3rd International Summer School on Astroparticle Physics "NIJMEGEN09"

Hadron Collider Results Impacting on Particle Astrophysics

Part II

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Alternative Talk Titles

"Looking for the Particles of the Early Universe in Collider Experiments"

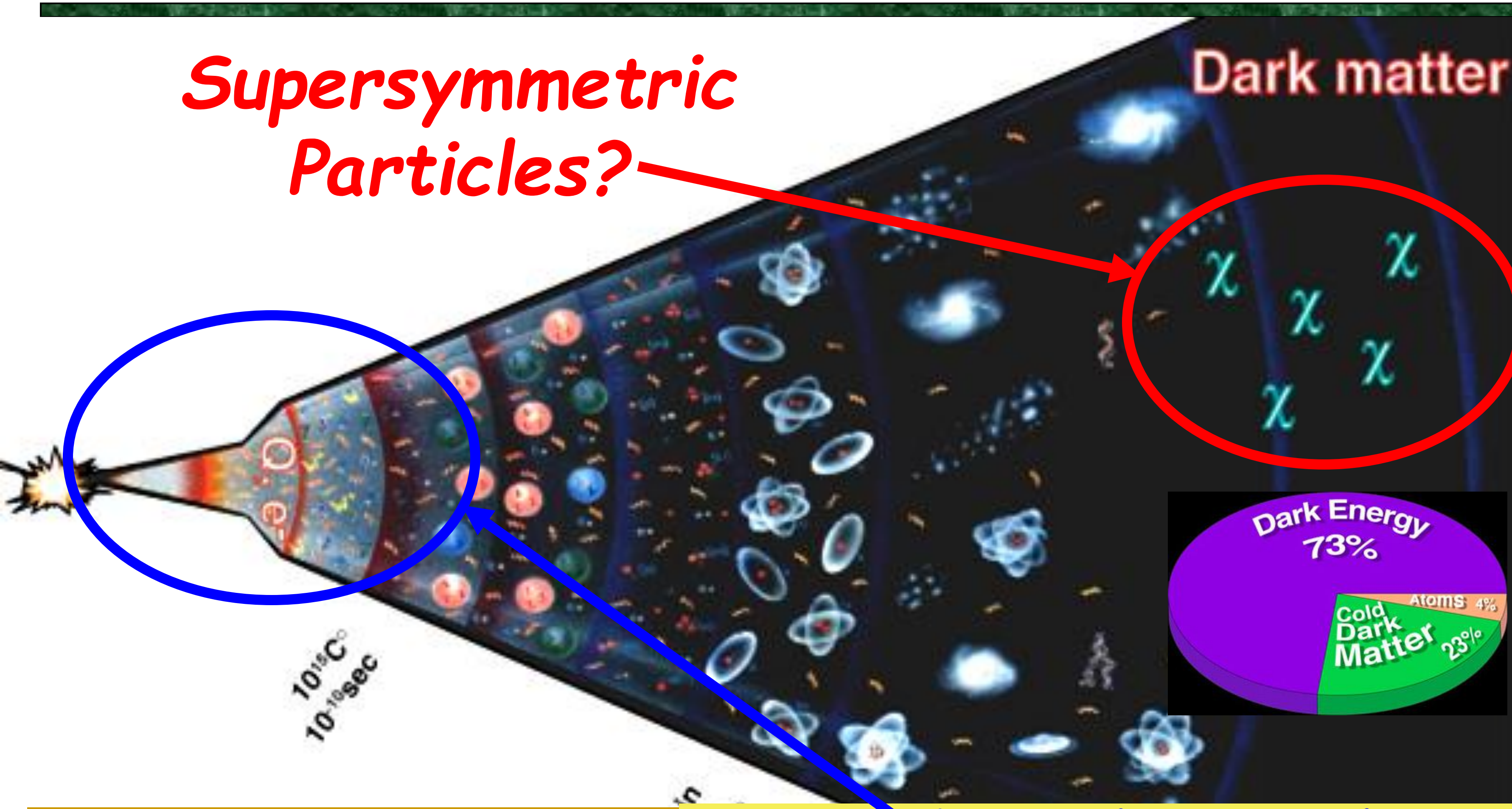
"Cosmo-Particle Searches at Collider Experiments

Outline

- What we know and what questions we're trying to answer
- Supersymmetry and other Ideas
- Searching for New Physics in Collider Physics Experiments
- Tevatron Results
- Some stuff about the LHC in advance of its turn-on

Dark Matter = Supersymmetric Particles?

Supersymmetric Particles?



SUSY provides a full calculation of $\Omega_{SUSY\ DM}$

Not good enough to simply provide a candidate, need to describe early Universe physics and correctly predict the Dark Matter relic density

Different Types of SUSY Solutions

Cold Dark matter Produced in the Early Universe

Sparticle Masses and Lifetimes matter

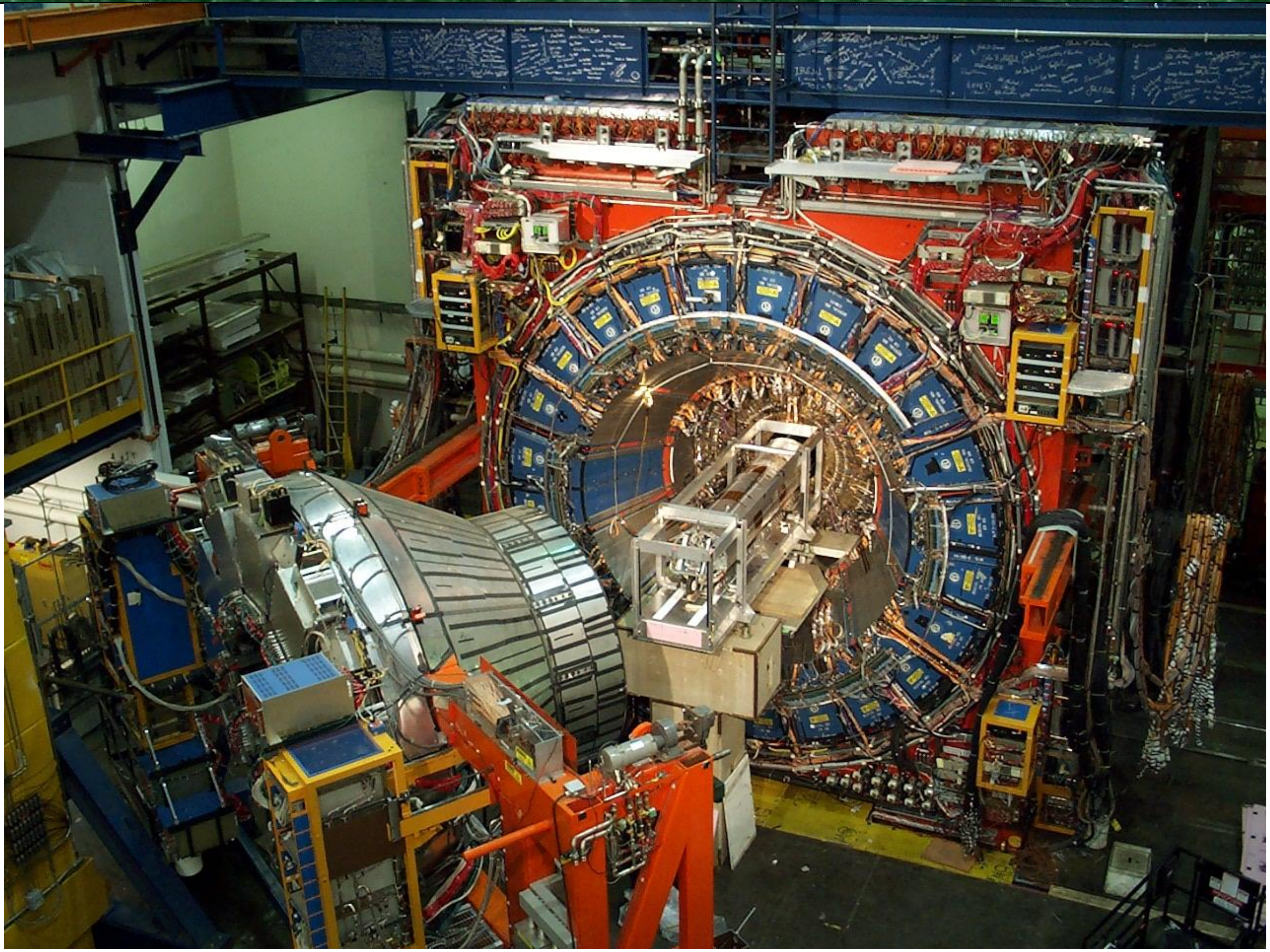
Warm Dark matter Produced later in time

Cold Dark matter Produced after a month or so

Can we Make and Discover Dark Matter?

- Lots of high energy collisions between particles in the <u>Early Universe</u>
- Recreate the conditions like they were RIGHT AFTER the Big Bang
- If we can produce Dark Matter in a collision then we can STUDY it

The CDF Detector



Powerful multi-purpose detector

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

Review

How does one search for new particles at the Tevatron?

- Bang a proton and an anti-proton together and look at what comes out (an event)
- Compare Missing Energy from Standard Model events to the expectations for SUSY/Dark Matter

Going from Collisions to experimental results

$$N_{events} = Luminosity \times \sigma_{production} \times Acceptance$$

How many collisions (events) passing a set of requirements

How many proton anti-proton collisions happened

How often a proton anti-proton collision produces a SUSY event

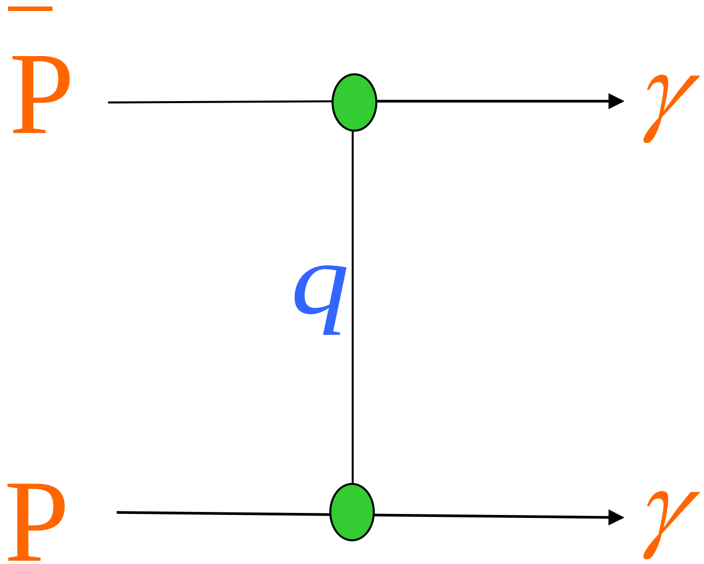
How well the detector does at detecting SUSY events. Usually estimated with Monte Carlo.

Also takes into account the requirements

Number of background events from Standard Model Sources follows the same procedure

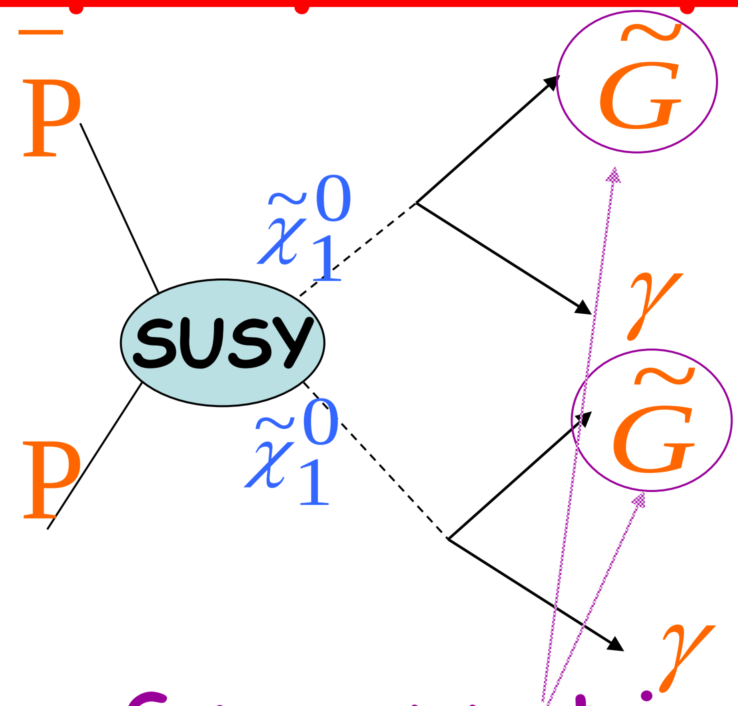
Example Final States: Two photons and Supersymmetry

Standard Model:



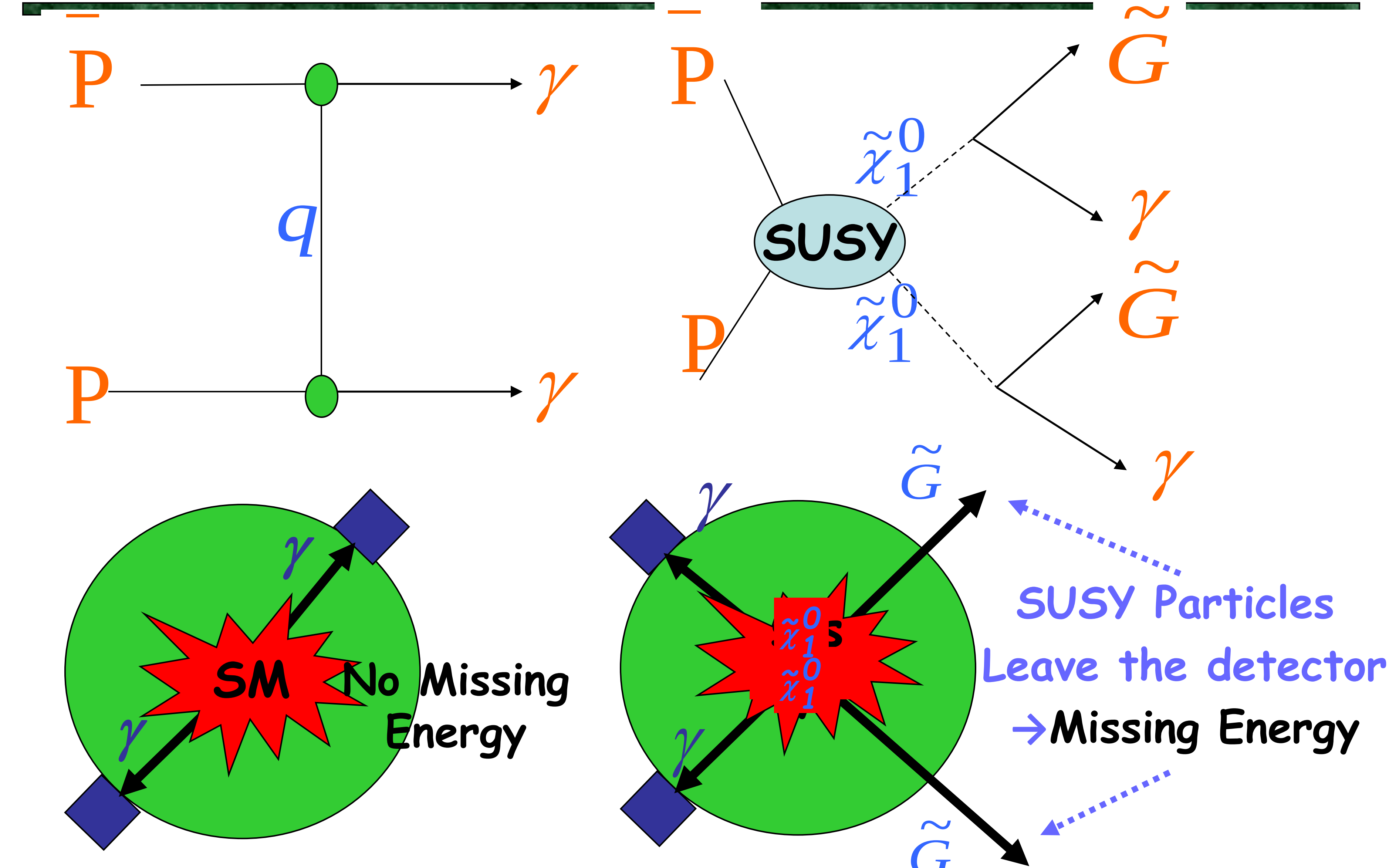
$\gamma\gamma$ +No Supersymmetric Particles in Final State

Supersymmetry:

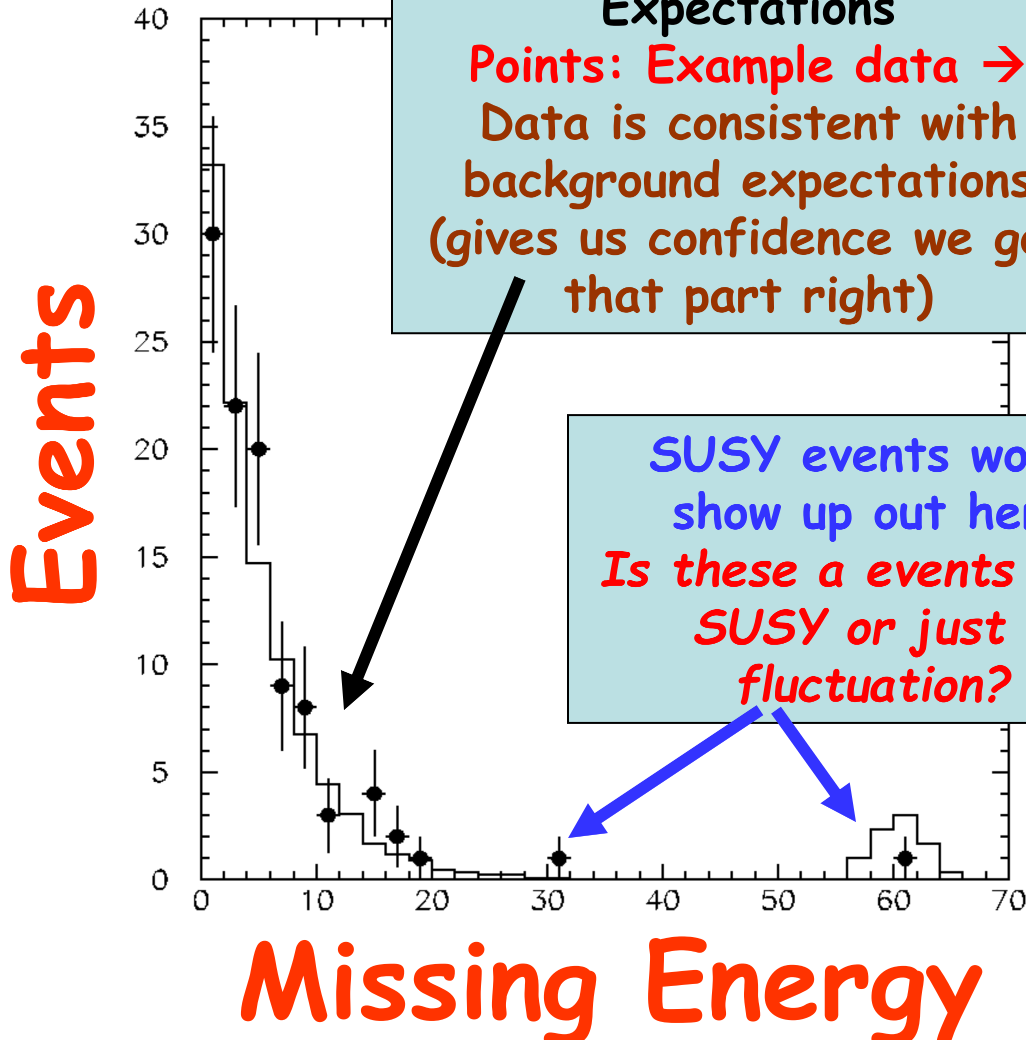


$\gamma\gamma$+Supersymmetric Particles in Final State

Standard Model: Supersymmetry:



Signal Vs. Background



Solid line: Background Expectations

Points: Example data → Data is consistent with background expectations (gives us confidence we got that part right)

SUSY events would show up out here

Is these a events from SUSY or just a fluctuation?

- Look at each event
- Put the measured missing energy in a histogram
- Compare the expected predictions from Standard Model and from SUSY

Three Types of Searches

1. There are some theories that are so compelling it is worth doing a systematic and deep search to see if it is realized in nature
2. To misquote a famous US Supreme Court Justice "I don't know exactly what I'm looking for, but I'd know it if I saw it"
   - Broad, model-independent searches
   - Events that are "un-Standard Model Like"
3. Follow up on any hints in our data or other people's data

Outline of the Searches

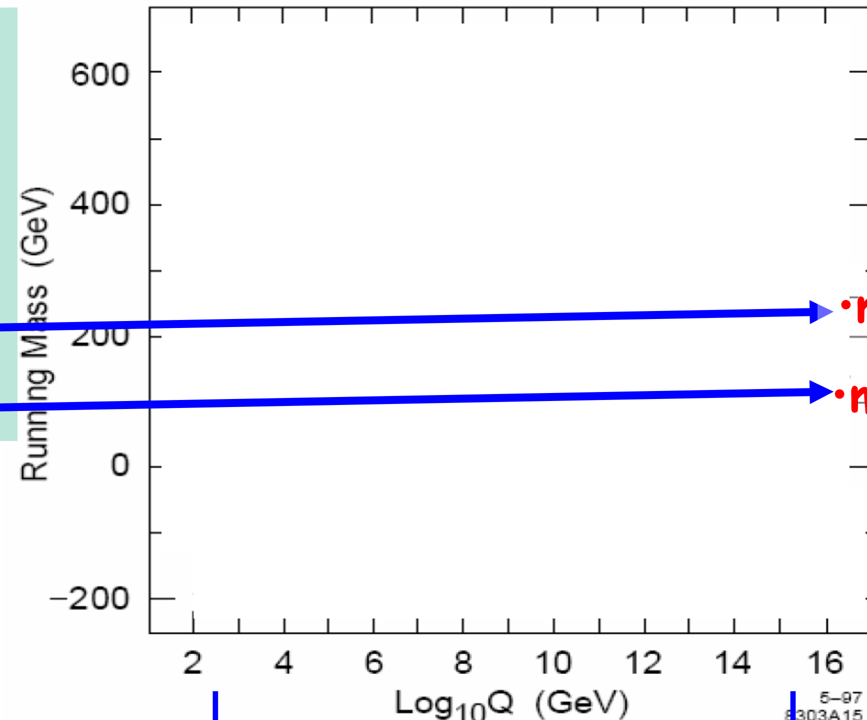
- mSUGRA Searches
  - –Squarks & Gluinos
  - –Gaugino Pair Production
  - –Indirect Searches
- Gauge Mediated Searches
- Other models
  - –CHAMPS
  - –R-Parity Violation
- Conclusions

mSUGRA

Minimal Supergravity: breaking is mediated by the gravity sector

At the unification scale:

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



$\cdot m_0$

$\cdot m_{1/2}$

mSUGRA or Constrained MSSM used as benchmark

EWK GUT

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

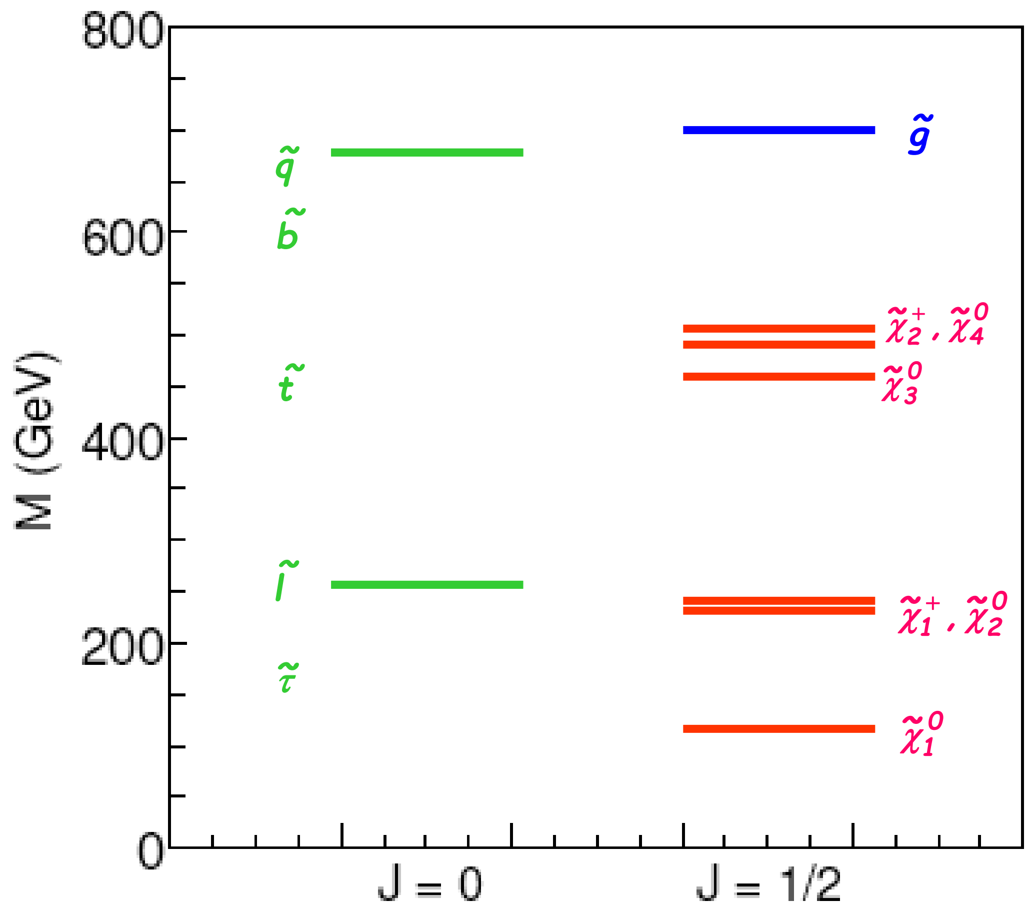
The Sparticle Masses

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 $\tan\beta$ Stop, Sbottom and Stau can get much lighter

→Can also have a significant effect on the branching ratios



Need complementary searches for low $\tan\beta$ and high $\tan\beta$

Golden Search Channels

Three main ways to look for minimal models with Cold Dark Matter Models (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

Aside before we begin…

- Most analyses will look like they were easy
- Noto Bene: It's 2009 and we're 8 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

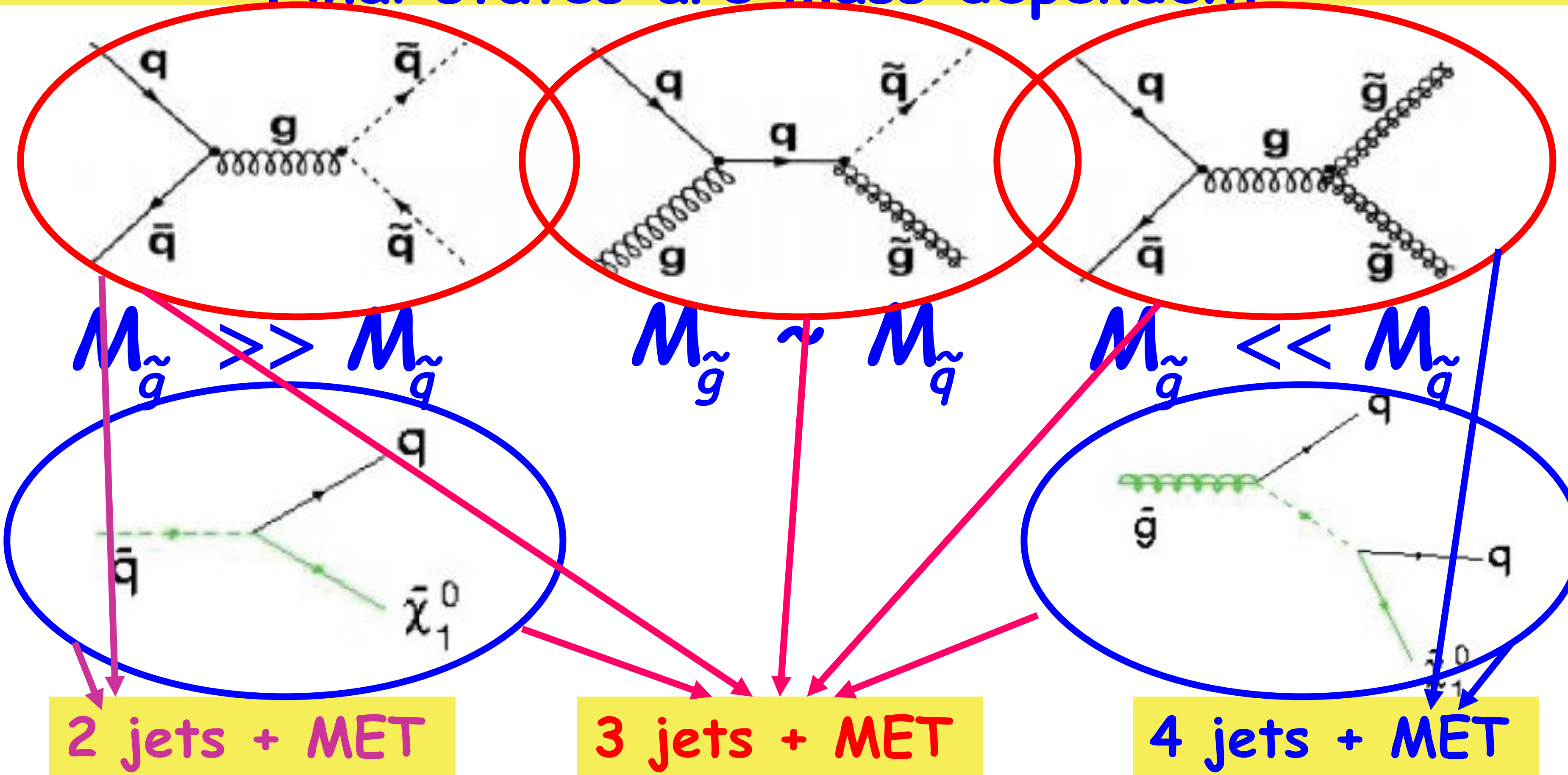
"It's a lot of work to make it look this easy"
– Joe DiMaggio

– Yogi Berra

Squark and Gluino Searches in Multijet + Met

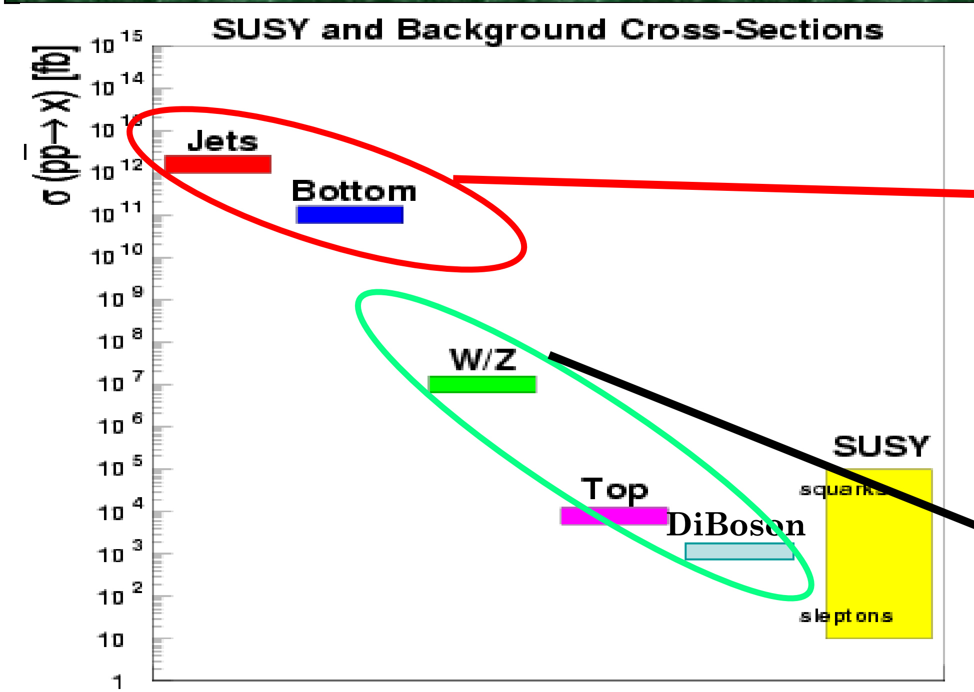
Three main production diagrams

Final states are mass dependent



3 separate final states + Unified Analysis ➔ best coverage

Start from difficult backgrounds

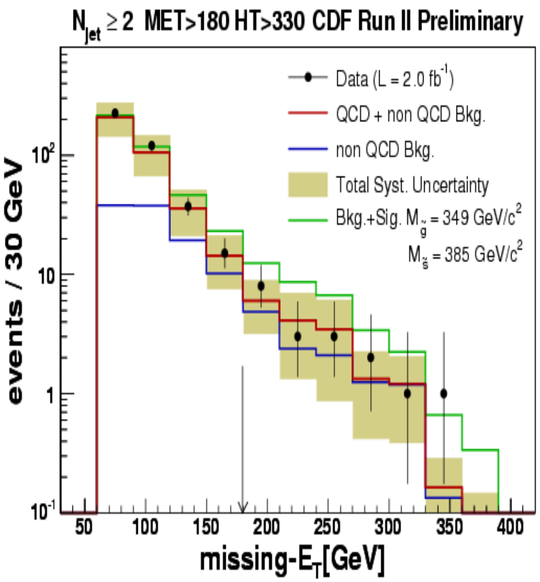


Note: Despite the huge production cross sections only about 25% of the final background is QCD

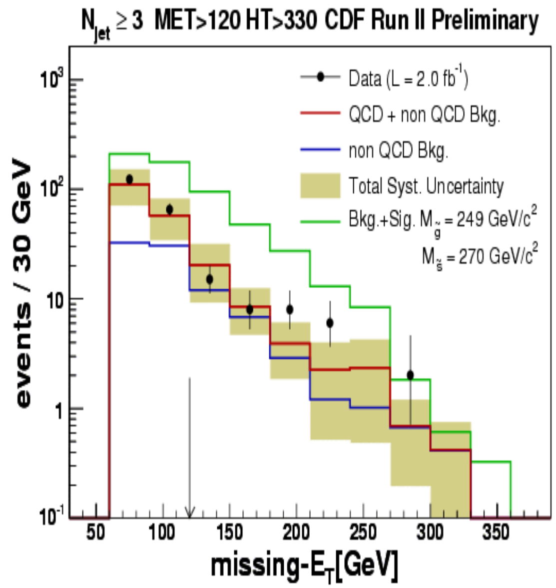
The rest is ttbar and other EWK processes

	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

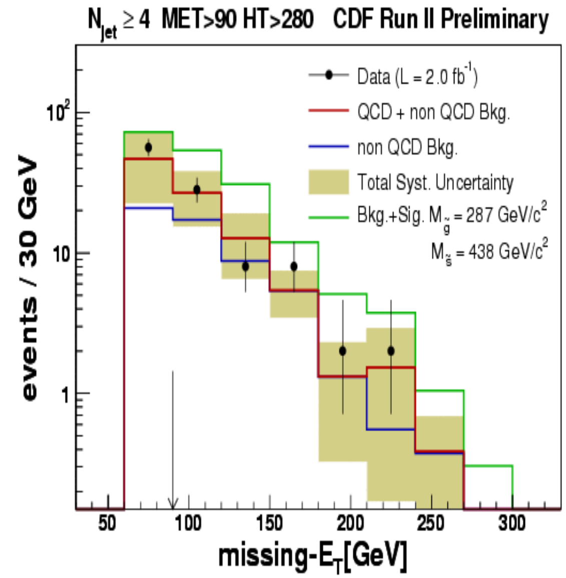
Unified Squark/Gluino Search



2 jets + MET



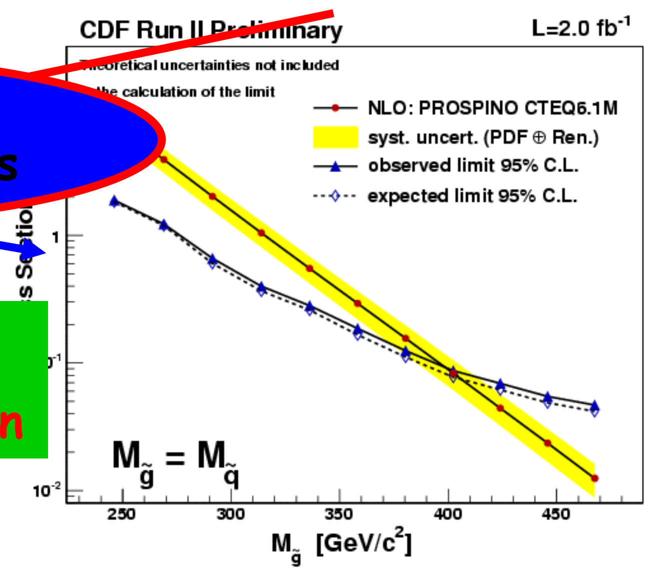
3 jets + MET



4 jets + MET

SUSY Interpreter

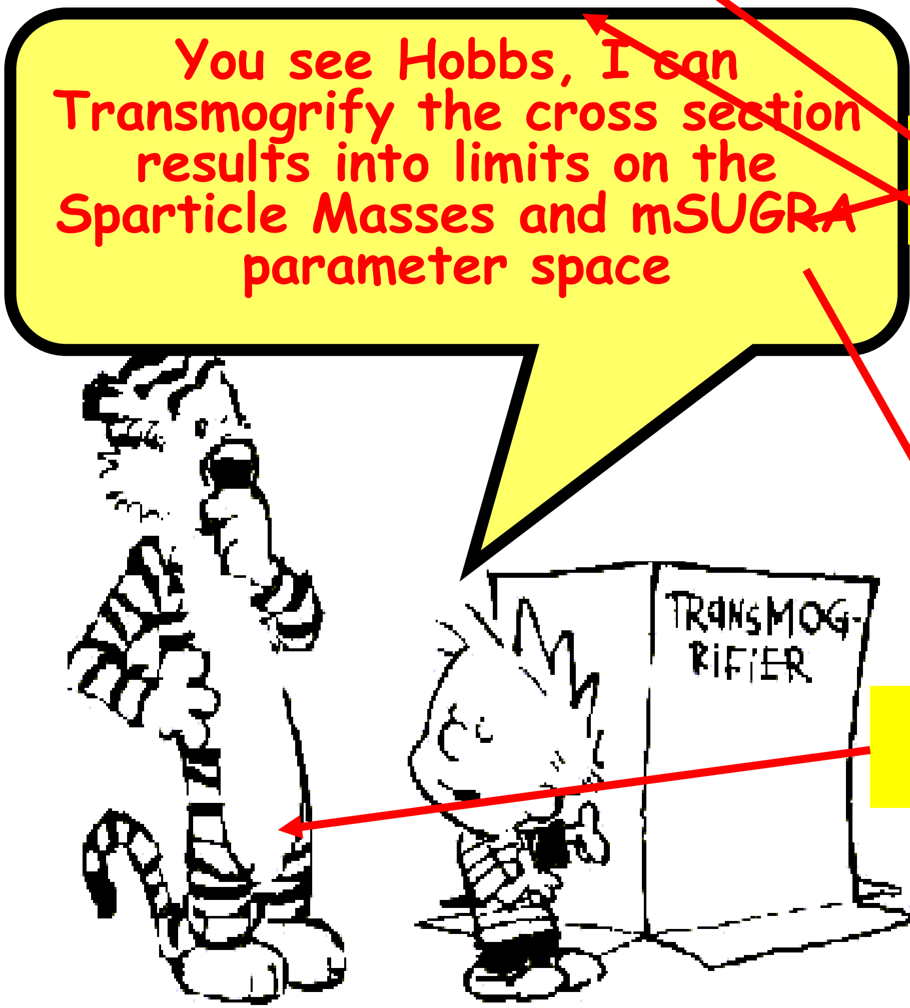
Set Cross Section Limits

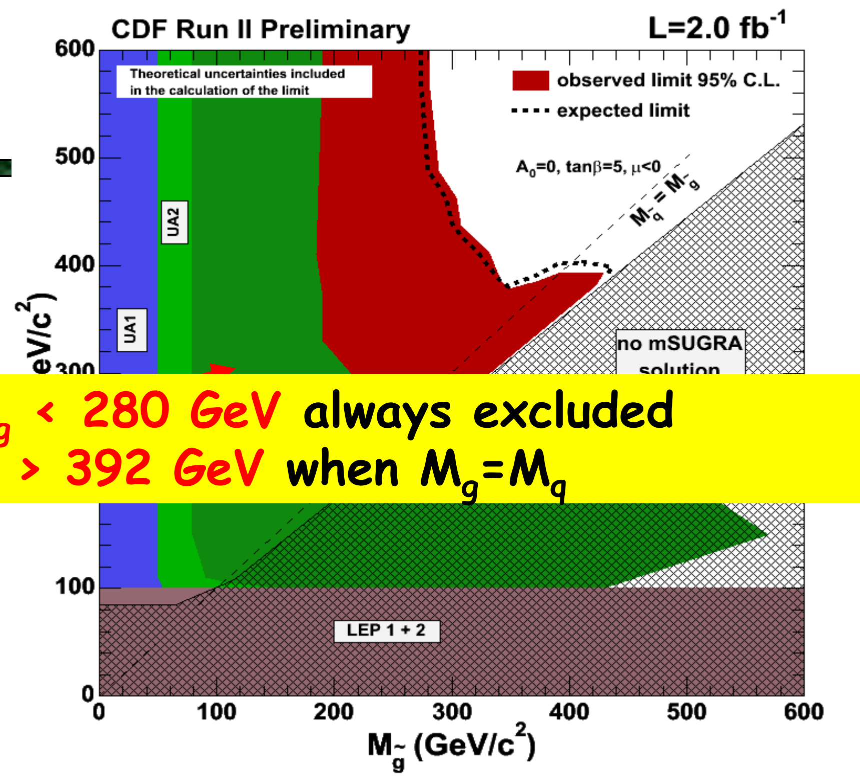


No evidence for new physics

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

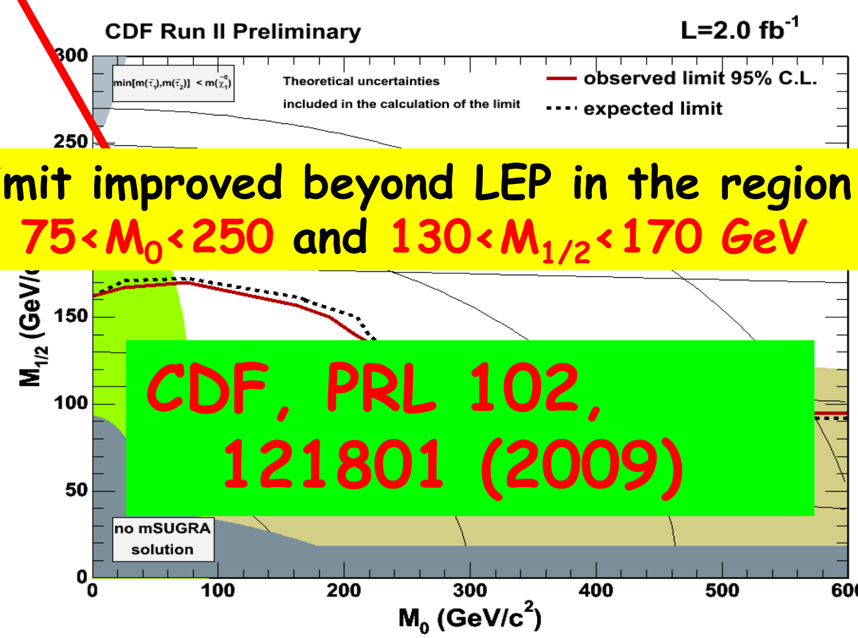
More limits…





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 in Multilepton + Met

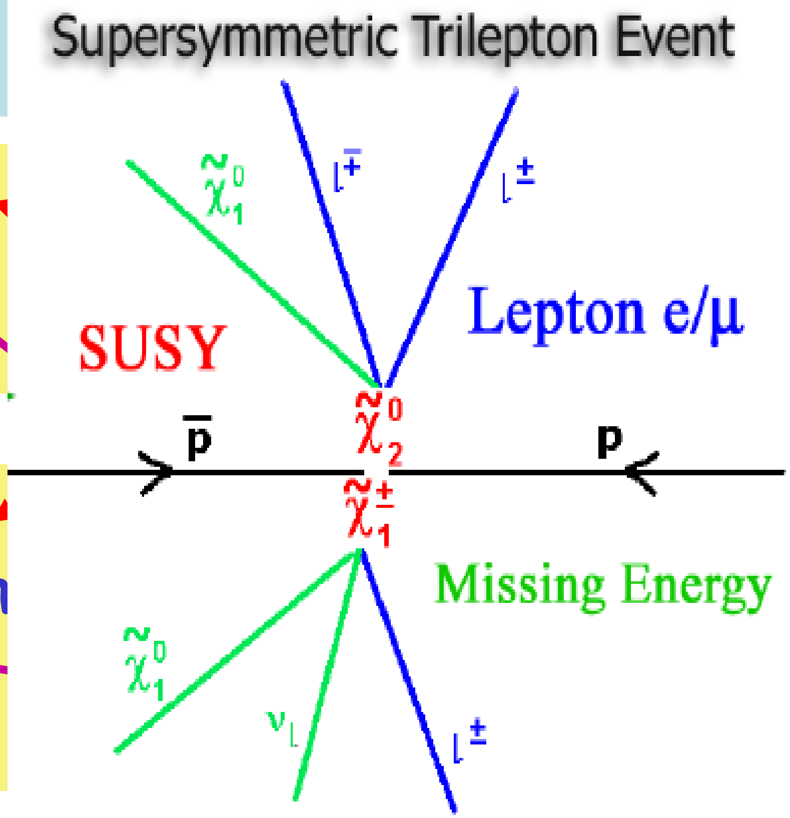
Chargino-Neutralino gives three low P_T leptons in the final state
Dominates the production cross section

5 separate final states + Unified Analysis → best coverage

eee, eeμ, eμμ, μμμ, eeτ, eμτ, & μμτ

2 Tight leptons + 1 track + MET

1 Tight lepton +1 Loose lepton +1 track + MET



eee, eeμ, eμμ & μμμ

3 Tight Leptons + MET

2 Tight leptons +1 Loose lepton + MET

1 Tight lepton + 2 Loose leptons + MET

Tight (= high purity) and Loose (=not as high purity, but better efficiency) leptons are e's or μ's

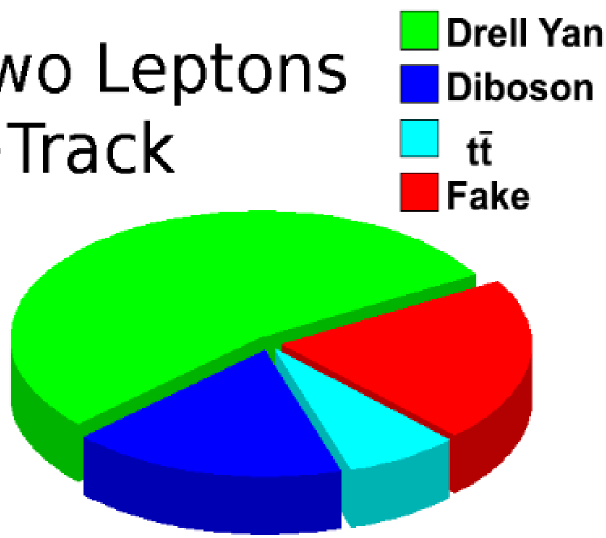
Tracks can be e's or μ's or τ's

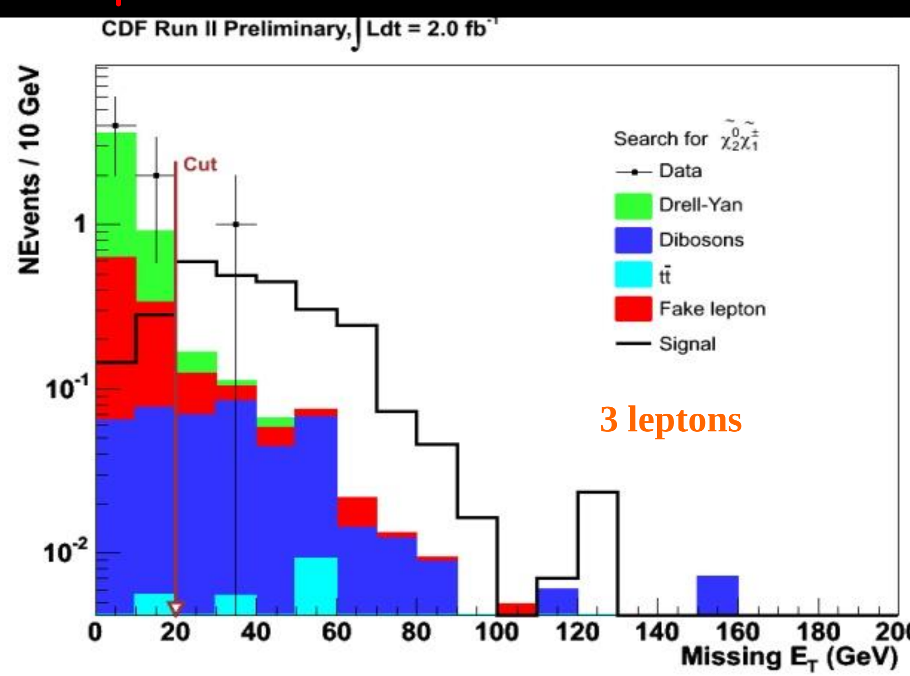
Unified Gaugino Pair Production Analysis

Three Leptons

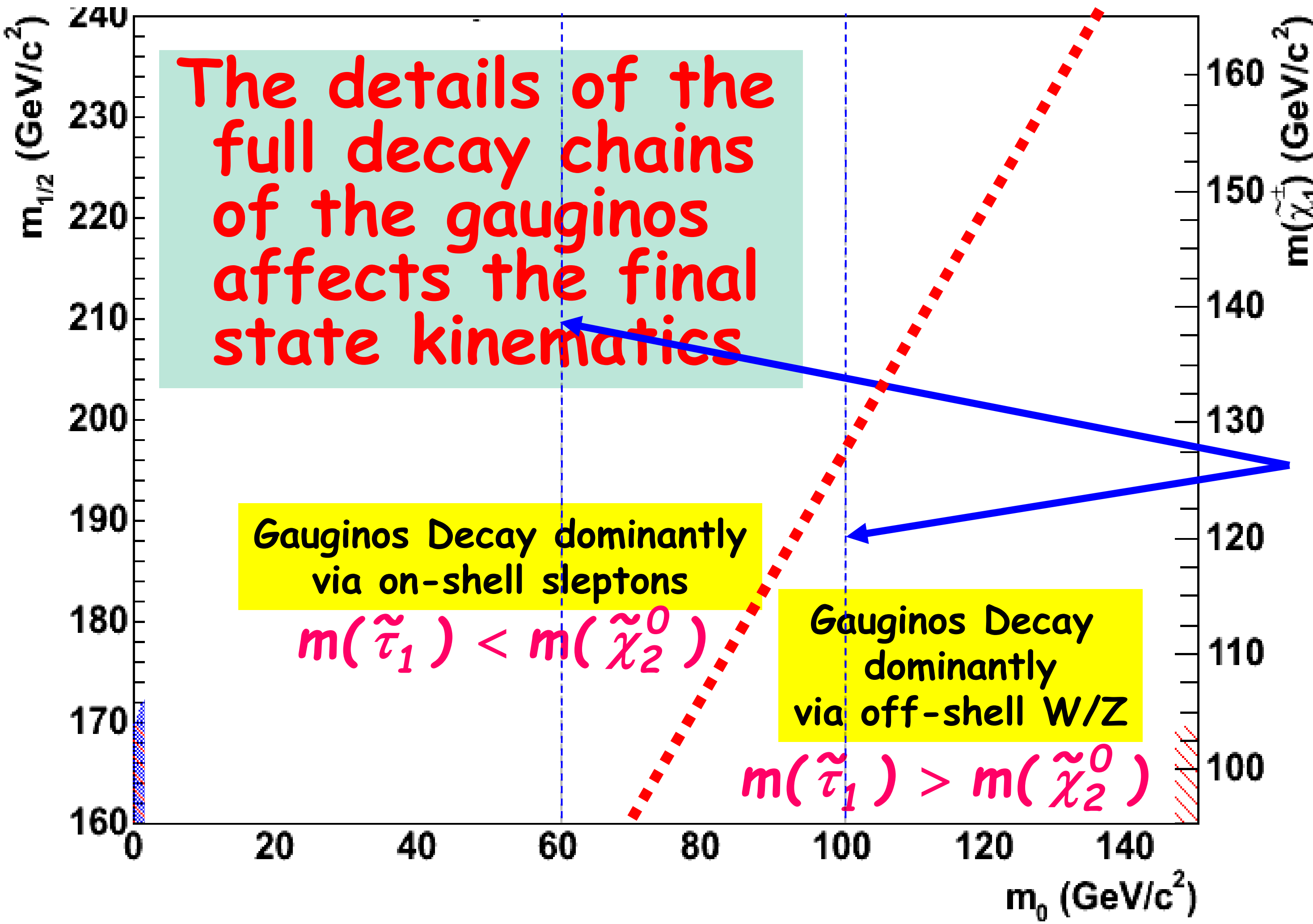
Channel	Background	Obs
3 Tight	0.49±0.04±0.08	1
2 Tight + 1 Loose	0.25±0.03±0.03	0
1 Tight + 2 Loose	0.14±0.02±0.02	0
Total Trilepton	0.88±0.05±0.13	1
2 Tight + 1 Track	3.22±0.48±0.53	4
1 Tight + 1 Loose + 1 Track	2.28±0.47±0.42	2
Total Dilepton +Track	5.5±0.7±0.9	6

Two Leptons +Track





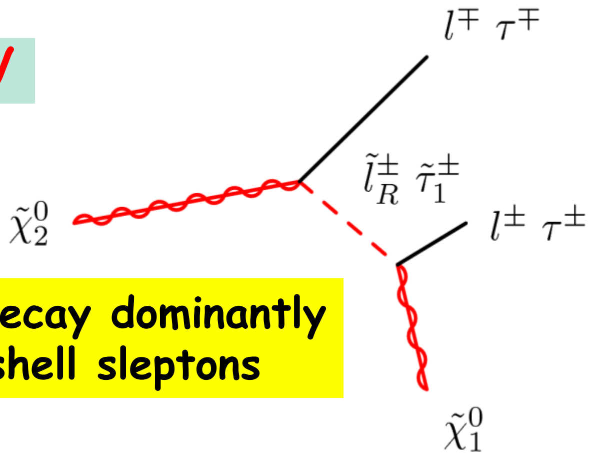
Trileptons in mSUGRA



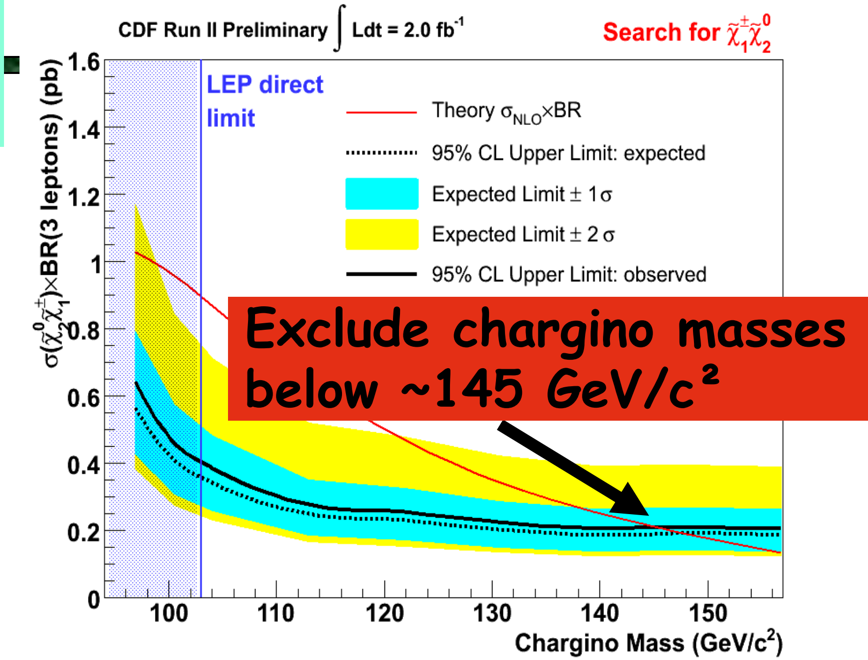
Look at the lines of constant M_0

Cross Section limits vs. chargino mass

M_0 = 60 GeV

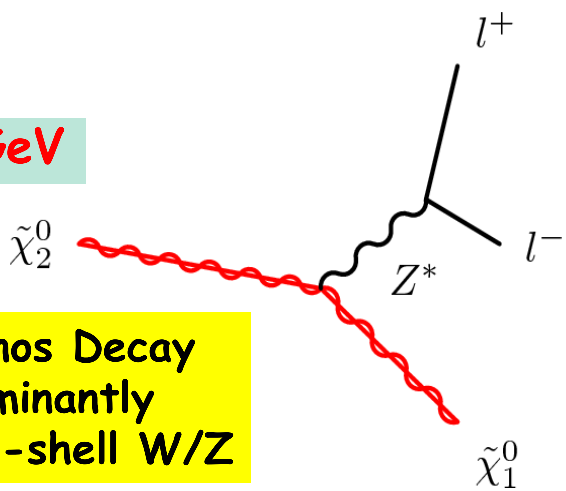


Gauginos Decay dominantly via on-shell sleptons

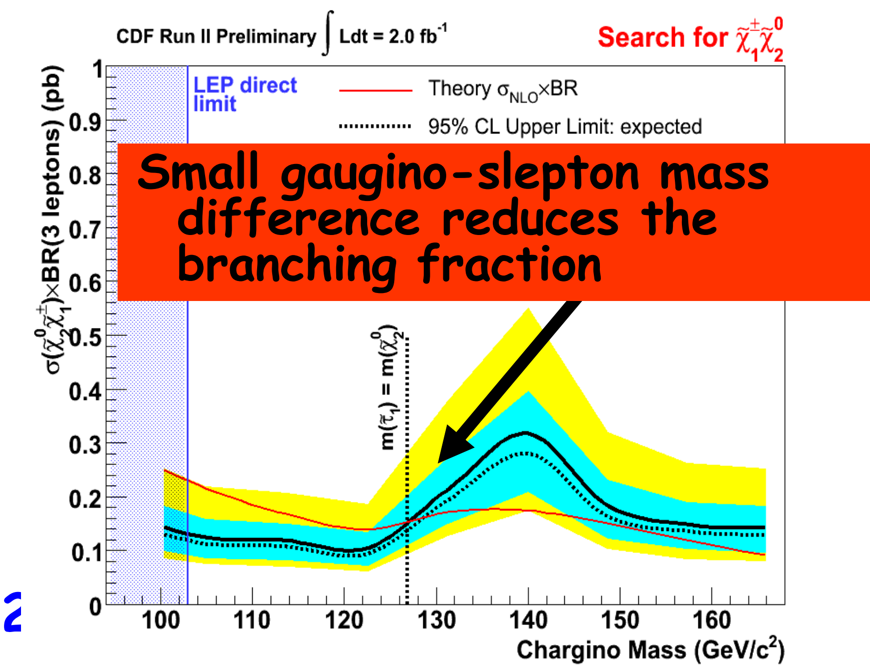


Exclude chargino masses below ~145 GeV/c²

M_0 = 100 GeV

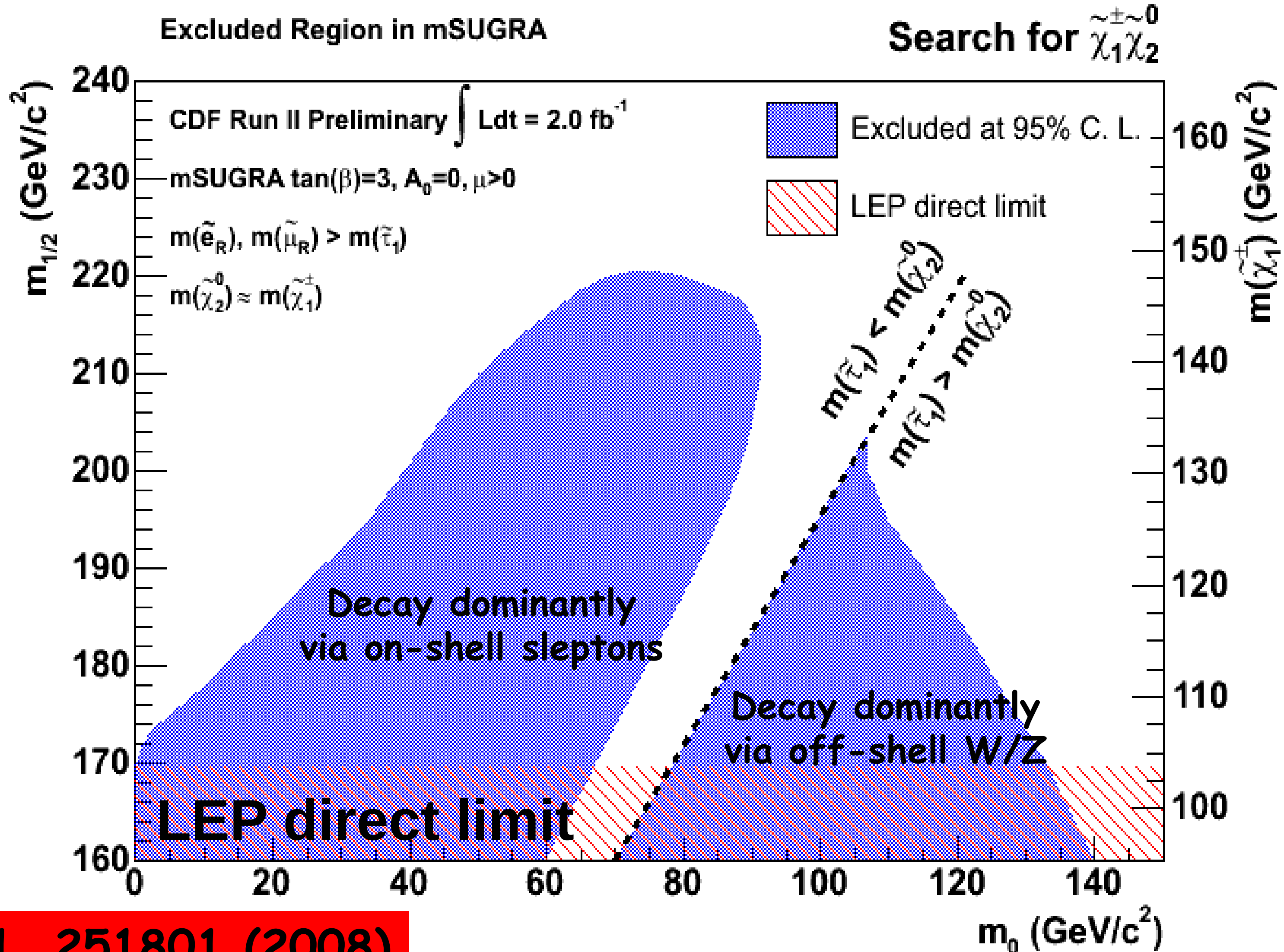


Gauginos Decay dominantly via off-shell W/Z



Small gaugino-slepton mass difference reduces the branching fraction

mSUGRA Exclusion Region

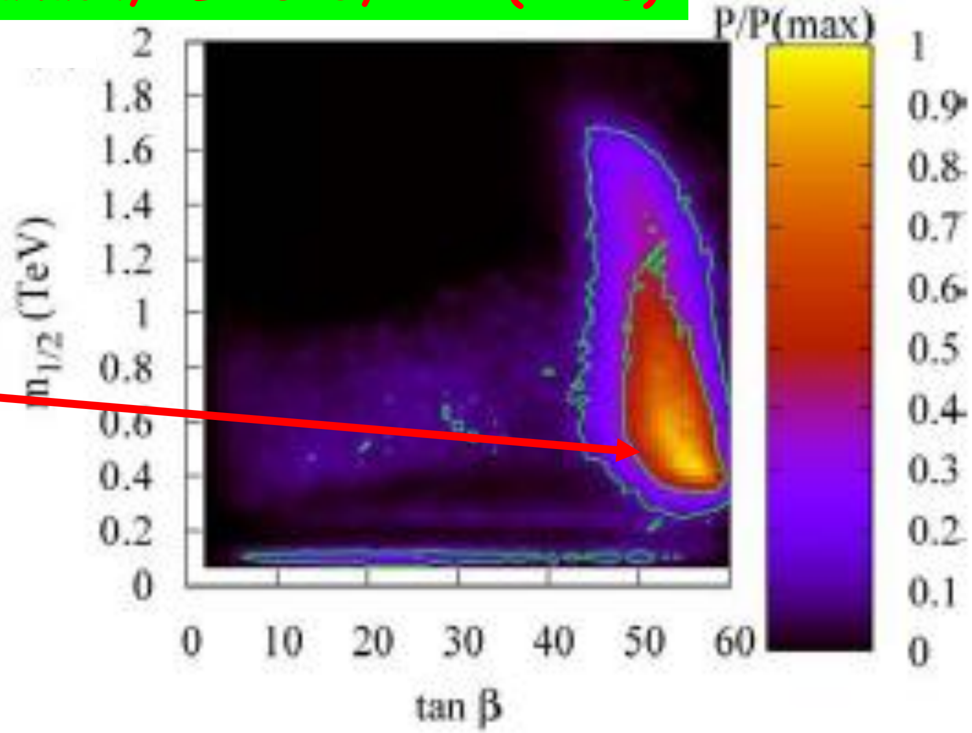


PRL 101, 251801 (2008)

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)



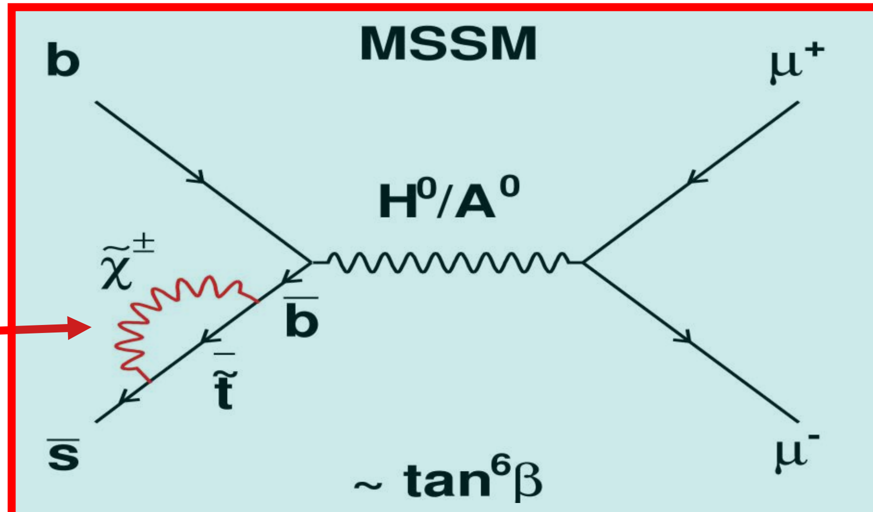
The Tevatron has moved towards having a full suite of high tanβ targeted searches

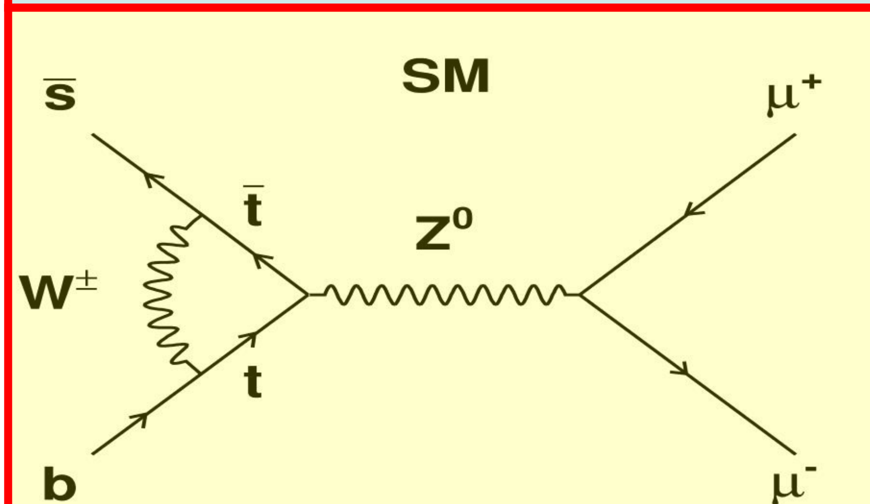
Indirect Search: $B_s \rightarrow \mu\mu$

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

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

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



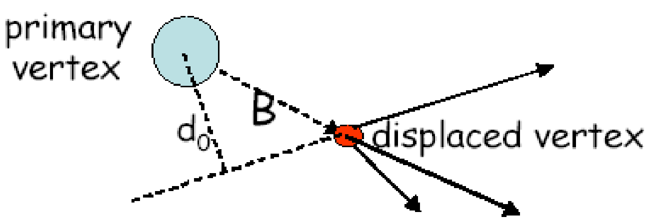


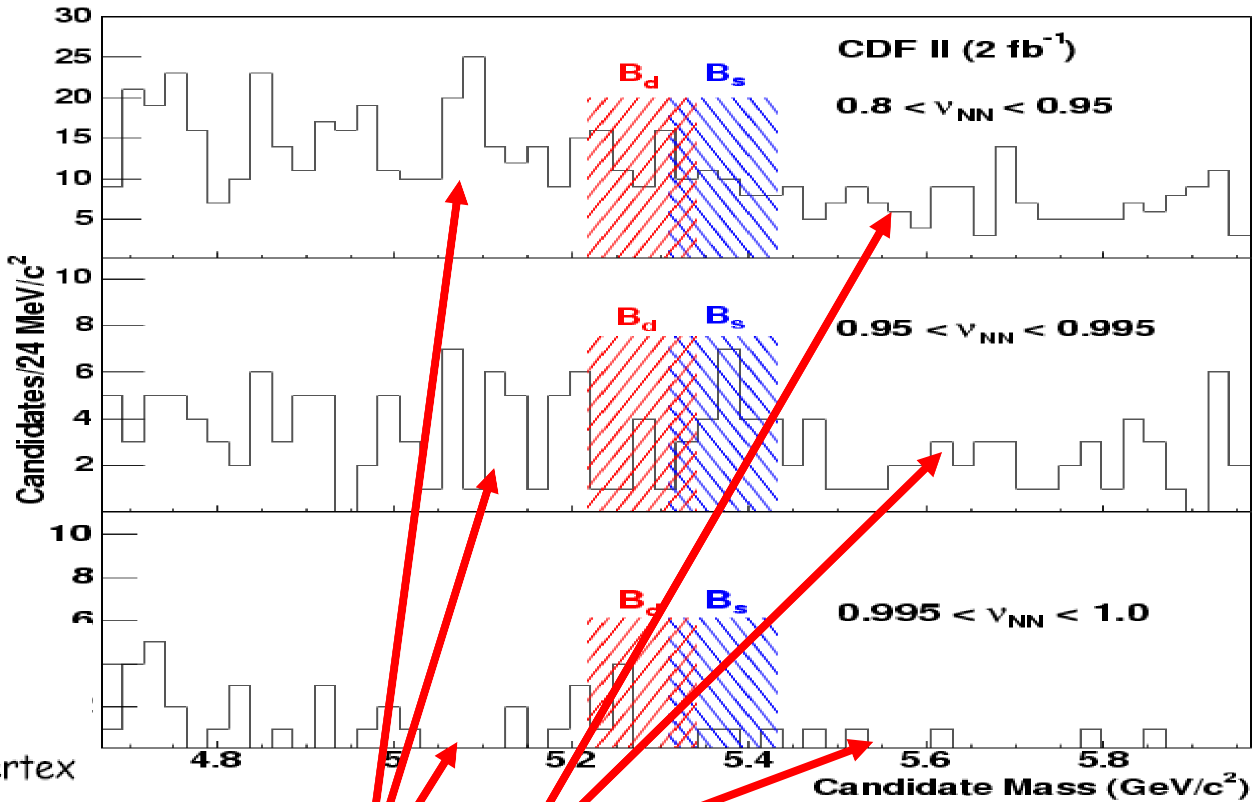
$$BR_{SM}(B_s \rightarrow \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$$

(Buchalla & Buras, Misiak & Urban)

Looking at the Data

Heavily optimized search using Neural Net Techniques





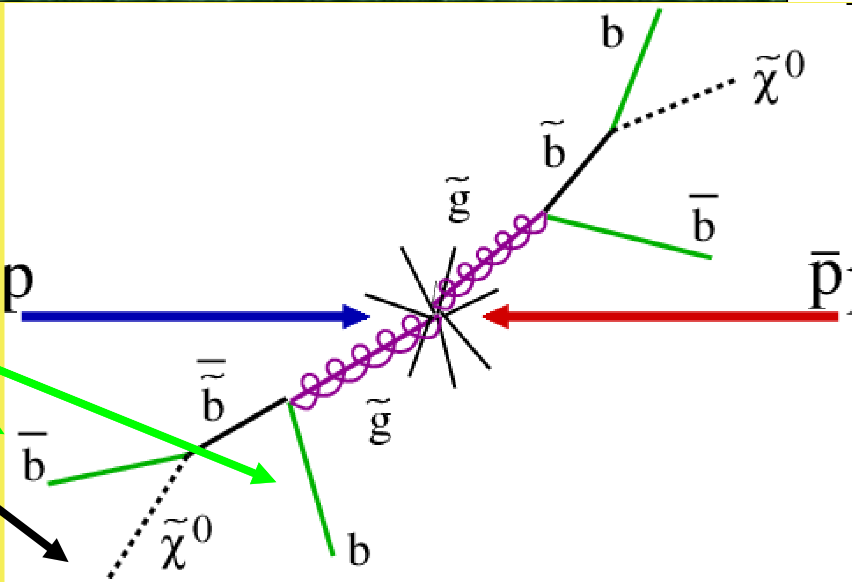
The backgrounds are combinatorial and estimated and checked from data using sideband techniques

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

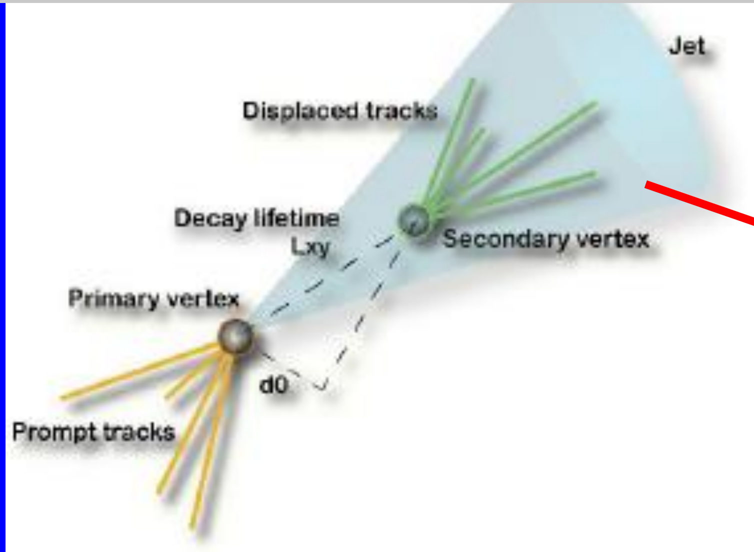
Sbottom Searches

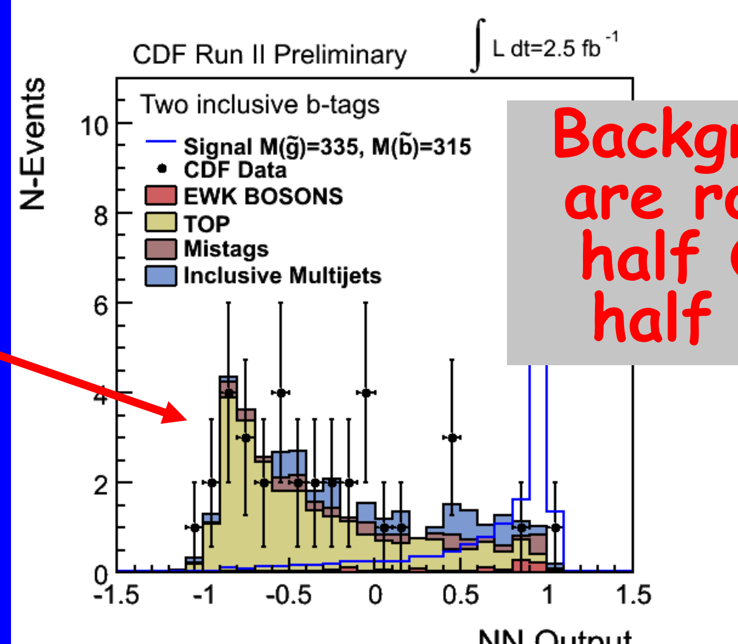
Two primary Sbottom searches in b+jets+Met

1. Sbottoms from gluinos
2. Direct sbottom pair production



Special tricks to identify b-quarks from their long lifetime



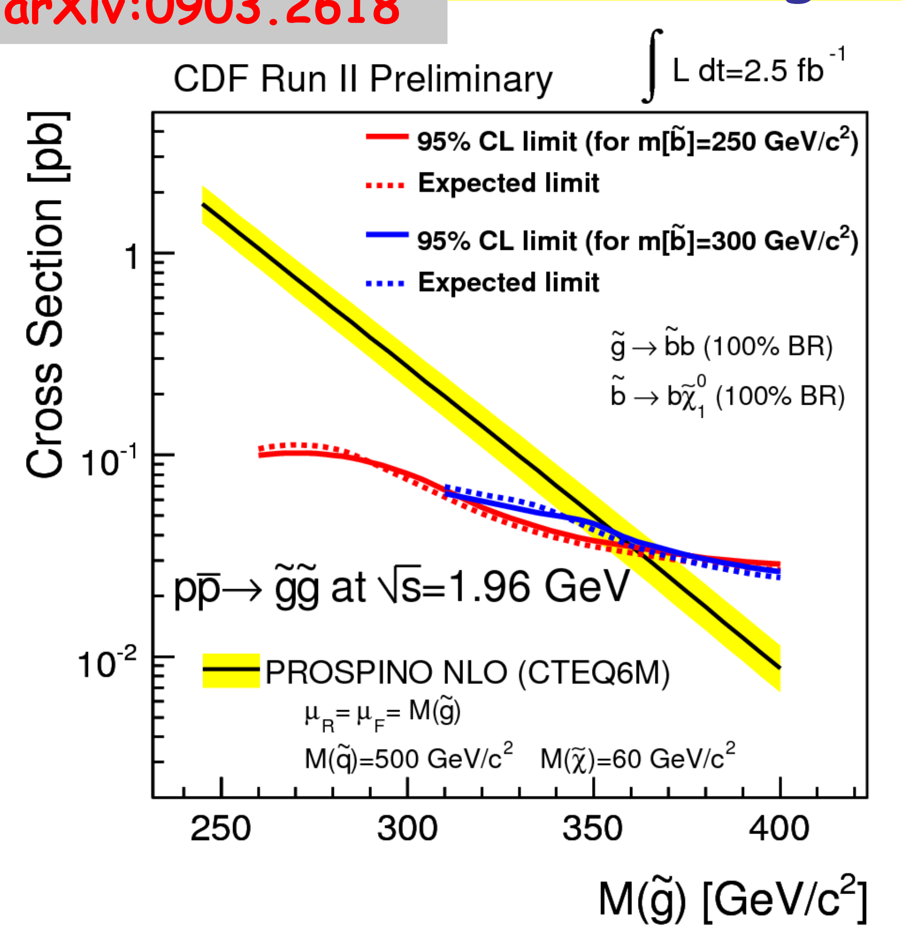


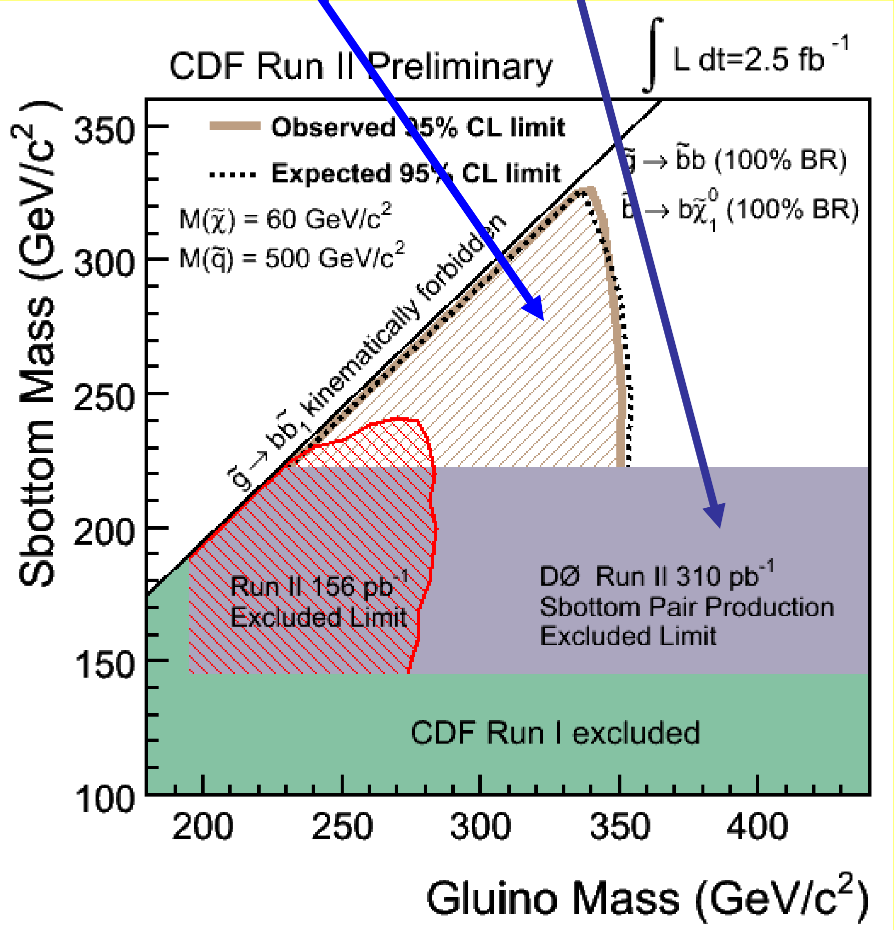
Backgrounds are roughly half QCD, half EWK

Limits on Sparticle Production

Most sensitive to large sbottom masses
Complementary to direct Sbottom searches which are gluino mass independent

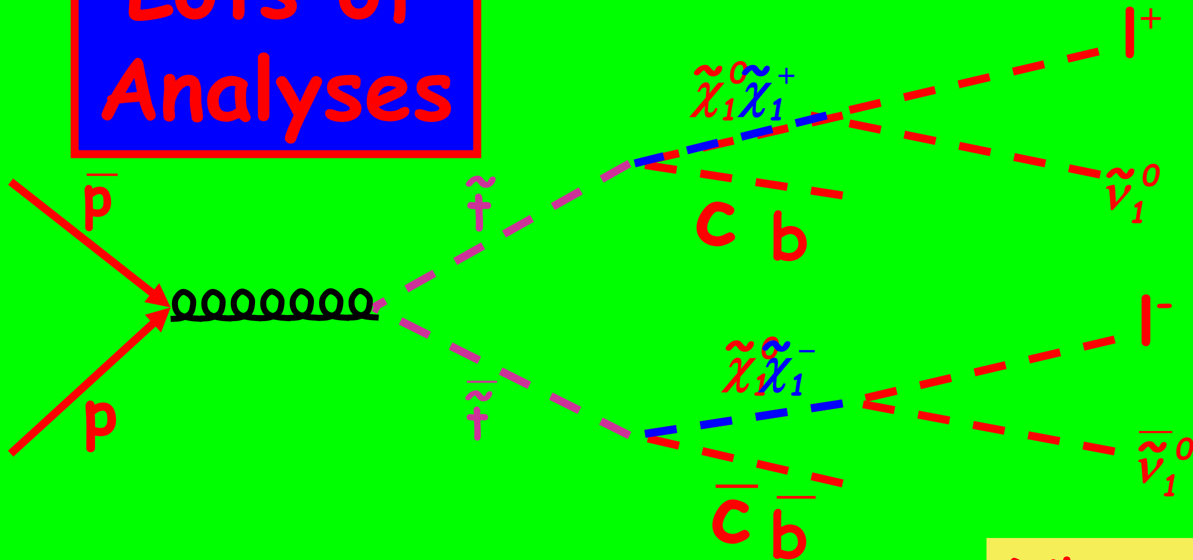
Submitted to PRL, arXiv:0903.2618





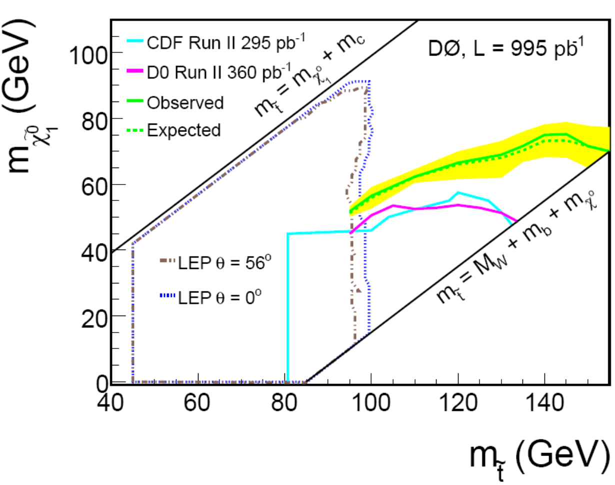
Lightest Squark = Stop?

Lots of Analyses

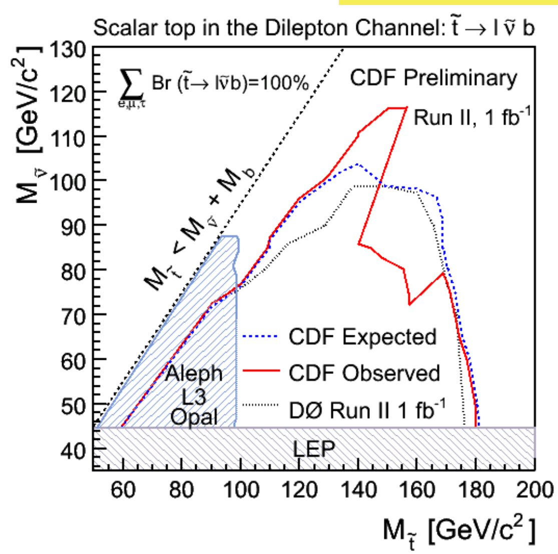


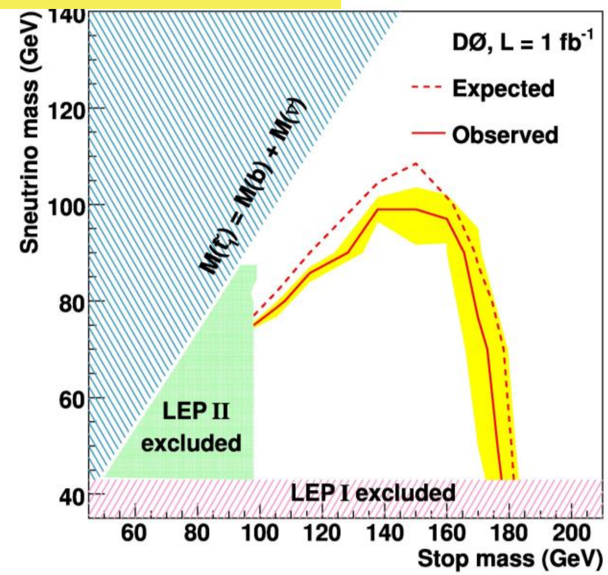
Direct counting Experiments

Charm+jet+MET



Dileptons+Jets+MET





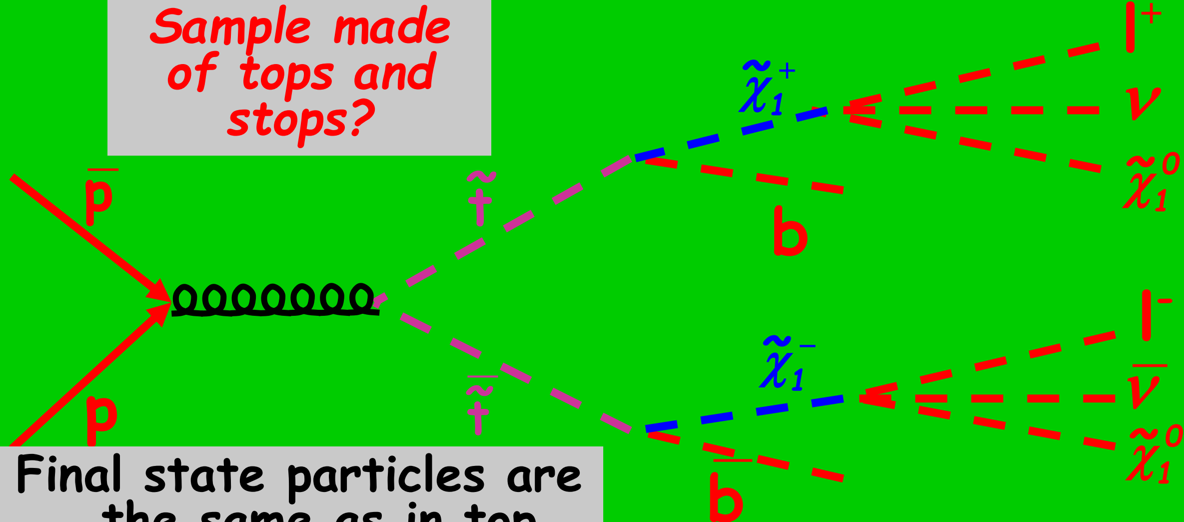
Stop Searches

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

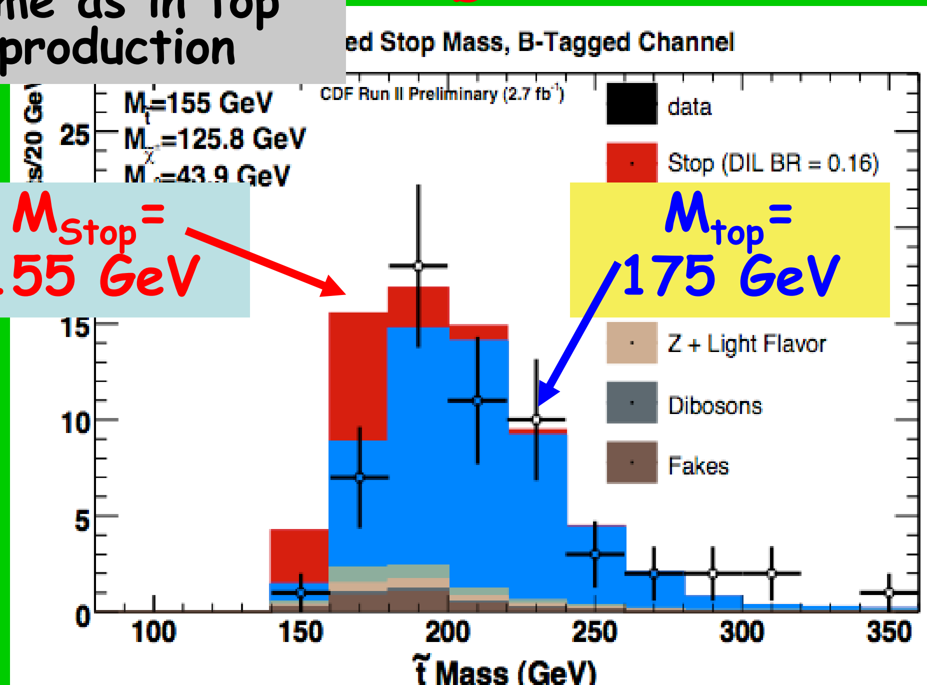
However, Some of the dilepton events in Run I didn't "look" like tops

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

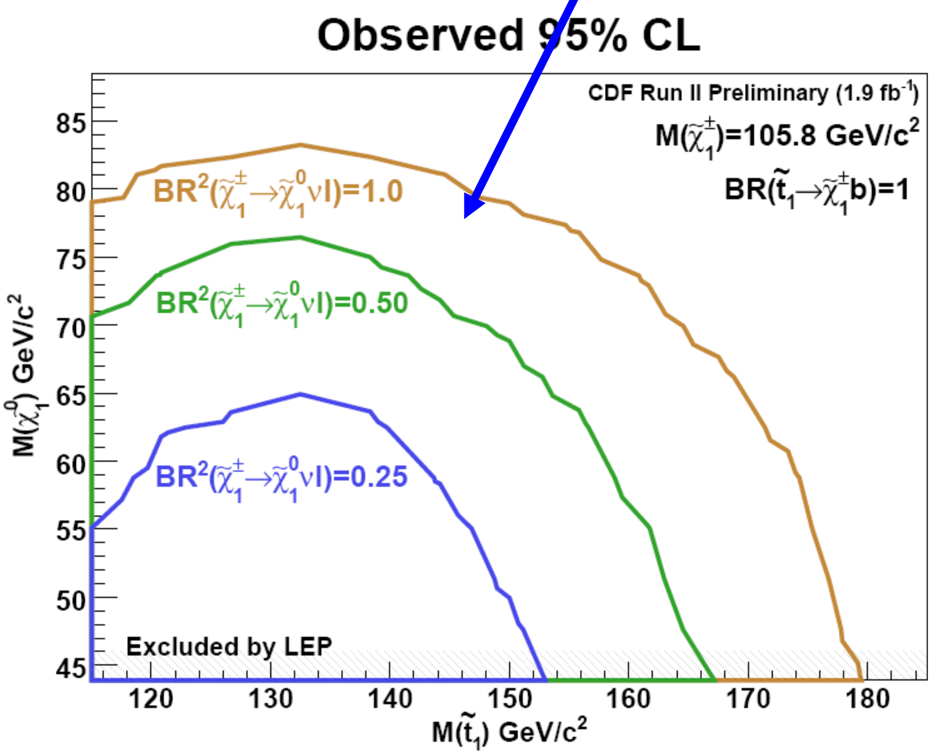


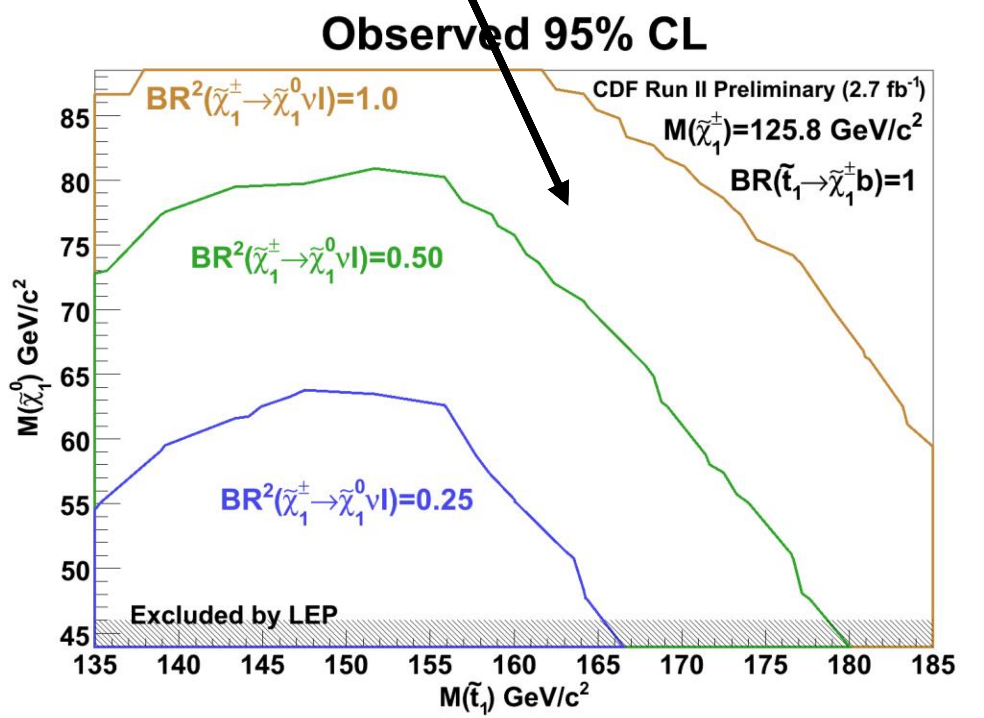
Can set limits on Stop Admixture

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

Branching Ratio limits are mass dependent…

Small chargino mass Large Chargino mass

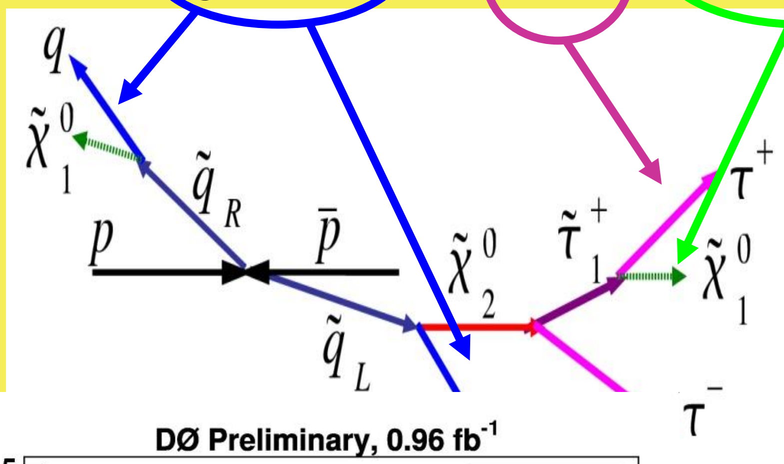




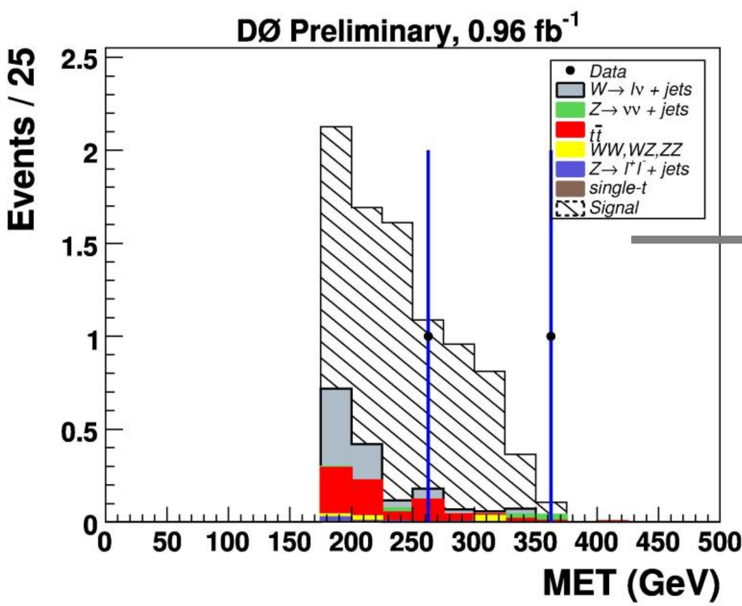
High tan$\beta \rightarrow$ Light $\tilde{\tau}$' s

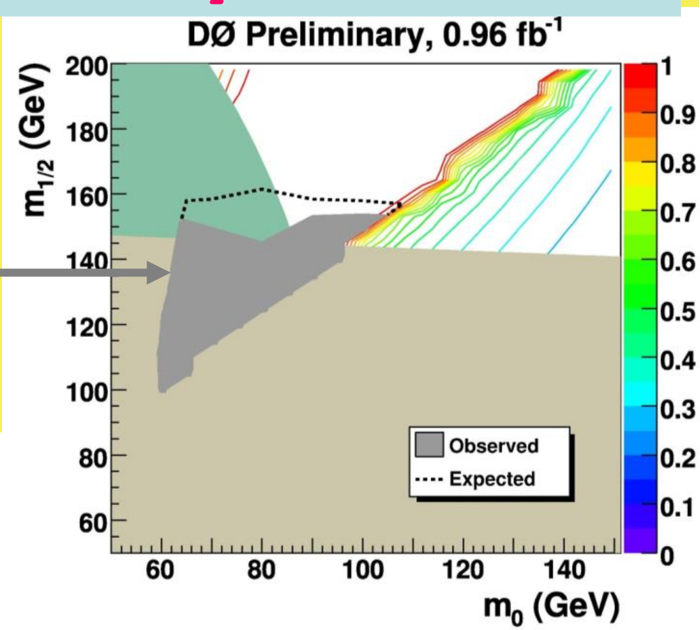
Complementary search for Squarks:

Jets + τ + Met



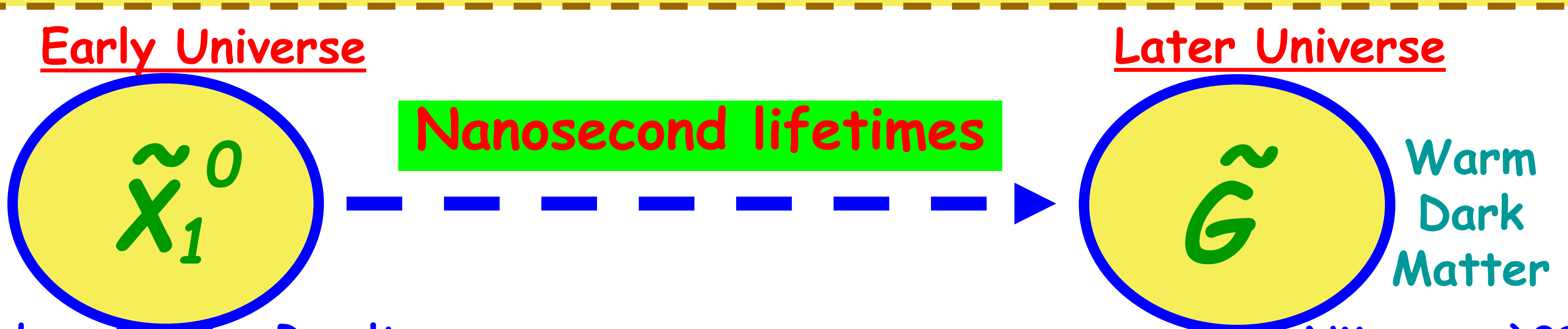
Recent Precision Cosmology data favors places like the co - annihilati on region $\rightarrow \tilde{\tau}$ has a mass in between the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$



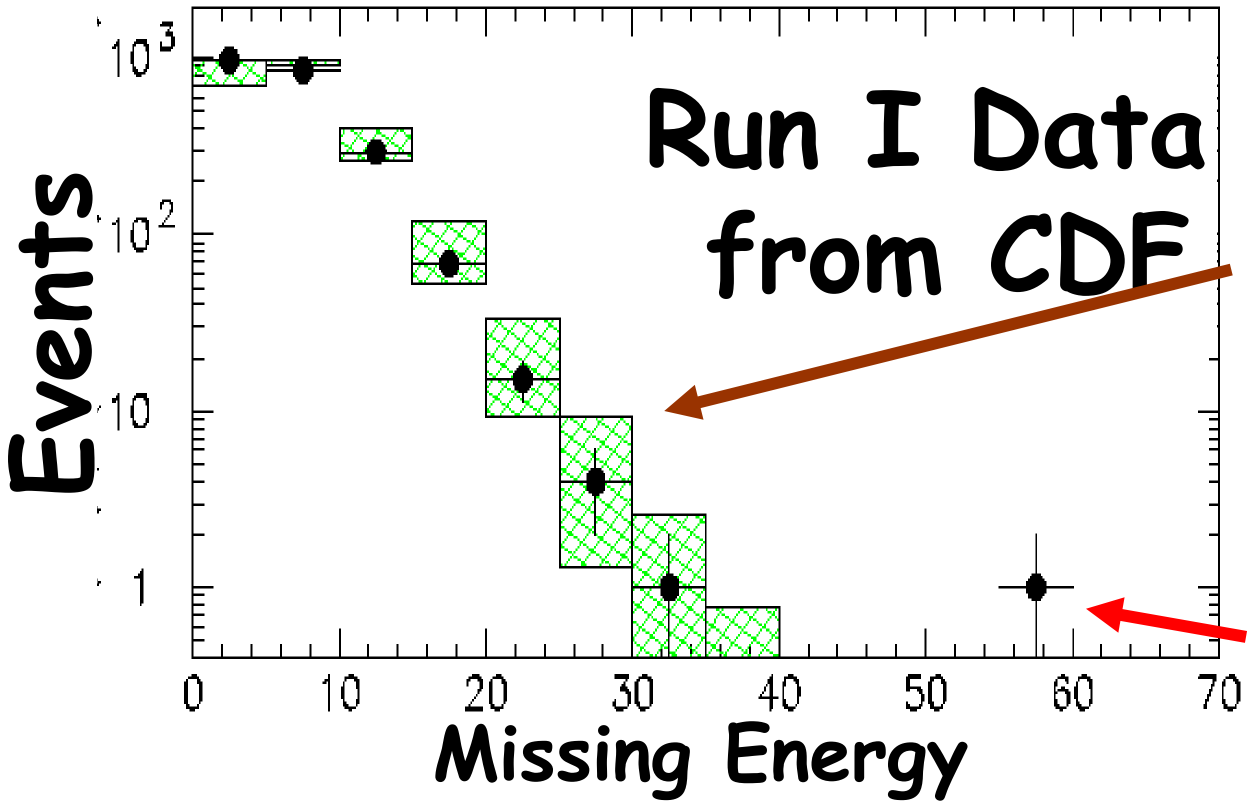


Gauge-Mediated SUSY Breaking Models

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



Search for anomalous $\gamma\gamma$ events at CDF



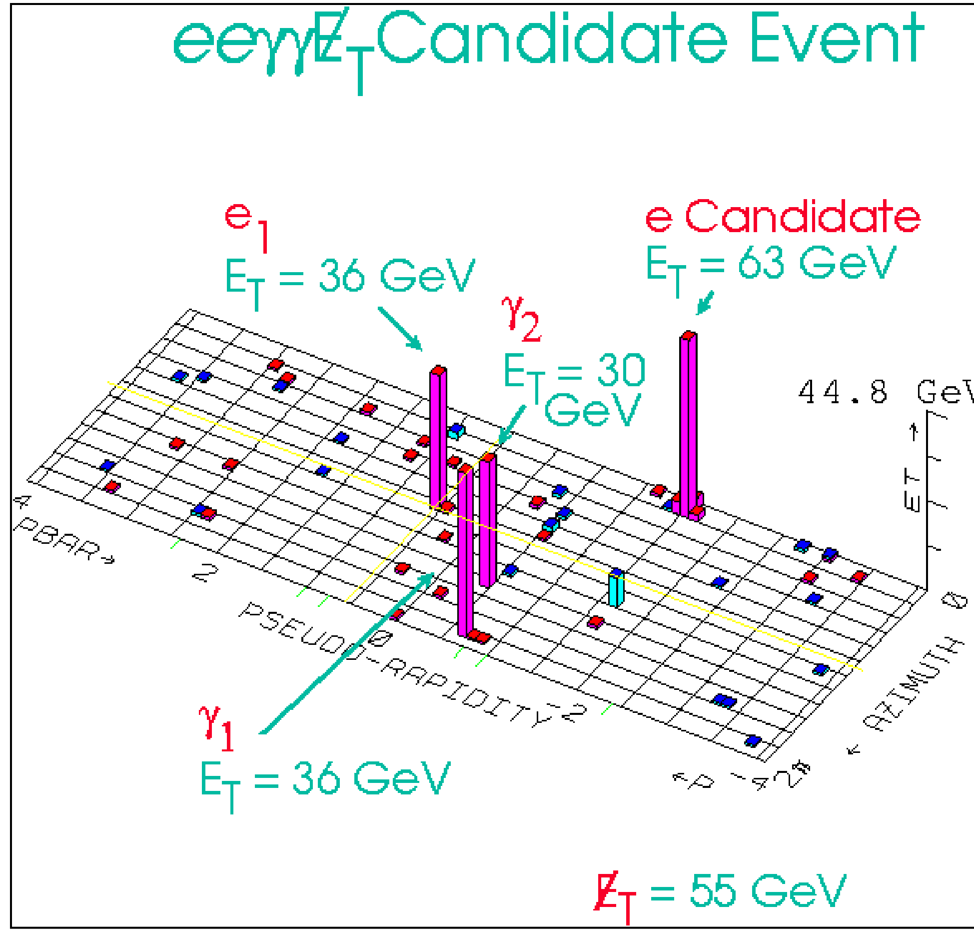
Data is consistent with background expectations (gives us confidence we got that part right)

One possible exception

CDF PRL 81, 1791 (1998), PRD 59, 092002 (1999)

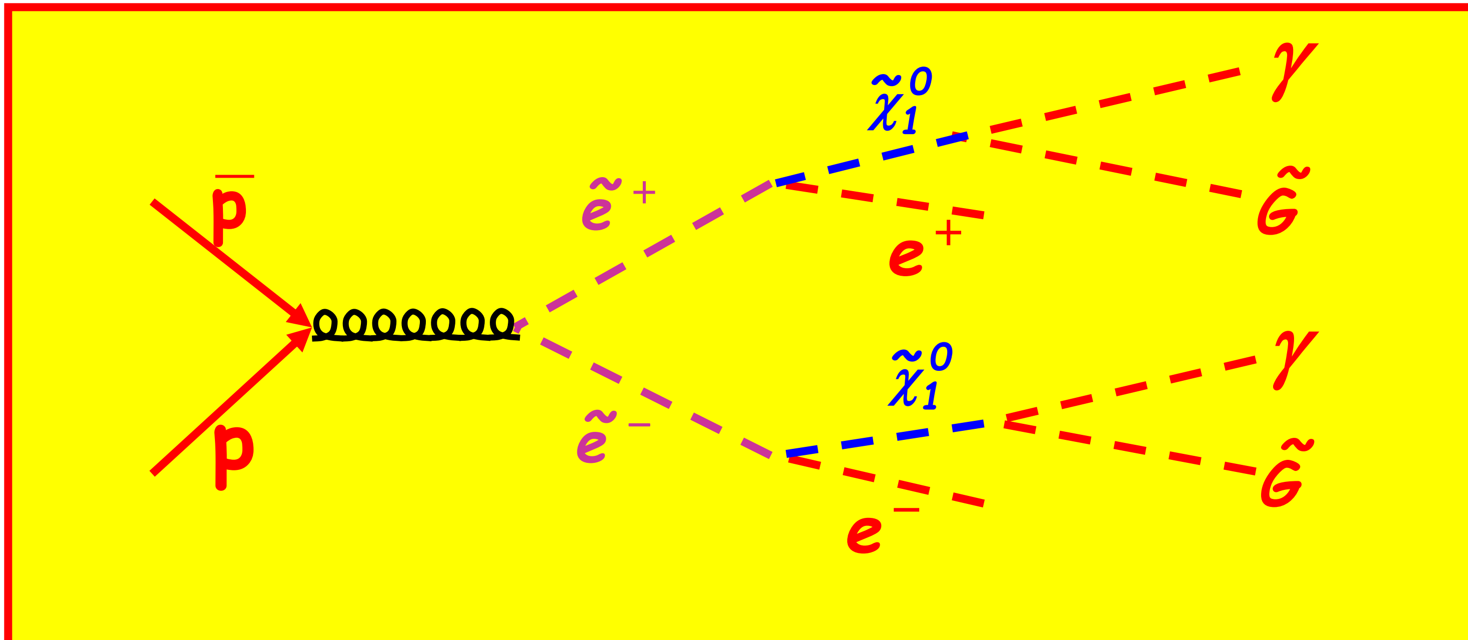
The interesting event on the tail

- In addition to γγ+Met this (famous) event has two high energy electron candidates
  - *Both are unexpected*
- Very unusual
- Good example of getting an answer which is far more interesting than what you asked for
- *How unusual? SM* Predicts about 10^{-6} or so



Is the $ee\gamma\gamma$+Met Candidate SUSY?

Selectron pair production and decay?

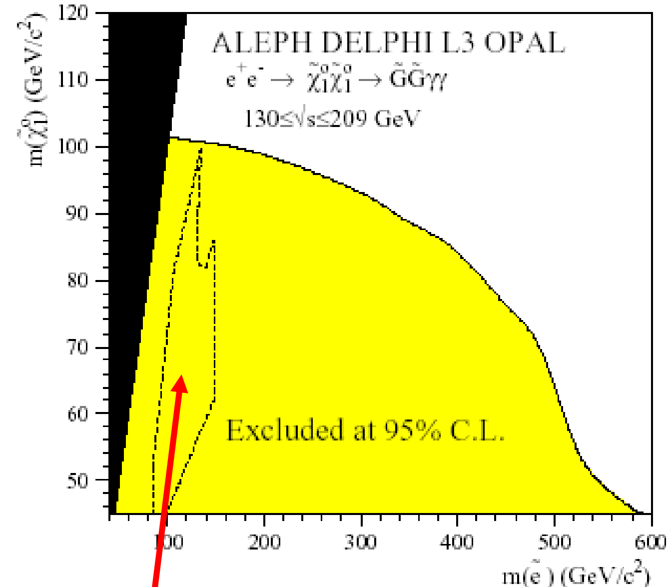


Others like it in the Tevatron Data?

None in Run I

Searches for More Events

- For most of the last ten years Tevatron searches have focused on low lifetime searches → γγ+Met
- Searches for more eeγγ+Met events have also been null in Run II
- *Maybe we haven't seen them because the lifetime is large and most of the SUSY events just leave the detector?*

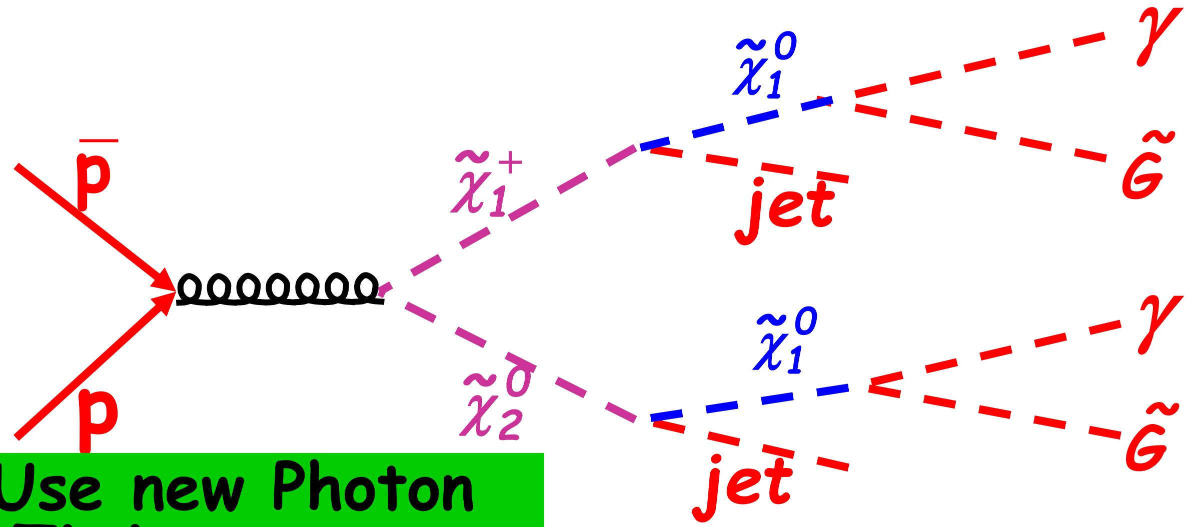


LEP limits make a Tenuous Assumption: Tevatron production rate is ~½ event per 100 pb^{-1}

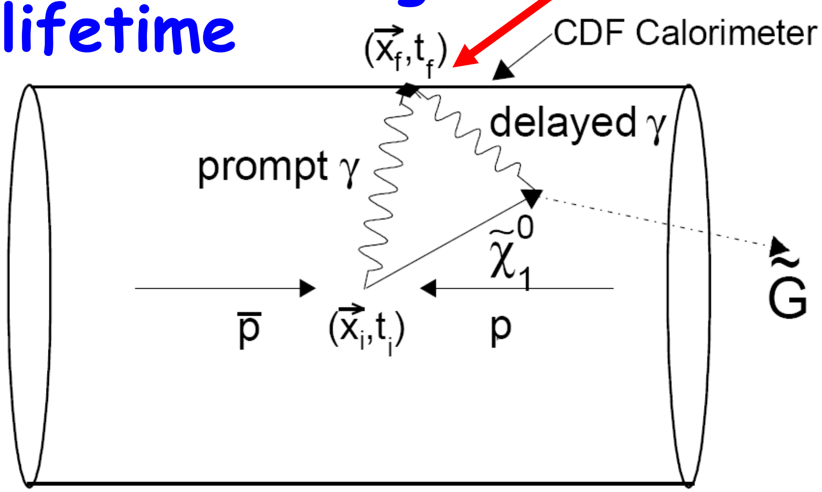
High and Low Lifetime Searches

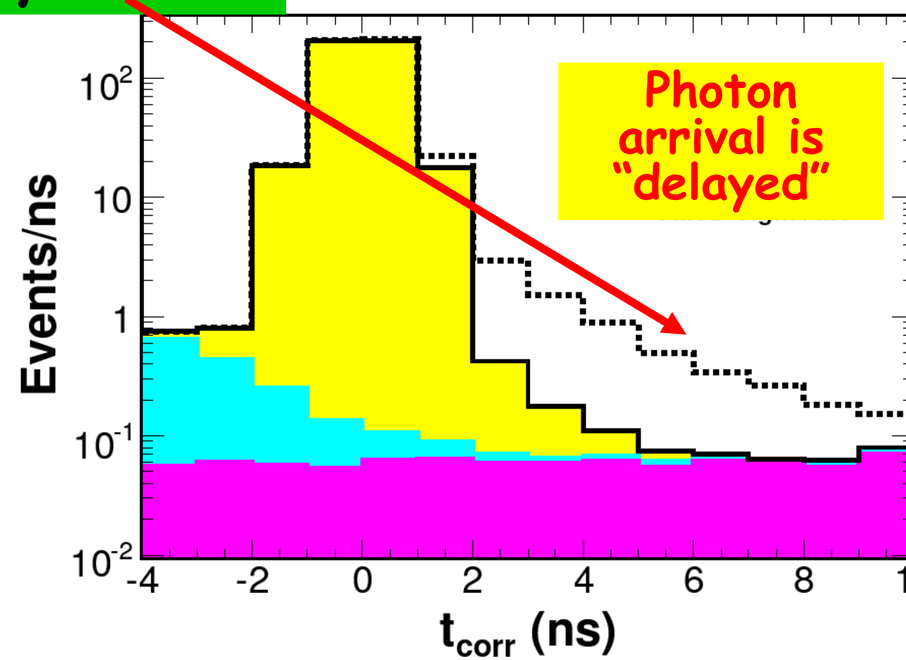
The lifetime and associated particle production dictate different final states

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



Use new Photon Timing system

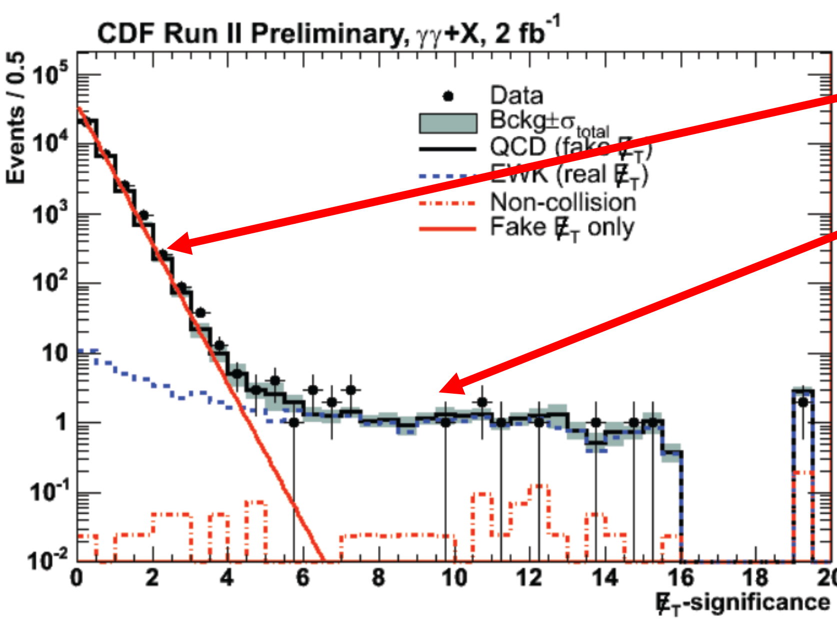




γγ+Met

New model independent search in γγ+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

	MetSig>3.0	MetSig>4.0	MetSig>5.0
Non-collision	0.89 ± 0.32	0.84 ± 0.30	0.77 ± 0.27
Fake Met (MetModel)	28.1 ± 6.8	3.6 ± 1.8	0.60 ± 0.83
"No γγ Vertex"	4.4 ± 2.0	2.5 ± 1.0	1.5 ± 0.7
γγγ (lost γ)	2.9 ± 1.0	2.2 ± 1.0	1.6 ± 1.0
EWK real MET	31.6 ± 2.0	26.7 ± 1.9	22.8 ± 1.7
Total	67.9 ± 7.5	35.8 ± 3.0	27.3 ± 2.3
Observed	82	31	23

No evidence for new physics

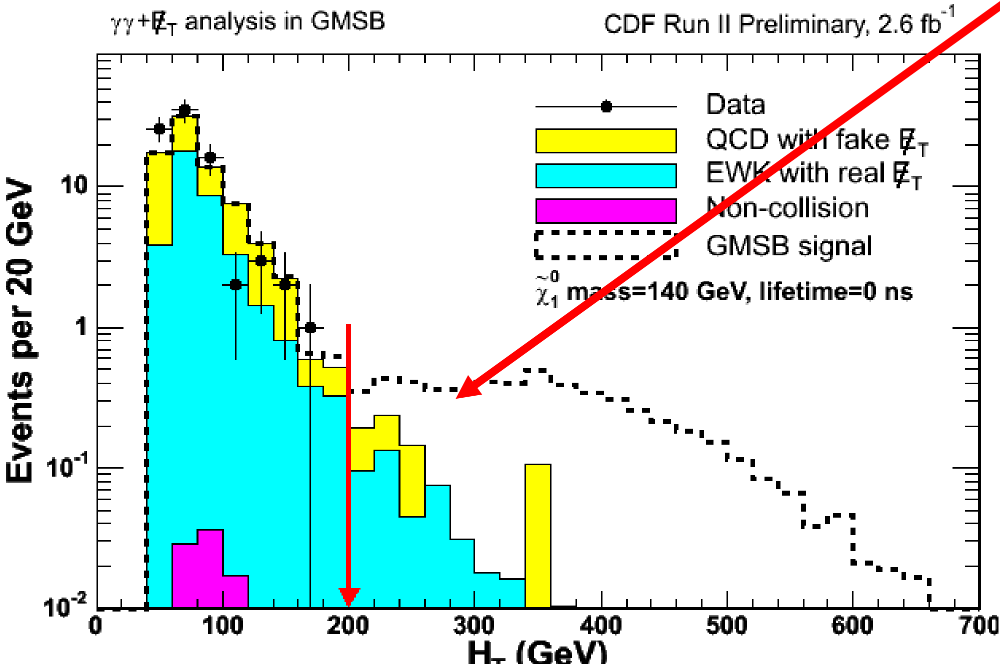
Ha… Da…

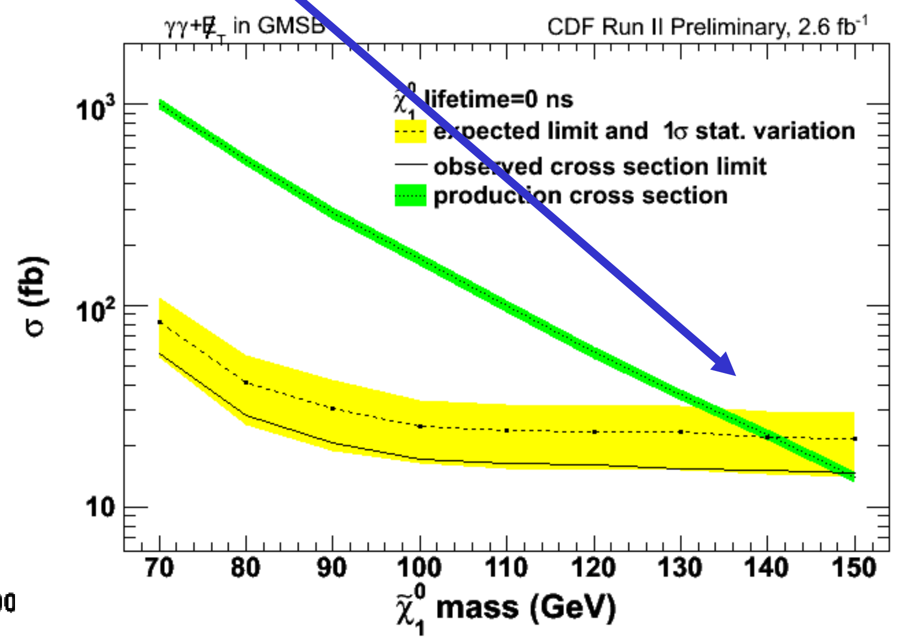
Low lifetime GMSB

Optimize the γγ+Met analysis for 0 ns lifetime:
Significant Met and Large H_T

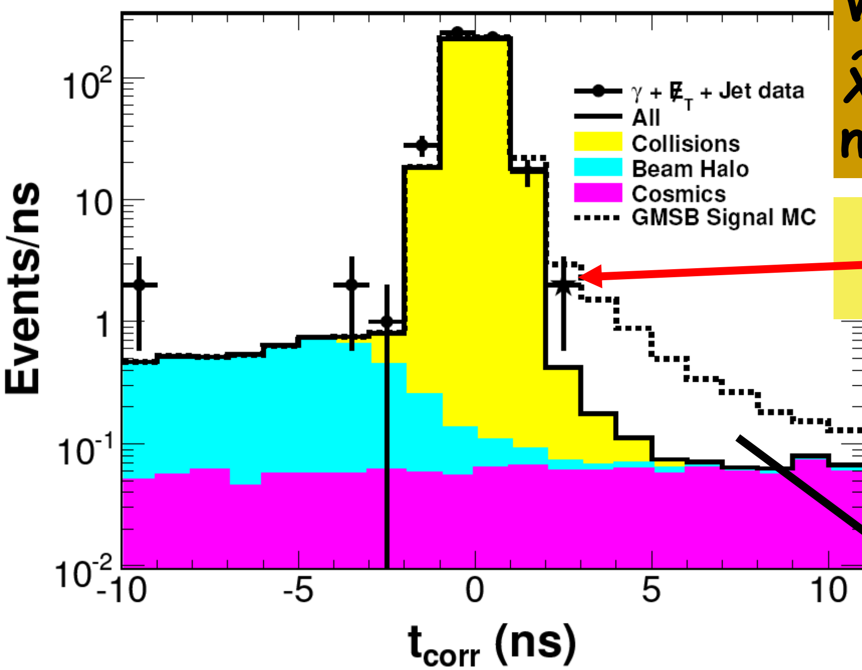
No evidence for new physics

Blessed with 2.6 fb^{-1}, GPS approved, PRL soon





All Neutralino Lifetime Searches

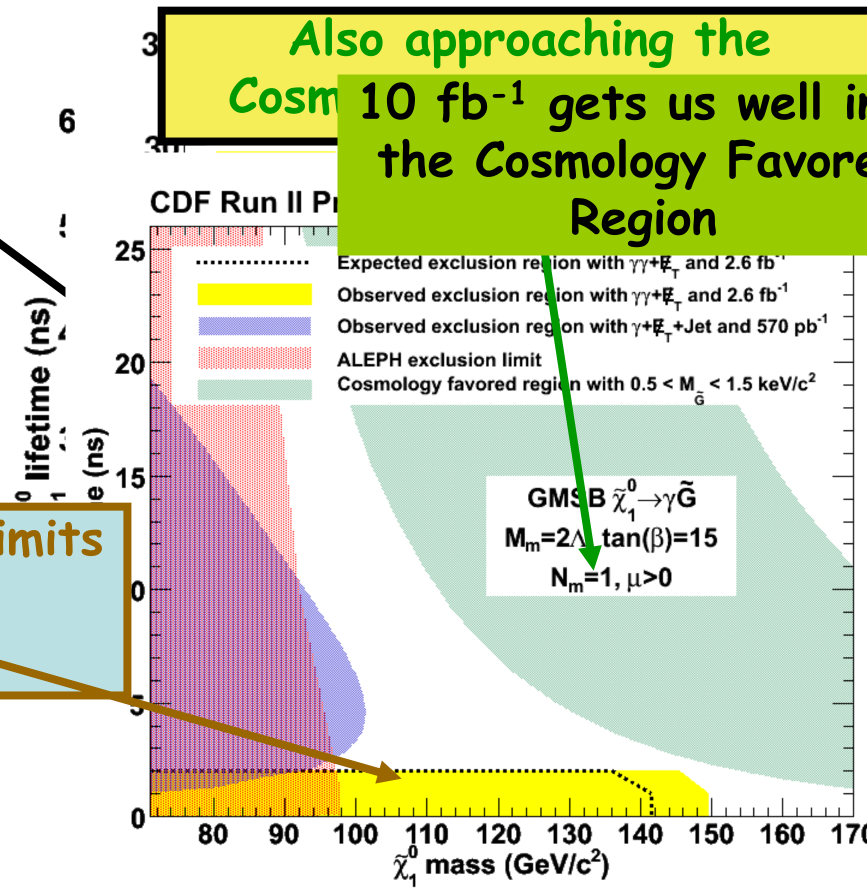


Warm dark matter models of GMSB with $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ favor keV $\tilde{G}$ masses and nanosecond $\tilde{\chi}_1^0$ lifetimes

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

Also approaching the Cosm...

10 fb^{-1} gets us well into the Cosmology Favored Region



CDF, PRL 99, 121801 (2007)

CDF, PRD 78, 0321015 (2008)

Combine $\gamma\gamma$+Met and Delayed Photon Limits
Set limits for zero and
Non-zero lifetimes

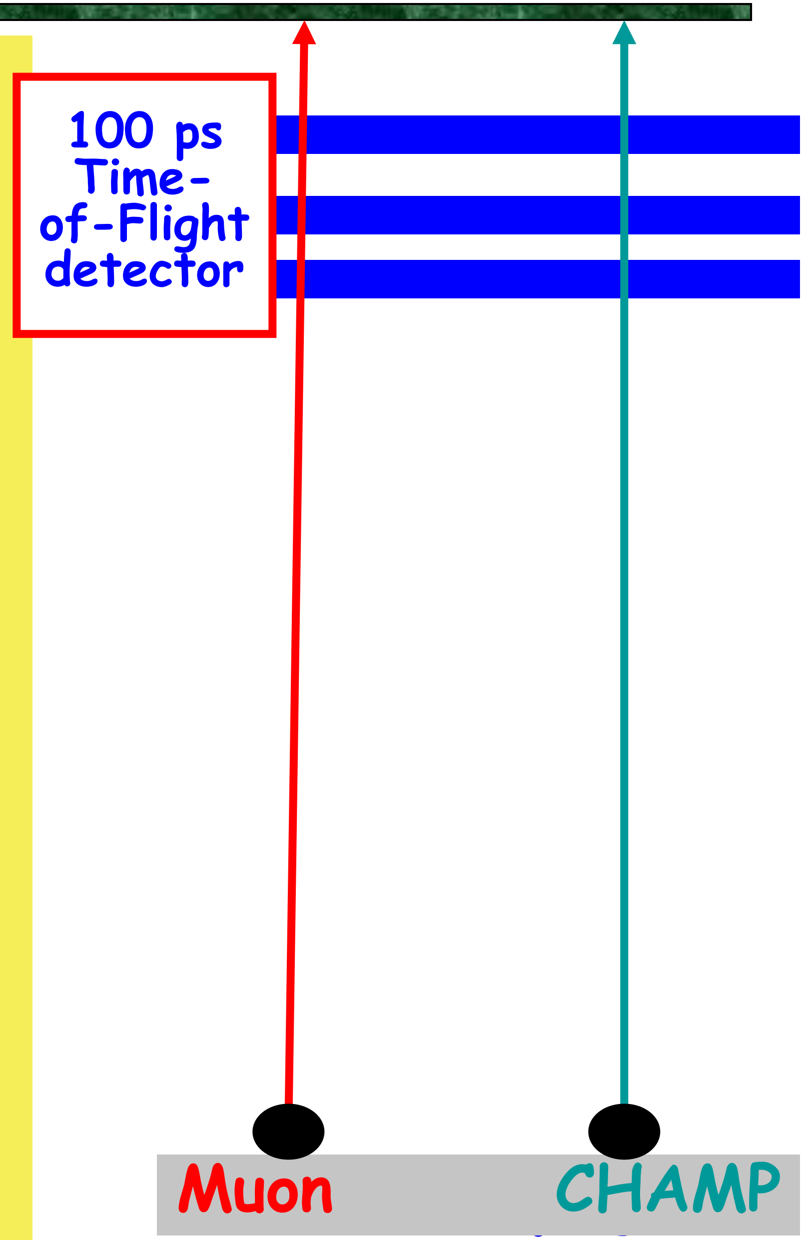
Lots of other possibilities

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)

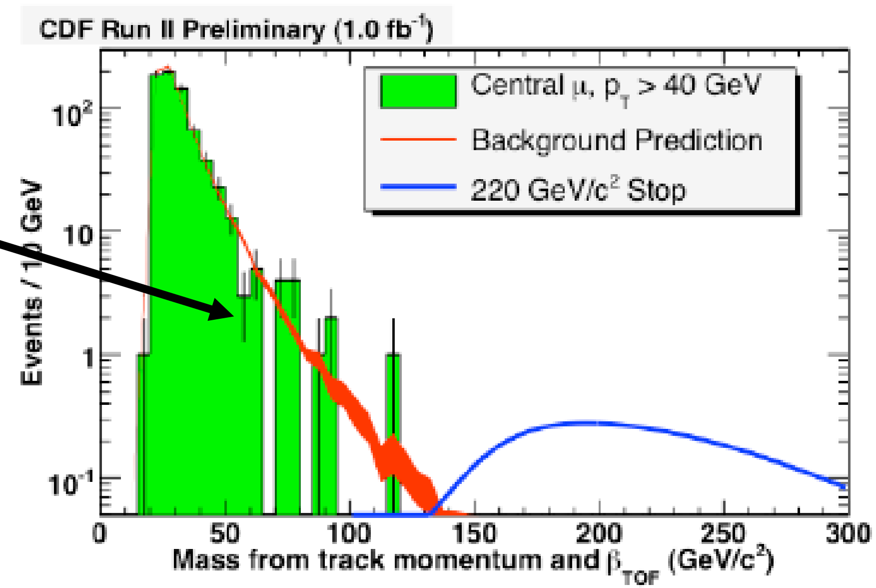
- New emphasis in the theory community about the role of long-lived sparticles in the Early Universe and today as Dark Matter
- Use timing techniques
  - Heavy particles arrive later
  - Can measure the "mass" of weakly interacting charged particles (muon-like)

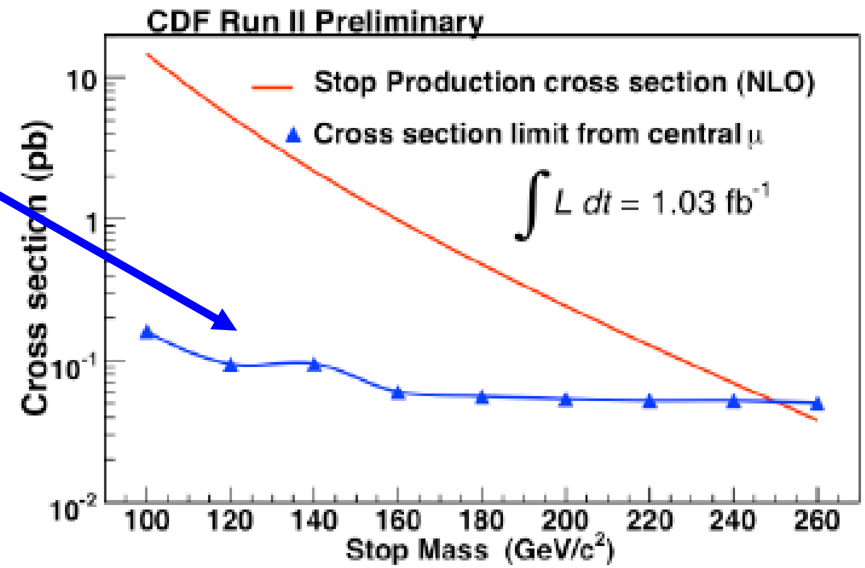


CHAMP Search

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

Accepted for publication in PRL, arXiv:0903.2618

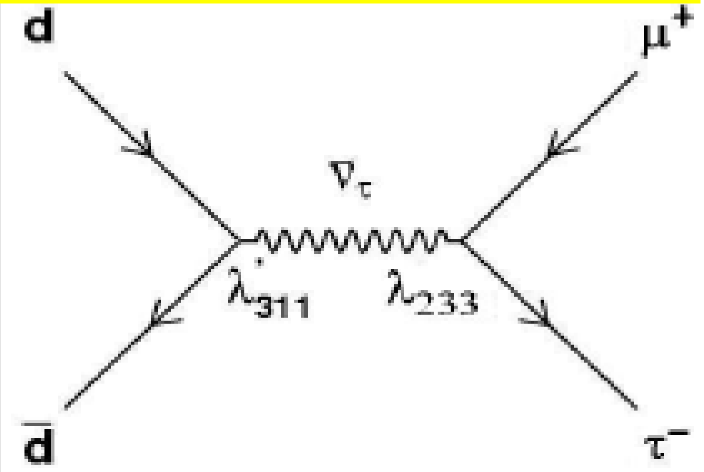


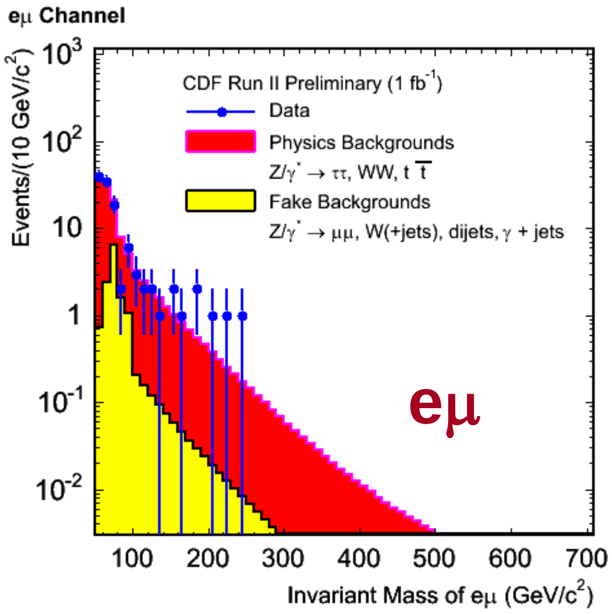


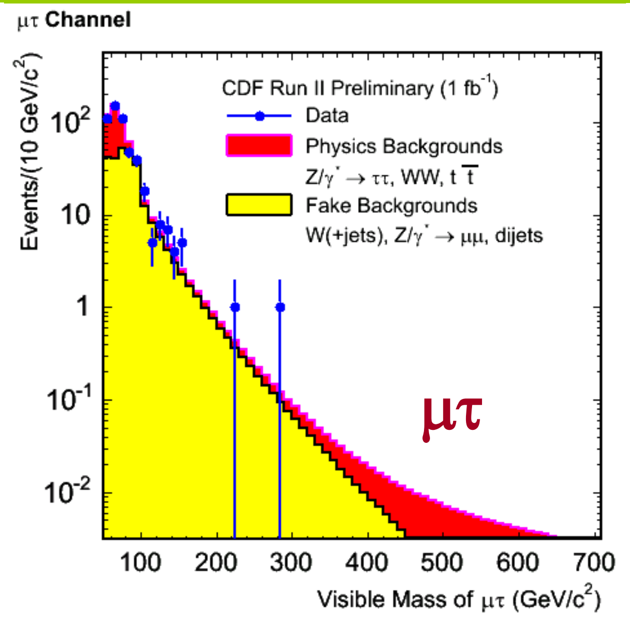
R-Parity Violating SUSY

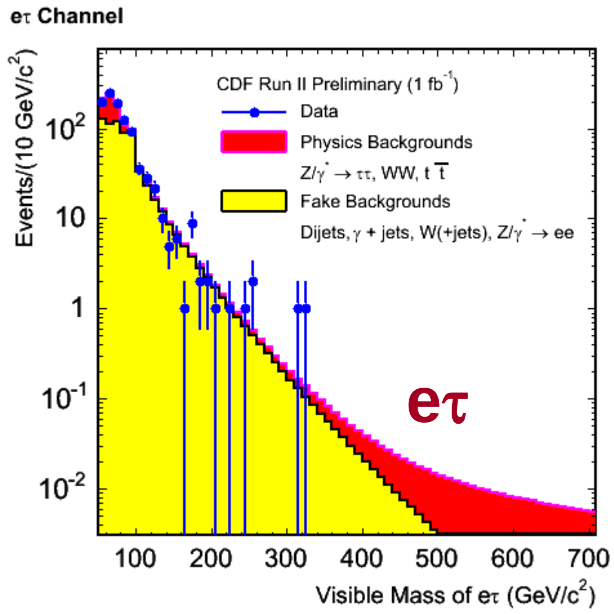
- One advantage of RPV SUSY is that single-sparticle production is allowed
- Decays also depend on the couplings
- Powerful new tau-ID tools

sneutrino $\rightarrow e\mu,\ \tau\mu,\ e\tau$







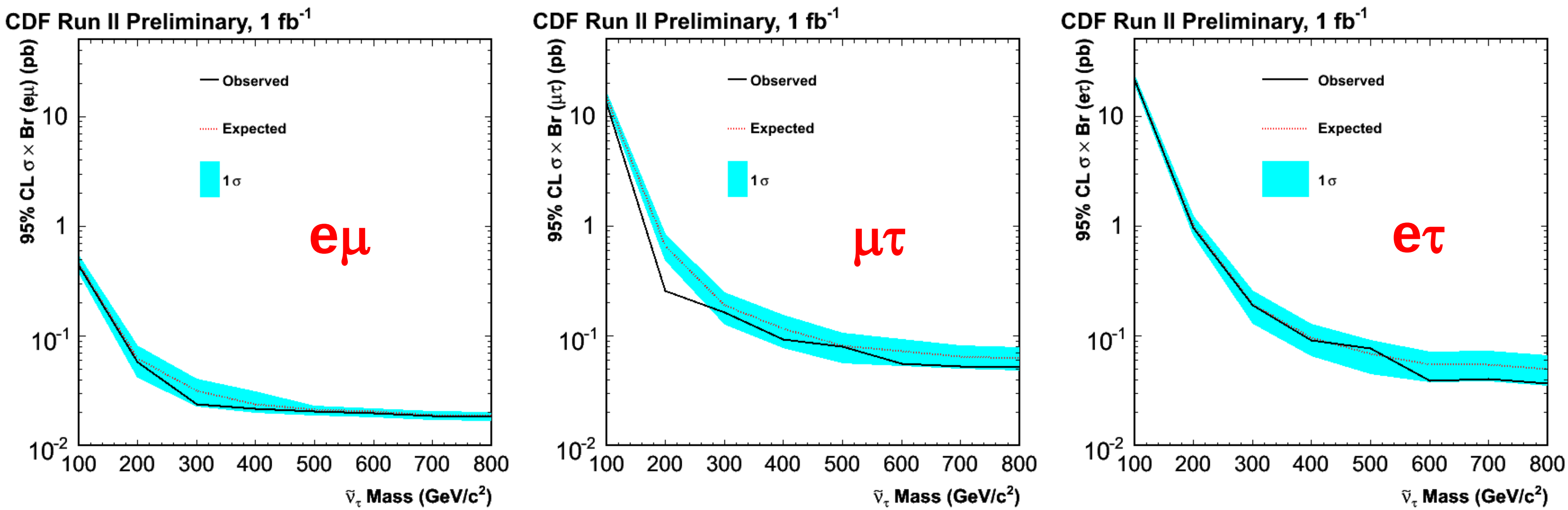


sneutrino →eμ, τμ, eτ

Backgrounds dominated by EWK and W+jet with misidentified leptons

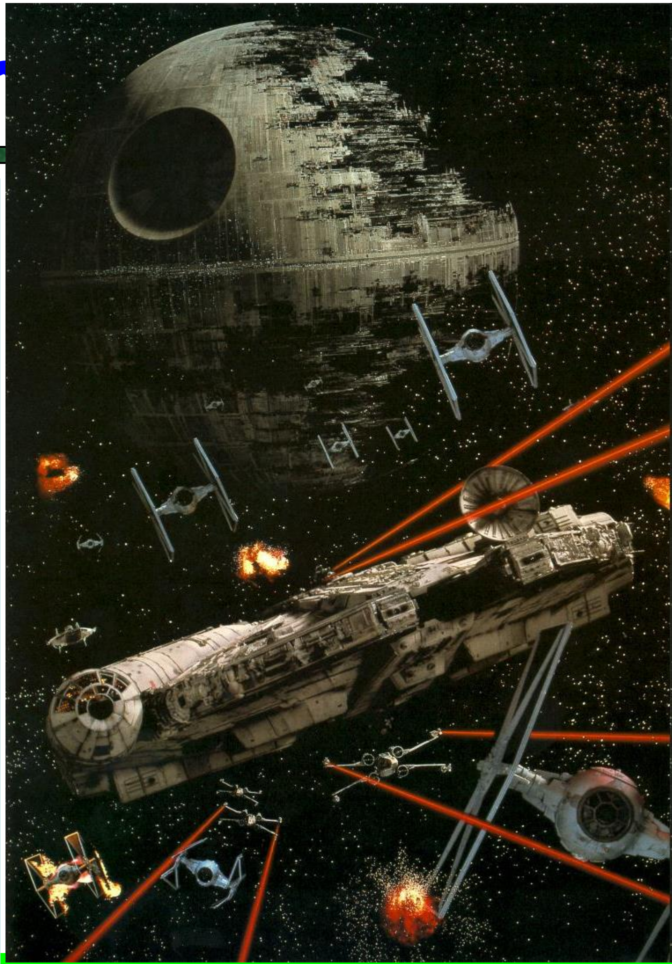
Set limits by extrapolating from low mass region

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



Tevatron Summ

- 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
- For the time being it is still leading the search for Cosmo-Particles

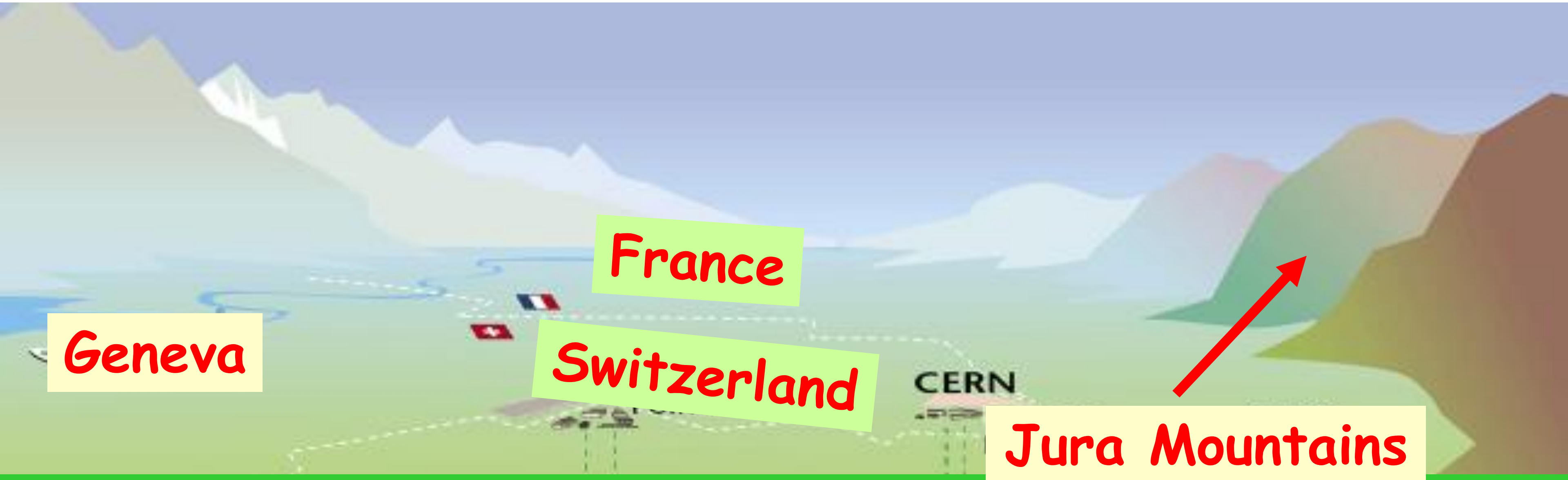


"Don't look back — something might be gaining on you"
-Satchel Paige

From the Tevatron to the LHC

- The Tevatron allows us to look at the conditions of the Early Universe about 1-10 ps after the Bang
  - 100 GeV particles
- The LHC allows us to go about a factor of 10 earlier
  - 1000 GeV particles

Where in the world is the LHC?

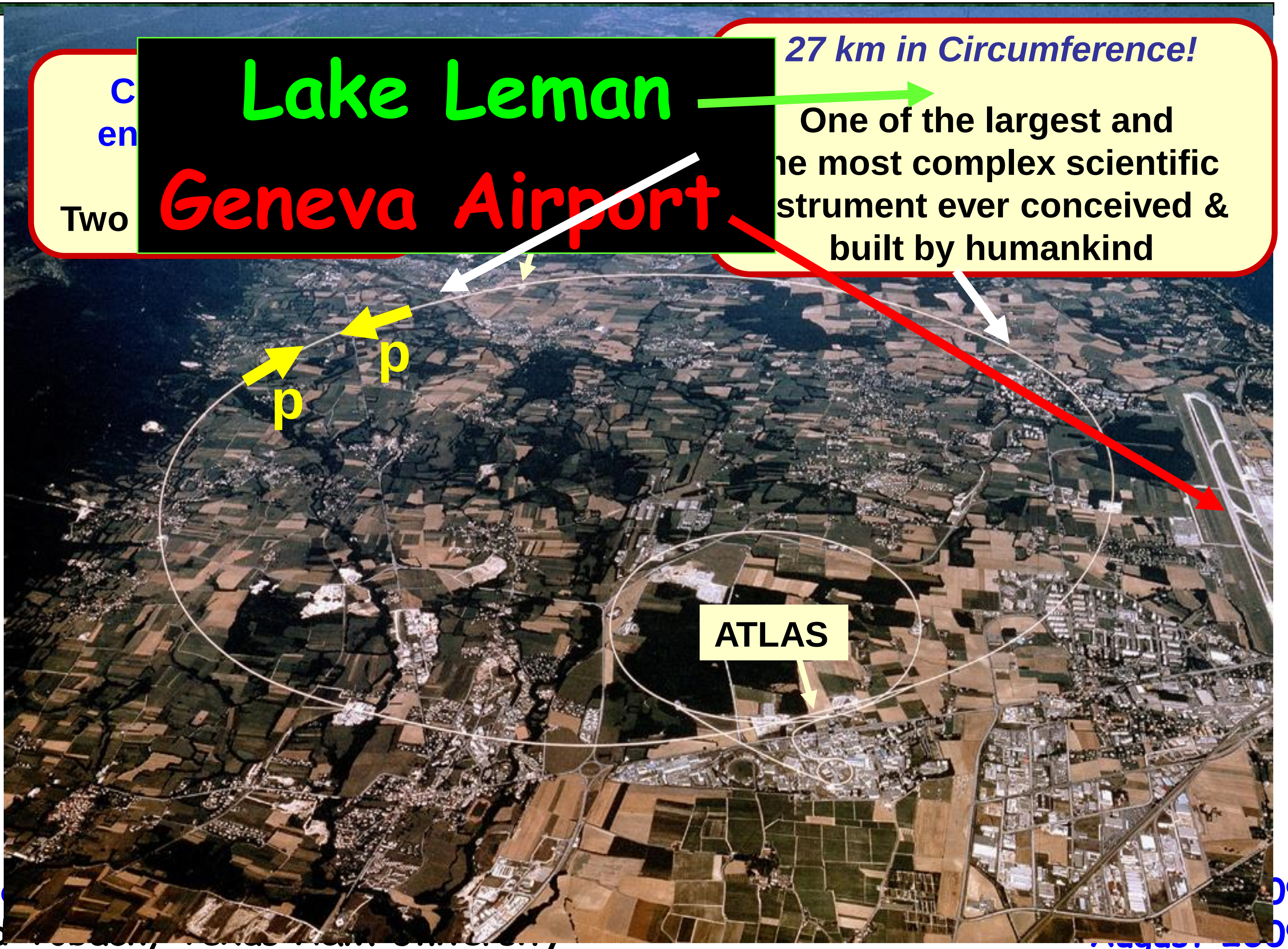


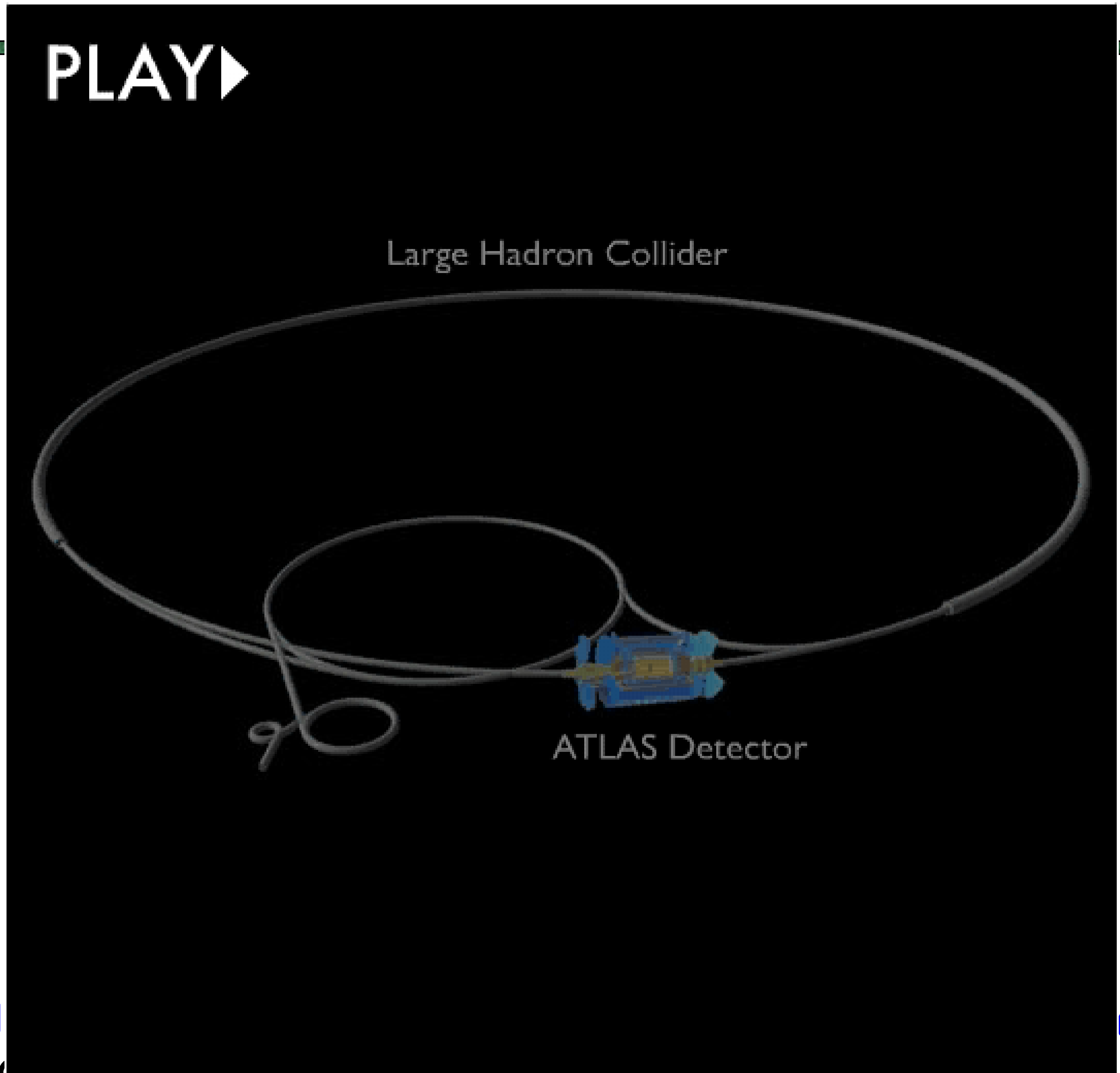
Actually… It's down here

100 meters
Underground!

The accelerator

Another view of the LHC

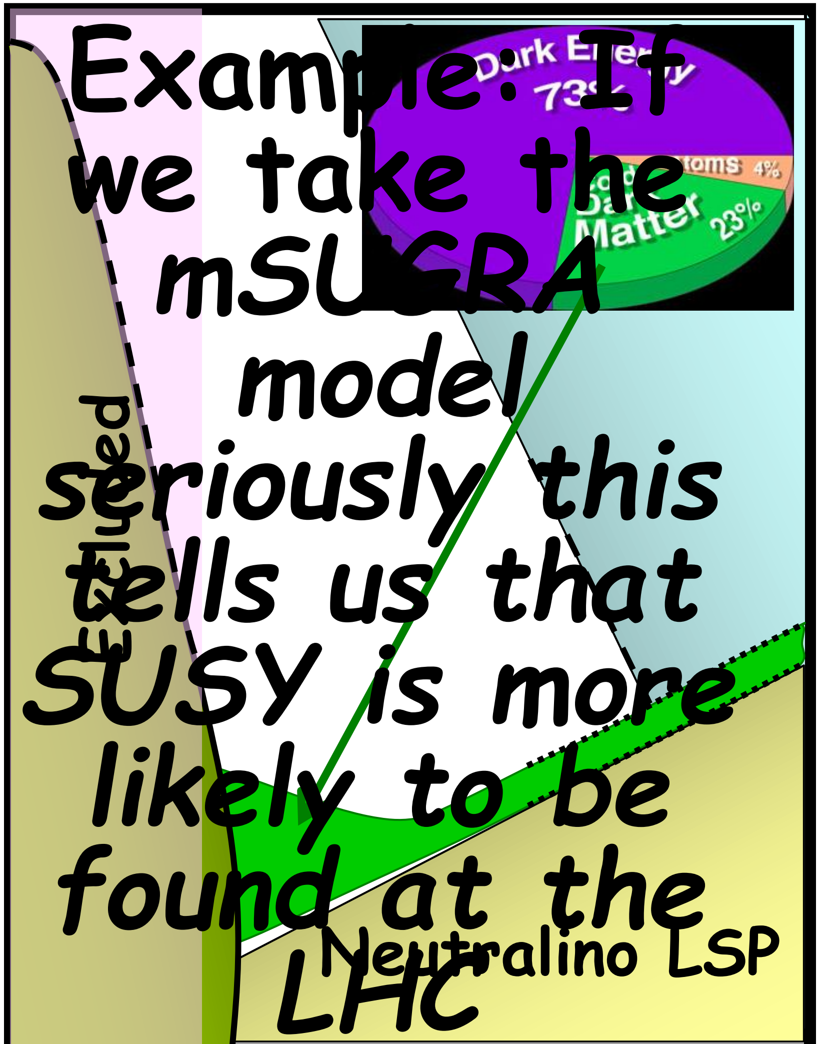



PLAY
Large Hadron Collider
ATLAS Detector

SUSY at the LHC?

- At the LHC energies, using the same techniques we should be able to produce SUSY particles
- Primary difference is Tevatron is Proton Anti-Proton, whereas LHC is Proton Proton → More sensitive to squark/gluino pair production if the masses are accessible

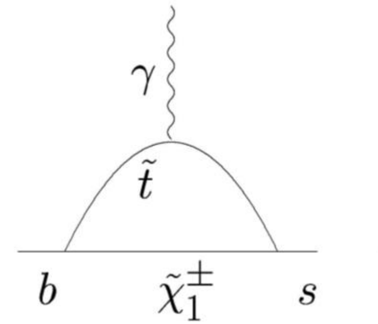
Experimental Constraints on mSUGRA



Example: If we take the mSUGRA model seriously this tells us that SUSY is more likely to be found at the LHC

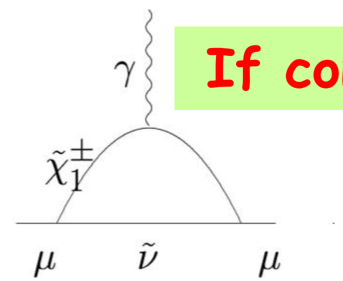
Higgs Mass (M_h)

Branching Ratio $b \rightarrow s\gamma$



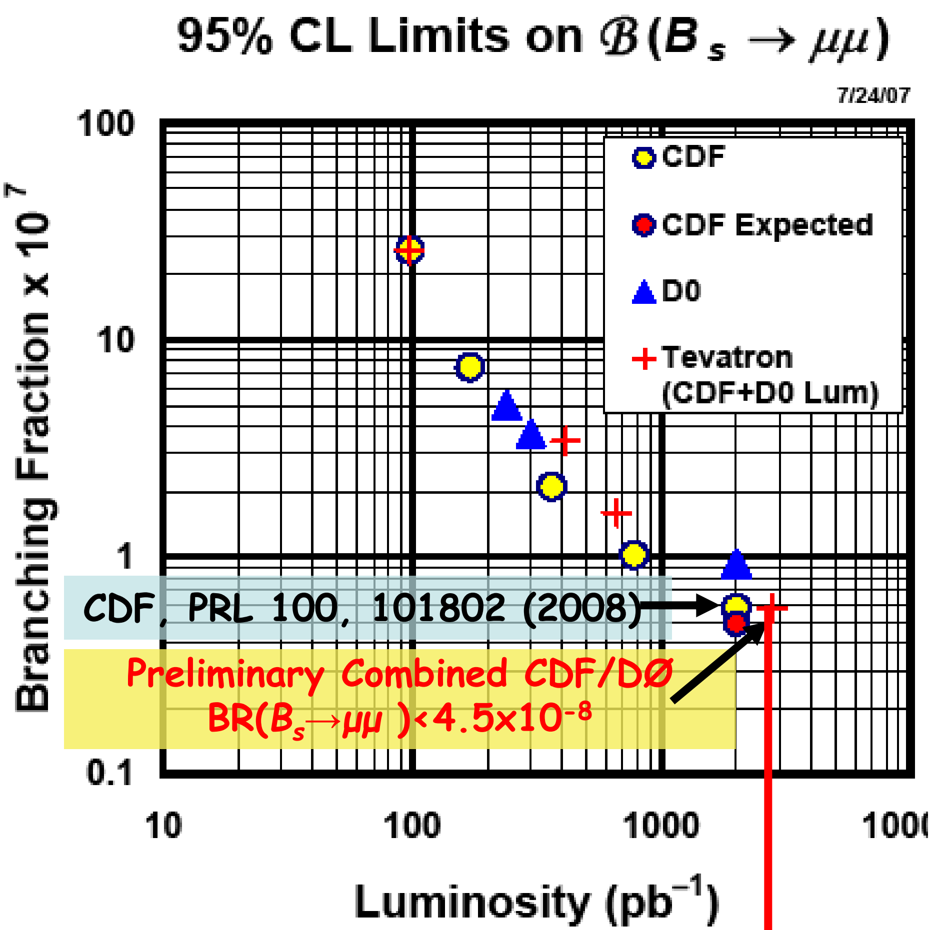
Magnetic Moment of Muon

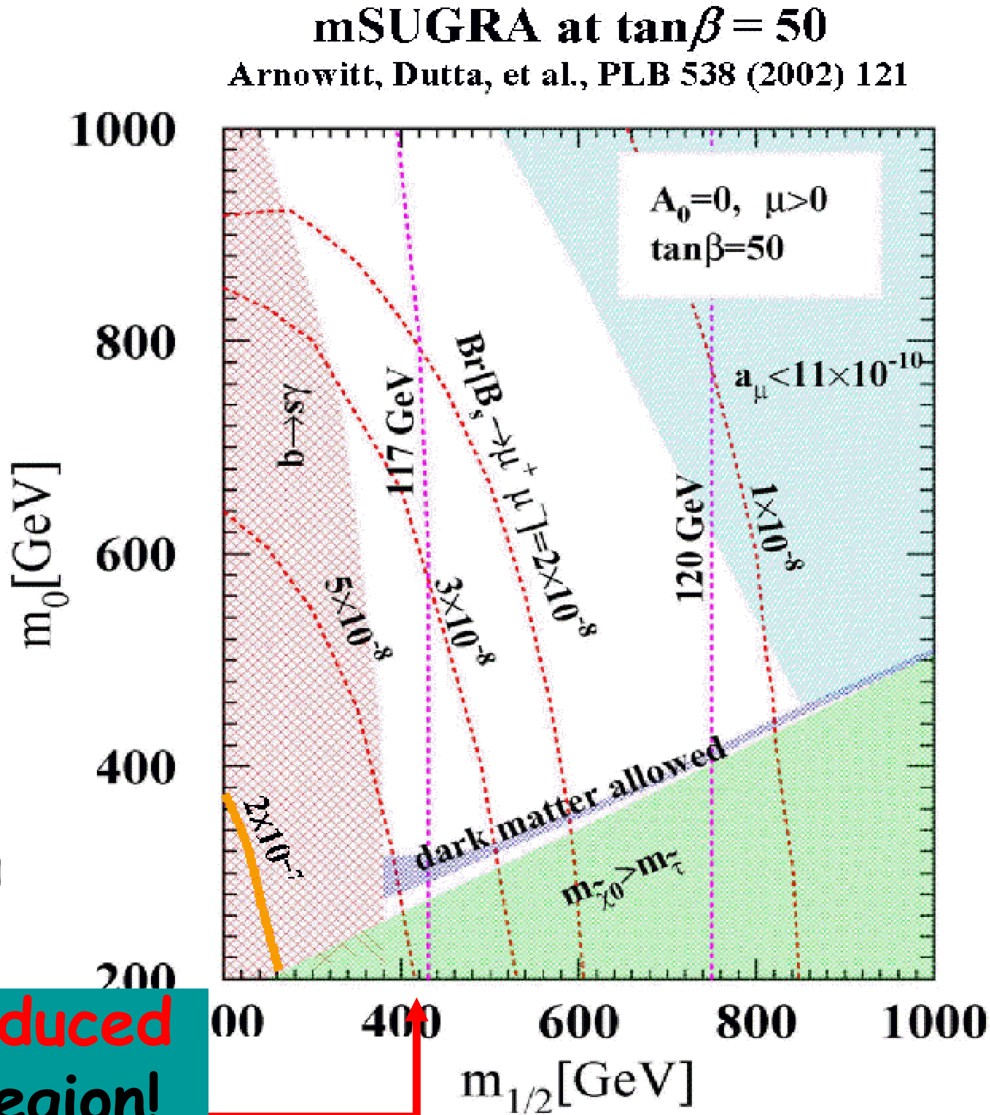
If confirmed…



WMAP Dark Matter Favored region

Only Limits on $B_s \to \mu\mu$ has sensitivity at the Tevatron in these models

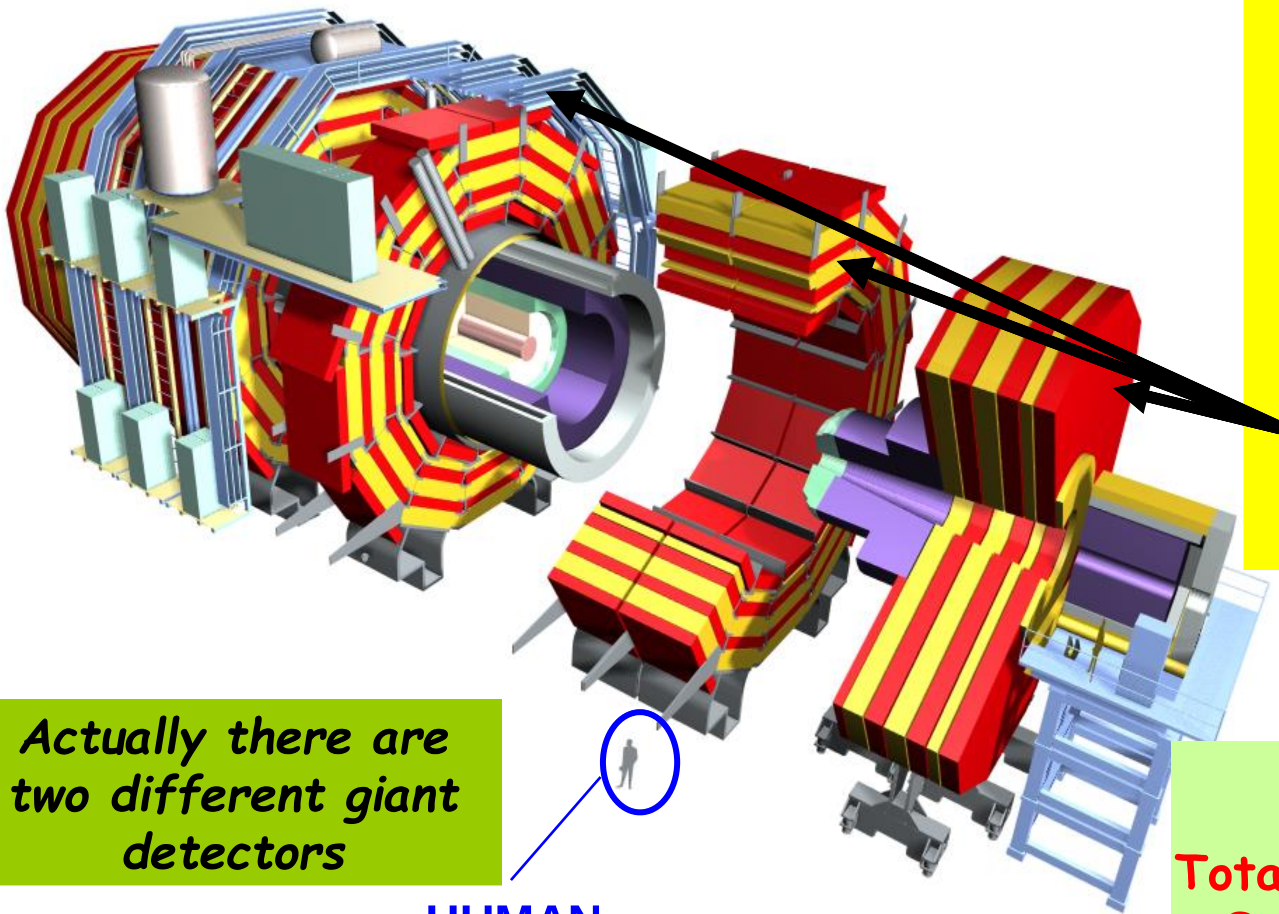




Squarks too heavy to be produced

Just entering the exciting region!

Use a Giant Detector



"Exploded view" of the Detector

All these pieces slide together

Actually there are two different giant detectors

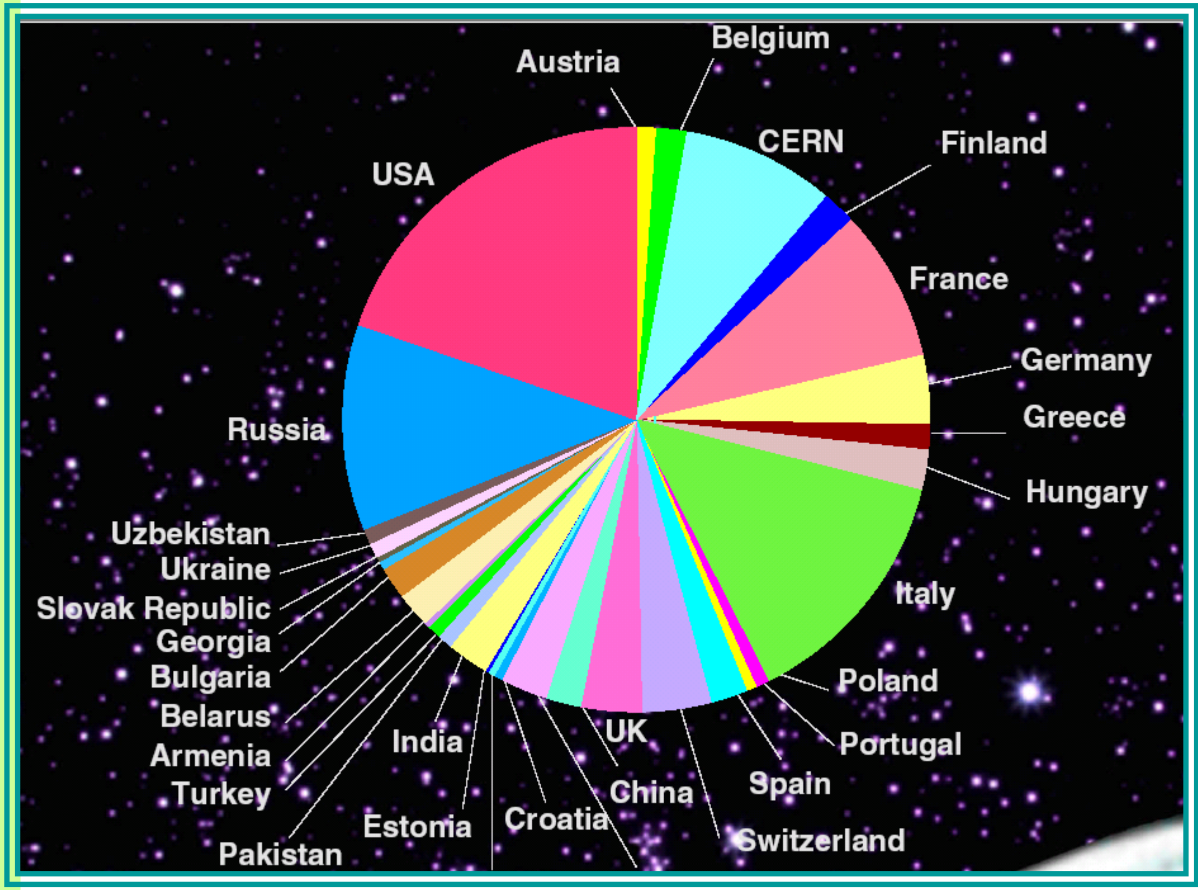
HUMAN

<u>Huge</u>

Total weight: 12,500 tons
Overall diameter: 15 m
Overall length: 21.6 m

International Project

Roughly 2,500 scientists from ~40 countries around the world on this huge project



Everyone is excited!

Detector Spokesperson describing the experiment to Stephen Hawking

From Swords to Plowshares

Workers in Murmansk sitting on brass casings of some decommissioned shells of the Russian Northern Fleet

Used in building the detector!

Hypothetical Timeline

Today: Phenomenologist's use data on both the Dark Matter density and the Standard Model results to constrain SUSY models → Tell the experimentalists at LHC where to look

- 2010-12: First evidence for SUSY particles at LHC
- 2013-15: Establish that we live in a Supersymmetric world
- 2015-2020: Precision measurements of the particle masses and SUSY parameters → compare Dark Matter relic density predictions to those from WMAP
- 20?? Compare to Direct Detection methods → *Does the SUSY LSP has the same properties as the dark matter in the Milky way?*

Combining Particle Physics with Cosmology

$$\Omega_{\mathrm{SUSY\ DM}} \stackrel{?}{=} \Omega_{\mathrm{CDM}}$$

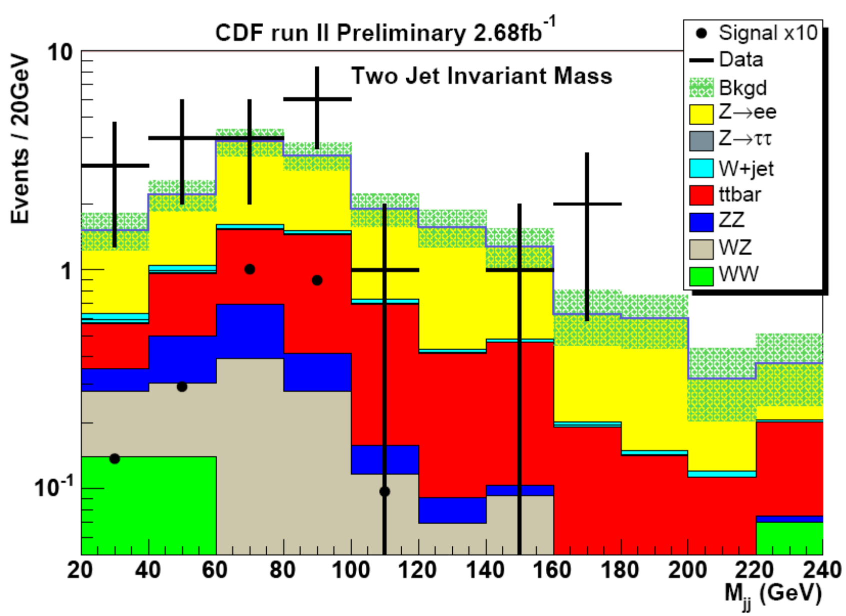
Conclusions

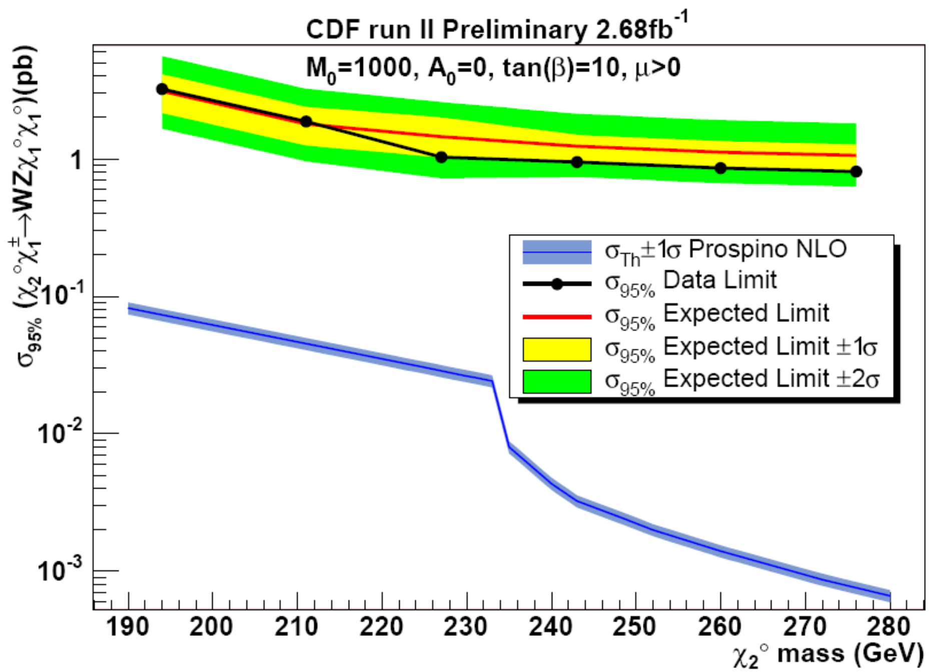
- The Tevatron continues to produce first class results, but the LHC, our "$9 Billion window to the Universe", is about to start taking lots of data
- If our understanding of Cosmology and Particle Physics are correct then we know what we are looking for and what it should look like in our detectors!
- Maybe something even *more interesting* will show up as we recreate and study the conditions <u>right after</u> the Big Bang in collider experiments
- The future is bright for Cosmo-Particle Physics! But, we have a lot on our plate as the LHC data starts to come in!

Lots of Gaugino Pair Searches

Another possibility is to look for

Very Heavy Gauginos→WZ+Met→eejj+Met





No evidence of new physics → set limits