Searches for Leptoquarks at the Tevatron

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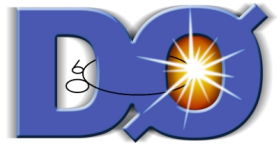

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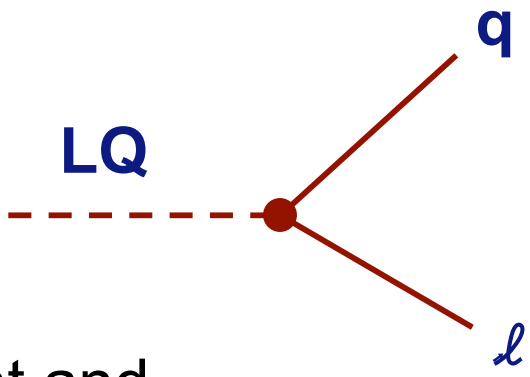
London, UK

Introduction

What are leptoquarks?

"Leptoquark" is a generic name for states which couple directly to a quark and a lepton.



- Assuming $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant and renormalizable interactions, every leptoquark:
  - belongs to a colour triplet representation of $SU(3)_C$
  - carries both a baryon and a lepton numbers

- The quantum numbers used to classify the different leptoquark states allowed by the symmetries are:
  - S: spin (0 or 1)
  - I_W: weak isospin (0, 1/2 or 1)
  - Q: electric charge (fractional)
  - F: fermion number (0 or -2)
  - H: chirality of the lepton (L or R)

$$|LQ\rangle \equiv |S, I_W, Q, F, H\rangle$$

Many possible leptoquarks…

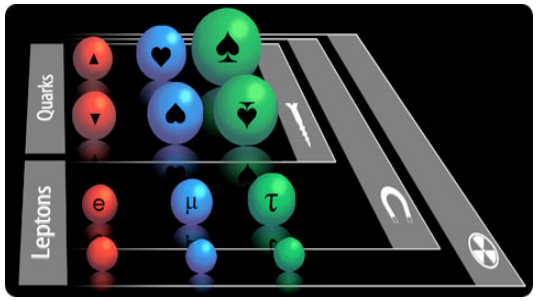
Type	Spin	I_{3W}	F=3B+L	Q	Decay	Coupling	β_e
S_{1L}	0	0	-2	-1/3	e^-u, νd	λ_L, $-\lambda_L$	1/2
S_{1R}	0	0	-2	-1/3	e^-u	λ_R	1
$\bar{S}_{1R}$	0	0	-2	-4/3	e^-d	λ_R	1
S_{3L}	0	1	-2	-4/3 -1/3 2/3	e^-d e^-u, νd νu	$-\sqrt{2}\,\lambda_L$ $-\lambda_L$, $-\lambda_L$ $\sqrt{2}\,\lambda_L$	1 1/2 0
R_{2L}	0	1/2	0	-5/3 -2/3	$e^-\bar{u}$ $\nu\bar{u}$	λ_L λ_L	1 0
R_{2R}	0	1/2	0	-5/3 -2/3	$e^-\bar{u}$ $e^-\bar{d}$	λ_R $-\lambda_R$	1 1
$\bar{R}_{2L}$	0	1/2	0	-2/3 1/3	$e^-\bar{d}$ $\nu\bar{d}$	λ_L λ_L	1 0
V_{2L}	1	1/2	-2	-4/3 -1/3	e^-d νd	λ_L λ_L	1 0
V_{2R}	1	1/2	-2	-4/3 -1/3	e^-d e^-u	λ_R λ_R	1 1
$\bar{V}_{2L}$	1	1/2	-2	-1/3 2/3	e^-u νu	λ_L λ_L	1 0
U_{1L}	1	0	0	-2/3	$e^-\bar{d}$, $\nu\bar{u}$	λ_L, λ_L	1/2
U_{1R}	1	0	0	-2/3	$e^-\bar{d}$	λ_R	1
$\bar{U}_{1R}$	1	0	0	-5/3	$e^-\bar{u}$	λ_R	1
U_{3L}	1	1	0	-5/3 -2/3 1/3	$e^-\bar{u}$ $e^-\bar{d}$, $\nu\bar{u}$ $\nu\bar{d}$	$\sqrt{2}\,\lambda_L$ $-\lambda_L$, λ_L $\sqrt{2}\,\lambda_L$	1 1/2 0

- The most general $\mathcal{L}_{\text{eff}}$ can describe up to 24 different leptoquarks for each generation!
- Generally, only a subset of these possible leptoquarks are contained in a particular model

⇒ **Important to look at each channel to discriminate between models**

Motivation

Is the apparent symmetry relating quarks and leptons fundamental or accidental?



This question has inspired many BSM theories which naturally contain leptoquarks

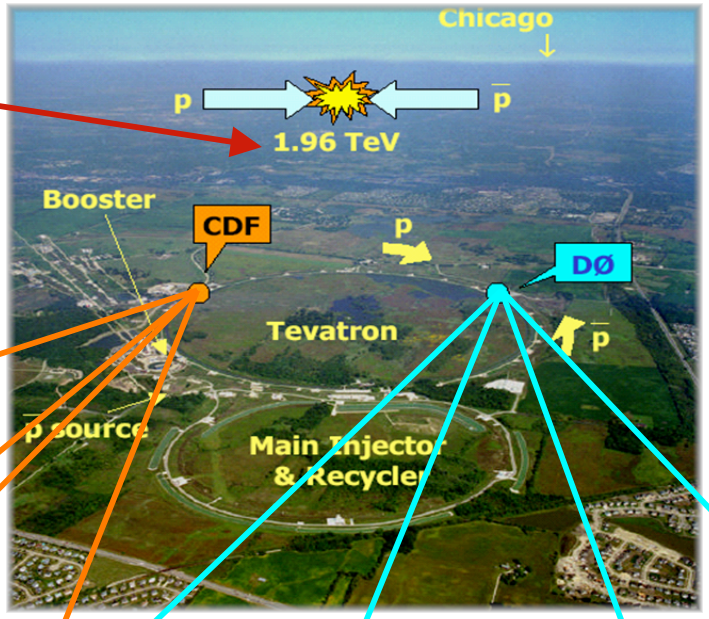
- composite models with quark and lepton substructure
- extended technicolor
- GUTs with different gauge groups (SU(5), SU(15), E_6, etc)

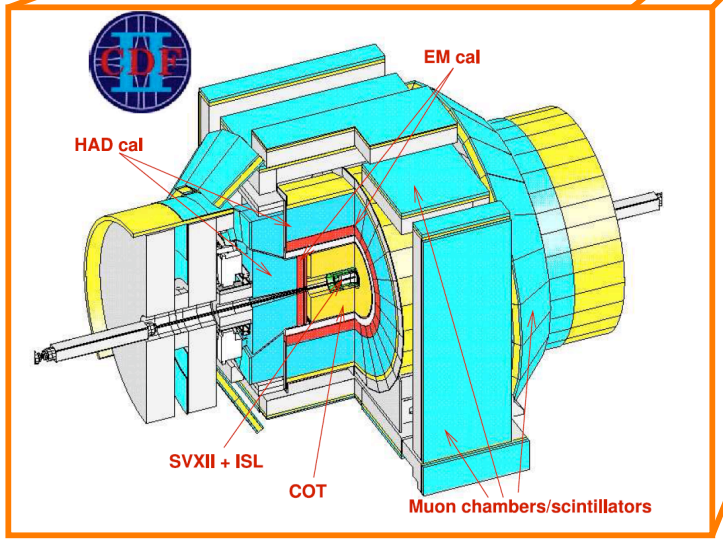
Leptoquarks can be light enough to be observable if:

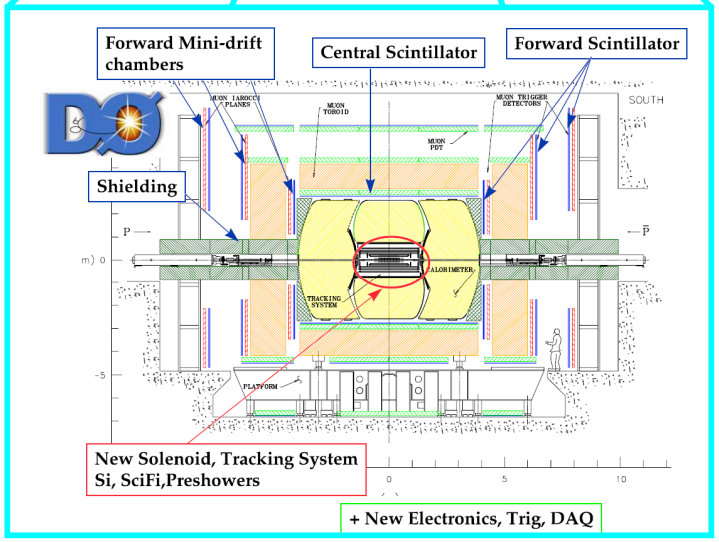
- lepton **and** baryon numbers are conserved (no proton decay)
- couplings to fermions are chiral (helicity suppression of $\pi^+ \rightarrow e^+ \nu_e$)
- couplings are family diagonal (avoid FCNC)

The Tevatron

- World's highest-energy accelerator in operation
- Collisions every 396 ns
- Delivered luminosity
  - Current: 3.7 fb^{-1}
  - Today's analyses: up to 2 fb^{-1}



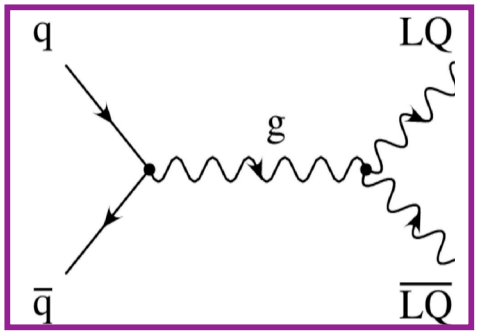




Leptoquark production

The Tevatron has enough energy to search for the direct production of a pair of leptoquarks

- Advantages of searching for leptoquark pair production:
  - Pairs are produced via strong interaction only ($q\bar{q} \rightarrow LQ\overline{LQ}$, $gg \rightarrow LQ\overline{LQ}$)



Dominant

  ⇒ Essentially independent of Yukawa couplings
    - Contribution from leptons in t-channel is negligible

  ⇒ Production rate depends on 1 parameter: M_{LQ}
    - Vector LQ production may also depend on some anomalous couplings
  - Can study 2nd and 3rd generation leptoquarks without having to assume Lepton Flavor Violation
  - Can study leptoquarks which couple only to quarks and neutrinos

Searches

- We will present both CDF and D0 searches for light leptoquarks in the following final states:
  - $\nu\nu jj$
  - $\mu\nu jj$
  - $\mu\mu jj$
  - $\tau\tau b\bar{b}$
  - $\nu\nu b\bar{b}$
  - $e\nu jj$
  - $eejj$

We can parameterize the production rate of these final states in terms of β_ℓ = Br(LQ$\rightarrow\ell$j):

$\sigma(\ell\ell jj) \propto \beta_\ell^2$

$\sigma(\ell\nu jj) \propto 2\beta_\ell(1-\beta_\ell)$

$\sigma(\nu\nu jj) \propto (1-\beta_\ell)^2$

Depending on the leptoquark type:

β_ℓ= 1, 1/2 or 0

Searches for 2nd generation leptoquarks

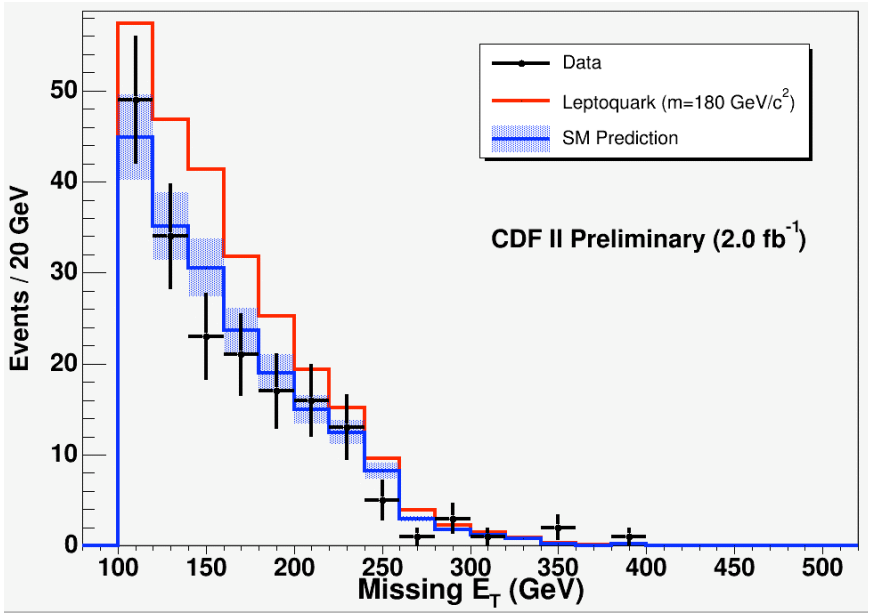
ννjj: the analyses

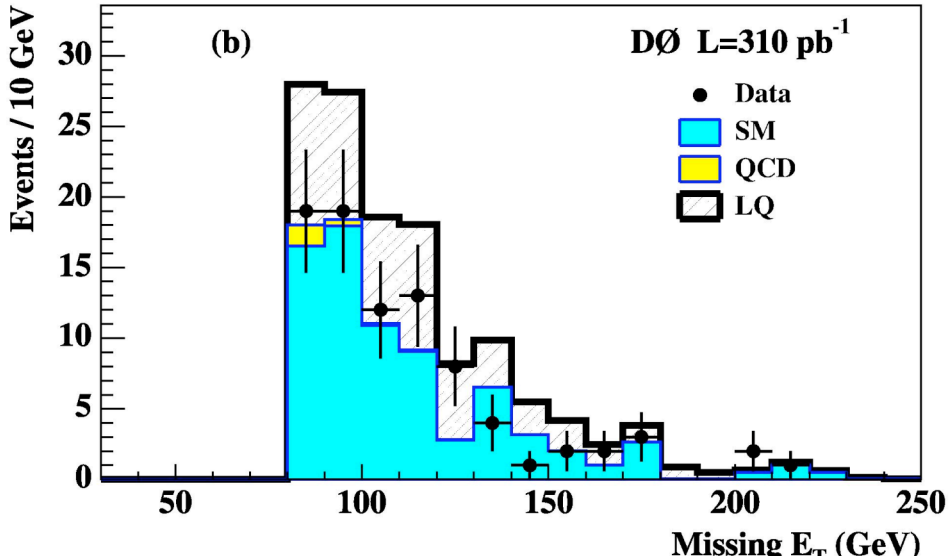
Main Backgrounds: Z→νν + 2-jets, W+jets, $t\bar{t}$, QCD

CDF: 2.0 fb^{-1}

D0: 310 pb^{-1}

A Signature-based search





- Search in 2 different regimes:
  - $\not\!\!E_T$ > 80 GeV, H_T > 125 GeV
  - $\not\!\!E_T$ > 100 GeV, H_T > 225 GeV
    - $H_T = E_T(jet_1) + E_T(jet_2)$

- $E_t(j_1)$ > 60 GeV, $E_T(j_2)$ > 50 GeV
- $\Delta\phi(met\text{-}j_i)^{max} - \Delta\phi(met\text{-}j_i)^{min} < 2.1$ rad
- $\Delta\phi(met\text{-}j_i)^{max} + \Delta\phi(met\text{-}j_i)^{min} < 4.9$ rad
- $\not\!\!E_T$ > 80 GeV

ννjj: the results

Data-driven Predictions:

- (80/125): 2312 ± 140 events
  - (E_T, H_T) = (80/125) GeV
- (100/225): 196 ± 29 events

Observations:

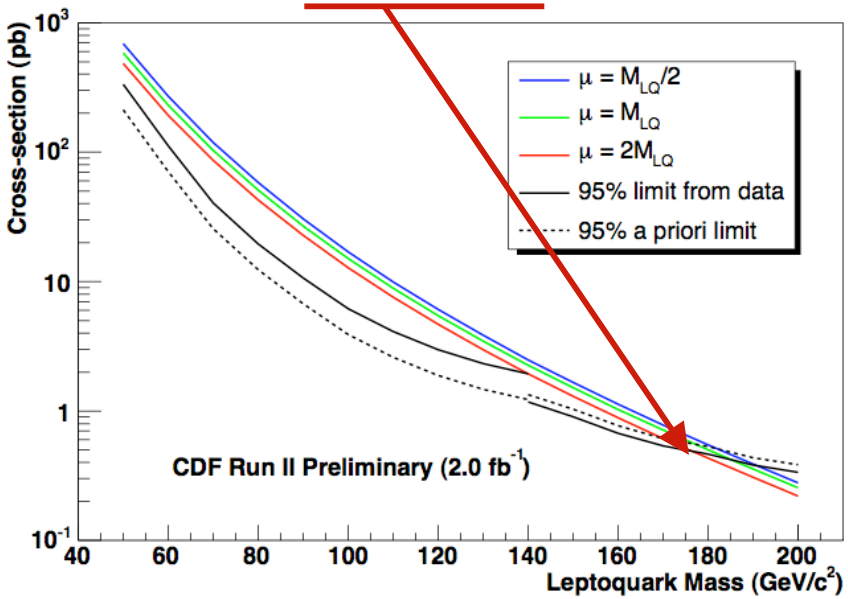
- (80/125): 2506 events
- (100/225): 186 events

Prediction : 75 ± 15 events

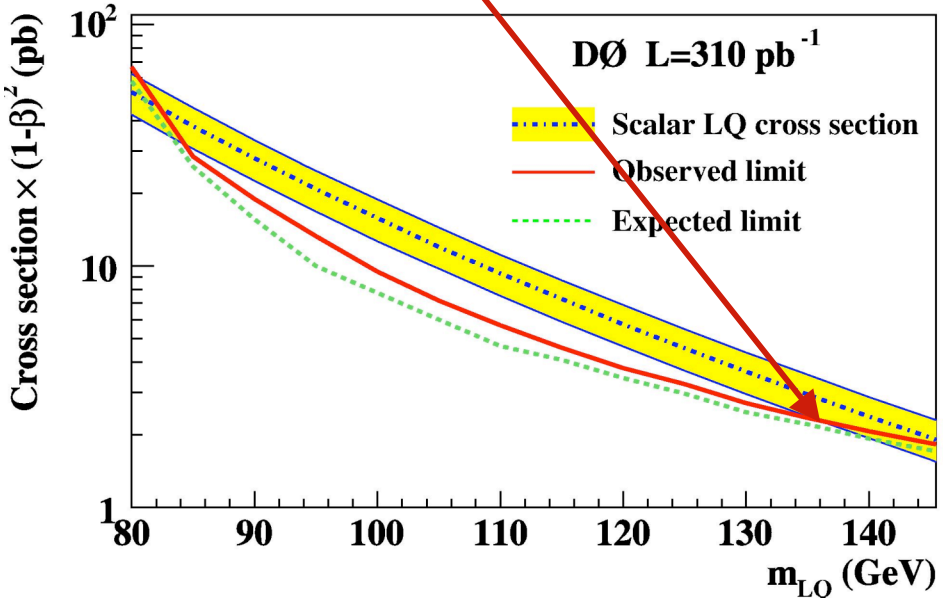
- $Z \to \nu\nu$ + jets: 46%
- $W \to \ell\nu$ + jets: 47%
- $t\bar{t}$ and fake: 6%

Observation: 86 events

Exclude at 95% CL
M_{LQ} > 177 GeV (β=0)



Exclude at 95% CL
M_{LQ} > 136 GeV (β=0)

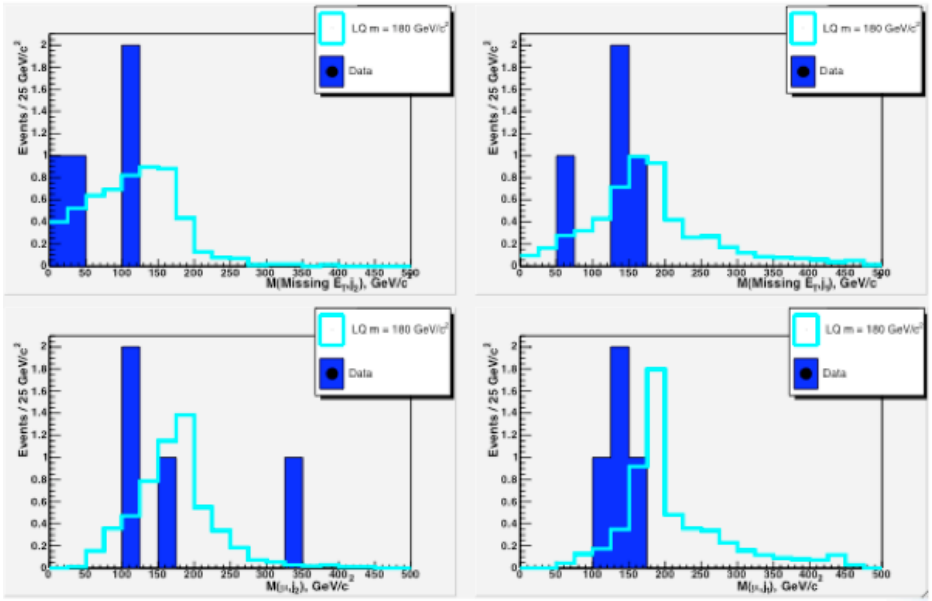


μνjj: the analyses

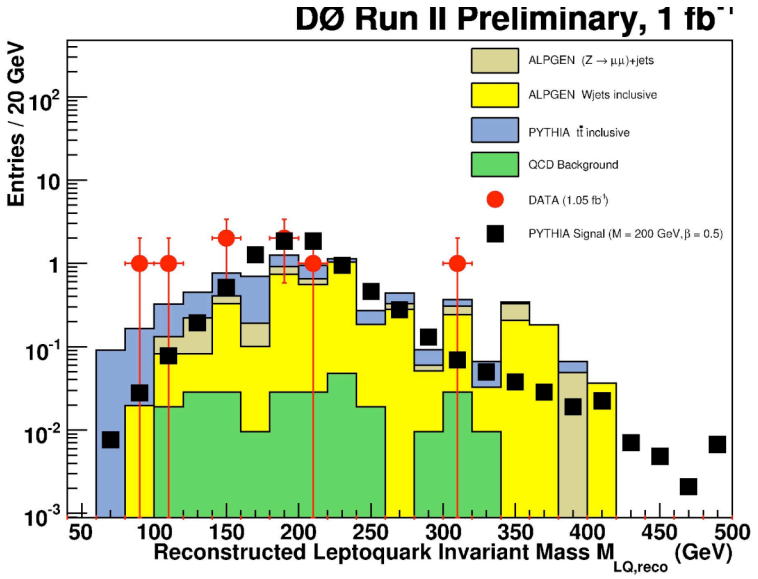
Main Backgrounds: W→μν + 2-jets, $t\bar{t}$, QCD(fake)

CDF: 198 pb^{-1}

- Met > 60 GeV and H_T > 80 GeV
  - $H_T = E_T(j_1)+E_T(j_2)$
- Selections of reconstructed and transverse LQ masses ($M_T(jet_i$-$\not{E}_T)$ and $M_{\mu jet\text{-}i}$) around nominal value



D0: 1.05 fb^{-1}



- $\not{E}_T$ > 30 GeV and S_T > 350 GeV
  - $S_T = E_T(j_1)+E_T(j_2)+E_T(\mu_1)+\not{E}_T)$
- $M_T(jet_1$-$\not{E}_T) \Leftrightarrow$ LQ reconstructed transverse mass
- Leptoquark mass $M_{\mu jet\text{-}i}$ within 100 GeV of each choice of $M_{LQ,gen}$

μνjj: the results

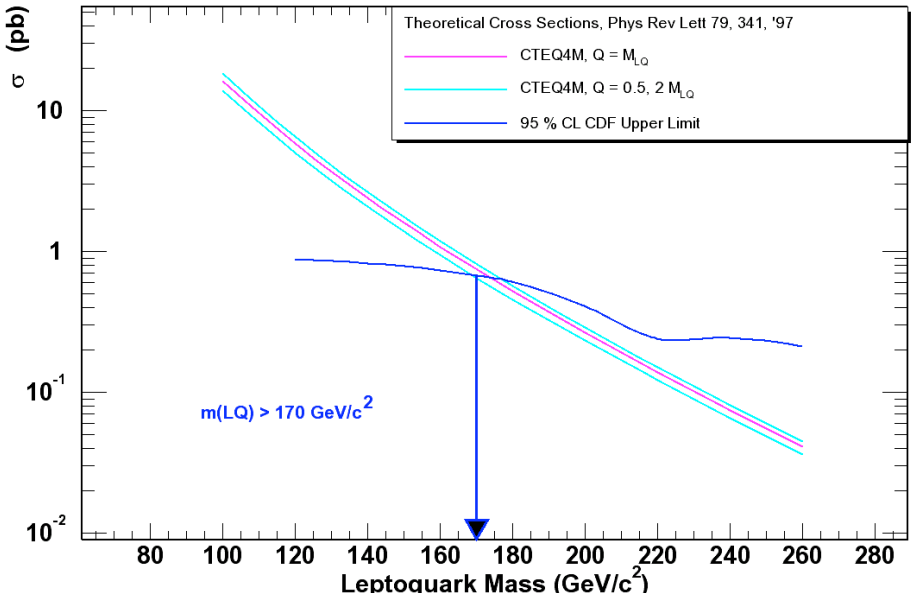
Prediction : 3.1 ± 0.5 events

- W/Z + jets: 60%
- $t\bar{t}$: 32%
- QCD (fake): 8%

Observation: 0

For M_{LQ} = 200 GeV

Exclude at 95% CL
M_{LQ} > 170 GeV (β=1/2)



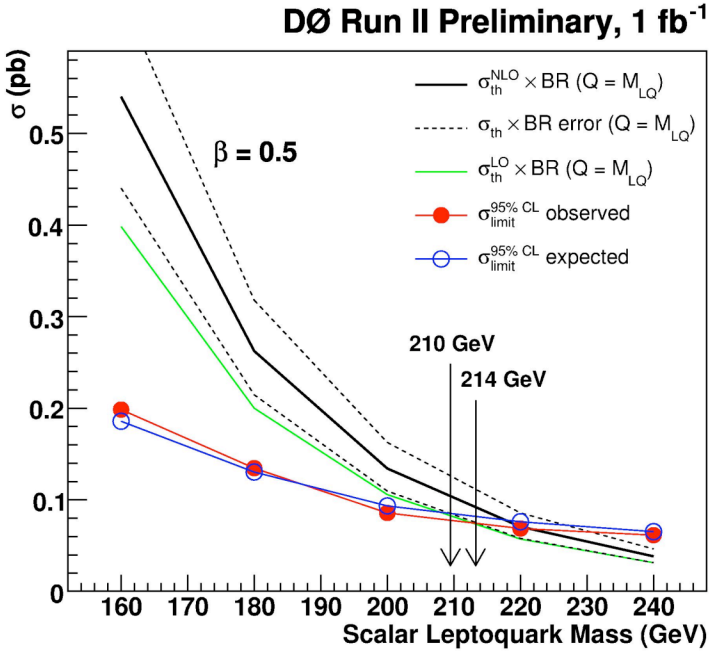
Prediction : 6.4 ± 1.1 events

- W/Z + jets: 61%
- $t\bar{t}$: 36%
- QCD (fake): 3%

Observation: 6

For M_{LQ} = 200 GeV

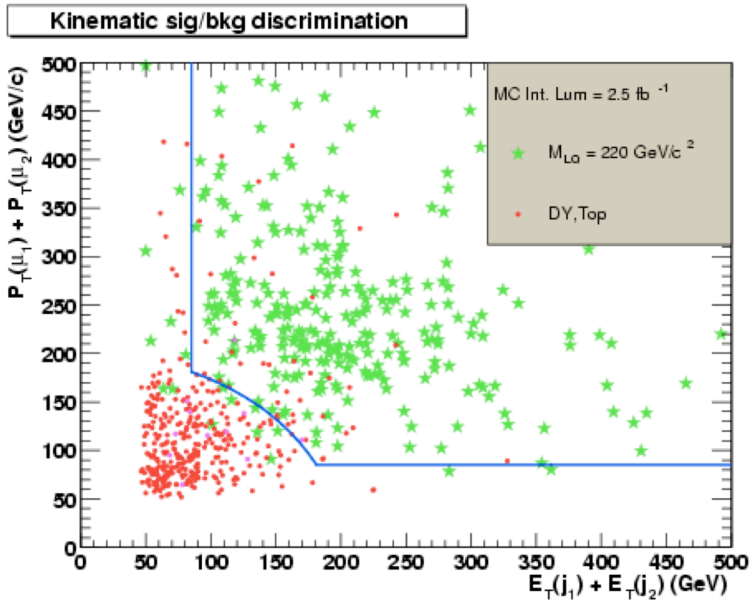
Exclude at 95% CL
M_{LQ} > 214 GeV (β=1/2)



μμjj: the analyses

Main Backgrounds: $Z/\gamma^* \rightarrow \mu\mu$ + 2-jets, $t\bar{t}$, QCD(fake)

CDF: 198 pb^{-1}



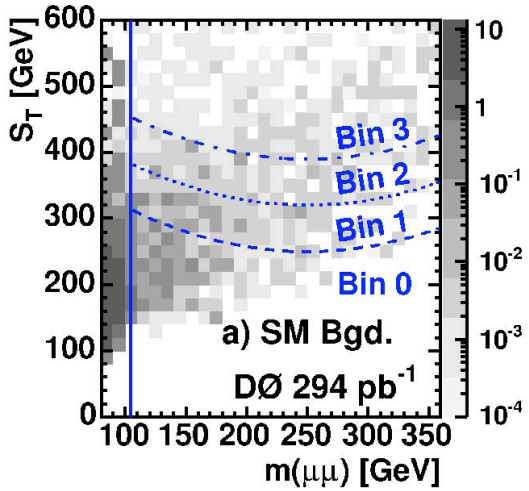
Selection region parameterized in terms of H_T(jets) and $H_T(\mu)$:

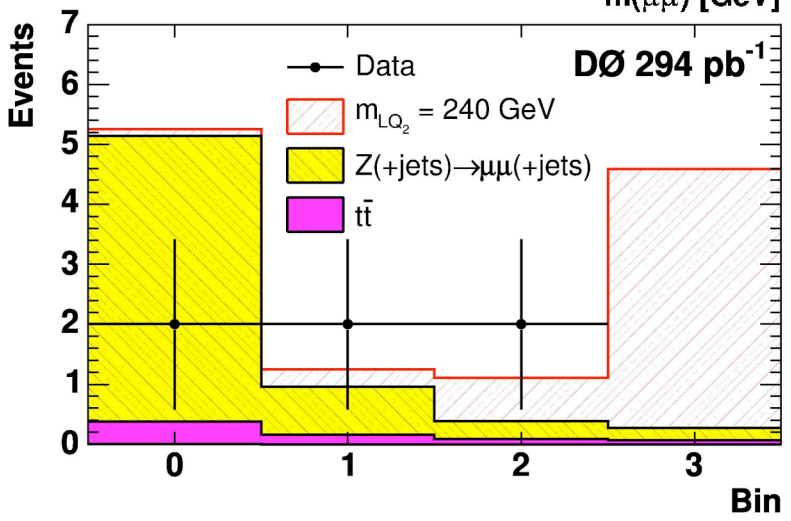
- $H_T(\text{jets}) \equiv E_T(j_1)+E_T(j_2) > 85$ GeV
- $H_T(\mu) \equiv E_T(\mu_1)+E_T(\mu_2) > 85$ GeV
- $\sqrt{(H_T(\text{jets})^2 + H_T(\mu)^2)} > 200$ GeV

D0: 294 pb^{-1}

Search in four regions of the $M_{\mu\mu}$ - S_T plane

$S_T = \Sigma[E_T(j_i)+E_T(\mu_i)]$





μμjj: the results

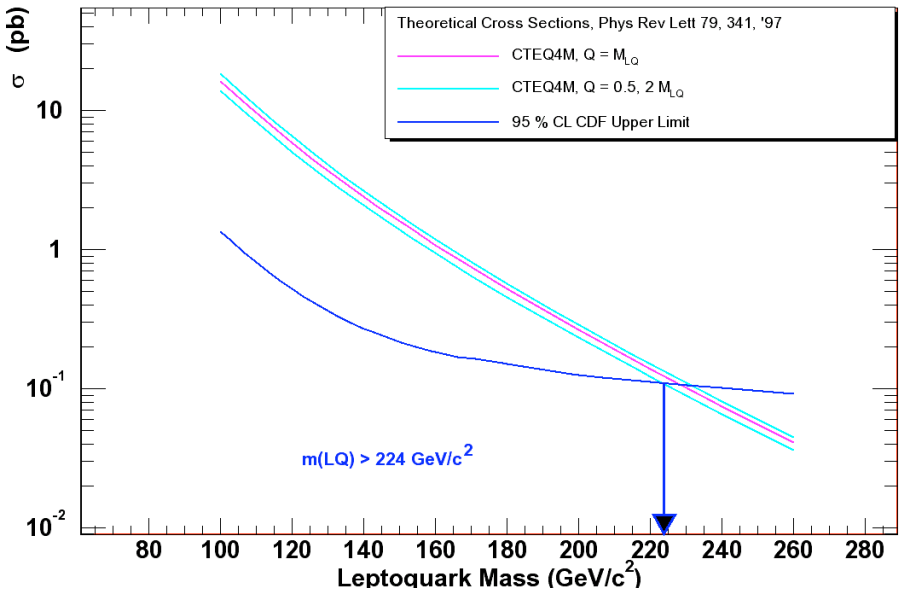
Prediction: 3.0 ± 1.0

- Z/γ* + jets: 57%
- QCD (fake): 33%

Observation: 2

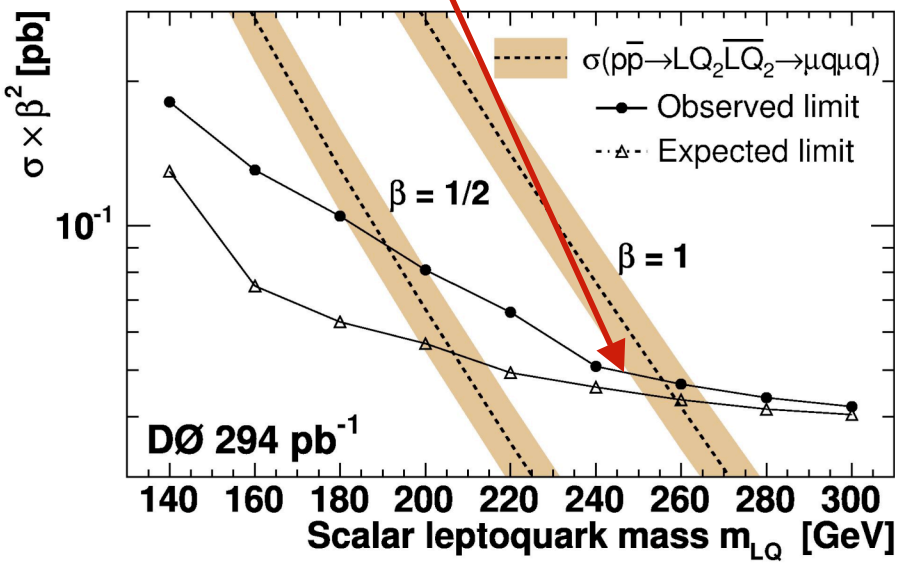
Predictions:	Observations:
Bin 0: 5.1 ± 1.6	Bin 0: 2
Bin 1: 1.0 ± 0.4	Bin 1: 2
Bin 2: 0.4 ± 0.1	Bin 2: 2
Bin 3: 0.3 ± 0.1	Bin 3: 0

Exclude at 95% CL
M_{LQ} > 224 GeV (β=1)



Likelihoods for all bins are combined

Exclude at 95% CL
M_{LQ} > 247 GeV (β=1)

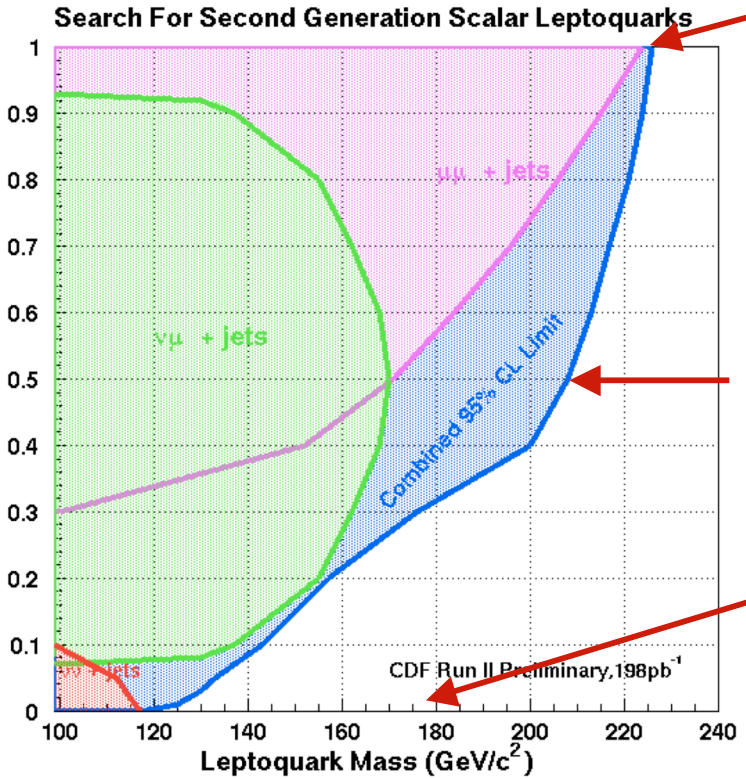


Combined results: 2nd generation

Parameterizing the results for μμjj, μνjj and ννjj as a function of β and combining them, yields:

CDF

To be updated



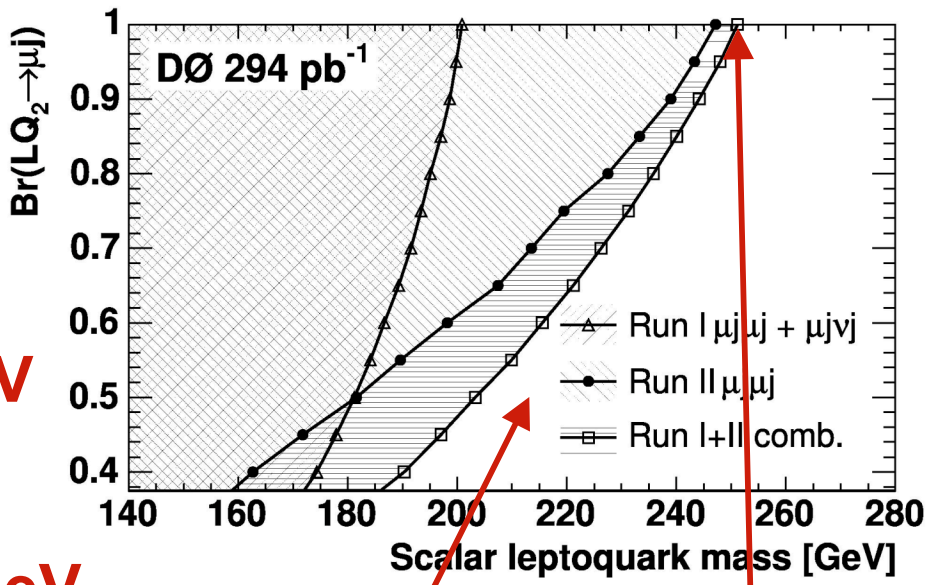
225 GeV

208 GeV

177 GeV

D0

To be updated



214 GeV

251 GeV

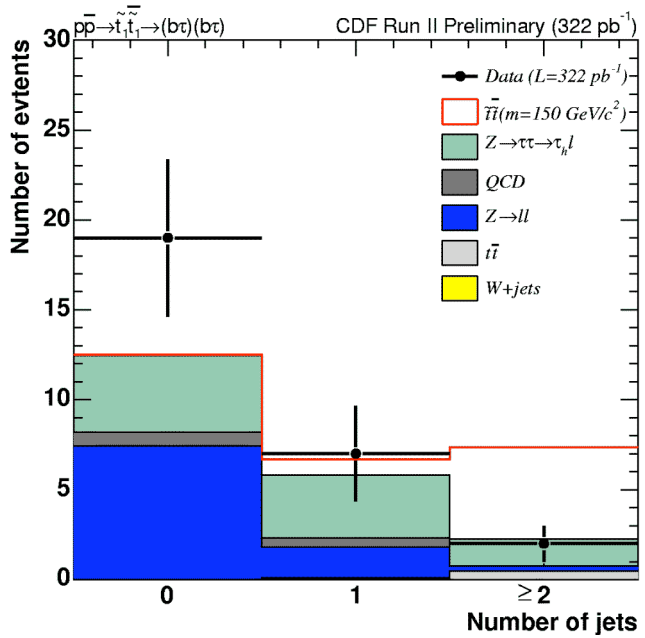
Searches for 3rd generation leptoquarks

ττjj: the analyses

Main Backgrounds: $Z/\gamma^* \rightarrow \tau\tau_h$ + 2-jets, $t\bar{t}$, QCD(fake)

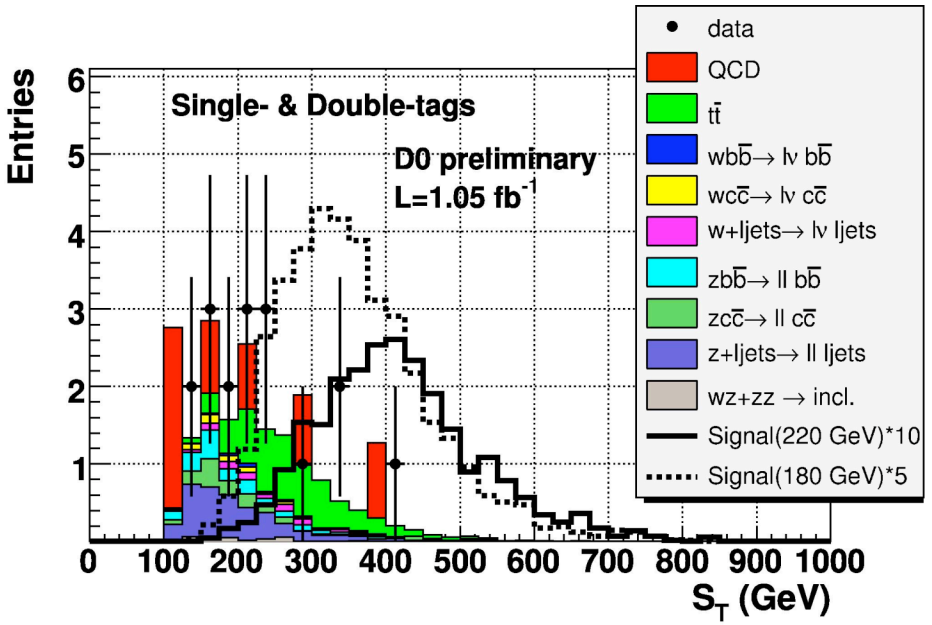
CDF: 322 pb^{-1}

$\tau_h = \pi^{\pm}\nu,\ \pi^{\pm}\pi^0\nu,\ \pi^{\pm}\pi^{\pm}\pi^{\pm}(\pi^0 s)\nu$



- tau channels: 1 τ_μ or τ_e and 1 τ_h
- No b-tagging is applied to jets
- $M_T(\ell\text{-}E_T) < 35$ GeV
  - $M_T > 35$ GeV used as control region
- N_{jet} in signal and control regions is an input in limit calculation

D0: 1.05 fb^{-1}

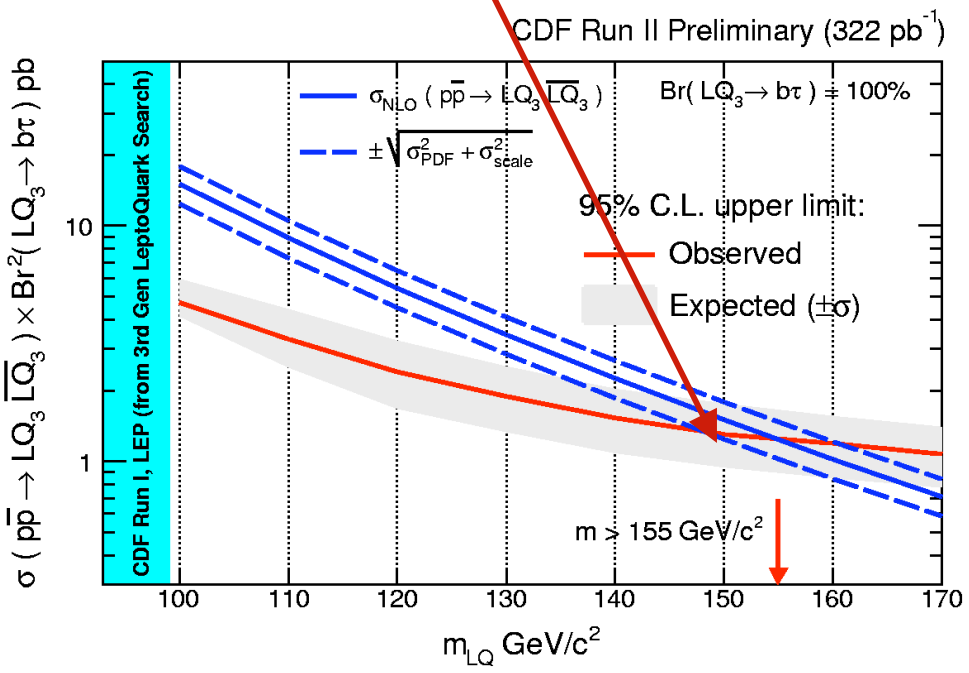


- tau channels: 1 τ_μ and 1 τ_h
- 2 samples: 1 and 2 b-tag jets
- S_T is an input in limit calculation
  - $S_T = E_T(j_1)+E_T(j_2)+E_T(\mu)+ E_T(\tau_h)+ \not{E}_T$

ττjj: the results

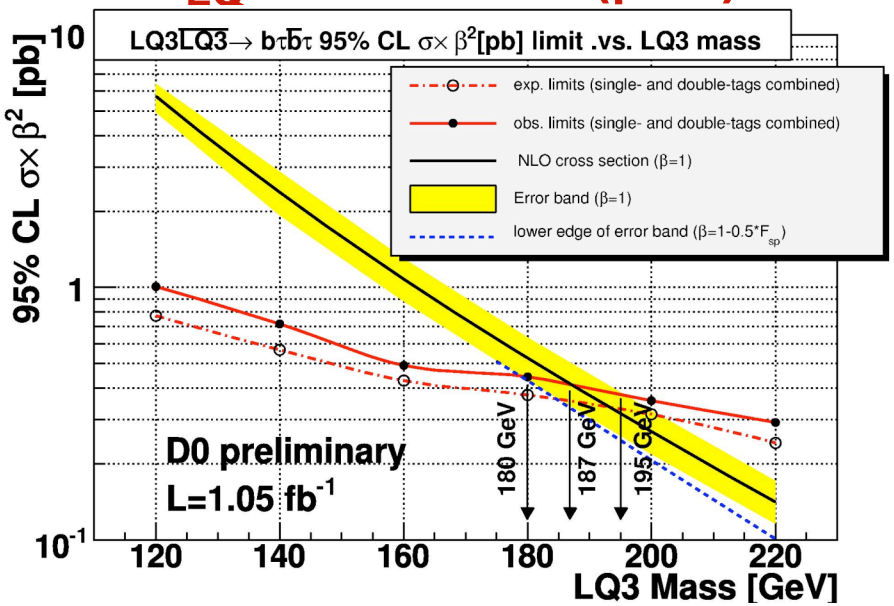
Predictions:	Observations:
$\tau_e\tau_h$: 2.0 ± 0.6	$\tau_e\tau_h$: 1
$\tau_\mu\tau_h$: 1.0 ± 0.6	$\tau_\mu\tau_h$: 1

Exclude at 95% CL
M_{LQ} > 151 GeV (β=1)



Predictions:	Observations:
1-tag: 14.8 ± 0.5	1-tag: 16
tt: 24%	
Z+jets: 40%	
2-tags: 3.6 ± 0.1	2-tags: 1
tt: 59%	
Z+jets: 10%	

Exclude at 95% CL
M_{LQ} > 180 GeV (β=1)

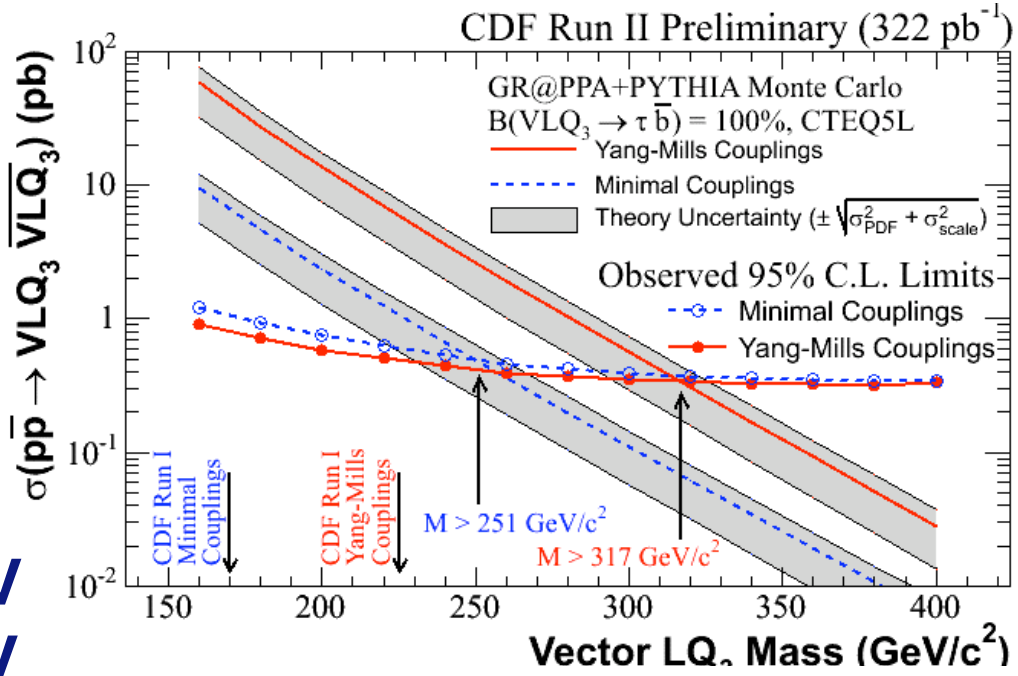


ττjj: Vector Leptoquark results

CDF: 322 pb^{-1}

- **A similar analysis constrains Vector Leptoquarks**
  - **Slightly different selections**
  - **2 kinematic regimes:**
    - **Function of $H_T = E_T(jets)+E_T(\mu_1)+\not{E}_T$**

Predictions:	Observations:
$H_T \in [250,400)$ GeV:	$H_T \in [250,400)$ GeV:
$\tau_e\tau_h$: 3.3 ± 0.6	$\tau_e\tau_h$: 5
$\tau_\mu\tau_h$: 2.2 ± 0.4	$\tau_\mu\tau_h$: 3
$HT \in [400,\infty)$ GeV:	$HT \in [400,\infty)$ GeV:
$\tau_e\tau_h$: 0.3 ± 0.1	$\tau_e\tau_h$: 0
$\tau_\mu\tau_h$: 0.2 ± 0.1	$\tau_\mu\tau_h$: 0



95% CL exclusion (β=1) :

Yang-Mills: M_{LQ} > 303 GeV

Minimal: M_{LQ} > 235 GeV

$\nu\nu b\bar{b}$: the results

CDF: 2.04 fb^{-1}

D0: 425 pb^{-1}

Previous dijets + $\not\!\!E_T$ results can be used to constrain all generations of Leptoquarks

- Acceptance for 3rd gen LQ is smaller than for 2nd gen LQ

Dedicated $b\bar{b}$ + $\not\!\!E_T$ analysis:

b-tagging of the jets

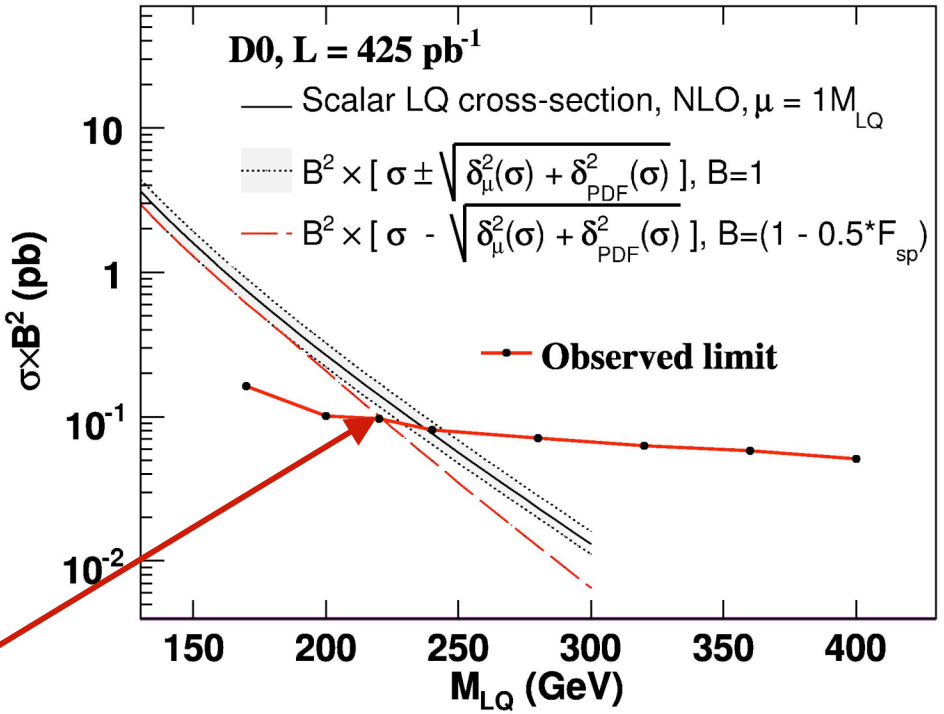
Prediction: 75 ± 15

Observation: 86

Exclude at 95% CL
M_{LQ} > 167 GeV (β=0)

CDF preliminary

Exclude at 95% CL
M_{LQ} > 229 GeV (β=0)



Searches for 1st generation leptoquarks

eνjj: the results

CDF: 203 pb^{-1}

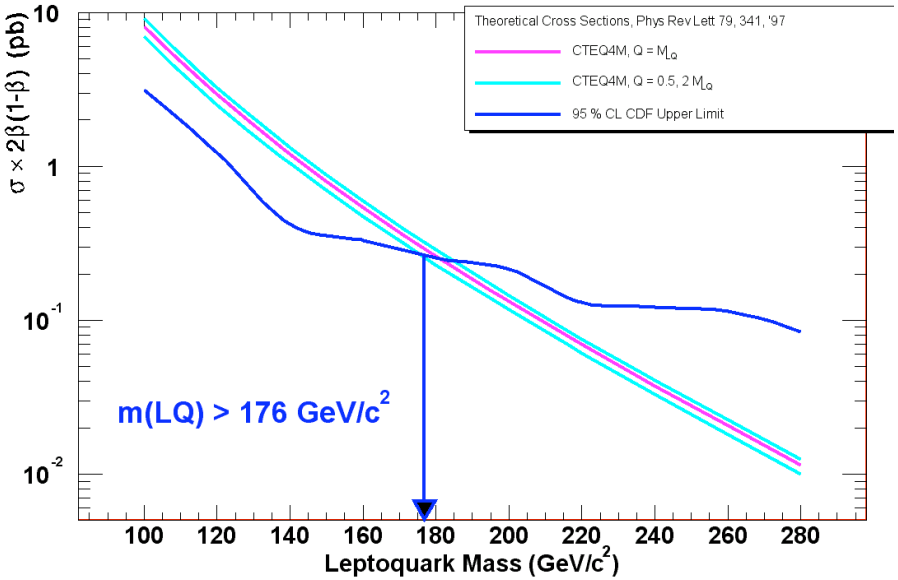
Prediction: 4.6 ± 1.2 events

- W/Z + jets: 56%
- $t\bar{t}$: 44%

Observation: 4

For M_{LQ} = 200 GeV

Exclude at 95% CL
M_{LQ} > 176 GeV (β=1/2)



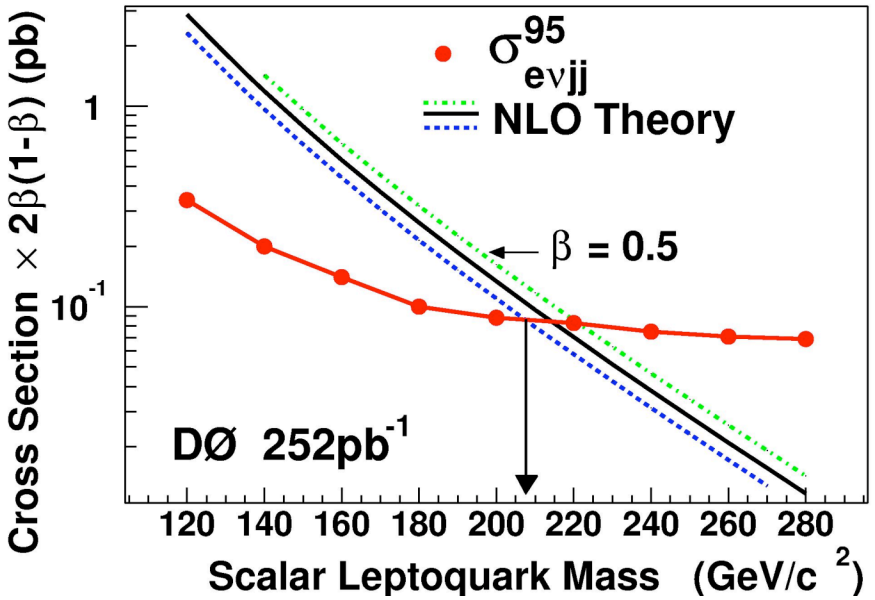
D0: 252 pb^{-1}

Prediction: 3.6 ± 1.2 events

- W/Z + jets: 61%
- $t\bar{t}$ + QCD: 19% + 20%

Observation: 1

Exclude at 95% CL
M_{LQ} > 208 GeV (β=1/2)



eejj: the results

CDF: 203 pb^{-1}

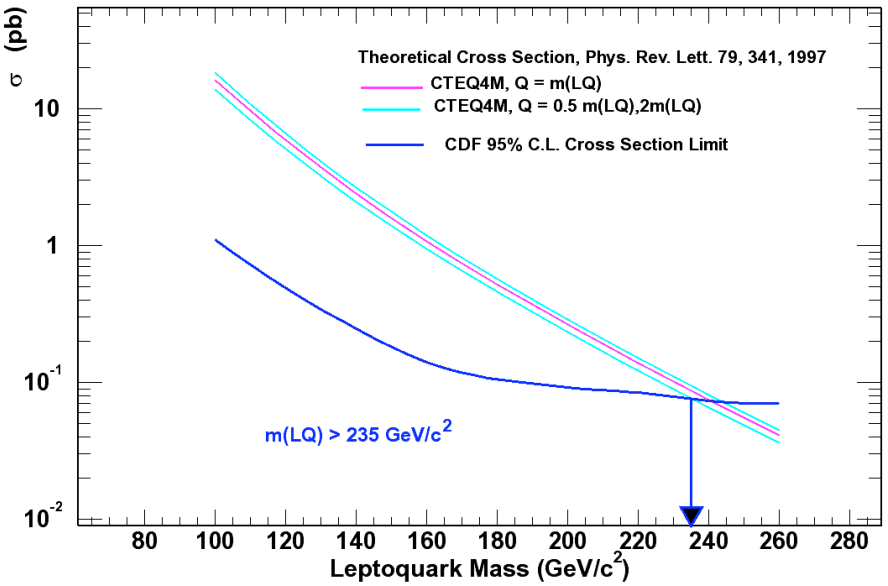
Predictions : 6.2 ± 2.2 events

- Z + jets: 31%
- QCD (fake): 65%

Observation: 4

For M_{LQ} = 200 GeV

Exclude at 95% CL
M_{LQ} > 235 GeV (β=1/2)



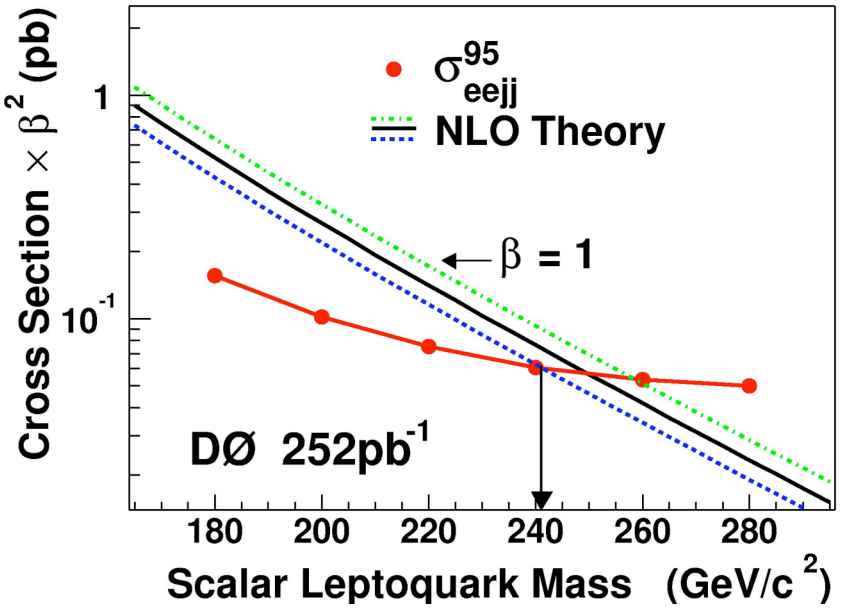
D0: 252 pb^{-1}

Predictions : 3.6 ± 1.2 events

- Z + jets: 41%
- QCD (fake): 50%

Observation: 1

Exclude at 95% CL
M_{LQ} > 241 GeV (β=1/2)



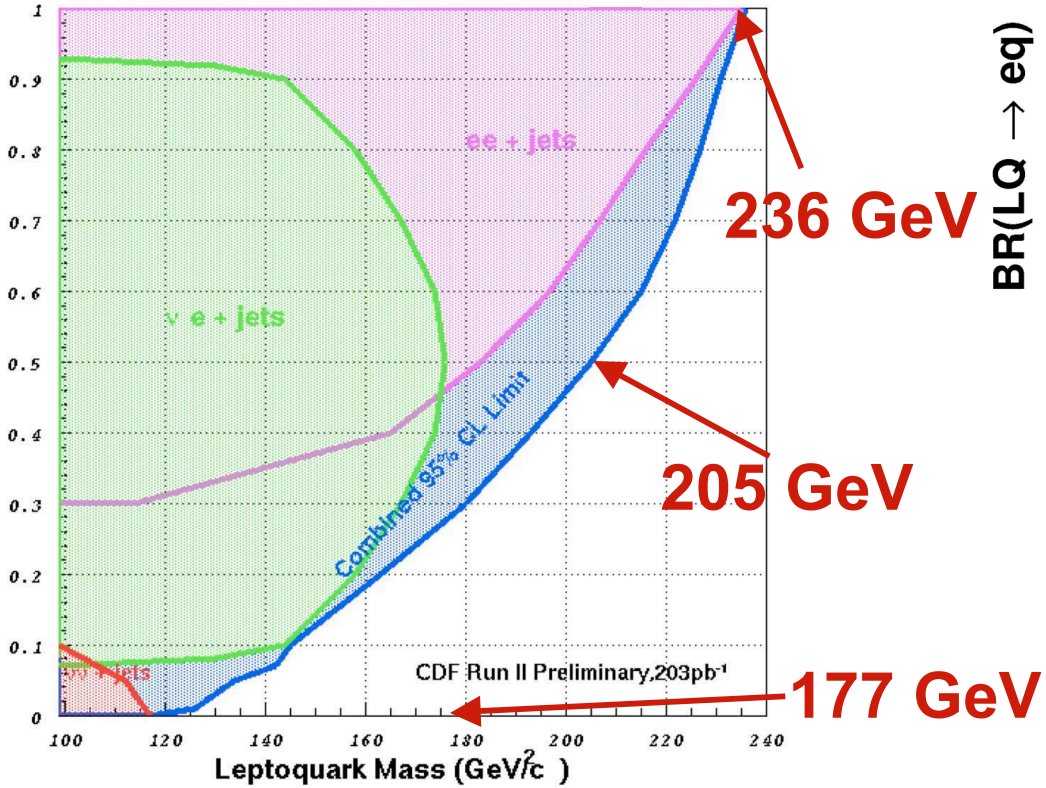
Combined results: 1st generation

Results from ννjj searches are applicable to both 2nd and 1st generation leptoquarks.

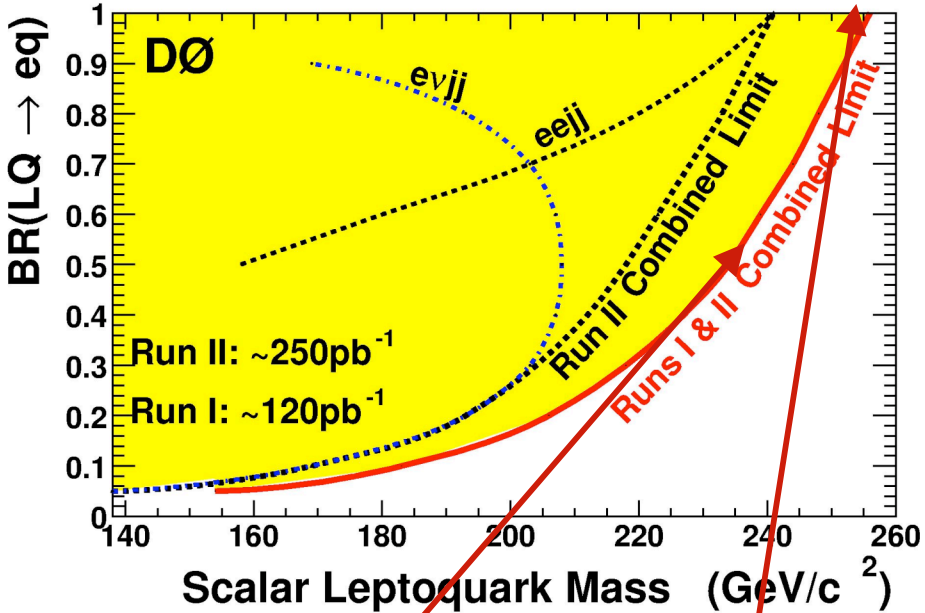
Can't distinguish the light quark jets

CDF

To be updated



D0



Conclusion

- CDF and D0 have performed searches for direct production of leptoquark pairs in many different final states
  - Results cover up to 2 fb^{-1} of data
- No evidence for leptoquarks has been found
  - Constraints on 1st, 2nd and 3rd generation leptoquarks

Summary of the limits on M_{LQ} (in GeV)

	1st	2nd	3rd
$\beta = 1$	236	225	151*
$\beta = 1/2$	205	208	-
$\beta = 0$	177	177	167

	1st	2nd	3rd
$\beta = 1$	256	251	180
$\beta = 1/2$	234	214	-
$\beta = 0$	136	136	229

*** 303 GeV for vector leptoquark with Yang-Mills couplings**