Displaced Axinos at the LHC

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In a nutshell

- Why would we want to look for Axinos?
- In what scenarios are collider searches for Axinos possible?
- What signal can we expect?
- How unique is this signal?

Outline

- SUSY
- Dark Matter
- Axions/Axinos
- Preliminary results

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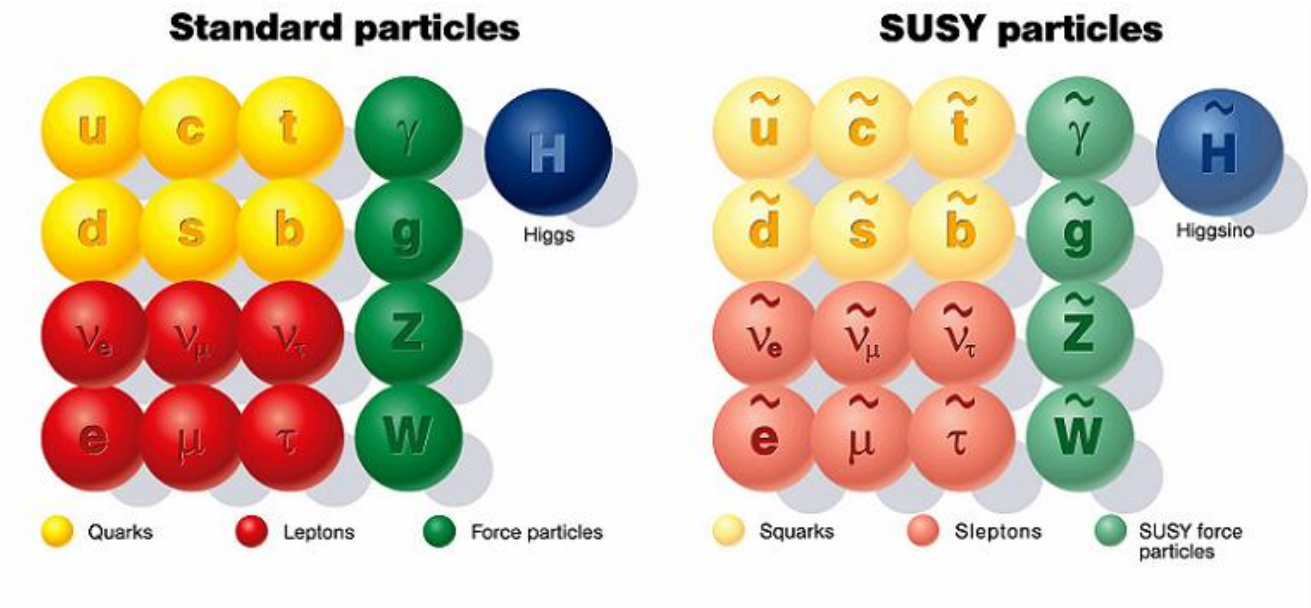
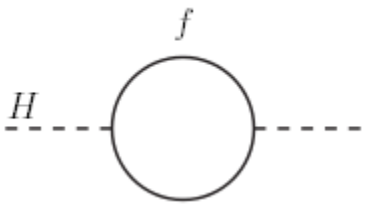


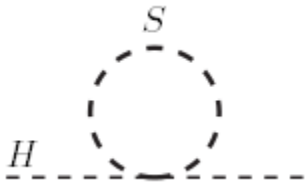
Motivation for SUSY

SUSY may answer many of the questions the SM leaves us with:

- Particle nature of dark matter
- Gauge coupling unification
- Connection to gravity
- Baryogenesis
- Dark Energy
- Inflation
- Solution to the hierarchy problem



$$\delta M_H^2 = +2\frac{|\lambda_f|^2}{16\pi^2}\Lambda^2 + \ldots$$

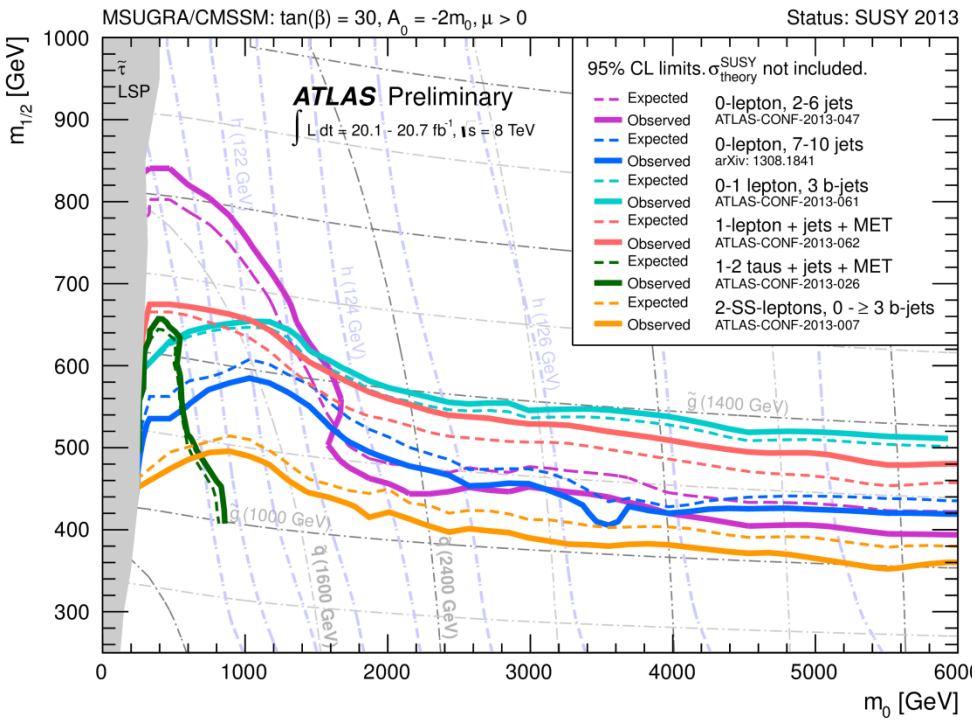


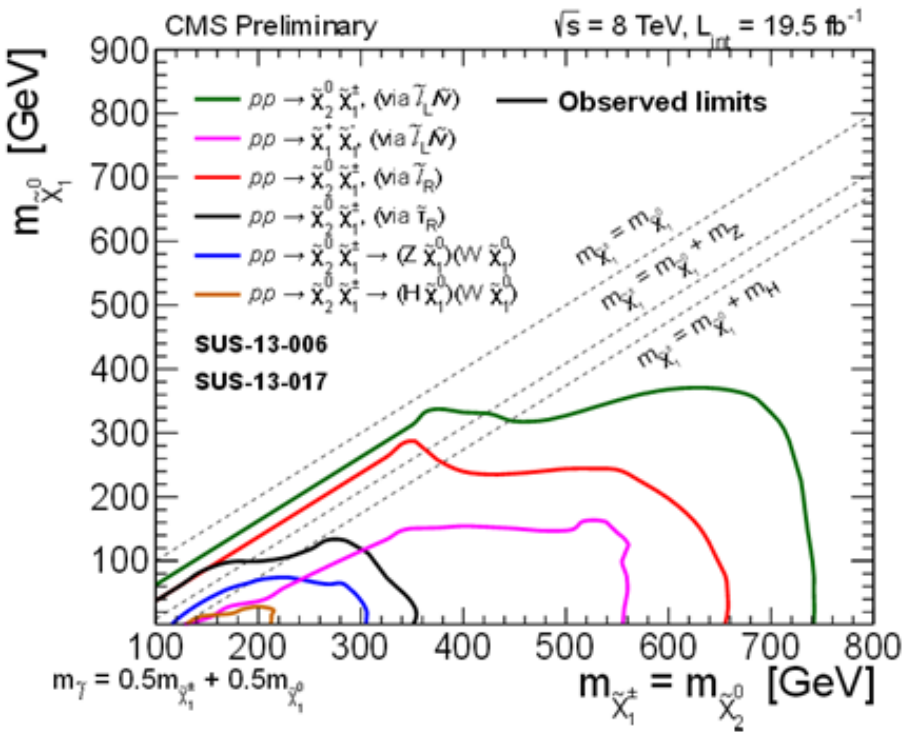
$$\delta M_H^2 = -2\frac{\lambda_{\tilde{f}}}{16\pi^2}\Lambda^2 + \ldots$$

$$\text{Supersymmetry} \Rightarrow |\lambda_f|^2 = \lambda_{\tilde{f}}$$

Desperately Seeking SUSY

The longer we don't see SUSY, the heavier and more unnatural it apparently becomes

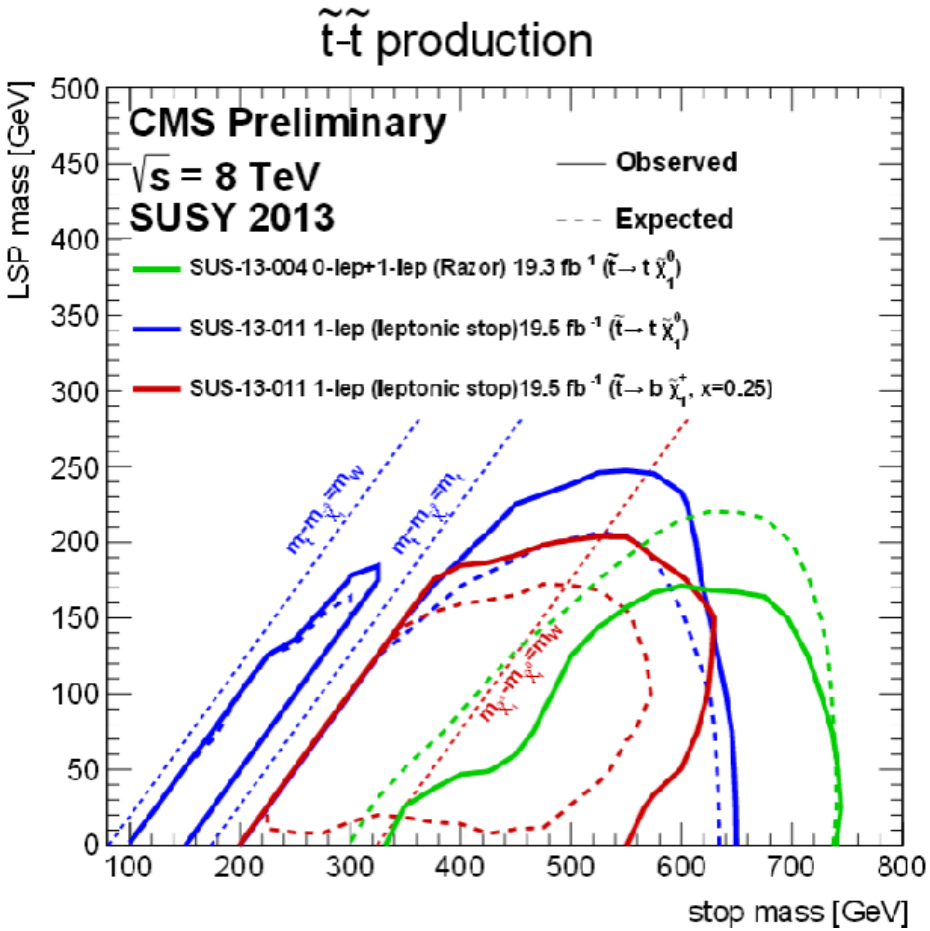




Hope Springs Eternal

In spite of the ever growing mass limits, SUSY is still alive

- The stop is the most important for naturalness, and limits are harder to obtain
- Level of tuning depends on more than JUST mass of stop
- Some scenarios claim low tuning with stop mass over a TeV



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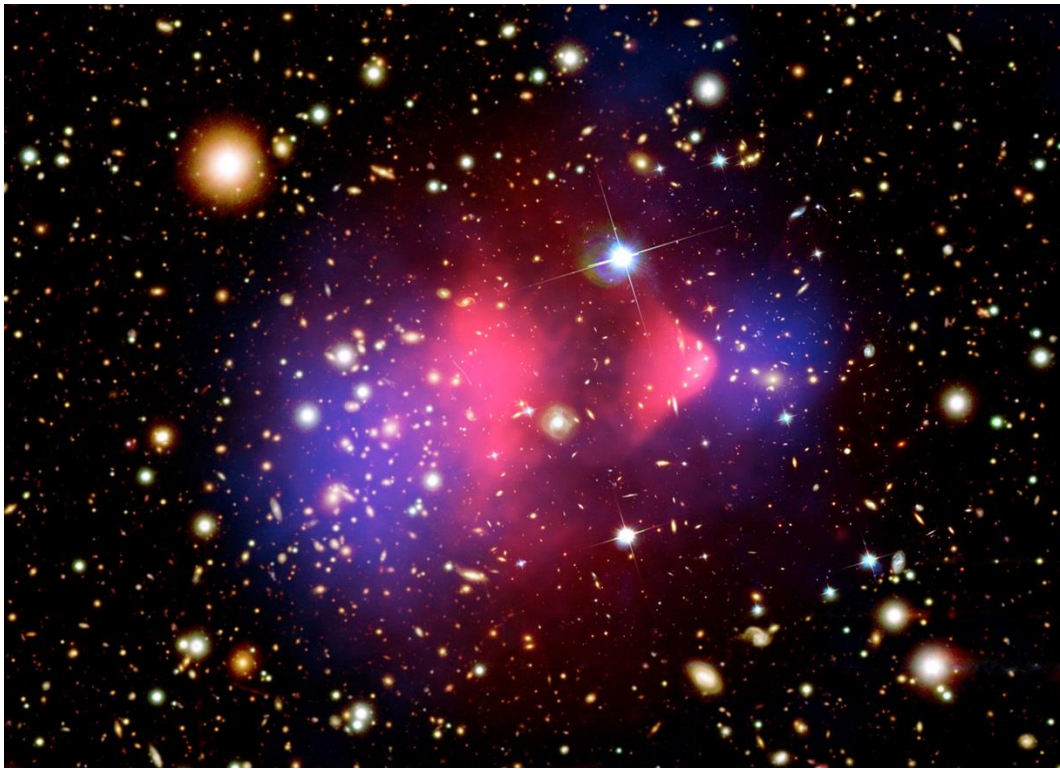
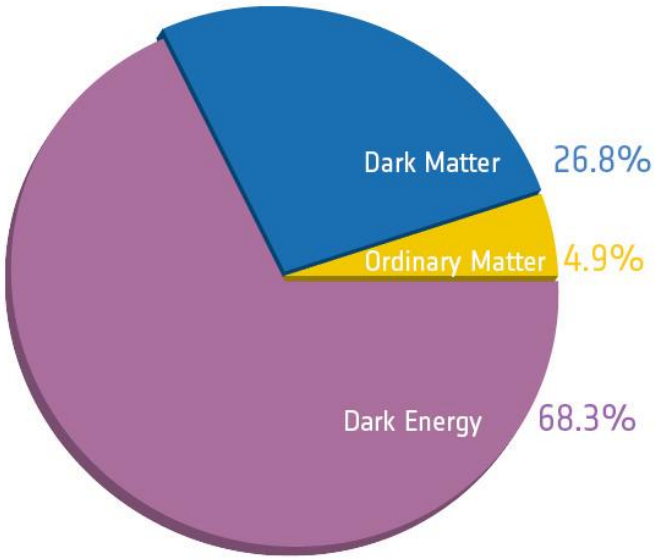


Problem of Particle Dark Matter

Various evidence points towards a massive non baryonic species of matter

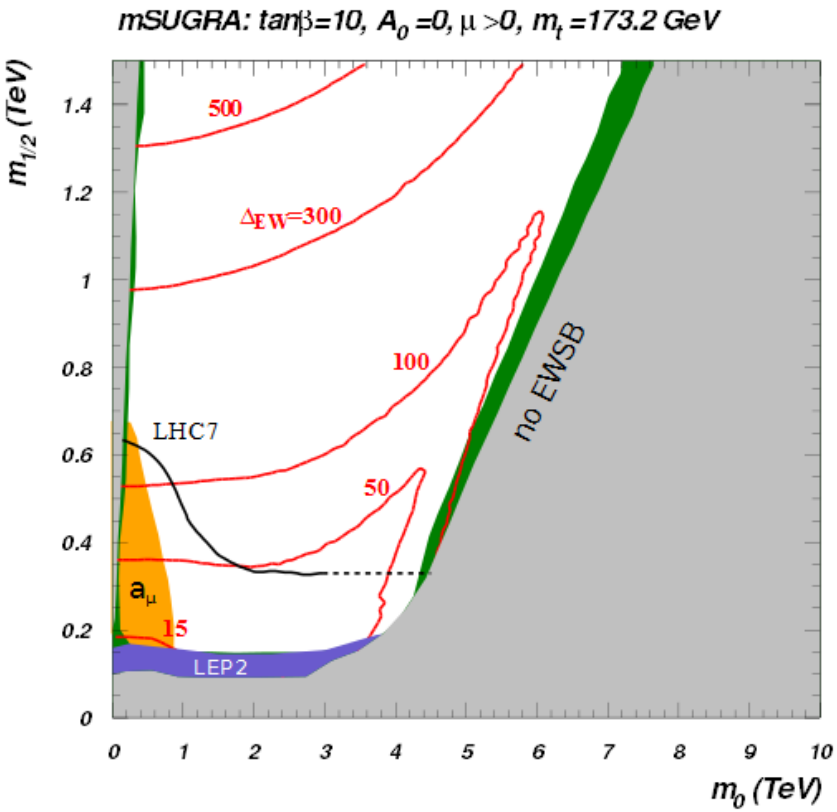
- Galactic rotation curves show there should be more mass than we see
- CMB measurements show a non baryonic matter contribution to the energy budget of the universe
- Bullet Cluster is strong evidence that dark matter is a particle and not (just) a modification to gravity
- SUSY's lightest neutralino, is massive and only weakly interacting, so it is a WIMP
- WIMPs give the correct order of magnitude for a thermally produced dark matter relic density



Dark Matter and Tuning

Accommodating a dark matter solution in SUSY can also introduce tuning

- Green region is only area with correct amount of dark matter
- Viable parameter space greatly reduced
- Red contours have same value for a measure of tuning
- Natural SUSY models (not in this plane) generically do not predict correct amount of dark matter

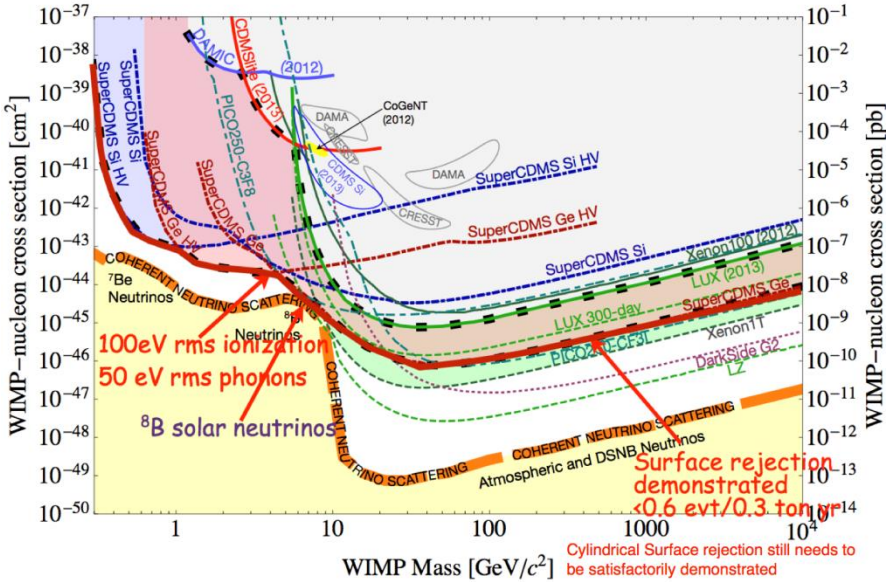


H.Baer et al, hep-ph/1210.3019

Evading constraints

Already many unsuccessful searches for particle dark matter in the generic SUSY scenarios

- Direct detection experiments looking for relic wimps interacting with detector on earth
- Indirect detection looks for products of DM annihilation or decay
- Collider searches for DM have varied strategies and can probe a variety of models
- A modified dark sector requires many of these constraints to be reinterpreted and may require new search strategies
- Wimps may not be the whole story even if SUSY plays a role in DM



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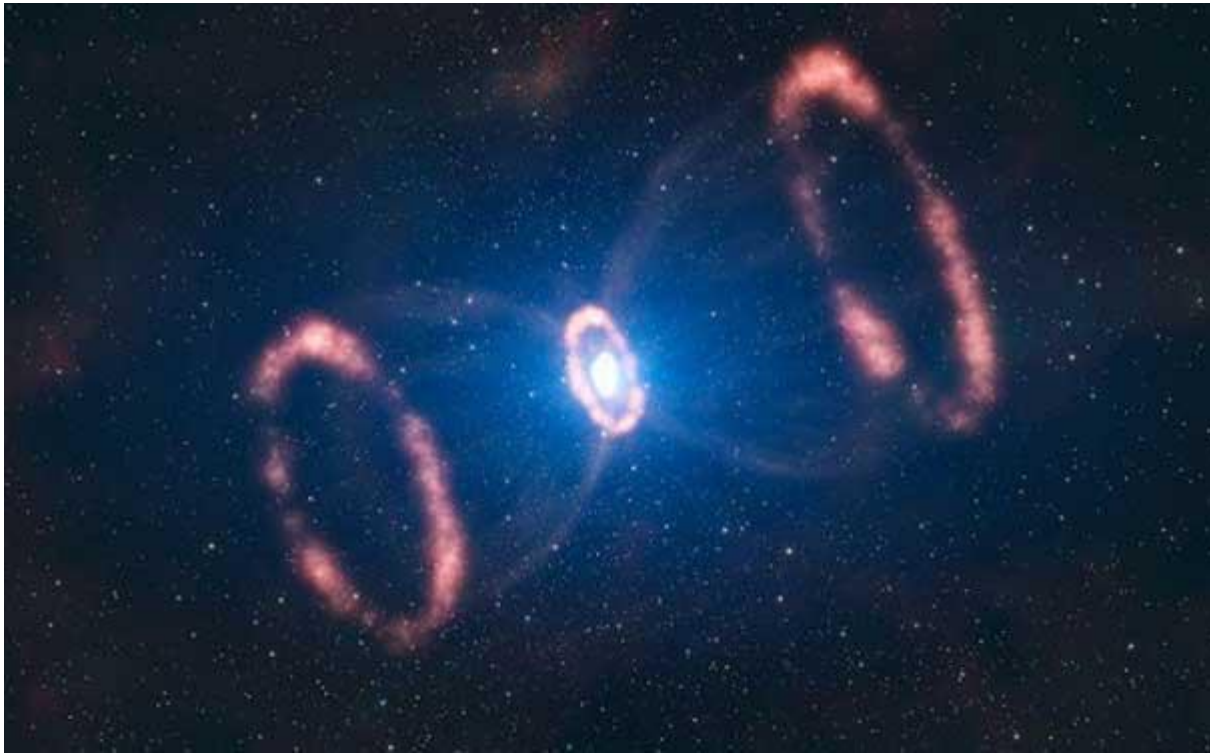


The Strong CP problem

CP violation allowed by QCD lagrangian $L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$

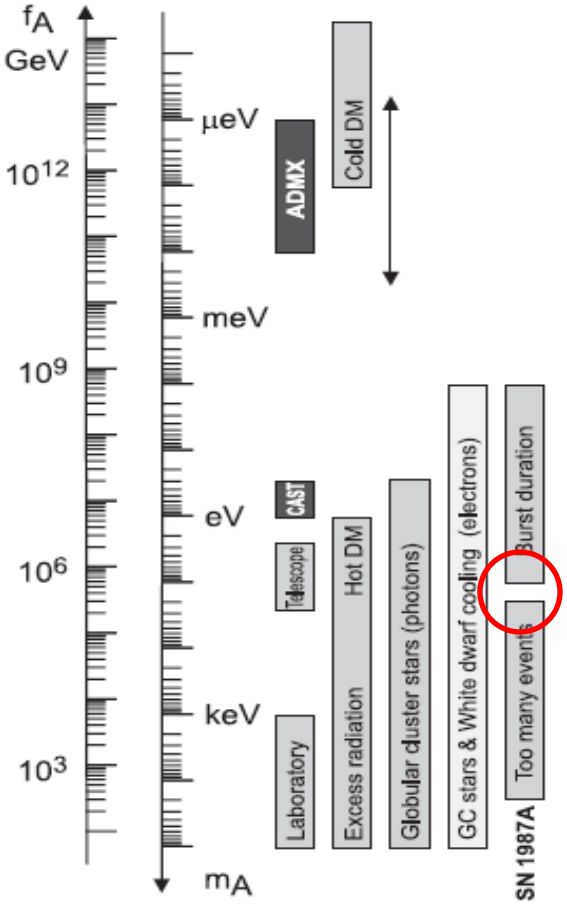
- Neutron EDM constrains $\theta < 10^{-9}$ so there is apparent tuning
- Make SM lagrangian invariant under a new global $U(1)_{pq}$ by adding axion field and introducing new scale f_a

$$L_{\rm total} = L_{\rm SM} + \bar{\theta} \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu} - \frac{1}{2} \partial_\mu a \partial^\mu a + L_{\rm int}[\partial^\mu a / f_a; \Psi] + \xi \frac{a}{f_a} \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

- $U(1)_{pq}$ is spontaneously broken and the axion is a (pseudo) goldstone boson
- $U(1)_{pq}$ allows shifts $a_{\rm phys} = a - < a >$
- At the minimum of the axion potential $< a > = -\frac{f_a}{\xi} \bar{\theta}$, the theta term cancels
- See Peccei, hep-ph/0607268 for a review

Constraining the Axion

PQ scale (f_a) can take any value in the theory, only experiments and observation constraints guide us



J. Beringer et al. (Particle Data Group), PRD86, 010001 (2012)

- Originally f_a was connected to weak scale, ruled out by lab experiments at bottom
- Most studies consider $f_a > 10^9$ GeV
- Variations of this plot are common, but it can be misleading, tests probe different couplings
- All couplings of the axion depend on f_a, but they also can contain model dependent factors:

$$L_{a\gamma\gamma} = \frac{\alpha}{4\pi} K_{a\gamma\gamma} \frac{a_{\text{phys.}}}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu}$$

- PQ scale could be as low as 3×10^5 GeV if we only have QCD coupling (only one needed to fix strong CP)
- Killing the other couplings means we lose many of our tests for axions . . .

PQ + MSSM = PQMSSM

Axions in SUSY are part of a super multiplet that also contains the saxion and the axino

- The saxion is a scalar with even R-parity, we can assume it is heavy and decouples
- The axino is a majorana fermion and has odd R-parity
- Dark matter abundance can be made up of any combination of three species: axion, axino and neutralino, depends on mass hierarchy and cosmology
- Solution to tuning in strong CP and makes satisfying constraints easier, so a natural scenario may be more viable, may be other benefits . . .
- Axino mass is very model dependent, we take it as a free parameter

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INFO: Process has 8 diagrams
INFO: Trying process: c d > c s n1 ax WEIGHTED=6
INFO: Trying process: c s > u d n1 ax WEIGHTED=6
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INFO: Process s d > d s n1 ax added to mirror process d s > d s n1 ax
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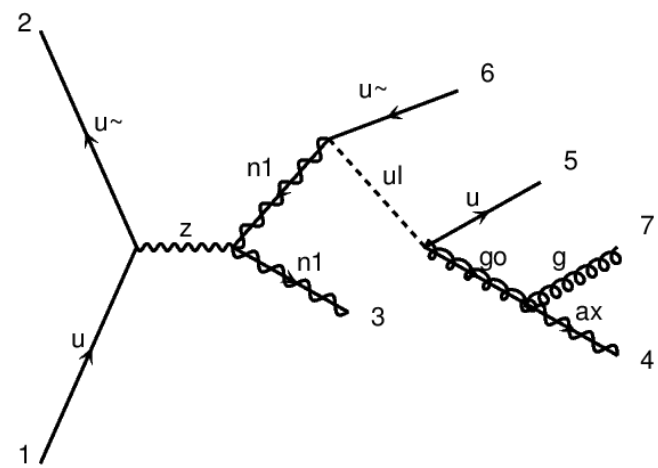
Collider Searches for Axinos

- Precedent axino collider signal in literature usually involve VERY weak coupling and a charged nlsp (e.g Frank Daniel Steffen arXiv:hep-ph/0507003)
- If we consider a PQ scale in the hadronic axion window we can think about neutral nlsps and displaced decays
- In this window of stronger coupling we only have one type of coupling for the axino

$$\mathcal{L}_{\tilde{a}\tilde{g}g} = i\frac{\alpha_s}{16\pi(f_a/N)}\bar{\tilde{a}}\gamma_5[\gamma^\mu,\gamma^\nu]\tilde{g}_A F_{A\mu\nu}$$

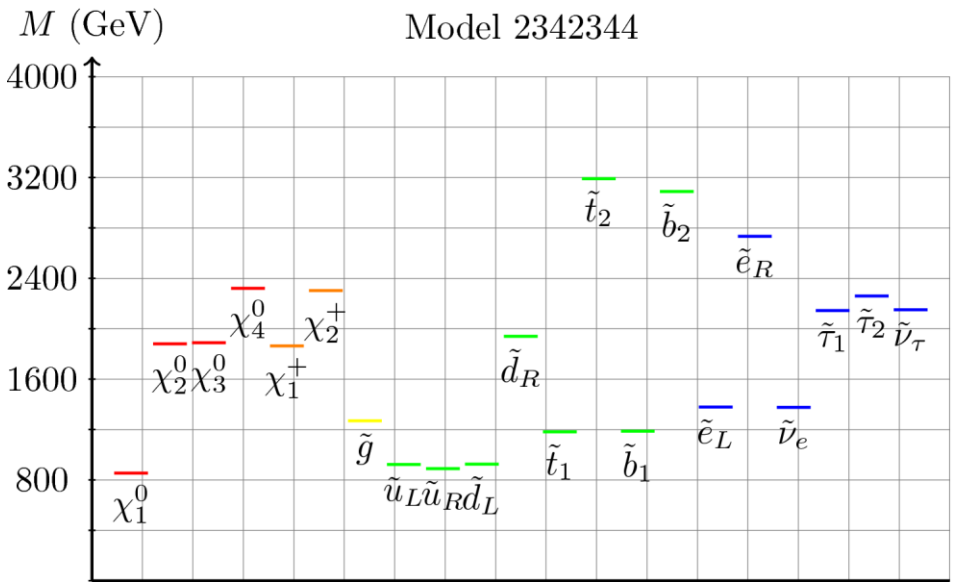
- Any SUSY particles produced will eventually decay to axinos and at least three jets because of R parity (branching fraction of 1)
- Production rate of signal should be just the inclusive SUSY rate, since any mess from the production should be well separated from the signal in the detector, provided the decay is displaced enough



A Benchmark model

As a test case, the "Bino Squark Co-annihilation" Scenario with a light axino is appropriate for several reasons

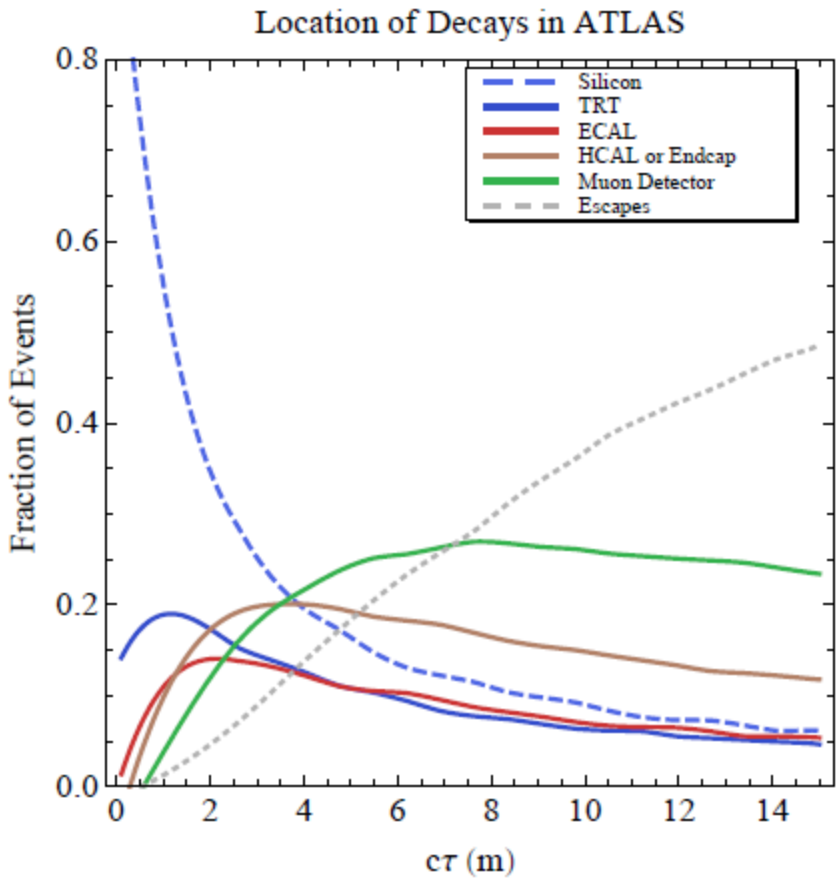
- Correct Higgs mass
- Evades current constraints
- Probable in next run of LHC
- No particular tricks or kinks, it is not a "special" model
- Not concerned with relic abundance predicted by the model, our addition of the axion/axino will change this anyways
- Benchmark not chosen for being particularly natural, but for being generic of what it is not yet excluded and still testable



Matthew W. Cahill-Rowley, et al arXiv:1305.2419v1 [hep-ph]

Compressed Spectra

- SUSY scenarios that have survived current collider searches are likely compressed
- For compressed scenarios like our benchmark and with the axino coupling in this "hadronic window" the decay length for neutralinos is optimal for searches, given detector geometry
- Benchmark authors also provide slopes of fixed Higgs mass, allowing us to look at varying levels of compression and the effect on the signal
- Axino search may have better reach for compressed scenarios, advantage of total SUSY production rate, but take a hit in efficiency of jet measurements in outer parts of detector



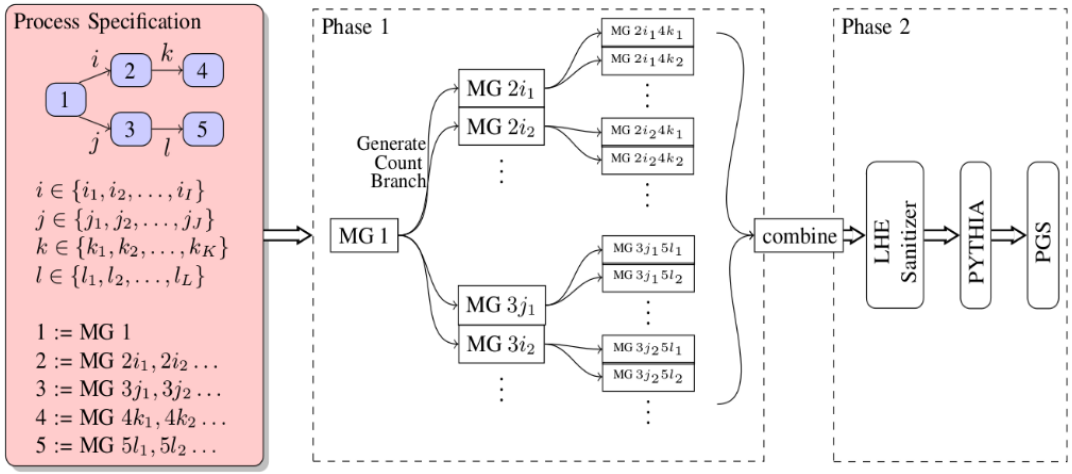
Patrick Meade, Matthew Reece and David Shih
arXiv:1006.4575v1 [hep-ph]

Tools for the Study

- SuSpect/SOFTSUSY for mass spectrum calculation, outputs SLHA
- Feynrules for generating Feynman rules and model files for Monte Carlo, outputs in various formats
- MadGraph (with assistance from evchain) for calculation of cross sections and distributions
- Analysis done with a modified version of the Chameleon package for Mathematica by Philip Schuster, Jesse Thaler and Natalia Toro
- May use micrOMEGAs for relic abundance calculation in the future, but these scenarios may be dominated by non-thermal production of DM

Necessity of evchain

- Long lived particles with extremely narrow widths make it difficult for madevent to sample the phase space for montecarlo
- Our events are cascades at the end of cascades, smallest process we can consider is 2 to 8 for the full event
- Evchain alleviates both of these problems as a “madgraph manager”, combining event files from multiple madgraph runs and performing the required boosts



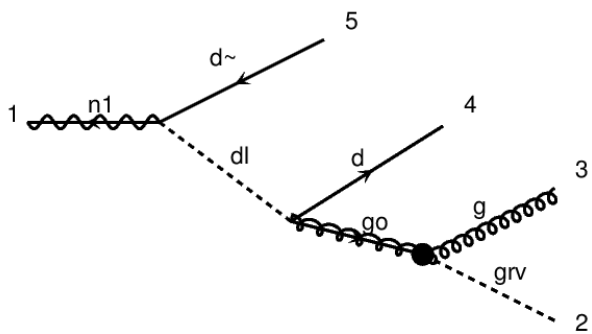
Ian Woo Kim and Kathryn M Zurek arXiv:1310.2617v1 [hep-ph]

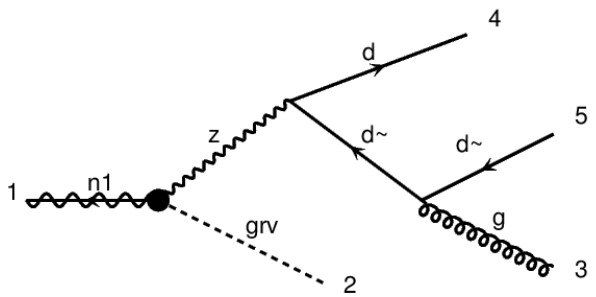
- Tool is available at https://github.com/hep-platform/evchain , but is still in development (author is very helpful)

Similar Model Signatures

Many models can predict multiple displaced jets:

- Hidden valley can do this, but many different scenarios possible
- RPV can do this, may be distinguishable by MET, again many scenarios possible
- Gravitino is the case we've looked at the most, plenty of literature describing similar searches
- Tried to create a gravitino scenario that mimicked ours as closely as possible and looked for ways to discriminate





- Our signature is always produced at a higher rate because of branching fraction of 1
- Neutralino decay to gravitino plus jets must always proceed through a Z

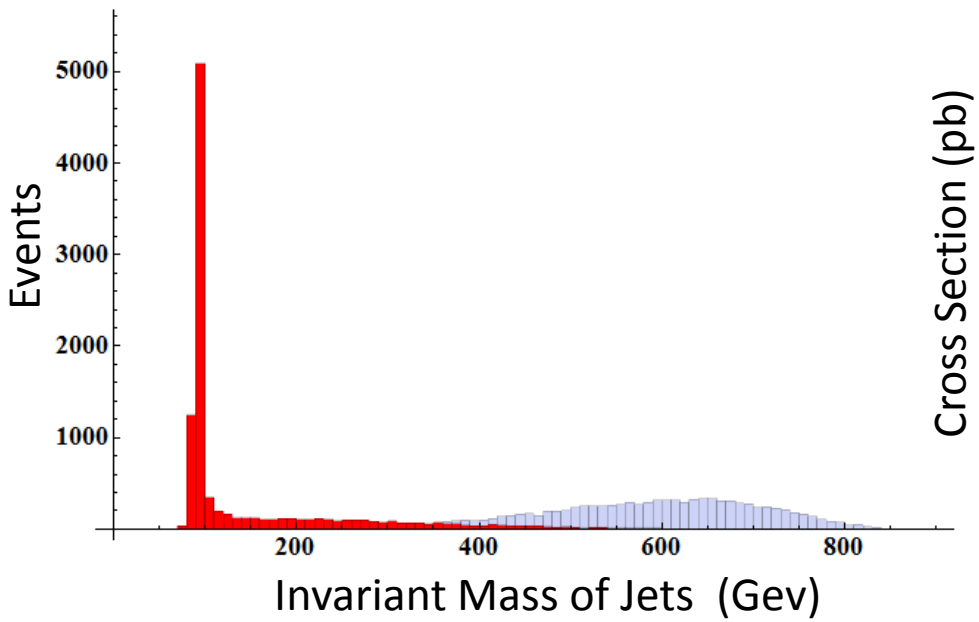
Prelim Results

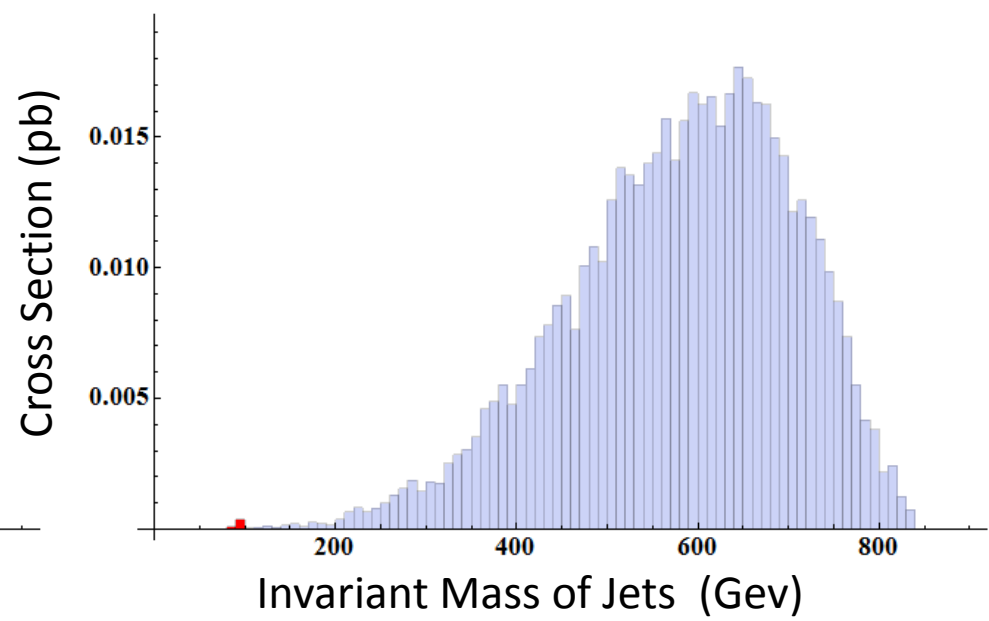
- Gravitino signature can be vetoed because of the Z
- Left plot normalized to # of events, showing shape differences
- Right plot normalized to cross section, showing difference in expected rates

σ_{susy} = 0.886 pb Total SUSY cross section at benchmark used for normalization

Γ_{signal} = 2.31 x 10^{-16}Gev Γ_{total}= 2.35 x 10^{-16} Gev Decays to Axinos in Blue

Γ_{signal} = 3.63 x 10^{-16}Gev Γ_{total}= 4.97 x 10^{-13} Gev Decays to Gravitinos in Red





Prelim Results

- The differences in topology also mean the MET is recoiling differently and can also be used to distinguish these two possibilities

σ_{susy} = 0.886 pb

Γ_{signal} = 2.31 x 10^{-16}Gev Γ_{total}= 2.35 x 10^{-16} Gev

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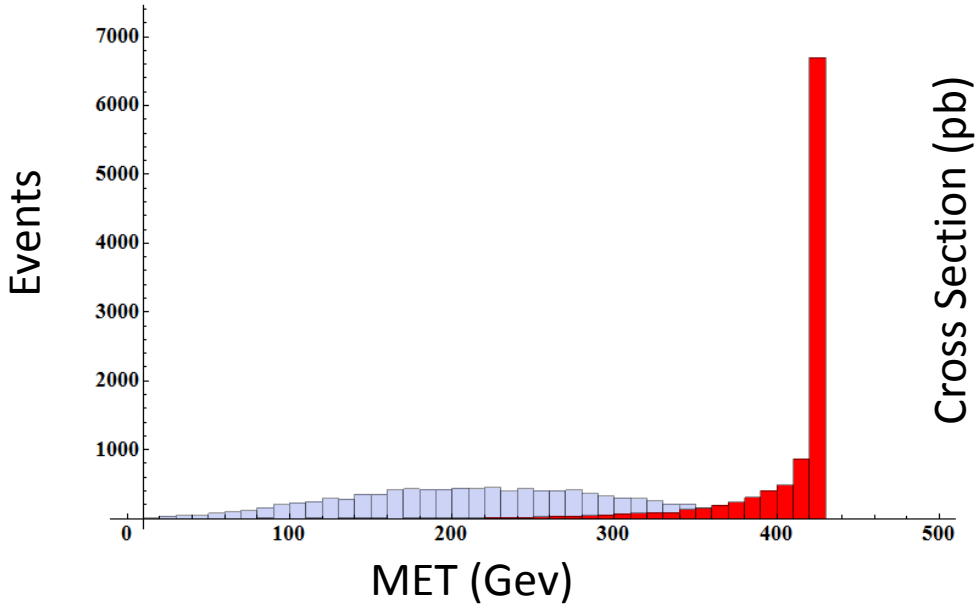
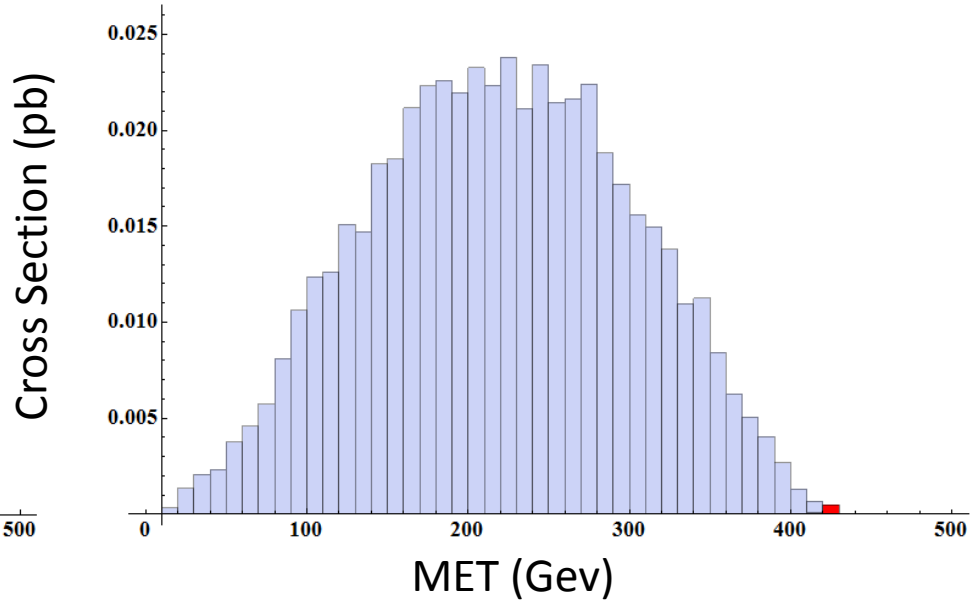
Decays to Axinos in Blue

Decays to Gravitinos in Red





Prelim Results

- With evchain we can produce distributions from the full event
- Decays starting from neutralino pair production will be the most boosted, compared to distributions of the decays alone

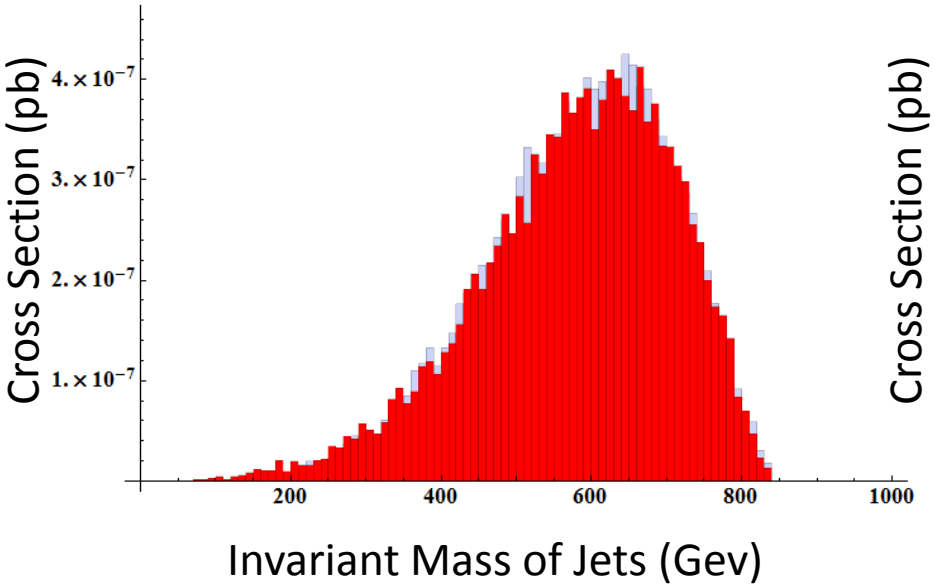
$\sigma_{n1\ pairs} = 2.13 \times 10^{-5}$ pb

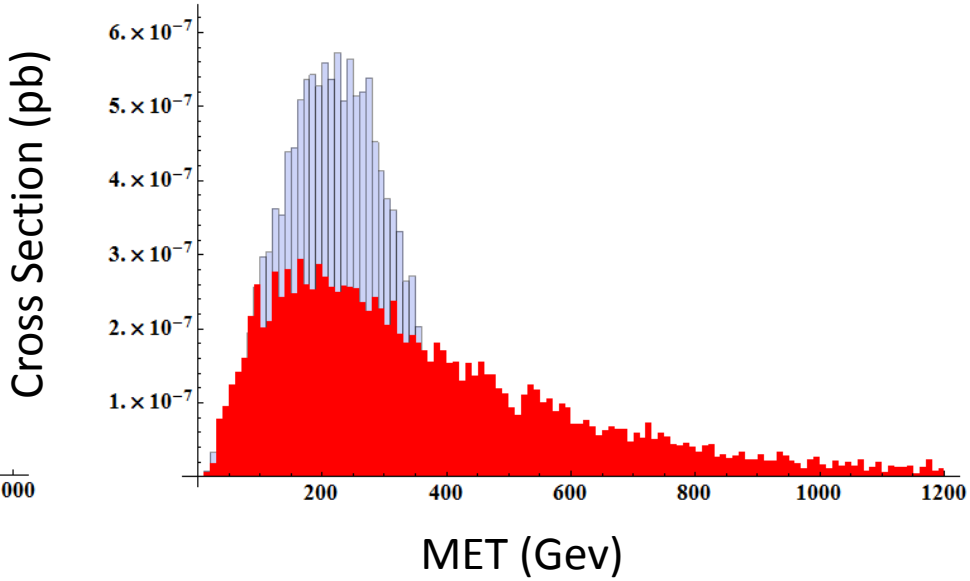
$\Gamma_{signal} = 2.31 \times 10^{-16}$ Gev $\Gamma_{total} = 2.35 \times 10^{-16}$ Gev

No normalization needed for full event

Decays to Axinos in Blue

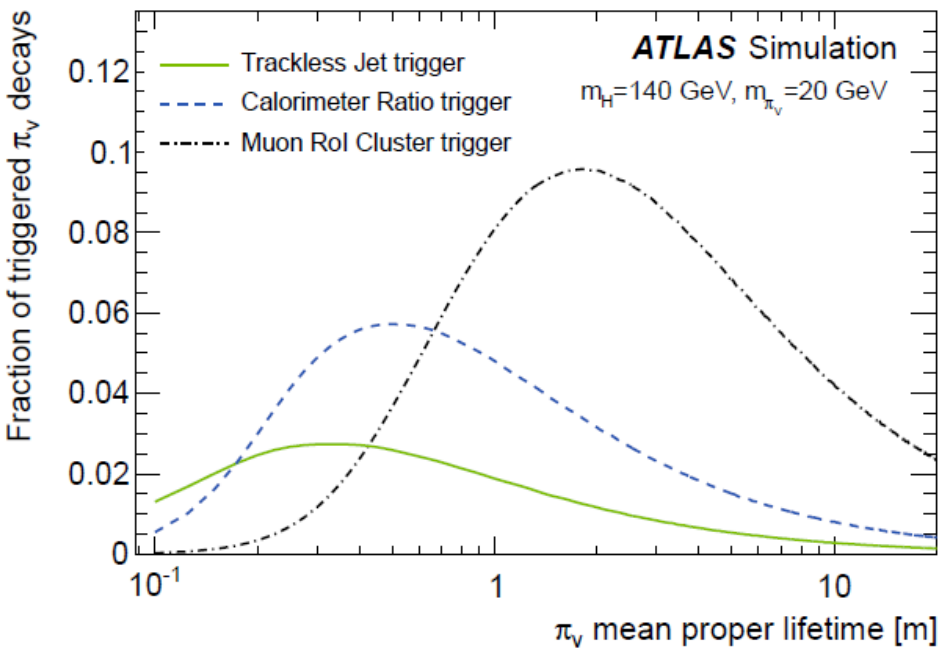
Full Event in Red





What can we actually see?

- Triggers developed for hidden valley models trigger on long lived neutral particles decaying to jets
- Our jets should be boosted for heavier neutralinos and our rates are favorable because of the branching fraction
- Expected depth of the decays in the detector seems ideal for compressed spectra with a hadronic axion
- With evchain, we can produce the full event and pass along the results to PYTHIA + PGS
- We plan on looking at this in more detail soon



In a nutshell

- Why would we want to look for Axinos?

  May be present in surviving SUSY scenarios with some added benefit,

  also because we can
- In what scenarios are collider searches for Axinos possible?

  Light (<10GeV) Axinos in the hadronic axion window with compressed SUSY spectra have decay lengths that fit our detectors well
- What signal can we expect?

  In the hadronic axion window there is only one relevant coupling and one topology, always have six jets and missing energy
- How unique is this signal?

  Distinguishable from similar gravitinos, but there are many other possible scenarios to consider

Questions?