The Search for Supersymmetry at CDF

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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

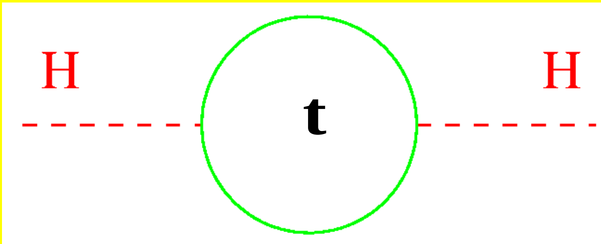
Gauge Bosons → Gauginos

Leptons → Sl

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

The hierarchy problem and how SUSY helps

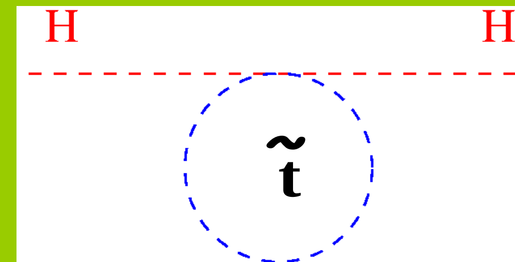
The Standard Model



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

$$\delta m_H^{\,2} \approx \Lambda^2 >> m_H^{\,2}$$

Supesymmetry



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

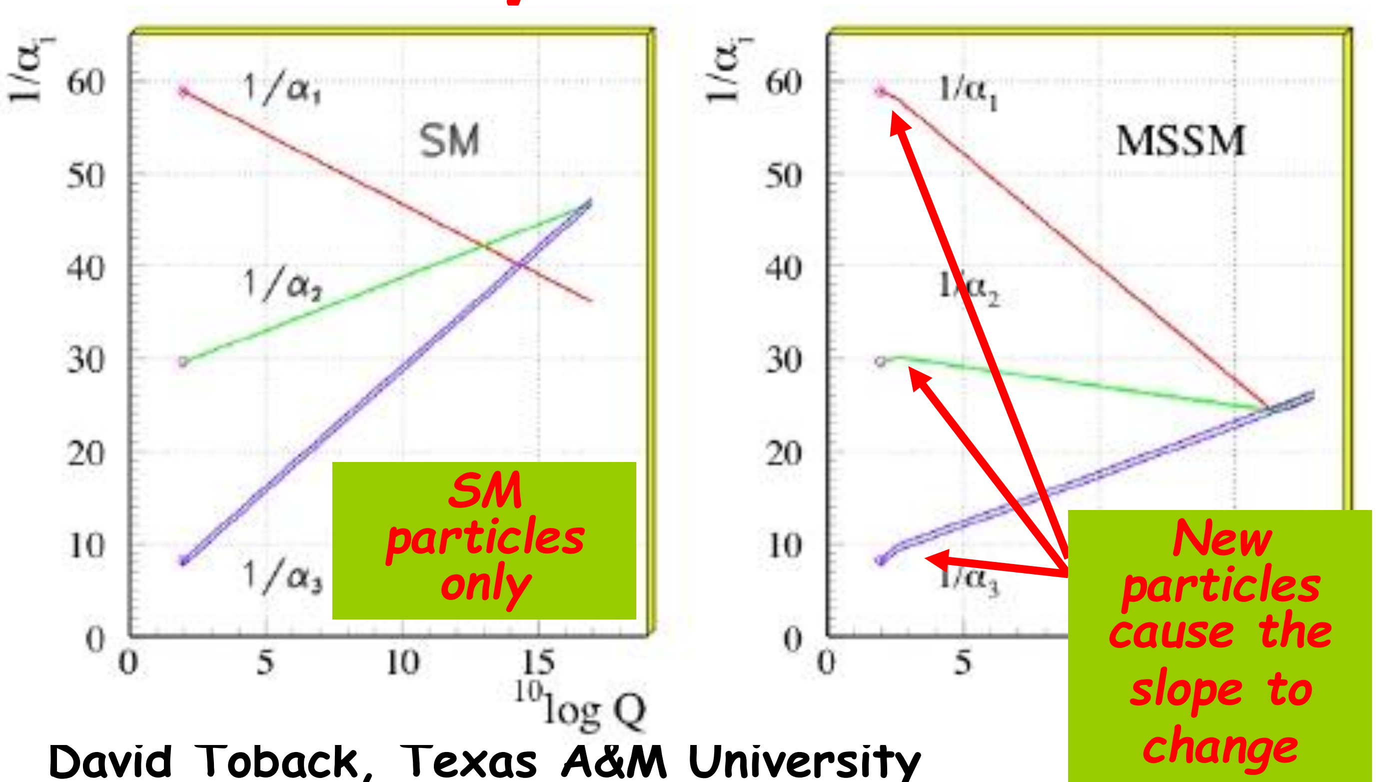
$$\delta m_H^{\,2} \approx O\left(\frac{\alpha}{\pi}\right) \times \left(m_B^{\,2} - m_F^{\,2}\right)$$

$< \mathrm{TeV}^2$

The one loop divergences will cancel, provided that the SUSY particles have masses below the Fermi scale

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



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

- There is no unique explanation of the symmetry breaking → need to 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
- R-Parity violating terms would also have to be small for lepton number violation and still allow neutrino mixing

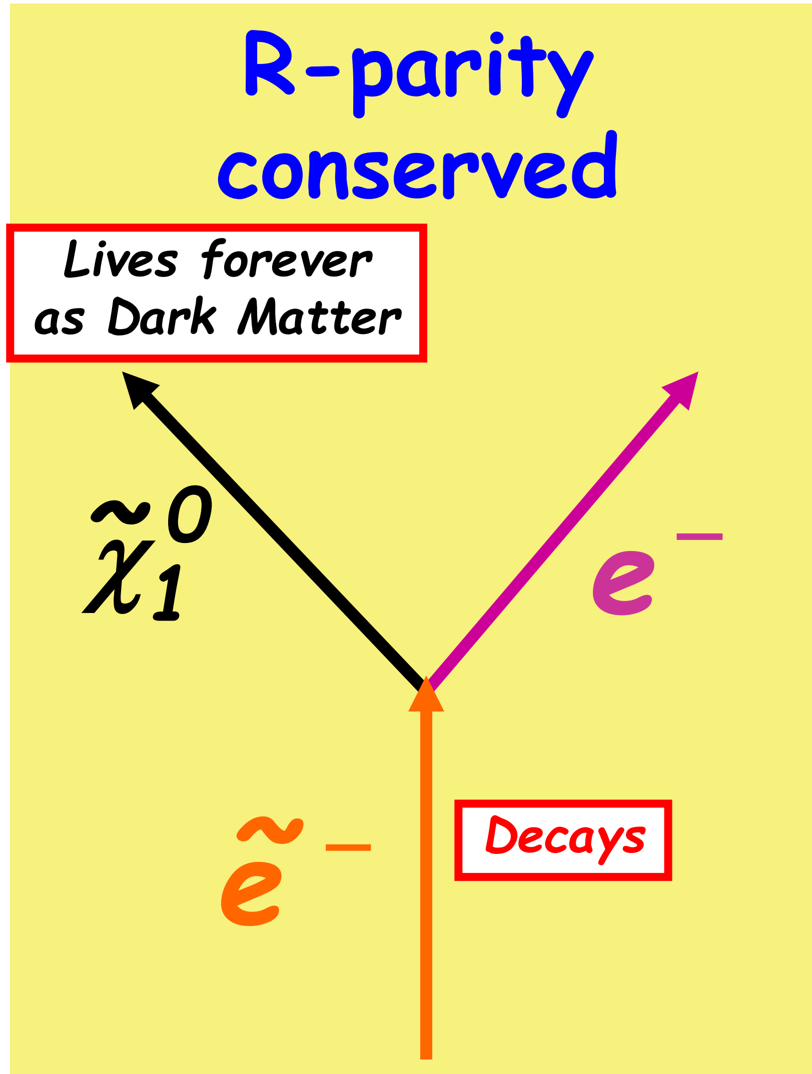
SUSY can provide a Dark Matter Candidate

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

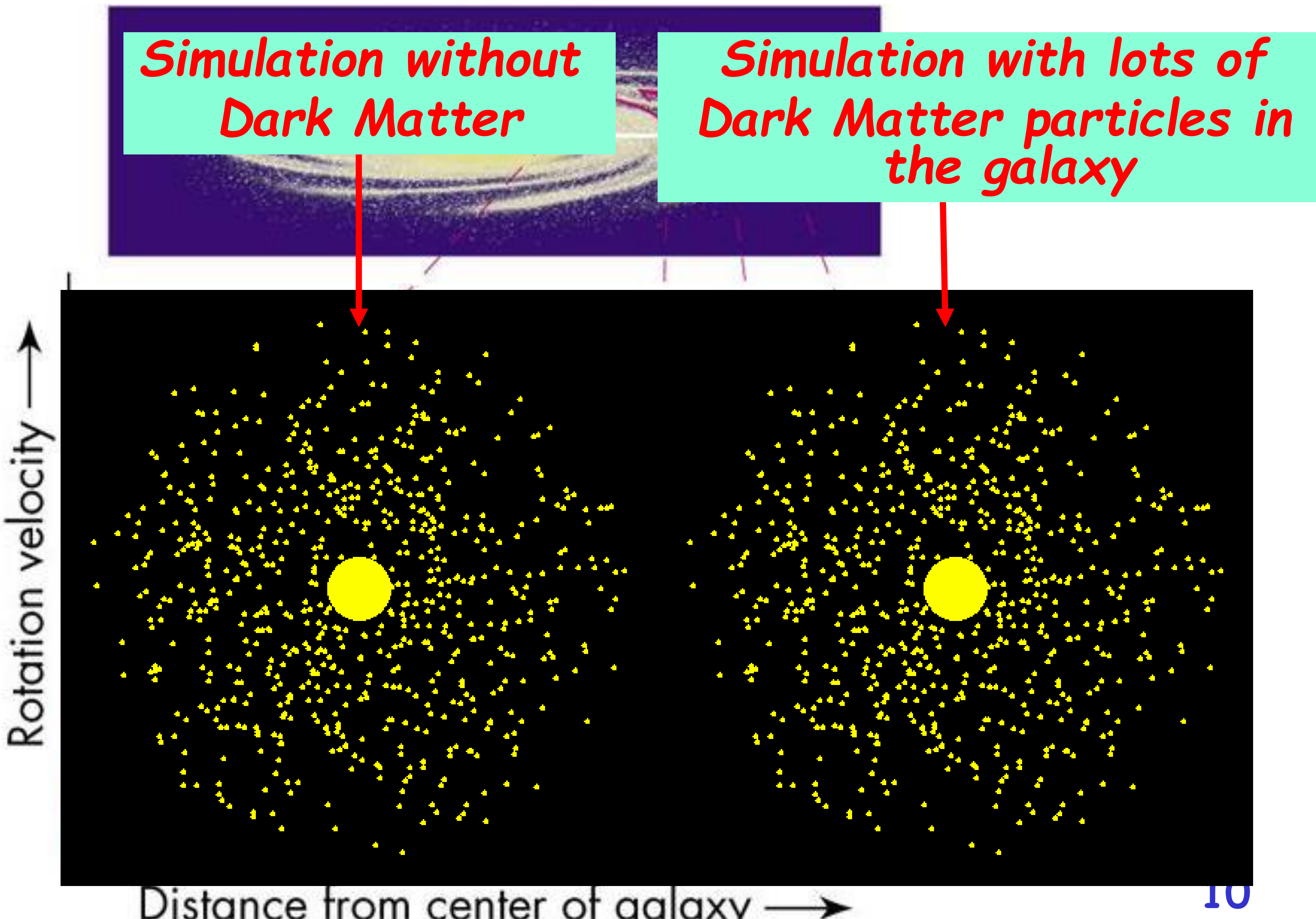
→Provides an excellent dark matter candidate

Worth saying a few words on the potential ties between Dark Matter, Cosmology and Supersymmetry

- Rotations of galaxies
- Bullet galaxies

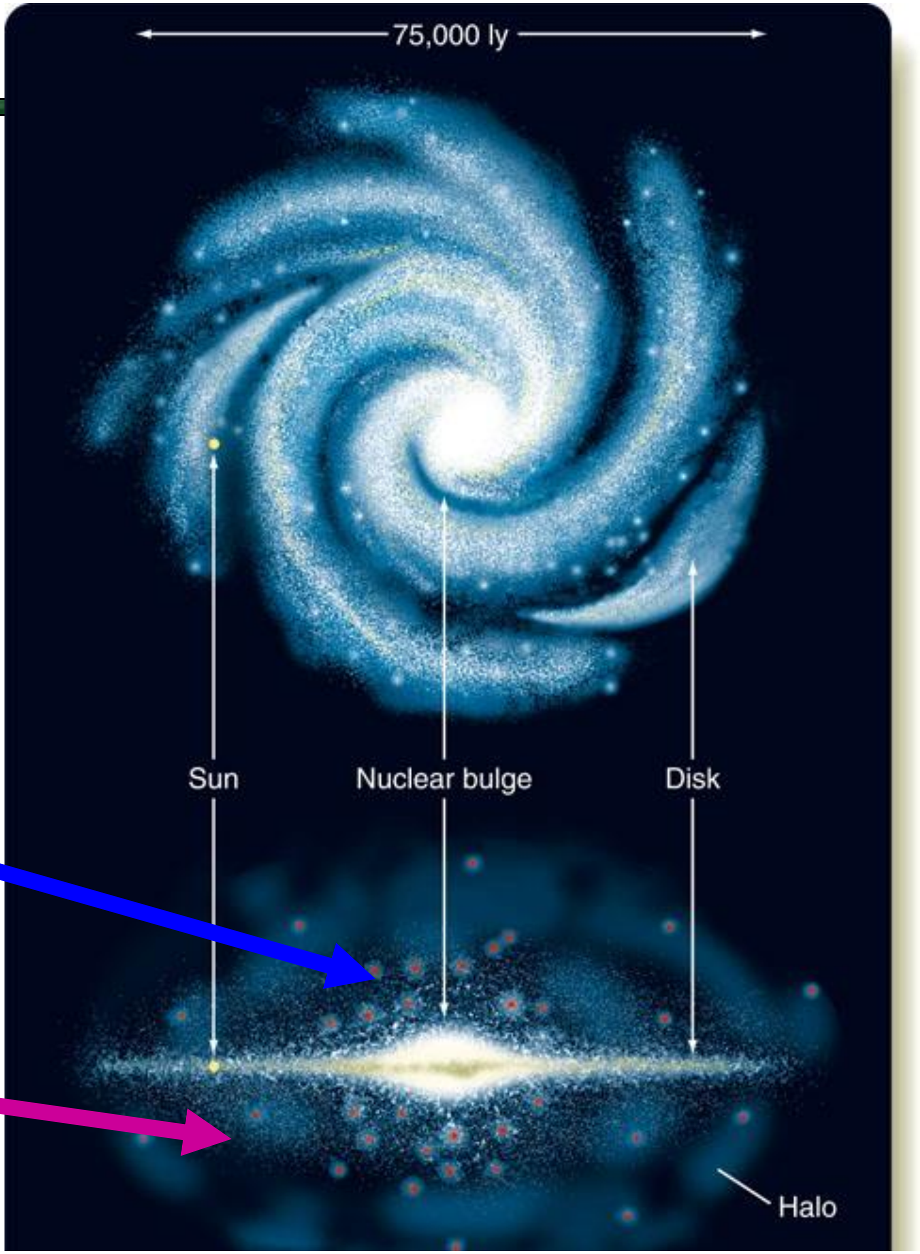


Astronomy: Galaxy Rotation



Dark Matter?

- Data well explained by lots of "Dark Matter" we can't see
- Mostly clumped at the center due to gravity
- Lots of it in a "halo" around the entire galaxy

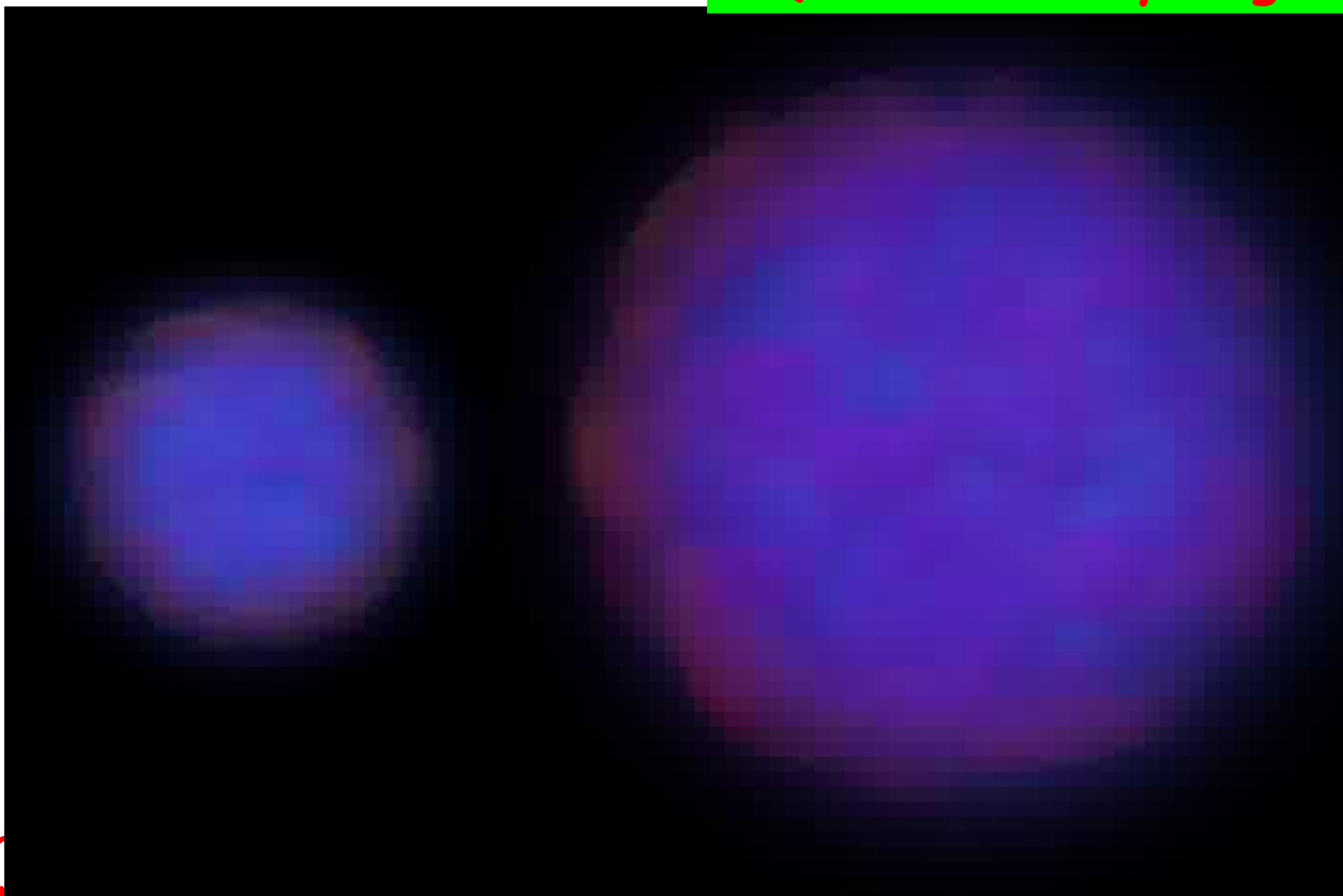


Evidence for Dark Matter as Particles:

Colliding Galaxies

Blue is the Dark Matter

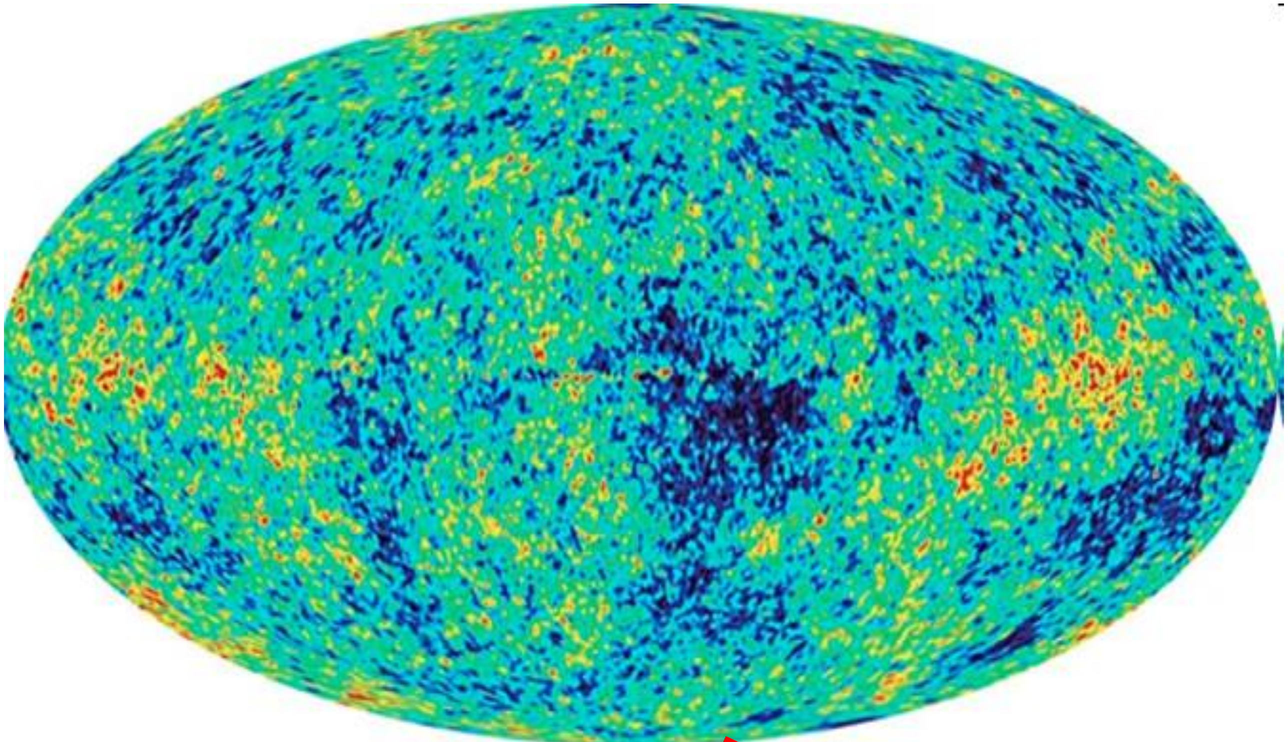
Red is the baryonic matter (Stars and Hydrogen gas)



Particle Physics solution to an Astronomy problem?

- **Good:** Predict massive stable particles that can collect in the galaxy and have an impact on the way it rotates
- **Better:** Provide both a model of particle physics and cosmology that gets the Early Universe Physics correct and correctly predicts the Dark Matter Relic Density

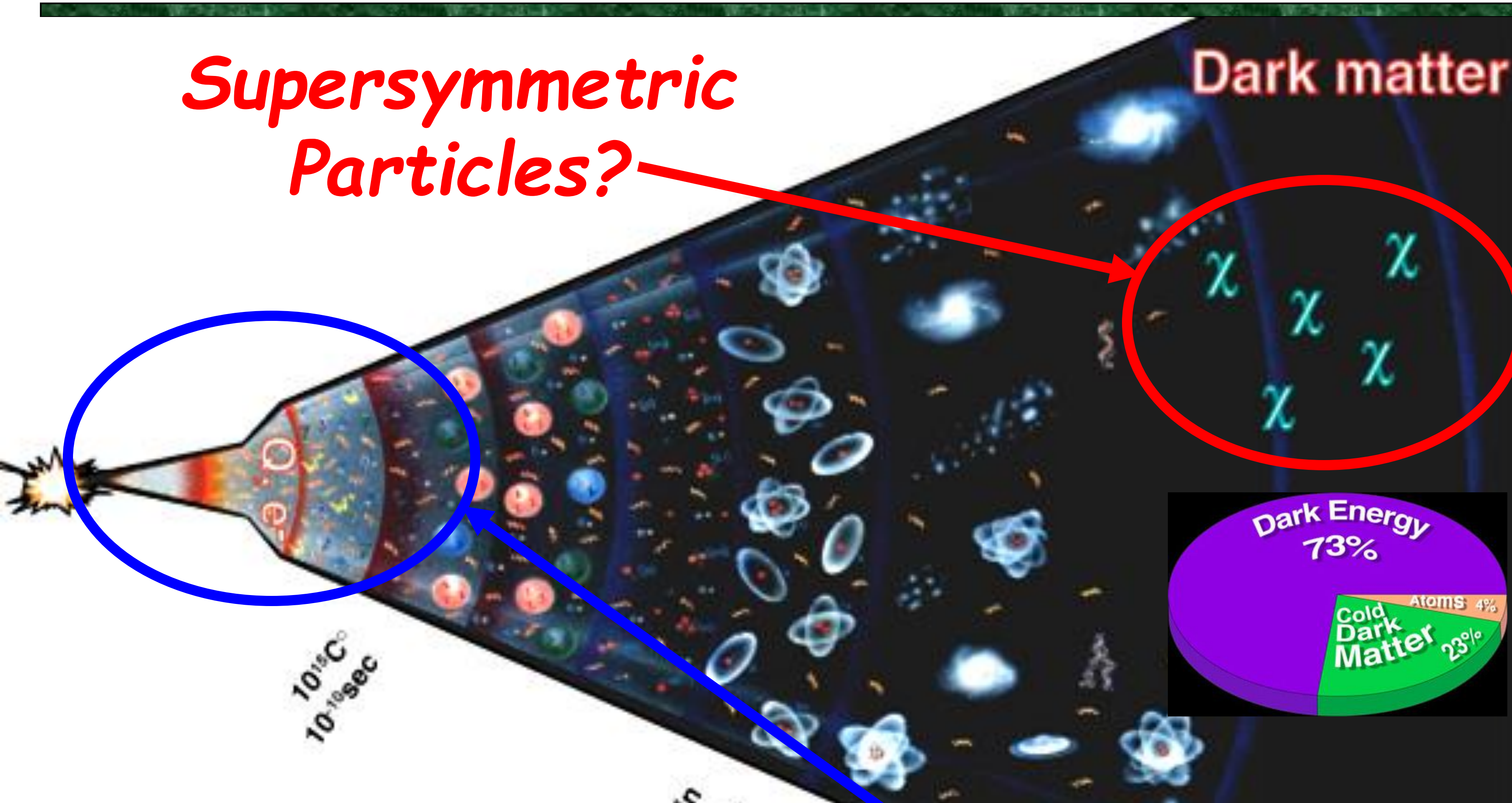
Entering the Era of Precision Cosmology



WMAP data currently measures the Dark Matter density to be $0.94 < \Omega_{DM}h^2 < 1.29$

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

Cosmology and Particle Physics?

Minimal Solution with Cold Dark Matter

- Minimal Solution → A particle produced in the early Universe is stable and weakly interacting → still here today
- CDM favored by most Cosmological models
- Lots of Supersymmetry models have a lightest particle that fits this description
- The minimal SUSY model that incorporates supergravity grand unification is known as mSUGRA → our baseline Cold Dark Matter search model

Non-Minimal Solution with Cold Dark Matter

- Many non-Minimal solutions to the Dark Matter we observe today
- Example: Long-lived Charged particles (CHAMPS) that decay to the Dark Matter

Example: CHAMP

$$\tilde{\tau} \rightarrow \tau \, \tilde{\chi}_1^0$$

Stable on the timescale of inflation	Stable on the timescale of the age of the Universe

Non-Minimal Solution with Warm Dark Matter

Warm Dark Matter also consistent with Astronomical data and inflation models

Example: Gauge Mediated SUSY with

$$\tilde{\chi}_1^0 \rightarrow \gamma \, \tilde{G}$$

Dark Matter is more complicated or has nothing to do with SUSY

- *Axions?*

Look for the most general models including R-Parity violating scenarios

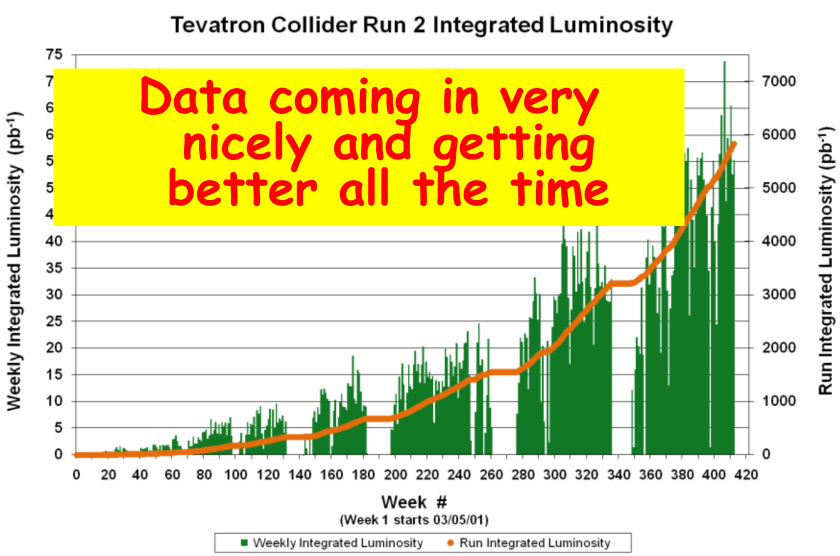
Outline of the Searches

- The Tevatron and the CDF Detector
- mSUGRA Searches
  - Squarks & Gluinos
  - Gaugino Pair Production
  - Indirect Searches
- Gauge Mediated Searches
- Other models
  - CHAMPS
  - R-Parity Violation
- Conclusions

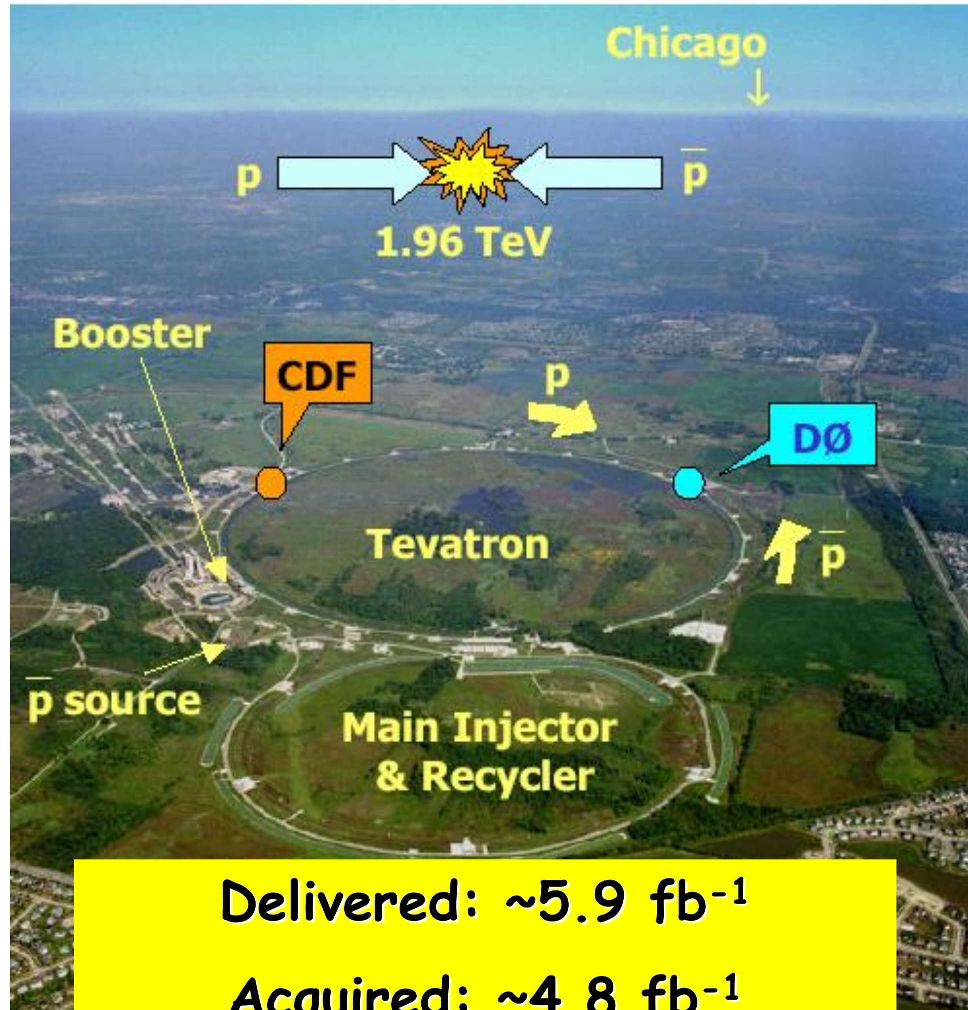
The Fermilab Tevatron

Protons and anti-protons collide with $\sqrt{s} = 1.96$TeV

- The Tevatron is the high Energy Frontier until LHC turn-on
- Rumours of running until 2012 to be complementary to LHC



Data coming in very nicely and getting better all the time



Delivered: ~5.9 fb^{-1}

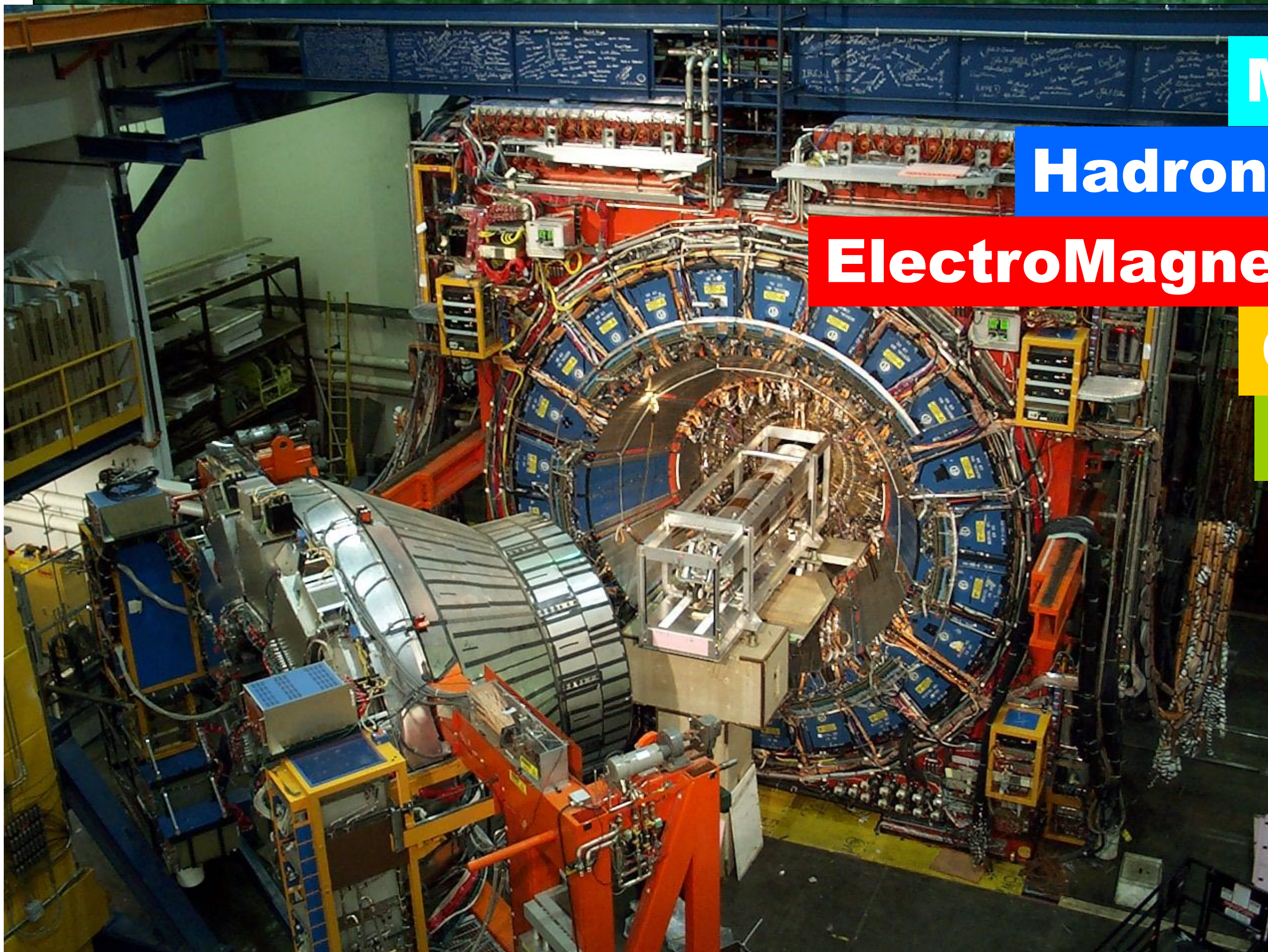
Acquired: ~4.8 fb^{-1}

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

(depending on the analysis)

arche
Texas A&M University

The CDF Detector



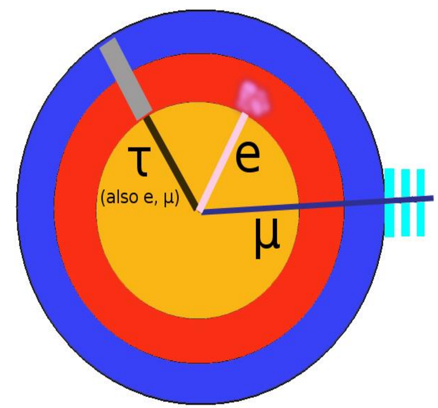
Muon Chambers

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 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

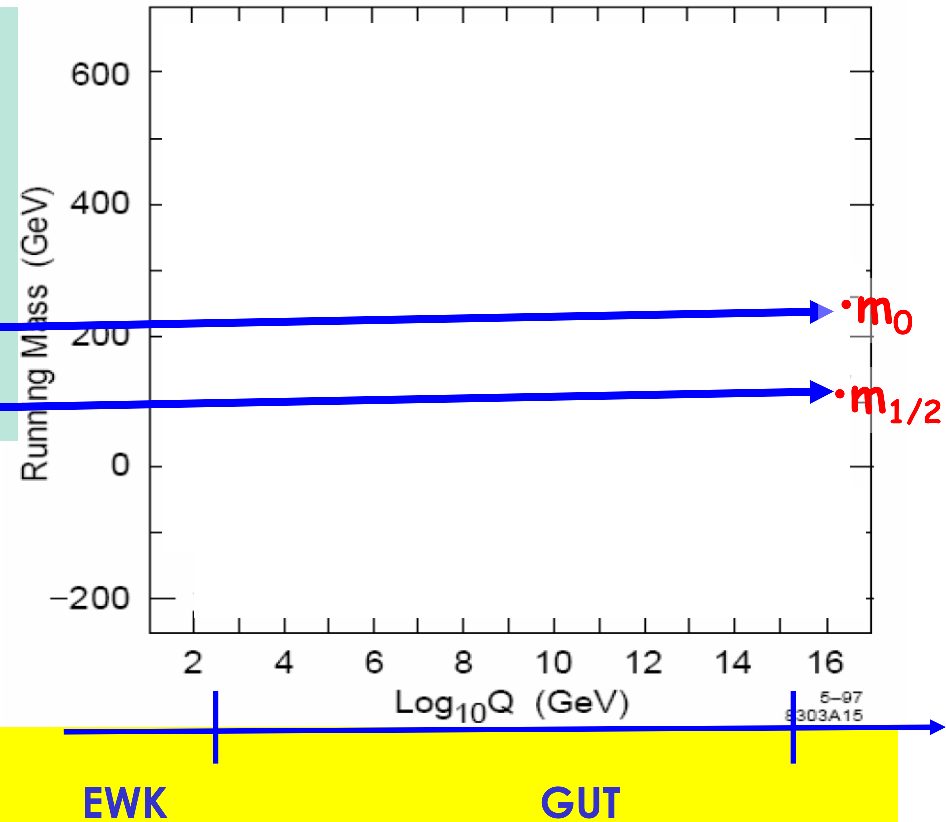
– Yogi Berra

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}
- $\tan\beta$: 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

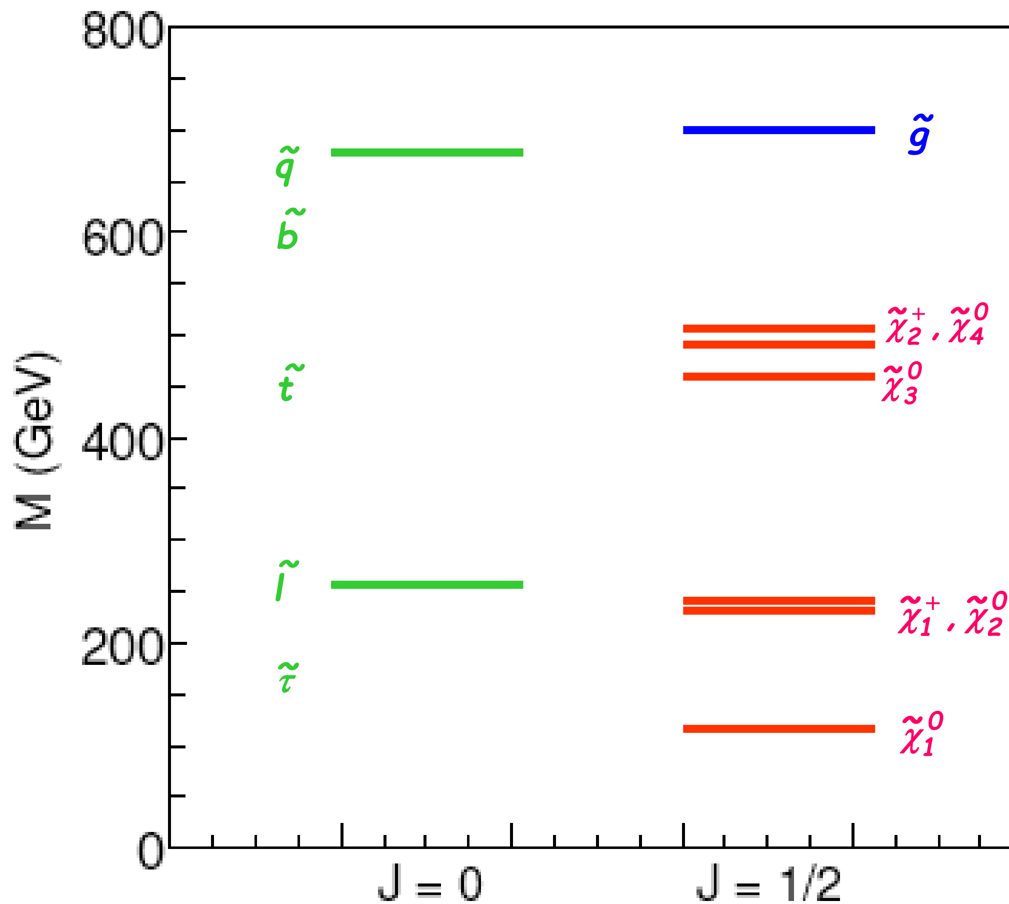
The Sparticle Masses

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 Models (mSUGRA-type models)

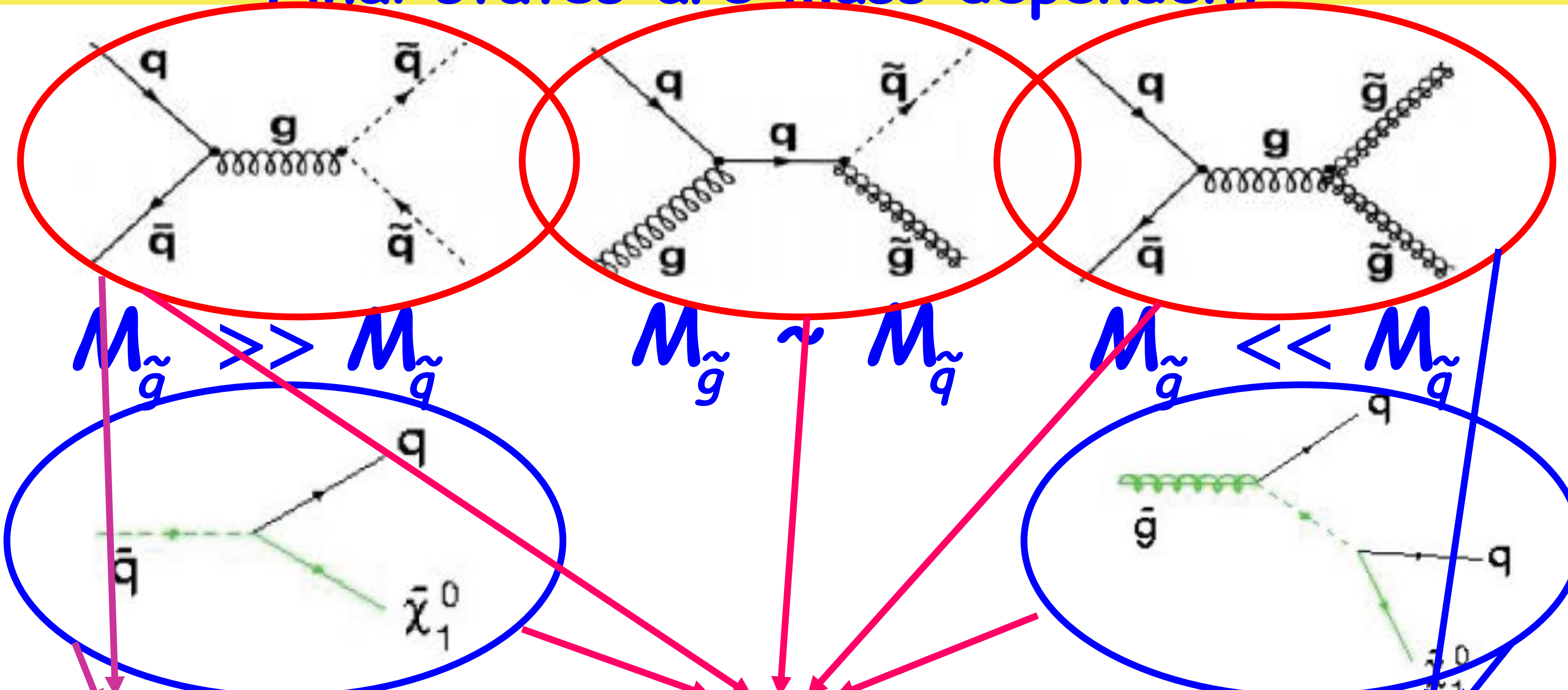
- Direct production of Squarks and Gluinos
  - Heavy, but strong production cross sections
- Direct production of the Gauginos
  - Lighter, but EWK production cross sections, also leptonic final states have smaller backgrounds
- Indirect search via sparticles in loops
  - Affect branching ratios

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

Squark and Gluino Searches in Multijet + Met

Three main production diagrams

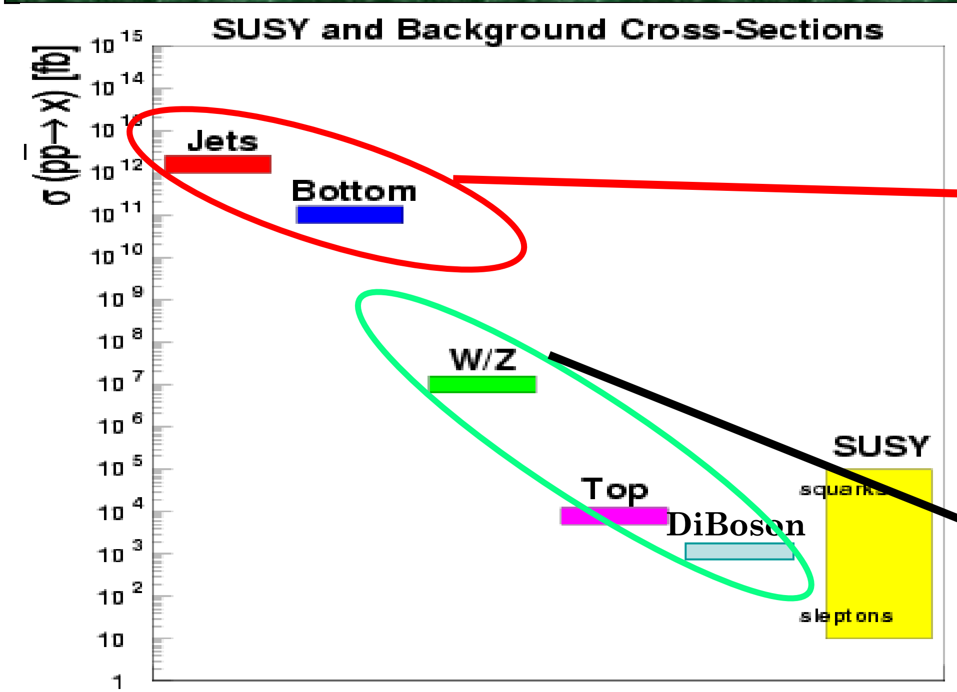
Final states are mass dependent



2 jets + MET | 3 jets + MET | 4 jets + MET

3 separate final states + Unified Analysis → best coverage

Start from difficult backgrounds

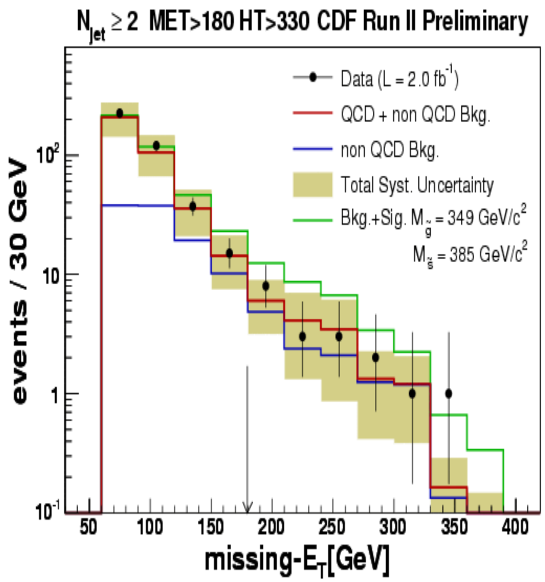


Note: Despite the huge production cross sections only about 25% of the final background is QCD

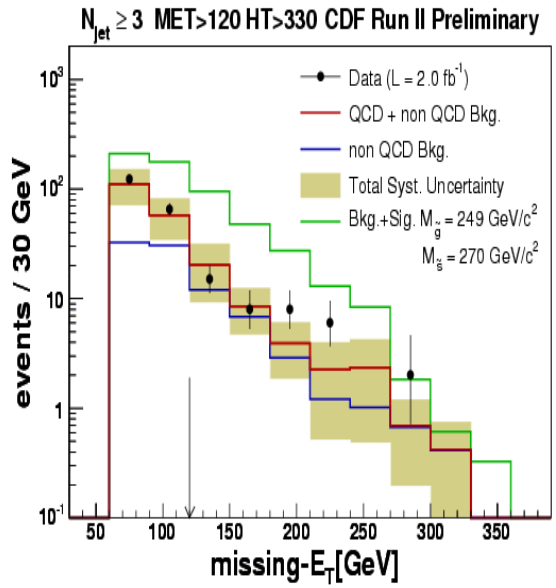
The rest is ttbar and other EWK processes

	2 jets	3 jets	4 jets
Selections	H_T>330, $\not{E}_T$>180 GeV/c²	H_T>330, $\not{E}_T$>120 GeV/c²	H_T>280, $\not{E}_T$>90 GeV/c²
Data	18	38	45
Expected SM	16±5	37±12	48±17

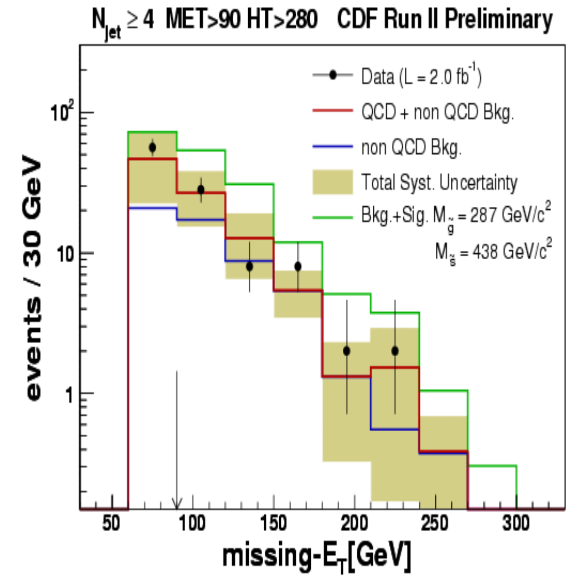
Unified Squark/Gluino Search



2 jets + MET

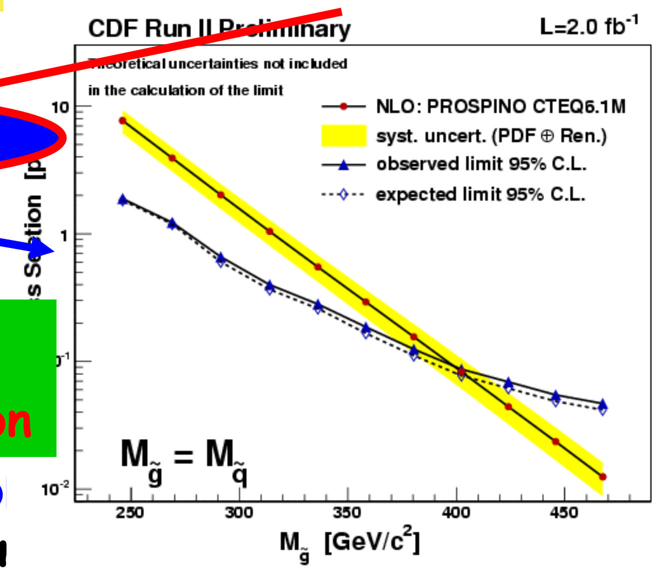


3 jets + MET



4 jets + MET

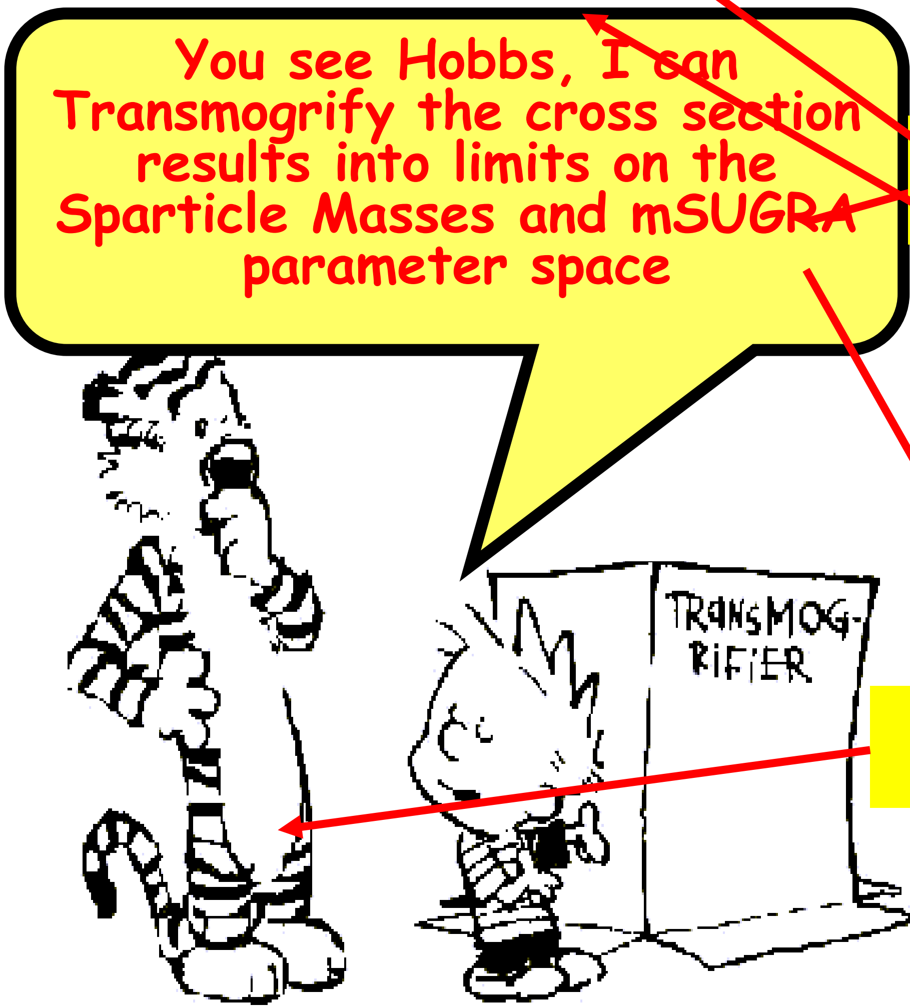
SUSY Interpreter

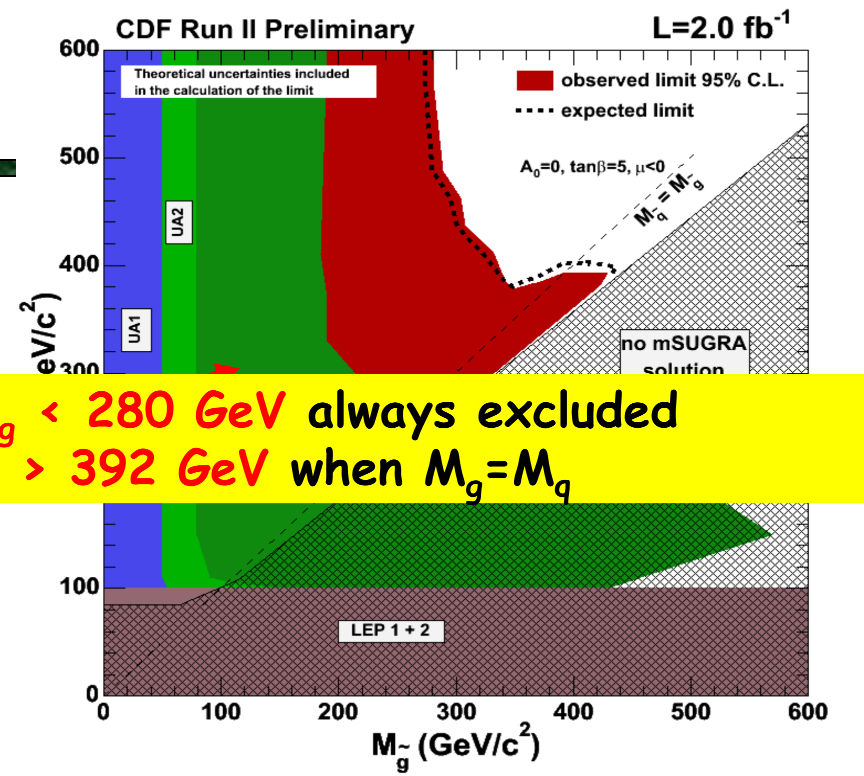


No evidence for new physics

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

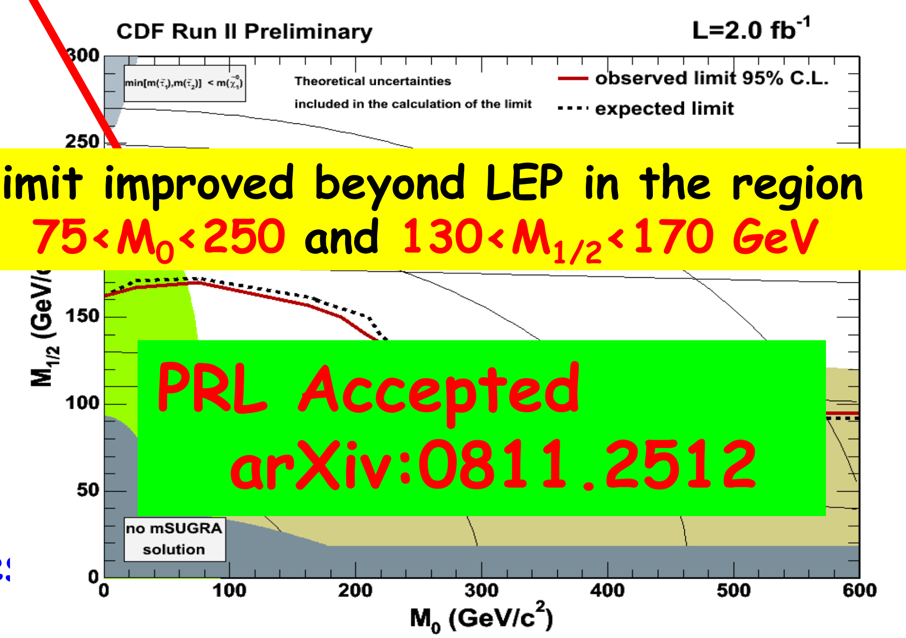
More limits…





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

PRL Accepted arXiv:0811.2512

Gaugino Pair Production in Multilepton + Met

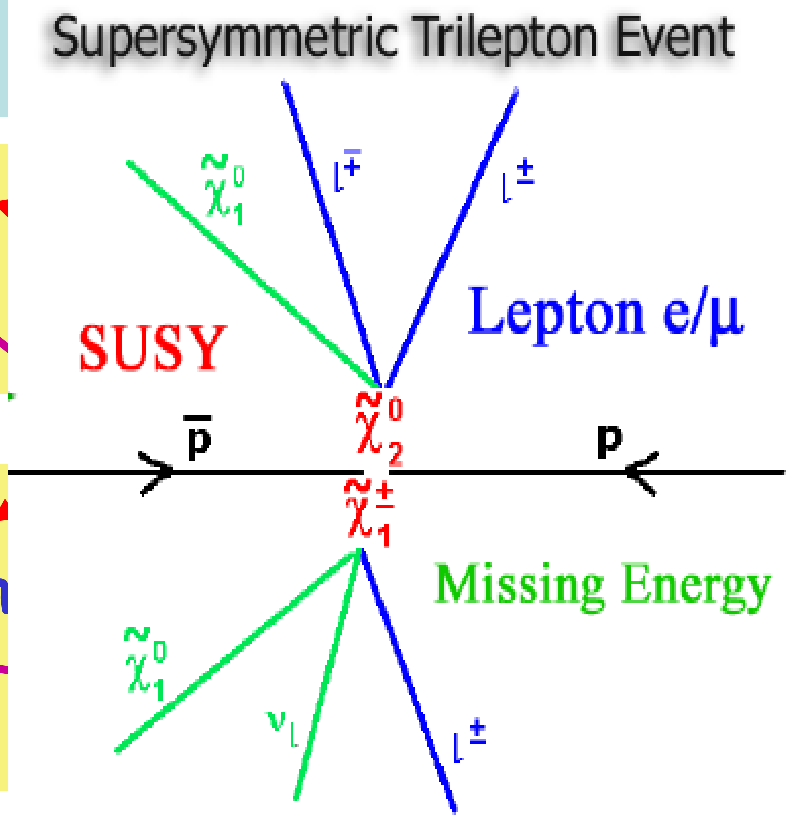
Chargino-Neutralino gives three low P_T leptons in the final state
Dominates the production cross section

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

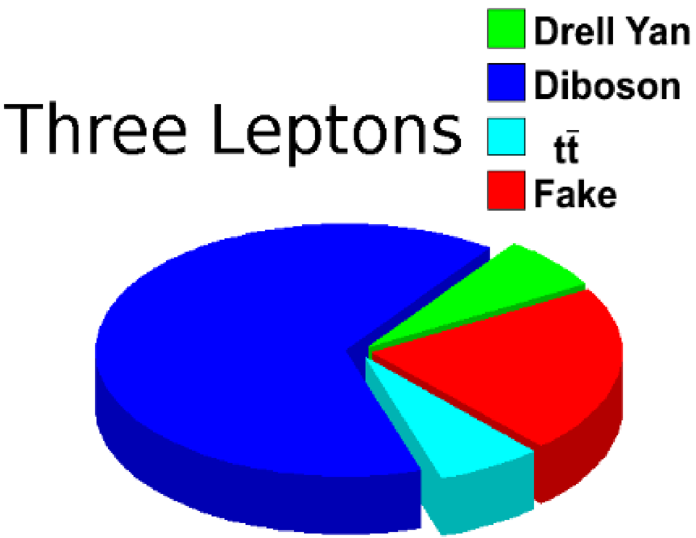
2 Tight leptons
+1 Loose lepton
+ MET

1 Tight lepton
+ 2 Loose leptons
+ MET

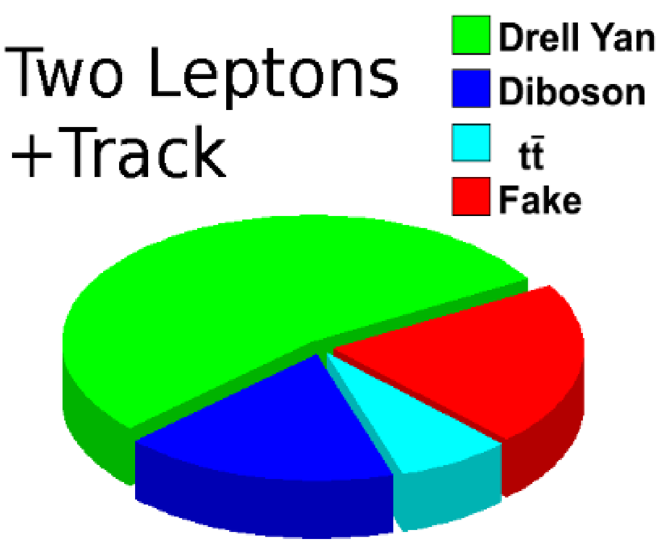
Tight (= high purity) and Loose (=not as high purity, but better efficiency) leptons are e's or μ's

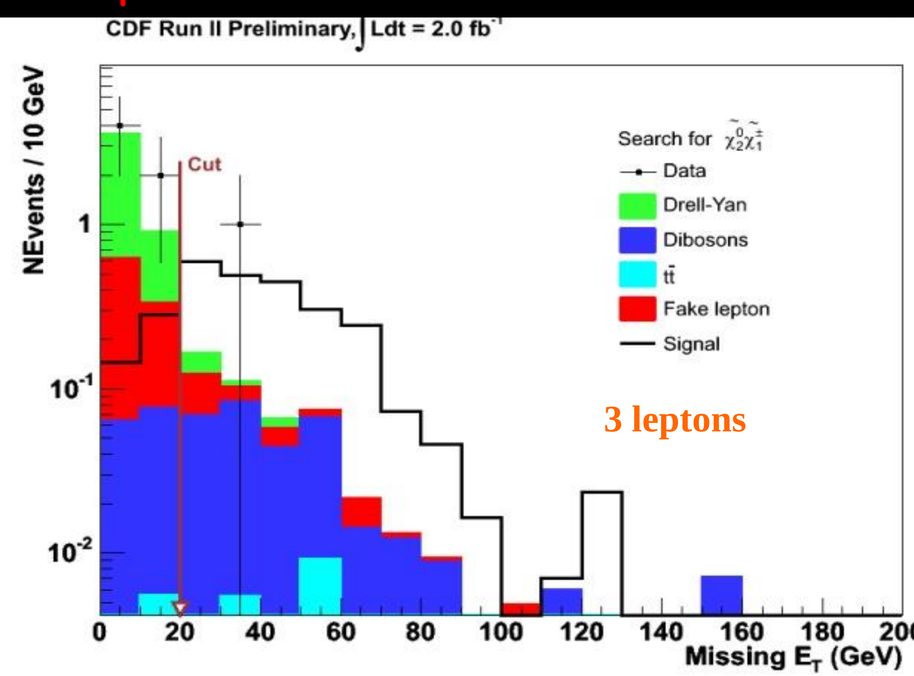
Tracks can be e's or μ's or τ's

Unified Gaugino Pair Production Analysis

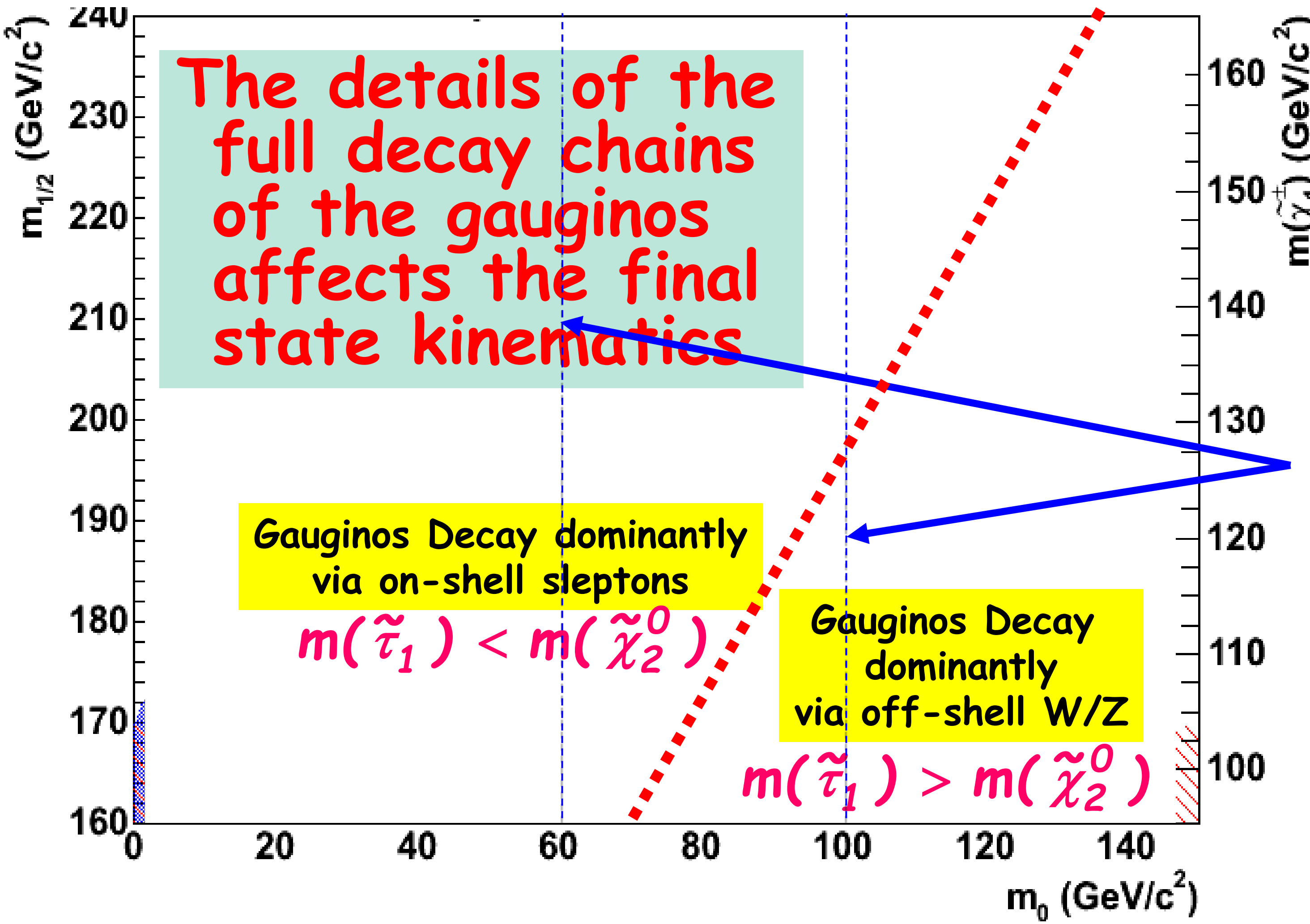


Channel	Background	Obs
3 Tight	0.49±0.04±0.08	1
2 Tight + 1 Loose	0.25±0.03±0.03	0
1 Tight + 2 Loose	0.14±0.02±0.02	0
Total Trilepton	0.88±0.05±0.13	1
2 Tight + 1 Track	3.22±0.48±0.53	4
1 Tight + 1 Loose + 1 Track	2.28±0.47±0.42	2
Total Dilepton +Track	5.5±0.7±0.9	6





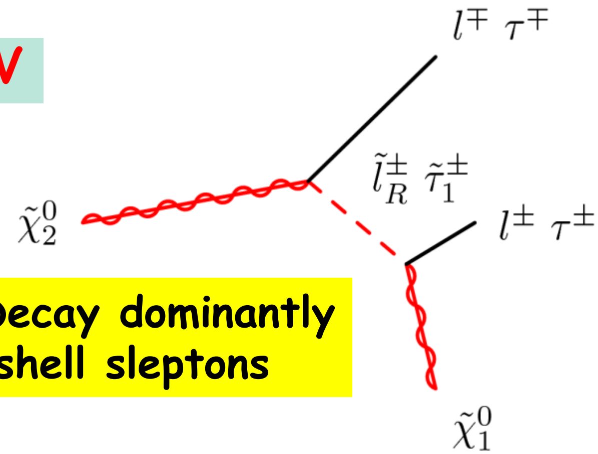
Trileptons in mSUGRA



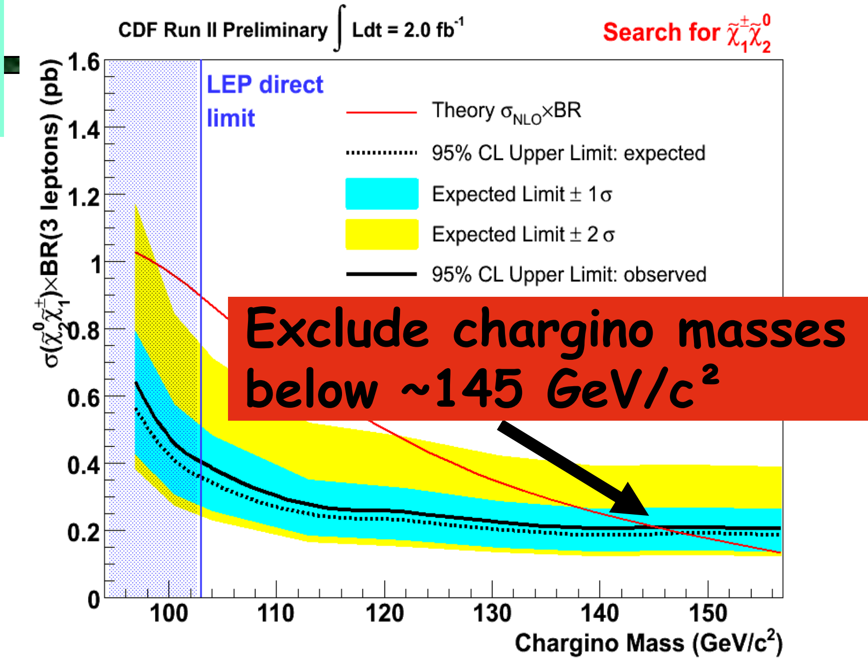
Look at the lines of constant M_0

Cross Section limits vs. chargino mass

M_0 = 60 GeV

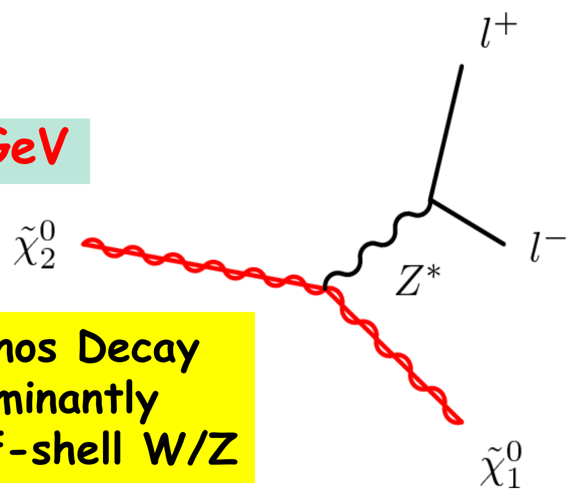


Gauginos Decay dominantly via on-shell sleptons

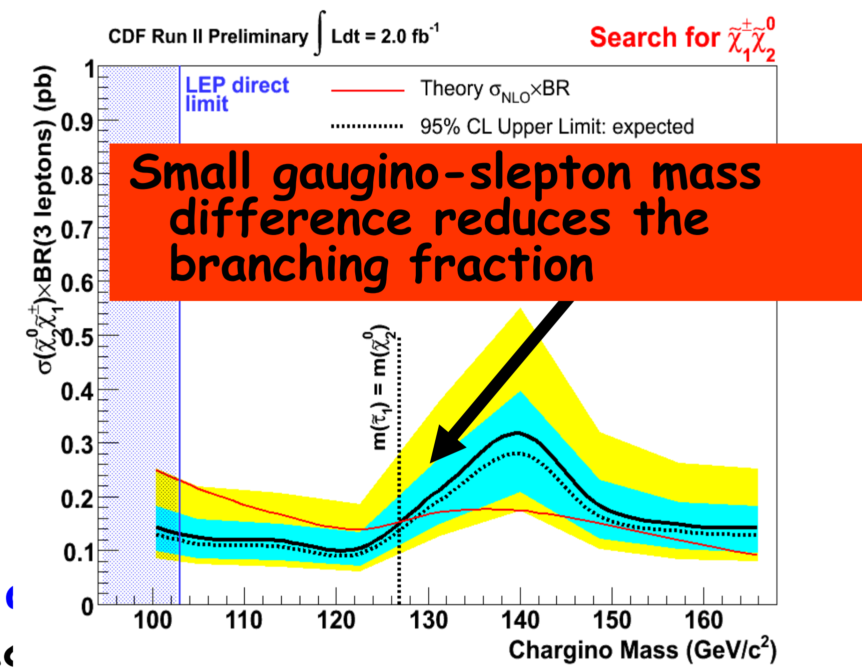


Exclude chargino masses below ~145 GeV/c²

M_0 = 100 GeV

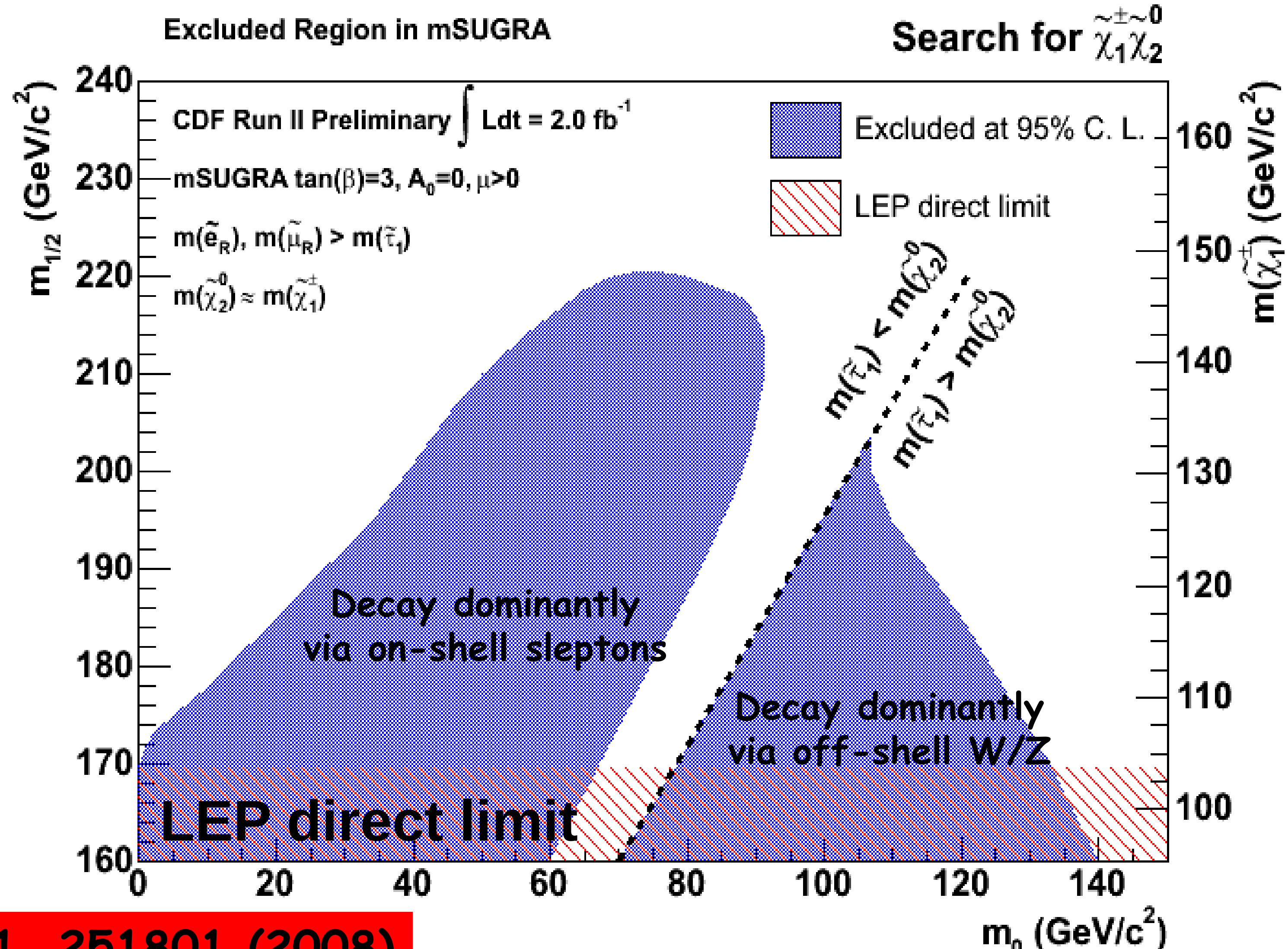


Gauginos Decay dominantly via off-shell W/Z



Small gaugino-slepton mass difference reduces the branching fraction

mSUGRA Exclusion Region

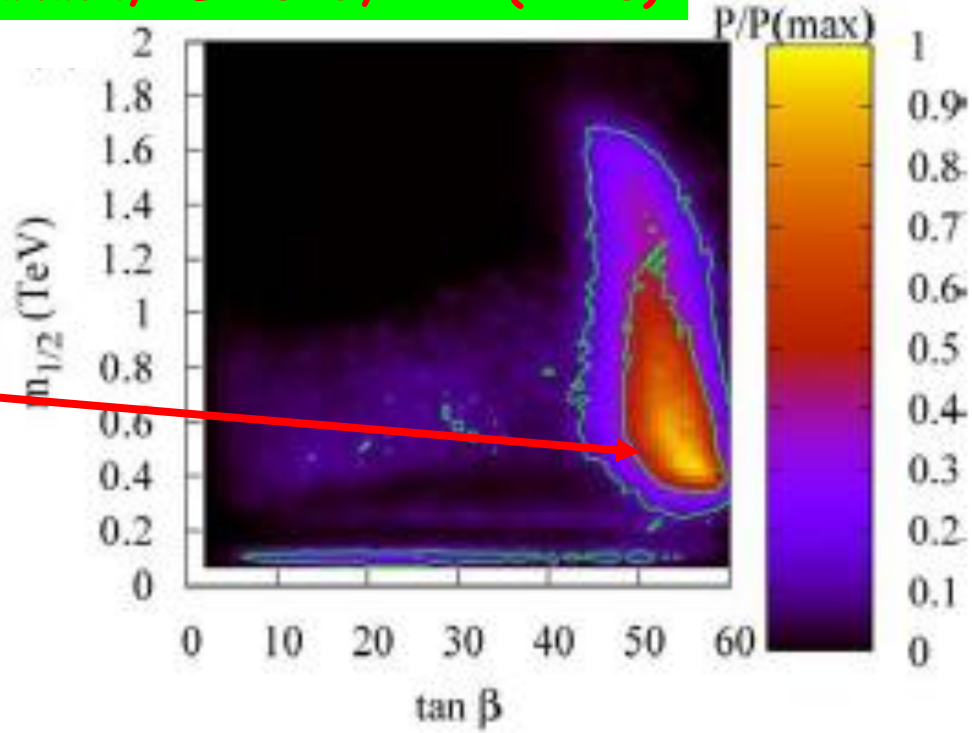


PRL 101, 251801 (2008)

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…

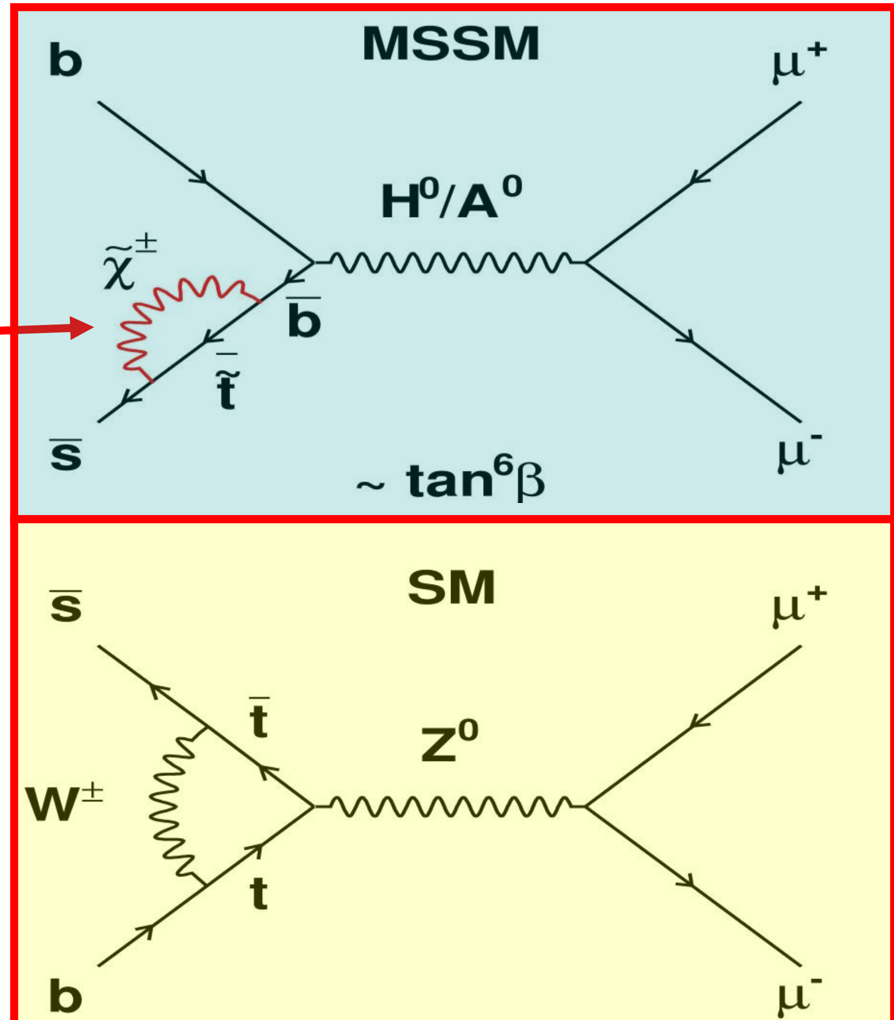
Allanach, PLB 635, 123 (2006)



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 $\tan\beta$ ($Br \propto \tan\beta^6$)

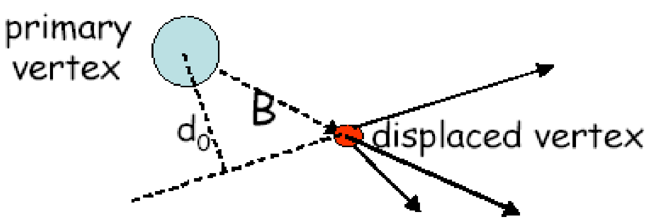
In the Standard Model, the FCNC decay of $B_S \rightarrow \mu^+\mu^-$ is heavily suppressed

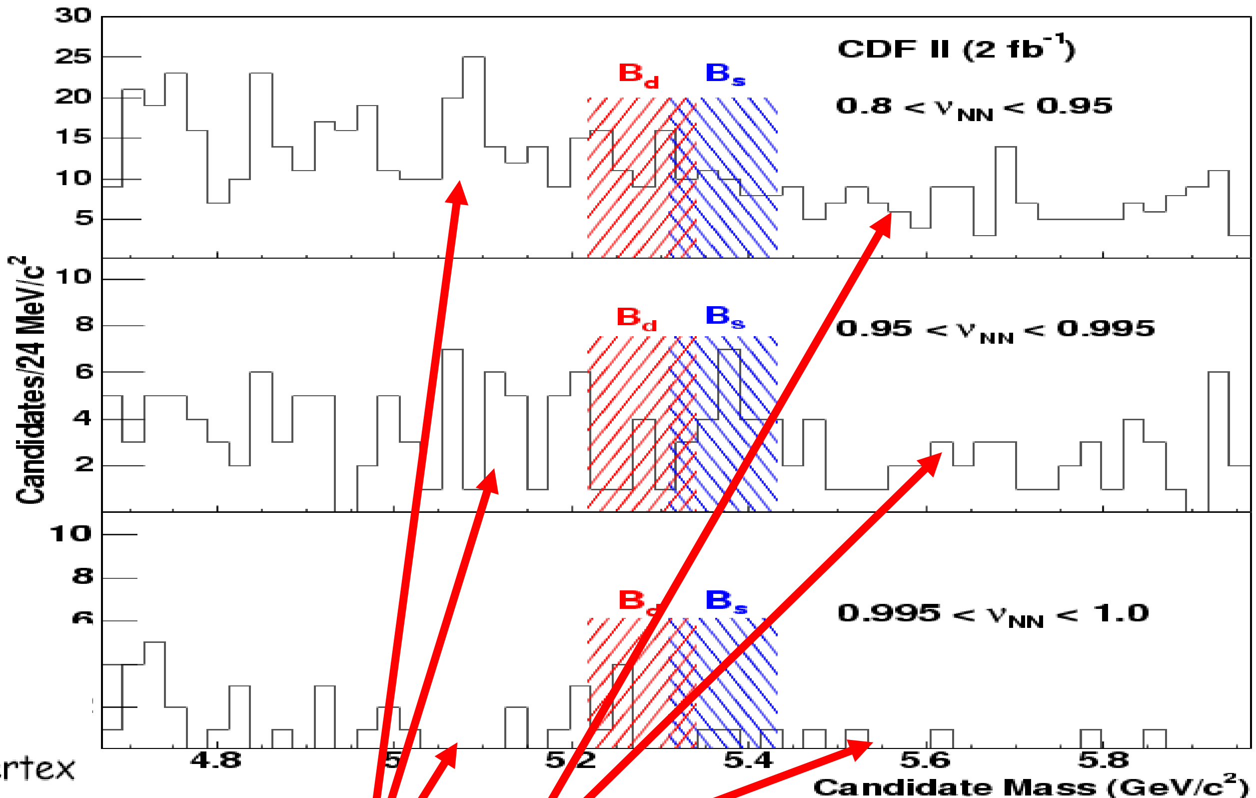
$$BR_{SM}(B_s \rightarrow \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$$

(Buchalla & Buras, Misiak & Urban)

Looking at the Data

Heavily optimized search using Neural Net Techniques

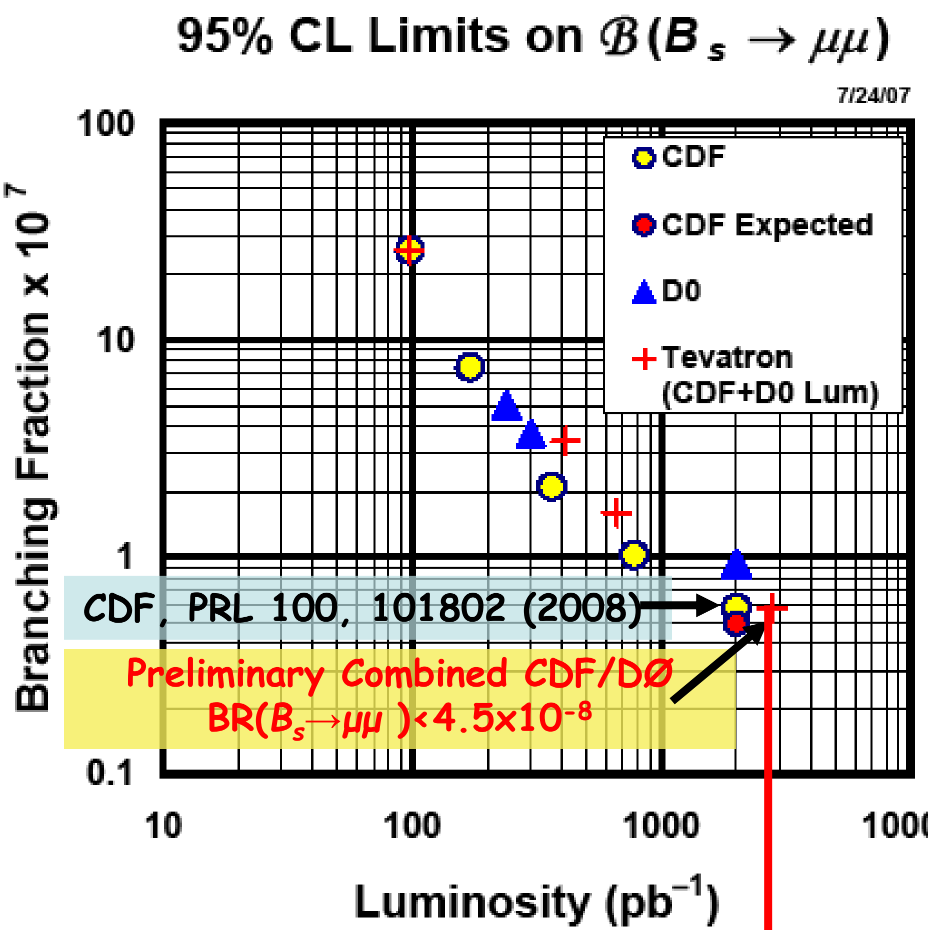


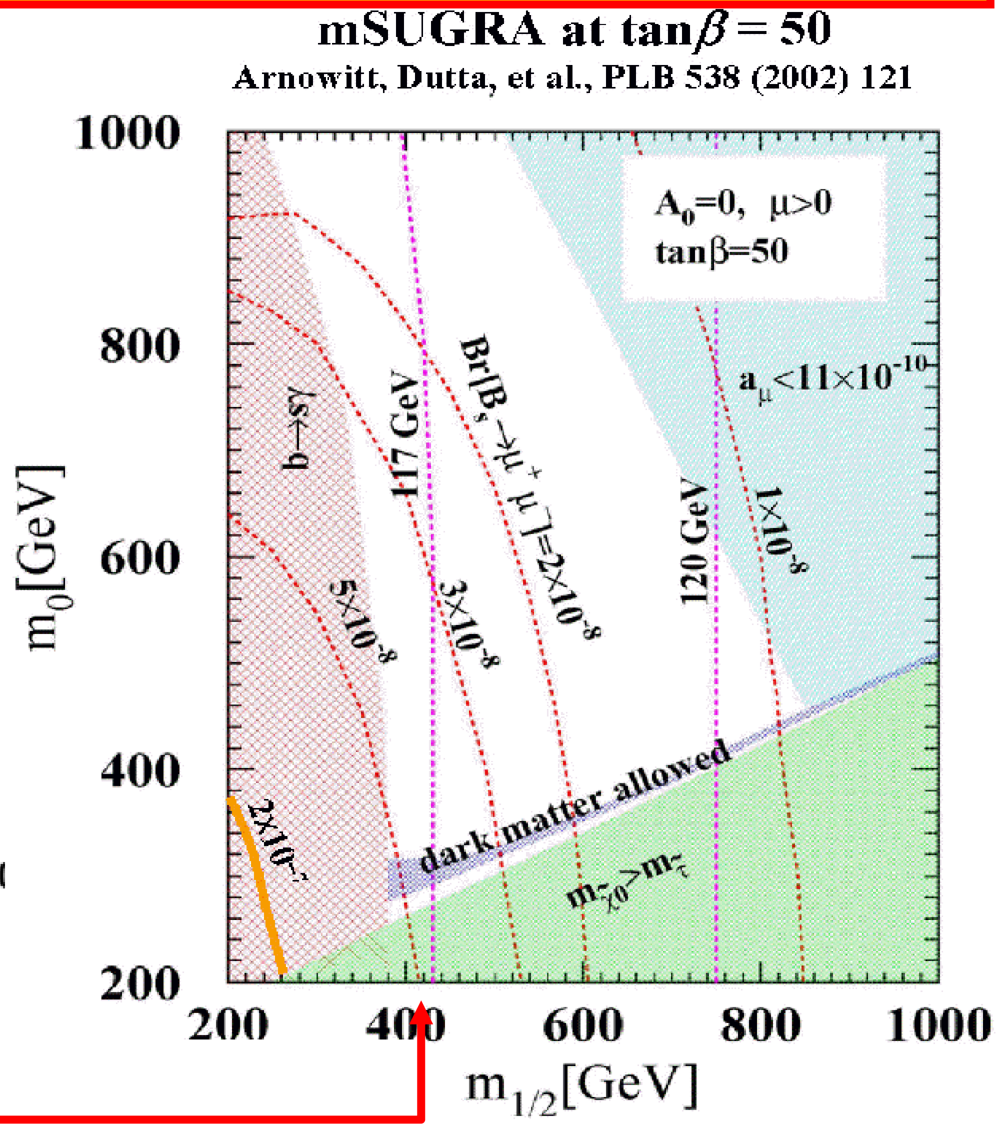


The backgrounds are combinatorial and estimated and checked from data using sideband techniques

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

Limits on Branching Ratios and mSUGRA



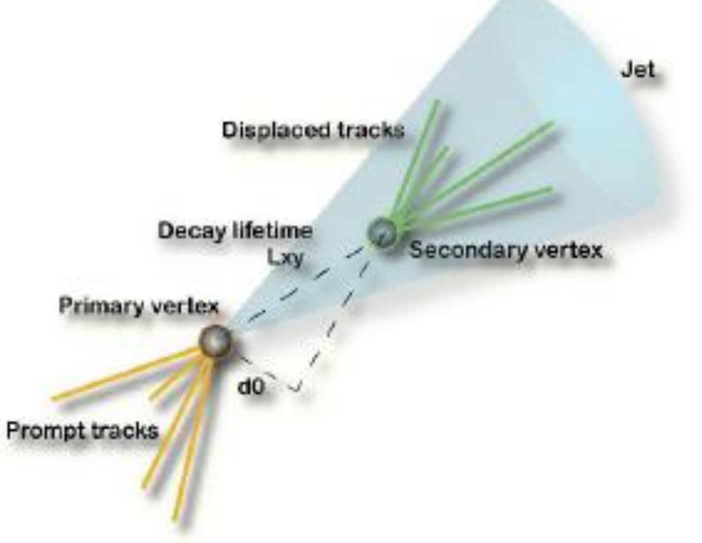


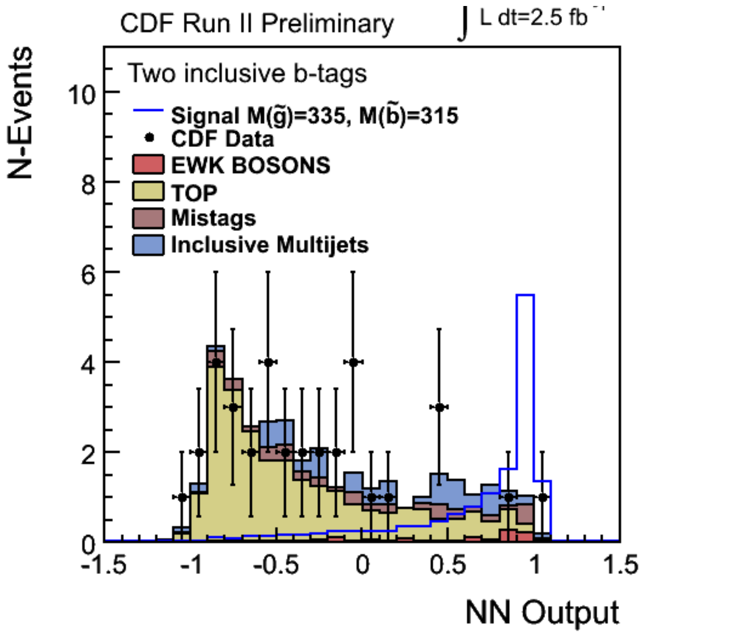
Factor of 10 above SM predictions

ty

Sbottom Searches

- Search for Sbottoms in b-jets+Met from gluino production
- Use b-tagging and Neural Net techniques

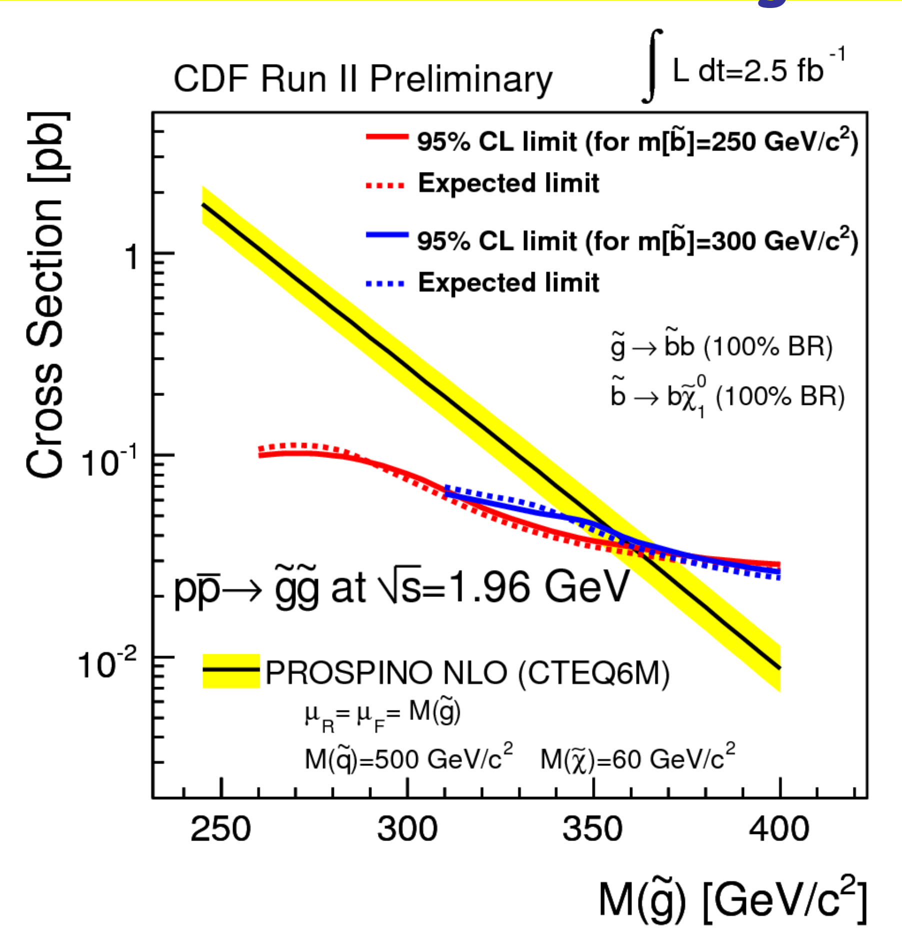


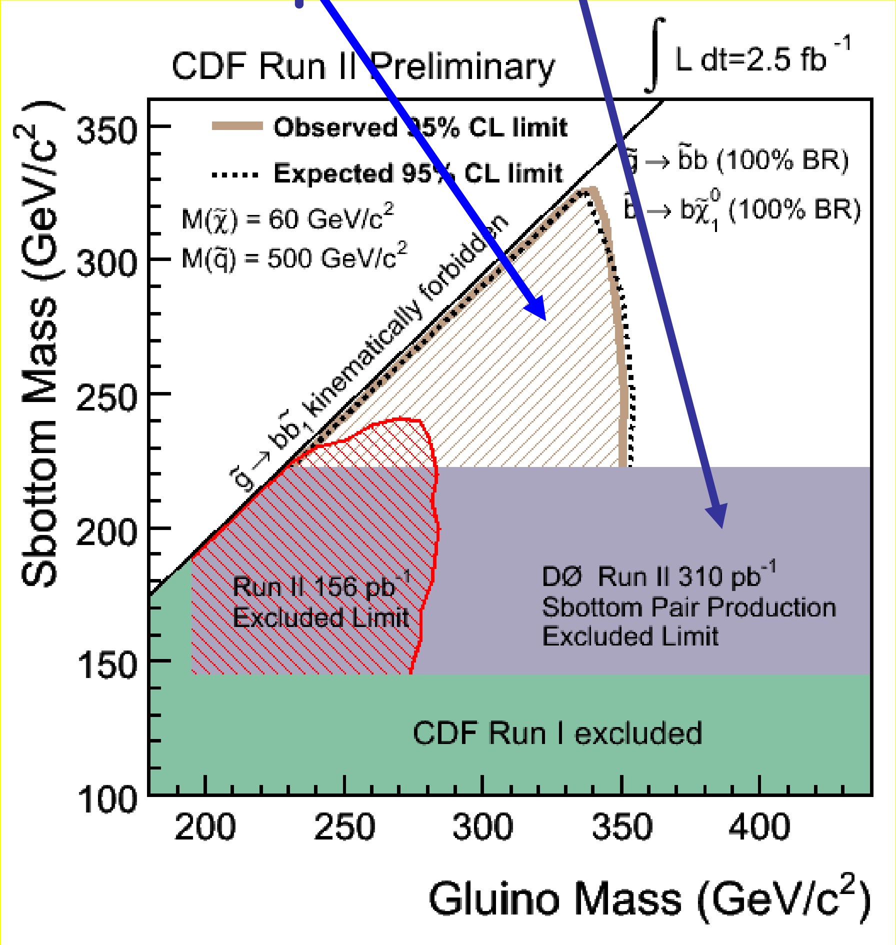


Limits on Sparticle Production

Backgrounds are roughly half QCD, half EWK

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





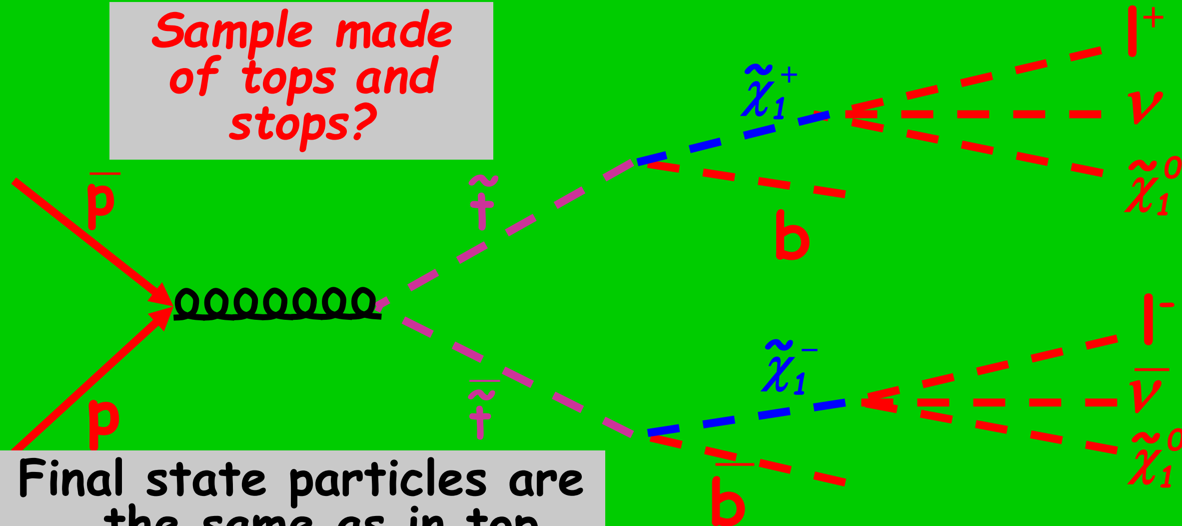
Stop Searches

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

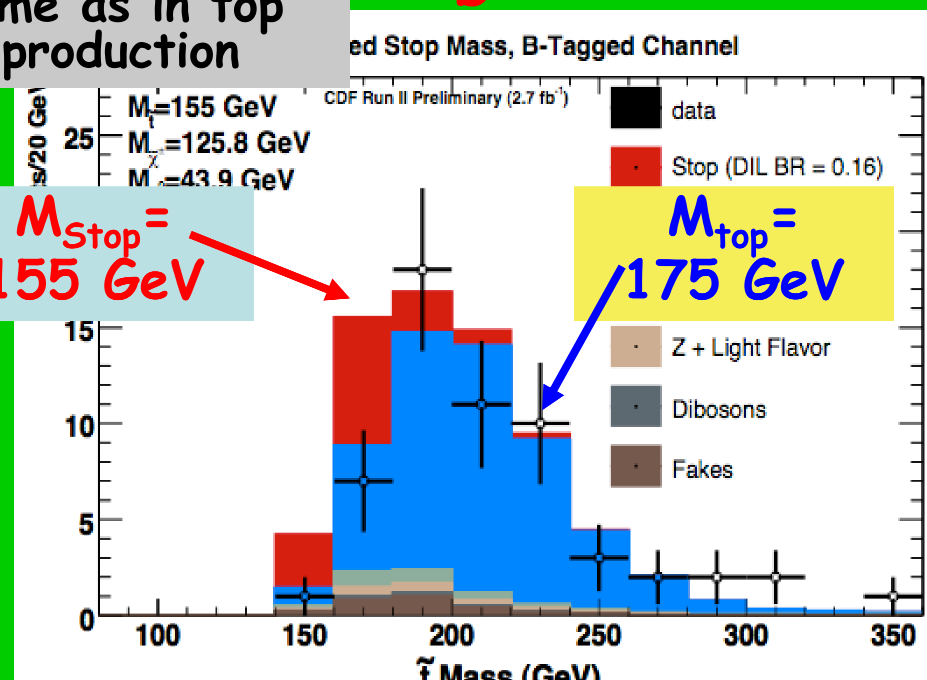
However, Some of the dilepton events in Run I didn't "look" like tops

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

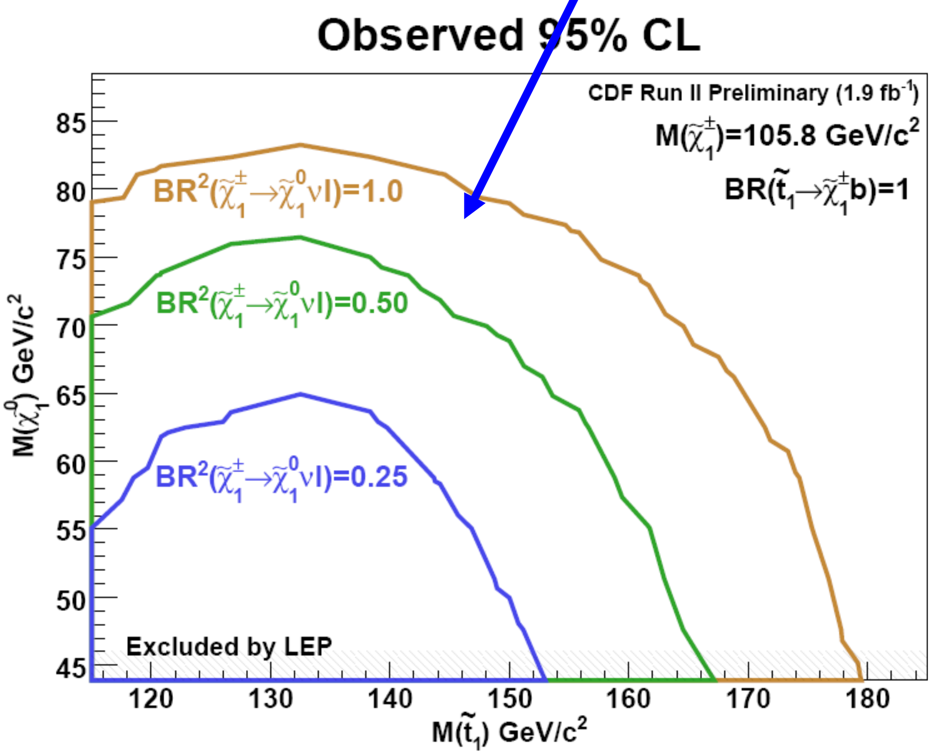


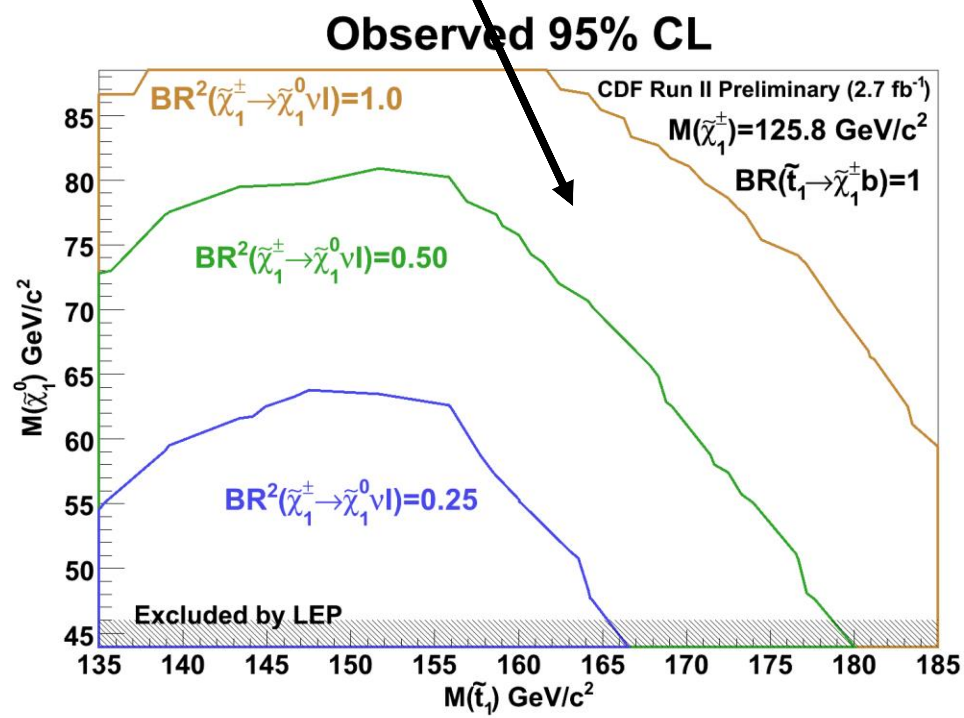
Can set limits on Stop Admixture

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

Branching Ratio limits are mass dependent…

Small chargino mass Large Chargino mass

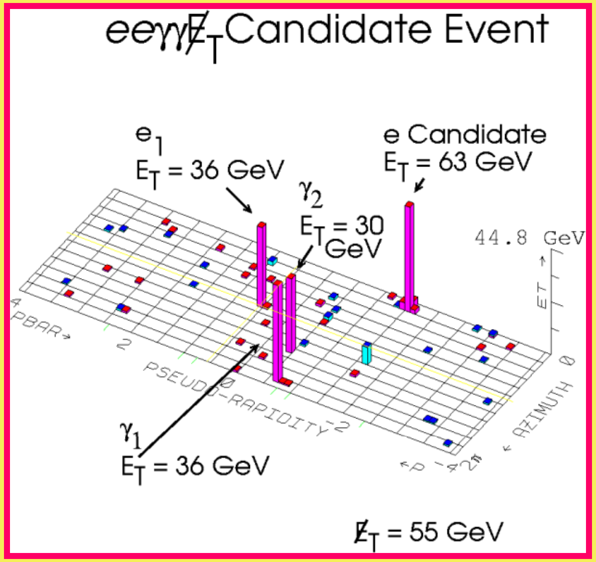




Gauge-Mediated SUSY Breaking Models

$\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ 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 eeγγ+Met candidate event

Early Universe

$\tilde{\chi}_1^0$

Nanosecond lifetimes

Later Universe

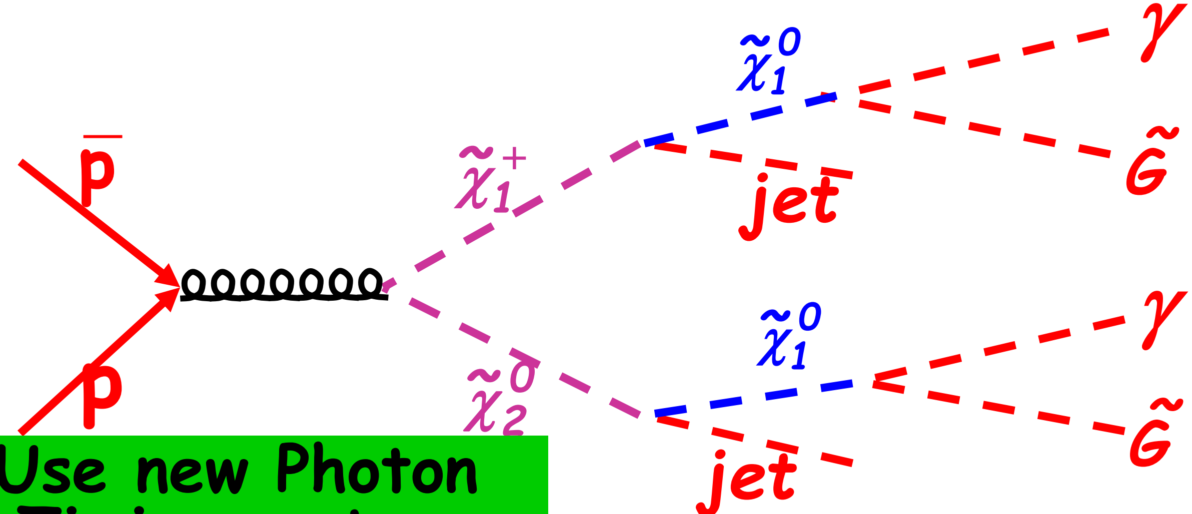
$\tilde{G}$

Warm Dark Matter

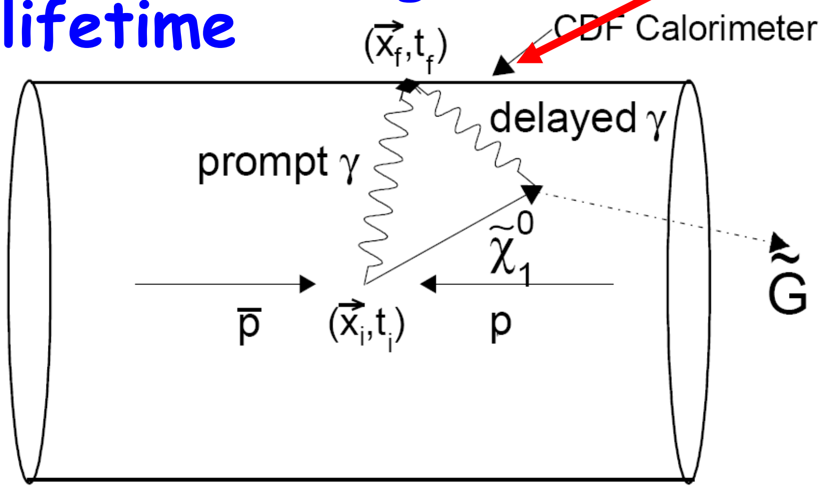
Three Separate Searches

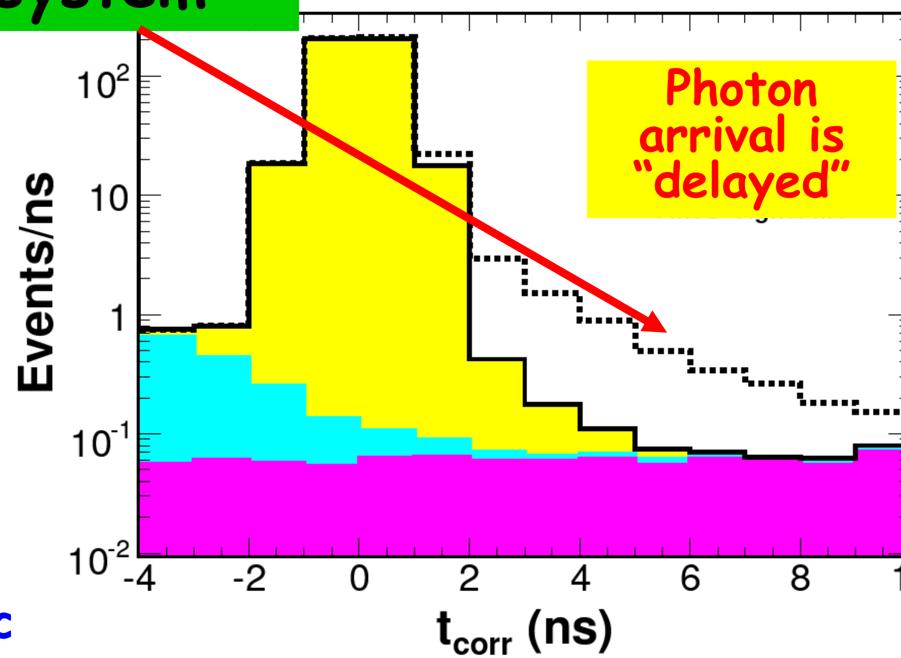
The lifetime and associated particle production dictate different final states

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

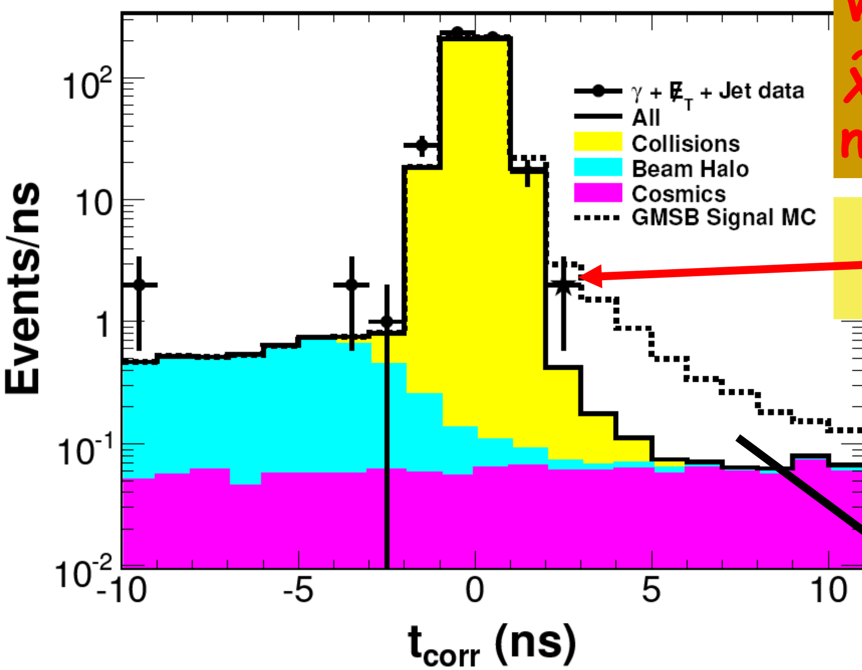


Use new Photon Timing system



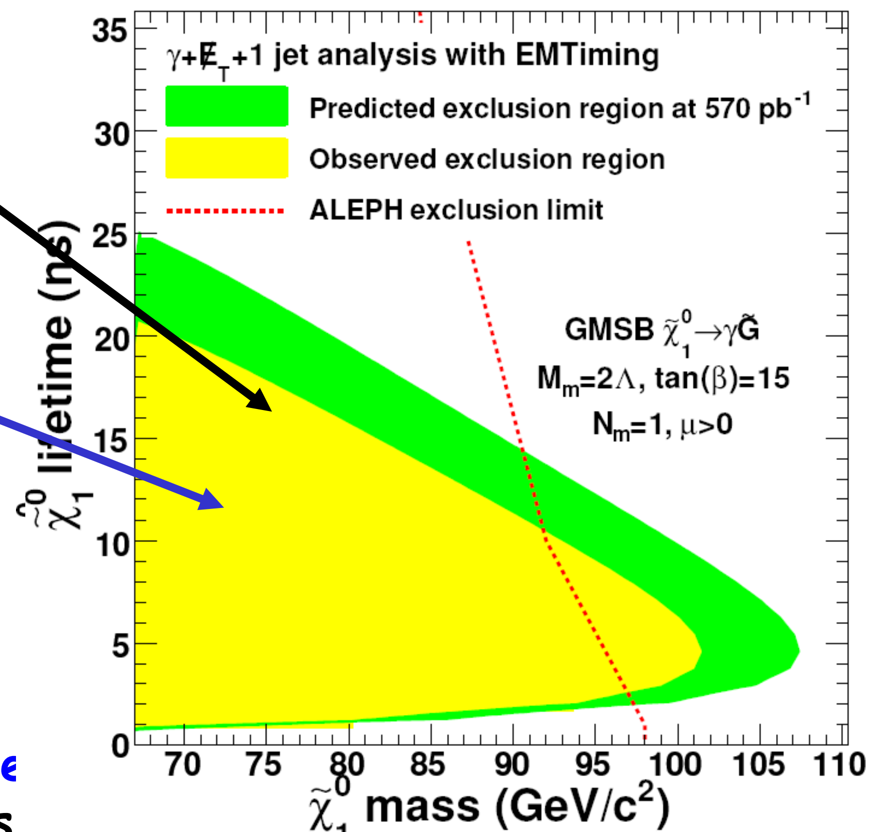


All Neutralino Lifetime Searches



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



Just starting to enter the Cosmology Favored Region

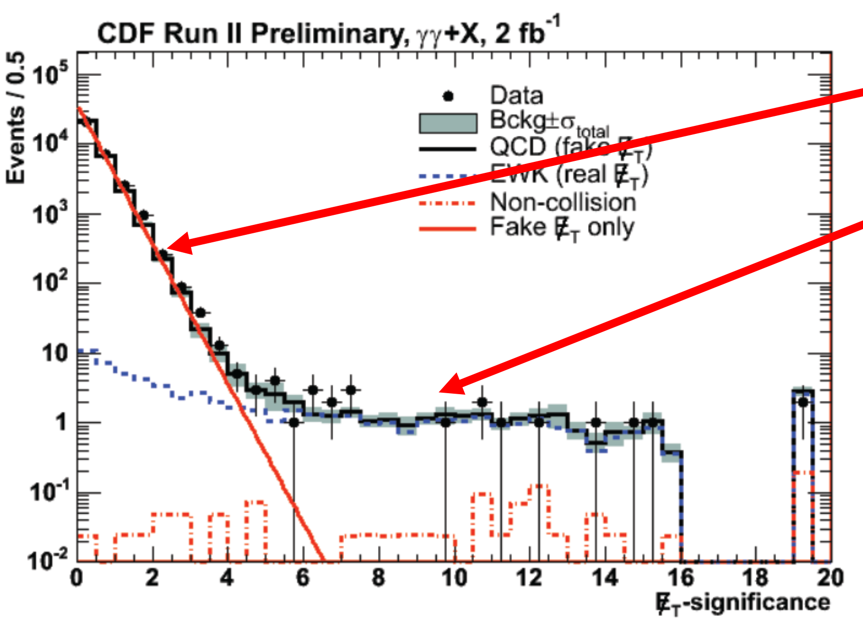
CDF, PRL 99, 121801 (2007)

CDF, PRD 78, 0321015 (2008)

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

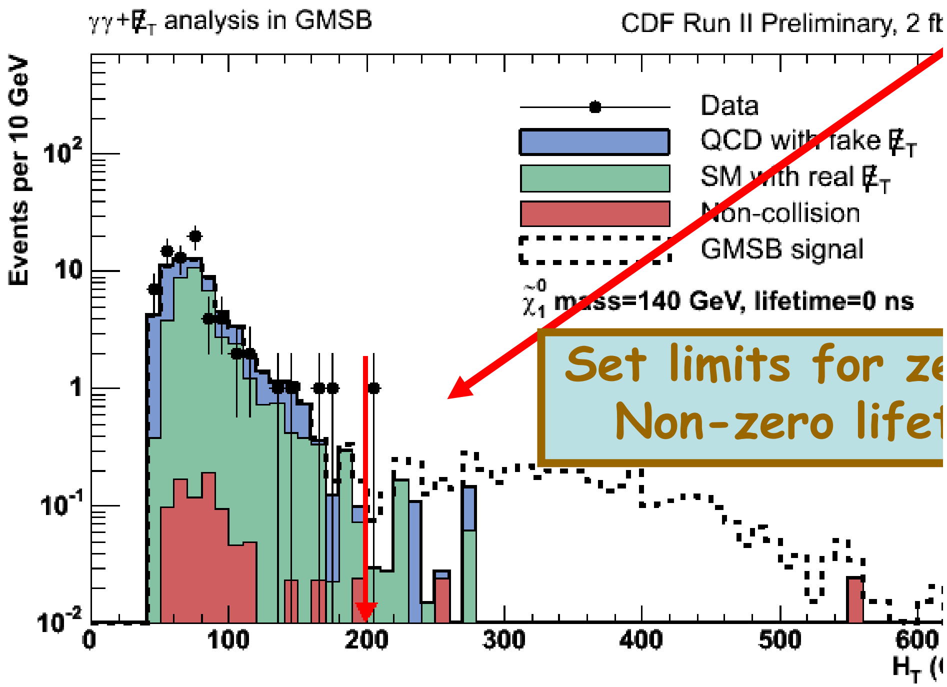
Hi
Fe

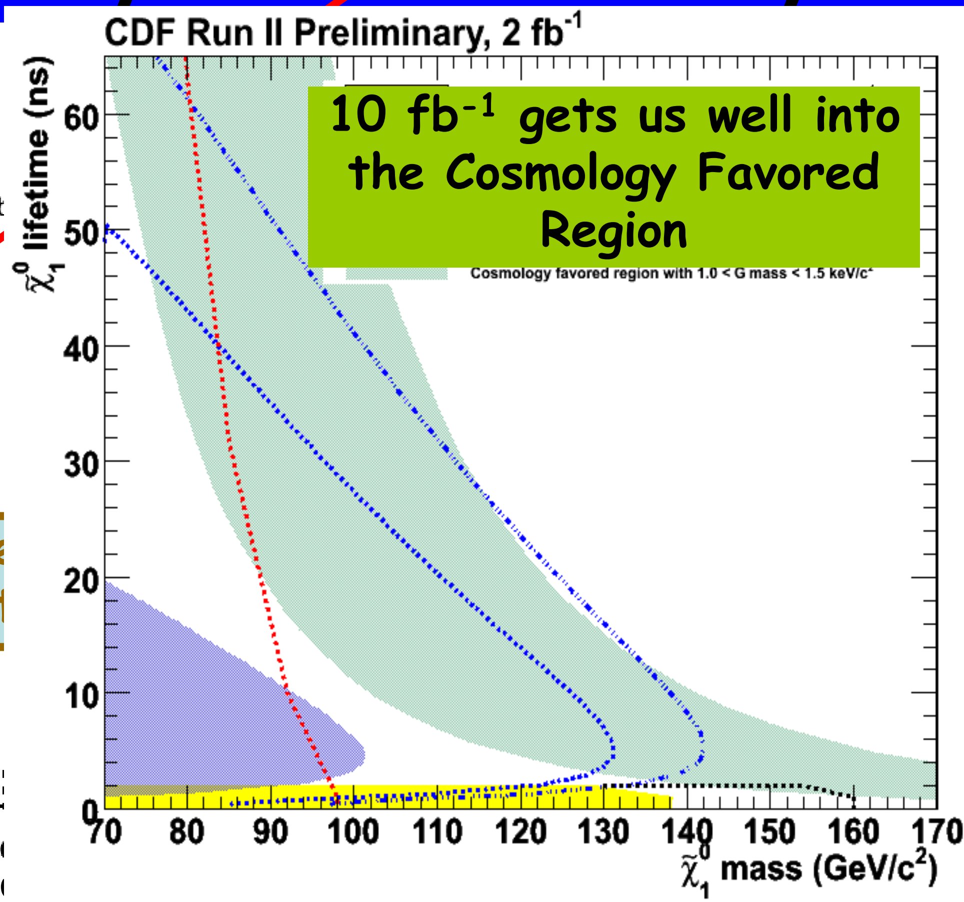
Gauge Mediated Supersymmetry

Optimize the γγ+Met analysis for 0 ns lifetime:

Significant Met and Large H_T

Complement to the Delayed Photon Analysis





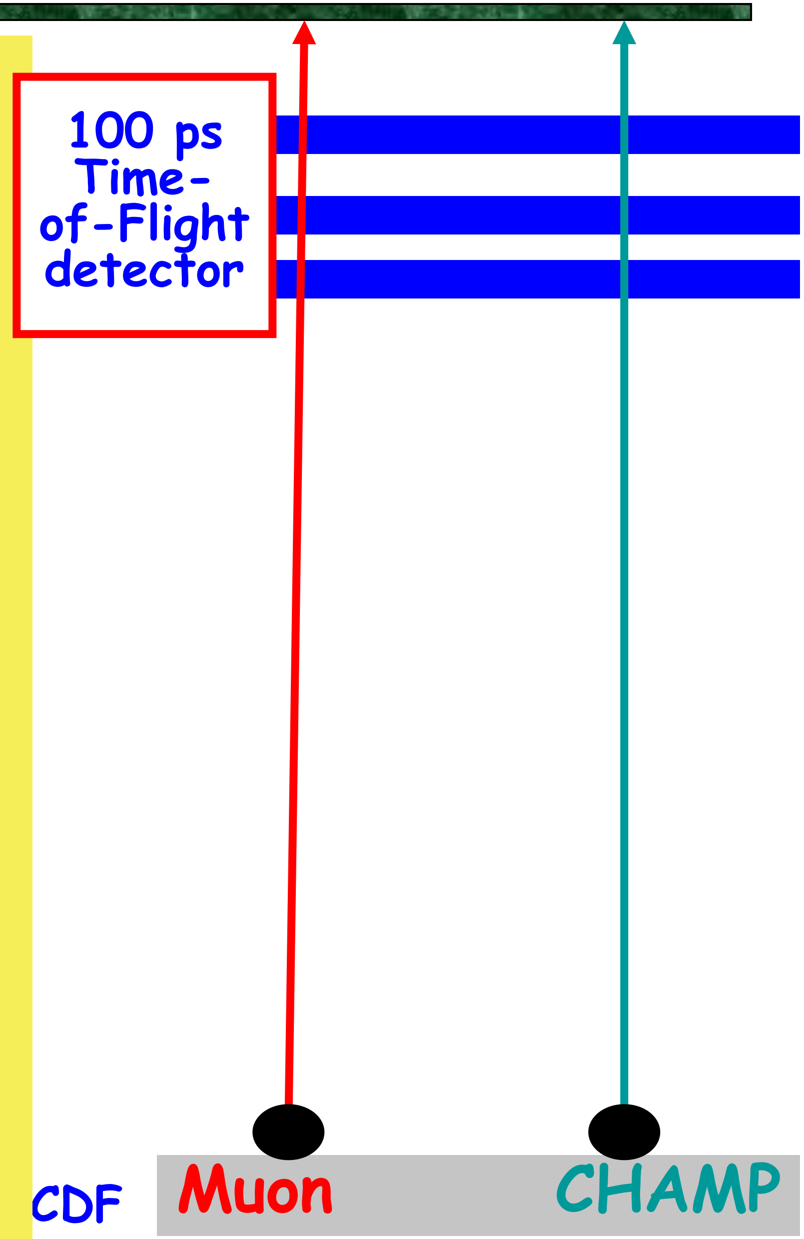
Lots of other possibilities

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)

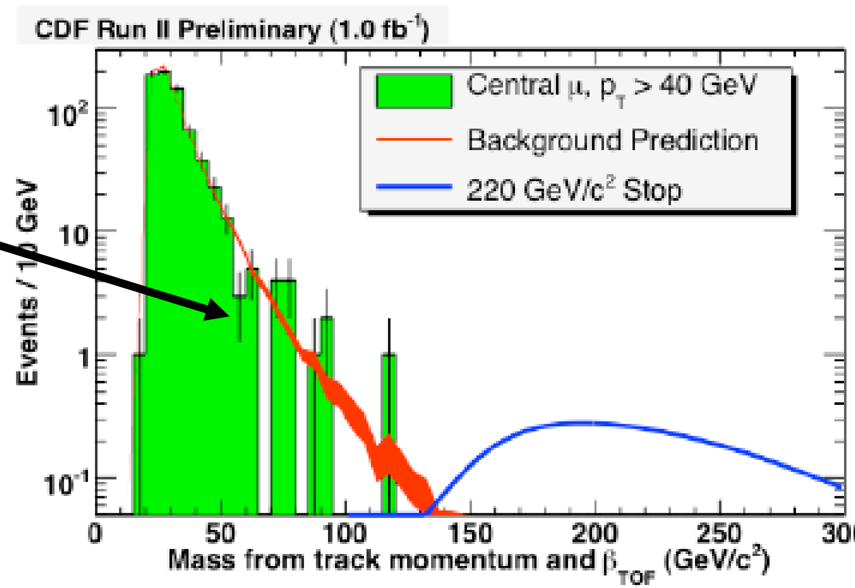


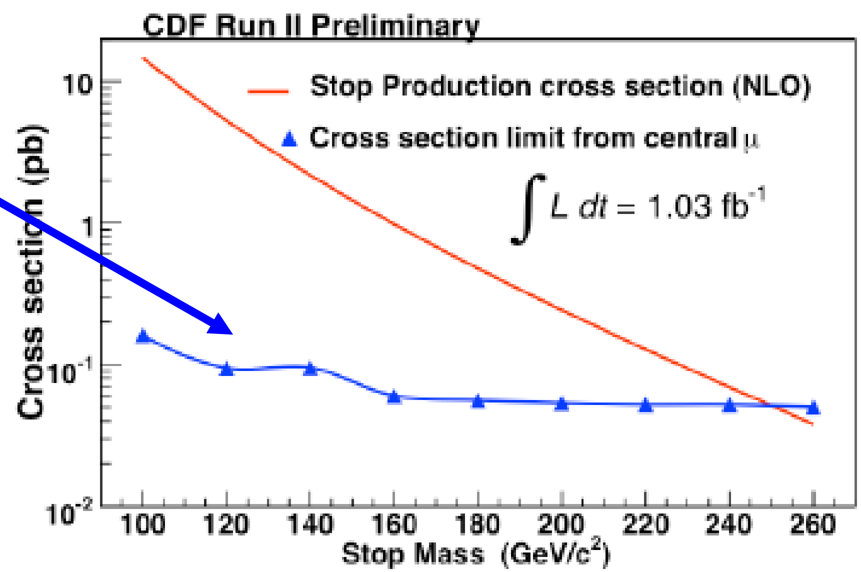
CDF

University

CHAMP Search

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

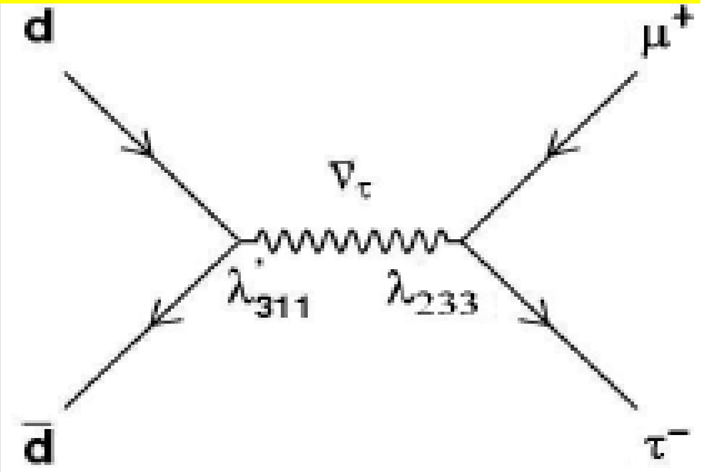


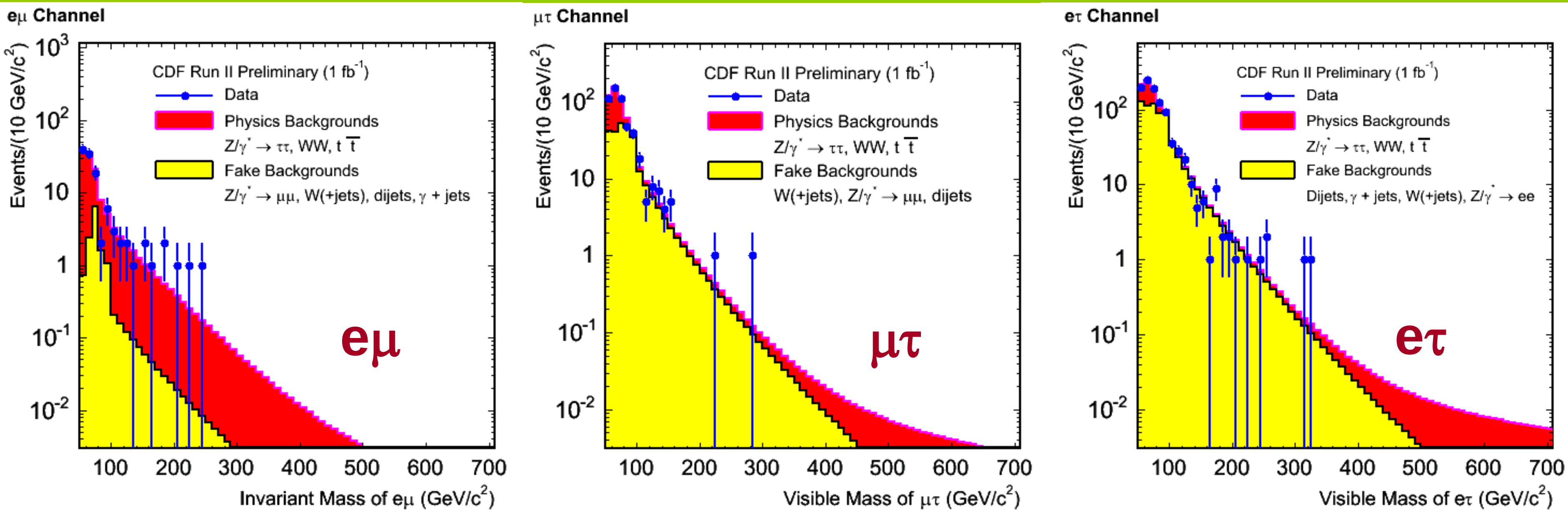


R-Parity Violating SUSY

- 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



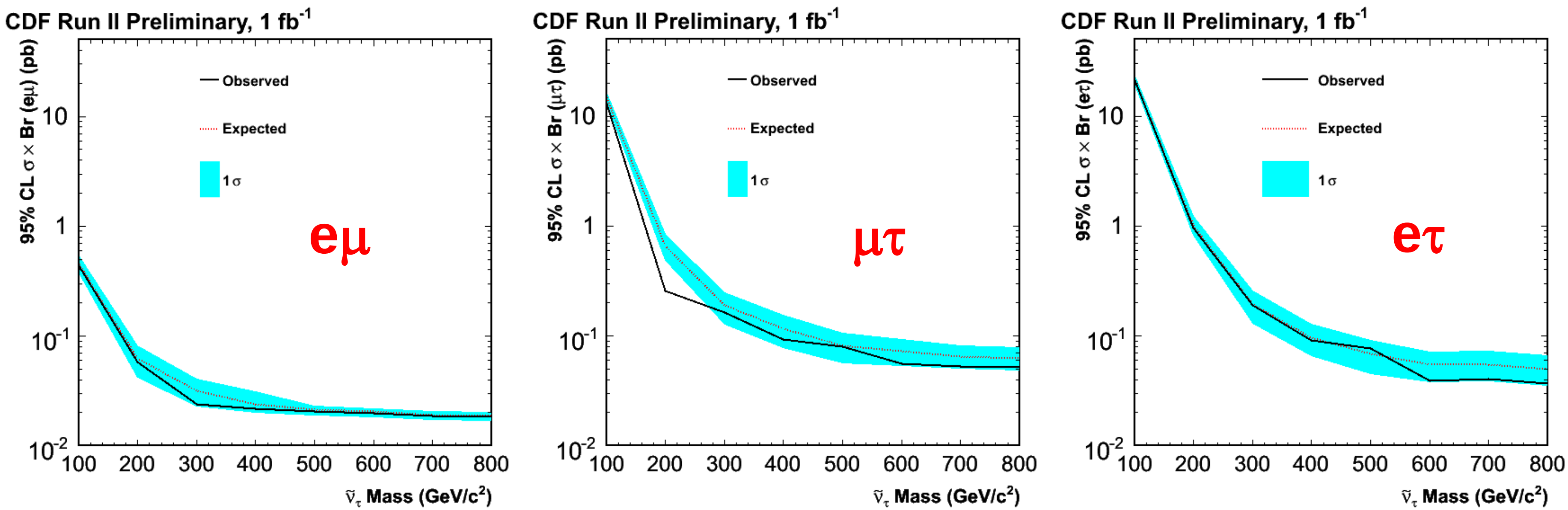


sneutrino $\rightarrow e\mu, \tau\mu, e\tau$

Backgrounds dominated by EWK and W+jet with misidentified leptons

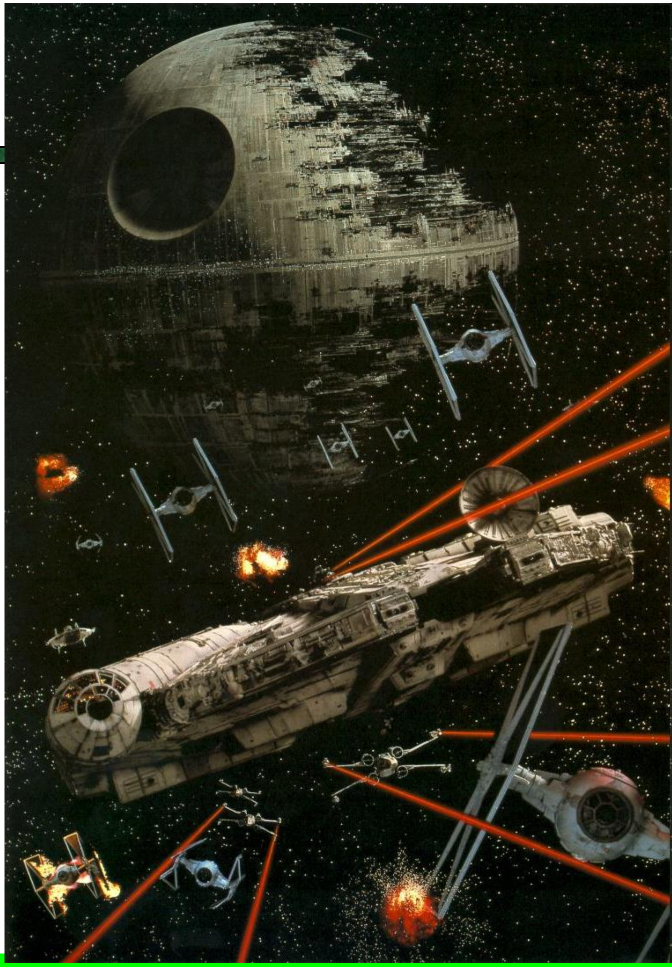
Set limits by extrapolating from low mass region

$\sigma \cdot$BR excluded at 95% C.L in the 10^{-2}:10^{-1} pb range



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
- For the time being we are still leading the search for Supersymmetry



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