Making SUSY Search Results Model Independent: CDF to LHC
& a Bit of Search Strategy

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(Rutgers)

LHC@BNL Workshop

BNL Jan 10, 2011

Outline

(Set to the tune of "I am a rambling man")

- **SUSY motivation (only a heuristic point).**
- **Evolution of "M.S.S.M." from Tevatron (CDF) to LHC (M.S.S.M. = MainStream Search Methods)**
- **Search strategy: Exclusive experimental channels.**
- **Interpretation strategy: exclusive "theory" channels. (Using CDF Trileptons as a working example)**

Not in this talk

- R-parity is not sacrosanct (Dark Matter could come from somewhere else)
- With leptonic RPV, LSP unstable → abundance of leptons
- If L conservation protects proton lifetime,

→Multi-jet (resonance) signature with copious strong production (but against QCD background).

$$(\tilde{q})(\tilde{q}) \longrightarrow (jjj)(jjj)$$

Most Effective Supersymmetry Motivation

The Tale of Hierarchy problem as told by a GenX physicist

PETER **SUSY**

(Higgs)

We can't find either because they eloped into the ether ….

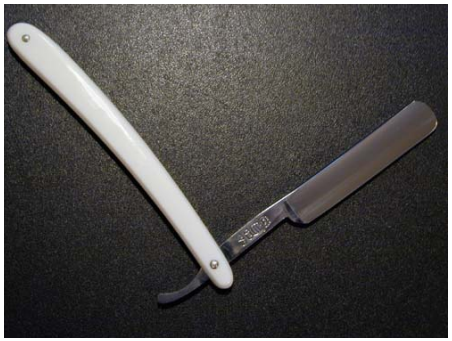
2nd Best Supersymmetry Motivation
(Best for experimentalists)

Supersymmetry doubles the particle spectrum. A big price, but we are very used to doubling the spectrum. (Occam's razor??)

Occam's Razor: Particle Physics Version

We like doubling the particle spectrum.

Single Blade (electron)



Single Blade → Twin Blade
(electron → positron)

2nd Best Supersymmetry Motivation
(Best for experimentalists)

RUTGERS

Supersymmetry doubles the particle spectrum. A big price, but we are very used to doubling the spectrum.

→ Assembling the electron (Murayama, TASI 2000 Lectures)

Electron $q=1.6\times10^{-19}$ Coul , radius $< 10^{-19}$m

[(200GeV)(10^{-18}m) ➔ $r_e < 10^{-18}$m (from g_e), LEP 2006: 10 TeV contact interaction ➔ $r_e < 10^{-20}$m]

$E_{assembly} \sim +q^2/r_e \sim 10^4$ MeV but $m_e \sim$ ½ MeV

➔ Large *negative* "bare mass"

m_e = 0.5 MeV = -9999.5 MeV + 10,000 MeV

FIX: Double the particle spectrum: positron i.e., new physics at ~100fm ~1MeV

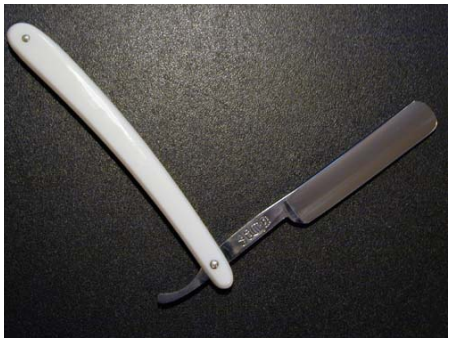
Weisskopf (1939): $E_{assembly} \sim +q^2/r_e$ cancelled by $E_{vacuum\ pair} \sim -q^2/r$ (e^+ from vacuum)

$$(m_e c^2)_{obs} = (m_e c^2)_{bare}\left[1 + \frac{3\alpha}{4\pi}\log\frac{\hbar}{m_e c r_e}\right]$$

Occam's Razor: Particle Physics Version

We like doubling the particle spectrum.

Single Blade (electron)

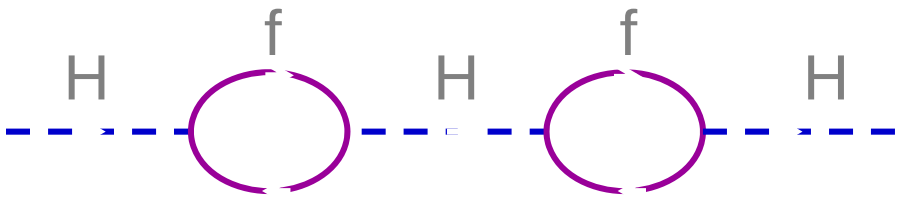


Single Blade → Twin Blade
(electron → positron)

Single Blade → Twin Blade →
MadMen Blades
(selectron??)

SUSY: Why?

Today: Higgs has the same hierarchy problem.



Radiative loops: M_H ~10^{15} GeV, but Higgs at 100 GeV (EW scale)

Delicate cancellations at 10^{15} GeV

OR

SUSY at TeV scale

- **stop loops cancel the top loops → "hierarchy problem" solved.**

BUT SUSY is badly broken. m(selectron) >> 511 KeV

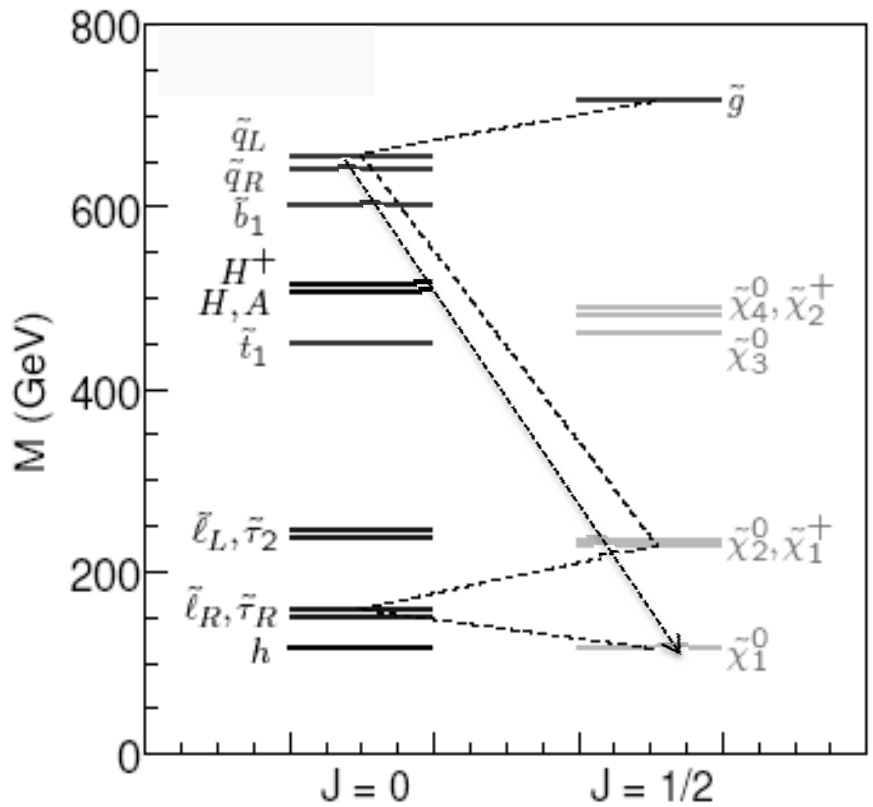
SUSY Breaking Defines Phenomenology

- Signatures depend on SUSY breaking, mass hierarchy and mixing

Many but not all models:
RGE running →
- Strongly interacting particles heaviest
- Weakly interacting (middle)

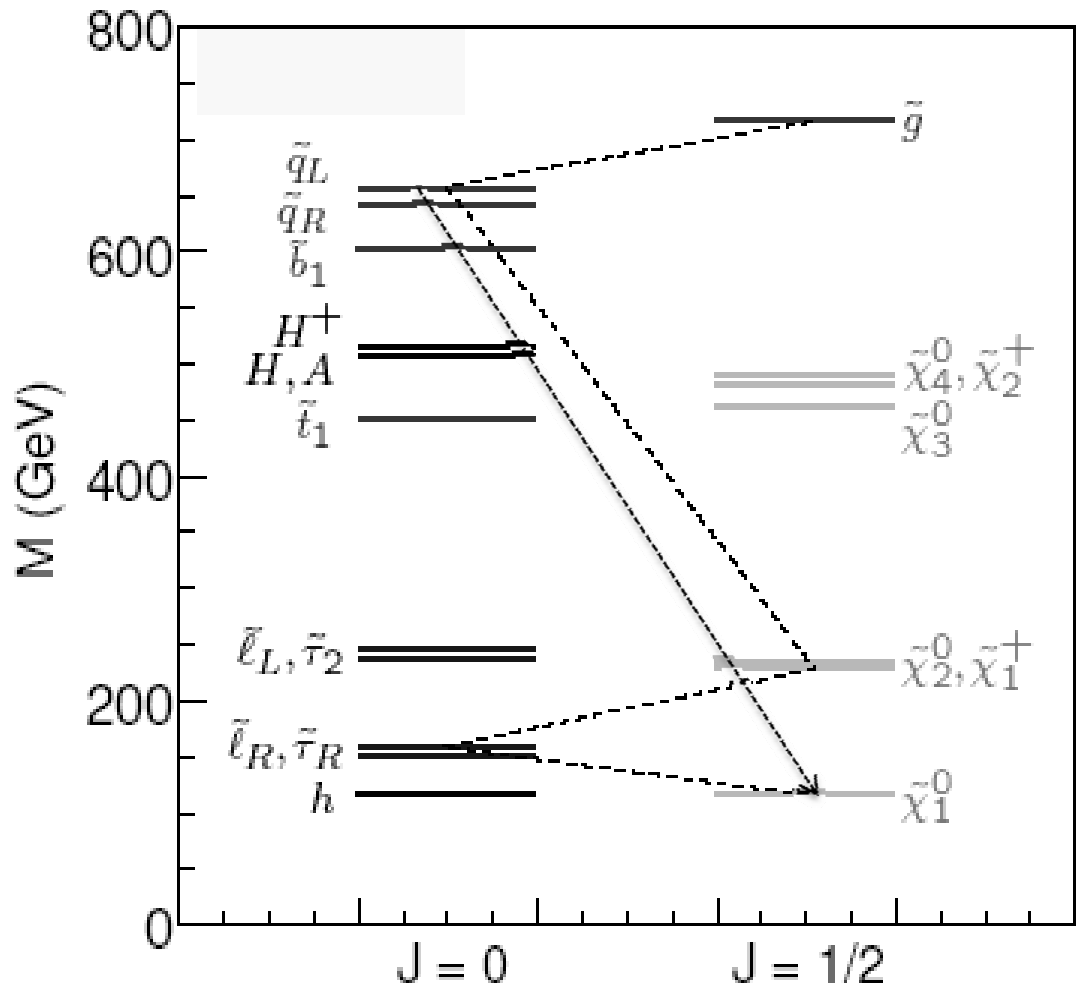
e.g. with R-parity, Stable Lightest Supersymmetric Particle (LSP)

→ Missing E_T (MET) signature (from LSP and neutrinos)



SUSY: MainStream Search Methods

- Chargino-Neutralino:
  trilepton + MET
- Squarks & Gluinos:
  Jets + MET
- Light LSP e.g. GMSB
  → diphoton +MET
  (well-known)
  → Multileptons
  (not well-known)
- Significance of compressed spectra for early searches
  → slepton-coNLSP
  GMSM
  (Split Messangers)



SUSY Breaking Defines Phenomenology BUT signatures evolve with root(s)

Tevatron:

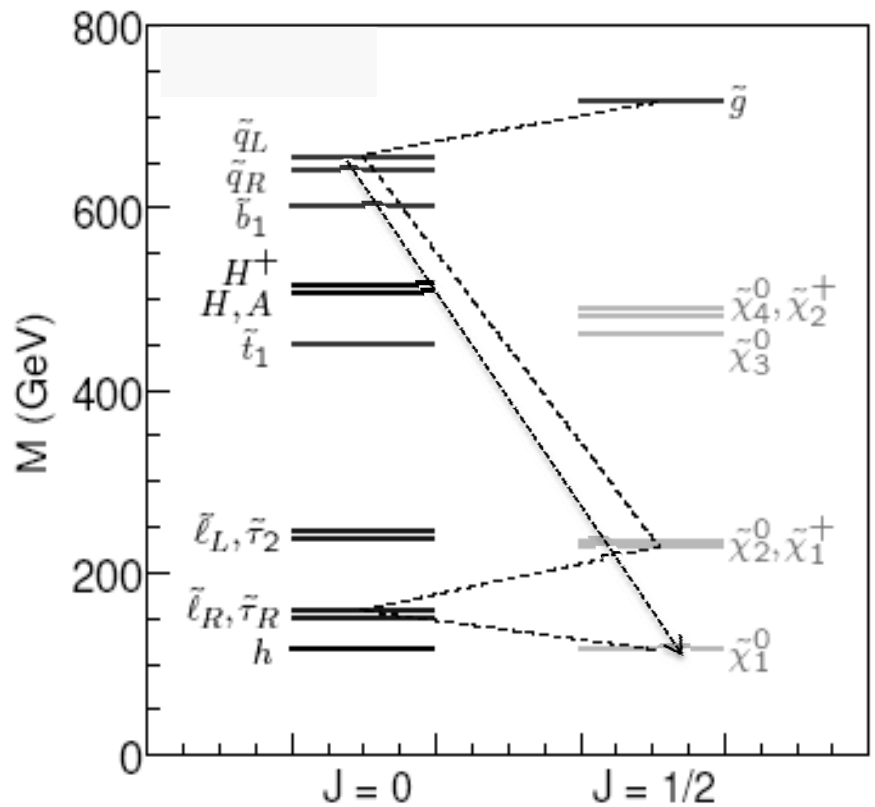
i) squarks too heavy for 2TeV → small strong cross section

ii) Direct EW competitive (since EW gauginos lighter than squarks)

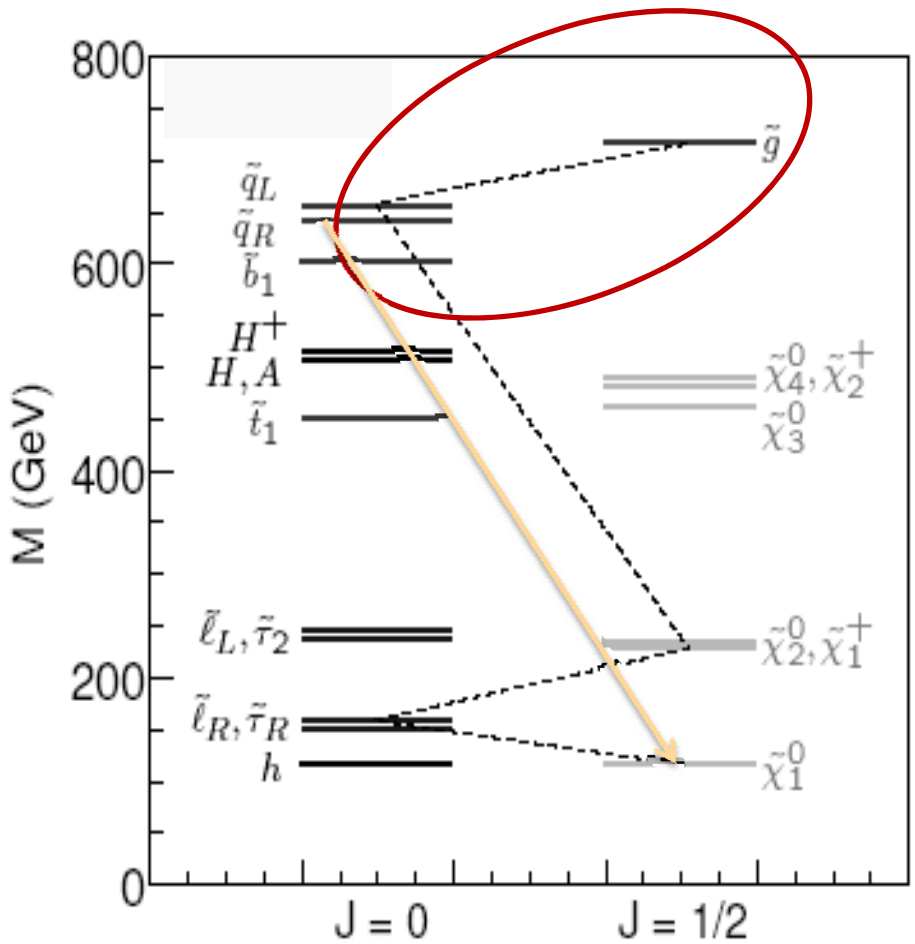
LHC:

strong production wins.

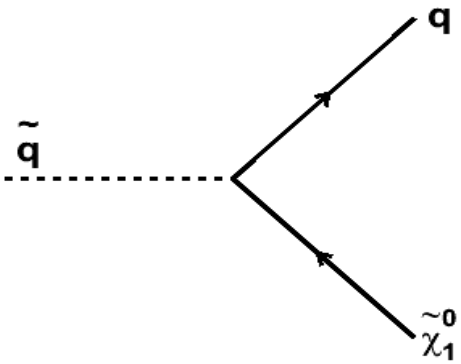
→ jetty signals (with a caveat)

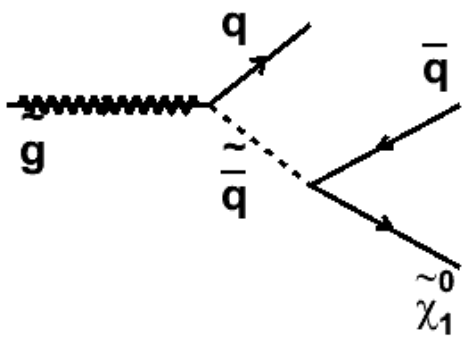


Jet/MET @ Tevatron



No of jets, Missing-E_t, H_t(=Σ jet E_t)

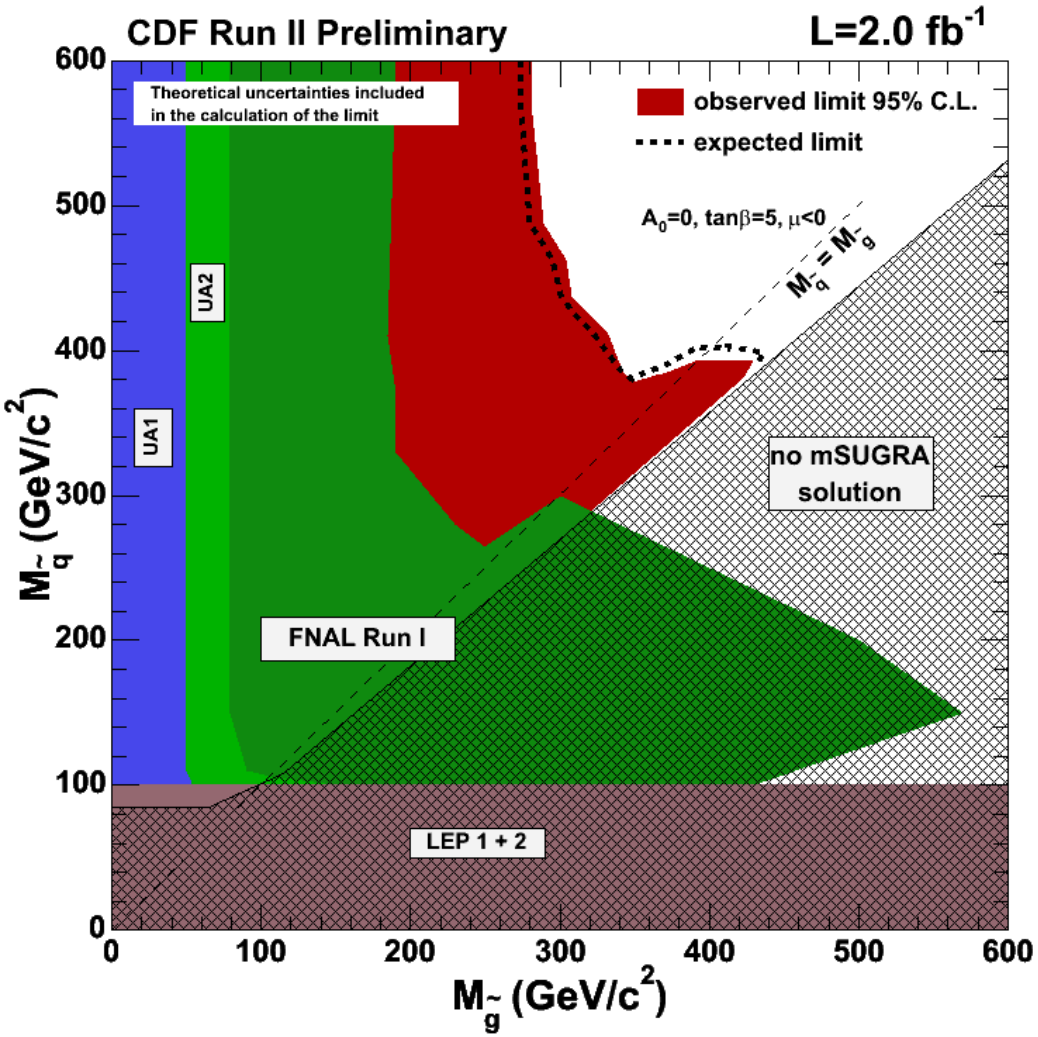




Jet & MET @ Tevatron

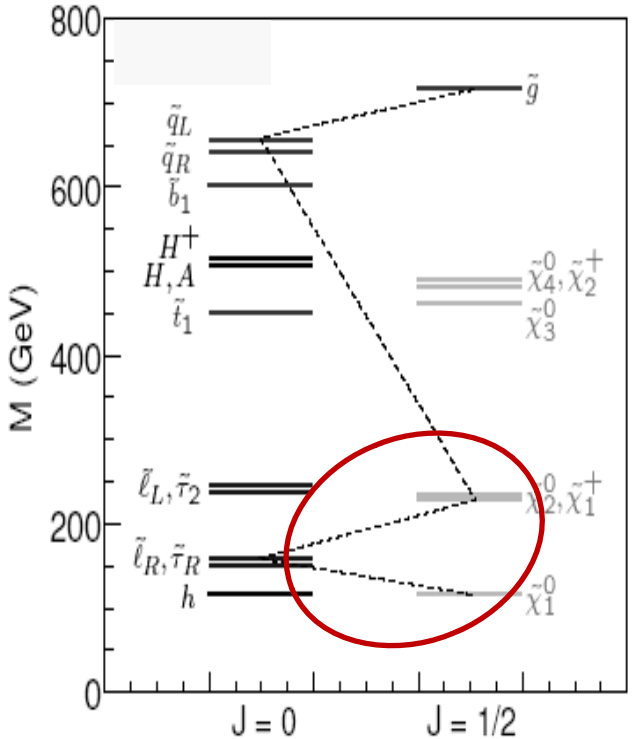
Gluino: m> 280 GeV/c^2 for all m(squark) (CDF) PRL 102,121801(2009)

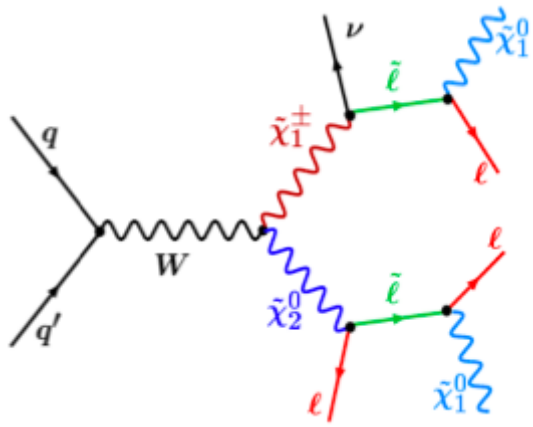
Squarks 380 GeV/c^2 for all gluino masses

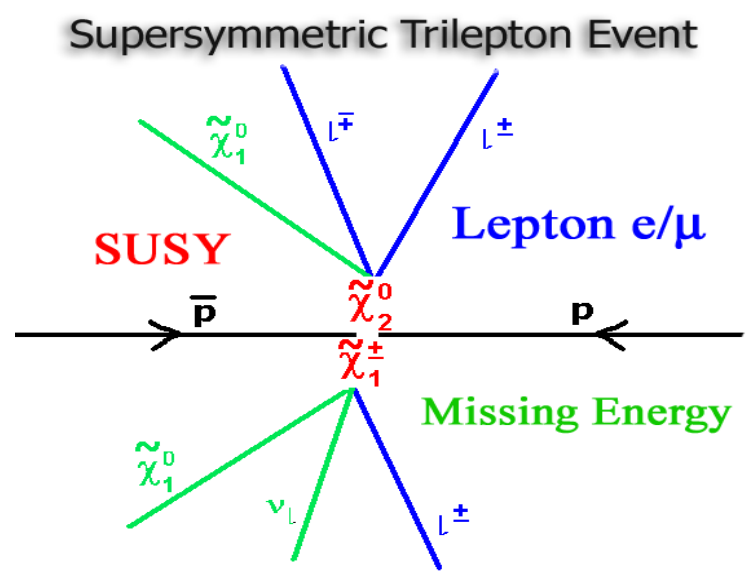


Penalty for seeking direct strong production
(Weak sector is lighter)

Charginos & Neutralinos at Tevatron



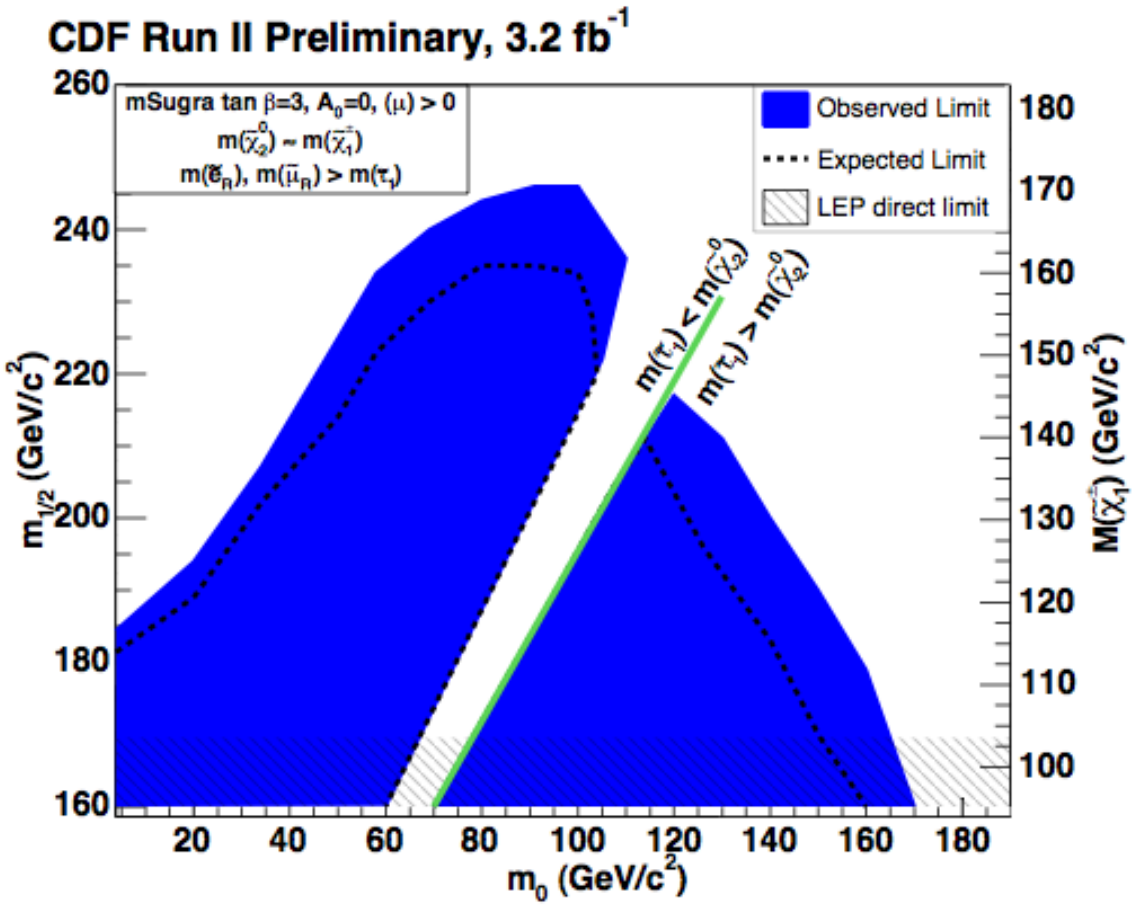




- **Clean "golden mode"**
  - **3 isolated leptons**
  - **Large MET**
  - **Small SM background**

- **Direct Electroweak**
- **σ×Br ~ pb**

Charginos and Neutralinos with $l^+l^-l^+$



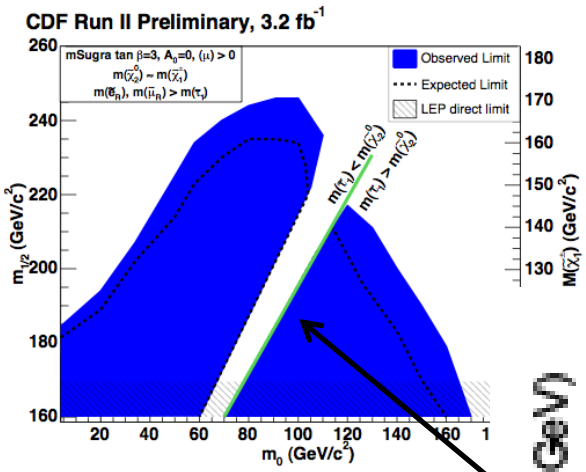
- **CDF**

2 fb^{-1} PRL 101,251801(2008)

3.2fb^{-1} prelim

$M(\chi^\pm)$ limits ~160GeV/c^2

EW Production (2TeV) → Color Production (7 TeV)



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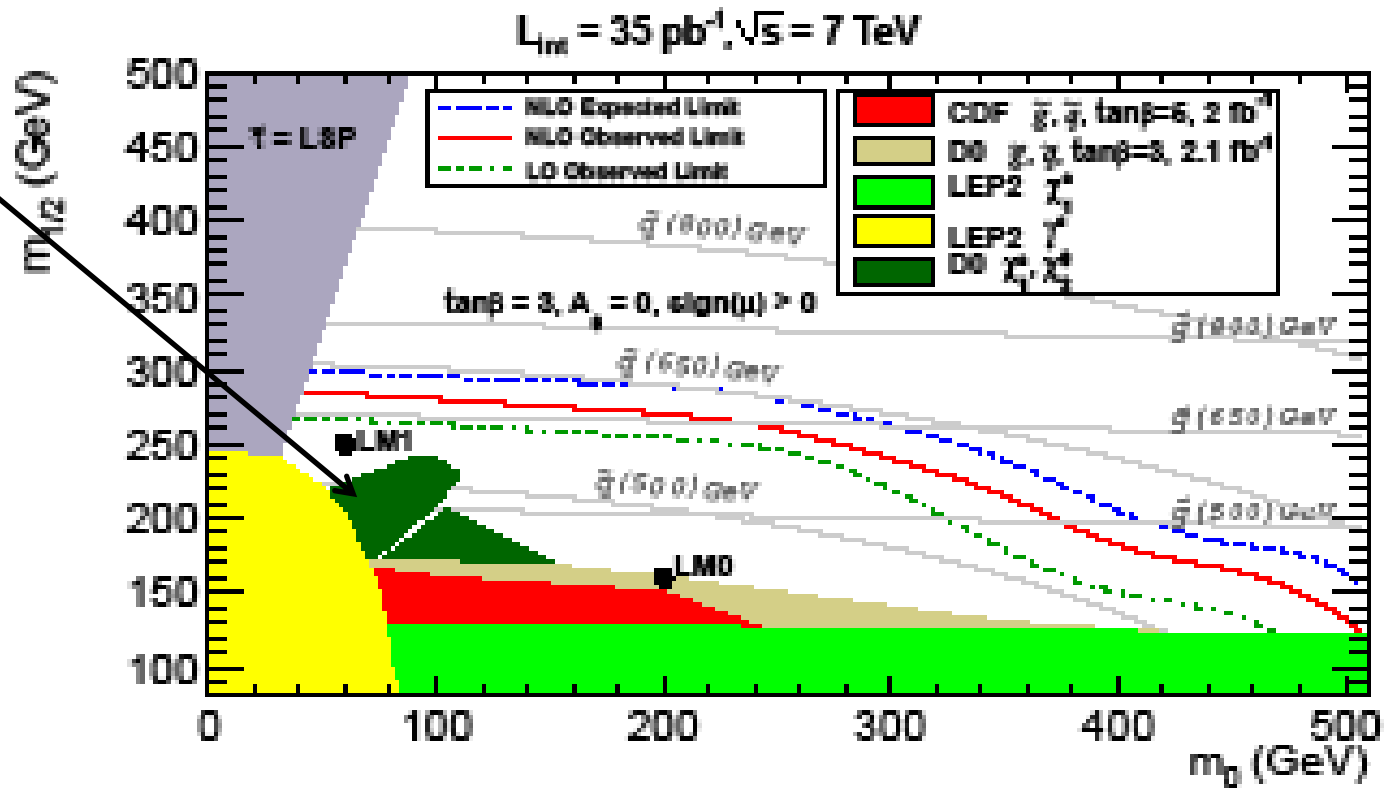
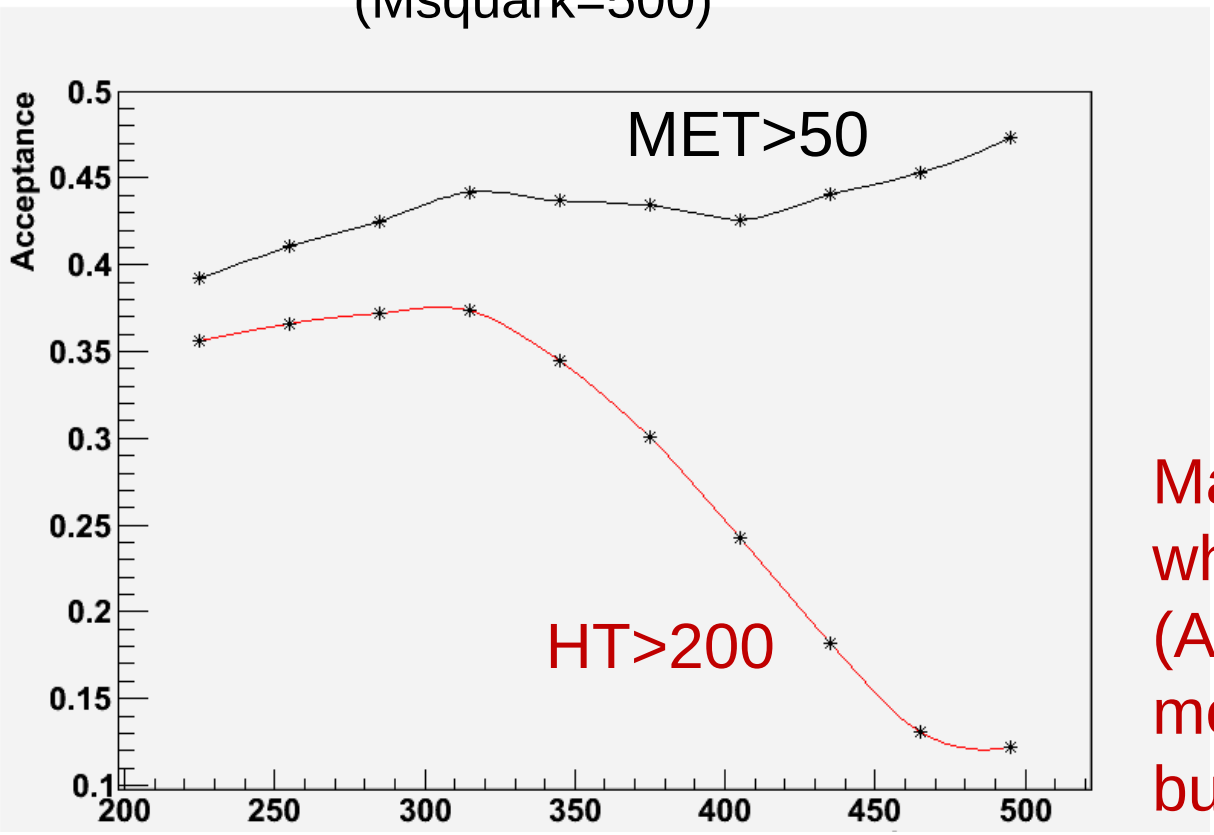


Why bother with lepton channels?

Hadronic Search Bias

a) Multileptons have higher S/B (important with more data)
b) Strong production can be captured by the Leptonic Sector

Multilepton Search Acceptance vs Bino Mass
(Msquark=500)



Make hadronic cuts only when needed.
(All hadronic searches, monolepton, OS dileptons but not for multileptons)

Search and Interpretation

- **Search strategy: Exclusive experimental channels.**

- **Interpretation strategy: exclusive "theory" channels. Use as an example: Dealing with tau complications in making Tevatron trilepton results model-independent.**

Main Citations

- **Search strategy: exclusive experimental channels:**

(CDF) Phys. Rev. Lett. 101, 251801 (2008) "Search for Supersymmetry in $p\bar{p}$ Collisions at $\sqrt{s}$=1.96 TeV Using the Trilepton Signature for Chargino-Neutralino Production"

- **Interpretation strategy: exclusive "theory" channels:**

"Addressing the Multi-Channel Inverse Problem at High Energy Colliders: A Model Independent Approach to the Search for New Physics with Trileptons"

Sourabh Dube, Julian Glatzer, Sunil Somalwar, Alexander Sood, Scott Thomas arXiv:0808.1605

"Channels" : Theory vs Expt (Multilepton Example)

- **For experimentalists (lepton = e,mu)**:
  - Number of leptons →3, 4 or more
  - Flavor of leptons → e or mu
  - Lepton Reconstruction
    - →High Quality: Tight e or mu (could be from a tau)
    - →Medium Quality: Loose e/μ, 1-prong τ as isolated track
    - →Low Quality: 3-prong tau's, possibly jumbled up tau's (a bad idea)
- **For Theorists (lepton = e, mu, tau):**
  - Number of leptons
  - Flavor of (parent) leptons (tau in particular)

Expt. Channels Give Observed Signals

CDF 2fb-1 Trilepton PRL 101, 251801 (2008) Exclusive channels:

Channel	$l_t l_t l_t$	$l_t l_t l_l$	$l_t l_l l_l$	$l_t l_t T$	$l_t l_l T$	$\sum$ (channels)
Drell-Yan	0.05	0.01	0.0	1.63	1.32	3.01
Diboson	0.29	0.20	0.08	0.61	0.38	1.56
Top-pair	0.02	0.01	0.03	0.22	0.18	0.46
Fake lepton	0.12	0.04	0.03	0.75	0.41	1.35
Total	0.49	0.25	0.14	3.22	2.28	6.4
Uncertainty	± 0.09	± 0.04	± 0.03	± 0.72	± 0.63	
Observed	1	0	0	4	2	7

(t – tight lepton, l – loose lepton, T – isolated track)

Observed minus expected → $N_{\textbf{observed signal}}$ in each channel

- Limit or measurement – No distinction.
- *No Model so far (although signal now "observed".)*

Now Need A Model

Channel	$l_t l_t l_t$	$l_t l_t l_l$	$l_t l_l l_l$	$l_t l_t T$	$l_t l_l T$	$\sum$ (channels)
Drell-Yan	0.05	0.01	0.0	1.63	1.32	3.01
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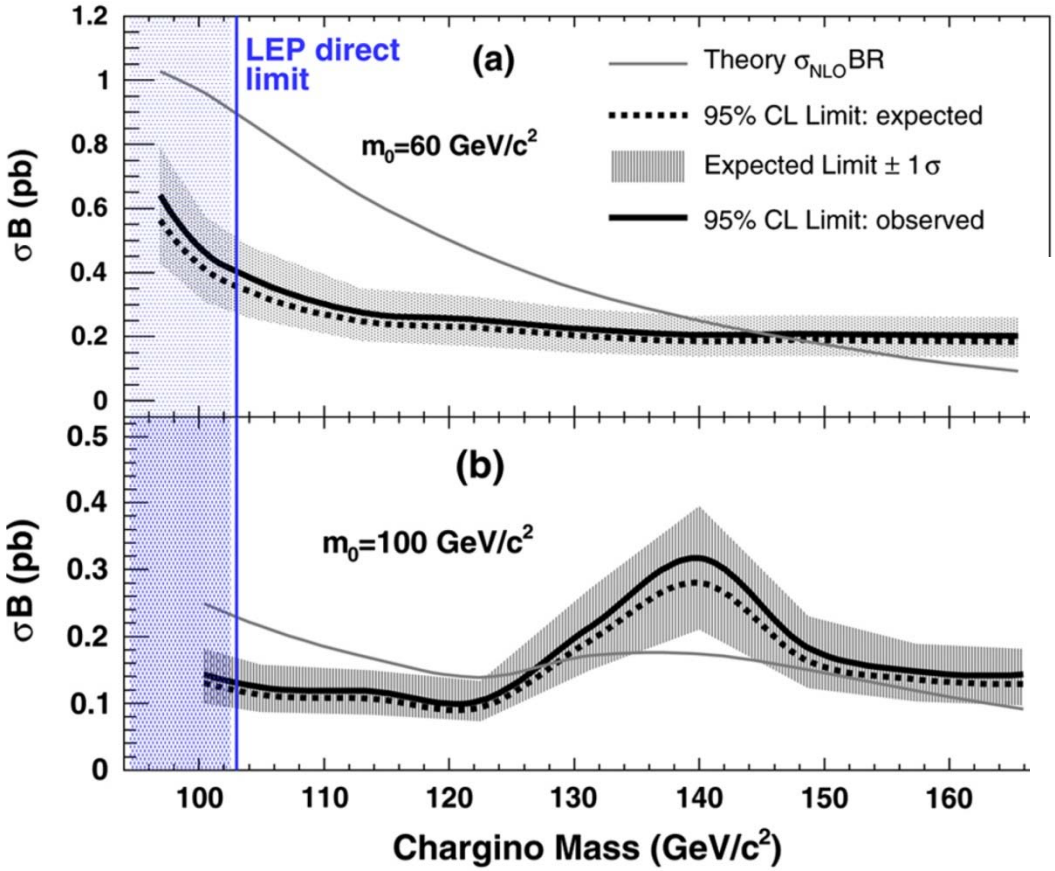
Uncertainty	± 0.09	± 0.04	± 0.03	± 0.72	± 0.63	
Observed	1	0	0	4	2	7
SUSY Signal	2.3	1.6	0.7	4.4	2.4	11.4

Model for the "observed" signal (for PRL purposes…) (mSUGRA, with profound apologies to the theory community for choosing this opaque parameter space)

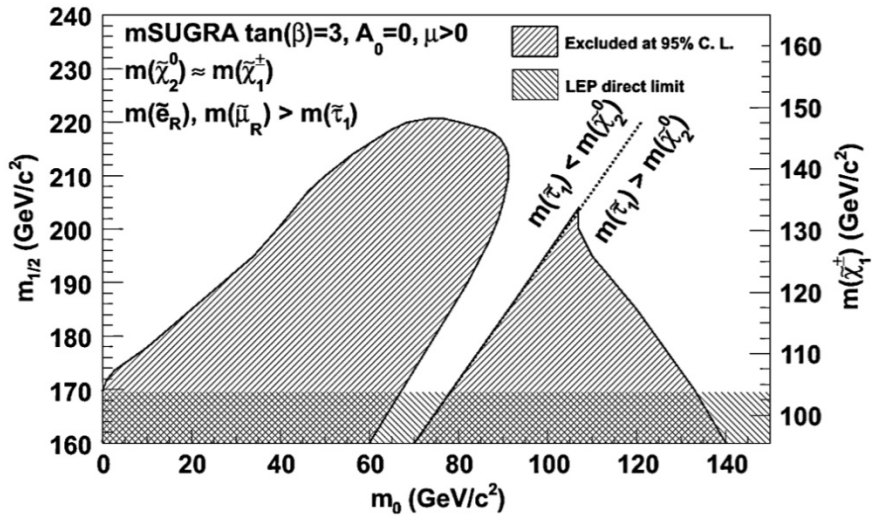
PRL 101, 251801 (2008). t – tight lepton, l – loose lepton, T – (isolated) Track

Expt.Channels → → → PRL (via a Rather Messy Scenario)

→ →sigma*BR vs Model Expectations →Contours (1st mSUGRA)



tan(beta) =3.

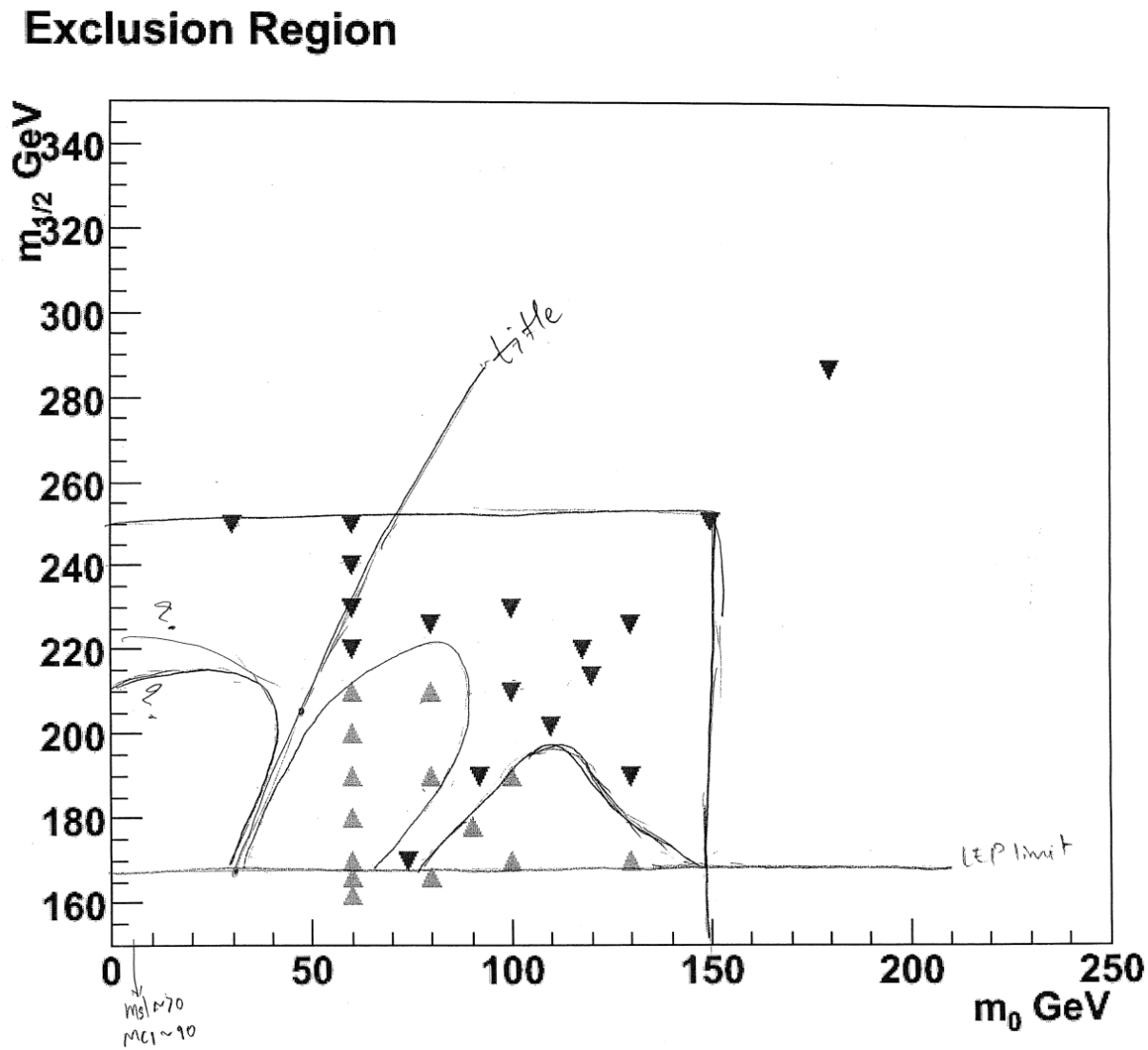


CDF 2fb-1 Trilepton PRL 101, 251801 (2008)

1st Post-LEP msugra Exclusion with CDF Trileptons

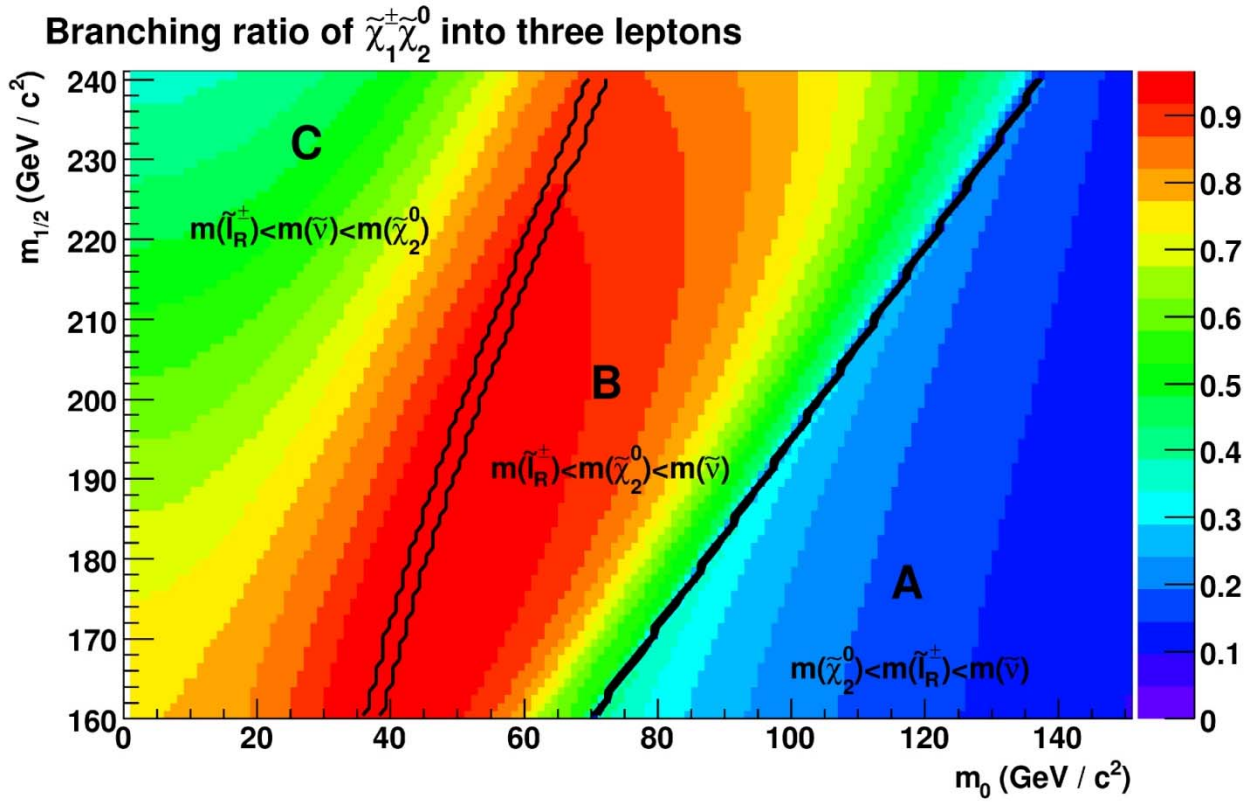
2 fb^{-1}

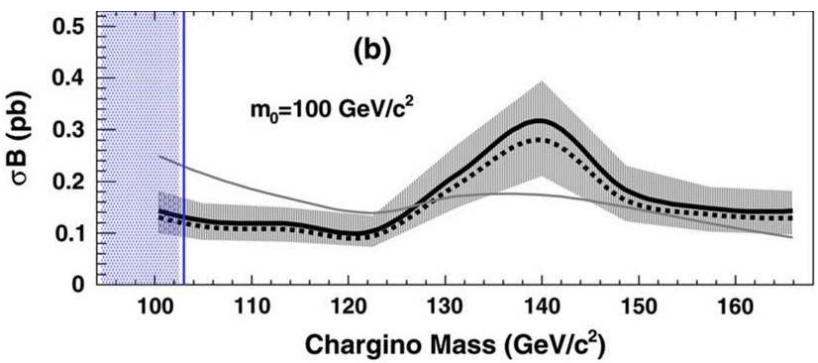
Excluded: ▲



Not a Pretty Scene

Tom Banks: "Nice work, Sunil, but we already know that mSUGRA does not describe Nature."





The Question

- Regardless of the motivation behind cuts, the analysis is done.
  - N(observed signal) /Luminosity written in stone (in many expt channels).

- How to map the experimental result onto theory channels?
  - Theory tau's show up as e, mu, clean isolated tracks, or as dirty pencil jets.

- Experimental acceptance is model dependent (specific topology).
  - Clean acceptance: kinematics: pt, eta, phi, met, angles..
  - Dirty acceptance: Isolation, resolution, tails, pileup…

"Just show sigma*BR. Why do you need models?"

What We Did After CDF Trileptons

Experimental [**σ**B] is model-dependent because of acceptance.

$$[\sigma B] = \frac{N}{LA}$$

N : Observed signal (excess over SM in several experimental channels)
L: Luminosity
A: Total acceptance
= Clean A (kinematic) times Dirty A (isolation etc)

Stay in the topology but factorize: Factorize out the "theory" channels

0 τ: (e/μ) (e/μ) (e/μ) 1 τ: (e/μ)(e/μ)τ 2 τ: (e/μ) ττ 3 τ: τττ

Provide: $[\sigma B]_{0\tau}$, $[\sigma B]_{1\tau}$, $[\sigma B]_{2\tau}$, and $[\sigma B]_{3\tau}$, where,

$$[\sigma B]_{0\tau} = N/LA_{0\tau} \text{ etc}$$

- Same observed signal N is used four times. The topology under consideration is split into four sub-topologies AT THE GENERATOR LEVEL.
- e/mu go together and are fine with the combined treatment.
- No approximations so far. Just providing the acceptance contributions.

How does it help?

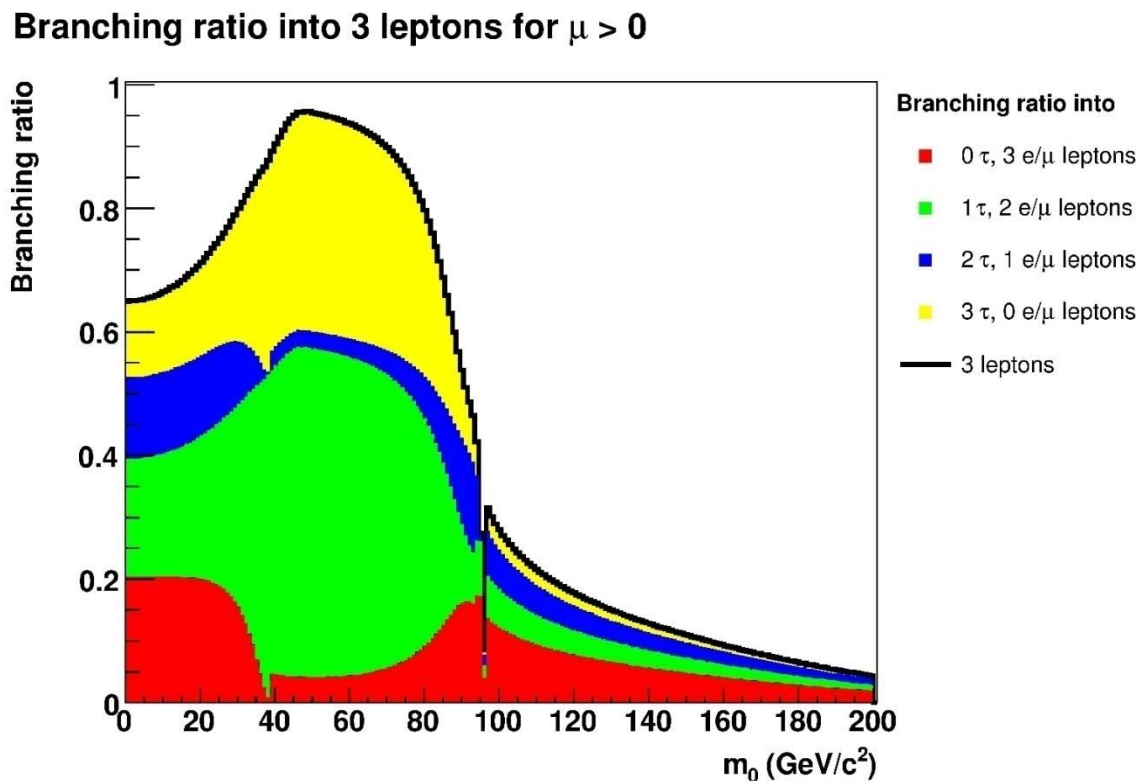
The signal is spread across four τ channels, and not always in a simple way.

$$N = \sum_{i=1}^{n} L\,\sigma\,B_i\,A_i$$

Rearrange:

$$\frac{1}{\sigma} = \sum_{i=1}^{n} \left(\frac{L\,A_i}{N}\right) B_i$$

But, $[\boldsymbol{\sigma}B]_i = N/La_i$, so



$$\boxed{\frac{1}{\sigma_{XM}} = \sum_i \frac{B_i}{[\sigma B]_i}}$$

How does it help?

$$\frac{1}{\sigma_{XM}} = \sum_i \frac{B_i}{[\sigma B]_i}$$

1. Run a topology 4 times (with generator level cuts) through analysis, calculate acceptances & publish $[\boldsymbol{\sigma}B]_{0\tau}$, $[\boldsymbol{\sigma}B]_{1\tau}$, $[\boldsymbol{\sigma}B]_{2\tau}$, & $[\boldsymbol{\sigma}B]_{3\tau}$.

2. A theorist has her own BR's ($=B_i$) (Maybe it is a different tan(beta))

3. Use the equation to combine the experiment and theory to get $\boldsymbol{\sigma}_{XM}$ (Experimentally measured cross section for the theorist's model.)

No approximations so far and we took care of the branching ratios. Branching ratios just an example.

→ We mapped the experimental result onto theory channels. (Basis or eigen channels that can be recombined with weights.)

An Example: Experimental Side

Luminosity = 0.1 fb-1, SM expectation=6, observed=9

→ Observed signal = 3

→ N/L = (3)/(0.1fb-1) = 30fb [=(**σ**B)A]

Pick the topology. It has four exclusive "theory" channels. Get acceptances, selecting the channels at generator level.

0 τ: (e/μ) (e/μ) (e/μ) (generator level) : Full acceptance	A_0=	11%
1 τ: (e/μ)(e/μ)τ	A_1=	5%
2 τ: (e/μ) $\tau\tau$	A_2=	3%
3 τ: $\tau\tau\tau$	A_3=	1.4%

→ $[\boldsymbol{\sigma}B]_0$ = (N/L)/A_0 = (30fb)/ (11%) = 0.27 pb

$[\boldsymbol{\sigma}B]_1$ = (N/L)/A_0 = (30fb)/ (5%) = 0.6 pb

$[\boldsymbol{\sigma}B]_2$ = (N/L)/A_0 = (30fb)/ (3%) = 1.0 pb

$[\boldsymbol{\sigma}B]_3$ = (N/L)/A_0 = (30fb)/(1.4%) = 2.1 pb

Experiment makes $[\boldsymbol{\sigma}B]_0$, $[\boldsymbol{\sigma}B]_1$, $[\boldsymbol{\sigma}B]_2$, and $[\boldsymbol{\sigma}B]_3$ public.

Example (contd): Theorist Side

$$\frac{1}{\sigma_{XM}} = \sum_i \frac{B_i}{[\sigma B]_i}$$

Theorist 1: tan(beta) = 2 etc, has σ = 1 pb
& BR's B_0=40%, B_1=B_2=B_3=0

$(1/\sigma_{XM})$ = (40%/0.27pb) + (0/0.6pb) + (0/1.0pb) + (0/2.1pb)

→ σ_{XM} = 0.7 pb Compare to σ_{theory} = 1 pb ← Ruled out

Theorist 2: tan(beta) = 8 (more tau's), also has σ = 1 pb
& BR's B_0=0, B_1=20%, B_2=20%, B_3=40%

$(1/\sigma_{XM})$ = (0/0.27pb) + (20%/0.6pb) + (20%/1.0pb) + (40%/2.1pb)

→ σ_{XM} = 1.4 pb Compare to σ_{theory} = 1 pb ← Not ruled out

Practical application: Reduces experimentalist's scanning burden.

Towards Model-independence

Part A : Exclusive theory channels

Define (experimental) channels, selection, SM expectations, N(Obs Signal), full acceptance (clean and dirty) for theory channels, and make public (for a given topology or model):

- $[\boldsymbol{\sigma}B]_i$'s for exclusive theory channels.
- A spreadsheet utility for combining $[\boldsymbol{\sigma}B]_i$'s and theory BR's.

Part B: Simplify/generalize topology (Next)

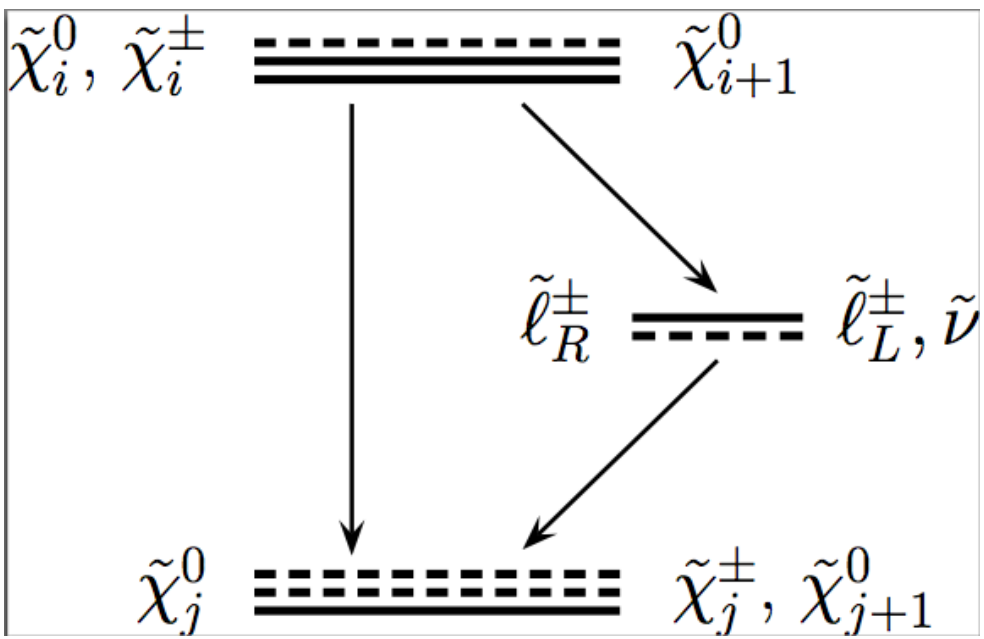
- No general solution, approximations and scatter-shot at best.
- Cover as many topologies as possible (We didn't, but LHC can.)
- $[\boldsymbol{\sigma}B]_i$'s get extra mileage out of each topology.

The emphasis here is on Part A: $[\boldsymbol{\sigma}B]_i$'s for exclusive theory channels.

mSUGRA → Simple Topology

1. Approximations begin
2. → Having a variety of topologies will be extremely useful.
3. Had to do some underhanded things at the Tevatron
4. → Being done in an organized/legal fashion @LHC
   (New Physics Characterization Group http://lhcnewphysics.org)

Here is the simplified model we used for CDF trileptons:



- **Three mass parameters**
  - **M (Lowest state mass)**
  - **ΔM_1 (Upper minus intermediate mass)**
  - **ΔM_2: (Upper minus lowest state mass)**

A Simple Topology Parameterization

(M = lowest, ΔM_1 =upper – middle, ΔM_2: upper – lowest)

- Dependence on M factors out: $f_i(M)$
- No intermediate particle case: $[\sigma B]_i)^{-1} = f_i(M) * g_i(\Delta M_2)$
- One intermediate particle case: $[\sigma B]_i)^{-1} = f_i(M)*h_i(\Delta M_1,\Delta M_2)$
- Taylor expansions:

$$f_i(M) = 1 + a_1(M) + a_2(M)^2$$

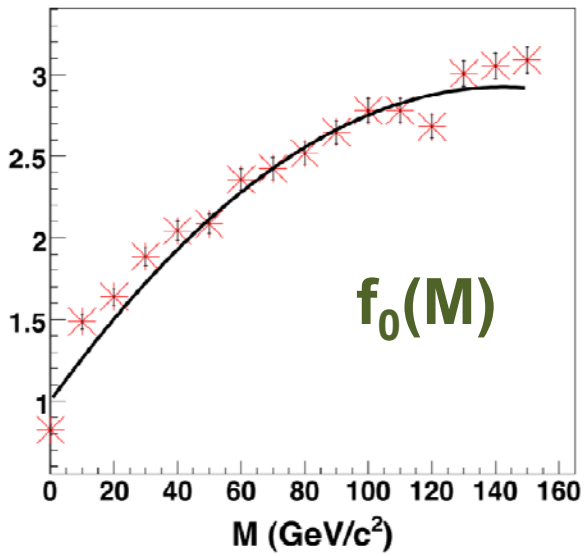
$$g_i(\Delta M_2) = b_0 + b_1(\Delta M_2) + b_2(\Delta M_2)^2$$

$$h_i(\Delta M_1,\Delta M_2) = c_0 + c_1(\Delta M_2) + d_1(\Delta M_1) + c_2(\Delta M_2)^2 + d_2(\Delta M_1)^2 + e_2(\Delta M_1*\Delta M_2)$$

A Simple Topology Parameterization

(M = lowest, ΔM_1 = upper–middle, ΔM_2: upper–lowest)

$$[\sigma B]_i)^{-1} = f_i(M) * g_i(\Delta M_2) \quad \text{or } f_i(M)*h_i(\Delta M_1,\Delta M_2)$$

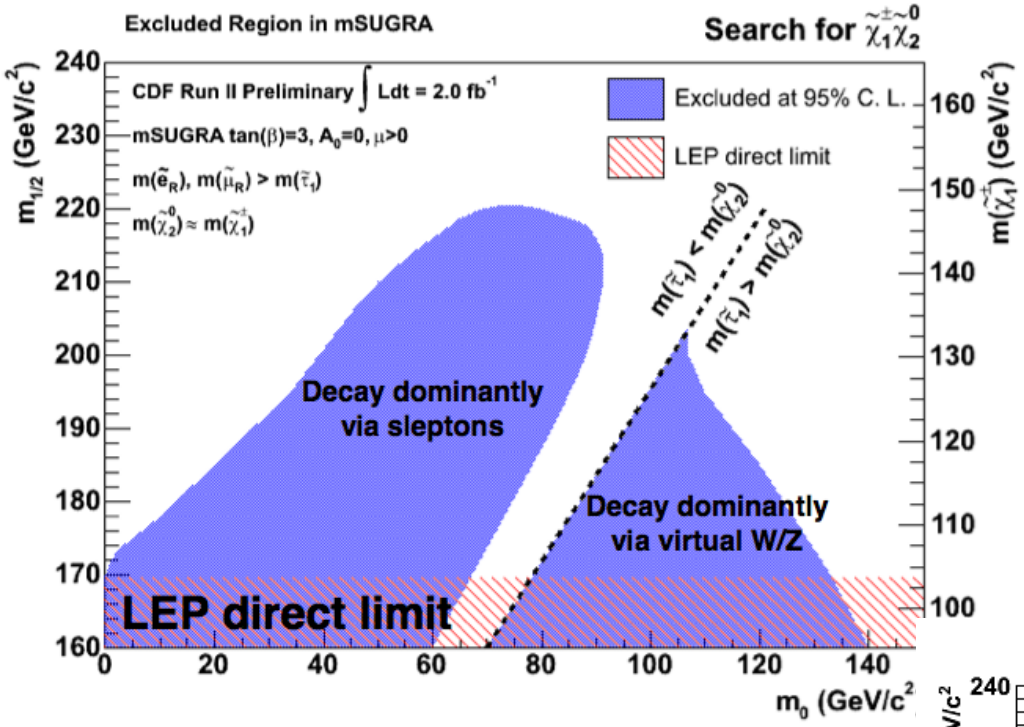


	0 τ's	1 τ's	2 τ's	3 τ's
	$f(M)$			
a_1	2.70×10^{-2}	4.48×10^{-2}	5.61×10^{-2}	4.27×10^{-2}
a_2	-9.48×10^{-5}	-1.69×10^{-4}	-2.29×10^{-4}	-1.59×10^{-4}
	$g(\Delta M_2)$			
b_0	-4.39	-3.59	-3.71×10^{-2}	2.11×10^{-1}
b_1	3.28×10^{-1}	1.72×10^{-1}	6.60×10^{-4}	-8.20×10^{-3}
b_2	-2.08×10^{-3}	-9.41×10^{-4}	1.51×10^{-4}	1.13×10^{-5}
	$h(\Delta M_1, \Delta M_2)$			
c_0	-2.84	-1.73	-2.67×10^{-1}	1.22×10^{-2}
c_1	1.92×10^{-1}	9.66×10^{-2}	8.71×10^{-3}	-9.86×10^{-4}
d_1	-3.60×10^{-2}	-3.74×10^{-2}	-4.36×10^{-3}	-1.01×10^{-3}
c_2	-1.56×10^{-3}	-7.36×10^{-4}	-7.91×10^{-5}	8.02×10^{-6}
d_2	-2.40×10^{-3}	-1.49×10^{-3}	-5.25×10^{-4}	-1.58×10^{-4}
e_2	2.72×10^{-3}	1.73×10^{-3}	5.66×10^{-4}	1.59×10^{-4}

An Excel spreadsheet at:
http://www.physics.rutgers.edu/pub-archive/0901

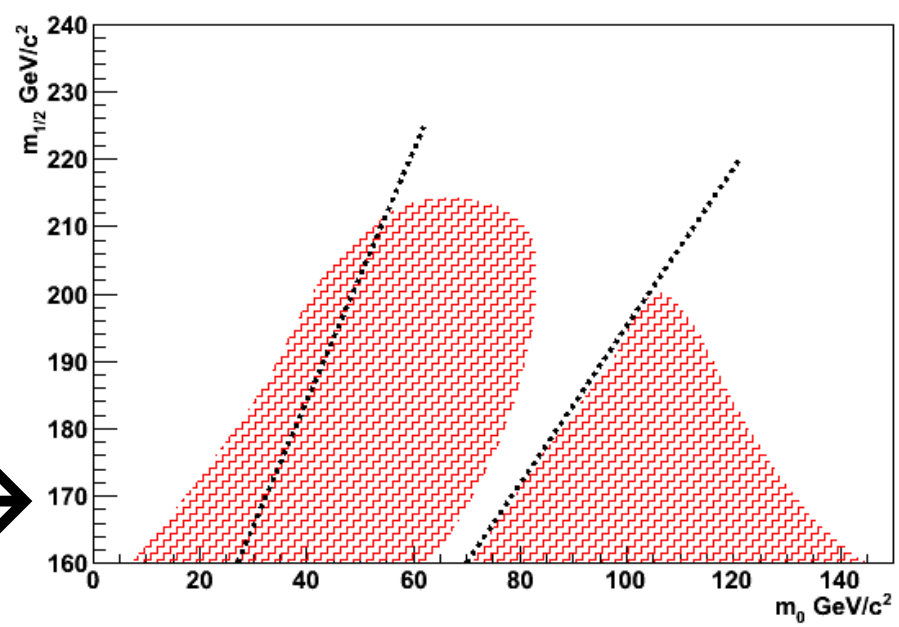
Good to 20-30% in the validity range

CDF Published vs "Model-Independent"



← CDF

arXiv:0808.1605



$$\frac{1}{\sigma_{XM}} = \sum_i \frac{B_i}{[\sigma B]_i}$$

& parameterized simplified topology →

Turning to LHC: How to Search (Exclusive Experimental Channels)

	$\lvert Q\rvert$	$\mathcal{N}_{\rm OSSF}$
$\ell\ell\ell\ell\ell$	≥ 0	≥ 0
$\ell\ell\ell\ell\tau_h$	$1,3,3,5$	0
$\ell\ell\ell\ell\tau_h$	$1,3$	$1,2,3$
$\ell\ell\ell\ell\tau_h$	0	0
$\ell\ell\ell\ell\tau_h$	0	$2,4$
$\ell\ell\ell\tau_h\tau_h$	$1,3,3,5$	0
$\ell\ell\ell\tau_h\tau_h$	3	$1,2$
$\ell\ell\ell\tau_h\tau_h$	1	$1,2$
$\ell\ell\ell\ell$	$2,4$	0
$\ell\ell\ell\ell$	2	$1,2,3$
$\ell\ell\ell\ell$	0	0
$\ell\ell\ell\ell$	0	$2,4$

	$\lvert Q\rvert$	$\mathcal{N}_{\rm OSSF}$
$\ell\ell\ell\tau_h$	$2,2,4$	0
$\ell\ell\ell\tau_h$	0	0
$\ell\ell\ell\tau_h$	2	$1,2$
$\ell\ell\ell\tau_h$	0	$1,2$
$\ell\ell\tau_h\tau_h$	$2,2,4$	0
$\ell\ell\tau_h\tau_h$	0	0
$\ell\ell\tau_h\tau_h$	$0,2$	1
$\ell\ell\ell$	$1,3$	0
$\ell\ell\ell$	1	$1,2$
$\ell\ell\tau_h$	3	0
$\ell\ell\tau_h$	$1,1$	0
$\ell\ell\tau_h$	1	1

	$\lvert Q\rvert$	$\mathcal{N}_{\rm OSSF}$
$\ell\tau_h\tau_h$	3	0
$\ell\tau_h\tau_h$	1	0
$\ell\ell$	2	0
$\ell\ell$	0	0
$\ell\ell$	0	1
$\ell\tau_h$	2	0
$\ell\tau_h$	0	0
ℓ	1	0

Table 7. Classification of all one through five object combinations of electrons, muons,

How to Disseminate Results?

THEORISTS

Provide topologies (and sub-topologies). Identify exclusive channels for each topology (start with Feynman diagrams for subtopologies, or generator level jets, met, # leptons… exclusive signatures)

COMMON

SLHA files, possibly LHE.
Generation Level Kinematic (Clean) Acceptances (pt, eta, met, angles…)

EXPERIMENTALISTS

(experimental) channels, selection, SM expectations, N(Obs Signal), full acceptances (clean and dirty) for theory channels, and make public

- N(Obs Signal)/L = (σBA) (very little effort)
- $[\sigma B]_i$'s for exclusive theory channels.
- Generation-level clean acceptances (see Common above).
- Simple utilities for combining $[\sigma B]_i$'s and theory BR's.

How will a theorist use the results?

"Back-of-the-envelope" Theorists

Identify a published topology that is closest to your topology
Input BR's into the spreadsheet utility
Compare theory and experimental cross section
(Fudge issues with different pt spectra etc)

Enterprising (Simulation-Savvy) Theorists

Run on experiment's simple public topologies (sigma*BR's)
SLHA files → Events → Generator level cuts → Verify the experimental values of Clean Acceptance
→ Normalize to experiment: Conclude the dirty acceptance (resolution, isolation etc) and use it as a correction factor
→ Switch to topology of interest, not necessarily a simple one.

Exclusive Channels: an Ambitious Example (Part I : Search Strategy)

Analyze data uniformly in (numerous) exclusive *experimental* channels ranked by SM background. Low background channels bring in signal & high statistics (background) channels serve as control samples.

# of bodies in final state = e's + mu's + tau candidates

- >=5 body channels (subdivided by # of tau candidates), then
- 4 body channels (subdivided ditto), then *(& the 1st diZ→4mu shows up!)*
- 3 body channels, then
- …
- Same-sign e/mu's, then
- …
- Monolepton
- Jets without leptons

MET, HT, Z-mass veto, # jets used to reduce SM background (hence a large number of channels). NO bias, e.g., due to HT usage.

Exclusive Channels: an Ambitious Example (Part II – Interpretation)

At the generator level, split the entire signal from a model (or a topology) into exclusive *theory* channels

- 5 or more leptons (e, mu and *actual* tau's), then
- 4 leptons (0,1,2,3,4 tau's), then
- 3 leptons (0,1,2,3 tau's), then
- …
- Same-sign e/mu's (additional leptons too soft to be above.), then
- …
- Monolepton
- Jets without leptons

$$\frac{1}{\sigma_{XM}} = \sum_i \frac{B_i}{[\sigma B]_i}$$

Works short of interference effects.
Complicated color chains: Each chain a channel (avoid interference)

- Identify theory channels and generate channel-tagged MC samples.
- ATLAS & CMS analysis groups produce exclusive combinable results [(σB_i)'s] for these channels (acceptance is coded).
- (σB_i)'s are listed on public webpages for the result.

Conclusions

- Exclusive experimental channels (of lepton quality, hadronic tau decays) approach gives most sensitivity and least bias.
- At the generator level, identify simpler constituent channels of a model and channel-tag the Monte Carlo. Make these sigma*Br's available to the phenomenologists.
- Get mileage out of a model/topology by providing sigma*Br' s for exclusive internal channels. Fewer scans.
- Easier to combine pieces intra and inter experiments (and brag about experiment's prowess).
- At the very least, factorize out branching ratios from the multidimensional parameter space.
- Only experimentalists can deal with the dirty acceptance, but providing generator-level clean acceptance allows enterprising theorists to tune simulations.