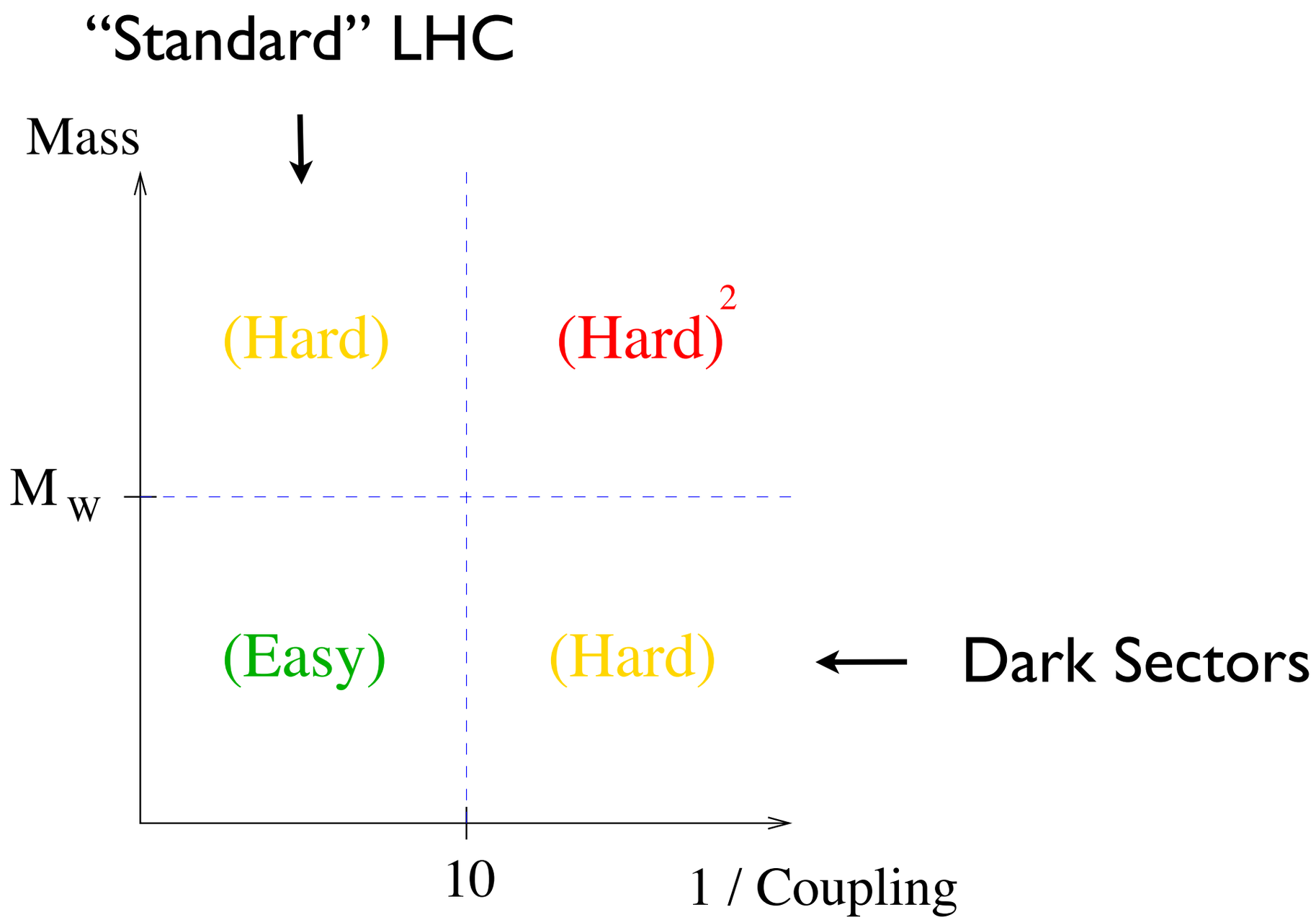
Higgs Connections to Dark Vectors

David E. Morrissey

November 8, 2016

Exotic Higgs Decays @ SLAC

Searching for New Phenomena



Portals to Dark Physics

- Three nice ways for new dark* physics to couple to us:

1. Vector Portal
   X^μ = dark (Abelian) vector

$$\epsilon X_{\mu\nu} F^{\mu\nu}$$

2. Higgs Portal
   Φ = dark scalar

$$\kappa \, |\Phi|^2 |H|^2$$

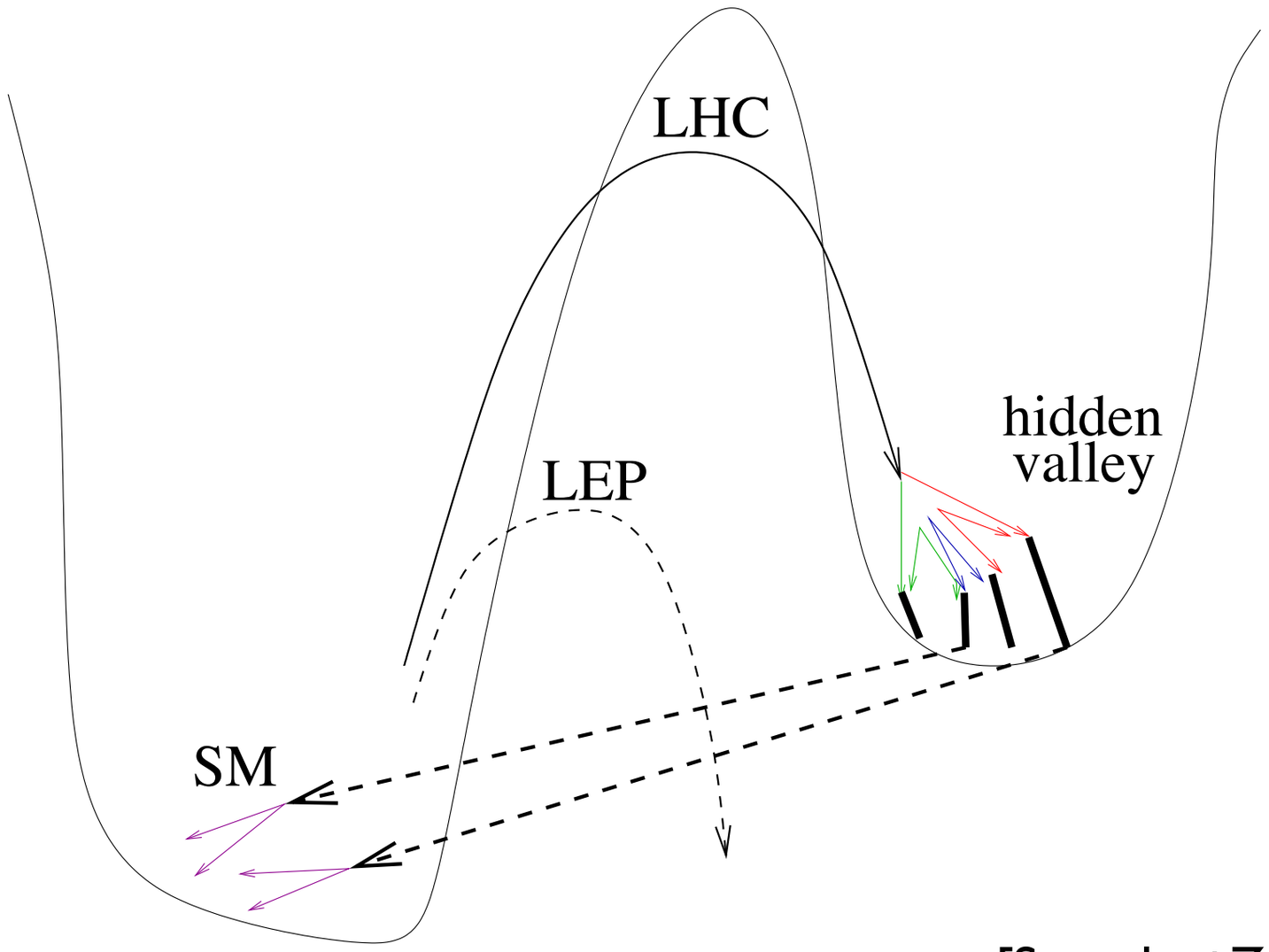
3. Neutrino Portal
   N = dark (singlet) fermion

$$\lambda \, N L \cdot H$$

* dark = hidden, may or may not be connected to dark matter

Another Portal: Hidden Valleys

- Massive connectors may also be accessed at the LHC:



[Strassler+Zurek 2006]

Another Portal: Hidden Valleys

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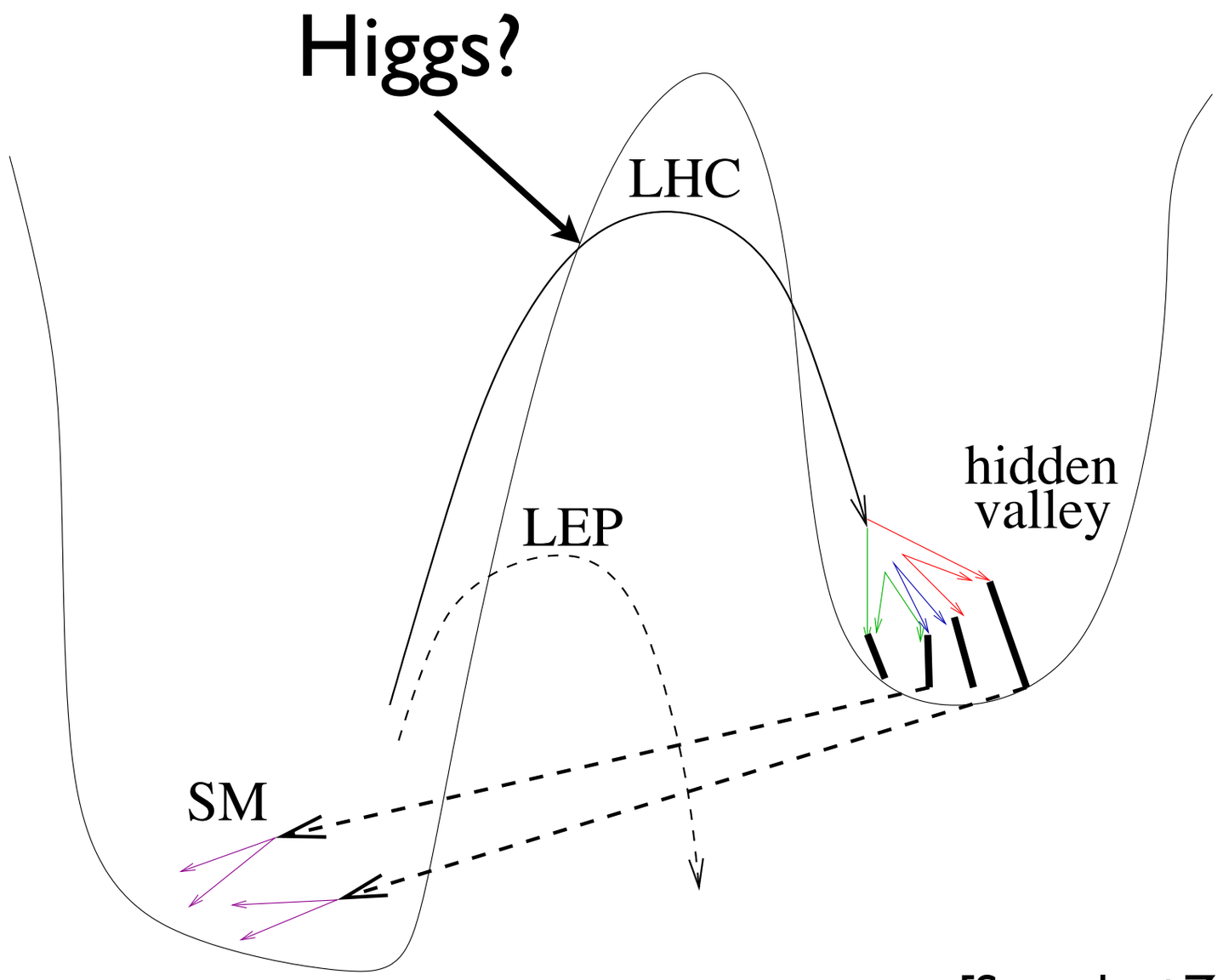
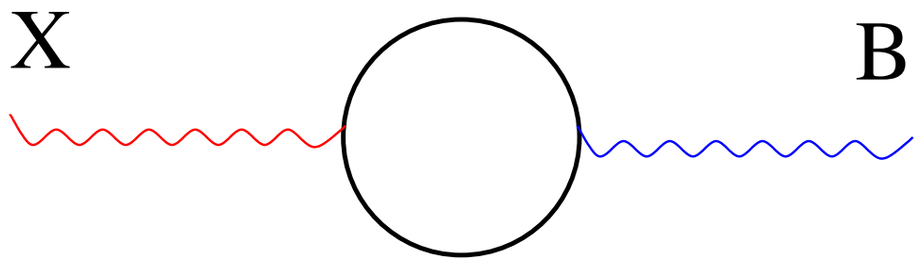


[Strassler+Zurek 2006]

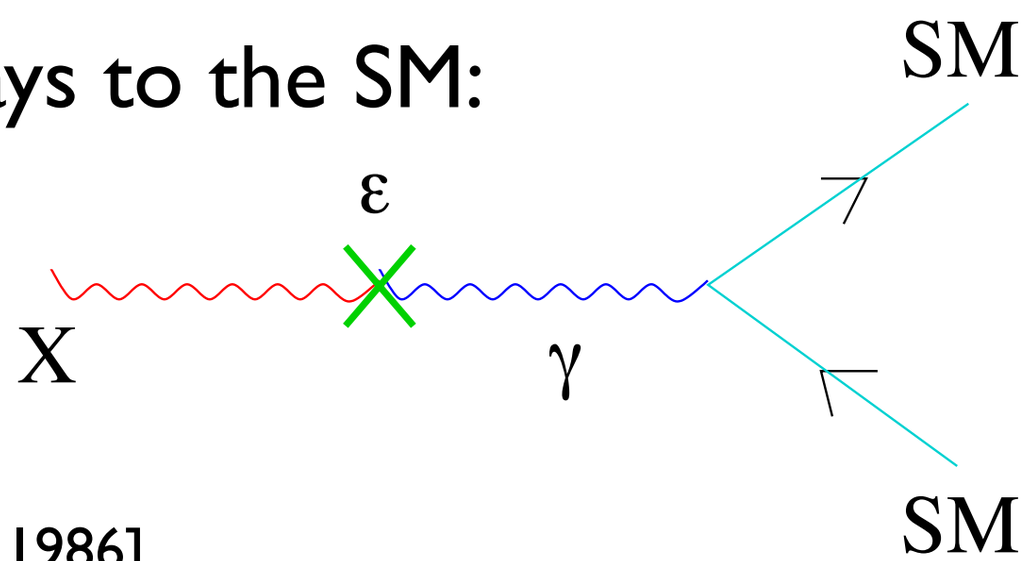
Vector Portal: ϵ

- Abelian dark vector X^μ:



$$\frac{\epsilon}{c_W} X_{\mu\nu} B^{\mu\nu} \rightarrow \epsilon X_{\mu\nu} F^{\mu\nu} - \epsilon\, t_W X_{\mu\nu} Z^{\mu\nu}$$

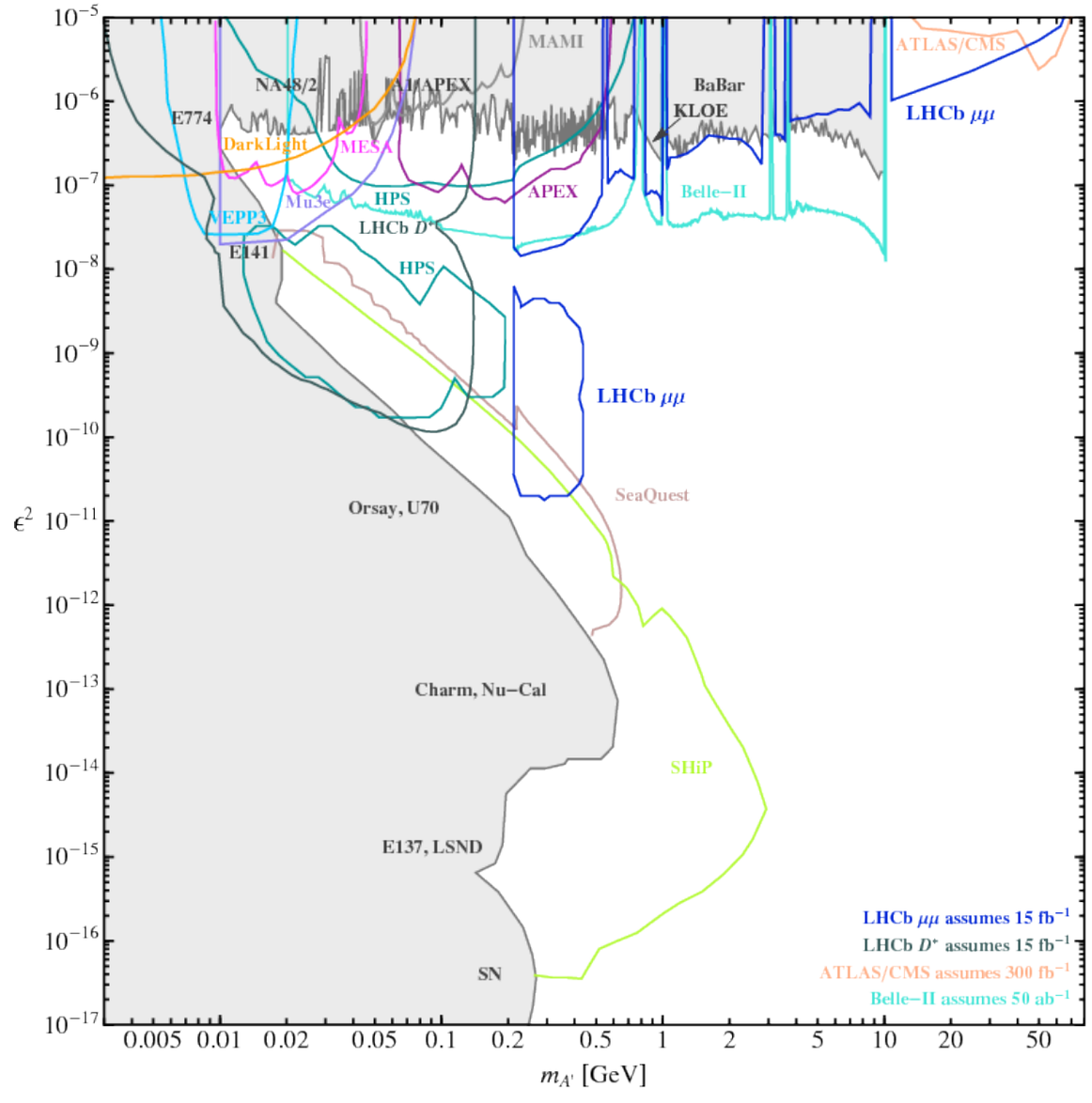
- Induces decays to the SM:



[Okun 1982; Holdom 1986]

Direct Vector Portal Limits

- Hidden vector X^μ, mass $m_x > 2m_e$, decays $X^\mu \to SM$:



[Bjorken, Essig, Schuster, Toro 2009; ...; Ilten *et al.* 2016]

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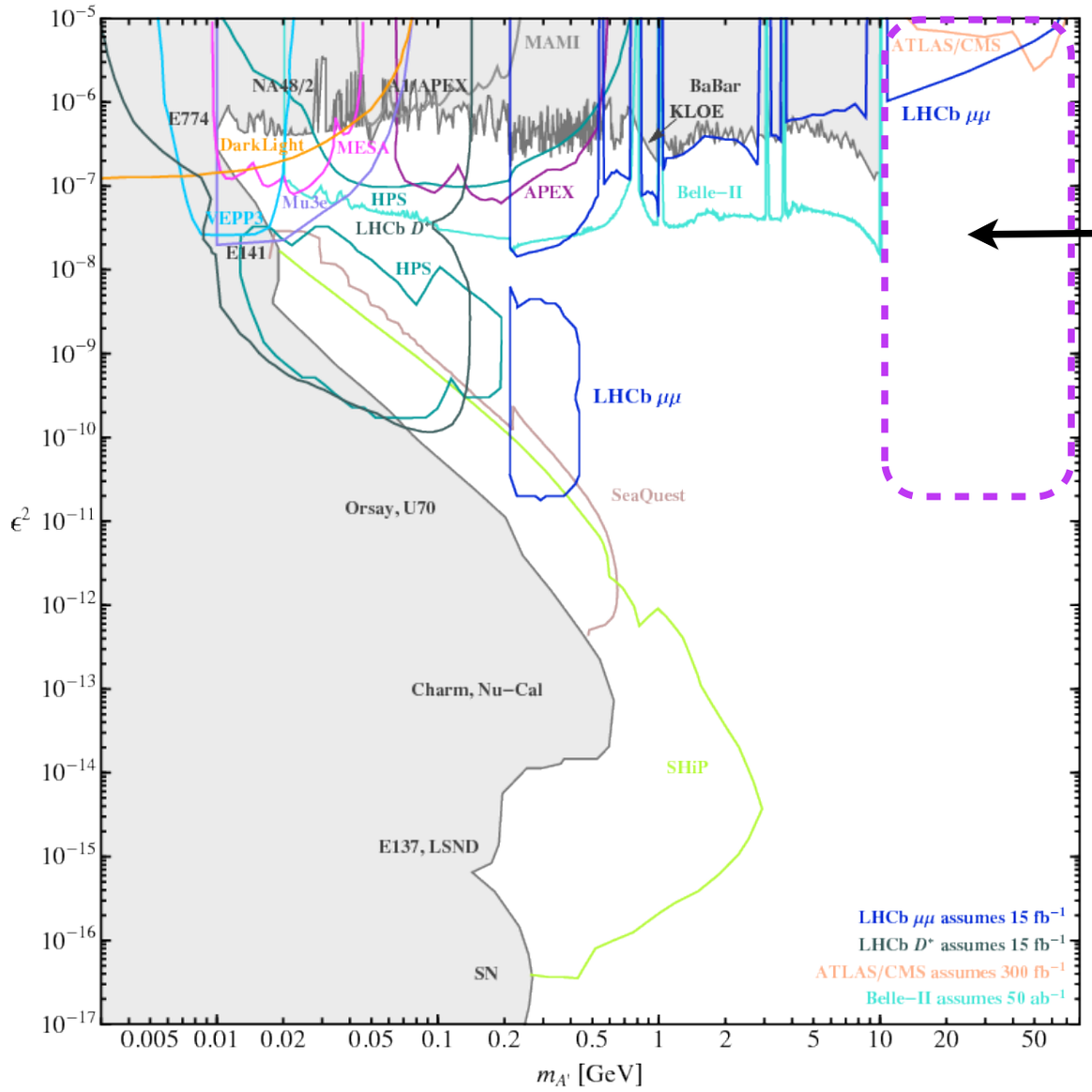
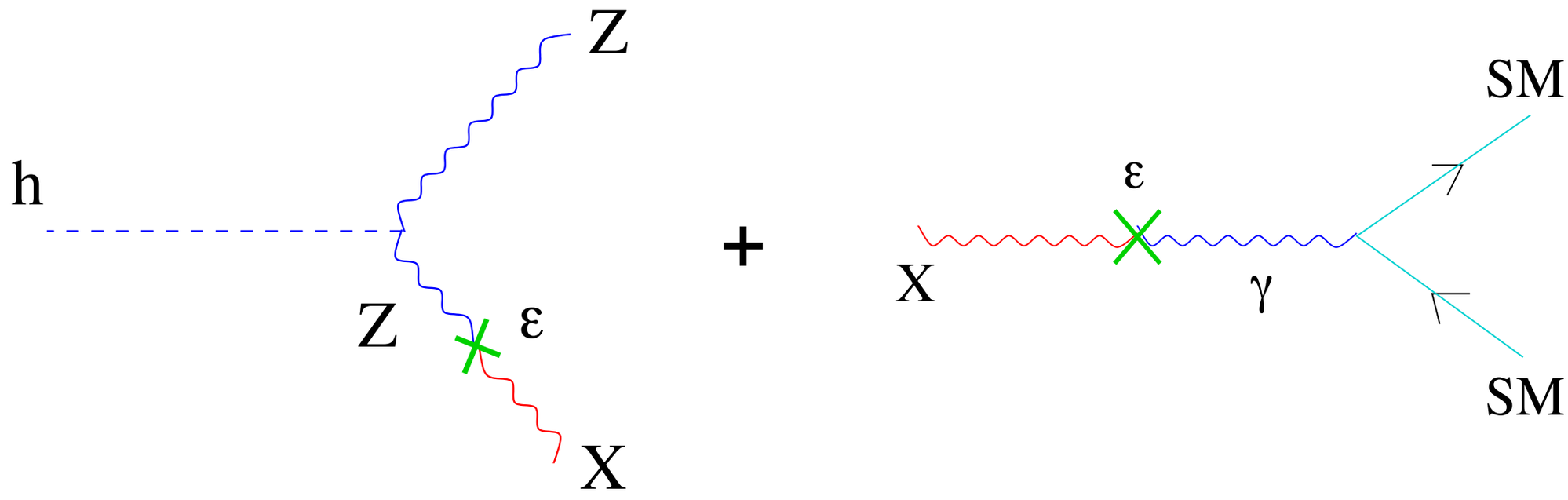


← Higgs?

[Bjorken, Essig, Schuster, Toro 2009; ...; Ilten *et al.* 2016]

Vector Portal and the Higgs

- Kinetic mixing also connects the dark vector to the Z.
- Higgs decay:



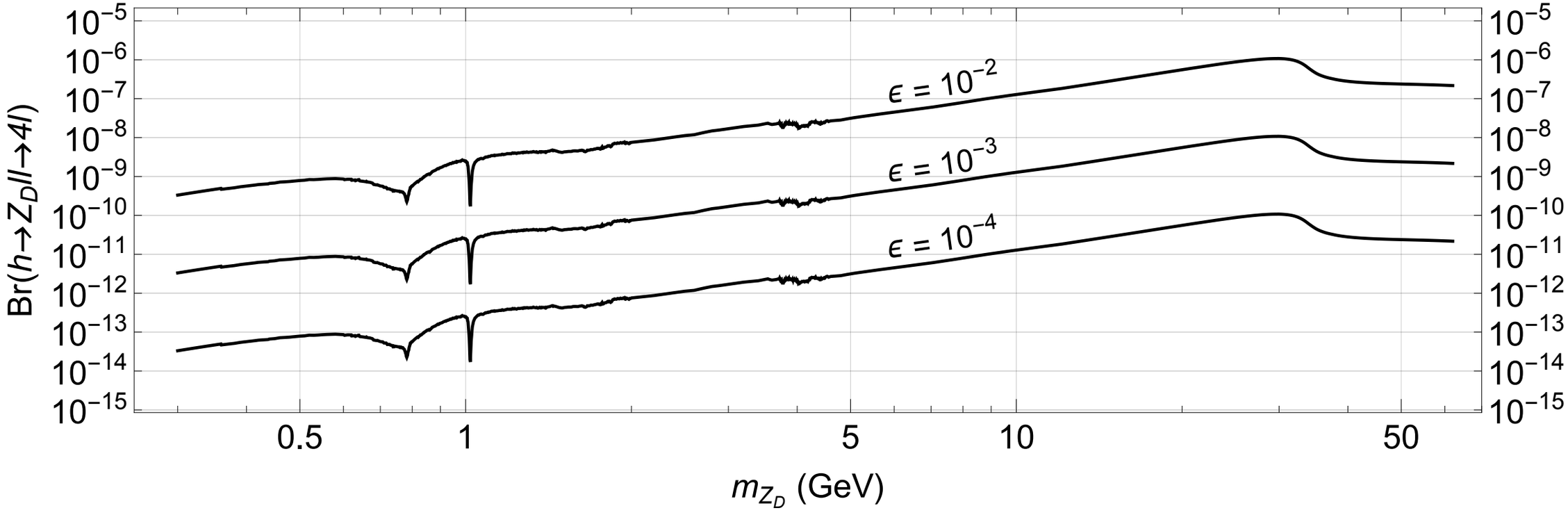
- Contributes to $h \to 4\ell$ when $X^\mu \to \ell\bar{\ell}$.

[Curtin *et al.* 2013; Falkowski+Vega-Morales 2014; Curtin *et al.* 2014]
[see also: Isidori, Manohar, Trott 2013]

Vector Portal and the Higgs

- Challenge:

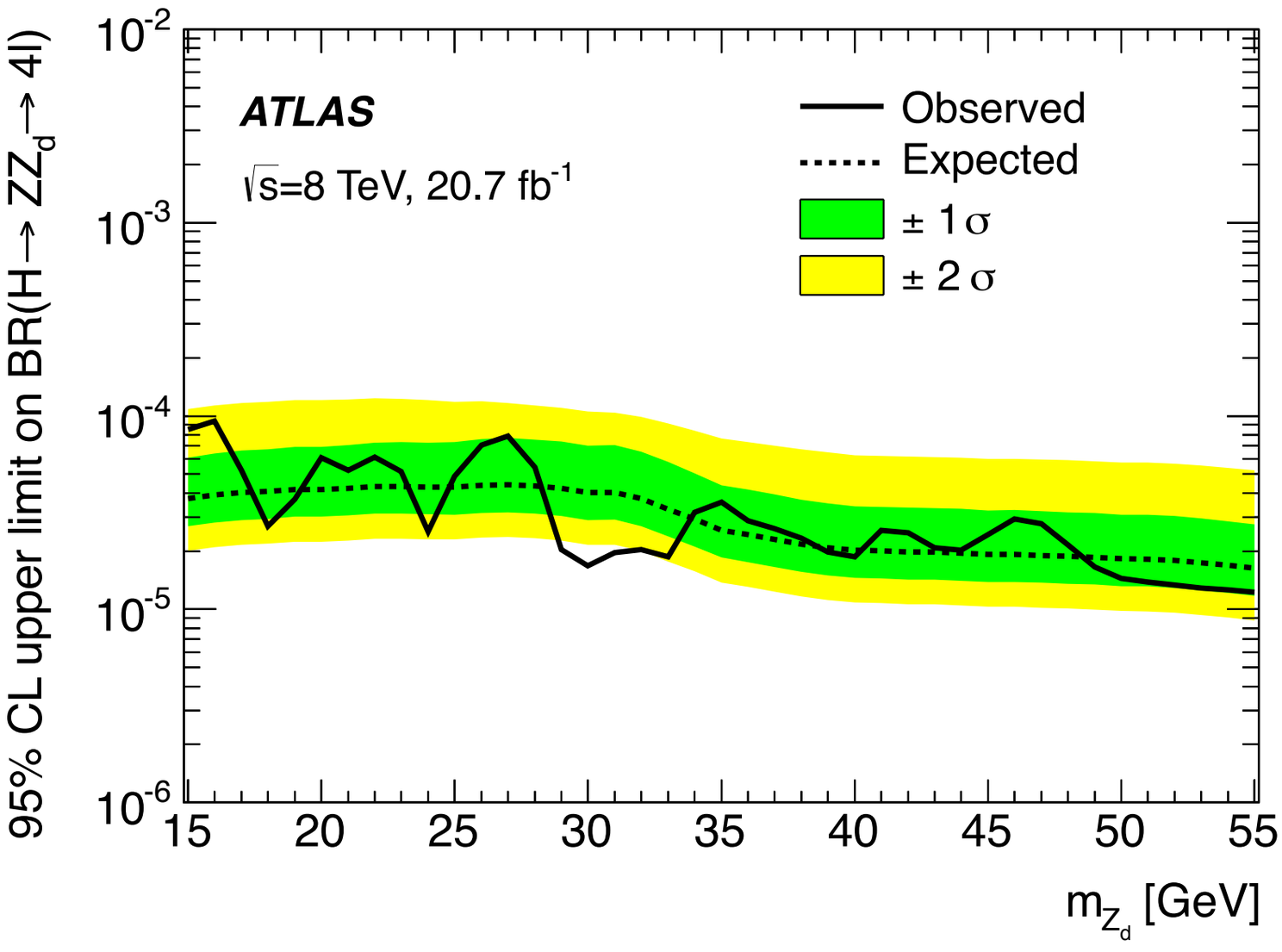
$$\mathrm{BR}(h \to XZ) \;\propto\; \epsilon^2 \left(\frac{m_x}{m_Z}\right)^2 \qquad (m_x \ll m_Z)$$



[Curtin, Essig, Gori, Shelton 2014]

Vector Portal and the Higgs

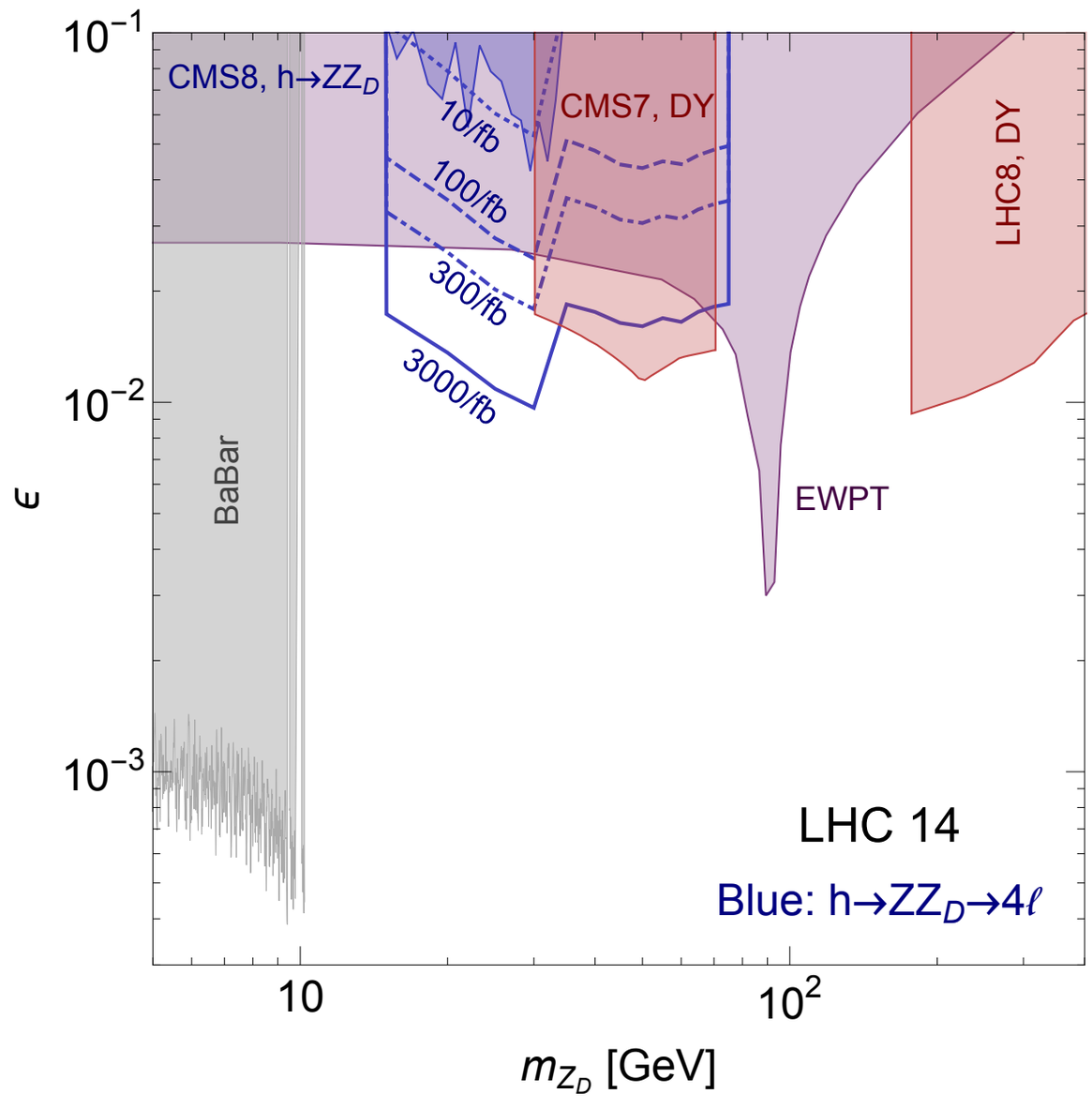
- ATLAS Search:



[ATLAS 2015]

Vector Portal and the Higgs

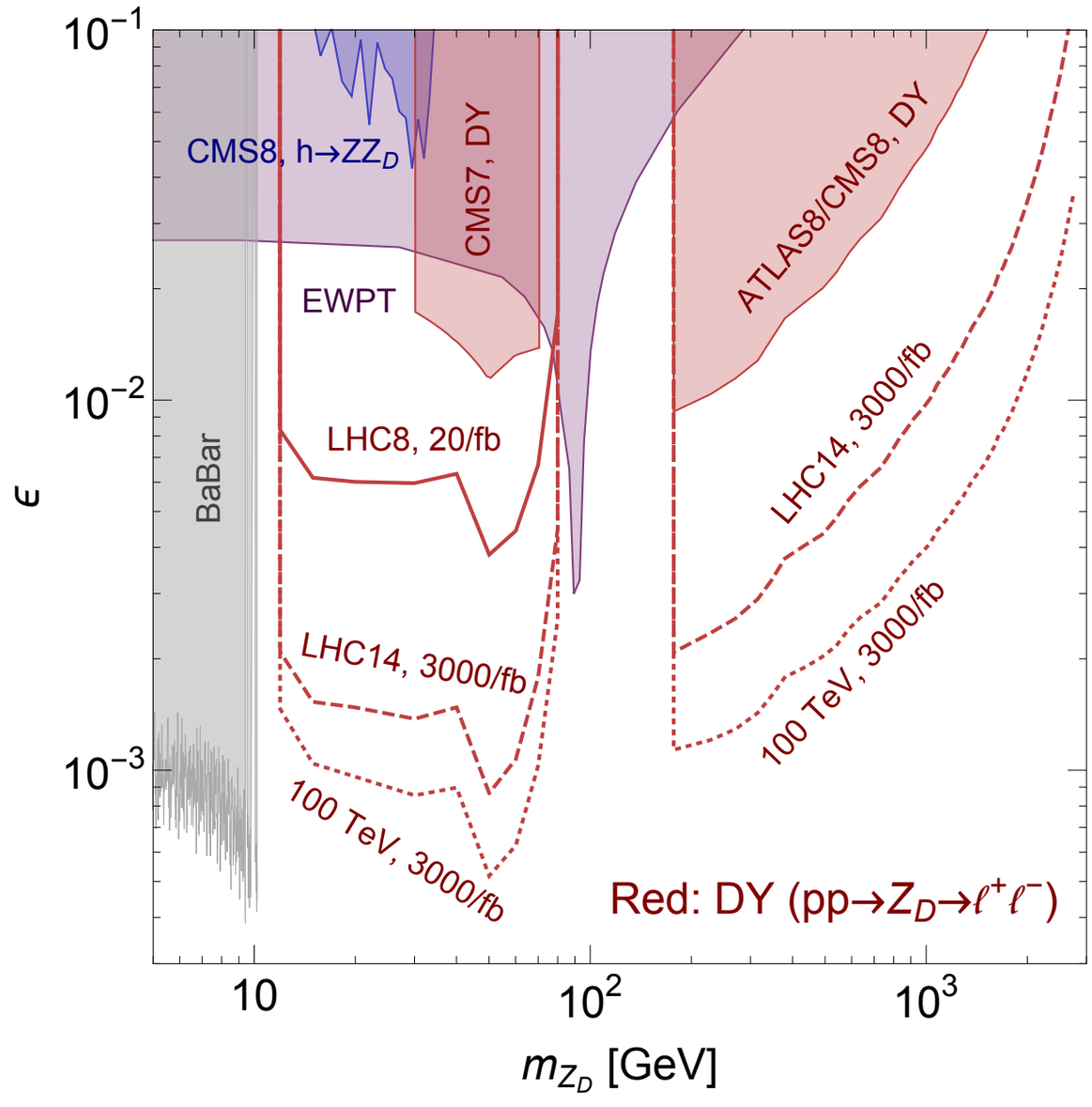
- LHC Reach:



[Curtin, Essig, Gori, Shelton 2014]

Vector Portal and the Higgs

- Drell-Yan $pp \to X \to \ell\ell$ usually does better:



[Curtin, Essig, Gori, Shelton 2014]

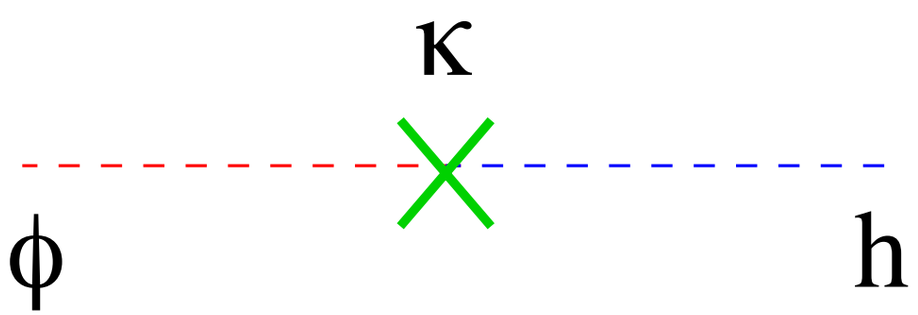
Higgs Portal (with Vector)

- Where does the X^μ mass come from?

  e.g. dark Higgs field: $\Phi(x) \to \eta + \phi(x)/\sqrt{2}$

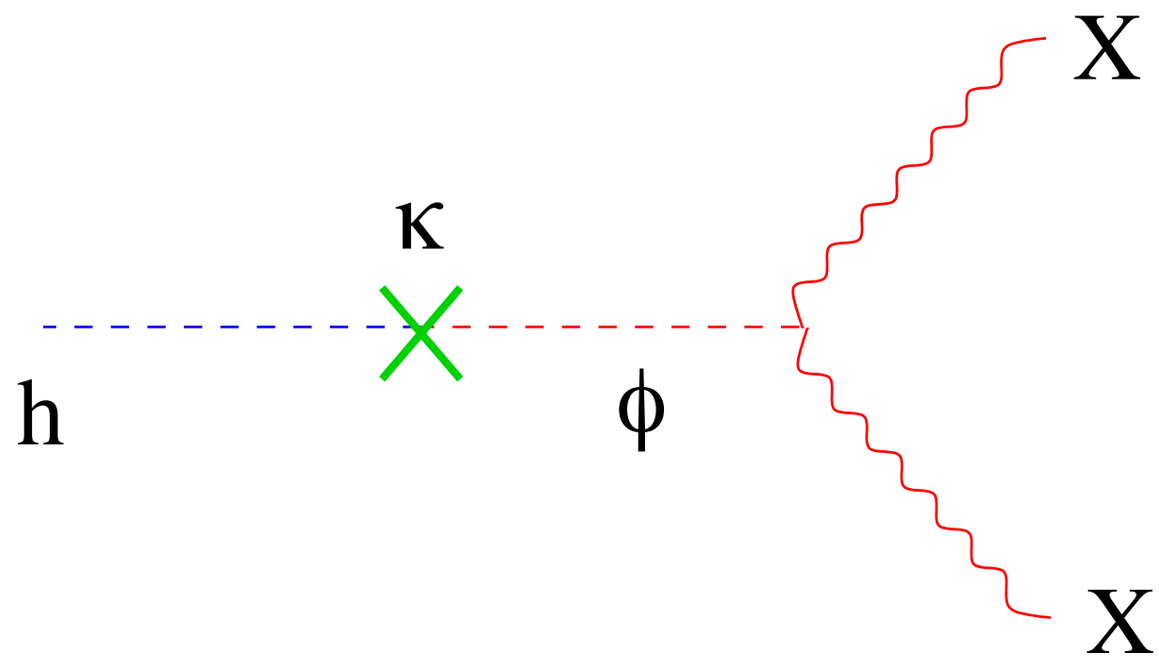
- Higgs portal coupling:

$$\kappa\,|\Phi|^2|H|^2 \;\to\; \kappa\left[\eta\,\phi + \sqrt{2}\phi^2\right] v\,h + \ldots$$



Higgs Portal (with Vector)

- Higgs portal induces new SM Higgs decay channels:

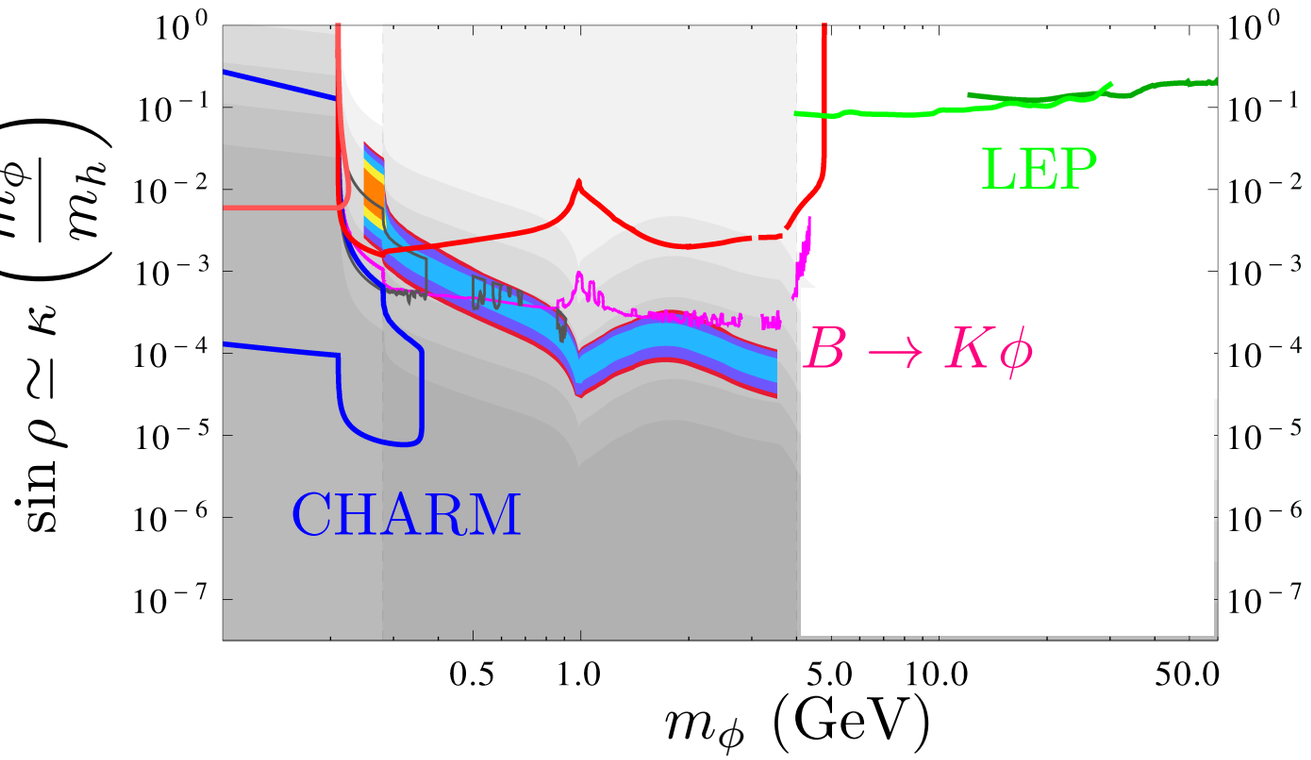


[Gopalakrishna, Jung, Wells 2008; ... ; Curtin *et al.* 2014]

- Contributes to $h \to 4\ell$ if $X^\mu \to \ell\bar{\ell}$.

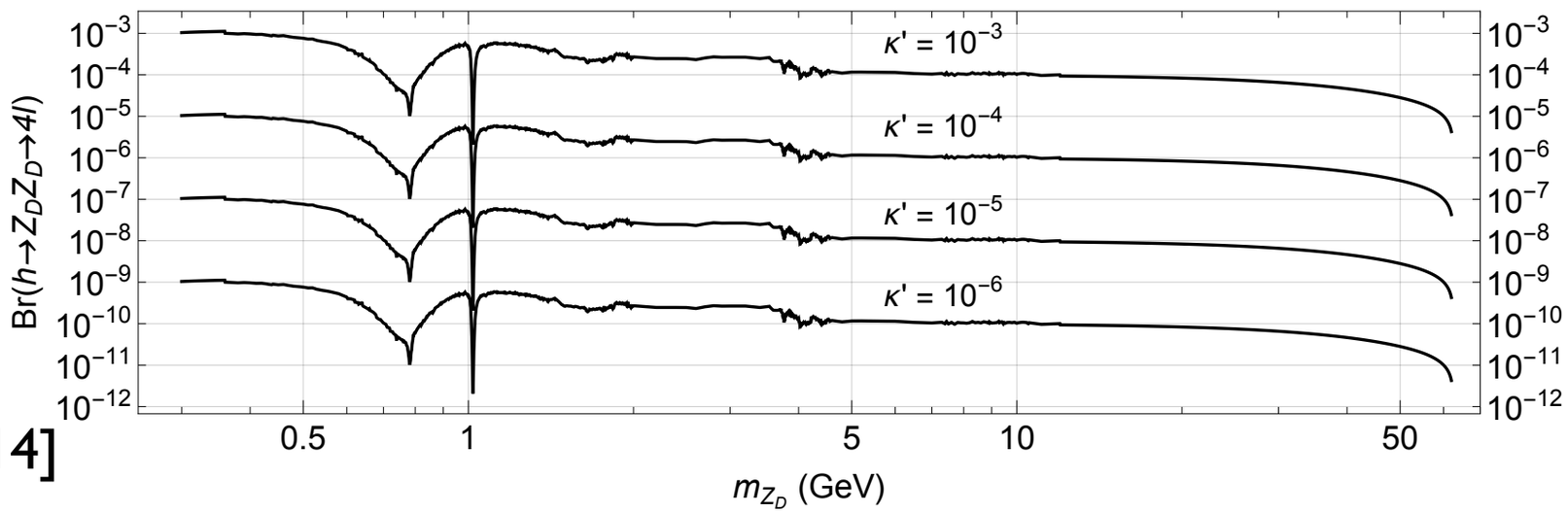
Higgs Portal (with Vector)

- Loosely constrained portal coupling allows large BR.



[Clarke 2015]

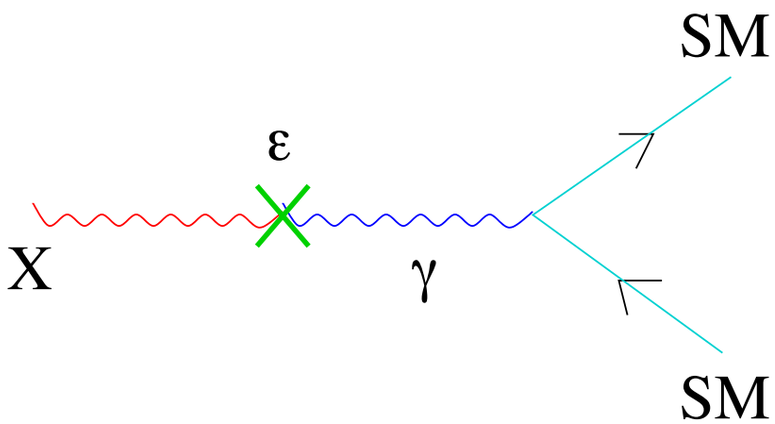
$(m_\phi < m_x)$

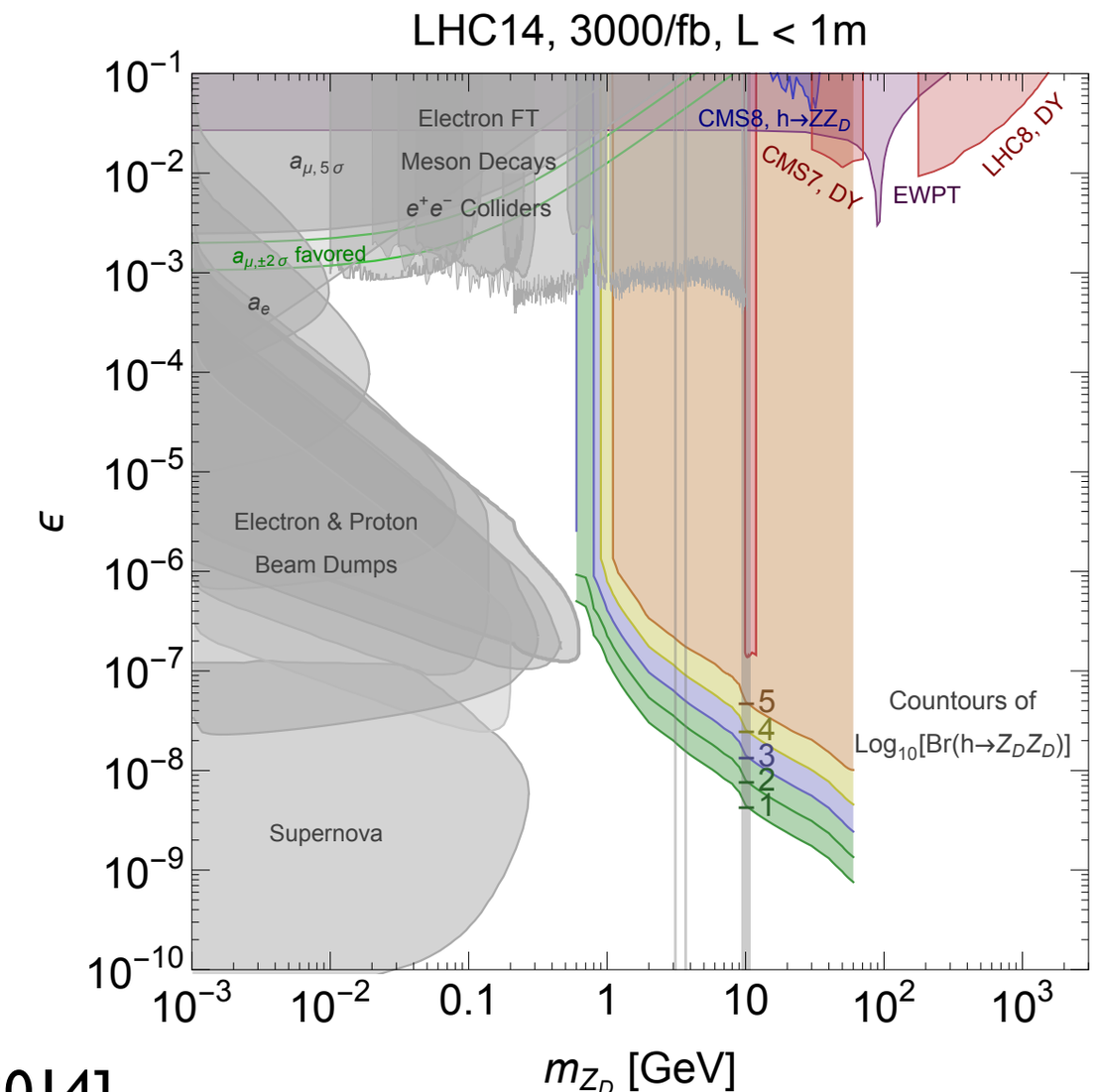


[Curtin, Essig, Gori, Shelton 2014]

Higgs Portal (with Vector)

- For $X^\mu \to SM + SM$ via gauge kinetic mixing, mixing parameter ϵ controls vector lifetime.

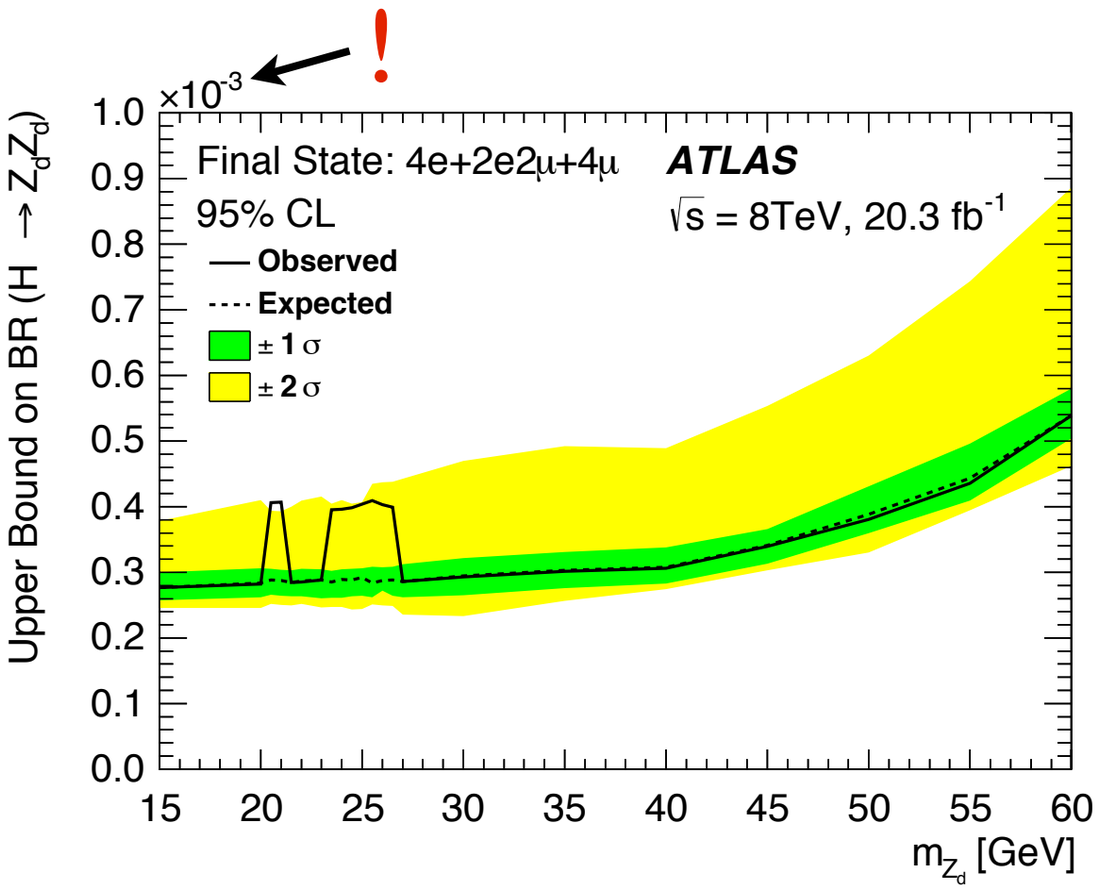


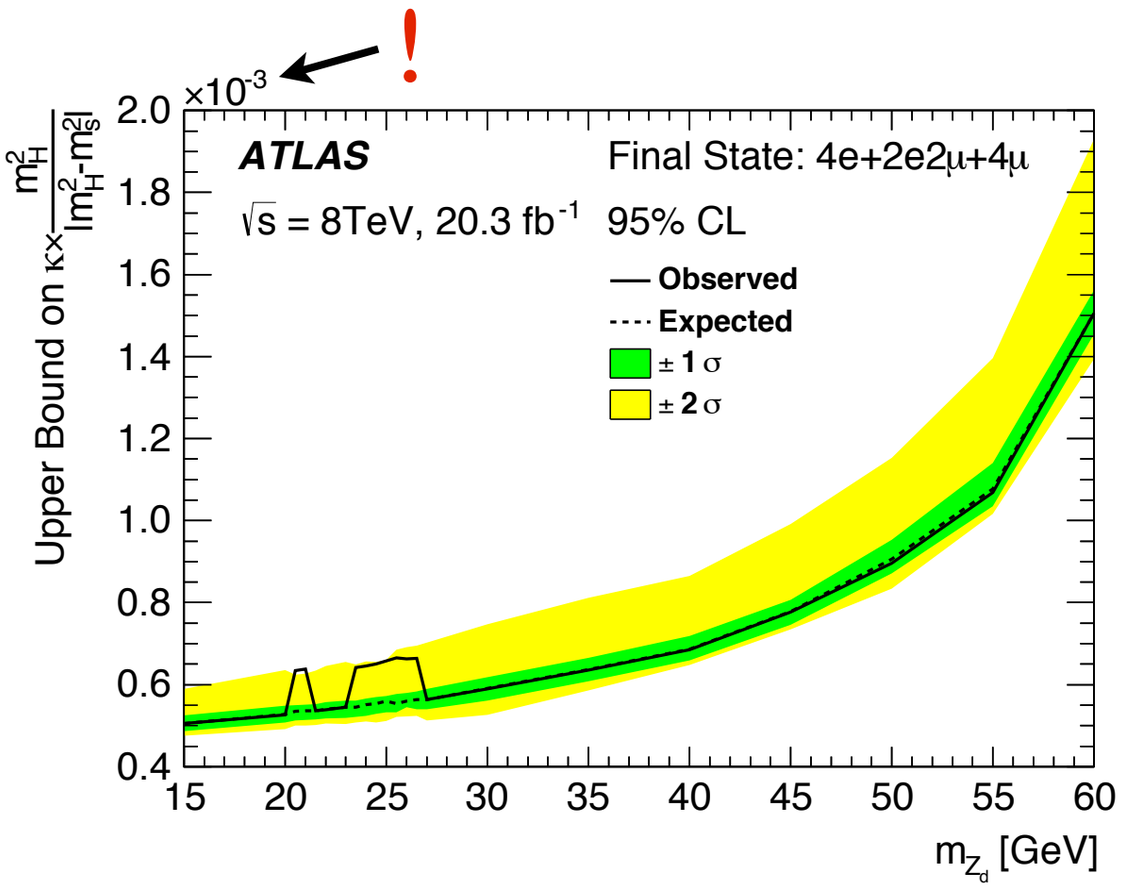


[Curtin, Essig, Gori, Shelton 2014]

Vector Portal and the Higgs

- ATLAS Search:





[ATLAS 2015]

Vectorized Neutrino Portal *

- Massive states can connect via the Higgs.
  e.g.

$$-\mathcal{L} \supset \lambda \bar{P} H N + m_N \bar{N} N + m_P \bar{P} P$$

$$P = (1, 2, -1/2)_x = \left(P^0,\, P^-\right)^t$$

$$N = (1, 1, 0)_x$$

- Both new states are charged under a dark group G_x.
- Common structure: Neut. Nat., Relaxation, ...
- Induces Higgs portal couplings in SUSY (via F-terms).

* No regular neutrinos are harmed in this process!

Vectorized Neutrino Portal

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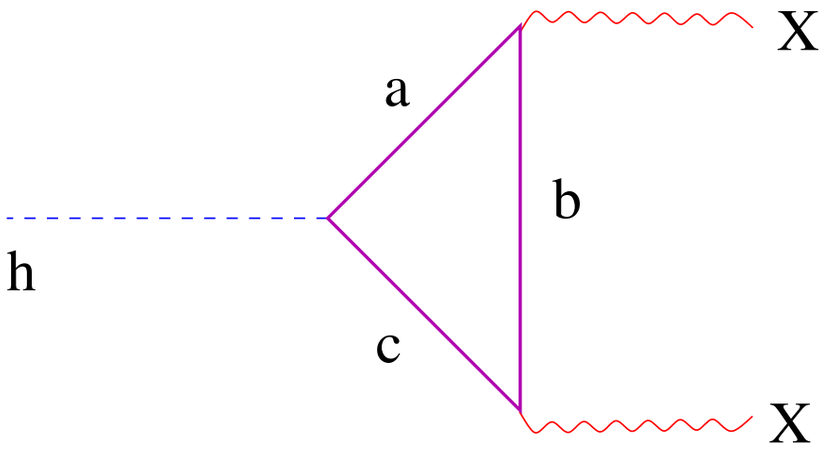
$$P = (1, 2, -1/2)_x = \left(P^0,\, P^-\right)^t$$

$$N = (1, 1, 0)_x$$

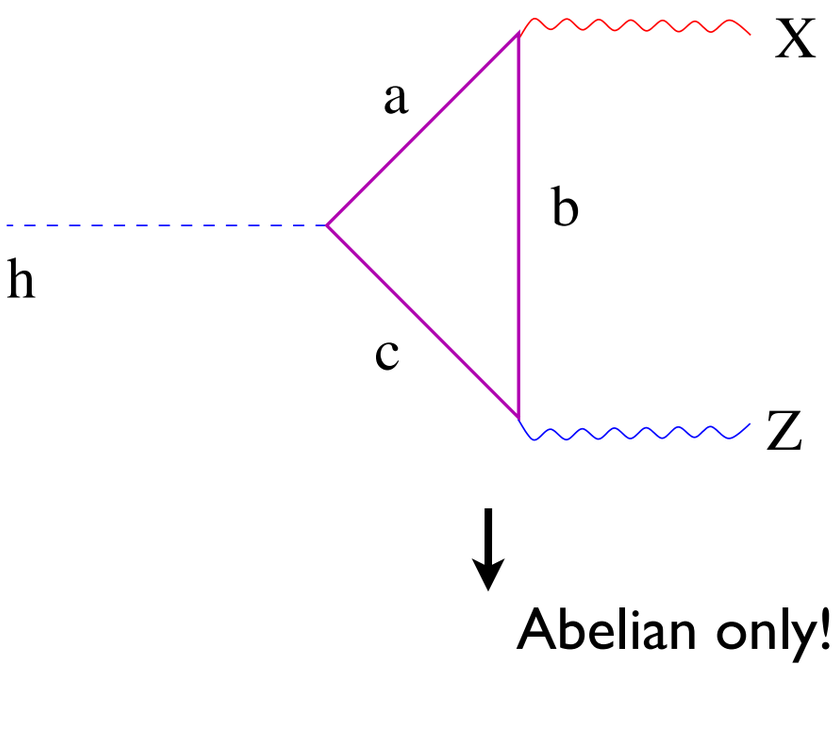
- EWSB mixes N, P^0 to make ψ_1^0, ψ_2^0.
  (May have interesting/challenging DM story.)
- Charged state P^- does not couple to the Higgs.

VNP: Higgs Connections to a Light Vector

- Massive states connect the Higgs to the hidden vector:



$$(abc) = (111),\ (222)$$



$$(abc) = (111),\ (222),\ (112),\ (221)$$

Abelian only!

[Lu, DM, Wijangco 161x.xxxx]

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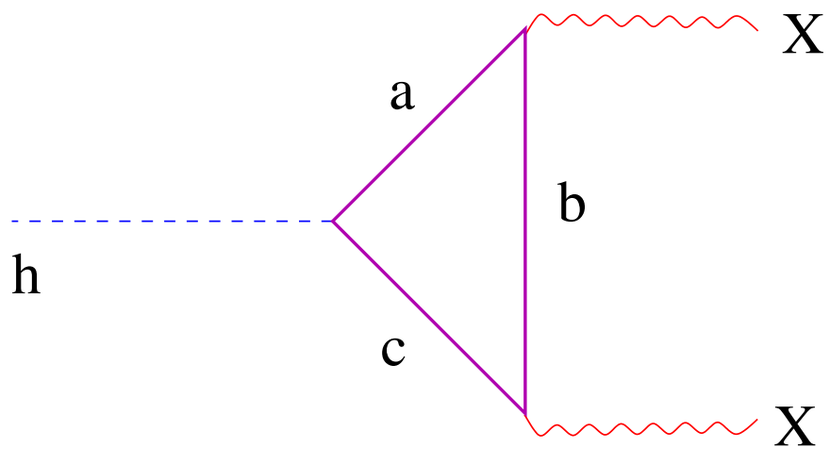


$$(abc) = (111),\ (222)$$

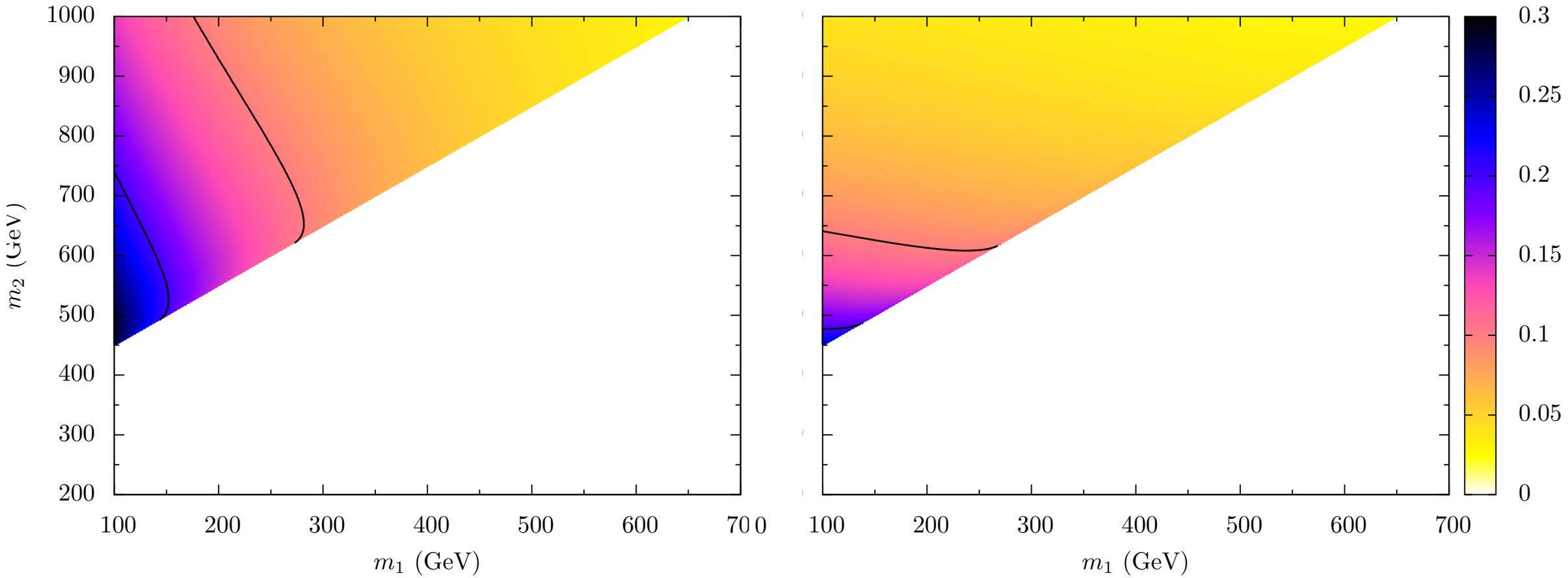
$$\mathcal{L}_{eff} \simeq -\frac{\alpha_x T_2(r)}{3\sqrt{2}\pi}\frac{\lambda^2 v}{m_1 m_2} h X_{\mu\nu} X^{\mu\nu}$$

[Lu, DM, Wijangco 161x.xxxx]

VNP: Precision Electroweak

- Main effect is captured well by the T parameter:

$$\lambda = 1.0$$

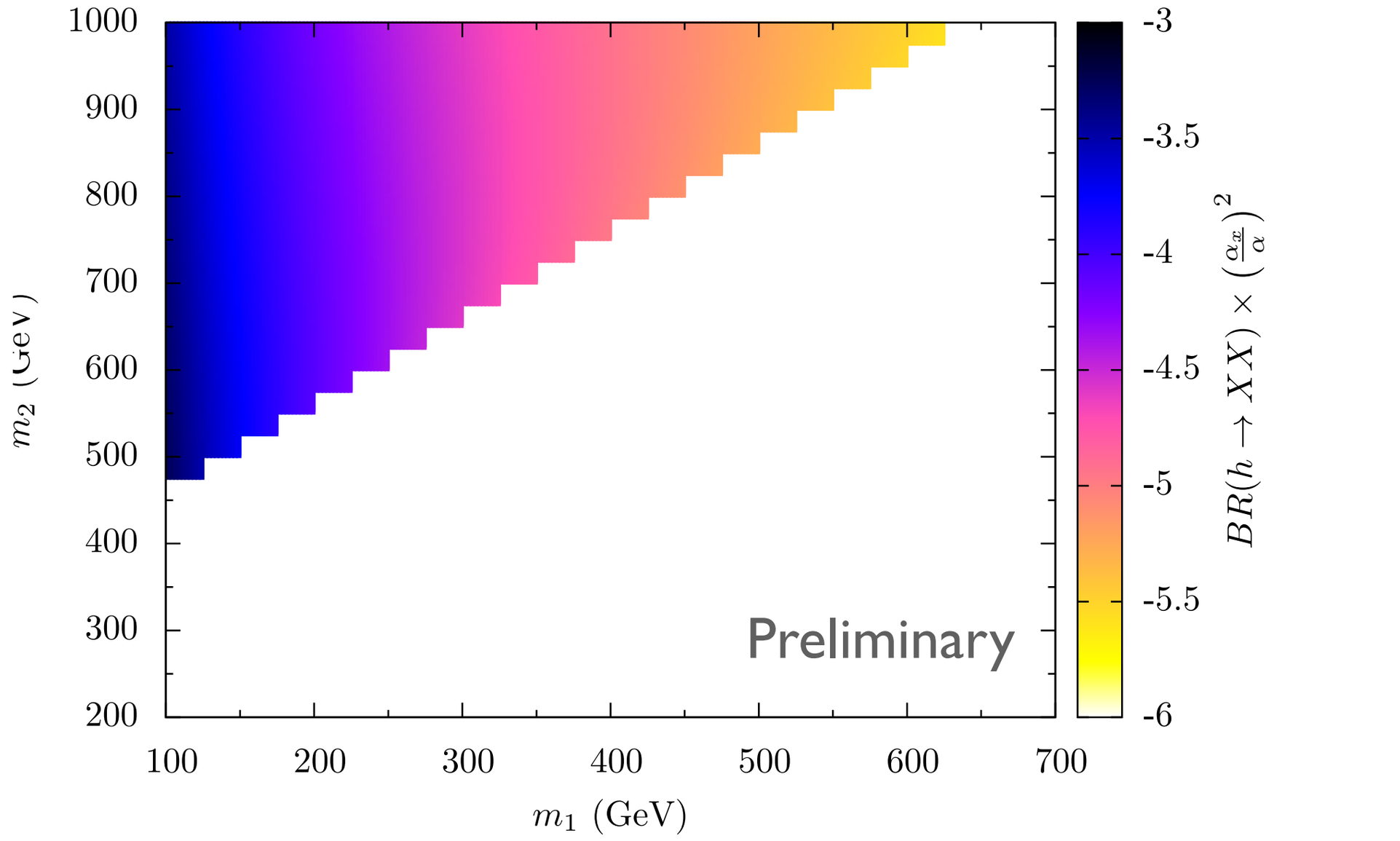


$m_P < m_N$ $\qquad$ $m_N < m_P$

[Lu, DM, Wijangco 161x.xxxx]

VNP: Higgs Connections to a Light Vector

- Branching fractions, $m_P < m_N$, $\lambda = 1.0$, $m_x = 15\,\mathrm{GeV}$:



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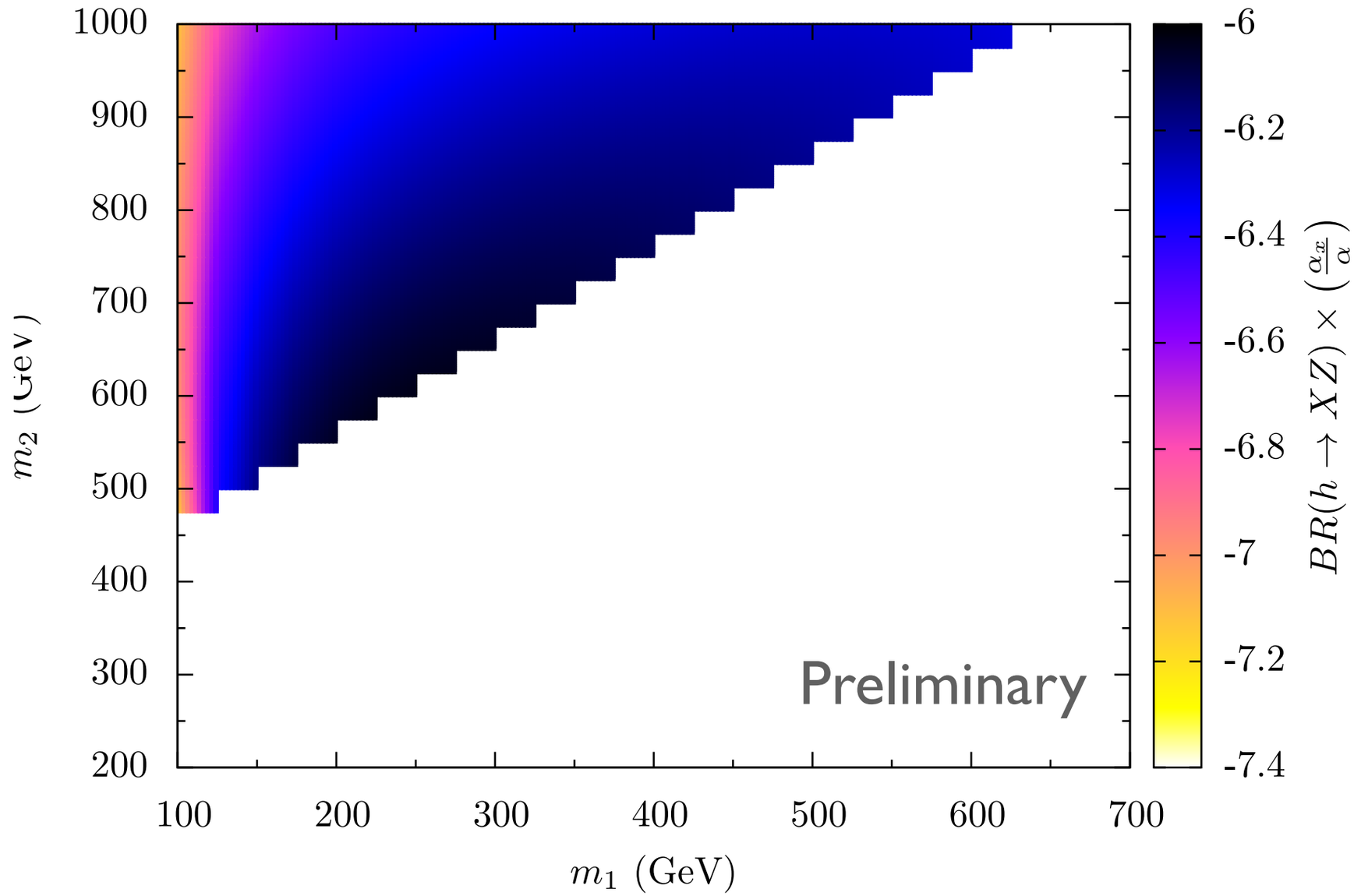


[Lu, DM, Wijangco 161x.xxxx]

VNP: Higgs Signals

- Signals depend on G_x and how X^μ decays.
- Abelian: $h \to XX,\ h \to XZ$

  Similar to previous cases for $X \to SM + SM$.

  (But different angular correlations in 4l.)
- Non-Abelian: $h \to XX$

  Decays of X to SM via

$$\mathcal{L}_{eff} \simeq \frac{\alpha_x \lambda^2 T_2(r)}{3\pi\, m_1 m_2} H^\dagger H\, X^{\mu\nu} X_{\mu\nu}$$

  Gives metastable glueballs or massive vector bosons.
- Other decays possible with more dark states...

Rich Dark Sectors

- Most studies have concentrated on minimal hidden sectors.
  e.g. Vector Portal with $X \to SM$ or $X \to DM$.

- A dark sector can be much "richer" than this:

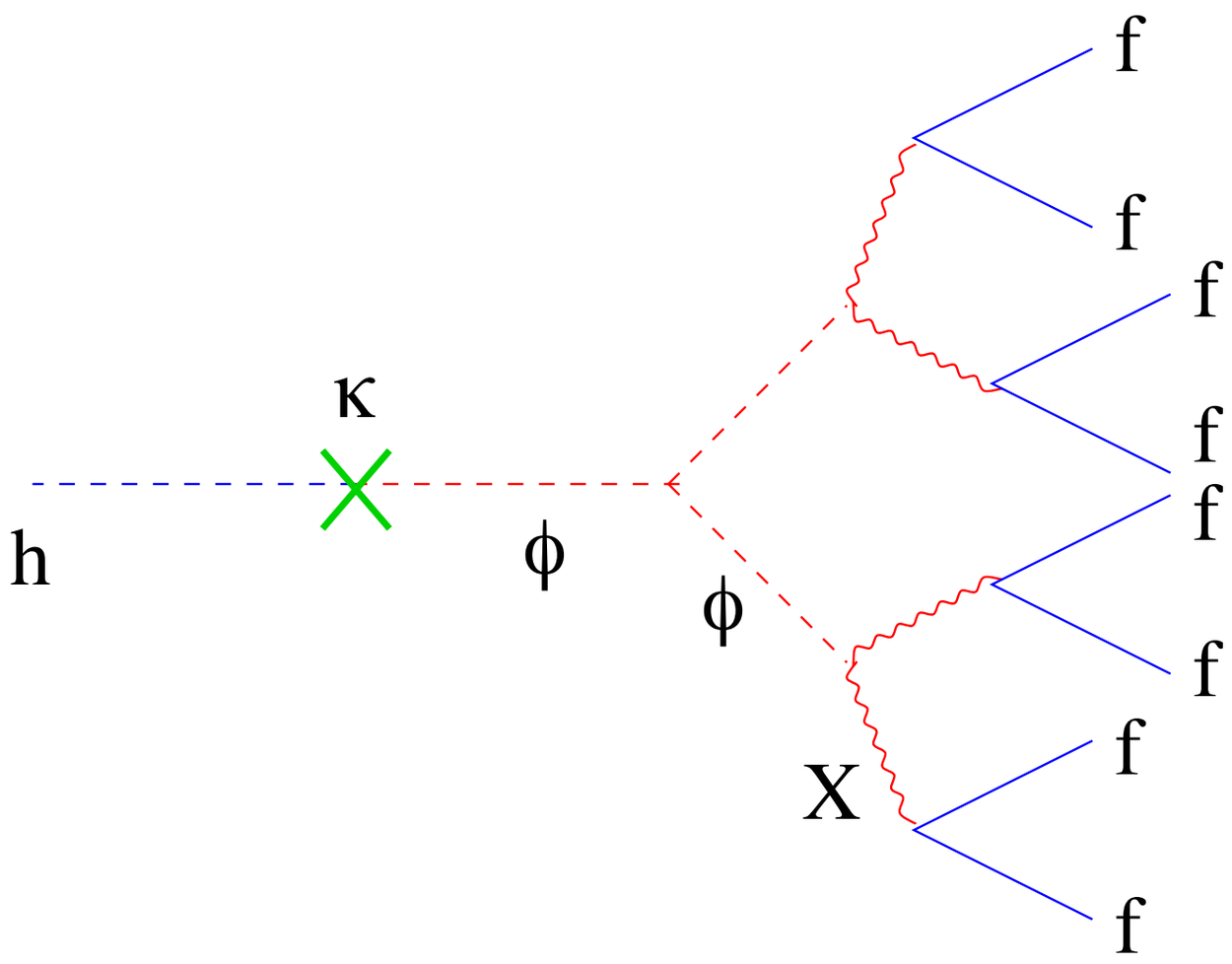
  - new states from dark symmetry breaking or naturalness
  - non-minimal dark matter: iDM, xDM, ADM, SIDM, ...
  - muons (*i.e.* the visible sector is complicated)

- Challenge: too many possibilities to list.

[J. Alexander *et al.* Dark Sectors 2016 Community Report]

Rich Dark Sectors: Example #1

- Dark vector with dark Higgs, $2m_x < m_\phi < m_h/2$.

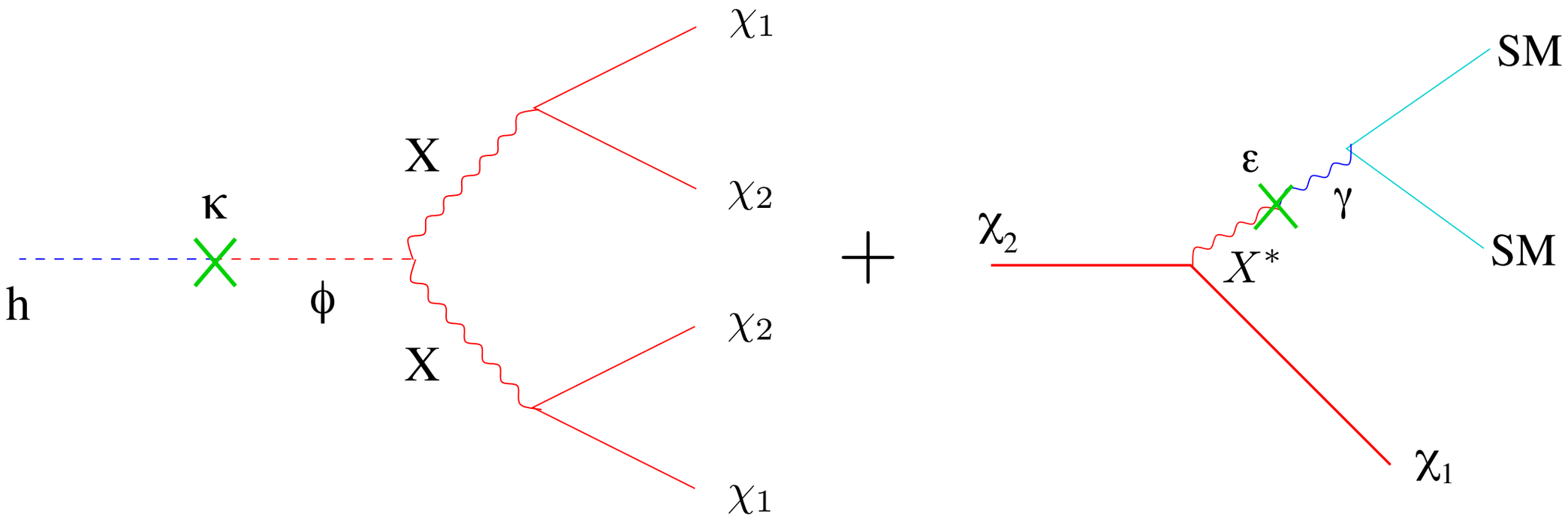


[Batell, Pospelov, Ritz 2009]

Rich Dark Sectors: Example #2

- Dark photon with two dark fermions χ_1, χ_2.
  Dominant vector decay is $X^\mu \to \chi_1 + \chi_2$

- Lighter χ_1 is stable, heavier χ_2 decays via off-shell X^μ.



[Spray, DM 2014; Izaguirre, Krnjaic, Shuve 2015]

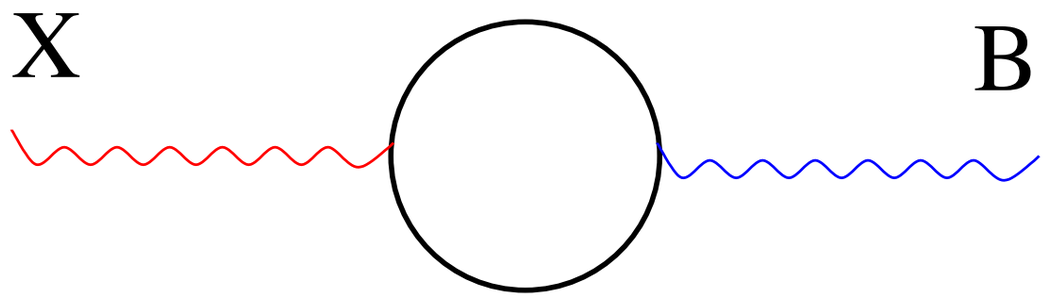
Summary

- Rare Higgs decays may be a useful tool for dark vectors.
- Exotic branching fractions are often constrained, but portal couplings can be effective.
- Minimal models produce straightforward signals.
- Rich dark sectors can be very complicated. What is the best way to proceed?

Extra Slides

Vector Portal: ϵ

- Can arise from loops of heavy matter M that is charged under both U(1)x and $U(1)_Y$. [Okun 1982; Holdom 1986]

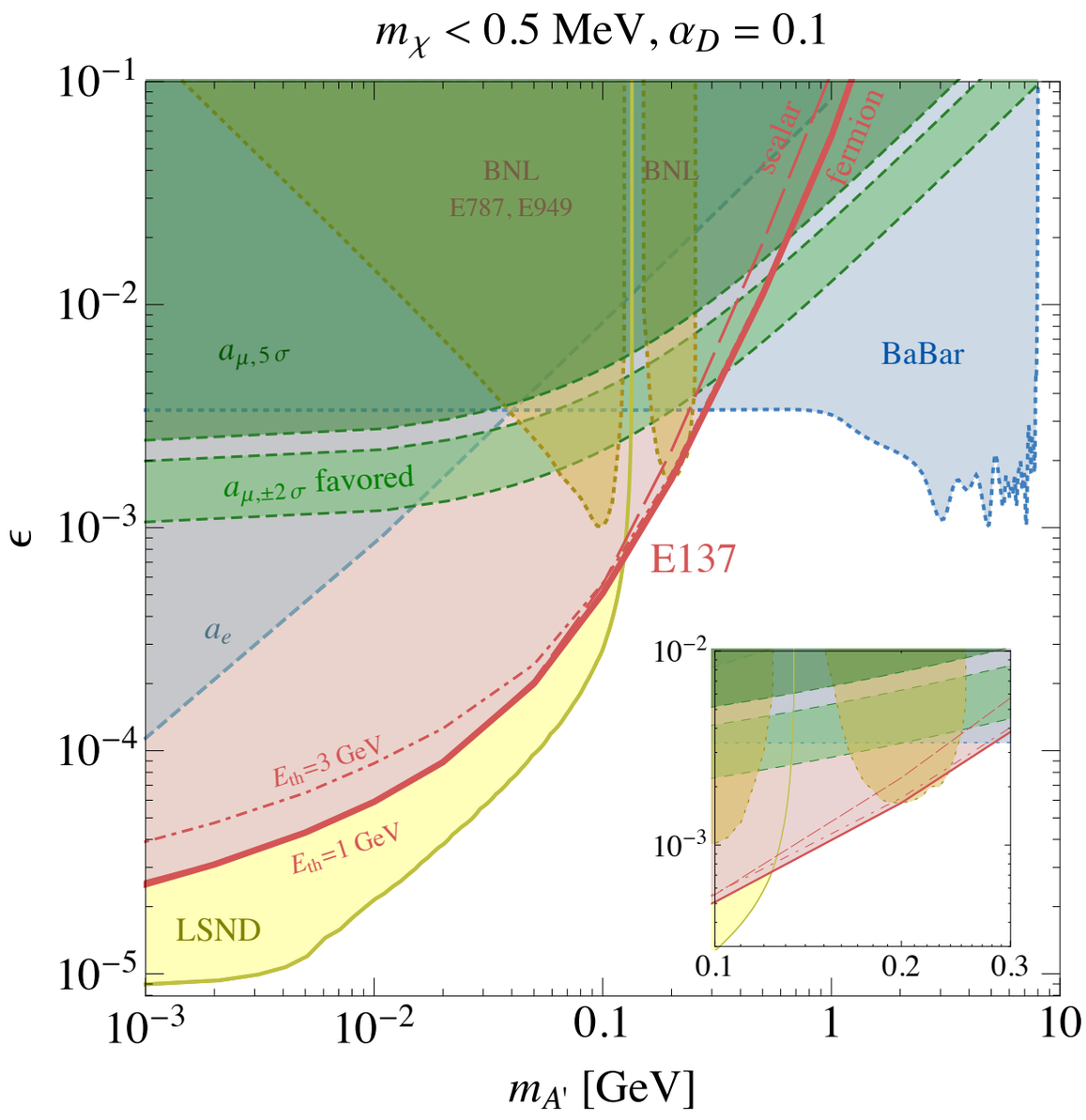


$$\epsilon \sim \frac{g_x g_Y}{(4\pi)^2} \ln\left(\frac{M}{\mu}\right) \sim 10^{-2} - 10^{-4}$$

- Can be further suppressed for many reasons.

Minimal Vector Portal: Combined Limits

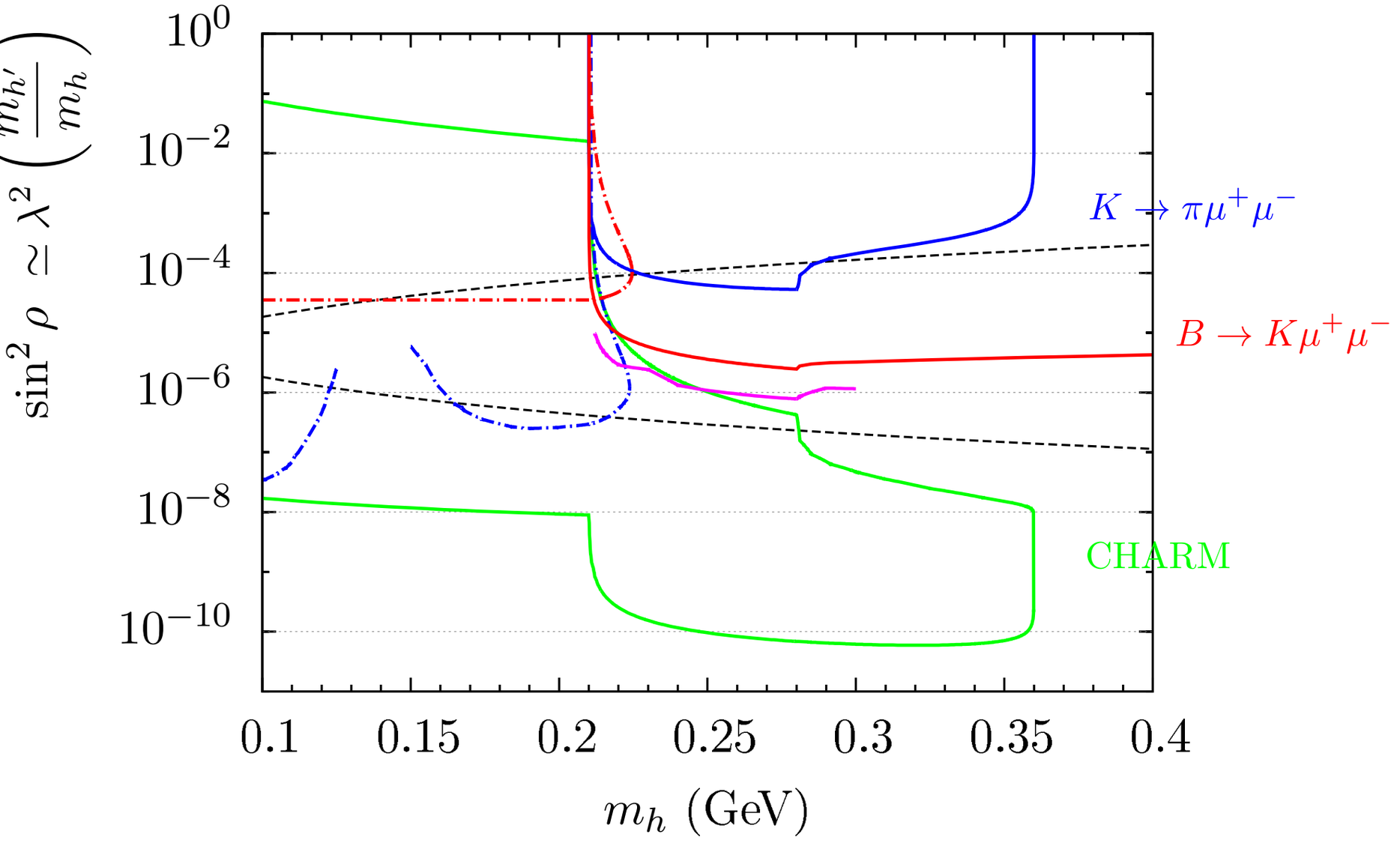
- Hidden vector X^μ, mass $m_x > 2m_e$, decays $X^\mu \to DM$:



[de Niverville *et al.* 2011, Essig *et al.* 2013; Batell *et al.* 2014; ...]

Minimal Higgs Portal: Combined Limits

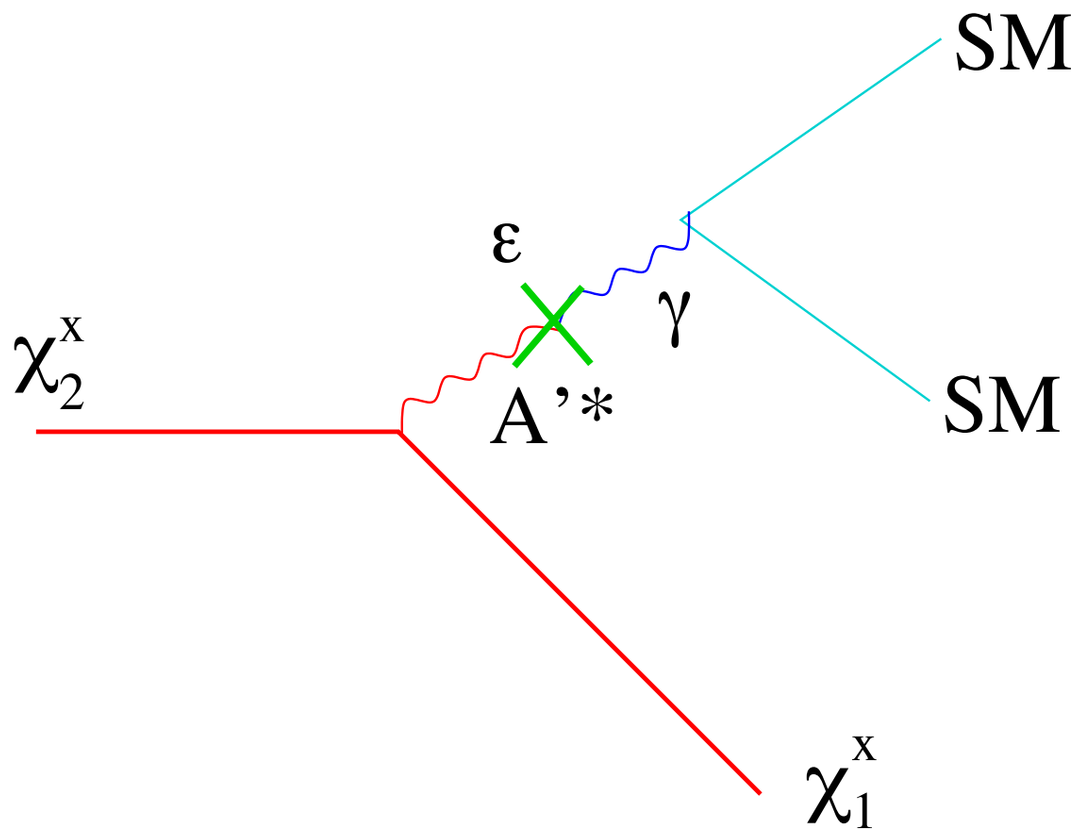
- Hidden Higgs h', mass $m_{h'}$, decays $h' \to SM$:



[...; Batell, Pospelov, Ritz 2009; Bezrukov+Gorbunov 2013; Clarke, Foot, Volkas 2013;...]

Case D: $A' \rightarrow \chi_1^x + \chi_2^x$

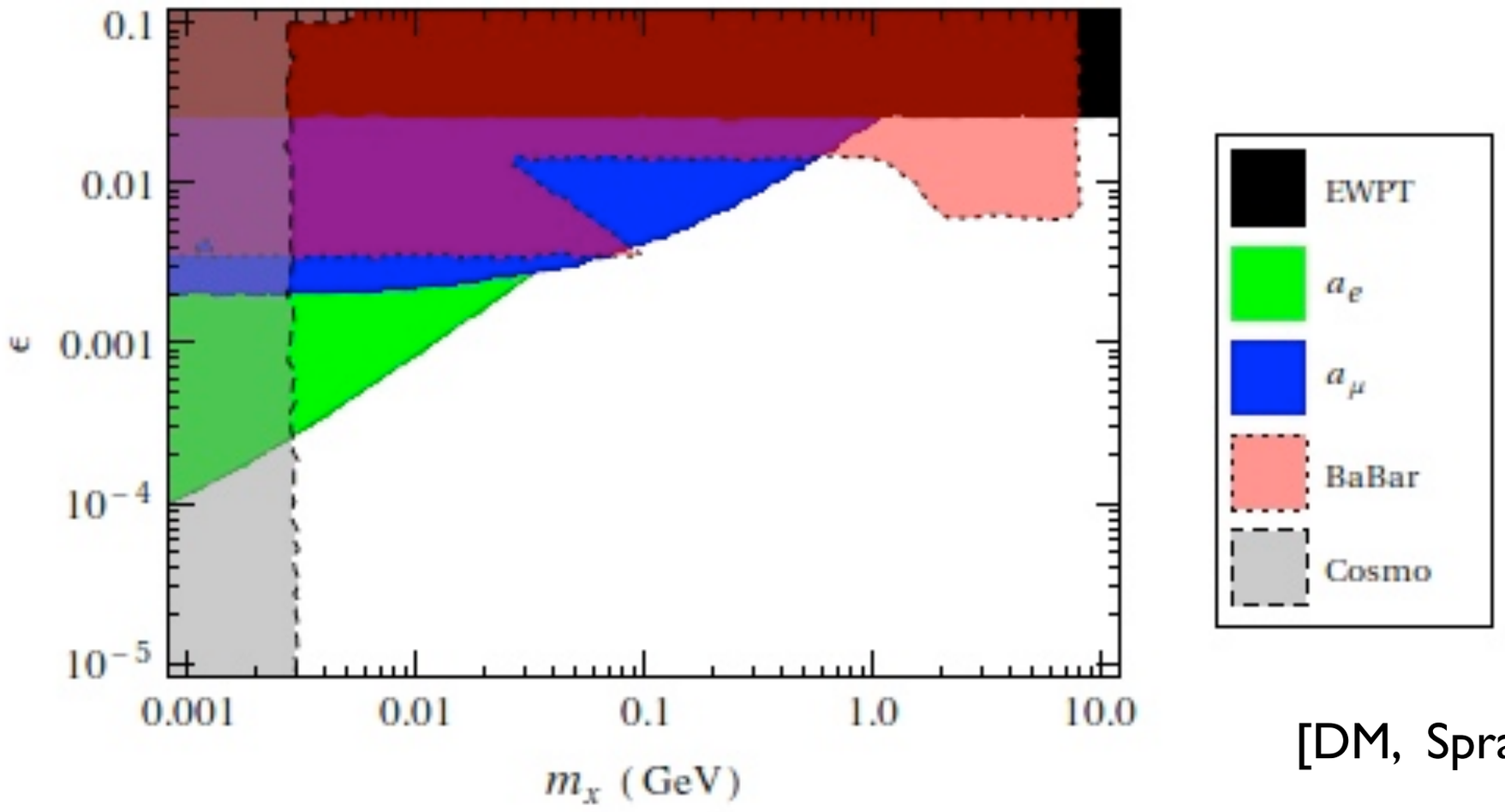
- Decays of χ_2^x:



- Lifetime depends on relative $\chi_{1,2}^x$ and X^μ masses.
- Choose parameters with $BR(X^\mu \rightarrow \chi_1^x \chi_2^x) = 0.9$.

Case D: Bounds from Meson Factories and ...

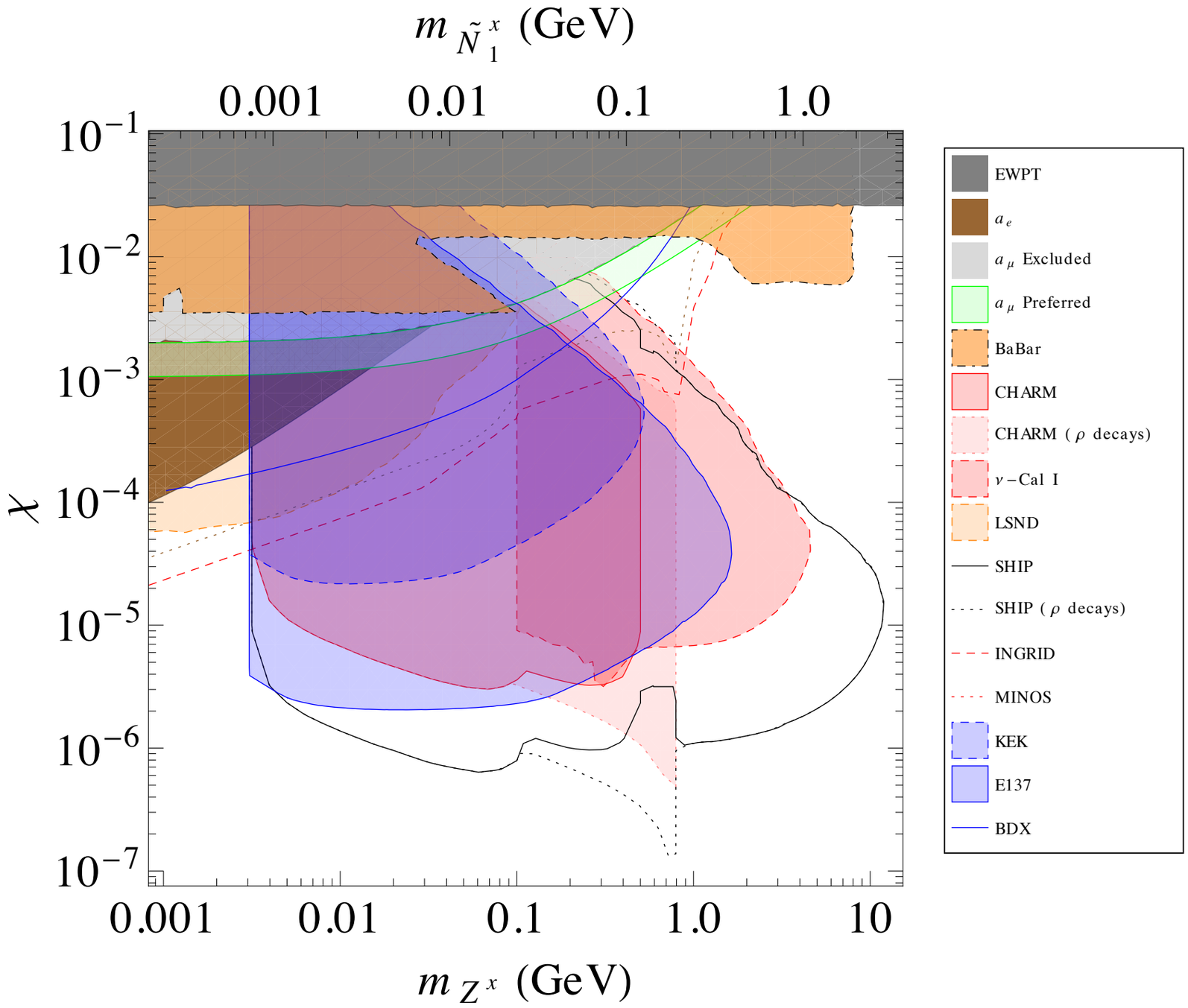
- Meson factories: BaBar $\Upsilon(ns) \to \gamma + (invisible)$
  Relevant for $\gamma c\tau \gtrsim 100\,\mathrm{cm}$, other searches not sensitive.



[DM, Spray 2014]

- (Cosmo: remnant χ_2^x decays after BBN starts.)

Case D: Bounds from Fixed Targets



[SHiP Physics, Alekhin, ..., DM, Spray, ... 2015]