Displaced Axinos at the LHC

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SUSY 2014 Manchester

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In a nutshell

- Why look for Axinos at a collider?
- When are collider searches possible?
- What signal can we expect?
- How unique is this signal?

(Real) Motivation

- So many models of new physics and DM, seem recycled, redundant, contrived, how can I contribute?
- Axion/axino DM scenarios well motivated in literature already, but collider pheno almost never considered
- Make minimum changes to vanilla scenario so collider pheno is possible and see what happens
- Common wisdom -> axions/axinos way too weakly coupled to matter at colliders

Outline

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

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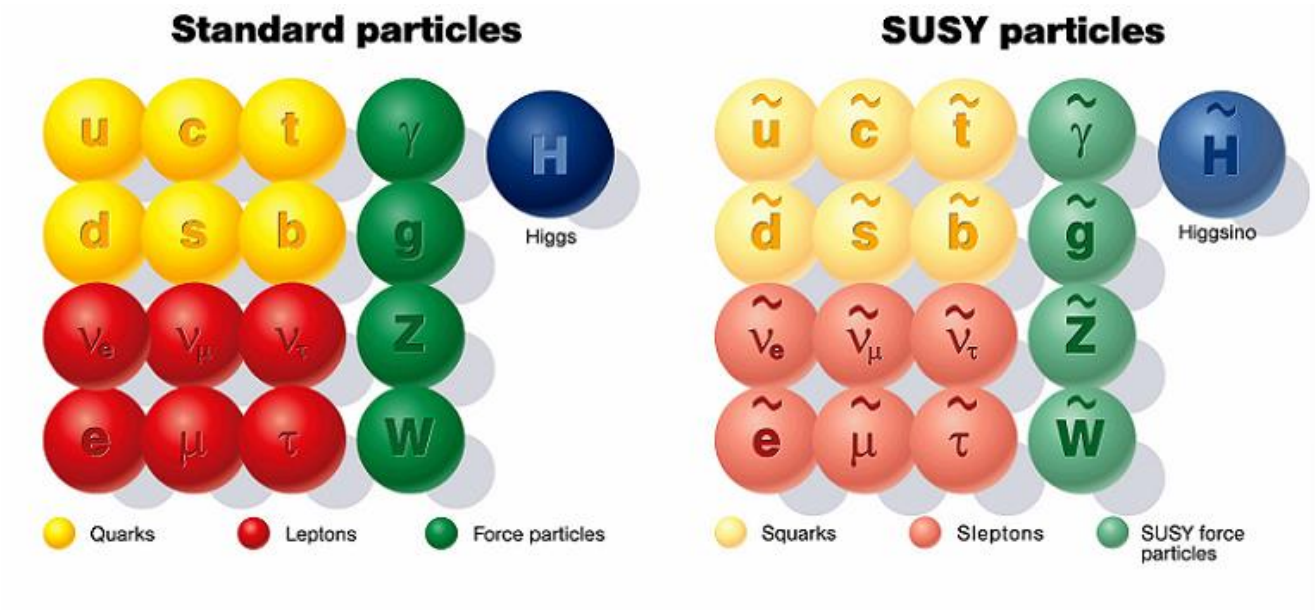
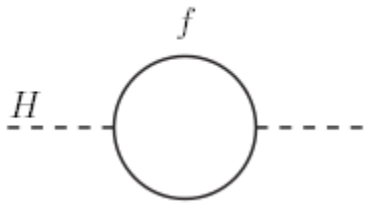


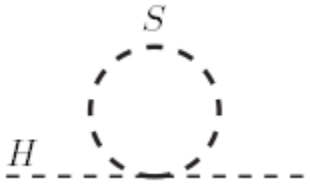
SUSY

Lots of reasons we like SUSY

- Particle nature of dark matter
- Gauge coupling unification
- Connection to gravity
- Baryogenesis
- Inflation
- Fix hierarchy problem



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

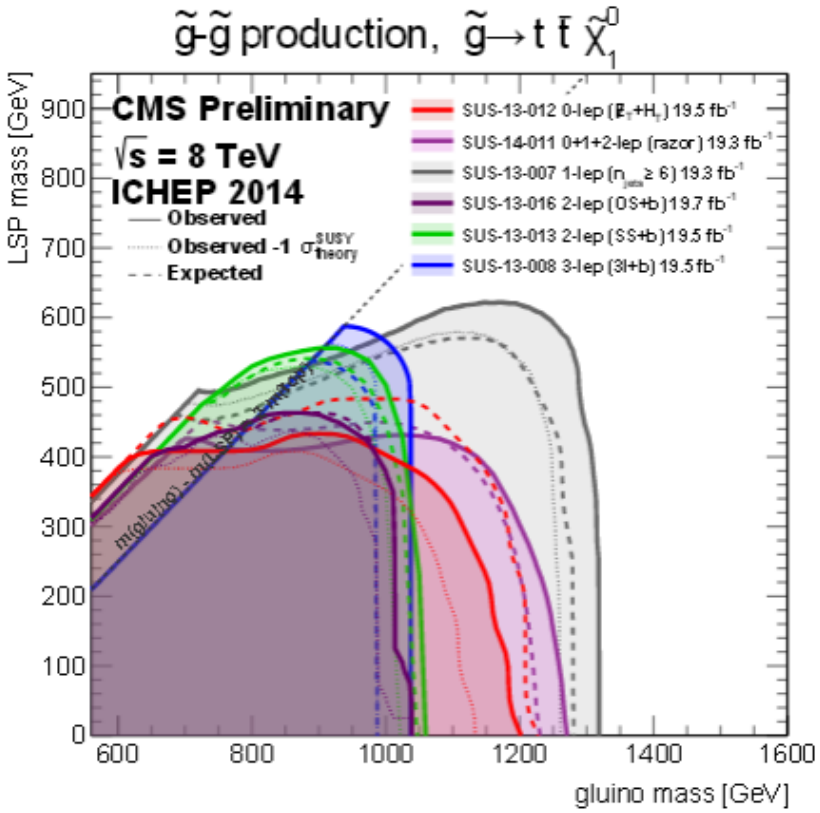


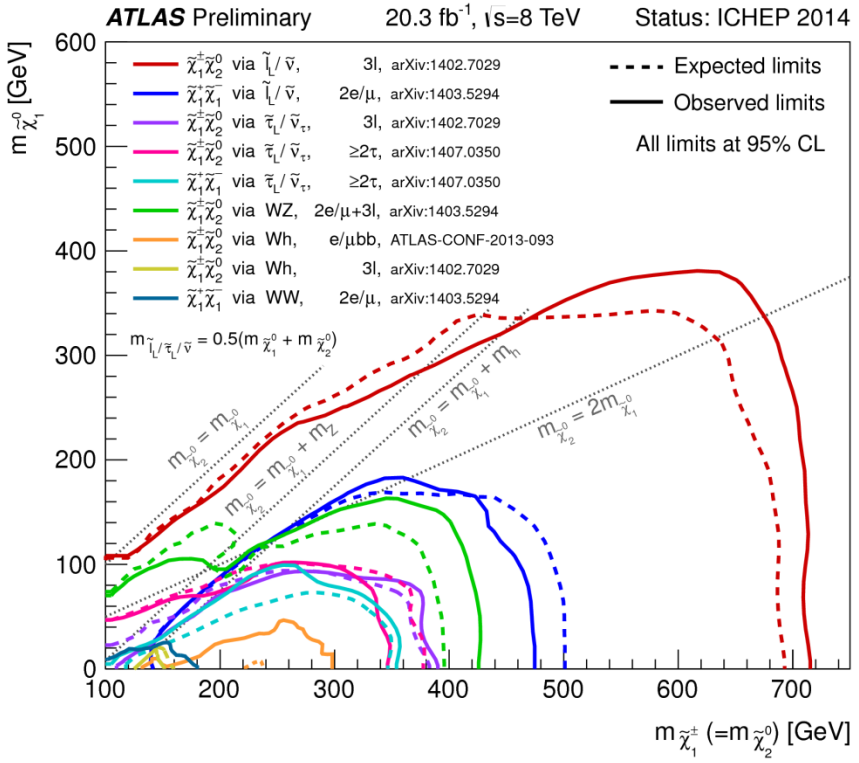
$$\delta M_H^2 = -2\frac{\lambda_{\tilde{f}}}{16\pi^2}\Lambda^2 + \ldots$$

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

Don’t see SUSY yet

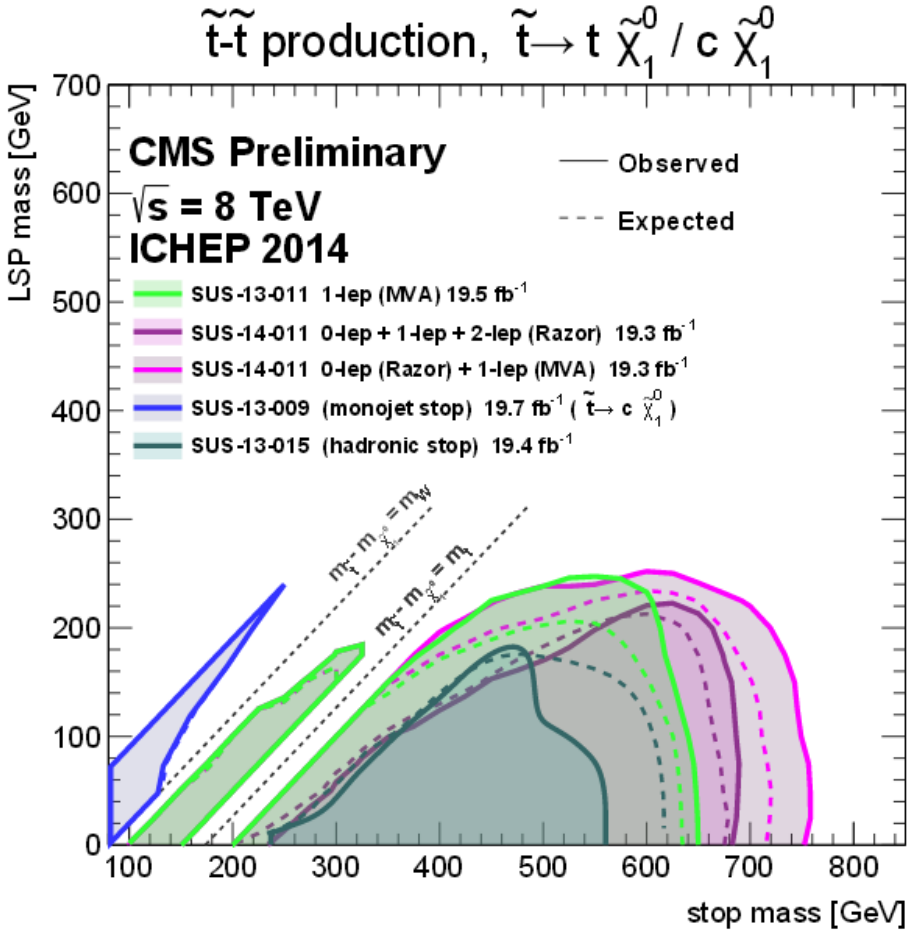
Naturalness seems less likely as time goes on





Hope Springs Eternal

- The stop is important, easy to miss
- Lots of scenarios cooked up, SUSY can still be natural
- Lots of other talks on this



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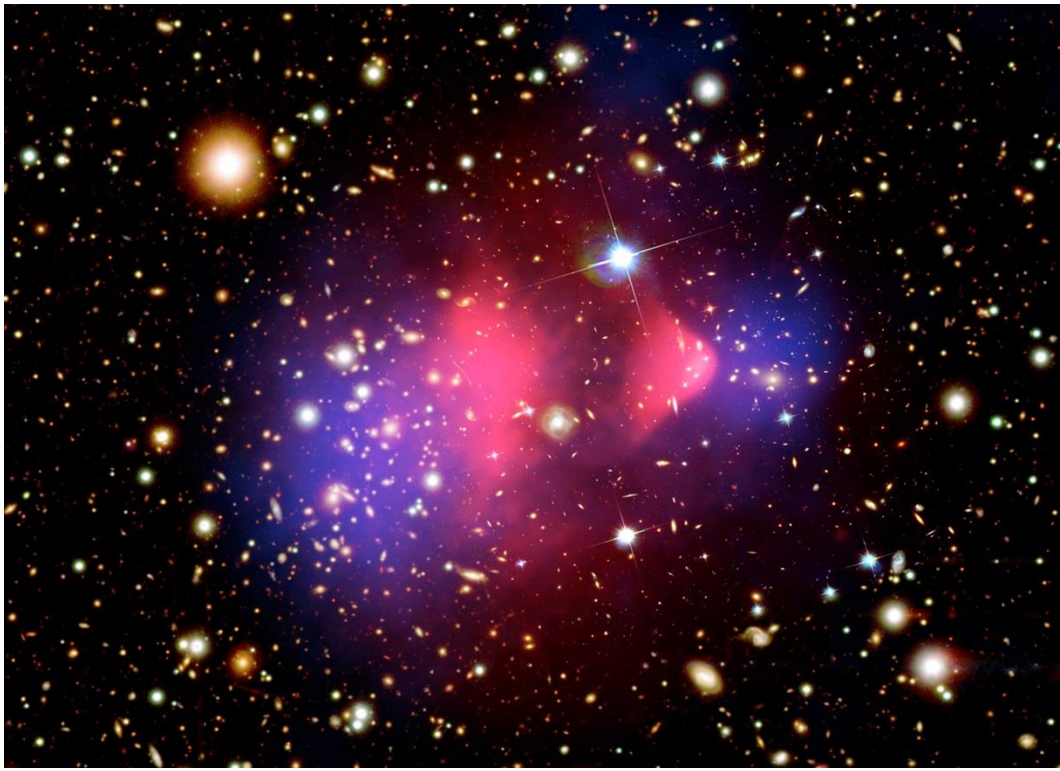
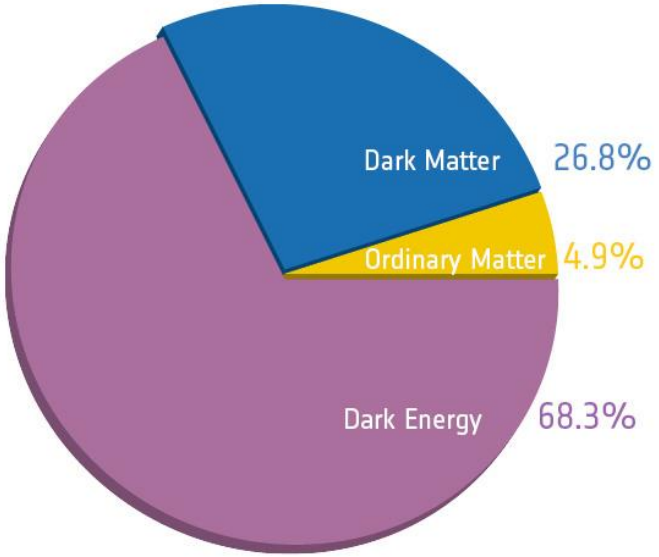


Dark Matter

Very confident that there is dark matter, but no details known

- Galactic rotation curves -> more mass than visible
- CMB measurements ->non baryonic matter component
- Bullet Cluster ->DM is a particle
- SUSY -> WIMPs
- WIMPs ->thermal DM

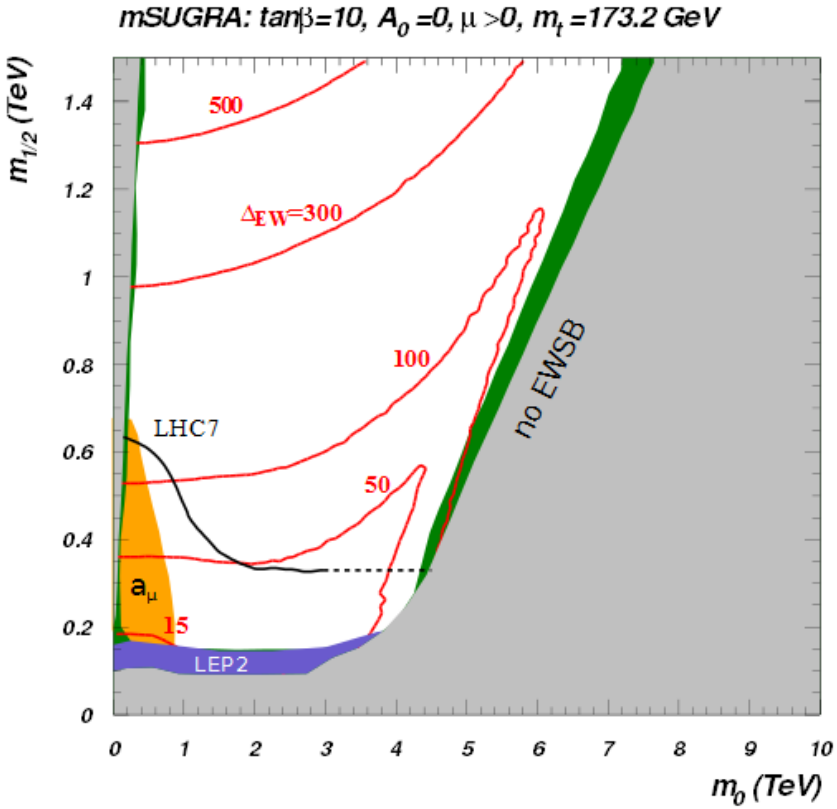


Dark Matter and Tuning

Requiring correct amount of DM from SUSY can introduce tuning

- Green region -> correct DM amount
- Correct DM -> restrictive parameter space!
- Red contours -> tuning measure
- Otherwise natural scenarios may not accommodate DM with just wimps

- Modified Dark sector changes whole story!

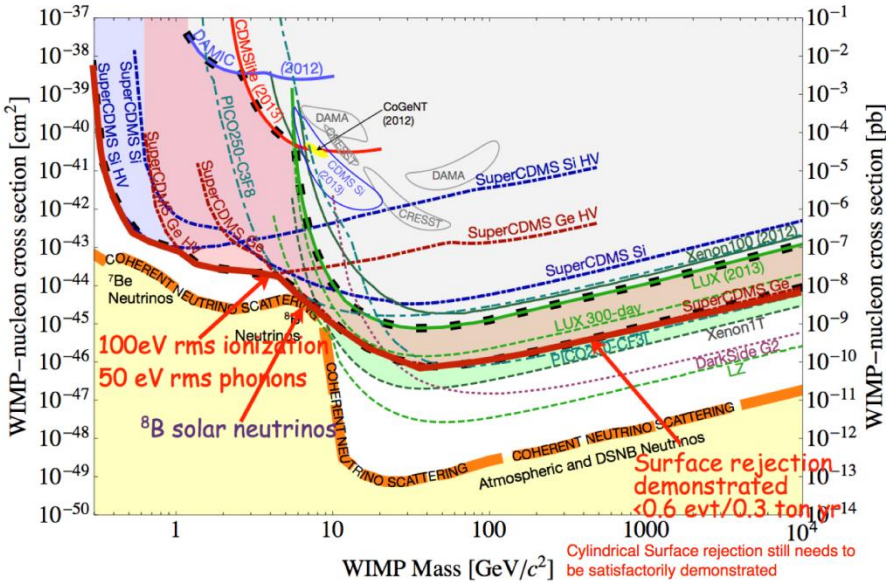


H.Baer et al, hep-ph/1210.3019

Don’t see DM yet either

Have searched for SUSY WIMPs in many ways, still possible, but parameter space closing

- Direct detection ->look for relics passing through earth (this plot)
- Indirect detection ->DM annihilation or decay
- Collider searches ->Most flexible, limited by imagination, analysis techniques
- Change dark sector -> change interpretation



- Wimps may not be the whole story even if SUSY plays a role in DM

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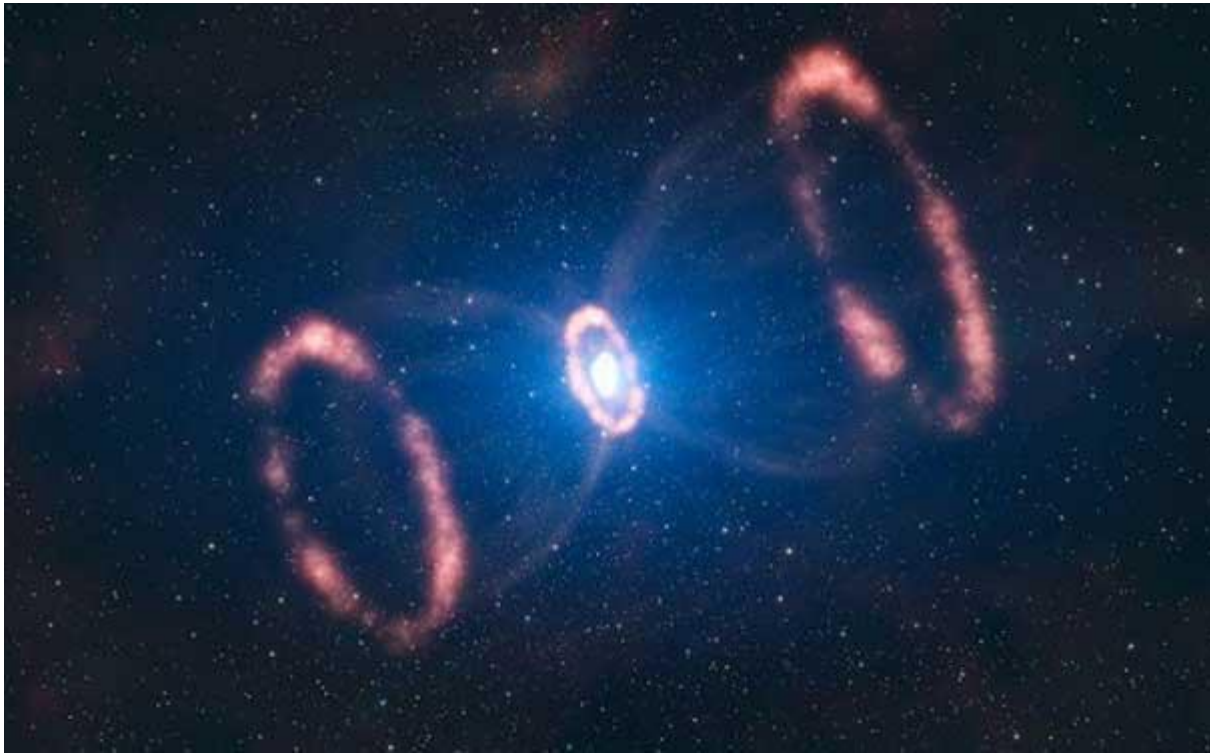


The Strong CP problem

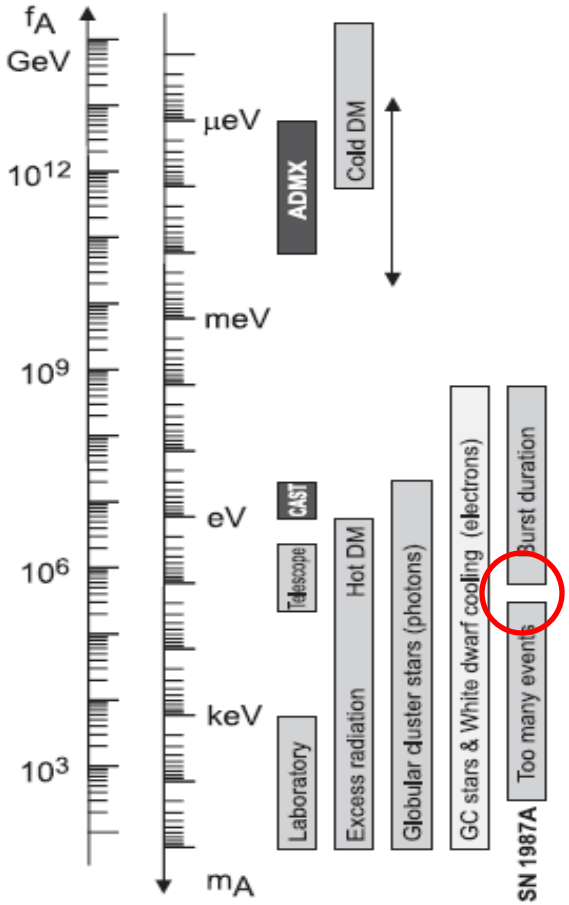
- CP violation in QCD: $L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$ with $\theta < 10^{-9}$ so looks like tuning
- Make SM lagrangian invariant under a new global $U(1)_{pq}$ by adding axion field and introducing new scale f_a

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

- $U(1)_{pq}$ is spontaneously broken and the axion is a (pseudo) goldstone boson
- $U(1)_{pq}$ allows shifts $a_{\text{phys}} = a - < a >$
- At the minimum of the axion potential $< a > = -\frac{f_a}{\xi} \bar{\theta}$, the theta term cancels
- Peccei Quinn scale (f_a) suppresses all interactions of the axion
- 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 constrain us



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

- Originally f_a guessed to be weak scale -> ruled out in lab
- Common wisdom -> $f_a > 10^9$ GeV
- Plot misleading -> constraints tests multiple couplings
- All couplings depend on f_a, but maybe also <u>model dependent</u> 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 as low as 3×10^5 GeV if only QCD coupling (only one needed to fix strong CP)
- Gap in constraints known as "hadronic axion window"
- Killing couplings means we lose many tests for axions . . .

PQ + MSSM = PQMSSM

Axions in SUSY are part of a super multiplet
with saxion and the axino

- Saxion -> scalar, even R-parity -> assume heavy and decouples
- Axino -> majorana fermion -> odd R-parity
- Total DM can be any combo of the three: axion, axino and neutralino
  -> depends on mass hierarchy and cosmology
- Solution to strong CP and evade constraints in DM searches
  -> natural scenario maybe more viable
- Axino mass -> model dependent -> 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
INFO: Trying process: c s > u s n1 ax WEIGHTED=6
INFO: Trying process: c s > c d n1 ax WEIGHTED=6
INFO: Trying process: c s > c s n1 ax WEIGHTED=6
INFO: Process has 8 diagrams
INFO: Crossed process found for c u~ > c u~ n1 ax, reuse diagrams.
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INFO: Process d c > c d n1 ax added to mirror process c d > c d n1 ax
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INFO: Process has 16 diagrams
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INFO: Process s d > d s n1 ax added to mirror process d s > d s n1 ax
INFO: Trying process: s s > d d n1 ax WEIGHTED=6
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Axinos at Colliders

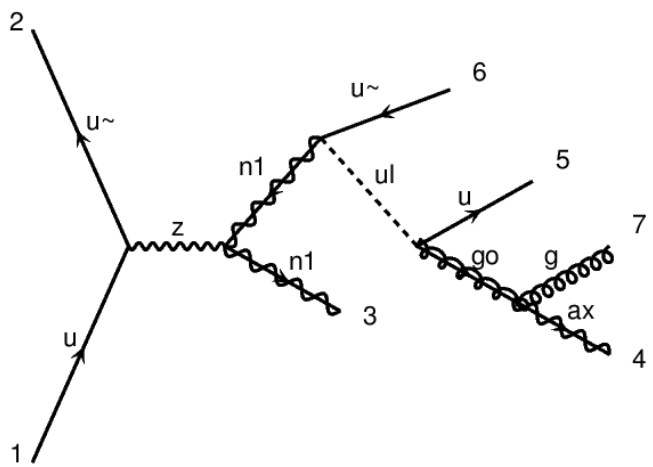
- Usually look for charged nlsp with slow decay to VERY weakly coupled axino (e.g Frank Daniel Steffen arXiv:hep-ph/0507003)
- Window of small PQ scale -> neutral nlsps with long decays to “hadronic axino”
- In window of stronger coupling we only have ONE type of interaction

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

- SUSY particles -> MUST decay to axinos and at least three jets because of R parity (branching fraction ~1)

- Production rate ->inclusive SUSY rate

  -> mess from the production well separated if decay is displaced enough

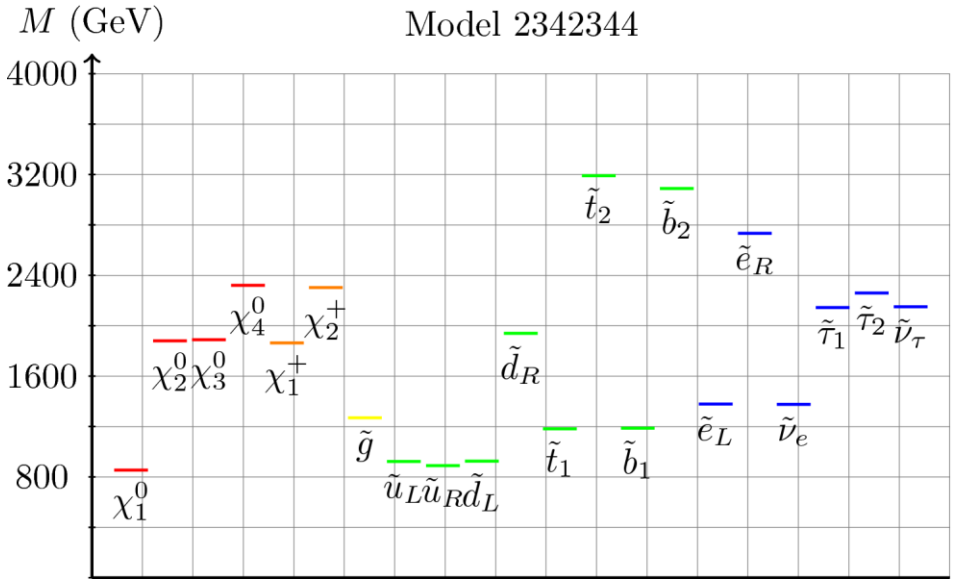


Benchmark model

"Bino Squark Co-annihilation" Scenario with a light axino

- Correct Higgs mass
- Evades current constraints
- Testable in next run of LHC
- No particular tricks or kinks

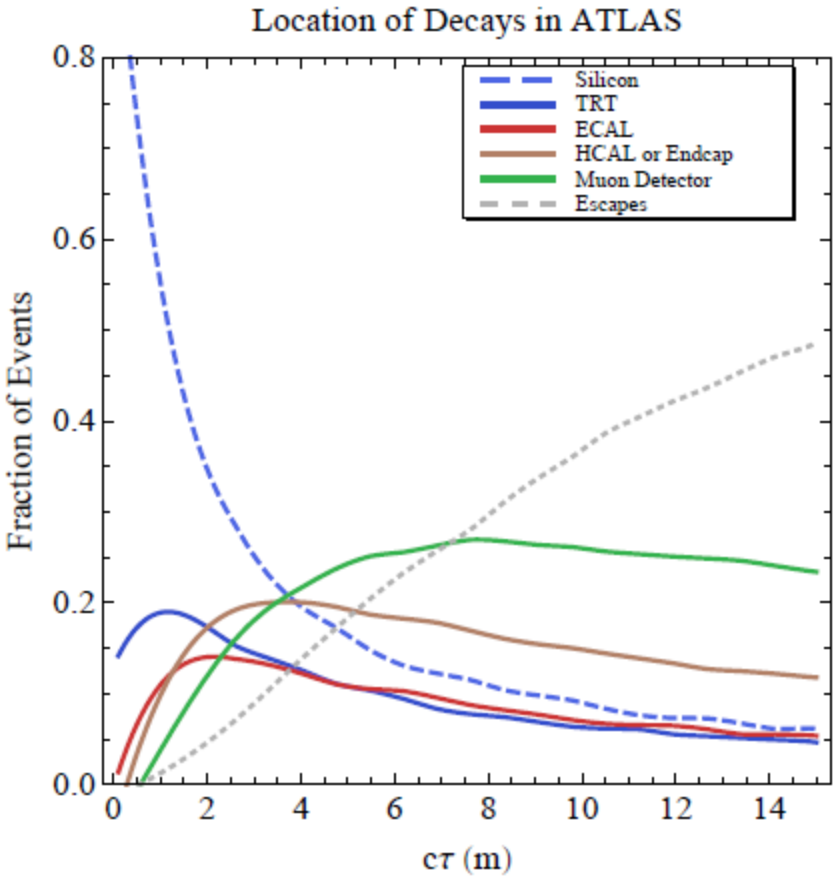
  -> not a "special" model
- Don't worry about relic abundance, Axino changes it anyway
- Benchmark not chosen for being particularly natural, but for being generic of what it is not yet excluded and still testable



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

Compressed Spectra

- Compressed SUSY-> usually hard to study
- Detector is the right size to study generic decay lengths in compressed scenarios with Axino
- Benchmark also has slopes of fixed Higgs mass -> look at varying compression and effect on signal
- If there's a hadronic axino, we may have more reach in compressed SUSY



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

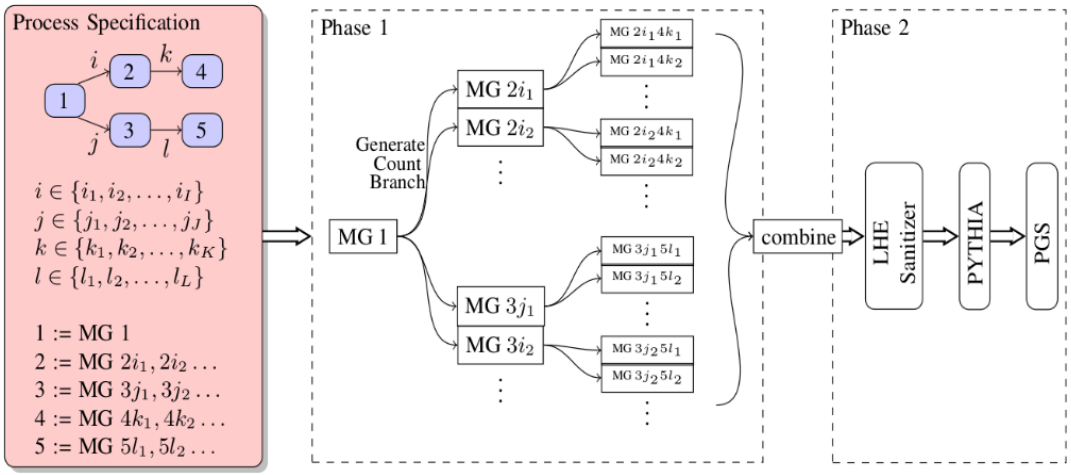
Tools

- SuSpect/SOFTSUSY -> mass spectra
- Feynrules -> implement model for MadGraph
- MadGraph (with evchain) -> cross sections and distributions
- Pythia -> showers/hadronization
- FastJet-> Clustering

- Analysis with a modified 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

evchain

- Long lived particles, narrow widths -> hard for MadEvent's montecarlo
- Our events are cascades at the end of cascades, smallest process we can consider is 2 to 8 for the full event
- evchain as a "MadGraph manager"-> combine event files for multiple MG runs and do necessary boosts



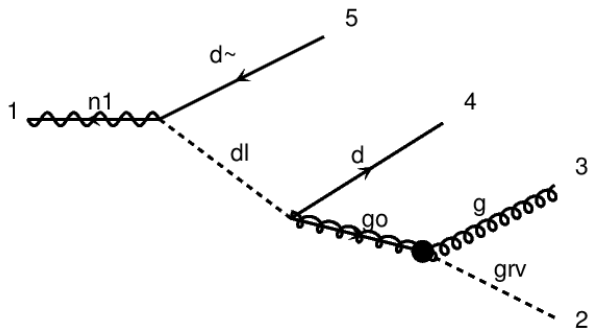
Ian Woo Kim and Kathryn M Zurek arXiv:1310.2617v1 [hep-ph]

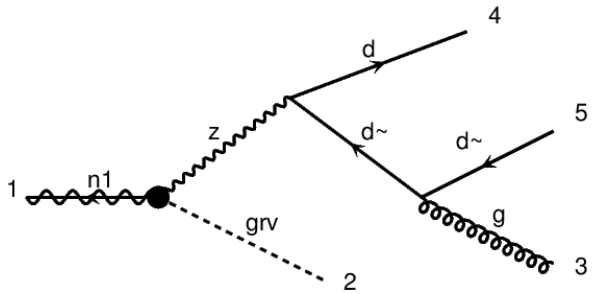
- Tool at https://github.com/hep-platform/evchain , but is still in development (author is very helpful)

Similar Models

Many models can predict multiple displaced jets:

- Hidden valley -> lots of possibilities
- RPV -> lots of possibilities -> distinguishable by MET?
- Gravitino -> 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





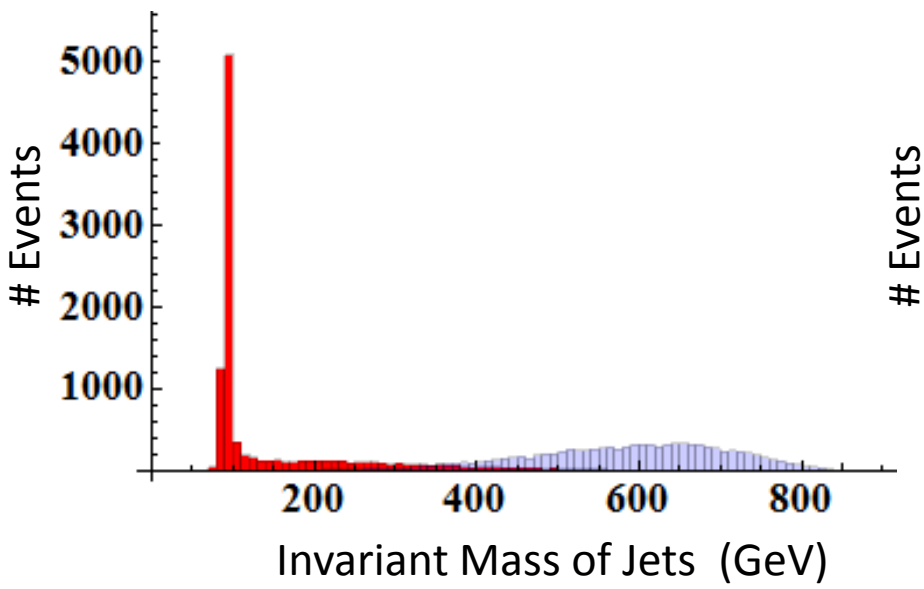
- Our signature is always produced at a higher rate because of branching fraction
- Neutralino decay to gravitino plus jets always has contribution from diagrams with a Z

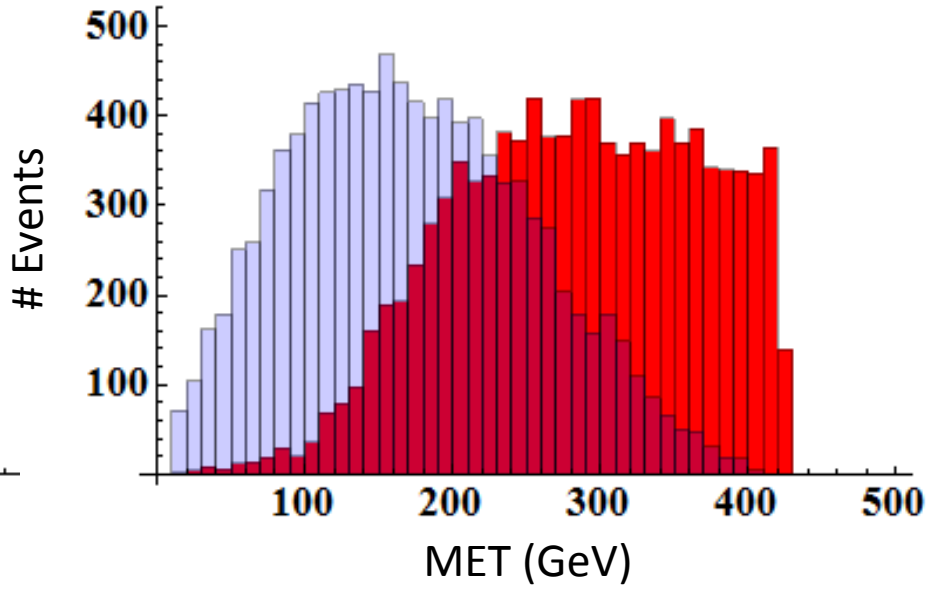
Neutralino Decays

- Gravitino signature can be distinguished because of the Z
- The differences in topology also means the MET is recoiling differently and can also be used to distinguish these two possibilities
- Plots are for 10 000 events produced in each model

Decays to Axinos in Blue

Decays to Gravitinos in Red



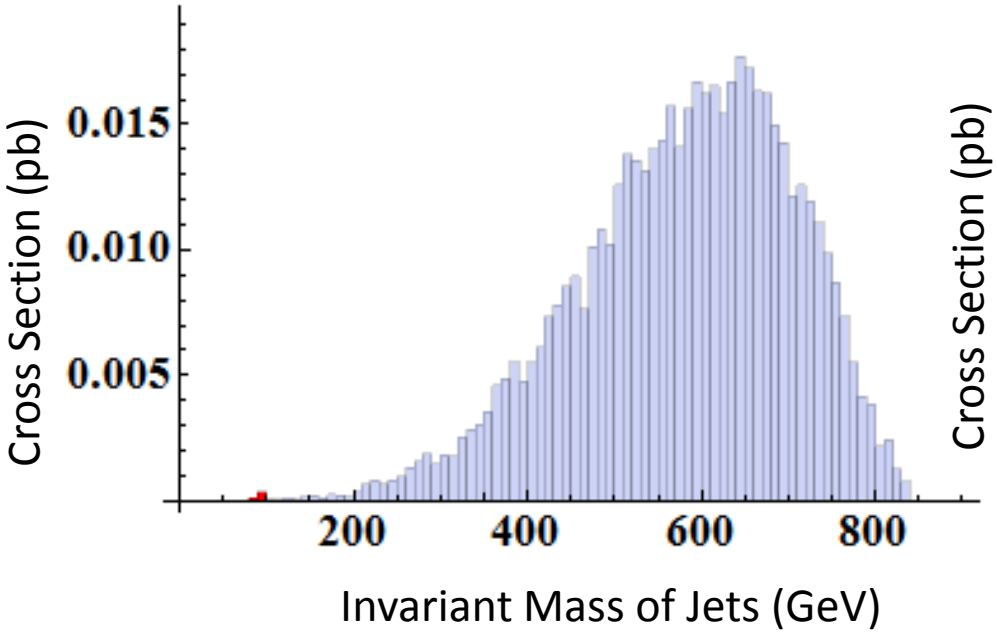


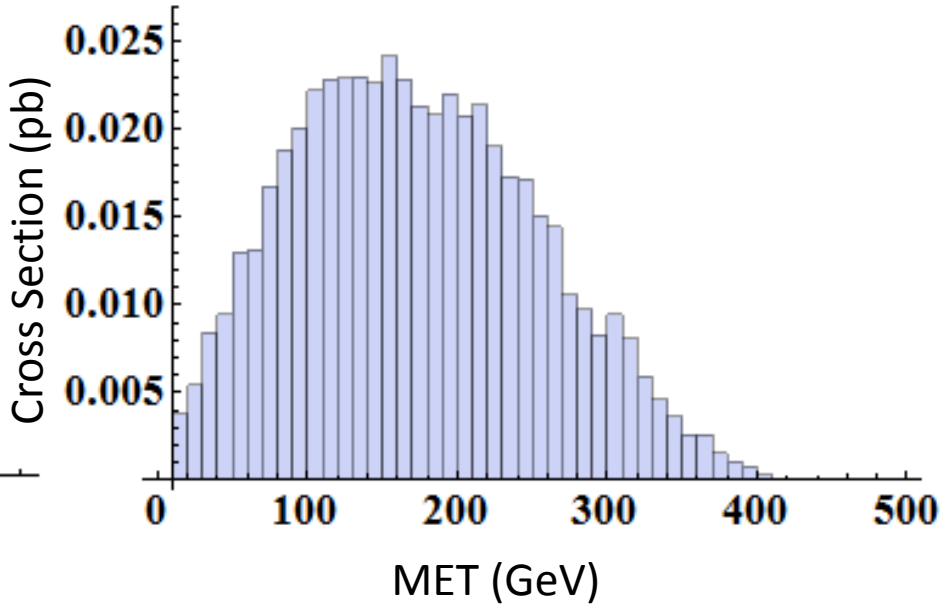
Neutralino Decays

- 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
- Large difference in branching ratio to jets between models
- For less "pointy" distributions we would not even see the red
- Other benchmarks may lessen difference, but Axino always higher BR to Jets





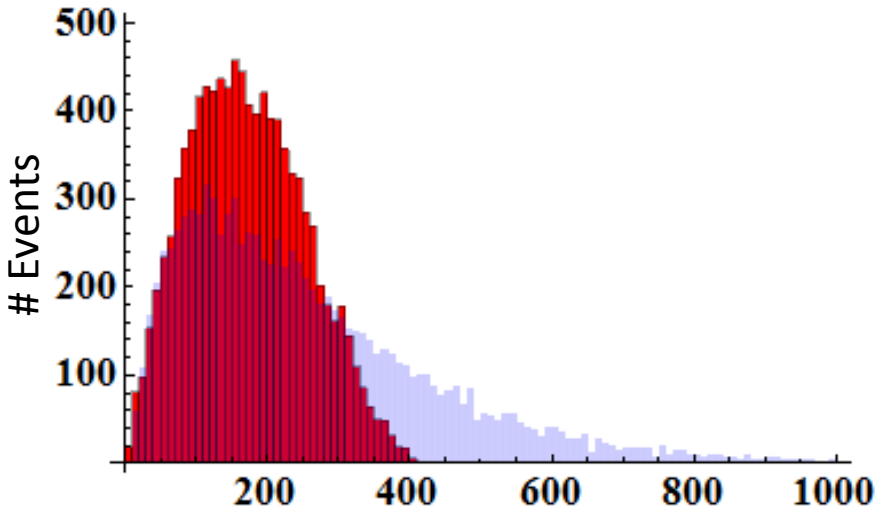
Boosted Events

- 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

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

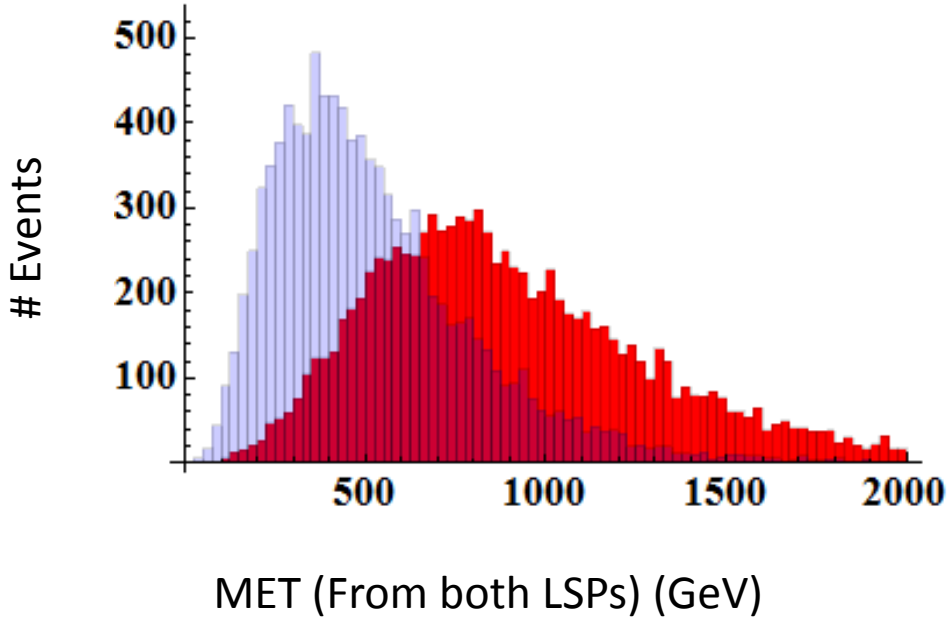
Full Axino Event in Blue

Decays to Axinos in Red



Full Axino Event in Blue

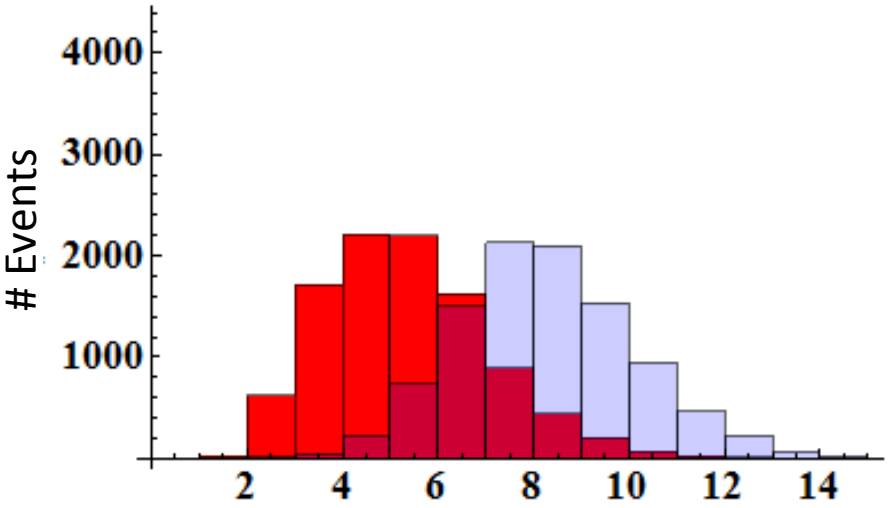
Full Gravitino Event in Red



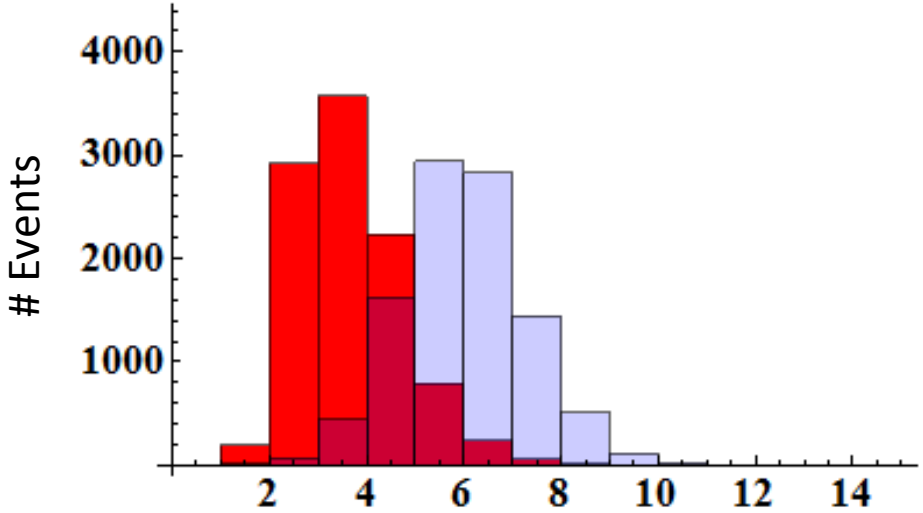
Showered/Clustered Events

- Number of jets noticeably different between models
- Softer jets thrown away (Pt< 40 GeV), eventually want to pass these events to detector simulation with triggers
- Jets at large angles (eta>2.5) thrown away also

Axino Model in Blue Gravitino Model in Red



Jets Before Cuts

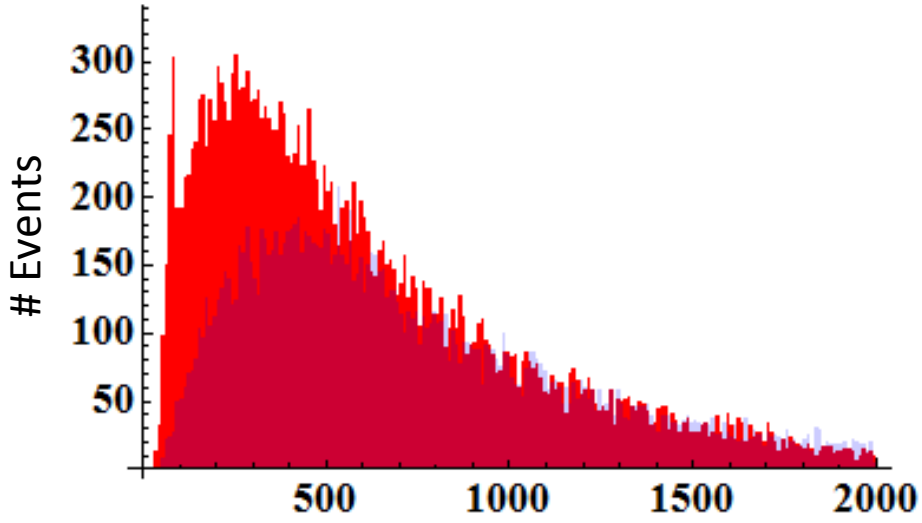


Jets After Cuts

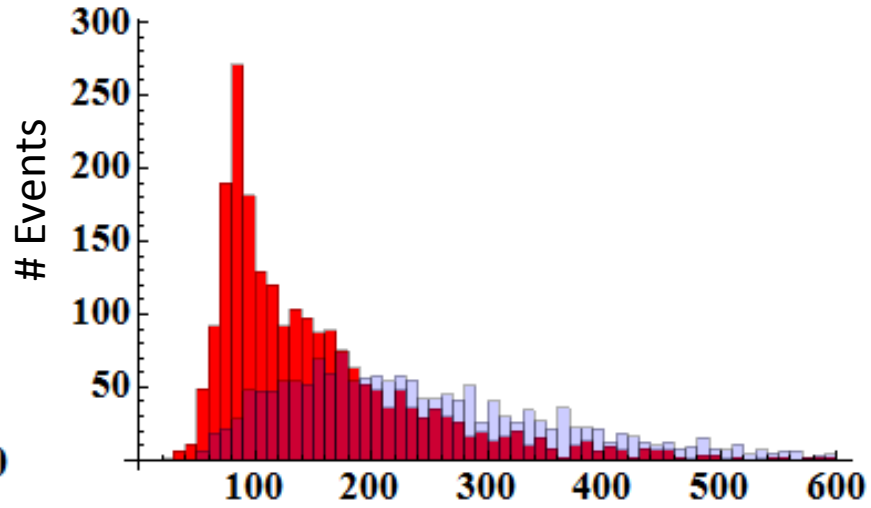
Finding the Z

- Harder to find Z in full event -> which jets to combine?
- Consider 4 jets only (largest # events to compare & small combinatorics)
- Can barely see Z with full combinatoric background
- Know which resonance were looking for-> take combinations that put us close
- Beware! Cherry picking jet combinations shapes background to look like signal

Axino Model in Blue Gravitino Model in Red



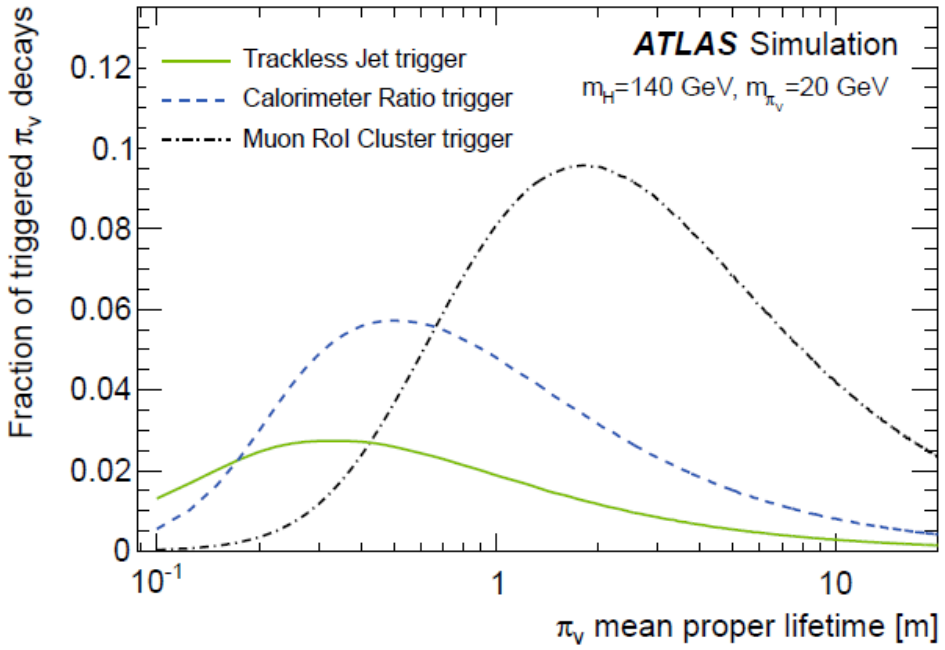
Jet Invariant mass (GeV)
(all combinations)



Jet Invariant Mass (GeV)
(select combinations)

What can we actually see?

- Triggers developed for hidden valley -> 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, compared to similar models
- Expected depth of the decays in the detector seems ideal for compressed spectra with a hadronic axino
- PGS requires modifications to work with our decays as produced by evchain
- Detector simulation with these triggers for our model is the next step



In a nutshell

- Why look for Axinos at a collider?

  -Maybe 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 MET and six jets

- How unique is this signal?

  -Distinguishable from gravitinos, but there are other possible scenarios

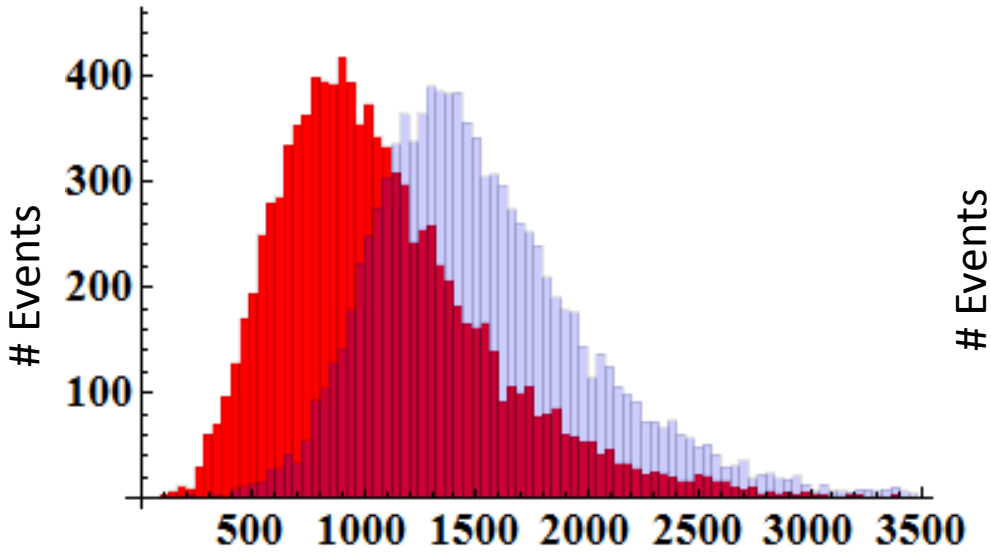
Questions?

Backup

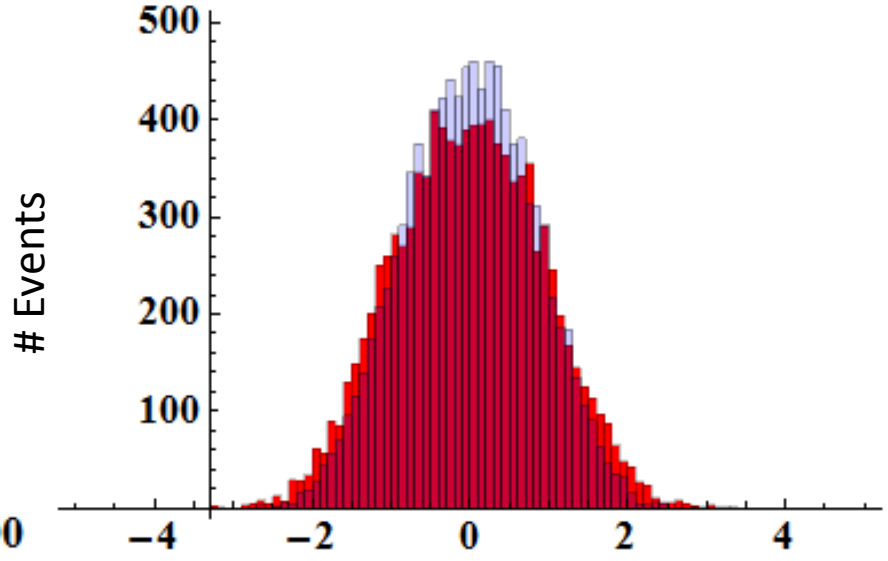
Other Observables

- More HT in Axino case
- Jets slightly more central in Axino case

Axino Model in Blue Gravitino Model in Red



Scalar Sum of Jet Pt



Eta of Leading Jet