Phenomenology of General Neutralino NLSPs

Matthew Reece
Princeton Center for Theoretical Science
At Cornell, February 17, 2010

P. Meade, MR, D. Shih, 0911.4130 (“Prompt Decays of General Neutralino NLSPs at the Tevatron”), and 1003.???? (“Long-Lived Neutralino NLSPs”)

Gauge Mediation

- How is SUSY breaking mediated to the SM?
- One hint: flavor. Difficult to achieve in gravity mediation, without many ingredients
- Gauge mediation is automatically flavor-blind
- This talk: some phenomenological aspects of gauge mediation at the Tevatron and LHC

(mostly prompt decays at Tevatron and long lifetimes at ATLAS)

Gauge Mediation

- The key phenomenological characteristic of gauge mediation is a light gravitino:

$$m_{3/2} = F_0/(\sqrt{3}M_{Pl})$$

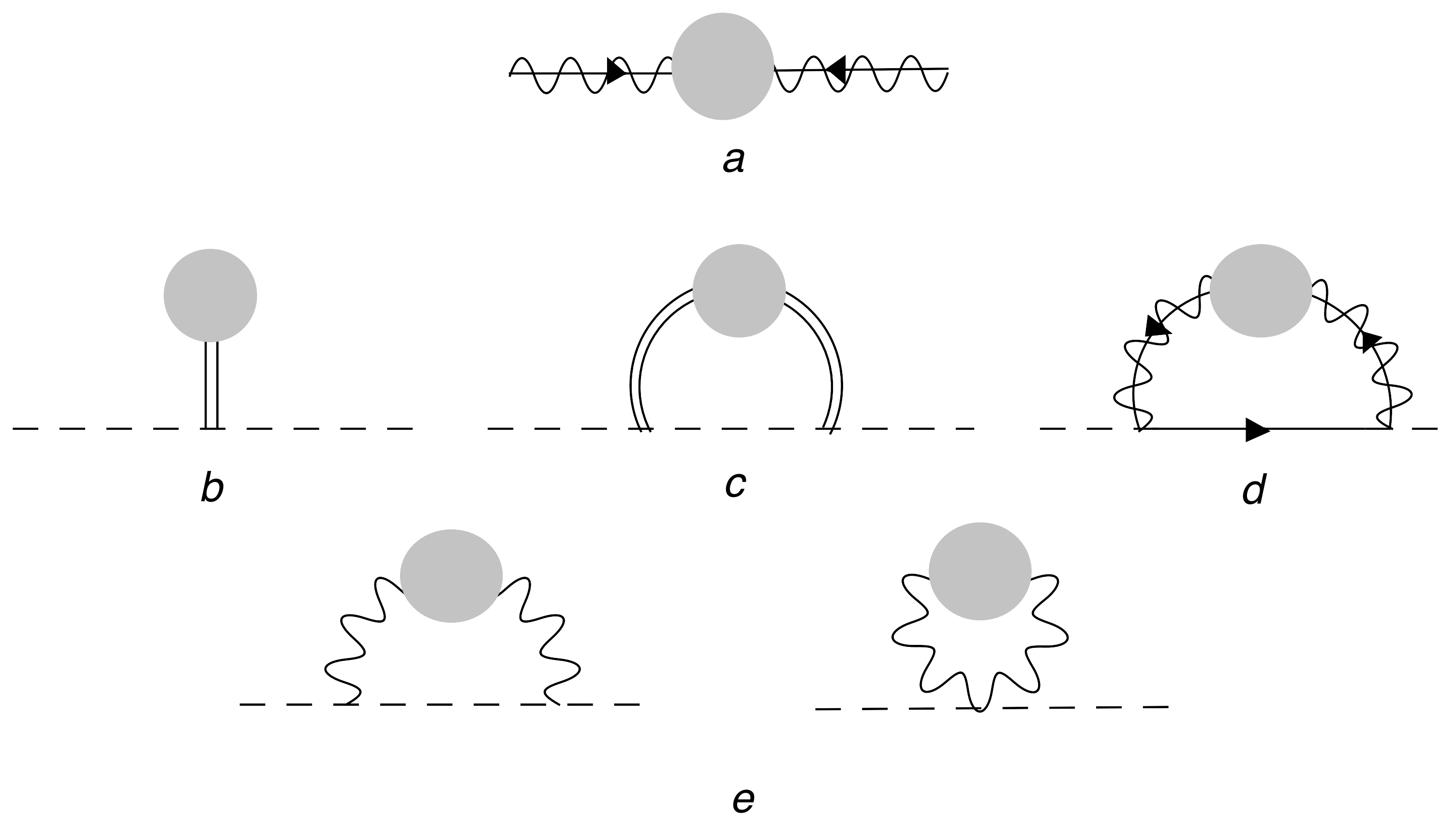
- SUSY-breaking scale $10\ \mathrm{TeV} \lesssim \sqrt{F_0} \lesssim 10^6\ \mathrm{TeV}$
- The lightest MSSM partner is the "NLSP," decaying down to the gravitino.
- This decay drives the phenomenology.

Beyond Minimal GMSB

- The simplest GMSB models (“minimal” or “ordinary” gauge mediation) predict that the NLSP is a bino or a stau.
- Small μ and Higgsino NLSP can help reduce fine-tuning (Agashe, Graesser, hep-ph/ 9704206)
- Higgsino NLSP is also common in “extra-ordinary gauge mediation,” i.e. generic renormalizable messenger models (Cheung, Fitzpatrick, Shih, 0710.3585)

General Gauge Mediation

- A SUSY-breaking hidden sector has a global symmetry weakly gauged by the SM



- Soft terms calculated from hidden-sector correlation functions (Meade, Seiberg, Shih, 0801.3278); extensions for μ/Bμ

GGM Phenomenology

- In general gauge mediation, any MSSM particle can be the NLSP
- Squark or gluino seems unlikely, and signal is just jets + Met
- Sleptons have been studied somewhat; sneutrinos also interesting (Katz/Tweedie)
- Our focus will be general neutralino NLSP (possibly with charginos as co-NLSPs)

NLSP Decays to Gravitino

Partial Widths:

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

Overall rate (easily long-lived!):

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

Limiting Cases

- Bino NLSP: $N_{11} \gg N_{12}, N_{13}, N_{14}$, decays to photons at least $c_W^2 \approx 76\%$ of the time.
- Wino NLSP: $N_{12} \gg N_{11}, N_{13}, N_{14}$. Very degenerate chargino and neutralino:

$$\Delta m \sim m_Z^4/\mu^3$$

- For most of the talk I will be assuming neutralino decays promptly down to the gravitino. In this case, wino chargino and neutralino are "co-NLSPs", with

$$\tilde{\chi}_1^+ \to W^+ + \tilde{G}$$

Limiting Cases

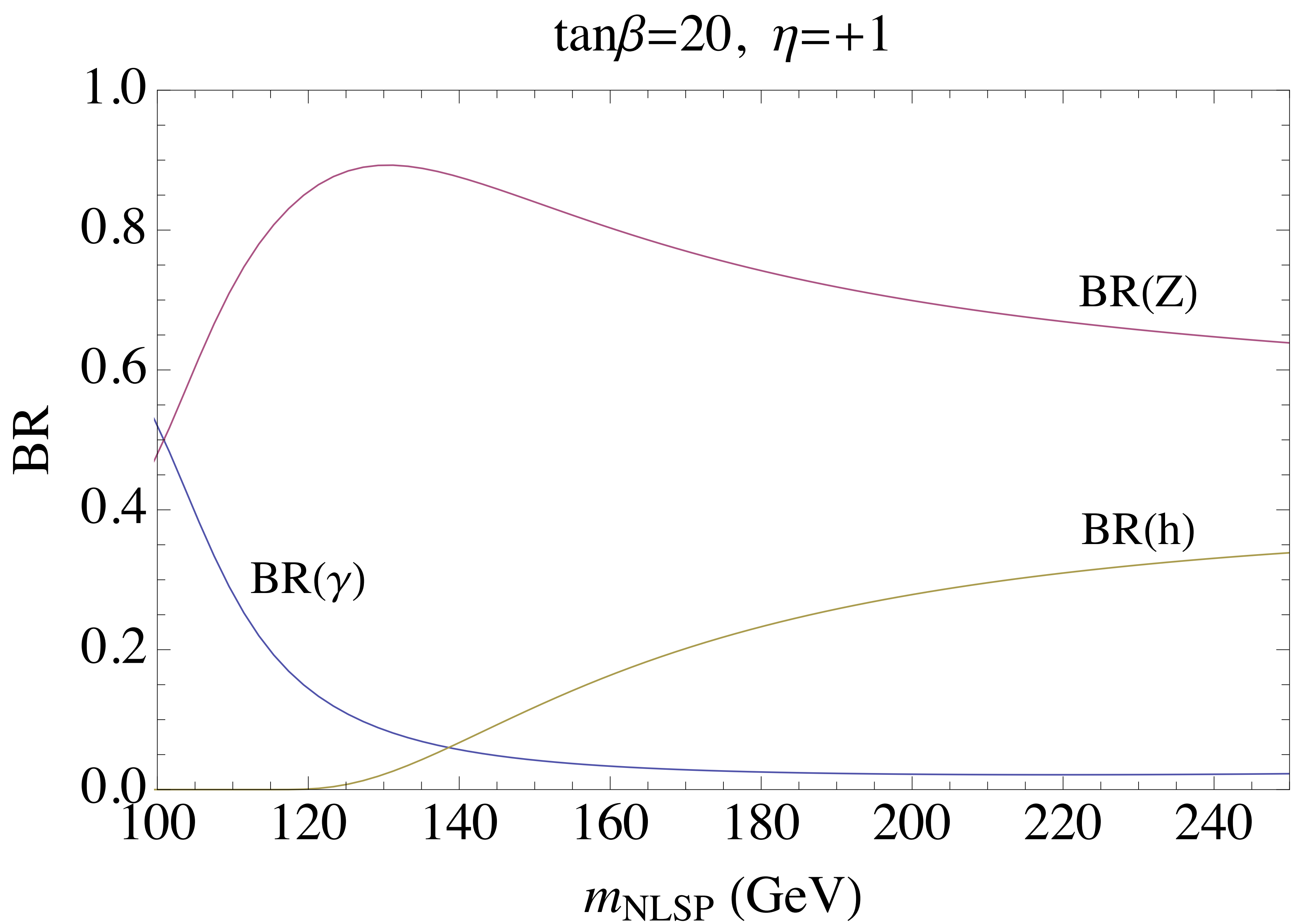
- Higgsino NLSPs can decay to either a Higgs + gravitino or a longitudinal Z + gravitino.
- At large tan(β) and large enough masses, these are 50/50.
- At small tan(β), depends on a sign:

$$N_{13} = -\eta N_{14} = \frac{1}{\sqrt{2}}$$

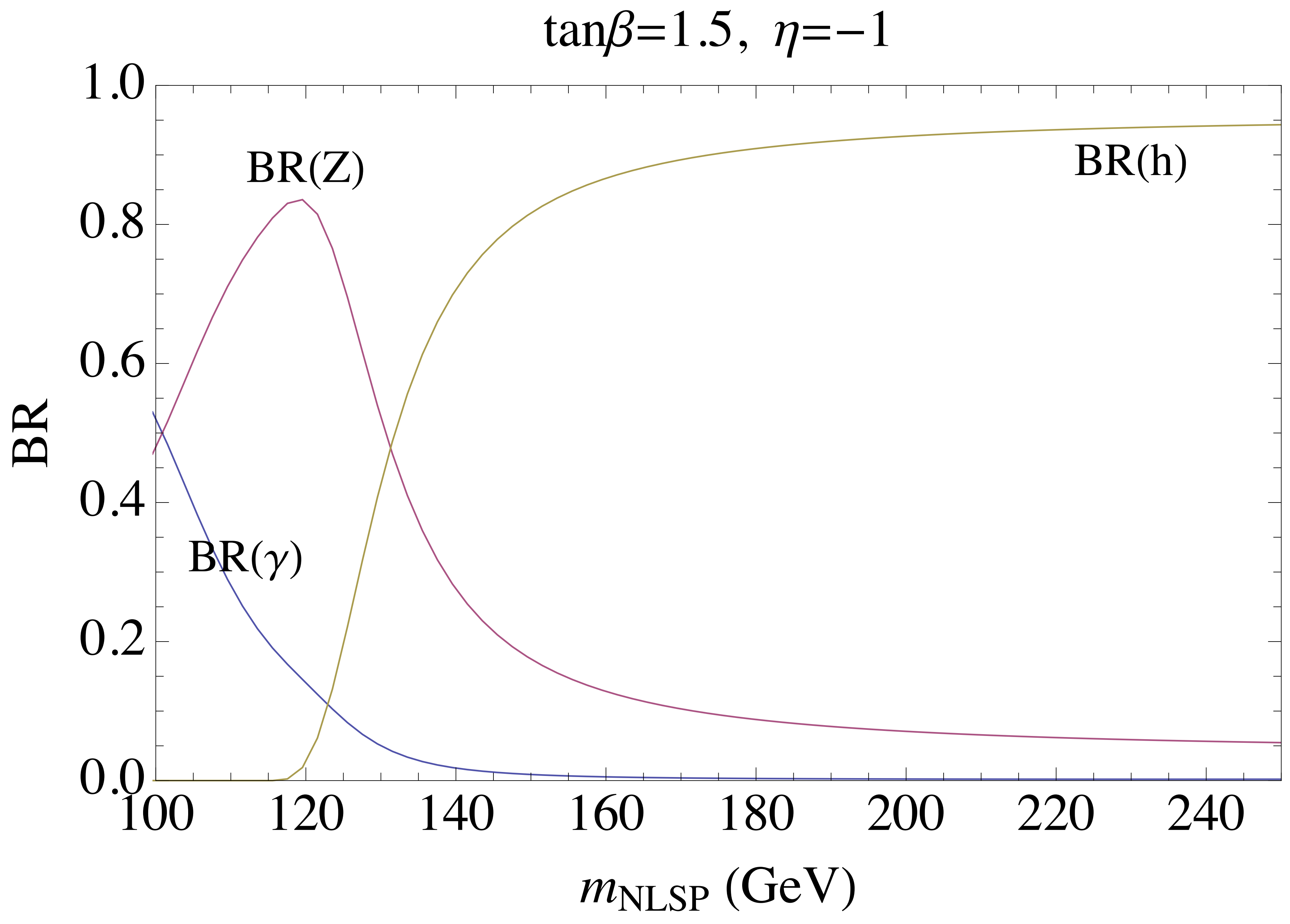
$$\eta \equiv \text{sign}(\mu) \times \text{sign}\left(\frac{M_1}{M_2} + \tan^2\theta_W\right)$$

- Will assume $M_1, M_2 > 0$. Ignoring the interesting case of chargino NLSP (see Kribs, Martin, Roy 0807.4936)

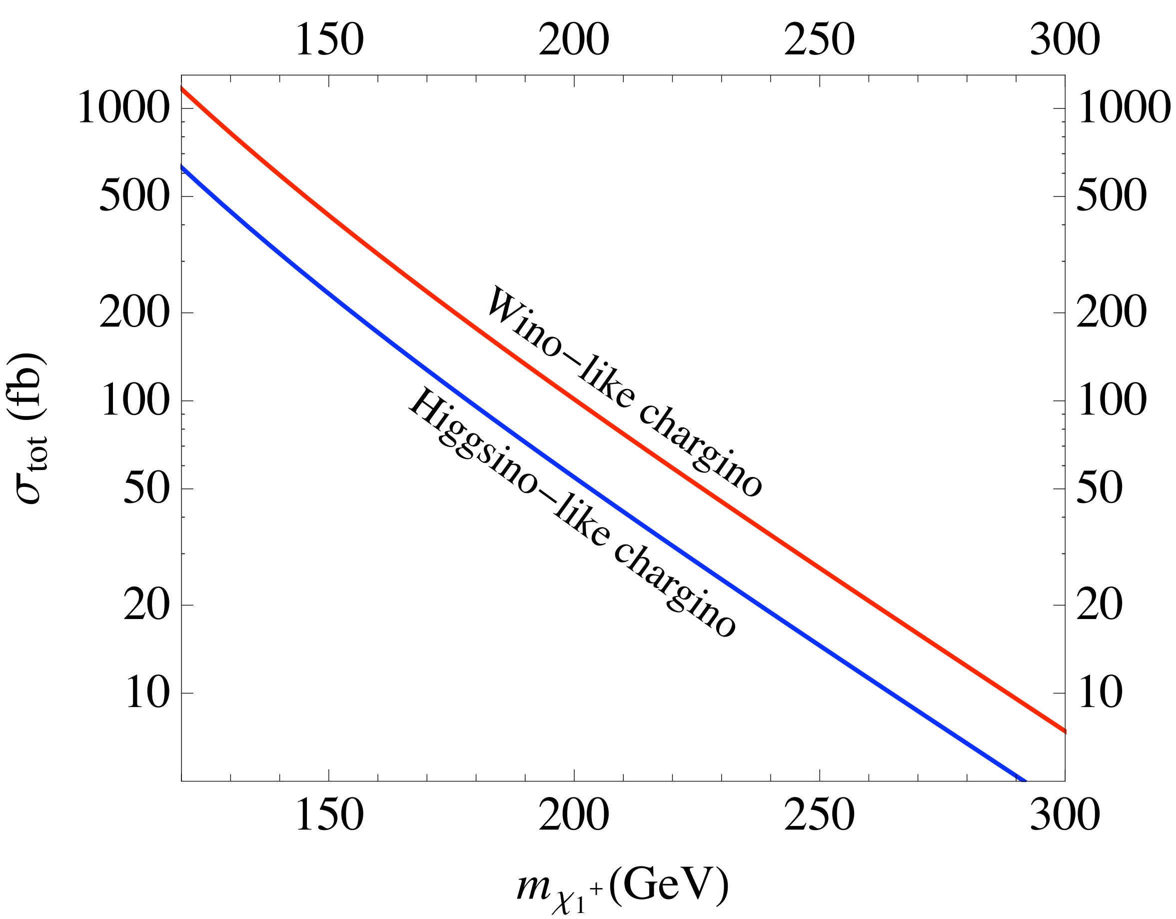
Z-Rich Higgsino

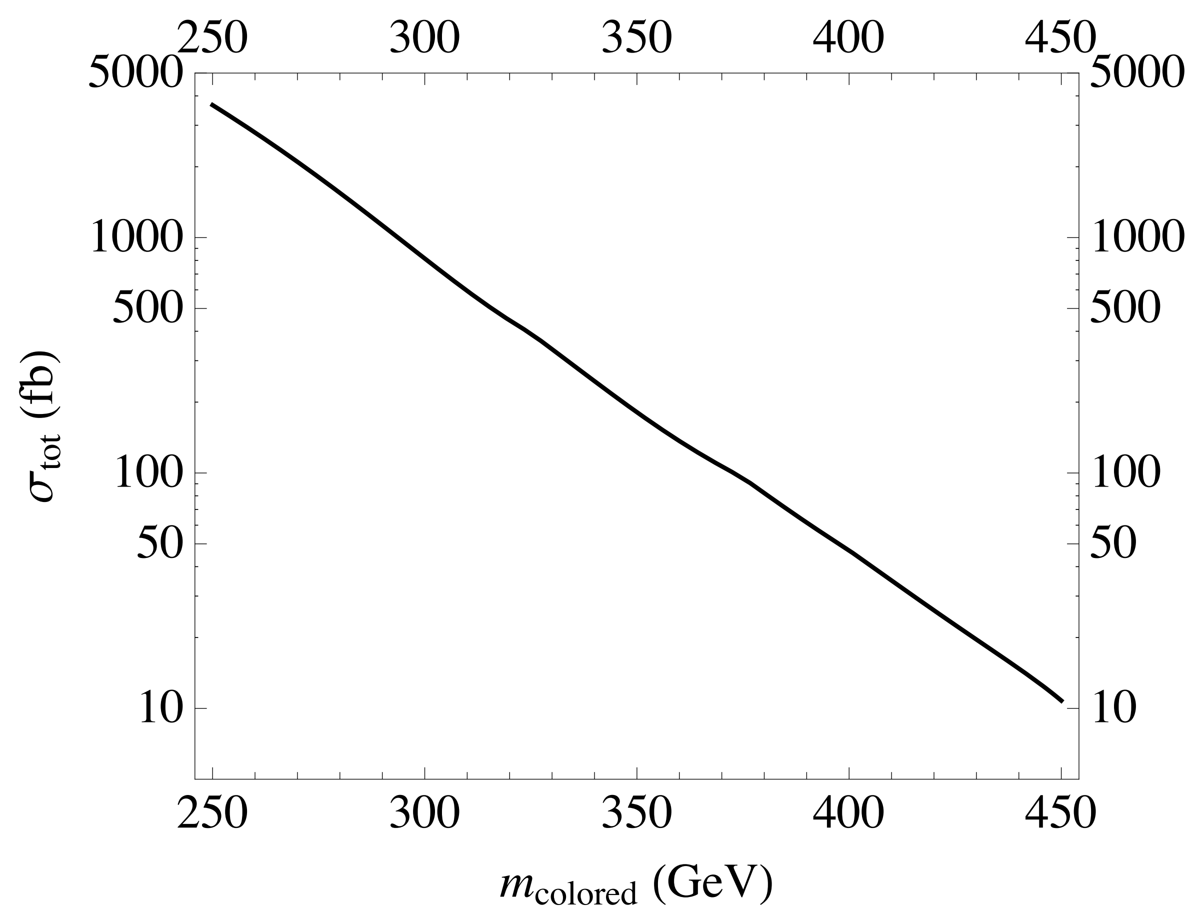


Higgs-rich Higgsino



Overall Rates at the Tevatron





We will be ignoring the possibility of strong production: could contribute if masses of squarks or gluinos are in the 300 - 450 GeV range.

Strategy

- We use Pythia to simulate signal and backgrounds (MadGraph for some)
- We use a PGS detector simulation, tuned to CDF and D∅ (painstakingly checked against data wherever possible)
- We analyze existing studies to estimate current bounds, and propose some new or improved searches
- Focus on γ or leptonic decays of W, Z (clean signal trumps small branching ratio)
- One exception: Higgs to b-jets?

γγ+Met

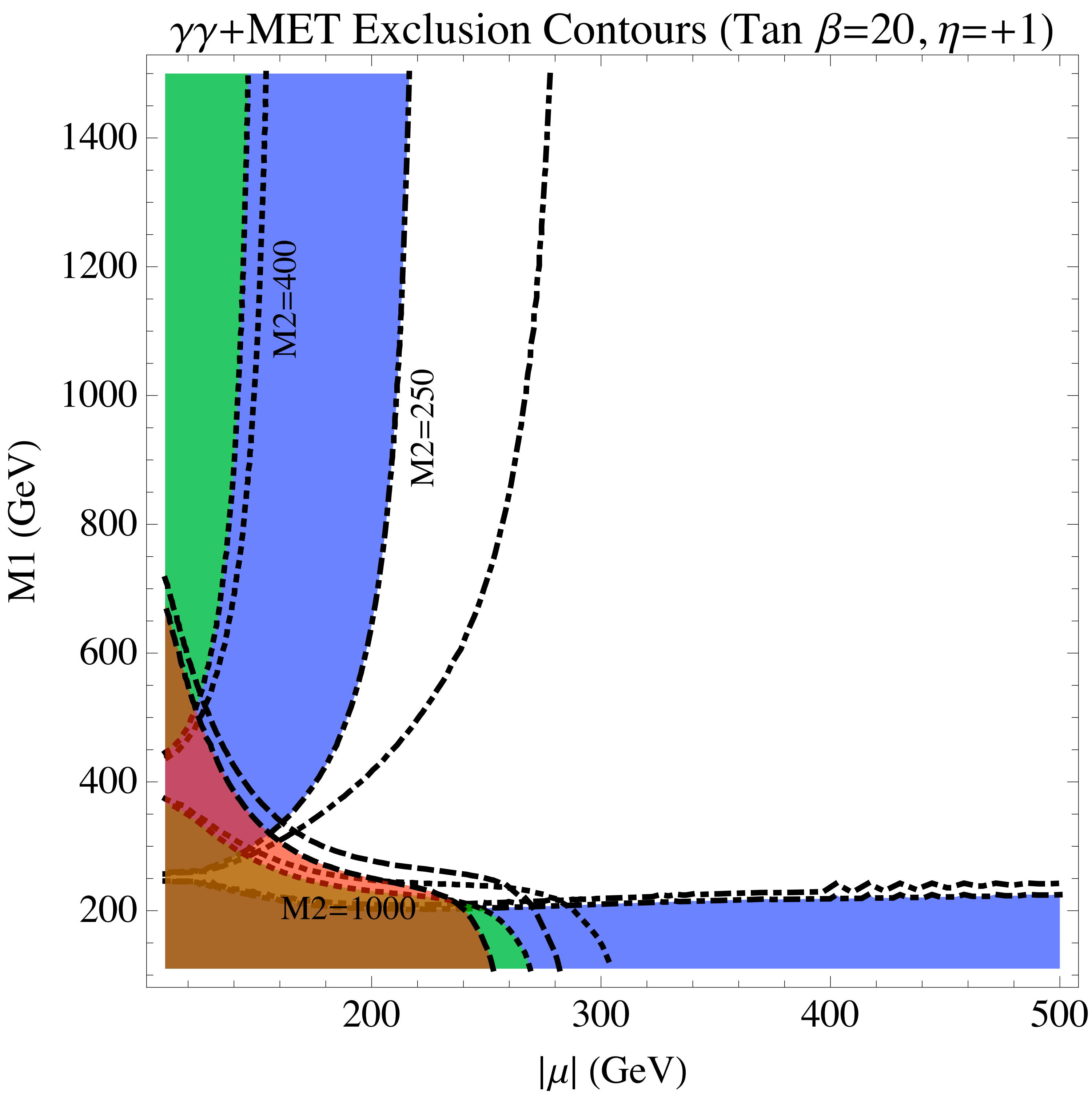
- As a classic MGM signature, this is well-studied experimentally.
- Most recent: CDF analysis of 2.6 fb^{-1} (0910.3606)
- 2 central 13 GeV photons (not back-to-back), Ht > 200 GeV, MEt of 3-sigma significance
- No events found, 1.2 expected

$$\sigma_{tot} \times \mathrm{Br}(\gamma)^2 \times \varepsilon \lesssim 1.2 \text{ fb}$$

$\gamma\gamma$+Met: Interpretation

- CDF interpreted this in terms of MGM, where the bino and wino mass are related; excluded winos at 300 GeV.
- Don't directly make binos, so cross section determined by heavier winos or higgsinos.
- Bound for wino above bino: 270 GeV.
- Could also have mixed bino/Higgsino or wino/Higgsino NLSP decaying to photons, which are directly produced

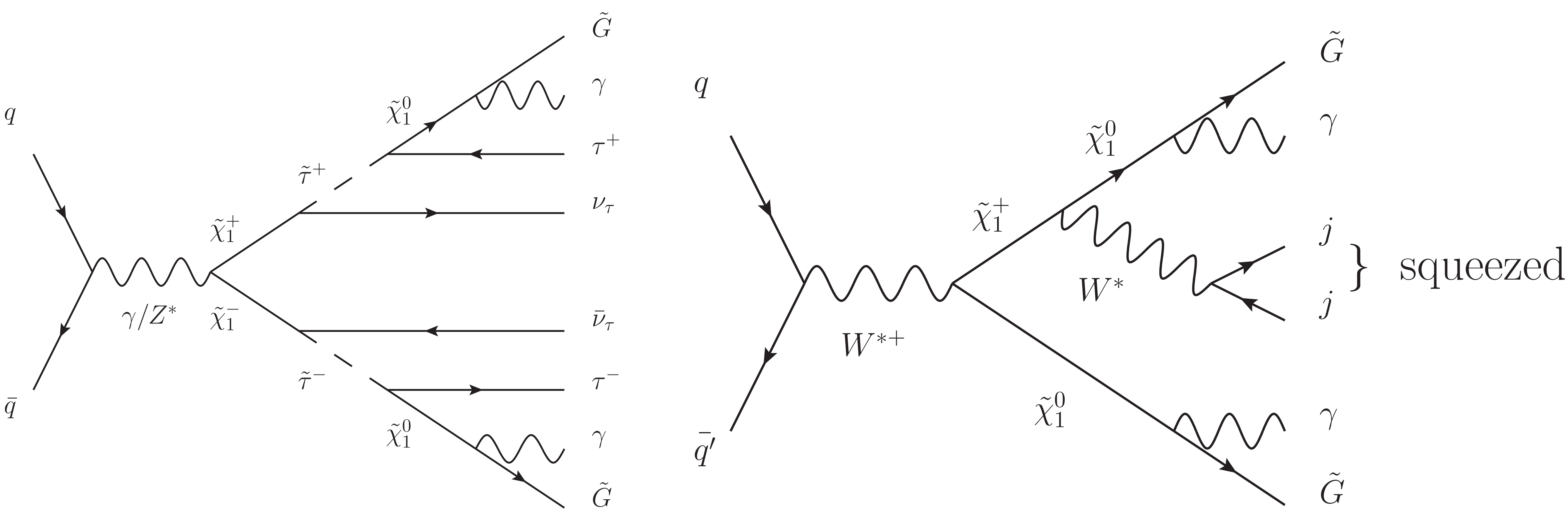
γγ+Met Exclusion



At bottom: bino-like NLSPs arising in decays of Higgsino or wino states.

At top left: Higgsino-like NLSPs, decaying by mixing with bino (or with wino)

Event Topology/ Kinematics



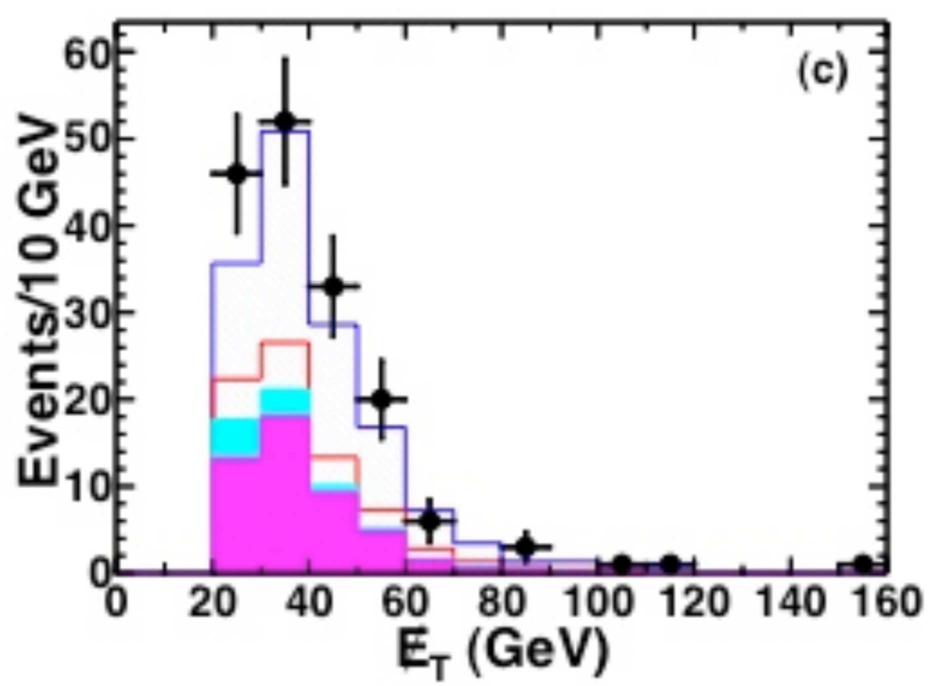
Wino co-NLSPs

- Produced chargino + neutralino or chargino pairs, not two neutralinos
- No γγ+Met limit
- Wγ+Met, WW+Met, WZ+Met possible
- WW+Met too much like SM WW; WZ +Met suffers from low Z to leptons branching ratio
- W(→lν)+γ+Met is ideal channel

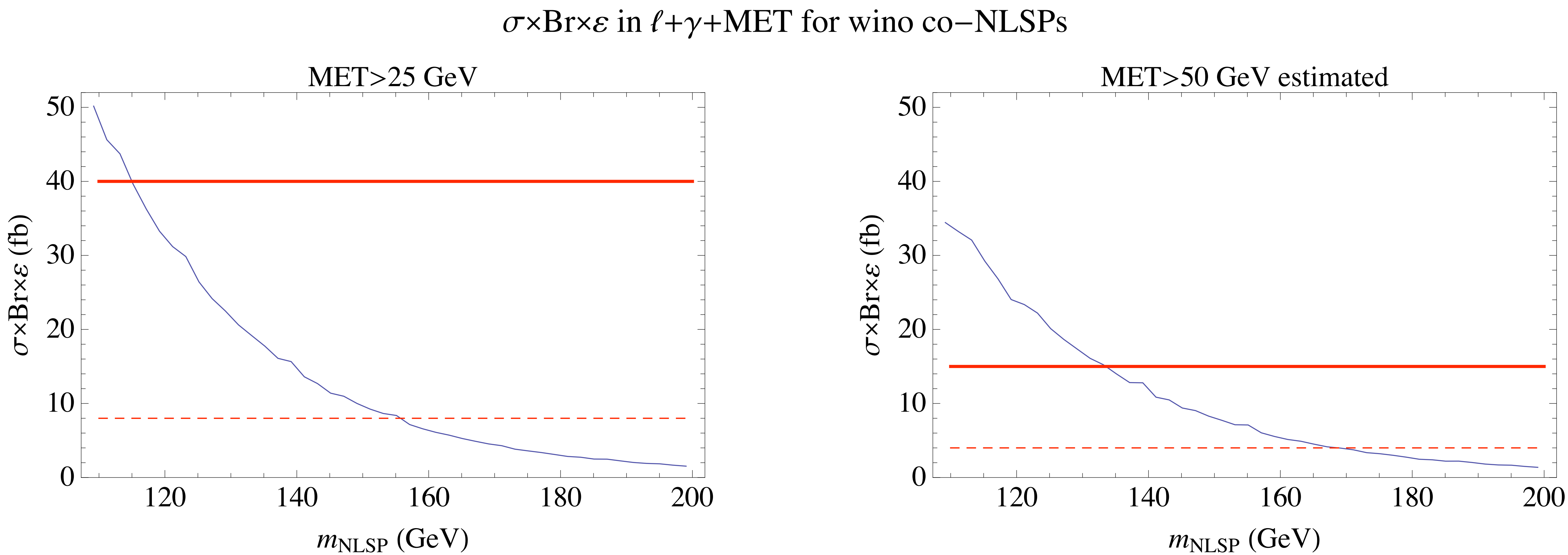
CDF lepton+γ+Met

hep-ex/0702029

- Signature-based search using 0.93 fb^{-1}
- At least one isolated central photon and at least one isolated central e or μ; Met > 25
- Already sets a limit, but better to take Met > 50 GeV:



Exclusion Estimates



We estimate that with 10 fb^{-1}, 5σ discovery is possible up to a wino mass of 140 GeV, or 3σ "evidence" up to 160 GeV.

Transverse mass may offer some extra improvement.

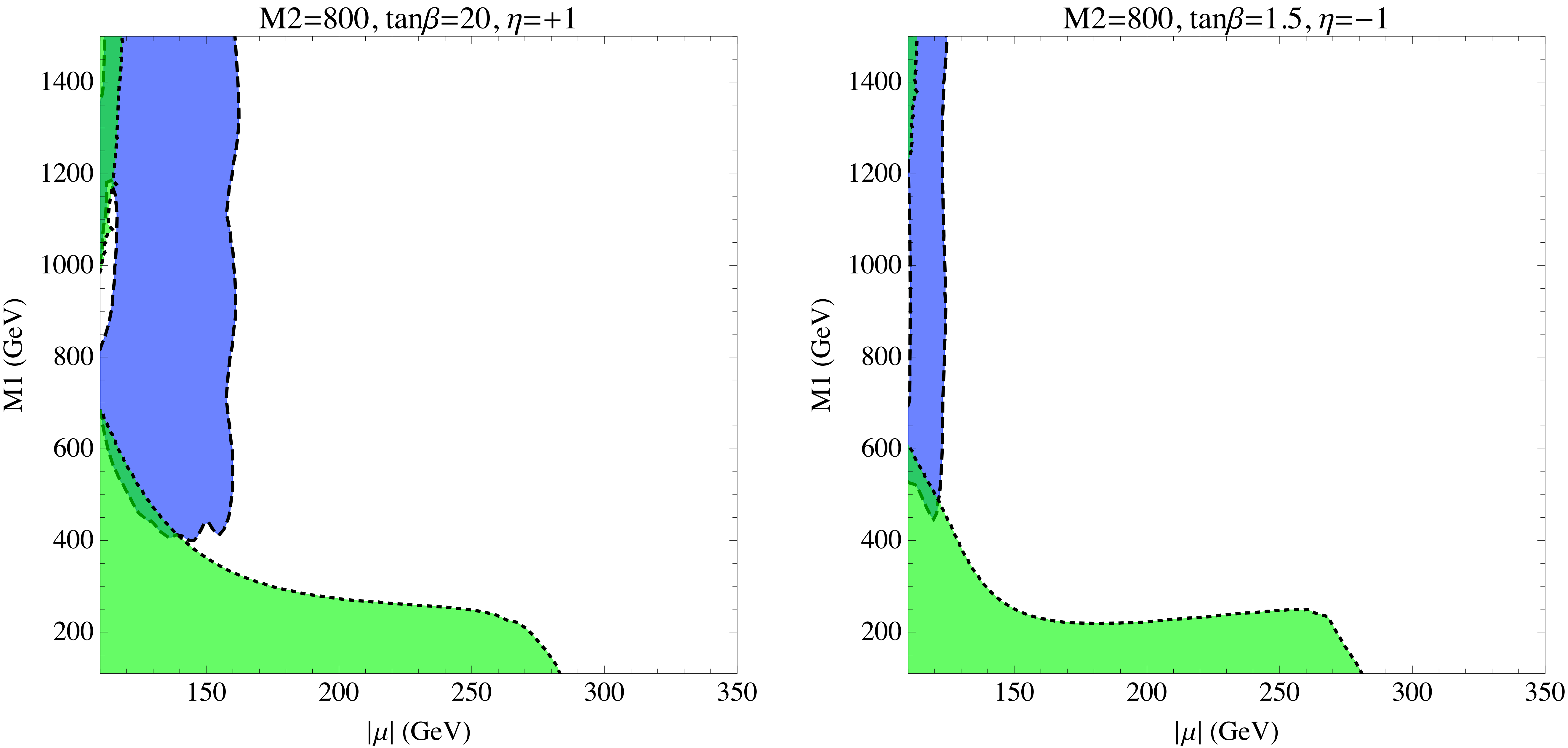
Higgsino NLSPs

- Generic Higgsinos decay to Z and Higgs equally, but the Tevatron can probe only lighter masses, where the Higgs decays are phase-space suppressed
- Best search channel: $Z(\rightarrow l^+l^-)$+MEt+X (inclusive)
- Several existing results (new physics searches, SM ZZ measurement) in this channel - no limit yet

CDF Z+Ht+Met

- This search is unpublished (but there is a blessed public result) work of Sasha Paramonov et al., using 0.94 fb^{-1}
- Central, opp. sign lepton pair with mass in (66, 116) GeV
- MEt > 25 GeV with 3 sigma significance
- Ht > 300 GeV (search was motivated by a heavy quark scenario)

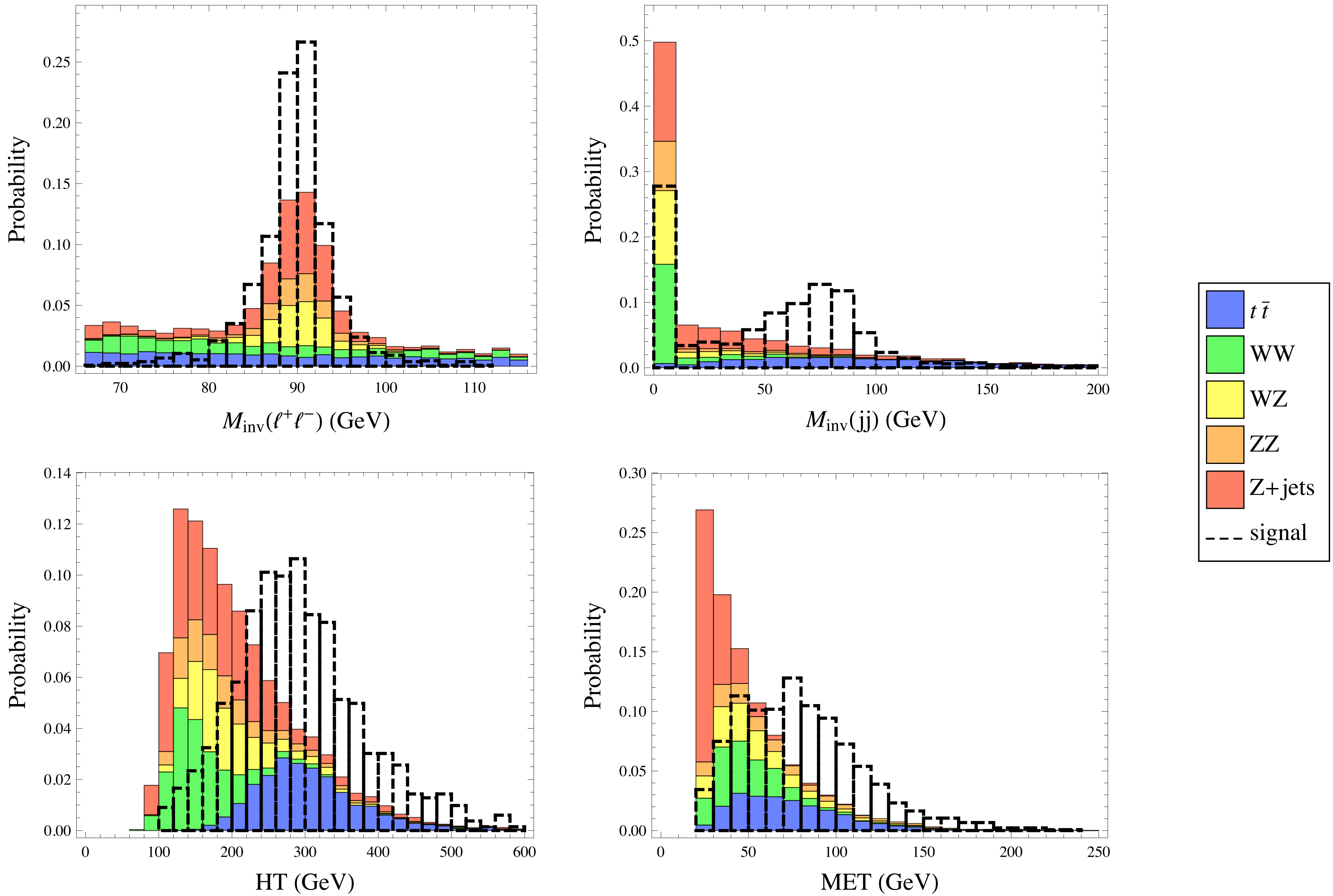
Z+Ht+MET Projected Exclusion with 10 fb^{-1}



Proposed Improvements

- The existing search will probe up to $\mu \approx 150$ GeV with no changes
- Ht > 300 is too hard for our signal (set by mass scale). Relax to 200 GeV.
- Backgrounds: Z+jets, top pairs, diboson
- Tighter mass window (80 -100) is very efficient at rejecting tops.
- Signal is at higher Met: cut at 40 GeV.

Kinematic Distributions in Signal and Backgrounds



Proposed Improvements

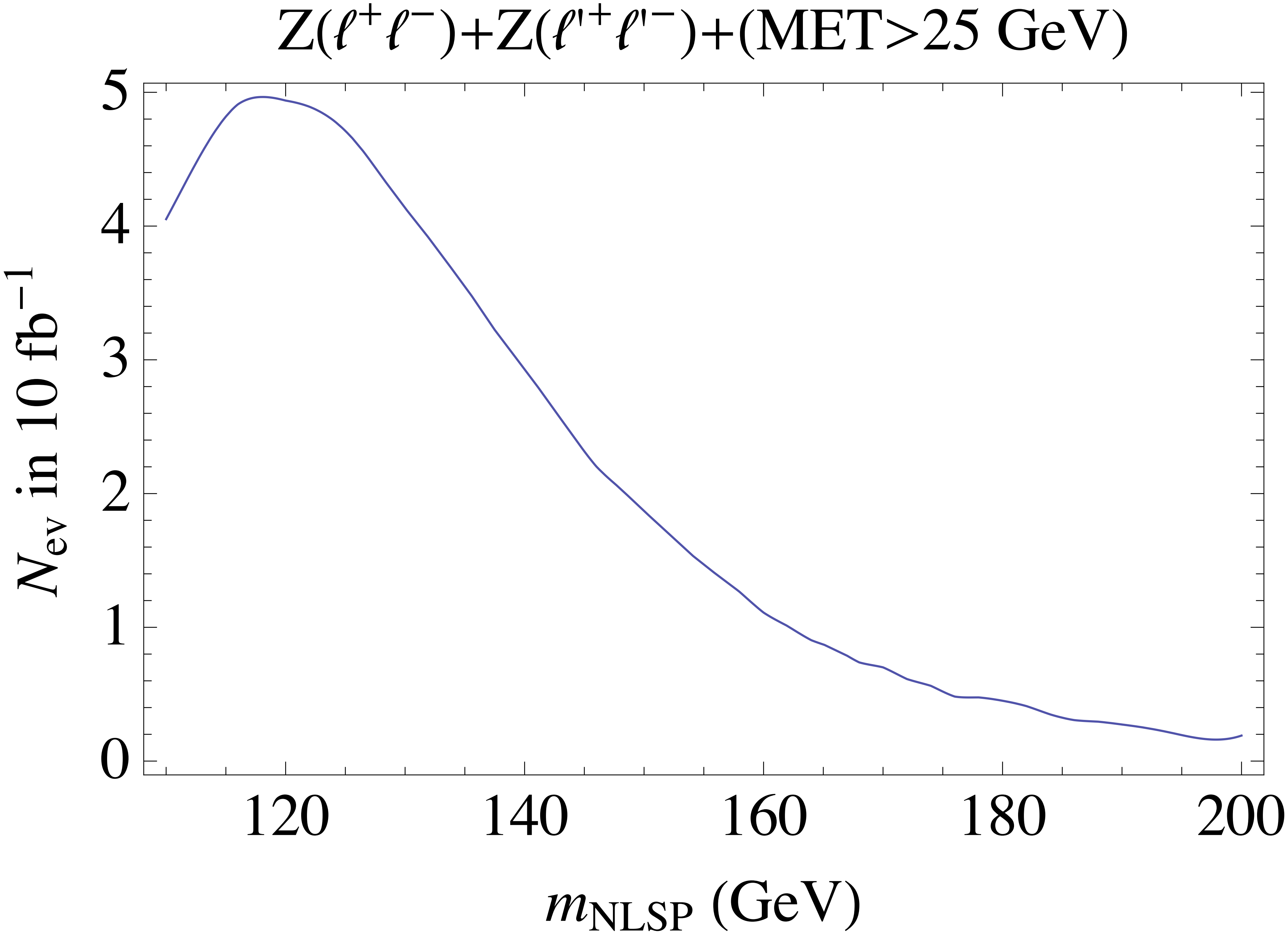
- With these simple improvements, can exclude μ below 170 GeV (5σ up to 135)

Table 1: Rates for a proposed $Z + H_T + \not{E}_T$ search

$N_{bg}(e^+e^-)$ (fb)	$N_{bg}(\mu^+\mu^-)$ (fb)	$N_{sig}(e^+e^-)$ (fb)	$N_{sig}(\mu^+\mu^-)$ (fb)
7.4	5.8	1.4	1.1

- This is with just cuts. Using more detailed kinematic information and statistical techniques, can probably do better.
- This is low-hanging fruit for the Tevatron: Z-rich Higgsino NLSPs are unconstrained so far.

ZZ to 4 Leptons



Very clean channel, very low rate. Possible discovery channel. Hinges on: how clean? Tail of MEt?

Higgs-rich Higgsinos

- For $\eta = -1$ (roughly, $\mu<0$), $\tan(\beta)\approx 1$, Higgsinos heavier than about 150 GeV go almost entirely to Higgses
- This suggests looking for events with multiple b-jets and missing Et
- Very challenging! Large backgrounds, large systematics, really beyond our control... Needs a careful analysis by experimentalists, with full detector sim.
- Nevertheless...

Plausibility

Table 2: Multi-b + $\not\!\!E_T$ rates in fb

Sample	A. bb + $\not\!\!E_T$ >50	B. bbb + $\not\!\!E_T$ >40	C. $bbbb$+$\not\!\!E_T$ >30
$t\bar{t}$	77.2	16.8	1.7
$Wb\bar{b}$	12.4	1.4	0.0
$Zb\bar{b}$	6.1	0.8	0.1
$b\bar{b}b\bar{b}$	4.8	9.1	1.6
Diboson	2.7	0.2	0.0
Total[a]	103.2	28.3	3.4
m_{NLSP} = 140 GeV[b]	5.2	3.1	1.0
m_{NLSP} = 160 GeV	7.1	4.1	0.9
m_{NLSP} = 180 GeV	6.2	3.3	0.7
m_{NLSP} = 200 GeV	4.5	2.3	0.5

[a] Includes only simulated backgrounds – not comprehensive.

[b] In all signal points listed, $M_1 = 500$ GeV, $M_2 = 800$ GeV, $\eta = -1$ and $\tan\beta = 1.5$.

Columns A and B have mass cuts: at least one pair of b-tagged jets with 60 GeV < M(bb) < 200 GeV at ΔR<2.5

Some Distributions

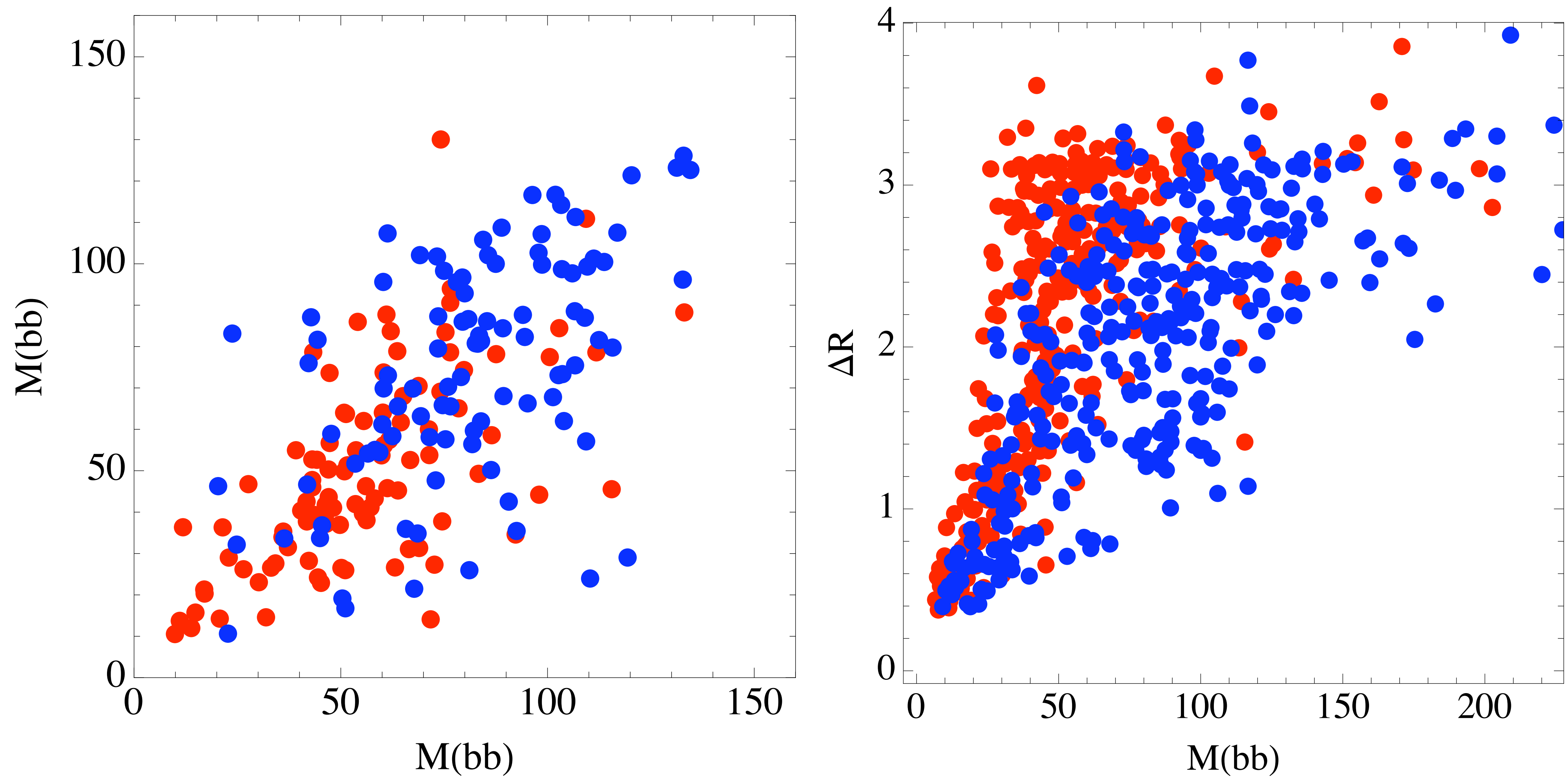


Figure 9: At left: nearest pairs of $M(bb)$ in partitions of 4 b-tagged jets, in 100 signal events (blue) and 100 $b\bar{b}b\bar{b}$ background events (red). At right: all combinatoric possibilities for invariant mass and ΔR between pairs of b-tagged jets in 50 signal events with 4 b-tags (blue) and 50 $b\bar{b}b\bar{b}$ background events with 4 b-tags (red). The signal point is $\mu = -140$ GeV, $M_1 = 510$ GeV, $\tan\beta = 1.5$, $M_2 = 800$ GeV.

Shape information will be vital if this channel can work.

Recap: Tevatron Exclusion Capabilities

Table 3: Summary of Results

NLSP Scenario	Search Channel	Current Est. Limit	Projected Limit
bino ($\mu \gg M_2 > M_1$)	$\gamma\gamma + \not{E}_T$	$m_{\tilde{\chi}_1^\pm} > 270$ GeV	$m_{\tilde{\chi}_1^\pm} >300$ GeV
wino co-NLSP	$W(\rightarrow \ell\nu) + \gamma + \not{E}_T$	$m_{NLSP} > 135$ GeV	$m_{NLSP} >170$ GeV
higgsino	$Z(\rightarrow \ell^+\ell^-) + \not{E}_T + X^a$	None	$m_{NLSP} > 150$ GeV
higgsino	$Z(\rightarrow \ell^+\ell^-) + \not{E}_T + X^b$	None	$m_{NLSP} > 170$ GeV
Higgs-rich higgsino	multi-b+$\not{E}_T$	None	$m_{NLSP} \not\gtrsim 160$ GeV?[c]

[a] Extrapolating an existing analysis.

[b] With an analysis optimized for higgsinos.

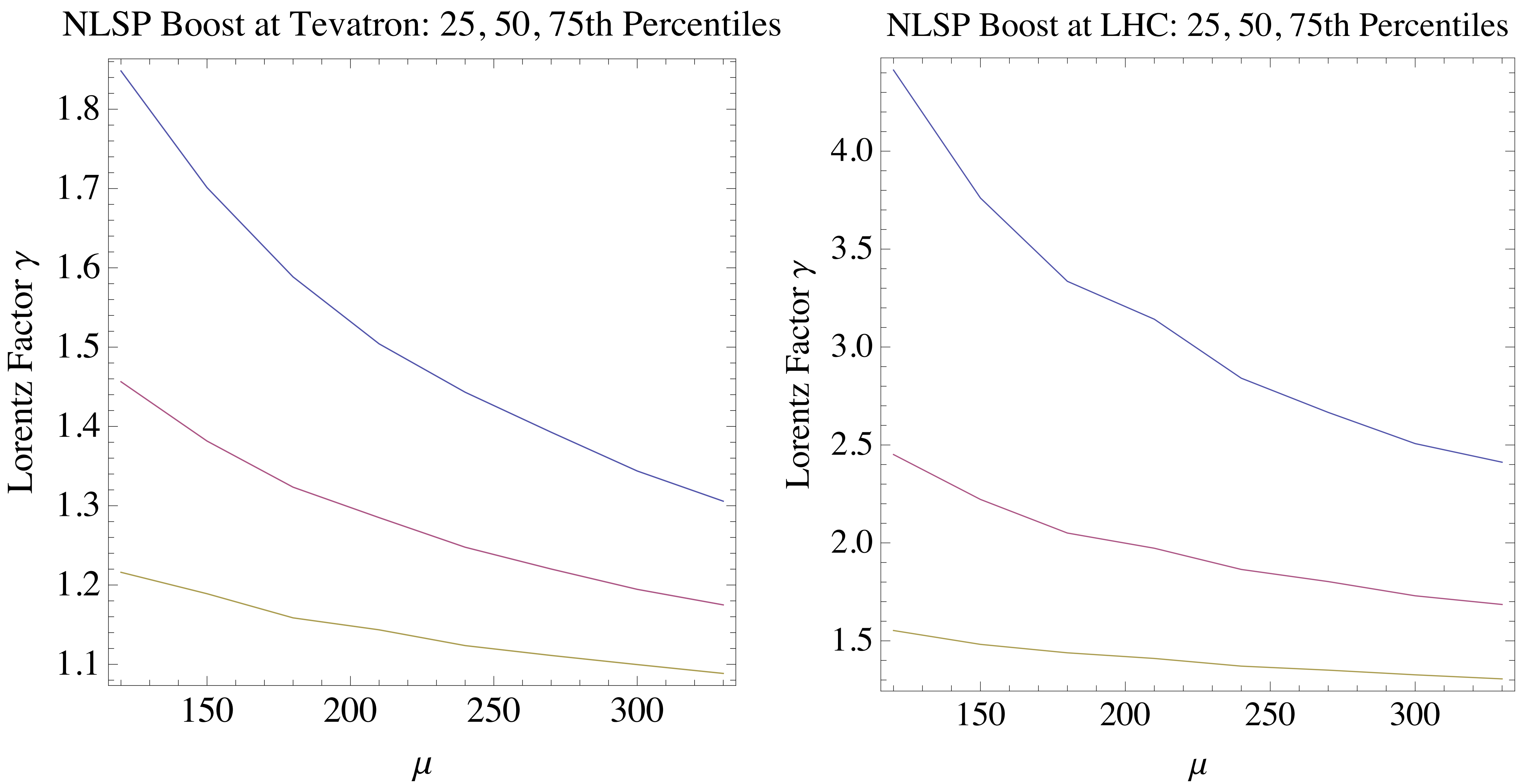
[c] In this case, it remains unclear how feasible an exclusion is.

The Tevatron has a large sample of well-understood data already recorded -- it would be a shame not to push it as far as possible!

Moving Forward

- What about the LHC? Again, γγ+MEt is well-studied and we can trust that the bounds will be improved.
- Recent ATLAS study of Z(→ll)+γ+MEt (0910.4062): 135 GeV reach with 3 fb^{-1}. Tevatron should already exclude this!
- Need LHC studies of the channels we already discussed....
- LHC's big advantage would be strong production. But backgrounds...?

Boosts



More energetic objects at the LHC. Possibility of using substructure analysis

(See Kribs, Martin, Roy, Spannowski, 0912.4731)

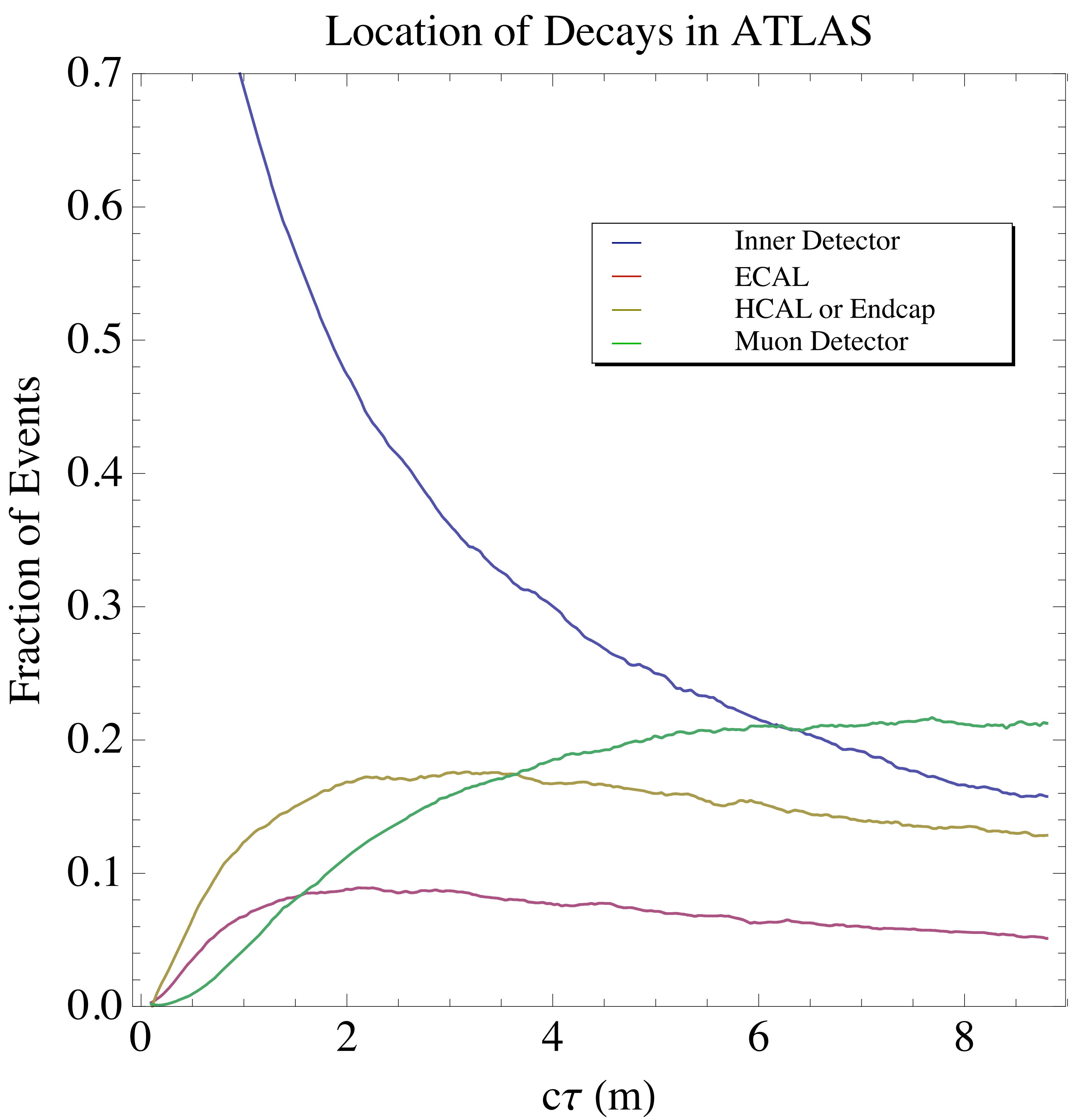
Delayed Decays

Generic in GMSB to have long lifetimes. If any value of $\sqrt{F_0}$ were equally likely, would expect decays outside the detector.

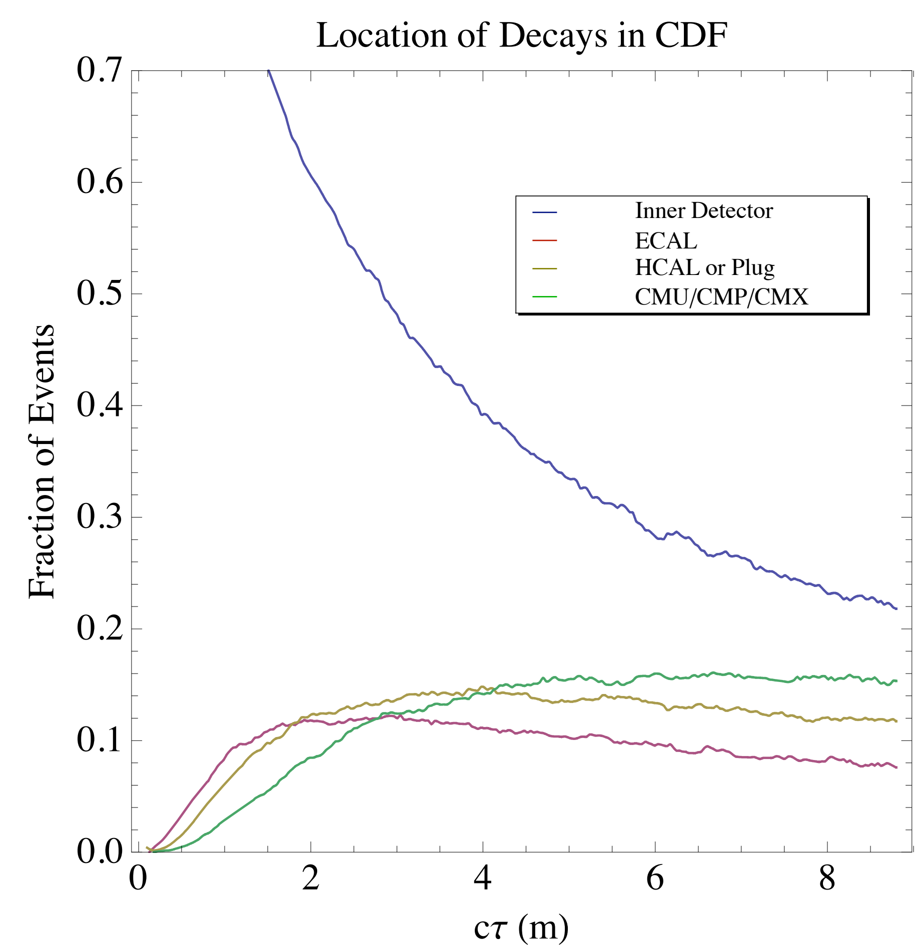
Macroscopic decays of order the detector size are especially interesting phenomenologically, although not obviously preferred theoretically.

- Measure lifetime, hence SUSY-breaking scale
- Better kinematic reconstruction -- hope to find NLSP rest frame, resolve vertex structure?

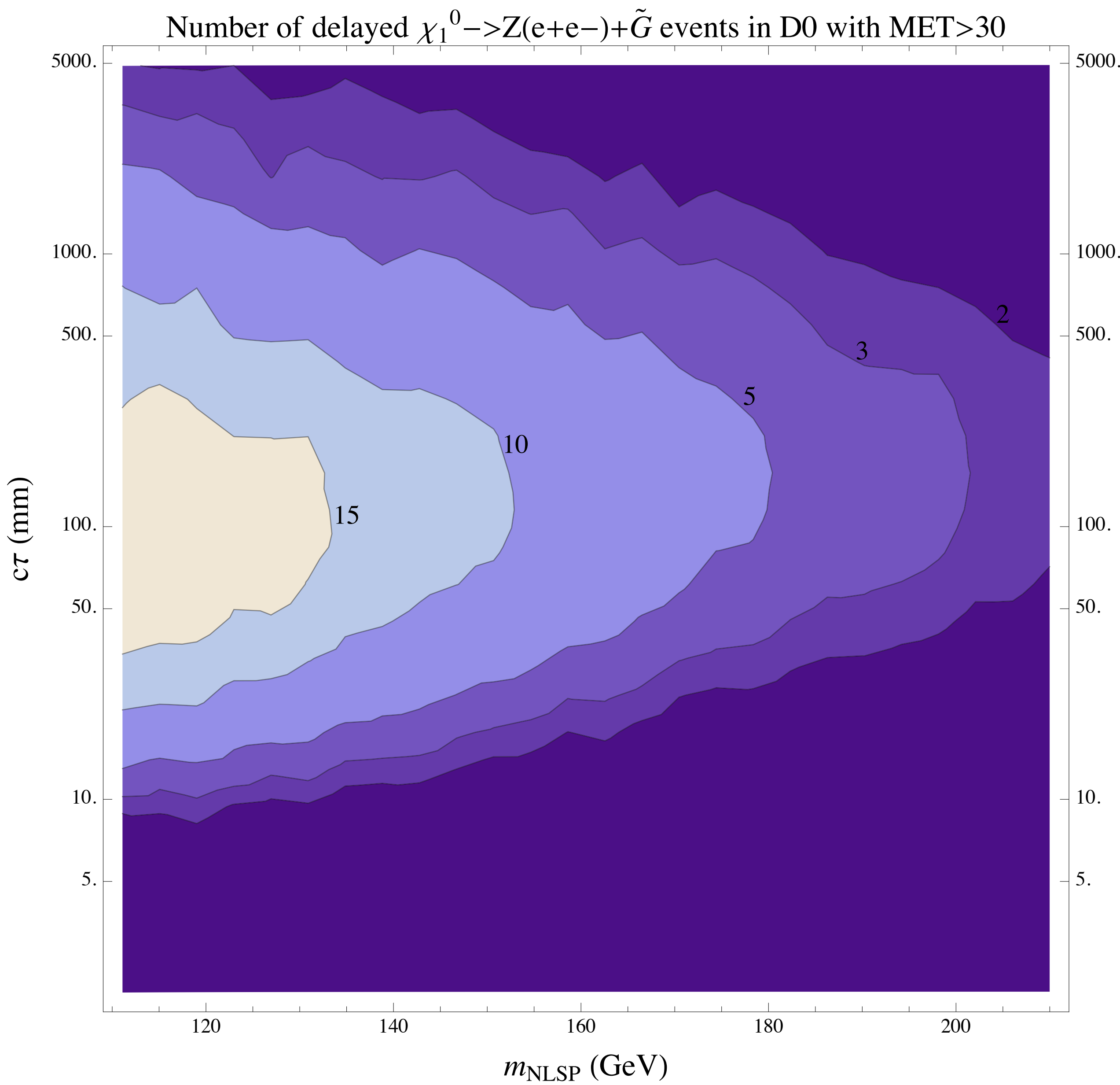
Displaced Decays: Where?



For a 150 GeV Higgsino, but mostly a function of cτ and geometry

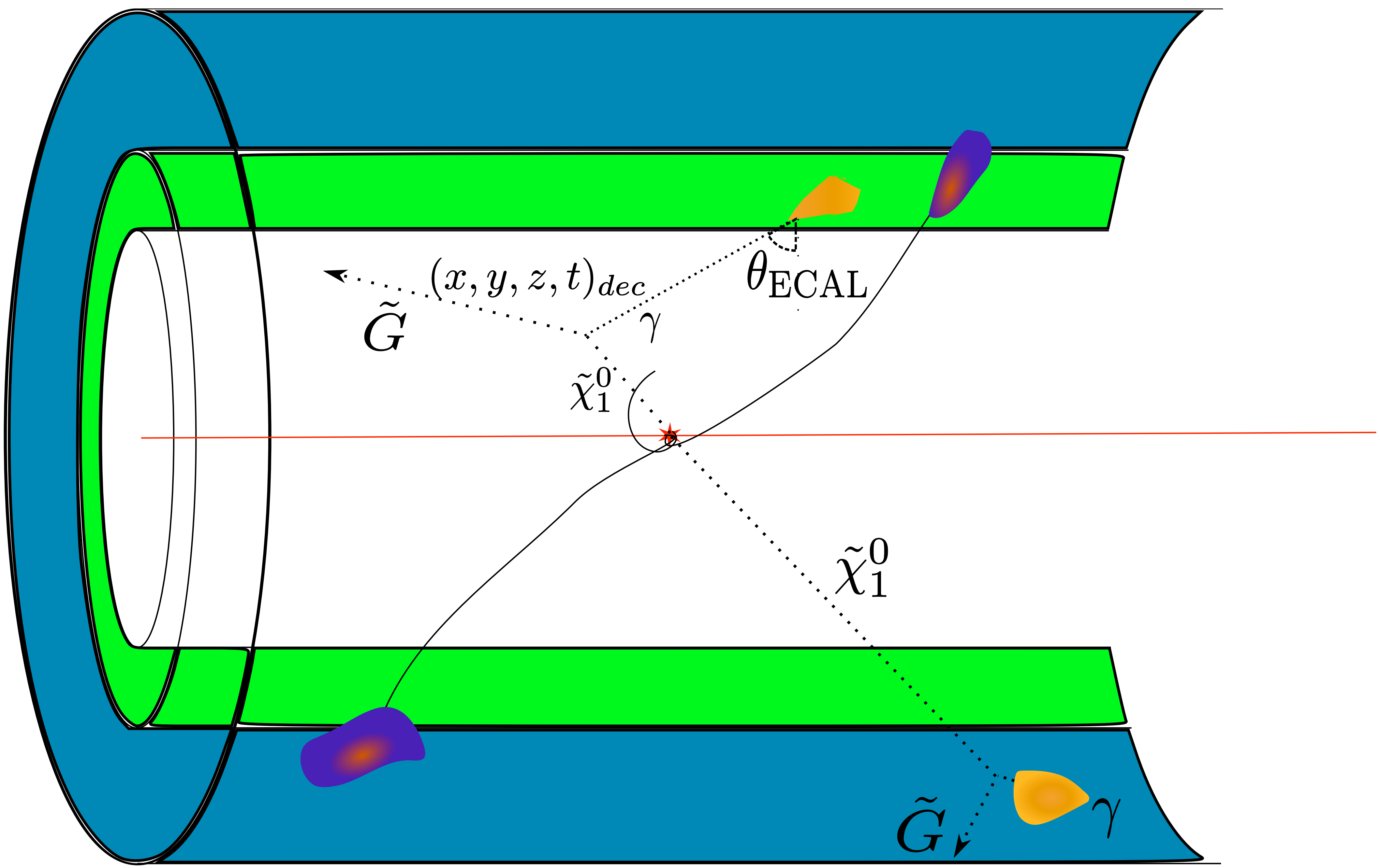


D0 Reach: Z to e^+e^-

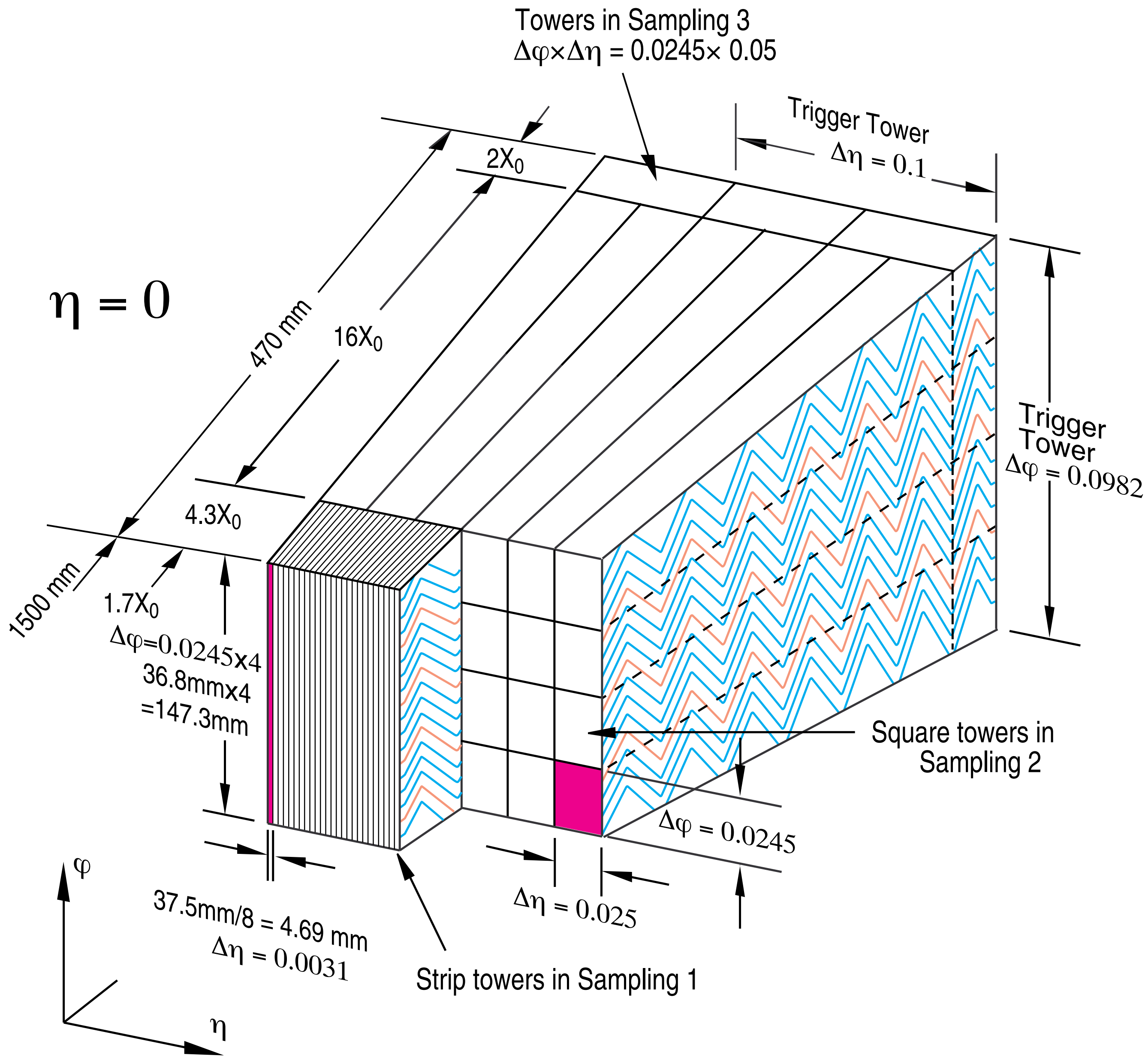


A simple extension of an existing study (0806.2223) can search for neutralino NLSPs

Displaced Neutralino Decays



Measurements



The ATLAS ECAL is granular: can measure the direction in η of an object traversing it (Resolution: $\sigma_\theta \approx 0.06/\sqrt{E}$, but degraded w/ eff. z vtx.)

Timing: 100 ps arrival time? (Disputed....)

See Kawagoe et al., hep-ph/0309031 for use of these measurements in minimal gauge mediation

Reconstruction: Z →ll

- Two massless particles hit the ECAL at known positions and times. Solve for the unknown decay vertex.
- Pointing gives $\frac{z_i - z_d}{\sqrt{(x_i - x_d)^2 + (y_i - y_d)^2}}$, timing

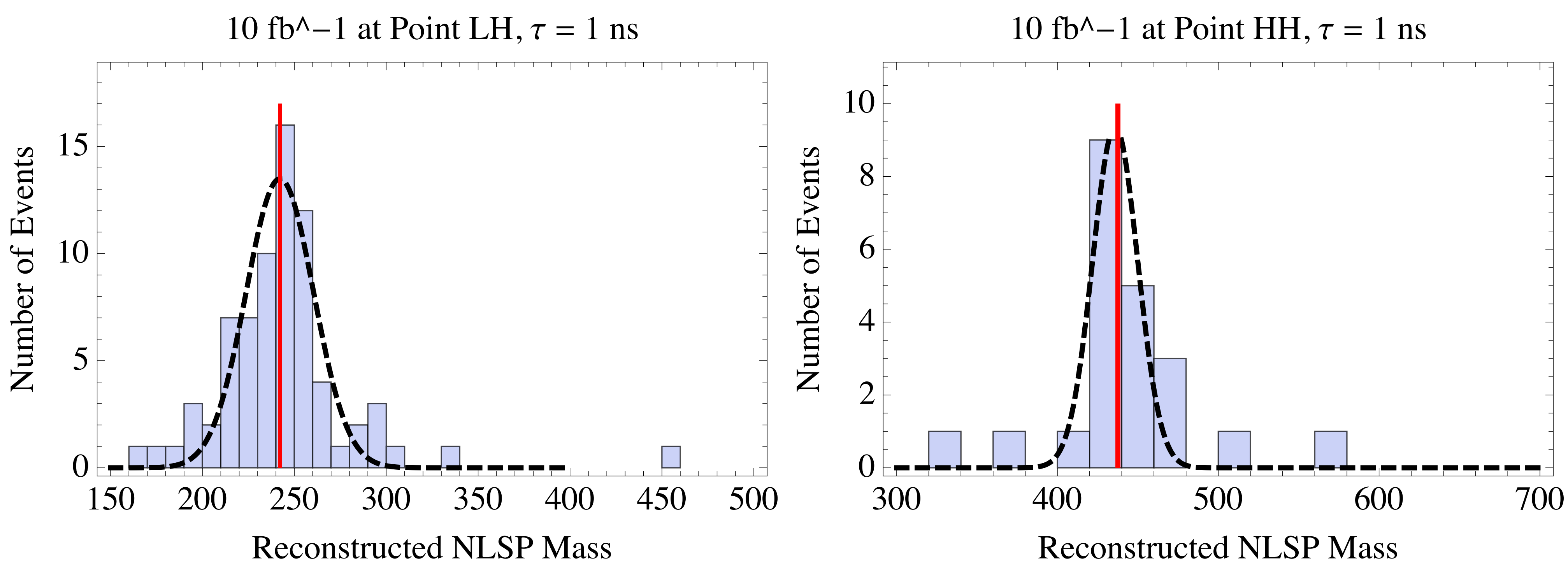
$$c(t_i - t_d) = |\mathbf{x}_i - \mathbf{x}_d|$$

- Four equations, four unknowns. Constraints: time order, speed < c.

Further Reconstruction

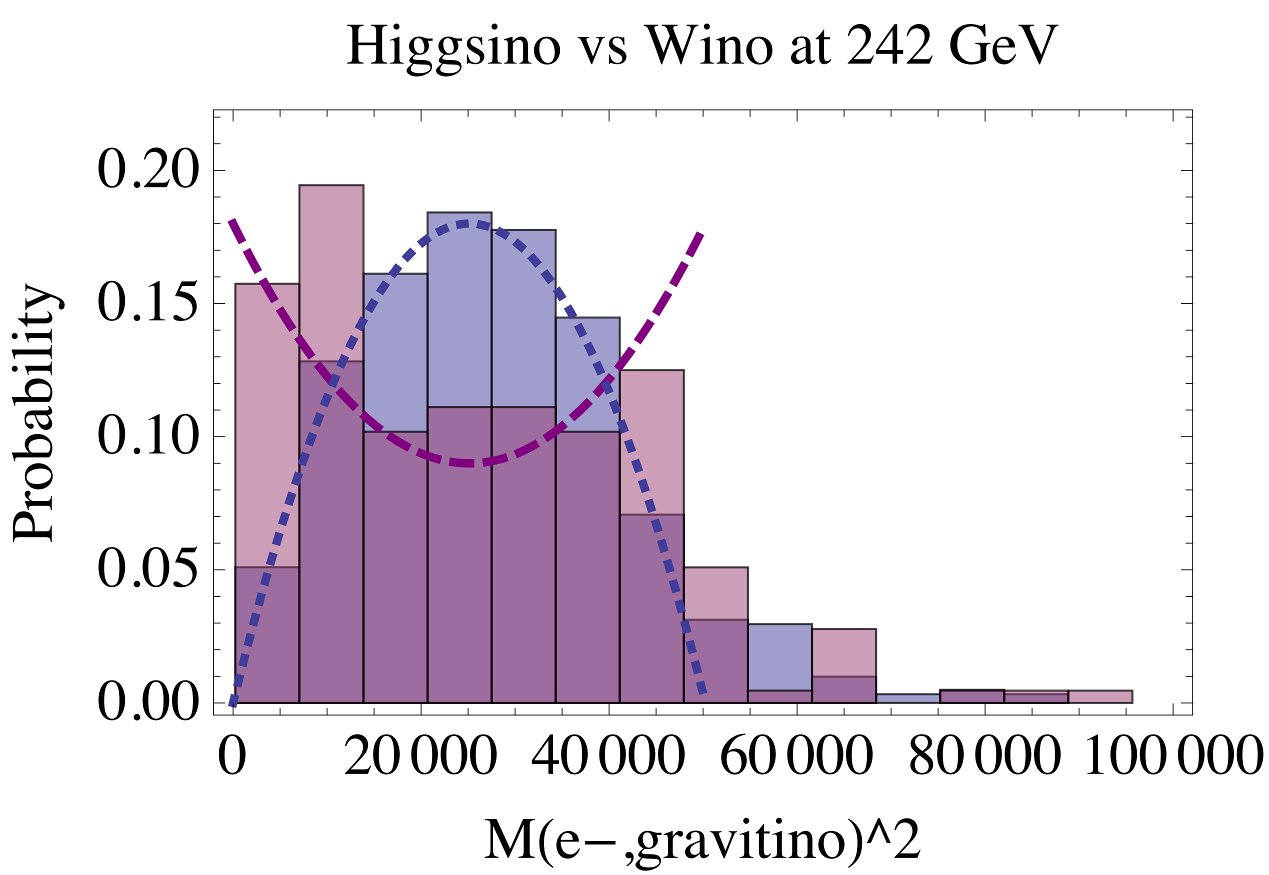
- Once we know the location and time of the NLSP decay, assuming a massless gravitino gives us the full four-vector:

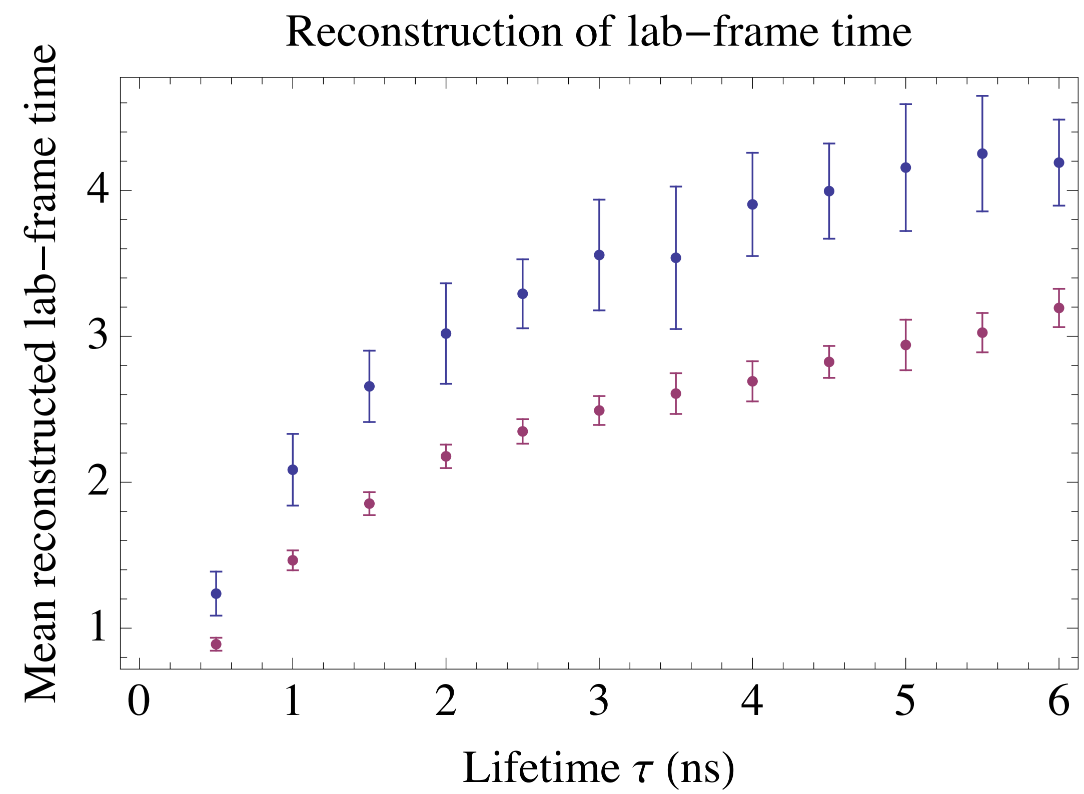
$$m_{\tilde{G}}^2 = (E_\chi - E_1 - E_2)^2 - (E_\chi \mathbf{v}_\chi - \mathbf{p}_1 - \mathbf{p}_2)^2 = 0$$



These plots show an improvement : χ^2 fit with TRT angle

Finding the underlying model





Accurate kinematic reconstruction gives information on polarization: longitudinal vs. transverse *Z* boson tells us Higgsino vs. Wino.

Lifetime determination is difficult

Conclusions

- General neutralino NLSPs relatively unconstrained.
- Tevatron has the opportunity for first limits on Higgsino NLSPs; it already constrains wino co-NLSPs (previously unexplored)
- Work in progress to see what the LHC can do.
- Long lifetimes can be a lot of fun -- capability of pushing the detector to do precision measurement