Beyond the Standard Model at High-Energy Colliders

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Relevant parallel sessions:

- SUSY
- Exotics I
- Exotics II

21 experimental talks:

- Tevatron: 10
- Hera: 4
- B-factories: 1
- LHC: 6

12 theory talks

In this review:

no Theory (cf. Carlos and Gustavo)

no prospects (wait until next year for LHC results)

… and hard choices had to be made:

Apologies !

Beyond the Standard Model…

The Standard Model:

The Poincaré group

In a 4-dimensional space-time

$SU(3)_c \times SU(2)_L \times U(1)_Y$

The Higgs mechanism

Three generations of
quarks and leptons

(Not covered today)

Beyond the Standard Model:

Extend Poincaré ⇒ Supersymmetry
and include gravitation (Supergravity)

Increase the number of space dimensions

Enlarge the gauge group ⇒ Z', W'

Alternative EWSB mechanisms
(TC, little Higgs, Higgsless…)

Relate quarks and leptons ⇒ Leptoquarks
Additional generations
Excited quarks and leptons
Compositeness…

Supersymmetry

Basics of the MSSM

(Minimal Supersymmetric extension of the Standard Model)

- **Minimal field content (with two Higgs doublets)**

spin-0	spin-1/2	spin-1
Squarks: $\tilde{q}_R$, $\tilde{q}_L$	q	
	Gluino: $\tilde{g}$	g
Sleptons: $\tilde{\ell}_R$, $\tilde{\ell}_L$	ℓ	
h,H,A	**Neutralino** $\chi_{i=1-4}$	Z, γ
$H^{\pm}$	**Charginos** $\chi^{\pm}_{i=1-2}$	$W^{\pm}$

Squarks & sleptons = "sfermions"

Charginos & neutralinos = gauginos

- **A priori > 100 parameters, undetermined in the absence of a specific SUSY breaking scheme.**

- **Reduced to a manageable level by invoking some unification of the soft SUSY-breaking terms at the GUT scale.**

- **Additional frequently made assumptions:**

"Standard SUSY"

R-parity conservation, where $R=(-1)^{3(B-L)+2S}$

- **SUSY particles are produced in pairs**
- **They (cascade) decay to the LSP which is stable**

Neutralino LSP

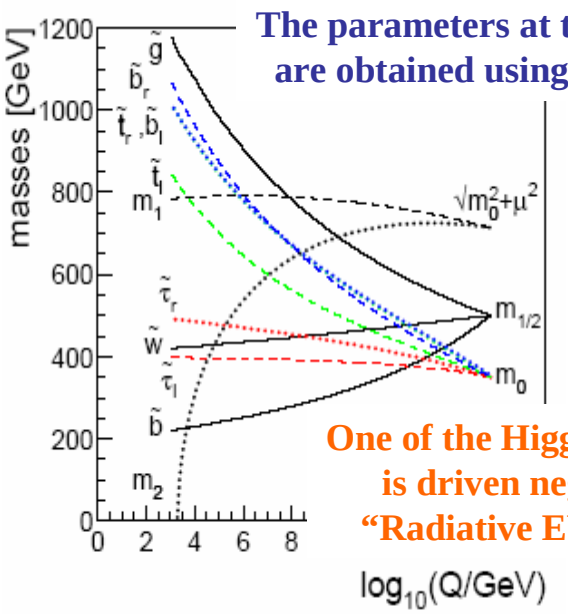
- **neutral and weakly interacting**
- **$\Rightarrow$ Missing energy**

No RPV today

Basics of mSUGRA

- The most widely studied model is mSUGRA:

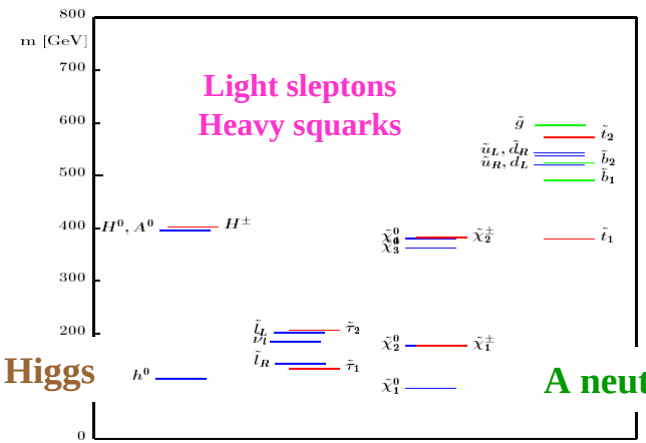
mo:	**common scalar mass at GUT scale**
m1/2:	**common gaugino mass at GUT scale**
Ao:	**common trilinear coupling at GUT scale**
sign(μ):	**supersymmetric Higgs mass term (μH1H2)**
tan(β):	**ratio of the vev's of the neutral Higgs fields at the EW scale**



The parameters at the EW scale are obtained using the RGEs.

One of the Higgs masses is driven negative: "Radiative EWSB"

A typical mSUGRAspectrum



Light sleptons
Heavy squarks

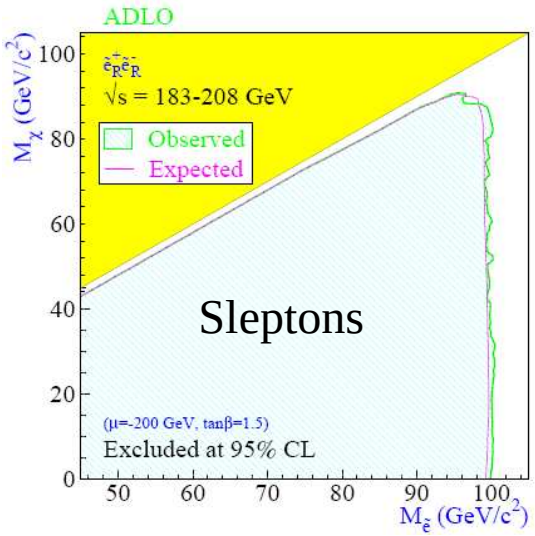
A stop lighter than the other squarks

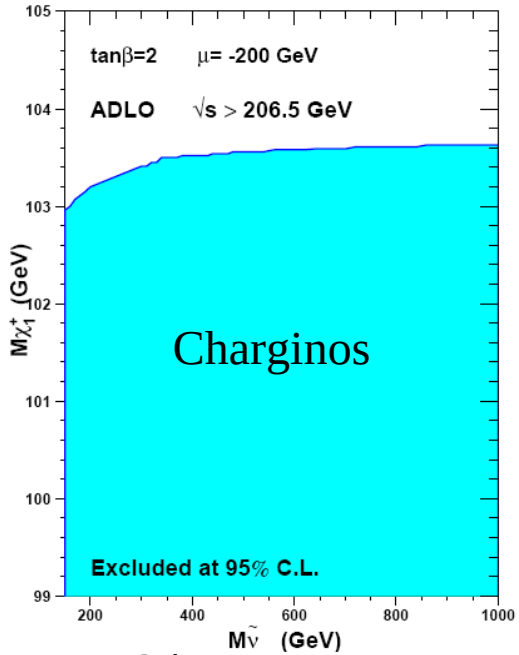
A light Higgs

A neutralino LSP

$M(\chi+) \sim M(\chi^0_2) \sim 2M(\chi^0_1)$
$M(\tilde{g}) \sim 3M(\chi+)$

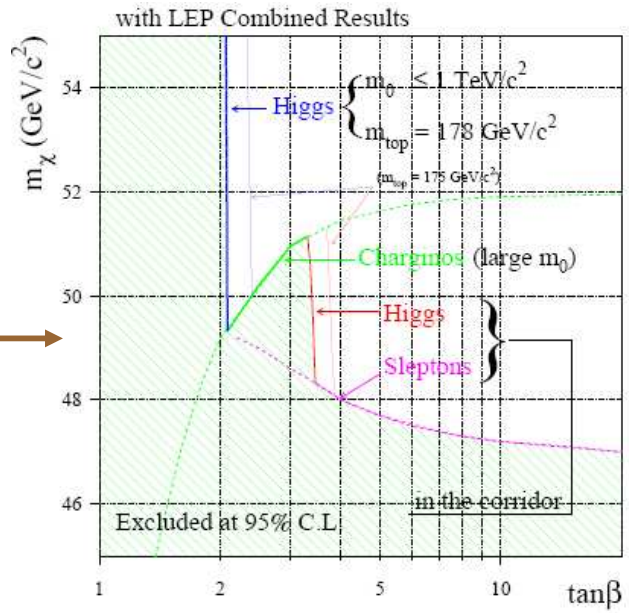
The LEP legacy

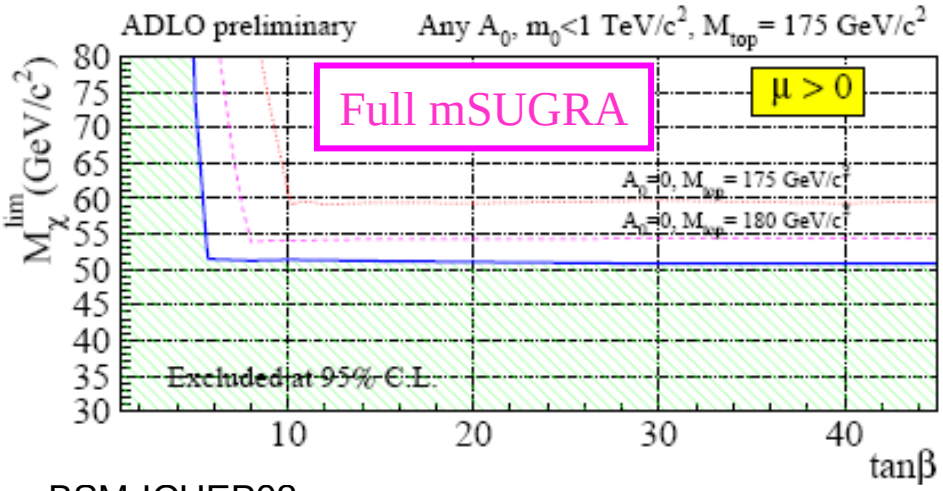




LSP mass limit

MSSM with sfermion and gaugino mass **unification**





SUSY searches at the Tevatron

Two main search streams at the Tevatron for "standard" SUSY:

Squarks and gluinos(*)

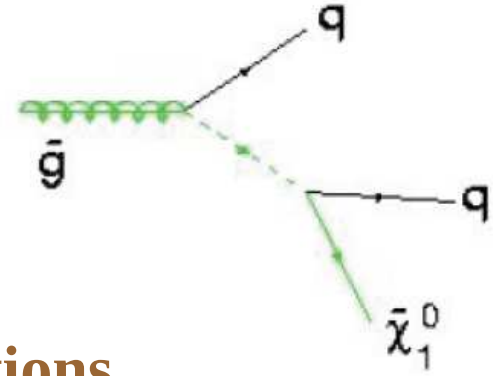
$\Rightarrow$ **Multijets + missing E_T**

Electroweak gauginos with leptonic decays

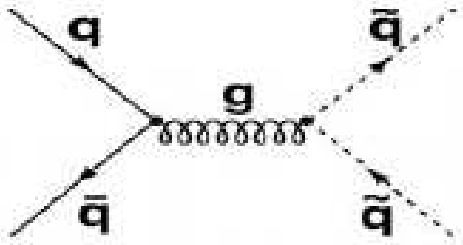
$\Rightarrow$ **Trileptons**

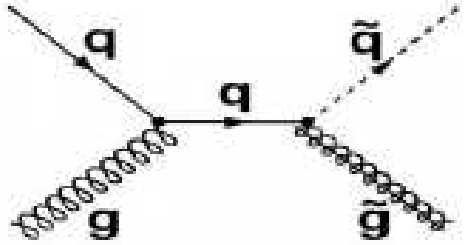
(*) Stop and sbottom in backup

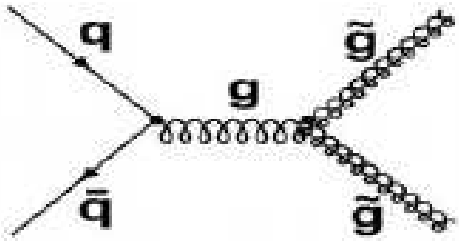
Squarks and gluinos



Strong production ⇒ Large cross sections







m(gluino) >> m(squark)	m(gluino) ~ m(squark)	m(gluino) << m(squark)
2 jets + MET	**3 jets + MET**	**4 jets + MET**

Analyses optimized for each of these topologies

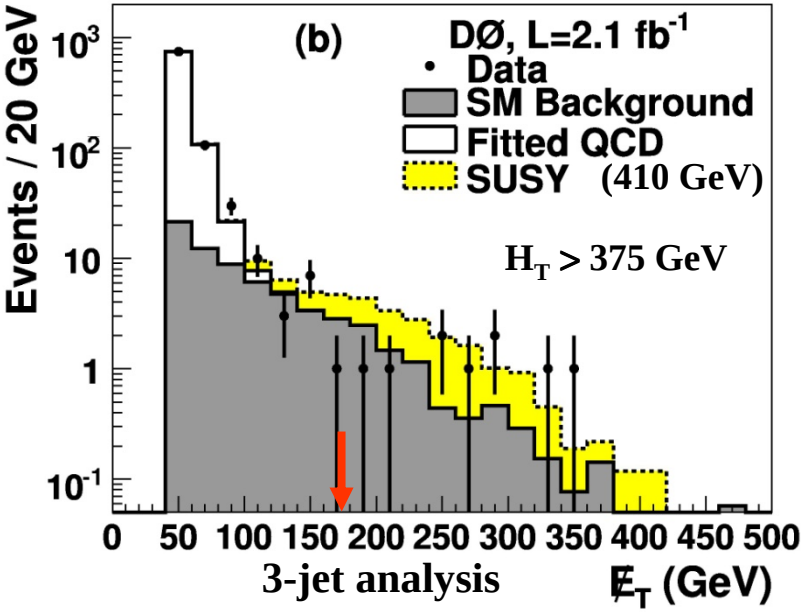
Cascade decays complicate the picture
⇒ a model is needed for the interpretation: mSUGRA

Main backgrounds:

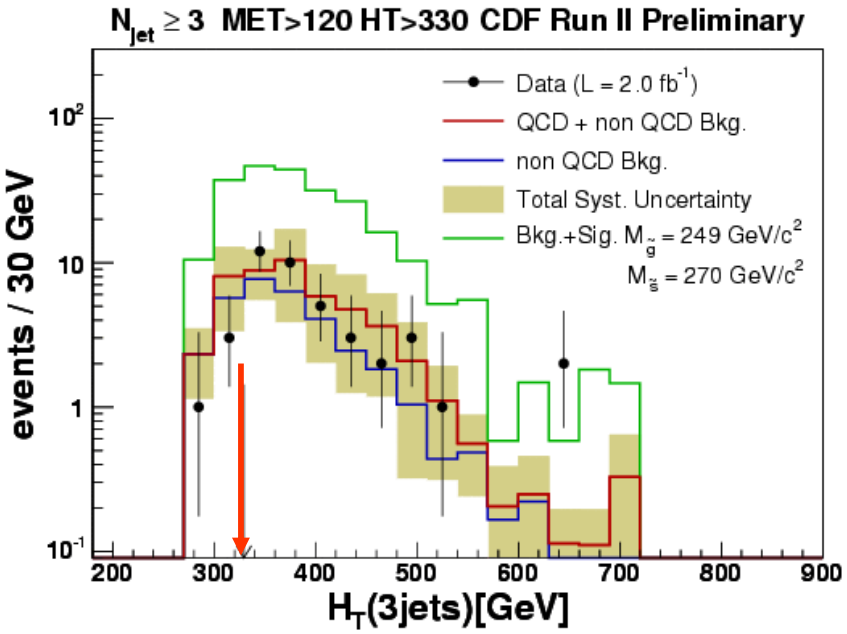
- Instrumental (QCD multijets with fake missing E_T)
- ($W \rightarrow$ lepton+ν) +jets (also from ttbar)
- ($Z \rightarrow \nu\nu$) +jets (irreducible)

Main analysis cuts:

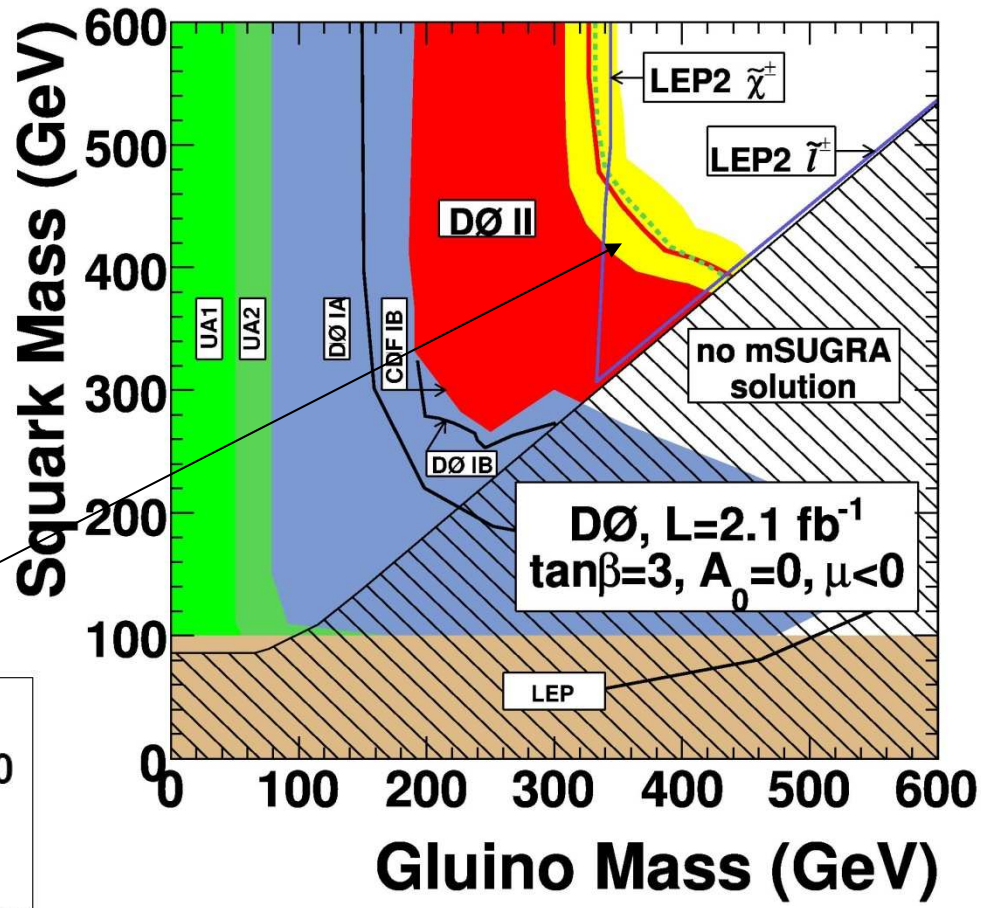
- Jet1,2(,3(,4)) p_T
- Angles (jet,missing ET)
- Lepton veto
- Missing E_T
- H_T = sum of jets p_T's



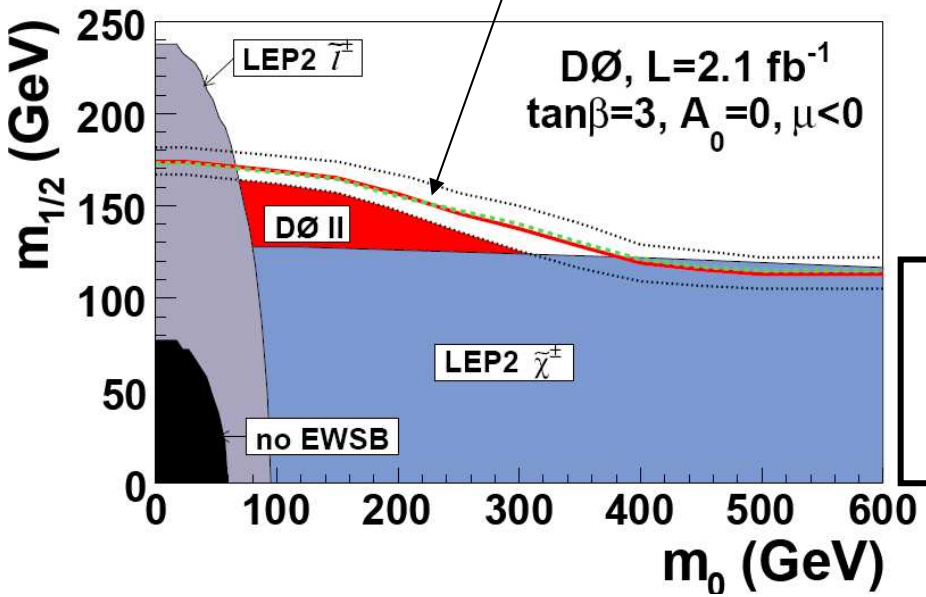
3-jet analysis



DØ Analysis	Background expected	Events observed
2-jets	11.1±2.9	11
3-jets	10.7±2.8	9
4-jets	17.7±4.5	20



The band represents the theoretical uncertainty (renormalization scale and PDFs)



For the "nominal" cross section:

M_{gl} > 408 GeV (when $M_{gl} \sim M_{sq}$)

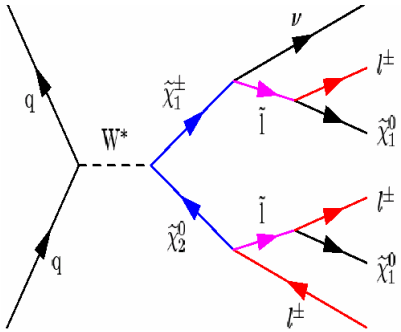
M_{gl} > 327 GeV & M_{sq} > 392 GeV

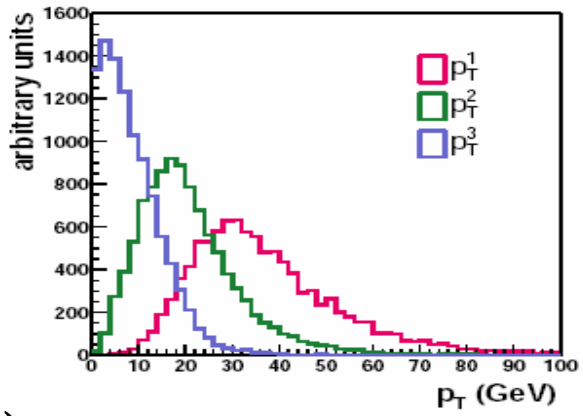
Similar results from CDF in backup

Trileptons

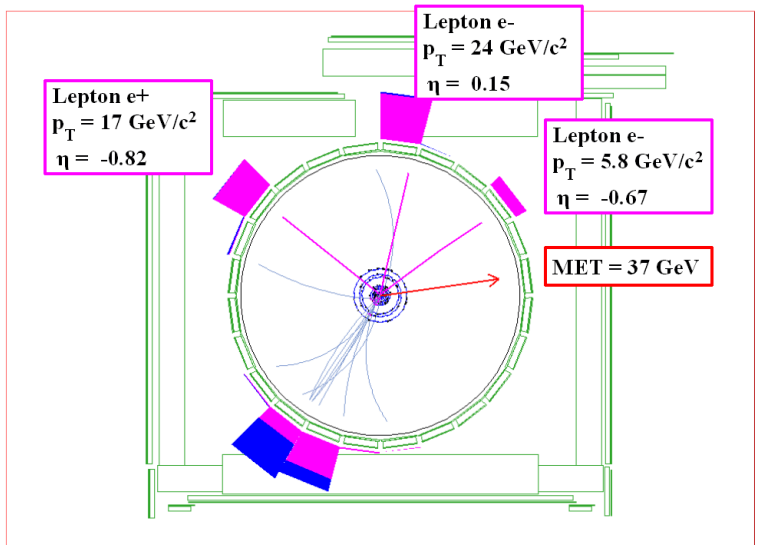
- Arise from chargino-neutralino associated production
- "Golden" SUSY signature but:
  - low cross sections (× BR)
  - soft leptons
  - taus (at large tanβ)

⇒ Combine many final states





(Also decays via W/Z exchange)



General strategy:

Two isolated (rather soft) e or μ

Require some Missing E_T (ν+2χ)

+ channel-dependent cuts (e.g. anti Z, ϒ)

- An isolated third lepton or track (sensitive to τ's)

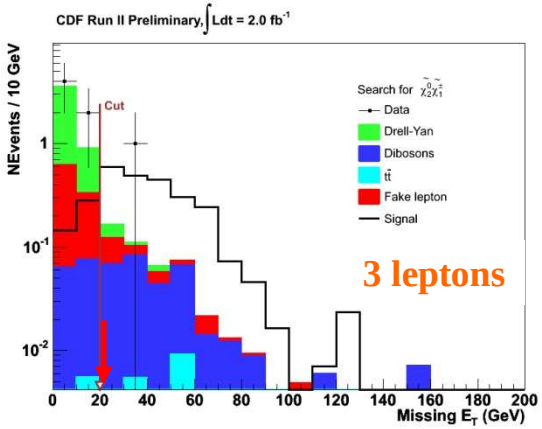
or

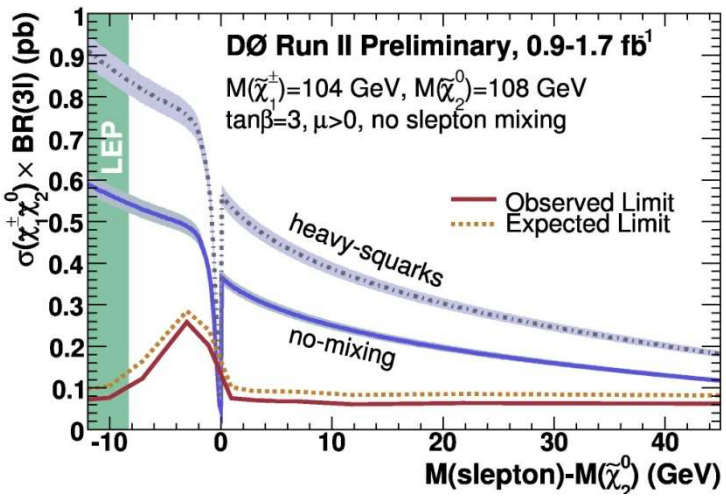
- Two same sign leptons

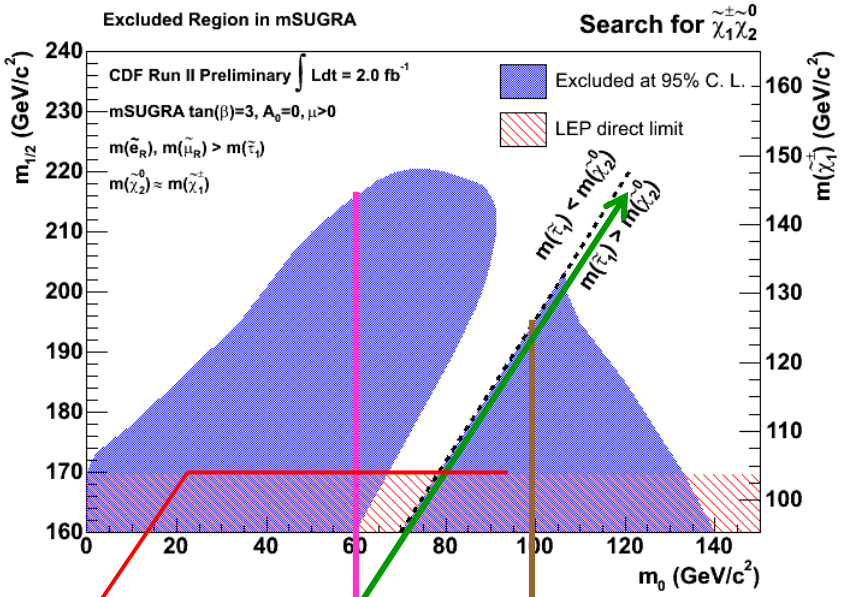
Main backgrounds: DY, WW, WZ, Wγ

(+ a bit of bb and mis-ID)

CDF ($2fb^{-1}$)	Background	Data
Total trilepton	0.88±0.05±0.13	1
Total dilepton+track	5.5±0.7±0.9	6







145 GeV

127 GeV

Chargino mass limits

In the direction of a DØ scan: 145 GeV

Another DØ scan

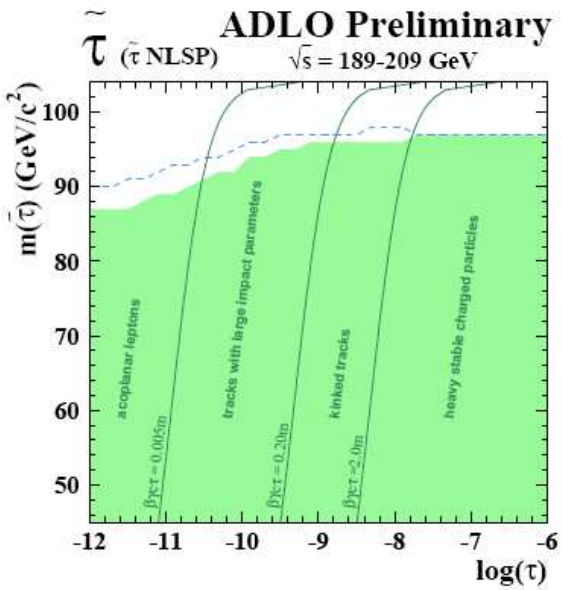
The gap is reduced by the same sign dimuon analysis.
(1 event, for 1.1 ± 0.4 expected, in 1 fb^{-1})

Gauge Mediated SUSY Breaking

- The LSP is a light gravitino G
- The phenomenology depends on the nature of the NLSP,
  - Stau
  - Neutralino
- and on its lifetime

A stau NLSP has been excluded up to ~ 87-97 GeV at LEP, depending on the lifetime.

No tighter limits at the Tevatron.

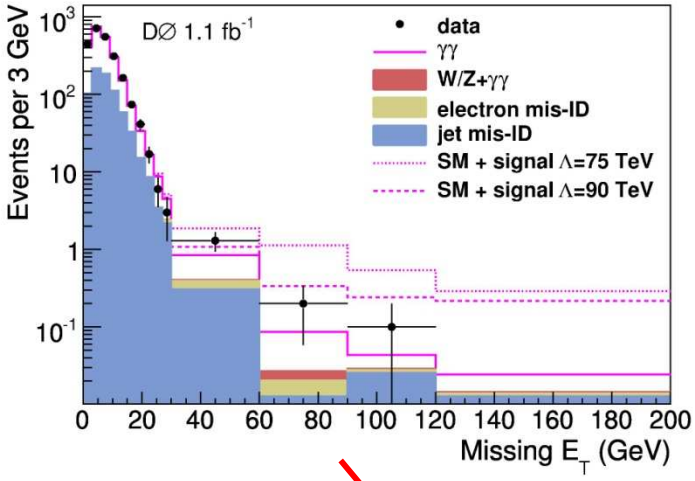


A neutralino NLSP, with $\chi \rightarrow \gamma G$, has been considered

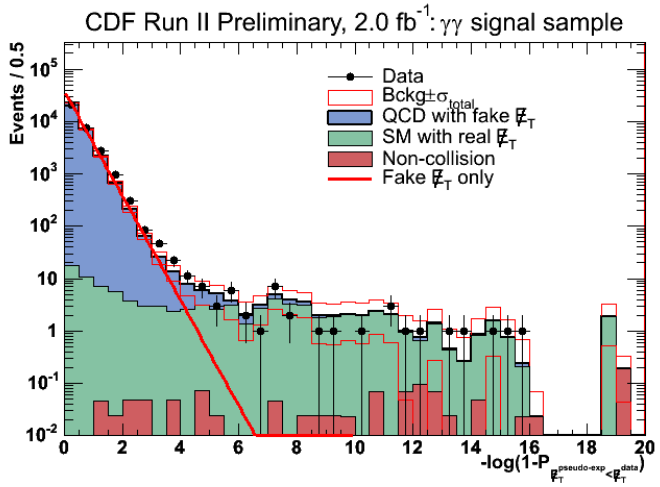
- **at LEP** (excluding the GMSB interpretation of the CDF Run I ee$\gamma\gamma$+MET event)
- **at the Tevatron**. (Only prompt decays today)

Non-prompt in backup

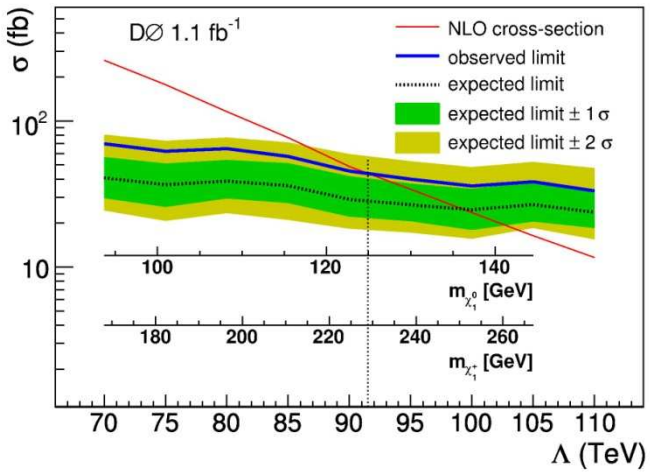
GMSB searches at the Tevatron



Pair production of SUSY particles
⇒ Inclusive search for γγ + missing E_T



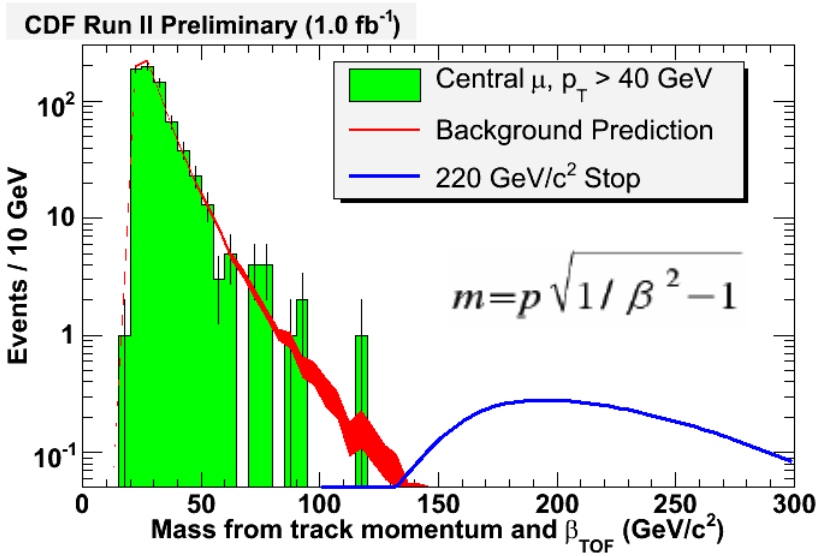
Missing E_T significance
No excess
No GMSB interpretation yet

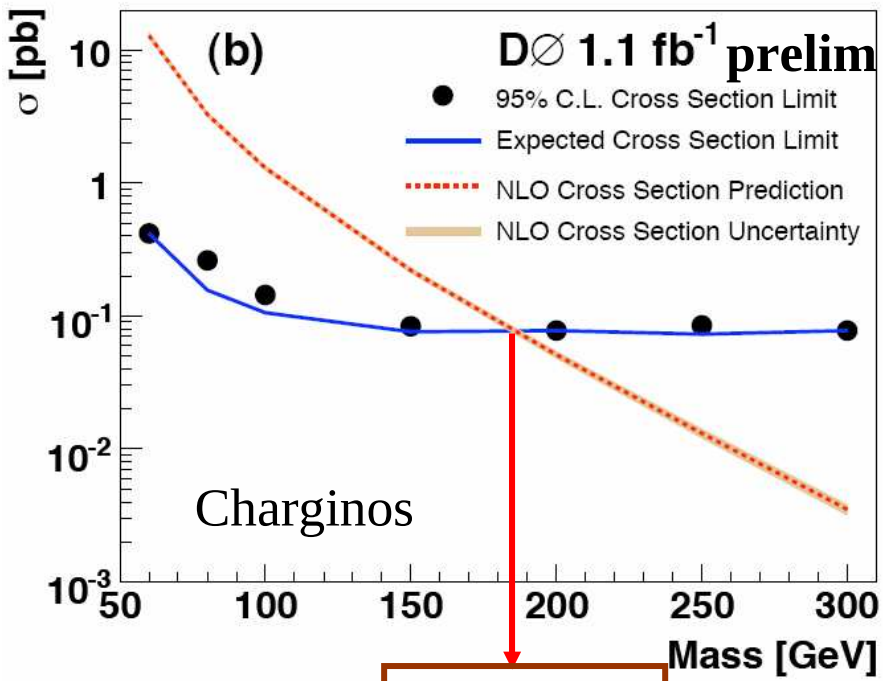


"mGMSB Snowmass slope"
(N=1, M_m = 2Λ, μ > 0, tanβ = 15)
Signal dominated by $\chi^\pm\chi^0_2$ production
m(χ±) > 229 GeV

Charged Massive Stable Particles

Long-lived charginos are expected in some AMSB models
with a "wino-LSP" (small $\chi^{\pm} - \chi_1^0$ mass difference)
They would appear like slowly-moving muons
⇒ Make use of the time of flight information





185 GeV

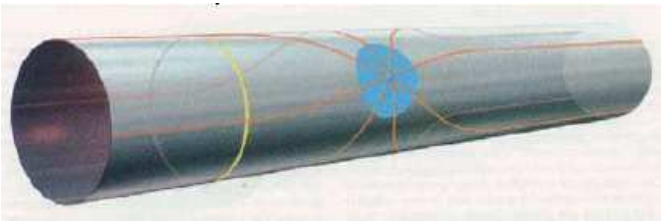
Interpretation for strongly interacting charged massive particles, such as stops with a small stop-χ mass difference
m(stop) > 250 GeV

Long-lived gluinos in backup

Extra Dimensions

Extra-dimensions

…come in many flavors: LED, TeV^{-1}, UED, RS



Today, only Large Extra Dimensions (ADD):

- **2 to 7 large (sub mm) EDs**
- **gravity propagates freely in the bulk**
- **KK excitations cannot be resolved**

$$M_{pl}^2 = 8\pi\, M_D^{n+2} R^n$$

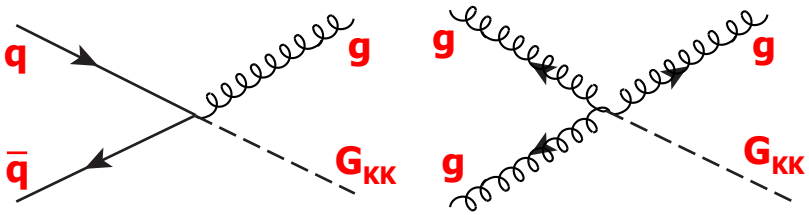
Two main search streams at the TeVatron:

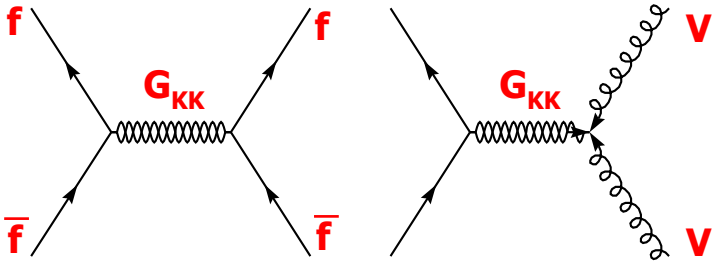
Real graviton emission

Apparent energy-momentum non-conservation in 3D-space

⇒ "Mono-jets or -photons"

Direct sensitivity to the fundamental Planck scale M_D





Virtual graviton exchange

Modifies SM cross sections

Sensitivity to the theory cutoff M_S

(M_S expected to be ~ M_D)

Monojets

CDF search in 1.1 fb^{-1}:

Main selection cuts:

- one high pT jet (> 150 GeV) (soft jets from ISR are allowed)
- isolated lepton veto
- Missing E_T away from jets
- Missing E_T > 120 GeV

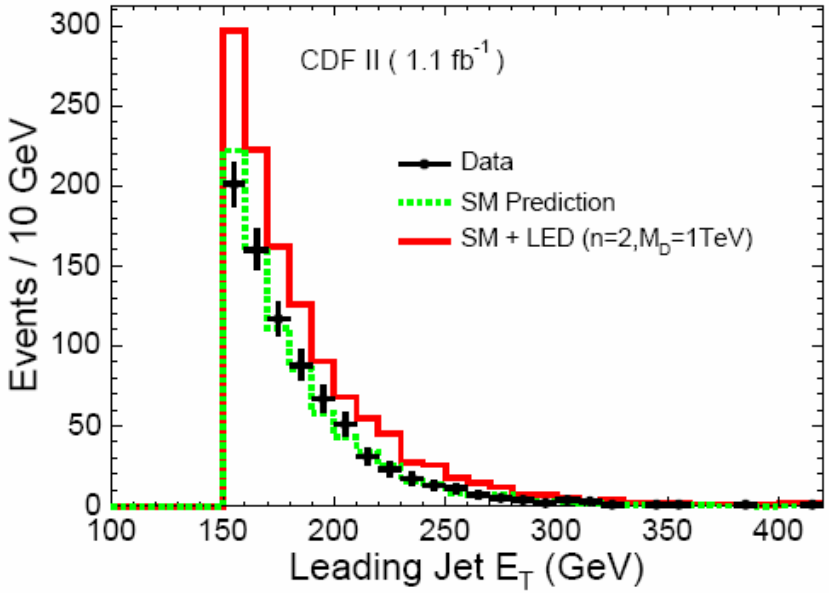
Main background: $(Z \rightarrow \nu\nu)$ +jet

Calibrated with $(Z \rightarrow ll$ and $W \rightarrow l\nu)$ + jet

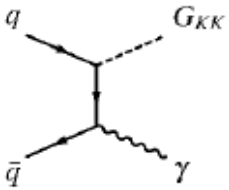
QCD is negligible

809 events selected

808 ± 62 expected



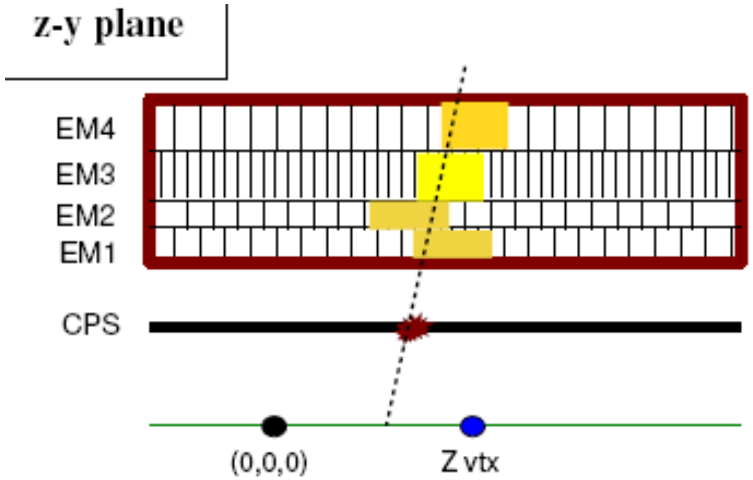
Monophotons



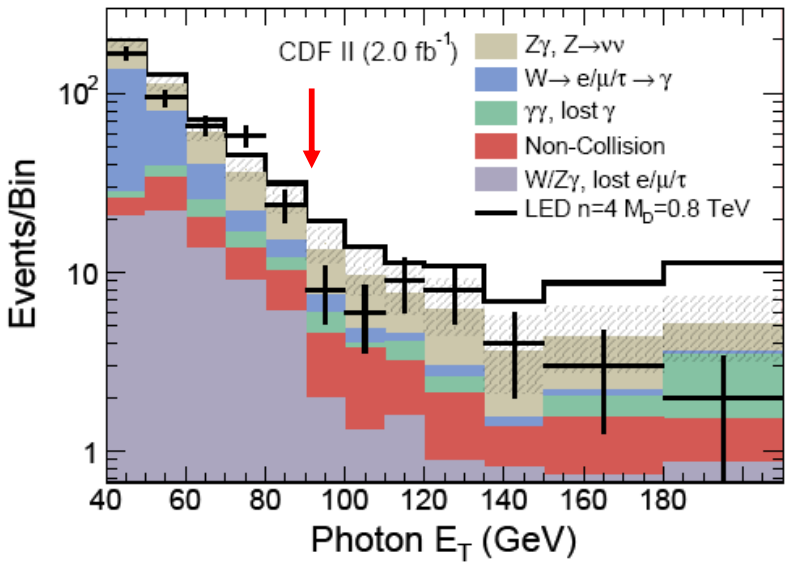
Main backgrounds:

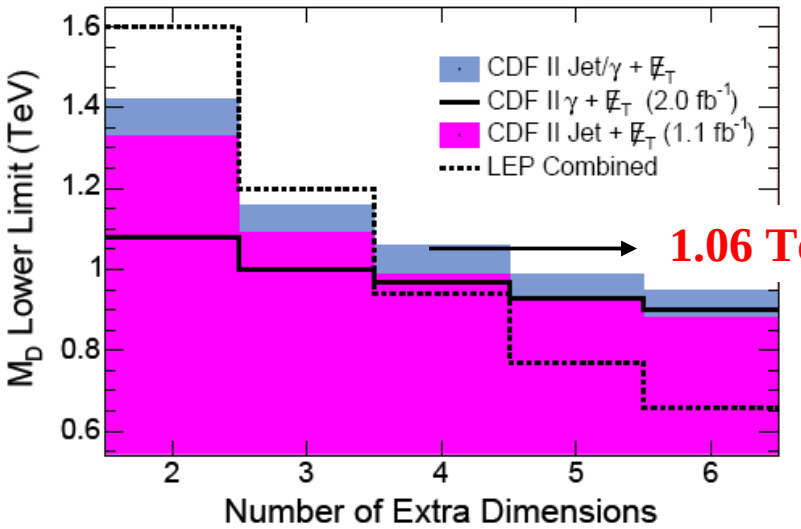
- **Beam halo, cosmics**
- **(Z→νν) + γ**

In addition to topological & kinematic cuts, CDF uses timing in the calorimeter, and DØ uses "photon pointing"



CDF: **40 events observed**
46.7 ± 3.0 expected





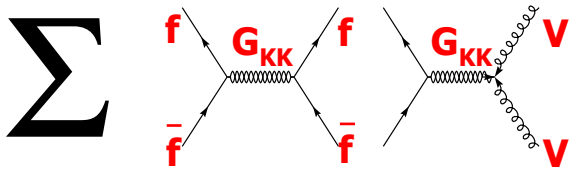
1.06 TeV

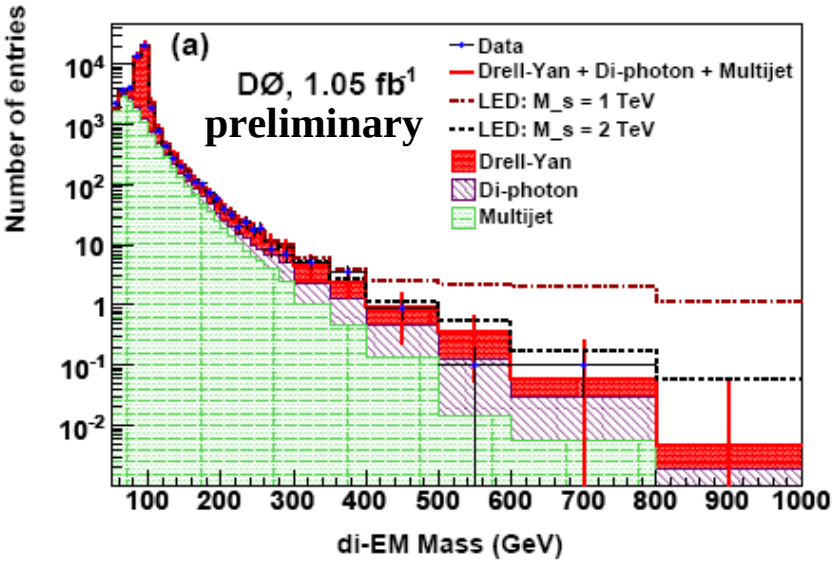
CDF jet & γ combination

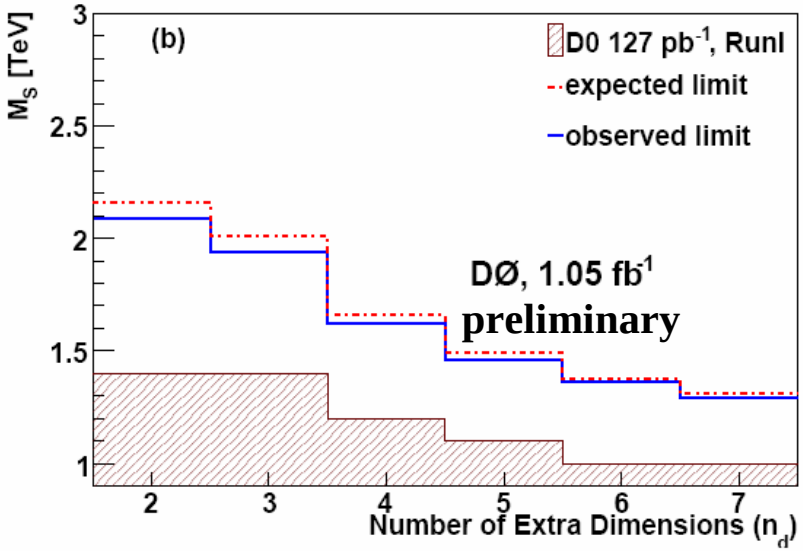
LED in High pT dielectrons & diphotons

The DØ search in 1 fb^{-1} combines ee and γγ to maximize the sensitivity. A 2D-fit in mass and cos θ* is performed to the sum SM+QCD+LED(M_S).

BR(γγ) = 2 BR(ee)





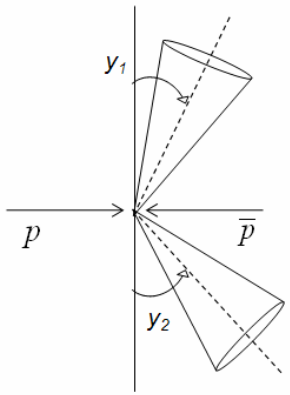


M_S > 1.62 TeV (GRW)

In HLZ formalism

LED in High pT dijets

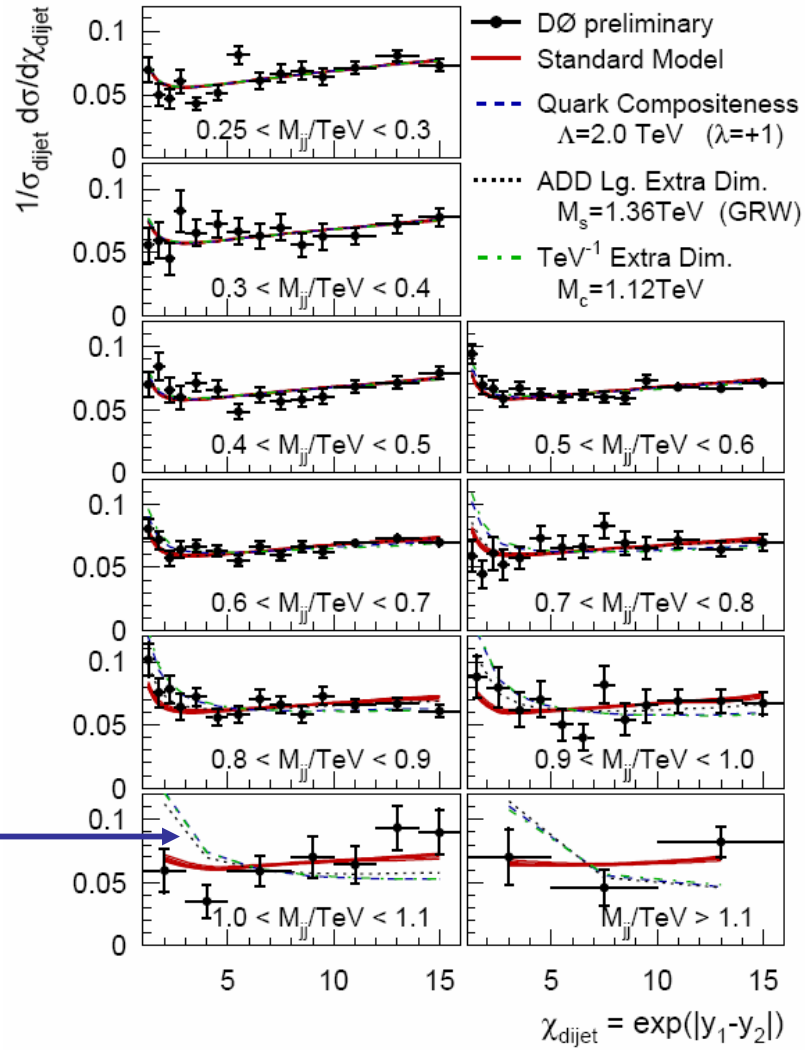
The dijet angular distribution is sensitive to new physics contributions, but is fairly insensitive to theoretical and experimental uncertainties.



$$\chi_{dijet} = \exp(|y_1 - y_2|) \approx \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

is analyzed as a function of the dijet mass in 0.7 fb^{-1} of DØ data

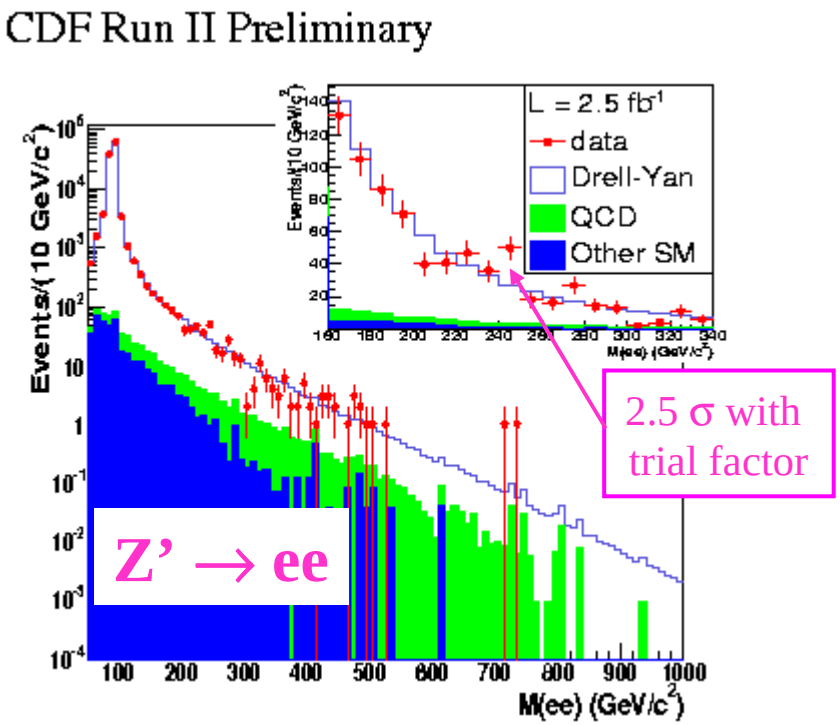
New physics ?

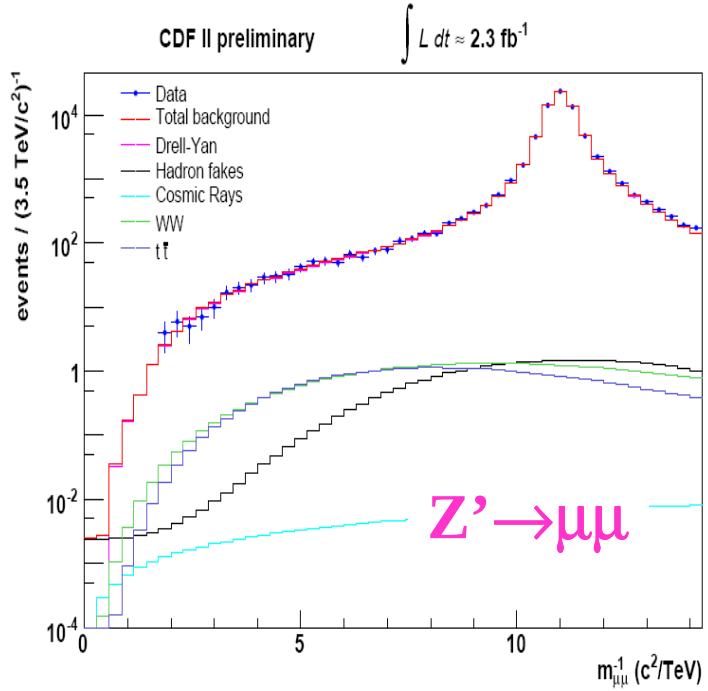


M_S > 1.48 TeV (GRW)

Other model-driven searches

Extra gauge bosons: Z’





M(Z’-seq.) > 966 GeV

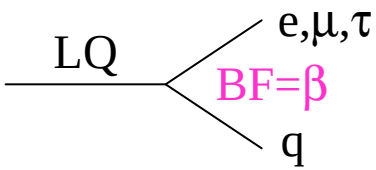
(somewhat lower limits in canonical E(6) models)

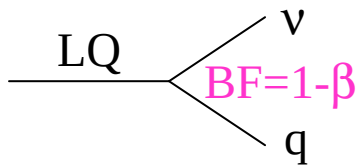
Plot in $1/m_{\mu\mu}$ (consistent with Gaussian resolution in $1/p_T$)

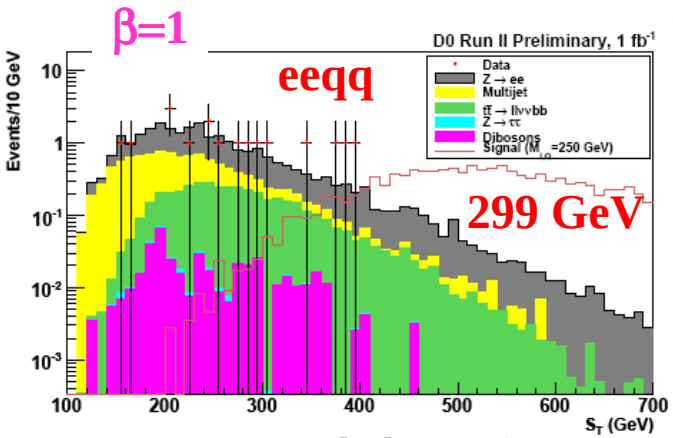
M(Z’-seq.) > 1030 GeV

Reminder: **M(W’-seq) > 1000 GeV** (DØ in 1 fb^{-1})

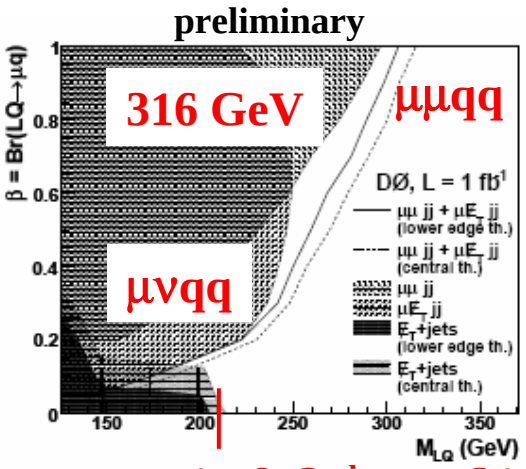
Scalar leptoquarks

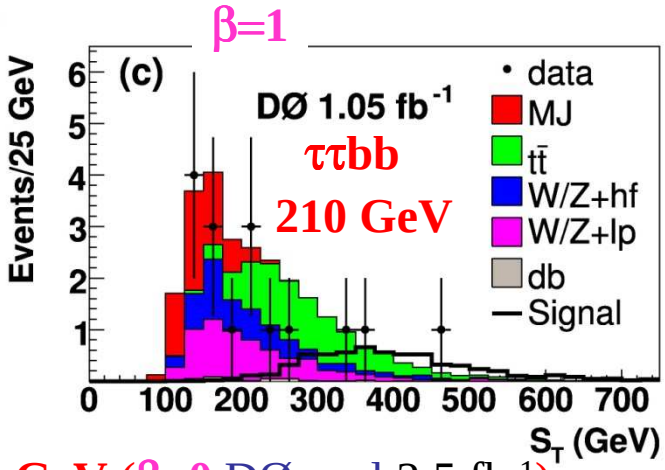






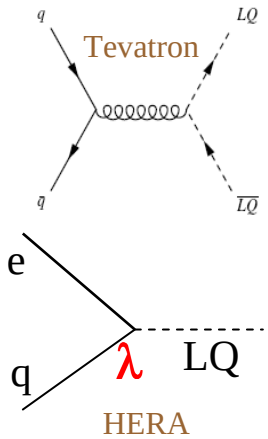
$S_T=\Sigma p_T(l1,l2,j1,j2)$

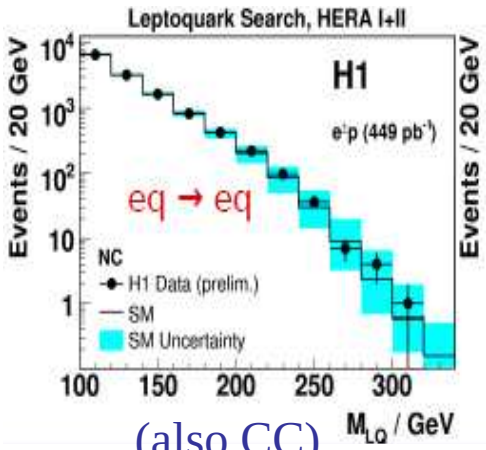




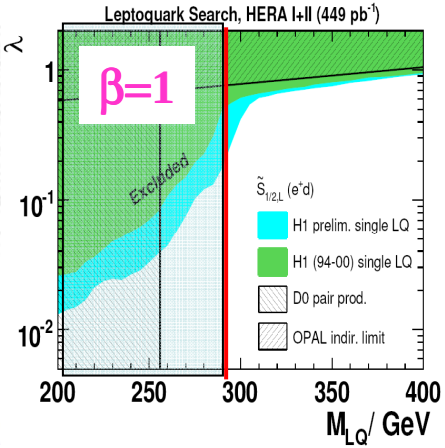
1st & 2nd gen: 214 GeV (β=0 DØ-prel 2.5 fb^{-1})

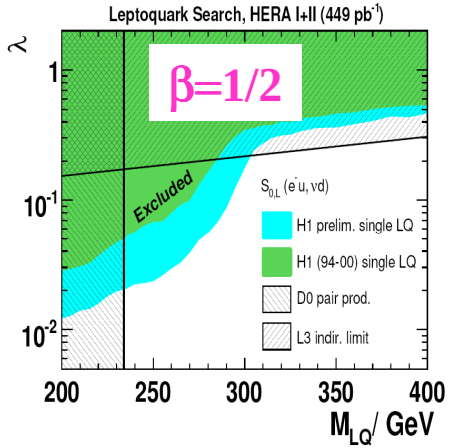
3rd gen: 229 GeV (β=0 DØ 425 pb-1)





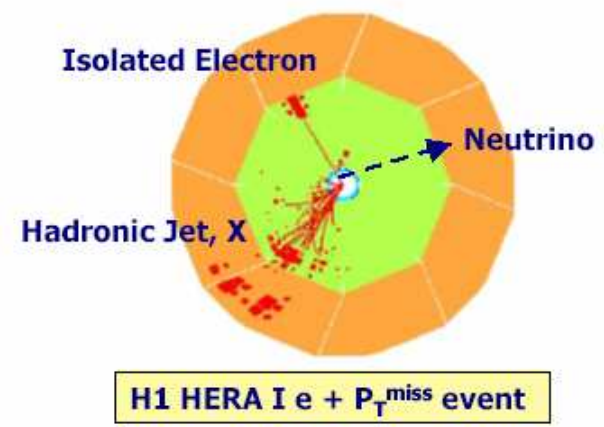
(also CC)



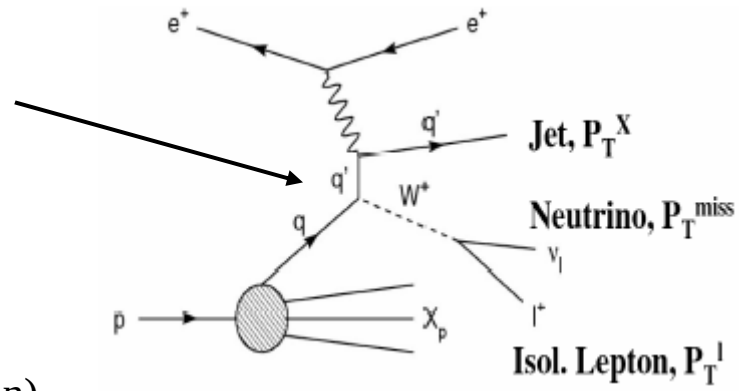


Having found nothing…
Look for “unexpected” anomalies

Isolated leptons at HERA



SM process: W+jet



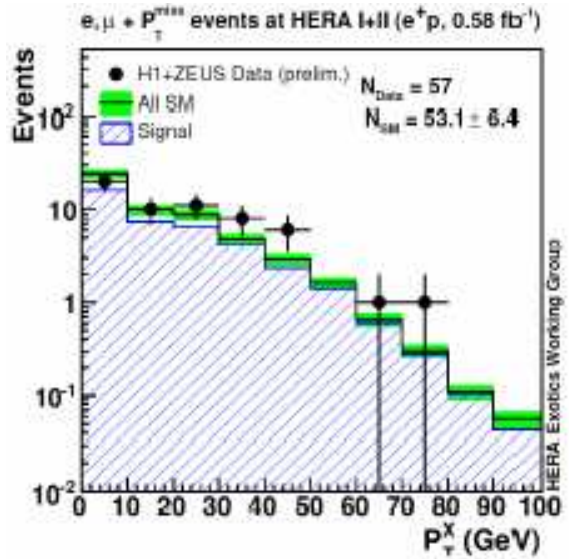
Excess seen by H1 in HERA-I e^+p data at high p_T^X (> 25 GeV)

Not seen by ZEUS (≠ selection)

Now with the full HERA-I+II statistics and two experiments with identical selections:

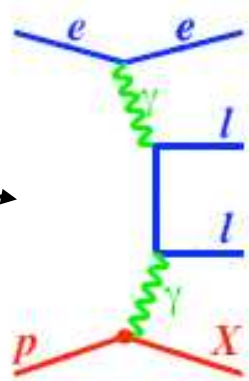
e^+p data	H1	ZEUS	H1+ZEUS
P_T^X>25 GeV	**17/7.1±0.9**	**6/7.5 ±1.1**	**23/14.6±1.9**

H1 – ZEUS consistency: 2σ
Combined significance: 1.8σ



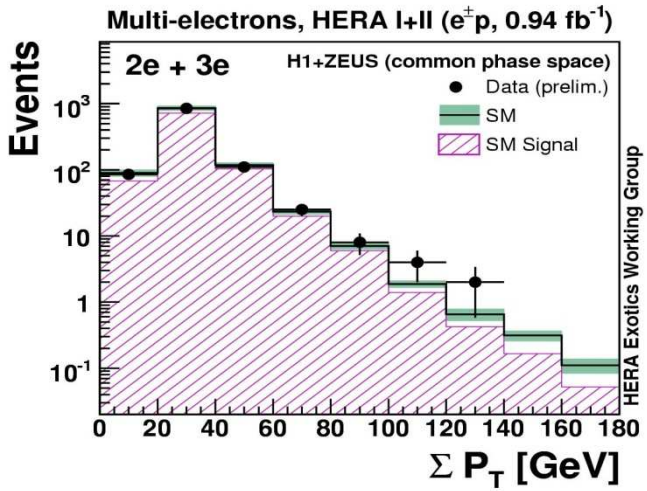
Multileptons at HERA

Multilepton production expected to be dominated by two-photon interactions



H1 selected events with 2 or 3 e or μ
with $\Sigma p_T > 100$ GeV
e^+p: 5 evts vs 0.96±0.12 expected
e^-p: 0 0.64±0.09

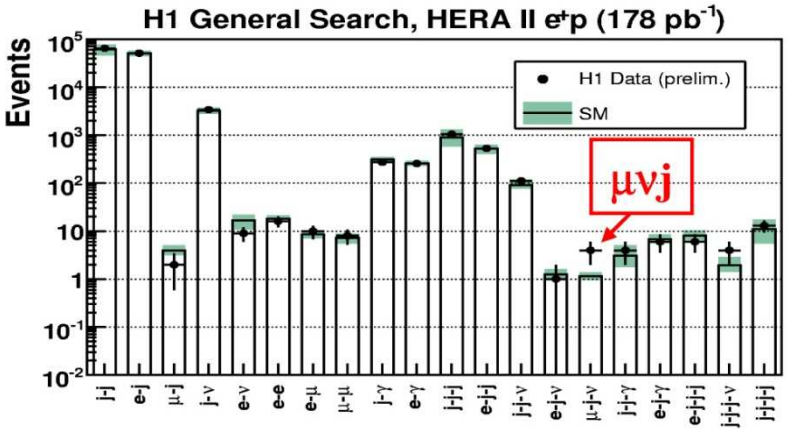
H1+Zeus performed a combination
in the 2 or 3 electron channel
e^+p: 5 evts vs 1.82±0.21 expected
e^-p: 1 1.19±0.14

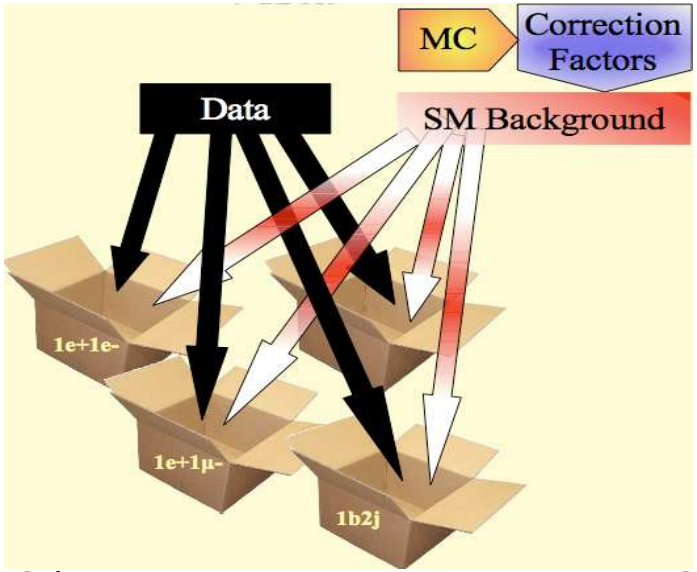


Grand (e and μ) combination underway

Global (model-independent) analysis

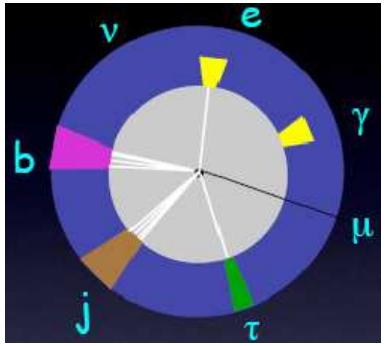
Initially at H1



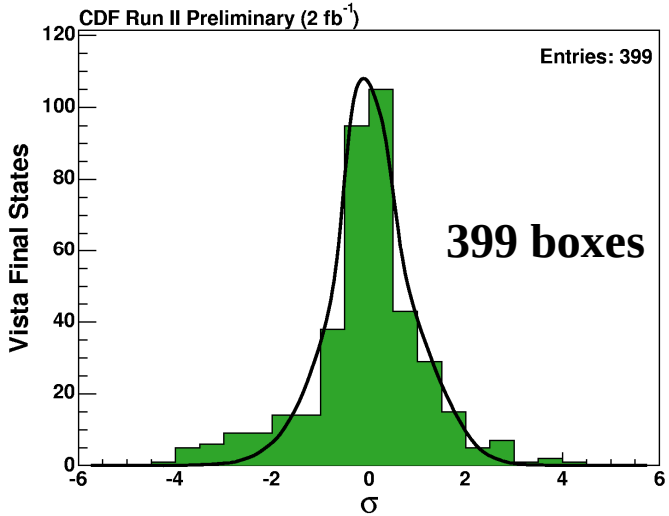


Now also CDF: "VISTA"

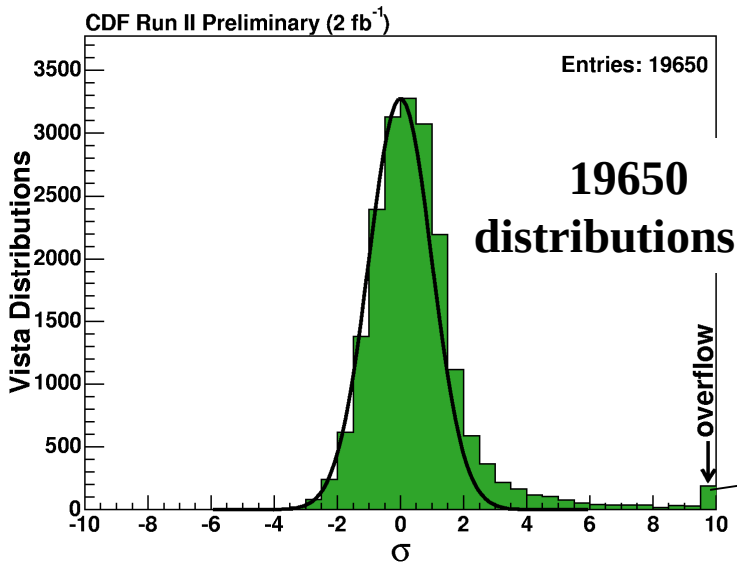
Categorize in terms of physics objects
(above some pT threshold)
and put events in exclusive boxes
(ej, μjj, γγ+MET, bbj,…)
as demanded by data



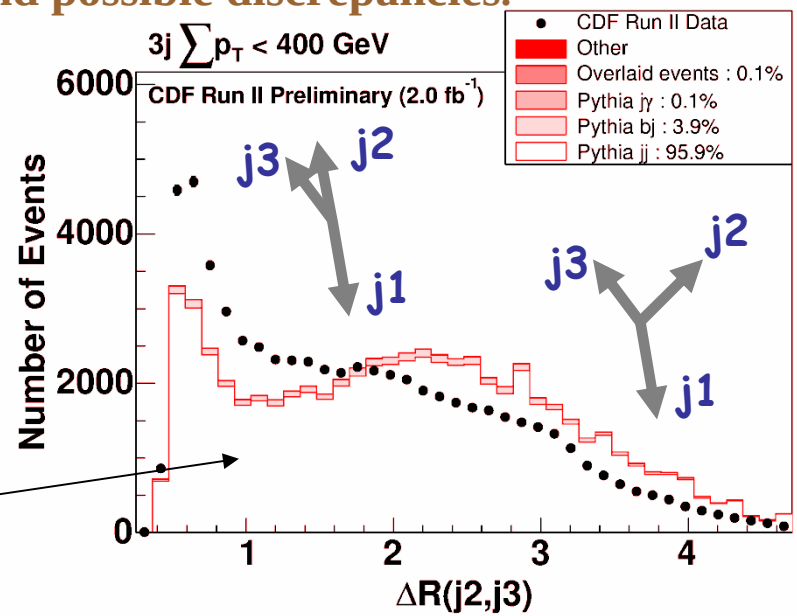
Improve SM description by adjusting a number of correction and normalization factors



Then look at a large number of distributions, and perform Kolmogorov-Smirnov tests to find possible discrepancies.



19650 distributions…



There are some, but very few, and not suggestive of "new physics", rather of an inadequate modeling of soft QCD

Once the bulk of the distributions is under control, look specifically at the high Σp_T tails ("Sleuth"), and check for mass bumps.

No more deviations than expected from statistics are found in 2 fb^{-1}

(taking into account the number of trials).

A similar conclusion was reached by H1

This exercise can be useful in case something was forgotten.

Otherwise, dedicated searches are (as expected) more sensitive

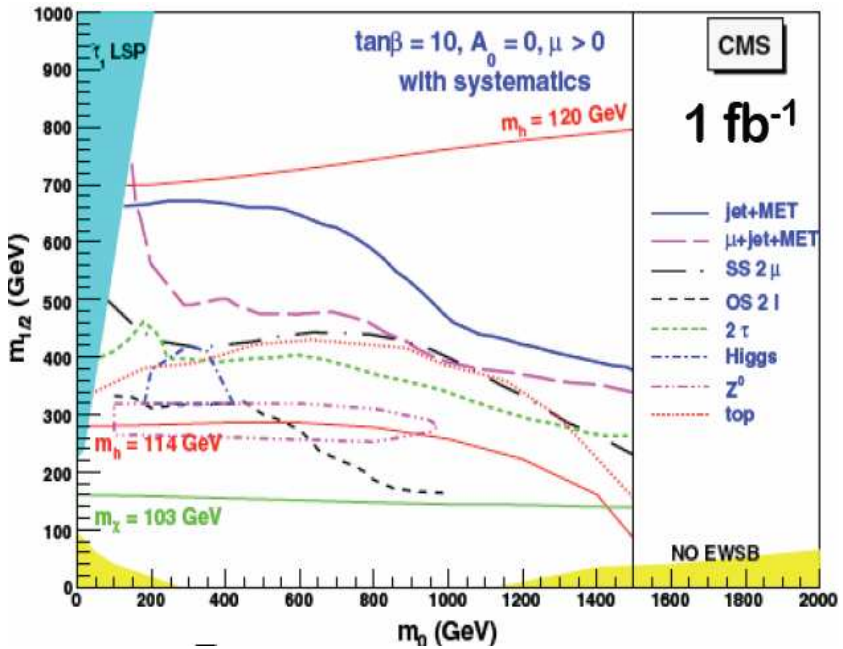
To conclude…

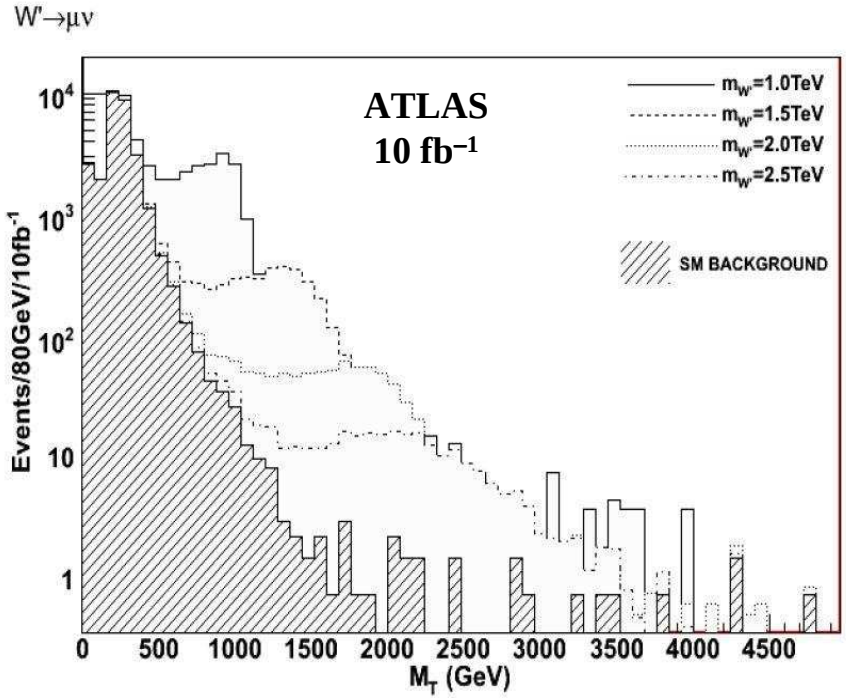
One year after the end of the HERA II run, H1 and ZEUS are delivering their final results, including combinations corresponding to an integrated luminosity of almost 1 fb^{-1}. A couple of intriguing anomalies in the H1 data will most likely remain unresolved in the foreseeable future.

Broad searches for phenomena beyond the standard model are being pursued by the CDF and DØ collaborations at the Tevatron, with steadily increasing integrated luminosities. Currently, results are reported by individual experiments with data samples corresponding to almost 3 fb^{-1}.

Unfortunately, there is at this point no sign of new physics, and the obvious way to provide rapidly constraints corresponding to the sensitivity expected with 6 fb^{-1} is to proceed with combinations of results of the two experiments.

…and time is running short…





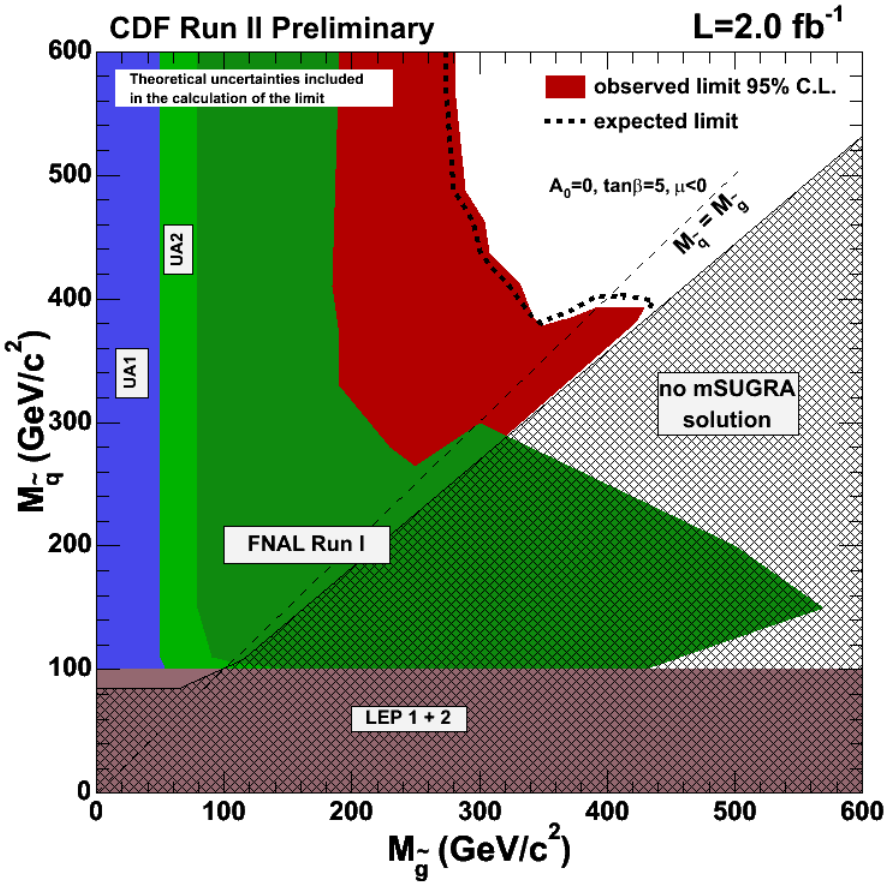
SUSY **W'**

Back up slides

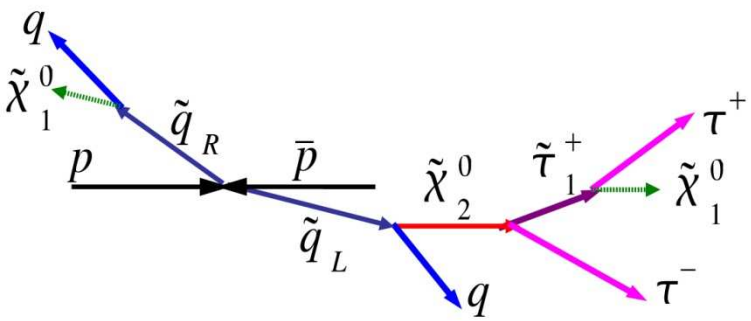
CDF search for squarks and gluinos.

Theoretical uncertainties included in the limit calculation

M(gluino) > 280 GeV
M(sq)=M(gl) > 392 GeV

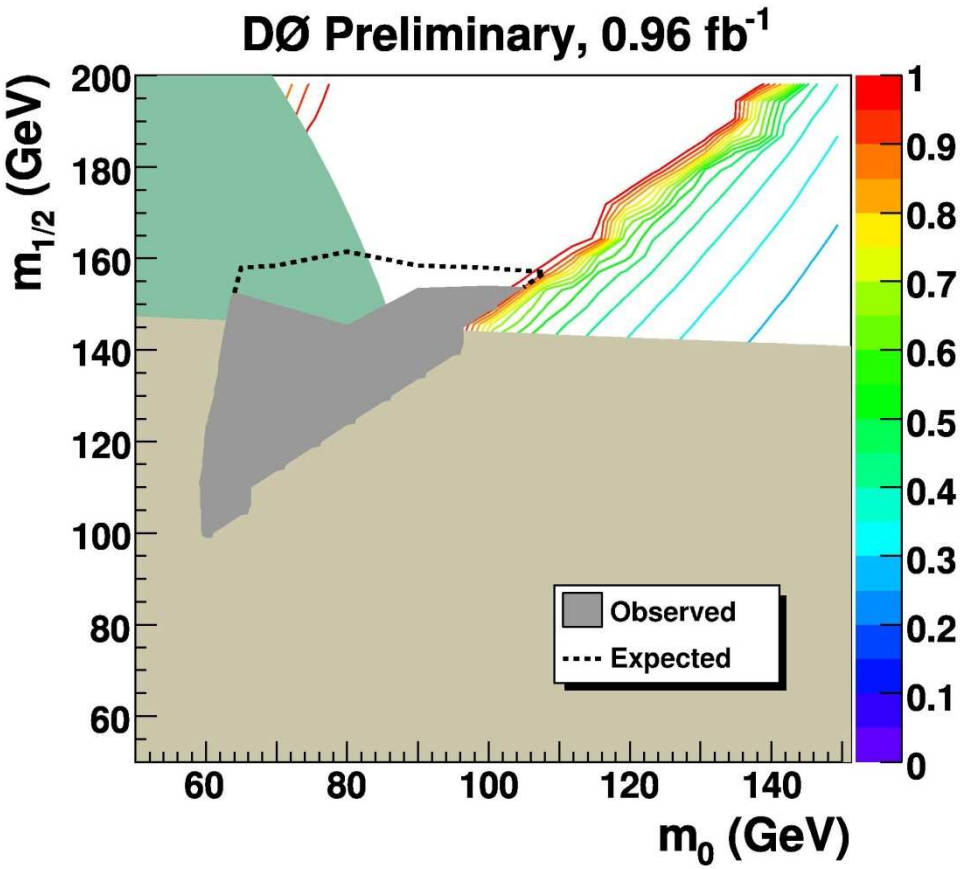


DØ search for squarks decaying into taus



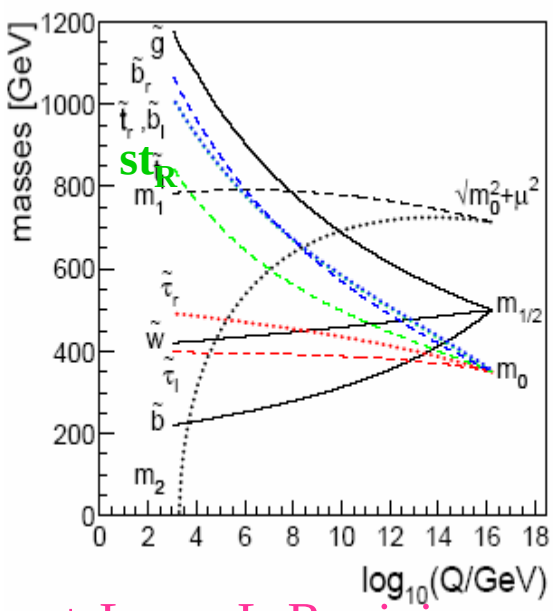
$\tan\beta = 15$
$\mu < 0$
$A_0 = -2m_0$

Lines = iso-BR for $\chi^+ \rightarrow \chi\tau^+\nu$



Stop

A light stop can be expected:
top-Yukawa impact in RGE

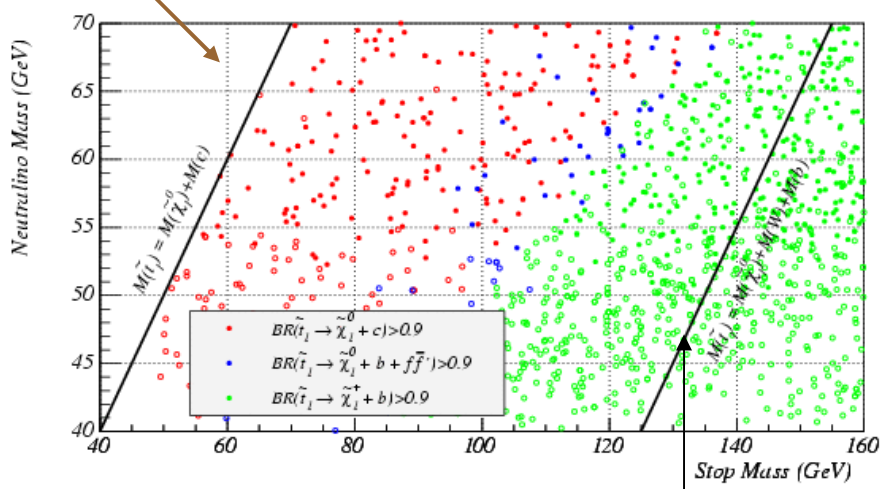


+ Large L-R mixing

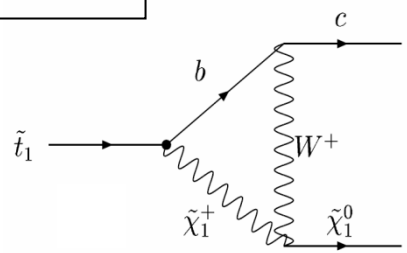
Depending on the mass hierarchy,
two main scenarios for stop decays:

mSUGRA scan

$\tilde{t}_1 \to c\,\tilde{\chi}^0$ $\tilde{t}_1 \to b\,\tilde{\chi}^{+/-}$



$\tilde{t}_1 \to c\,\tilde{\chi}^0$



relevant up to $m(\tilde{t}) = m(b)+m(W)+m(\chi)$
if gaugino mass unification is dropped

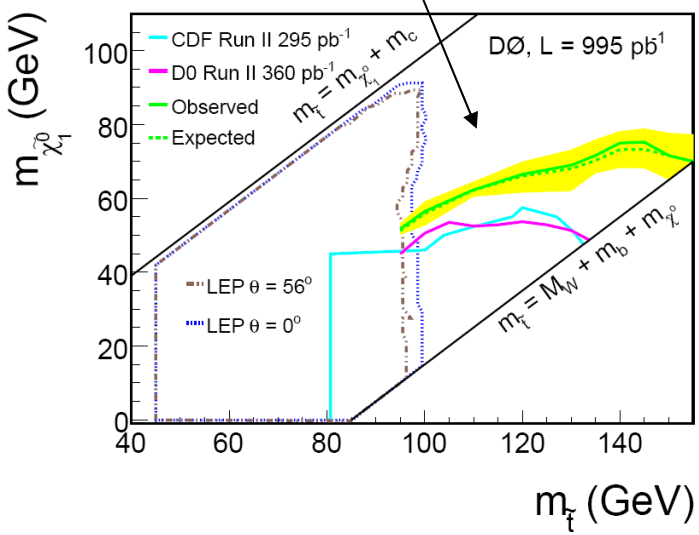
$$\tilde{t}_1 \to c\,\tilde{\chi}^0$$

While for generic squarks,
the mass range of interest
is ~ 400 GeV,
it is here ~ 150 GeV
(only one quark specie)

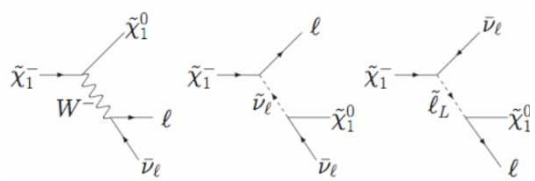
HF-tagging comes to help !

2 jets, with ≥ 1 c-jet (soft tag)
missing E_T and HT cuts
optimized for various m(st),m(χ)

This region is very difficult:
soft jets, low MET

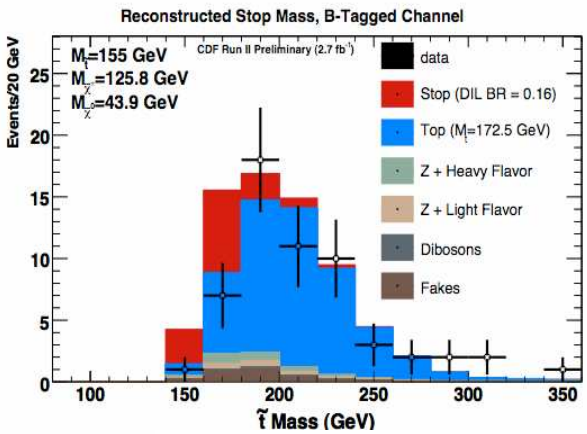


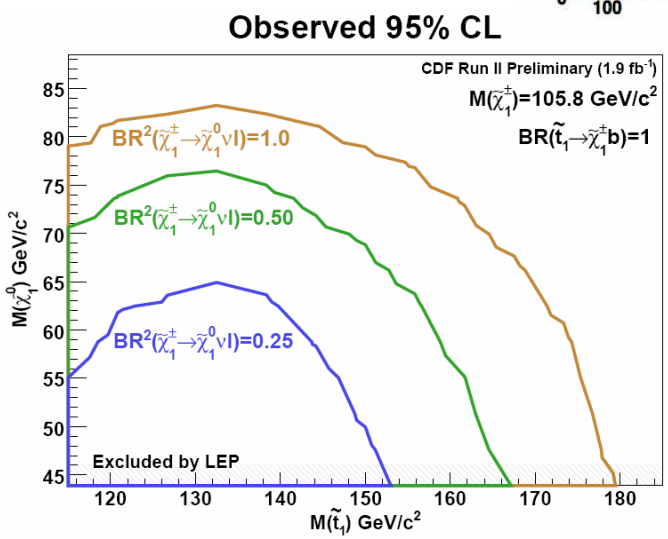
$$\tilde{t}_1 \to b\,\tilde{\chi}^{+/-}$$



Leptonic branching fraction enhanced for light sleptons

The final state is similar to top pairs in dileptons, with additional missing ET from the neutralinos.
Use a **"reconstructed stop mass"** to discriminate.



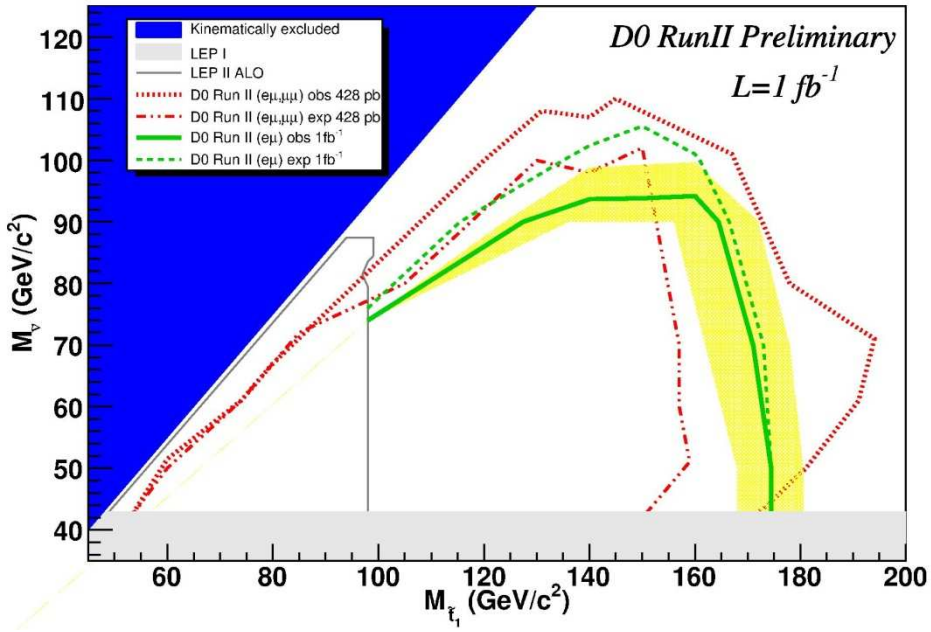


No sensitivity yet for heavy sleptons (BR=0.1)

DØ search for stop → b l sneutrino

Results in the e-μ channel

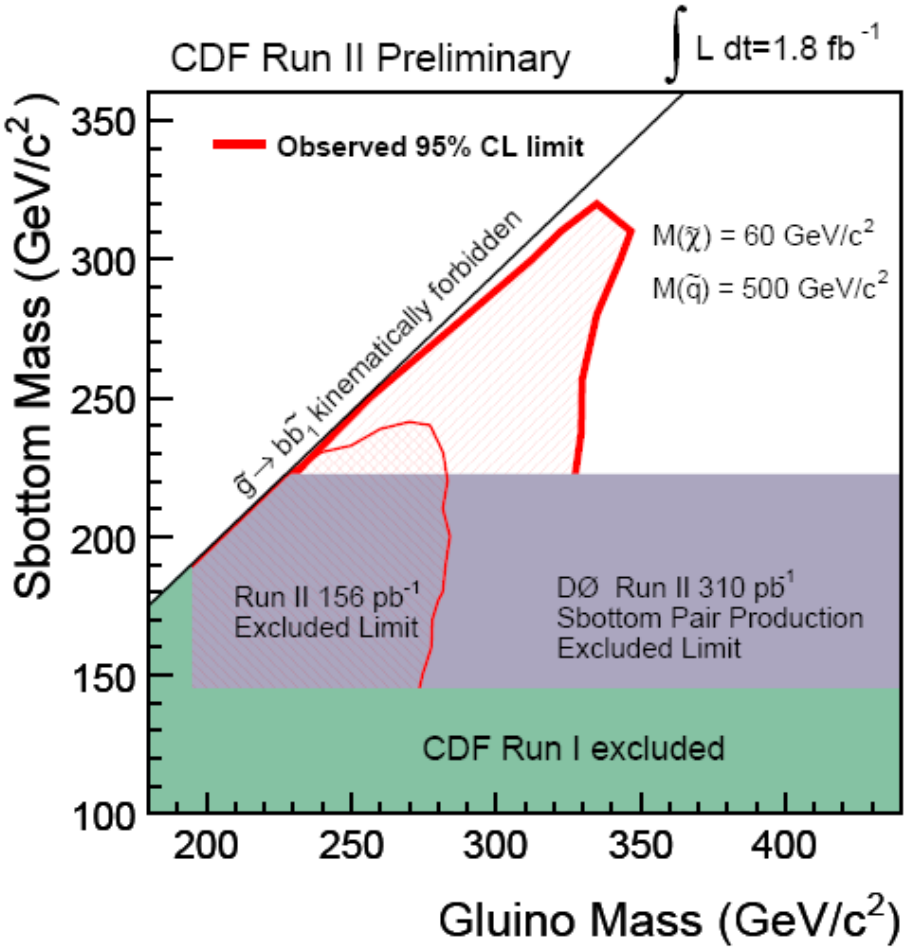
100% leptonic BR assumed
Equal e-μ-τ fractions



CDF search for sbottoms in gluino decays

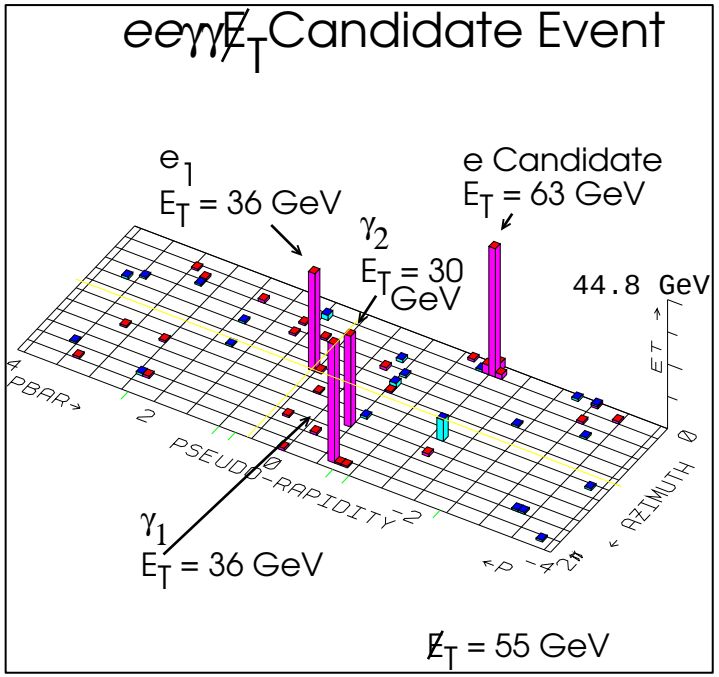
Gluino → b sbottom
Sbottom →b χ

Gluino pair → 4b + MET



Searches at LEP

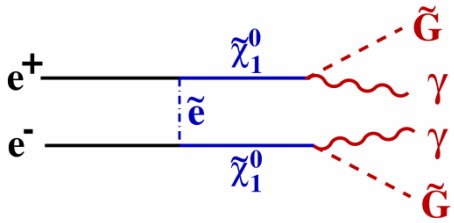
Remember ?

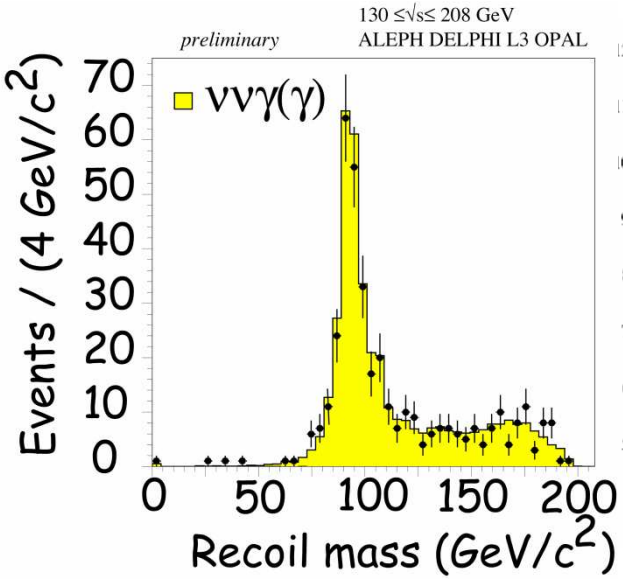


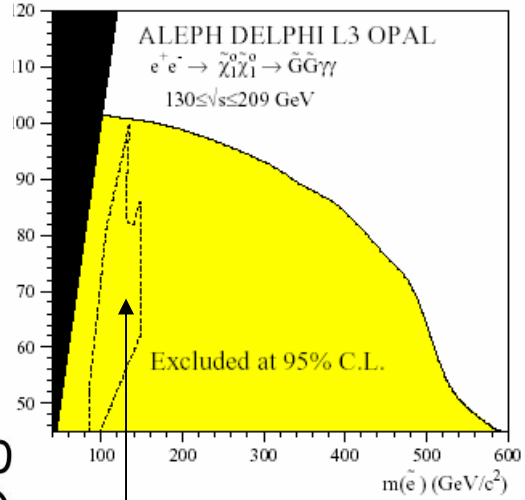
eeγγ+MET

CDF – Run I

At LEP, look for
χ pair production:
γγ + missing energy





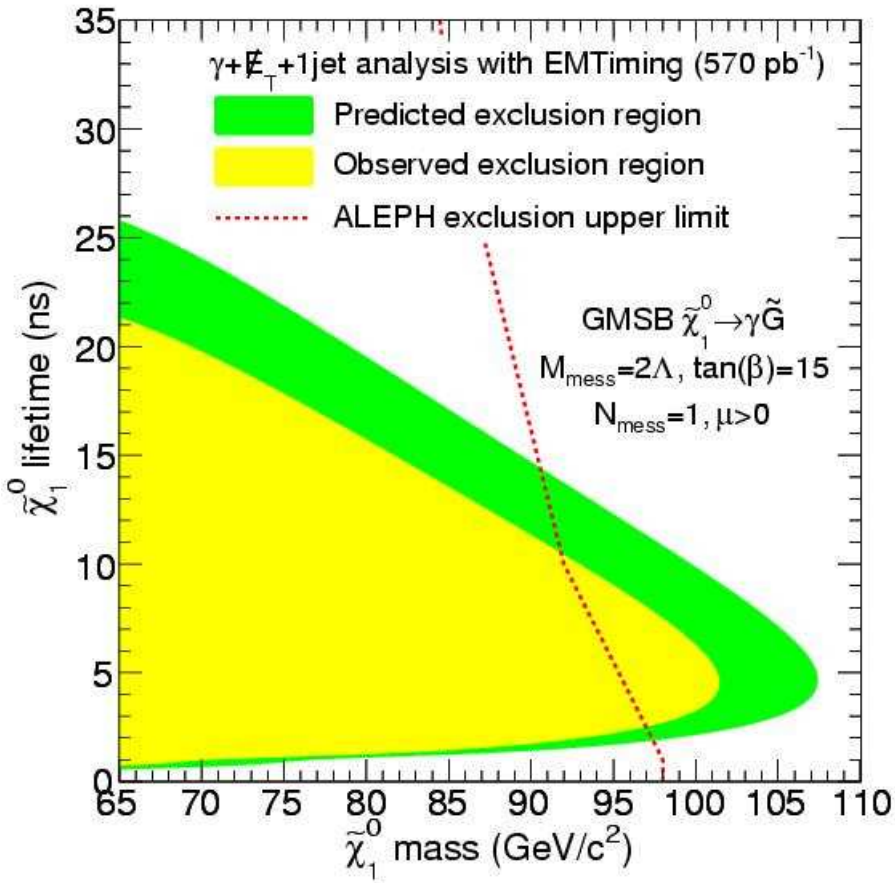


Interpretation as sel→eχ→eγG

CDF search for long-lived neutralinos

In GMSB

Using timing information in calorimeter

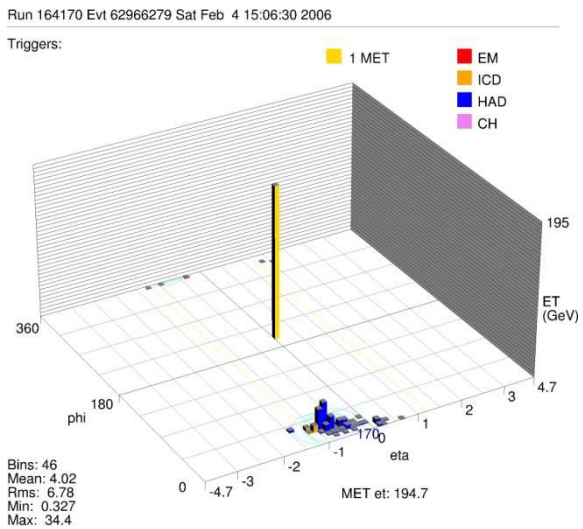


Long-lived Gluinos

In "Split-SUSY", squarks are ultra-heavy ⇒ long-lived gluinos

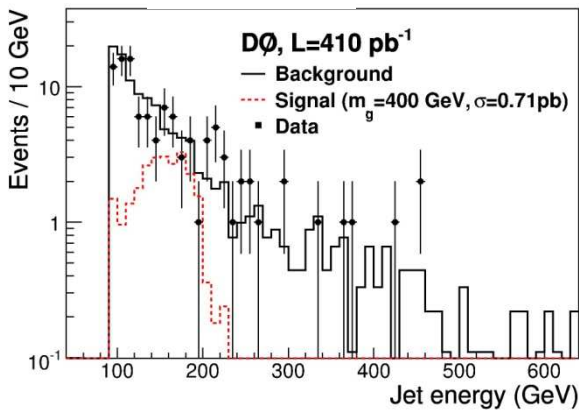
Such gluinos form R-hadrons which may stop in the calorimeter.

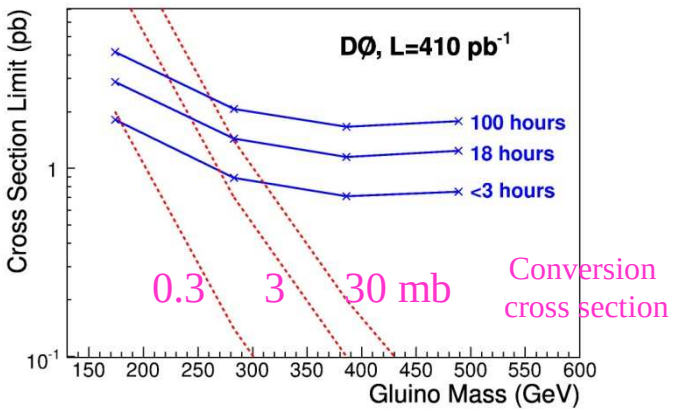
(A. Arvanitaki et al., arXiv:hep-ph/0506242)



After a while, they decay into a gluon + χ_1^0

(q-qbar-χ_1^0 also possible).





Strategy:
look for a randomly oriented monojet in an otherwise empty event
(diffractive-gap trigger).

Backgrounds:
beam and cosmic muons, measured in data.

For m_χ < ~100 GeV gluino masses up to ~ 270 GeV are excluded

LED at HERA

Fit to NC DIS data yields limits on M_S …

ZEUS (94-06 data):

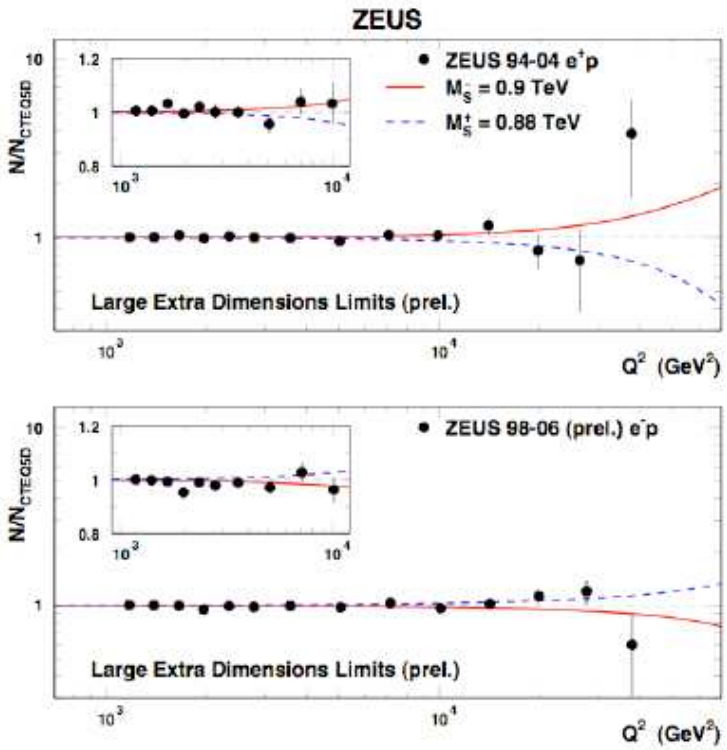
$M_S^- > 0.90$ TeV at 95% CL

$M_S^+ > 0.88$ TeV at 95% CL

H1 (HERA I data):

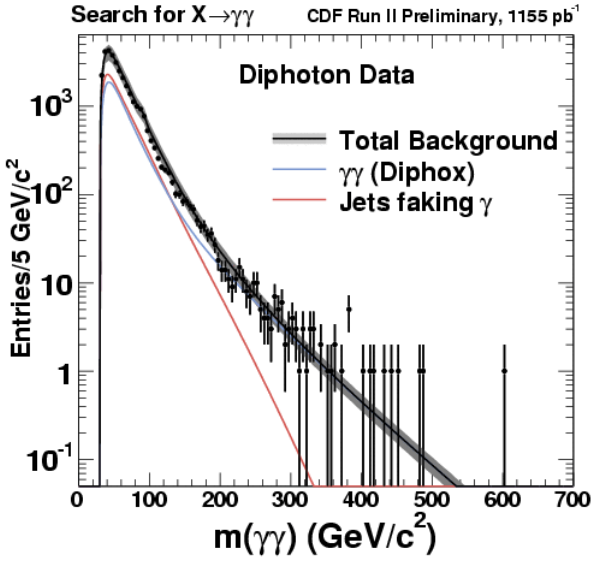
$M_S^- > 0.78$ TeV at 95% CL

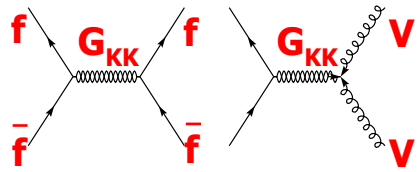
$M_S^+ > 0.82$ TeV at 95% CL

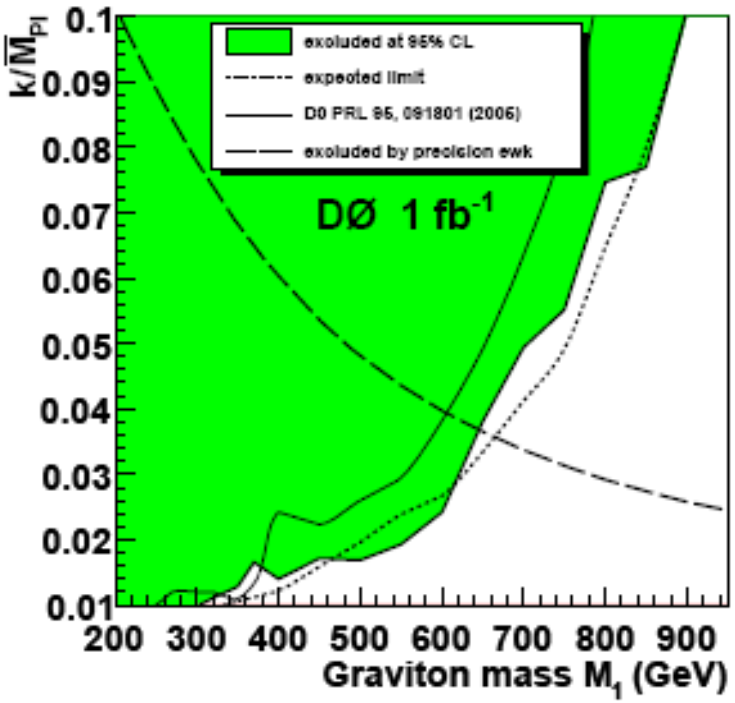


Randall – Sundrum gravitons

Here too, most of the sensitivity is in diphotons (BR = 2*ee)
But now look for a narrow resonance in the mass spectrum







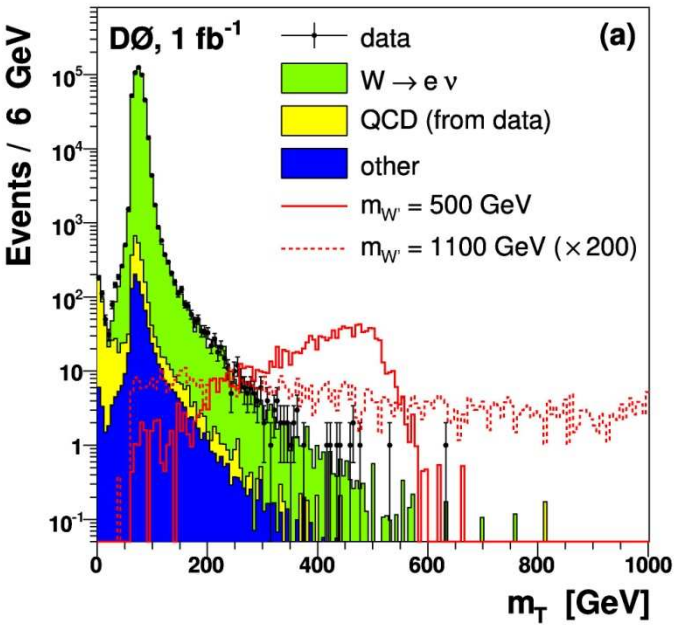
Two model parameters:
Mass and coupling (κ/M_{Pl})

For κ/M_{Pl} = 0.1: M > 900 GeV

CDF in μμ with 2.3 fb⁻¹: M > 921 GeV for κ/MPl = 0.1

ExtraW’

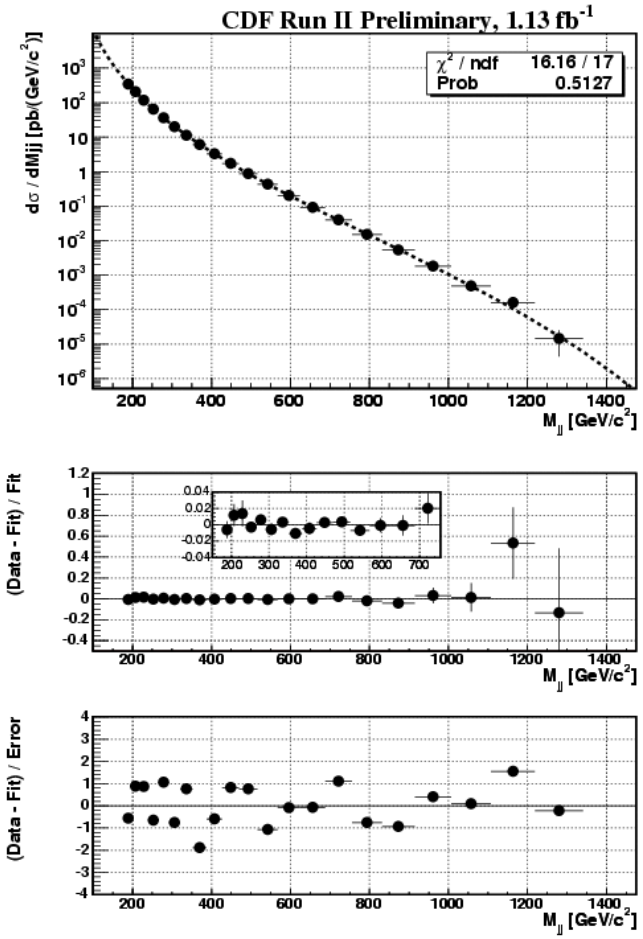
W’ → eν

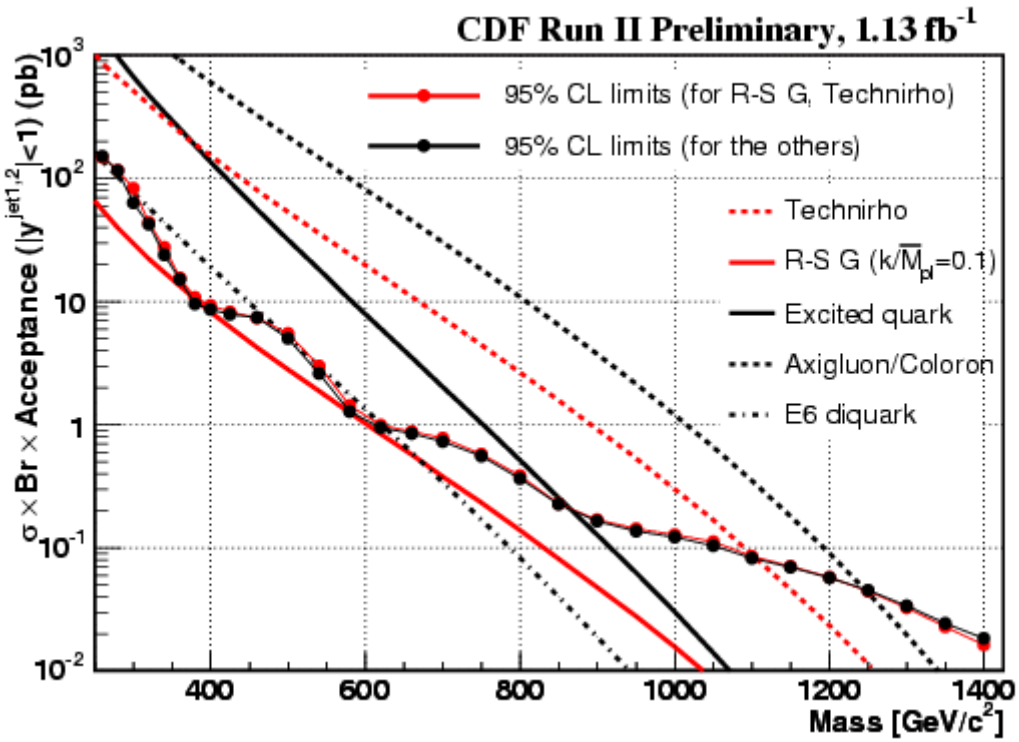


M_T = M(electron-p_T,missing-E_T)

M(W’-seq.) > 1000 GeV

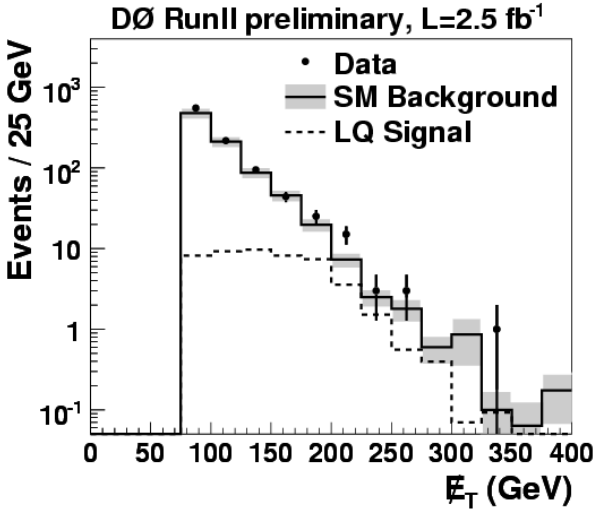
CDF search for dijet resonances





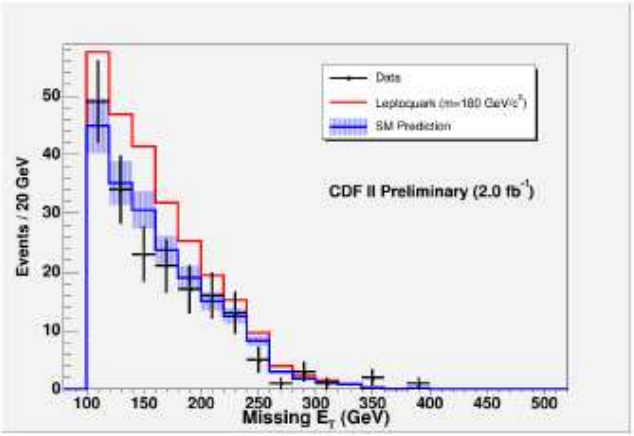
Limit up to 1.25 TeV for axigluons

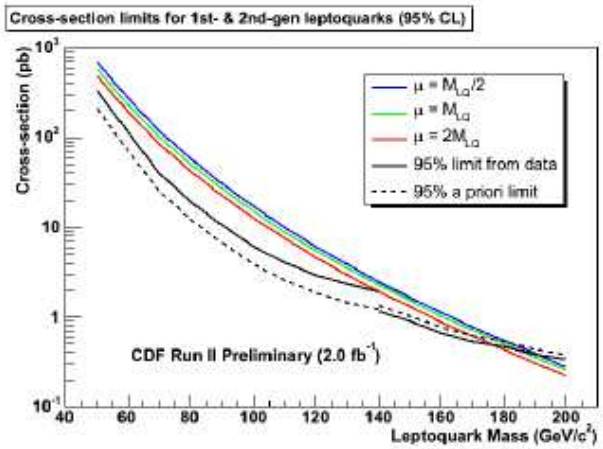
Leptoquarks (β=0)

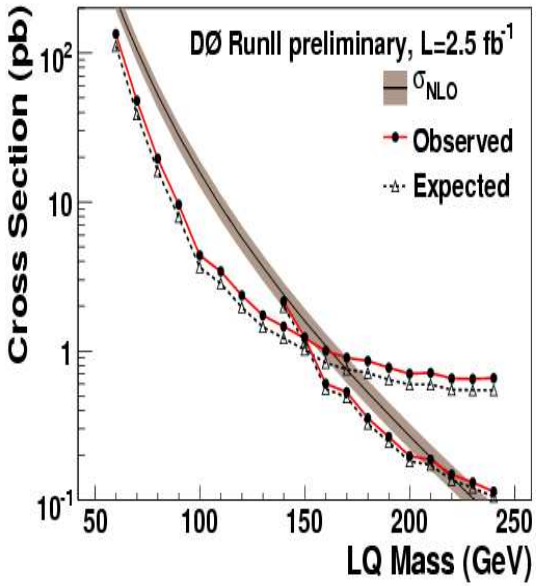


Limits on Scalar Leptoquark Model:

Leptoquark Generation	Lower Mass Limit (GeV/c^2)
1st or 2nd	177
3rd	167



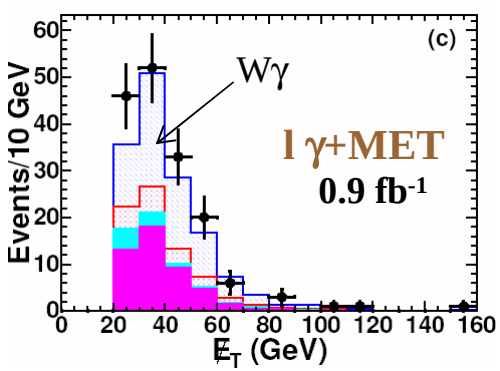


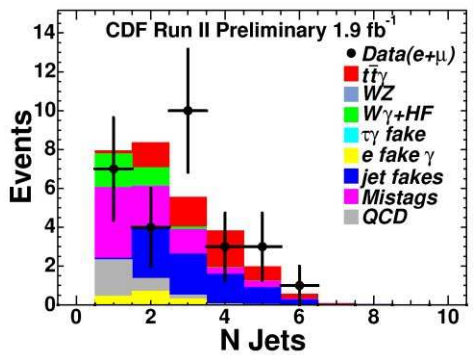


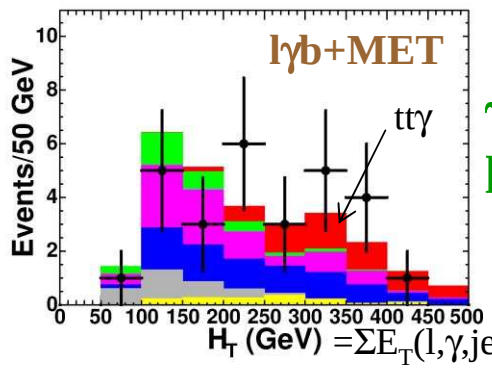
Signature based searches

CDF checked event counts and kinematic distributions in many channels:

llγ, lγγ
γγγ
lγ+MET
γγ+MET





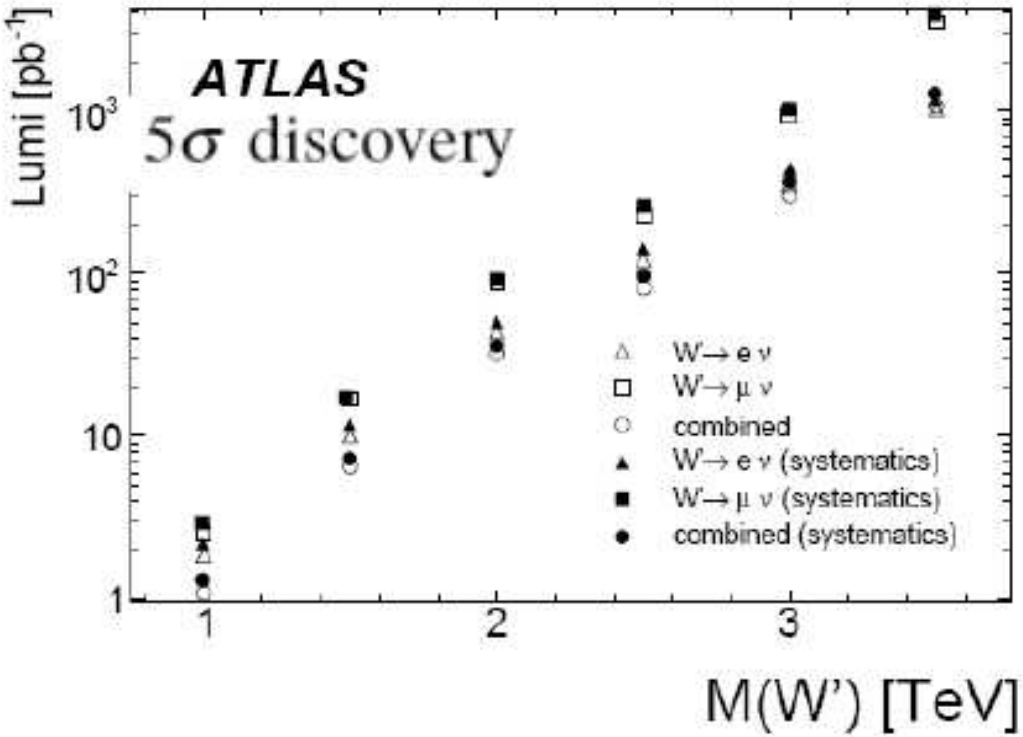


$=\Sigma E_T(l,\gamma,\text{jets},\text{MET})$

γbj+MET
lγb+MET

No deviation from SM in 1 to 2 fb-1

W' discovery potential at the LHC



The end