



Physics at LHC-2008

29 September - 4 October 2008, Split - CROATIA

*The Search for
Supersymmetry and Beyond
the Standard Model
Physics at the Fermilab
Tevatron*

David Toback
Texas A&M University
For the
CDF and DØ collaborations



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 3 fb⁻¹
of data

Split 2008
Sept 30, 2008

SUSY and BSM Searches at the Tevatron
David Toback, Texas A&M University

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 $e\bar{e}\gamma + \text{Met}$ 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

Cosmology and Particle Physics?

Minimal Solution/ Cold Dark Matter

- Favored by most Cosmological models
- Minimal Solution → A particle produced in the early Universe is stable and weakly interacting → still here today
- 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/ Warm Dark Matter

- Warm Dark Matter consistent with Astronomical data and inflation models
- Many non-Minimal solutions to the Dark Matter we observe today

Example : Gauge Mediated SUSY with

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

Stable on the timescale of inflation

Stable on the timescale of the Universe

Dark Matter is more complicated/Not directly specified

- Infinite variety of Models to check for
- Search for the most compelling theories
 - CHAMPS
 - Extra Dimensions
- Another possibility: *We're at the Frontier! just look for Hints (you idiot)!*



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

Golden Channels

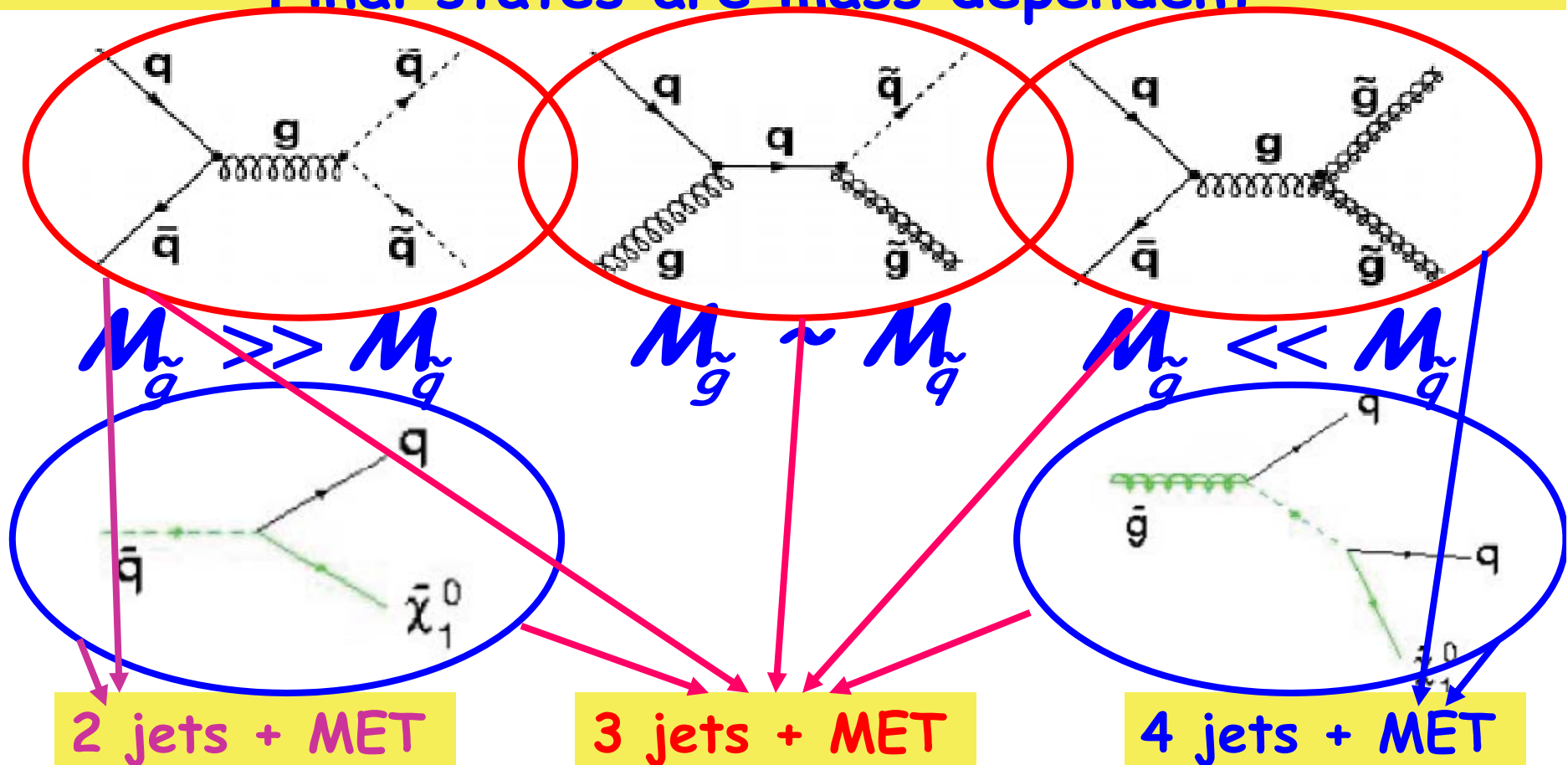
Three main ways to look for minimal/Cold Dark Matter Models in mSUGRA type models

- 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 $\tan\beta$, then move to searches with high $\tan\beta$

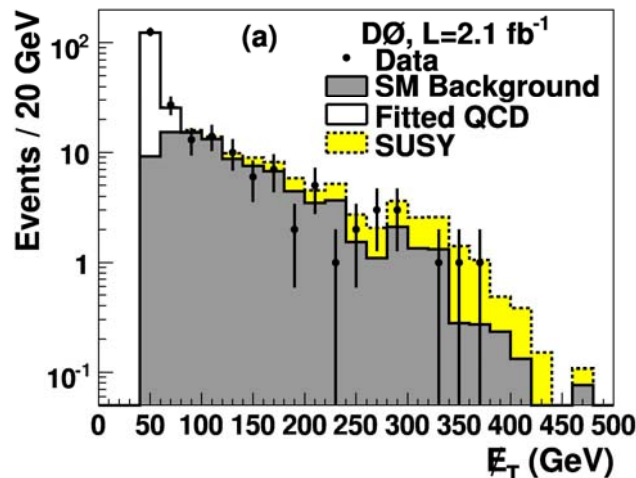
Squark and Gluino Searches in Multijet + Met

Three main production diagrams
Final states are mass dependent

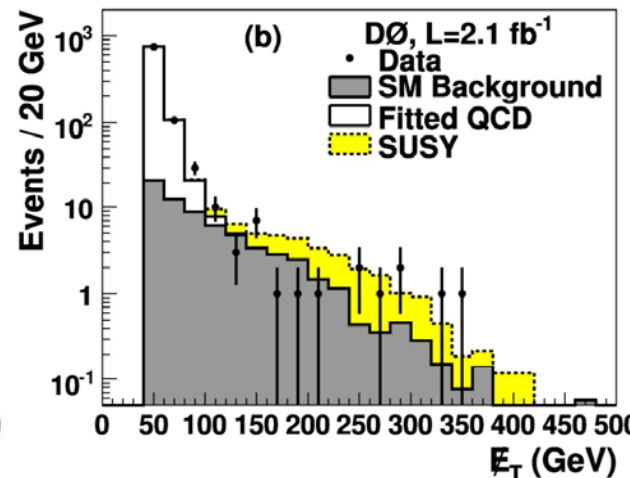


3 separate final states + Unified Analysis \rightarrow best coverage

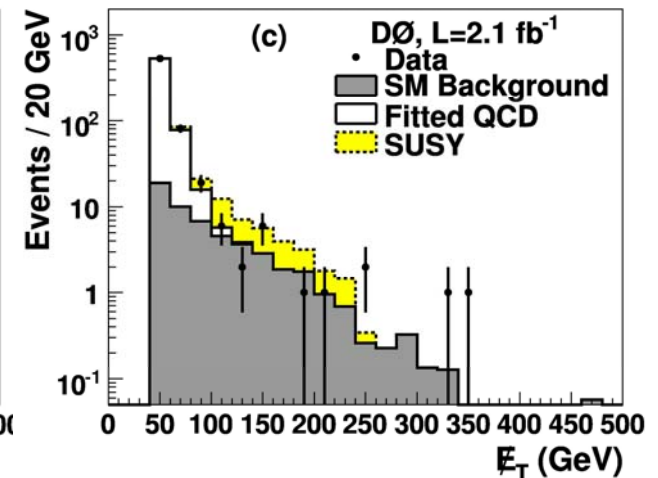
Unified Squark/Gluino Search



2 jets + MET



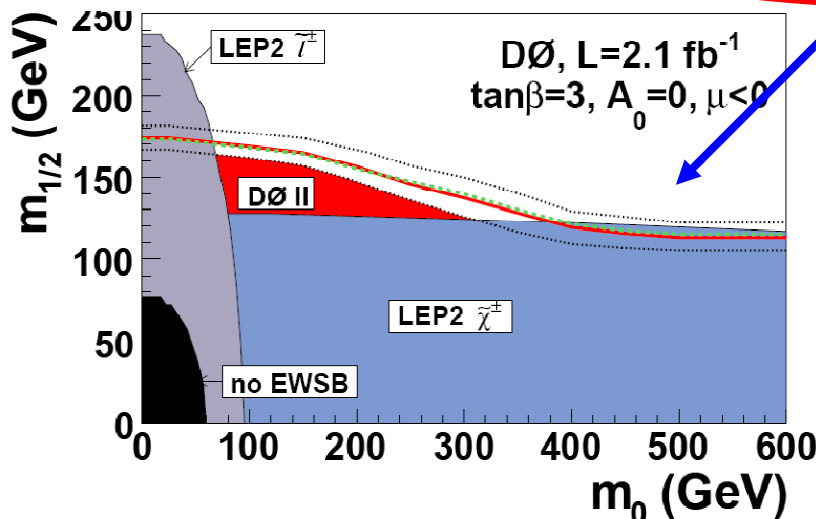
3 jets + MET



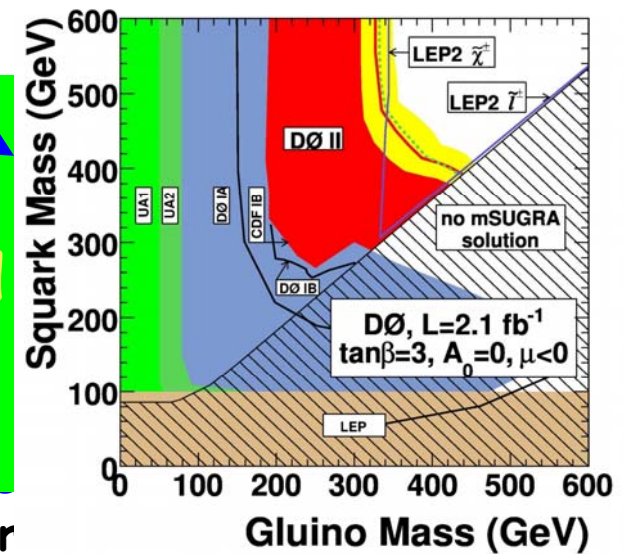
4 jets + MET

$D\bar{D}$, PLB 660, 449 (2008)

SUSY Interpreter



Comparable results from CDF public and nearing publication



Texas A&M Univer

Gaugino Pair Production in Multilepton + Met

Chargino-Neutralino gives three leptons in the final state

Dominates the production cross section

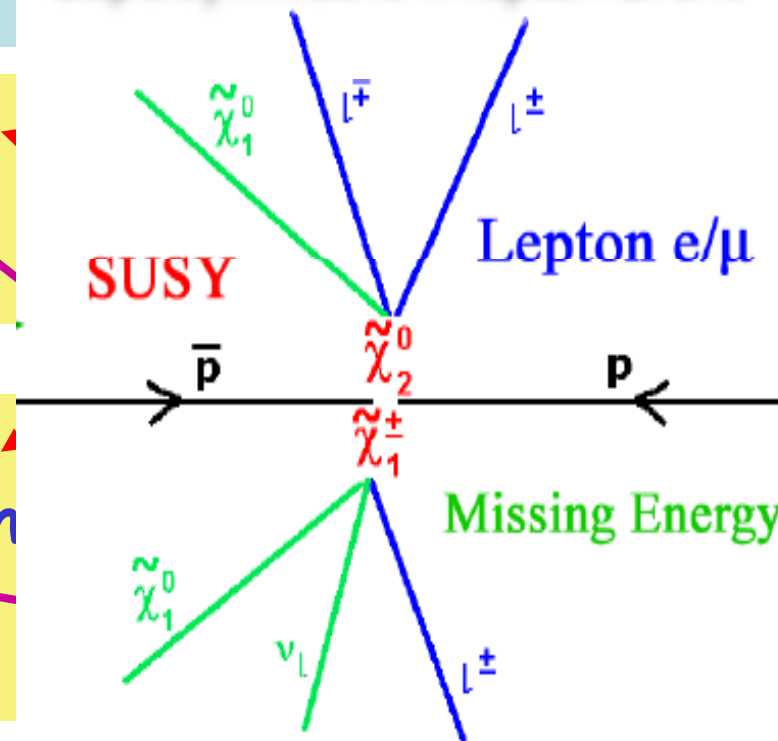
5 separate final states + Unified Analysis \rightarrow best coverage

$eee, ee\mu, e\mu\mu, \mu\mu\mu,$
 $eet, e\mu\tau, \& \mu\mu\tau$

2 Tight leptons
+ 1 track
+ MET

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

Supersymmetric Trilepton Event



$eee, ee\mu, e\mu\mu \& \mu\mu\mu$

3 Tight Leptons
+ MET

2 Tight leptons
+ 1 Loose lepton
+ MET

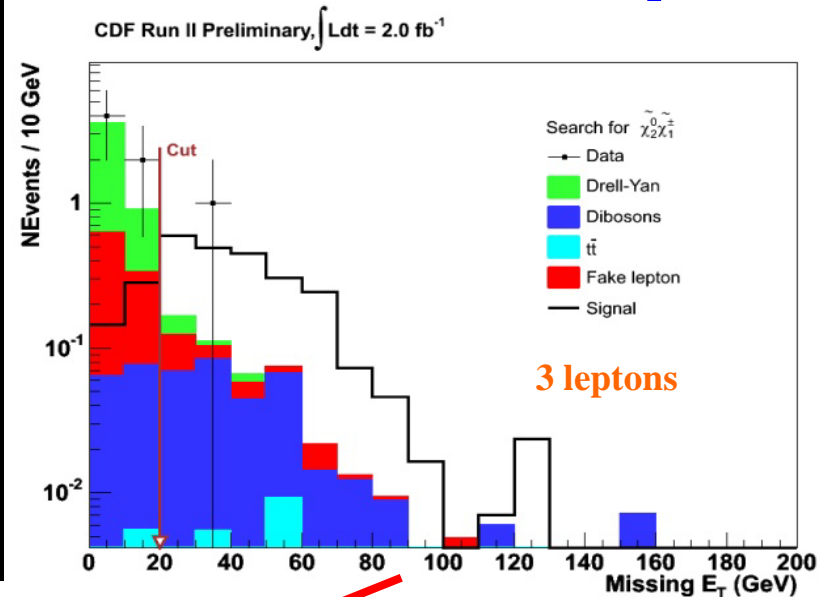
1 Tight lepton
+ 2 Loose leptons
+ MET

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

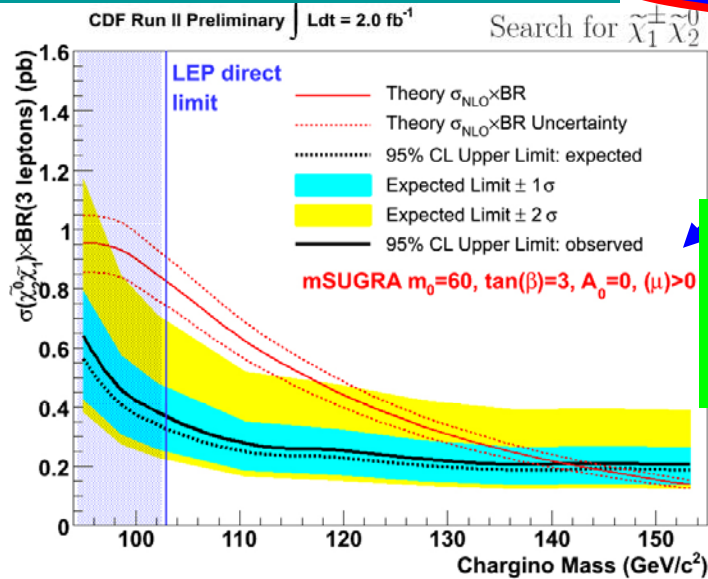
Unified Gaugino Pair Production Analysis

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



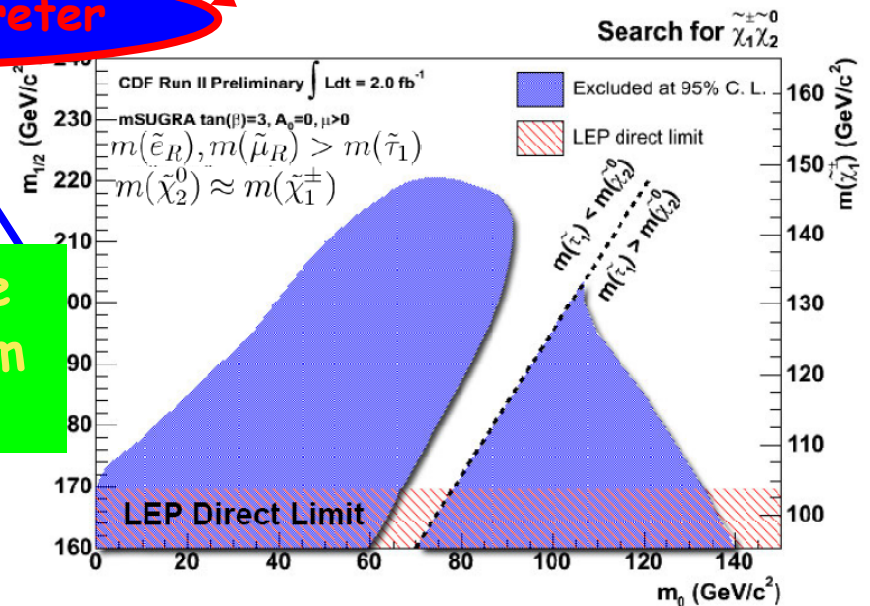
CDF, Submitted to PRL,
arXiv:0808.2446

SUSY Interpreter



Comparable
results from
DØ

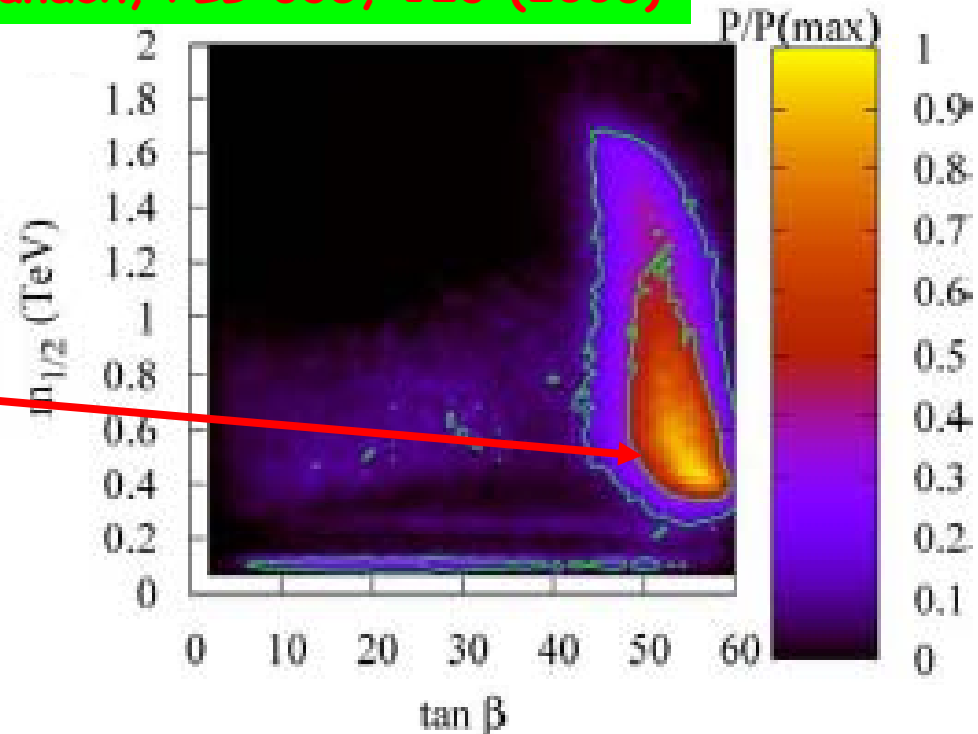
SM Search
Jackson, Texas



High $\tan\beta$

- Likelihood fits including Higgs mass limits, $g-2$, and other experimental data to the MSSM in the plane of $m_{1/2}$ and $\tan\beta$
 - Prefers high $\tan\beta$
- 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)

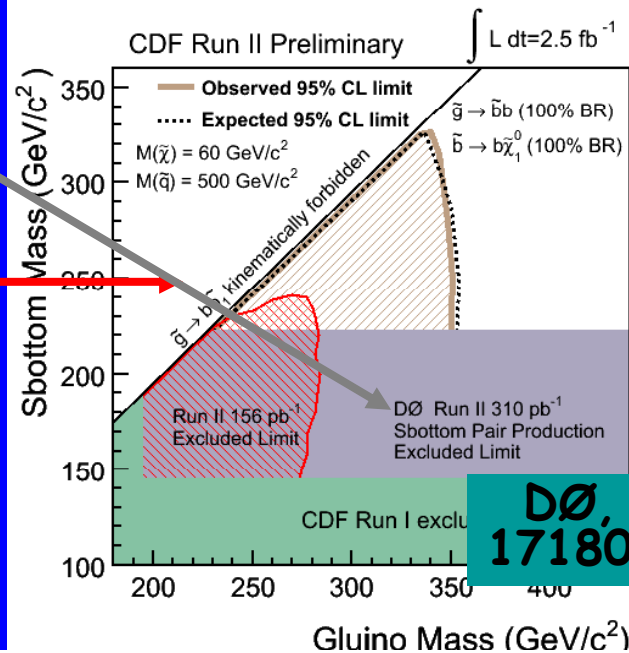
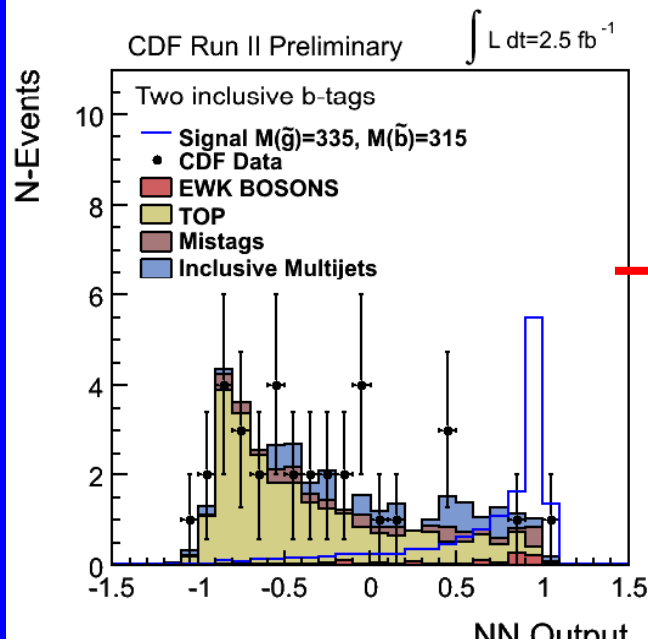
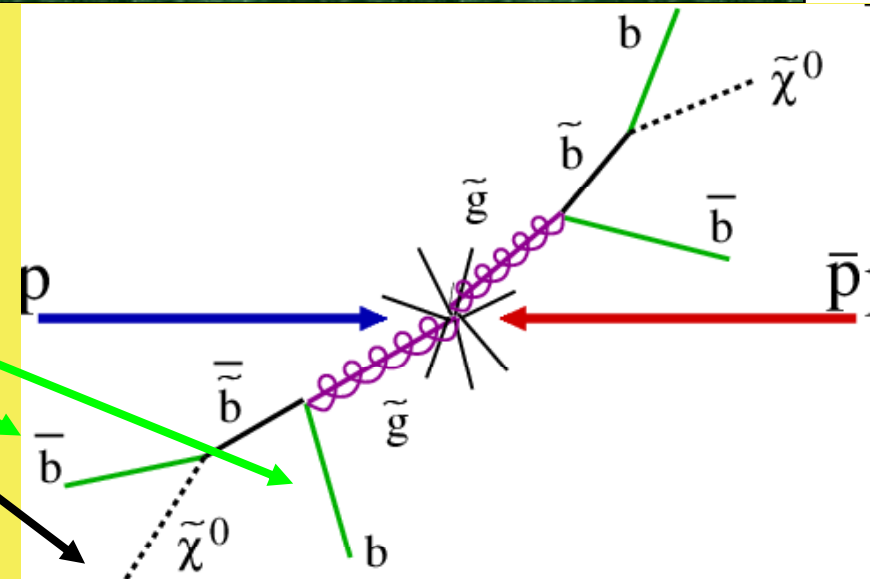


Emphasis on $\tan\beta$ just starting during SUSY-Higgs Workshop
Now we have a full suite of high $\tan\beta$ targeted searches

Sbottom Searches

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

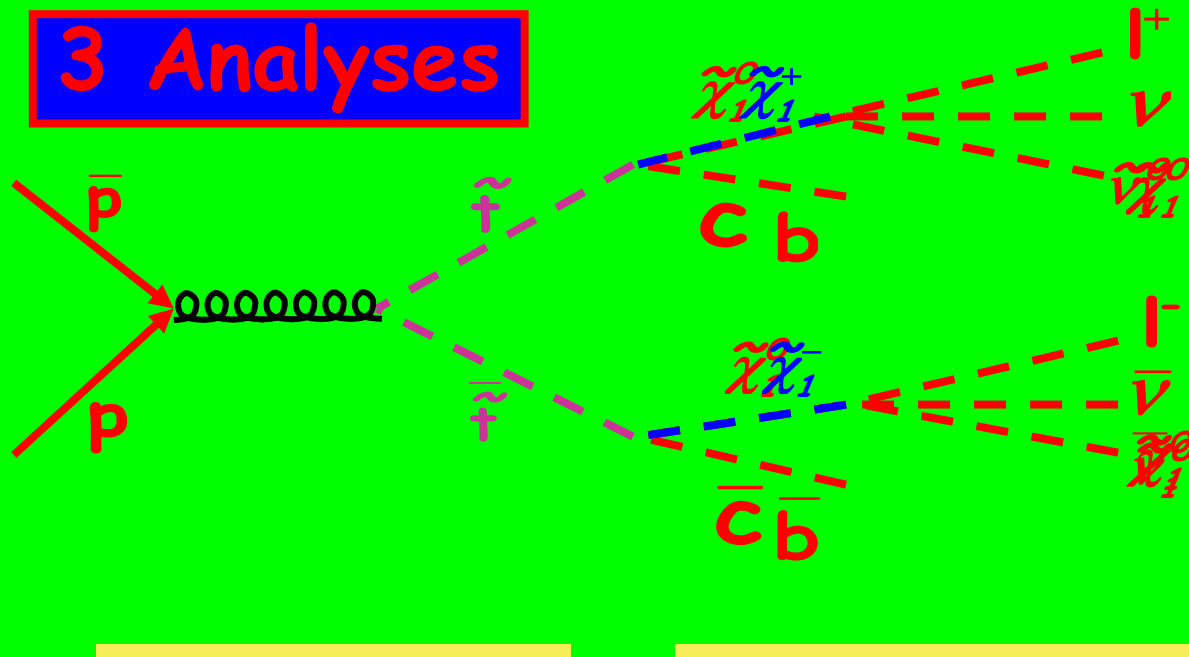
1. Sbottoms from gluinos
2. Direct sbottom pair production



DØ, PRL 97
171806 (2006)

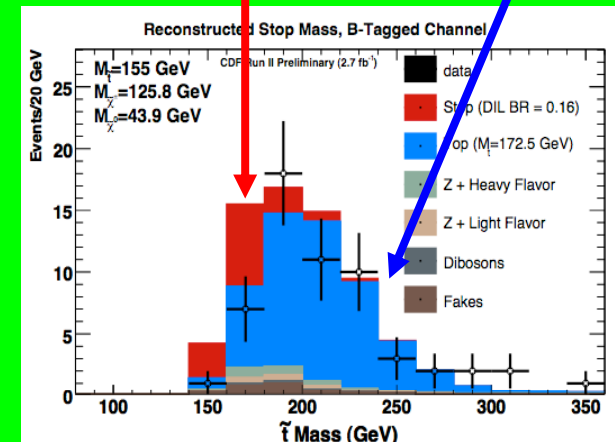
Stop Searches

3 Analyses



$M_{\text{Stop}} = 155 \text{ GeV}$

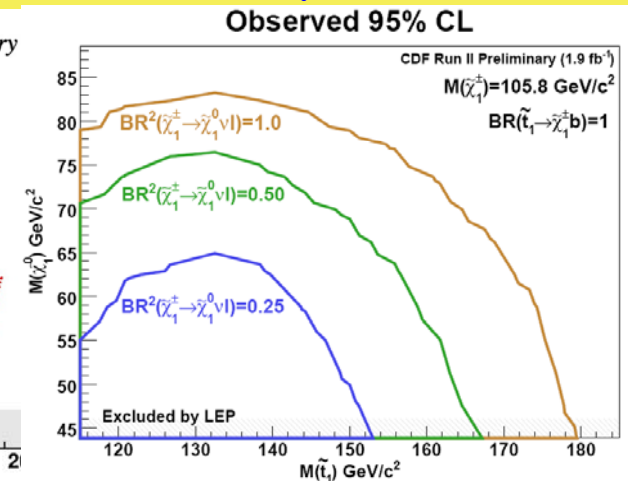
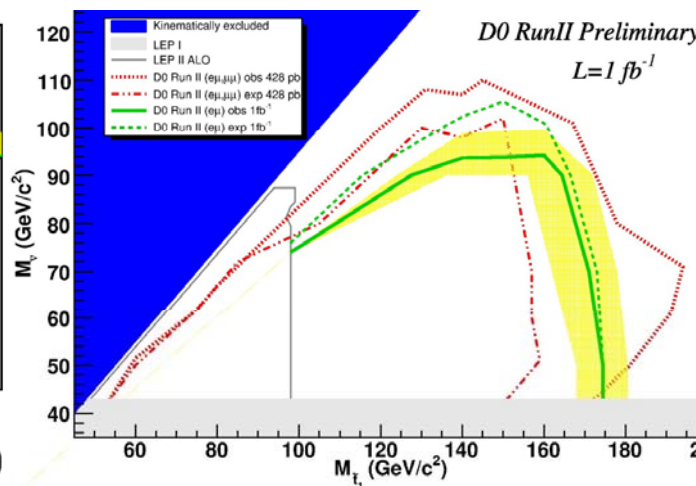
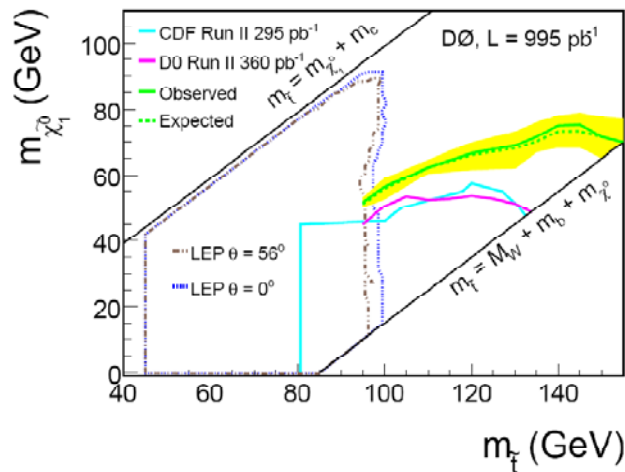
$M_{\text{top}} = 175 \text{ GeV}$



Charm+jet+MET

Dileptons+Jets+MET

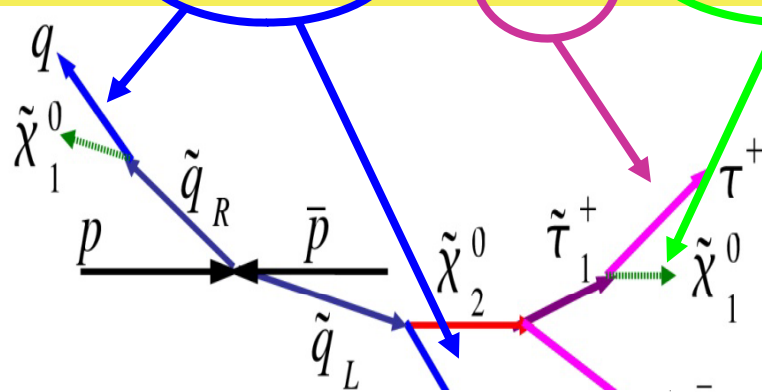
Dileptons+Jets+MET
Fit for Stop Admixture



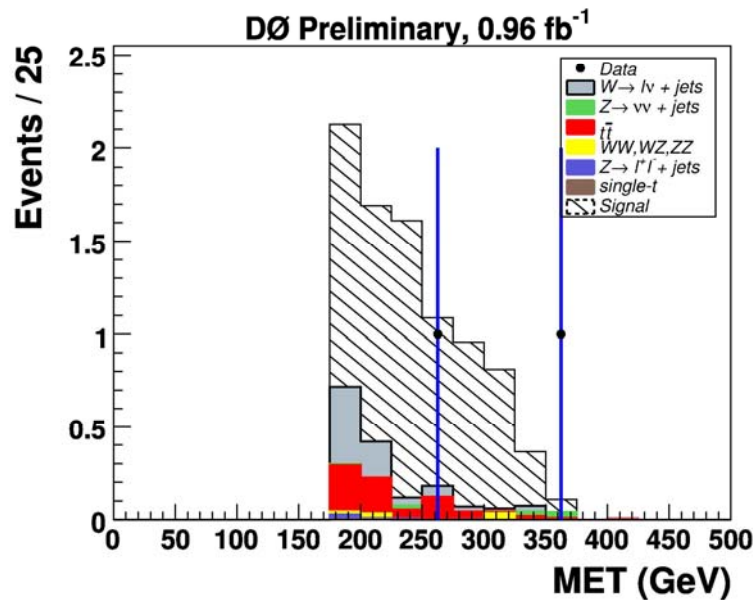
High $\tan\beta \rightarrow$ Light $\tilde{\tau}'$ s

Complementary search for Squarks:

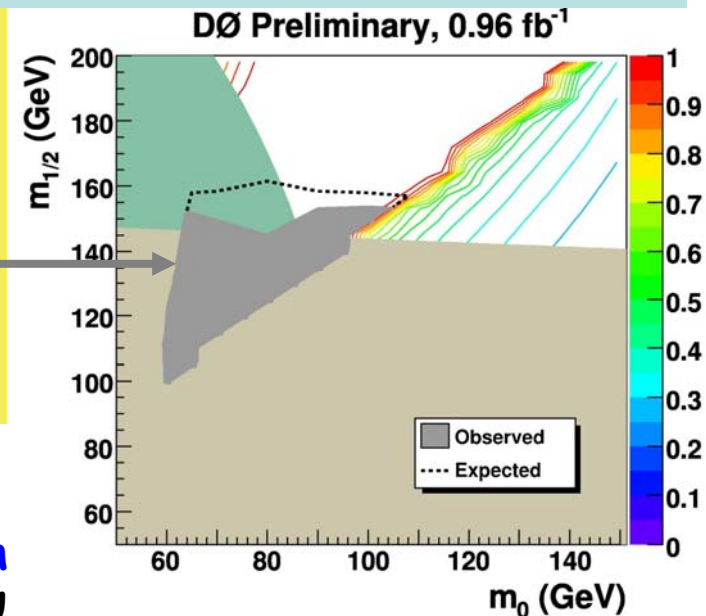
Jets + τ + Met



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



Searches at the University of Texas A&M U

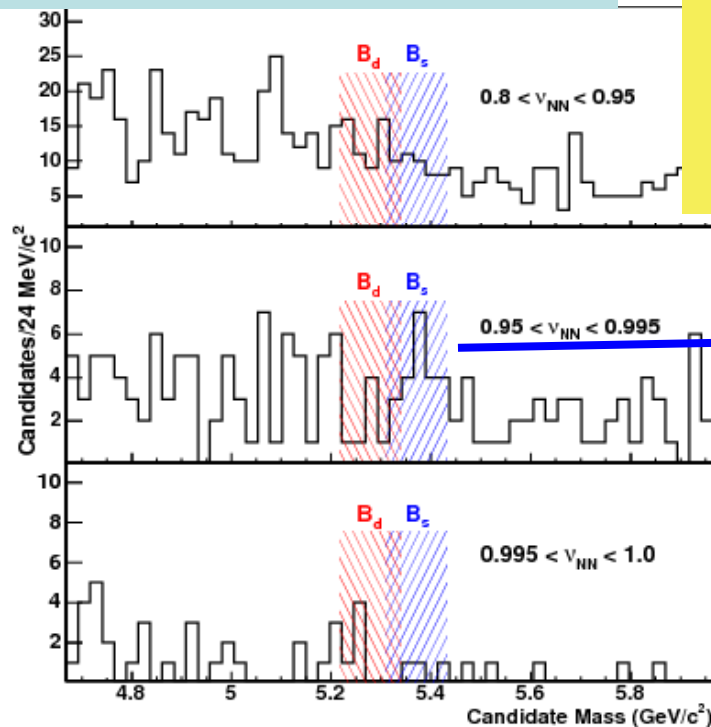


Indirect Search: $B_s \rightarrow \mu\mu$

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

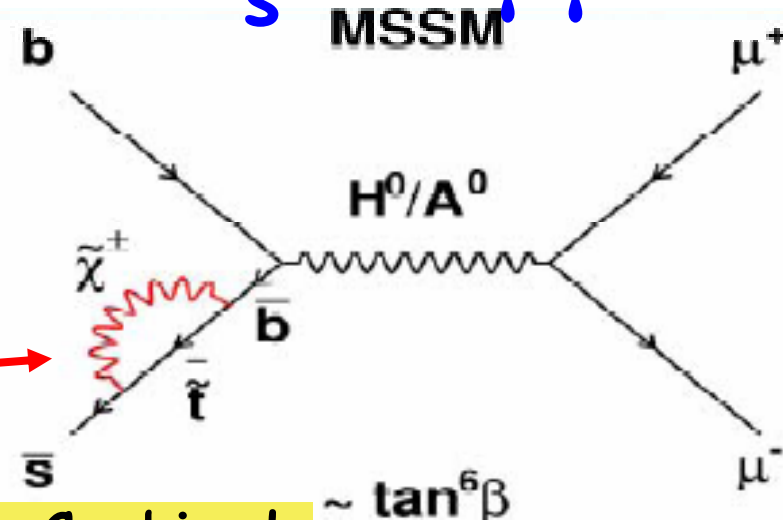
Especially sensitive at high $\tan\beta$ ($\propto \tan\beta^6$)

CDF, PRL 100, 101802 (2008)

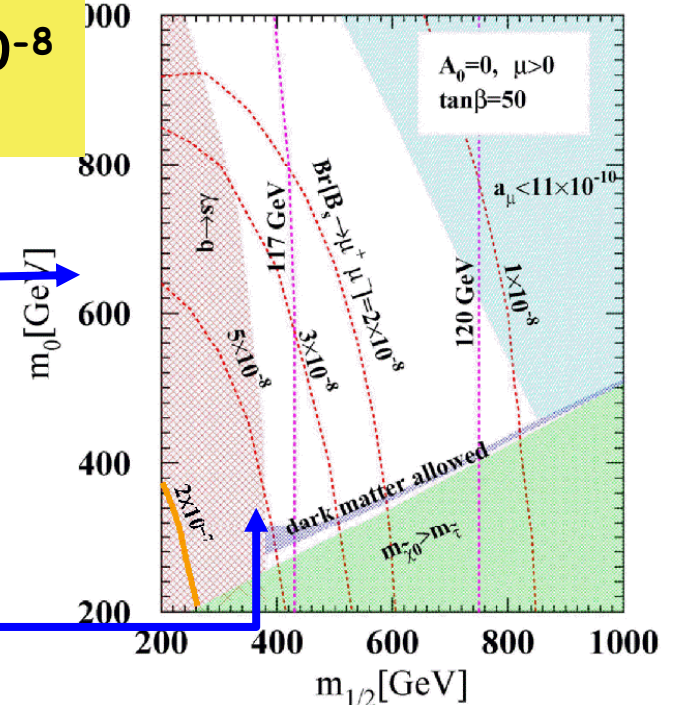


Preliminary Combined CDF/DØ
 $BR(B_s \rightarrow \mu\mu) < 4.5 \times 10^{-8}$
 @95%

$BR_{SM} = 3.5 \times 10^{-9}$

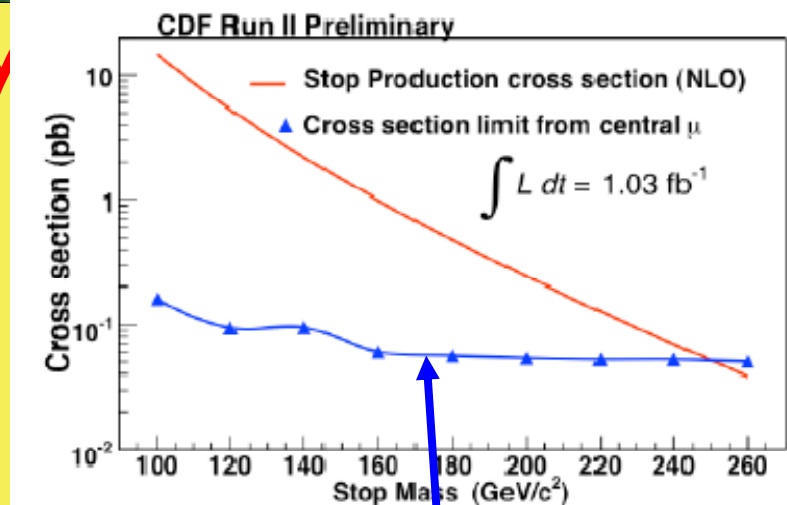


mSUGRA at $\tan\beta = 50$
 Arnowitz, Dutta, et al., PLB 538 (2002) 121

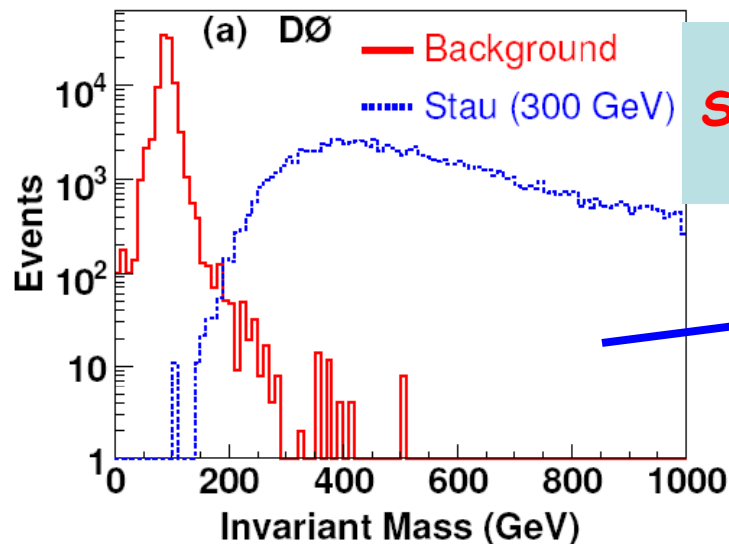


Long-Lived Charged Sparticles (Champs)

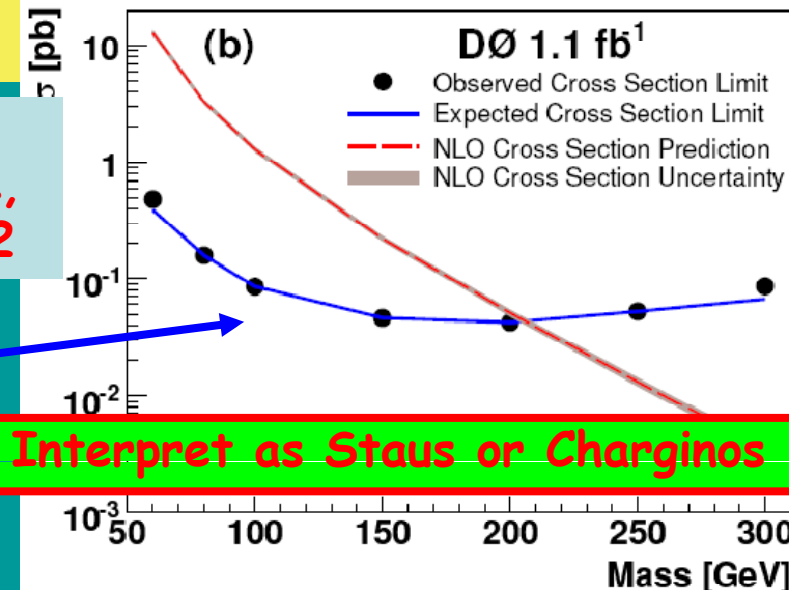
- New emphasis in the theory community about the role of long-lived sparticles in the Early Universe and today as Dark Matter
- Use timing techniques measure the “mass” of weakly interacting charged particles (muon-like)



CDF also interpret as Stops



DØ,
Submitted to PRL,
arXiv:0809.4472

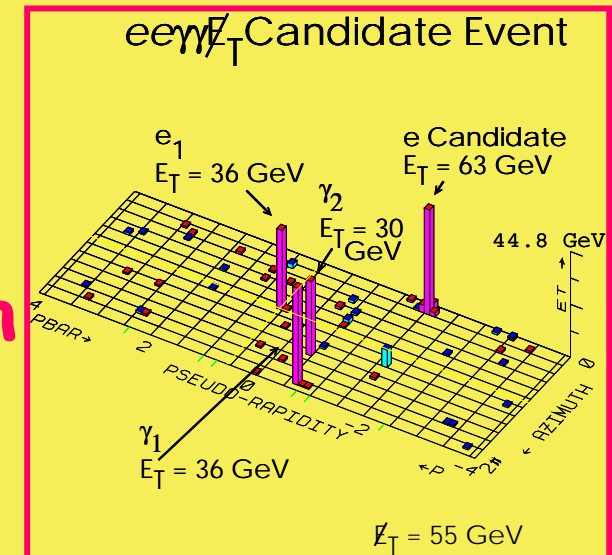


Interpret as Staus or Charginos

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 $e e \gamma + \text{Met}$
candidate event

Early Universe



Nanosecond lifetimes

Later Universe

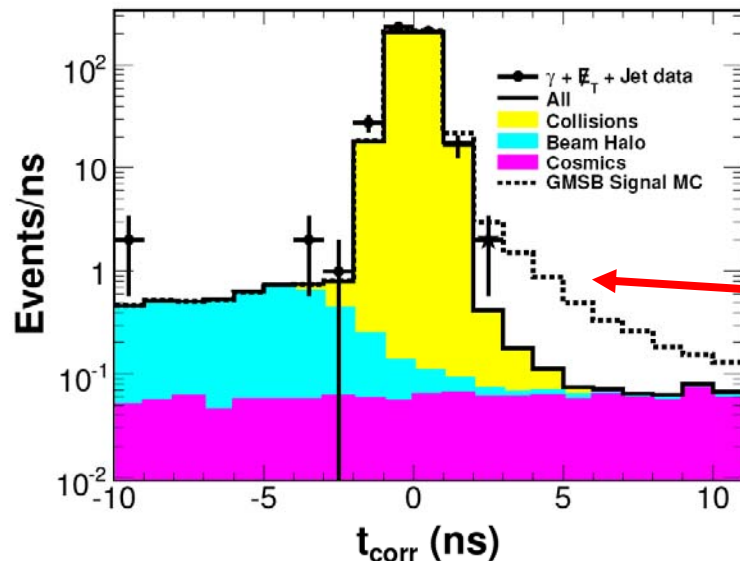


Warm
Dark
Matter

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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 $\gamma + \text{Met} + \text{Jet}$ events

Not envisioned in SUSY-Higgs Workshop

Preliminary studies indicate that the 0 ns lifetime results from DØ should hold up to a lifetime of about a ns

Fall off quickly after that

Just starting to enter the Cosmology Favored Region

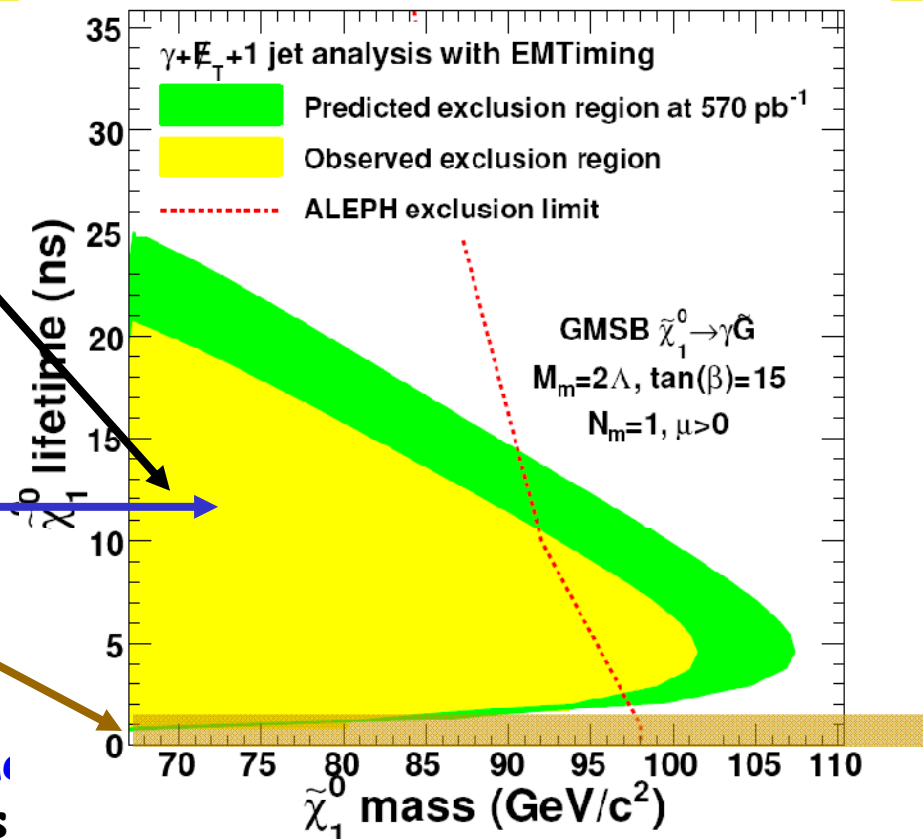
CDF, PRL 99, 121801 (2007)

DØ, PLB 659, 856 (2008)

CDF, PRD 78, 0321015 (2008) Search

Sept 30, 2008

David Toback, Texas



Other stuff

- A number of things in the SHW that were never really addressed again for example track with "Kinks"
- Lots of things searched for but no hints found... (no time for them here...)
 - R-Parity Violating SUSY Scenarios
 - Technicolor
 - Excited/composite quarks & leptons
 - Leptoquarks
 - Extra generations (b' & t')
 - Extra gauge groups (W' & Z')
 - Others

**Move on to Extra Dimensions
Then to model-independent
searches**

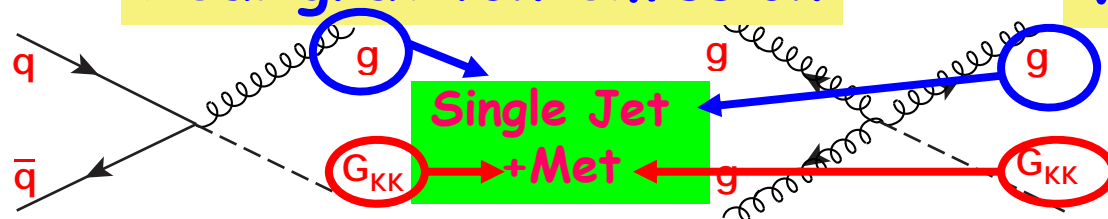
Extra Dimensions

- Lots of different types of models

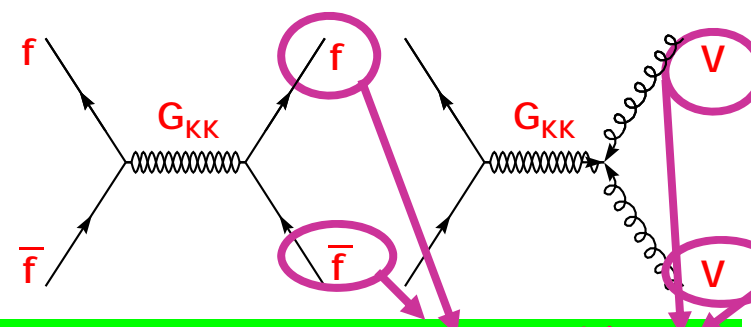


- Two primary production types

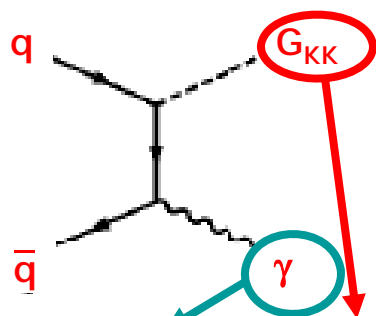
Real graviton emission



Virtual graviton exchange

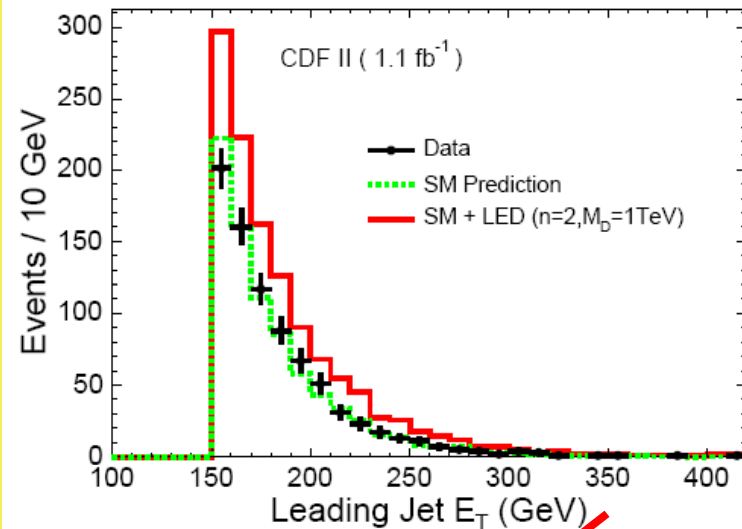


1) Mass resonances in ee and/or $\gamma\gamma$
2) Production enhancement

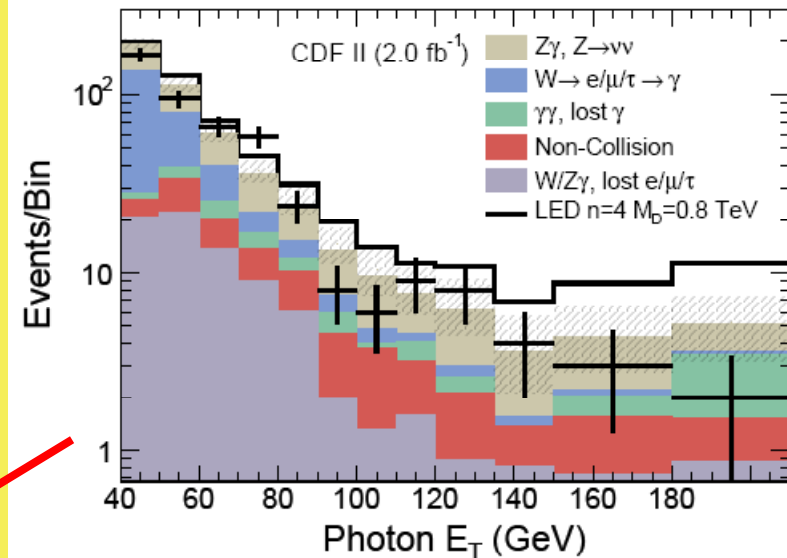


Unified Graviton Emission Analysis

Single Jet + Met



Single Photon + Met

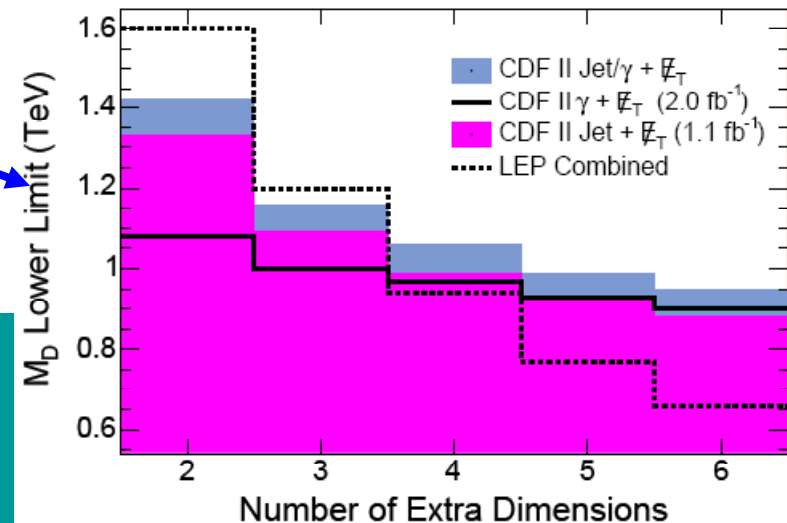


LED Interpreter

Combine both analyses to improve the sensitivity to the Plank Scale M_D

CDF, Submitted to PRL,
arXiv:0807.3132

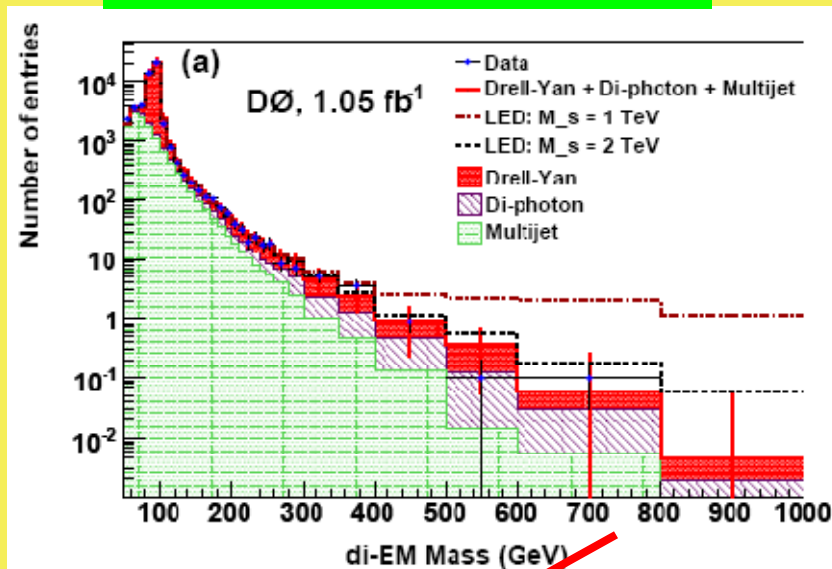
Comparable results from DØ nearing publication



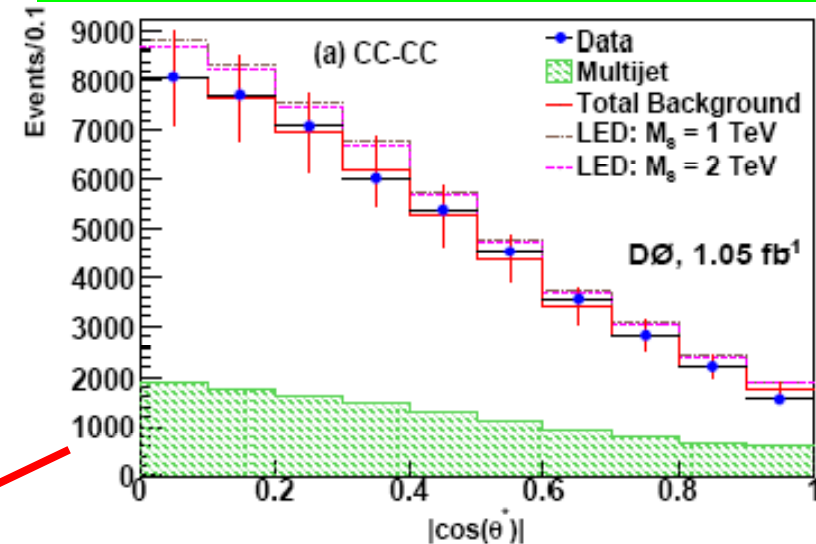
Unified Graviton Exchange Analysis

Combine ee and $\gamma\gamma$ Final States in the same analysis

Invariant Mass



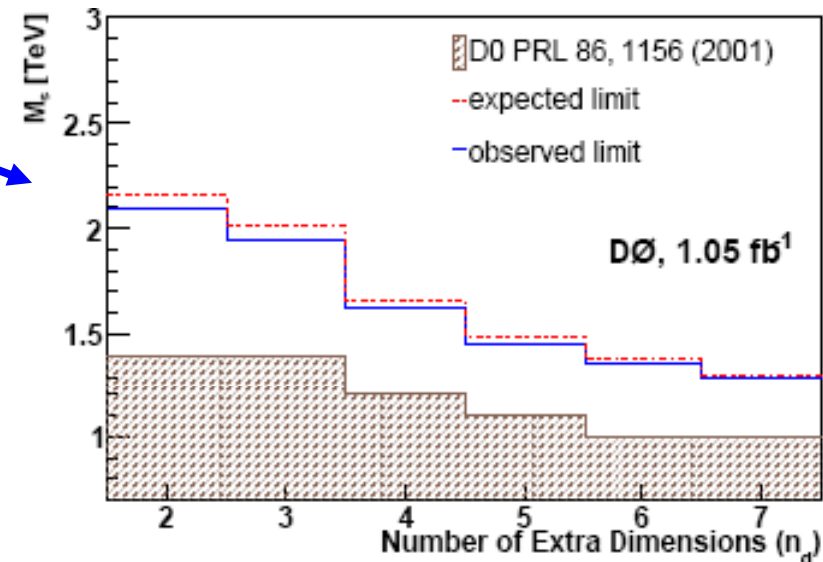
$\cos \theta^*$ Distribution



LED Interpreter

Combine both distributions to improve the sensitivity to M_s

$D\mathcal{O}$, Submitted to
arXiv:0809.2813



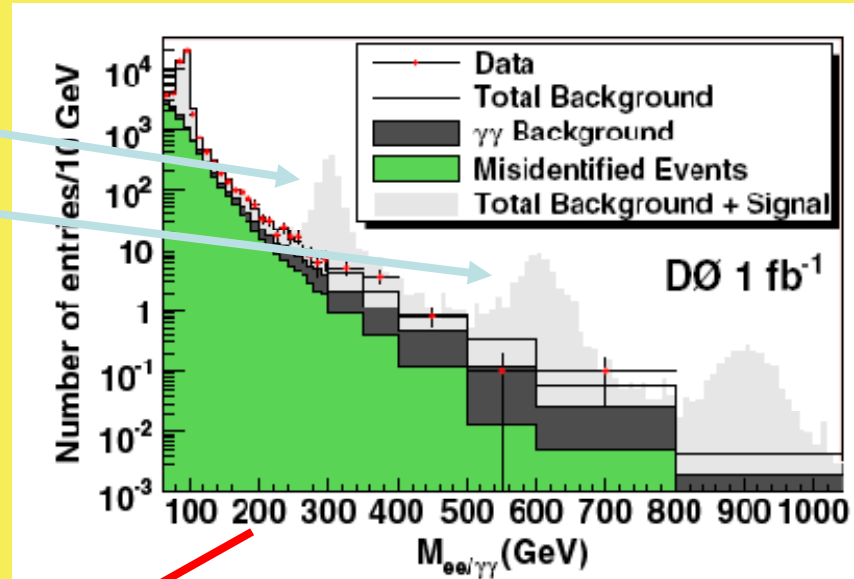
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SUSY and BSM Search
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Unified Randall-Sundrum Graviton Analysis

Combine ee and $\gamma\gamma$ Final States in the same analysis

Look for
Invariant Mass
bumps



LED Interpreter

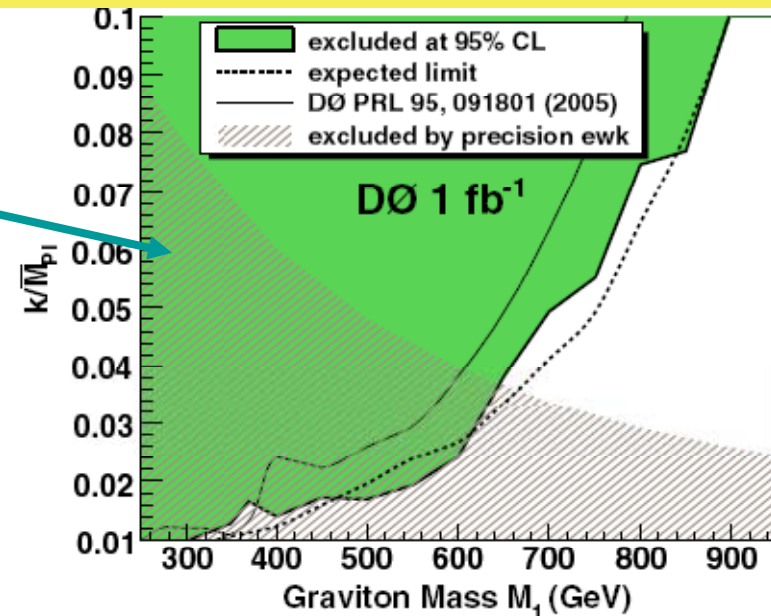
Search the combined data set
to improve the sensitivity to M_S

DØ, PRL 100 091802 (2008)

Comparable results from
CDF in the $\gamma\gamma$ final state

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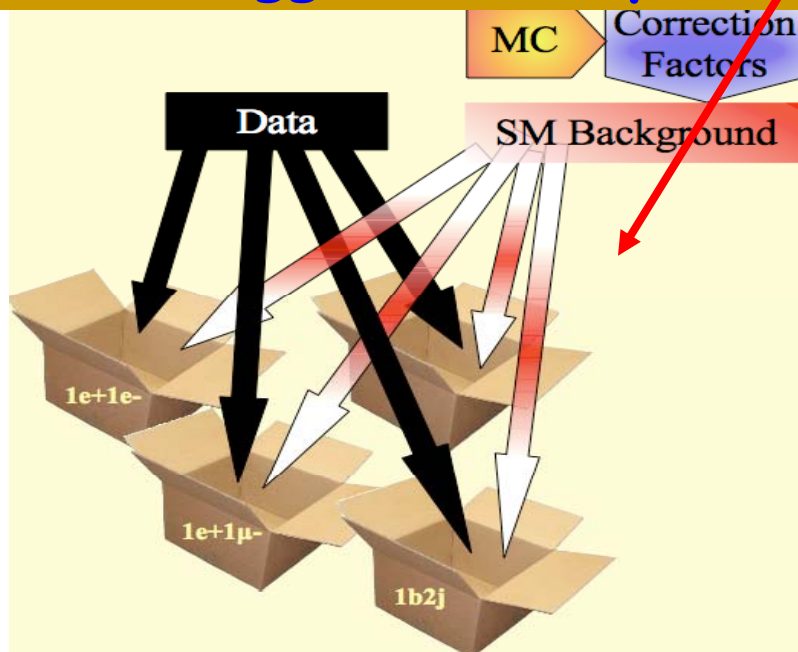
Model-Independent Search Strategies

We're sitting at the high energy frontier... we know what the SM should look like → Just do some hint finding

Look for any distribution that doesn't look SM-like

Sleuth first published in 2000
→ Not envisioned in the SUSY-Higgs workshop

Categorize each event by its final state and systematically look at distributions



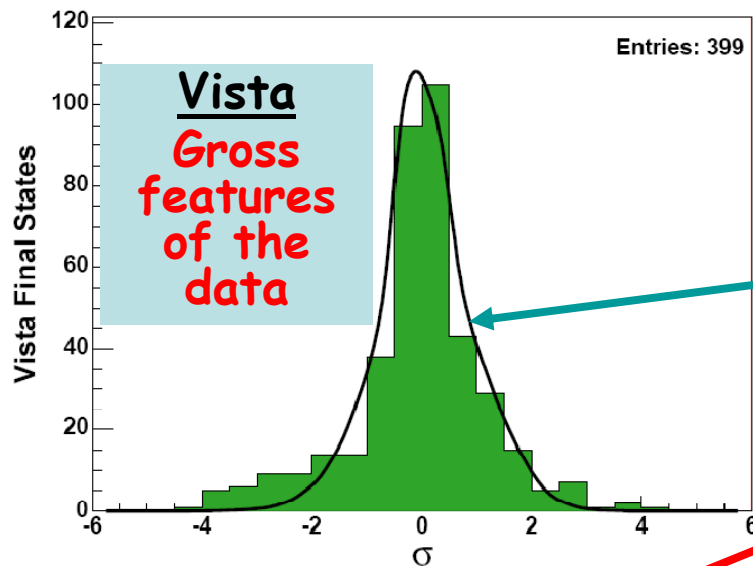
Especially useful in case our targeted searches are looking in the wrong places

Remember that the CDF $e\bar{e}\gamma\gamma + \text{Met}$ Candidate was unexpected...

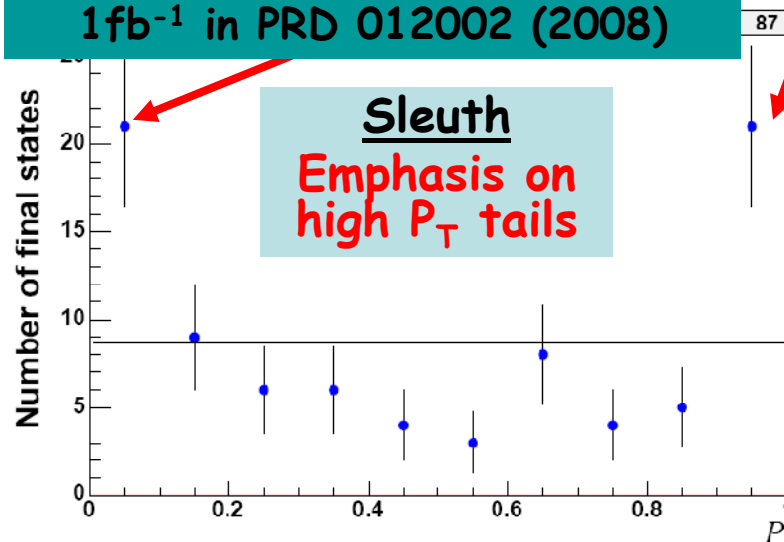
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as A&M University

Look for Systematically “unlikely” Distributions



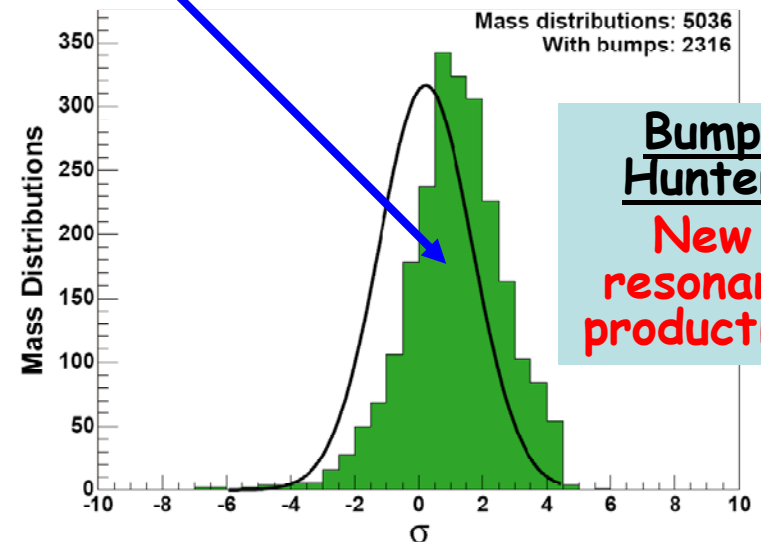
CDF, Submitted to PRD RC,
arXiv:0809.3781
 1 fb^{-1} in PRD 012002 (2008)



Enormous numbers of
distributions and dataset
considered

Variation is largely as
expected in 2 fb^{-1}

Some appear anomalous but
none are suggestive of “new
physics”, rather over or
underestimation of
systematic errors

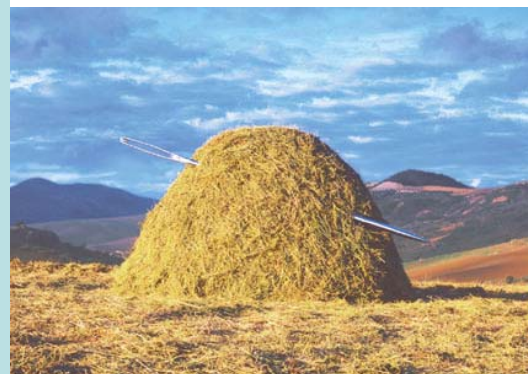


Conclusions

- The search program for Supersymmetry and Beyond the Standard Model Physics at the Fermilab Tevatron is both deep and broad
- Unfortunately, despite almost 3 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

- Lots of talk about how easy it will be to combine final states and CDF/DØ results
 - 8 years in:
 - Finally publishing first unified analyses
 - Only two examples of combined CDF and DØ SUSY search results
 - Experiments have focused on doing more and better searches rather than combining
- Clear vision of searches to be done →
 - The searches in 10 years will likely look different from what we predict now
 - Some of the questions will be answered, some exciting new things will die away, things we never envisioned may come to dominate our every day thinking



Perhaps things
will LOOK
different at
the LHC

Maybe we'll
discover
Split-SUSY
quickly and
spend the
next 10
years
measuring it