Search for New Physics at Fermilab

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1. **Introduction**

   Selected topics from CDF, DØ , E832(KTeV), and CCFR(NuTeV) collaborations are:

2. **LeptoQuarks (LQ)**
3. **Supersymmetry (SUSY)**
4. **Higgs**
5. $X_{NP} \to jj$, W'/Z', **Stable Charged Particles**
6. **Neutrino physics** ($\nu_\mu \to \nu_e$ **oscillation** *etc.*)

7. **Summary**

Introduction

Curriculum Vita

Personal

Name	Standard Model $SU(3) \times SU(2) \times U(1)$
Year of Birth	1967

Education

1995	Ph.D. - "Top Discovery" @Fermilab Tevatron (1.8 TeV $p\overline{p}$)
1983	M.S. - "$W^{\pm}/Z$ discovery" @CERN Sp$\overline{p}$S (540 GeV $p\overline{p}$)
1973	B.S. - Neutral current @CERN SPS (400 GeV p)

Research

1997-Present	Searching for new particles beyond the SM.
1967 -1996	Does explain all data in the world.
	Does not provide the answers to various questions Why is the top quark mass so heavy ? Why $\sin^2\theta_W = 0.2325$? Why L.H. ? , GUT ? *etc.*

Search for LeptoQuarks (LQ)

LQ: Color-triplet boson which couples both to a quark and a lepton; $\beta \equiv Br(LQ \to \ell^{\pm} + q)$

HERA: high-Q^2 $e\ j$ events as LQ interaction

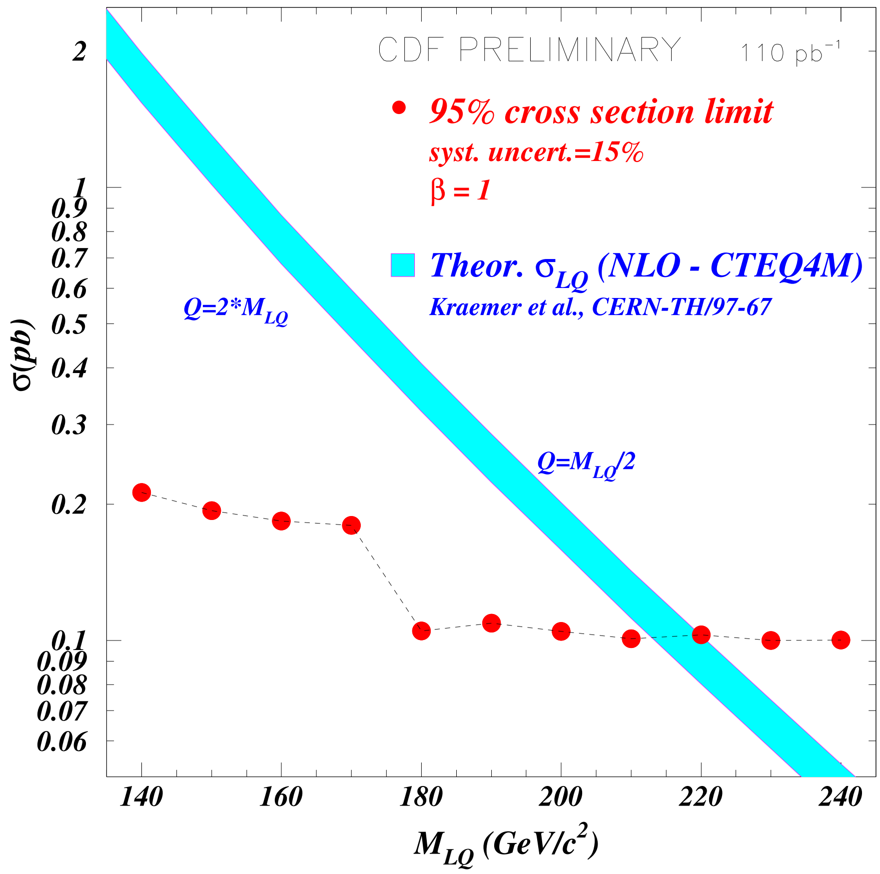
$$e^+ p \longrightarrow LQ_1 \xrightarrow{\beta \cong 1} \overbrace{e^+ + q}^{200\ \mathrm{GeV/c^2}}$$

CDF/ DØ : 3 generations

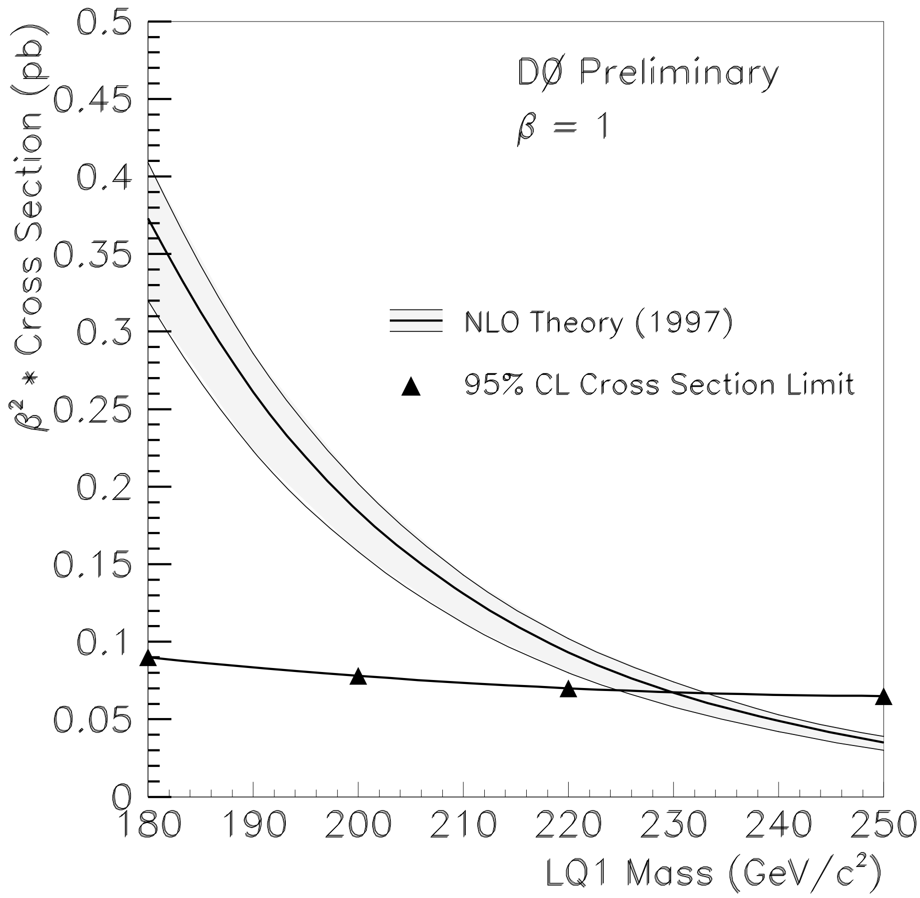
$$\begin{array}{llll} p\bar{p} \to LQ\overline{LQ} \to & (\ell^- j)(\ell^+ j) & \beta^2 & \surd \\ & (\ell^{\pm} j)(\nu j) & 2\,\beta(1-\beta) & \surd \\ & (\nu j)(\bar{\nu} j) & (1-\beta)^2 & \surd \end{array}$$

- Strong (less-model dependent) production
- NLO cross sections

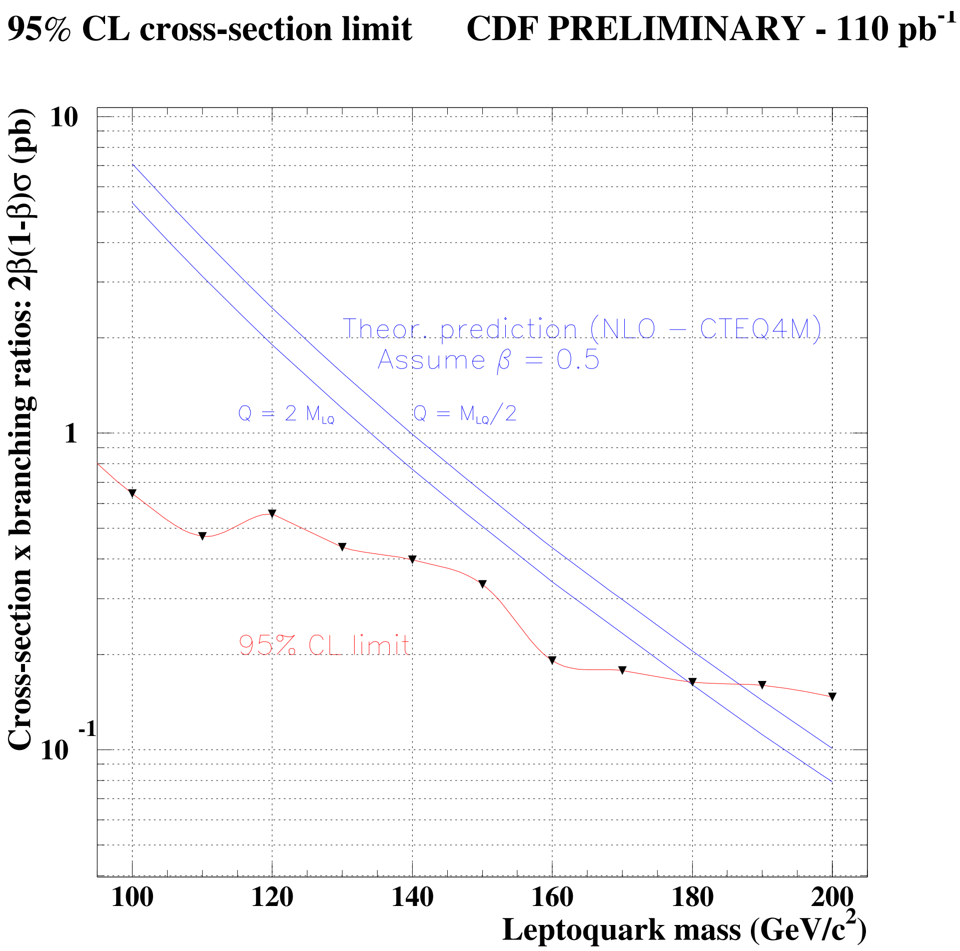
CDF LQ1: $(eejj)$



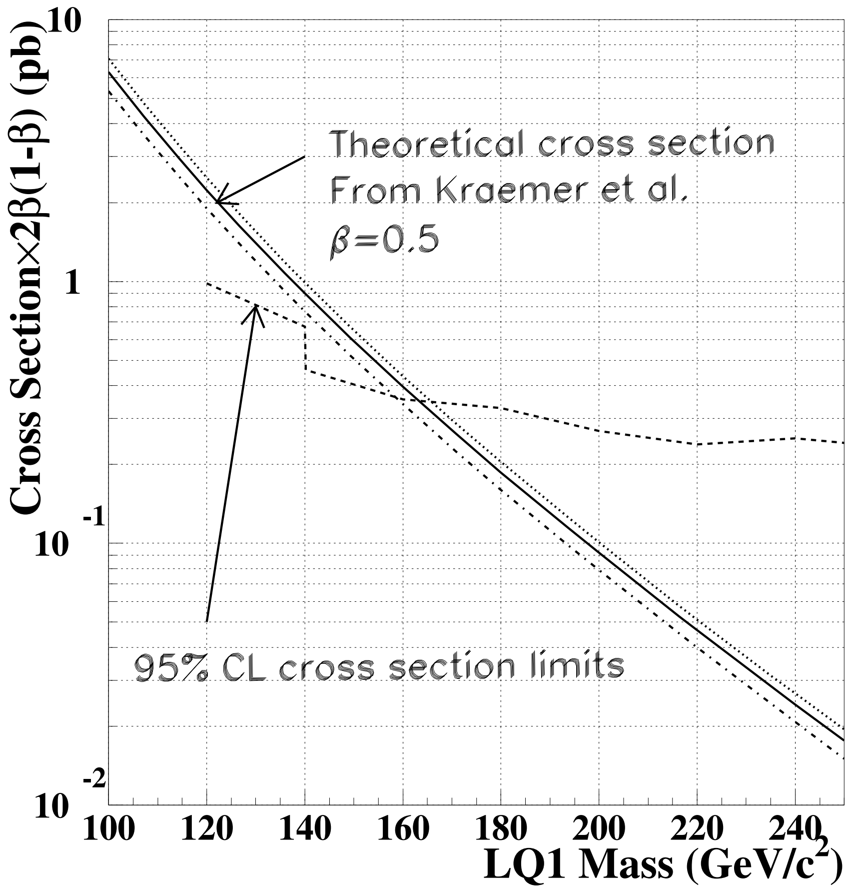
DØ LQ1: $(eejj)$



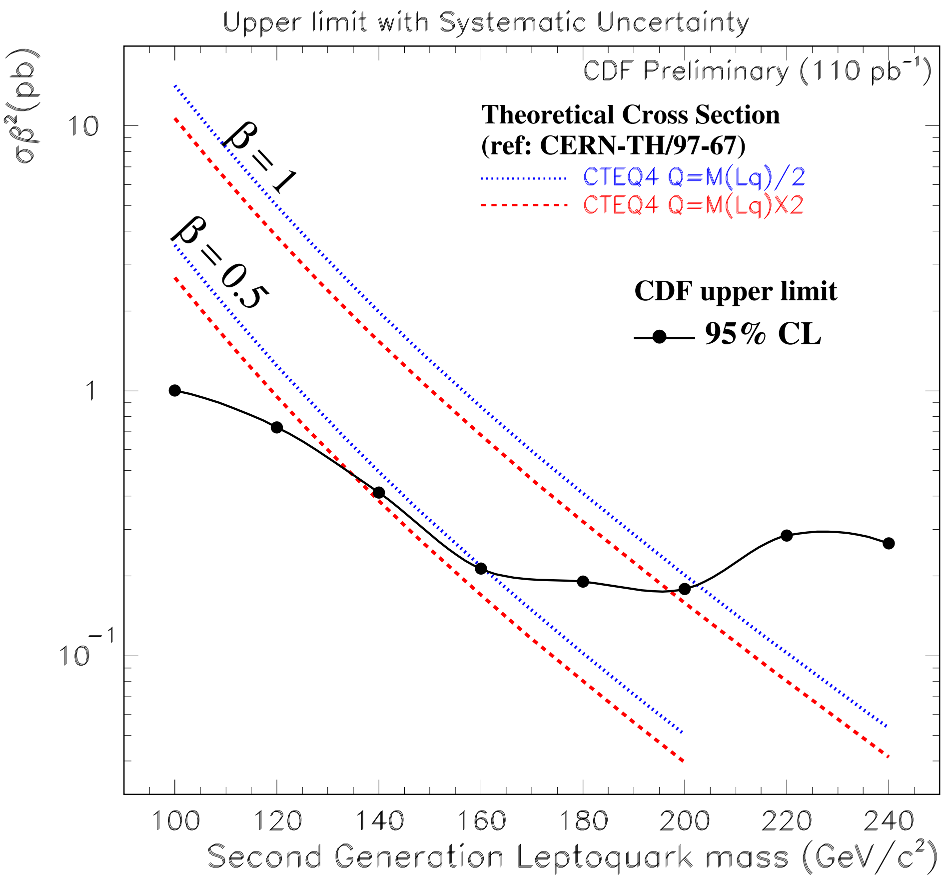
CDF LQ1: $(e\nu jj)$



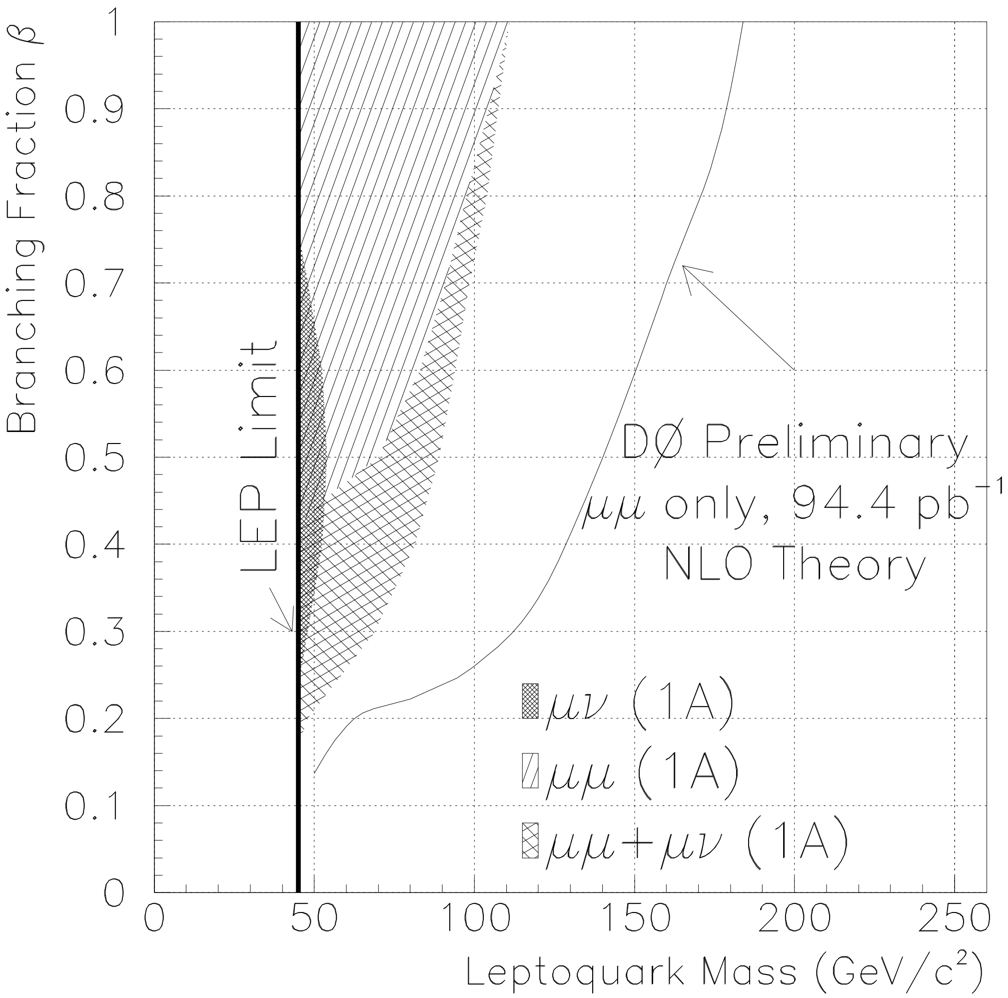
DØ LQ1: $(e\nu jj)$



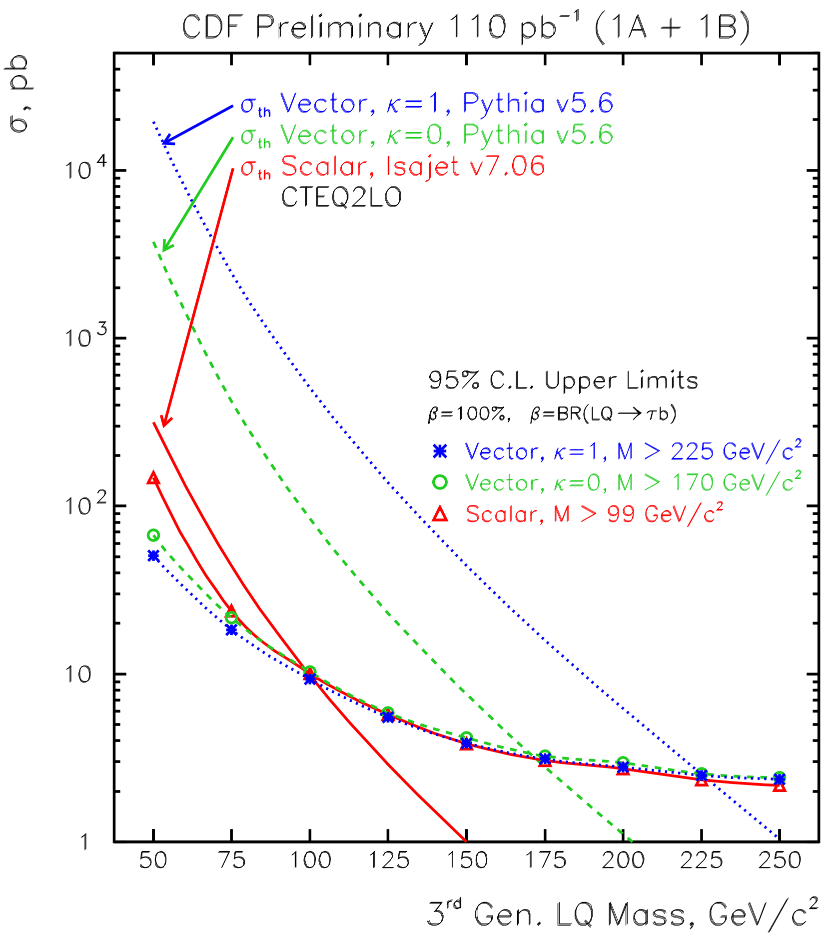
CDF LQ2: $(\mu\mu jj)$



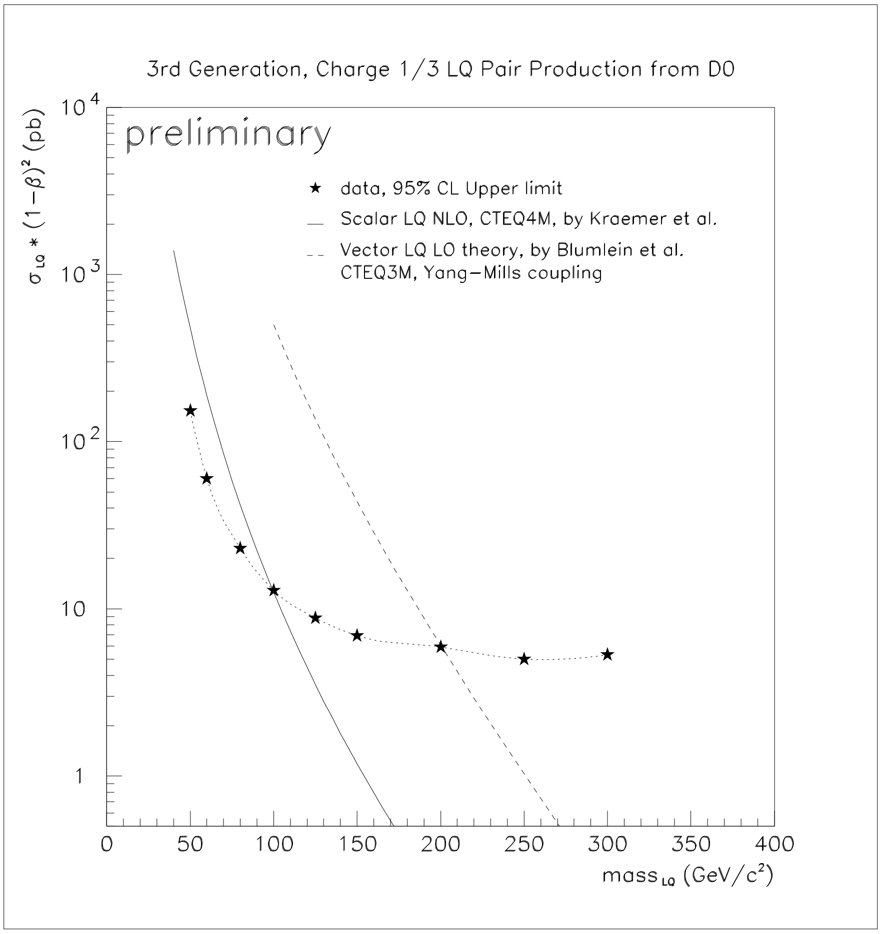
DØ LQ2: $(\mu\mu jj)$



CDF LQ3: $(\tau^+\tau^- jj)$



DØ LQ3: $(\nu\bar{\nu}jj)$



Summary of Preliminary Results on LQ Searches

	CDF (110 pb^{-1})	DØ (123 pb^{-1})
LQ1	$ee + jj$ and Z veto	
	$\sum E_T(e)$ and $\sum E_T(j)$	$\sum E_T(e) + \sum E_T(j)$
	Mass balance	—
	$e\nu + jj$ and High $M_T(e, \not{E}_T)$	
	b veto/Kinematical cuts	Kinematical cuts
	Mass balance	
Mass Limits (NLO)		
$eejj$ $\beta = 1.0$	210 GeV/c^2	225 GeV/c^2
$eejj$ $\beta = 0.5$	158 GeV/c^2	176 GeV/c^2
$e\nu jj$ $\beta = 0.5$	180 GeV/c^2	160 GeV/c^2
$eejj + e\nu jj$ $\beta = 0.5$	n/a	192 GeV/c^2

	CDF (110 pb^{-1})	DØ (94 pb^{-1})
LQ2	$\mu\mu + jj$ and Z veto	
	—	$\sum E_T(\mu) + \sum E_T(j)$
	Mass balance	Top veto
Mass Limits (NLO)		
$\mu\mu jj$ $\beta = 1.0$	195 GeV/c^2	184 GeV/c^2
$\mu\mu jj$ $\beta = 0.5$	n/a	140 GeV/c^2

	CDF (110 pb^{-1})	DØ (92 pb^{-1})
LQ3	$\tau^+\tau^- + b\bar{b}$	$\nu_\tau\bar{\nu}_\tau + b\bar{b}$
	$(\tau_1 \to \ell + X,\ \tau_2 \to h's)$	(from 3 triggers)
Mass Limits	(LO - published)	(NLO)
	99 GeV/$c^2 (\beta = 1)$	98 GeV/$c^2 (1 - \beta = 1)$

Search for SUSY Particles

Minimal Supersymmetric Standard Model (MSSM):

Supersymmetrized (fermion $\leftrightarrow$ boson)
Standard Model with two Higgs doublets

CDF/ DØ :

1. SuperGravity (SUGRA) constraint MSSM:

   $\Rightarrow$ the lightest neutralino ($\tilde{\chi}_1^0$) is the lightest supersymmetric particle (LSP)

   $\Rightarrow$ the LSP is stable (R-parity is conserved)

   $\Rightarrow$ $\not\!\!E_T$ signature

2. Gauge mediated SUSY: $\tilde{\chi}_1^0 \rightarrow \gamma\ \tilde{G}$

   $\Rightarrow$ gravitino ($\tilde{G}$) is a stable LSP

   $\Rightarrow$ $\gamma + \not\!\!E_T$ signature

CDF:

3. $\tilde{c}_L \xrightarrow{\not R_p} e^+\ d_R$

E832(KTeV):

4. Long-lived hadrons containing light gluino

SUSY: $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow (\ell\ \nu\tilde{\chi}_1^0)\ (\ell\ell\ \tilde{\chi}_1^0)$

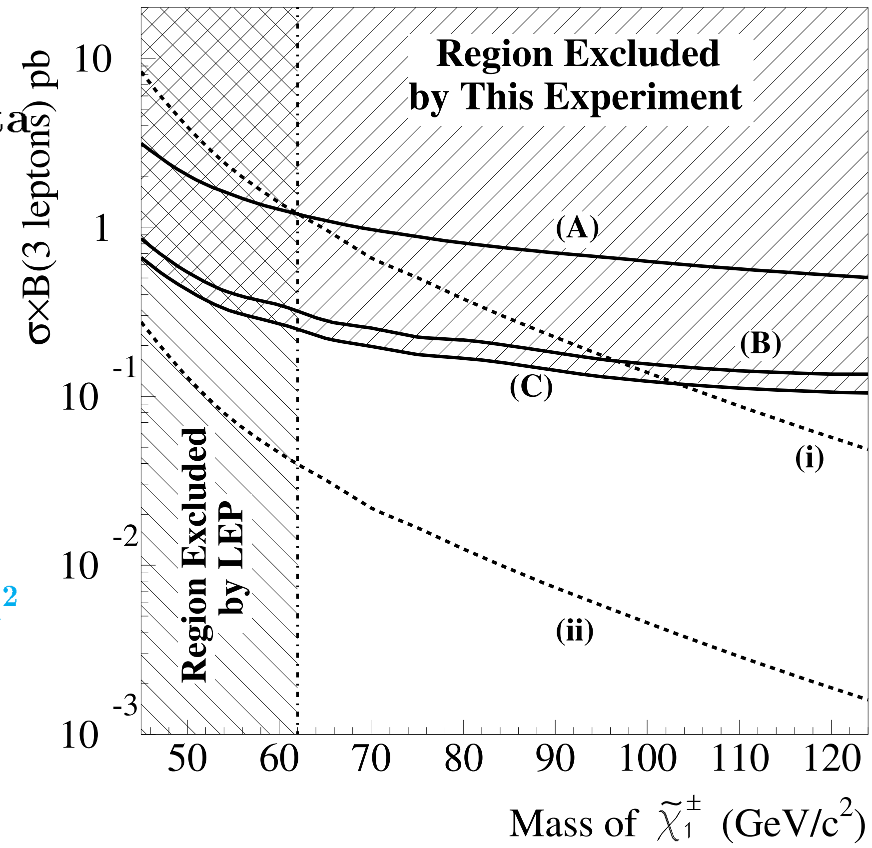
SUSY: $\tilde{\chi}_1^{\pm}$**(chargino)** $\leftrightarrow W^{\pm}$
$\tilde{\chi}_2^0$**(neutralino)** $\leftrightarrow Z^0$

DØ/CDF: $M_{\tilde{\chi}_1^{\pm}} \cong M_{\tilde{\chi}_2^0} \cong 2\ M_{\tilde{\chi}_1^0}$ **(LSP)**

√ **DØ limits on $\sigma \cdot Br$(single trilepton mode)**

(A) 1992-93 data
(B) 1994-95 data
(C) Combined data

LEP limit:
$M_{\tilde{\chi}_1^{\pm}} \gtrsim \sqrt{s}/2$
$= 85\ \ \mathrm{GeV}/c^2$



Br varies from (i) 1/9 [1] to (ii) 0.0036 [2] depending on slepton ($\tilde{\ell}$) and sneutrino ($\tilde{\nu}$) masses.

√ **$\sigma \cdot Br < 0.2$ pb (DØ) and 0.15 pb (CDF preliminary) at $M_{\tilde{\chi}_1^{\pm}} = 70\ \ \mathrm{GeV}/c^2$ at 95% C.L. (≅100 pb^{-1})**

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[1] $M_{\tilde{\nu}} > M_{\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0} > M_{\tilde{\ell}}$

[2] $M_{\tilde{\ell}}, M_{\tilde{\nu}} > M_{\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0}$

SUSY: $\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\bar{\tilde{q}} \to \not{E}_T + n$-jets, $\ell\ell + X$

SUSY: SUGRA-constraint MSSM

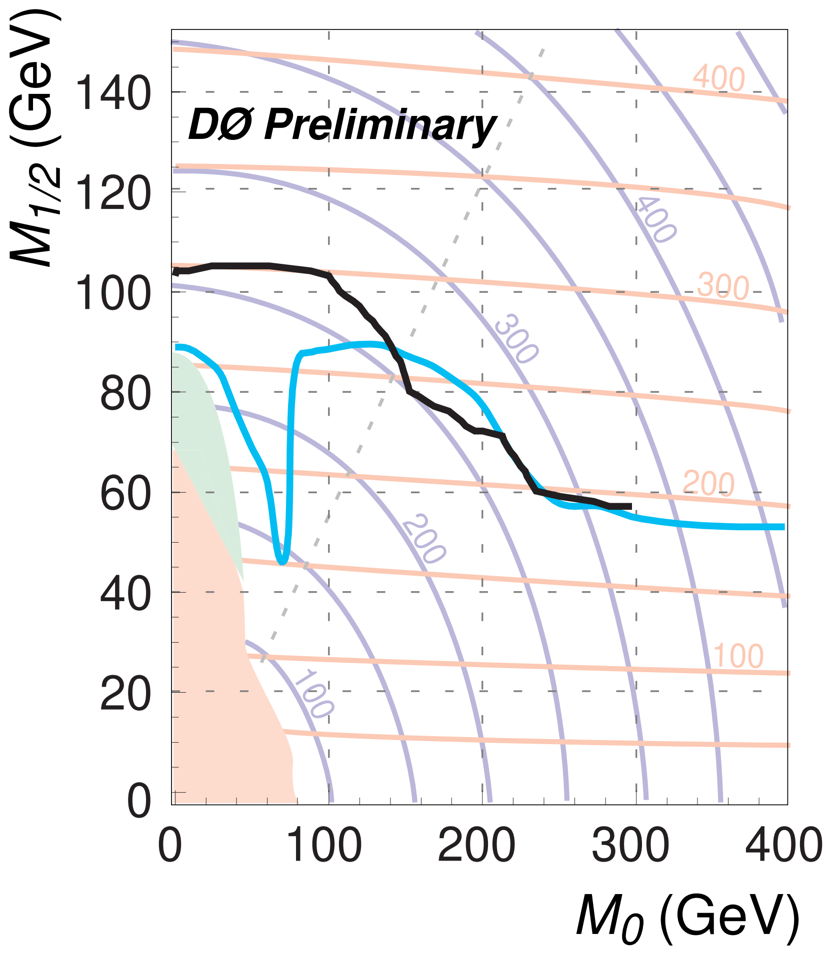
$$e.g., \ \tilde{u} \to d\tilde{\chi}_1^+ \to d\ q\bar{q}'\tilde{\chi}_1^0 \text{ or } d\ \ell^+\nu\tilde{\chi}_1^0$$

DØ/CDF: $M_{\tilde{\chi}_1^\pm} \cong M_{\tilde{\chi}_2^0} \cong 2\ M_{\tilde{\chi}_1^0}$ (LSP)

√ DØ premilinary limits on $M_{1/2}(M_{\tilde{g}})$ vs $M_0(M_{\tilde{g}}, M_{\tilde{q}})$: ($\tan\beta = 2,\ A = 0,\ \mu < 0$)

(a) $\not{E}_T + jets$ (79 pb^{-1})

(b) ee channel (93 pb^{-1})



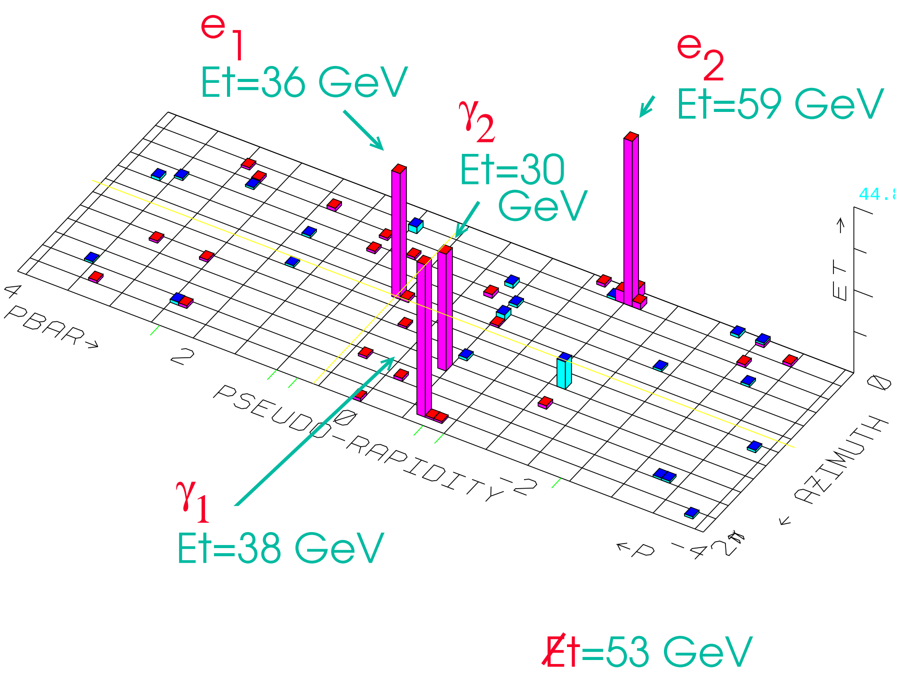
$M_{\tilde{q}} > 260\ \ \text{GeV}/c^2\ (M_{\tilde{q}} = M_{\tilde{g}})$

√ CDF preliminary limits are similar to DØ on (a) $\not{E}_T + jets$ and (b) $ee, \mu\mu, e\mu + jets$ channels

SUSY: $\tilde{S}\bar{\tilde{S}} \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 + X$
$\to \gamma\gamma + \not{E}_T + X$

2-years old "$ee\gamma\gamma\not{E}_T$" event from CDF

Event: $2\, e + 2\, \gamma + \not{E}_t$



Gauge mediated SUSY: $\tilde{\chi}_1^0 \to \gamma \tilde{G}(\mathrm{LSP})$

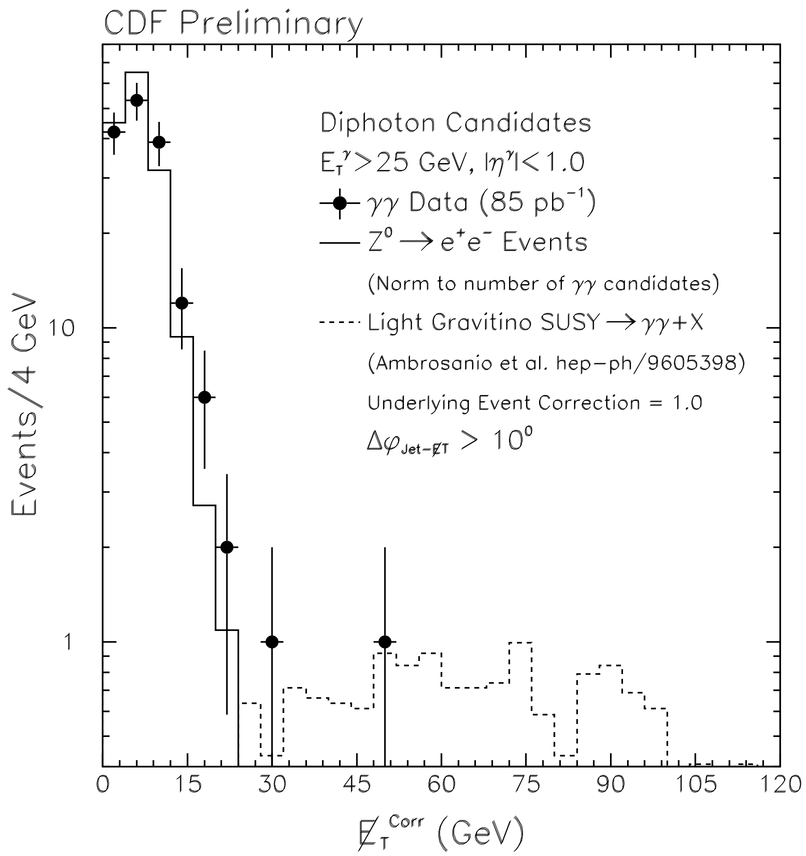
Signature: $\gamma\gamma + \not{E}_T + X$ (X = leptons or jets)

✓ $\tilde{\ell}\, \bar{\tilde{\ell}} \to (\ell \tilde{\chi}_1^0)\ (\bar{\ell} \tilde{\chi}_1^0) \to \ell^+ \ell^- + \gamma\gamma + \not{E}_T$

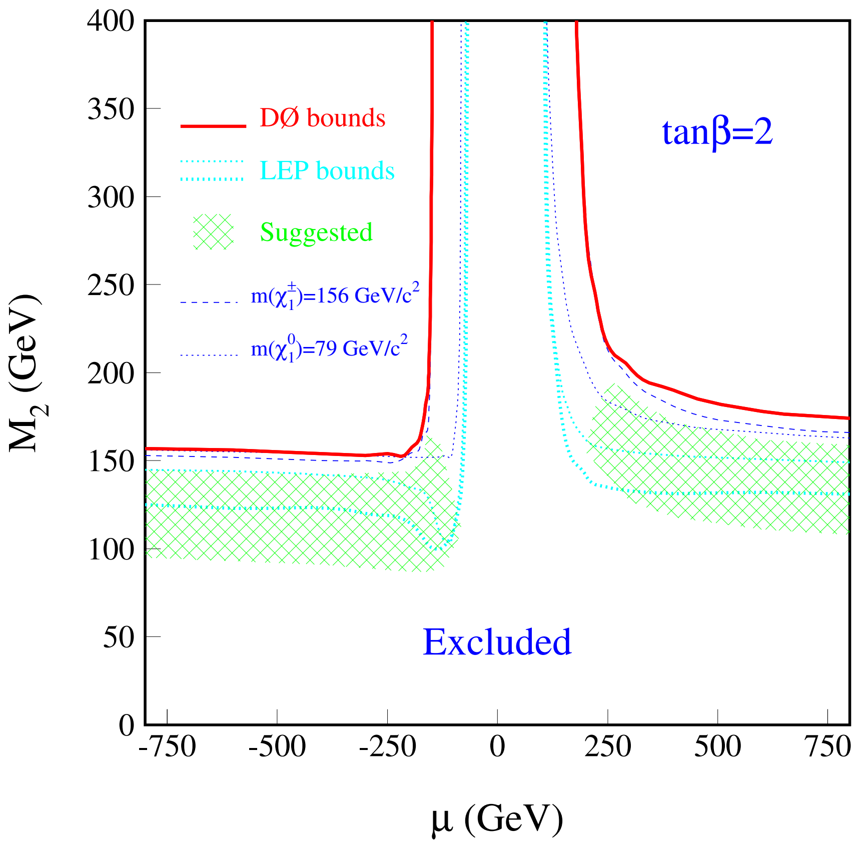
✓ $\tilde{q}\bar{\tilde{q}} \to (q \tilde{\chi}_2^0)\ (\bar{q} \tilde{\chi}_2^0) \to q q' \bar{q}' \tilde{\chi}_1^0 + \bar{q} q' \bar{q}' \tilde{\chi}_1^0$

$\to \gamma\gamma$ + 6-jets + $\not{E}_T$

CDF: $\not\!\!E_T$ distribution



DØ : SU(2) gaugino mass M_2 vs μ



SUSY: R_p Violating c-squark ($\tilde{c}_L$) Decay

HERA: can interpret high Q^2 events as R-parity violating ($\not{R}_p$) SUSY via $\lambda'_{121} L_1 Q_2 D_1^c$ interaction

$$e^+ p \xrightarrow{\not{R}_p} \tilde{c}_L \xrightarrow{\not{R}_p} e^+ + d_R$$

Fermilab Tevatron: $p\overline{p} \to$ LS $ee+ \geq$2 jets

(1) $\tilde{g}\tilde{g} \xrightarrow{R_p} (\bar{c}\tilde{c}_L)\ (\bar{c}\tilde{c}_L) \xrightarrow{\not{R}_p} [\bar{c}(e^+ d)]\ \ [\bar{c}(e^+ d)]$ $\surd$

(2) $\tilde{q}\bar{\tilde{q}} \xrightarrow{R_p} (q\tilde{\chi}_1^0)\ (\bar{q}\tilde{\chi}_1^0) \xrightarrow{\not{R}_p} q\ (q\overline{q}' e^\pm)\ \bar{q}\ (q\overline{q}' e^\pm)$

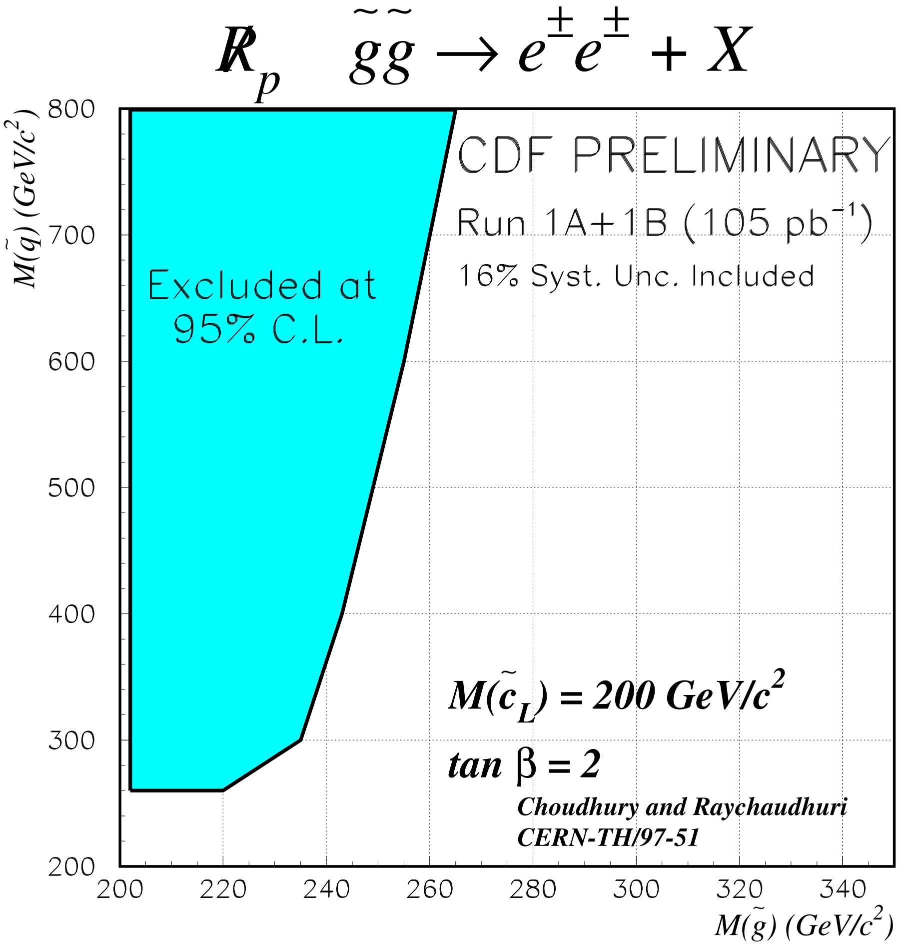
CDF: Null result with $E_T > 15$ GeV (e and j)

$$(1)\ \tilde{g}\tilde{g} \xrightarrow{R_p} (\bar{c}\tilde{c}_L)\ (\bar{c}\tilde{c}_L) \xrightarrow{\not{R}_p} [\bar{c}(e^+d)]\ \ [\bar{c}(e^+d)]$$

- $M_{\tilde{g}} > M_{\tilde{c}_L} = 200\ \mathrm{GeV}/c^2$
- $M_{\tilde{q}\neq\tilde{c}_L}$ - Free parameter
- $Br(\tilde{g} \to \bar{c}\tilde{c}_L)$ - depending on $M_{\tilde{q}}$
- $Br(\tilde{c}_L \to e^+\, d_R) = 100\%$ - favored by HERA's high-Q^2 ej events

CDF preliminary limit: $\sigma \cdot Br(\tilde{g}\tilde{g} \to e^{\pm}e^{\pm}) < 0.2$ pb

Excluded region on $M_{\tilde{q}}$-$M_{\tilde{g}}$ plane:



$$(2)\ \tilde{q}\bar{\tilde{q}} \xrightarrow{R_p} (q\tilde{\chi}_1^0)\,(\bar{q}\tilde{\chi}_1^0) \xrightarrow{\not{R}_p} q\,(q\bar{q}'e^{\pm})\,\bar{q}\,(q\bar{q}'e^{\pm})$$

- Lepton number violating $\tilde{\chi}_1^0$ (LSP) decays:

$$\tilde{\chi}_1^0 \to e^+\bar{c}d,\ e^-c\bar{d},\ \bar{\nu}_e\bar{c}u,\ \nu_e c\bar{u}.$$

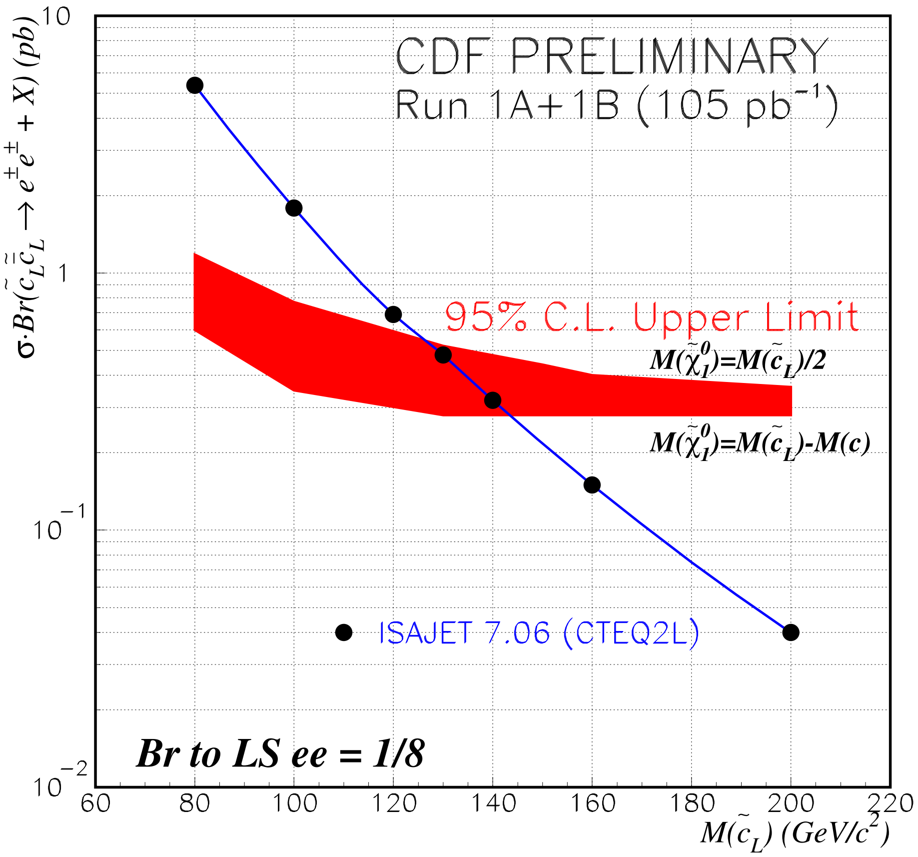
$\Rightarrow Br(LS\ ee) = 1/8$

- $M(\tilde{\chi}_1^{\pm}) > M(\tilde{c}_L) > M(\tilde{\chi}_1^0)$
- $Br(\tilde{q} \to q\ \tilde{\chi}_1^0) = 100\%$

CDF preliminary limit: $\sigma \cdot Br \lesssim 0.3$ pb (95% C.L.)
(depending on $M_{\tilde{\chi}_1^0}$ and $M_{\tilde{q}}$)

Example: If $\tilde{q} = \tilde{c}_L$, $M_{\tilde{c}_L} > 125$ - 145 GeV$/c^2$

$$\not{R}_p \quad \tilde{c}_L\bar{\tilde{c}}_L \to c\,\tilde{\chi}_1^0\,\bar{c}\,\tilde{\chi}_1^0 \to e^{\pm}e^{\pm} + X$$



SUSY: Light Gluino

Light gluino scenario:

- Prediction of long-lived hadronic states containing light gluino (0.1 - 1.0 GeV/c^2)
- Connections to Cold Dark Matter (Farrar-Kolb), Strong-CP, *etc*

R^0: lightest $g\,\tilde{g}$ state ($\cong$2 GeV/c^2)

Expectation for $M_{R^0} = 2$ GeV/c^2 in a neutral kaon beam produced by 800 GeV/c protons in pN collisions:

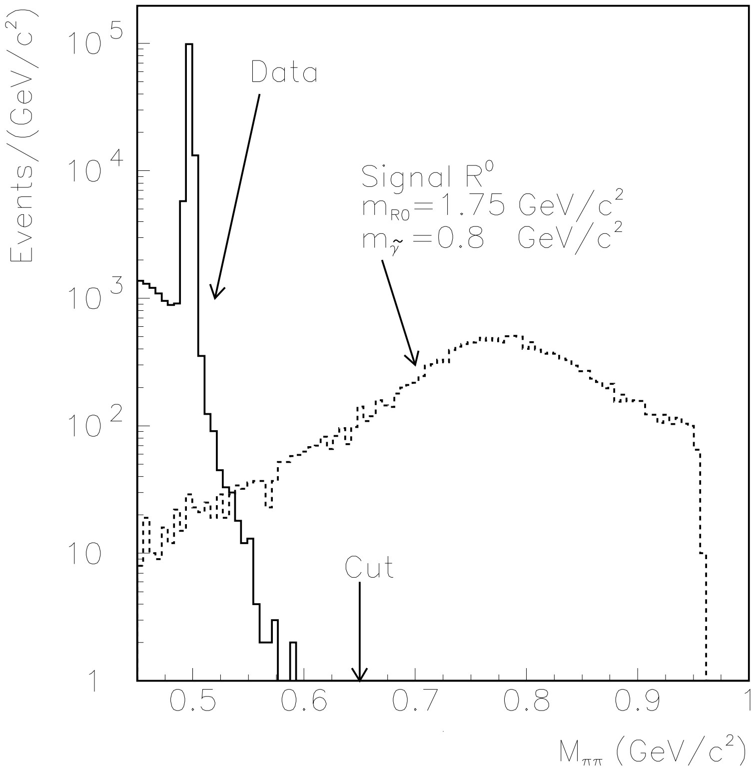
- $\sigma(p + N \to R^0 + X) = \mathcal{O}(10\ \mu\text{b})$
- Spontaneous appearance of ρ in neutral kaon beam:

$$R^0 \to \tilde{\gamma}\rho \ \ ,\ \rho \to \pi^+\pi^-$$

- R^0/K_L^0 ratio $= 10^{-4}$ to 10^{-3}
- $\tau_{R^0} = 10^{-10}$ to 10^{-5} sec.

E832(KTeV): Look for high-mass $\pi^+\pi^-$ events in one day of data (1.9×10^{15} protons)

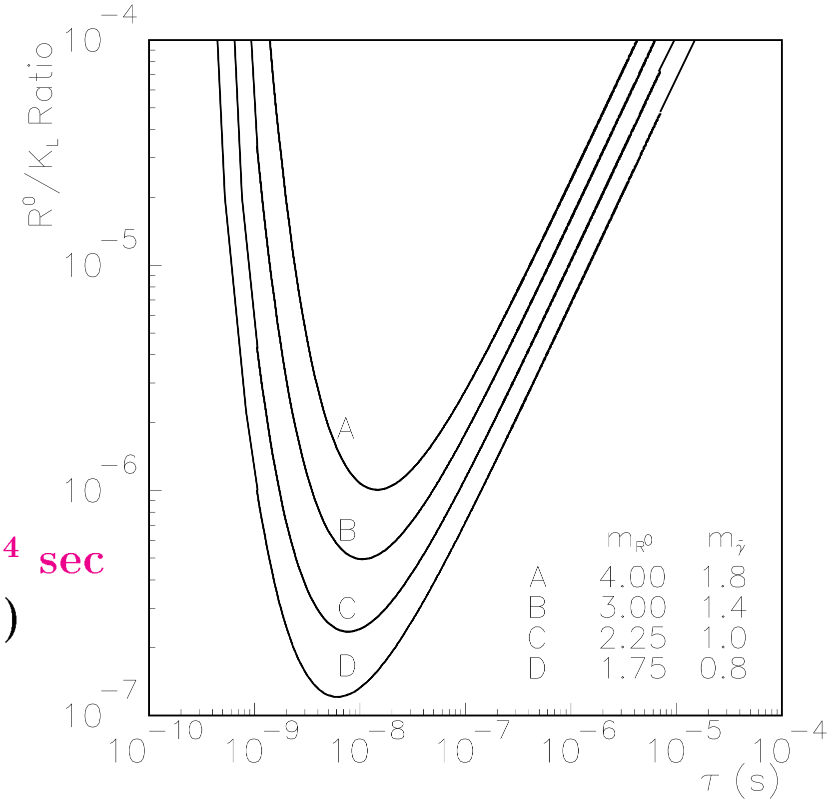
E832(KTeV):
No $\pi^+\pi^-$ events with $M_{\pi\pi} > 648$ MeV$/c^2$



R^0/K^0_L: approaching 10^{-7} ($M_{R^0}/M_{\tilde{\gamma}} \cong 2.2$)

Signal regions:
$M_{R^0} \cong 2$ GeV$/c^2$
$\tau_{R^0} = 10^{-10}$ - 10^{-5} sec
$R^0/K_L \cong 10^{-4}$ - 10^{-3}

Excluded (90% C.L.):
M_{R^0} : 1.2 - 4.6 GeV$/c^2$
τ_{R^0} : 3×10^{-10} - 7×10^{-4} sec
(depending on $M_{R^0}/M_{\tilde{\gamma}}$)



Very clean signal: full KTeV data sample should find or further restrict R^0

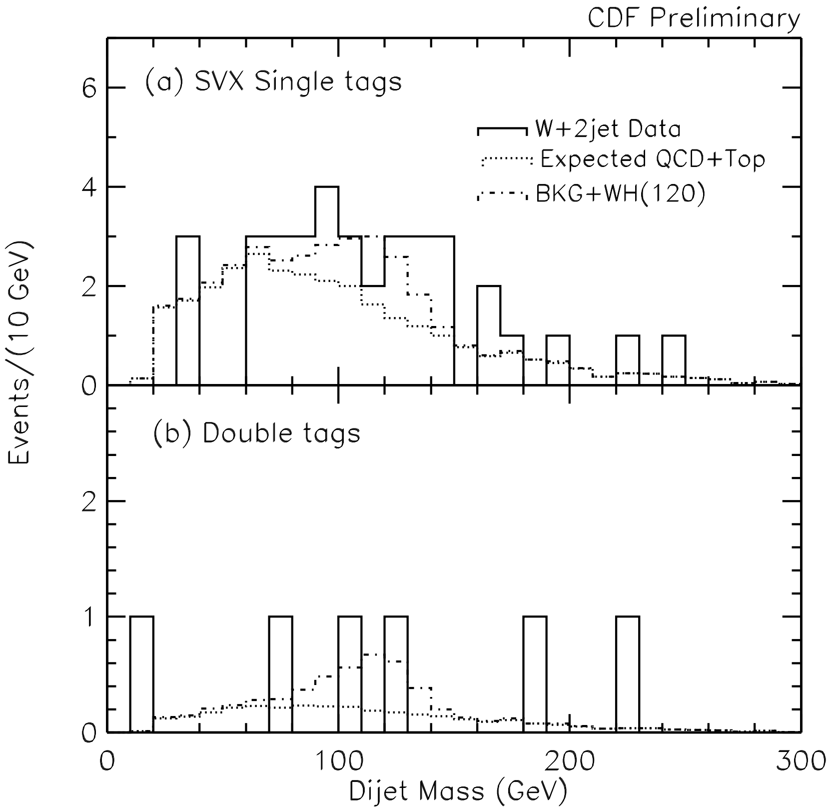
Higgs: $W + H^0(\to b\bar{b})$

CDF/DØ's general search: $p\bar{p} \to W + X$

Models for $X(\to b\bar{b})$: H^0, π_T

CDF/DØ analyses: $W \to \ell\nu$, $H^0 \to b\bar{b}$

LEP limits on M_{H^0}:
70.7 GeV/c^2(ALEPH)
65.0 GeV/c^2(DELPHI)
69.5 GeV/c^2(L3)
68.8 GeV/c^2(OPAL)

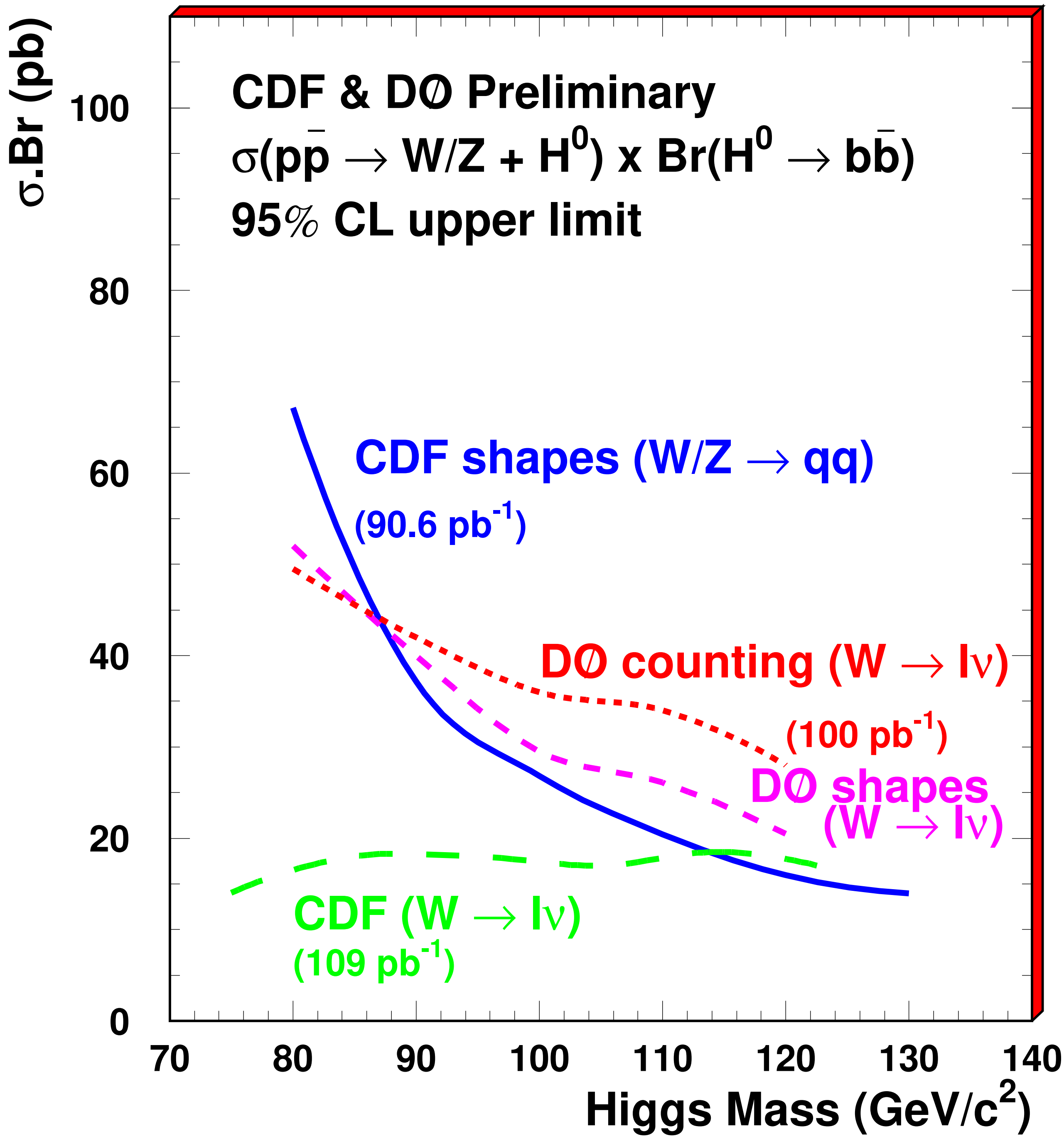


Note: BKG+WH(120) is its best fit to the data.

	CDF		DØ
b-tagging	*secondary* vertex		μ in jet
# of b-tags	≥ 1	2	≥ 1
Data	**36**	**6**	**27**
BG	30 ± 5	3.0 ± 0.6	25 ± 3

CDF analysis: $W \to q\bar{q}$, $H^0 \to b\bar{b}$
(large Br and large BG)

CDF&DØ Limits: counting and lineshape fits

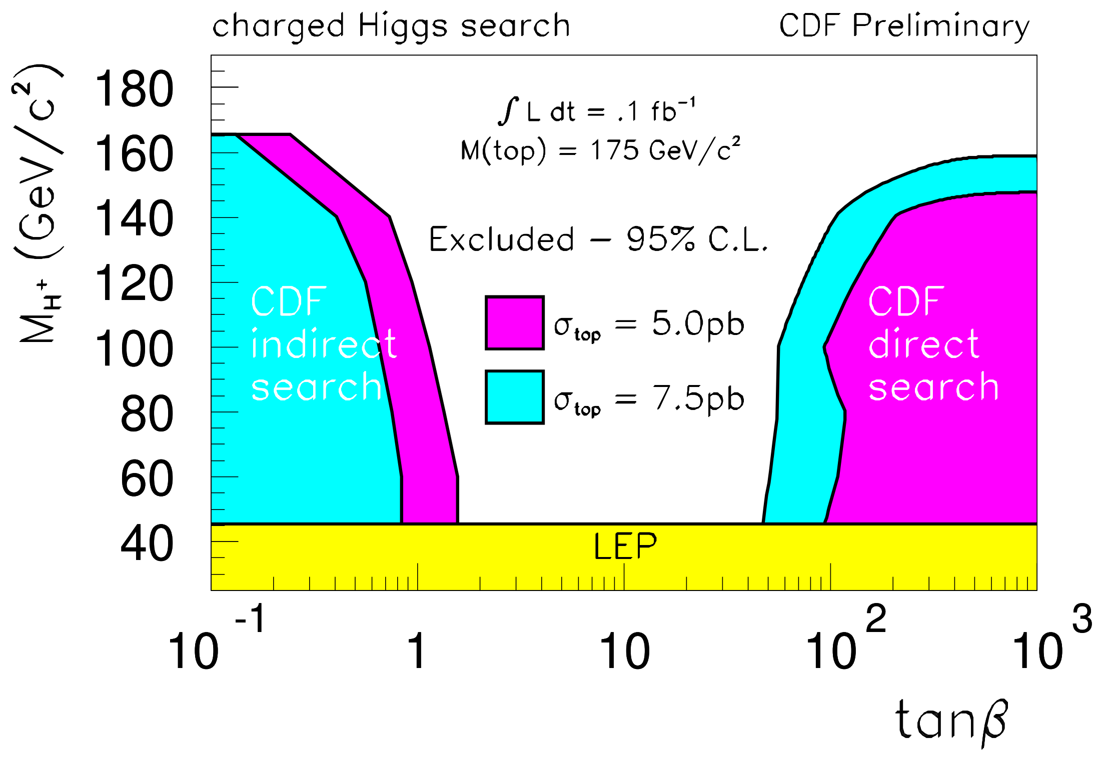


Note: Prediction on $\sigma \cdot Br$ is less than 1 pb ($70 \text{ GeV}/c^2 < M_H < 140 \text{ GeV}/c^2$)

Charged Higgs: $H^{\pm}$

Two CDF seaches in top decay ($t \to H^+ b$):

1. $\tan\beta \gtrsim 100$: $H^+ \to \tau^+ \nu$ decay is dominant
   - $t\bar{t} \to H^+ b H^- \bar{b} \to \tau^+ \tau^- \nu_\tau \bar{\nu}_\tau b\bar{b}$
2. $\tan\beta \lesssim 1$: $H^+ \to c\,\bar{s}$ decay is dominant
   - The SM top dilepton and $\ell + jets$ event yields are reduced by H^+ decay channel.



New Particle $X \to j_1 j_2$

X: q^*, W', Z', g_A, Color octet technirhos, E_6 diquarks

Assume: M_{jj} resolution is dominated by jet energy resolution and QCD radiation effect

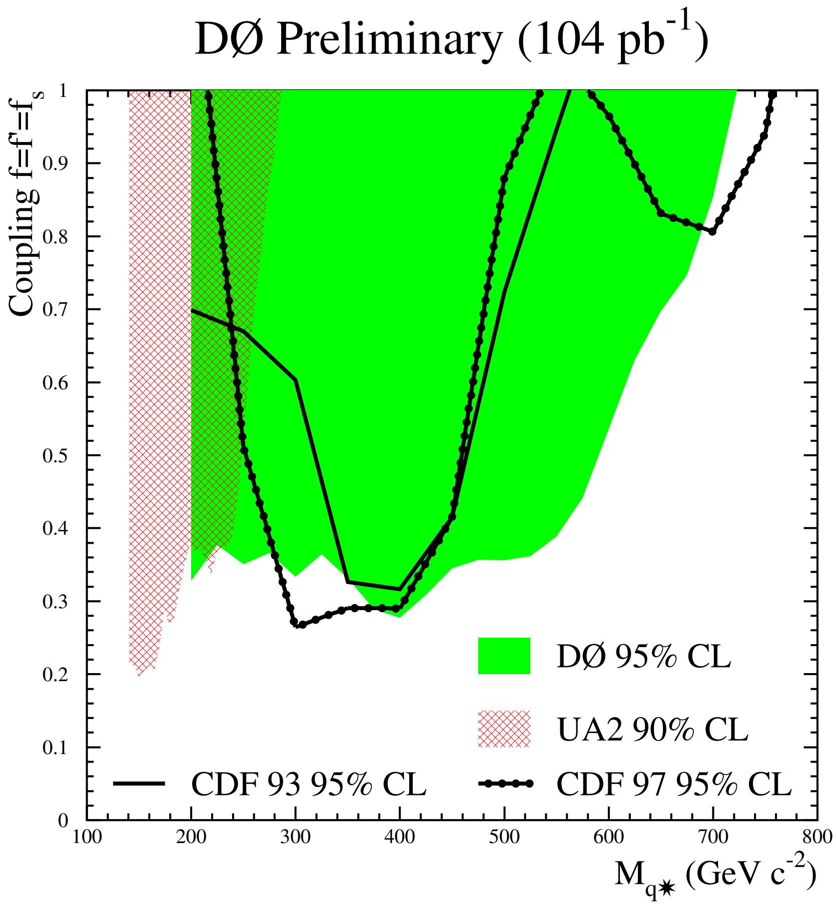
Analysis: Upper limits on $\sigma \cdot Br(X \to jj)$ by fitting the data (M_{jj}) to the background parameterization and mass resonance shape simultanouly for two leading jets passing;

	CDF (106 $\mathbf{pb}^{-1}$)	DØ (104 $\mathbf{pb}^{-1}$)
$X \to j_1 j_2$	$\lvert\eta\rvert < 2$	$\lvert\eta\rvert < 1$
	$\lvert\cos\theta^*\rvert < 2/3$	$\lvert\eta_1 - \eta_2\rvert < 1.6$

Example (q^*):

Excluded (95% CL)
($f = f' = f_s = 1$)
DØ 200-725 GeV/c^2

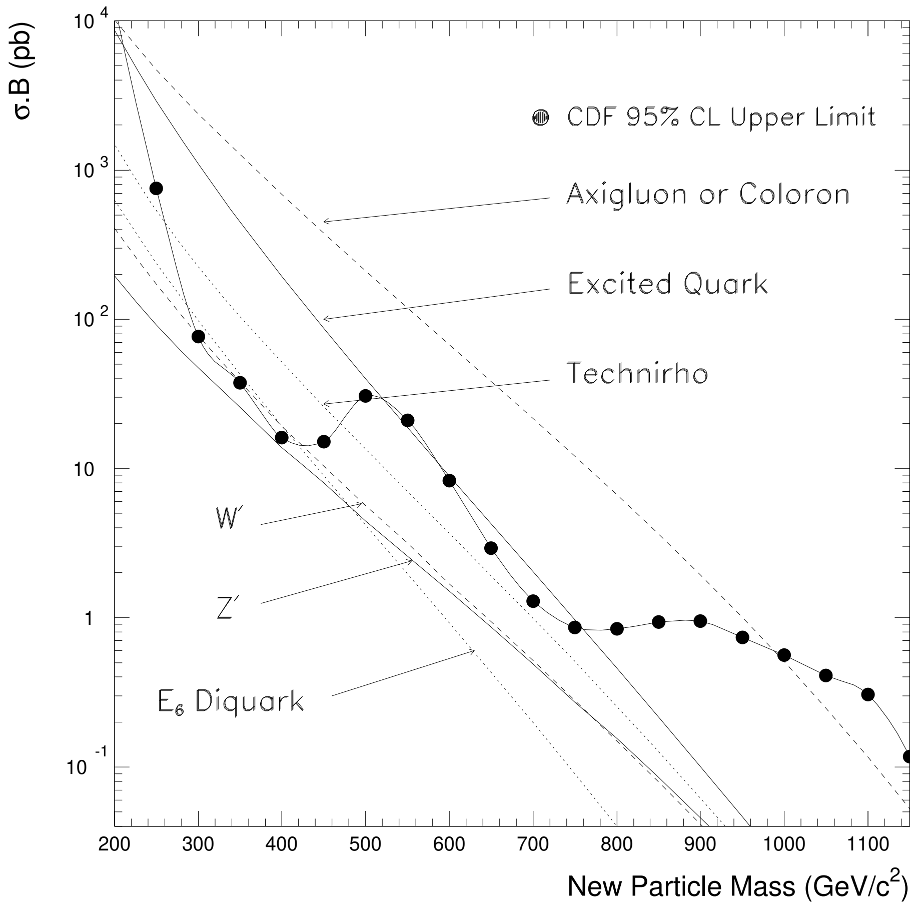
CDF 200-520 GeV/c^2
580-760 GeV/c^2



Summary of Mass Exclusion:

	Mass Exclusion (**GeV**/c^2)	
	CDF	DØ
q^*	200-520, 580-760	200-725
W'	300-420	340-680
Z'	none	365-615
g_A	200-980	n/a
ρ_T	260-480	n/a
E_6	290-420	n/a

Note: a single bin near 550 GeV/c^2 (2.6σ above the BG fit) weakens some CDF limits...



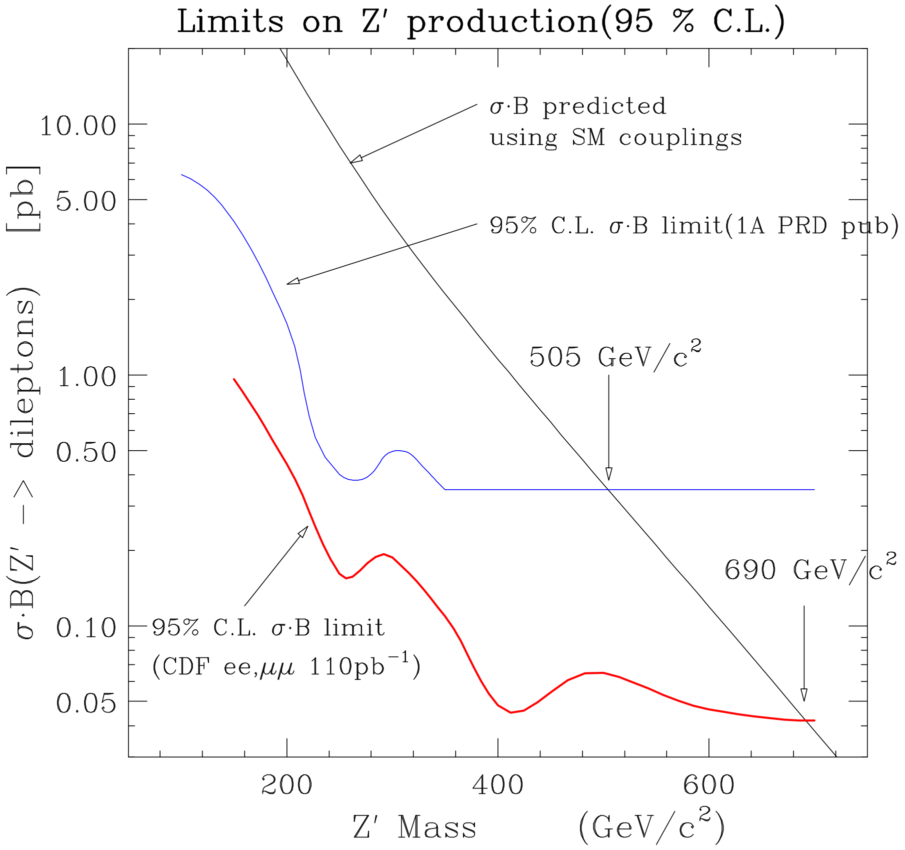
$Z' \to \ell^+\ell^-$

Models for Z':

Left-Right model - additional $SU(2)_R$
String inspired extensions

CDF/DØ : $Z' \to \ell^+\ell^-$ search assuming $\lambda^2 = 1$

CDF PRELIMINARY



Mass Limits (Preliminary):

CDF: $M_{Z'} > 690$ GeV$/c^2$ (110 pb^{-1}, $ee + \mu\mu$)

DØ : $M_{Z'} > 670$ GeV$/c^2$ (109 pb^{-1}, ee)

$W' \to \ell\, \nu$

W': like heavy W

$$W' \to f_i f_j \propto (a + b\gamma_5)$$

$$\Gamma(W' \to f_i f_j) \propto \frac{a^2 + b^2}{2} \equiv \lambda^2$$

Assume: light & stable ν_R if $\nu = \nu_R$

CDF/DØ : $W' \to \ell\nu$ search assuming[3] $\lambda^2 = 1$

(Preliminary)		CDF	DØ
$W' \to e\ \nu$	Analysis	19.7 pb^{-1} High E_T $e + \not\!\!E_T$ Z veto $M_T(e, \not\!\!E_T)$	74.4 pb^{-1} High E_T e — $E_T(e)$ & $M_T(e, \not\!\!E_T)$
Mass Limits	$(\lambda = 1.0)$	652 GeV/c^2	720 GeV/c^2

$W' \to \mu\ \nu$	Analysis	90 pb^{-1} High E_T $\mu + \not\!\!E_T$ Z veto $M_T(\mu, \not\!\!E_T)$	— — — —
Mass Limits	$(\lambda = 1.0)$	646 GeV/c^2	—

[3] $a = 1$, $b = -1$, $\lambda^2 = 1$ (standard strength)

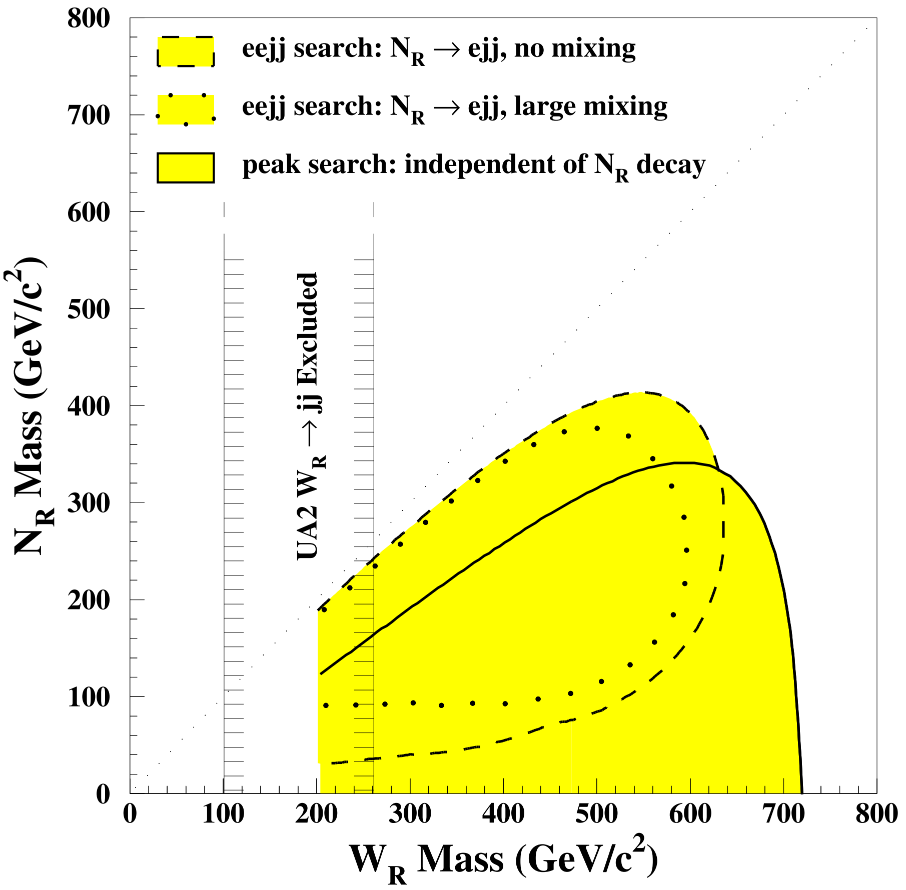
R.H. W': $W_R \to e\ N_R$

R.H. W': $W_R \to eN_R$
Heavy neutrino: $N_R \to e\ W'^* \to e\ (q\bar{q}')$

Note: If W_R -W mixing occurs, then leptonic decays of W' are also possible

DØ analyses:

(a) Peak search: Jacobian peak on $E_T(e)$ (for lighter N_R)
(b) $eejj$ search: $2e + 2j$ (with Z veto) (for heavier N_R)



Mass Limits (Preliminary):

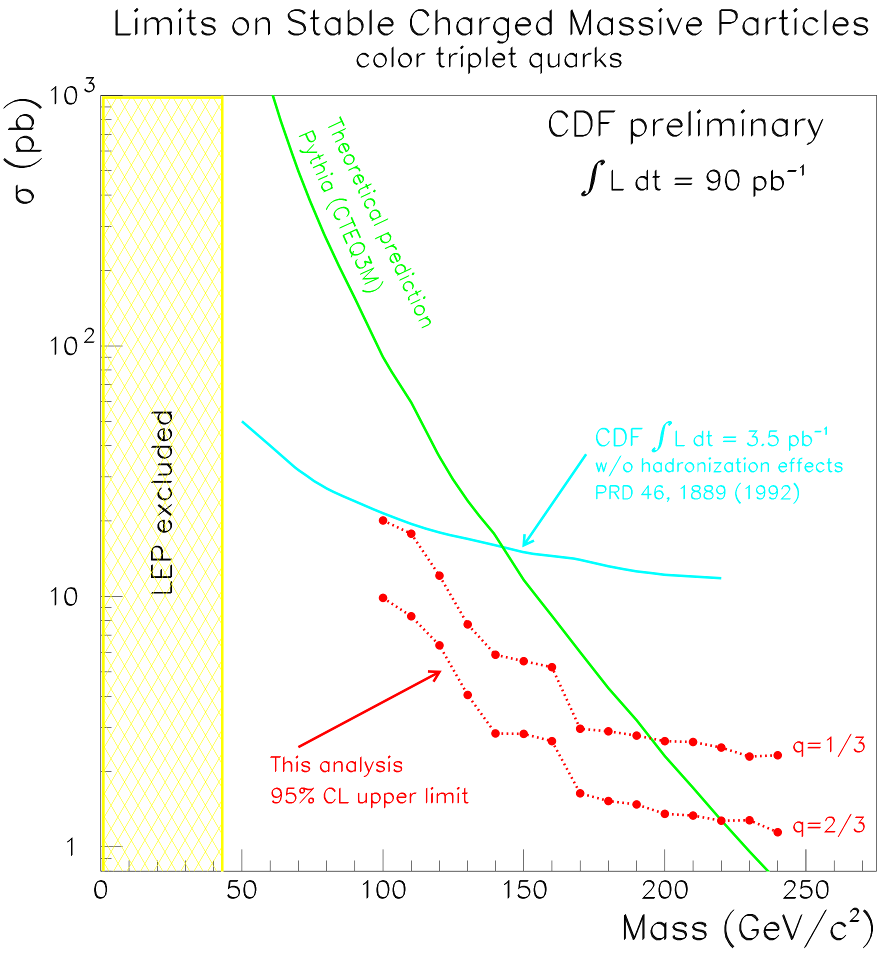
$$M_{W_R} > 720\ \ \mathrm{GeV}/c^2\ \ (M_{N_R} \ll M_{W_R})$$
$$M_{W_R} > 650\ \ \mathrm{GeV}/c^2\ \ (M_{N_R} \sim M_{W_R}/2)$$

Stable Charged Massive Particle

"Stable" means $\gamma\,\tau > 10^{-8}$ sec

CDF: general search for slow moving objects based on charged-particle energy loss rate in the tracking chambers due to ionization

CDF limits: stable 4th-generation quarks (b', t')



$$M_{b'} > 190\ \ \mathrm{GeV}/c^2; \quad M_{t'} > 220\ \ \mathrm{GeV}/c^2$$

$\nu_\mu \rightarrow \nu_e$ Oscillation

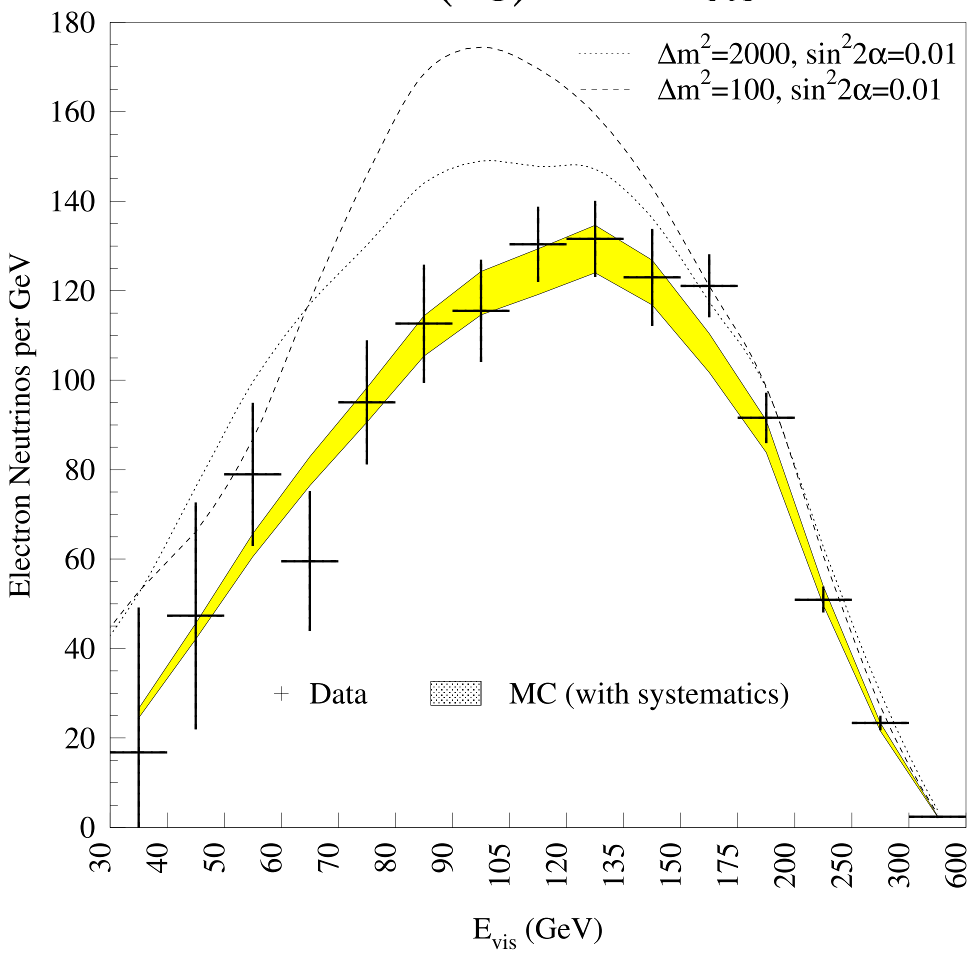
Two-generation mixing:

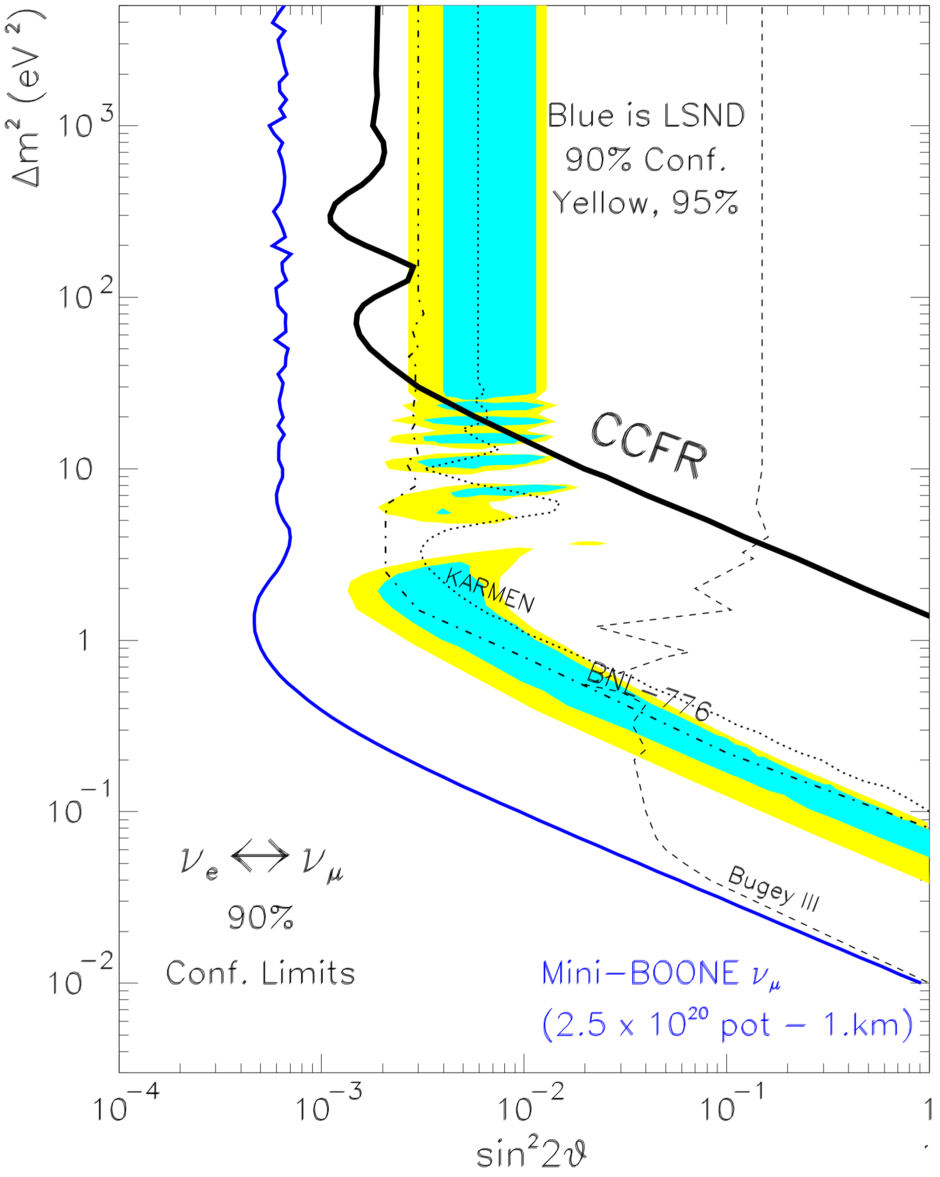
$$P(\nu_1 \rightarrow \nu_2) = \sin^2 2\alpha \;\; \sin^2\left(\frac{1.27\ \Delta m^2\ L}{E_\nu}\right)$$

LSND exp.: Evidence for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at $\sin^2 2\alpha \cong 10^{-2}$ and $\Delta m^2 \geq 1$ eV^2

CCFR: the measured ν_e flux compared to the prediction from a detailed beamline simulation

Flux(ν_e) vs. E_{vis}





CCFR: excludes the high Δm^2 ($\gtrsim$25 eV^2) region favored by LSND.

Mini-BOONE: can study the entire region favored by LSND.

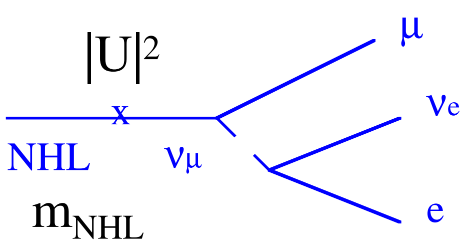
FYI: CCFR also reports on limits on $\nu\nu qq$ contact interactions by looking at ν_μ-NC and ν_μ-CC cross sections: Λ_{H_ℓ,H_q} >1.3 - 8.3 TeV - comparable to the $\ell\ell qq$ interaction limits by CDF

Neutral Heavy Leptons at NuTeV

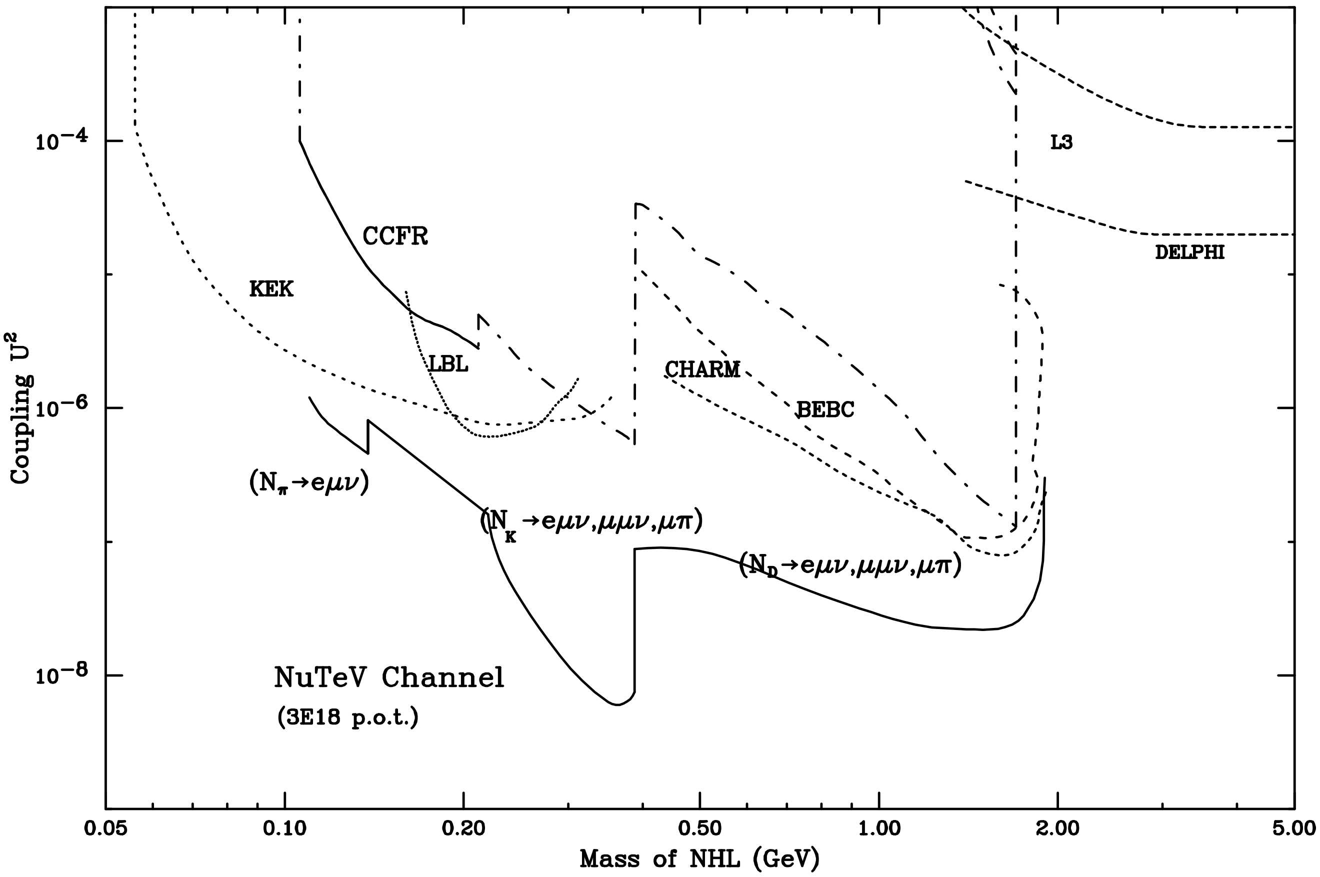
Neutral Heavy Lepton (NHL) in extensions of the SM interacts through mixing with light neutrinos

For Example:

$\mathrm{NHL} \rightarrow e\mu\nu$



Expected Sensitivity of the NuTeV NHL Search



Summary

$\surd$ Selected topics presented here are:

1. LQ - CDF and DØ exclude the s-channel production ($\beta \cong 1$) favored by HERA high-Q^2 events
2. SUSY - KTeV excludes a light gluino scenario over substantial phase space
3. H^0 - $\sigma \cdot Br \lesssim$ 20 pb for $W + H^0$
4. $H^\pm$ - $M_{H^\pm} \gtrsim 150$ GeV$/c^2$ for $\tan\beta \gtrsim 200$
5. $X \to jj$ - Mass limits near 1 TeV$/c^2$
6. W'/Z' - Mass limits near 700 GeV$/c^2$
7. Stable particles - Mass limits $\sim$200 GeV$/c^2$
8. $\nu_\mu \to \nu_e$ oscillation - CCFR excludes the high Δm^2 region favored by LSND
9. Compositeness scale - $\Lambda > 1$ - 8 TeV
10. Heavy neutral lepton at NuTeV - coming

$\surd$ FERMILAB Tevatron makes many new physics searches possible, which are complementary to the other laboratory's searches (CERN-LEP, DESY-HERA, LANL-LSND, SLAC, BNL, KEK, BEBC, *etc.*)

$\surd$ More data is needed to either find or exclude new physics.