
# Model-independent considerations of dark sectors

With R. Contino, K. Max, and ongoing work with R. Contino, M. Costa,
S. Verma, M. Reece and C. Cesarotti
Based on 2012.08537 + 21xx(s)

SCUOLA NORMALE SUPERIORE

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**Harvard**

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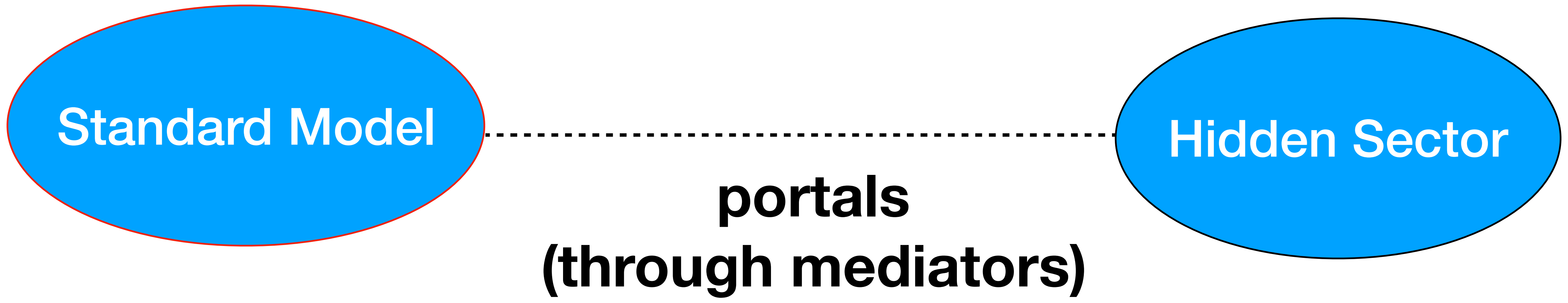
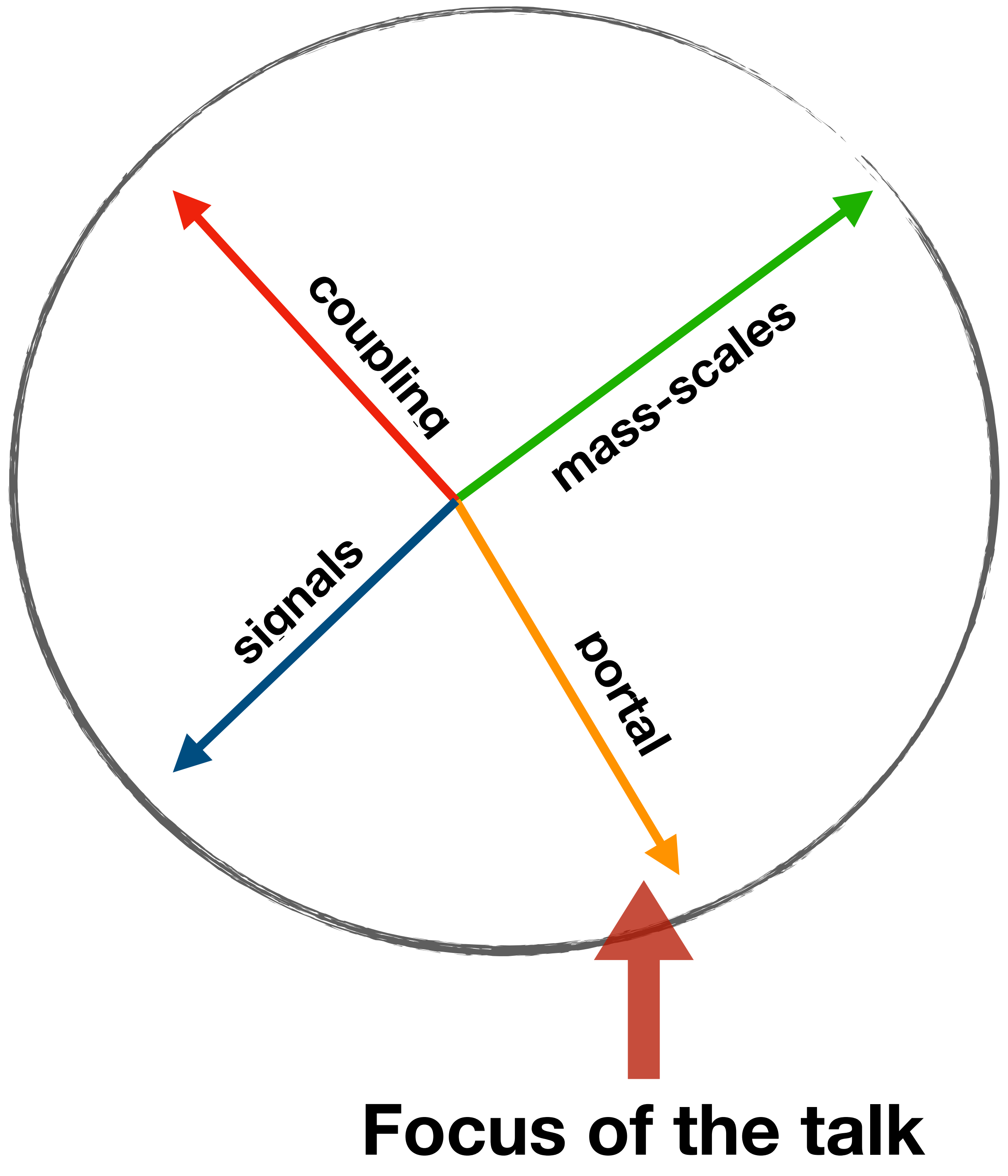
# Hidden sectors

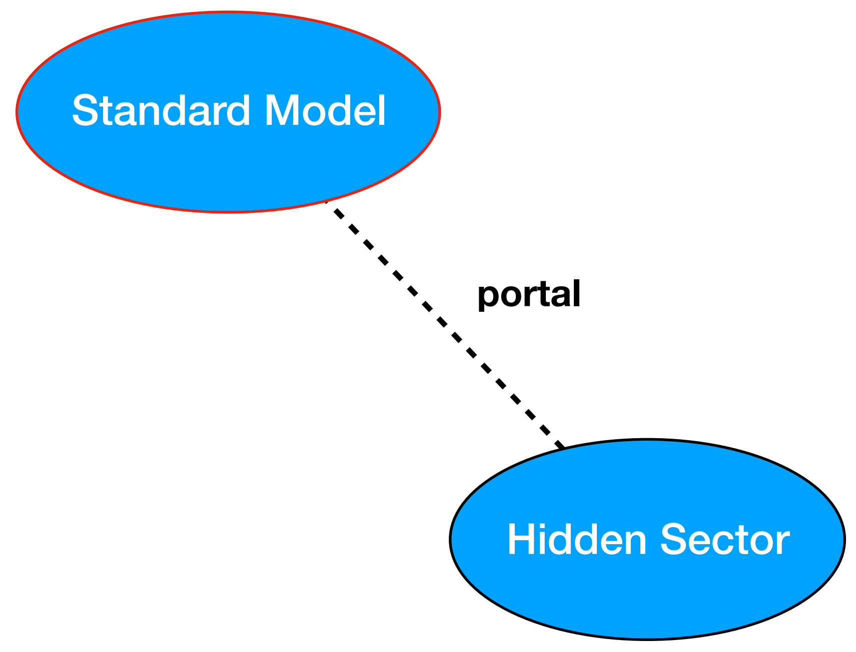



- Several BSM scenarios naturally give hidden sectors at low energies.
- Dark matter may be part of a sector with its own particles and dynamics.




**The range of possibilities is vast!**

# Portals to the Hidden sector




For heavy mediators, we can write the portal as a contact interaction.

**Natural to consider gauge invariant operators**

$$\lambda\, \mathcal{O}_{\rm SM}\, \mathcal{O}_{\rm HS}$$

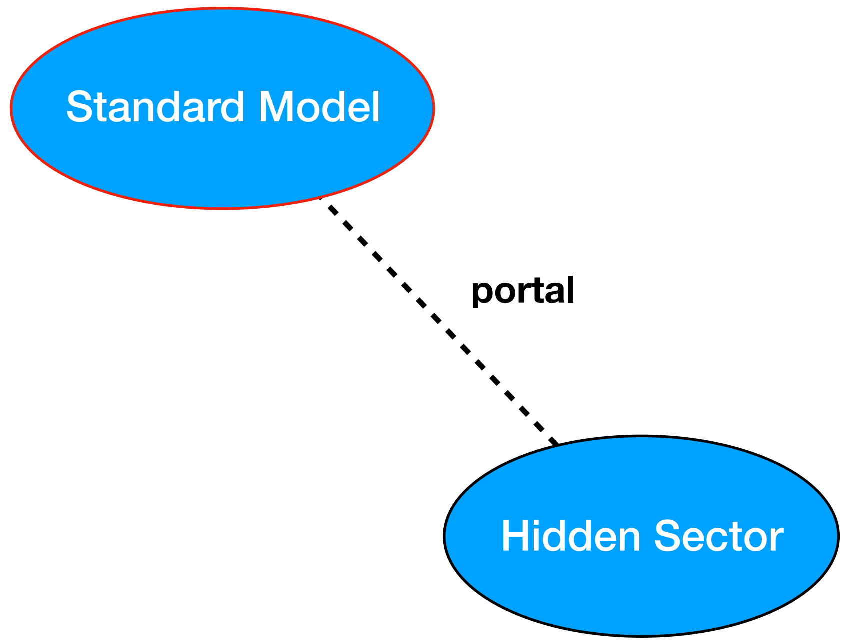
**What about the operators on the HS side?**

| Operator | Dimension |
|---|---|
| $H^\dagger H$ | 2 |
| $B_{\mu\nu}$ | 2 |
| $\ell H$ | 5/2 |
| $J_\mu^{SM} = \bar\psi\gamma^\mu\psi,\ H^\dagger i\overleftrightarrow{D}_\mu H$ | 3 |
| $O_{\mu\nu}^{\rm SM} = F_{\mu\alpha}^i F_\nu^{\alpha\, i},\ D_\mu H^\dagger D_\nu H,\ \bar\psi\gamma_\mu D_\nu\psi$ | 4 |
| $O_{SM} = \bar\psi i \not{D}\psi,\ D_\mu H^\dagger D^\mu H,\ F_{\mu\nu}F^{\mu\nu},\ F_{\mu\nu}\tilde F^{\mu\nu},\ \bar\psi_L H\psi_R,\ (H^\dagger H)^2$ | 4 |

Can we use general principles of Quantum Field Theories to write down a minimal set of operators (and hence portals) that *must* exist?

**Assuming the hidden sector is a local and natural QFT, we *can* make progress.**

# Portals to the Hidden sector



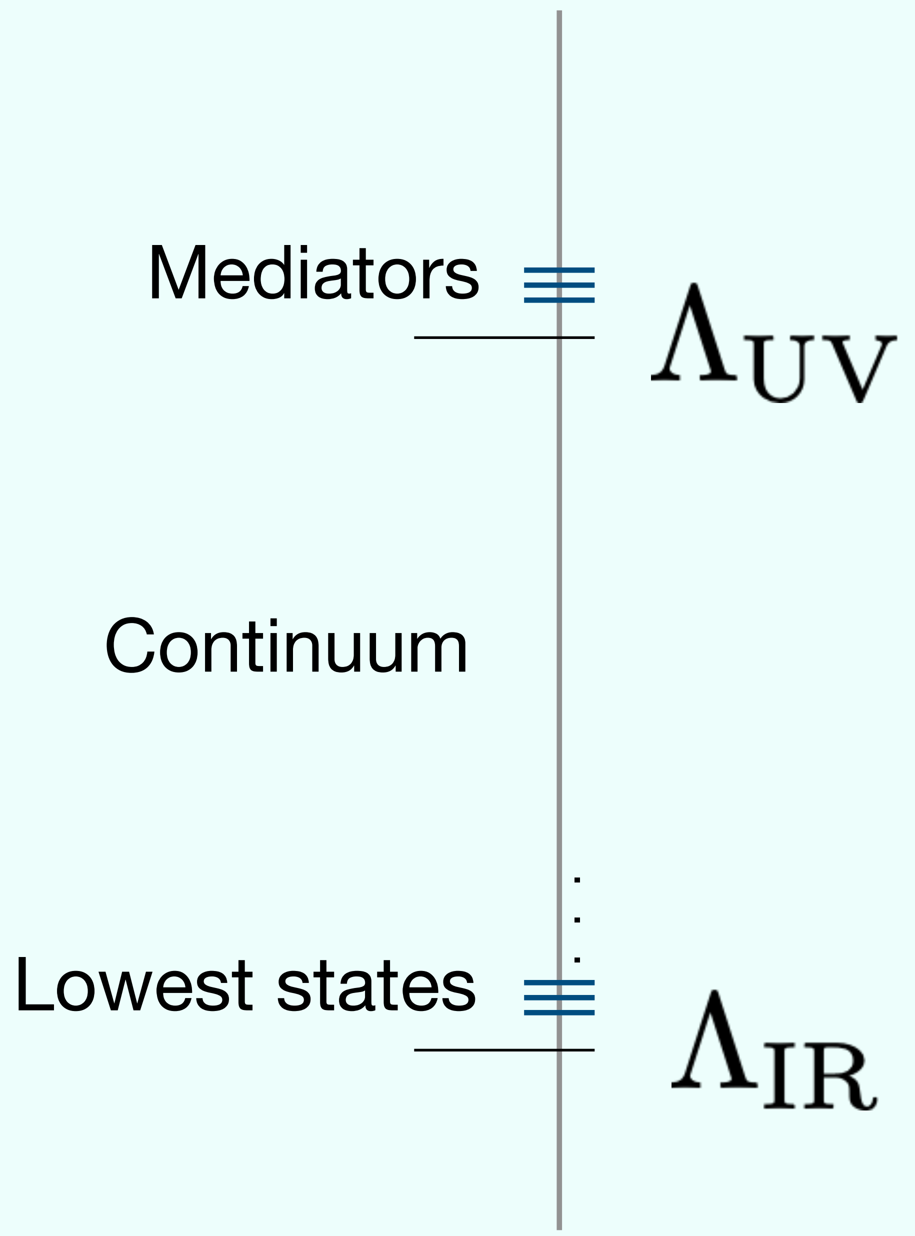

Consider a dark sector characterized by two scales (with a possible hierarchy between them).

The sector can be weakly or strongly coupled.

The dynamics between the scales is approximately scale invariant.

## Minimal and Natural Hidden Sectors

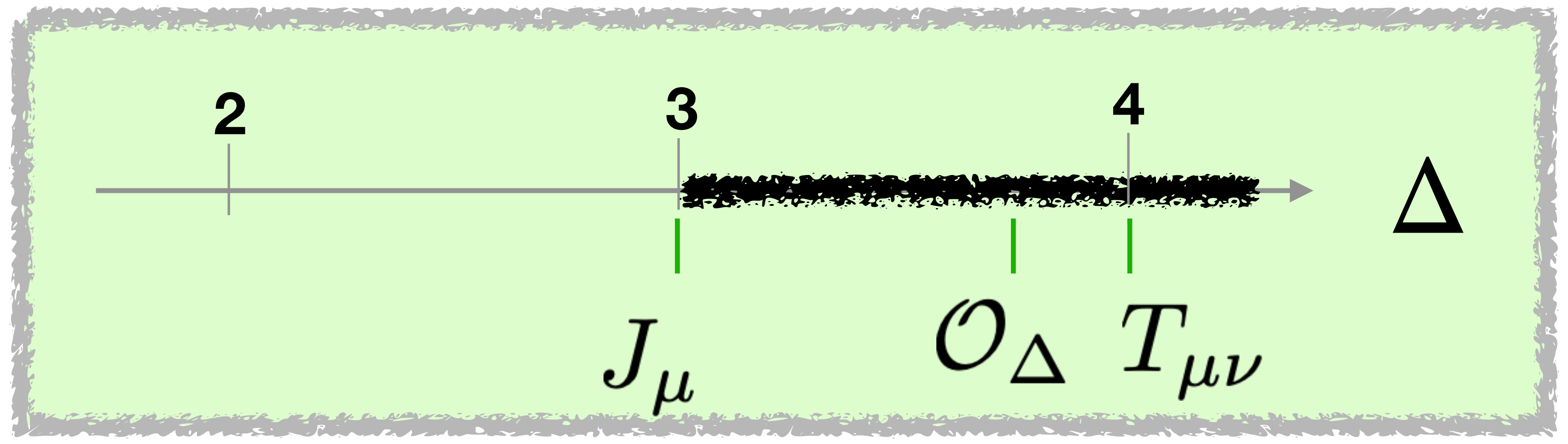
$$\Lambda_{\mathrm{UV}} \gg \Lambda_{\mathrm{IR}}$$



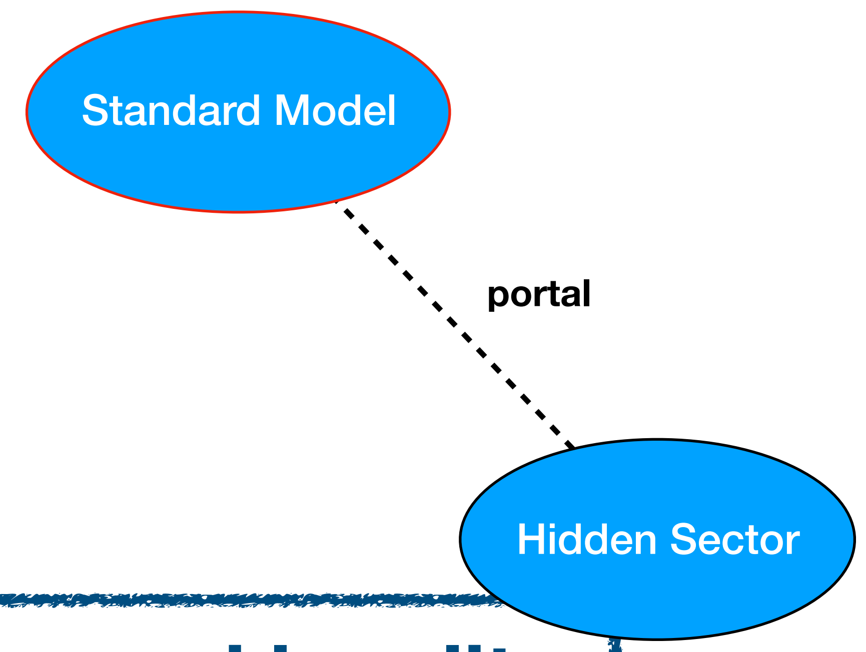

Strongly coupled sectors are natural candidates.

## What are the lowest dimension operators?

- Operators for conserved currents only. $J_\mu\,, T_{\mu\nu}$
- A natural separation of scales in the hidden sector: no highly relevant scalar operators. $\mathcal{O}_\Delta\,, \Delta \lesssim 4$



# Portals to the Hidden sector




**These are the portals expected on general principles of gauge invariance, Lorentz invariance and locality.**

| | | |
|---|---|---|
| $D < 6$ | $\frac{\kappa_O}{\Lambda_{\rm UV}^{\Delta-2}}(H^\dagger H)\mathcal{O}_\Delta$ | Natural |
| $D = 6$ | $\frac{\kappa_J}{\Lambda_{\rm UV}^{2}} J_\mu^{\rm SM}\, J^\mu_{\rm DS}$ | Reasonable |
| $D = 8$ | $\frac{\kappa_T}{\Lambda_{\rm UV}^{4}} T^{\mu\nu}_{\rm DS} O^{\rm SM}_{\mu\nu}$ | Minimal |

**Irrelevant Portals**

**Less elusive new sectors with marginal or relevant portals have been thoroughly studied in the literature**

**e.g. Twin Higgs/Neutral-Naturalness, Unparticles, Higgs portal, dark photon…**

**e.g.**

- **Confining SU(N) gauge sectors with heavy matter content.**
- **Heavy scalar and a light fermion.**
- **Extended RS models with more than 2 branes.**

Easy to construct examples:
see 2012.08537 for details
(also backup slides)

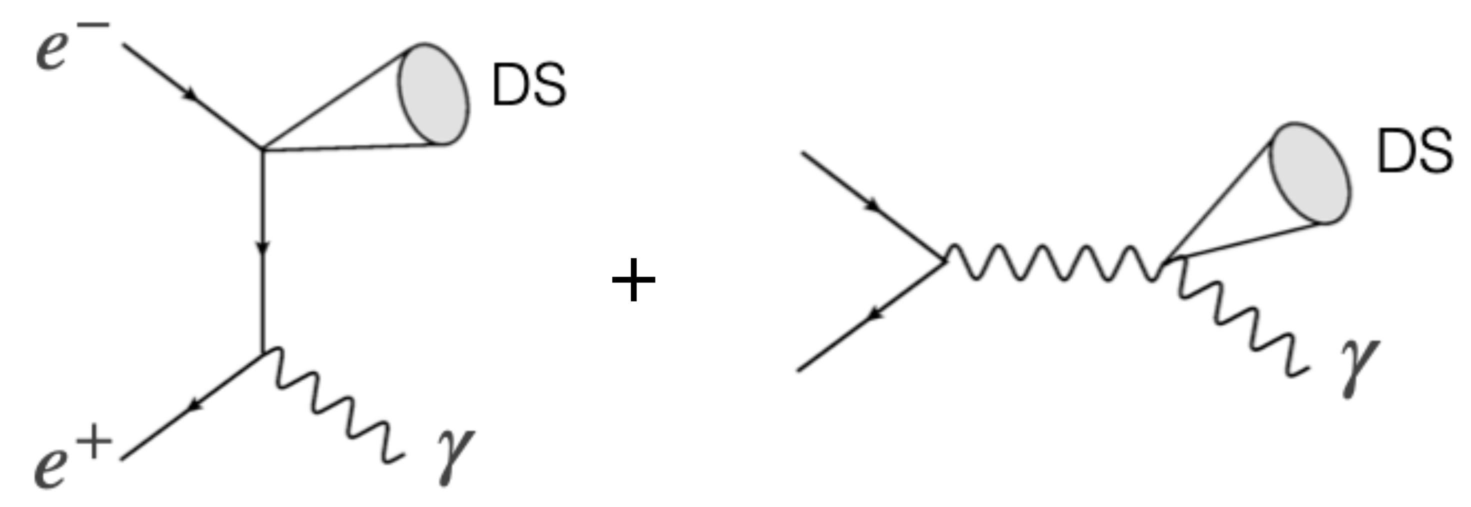
# An example

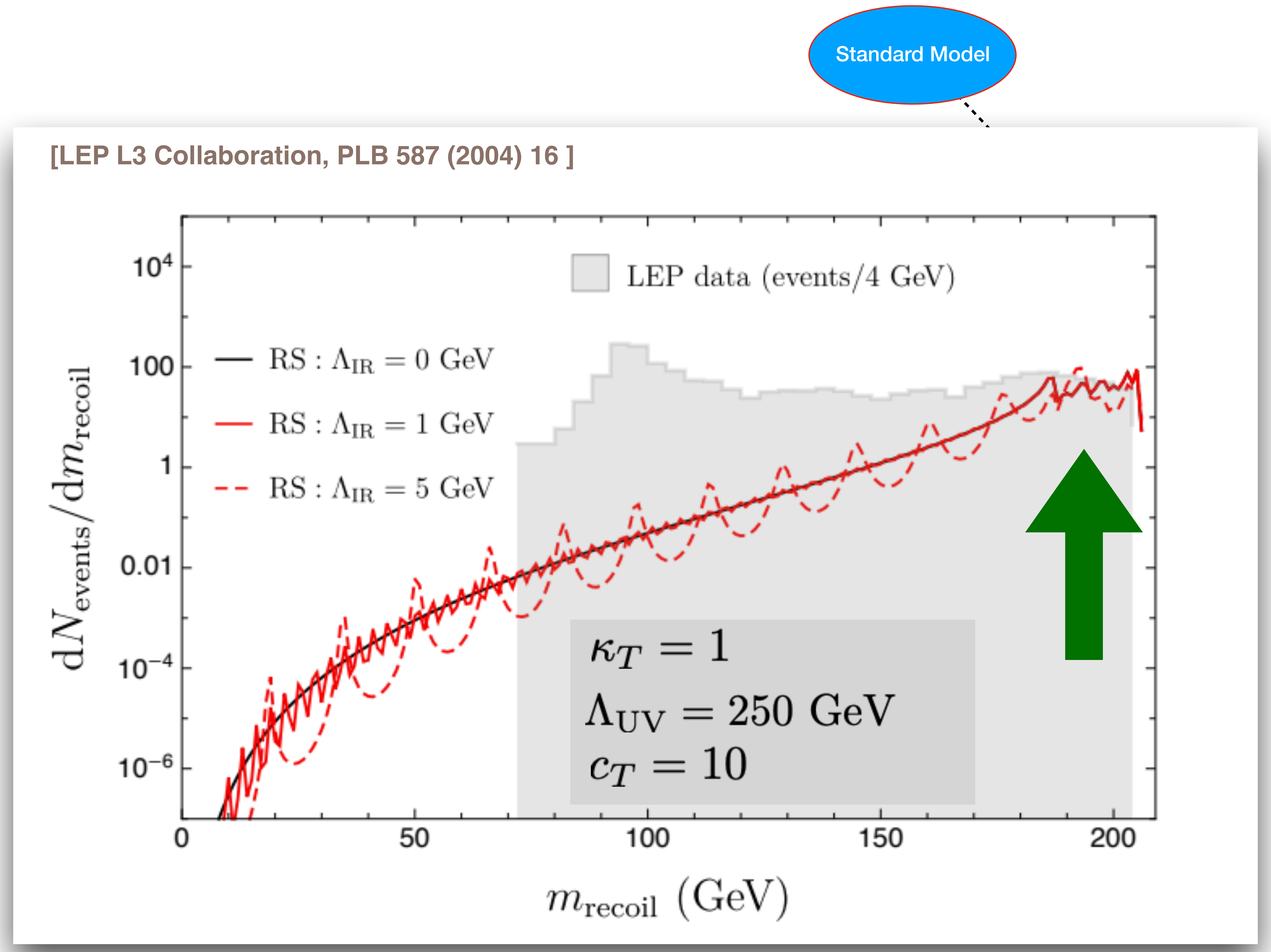
Consider a DS with a dim-8 portal interaction with the SM

$$\frac{\kappa_T}{\Lambda_{\rm UV}^4}\left(F_\alpha^\mu F^{\alpha\nu} + \bar{e}\gamma^\mu D^\nu e\right) T_{\mu\nu}^{\rm DS}$$

The probe of such a portal is the process:

$$e^+e^- \to \gamma + {\rm DS}$$



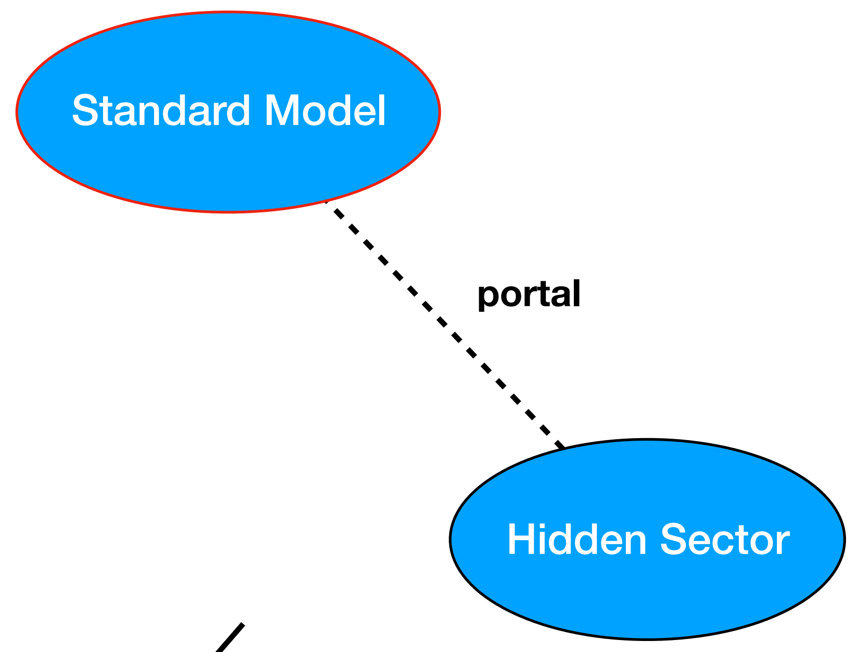




- **Largest contribution from events with highest momentum in the DS, away from the threshold.**
- **Necessitates assessing the EFT validity carefully.**

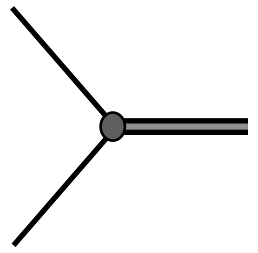
**The importance of threshold contribution depends on dimensionality of portal and energy range probed (c.f with relevant portals)**

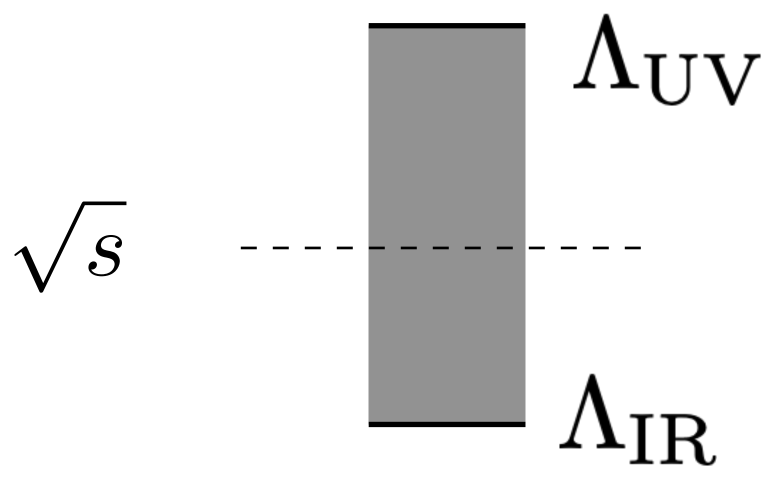
# Experimental Probes

## (without specifying explicit field content)




### Direct HS production






Energy scale
of experiment

Continuum Regime: being inclusive on the final state allows using optical theorem. Signal is Missing Energy.

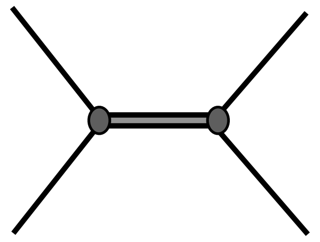
$$\sum_n \int d\Phi_D |\langle \Omega | \mathcal{O}_{\rm HS} | n \rangle|^2 = 2\,{\rm Im}\,\langle \Omega | \mathcal{O}_{\rm HS} \mathcal{O}_{\rm HS} | \Omega \rangle$$

$$\langle \mathcal{O}_{\rm HS}(p)\, \mathcal{O}_{\rm HS}(-p) \rangle \sim \frac{c}{16\pi^2} \left( p^{2\Delta-4} + p^{2\Delta-6}\Lambda_{\rm IR}^2 + \cdots + \Lambda_{\rm IR}^{2\Delta-4} \right)$$

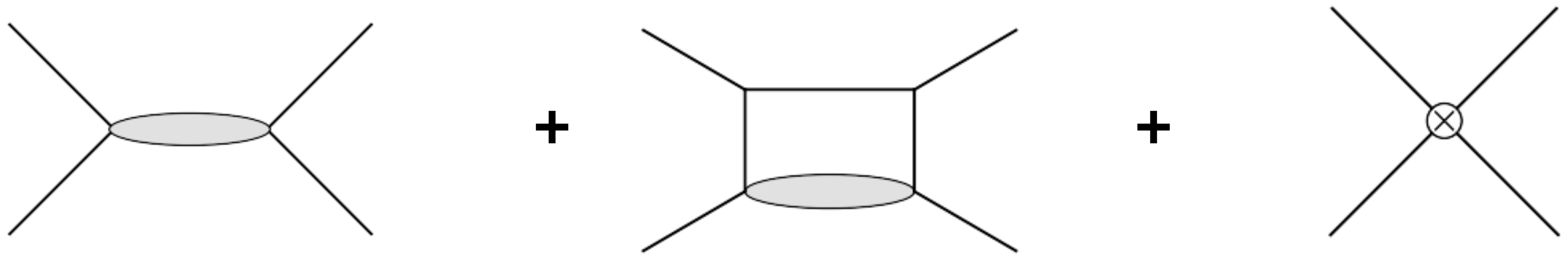
With some additional assumptions, this can be used for probing LLP signals as well.

Need: $\tau_{\rm LLP}$ , $\langle n_{\rm LLP} \rangle$ , $\langle \gamma_{\rm LLP} \rangle$.

### Indirect HS production



Depending on observable, the result can be UV sensitive



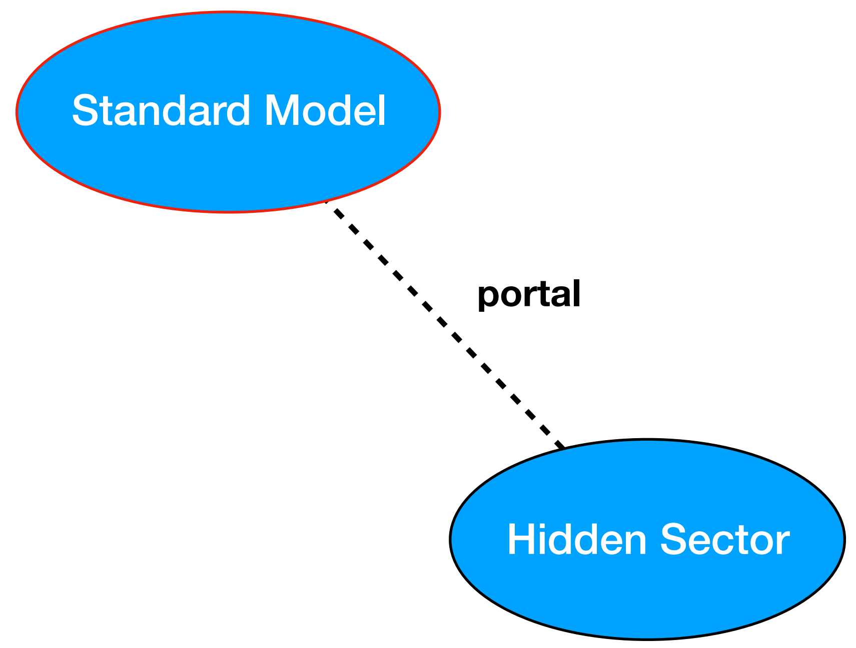

tree-level DS exchange

1-loop DS exchange

A threshold effect: Contact term to regulate the divergences in the DS EFT, from mediators.

If the UV contribution is dominant, this does not probe the DS directly. (e.g. no condition on $\Lambda_{\rm IR}$ , rather only on $\Lambda_{\rm UV}$).

# Relevant experimental probes



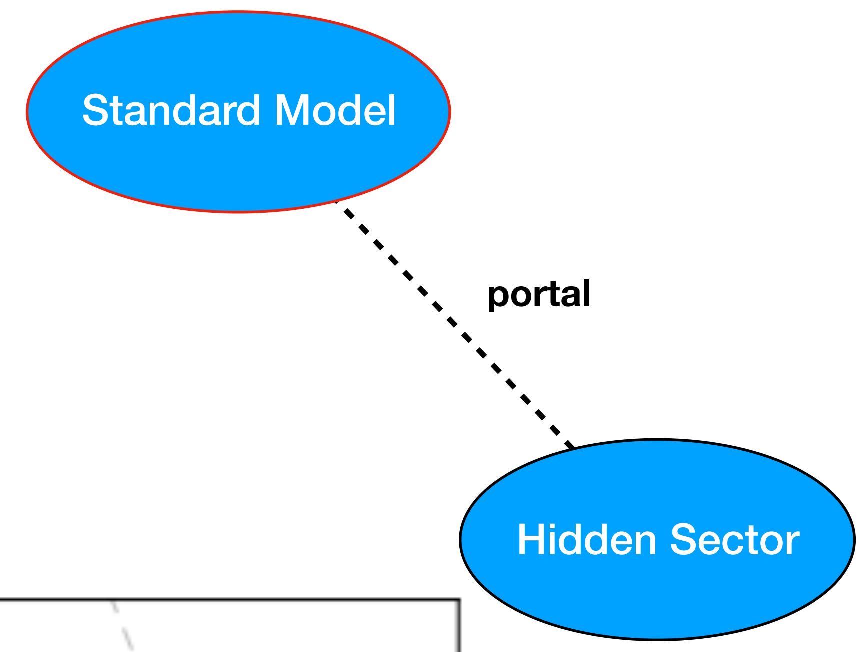

**DS direct production**

- Z and Higgs decays
- Non-resonant production at LEP and LHC (mono-X searches)
- High Intensity experiments (Fixed-target, beam dump, FC Meson decays)
- Supernova and Stellar evolution
- Positronium lifetime

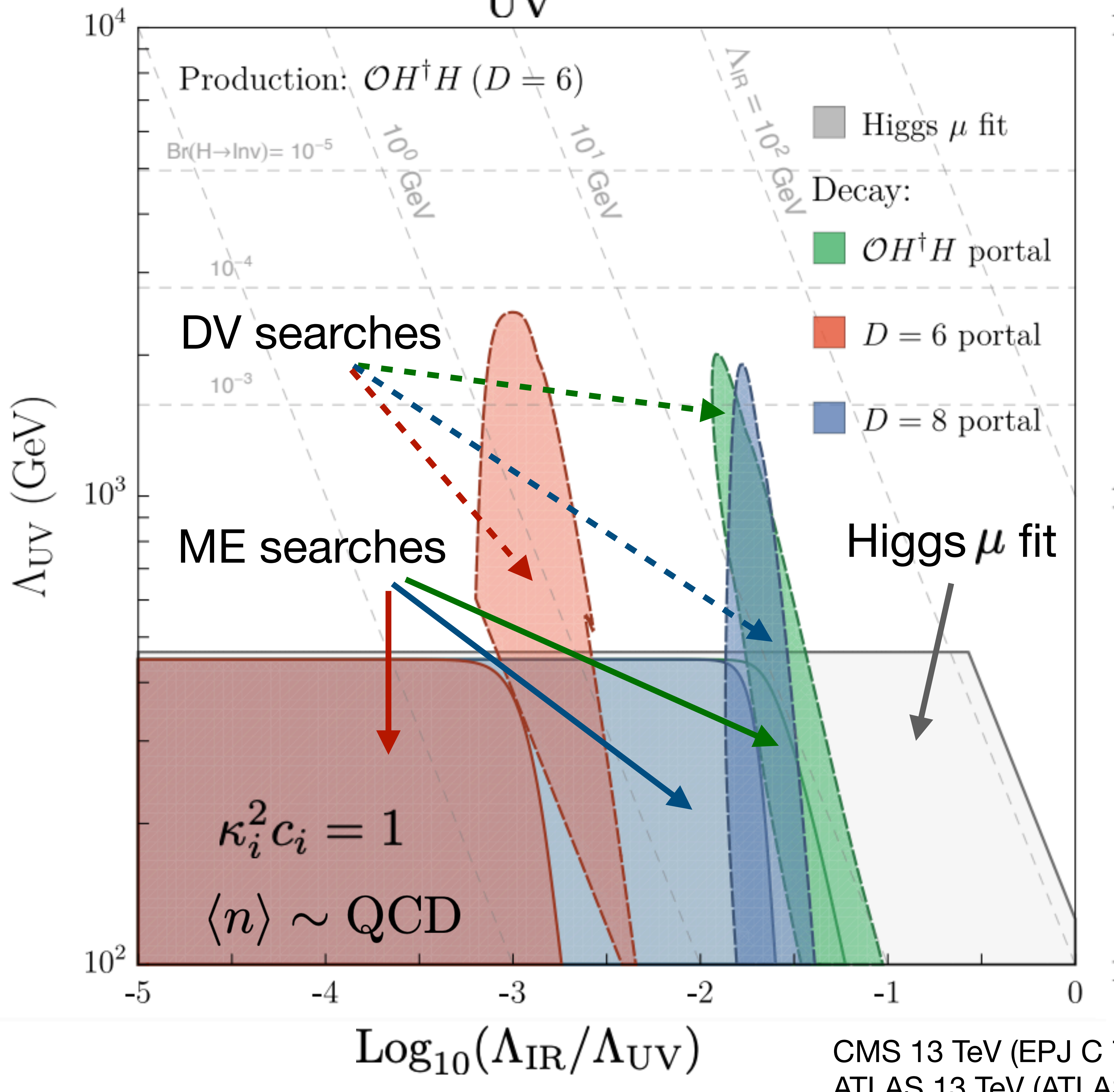
**DS virtual exchange**

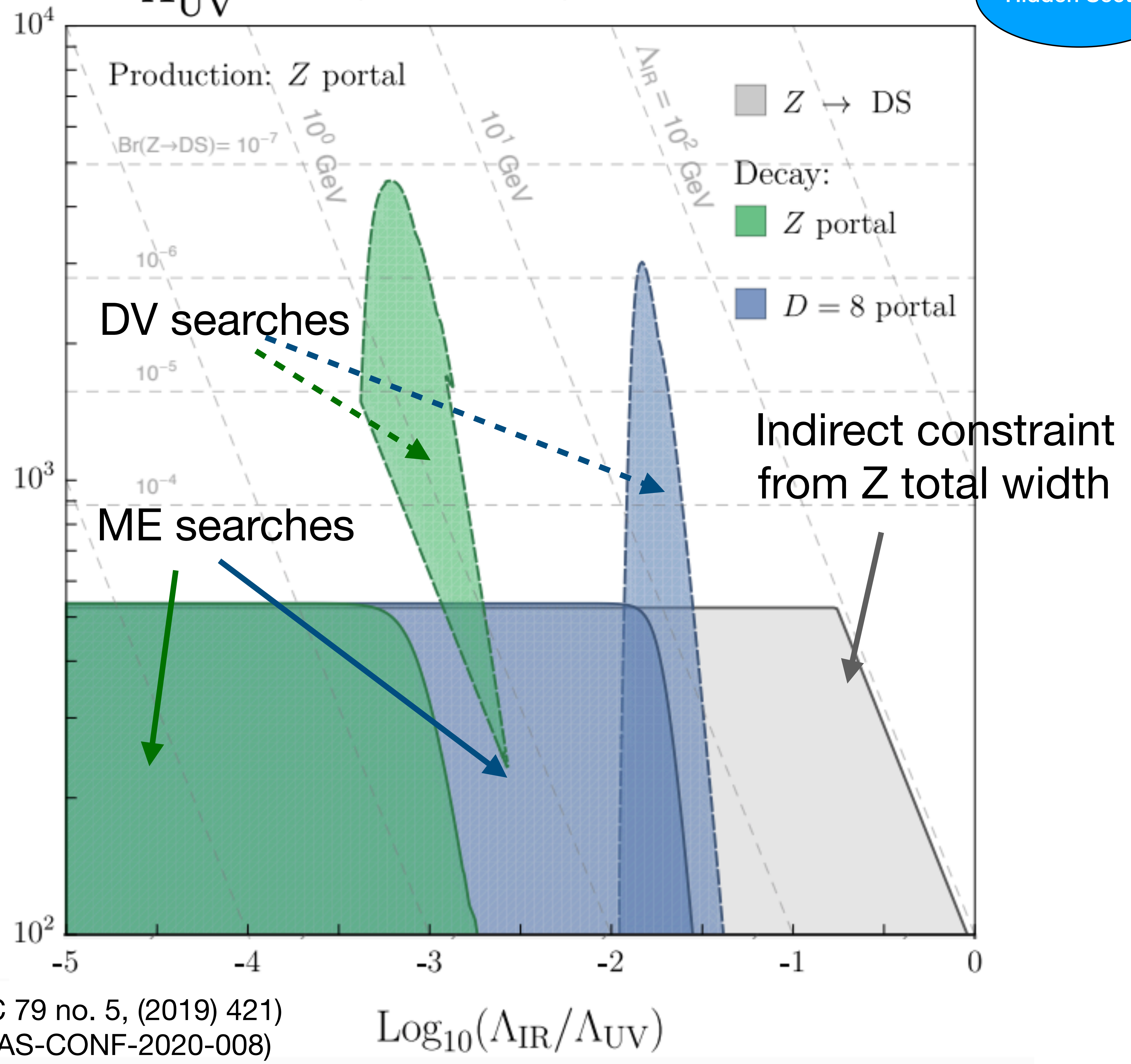
- Fifth Force experiments
- EWPT

# Bounds: Higgs and Z physics



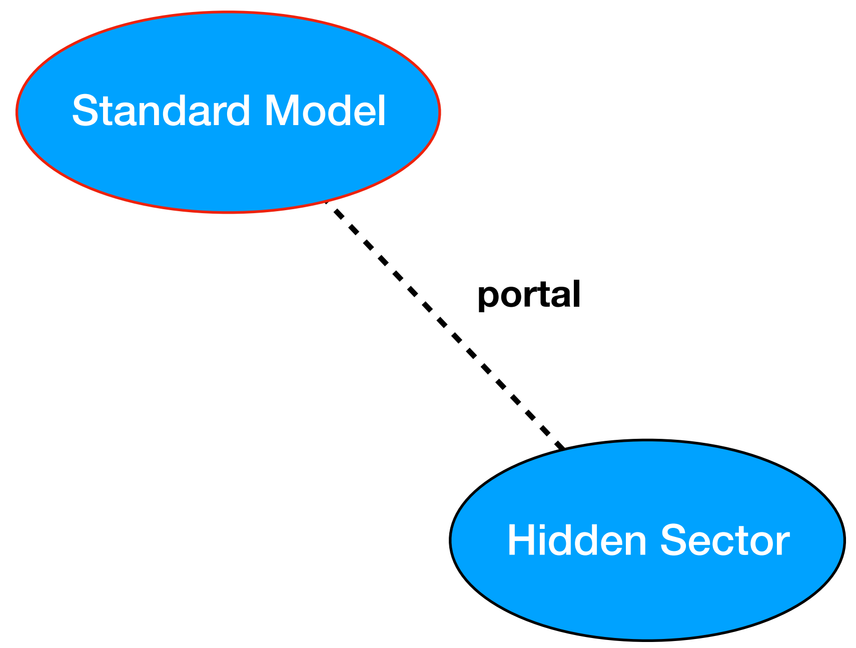

**Relevant (production) portal:** $\frac{\kappa_{\mathcal{O}}}{\Lambda_{\rm UV}^{\Delta_{\mathcal{O}}-2}}\mathcal{O}H^\dagger H$ $\qquad$ $\frac{\kappa_J}{\Lambda_{\rm UV}^2} J^\mu_{\rm DS}\left(H^\dagger i \overleftrightarrow{D}_\mu H\right)$

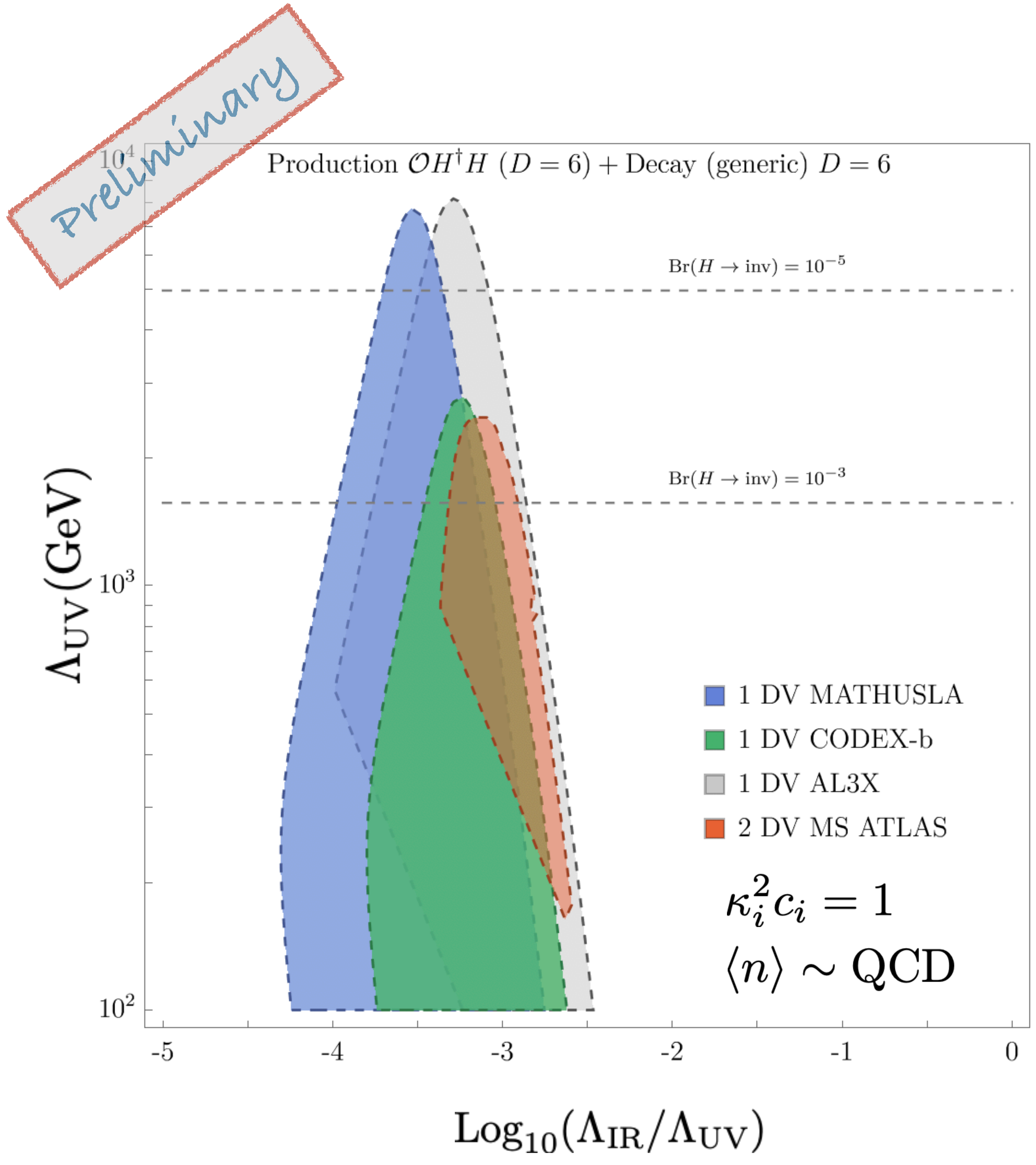



CMS 13 TeV (EPJ C 79 no. 5, (2019) 421)
ATLAS 13 TeV (ATLAS-CONF-2020-008)
ATLAS PRD 99 (2019) 052005,
ATLAS PRD 101 (2020) 052013

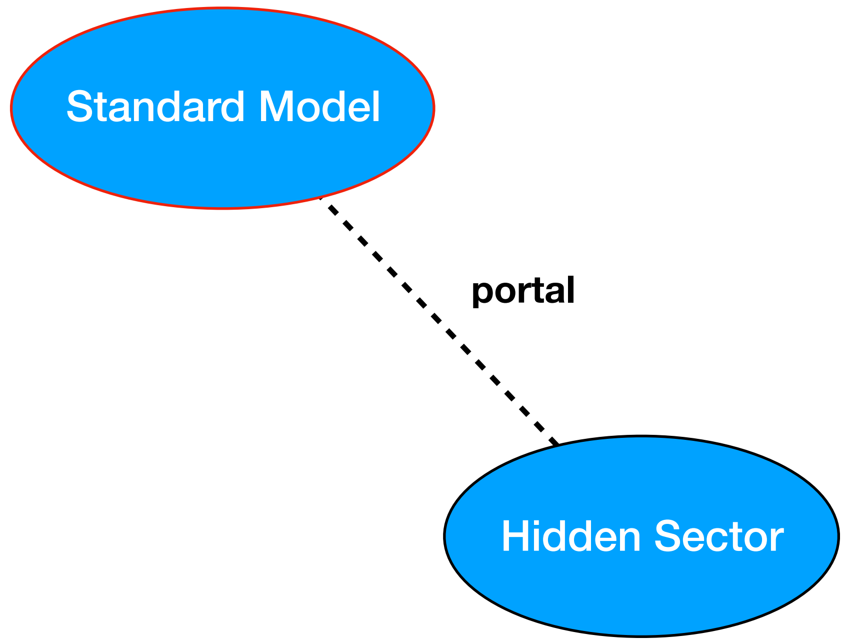
# Bounds: Higgs and Z physics




**Future experimental proposals cover a significant part of the parameter space**

# Bounds: non-mixing portals




**Relevant portal:**

D = 6

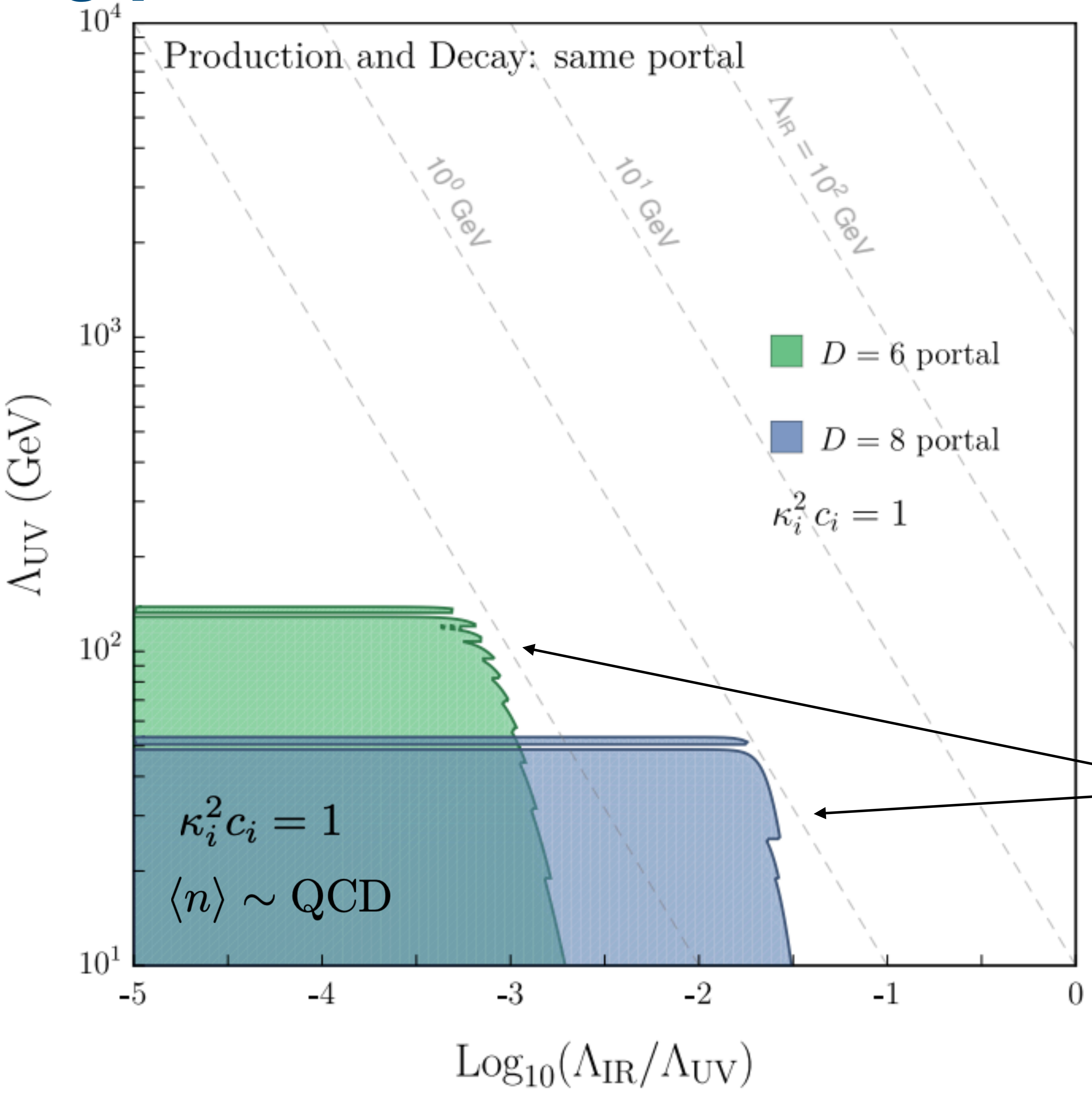
$$\frac{\kappa_J}{\Lambda_{\rm UV}^2} J^{\mu}_{\rm DS}\, \bar{e}\gamma_\mu e$$

D = 8

$$\frac{\kappa_T}{\Lambda_{\rm UV}^4} T^{\mu\nu}_{\rm DS}\, (F^{\mu}_{\alpha} F^{\alpha\nu} + \bar{e}\gamma_\mu D_\nu e)$$

**Mono-photon searches at LEP**
(PLB 587 2004, 16-32, EPJ C18 2000, 253-272)

**No bounds from LHC from EFT consistency**




EFT consistency

**Much weaker constraints (c.f. earlier portals)**

# High-intensity experiments

(consider JJ portal)

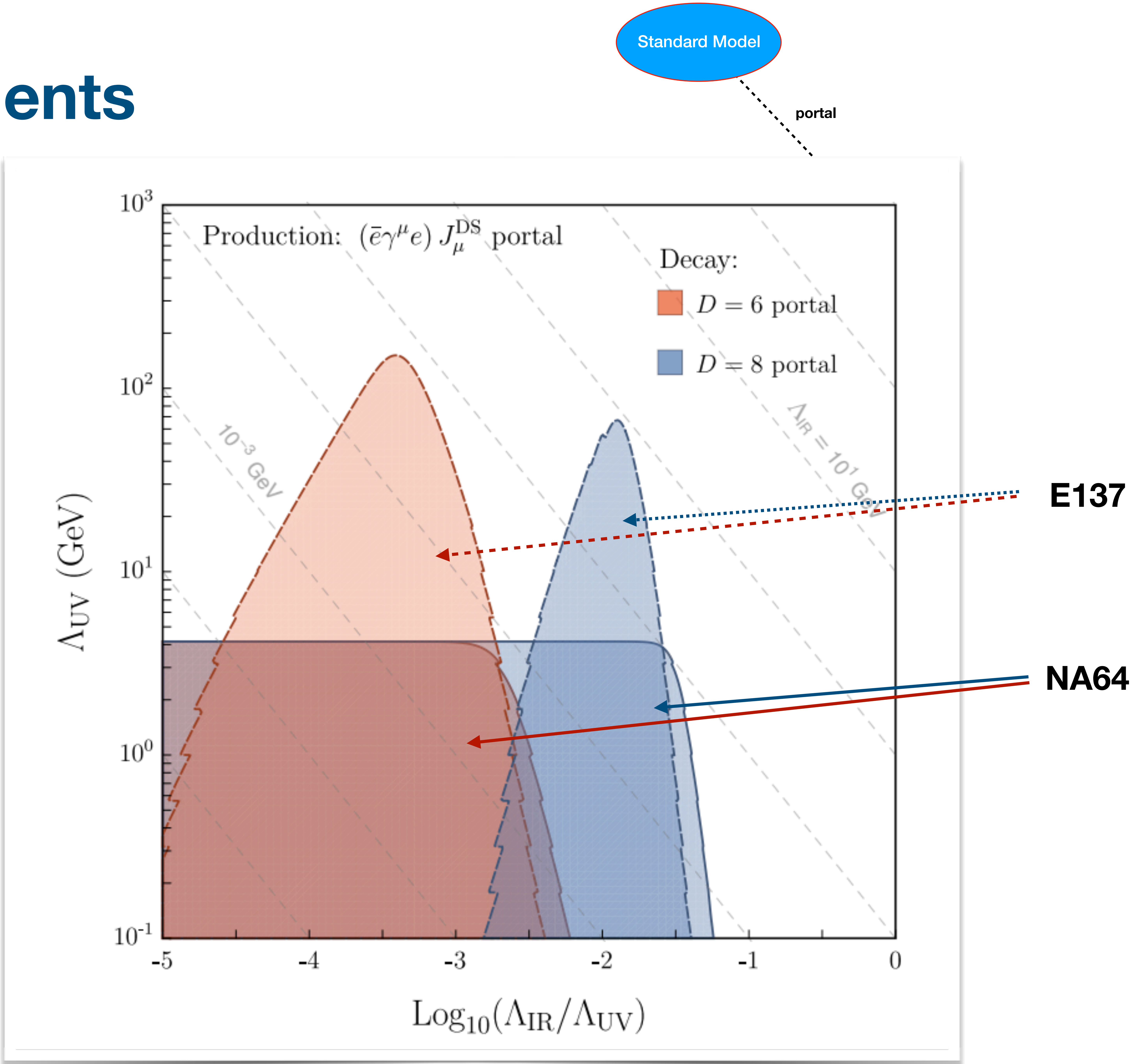
NA64

$$\sigma(eN \to eN + DS) = 0.8 \times 10^{-41}\text{cm}^2\ (c_J\kappa_J^2)\left(\frac{500\ \text{GeV}}{\Lambda_{\text{UV}}}\right)^4$$

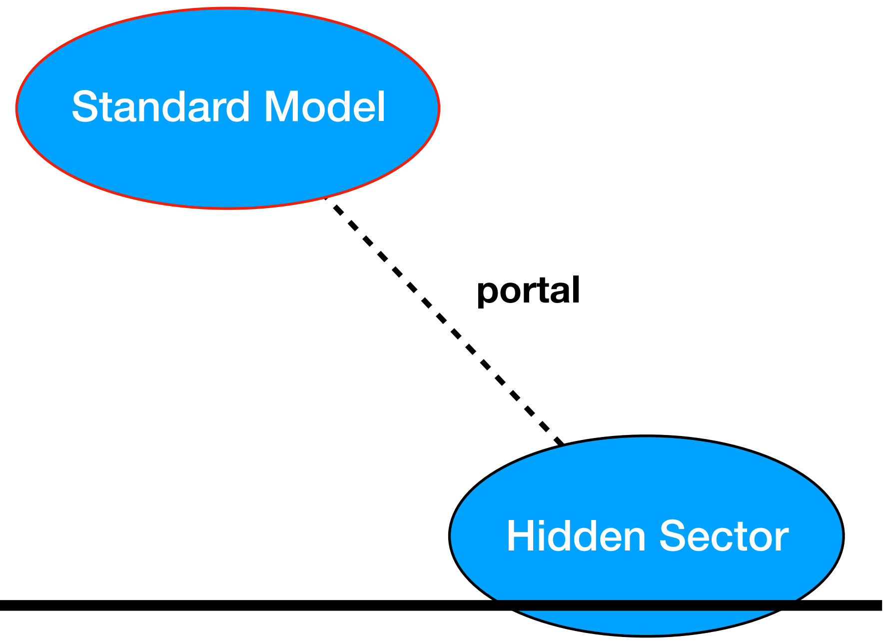
E137

$$\sigma(eN \to eN + DS) = 0.4 \times 10^{-43}\text{cm}^2\ (c_J\kappa_J^2)\left(\frac{500\ \text{GeV}}{\Lambda_{\text{UV}}}\right)^4$$

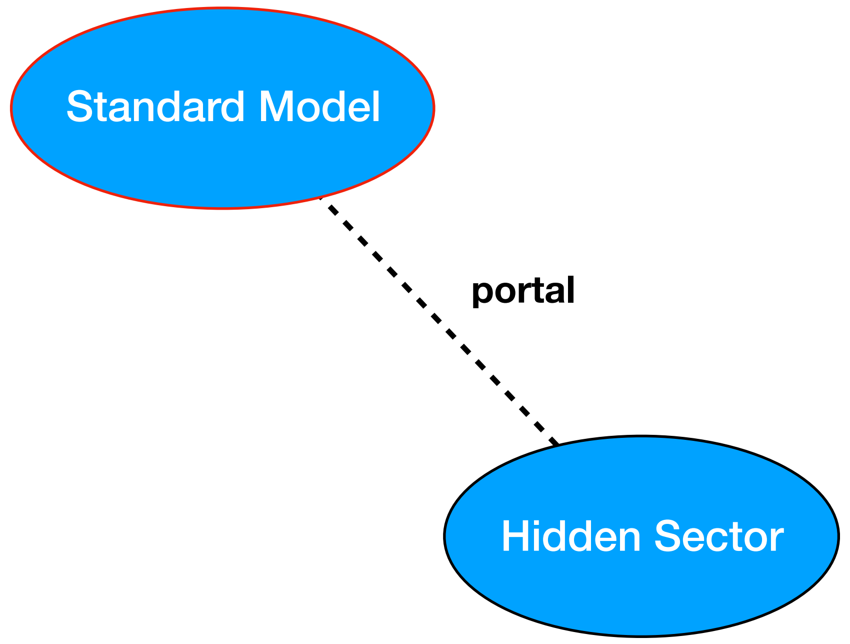
- **Weaker constraints than colliders.**
- **DV nature of signal allows a higher UV reach but in limited IR range.**
- **High POT compensates for low incident E.**



# Other constraints:

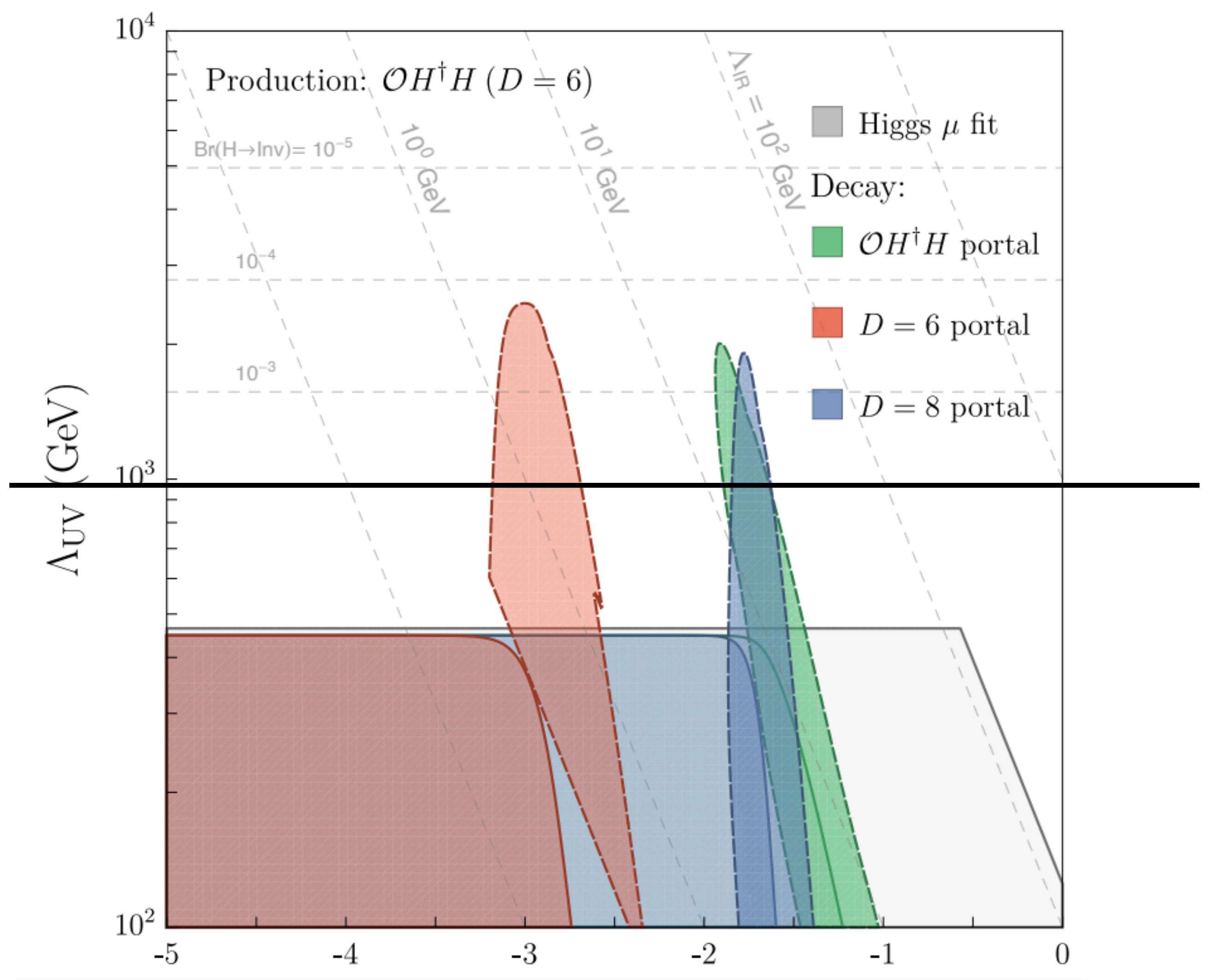


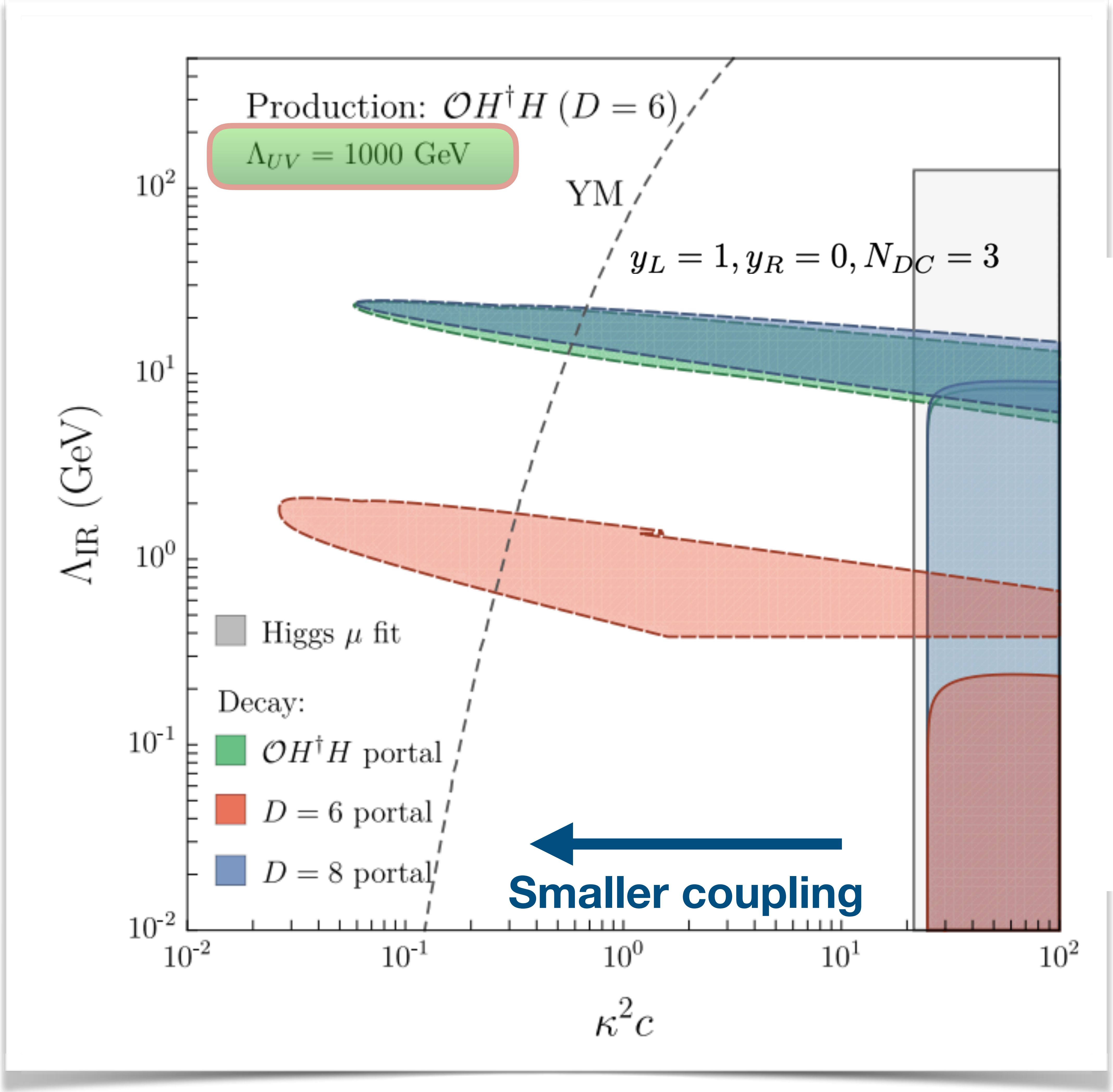

| | | |
|---|---|---|
| Meson decays | | |
| | Annihilation decays | $\Lambda_{\rm UV} < 2.3\ {\rm GeV}\ (c_J \kappa_J^2)^{1/4},\ \ \Lambda_{\rm IR} \lesssim 0.6\ {\rm MeV} (c_J \kappa_J^2)^{-0.18}$ |
| | Radiative decays | $\Lambda_{\rm UV} < 83\ {\rm GeV}\ (c_J \kappa_J^2)^{1/4},\ \ \Lambda_{\rm IR} \ll 90\ {\rm MeV} (c_J \kappa_J^2)^{-0.17}$ |
| | | $\Lambda_{\rm UV} < 1.3\ {\rm GeV}\ (c_{\mathcal{O}} \kappa_{\mathcal{O}})^{1/4},\ \ \Lambda_{\rm IR} \ll 800\ {\rm MeV} (c_{\mathcal{O}} \kappa_{\mathcal{O}}^2)^{-0.1}$ |
| Energy Loss | | |
| | SN | $\Lambda_{\rm UV} < 400\ {\rm GeV}\ (c_J (\kappa_J^{(nn)})^2)^{1/4},\ \ \Lambda_{\rm IR} \ll \min(T_{\rm SN}, 90\ {\rm MeV} (c_J (\kappa_J^{(nn)})^2)^{-0.19}$ |
| | HBS | $\Lambda_{\rm UV} < 62\ {\rm GeV}\ (c_J (\kappa_J^{(ee)})^2)^{1/4},\ \ \Lambda_{\rm IR} \ll \min(T_{\rm HB}, 10\ {\rm MeV} (c_J (\kappa_J^{(nn)})^2)^{-0.23}$ |
| Positronium lifetime | | |
| | to DS | $\Lambda_{\rm UV} < 346\ {\rm MeV}\ (c_J \kappa_J^2)^{1/4},\ \ \Lambda_{\rm IR} \ll 3\ {\rm MeV} (c_J \kappa_J^2)^{-0.19}$ |
| | to DS + photon | $\Lambda_{\rm UV} < 3.6\ {\rm MeV}\ (c_T \kappa_T^2)^{1/8},\ \ \Lambda_{\rm IR} \ll 0.4\ {\rm MeV} (c_T \kappa_T^2)^{-0.1}$ |
| Fifth force | | $\Lambda_{\rm UV} < 0.2\ {\rm MeV}\ (c_J \kappa_J^2)^{1/4},\ \ \Lambda_{\rm IR} \ll 1\ {\rm keV}$ |

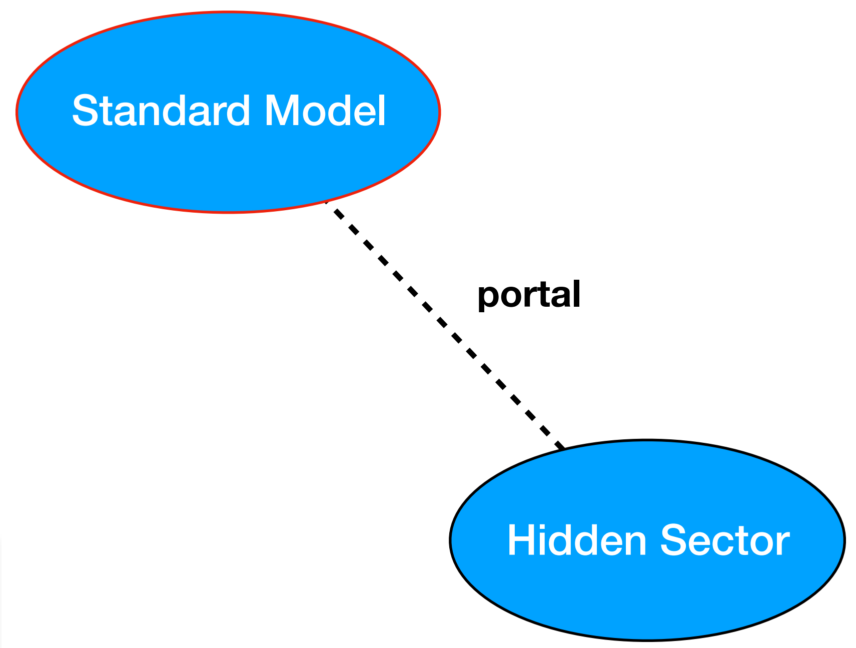



# Lessons so far:

**Take UV physics to be heavier than ~ TeV.**
**What reach do we have on the IR scale?**



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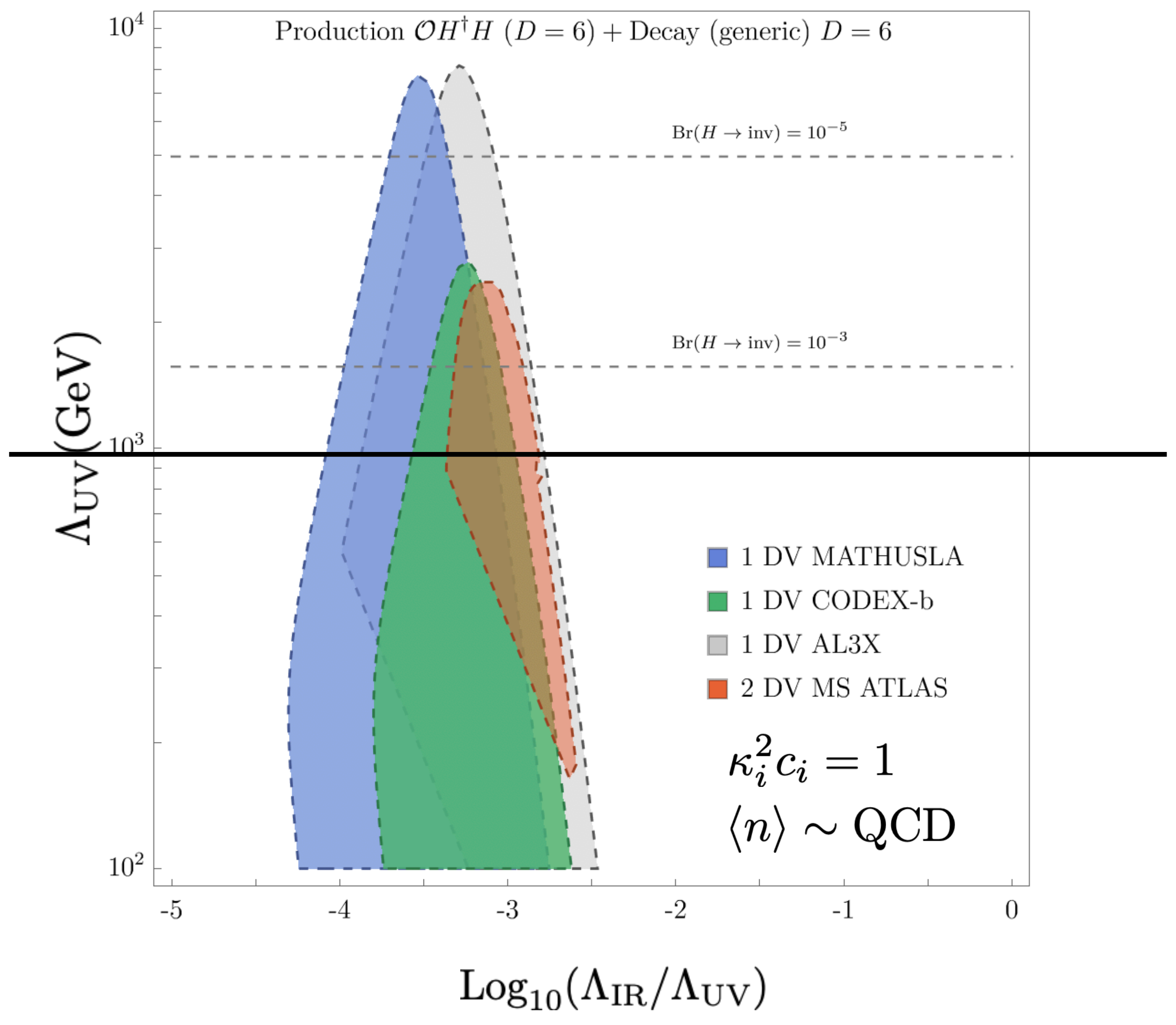
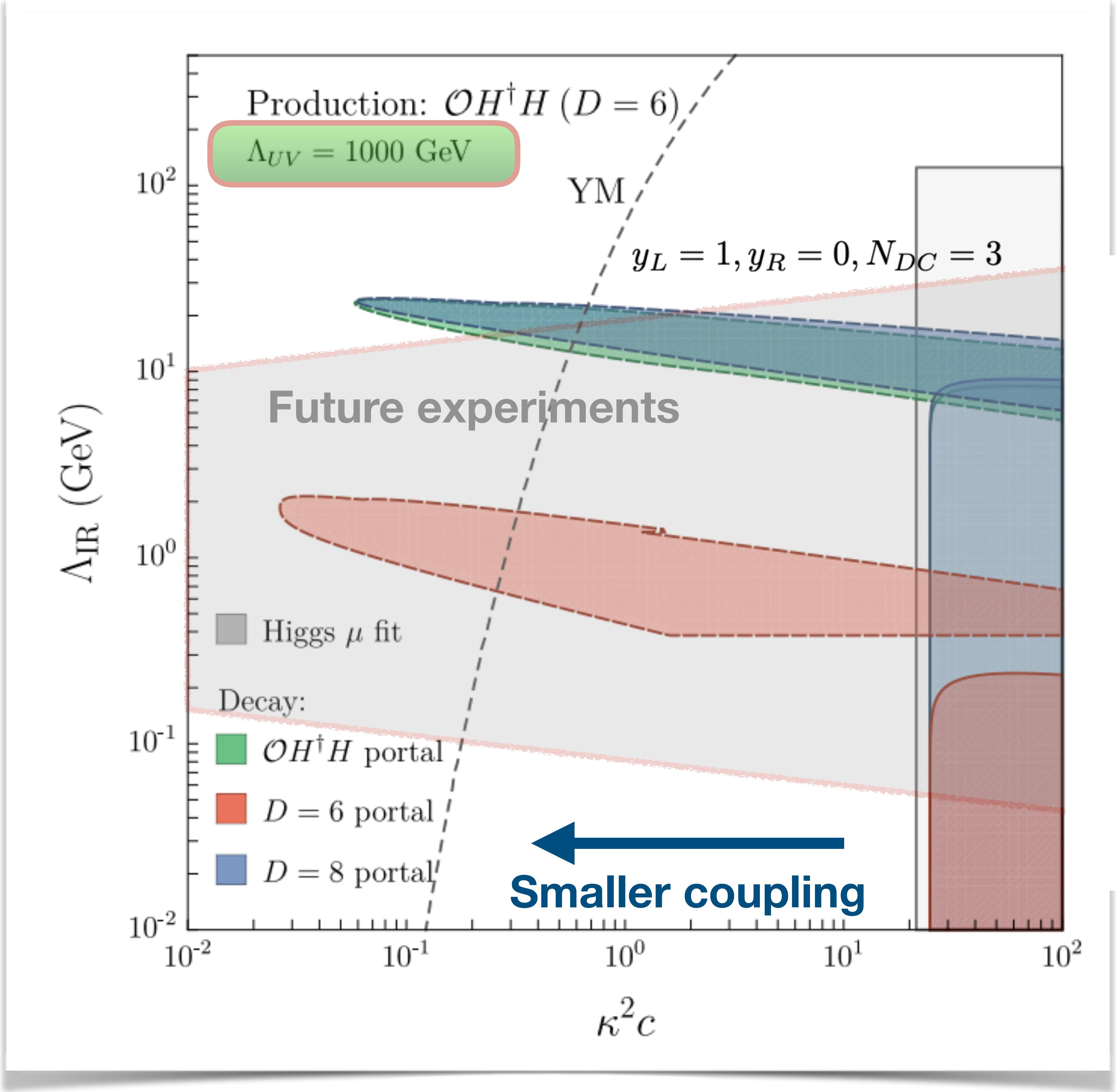
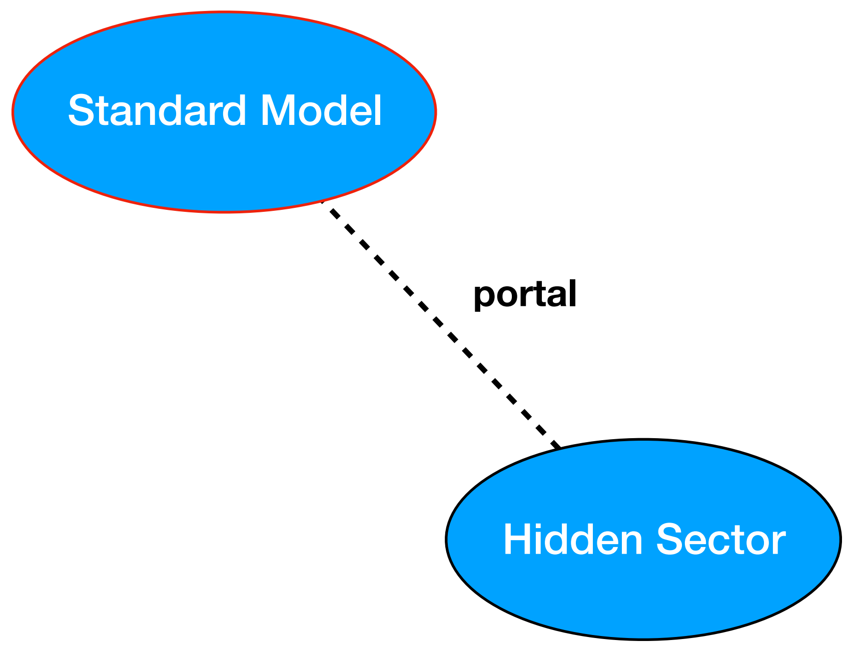



**Probably an altogether different kind of probe is needed to reach lower IR values.**



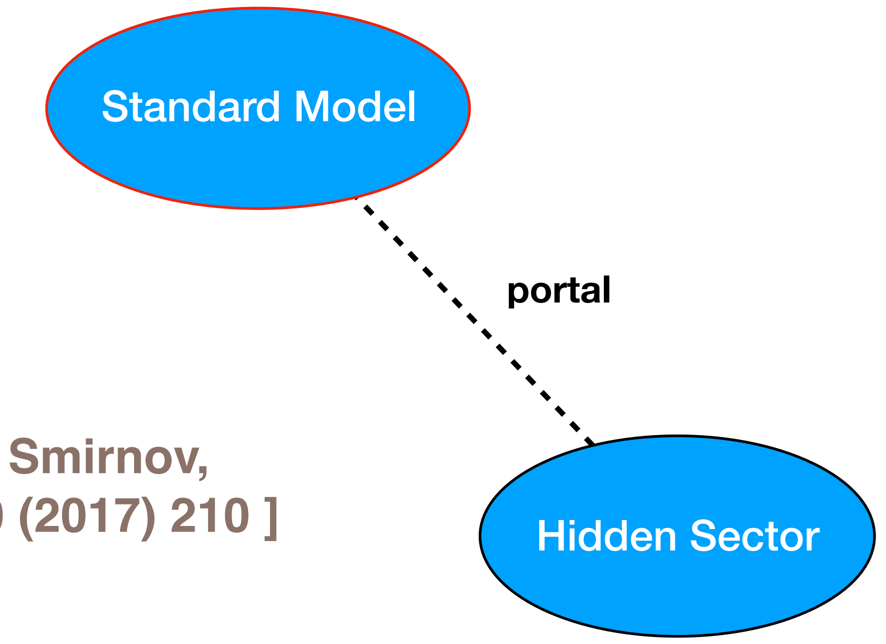

# Summary

- Big chunks of parameter space unconstrained at the moment.
- Future experimental proposals are crucial to probe them.
  - DV searches are the most constraining when applicable.
  - Future Higgs/Z factories will constrain the mixing portals strongly.
- Several usual probes are UV sensitive and do not constrain DS directly.
- Cosmological considerations will provide a complimentary probe, but usually come with more assumptions.

# Thank you!

# Extra slides

# Example: strong coupling
# Pure (confining) YM

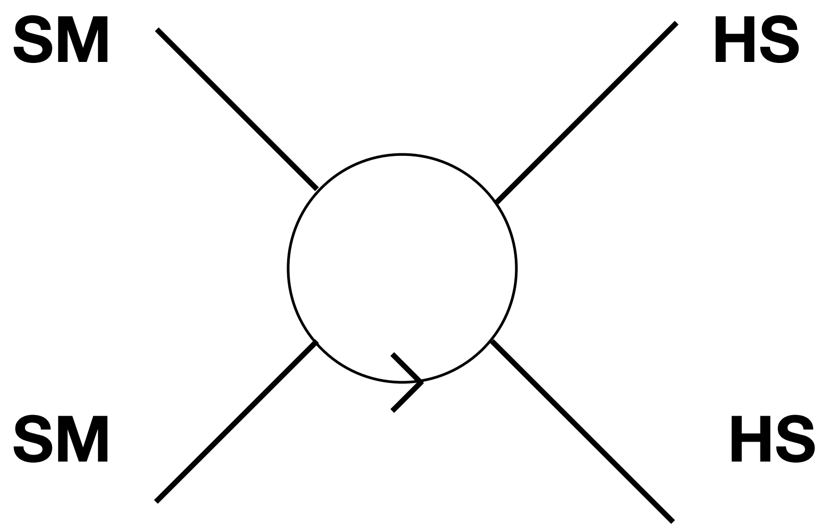



[ Mitridate, Redi, Smirnov, Strumia JHEP 10 (2017) 210 ]

A confining $SO(N_{DC})$ gauge group with a singlet (Majorana) $N(1_0)$ and a doublet (Dirac) $L(2_{-1/2})$ .

$$\Delta\mathcal{L} = -\frac{1}{4g_{DC}^2}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \bar{L}(i\not{D} - m_L)L + \frac{1}{2}\bar{N}(i\not{D} - m_N)N$$
$$-\left(y_L\,\bar{N}P_L LH + y_R\,\bar{N}P_R LH + h.c.\right),$$

For $m_L\,, m_N \gg \Lambda_{DC}$ , the low energy is a pure YM dark sector, with portals




Heavy fermions
as the mediators

$$\sim \frac{\alpha_{DC}}{4\pi}\left(|y_L|^2 + |y_R|^2\right)\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu}\,H^\dagger H$$

$$\frac{\kappa_O}{\Lambda_{\rm UV}^{\Delta-2}}(H^\dagger H)\mathcal{O}_\Delta$$

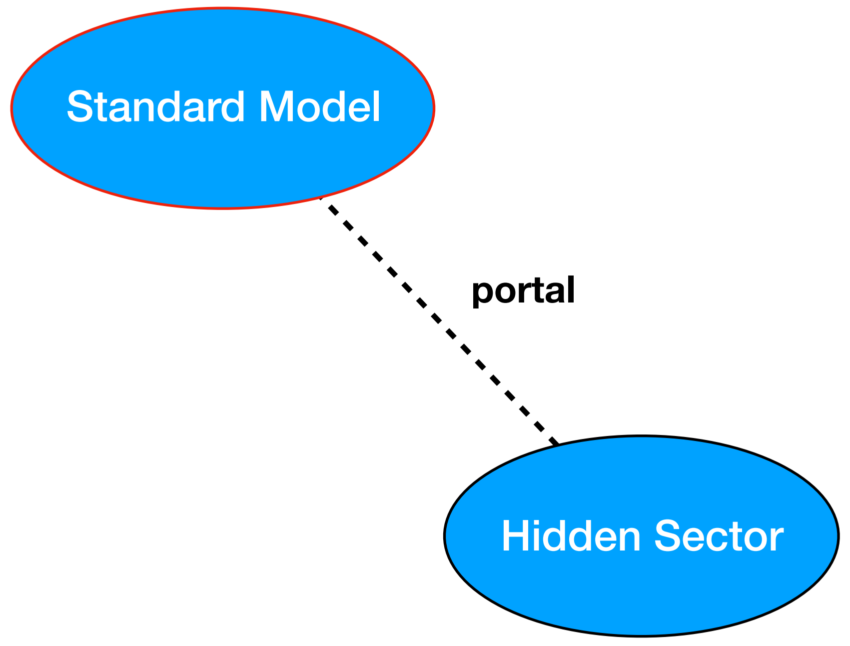
$$\Lambda_{\rm IR} \sim \Lambda_{\rm DC}$$

$$\Lambda_{\rm UV} \sim m_L,\, m_N$$

$$\mathcal{O} \sim \mathcal{G}_{\mu\nu}\,\mathcal{G}^{\mu\nu}$$

$$\kappa \sim \alpha\, y^2$$

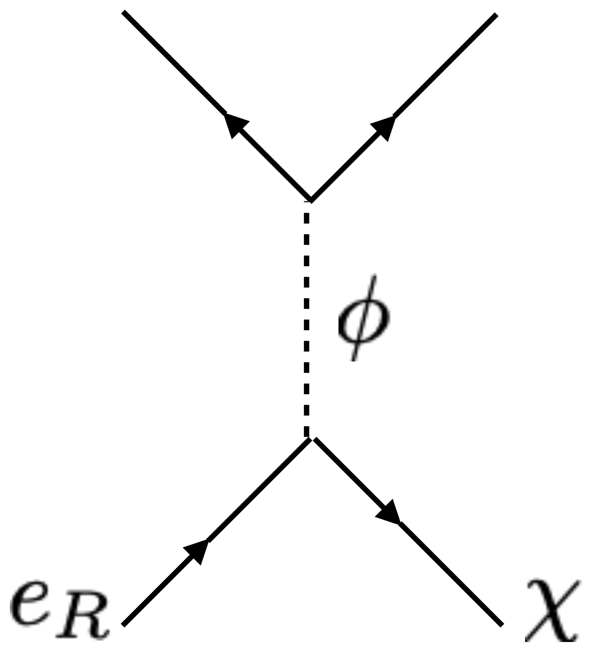
# Example: weak coupling
# Free Fermion (FF)




A SM-neutral Majorana fermion $\chi$ and a scalar $\phi$ with hyper charge -1, both odd under a dark parity.

$$\Delta\mathcal{L} = (D_\mu\phi)^\dagger(D^\mu\phi) + \frac{1}{2}\bar{\chi}(i\not{\partial} - m_\chi)\chi + (y\,\bar{e}_R\phi\chi + h.c.) - m_\phi^2\phi^\dagger\phi - \lambda_\phi(\phi^\dagger\phi)^2\,.$$

For $m_\phi \gg m_\chi$, we can integrate out the scalar.




$$\sim \frac{y^2}{m_\phi^2}\bar{e}_R\gamma_\mu e_R\,\bar{\chi}\gamma^\mu\gamma^5\chi$$

$$\frac{\kappa_J}{\Lambda_{\rm UV}^2} J_\mu^{\rm SM}\, J_{\rm DS}^\mu$$

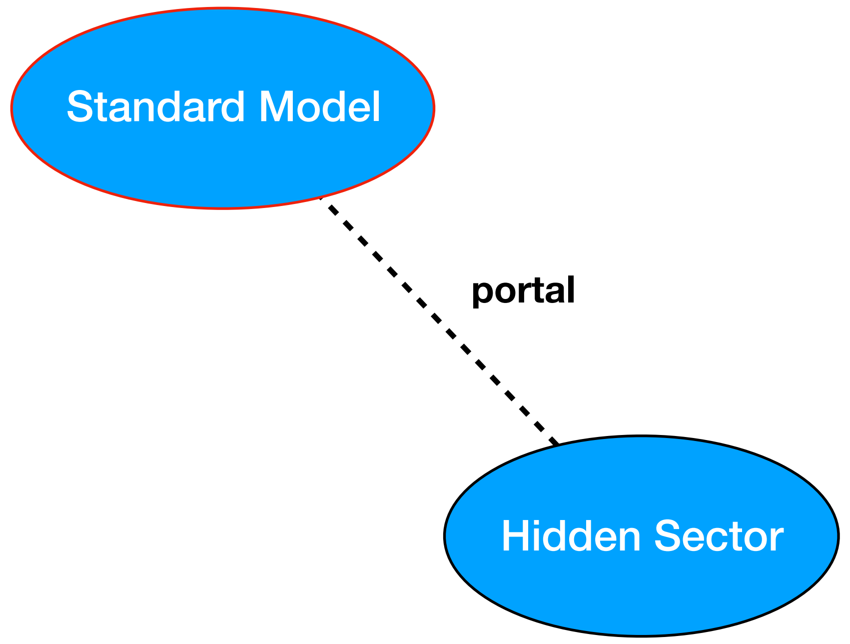
$$\Lambda_{\rm UV} \sim m_\phi$$

$$\Lambda_{\rm IR} \sim m_\chi$$

$$J_\mu \sim \bar{\chi}\gamma^\mu\gamma^5\chi$$

$$\kappa \sim y^2$$

# Example: 5D RS dark sector




5D RS scenario with SM on UV brane, and brane localized interactions

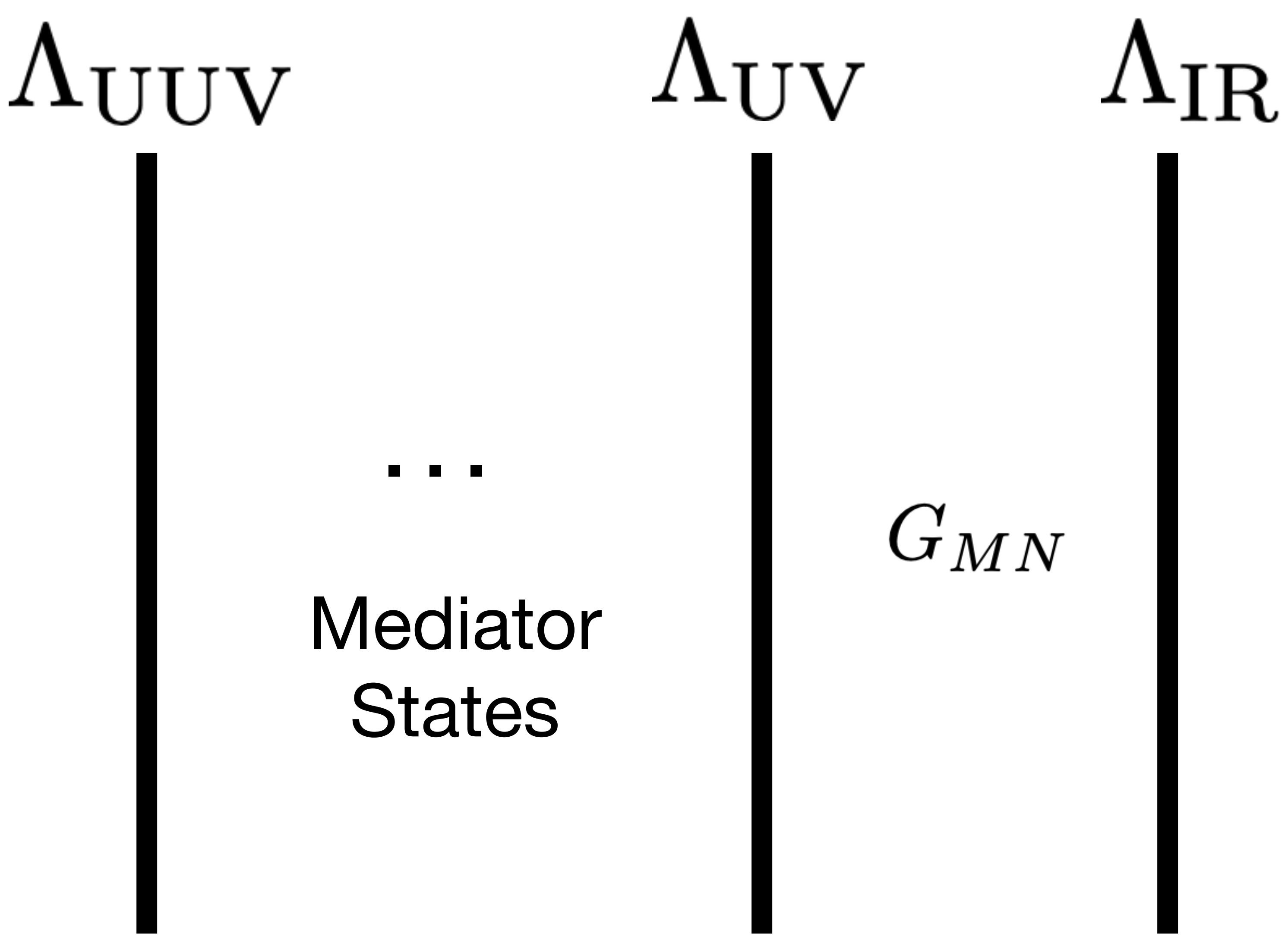
$$\int d^4x\sqrt{-g}\left(M_0^2 R + \frac{1}{\Lambda_{\rm UV}^2} R_{\mu 5\nu 5} T_{SM}^{\mu\nu}\right) .$$

After a KK decomposition, the interaction between the SM and the DS states ( = KK gravitons) in the 4D effective action is captured by the operator

$$\sim \frac{(k^3/M_5^3)}{M_5^4} T_{\mu\nu}^{DS} T_{SM}^{\mu\nu}$$

where $T_{\mu\nu}^{DS}$ excites KK gravitons.

can be thought as the low energy limit of a multi brane RS theory (Agashe et al, 1608.00526)




Refer to 2012.08537 for a comprehensive list of the models, with other details.

$$\frac{\kappa_T}{\Lambda_{\rm UV}^4} T_{\mu\nu}^{\rm SM}\, T_{\rm DS}^{\mu\nu}$$

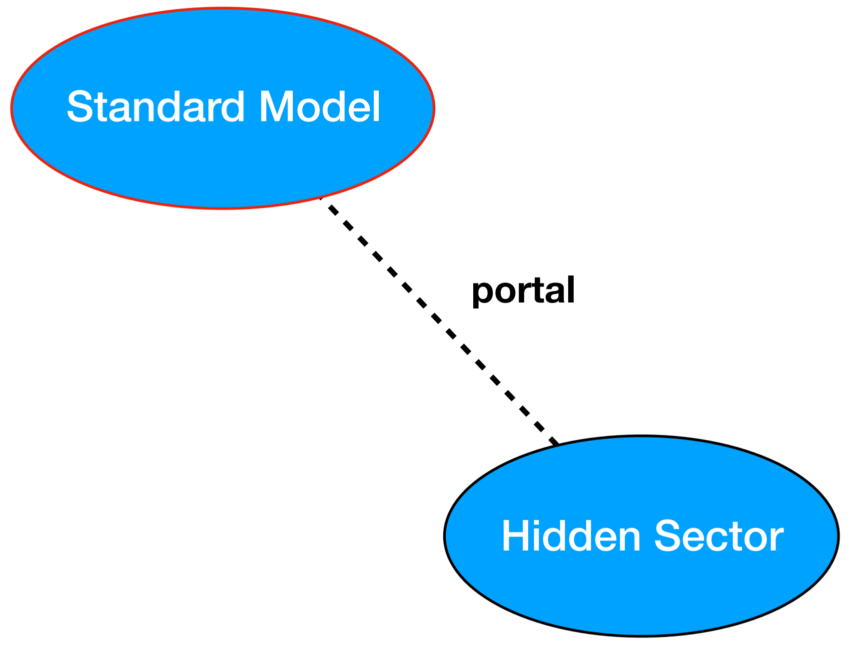
$$\Lambda_{\rm UV} \sim \text{UV brane}$$

$$\Lambda_{\rm IR} \sim \text{IR brane}$$

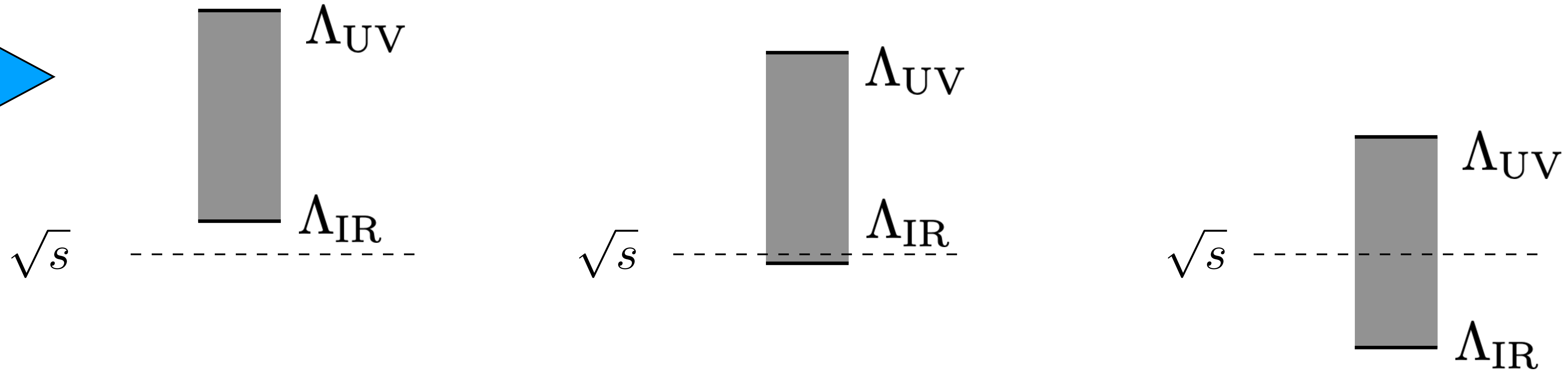
$$T_{\mu\nu} \sim G_{MN}$$

$$\kappa \sim k^3/M_5^3$$

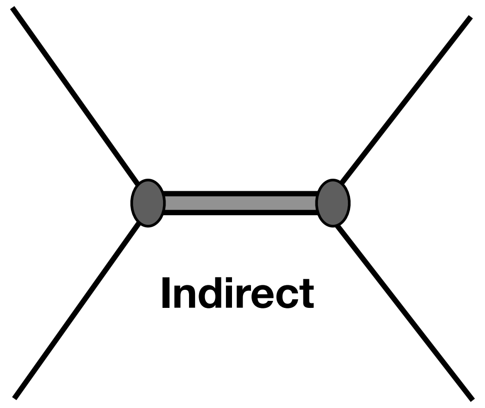
# Classification of effects

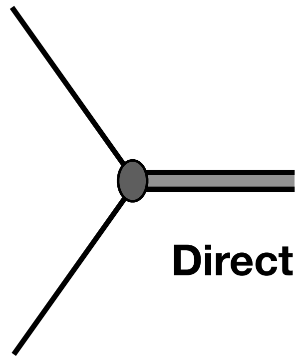



**Energy**




**Effect**




| | | Indirect Regime | Threshold Regime | Continuum Regime |
|---|---|---|---|---|
| Indirect | HS | SM EFT | Spectrum dependent signal | Spectrum independent signal |
| | UV | does not probe DS directly | | |
| Direct | HS | ✗ | | |
| | UV | ✗ | ✗ | ✗ |

**Focus on the continuum regime for minimal dependence on a model.**

**Look for:**

- **Missing Energy**
- **LLPs**
- **High Multiplicity decays**

# EFT validity:

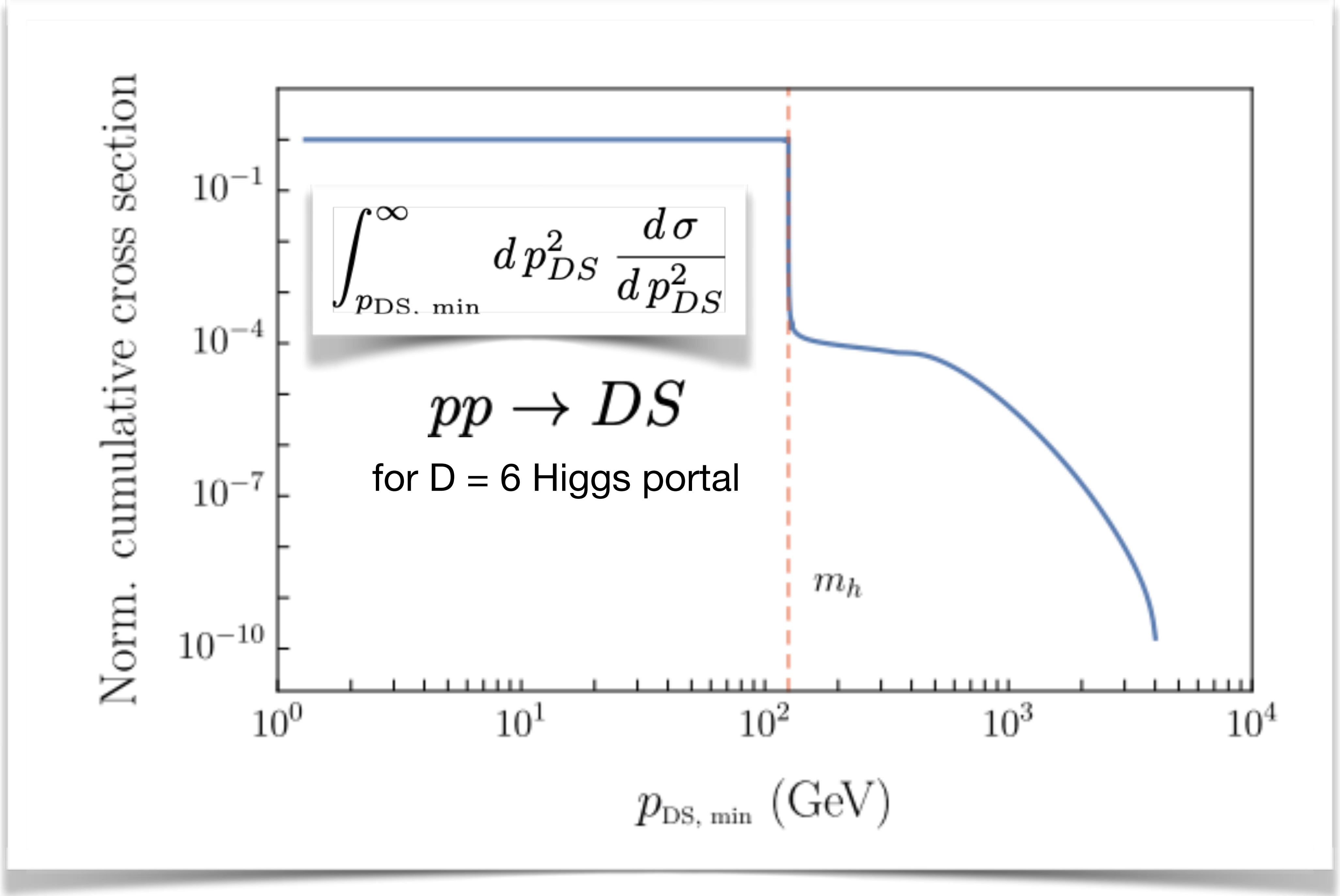
## Resonant vs Non-Resonant portals

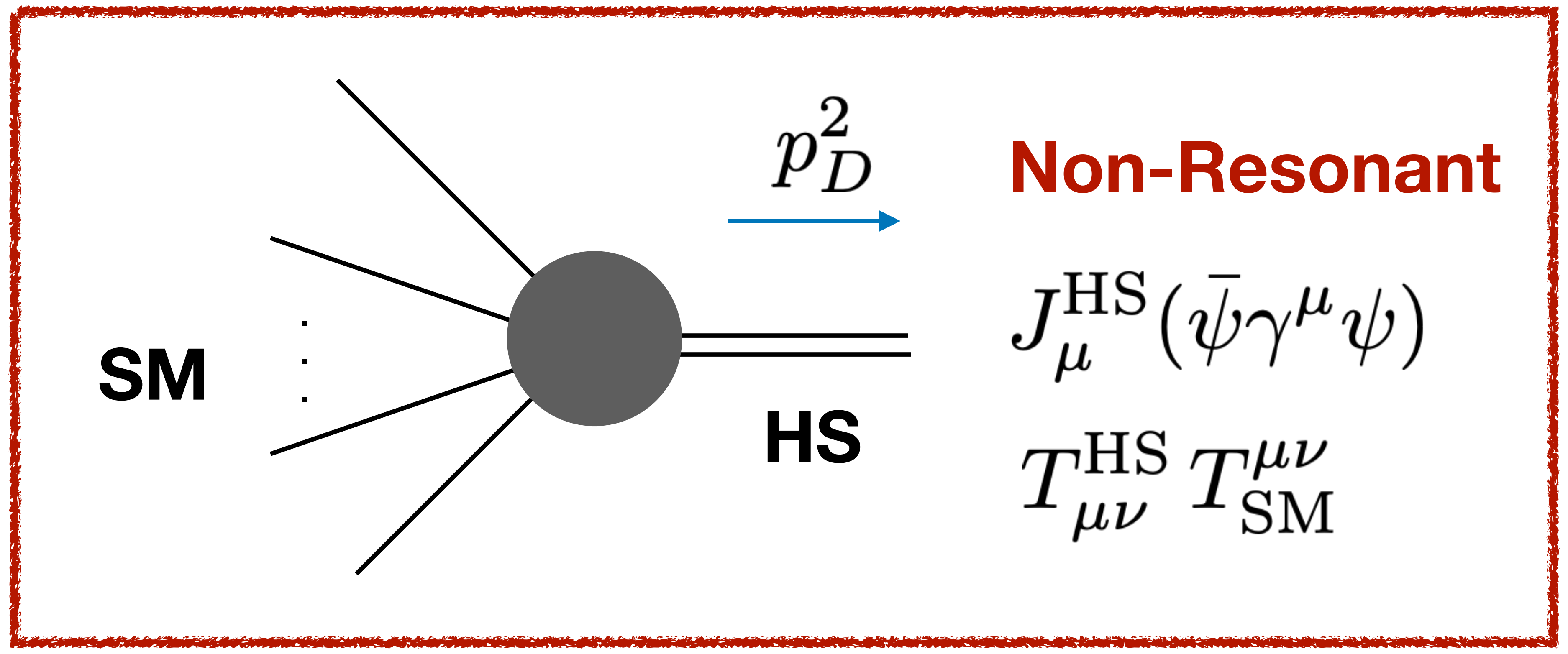
To be in the continuum limit and to be in the validity of portal interactions to arise from integration out heavy physics:

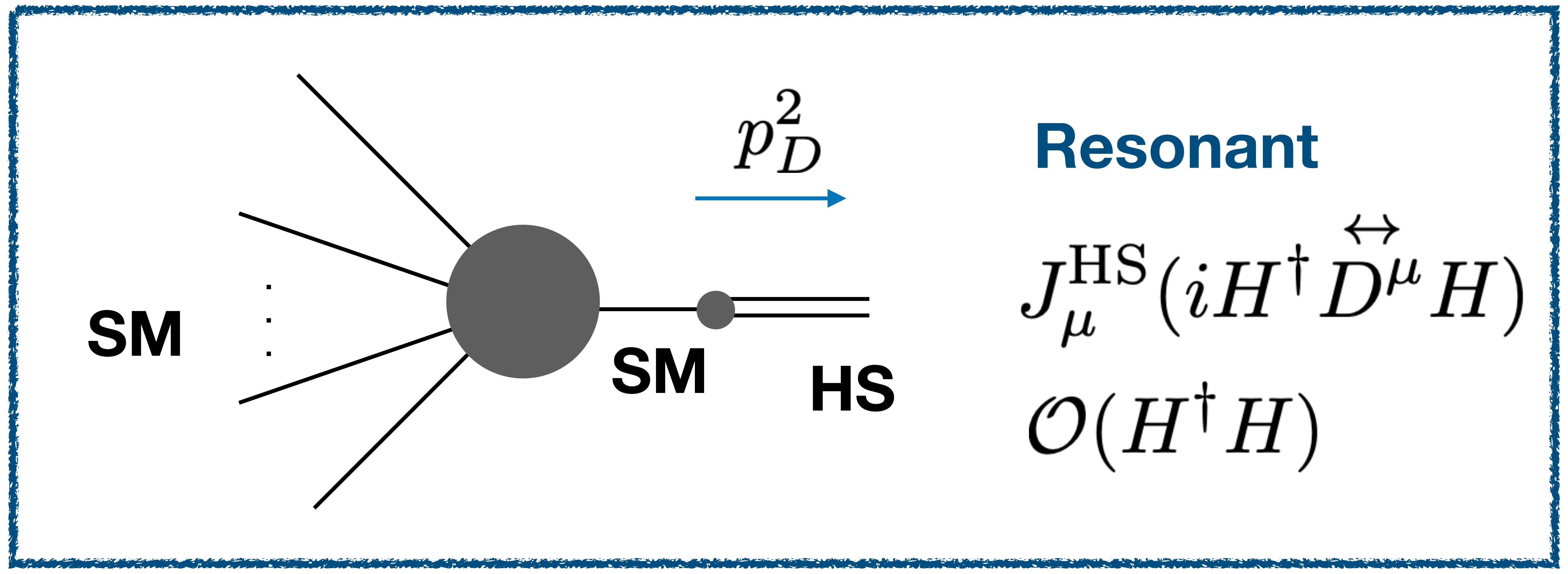
$$\Lambda_{\rm IR}^2 \ll p_{\rm DS}^2 \ll \Lambda_{\rm UV}^2$$

Depending on the process, constraints from data (from a given range in pDS) should only constrain the UV and IR scales that satisfy the criteria.

In practice, this depends on the nature of the portal:

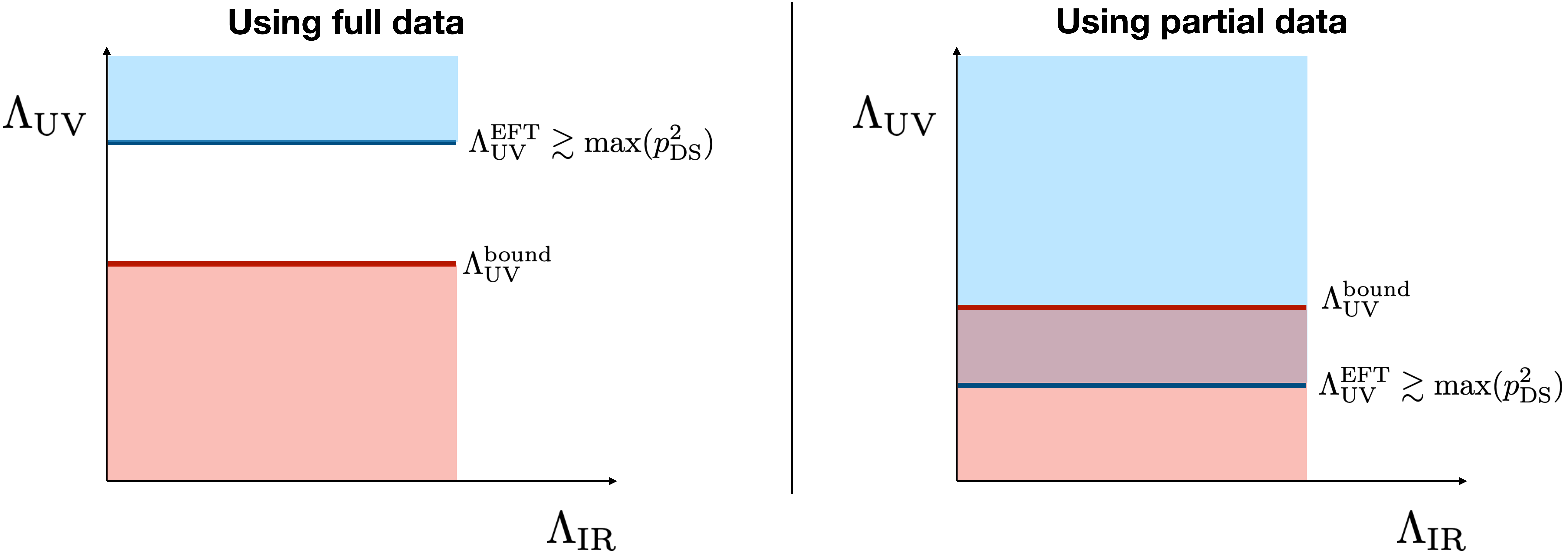


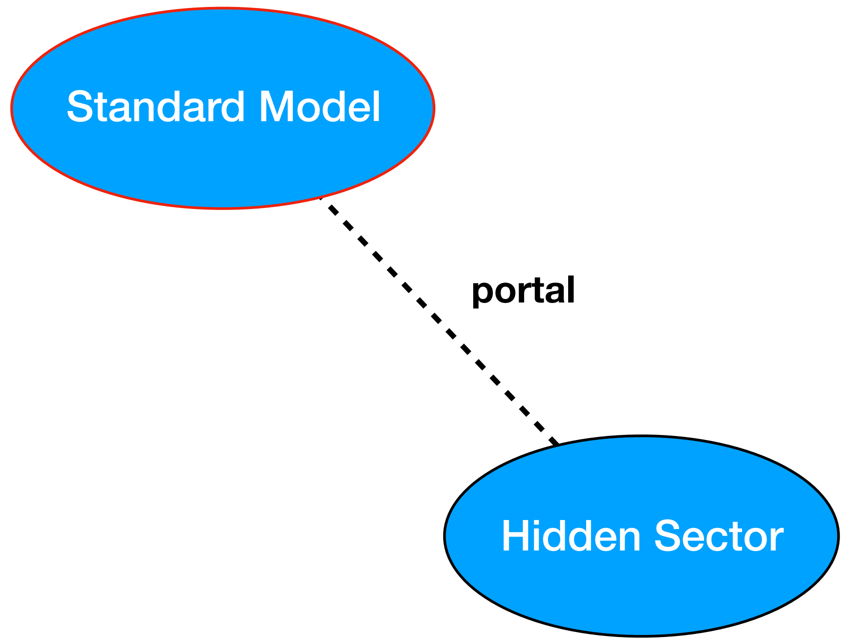



# EFT validity:

## a cartoon




**In practice: iterate over this procedure and take a union.**
**This will only matter for *non-resonant* portals.**




# High-intensity experiments

Standard lore: such experiments are a good probe of dark sectors.
Small coupling is compensated by high intensity.

e.g. Fixed target experiment (NA64), Beam dump experiment (E137), Meson decays (BESIII, BABAR)

Cross-section for DS production scales as: $\sigma \sim (c\kappa^2/E^2)(E/\Lambda_{\rm UV})^{2D-8}$

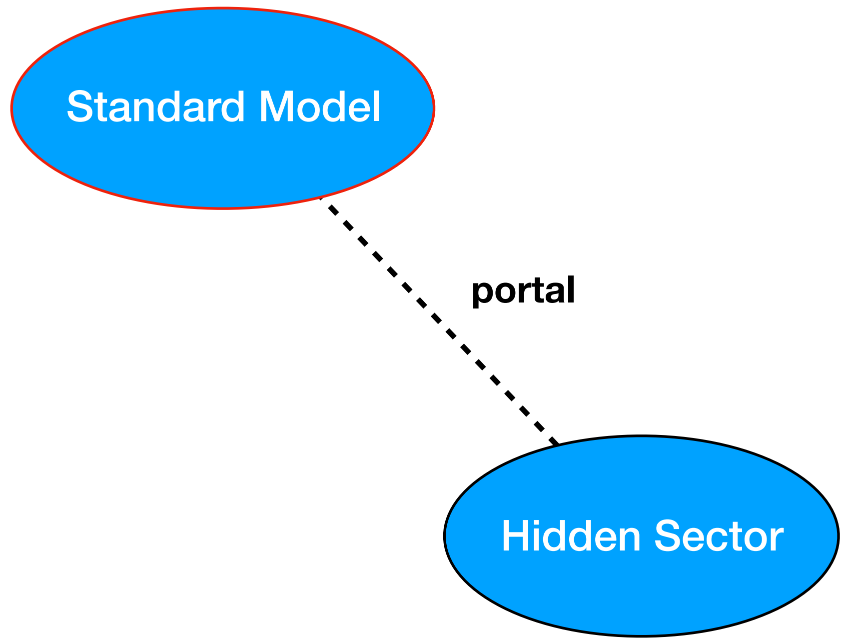
A naive estimate for the number of events gives:

$$\frac{N_{collider}}{N_{target}} = \frac{\sigma_{collider}\,\mathcal{L}_{collider}}{\sigma_{target}\,\mathcal{L}_{target}} \sim 10^{-3}\left(\frac{E_{collider}}{E_{target}}\right)^{2D-10}\left(\frac{\mathcal{L}_{collider}}{100\,\mathrm{fb}^{-1}}\right)\left(\frac{10^{20}}{N_{\rm POT}}\right)$$

Using $\mathcal{L}_{\rm target} = N_{\rm POT}\,\ell\rho,\ \ell = \ 10\ \mathrm{cm},\ \rho = 10^{23}$

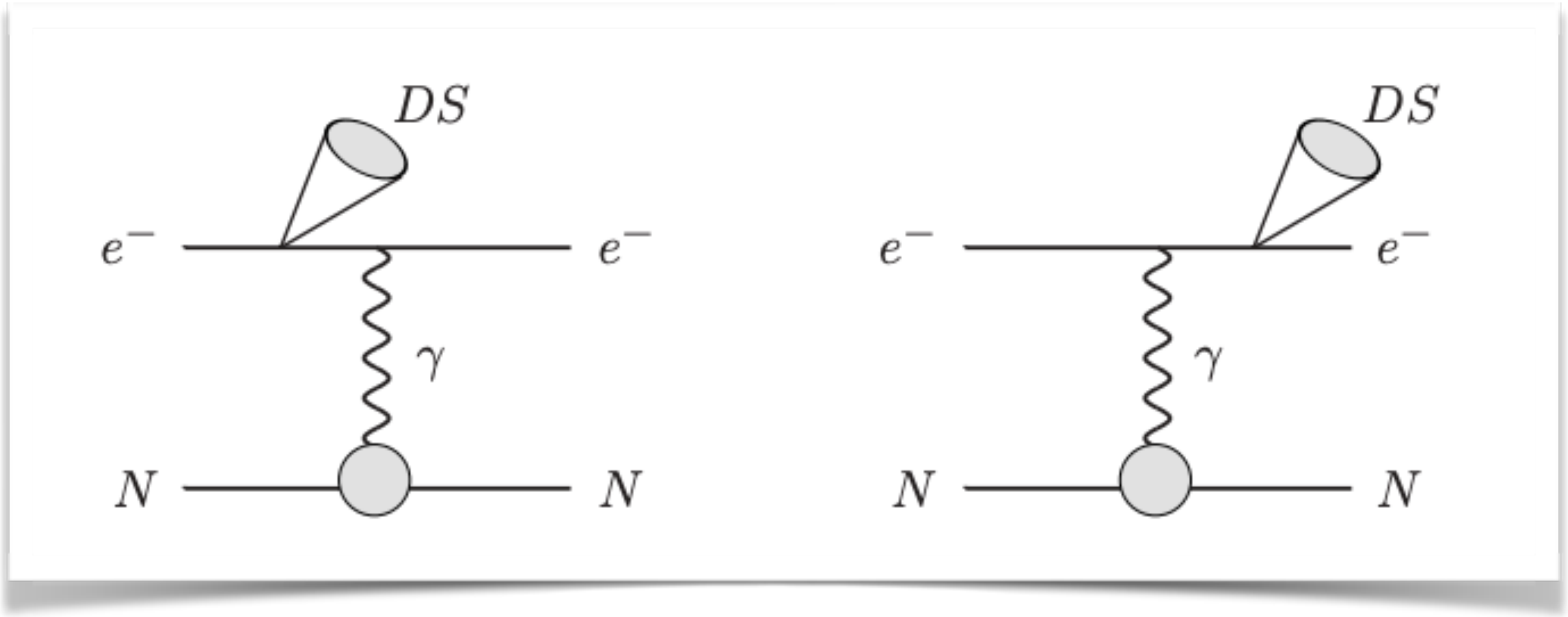
**D > 5 : colliders will give more stringent bounds**

# High-intensity experiments
(consider JJ portal)




NA64 (at CERN)

- A high energy electron beam (E0 = 100 GeV) hits a lead target (ECAL).
- DS excitation decay outside the detector (the HCAL) if sufficiently long lived.
- The HCAL itself is used to veto any hadronic activity (nucleus breaking, deep inelastic scattering).
- POT ~ 10^11




**Process: eN -> eN + ME**

E137 (at SLAC)

- A 20 GeV electron beam hits aluminum plates.
- The particles produced by the collision must traverse a hill of 179 m in thickness before reaching a 204 m-long open region followed by a detector.
- POT ~ 10^20

# High-intensity experiments

(consider JJ portal)

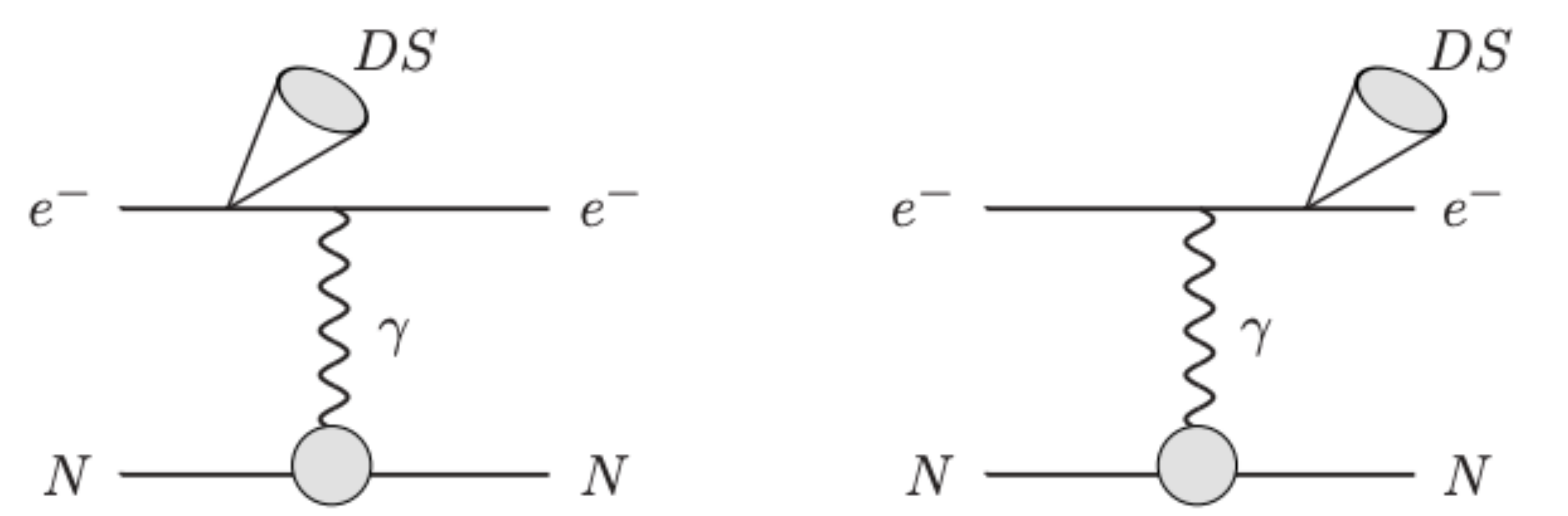
**The constraints on dark photon model can be used to constrain the portal:**

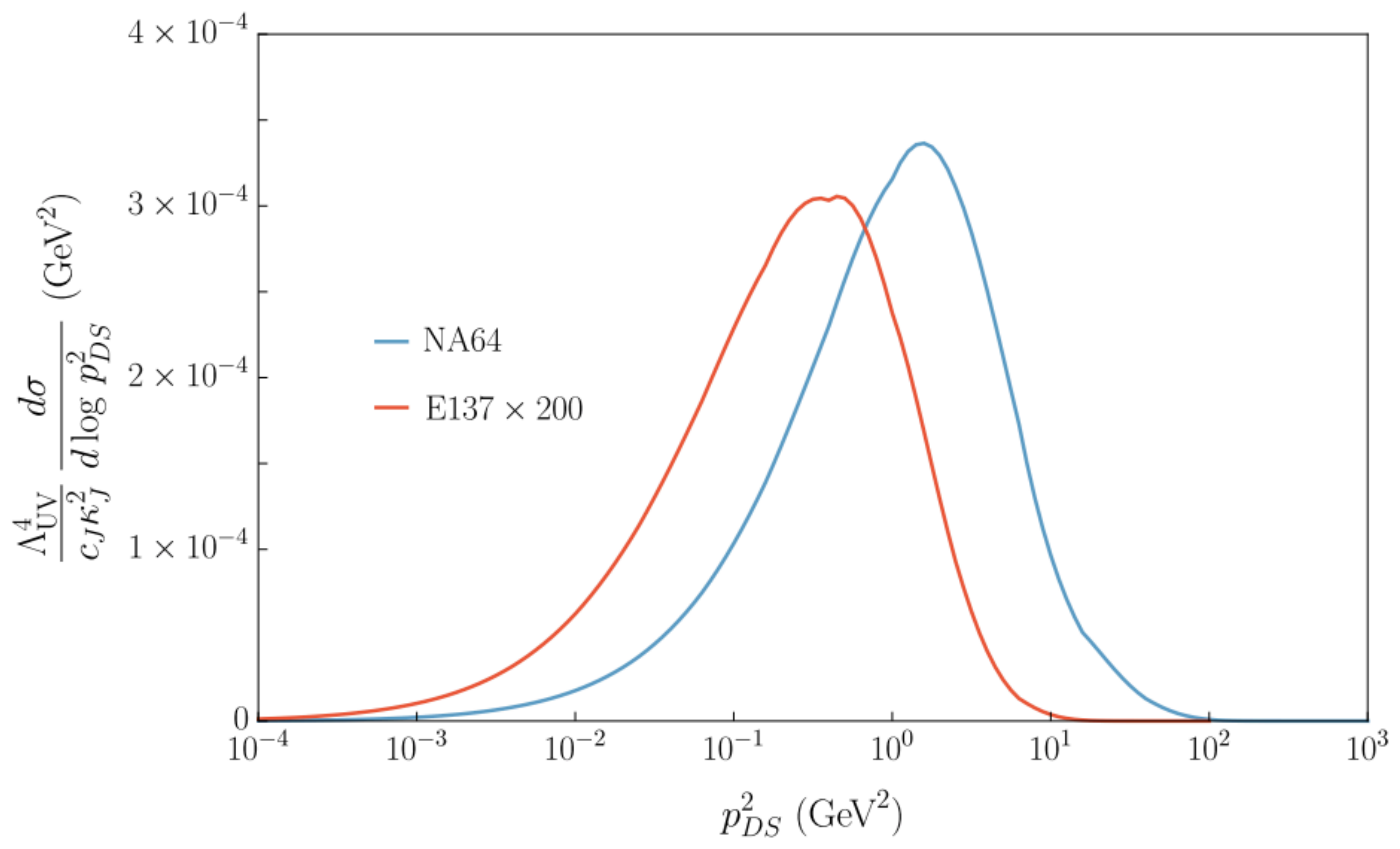
$$\sigma(eN \to eN + DS) = \frac{\kappa_J^2}{\Lambda_{\rm UV}^4} \frac{1}{4E_0 m_N} \frac{1}{2\pi} \int dp_{DS}^2 \int d\Phi_3 \, \mathcal{M}_\mu \mathcal{M}_\nu^* \, G(t) \times 2\,{\rm Im}\left[ i\langle 0|T(J_{DS}^\mu(p_{DS}) J_{DS}^\nu(-p_{DS}))|0\rangle \right] ,$$

**For a dark photon model:** $\pi\delta(p_{\rm DS}^2 - m_{\gamma'}^2) \sum_{\rm pol} \epsilon_\mu \epsilon_\nu^*$

$$\frac{d\sigma}{dp_{DS}^2}(eN \to eN + DS) = \frac{\kappa_J^2 c_J}{\Lambda_{\rm UV}^4} \frac{p_{DS}^2}{96\pi^2} \frac{\sigma(eN \to eN + A_D)}{(\varepsilon e)^2}$$

Standard Model




DS with a JJ portal is equivalent to DP with a mass between 0.1-10 GeV.

(max momentum transfer is ~ 1 GeV$^2$, so deep inelastic scattering is not relevant.)

# High-intensity experiments

(consider JJ portal)

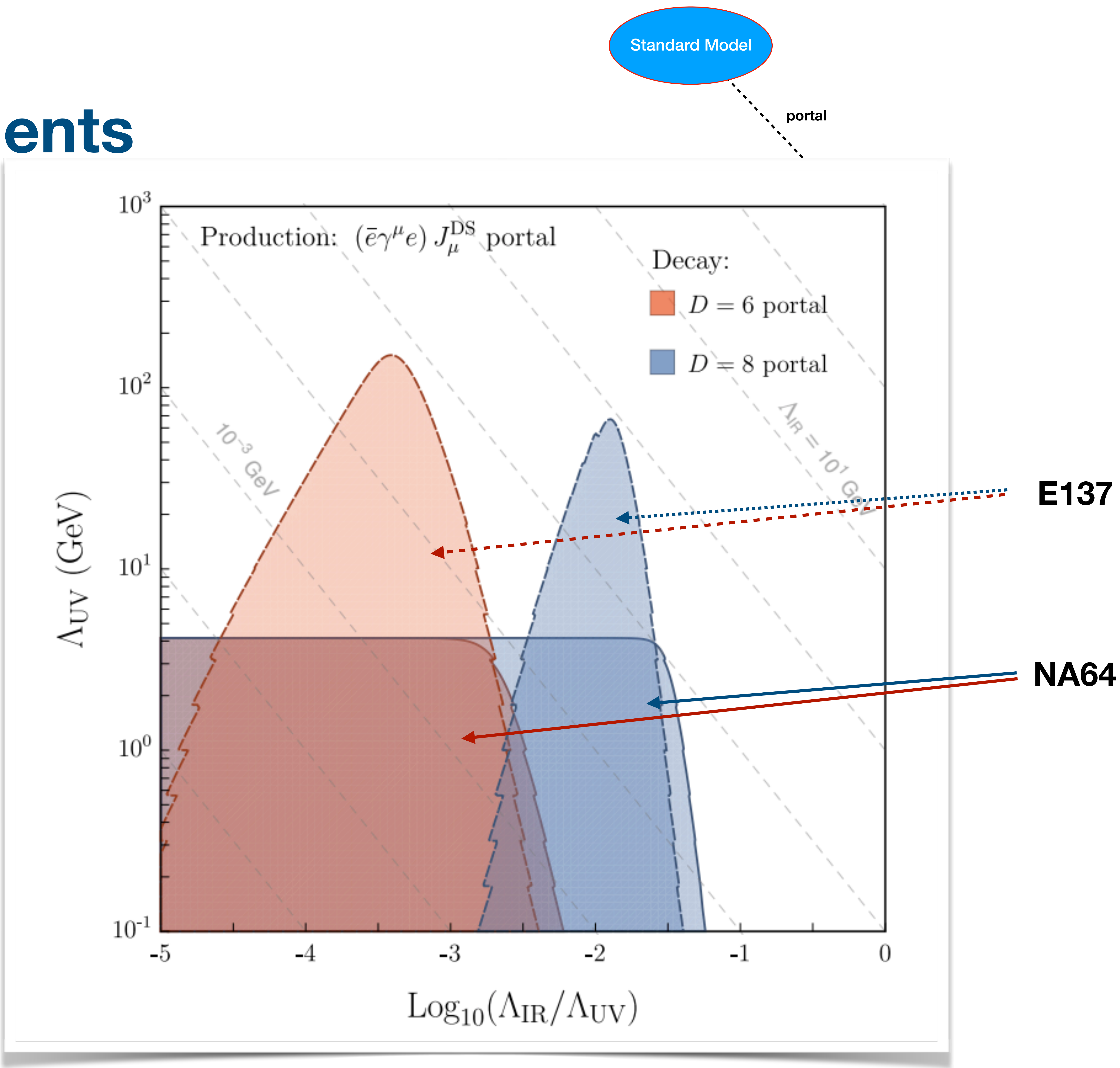
NA64

$$\sigma(eN \to eN + DS) = 0.8 \times 10^{-41}\text{cm}^2\ (c_J \kappa_J^2) \left(\frac{500\text{ GeV}}{\Lambda_{\rm UV}}\right)^4$$

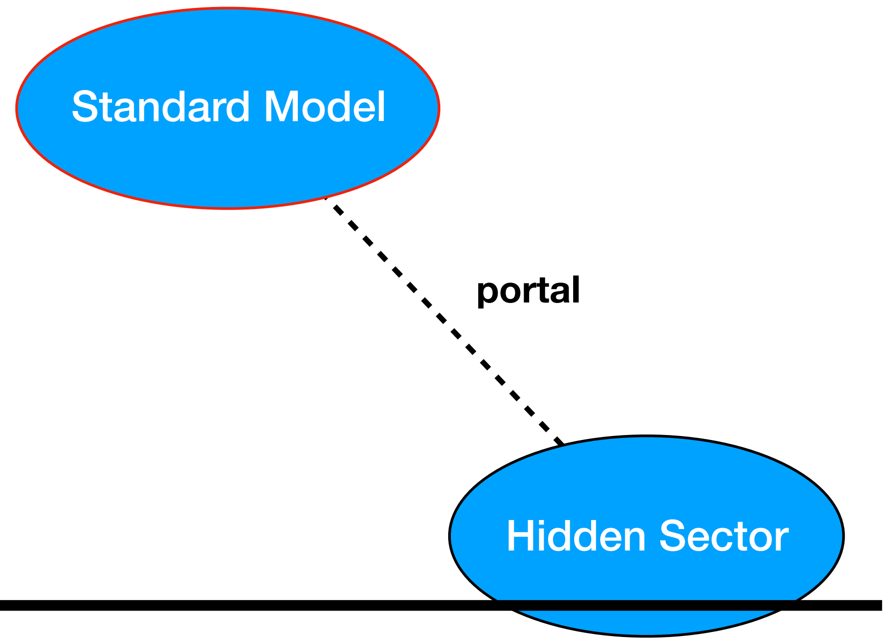
E137

$$\sigma(eN \to eN + DS) = 0.4 \times 10^{-43}\text{cm}^2\ (c_J \kappa_J^2) \left(\frac{500\text{ GeV}}{\Lambda_{\rm UV}}\right)^4$$

- **Weaker constraints than colliders.**
- **DV nature of signal allows a higher UV reach but in limited IR range.**
- **High POT compensates for low incident E.**



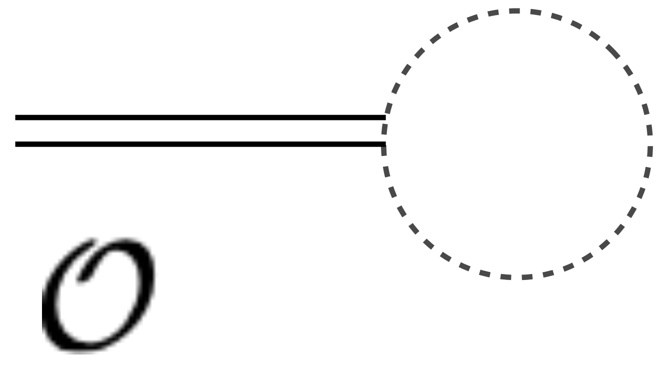
# Other constraints:




| | | |
|---|---|---|
| **Meson decays** | | |
| | Annihilation decays | $\Lambda_{\rm UV} < 2.3~{\rm GeV}~(c_J\kappa_J^2)^{1/4},~~\Lambda_{\rm IR} \lesssim 0.6~{\rm MeV}(c_J\kappa_J^2)^{-0.18}$ |
| | Radiative decays | $\Lambda_{\rm UV} < 83~{\rm GeV}~(c_J\kappa_J^2)^{1/4},~~\Lambda_{\rm IR} \ll 90~{\rm MeV}(c_J\kappa_J^2)^{-0.17}$ |
| | | $\Lambda_{\rm UV} < 1.3~{\rm GeV}~(c_{\mathcal{O}}\kappa_{\mathcal{O}})^{1/4},~~\Lambda_{\rm IR} \ll 800~{\rm MeV}(c_{\mathcal{O}}\kappa_{\mathcal{O}}^2)^{-0.1}$ |
| **Energy Loss** | | |
| | SN | $\Lambda_{\rm UV} < 400~{\rm GeV}~(c_J(\kappa_J^{(nn)})^2)^{1/4},~~\Lambda_{\rm IR} \ll \min(T_{\rm SN}, 90~{\rm MeV}(c_J(\kappa_J^{(nn)})^2)^{-0.19}$ |
| | HBS | $\Lambda_{\rm UV} < 62~{\rm GeV}~(c_J(\kappa_J^{(ee)})^2)^{1/4},~~\Lambda_{\rm IR} \ll \min(T_{\rm HB}, 10~{\rm MeV}(c_J(\kappa_J^{(nn)})^2)^{-0.23}$ |
| **Positronium lifetime** | | |
| | to DS | $\Lambda_{\rm UV} < 346~{\rm MeV}~(c_J\kappa_J^2)^{1/4},~~\Lambda_{\rm IR} \ll 3~{\rm MeV}(c_J\kappa_J^2)^{-0.19}$ |
| | to DS + photon | $\Lambda_{\rm UV} < 3.6~{\rm MeV}~(c_T\kappa_T^2)^{1/8},~~\Lambda_{\rm IR} \ll 0.4~{\rm MeV}(c_T\kappa_T^2)^{-0.1}$ |
| **Fifth force** | | $\Lambda_{\rm UV} < 0.2~{\rm MeV}~(c_J\kappa_J^2)^{1/4},~~\Lambda_{\rm IR} \ll 1~{\rm keV}$ |

# Stability of hierarchy

$$\mathcal{O} H^\dagger H$$




Higgs legs can be closed into a loop, giving a contribution that is a marginal deformation of the CFT

$$\kappa_O \lesssim 16\pi^2 \left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}}\right)^{4-\Delta_\mathcal{O}}$$ (UV contribution)

$$\kappa_O \lesssim \frac{\Lambda_{\rm IR}^2}{v_{\rm EW}^2} \left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}}\right)^{2-\Delta_\mathcal{O}}$$ (EW contribution)

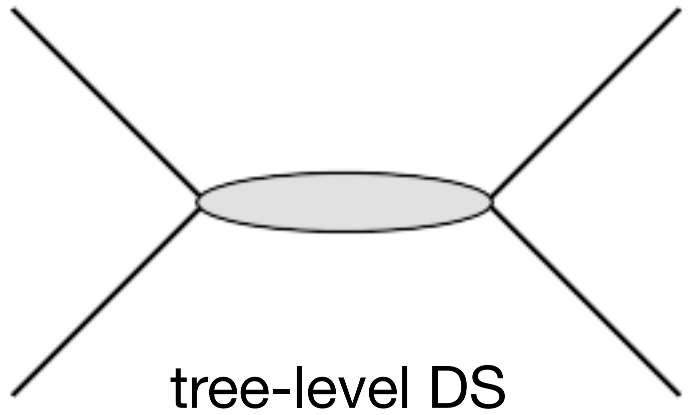
Assuming mediators heavier than EW scale,

$$\Lambda_{\rm UV} > 4\,\pi\, v_{\rm EW}$$

The UV contribution is bigger, unless some UV mechanism that suppresses it.

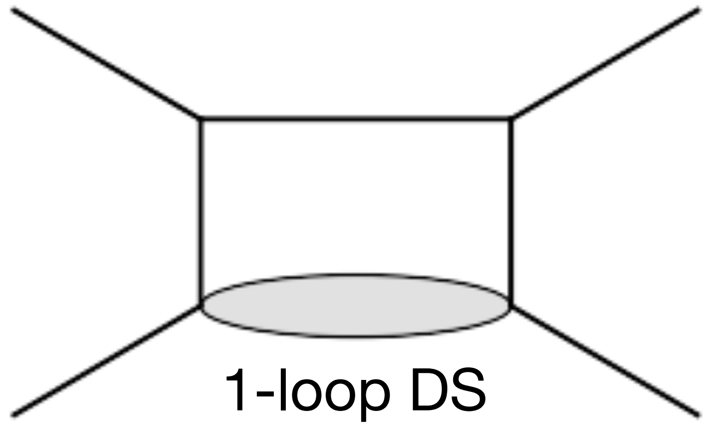
# Importance of UV effects

For virtual effects parametrized by local operators, both DS and UV (mediator) states contribute. It can be a tree level or a loop effect.



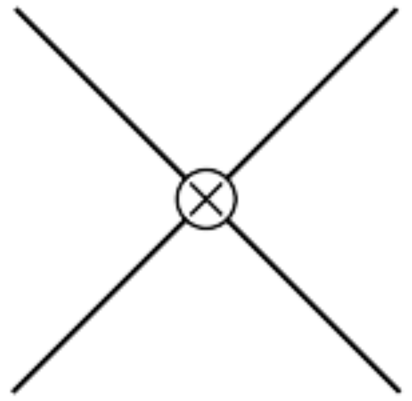
tree-level DS exchange

,



1-loop DS exchange

but also



contact term to regulate the divergences in the DS EFT, from mediators. A threshold effect.

E < ΛIR, the contributions from both DS and UV states are local and parametrized by dim-6 operators. As such, they are qualitatively indistinguishable at low energy. Furthermore, for D ≥ 5 the UV threshold correction is always larger than the RG running, which in turn dominates (for D even) over the IR thresholds. For 4 < D < 5, instead, the DS exchange gives only an IR threshold contribution, which can (depending on the UV dynamics) be larger than the one generated by heavy mediators at ΛUV.

E > ΛIR, then for D ≥ 5 the UV threshold corrections are larger than the long-distance effects, which in turn are larger than the RG running. In principle, one could distinguish experimentally the long-distance from local effects, since the former induce a non-analytic dependence of the cross section on the energy. For 4 < D < 5, the DS exchange generates only a long-distance contribution, which can win over the UV effect induced by heavy mediators.

To summarize, UV thresholds are expected to give the most important virtual effects for D ≥ 5; portals with 4 < D < 5, instead, generate only long-distance (for E > ΛIR) or IR threshold (for E < ΛIR) corrections, and can give the largest indirect contribution.

Consider *n* SM external legs, at *l* loops

$$\Delta c_6(\Lambda_{\rm UV}) \sim g_{SM}^{n-4}\,\frac{\kappa^2}{\Lambda_{\rm UV}^2}\,\frac{c}{16\pi^2}\left(\frac{g_{SM}^2}{16\pi^2}\right)^{\ell}$$ **UV**

$$\Delta c_6(\mu) \sim g_{SM}^{n-4}\,\frac{\kappa^2}{\Lambda_{\rm UV}^2}\,\frac{c}{16\pi^2}\left(\frac{g_{SM}^2}{16\pi^2}\right)^{\ell}\left(\frac{\bar\Lambda^2}{\Lambda_{\rm UV}^2}\right)^{D-5}\log\frac{\mu}{\Lambda_{\rm UV}}$$ **RG**

$$\Delta c_6(\Lambda_{\rm IR}) \sim g_{SM}^{n-4}\,\frac{\kappa^2}{\Lambda_{\rm UV}^2}\,\frac{c}{16\pi^2}\left(\frac{g_{SM}^2}{16\pi^2}\right)^{\ell}\left(\frac{\bar\Lambda^2}{\Lambda_{\rm UV}^2}\right)^{D-5}$$ **IR**

$$\frac{\Delta R}{R} \sim \frac{\kappa^2 c}{16\pi^2 g_{SM}^2}\left(\frac{g_{SM}^2}{16\pi^2}\right)^{\ell}\left(\frac{s}{\Lambda_{\rm UV}^2}\right)^{D-4}$$ (long range) **IR**