Model agnostic probes of Dark Sectors at ν experiments

Marco Costa
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based on 2211.13253

In collaboration with Rashmish K. Mishra and Sonali Verma

Which Dark Sector?

We know DM interacts feebly with SM

1) DM charged under the SM forces: $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

WIMPs, Minimal DM

Fornengo, Cirelli, Strumia, 0512090
and many more!

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2) DM is a SM singlet

→ Portal models $\mathcal{O}_{\mathrm{DS}}\mathcal{O}_{\mathrm{SM}}$

→ Gravity only

Renormalizable Portal models

$\mathcal{O}_{\rm DS}\mathcal{O}_{\rm SM}$

"Hidden Valleys"

Strassler, Zurek 0604261

Renormalizable portals

MeV-GeV DM

$SH^\dagger H$

Higgs portal

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

Kinetic mixing portal

$H^{c\dagger}\bar{N}l$

Neutrino portal

Light, feebly coupled: **High Intensity experiments**

Batell, Pospelov, Ritz 0906.5614
deNiverville, McKeen, Ritz 1205.3499
deNiverville, Chen, Pospelov, Ritz 1609.01770
Buonocuore, Frugiuele, deNiverville 1912.09346
and many many more!

Non-renormalizable Portal models

Contino, Max, Mishra 2012.08537
Darme, Ellis, You 2001.01490
Cheng, Li Salvioni 2110.10691

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Non-Renormalizable portals

In some models are leading terms in EFT

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Non-Renormalizable portals

In some models are leading terms in EFT

generalized Higgs portal

$$\frac{k}{\Lambda_{\rm UV}^{\Delta-2}}\mathcal{O}_{\rm DS}H^\dagger H$$

NP scale, elusive

$$\Delta \sim 4$$

Z portal

$$\frac{k}{\Lambda_{\rm UV}^2}H^\dagger \overleftrightarrow{D_\mu} H J^\mu_{\rm DS}$$

Current-Current

$$\frac{k}{\Lambda_{\rm UV}^2}J^{\rm SM}_\mu J^\mu_{\rm DS}$$

No need to specify DS fields

generic DS conserved current

Examples

Contino, Max, Mishra 2012.08537
Darme, Ellis, You 2001.01490
Cheng, Li Salvioni 2110.10691

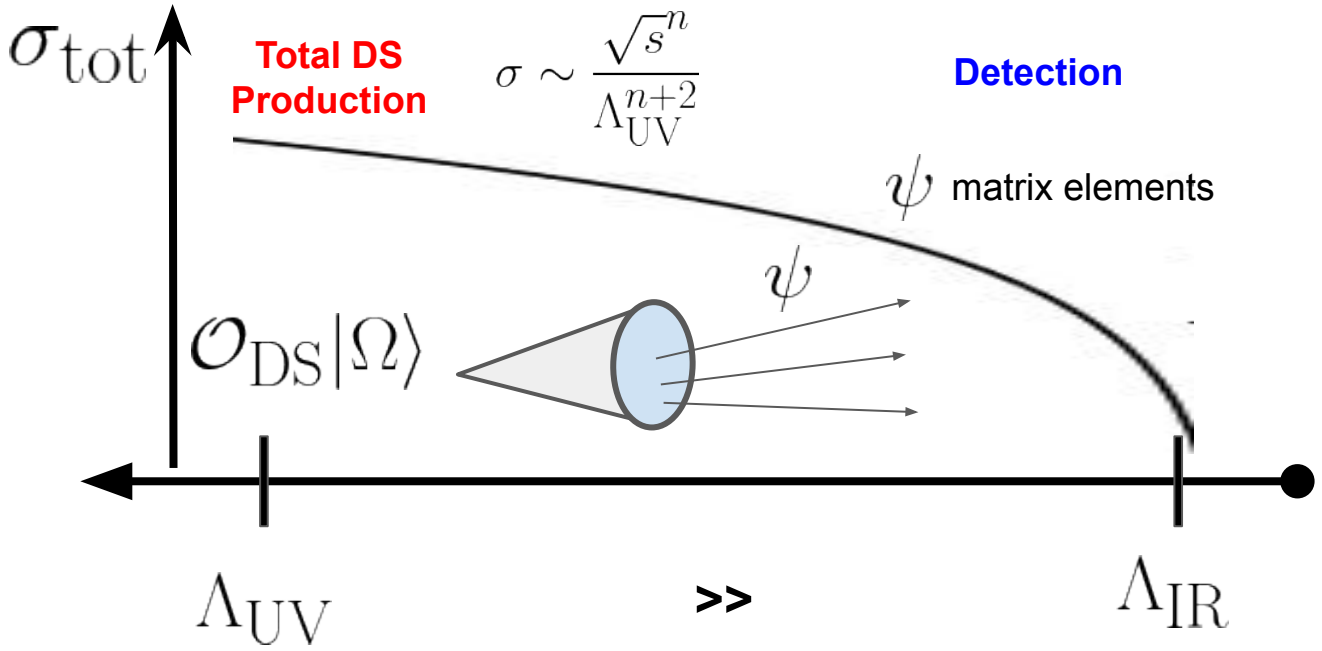
	Model	$\mathcal{O}_{\rm DS}\mathcal{O}_{\rm SM}$	Mediated by
Strongly coupled	Dark QCD Ψ^a	$\bar{\Psi}\gamma^\mu\Psi H^\dagger \overleftrightarrow{D}_\mu H$ $\bar{\Psi}\Psi H^\dagger H$	Q^a charged under both gauge groups
Weakly coupled	ν below EWSB	$\bar{\nu}\gamma^\mu P_L \nu J^{Z,\rm SM}_\mu$	Z, W

Anatomy of non-renormalizable portal model

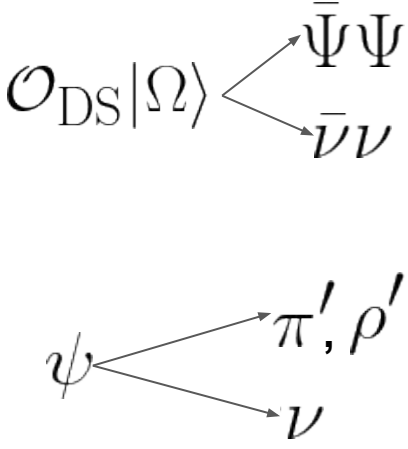
Heavy mediator scale

Lightest Dark Sector Particle (LDSP) ψ (not DM necessarily)

Anatomy of non-renormalizable portal model



Examples



Heavy mediator scale

Conformal regime does not care about details

Lightest Dark Sector Particle (LDSP) ψ (not DM necessarily)

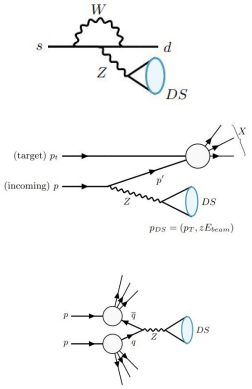
ν experiments as beam dumps

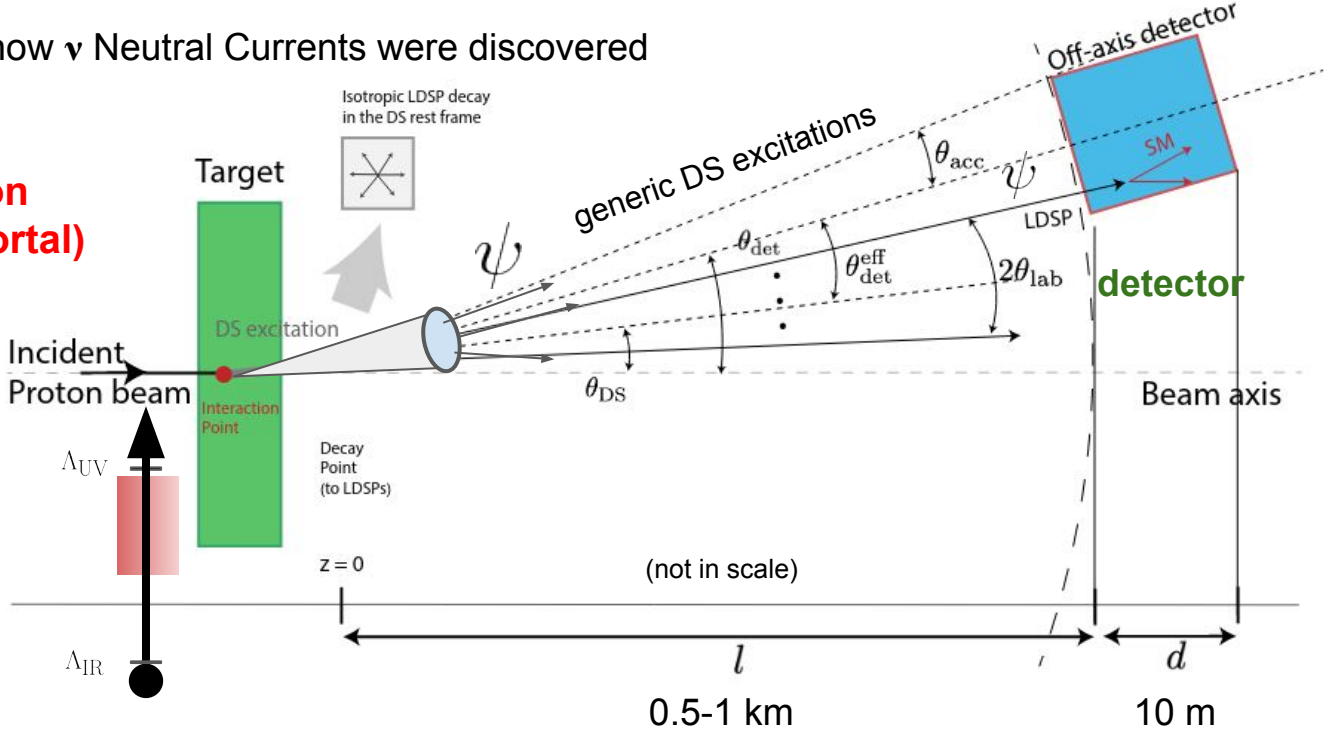
How to probe these DS sectors? High Intensity

for ex.: Batell, Pospelov ,Ritz 0906.5614

IDEA: copy how ν Neutral Currents were discovered

production (non-reno portal)





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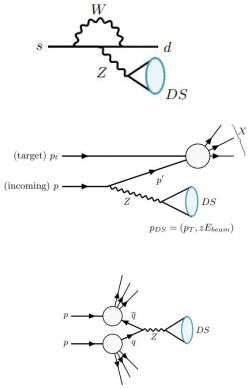
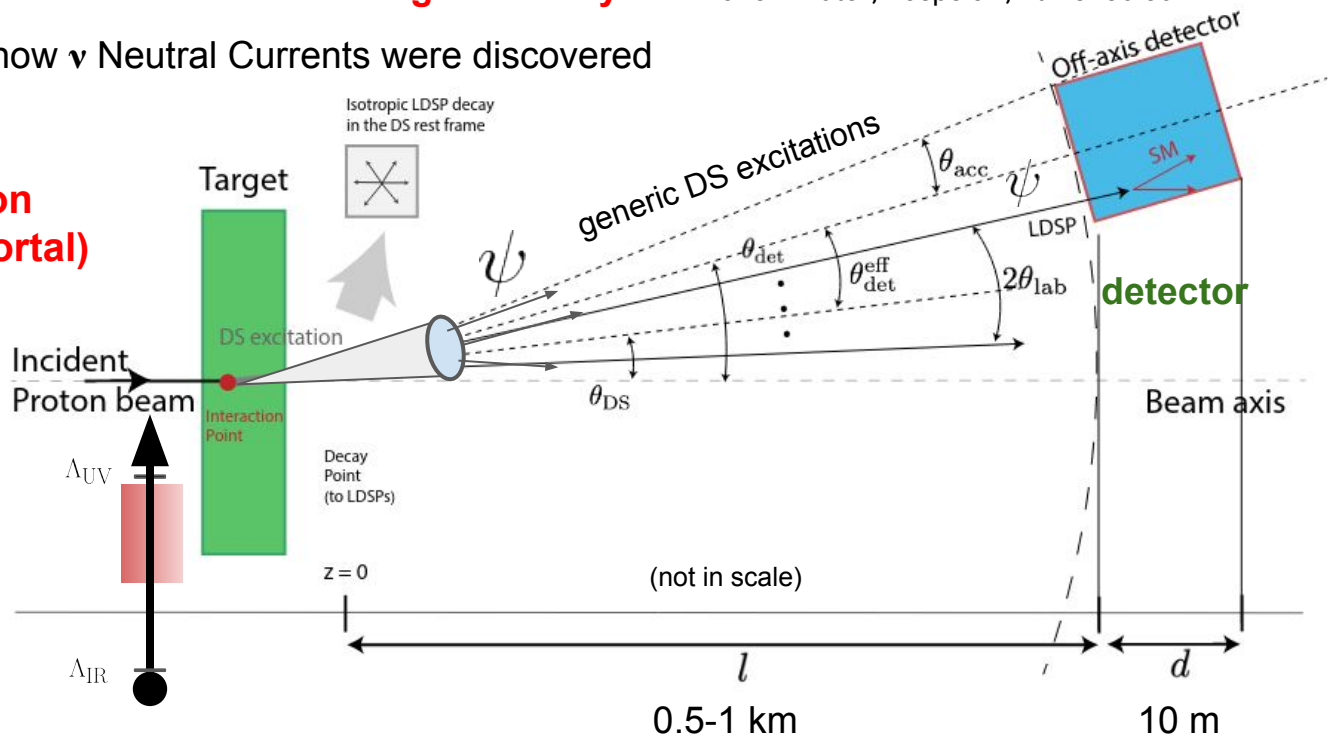
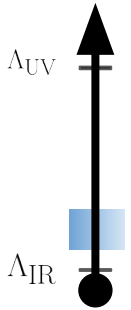




detection

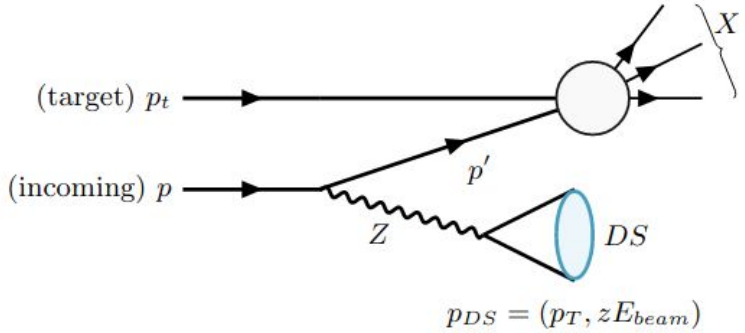


Production modes at ν experiments

"Direct" production

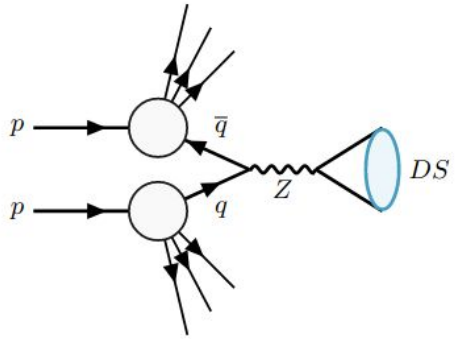
$$\frac{k}{\Lambda_{UV}^2} H^\dagger \overleftrightarrow{D_\mu} H J^\mu_{DS}$$

Bremsstrahlung



$$p^2_{DS} \gtrsim \Lambda^2_{QCD}$$

Drell-Yan like



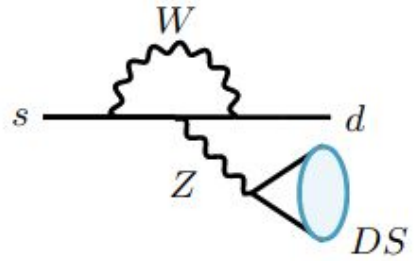
$$p^2_{DS} \gtrsim \Lambda^2_{QCD}$$

Production modes at ν experiments

Meson decays

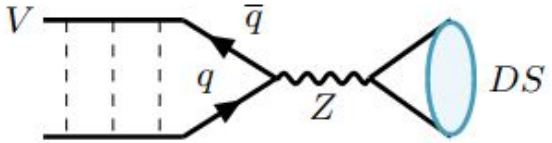
$$\frac{k}{\Lambda_{\rm UV}^2} H^\dagger \overleftrightarrow{D_\mu} H \, J^\mu_{\rm DS}$$

"Radiative"



$$K \to \pi + \mathrm{DS}$$
$$\eta \to \gamma + \mathrm{DS}$$

Annihilation



$$\phi \to \mathrm{DS}$$

Model-independent production computation

Conformal regime does not care about details

Contino, Max, Mishra 2012.08537

Inclusive Production

$$\sigma \propto \int \mathrm{d}\Phi_{\rm DS} \sum_n |\langle \mathrm{DS}|\mathcal{O}_{\rm DS}|\Omega\rangle|^2 = 2i\ \mathrm{Im}\left[\langle\Omega|\mathcal{O}_{\rm DS}\mathcal{O}_{\rm DS}|\Omega\rangle\right]$$

DS "internal phase space" at fixed $p_{\rm DS}$

optical theorem

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Inclusive Production ⟹ **Model independent**

$$\sigma \propto \int \mathrm{d}\Phi_{\rm DS} \sum_n |\langle \mathrm{DS}|\mathcal{O}_{\rm DS}|\Omega\rangle|^2 = 2i\,\mathrm{Im}\left[\langle\Omega|\mathcal{O}_{\rm DS}\mathcal{O}_{\rm DS}|\Omega\rangle\right]$$

optical theorem

DS "internal phase space" at fixed $p_{\rm DS}$

$c_{\mathcal{O}} p_{\rm DS}^{2\Delta}$ **Conformality**

Rest: fixed by $\mathcal{O}_{\rm SM}$:

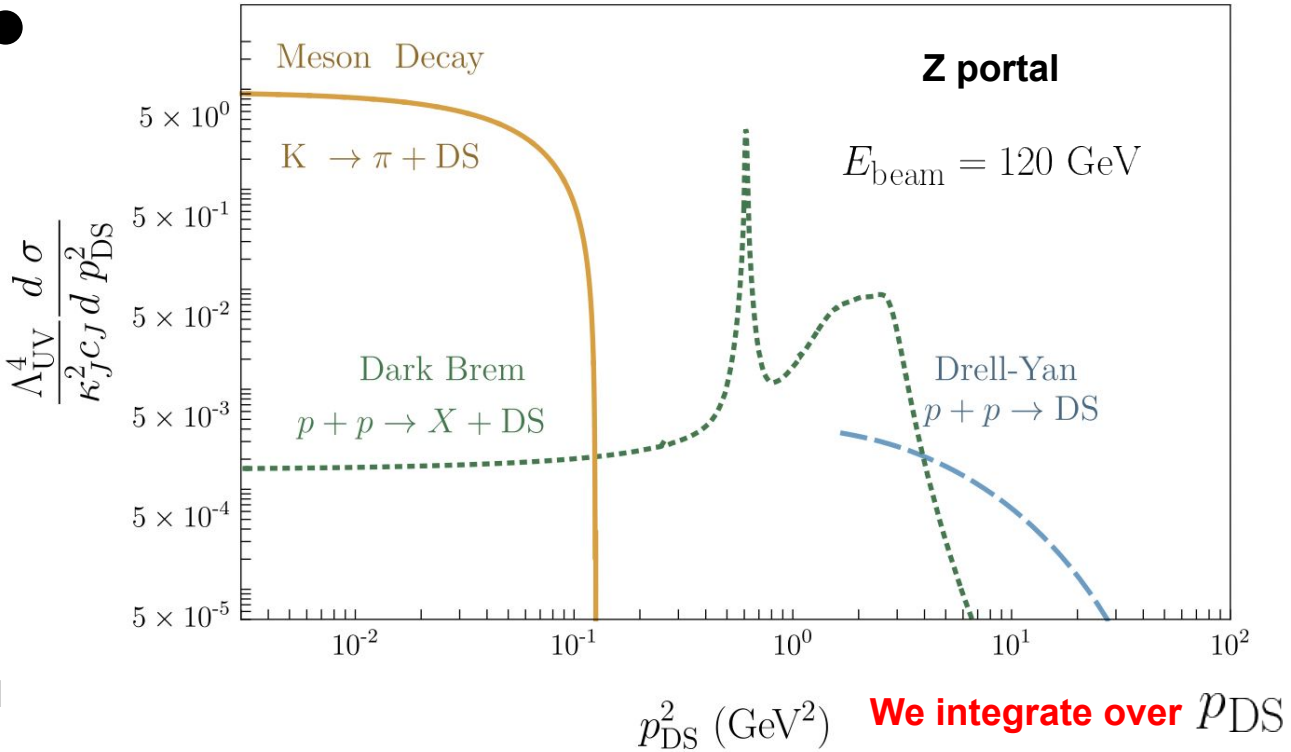
Integrate $p_{\rm DS}$

Z Portal production results

$$\frac{k}{\Lambda_{\rm UV}^2} H^\dagger \overleftrightarrow{D_\mu} H J^\mu_{\rm DS}$$

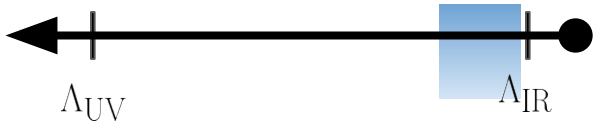
$$\frac{k}{\Lambda_{\rm UV}^2} v m_Z Z_\mu J^\mu_{\rm DS}$$

$$\frac{k}{\Lambda_{\rm UV}^{\Delta-2}} \mathcal{O}_{\rm DS} H^\dagger H$$ too suppressed



We integrate over $p_{\rm DS}$

Detection at ν experiments



Contino, Max, Mishra 2012.08537

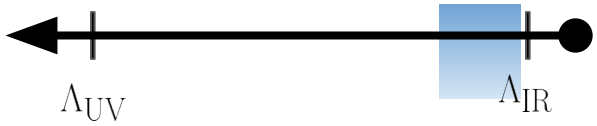
Detection: depends on ψ properties

Scatter $\langle \psi_j(p_f) | \mathcal{O}_{\rm DS} | \psi_i(q_i) \rangle$

Scattering depend on splittings, extra form factors,...

(how ν NC were discovered)

Detection at ν experiments



Contino, Max, Mishra 2012.08537

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Scatter

$$\langle \psi_j(p_f)|\mathcal{O}_{\rm DS}|\psi_i(q_i)\rangle$$

Scattering depend on splittings, extra form factors,...

(how ν NC were discovered)

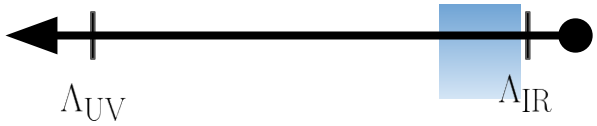
Decay to SM

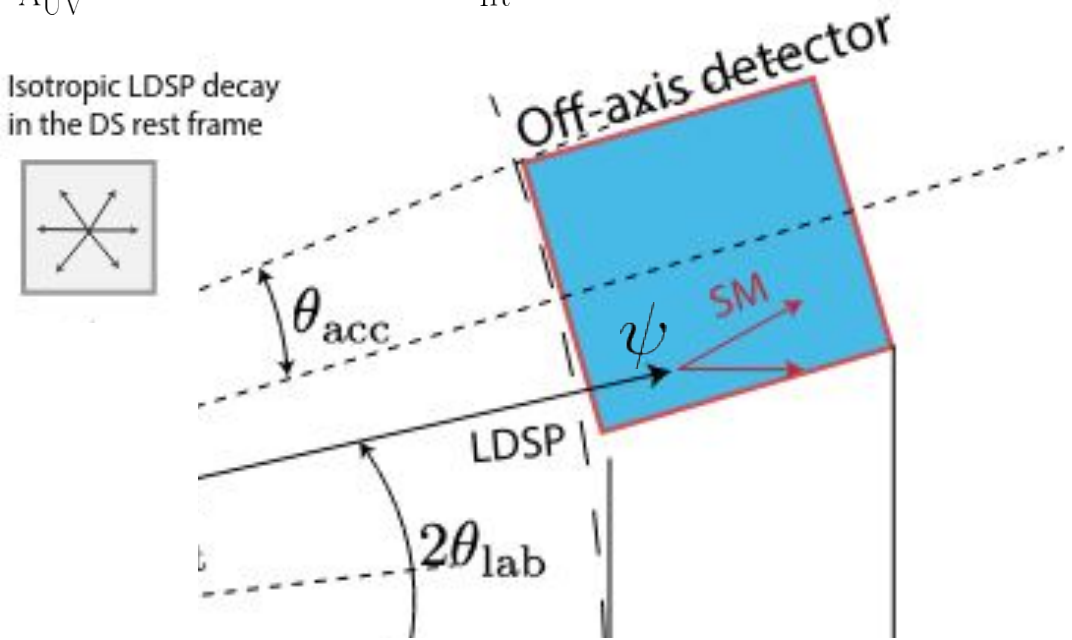
$$\langle \psi|\mathcal{O}_{\rm DS}|\Omega\rangle \sim f\Lambda_{\rm IR}^{\Delta-2}$$

$$f \sim c_{\mathcal{O}}\Lambda_{\rm IR}/4\pi$$

BR **inherited** by $\mathcal{O}_{\rm SM}$:

Detection at ν experiments





Signature:
two separated e+e- showers
(or other allowed charged particles)

(Reducible) backgrounds from ν scattering:
NCQE pi0-> misreconstructed photons
or
CC events
under control!

Batell, Berger, Ismail 1909.11670
Foroughi-Abari, Ritz 2004.14515
Berryman, de Gouvea, Fox, Kayser, Kelly, Raaf 1912.07622
and others

Results

$$\frac{k}{\Lambda_{\rm UV}^2} H^\dagger \overleftrightarrow{D_\mu} H \, J^\mu_{\rm DS}$$

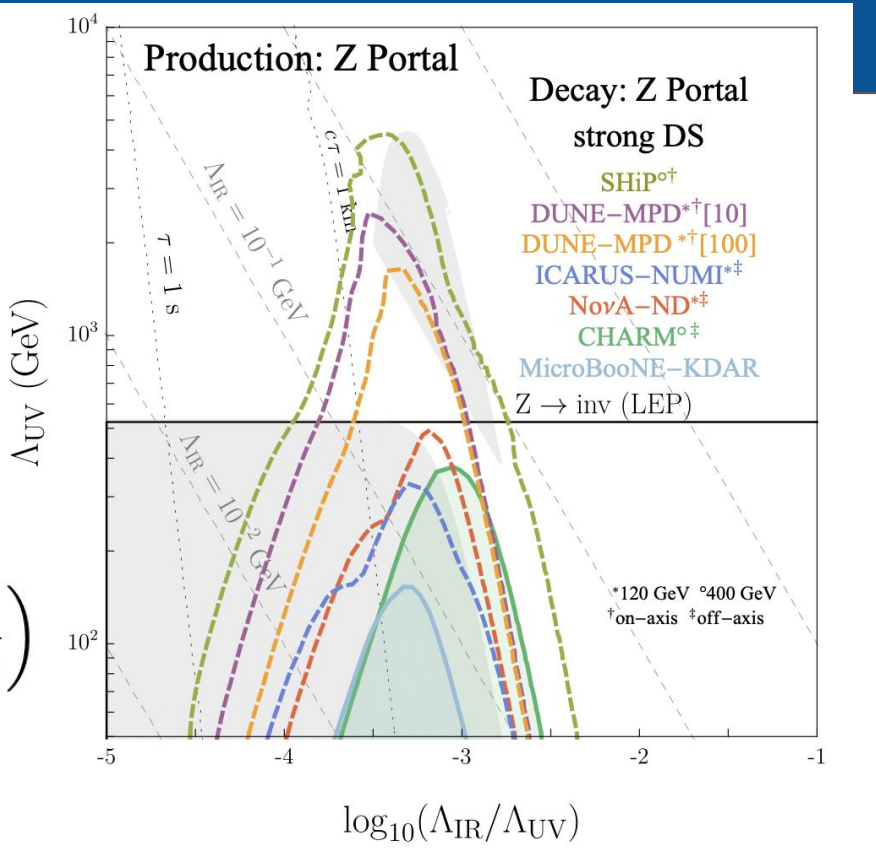
Strongly coupled

10 events line

$$S \simeq \frac{N_{\rm POT}}{\sigma_{pN}} \times \sigma_{\rm DS} \times n_{\rm DS} P_{\rm dec} \times \epsilon_{\rm geo}$$

$$P_{1,\rm dec} = \exp\left(-\frac{l}{c\tau(\gamma\beta)_{\rm LDSP}}\right) - \exp\left(-\frac{l+d}{c\tau(\gamma\beta)_{\rm LDSP}}\right)$$

$$\langle n \rangle = A \left(\frac{1}{\log(\langle E \rangle^2/\bar{\Lambda}^2)}\right)^B \exp\left(\frac{C}{\sqrt{\log(\langle E \rangle^2/\bar{\Lambda}^2)}}\right)$$



Conclusions

- Many possible portal models
- Can we study them in a **model independent** way at ν exp.?

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- **Decay signal**: depends on single form factor, **high S/N ratio**

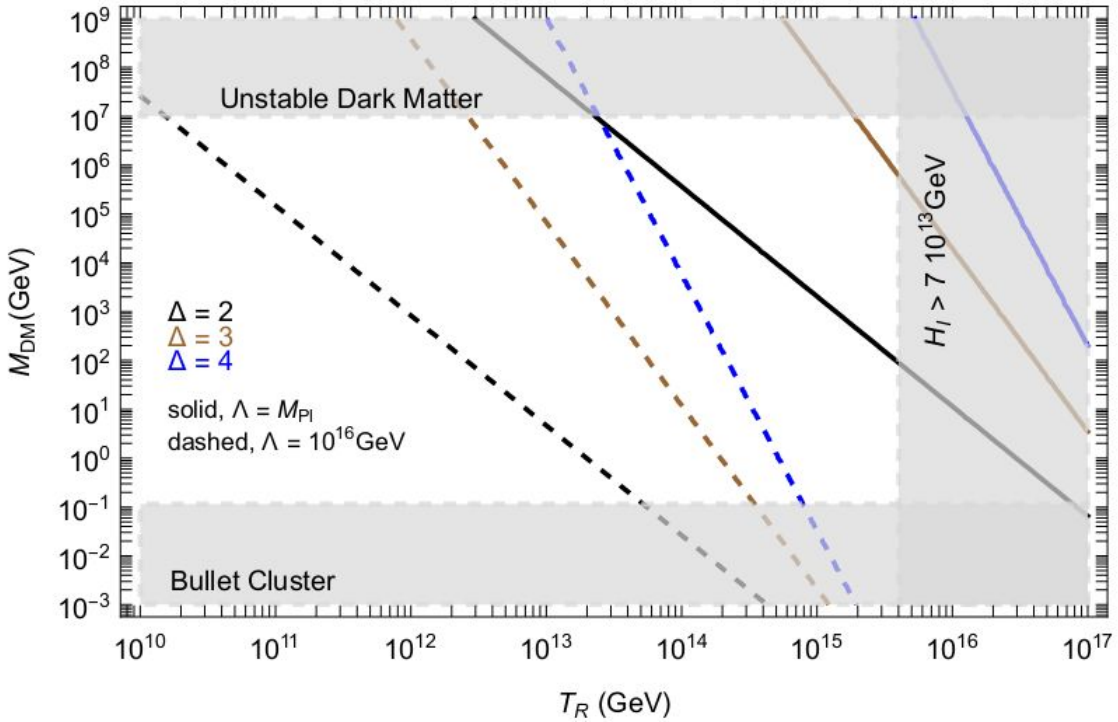
Conclusions

- Many possible portal models
- Can we study them in a **model independent** way at ν exp.?
- **Production**: **Yes** for non-renormalizable portal models
- **Decay signal**: depends on single form factor, **high S/N ratio**
- Z portal/JJ portal can be probed at ν exp. (assuming bkg under control)
- Interesting region for masses in 0.1-1 GeV range, cutoffs at TeV.

Thanks for the attention!

Backup

Cosmology



Redi, Tesi 2107.14801

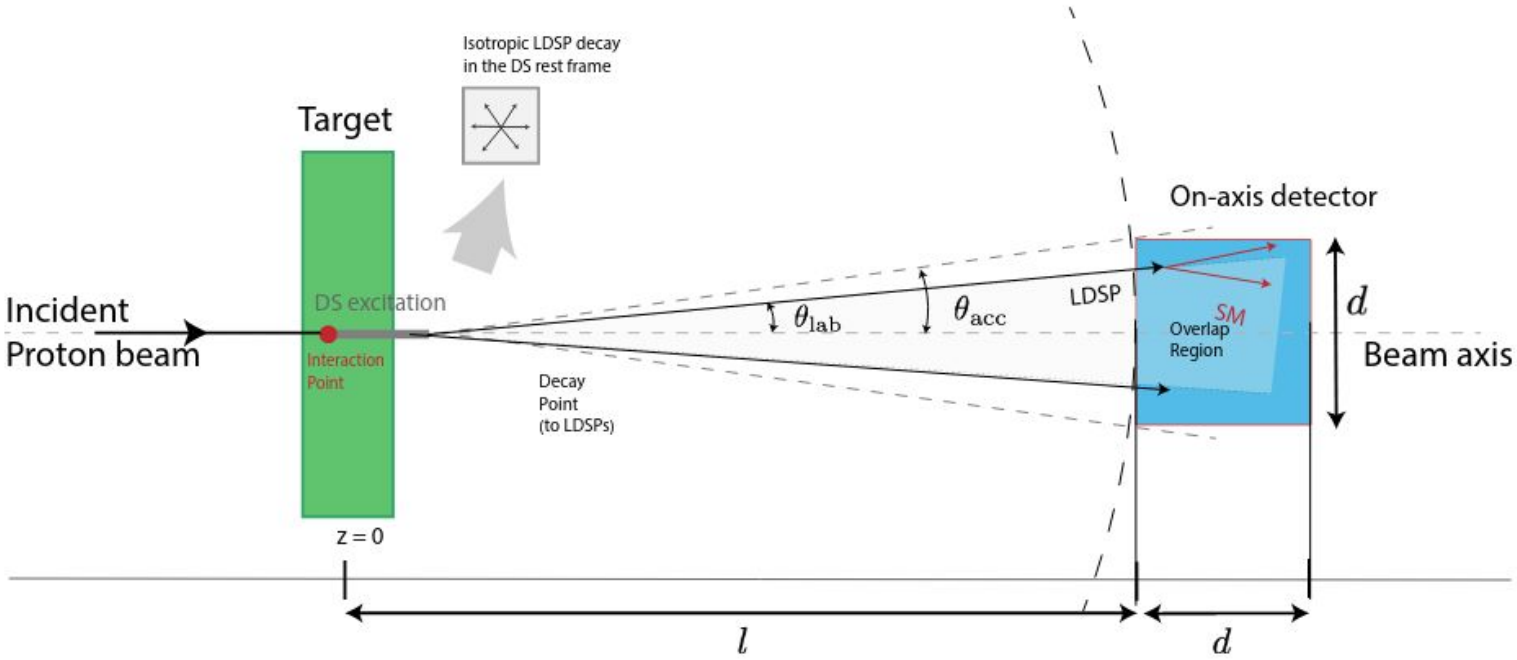
Hong, Kurup, Perelstein 1910.10160

From Redi, Tesi 2107.14801

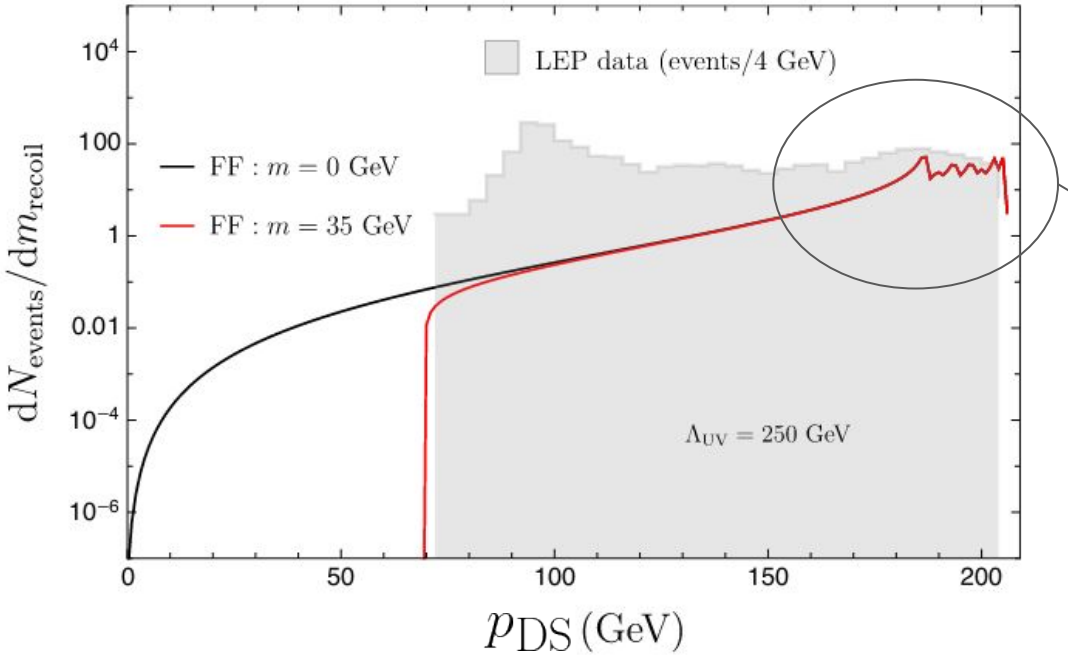
Freeze-in is a possibility
(although for very high cutoffs in model indep. scenario)

$$f_L H f_R \to CFT$$

Detection at ν experiments



Production through non-renormalizable portals



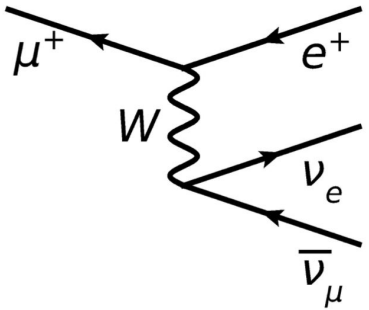
From Contino, Max, Mishra 2012.08537

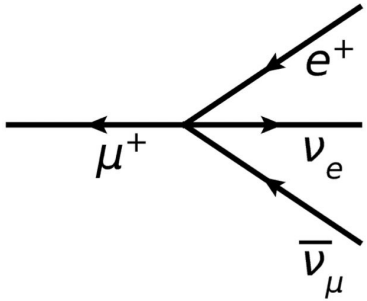
Peak at high $p_{\rm DS}$

A ν perspective on neutral currents

High E 10^2 GeV >> $p_\nu^2 \sim m_\mu^2$ >> m_ν Low E

$\Lambda_{UV} = M_{Z.W}$ **Conformal regime** Λ_{IR}





hypothetical experiment producing ν via muon decays

Gargamelle

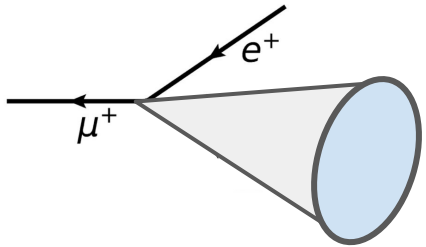
A ν perspective on neutral currents

High E 10^2 GeV >> $p_\nu^2 \sim m_\mu^2$ >> m_ν Low E

$\Lambda_{\rm UV} = M_{Z,W}$

Conformal regime does not care about DS details

$\Lambda_{\rm IR}$

$\mathcal{O}_{\rm DS}|\Omega\rangle =$ 

$= \bar{\nu}\nu$

$\mathcal{O}_{\rm DS} = \bar{\nu}\gamma^\mu P_L \nu$

Strongly coupled benchmark

$$\langle n \rangle = A \left(\frac{1}{\log(\langle E \rangle^2 / \bar{\Lambda}^2)} \right)^B \exp\left(\frac{C}{\sqrt{\log(\langle E \rangle^2 / \bar{\Lambda}^2)}} \right), \qquad \begin{array}{ll} A = 0.06 & C = 1.8 \\ B = 0.5 & \bar{\Lambda} = 0.1\,\Lambda_{\mathrm{IR}} \end{array}$$

From Webber, Phys.Lett.B 143(1984) 501-504

Other terrestrial bounds on the models

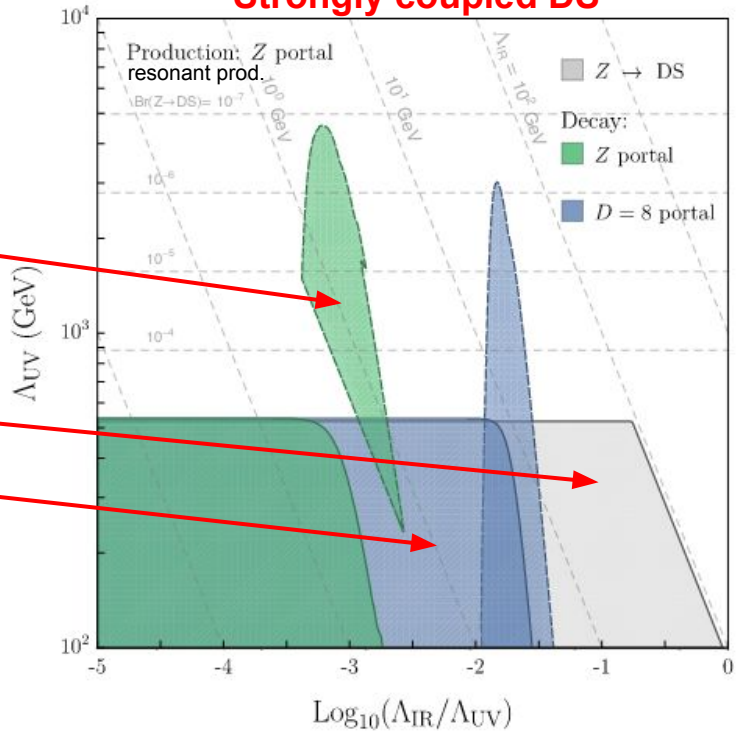
short $c\tau$

- Prompt decays
- Displaced Vertex @ LHC
- Beam dumps (E137)
- Z/H invisible width
- Missing energy @ LEP/LHC
- Missing energy (NA64)
- Rare hadron decays (BESSIII, BaBar, ...)

long $c\tau$

Contino, Max, Mishra 2012.08537

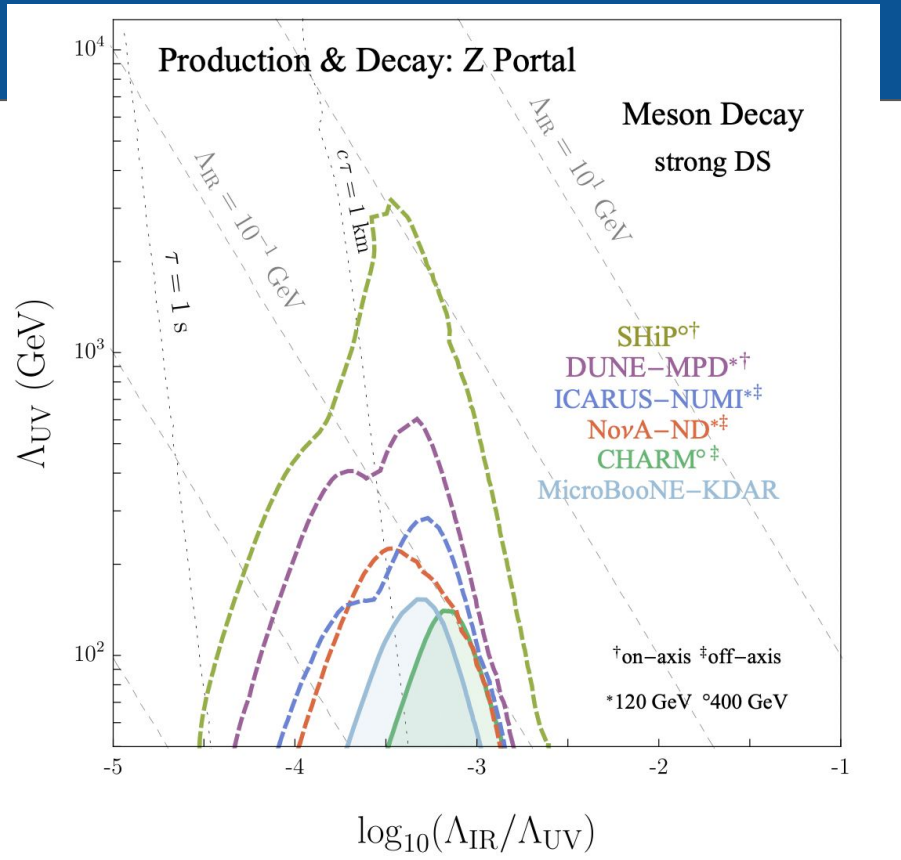
Strongly coupled DS



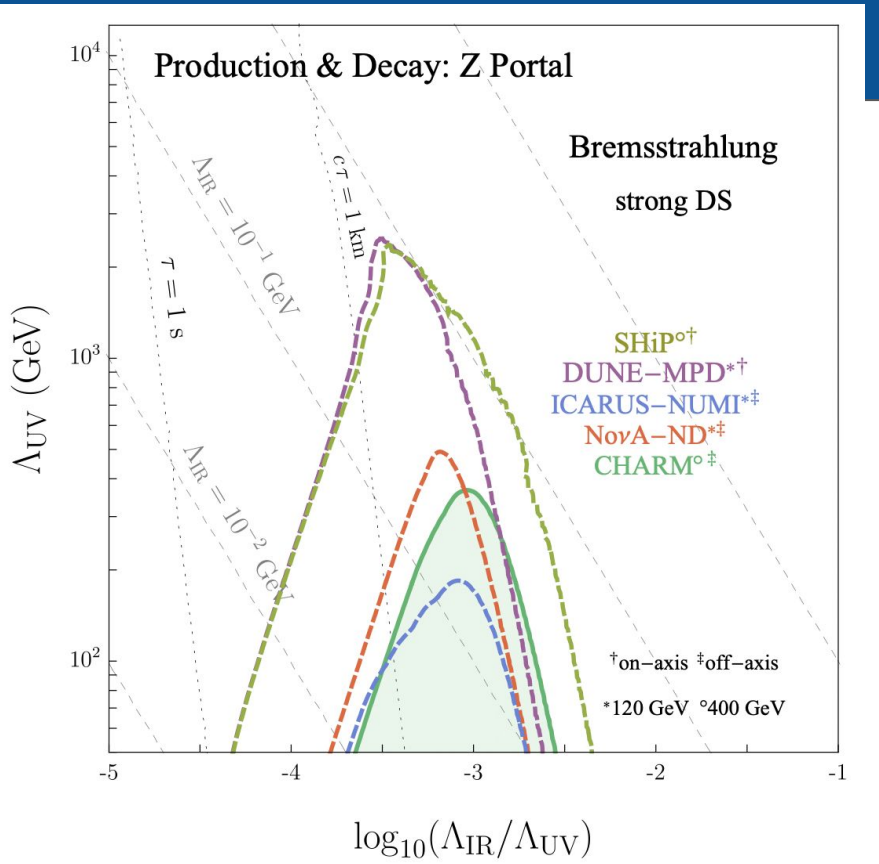
Experimental parameters

Experiment	N_{POT} (total)	E_{beam} (GeV)	l (m)	d (m)	Off-axis angle, θ_{det} (rad)	θ_{acc} (rad)
CHARM [78, 85, 86]	2.4×10^{18}	400	480	35	0.01	0.003
NOνA-ND [47, 84]	3×10^{20}	120	990	14.3	0.015	0.002
MicroBooNE (KDAR) [81]	1.93×10^{20}	120	100	10.4	-	0.013
ICARUS-NuMI [11, 16]	3×10^{21}	120	803	19.6	0.097	0.005
DUNE-MPD[14, 87]	1.47×10^{22}	120	579	5	0	0.004
SHiP [65, 77]	2×10^{20}	400	64	50	0	0.078

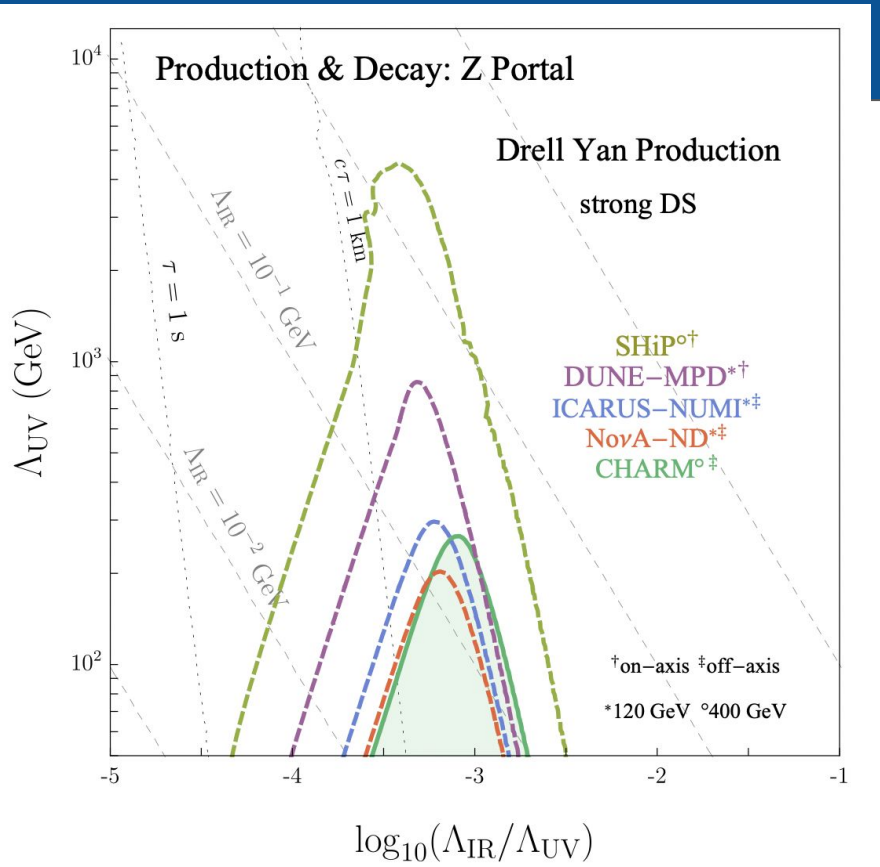
Strongly coupled: mesons



Strongly coupled: brem



Strongly coupled: DY



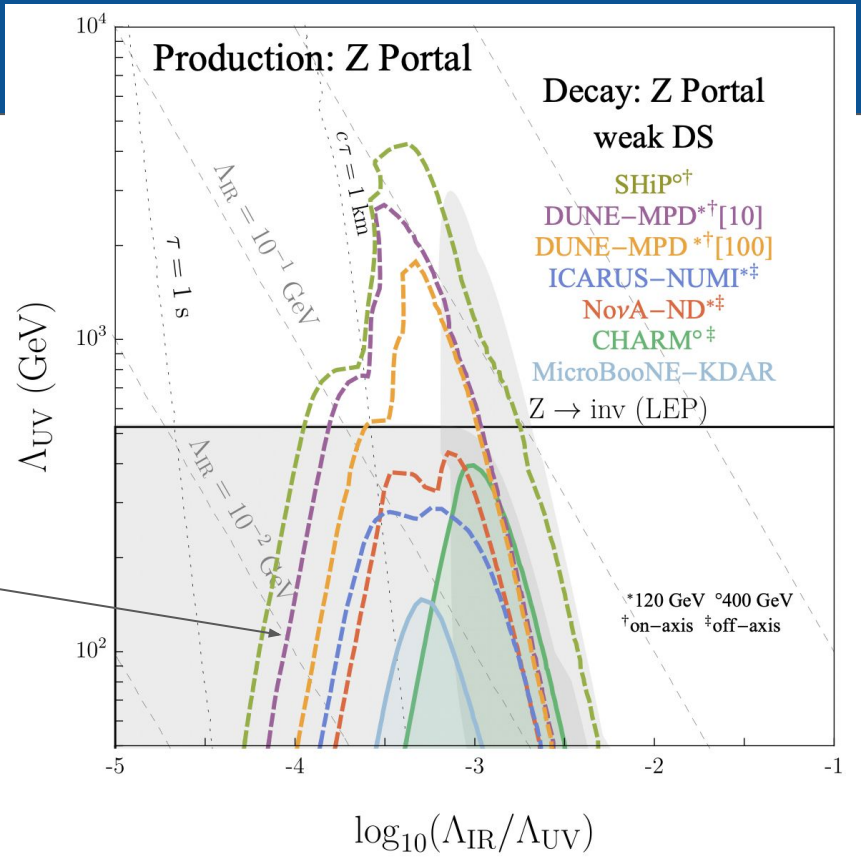
Weakly coupled results

$$S \simeq \frac{N_{\rm POT}}{\sigma_{pN}} \times \sigma_{\rm DS} \times n_{\rm DS} P_{\rm dec} \times \epsilon_{\rm geo}$$

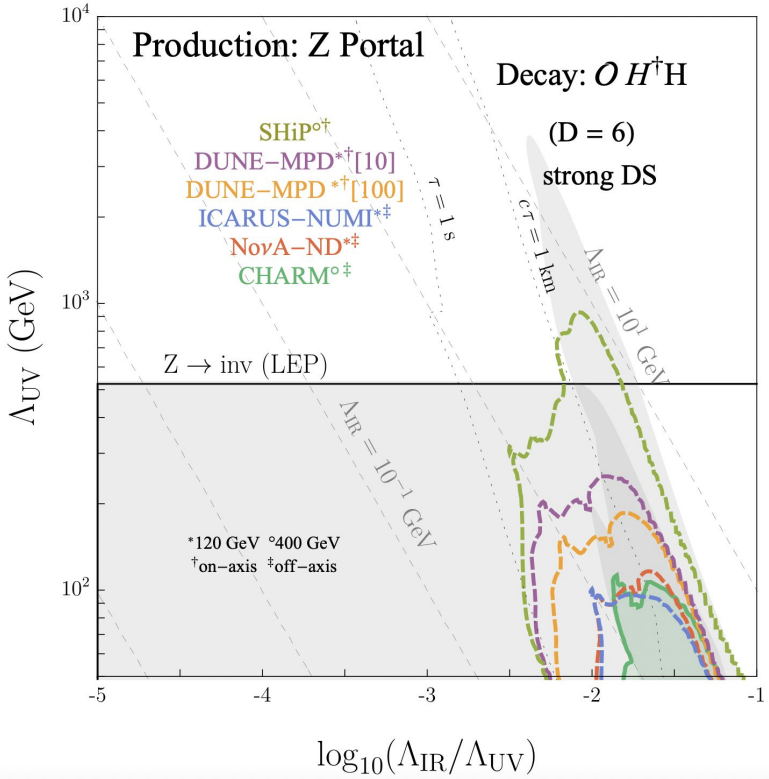
$$n_{\rm DS} = 2$$

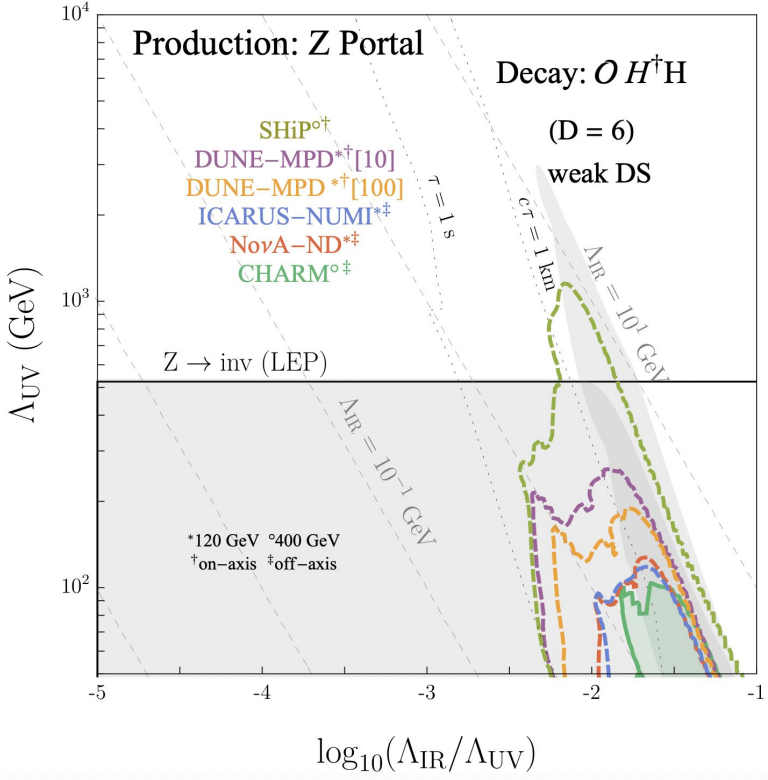
Long lifetime regime

$$S \propto \Lambda_{\rm IR}^6 / \Lambda_{\rm UV}^8$$

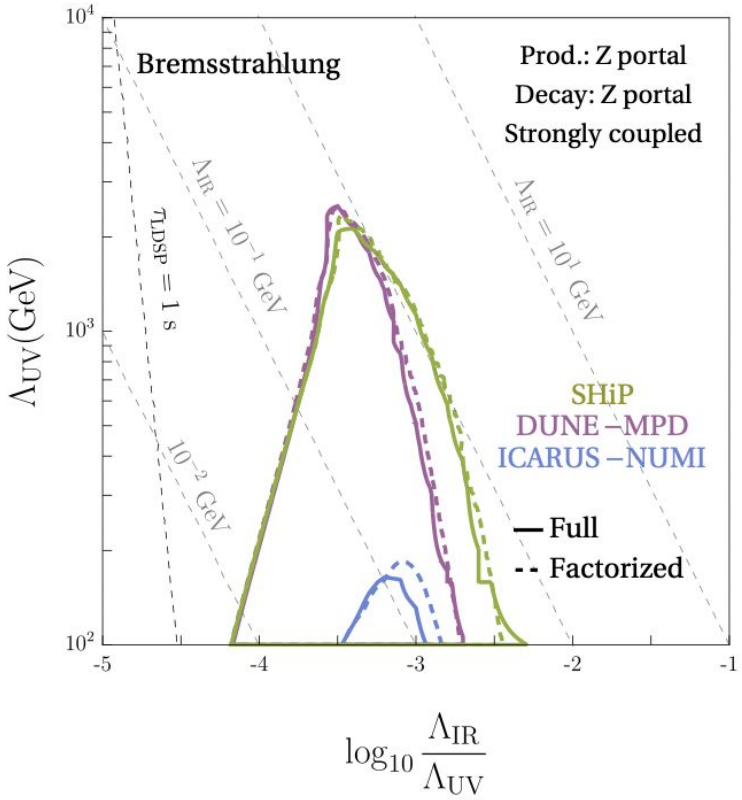


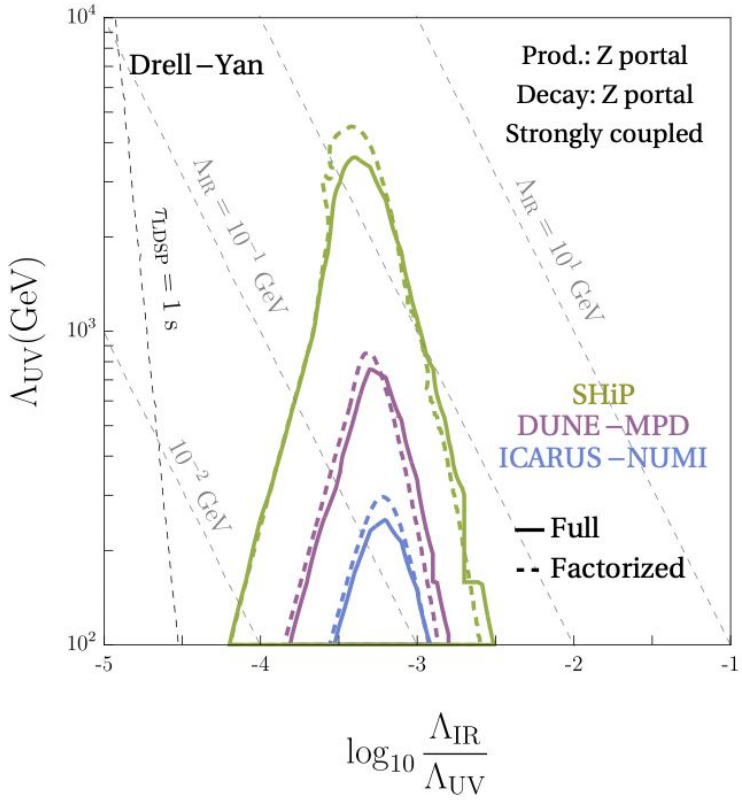
Decay through Higgs portal



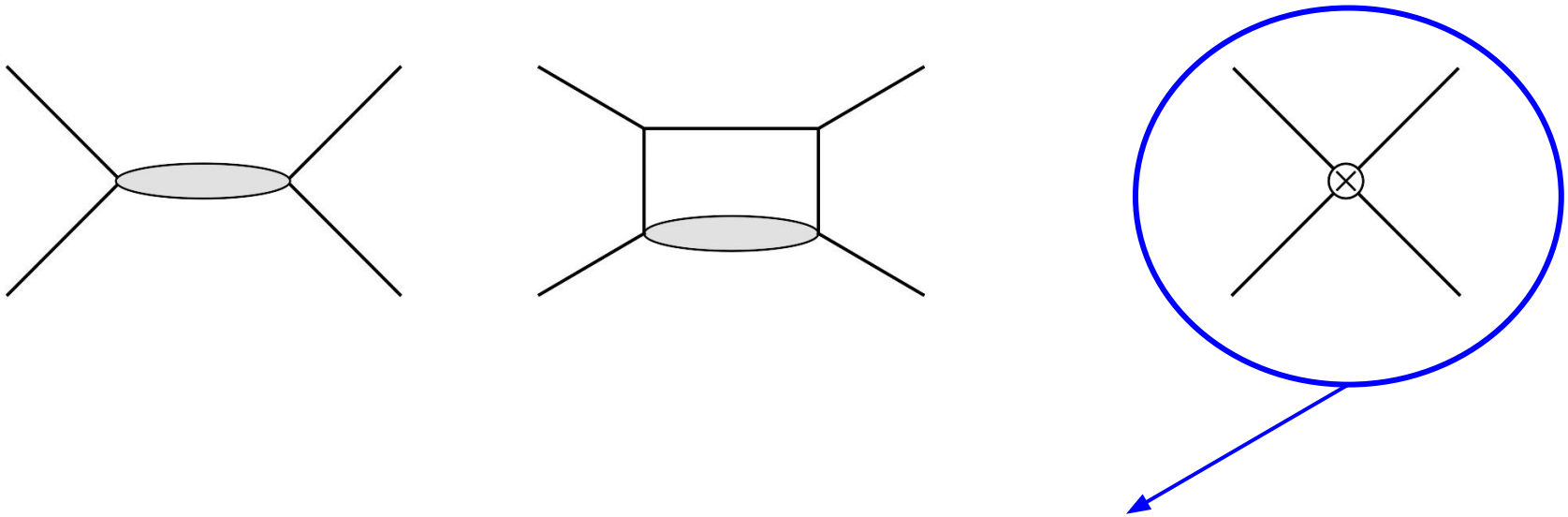


Full vs Factorized computation





EWPT



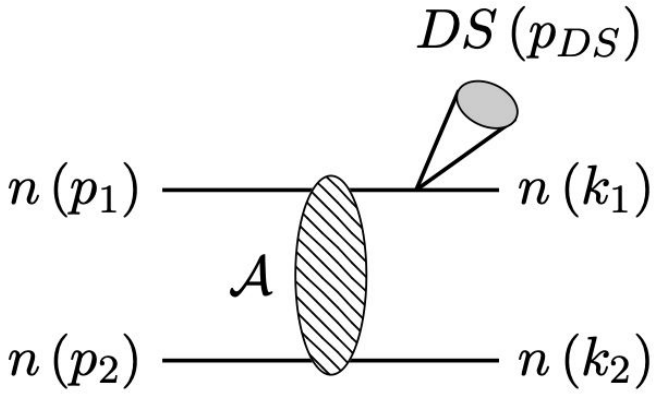
For D>6 virtual effects dominated by **UV-dependent counterterms**

Astrophysical bounds

SN cooling

$$\Lambda_{\rm UV} \gtrsim 400\,{\rm GeV}$$

for masses <<100 MeV



Bounds from LESNe

Improve > 1 order of magnitude wrt colliders, for masses <<100 MeV

Caputo,Janka,Raffelt, Vitagliano 2201.09890