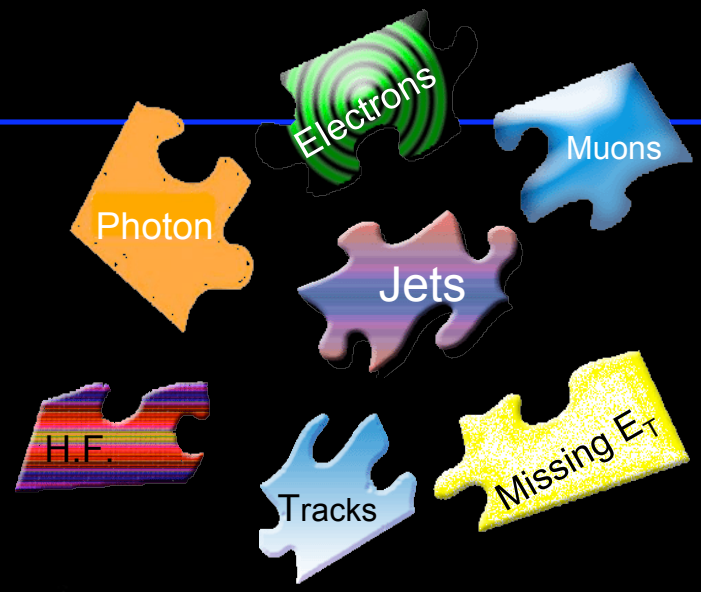
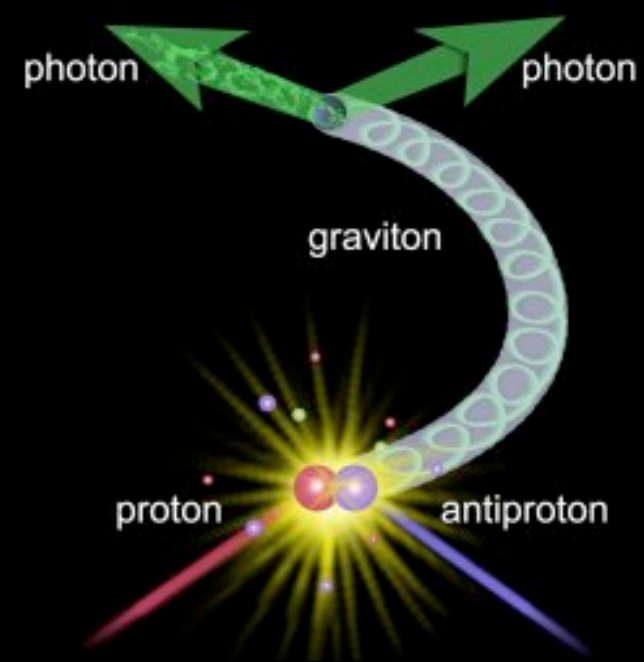
Search for New Physics at the Tevatron

Simona Rolli
Tufts University
(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

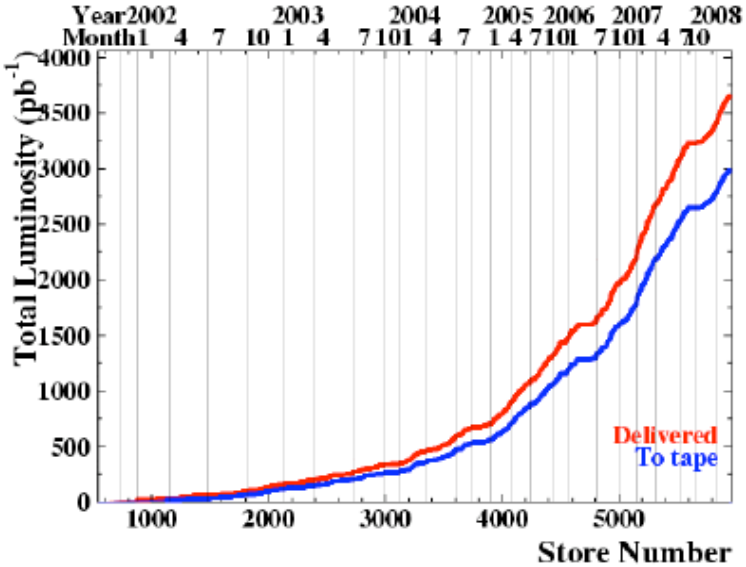




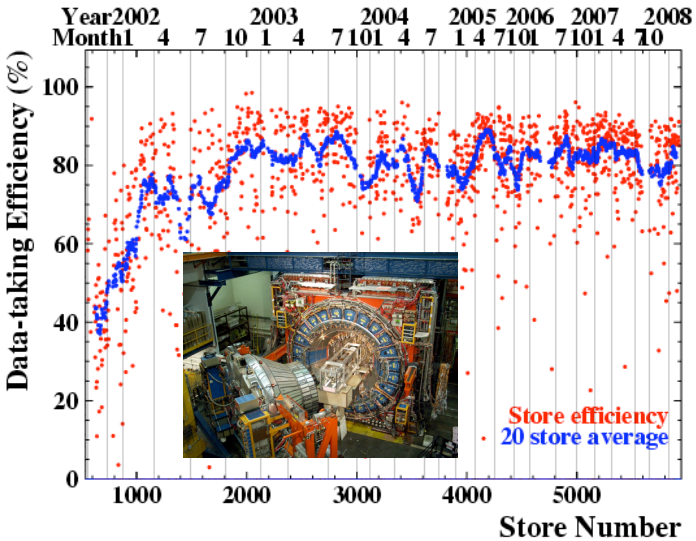
TeVatron Status

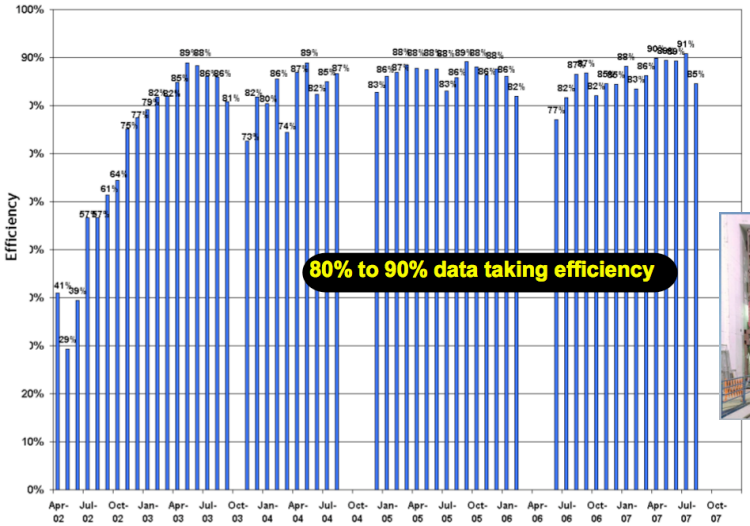
The TeVatron is doing very well!

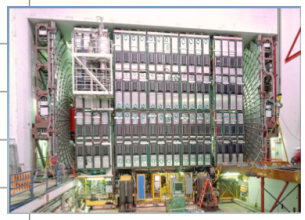
Luminosity Profile



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

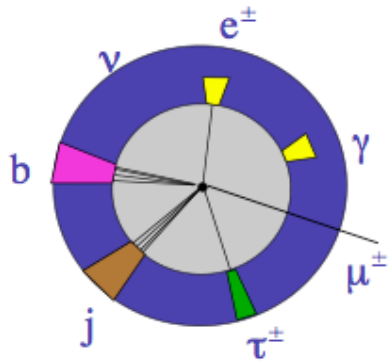






Signatures and Physics Objects

- Physics Objects
  - Tracks
  - Jets
  - Electron
  - Photons
  - Neutrinos
  - Muons

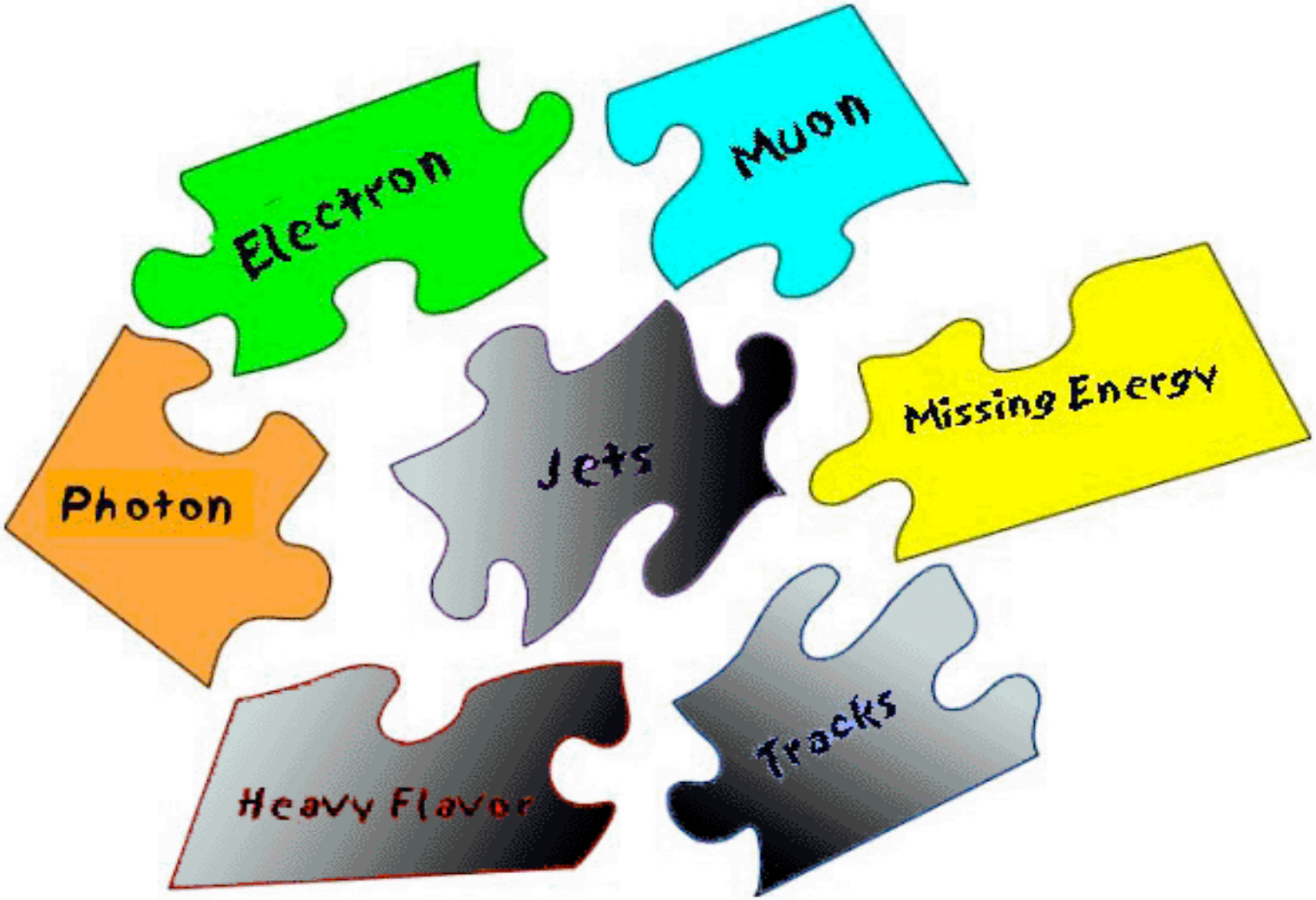


- Detector Components
  - Tracking system
    - Large drift chambers
    - Precise Silicon detectors
  - Calorimeters
  - Muon Chambers

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 $S/\sqrt{B}$

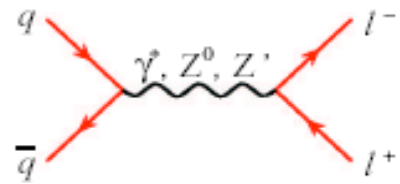
Leptons,Photons and MET

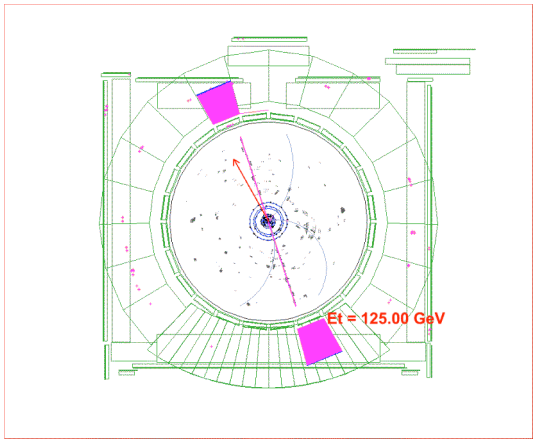


Searches in dilepton final states

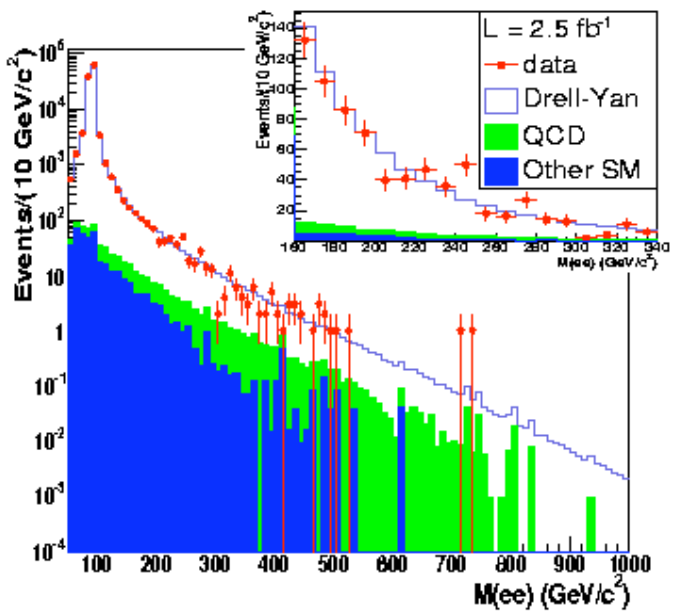
Old fashion mass bump hunt..

Z production and decay into ee/μμ is precisely measured at the TeVatron (standard candles)
Lepton ID/Reco and Trigger efficiencies are high and very well understood
Background is low and easily determined (QCD fakes)
Clean events





CDF Run II Preliminary



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

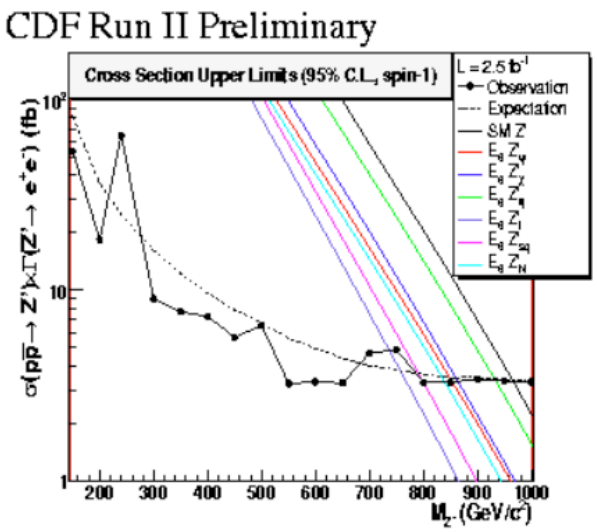
The largest discrepancy shown by an unbinned maximum likelihood ratio is 3.8σ in the range 228 – 250 GeV

- 0.6% probability of seeing this size discrepancy in the range 150-1000 GeV

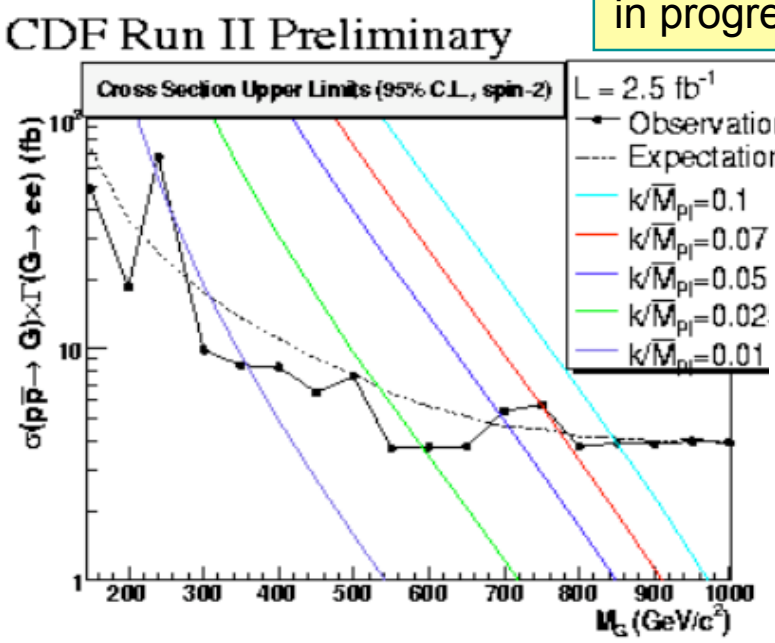
Testing different models

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.

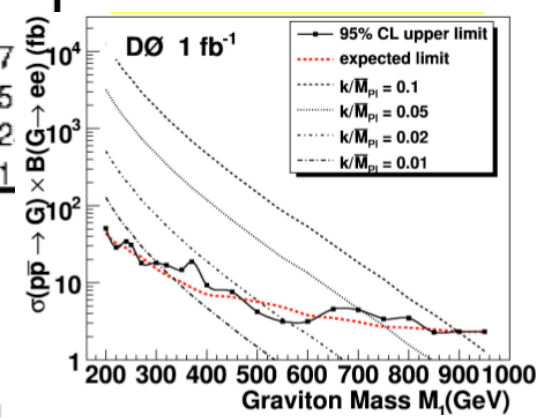
μμ channel analyzed with the same strategy. Update to $2fb^{-1}$ in progress



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



Exclude (at 95% CL) RS Gravitons below 850 GeV for $k/\overline{M}_{pl} = 0.1$



Exclude below 900 GeV for $k/M_{pl} = 0.1$

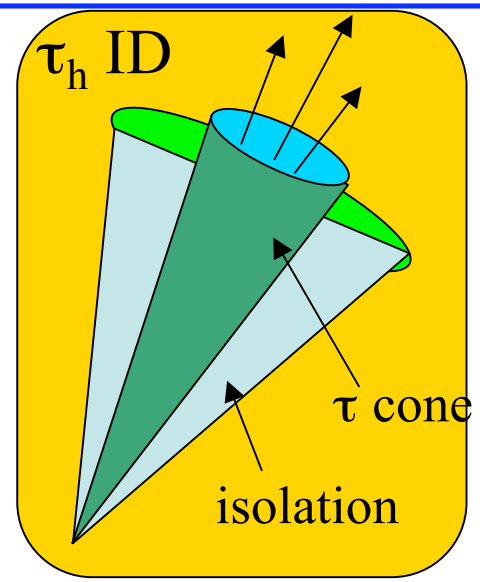
Tau final states

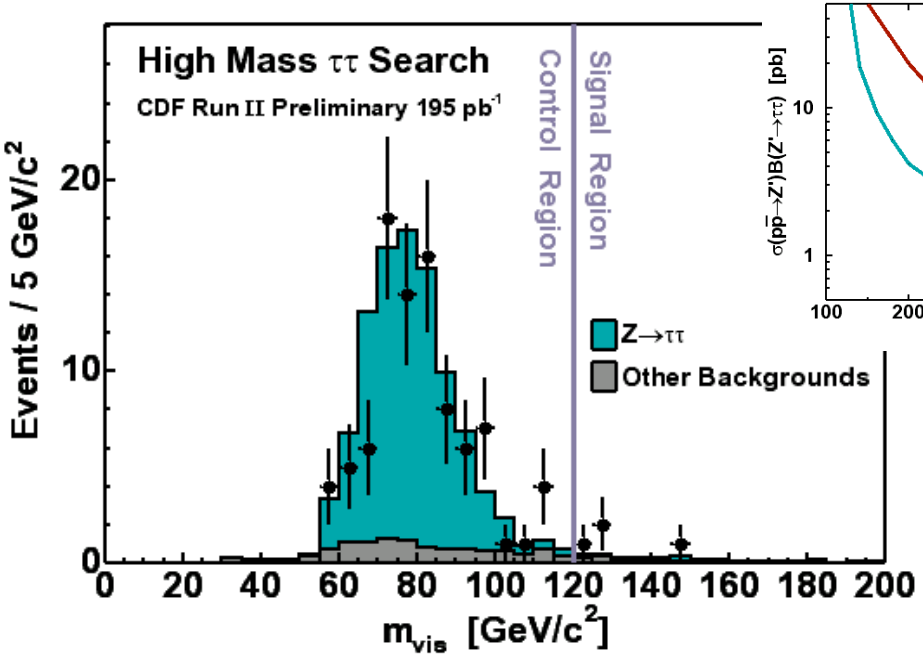
Ditaus final states are selected where

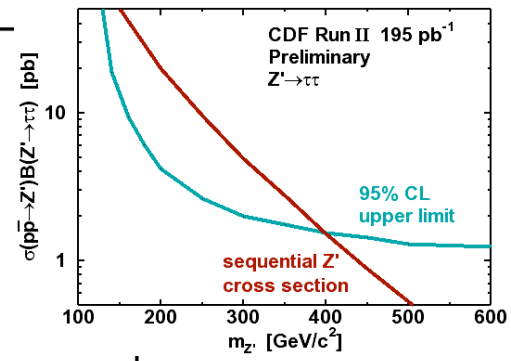
- One tau decays leptonically: e/μ (CDF) μ (DØ) (plus ν's)
- p_T > 10 GeV/c (CDF), p_T > 15 GeV/c (DØ)

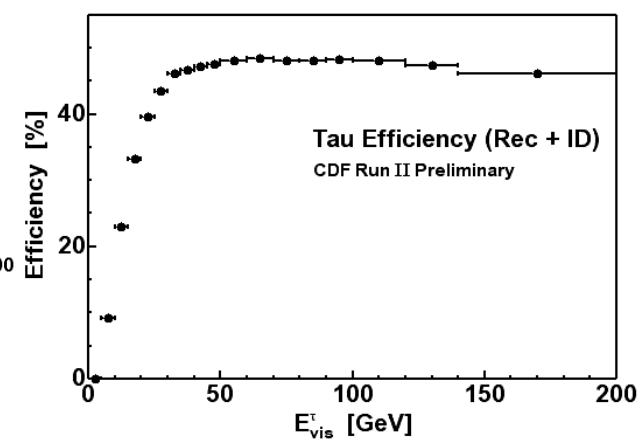
-Other tau hadronic (and ν_τ)

- -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)



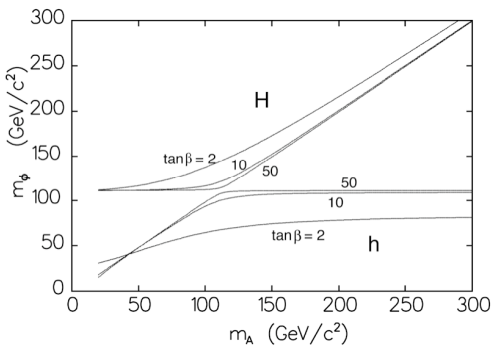




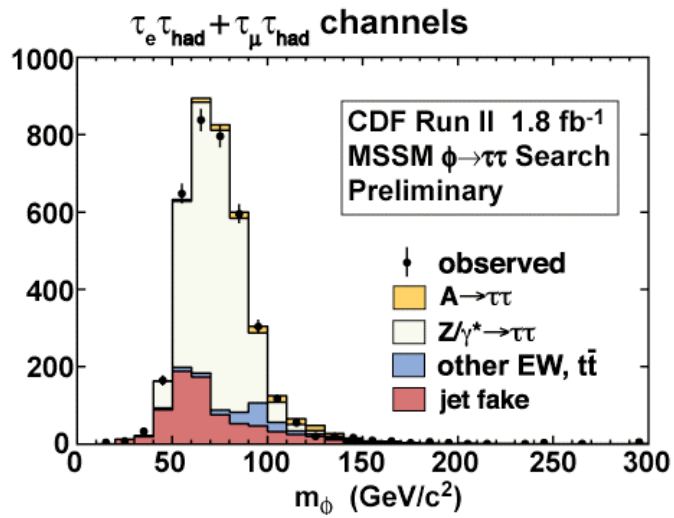


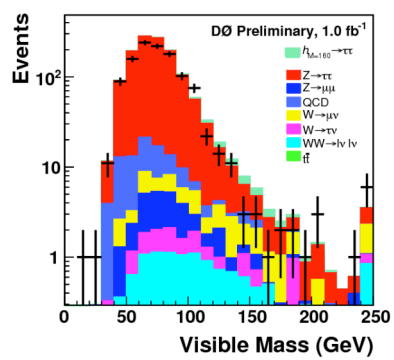
MSSM Higgs $\phi \rightarrow \tau\tau$

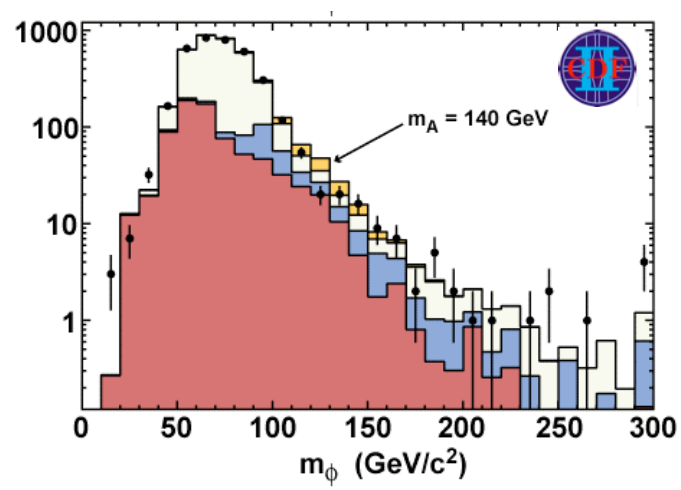
- In the MSSM framework the Higgs neutral sector simplifies at high tanβ
- A and h/H become degenerate



- 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





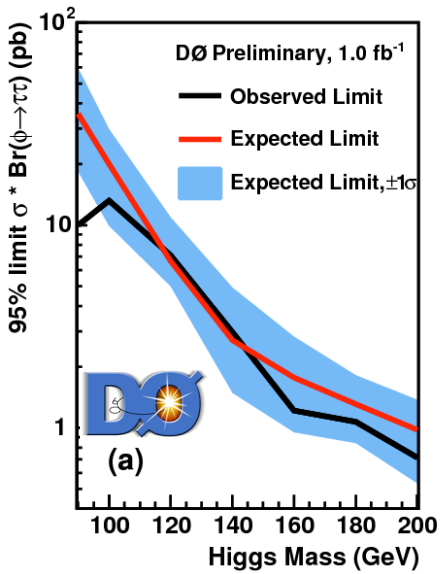


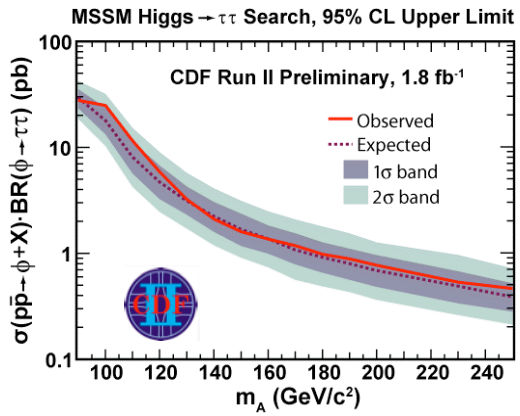
- No excess in e/μ + τ_{had} channel (slight excess for CDF in 2007)

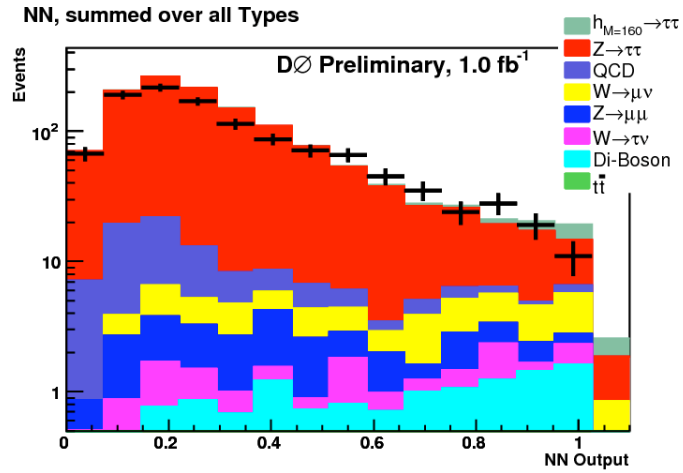
$\phi \rightarrow \tau\tau$ Results

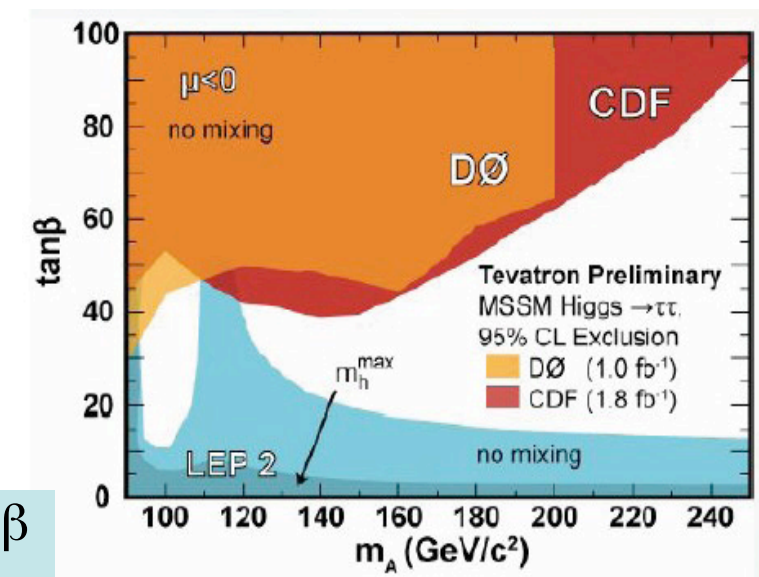
At D0 the results are similar

- One input to search NN, along with lepton, tau kinematics
- Do not see any excess



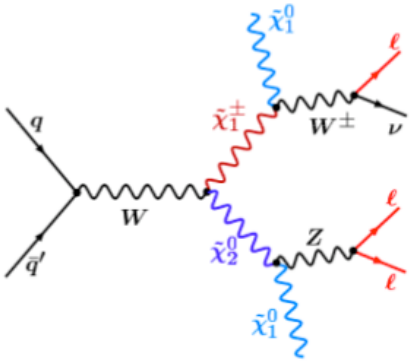




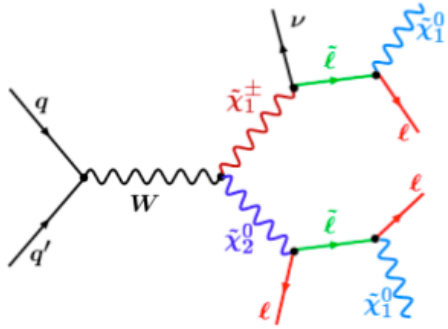


Interpret σ x BR limits as limits on $\tan\beta$ vs m_A in MSSM benchmark scenarios

Multileptons final states: SUSY in Trileptons

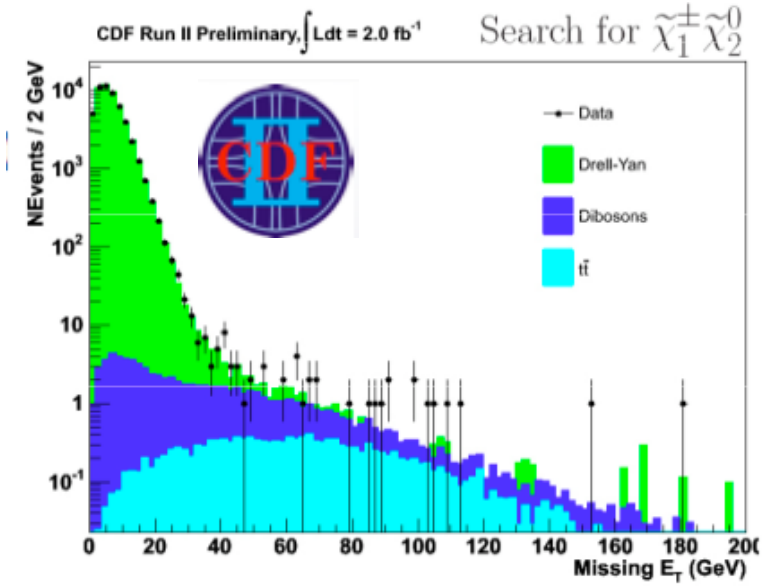


Decays through W/Z favorable for heavy sleptons, but BR to leptons low

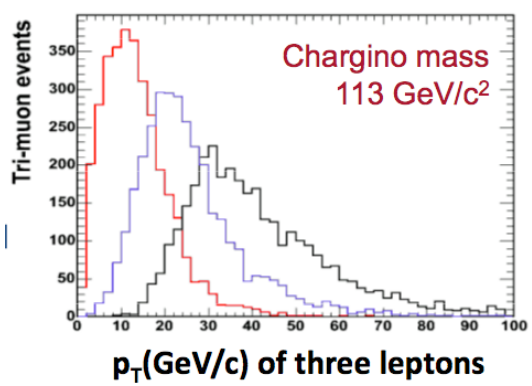


Decays through sleptons guarantee final leptons, but also preference to $\tilde{\tau} \rightarrow \tau$

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



CDF includes isolated tracks to reconstruct some of the hadronic taus
The P_T of the leptons can be really low (CDF considers leptons up to 5 GeV/c)



- Selection (signal region):
  - p_T (15,10/5,5) GeV/c
  - MET>20 GeV (DY and QCD rejection)
  - $N_{jets} \leq 1$ 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

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

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

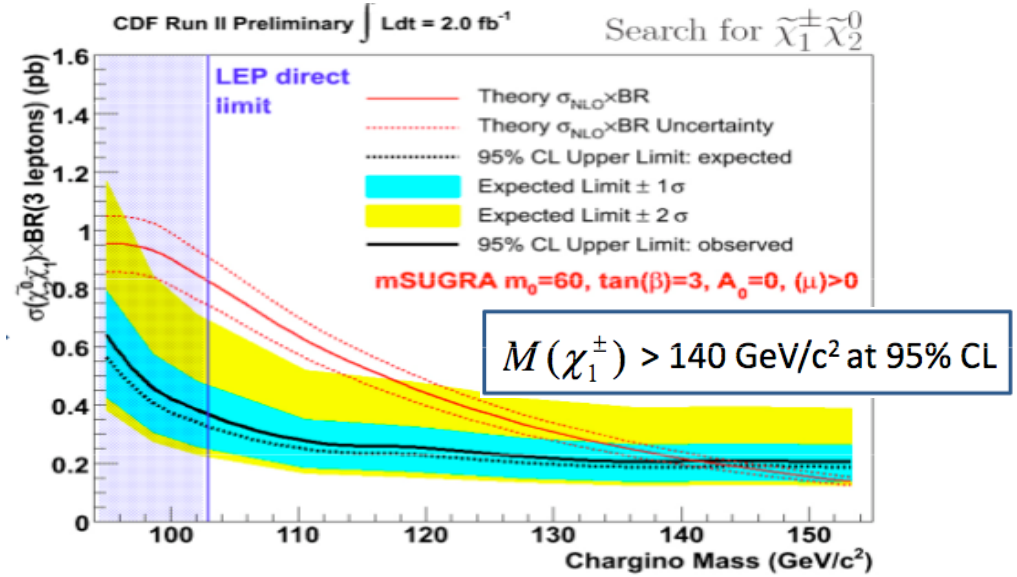
Similar cuts at D0

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 fb^{-1}

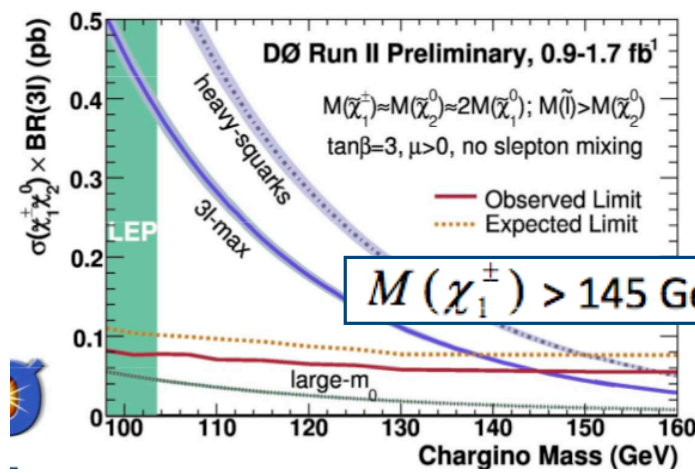
Analysis	Backg.	Signal	DATA
Trilepton	0.9 ± 0.1	4.5 ± 0.6	1
Dilepton+Track	6.9 ± 0.9	5.5 ± 1.1	6



$M(\chi_1^{\pm})$ > 140 GeV/c^2 at 95% CL

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
$\mu^{\pm}\mu^{\pm}$	0.9	1.1 ± 0.4	0.6 – 3.7	1



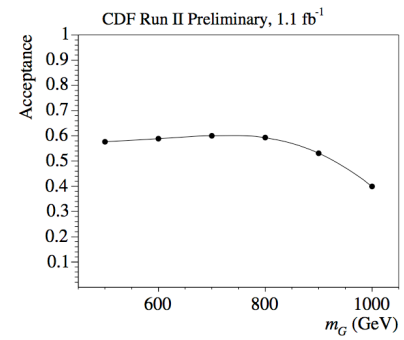
$M(\chi_1^{\pm})$ > 145 GeV/c^2 at 95% CL

MSugra inspired model with no-slepton mixing

Multilepton final states: LED in ZZ

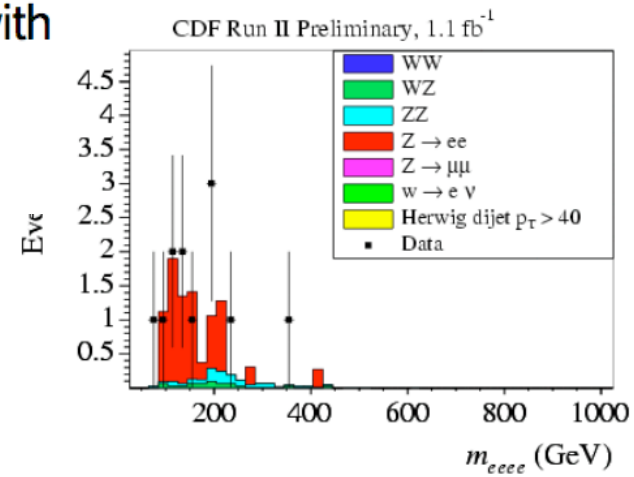
eeee final state

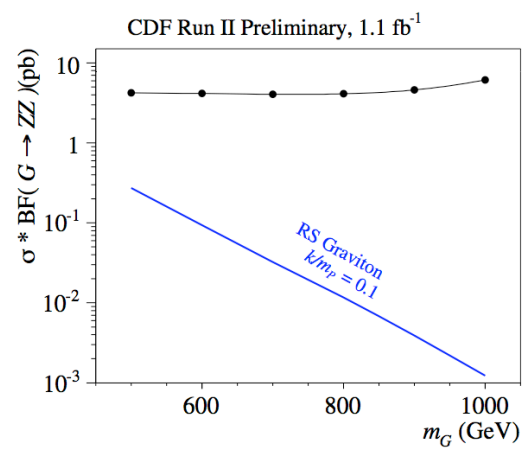
To maximize lepton identification efficiency isolated track electron candidates are considered and some of the most stringent ID requirements for high P_T electrons are released.
High signal efficiency is obtained for RS Graviton model (40-60%)



Estimate background from data

- Use low-mass *eeee* events and events with hadronic fakes, extrapolate to signal region



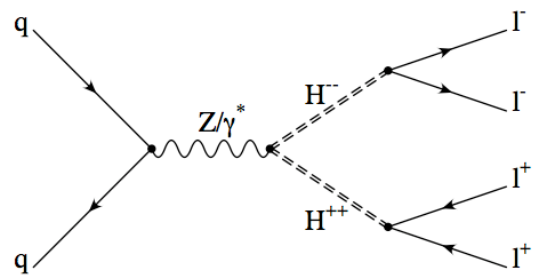


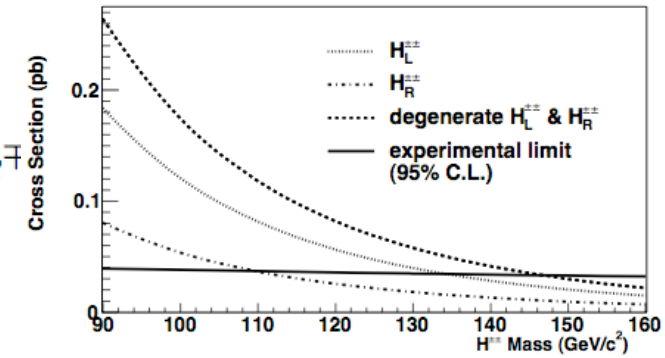
Limit still above theory

Multi leptons final states: Doubly Charged Higgs

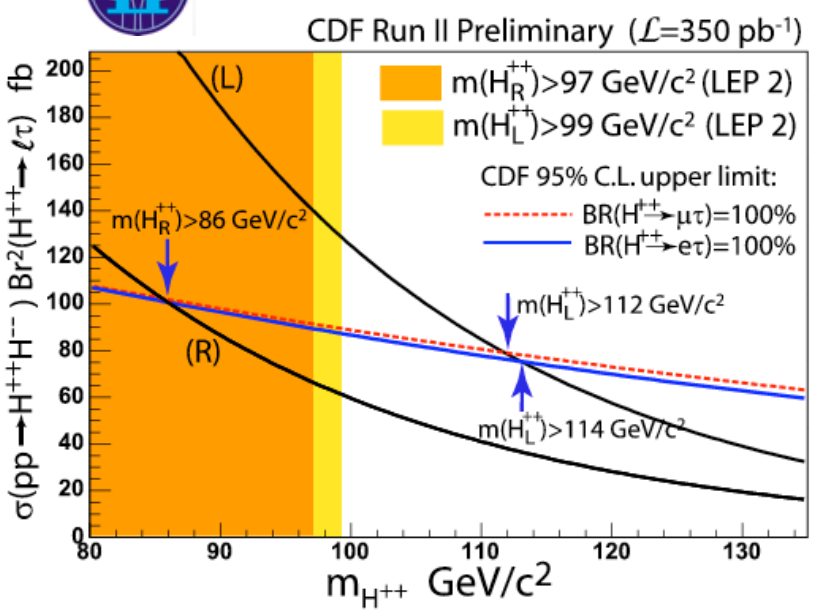
4 leptons final state

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

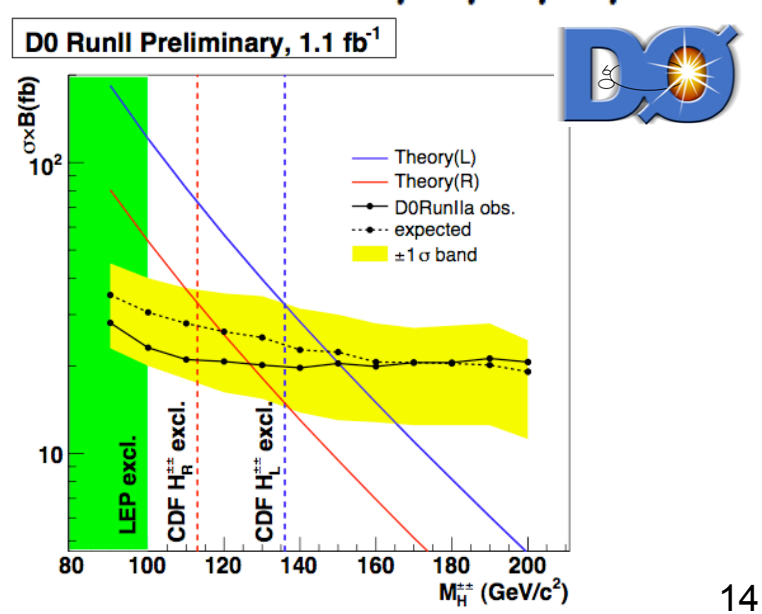




- $H^{++}H^{--} \to l^+\tau^+l^-\tau^-$



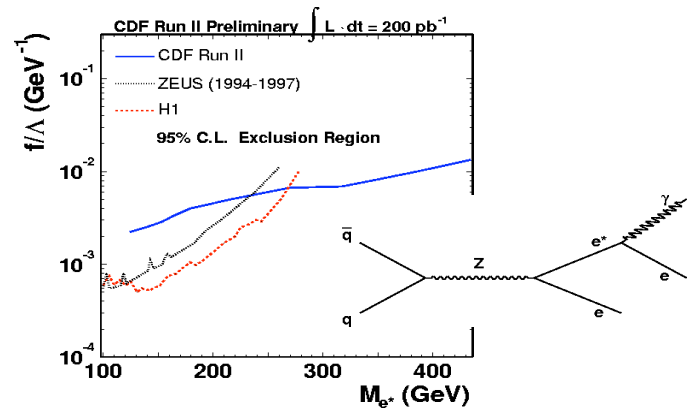
- $H^{++}H^{--} \to \mu^+\mu^+\mu^-\mu^-$



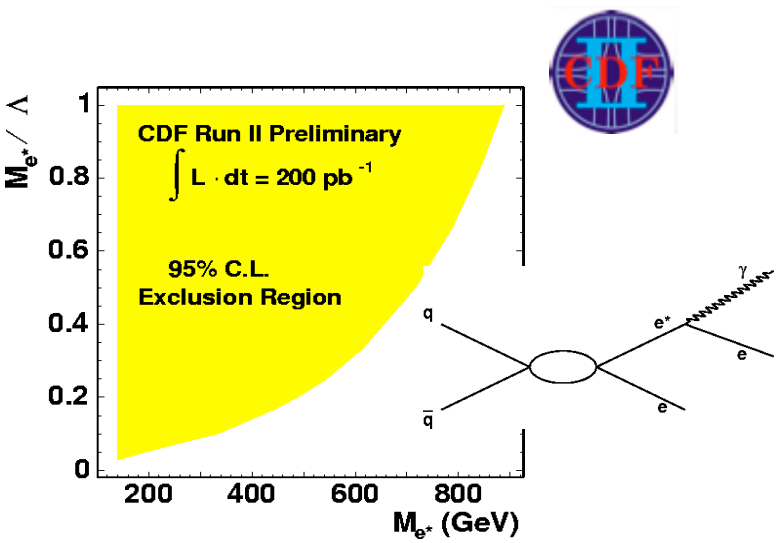
Lepton+γ final states: Excited leptons

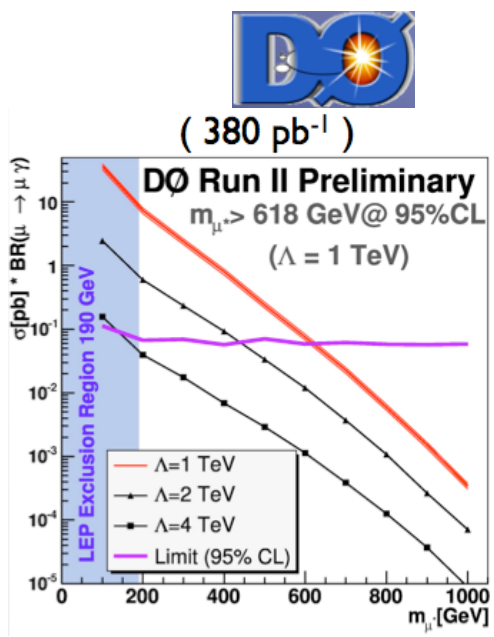
Observation of excited states of quarks and leptons might confirm the hypothesis that they are not elementary particles , but composite states

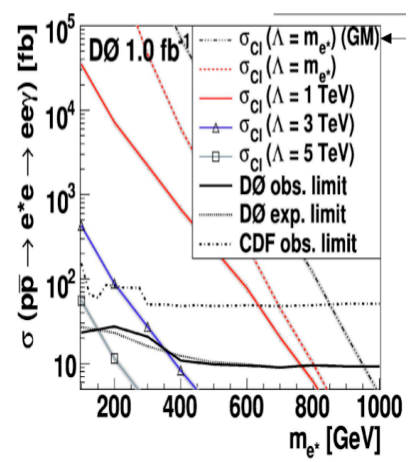
Select events with eeγ (μμγ) in the final state and look for resonance in M(eγ) or M(μγ)



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



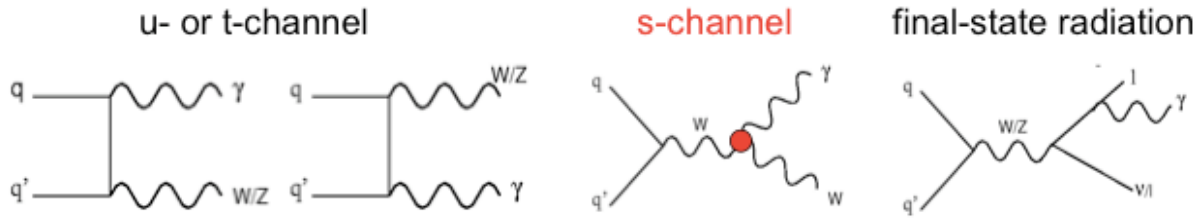


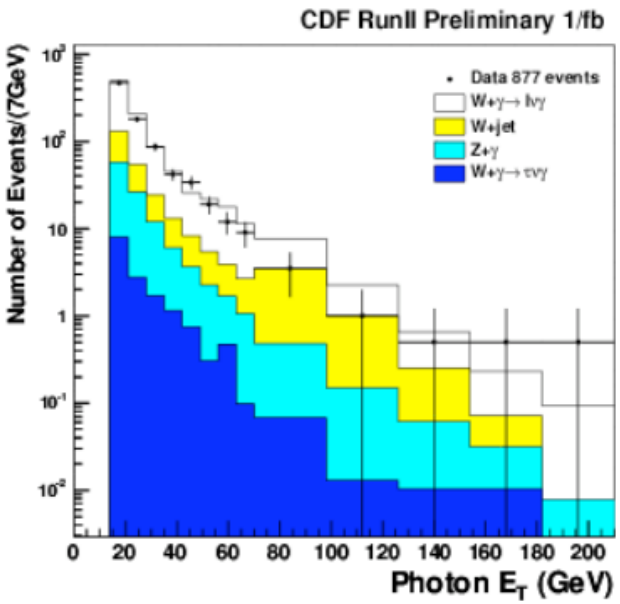


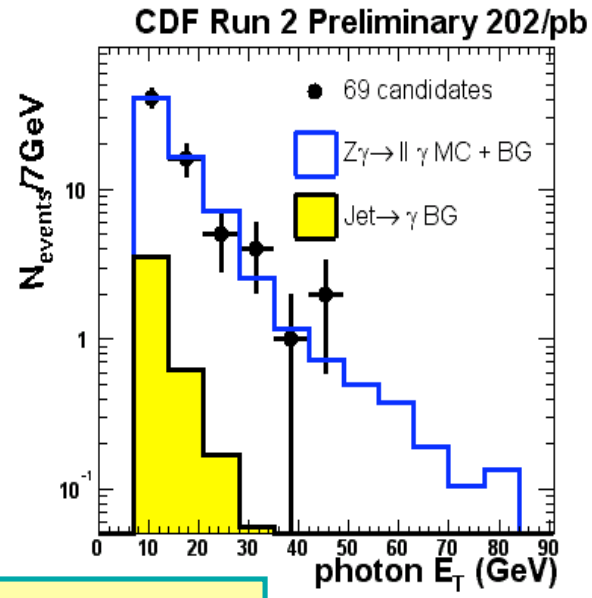
No CI Interactions

Lepton+γ+MET final states: Wγ and Zγ

Test of gauge couplings (as predicted by the SM) and a window on new physics

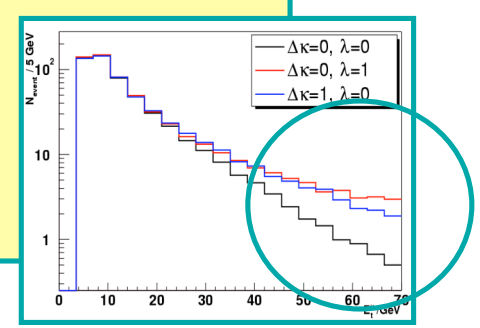




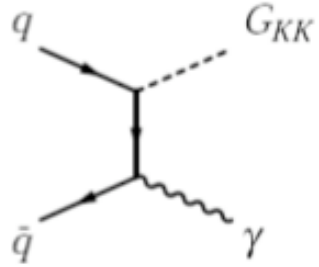


Now V+γ cross-sections well established, we are:

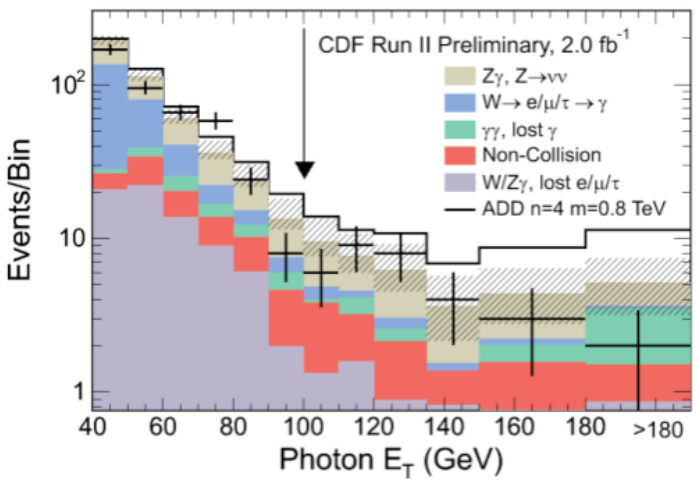
- optimizing sensitivity to anomalous coupling and new physics
- testing the Standard Model in ways unique to the TeVatron (e.g. observing RAZ in W γ production)



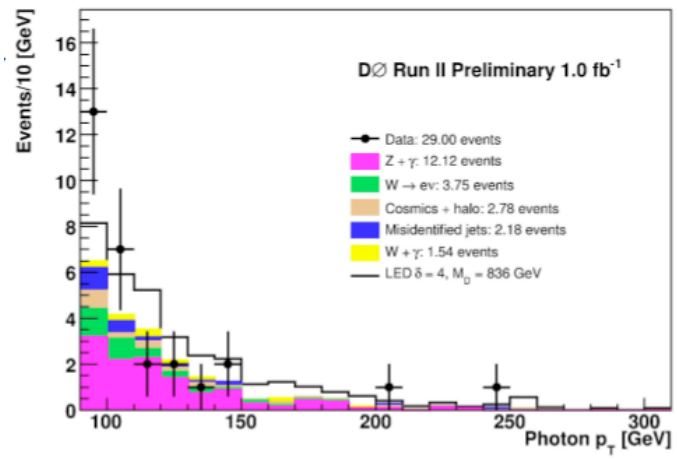
γ+MET final states: LED



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

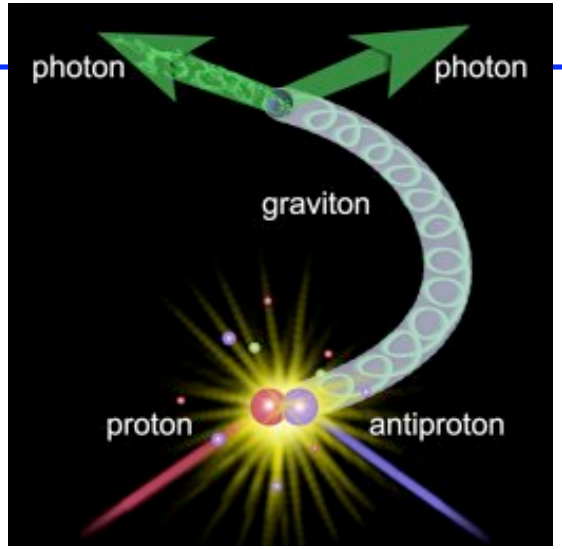


CDF RunII Preliminary, 2.0 fb^{-1}			
N LED	α (%)	σ^{95}_{obs} fb	M_D^{obs} GeV
2	7.2	84.7	1080
3	7.2	84.7	1000
4	7.6	80.4	970
5	7.3	82.7	930
6	7.2	84.4	900



Number of extra dimensions	*95% CL Limit on Fundamental Mass Scale (M_D) (GeV)*
2	884
3	864
4	836
5	820
6	797
7	797
8	778

Diphotons:LED

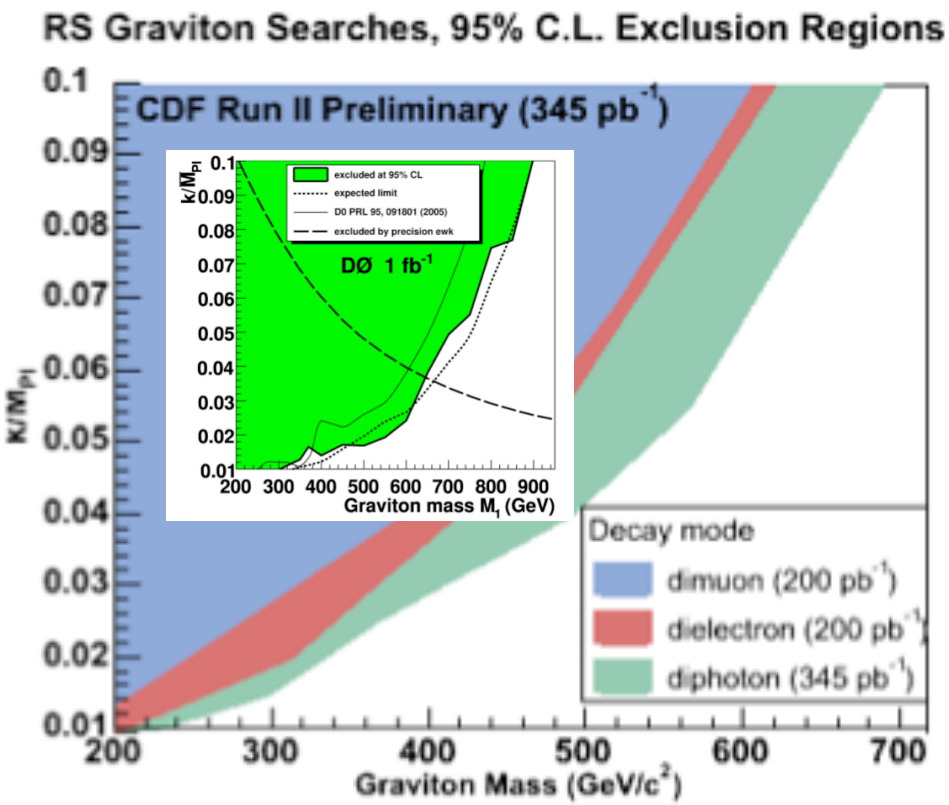


- The search for new particles decaying to diphotons uses the RS graviton model to express sensitivity to Kaluza-Klein graviton resonances
- Randall-Sundrum graviton model

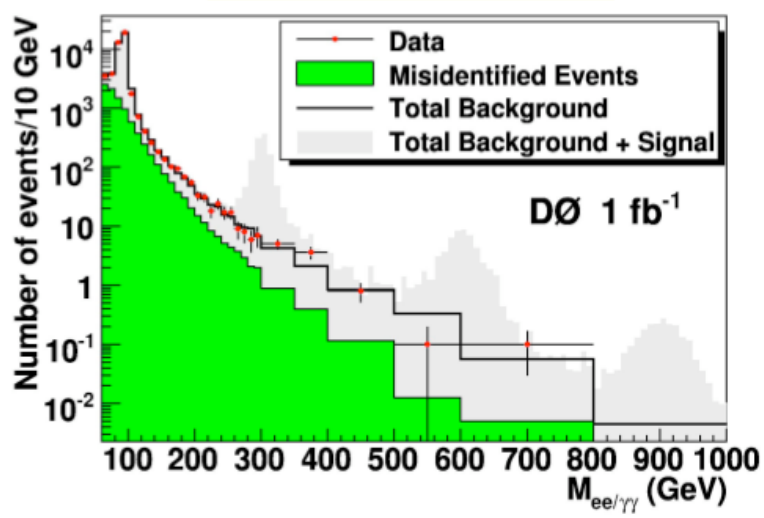
  4-dimensional metric multiplied by *warp* factor

The coupling of individual KK states to matter is set by the weak scale (parameters : M_G and $k/M_{P\ lanck}$)

KK states can be observed as spin 2 resonances



PRL **100**, 091802 (2008)

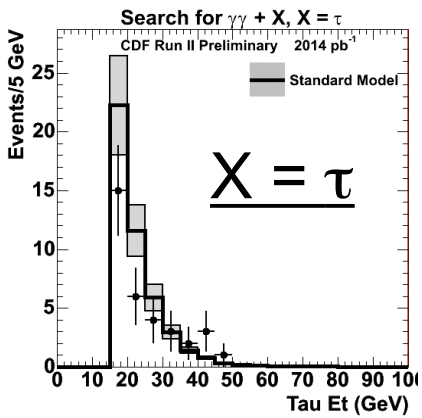


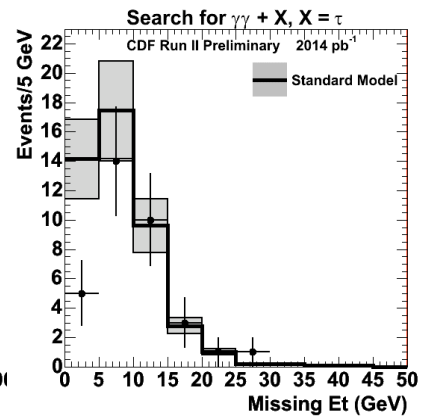
Combined with dilepton searches

Diphoton+X

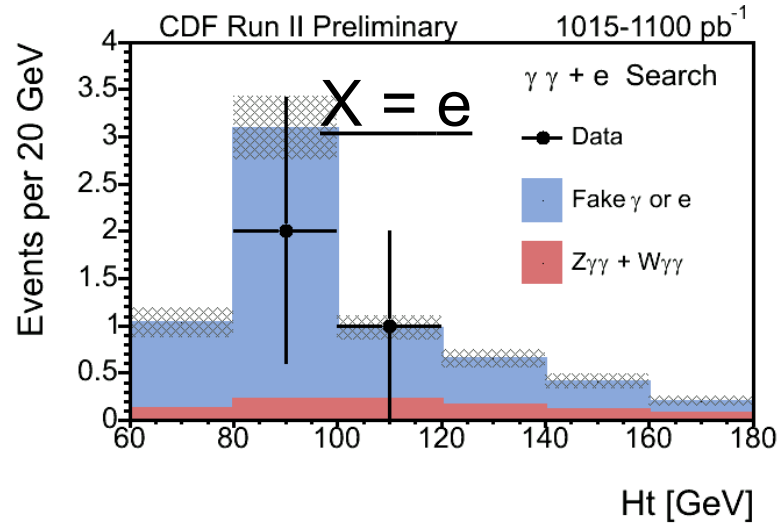
Search for $\gamma\gamma$ + X

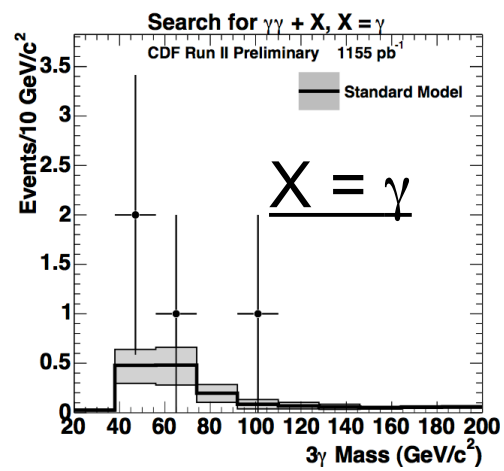
Nominal high E_T object identification and kinematic selections are used.
The observed event counts is reported as well as SM prediction for various kinematic distributions





Data driven bkg estimate
(fake τ)



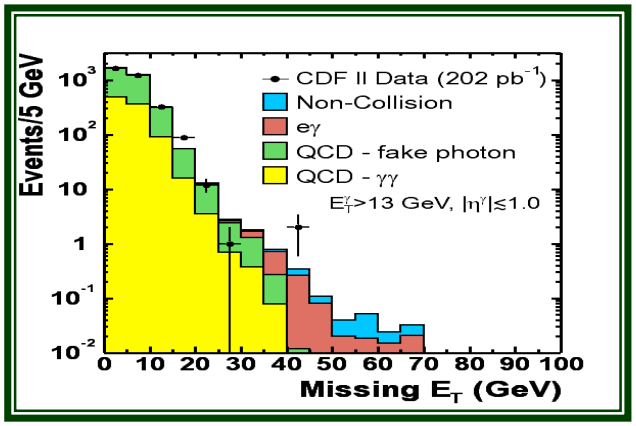


Good agreement between data and SM predictions
- Continue to add objects in γγ+X Search

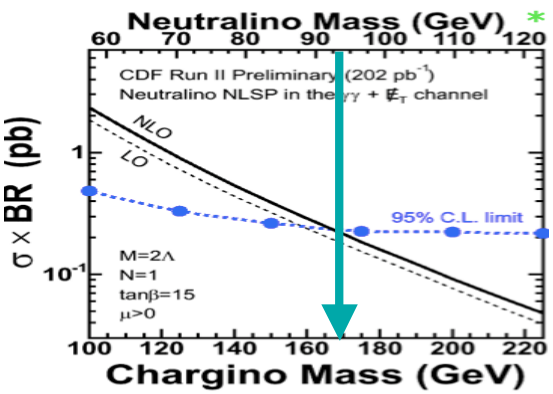
diphoton + MET: GMSB SUSY

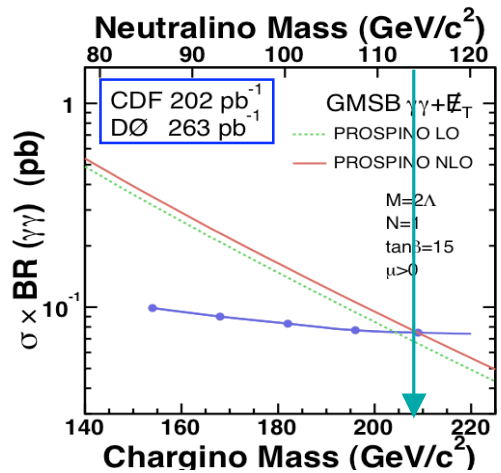
GMSB scenario
NLSP = $\chi^0_1 \to \gamma \tilde{G}$

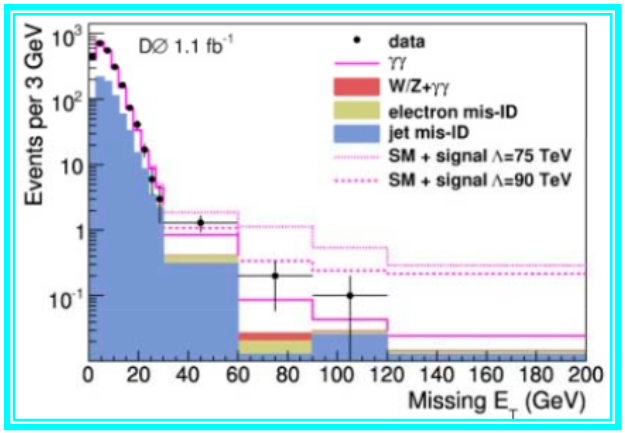
$p\bar{p} \to (X \to) \chi^0_1 \chi^0_1$ → $2\gamma + \not{E}_T$

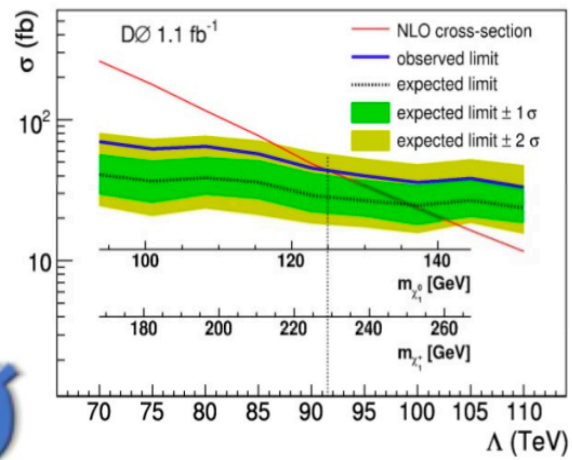


For Missing Energy > 45 GeV
Expected: 0.60 ± 0.50
Observed : 0

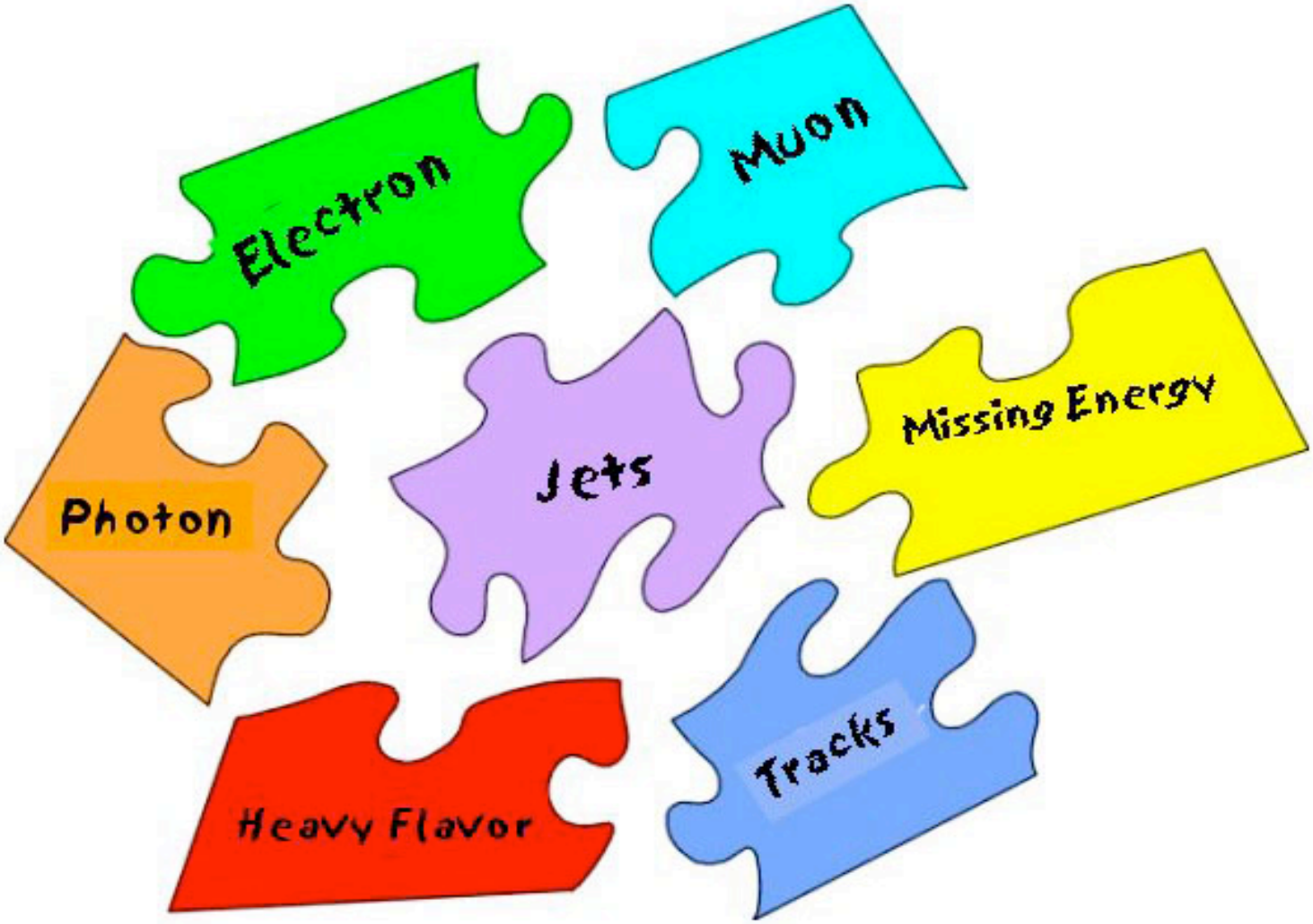








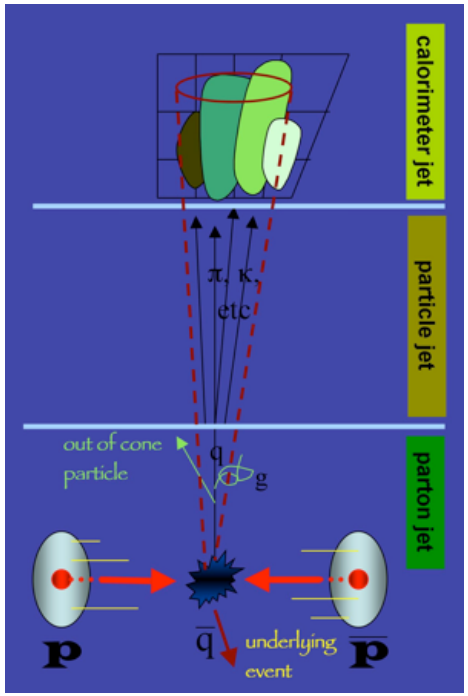
Adding jets and flavor tagging



Jets and Heavy Flavor

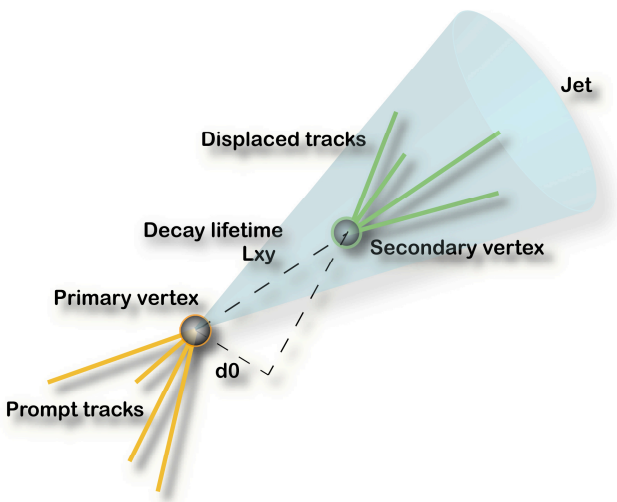
Hadronic jets are reconstructed using several algorithms: Cone,Midpoint, KT etc..

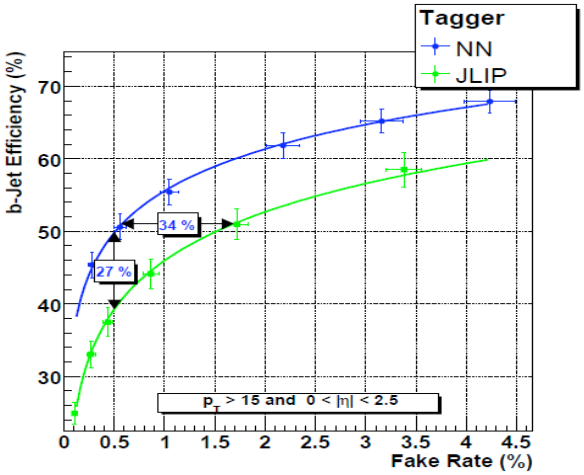
Measured jet energies are corrected to scale them back to the final state particle level jet . Additionally there are corrections to associate the measured jet energy to the parent parton energy, so that direct comparison to the theory can be made. Currently the jet energy scale is the major source of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

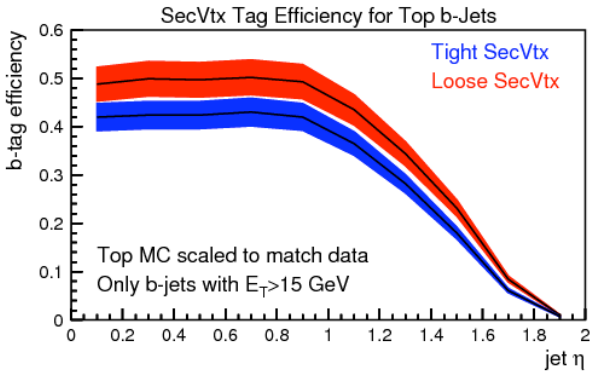


B-jet identification is implemented via:

- -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



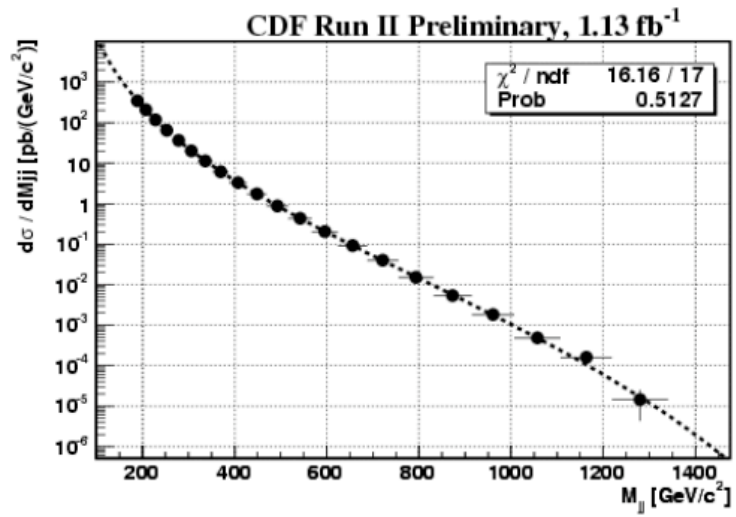




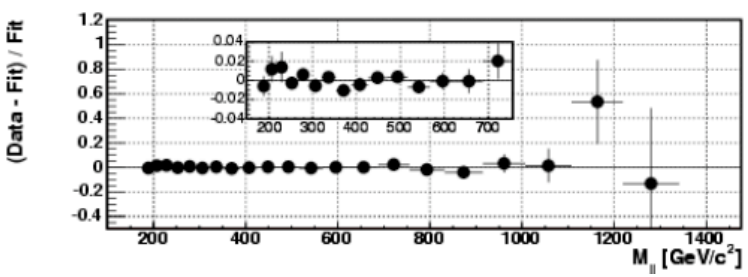
Dijets final state: mass bumps

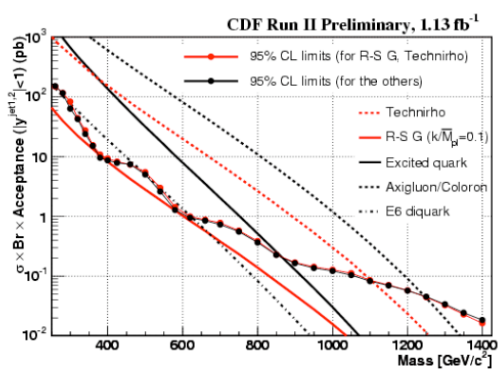
Another mass bump hunt…

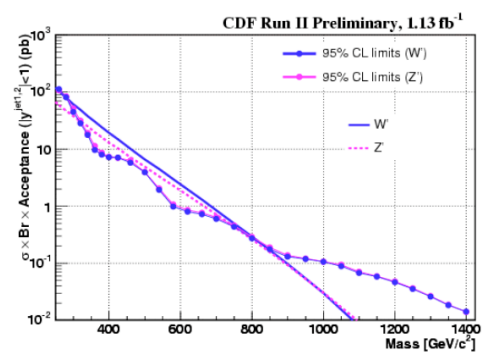
- Choose events with two high-p_T jets with rapidity less than 1.0. Look for an excess in the dijet mass spectrum for masses above 180 GeV
- Possible signals include excited quarks, W', Z', and Randall-Sundrum gravitons
- Find functional form of of dijet spectrum in pythia and herwig, fit to data. Look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

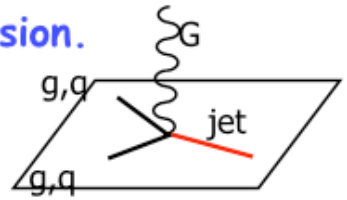


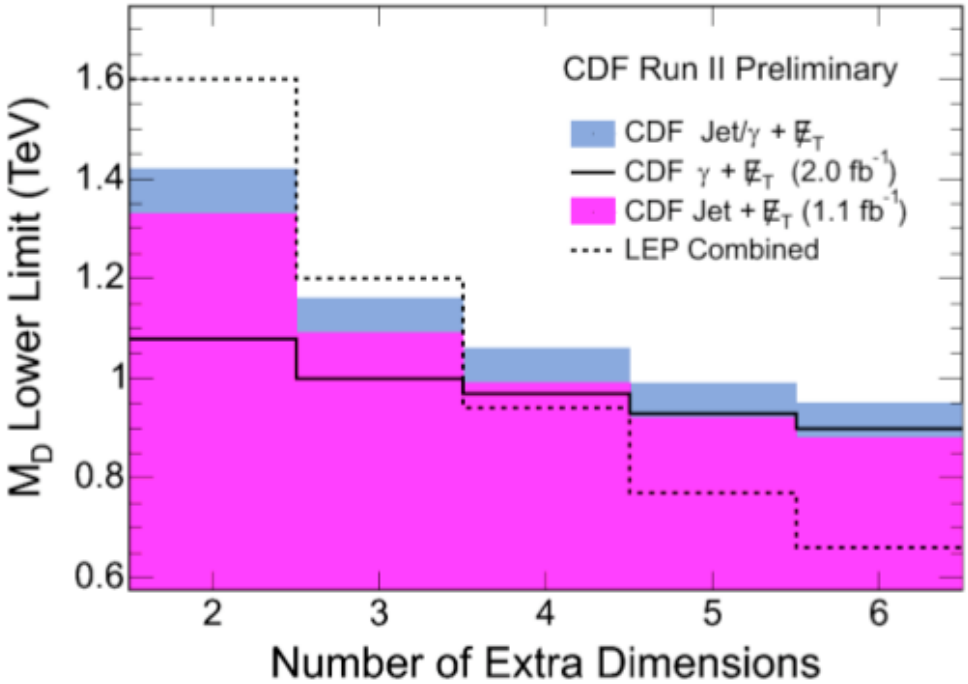


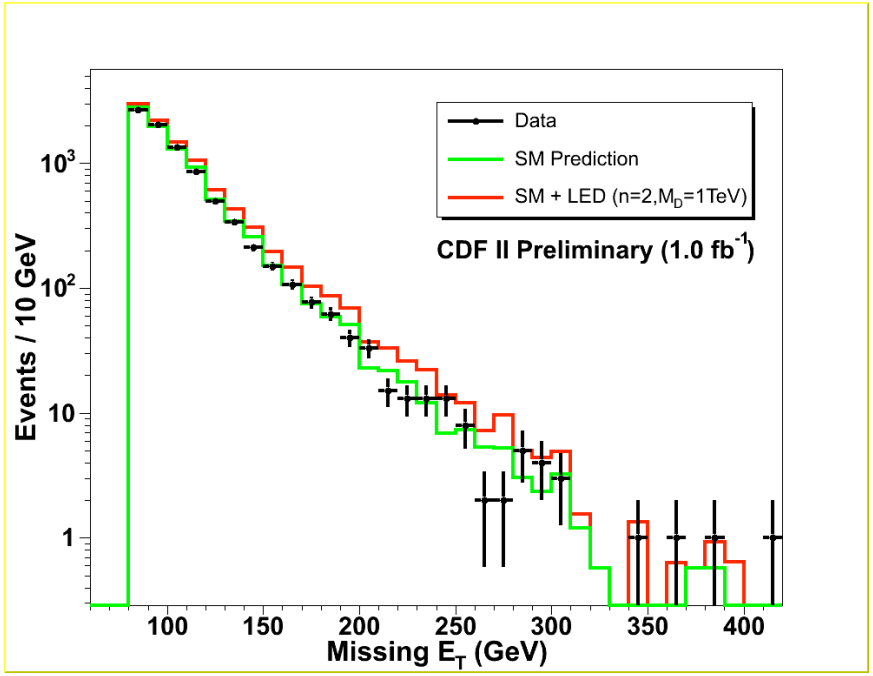


Single jet + MET: LED

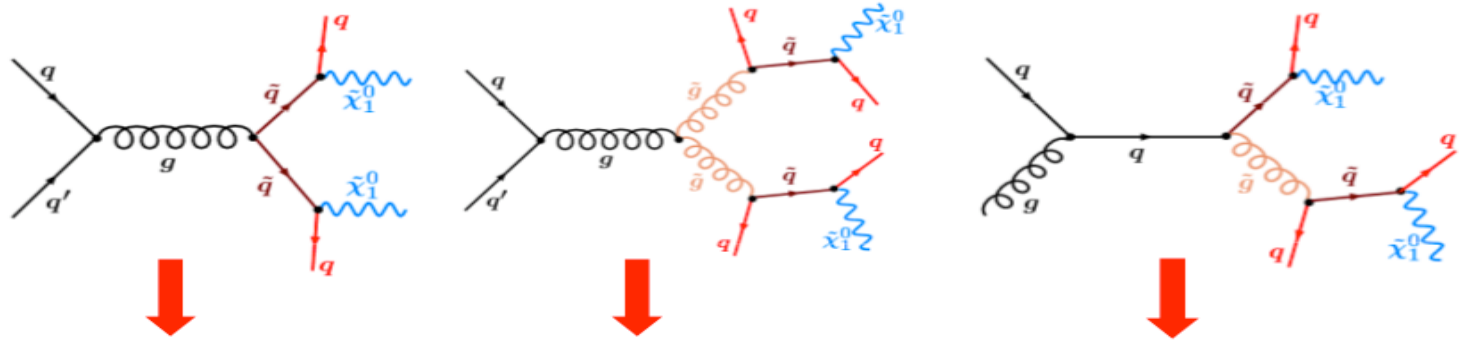
Mono-jet channel where a jet recoils against the graviton which leaves the usual 3D dimension.







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)

Lepton veto
$\Delta\phi$ jet-MET
QCD bckg from low MET data

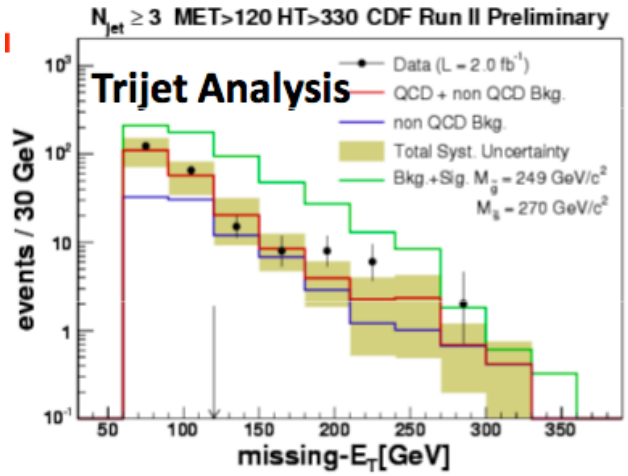
(hep-ex/0712.3805, *PLB 660, 449 (2008)*)

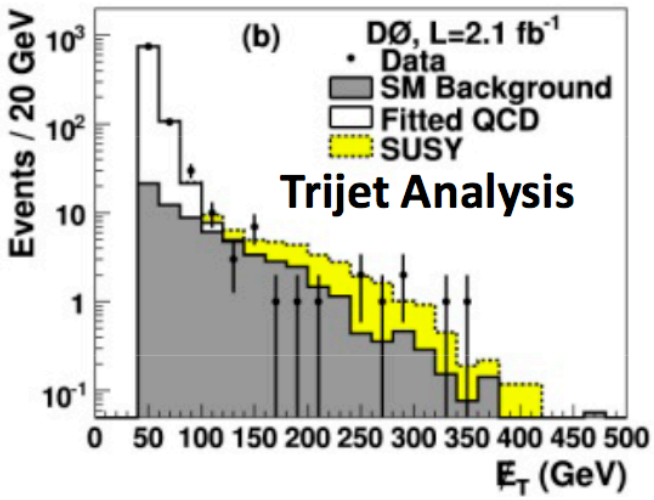
Analysis	HT cut (GeV)	MET cut (GeV)	Jet Et (GeV)	Bckg.	DATA
Dijet	325	225	35,35	11 ± 1 +3/-2	11
Trijet	375	175	35,35,35	11 ± 1 +3/-2	9
4-jet	400	100	35,35,35,20	18± 1 +6/-3	20

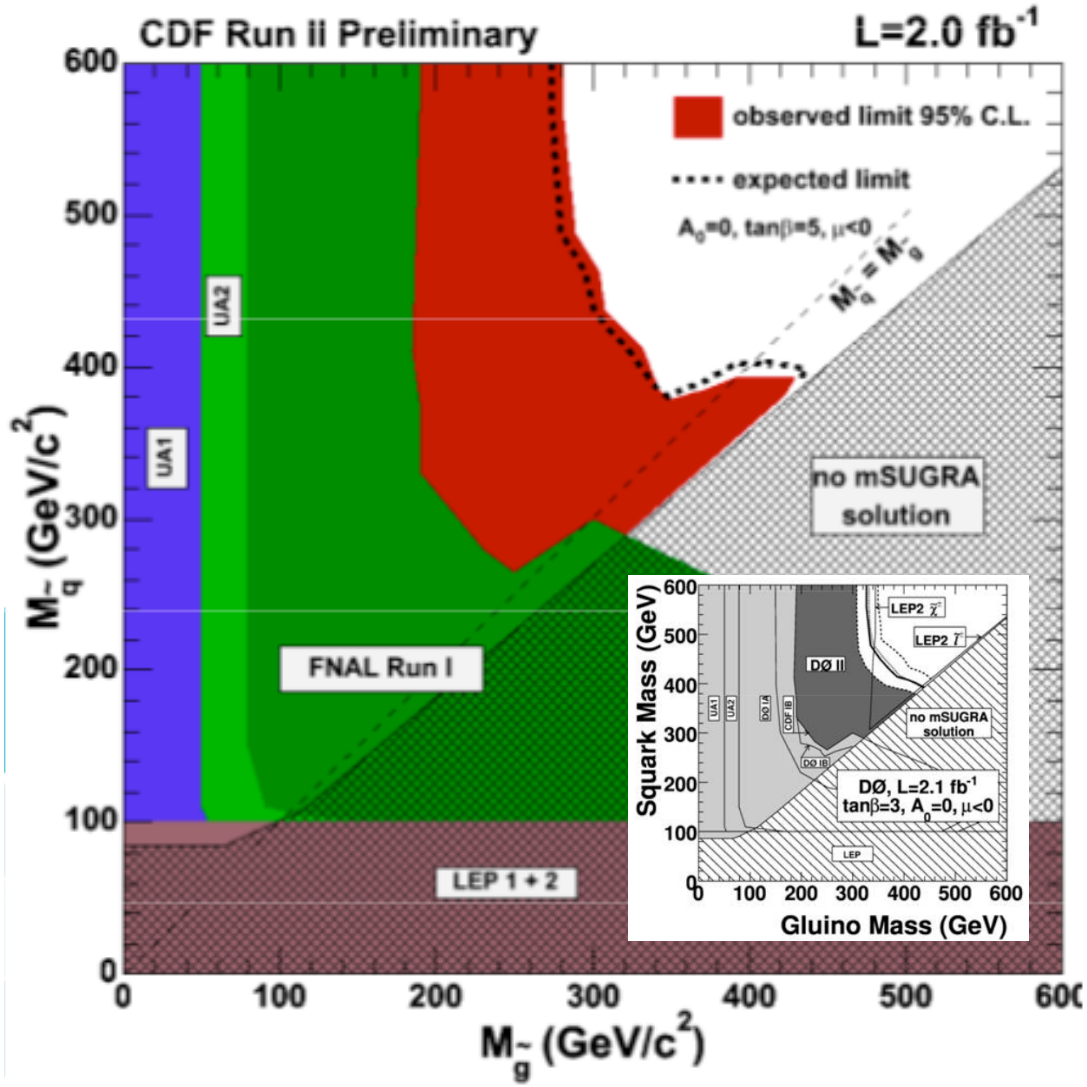
CDF Run II Preliminary, $\mathcal{L}$ = 2.0 fb^{-1}

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

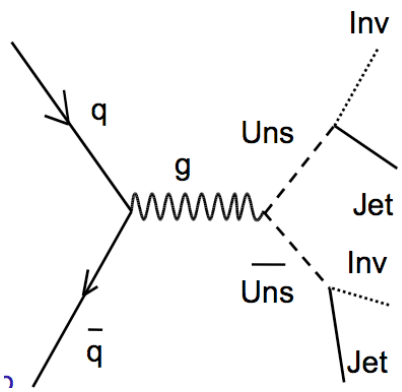
SUSY in MET + jets







Jets+MET final state

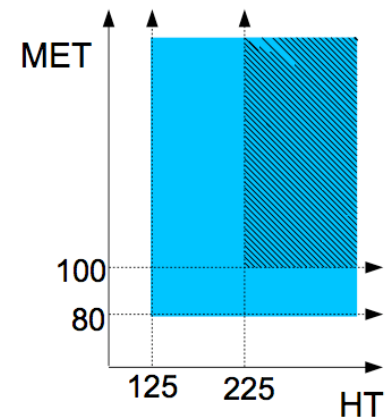


The analysis is a counting experiment examining two different kinematic regions (each region being more sensitive to different models).
Cuts are not optimized for a specific model.

Main backgrounds:

- $Z \rightarrow \nu\nu$ + jets (irreducible background)
- $W \rightarrow l\nu$ + jets (with charged lepton lost)
- Residual QCD and non-collision backgrounds.

Data driven extrapolation



- Leptoquark models
  - LQ pairs, each decaying to quark and neutrino.
- MSSM (non-mSUGRA, R-parity conserved)
  - Squark pairs, each decaying to quark and neutralino.

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

Background	125/80	225/100
$Z \rightarrow \nu\nu$	777 ± 49	71 ± 12
$W \rightarrow \tau\nu$	669 ± 42	50 ± 8
$W \rightarrow \mu\nu$	399 ± 25	33 ± 5
$W \rightarrow e\nu$	256 ± 16	14 ± 2
$Z \rightarrow ll$	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

MET+jets: LeptoQuarks

Leptoquarks (LQ) are hypothetical particles which appear in many SM extensions to explain **symmetry between leptons and quarks**

- SU(5) GUT model
- superstring-inspired models
- 'colour' SU(4) Pati-Salam model
- composite models
- Technicolor

- They couple to leptons and quarks of the same generation
  - Decay is governed by Br(LQ→ql)

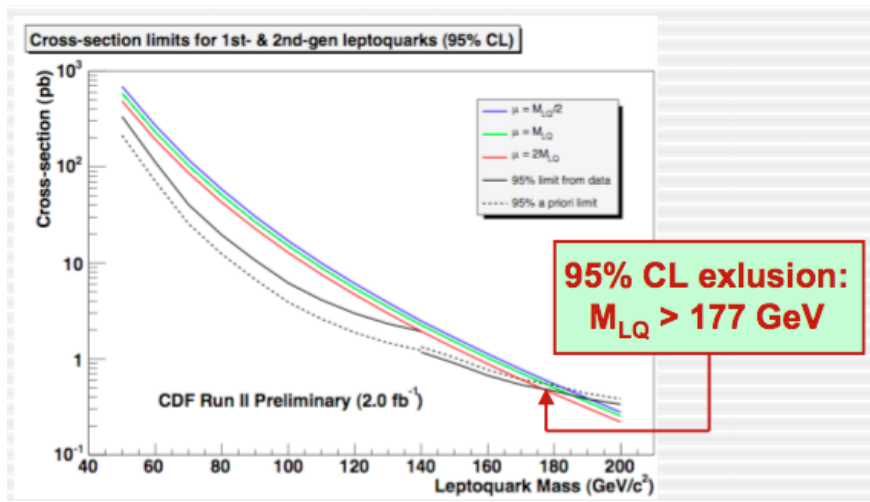
1st Generation	2nd Generation	3rd Generation
$LQ\,\overline{LQ} \to e^- e^+ q\bar{q}$	$LQ\,\overline{LQ} \to \mu^+ \mu^- q\bar{q}$	$LQ\,\overline{LQ} \to \tau^+ \tau^- q\bar{q}$
$LQ\,\overline{LQ} \to e^\pm \nu_e q_i q_j$	$LQ\,\overline{LQ} \to \mu^\pm \nu_\mu q_i q_j$	$LQ\,\overline{LQ} \to \tau^\pm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

Signature:

$LQ\,LQ \to llqq$	2 leptons+2jets	$BR = \beta^2$
$LQ\,LQ \to l\nu qq$	1 lepton+MET+2jets	$BR = 2\beta\,(1-\beta)$
$LQ\,LQ \to \nu\nu qq$	MET+2jets	$BR = (1-\beta)^2$

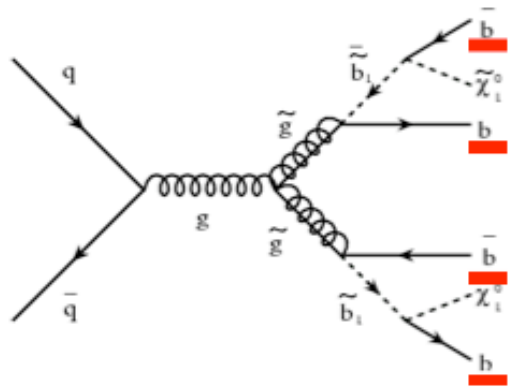
Acceptances from MC were derived for different values of LQ mass for all generations.

1st generation: M_{LQ} = 179 GeV ⇔ $\sigma(pp \to LQ\,\overline{LQ}) < 0.45$ pb
2nd generation: M_{LQ} = 177 GeV ⇔ $\sigma(pp \to LQ\,\overline{LQ}) < 0.49$ pb
3rd generation: M_{LQ} = 167 GeV ⇔ $\sigma(pp \to LQ\,\overline{LQ}) < 0.70$ pb



HF final states: sbottom from gluinos

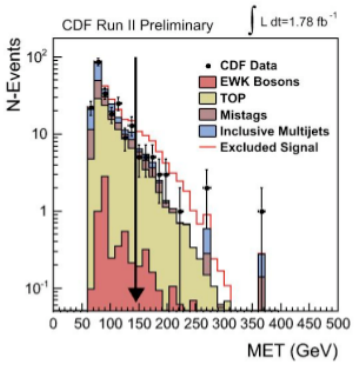
If the sbottom is significantly lighter than the other squarks, the two body decay of gluino into bottom/sbottom is kinematically allowed

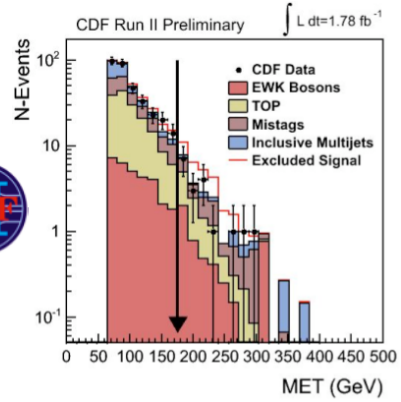


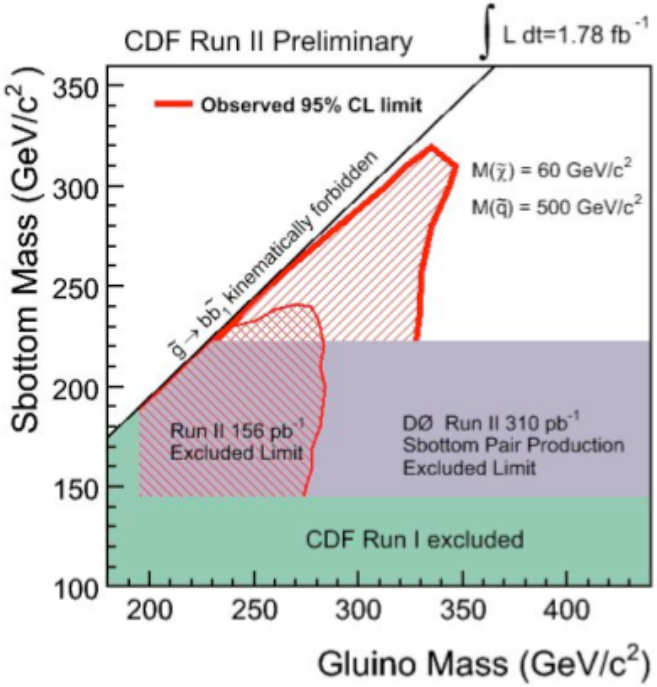
The sbottom decays into a bottom and LSP, giving rise to a final state with <u>4 b-jets and missing energy</u>

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

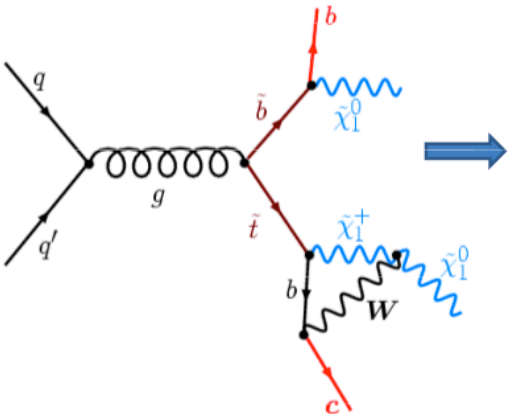
Large Δm between $\tilde{g}$ and $\tilde{b}$
$M(\tilde{g})$ = 320 GeV/c^2, $M(\tilde{b})$ = 250 GeV/c^2, $M(\tilde{\chi})$ = 60 GeV/c^2
Small Δm between $\tilde{g}$ and $\tilde{b}$
$M(\tilde{g})$ = 300 GeV/c^2, $M(\tilde{b})$ = 280 GeV/c^2, $M(\tilde{\chi})$ = 60 GeV/c^2







Stop searches

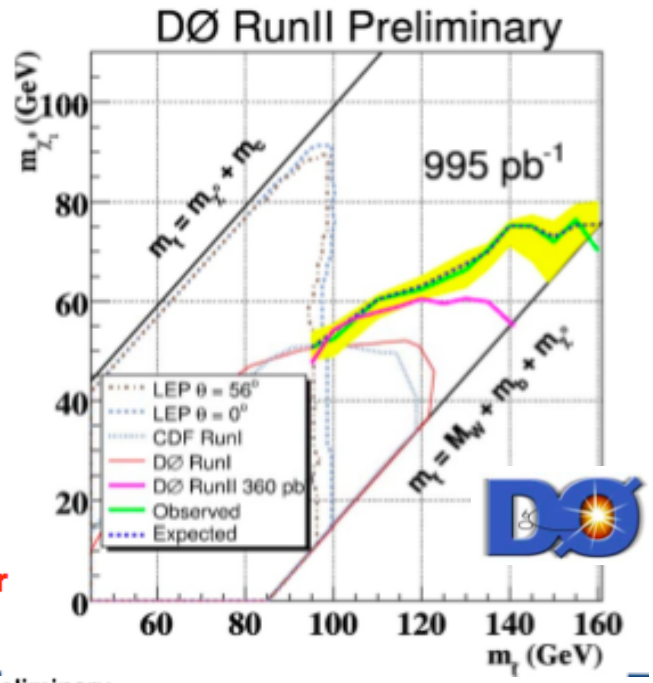


Light stop and sbottom production and decay

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)

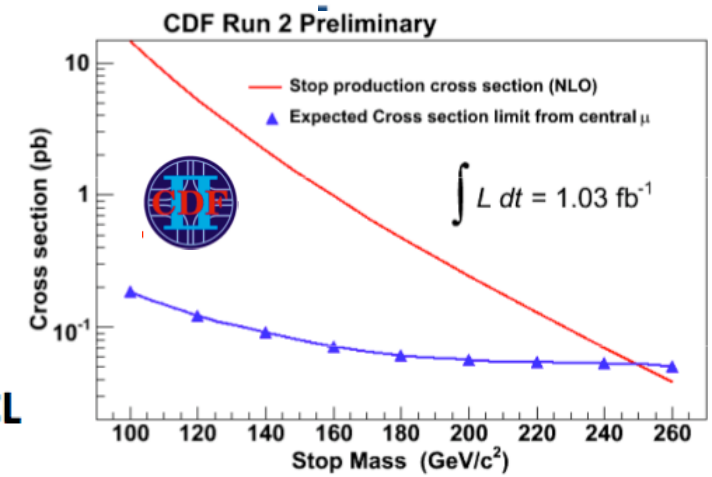
Exclusion: stop mass <149 GeV/c² for neutralino mass of 63 GeV/c²



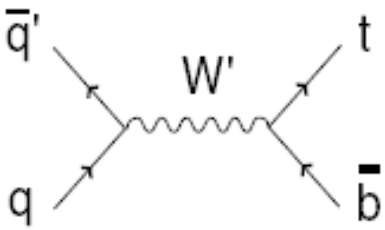
Other option is that stop does not decay in the detector (CHAMP)

- Slow particle signature : slowly-moving highly-ionizing highly-penetrating particle
  - Will look like muon with possible calorimetry energy deposition
- Goal: Measure Time of Flight mass of tracks

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

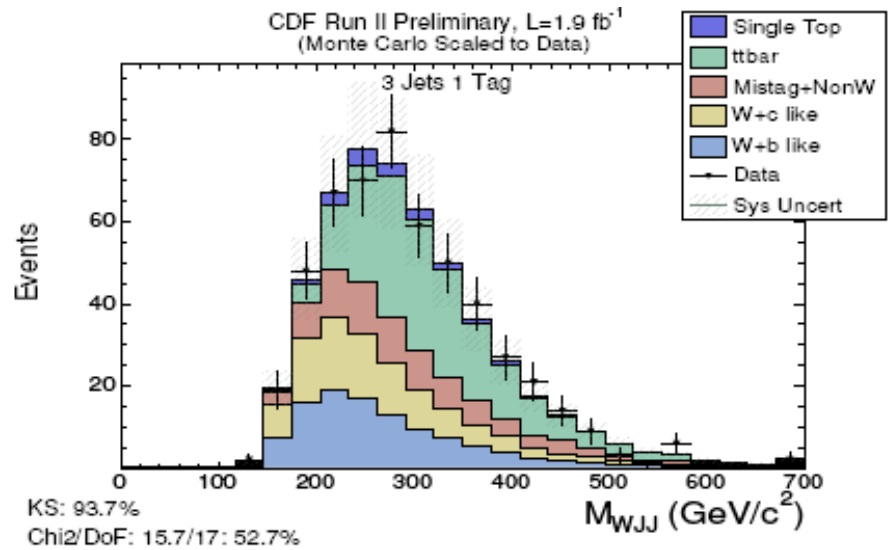


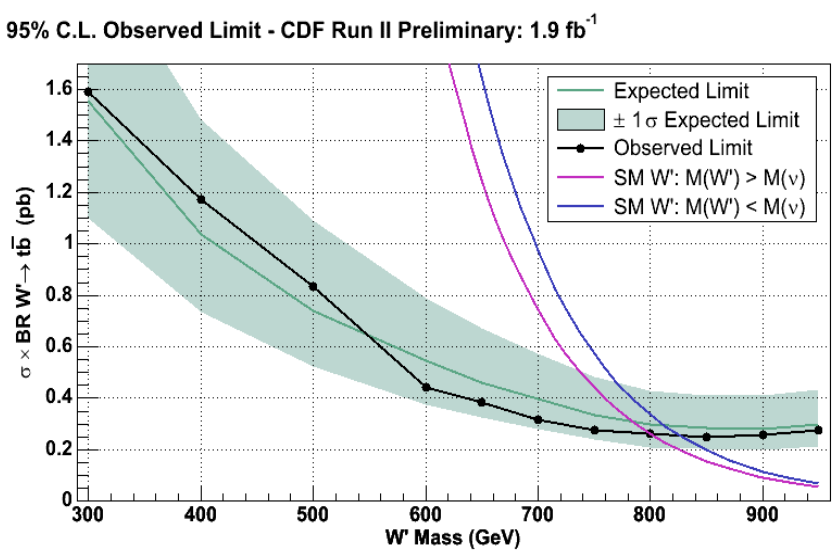
Heavy flavor final states: W'→ tb



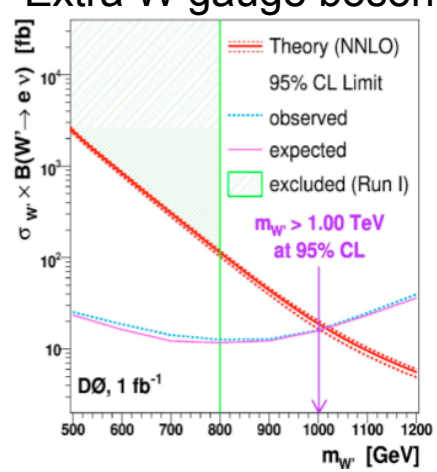
Search for resonant tb*(+cc)* pair production

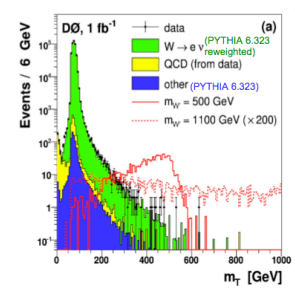
In W+2 jets and +3 jets channels (semileptonic W), look for unexpected structure in M(Wjj)



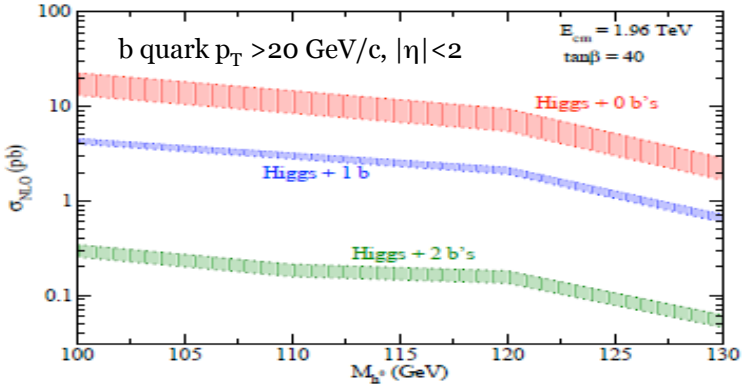


Extra W gauge boson decaying into eν

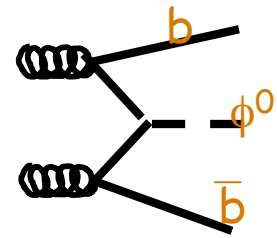




HF final states: $\phi \rightarrow bb$

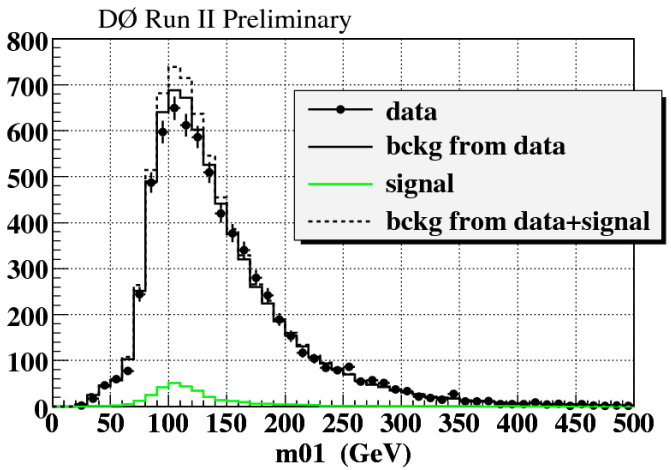


Inclusive H → b$\underline{b}$ is too hard due to QCD background

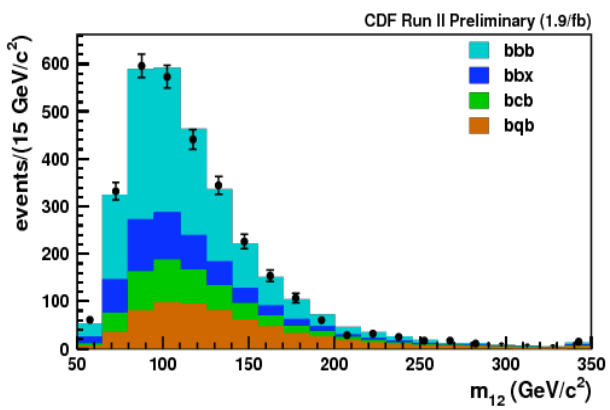


Require one additional bottom quark jet besides the two from Higgs decay

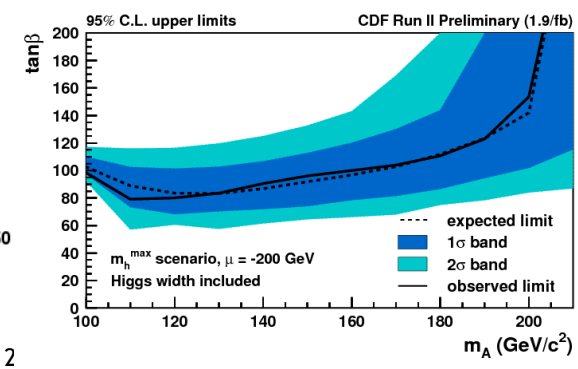
"3b" channel best compromise between signal and background rates



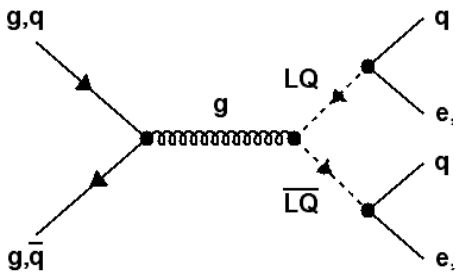
Search uses invariant mass of the two leading jets m_{01} in triple-tagged events
No excess observed



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



More complex signatures: leptoquarks



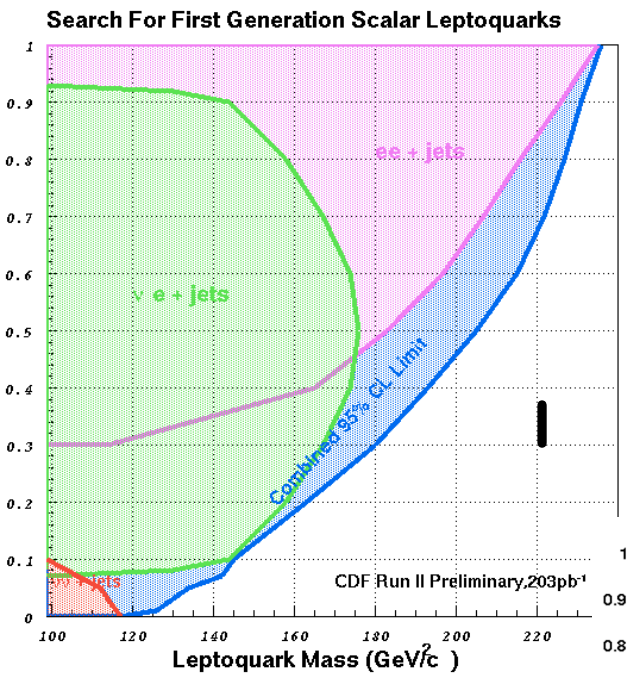
1st Generation	2nd Generation	3rd Generation
$LQ\,\overline{LQ} \to e^- e^+ q\bar{q}$	$LQ\,\overline{LQ} \to \mu^+ \mu^- q\bar{q}$	$LQ\,\overline{LQ} \to \tau^+ \tau^- q\bar{q}$
$LQ\,\overline{LQ} \to e^\pm \nu_e q_i q_j$	$LQ\,\overline{LQ} \to \mu^\pm \nu_\mu q_i q_j$	$LQ\,\overline{LQ} \to \tau^\pm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

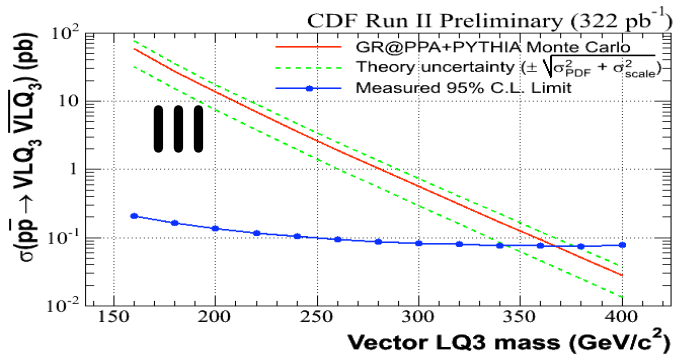
Signature:

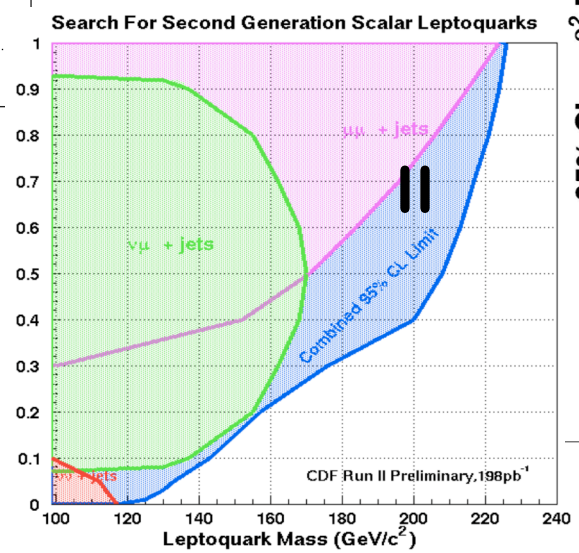
$LQ\,LQ \to llqq$	2 leptons+2jets	$BR = \beta^2$
$LQ\,LQ \to l\nu qq$	1 lepton+MET+2jets	$BR = 2\beta\,(1-\beta)$
$LQ\,LQ \to \nu\nu qq$	MET+2jets	$BR = (1-\beta)^2$

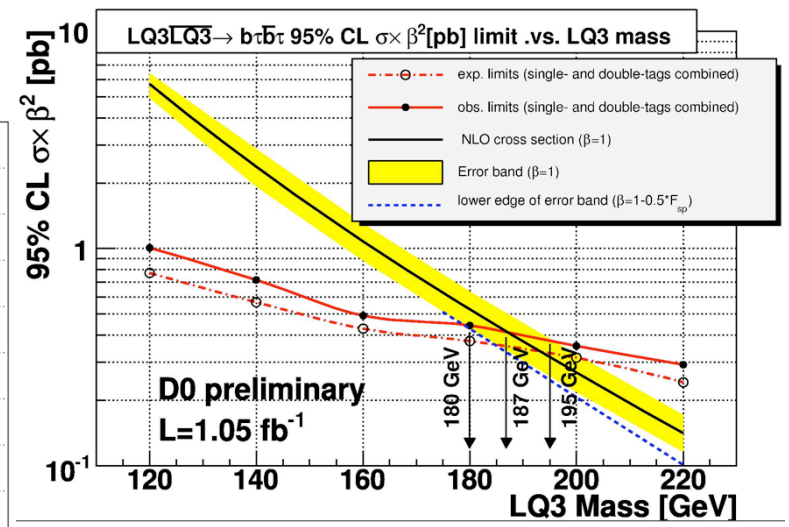
<u>Analysis:</u> counting experiment
A series of cuts is applied in sequence with the goal of
reducing the background (W/Z + jets and top)
enhancing the signal retention
<u>Cuts are optimized</u> to give the maximum S/B
Final number of events are compared with SM expectation
<u>No excess -> limits on production cross section</u>

Leptoquark Results



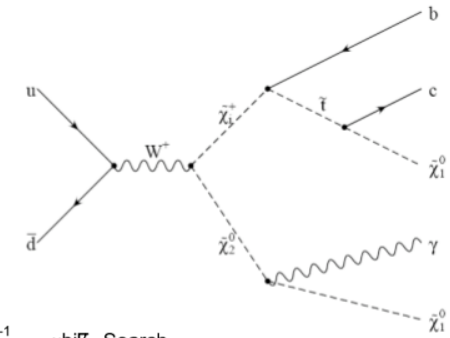






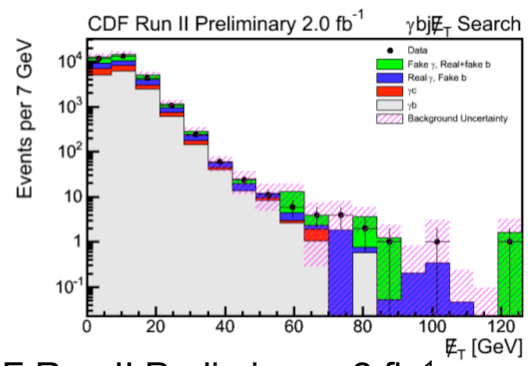
More complex signatures: γ+b+jets+MET

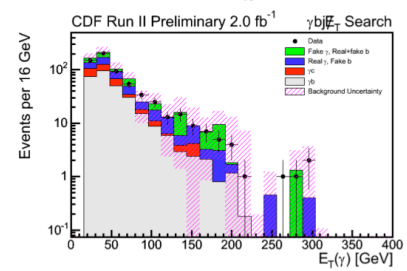
A handful of exotic processes would give rise to a final state signature comprising γ+b+jets+MET
Many anomalies could be reduced to detector mis-measurements.

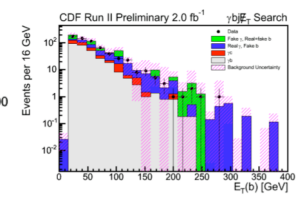


Low energy SUSY with radiative decay of the neutralino

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





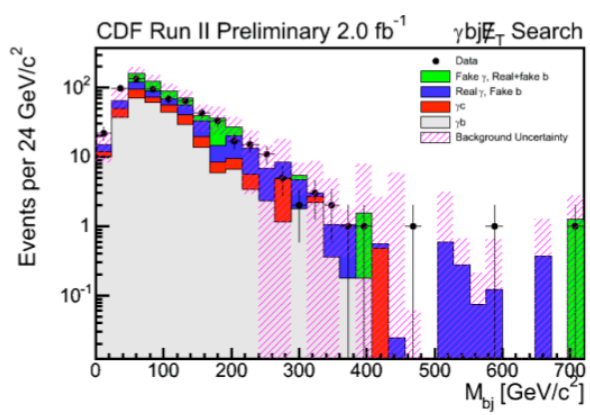


CDF Run II Preliminary, 2 fb^{-1}

Main background (from data and MC)

	Fake γ	Real γ
Fake b-tag	A	B
Real b-tag	C	D

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



Final Remarks

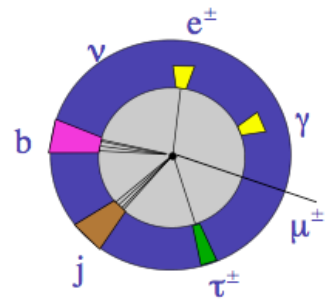
- The results presented are by far not exhaustive
- Even when a signature-based approach is advocated, results are presented in the end as a function of specific models (typical case dilepton searches, high P_T Z's etc)
- And when the result is presented as a testing of a model, there is always a check on control regions, defined by their signature…
- So, what is all this fuss about model-based and signature-based approaches ?
- I believe that *both are to be pursued in a balanced way: both have their pros and cons:*
  - **A) Traditional model driven analyses**
    - pick a favorite theoretical model ☹ **might become soon outdated!**
    - pick a process, choose the best signature(s): optimize selection acceptances based on signal MC
    - calculate the background ☺ **best optimization!**
    - evaluate the limit or discovery your signal ☺ **in timely fashion allows theory testing!**
  - **B) Signature based approach**
    - pick a specific signature (i.e. diphoton+X) ☺ **open to a whole lot of models!**
    - define your sample in terms of known processes ☹ **Not the best optimization !**
    - publish estimates of acceptances & cross section information useful for theorists ..but how much?? Detector effects are detector specific or we would all be using PGS! ;-)
    - see an excess? Inconsistency with SM? Test one or more models later …(but the experiments will never release a controversial results for theorists to interpret, this is just sociology 101)
    - Quero-like access to the data? Is the astrophysical model suitable for HEP?

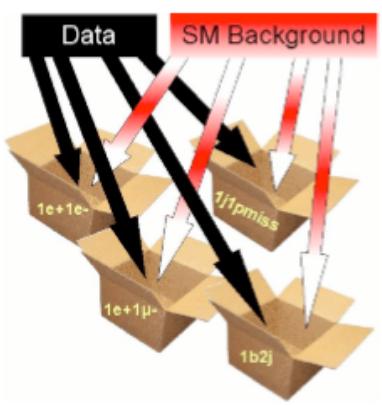
Global Searches

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





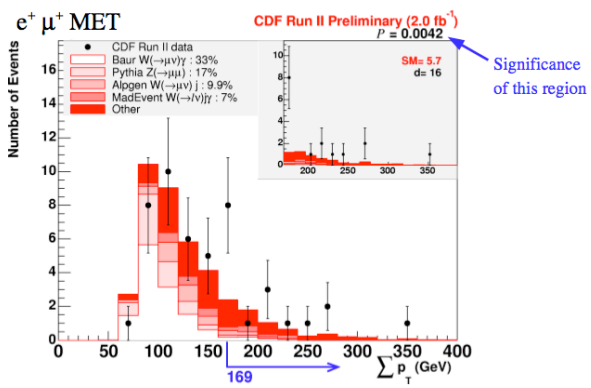
Pythia and MadEvent are used to implement the SM theoretical prediction (CdfSim emulates the detector response)

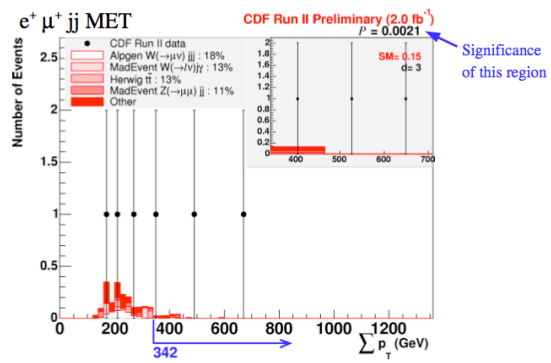
Many correction factors are used to obtain the *true* SM predictions (shouldn't a global search work globally?)

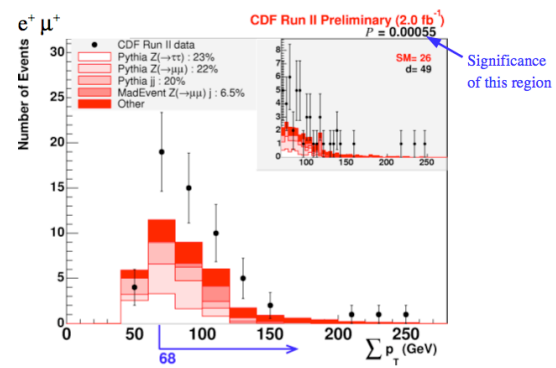
- theory k-factors etc
- experimental efficiencies and Scale Factors, fake rates etc

Global Searches

Shape Discrepancies:
Most shape discrepancies caused by difficulty in modeling soft jet emission
No claim of new physics can be motivated by such discrepancies
Bump Hunter:
The significance is estimated via pseudo-experiments
The only discovery level bump found is still to be attributed to the same bad modeling of QCD soft radiation
Excess of data at high sum-p_T
A few final states gives some excess but only ~8% of hypothetical CDF experiments are expected to give a more interesting excess purely by chance







Conclusions

Many exciting results are currently produced at the Tevatron!
We are still the place of interest!

Many of the results interplay nicely :
from testing the SM processes to searches for Exotica
same signature, different physics

The experiments are working hard despite the dire budget situation

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