Overview of sub-GeV Physics in the Dark sector (theory side)

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IP2I – UCBL

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Outline

Introduction : dark sectors and Feebly Interacting Particles

Classifying portal interactions to understand dark sectors

How to produce dark sector particles with a $e^{\pm}$ beam

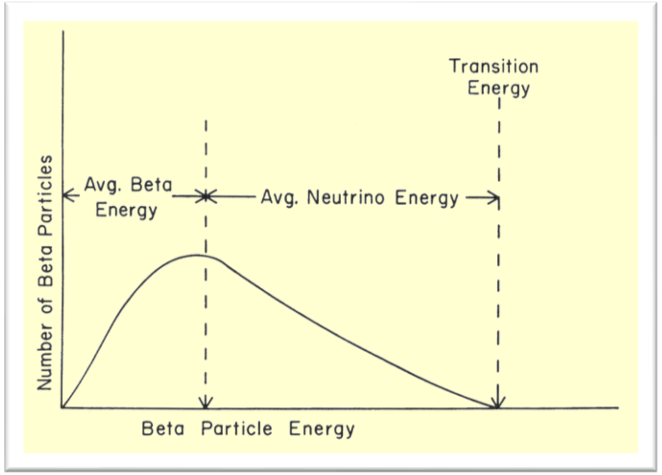
Back in time: neutrinos as a dark sector

- In the thirties, the study of beta nuclei decays led to a puzzling situation
  - → Energy conservation appeared broken …

$$ {}^{1}_{0}n \longrightarrow {}^{1}_{1}p^{+} + e^{-} + \bar{\nu}_e \quad \rightarrow \quad {}^{60}_{27}Co \longrightarrow {}^{60}_{28}Ni + e^{-} + \bar{\nu}_e $$

Only this part « known »!

Illustration P. Sprawls



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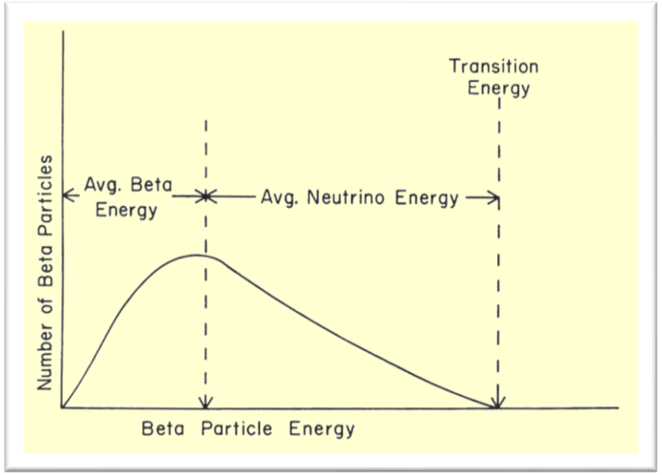


Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines […] will explain to you in more detail, how because of the "wrong" statistics of the N and Li^{6} nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, […]

W. Pauli

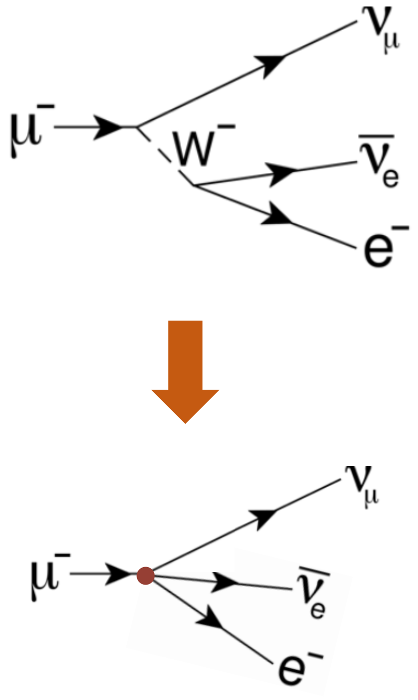
Pauli's letter of the 4th of December 1930

Back in time: neutrinos as a dark sector

- Neutrinos were the first « dark » particles

→ Their suppressed interaction arise from UV physics: the heavy EW gauge bosons

$$O_{Fermi} \propto \frac{g_W^2}{M_W^2}(\bar{\nu}_{e,L}\gamma_\mu e_L)(\bar{\mu}_L\gamma^\mu \nu_{\mu,L})$$



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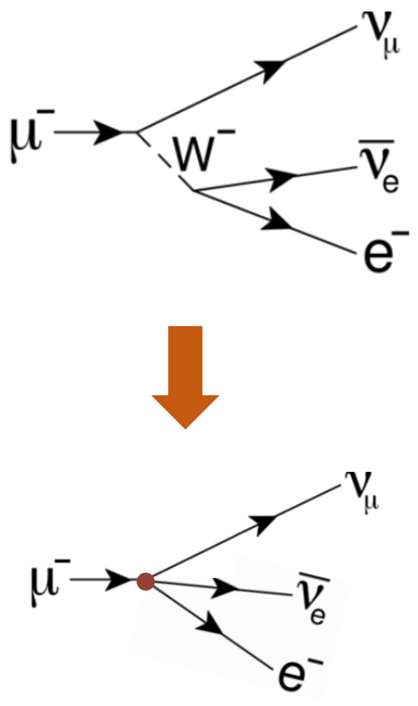
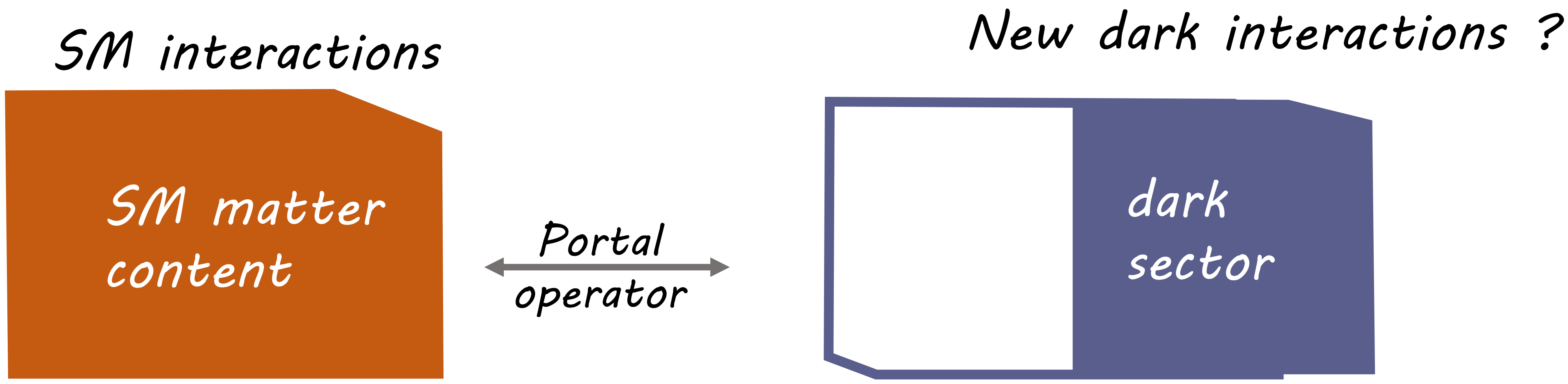


- In modern language, the Fermi operator acts as a « portal » between the « dark » neutrinos sector and the lepton and quark one

$$O_{Fermi} \propto \frac{g_W^2}{M_W^2} (\bar{\mu}_L\gamma_\mu e_L)(\bar{\nu}_{e,L}\gamma^\mu \nu_{\mu,L})$$

(use Fierz identities to exchange fermions)

From DM properties to mediator searches



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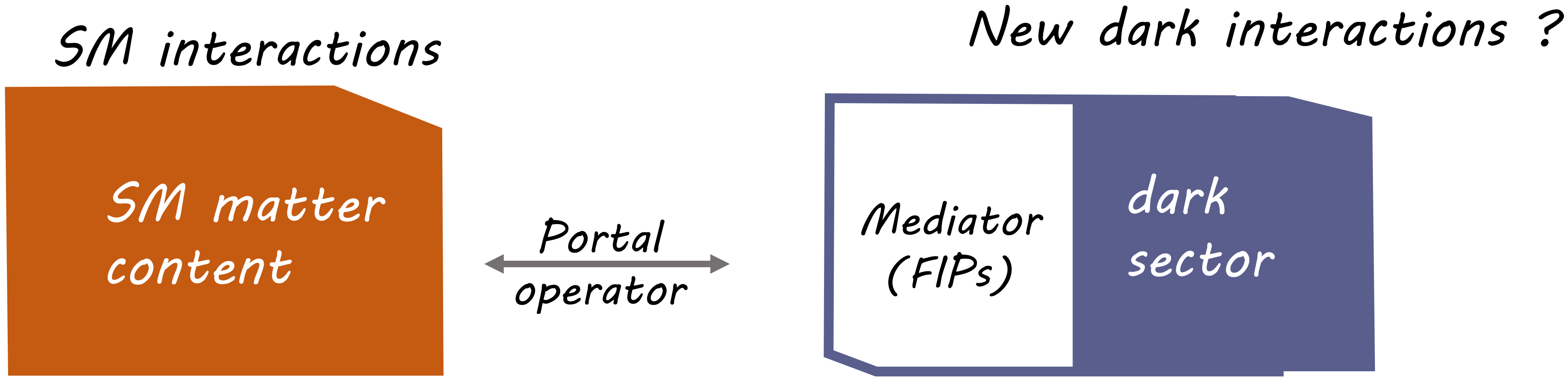

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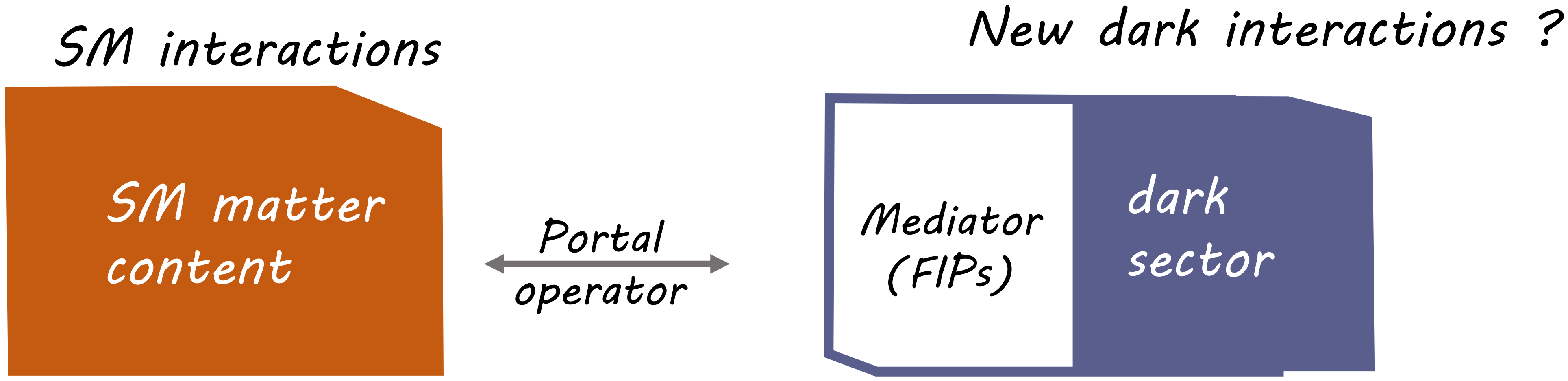


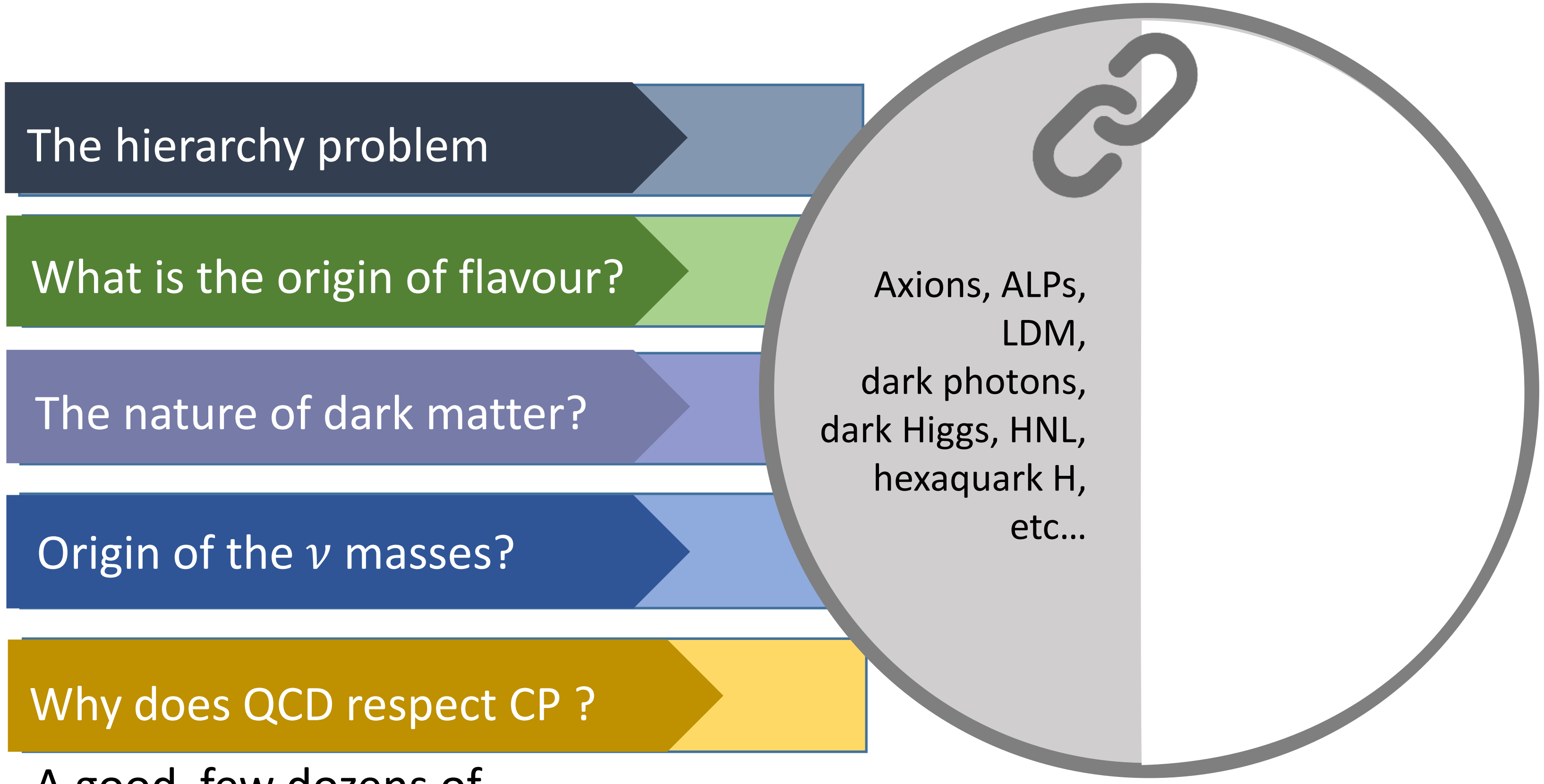
- Thus we also need a gauge singlet combination on the SM-side

- To be light but hidden, we need new particles to be completely neutral under the SM interactions (otherwise we would have seen them)

$$O_{portal} = \frac{1}{\Lambda^n} (SM)(Dark\ sectors)$$

FIPs: Feebly Interacting Particles

- FIPs = the particle interacting the most with the SM = “new neutral particle which interacts with the SM via suppressed new interactions”



A good few dozens of anomalies

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The hierarchy problem

What is the origin of flavour?

The nature of dark matter?

Origin of the ν masses?

Why does QCD respect CP ?

A good few dozens of anomalies

Axions, ALPs, LDM, dark photons, dark Higgs, HNL, hexaquark H, etc…

Searches and constraints in the MeV-GeV range mostly driven by low energy accelerators

Belle-II, NA62, KOTO,…
Mono-γ, Désintégration B,K rares, etc.

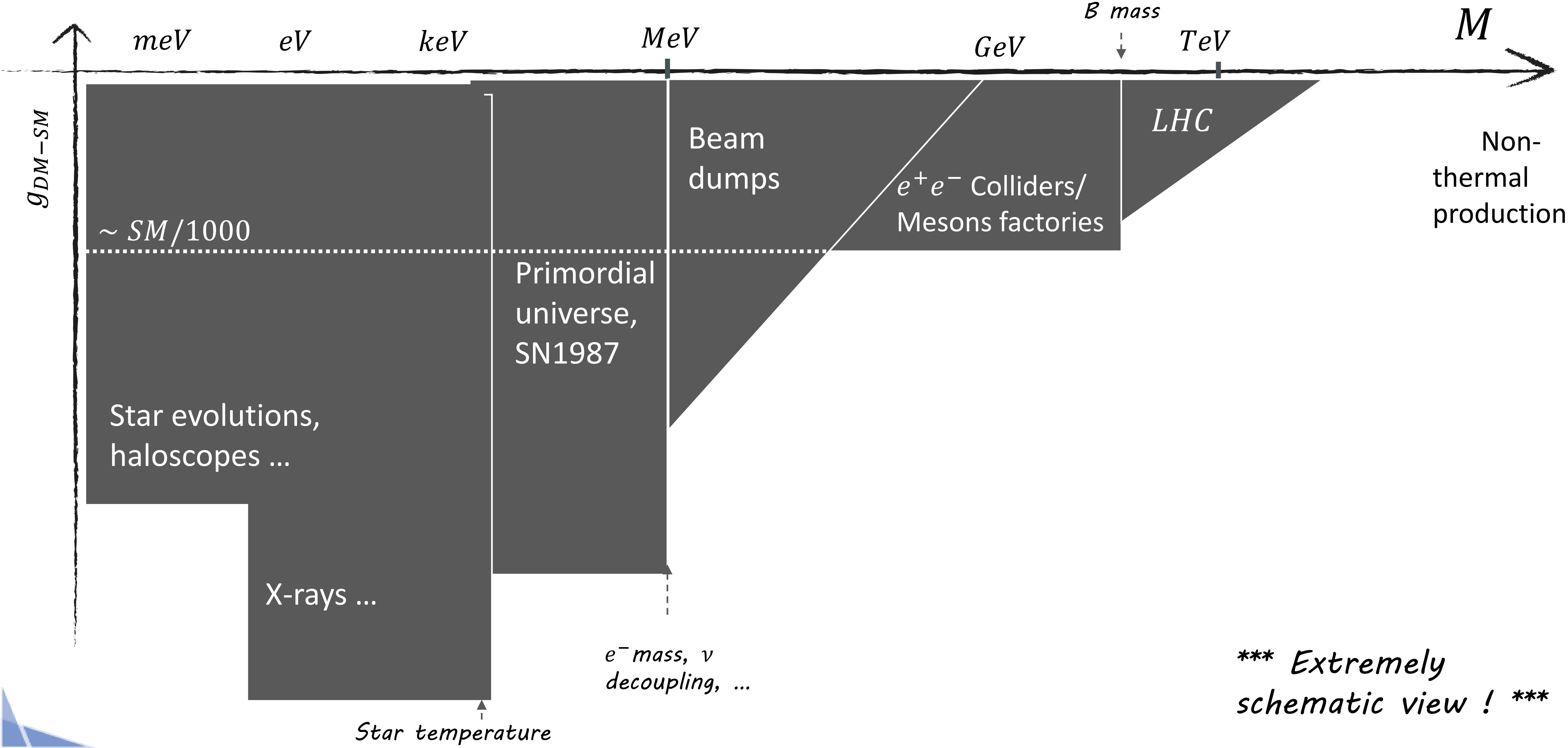
PADME, NA64, NA62, KOTO…
Light mesons decay & fixed targets

SBN, T2K, KM3Net, DUNE, JUNO
Light DM scattering, sterile neutrino & oscillations

ATLAS, CMS, ALICE, LHCb
(+ program LLP: FASER, Codex-B…)
LLP search, displaced vertex

→ See Mariangela Bondi's talk

An example : FIP mediator and dark matter



*** Extremely schematic view ! ***

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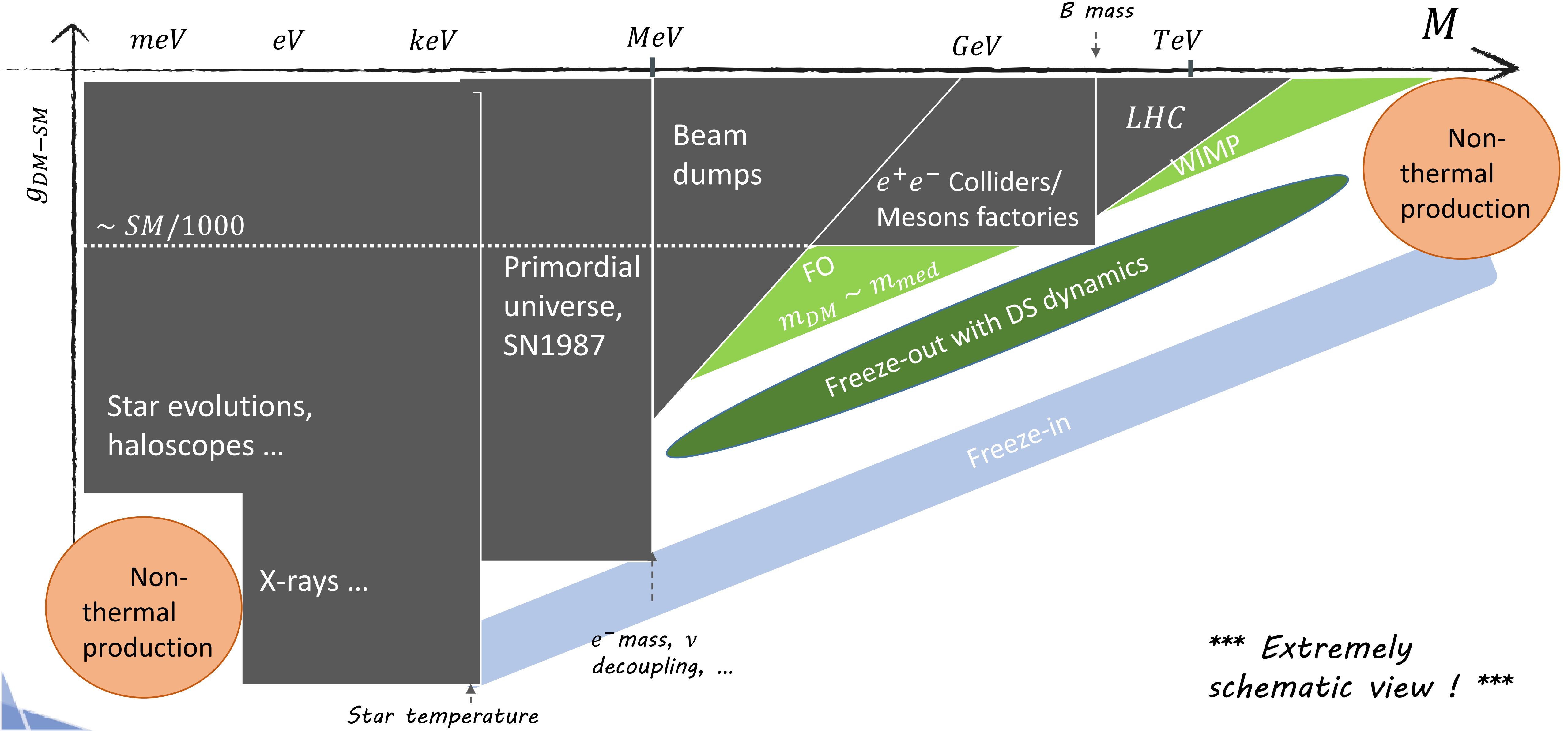

*** Extremely schematic view ! ***

The main concept: portals

Summary: portal interactions

- FIPs are neutral particle, must be coupled to a neutral “current” in the SM

	SM operator		FIPs / dark sector
Scalar portal	$\|H\|^2 \quad (d=2)\,,$	$\longmapsto$	Dark Higgs
Vector portal	$F_{\mu\nu} \quad (d=2)\,,$	$\longleftrightarrow$	Dark photon
Neutrino portal	$LH \quad (d=5/2)$	$\longleftrightarrow$	HNL

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- The three simplest cases will make the FIP "**inherits" the interactions of a SM counterparts : the Higgs, the photon and the neutrinos**

- Each portal operator is controlled by a small parameters, a mixing angle for the scalar and neutrinos portal, and the so-called kinetic mixing for the vector portal.

Portal interactions: it's all about the mediator

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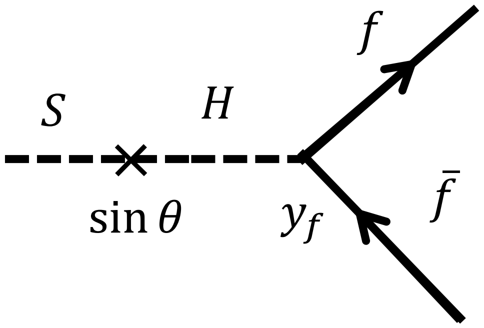
Scalar portal	$\lvert H\rvert^2 \quad (d=2)\,,$	$\longleftrightarrow$	$\lvert S\rvert^2$	Dark Higgs

Mixes with the standard Higgs

$O_{scalar} = \lambda_{SH}\lvert H\rvert^2\lvert S\rvert^2$ ➡ Induces a mass mixing between H and S

→ Light new scalars inherit the SM Higgs flavourful couplings

→ Tiny coupling to first generation fermions …



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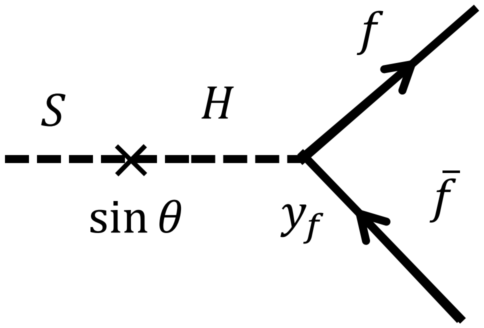
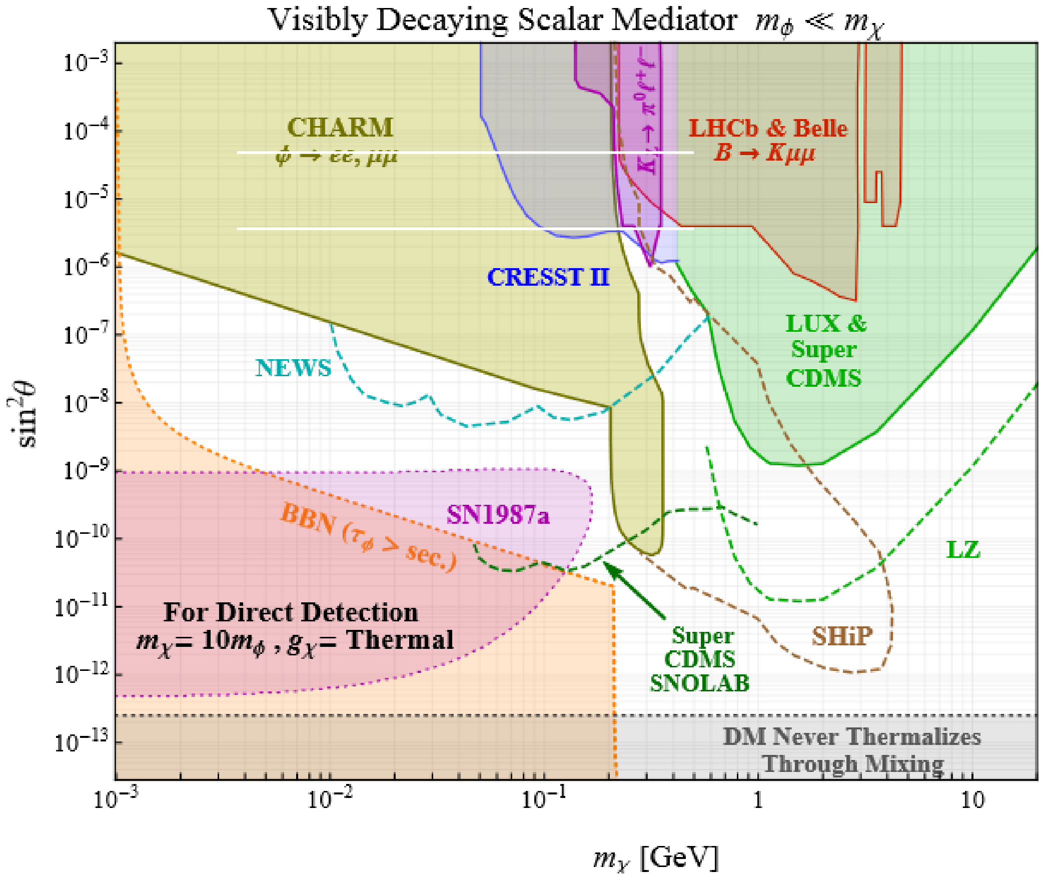




Krnjaic 1512.04119

Portal interactions – Vector portal

	SM operator	FIPs / dark sector	
Vector portal	$F_{\mu\nu} \quad (d=2)\,,$ $\longleftrightarrow$	$F'^{\mu\nu}$	Dark Photon

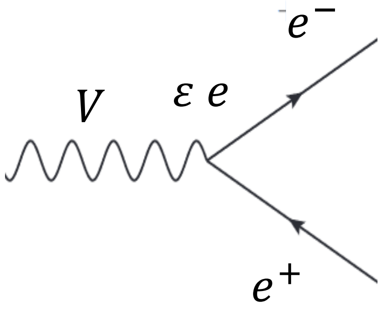
Mixes with the hypercharge / photon

$O_{vector} \propto \varepsilon\, F_{\mu\nu}\, F'^{\mu\nu}$ ➡ Induces kinetic mixing between the photon and the dark photon

- After recovering proper kinetic terms, the dark photon inherits a fraction of the EM current

→ Easily produced from electrons/positrons experiments

→ Relatively fast decay rates



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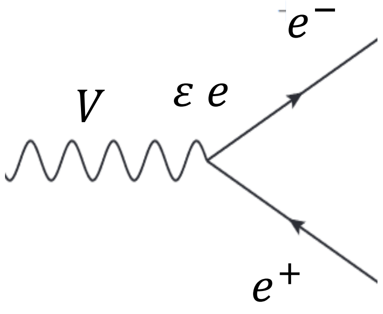

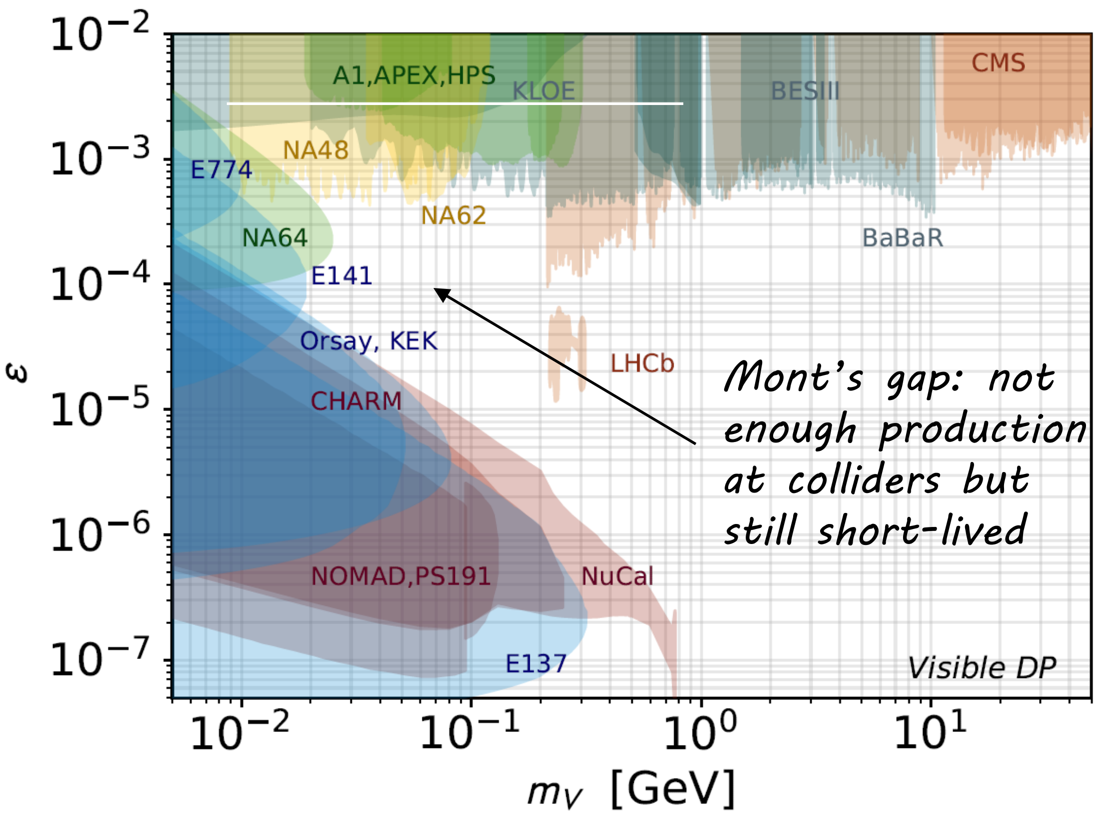

Portal interactions – Neutrino portal

Neutrino portal	SM operator	FIPs / dark sector	HNL	
	$L_i H \quad (d = 5/2)$ ⟷	N		*Mixes with neutrinos*

$O_\nu \propto y_N \, L_i \cdot H \, N$ ➡ Induces mass mixing between the neutrinos and the HNL

- Inherits the one (or several) of the neutrinos interactions
  - →Typically much longer lifetime, no Mondt's gap in this case !
  - →Dominant production via meson decays at sub-GeV masses

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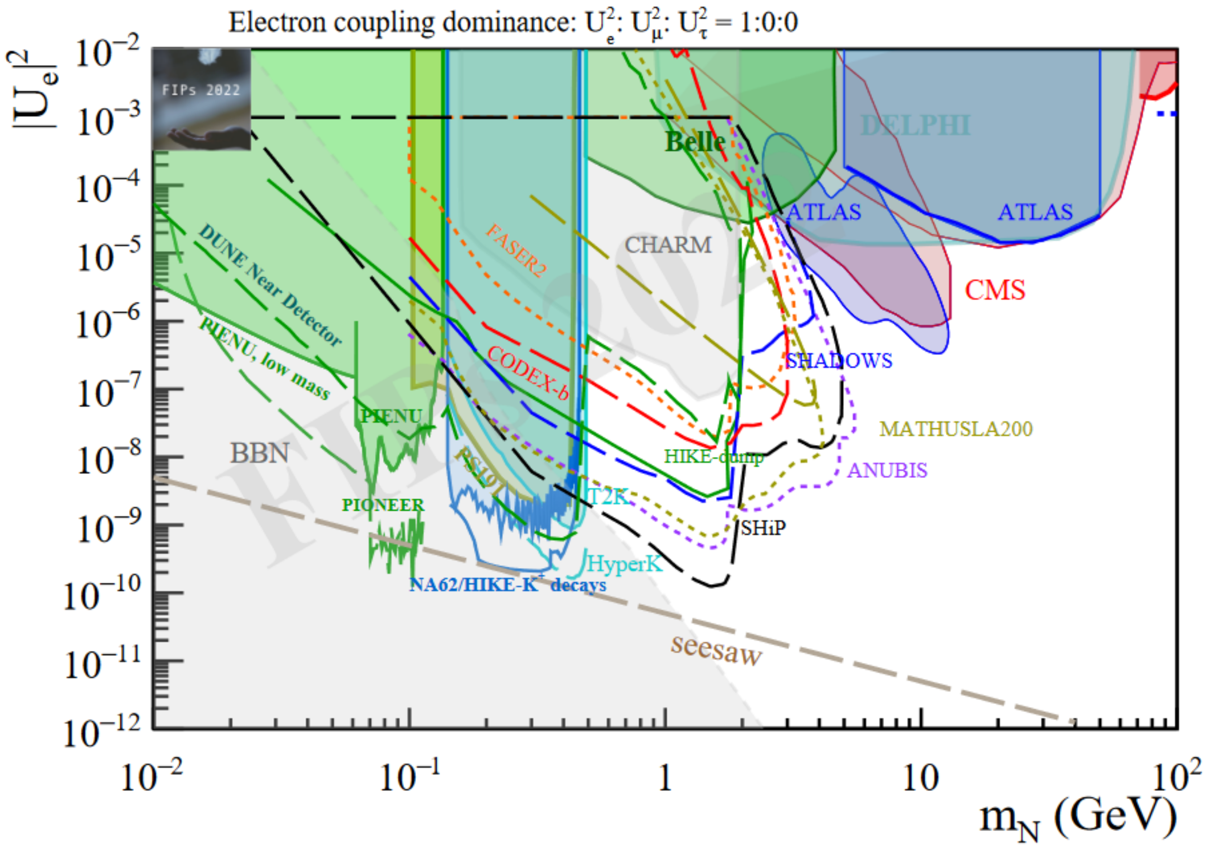

Dimension 3 portals and UV theories

- Starting from dimension 3 portal the UV theory typically has a strong impact on the structure of the low energy interactions

flavour violation, flavour non-universality, scalar vs vector operators, etc...

$$\bar{Q}_{L,i}\gamma^\mu Q_{L,j}, \bar{e}_i\gamma^\mu e_j, \ldots$$

$$V_\mu \left(\bar{e}_i\gamma^\mu e_j + \cdots\right)$$

New gauge group, for instance $L_\mu - L_\tau, B - L\ldots$ The breaking of this gauge group introduces a new scale

$$M_V \propto g\, v_{B-L}$$

Experimentally small gauge coupling and GeV-scale particle → large VEV

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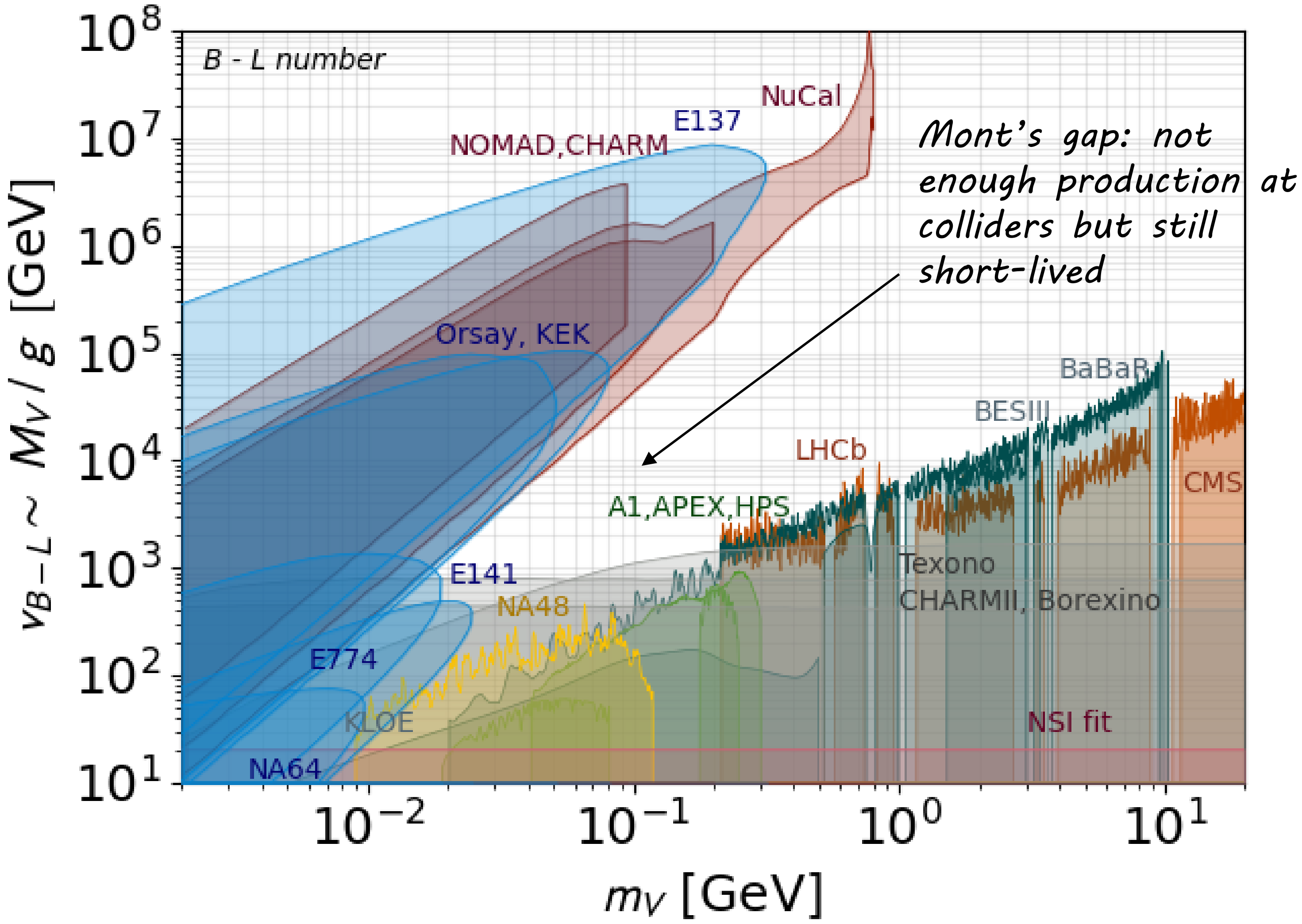
$$\frac{1}{\Lambda^2}\bar{\chi}_i\gamma^{\mu}\chi_j\left(\bar{e}_i\gamma^{\mu}e_j + \cdots\right)$$

Fermi-like theories: generic for all new UV theories with a light dark fermionic sector.

Probing FIPs can mean testing UV theories

- Consider as an example a new B-L gauge bosons, with mass $M_V \propto g\, v_{B-L}$ arising from the VeV v_{B-L} of a new scalar
- Thus, M_V/g is directly linked toa UV new scale

  → Testing these portals means testing physics at very large energy



Producing dark sectors in e^+/e^--based accelerators

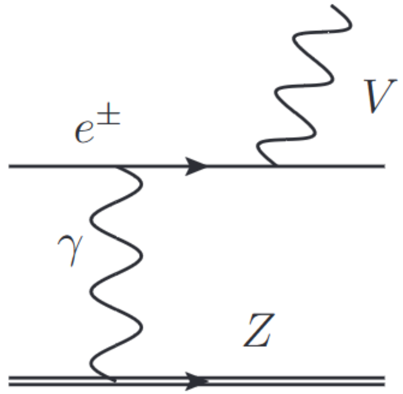
Dark sector production in $e^{\pm}$ machines

- Let's consider a new bosonic FIP (since those are the ones with the best prospects in e^{+}/e^{-} experiments

→ Electron-only machines mostly rely on Bremsstrahlung process

Bremsstrahlung

$$\sigma_{brem} \sim \alpha_{em}^{3} \frac{\varepsilon^2 Z^2}{m_V^2} \log(\dots)$$



For a dark photon

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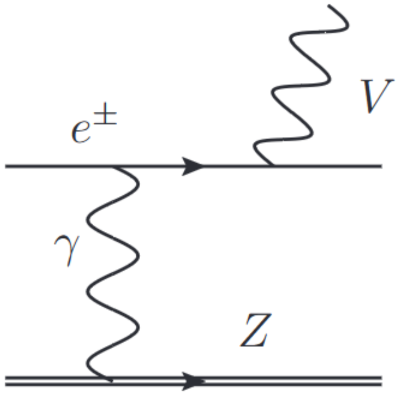
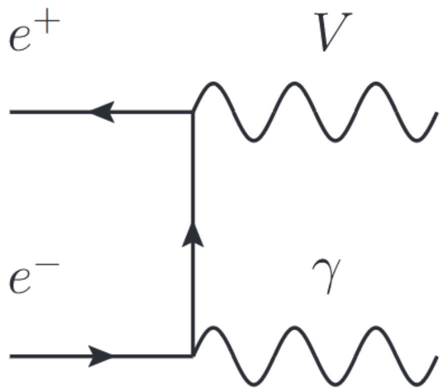


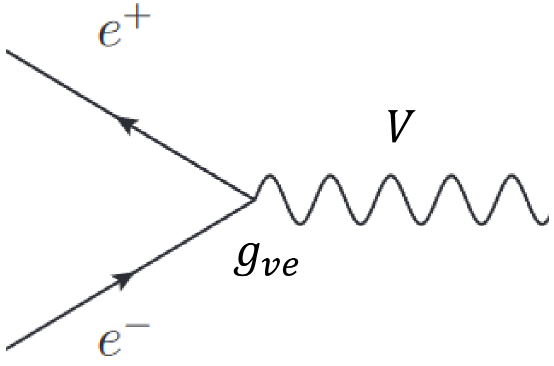
For a dark photon

→ Positron machines have more channels (owing to possible annihilation on beam target's electrons)



Associated/mono-γ

$$\sigma_{asso} \sim \alpha_{em}^{2} \frac{\varepsilon^{2} Z}{m_e E_{+}} \log(\ldots)$$



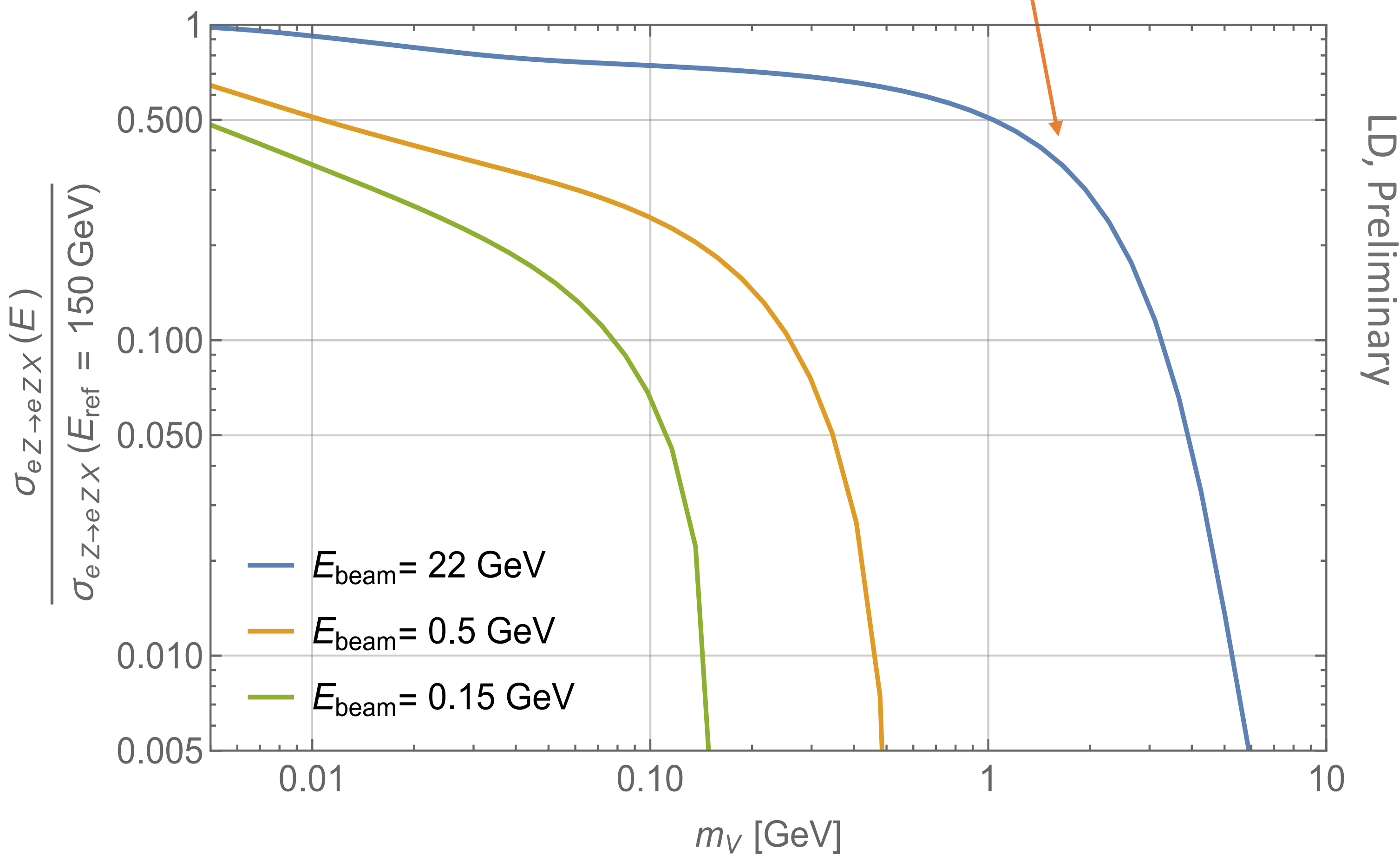
Resonant

$$\sigma_{res} \sim \frac{Z\, \alpha_{em}\, \varepsilon^{2}}{m_e} \delta(E_{+} - E_{res})$$

Beam energy dependence

- For bremsstrahlung, the CS depends only feebly on the actual e^+/e^- energy
  - Intensity, signal efficiencies, and control of the background are the important parameters!

Significant reduction only near beam energy



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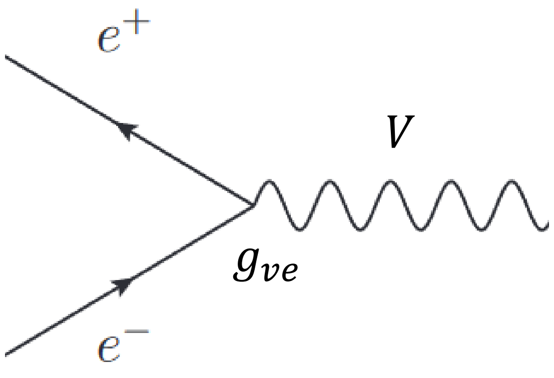
- For resonant production one needs to meet the resonance condition

$$E_+ = \frac{m_V^2}{2m_e}$$

→For a 22 GeV beam, resonant production will test masses around 150 MeV.

- For associated production: the smaller the better since $\sigma \propto \frac{log(s)}{s}$, as long as $E \gg E_{res}^{NP}$

Concerning resonant production…



- We will be interested into the simplest possible mechanism for new bosons : $e^+e^- \to V$, resonant production

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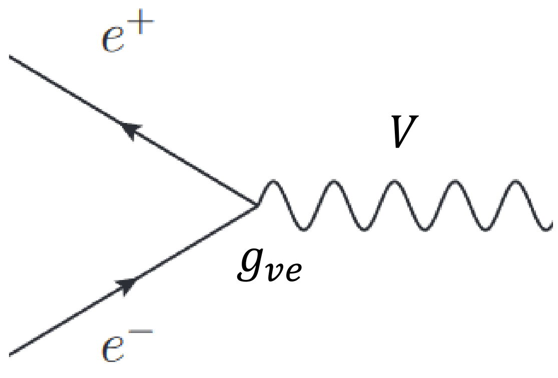

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- Significantly larger CS than $e^+e^- \to \gamma V$, and bremsstrahlung process

- What are the trade-offs for resonant production ?

  → First, we need to find positrons somewhere. Typically, this implies a certain loss in energy + beam intensity

  → Then we need to hit the resonant energy $\quad s_{CoM} = 2\, m_e\, E_{res} = M_V^2$

How to get to the exact energy ?

(1) Study models with large invisible width Γ_V^{inv} → Typically extremely important for DM-motivated models !

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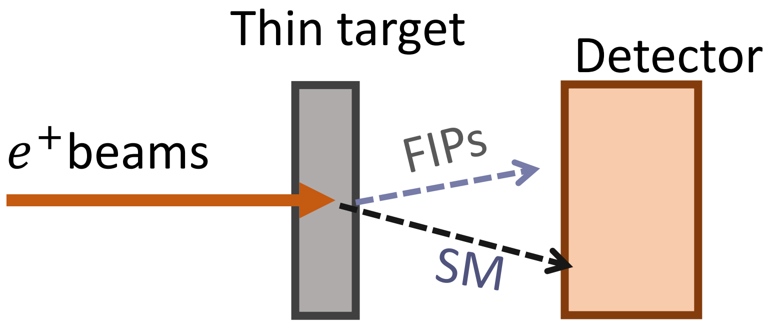
(2) Vary the beam energy

→ ”Scanning” procedure is required, varying the beam energy on non-negligible range

See e.g. 1802.04756



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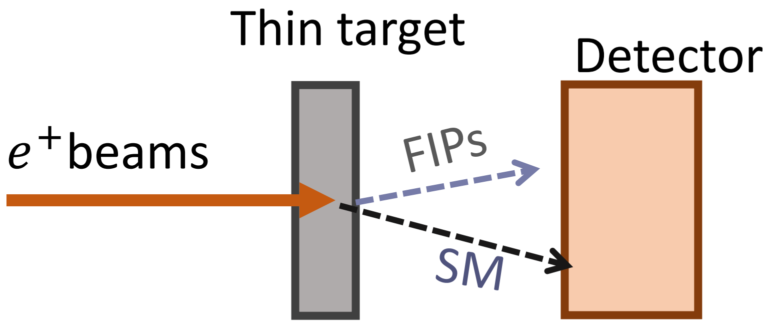
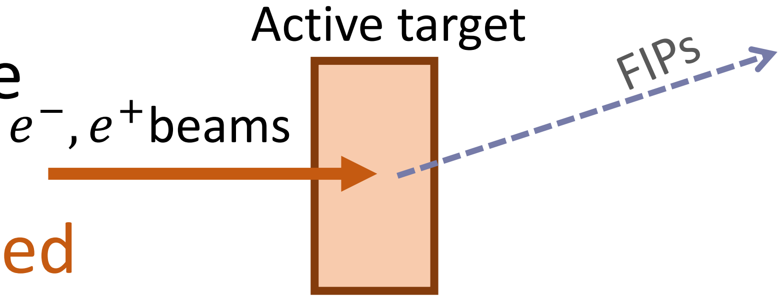


(3) Use energy loss and secondary e^+ production in the target to “scan” naturally various positron energies

→Requires a “not-too-thin” target to allow some evolution of the beam

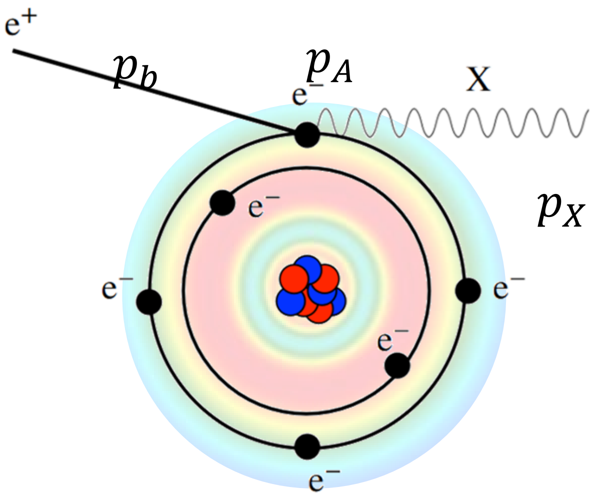
→ Works to a certain extent also in electron-based machines



See e.g. 1802.03794, 2105.04540, 2206.03101

How to get to the exact energy ? (2)

(4) Use the fact that electrons in a material are in bound states around nuclei !



- The true process involve a positron interacting with an entire electronic cloud:
  → Electrons are bounded and in momentum space they have their momentum density distribution

Strong similarities with DIS off nuclear targets …

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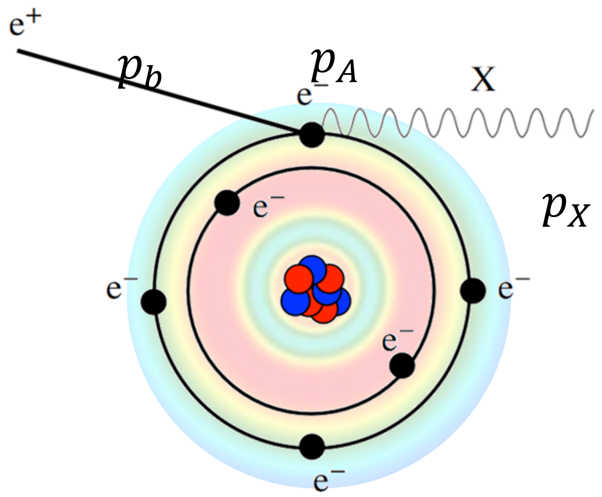

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Strong similarities with DIS off nuclear targets …

- Both a blessing and a curse, corresponding to the two main cases in which one needs to use this formalism
  →If one want to have a precise prediction for the CoM in order to scan for resonances (see X17)

$$s \sim 2E_b\,(E_A - p_{A,z})$$

  →If one wants to have as high a CoM energy as possible : use high-momentum core electrons, then atoms act as a « particle accelerators » !

Conclusion

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- Sub-GeV dark sectors are a generic class of extension of the Standard Model
- They arise quite typically from new UV theories designed to solve various flaws of the SM, and are often the smoking gun of a larger symmetry at work in the UV
- Their interaction with the SM can be classified, leading to a small number of « portals » to test experimentally
- For an e^+ or e^- various production channels are available, with larger rates possible in $e^+ -$ based experiments.

Backup

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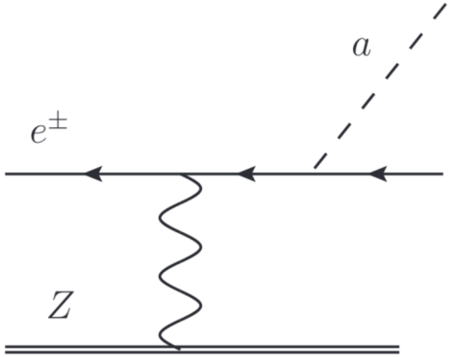
Bremsstrahlung

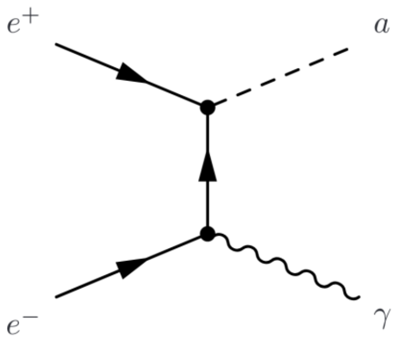
$$\sigma_{ae} \propto \alpha_{\rm em}^2 g_{ae}^2 \frac{m_e^2}{m_a^2}$$



For an ALP/axion X17

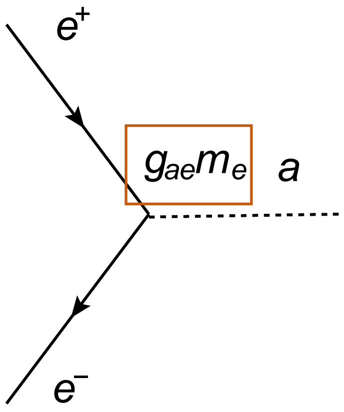
→ Positron machines have more channels (owing to possible annihilation on beam target's electrons)

For an ALP



Associated/mono-γ

$$\sigma_{ae} \sim \alpha_{\rm em} g_{ae}^2 \frac{m_e^2}{2s} \log\left(\frac{s}{m_e^2}\right)$$



etc…

Resonant

$$\sigma_{res} \sim \pi g_{ae}^2 m_e \delta(E_+ - E_{res})$$

Energy matters for decay lengths!

- Bremsstrahlung extracts most of the energy of the beam (even for heavy FIP)

$$\gamma_{FIP}\ell_{FIP} \sim 7\text{ cm}\left(\frac{E_{FIP}}{22\text{ GeV}}\right)\left(\frac{200\text{ MeV}}{m_{FIP}}\right)\left(\frac{3\cdot 10^{-5}}{g_{Xe}}\right)^2$$ (Vector)

$$\gamma_{FIP}\ell_{FIP} \sim 7\text{ cm}\left(\frac{E_{FIP}}{22\text{ GeV}}\right)\left(\frac{200\text{ MeV}}{m_{FIP}}\right)\left(\frac{0.05\text{ GeV}^{-1}}{g_{Xe}}\right)^2$$ (ALP)

→ Make displaced signatures viable for higher energy experiments

- Similarly FIP from resonant production inherits all the beam energy

$$E_{FIP}^{\text{res}} = \frac{m_{FIP}^2}{2\, m_e} \simeq 22\text{ GeV}$$

- Not the case of associate production $e^+e^- \to \gamma\, FIP$

The dark matter motivation

Adapted from 1807.01730 and N. Toro – FIP 2022

What do we know about dark matter ?

→Does not interact nor decay too much

→We know how much there is

$\Omega h^2 \simeq 0.12$

Planck 2018

Interesting to classify the DM candidates following how they actually reach the required density

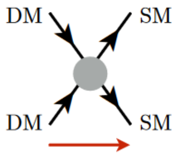
Was DM in thermal equilibrium with the SM ?

UV insensitive ! Yes !

How was it's abundance depleted then ?

Directly to SM

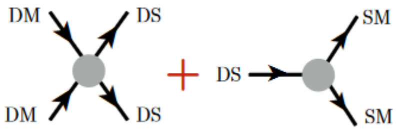
Vanilla freeze-out



WIMP, Sub-GeV Relic, Asymmetric variants

By steps to the SM

Dark sector FO



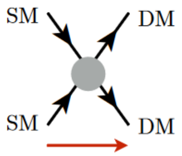
Secluded, SIMP, ELDER, Asymmetric variants

No

Was it produced from the SM thermal bath ?

Yes

Freeze-in & friends

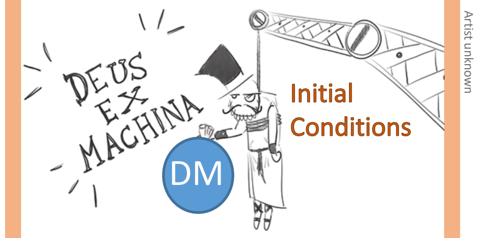


freeze-in, sterile-neutrino, superWIMP

No

Abundance from another mechanism (e.g. misalignement)

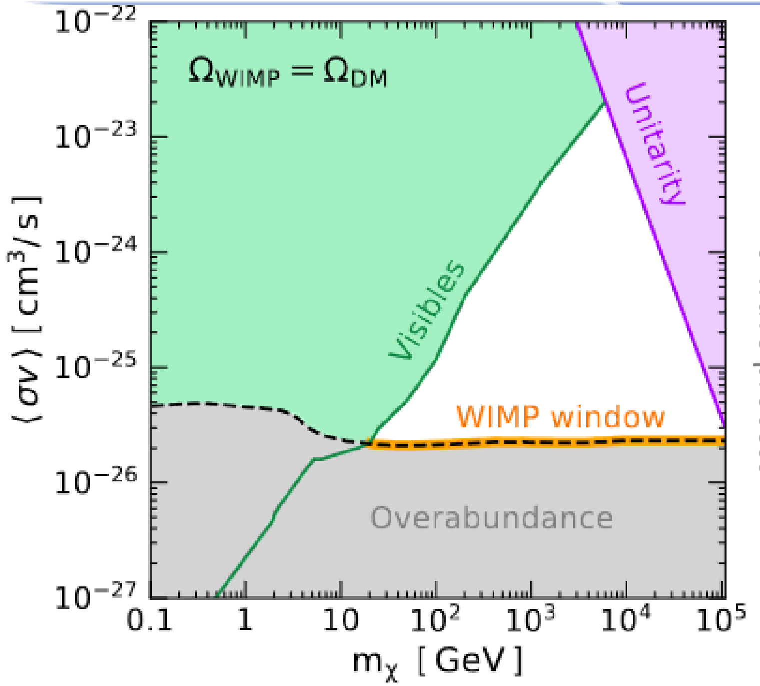
Axions & friends



QCD axion, ALP, WIMPZILLA, late decays, primordial BH

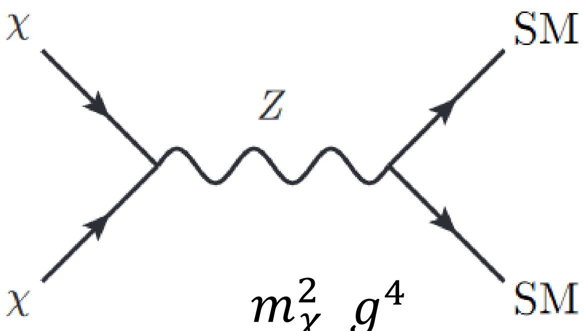
Sub-GeV dark matter

- The WIMP window is constrained by, e.g. :
  - →Unitarity of its interactions
  - →Lee-Weinberg bound
  - →CMB constraints: one should not inject ionising particles at late (CMB) time



Leane et al. 1805.10305, s-wave process

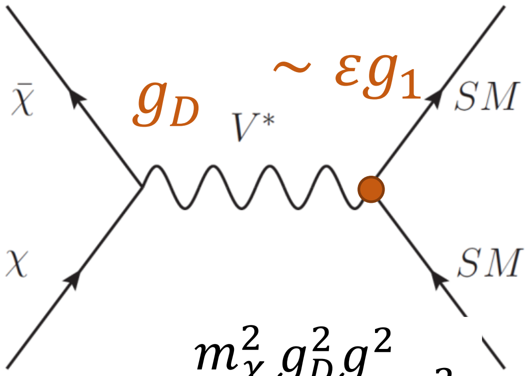
- Copying the WIMP freeze-out idea at low mass implies extending the model with a new mediator with small coupling with the SM



$$\sigma v \sim \frac{m_\chi^2}{m_Z^4}\frac{g^4}{32\pi}$$

$$(\sigma v)_{DM} \sim 4 \cdot 10^{-9}\ \mathrm{GeV}^{-2}$$

$$g_D \varepsilon \sim g \frac{m_{DM}}{m_{WIMP}}$$



$$\sigma v \sim \frac{m_\chi^2}{m_V^4}\frac{g_D^2 g^2}{32\pi}\varepsilon^2$$

Below the GeV, at $m_\chi < m_V$, need $\varepsilon < 10^{-3}$

Can be p-wave, etc…

Axion-like particle – dim 5

- An axion-like particle (ALP) a, interacts via two portal operators : $\bar{l}\gamma^{\mu}\gamma^{5}l$ and $F^{\mu\nu}\tilde{F}^{\mu\nu}$

$$\mathcal{L} \subset \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_a^2 a^2 + \frac{1}{4}g_{a\gamma}a\boxed{F_{\mu\nu}\tilde{F}^{\mu\nu}} + \sum_{l=e,\mu,\tau}\frac{g_{al}}{2}(\partial_\mu a)\boxed{\bar{l}\gamma^\mu\gamma^5 l}$$

- We can "hide" the ALP via a coupling to a dark current

$$\mathcal{L} \supset \frac{g_{a\chi}}{2}(\partial_\mu a)\mathcal{J}^{\mu}_{5,D}$$

- Origin: approximate symmetry in Higgs UV sector

→Typical ALP model arise as pNGB from a bigger scalar sector, with mass term protected by an approximate global symmetry

→Coupling can be represented either in Yukawa or "derivative form", in both cases, large couplings must arise from small scale VEVs.

$$\mathcal{L}_R^{\rm eff} = \frac{1}{2}\partial_\mu a^0 \partial^\mu a^0 - i\sum_{f=u,d,e}\frac{m_f}{v_a}\chi_P^f\, a^0 \bar{\psi}_f\gamma_5\psi_f\ ,$$

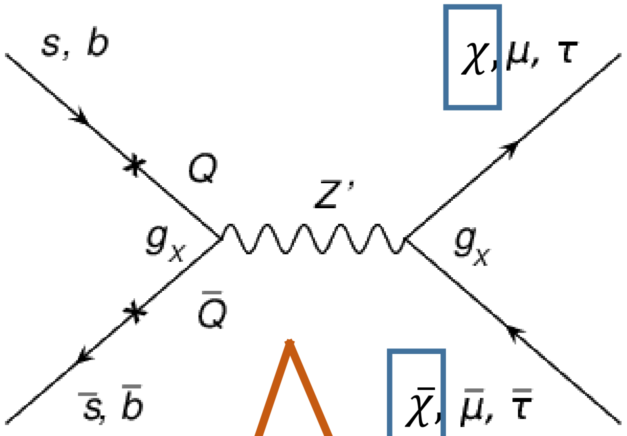
⟺

$$\mathcal{L}_{NR}^{\rm eff} = \frac{1}{2}\partial_\mu a^0\partial^\mu a^0 - \frac{\partial_\mu a^0}{2v_a}\sum_{f=u,d,e,\nu}\left(\chi_V^f\ \bar{\psi}_f\gamma^\mu\psi_f + \chi_A^f\ \bar{\psi}_f\gamma^\mu\gamma_5\psi_f\right)$$
$$+\frac{a^0}{16\pi^2 v_a}\left(g_s^2 N_C^{eff} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} + g^2 N_L^{eff} W_{\mu\nu}\tilde{W}^{\mu\nu} + g'^2 N_Y^{eff} B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

Dimension 6 operators

- Following the example of neutrinos: fermions portal are straightforwardly obtained if new UV theories with a light dark sector.

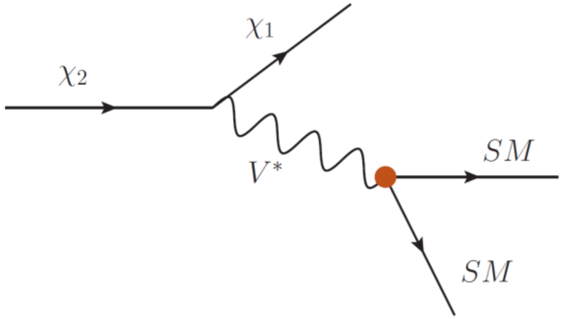
  → E.g. new vector mediator
  replace the muons with a dark fermion



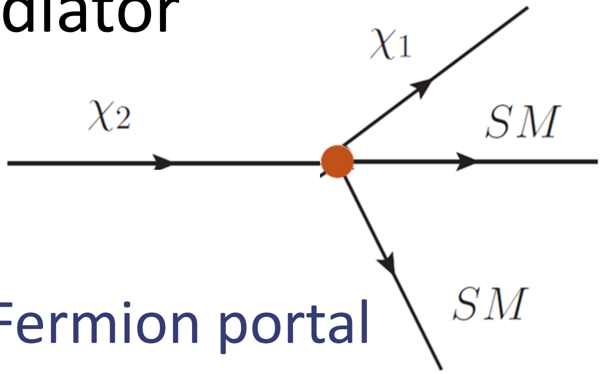
$\bar{\chi}\gamma^{\nu}\chi\,\bar{\mu}\,\gamma_{\nu}\mu$ $\quad$ $\bar{b}\gamma^{\nu}P_L s\,\bar{\chi}\,\gamma_{\nu}\chi$

$O_9 \sim \bar{b}\gamma^{\nu}P_L s\,\bar{\mu}\,\gamma_{\nu}\mu$

- Another example inelastic dark matter setups, where a GeV-scale state decay into a lighter one (e.g. dark matter) via a heavy mediator



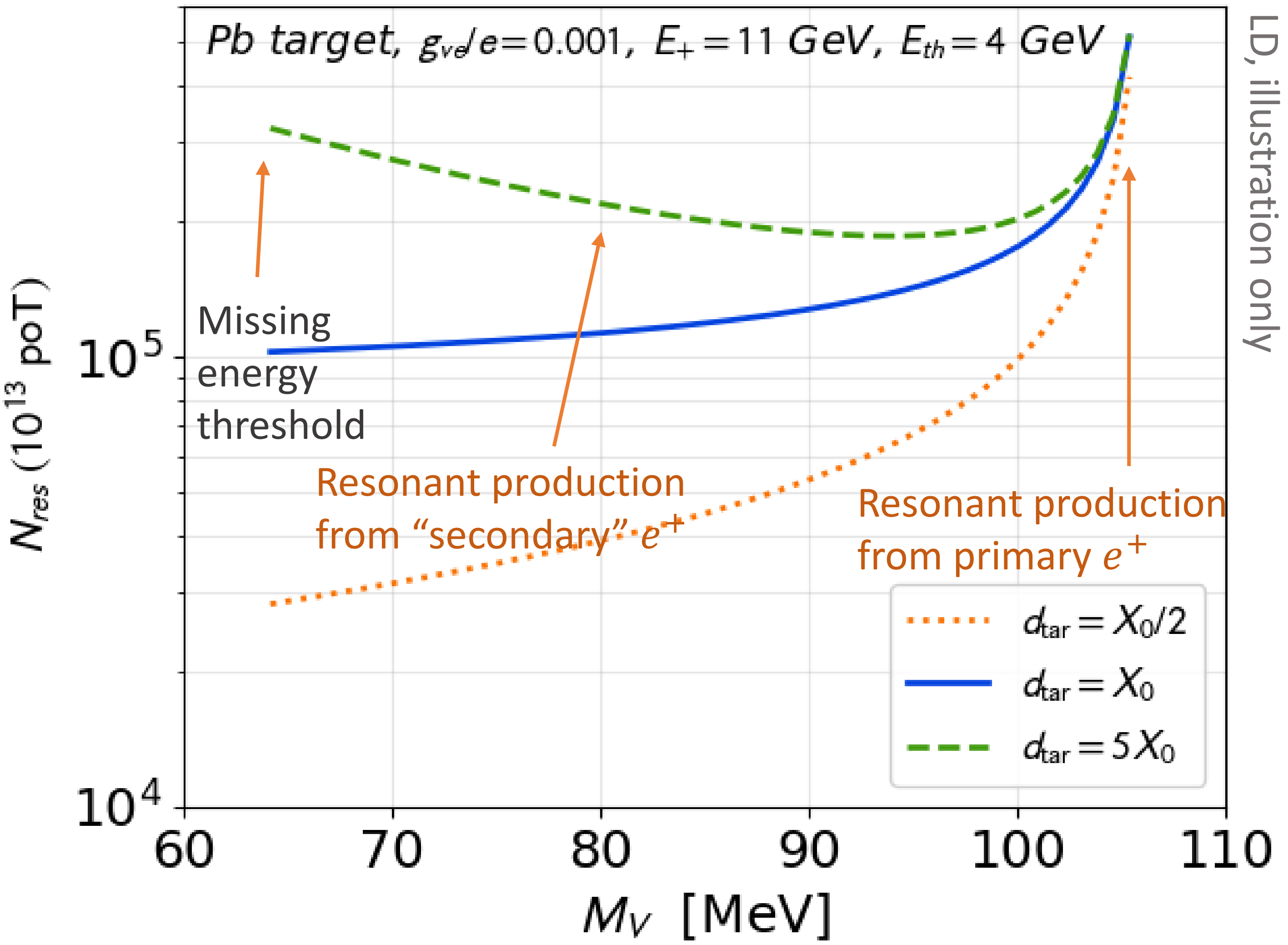
Integrate out V^* →



Fermion portal

The thick target approach

- Use straggling and bremsstrahlung processes to degrads the beam energy
- Effective to probe a large range of masses without varying the beam energy too much
- But FIP production occurs directly in the shower
  - →Requires either a displaced signal or missing energy to escape background
  - →This works as soon as we have a coupling to neutrinos …



FIPs production in the lab

$e^{\pm}Z, pZ$ → Mesons: f_{π^0}, f_η, f_K, …
EM processes: $T_{e^\pm}, T_\gamma$ →

e^+e^-, pp →

Flavoured mesons decay
$B \to K\,X, K \to \pi X, K \to inv$ or $D, B, J/\Psi \to \ell N$ etc …

→ Flavoured FIPs, Higgs portal and neutrinos portal

Light mesons decay
$\pi^0, \eta \to \gamma\,V$; $\rho, \omega \to V$ or $\pi^0 \to a$; $\pi^0, \eta \to \chi\chi$ etc …

EM-derived processes
$e^+e^- \to V\gamma, a\,\gamma$; $e\,N \to e\,N\,V$, etc …

→ Vector portal, ALP/fermion portal

- Mesons decays estimations
  - No automatic tool available (new light states: not possible to apply standard WET-based tools)

  → Analytical calculation required. BR usually estimated by standard techniques (χPT, Vector Meson Dominance, …)

  For VMD, see e.g. Fujiwara et al. (1985)

→ Limit on rare BR, $B \to K, K \to \pi$, $\pi \to inv.$, etc…

- EM-derived processes
  - For collider experiments: standard MC tools can be used (MG5_aMC@NLO, CalcHEP, etc…) Alwall et al. 2014, Belyaev et al. 2012
  - For beam dump → must include the track-lengths information, nucleus form factors…

→ Limits on mono-photon search @ BaBar/NA64/LEP

Anomalies: (non-exhaustive) list

ASTROPHYSICS/COSMO

- Low primordial Li^7 (e.g 1203.3551) → Decaying FIP …
- Magnificent Seven (e.g 1910.04164) → Axions…
- Stellar cooling hints (e.g. 2003.01100) → Axions…
- Xenon 1T e-scattering (2006.09721) → LDM, keV dark photon
- Hubble rate tension (2103.01183) → Decaying DM, axion, …
- DM small-scale (e.g. 1912.06681) → LDM with FIP mediator

PRECISION/NEUTRINOS

- Proton charge radius (e.g 1502.05314) → Scalar/vector FIP …
- $(g-2)_{e,\mu}$ (e.g. 2006.04822 and 1812.04130, Morel 2020) → Scalar/vector FIP …
- Atomki X17 (1910.10459) → Scalar/vector FIP …
- MiniBooNE ν_e excess (e.g 1812.08768) → ν_R+ light FIPs

High-energy

- Hints in top-observables (e.g. 2011.06514) → Sub-EW scale top-philic particle

SAVEUR

- $b \to s$ et $b \to c$ non-universalité (e.g 1807.11373) → FIP + UV physics
- CKM non-unitarité (e.g 2103.05549)
- KOTO $K_L \to \pi^0 inv.$ anomalie (1910.07148) → Scalar FIP
- Kaons CPV ratios and ΔA_{CP} in D^0 (e.g. 1911.06211)