UC Davis Theory Seminar, April 14th, 2014

Light Hidden Sectors at Fixed-Target Experiments

`arXiv:1402.4817`
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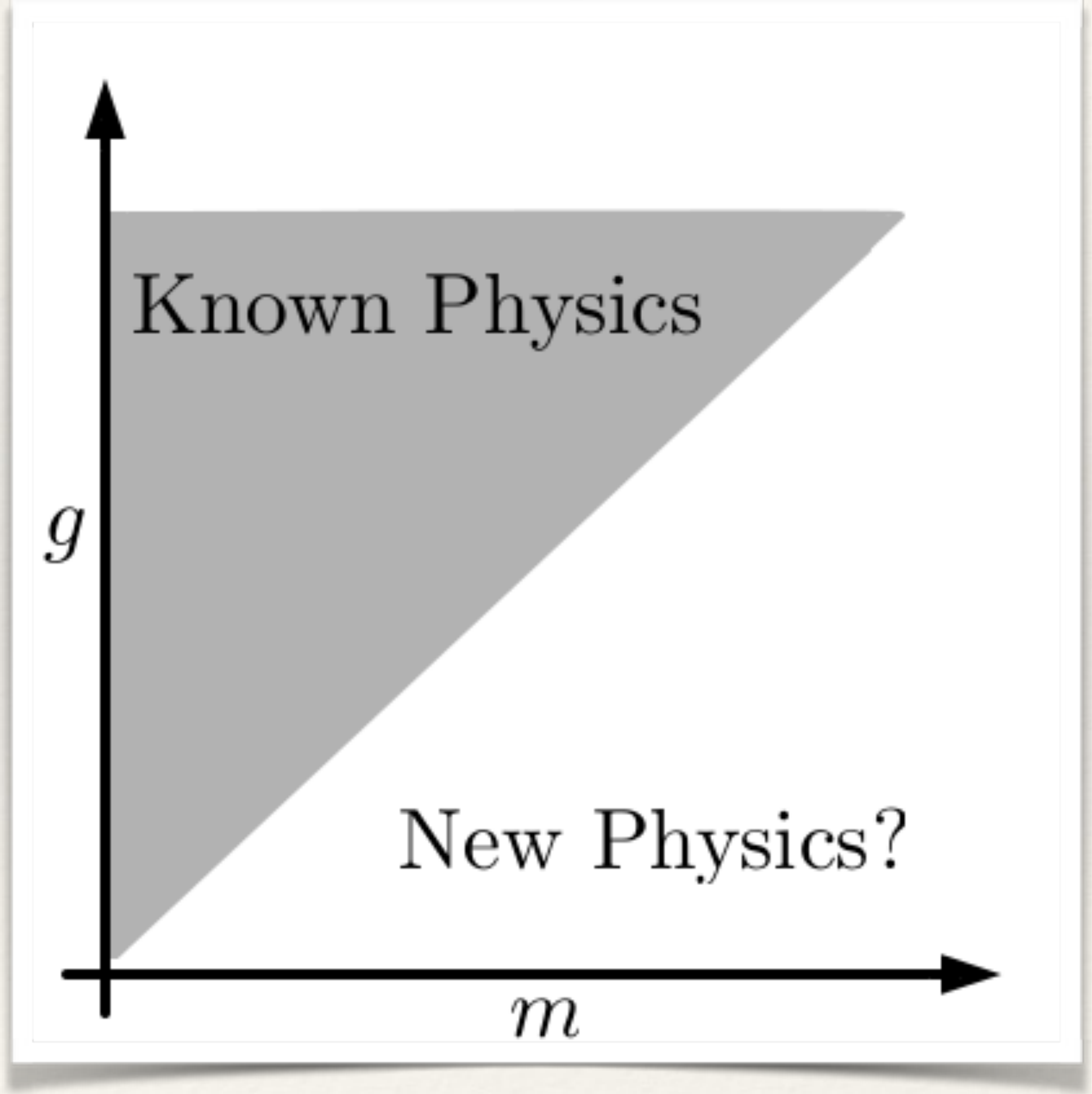
Outline

1. Introduction and Motivation
2. Theory: Model and Decays
3. Non-Fixed Target Limits
4. Electron Fixed Target Limits
5. Proton Fixed Target Limits
6. Conclusions

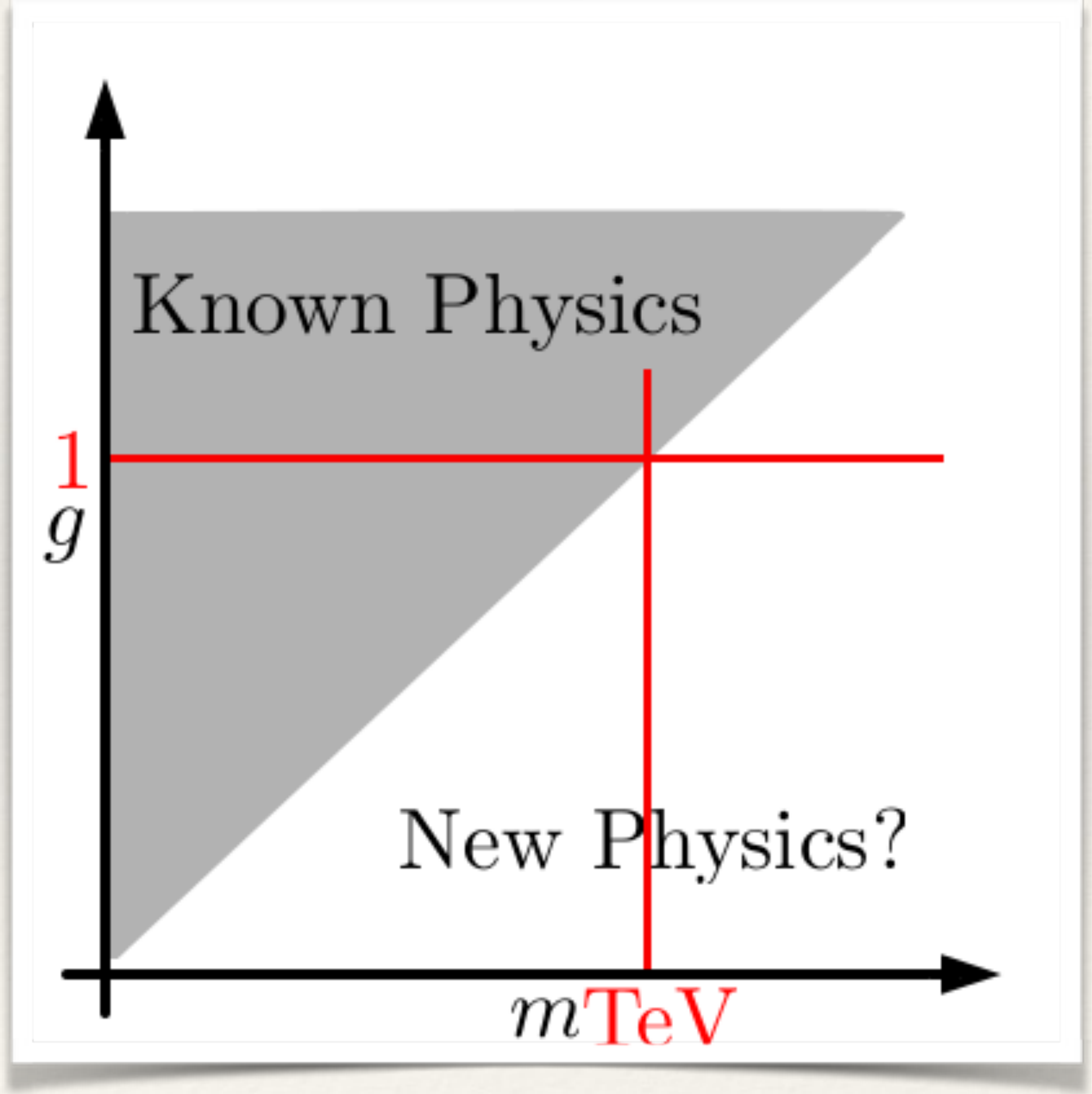
Introduction and Motivation

Hidden Sectors



- Heavy stuff harder to probe!
  Increase $m \Rightarrow$ See only larger g

Hidden Sectors



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- g~$O(1)$ implies NP is TeV-scale
  - *e.g.* NP has gauge couplings

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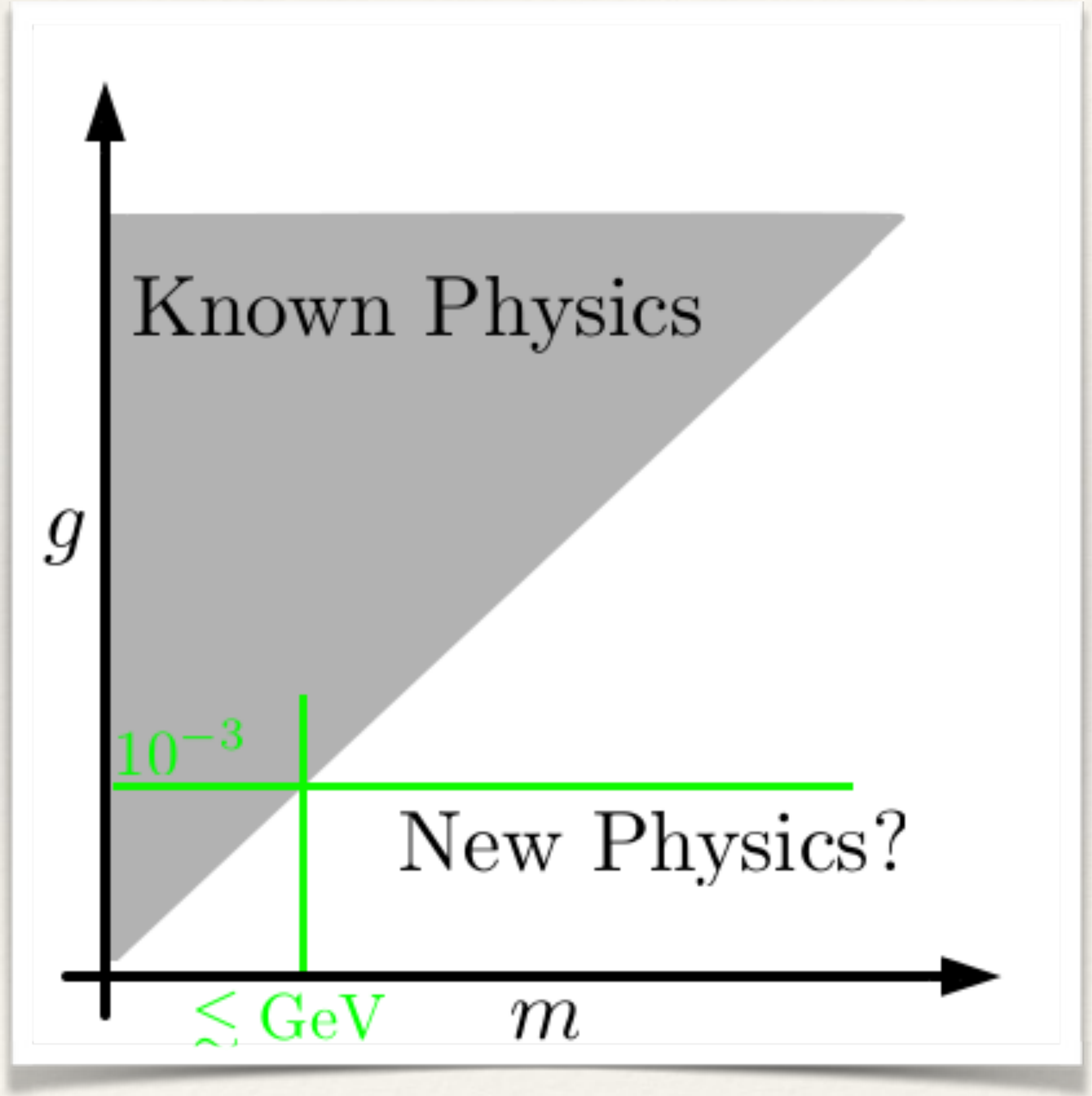
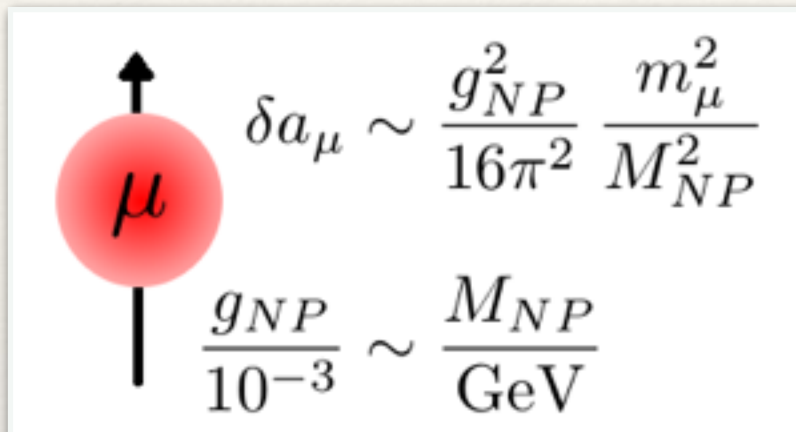
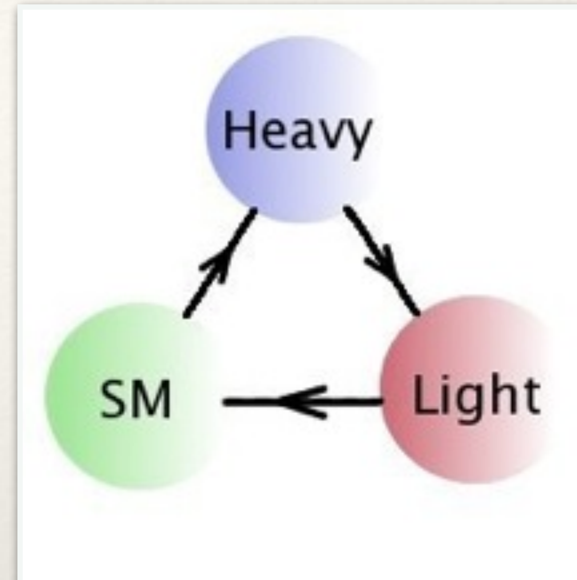


- Heavy stuff harder to probe! Increase $m \Rightarrow$ See only larger g
- $g \sim O(1)$ implies NP is TeV-scale
  - *e.g.* NP has gauge couplings
- $g \ll O(1)$ lets NP be light
  - Hidden sector gauge-neutral

Thinking of New Light Stuff

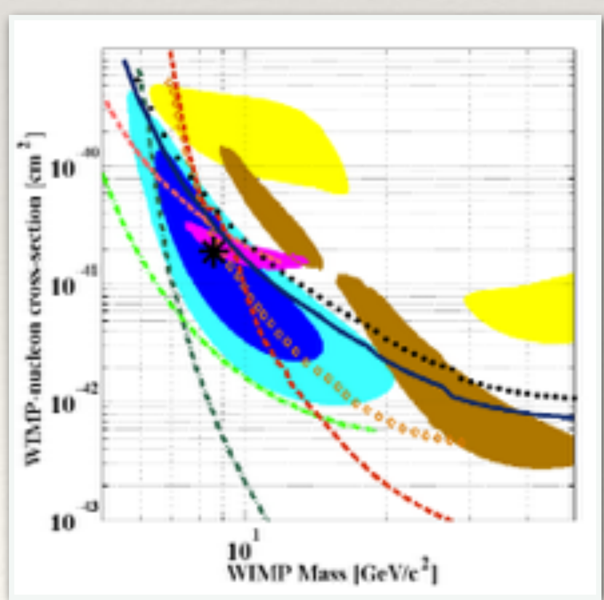
- μ Anomalous Magnetic Moment

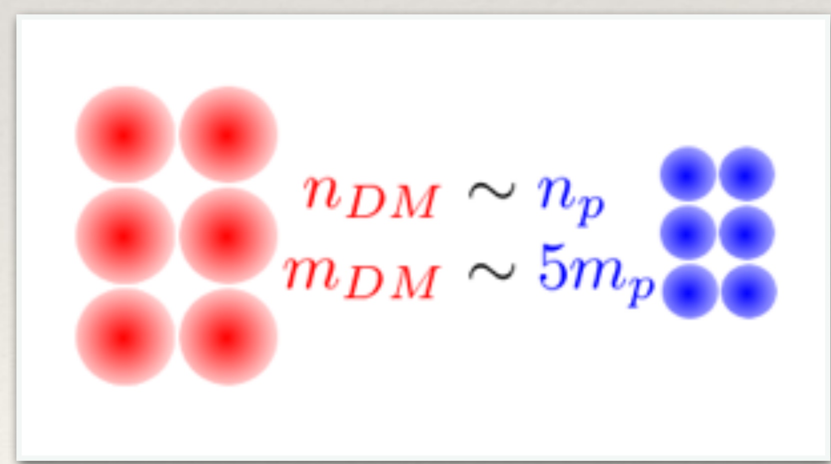




- Hidden Valleys

- Dark Matter Anomalies





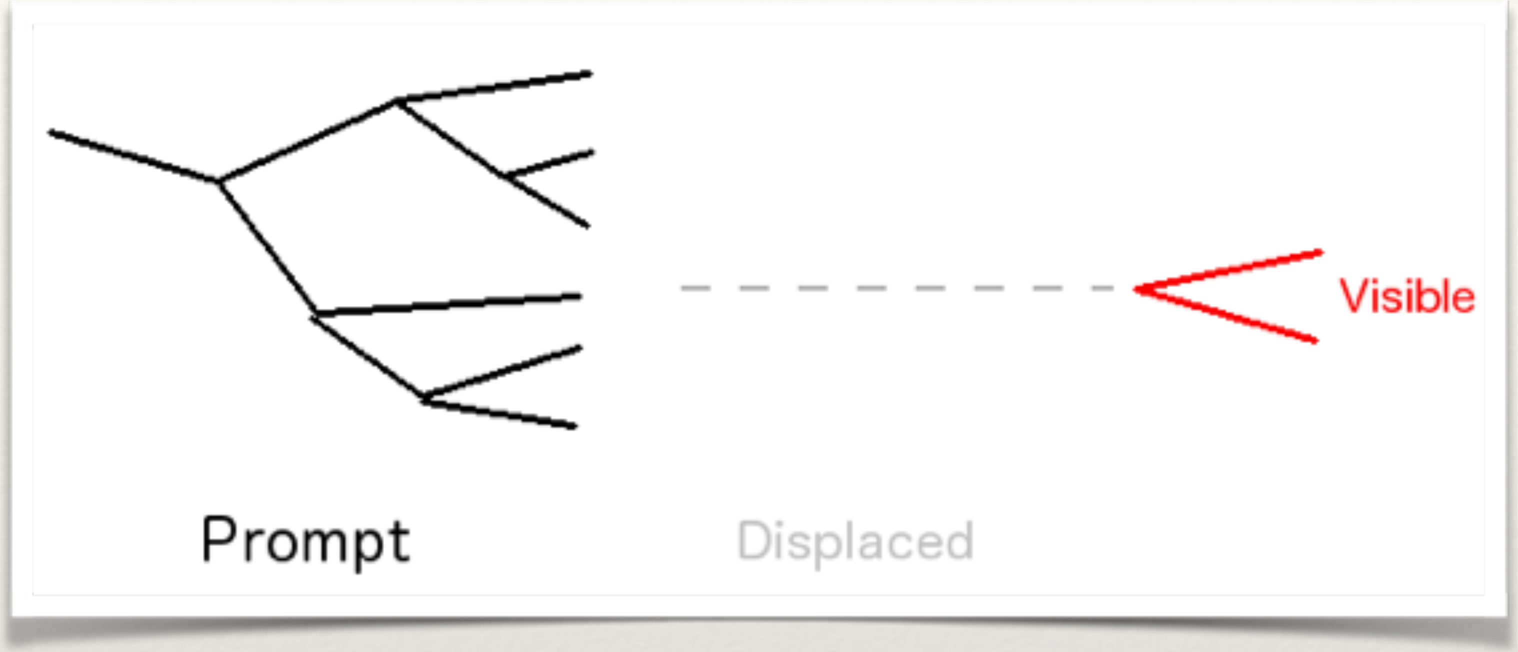
- Asymmetric Dark Matter

Fixed Target Experiments

- The other part of the title
- Examples of the Intensity Frontier:
  - High luminosity
    - Probe small coupling to SM
  - Low/Controlled backgrounds
    - Searches restricted to low mass

- One of the standard tools/proposals to limit Hidden Sectors

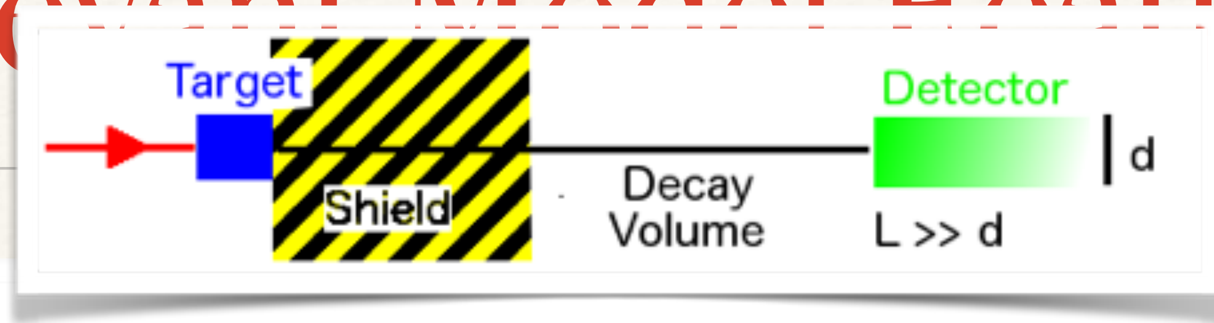
Relevant Model Features

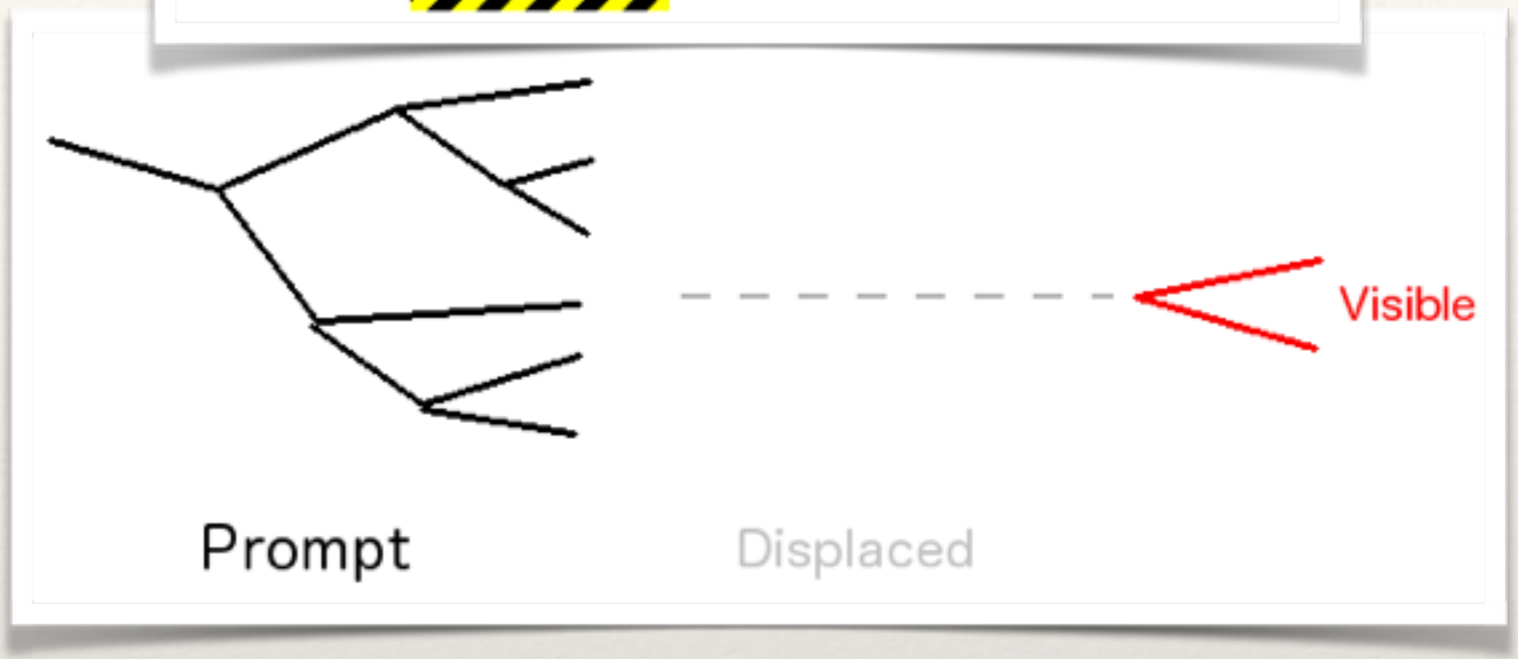


- Production and prompt decays
- Long-lived or Stable State(s)
- Decay or Scattering of latter state(s)

- What is the long-lived state?
- How is it produced?
- How does it decay/scatter?

Relevant Model Features





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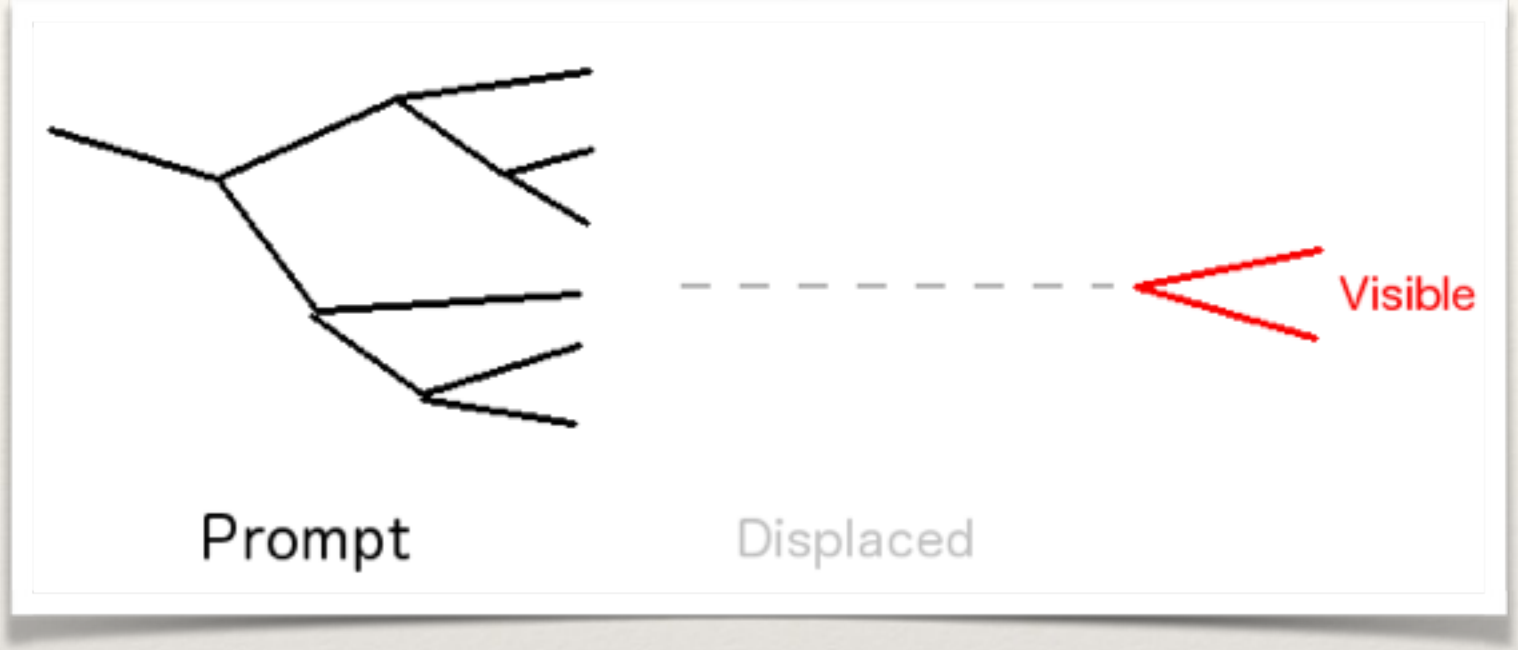

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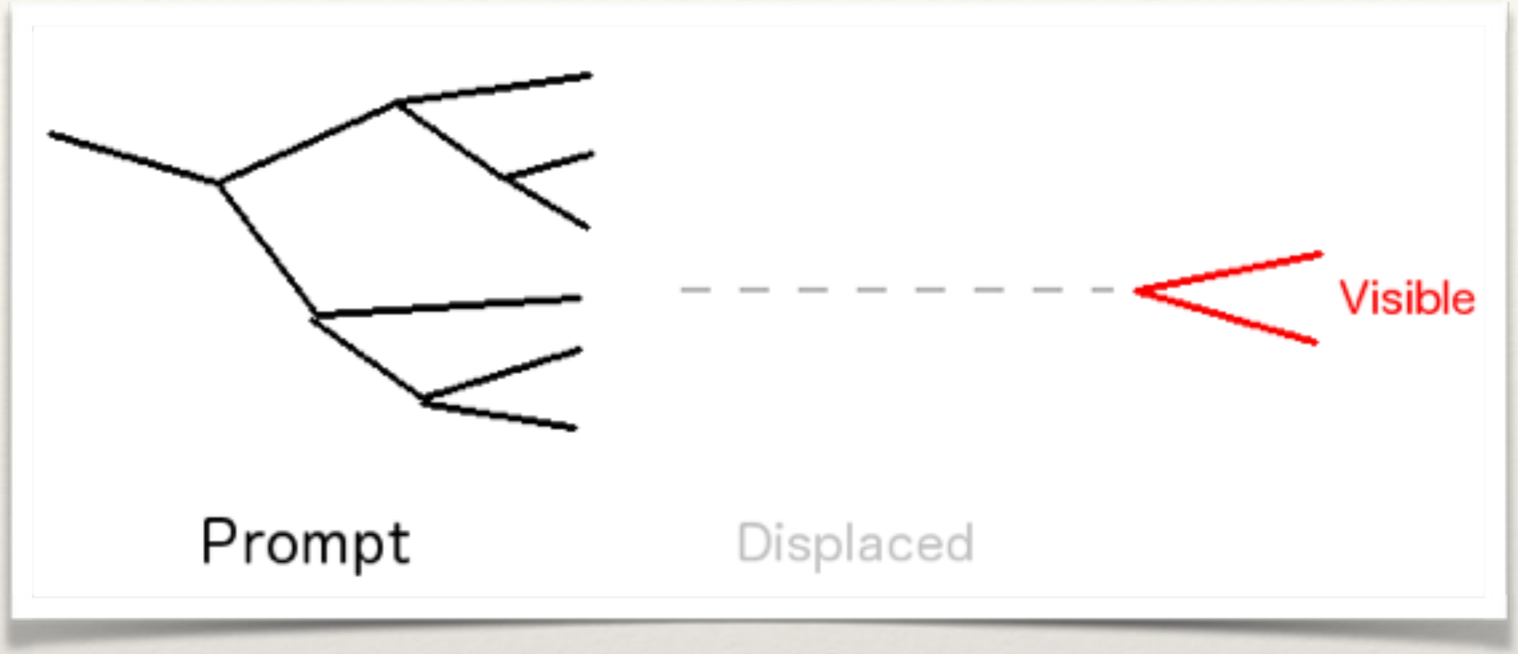

- Production and prompt decays
- Long-lived or Stable State(s)
- Decay or Scattering of latter state(s)

- What is the long-lived state?
- How is it produced?
- How does it decay / scatter?

Portals

- Three renormalisable couplings between SM and gauge-neutral operators

$$-\frac{1}{2}\epsilon\, B^{\mu\nu} X_{\mu\nu}$$

$$-\frac{1}{2}\lambda\,(H^\dagger H)\,(\Phi^\dagger\Phi)$$

$$y\,\bar{L}\,H\,N$$

- Vector Portal: γ
  - Massless
  - Couples ∝ ε e Q
- Higgs Portal
  - LHC Only
  - Easy(?) to produce
- Neutrino Portal
  - Near-massless
  - Hard to produce

Portals

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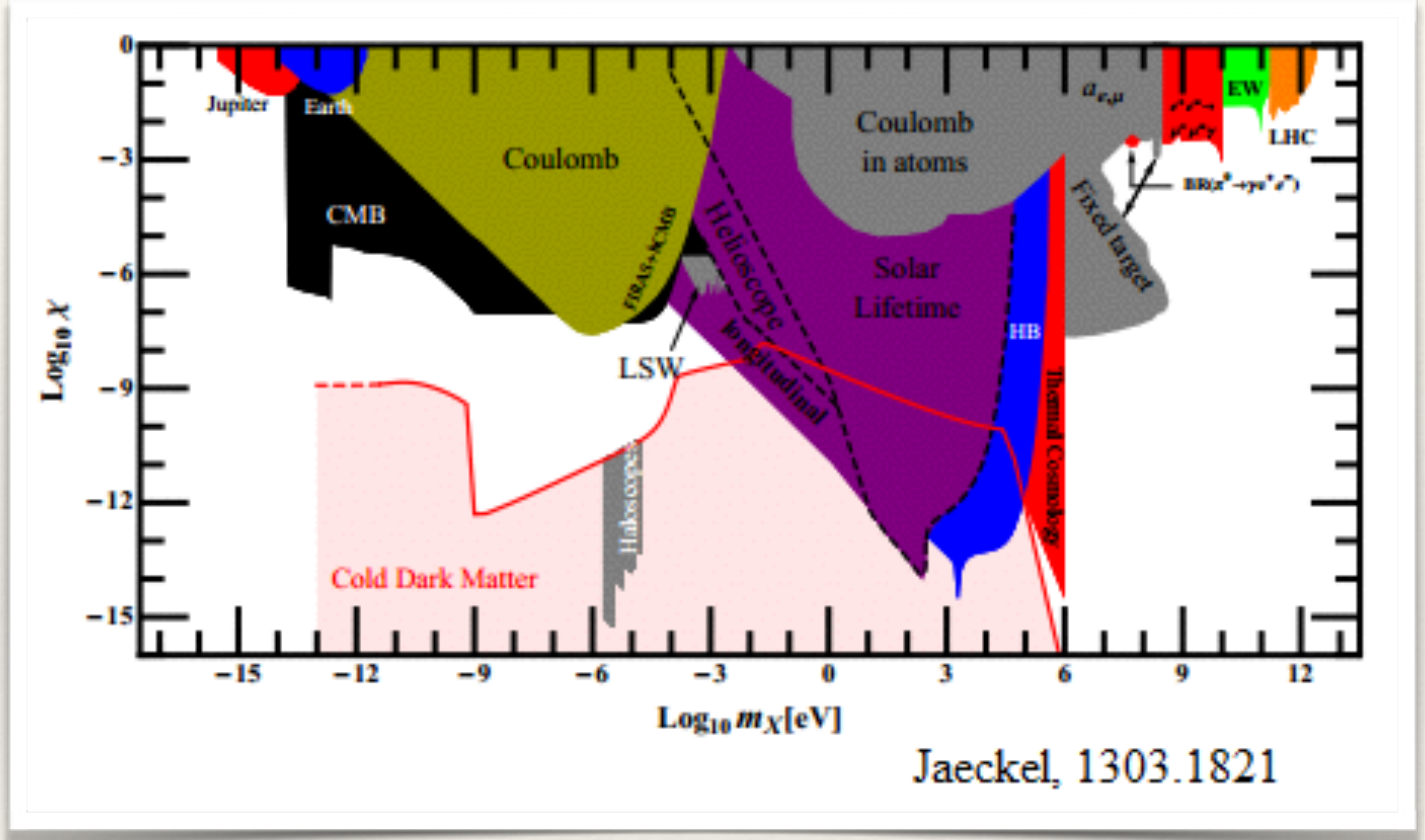
  - One-Loop generated → $\varepsilon \sim 10^{-3}$

Vector Kinetic Mixing Limits

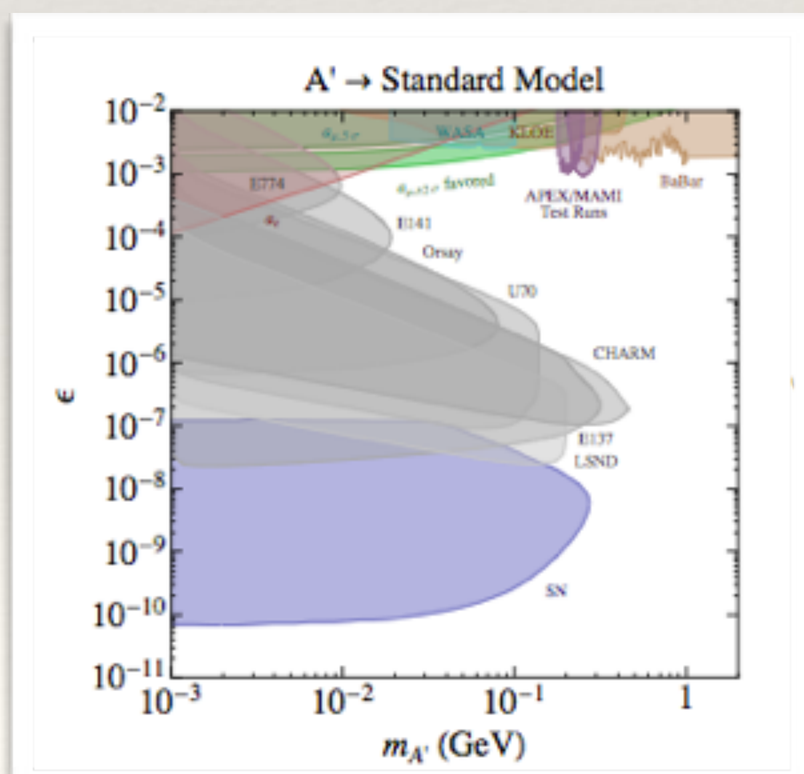


- Many previous studies and limits!
- GeV-scale relatively unconstrained

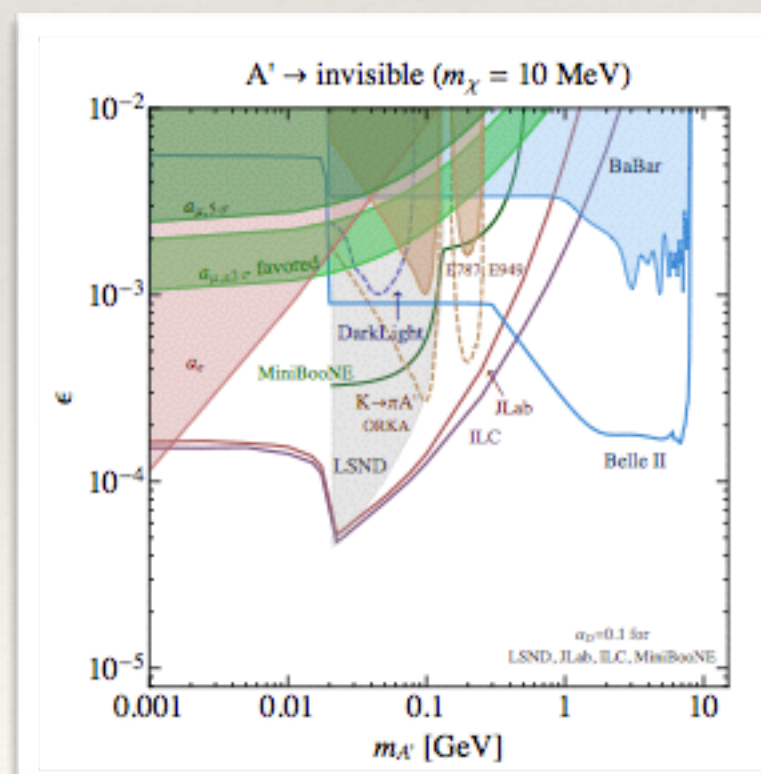
Assumptions!

- Existing (GeV-scale) searches assume either: `[1311.0029]`

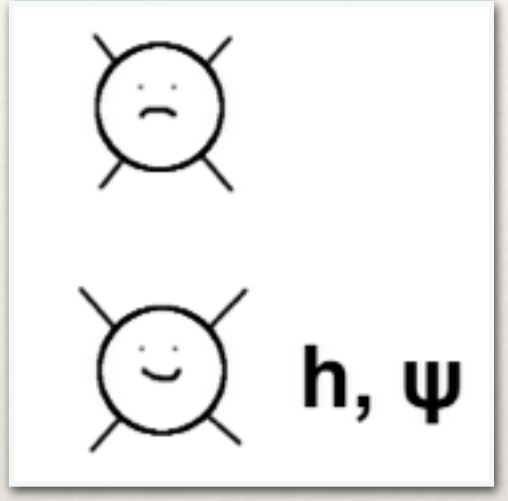
- $X \to l^+ l^-$
  - Beam dump limits at small ε and m
  - Motivated as minimal model



- $X \to$ invisible
  - Weaker limits from neutrino expts
  - Motivated from dark matter



General Hidden Sector

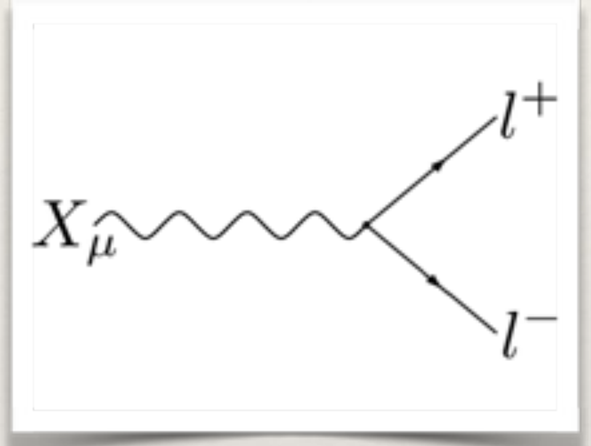


- Possible that hidden sector is minimal
- But also possible that it is not
  - *e.g.* Higgses to give vector mass
  - Fermions other than just DM
- Qualitatively new possibility:
  Hidden Vector → Hidden Sector → Standard Model

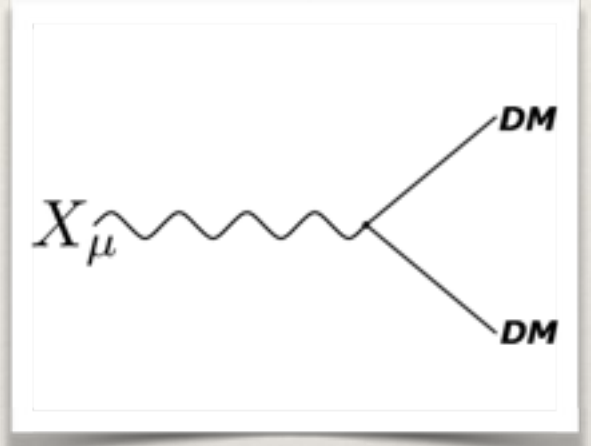
General Hidden Sectors

- Multiple possible vector decays:

- Direct Decay to Visible Sector

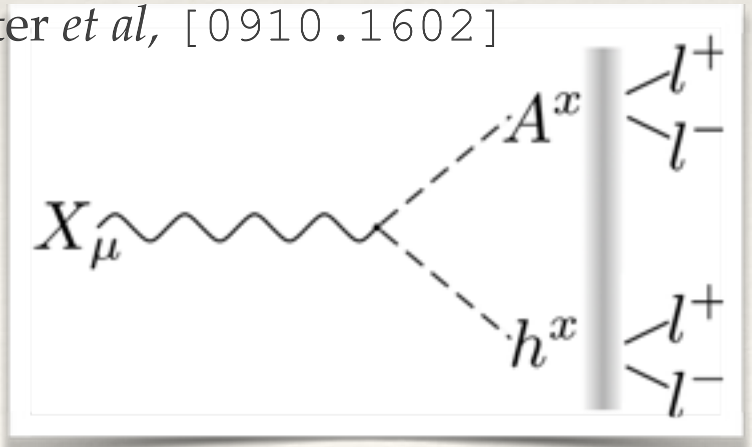


- Invisible Decay

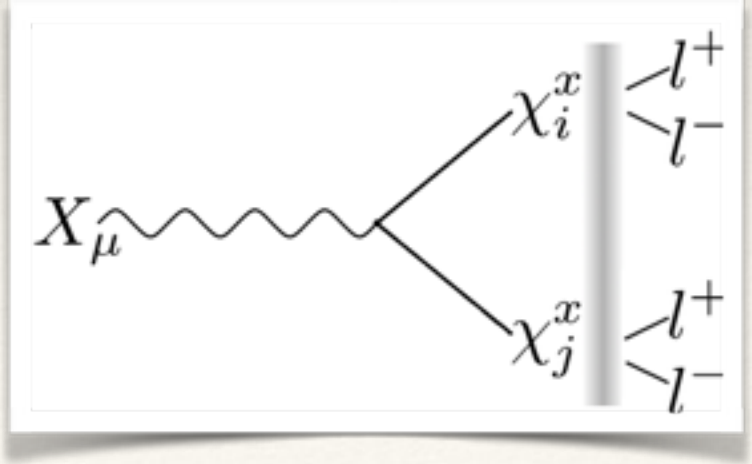


- Decay to SM via Hidden Scalars

- Schuster *et al*, [0910.1602]



- Decay to SM via Hidden Fermions



Can we construct a model with all these decay modes?

The Model

A Minimal Supersymmetric Hidden Sector

- We don't need to build a model: already had one! [1112.2705]
- Supersymmetric: has both hidden scalars and fermions
- If add R-parity, lightest fermion is stable
- Minimal model with $U(1)_x$ gauge symmetry:
  - Vector field X^μ plus gaugino $\tilde{X}$
  - Two Higgses H, H' plus Higgsinos $\tilde{H}$, $\tilde{H}'$
  - Minimal anomaly-free content

A Minimal Supersymmetric Hidden Sector

- We don't need to build a model: already had one!
- Supersymmetric: has both hidden scalars and fermions
- If add R-parity, lightest fermion is stable
- Minimal model after breaking $U(1)_x$:
  - Massive vector field Z^x
  - Two real scalars $h^x{}_{1,2}$ and one pseudoscalar A^x
  - Three Majorana fermions $\chi^x{}_{1,2,3}$

Parameter Space

- Model has seven parameters (over MSSM):

- Supersymmetric:
  - Gauge coupling g_x
  - Kinetic Mixing ε

$$\mathcal{L} \supset \frac{1}{2}\epsilon\, X^{\mu\nu} F_{\mu\nu}$$

  - Higgsino Mass μ'

- SUSY-breaking:
  - Vector mass m_{Zx}
  - Pseudoscalar mass m_{Ax}
  - Ratio of Higgs vevs $\tan\zeta$
  - Gaugino mass M_x

- Hidden Sector masses ε-suppressed if only feel SUSY breaking through kinetic mixing.

Model as Benchmark

- Model is:
  - Minimal;
  - Has all four simple decay modes;
  - Has more complex decay chains
- Can be studied on own merits
- OR as framework to examine general hidden sectors

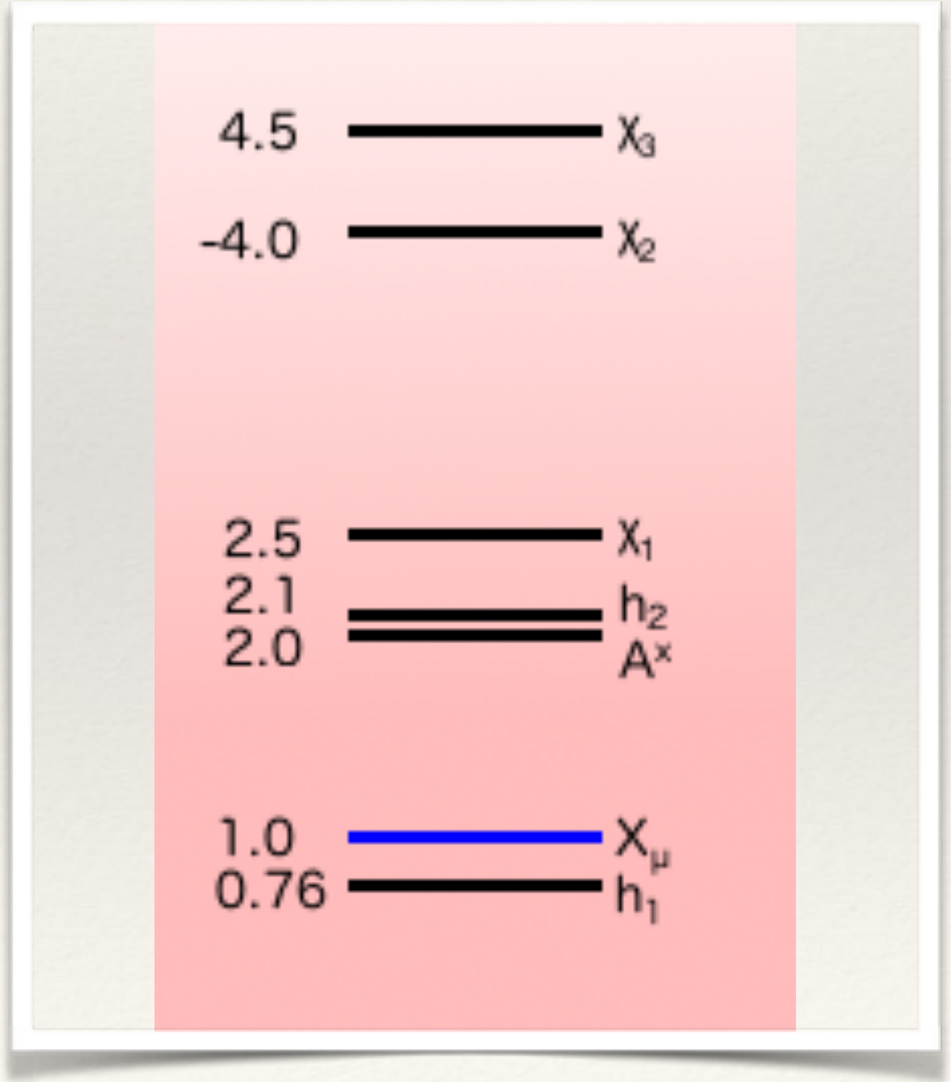
Benchmark Slope A: $Z^x \to$ SM

m	2.0
M	3.0
μ’	4.0

- Vector has no hidden decays
- Must decay to SM particles
- Generically true when

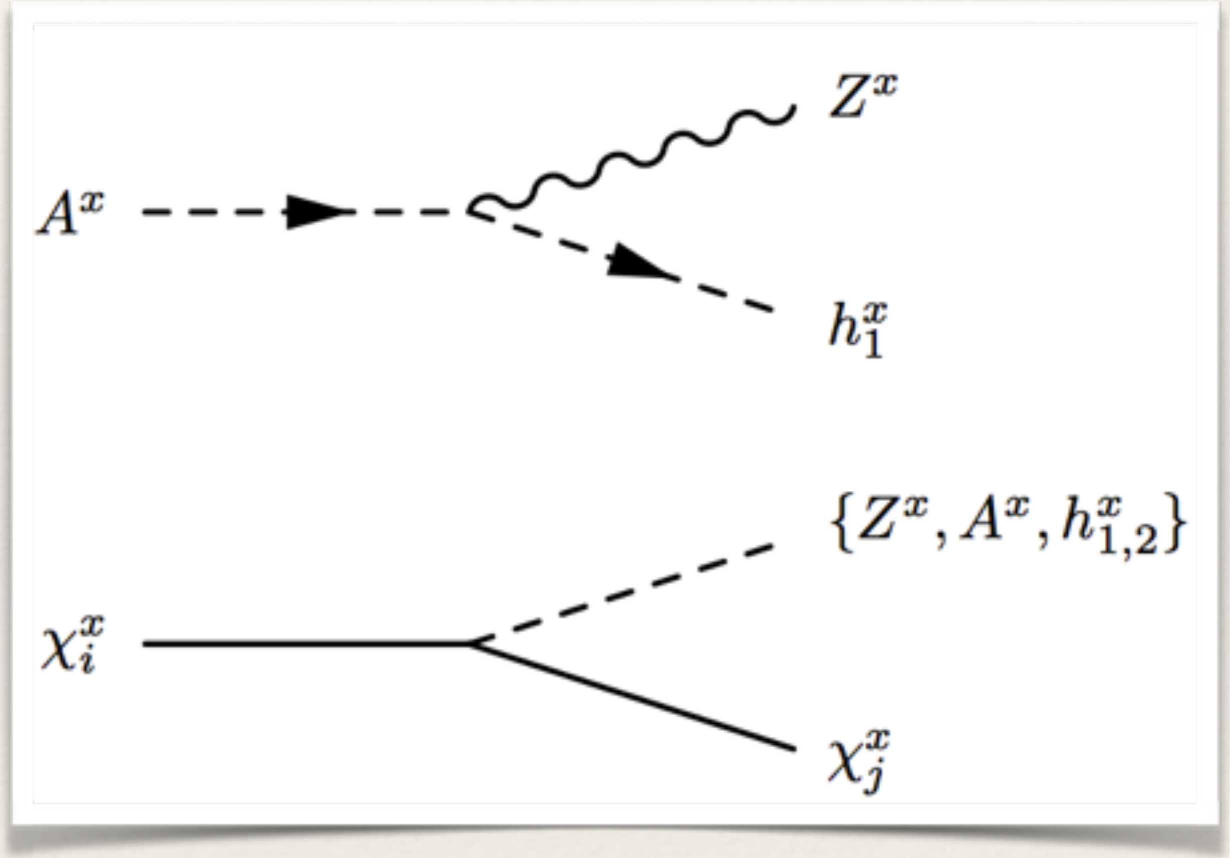
$$m_{Z^x} < m_{A^x},\ \mu',\ M_x$$

- Can still produce HS through off-shell vector



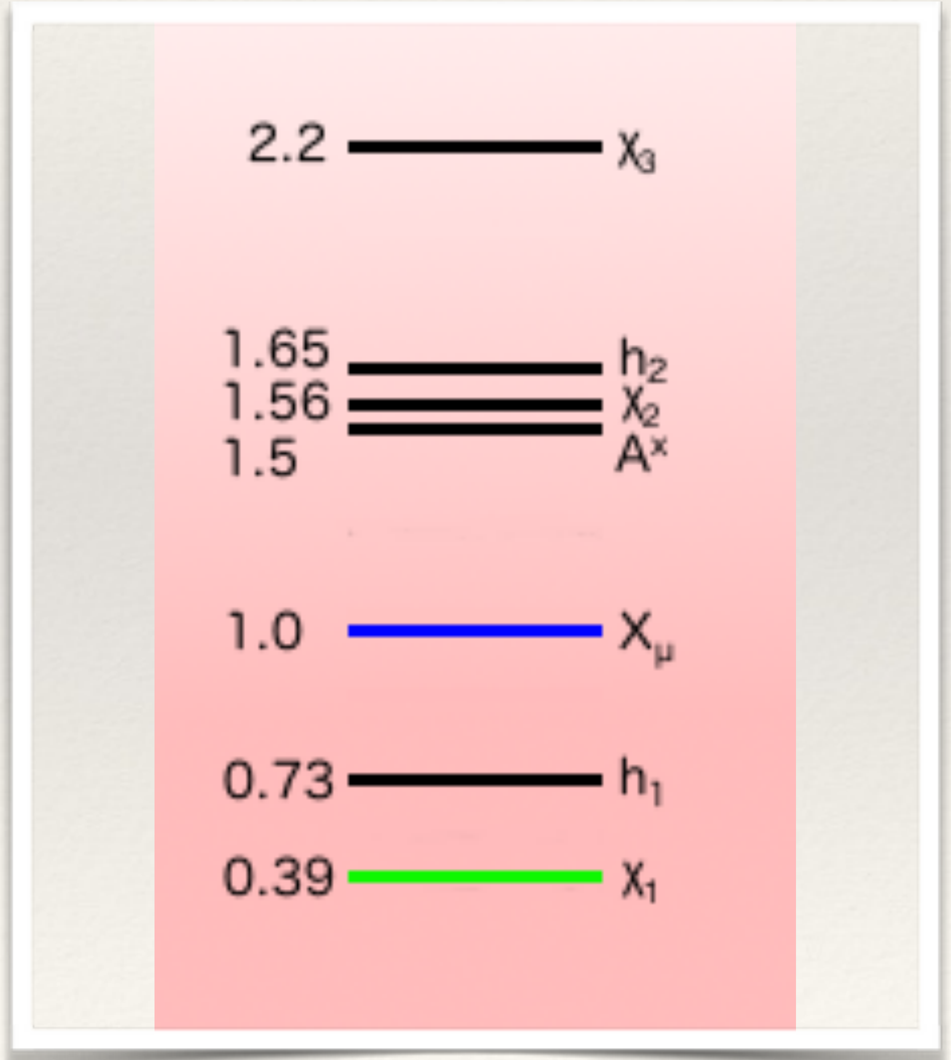
Hidden State Decays

- What states are long-lived?
- A^x: NO
  - On-shell decay to $Z^x + h^x$
- Fermions: NO
  - On-shell decay to $\chi + S^x$
- Scalar: YES
  - Suppressed decays to SM



Benchmark Slope B: $Z^x \to \mathrm{Inv}$

m	1.5
M	1.0
μ’	1.5



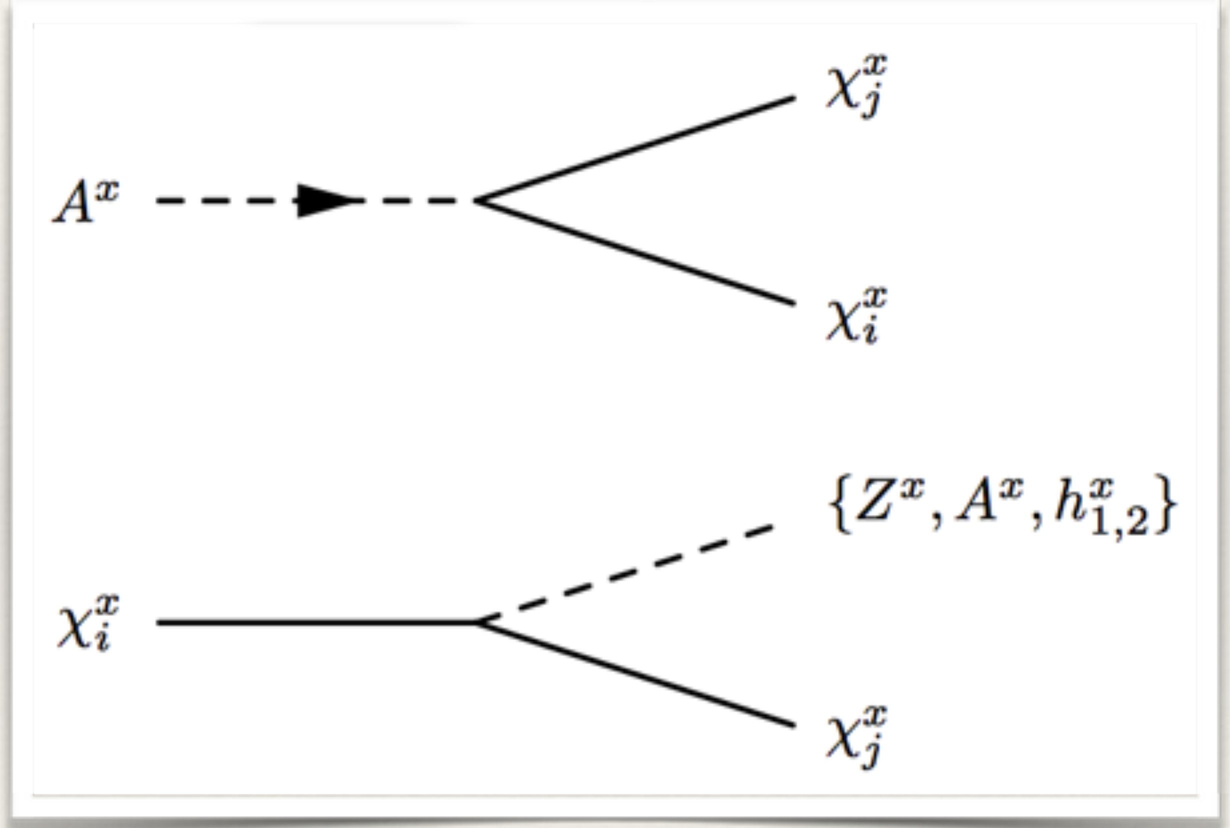
- Vector has one hidden decay:
  - To lightest (stable) fermion
- Generically true when

$$M_x < m_{Z^x} < m_{A^x},\, \mu'$$

- Can still get visible HS signals through off-shell vector

Hidden State Decays

- What states are long-lived?
- A^x: NO
  - On-shell decay to χ χ
- Fermions: NO
  - On-shell decay to χ + S^x
- Scalar: YES
  - Suppressed decays to SM



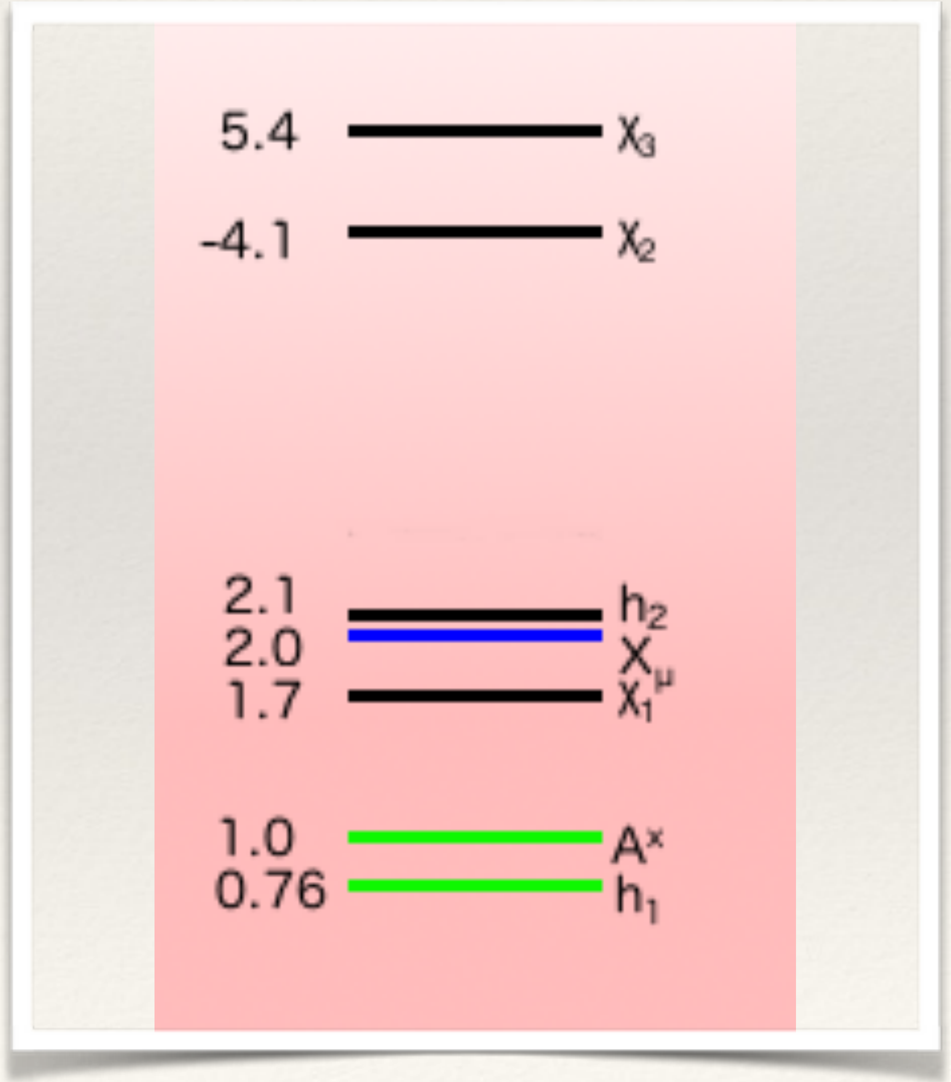
Benchmark Slope C: $Z^x \to$ Scalars

m	0.5
M	1.5
μ’	2.0

- Vector decays to hidden scalars
  - Scalars must decay to SM!
- Generically true when

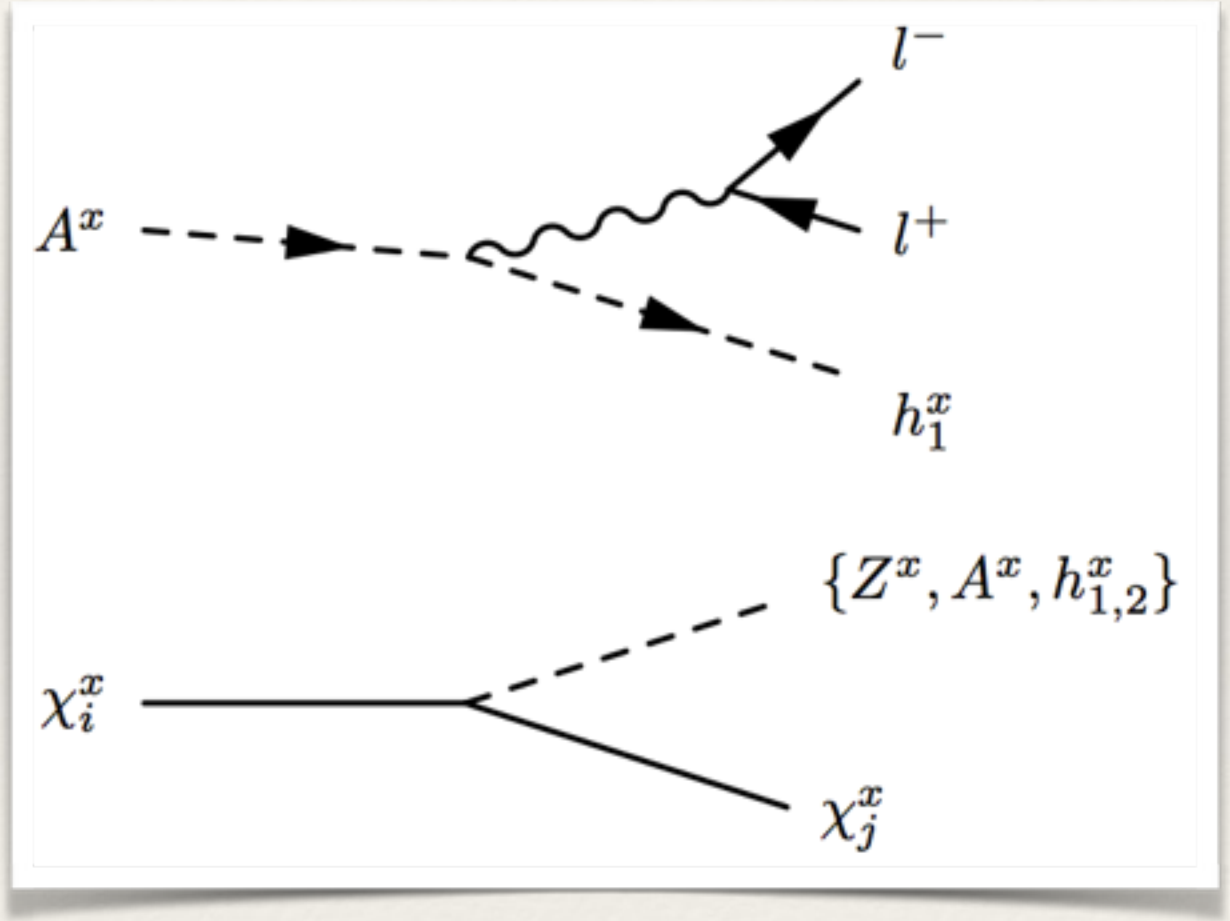
$$m_{A^x} < m_{Z^x} < \mu',\, M_x$$

-



Hidden State Decays

- What states are long-lived?
- A^x: YES
  - Off-shell decay to SM + h^x
- Fermions: NO
  - On-shell decay to χ + S^x
- Scalar: YES
  - Suppressed decays to SM

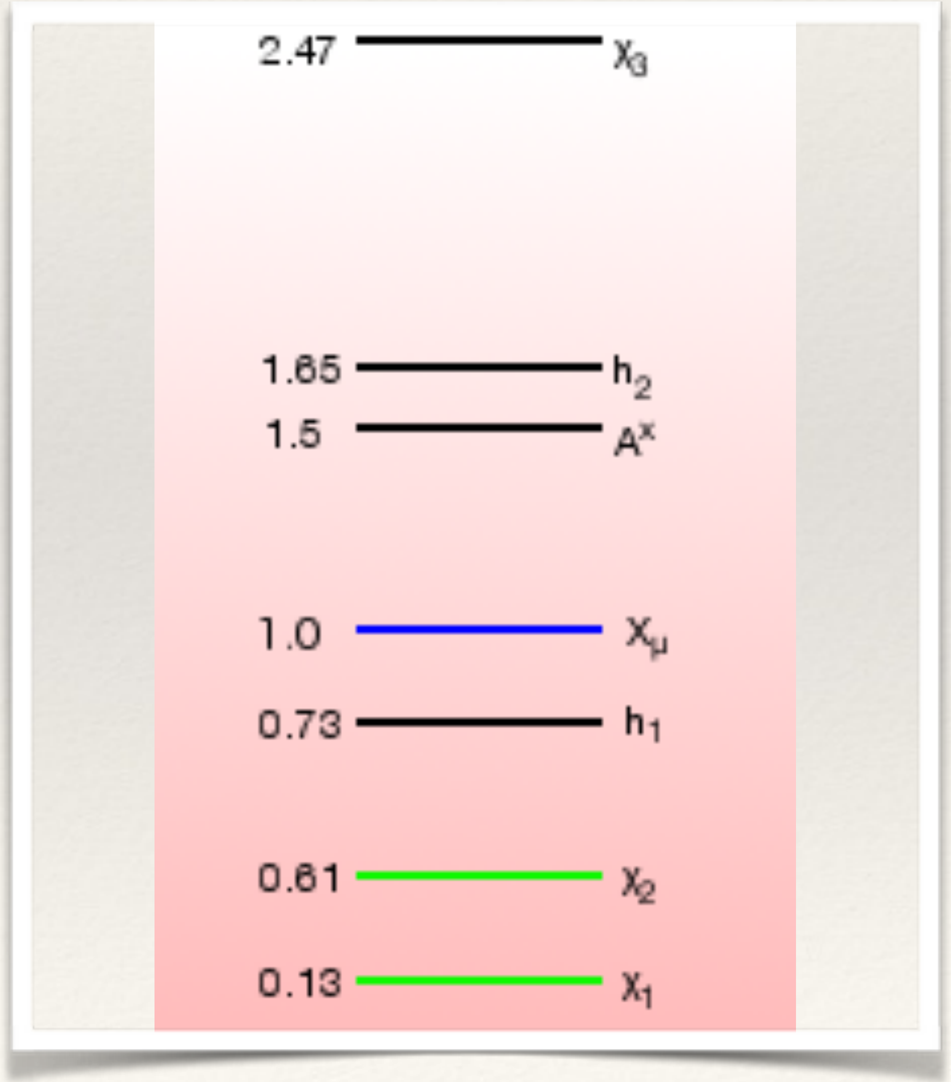


Benchmark Slope D: $Z^x \to$ Fermions

m	1.5
M	3.0
μ'	0.5

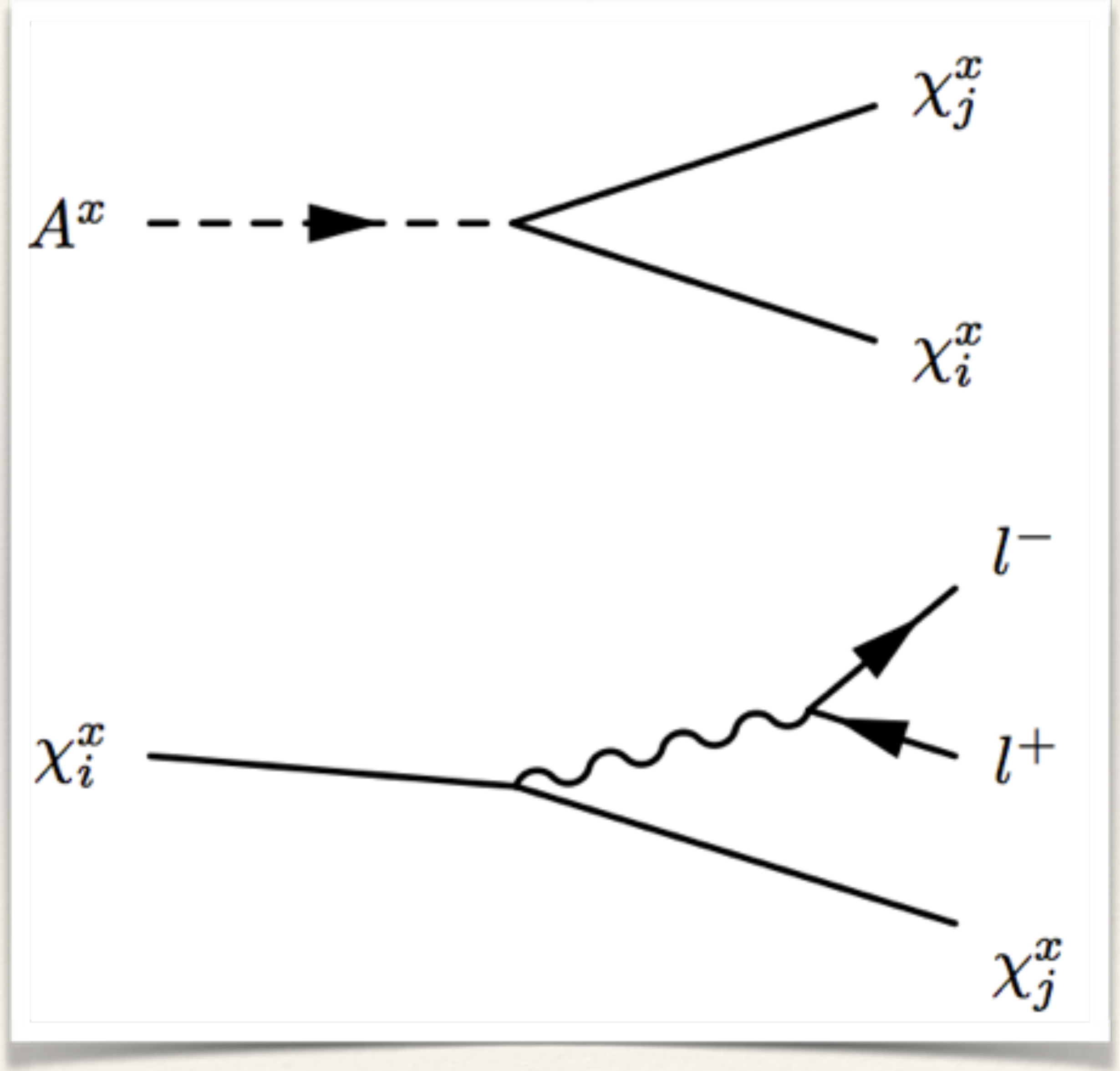
- Vector decays to HS fermions
  - χ^x_2 must decay to SM!
  - $\mathrm{BR}(Z^x \to \chi^x_2) = 94\%$
- Generically true when

$$\mu' < m_{Z^x} < m_{A^x},\ M_x$$



Hidden State Decays

- What states are long-lived?
- A^x: NO
  - On-shell decay to χ χ
- Fermions: YES
  - Off-shell decay to χ + SM
- Scalar: NO
  - Suppressed decays to χ χ



A Higgs Portal from Vector Portal

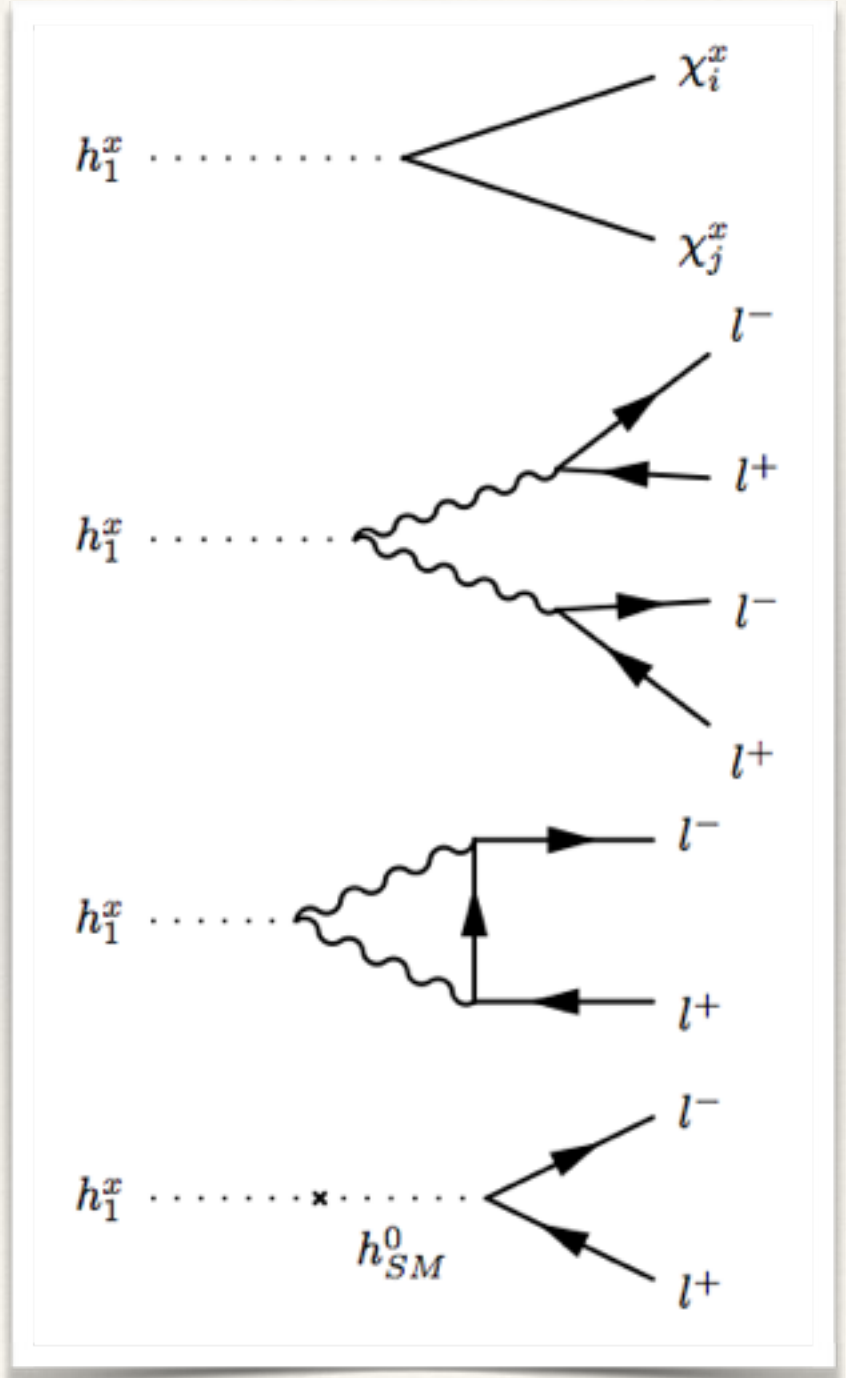
- One important consequence of SUSY in our model
- Kinetic mixing comes from mixing of superfields:

$$\int d^2\theta\, X^\alpha B_\alpha \supset X^{\mu\nu} B_{\mu\nu} + 2 D_X D_B \rightsquigarrow (H^\dagger H - H'^\dagger H')\,(H_u^\dagger H_u - H_d^\dagger H_d)$$

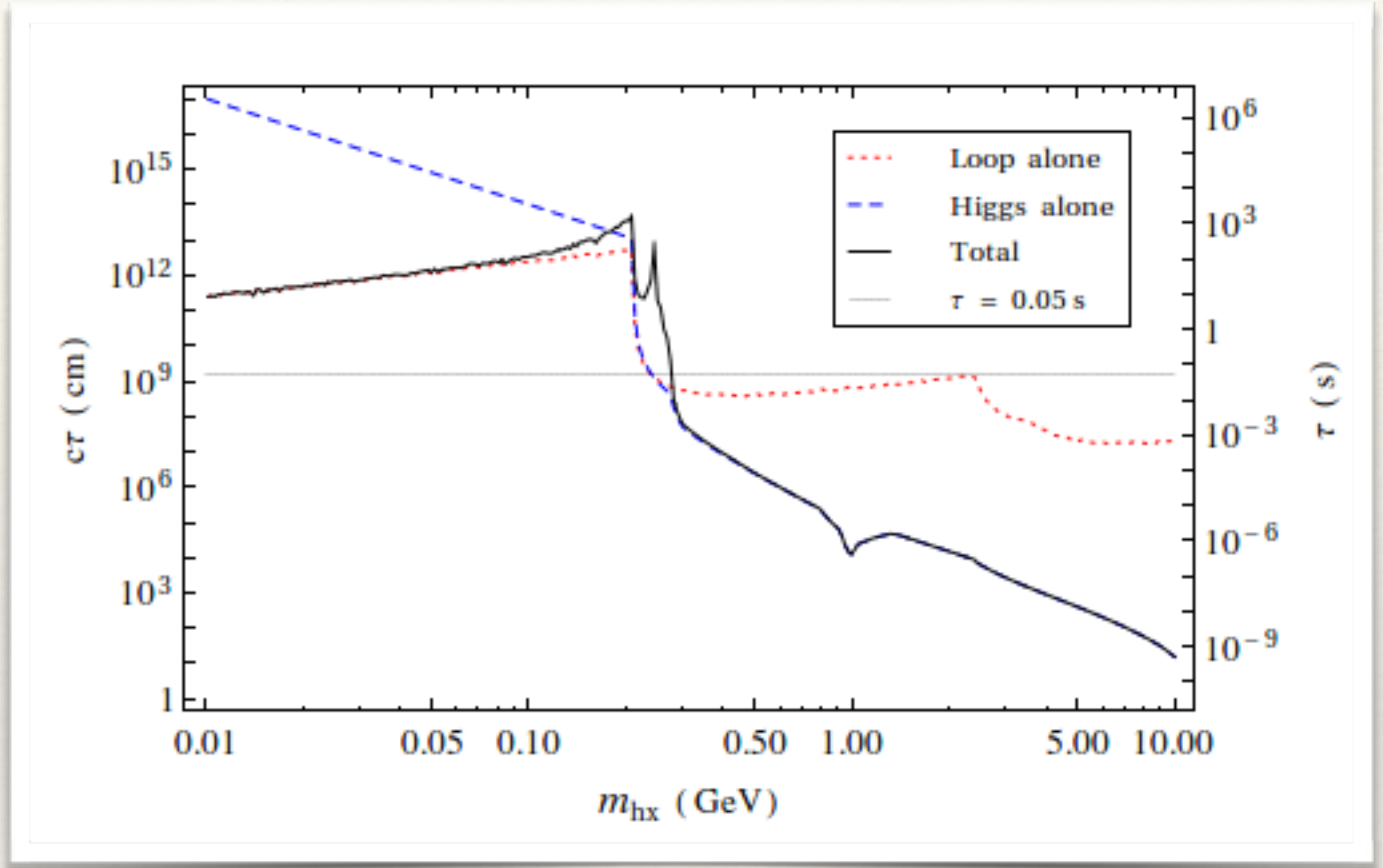
- In SUSY, a Vector Portal implies a Higgs Portal
- Higgs mixing highly suppressed, $\sim \epsilon m_{Z^x}^2 / m_Z^2$
  - BUT! new channel for hidden Higgs decays

Hidden Higgs Decays

- Lightest scalar:
  - No HS bosonic decays
  - HS fermion decays (Slope D)
  - Decays to SM:
    - Four-body
      (irrelevant, Batell *et al.* [0903.0363])
    - Vector loop
    - Higgs mass mixing
- Scalar is always long-lived



Effects of Mass Mixing

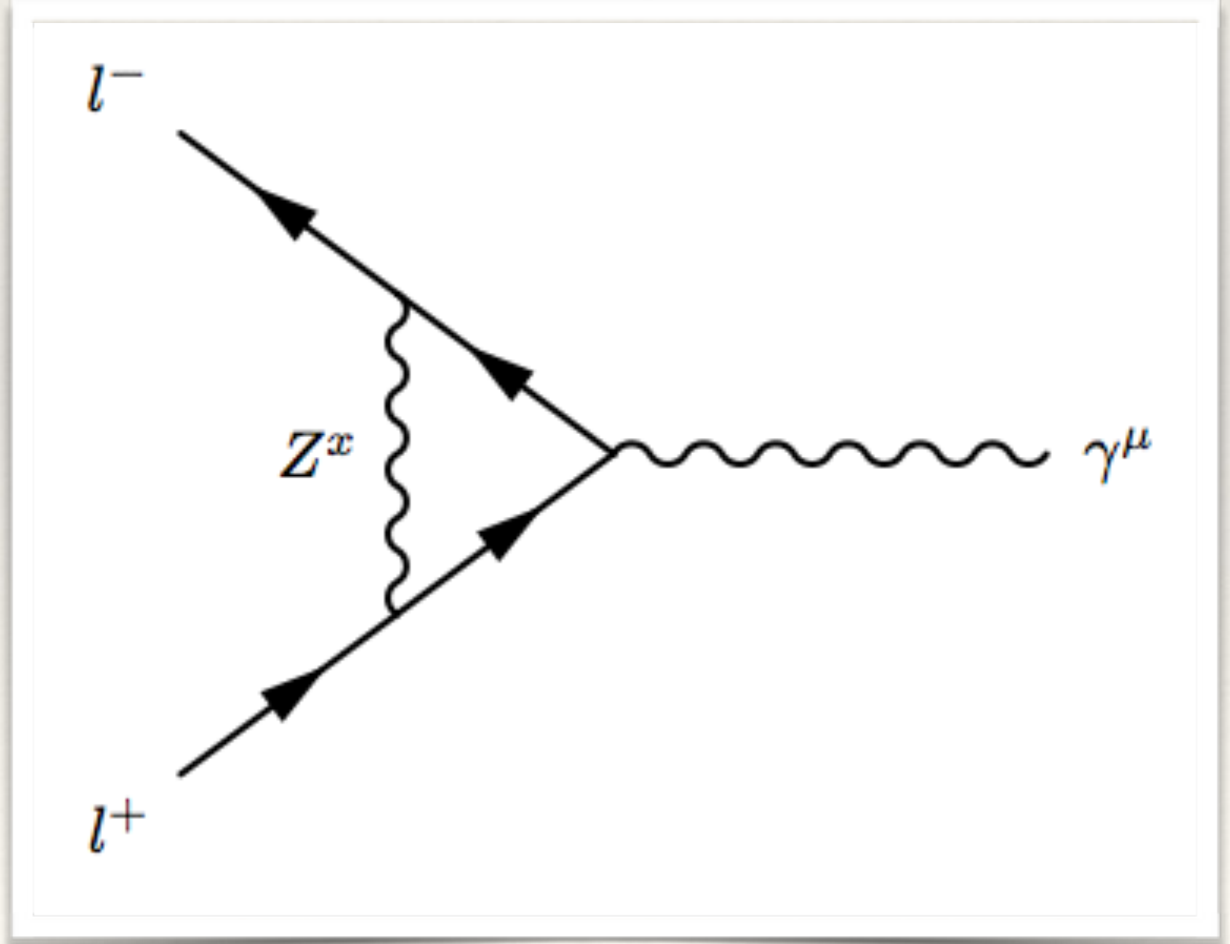


- Decay through mass mixing dominant above pion threshold
- Show results with and without mass mixing

Non-Beam Dump Limits

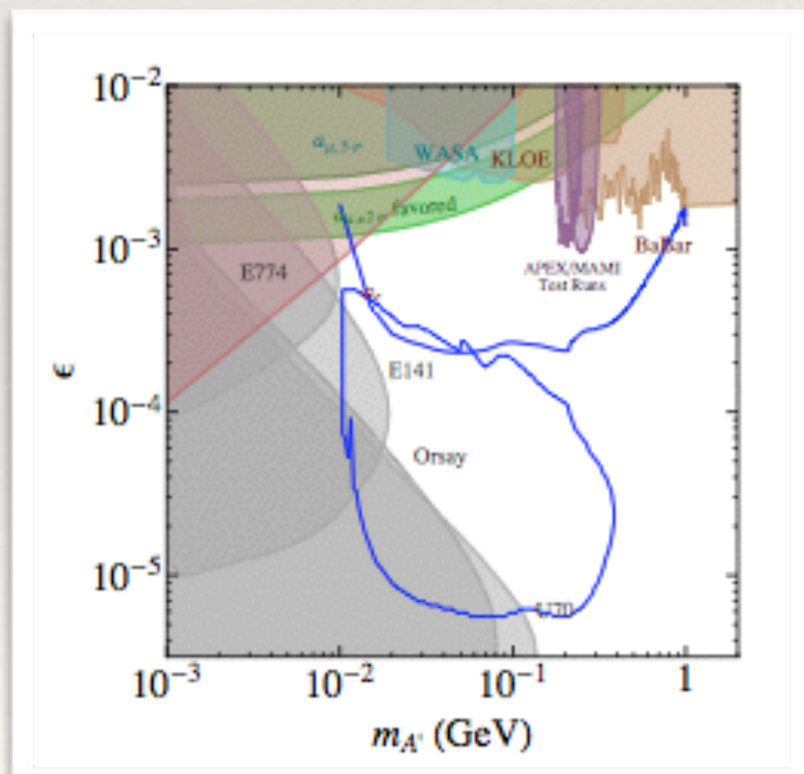
Model-Independent Limits

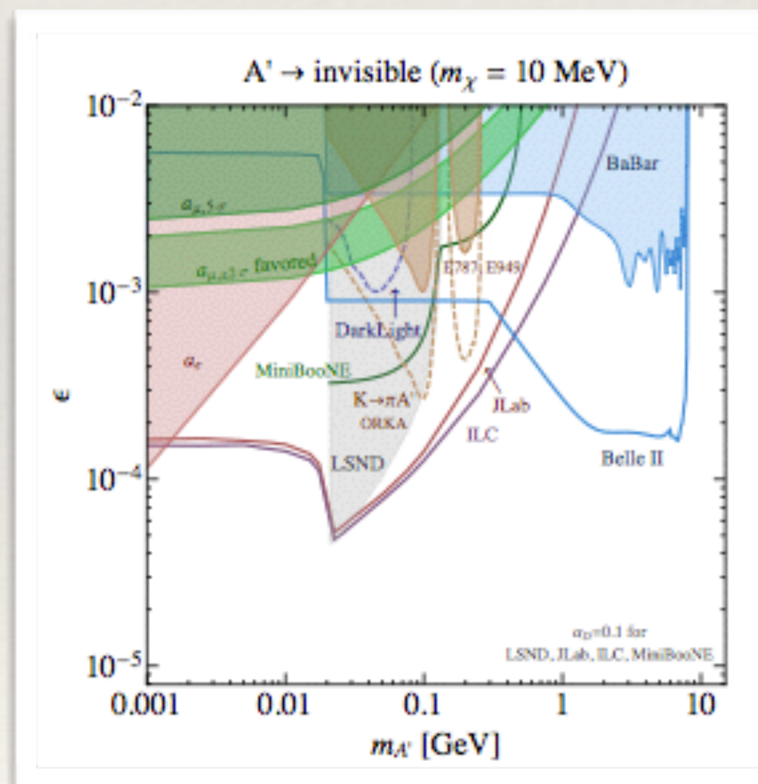
- Electroweak Precision: (m_Z)
  - Kinetic Mixing Modifies Z
  - $\varepsilon \lesssim 0.026$ [Hook *et al*, `1006.0973`]
- Anomalous Magnetic Moments
  - Intro QFT Calculation
  - Limits from a_e and a_μ
- Possible explanation of δa_μ
- Details: Pospelov, `[0811.1030]`



Meson Decays: Slopes A and B

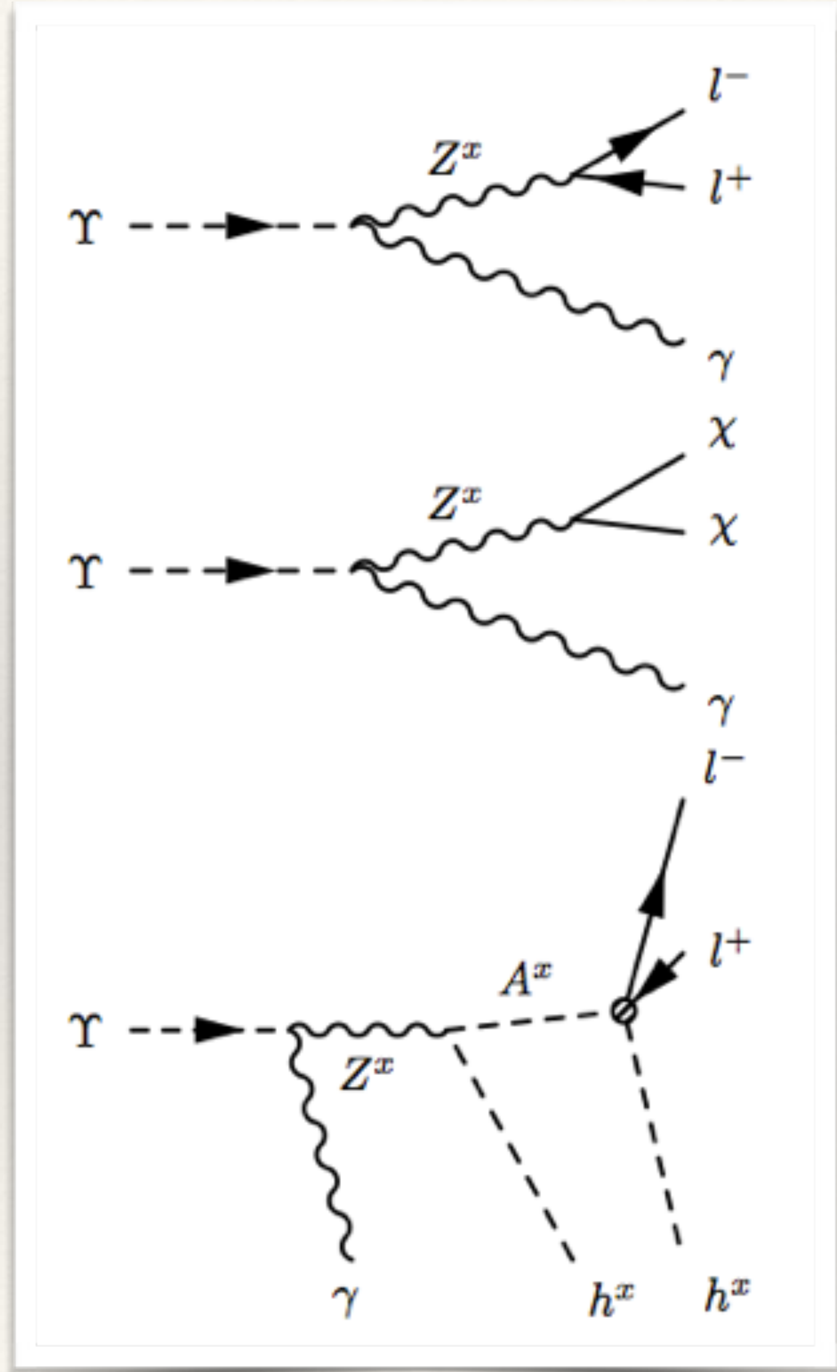
- BaBar Υ (3s, 2s) $\rightarrow \gamma\, a^0 \rightarrow \gamma\, \mu^+\, \mu^-$
- KLOE $\varphi \rightarrow \eta\, Z^x \rightarrow \eta\, e^+\, e^-$
- WASA $\pi^0 \rightarrow \gamma\, Z^x \rightarrow \gamma\, e^+\, e^-$
- BaBar Υ (3s) $\rightarrow \gamma\, a^0 \rightarrow \gamma + \text{inv}$
- E787, E949 $K^+ \rightarrow \pi^+\, \nu\, \overline{\nu}$



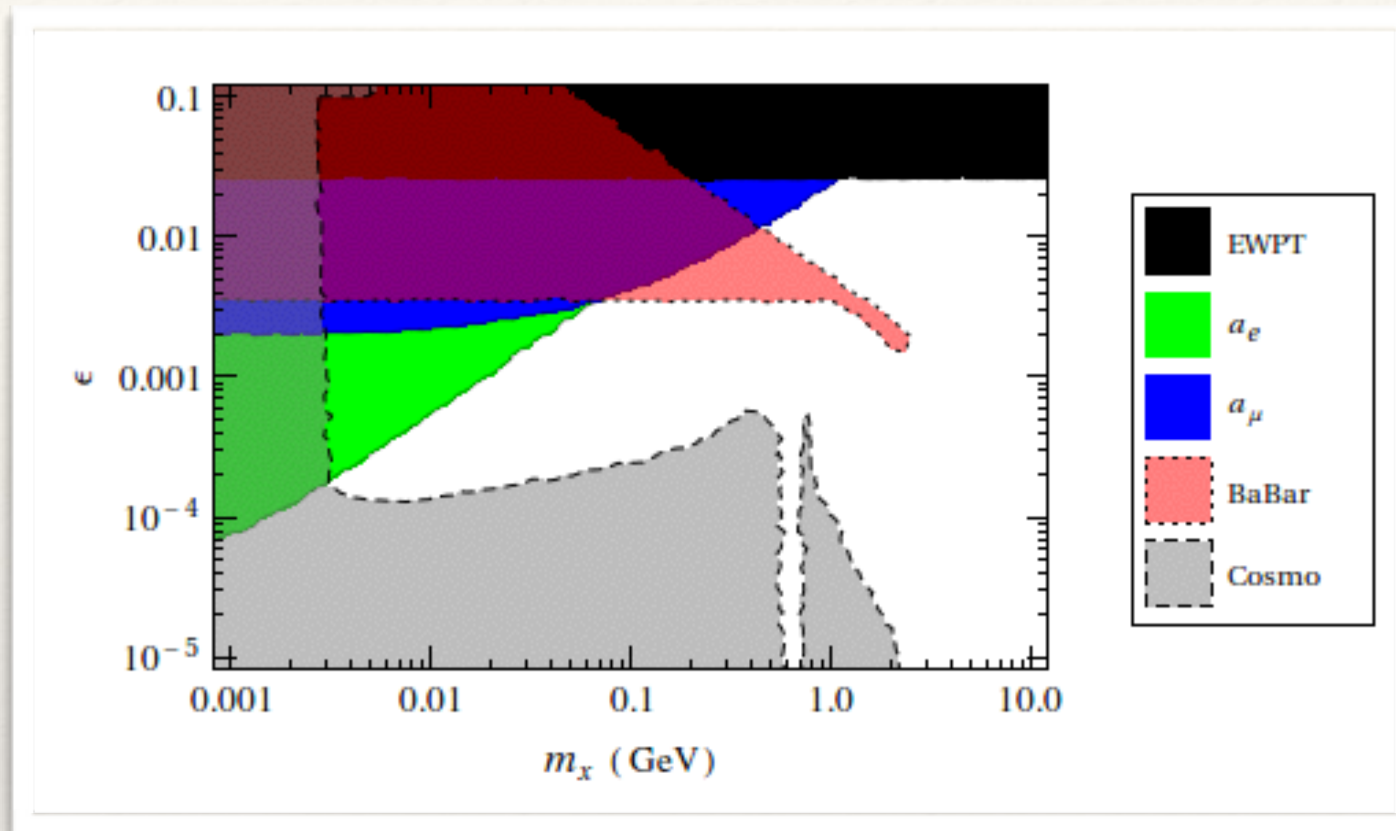


Meson Search Topologies

- Search Topologies:
  - Visible decays: Total energy = E_{Par}
  - Invisible decays: MET + tag
- If $Z^x \to$ Hidden Sector, instead have:
  - Tag + lepton pair + MET
  - Tag + $l^+l^-l^+l^-l^+l^-$
- These searches not done; no limits

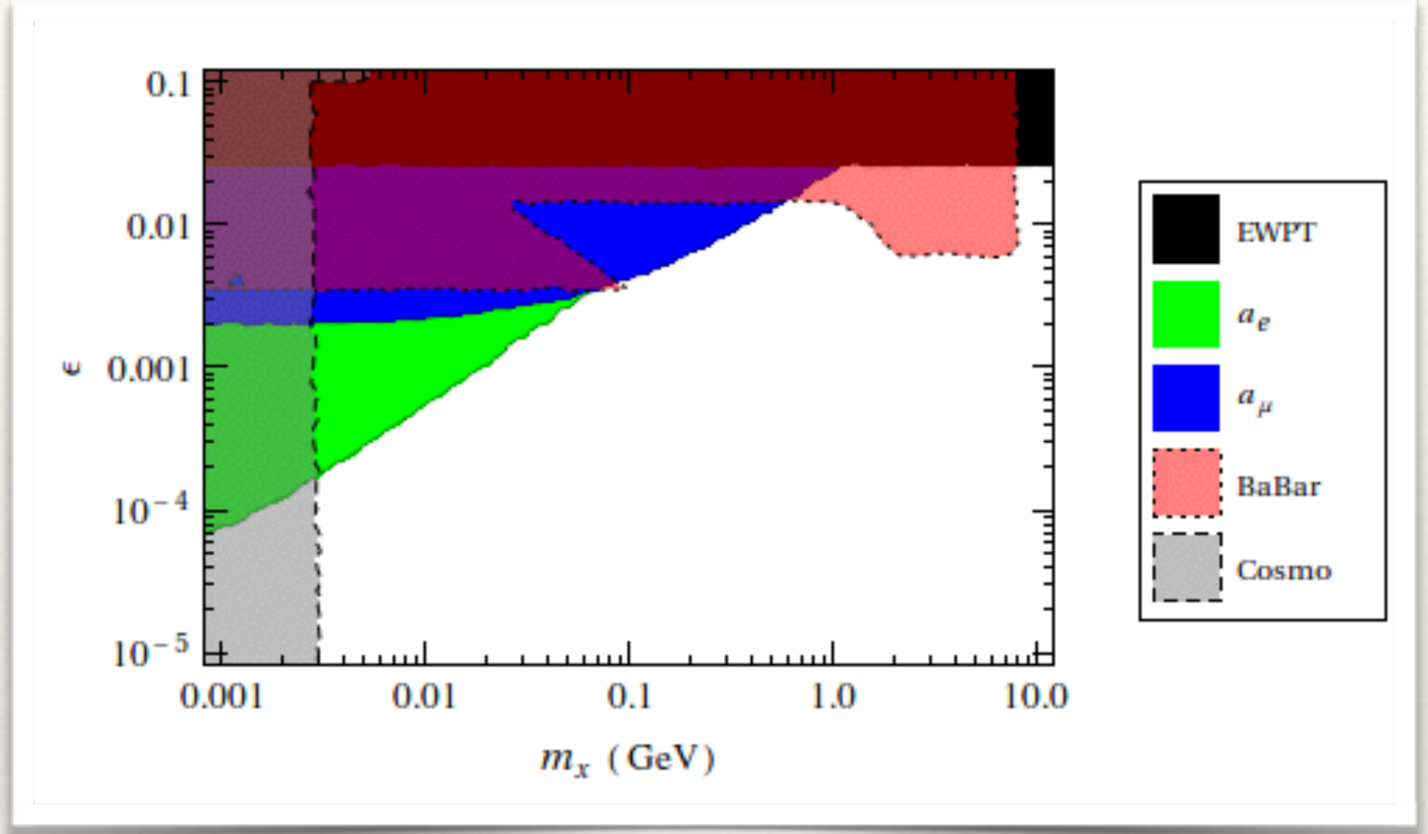


Meson Decays C: $Z^x \to$ Scalars



- Cosmology limits: CMB/BBN (late h^x decays)
- Limits from BaBar Υ (3s) $\to \gamma + Z^x \to \gamma + h^x + A^x \to \gamma +$ inv
- Not shown: E787, E949 $K^+ \to \pi^+ \ \nu \, \overline{\nu}$ limits for ε ≳ 0.01

Meson Decays D: $Z^x \to$ Fermions

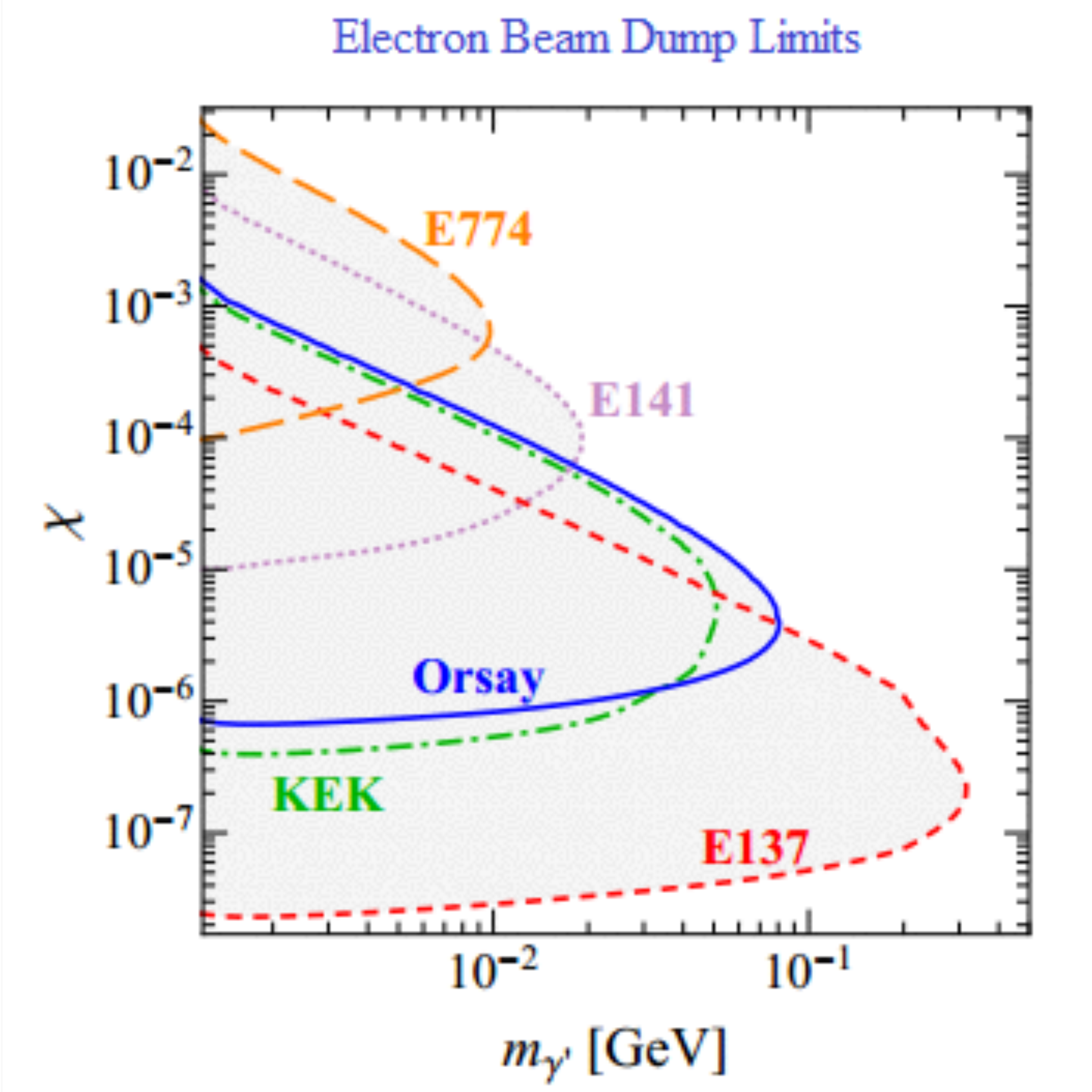


- Cosmology limits from $\chi^x{}_2$ decays
- BaBar limits again from invisible search

$$\Upsilon\,(3s) \to \gamma + Z^x \to \gamma + \chi^x{}_1 + \chi^x{}_{1,2} \to \gamma + \text{inv}$$

Electron Fixed Target Limits

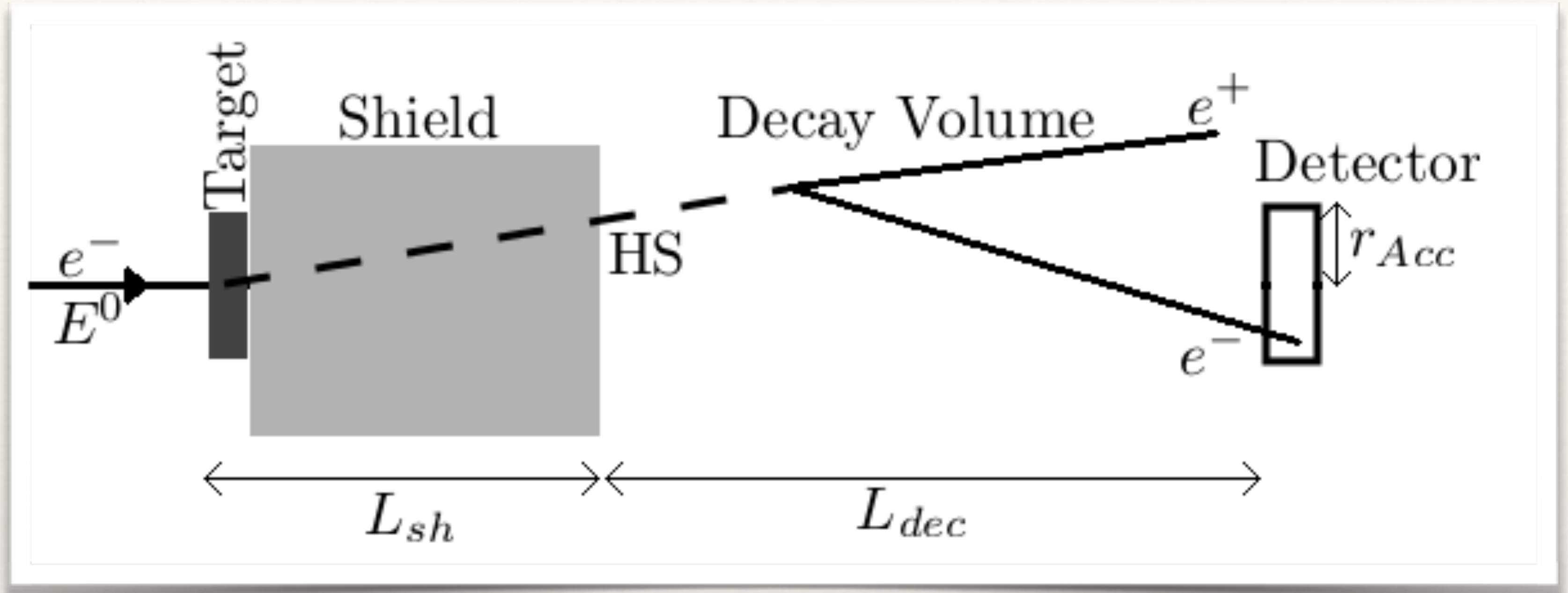
Fixed Target Experiments



Andreas et al, 1209.6083

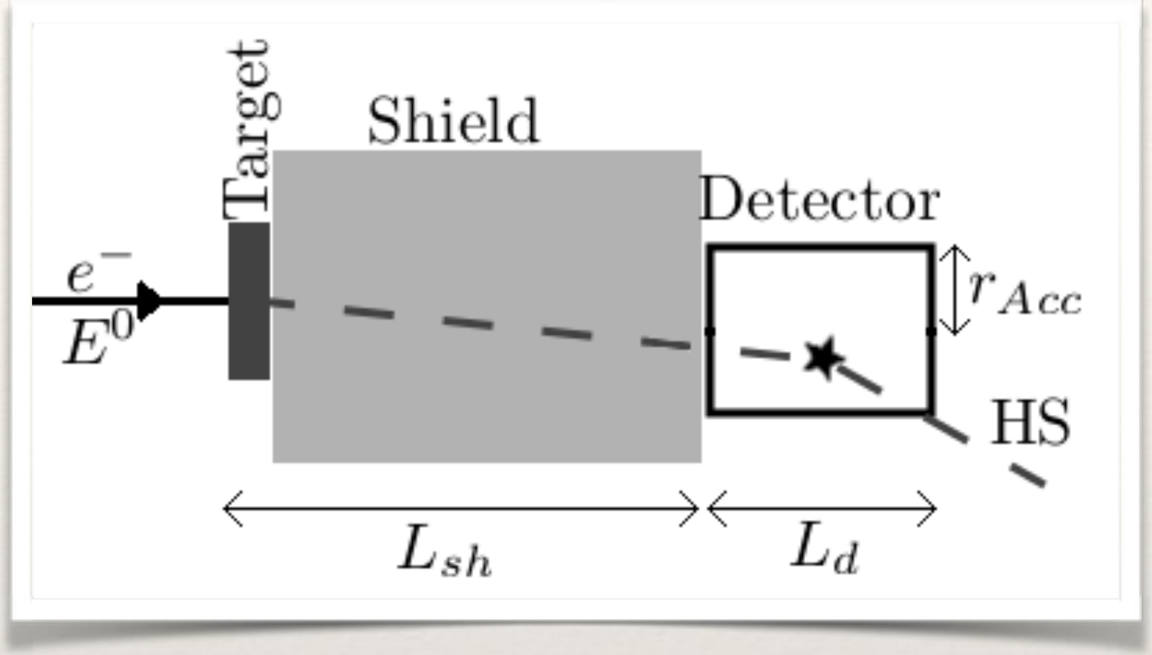
- Z^x couples to EM current
- Production from e is obvious!
- Recasting old experiments has placed important limits
- Proposed new searches for light DM/ to fill in the gaps

Visible Searches



- Most common searches for displaced decays to SM
- Includes all past and most current/proposed experiments
- Past searches discussed only Z^x as metastable: $\Rightarrow$ limits at low m_{Z^x}, ε
- We have A^x, h^x and χ^x also possibly long-lived: $\Rightarrow$ limits at high m_{Z^x}, ε?

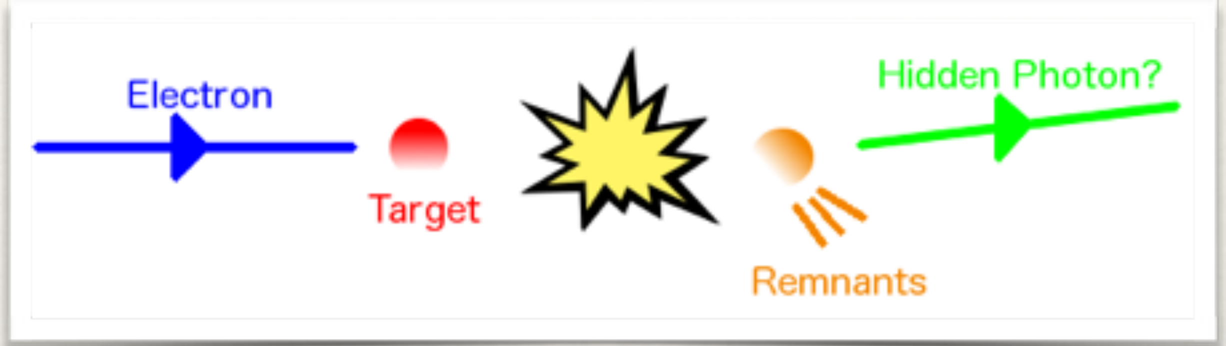
Invisible Scattering Searches

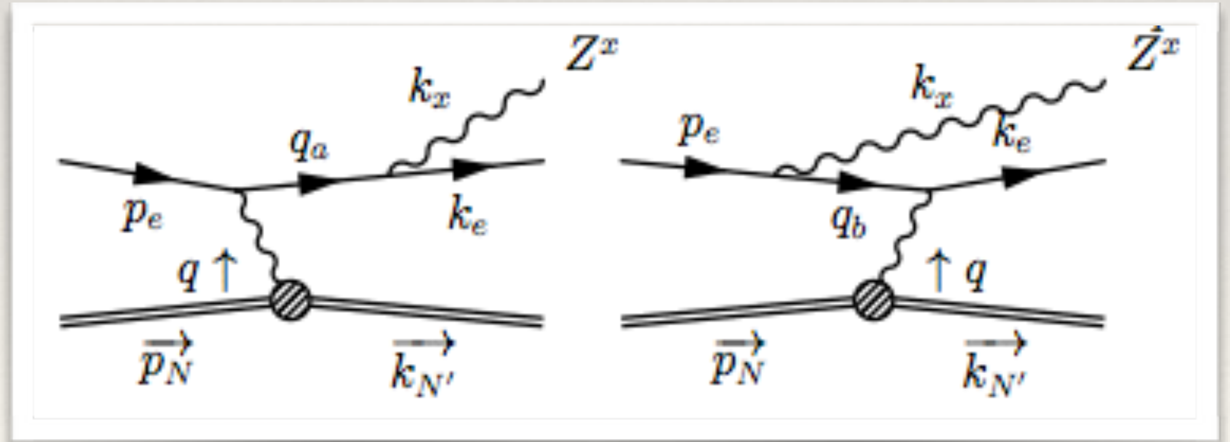


- Proposed experiments at JLab `[1307.6554]`, CERN `[1312.3309]`
- Searches motivated by light DM
- Usual assumption is Z^x decays to single stable particle
- Our long-lived states A^x, h^x and χ^x may also contribute

Production: On-Shell

- On-shell Z^x is usual & easy case
- Complicated target:
  - Electron cloud, nuclear structure etc.
- Use Form-Factors
- Weizsäcker-Williams Approx.
  - Electron rest frame
  - Target is cloud of virtual γ





Weizsäcker-Williams Approximation

- Express $\sigma(eN)$ in terms of $\sigma(e\gamma)$

$$m_e \ll m_{Zx} \ll E_e$$

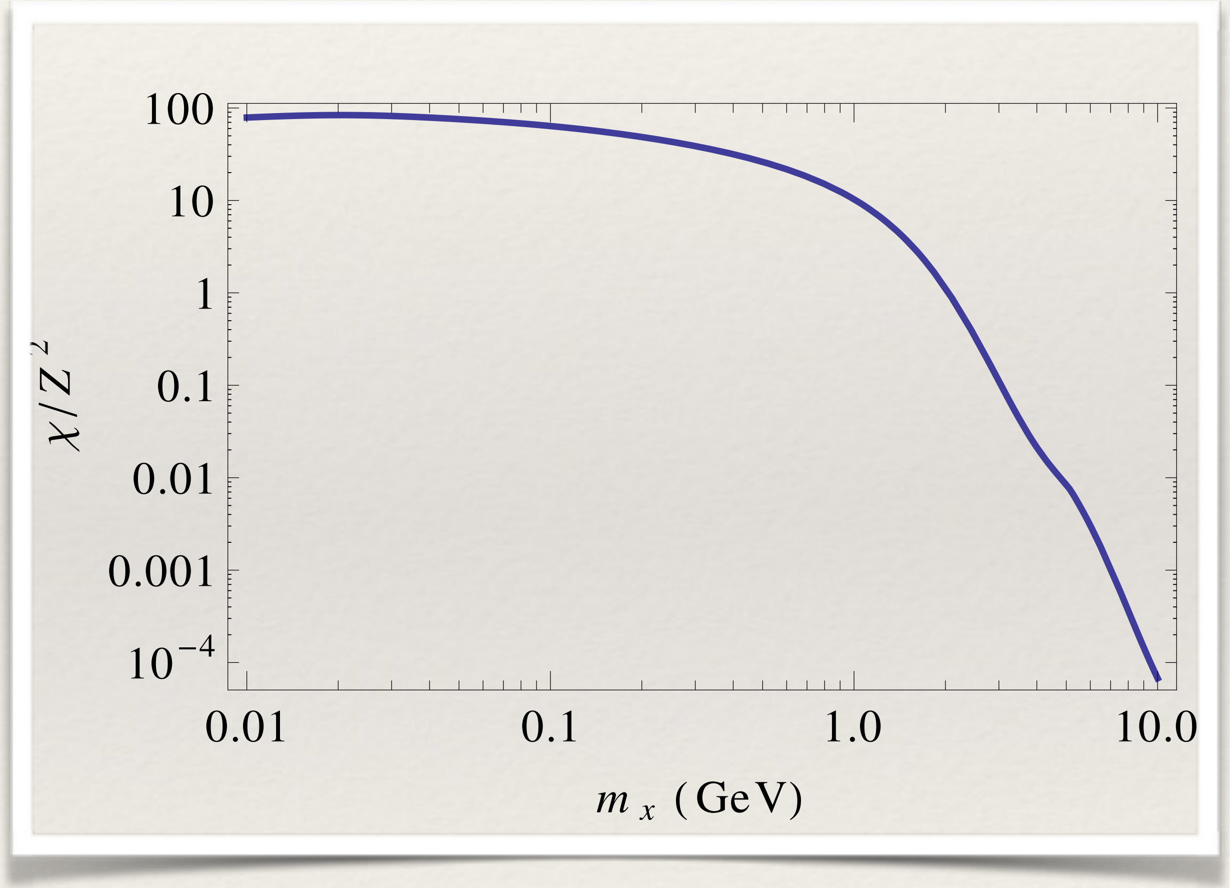
$$E_x \quad \vartheta^2 \ll E_e$$

$$\frac{d\sigma\left(eN \to eZ^x N'\right)}{d(p_e \cdot k_x)\, d(p_N \cdot k_x)} = \frac{\alpha}{\pi} \frac{d\sigma\left(e\gamma \to eZ^x\right)}{d(p_e \cdot k_x)}\bigg|_{q=q^*} \frac{\chi}{p_N \cdot k_e}.$$

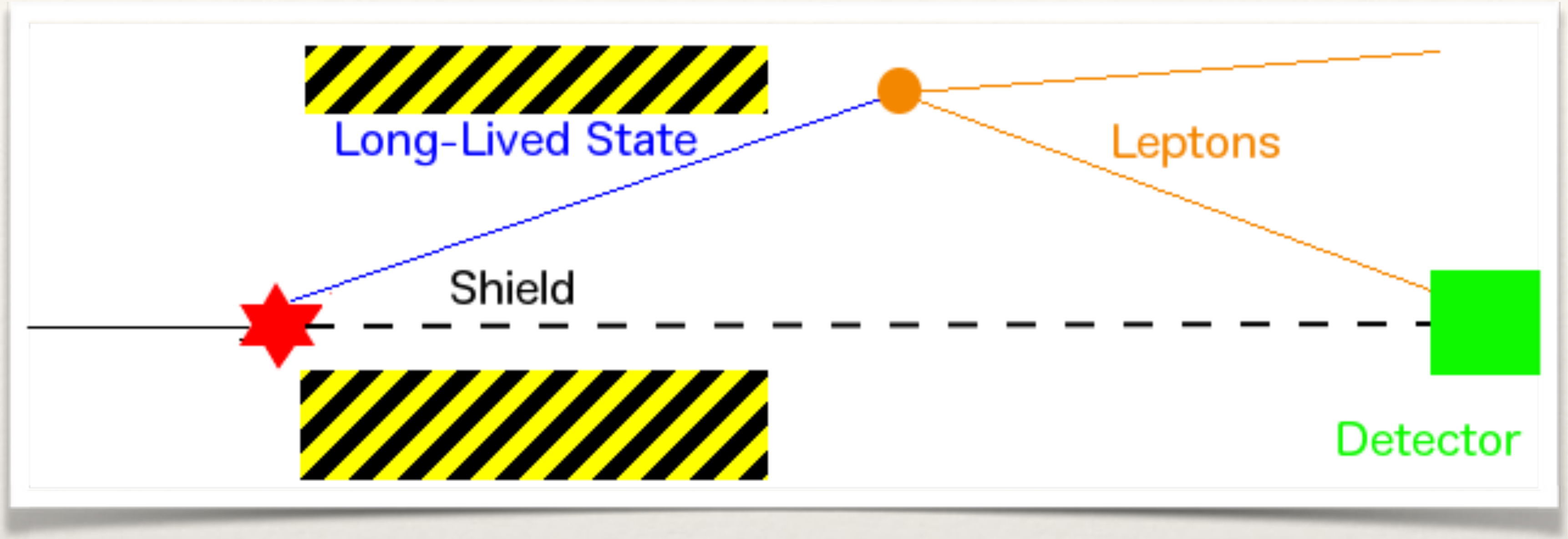
- All target dependence in Form-Factor integral χ

$$\chi \sim \int \frac{\mathrm{d}t}{t^2} \int \mathrm{d}M_f^2 \sum W(t, M_f^2)$$

- Small angle quasi-elastic scattering dominates



Acceptances



- Use simple Monte Carlo to convert N_{Zx} to N_{sig}
  - Visible: $N_{\text{sig}} = N_{Zx}$ x Branching Ratio x Prob. decay x Prob. daughter hits detector & is seen
  - Invisible: $N_{\text{sig}} = N_{Zx}$ x Branching Ratio x Prob. hits detector x Prob. scatters

Experimental Details

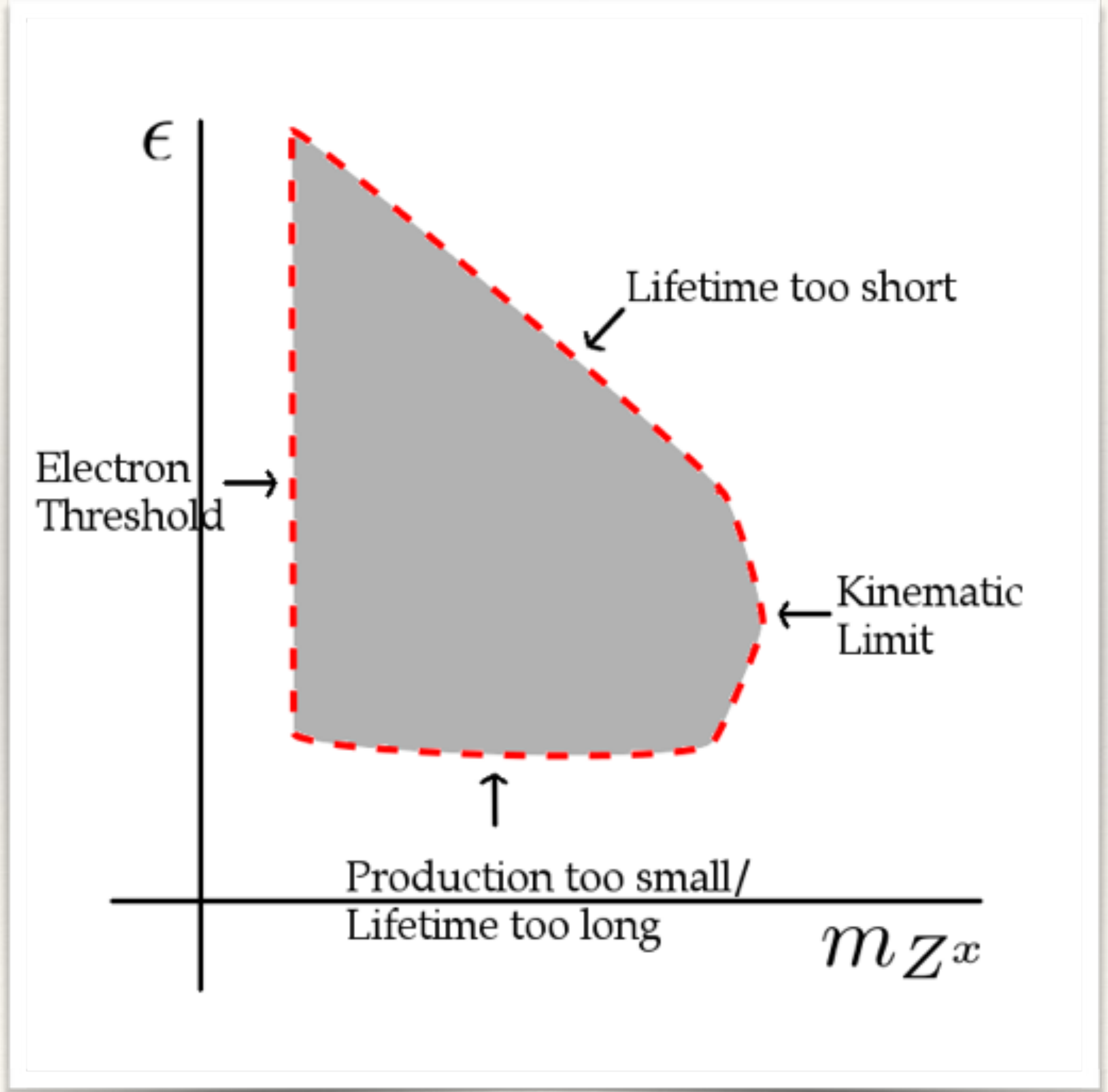
- Previous searches:
  - All somewhat relevant
  - Thresholds important

Experiment	Target	E_0	N_e	L_{sh}	L_{dec}	E_{thr}	r_{Acc}	$N_{95\%}$
E137	Al	20	1.87×10^{20}	179	204	2	1.5	3
E141	W	9	2×10^{15}	0.12	35	4.5	0.0375	3419
E774	W	275	5.2×10^{9}	0.3	2	27.5	0.1	18
KEK	W	2.5	1.69×10^{17}	2.4	2.2	0.1	0.047	3
Orsay	W	1.6	2×10^{16}	1	2	0.75	0.15	3
JLab	Al	12	10^{20}	10			1	

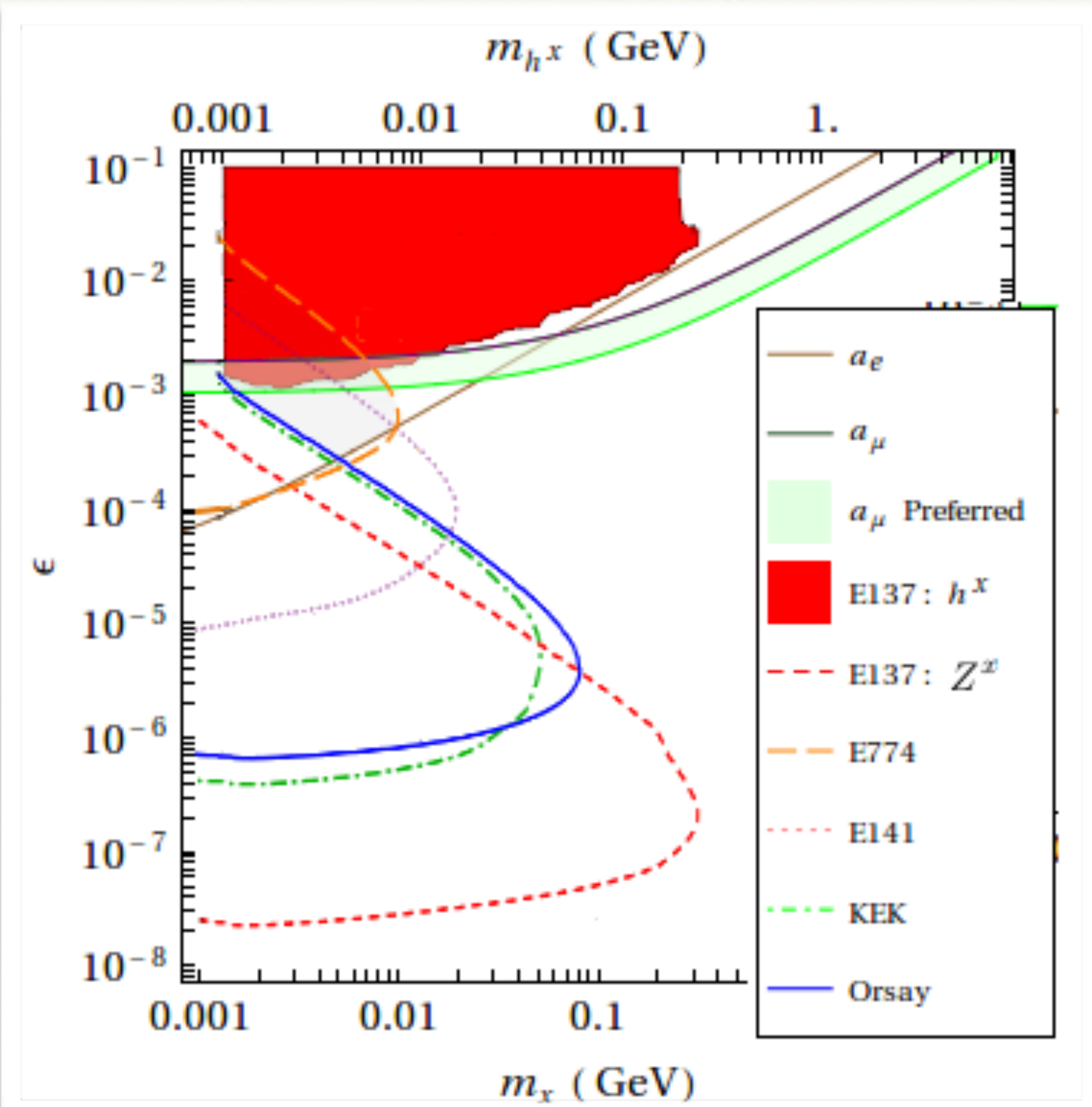
- Current/Future searches
  - Many impose cut: $E(e^+) + E(e^-) = E_{\text{beam}}$
  - Insensitive to h^x, A^x, χ^x decays

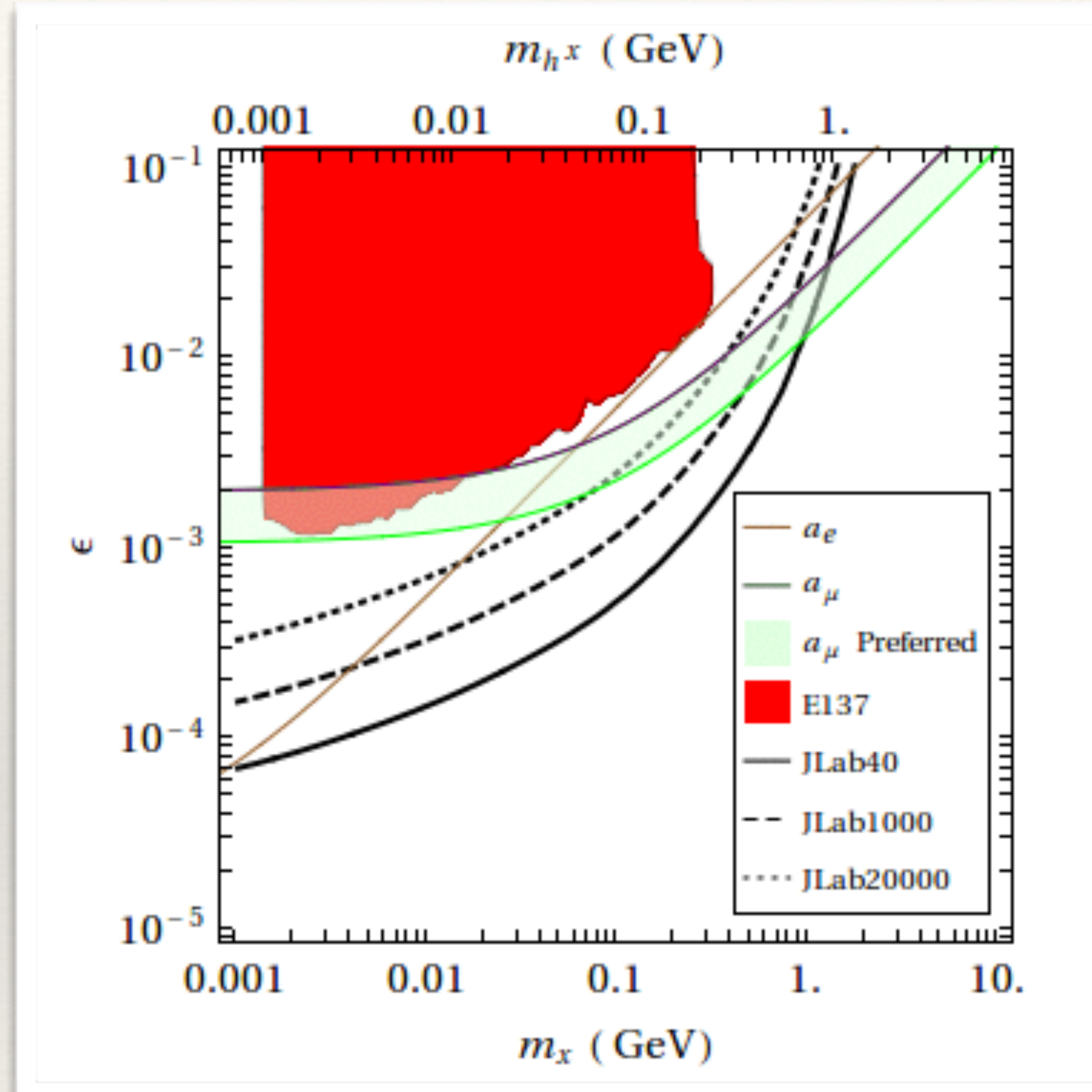
- MAMI
- APEX
- HPS
- CERN SPS (Visible)
- DarkLight

General Exclusion Limits



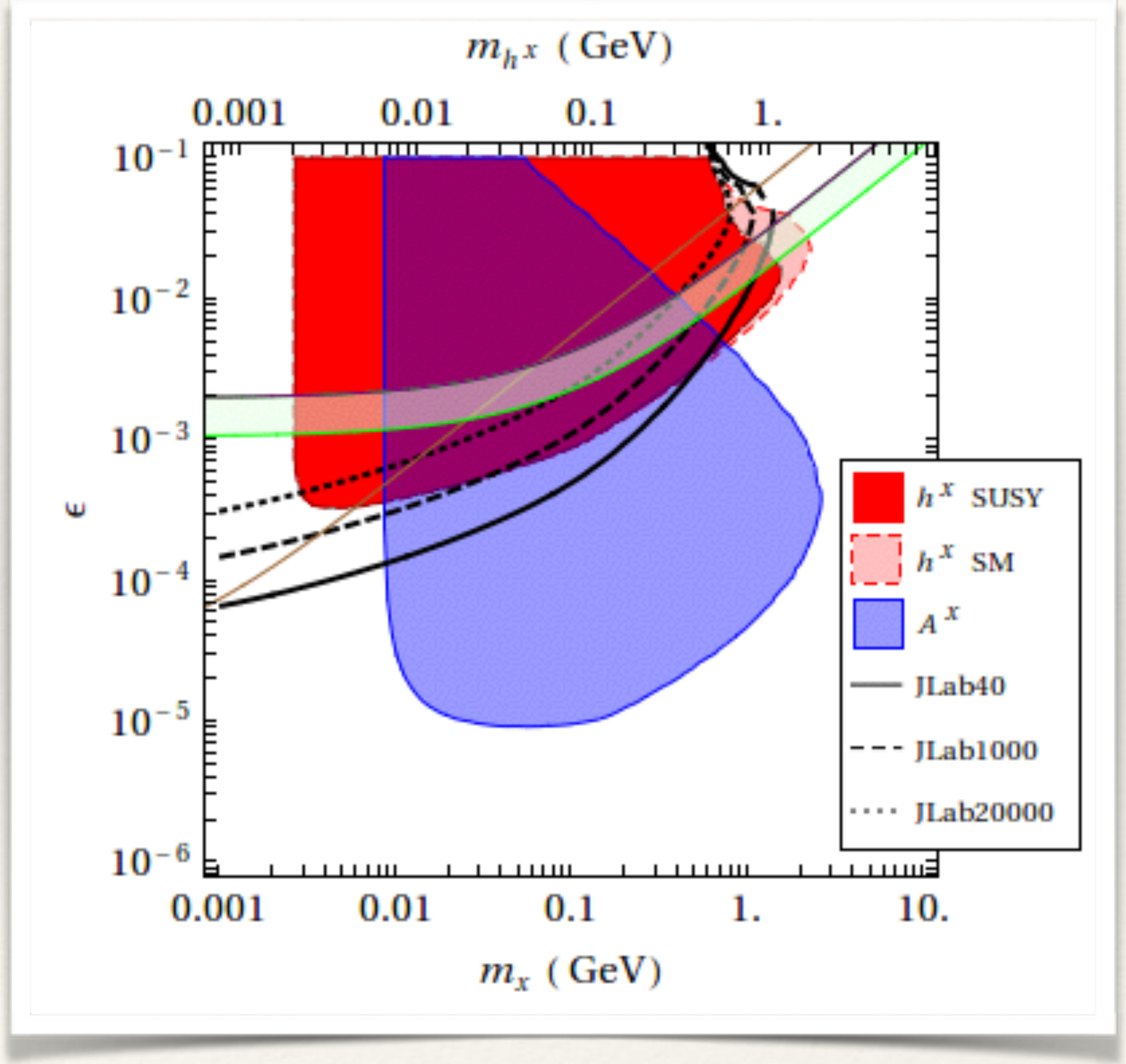
Limits: Slopes A and B





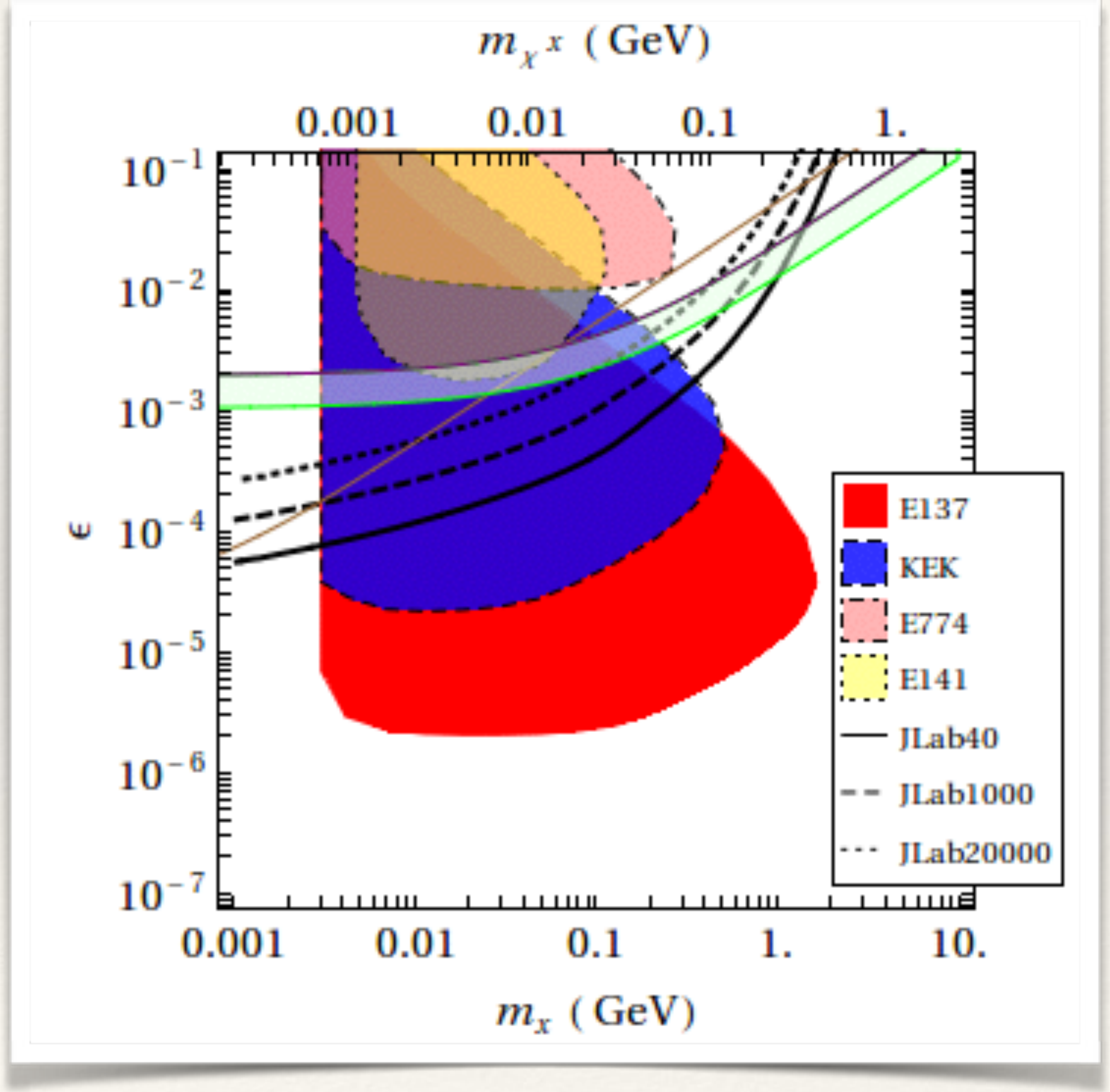
- New limits from Higgsstrahlung production
- But ultimately weaker than limits from a_e

Limits: Slope C: $Z^x \to$ Scalars



- Only E137 and JLab set limits
- Limits from h^x depend on Higgs mass mixing
- Limits from A^x stronger (longer lived) but less robust
- Limits from invisible search from h^x scattering

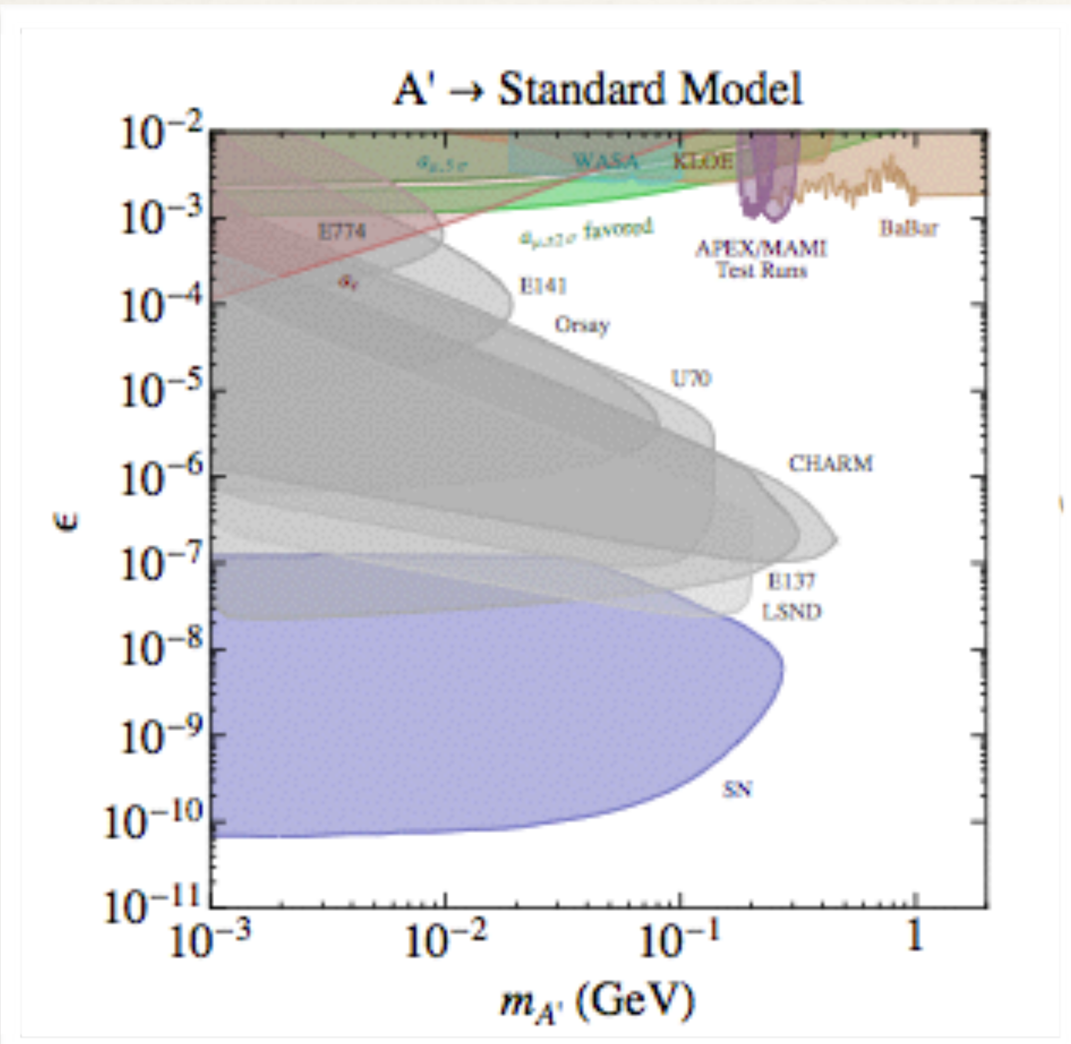
Limits: Slope D: $Z^x \to$ Fermions

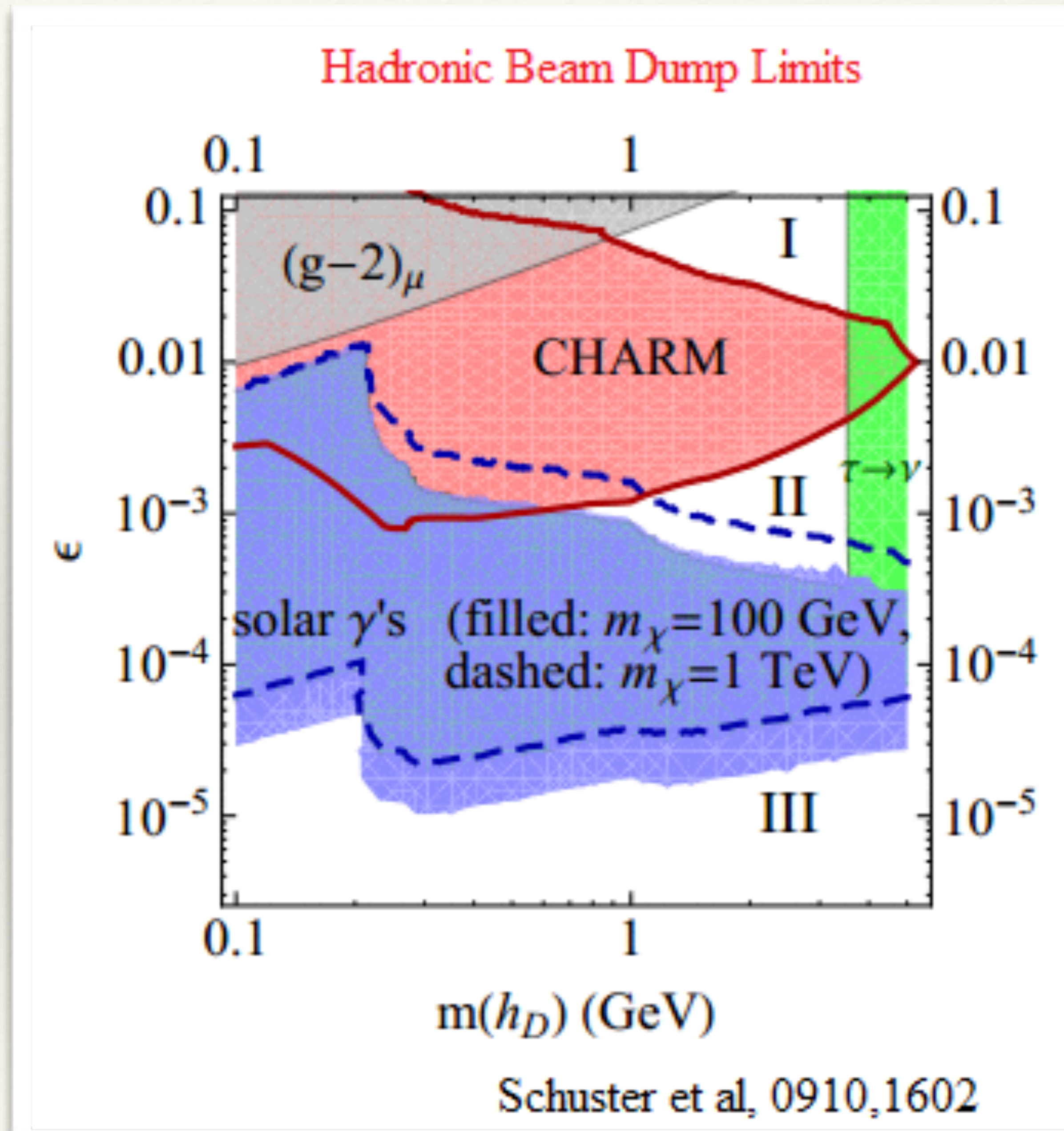


- Limits from several expts
- Set by $\chi^x{}_2$ decays: no mass mixing dependence
- JLab search sees $\chi^x{}_1$ scattering

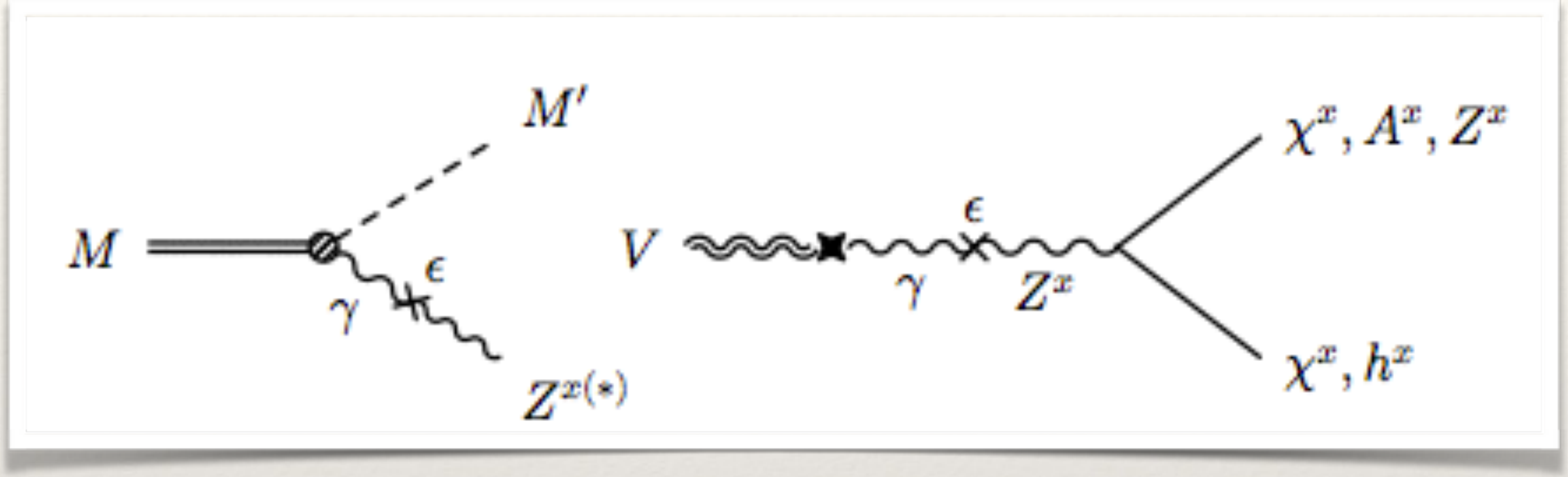
Proton Fixed Target Limits

Previous Studies





Production: Low Mass



- Light (≲ GeV) hidden states produced in meson decay
- Kinetic Mixing with daughters:

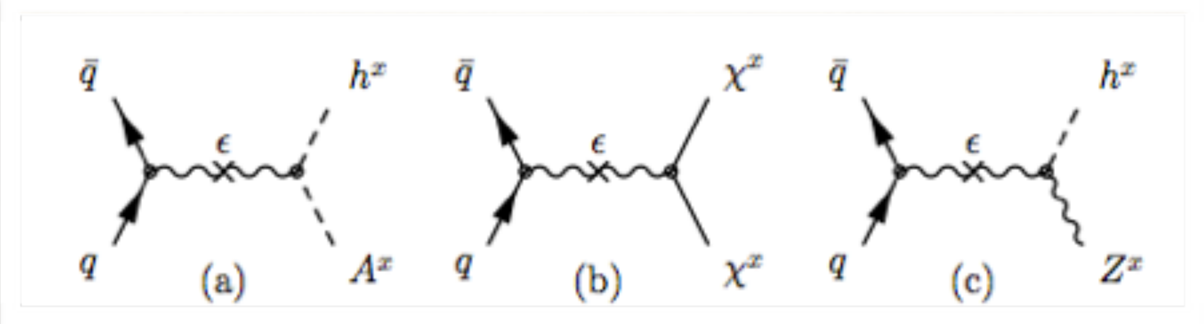
$$\pi^0 \to \gamma\, Z^x$$
$$\Delta \to Z^x\, N$$

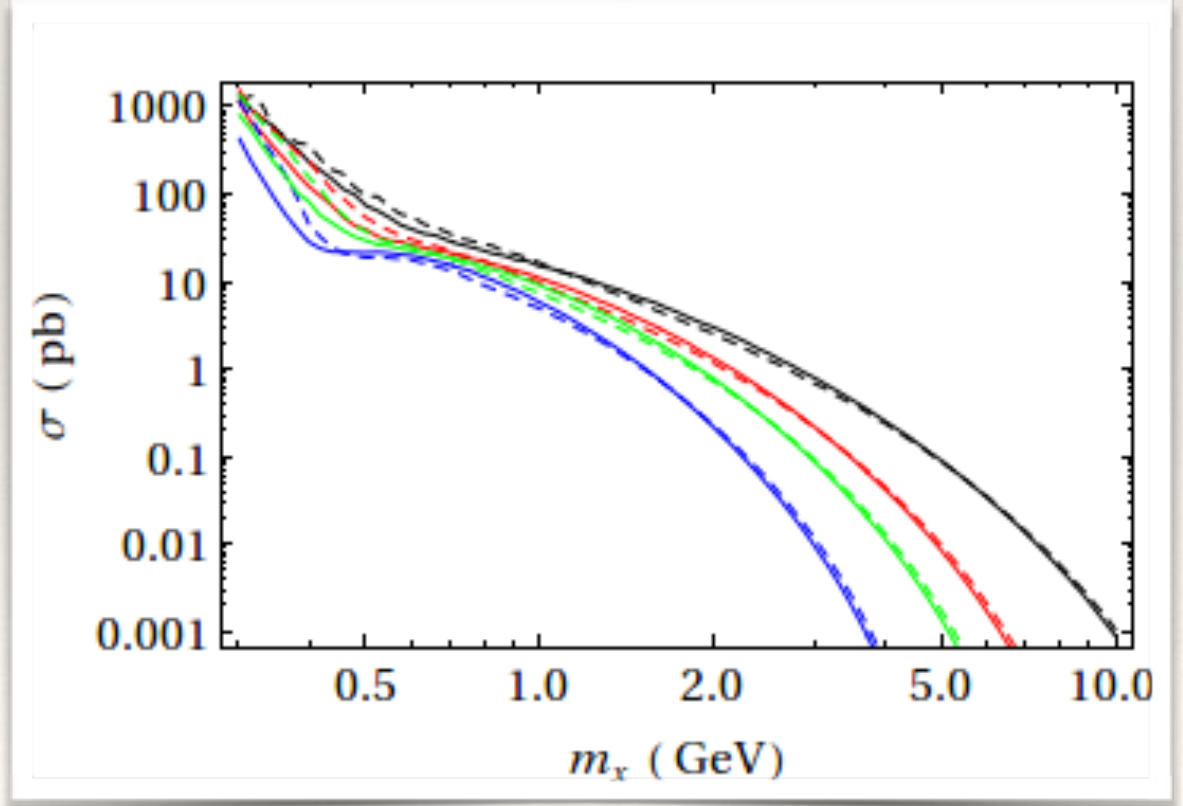
- Kinetic Mixing with parent:

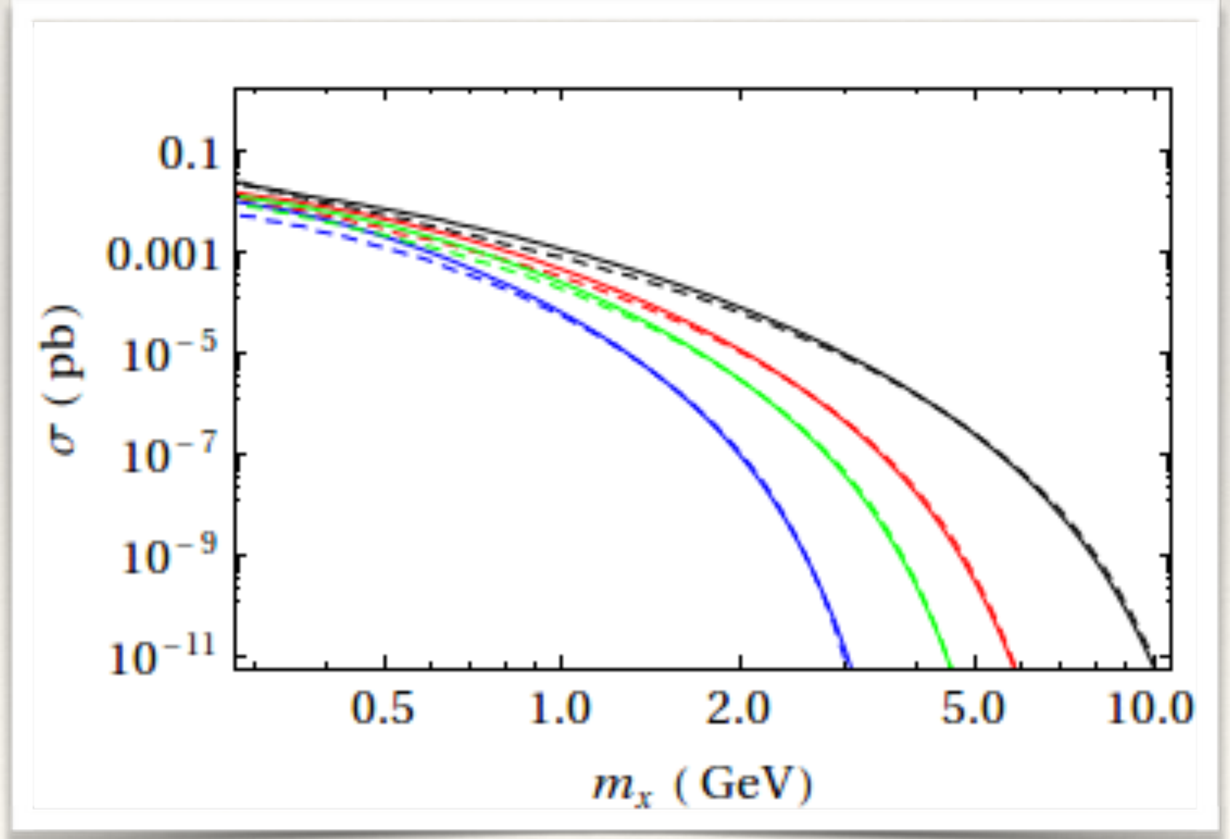
$$\rho \to \gamma \to Z^x \to \mathrm{HS} + \mathrm{HS}$$

Production: High Mass

- Heavy (≳ GeV) hidden sectors produced in partonic collisions
- Use σ with first α_s corrections







Experiments

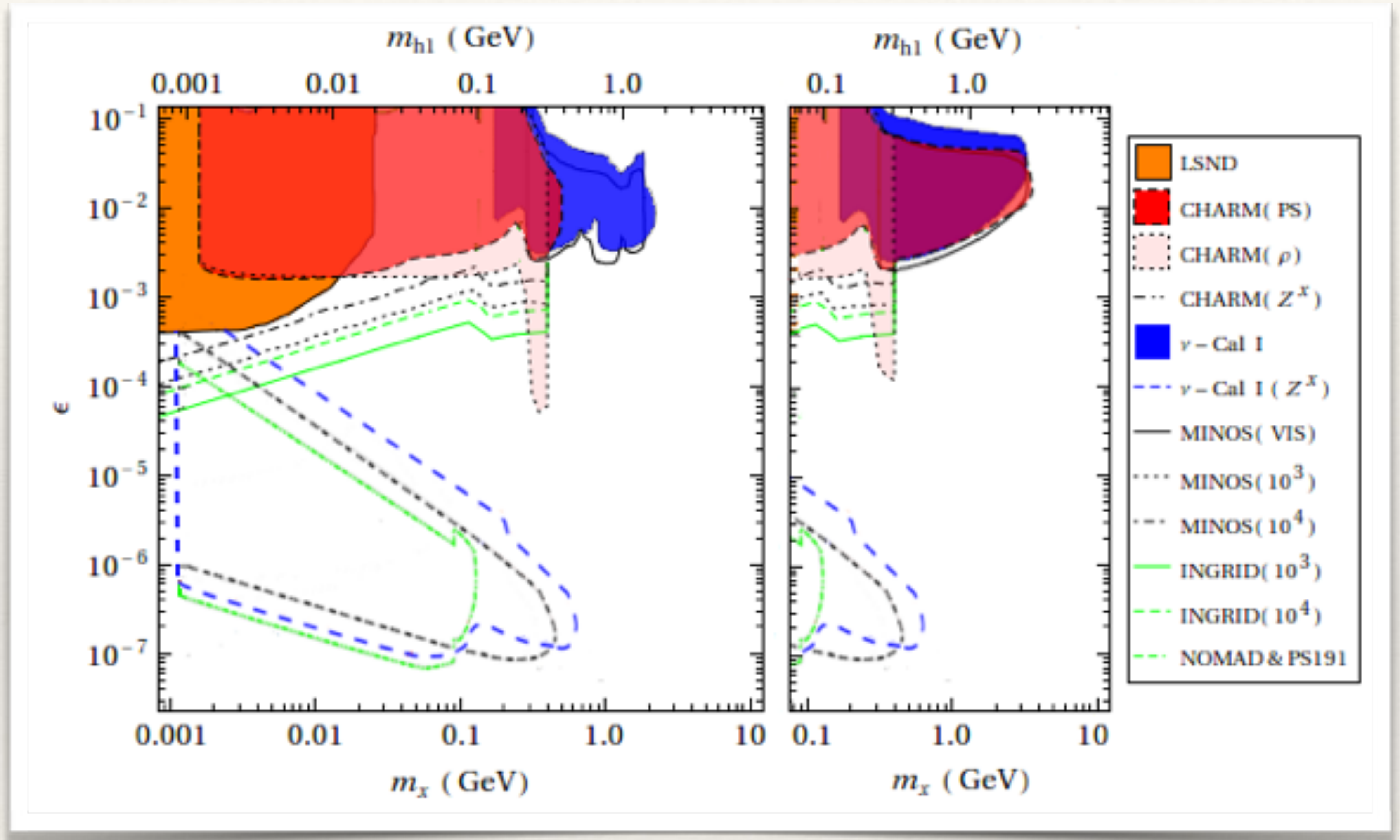
- Several past / current searches
- Visible: CHARM, MINOS, ν-Cal I, LSND
- Invisible (neutrino): MINOS, INGRID, LSND
- Inferior limits from NOMAD, PS-191, ND280, MiniBooNE
- Future limits from Project X, AFTER@LHC

Experiment	Target	E_p	N_p	L_{sh}	L_d	A_{acc}
CHARM [81,82]	Cu	400	2.4×10^{18}	480	35	4.8
MINOS [83,84]	C	120	1.407×10^{21}	1040	1.3	3.1
ν-Cal I [85]	Fe	70	1.71×10^{18}	64	23	6.76
INGRID [86]	C	30	5×10^{21}	280	0.585	21.5
LSND [87,88]	See text	0.798	See text	30	8.3	25.5

Experiment	E^e_{thr}	E^μ_{thr}	κ^e_{Eff}	κ^μ_{Eff}	N_{up}
CHARM	5	5	0.51	0.85	3
MINOS	-	1	-	0.8	10
ν-Cal I	3	3	0.7	0.9	7.76
LSND	0.015	-	0.19	-	10^3

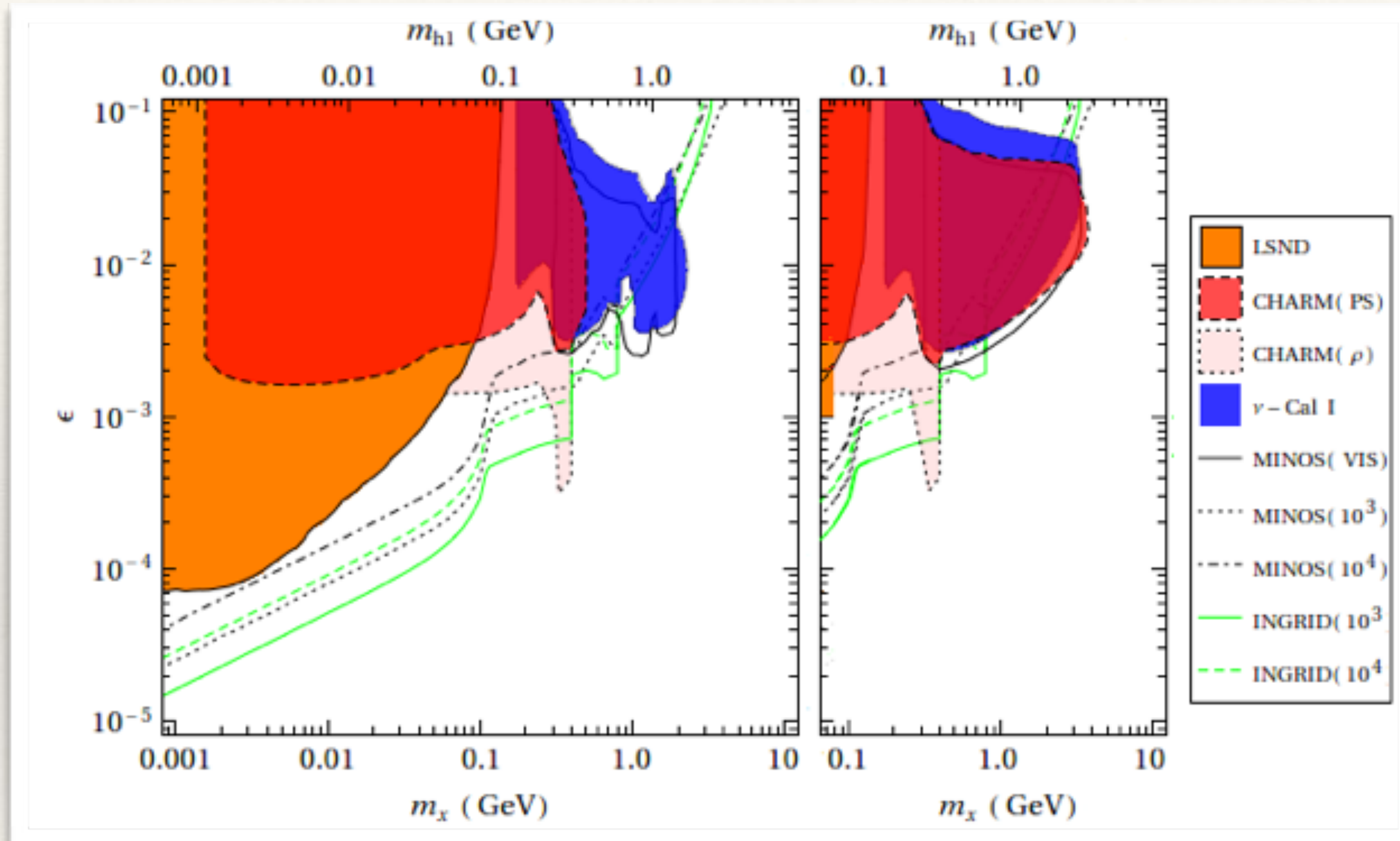
Experiment	n_e	n_N	κ_{eff}	N_{up}
MINOS	-	5×10^{24}	0.8	10^3–10^4
INGRID	-	5×10^{24}	0.8	10^3–10^4
LSND	5.1×10^{23}	-	0.19	10^3

Limits: Slope A: $Z^x \to$ SM



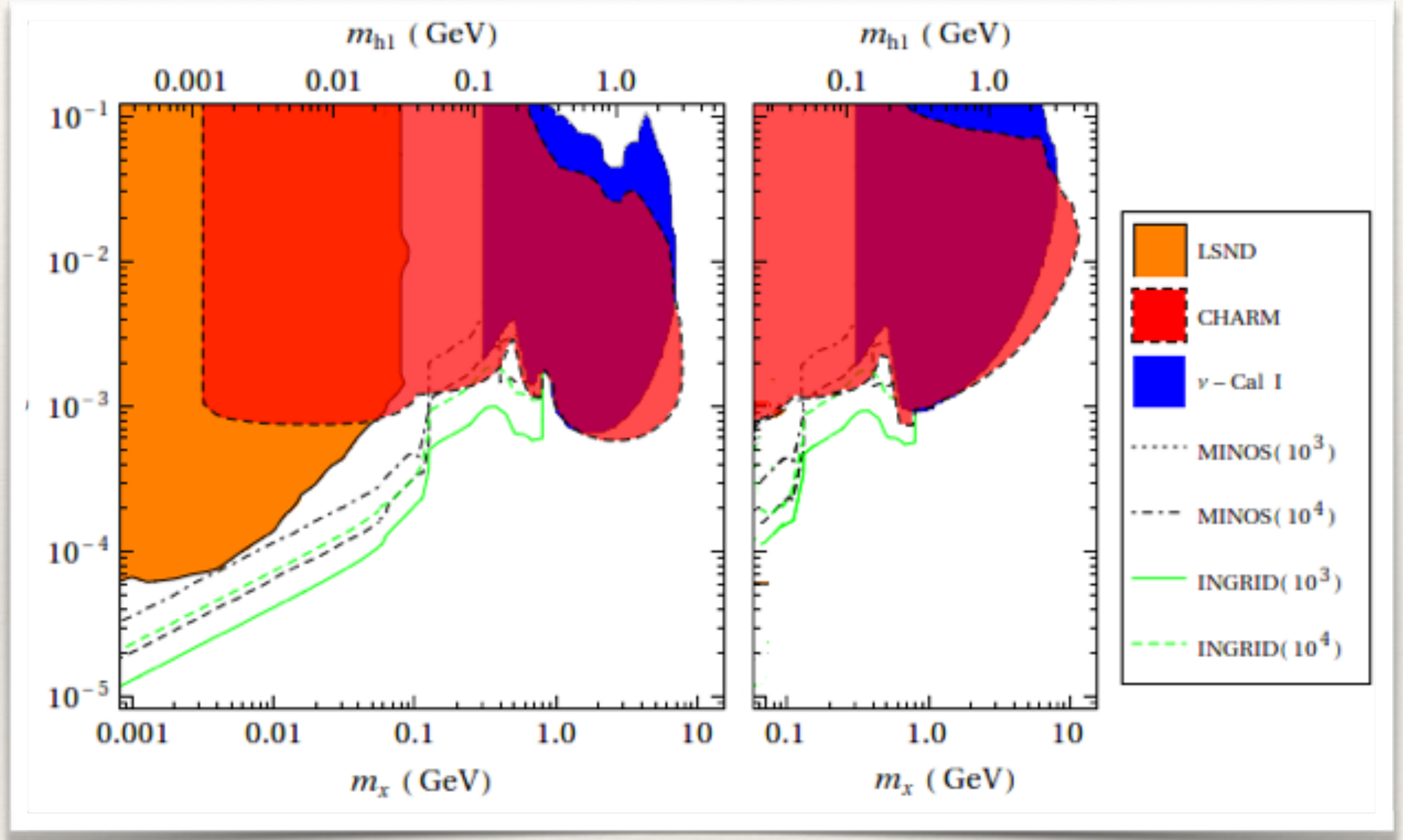
- Dependence on Higgs mixing
- Strong limits from ρ $\to$ Z^x h^x
- New limits at higher m_{Z^x}, ε than old
- Neutrino expt limits from h^x

Limits: Slope B: $Z^x \to$ Inv



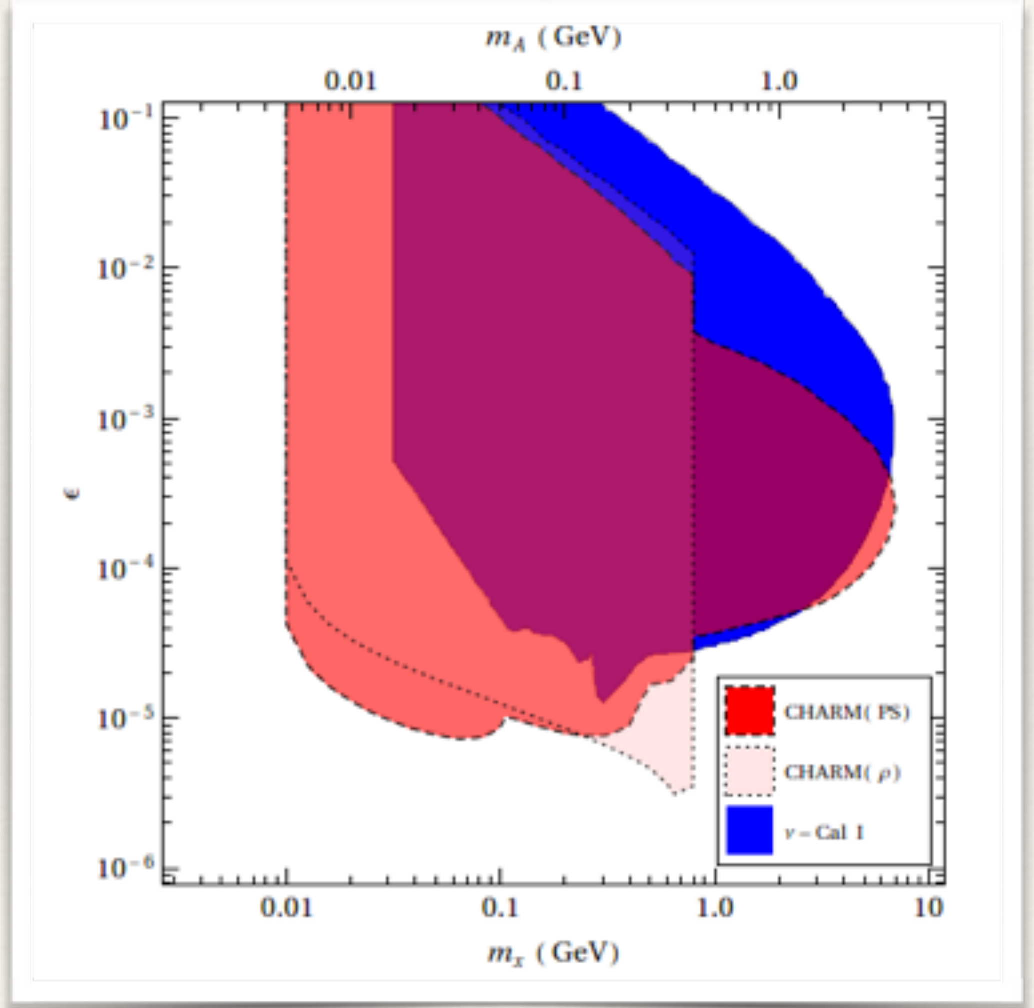
- Limits from h^x similar to A (note different scale)
- Stronger limits from Neutrino experiments (χ^x scattering)

Limits: Slope C: Scalars



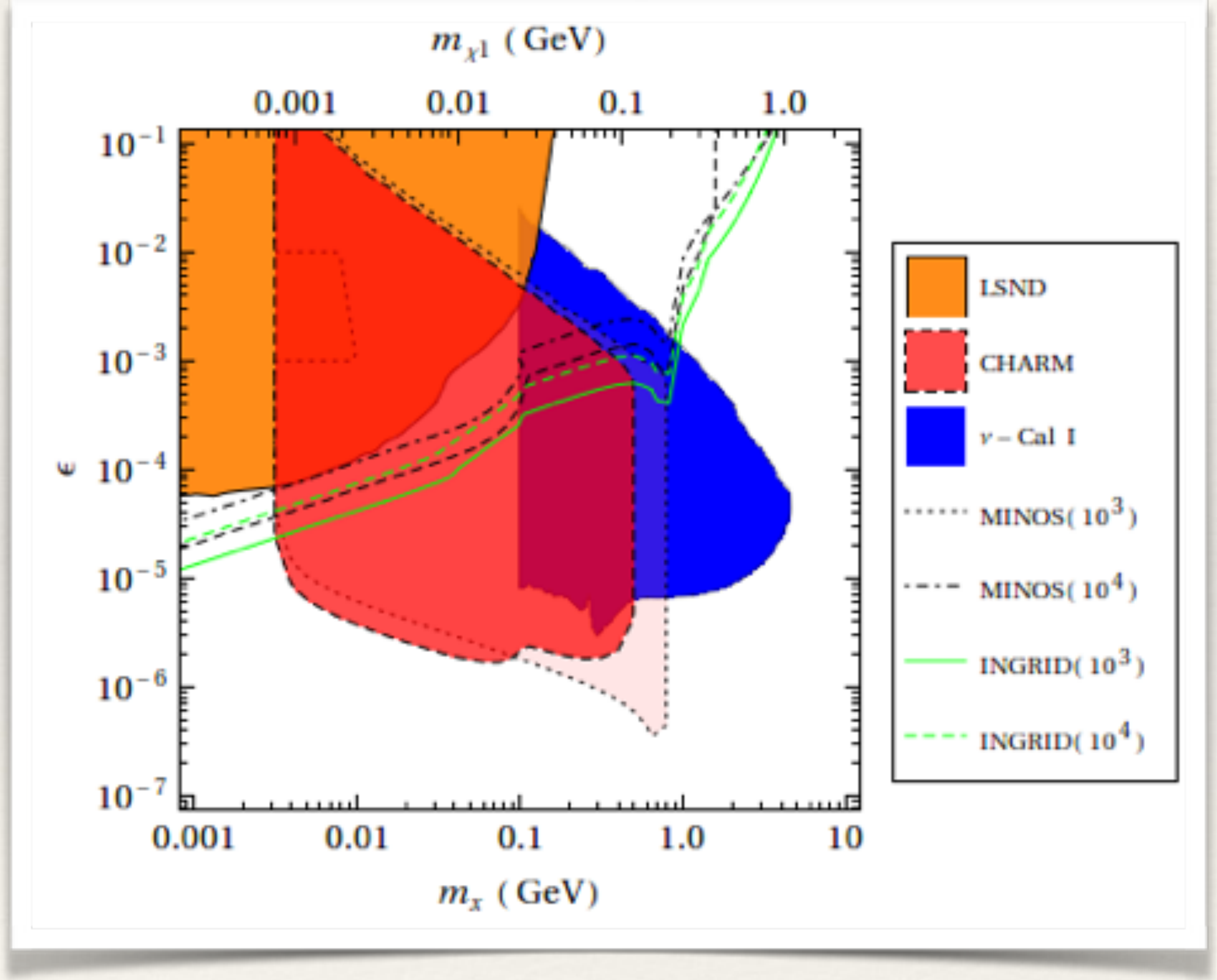
- Dependence on Higgs mixing
- Stronger limits than Slopes A, B
- Limits without mixing comparable
- Neutrino expt limits from h^x

Limits: Slope C: Pseudoscalars



- No mass-mixing dependence
- Upper limits for A^x short-lived
- ν-Cal I better in this region: detector closer to target!

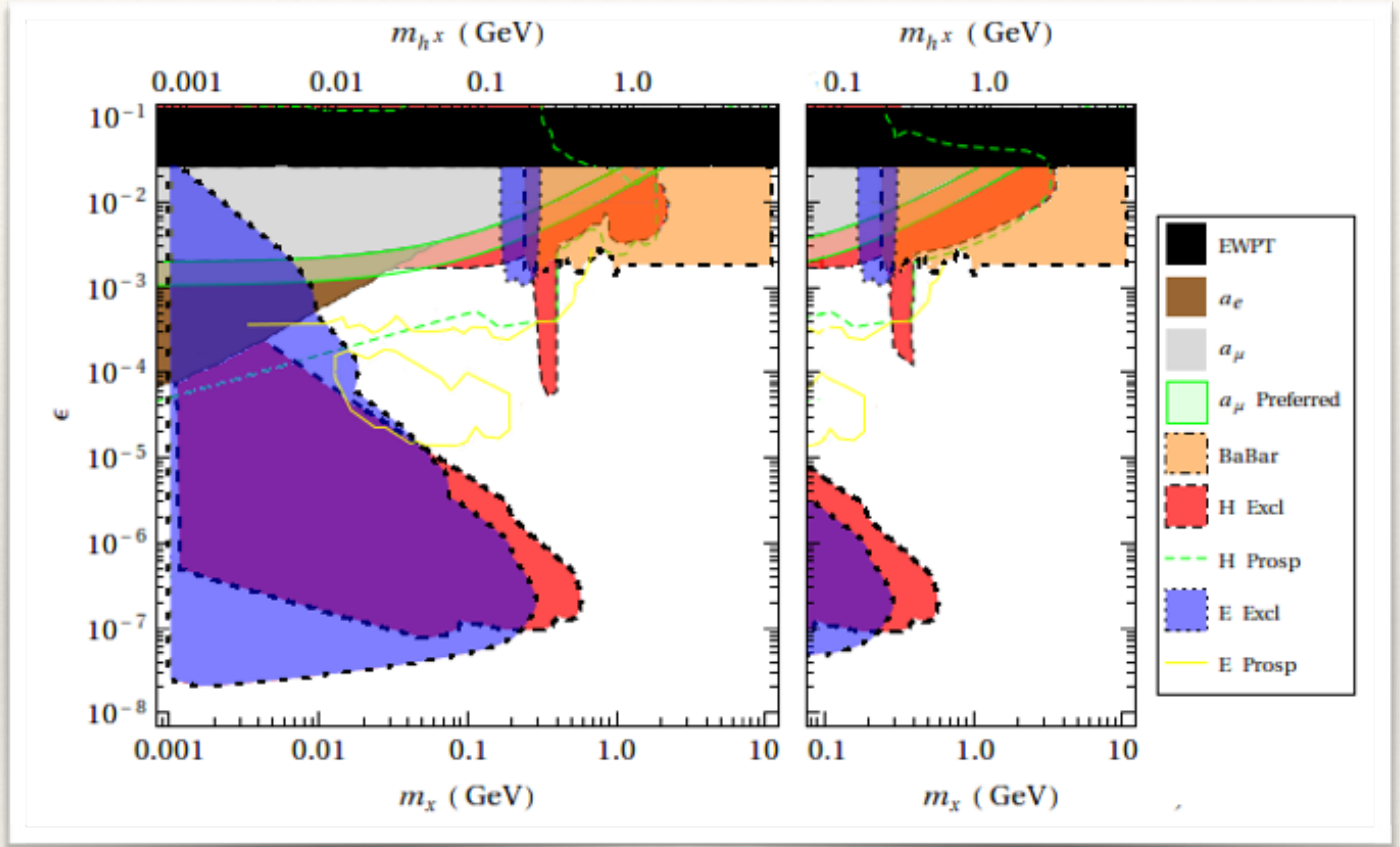
Limits: Slope D: $Z^x \to$ Fermions



- No mass-mixing dependence
- Upper limits for χ^x short-lived
- ν-Cal I again better here
- Visible searches better than prospective neutrino limits except at high mass

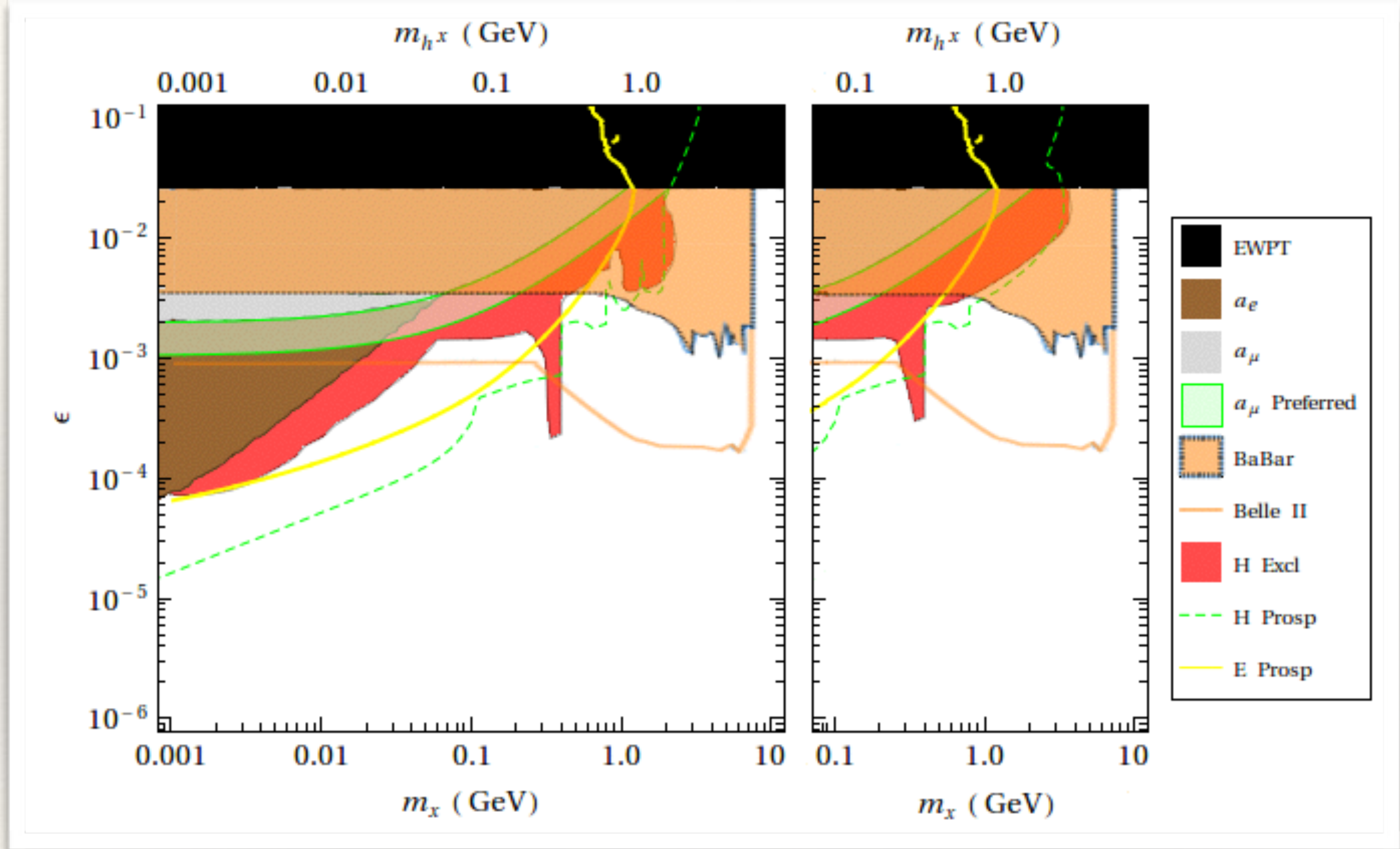
Combined Limits

Benchmark A



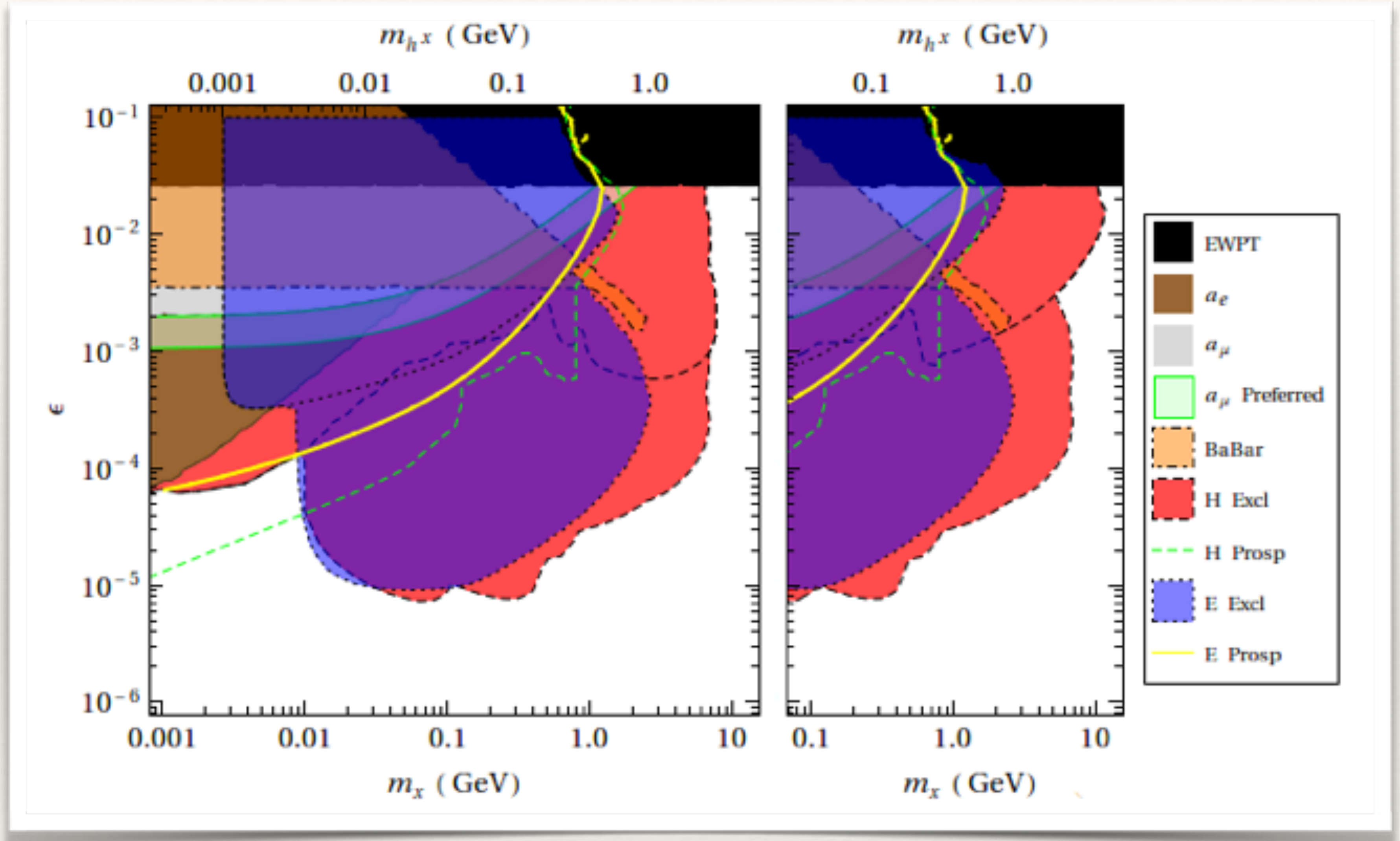
- Limits from CHARM only new ones
- Nearly exclude region that explains a_μ!

Benchmark B



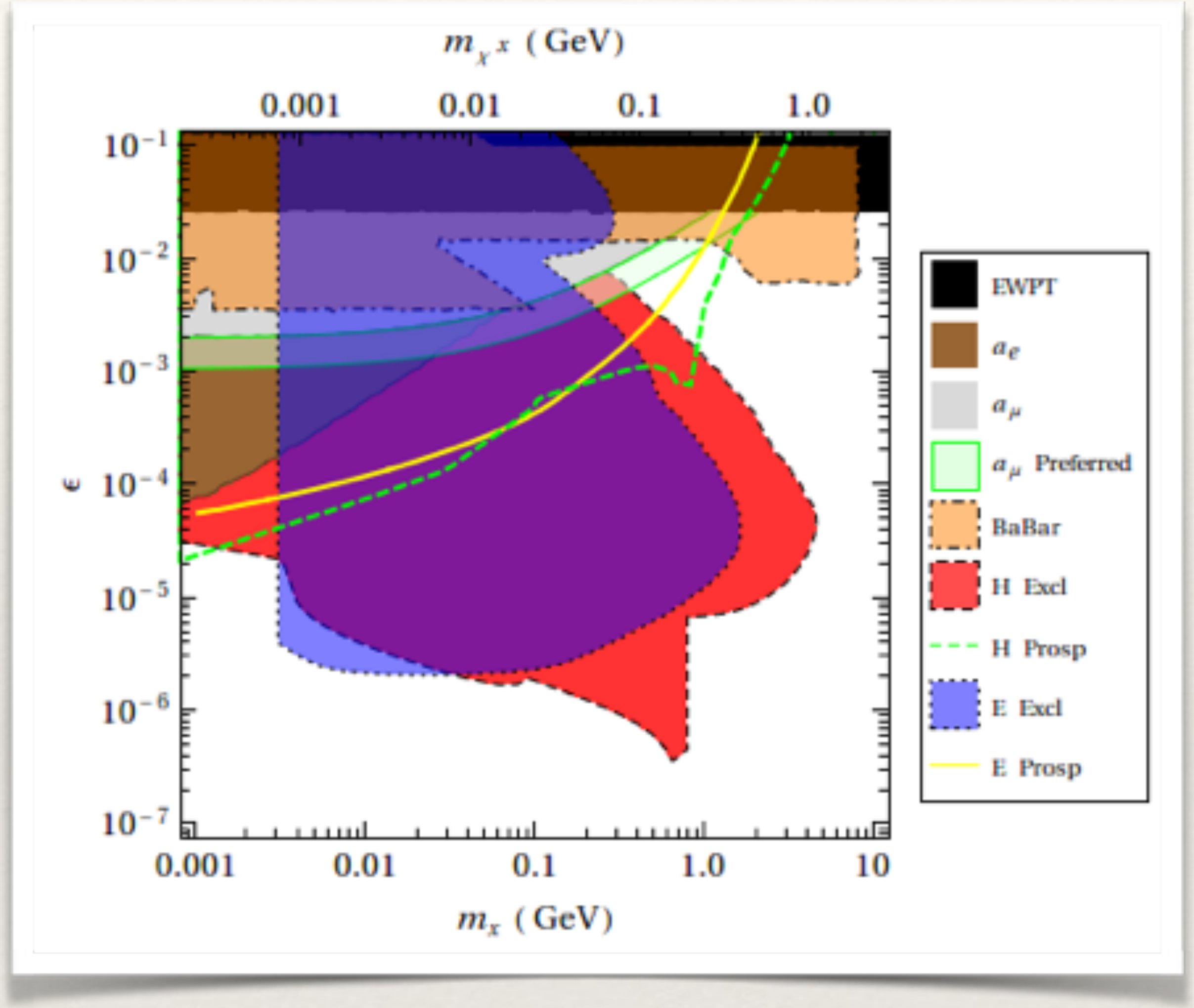
- Limits from CHARM + LSND fully exclude a_μ-preferred region!

Benchmark C



- Upper/lower regions with/without A^x
- First limits in SUSY case
- Limits much expanded in non-SUSY case
- a_μ-preferred region excluded!
- If CMB/BBN limits included, exclude $m_{Z^x} < 1$ GeV (except near μ threshold)

Benchmark D



- First limits on this case
- CMB/BBN limits at $\varepsilon < 10^{-8}$
- a_μ-preferred region NOT excluded! (h^x decays invisibly) But probed by JLab & INGRID

Conclusions

- Hidden Sectors coupling through kinetic mixing can have richer phenomenology than usually considered
- Have discussed a simple model that illustrates this
- Limits on Z^x decaying to scalars/fermions with visible decays much expanded/completely new
- Difficult to explain a_μ with hidden vector if it is higgsed, and the Higgs decays visibly