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

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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

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

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

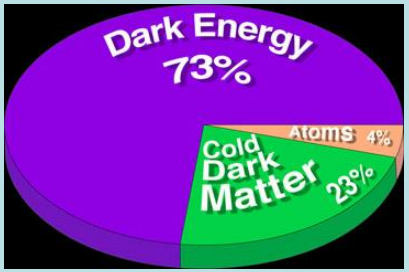
Example : Gauge Mediated SUSY with

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

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)!*



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

Golden Channels

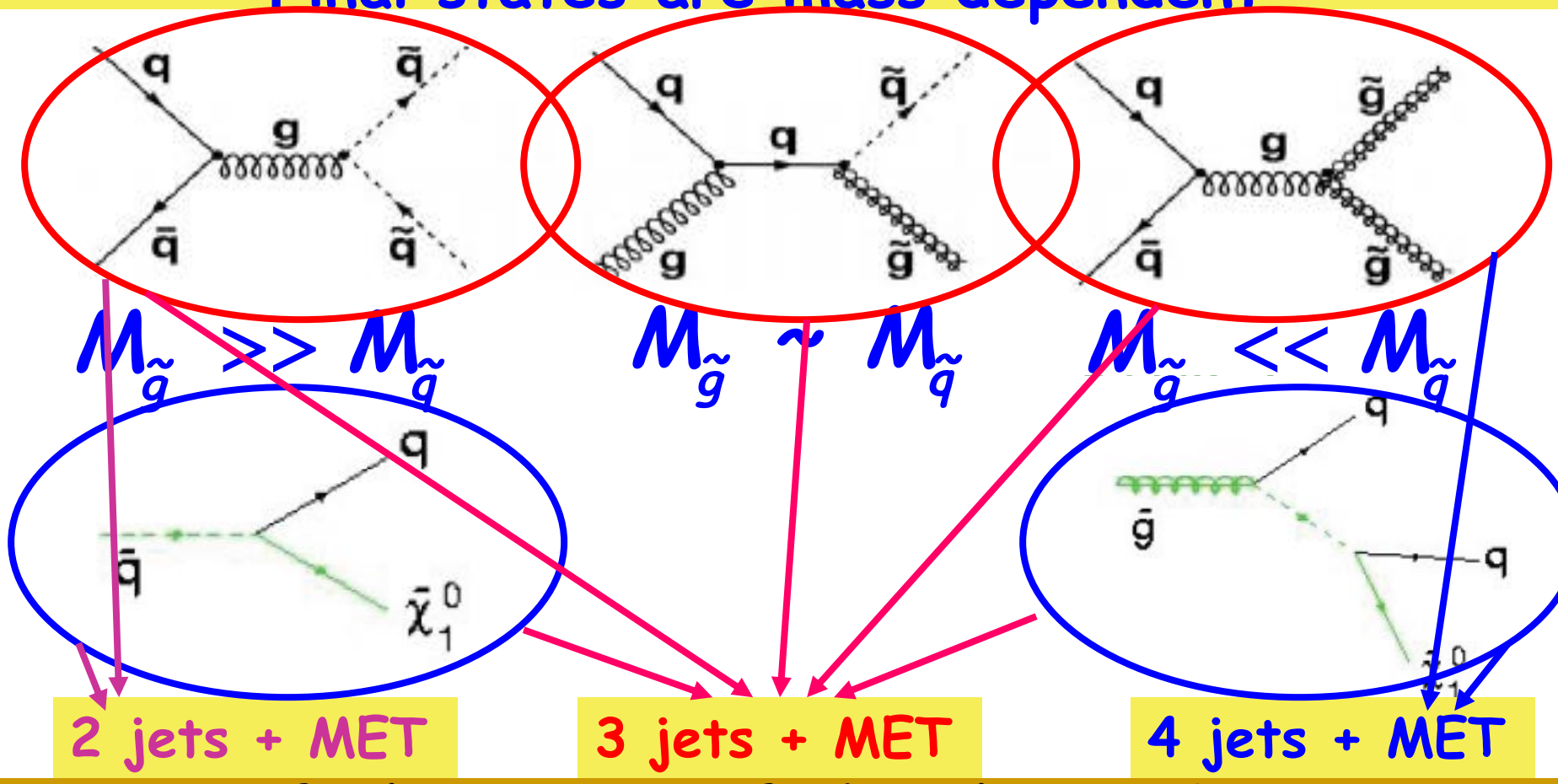
Three main ways to look for minimal/Cold Dark Matter Models in mSUGRA type models

- 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 tanβ, then move to searches with high tanβ

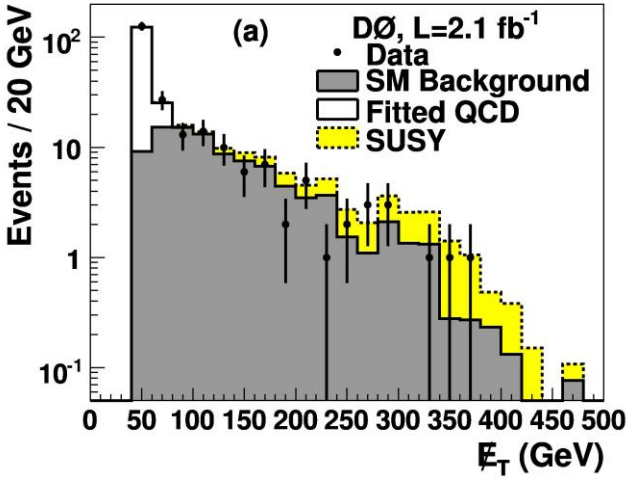
Squark and Gluino Searches in Multijet + Met

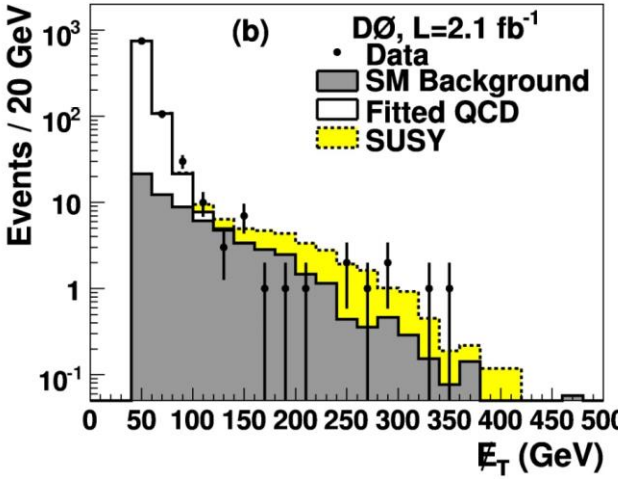
Three main production diagrams
Final states are mass dependent

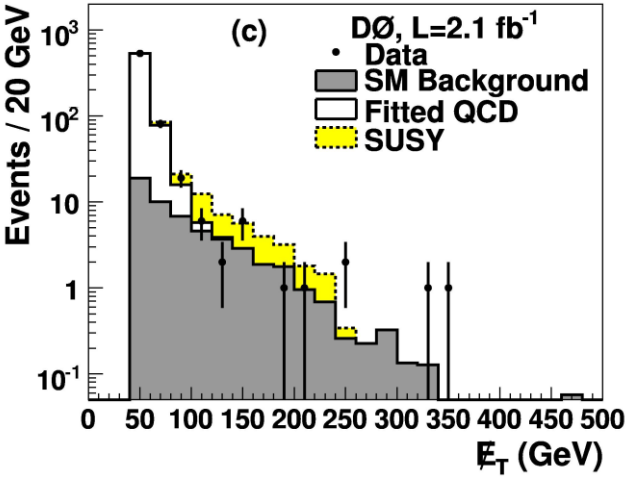


3 separate final states + Unified Analysis ➔ best coverage

Unified Squark/Gluino Search



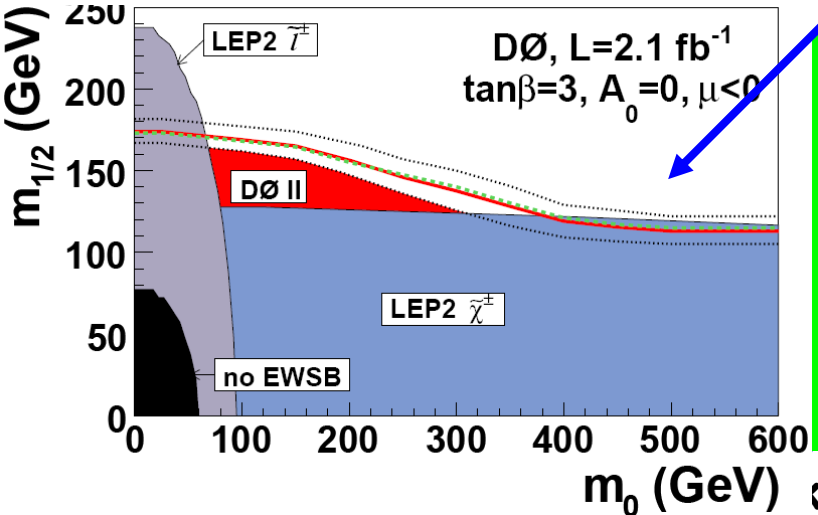




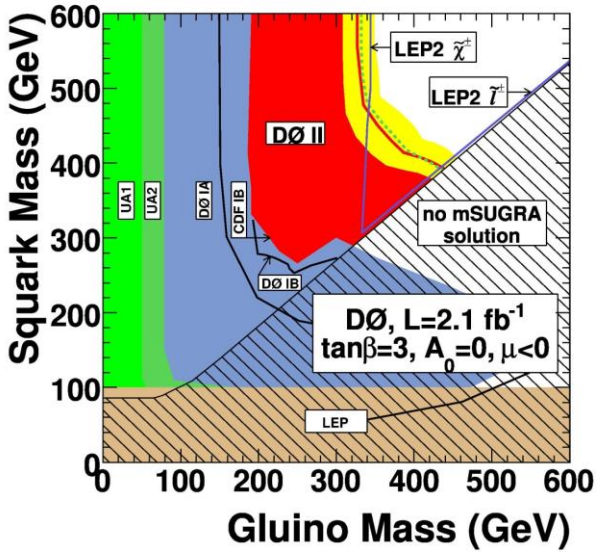
2 jets + MET | **3 jets + MET** | **4 jets + MET**

DØ, PLB 660, 449 (2008)

SUSY Interpreter



Comparable results from CDF public and nearing publication



Gaugino Pair Production in Multilepton + Met

Chargino-Neutralino gives three leptons in the final state

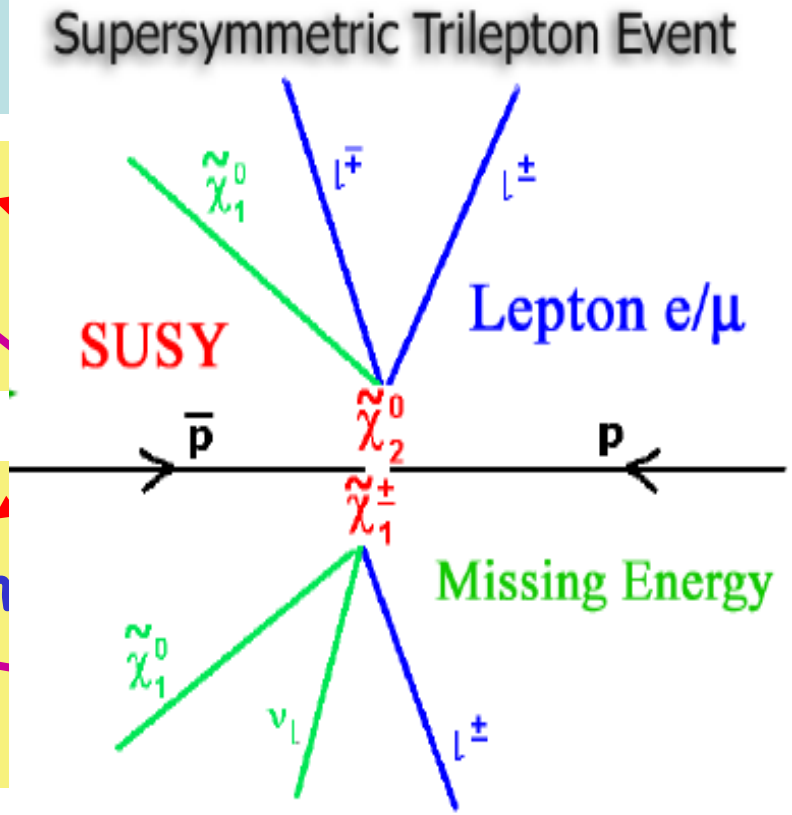
Dominates the production cross section

5 separate final states + Unified Analysis ➔ 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

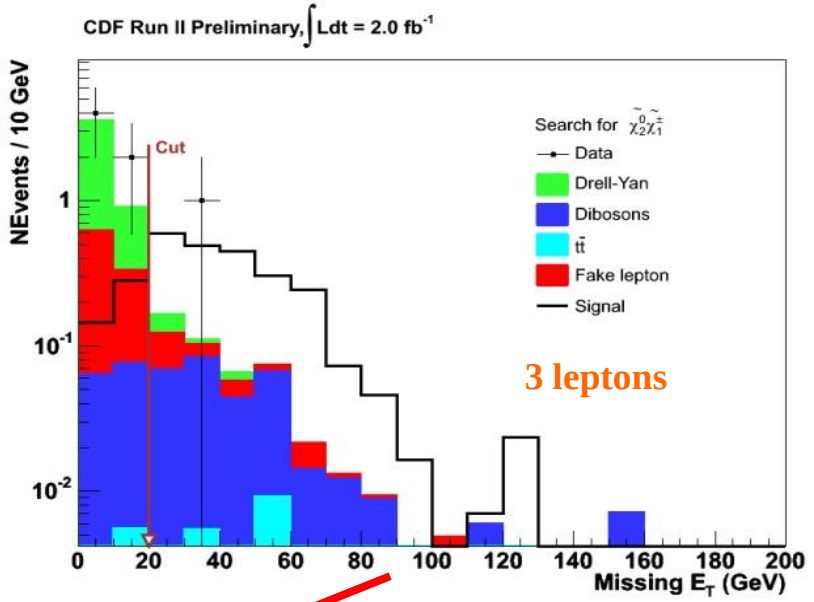
1 Tight lepton + 2 Loose leptons + MET

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

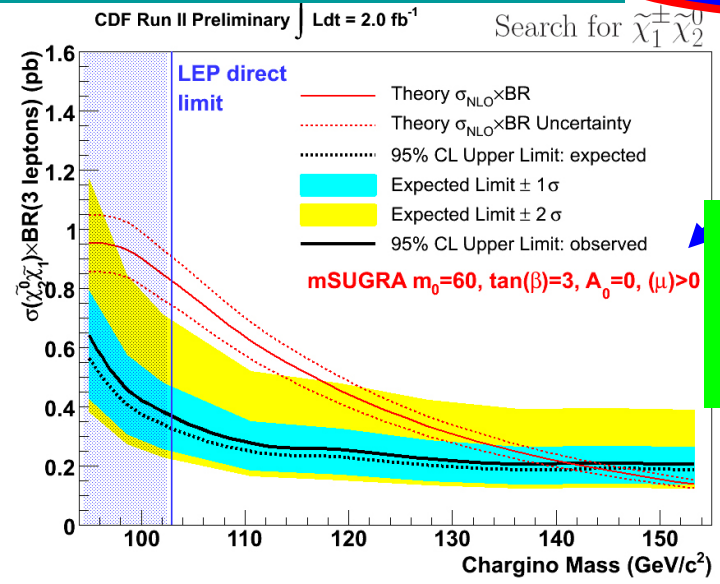
Unified Gaugino Pair Production Analysis

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

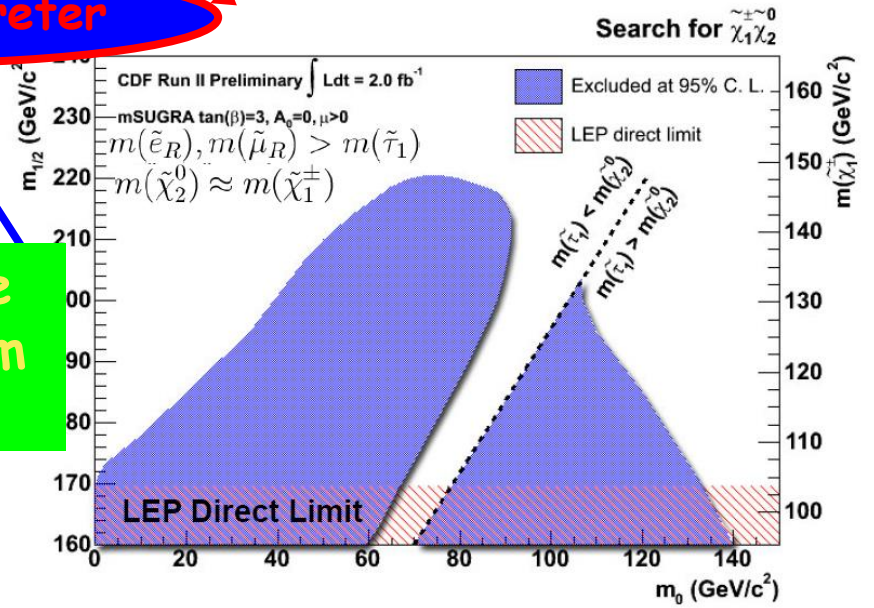


CDF, Submitted to PRL, arXiv:0808.2446

SUSY Interpreter



Comparable results from DØ

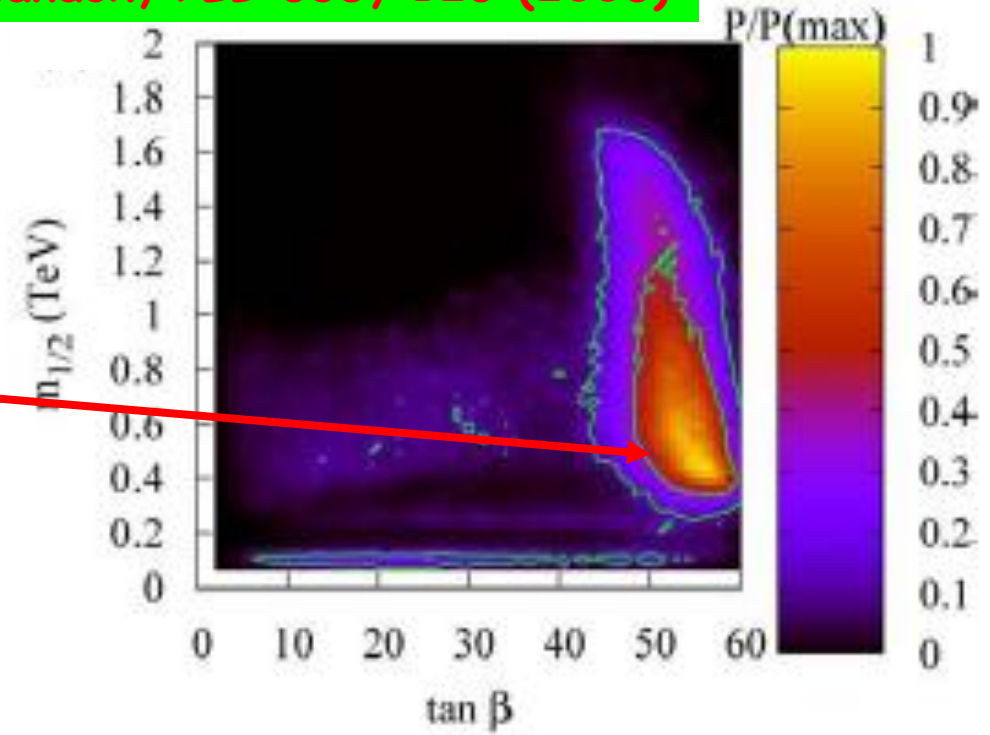


SSM Searche
ack, Texas

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)



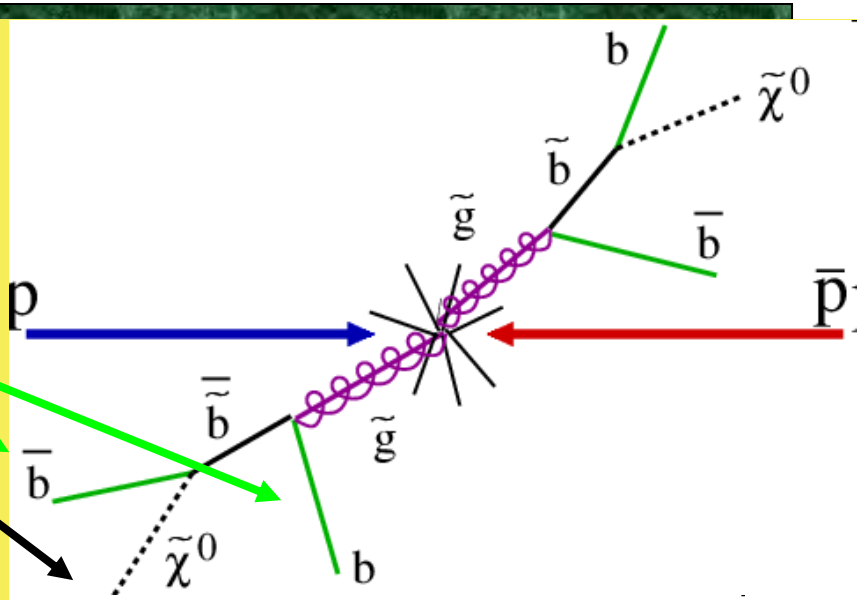
Emphasis on tanβ just starting during SUSY-Higgs Workshop

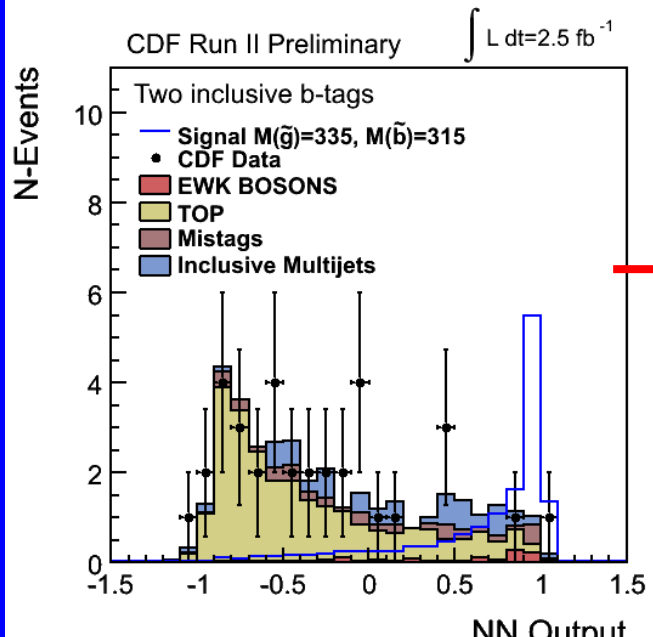
Now we have a full suite of high tanβ targeted searches

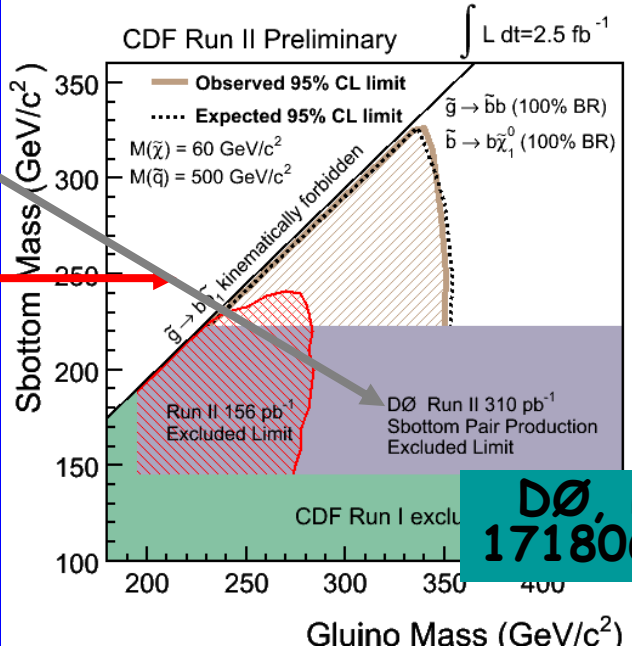
Sbottom Searches

Two primary Sbottom searches in b+jets+Met

1. Sbottoms from gluinos
2. Direct sbottom pair production



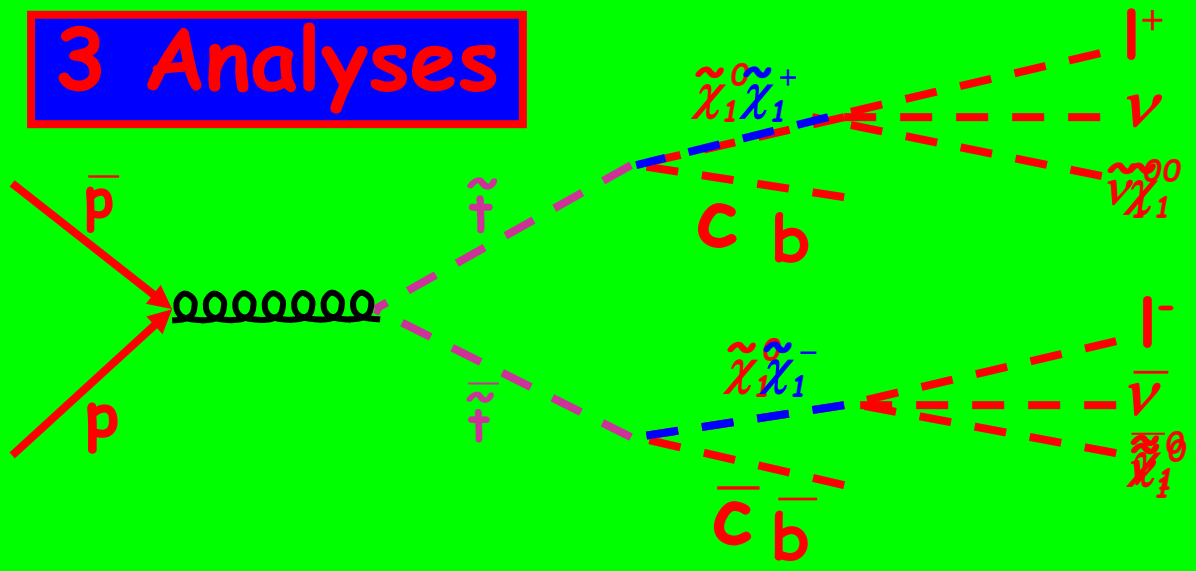




DØ, PRL 97 171806 (2006)

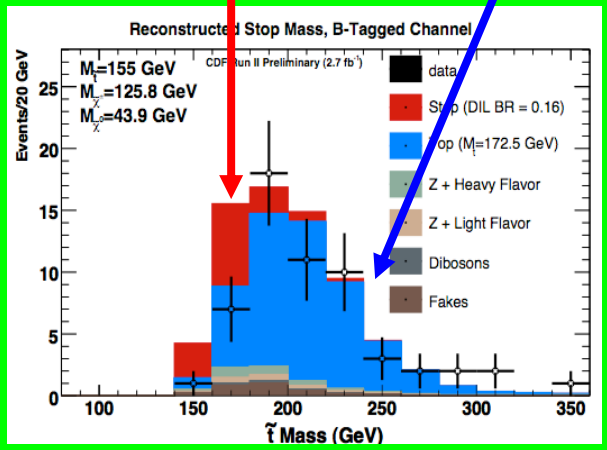
Stop Searches

3 Analyses

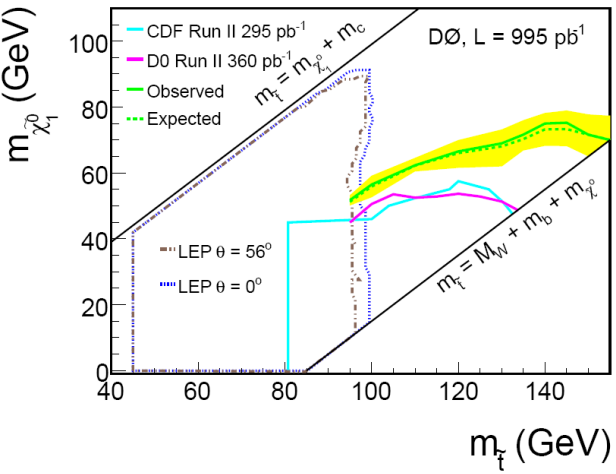


M_{Stop} = 155 GeV

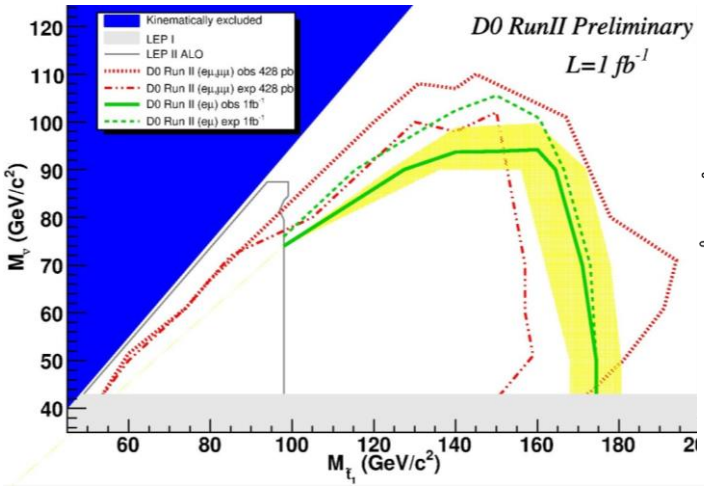
M_{top} = 175 GeV



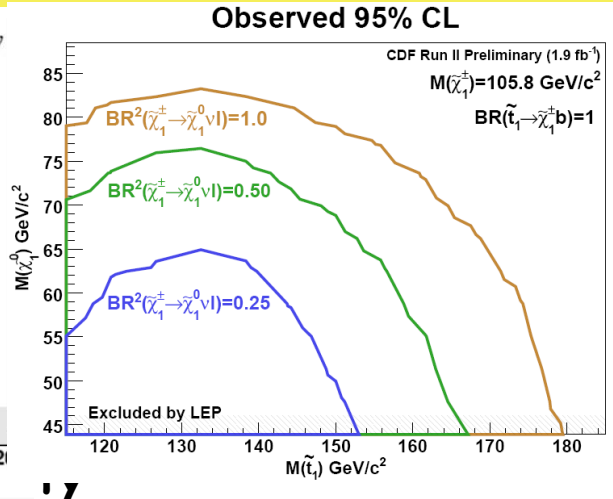
Charm+jet+MET



Dileptons+Jets+MET



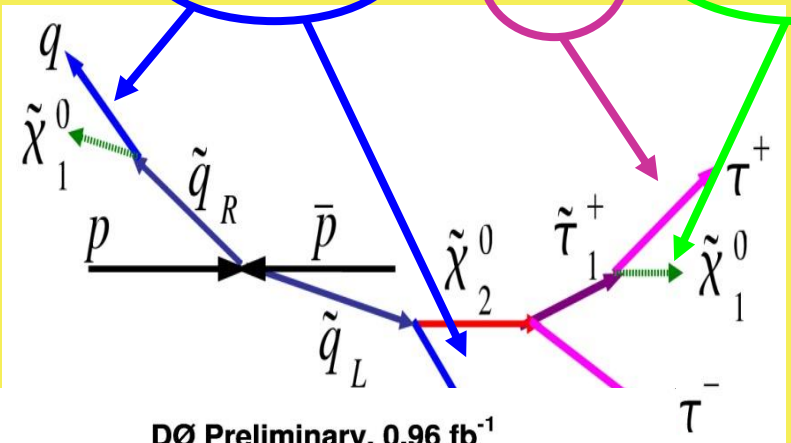
Dileptons+Jets+MET Fit for Stop Admixture



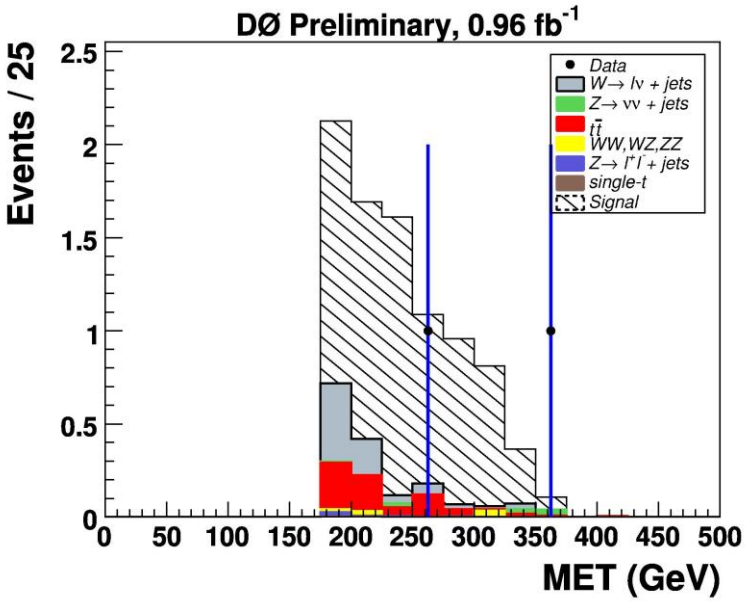
High tanβ → Light $\tilde{\tau}$'s

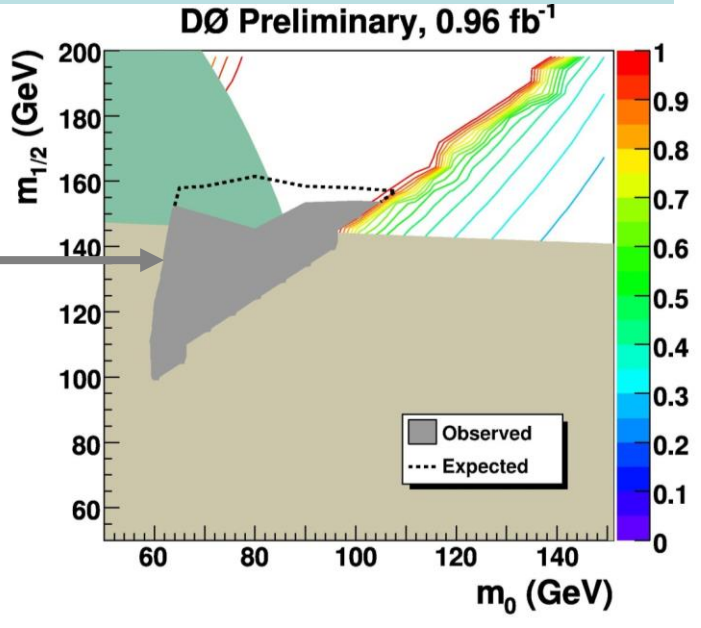
Complementary search for Squarks:

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 $\tilde{\chi}_1^0$



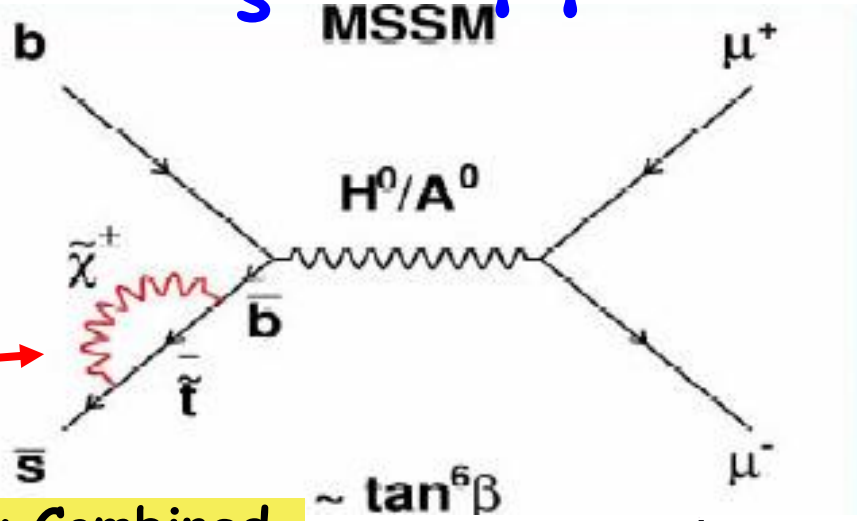


SM Searches at th
ck, Texas A&M U

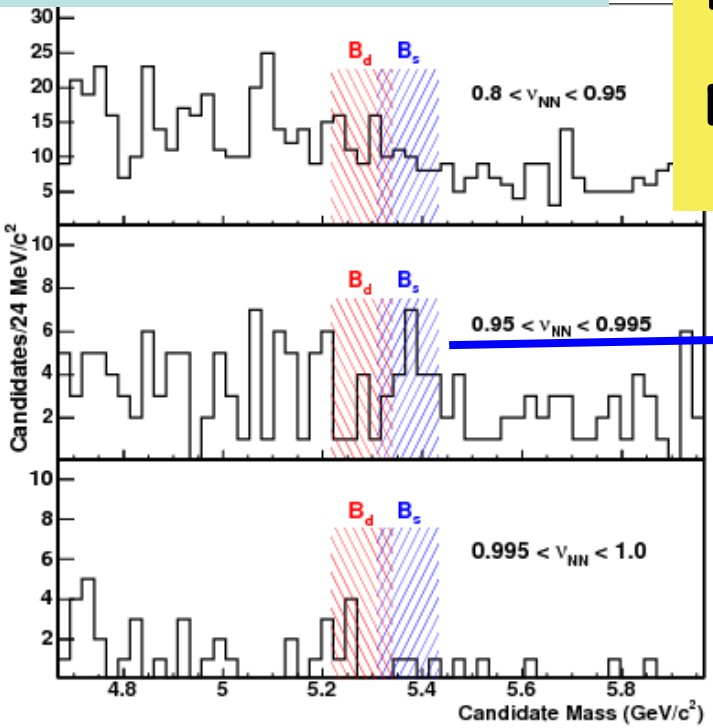
Indirect Search: $B_s \rightarrow \mu\mu$

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 tanβ ($\propto \tan\beta^6$)



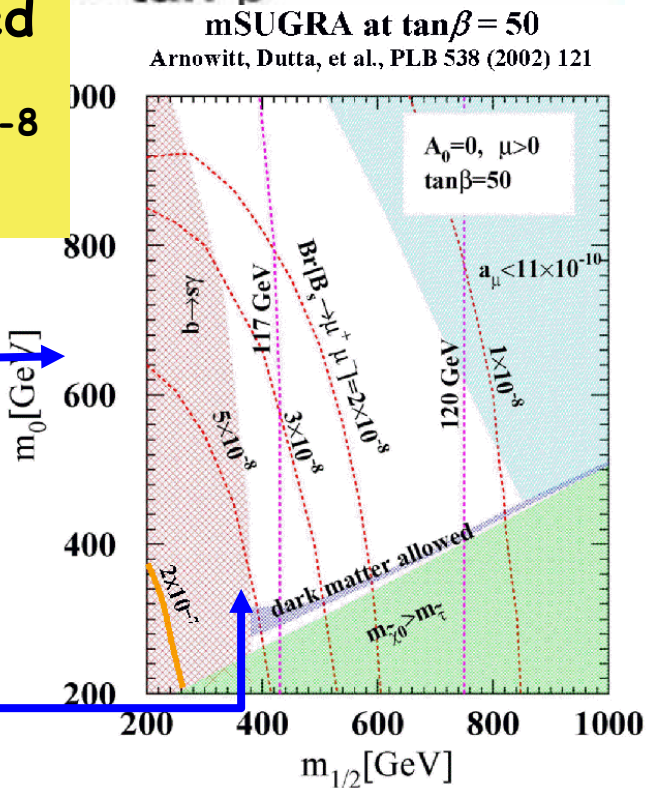
CDF, PRL 100, 101802 (2008)



Preliminary Combined CDF/DØ

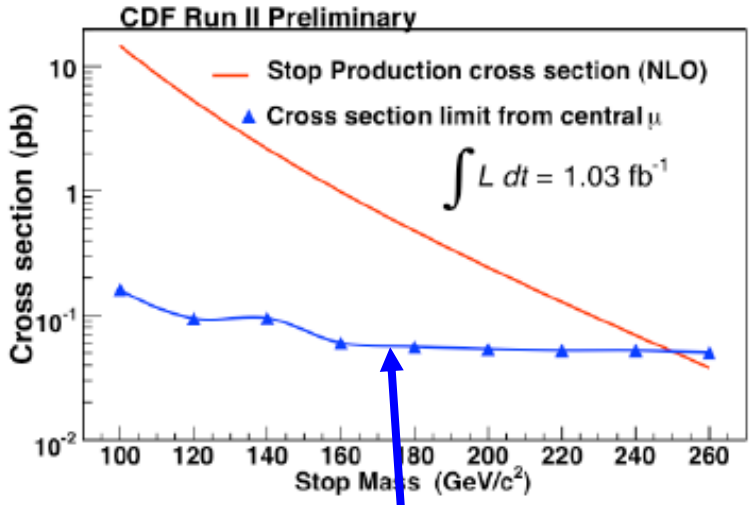
$BR(B_s \rightarrow \mu\mu) < 4.5\times10^{-8}$ @95%

$BR_{SM} = 3.5\times10^{-9}$

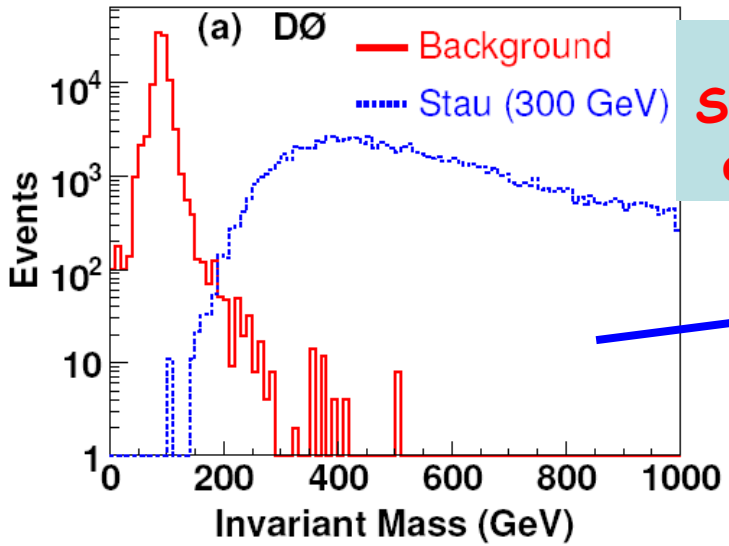


Long-Lived Charged Sparticles (Champs)

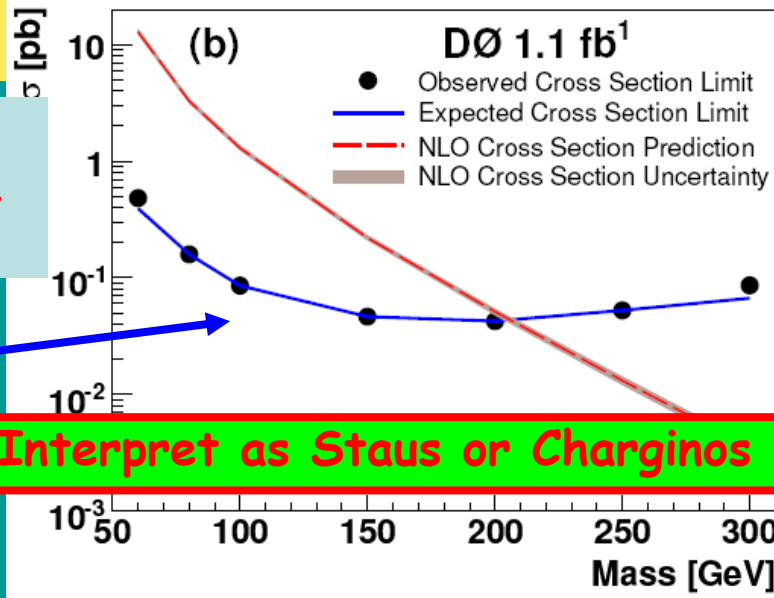
- New emphasis in the theory community about the role of long-lived sparticles in the Early Universe and today as Dark Matter
- Use timing techniques measure the "mass" of weakly interacting charged particles (muon-like)



CDF also interpret as Stops



DØ, Submitted to PRL, arXiv:0809.4472

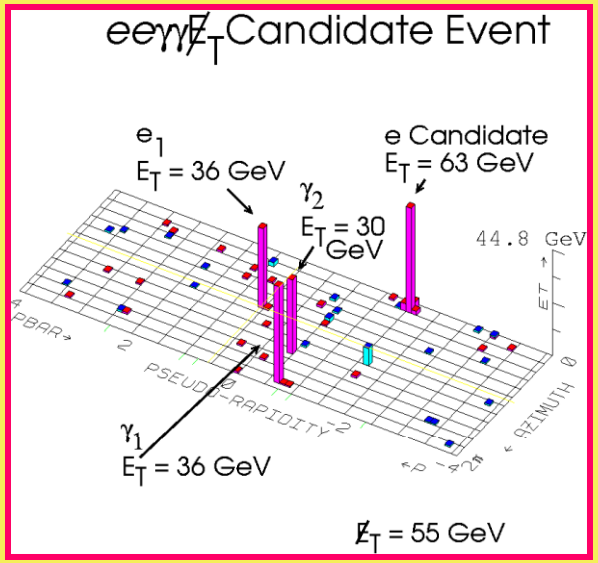


Interpret as Staus or Charginos

Gauge-Mediated SUSY Breaking Models

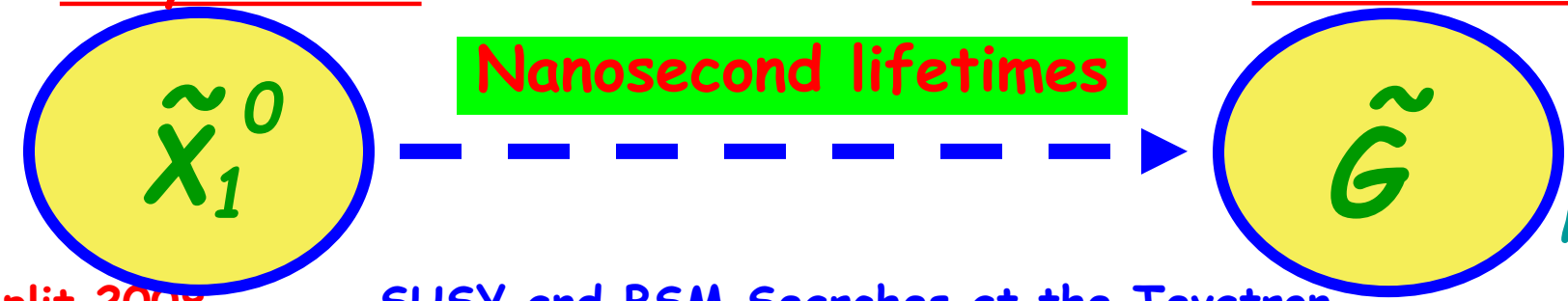
$\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ models provide
a warm dark matter candidate
Consistent with Astromincal
observations and models of inflation

More natural solution for FCNC problems than mSUGRA



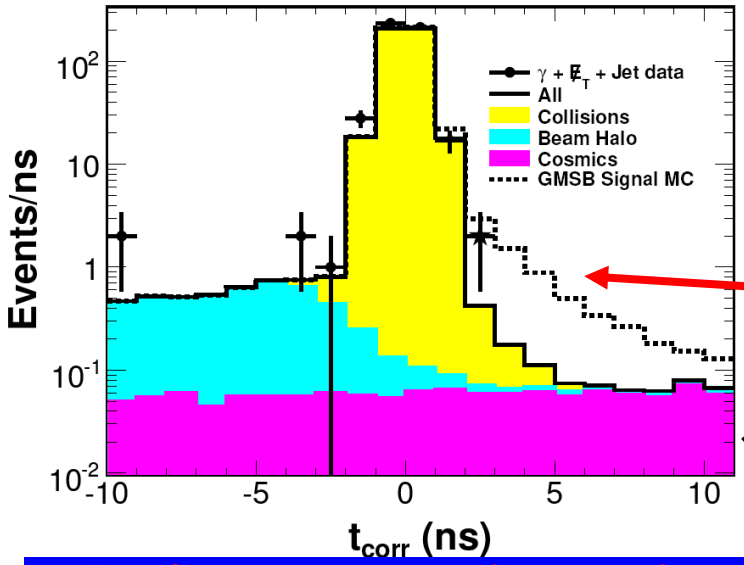
CDF Run I eeγγ+Met candidate event

Early Universe



Later Universe

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

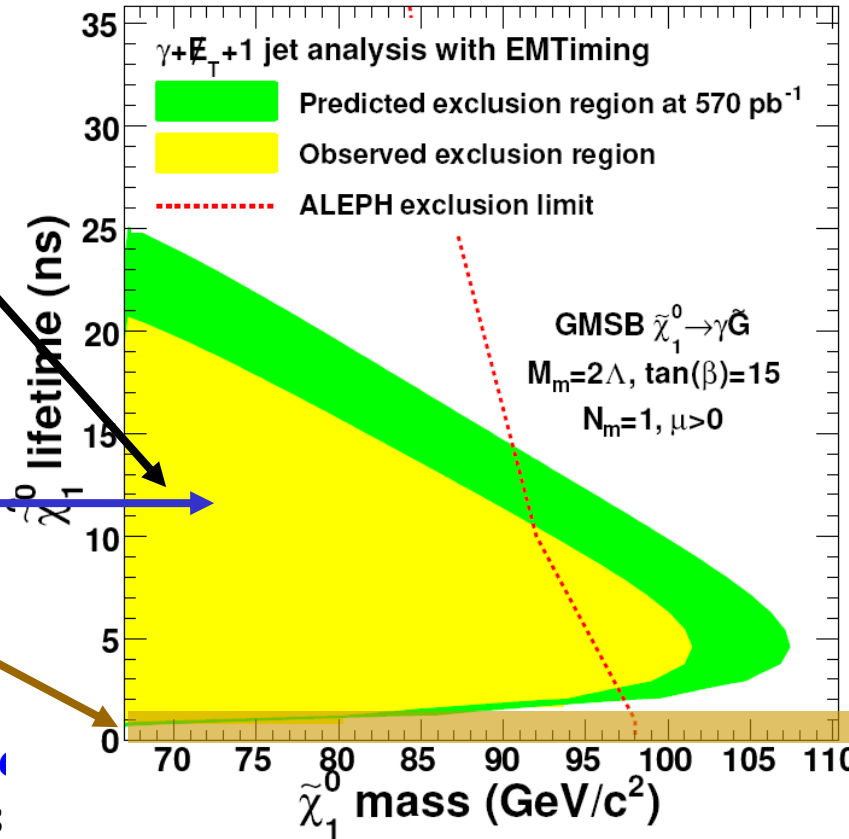
Measure the time of arrival of photons in γ+Met+Jet events

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)

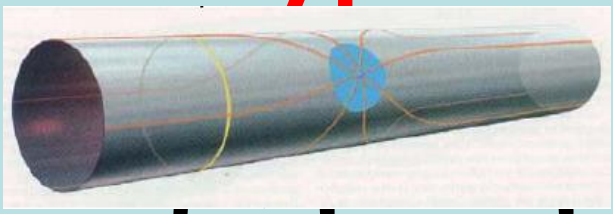
Other stuff

- 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

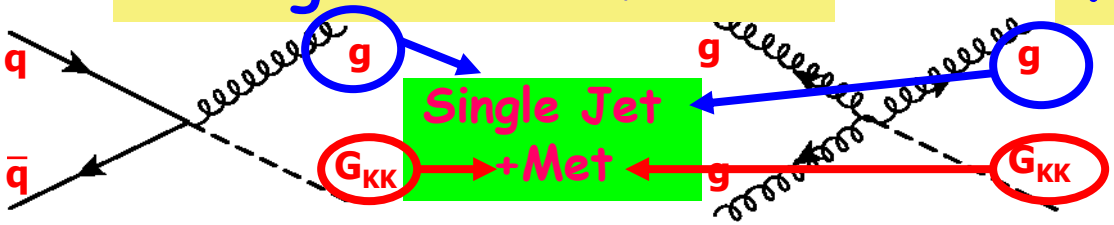
Extra Dimensions

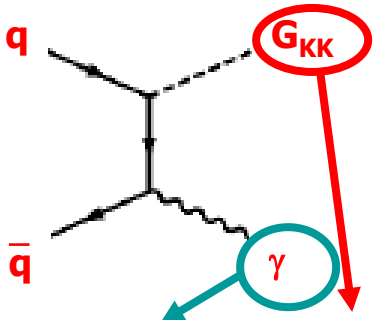
- Lots of different types of models



- Two primary production types

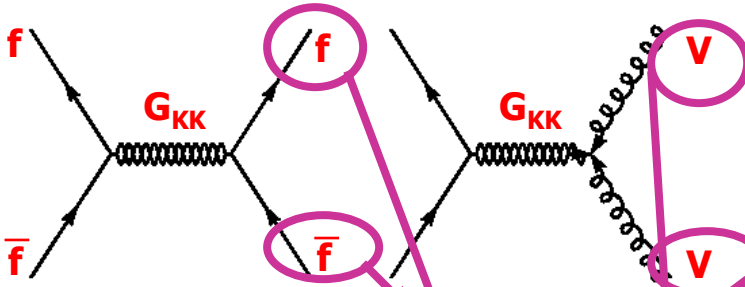
Real graviton emission





Single Photon + Met

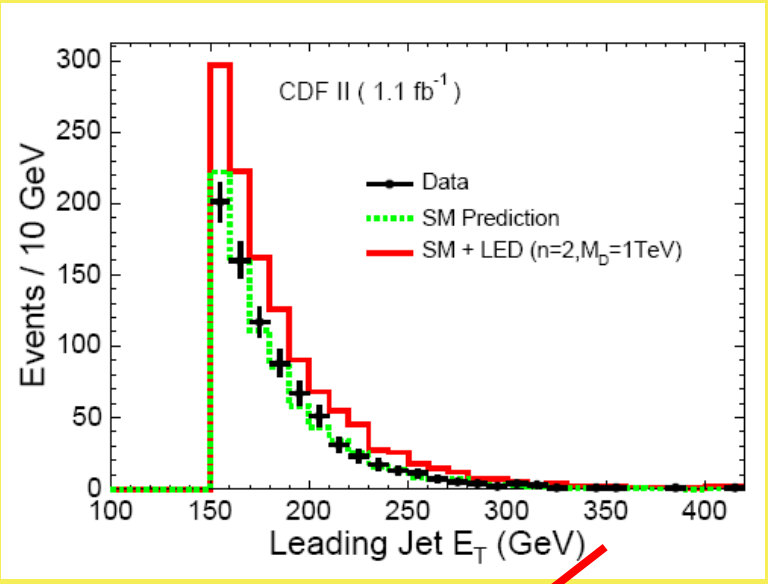
Virtual graviton exchange



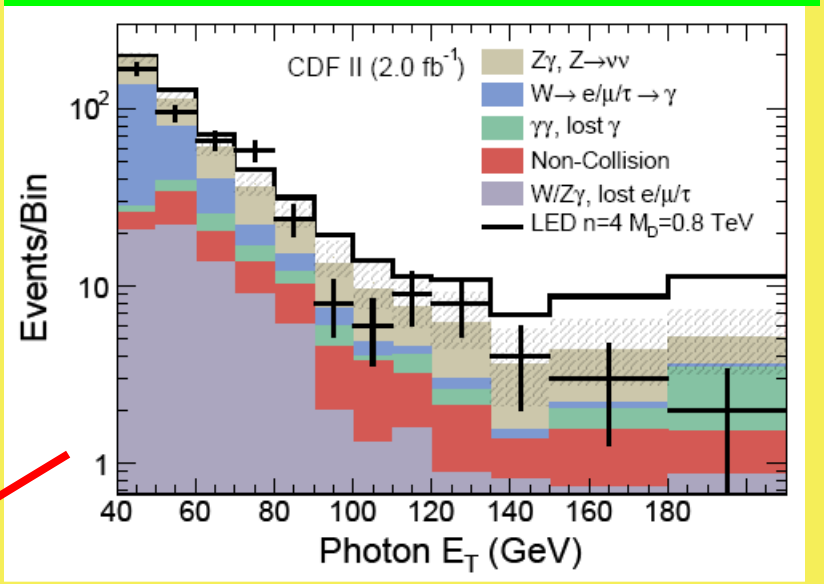
1) Mass resonances in ee and/or γγ
2) Production enhancement

Unified Graviton Emission Analysis

Single Jet + Met

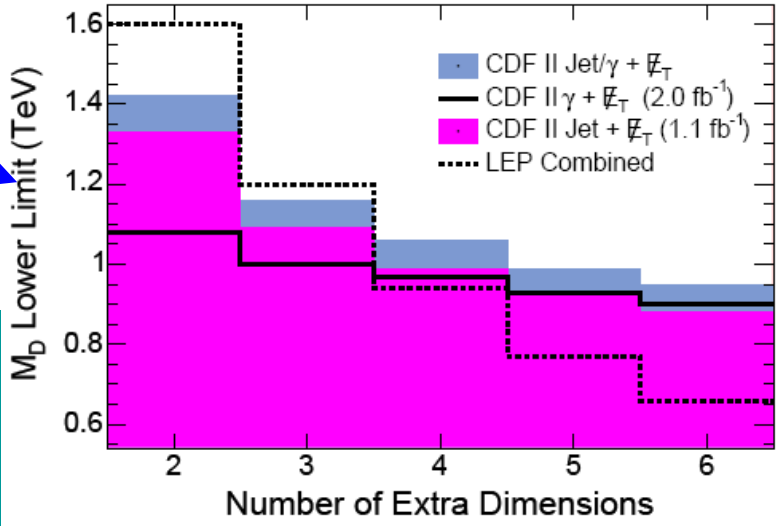


Single Photon + Met



LED Interpreter

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



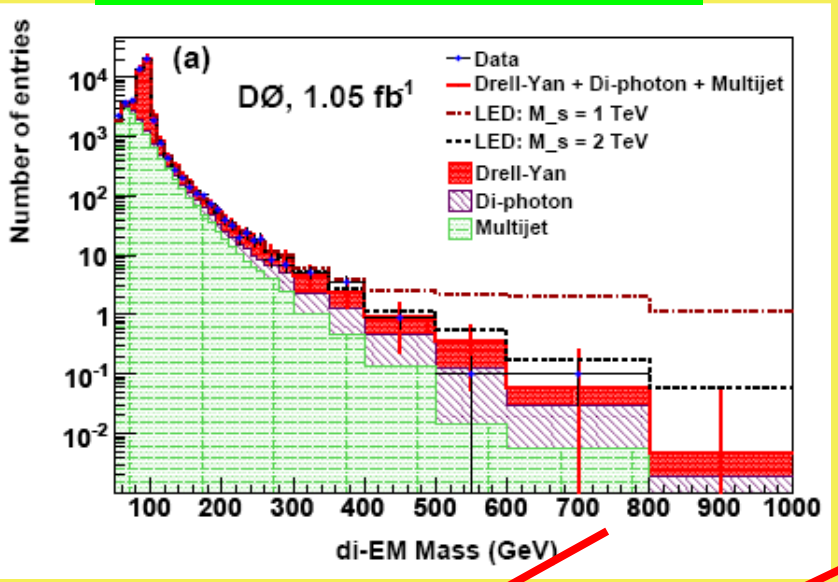
CDF, Submitted to PRL, arXiv:0807.3132

Comparable results from DØ nearing publication

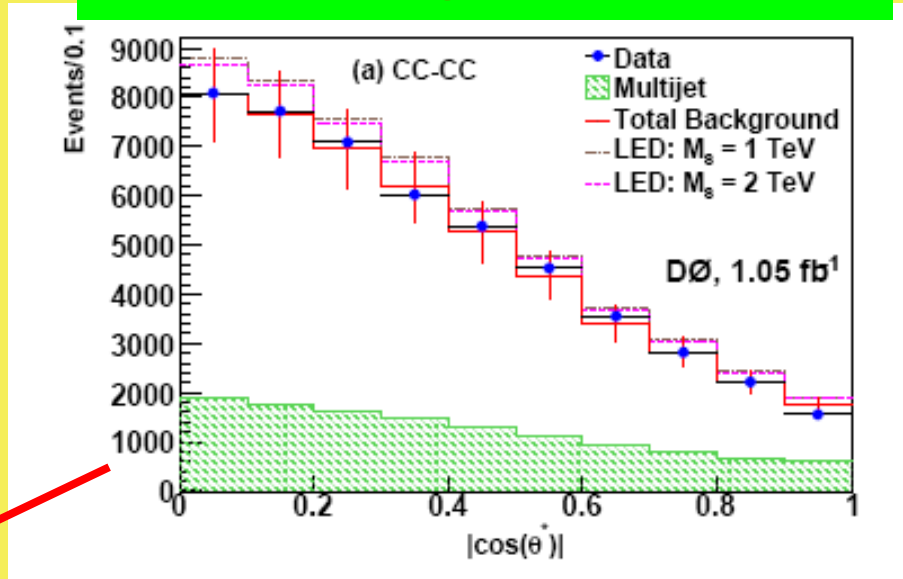
Unified Graviton Exchange Analysis

Combine ee and γγ Final States in the same analysis

Invariant Mass



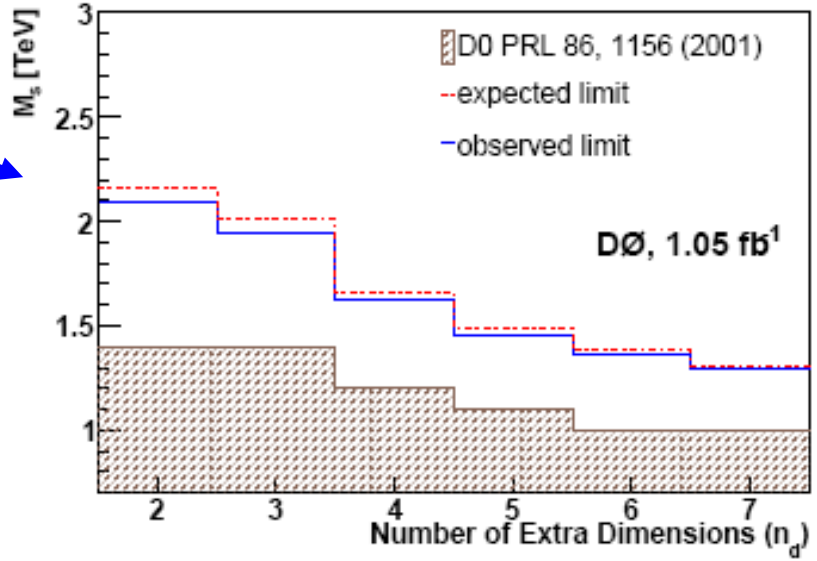
cos θ* Distribution



LED Interpreter

Combine both distributions to improve the sensitivity to M_S

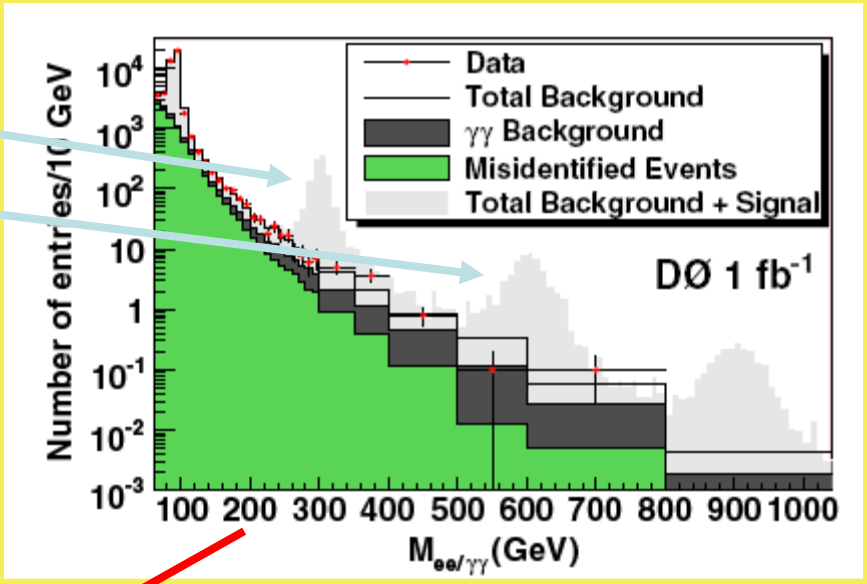
DØ, Submitted to arXiv:0809.2813



Unified Randall-Sundrum Graviton Analysis

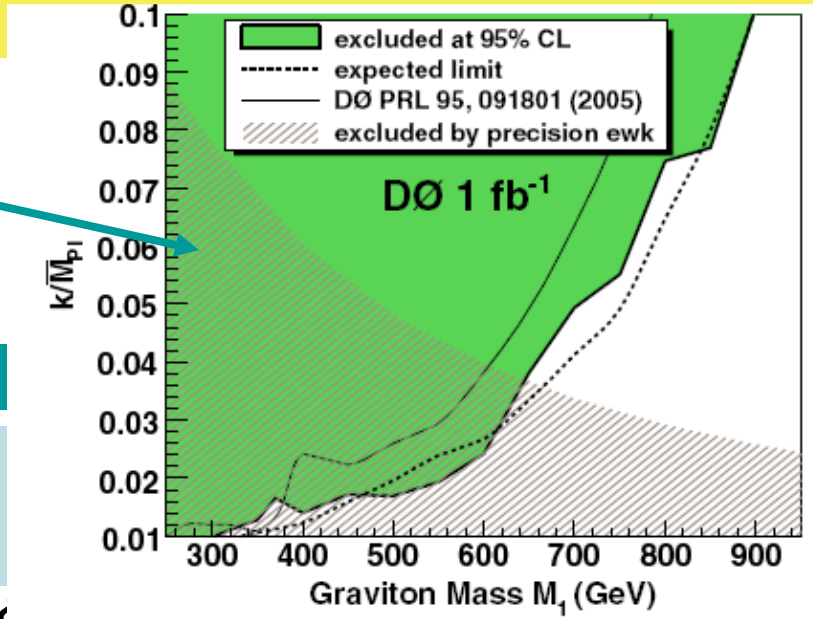
Combine ee and $\gamma\gamma$ Final States in the same analysis

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

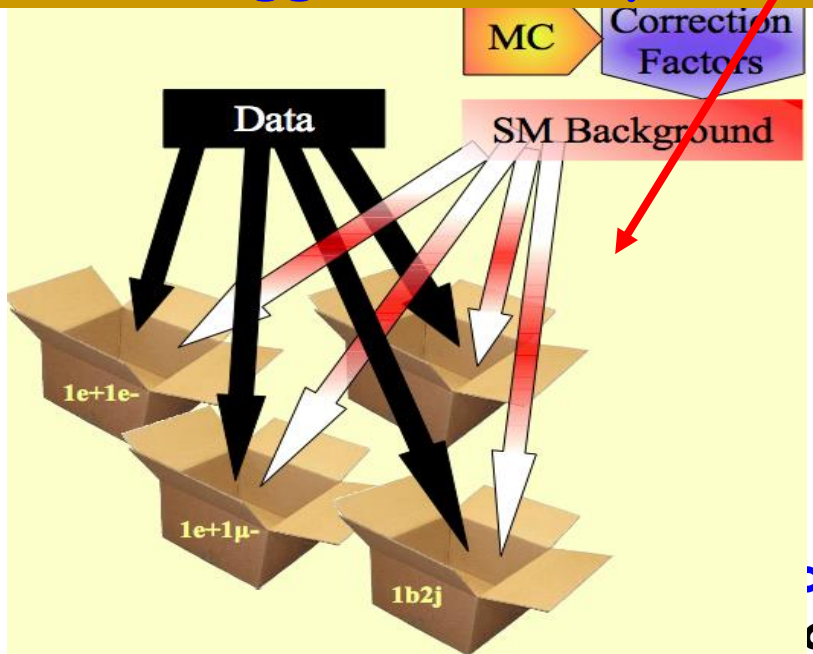
Model-Independent Search Strategies

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

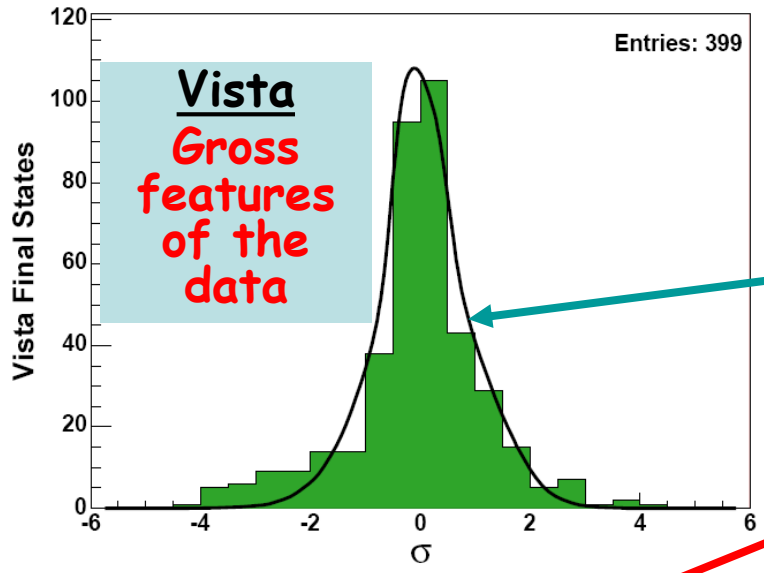
Categorize each event by it's final state and systematically look at distributions



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

Remember that the CDF eeγγ+Met Candidate was unexpected…

Look for Systematically "unlikely" Distributions



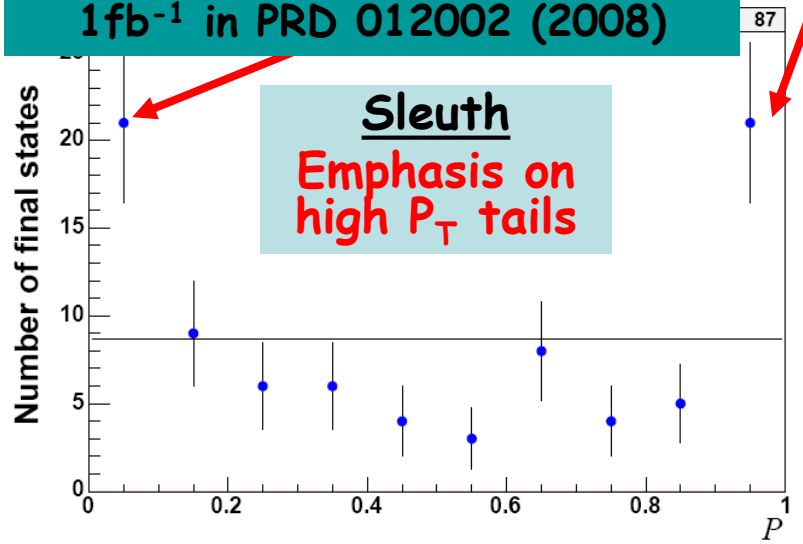
Vista
Gross features of the data

Enormous numbers of distributions and dataset considered

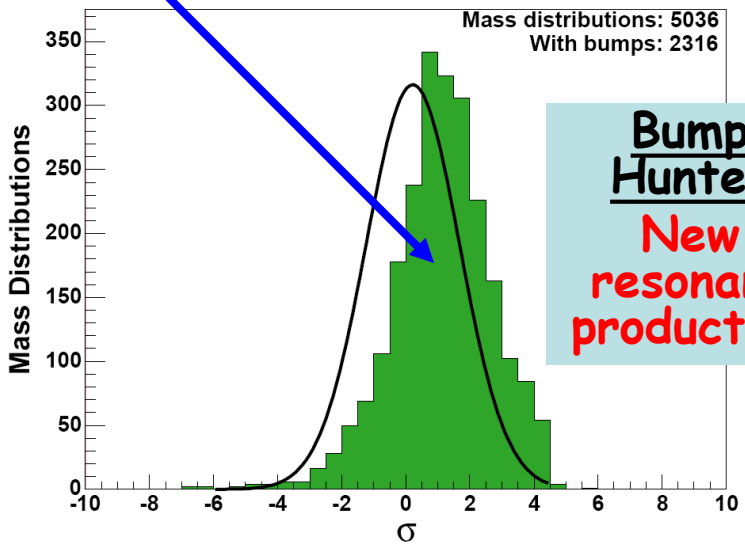
Variation is largely as expected in 2 fb^{-1}

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

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



Sleuth
Emphasis on high P_T tails



Bump Hunter
New resonant production

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