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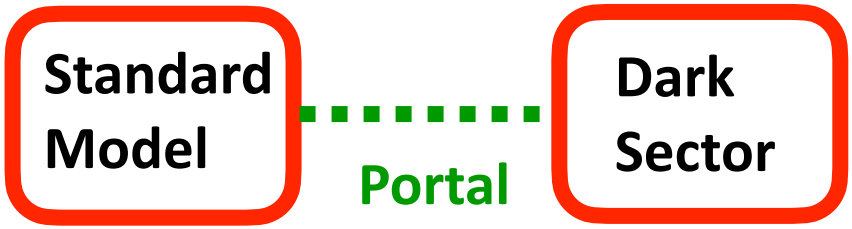
# Searching for inelastic dark matter with future laboratory experiments

Based on JHEP 03 (2021) 272 with E. Bertuzzo and JHEP 08 (2022) 100 with A.Scaffidi and E. Bertuzzo

TeVPA 2022

11 August 2022

# Motivations

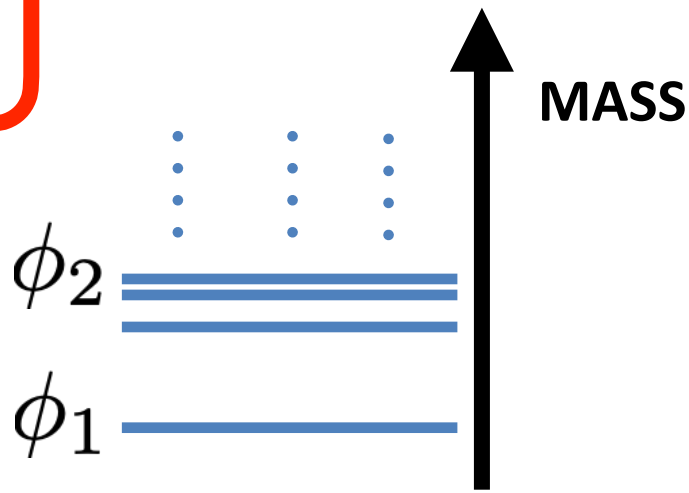



$\frac{\epsilon}{2} F'_{\mu\nu} B_{\mu\nu}$ Vector portal

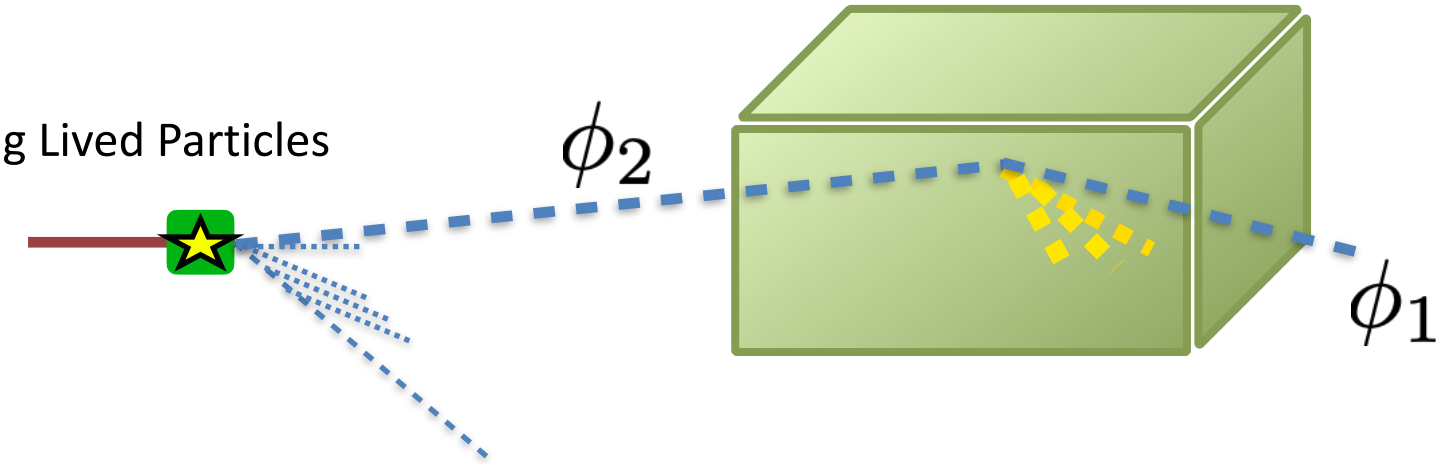
$H^\dagger H(\mu S + \lambda S^2)$ Scalar portal

$yLHN$ Neutrino portal

$\frac{1}{\Lambda^2} J_\mu^{SM} J_\mu^{DS}, \ldots$ Higher dimensional operators portals




Search for Long Lived Particles



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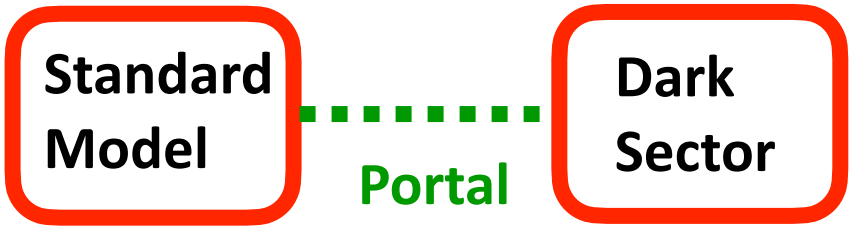


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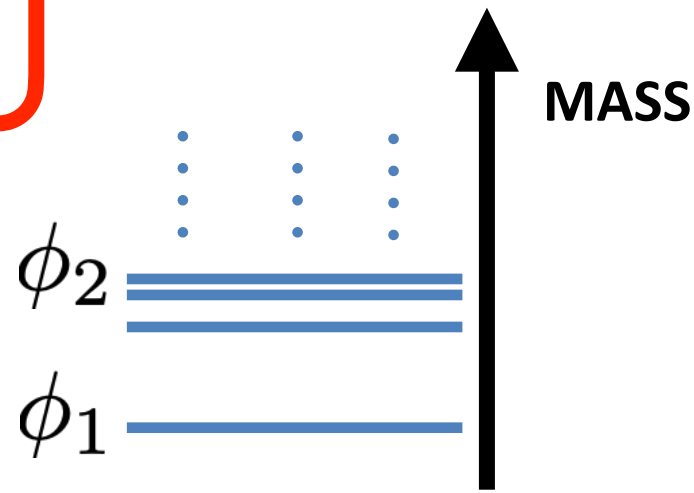


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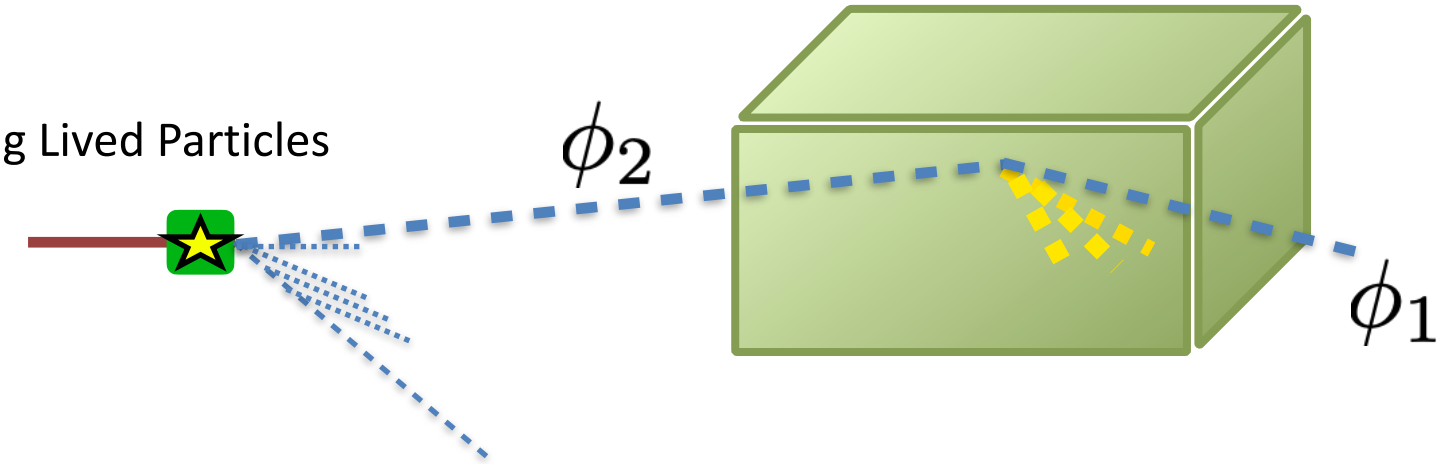
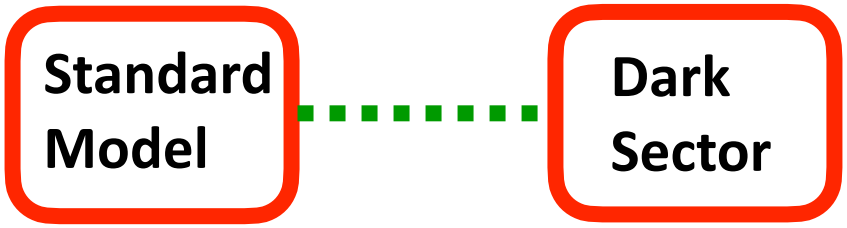


# Dark photon mediator




$$\mathcal{L}_{int} = \frac{\epsilon}{2\cos\theta_w} A'_{\mu\nu} B^{\mu\nu}.$$

Consider a dark photon coupled to two dark sector states splitted in mass: **Inelastic DM**

- Fermionic iDM $\quad \mathcal{L}^{\chi}_{int} = i g_d \, \bar{\chi}_2 \gamma^\mu \chi_1 A'_\mu$
- Scalar iDM $\quad \mathcal{L}^{\phi}_{int} = g_d \left(\partial^\mu \phi_1 \phi_2 - \phi_1 \partial^\mu \phi_2\right) A'_\mu$
- SM-DS $\quad \mathcal{L}_{int} = e\,\epsilon A'_\mu \sum_f \bar{f} Q_f \gamma^\mu f,$
- iDM mass splitting $\quad \Delta = \frac{m_2 - m_1}{m_1}$

# Framework

- Almost degenerate dark states -> suppressed DM-nuclei interactions. Evade bounds from direct detection
- Coannihilation processes in the early Universe: obtain thermal DM candidate
- Evade CMB and indirect detection constraints
- The mediators should be relatively light to explain the DM abundance

# Proposed LLPs experiments

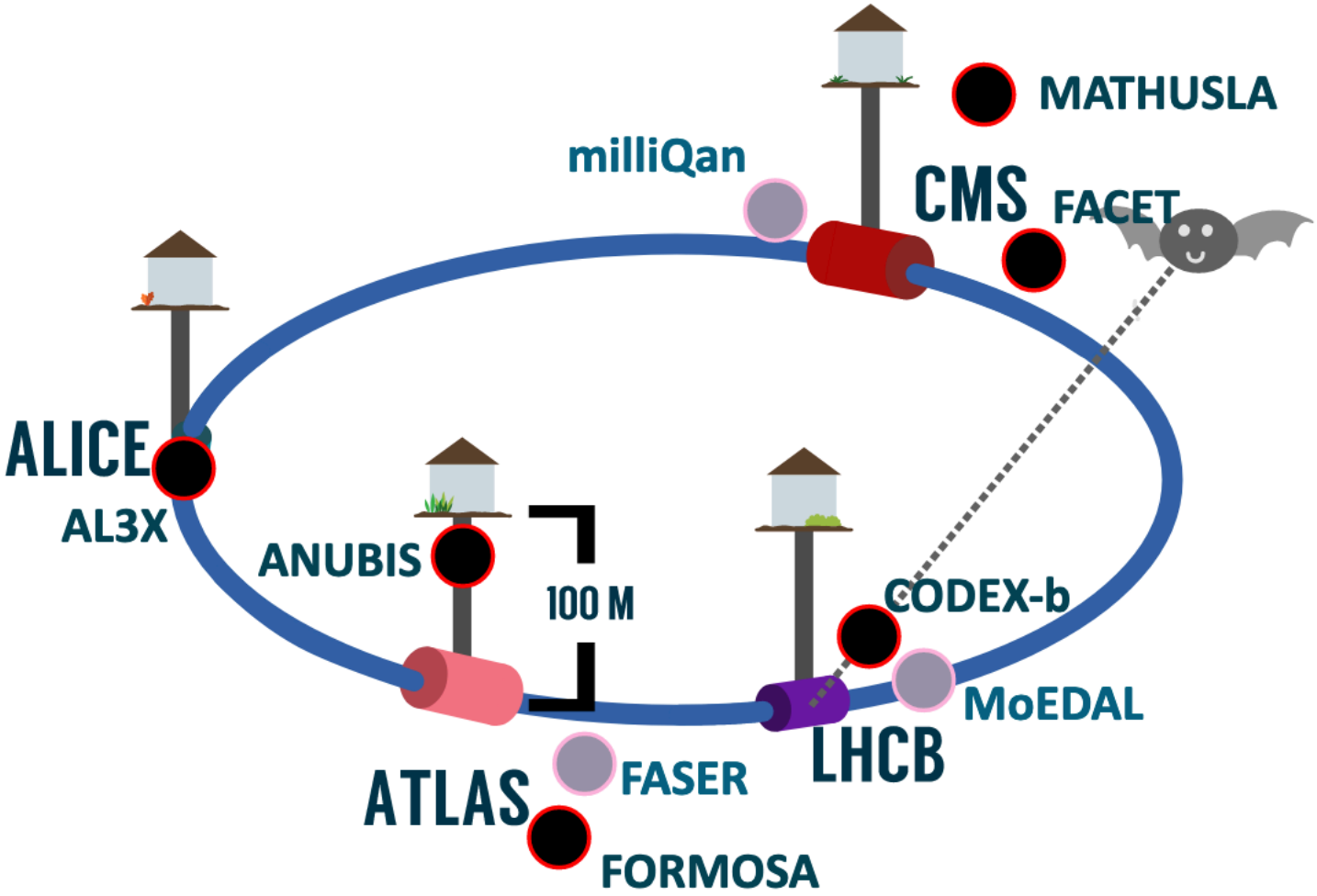
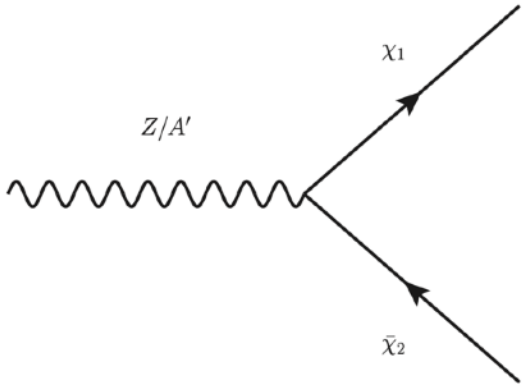


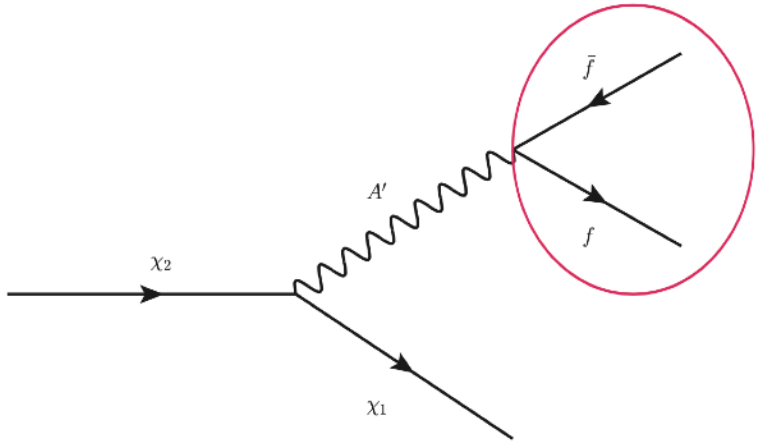

Image credit: Heather Russell

# Signatures of iDM at LHC

- Dominant production channels for masses > O(GeV): Drell-Yan processes

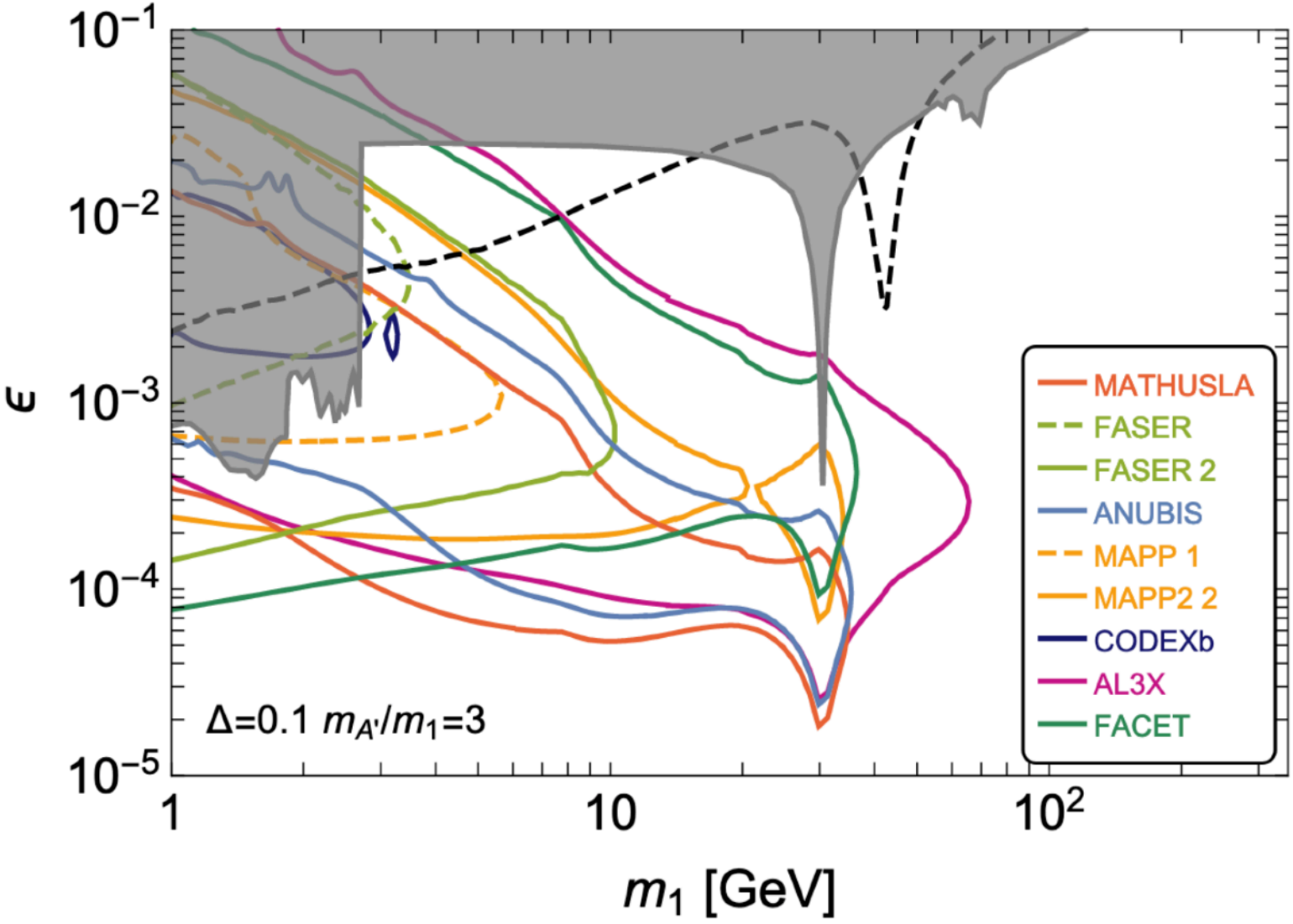



- Detection




Extend work from: **Berlin, Kling PRD 99 (2019) 1**

# Forecasting sensitivities



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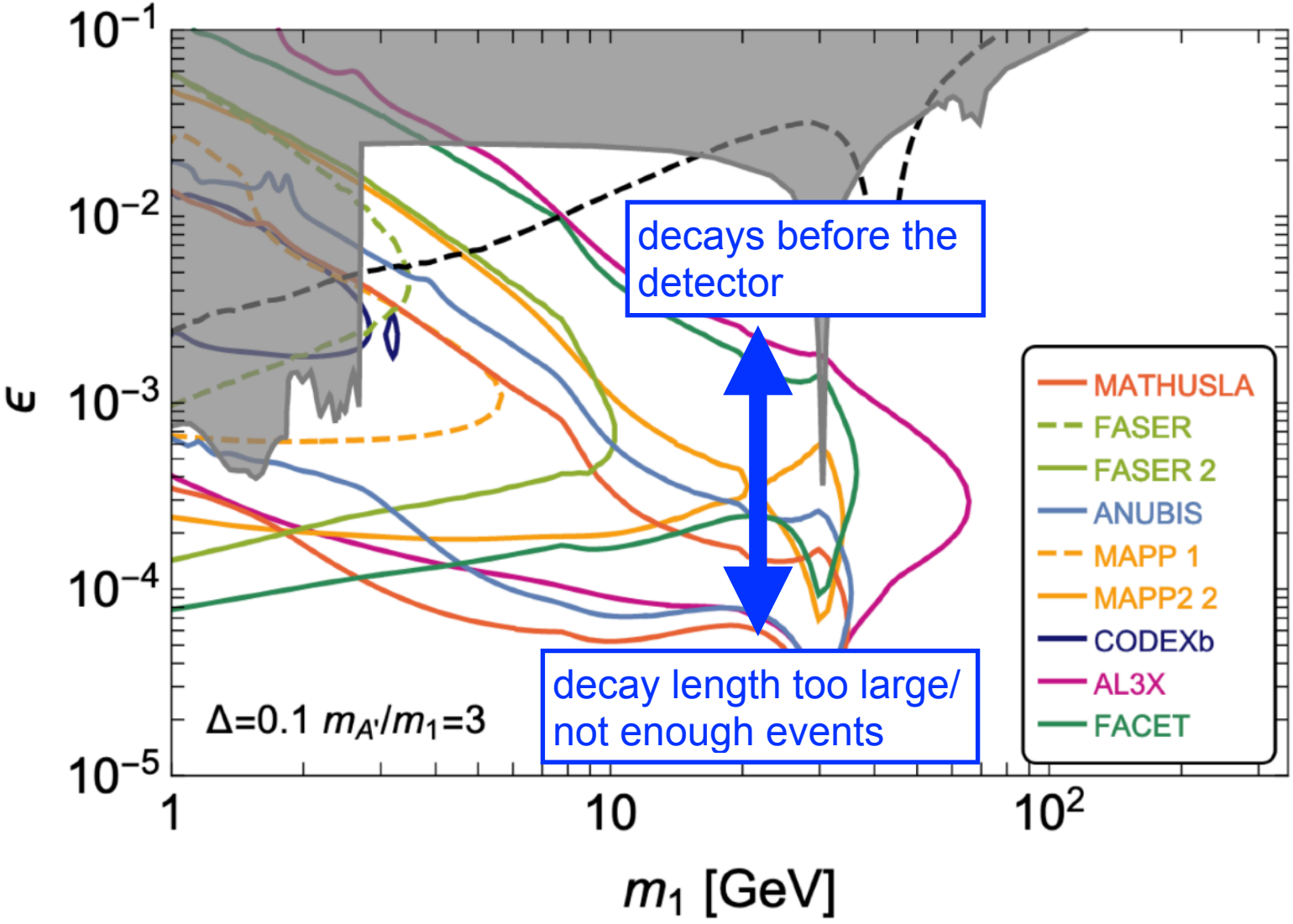

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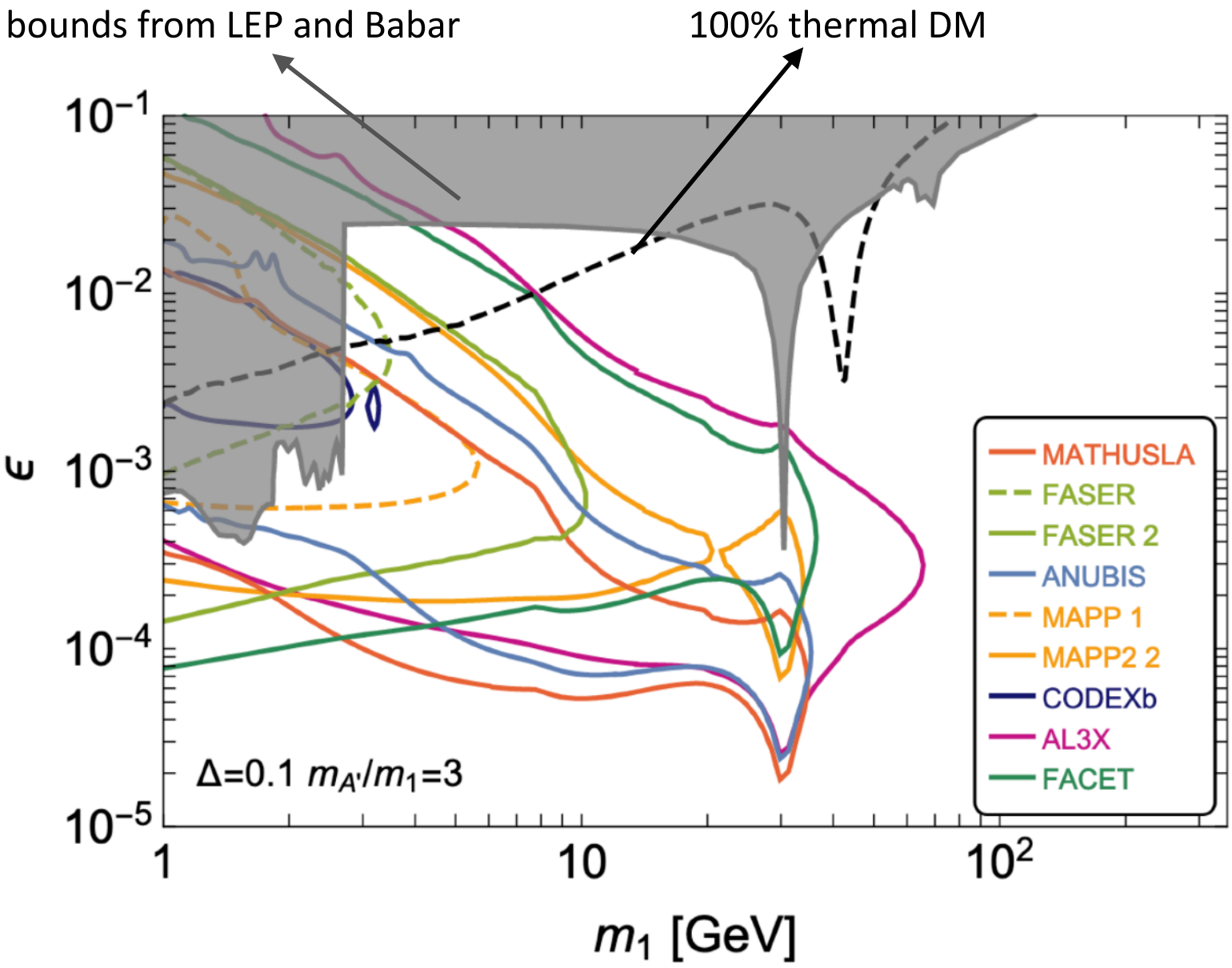

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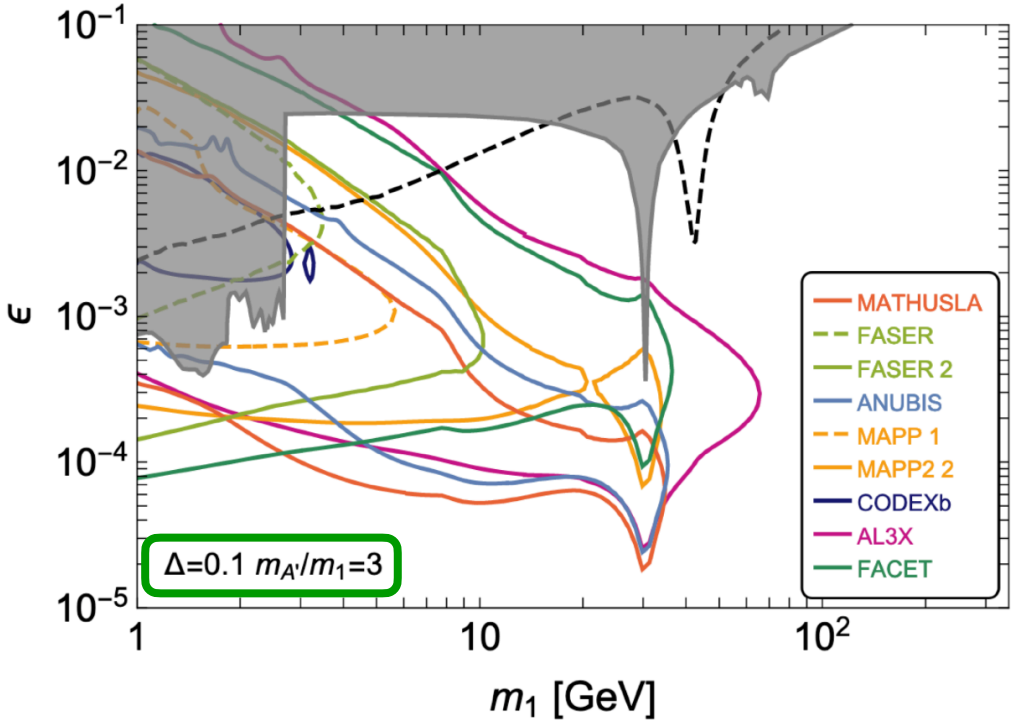


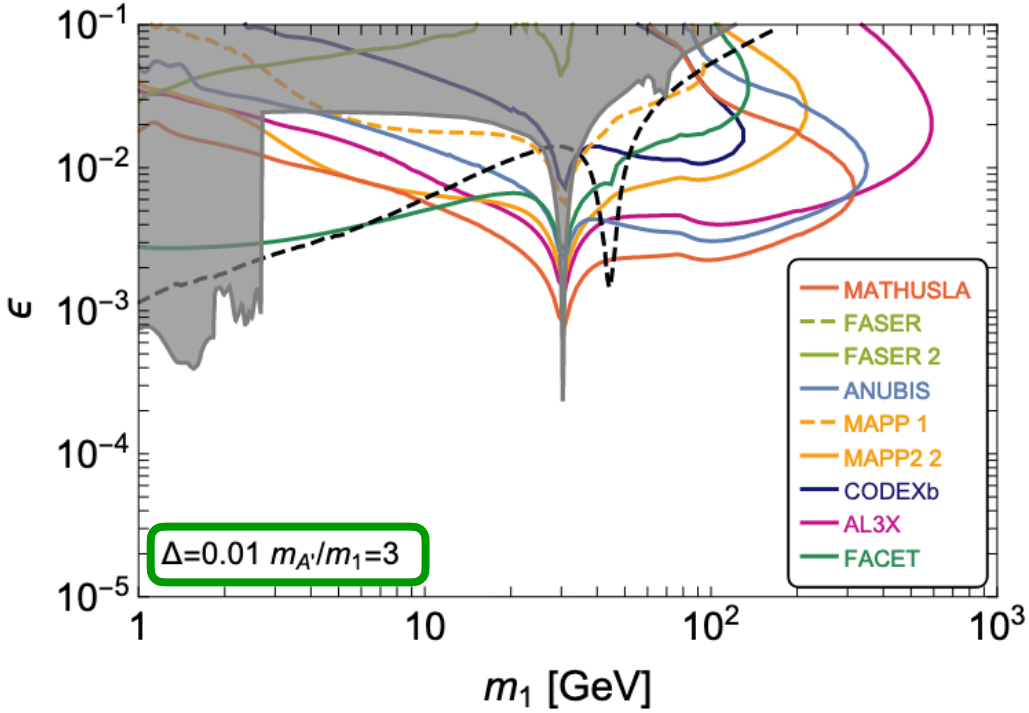

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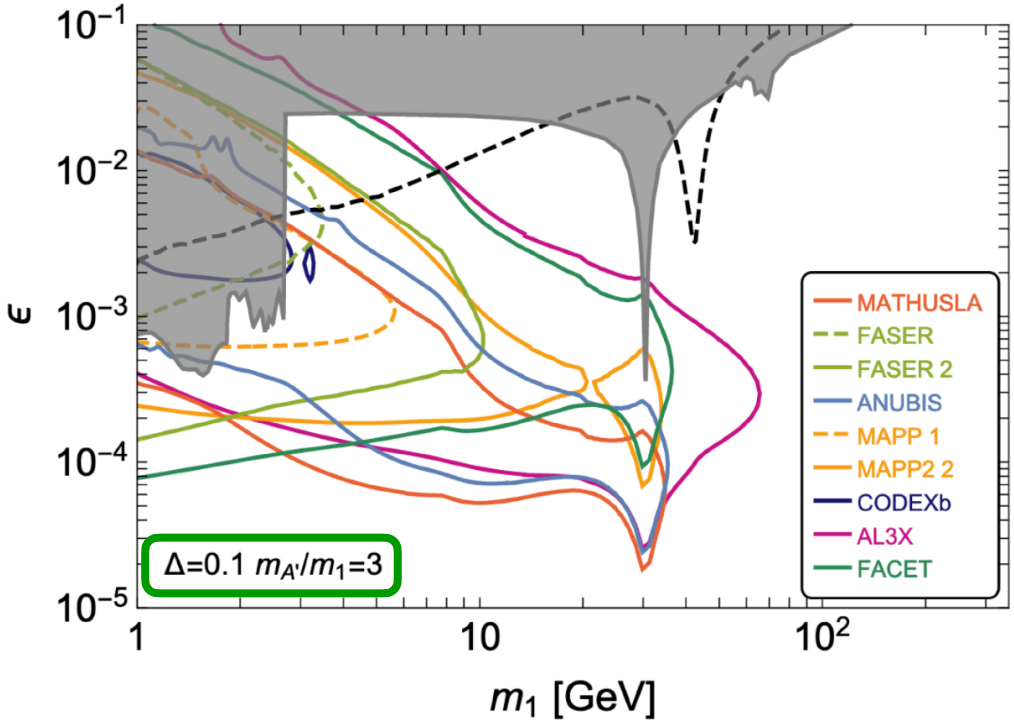
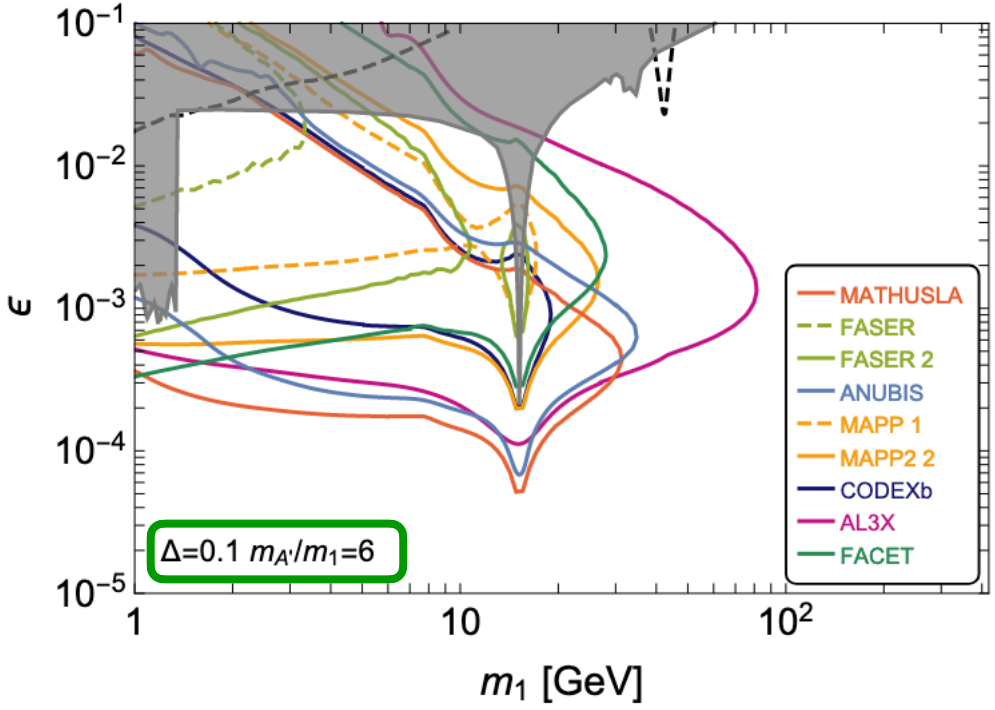


# EFT framework

**Standard Model** — Portal — **Dark Sector**

See also

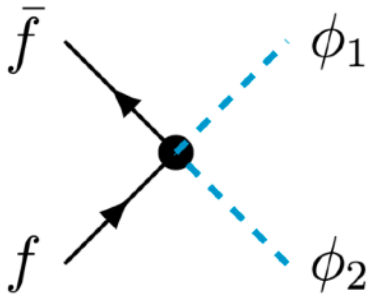
Darme, Ellis, You
JHEP 07 (2020) 053

$$\mathcal{L}_{EFT} = \frac{J^\mu_\phi}{\Lambda^2}\left(\sum_{f_L} c_{f_L}\bar{f}_L\gamma_\mu f_L + \sum_{f_R} c_{f_R}\bar{f}_R\gamma_\mu f_R\right) + \dots$$

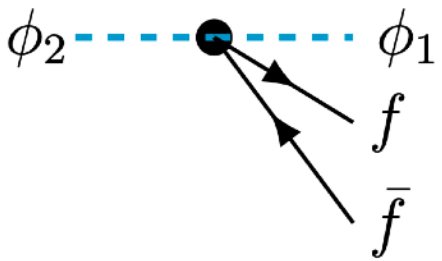
$$\phi = \frac{\phi_1 + i\phi_2}{\sqrt{2}} \qquad \delta = \frac{m_2 - m_1}{m_1}$$

$$J^\mu_\phi = i[(\partial^\mu\phi^\dagger)\phi - \phi^\dagger(\partial^\mu\phi)] = (\partial^\mu\phi_2)\phi_1 - \phi_2(\partial^\mu\phi_1)$$

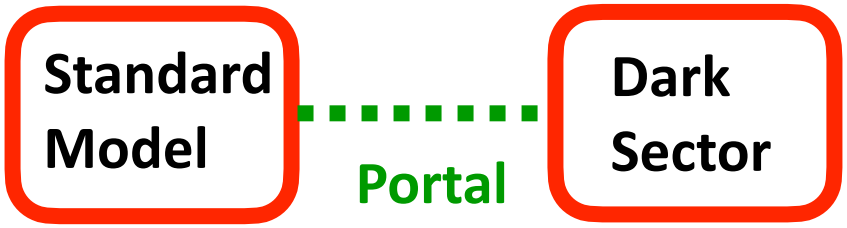
Production




Decay



# EFT framework

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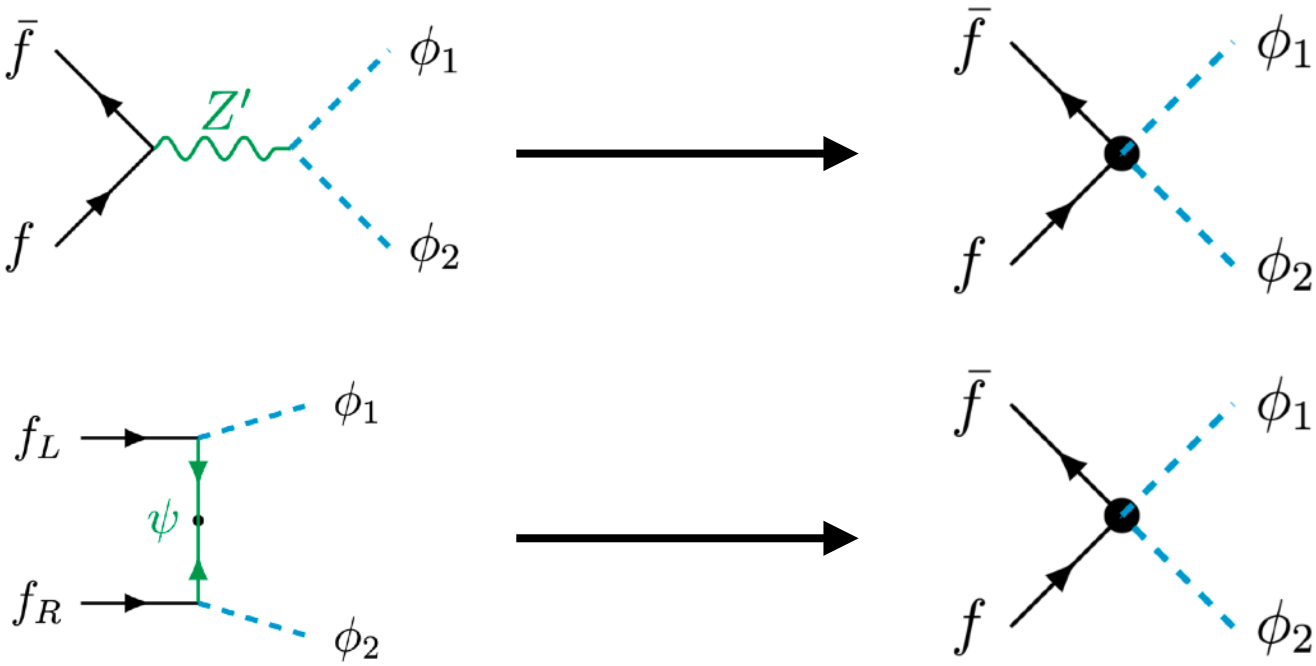


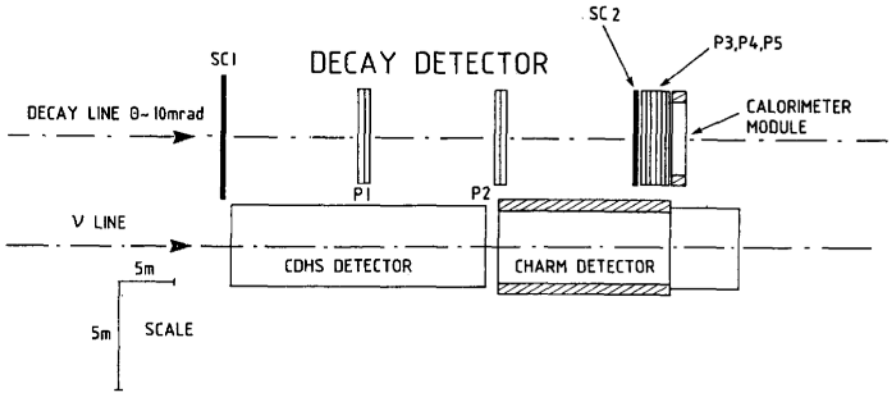
# Fixed target experiments

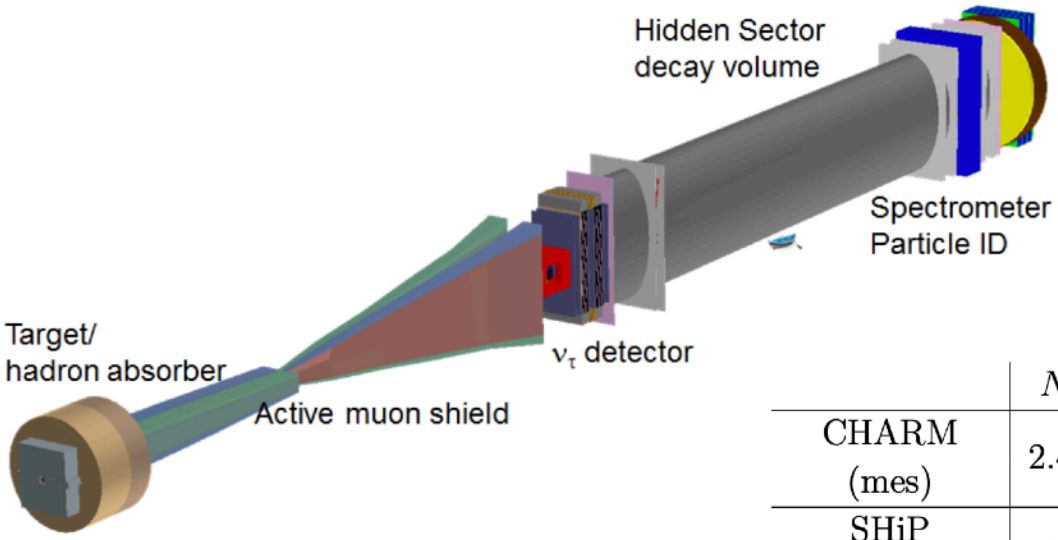
400 GeV proton beam on a fixed target, $\sqrt{s} \simeq 28$ GeV

## CHARM

Recast a search for Heavy Neutrinos decaying into leptons

**CHARM Collaboration, PLB 166 (1986) 473**




## SHiP

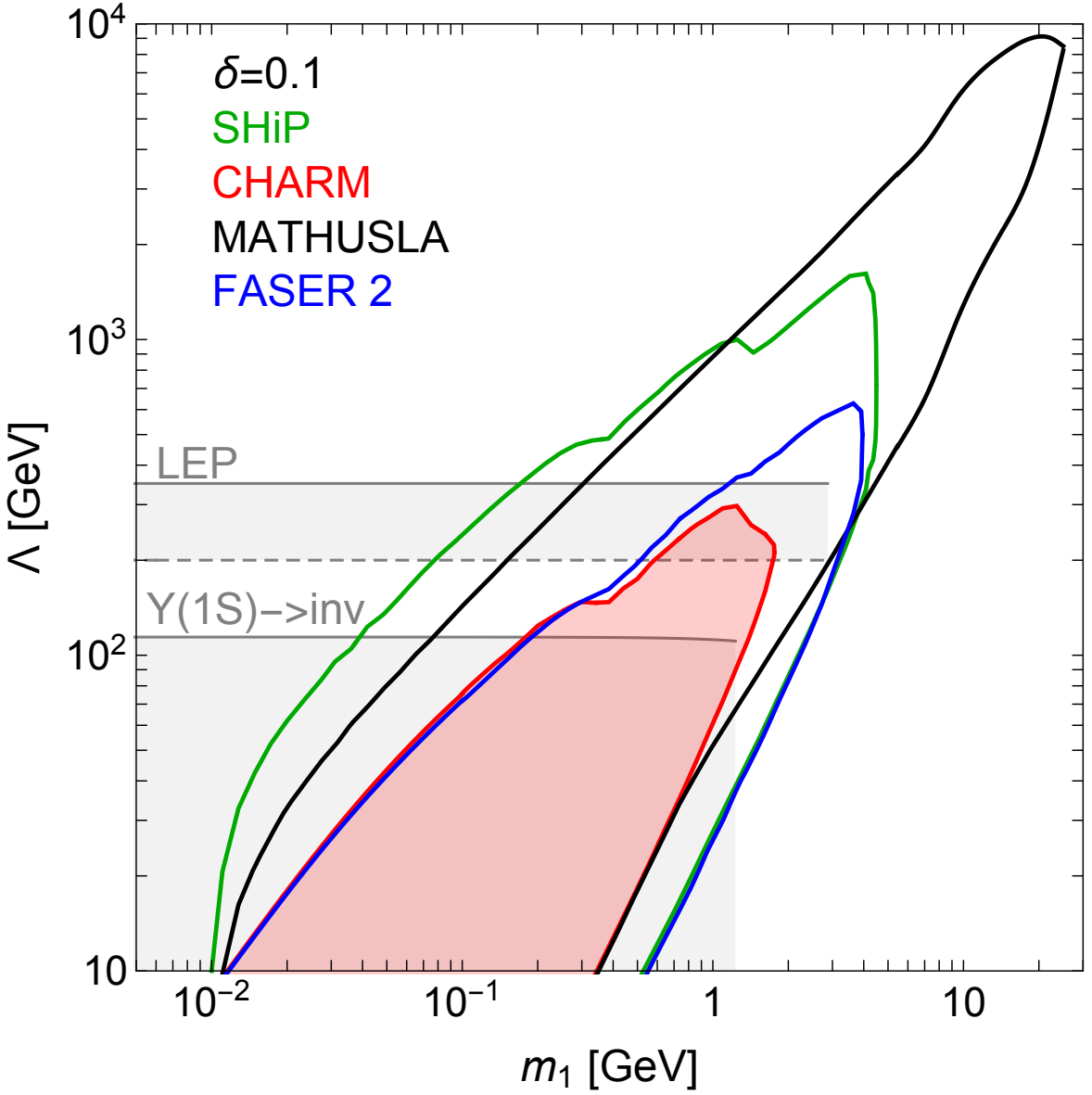
Proposed proton beam-dump experiment at the CERN SPS

| | $N_{\rm POT}/\mathcal{L}$ | $\theta_{\phi_2}$ [mrad] | $L$ [m] | $L_{\rm dec}$ [m] | $\epsilon$ |
|---|---|---|---|---|---|
| CHARM (mes) | $2.4 \times 10^{18}$ | $6.8 \leq \theta_{\phi_2} \leq 12.6$ | 480 | 35 | $\epsilon_e = 0.65$ * <br> $\epsilon_\mu = 0.75$ * |
| SHiP (mes) | $2 \times 10^{20}$ | $\lvert\theta_{\phi_2}\rvert \leq 36.9$ | 58 | 50 | $\epsilon_i = 1$ |

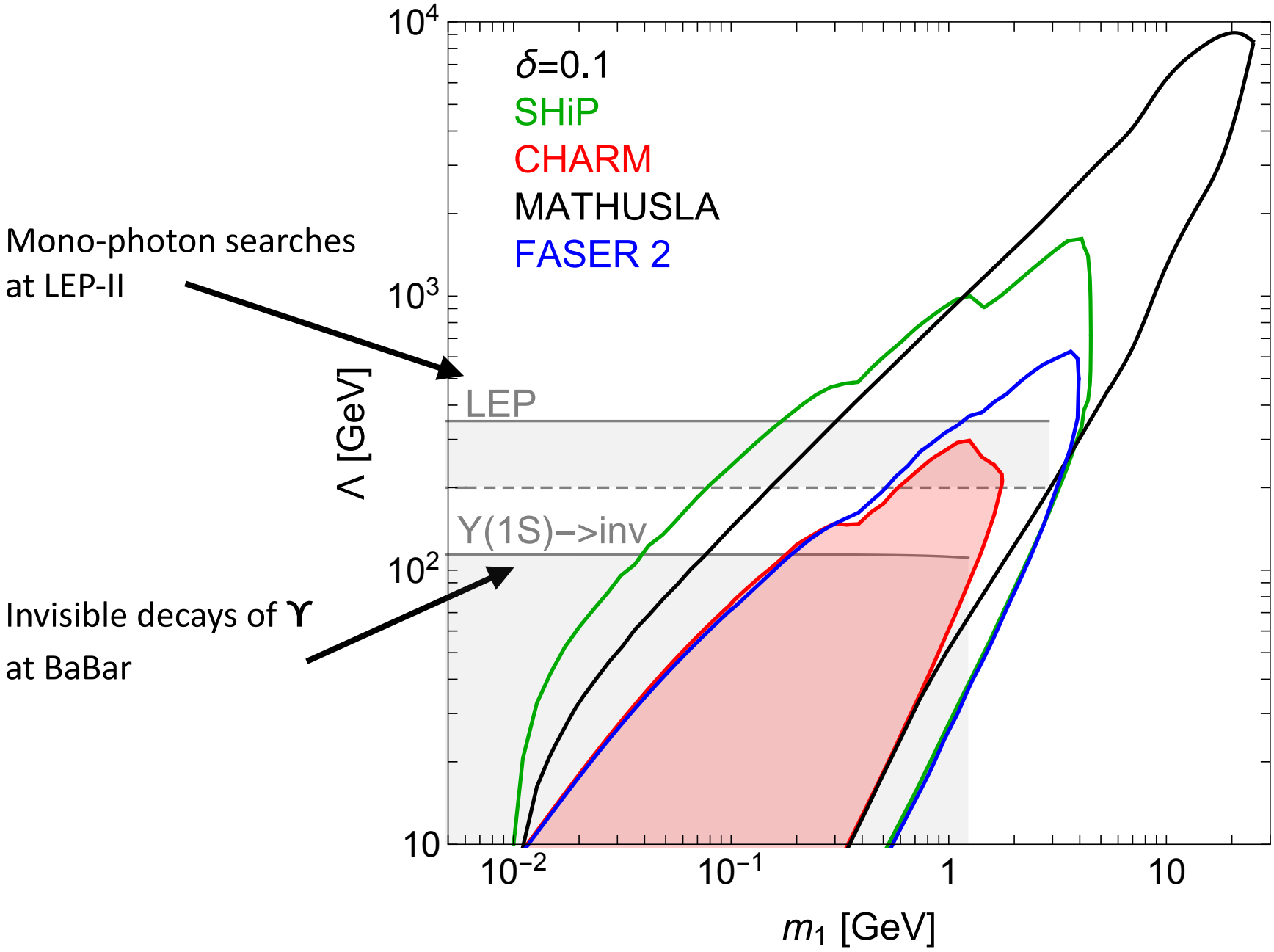
Other relevant experiments: **E137, MiniBooNE, LSND**

# Sensitivity contours

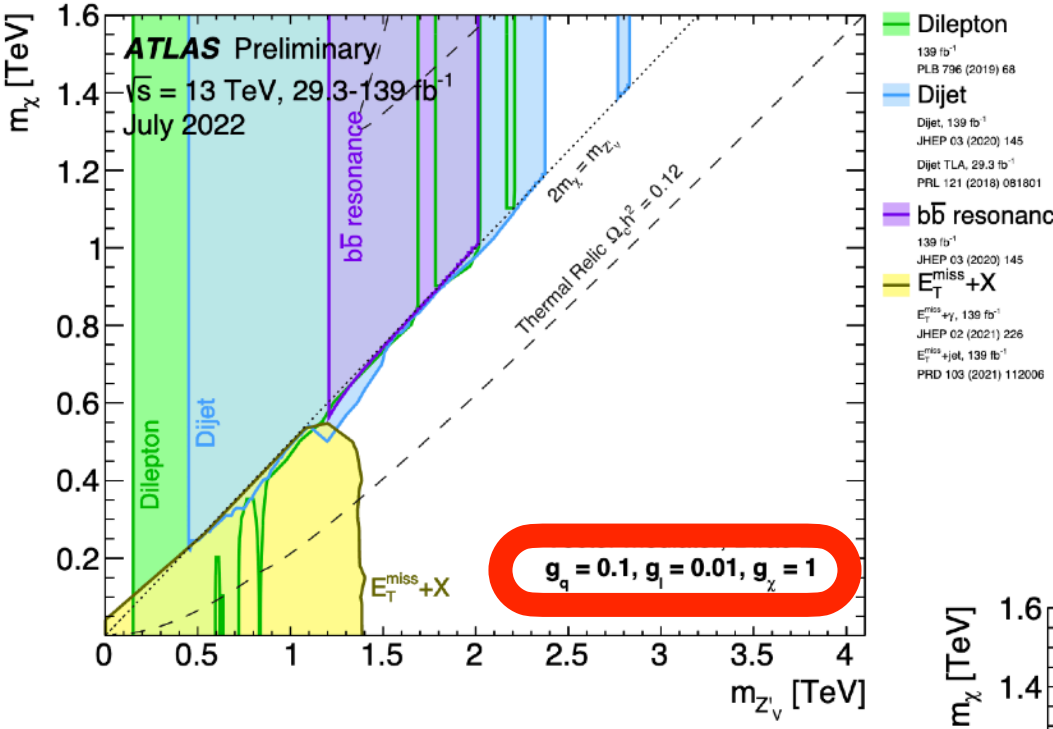
$$\mathcal{L}_{EFT} = \frac{J^{\mu}_{\phi}}{\Lambda^2}\left(\sum_{f_L} c_{f_L}\bar{f}_L\gamma_\mu f_L + \sum_{f_R} c_{f_R}\bar{f}_R\gamma_\mu f_R\right) \qquad c_{f_L} = c_{f_R} = 1$$



# Sensitivity contours

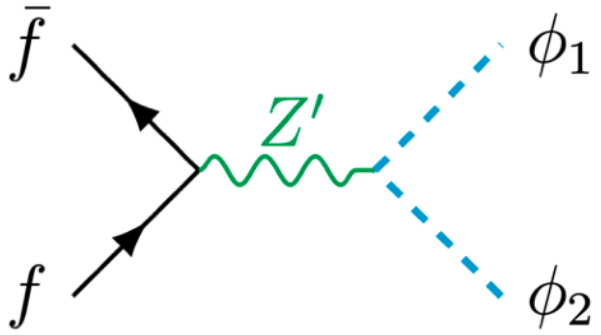


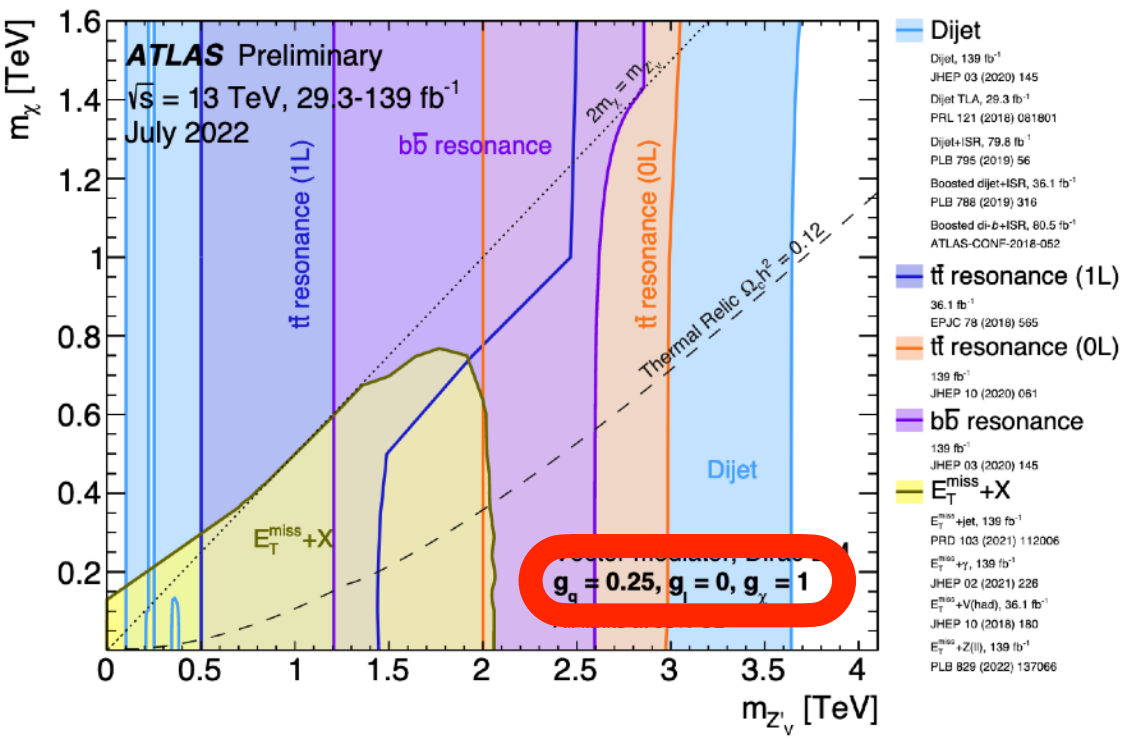
# Simplified DM models at LHC









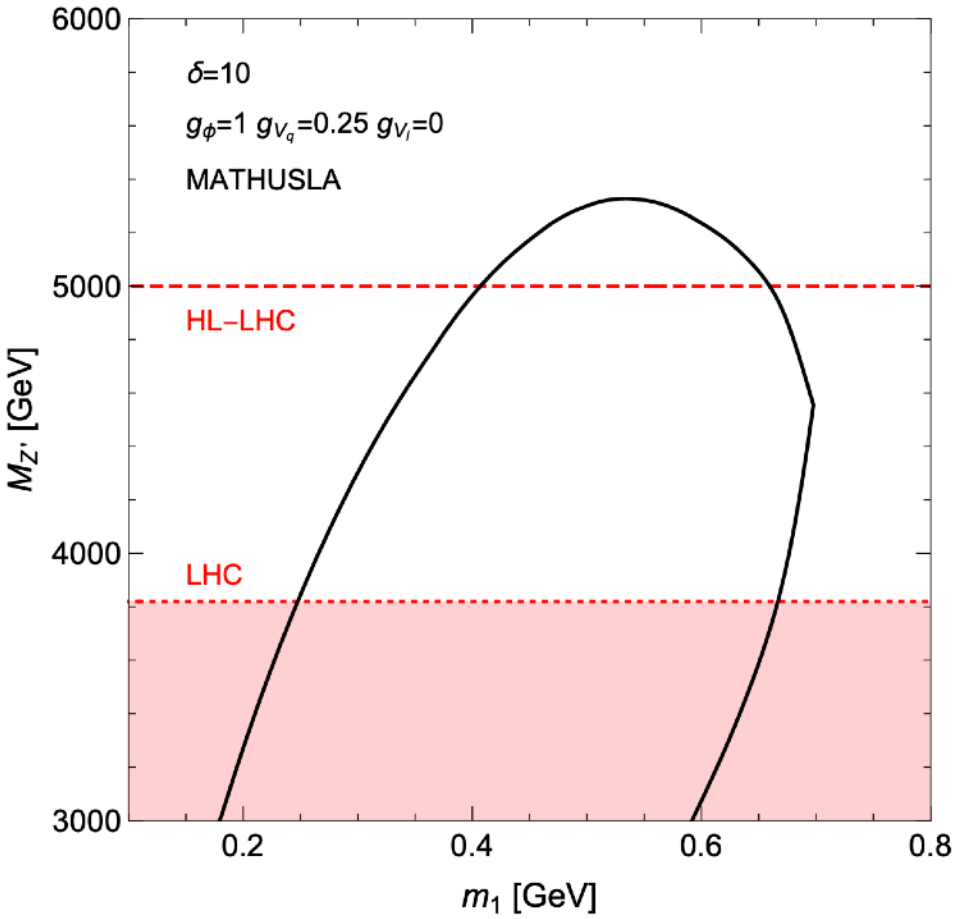


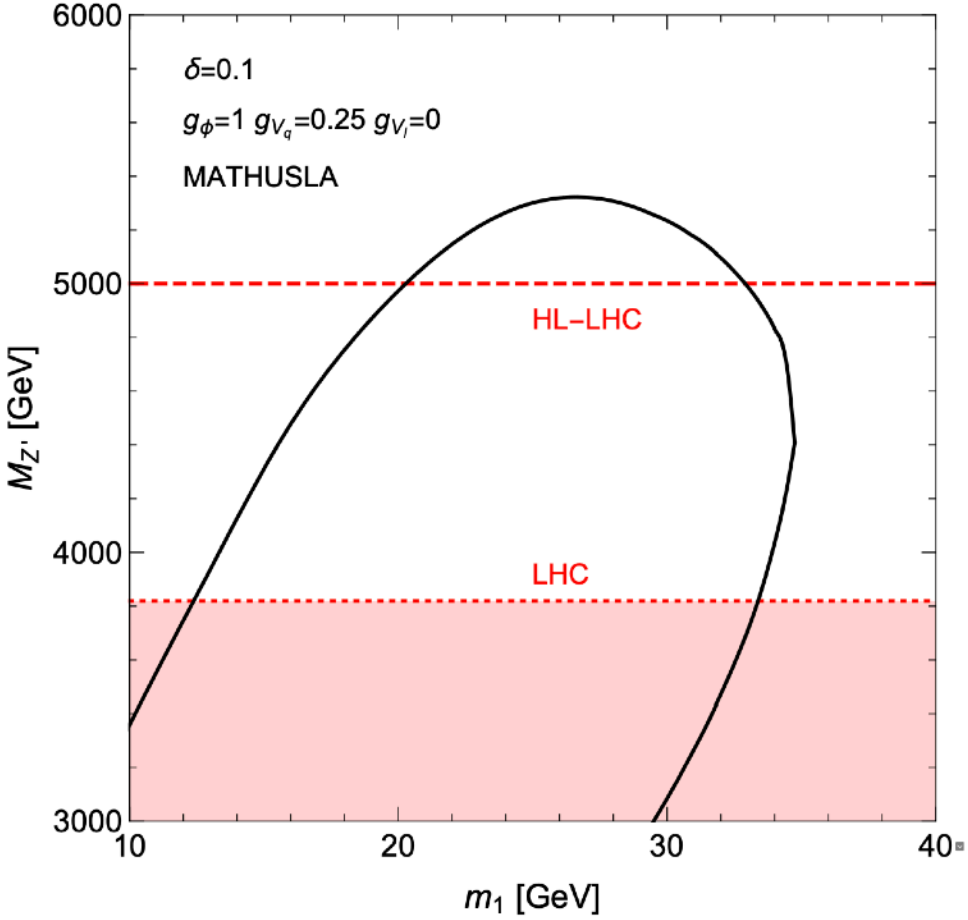


ATLAS Coll.
"Dark matter summary plots for s-channel, 2HDM+a and Dark Higgs models",

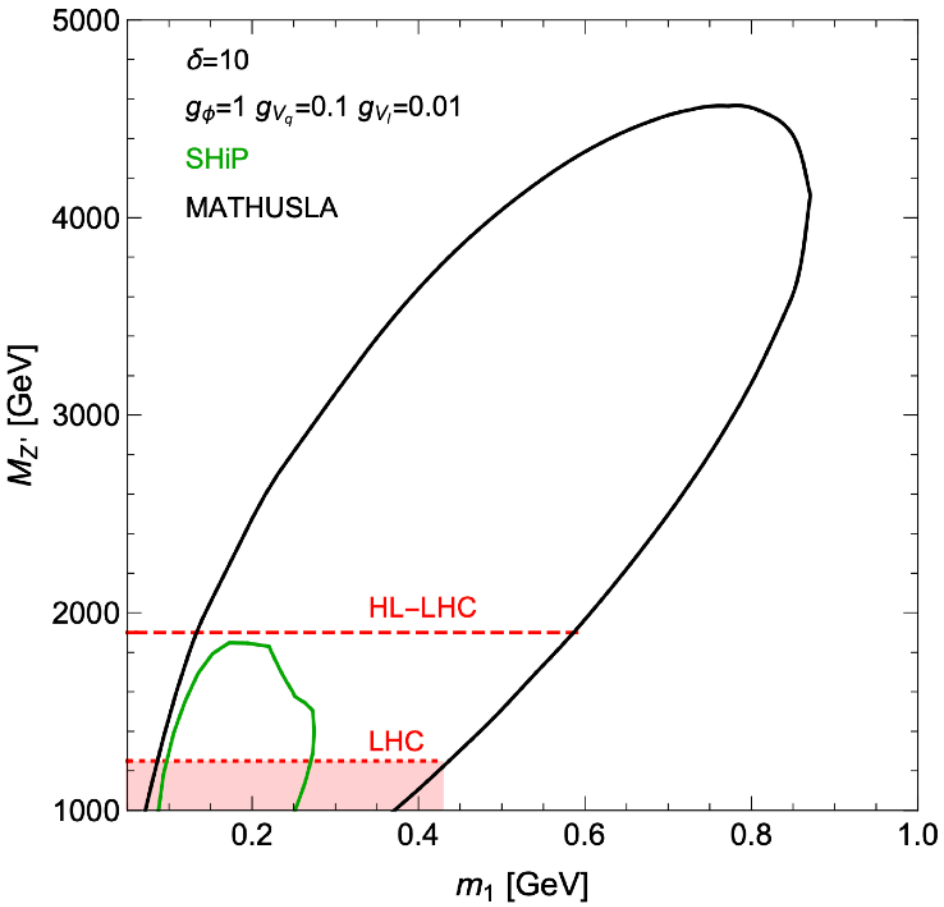
https://cds.cern.ch/record/2816368/files/ATL-PHYS-PUB-2022-036.pdf

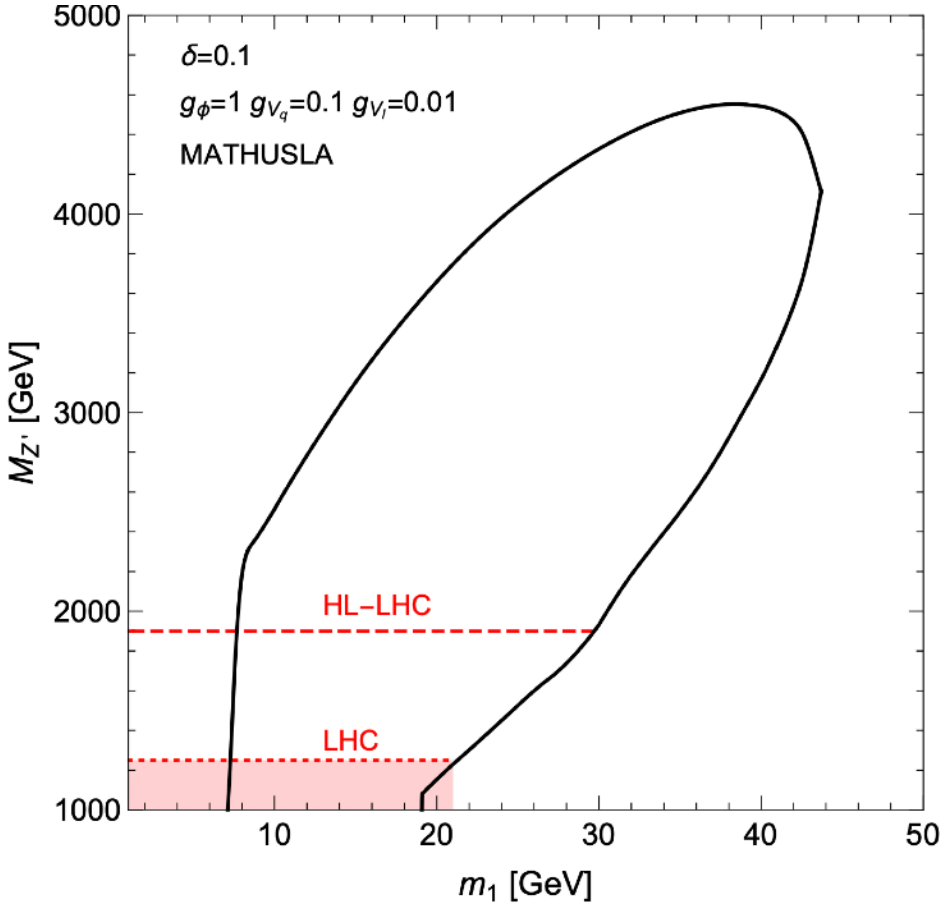
# Heavy Z' - I


δ=10
$g_\phi$=1 $g_{V_q}$=0.25 $g_{V_l}$=0
MATHUSLA
HL–LHC
LHC
6000
5000
4000
3000
0.2
0.4
0.6
0.8
$M_{Z'}$ [GeV]
$m_1$ [GeV]


δ=0.1
$g_\phi$=1 $g_{V_q}$=0.25 $g_{V_l}$=0
MATHUSLA
HL–LHC
LHC
6000
5000
4000
3000
10
20
30
40
$M_{Z'}$ [GeV]
$m_1$ [GeV]

# Heavy Z’ - II

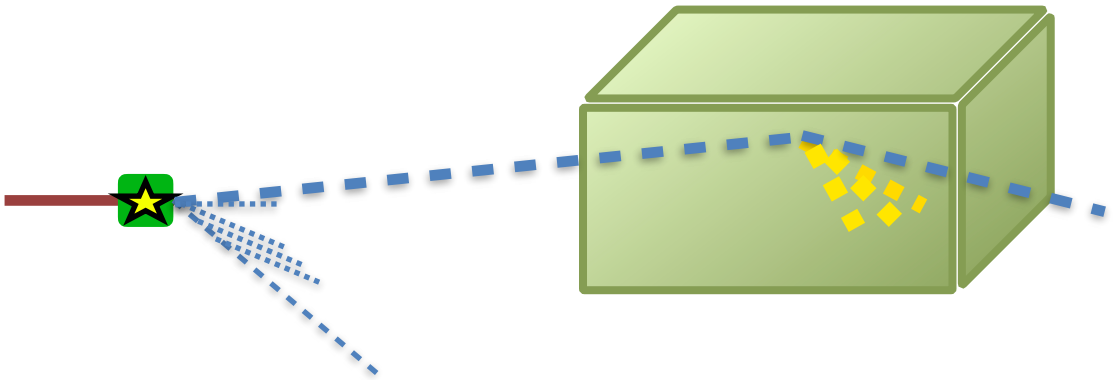

δ=10
$g_\phi$=1 $g_{V_q}$=0.1 $g_{V_l}$=0.01
SHiP
MATHUSLA
HL–LHC
LHC
$M_{Z'}$ [GeV]
$m_1$ [GeV]
5000
4000
3000
2000
1000
0.2
0.4
0.6
0.8
1.0


δ=0.1
$g_\phi$=1 $g_{V_q}$=0.1 $g_{V_l}$=0.01
MATHUSLA
HL–LHC
LHC
$M_{Z'}$ [GeV]
$m_1$ [GeV]
5000
4000
3000
2000
1000
10
20
30
40
50

# Conclusions

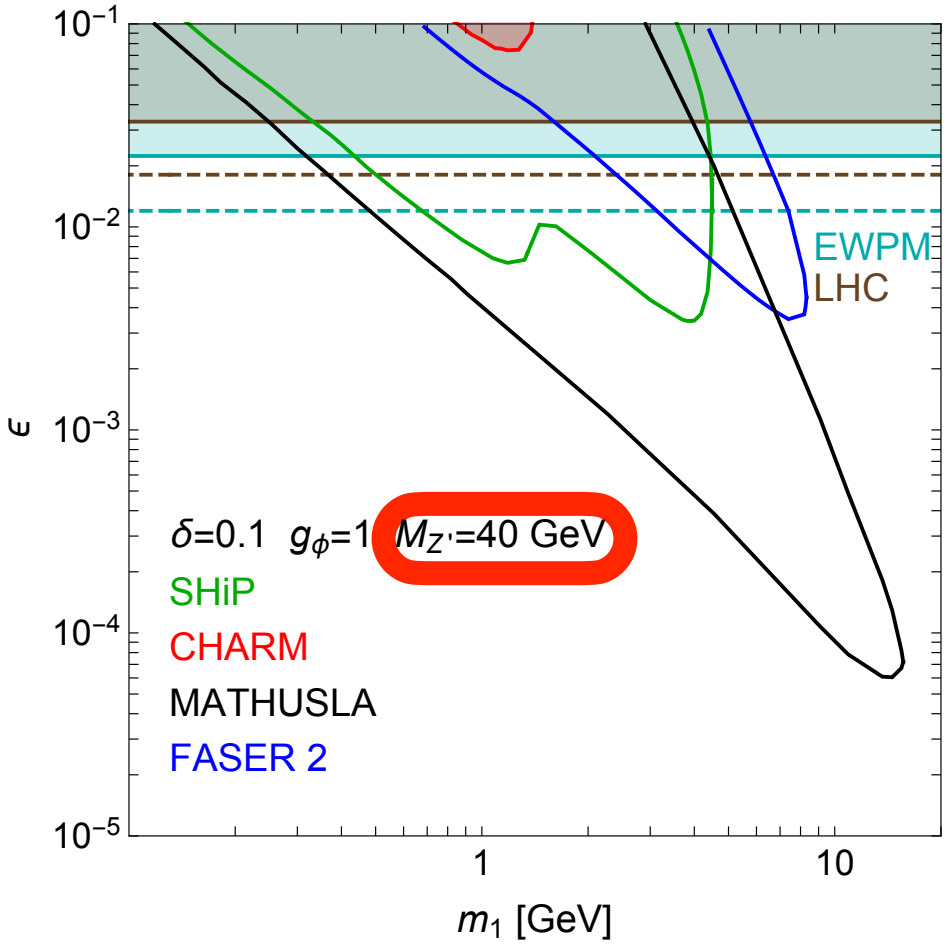
Explored a dark sector containing inelastic dark matter

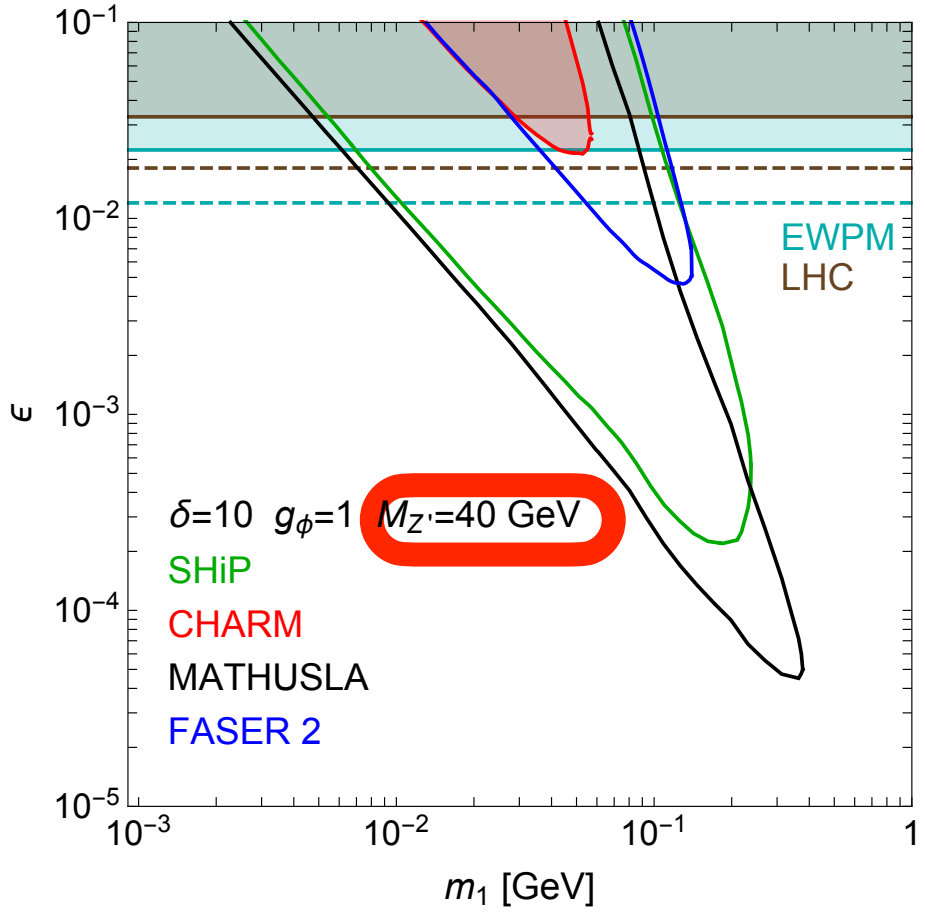
This scenario can be tested at future proposed LHC experiments for long-lived particles (FASER, MATHUSLA,…) and beam dump experiments



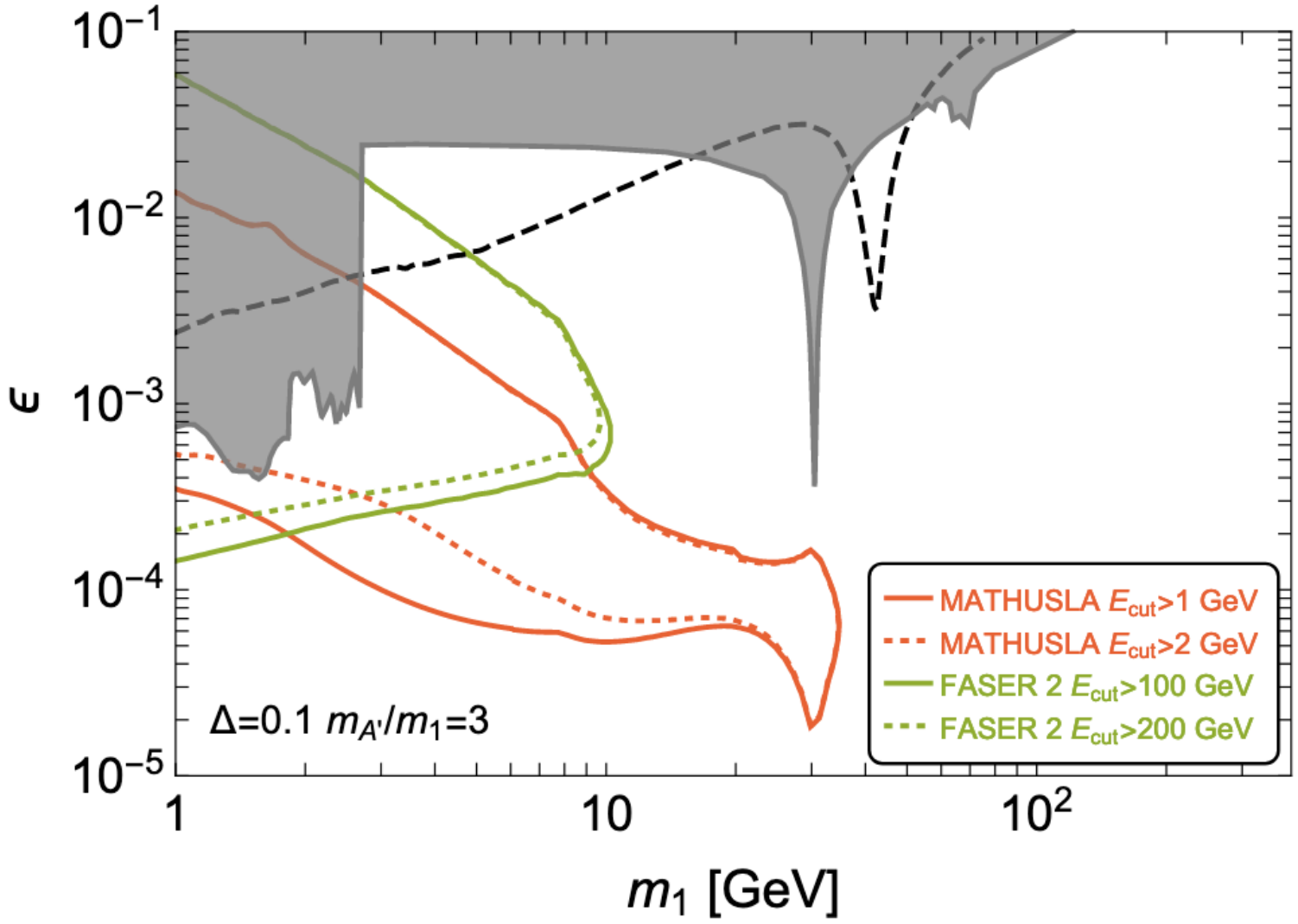
# Dark Photon

$$\mathcal{L} \supset \frac{\epsilon}{2\, c_w} F'_{\mu\nu} B_{\mu\nu}$$



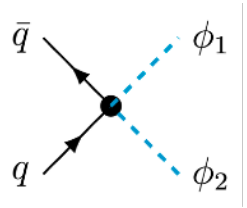
# Forecasting sensitivities



# Production of dark scalars

**From meson decays** $N_M^{\phi_2} = N_{\rm POT}\, N_M\, {\rm BR}(M \to \phi_1\, \phi_2 + {\rm X})$

**From direct QCD parton production**




Validity of the EFT:

$$\sqrt{\hat{s}} \leq \Lambda$$

↑ com energy of the event

Racco, Wulzer, Zwirner JHEP 05 (2015) 009

@ LHC