Searching for the DFSZ Axino in Collider Experiments

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Motivation

The QCD Axion

- The QCD lagrangian contains a so-called θ term which violates CP symmetry:

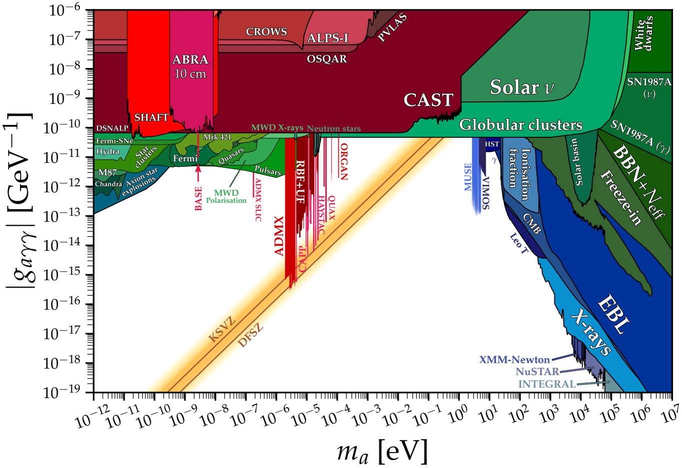
$$\mathcal{L}_{\text{QCD}} \supset \frac{\overline{\theta}}{64\pi^2} \varepsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

- This CP violation implies the existence of a neutron electric dipole moment, but the current experimental upper limit on the neutron EDM is $\sim 10^{-26}$ e cm.[1]
- The axion is a proposed solution to this issue in which a global $\mathrm{U}(1)$ symmetry is introduced. The field which breaks this symmetry obtains a VEV which cancels the θ term dynamically.

[1] C. Abel et al., "Measurement of the permanent electric dipole moment of the neutron", Physical Review Letters **124**, 081803 (2020).

Axion Coupling Limits

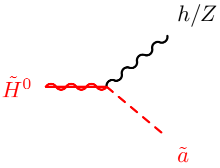
- Axion couplings are proportional to $\frac{1}{f_a}$ where f_a is the axion decay constant.
- f_a is constrained to be large by cosmological observations, and thus interactions between the QCD axion and standard model are too feeble to be seen at colliders.

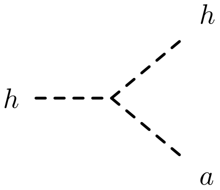


https://cajohare.github.io/AxionLimits/docs/ap.html

Why Search for the Axino at Colliders?

- The axino is the fermionic supersymmetric partner of the axion.
- Axinos can appear in the decays of heavier SUSY particles in the case where R-parity is conserved.[2]

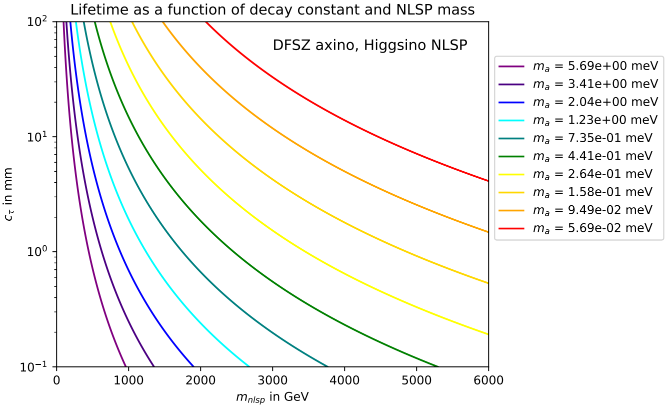




[2] C. Redino and D. Wackeroth, "Exploring the hadronic axion window via delayed neutralino decay to axinos at the LHC", Physical Review D **93**, 10.1103/physrevd.93.075022 (2016)

Axino-Axion Connection

- Axion **and** axino couplings depend on the axion decay constant f_a.
- The decays of heavier SUSY particles into axinos can be long lived with lifetimes depending on f_a producing a displaced vertex.



$$c\tau = (8.99\ \mathrm{mm})\left(\frac{f_a}{10^{10}\ \mathrm{GeV}}\right)^2\left(\frac{1\ \mathrm{TeV}}{m_{\mathrm{nlsp}}}\right)^3 \qquad m_a = (5.691\ \mathrm{meV})\left(\frac{10^9}{f_a}\right)$$

The Supersymmetric DFSZ Axion Model

- The supersymmetric DFSZ axion model introduces the following Kim-Nilles term to the superpotential:

$$W \supset \frac{2\mu}{f_a^2 N_{\mathrm{DW}}^2} P^2 H_u H_d$$

- Where P is the Peccei-Quinn (PQ) symmetry breaking field, μ is the Higgs mass parameter, f_a is the axion decay constant, and N_{DW} is the axion domain wall number.
- Expanding $P = \frac{N_{\mathrm{DW}} f_a}{\sqrt{2}} + A$, we obtain the following:

$$W \supset \mu H_u H_d + \frac{\sqrt{2}N}{N_{\mathrm{DW}}} \frac{\mu}{f_a} A H_u H_d$$

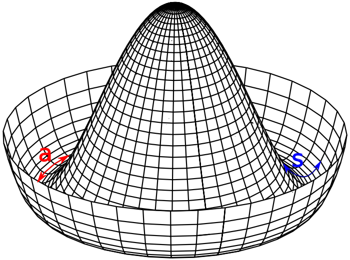
  Where N is the QCD anomaly
- This can generate the Higgs μ term at EW scale solving the μ problem.[3]

[3] G. Barenboim et al., "Implications of an axino LSP for naturalness", Physical Review D **90**, 10.1103/physrevd.90.035020 (2014)

Axion Superfield

- A is a chiral superfield containing the axion, saxion, and axino (and auxiliary field F_A):

$$A = \frac{1}{\sqrt{2}}(s + ia) + \sqrt{2}\tilde{a}\theta + F_A\theta\theta$$

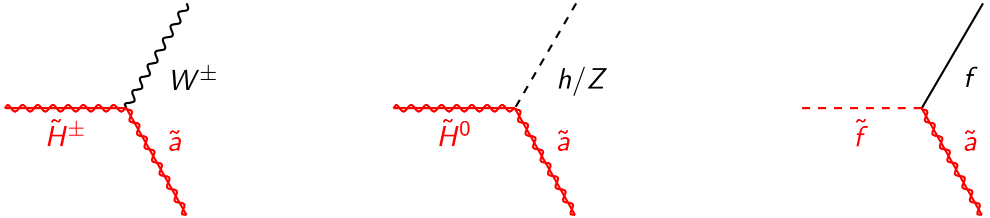


- The axion and saxion correspond to the different degrees of freedom of the complex scalar field. The saxion, like the axion is R-parity even, so it may be more challenging to see in colliders.

image modified from `https://commons.wikimedia.org/wiki/File:Mexican_hat_potential_polar.svg`

DFSZ Axino Couplings

- The superpotential induces couplings with the Higgs sector.
- The higgses and particles which couple to the higgs like fermions then carry a charge associated with the global $\mathrm{U}(1)$ Peccei-Quinn symmetry.
- Through mixing between the neutralinos and charginos, we additionally get effective couplings to the Z boson, W boson, and fermions.



Monte-Carlo Model Implementation

Axino Model Superpotential and Lagrangian

- FeynRules[4] and SARAH[5] were used for model implementation. The resulting UFO could then be used to generate Monte Carlo events with MadGraph.[6]
- We add a term to the superpotential for the MSSM FeynRules and SARAH models:

$$W_{\text{axion}} = \frac{\sqrt{2}\mu}{3f_a} A H_u H_d \rightarrow \mathcal{L}_{\tilde{a}} = -\frac{\sqrt{2}\mu}{3f_a}\left(\tilde{a}\tilde{H}_u H_d + \tilde{a} H_u \tilde{H}_d\right)$$

- We use $f_a \propto \frac{1}{m_a}$ to write the axion decay constant in terms of the axion mass, m_a.

[4] A. Alloul et al., "Feynrules 2.0—a complete toolbox for tree-level phenomenology", Computer Physics Communications **185**, 2250–2300 (2014)

[5] F. Staub, "Sarah 4: a tool for (not only susy) model builders", Computer Physics Communications **185**, 1773–1790 (2014)

[6] J. Alwall et al., "Computing decay rates for new physics theories with feynrules and madgraph 5_amc@ nlo", Computer Physics Communications **197**, 312–323 (2015)

Axino-Neutralino Mixing Matrix

- As an initial test, we are considering a model where the lightest supersymmetric particle is mostly axino and the next to lightest supersymmetric particle is mostly higgsino.
- The mixing between the neutralino mass basis and the gauge basis is given by a 5×5 matrix which now includes the axino mixings:

$$\begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \end{pmatrix} = \begin{pmatrix} N_{11} & N_{12} & N_{13} & N_{14} & N_{15} \\ N_{21} & N_{22} & N_{23} & N_{24} & N_{25} \\ N_{31} & N_{32} & N_{33} & N_{34} & N_{35} \\ N_{41} & N_{42} & N_{43} & N_{44} & N_{45} \\ N_{51} & N_{52} & N_{53} & N_{54} & N_{55} \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_u^0 \\ \tilde{H}_d^0 \\ \tilde{a} \end{pmatrix}$$

Perturbative Diagonalization of the Neutralino Mass Matrix

- In the limit where the mixing between the axino and other neutralinos is small and where the axino mixes only with the higgsinos, we can perturbatively diagonalize the neutralino mixing matrix.
- The neutralino mass matrix can be approximately diagonalized by:

$$\hat{M} = UMU^T \approx \mathrm{diag}(M_1, M_2, \mu, -\mu, m_{\tilde{a}})$$

- The off-diagonal entries can then be treated as perturbations. The first order correction to the off-diagonal entries in nondegenrate perturbation theory[7]:

$$V^{(1)}_{nm} = \frac{\hat{M}_{mn}}{M_{mm} - M_{nn}}$$

- Where $N = VU$ is the full mixing and the diagonalized mass matrix is given by:

$$M_D = NMN^T$$

[7] K. J. Bae et al., "Cosmology of the dfsz axino", JCAP **2012**, 013 (2012)

Approximate Mixing Matrix with First Order Correction

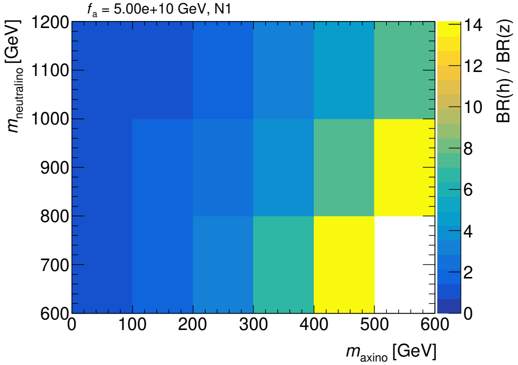
$$N = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{y_a v(-\cos(\beta)+\sin(\beta))}{2(m_{\tilde{a}}+\mu)} \\ 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & -\frac{y_a v(\cos(\beta)+\sin(\beta))}{2(m_{\tilde{a}}-\mu)} \\ 0 & 0 & \frac{y_a v(\mu\cos(\beta)+m_{\tilde{a}}\sin(\beta))}{\sqrt{2}(m_{\tilde{a}}^2-\mu^2)} & \frac{y_a v(m_{\tilde{a}}\cos(\beta)+\mu\sin(\beta))}{\sqrt{2}(m_{\tilde{a}}^2-\mu^2)} & 1 \end{pmatrix}$$

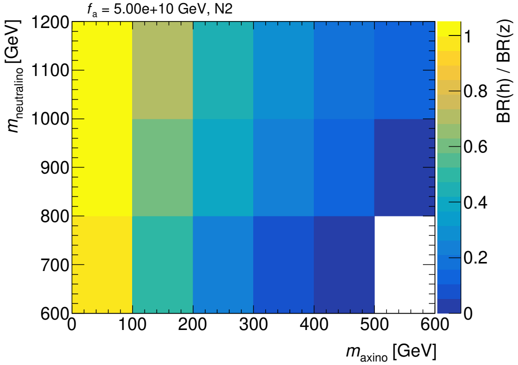
- Where $y_a = \frac{\sqrt{2}\mu}{3f_a}$ and v is the electroweak VEV.

Validation

h/Z Branching Ratio $f_a \sim 10^{10}$

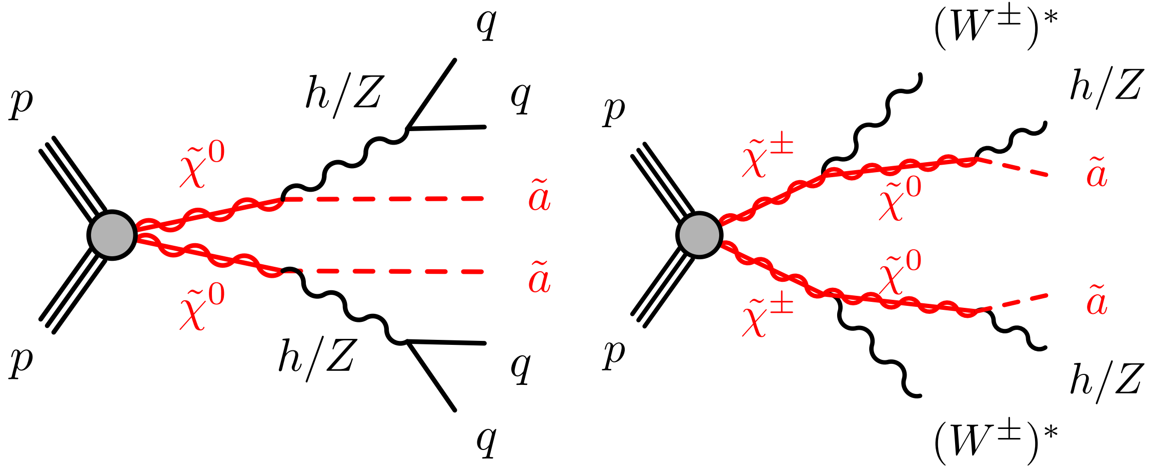
- Calculations done in MadWidth
- As expected, in the limit of large $\tan(\beta)$ and small axino mass, the branching ratio is about even. The coupling to the Z becomes more dominant for one of the mostly-higgsino states (left) and the coupling to higgs becomes more dominant for the other mostly higgsino state (right).





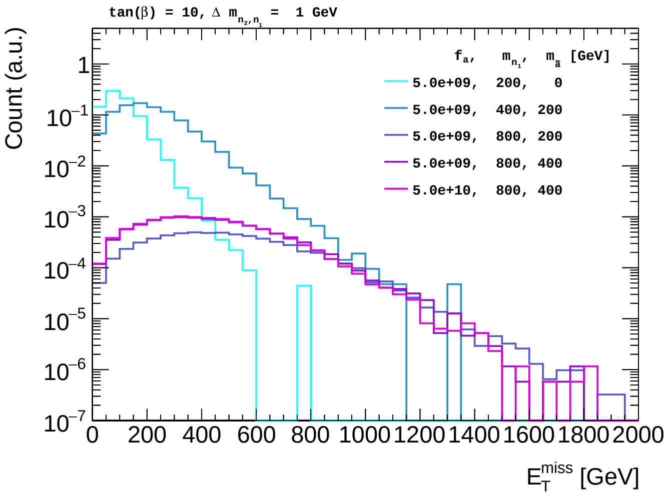
Event Generation Results

Some Processes Which May Be Observable



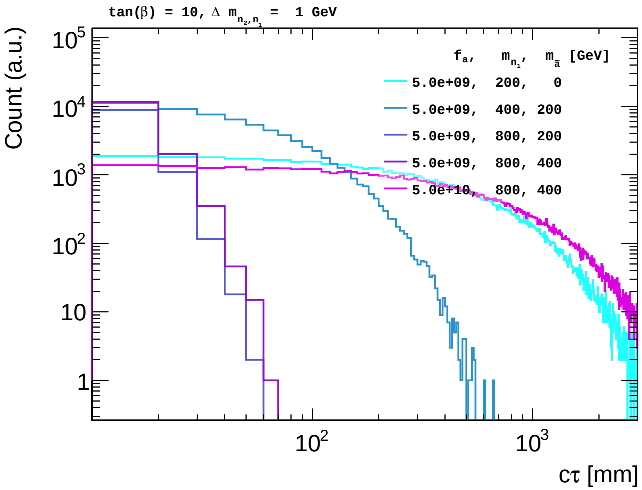
Missing Transverse Energy

- The missing transverse energy is primarily sensitive to axino mass.
- Makes sense because the invisible axino is what leads to most of the missing energy signature.



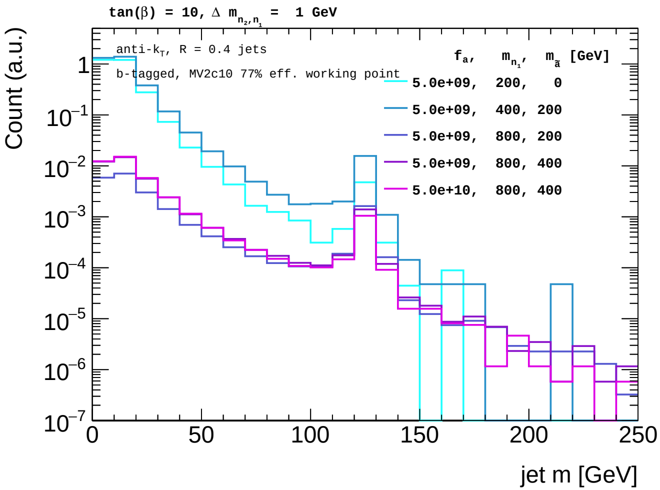
Decay Lifetime

- Mostly higgsino decays to a mostly axino state can be long-lived and may lead to observable displaced vertex signals in collider experiments for a wide range of axino and NLSP masses.



Large-R Jets Mass

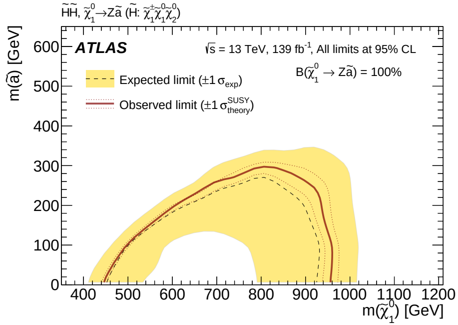
- Note the peak at the Higgs mass
- This indicates a boosted Higgs which is yet another useful signature of these processes which is good to identify.



Conclusions

Outlook for an Axino Search at Colliders

- An all-hadronic final state EWKino search was conducted by ATLAS and used prompt decays to look for axinos.
- We aim to consider more explicit axion/axino models (DFSZ and KSVZ) so that we might place model-dependent limits on f_a.



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-41/fig_17a.pdf

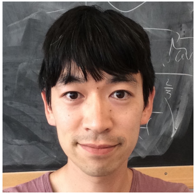
What's Next?

- Implement a spectrum generator using SPheno interfaced with our SARAH model
- Consider NLSP choices other than higgsinos
- R-parity violating case
- Implement an MSSM + KSVZ axion/axino model
- Full-fledged axino model in FeynRules and SARAH to be released to the community

Thanks!

Axion/Axino Analysis Team at the Univeristy of Chicago

David Miller



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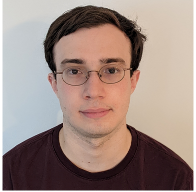

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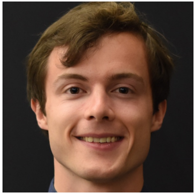

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