Searches for Multiple Species of Dark Matter at the LHC

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Outline

- SUSY
- Dark Matter
- Axions/Axinos
- Work in Progress

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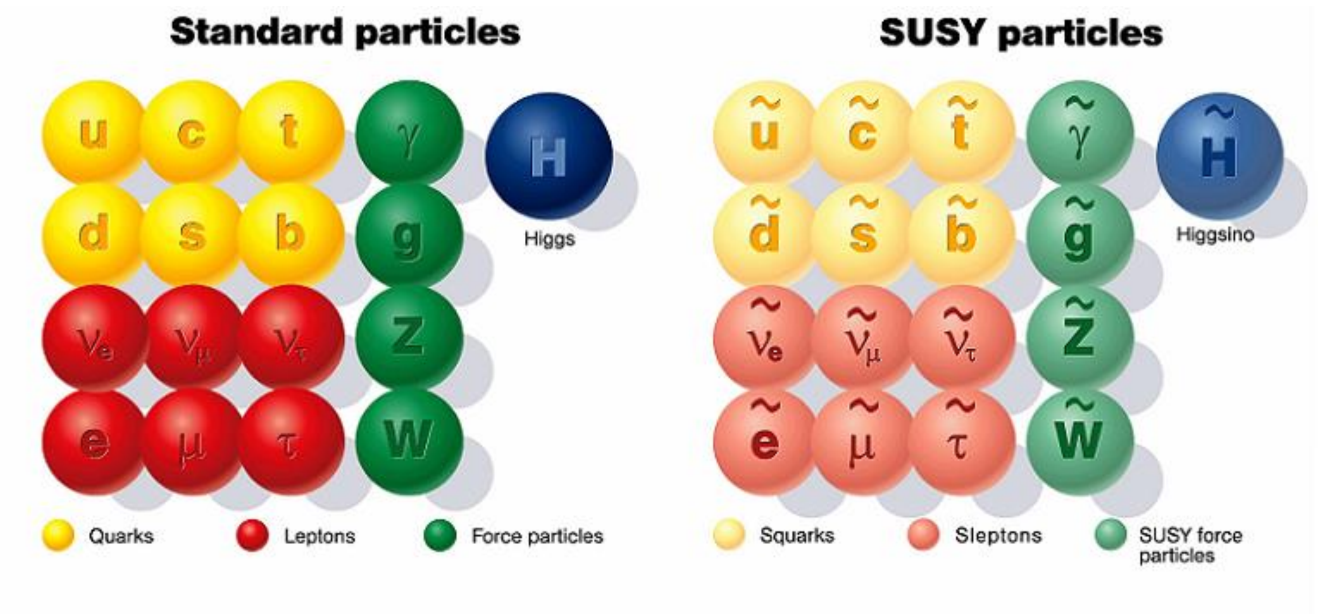
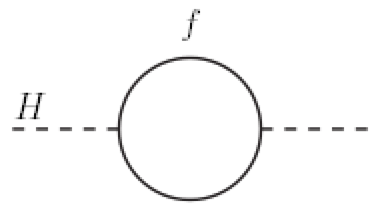


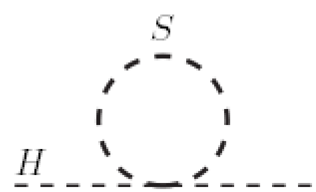
Motivation for SUSY

SUSY can 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



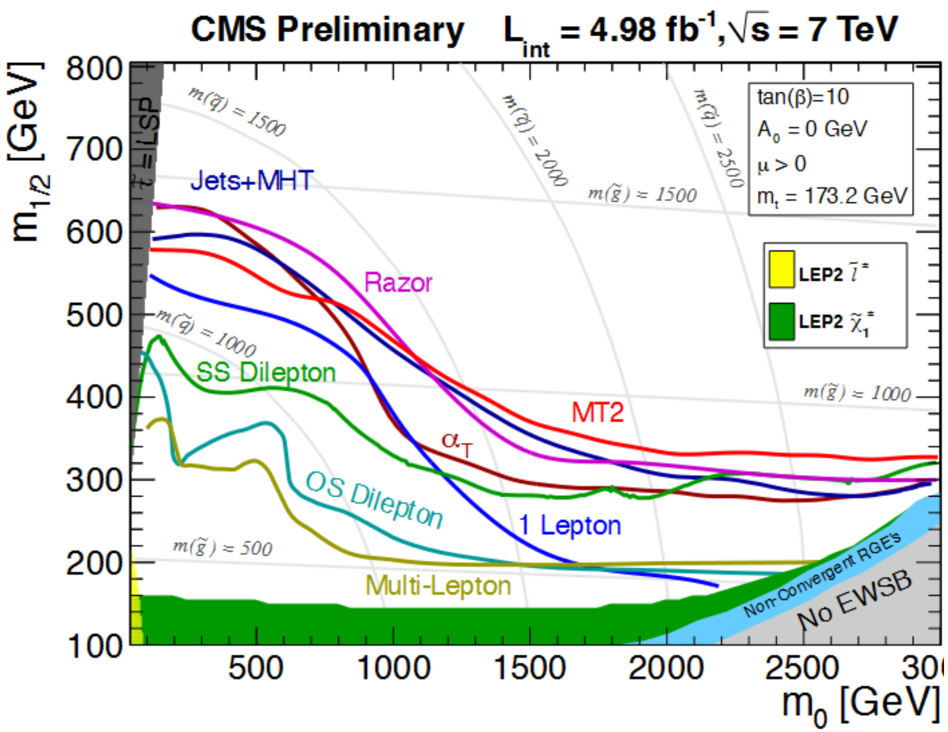
$$\delta M_H^2 = +2\frac{|\lambda_f|^2}{16\pi^2}\Lambda^2 + \ldots$$

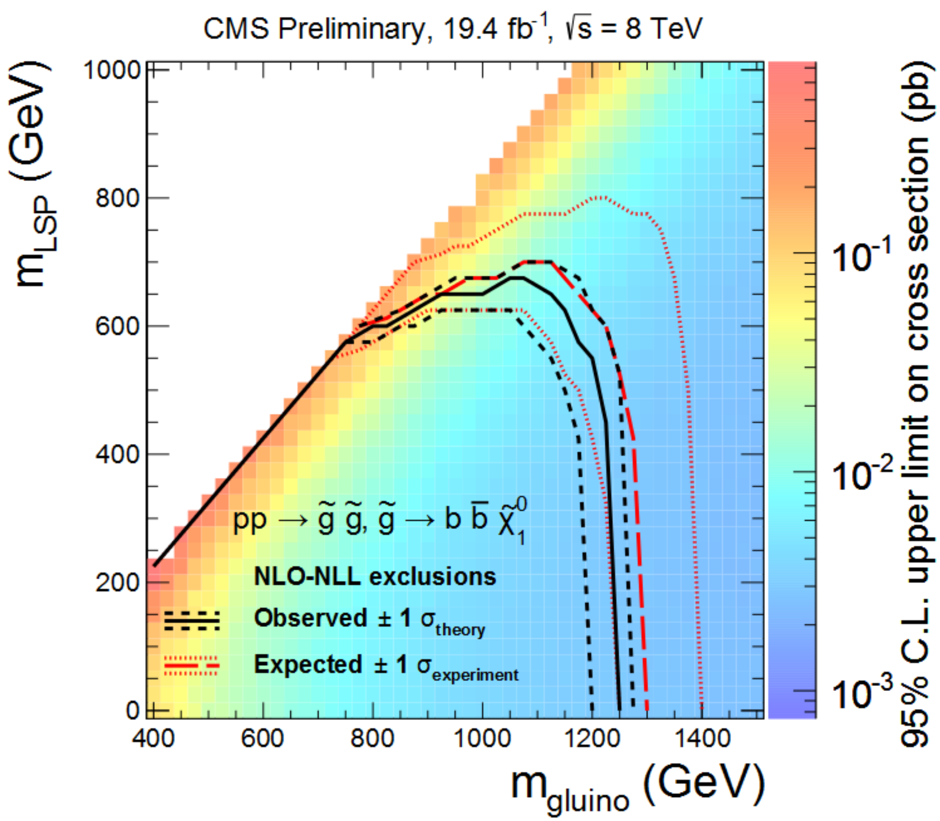


$$\delta M_H^2 = -2\frac{\lambda_{\tilde{f}}}{16\pi^2}\Lambda^2 + \ldots$$

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

SUSY is getting heavy. . .

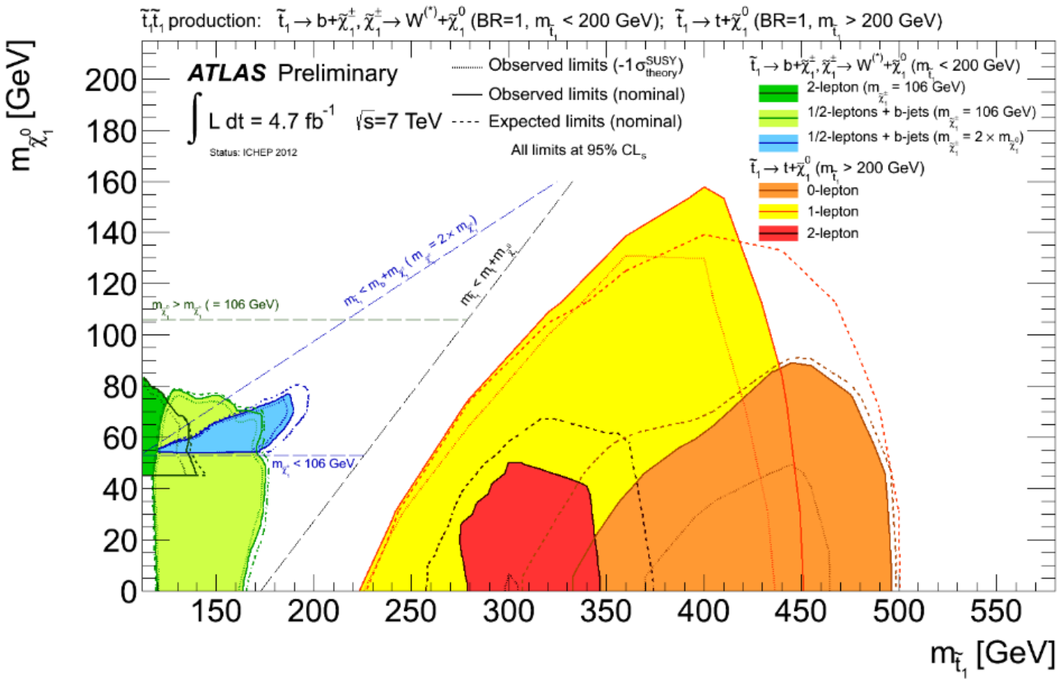




Hope for Naturalness?

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

- The stop is the most important, 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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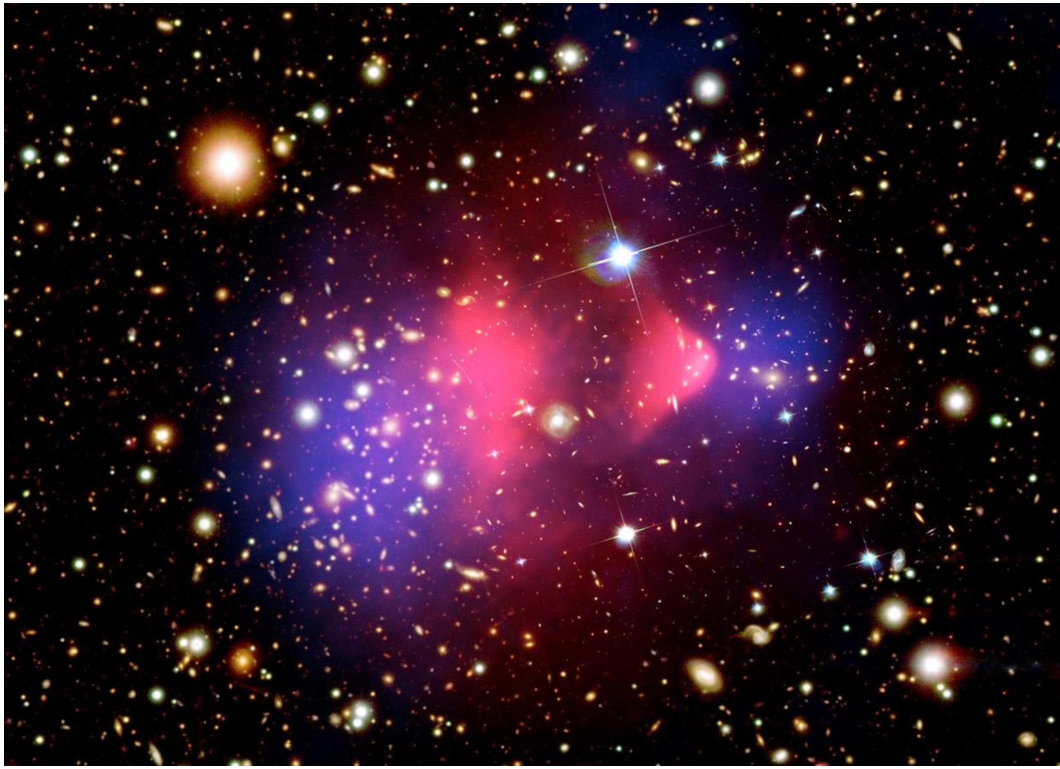
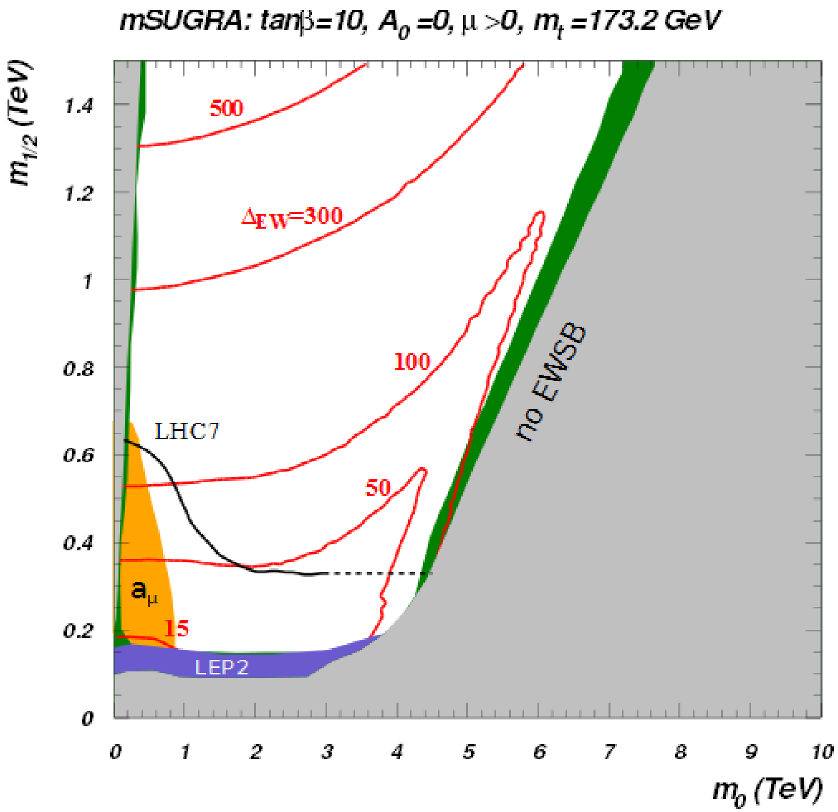


Dark Matter and Tuning

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

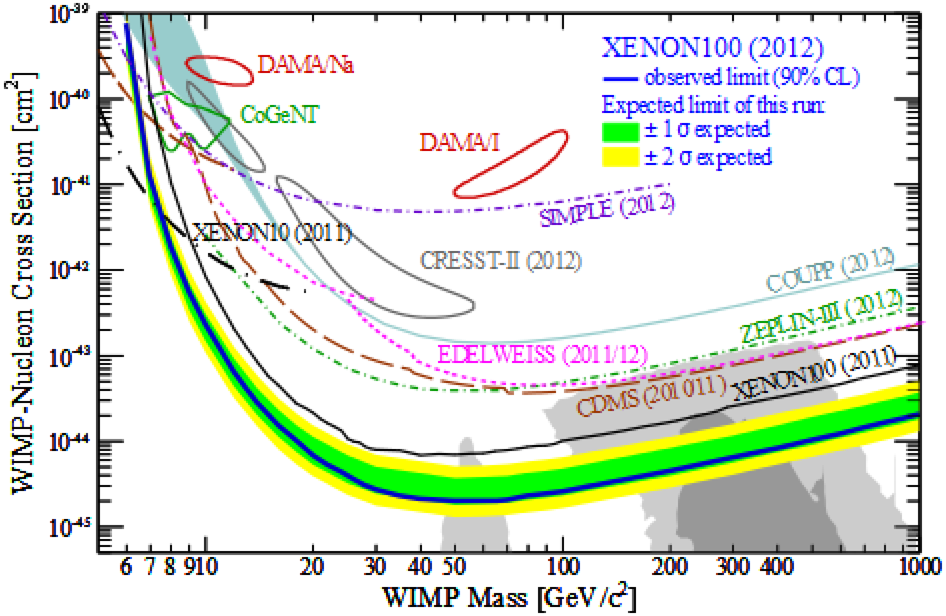


H.Baer et al, hep-ph/1210.3019

Multiple Dark Matters

Models with multiple Dark Matters are introduced for various reasons

- Possible signals in different experiments can be made consistent
- Limits from current experiments must be reinterpreted
- Allows more SUSY scenarios to be viable, including those with low tuning
- No strong reason why there should be only one type of dark matter particle
- Models are not difficult to make, but come at cost of more difficult phenomenology



Lavina, hep-ex/1103.5413

Examples of Multiple Dark Matters

Any extension of the standard model with a stable dark matter candidate can have two (or more) such candidates when there is a super symmetry. In addition to the usual neutralino we have:

- Axions + axinos
- Right handed neutrinos and right handed sneutrinos
- Gravitinos
- Various others

- See Dienes and Thomas, hep-ph/1107.0721 for a unique example (non SUSY) and a good list of references

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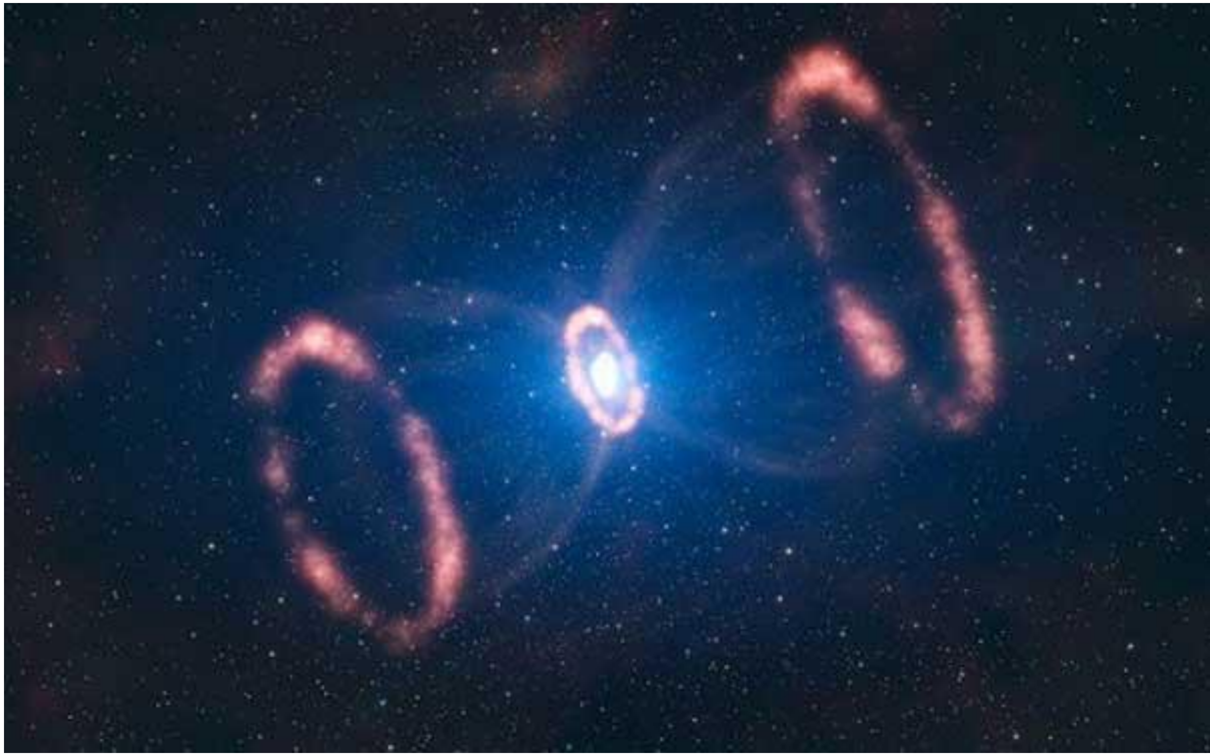


The Strong CP problem

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

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

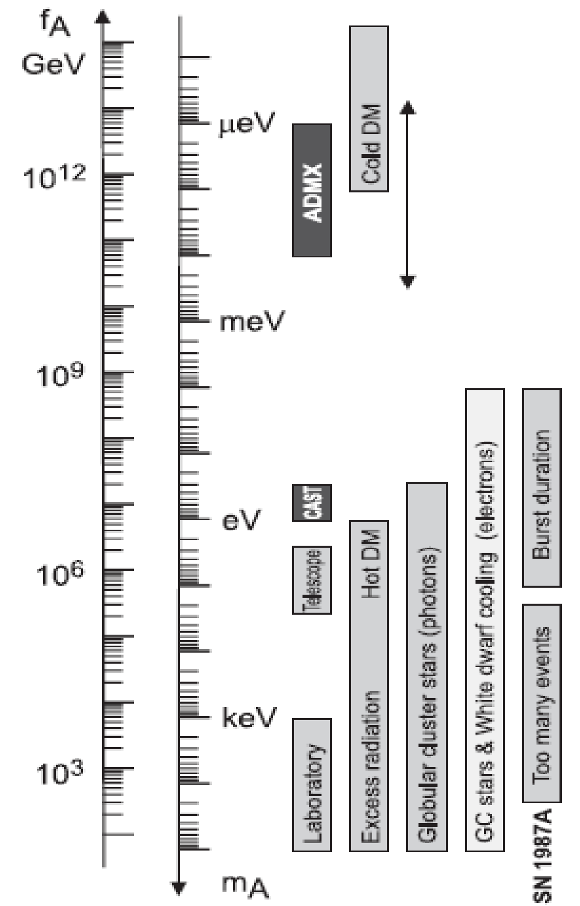
- $U(1)_{pq}$ is spontaneously broken, and the axion is a (pseudo) goldstone boson
- $U(1)_{pq}$ allows shifts $a_{\text{phys}} = a - < a >$
- At the minimum of the axion potential $< a > = -\frac{f_a}{\xi}\bar{\theta}$, the theta term cancels
- See Peccei, hep-ph/0607268 for a review

Constraining the Axion

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

- 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

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



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

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

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

- 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, helps with little hierarchy in SUSY, and makes satisfying constraints easier, maybe other benefits . . .
- Models may be too good at evading direct and indirect bounds . . .
- See Baer et al, hep-ph/1103.5413

Collider Searches for Multiple Dark Matters

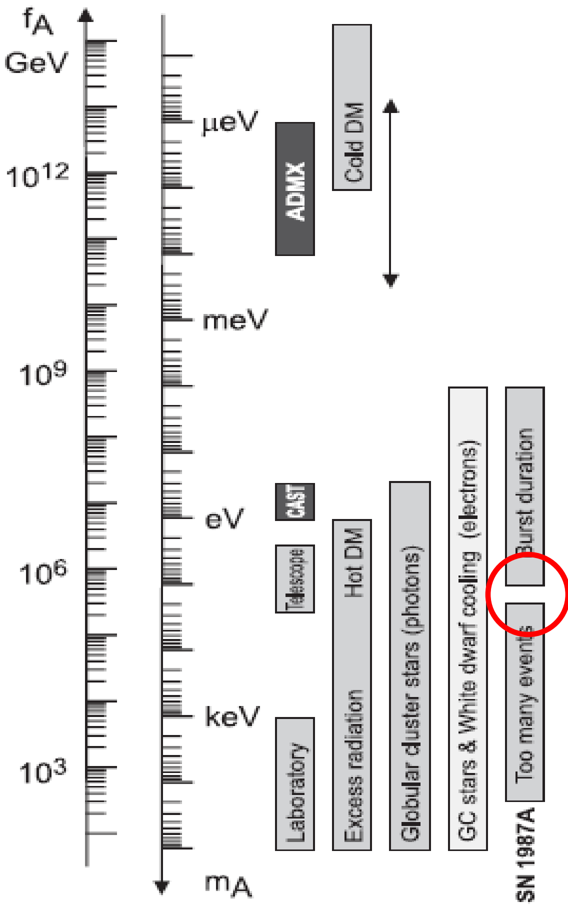
Want to find evidence of neutralino AND the axino to support models like this

- Precedent axino collider signal in literature usually requires VERY weak coupling and a charged nlsp, in which axion and axino are DM, but not neutralino
- Here we want to explore scenarios where axino and neutralino are both produced
- Requires axino mass small enough to be produced, but large enough that it can be the nlsp (models are flexible here)
- Requires the coupling to not be too small, this is trickier . . .

The Hadronic Axion Window

How do we produce an axino with such a small coupling?

- Constraints are on various model dependent couplings
- Can have models where electron and photon couplings vanish, making many of these constraints irrelevant
- Supernova constraints are harder to avoid, directly probe gluon coupling which is generic to QCD axions
- PQ scale could be as low as $3\text{x}10^5$ GeV
- Killing the other couplings means we lose many of our tests for axions . . .



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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
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INFO: Process has 8 diagrams
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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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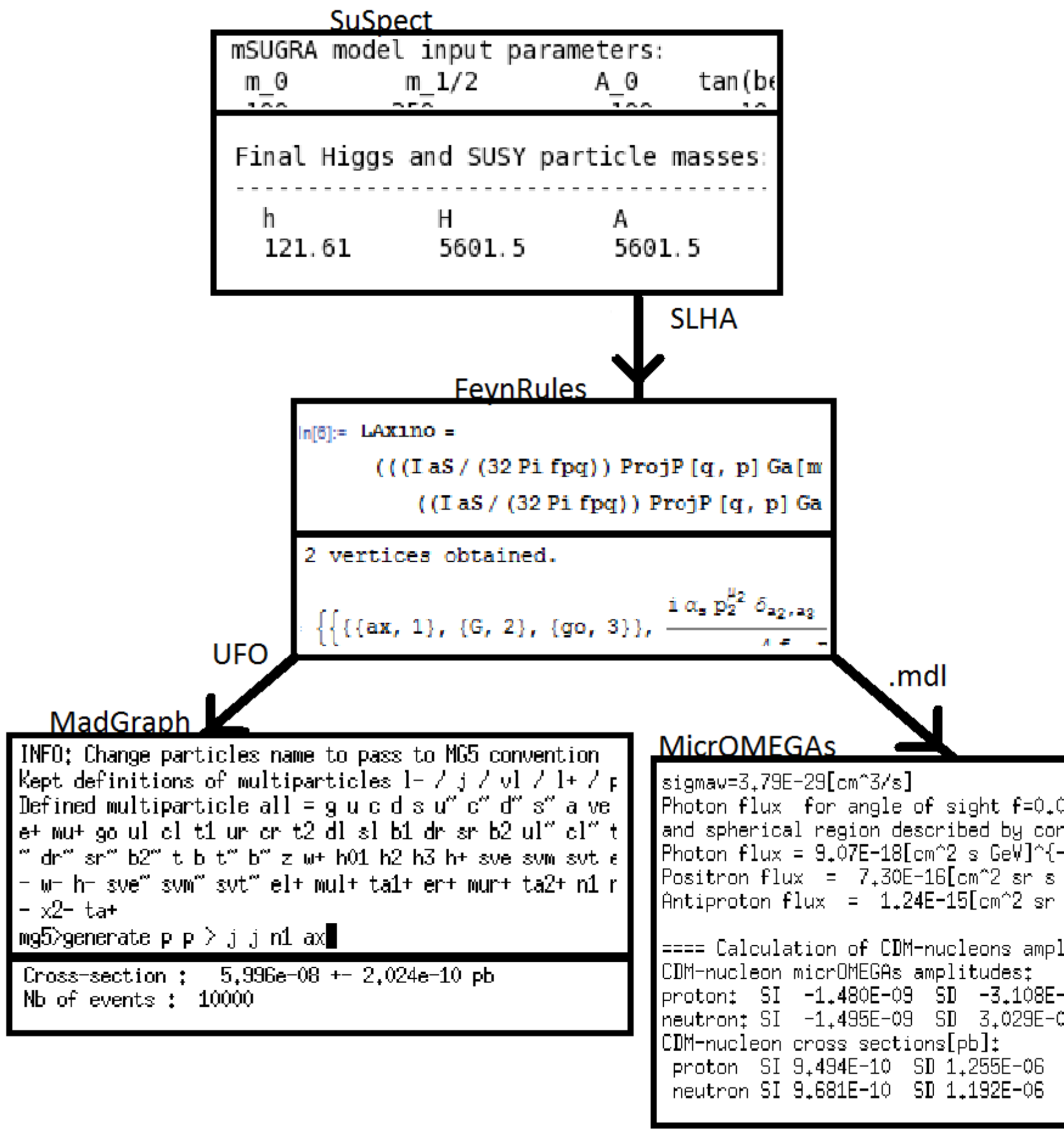
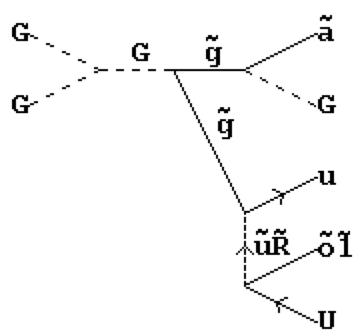
Tools for the Study

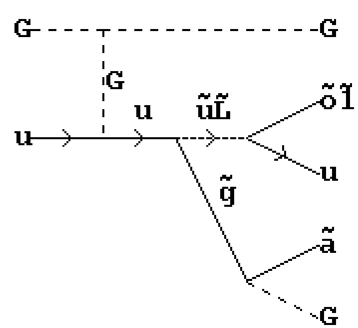
- SuSpect for mass spectrum calculation, outputs SLHA
- Feynrules for generating Feynman rules/ model files for Monte Carlo, outputs in various formats (previously LanHEP)
- MadGraph for calculation of cross sections and distributions (previously CalcHEP)
- MicrOMEGAs for calculation of relic density, direct and indirect detection rates

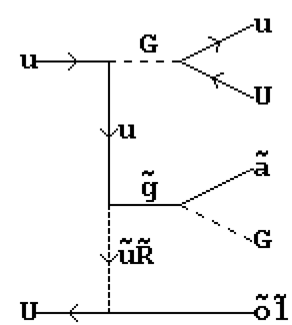


Axino Search Channels

- Consequence of bringing the PQ scale down is that we kill most of the couplings, but we are guaranteed the coupling with gluino and gluon
- With the smallest unconstrained PQ scale (10^5 GeV) the best preliminary results obtained is ~0.48 attobarns in the 3 jet channel, but we hope to do better in other channels
- Attobarn scale physics should be visible at the High Luminosity LHC (HL-LHC) with a proposed 3000 fb^{-1} collected in 10 years.
- Collider tests of lower PQ scales (10^4 GeV) to verify super nova data become much easier, and would still be one of very few probes into this range of hadronic axion coupling

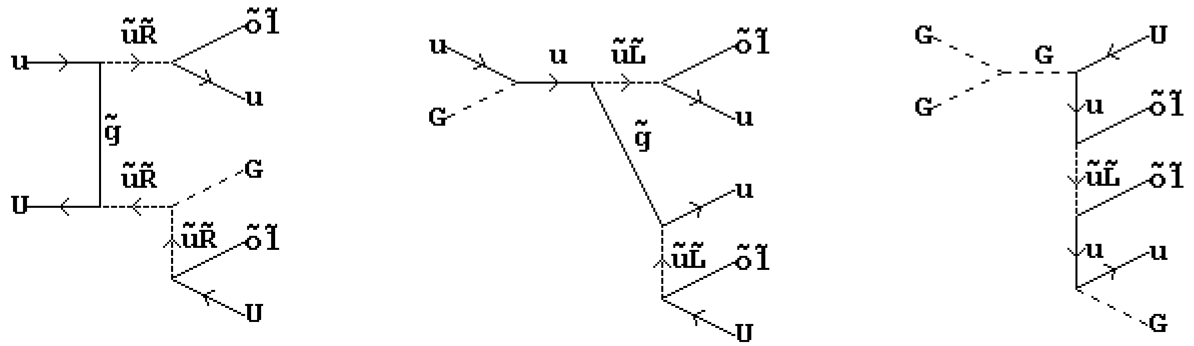






Backgrounds

- Good news is that the SM background should be small (assuming sizable MET)
- Search channels can have large jet or lepton multiplicity
- Bad news is that it's the same basic signature as the neutralinos
- 3 Jet and neutralino pair cross section at same model point as our current best signal is ~10picobarns (a factor of more than 10^7 larger then our signal)

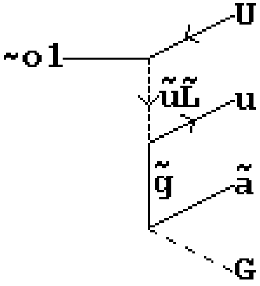


- Topologies are different, may be chance to distinguish the two with careful phenomenology, visible particles may have distinguishable features
- There are precedent studies to distinguish multiple DMs from looking at the invariant mass distribution when there are enough jets

Prolonged Decays

Even if production of neutralinos with axinos is simply too rare, models like this can still be explored with prolonged decays of the nlsp

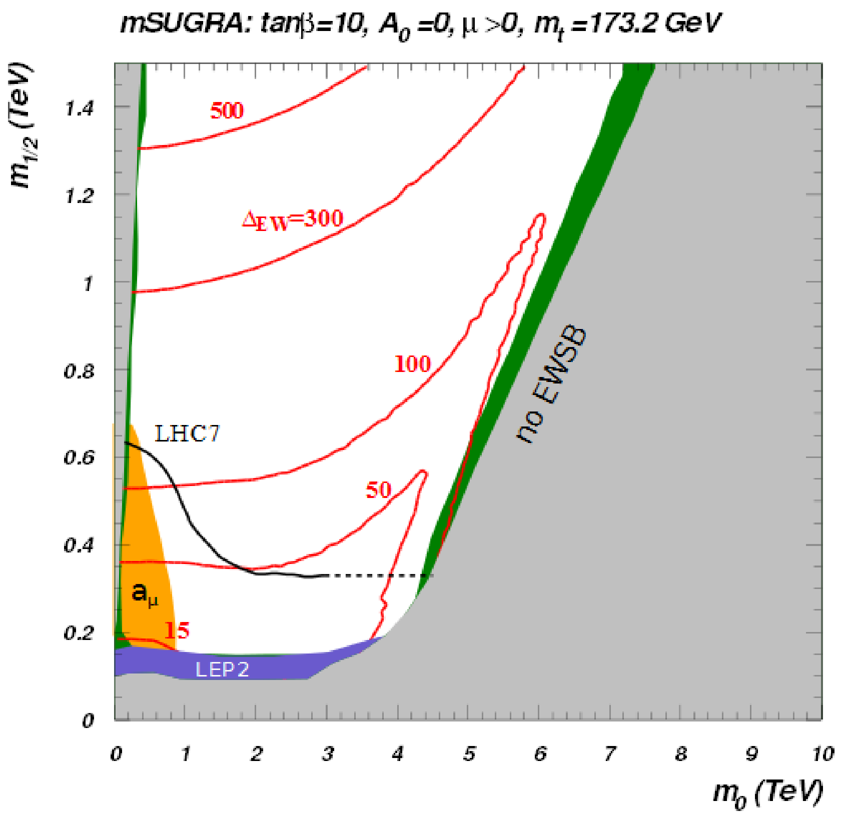
- Signature is 3 jets from displaced vertex
- Need to consider constraints from similar searches
- If the gluino is sufficiently long lived we need to consider constraints from searches for R-hadrons



- This search is a "safer" strategy than looking for production of both axino and neutralino, but this strategy can only probe an axino lsp, whereas the other strategy can probe either as lsp
- If the neutralino is the lsp, this prolonged decay would simply be "skipped" in the vast majority of SUSY decay chains

Outlook

- Work seems overly hopeful, search starts AFTER SUSY is discovered,
- If there is evidence for SUSY any where NOT in the green bands, then these models become much more attractive, or SUSY has nothing to do with dark matter (RPV?)
- To evade tuning, SUSY models may need to be non-constrained or non-minimal
- Extensions to the dark sector do not have to be complicated
- Even if this model is a toy, could help in the study of other multi DM models



To be continued