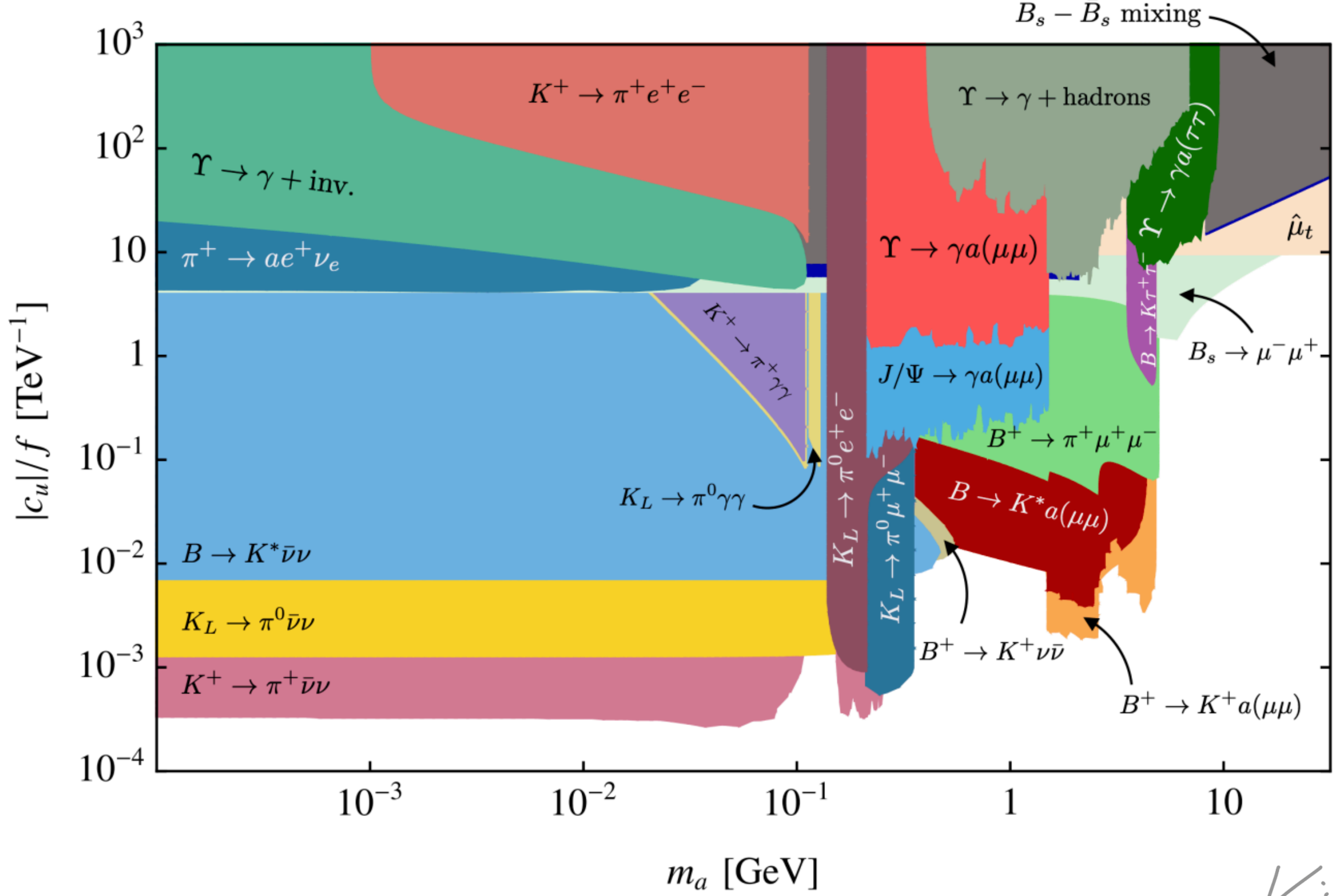
[Bauer et al. '20]

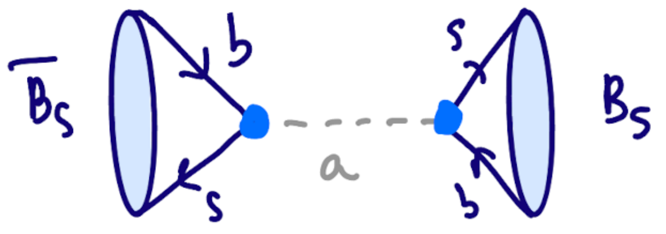
III. Looking for visible ALPs @ Belle-II

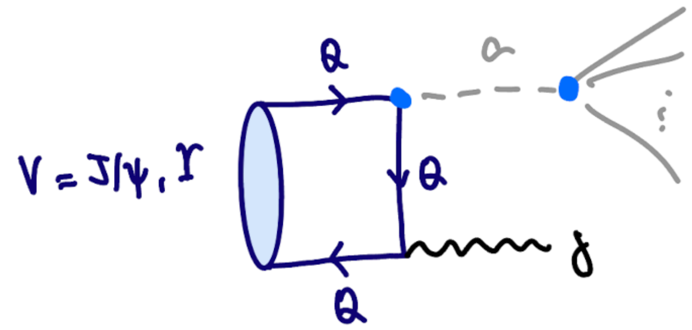
$c_{u_R}^{ij} = \delta^{ij}$

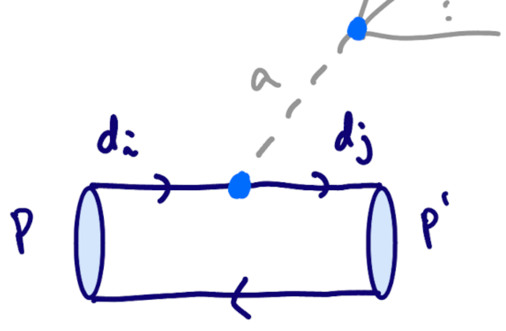
Benchmark: universal coupling to up-quarks in the UV

[Bauer et al. '20]









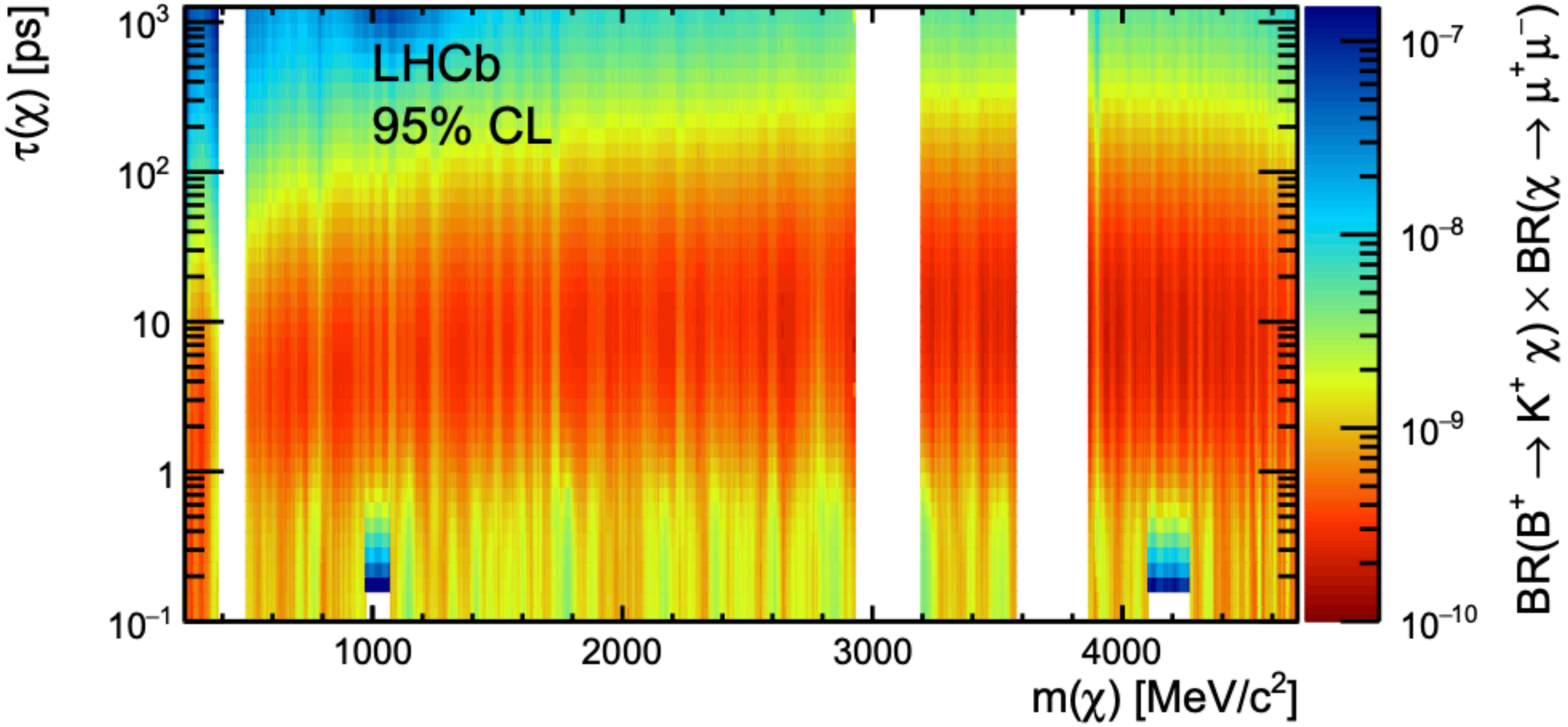
[Intermezzo] $B \to K^{(*)} a(\to \mu\mu)$ at LHCb

- A **caveat** of **searches** for **long-lived particles** (such as ALPs) decaying into visible final states is the **dependence** of the signal yields on the **lifetime** (very model-dependent!).

[Dobrich et al. '18]

- Good examples are the searches of $B \to K^{(*)} a(\to \mu\mu)$ by LHCb, which provide not only the limit on the branching fraction but also its **dependence on the lifetime** (τ_a):

[LHCb, 1508.04094,1612.07818]



⇒ It is **straightforward** to **reinterpret these results** for any ALP model!

Concrete examples

- Vector Portals
- ALPs
- Sterile neutrinos

IV. Sterile neutrinos

see e.g. [Criado et al. 2104.14443]

The EFT used to describe BSM changes if new light particles are assumed:

- **Example:** SM + fermion singlet (RH neutrino, N_R)

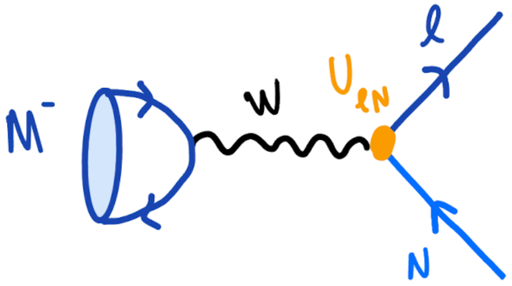
Majorana mass

Neutrino Yukawa

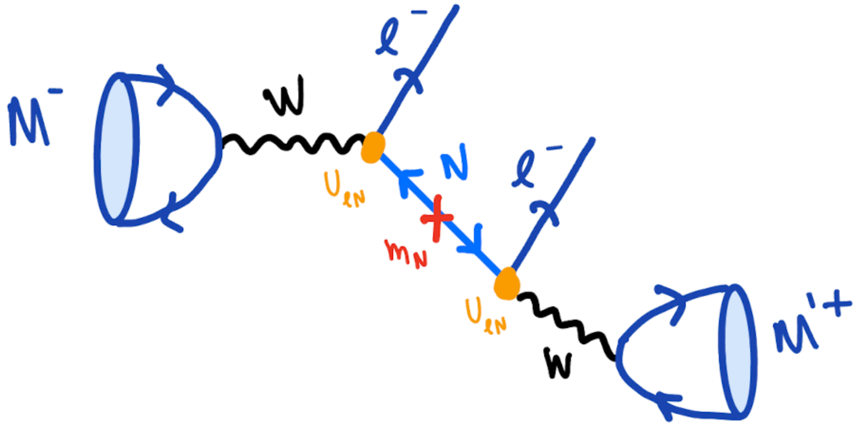
$$\mathscr{L}_{\text{eff}} \supset -\frac{1}{2}\bar{N}_R^C \boldsymbol{M}_{N_R} N_R - \left(\bar{L}\boldsymbol{Y}_\nu \tilde{H} N_R + \text{h.c.}\right) + \frac{1}{\Lambda}(H^\dagger H)(\bar{N}_R^C \boldsymbol{c}_{\nu H}^{(5)} N_R) + \frac{1}{\Lambda}(\bar{N}_R^C \sigma_{\mu\nu} \boldsymbol{c}_{\nu B}^{(5)} N_R)B^{\mu\nu} + \mathcal{O}(\Lambda^{-2})$$

The **mixing** of **active** and **sterile neutrinos** after EWSB can give rise to signatures at experiments such as Belle-II and LHCb.

see e.g. [LHCb 2011.05263]



Higher-dimensional operators can induce **new phenomena** such as the (transition) neutrino magnetic moment.



IV. Sterile neutrinos

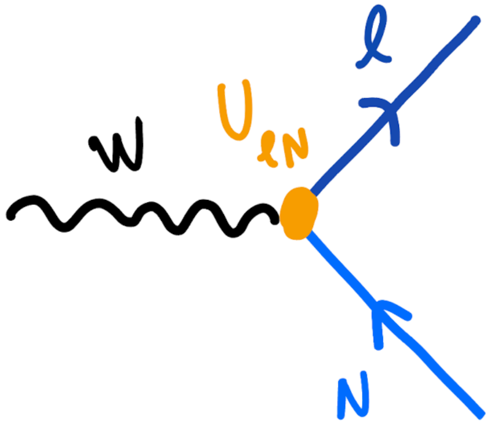
For simplicity, let us first *neglect higher-dimensional operators*:

- The neutrino Yukawa induces the **mixing** of **active** and **sterile neutrinos**:

The 3×3 PMNS matrix in no longer unitary!

$$U = \left(\begin{array}{c:cc} U^{3\times3}_{\text{PMNS}} & \begin{matrix} U_{eN} \\ U_{\mu N} \\ U_{\tau N} \end{matrix} & \cdots \\ \hdashline & & \end{array}\right)$$

$$\mathcal{L} \supset \frac{g}{\sqrt{2}} W^-_\mu \sum_{\alpha=e,\mu,\tau} \sum_{i=1}^{3+N} U_{\alpha i}\, \bar{\ell}_\alpha \gamma^\mu P_L \nu_i + \text{h.c}$$



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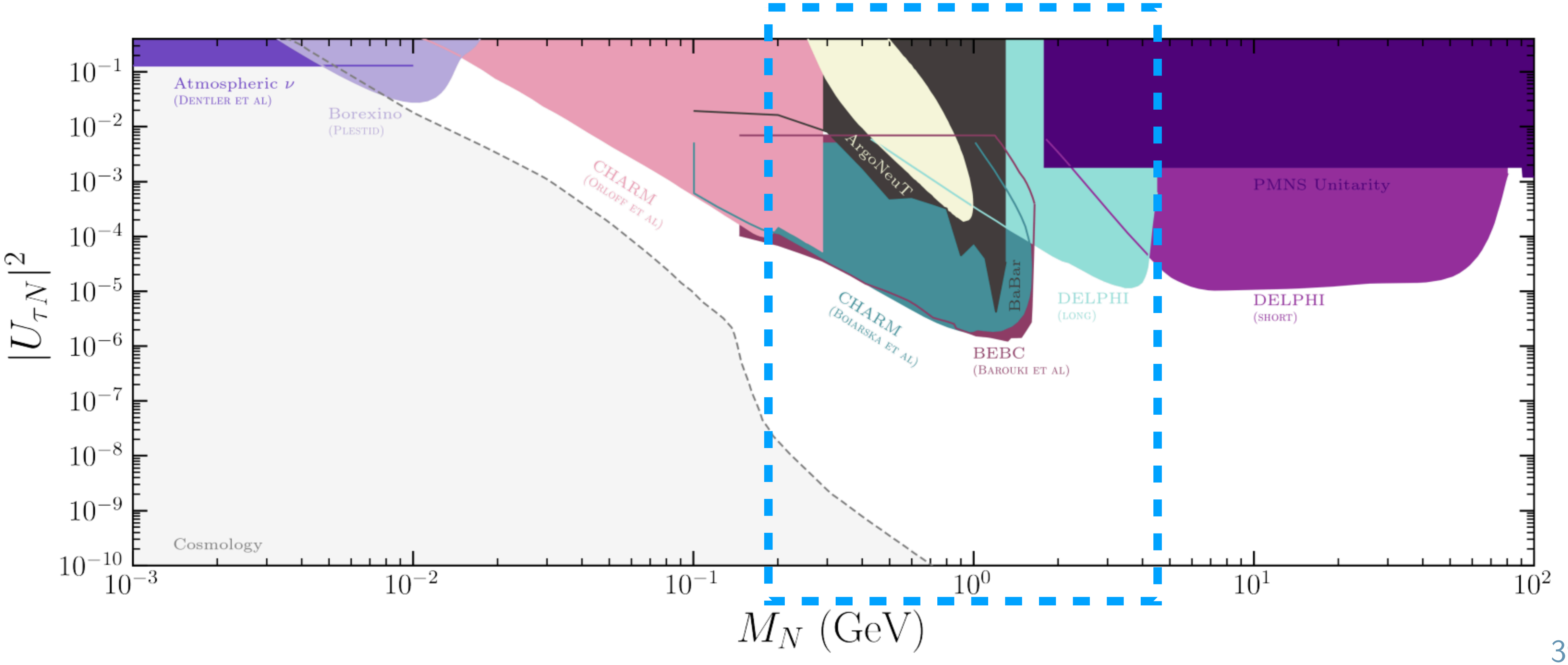
- Possible **experimental signatures**:
  - $P \to \ell N$
  - $P \to P' \ell N$
  - $P \to P' \nu N$
  - $\tau \to P N$
  - LNV decays.

[Fernandez-Martinez et al., '23]



IV. Sterile neutrinos (bis)

- There is a **rich phenomenology** associated with **higher-dimensional** operators with **right-handed neutrinos.**

see e.g. [Altmannshofer et al. '18], [Chala et al. '21]...

- In B-physics, they could *e.g.* induce a **different q^2-shape** of **$B \to K\nu\bar{\nu}$ decays** — *impossible with operators made only of LH neutrinos!*

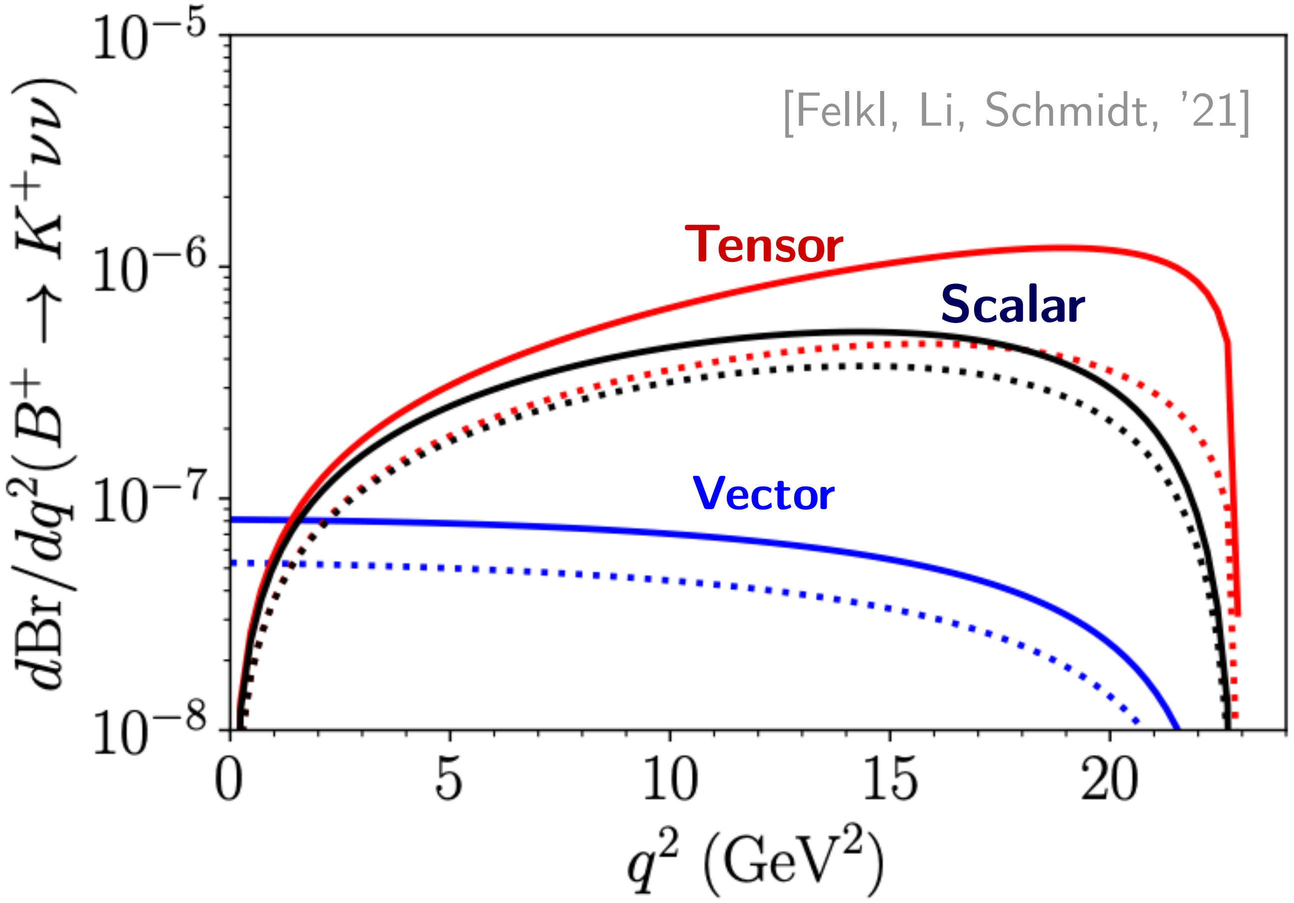
[Piazza, Becirevic, **OS**. '23]

$$\mathcal{O}_{V_{LR}} = \left(\bar{s}\gamma^{\mu}P_L b\right)\left(\bar{N}\gamma^{\mu}P_R N\right)$$

$$\mathcal{O}_{S_{RL}} = \left(\bar{s}P_R b\right)\left(\bar{N}P_L \nu\right)$$

$$\mathcal{O}_{T_L} = \left(\bar{s}\sigma^{\mu\nu}P_L b\right)\left(\bar{N}\sigma_{\mu\nu}P_L \nu\right)$$

... and $(L \leftrightarrow R)$



Measurements of the **q^2-shape** of $B \to K\nu\bar{\nu}$ decays could **probe such scenarios!**

see also [Bolton et al. 24]

Summary

Summary

- There must be **physics beyond the SM**, but current **data does not favor any specific scenario** — *which UV completion? at which energy scale?*
- There is a growing interest in scenarios with **light and weakly interacting particles**, as they are often associated with different experimental signatures — in many cases, *yet unexplored*.
- Some of these scenarios are **interesting and theoretically motivated**, which could be e.g. related to the issue of Dark Matter or other SM problems.
- They often lead to **model-dependent signatures** due to the light particles in the spectrum — *which will depend on their nature and/or the flavor ansatz for their couplings to the SM.*
- The notion of **dark sector** is useful (renormalizable or not), which helps us to define consistent **benchmark scenarios** for searches for light particles (visible or invisible).
- **Flavor experiments** such as Belle-II can help us **push the boundaries** via the usual **precision tests**, but also by looking for **light new physics scenarios**.

Many opportunities to explore with current/future data!

References

- Snowmass Dark Sector Physics Report

  arXiv:hep-ph/2209.04671

- Physics Beyond Colliders at CERN

  arXiv:hep-ph/1901.09966

- Exploring Dark Sectors with High-Intensity Exps.

  arXiv:hep-ph/2207.06905

- Lectures on Dark Sectors, Invisibles'17

  Brian Batell, https://indico.cern.ch/event/592370/

- Flavor phenomenology of ALPs:

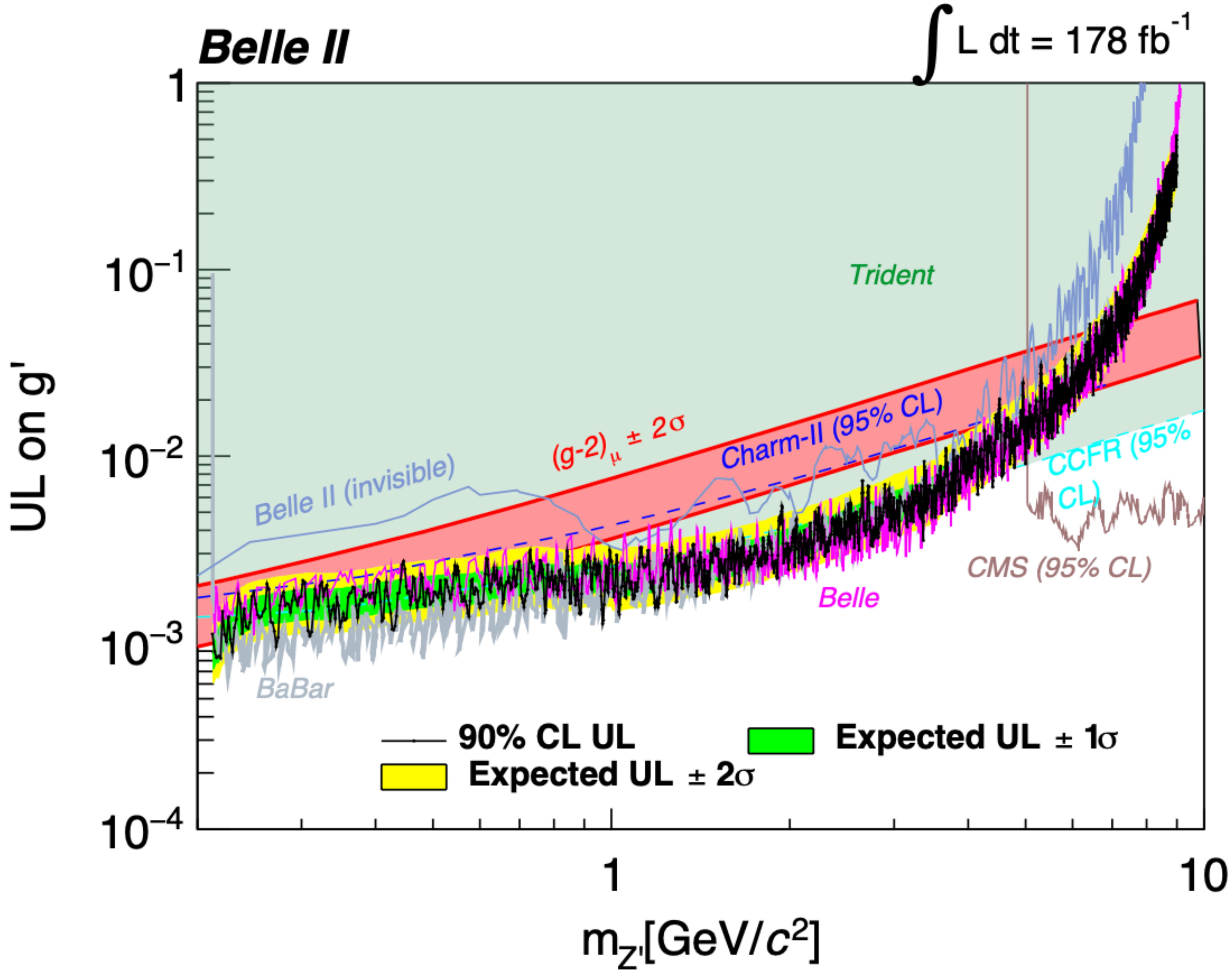
  Bauer et al., arXiv:hep-ph/2110.10698

- Heavy Neutral Leptons:

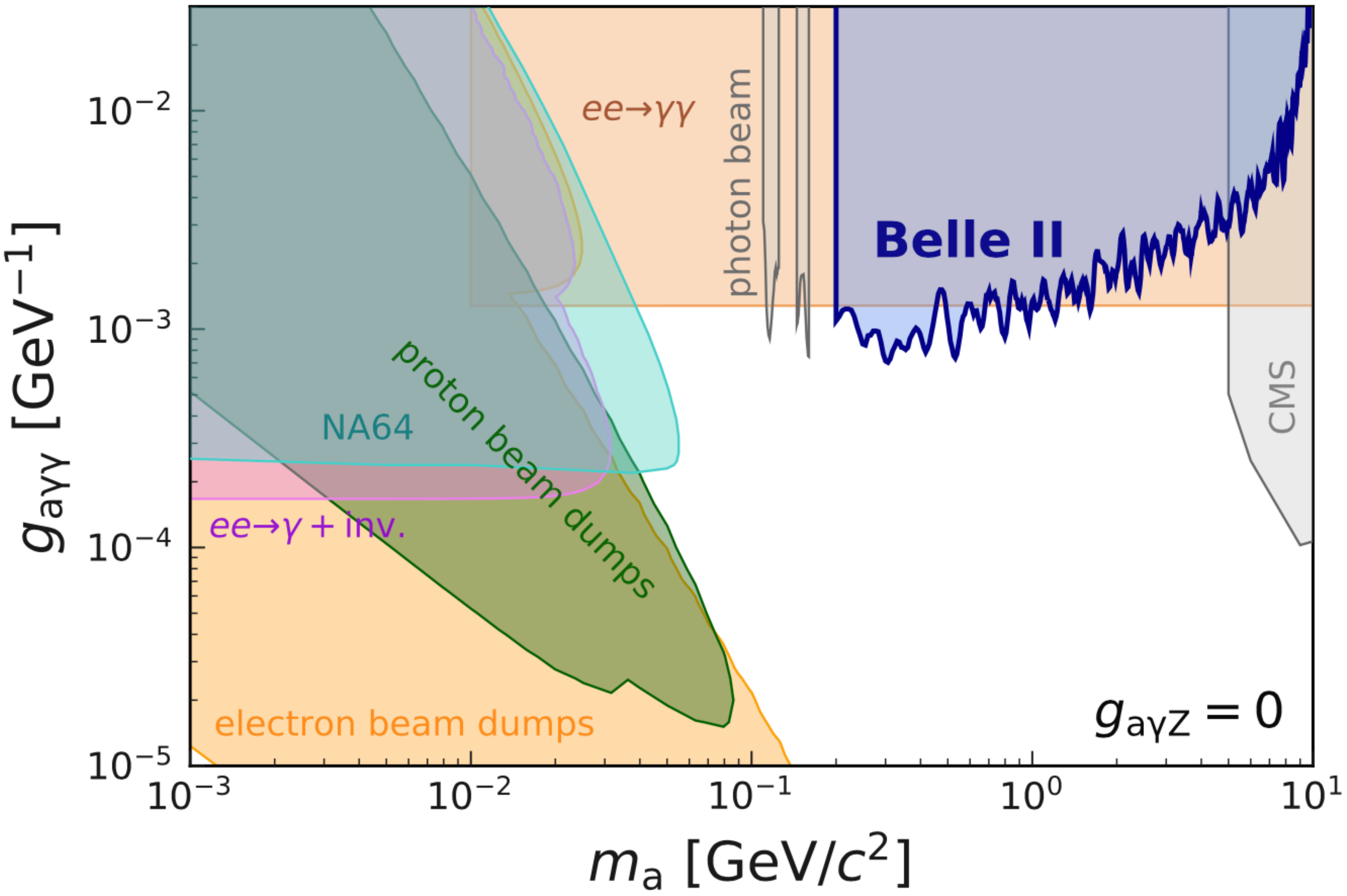
  Férnandez Martinez et al., arXiv:hep-ph/2304.06772

Thank you!

Back-up


Belle II
∫L dt = 178 fb^{-1}
UL on g'
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
10
$m_{Z'}$[GeV/c^2]
Trident
$(g-2)_\mu \pm 2\sigma$
Charm-II (95% CL)
Belle II (invisible)
CCFR (95% CL)
CMS (95% CL)
Belle
BaBar
90% CL UL
Expected UL ± 1σ
Expected UL ± 2σ

ALPs at Belle-II



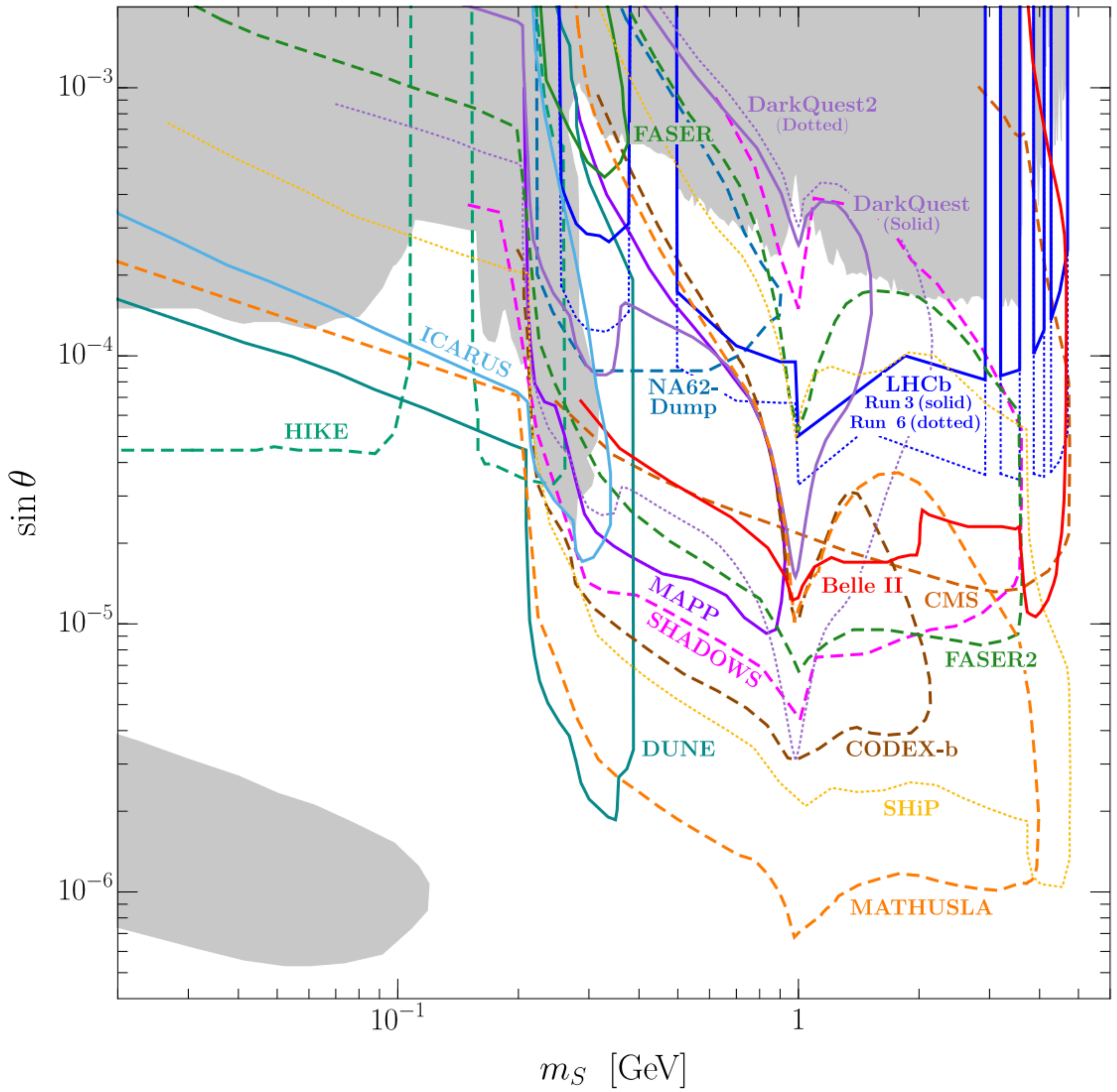
Dark Higgs

$$-\mathscr{L} \supset (A\,S + \lambda_S\,S^2)\,H^\dagger H$$

EWSB induces the **mixing** between the **dark Higgs** (S) and the SM-Higgs (h):

- Mixing angle θ .
- S couplings to SM particles are proportional to $\sin\theta$
- Only two parameters: $\{m_S,\, \sin\theta\}$

[Batell et al. '22]

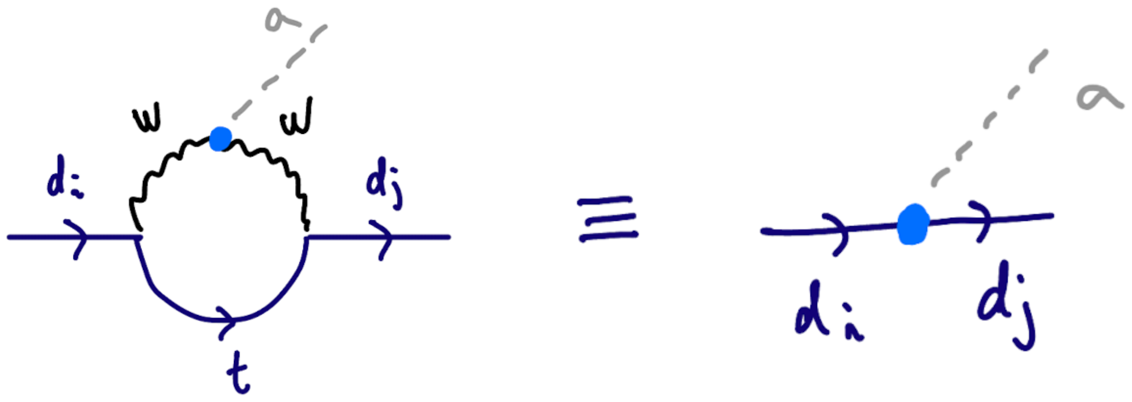


III. Looking for ALPs @ Belle-II

$c_{WW} = 1$

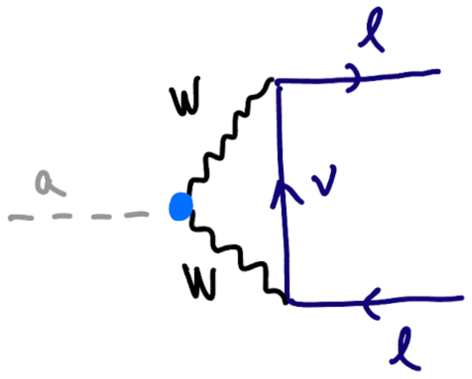
Benchmark: coupling to $SU(2)_L$ gauge bosons in the UV

- **ALP production:**

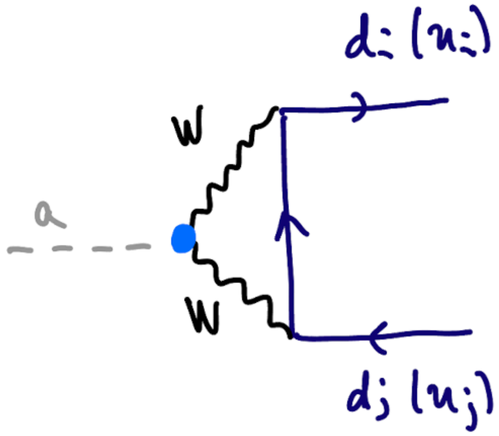


Dominant production through **FCNC** processes

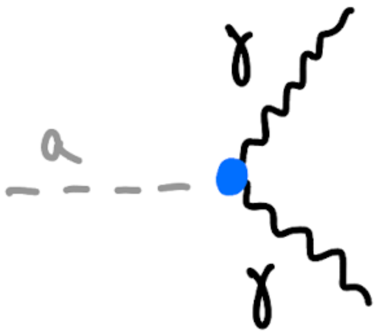
- **ALP decays:**



Leptons



Hadrons



Photons

[Bauer et al. '20]

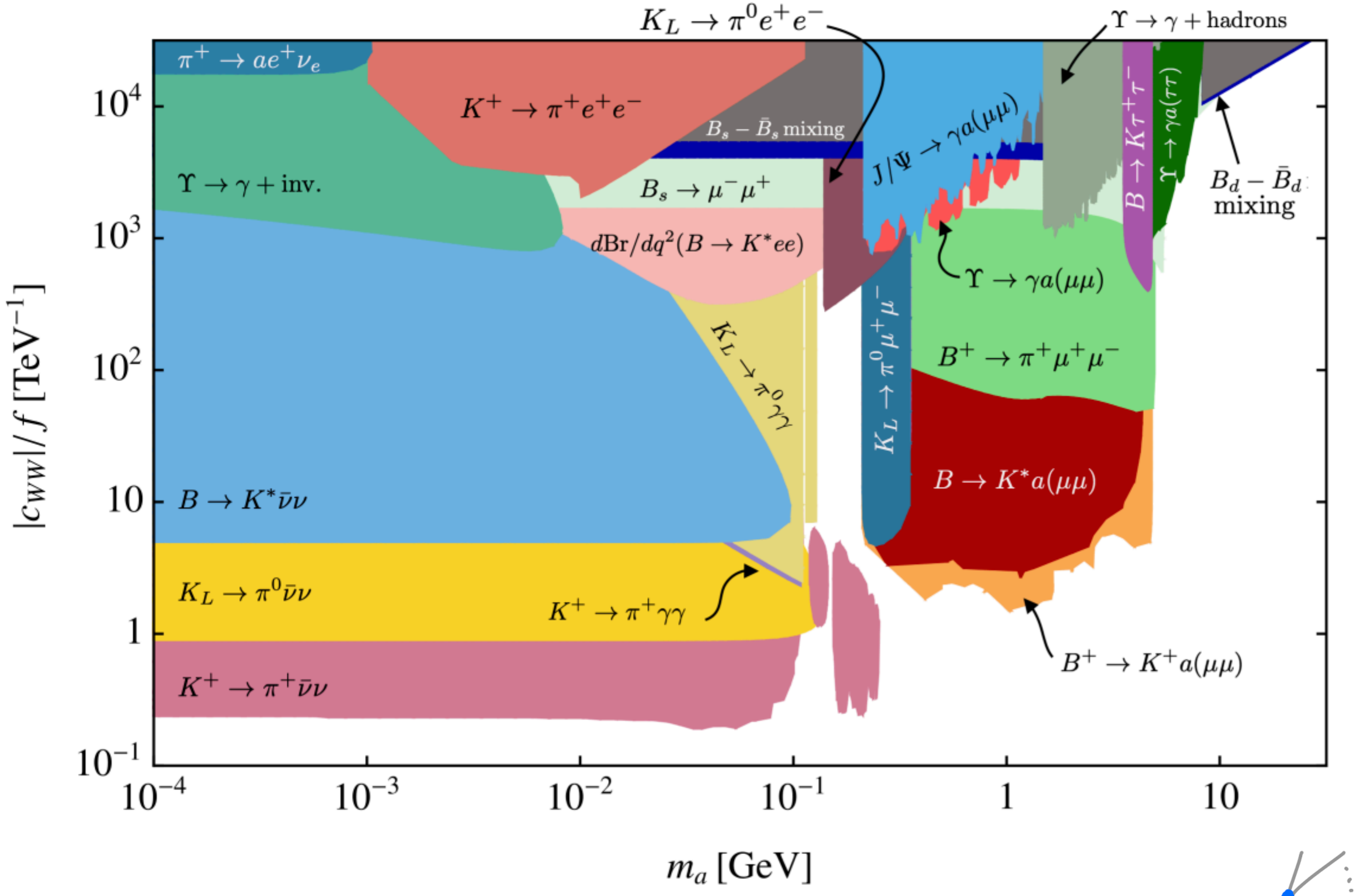
ALP production and decays are induced by the same couplings

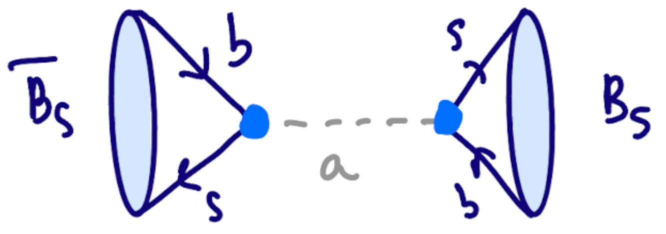
III. Looking for ALPs @ Belle-II

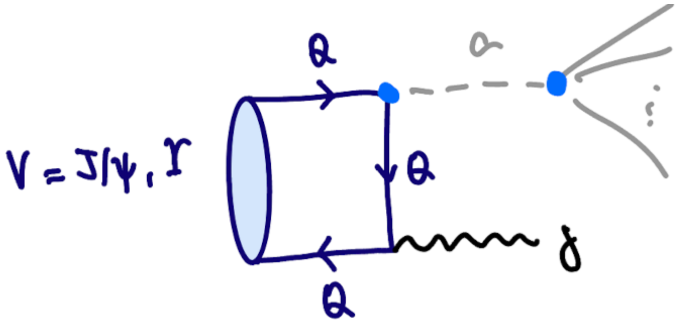
$c_{WW} = 1$

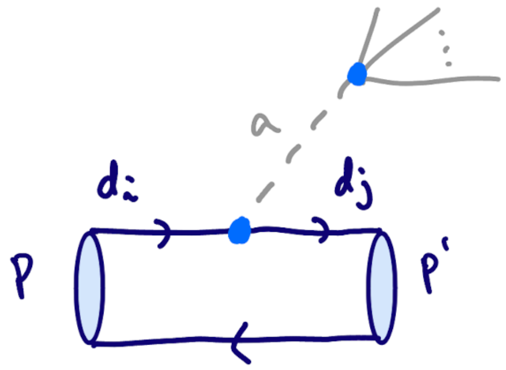
Benchmark: coupling to $SU(2)_L$ gauge bosons in the UV

[Bauer et al. '20]









[Reminder] Strategy

- Consider a (light) mediator X coupled to the SM:

Parameters:

$$\begin{cases} m_X & \equiv \text{mediator mass} \\ g_{\text{SM}} & \equiv \text{coupling(s) to the SM} \\ g_{\text{dark}} & \equiv \text{coupling(s) to the dark sector} \end{cases}$$

(+ DM mass)

- The same **portal coupling** (g_{SM}) can **induce decays** back to **visible states**:

$\Rightarrow$ **Visible/displaced/long-lived** signatures are **possible**, depending on $\{m_X, g_{\text{SM}}\}$, as well as g_{dark} if there are dark sector particles lighter than m_X.

$$\Gamma(X \to \text{SM}) \propto g_{\text{SM}}^2\, m_X$$

$$\Gamma(X \to \text{dark}) \propto g_{\text{dark}}^2\, m_X$$

(If kinematically allowed)

e.g., for $|g_{\text{dark}}| \lll |g_{\text{SM}}|$