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Light Hidden Sectors at Fixed-Target Experiments

arXiv:1402.4817

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Outline

1. Introduction and Motivation

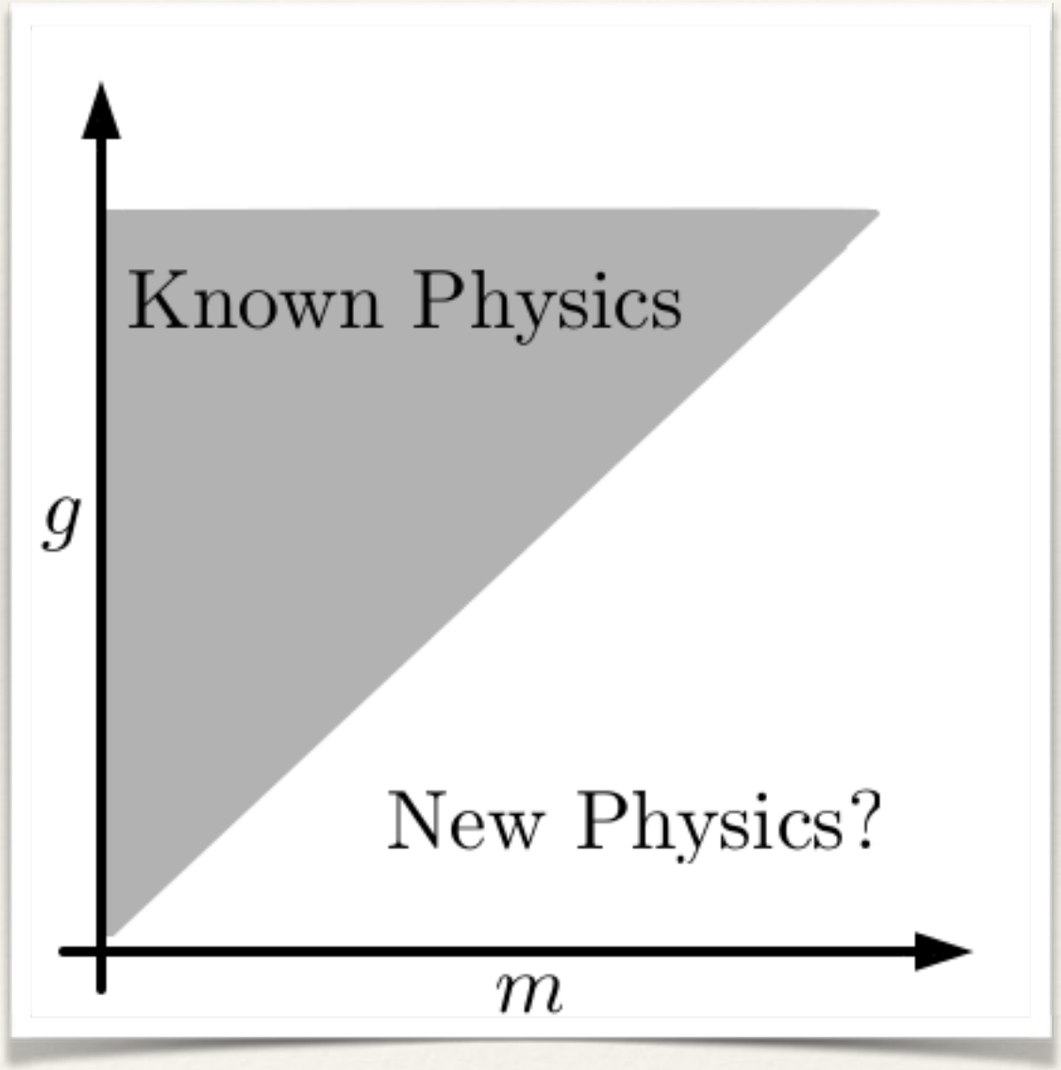
2. Theory: Model and Benchmarks

3. Fixed Target Limits

4. Conclusions

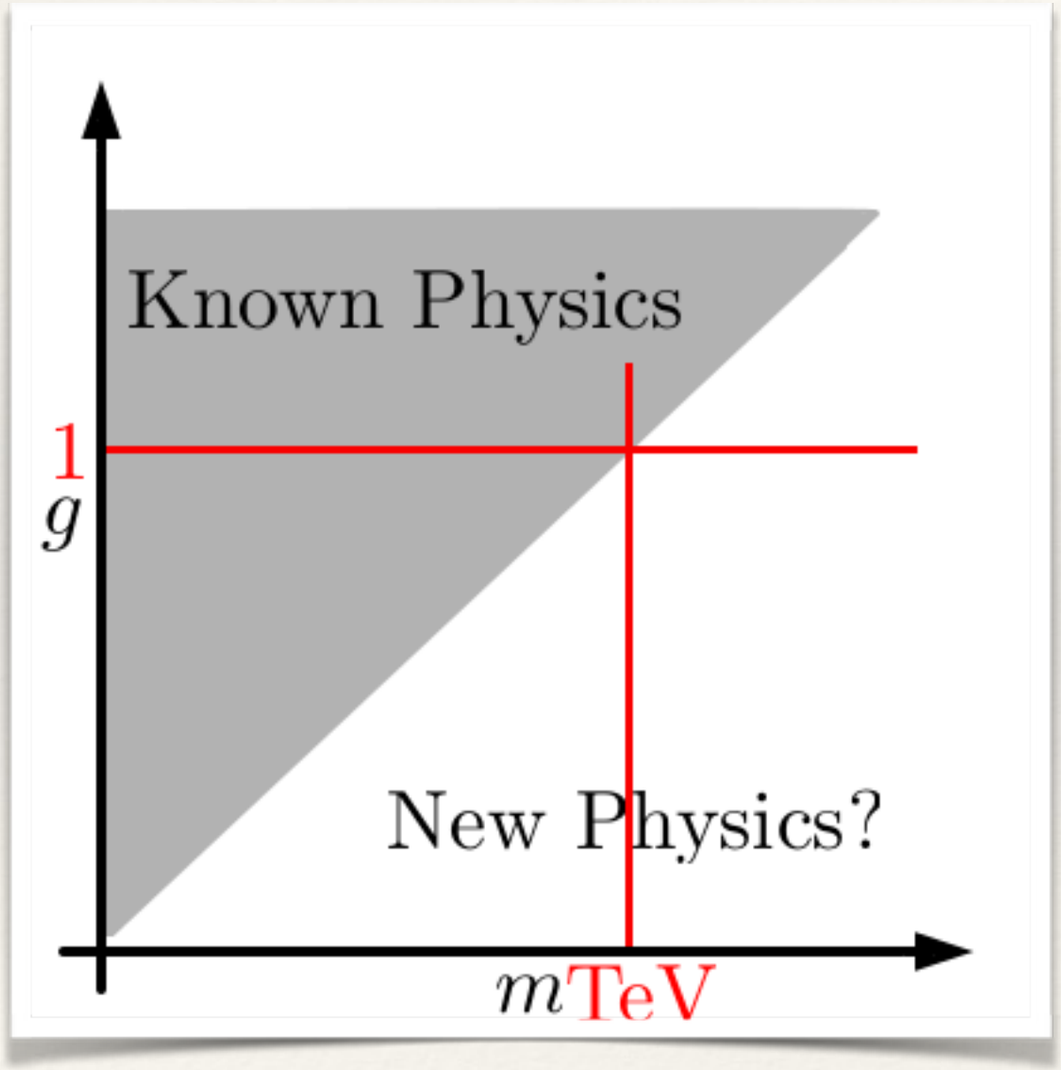
Introduction and Motivation

Hidden Sectors



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

Hidden Sectors



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  - *e.g.* NP has gauge couplings

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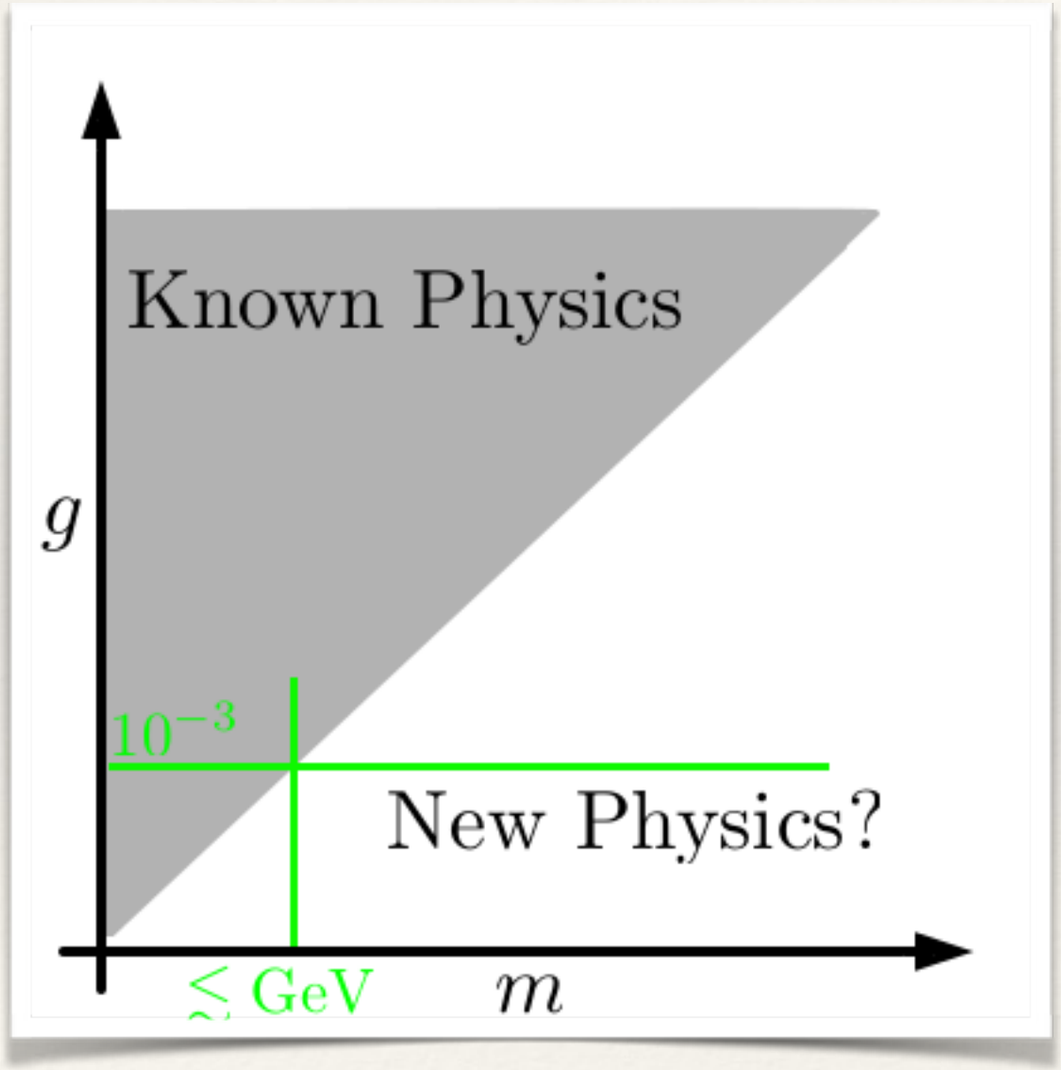
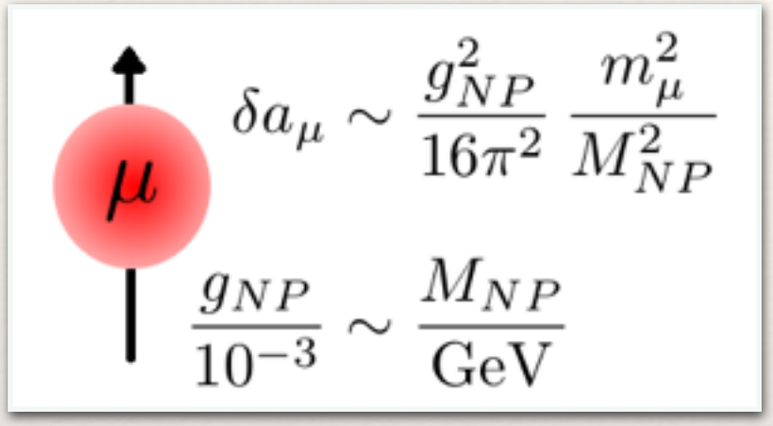


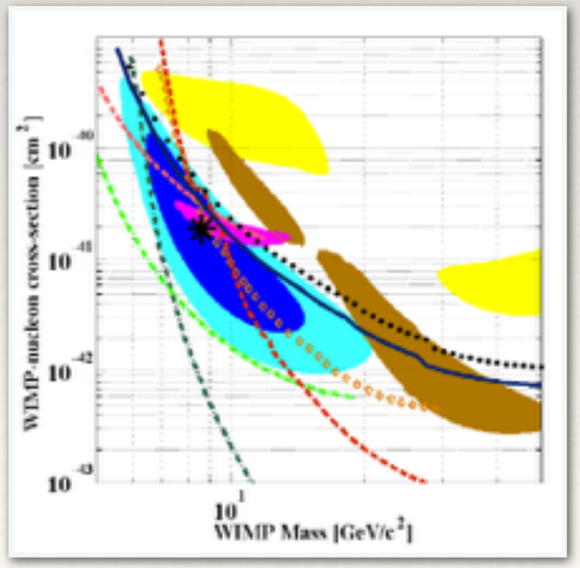
- Heavy stuff harder to probe! Increase $m \Rightarrow$ See only larger g
- $g \sim O(1)$ implies NP is TeV-scale
  - *e.g.* NP has gauge couplings
- $g \ll O(1)$ lets NP be light
  - Hidden sector gauge-neutral

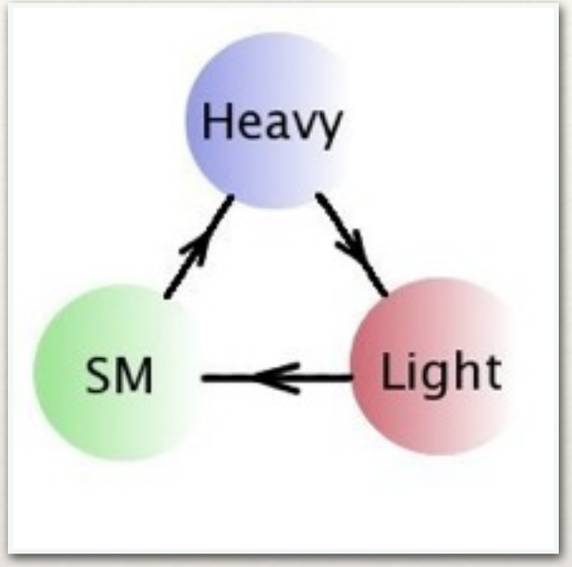
Thinking of New Light Stuff

- μ Anomalous Magnetic Moment

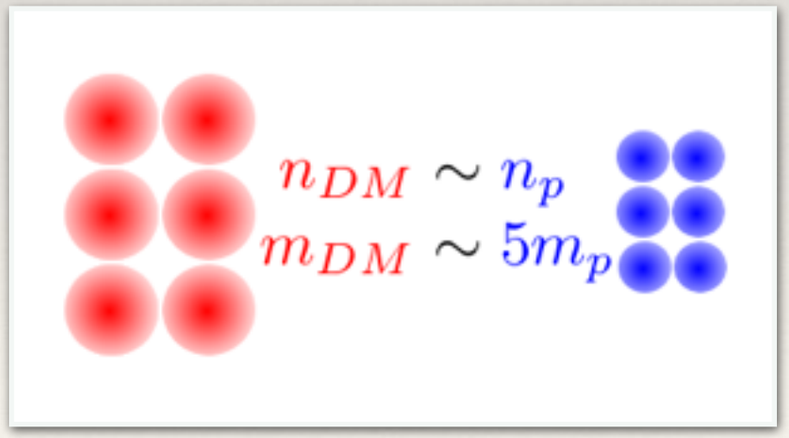


- Dark Matter Anomalies





- Hidden Valleys



- Asymmetric Dark Matter

Portals

- Three renormalisable couplings between SM and gauge-neutral operators

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

- Vector Portal: γ
  - Photon Massless
  - X Couples $\propto \varepsilon$ e Q

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

- Higgs Portal
  - LHC Only
  - Easy(?) to produce

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

- Neutrino Portal
  - Neutrino Light
  - N Hard to detect

Portals

- Three renormalisable couplings between SM and gauge-neutral operators

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

- Vector Portal: γ
  - Massless
  - Couples $\propto \varepsilon\, e\, Q$
    - One-Loop generated → $\varepsilon \sim 10^{-3}$

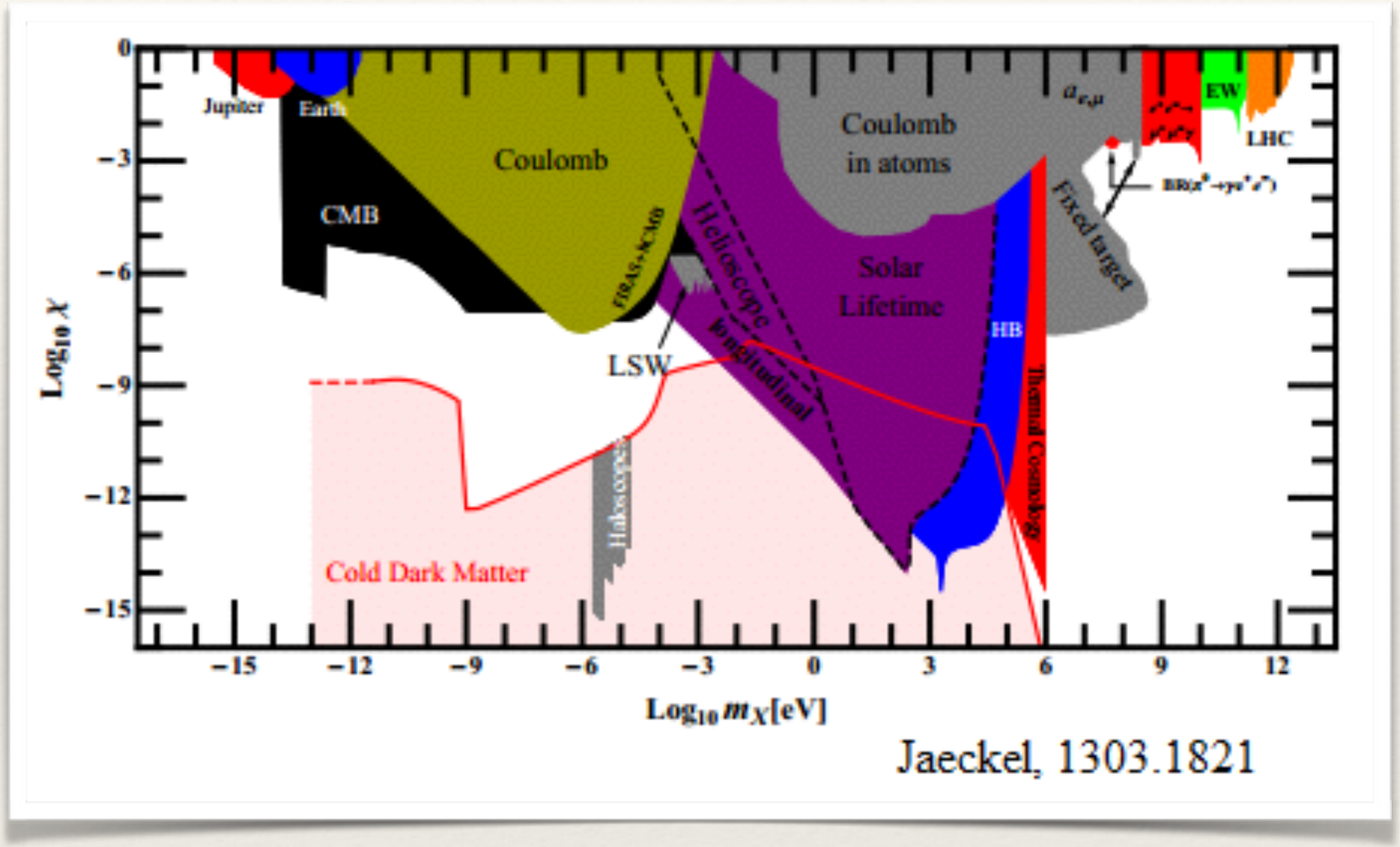
$$-\frac{1}{2}\lambda\,(H^\dagger H)\,(\Phi^\dagger \Phi)$$

- Higgs Portal
  - LHC Only
  - Easy(?) to produce

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

- Neutrino Portal
  - Near-massless
  - Hard to produce

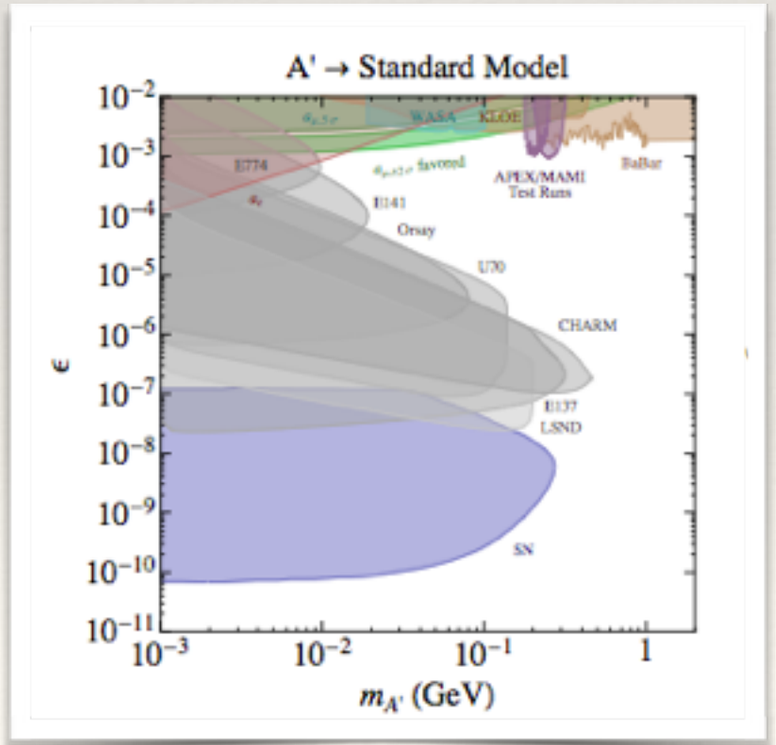
Vector Kinetic Mixing Limits



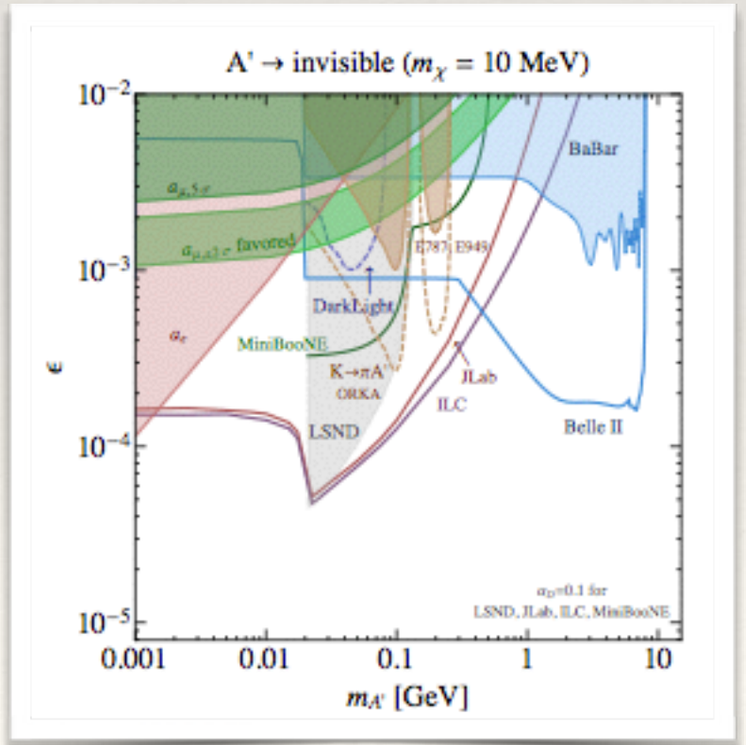
- Many previous studies and limits!
- GeV-scale relatively unconstrained

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



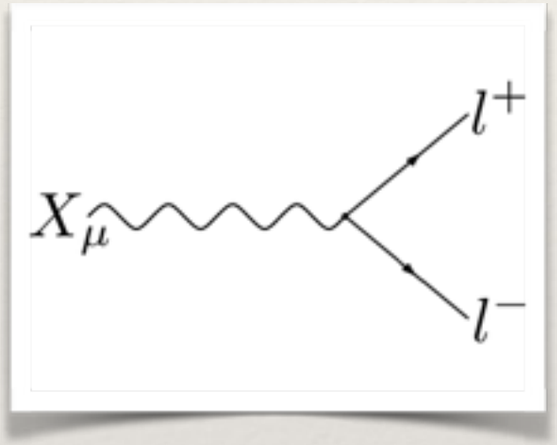
- $X \to$ invisible
  - Weaker limits from neutrino expts
  - Motivated from dark matter



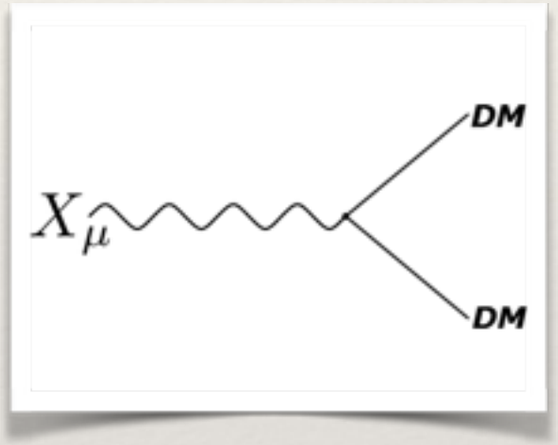
General Hidden Sectors

- Multiple possible vector decays:

- Direct Decay to Visible Sector

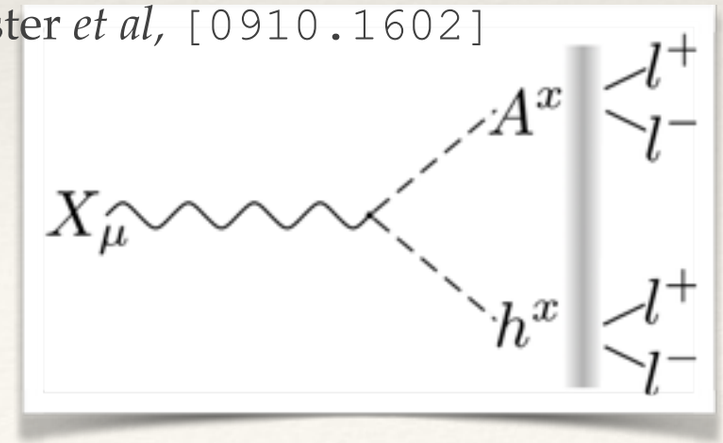


- Invisible Decay

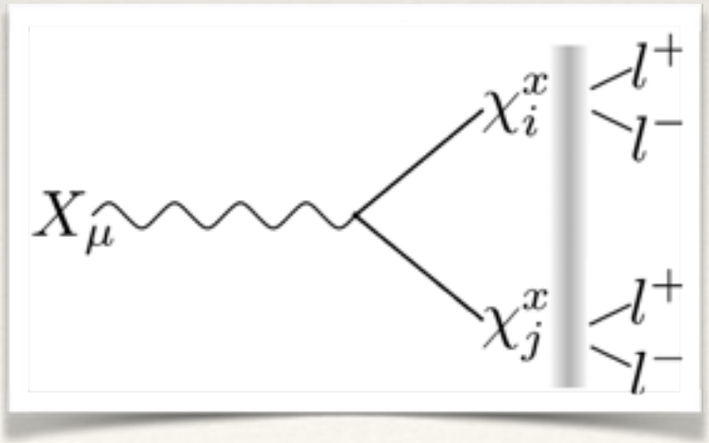


- Decay to SM via Hidden Scalars

- 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 $\chi^x{}_{1,2,3}$

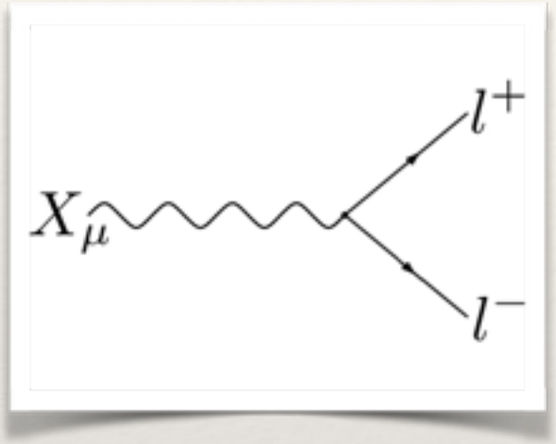
Model as Benchmark

- 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

Four Benchmark Slopes

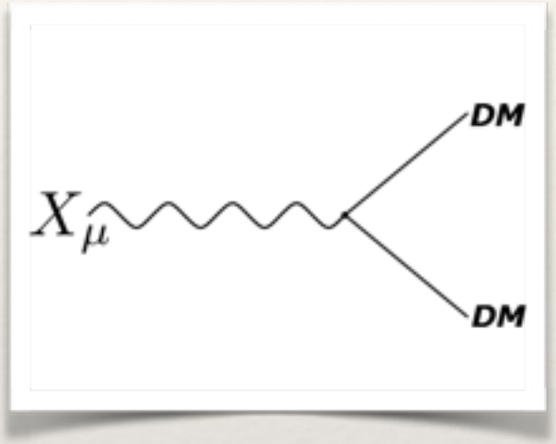
- Slices of parameter space: fixed ratios of mass parameters

A

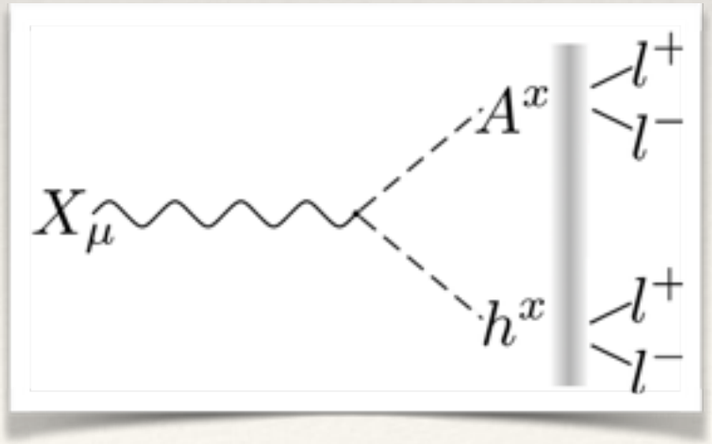


$m_{Z^x} < m_{A^x}, \mu', M_x$

B

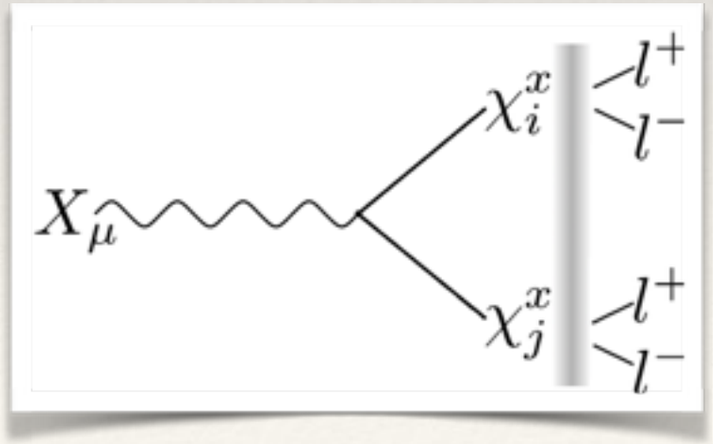


$M_x < m_{Z^x} < m_{A^x}, \mu'$



C

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

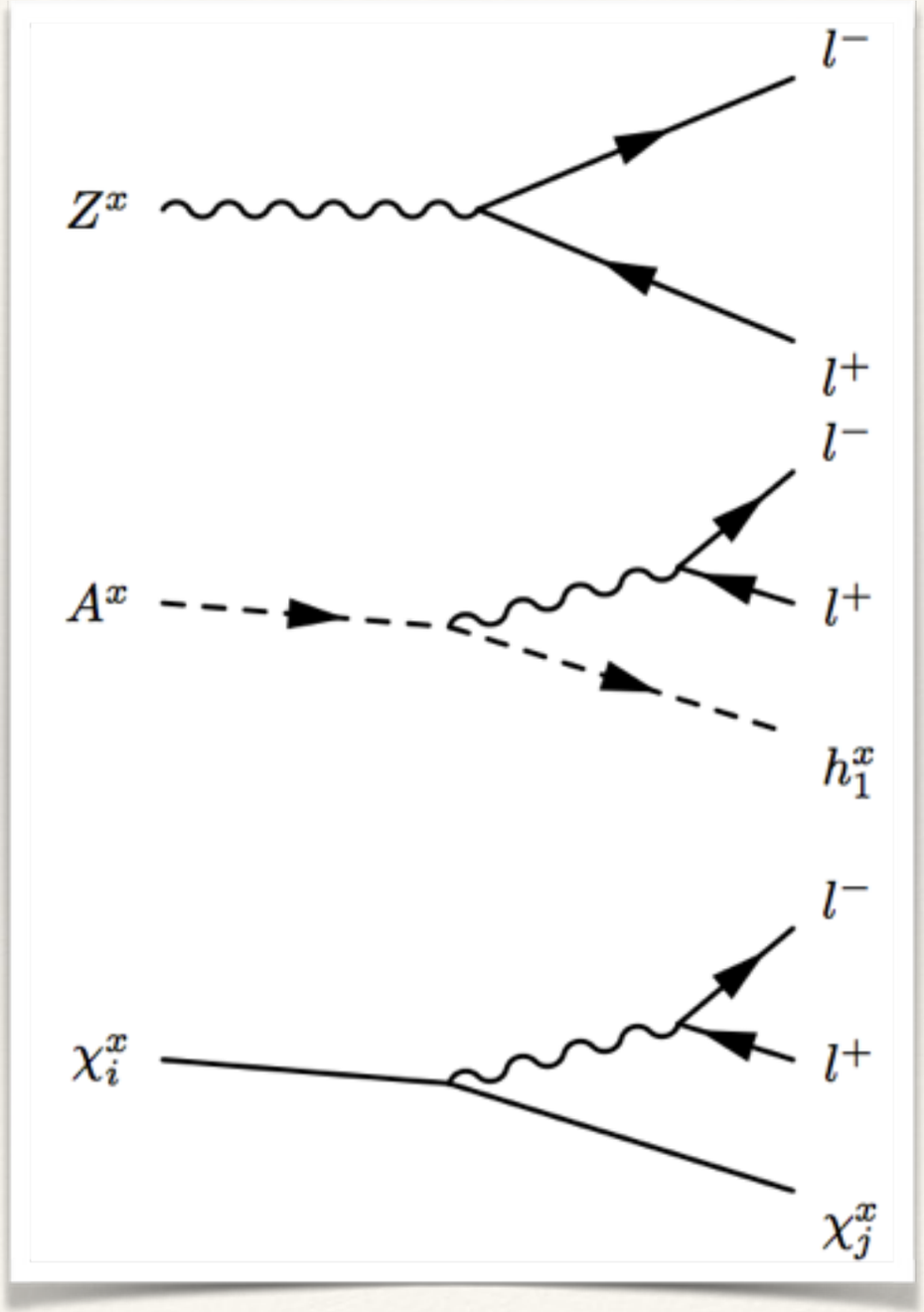


D

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

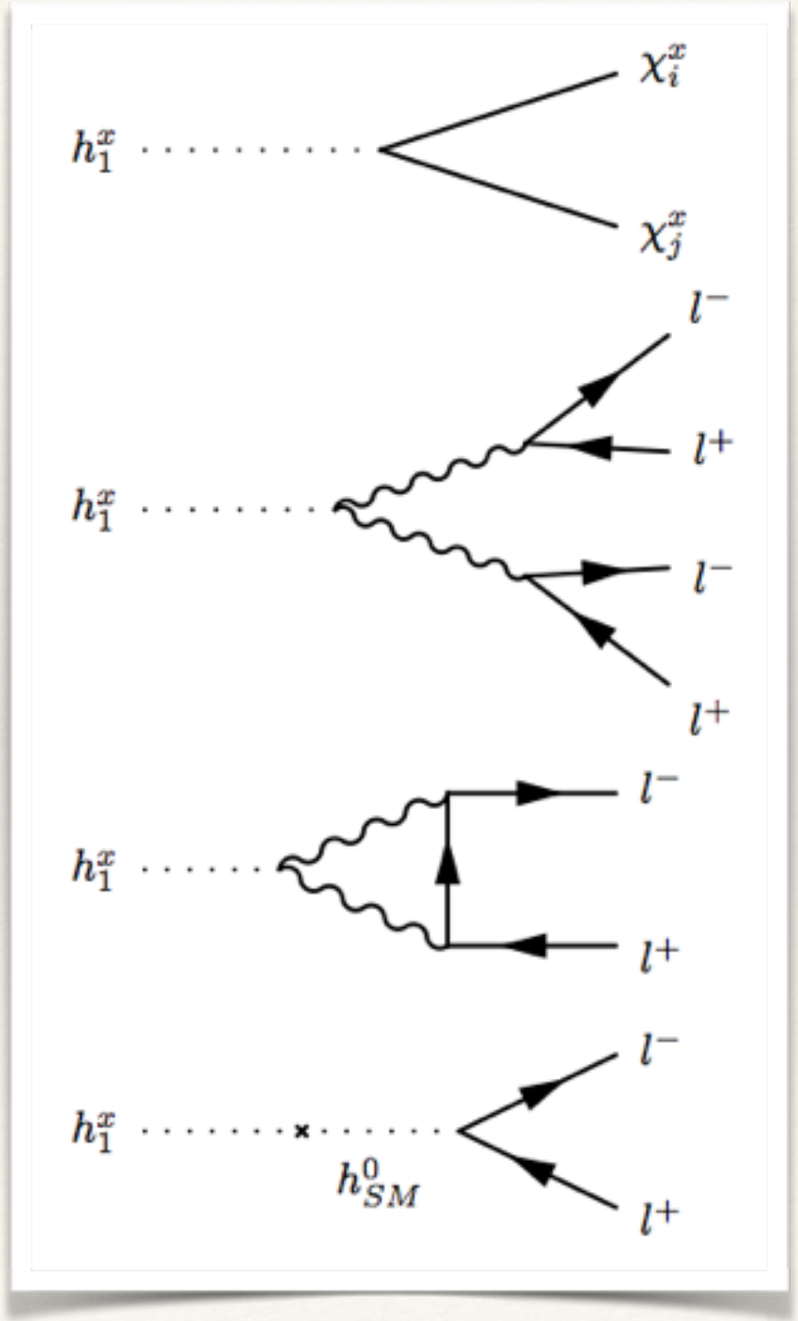
Pseudoscalar and Fermion Decays

- Signals: long-lived states
- Coupling suppression
  - (Case A)
- Stable fermion (all cases)
- Phase space suppression:
  - A^x (Case C)
  - χ (Case D)



Hidden Higgs Decays

- Lightest scalar:
  - No HS bosonic decays
  - HS fermion decays (Case D)
  - Decays to SM:
    - Four-body
      (irrelevant, Batell *et al.* [0903.0363])
    - Vector loop
    - Higgs mass mixing
- Always long-lived: Cases A—C



Fixed Target Limits

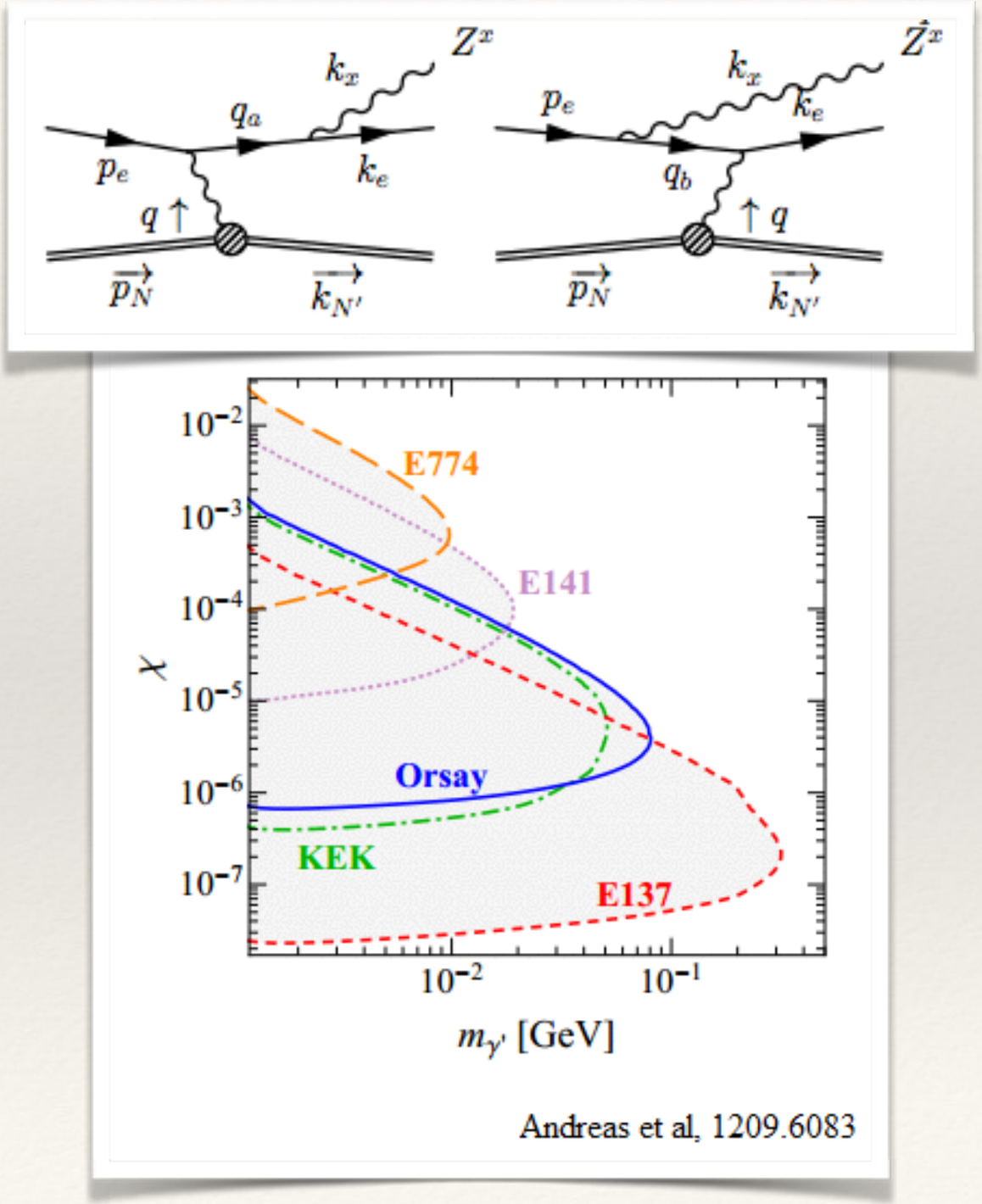
Fixed Target Experiments

- 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

Electron Experiments

- Z^x couples to EM current
- Production from e is obvious!
- Recasting old experiments has placed important limits
- Proposed new searches
  - BUT miss Cases C, D
- Small angle quasi-elastic scattering dominates



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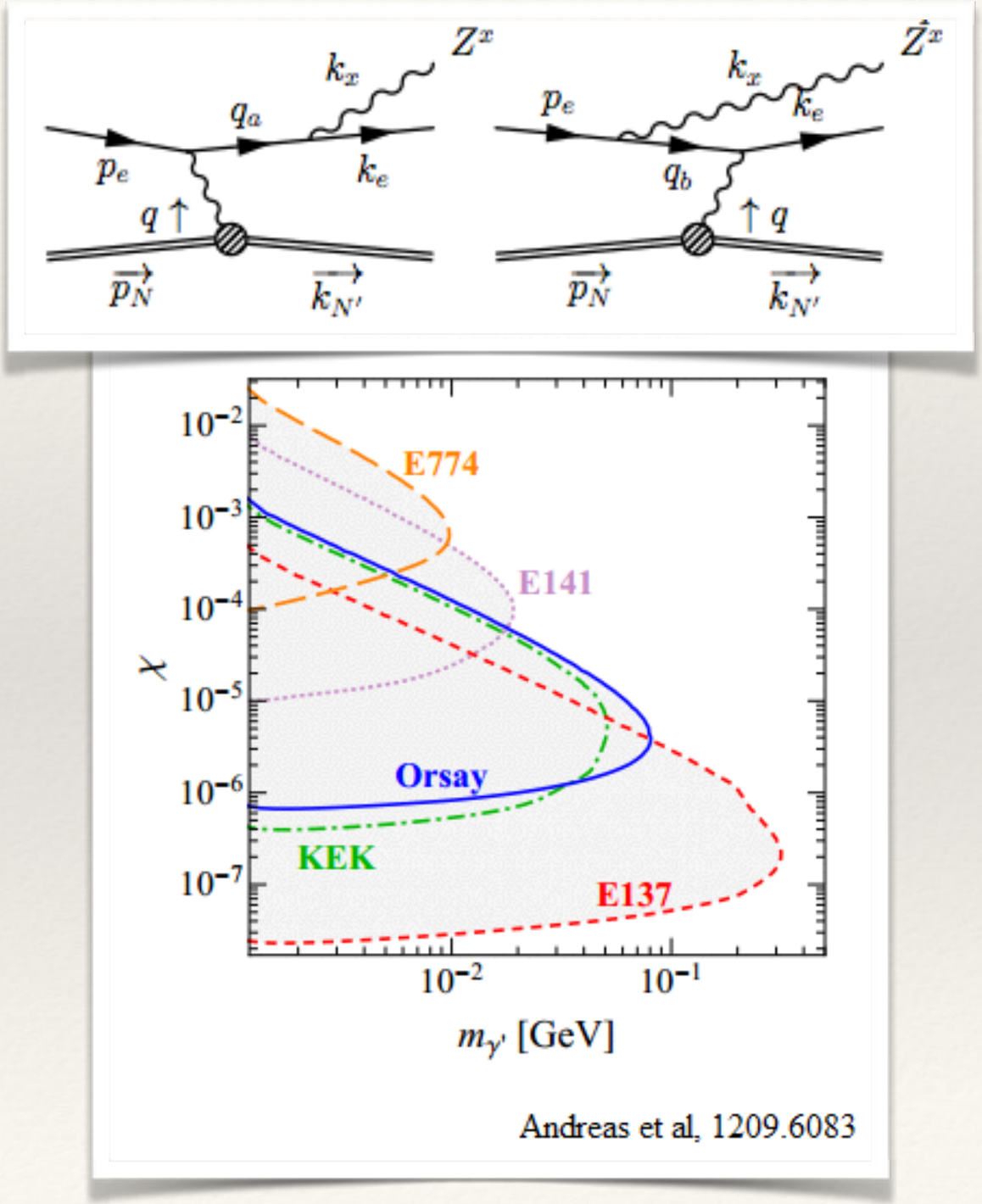
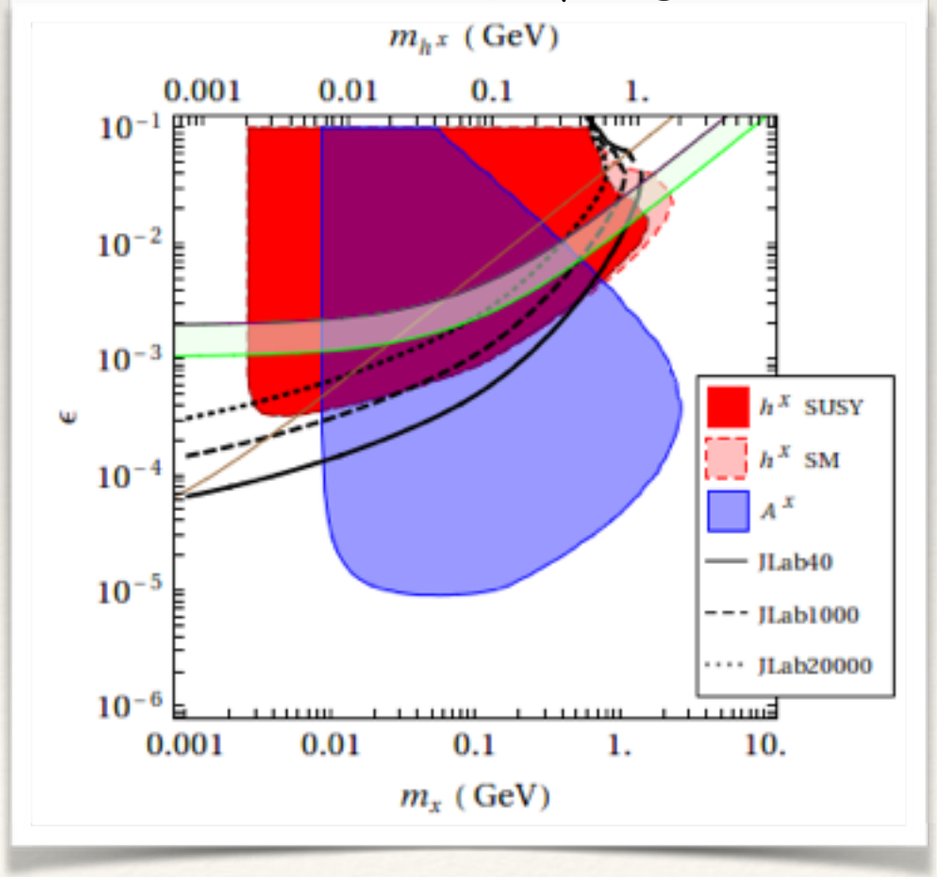


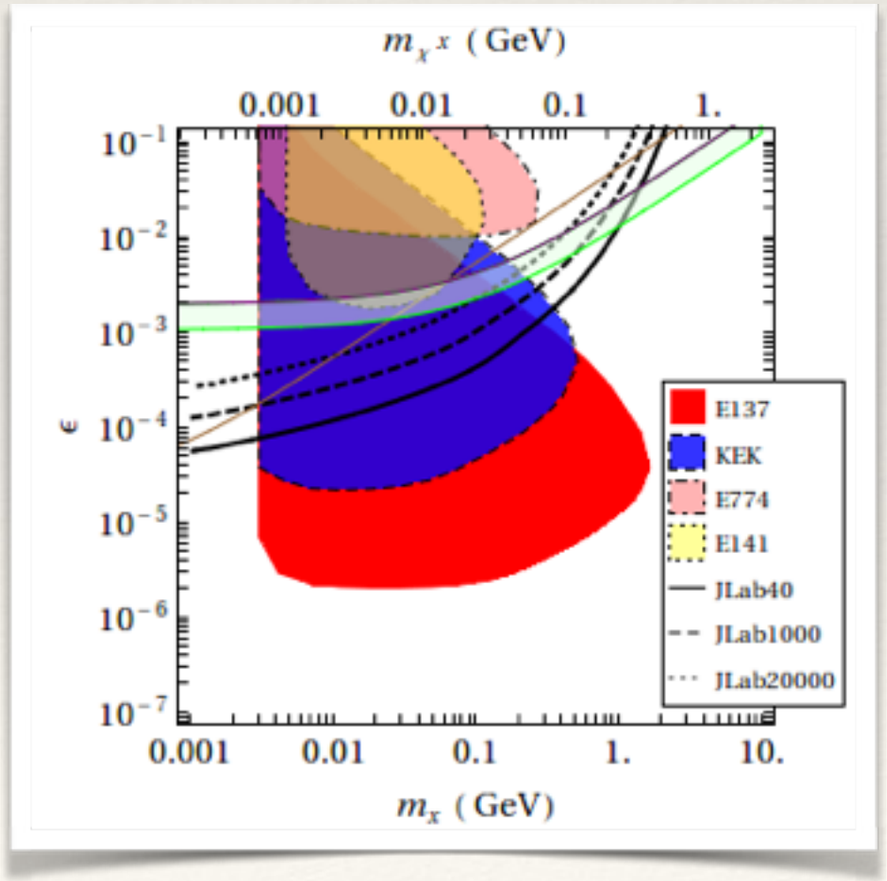
Results

- No h^x limits in Case A or B

- Case C:
  - Completely new h^x and A^x limits
  - Exclude much of a_μ region



- Case D:
  - First limits on this decay type
  - All from χ^x_2 decays



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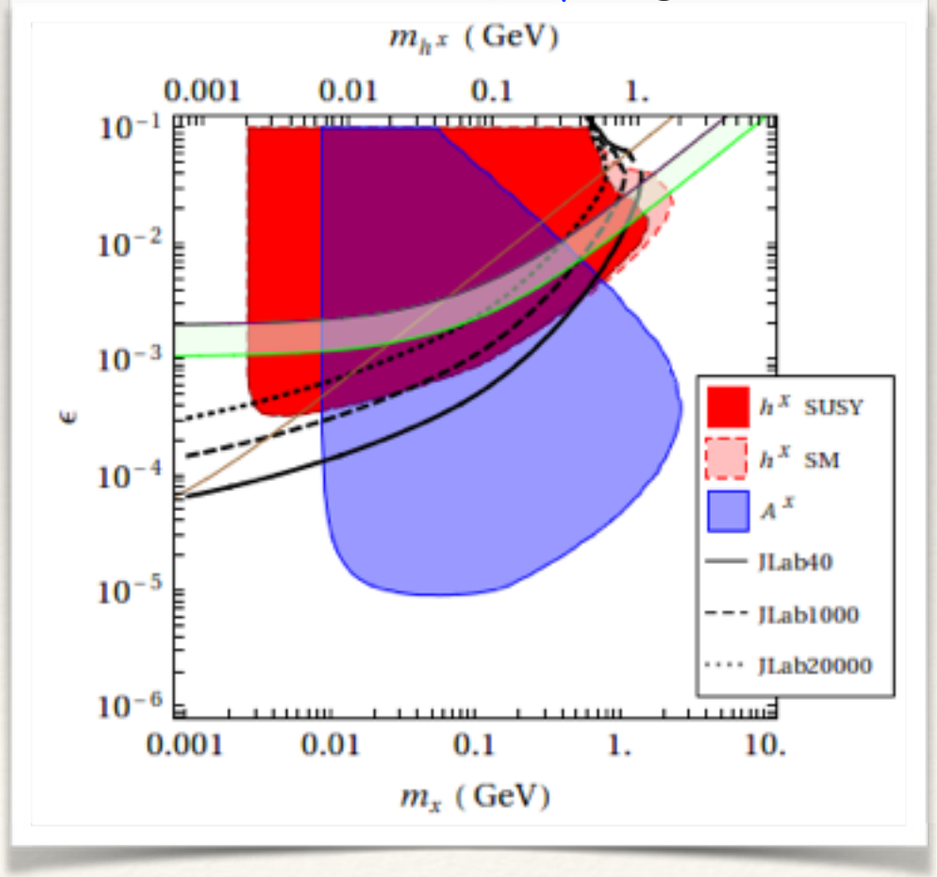

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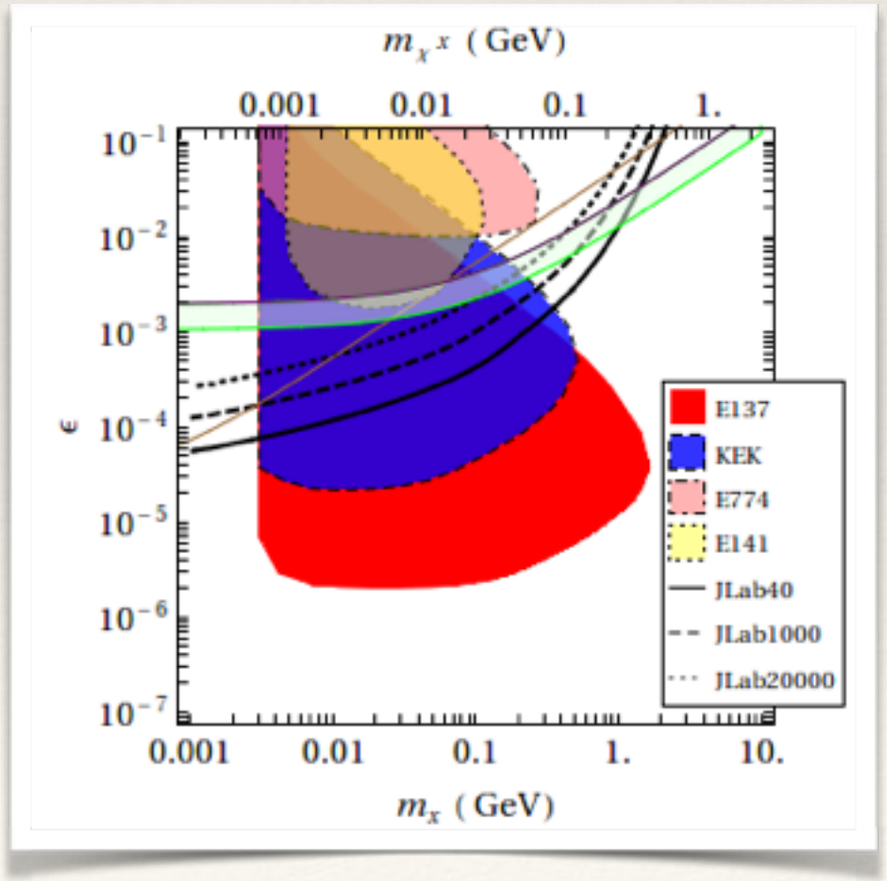

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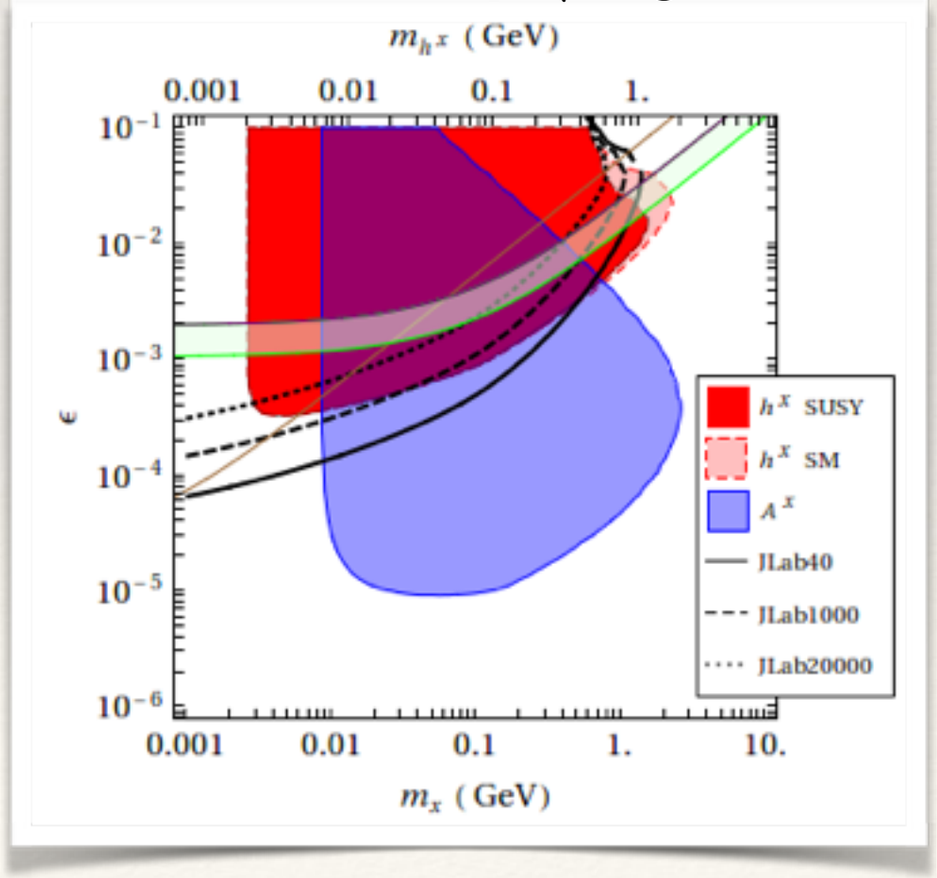
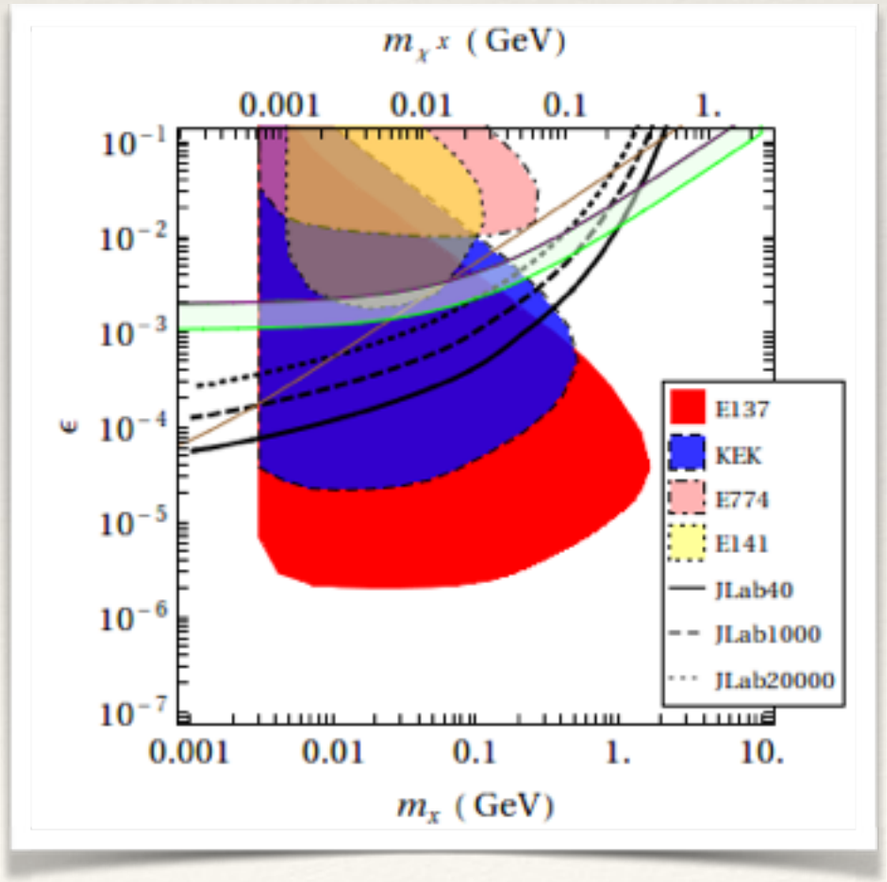


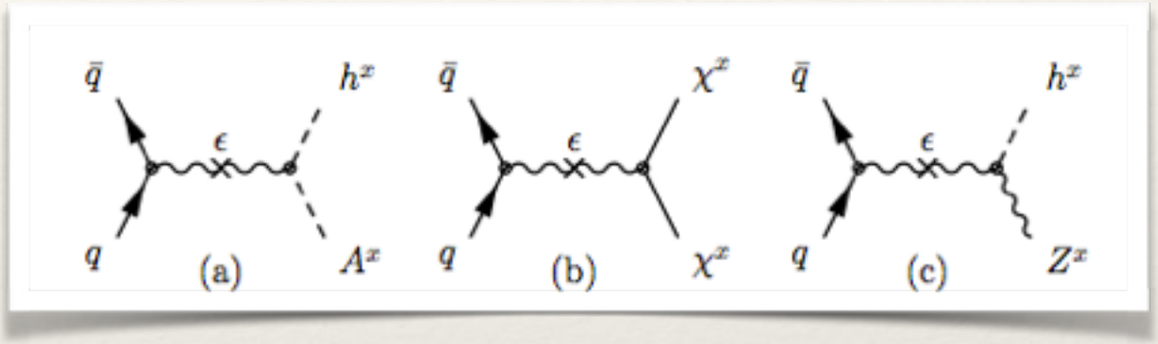
- Case D:
  - First limits on this decay pattern
  - All from χ^x_2 decays



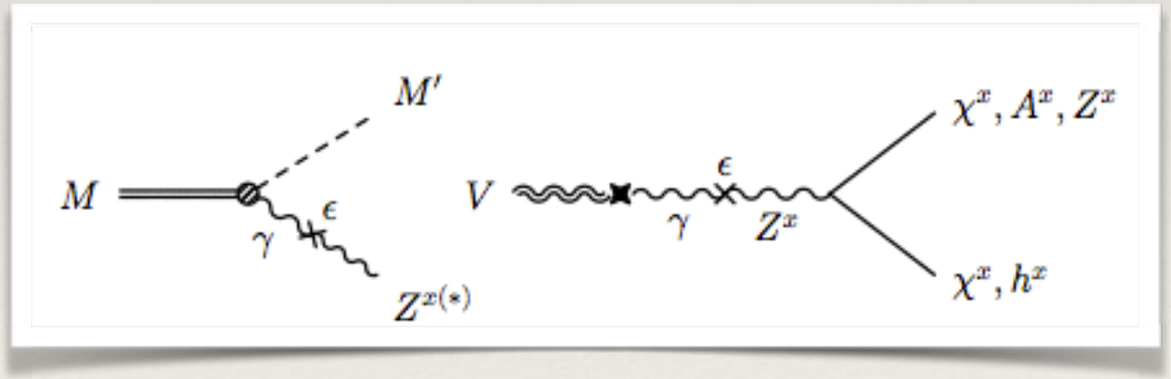
Proton Experiments

- Benefit from luminosity
- Easy to compute (for me!)
- One previous study:
  - $Z^x \to$ scalars $\to$ leptons
  - No mass mixing
- Many prospective limits from neutrino expts
- Strong limits from h^x!

High Mass: Partonic Production



Low Mass: Meson Decays



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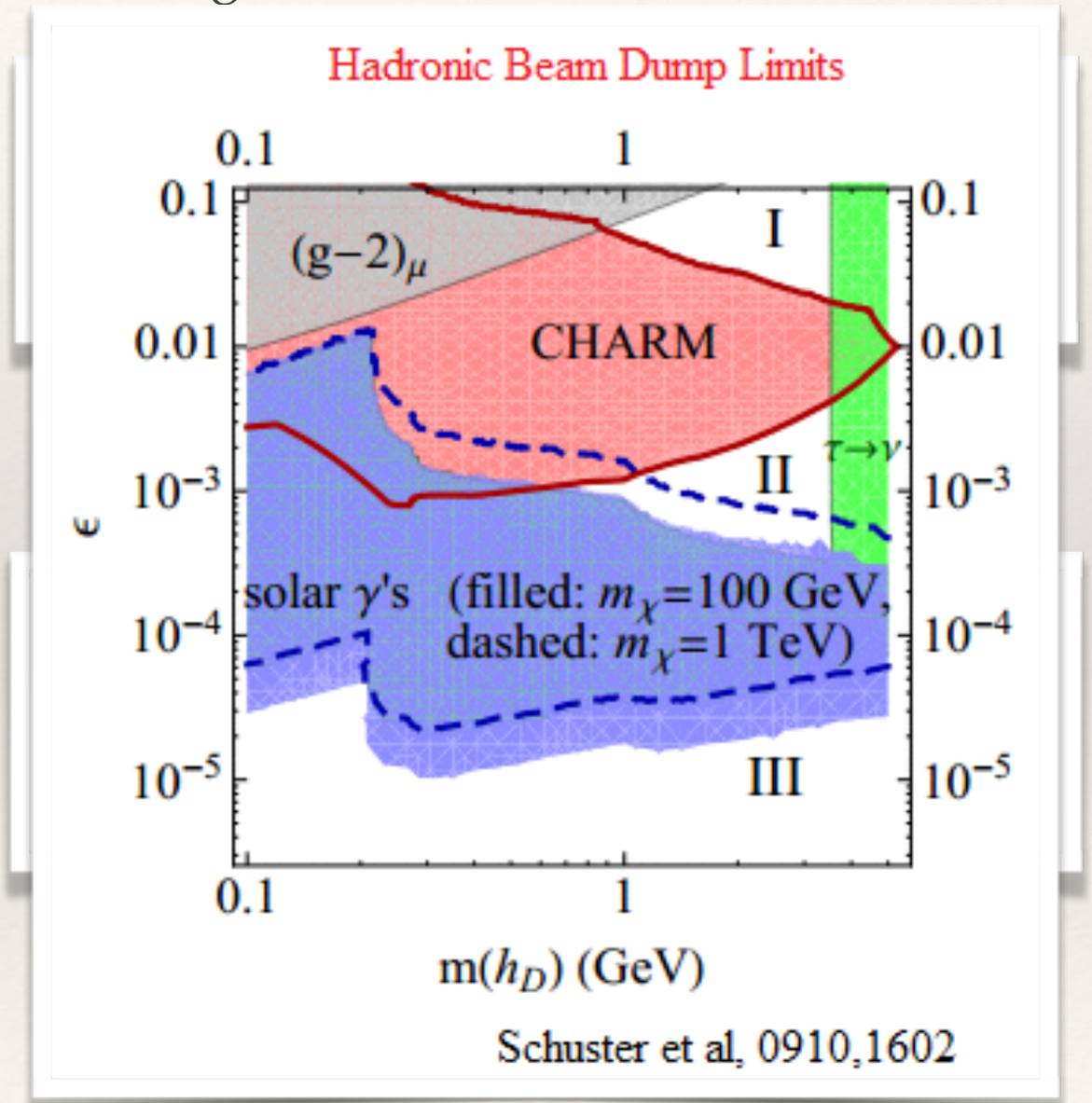

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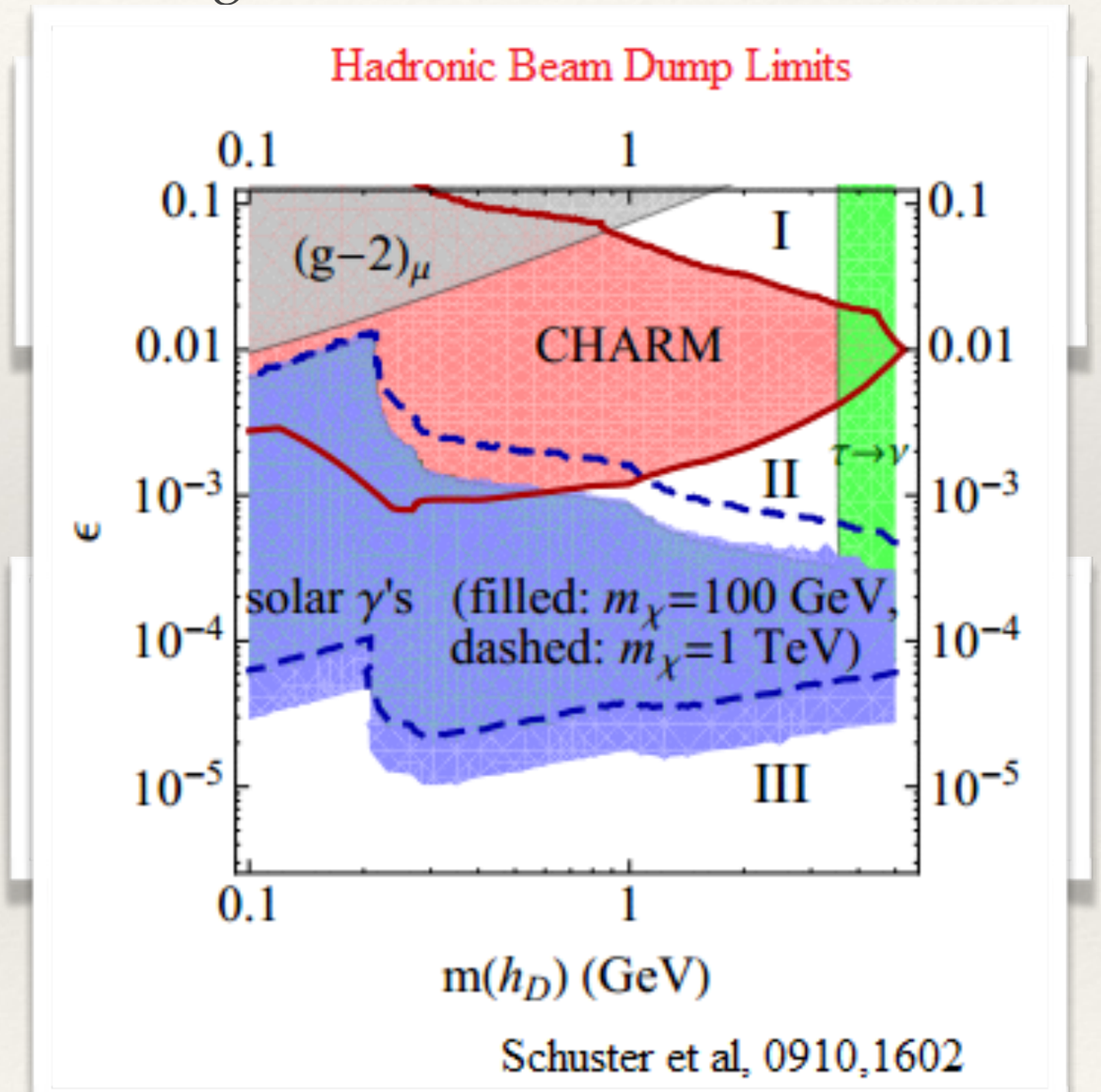
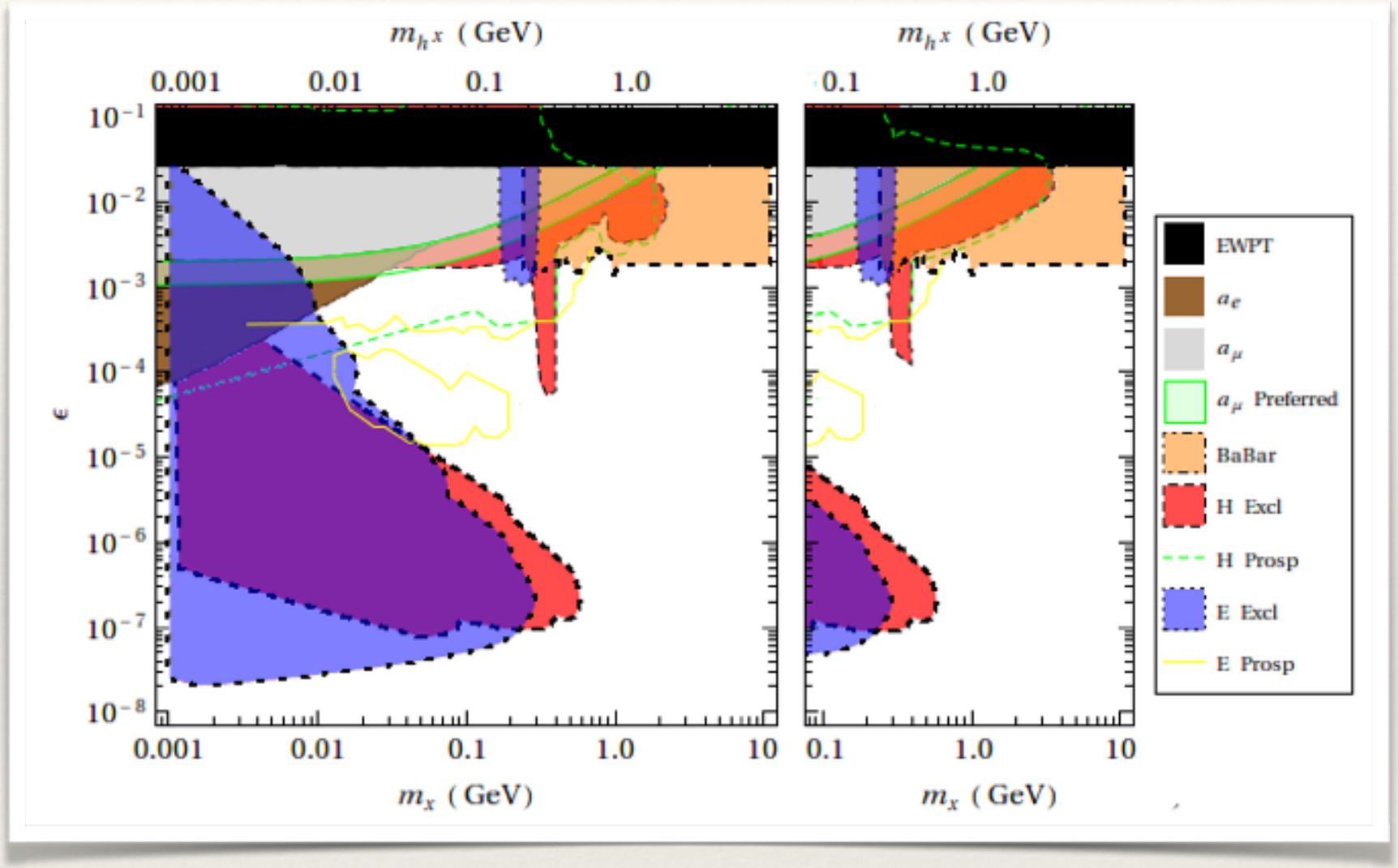
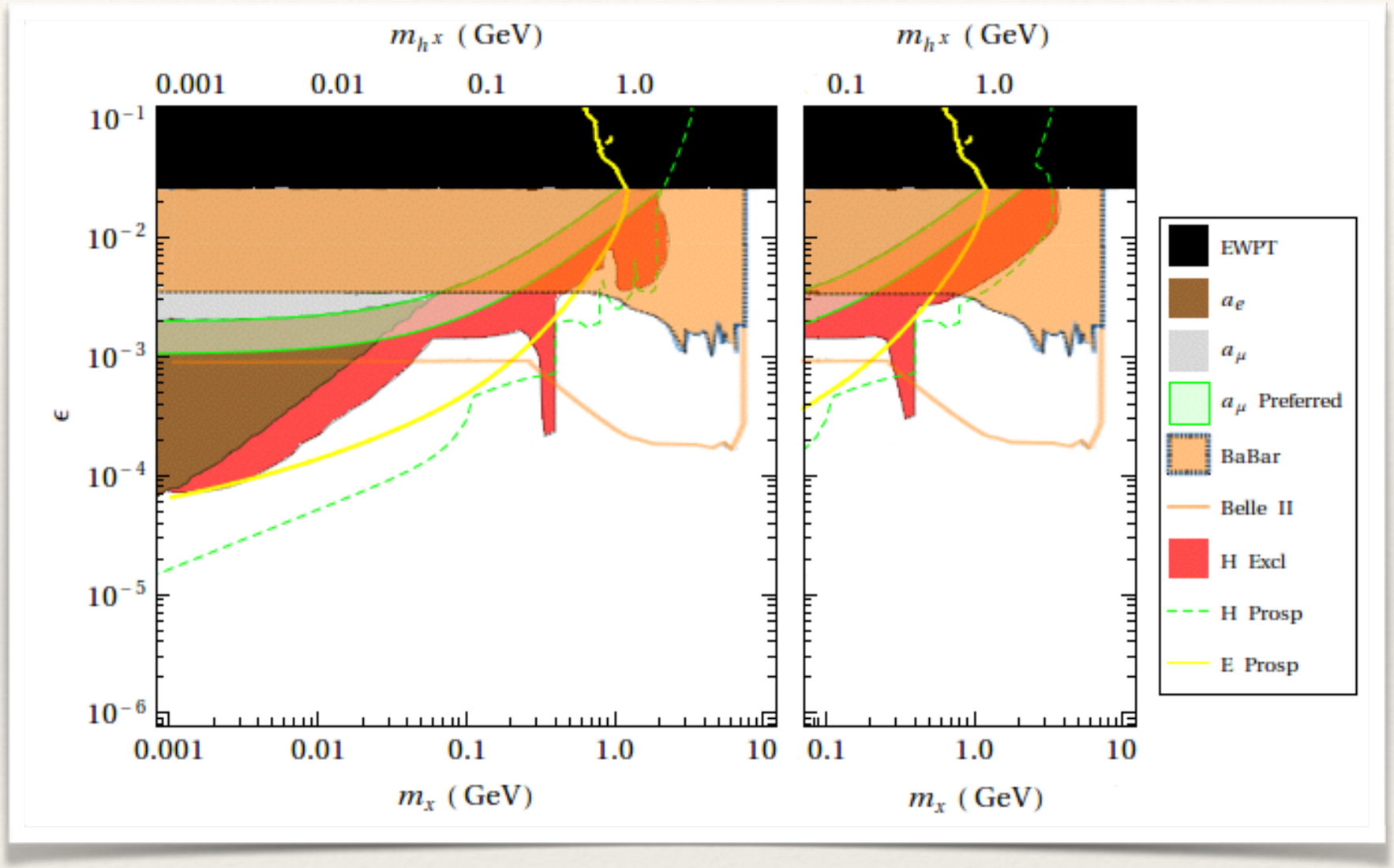


Benchmark A



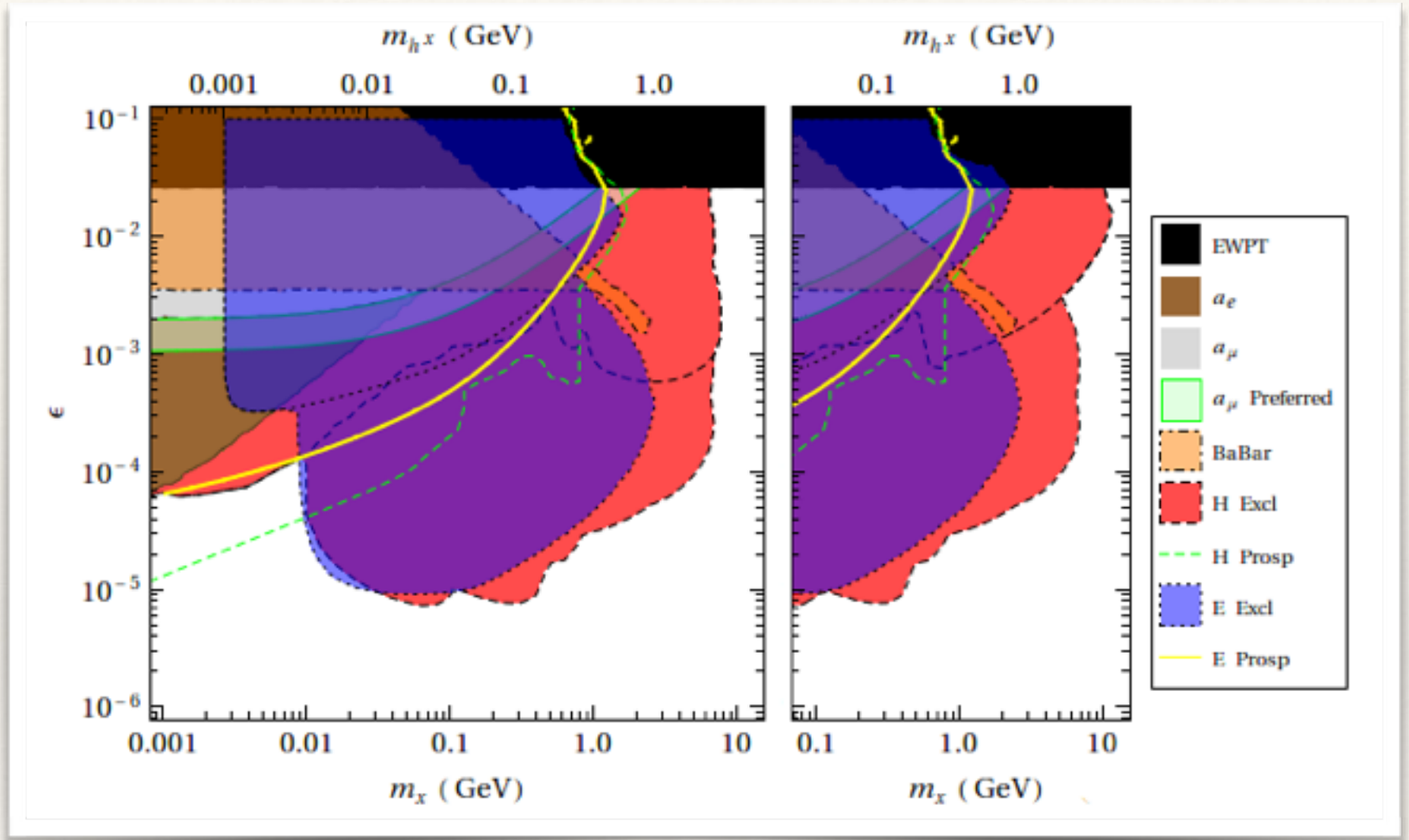
- Limits from CHARM only new ones
- Nearly exclude region that explains a_μ!

Benchmark B



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

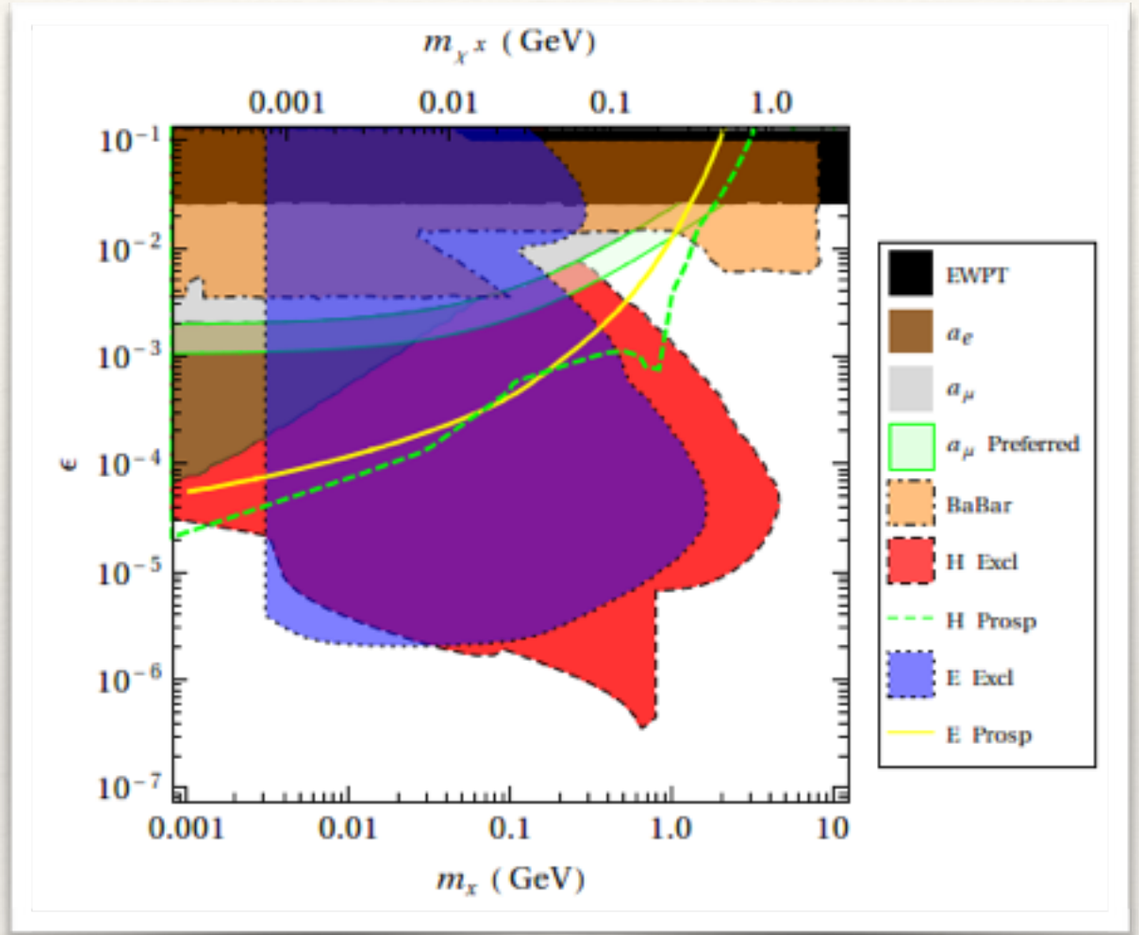
Benchmark C



- 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 $m_{Zx} < 1$ 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

Back-Up Slides

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.

Structure of Hidden Sector

- Hidden sector very similar to neutral sector of MSSM

$$m_{Z^x} \leftrightarrow m_Z \quad m_{A^x} \leftrightarrow m_A \quad M_x \leftrightarrow M_B \quad \mu' \leftrightarrow \mu \quad \tan\zeta \leftrightarrow \tan\beta$$

- Fermion sector: as MSSM neutralinos, without $\tilde{W}$

$$\tilde{X} \leftrightarrow \tilde{B} \quad \tilde{H} \leftrightarrow \tilde{H}_u \quad \tilde{H}' \leftrightarrow \tilde{H}_d$$

- Scalar sector: as MSSM neutral Higgses

$$H \leftrightarrow H_u^0 \quad H' \leftrightarrow H_d^0$$

- At tree level, $m_{h^x} < m_{Zx}$

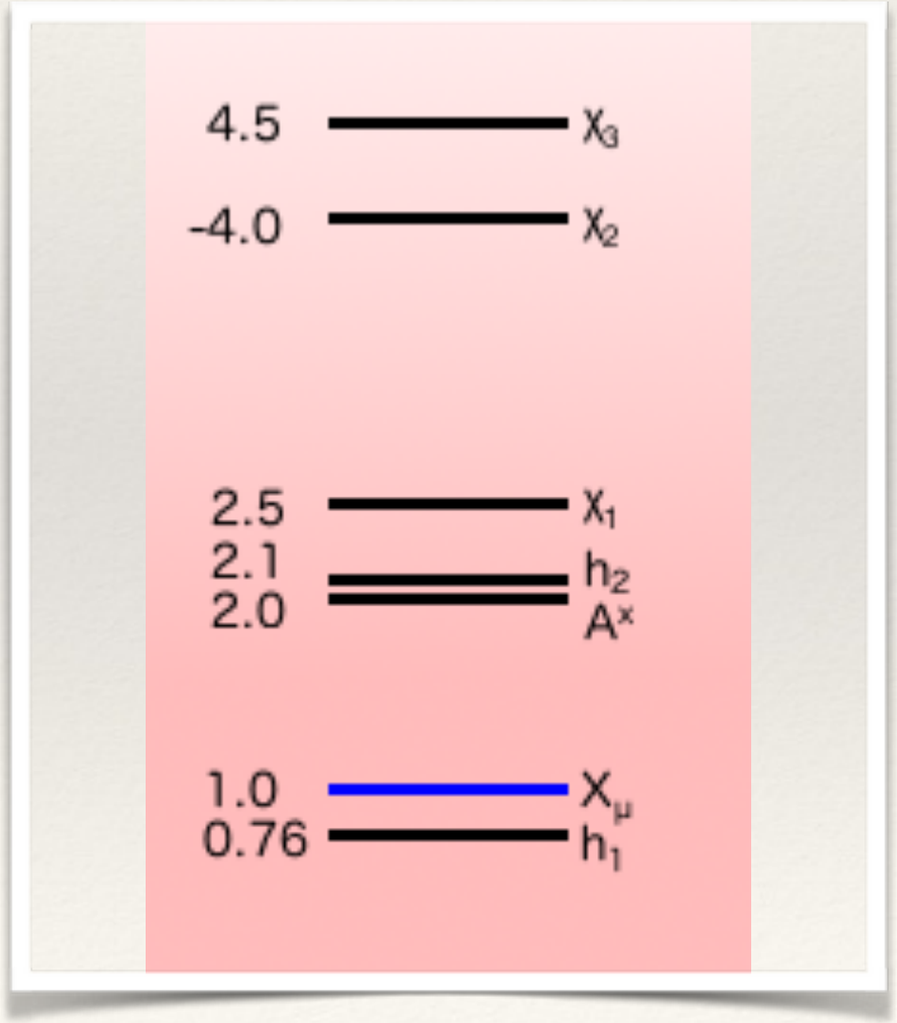
Benchmark Slope A: $Z^x \to$ SM

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



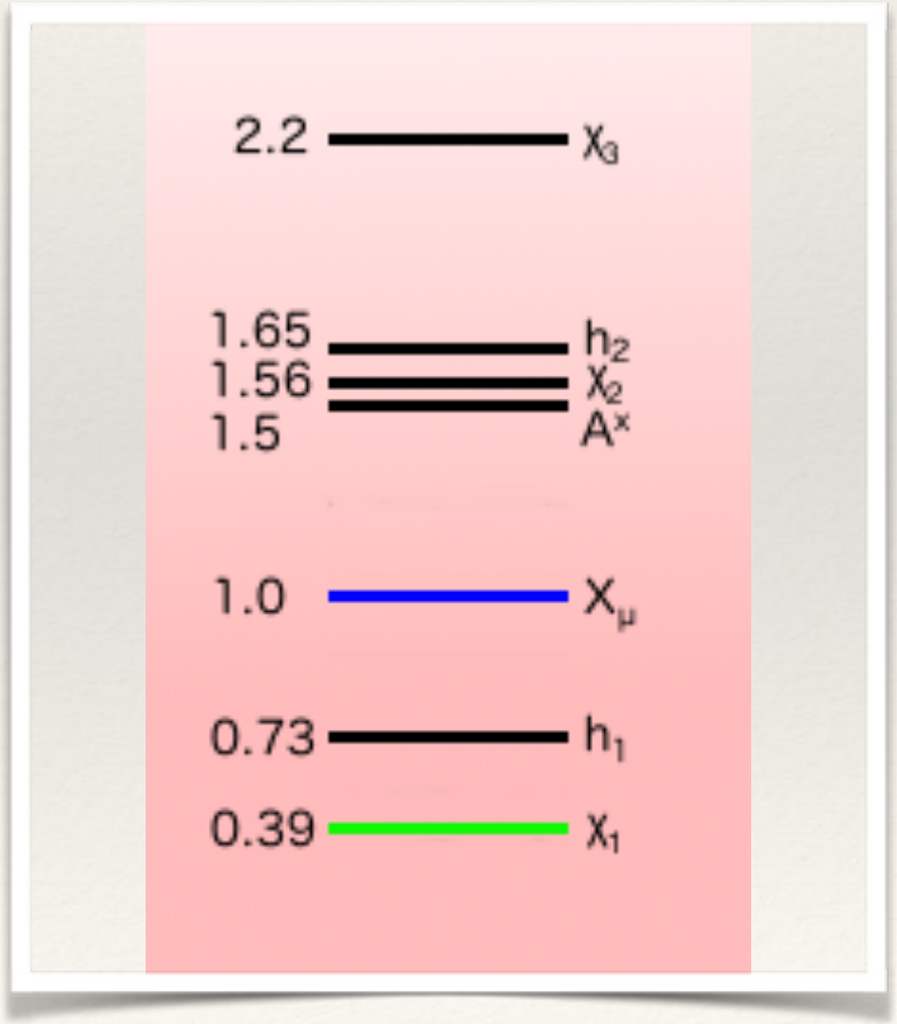
Benchmark Slope B: $Z^x \to \text{Inv}$

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



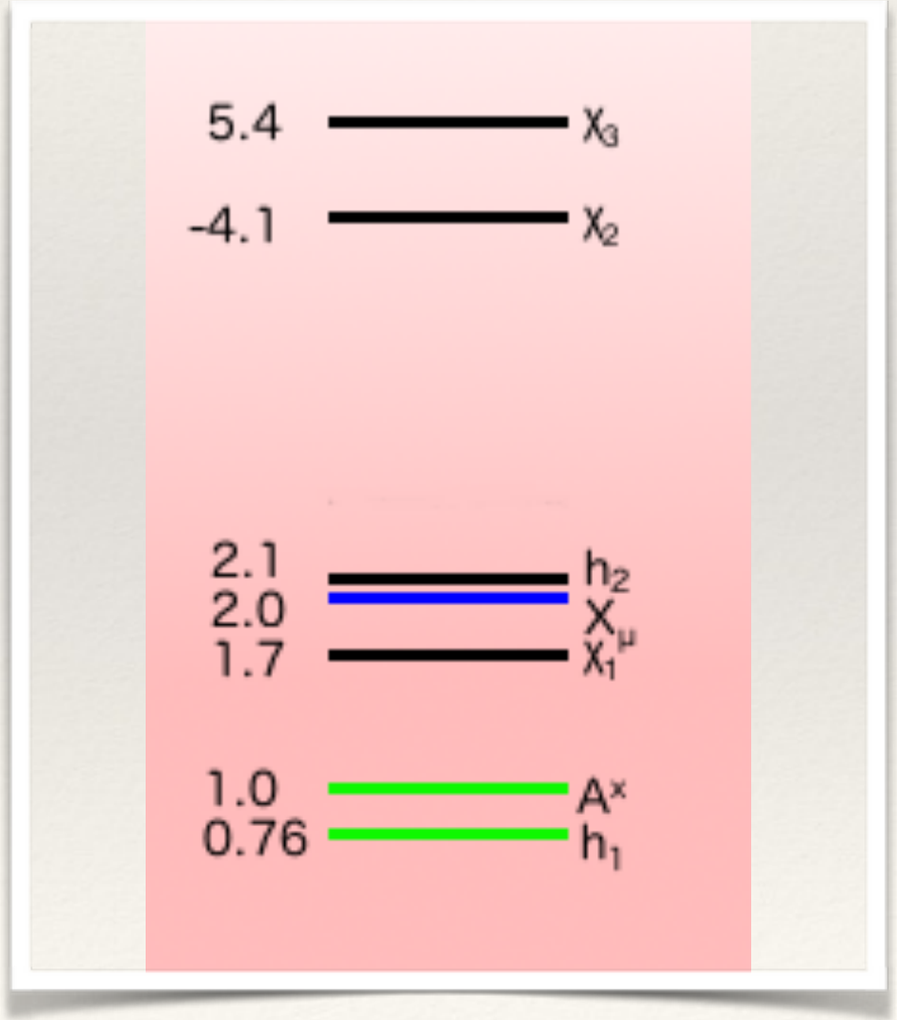
Benchmark Slope C: $Z^x \to$ Scalars

m	0.5
M	1.5
μ'	2.0

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

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

-

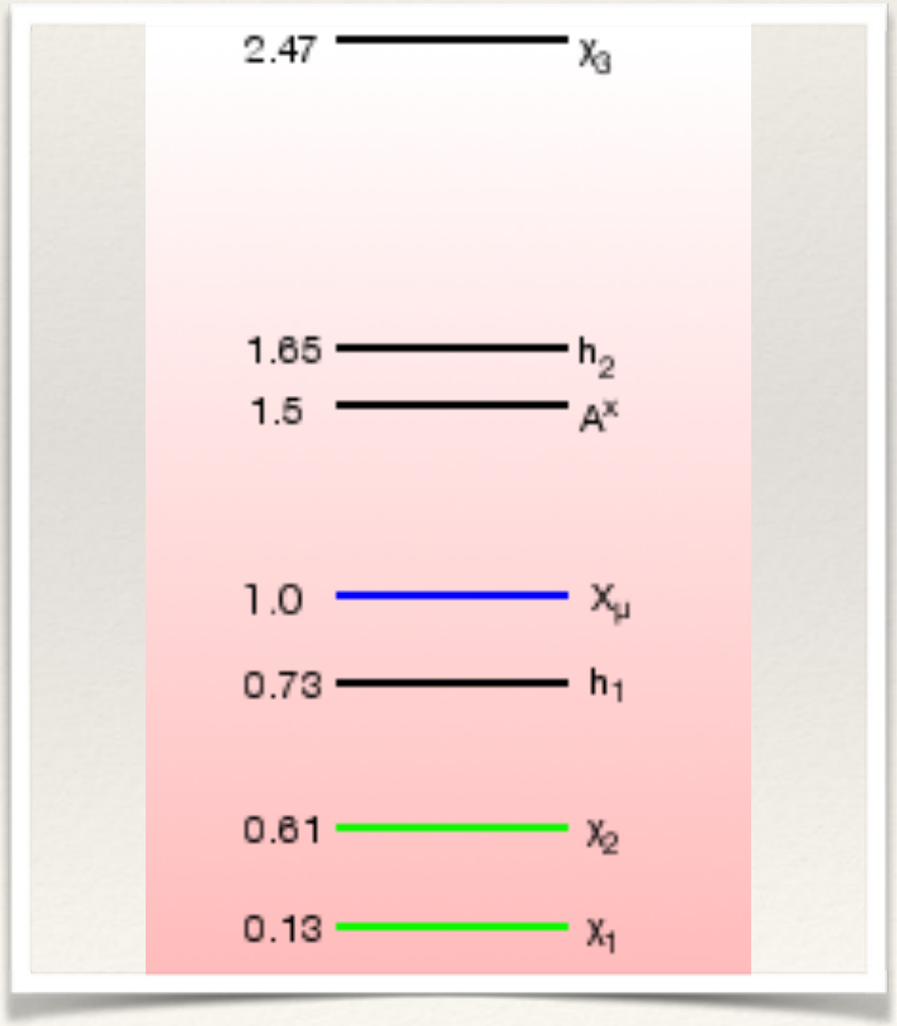


Benchmark Slope D: $Z^x \to$ Fermions

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

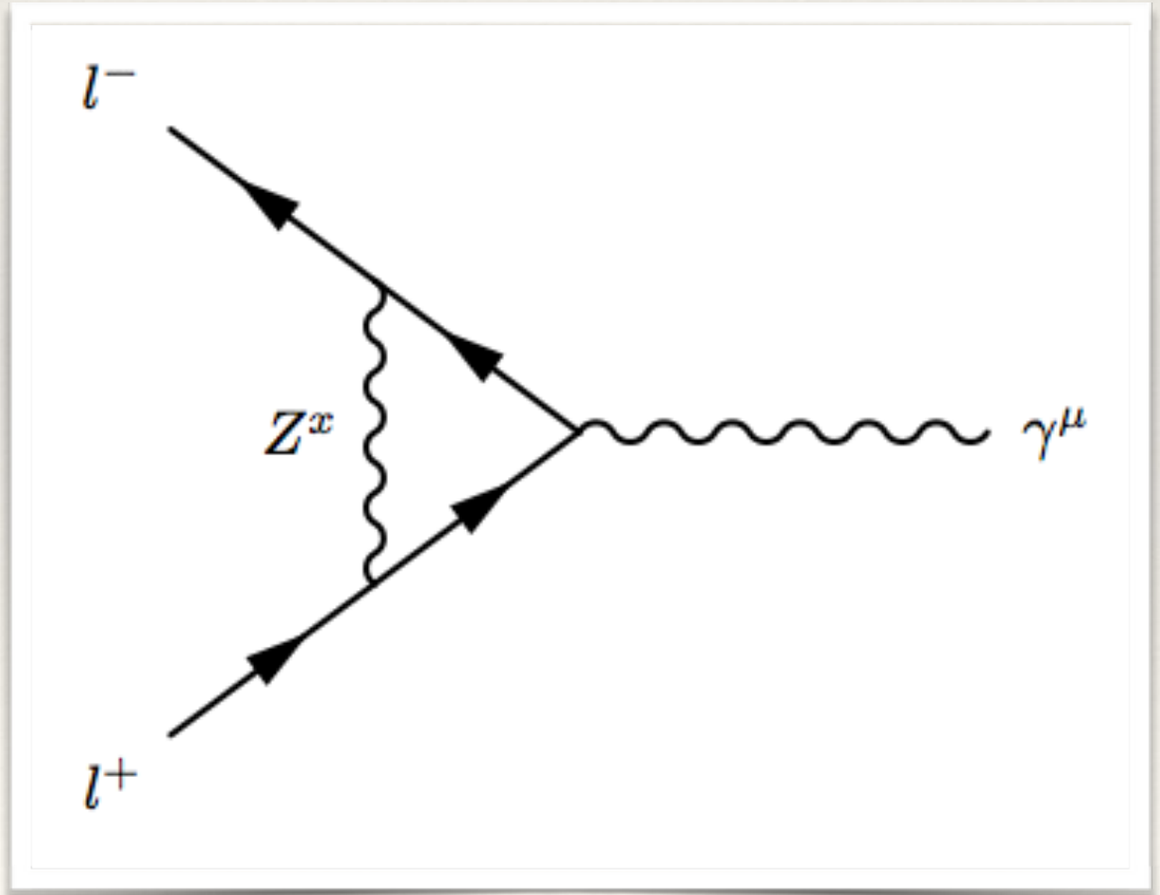
$$\mu' < m_{Z^x} < m_{A^x},\, M_x$$



Non-Beam Dump Limits

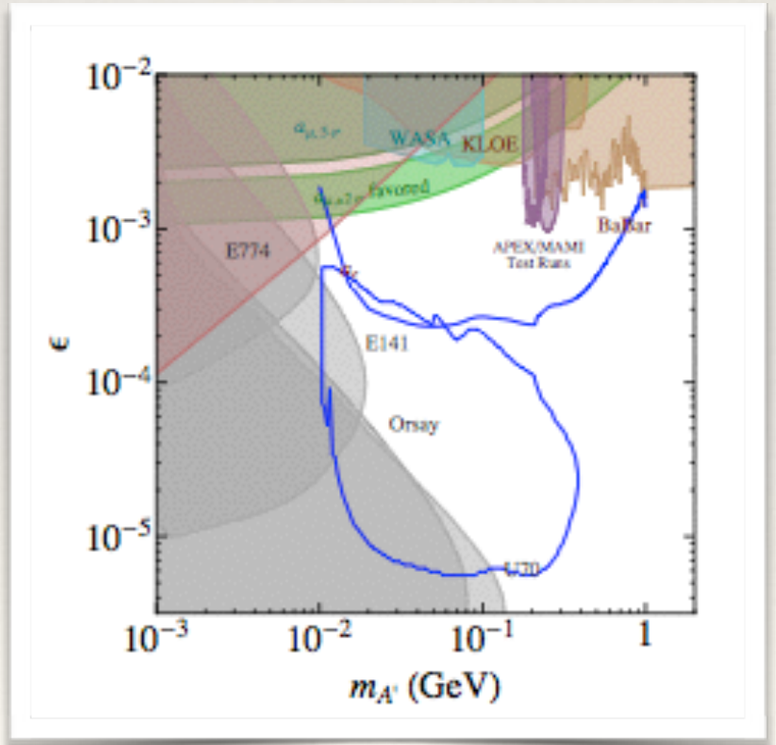
Model-Independent Limits

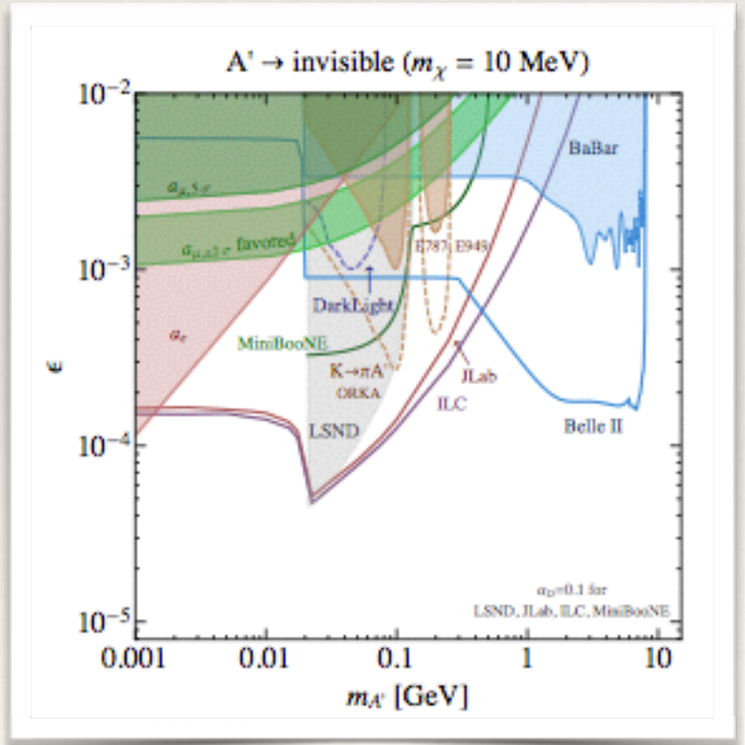
- Electroweak Precision: (m_Z)
  - Kinetic Mixing Modifies Z
    - $\varepsilon \lesssim 0.026$ [Hook *et al*, `1006.0973`]
- Anomalous Magnetic Moments
  - Intro QFT Calculation
  - Limits from a_e and a_μ
- Possible explanation of δa_μ
- Details: Pospelov, `[0811.1030]`



Meson Decays: Slopes A and B

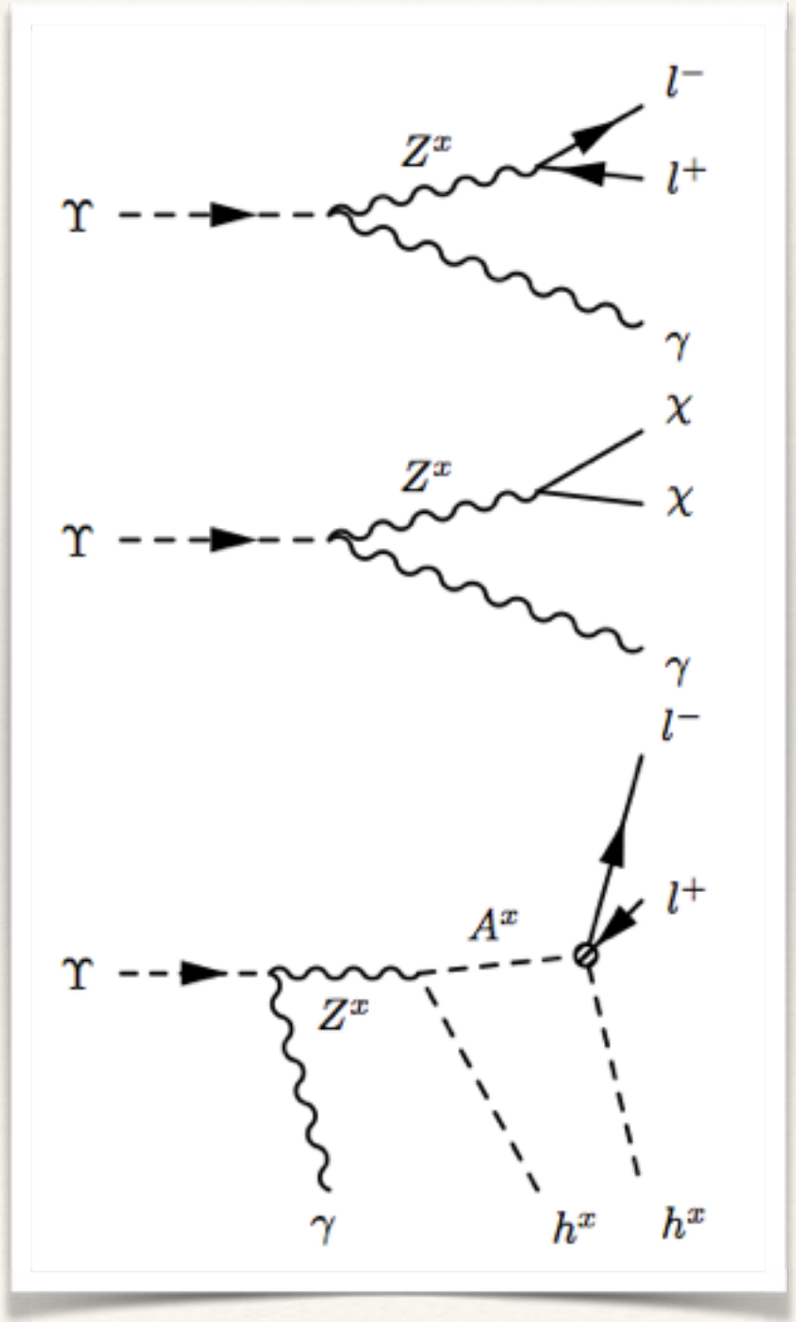
- BaBar Υ (3s, 2s) $\to \gamma\ a^0 \to \gamma\ \mu^+\ \mu^-$
- KLOE $\varphi \to \eta\ Z^x \to \eta\ e^+\ e^-$
- WASA $\pi^0 \to \gamma\ Z^x \to \gamma\ e^+\ e^-$
- BaBar Υ (3s) $\to \gamma\ a^0 \to \gamma + \text{inv}$
- E787, E949 $K^+ \to \pi^+\ \nu\ \overline{\nu}$



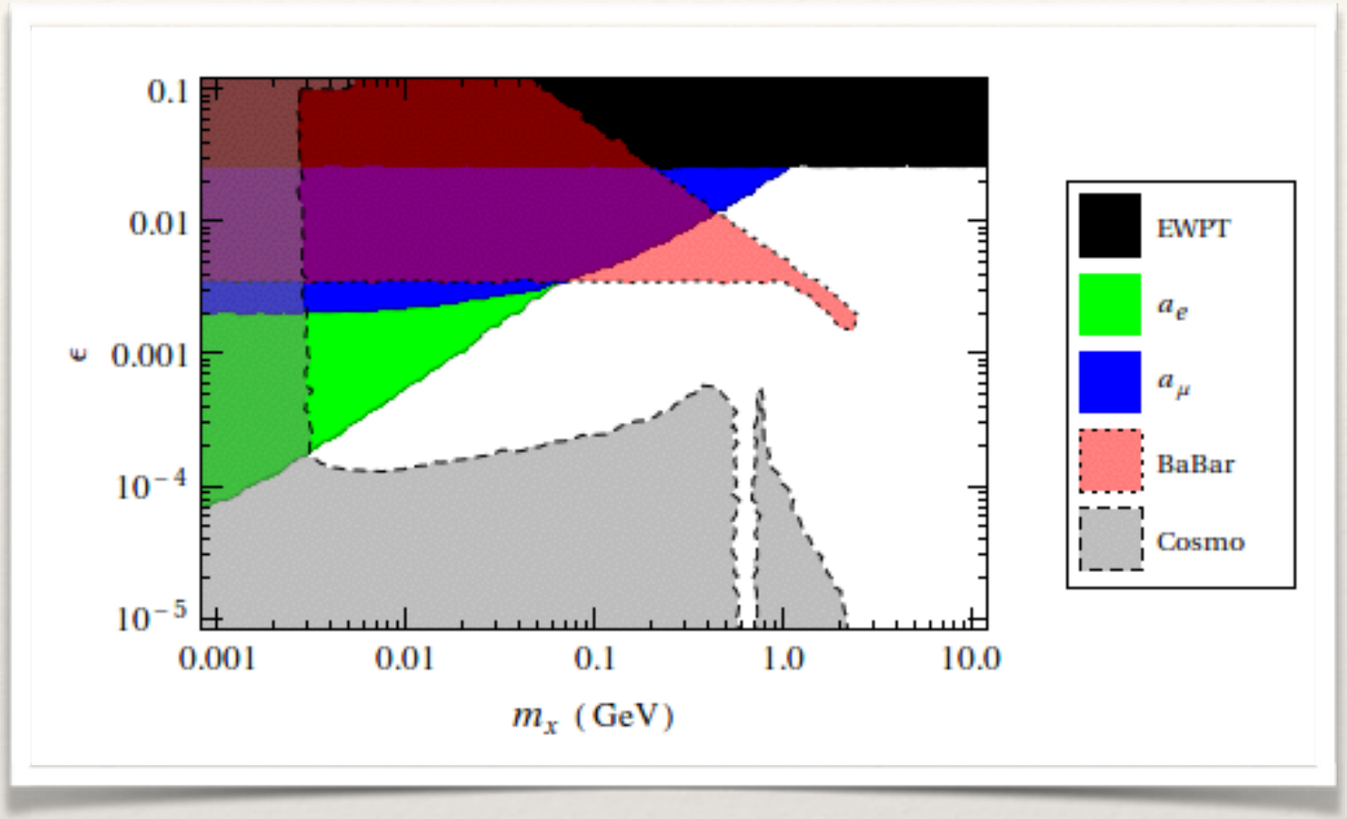


Meson Search Topologies

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

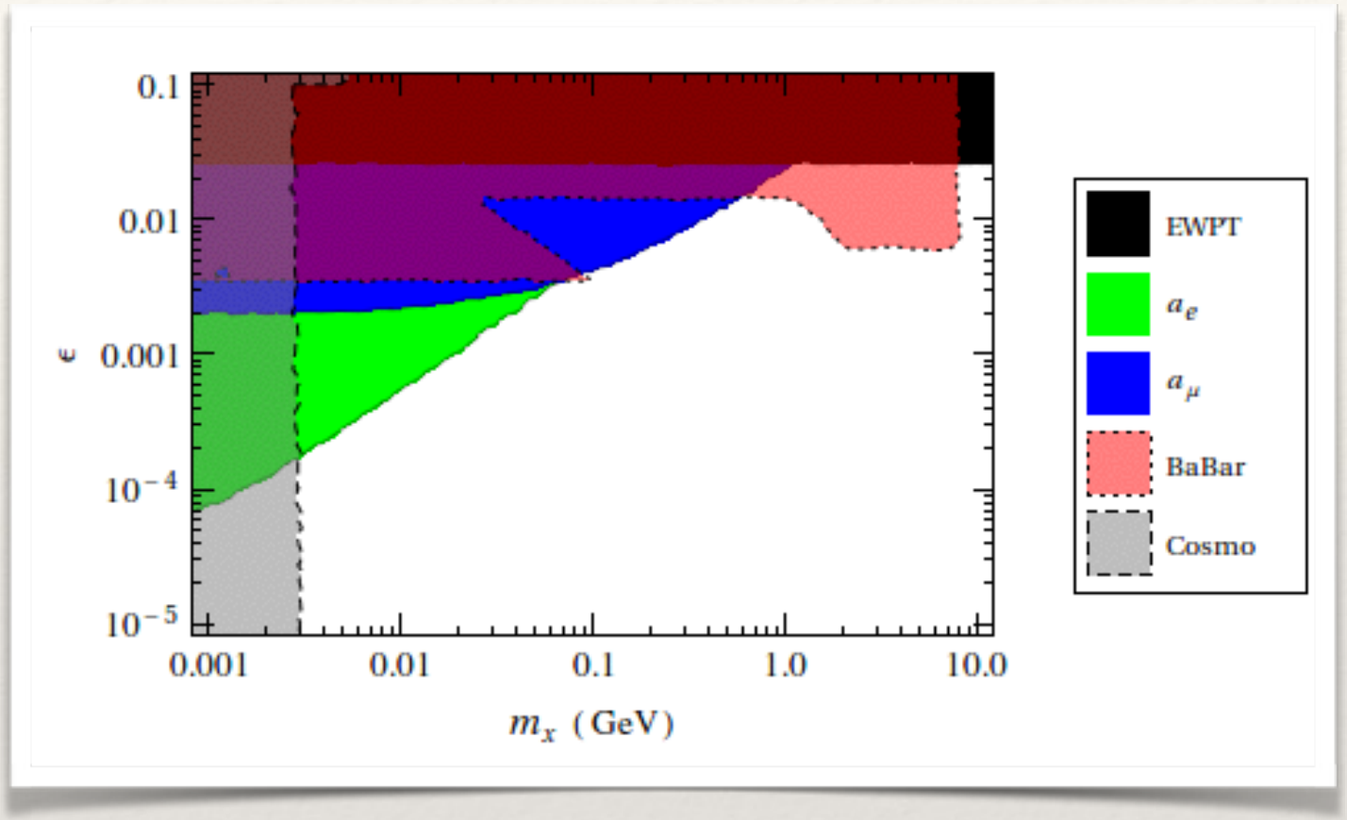


Meson Decays C: $Z^x \to$ Scalars



- 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 $K^+ \to \pi^+ \nu \bar{\nu}$ 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

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

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

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