LHC Signatures of a Minimal Supersymmetric Hidden Valley

arXiv:1112.2705

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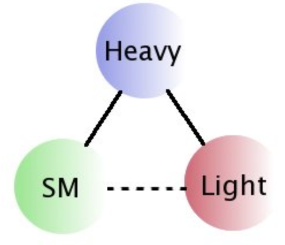
TRIUMF Workshop on LHC Results, 16th December 2011

Helpful Notes on Hidden Valleys



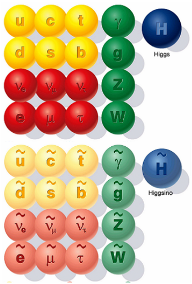
Essential Features of a Hidden Valley:

- New light sector $\mathcal{O}(\text{GeV})$
- New heavy sector $\mathcal{O}(\text{TeV})$
- Feeble SM-light coupling
- Efficient heavy-SM and -light couplings

At LHC, SM $\rightarrow$ Heavy $\rightarrow$ Light $\rightarrow$ SM

New, interesting signals BUT! broad, ill-defined model space

Simple Review of Supersymmetry

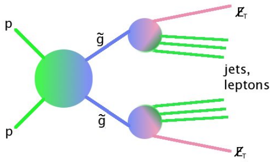


Well-motivated extension of SM

- Symmetry relating fermions $\leftrightarrow$ bosons
- Exception to Coleman-Mandula Theorem
- $\mathcal{O}$(TeV)-scale partners of SM particles (With opposite spin-statistics)
- Solves hierarchy problem

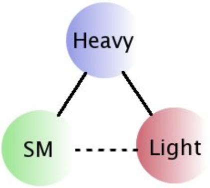
R-Parity:

- Discrete symmetry: SM Even, New particles Odd
- Added for proton stability, DM
- Characterises SUSY events



Supersymmetric Hidden Valleys

A Tasty Blend

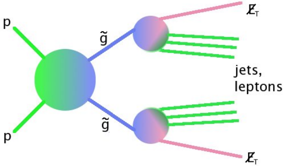


What do hidden valleys gain from SUSY?

- Get heavy sector for free
- “Natural” hierarchy of scales
- Concrete implementation

What does supersymmetry gain?

- New phenomenology
- Light sectors in GUTs
- Light dark matter?



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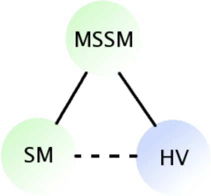

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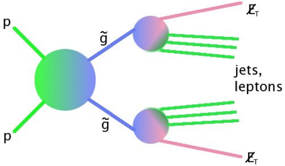

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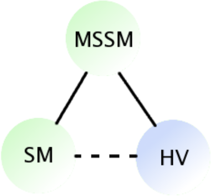

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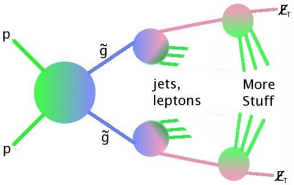
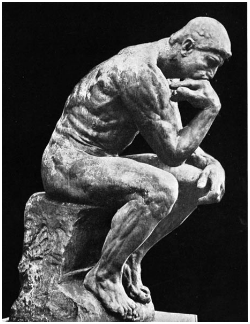


Philosophy

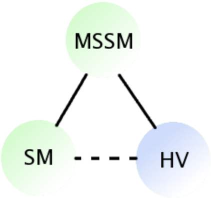


Our point is not that this model is True

Our point is that it is Minimal yet Diverse

That is, a Benchmark

Overview and New Particle Content



- Starting point: MSSM
- Hidden sector SM-neutral
- Supersymmetric sector-coupling
- Options:
  - Chiral superfield, Higgs portal
  - Vector superfield, kinetic mixing

New Fields:

1. Vector superfield
2. Two Higgs superfields

1. Massive vector X_μ
2. Three real scalars $h^x_{1,2}, A^x$
3. Three Majorana fermions $\chi^x_{1,2,3}$

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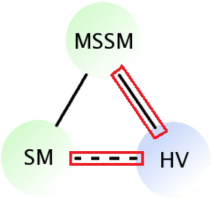

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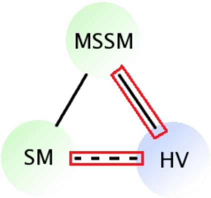

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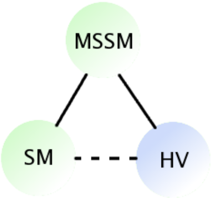

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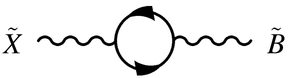
Kinetic Mixing

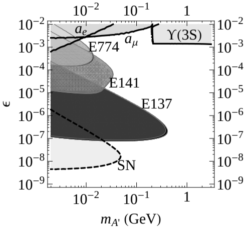
$$\mathcal{L} \supset \int \mathrm{d}^2\theta \, \frac{\epsilon}{2} B^\alpha X_\alpha$$
$$\supset \epsilon \Big(-\frac{1}{2} B_{\mu\nu} X^{\mu\nu} + \frac{i}{2}\tilde{B}^\dagger \bar{\sigma} \cdot \partial \tilde{X} + \frac{i}{2}\tilde{X}^\dagger \bar{\sigma} \cdot \partial \tilde{B} + D_Y D_X \Big)$$

- $X_\mu \to$ SM;
- (Rare) $Z \to$ HV
- $\tilde{B} \to$ HV
- SUSY *to* HV
- $h_1^x \to$ SM
- (Rare) Higgs $\to$ HV

Possible source:



Expect $\epsilon \sim 10^{-2} - 10^{-4}$



[0906.0580, Bjorken, Essig, Schuster, Toro]

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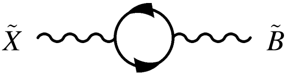

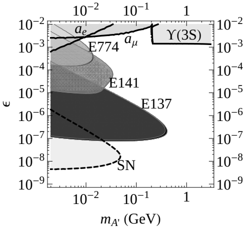

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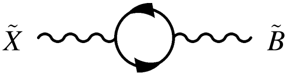

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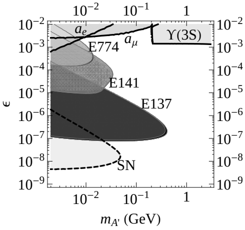

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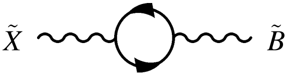

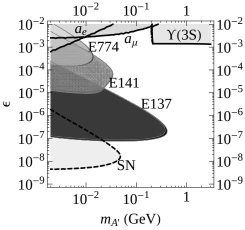

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The Hidden Sector Lagrangian

New Supersymmetric terms:

$$W = W_{MSSM} - \mu' \, H \, H'$$

(plus gauge, Kähler terms $\to g_x, \epsilon$)

Agnostic ~~SUSY~~; hidden soft terms generic, real & $\mathcal{O}(\text{GeV})$

$$-\mathcal{L}_{hid,soft} = {m_H}^2 \, |H|^2 + {m_{H'}}^2 \, |H'|^2 + \left(-b' \, H \, H' + \frac{1}{2} M_x \tilde{X} \tilde{X} + h.c. \right)$$

7 new parameters $m_x, m_{A^x}, \tan\zeta$

Mixing matrices: Fermion P, Scalar R

(See paper for details)

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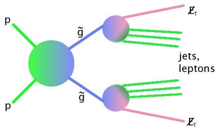
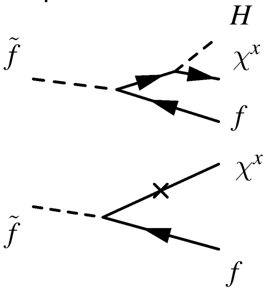
The Nature of the LSMP

LSMP: The Lightest SM Partner

: stable without HV (R-Parity)



LSMP decay is dominant HV production.



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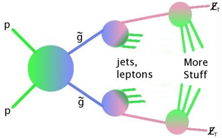

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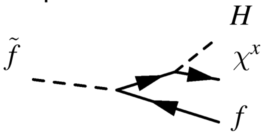

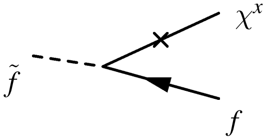

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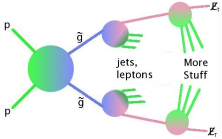

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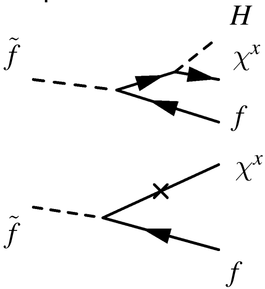

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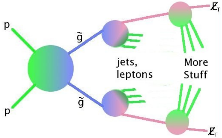

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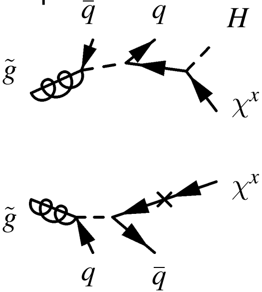

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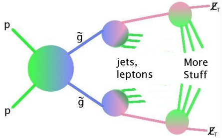

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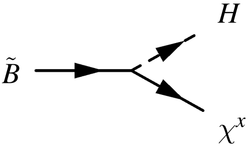

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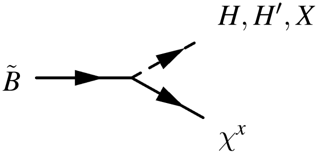
Decays of a Neutralino LSMP



- LSMP decays via kinetic-mixing:

$$\mathcal{L} \supset \sqrt{2} g_x \epsilon \left(H^* \tilde{H} \tilde{B} - H'^* \tilde{H}' \tilde{B} \right)$$

- Decay to fermion + boson
- All seven hidden states accessible (Goldstone boson $\rightarrow$ vector)

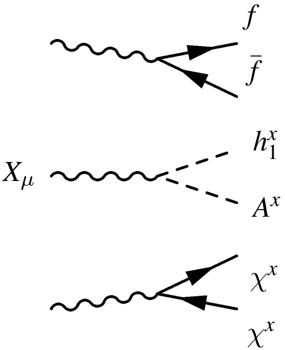
Branching Ratios:

$$\tilde{B} \rightarrow \begin{cases} A^x + \sum \chi^x & 0.25 \\ h_1^x + \sum \chi^x & 0.25 \\ h_2^x + \sum \chi^x & 0.25 \\ X_\mu + \sum \chi^x & 0.25 \end{cases}$$

$$\tilde{B} \rightarrow \begin{cases} \chi_1^x + \sum S^x & |P_{11}|^2 + |P_{12}|^2 \\ \chi_2^x + \sum S^x & |P_{21}|^2 + |P_{22}|^2 \\ \chi_3^x + \sum S^x & |P_{31}|^2 + |P_{32}|^2 \end{cases}$$

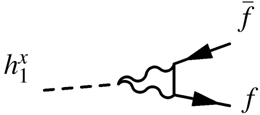
Decay Width $\Gamma \sim 10^{-18}$ s.

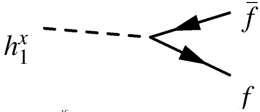
The Hidden Vector



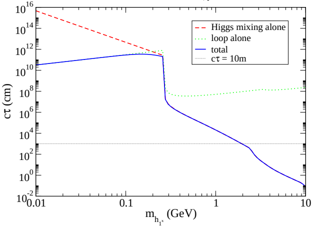
- X_μ-SM coupling from kinetic mixing
  $\Rightarrow$ Strength $\epsilon Q e c_w$
- So vector can decay to SM
- Vector produced boosted
  $\Rightarrow$ Decay products boosted
- Two boosted, collimated quarks/leptons
- BUT! X_μ can also decay to HV
- Hidden decays dominate if allowed

The Lightest Hidden Scalar





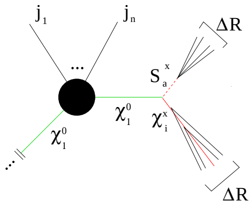
- h_1^x lightest hidden boson
- Often has no hidden decays
- Can decay to SM:
  1. X_μ loop
  2. Mass mixing with Higgs
- Mass mixing dominates . . .
- . . . But still collider-stable



Other Hidden Sector Particles

- χ_1^x is stable by R-parity
- Other particles usually decay within hidden sector
- Exceptions DO exist:
  - $A^x \to h_1^x X_\mu^* \to h_1^x f\bar{f}$
  - $h_2^x \to A^x X_\mu^* \to A^x f\bar{f}$
  - $\chi_2^x \to \chi_1^x X_\mu^* \to \chi_1^x f\bar{f}$
- Note: the second implies the first

Lepton Jets



- LSMP decay products boosted
- Collimated in angle
  $\Delta R \sim 1/\gamma \sim m_{hid}/m_{LSMP} \sim 10^{-3}$
- If leptons produced:
  Lepton jet
- If quarks produced:
  Jet with substructure
- Both case tricky
- Both cases, Two hard subobjects
- Call either an HV Jet

Displaced Vertices

For our values of ϵ and masses

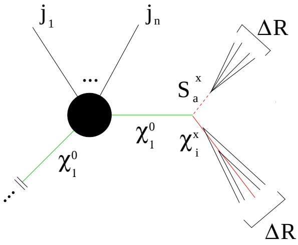
- X_μ always prompt
- h_1^x always collider stable

Displaced vertices only from Three Body decays

Can have a range of metastable lifetimes
From $c\tau \ll$ mm – $c\tau \gg$ km

Obviously, things that leave tracks easier to see

Putting it All Together



$$\{\text{MSSM cascade}\} \oplus \left\{ \begin{matrix} \text{0 HV jets} \\ \text{1 HV jet} \\ \text{2 HV jets} \\ \text{3 HV jets} \\ \text{4 HV jets} \end{matrix} \otimes \begin{matrix} \text{prompt/} \\ \text{displaced} \\ \text{track} \end{matrix} \right\}$$

Definition of the Scan

Explore parameter space:

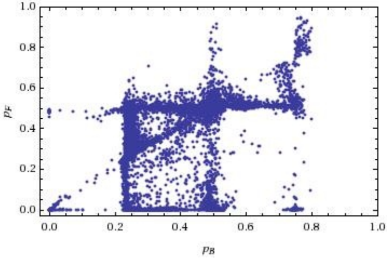
- Scan with log priors
- 20 000 points
- Decay tables:
  - Calculate with BRIDGE
  - Hidden states & LSMP
- Boosts:
  $E_{hid} = m_{LSMP}/2 = 150$ GeV
- Particles $\rightarrow$ decay tables
- Find all LSMP final states & branching ratios

Parameter	Range
m_x	(0.1, 10) GeV
m_{A^x}	(0.1, 10) GeV
M_x	(0.1, 10) GeV
μ'	$\pm$ (0.1, 10) GeV
$\tan\zeta$	(0.1, 10)

Fix:

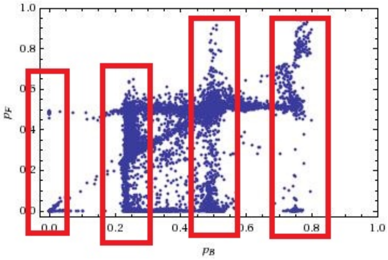
- g_x = 0.3
- $\epsilon = 10^{-3}$
- LSMP:
  300 GeV pure Bino

Number of "HV Jets"



- $\mathcal{P}_B = \sum \tilde{B} \to S^x \to$ SM
- $\mathcal{P}_F = \sum \tilde{B} \to \chi^x \to$ SM
- $\mathcal{P}_B \in (0, 0.8)$
- $\mathcal{P}_F \in (0, 1)$
- Obvious structure here.

Structure I: Hidden Sector Bosons

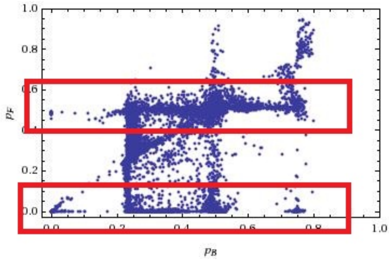


Structure in $\mathcal{P}_B$:

- Favours 0, 0.25, 0.5, 0.75
- Recall: $\mathrm{Br}(\tilde{B} \to S^x) = 0.25$
- 0: $X_\mu \to$ hidden
- 0.25: $X_\mu \to$ SM
- 0.5: $X_\mu, A^x \to$ SM
- 0.75: $X_\mu, A^x, h_x^2 \to$ SM
- Note: h_1^x collider stable

Elsewhere: $S^x \to \chi^x \chi^x$

Structure II: Hidden Sector Fermions

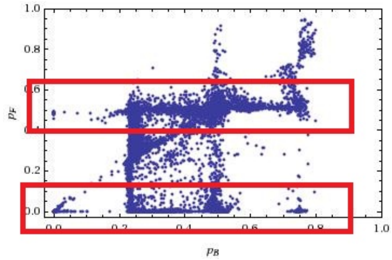


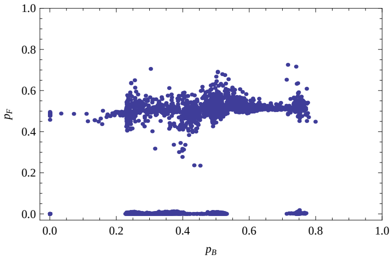
Structure in $\mathcal{P}_F$:

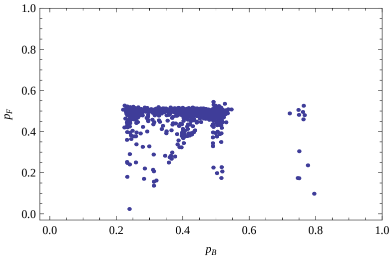
- Agglomerations at 0, 0.5
- Light Higgsinos:
  - $\chi_2^x \to h_1^x \chi_1^x$ invisible
  - χ_2^x off-shell visible
- Heavy Higgsinos

  Decays to h_1^x, X_μ

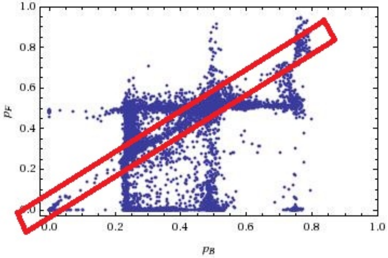
Structure II: Hidden Sector Fermions







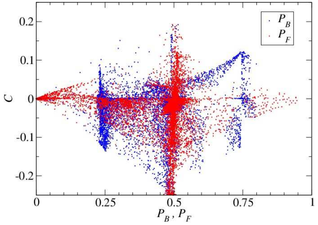
Structure III: Hidden Sector Fermions & Bosons



Last structure: $\mathcal{P}_B \approx \mathcal{P}_F$

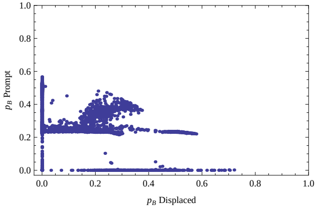
- $\chi_j^x \to S^x \chi_i^x$
- Fermions decay to all scalars
- OR to most scalars

Correlations in Hidden Cascades



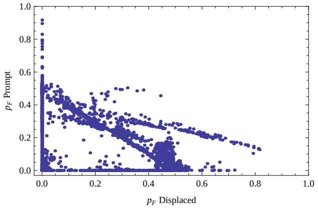
- Average no. HV Jets $\mathcal{P}_B + \mathcal{P}_F$
- But decays correlated
- Define $\mathcal{C} = \mathcal{P}_B\mathcal{P}_F - \tilde{\mathcal{P}}_2$
- $\mathcal{C}$, $\mathcal{P}_B$ and $\mathcal{P}_F$ define Bino decay

Long-Lived Bosons



- All Displaced: $X_\mu \to$ hidden
- All Prompt: All two-body
- Mixed: $X_\mu \to$SM, A^x off-shell

Long-Lived Fermions



- All Displaced:
  - χ_2^x off-shell; or
  - $X_\mu \to$ hidden
- All Prompt: All two-body
- The rest: off-shell scalars

Five Sample Points

Now have overview of parameter space

Select Five points for further study

Selected based on phenomenology, not spectrum:

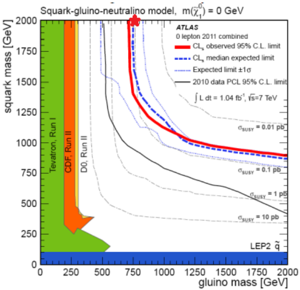
1. Invisible: $\mathcal{P}_B \approx \mathcal{P}_F \approx 0$
2. Vector only: $\tilde{B} \to X_\mu \to$SM, $\tilde{B} \to \chi^x, S^x$ invisible
3. Pure displacement: $X_\mu \to$ hidden, but three-body A^x
4. Lots of stuff; $\mathcal{P}_B \approx \mathcal{P}_F \approx 0.5$, complex decay chains
5. Multiple Displaced; $X_\mu \to$SM, A^x and χ_2^x three-body

See paper for parameters, spectra

Generating Events

We don't care about MSSM phenomenology
$\Rightarrow$ Take simplified spectrum:

- 300 GeV Bino
- 800 GeV gluino
- Everything else 2.5 GeV
- Not ruled out Yet!



Model $\Rightarrow$ FeynRules, MadGraph
$\Rightarrow$ 50 000 events $pp \to \tilde{g}\tilde{g}$ 7 TeV

- $\sigma \sim 200$ fb
- Everything else irrelevant
- 4 jets from gluinos + HV cascades

Defining "Collider" Objects

Experimentalists look away now!

A "HV Jet":

1. (At least) Two partons, $p_T > 20$ GeV and $\Delta R < 0.1$
2. Within $\Delta R < 0.4$, extra $p_T < 3$ GeV
3. No distinction between leptons vs quarks, gluons
4. No showering, detector resolution effects

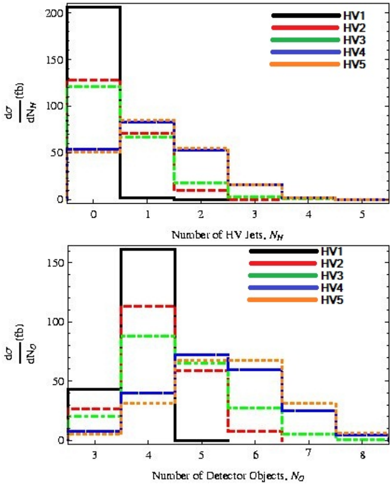
A "Jet":

1. Not an HV Jet
2. $p_T > 20$ GeV
3. Jet Size $R = 0.4$

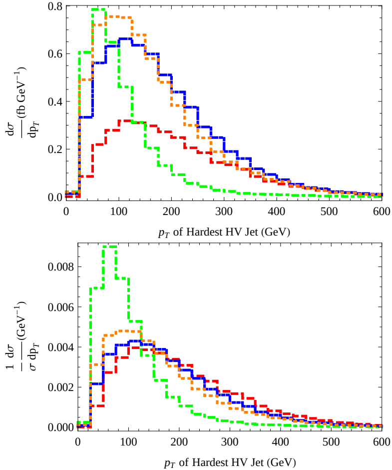
Tag Efficiencies & Number of (HV) Jets

Point	HV Jet Tag Efficiency
HV2	88%
HV3	50%
HV4	62%
HV5	55%

Note: most failed HV jets tagged as jets

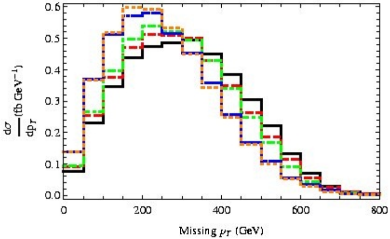


HV Jet p_T



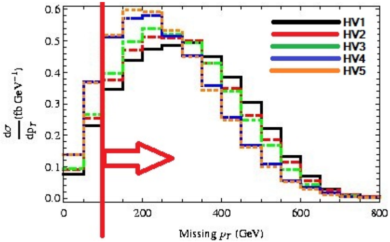
- HV2: hardest HV jets (all from $X_\mu \to f\bar{f}$)
- HV3 notably soft (all from $A^x \to h_1^x f\bar{f}$)

Missing Transverse Energy



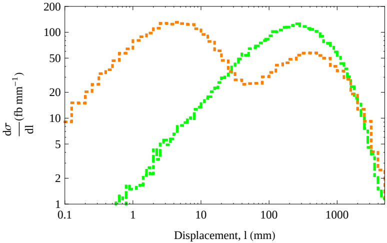
- More visible $\Rightarrow$ less $\not{E}_T$
- Still lots of $\not{E}_T$ in all cases

Missing Transverse Energy



- More visible $\Rightarrow$ less $\not{E}_T$
- Still lots of $\not{E}_T$ in all cases

Displaced Vertices



- Again: no detector effects
- HV5 “double-bump”:
  hint to HV structure?

Monojets

Benchmark	Monojet Branching Ratio
HV1	0%
HV2	27%
HV3	10%
HV4	18%
HV5	12%

[Used ATLAS LowPT Tags]

$pp \to 2$ LSMP $\to$ monojets

- Irrelevant for Bino LSMP
- Interesting for Wino, Higgsino?
- Possible for all but HV1

- MSSM + Higgsed U(1) is Minimal SUSY HV
- Model has Diverse phenomenology:
  R-Hadrons, displaced vertices, lepton jets, monojets . . .
- It is therefore a possible Benchmark
- We have Scanned HV Parameter Space
  And studied 5 points in more depth