GGM AND COLLIDERS

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YITP

Based on

PM, M. Reece, D. Shih **arXiv:0911.4130 + 1006.4575**

Outline

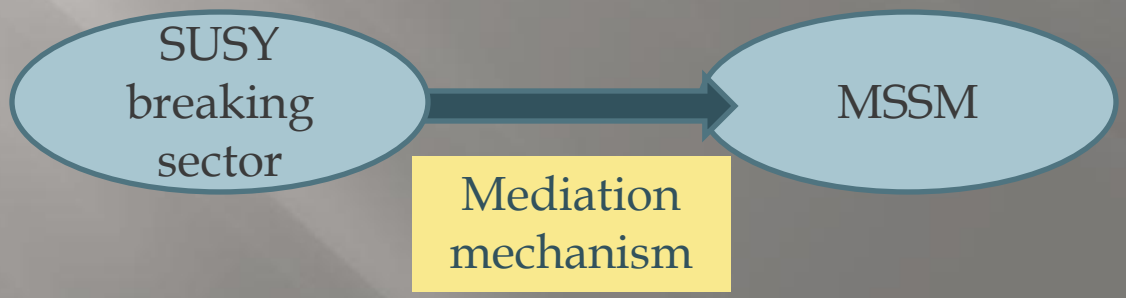
- SUSY and GGM Overview
  - Most ``conservative" and most expansive set of possibilities that are theoretically motivated
- Collider signatures of GGM: Searching for generic NLSPs
  - Bino, Wino, Higgsino Searches
- Delayed NLSPs
  - Early LHC discoveries

Supersymmetry

- The world around us is not supersymmetric
- What we really are interested in measuring is how SUSY is broken, parameterized by soft SUSY breaking parameters:

$$M_1, M_2, M_3, m^2_{QUDLE},$$
$$\mu, B\mu, m^2_{H_u,H_d}, A-terms$$

- Given by some theory that mediates ~~SUSY~~ to us



Two Basic Mediation Mechanisms

- Gravity Mediation or Gauge Mediation

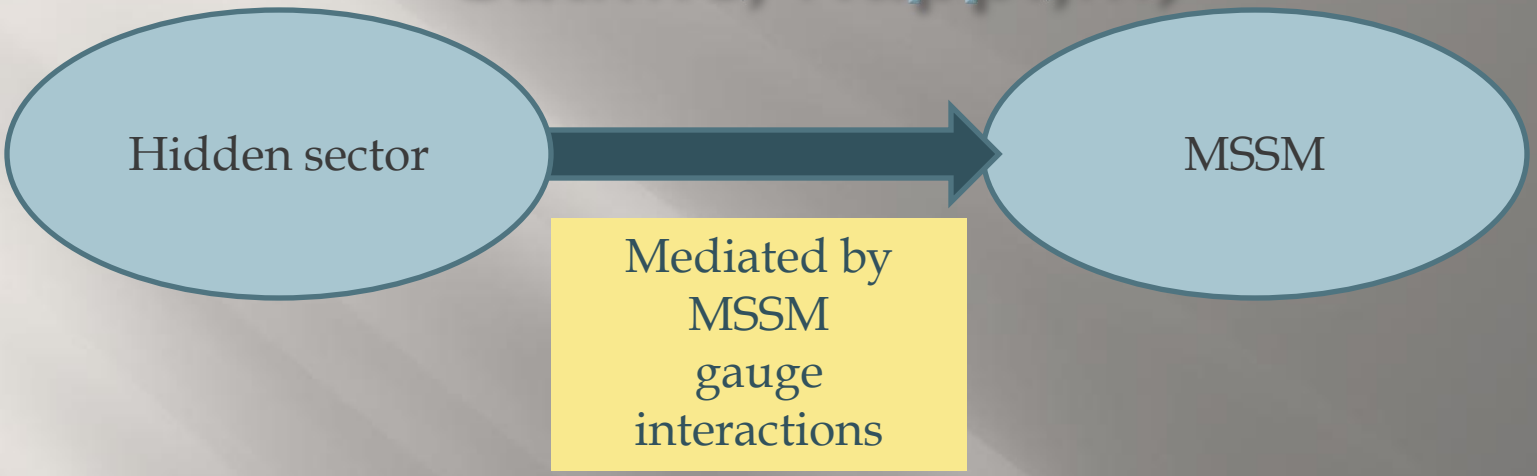
Gravity

Flavor problems
Ad hoc
DM candidate

Gauge

Flavor works great
Calculable
DM not as simple

Gauge Mediation (Ovrut,Dine,Claudson,Wise,Alvarez-Gaume, Nappi,…)



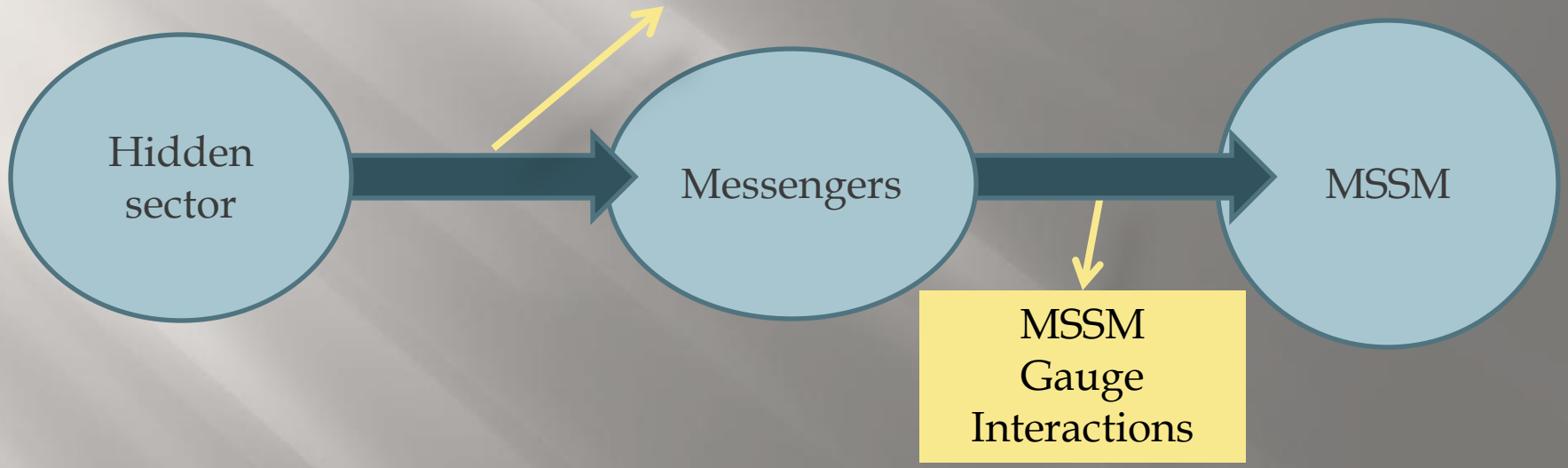
- Gives solution for flavor problem of MSSM
- Allows for calculable models of both SUSY breaking and its mediation
- Allows for models of DSB as an explanation of the TeV scale naturally (Witten)

Minimal Gauge Mediation

(Dine, Nelson, Shirman, ...)

$$\langle X \rangle = M + \theta^2 F$$

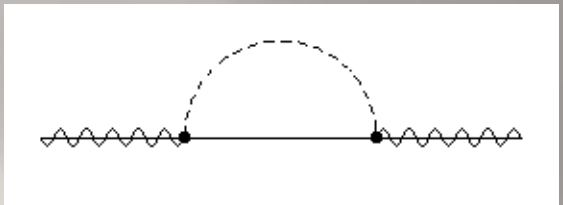
$$W = X \Phi \tilde{\Phi} + \ldots$$



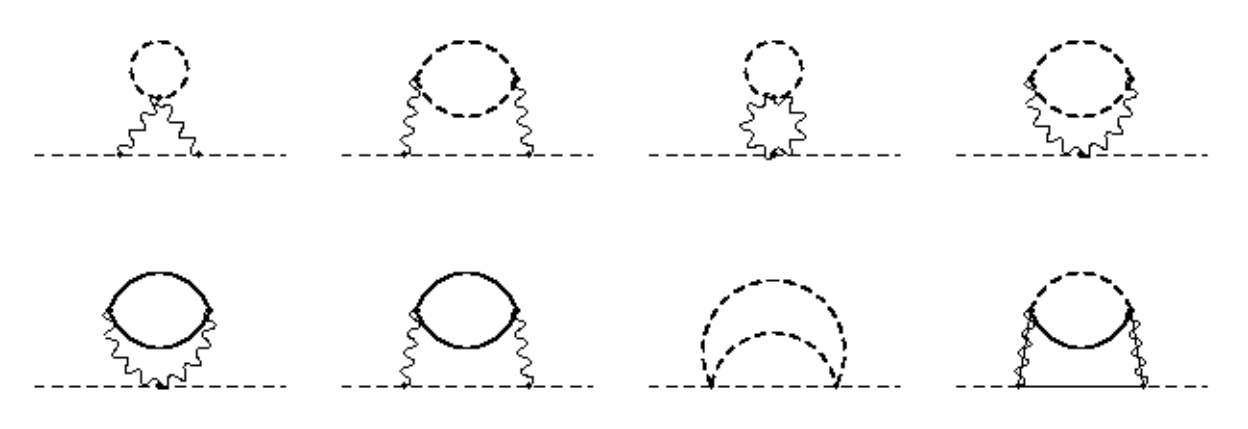
Messenger spectrum is not supersymmetric

$$m_{\pm}^2 = M^2 \pm F$$

Calculation of Soft Masses in MGM



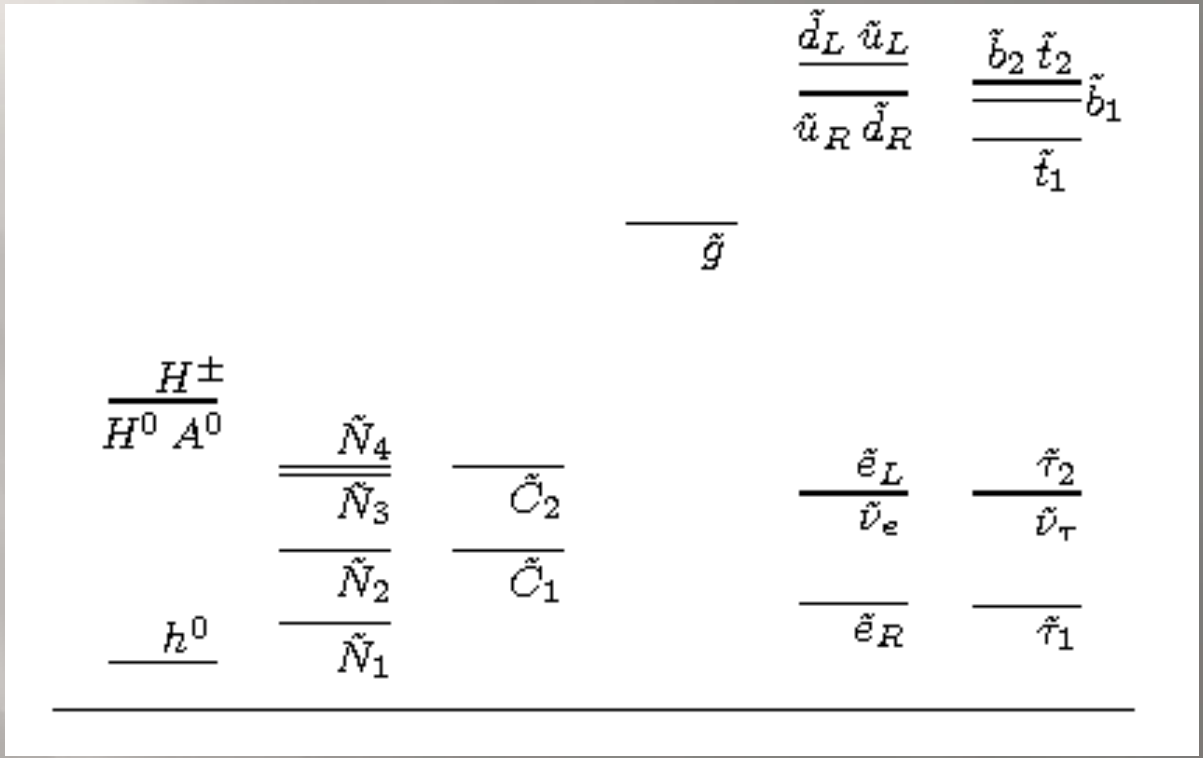
$$m_{\lambda_r} \sim \alpha_r \frac{F}{M}$$



$$m_{\tilde{f}} \sim \frac{F^2}{M^2} \sum_{r=1}^{3} \alpha_r^2 c_2^r$$

$$m_{\tilde{f}} \sim m_\lambda \sim \alpha \frac{F}{M}$$

Typical Spectrum of mGMSB



Colored sparticles typically are the heaviest, followed by weak, then hypercharge

Light Gravitino

$$m_{3/2} \sim \frac{F}{M_{Pl}}$$

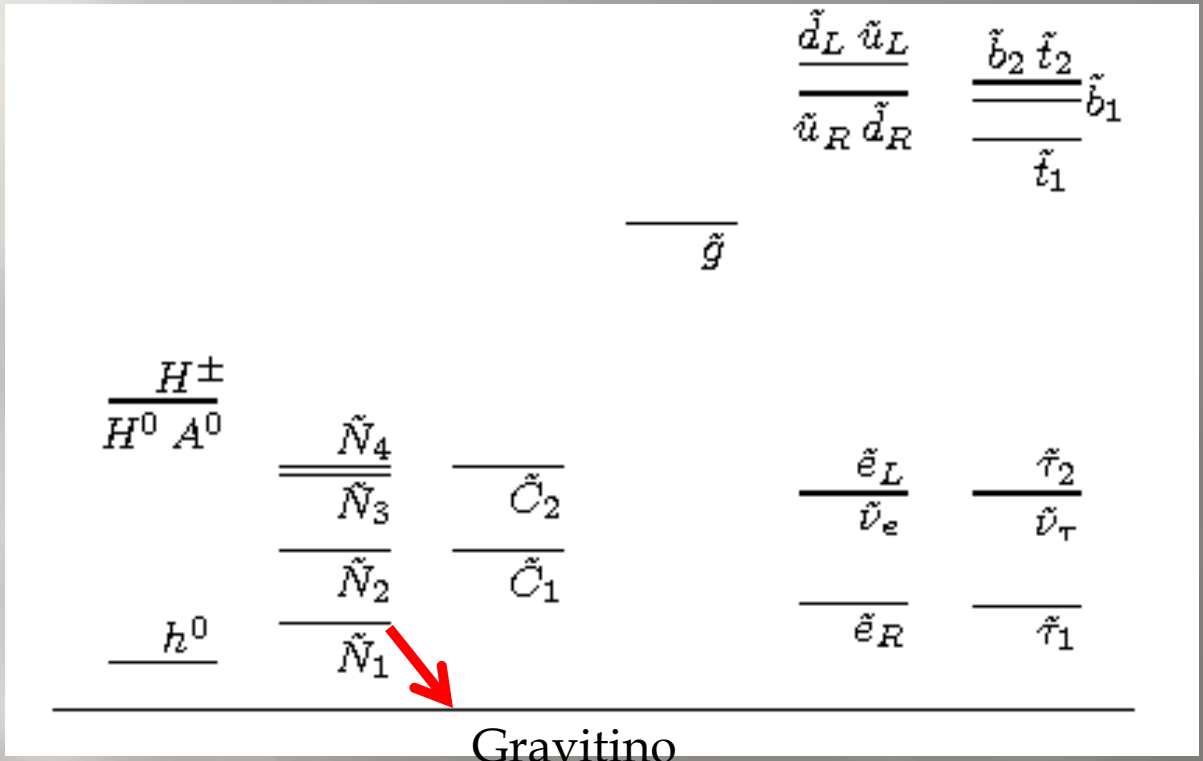
In gravity mediation

$$m_{3/2} \sim \frac{F}{M_{Pl}} \sim m_\lambda \sim m_{QUDLE}$$

In gauge mediation

$$m_{3/2} \ll m_\lambda, m_{QUDLE}$$

NLSP decays!



The old LSP is now the NLSP and always decays to the gravitino!

e.g. $\chi_1^0 \to \tilde{G} + \gamma$

Predictions of Minimal Gauge Mediation *Everyone** knows them!

SEARCHES FOR NEW PHYSICS IN DIPHOTON EVENTS IN $\bar{p}p$ COLLISIONS AT $\sqrt{s} = 1.8$ TEV

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CHICAGO, ILLINOIS

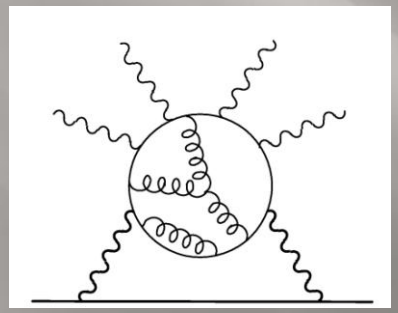
DECEMBER, 1997

Predictions of Minimal Gauge Mediation Everyone* knows them!

- NO FCNCs
- Gravitino LSP
- $\gamma\gamma$+MET!! (bino or stau NLSP)
- Colored stuff heaviest, followed by SU(2), then U(1)
  - Fixed ratio of masses
  - Relations between gaugino/sfermion masses
- $\mu/B\mu$ problem
- Small A-terms
- Overly predictive in some sense!

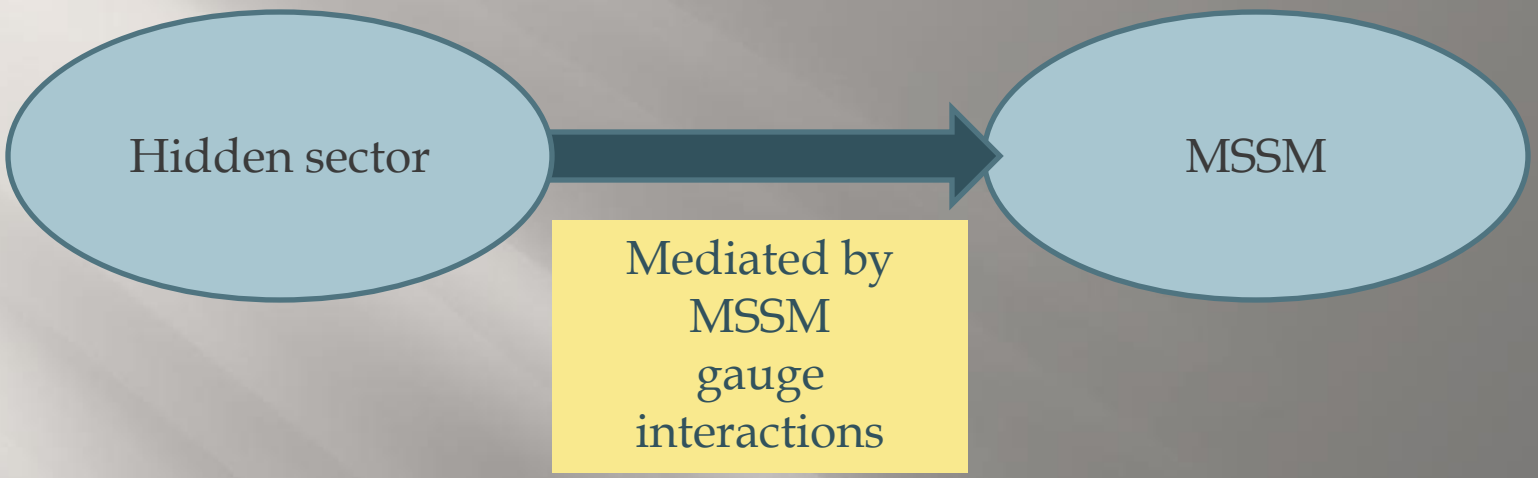
Does this cover the set of all GMSB models?

- Have we missed weakly coupled models?
- How do we calculate in strongly coupled models?

$m^2_{QUDLE} \sim$  ?

- Is the phenomenology always diphoton + MET?
- General Gauge Mediation (PM, N. Seiberg, D.Shih)

Define Gauge Mediation!



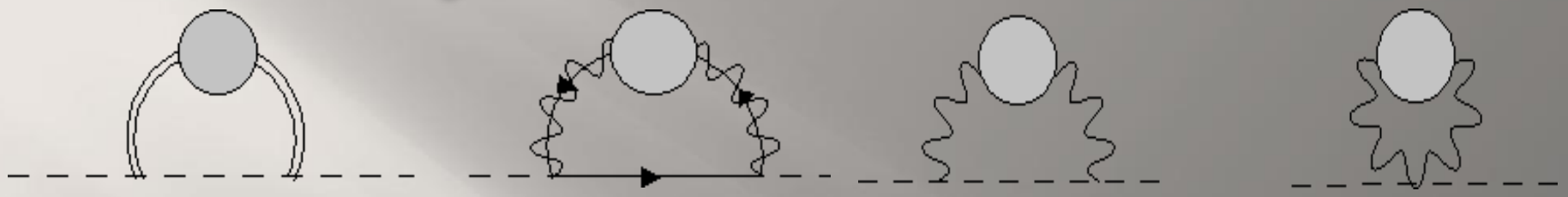
$$\lim \alpha_r \to 0$$

Hidden sector and MSSM decouple

From this point of view:

- Hidden sector can be weakly or strongly coupled
- Can include messengers or NOT!
- Can have other exotics under MSSM gauge groups

Sparticle masses



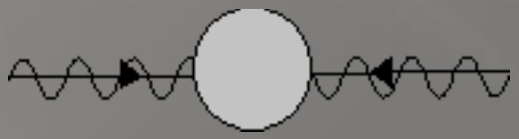
$$\frac{1}{2}g^2(C_0(p^2)D^2 - C_{\frac{1}{2}}(p^2)i\lambda\sigma^\mu\partial_\mu\bar{\lambda} - \frac{1}{4}C_1(p^2)F^2_{\mu\nu})$$

Sfermion masses generated at **ONE** loop in MSSM

$$m^2_{\tilde{f}} = -\alpha^2\int dp^2(C_0(p^2) - 4C_{\frac{1}{2}}(p^2) + 3C_1(p^2))$$

Gaugino masses are now **tree level** in MSSM

$$-\frac{1}{2}g^2MB(p^2)\lambda\lambda$$



What is Gauge Mediation?

11) **Theories with gauge mediated supersymmetry breaking.**
G.F. Giudice, R. Rattazzi (CERN) . CERN-TH-97-380, Jan 1998. 102pp.
Published in **Phys.Rept.322:419-499,1999**.
e-Print: **hep-ph/9801271**

TOPCITE = 500+
References | LaTeX(US) | LaTeX(EU) | Harvmac | BibTeX | Keywords | Cited 683 times
Abstract and Postscript and PDF from arXiv.org (mirrors: au br cn de es fr il in it jp kr ru tw uk za aps lanl)
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→ **6 Numbers**

ARBITRARY GAUGINO MASSES!
ARBITRARY SCALARS UP TO THE SUM RULES!

$$m_Q^2 - 2m_U^2 + m_D^2 - m_L^2 + m_E^2 = 0$$
$$2m_Q^2 - m_U^2 - m_D^2 - 2m_L^2 + m_E^2 = 0$$

General Gauge Mediation Overview

- General Gauge Mediation
  - Still solve FCNC problem
  - 3 complex independent parameters for gaugino masses
  - 3 parameters for characterizing sfermion masses
  - Small A terms
  - Gravitino LSP
  - Encompasses ALL models

What to do with this?

- Most searches for GMSB focused on diphoton + MET
- Phenomenology dictated primarily by three things
  - Overall production cross section
  - Identity of NLSP
  - Prompt or delayed decays
- What are the bounds on Gauge Mediation with this new understanding? What are the discovery possibilities? What are the interesting channels?

Who can be the NLSP

- Colored NLSP, straightforward strong bounds
- Slepton NLSP, small production at a hadron collider (well studied in case of staus)
  - See recent work by Ruderman and Shih (1009.1665)
- Neutralino and Chargino NLSPs, robust, relatively unstudied, and the Tevatron can say a lot about this case and the LHC can see it easily…

Generic Neutralino NLSP

- Can be a combination of Bino, Wino, and Higgsino
- Can focus on a minimal module

$$M_1, M_2, \mu, \tan\beta$$

- This sets the cross section unambiguously, however there is the possibility for a larger cross section by including colored sparticles

Generic Neutralino NLSP

$$\begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$

$$\tilde{\chi}_1^0 = \sum_{i=1}^{4} N_{1i} \tilde{\psi}_i^0$$

$$\tilde{\psi}_i^0 = (\tilde{B}, \tilde{W}, \tilde{H}_d^0, \tilde{H}_u^0)$$

Decay modes and partial widths

$$\begin{aligned}
\Gamma(\tilde{\chi}_1^0 \to \tilde{G} + \gamma) &= |N_{11} c_W + N_{12} s_W|^2\, \mathcal{A} \\
\Gamma(\tilde{\chi}_1^0 \to \tilde{G} + Z) &= \left(|N_{12} c_W - N_{11} s_W|^2 + \frac{1}{2} |N_{13} c_\beta - N_{14} s_\beta|^2 \right) \left(1 - \frac{m_Z^2}{m_{\tilde{\chi}_1^0}^2} \right)^4 \mathcal{A} \\
\Gamma(\tilde{\chi}_1^0 \to \tilde{G} + h) &= \frac{1}{2} |N_{13} c_\beta + N_{14} s_\beta|^2 \left(1 - \frac{m_h^2}{m_{\tilde{\chi}_1^0}^2} \right)^4 \mathcal{A}
\end{aligned}$$

Focus on Three Limits

- Bino NLSP
  - Decays to photons at least 76% of the time
- Wino NLSP
  - Mix of Z and photon decays
  - Co-NLSP so you also have chargino decays to W+gravitino
- Higgsino NLSP
  - 3 regions, Z-rich, Higgs rich, or mixed case

Decay Length of NLSP

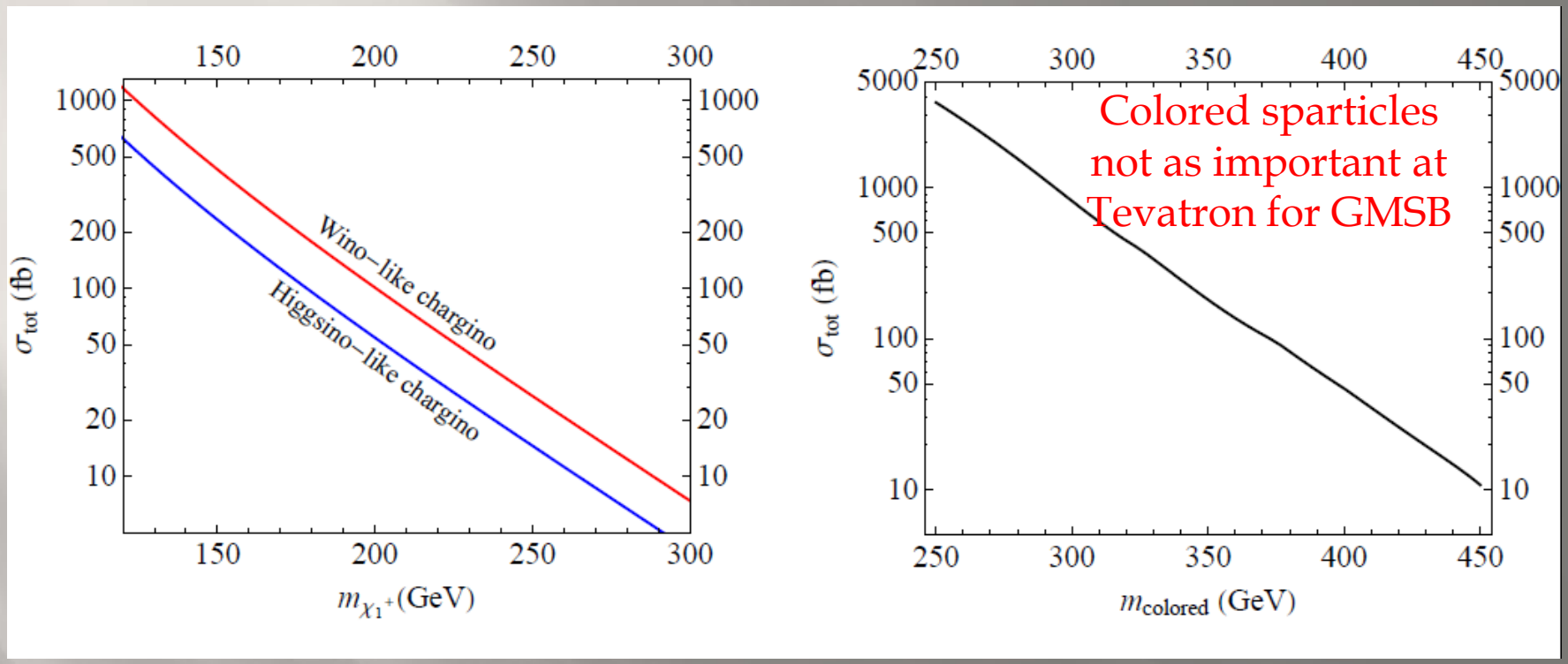
$$\mathcal{A} = \frac{m_{\tilde{\chi}_1^0}^5}{16\pi F_0^2} \approx \left(\frac{m_{\tilde{\chi}_1^0}}{100\ \mathrm{GeV}}\right)^5 \left(\frac{100\ \mathrm{TeV}}{\sqrt{F_0}}\right)^4 \frac{1}{0.1\ \mathrm{mm}}$$

Viable range for SUSY breaking scale in GMSB

$$10\ \mathrm{TeV} \lesssim \sqrt{F_0} \lesssim 10^6\ \mathrm{TeV}$$

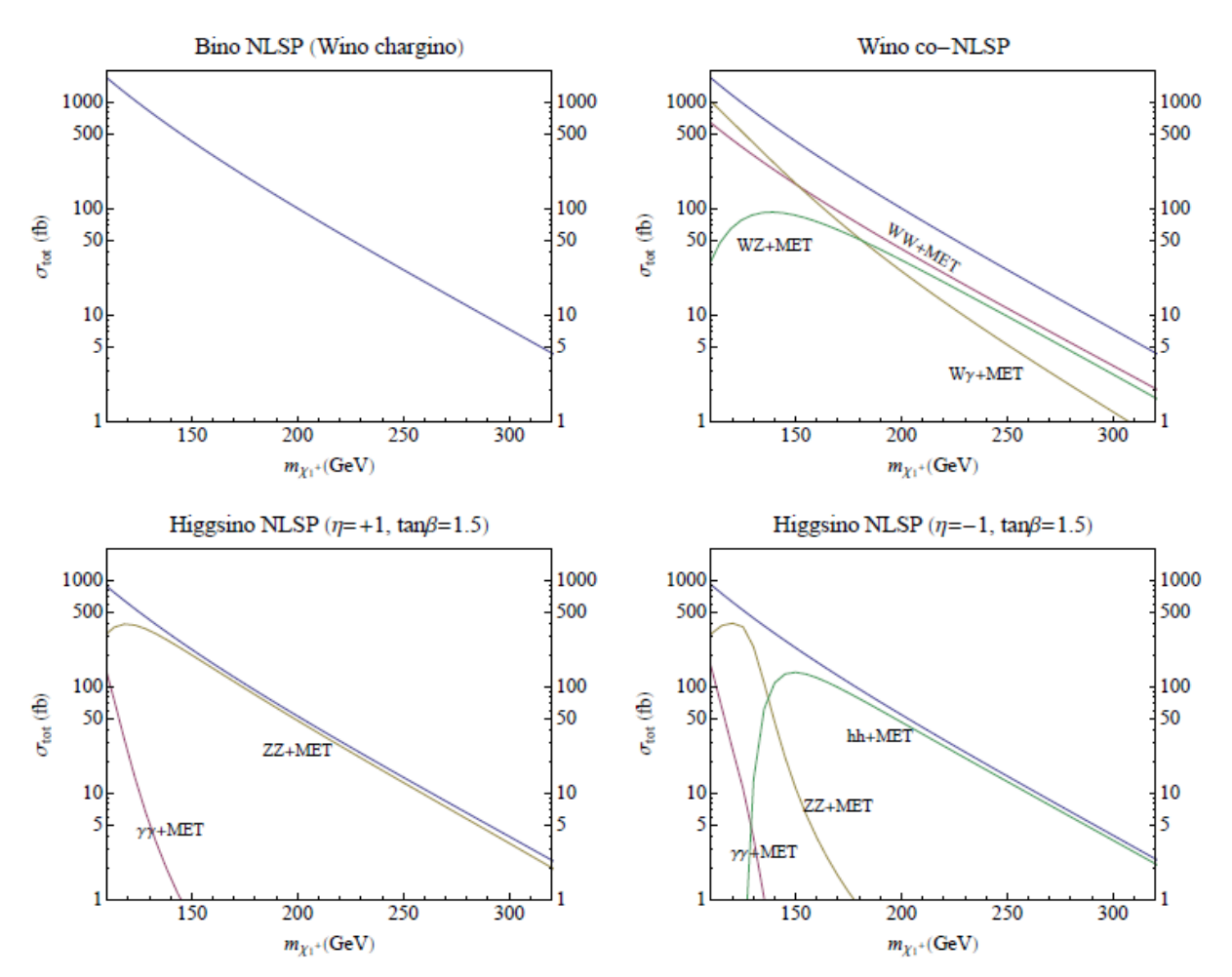
Macroscopic decays for values larger than about 100 TeV

Cross Section and Tevatron vs LHC



Unless you assume colored particles the Tevatron still is very useful!

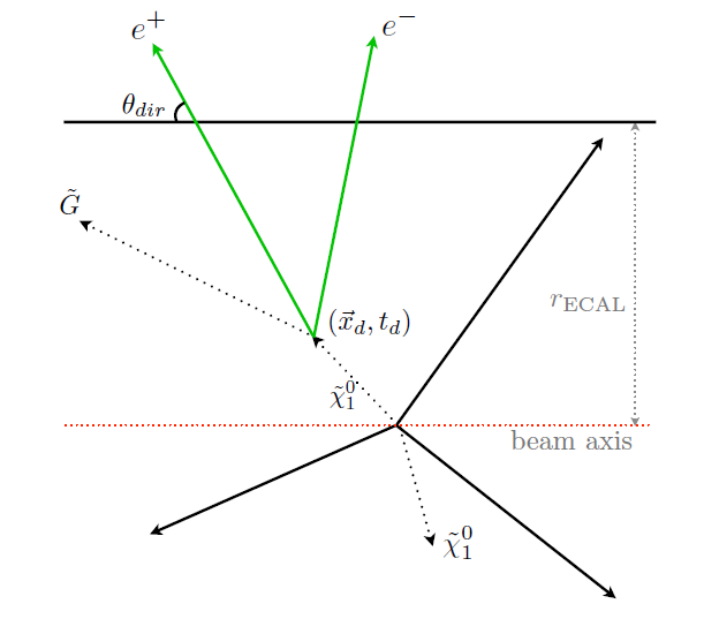
What are the interesting channels at the Tevatron?



There are still discovery channels at the Tevatron

Delayed NLSP decays

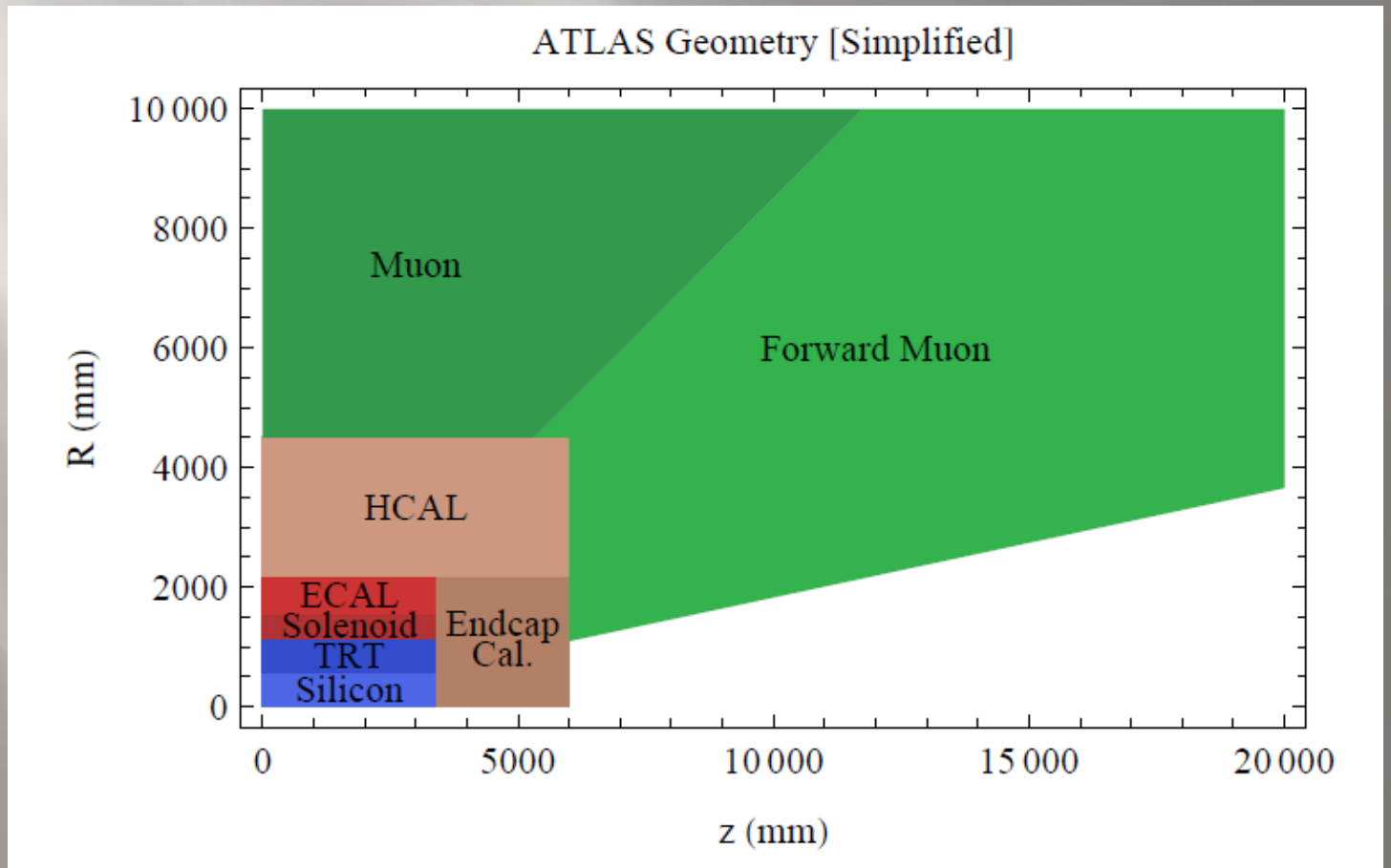
- Have the exact same story as before but now you can have displaced Z,h, and photon decays (again only photon case has been studied in detail)

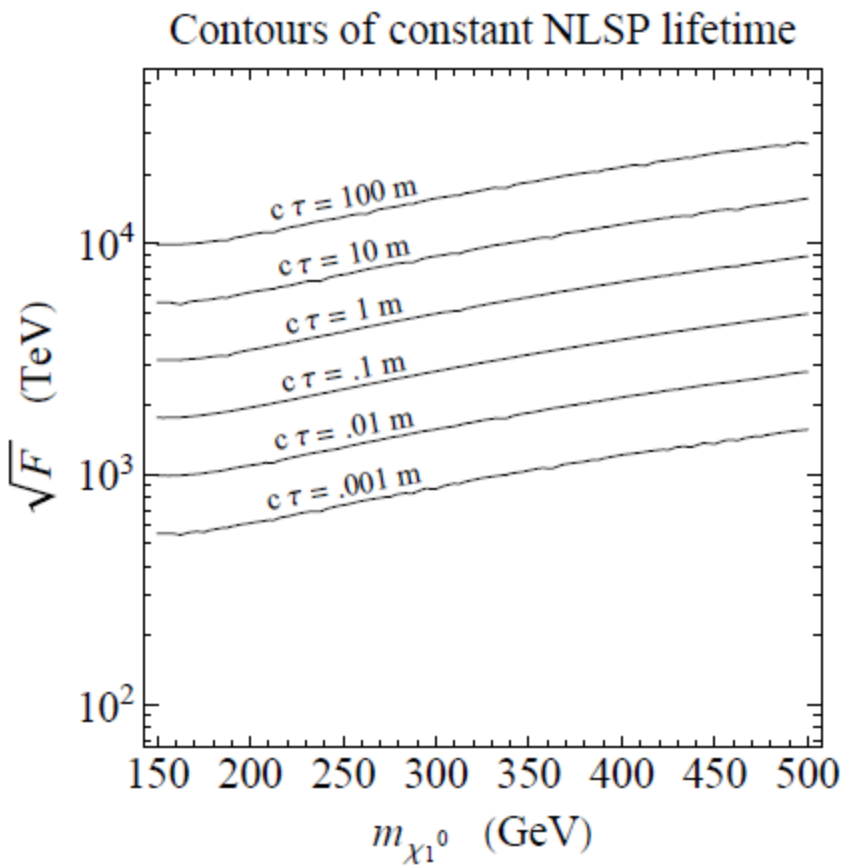


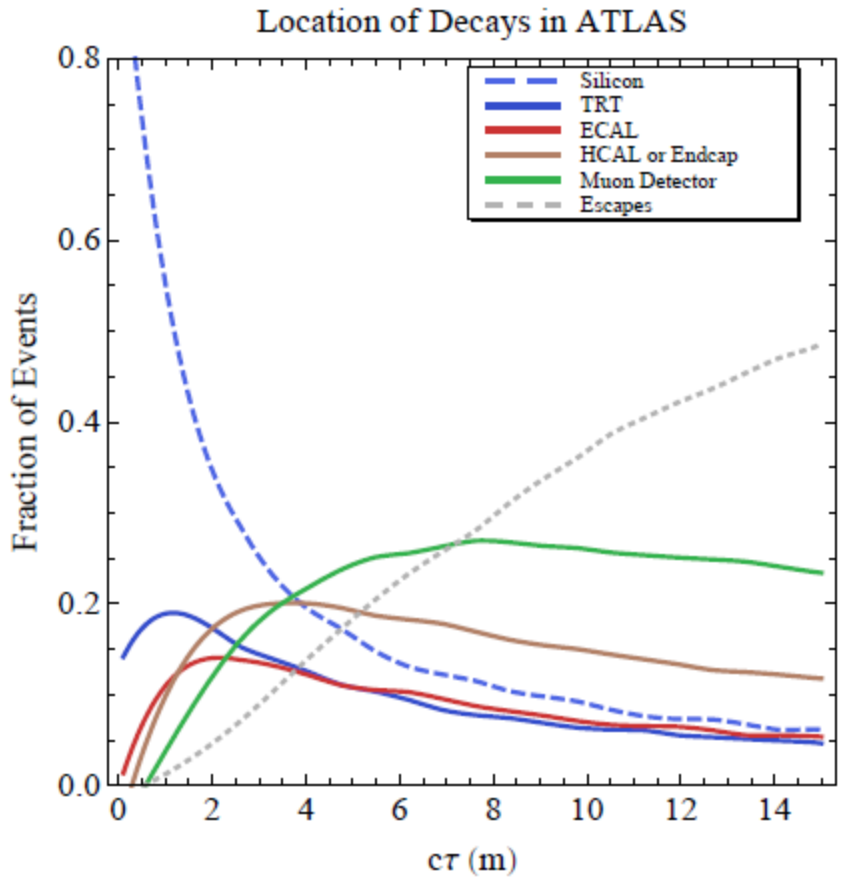
- Golden signals and first inverse fb discoveries at the LHC
  - Depends on the production cross section but GGM has no prejudice against light colored superpartners

Where does it decay?

- Harder to search for than prompt, strongly depends where it decays, how do you find it, how do you trigger on it, etc…

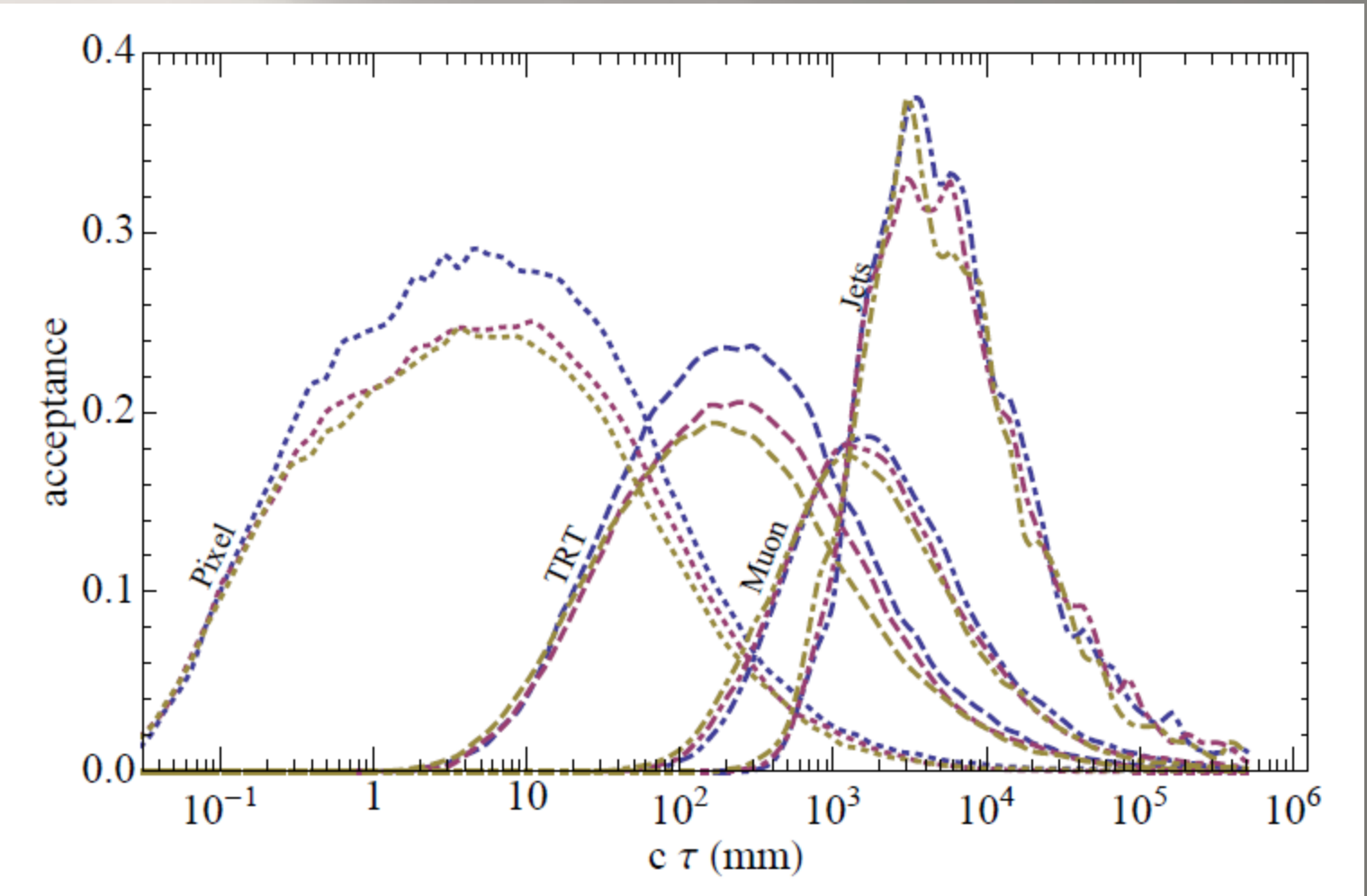


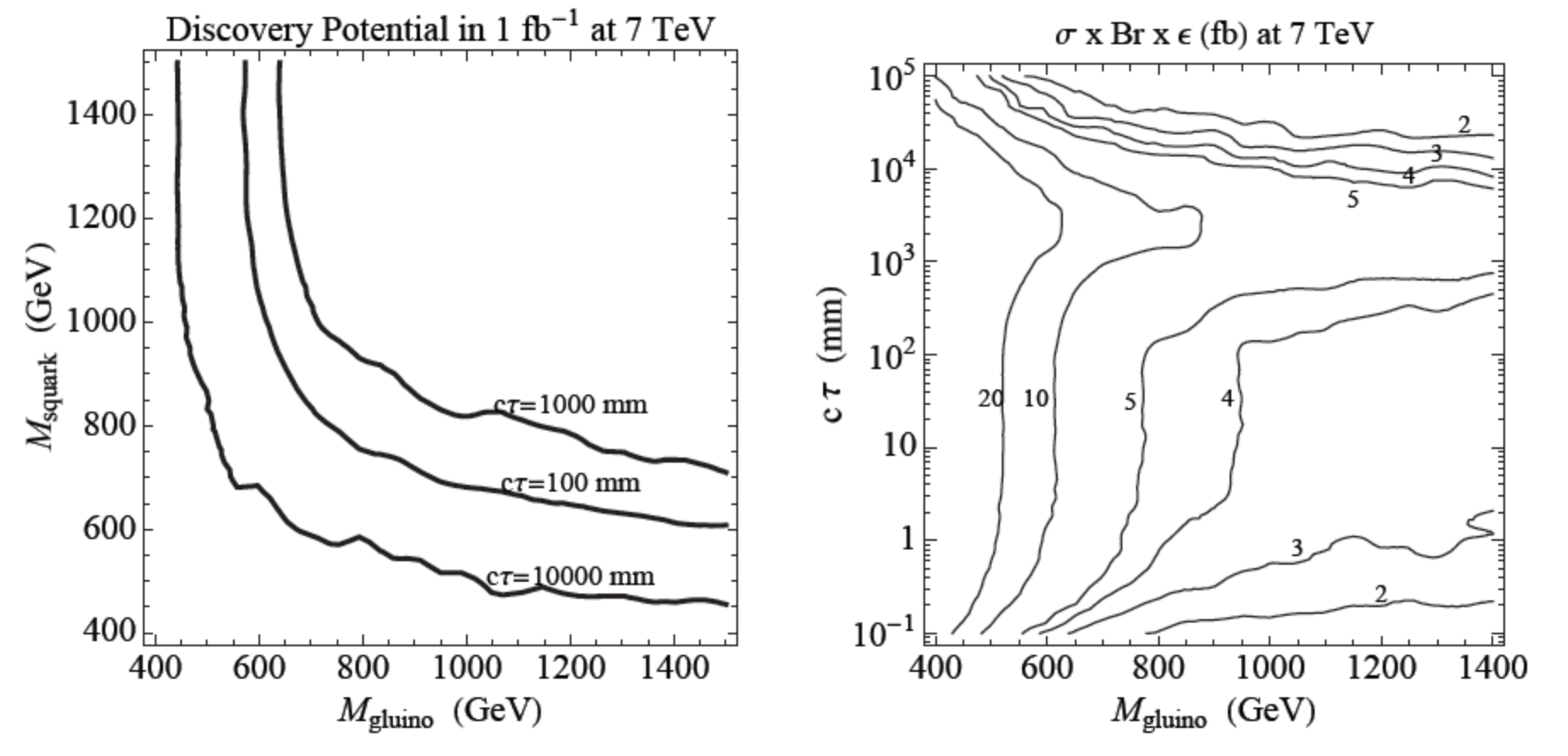




$$\mathcal{A} = \frac{m_{\tilde{\chi}_1^0}^5}{16\pi F^2} \approx \left(\frac{m_{\tilde{\chi}_1^0}}{100\ \text{GeV}}\right)^5 \left(\frac{100\ \text{TeV}}{\sqrt{F}}\right)^4 \frac{1}{0.1\ \text{mm}}$$

Inclusive Z->X acceptance





Can also reconstruct the event kinematics completely without having to rely on other measurements not in the first inv fb though…

Conclusions

- Gauge Mediation has a much larger variety of phenomena than previously envisioned
- Prompt signature with final states not studied in much detail and can be amazing…
  - Higgses in every SUSY event!
- Delayed signatures just as probably and just as interesting as more ``exotic" models
  - Can give additional information about the scale of SUSY breaking