The Search for Supersymmetry at CDF in the LHC Era

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Why Search for Supersymmetry?

There are some theories that are so compelling that it's worth doing a comprehensive and systematically deep set of searches to see if they are realized in nature

→Supersymmetry is such a theory

First things First: *What is Supersymmetry and why do we care?*

Not Your Typical Introduction

Typical Introduction:

1. Lay out the theoretical issues
2. Describe how the introduction of SUSY particles solves the problems
3. Touch on other problems that SUSY can solve

My introduction:

- Just touch on the important theoretical issues, focus instead on the "other" experimental results that constrain which versions of SUSY we look for

Then I'll about how we search for SUSY at the Tevatron

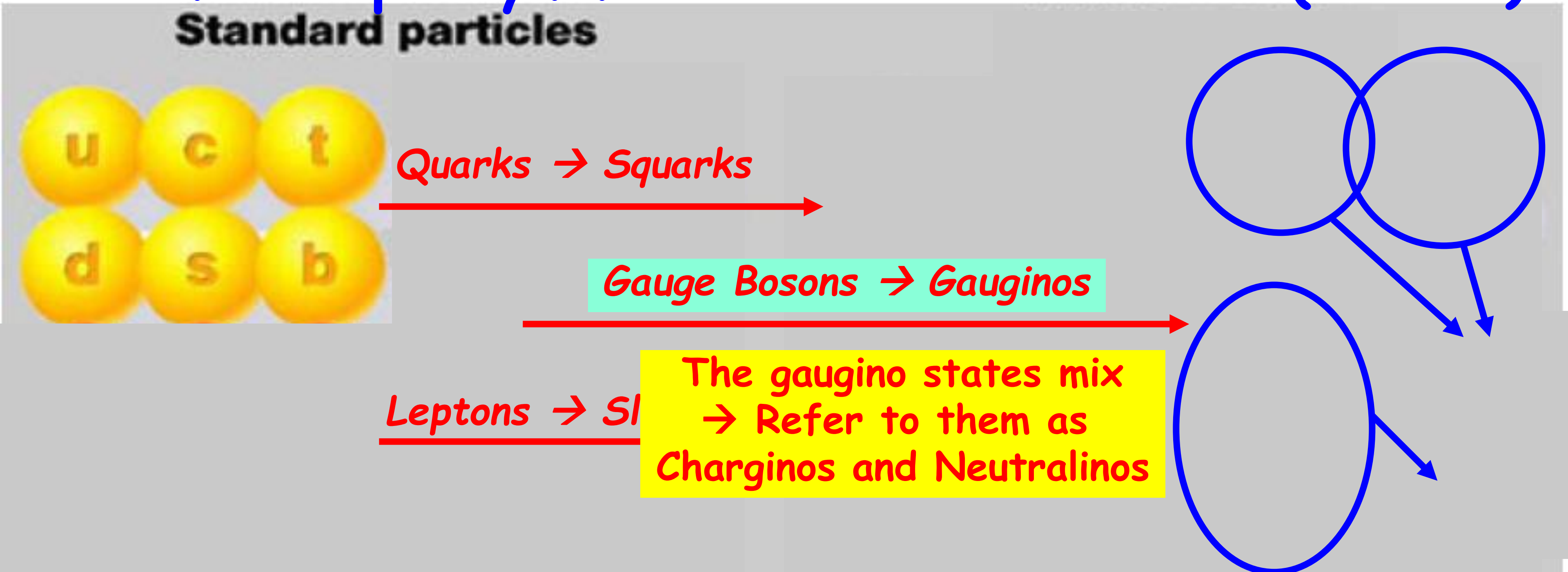
What is Supersymmetry?

Supersymmetry (SUSY) is a theory that postulates a symmetry between fermions and bosons

Q|Boson> = |Fermion>

Q|Fermion> = |Boson>

Minimal Supersymmetric Standard Model (MSSM)



Quarks → Squarks

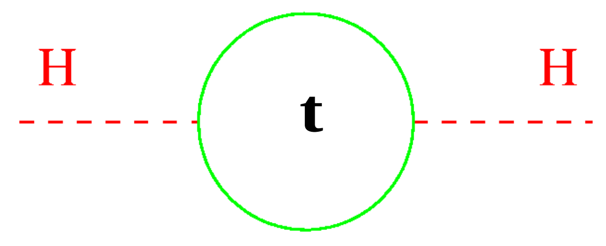
Gauge Bosons → Gauginos

Leptons → Sl

The gaugino states mix
→ Refer to them as
Charginos and Neutralinos

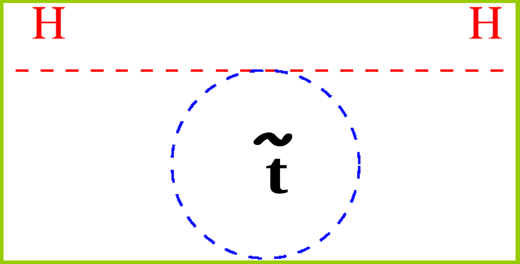
Example of How SUSY Helps: The Hierarchy Problem

The Standard Model



Corrections to Higgs boson mass not only finite, but in fact divergent

Supersymmetry



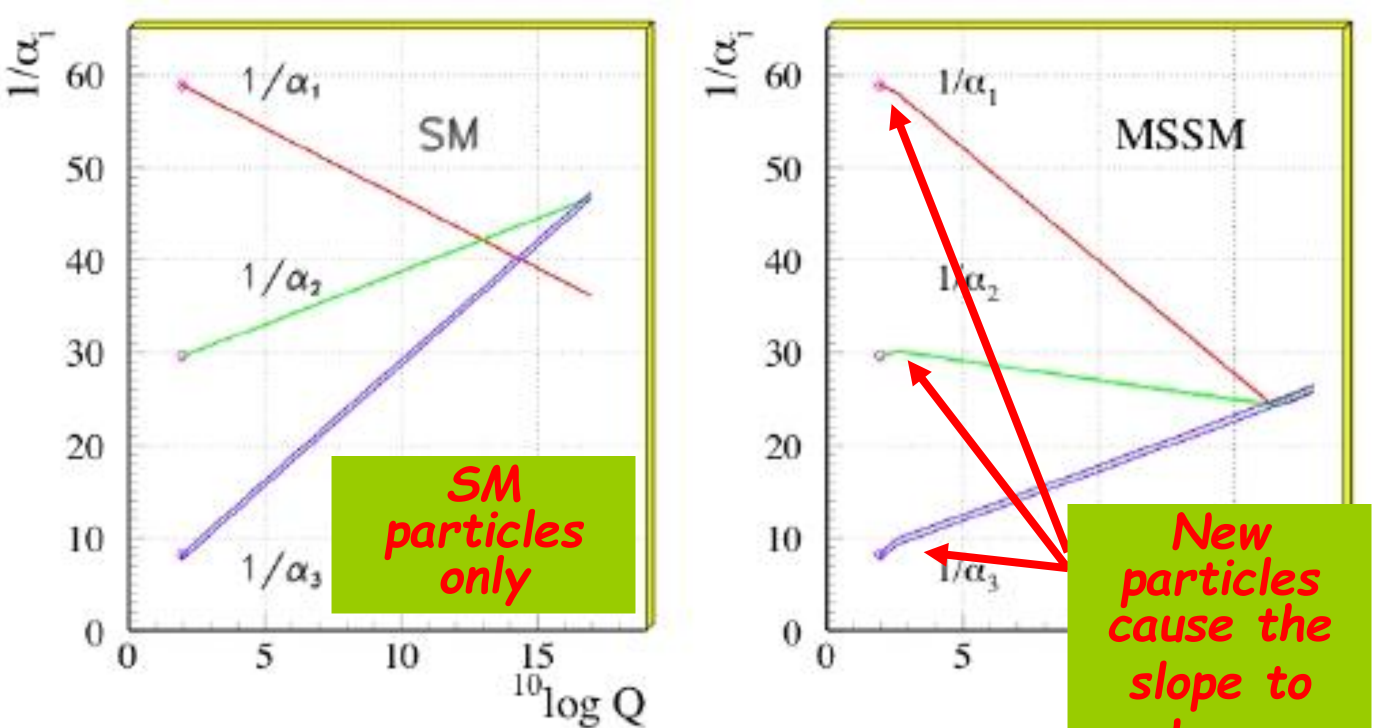
Fermion and Boson contributions to the Higgs cancel nearly exactly in supersymmetry

$$\delta m_H{}^2 \propto (m^2_{Boson} - m^2_{Fermion})$$

The one loop divergences will cancel, provided that the SUSY particles have masses that are small enough

SUSY and the Coupling Constants

Another issue is that adding extra particles provides a "natural" way for the running of the coupling constants to unify at the GUT Scale



SM particles only

New particles cause the slope to change

Advantages and Disadvantages of SUSY

- There is no unique explanation of the origin of the sparticle masses or couplings
- With all these new couplings and particles it's possible we could have our known SM particles decaying through loops
  - Any version that predicts/allows a quick proton decay is clearly wrong
  - Any version that has the same mass for the particles and the sparticles must be wrong
    - Haven't observed any bosonic electrons in nature

    → $m_{positron} = m_{electron} \neq m_{selectron}$

→SUSY is broken somehow

Different Ways to Proceed

No unique explanation of symmetry breaking → make some assumptions

- Can put in masses and couplings by hand
  - General SUSY has over 100 new parameters
- Use experimental constraints and theoretical prejudices to further restrict the parameter space
  - To protect the proton lifetime can define R-parity = $(-1)^{3(B-L)+2s}$ and assert that it's conserved

→R = 1 for SM particles

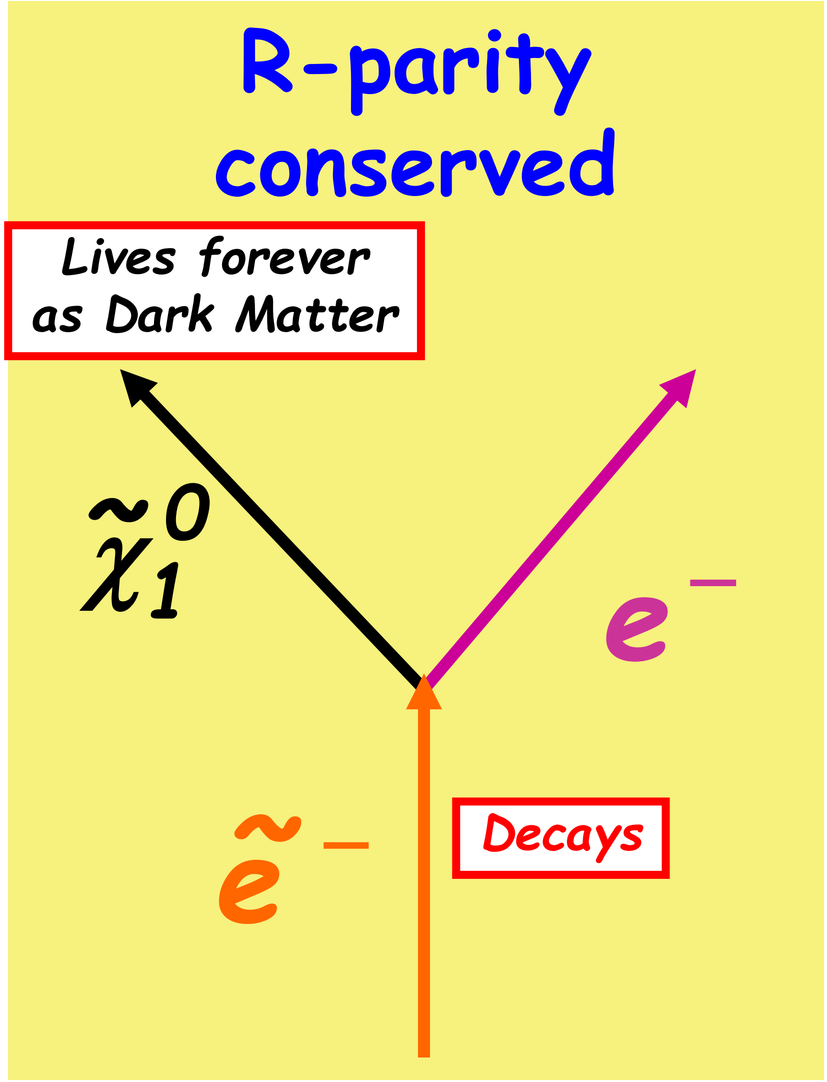
→R = -1 for MSSM partners

SUSY can provide a Dark Matter Candidate

If R-Parity is conserved then the lightest SUSY Particle can't decay and, if neutral

→Provides an excellent dark matter candidate

Provides the tie between Particle Physics, Astronomy and Cosmology?



R-parity conserved

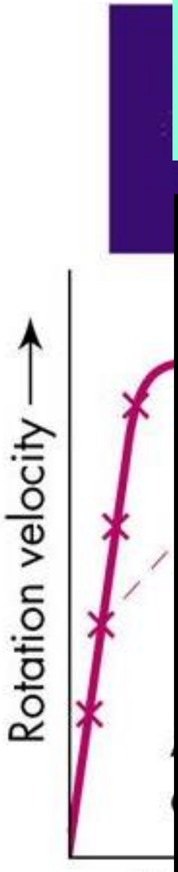
Lives forever as Dark Matter

Decays

Dark Matter in Astronomy and Cosmology

Galaxy Rotation Data

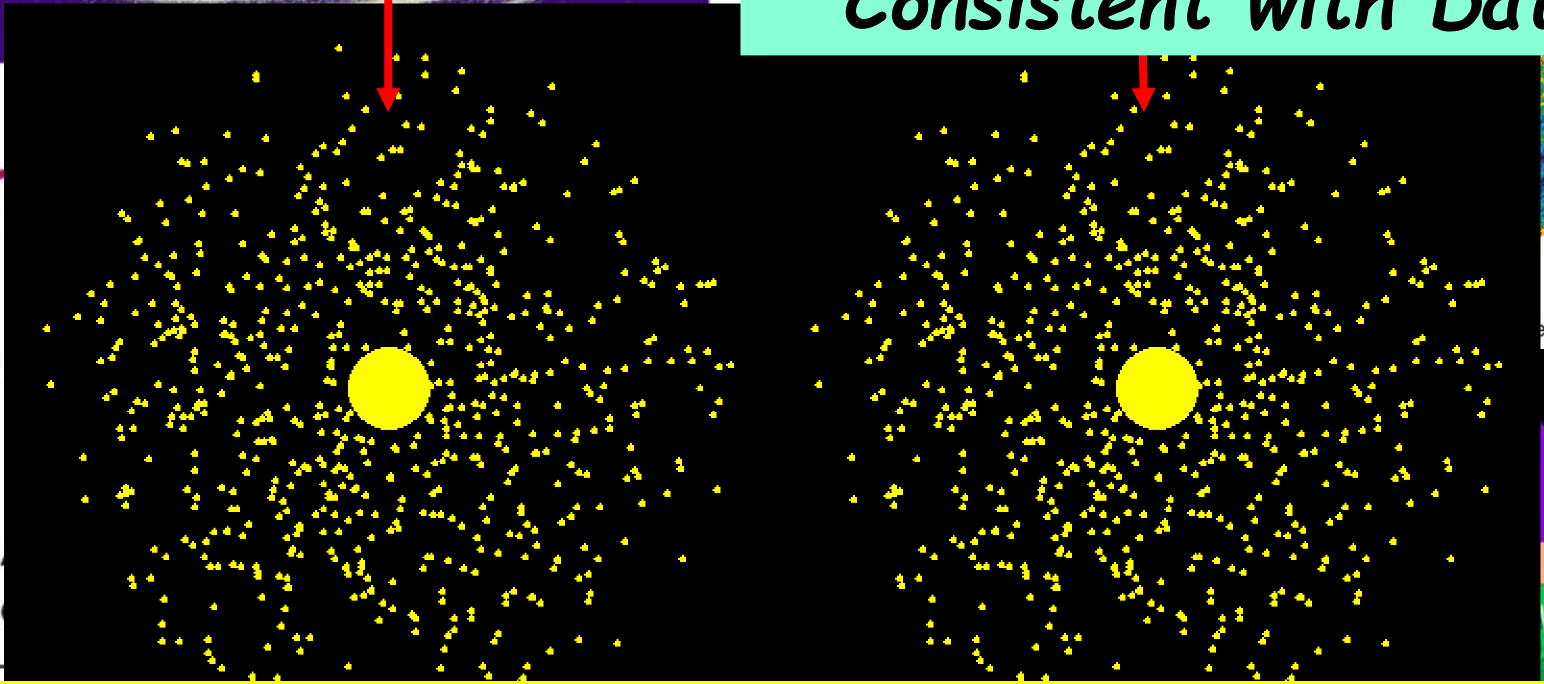
Cosmic Microwave Background Data

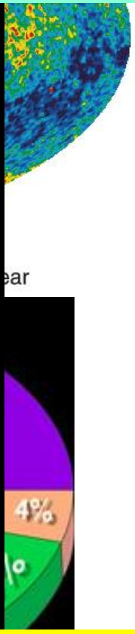


Simulation without Dark Matter

Simulation with Dark Matter

Consistent with Data





Galaxy Rotation Simulation with and without Dark Matter

Particle Physics solution to an Astronomy/Cosmology problem?

- **Good:** Predict massive stable particles that explain Dark Matter effects
- **Better:** Provide both a model of particle physics and cosmology that is consistent with Early Universe Physics and evolves into the observed amount of Dark Matter today

Dark Matter = Supersymetric Particles?

__Astronomy, Cosmology and Parti sics:__
The Dark Matter in the de
up of LOTS of n t

Ga Universe like
is still here today!

Big Bang!
Then Universe gets bigger

SUSY provides a
a full calculation

Want to do more than simply provide a candidate, want to describe early Universe physics and correctly predict the Dark Matter relic density

Different Types of SUSY Solutions

Cold Dark matter (~100 GeV) Produced in the Early Universe

Warm Dark matter (~1 keV) Produced later in time

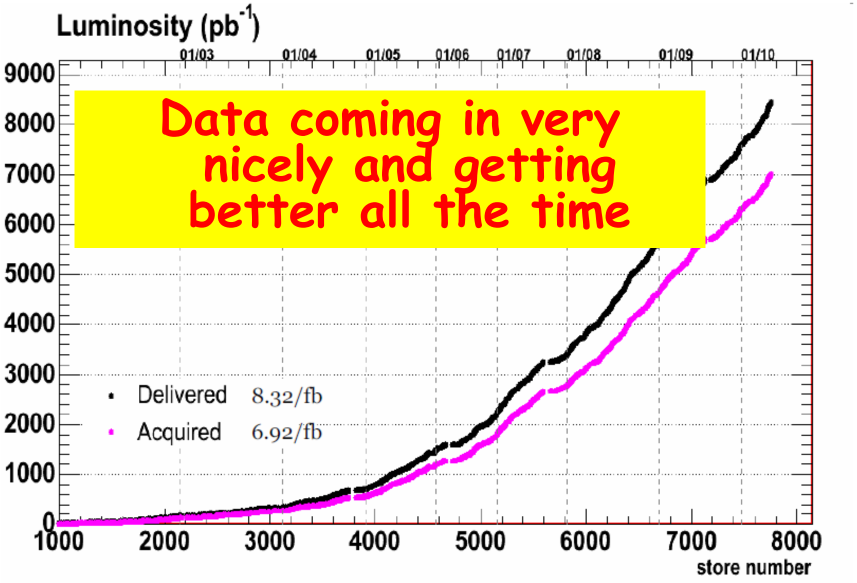
Sparticle Masses and Lifetimes deeply affect the particles in the Early Universe and Today

Outline of the Searches

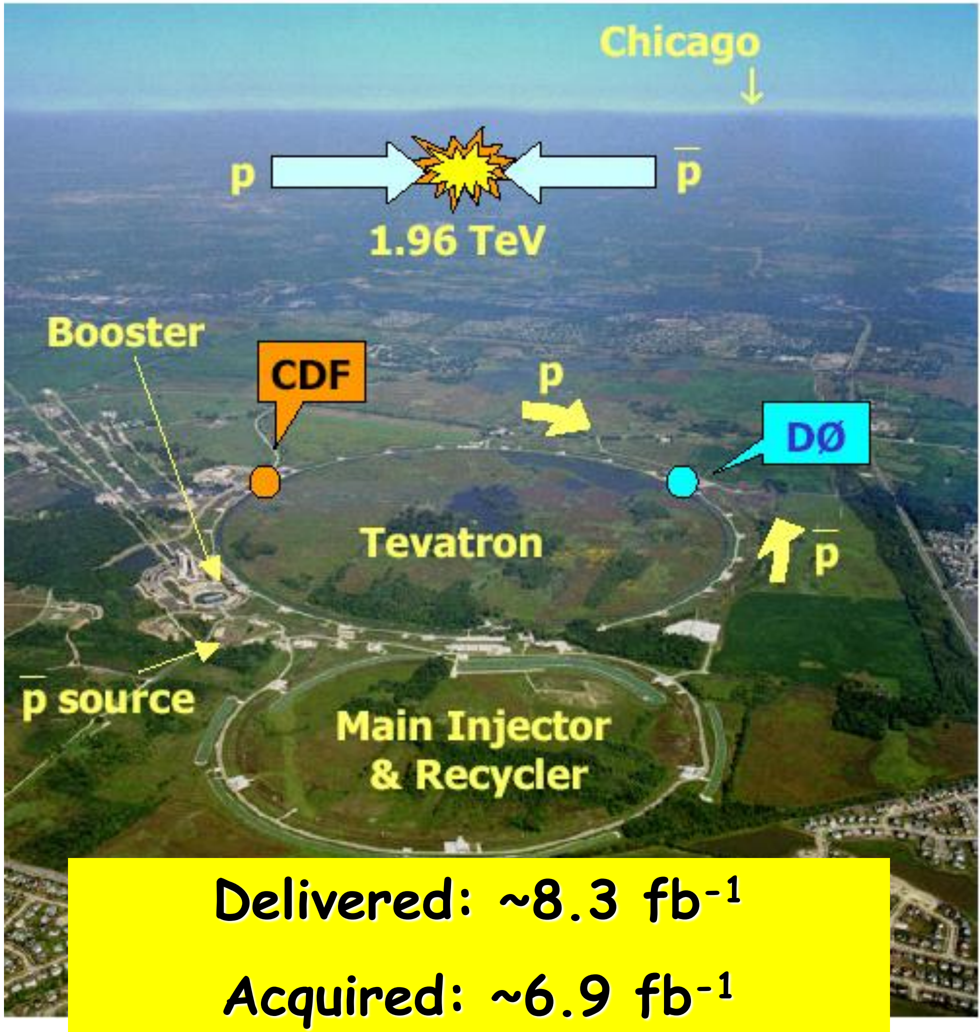
- The Tevatron and CDF
- mSUGRA Searches
  - -Squarks & Gluinos
  - -Gaugino Pairs
  - -Indirect Searches
- Gauge Mediated Searches
- Other ideas: CHAMPS
- Conclusions

The Fermilab Tevatron

- Protons and anti-protons collide with $\sqrt{s} = 1.96$TeV
- Running until at least 2011
- Rumours of running 3 more years to be complementary to LHC



Data coming in very nicely and getting better all the time



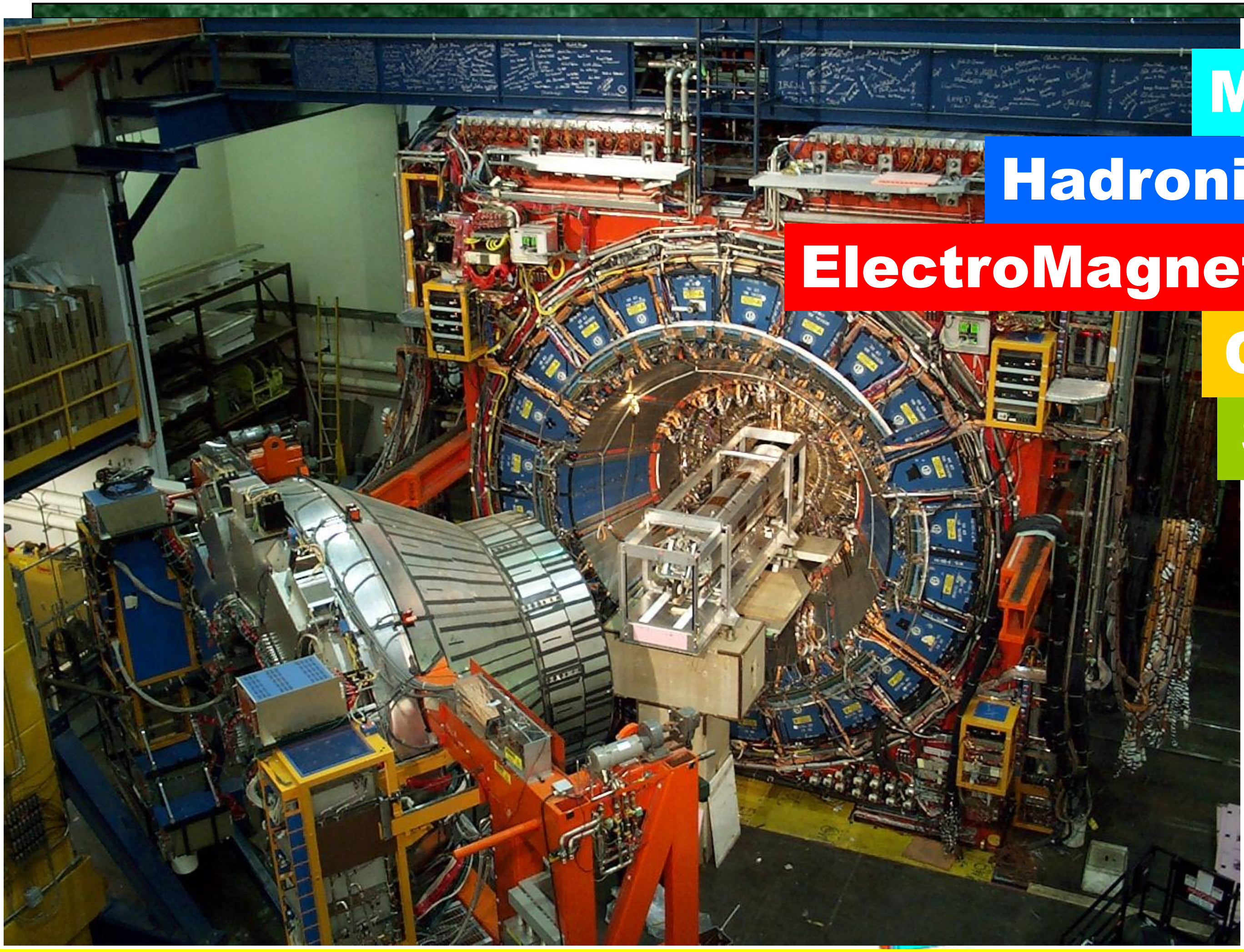
Delivered: ~8.3 fb^{-1}

Acquired: ~6.9 fb^{-1}

Analyzed: ~2-3 fb^{-1}

(depending on the analysis)

The CDF Detector



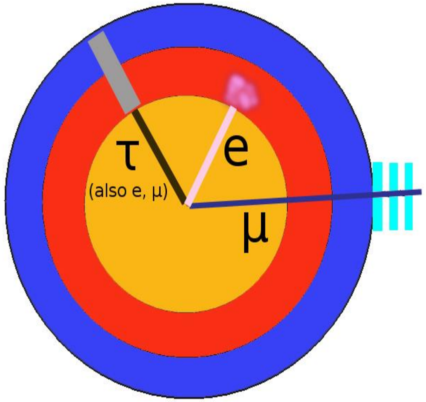
Muon Chambers

Hadronic Calorimeters

ElectroMagnetic Calorimeter

Central Tracker

Silicon Tracker



Powerful multi-purpose detector

High quality identification for electrons, muons, taus, jets, Missing Energy, photons, b's etc.

Aside before we begin…

- Most analyses will look like they were easy
- Noto Bene: It's 2010 and we're 9 years into running
- This is a lot harder than it looks and it takes a lot longer than it should
- I'll try to comment periodically on lessons for LHC

"It's a lot of work to make it look this easy"

– Joe DiMaggio

– Yogi Berra

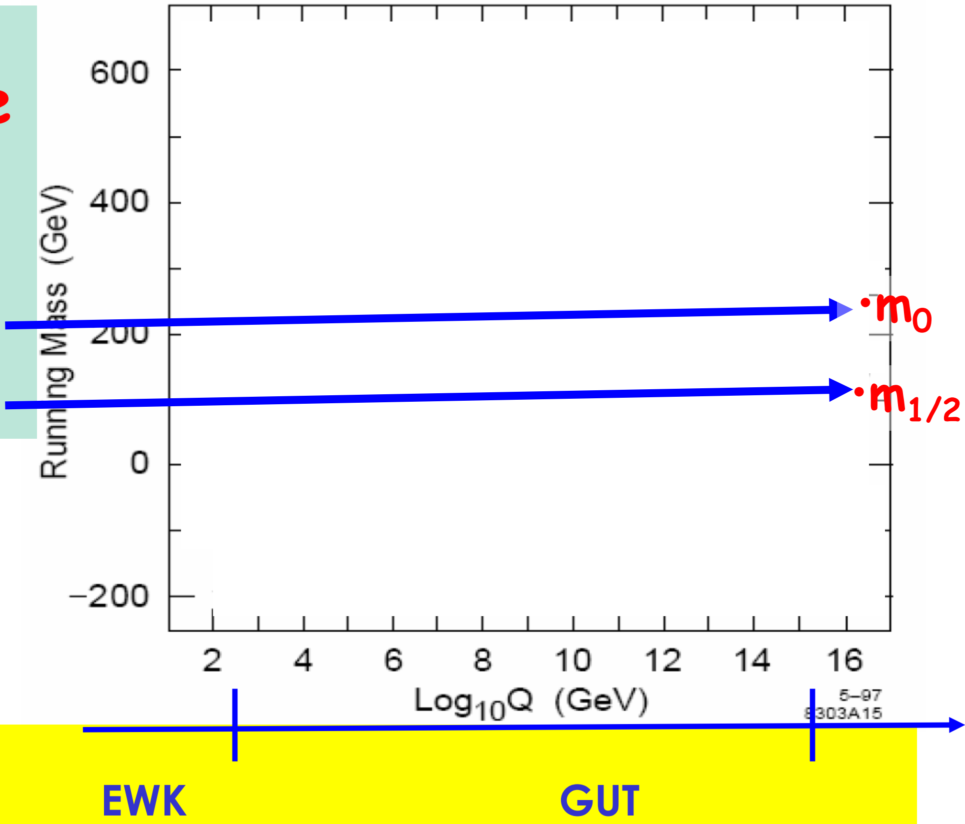
mSUGRA

Minimal Supergravity: breaking is mediated by the gravity sector

At the unification scale:

- scalars have mass m_0
- gauginos have mass $m_{1/2}$

mSUGRA or Constrained MSSM used as benchmark



5 free parameters (at M_{GUT}) determine the sparticle masses

- m_0: common scalar mass at M_{GUT}
- $m_{1/2}$: common gaugino mass at M_{GUT}
- tanβ: Ratio of the Higgs VEV
- A_0: common trilinear coupling at M_{GUT}
- sign(μ): μ is the Higgsino mass parameter

We'll come back to this one

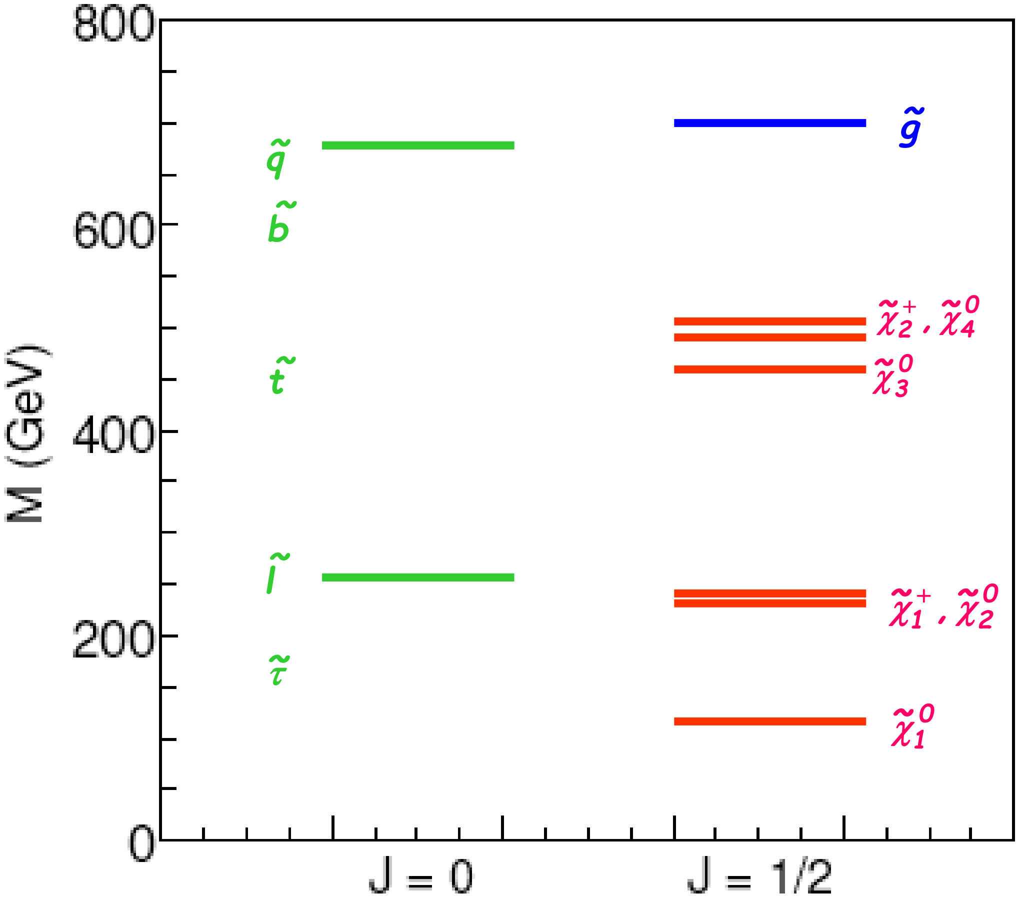
The Sparticle Masses

In a typical mSUGRA scenario

- Squarks and gluinos are heavy
- 1st and 2nd generation squarks are mass degenerate
- The lightest neutralino is the LSP
  - Dark Matter candidate

For large values of tanβ Stop, Sbottom and Stau can get much lighter

→Can also have a significant effect on the branching ratios



Need complementary searches for low tanβ and high tanβ

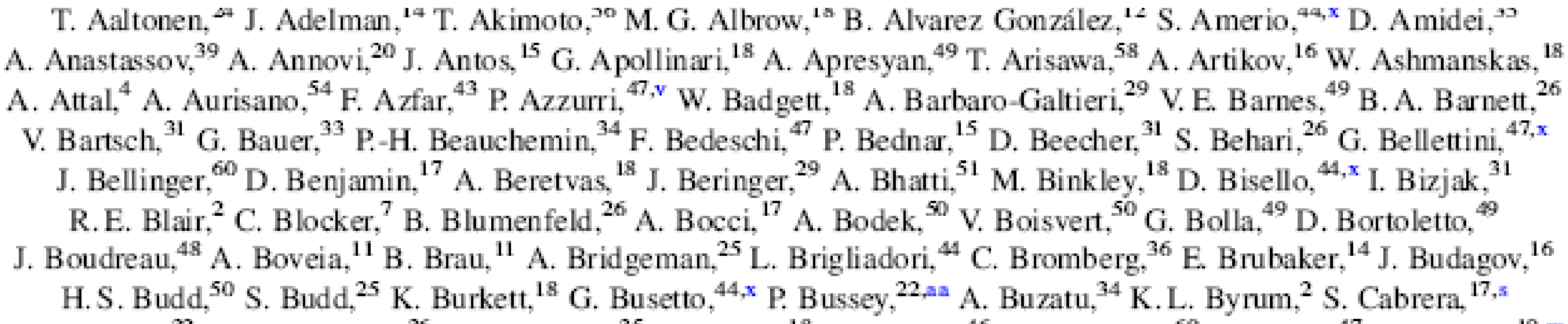
Golden Search Channels

Three main ways to look for minimal models with Cold Dark Matter (mSUGRA-type models)

- Direct production of Squarks and Gluinos
  - Heavy, but strong production cross sections
- Direct production of the Gauginos
  - Lighter, but EWK production cross sections, also leptonic final states have smaller backgrounds
- Indirect search via sparticles in loops
  - Affect branching ratios

Start with low tanβ, then move to searches with high tanβ

Move on to the results from me and about 700 of my closest friends at CDF…

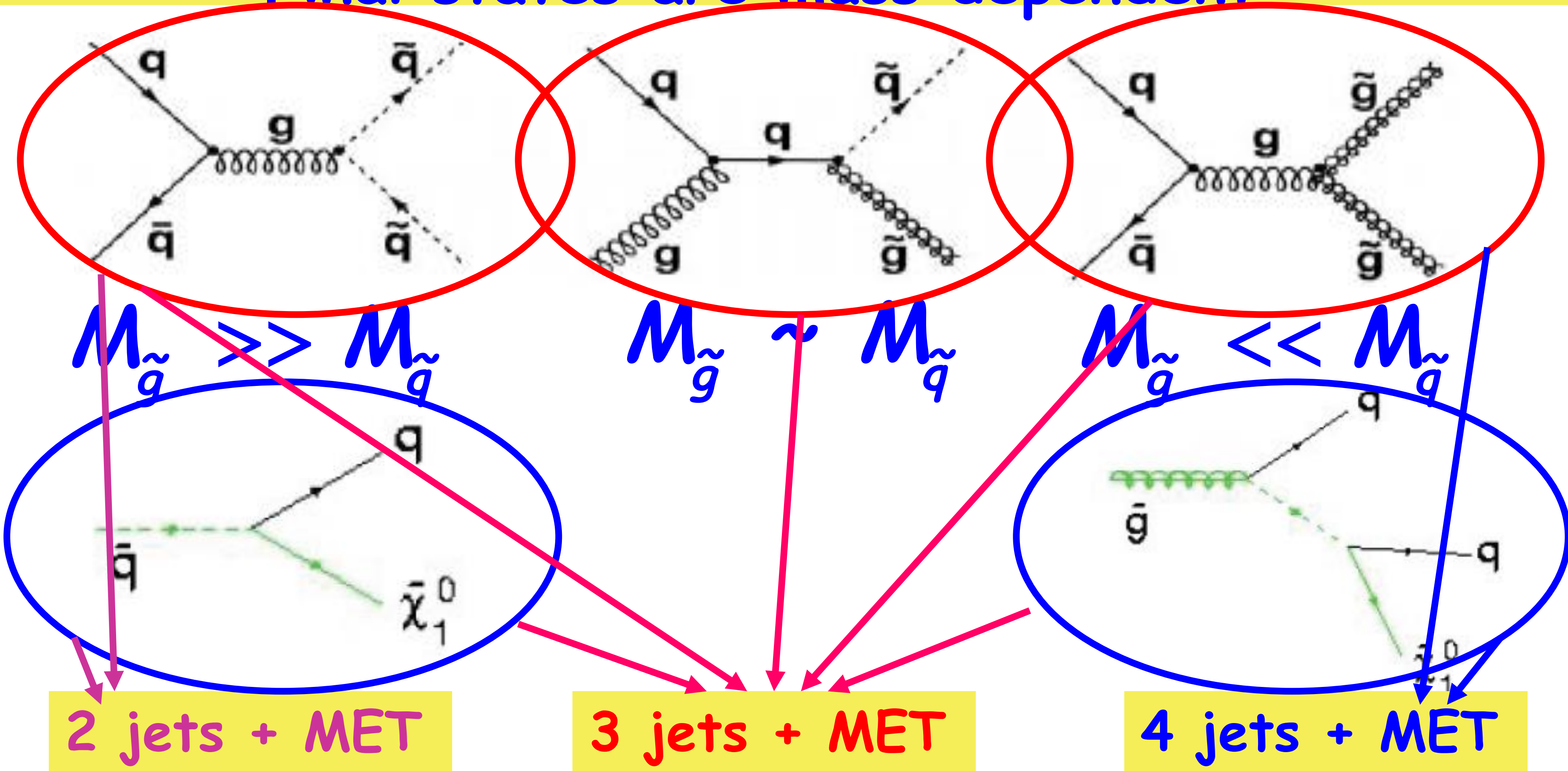


T. Aaltonen,[24] J. Adelman,[14] T. Akimoto,[56] M. G. Albrow,[18] B. Alvarez González,[12] S. Amerio,[44,x] D. Amidei,[35]
A. Anastassov,[39] A. Annovi,[20] J. Antos,[15] G. Apollinari,[18] A. Apresyan,[49] T. Arisawa,[58] A. Artikov,[16] W. Ashmanskas,[18]
A. Attal,[4] A. Aurisano,[54] F. Azfar,[43] P. Azzurri,[47,v] W. Badgett,[18] A. Barbaro-Galtieri,[29] V. E. Barnes,[49] B. A. Barnett,[26]
V. Bartsch,[31] G. Bauer,[33] P.-H. Beauchemin,[34] F. Bedeschi,[47] P. Bednar,[15] D. Beecher,[31] S. Behari,[26] G. Bellettini,[47,x]
J. Bellinger,[60] D. Benjamin,[17] A. Beretvas,[18] J. Beringer,[29] A. Bhatti,[51] M. Binkley,[18] D. Bisello,[44,x] I. Bizjak,[31]
R. E. Blair,[2] C. Blocker,[7] B. Blumenfeld,[26] A. Bocci,[17] A. Bodek,[50] V. Boisvert,[50] G. Bolla,[49] D. Bortoletto,[49]
J. Boudreau,[48] A. Boveia,[11] B. Brau,[11] A. Bridgeman,[25] L. Brigliadori,[44] C. Bromberg,[36] E. Brubaker,[14] J. Budagov,[16]
H. S. Budd,[50] S. Budd,[25] K. Burkett,[18] G. Busetto,[44,x] P. Bussey,[22,aa] A. Buzatu,[34] K. L. Byrum,[2] S. Cabrera,[17,s]

Squark and Gluino Searches in Multijet + Met

Three main production diagrams

Final states are mass dependent



$M_{\tilde{g}} >> M_{\tilde{q}}$

$M_{\tilde{g}} \sim M_{\tilde{q}}$

$M_{\tilde{g}} << M_{\tilde{q}}$

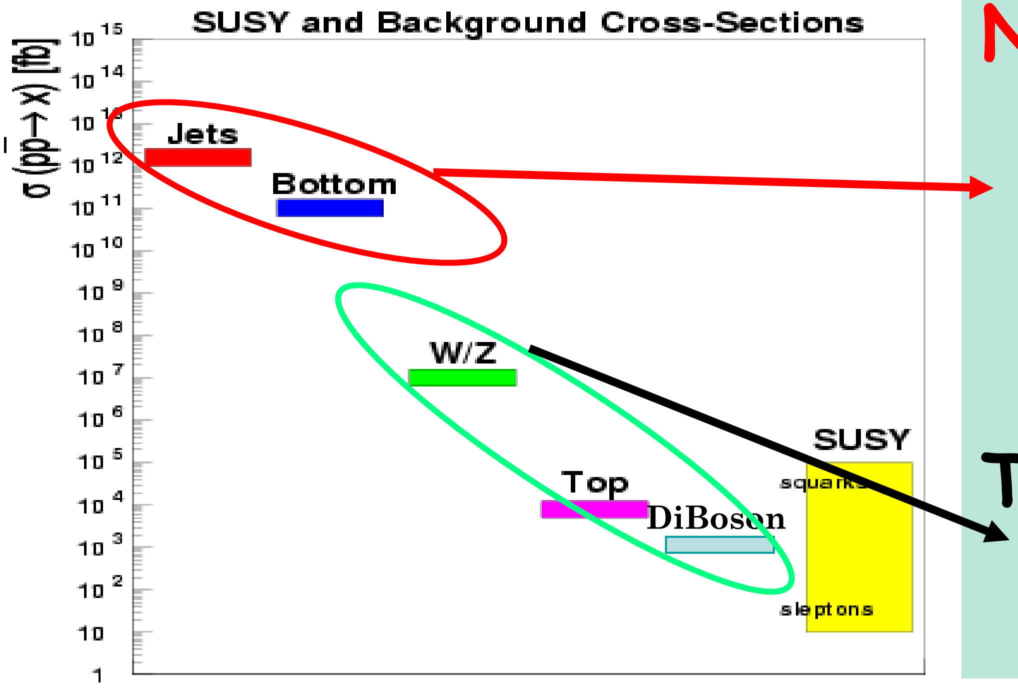
2 jets + MET

3 jets + MET

4 jets + MET

3 separate final states + Unified Analysis ➔ best coverage

Start from difficult backgrounds

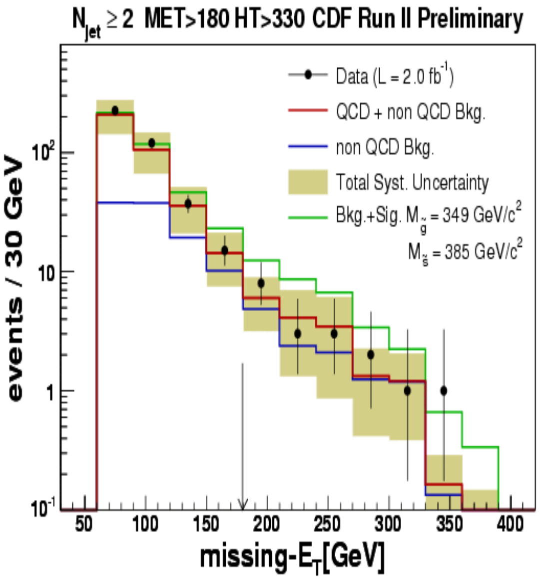


Note: Despite the huge production cross sections only about 25% of the final background is QCD

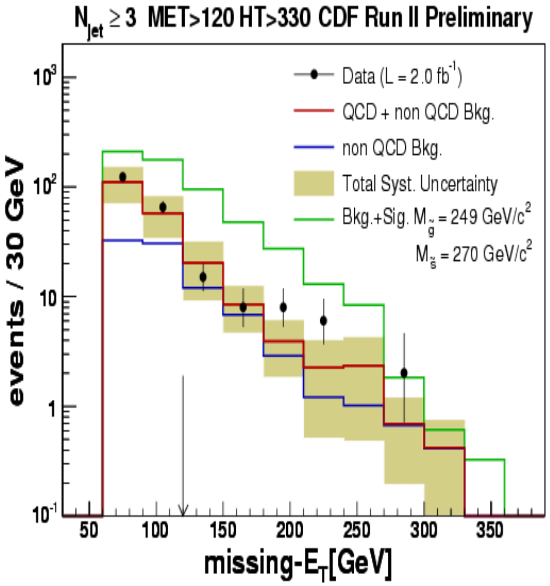
The rest is ttbar and other EWK processes

	2 jets	3 jets	4 jets
Selections	$H_T>330$, $\not{E}_T>180$ GeV/c^2	$H_T>330$, $\not{E}_T>120$ GeV/c^2	$H_T>280$, $\not{E}_T>90$ GeV/c^2
Data	18	38	45
Expected SM	16±5	37±12	48±17

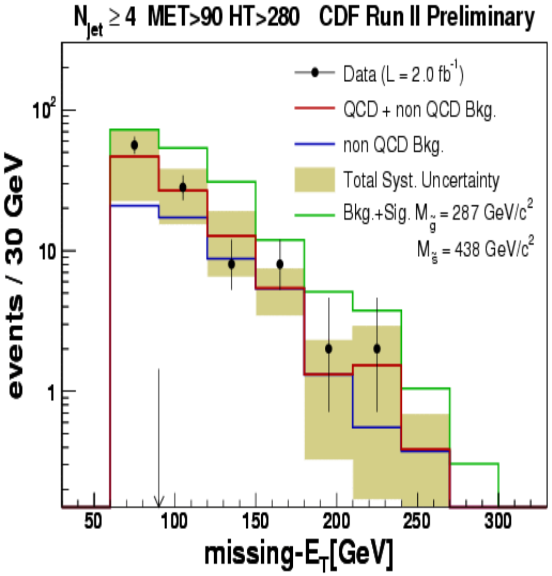
Unified Squark/Gluino Search



2 jets + MET



3 jets + MET



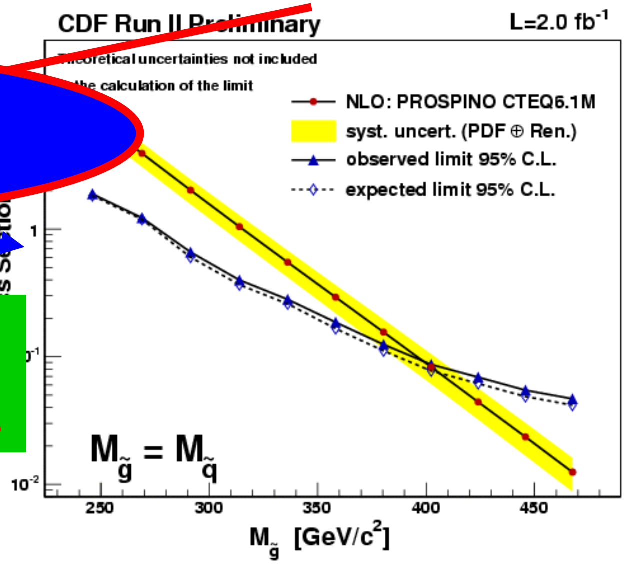
4 jets + MET

SUSY Interpreter

Set Cross Section Limits

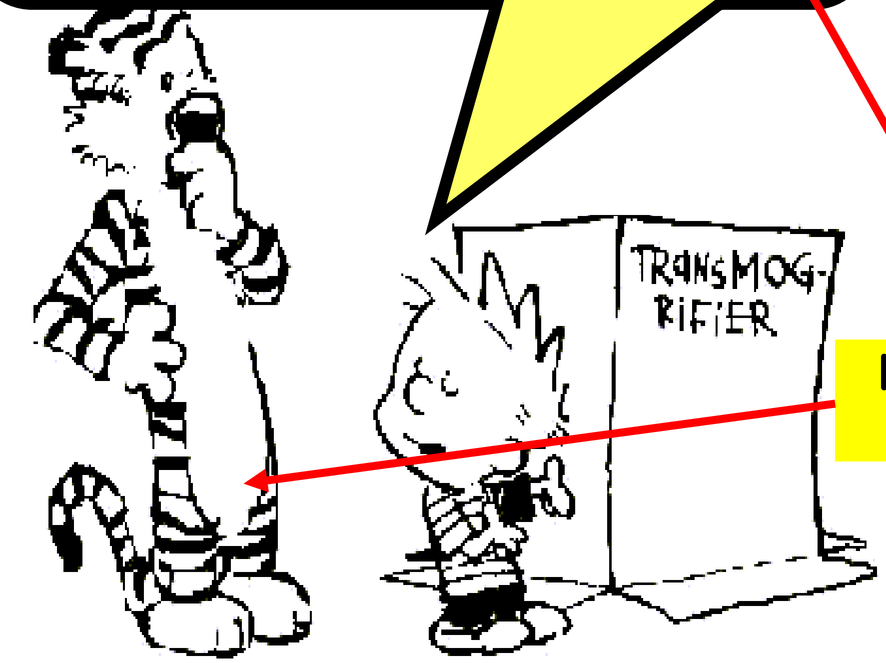
No evidence for new physics

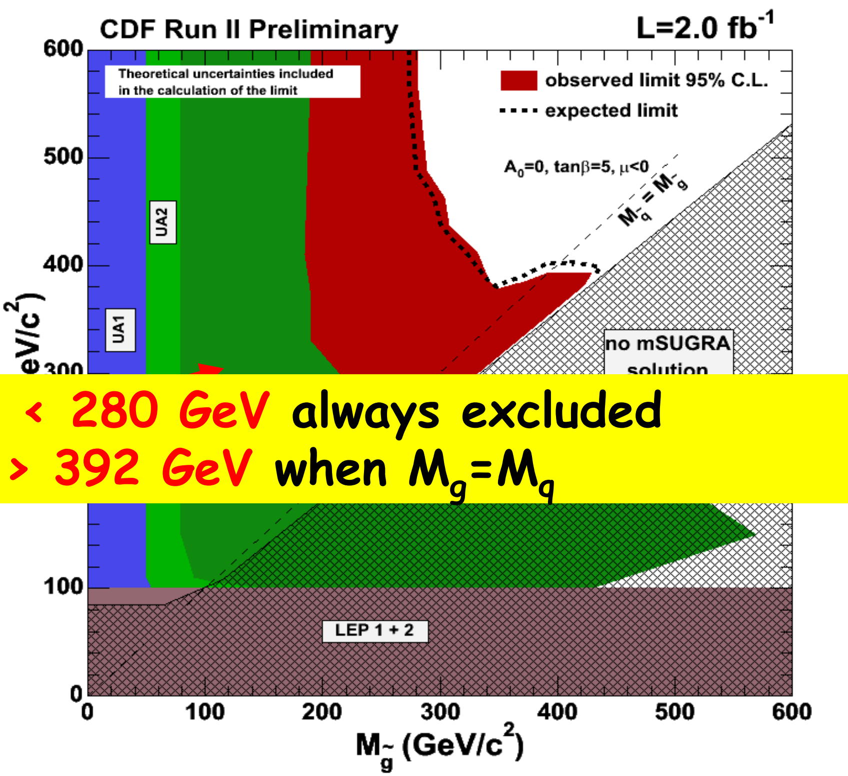
As with most CDF results, there are comparable DØ results which I won't touch on



More limits…

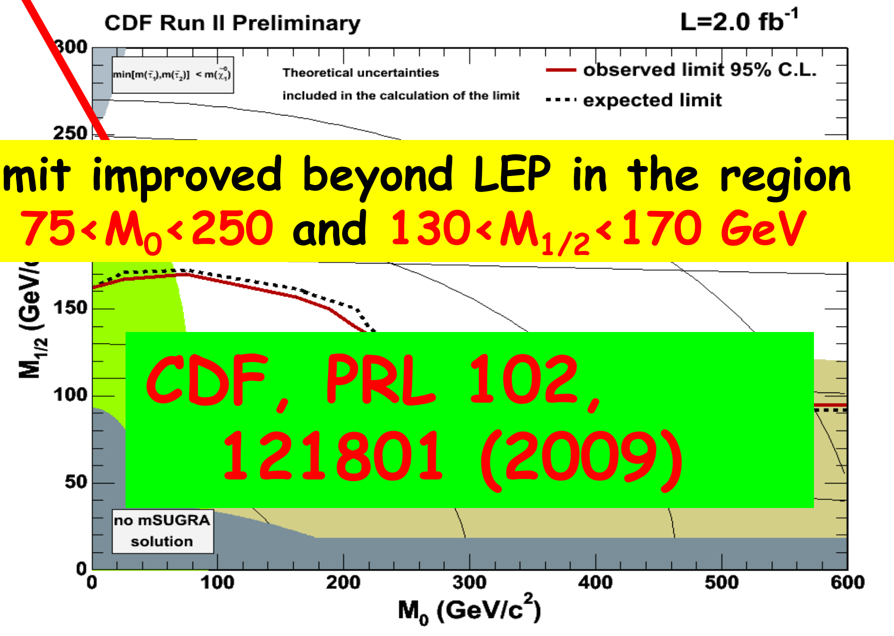
You see Hobbs, I can Transmogrify the cross section results into limits on the Sparticle Masses and mSUGRA parameter space





M_g < 280 GeV always excluded

M > 392 GeV when M_g=M_q



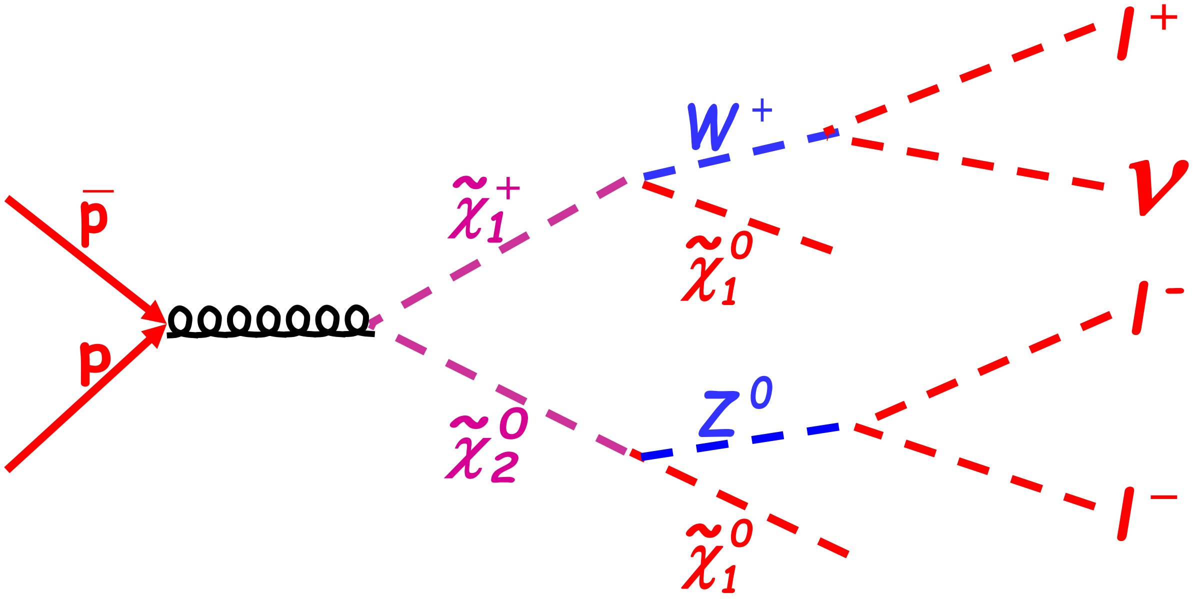
limit improved beyond LEP in the region 75<M_0<250 and 130<$M_{1/2}$<170 GeV

CDF, PRL 102, 121801 (2009)

Gaugino Pair Production

Chargino-Neutralino gives three low energy leptons in the final state

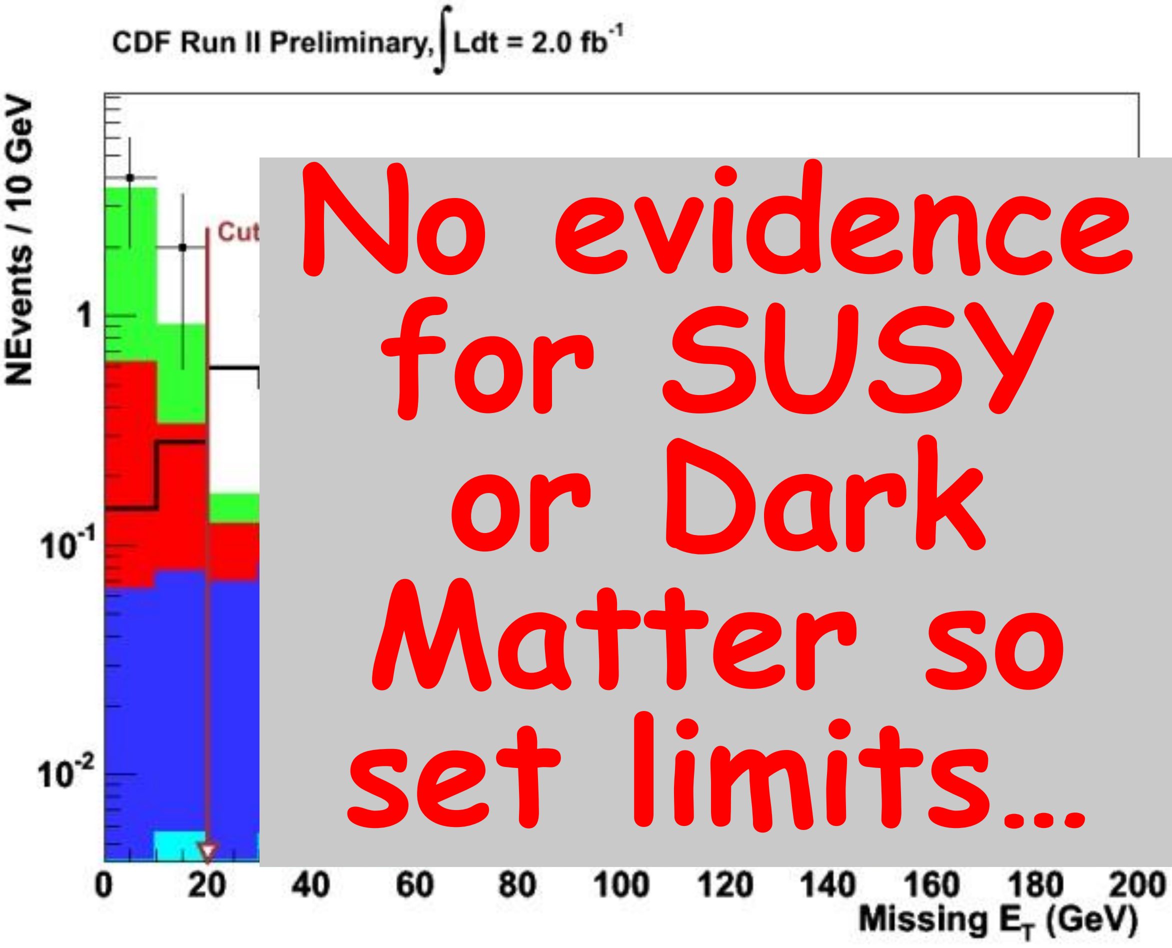
Dominates the production cross section



eee eeτ
eeμ μμτ
eμμ eμτ
μμμ

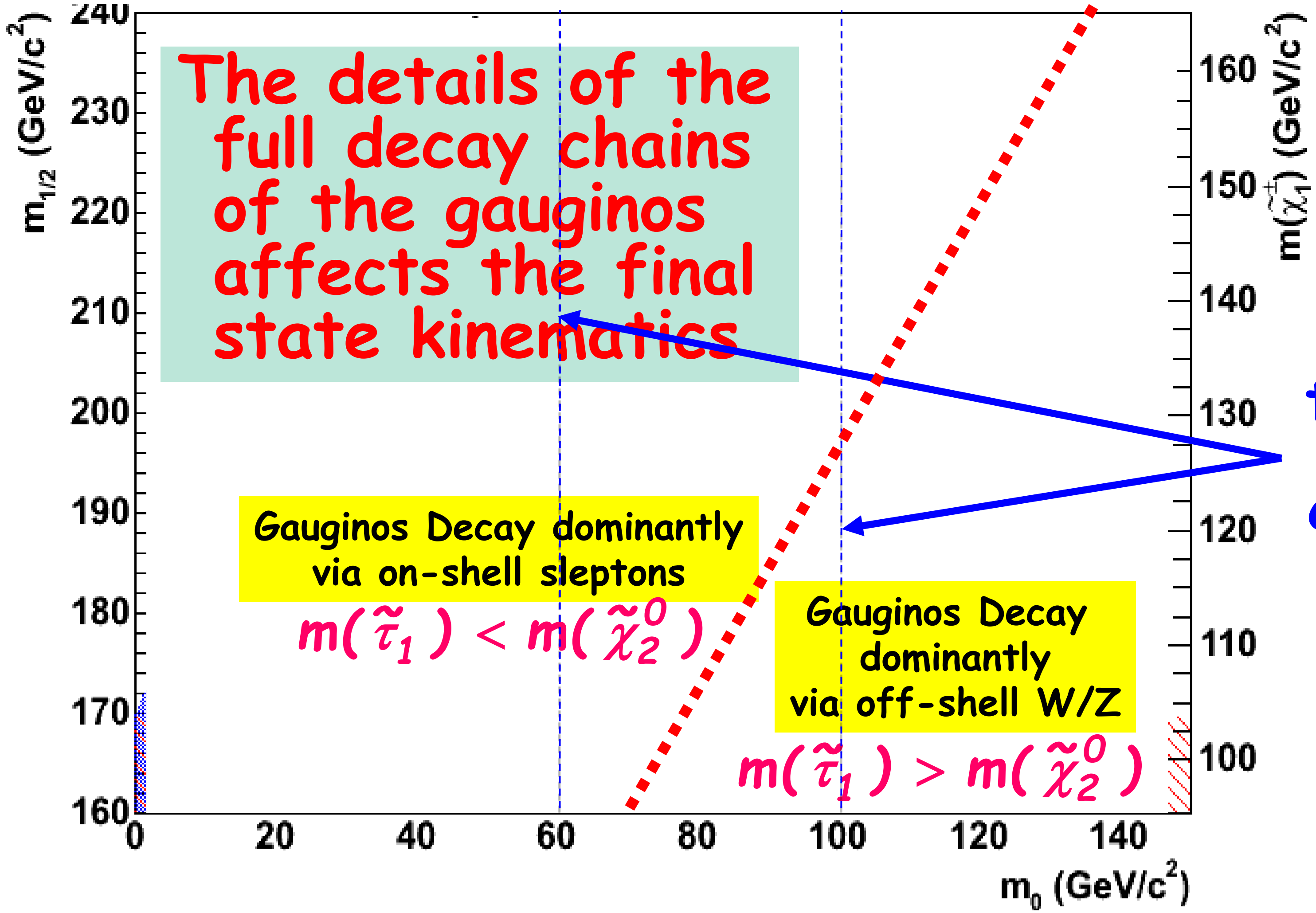
Lots of separate final states + Unified Analysis
➔ best coverage

SUSY in Trilepton Events?



No evidence for SUSY or Dark Matter so set limits…

Trileptons in mSUGRA



The details of the full decay chains of the gauginos affects the final state kinematics

Gauginos Decay dominantly via on-shell sleptons

$m(\tilde{\tau}_1) < m(\tilde{\chi}_2^0)$

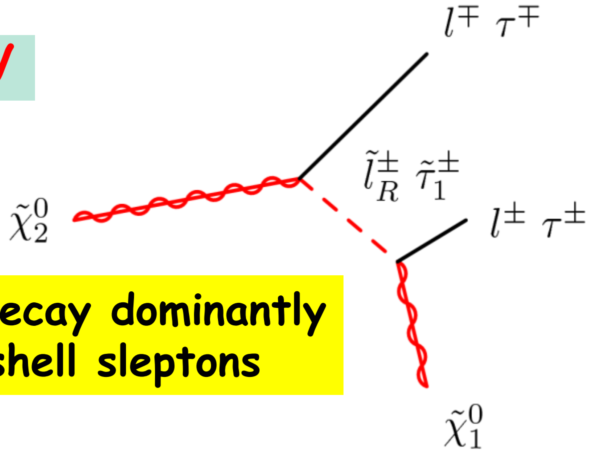
Gauginos Decay dominantly via off-shell W/Z

$m(\tilde{\tau}_1) > m(\tilde{\chi}_2^0)$

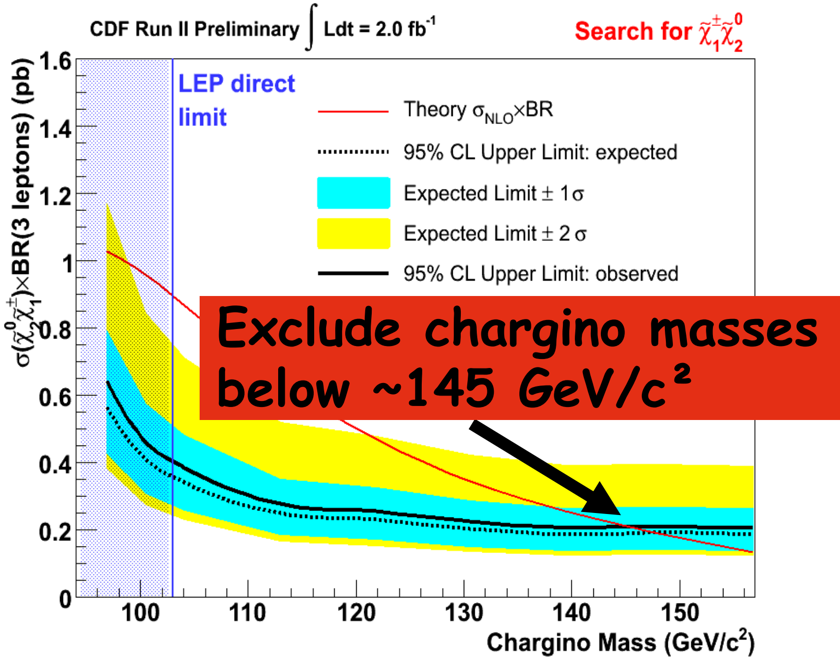
Look at the lines of constant M_0

Cross Section limits vs. Chargino Mass

M_0 = 60 GeV

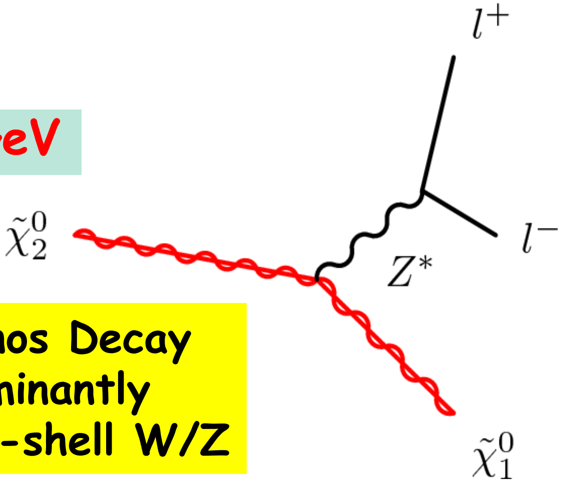


Gauginos Decay dominantly via on-shell sleptons

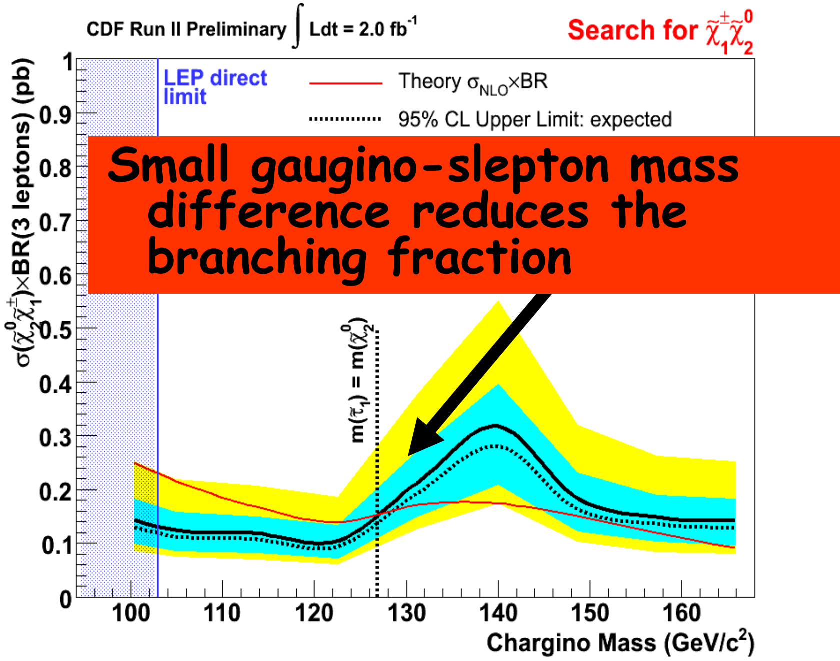


Exclude chargino masses below ~145 GeV/c²

M_0 = 100 GeV

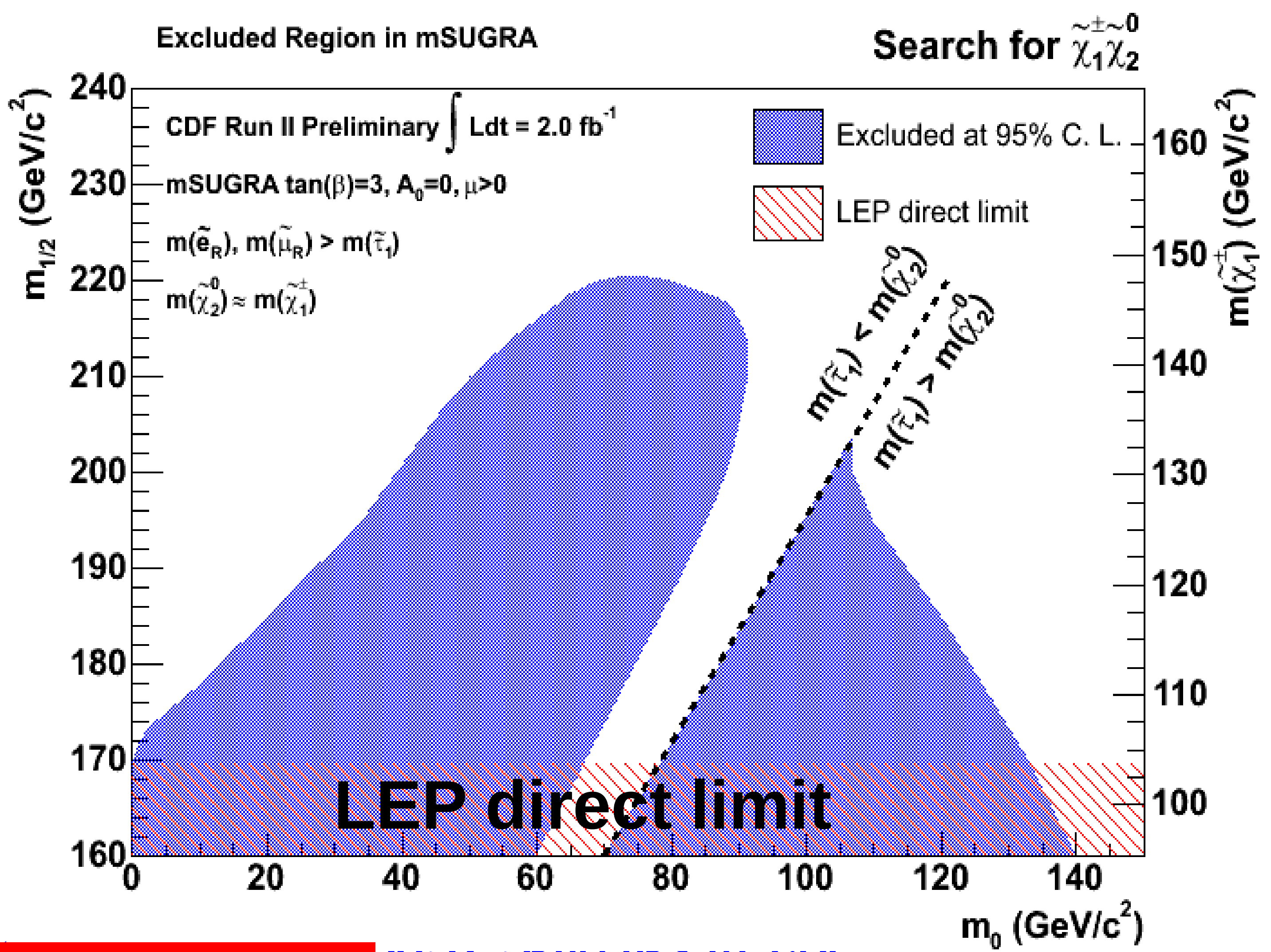


Gauginos Decay dominantly via off-shell W/Z



Small gaugino-slepton mass difference reduces the branching fraction

mSUGRA Limits from Trilepton Events

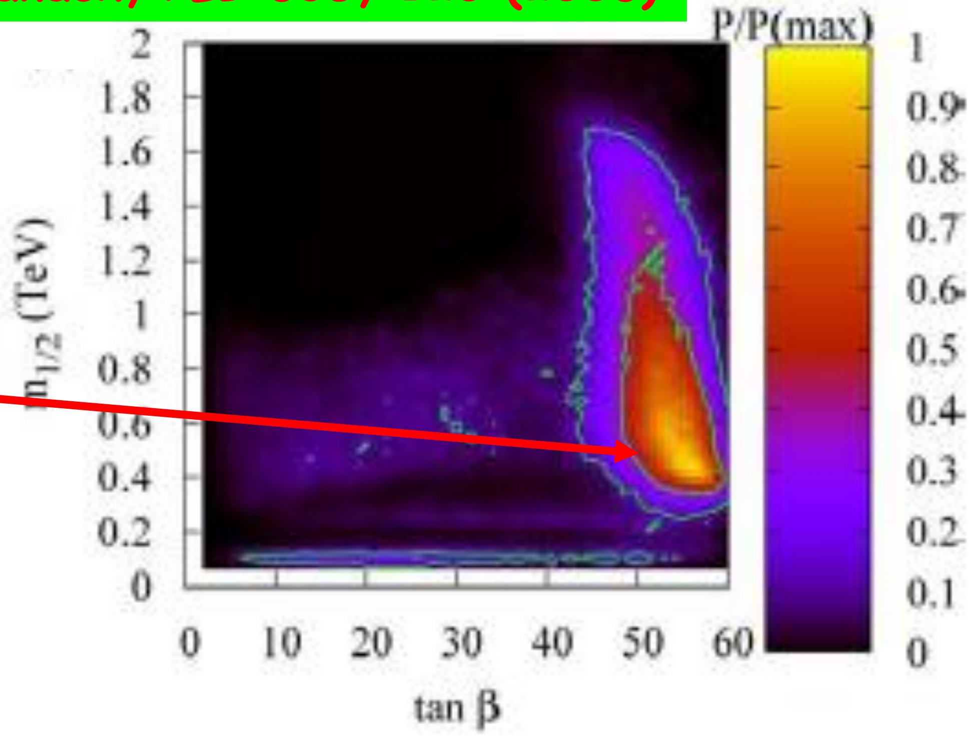


PRL 101, 251801 (2008)

High Tanβ

- Likelihood fits including Higgs mass limits, *g*-2, and other experimental data to the MSSM in the plane of $m_{1/2}$ and tanβ
  - Prefers high tanβ
- Stop and Sbottom masses can be very different than the other squark masses
- Gaugino branching fractions to τ's can rise to 100% as the stau gets light…

Allanach, PLB 635, 123 (2006)



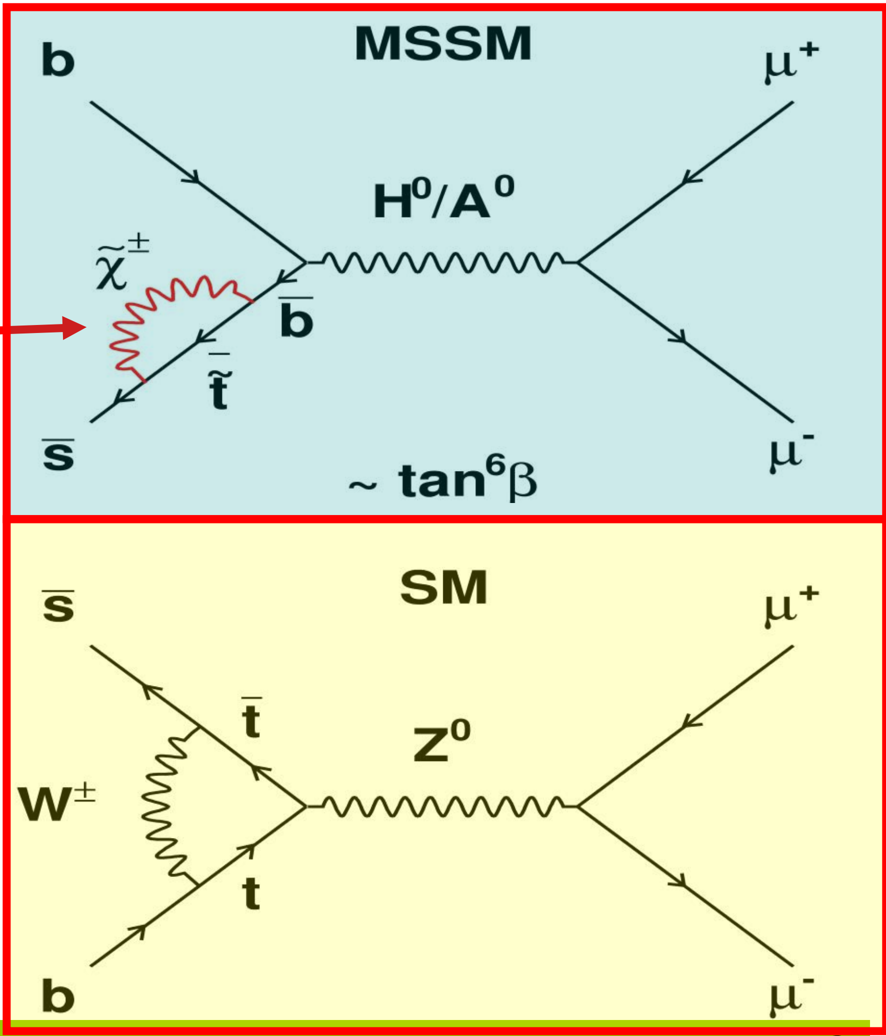
The Tevatron has moved towards having a full suite of high tanβ targeted searches

Indirect Search: $B_s \to \mu\mu$

The search for $B_s \to \mu\mu$ is perhaps the most sensitive to SUSY since sparticles show up in loops

Especially sensitive at high tanβ ($Br \propto \tan\beta^6$)

In the Standard Model, the FCNC decay of $B_s \to \mu^+\mu^-$ is heavily suppressed

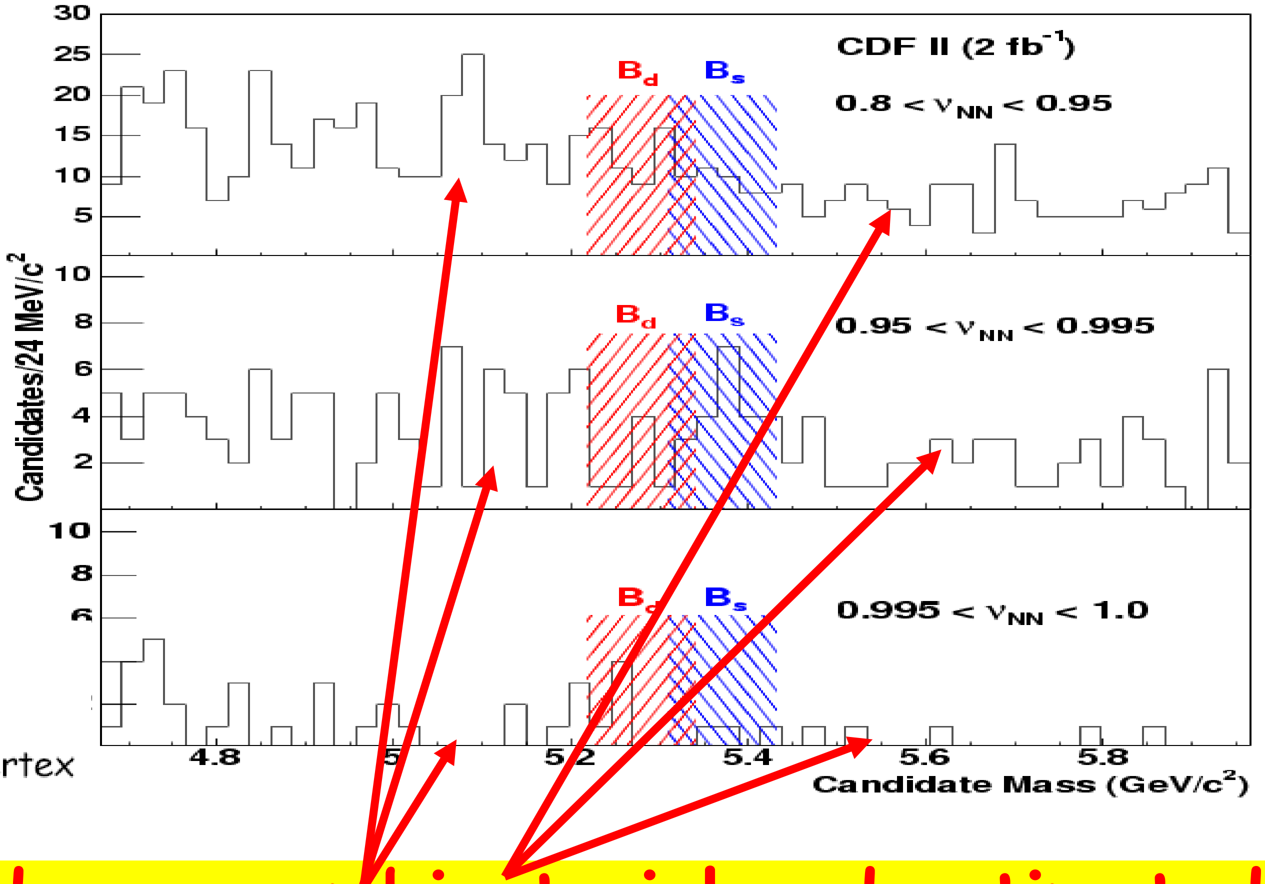


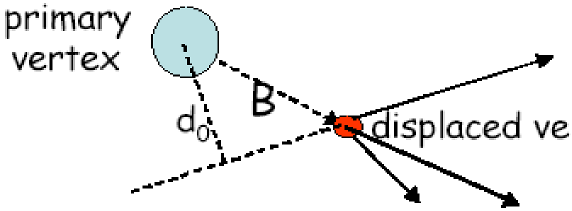
$$BR_{SM}(B_s \to \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$$

(Buchalla & Buras, Misiak & Urban)

Looking at the Data

Heavily optimized search using Neural Net Techniques

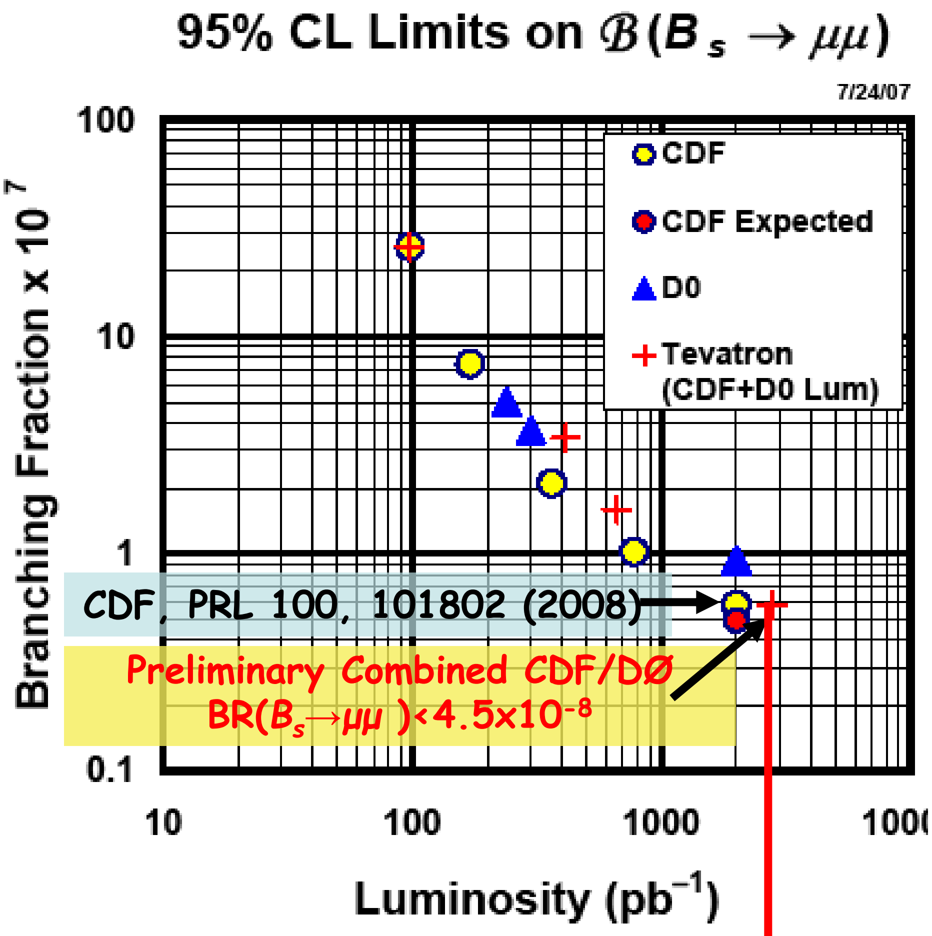




The backgrounds are combinatorial and estimated and checked from data using sideband techniques

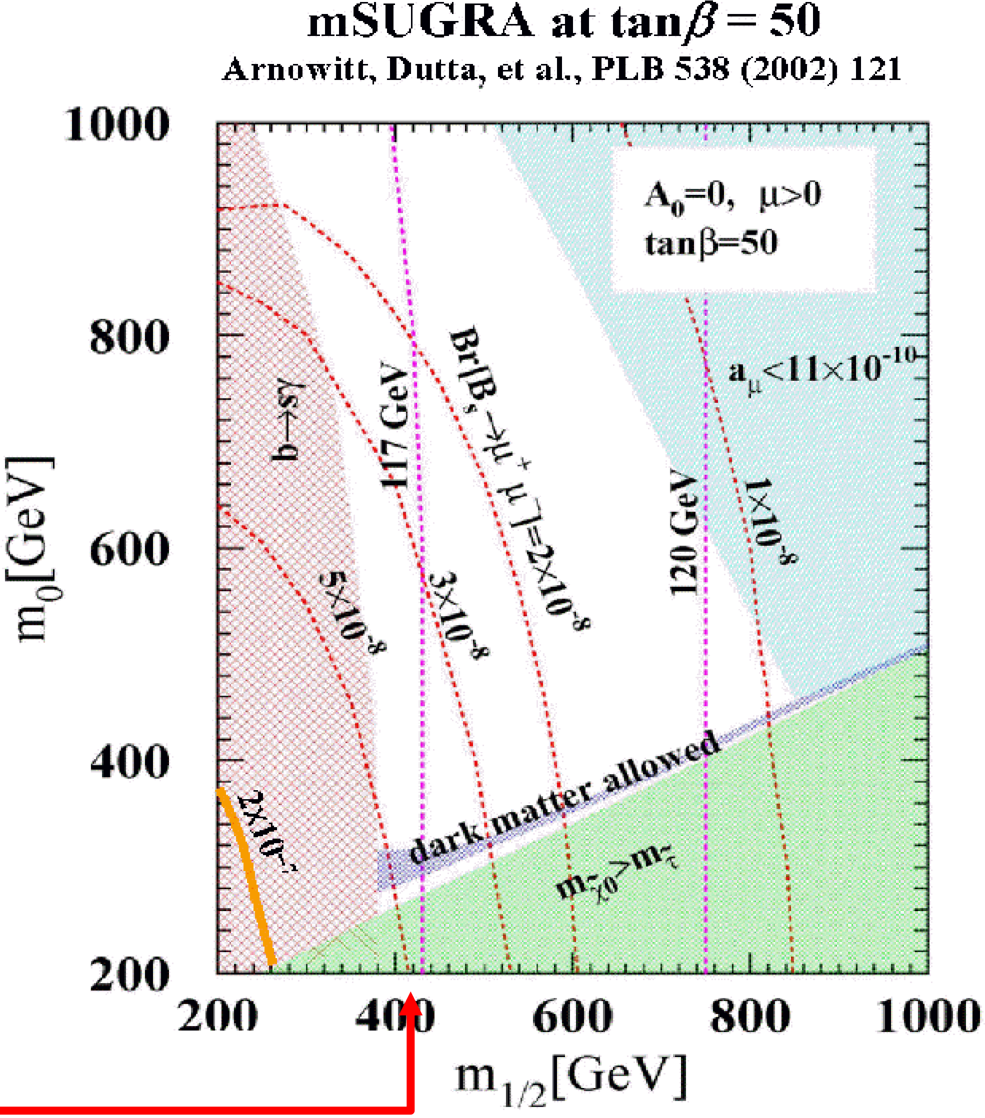
Can't predict the backgrounds from MC → Makes predictions for sensitivity at the LHC precarious

Limits on Branching Ratios and mSUGRA


95% CL Limits on $\mathcal{B}(B_s \to \mu\mu)$

CDF, PRL 100, 101802 (2008)

Preliminary Combined CDF/DØ $BR(B_s \to \mu\mu) < 4.5\times10^{-8}$


mSUGRA at $\tan\beta = 50$

Arnowitt, Dutta, et al., PLB 538 (2002) 121

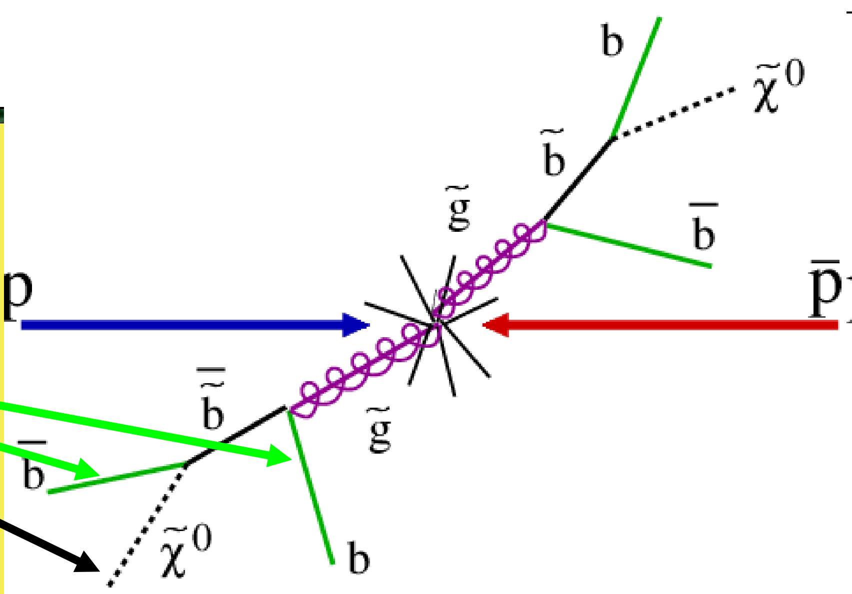
Factor of 10 above SM predictions

ty

Sbottom Searches

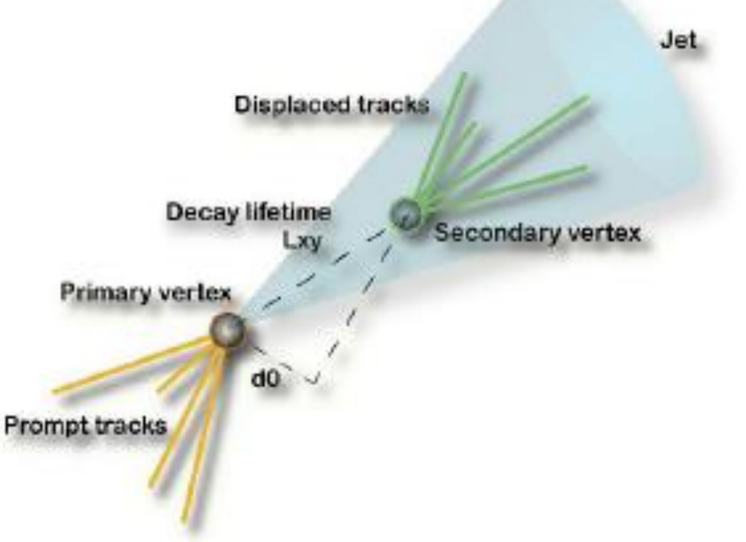
Two primary Sbottom searches in *b+jets+Met*

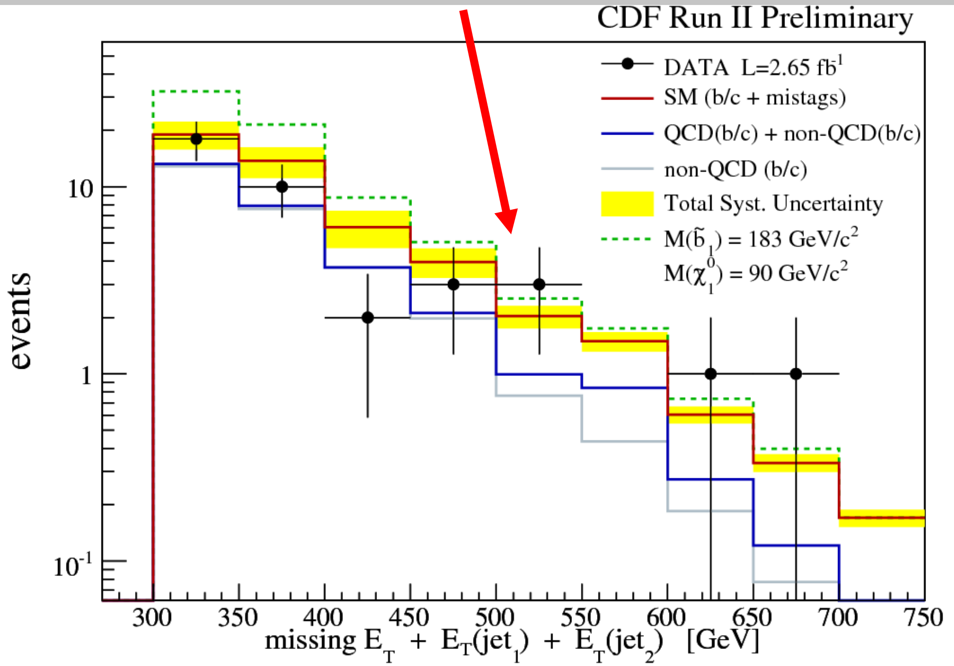
1. Sbottoms from gluinos
2. Direct sbottom pair production



Backgrounds are roughly half QCD, half EWK

Special tricks to identify *b*-quarks from their long lifetime





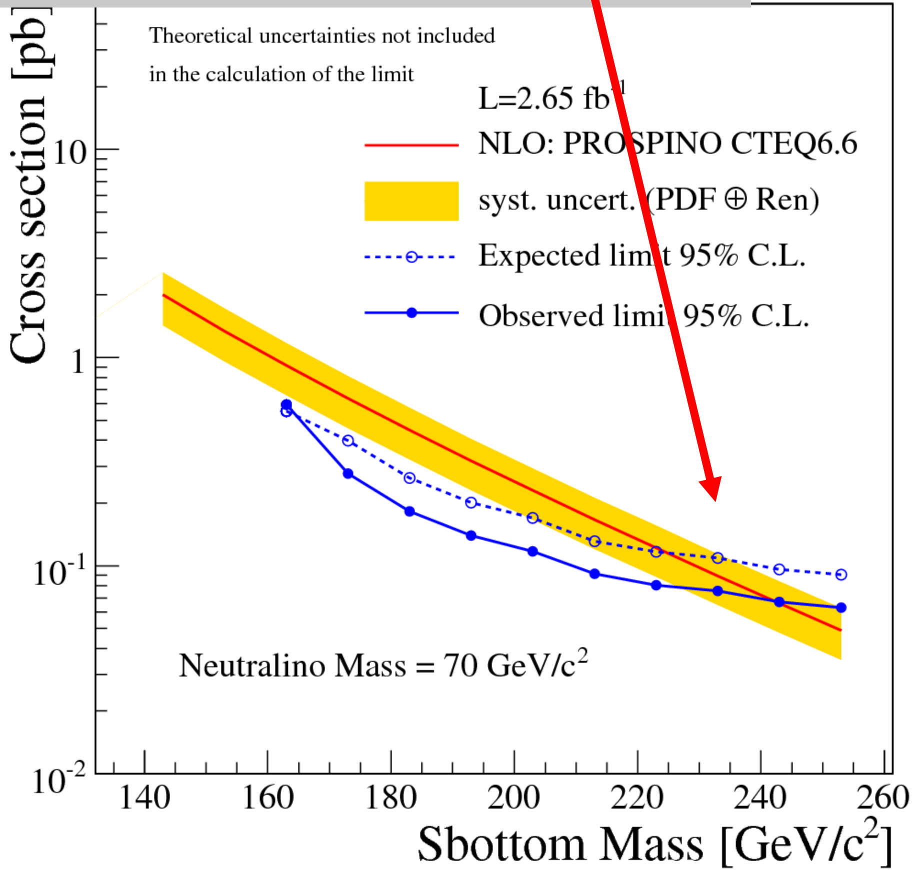
Limits on Sparticle Production

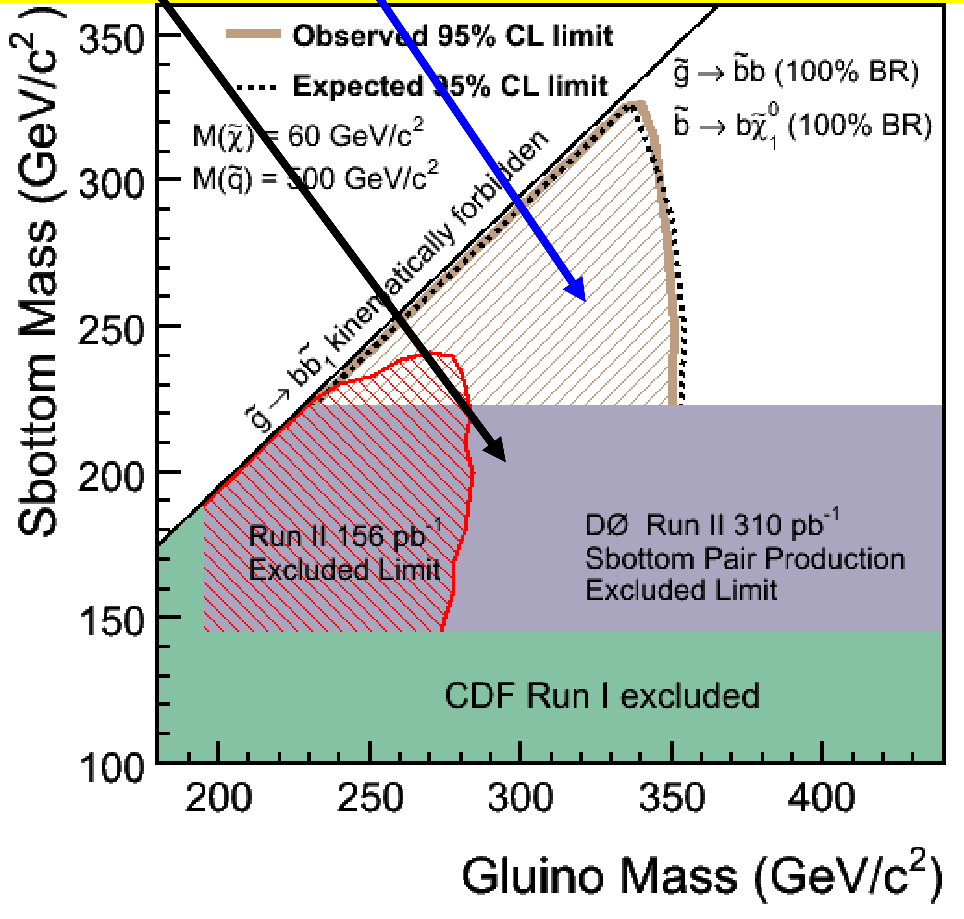
Direct Sbottom searches are Gluino mass independent

Gluino Pair Production gives best sensitivity to large sbottom masses

Both are Complementary

CDF: PRL 102, 221801 (2009)

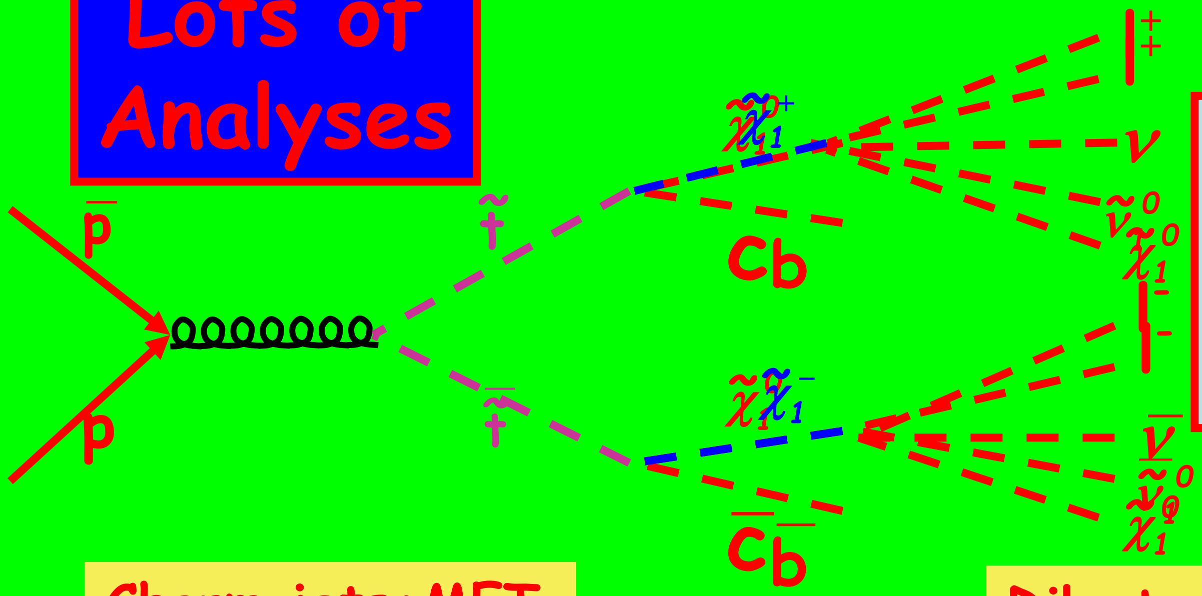




Lightest Squark = Stop?

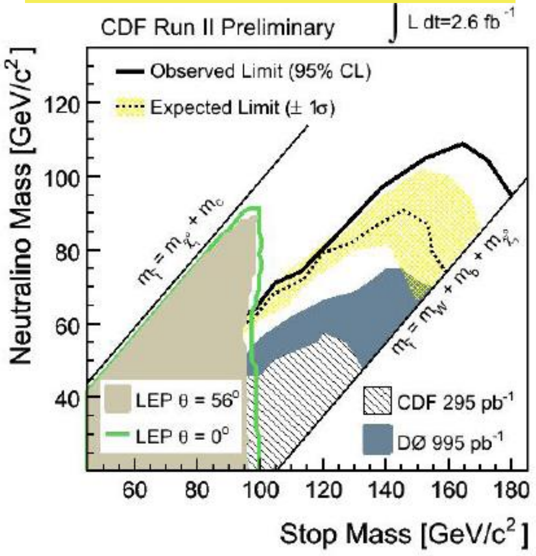
Lots of Analyses

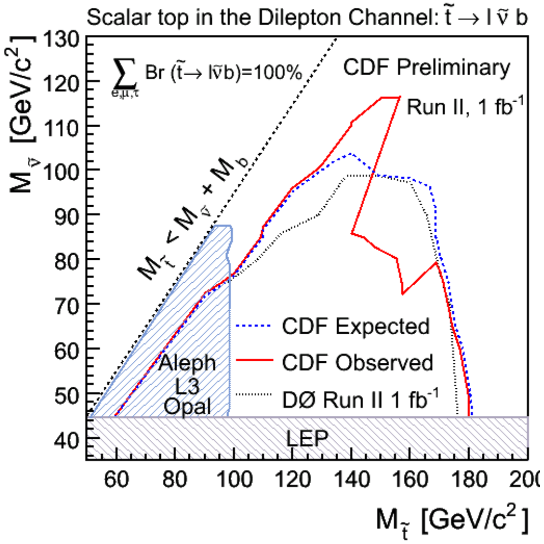
Direct Counting Experiments and Sophisticated Fitting Methods

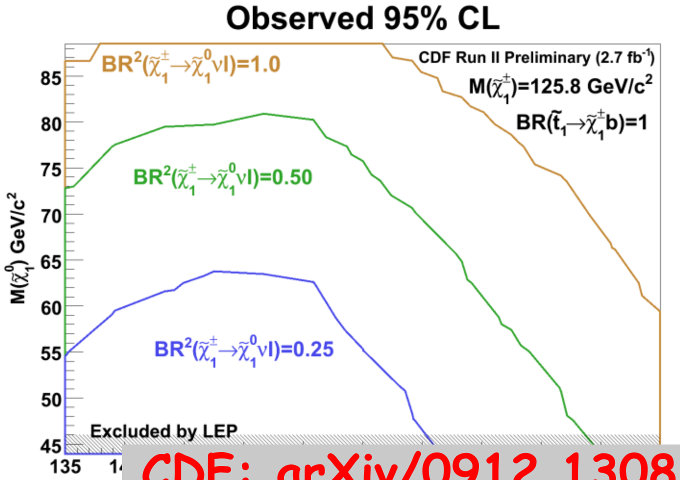


Charm jets+MET

Dileptons+Jets+MET





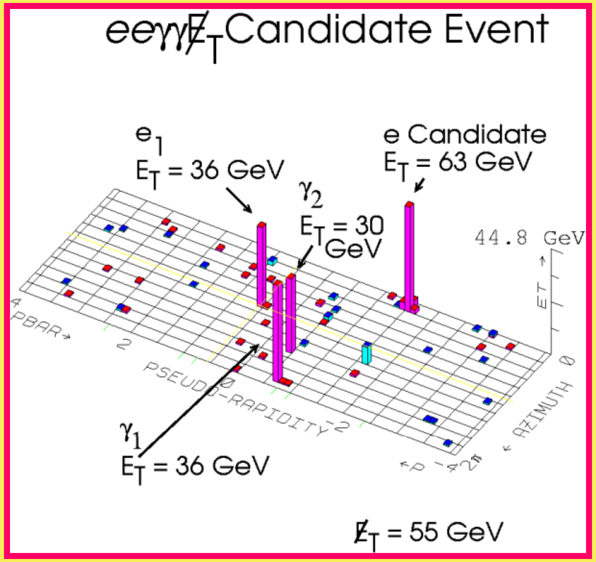


CDF: arXiv/0912.1308 accepted to PRD

Gauge-Mediated SUSY Breaking Models

$\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ models provide a warm dark matter candidate Consistent with Astronomical observations and models of inflation

More natural solution for FCNC problems than mSUGRA



CDF Run I $ee\gamma\gamma$+Met candidate event

Early Universe

$\tilde{\chi}_1^0$

Nanosecond lifetimes

Later Universe

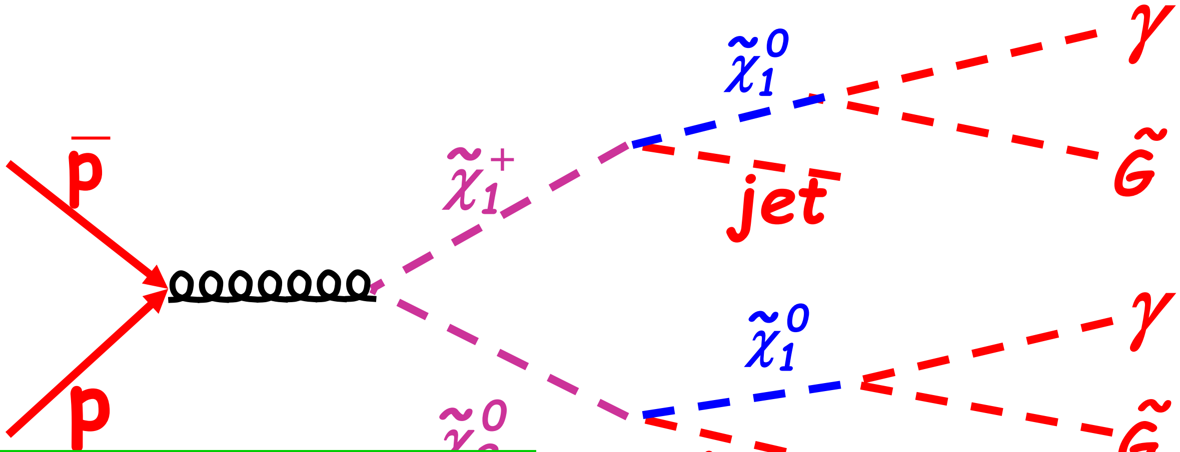
$\tilde{G}$

Warm Dark Matter

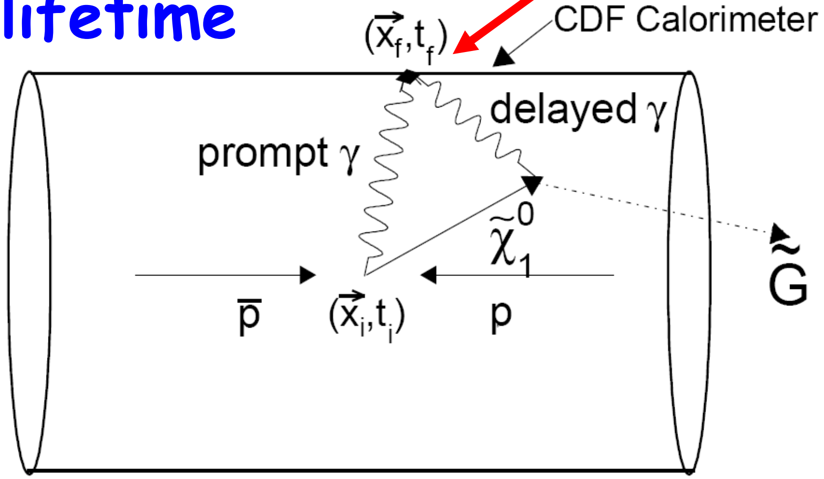
High and Low Lifetime Searches

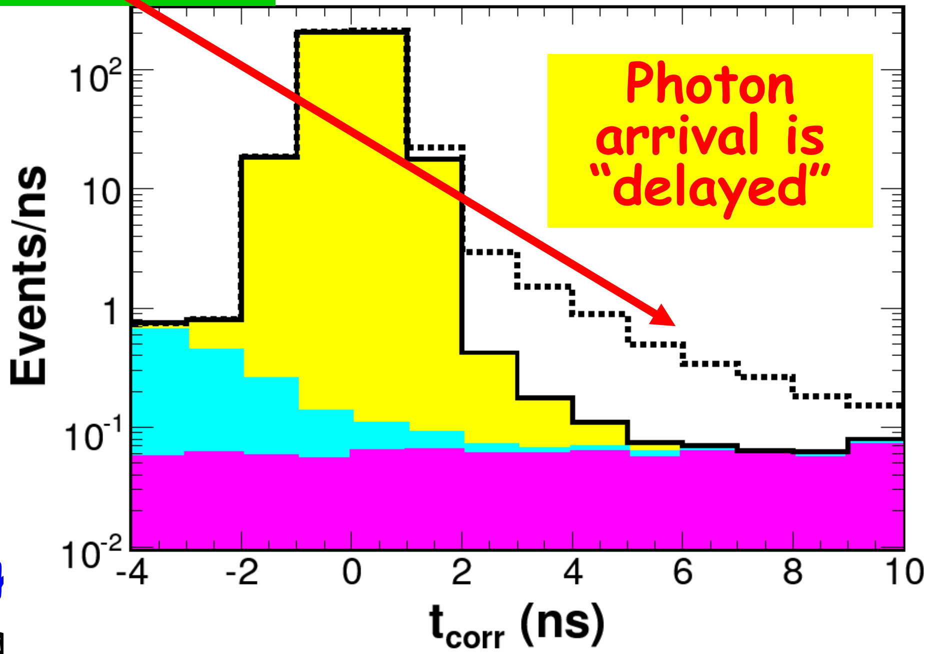
The lifetime and associated particle production dictate different final states

- $\gamma\gamma$+Met for small lifetime
- Delayed Photon +Met for large lifetime



Use new Photon Timing system



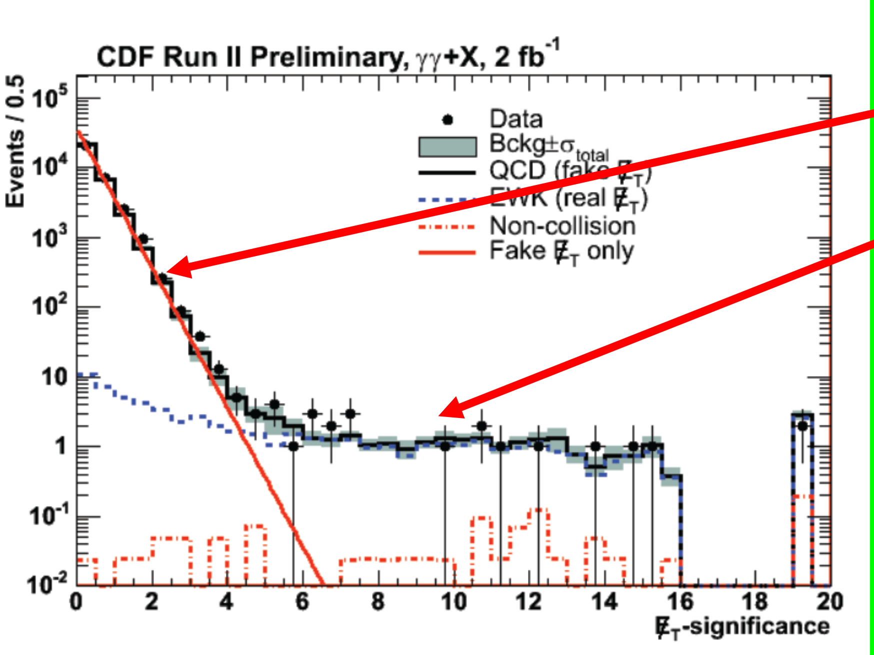


Photon arrival is "delayed"

$\gamma\gamma$+Met

New model independent search in $\gamma\gamma$+Met

New tool: Sophisticated mechanism to measure the significance of the Met measurement



Can straightforwardly separate QCD backgrounds with no intrinsic Met from EWK that does

No evidence for new physics

Next move to set limits on GMSB models

arXiv: 0910.5170
(submitted to PRD)

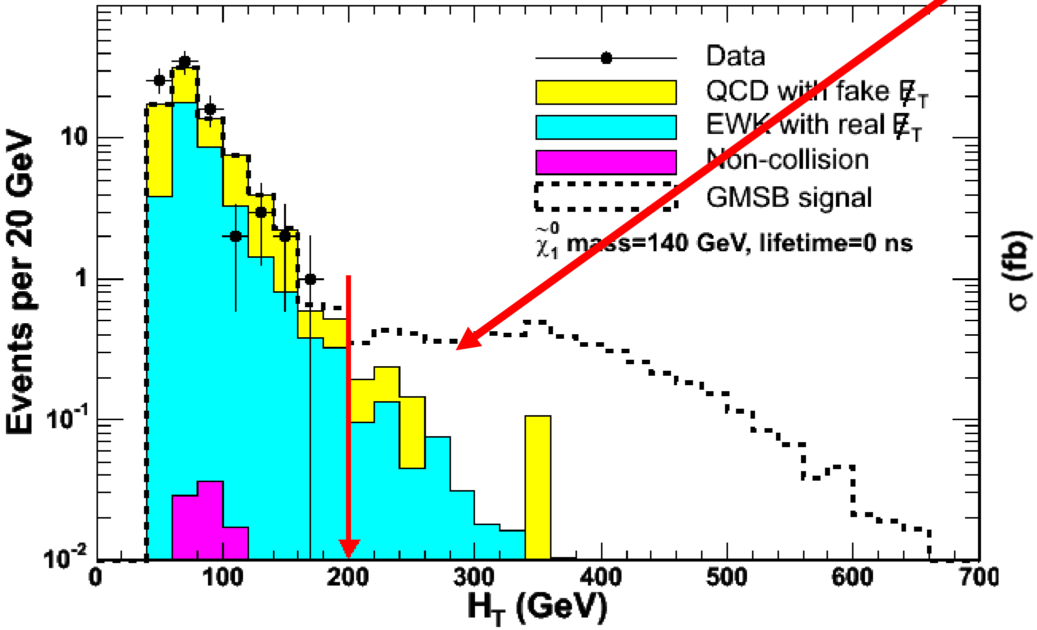
Low lifetime Neutralinos

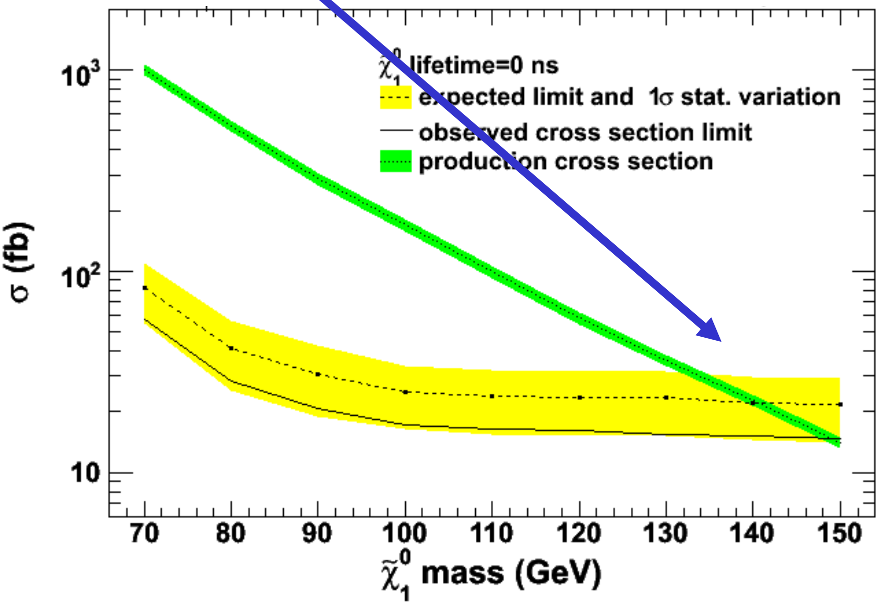
Optimize the $\gamma\gamma$+Met analysis for a lifetime« 1 ns :

Significant Met and Large "other energy"

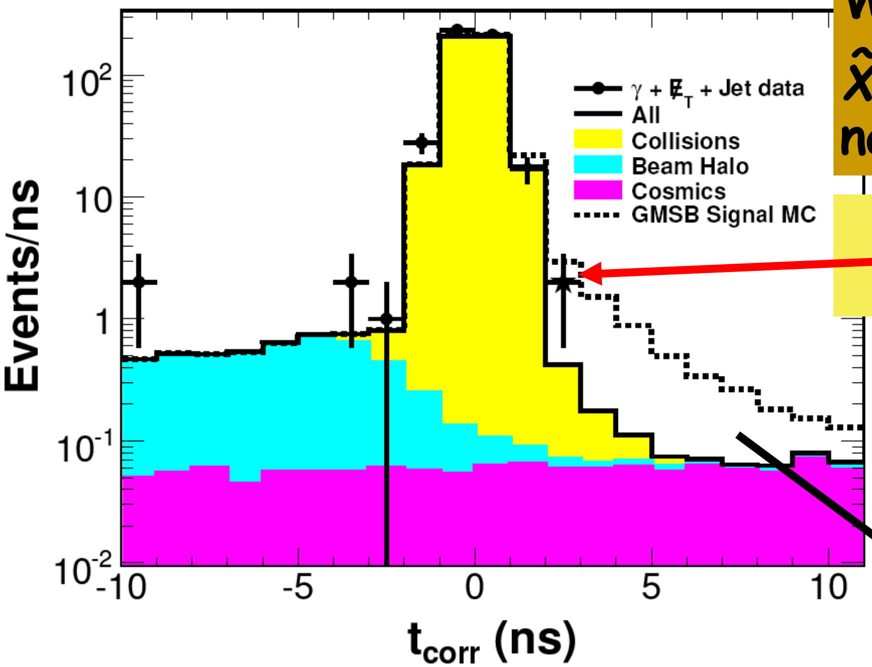
No evidence for new physics

PRL 104, 011801 (2010)





Nanosecond Neutralino Lifetime Searches



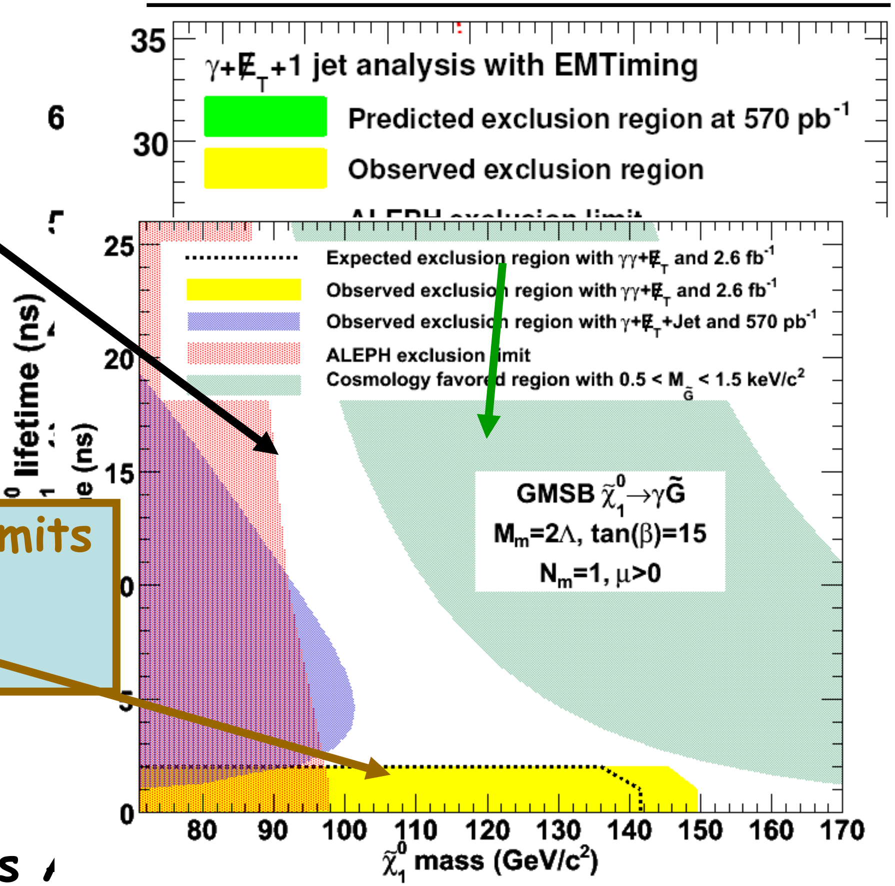
Warm dark matter models of GMSB with $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ favor keV $\tilde{G}$ masses and nanosecond $\tilde{\chi}_1^0$ lifetimes

Measure the time of arrival of photons in γ+Met+Jet events

CDF, PRL 99, 121801 (2007)

CDF, PRD 78, 032015 (2008)

Combine γγ+Met and Delayed Photon Limits
Set limits for zero and
Non-zero lifetimes



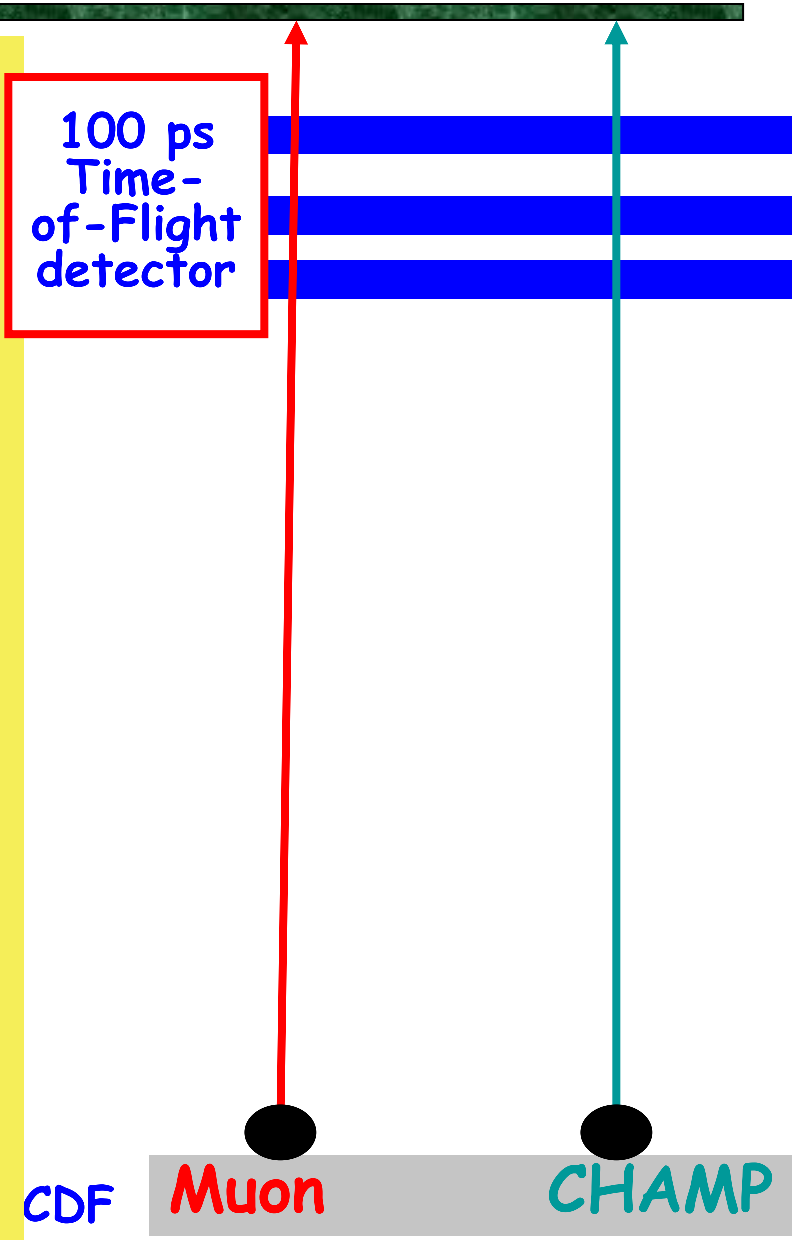
Lots of other possibilities

Two worth mentioning here:

1. CHAMPS
   - Charged Massive quasi-stable particles
   - Like GMSB in that the lightest abundant sparticle in the early universe is different than it is today
2. R-parity Violating SUSY
   - Perhaps Supersymmetry is correct but has nothing to do with the Dark Matter problem (Axions?)
   - Still worth looking for, just harder to know where to look

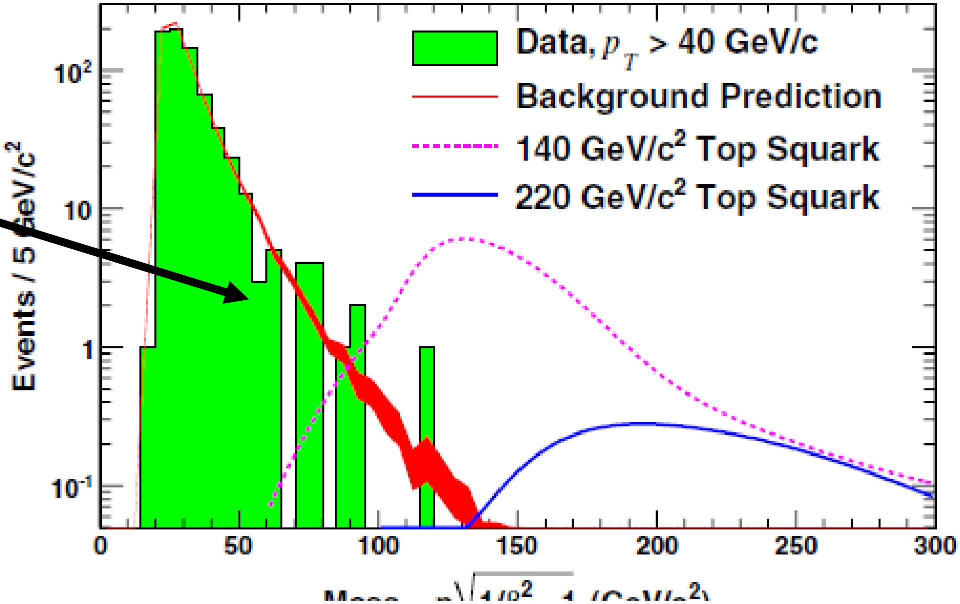
Long-Lived Charged Sparticles (Champs)

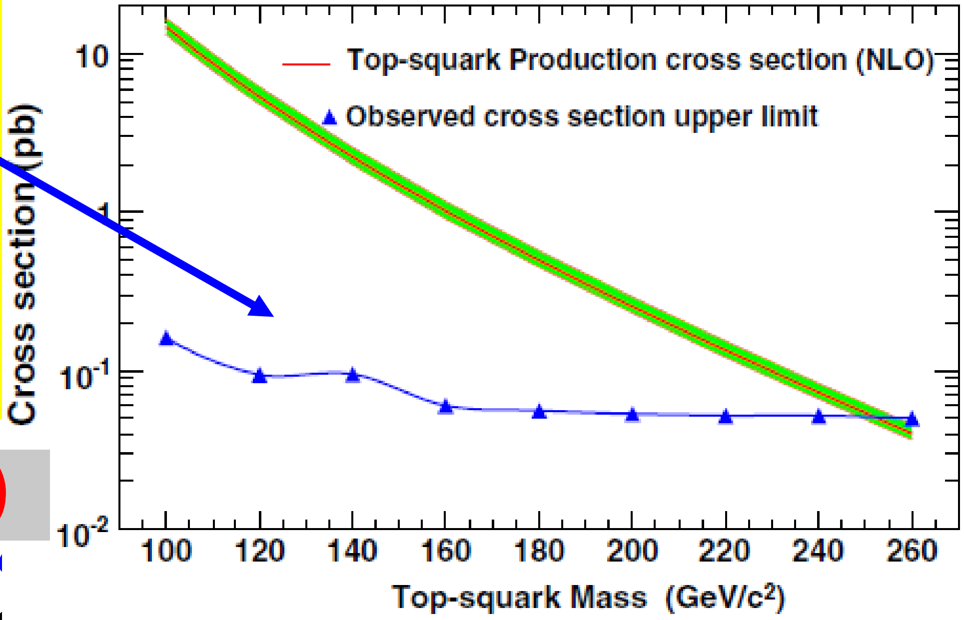
- New emphasis in the theory community about the role of long-lived sparticles in the Early Universe and today as Dark Matter
- Use timing techniques
  - Heavy particles arrive later
  - Can measure the "mass" of weakly interacting charged particles (muon-like)



CHAMP Search

- Dominated by measurement resolution
- Can set limits on stop, staus and charginos
  - Small differences between each





PRL 103, 021802 (2009)

The Tevatron in the LHC Era
3 more years of running?

<u>Gaugino Pair Production</u>

understood detector, Tevatron will likely push here

<u>CHAMPS</u>

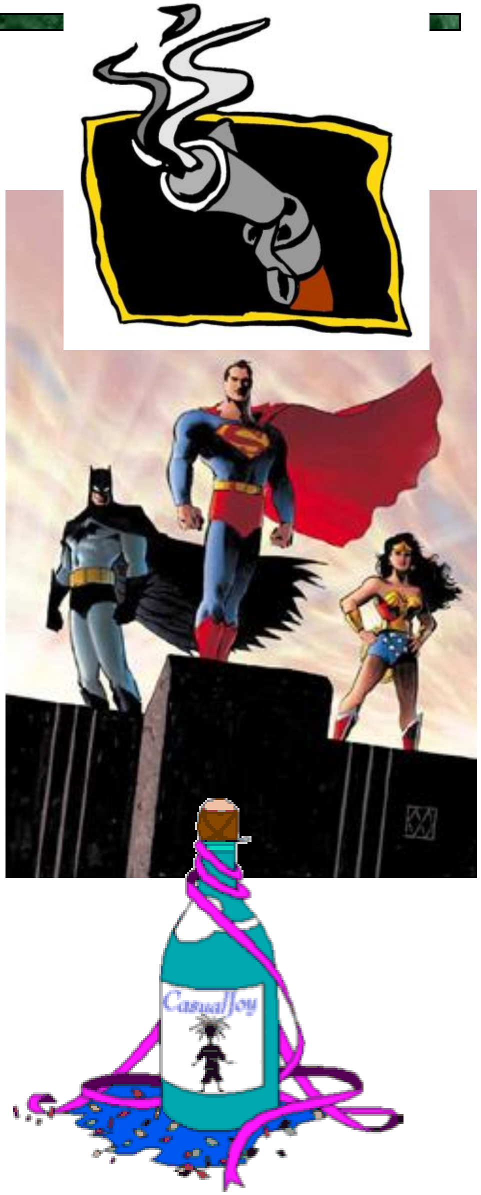
Needs a well understood detector, more than 5 times the data take → gives Tevatron a competitive advantage for awhile

- Low Mass Higgs
- $B_s \rightarrow \mu\mu$
- Long-lifetime GMSB
- CHAMPS

- Squarks & Gluinos
- Low-lifetime GMSB

Conclusions

- The Tevatron has performed a broad and deep set of searches for Supersymmetry in ~3 fb^{-1}
  - Unfortunately, no sign of new physics
- The Tevatron is still running beautifully and the detectors are collecting data at unprecedented levels
- If our understanding of Cosmology and Particle Physics are correct, the discovery of Supersymmetry may be just around the corner!

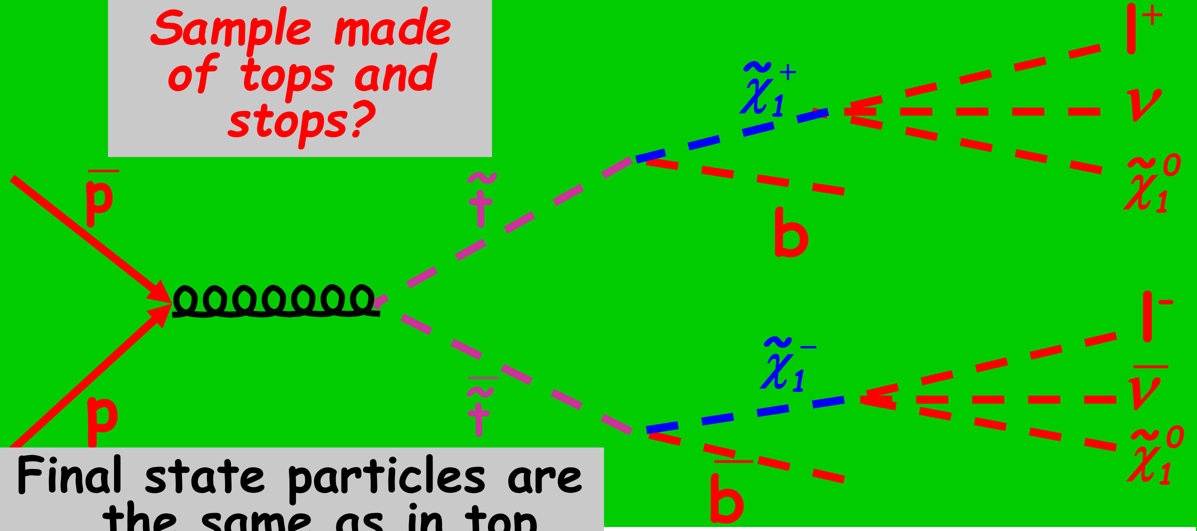


Stop Searches

Dilepton+Jets+Met sample is a fairly pure sample of top-pair production

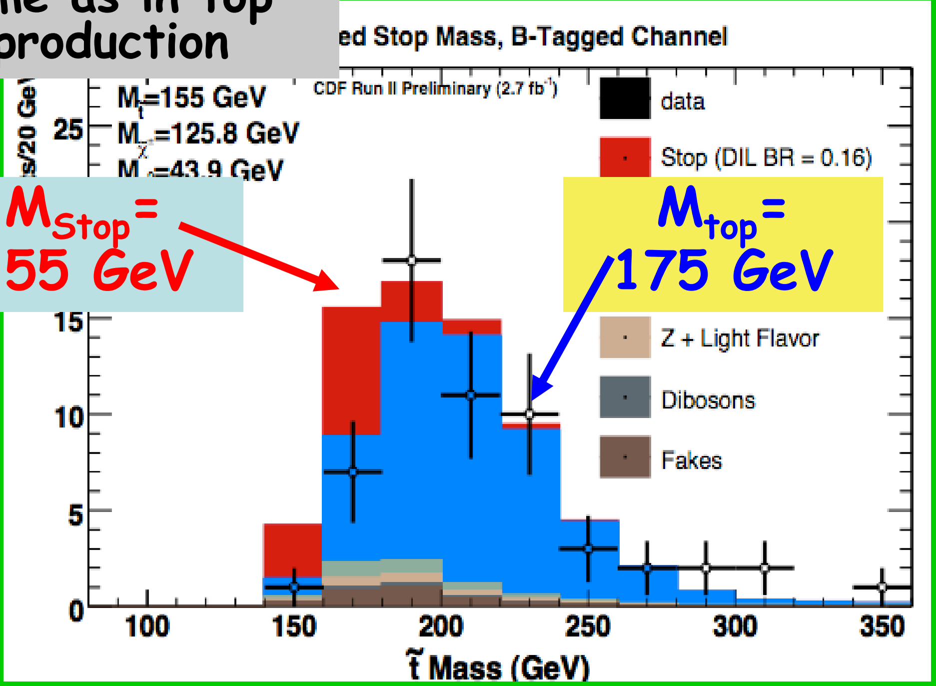
However, Some of the dilepton events in Run I didn't "look" like tops

Do a systematic fit of the kinematics for any evidence of light stops



Sample made of tops and stops?

Final state particles are the same as in top pair production



M_{Stop}= 155 GeV

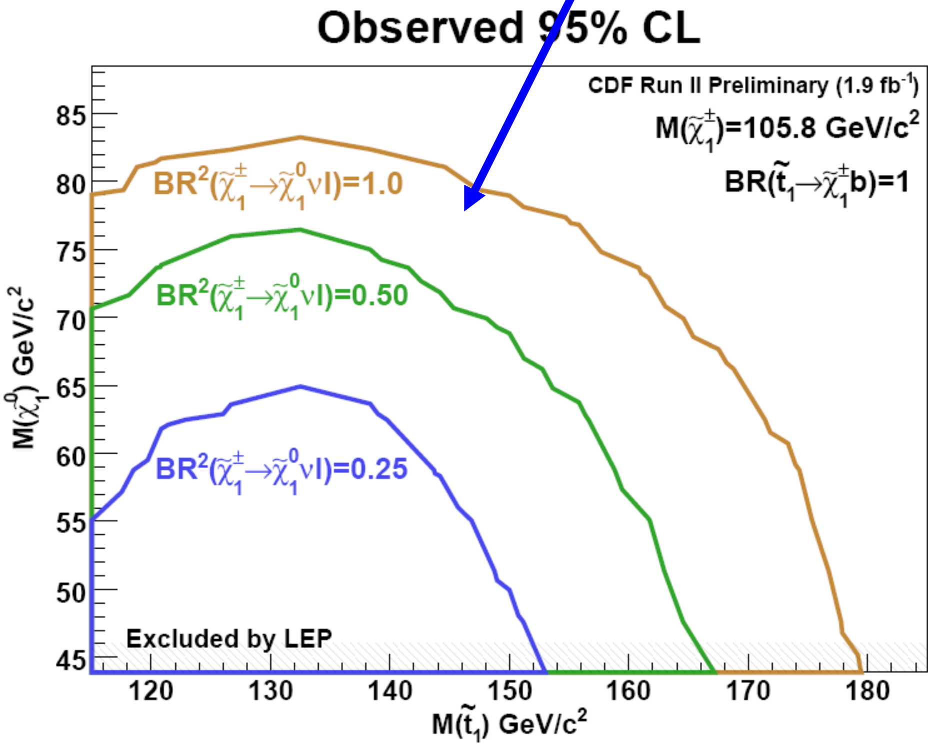
M_{top}= 175 GeV

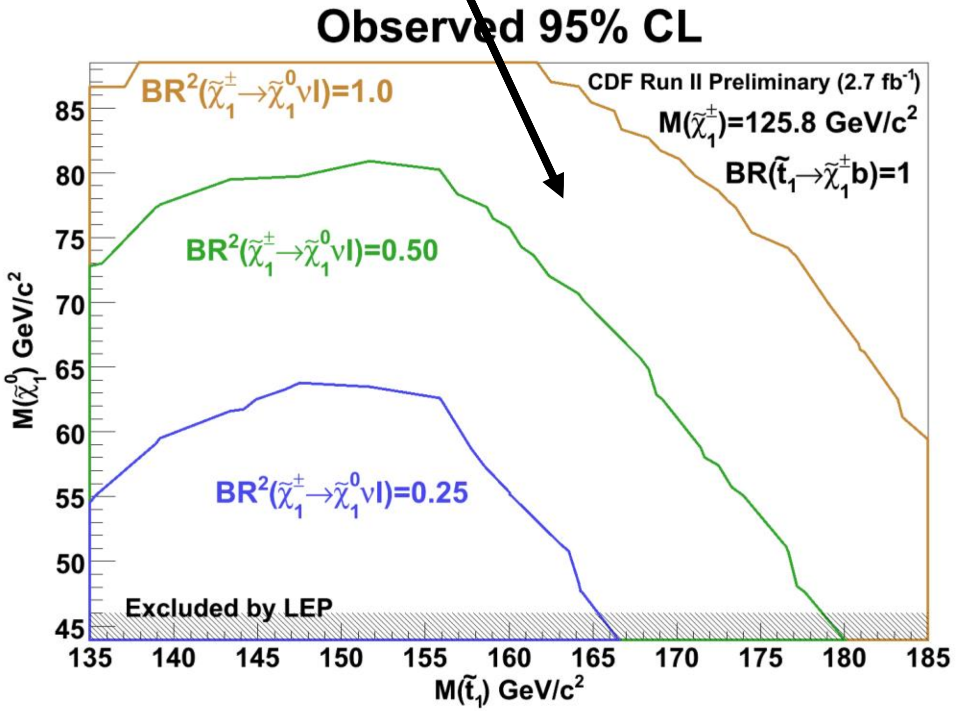
Can set limits on Stop Admixture

$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm} \rightarrow b\tilde{\chi}_1^0 l\nu$$

Branching Ratio limits are mass dependent…

Small chargino mass Large Chargino mass

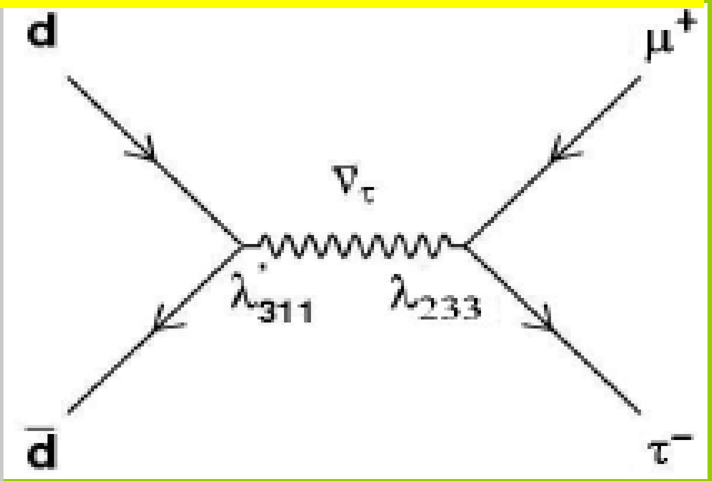


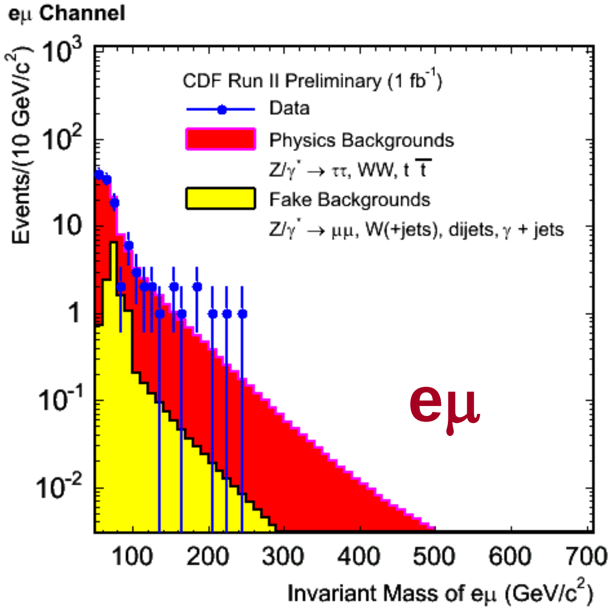


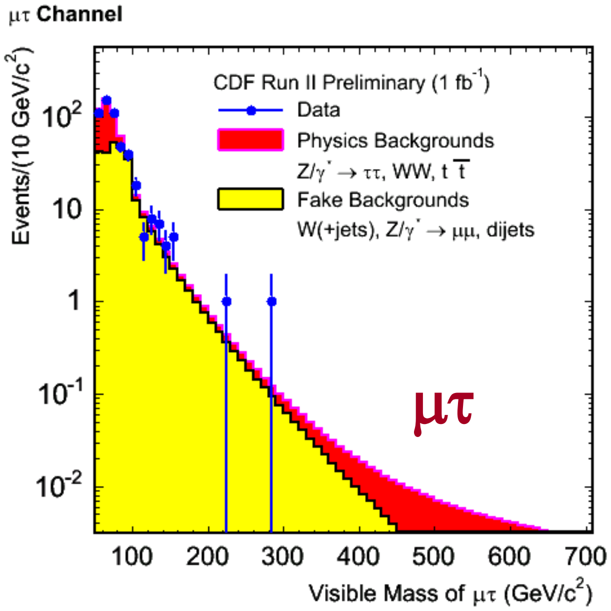
R-Parity Violating SUSY

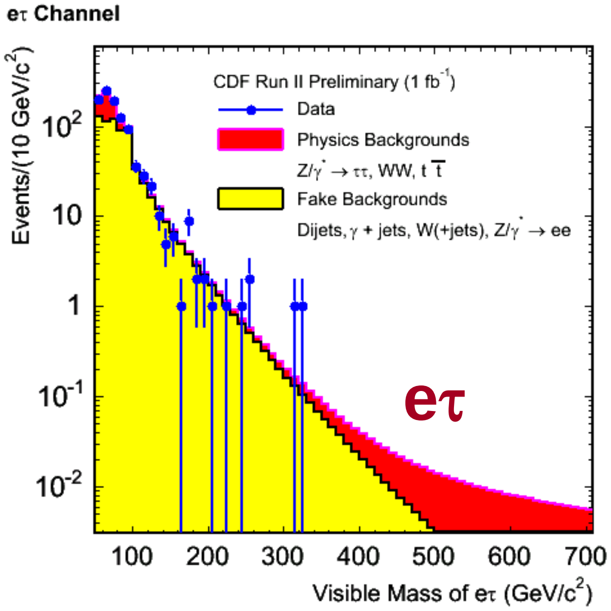
- One advantage of RPV SUSY is that single-sparticle production is allowed
- Decays also depend on the couplings
- Powerful new tau-ID tools

sneutrino →eμ, τμ, eτ




eμ Channel


μτ Channel


eτ Channel

sneutrino →eμ, τμ, eτ

Backgrounds dominated by EWK and W+jet with misidentified leptons

Set limits by extrapolating from low mass region

σ·BR excluded at 95% C.L in the 10^{-2}:10^{-1} pb range