# Hidden Valley Models

Caleb Gemmell



M. J. Strassler and K. M. Zurek, Phys. Lett. B 651 (2007) 374 [arXiv:hep-ph/0604261]

# Overview

- A General Model
- Portals
  - Heavy mediator
  - Higgs
  - Vector / kinetic mixing
  - Neutrino
- Theoretical Motivations
  - Hierarchy Problem
  - Dark matter Candidates
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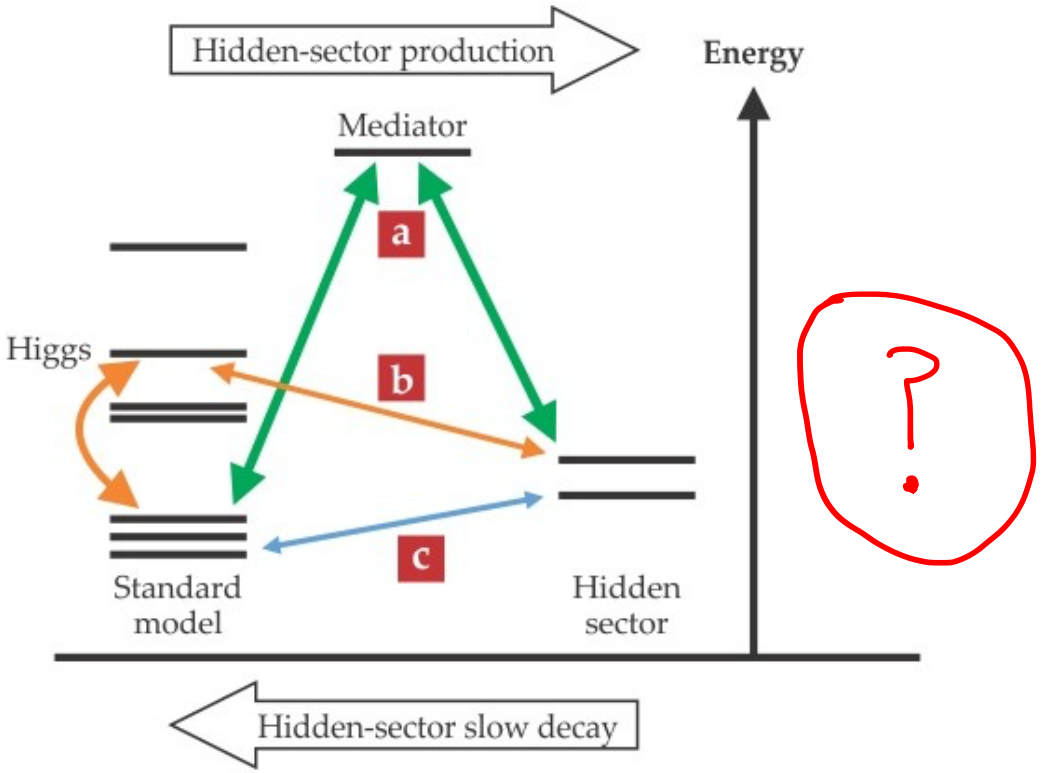
  - Dark Showers / Jets
  - Invisible Higgs decays
  - MATHUSLA (Long Lived Particles)

# A General Hidden Valley Model




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

?

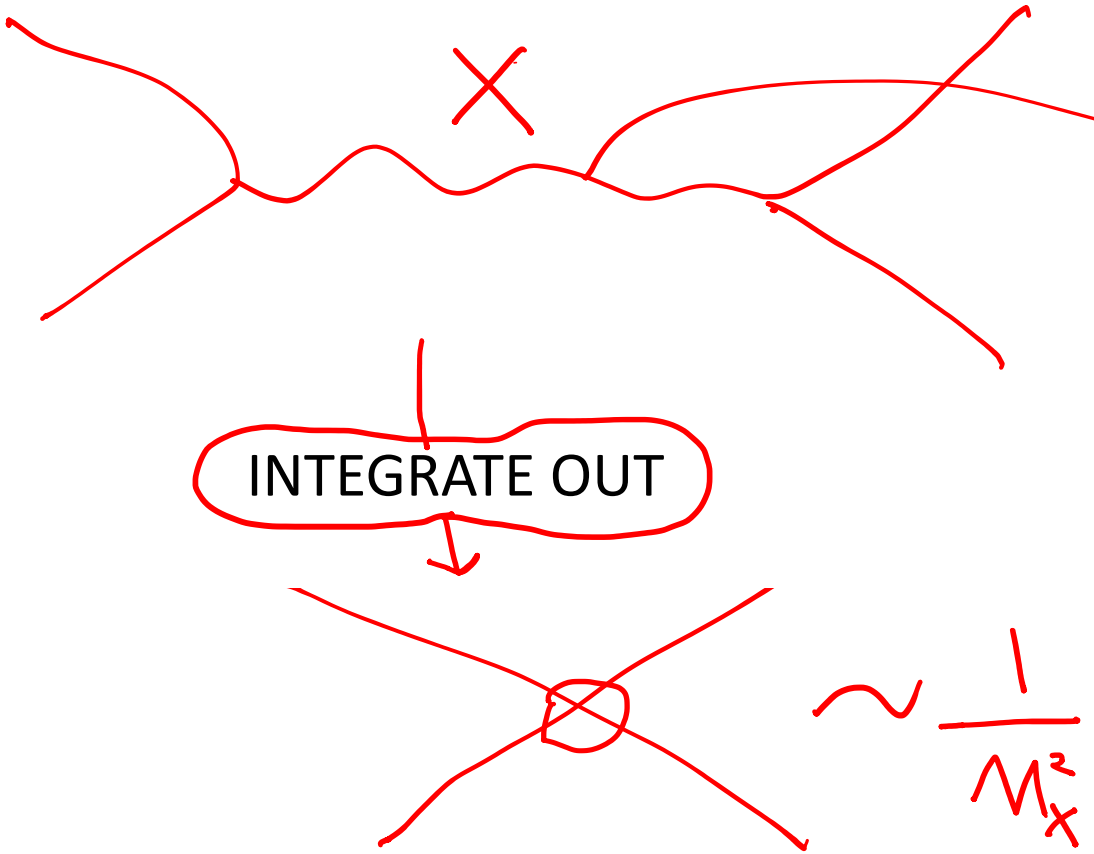
$G_{HV}$



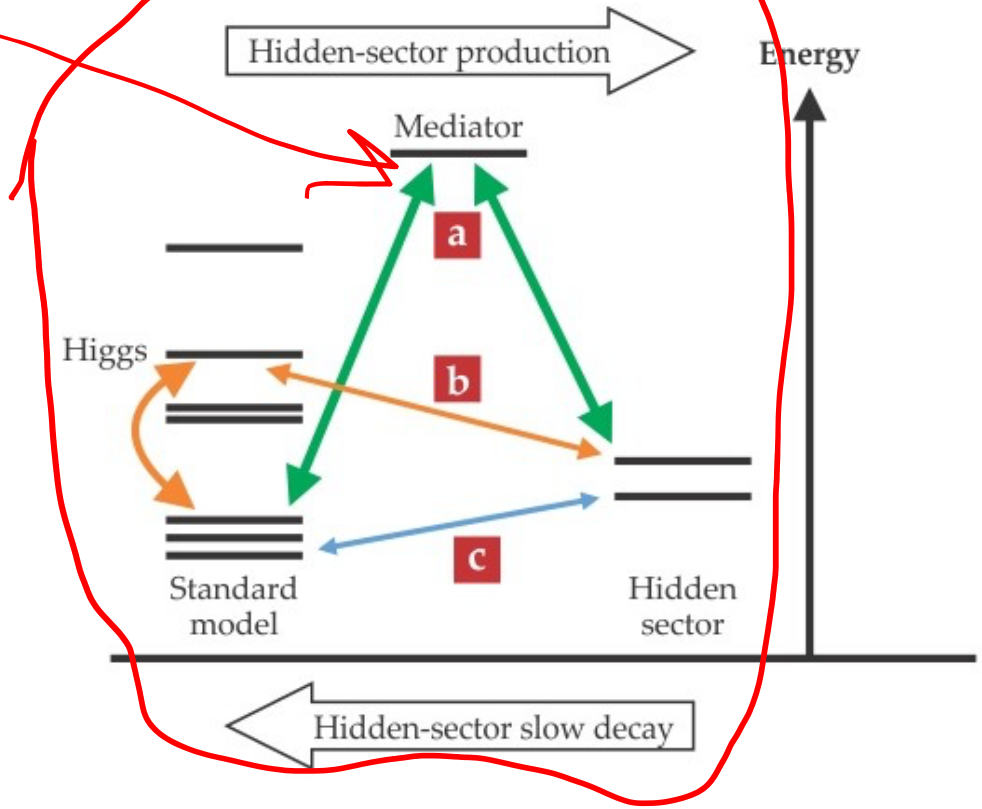
https://physicstoday.scitation.org/doi/10.1063/PT.3.3594

# Portals

# a) Heavy Mediator




GAUGED



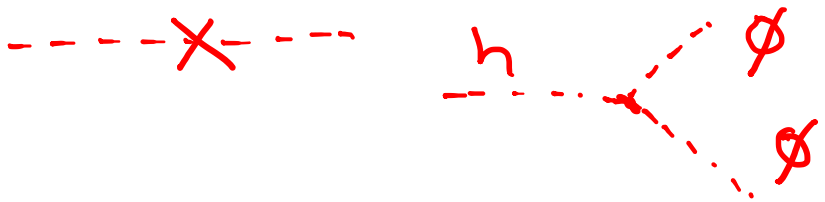

BROKEN SYMMETRY

# b) Higgs Portal

$\mathcal{L} \subset |H|^2 |\phi|^2$

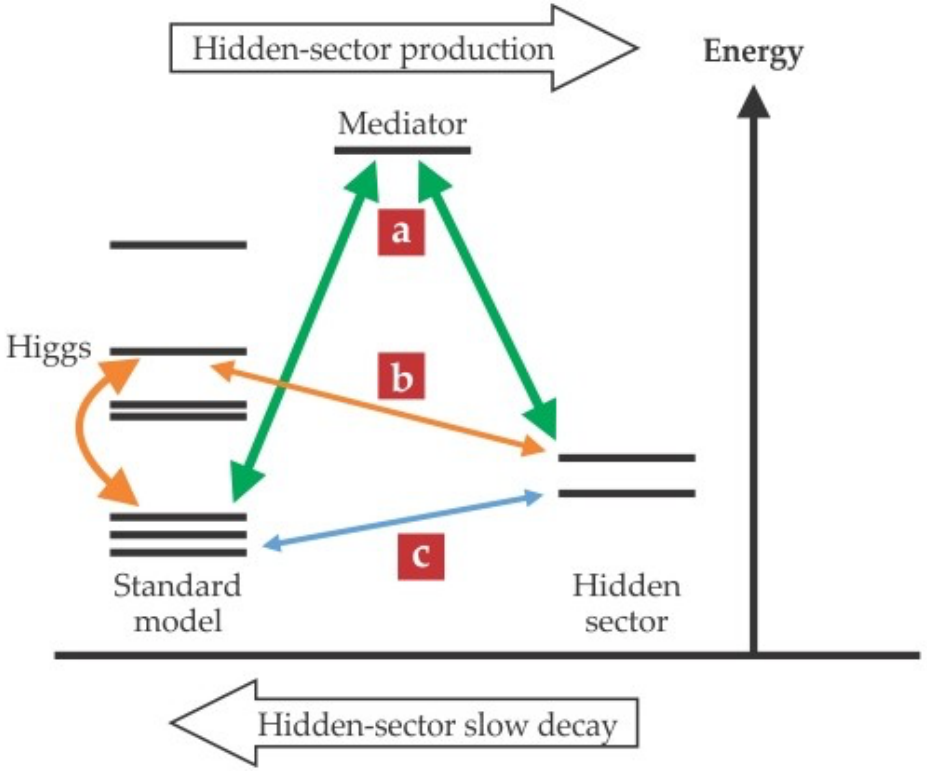
if $\langle \phi \rangle \neq 0$:

- $h\phi$, $h\phi^2$, $h^2\phi$, $h^2\phi^2$



if $\langle \phi \rangle = 0$:

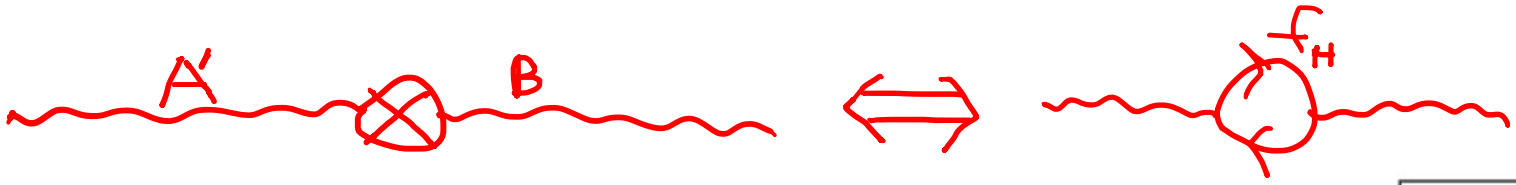
- $h\phi^2$, $h^2\phi^2$






B. Patt and F. Wilczek, "Higgs-field portal into hidden sectors," arXiv:hep-ph/0605188 [hep-ph].

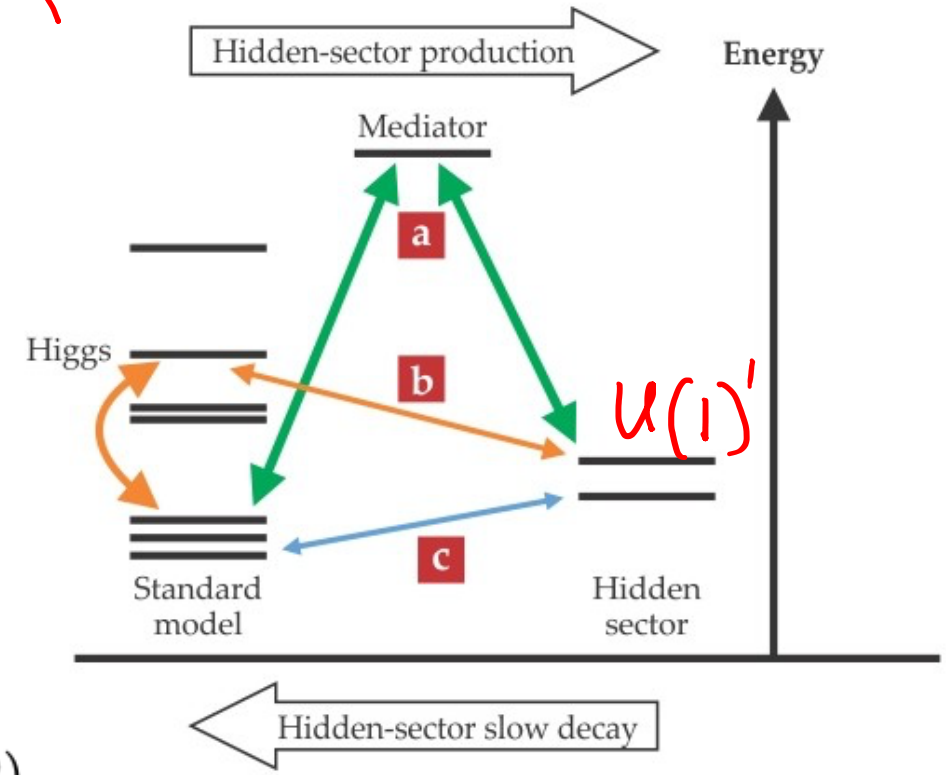
# c) Vector Portal / Kinetic Mixing




$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\not{\partial} + ie'\not{A}' + iM_{\rm mCP}\right)\psi - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}. \quad (1)$$

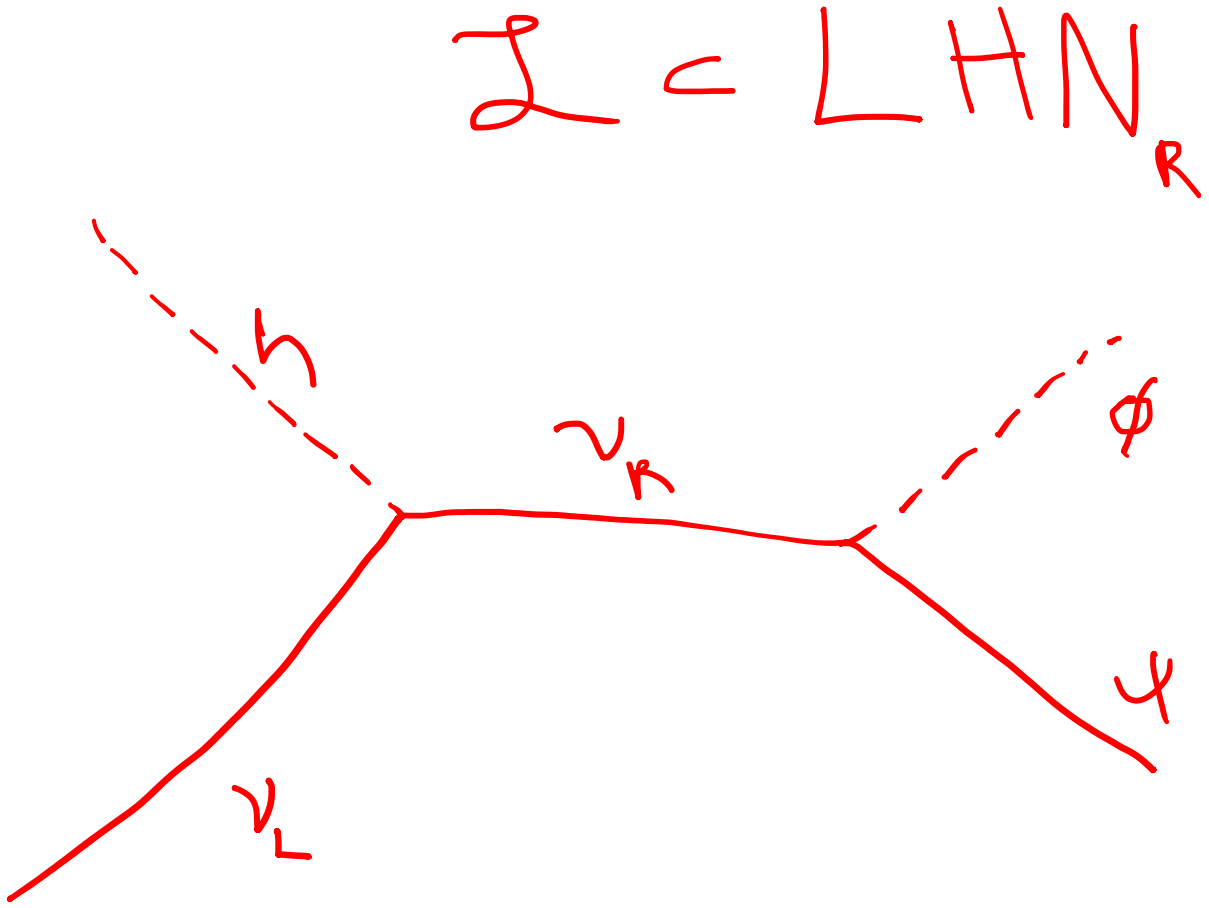
$$A'_\mu \to A'_\mu + \kappa B_\mu$$

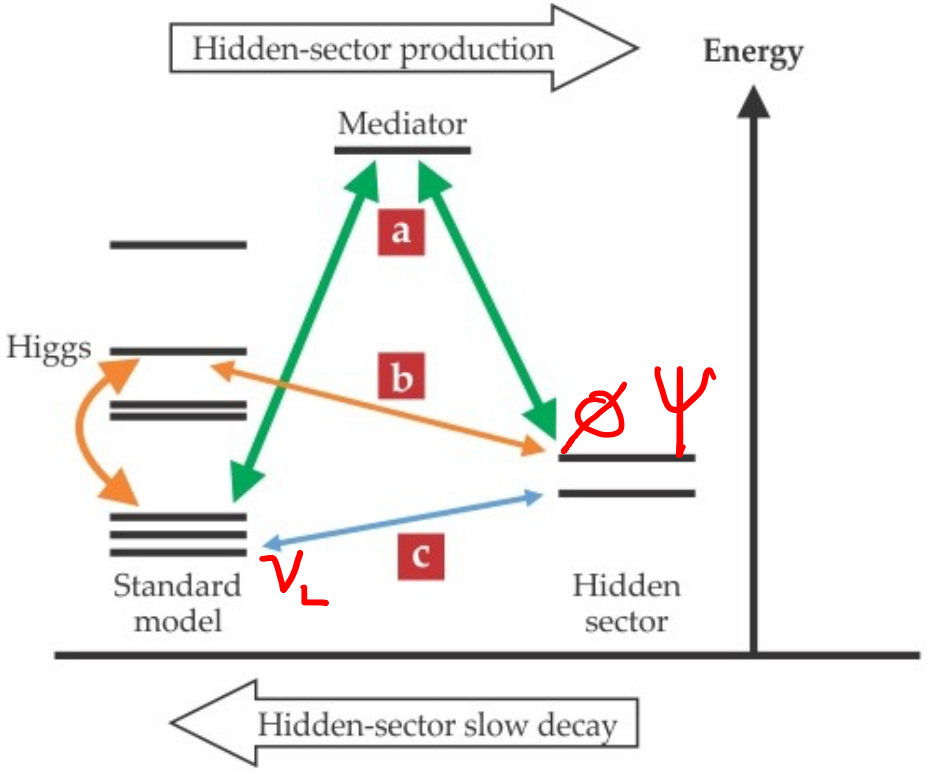
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\not{\partial} + ie'\not{A}' - i\kappa e'\not{B} + iM_{\rm mCP}\right)\psi. \quad (2)$$


B. Holdom, "Two U(1)'s and Epsilon Charge Shifts," Phys. Lett. 166B (1986) 196–198.
A. Haas, C. S. Hill, E. Izaguirre, and I. Yavin, Phys. Lett. B746, 117 (2015), arXiv:1410.6816 [hep-ph]

# extra) Neutrino Portals



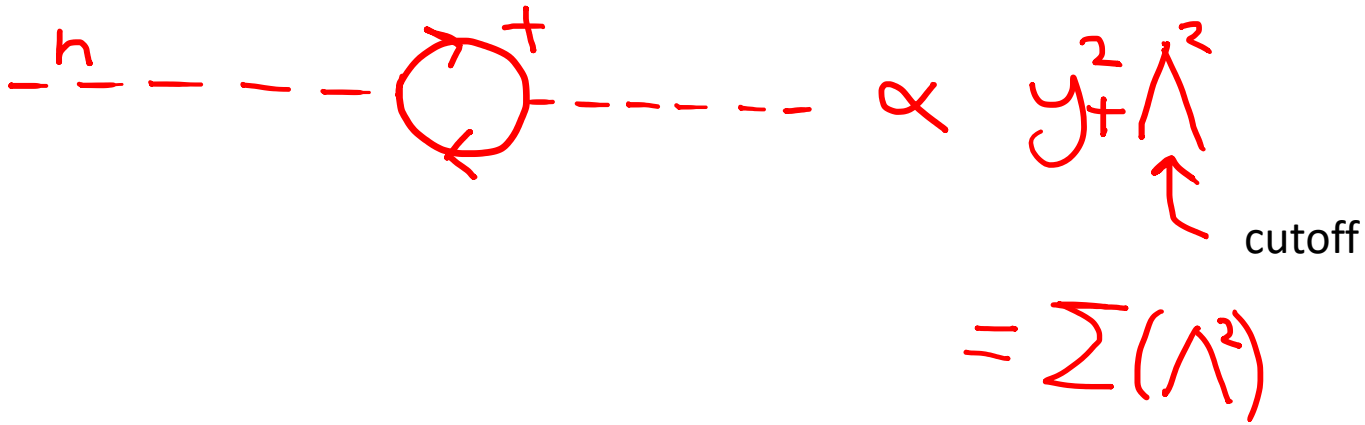



A. Falkowski, J. Juknevich, and J. Shelton, "Dark Matter Through the Neutrino Portal," arXiv:0908.1790 [hep-ph]

# Theoretical Motivations

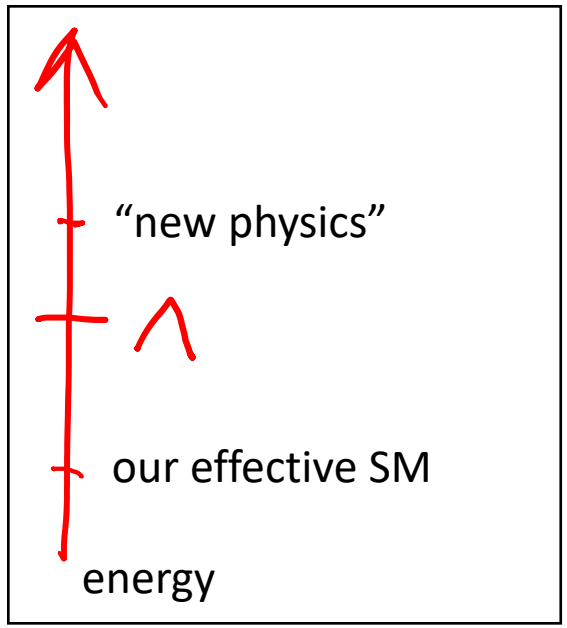
# Hierarchy Problem:

*Why is the Higgs mass so small ??*




$$\propto y_t^2 \Lambda^2$$

$$= \Sigma(\Lambda^2)$$




$$m_p^2 = m_R^2 - \Sigma(\Lambda^2)$$

fine tuning

Fine tuning surpasses 10% at cutoff scales around 1.5TeV, which is when we would expect new physics to kick in.

Expect, for a natural theory: $m_p \sim \Lambda$

$\Rightarrow$

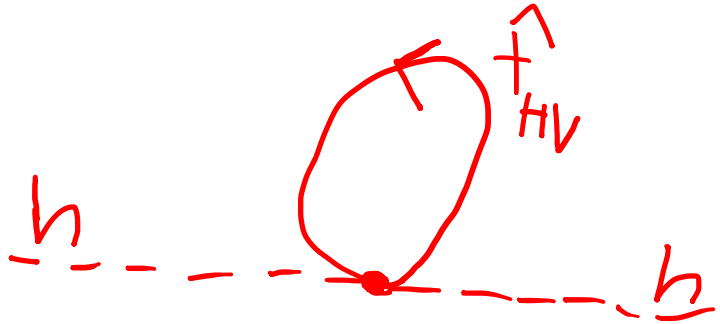
Solution ? SYMMETRY

# Twin Higgs Model

$$\mathcal{L} = \mathcal{L}_{SM} + \hat{\mathcal{L}}_{HV}$$

$$(SM \sim HV)$$

$$\phi_{SM} \xleftrightarrow{\mathbb{Z}_2} \phi_{HV}$$



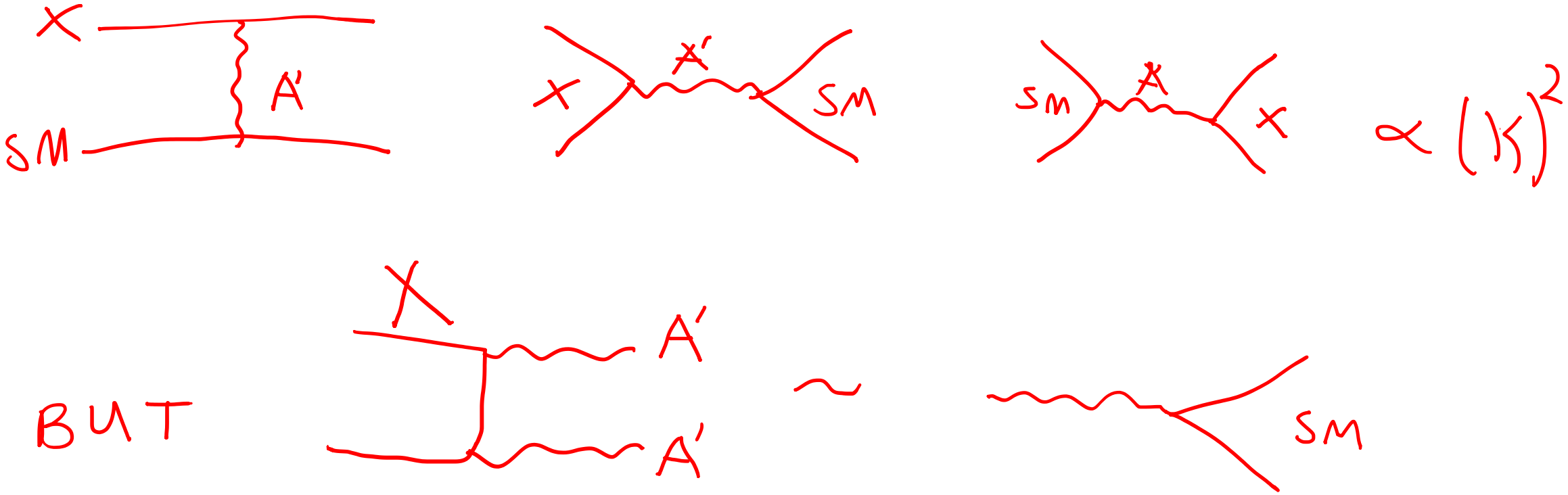

$$\delta m_h^2 \propto y_t^2 - \hat{y}_t^2$$



Z. Chacko, H.-S. Goh, and R. Harnik, The Twin Higgs: Natural electroweak breaking from mirror symmetry, Phys. Rev. Lett. 96 (2006) 231802, [hep-ph/0506256]

# Dark Matter Candidates

- Single Fermion, $\chi$ gauged under new U(1), $A'$
- Most like standard WIMP model






L. Randall and W. L. Xu, Searching for Dark Photon Dark Matter with Cosmic Ray Antideuterons, 1910.14669.

# Dark Matter Candidates

- Dark SU(N) x U(1), two flavours: $u', d'$
- Confining scale, hadronise: $m' < \Lambda'$

STABLE: $u'\bar{d}'$, $\bar{u}'d'$ (no 'weak' force)

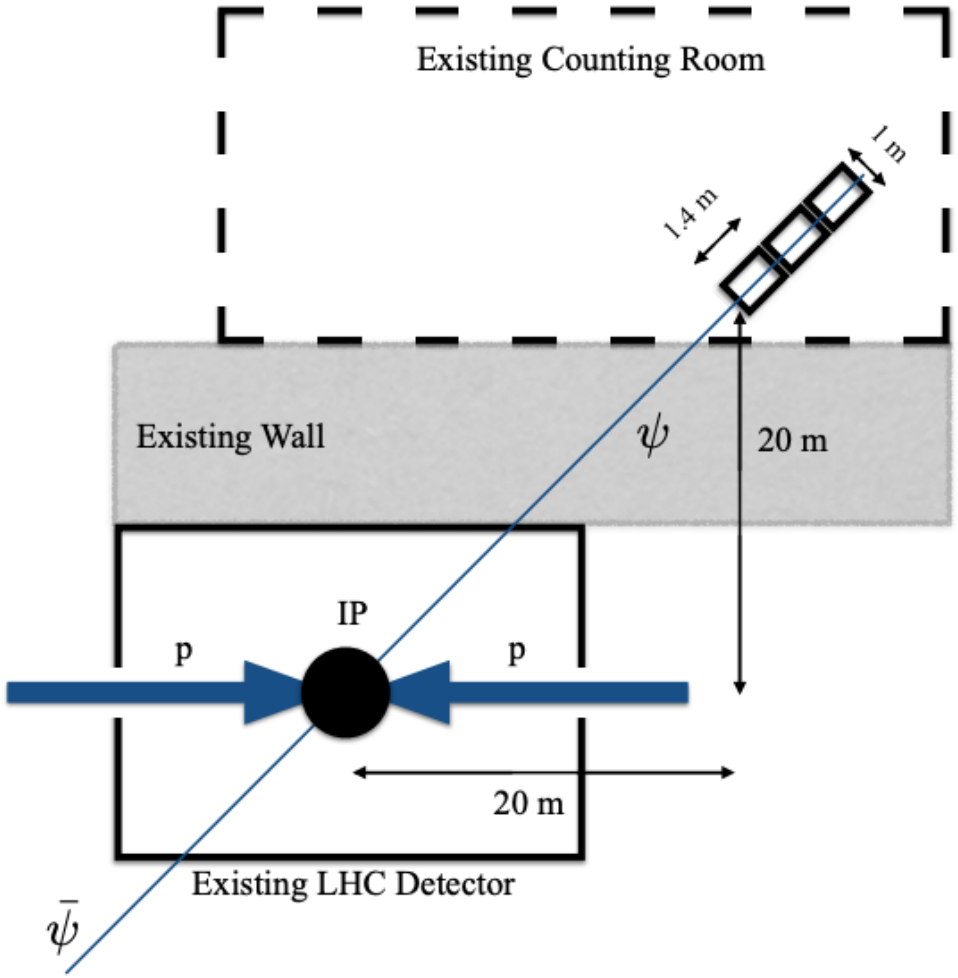
UNSTABLE: $u'\bar{u}'$, $d'\bar{d}'$




M. J. Strassler and K. M. Zurek, Phys. Lett. B 651 (2007) 374 [arXiv:hep-ph/0604261]

# Experimental Constraints and Searches

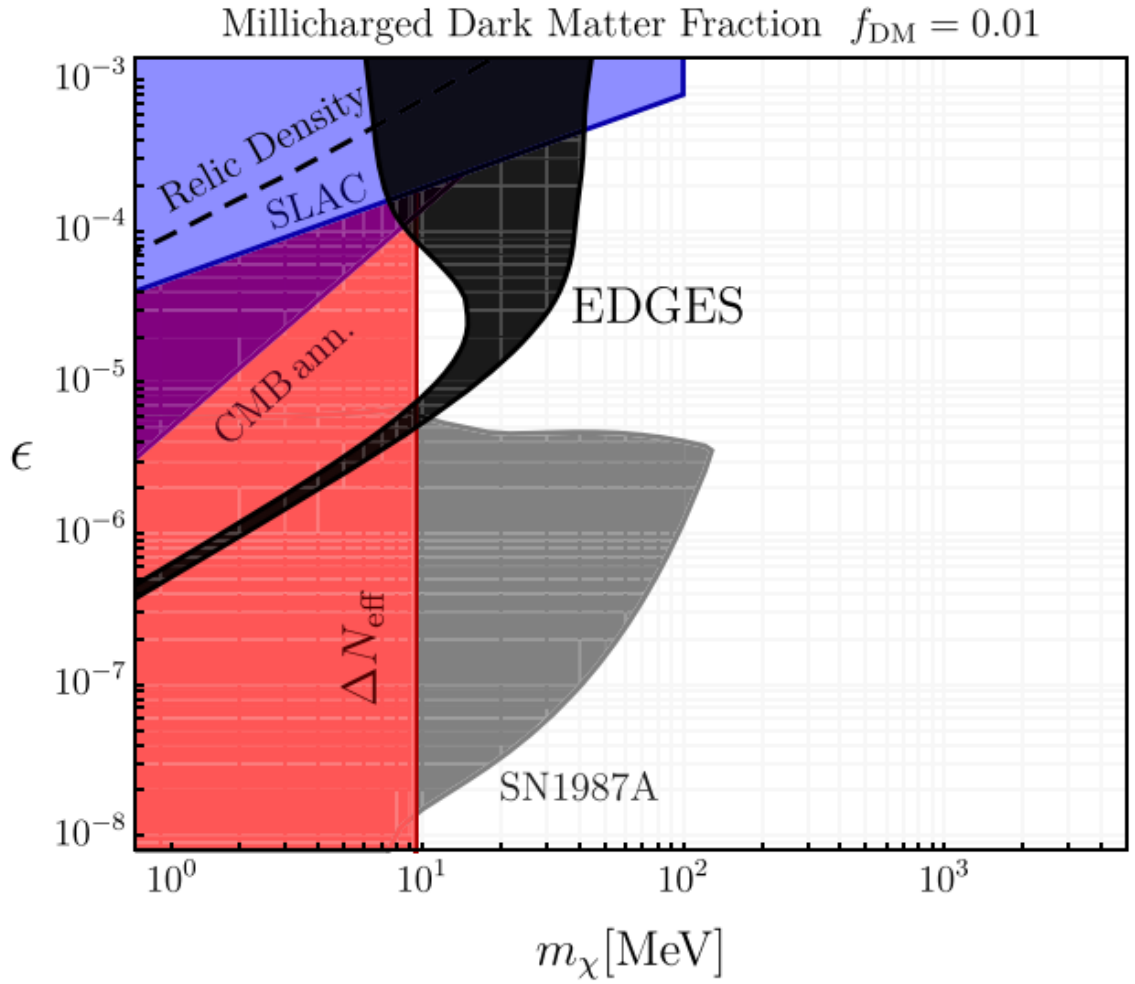
# MilliQan






A. Haas, C. S. Hill, E. Izaguirre, and I. Yavin, Phys. Lett. B746, 117 (2015), arXiv:1410.6816 [hep-ph]

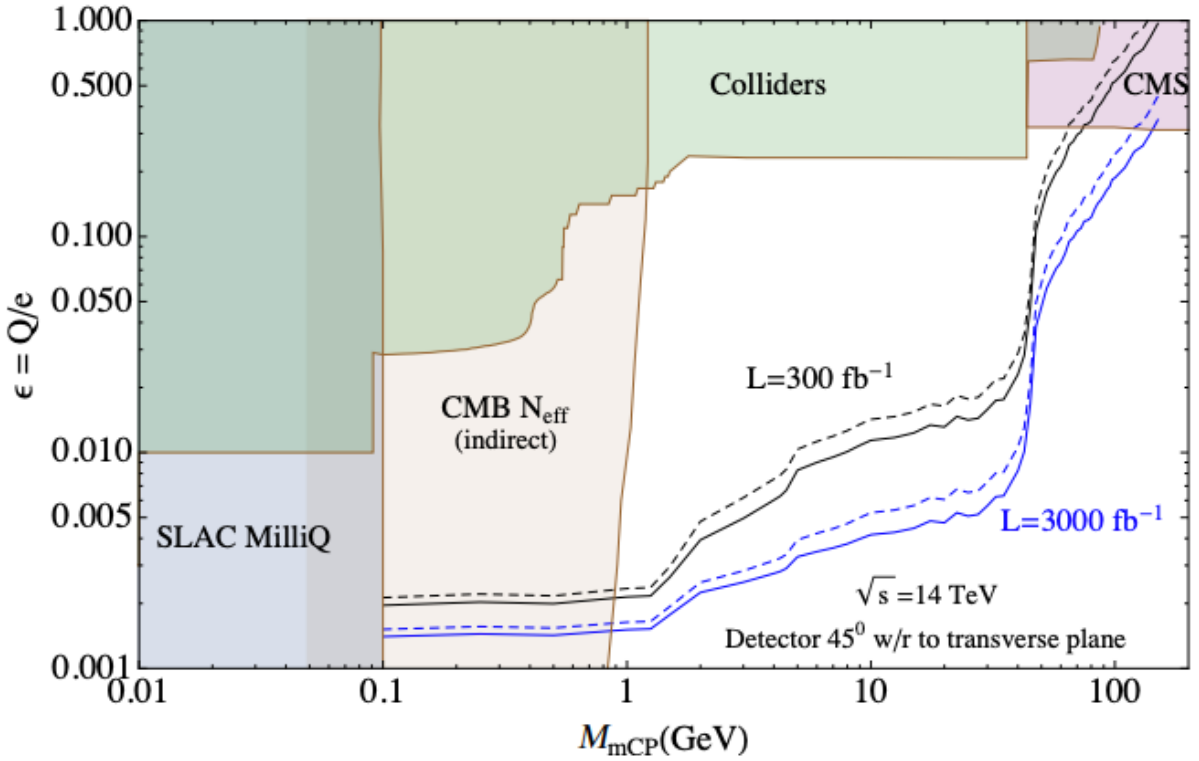
# Observed Constraints






A. Berlin, D. Hooper, G. Krnjaic, and S. D. McDermott, Phys. Rev. Lett. 121, 011102 (2018).

# Observed Constraints






A. Haas, C. S. Hill, E. Izaguirre, and I. Yavin, Phys. Lett. B746, 117 (2015), arXiv:1410.6816 [hep-ph]

# Dark Showers

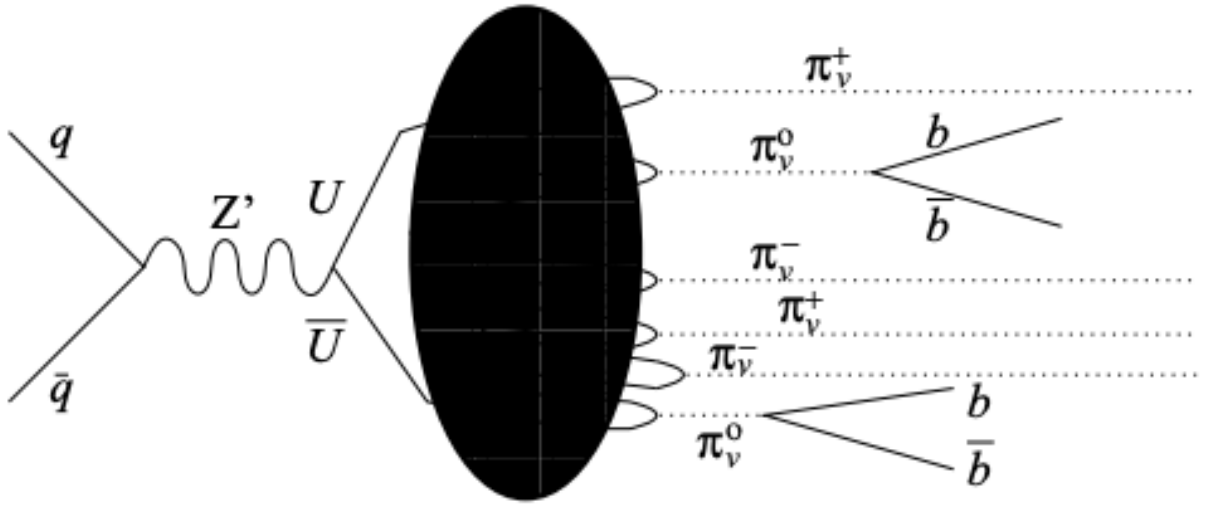
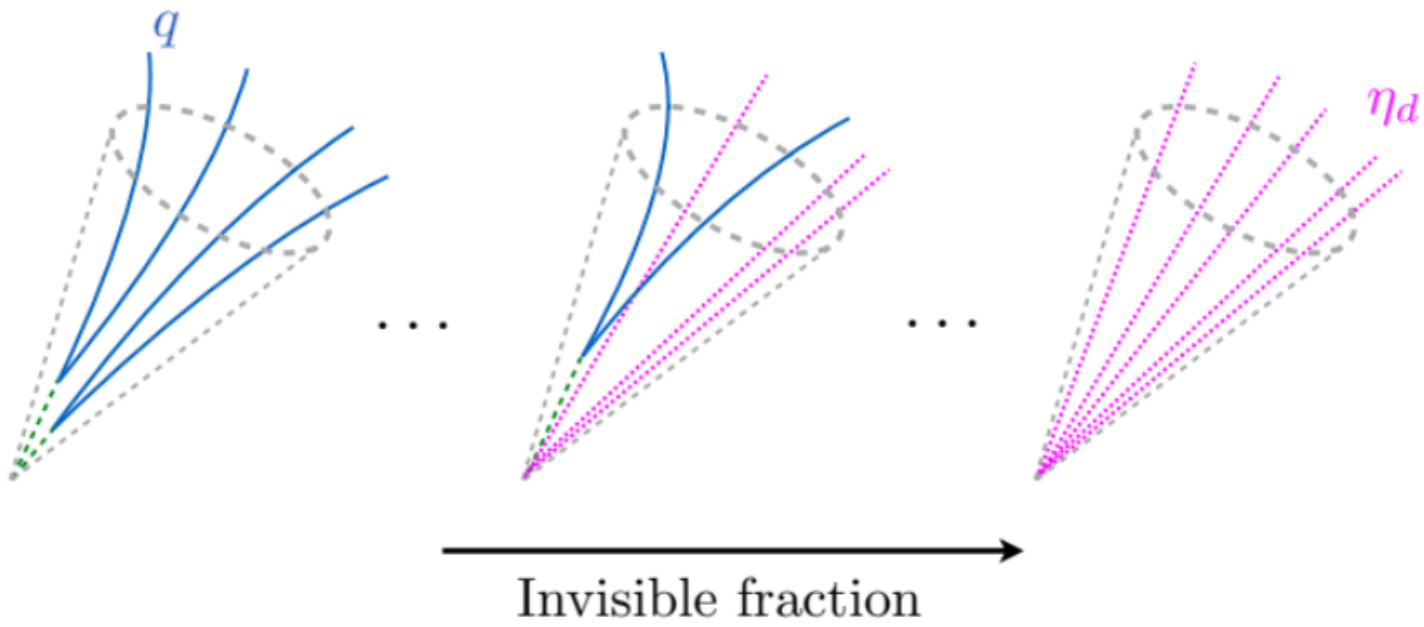



FIG. 3: A possible event in the two-light-flavor regime; note $\pi_v^{\pm}$ is electrically neutral and invisible.



M. J. Strassler and K. M. Zurek, Phys. Lett. B 651 (2007) 374 [arXiv:hep-ph/0604261]

# Semi-visible Jets




Jet + Missing Energy searches
(missed by current minimum angular separation conditions)



T. Cohen, M. Lisanti, and H. K. Lou, Semivisible Jets: Dark Matter Undercover at the LHC, Phys. Rev. Lett. 115.17 (2015) p. 171804, arXiv: 1503.00009 [hep-ph]

# Invisible Higgs Decays

**Table 11.9:** Summary of the channels searched for and the corresponding 95% CL limits from ATLAS and CMS on the branching fraction for the Higgs boson decay to invisible particles assuming a SM Higgs boson production cross section. The results in parentheses are the expected exclusions.

| | ATLAS (Run 1) | ATLAS (Run 2) | CMS (Run 1) | CMS (Run 2) |
|---|---|---|---|---|
| ggF (monojet); $H \to$ inv. | – | – | 67 (71) % | 66 (59)% |
| VBF; $H \to$ inv. | 28 (31) % | 37 (28) % | 57 (40) % | 33 (25) % |
| ZH; $Z \to \ell^+\ell^-$; $H \to$ inv. | 75 (62)% | 67 (39) % | 75 (91) % | 40 (42)% |
| VH; $Z, W \to jj$; $H \to$ inv. | 78 (86)% | 83 (58) % | – | 50 (48)% |
| ZH; $Z \to b\bar{b}$; $H \to$ inv. | – | – | 182 (189)% | – |
| Combination | 25 (27)% | 38 (21)% | – | 26 (20) % |
| Run 1 & 2 Combination | 26 (17)% | | 19 (15)% | |
| $t\bar{t}H$; $H \to$ inv. | – | – | – | 46 (48)% |



M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018) and 2019 update

# Invisible Higgs Decays (ATLAS)

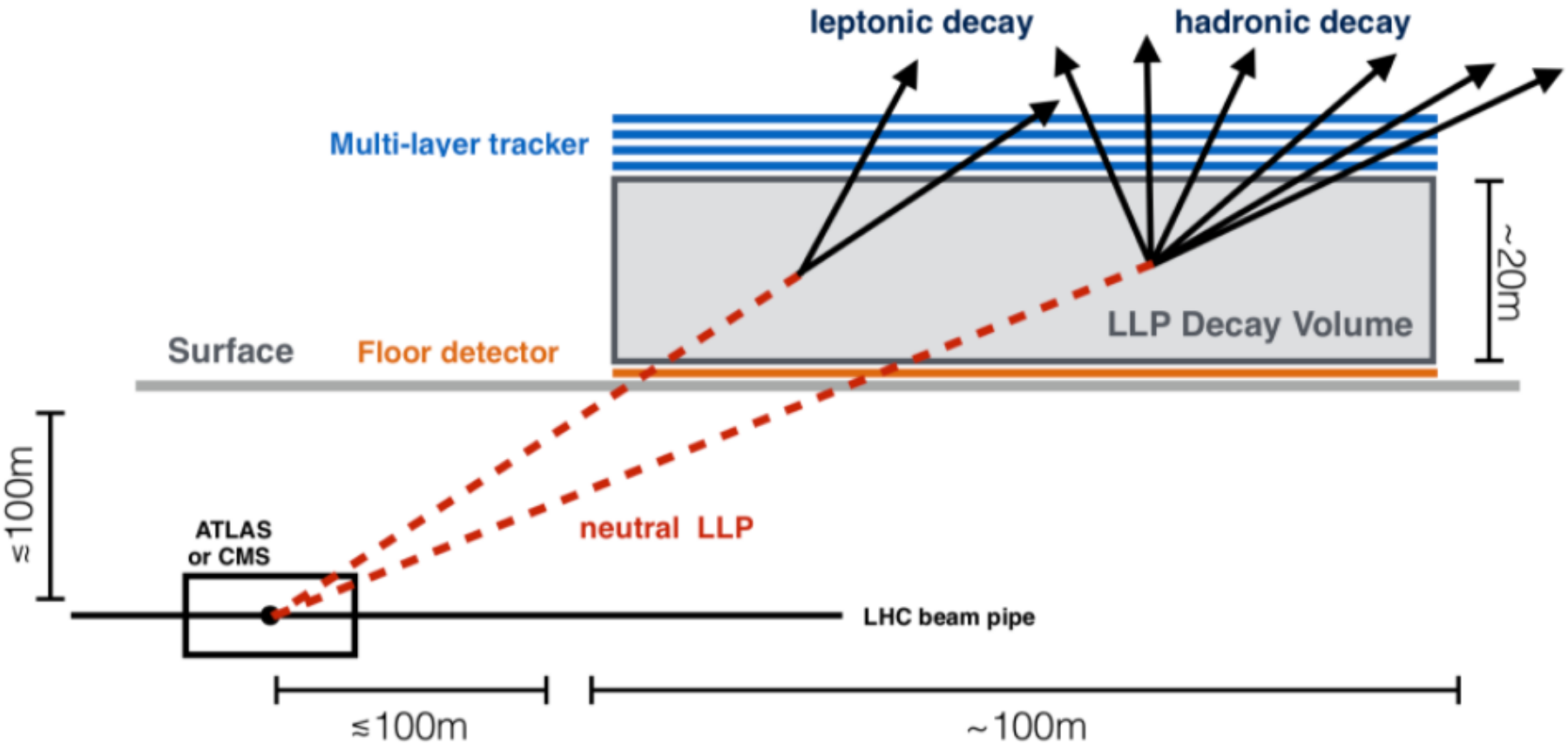
Table 1: Observed and expected upper limits on $\mathcal{B}_{H\to\text{inv}}$ at 95% CL from direct searches for invisible decays of the 125 GeV Higgs boson and statistical combinations. Also given are the observed $p$-values under the SM hypothesis.

| Analysis | $\sqrt{s}$ | Int. luminosity | Observed | Expected | $p_{\text{SM}}$-value | Reference |
|---|---|---|---|---|---|---|
| Run 2 VBF | 13 TeV | 36.1 fb$^{-1}$ | 0.37 | $0.28^{+0.11}_{-0.08}$ | 0.19 | [36] |
| Run 2 $Z(\text{lep})H$ | 13 TeV | 36.1 fb$^{-1}$ | 0.67 | $0.39^{+0.17}_{-0.11}$ | 0.06 | [37] |
| Run 2 $V(\text{had})H$ | 13 TeV | 36.1 fb$^{-1}$ | 0.83 | $0.58^{+0.23}_{-0.16}$ | 0.12 | [38] |
| Run 2 Comb. | 13 TeV | 36.1 fb$^{-1}$ | 0.38 | $0.21^{+0.08}_{-0.06}$ | 0.03 | this Letter |
| Run 1 Comb. | 7, 8 TeV | 4.7, 20.3 fb$^{-1}$ | 0.25 | $0.27^{+0.10}_{-0.08}$ | — | [35] |
| Run 1+2 Comb. | 7, 8, 13 TeV | 4.7, 20.3, 36.1 fb$^{-1}$ | 0.26 | $0.17^{+0.07}_{-0.05}$ | 0.10 | this Letter |



M. Aaboud et al. (ATLAS Collaboration), Combination of Searches for Invisible Higgs Boson Decays with the ATLAS Experiment, Phys. Rev. Lett. 122, 231801 (2019).

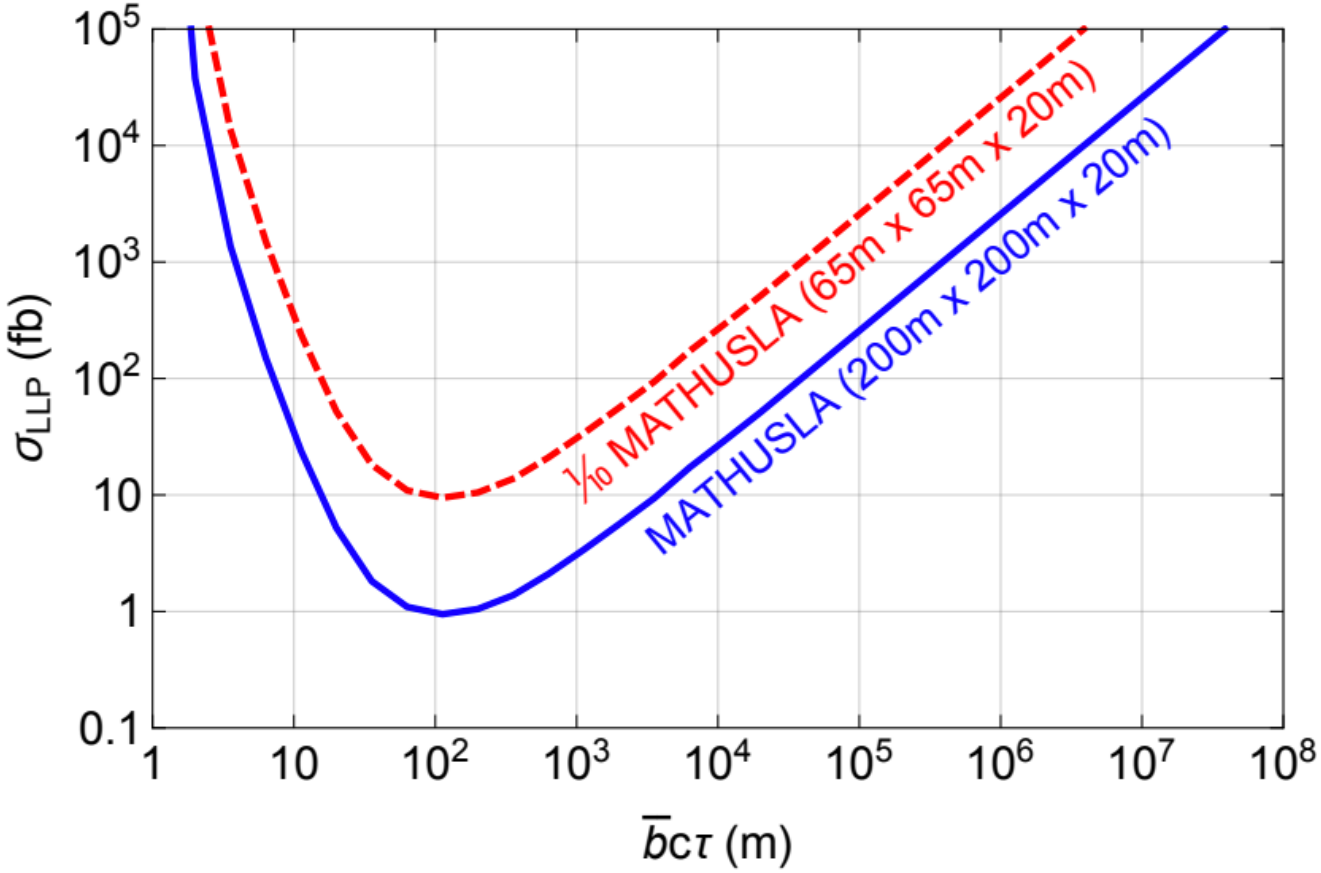
# MATHUSLA






D. Curtin et al., (2018), arXiv:1806.07396 [hep-ph].

# MATHUSLA


$10^5$
$10^4$
$10^3$
$10^2$
10
1
0.1
$\sigma_{LLP}$ (fb)
1
10
$10^2$
$10^3$
$10^4$
$10^5$
$10^6$
$10^7$
$10^8$
$\bar{b}c\tau$ (m)
1/10 MATHUSLA (65m x 65m x 20m)
MATHUSLA (200m x 200m x 20m)

# Thank you !

Questions ?