Search for New Physics at the Tevatron

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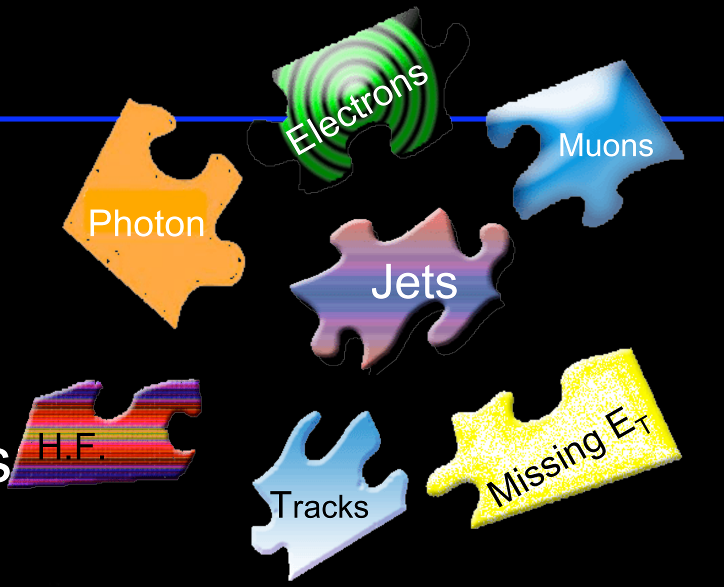
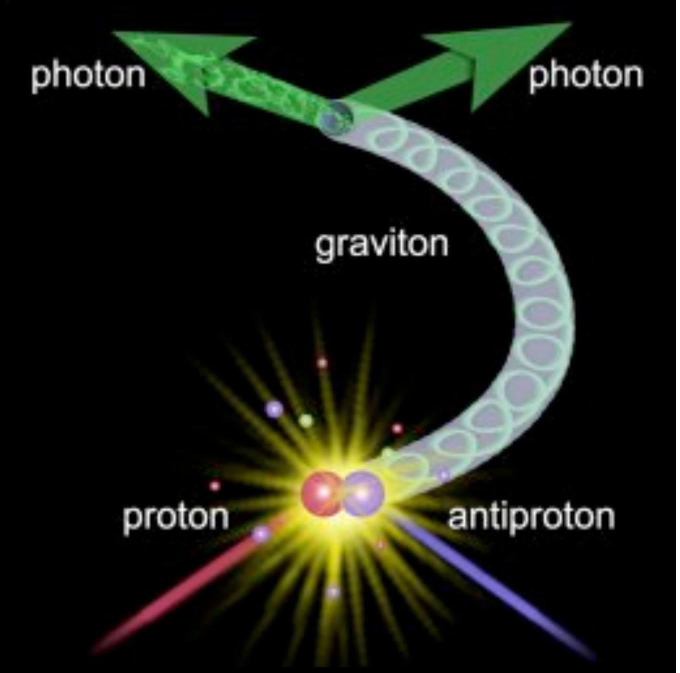
(on behalf of the CDF and D0 Collaborations)

Outline of the talk



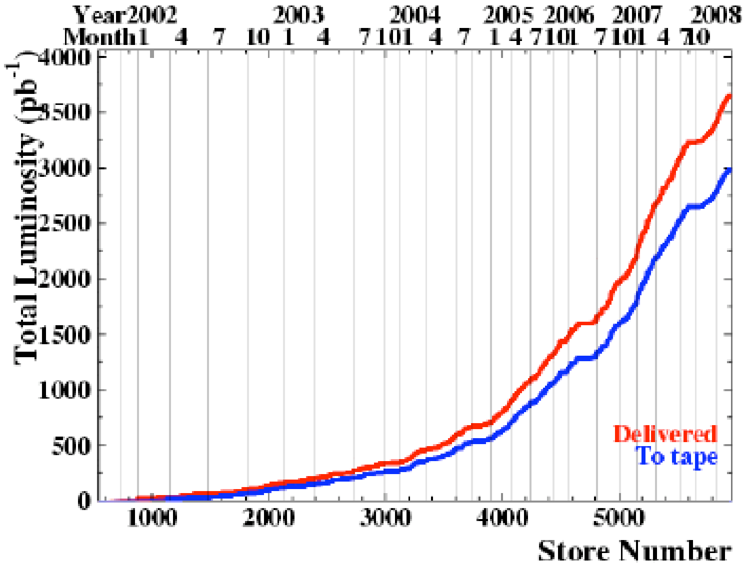
- TeVatron status
- Physics Processes and their signatures
  - from simple objects to complex final states
    - **leptons-only final states (and isolated tracks)**
    - **… + Missing Energy and Photons**
    - **… + Jets and heavy flavors**
  - Specific model testing and global searches
- Final remarks and conclusions



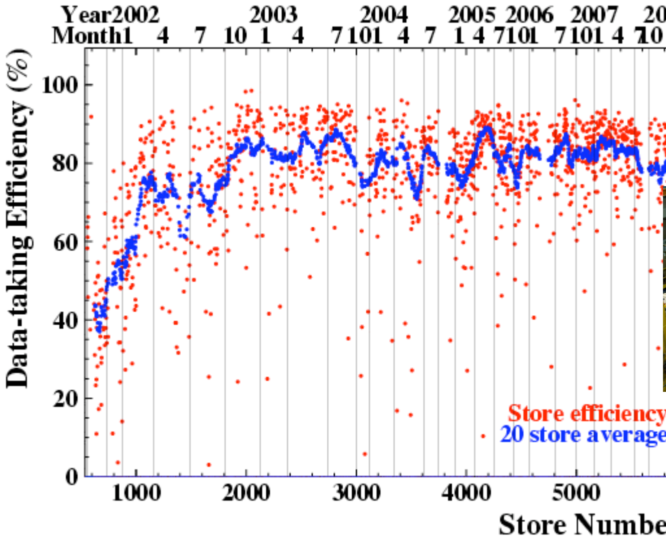
TeVatron Status

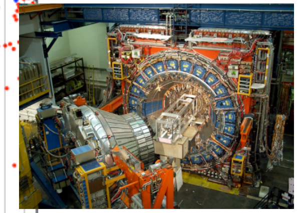
The TeVatron is doing very well!

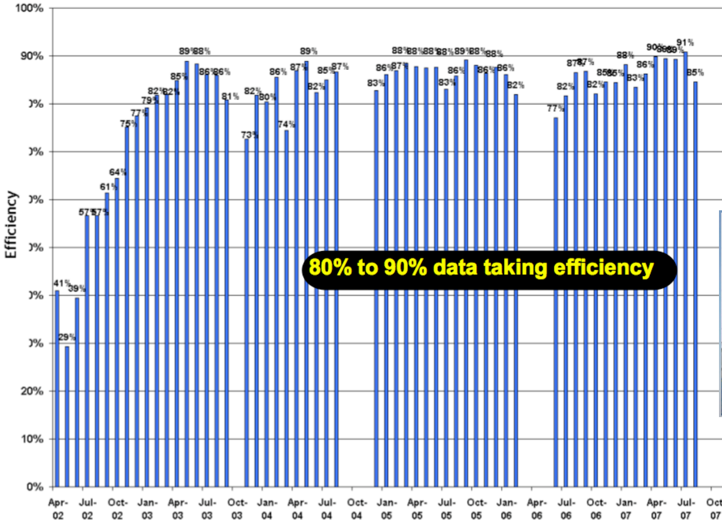
Luminosity Profile



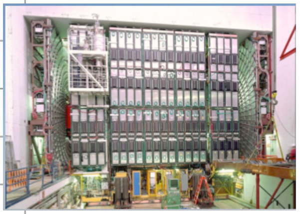
Delivered Lumi. > 3.6 fb^{-1}
Good for analysis ~ 3. fb^{-1}







80% to 90% data taking efficiency



Signatures and Physics Objects

We study physics processes organizing them by their signature

Leptons-only final states

- e/μ identification well understood
- τ id a little more complex
- Straightforward and highly efficient approach to search for anomalies

- … + Missing Energy and Photons
  - Wealth of models and exotic processes
  - Need accurate understanding of detector effects
- … + Jets and heavy flavors
  - More complex signatures
  - Maintaining high $S/\sqrt{B}$

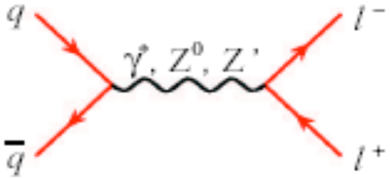
When a <u>signature-based</u> approach is advocated, final results are generally interpreted in terms of specific models (typical case dilepton searches, MET + jets)

When the analysis is <u>model driven</u> and results are presented as testing of a specific model, there is always a check on control regions, defined in terms of the process signature (blind analyses)

The two approaches are usually pursued in a balanced and complementary way

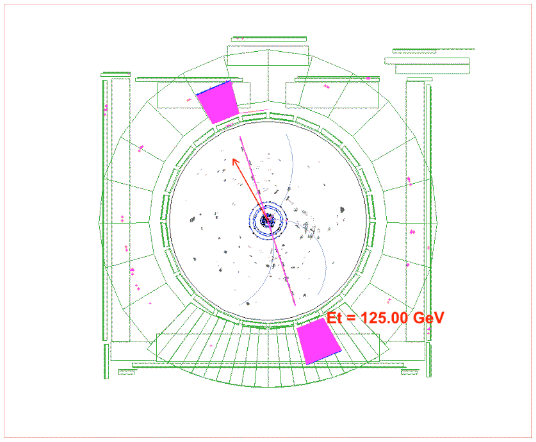
Leptons,Photons and MET

Searches in dilepton final states



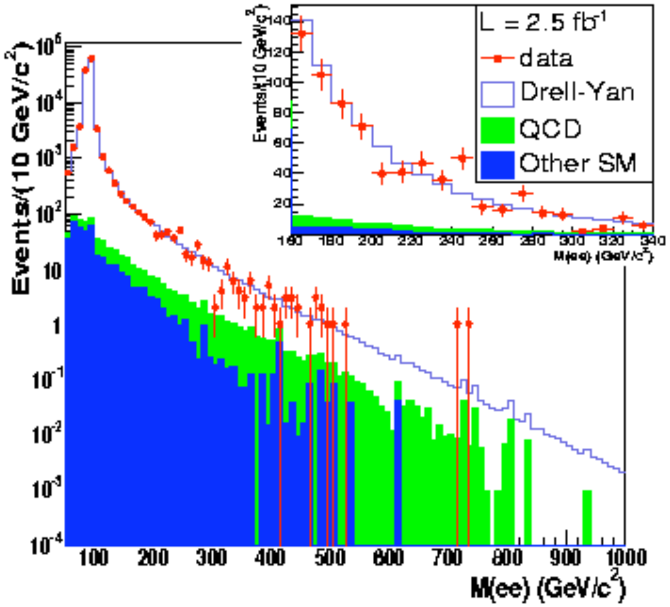
Old-fashioned mass bump hunt..

-Z production and decay into ee/μμ precisely measured
-Lepton ID/Reco and Trigger efficiencies high and very well understood
-Background low and easily determined (QCD fakes)
-Clean events



At CDF the dielectron mass spectrum is scanned in search for excesses in above 150 GeV/c^2

CDF Run II Preliminary



The most significant region of excess for an e^+e^- invariant mass window of 240 GeV/c^2

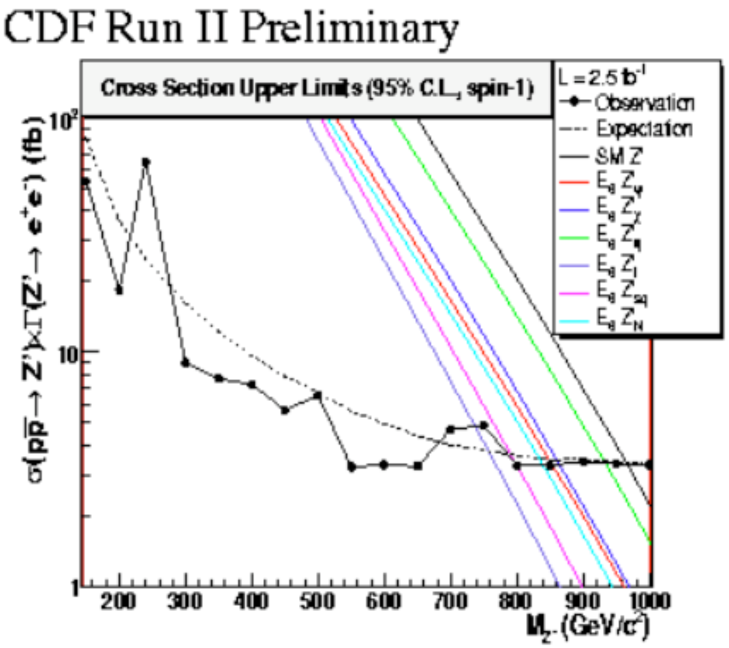
3.8 standard deviations above the SM prediction
Excess is monitored (data period) Cross-check in muons

The probability of observing a background fluctuation with significance equal to or greater than 3.8 anywhere in the mass range of 150-1,000 GeV/c^2 is about 0.6%, corresponding to a 2.5 σ significance.

Testing different models

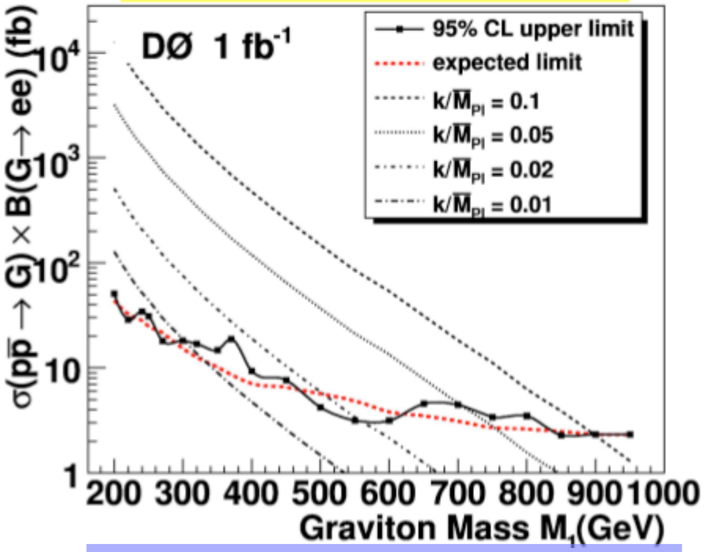
Once the data spectrum is well understood in terms of SM background, from MC, the acceptances for resonant states for different spin particles are derived (Z’, RS Graviton) and the expected number of BSM events is calculated.
In the absence of an excess of data, 95% CL limits on production cross-sections and mass of the particles are set.

$\mu\mu$ channel analyzed with the same strategy.
Update to 2fb^{-1} in progress



Exclude (at 95% CL) Z' with SM coupling below 966 GeV

PRL 100, 091802 (2008)



Exclude at 95% CL RS Gravitons below 900 GeV for k/M_{Pl} = 0.1 (CDF limit 850 GeV)

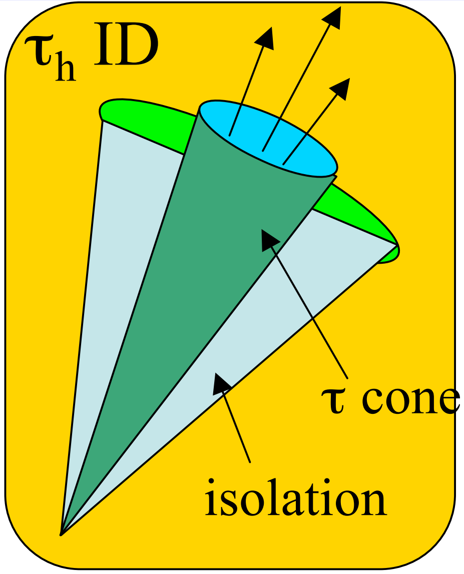
Tau final states

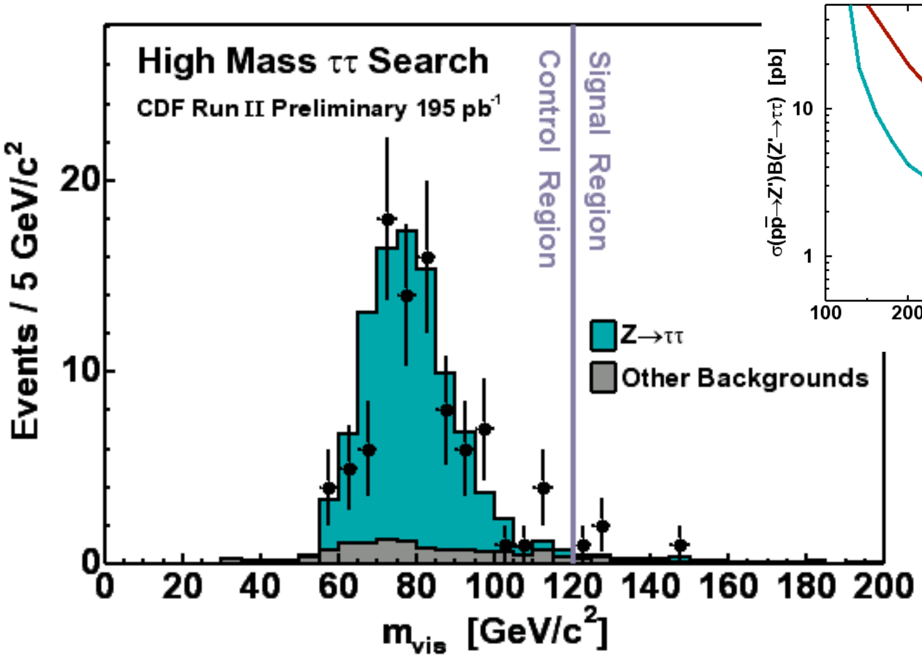
Ditaus final states are selected where

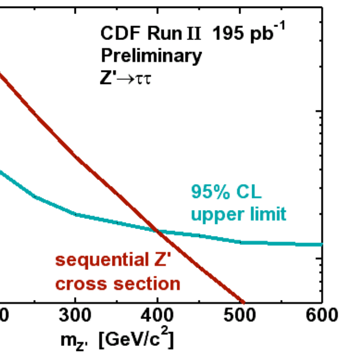
- One tau decays leptonically: e/μ (CDF) μ (DØ) (plus ν's)
- p_T > 10 GeV/c (CDF), p_T > 15 GeV/c (DØ)

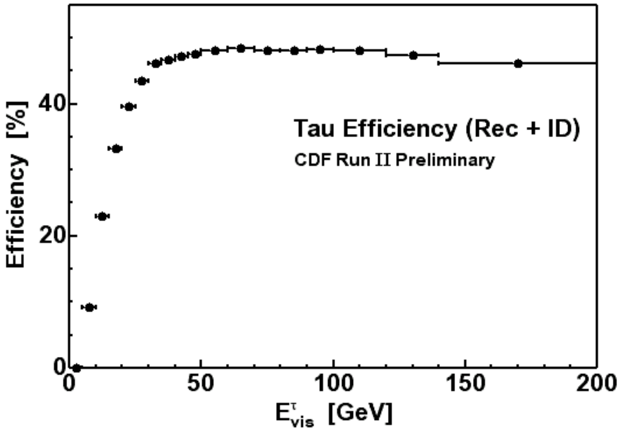
-Other tau hadronic (and ν_τ)

  - One or three tracks ($\Sigma q_{trk} = \pm 1$), opposite to lepton
  - CDF : isolation 30°, shrinking τ cone (10° → 3°)
  - DØ : three types ($\pi^\pm$, $\pi^\pm\pi^0$, 3-prong), NN score
    - No electron veto (allows eμ)
  - p_T > 15 GeV/c (1-prong), 20 GeV/c (3-prong)



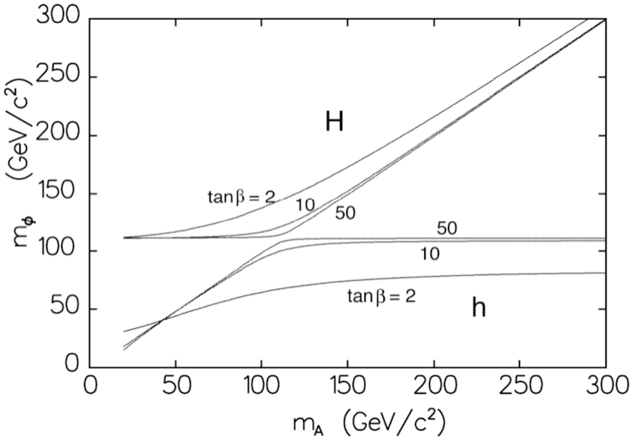






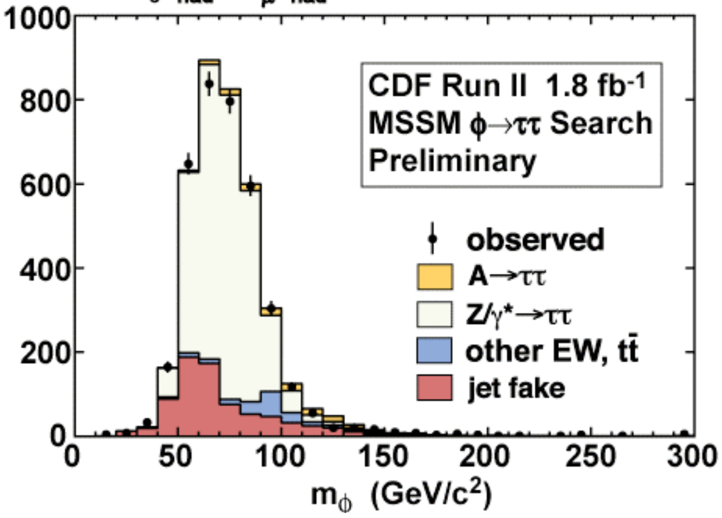
MSSM Higgs $\phi \rightarrow \tau\tau$

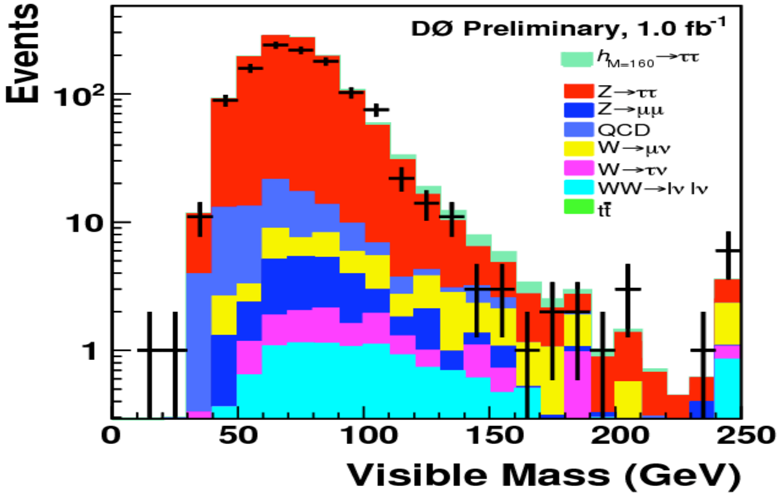
- In the MSSM framework the Higgs neutral sector simplifies at high tanβ
- A and h/H become degenerate
- Other scalar SM-like, low cross section



- Only need to search for a single mass peak (ϕ)
- For the A and its twin h/H, at high tanβ decays into $b\bar{b}$ (90%) and $\tau\tau$ (10%) dominate

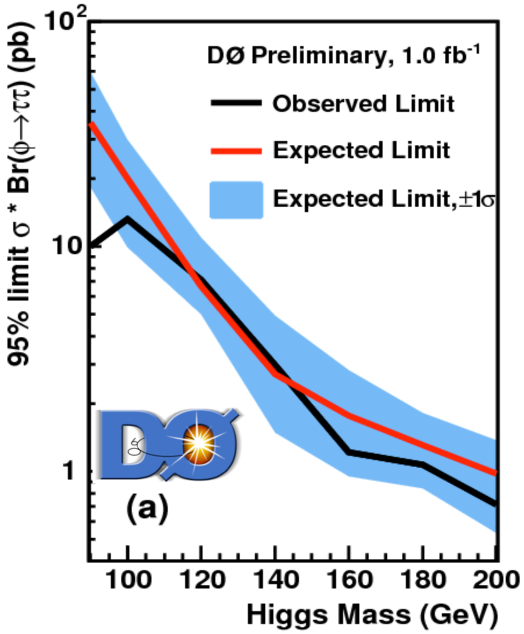
$\tau_e\tau_{had} + \tau_\mu\tau_{had}$ channels

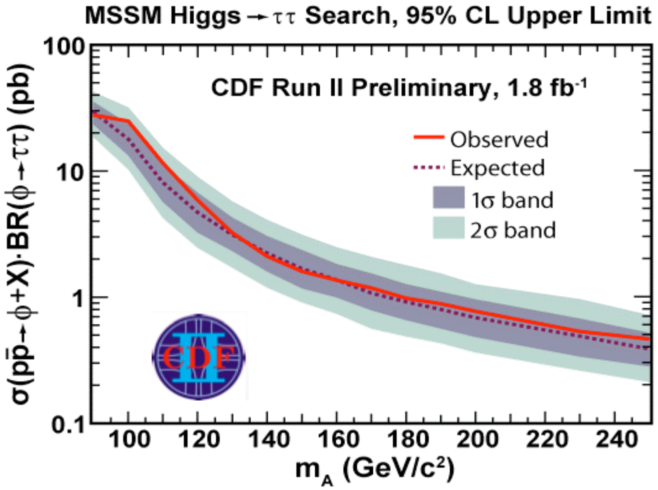


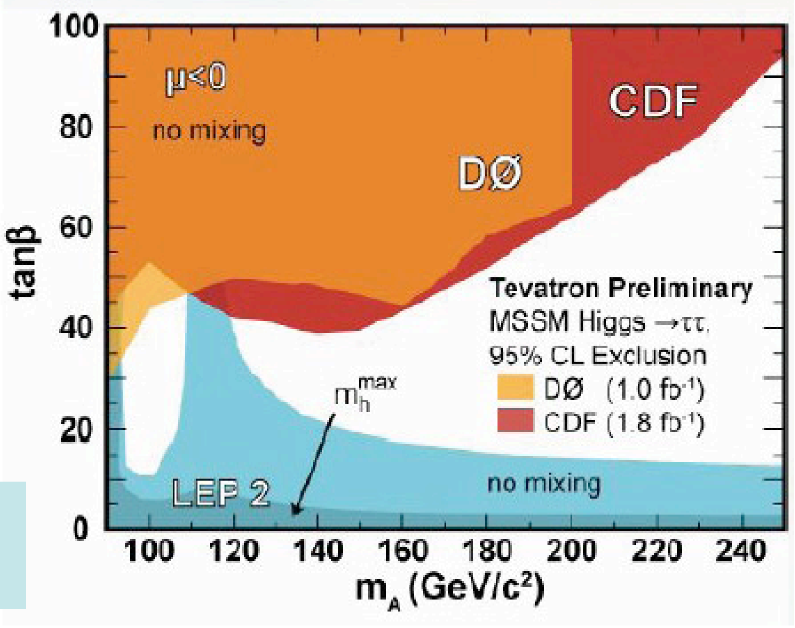


- No excess in e/μ + τ_{had} channel (slight excess for CDF in 2007)

$\phi \rightarrow \tau\tau$ Results

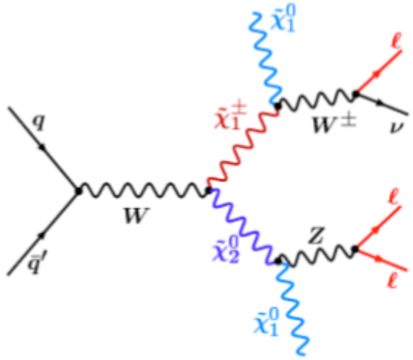




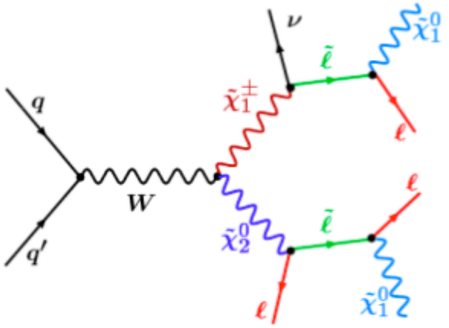


Interpret σ x BR limits as limits on tanβ vs m_A in MSSM benchmark scenarios

Multileptons final states: SUSY in Trileptons

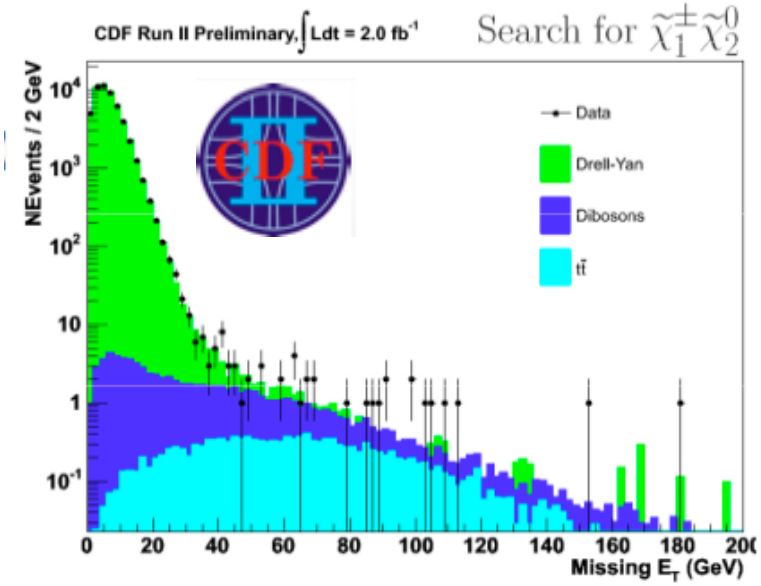


Decays through W/Z favorable for heavy sleptons, but BR to leptons low



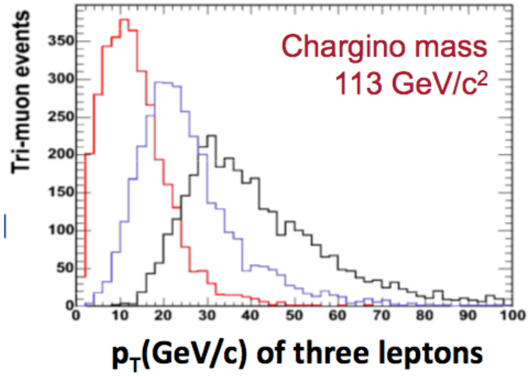
Decays through sleptons guarantee final leptons, but also preference to $\tilde{\tau} \rightarrow \tau$

Chargino Neutralino cascade decay results in a signature of (3 leptons or 2 leptons + track) and MET



Control regions in MET vs $M_{\ell\ell}$ phase-space

- Signal region is investigated only after validating backgrounds in control regions (a blind analysis)



- Selection (signal region):
  - p_T (15,10/5,5) GeV/c
  - MET>20 GeV (DY and QCD rejection)
  - N_{jets} ≤ 1 and H_T < 80 (top rejection)
  - Z-mass veto (DY rejection)
  - Dilepton Mass above 20 GeV/c² (QCD and resonance rejection)
- Trilepton backgrounds:
  - DY+fake, Z+γ, diboson

Similar cuts at D0

SUSY in Trileptons

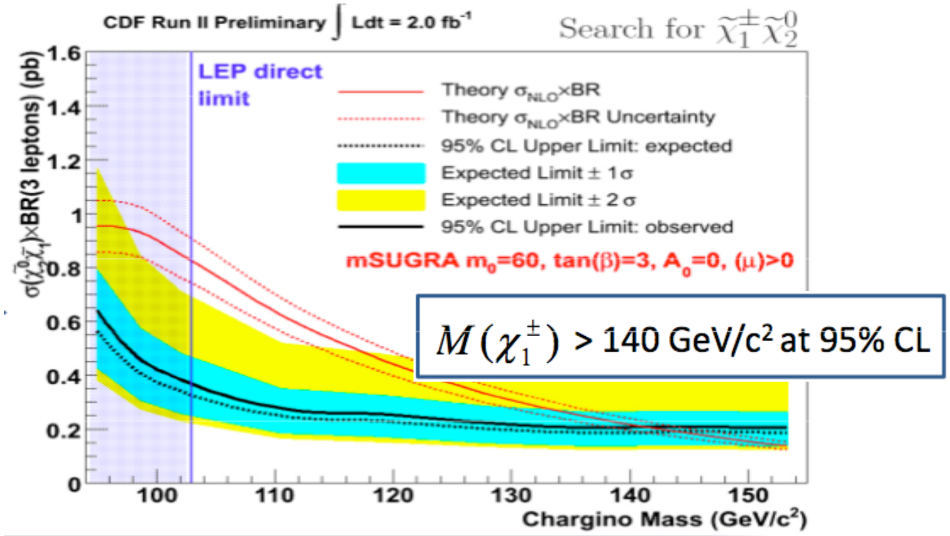
- Signal region is investigated only after validating backgrounds in control regions (a blind analysis)
- Good agreement with SM background

CDF Run II Preliminary, $\mathcal{L} = 2.0\ \text{fb}^{-1}$

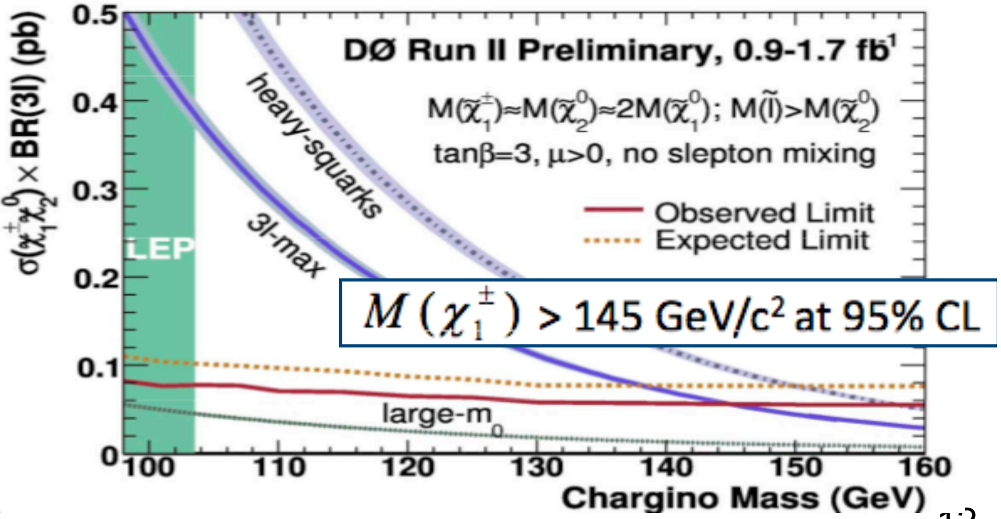
Analysis	Backg.	Signal	DATA
Trilepton	**0.9 ± 0.1**	4.5 ± 0.6	1
Dilepton+Track	**6.9 ± 0.9**	5.5 ± 1.1	6

DØ Run II Preliminary,

Analysis	$\mathcal{L}$ (fb)	Backg.	Signal	DATA
ee+ℓ	0.6	**1.0 ± 0.3**	0.5 – 0.2	0
μμ+ℓ	1	**$0.3^{+0.7}_{-0.03}$**	0.5 – 2.5	2
eμ+ℓ	1	**$0.9^{+0.4}_{-0.1}$**	1 – 4	0
ee+ℓ	1.1	**0.8 ± 0.7**	1.7 – 4.7	0
μ±μ±	0.9	**1.1 ± 0.4**	0.6 – 3.7	1



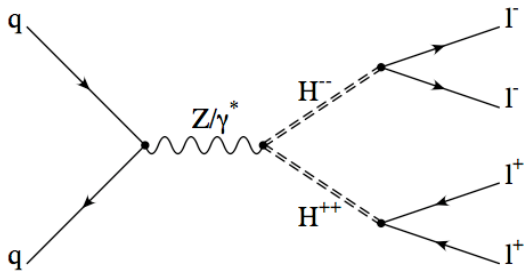
$M(\chi_1^{\pm})$ > 140 GeV/c² at 95% CL



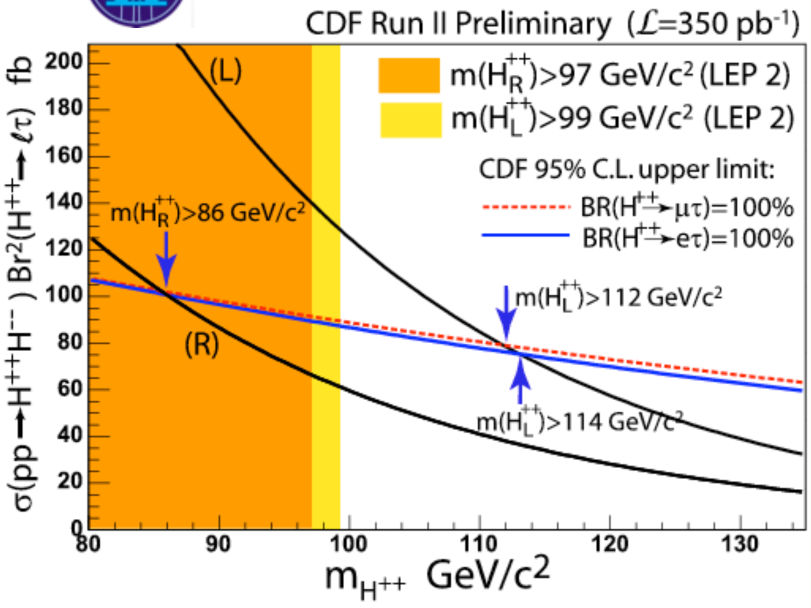
$M(\chi_1^{\pm})$ > 145 GeV/c² at 95% CL

Multi leptons final states: Doubly Charged Higgs

4 leptons final state



- $H^{++}H^{--} \to l^+l^+l^-l^-$
- $H^{++}H^{--} \to \mu^\pm\mu^\pm e^\mp e^\mp$
- $H^{++}H^{--} \to l^+\tau^+l^-\tau^-$



- $H^{++}H^{--} \to \mu^+\mu^+\mu^-\mu^-$

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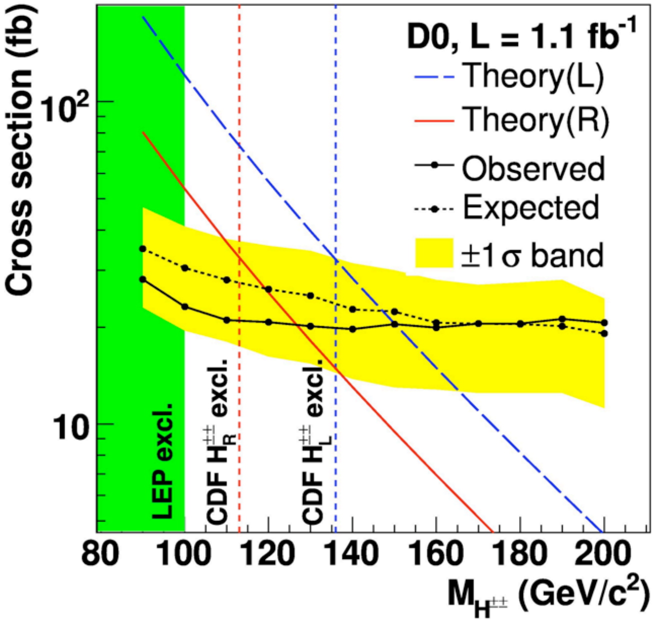
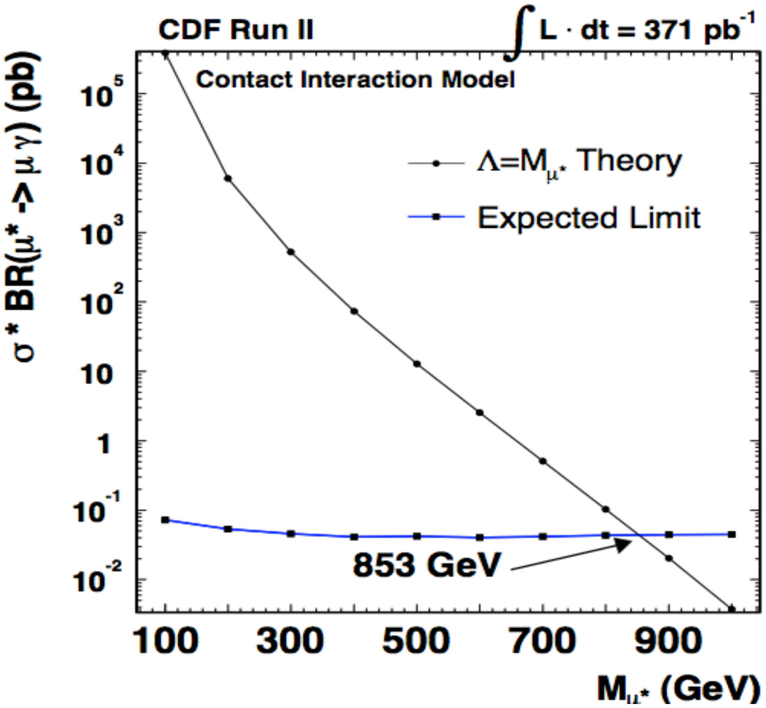


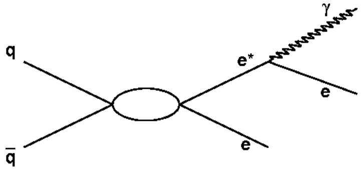
Lepton+γ final states: Excited leptons

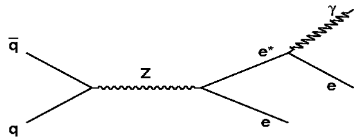
Observation of excited states of quarks and leptons might confirm the hypothesis that they are not elementary particles , but composite states

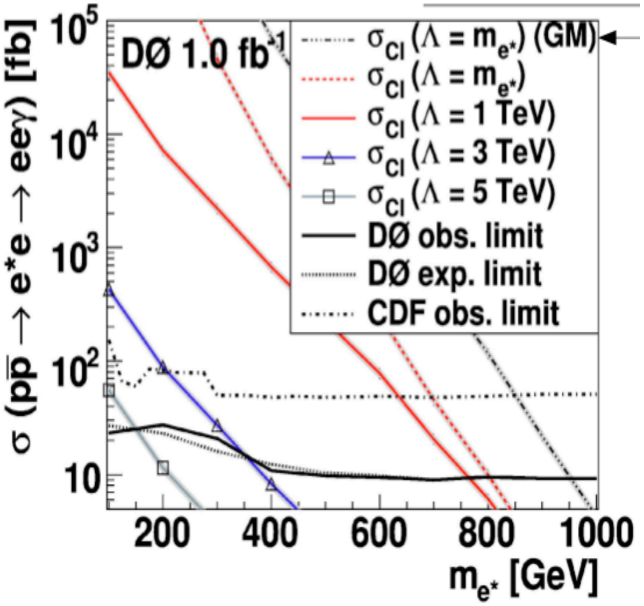
Select events with eeγ (μμγ) in the final state and look for resonance in M($e\gamma$) or M($\mu\gamma$)



At Tevatron, e^* /μ^* can be produced via contact interactions or gauge mediated interactions

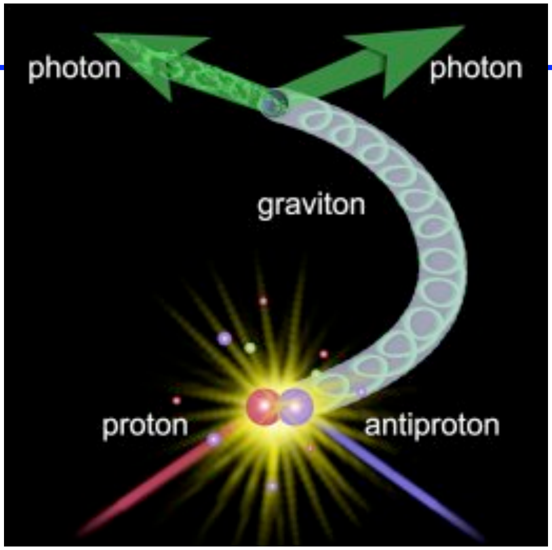




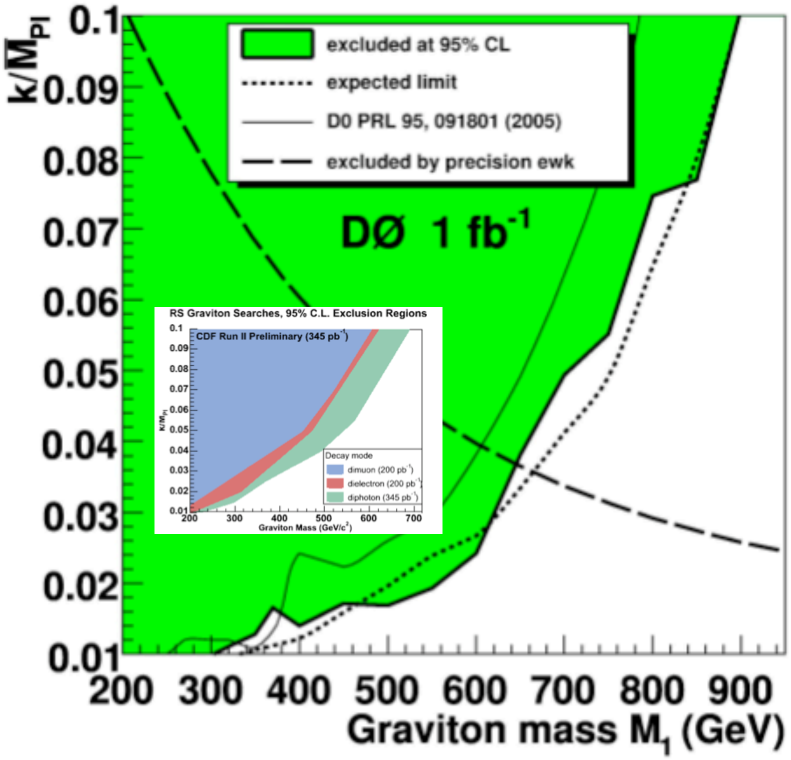


No CI Interactions

Diphotons:LED



The search for new particles decaying to diphotons uses the RS graviton model to express sensitivity to Kaluza-Klein graviton resonances (spin 2 resonance)



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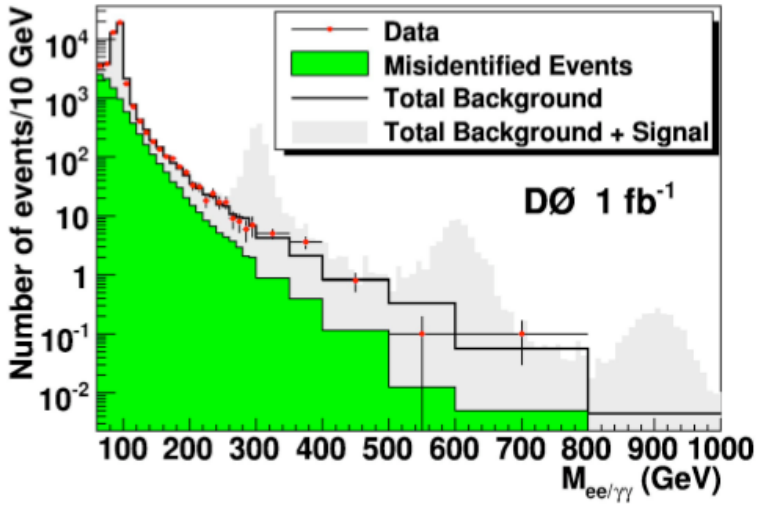
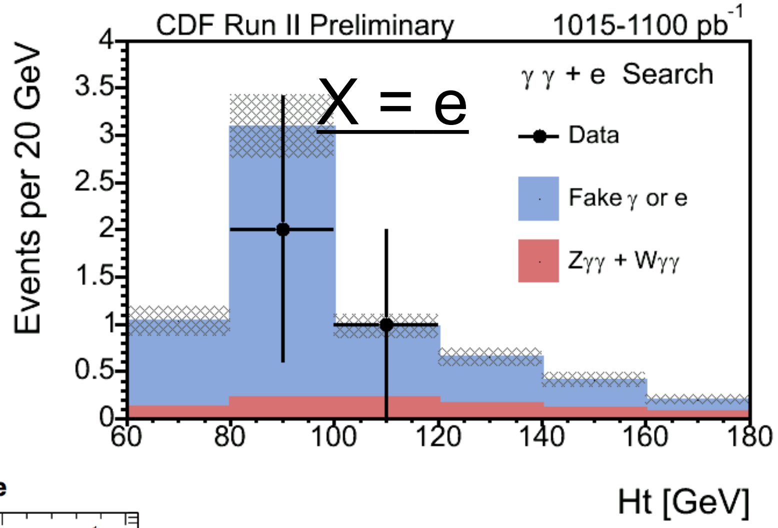
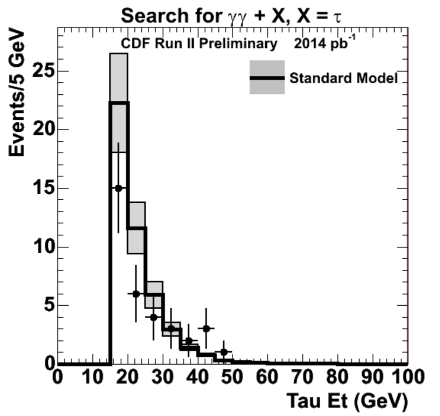


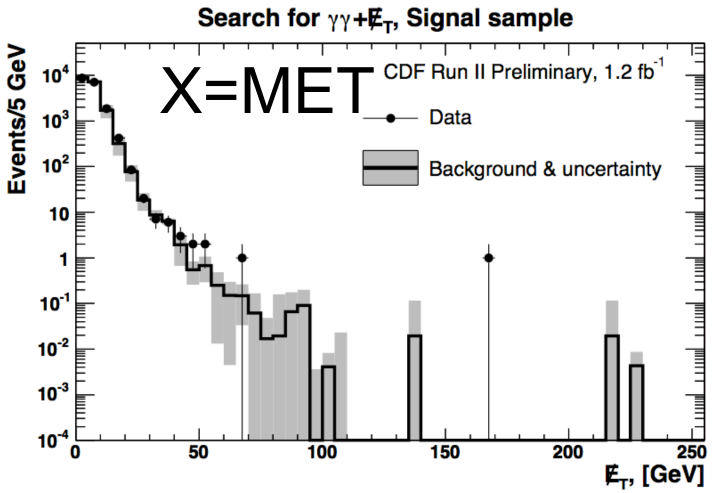
Combined with dilepton searches

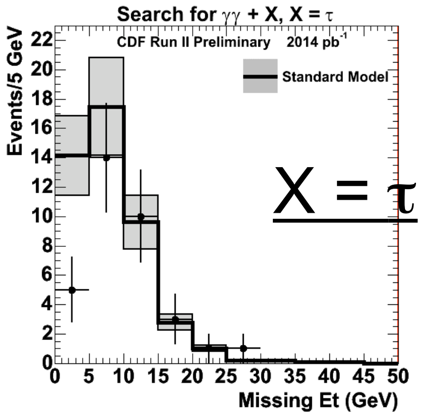
Diphoton+X

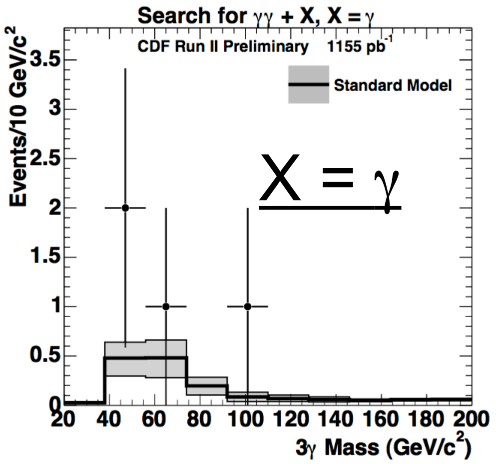
Nominal high E_T object identification and kinematic selections are used.
The observed event counts is reported as well as SM prediction for various kinematic distributions









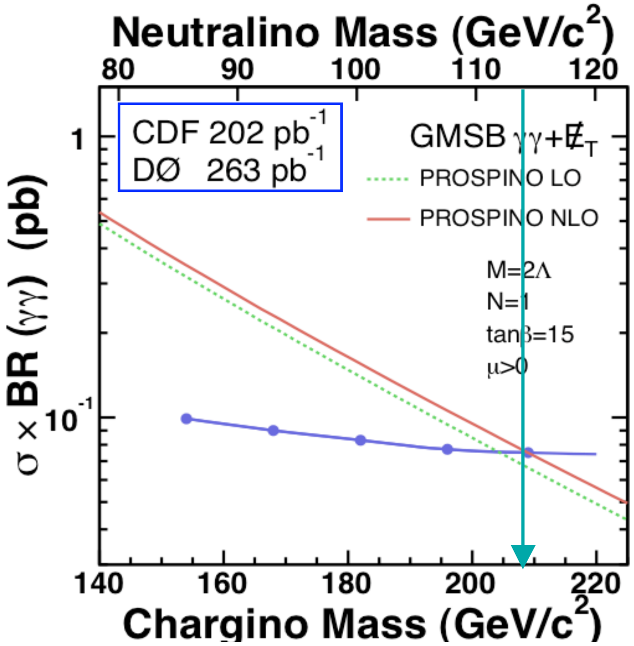


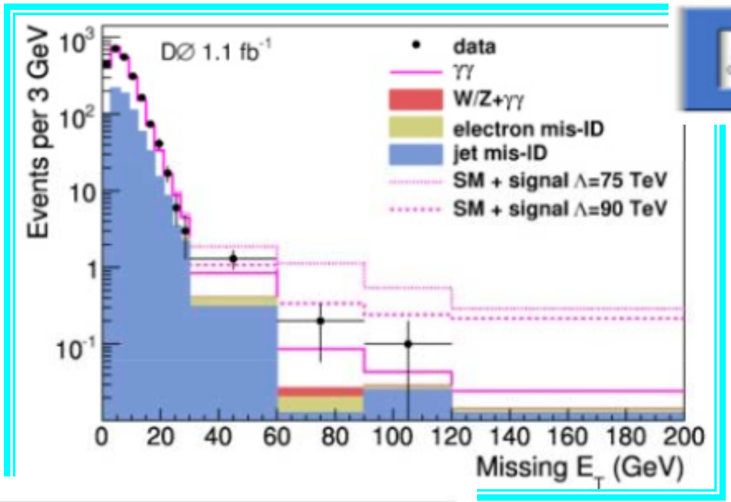
Good agreement between data and SM predictions

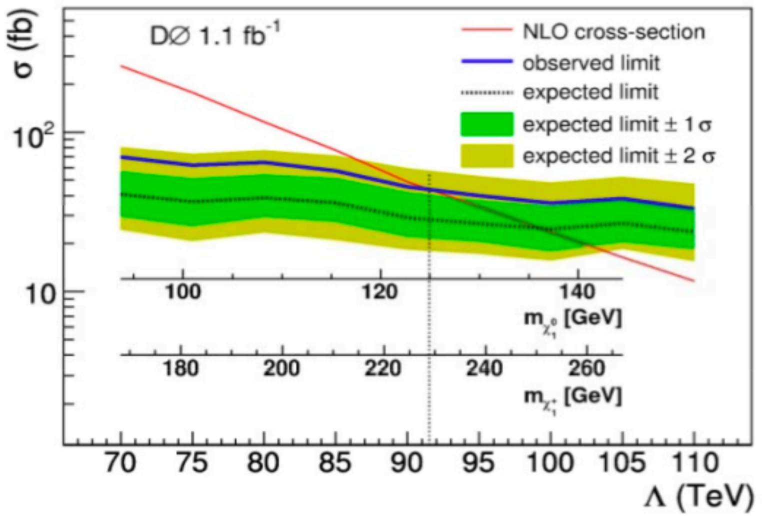
diphoton + MET: GMSB SUSY

GMSB scenario
NLSP = $\chi^0_1 \rightarrow \gamma \tilde{G}$

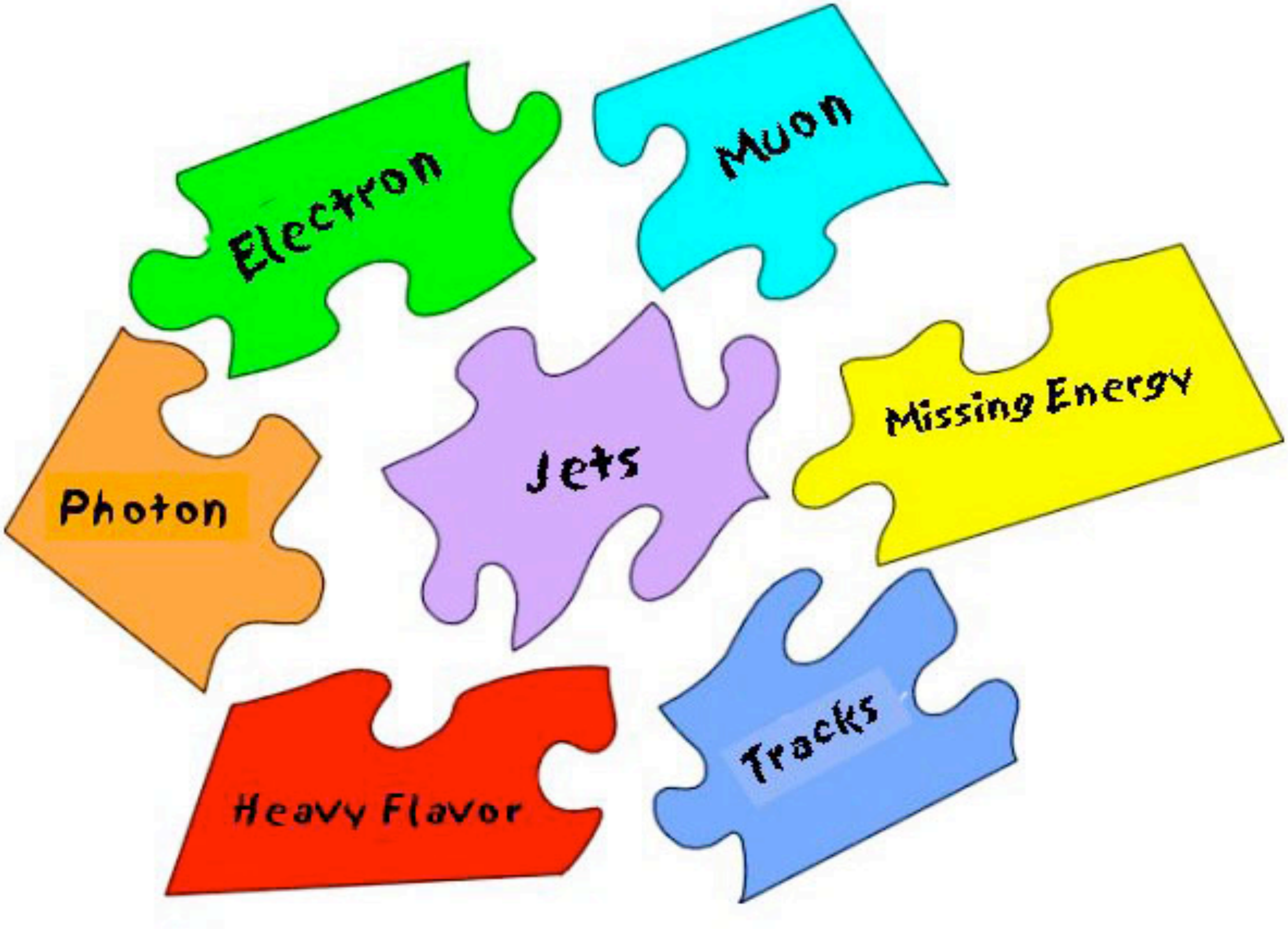
$p\bar{p} \rightarrow (X \rightarrow)\ \chi^0_1\, \chi^0_1$ → $2\gamma + \not{E}_T$







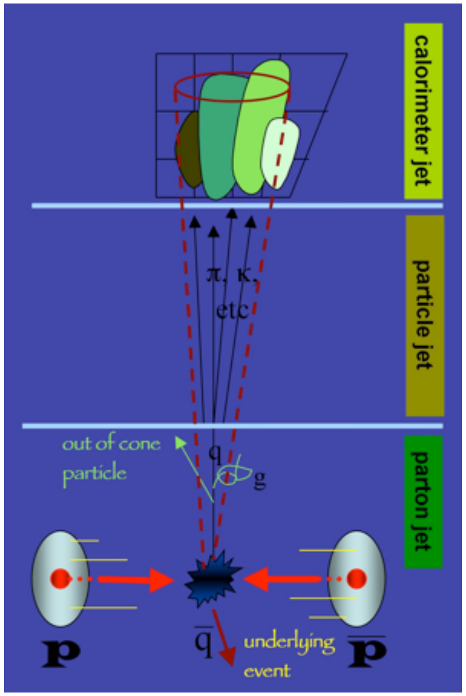
Adding jets and flavor tagging



Jets and Heavy Flavor

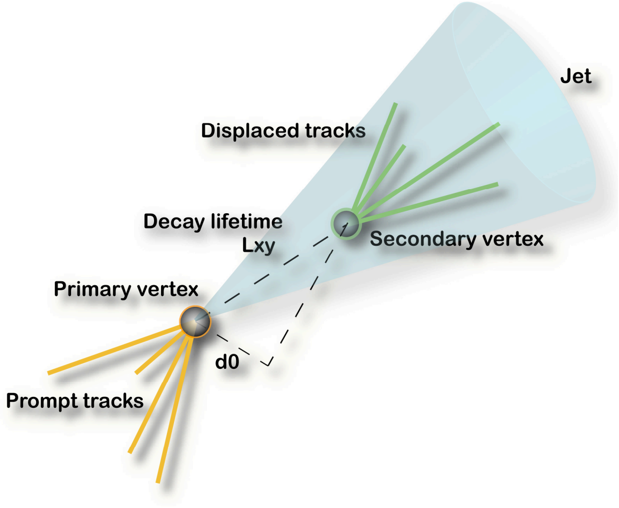
Hadronic jets are reconstructed using several algorithms: Cone,Midpoint, KT etc..

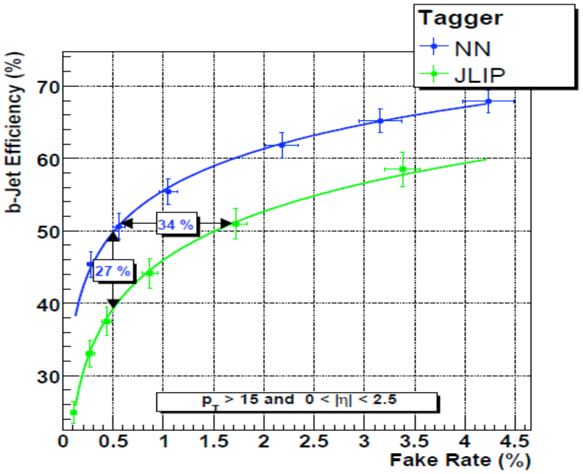
Measured jet energies are corrected to scale them back to the final state particle level jet . Additionally there are corrections to associate the measured jet energy to the parent parton energy, so that direct comparison to the theory can be made. Currently the jet energy scale is the major source of uncertainty in the measurement of the top quark mass and inclusive jet cross section

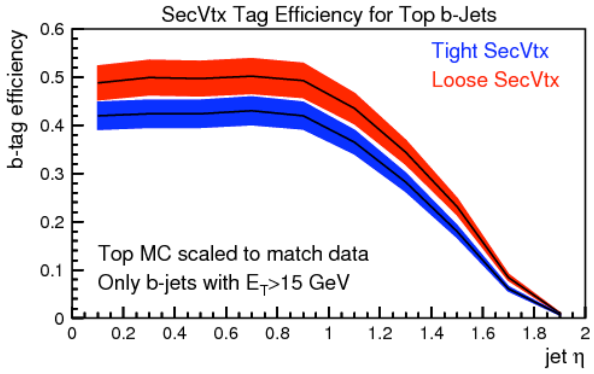


B-jet identification is implemented via:

- -displaced vertices with L_{xy}/σ cut (CDF)
- -Vertex mass separation (CDF)
- -combining vertex properties and displaced track info with NN (D0)
  - -Tag to η beyond 2



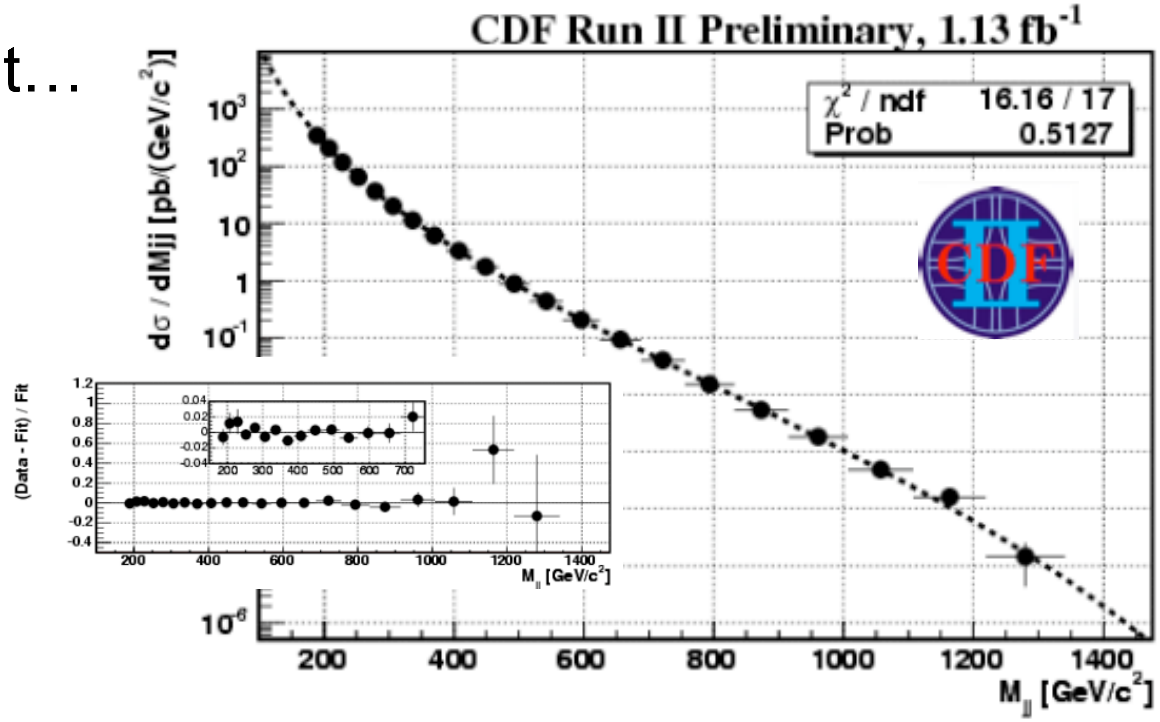




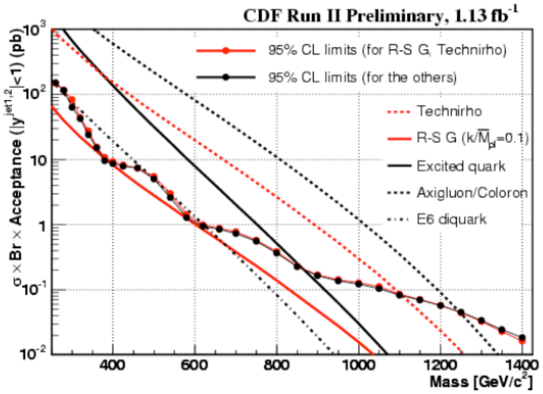
Dijets final state: mass bumps

Another mass bump hunt…

- Choose events with two high-p_T jets with rapidity less than 1.0. Look for an excess in the dijet mass spectrum for masses above 180 GeV
- Possible signals include excited quarks, W', Z', and Randall-Sundrum gravitons
- Find functional form of of dijet spectrum in pythia and herwig, fit to data. Look for “bumps” in the data minus fit plot

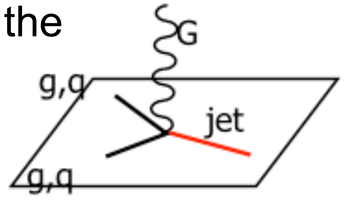


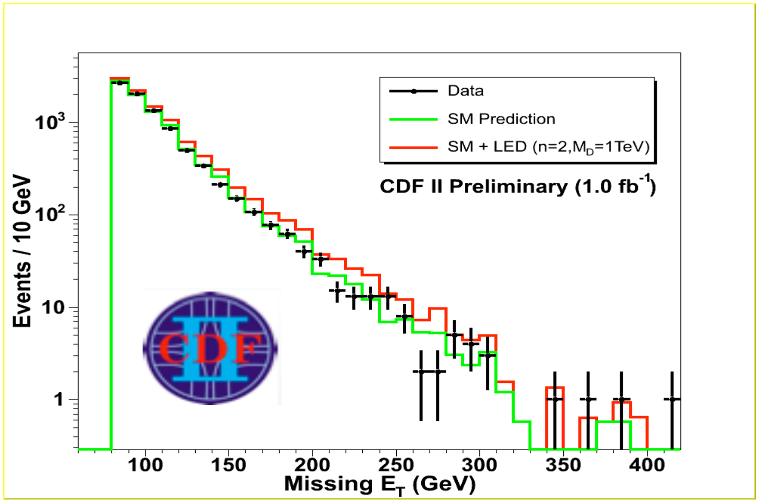
- No significant resonant structure is observed, so limits are set on various models
- Excludes (at 95% CL) excited quarks from 260-870 GeV, W' from 280-840 GeV, and Z' from 320-740 GeV

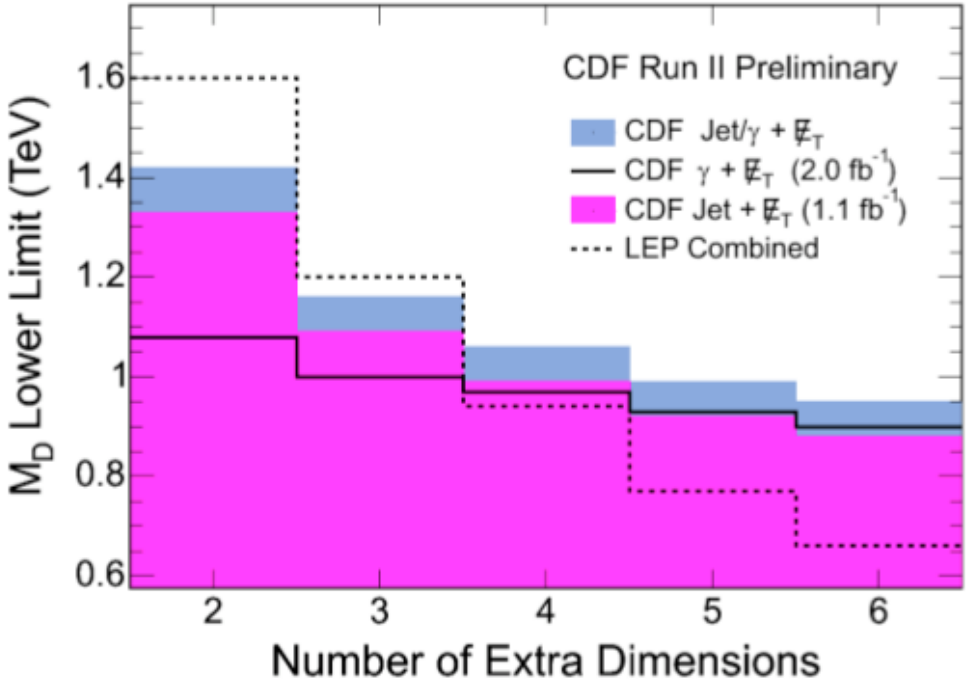


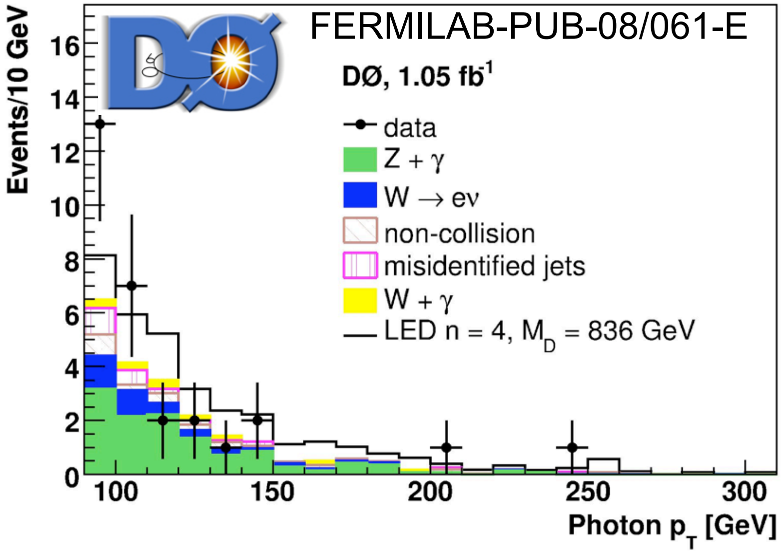
Single jet + MET: LED

A Kaluza-Klein graviton is produced in association with a jet (or photon). The graviton escapes detection, leaving a monojet (monophoton) signature in the detector

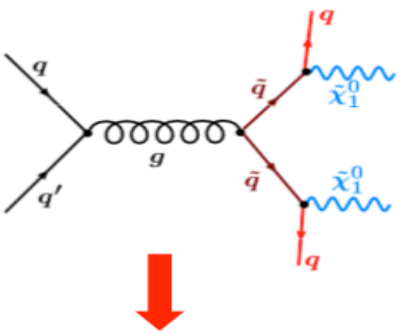




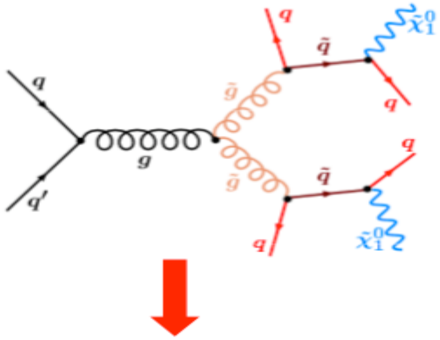




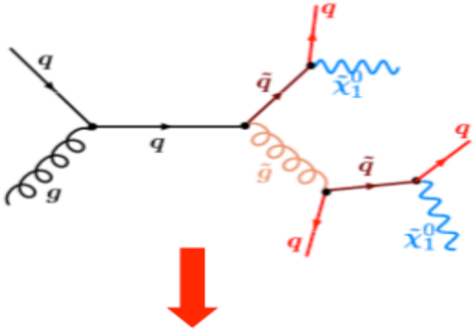
MET + jets:
SUSY squarks and gluinos



Result: 2 jets and MET

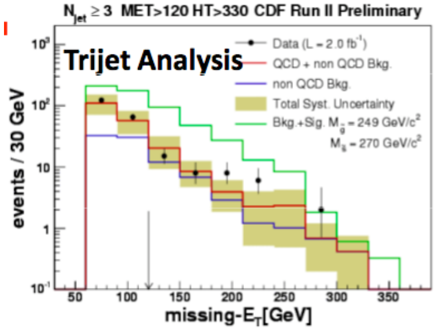


Result: 4 jets and MET



Result: 3 jets and MET

- Although the production is strong, the analyses are challenging due to QCD-multijet and W/Z+jet backgrounds
  - Solution: break-down analyses in jet-multiplicity bins and optimize separately (using MET and HT ← Sum of jet E_T)



D0,PLB 660, 449 (2008), $\mathcal{L}$=2.1fb^{-1}

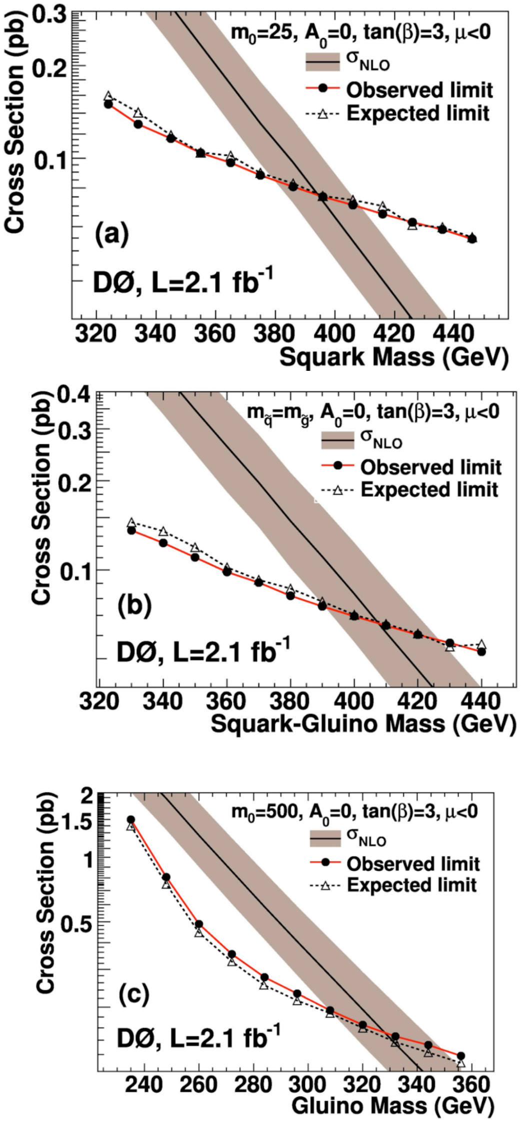
Analysis	HT cut (GeV)	MET cut (GeV)	Jet Et (GeV)	Bckg.	DATA
Dijet	325	225	35,35	11 ± 1 +3/-2	11
Trijet	375	175	35,35,35	11 ± 1 +3/-2	9
4-jet	400	100	35,35,35,20	18± 1 +6/-3	20

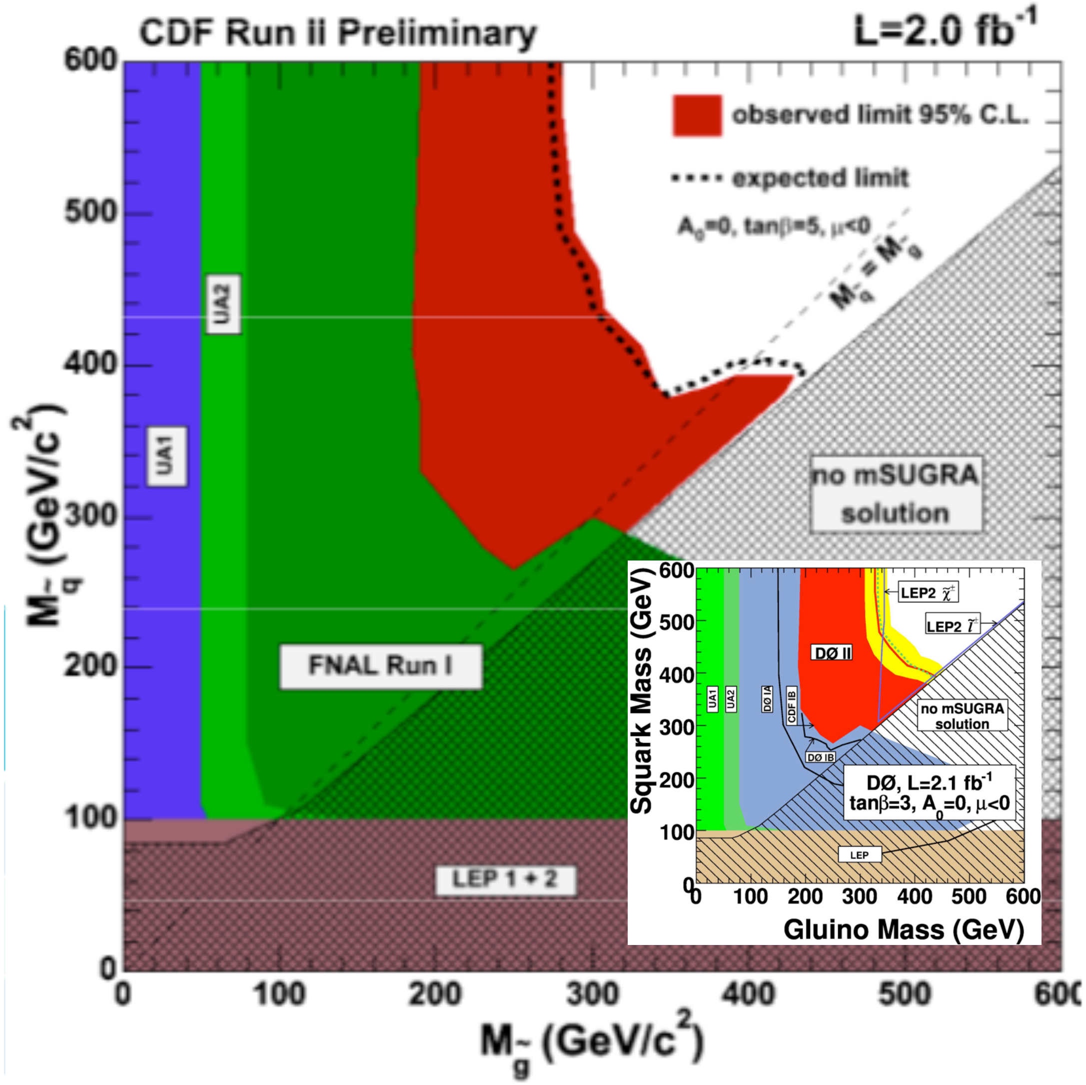
CDF Run II Preliminary, $\mathcal{L}$ = 2.0 fb^{-1}

Analysis	HT cut (GeV)	MET cut (GeV)	Jet Et (GeV)	Bckg.	DATA
Dijet	330	180	165,100	16 ± 5	18
Trijet	330	120	140,100,25	37± 12	38
4-jet	280	90	95,55,55,25	48 ± 17	45

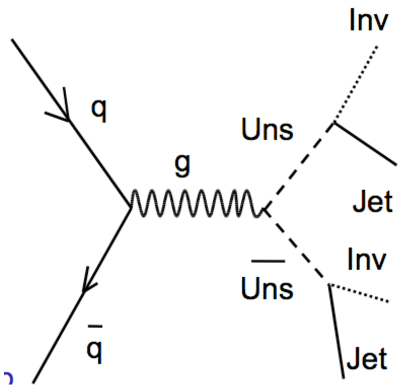
SUSY in MET + jets

Phys. Lett. B 660 , 449 (2008)





Jets+MET final state: Leptoquarks

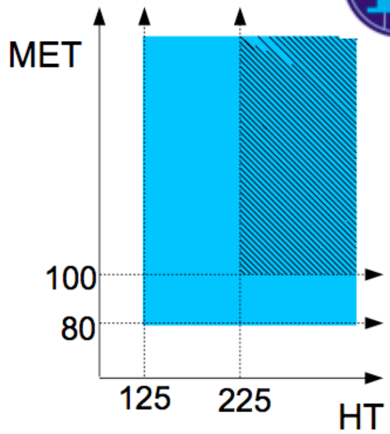


The analysis is a counting experiment examining two different kinematic regions (each region being more sensitive to different models). Cuts are not optimized for a specific model.

Main backgrounds:

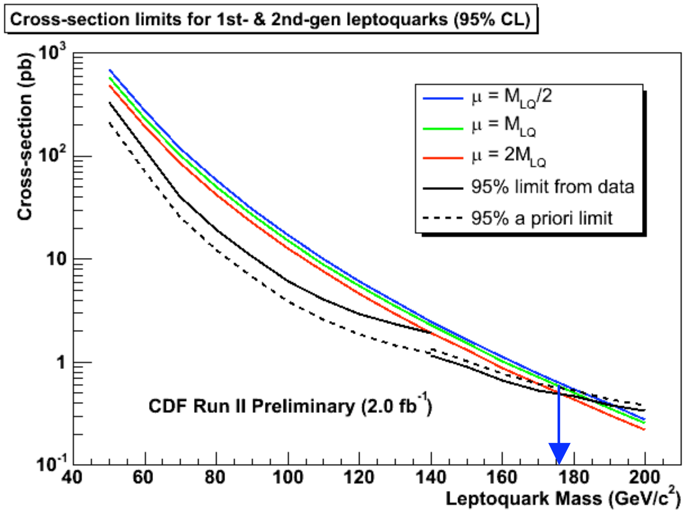
- Z → ν ν + jets (irreducible background)
- W → *l* ν + jets (with charged lepton lost)
- Residual QCD and non-collision backgrounds.

Data driven prediction



CDF Run II Preliminary, 2fb^{-1}

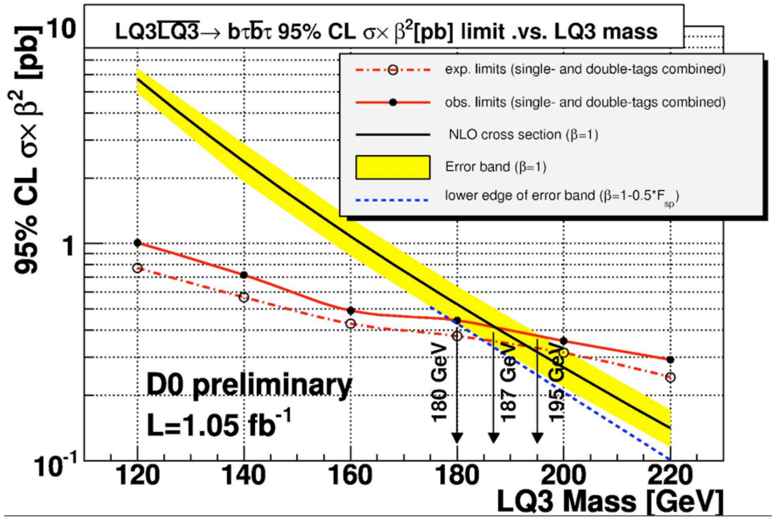
Background	125/80	225/100
Z → νν	777 ± 49	71 ± 12
W → τν	669 ± 42	50 ± 8
W → μν	399 ± 25	33 ± 5
W → eν	256 ± 16	14 ± 2
Z → ll	29 ± 4	2 ± 0
QCD	49 ± 30	9 ± 9
γ + jets	55 ± 13	5 ± 3
top	74 ± 9	11 ± 2
non-collision	4 ± 4	1 ± 1
Total	2312 ± 140	196 ± 29
Observed	2506	186

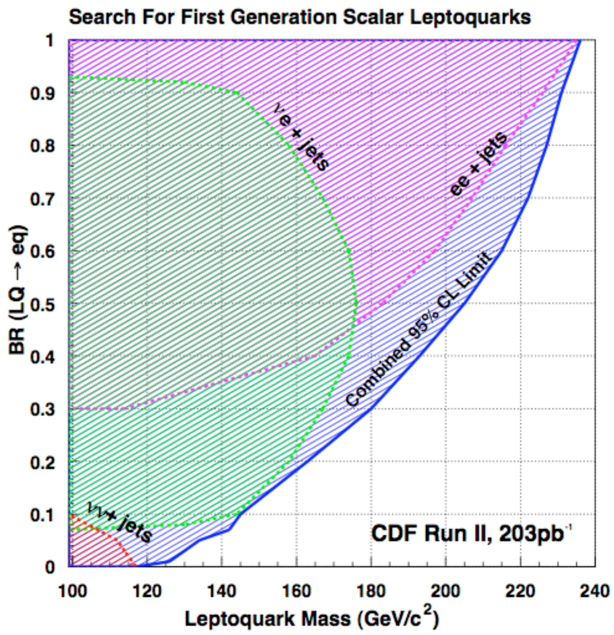


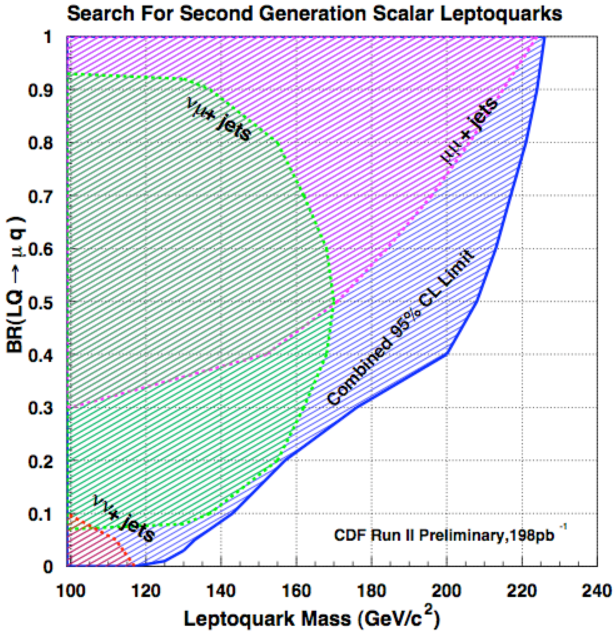
Other LeptoQuarks Results

1st Generation	2nd Generation	3rd Generation
$LQ\,\overline{LQ}\to e^-e^+ q\bar{q}$	$LQ\,\overline{LQ}\to \mu^+\mu^- q\bar{q}$	$LQ\,\overline{LQ}\to \tau^+\tau^- q\bar{q}$
$LQ\,\overline{LQ}\to e^\pm\nu_e q_i q_j$	$LQ\,\overline{LQ}\to \mu^\pm\nu_\mu q_i q_j$	$LQ\,\overline{LQ}\to \tau^\pm\nu\, q_i q_j$
$LQ\,\overline{LQ}\to \nu_e\nu_e q\bar{q}$	$LQ\,\overline{LQ}\to \nu_\mu\nu_\mu q\bar{q}$	$LQ\,\overline{LQ}\to \nu_\tau\nu_\tau q\bar{q}$

β = Br(LQ→lq)

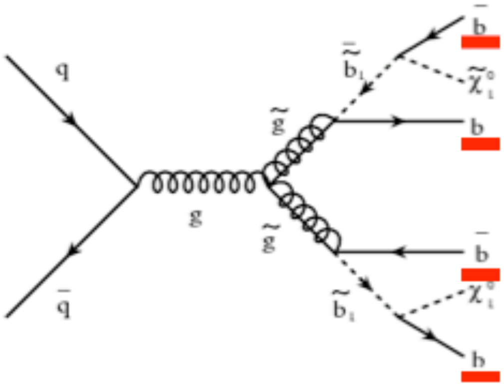






HF final states: sbottom from gluinos

If the sbottom is significantly lighter than the other squarks, the two body decay of gluino into bottom/sbottom is kinematically allowed



The sbottom decays into a bottom and LSP, giving rise to a final state with <u>4 b-jets and missing energy</u>

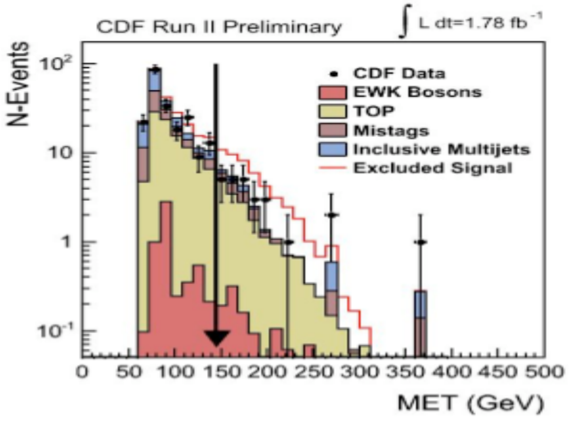
The analysis is optimized for 2 points in the SUSY parameter space:

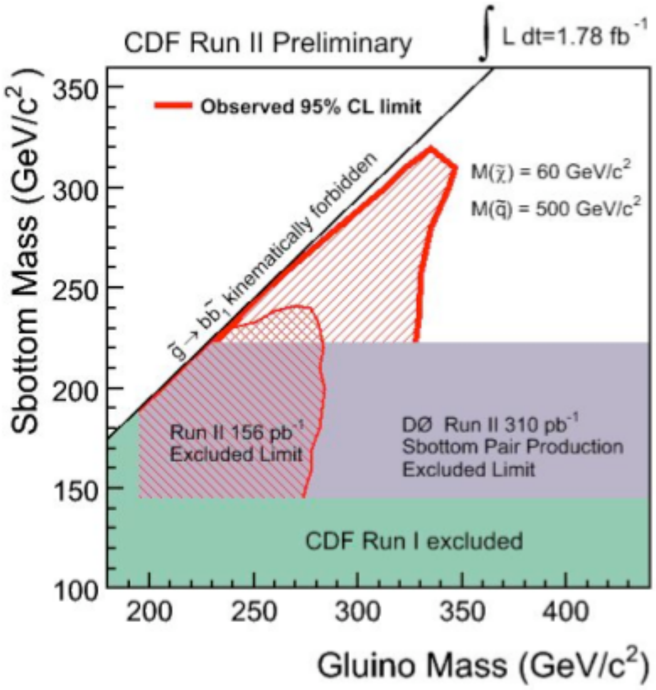
Large Δm between $\tilde{g}$ and $\tilde{b}$

$M(\tilde{g}) = 320$ GeV/c^2, $M(\tilde{b}) = 250$ GeV/c^2, $M(\tilde{\chi}) = 60$ GeV/c^2

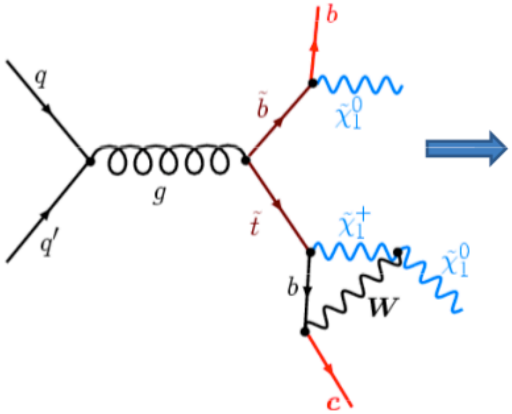
Small Δm between $\tilde{g}$ and $\tilde{b}$

$M(\tilde{g}) = 300$ GeV/c^2, $M(\tilde{b}) = 280$ GeV/c^2, $M(\tilde{\chi}) = 60$ GeV/c^2





Stop searches



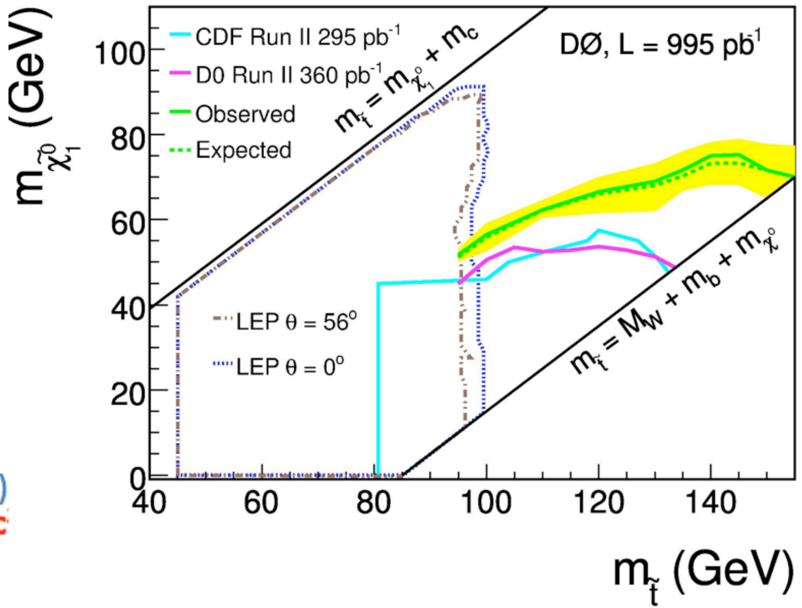
Light stop and sbottom production and decay

Stops to charm

- Exactly 2 jets (reduction of QCD)
- Jet pt cuts (20,40 GeV/c) and angular separation of jets (reduces QCD and W+jets)
- Angle between jets and met (reduction of QCD)
- Flavor tagging using Neural Network (impact parameter, secondary vertex information)

Exclusion: stop mass <149 GeV/c
neutralino mass of 63 GeV/c²

Fermilab-PUB-08/063-E

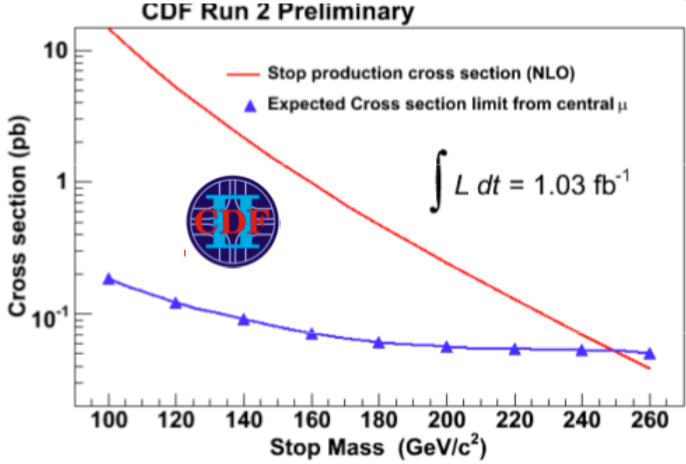


Other option is that stop does not decay in the detector (CHAMP)

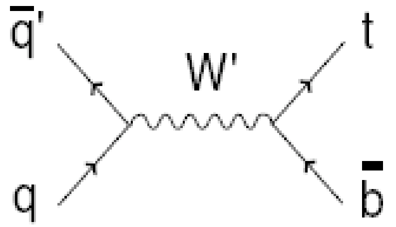
- Slow particle signature : slowly-moving highly-ionizing highly-penetrating particle
  - Will look like muon with possible calorimetry energy deposition

• Particle mass is measured using Time of Flight

Stable stop mass > 250 GeV/c² at 95% CL

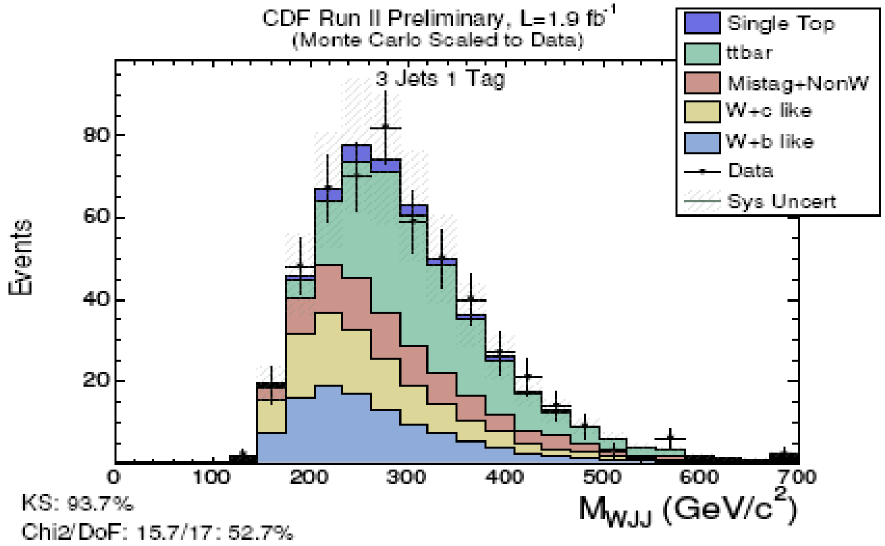


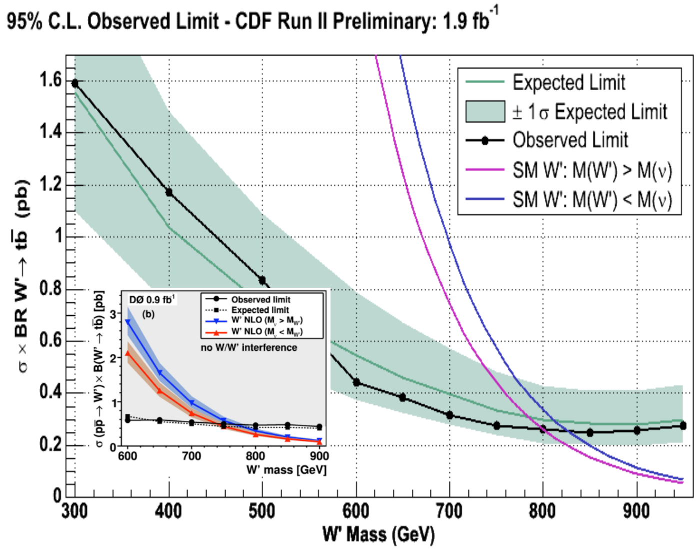
Heavy flavor final states: W’→ tb



Search for resonant tb*(+cc)* pair production

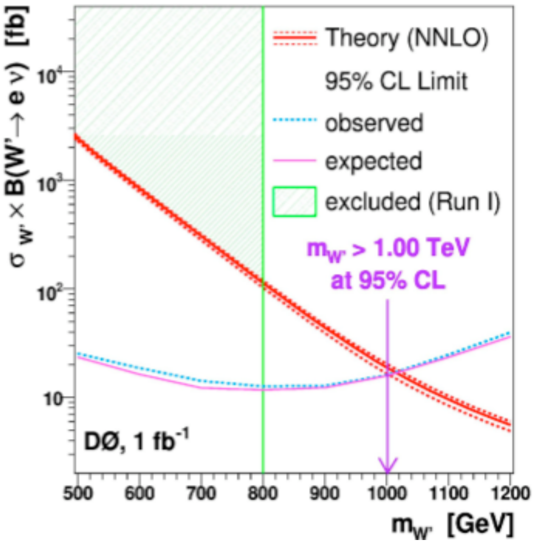
In W+2 jets and +3 jets channels (semileptonic W), look for unexpected structure in M(Wjj)

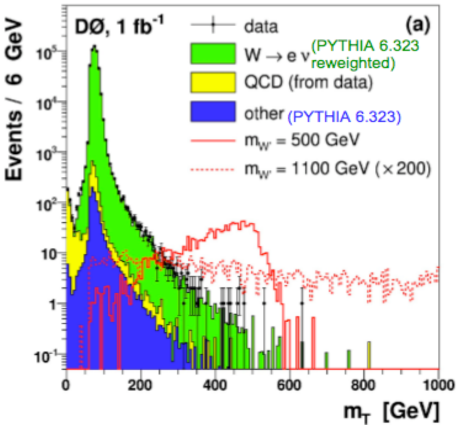




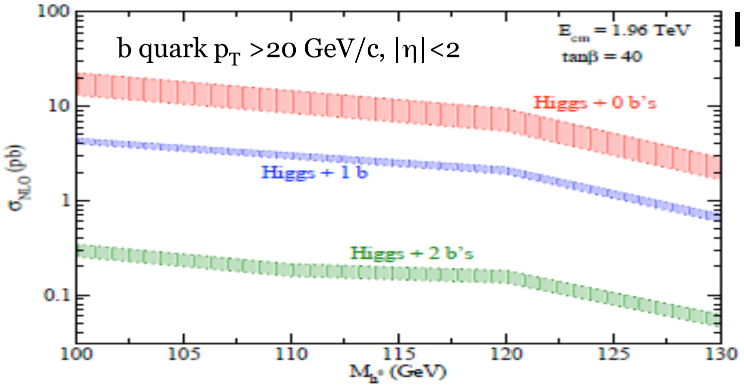
Extra W gauge boson decaying into eν

Phys. Rev. Lett. 100 , 031804 (2008

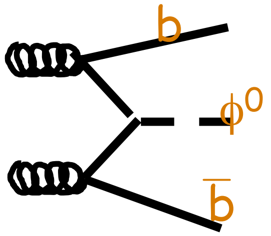




HF final states: $\phi \rightarrow bb$

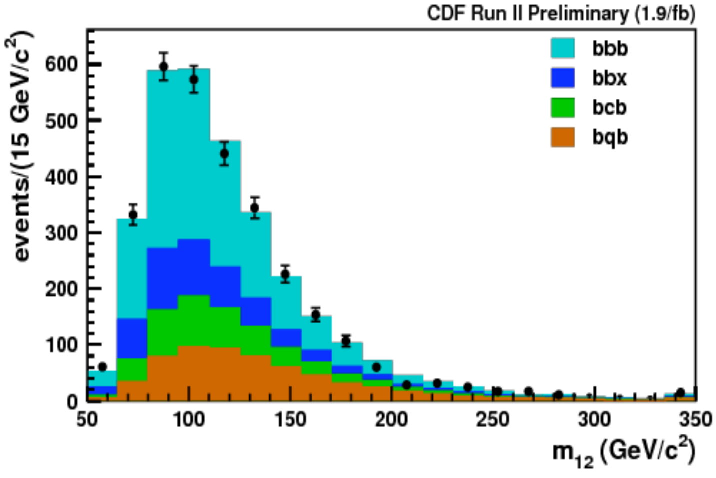


Inclusive H → b$\underline{b}$ is too hard due to QCD background

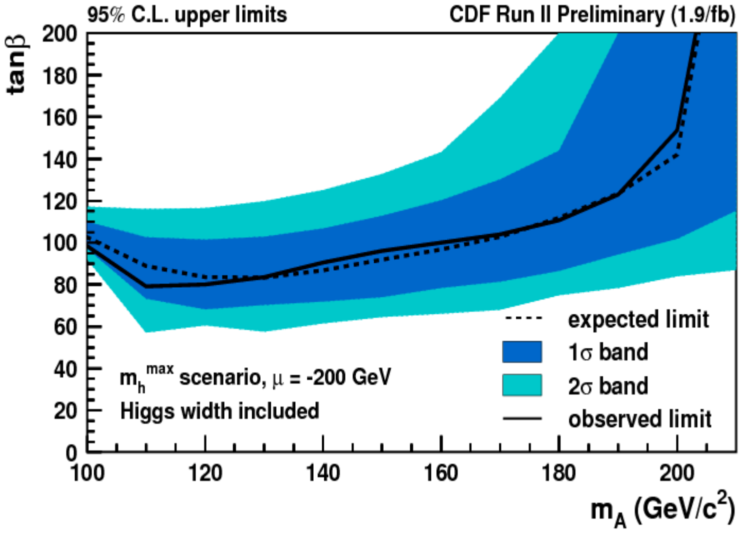


Require one additional bottom quark jet besides the two from Higgs decay

“3b” channel best compromise between signal and background rates

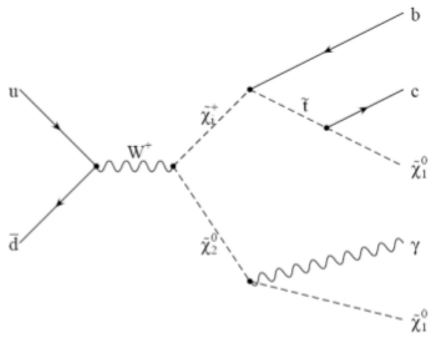


Search in mass of two lead jets m_{12}
No excess observed



More complex signatures: γ+b+jets+MET

A handful of exotic processes would give rise to a final state signature comprising γ+b+jets+MET
Many anomalies could be reduced to detector mis-measurements.



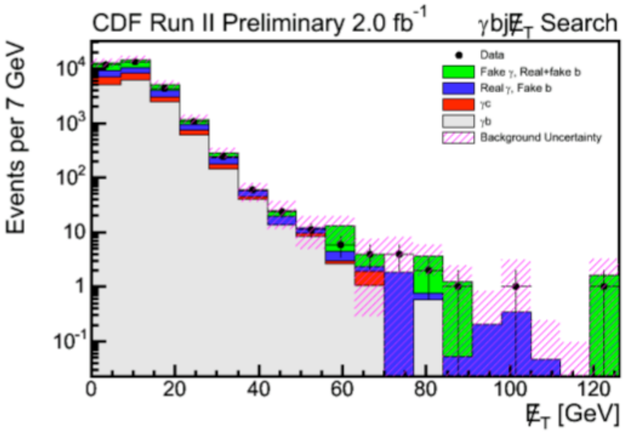
Low energy SUSY with radiative decay of the neutralino

Selection:
One high E_T photon
≥ 2 jets
≥ 1 tagged jet
Large MET (> 25 GeV)
Topological cuts

Main background is dominated by fake γ or b. Calculated using MC or data

CDF Run II Preliminary, 2 fb^{-1}

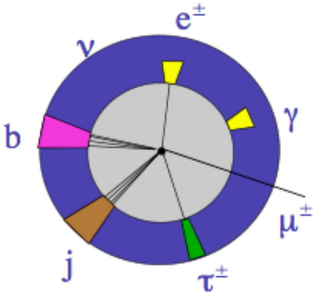
Source	Number
γb	291 ± 7 (stat.) ± 50 (syst.)
γc	92 ± 25 (stat.) ± 45 (syst.)
Fake b, real γ	141 ± 6 (stat.) ± 30 (syst.)
Fake γ	113 ± 49 (stat.) ± 54 (syst.)
Total	637 ± 54 (stat.) ± 128 (syst.)
Data	617



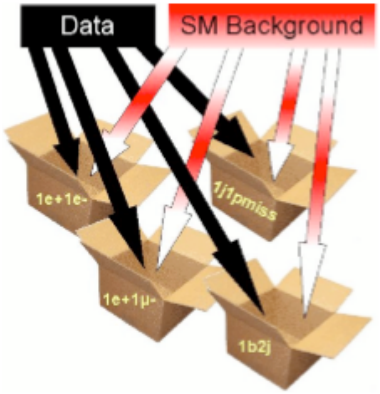
Global Searches

The goal is to perform a model-independent global search of high P_T data:

- -study bulk features of high P_T data;
- -search for resonances invariant mass distributions
- -search for significant excesses at high sum-p_T



Physics objects are categorized and events selected and partitioned into ~400 exclusive final states



The whole high P_T region is monitored at once

Pythia and MadEvent are used to implement the SM theoretical prediction (CdfSim emulates the detector response)

Many correction factors are used to obtain the *true* SM predictions (shouldn't a global search work globally?)

- theory k-factors etc
- experimental efficiencies and Scale Factors, fake rates etc

Currently observed discrepancies are explained in terms of incorrect MC modeling

Conclusions

Many exciting results are continuously produced at the Tevatron!

We are still the place of interest and will be for a few more years!

The search for physics beyond the SM is carried on through a careful analysis of various final states using model driven as well as signature based approaches.

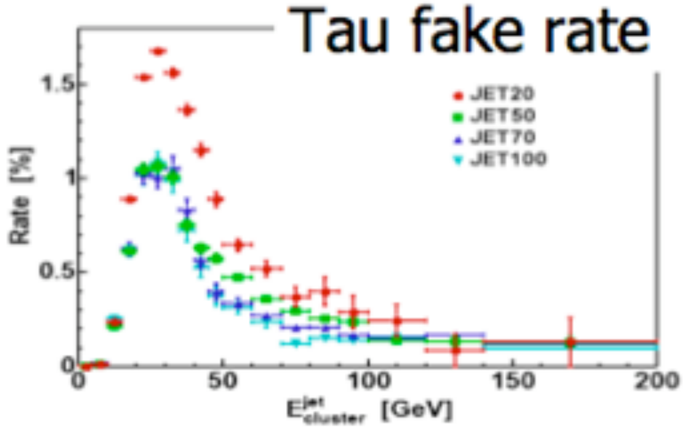
A bump can be around the corner before the LHC turns on….

Backup

Lepton Efficiencies

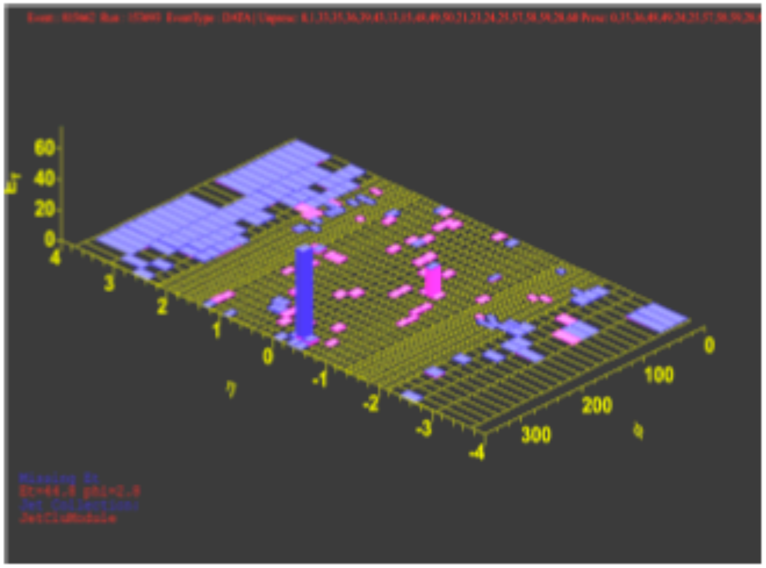
- Compare "typical" high-pt (>20 GeV) isolated lepton efficiency and fake rates

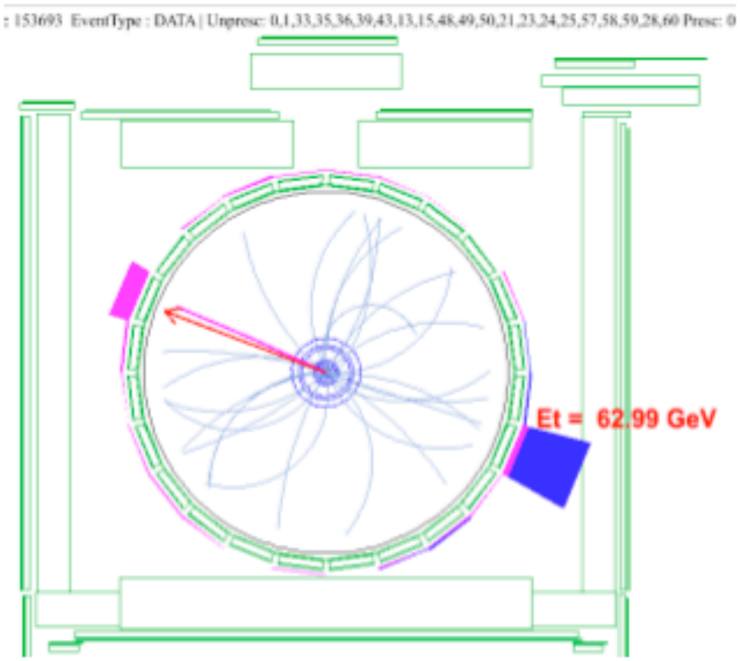
Lepton	Efficiency	Fake Rate
electron	~80%	~0.01%
muon	~85%	~0.01%
tau (box cuts)	~45%	~1-0.1%
tau (neural net)	~80%	~5-1%



Tau fake rate

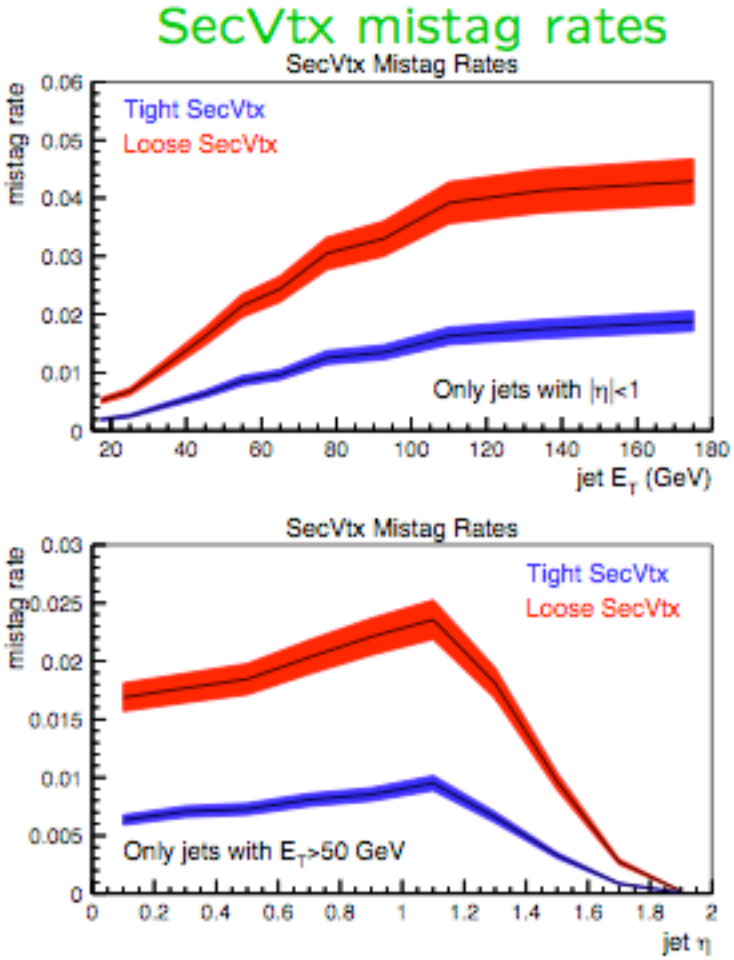
Z Tau event



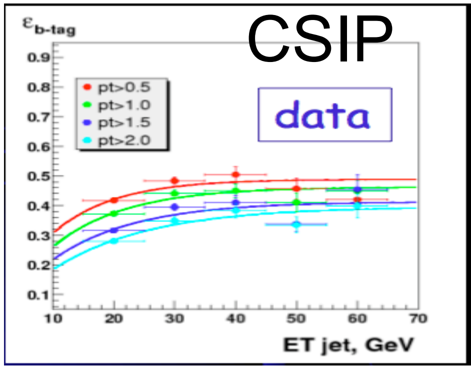


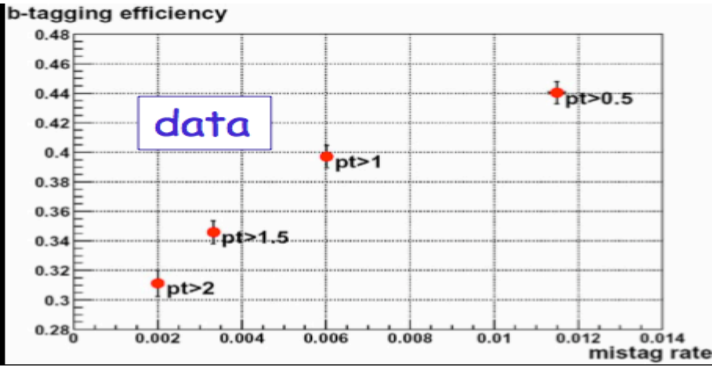
Mass (τ_e + τ_h + MET) = 129 GeV/c^2

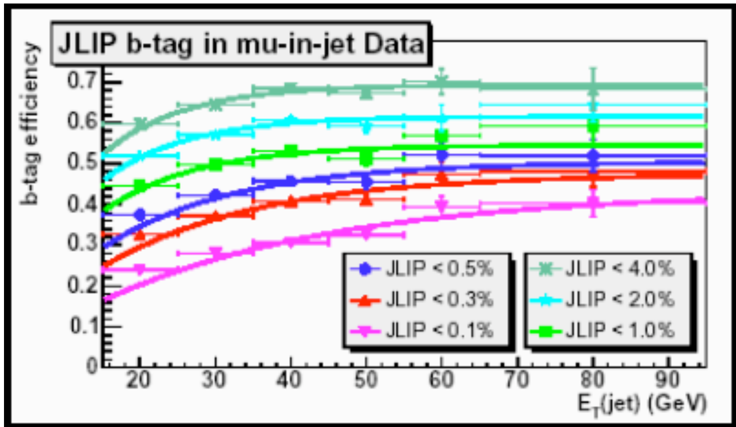
Btagging Mistag Rate



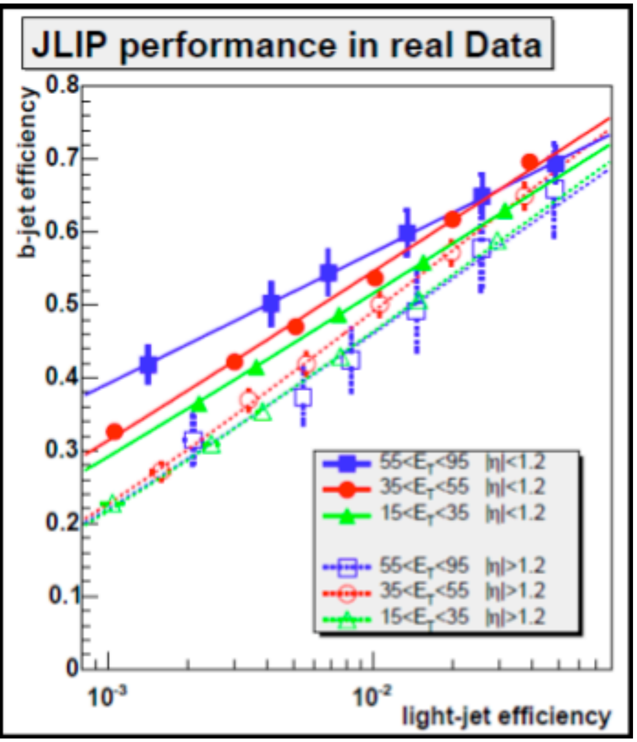
D0 btagging



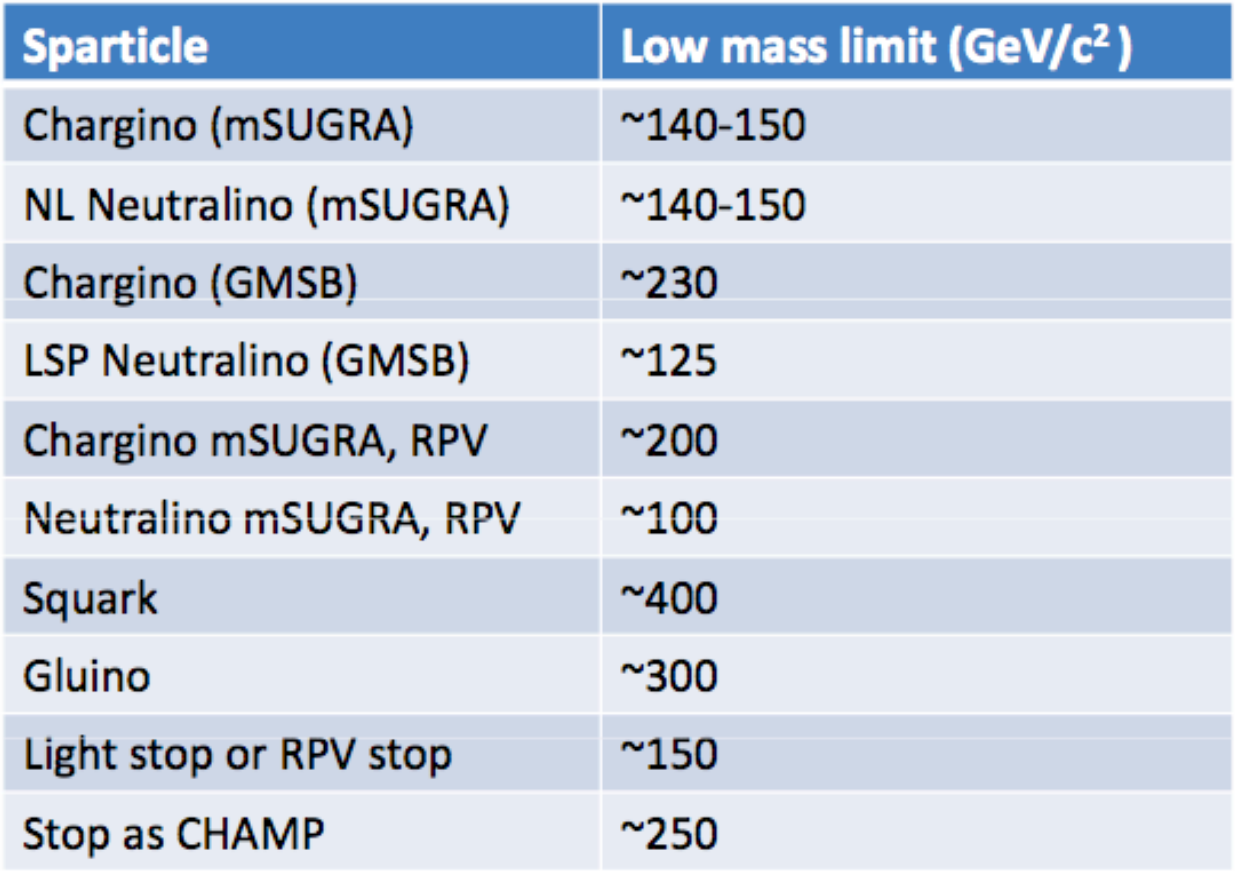




- 6 operating points



SUSY current status



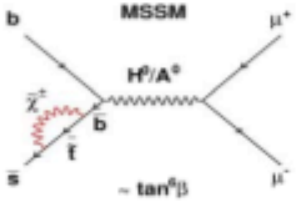
Sparticle	Low mass limit (GeV/c^2)
Chargino (mSUGRA)	~140-150
NL Neutralino (mSUGRA)	~140-150
Chargino (GMSB)	~230
LSP Neutralino (GMSB)	~125
Chargino mSUGRA, RPV	~200
Neutralino mSUGRA, RPV	~100
Squark	~400
Gluino	~300
Light stop or RPV stop	~150
Stop as CHAMP	~250

http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm

http://www-cdf.fnal.gov/physics/exotic/exotic.html

$B_s \rightarrow \mu\mu$

Sensitive to new physics: if no observation, it can strongly constraint SUSY models



SM prediction:
BR = 3.42 ×10^{-9}

SUSY enhancement
~$(\tan\beta)^6$

- Data sample dominated by random combinatorial background
- Extract signal with Neural Net based discrimina

B_s and B_d considered separately:

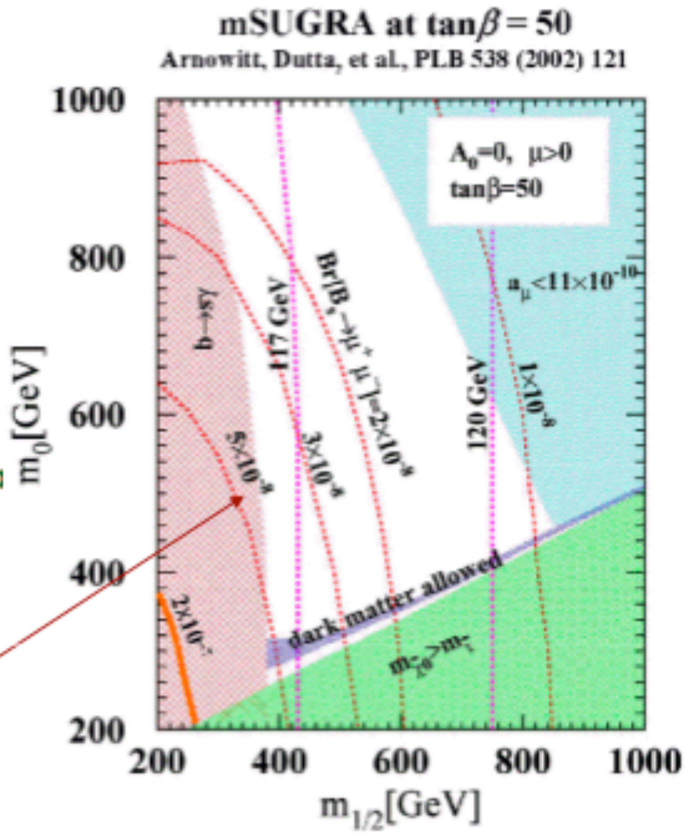
$B_s \rightarrow \mu\mu$ 3 observed events (3.6+/-0.3 exp.bkg.)

$B_d \rightarrow \mu\mu$ 6 observed events (4.3+/-0.3 exp.bkg.)

No significant excess → exclusion limit

$Br(B_s \rightarrow \mu\mu) < 5.8 \times 10^{-8}$ @ 95% CL
$Br(B_d \rightarrow \mu\mu) < 1.8 \times 10^{-8}$ @ 95%CL

Comb CDF/D0


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

BR($B_s \rightarrow \mu\mu$) <
1.5x10^{-7} @95% CL

hep-ex/0508058