Physics Beyond the Standard Model

David Toback

Texas A&M University

For the

CDF and DØ collaborations

Mini-Symposia on Searches

Exciting New Search Results from the Tevatron

Our speakers will show a fun subset today, including

- The Dijet Mass Spectrum and a Search for Quark Compositeness at CDF
- Search for charged massive long-lived particles at DØ
- Search for scalar top decaying into charm and neutralino at CDF
- Setting Limits on Gauge Mediated Supersymmetry Breaking Models with Photons at CDF
- Search for trilepton SUSY signal at CDF

In this talk I'll provide an overview for these searches to place them in context

Also, see Dave Hedin's Plenary in Session T2 at 3:30PM today where lots of other, similar, topics will be covered

The experiments Results pages – contain many more

- http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm
- http://www-cdf.fnal.gov/physics/exotic/exotic.html

Tevatron Searches: *Looking Back and Looking Forward*

The LHC era has started but the Tevatron is still collecting data and leading the search for Supersymmetry and Beyond the Standard Model Physics

It's been 10 years since the Fermilab SUSY-Higgs Workshop → take time to look back and remind ourselves what we focused on back then

Use this as a context for today's searches to provide insight about what things might look like 10 years from now

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

Most results today with between 1 and 4 fb^{-1} of data

Run II SUSY-Higgs Workshop View

The SUSY-Higgs workshop was held in 1998 to study the prospects for the Tevatron

5 main topics:

1. mSUGRA
2. GMSB
3. RPV
4. BSM (Extra Dimensions)
5. Higgs

Clearly envisioned much of the very broad and deep Tevatron search program

What's different in our thinking?

What's the same?

- mSUGRA: Still at the forefront of our searches → benchmark model for SUSY
- GMSB: Came into vogue after the Run I CDF eeγγ+Met candidate event. Still popular today
- RPV: Harder to decide what versions are important
- BSM: Many of these models have been searched for in great detail, (W', Z', leptoquarks, etc)
  - Notable exceptions: Extra Dimensions which has taken on prominence since 1998
  - Long-lived heavy particles
- Higgs: Compelling as it ever was

Omissions? Not envisioned?

- No model-independent search methods
- Precision Cosmology data

"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" – Anonymous

What is Supersymmetry?

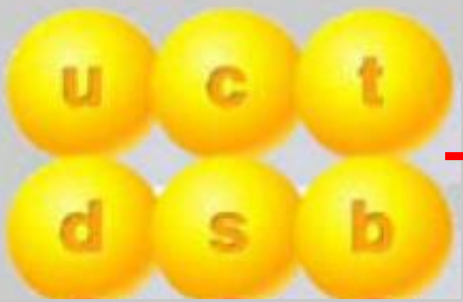
Supersymmetry (SUSY) is a theory that postulates a symmetry between fermions and bosons

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle$$

$$Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$

Minimal Supersymmetric Standard Model (MSSM)

Standard particles

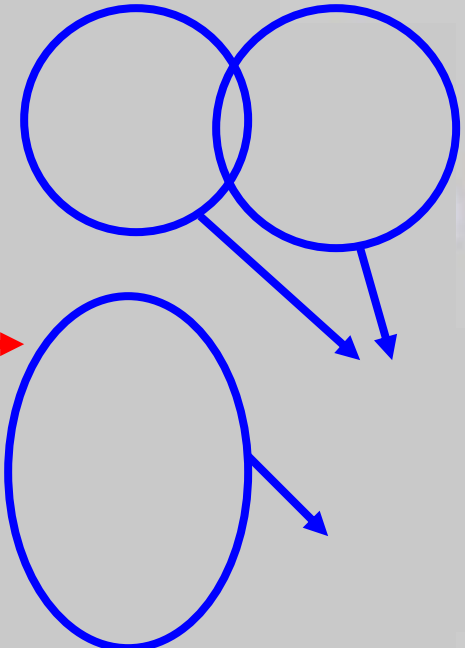


Quarks → Squarks

Gauge Bosons → Gauginos

Leptons → Sl

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

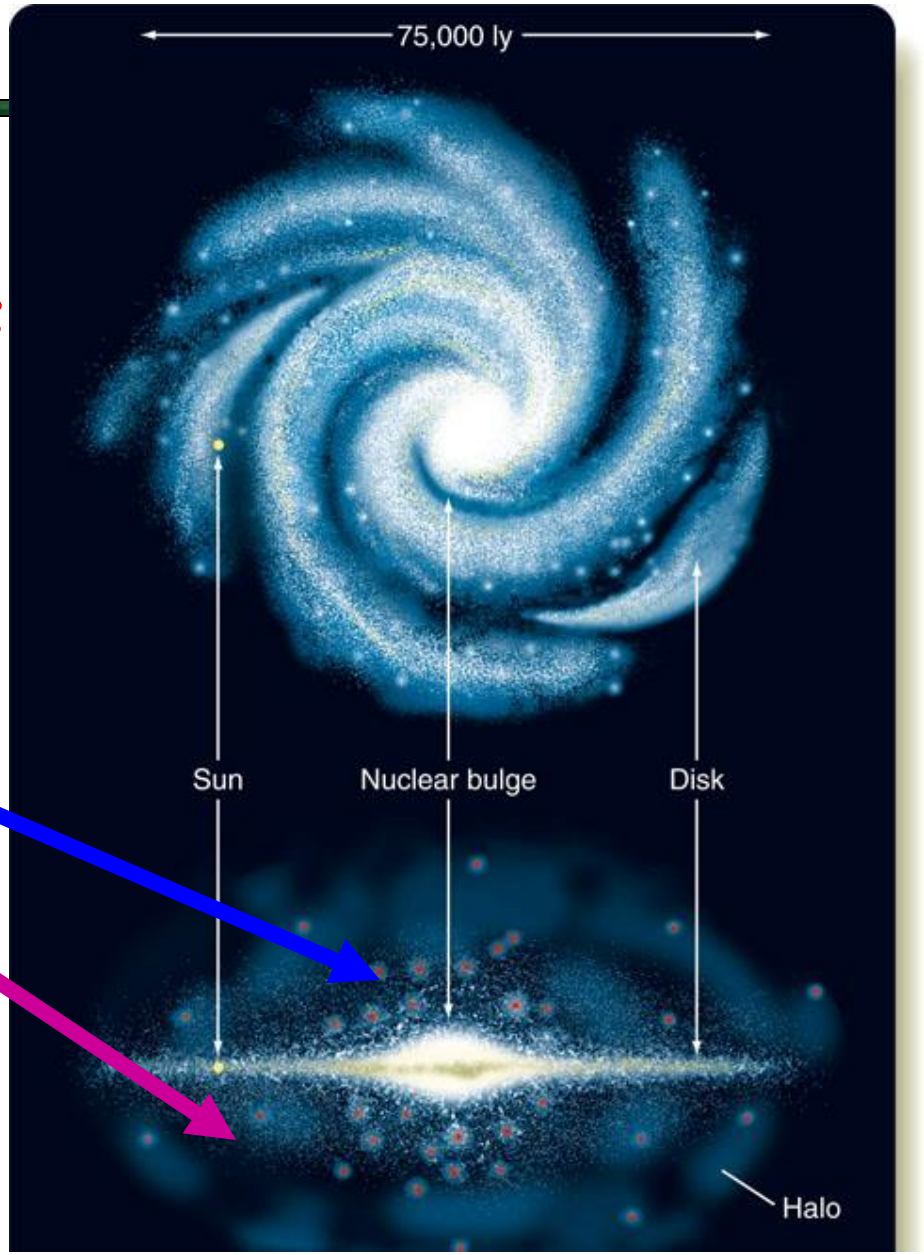


Dark Matter?

Galaxy structure and rotations well explained by lots of "Dark Matter" we can't see directly

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 part from lensing only
"Fast ➔ Dark Matter"

Red part from x-ray observations light
"Slow ➔Stars"

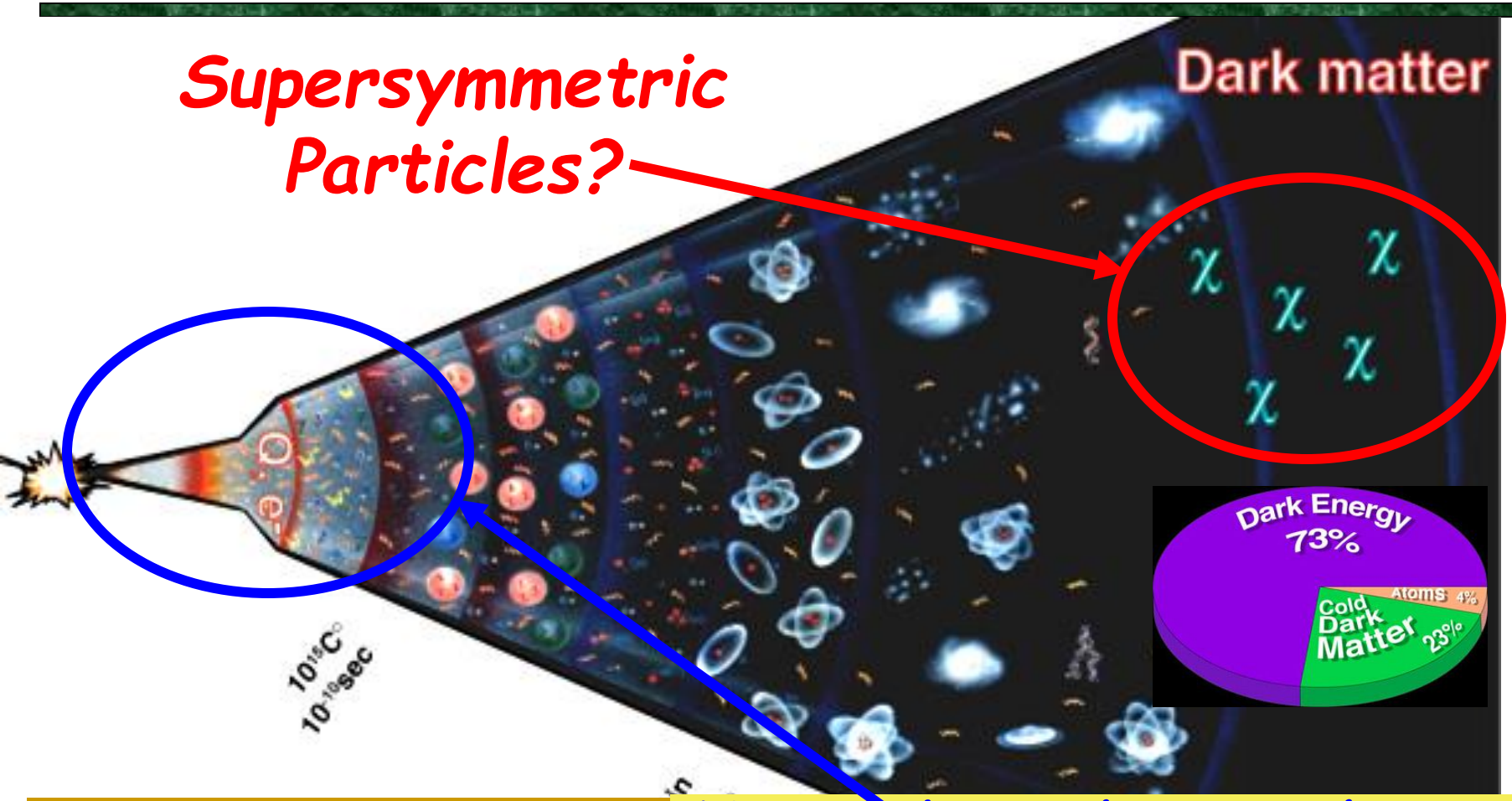
Physics Beyond the Standard Model
David Toback, Texas A&M University

APS April Meeting
Mini-Symposium May, 2009

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

Dark Matter = 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

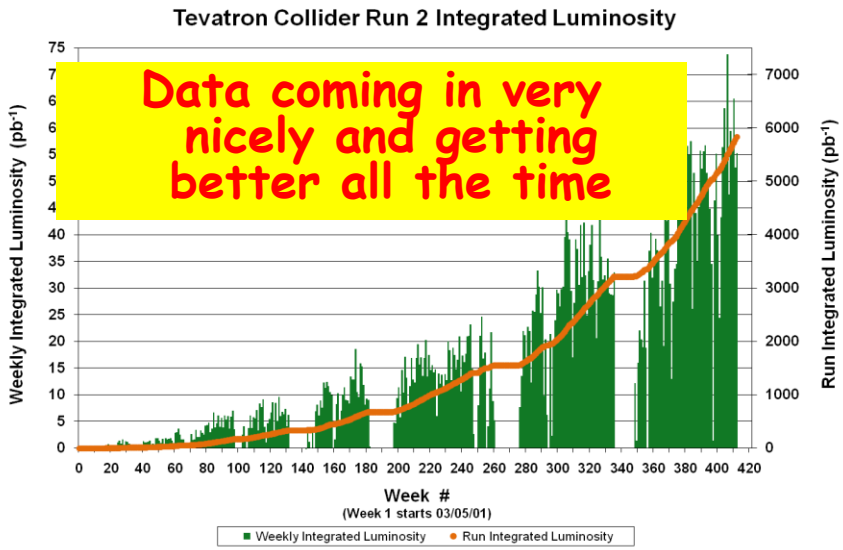
Outline of the Searches

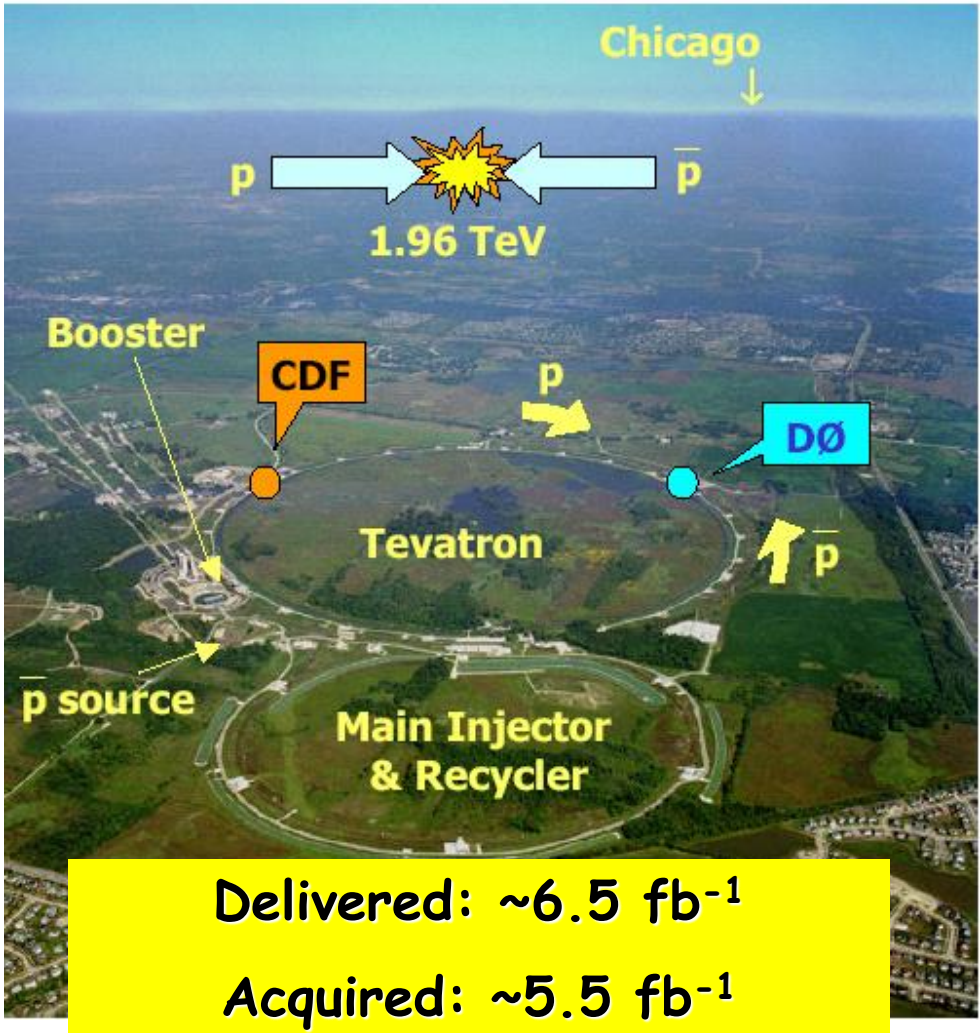
- The Tevatron and the Detectors
- mSUGRA Searches
  - -Squarks & Gluinos
  - -Gaugino Pair Production
  - -Indirect Searches
- Gauge Mediated Searches
- Conclusions

The Fermilab Tevatron

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

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





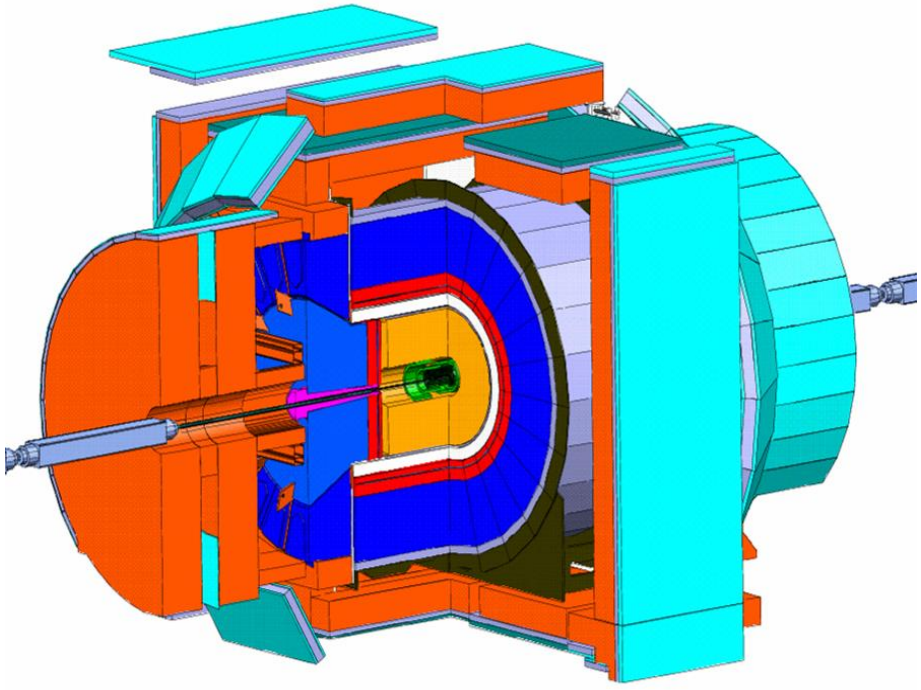
Delivered: ~6.5 fb^{-1}

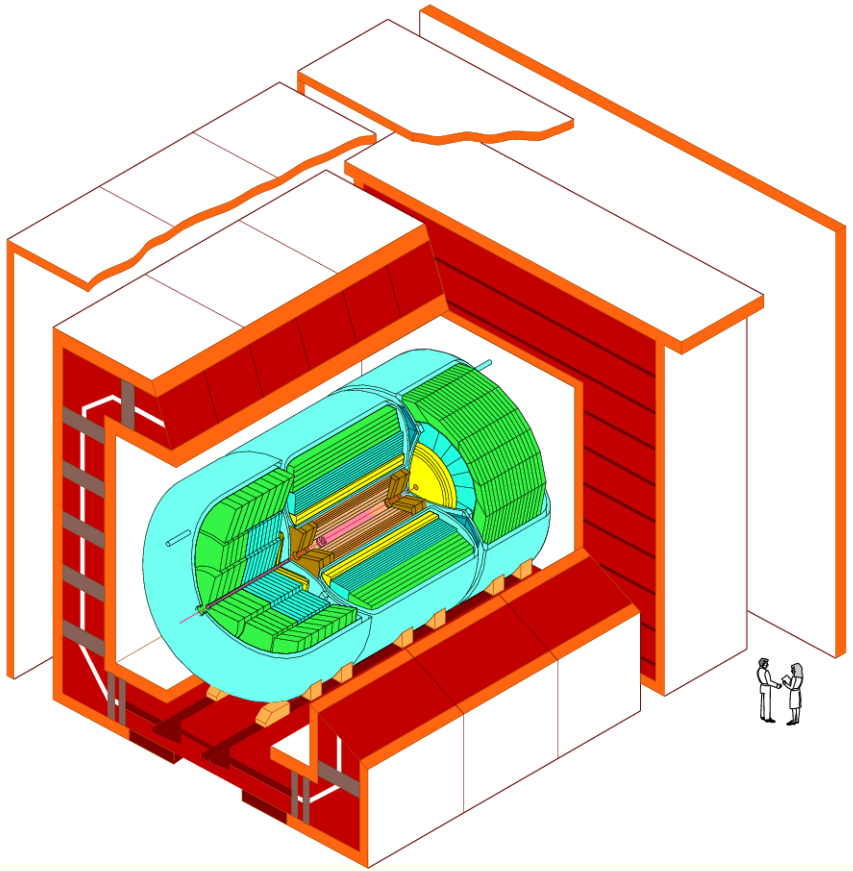
Acquired: ~5.5 fb^{-1}

Analyzed: ~2-4 fb^{-1}

(depending on the analysis)

The CDF and DØ Detectors





Powerful multi-purpose detectors

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

Aside for our LHC Friends

Most analyses will look like they were easy

Nota 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

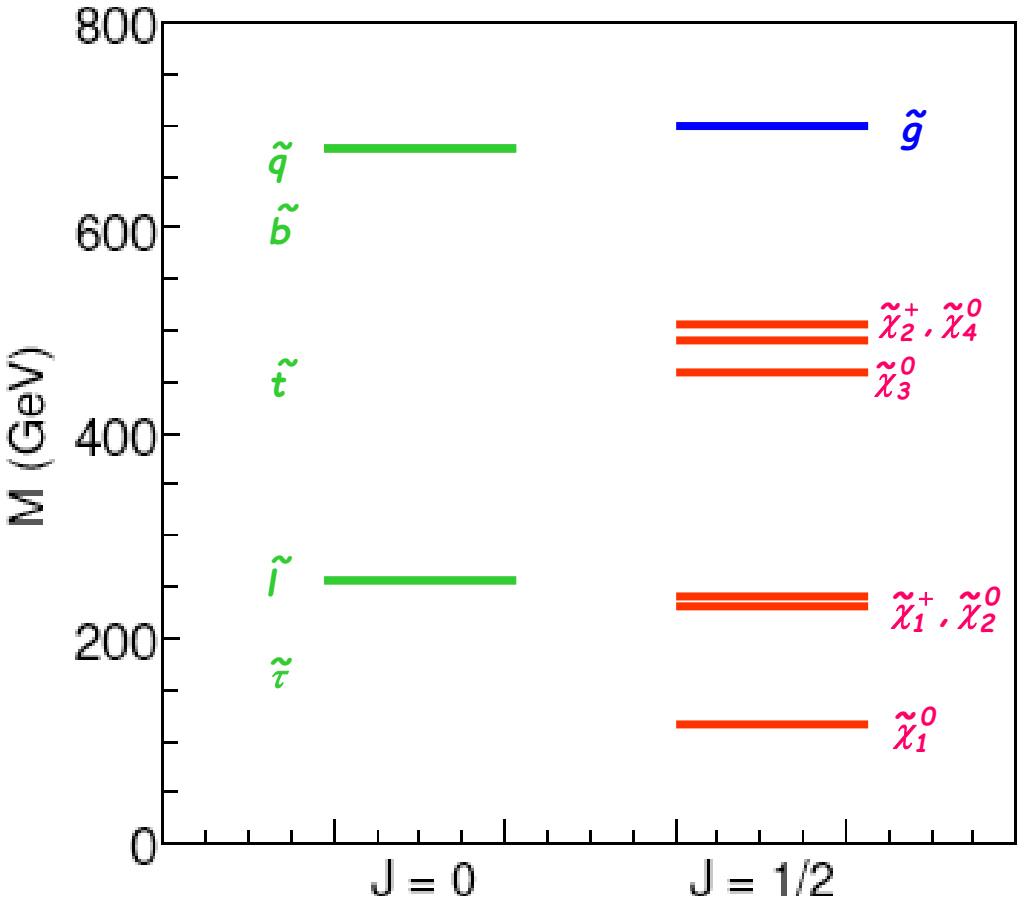
The Sparticle Masses

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 Channels

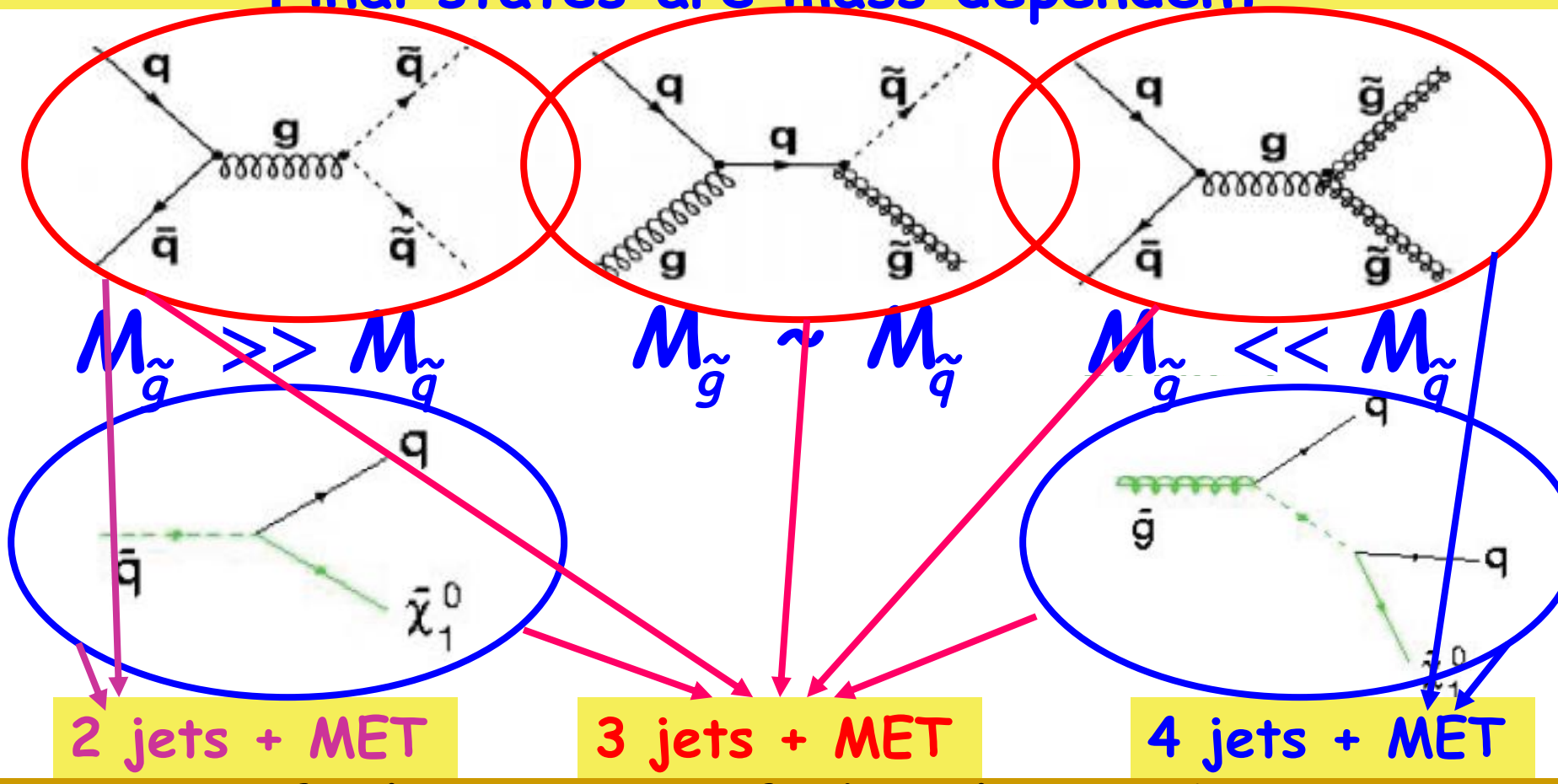
Three main ways to look for minimal/Cold Dark Matter Models in mSUGRA type models

- 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

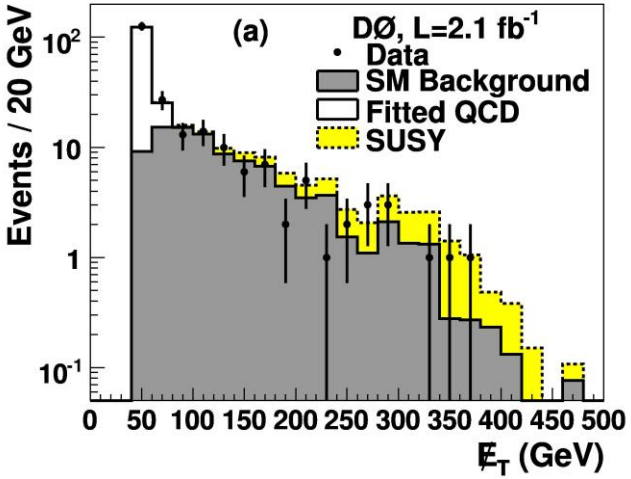
Squark and Gluino Searches in Multijet + Met

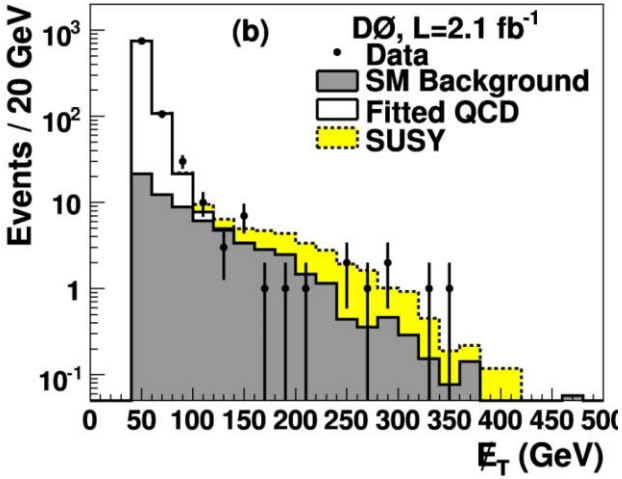
Three main production diagrams
Final states are mass dependent

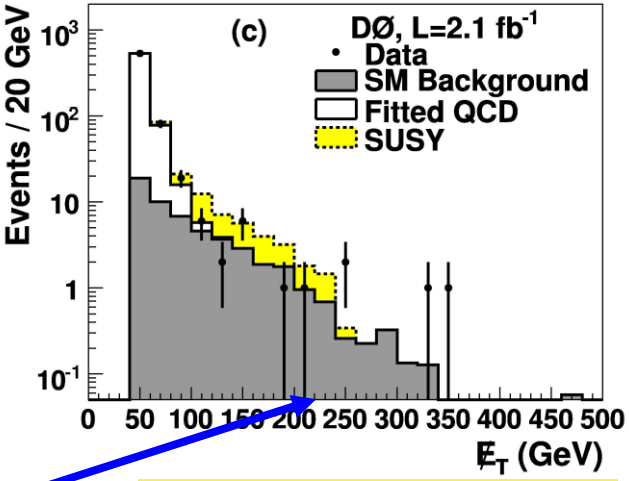


3 separate final states + Unified Analysis ➔ best coverage

Unified Squark/Gluino Search





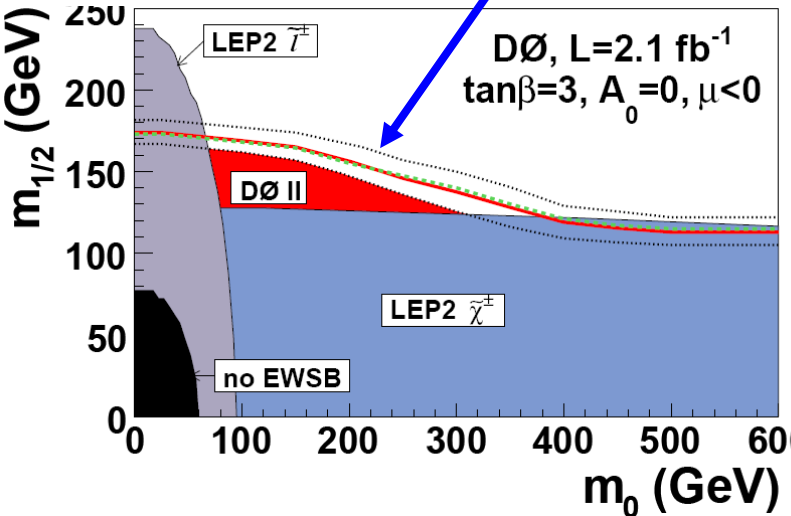


2 jets + MET

3 jets + MET

4 jets + MET

SUSY Interpreter



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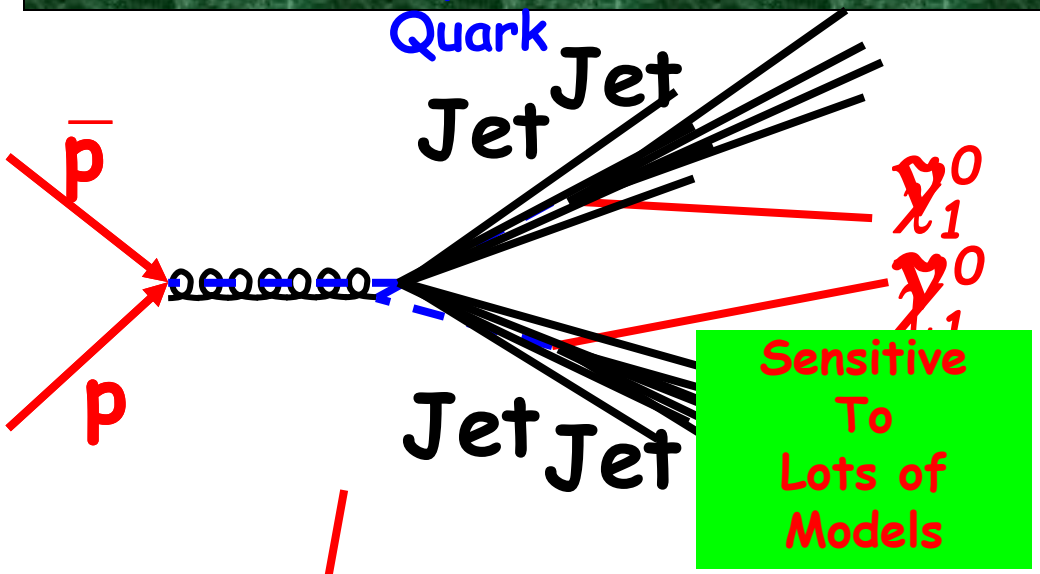
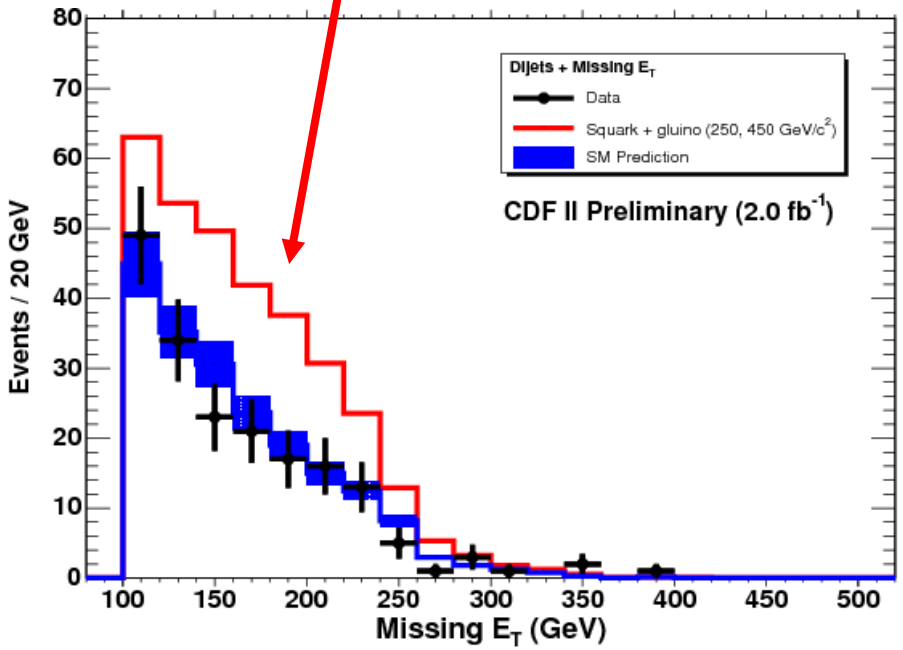
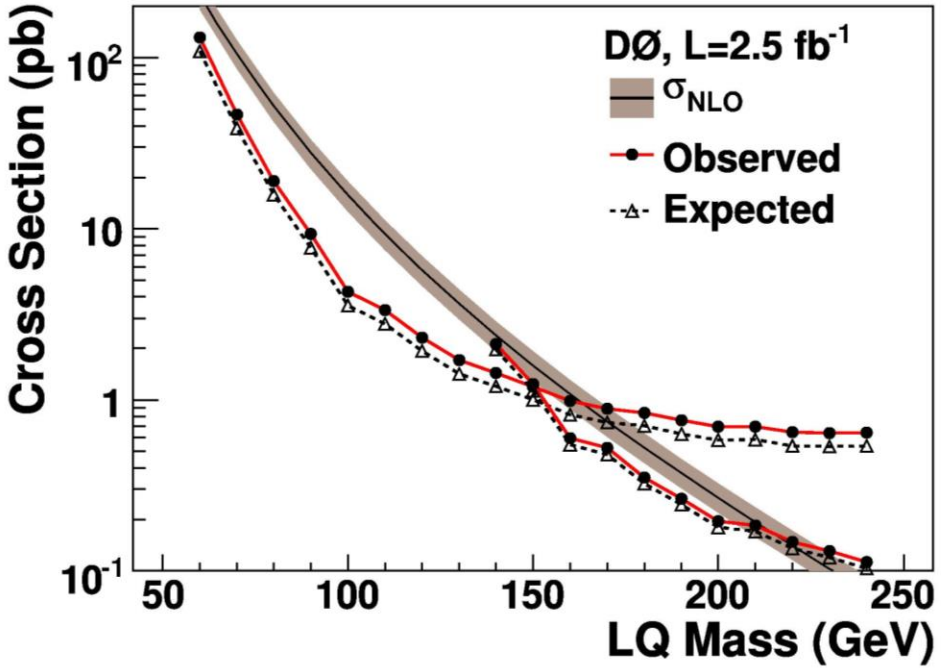
New Physics in Dijet + Met



Sensitive To Lots of Models

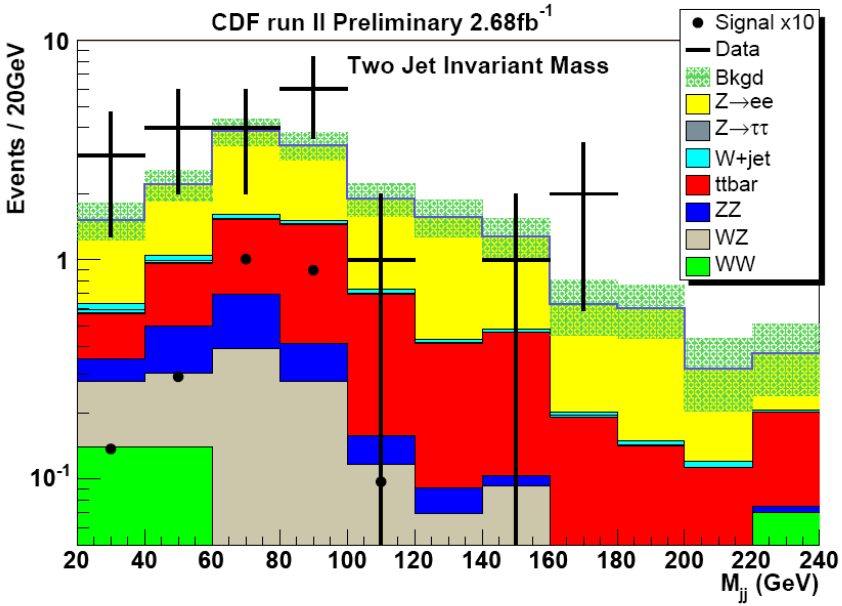
Also Sensitive To Lots of Models

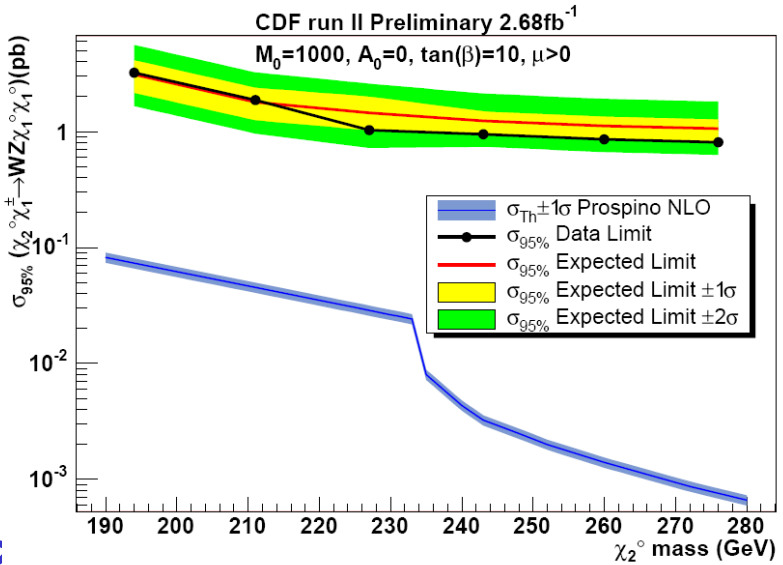




Lots of Gaugino Pair Searches

- Best current limits from Trileptons
  - Hedin's talk
- New version coming
  - Vogel's talk later this session
- New: Heavy Gauginos
  →WZ+Met→eejj+Met

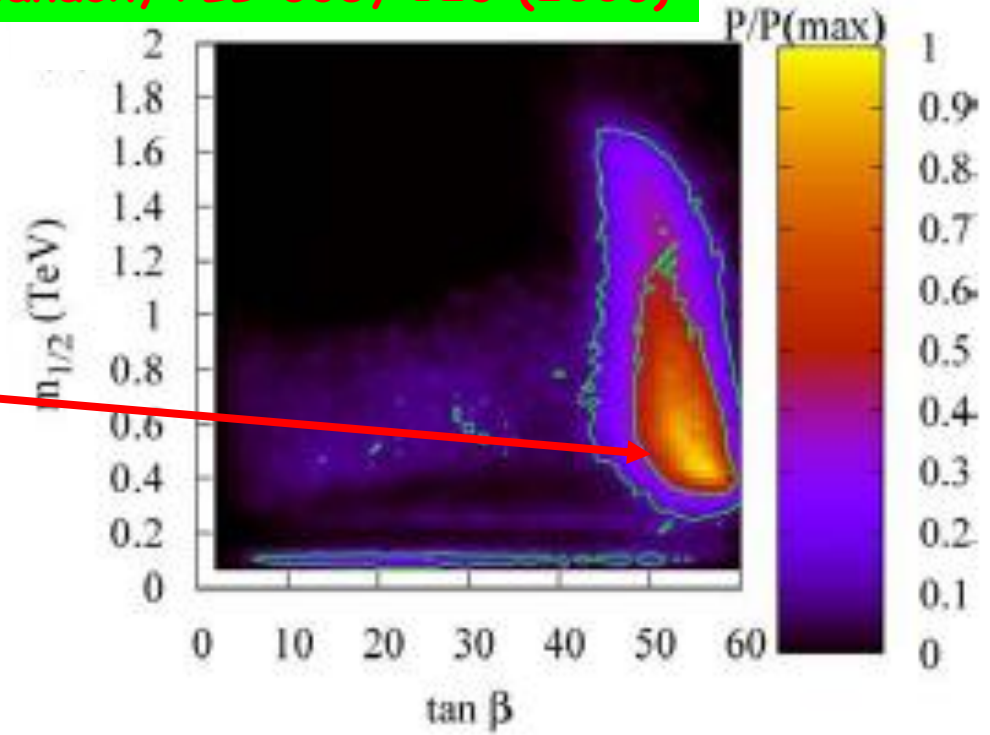




High Tanβ

- 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)



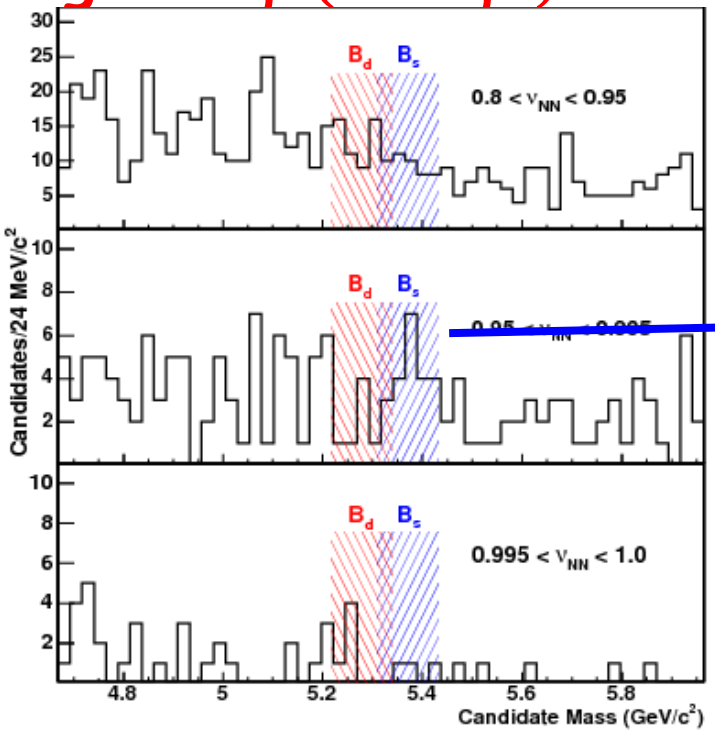
Emphasis on tanβ just starting during SUSY-Higgs Workshop

Now we have a full suite of high tanβ targeted searches

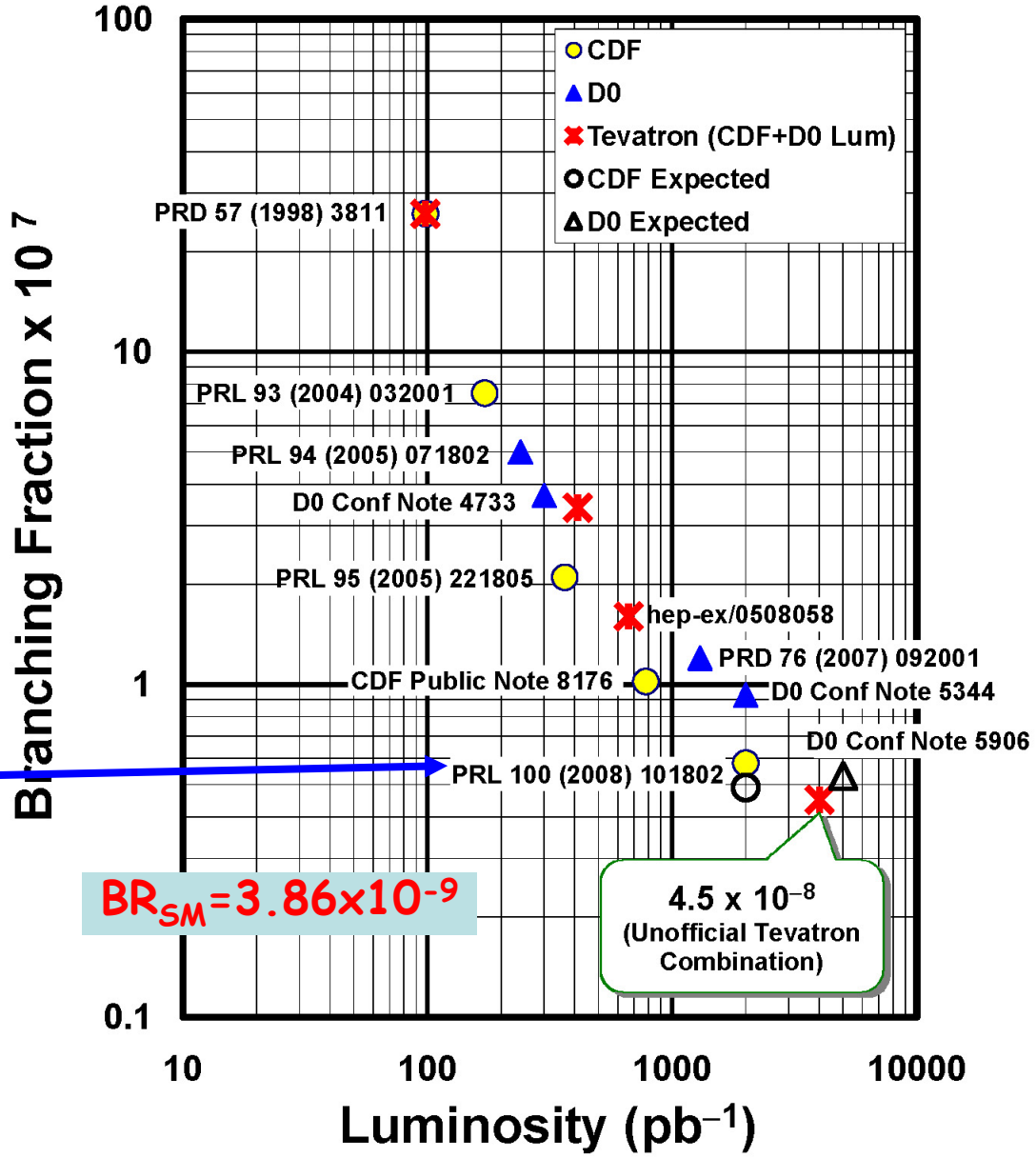
Indirect S

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



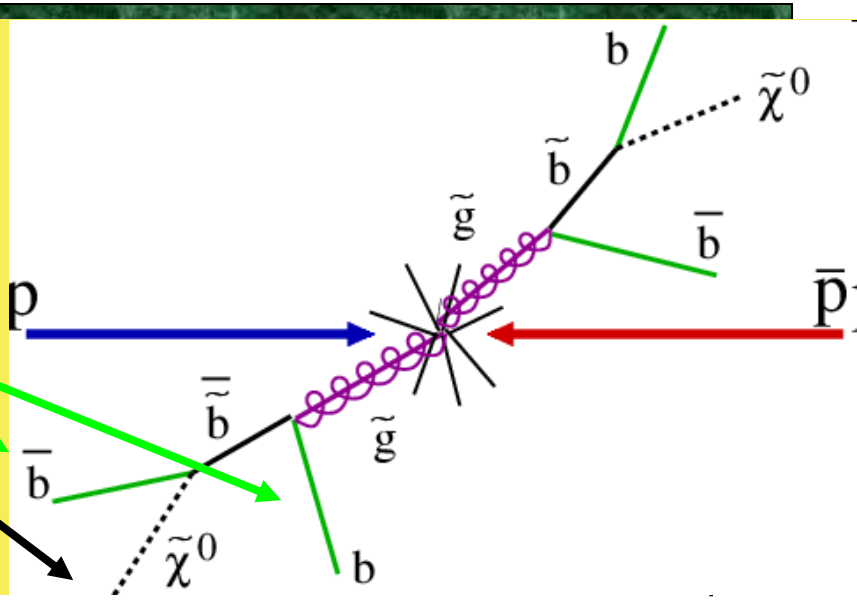
95% CL Limits on $\mathcal{B}(B_s \rightarrow \mu\mu)$

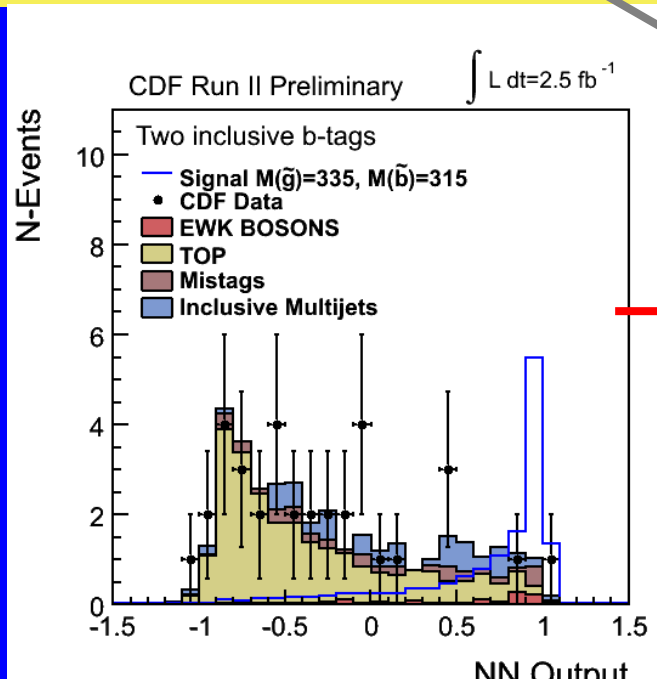


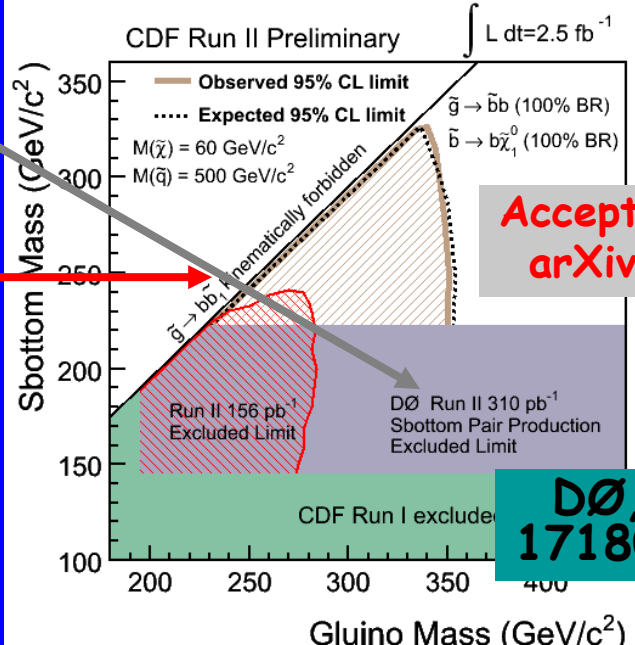
Sbottom Searches

Two primary Sbottom searches in b+jets+Met

1. Sbottoms from gluinos
2. Direct sbottom pair production





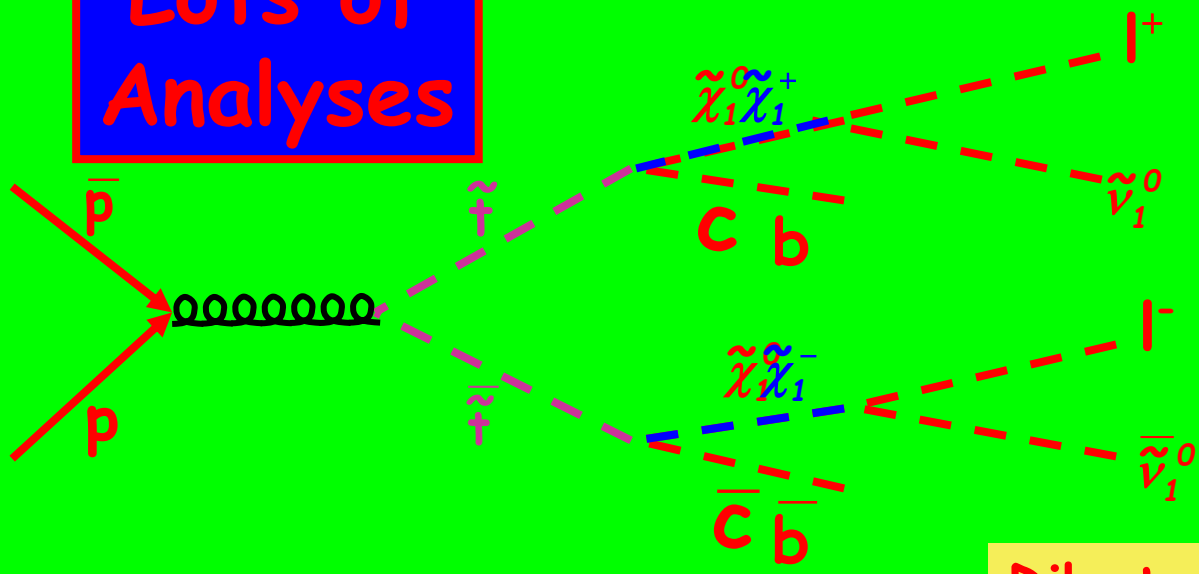


Accepted to PRL, arXiv:0903.2618

DØ, PRL 97 171806 (2006)

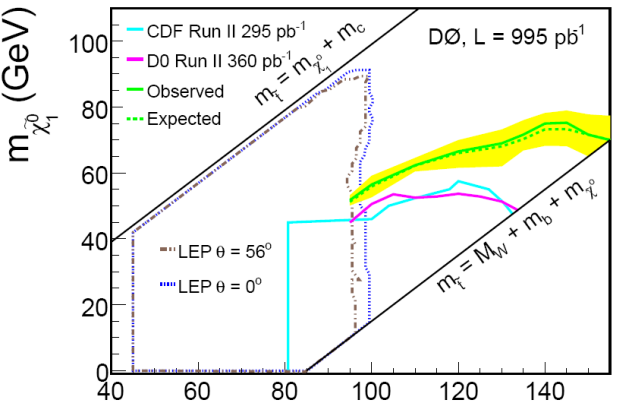
Stop Searches

Lots of Analyses

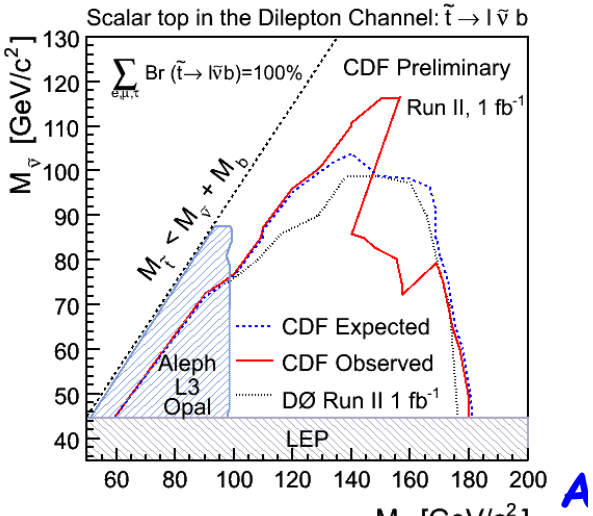


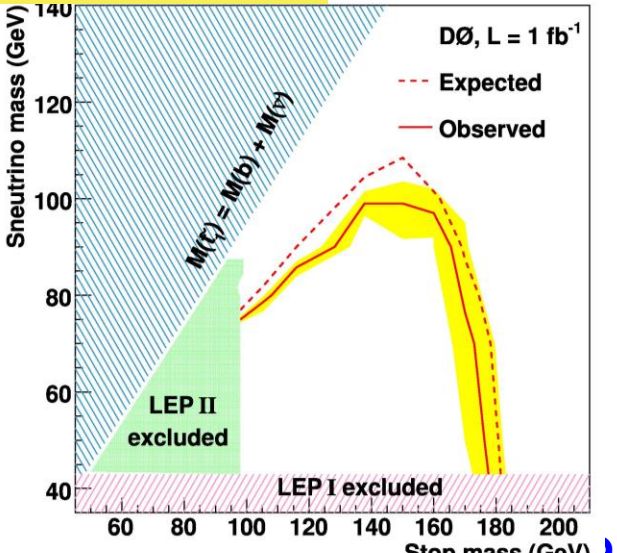
Direct counting Experiments

Charm+jet+MET



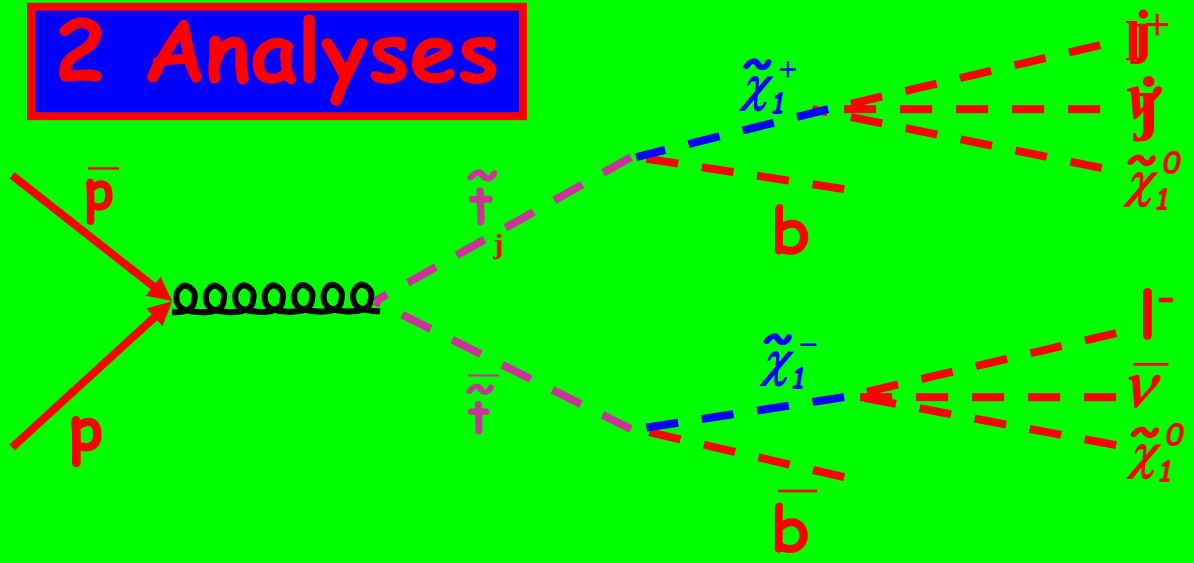
Dileptons+Jets+MET





Other Stop Searches

2 Analyses



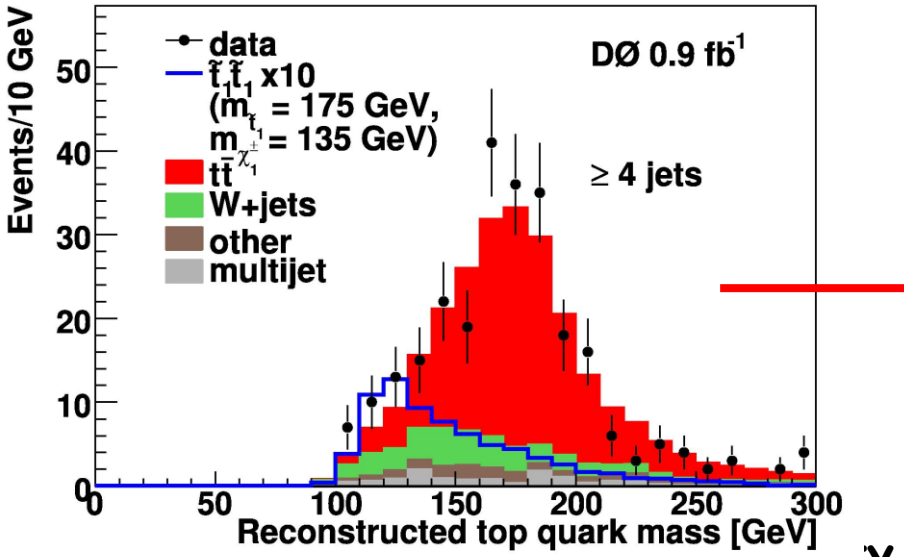
Fit for Stop Admixture in top sample

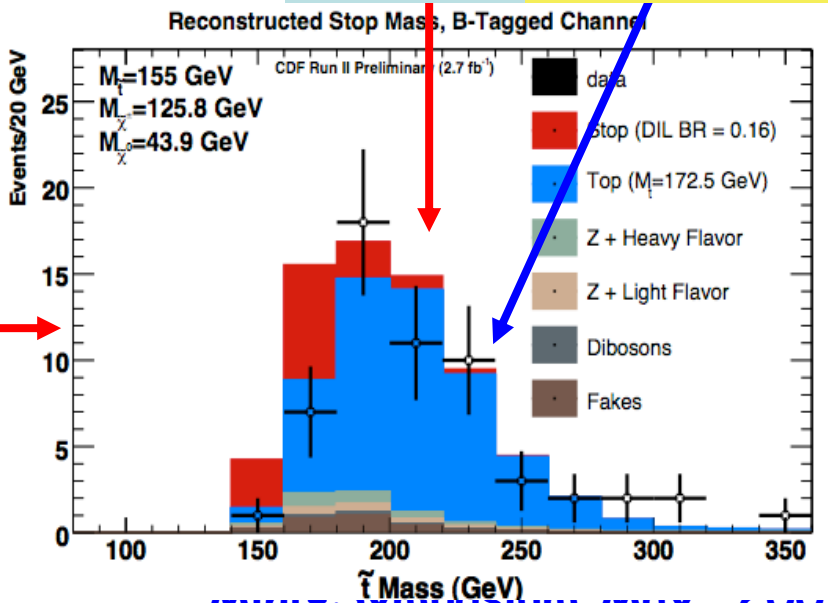
Lepton+Jets+MET

Dileptons+Jets+MET

M_{Stop} = 155 GeV

M_{top} = 172.5 GeV

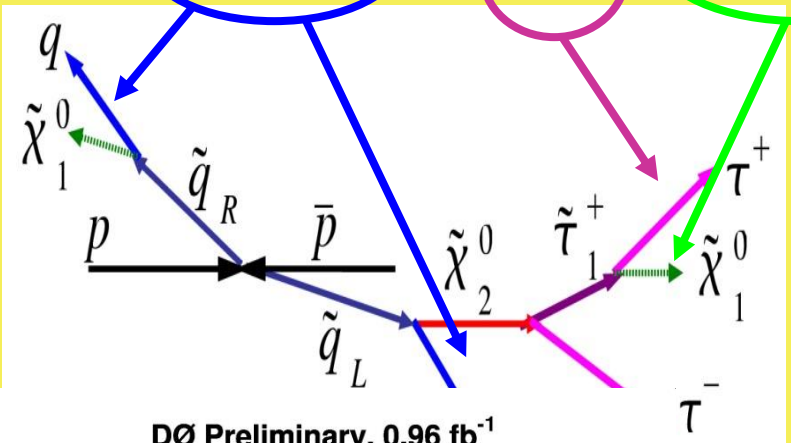




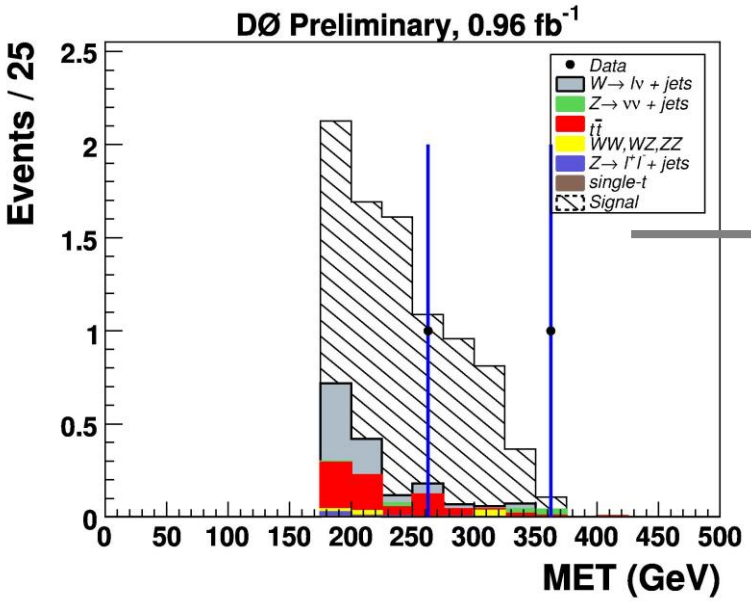
High tanβ → Light $\tilde{\tau}$'s

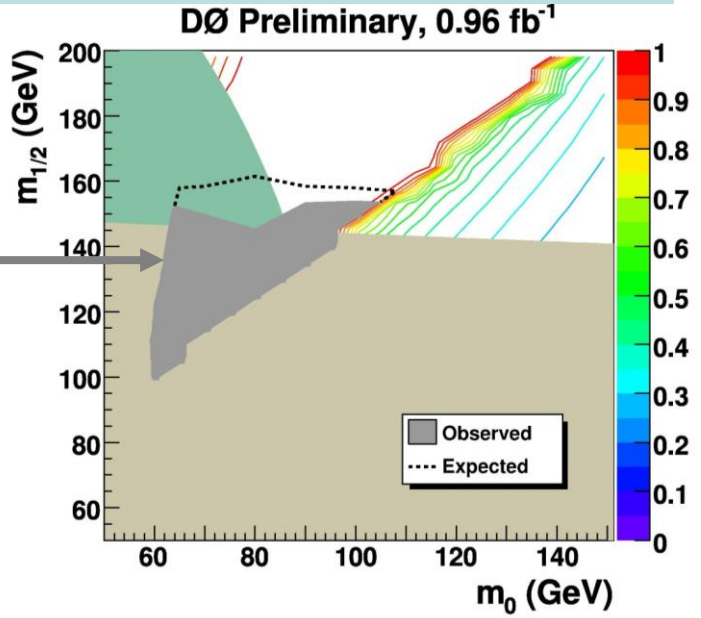
Complementary search for Squarks:

Jets + τ + Met



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





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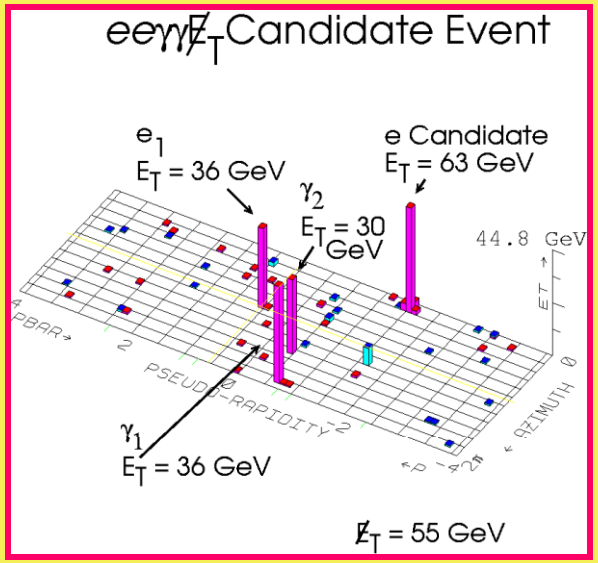
Gauge-Mediated SUSY Breaking Models

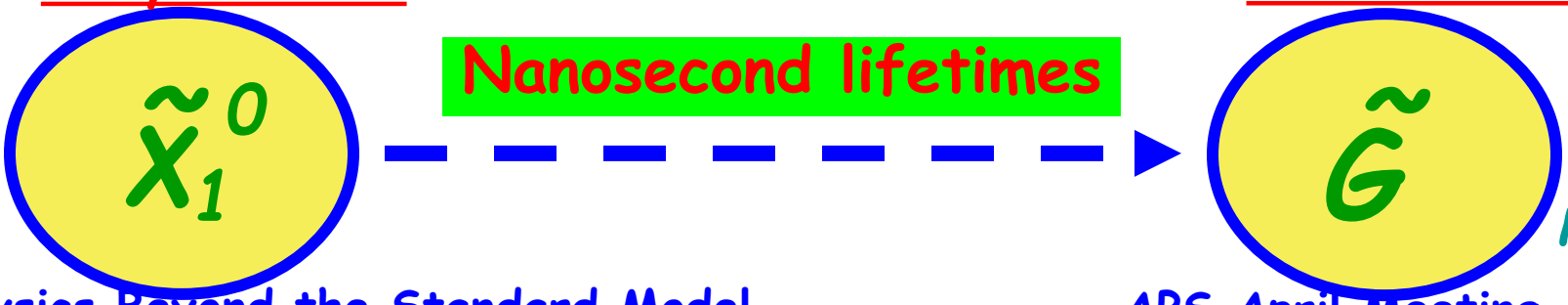
$\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ models provide a warm dark matter candidate Consistent with Astronomical observations and models of inflation

More natural solution for FCNC problems than mSUGRA



CDF Run I eeγγ+Met candidate event

Early Universe

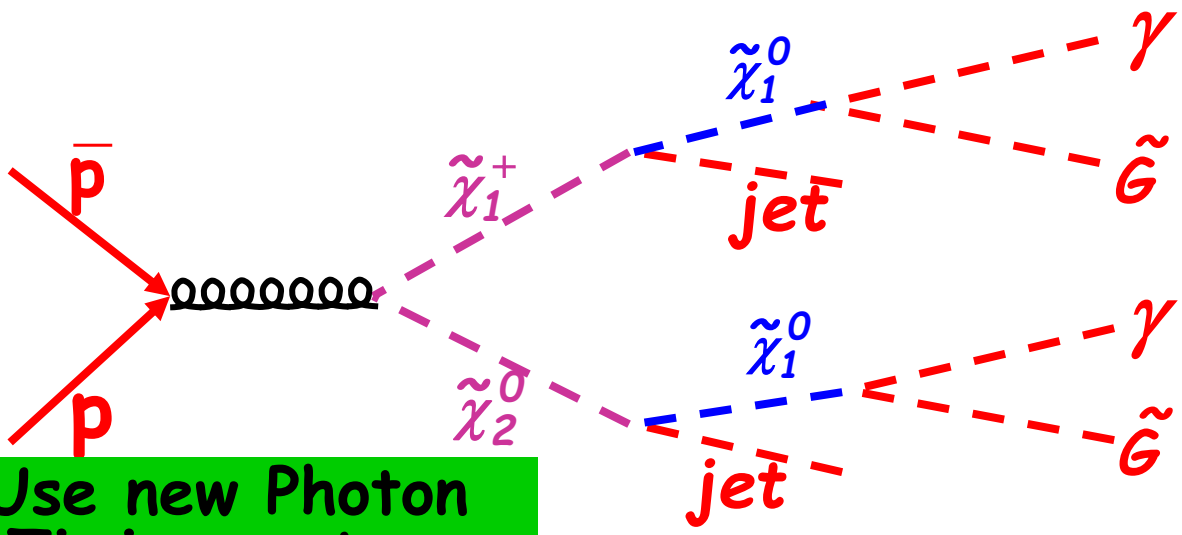


Later Universe

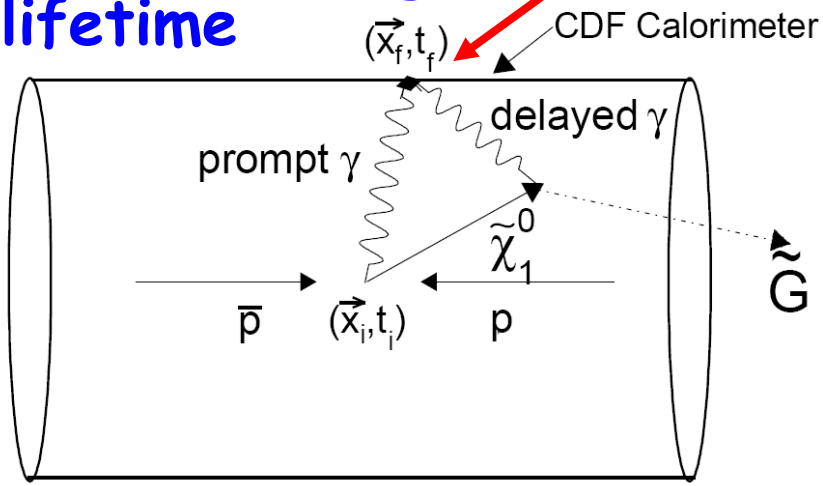
High and Low Lifetime Searches

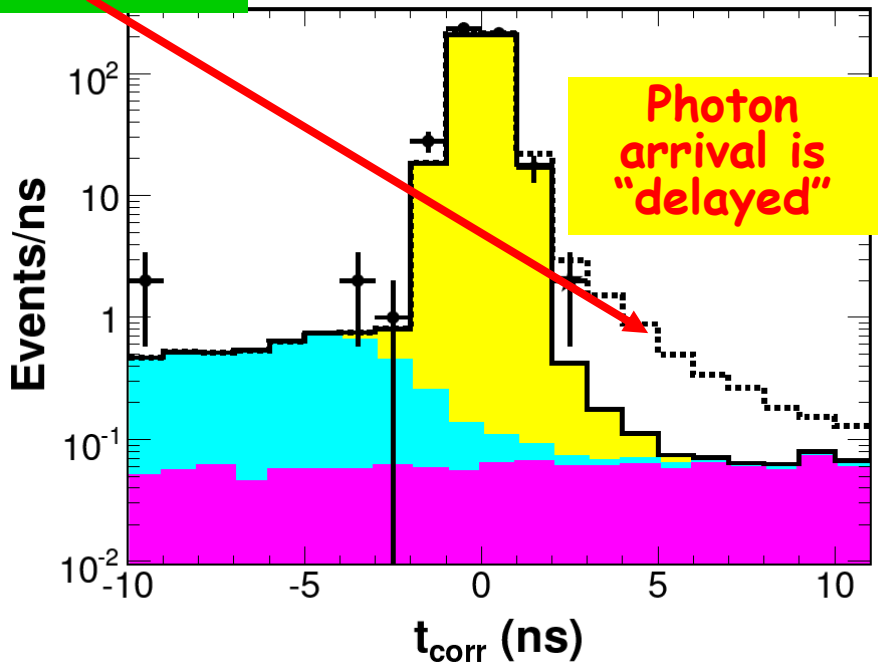
The lifetime and associated particle production dictate different final states

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



Use new Photon Timing system



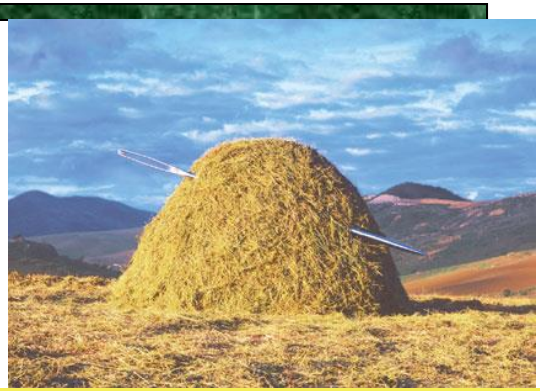


Conclusions

- The search program for Beyond the Standard Model Physics at the Fermilab Tevatron is both deep and broad
- Unfortunately, despite almost 4 fb^{-1} of data analyzed there is no sign of new physics

Observations from the perspective on the grand plans of the SUSY-Higgs Workshop

- Most searches have done as well or better than we expected
- Some of today's questions will be answered
- Some of today's hot new topics will die away
- Some searches and questions we never envisioned may come to dominate our every day thinking

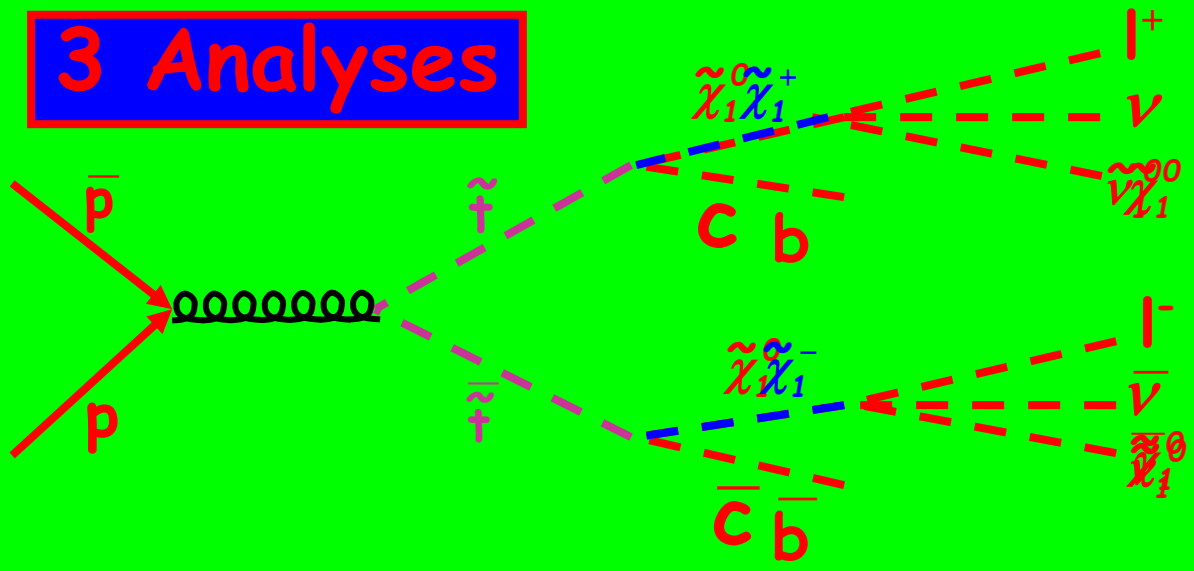


Perhaps, looking back 10 years from now, the view from 10 years worth of LHC LHC data will make things LOOK different

End of Talk

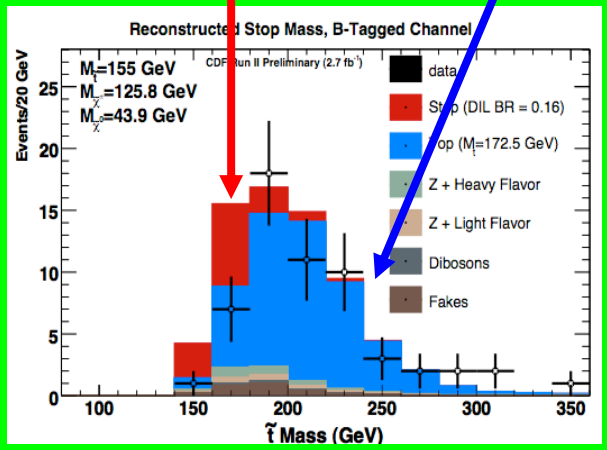
Stop Searches

3 Analyses

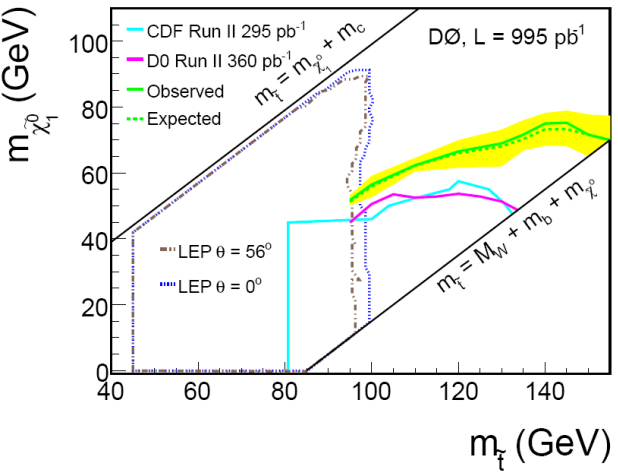


M_{Stop} = 155 GeV

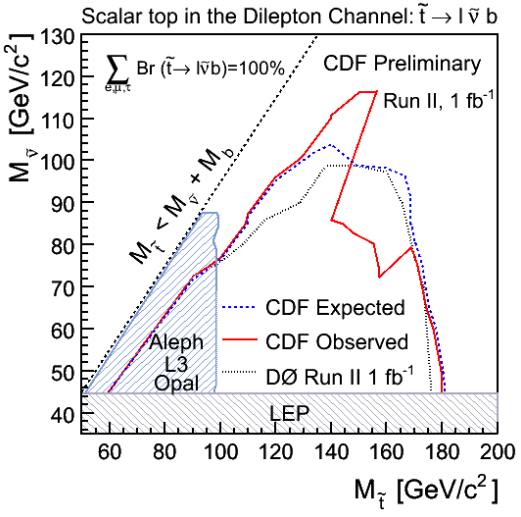
M_{top} = 175 GeV



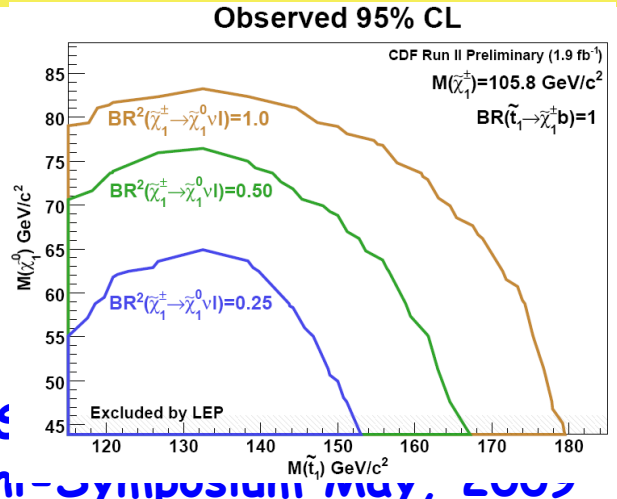
Charm+jet+MET



Dileptons+Jets+MET



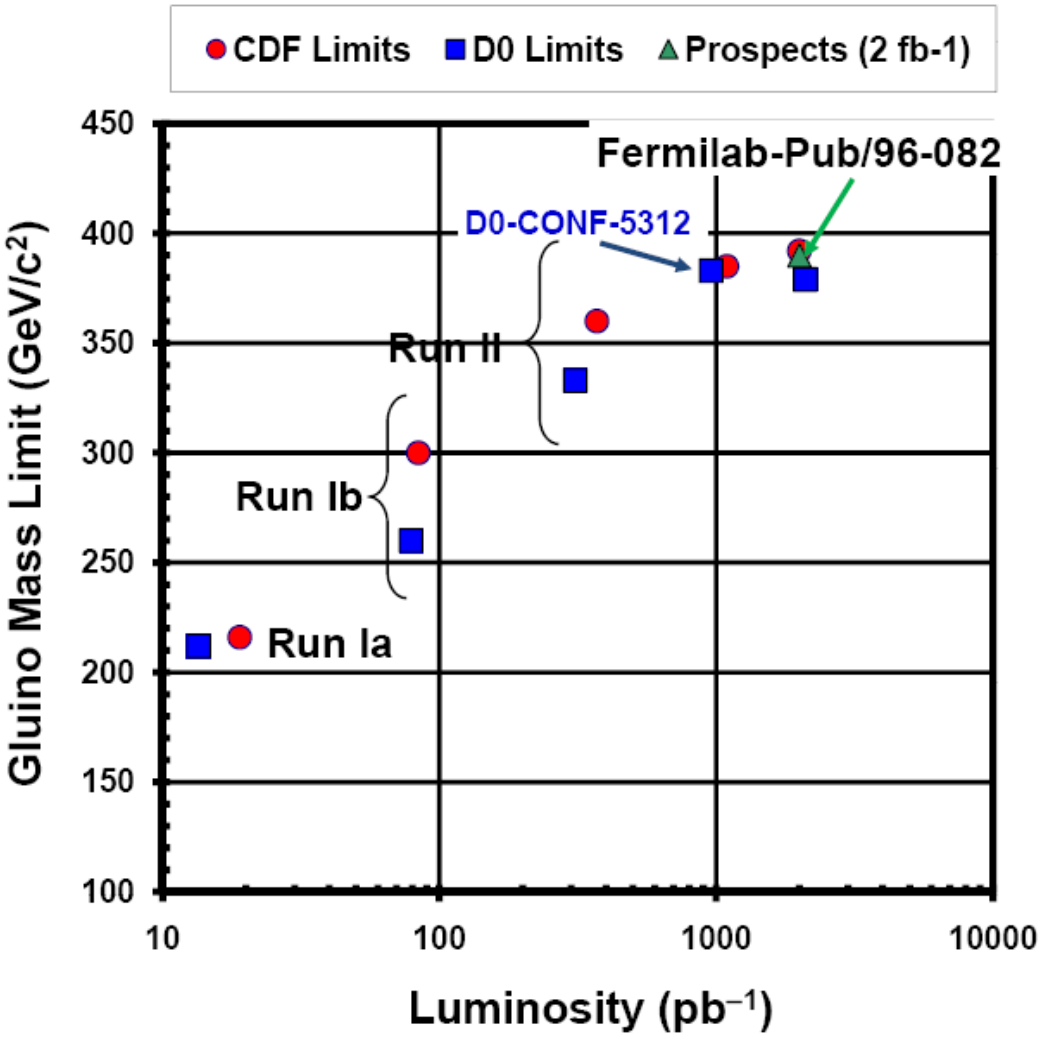
Dileptons+Jets+MET Fit for Stop Admixture



APS Mini-Symposium May, 2009

Run II

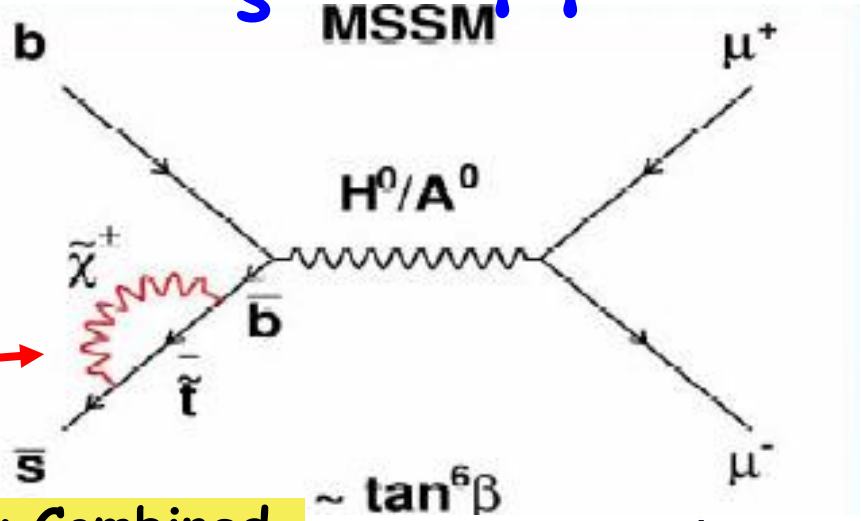
[M(gluino) = M(squark)]



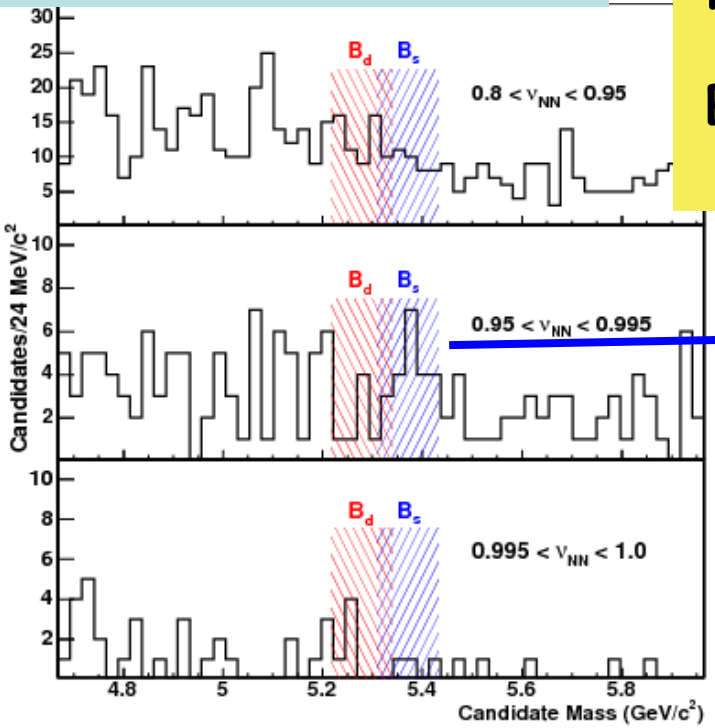
Indirect Search: $B_s \rightarrow \mu\mu$

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



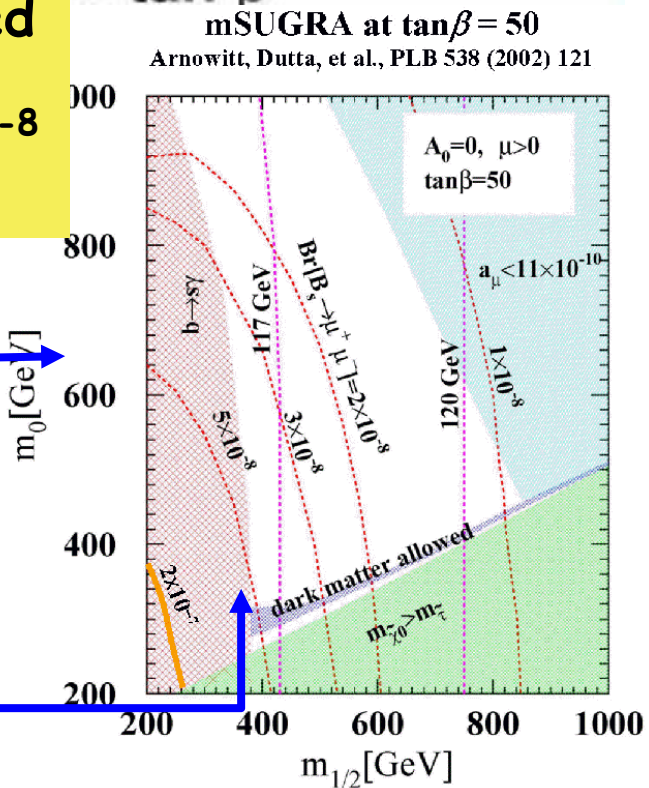
CDF, PRL 100, 101802 (2008)



Preliminary Combined CDF/DØ

$BR(B_s \rightarrow \mu\mu) < 4.5\times10^{-8}$ @95%

$BR_{SM} = 3.86\times10^{-9}$

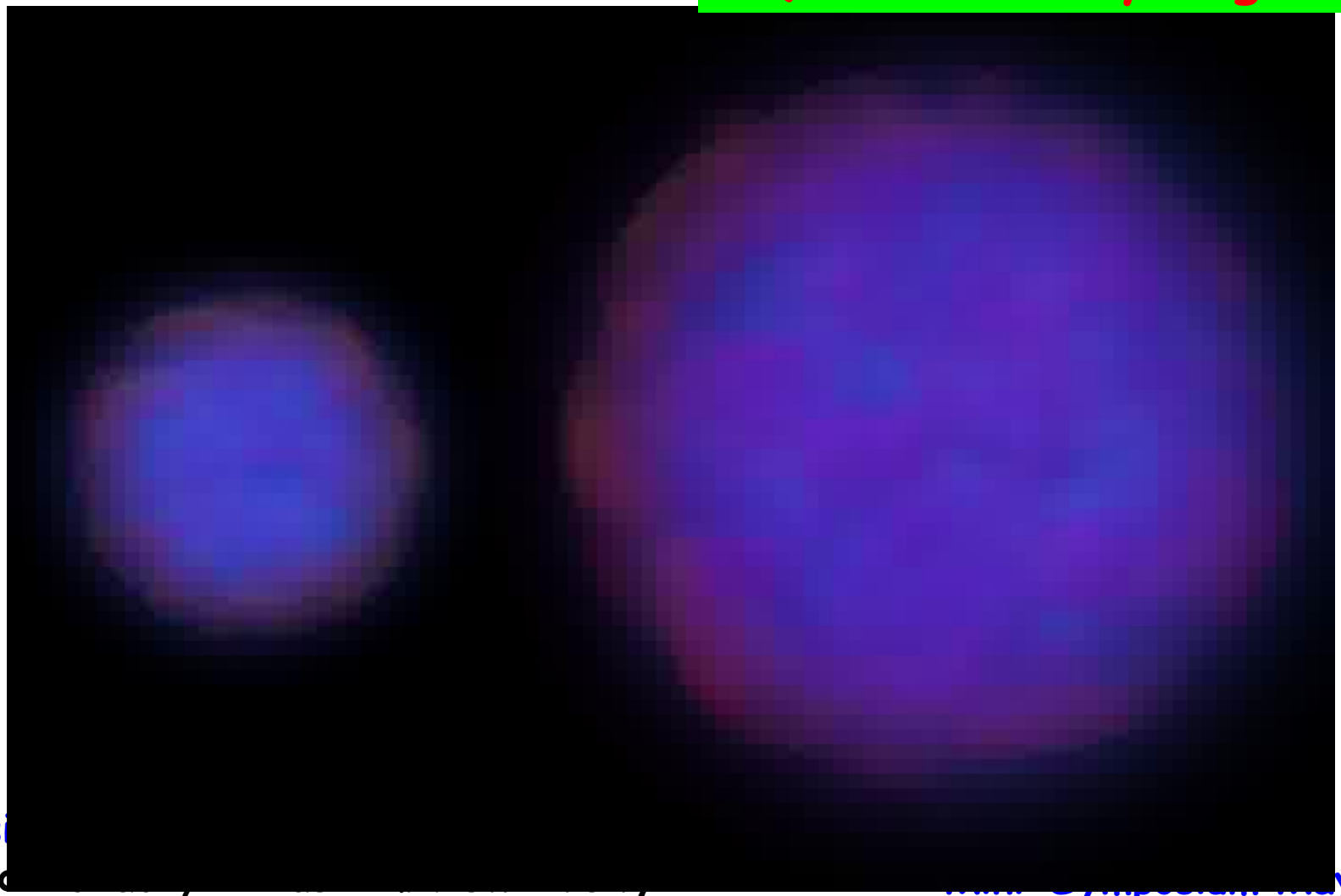


Evidence for Dark Matter as Particles:

Colliding Galaxies

Blue is the Dark Matter

Red is the baryonic matter
(Stars and Hydrogen gas)



Evidence for This in Nature?

Colliding Galaxies Observed in 2006!

Blue is the part from lensing only

"Fast ➔ Dark Matter"

Red part from x-ray observations light

"Slow ➔Stars"