The Status of Super-Symmetry 2011

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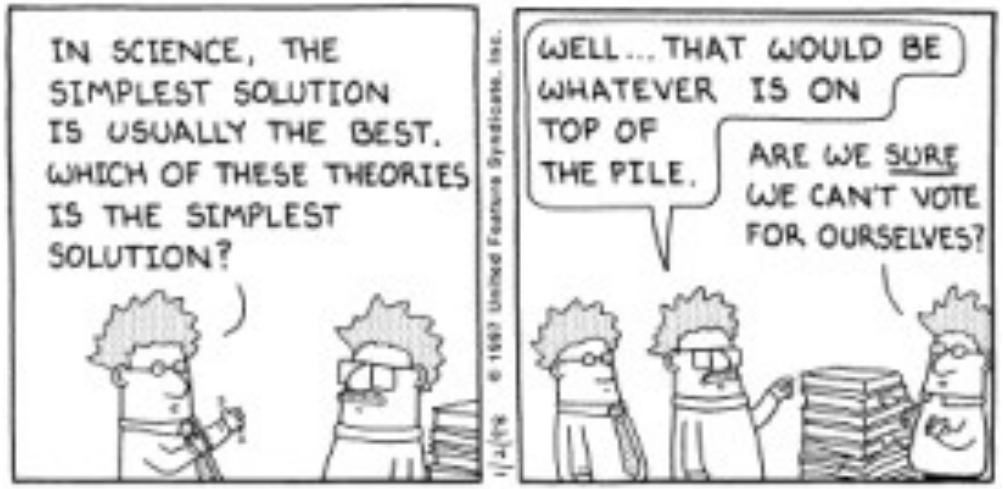
September 1, 2011

Why Super-Symmetry ?



Theorists Experimentalist

Experimentalists Deal in Signatures …

Super-Symmetry is a Great Signature Generator

Search for Super-Symmetry at the Weak Scale

Low Energy High Precision Indirect Searches -
Violation of Global Symmetries, …

High Energy Direct Searches -
Production and Decay of Super-Partners

This Talk …

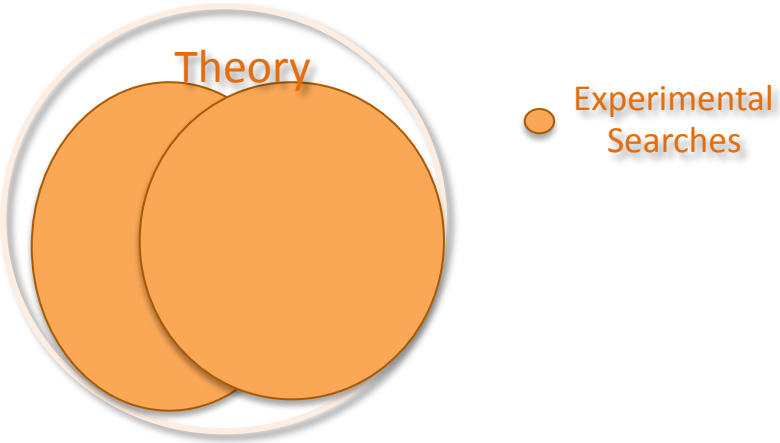
The Direct Search for Super-Partners has been Underway for O(30) years

SPS, LEPI	m > O(50) GeV
LEPII	m > O(100) GeV
Tevatron	m > O(300) GeV
LHC	m > O(1000) GeV

Mass Scale for Some of the Super-Partners – In Some Channels

The Searches have Been Heroic – but Incomplete

Underlying Theoretical Framework
Models
Simulations
Signatures
Experimental Signature Search


Theory
Experimental Searches

SUSY: No Single Definitive Prediction –
Just Hope that Some of the Super-Partners are Kinematically Accessible

Make (Prioritized) List of Signatures and Do the Experimental Searches

Direct Searches for Super-Symmetry

Super-Partners + Super-Interactions

+ Goldstino

+ New Interactions (~~R-Symmetry~~, B <u>or</u> L Conserved)

+ Global Symmetry Violation (Lepton Flavor, …)

+ New Global Symmetries ($U(1)_R$, …)

+ New Matter fields (Vector Like, Dark Matter, …)

+ New Higgs fields (Singlets, …)

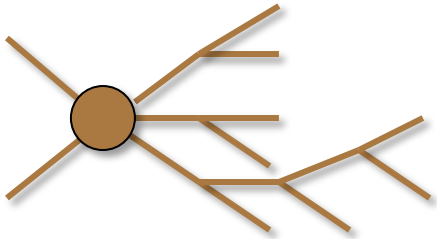
+ New Gauge Interactions (Abelian, Non-Abelian)

+ …

Current Experimental Era: (Pre-Discovery)

Signatures Most Important Metric

Organize with Production and Decay Topologies



Parameterized by

Mass Spectrum,
Spins + Quantum Numbers (or Decay Distributions)

Topologies Factorize Mapping Data ←→ Theory

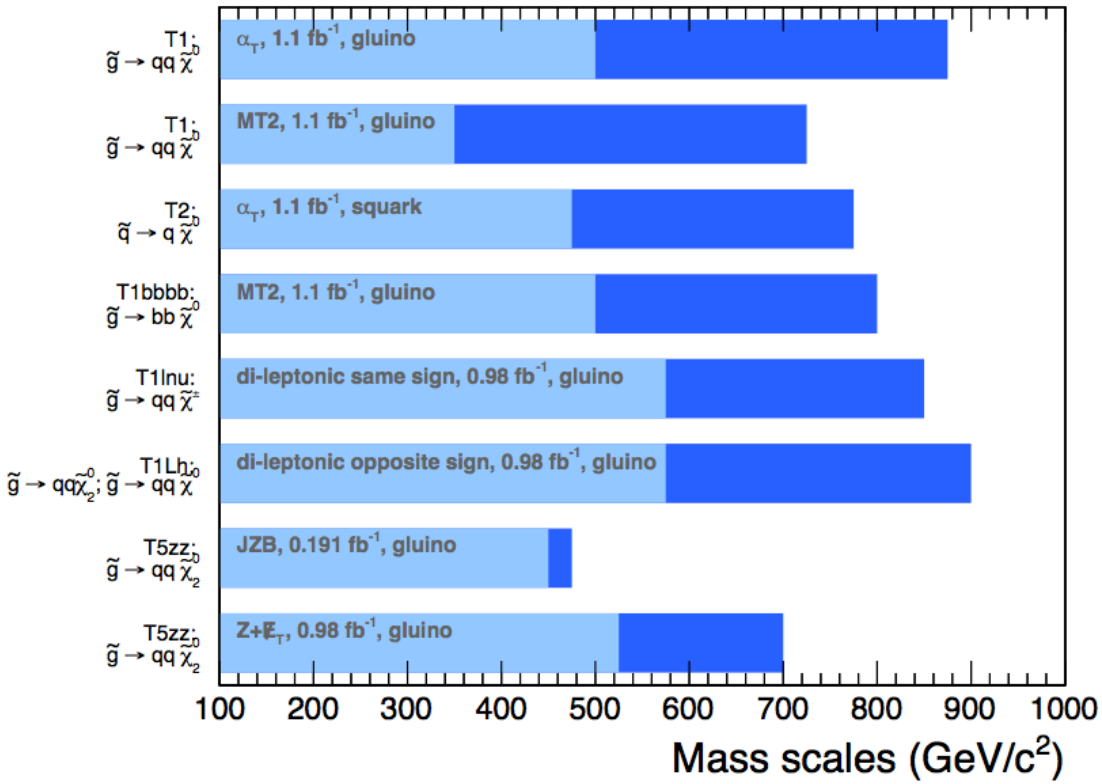
- Production σ's Factor Out of Problem
- Cascade Br's Factor Out of Problem
- Multiple Topologies + Multiple Channels Easily Combined
- No Relation Among $\sigma_t, Br_{\alpha t}, m_{it}$ Need be Specified
- Can Add More Topologies Later
  (Since Don't Simulate Combinations of Topologies)

Simplified Models for LHC New Physics Searches arXiv:1105.2838 [hep-ph]

Signatures of New Physics at the LHC http://www.lhcnewphysics.org

Results for SUSY Topologies

Ranges of exclusion limits for gluinos and squarks, varying $m(\tilde{\chi}^0)$
CMS preliminary



For limits on $m(\tilde{g})$, $m(\tilde{q}) >> m(\tilde{g})$ (and vice versa). $\sigma^{prod} = \sigma^{NLO\text{-}QCD}$.

$$m(\tilde{\chi}^\pm), m(\tilde{\chi}^0_2) = \frac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}.$$

$m(\tilde{\chi}^0)$ is varied from 0 GeV/c^2 (dark blue) to $m(\tilde{g})$-200 GeV/c^2 (light blue).

Focus on Signatures Parameterized by Production and Decay Topologies

↳ This Talk … 2011 … LHC

Focus on Signatures Parameterized by Production and Decay Topologies

This Talk … 2011 … LHC

Models for Ultraviolet Completion of SUSY Breaking Messenger Sector (Post-Discovery)

Cosmological or Low Energy Constraints (Many Assumptions)

Focus on Signatures Parameterized by Production and Decay Topologies

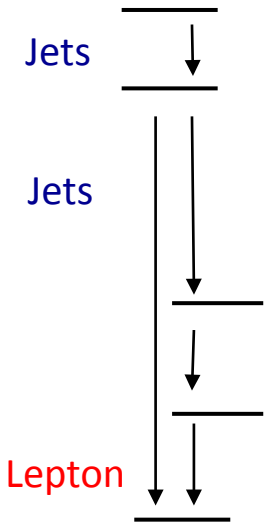
This Talk … 2011 … LHC

Models for Ultraviolet Completion of SUSY Breaking Messenger Sector (Post-Discovery)

Cosmological or Low Energy Constraints (Many Assumptions)

"Tuning" of "Remaining" SUSY Parameter Space (…)

SUSY Topologies



Produce Super-Partners in Pairs
or Possibly Resonantly if R-Sym Violation

SM Particles Emitted in Cascade
Decays of Super-Partners

R-Symmetry Conserved Violated

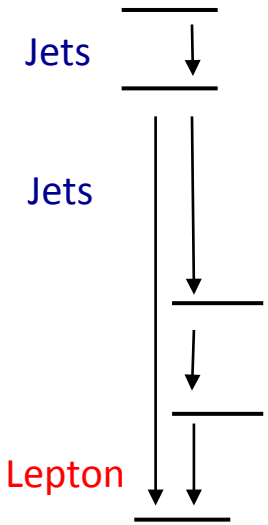
Lightest Super-Partner Stable Un-Stable

Detect Passage Through Detector

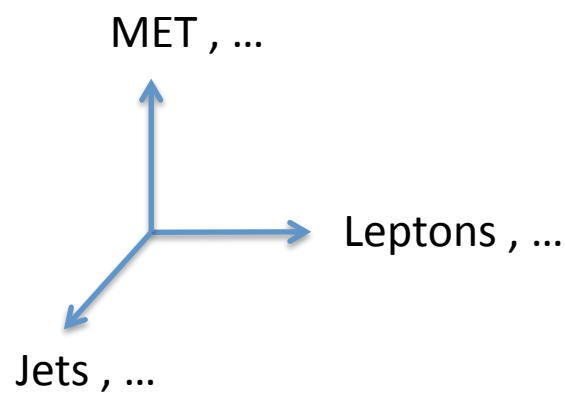
Generic Non-Degenerate Spectrum - High p_T Isolated Objects:

Jets, b-Jets, Electrons, Muons, Taus,
Z-Bosons, Photons, MET, Top Quarks + Lightest Super-Partner(s)

SUSY Topologies



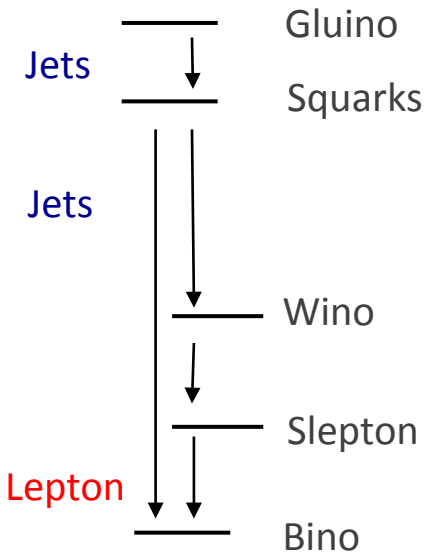
Signature Space



Searches are Built Around SM Backgrounds –

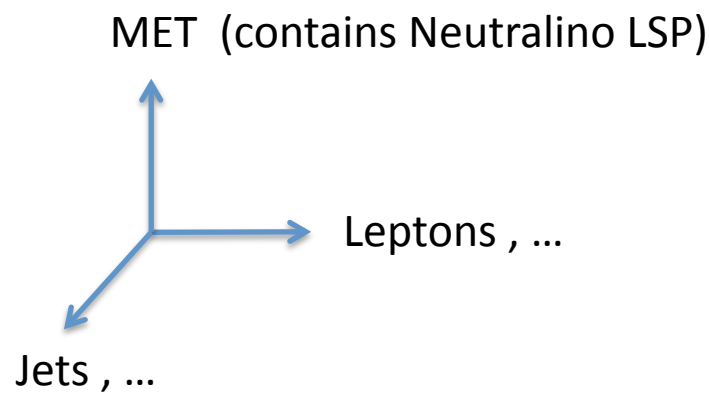
Design Searches Away from "Origin" of Signature Space
Along Some Axis or Axes

Canonical SUSY Topology – Stable Neutralino LSP



Stretched
Gauge
Ordered
Spectrum

Signature Space



MET + X searches:

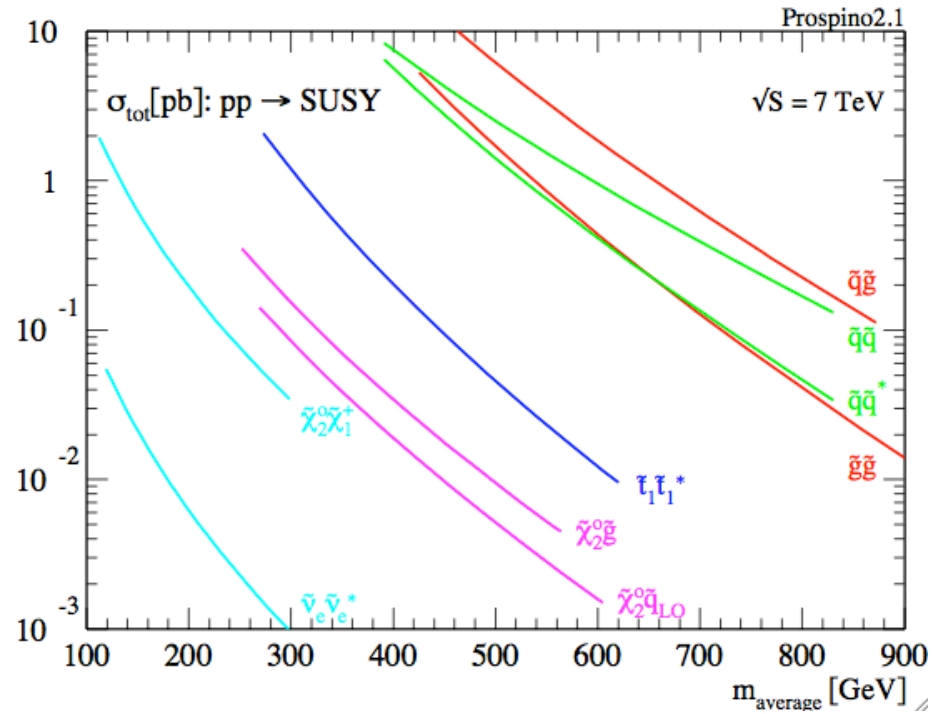
Organize by $N_{leptons}$: X = Jets + 0 Leptons
Jets + 1 Lepton
Jets + 2 OS Leptons
Jets + 2 SS Leptons
3 Leptons
4 or More Leptons

Compression - Degeneracies Can Soften Emitted Particles

Weaken Signature

LHC Signatures

Irreducible Pair Production

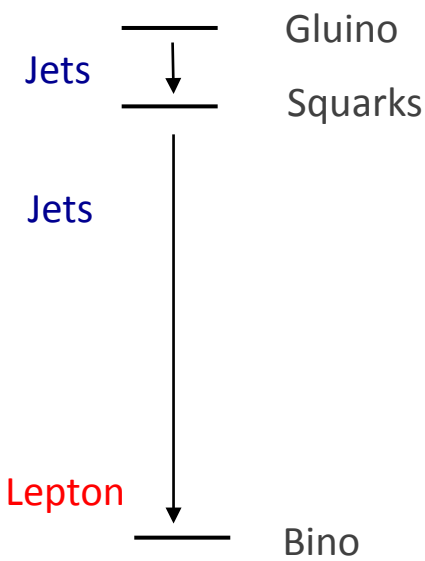


Beyond Tevatron Reach in Relatively Low Background Final States

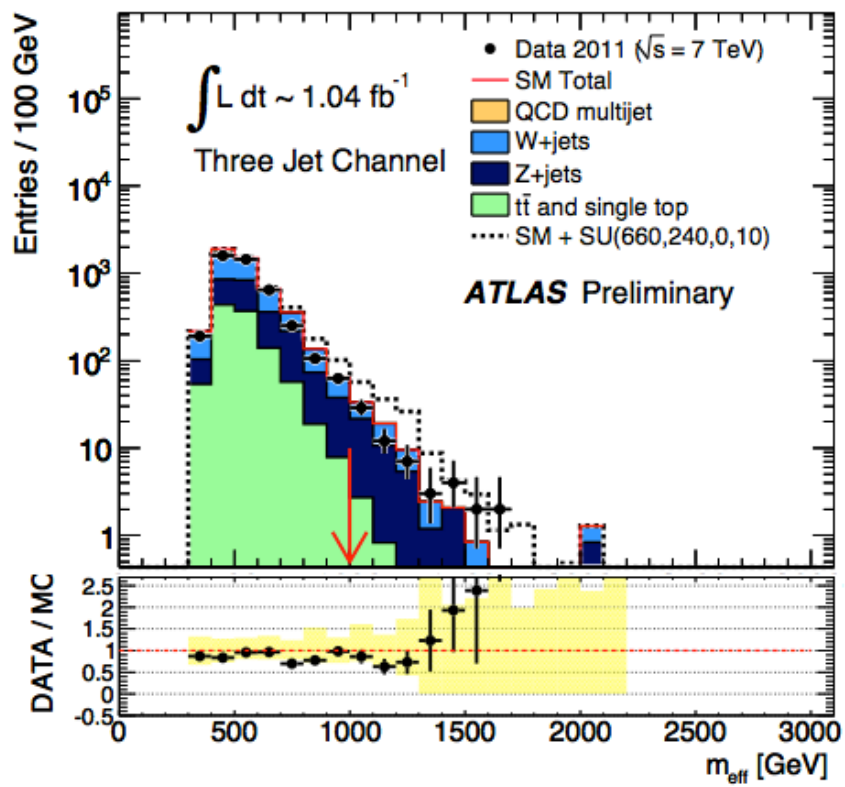
Strong Production > $O(pb^{-1})$ (All That's Been Probed So Far)

Weak Production > $O(fb^{-1})$ (Starting to Probe Now)

Jets + MET Signature

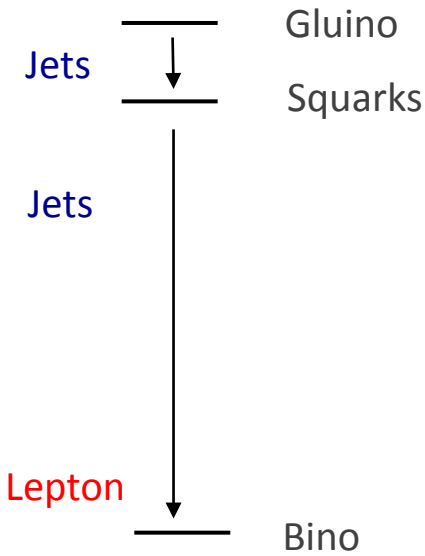


$N_{lepton} = 0$



$$m_{eff} = \sum_{i=1}^{n} |\vec{p}_T^{\,jet\ i}| + E_T^{miss}$$

Jets + MET Signature



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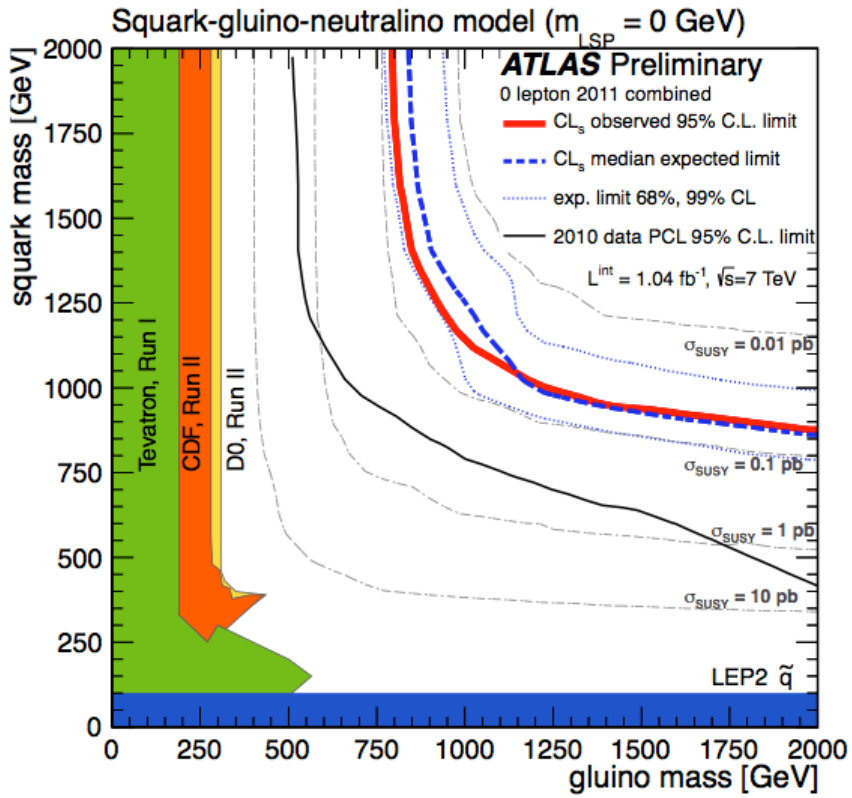
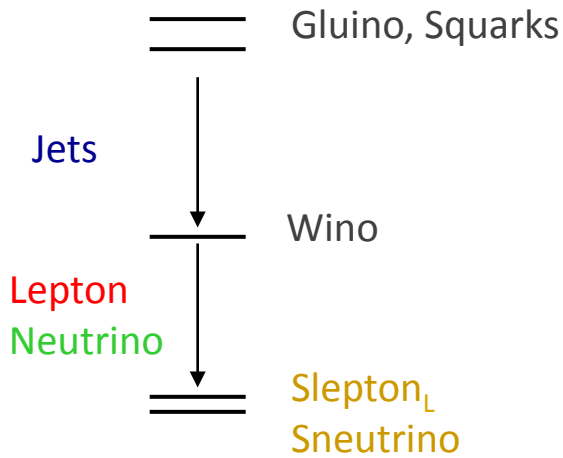
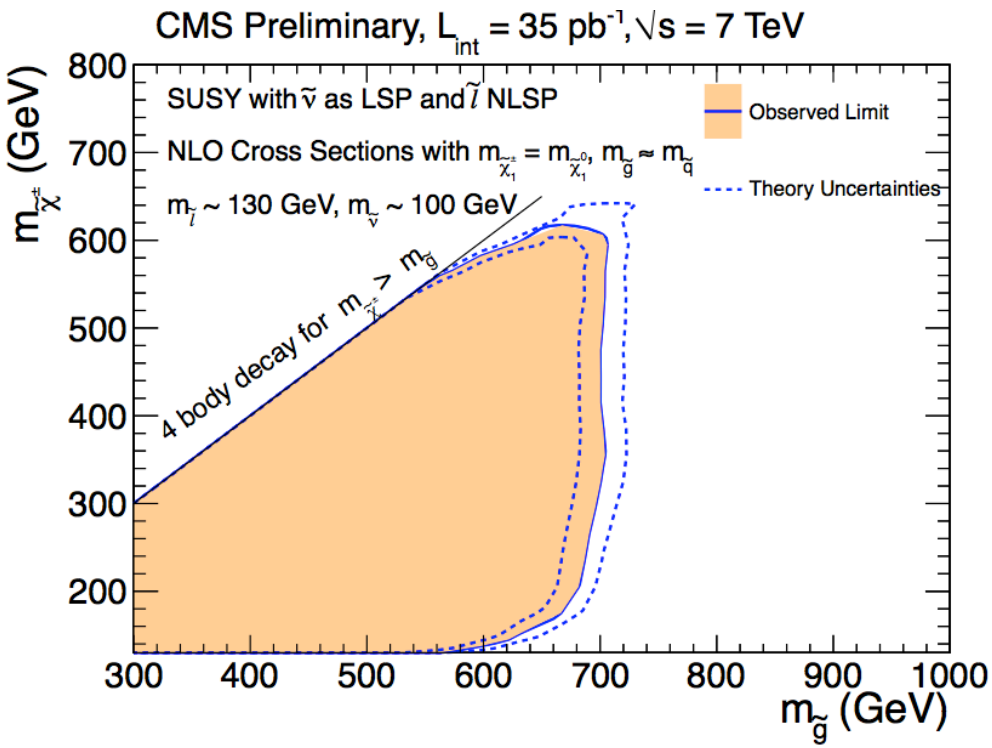


Same Sign Leptons + Jets + MET Signature





Three or More Leptons (+ MET) Signatures

Data: CMS 35 pb^{-1}

Compare Tevatron Tri-Lepton Searches

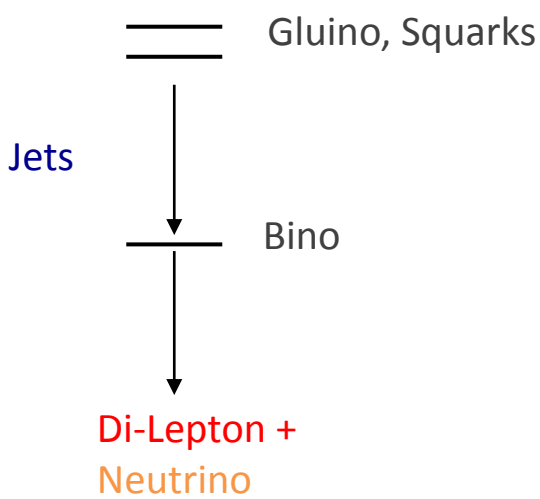
	After Lepton ID Requirement					MET > 50 GeV		H_T > 200 GeV		ML01 Signals	
	Z +jets	$t\bar{t}$	VV +jets	ΣSM	Data	ΣSM	Data	ΣSM	Data	MET > 50	H_T > 200
Channel	3-lepton channels										
ll(OS)e	1.7	0.1	1.2	4.4 ± 1.5	6	0.1 ± 0.1	0	0.2 ± 0.1	1	121.4	141.5
ll(OS)μ	2.83	0.2	1.7	4.7 ± 0.5	6	0.10 ± 0.1	0	0.1 ± 0.1	0	123.6	120.8
ll(OS)T	121.5	0.5	0.7	123 ± 16	127	0.4 ± 0.1	0	–	–	80.5	–
ll(OS)τ	476	2.7	3.9	484 ± 77	442	–	–	0.6 ± 0.2	1	–	68
ll′T	0.72	0.5	0.2	1.7 ± 0.7	3	0.4 ± 0.2	2	–	–	18.6	–
ll′τ	4.7	2.9	0.6	11.2 ± 2.5	10	–	–	0.4 ± 0.1	1	–	12.3
ll(SS)l′	0.13	0.1	0.0	0.2 ± 0.1	0	0.2 ± 0.1	0	0	0	2.8	2.8
ll(SS)T	0.25	0.0	0.1	0.7 ± 0.4	3	0.1 ± 0.1	0	–	–	9.0	–
ll(SS)τ	1.4	0.0	0.1	3.0 ± 1.1	3	–	–	0.0 ± 0.1	0	–	6.9
Σ lll(T)	127.1	1.4	3.8	135 ± 16	145	1.3 ± 0.2	2	–	–	355.9	–
Σ lll(τ)	486.8	6.0	7.5	507 ± 77	467	–	–	1.3 ± 0.3	3	–	349.5
lTT	47.1	0.33	0.1	48 ± 9	30	0.4 ± 0.1	0	–	–	8.0	–
Channel	4-lepton channels										
llll	0	0	0.2	0.2 ± 0.1	2	0	0	0	0	163.9	149.2
lllT	0	0	0.1	0.1 ± 0.1	0	0	0	–	–	62.3	–
lllτ	0	0	0.1	0.1 ± 0.1	0	–	–	0	0	–	33.2
llTT	0	0	0	0.0 ± 0.1	0	0	0	–	–	20.6	–
llττ	3.1	0.1	0.1	3.2 ± 0.7	5	–	–	0	0	–	16.8
Σ llll(T)	0	0	0.3	0.3 ± 0.1	2	0	0	–	–	246.8	–
Σ llll(τ)	3.1	0.1	0.4	3.5 ± 0.7	5	–	–	0	0		199.2

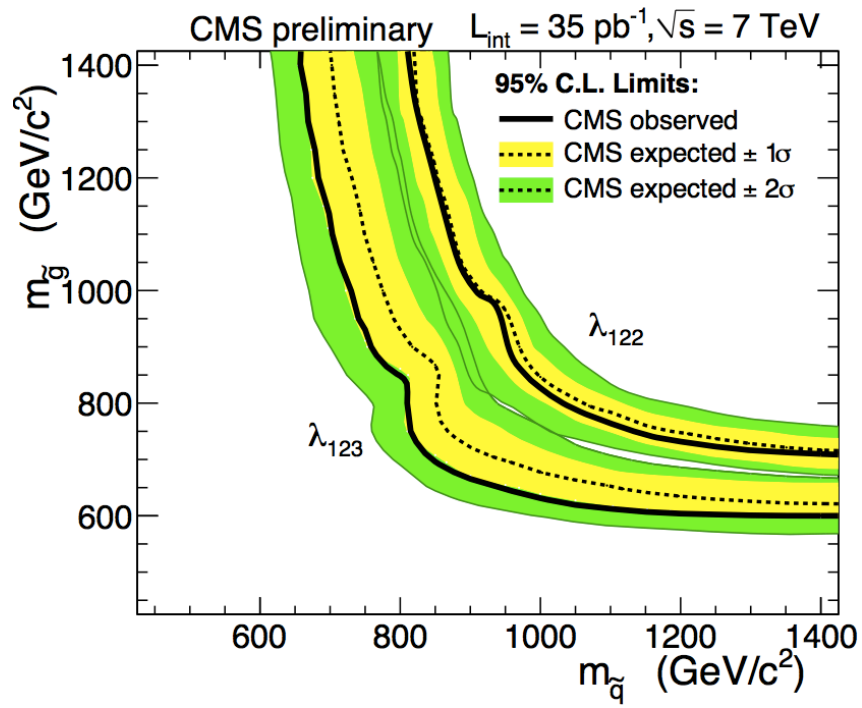
Combine Exclusive Channels

Three or More Leptons (+ MET) Signatures

Leptonic RPV

$$W = \lambda_{ijk} \; L_i \, L_j \, e_k$$





Beyond Tevatron – O(pb^{-1})

3rd Generation Enrichment

Standard Model Particles Emitted in
Cascade Decays may be 3rd Generation Enriched by
Left-Right Super-Partner Mixing

Taus : Identification More Difficult than
Electron or Muon - Reduces Sensitivity

Bottoms: b-tagged Jets – Generally Reduces Backgrounds
Increased Sensitivity

Tops: Reconstruction can be Challenging …
or in Simple Signatures an Opportunity

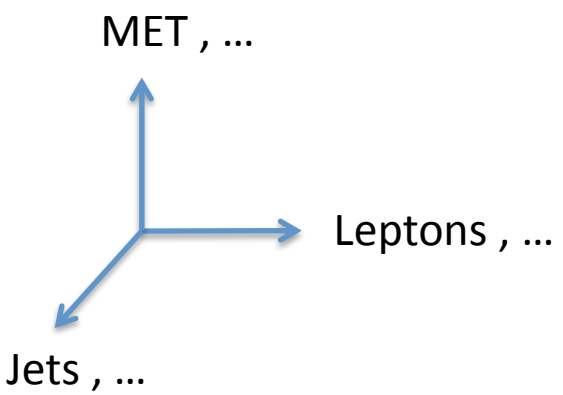
The Variables MET, HT, ST, m_{eff}, …

Very Blunt Instruments

Useful Far Out Along Axes in the Signature Space where SM Backgrounds are Low

Low "Temperature" Regions of Phase Space

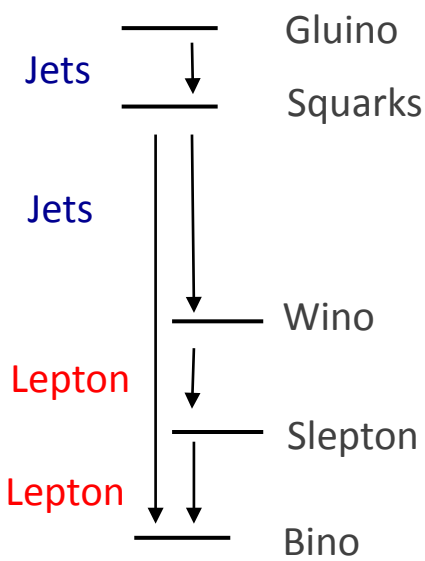
Searches are Effectively Thermal in these Low "Temperature" Regions



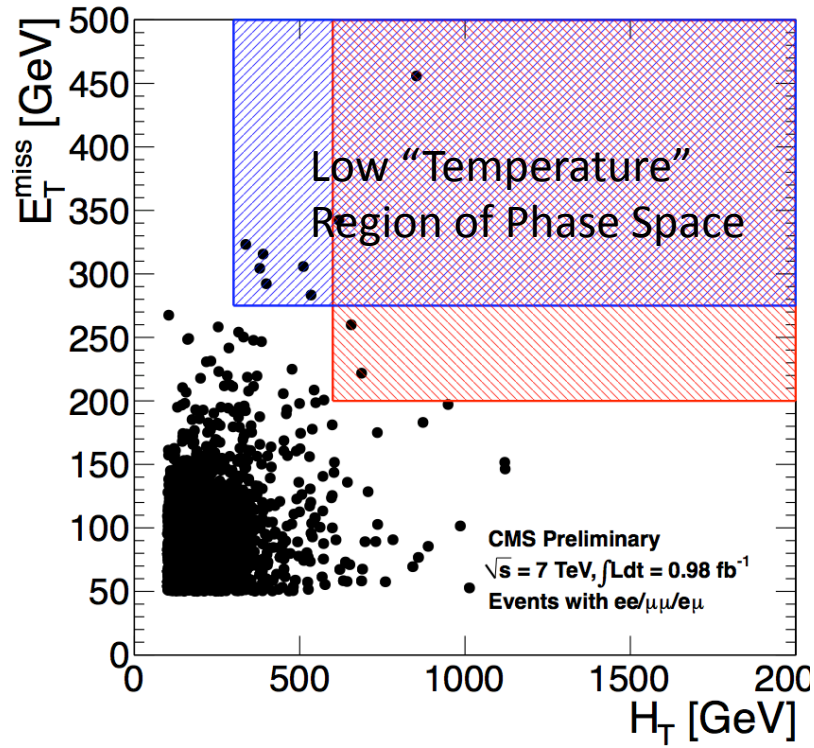
Kinematic Correlations are Required for More Refined Measurements Closer to the Origin of Signature Space (Less Inclusive)

Signal Might be Buried There Under SM Background
Low ST, MET, … , Top or Tau Enriched

Opposite Sign Di-Leptons + Jets + MET Signature



Significant SM Top Background
Near Origin of MET-HT Space



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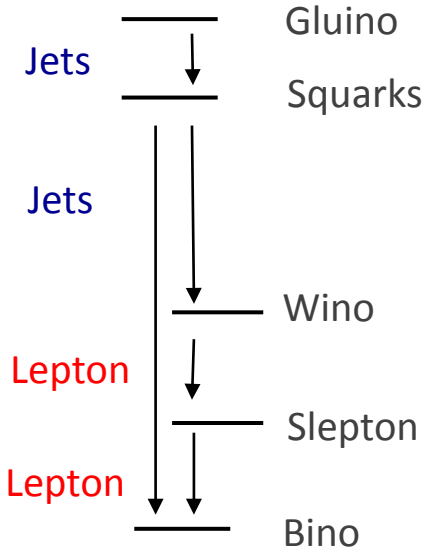

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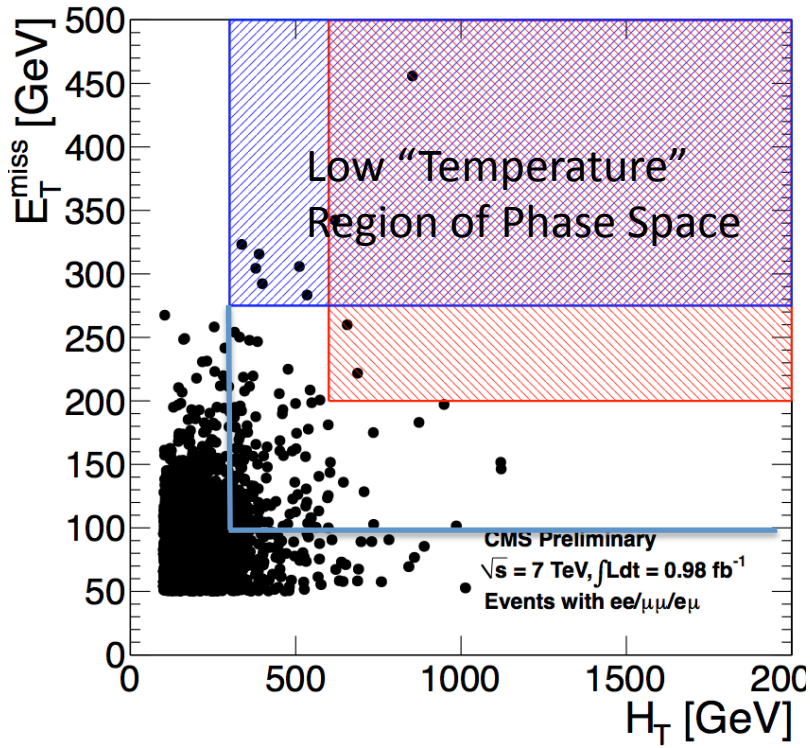

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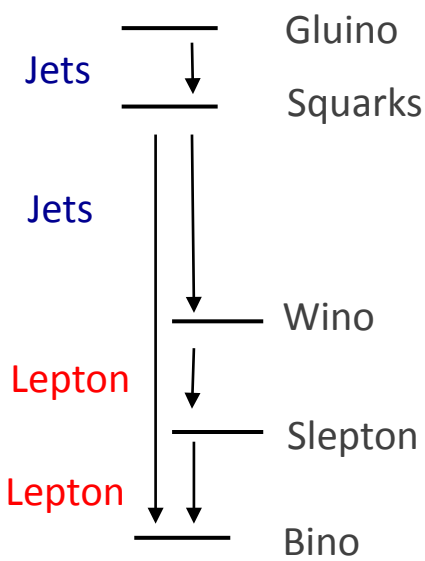
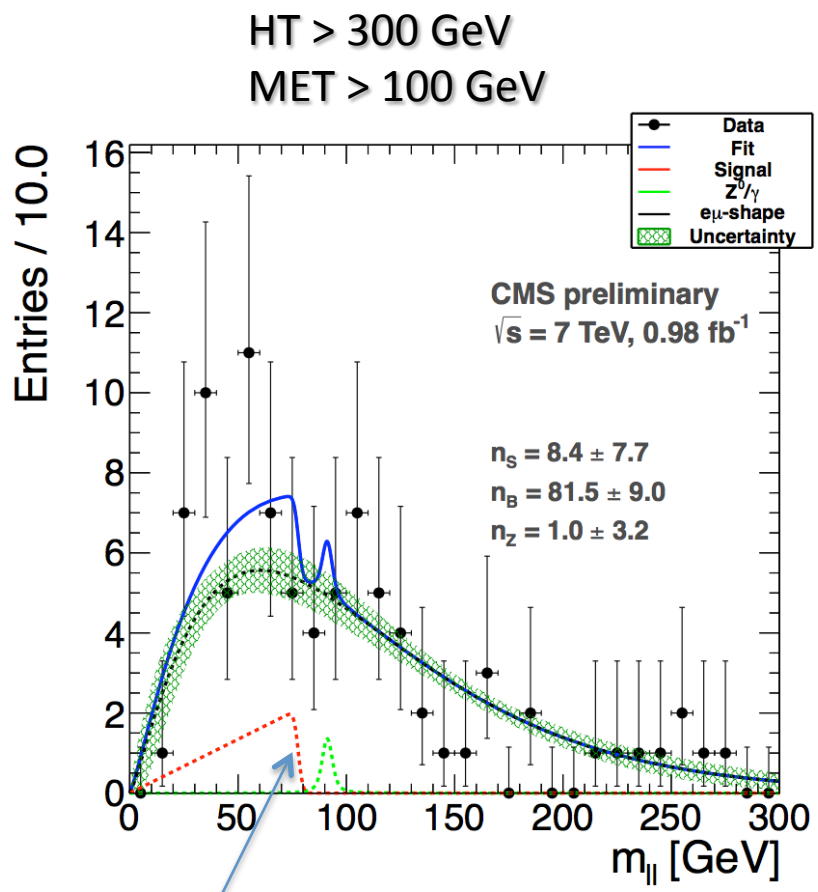
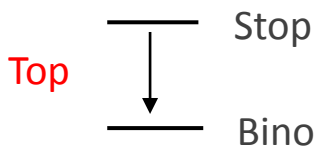
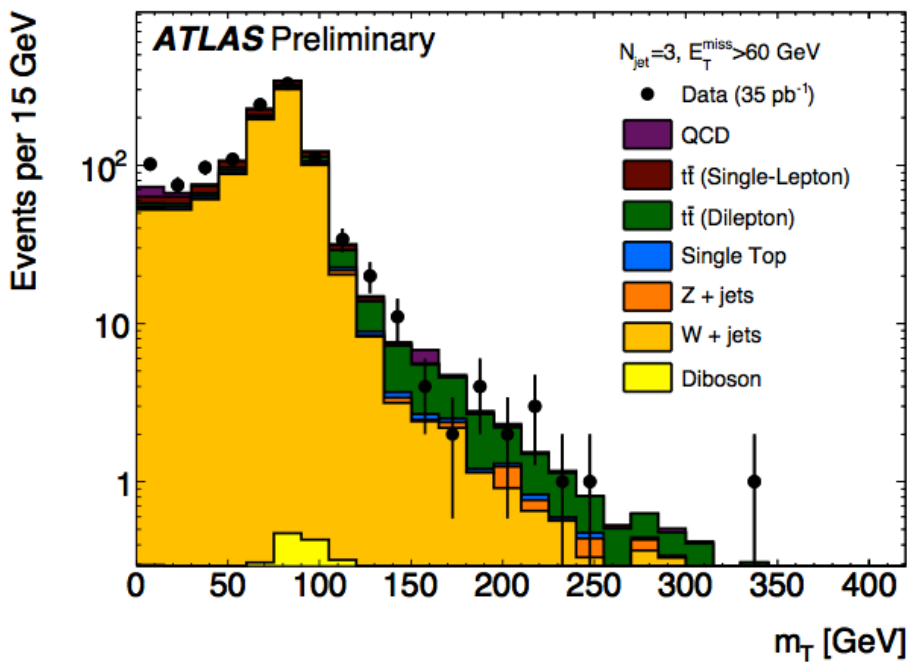




Mono-Lepton + Jets + MET Signature

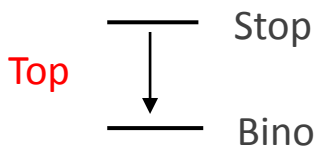


N_{jet}=3 MET > 60 GeV

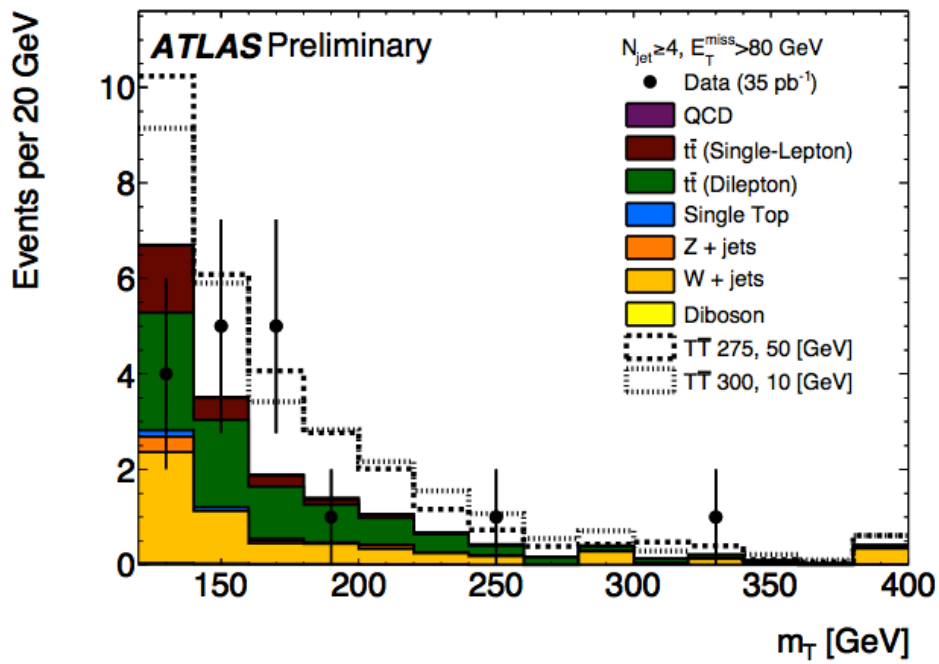


Lepton-MET Transverse Mass

Mono-Lepton + Jets + MET Signature



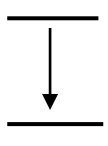
N_{jet}>3 MET > 80 GeV



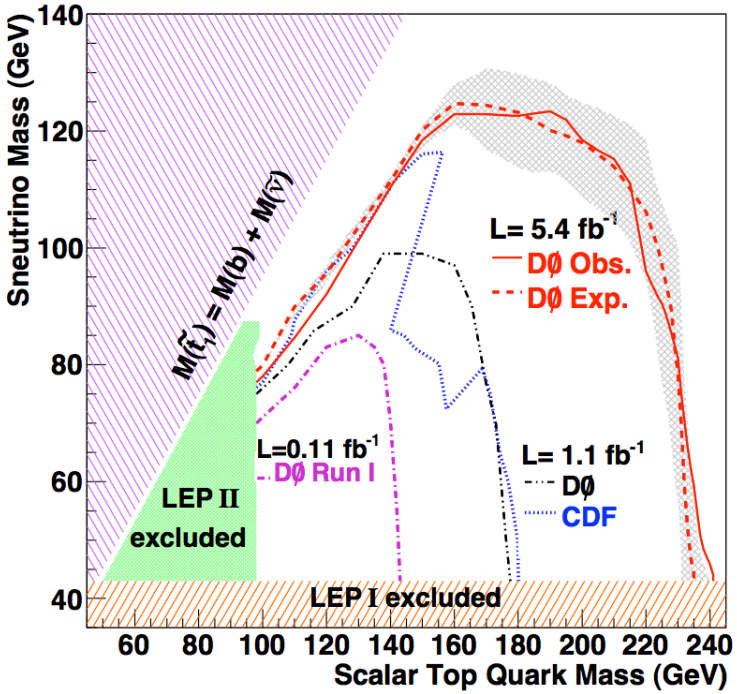
Lepton-MET Transverse Mass

Opposite Sign Di-Leptons + Jets + MET Signature

bottom + lepton



Kinematic Fit or
Multi-Variate Analysis
Distinguish from
SM Top Background

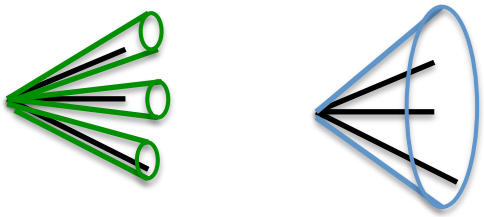


Multi-Jet Signature

Boosted Tri-Jet Resonance

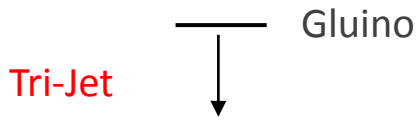
Focus on Resolved Individual Jets

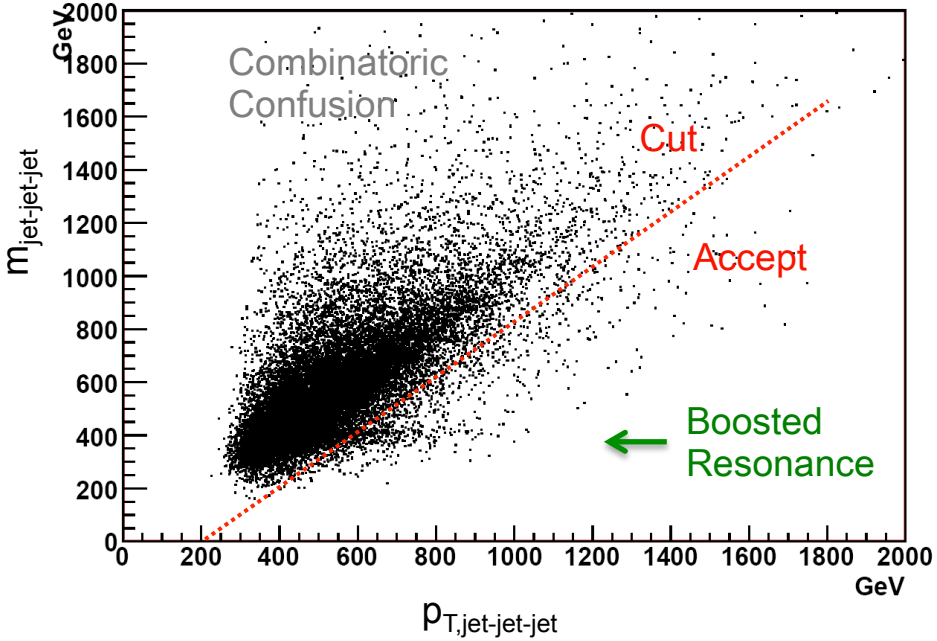
Rather Than Giant Merged Jets



QCD Fills Up Phase Space

↳ Approximately Scale Invariant





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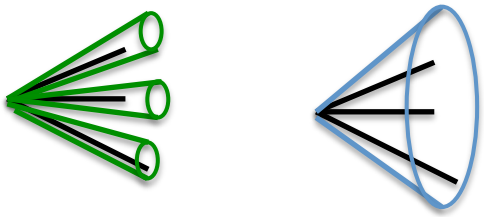

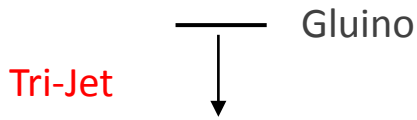

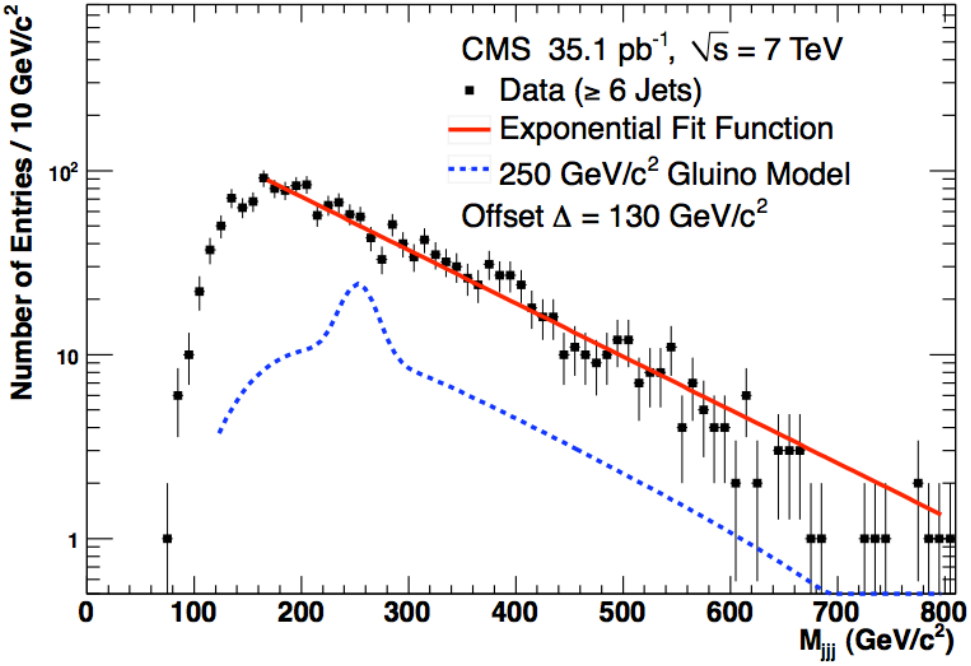

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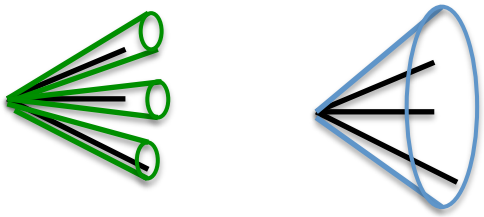
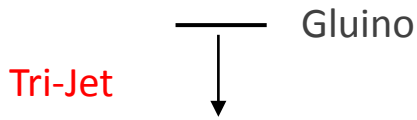
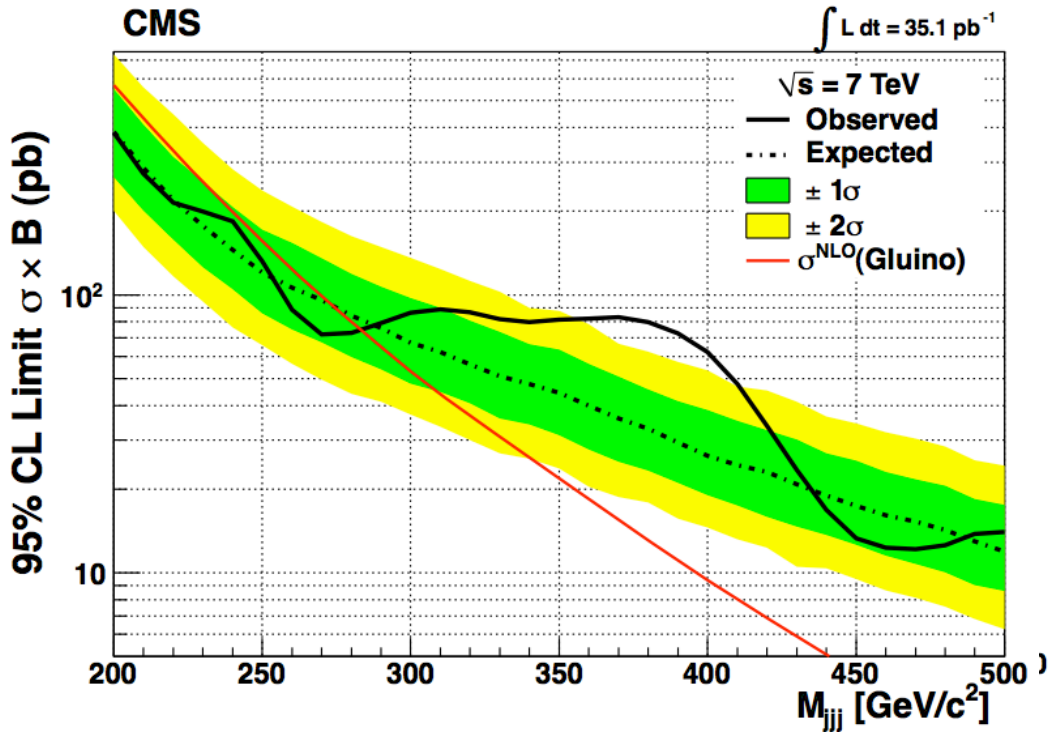




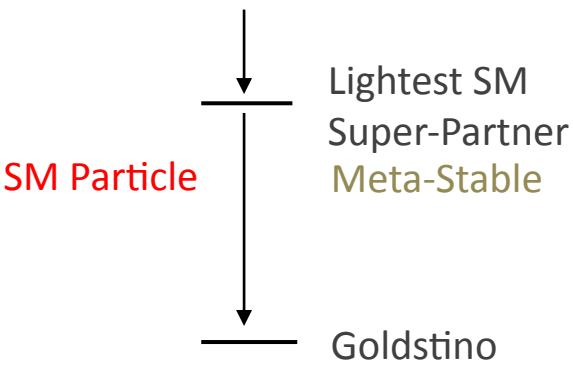


All Blunt “Thermal” Searches Can be Improved With Refined Kinematics …

But Become Less Inclusive …

The Scale of Super-Symmetry Breaking

Possible Decay to Goldstino (component of gravitino)
Provides a Natural Classification of Inclusive Signatures



- Prompt Decay — < O(100) TeV
- Decay Within Detector — O(100) TeV
- Effectively Stable in Detector — > O(100) TeV

Finite Gap → Emitted SM Particle - high p_T

Blunt "Thermal" Analyses that Capture Final Decays to Goldstino are Robustly Inclusive

SUSY Inclusive Signatures

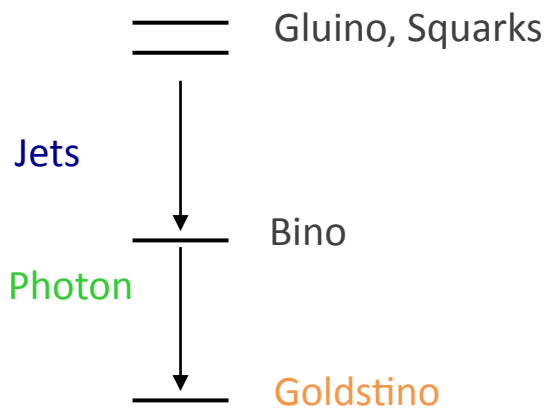
TABLE 24. Experimental signatures for different NLSP scenarios. LNIP ≡ Large Negative Impact Parameter. MIT ≡ Minimum Ionizing Track (muon candidate). HIT ≡ Highly Ionizing Track (anomalously large dE/dx). CC-HIT ≡ Charge Changing Highly Ionizing Track. CE-HIT ≡ Charge Exchange Highly Ionizing Track. H-HIT ≡ Hadronic Highly Ionizing Track. TOF ≡ large Time of Flight measurement. X ≡ Additional partons in the final state. If the decay length is comparable to the size of the detector, then signatures from two or three columns can appear simultaneously.

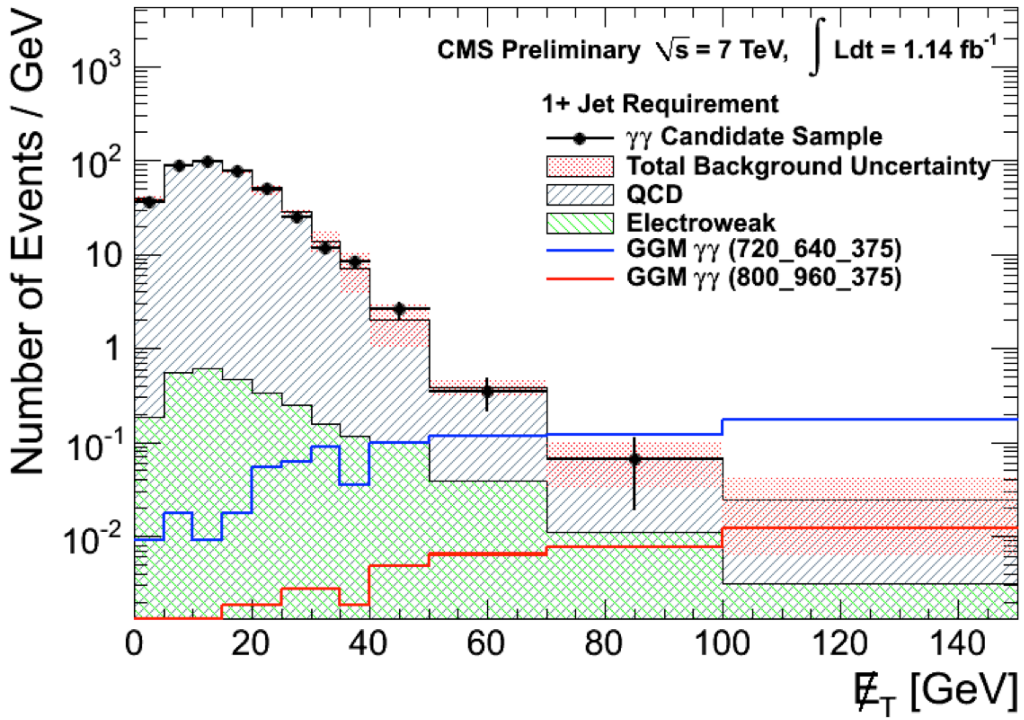
NLSP	Prompt Decay	Macroscopic Decay Length	Long-lived
Bino-$\widetilde{\chi}_1^0$	$\gamma\gamma\ X\ \not{E}_T$	(Displaced γ) $X\ \not{E}_T$ TOF	$X\ \not{E}_T$
Higgsino-$\widetilde{\chi}_1^0$	$(\gamma, h, Z)(\gamma, h, Z)\ X\ \not{E}_T$ $[\gamma b\ X\ \not{E}_T,\ \ \gamma bjX\not{E}_T,$ $\gamma jj\ X\ \not{E}_T,\ \ \gamma X\not{E}_T,$ $b\bar{b}\ X\ \not{E}_T,\ \ bbb\ X\ \not{E}_T,$ $\gamma\ell\ell\ X\ \not{E}_T,\ \ \ell\ell\ell\ell\ X\ \not{E}_T]$	(Displaced γ , Displaced Z , LNIP b-jets) $X\ \not{E}_T$ TOF	$X\ \not{E}_T$
$\widetilde{\tau}_1$	$\tau^\pm\tau^\pm\ X\ \not{E}_T$ $\ell^\pm\ell^\pm\ X\ \not{E}_T$ $\tau\tau\tau\ X\ \not{E}_T$ $\tau\tau\ell\ X\ \not{E}_T$ $\tau\ell\ell\ X\ \not{E}_T$ $\ell\ell\ell\ X\ \not{E}_T$ $\tau\tau\ell\ell\ X\ \not{E}_T$ $\tau\ell\ell\ell\ X\ \not{E}_T$	HIT $\rightarrow \tau$ kinks HIT $\rightarrow e, \mu$ kinks	HITs Same-Charge HITs Same-Charge MITs $\ell\ell\ell X\not{E}_T$ $\ell\ell\ell\ell X\not{E}_T$ CC-HITs TOF
$\widetilde{\ell}$ co-NLSP	(as for Stau NLSP, but with different profiles, lepton democracy) $\ell\ell\ell\ell\ X\ \not{E}_T$	HIT $\rightarrow e, \mu, \tau$ kinks	HITs $\ell\ell\ell X\not{E}_T$ $\ell\ell\ell\ell X\not{E}_T$ TOF
$\widetilde{Q}$	$jj\ X$ $cc\ X\ \not{E}_T$ $bb\ X\ \not{E}_T$ $tt\ X\ \not{E}_T$ Same-Charge $tt\ X\ \not{E}_T$	Displaced jets H-HIT $\rightarrow$ jet kinks LNIPs Mesino Oscillations	CE-HITs H-HITs $\not{E}_T$ TOF
$\widetilde{g}$	$jj\ X\ \not{E}_T$	Displaced jets LNIPs	CE-HITs H-HITs $\not{E}_T$ TOF

Run II Workshop:
hep-ph/0008070

Di-Photon + Jets + MET Signature

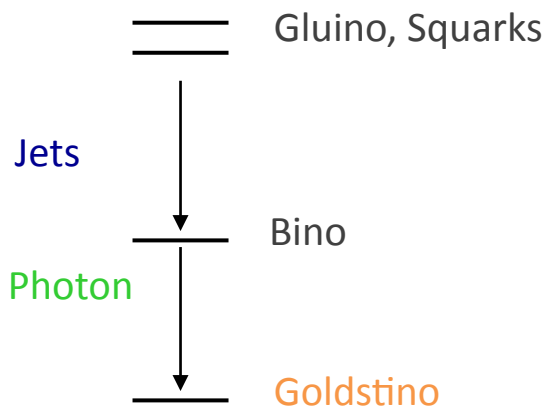
Prompt Decay

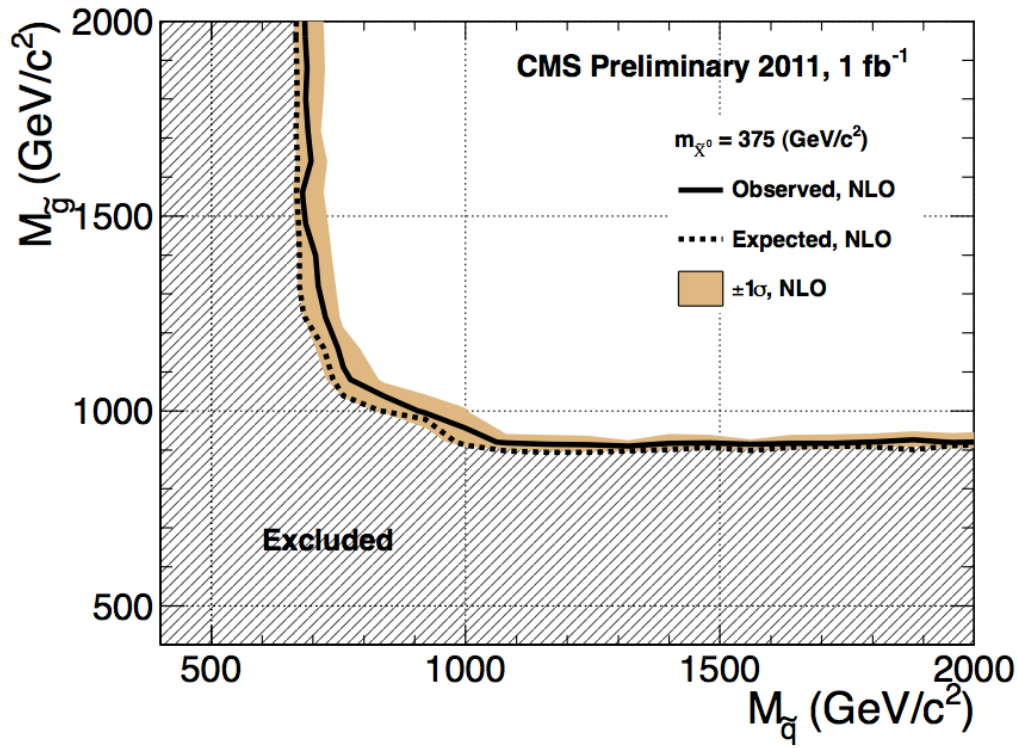




Di-Photon + Jets + MET Signature

Prompt Decay



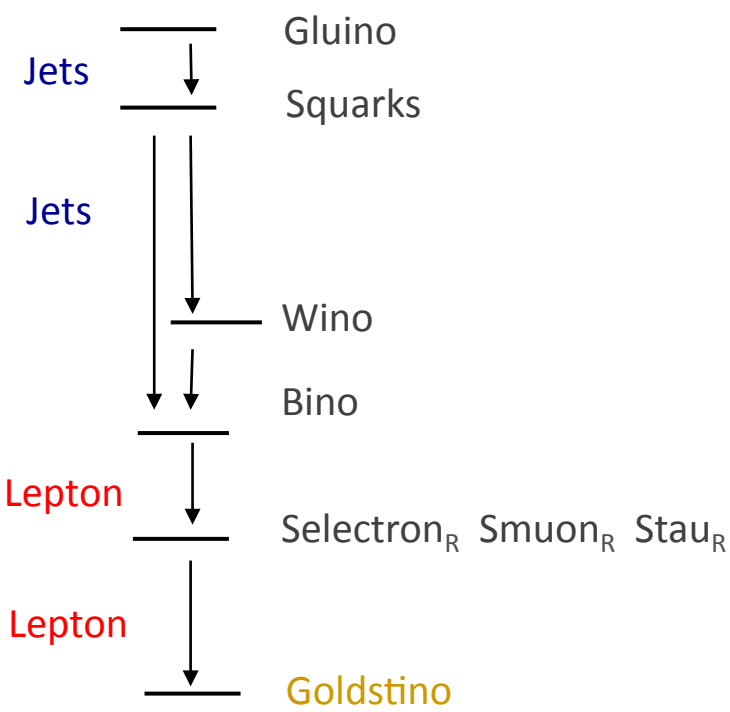


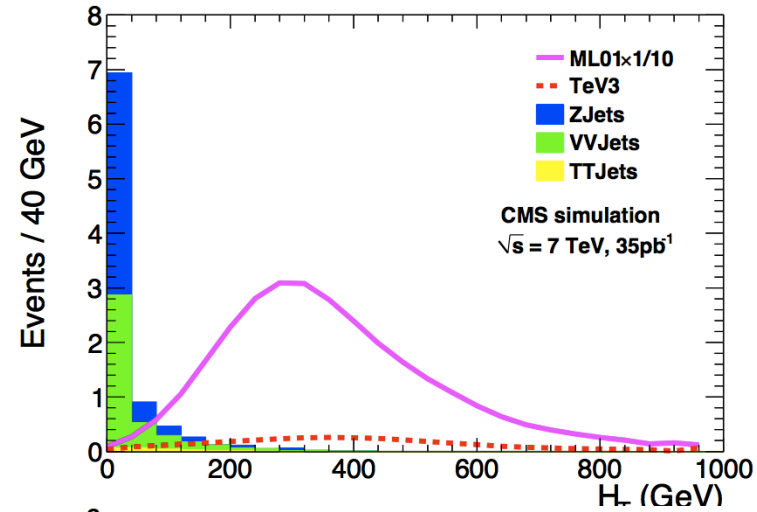
Three and Four Leptons (+ MET) Signature

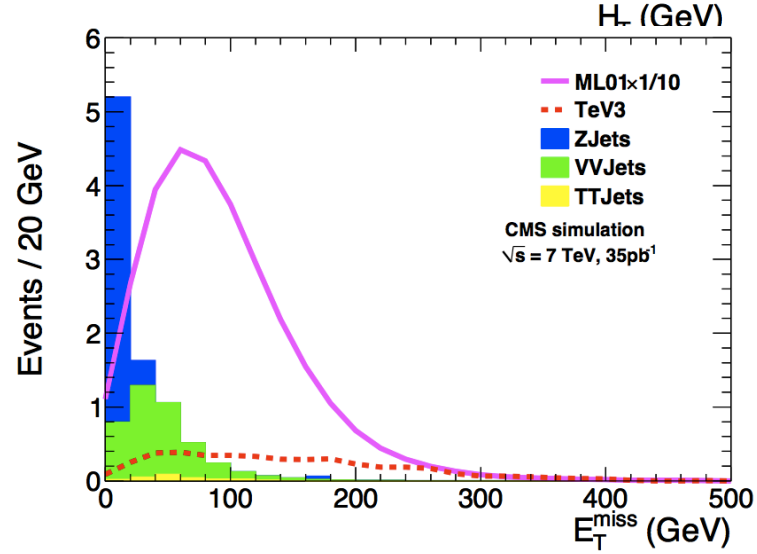
Slepton co-NLSP

Prompt Decay

m_{gluino} = 450 GeV
m_{squark} = 360 GeV



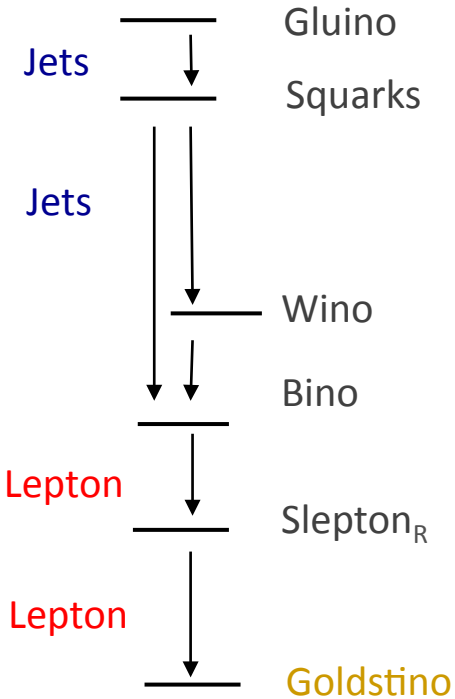




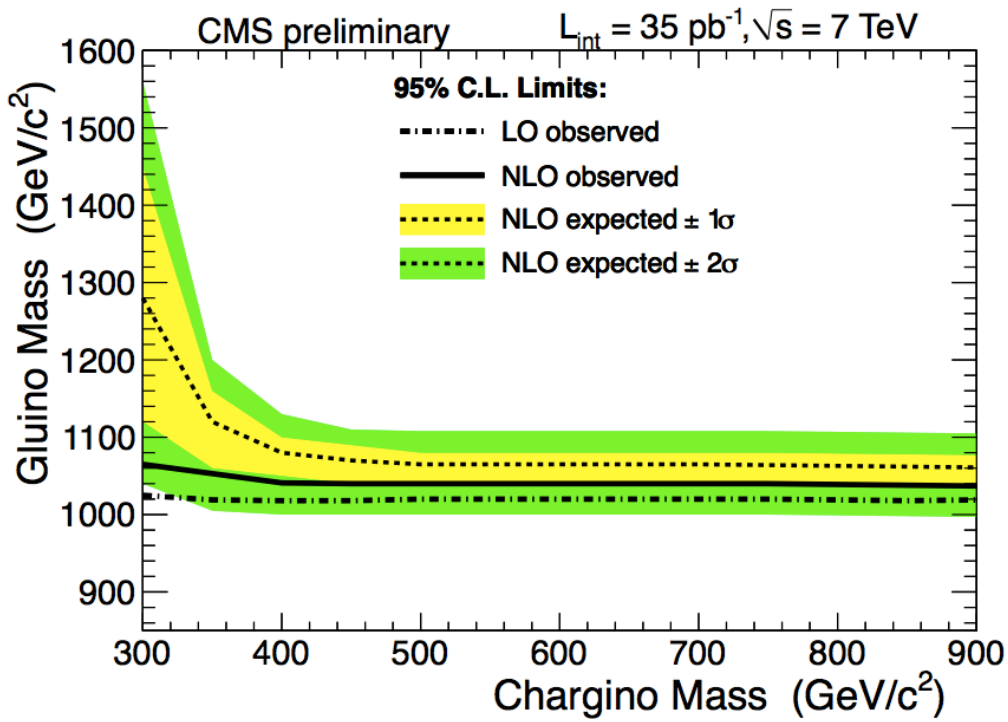
Beyond Tevatron – O(pb^{-1})

Three and Four Leptons (+ MET) Signature

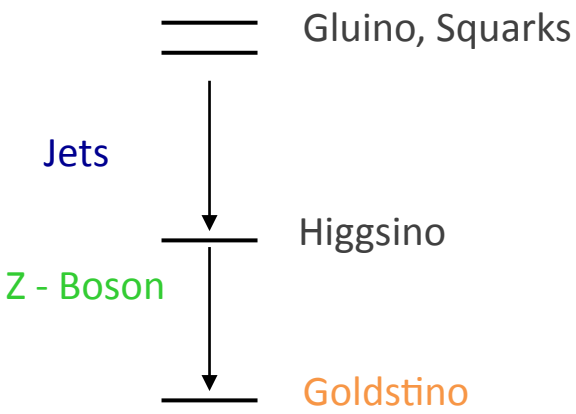
Slepton co-NLSP



Prompt Decay

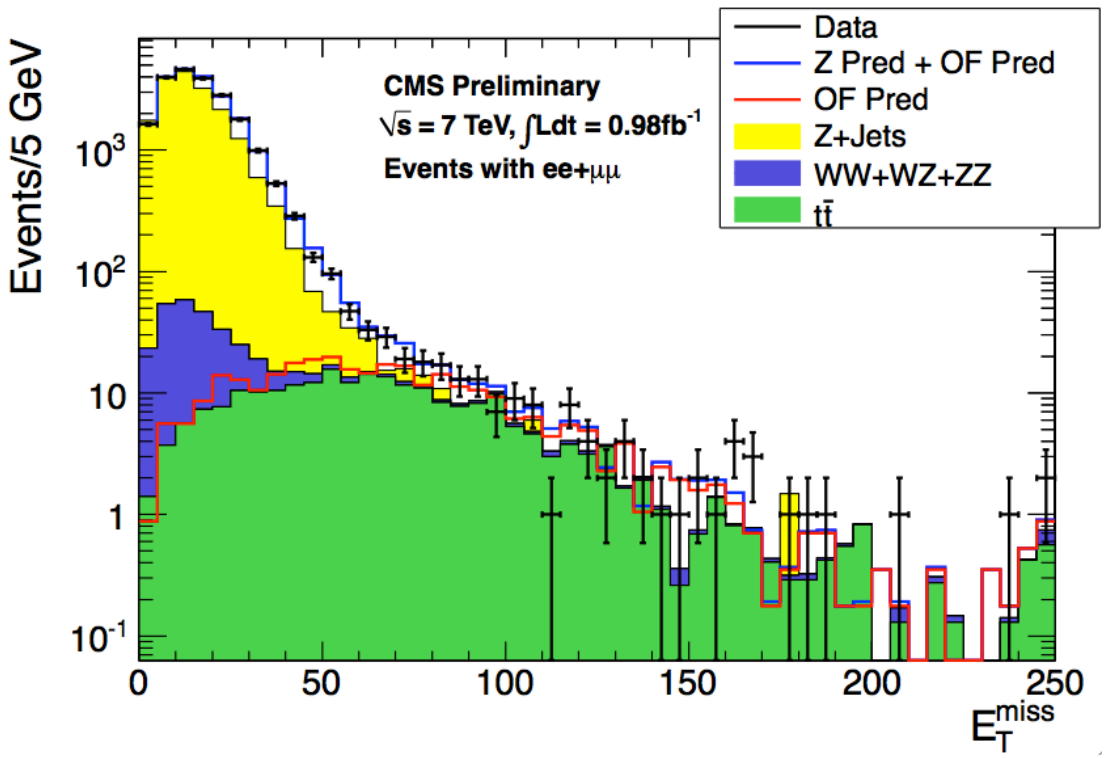


Z Bosons + Jets + MET Signature



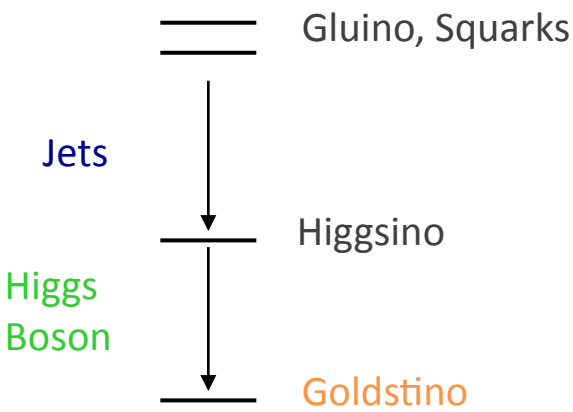
Prompt Decay

Z + 2 jets



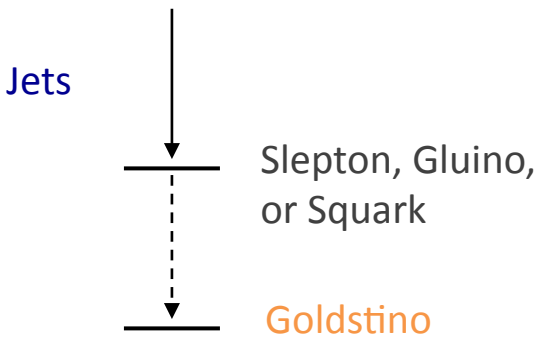
Higgs Bosons + Jets + MET Signature

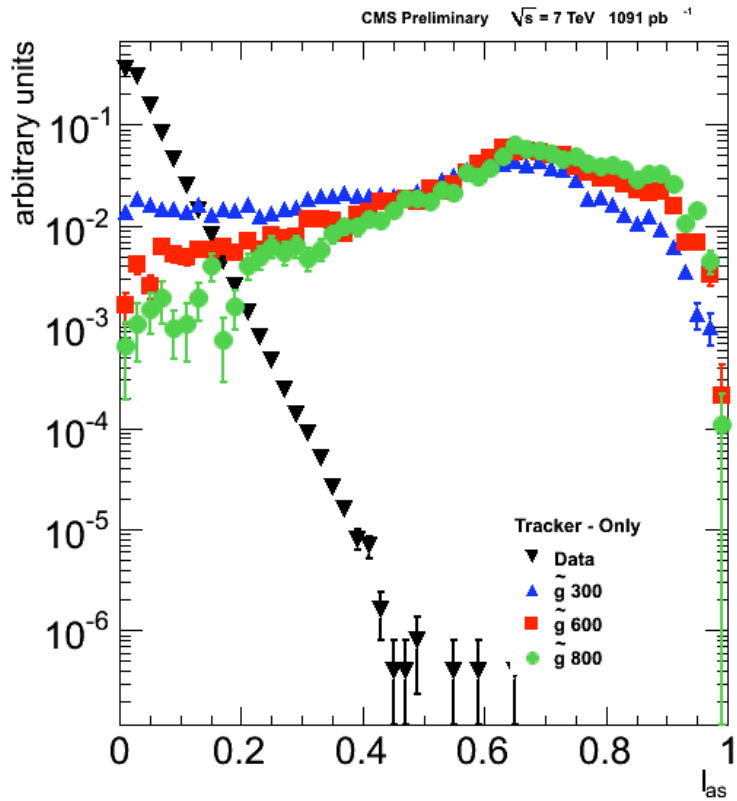
Prompt Decay



Heavy Charged Slepton, Mesino, R-Hadron Signature

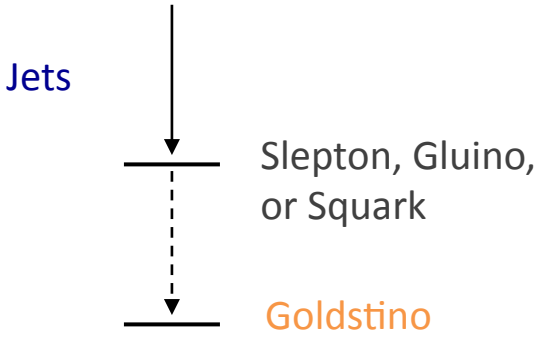
Meta-Stable - Transit Detector
High pT, High DE/Dx, Low Velocity

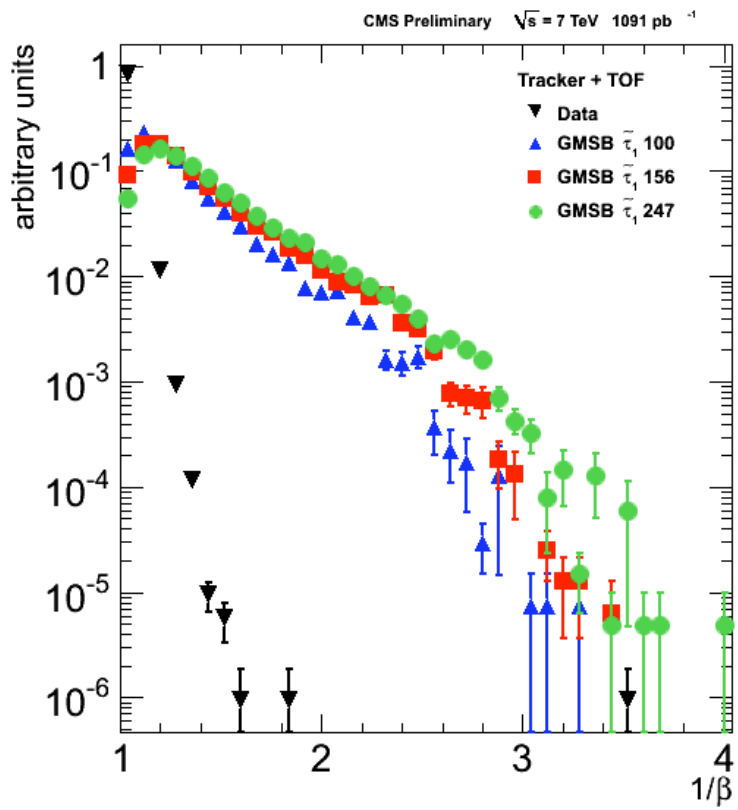




Heavy Charged Slepton, Mesino, R-Hadron Signature

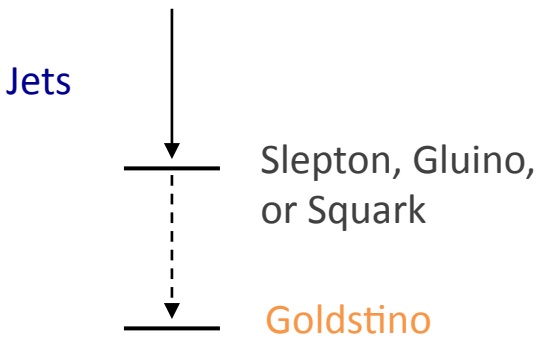
Meta-Stable - Transit Detector
High pT, High DE/Dx, Low Velocity

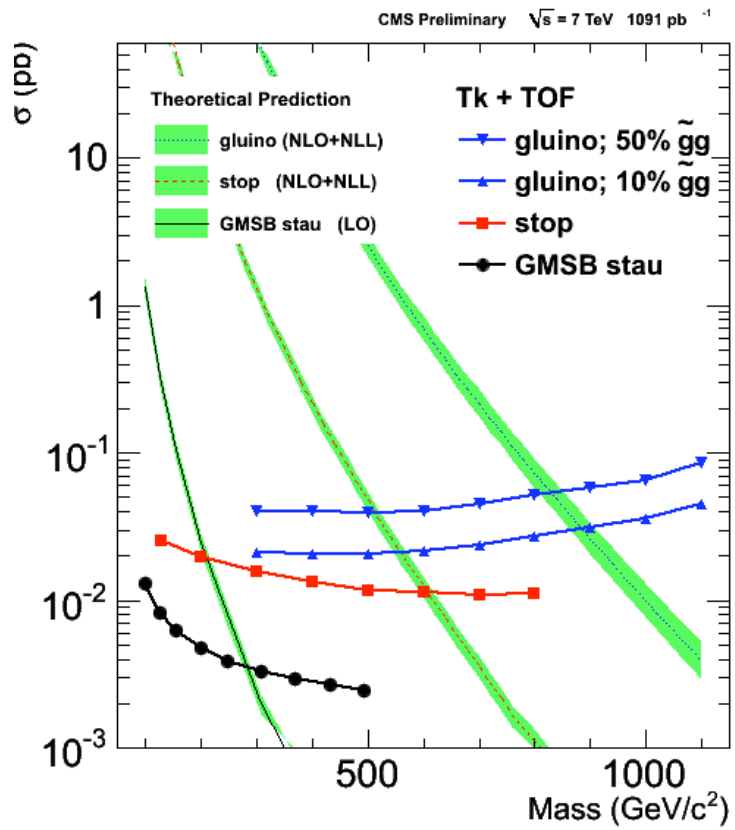




Heavy Charged Slepton, Mesino, R-Hadron Signature

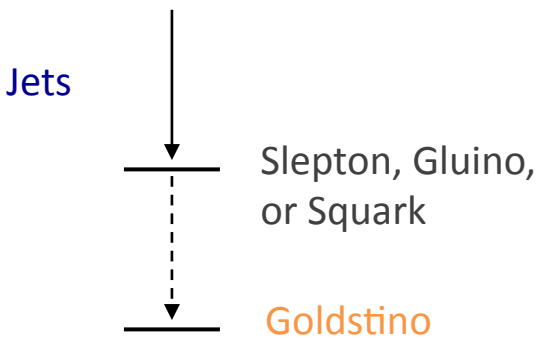
Meta-Stable - Transit Detector
High pT, High DE/Dx, Low Velocity

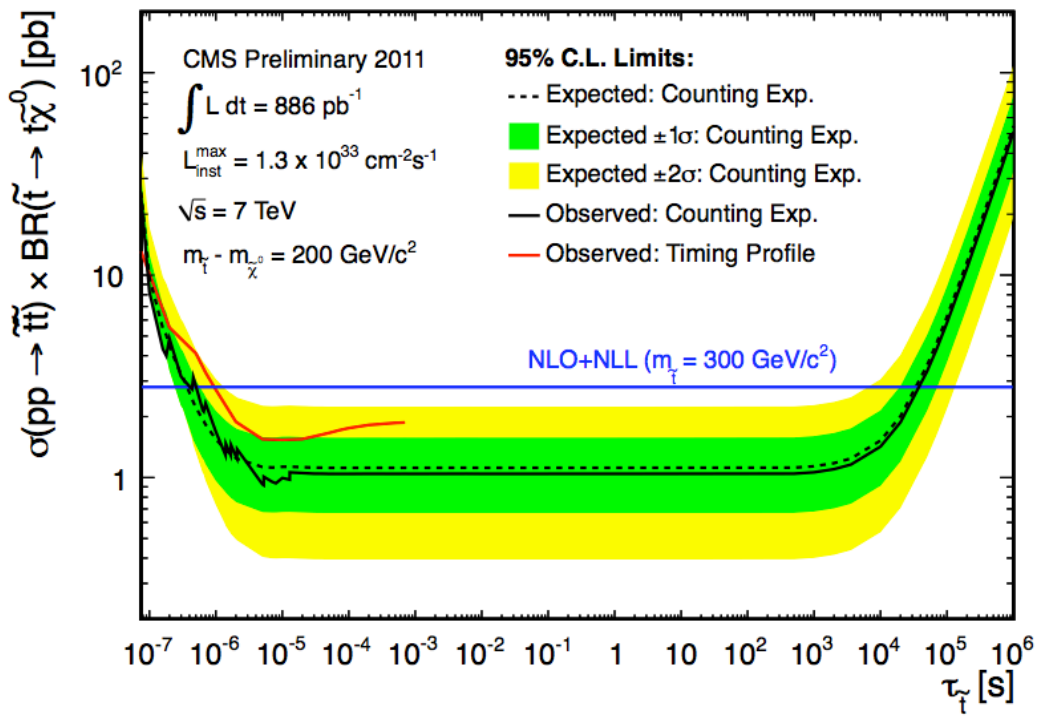




Stoped Slepton, Mesino, R-Hadron Signature

Meta-Stable – Some Stop in Detector and Decay Later Out of Time

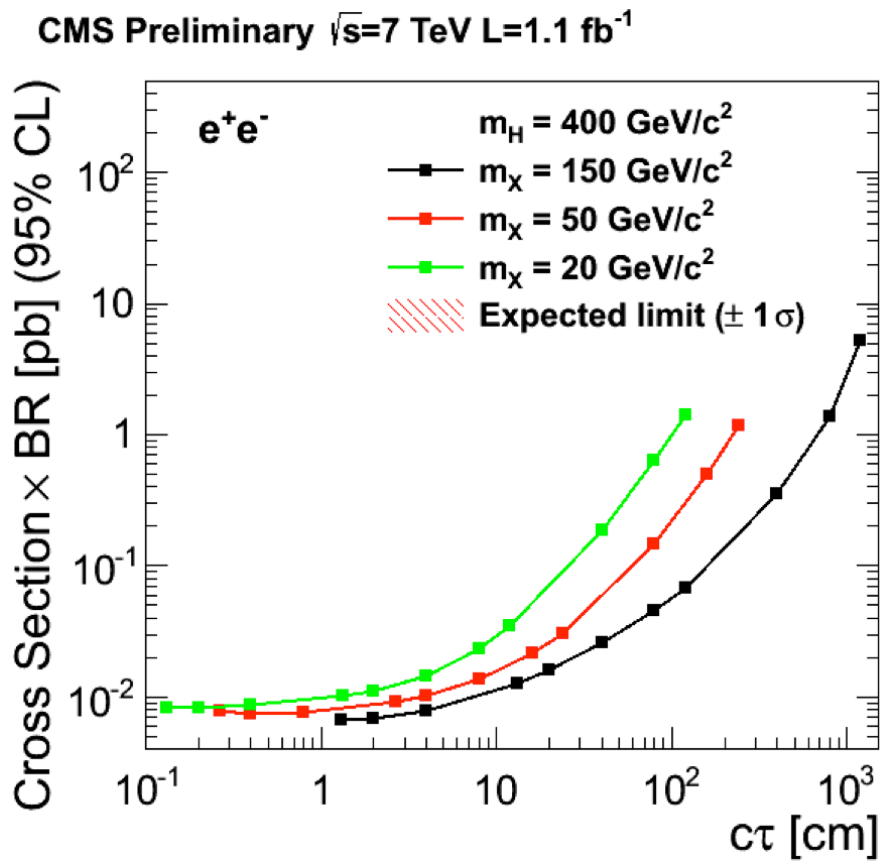




Probe Squarks O(350) GeV

Displaced Vertices, Non-Pointing Track Signatures

Meta-Stable – Decay While Transiting Detector



Atlas - Displaced RPV Decay

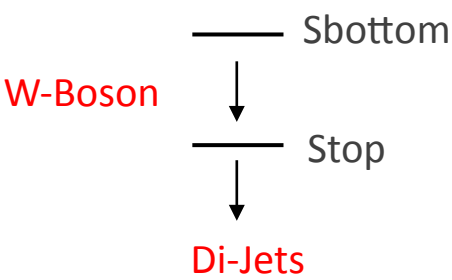
Displaced Vertices, Non-Pointing Track Signatures

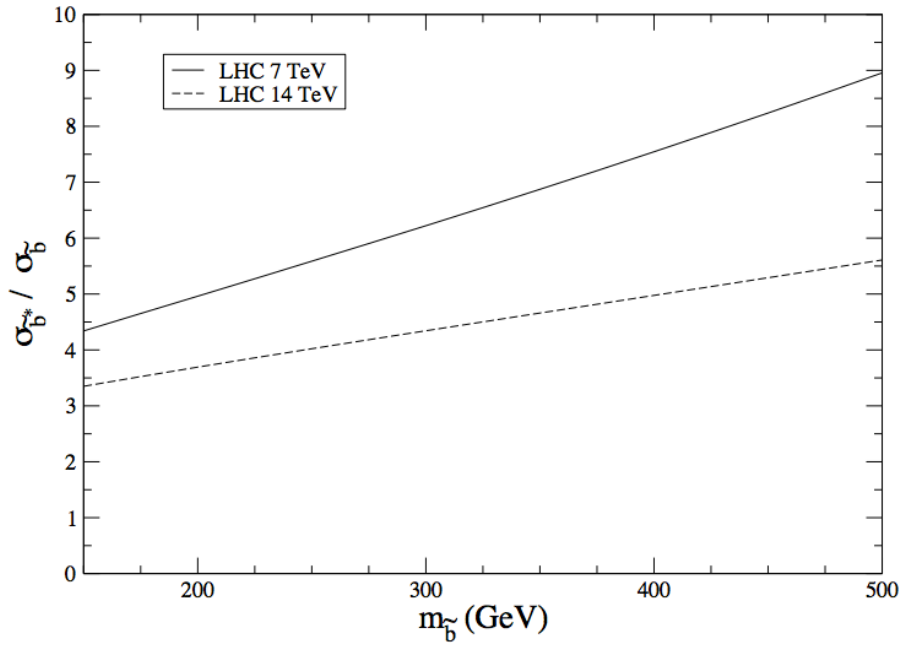
Meta-Stable – Decay While Transiting Detector

- Non-Pointing Photons
- Non-Pointing Leptons or Tracks
- Displaced Z-Bosons
- Displaced Vertices
- Displaced Higgs Boson
  Large Negative Impact Parameter (LNIP)

SUSY Topology and Signature Space is Enormous

R-Sym Violation – Resonant Production





There are Certainly Many Un-Studied Signatures …

SUSY in the LHC Era

Signature Space is Enormous !!

So far Probed (beyond Tevatron) Strong Production in
Relatively Low Background Final States
(Search first for what can be discovered first)

Starting to Probe (beyond Tevatron) Weak Production in
Relatively Relatively Low Background Final States

"Thermal" Analyses with Blunt Varianbles Well Underway

More Refined Analyses Have Begun

Many Opportunities to Dig Towards Origin of Signature Space

Many Signatures Not Yet Receiving (Enough) Attention
Displaced vertices, Displaced Z-Bosons, Displaced Higgs – LNIPs, …

A lot of Signature Space has been Mowed Down

A lot of Uncut Territory Remains

The Status of Super-Symmetry 2011

No Discovery to Report Quite Yet

But Stayed Tuned …

Extra Slides:

The Large Hadron Collider will Either

1. Discovery Super-Symmetry
2. Rule it Out (Psychologically)

We are Now

Part Way to One of These Outcomes …