LOW-SCALE SUSY BREAKING:

COLLIDERS AND COSMOLOGY

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PRINCETON CTS
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Based on: 1006.4575 with Patrick Meade and David Shih;
work in progress with JiJi Fan, Lian-Tao Wang, & others

SOME QUESTIONS:

- Is SUSY realized in nature?
- If so, at what scale is it broken?
- How is this breaking mediated to the Standard Model?

- Does an axion solve the strong CP problem?
- If so, at what scale is Peccei-Quinn broken?
- What happened before nucleosynthesis?

GOALS

A goal of this talk is to suggest that how you answer the first set of questions should affect how you think about the second.

Another goal of this talk is to motivate some possible exotic collider signatures, and show that more work is still needed to understand how the LHC can find the unexpected.

EXOTICA AT THE LHC

Recent years have seen interest in a number of collider signatures going beyond traditional "prompt particles + MET" searches:

- Hidden valleys (Strassler & Zurek)
- Quirks (Kang & Luty)
- Stopped Gluinos from Split SUSY(Arvanitaki et al.)
- R-parity Violation at LHCb (Kaplan & Rehermann)
- Asymmetric DM (Chang & Luty)
- Lepton Jets (Arkani-Hamed & Weiner)
- Many more...

WHY EXOTIC SIGNATURES?

- I have confidence in experimentalists: new physics in jets, leptons, and missing ET will be found, eventually, if it is there. (Maybe even if it isn't.)
- What needs more thought are less traditional places new physics could hide.
- Exotic signatures arise very naturally; in this talk I will show you several different ones that emerge from thinking about low-scale SUSY breaking.

MOTIVATING EXOTICA

- I would hope that experimentalists will think about possible exotic signatures in a model-independent way: are unexpected things happening in some events?
- As a theorist, though, it's easier to motivate myself to think about these signatures if I can attach them to plausible BSM scenarios.
- So as a first step, let's consider NLSP decays in gauge mediation....

SUSY CLASSIFICATION

(A broad-brush caricature.)

- Low-scale breaking: $m_{3/2} < 1$ GeV. Flavor blind gauge mediation. Worries: μ/B_μ, little hierarchy, R breaking (gaugino vs. scalar masses). Questions in **effective field theory**.

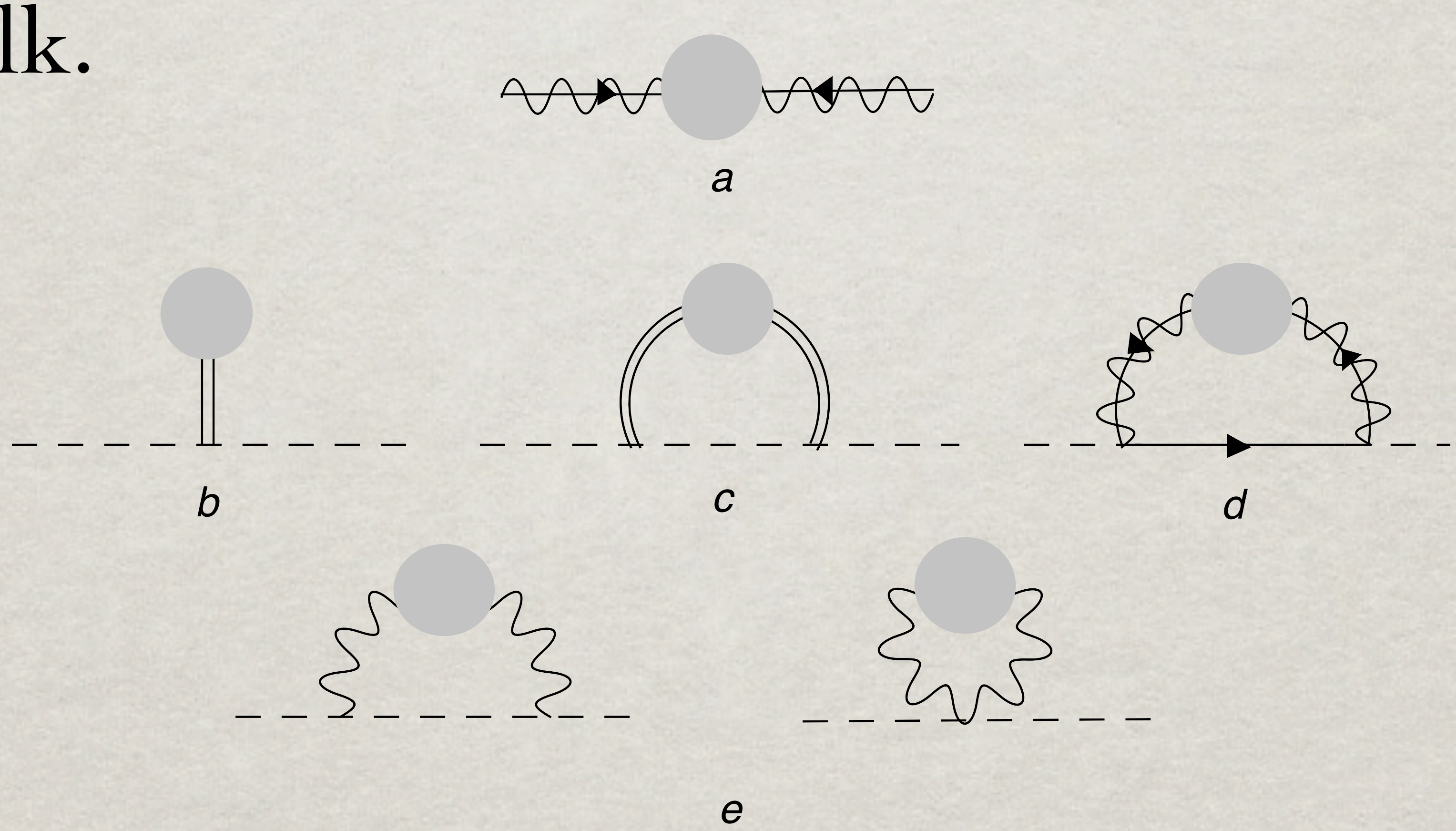
- Generic gravity mediation: $m_{3/2} \sim 1$ TeV. Arbitrary Planck-suppressed operators. Worries: flavor? Underlying structure?

- Anomaly mediation & relatives: $m_{3/2} \sim 100$ TeV. Respect flavor. Worries: sequestering, μ

(This omits interesting possibilities; R-symmetric gravity mediation, for example.)

GMSB & NLSPs

- **Gauge mediation** will be the paradigm for most of this talk.



- Hidden sector breaks SUSY, has global symmetry weakly gauged by SM groups

- GGM (Meade, Seiberg, Shih): current-current correlators encode soft masses

LOW-SCALE SUSY BREAKING

- What scale do we expect SUSY to be broken at?
- GMSB works for $m_{3/2}$ from below an eV up to about a GeV; above that, F/M_P flavor corrections are dangerous. (Could go higher, with sequestering.)
- Some scenarios (direct mediation, single-sector models, Komargodski/Seiberg approach to μ problem) favor small F ($m_{3/2} \sim$ 1 eV to 10 keV)
- This is mostly what I have in mind, although the case $m_{3/2} \sim$ 1 GeV is also interesting (“sweet spot”)

Lifetimes

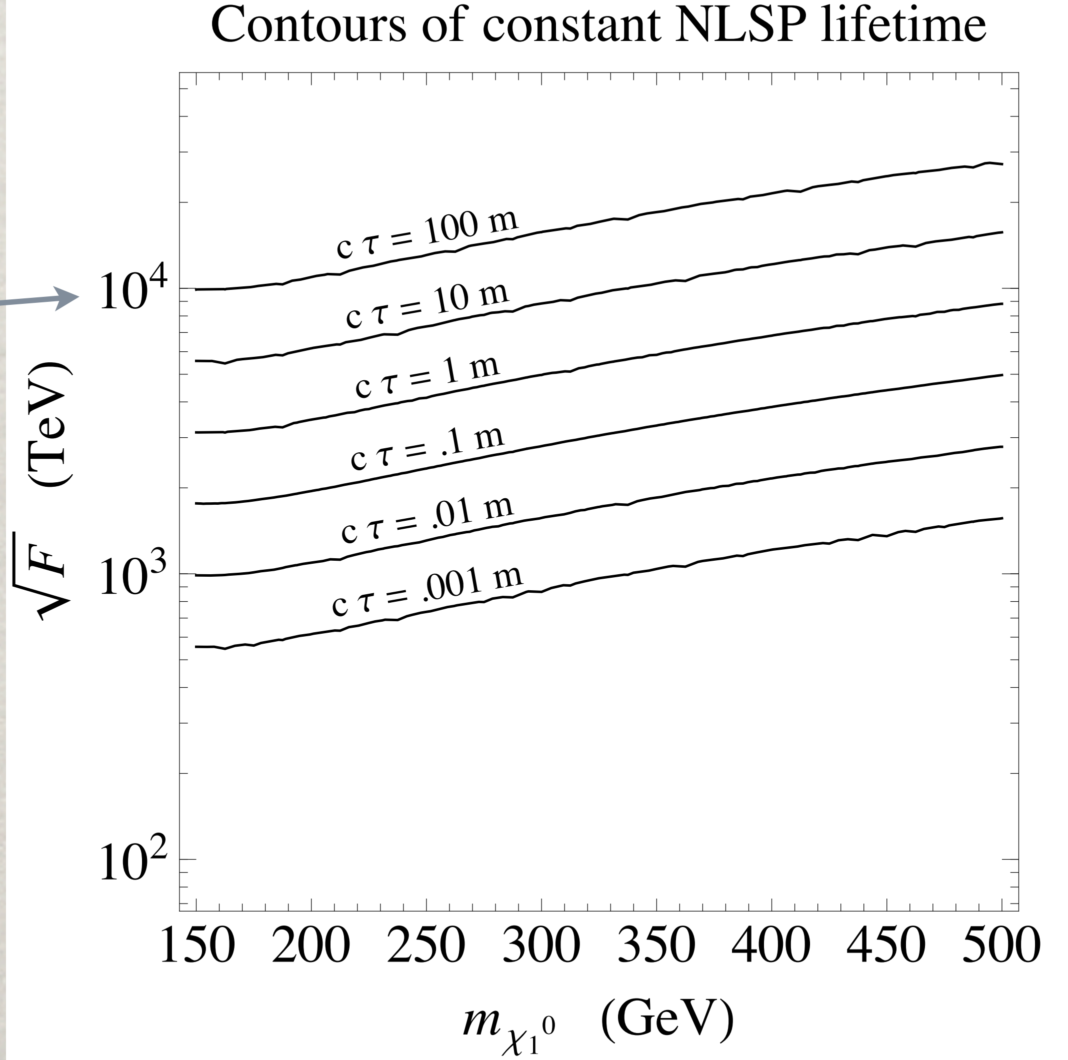
- NLSP decays to gravitino through goldstino coupling
- Suppressed by the SUSY-breaking scale *F:*

$$\mathcal{A} = \frac{m^5_{\tilde{\chi}^0_1}}{16\pi F^2} \approx \left(\frac{m_{\tilde{\chi}^0_1}}{100\text{ GeV}}\right)^5 \left(\frac{100\text{ TeV}}{\sqrt{F}}\right)^4 \frac{1}{0.1\text{ mm}}.$$

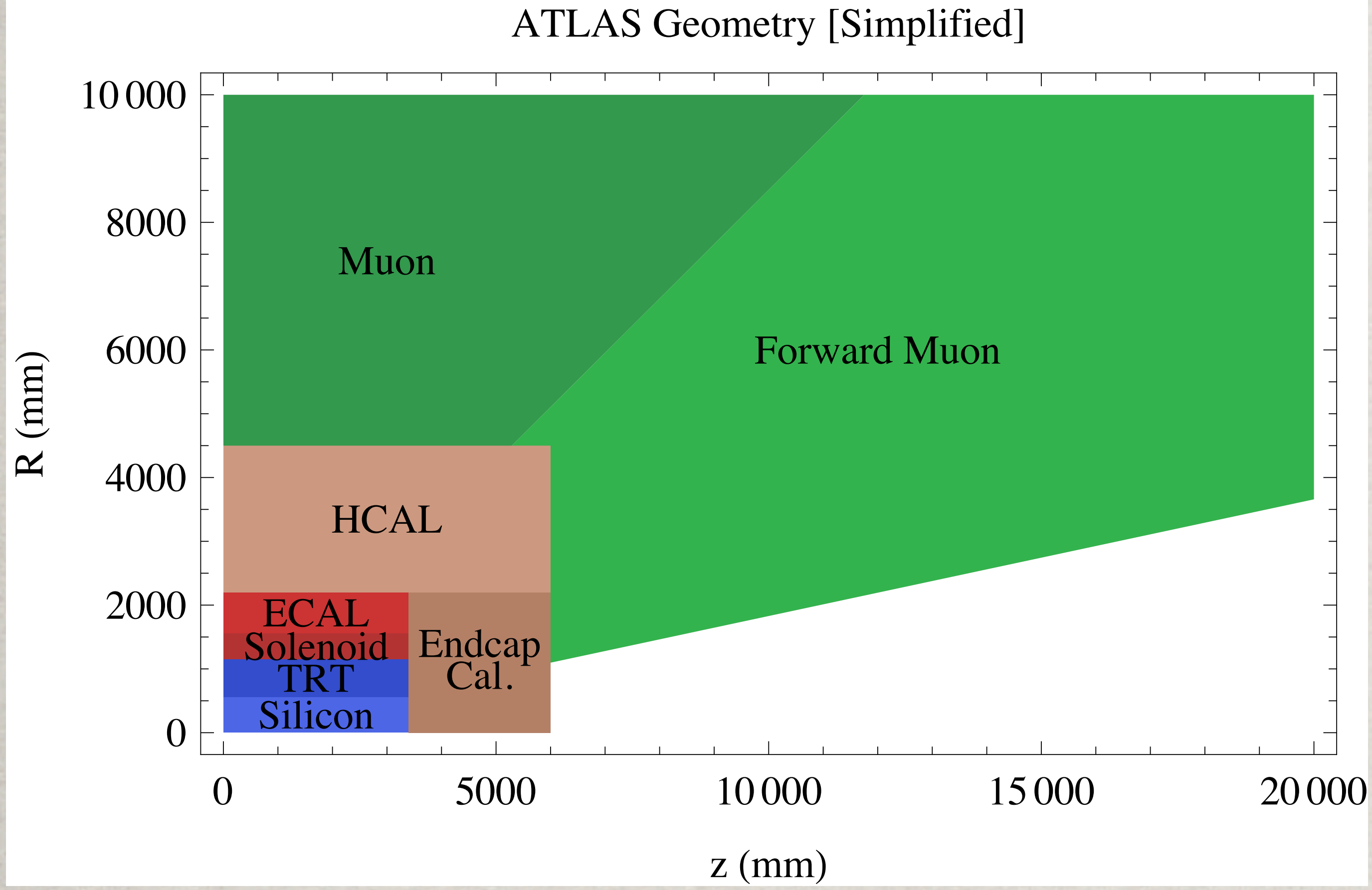
$$m_{3/2} \sim 10\,\mathrm{KeV}$$

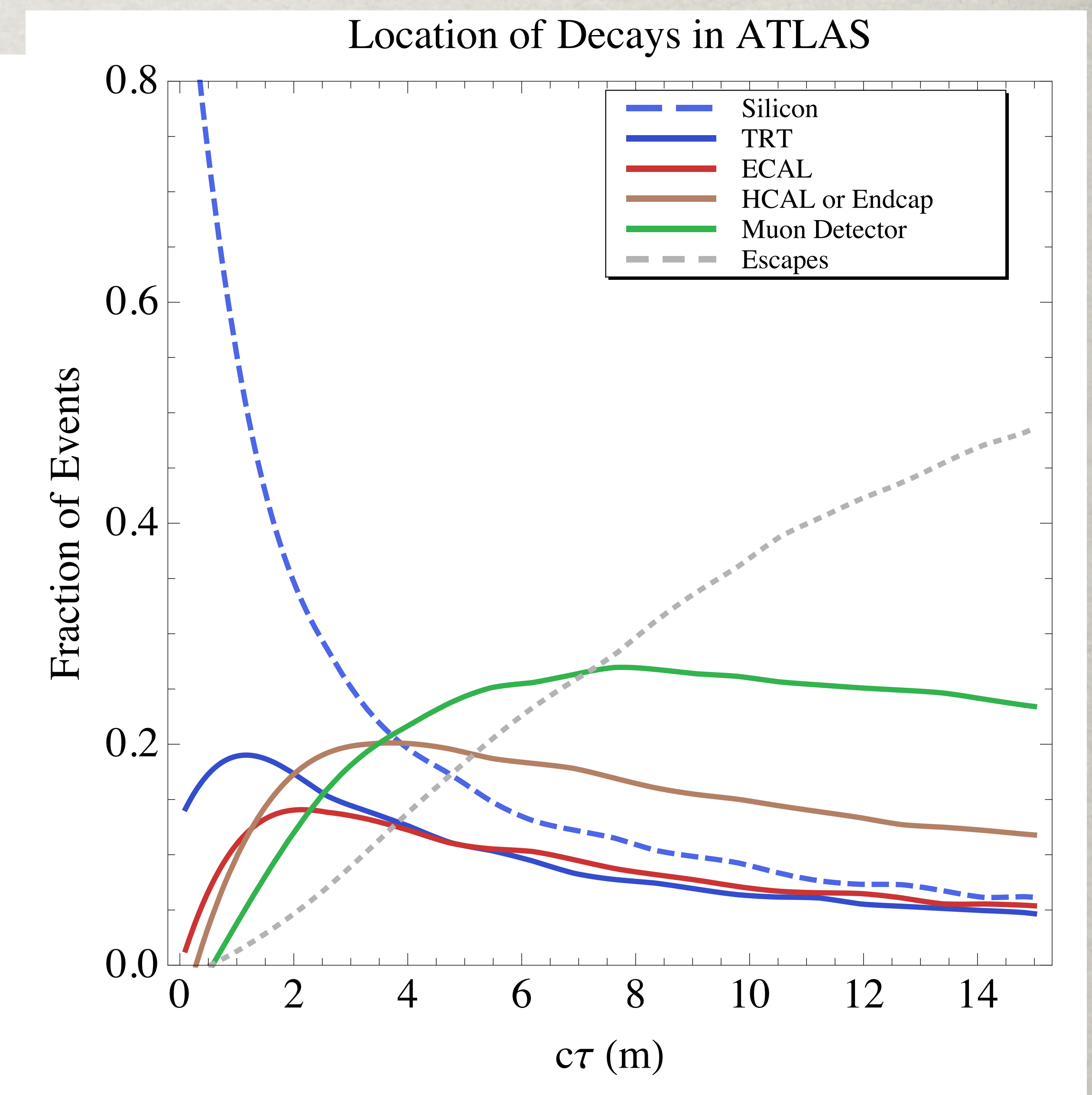
Charged NLSPs can be “CHAMPS”: highly ionizing tracks

Neutrals are trickier: look for their decay products



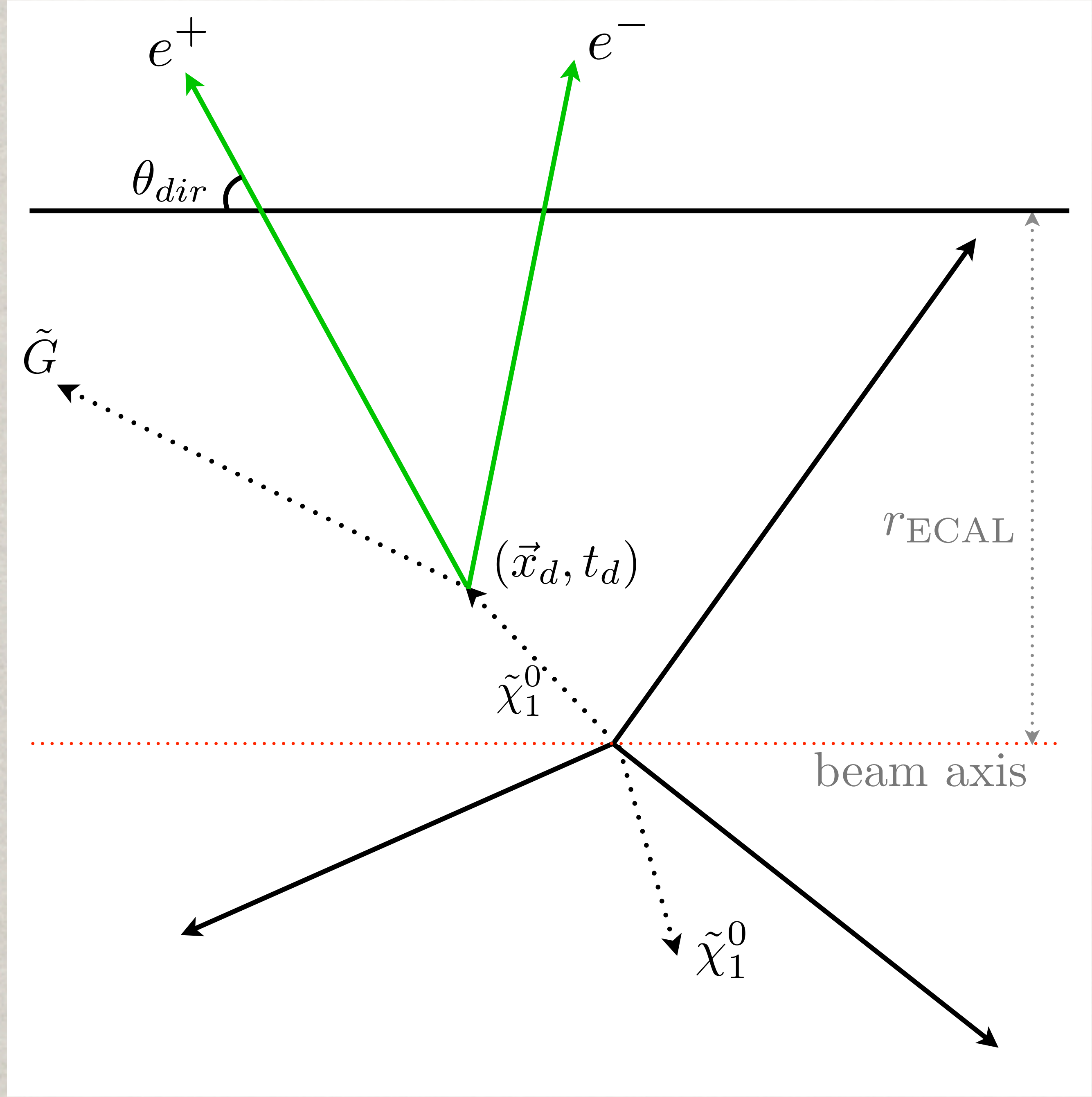
WHERE DO DECAYS HAPPEN?





Calorimeters are the crudest parts of the detector, but we can afford to ignore them.

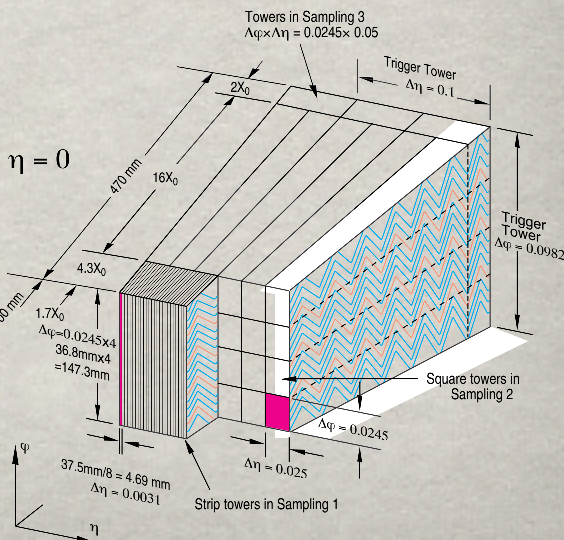
SCHEMATIC OF A LONG LIFETIME EVENT



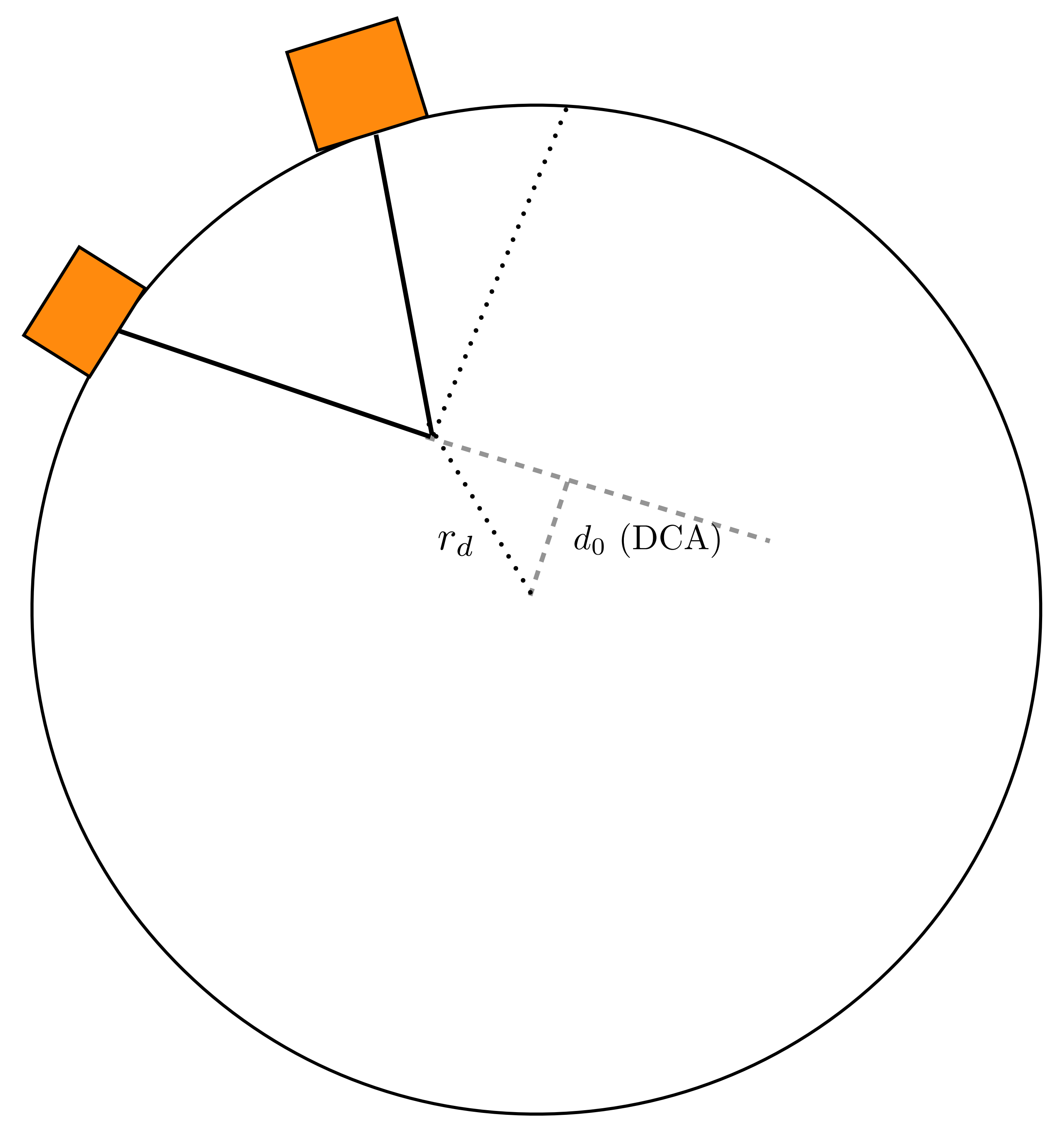
If decay vertex $x_{\rm d}$ is displaced enough, electron tracks will not be reconstructed.

At first pass, this might be a diphoton plus missing energy ("$\gamma\gamma$+Met") event.

Granular ECAL measures $\theta_{\rm dir}$:



EXTRAPOLATING BACK



r_d: Decay radius; use absence of hits closer to beamline

d_0: Impact parameter or distance of closest approach; find via track fitting

t_{det}: Time of detector signal in calorimeter

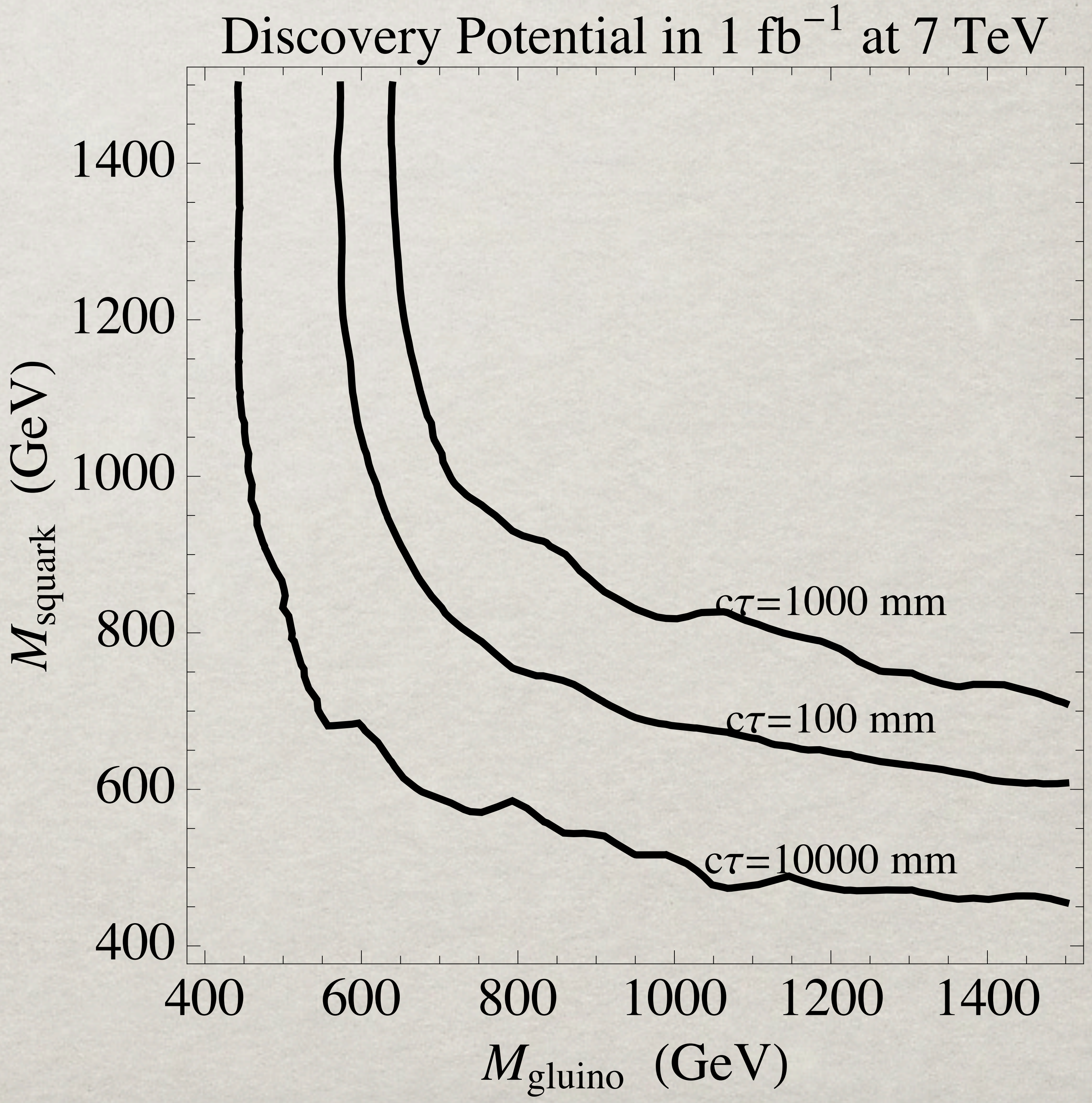
DISCOVERY POTENTIAL

Choose cuts for 5σ confidence decay is not prompt.

Contours of constant estimated #events: $\sigma \times \mathrm{Br} \times \varepsilon = 5$.

(Implicit assumption: background is tiny.)

Fixed NLSP mass of 250 GeV.



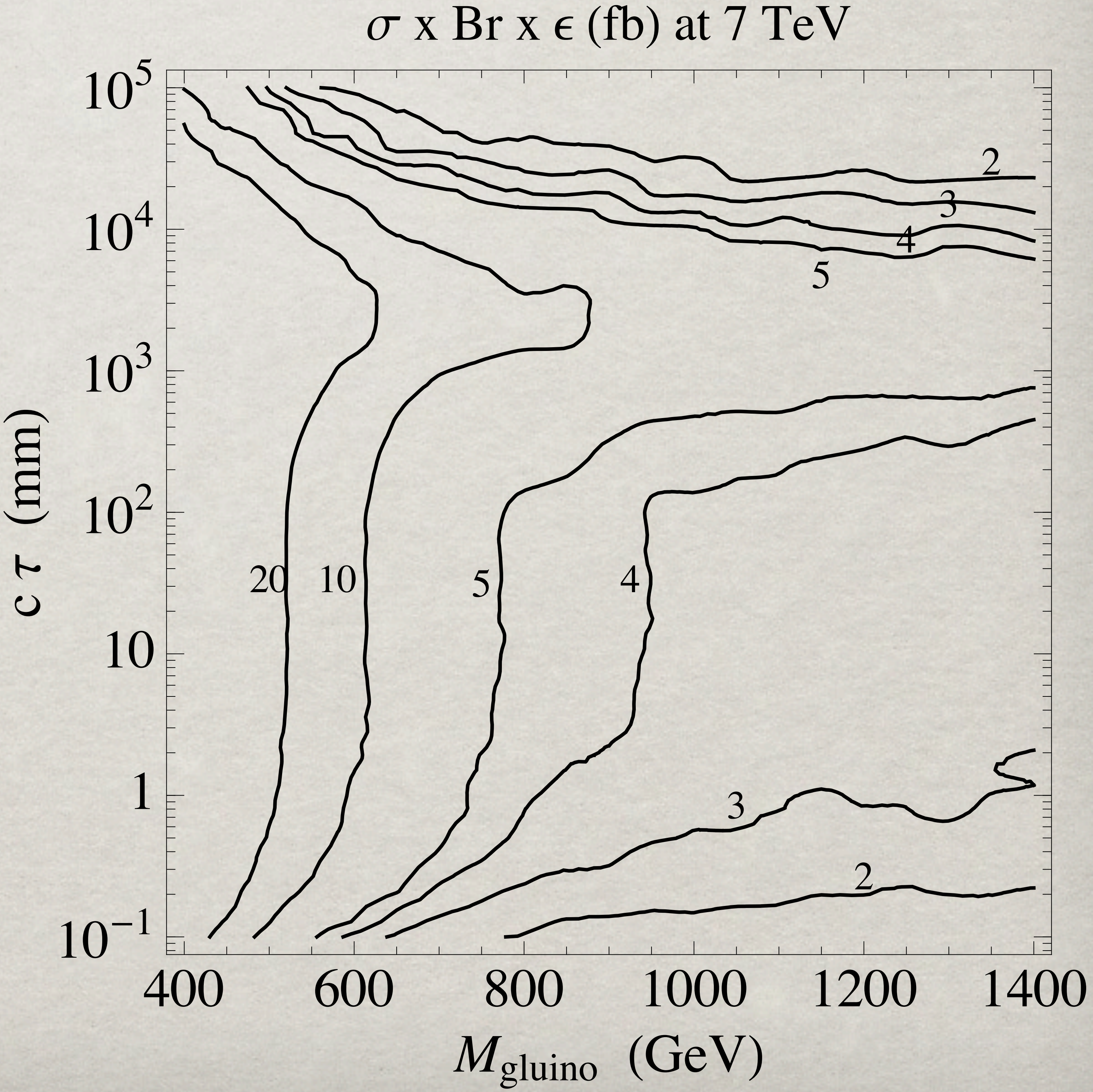
DISCOVERY POTENTIAL

Contours of constant estimated #events.

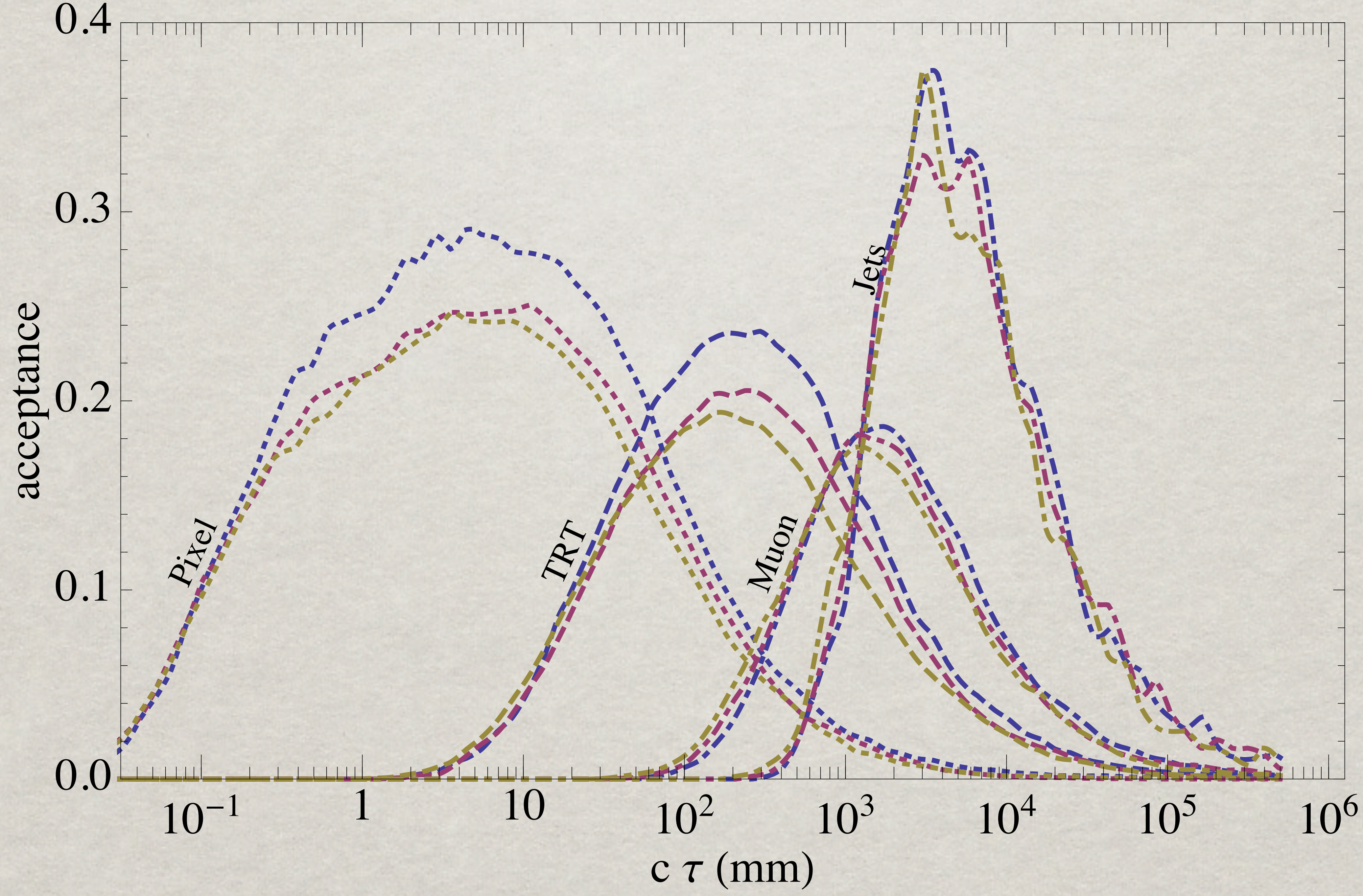
All squarks are at 1 TeV.

Fixed NLSP mass of 250 GeV.

EWK production is accessible at $c\tau \approx 1$ m.



ACCEPTANCE ESTIMATE: SIX ORDERS OF MAGNITUDE!



Jets have been rescaled by Br($Z\rightarrow$jets)/Br($Z\rightarrow e^+e^-$)

FITTING AN EVENT

We would like to measure all properties of the decay chain

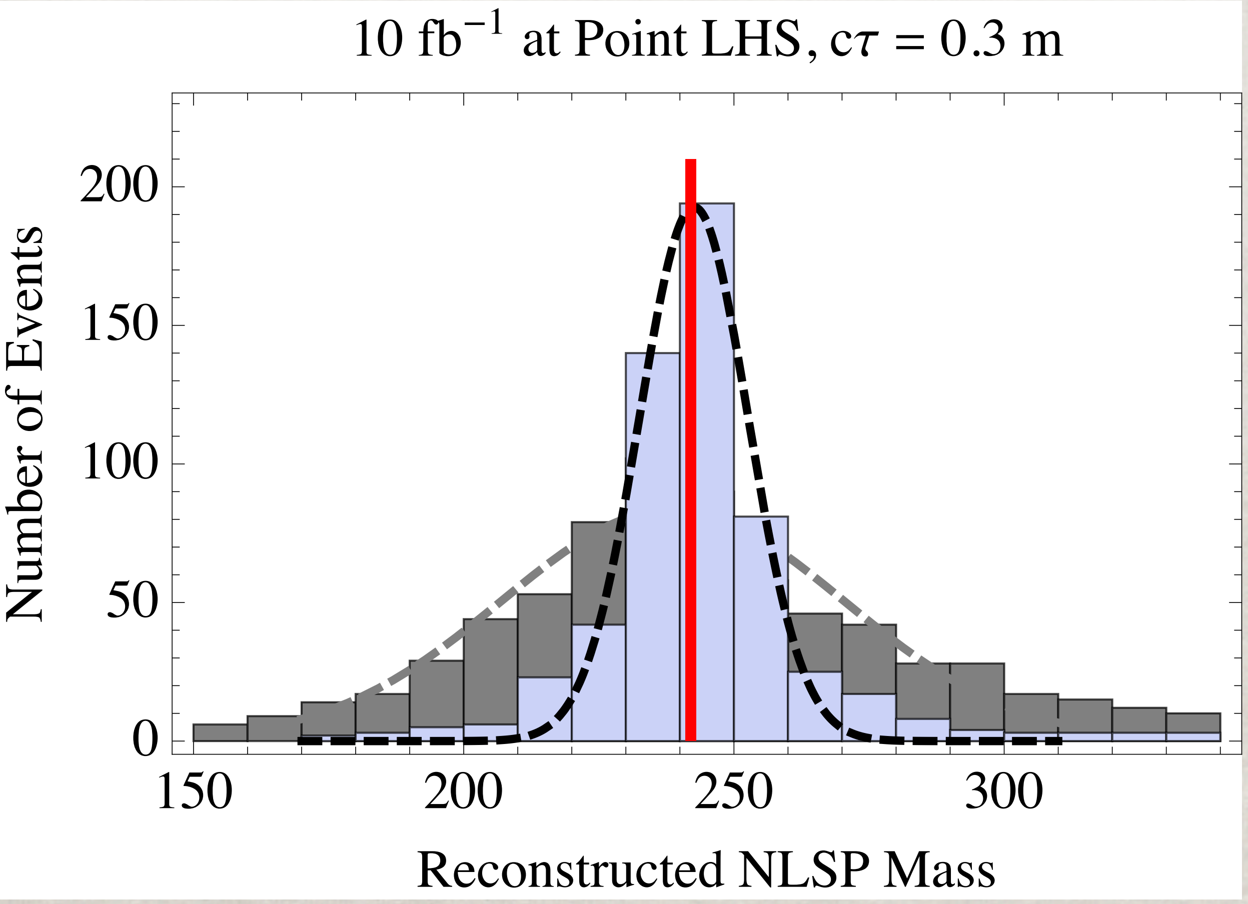
$$\tilde{\chi}_1^0 \rightarrow \tilde{G} + Z \rightarrow \tilde{G} + e^+ + e^-$$

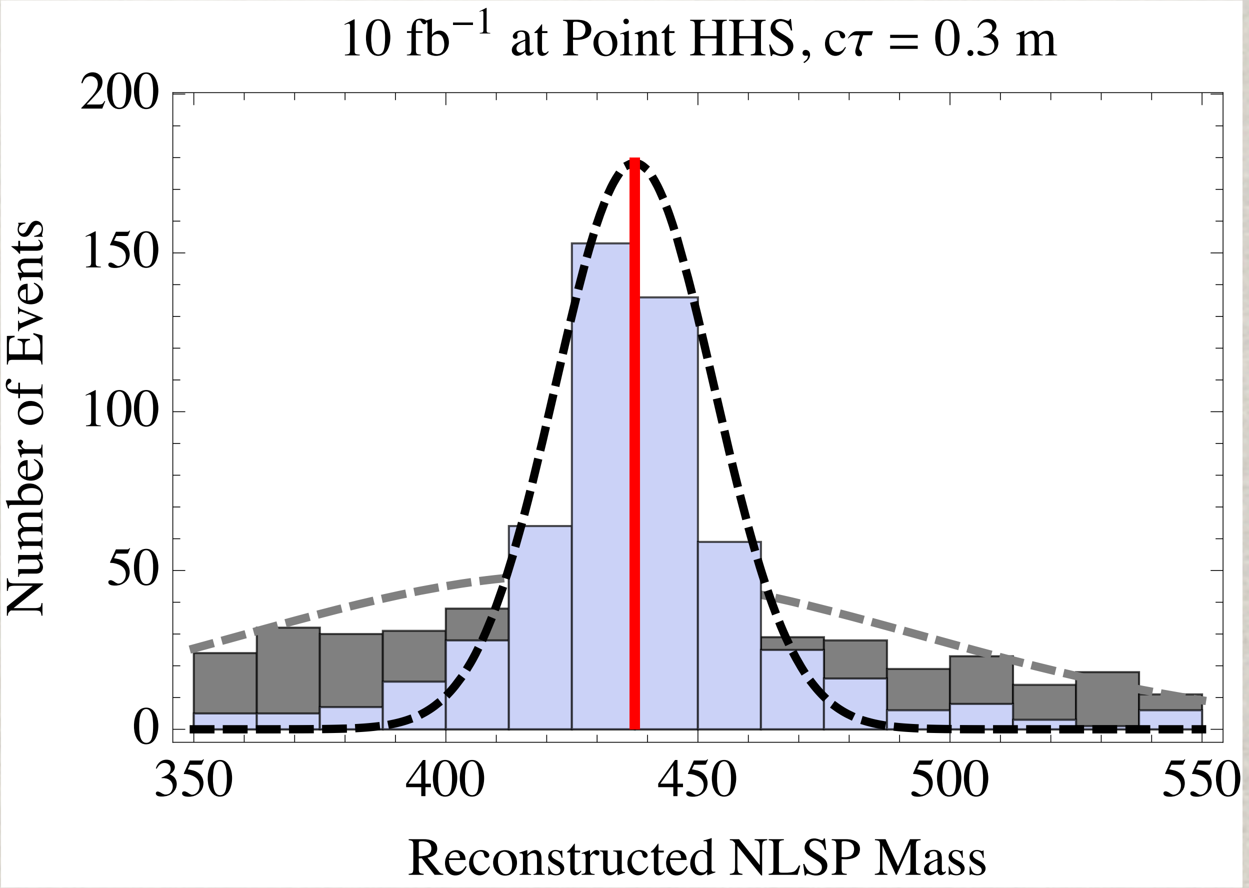
This would mean measuring the decay vertex and time, $(\boldsymbol{x}_\mathrm{d}, t_\mathrm{d})$, and the momenta $\mathbf{p}(e^+)$ and $\mathbf{p}(e^-)$. These are 10 unknowns.

ATLAS ECAL measures 5 numbers: the energy, position in η and ϕ, time of arrival, and direction in θ. Measuring these 5 numbers for both the e^+ and e^- is enough to fully reconstruct the decay!

RECONSTRUCTION

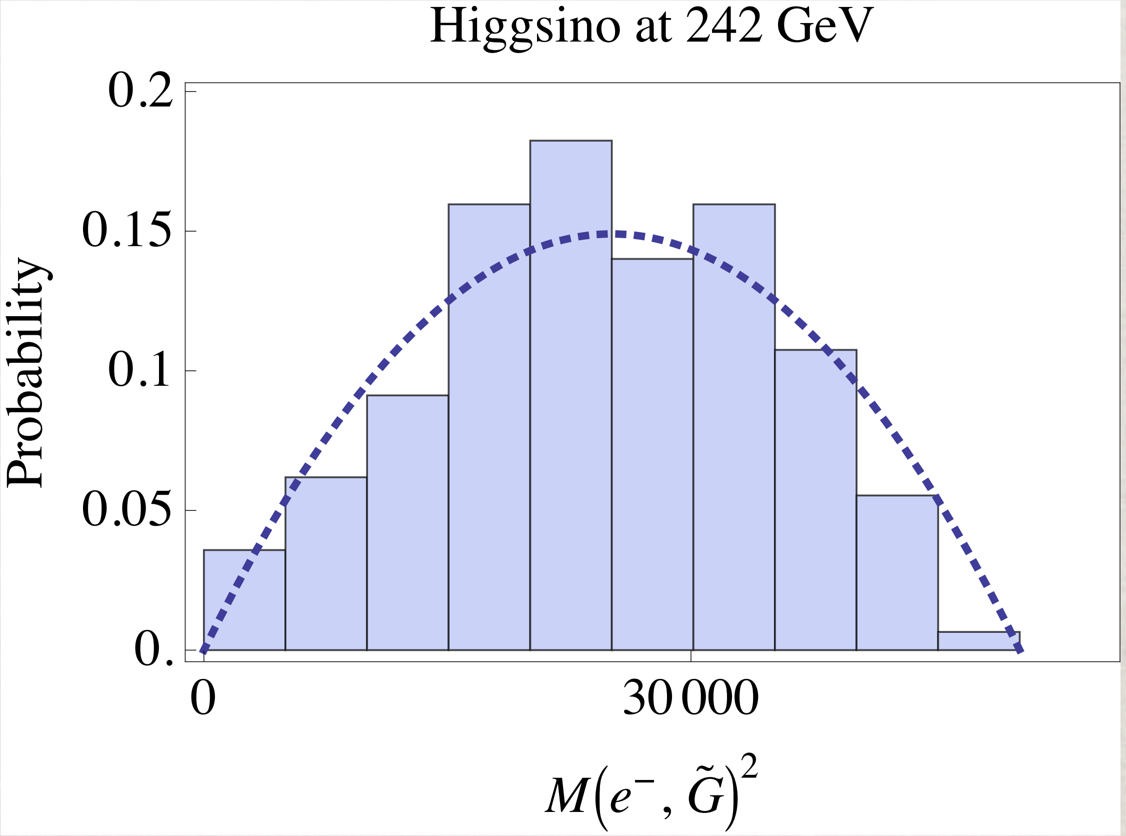
Add in TRT information and fit (needs new outside-in tracking algorithm; outside scope of this talk):

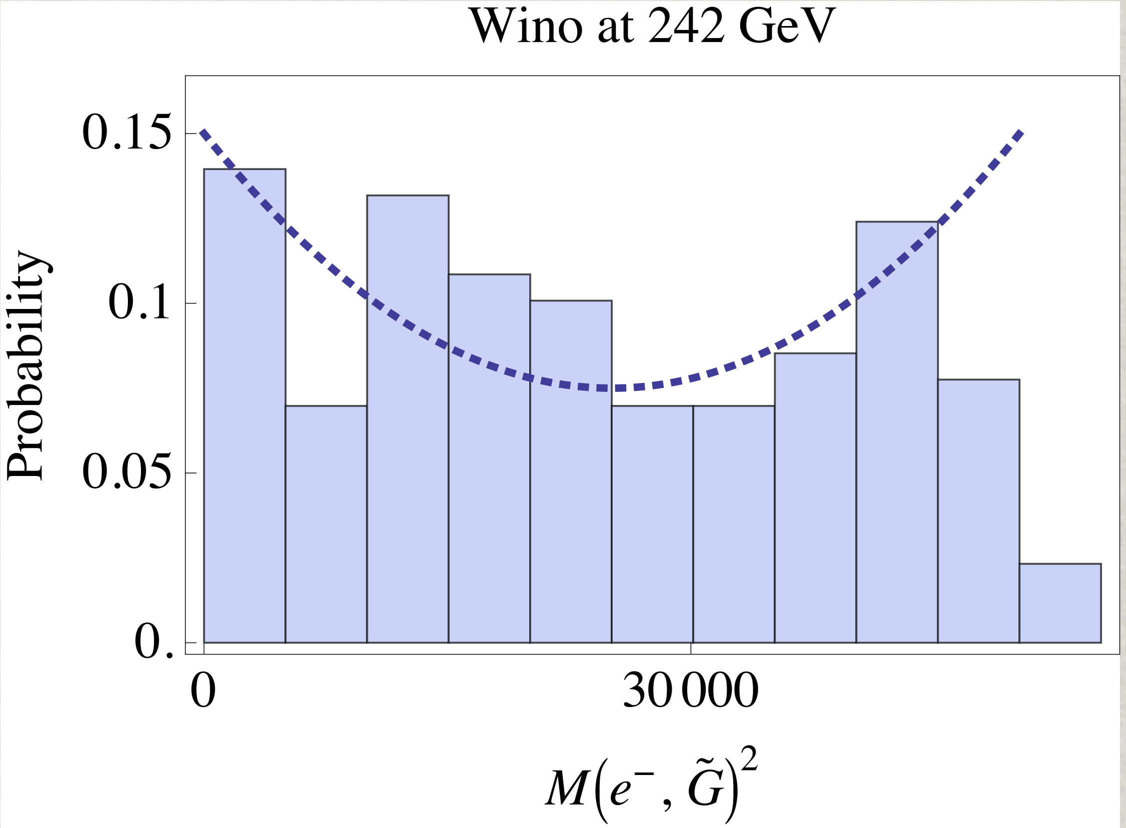




Get an accurate measure of NLSP mass (assuming gravitino is effectively massless).

MEASURING DETAILS OF VERTICES


Higgsino at 242 GeV

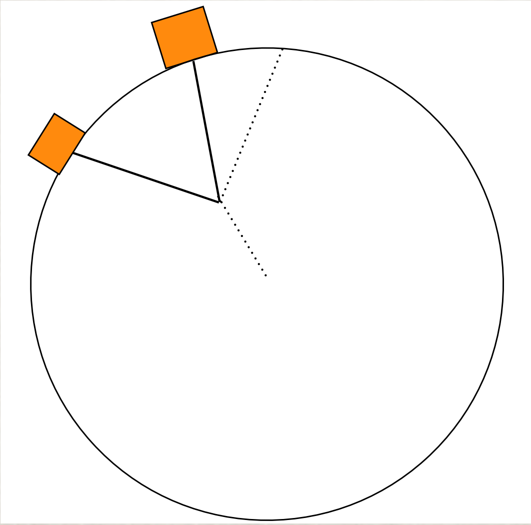

Wino at 242 GeV

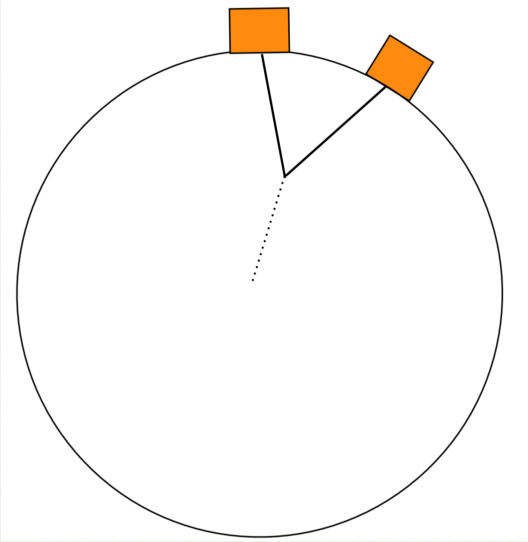
Accurate kinematic information allows more details to be measured: here, angular distributions sensitive to polarization of the *Z*.

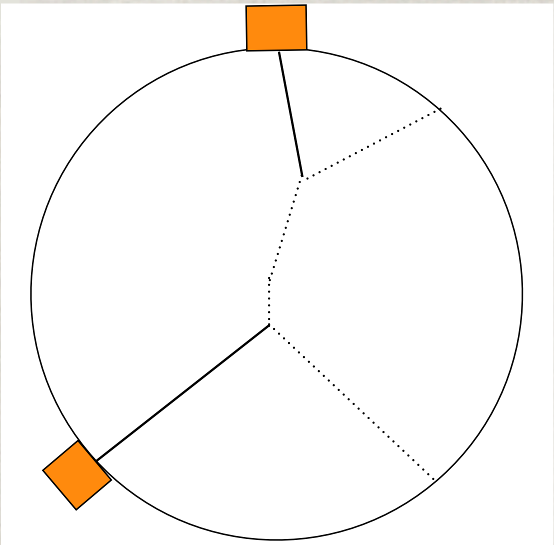
Shown: $c\tau$ = 0.3 m, 10 fb^{-1} @ 14 TeV.

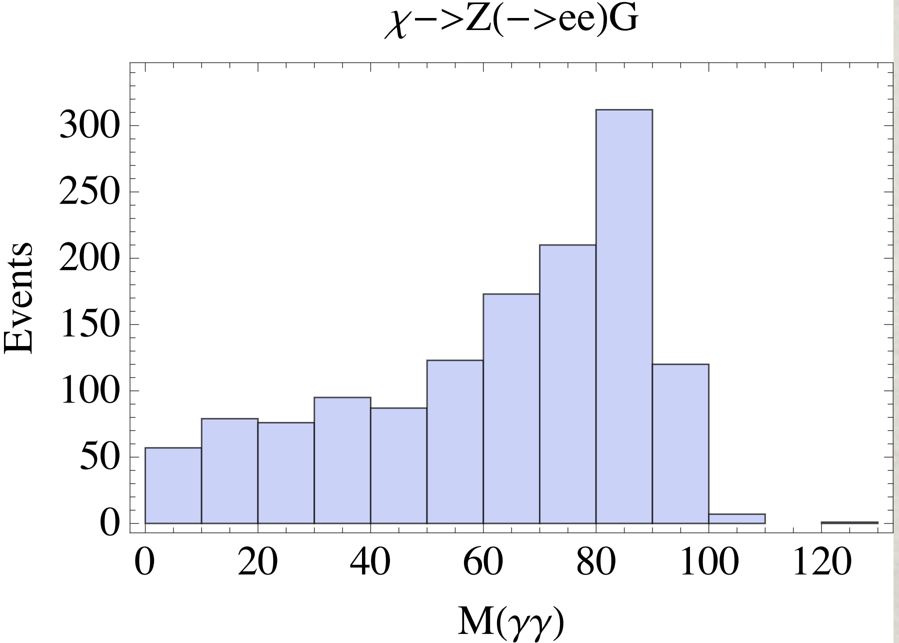
“DIPHOTON” DIAGNOSTICS

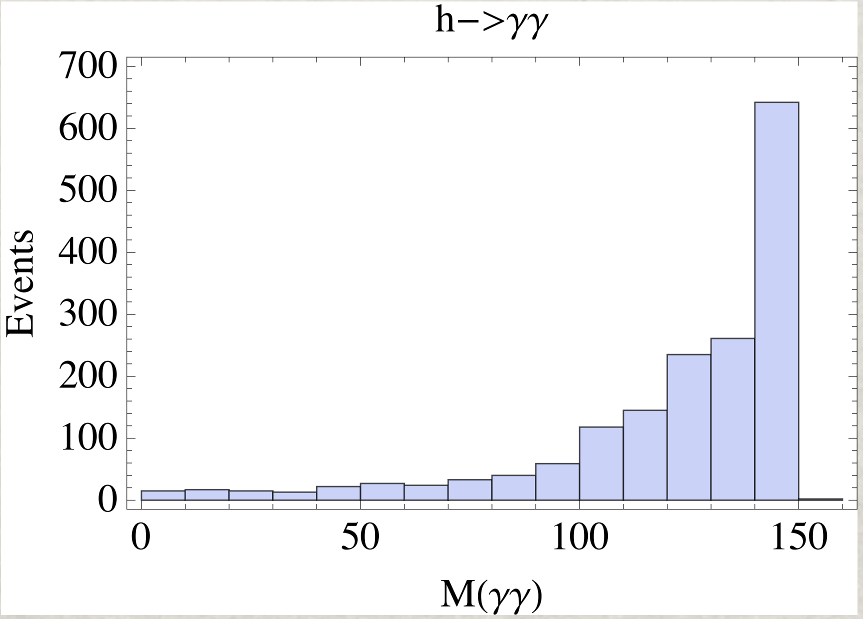
(Germ of an idea from discussion with M. Strassler & Y. Gershtein.)

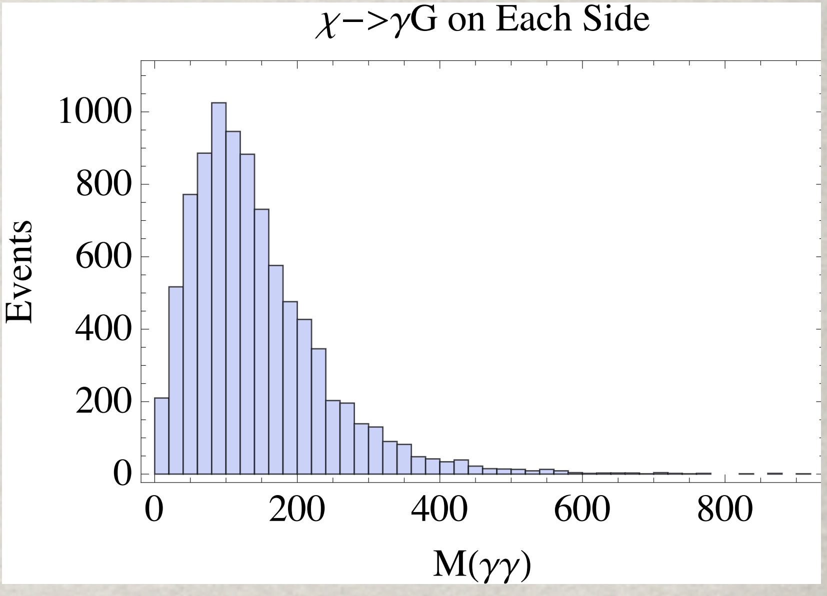


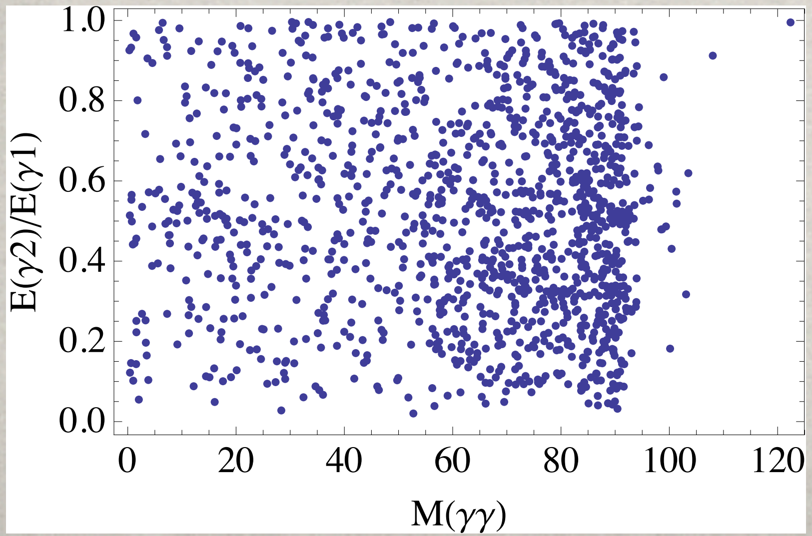


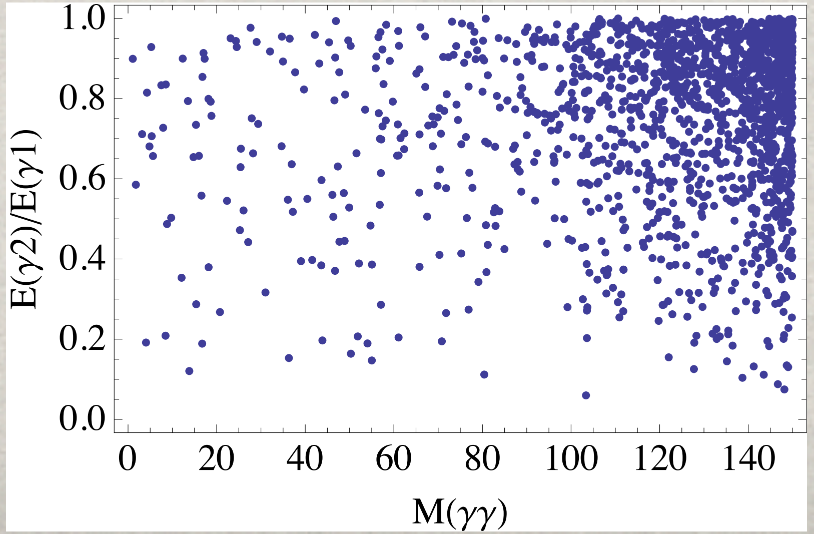


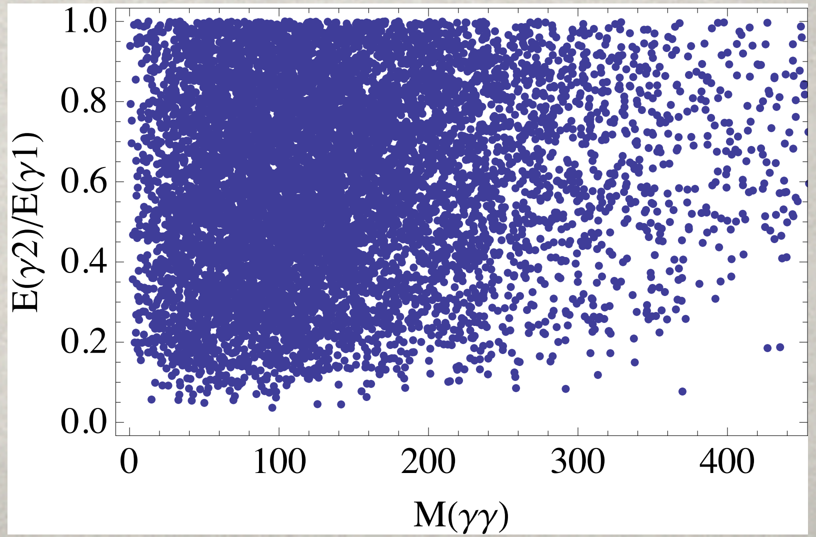












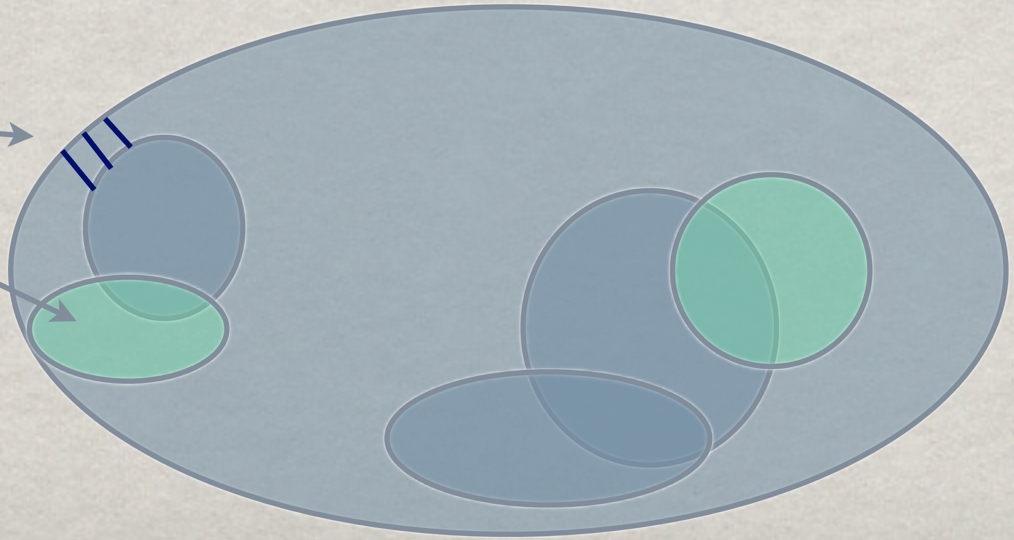
ON TO COSMOLOGY...

- Now I'm going to veer in a different direction. Bear with me; it's not completely unrelated.
- I want to investigate moduli and their implications for low-scale SUSY breaking.
- The main issue will be cosmology.
- In the end, this will lead us back to possible exotic collider physics.

MODULI

- In string compactifications, one generically finds that gauge couplings are not fixed numbers, but are determined by the values of scalar fields called **moduli**.

- For example, suppose gauge fields arise from D7 branes wrapping a 4-dimensional volume:



Fluxes & branes generate potentials for moduli.

The volume of each cycle in the CY is controlled by a Kähler modulus, which also sets gauge couplings on wrapped branes.

PROPERTIES OF MODULI

(The prototypical modulus for this talk is a Kähler modulus in IIB compactifications.)

- Typical field values are order M_{Planck}; couplings are M_{Planck}-suppressed.
- Often, axionic shift symmetries: $T = 1/g^2 + i\theta/8\pi^2$, which are exact at a discrete level ($\theta \rightarrow \theta + 2\pi$) and approximate at the continuous level.
- ⇒Superpotentials arise from instantons: e^{-cT}.
- New fields become light at $T \rightarrow 0$ (e.g. branes wrapped on shrinking volume), so divergent metric in field space, e.g.:

$$K = -3M_P^2 \log(T + T^\dagger)$$

$$\mathcal{L} \supset \frac{3}{(T + T^\dagger)^2} \partial_\mu T^\dagger \partial^\mu T$$

LOCAL SUSY BREAKING

- For **low-scale** SUSY breaking, as in gauge mediation, we want to imagine the SUSY breaking sector (an O'Raifeartaigh model, ISS, IYIT, ...) is realized locally in the Calabi-Yau, as a low energy EFT.
- We want the moduli to be stabilized independently, in a **supersymmetric** way.
- Naïvely, the moduli masses shouldn't care about the scale of SUSY breaking.

KKLT

- As a toy version of the moduli sector, consider the KKLT model of a Kähler modulus:

$$K = -3M_P^2 \log(T + T^\dagger)$$

$$W = W_0 + Ae^{-aT}$$

- This theory has a supersymmetric minimum at:

$$T_* \approx \frac{1}{a} \log\left|\frac{2A}{3W_0}\right|$$

$$V_{AdS} = -\frac{a^2 A^2 e^{-2aT_*}}{6M_P^2 T_*}$$

$$m_t \approx \sqrt{2}\,(aT_*)\, m_{3/2}$$

ADDING SUSY BREAKING

- Let's add a SUSY-breaking sector that is even more of a toy:

$$K = X^\dagger X - \frac{(X^\dagger X)^2}{\Lambda^2}$$

$$W = fX$$

- The Kähler correction is a stand-in for some dynamics that wants X to be zero.

$$V \supset e^{K/M_P^2} K^{X^\dagger X} |D_X W|^2$$

$$\approx \frac{1}{(T + T^\dagger)^3} |f|^2$$

(Note here the assumption that T has noncanonical Kähler potential is playing a key role in giving T an F-term VEV in the end.)

- Now $\partial_T V$ will no longer be quite zero....

CONSEQUENCES

- The T-dependence in this term shifts the VEV T_*, but only by an amount of order $1/T_*$
- Canceling the c.c. to get a Minkowski minimum sets: $$f \approx \frac{2aT_* Ae^{-aT_*}}{\sqrt{3}M_P} = (2T_*)^{3/2} m_{3/2}$$
- Hence, the final gravitino mass is now roughly that of the old AdS minimum, and *still* we have: $$m_t \sim m_{3/2} \log \frac{M_P}{m_{3/2}}$$

The modulus is heavy only by a log. For instance: at $m_{3/2}$~10 eV, the modulus mass is only ~ 0.6 keV!

HOW GENERAL IS IT?

- Calculating in an example is a useful exercise, but in the end it is meaningless unless we extract a general lesson.
- Are the moduli always light? Certainly not at the level of supergravity. Many possible $V(T)$.
- But: I claim that making them many orders of magnitude heavier than the gravitino mass always comes at the cost of a tuning.
- Important: this is a **different** tuning than canceling the c.c.!

TUNING THE RACETRACK

- Instructive example where we can tune moduli to be heavy: $W = W_0 - Ae^{-aT} + Be^{-bT}$

- *Minkowski* minimum by fixing $D_T W=0, W=0$:

$$t_*^0 = \frac{1}{a-b}\log\frac{aA}{bB}; \quad W_0^0 = Ae^{-at_*^0}\left(1-\frac{a}{b}\right)$$

- Small displacement makes shallow AdS minimum with heavy modulus:

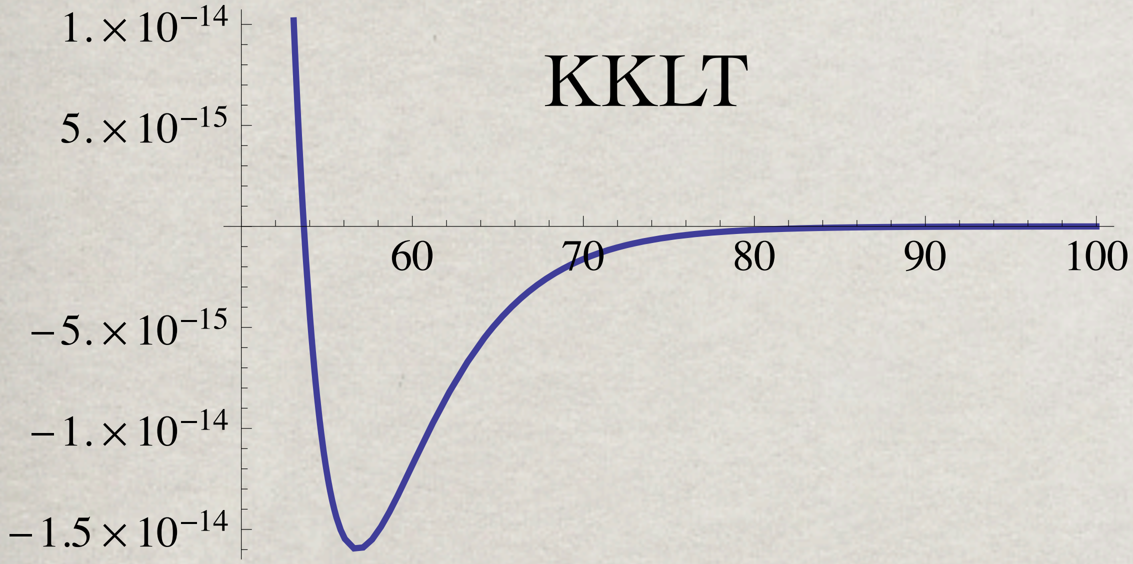
$$\delta t_* = \frac{\sqrt{3}}{2(b-a)t_*^0}\frac{f_0 M_P}{aAe^{-at_*^0}} \sim \frac{m_{3/2}}{m_\tau} \ll 1$$

$$\delta W_0 = \frac{f_0 M_P}{\sqrt{3}}$$

CLEARER IN PICTURES:

AdS minimum with equal depth at same value of T in all cases.

Exhibits A and B: typical shallow AdS minima, $m_T \sim m_{3/2}$.



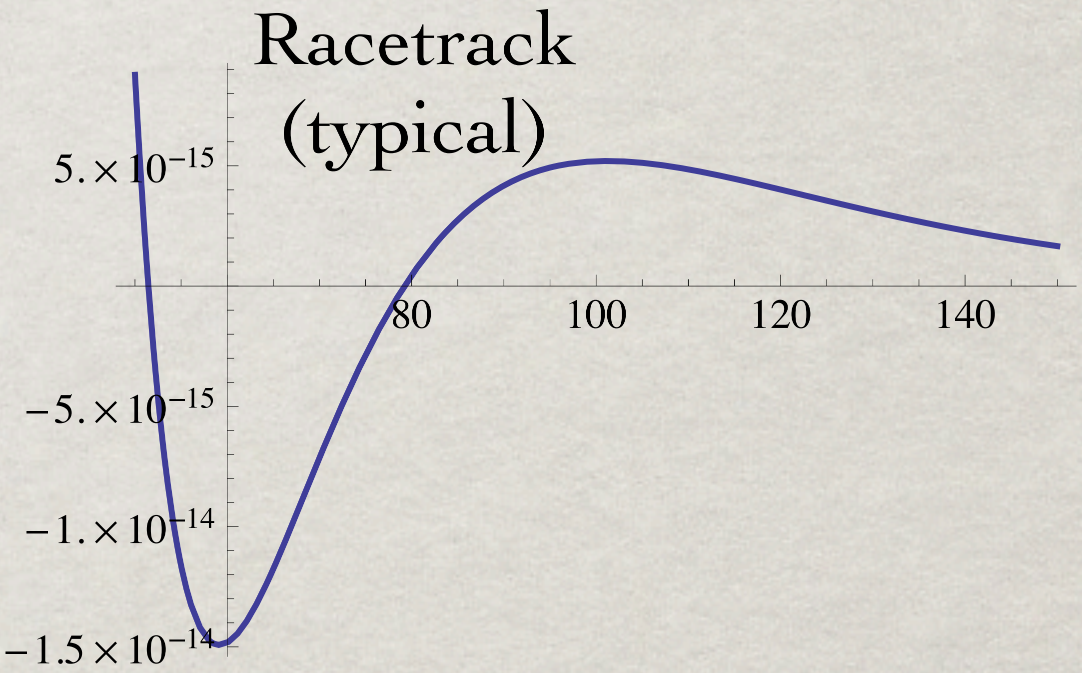
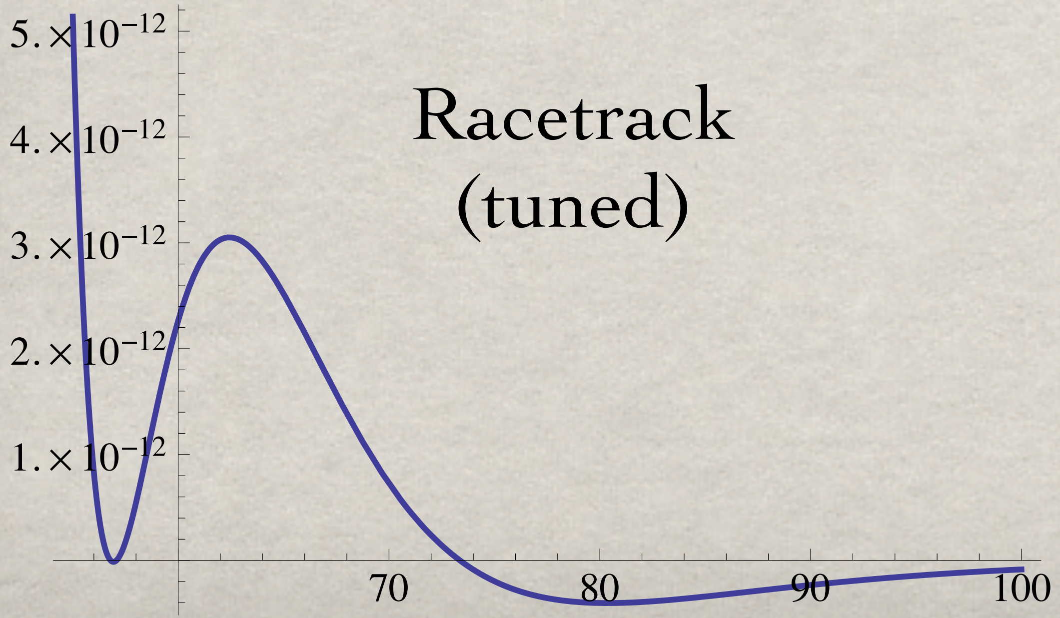


Exhibit C: tuned shallow AdS minimum, $m_T >> m_{3/2}$.



Looks unlikely, at least without knowing the distribution of vacua in the landscape, or invoking anthropics...

This makes me uncomfortable, as an effective field theorist.

THE MORAL

- Cutting through the details, the essence of the story is:
- SUSY breaking gives $+|f|^2$ contributions to V.
- They must be canceled by $-|f|^2$ contributions.
- Moduli terms around the minimum scale like $m_T^2 M_P^2$.
- Without tuning, then, $m_T \sim f/M_P$, with factors possibly depending on $T >> 1$ at the minimum.

GRAVITINO PROBLEMS

- Even if we tune $m_T >> m_{3/2}$, in these scenarios the modulus will generally have an F-term once we couple to SUSY breaking.
- Its branching ratio to a pair of gravitinos is rarely tiny.
- Modulus can decay before BBN, but have to check that gravitinos don't spoil successful cosmology. Beyond the scope of this talk.

COSMOLOGY

- I've argued light moduli are generic for GMSB.

- This suggests that a variant of the "Polonyi problem" (Coughlan et al., Phys.Lett.B131 (1983) 59) is severe and difficult to avoid in low-scale SUSY breaking, without tuning.

- During inflation, moduli are typically displaced from their true minimum by distances of order M_{Planck} in field space.

- Later, they will dominate the energy density, and with $\Gamma \sim m_T^3/M_{Planck}^2$, do not decay before BBN.

RESPONSES

- One fair response would be to tell me the UV completion might not be string theory. (It would be interesting to try to construct an AdS/CFT argument for the existence of moduli independent of particular compactifications.)
- Another would be to turn your hopes to high-scale SUSY breaking. This is fair.
- High-scale SUSY breaking has its own moduli problems, but they might be more easily addressed or exploited (Moroi, Randall hep-ph/9906527; Kane & collaborators)

OPTIMISM: THE CASE FOR GMSB

- Could mean lots of physics is not so far away in energy.
- Moduli begin oscillating at $H \sim m_T$, which is not too far above $m_{3/2}$; in other words, at temperatures of order F.
- Problems must be solved **after** this.
- For low-scale SUSY breaking, then, many problems you might have relegated to high-scale physics (like baryogenesis) probably happen at fairly low scales.
- Possibility of **correlating** how we think about SUSY breaking with how we think about other problems.

ONE POSSIBLE WAY OUT

- Now I want to lead you through one possible way out of the problem. It is the most satisfying way I know, but it is complicated.
- The most palatable model-building solution is to tie the solution of the moduli problem to other physics: namely, strong CP and the μ term.
- Most ingredients have been around for a while, but the big picture and its possible experimental signatures don't seem to have cohered.

(Most comprehensive GMSB cosmology ref.: de Gouvêa, Moroi, Murayama, hep-ph/9701244)

INFLATING AWAY MODULI

- My goal is to make a version of a solution proposed in the early literature, but less ad hoc.

- It is well-known that a late period of inflation at a low scale, after the moduli begin oscillating, can dilute their abundance. (Randall & Thomas, hep-ph/9407248)

- One version of this is thermal inflation. (Lyth & Stewart, hep-ph/9510204)

- Need: a field trapped at the origin by thermal corrections, which eventually rolls out to a large VEV.

(# e-folds ~ log(vev/mass), enough to dilute moduli but keep primordial density perturbations)

PECCEI-QUINN

- Consider the following axion model:

$$W = c_Q S Q_1 Q_2 + c_H \frac{S^2}{M_P} H_u H_d + \frac{c'}{M_P} S^3 Y + W_{GMSB}$$

(Closely related: Kim, Nilles Phys.Lett. B138 (1984) 150; Choi, Chun, Kim hep-ph/9608222 in the gravity mediation context)

- Here the Q fields are vectorlike quarks, not MSSM fields. This gives a hadronic axion model. (Need a large discrete symmetry to solve strong CP.)

- The F_Y equation stabilizes S at the origin in the absence of SUSY breaking. ($f_a \to 0$ as $F \to 0$)

- Finite-temperature effects will give $T^2|S|^2$ terms.

PQ BREAKING

- In the SUSY limit, $V(S) = |c'|^2\ |S|^6/M_P^2$.
- GMSB gives soft masses to Q_1, Q_2. These then induce a (gentle) potential for S (at $S >> F$):

$$V_{GMSB}(S) \approx -\frac{8\alpha_s^2}{3(4\pi)^4}|F|^2 \log^3 \frac{|c_Q S|^2}{M_{mess}^2}$$

(Arkani-Hamed, Giudice, Luty, Rattazzi, hep-ph/9803290)

- The minimum determines the PQ scale in terms of F and M_P (and $>> \sqrt{F}$):

$$S_0 = \left(\frac{2\sqrt{2}\alpha_s}{c'(4\pi)^2}|F|M_P \log \frac{|c_Q S|^2}{M_{mess}^2} \right)^{1/3}$$

COMMENTS

- A string axion would not do; these will typically have much larger PQ scale, and are themselves part of the moduli problem.
- A model like $W = Z(S_+S_- - f_a^2)$ is less satisfying; need to explain the scale f_a, and no preferred zero point for saxion.
- Instead, we have the nice feature that S is kept at 0 by thermal corrections until temp. drops below scale of soft masses, then slow rolls out to f_a.

SAXION-HIGGS MIXING

- The term $c' S^2 H_u H_d / M_P$ gives a μ term, potentially helping with a thorny point of GMSB phenomenology. (B_μ contribution small)

- Not just a convenience: crucial for reheating!

- Also, gives a decay $\tilde{H}_{u,d} \to \tilde{S} H_{u,d}$ with coupling $c_H S_0 / M_P = \mu / S_0$, i.e. f_a-suppressed. (If axino is light: depends on c'.)

- At $\mu = 250$ GeV, $f_a = 10^{11}$ GeV, find $c\tau = 12$ m.

Long-lived Higgsino decay to Higgs (or longitudinal Z) + axino: nearly the same signal we've discussed before!

LONG-LIFETIME NLSPS

- To recap, we started with the usual GMSB scenario and saw that we could have $\tilde{H} \to H(\text{or } Z_L) + \tilde{G}$

- Now we've seen that the Kim/Nilles μ term can lead to the decay $\tilde{H} \to H(\text{or } Z_L) + \tilde{S}$ on detector length scales.

(Has been mentioned before: Nakamura, Okumura, Yamaguchi 0803.3725 "Axionic Mirage Mediation")

- Depending on the values of F and f_a, either one could predominate.

- If the axino dominates, could be gravity mediation!

- Axino will typically be a substantial fraction of the Higgsino mass. So kinematics will be different. (The reconstruction techniques I discussed earlier don't resolve the base of the mass scale; work in progress to see what can be done.)

- GMSB case could have a reasonable fraction of decays to $\gamma + \tilde{G}$

BARYOGENESIS?

- The saxion-Higgs mixing allows reheating above BBN. But, depending on parameters, often reheat below the electroweak phase transition. (T_R correlated with μ.)

- Affleck-Dine? Unclear. Need to check for *Q*-ball problems (Berkooz, Chung, Volansky hep-ph/0507218)

- Low-temperature baryogenesis? Examples: Dimopoulos-Hall (*UDD* R-parity violation); darkogenesis (Shelton & Zurek, e.g. X^2UDD)

- Potentially need squarks to be light. (Generic for O*UDD*?)

CIRCLING BACK

- At the beginning, we had a list of some exotic signatures, which included in part:
  - Stopped Gluinos from Split SUSY(Arvanitaki et al.)
  - R-parity Violation at LHCb (Kaplan & Rehermann)
  - Asymmetric DM (Chang & Luty)
- The first could arise from gluino NLSPs with loop-suppressed decay to gluon + axino.
- The others could be related to the way baryogenesis works after a low reheat temp.

SUMMARY

- We’re in the LHC era! Let’s make sure we’re not missing something exotic and exciting.
- Traditional GMSB pheno. can lead to displaced decays. Possibility of early discovery or precise measurements.
- Taking the moduli problem seriously, one of the least ad hoc scenarios involves thermal inflation driven by a saxion, with MSSM couplings to reheat.
- This leads to its own suite of possible exotic collider signatures. (Plus possible axion dark matter, etc.)
- This is very much work in progress - still a lot of details and alternative scenarios to think through.

BACKUP SLIDES

RESOLUTIONS

	Measurement	Resolution
ECAL	E	$\delta E \sim 0.1\sqrt{E\text{ GeV}}$
	$\eta_{det}, \varphi_{det}$	$\sigma_\eta = 0.004/\sqrt{E/\text{GeV}}, \sigma_\varphi = 0.005/\sqrt{E/\text{GeV}}$
	θ_{dir}	$\sigma_\theta = \left(0.080 + \frac{\lvert z_{e.v.}\rvert}{100\text{ cm}}0.340\right)/\sqrt{E/\text{GeV}}$
	t_{det}	$\sigma_t = 100$ ps
TRT	φ_{dir}	$\sigma_{\varphi_{dir}} = 1$ mrad
Muon	p	$\sigma_p = 0.04p$
	θ_{dir},φ_{dir}	$\sigma_{\varphi_{dir}} = \sigma_{\theta_{dir}} = 15$ mrad
	t_{det}	$\sigma_t = 2$ ns

Table 1: Measured parameters and their resolutions in the ATLAS detector. The *det* subscripts refer to a position or absolute time measured in the detector. The *dir* subscripts refer to the direction of the energy/momentum as measured by the detector. The "effective z-vertex" $z_{e.v.}$ is found by extrapolating the particle's direction back in the $z - r$ plane to the point at which it intersects the $r = 0$ axis.

Cuts Shared by Discovery and Reconstruction Analyses:	
$\lvert\eta_{det}\rvert < 0.8$	Passes through barrel TRT
$r_d < 800$ mm	Leaves sufficiently many TRT hits for track to be found
$\Delta R(e^+, e^-) > 0.4$	Well-separated, unlike conversions
$E_T > 20$ GeV	Triggerable (2gamma20)
Cuts Specific to Discovery with Silicon:	
$r_d < 50$ mm	Electrons pass through all Si layers
$r_d > 0.05$ mm	Reduce background
DCA > 0.05 mm (either)	Reduce background
Cuts Specific to Discovery with TRT:	
$r_d > 1$ cm	Reduce background
DCA > 1 cm (either)	Reduce background
Cuts Specific to Reconstruction with ECAL+TRT:	
$z_{e.v.} < 1200$ mm	Pointing resolution not too degraded
$\Delta t > 0.3$ ns	Significantly delayed

Table 2: Cuts defining acceptance for $Z \to e^+e^-$ analyses. Unless marked "(either)", all cuts apply to *both* electrons in the decay.

Cuts Shared by Discovery and Reconstruction Analyses:	
$r_d < 4500$ mm	Passes through all muon layers
$\|\eta_{det}\| < 1.1$ at $r = 4.5, 7.0, 10.0$ m	Contained in the central muon spectrometer
Separation > 30 mm at $r = 4.5, 7.0, 10.0$ m	Resolve two muons
$r_d > 500$ mm	Significantly displaced vertex
$p_T > 20$ GeV	Triggerable
$\Delta t < 6$ ns (either)	Correct bunch-crossing ID

Table 3: Cuts defining acceptance for $Z \to \mu^+\mu^-$ analyses. Unless marked "(either)", all cuts apply to *both* muons in the decay. We take Δt to be measured at a radius of 7000 mm.