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, Josh Ruderman, Lian-Tao Wang

Goals

A goal of this talk is to suggest that there are interesting, and under-explored, connections between the cosmology of supersymmetric theories with moduli, the strong CP problem, and collider signals.

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.

Quick Review: SUSY Breaking & Scales

- One measure of how badly supersymmetry is broken is the gravitino mass, $m_{3/2}$.
- This is related to a fundamental measure of SUSY breaking, F_0 (dimensions of mass^2), by $m_{3/2} \sim F_0/M_P$.
- Throughout the talk: scenarios with superpartners at the 100 GeV to TeV scale (visible at LHC).

Quick Review, 2

- With $m_{SUSY} \sim 100$ GeV, there are still a variety of possible fundamental SUSY breaking scales.
- "Gravity mediation": Planck-suppressed operators, $m_{SUSY} \sim F_0/M_P$ means $\sqrt{F_0} \sim 10^{10}$ GeV (the *intermediate* scale), $m_{3/2} \sim 100$ GeV.
- Anomaly mediation: extra suppression, $m_{SUSY} \sim \alpha/(4\pi)\, F_0/M_P$, $m_{3/2} \sim 100$ TeV.
- Low-scale SUSY breaking: "messengers," $m_{SUSY} \sim \alpha/(4\pi)\, F_0/M_{mess}$, $m_{3/2}$ as light as meV.

Quick Review, 3

- In this talk I'll be saying "low-scale SUSY breaking" and "gauge mediation" interchangeably.

- GMSB, or gauge mediation, is the most natural way to communicate SUSY breaking to the Standard Model at low scales.

- I'll mostly consider $m_{3/2} \sim$ keV or lower. (Escapes gravitino cosmology constraints: Moroi et al., 1993)

- The gravitino is very light: other superpartners decay to it.

Outline, 1

- Begin with some collider physics of GMSB: will review work with Meade & Shih on long-lived neutralinos.

- General idea: if particles enter a detector from a direction different from the line back to the interaction point, have more observables, and thus can measure more precisely.

- Neutralino to Z + gravitino, Z to two leptons give a clean example of the LHC's precision power for long lifetimes

Outline, 2

- Detour to cosmology

- Argue that a *generic* expectation is that there are "moduli," weakly-coupled scalar fields, of order the gravitino mass (~ keV or lower, here), with Planck-scale expectation values in the early universe. (*Even* for SUSY-stabilized moduli.)

- Review moduli cosmology: they must move to their true minimum, where they oscillate and dominate energy density. Too weakly coupled to reheat above BBN. (cf Coughlan et al., '83)

Outline, 3

- Best solution: low-scale inflation (Randall & Thomas, '94) to dilute them; need an inflaton that couples more strongly
- A *saxion* (scalar associated with solution of strong CP problem) can do the job with minimal ad hoc tinkering
- Predicts new collider signature: decay to axino
- Interesting challenge to distinguish from GMSB signature with gravitino ↔ axino

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 (Kaplan, Luty, Zurek; 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.)

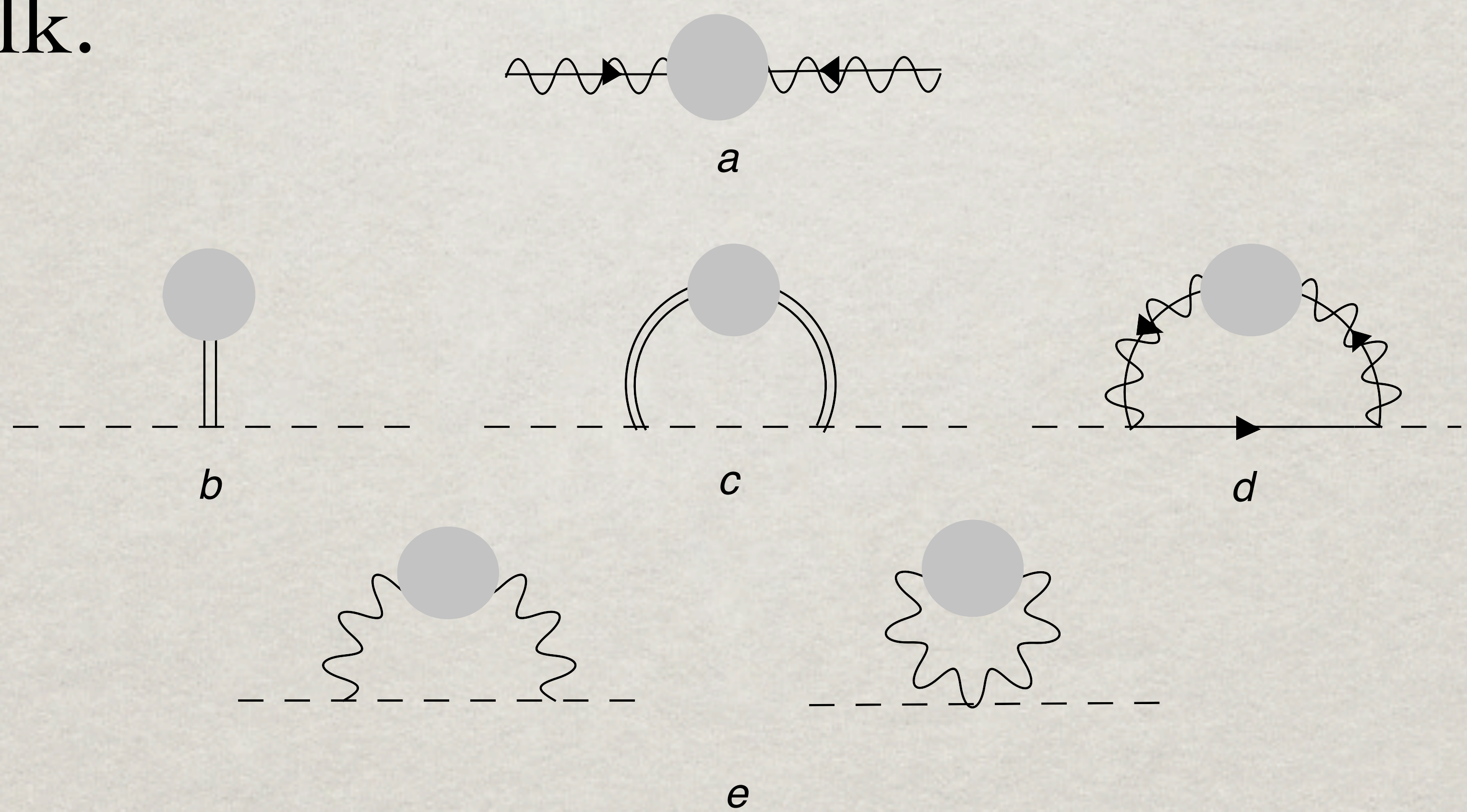
- What needs more thought are less traditional places new physics could hide.

- Exotic signatures arise very naturally; in this talk I will show you a few different ones that emerge from thinking about low-scale SUSY breaking.

- As a theorist, it's easiest to feel motivated to study exotic signatures if they emerge from nice models.

GMSB

- **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

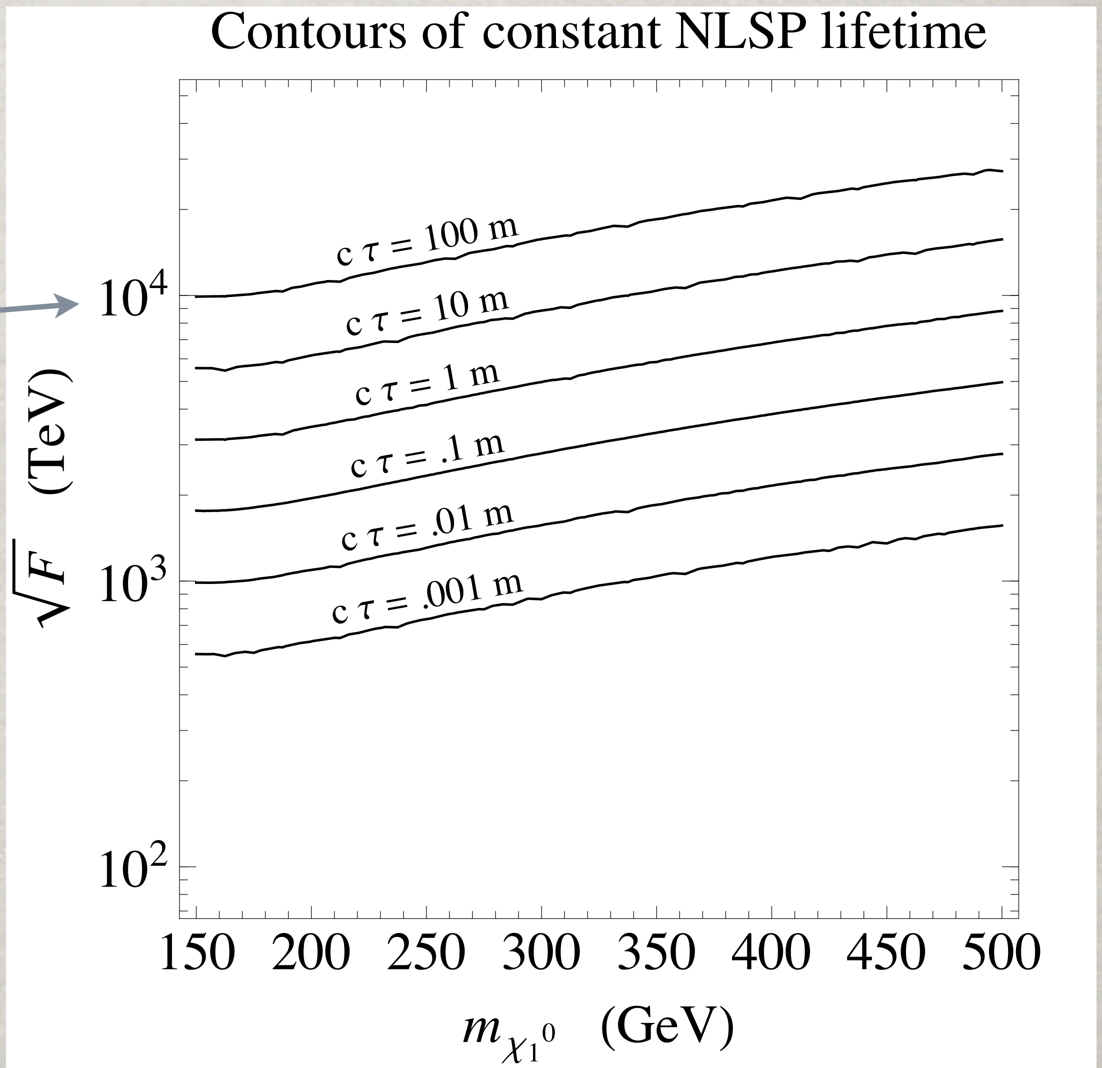
- What scale do we expect SUSY to be broken at?
- GMSB works for $m_{3/2}$ from below an eV up to about a GeV; above that, F/M_P flavor corrections are dangerous. (Could go higher, with sequestering.) Ideal for *effective field theory*.
- Some scenarios (direct mediation, single-sector models, Komargodski/Seiberg 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:*

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

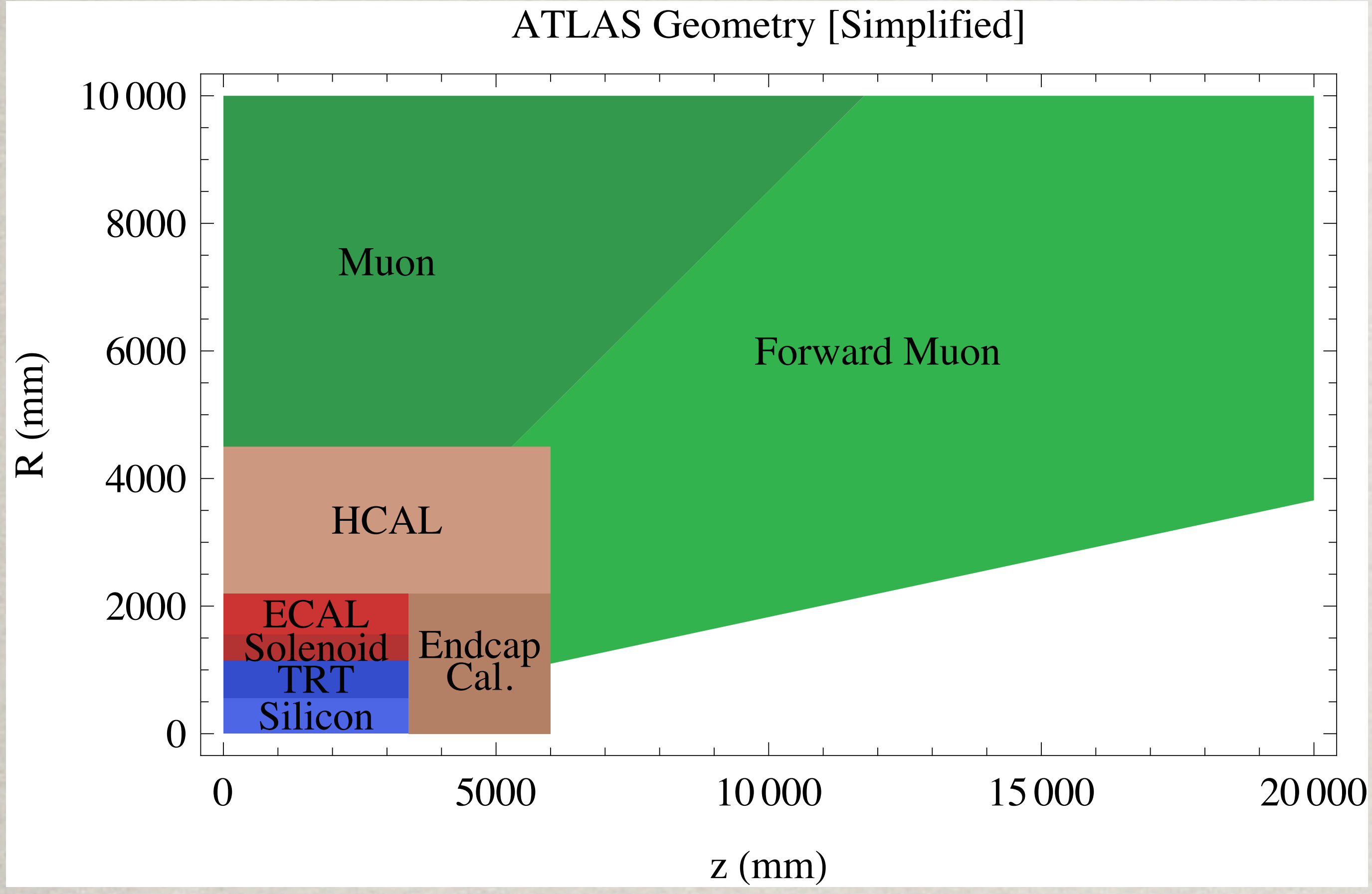
$$m_{3/2} \sim 10\,\text{KeV}$$

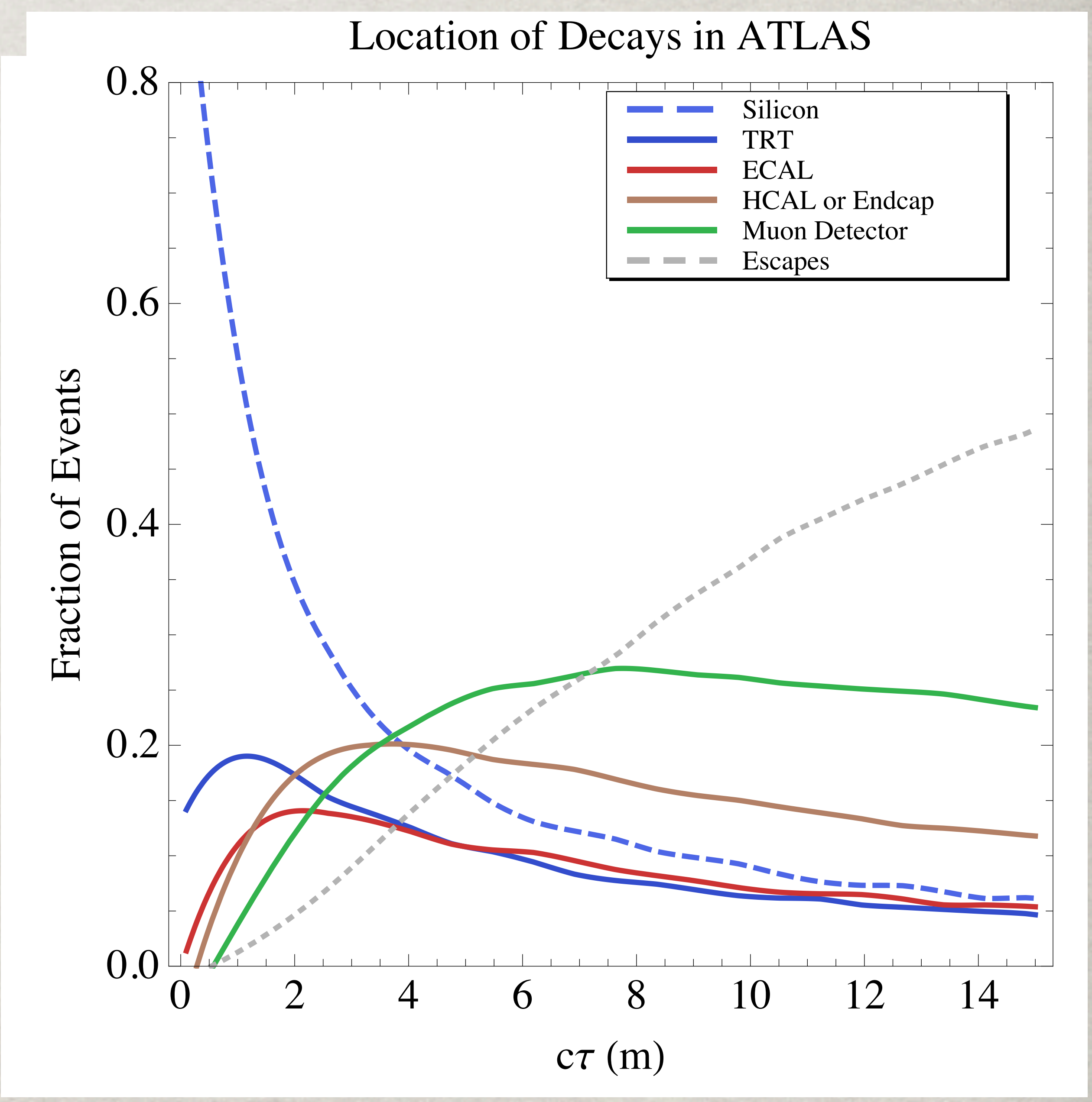


Charged NLSPs can be "CHAMPS": highly ionizing tracks

Neutrals are trickier: look for their decay products

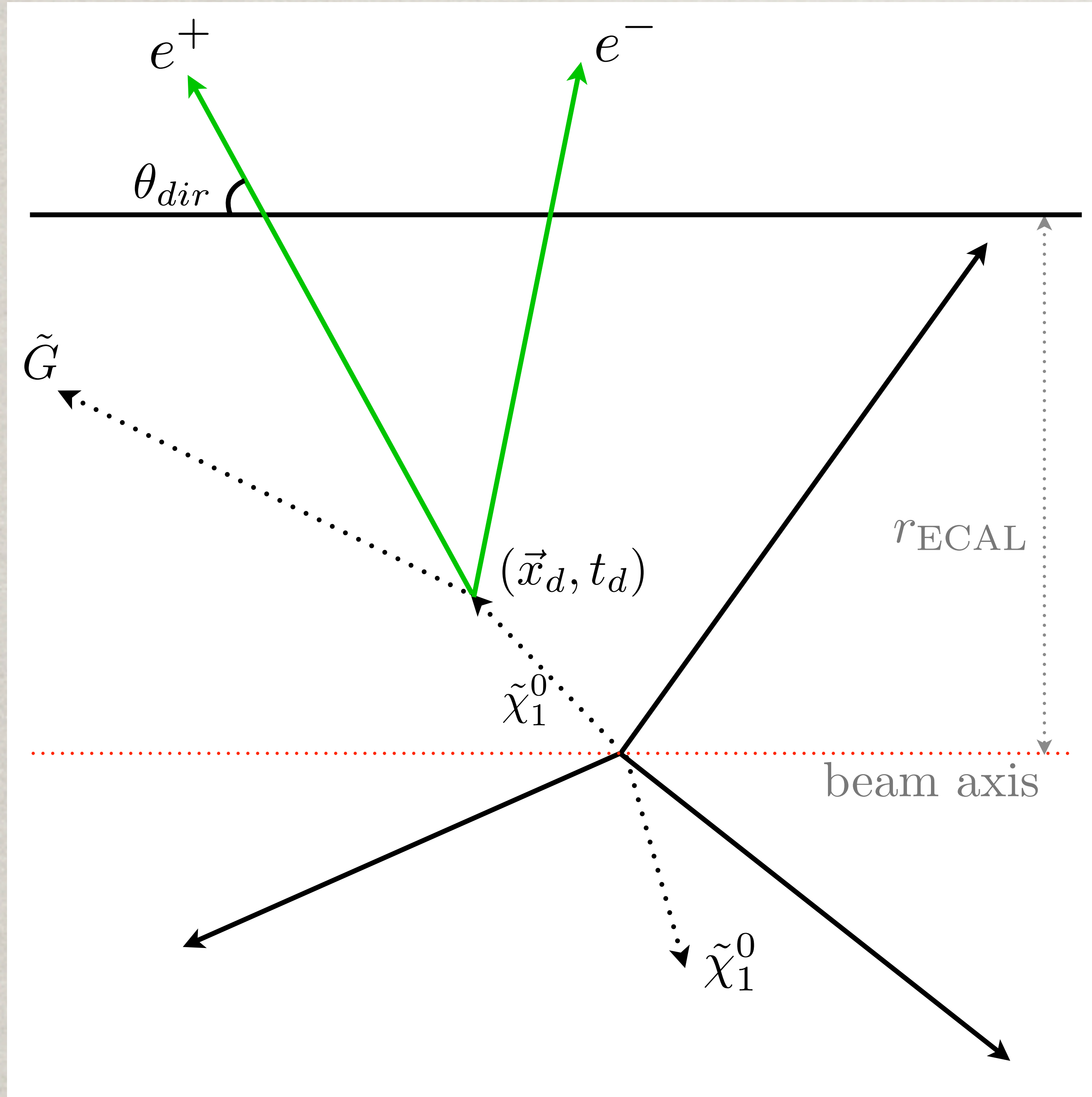
Where Do Decays Happen?





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

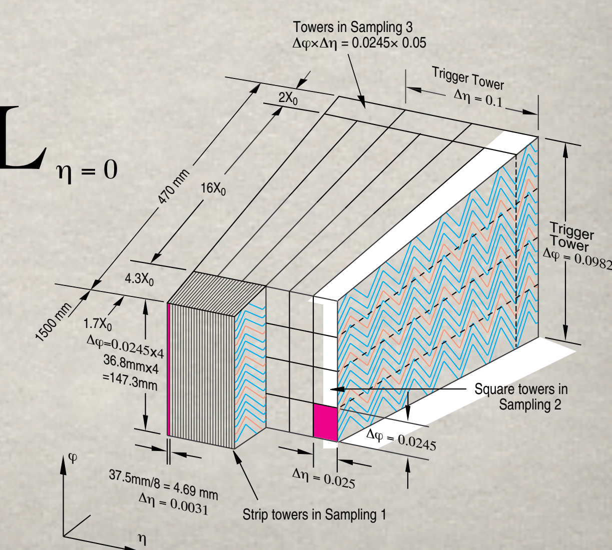
Schematic of a Long Lifetime Event



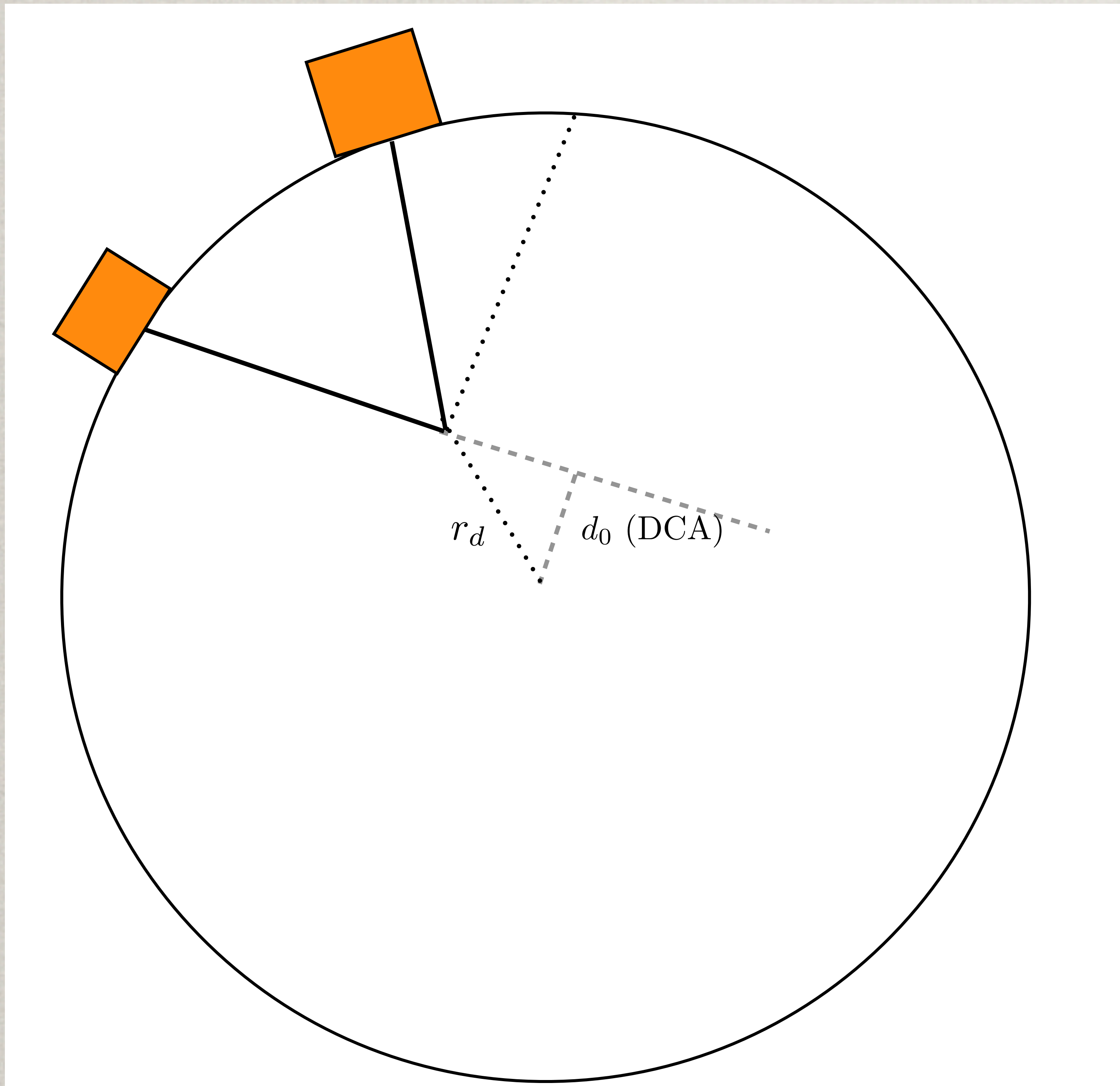
If decay vertex x_{d} is displaced enough, electron tracks will not be reconstructed.

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

Granular ECAL measures θ_{dir}:



Extrapolating Back



$r_{\rm d}$: Decay radius; use absence of hits closer to beamline

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

$t_{\rm det}$: Time of detector signal in calorimeter

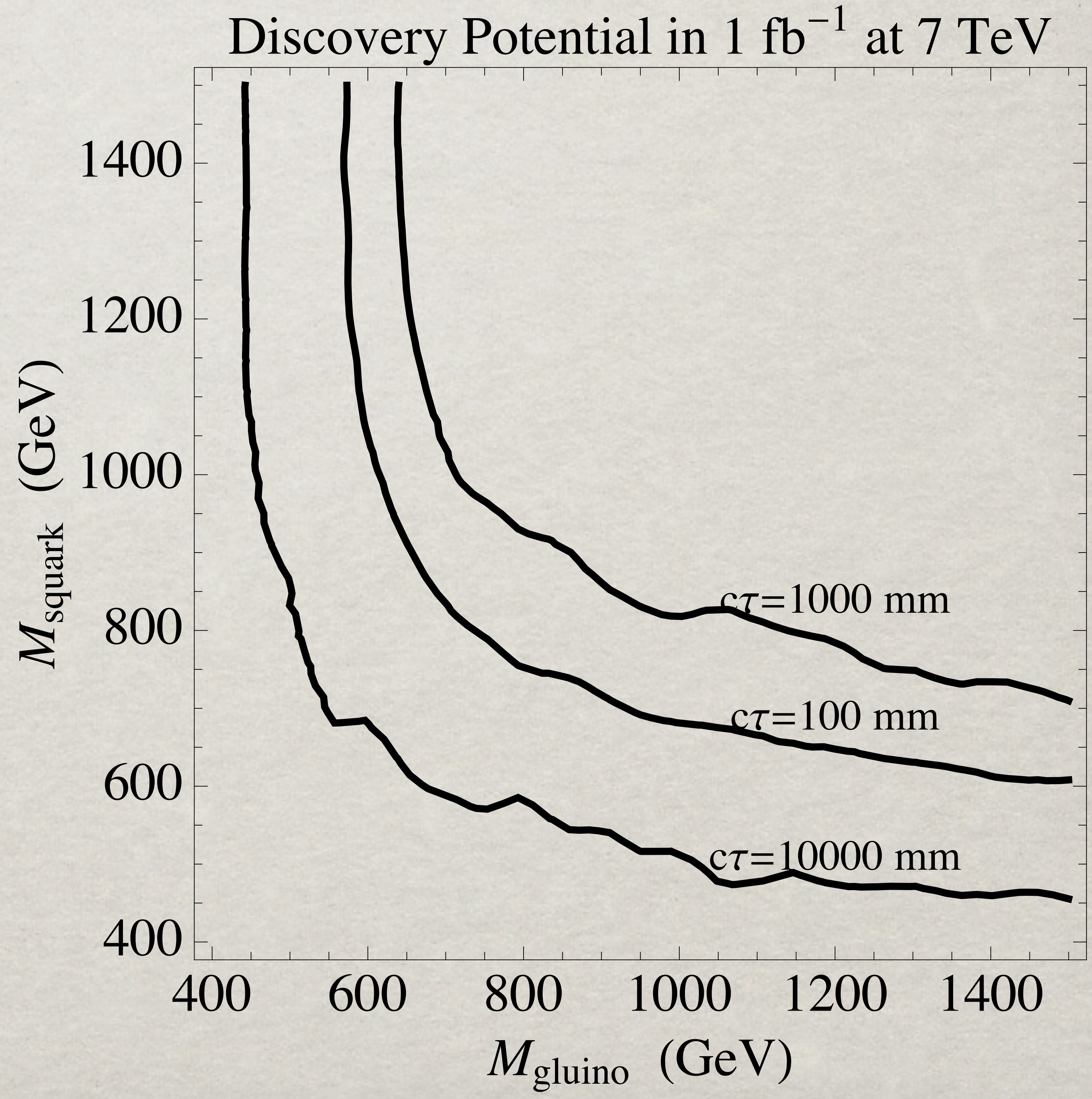
Discovery Potential

Choose cuts for 5σ confidence decay is not prompt.

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

(Implicit assumption: background is tiny.)

Fixed NLSP mass of 250 GeV.



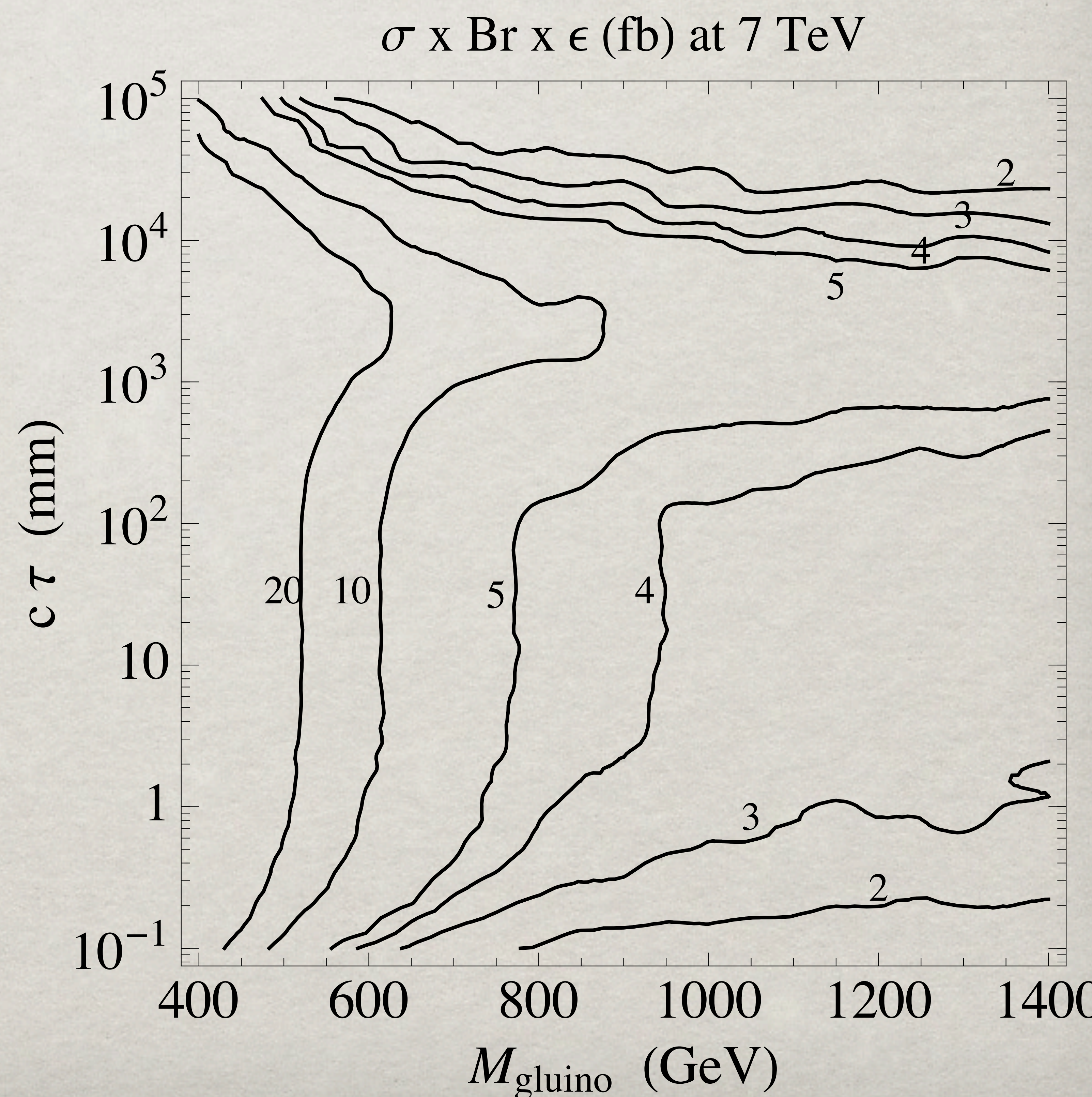
Discovery Potential

Contours of constant estimated #events.

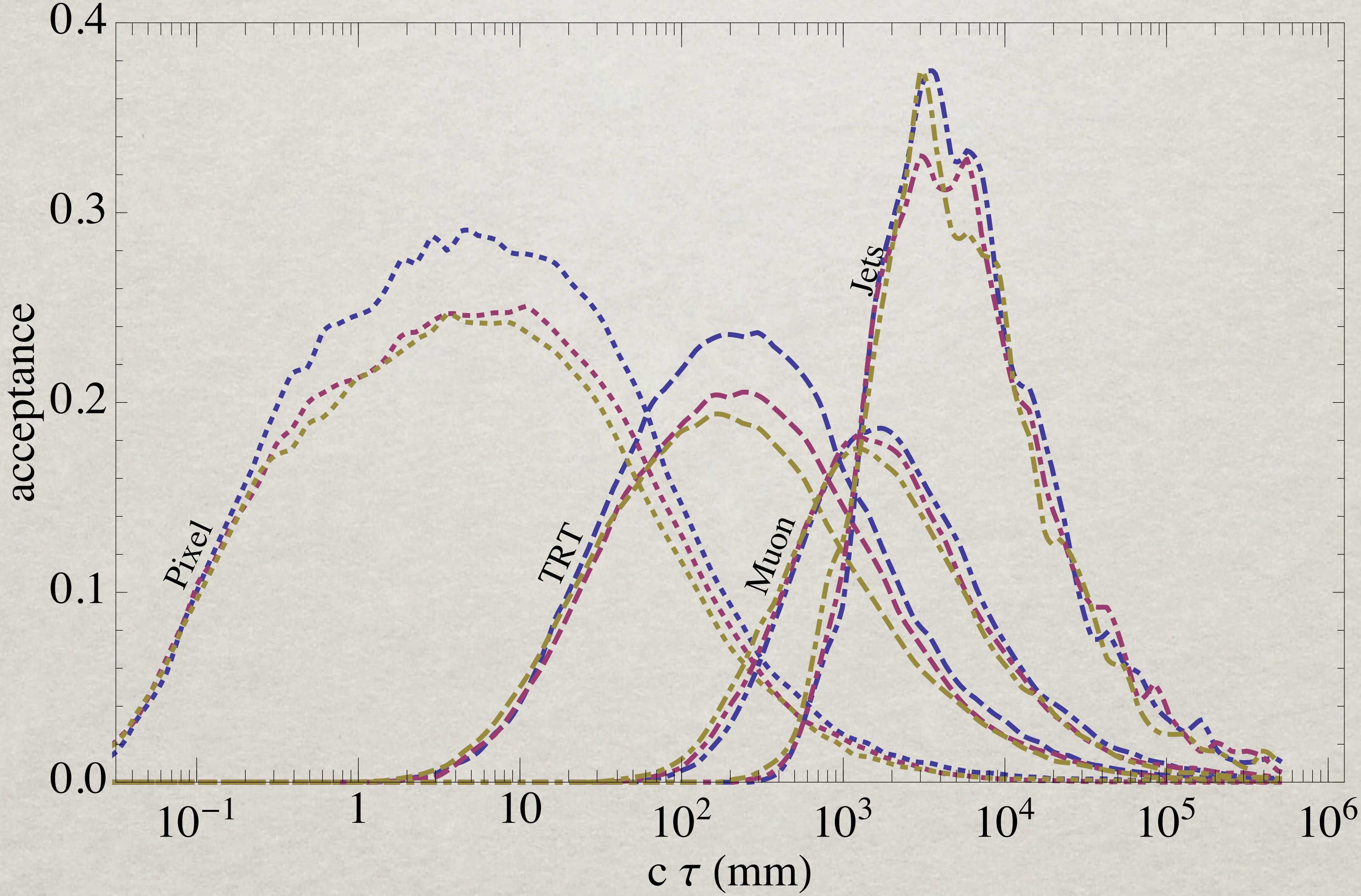
All squarks are at 1 TeV.

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 $\mathrm{Br}(Z \rightarrow \text{jets})/\mathrm{Br}(Z \rightarrow e^+e^-)$

Fitting an Event

We would like to measure all properties of the decay chain

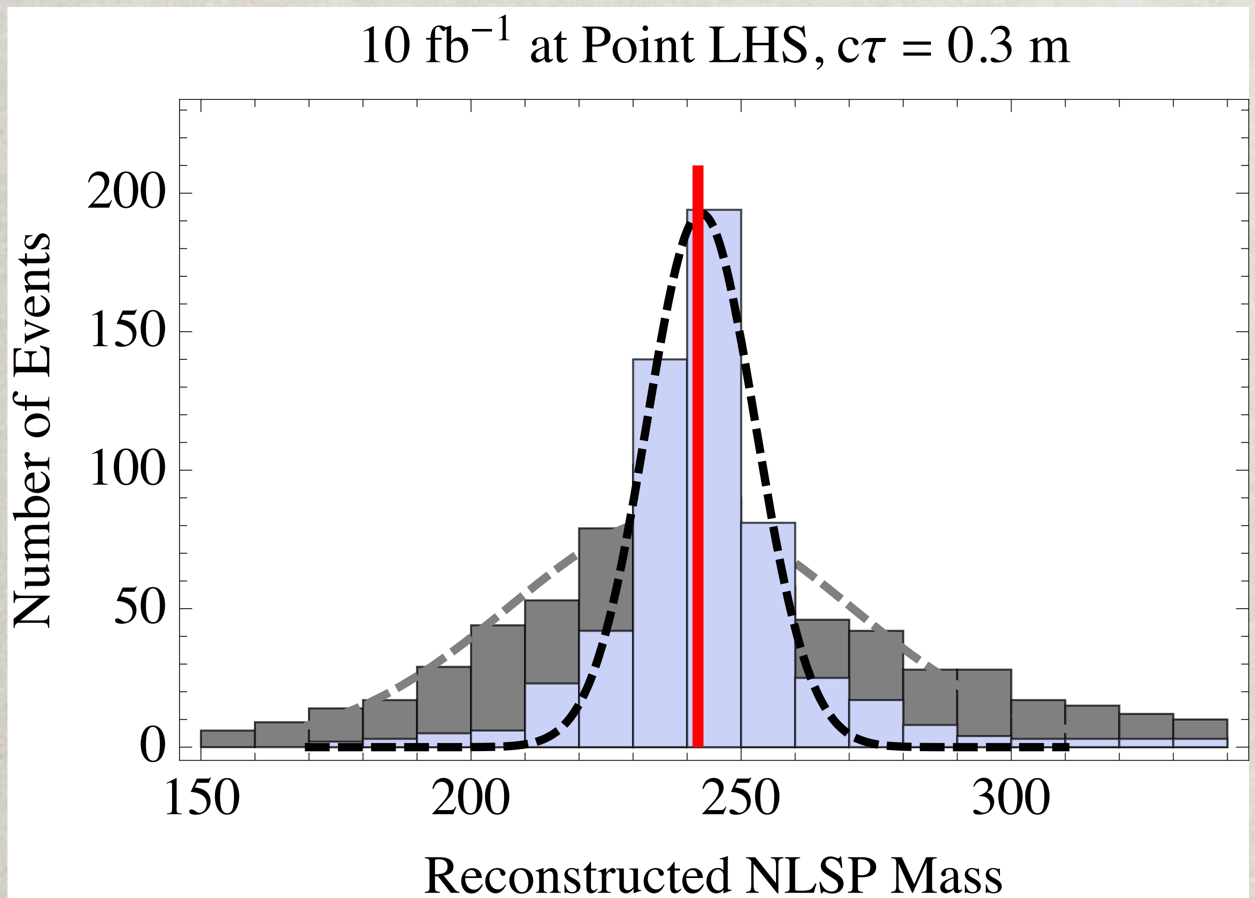
$$\tilde{\chi}_1^0 \rightarrow \tilde{G} + Z \rightarrow \tilde{G} + e^+ + e^-$$

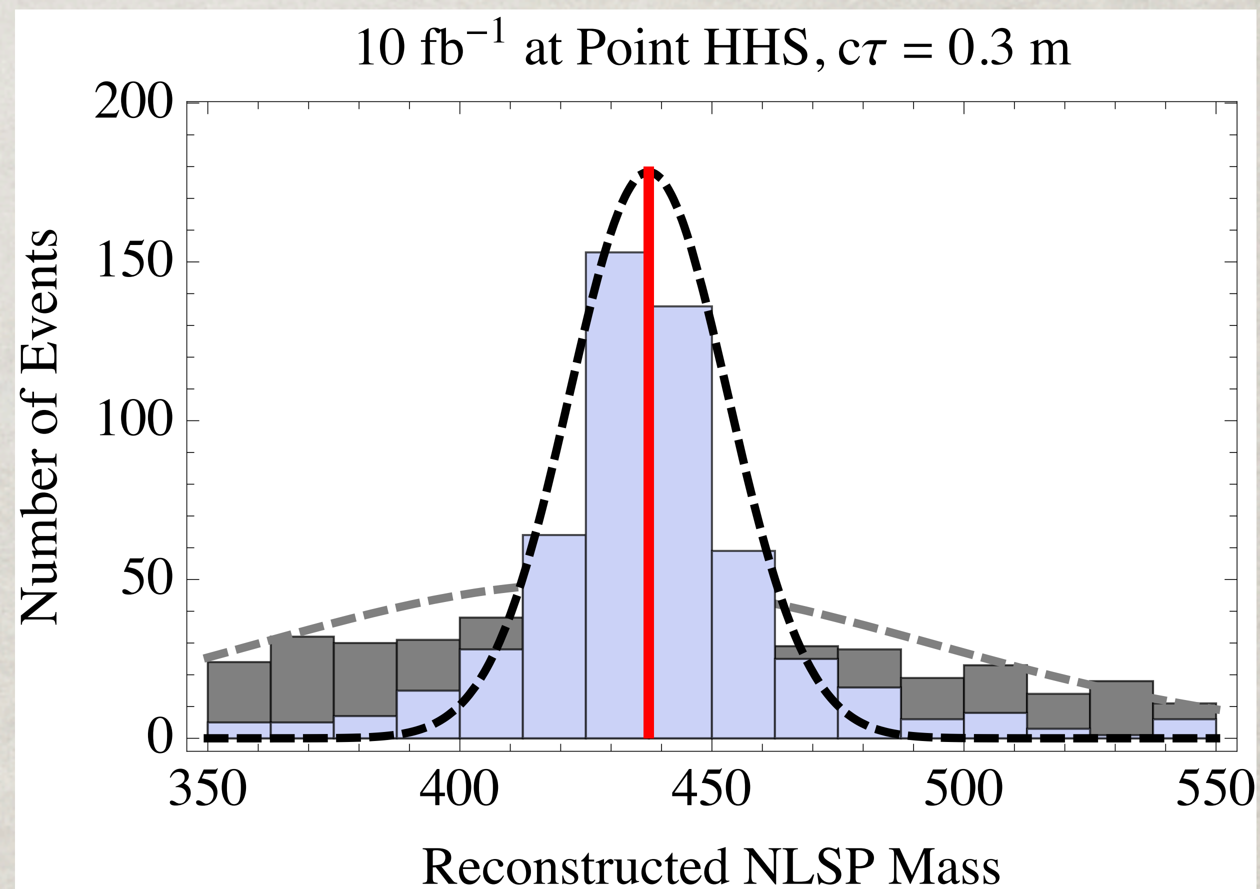
This would mean measuring the decay vertex and time, ($\boldsymbol{x}_\mathrm{d}$,$t_\mathrm{d}$), and the momenta $\mathbf{p}(e^+)$ and $\mathbf{p}(e^-)$. These are 10 unknowns.

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

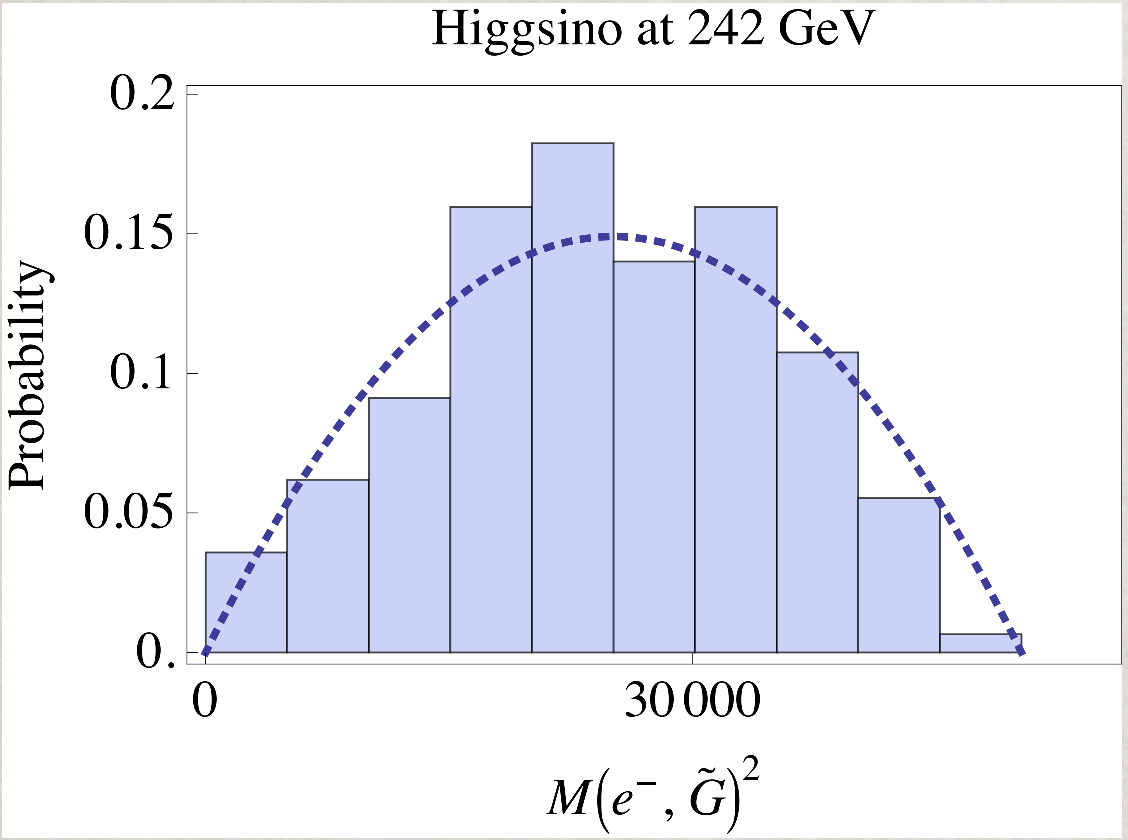
Add in TRT (tracking) information and fit (needs new outside-in tracking algorithm; outside scope of this talk):

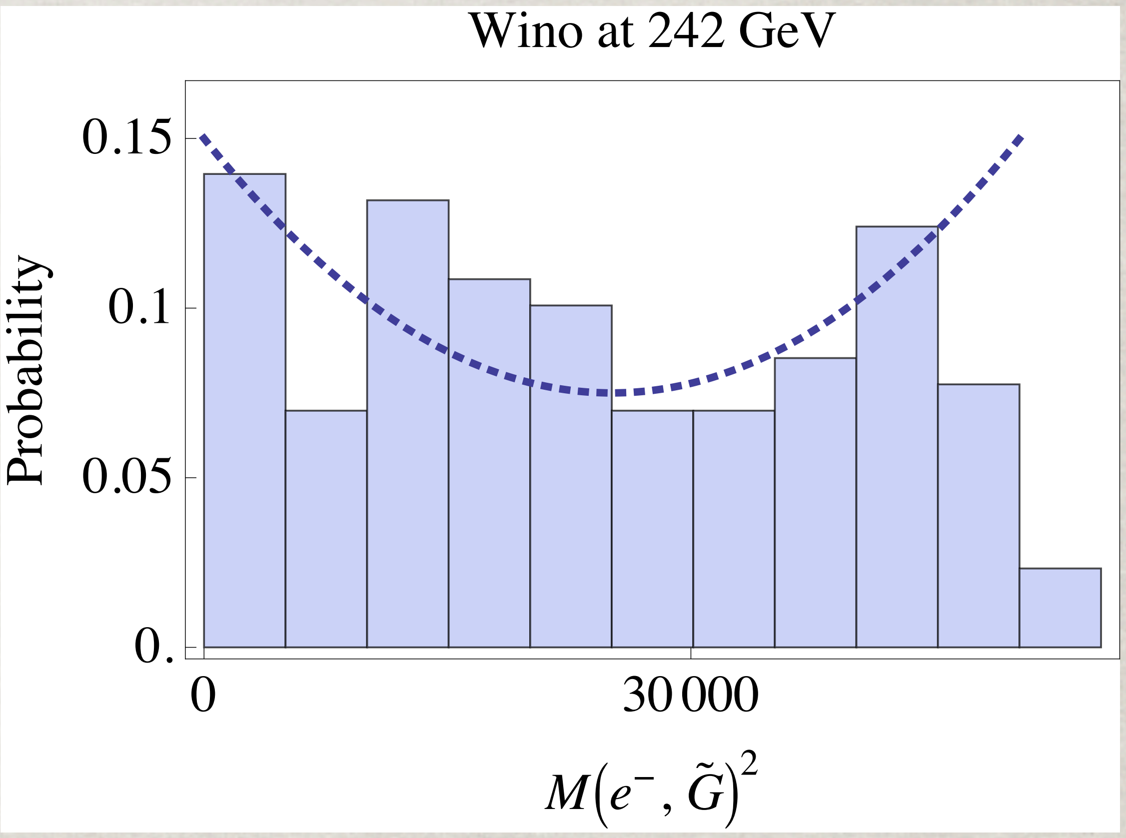




Get an accurate measure of NLSP mass (assuming gravitino is effectively massless).

Measuring Details of Vertices





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.

On to Cosmology...

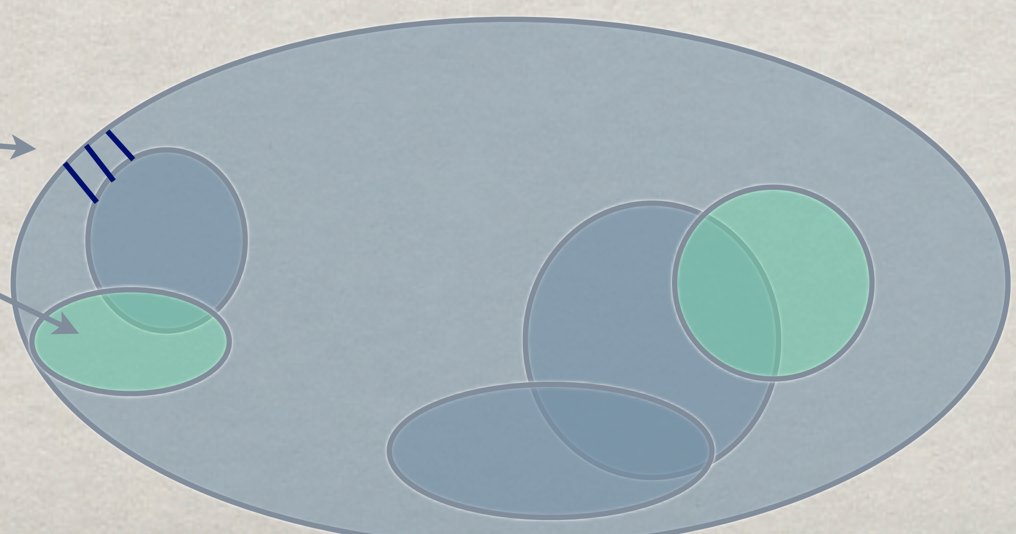
- Now I'm going to veer in a different direction. Bear with me; it's not completely unrelated.
- I want to investigate moduli and their implications for low-scale SUSY breaking.
- The main issue will be cosmology.
- In the end, this will lead us back to possible exotic collider physics.

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.
- $\Rightarrow$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.
- (Otherwise $m \sim m_{3/2}$ is obvious.)
- 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: $f \approx \frac{2aT_* A e^{-aT_*}}{\sqrt{3}M_P} = (2T_*)^{3/2} m_{3/2}$
- 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!

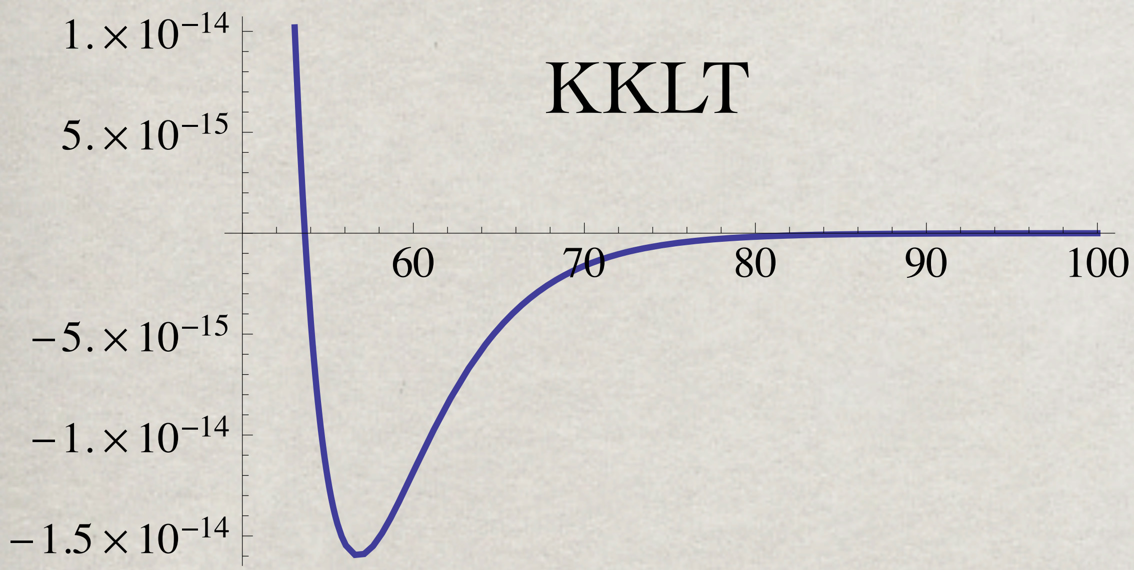
How General Is It?

- 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.!

Clearest In Pictures:

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

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



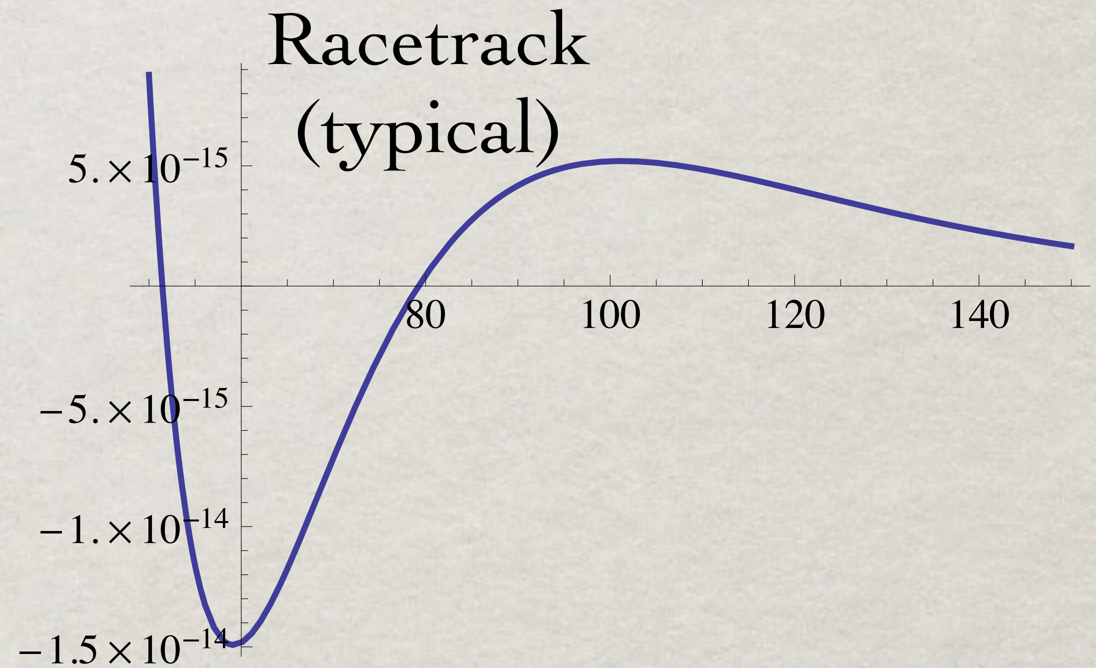
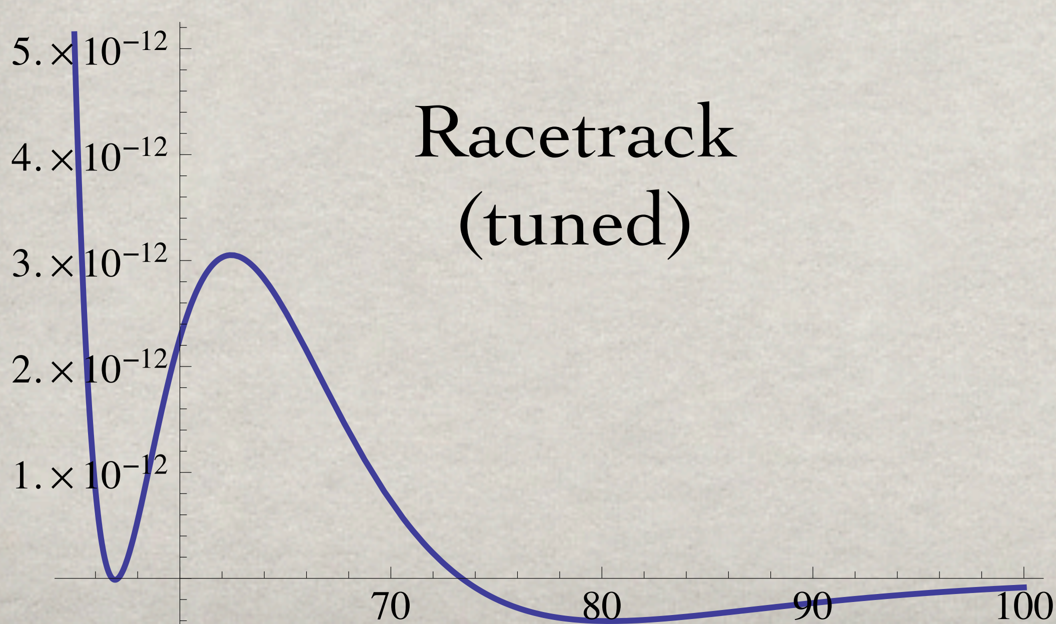


Exhibit C: tuned shallow AdS minimum, $m_T >> m_{3/2}$.



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.

Tuning and Gravitinos

- 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.
- Also, MSSM partners decay to gravitinos.
- Modulus can decay before BBN, but have to check that gravitinos don't spoil successful cosmology. (Work in progress.)

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); **Choi, Chun, Kim, Park, Shin 1102.2900 (last week!)**

- 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 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")

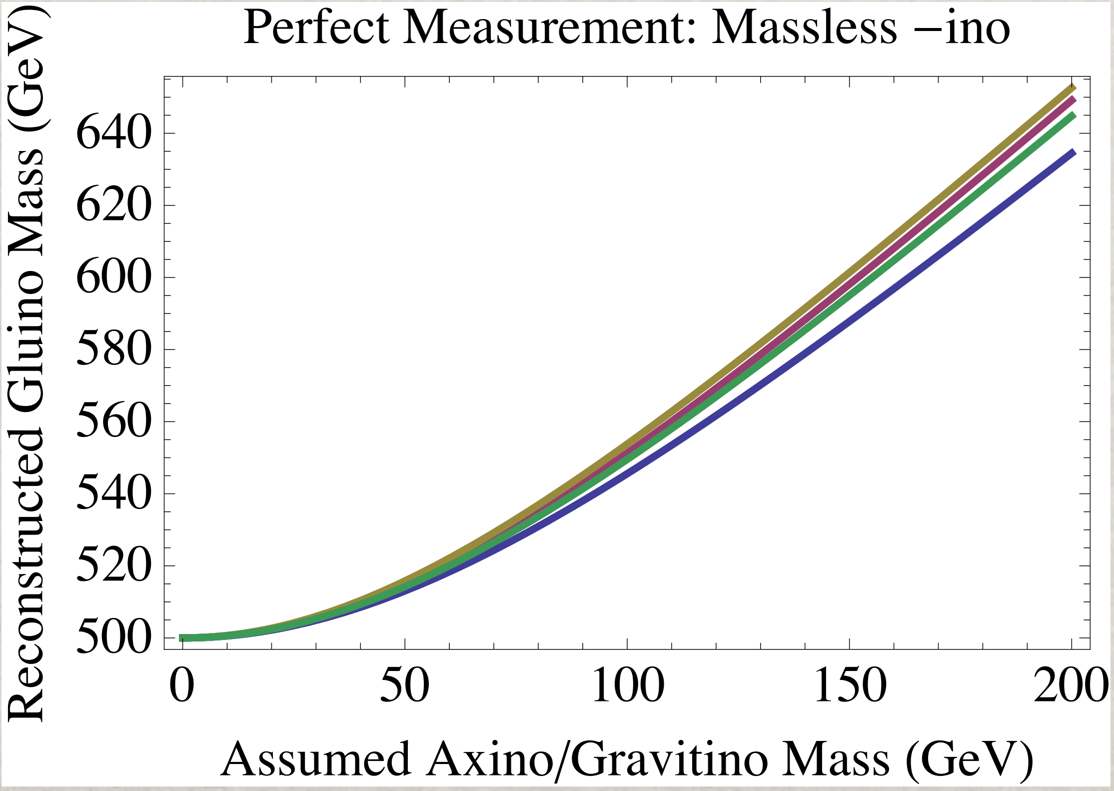
- Depending on the values of F and f_a, either one could predominate.

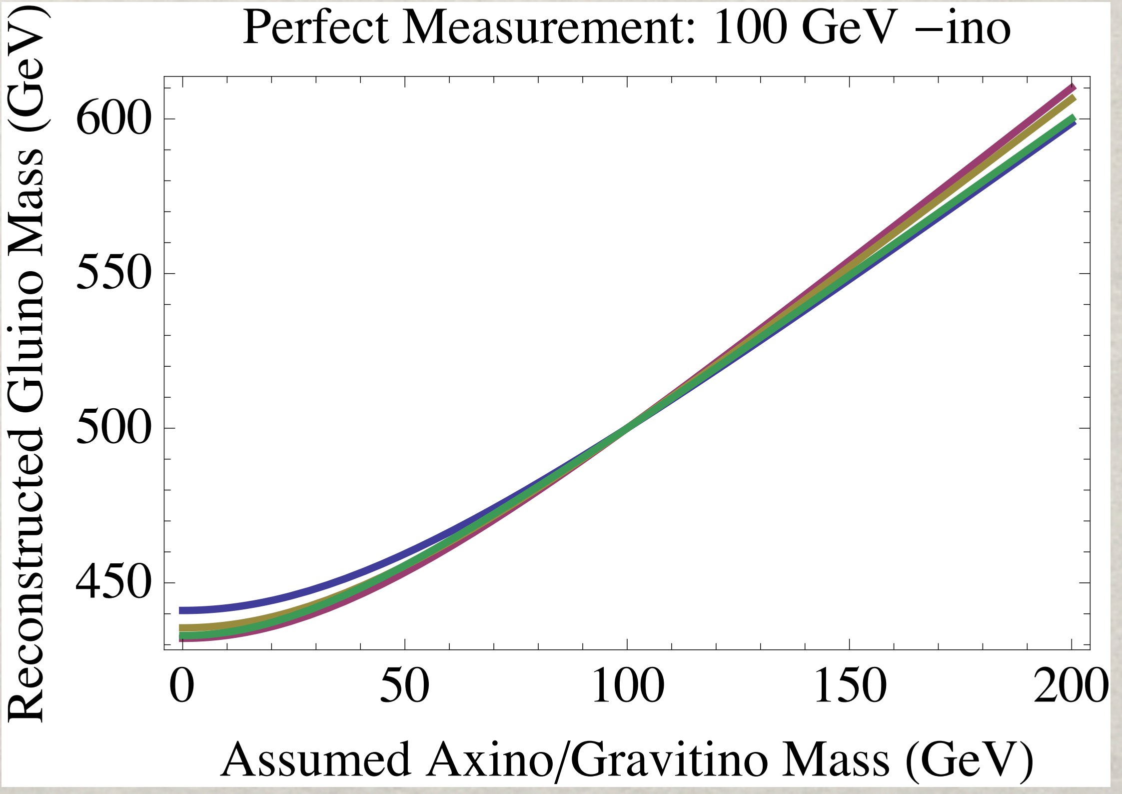
- If the axino dominates, could be gravity mediation!

- GMSB case could have a reasonable fraction of decays to $\gamma + \tilde{G}$, which is down by a loop for axinos.

Axino v. Gravitino

- Convincing sign physics is something *other* than just low-scale GMSB: a nonzero mass for the "gravitino"
- For instance, axino mass is order μ
- One option? Gluino mass in chain $\tilde{g} \to b\bar{b}\tilde{\chi}_1^0 \to b\bar{b}Z\tilde{G}$ (combinatoric difficulties; need high precision)





Another Option

While determining masses higher up the chain might still prove to be a viable option (esp. if sleptons happen to be in the right place!), I'll try a different approach.

Work in progress; I can't say definitively it will work.

Worst case: interesting extension of earlier work with Meade and Shih to $H \rightarrow \tau^+\tau^-$.

Mass Determination, 1

Earlier I explained that for $\tilde{\chi}_1^0 \to \tilde{G} + Z \to \tilde{G} + e^+ + e^-$ we can measure the decay ($\boldsymbol{x}_\mathbf{d}$, t_d), and $\mathbf{p}(e^+)$, $\mathbf{p}(e^-)$.

Thus we know the Z four-momentum and the neutralino's speed, but not its energy.

This means we can **boost** the Z to the χ^0 rest frame, where its energy is:

$$E_{Z;0} = \frac{m^2_{\tilde{\chi}_1^0} + m^2_Z - m^2_{\tilde{G}}}{2m_{\tilde{\chi}_1^0}}$$

This is the invariant combination of the mass of the χ^0 and the gravitino (or axino) that we measure.

Mass Determination, 2

On the other hand, suppose we could detect and reconstruct Higgs decays equally accurately. Then we would be able to measure the Higgs energy in the χ^0 rest frame,

$$E_{h;0} = \frac{m^2_{\tilde{\chi}^0_1} + m^2_h - m^2_{\tilde{G}}}{2m_{\tilde{\chi}^0_1}}$$

And we could then separately discern the neutralino and gravitino (or axino) masses from the combinations:

$$E_{h;0} - E_{Z;0} = \frac{m^2_h - m^2_Z}{2m_{\tilde{\chi}^0_1}}$$

$$\frac{E_{h;0}}{E_{Z;0}} = \frac{m^2_{\tilde{\chi}^0_1} - m^2_{\tilde{G}} + m^2_h}{m^2_{\tilde{\chi}^0_1} - m^2_{\tilde{G}} + m^2_Z}$$

How Small Are the Effects?

To illustrate: $E_{Z;0}$ = 141.6 GeV for m_χ = 250 GeV and a massless gravitino, and also for m_χ = 261 GeV and a 50 GeV axino, or m_χ = 289 GeV and a 100 GeV axino.

For a 120 GeV Higgs, these cases give $E_{H;0}$ = 153.8 GeV, 153.3 GeV, and 152.2 GeV, respectively.

This is asking a lot of precision from a hadron collider! Can we distinguish 0 from 50 GeV, or at least 0 from 100 GeV?

Higgs to Tau+ Tau-

- If $H \rightarrow \tau^+\tau^-$ is our search channel, the earlier techniques let us extrapolate tracks back to a vertex ($\boldsymbol{x}_\mathbf{d}$, t_d), and measure **visible** momenta, $p_\mathrm{vis}(\tau^+)$, $p_\mathrm{vis}(\tau^-)$.

- **Collinear approximation**: $p(\tau^+) \approx x\, p_\mathrm{vis}(\tau^+)$, and $p(\tau^-) \approx y\, p_\mathrm{vis}(\tau^-)$.

- **Higgs mass constraint**: $(p(\tau^+) + p(\tau^-))^2 \approx m_\mathrm{h}{}^2$. This implies $2xy\, p_\mathrm{vis}(\tau^+) \cdot p_\mathrm{vis}(\tau^-) \approx m_\mathrm{h}{}^2$, so $y \approx C/x$ for known C.

- Have one more unknown and no constraint!

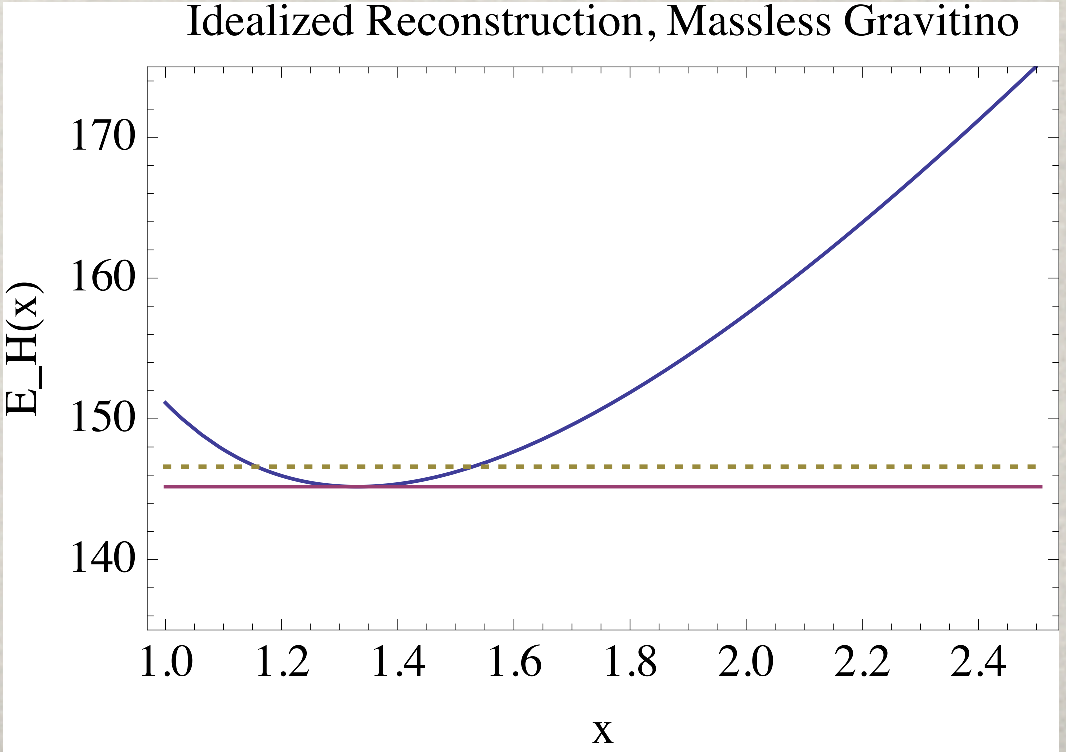
Higgs to Tau+ Tau-

- The quantity we really want to measure is the Higgs energy in the χ^0 rest frame,

$$E_{H;0}(x) = \gamma\left(xE_{vis}(\tau^+) + yE_{vis}(\tau^-) - \vec{\beta}\cdot(x\vec{p}_{vis}(\tau^+) + y\vec{p}_{vis}(\tau^-)\right)$$

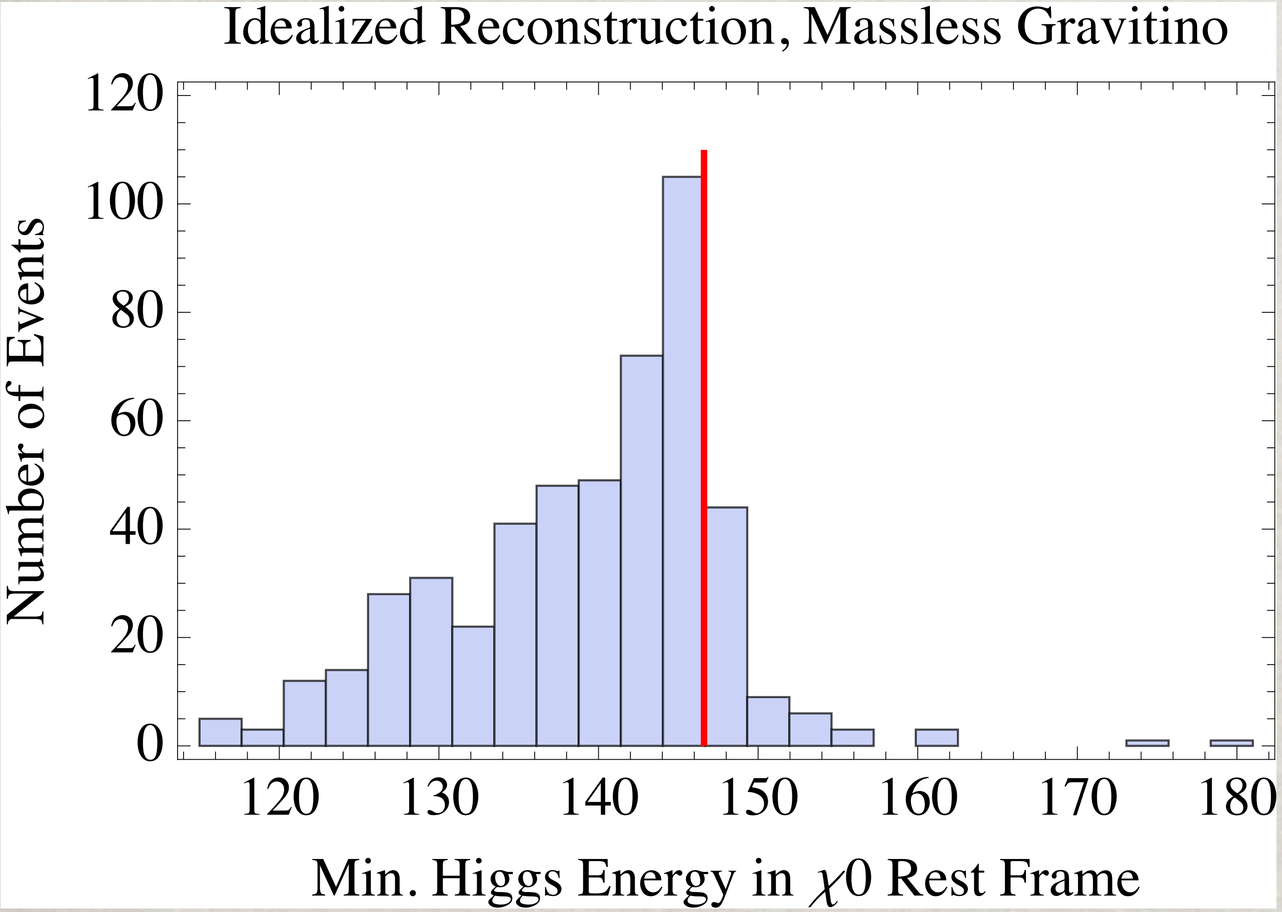
- Using $y \approx C/x$, this is a linear combination of x and C/x, and we know $x \geq 1$ and $y \geq 1 \Rightarrow x \leq C$.

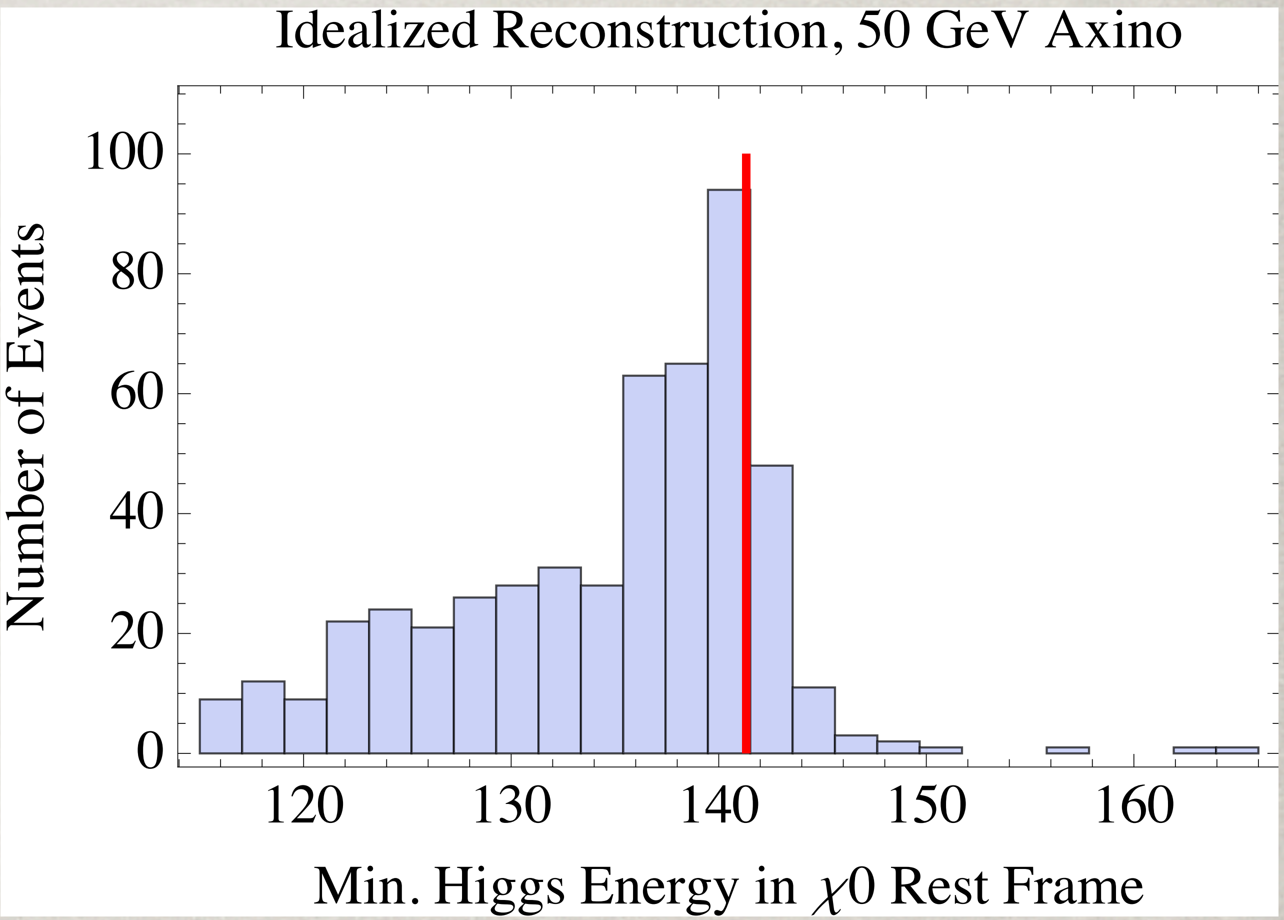
- Read off the *minimum*, which must be less than the true $E_{H;0}$. (Usually turns out to be close to it!)



Axino Mass Determination

Warning! Plots assume perfect reconstruction. Work on a more realistic estimate is underway.





Edge isn't sharp due to tau mass. It moves from 146.6 GeV down to 141.3 GeV as axino mass increases to 50 GeV.

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? Dimopoulos-Hall (UDD R-parity violation) is **ruled out** for gauge mediation. Darkogenesis? (Shelton & Zurek, e.g. X^2UDD)
- Potentially need squarks to be light. (Generic for OUDD?)
- Room for more exotic collider signatures!

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. Axino vs. gravitino?

- 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	$\sigma_p = 0.04p$
	$\theta_{dir}, \varphi_{dir}$	$\sigma_{\varphi_{dir}} = \sigma_{\theta_{dir}} = 15$ 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 $Z \rightarrow e^+e^-$ 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.

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:

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

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