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Light Hidden Sectors at Fixed-Target Experiments

`arXiv:1402.4817`
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Andrew Spray (Melbourne)

Outline

1. Introduction and Motivation

2. Theory: Model and Decays

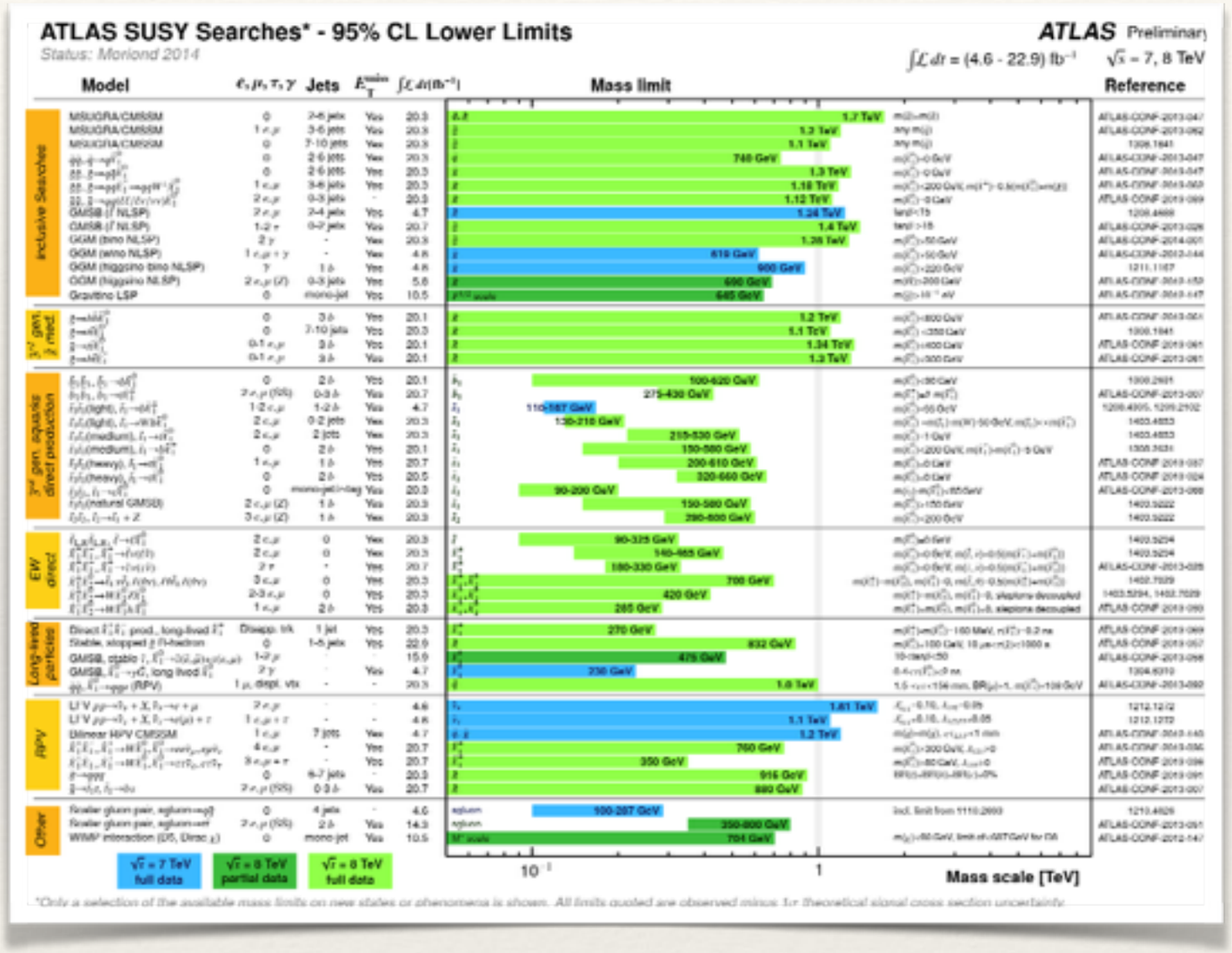
3. Fixed Target Experiments

4. Combined Limits and LHC Implications

5. Conclusions

Introduction and Motivation

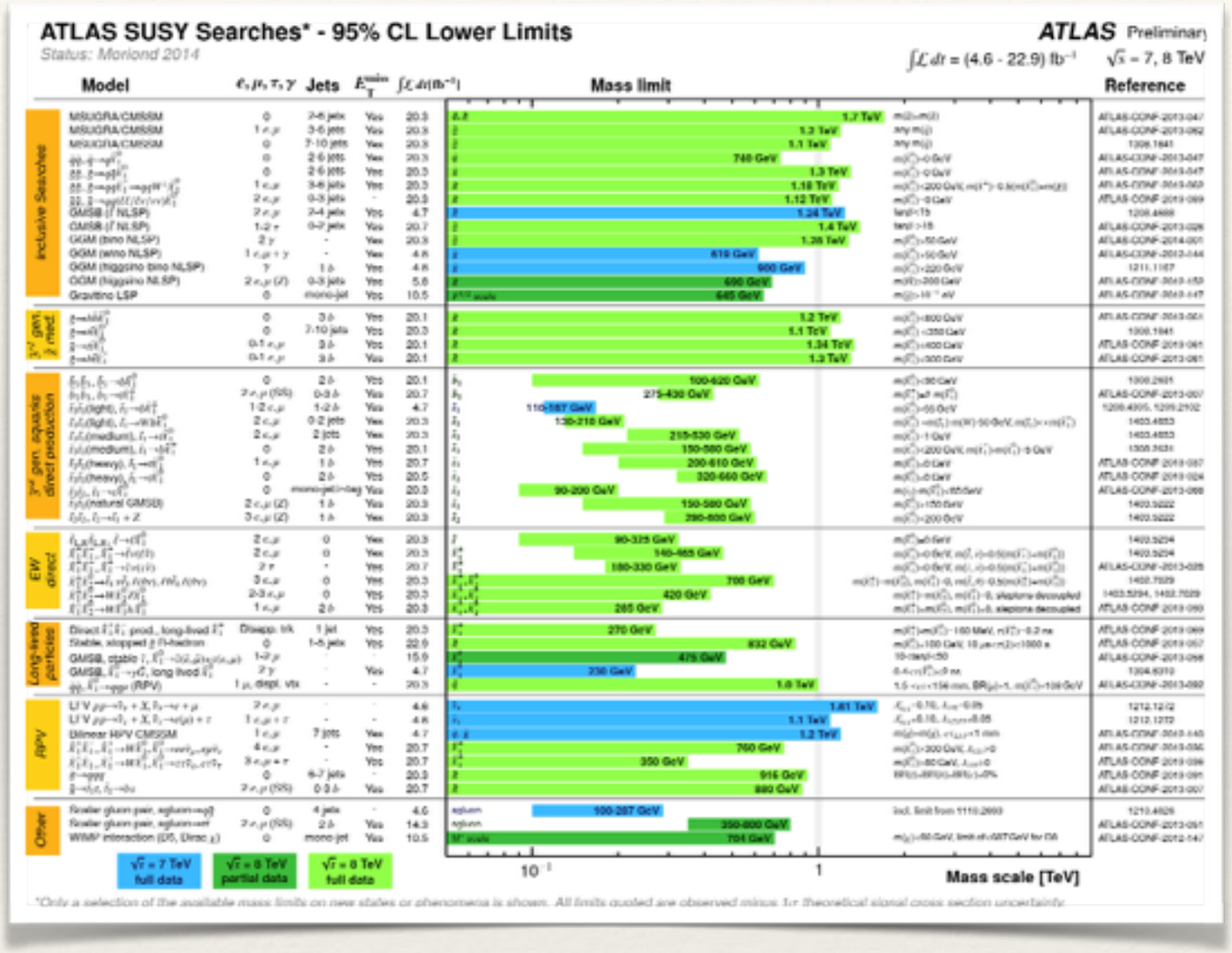
Supersymmetry



- It's not dead, only resting

- Strongest limits use MET

Supersymmetry



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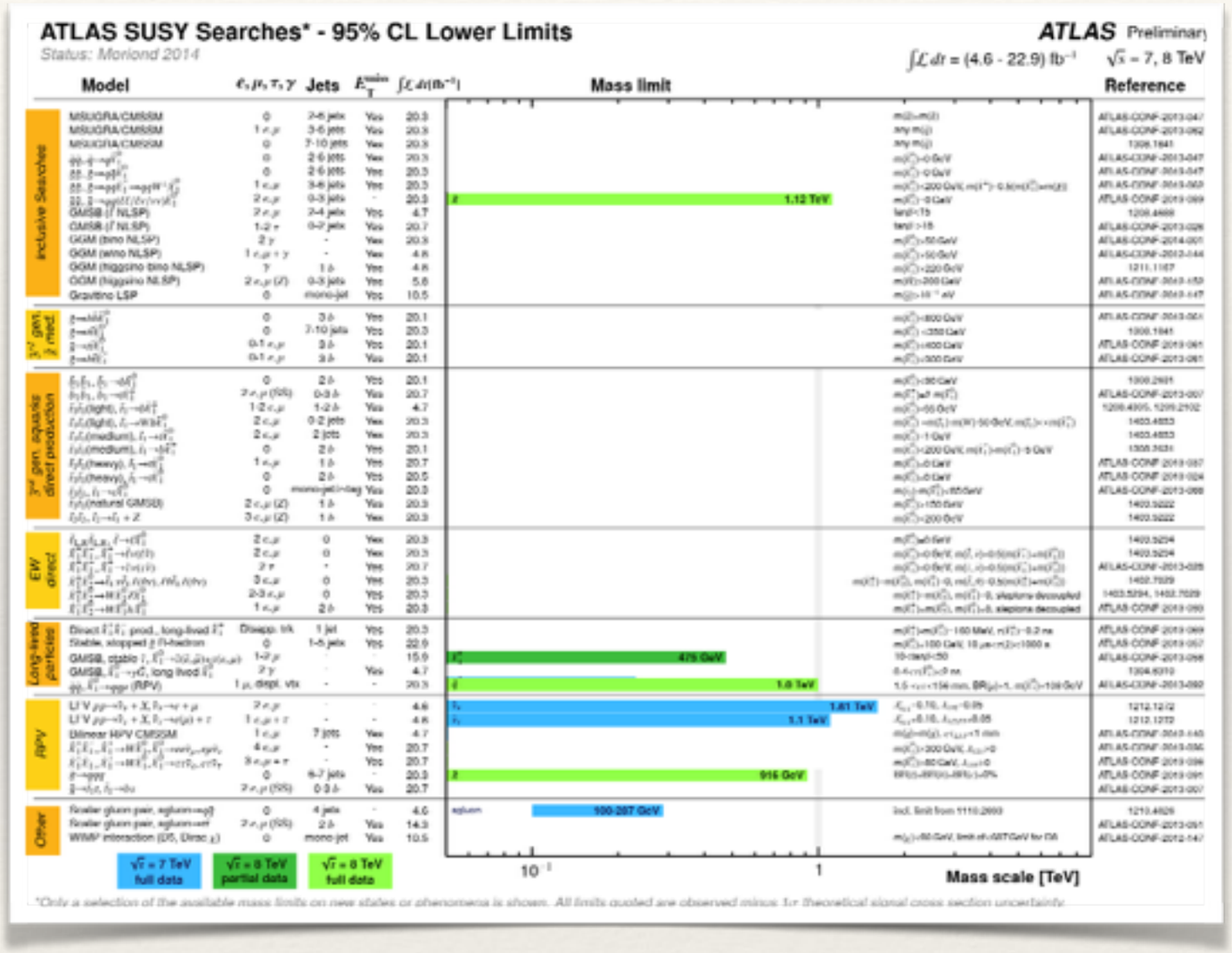

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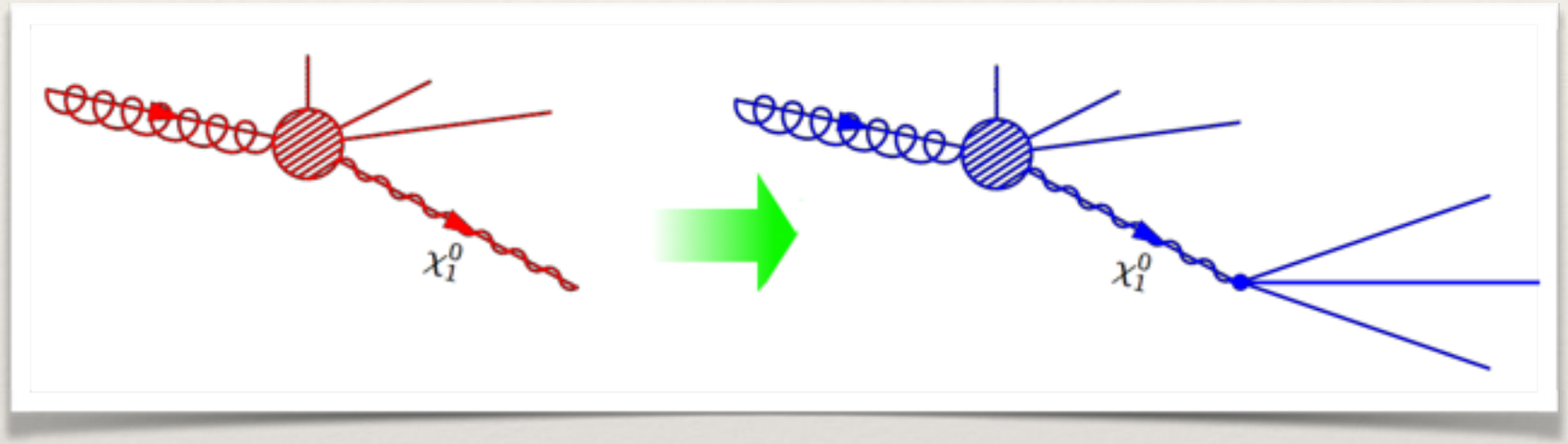
Suppressing MET

- Lots of model building to suppress MET
- Most popular option: R-Parity Violation



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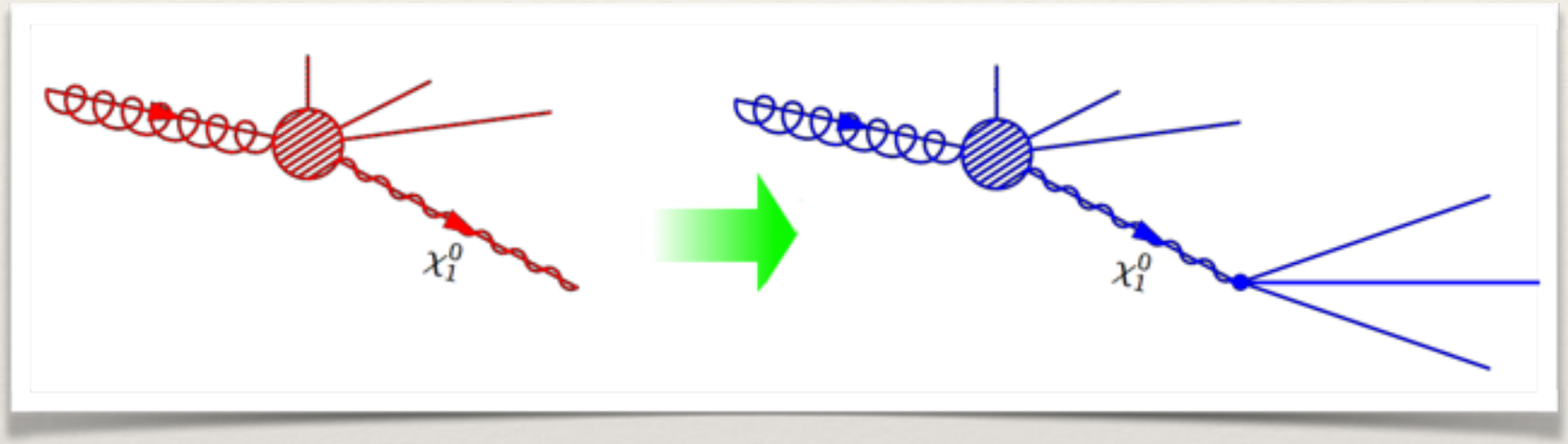

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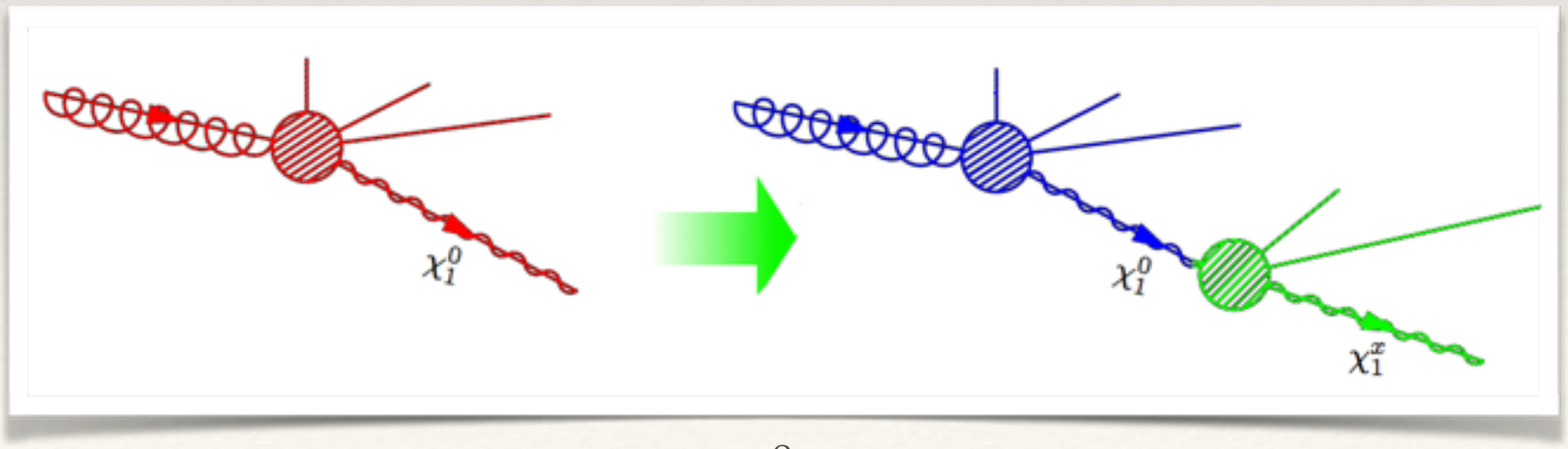
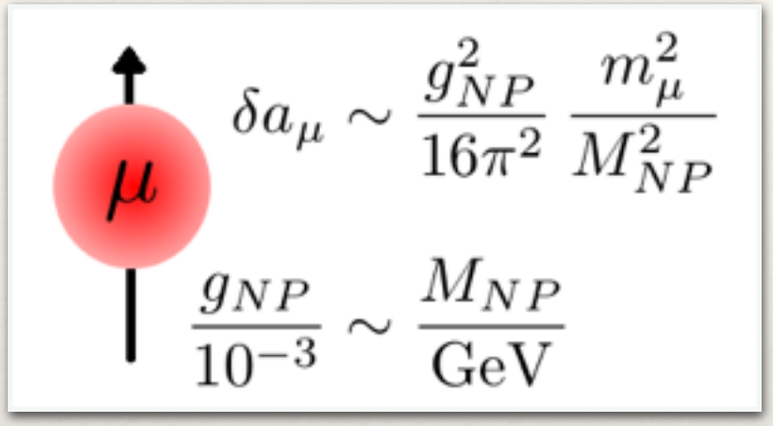
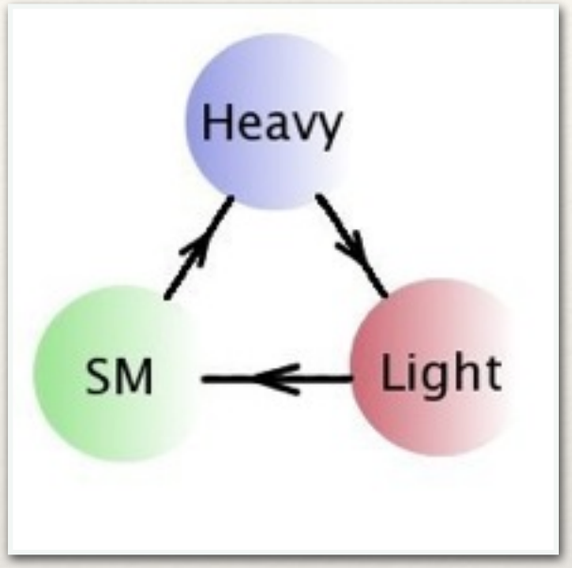


Thinking of New Light Stuff

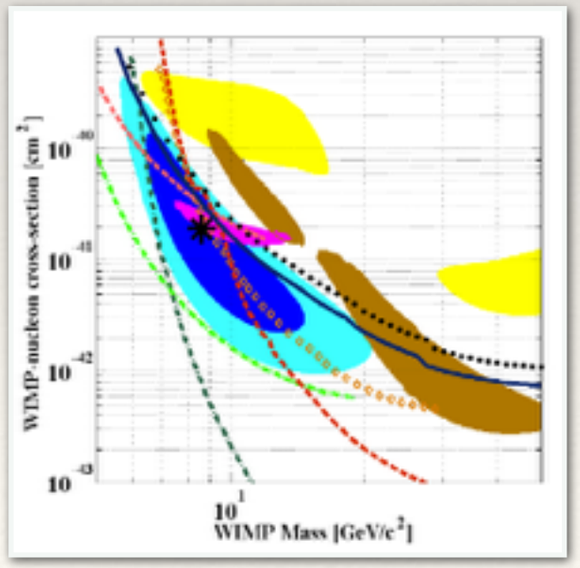
- μ Anomalous Magnetic Moment

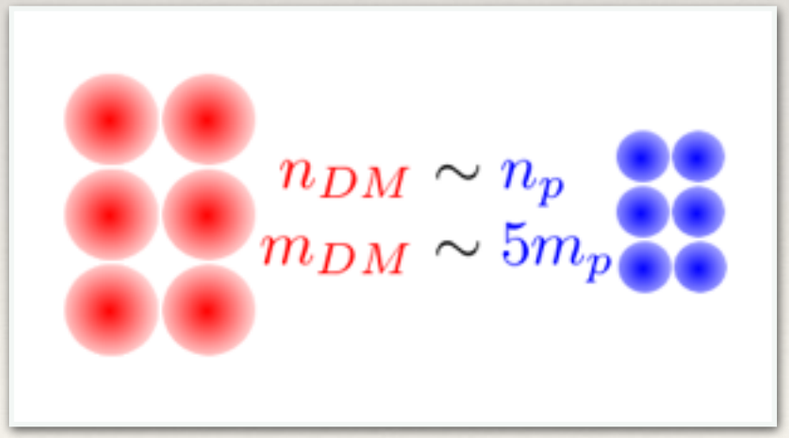




- Hidden Valleys

- Dark Matter Anomalies





- 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
  - Massless
  - 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
  - Near-massless
  - Hard to produce

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

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

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  - LHC Only
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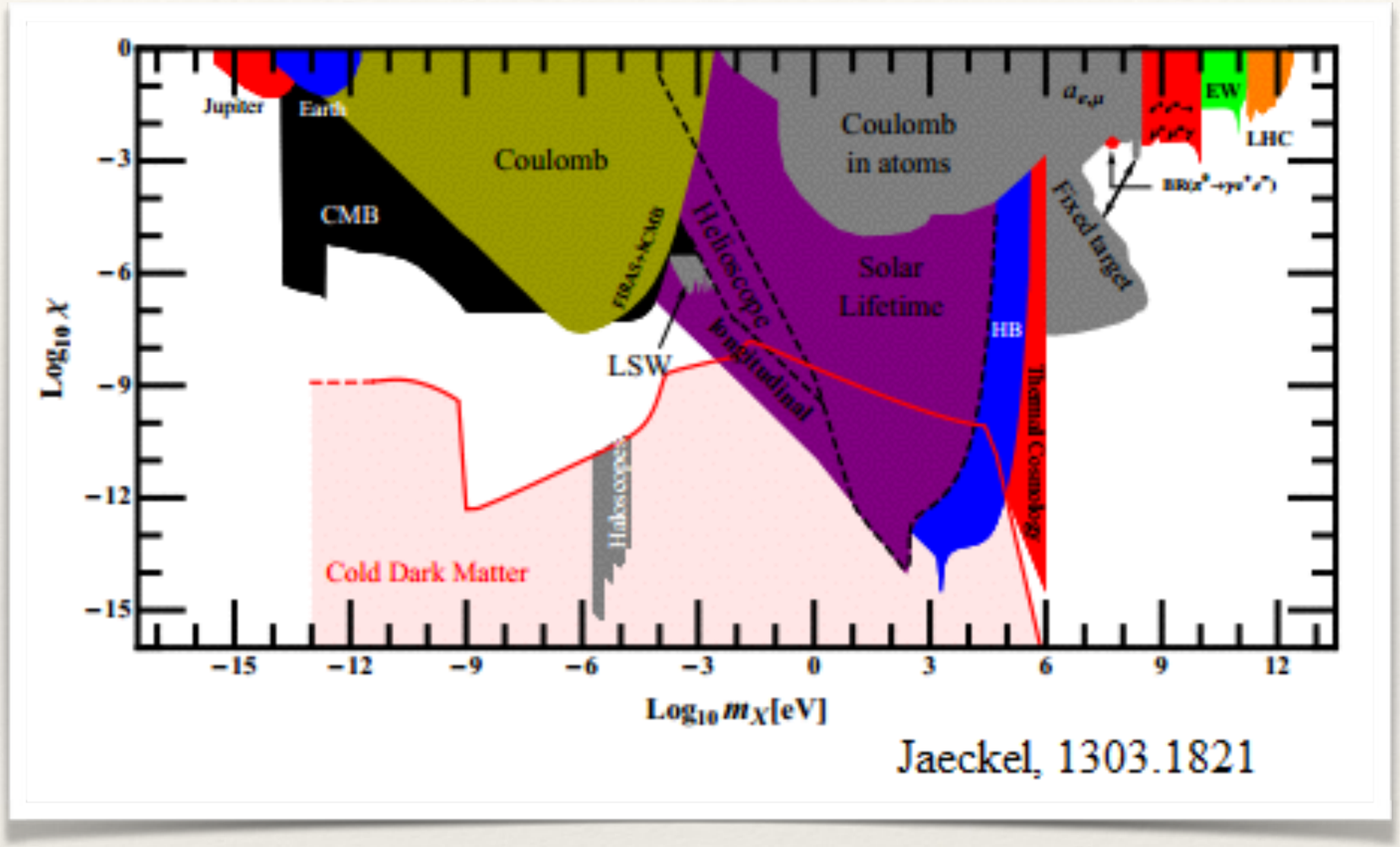
Vector Kinetic Mixing Limits

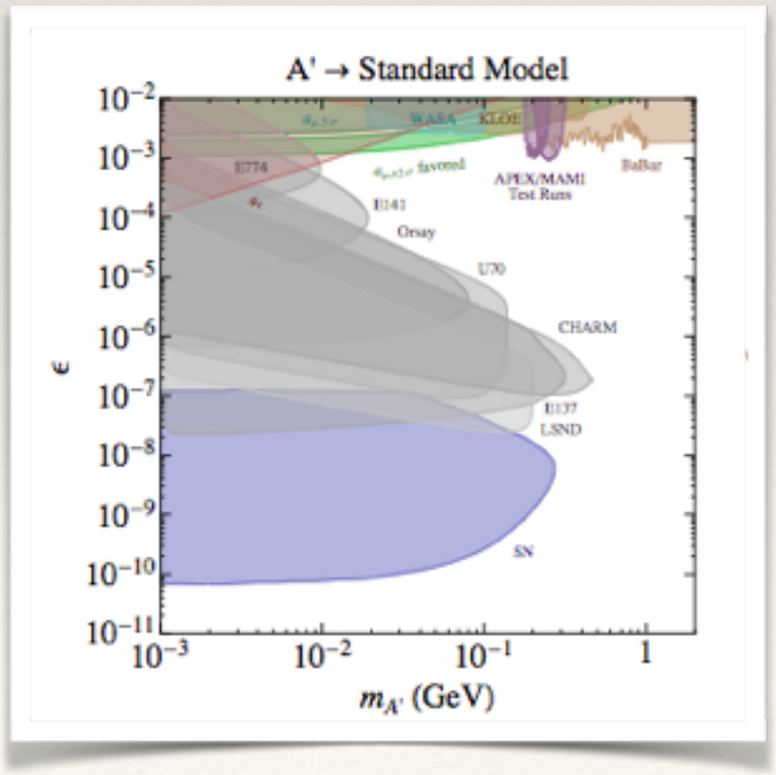


- Many previous studies and limits!
- GeV-scale relatively unconstrained

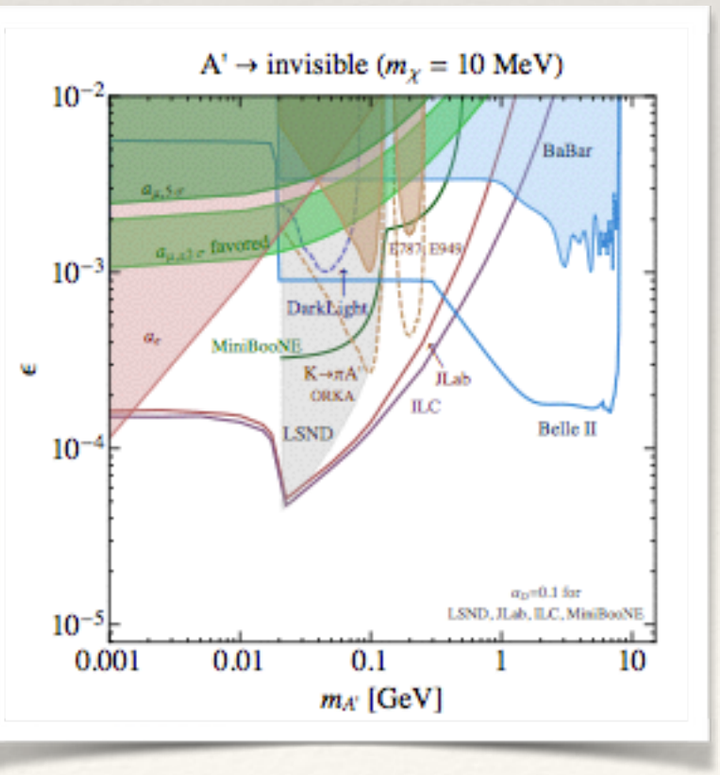
Assumptions!

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

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



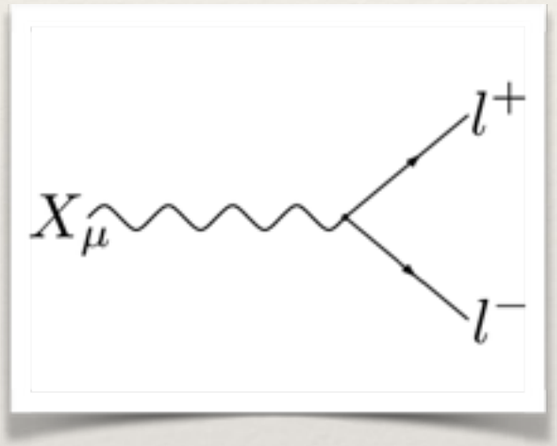
- $X \to$ invisible
  - Weaker limits from neutrino expts
  - Motivated from dark matter



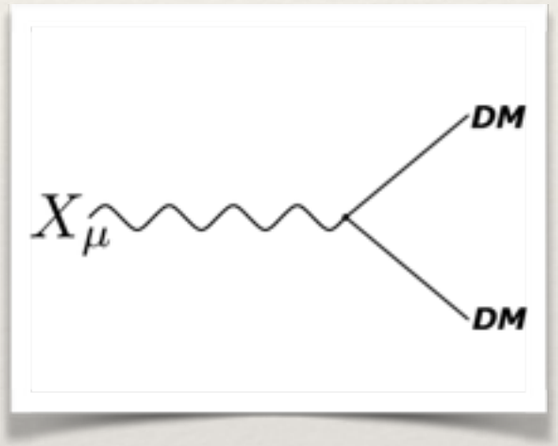
General Hidden Sectors

- Multiple possible vector decays:

- Direct Decay to Visible Sector

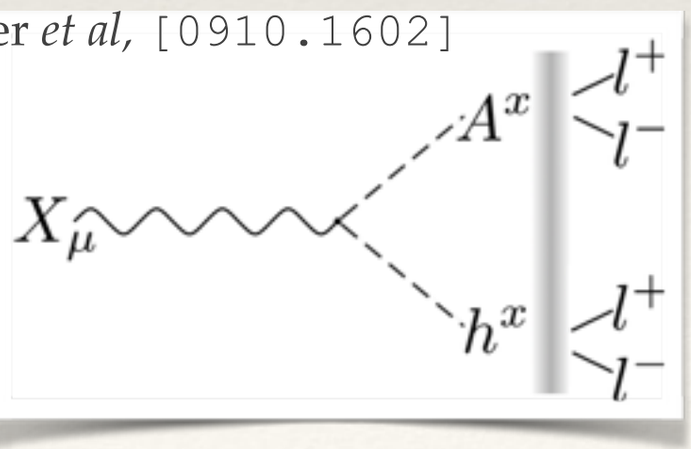


- Invisible Decay

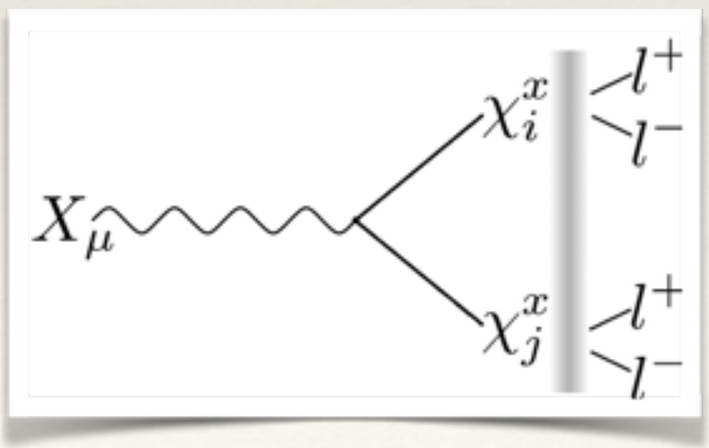


- Decay to SM via Hidden Scalars

- Schuster *et al,* [0910.1602]



- Decay to SM via Hidden Fermions

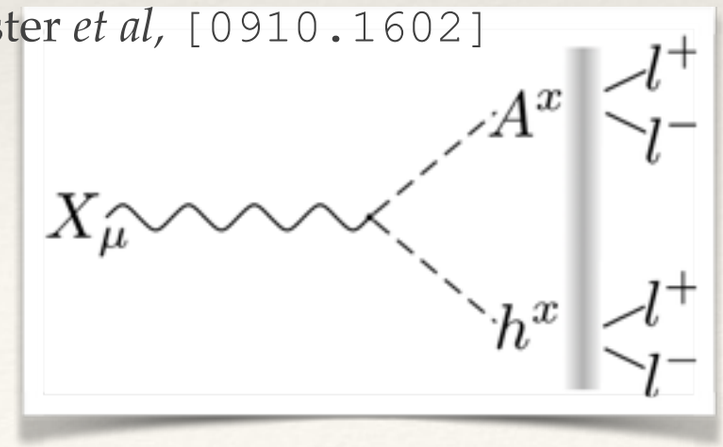


General Hidden Sectors

- Multiple possible vector decays:

Particularly relevant for SUSY Hidden Sectors!

- Decay to SM via Hidden Scalars
- Schuster *et al*, [0910.1602]



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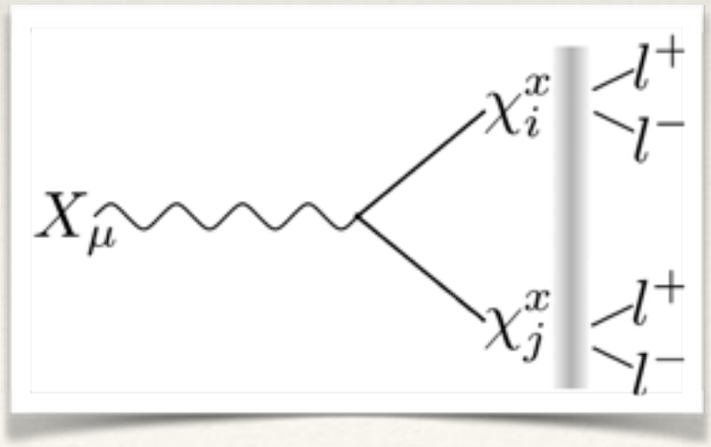


The Model

A Minimal Supersymmetric Hidden Sector

- No need to build a model: already had one! [1112.2705]
- 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

- No need to build a model: already had one! [1112.2705]
- 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'

$$W \supset \mu'\, H\, H'$$

- 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.

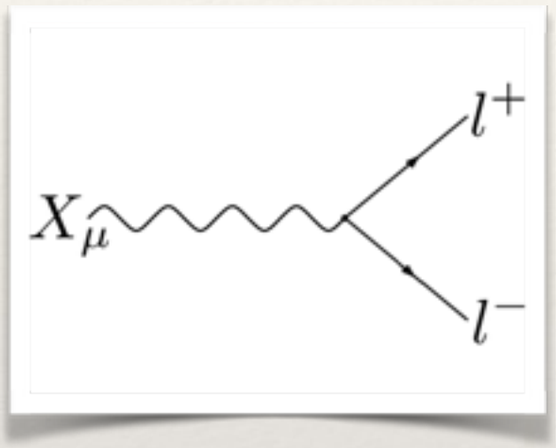
Model as Benchmark

- 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

Four Benchmark Slopes

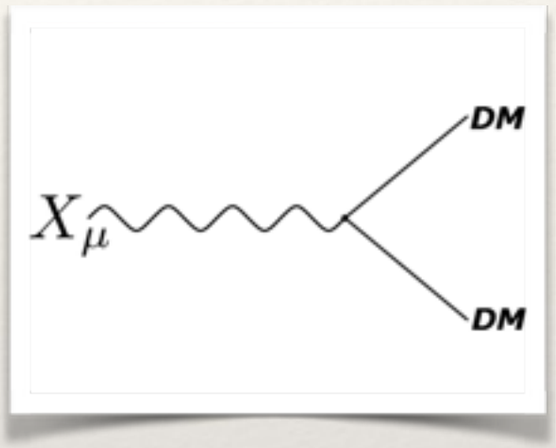
- Slices of parameter space: fixed ratios of mass parameters

A



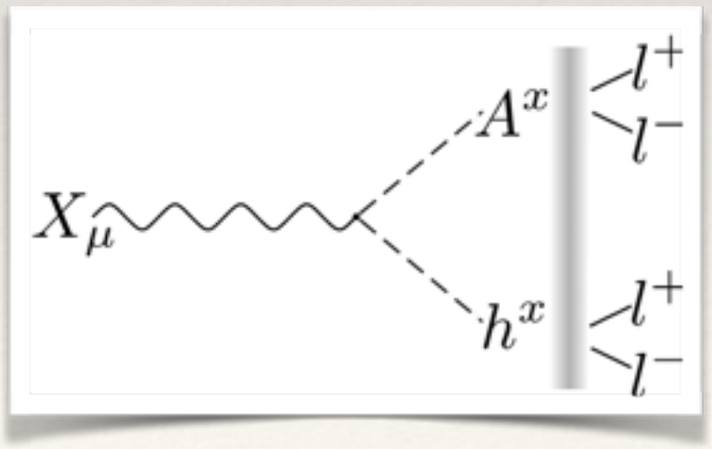
$m_{Z^x} < m_{A^x},\ \mu',\ M_x$

B



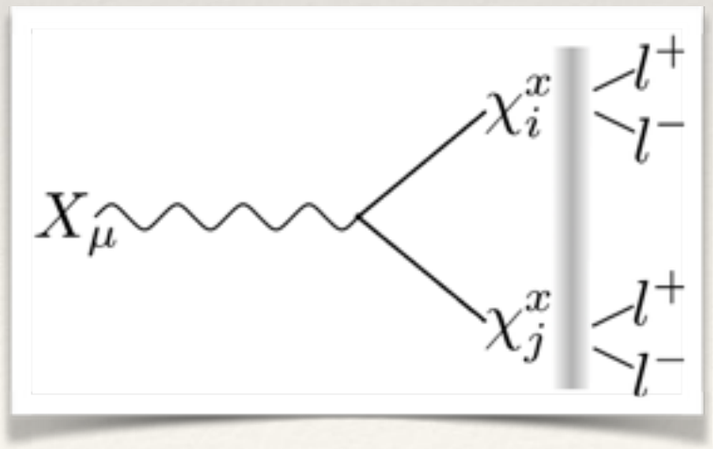
$M_x < m_{Z^x} < m_{A^x},\ \mu'$

C



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

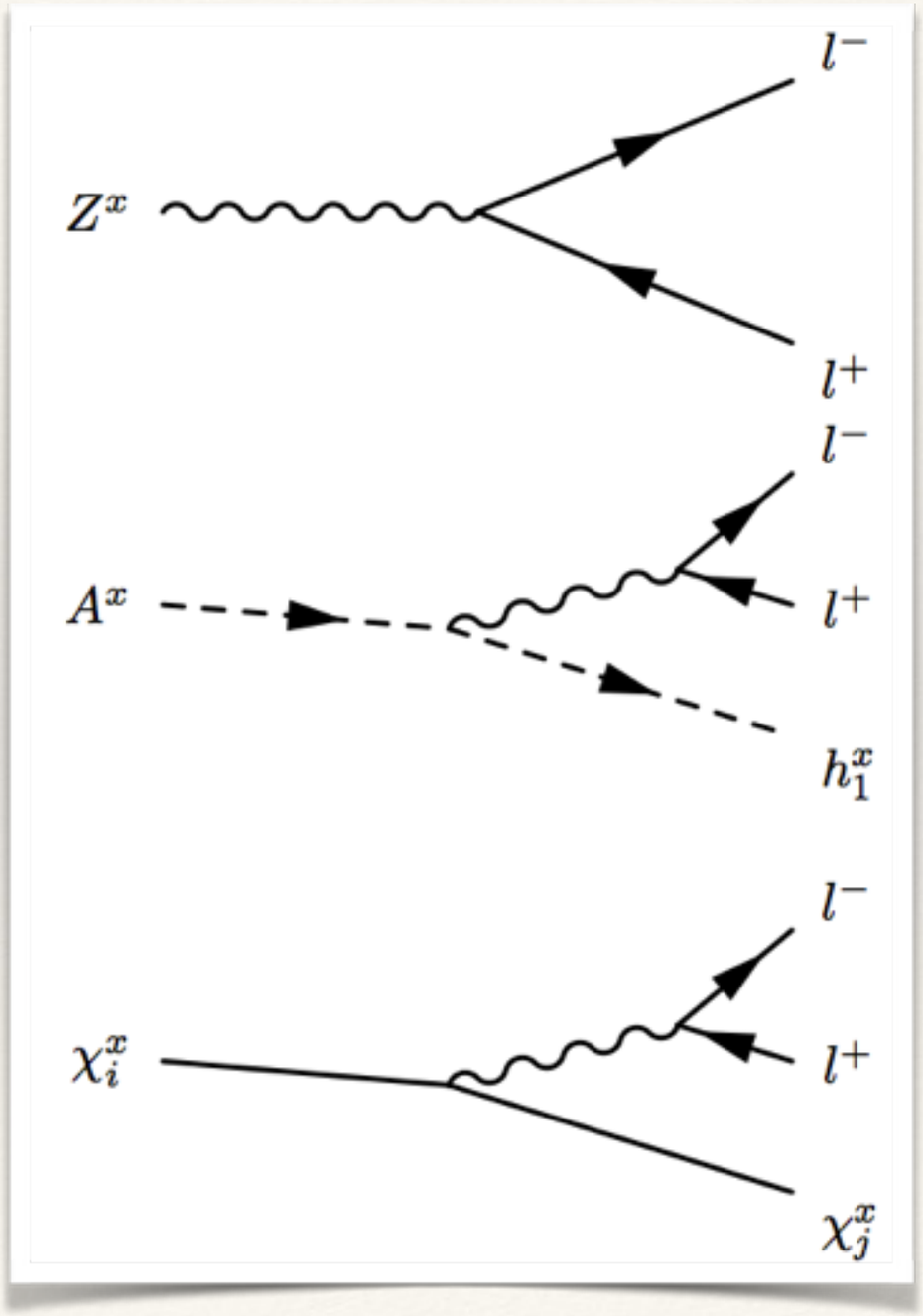
D



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

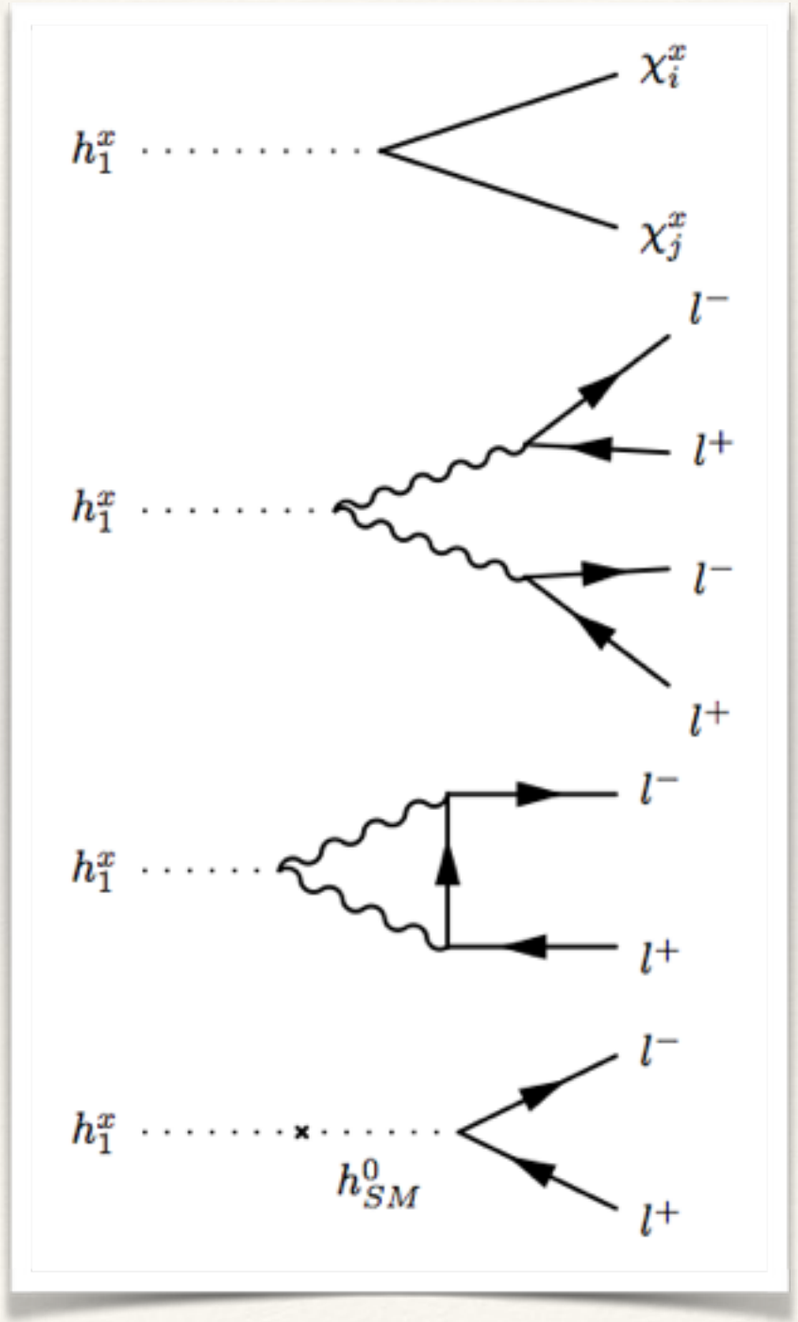
Pseudoscalar and Fermion Decays

- 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 Experiments

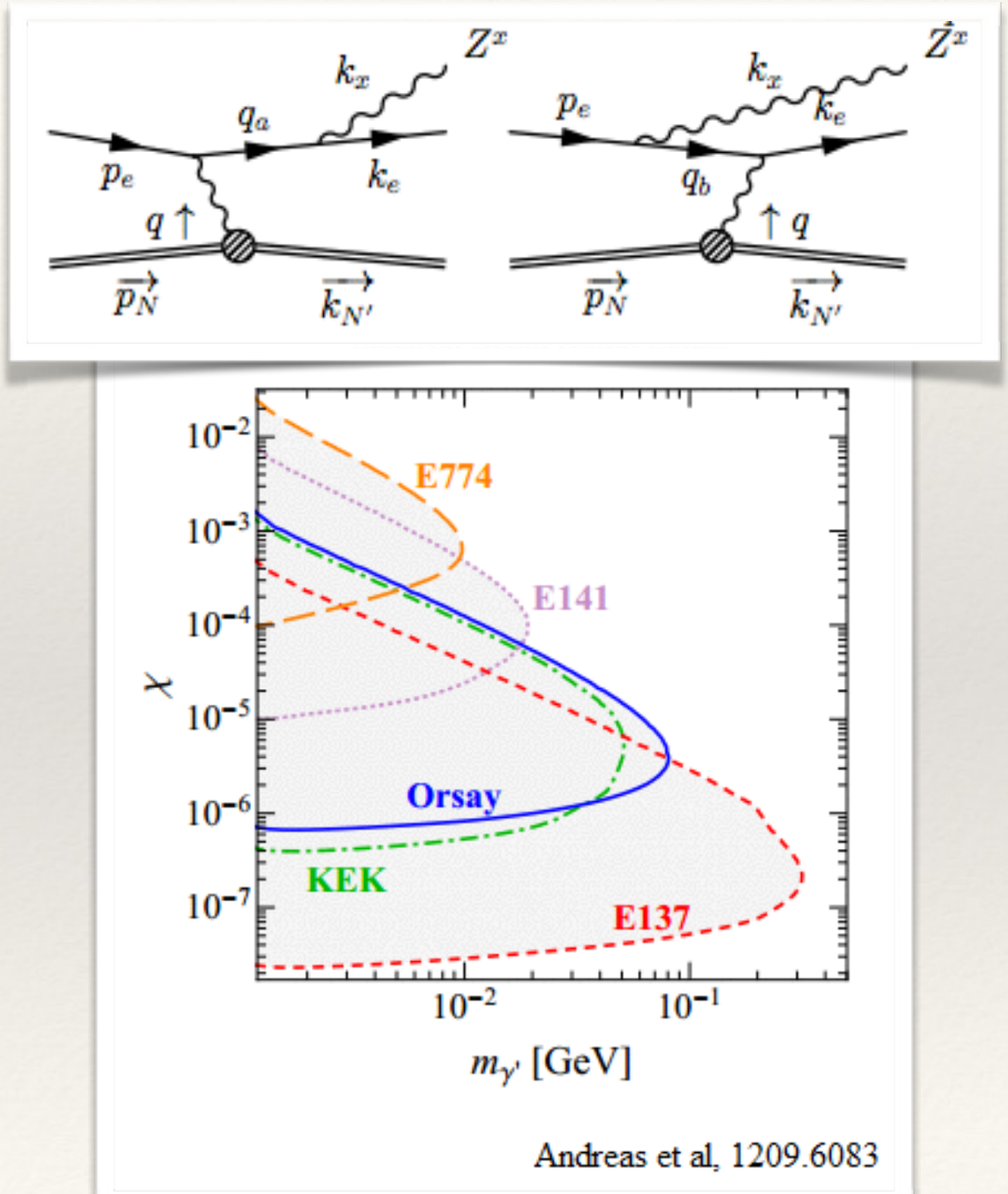
Fixed Target Experiments

- 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

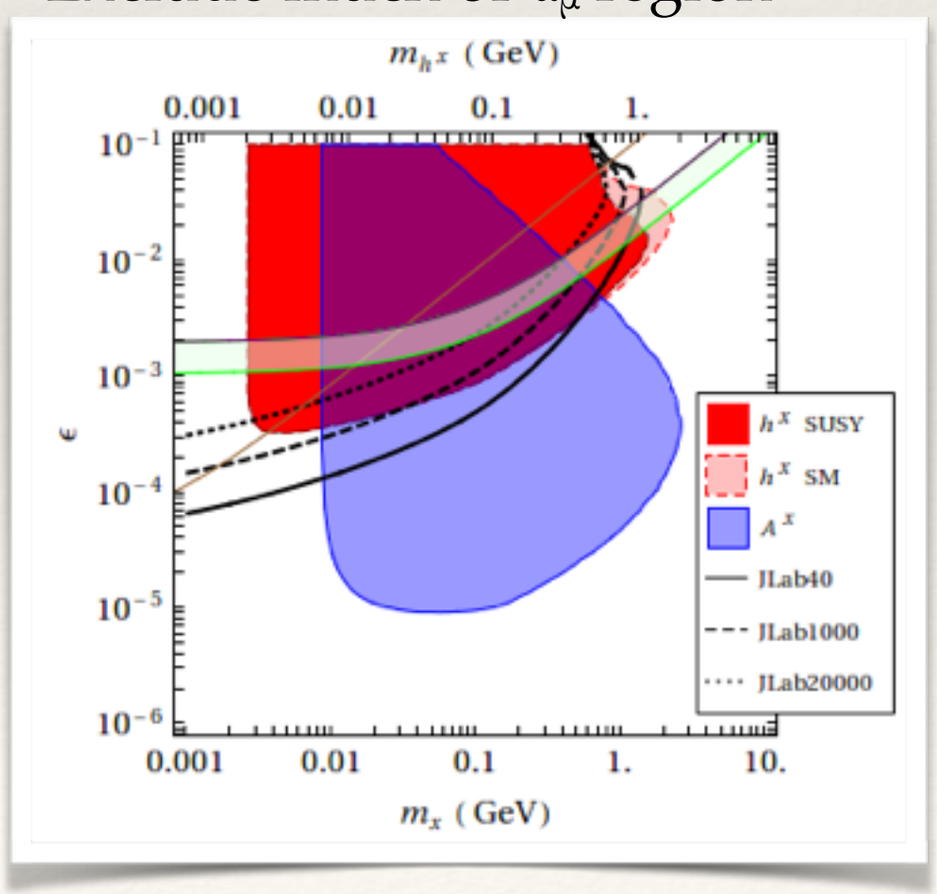
- Z^x couples to EM current
- Production from e is obvious!
- Recasting old experiments has placed important limits
- Small angle quasi-elastic scattering dominates



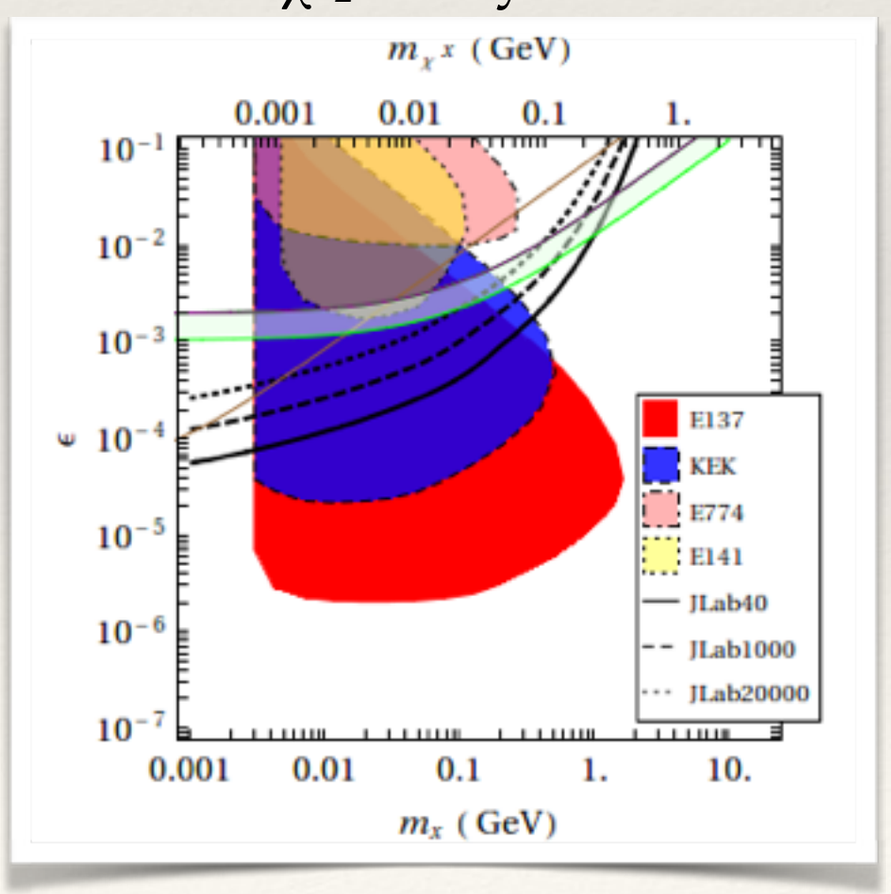
Results

- 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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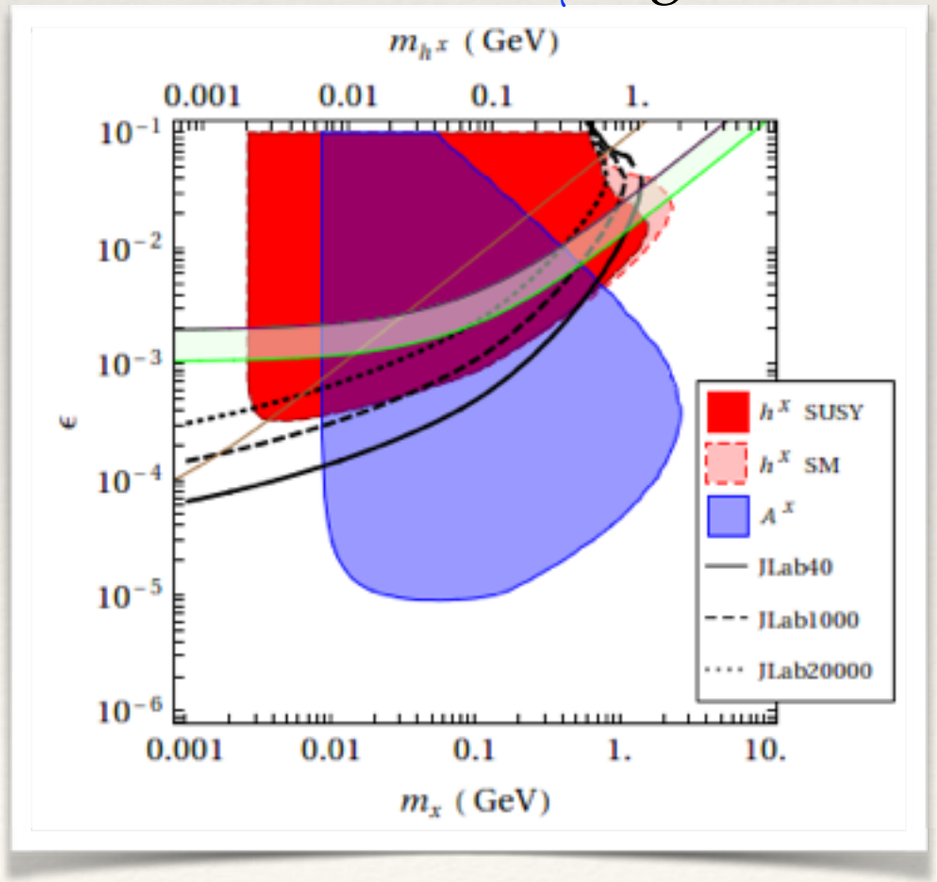

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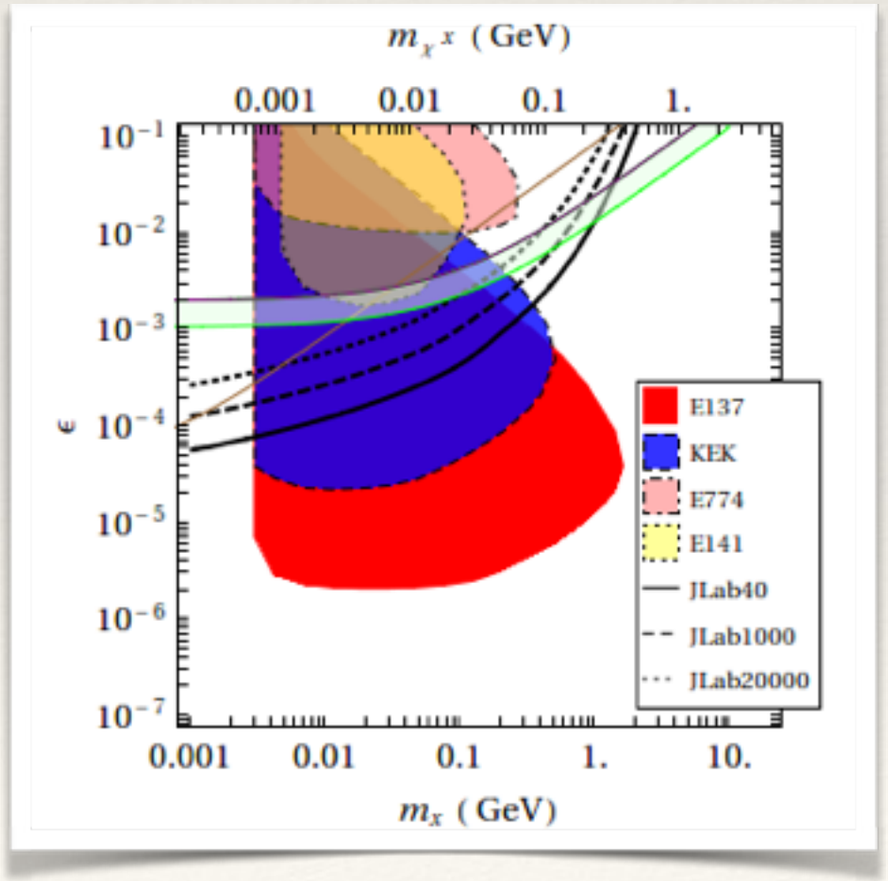

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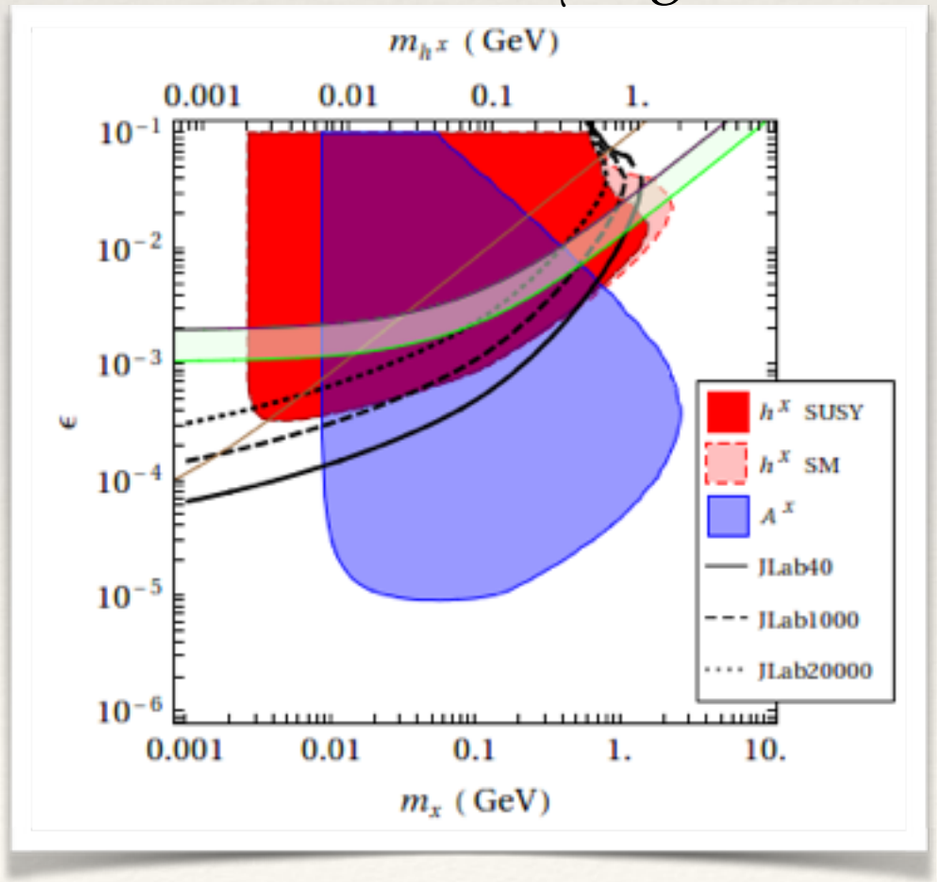

- Case D:
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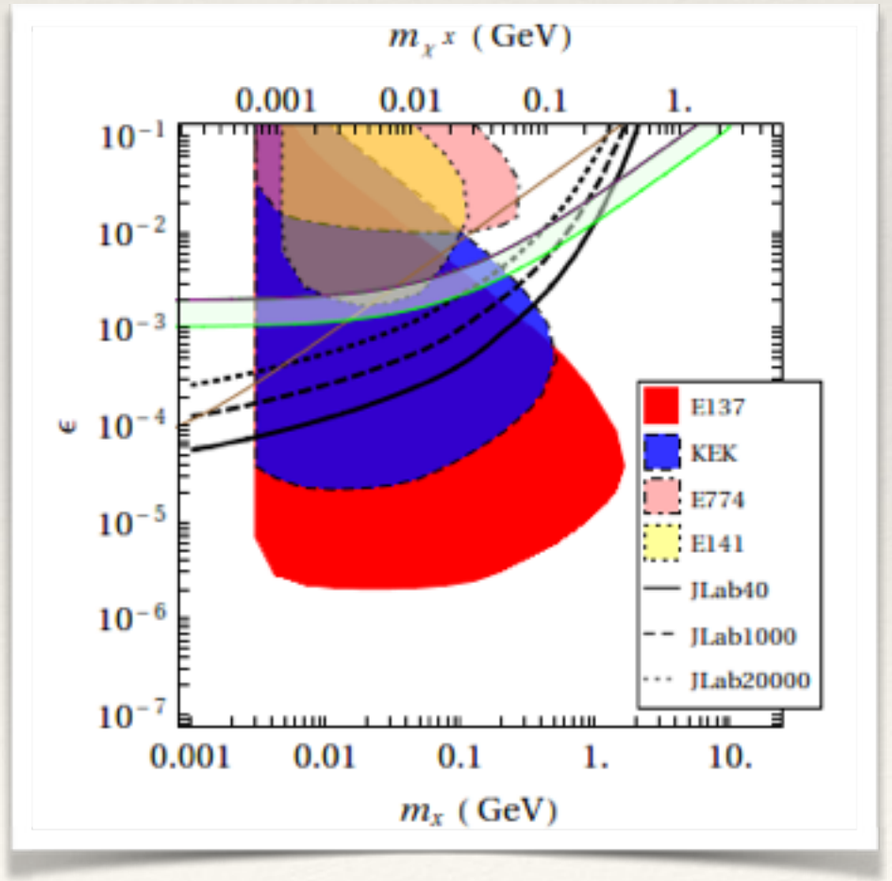
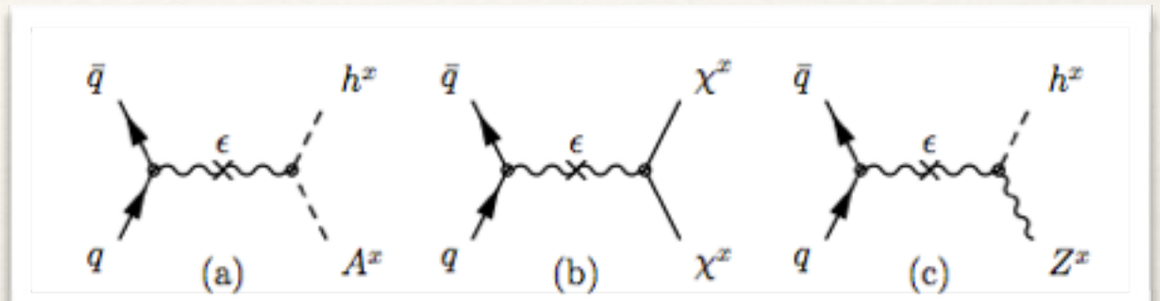


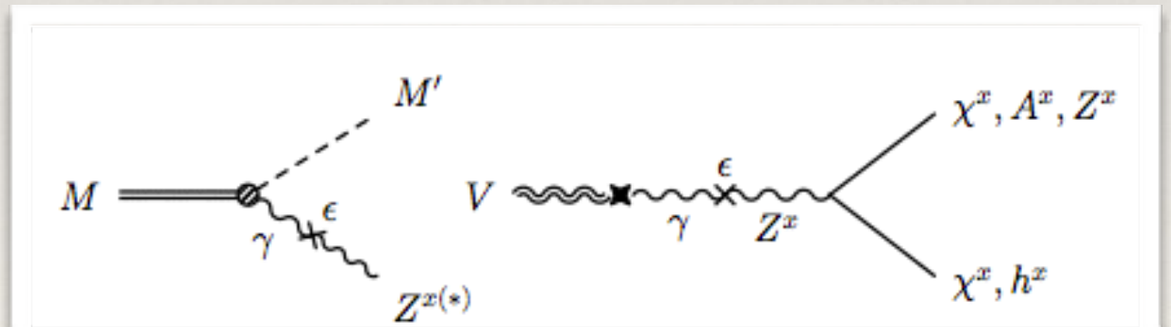
Proton Experiments

- 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

High Mass: Partonic Production



Low Mass: Meson Decays



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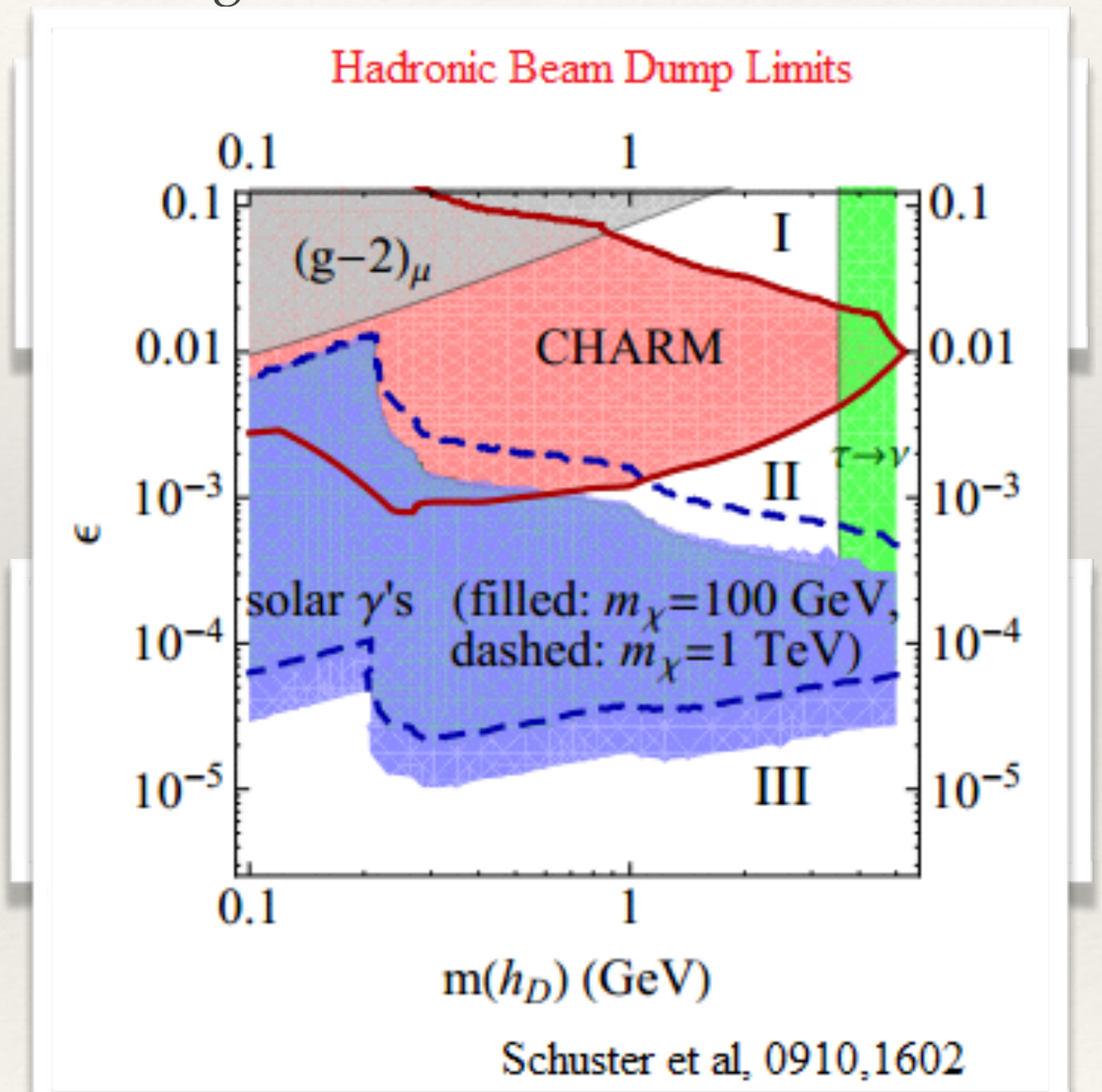
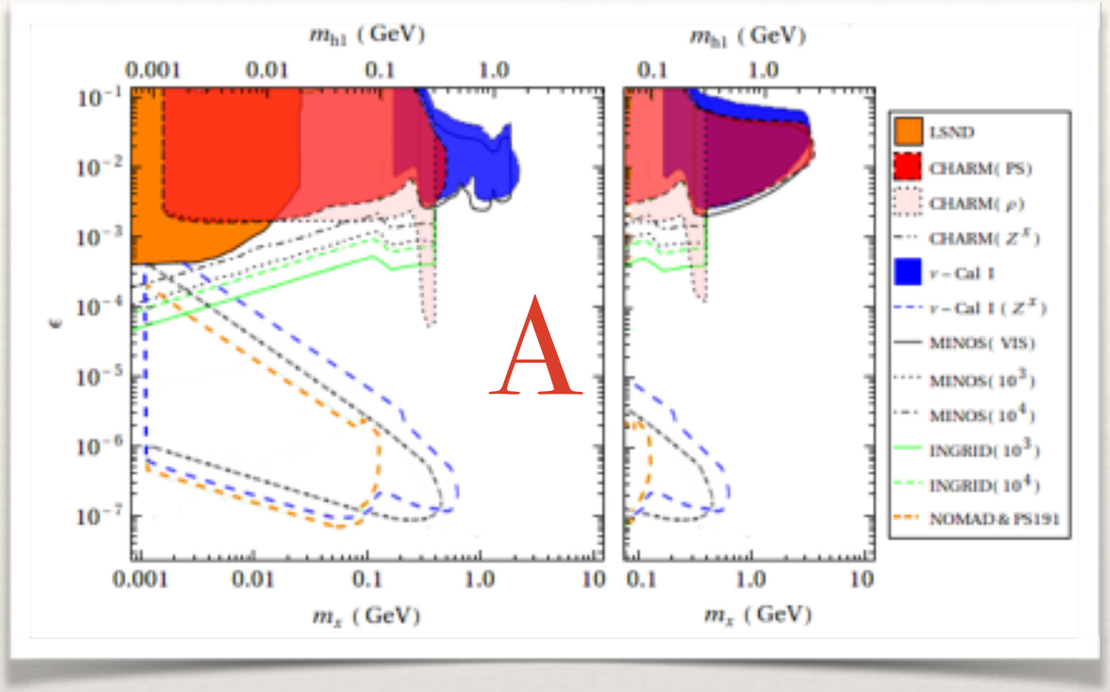
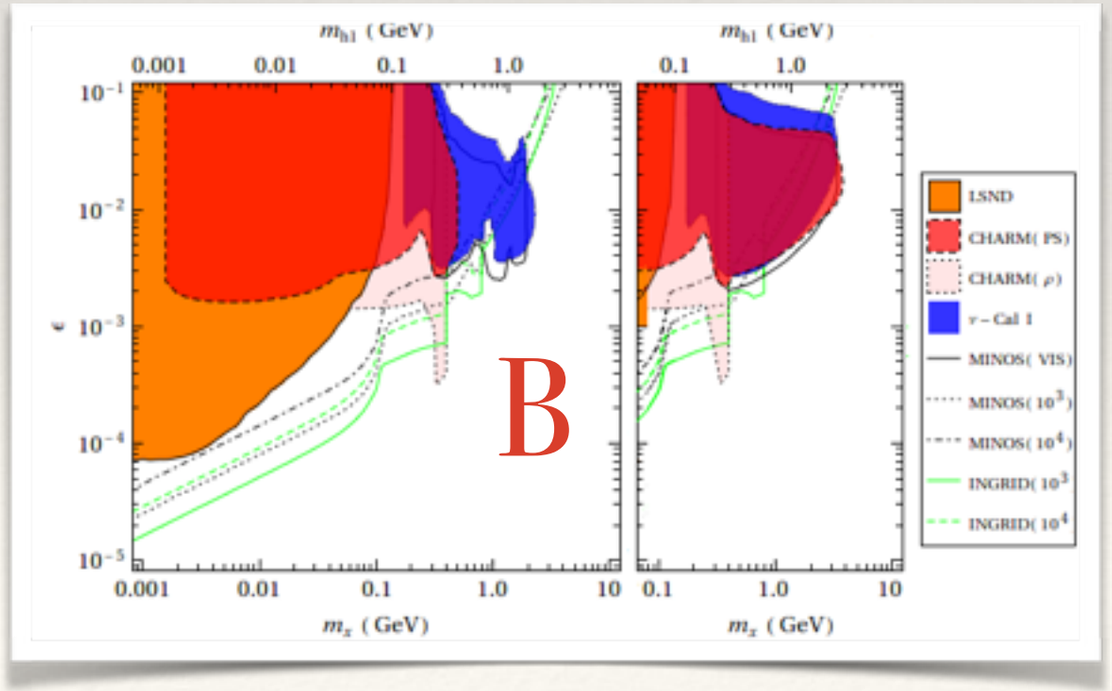


Slopes A and B

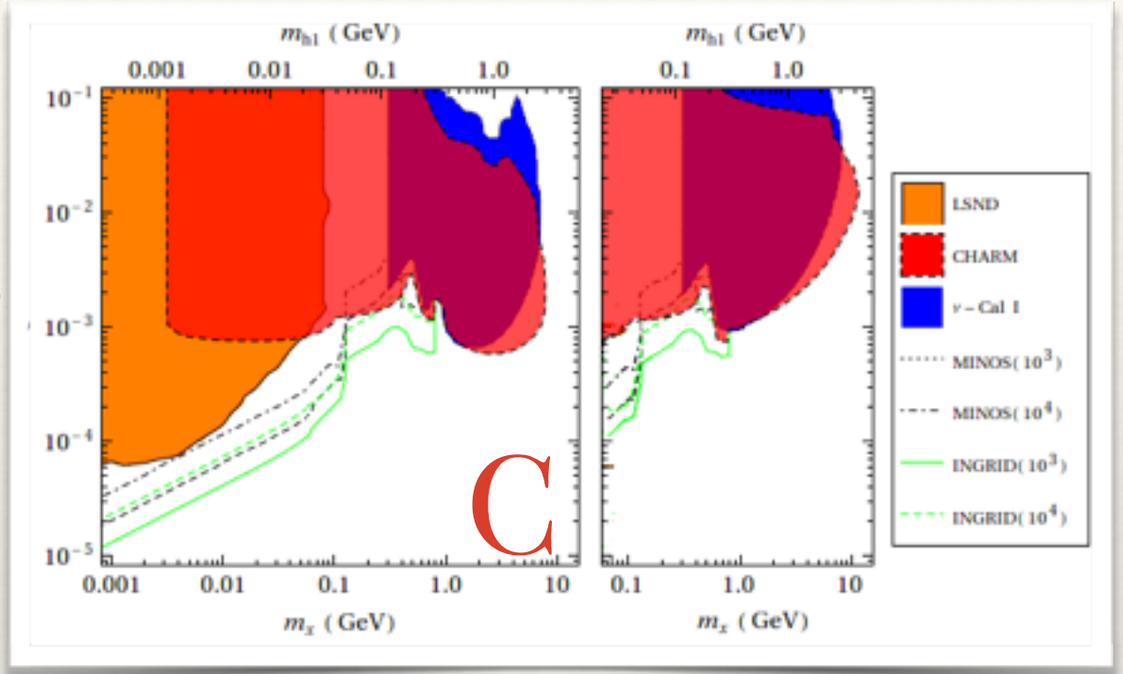
- A: Old limits at low m and/or ε
- B: Old LSND limits at low m
- Various new limits
- Most important: $\rho \to Z^x\ h^x \to e^+\ e^-$
- Less important: $qq \to Z^{x(*)}$

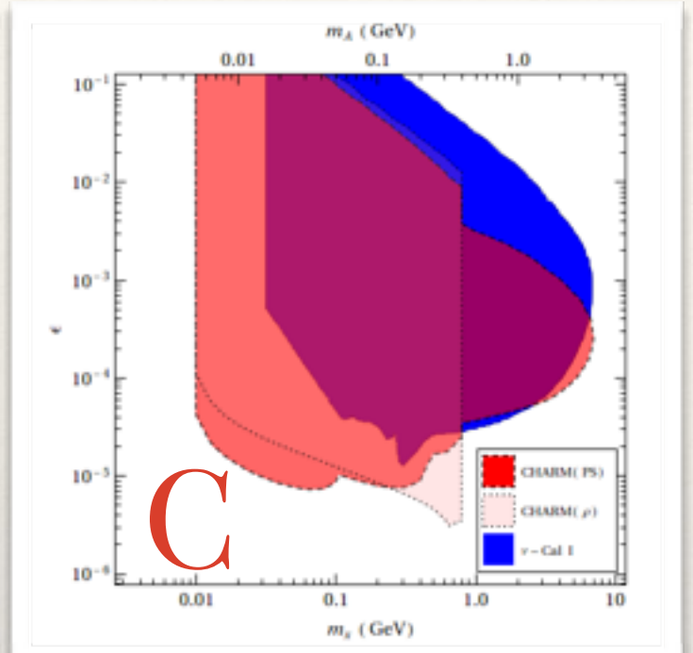




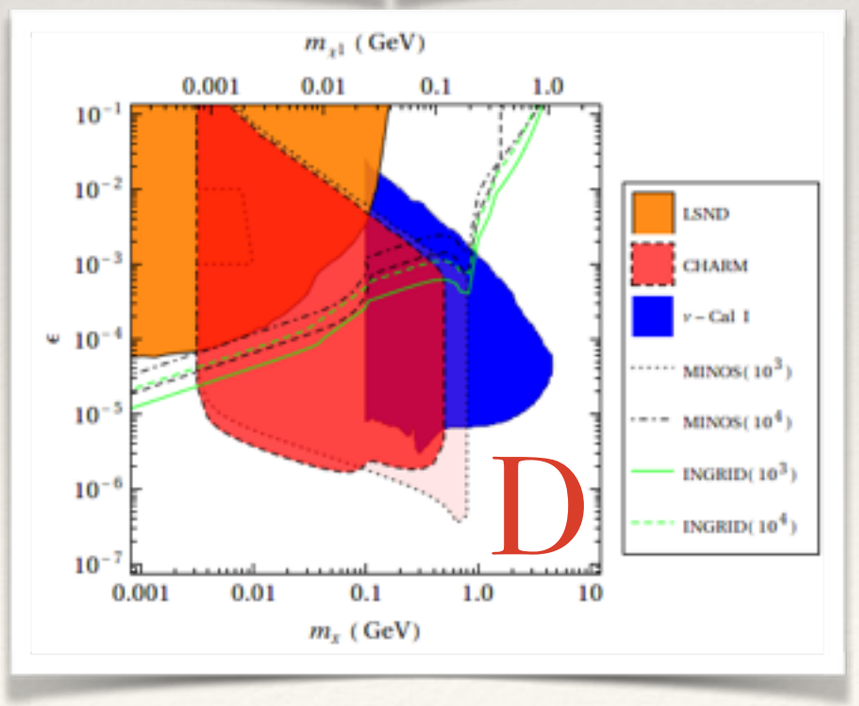
Slopes C and D

- C: Expand limits
- D: First limits





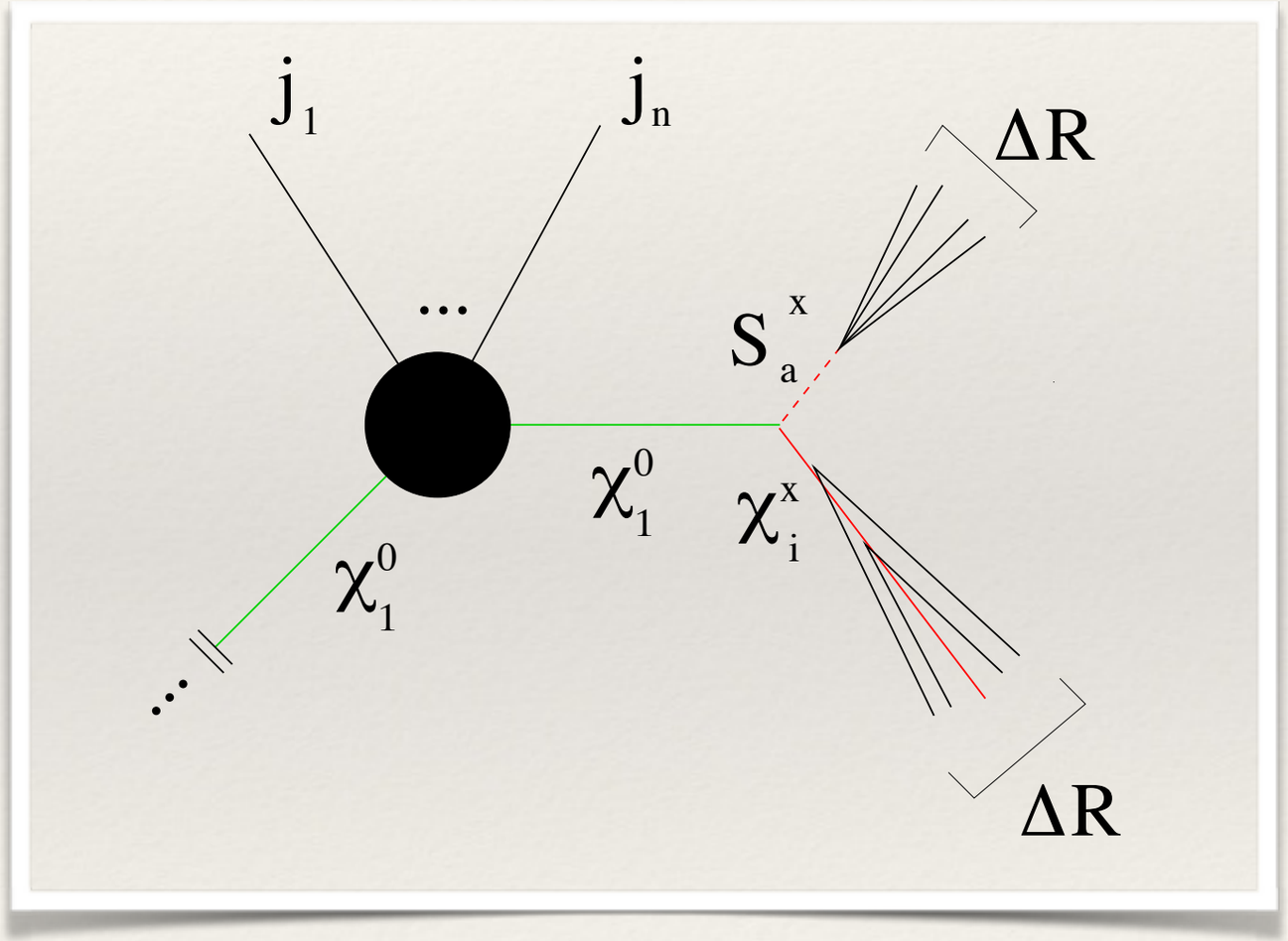
- All limits: $Z^x \rightarrow$ hidden states
- Run to large masses (~10 GeV!)
- And low $\varepsilon \sim 10^{-5}$ or 10^{-6}



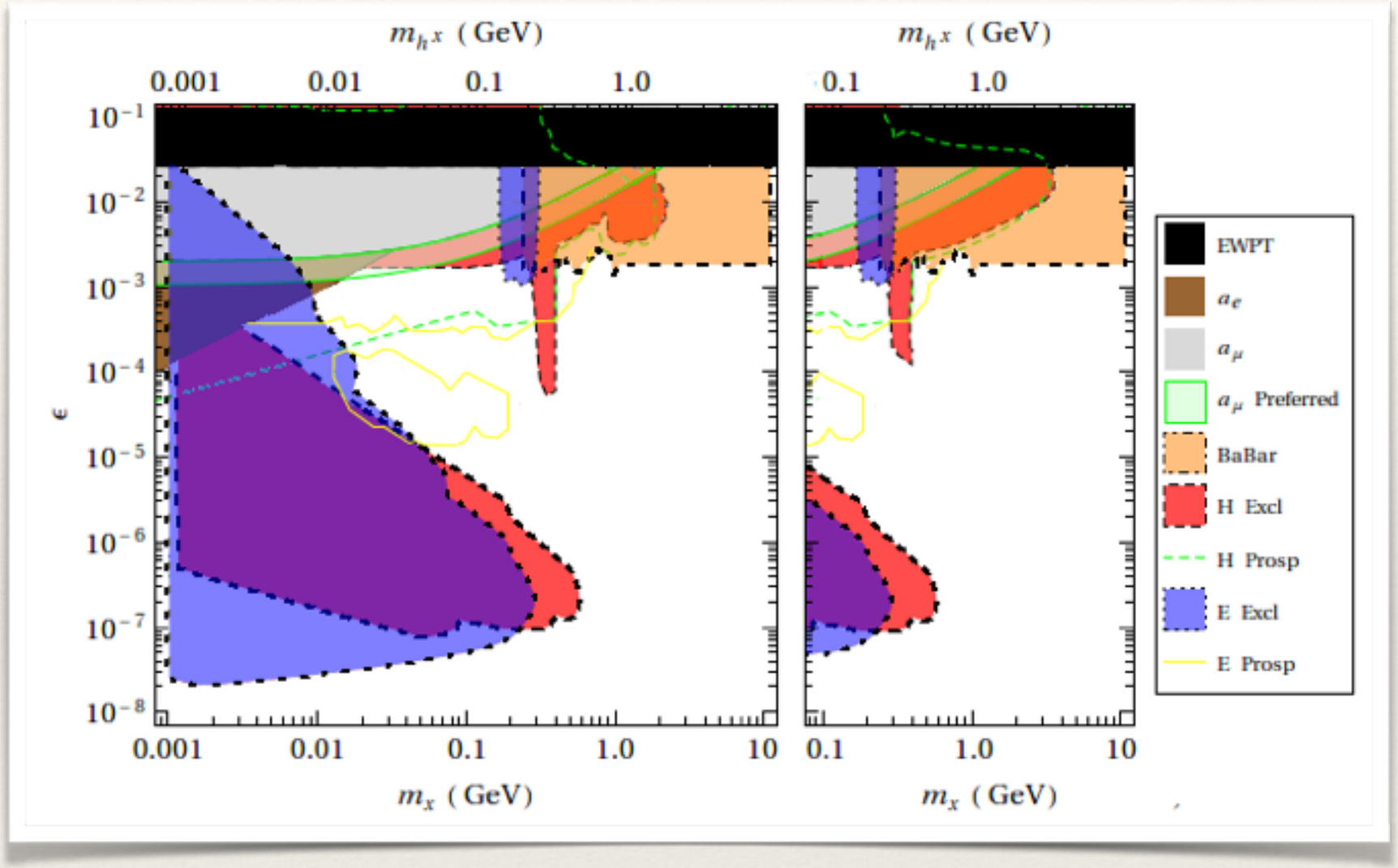
Combined Limits and LHC Implications

Common Event Features

- Phenomenology depends on nature of LOSP
- Simplest possibility: neutralino
- Decays to HS fermion + boson
- 25% B.R. to each boson
- Lightest scalar always invisible

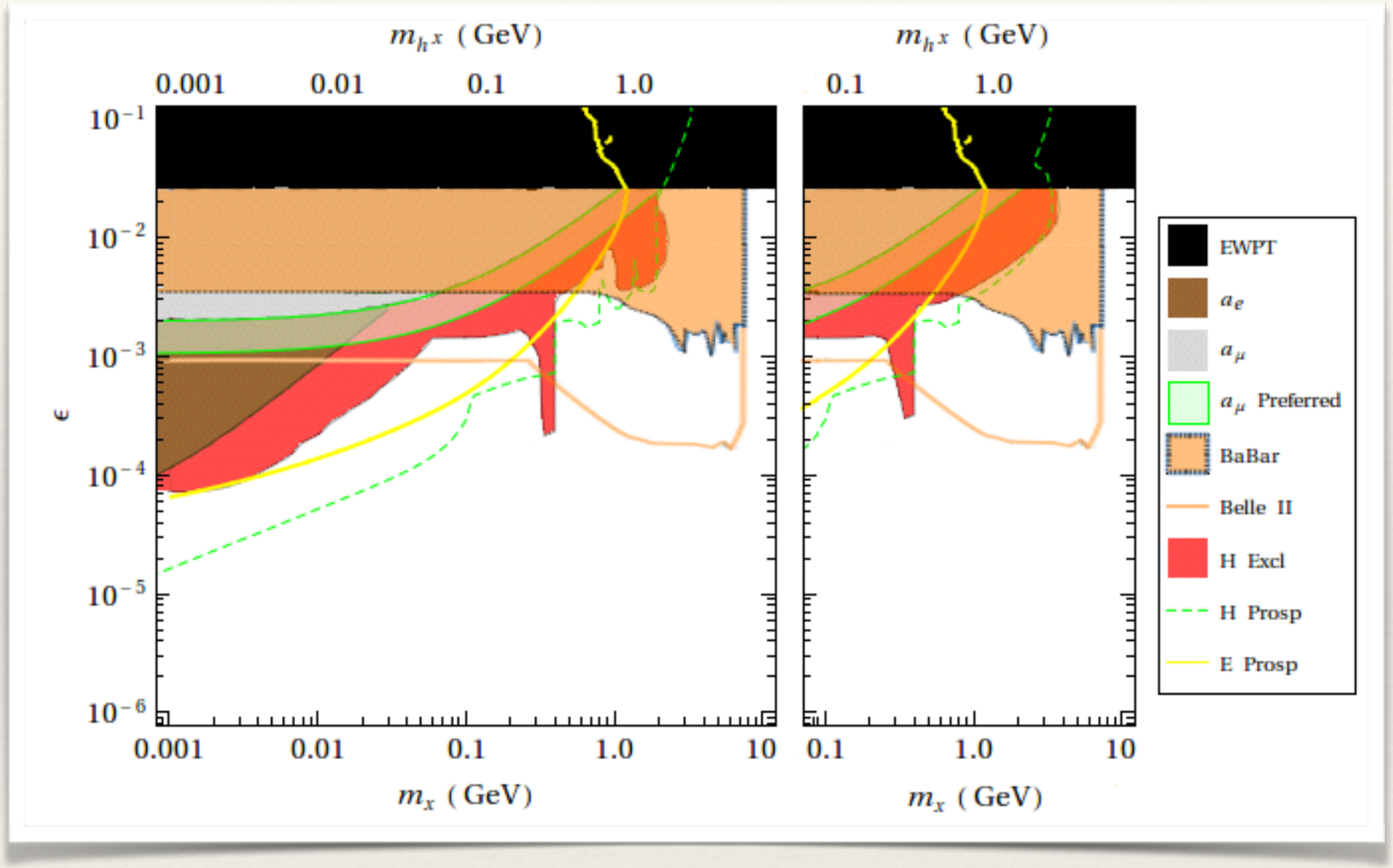


Benchmark A



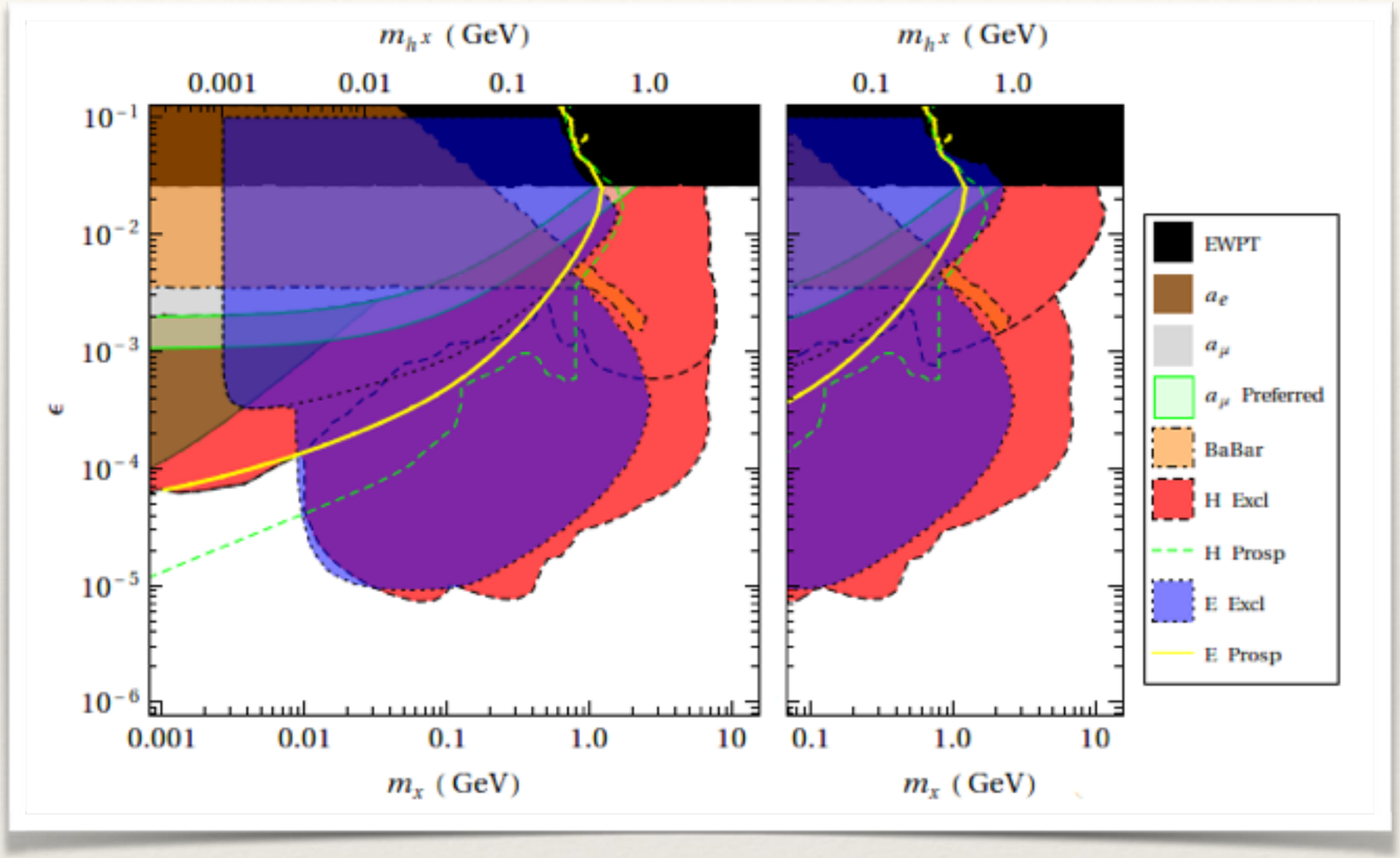
- Only new limits from CHARM
- Nearly exclude region that explains a_μ!
- Weakest LHC limits: least MET
- Strongest low-energy limits

Benchmark B



- Limits from CHARM + LSND fully exclude a_μ-preferred region!
- Strongest LHC limits: Weakest low-energy limits

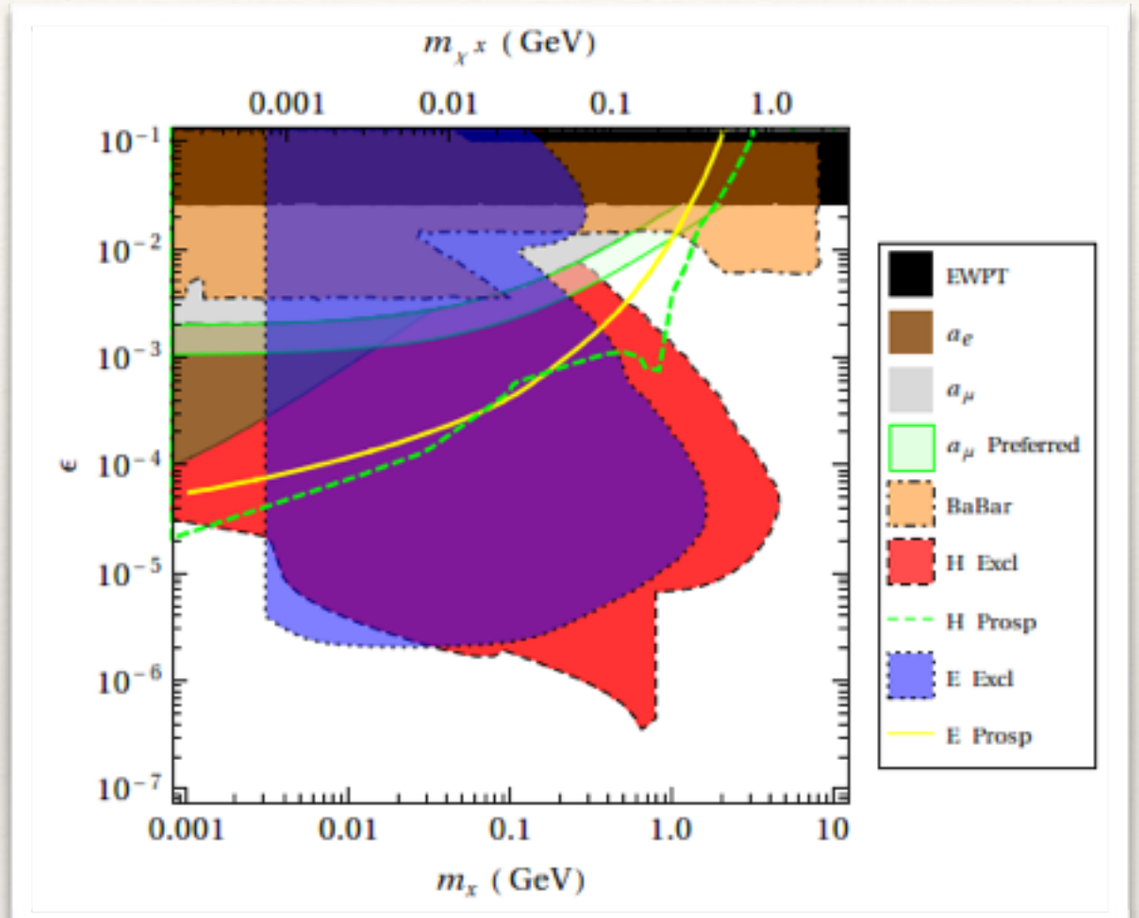
Benchmark C



- Limits much expanded, especially at low mass

- a_μ-preferred region excluded!
- LHC situation between A and B

Benchmark D



- First limits on this case
- a_μ-preferred region NOT excluded! (h^x decays invisibly)
- But probed by JLab & INGRID
- LHC situation between A and B

Conclusions

- Hidden Sectors coupling through kinetic mixing can have richer phenomenology than usually considered
- 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
- Low- and high-energy limits on SUSY hidden sectors complementary

Back-Up Slides

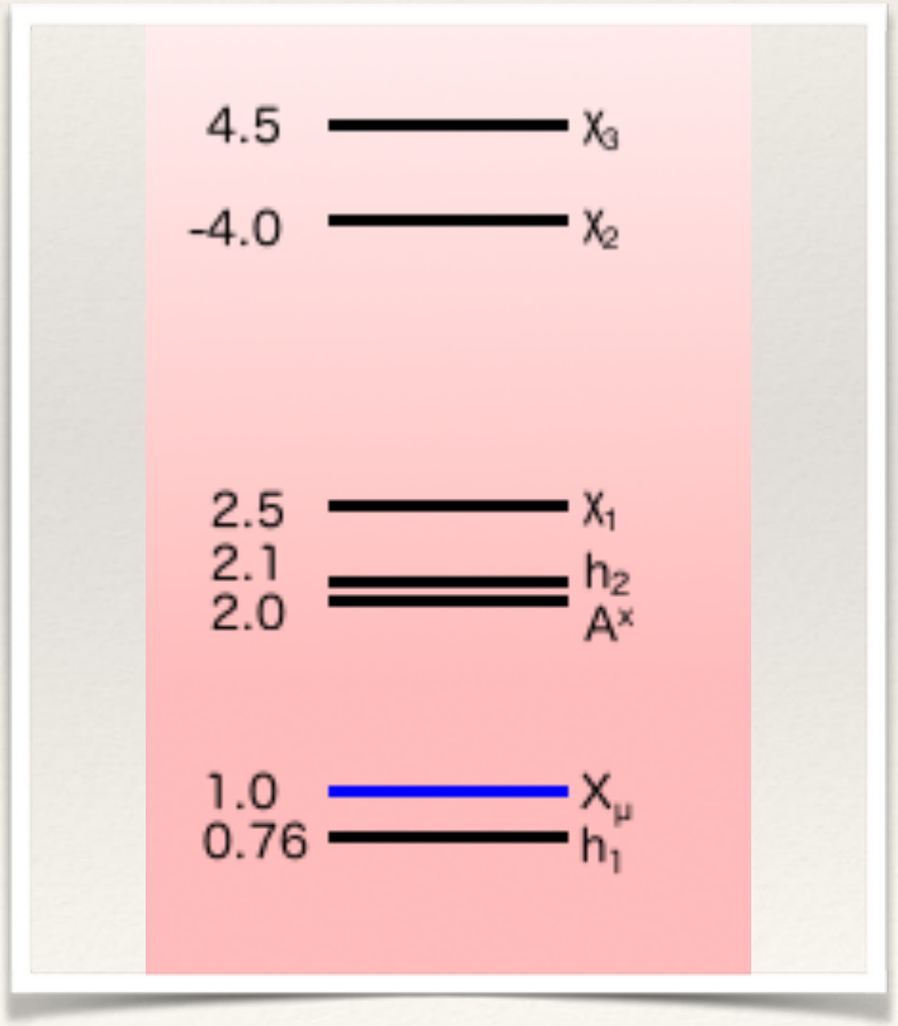
Benchmark Slope A: $Z^x \to \mathrm{SM}$

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



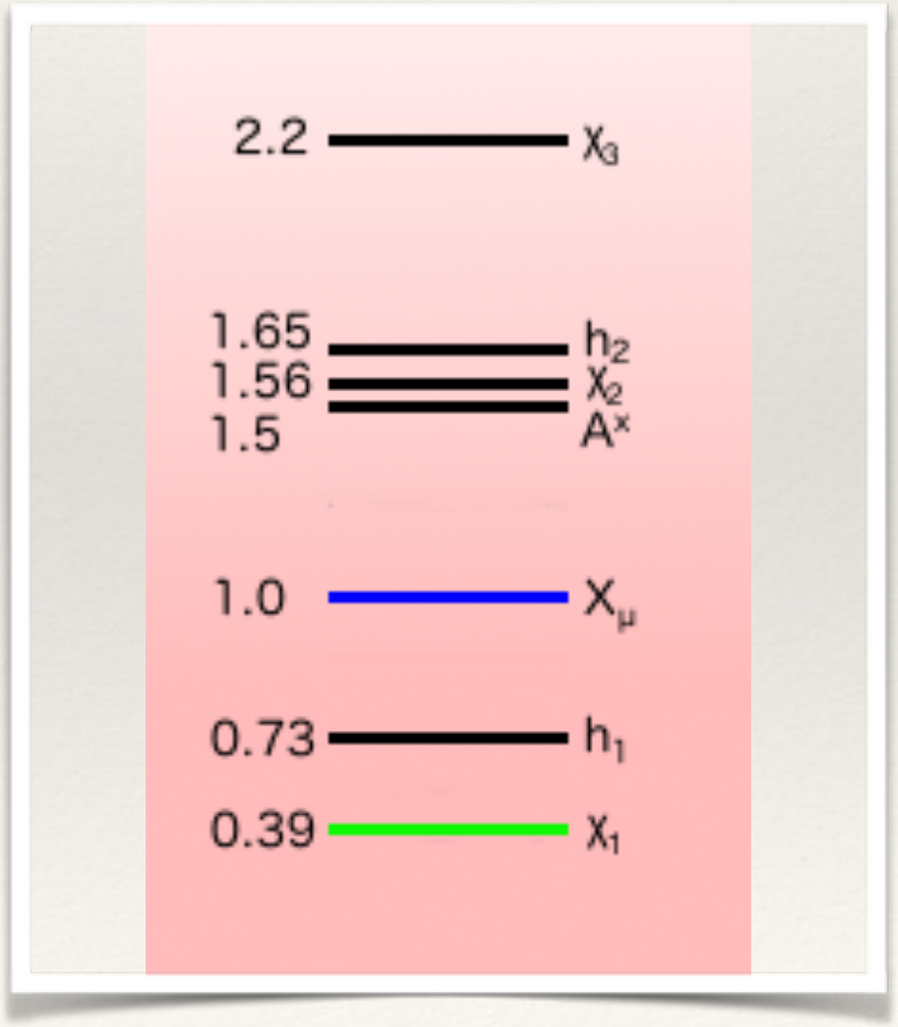
Benchmark Slope B: $Z^x \to \text{Inv}$

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



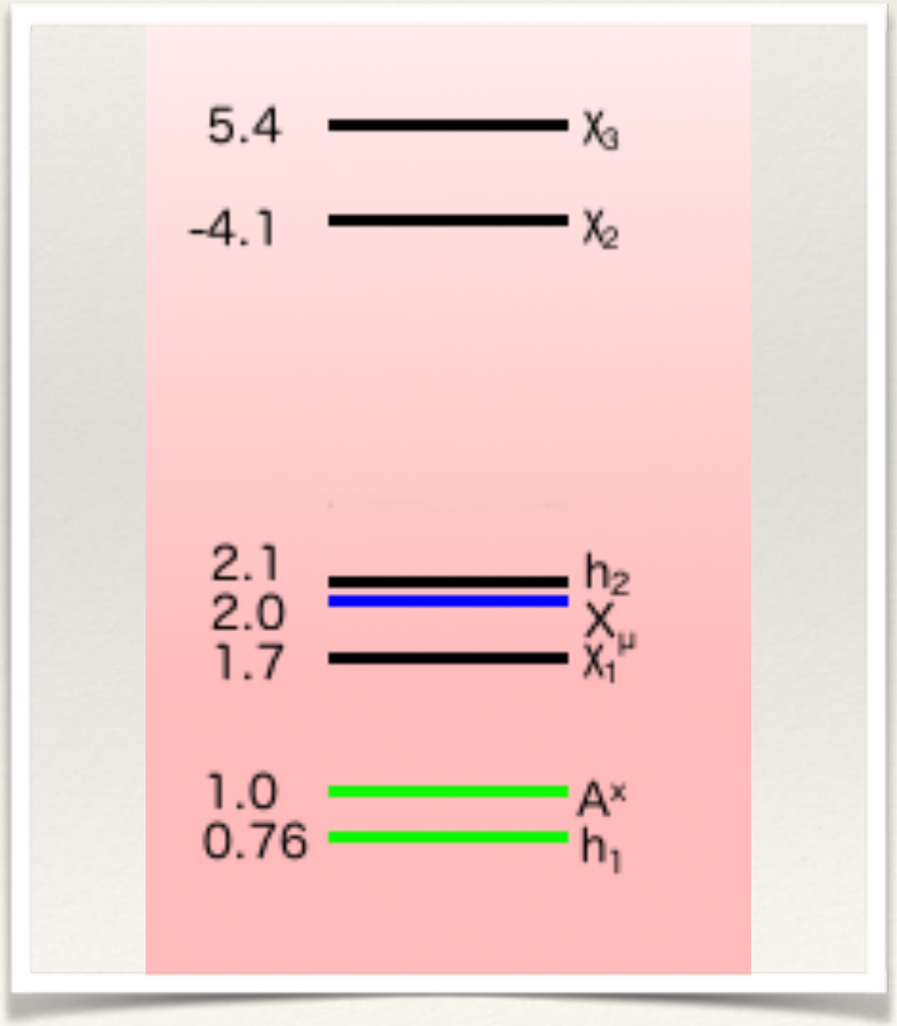
Benchmark Slope C: $Z^x \to$ Scalars

m	0.5
M	1.5
μ’	2.0

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

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

-

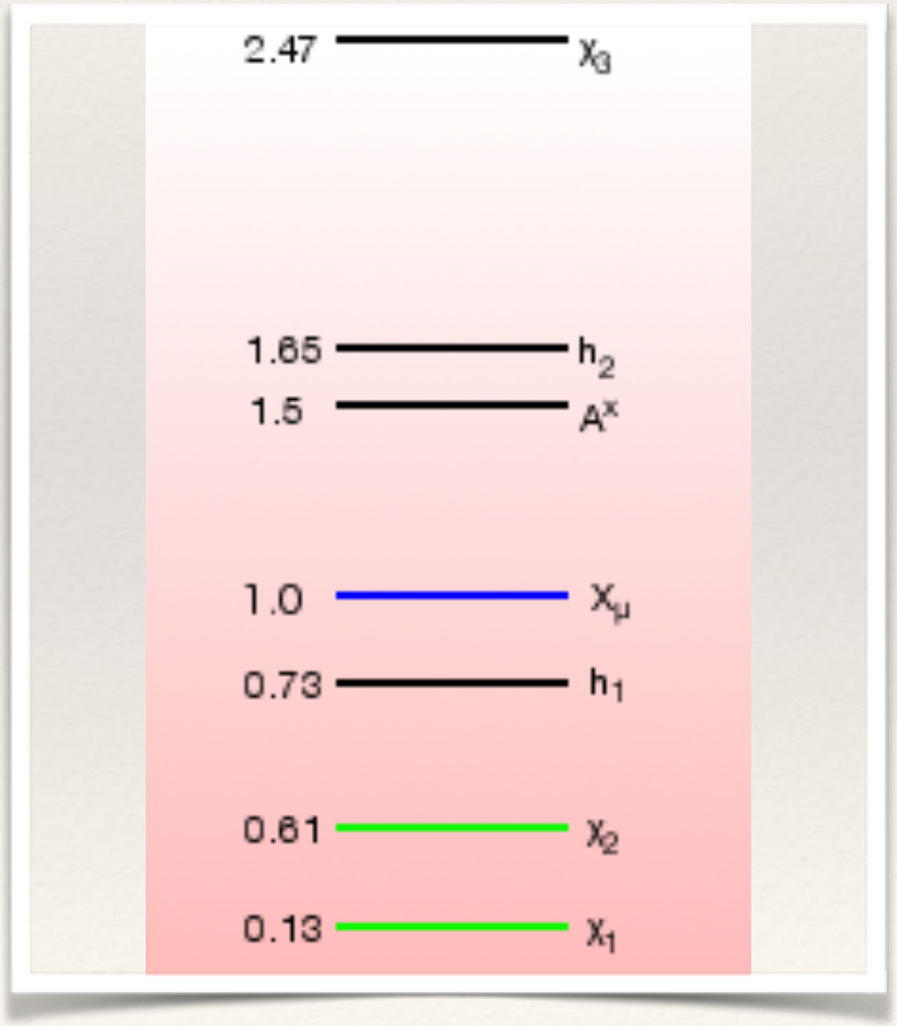


Benchmark Slope D: $Z^x \to$ Fermions

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

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

m	1.5
M	3.0
μ'	0.5



A Higgs Portal from Vector Portal

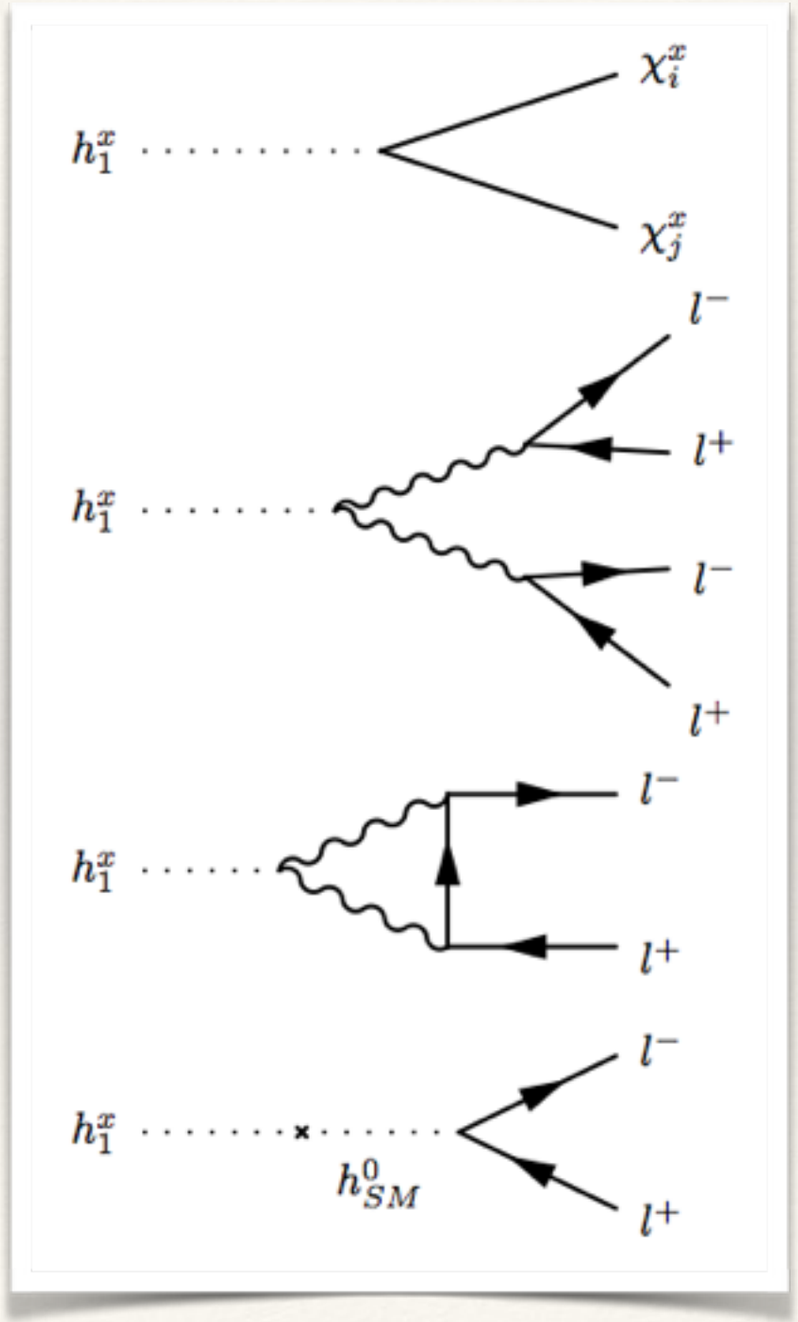
- One important consequence of SUSY in our model
- Kinetic mixing comes from mixing of superfields:

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

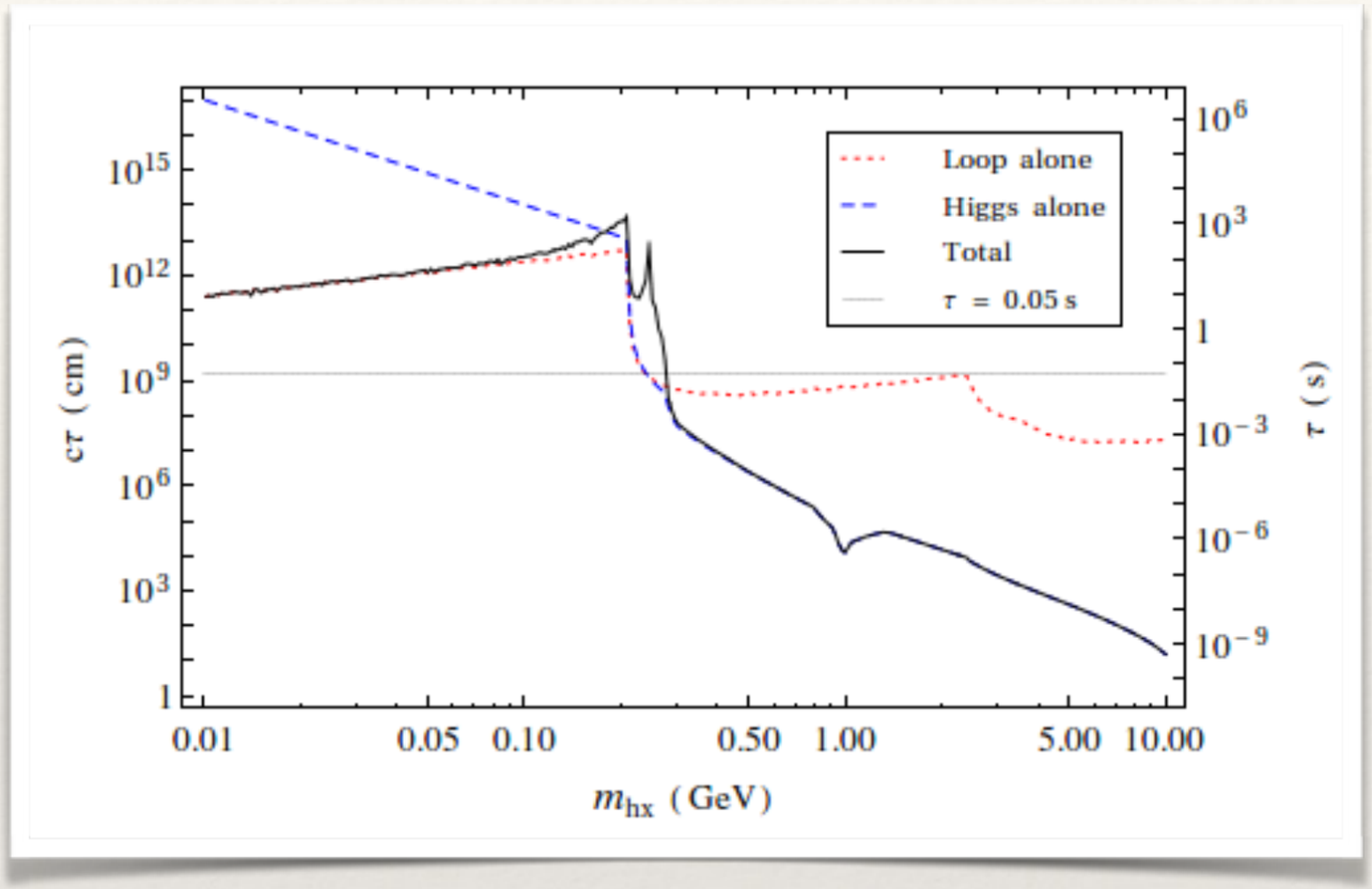
- In SUSY, a Vector Portal implies a Higgs Portal
- Higgs mixing highly suppressed, $\sim \epsilon m_{Z^x}^2 / m_Z^2$
  - BUT! new channel for hidden Higgs decays

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



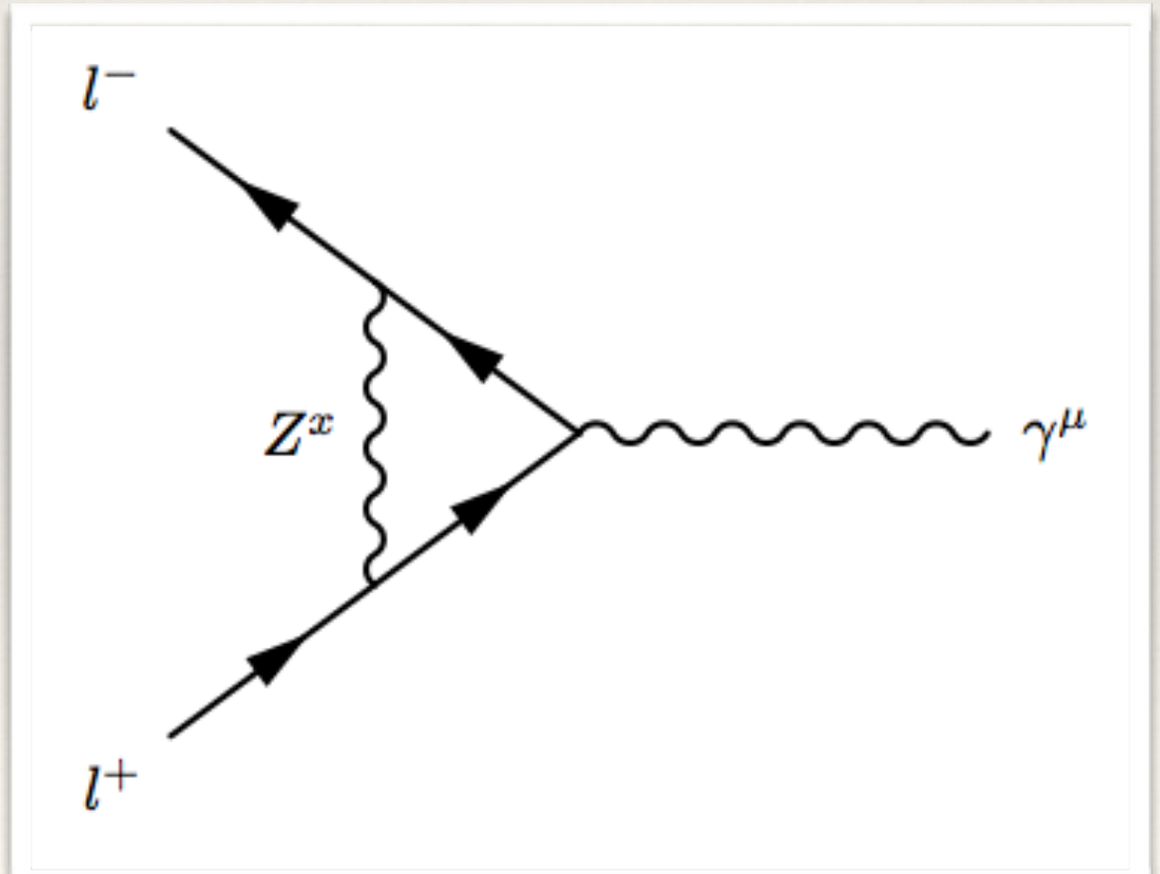
Effects of Mass Mixing



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

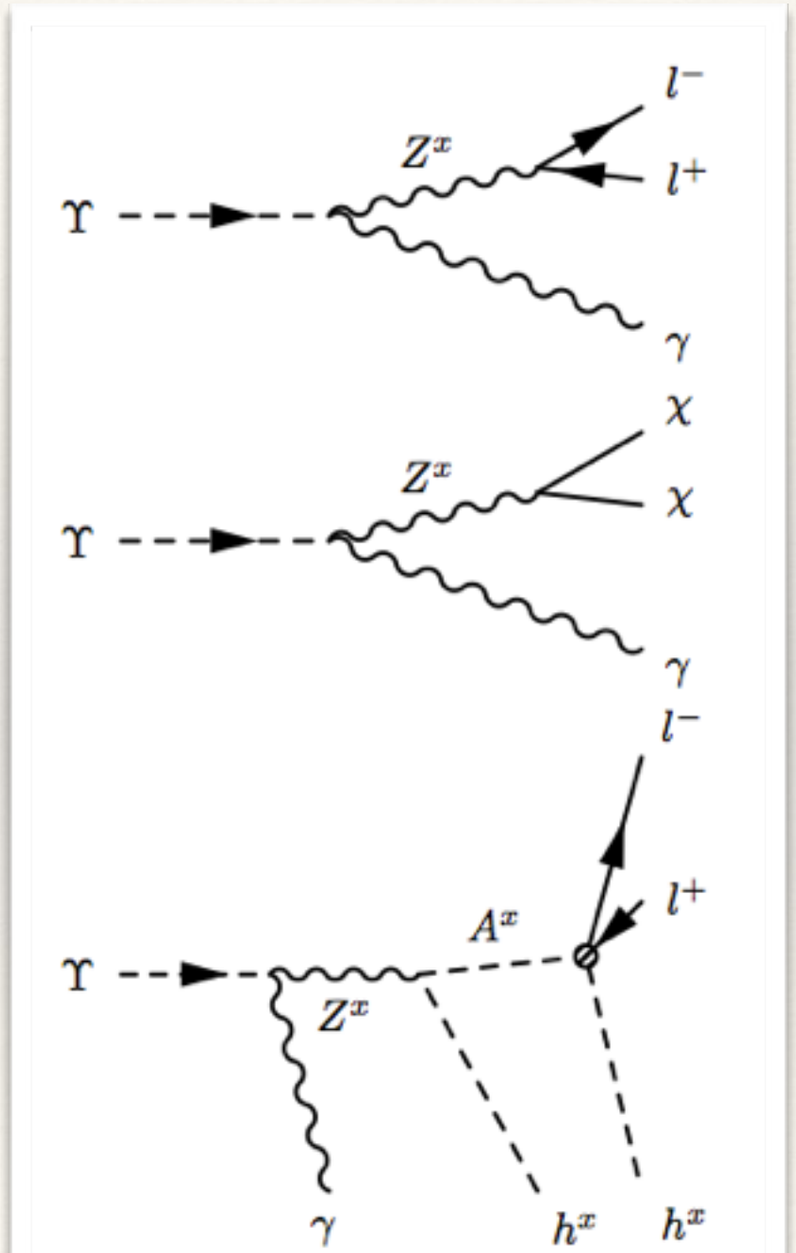
Model-Independent Limits

- 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]



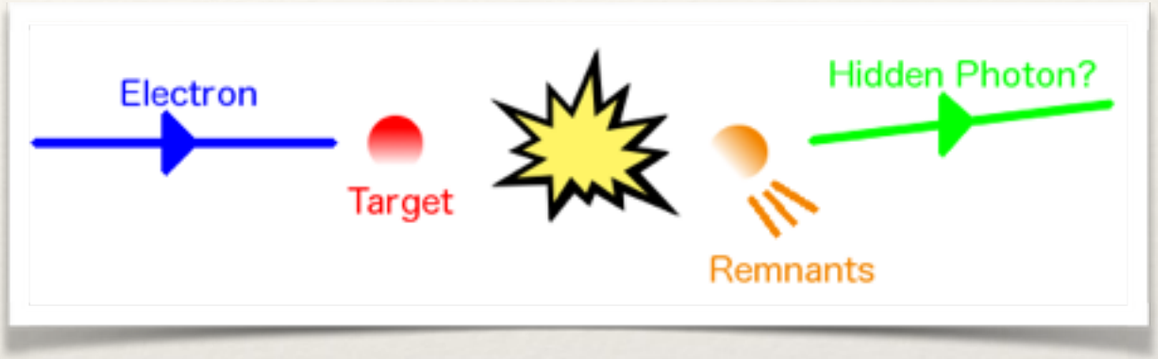
Meson Search Topologies

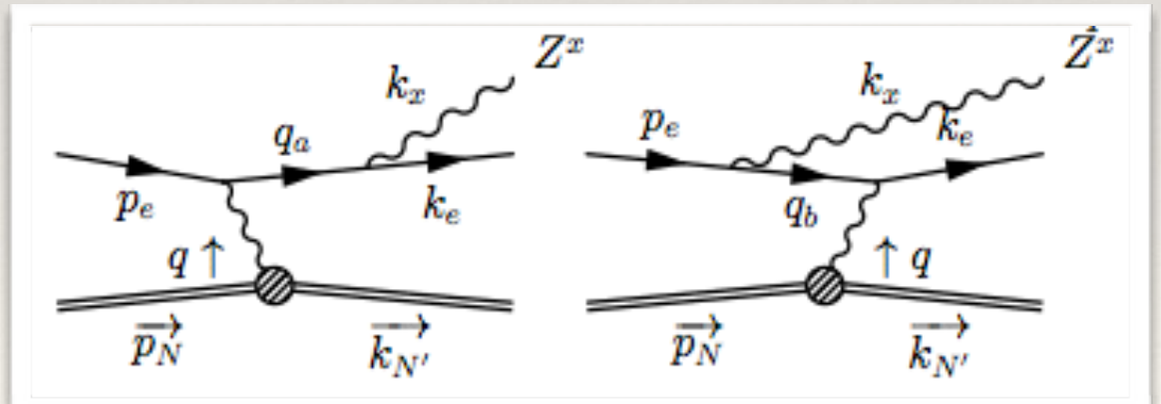
- Search Topologies:
  - Visible decays: Total energy = E_{Par}
  - Invisible decays: MET + tag
- If $Z^x \rightarrow$ Hidden Sector, instead have:
  - Tag + lepton pair + MET
  - Tag + $l^+l^-l^+l^-l^+l^-$
- These searches not done; no limits



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 $\sigma(e\gamma)$

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

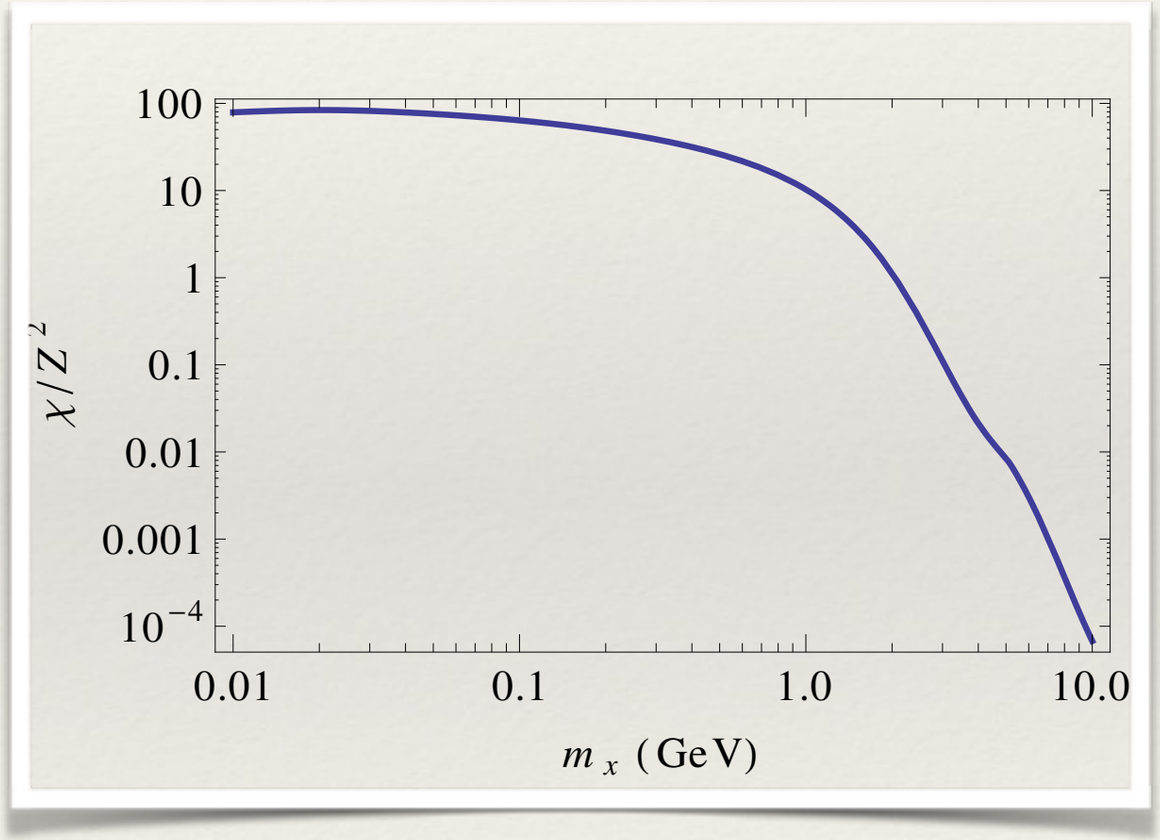
$$E_x \ \vartheta^2 \ll E_e$$

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

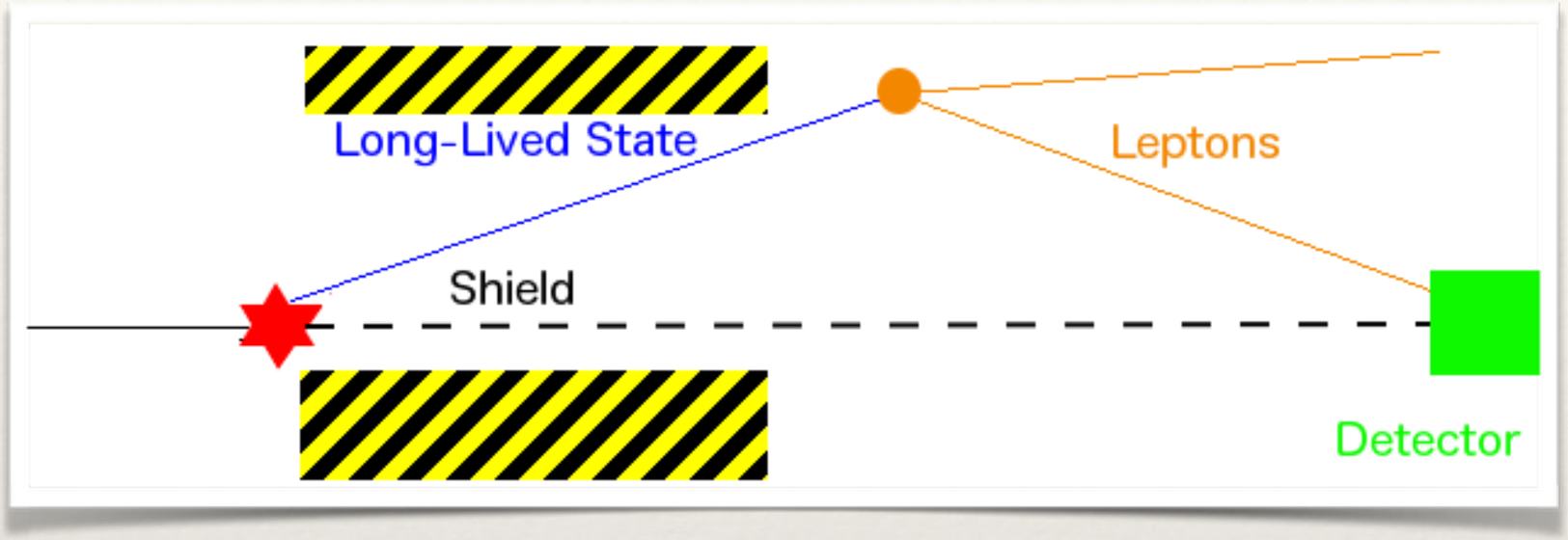
- All target dependence in Form-Factor integral χ

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

- Small angle quasi-elastic scattering dominates



Acceptances



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

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