Search for First Generation Leptoquarks at DØ

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Why search for leptoquarks?

Review of current Tevatron results

DØ searches for first generation leptoquarks in three channels: $\nu\nu jj$, $eejj$, and $e\nu jj$

Combined first generation limits

Conclusions

What are Leptoquarks?

Leptoquarks (LQ) appear in many Standard Model extensions to explain the symmetry between quarks and leptons.

As such, they couple to leptons and quarks and carry color, fractional electric charge, baryon (B) and lepton (L) numbers and can be classified by fermion number $F=3B+l$

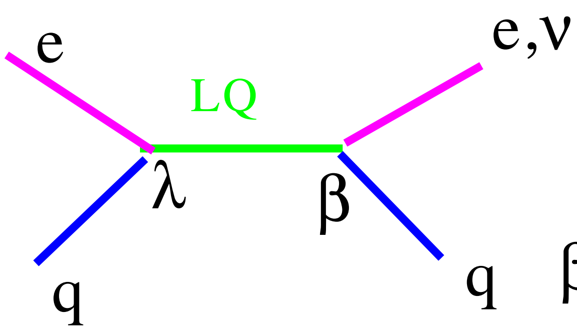
LQs can be scalars (spin 0) or vectors (spin 1)

LQ appear in 3 generations corresponding to 3 lepton/quark generations.

Low mass leptoquarks with universal couplings to all flavors would give rise to flavor changing neutral currents. This is constrained by HERA and low energy results.

Leptoquarks at HERA

H1 and ZEUS reported an excess of high Q^2 events in e^+p data



$\beta = B(LQ \rightarrow l^{\pm}q)$

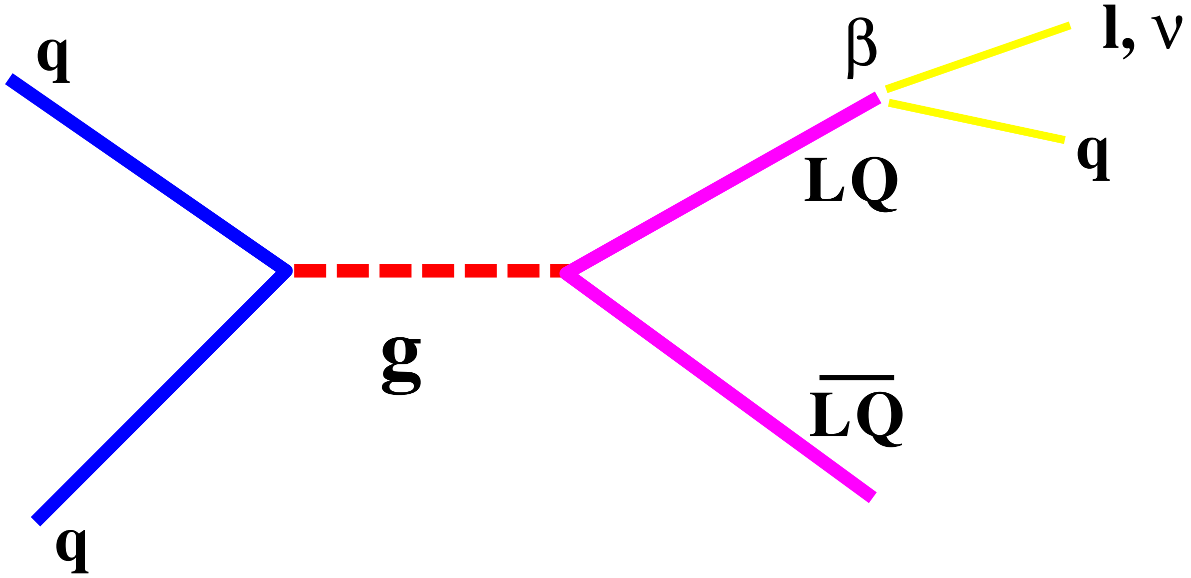
λ is LQ−e−q coupling

Cross section is proportional to $\beta(\lambda q_e)^2/4\pi$

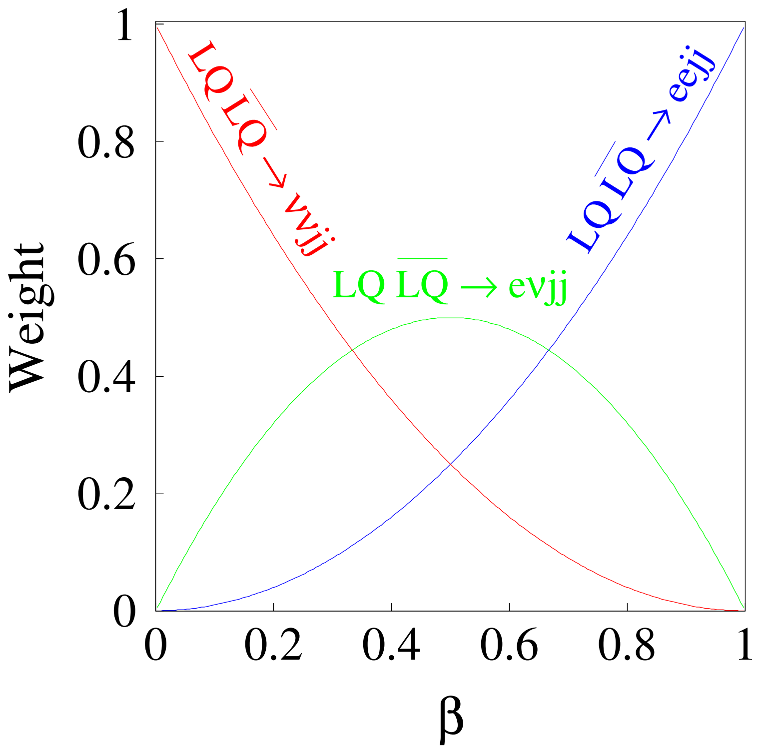
The most straightforward explanation of the HERA data as a LQ hypothesis proposes a narrow resonance with M ~ 200 GeV/c^2 and 100% branching fraction into eq.

However, recent work allows for explanations with non−zero braching fractions into νq

Leptoquarks at the Tevatron



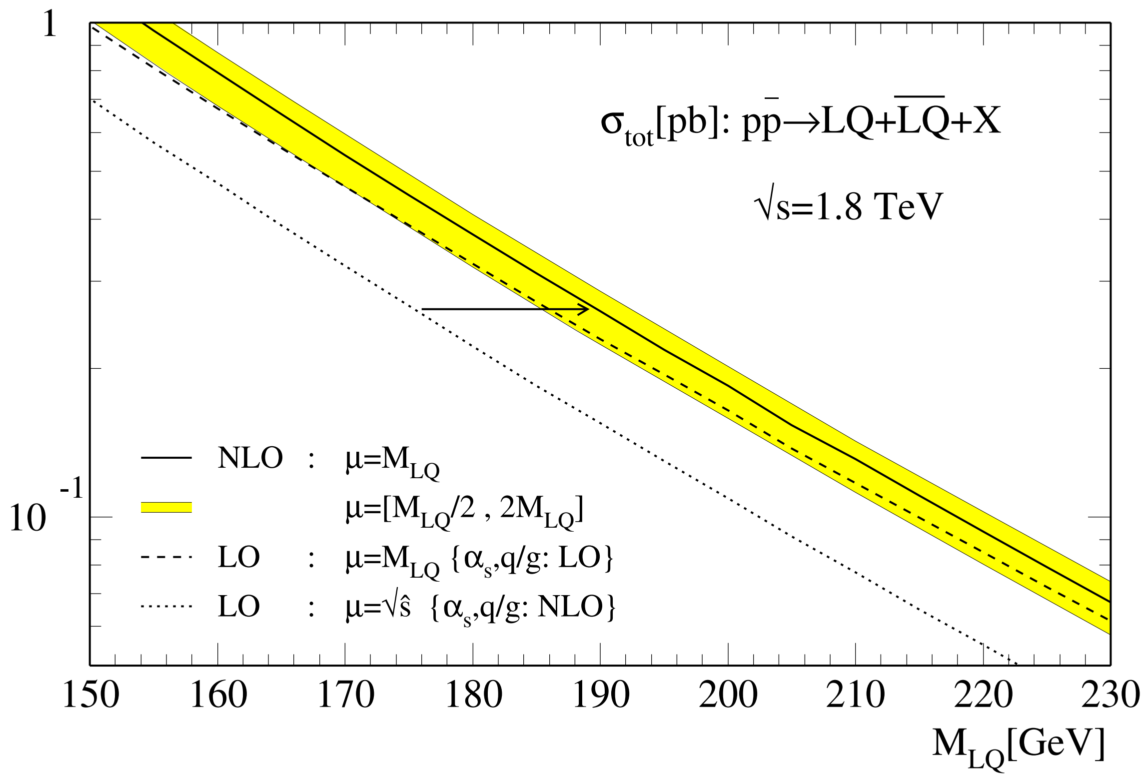
Leptoquarks are pair produced by gluon fusion and qq annihilation. Production cross section depends on the leptoquark mass and spin.



Cross section insensitve to λ

$\beta = B(LQ \to l^{\pm}q)$
eq: $\beta = 1$
νq: $\beta = 0$

Leptoquarks at the Tevatron



Krämer et al. PRL 79, 341 (1997)

All Tevatron leptoquark analyses now use NLO cross sections with $\mu = 2M_{LQ}$

Current Tevatron Results

Third Generation
CDF:
$\tau\tau jj$ $M_{sLQ} > 99$ GeV/c^2 for q = 2/3,4/3
$M_{vLQ} > 225$ GeV/c^2 for q = 2/3,4/3

DØ:
$\nu\nu bb$ $M_{sLQ} > 98$ GeV/c^2 for q = 1/3
$M_{vLQ} > 201$ GeV/c^2 for q = 1/3

Second Generation $\mu\mu jj$ channel

CDF: $M_{sLQ} > 197$ GeV/c^2 for $\beta = 1$
DØ: $M_{sLQ} > 184$ GeV/c^2 for $\beta = 1$

First Generation
CDF:
eejj $M_{sLQ} > 213$ GeV/c^2 for $\beta = 1$
$e\nu jj$ $M_{sLQ} > 180$ GeV/c^2 for $\beta = 1/2$

DØ:
eejj $M_{vLQ} > 298$ GeV/c^2 for $\beta = 1$
$e\nu jj$ $M_{vLQ} > 270$ GeV/c^2 for $\beta = 1/2$

DØ scalar results to be presented.

Yang−Mills coupling assumed for vLQ

$LQ\ \overline{LQ} \longrightarrow \nu\nu jj$

Run 1a DØ search for $\tilde{t} \rightarrow c\tilde{\chi}_1^0$ has the same final state –– two jets + $\not{E}_T$ (PRL 76, 1996)

Use same cuts and background estimates from the sTop seach to set a limit on the production of first generation leptoquarks.

Selection Requirements:

Run 1a single interaction data 7.4 ± 0.4 pb^{-1}
Data collected with a $\not{E}_T$ trigger with $\not{E}_T > 40$ GeV.

Analysis requirements:

$\not{E}_T > 40$ GeV
2 Jets with $E_T > 30$ GeV
$90^\circ < \Delta\phi\,(j_1, j_2) < 165^\circ$
$10^\circ < \Delta\phi(j_1, \not{E}_T) < 125^\circ$
$10^\circ < \Delta\phi(j_{3,4}, \not{E}_T)$

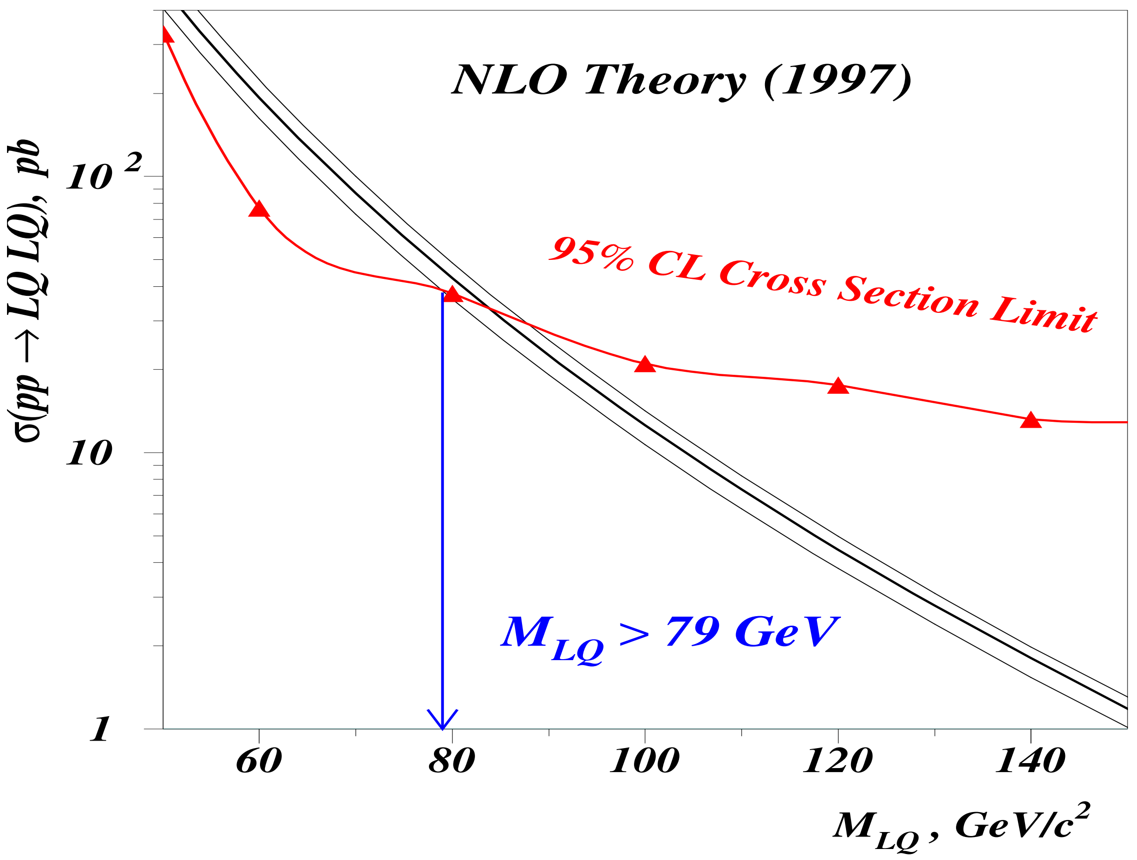
Events with muons or electrons with $E_T > 10$ GeV are vetoed

3 events observed with 3.5 ± 1.2 events predicted background.

$LQ\ \overline{LQ} \longrightarrow \nu\nu jj$

Signal samples
ISAJET generator with GEANT based detector simulation. Applied kinematic cuts and trigger turn–on factor.

Efficiencies range from 0.4% – 6%



95% CL cross section upper limit
Using NLO theory with $\mu = 2M_{LQ}$

$M_{LQ} > 79$ GeV/c^2 at 95% CL for $\beta = 0$

Optimized Searches

1) Make preliminary cuts based on event topology and trigger requirements

2) Remove vector boson background with mass cut.

3) Multivariate analysis used to obtain cuts that give high signal efficiency for small fixed background.

4) Mass analysis used as a cross check

5) In the absense of a signal, calculate 95% CL cross section upper limit as a function of leptoquark mass

This strategy applied to scalar leptoquarks

$LQ\overline{LQ} \longrightarrow eejj$ (submitted to PRL)

$LQ\overline{LQ} \longrightarrow e\nu jj$ (this talk)

$LQ\ \overline{LQ} \longrightarrow eejj$

Data Sample: 123 pb^{-1} collected on triggers requiring two EM clusters

Event vertex was determined by finding the vertex associated with the EM clusters

Electron identification:

$|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$
Tight electron:
Calorimeter cluster shape,
EM fraction and isolation, ionization information in the tracking systems and match between calorimeter cluster and track.

Loose electron:
Calorimeter cluster shape, EM fraction and isolation.

Jet identification: 0.7 cone jets $|\eta| < 2.5$
with $E_T > 15$ GeV

Jets and electrons isolated by $\Delta R > 0.7$

$LQ\ \overline{LQ} \longrightarrow eejj$

Basic cuts:

2 electrons $E_T > 20$ GeV (1 tight)
2 or more jets $E_T > 15$ GeV
veto events with $82 < M_{ee} < 100$ GeV/c^2

101 events in 123 pb^{-1}

Signal Samples: ISAJET v7.22 with
GEANT based detector simulation
80 GeV/c^2 $< M_{LQ} <$ 260 GeV/c^2
Cross sections used NLO calculation.

Background Samples:

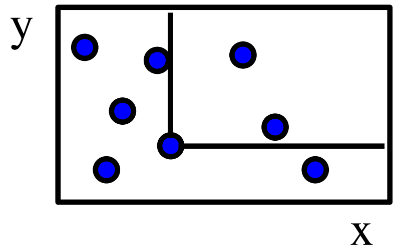
Drell–Yan + 2 jets production
ISAJET generation in 4 M_{ee} bins.
Cross section normalized to Z boson region for Z + 2 jets.

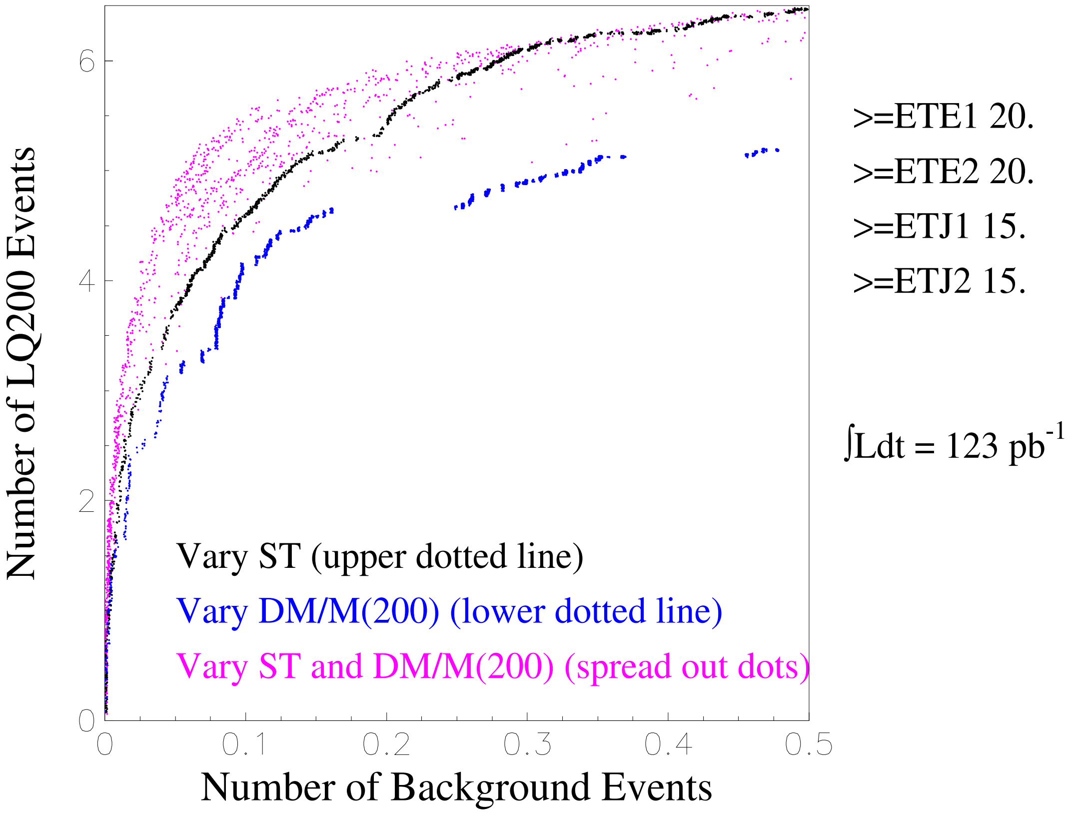
$t\bar{t}$ production l^+l^- + jets
HERWIG v5.7
Measured DØ cross section
5.5 ± 1.8 pb for $M_{top} = 173.3$ GeV/c^2

Multijet
Collider data, low E_T 3 jet trigger
0.9 pb^{-1} data corresponding to 400K events

$LQ\ \overline{LQ} \longrightarrow eejj$

Random Grid Search: Maximize signal efficiency for small fixed background

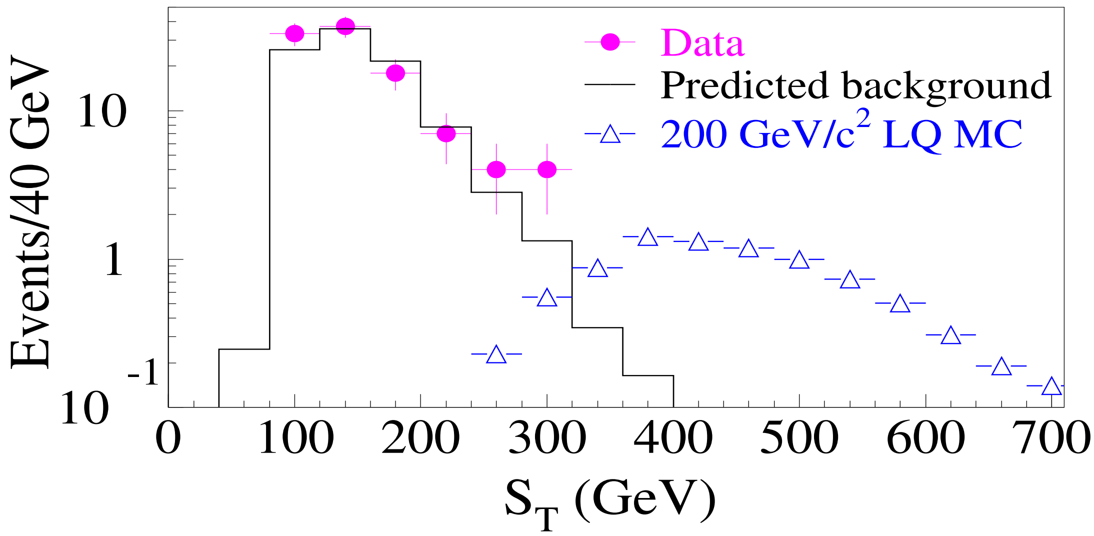




$$DM/M(M_{LQ}) = \mathrm{sqrt}((Mej_1 - M_{LQ})^2 + (Mej_2 - M_{LQ})^2)/M_{LQ}$$

$$S_T = (E_T(e_1) + E_T(e_2) + \Sigma\, E_T(j_i))$$

$LQ\ \overline{LQ} \longrightarrow eejj$



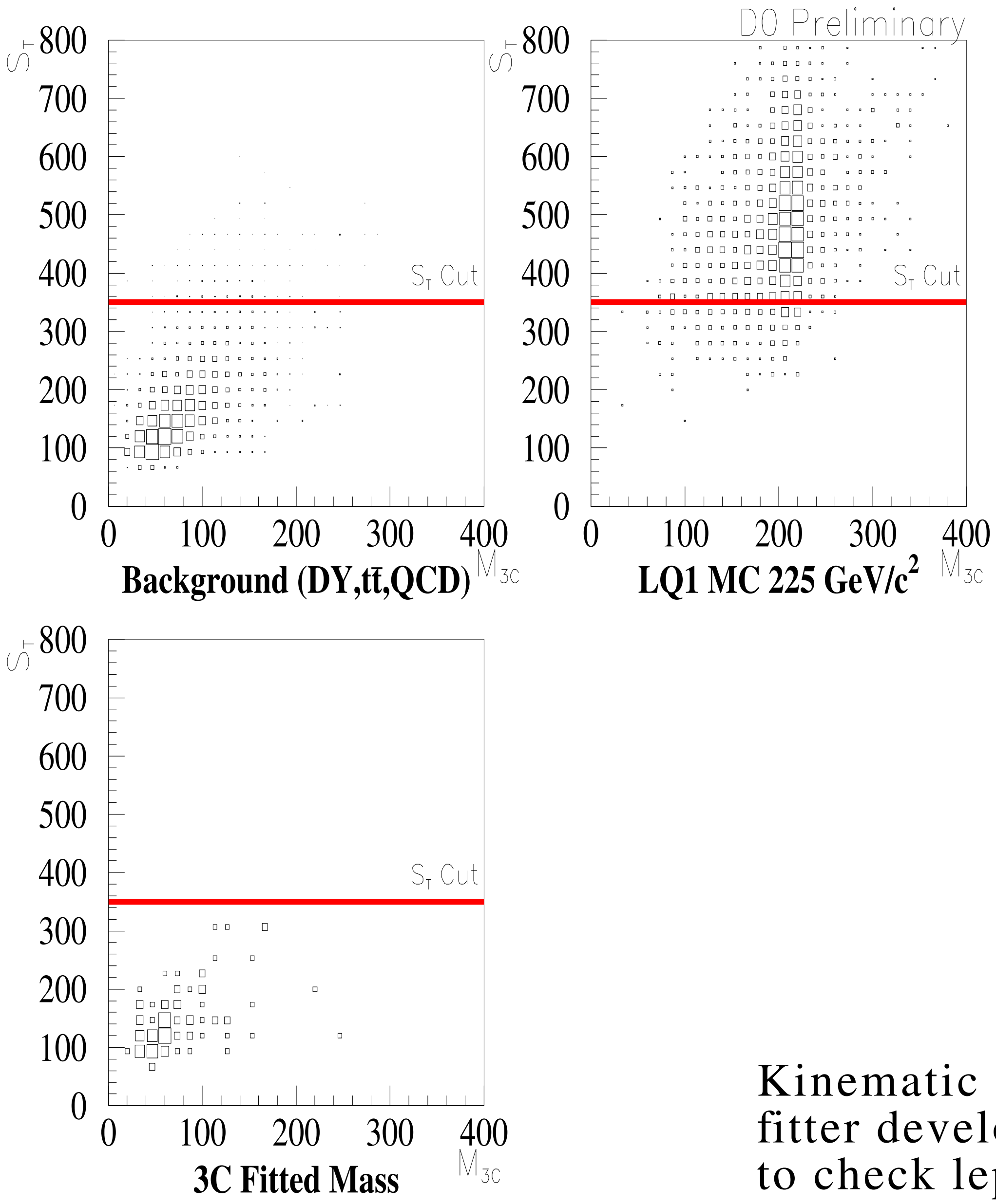
S_T > 350 GeV leads to ~0.4 predicted background

Signal efficiencies range from 9% – 39% MC used for kinematic cuts with particle ID efficiencies from Z data.

Total systematic errors 16% – 13%

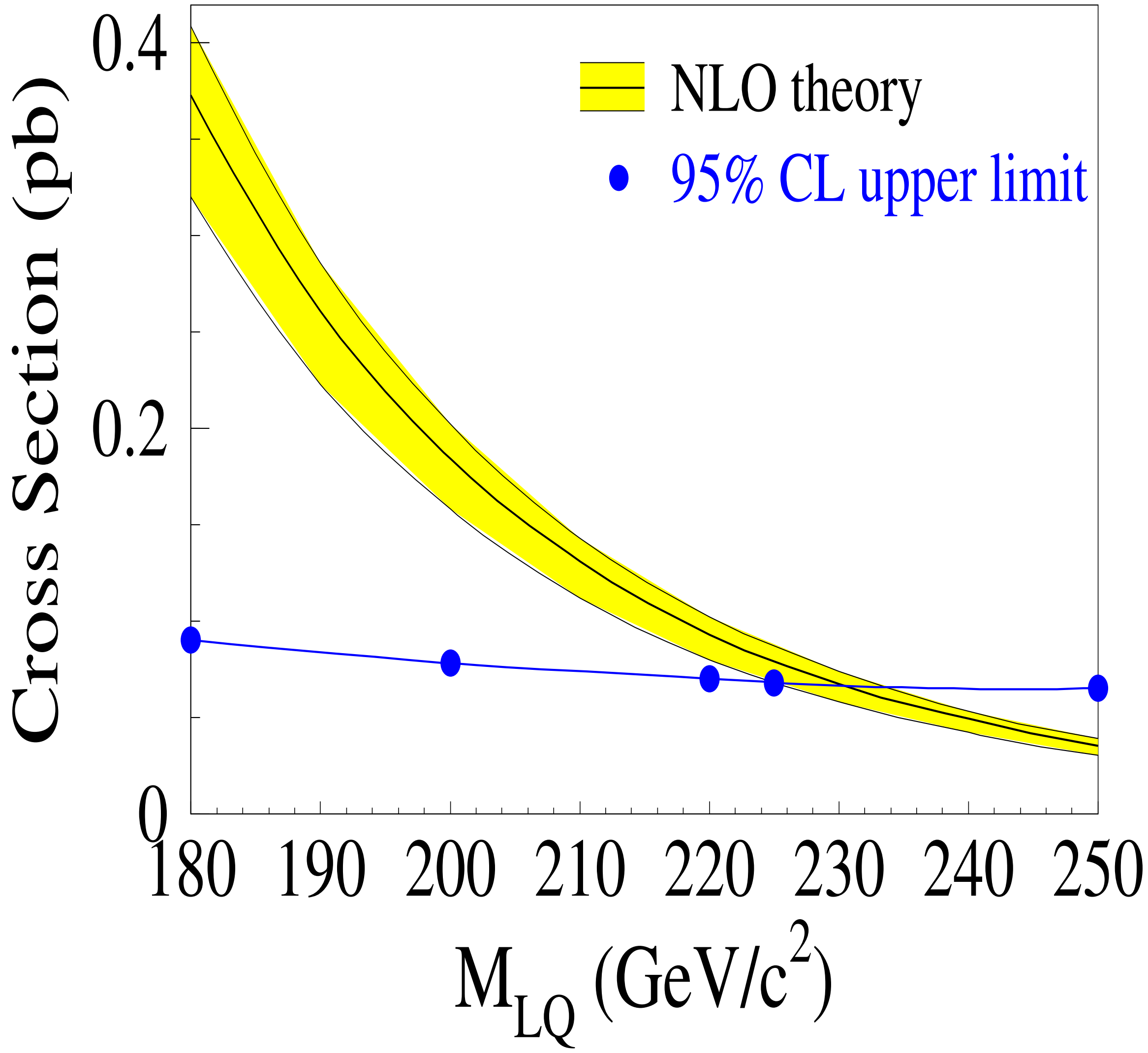
Background	Number of events
Drell–Yan	0.18 ± 0.04
$t\bar{t}$	0.11 ± 0.04
Multijet	0.16 ± 0.02
Total	0.44 ± 0.06

$LQ\ \overline{LQ} \longrightarrow eejj$



Kinematic
fitter developed
to check leptoquark
hypothesis

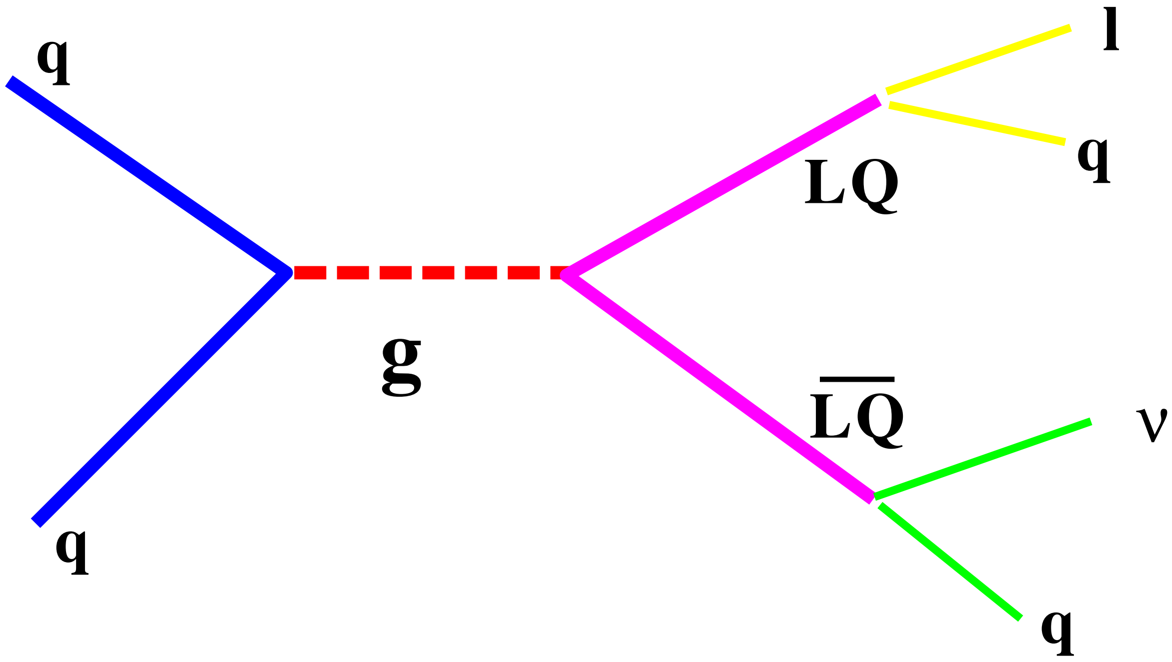
$LQ\ \overline{LQ} \longrightarrow eejj$



95% CL cross section upper limit for $\beta = 1$
Using NLO theory with $\mu = 2M_{LQ}$

$M_{LQ} > 225$ GeV/c^2 at 95% CL

$LQ\ \overline{LQ} \longrightarrow e\nu jj$

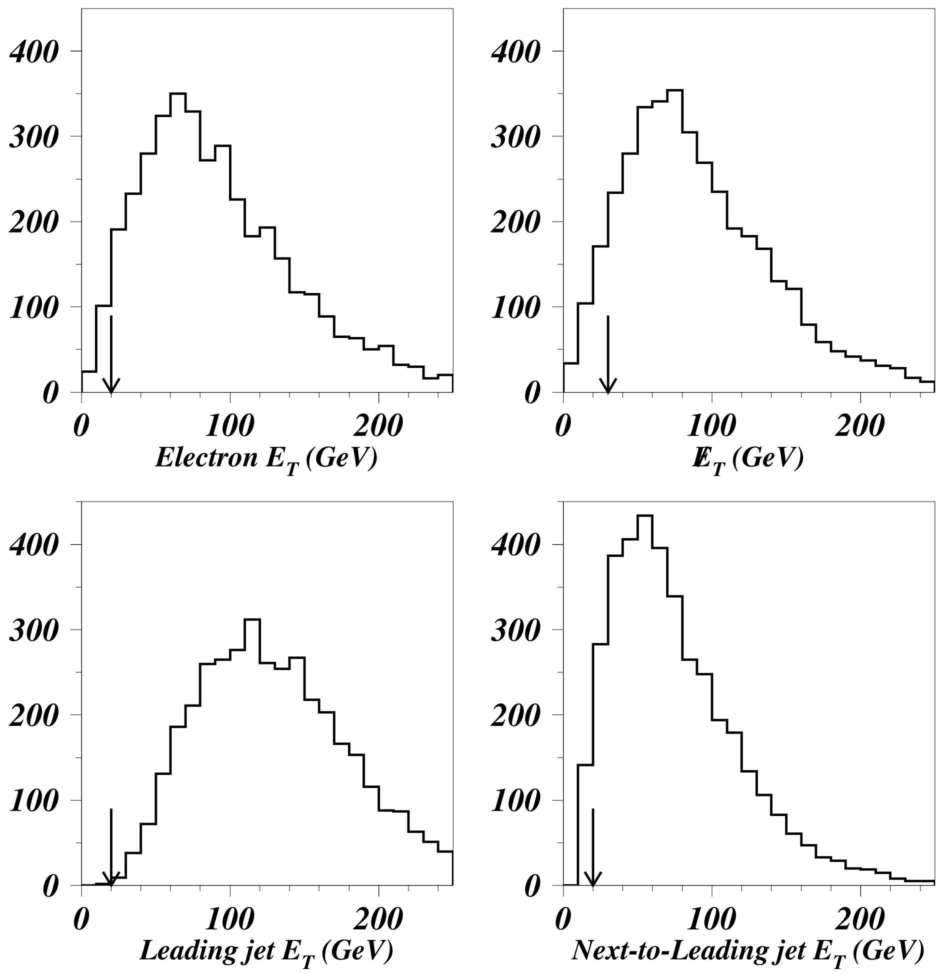


DØ has conducted an optimized search in the eνjj channel

This channel has maximum sensitivity at $\beta = 1/2$.

$LQ\ \overline{LQ} \longrightarrow e\nu jj$

Signal Distributions For M_{LQ} = 180 GeV/c^2



Data Sample: 115±6 pb^{-1}

Run 1a EM Cluster E_T>20 GeV 11.2 pb^{-1}

Run 1b EM Cluster E_T>20 GeV
$\not\!E_T$ > 15 GeV 92.9 pb^{-1}

Run 1c EM Cluster E_T>20 GeV
$\not\!E_T$ > 15 GeV
Jet E_T > 10 GeV 10.5 pb^{-1}

$LQ\ \overline{LQ} \longrightarrow e\nu jj$

Event vertex determined by EM cluster

Data not used during "calorimeter recovery" to prevent main ring contamination of $\not{E}_T$ retains 94 ±0.01% calculated from $Z \longrightarrow ee$ + 2 jets

The tight electron identification criterion from eejj analysis is used.

Basic Cuts:

1 tight electron with $E_T > 20$ GeV
2 or more jets with $E_T > 20$ GeV
$\not{E}_T > 20$ GeV

Run 1c trigger required a jet. Offline, the jet is fully efficient at 30 GeV. Turn on curve studied from data and folded into signal and background samples.

3091 events in 115 pb^{-1}

$LQ\ \overline{LQ} \longrightarrow e\nu jj$

Signal Samples:

ISAJET v7.22 with GEANT based detector simulation for $80 < M_{LQ} < 240$ GeV/c^2

Cross Sections used are NLO calculation with $\mu=2M_{LQ}$.

Background Samples:

W+2 jets
VECBOS with HERWIG underlying event modeling and GEANT based detector simulation.

$t\bar{t}$ production l^+l^- + jets, $l^\pm$ + jets
HERWIG v5.7 with GEANT based detector simulation.
Measured DØ cross section
5.5 ± 1.8 pb for Mtop = 173.3 GeV/c^2

$LQ\ \overline{LQ} \longrightarrow e\nu jj$

Multijet Background:

Calculated from 3 jet sample with single interactions and $|Z_{vtx}| < 50$ cm

Each jet assigned the role of the electron and the resulting "electron" + 2 jet "event" is tested against the kinematic cuts. The number of "events" that pass the kinematic cuts are multipled by the electron misidentification probability $f_e = (3.5 \pm 0.35)\ 10^{-4}$

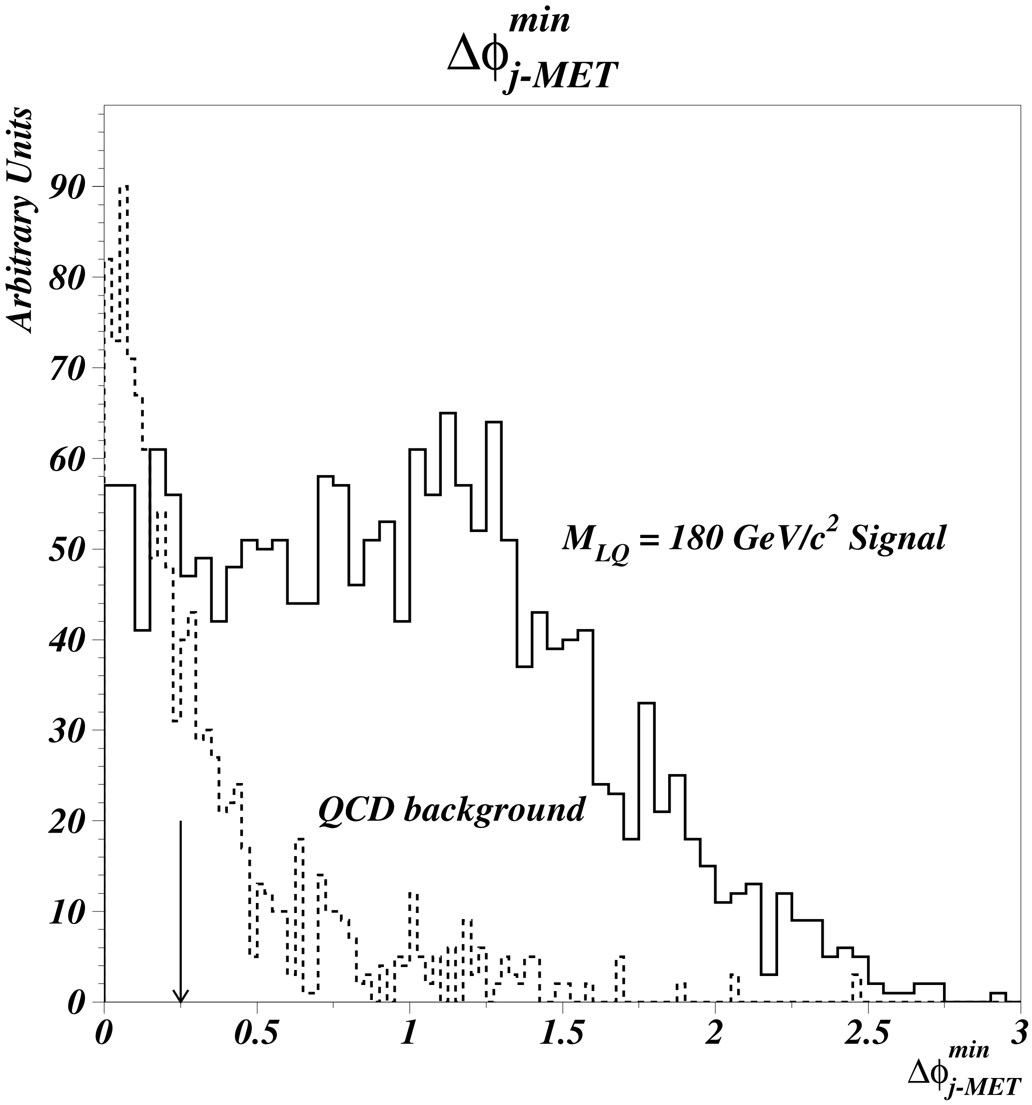
Luminosity in multijet sample 0.9 pb^{-1}. Scale to 115 pb^{-1} and corrected for single vertex requirement using Z + 2 jets data.

Multijet background falls off quickly with $\not{E}_T$

basic cuts:
1 tight electron with $E_T > 20$ GeV
2 or more jets with $E_T > 20$ GeV
$\not{E}_T > 30$ GeV

$LQ\ \overline{LQ} \longrightarrow e\nu jj$

In multijet background, mismeasured jets lead to $\not{E}_T$ that lies along a jet in ϕ



Veto Min($\Delta\Phi(j_i, \not{E}_T)$) < 0.25 radians when $\not{E}_T$ < 120 GeV

$LQ\ \overline{LQ} \longrightarrow e\nu jj$

Top events contain muons from b cascade decays and $W \rightarrow \mu\nu$.
Veto clean muons
Rejection factor of 1.9 ± 0.1 against top events with 0.97 ± 0.01 efficiency for LQ events.

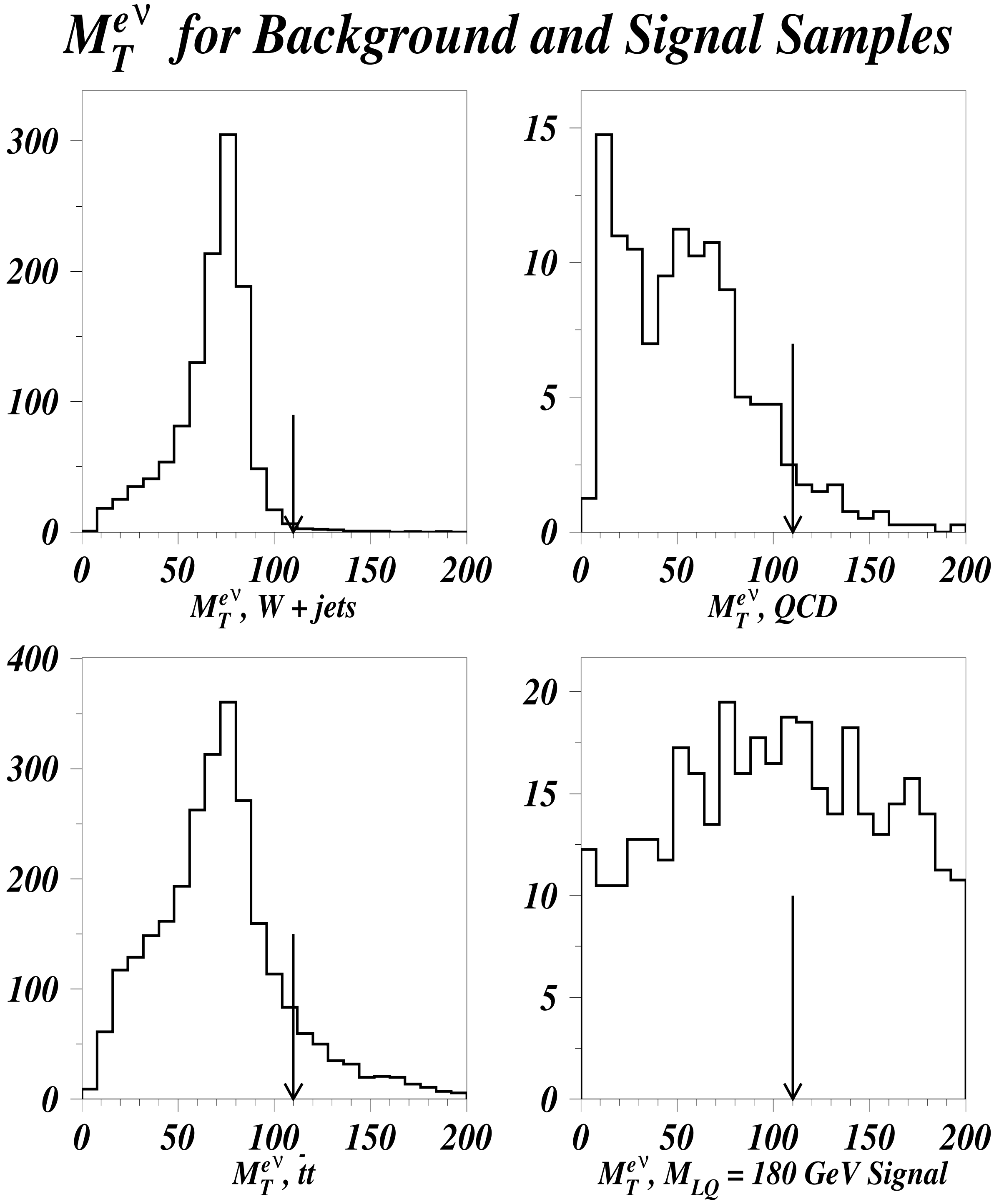
Intermediate Cuts:
1 tight electron with $E_T > 20$ GeV
2 or more jets with $E_T > 20$ GeV
$\not{E}_T > 30$ GeV
veto $\mathrm{Min}(\Delta\Phi(j_i, \not{E}_T)) < 0.25$ radians when $\not{E}_T < 120$ GeV
Veto muons

1094 events in 115 pb^{-1} with
75 ± 15 events from multijet sources
12 ± 4 events from $t\bar{t}$ production

Normalize W + 2 jets MC to remaining sample. Consistent with VECBOS background

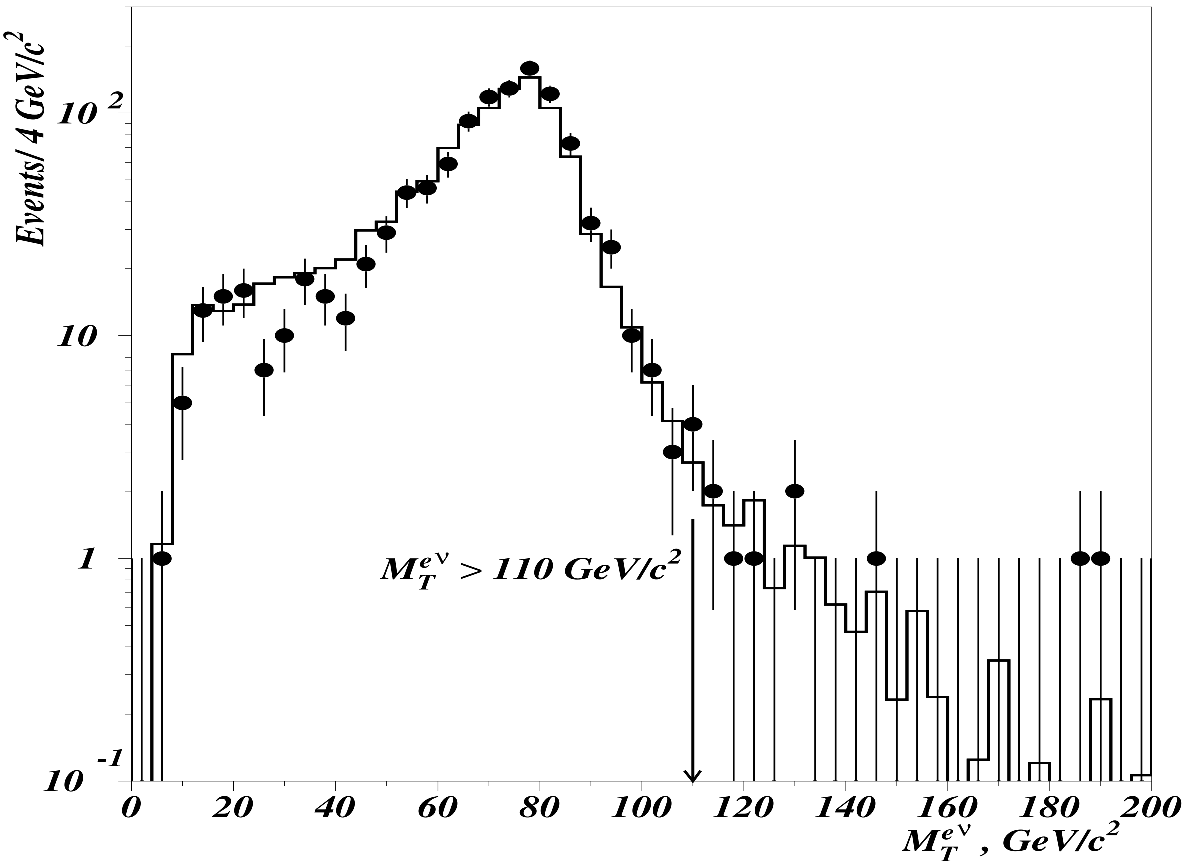
Method reduces energy scale and MC cross section systematic errors.

$LQ\ \overline{LQ} \longrightarrow e\nu jj$



$M_T(e\nu)$ distributions for signal and background

$LQ\ \overline{LQ} \longrightarrow e\nu jj$



$M_T(e\nu) > 110$ GeV/c^2
14 events in 115 pb^{-1} with
17.8 ± 2.2 events predicted background

11.7 ± 1.8 from W + 2 jet
2.0 ± 0.7 from tt production
4.1 ± 1.0 from Multijet

$LQ\ \overline{LQ} \longrightarrow e\nu jj$

Random Grid Search used to determine the variables with most discrimination.

Two variables chosen:

$$S_T^{J_1 J_2} = E_T^{J_1} + E_T^{J_2} + E_T^{e} + \not{E}_T$$

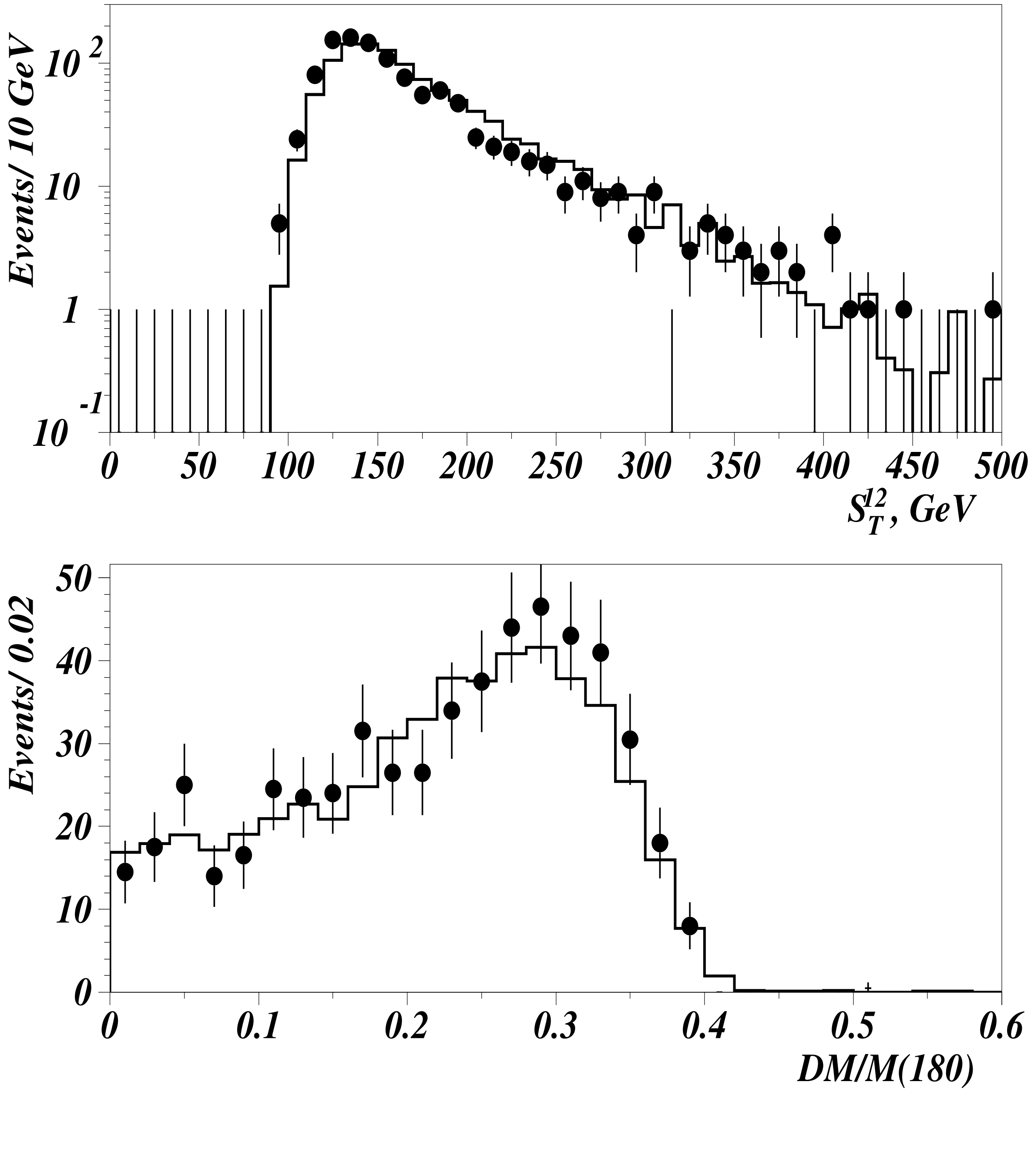
$$dM/M(M_{LQ}) = \\ \mathrm{MIN}\left(\left|(M(eJ_1) - M_{LQ})/M_{LQ}\right|, \left|(M(eJ_2) - M_{LQ})/M_{LQ}\right|\right)$$

where M_{LQ} = Fixed mass of a LQ hypothesis

For $M(eJ_1) \sim M_{LQ}$

$dM/M(M_{LQ})$ is close to 0

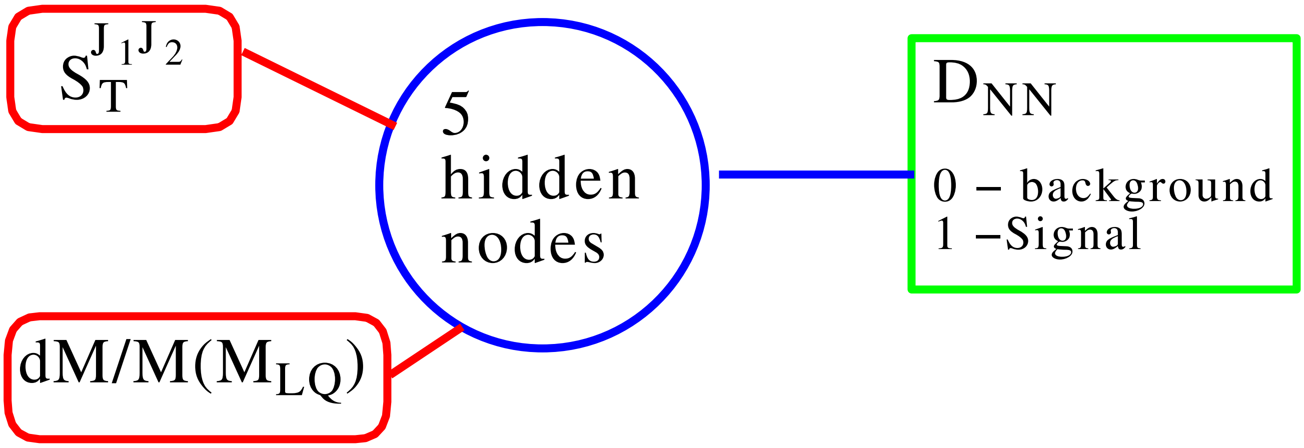
$LQ\ \overline{LQ} \longrightarrow e\nu jj$



$S_T^{J_1J_2}$ and dM/M(180) for data and background

$LQ\ \overline{LQ} \longrightarrow e\nu jj$

Neural Network Analysis:



Network trained with signal MC samples and the appropriate mixture of the background samples after the $M_T(e\nu)$ cut

For two input nodes, the behavior of the network can be examined by looking at the contours in constant D_{NN}

$LQ\ \overline{LQ} \longrightarrow e\nu jj$

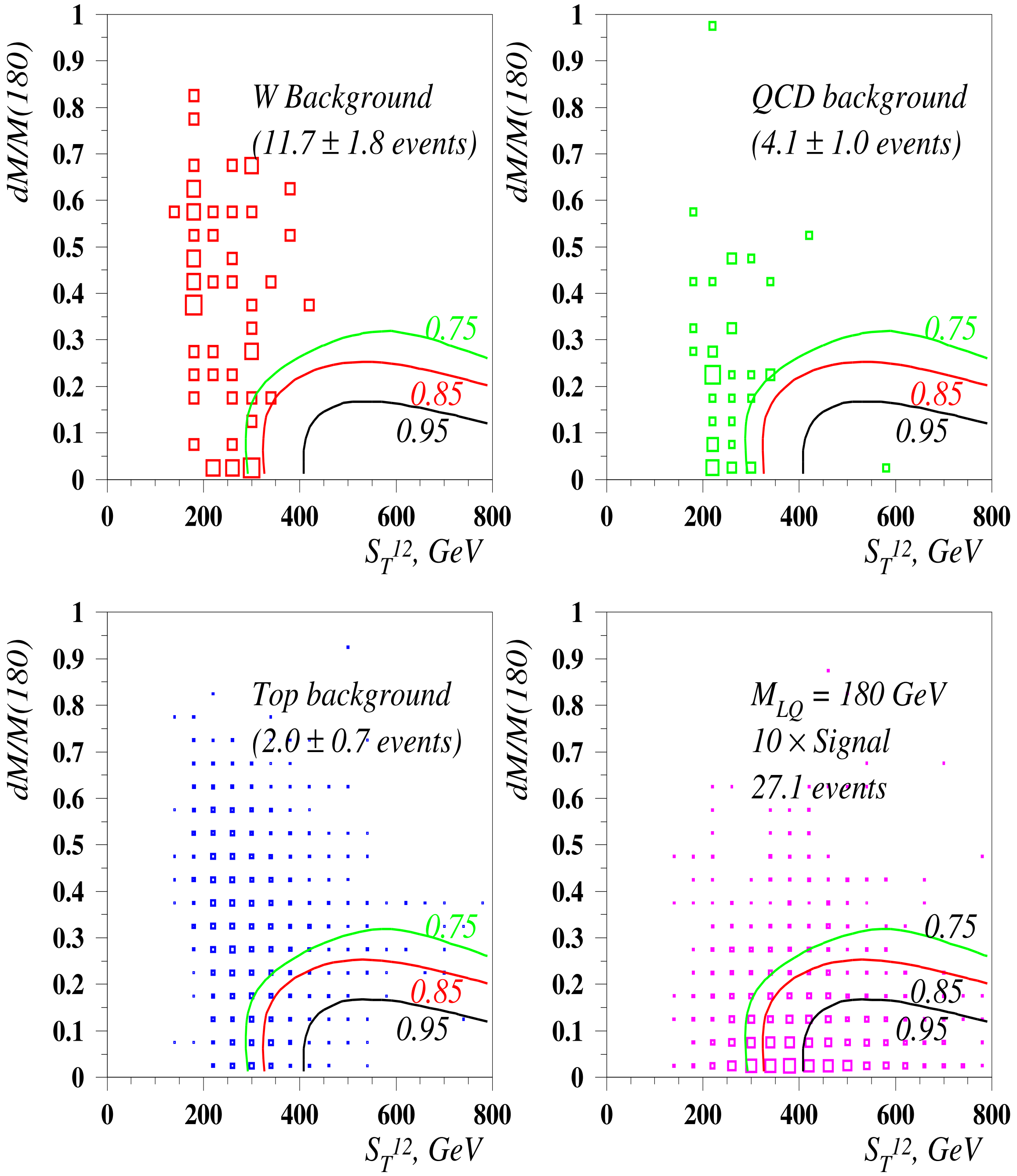
The Network was checked for stability

number of hidden nodes	efficiency (%)	background (events)
3	14.4	0.267
5	14.6	0.283
7		

The network is also stable under different training samples

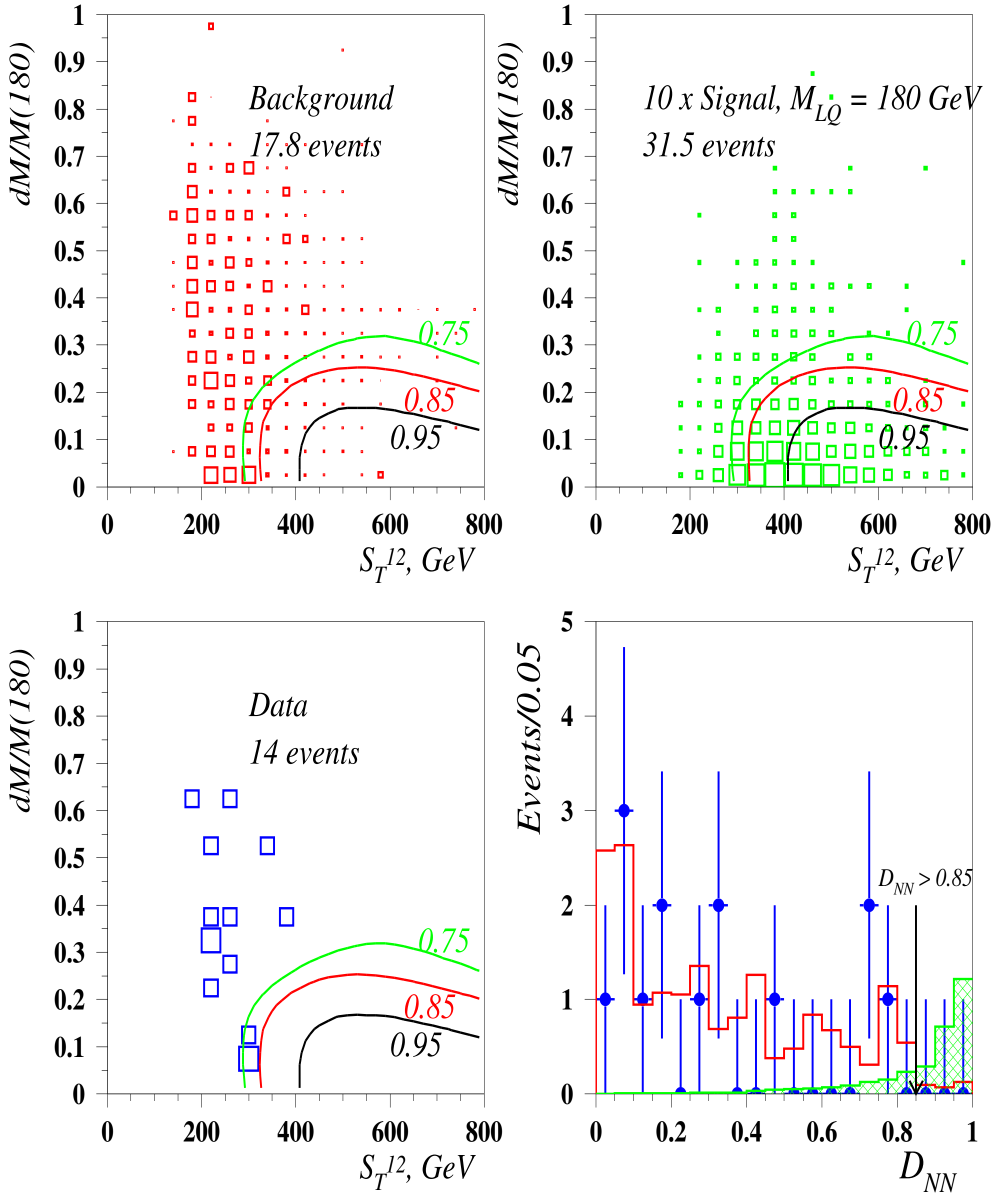
If rectangular cuts are used, drawing a box to correspond to 0.4 events, the efficiency is 10% lower.

$LQ\ \overline{LQ} \longrightarrow e\nu jj$



Sources of background and a signal sample after $M_T(e\nu)$ cut

LQ $\overline{\text{LQ}}$ ⟶ eνjj



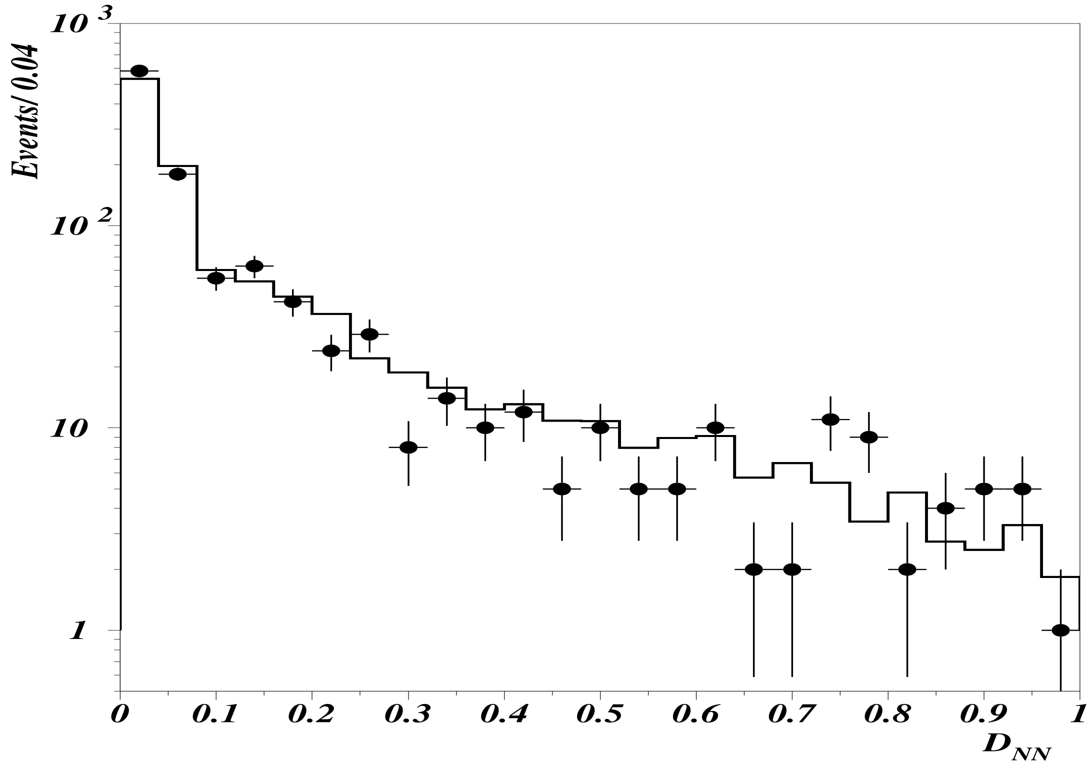
Background, data, and signal after $M_T(e\nu)$ cut

$LQ\ \overline{LQ} \longrightarrow e\nu jj$

For Neural Network with dM/M(180) the goal of ~0.4 background events is achieved with $D_{NN} > 0.85$

$D_{NN} > 0.85$:
0 events observed in 115 pb^{-1} with
0.29 ± 0.25 events predicted background

0.0 +0.2 from W + 2 jet production
0.2 ± 0.1 from tt production
0.1 ± 0.1 from Multijet



$LQ\ \overline{LQ} \longrightarrow e\nu jj$

dM/M(180) trained network is the best choice for $\beta = 1/2$.

To extend the cross section limit lower in β, additional networks trained at M_{LQ} = 120, 140, 160, 200, and 220

At low M_{LQ}, dM/M is no longer needed to discriminate against top background.

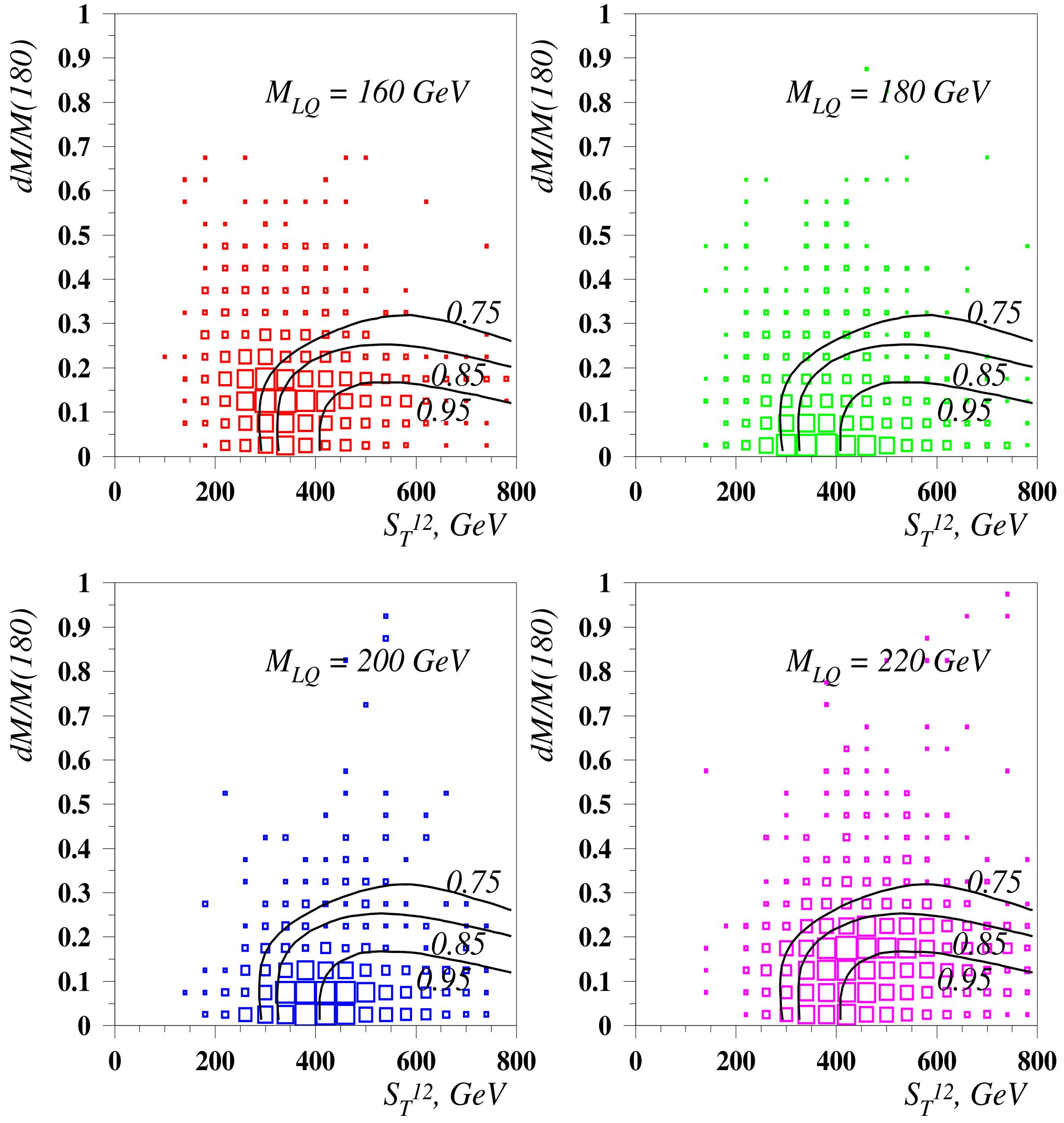
For M_{LQ} = 100, 120 use $S_T^{J_1 J_2}$ only.

$S_T^{J_1 J_2} > 400$ GeV (for low mass M_{LQ})

0 events observed in 115 pb^{-1} with
0.6 ± 0.3 events predicted background

0.22 ± 0.22 from W + 2 jet production
0.19 ± 0.07 from tt production
0.19 ± 0.07 from Multijet

LQ $\overline{LQ}$ ⟶ eνjj



LQ signal samples before $M_T(e\nu)$ cut

$LQ\ \overline{LQ} \longrightarrow e\nu jj$

Signal efficiencies and systematic errors

Efficiencies range from 1.15% – 19.37%

M_{LQ}	Efficiency	NLO σ
80 GeV/c^2	0.3%	17.98 pb
100 GeV/c^2	1.2%	5.34 pb
120 GeV/c^2	2.5%	1.90 pb
160 GeV/c^2	11.0%	0.34 pb
180 GeV/c^2	14.7%	0.16 pb
200 GeV/c^2	19.4%	0.08 pb

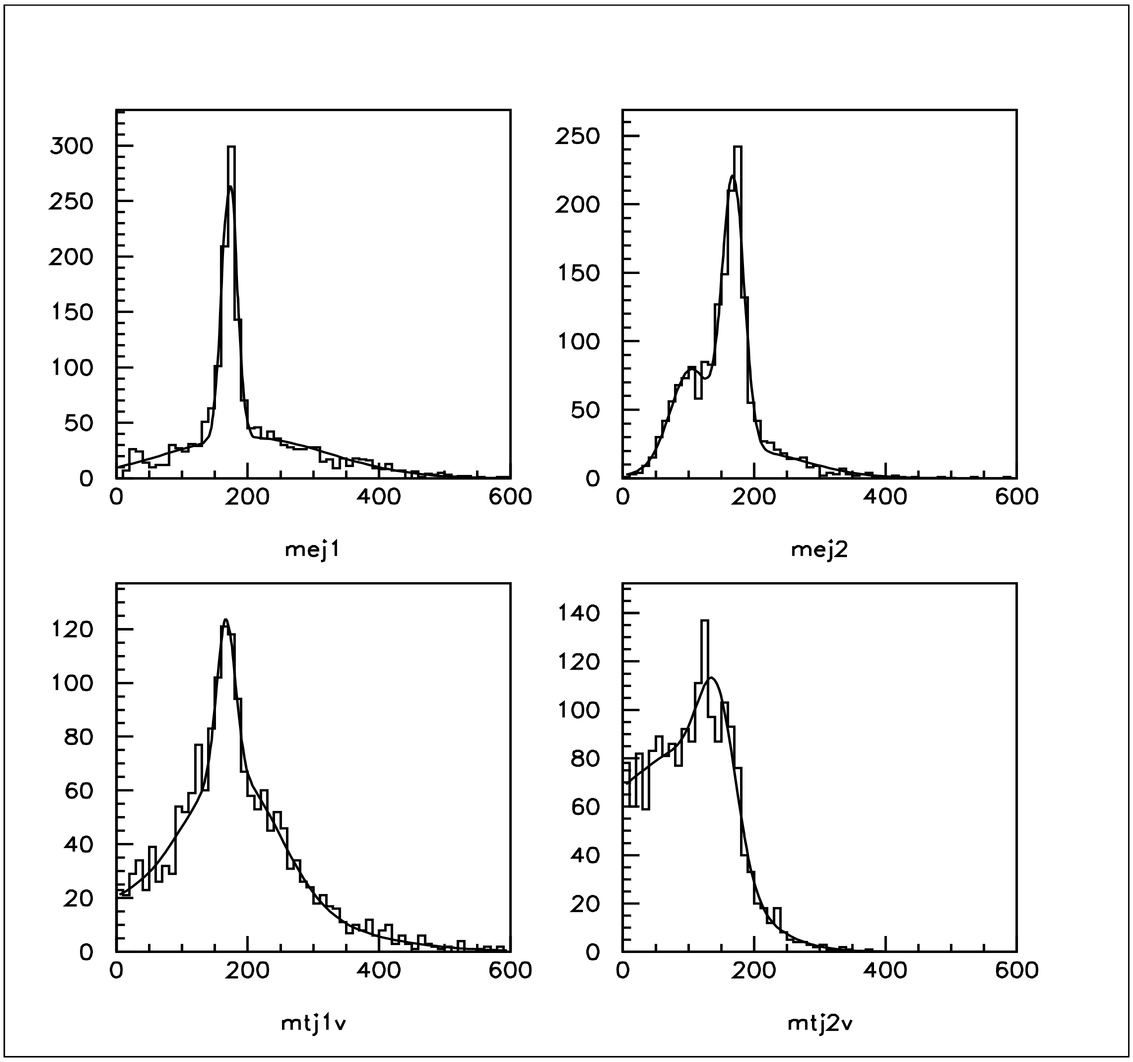
Systematic Errors for M_{LQ} = 180 GeV/c^2

Particle ID	5%
Detector Smearing	3%
Jet energy scale	3%
Gluon radiation	4%
PDF and Q^2	5%
MC statistics	3%
Luminosity	5%
Total	**10%**

$LQ\ \overline{LQ} \longrightarrow e\nu jj$

Mass estimation:

Choose variables which are uncorrelated and are related to the mass of the leptoquark and derive the probability densities $f_{ij}(x_i)$ for those variables at j = fixed M_{LQ}

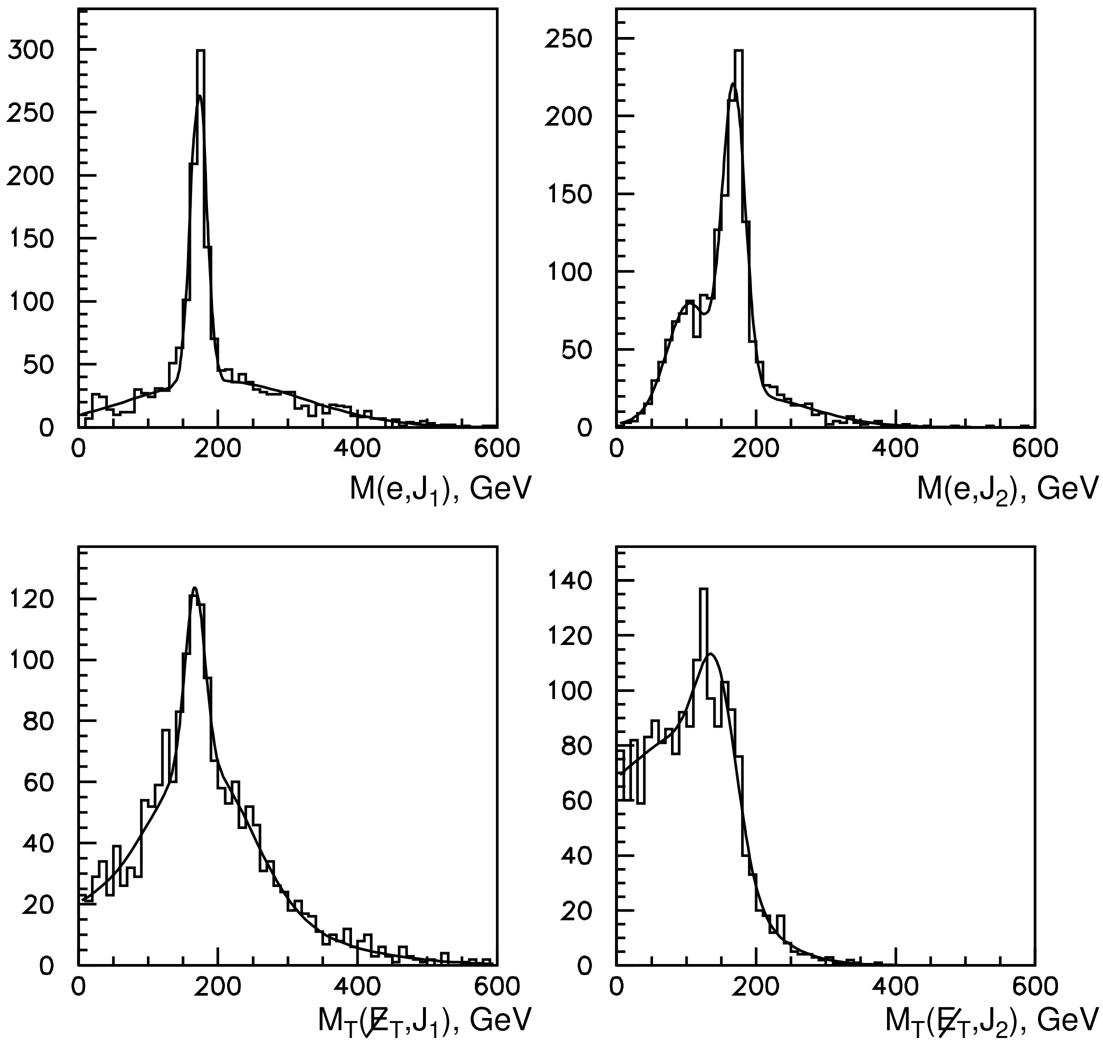


$$x_i = M(eJ_1),\ M(eJ_2),\ M_T(\nu J_1),\ M_T(\nu, J_2)$$

$LQ\ \overline{LQ} \longrightarrow e\nu jj$

$f_{ij}(x_i)$ constructed by fitting MC signal distributions to three gaussians for each available M_{LQ}

Construct the functions $g_i(x_i, M_{LQ})$ interpolating the $f_{ij}(x_i)$ parameterizations



$LQ\ \overline{LQ} \longrightarrow e\nu jj$

Construct likelihood functions corresponding to physical combinations of masses (ie. functions corresponding to $M(eJ_1)$ and $M_T(\nu J_2)$ are paired)

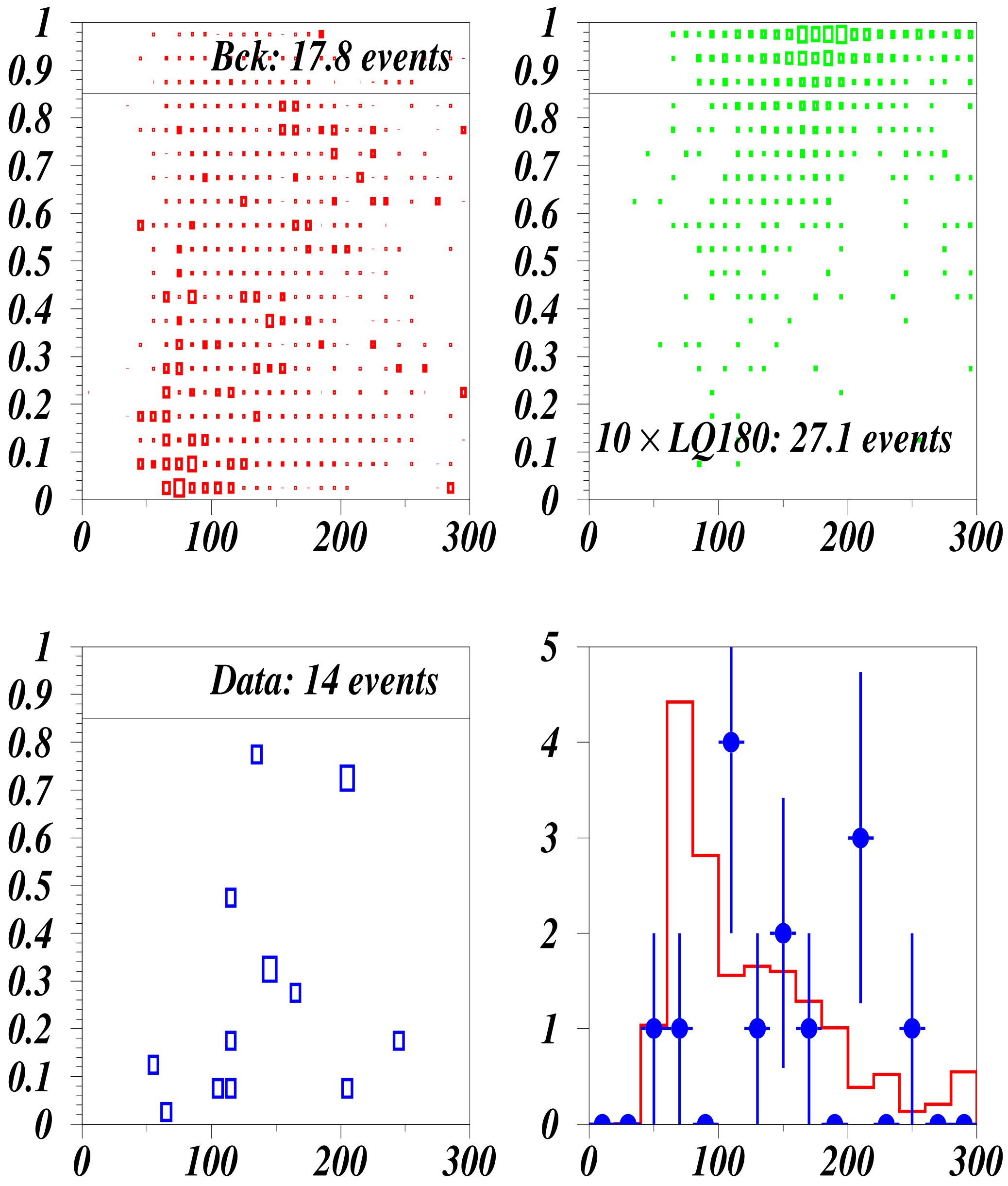
$$L_1(M) = \log(g_1(x_1,M)) + \log(g_2(x_2,M))$$
$$L_2(M') = \log(g_3(x_3,M')) + \log(g_4(x_4,M'))$$

Find solutions M, M´ that maximizes likelihoods for each of the 14 events in the M_T cut sample.

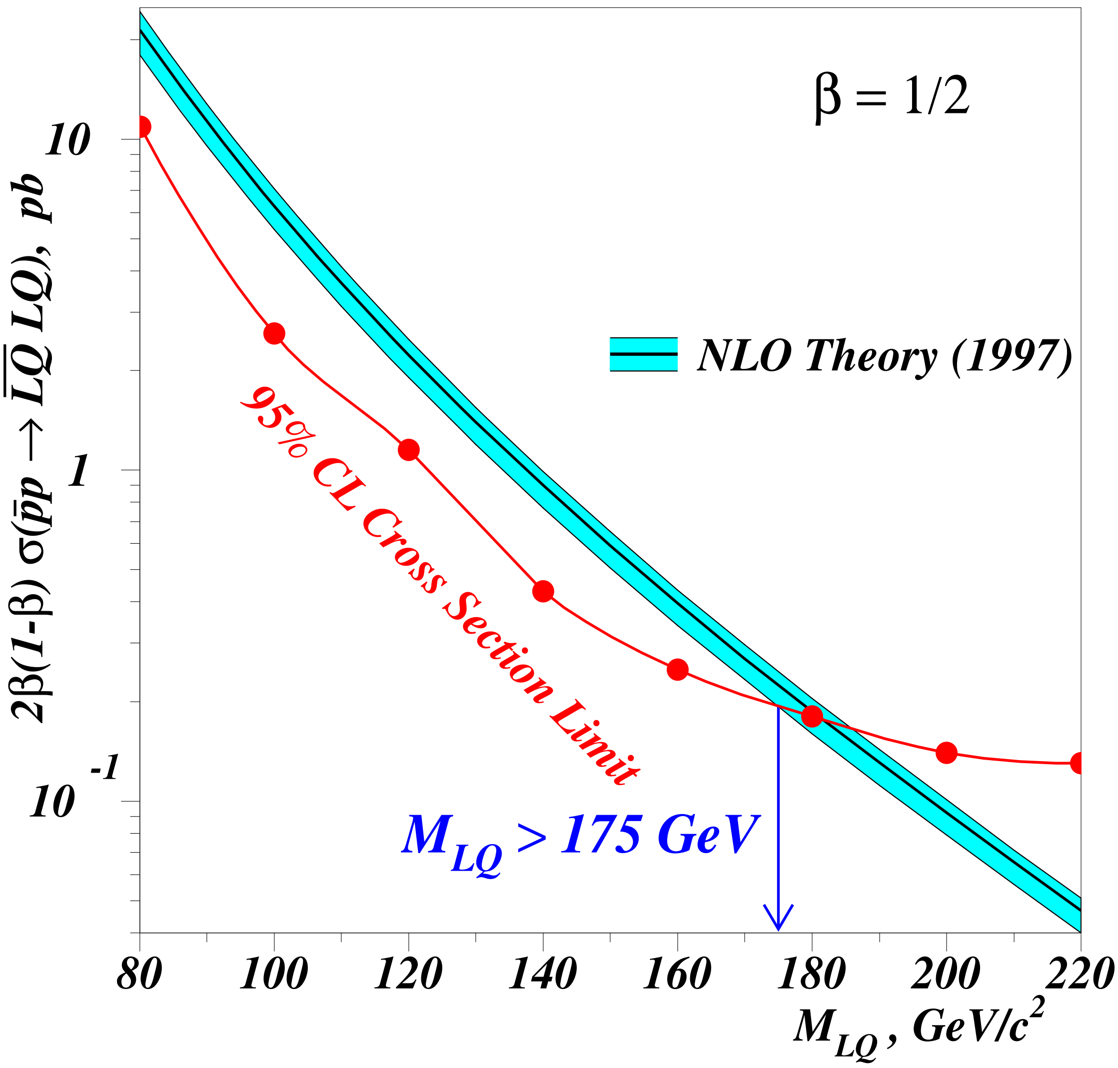
Using the maximum of the two likelihoods gives the correct assignment of the ej and νj pairs 87% of the time based on generator level studies

Estimated masses for the 14 events range from 50 GeV/c^2 – 250 GeV/c^2

LQ $\overline{LQ}$ $\longrightarrow$ eνjj



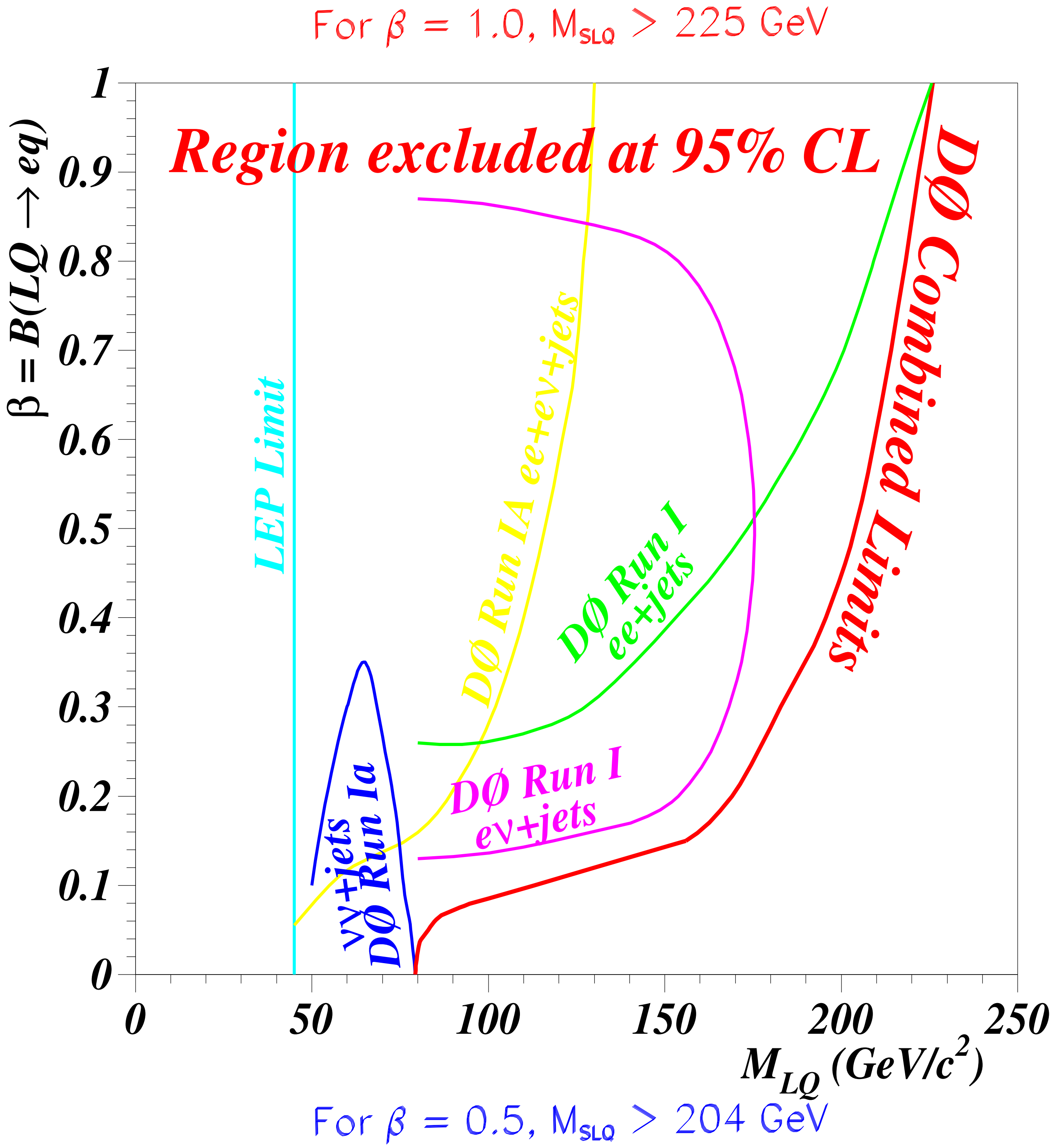
$LQ\ \overline{LQ} \longrightarrow e\nu jj$



95% CL cross section upper limit for $\beta = 1/2$
Using NLO theory with $\mu = 2M_{LQ}$

$M_{LQ} > 175$ GeV/c^2 at 95% CL

Combined M_{LQ} vs β limit



M_{LQ} > 204 GeV/c^2 for β = 1/2 at 95% CL

Conclusions

No evidence for the production of leptoquarks in the DØ run 1 data set.

For first generation scalar leptoquarks using NLO cross sections with $\mu = 2M_{LQ}$:

$\beta = 1$:

$M_{LQ} > 225$ GeV/c^2 at 95% CL

$\beta = 1/2$:

$M_{LQ} > 204$ GeV/c^2 at 95% CL

$\beta = 0$

$M_{LQ} > 79$ GeV/c^2 at 95% CL

$M_{LQ} > 200$ GeV/c^2 at 95% CL for $\beta = 0.4$

These analyses exclude the interpretation of the HERA events as leptoquarks with a mass around 200 GeV/c^2 for $\beta = 1$

pb^{-1}

E_T

$S_T^{J_1 J_2}$

GeV/c^2

η

$\not\!E_T$

$dM/M(M_{LQ})$

GeV/c^2

$M_T(e\nu)$