Search For Leptoquarks at DØ

Greg Landsberg

(Fermilab)

University of Michigan

at Ann Arbor

HEP Seminar

January 19, 1998

Outline

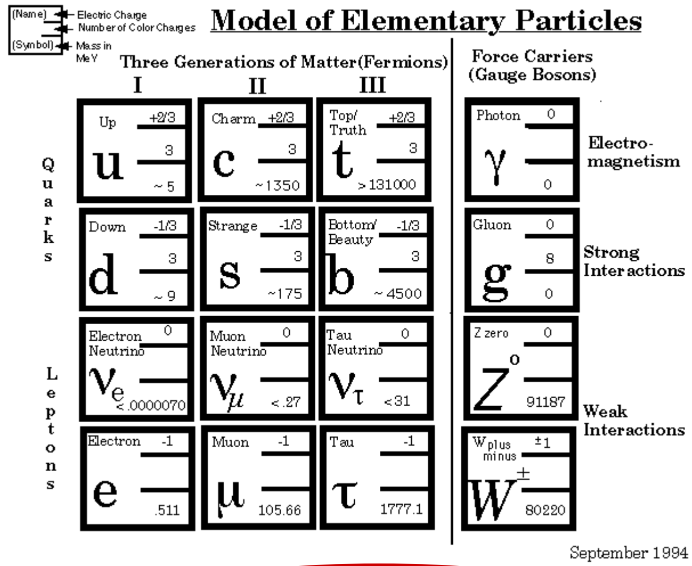
- Introduction: Symmetries in HEP
- LQ Phenomenology
- LQ Production at HERA
- LQ Production at the Tevatron
- Previous Tevatron Results
- DØ Detector
- Optimization Strategy
- First Generation LQ Search at DØ
  - ee+jets channel
  - eν+jets channel
  - νν+jets channel
- Second Generation LQ Search
- Third Generation LQ Search
- Conclusions

One Hundred Years of Particle Physics

1897 - Discovery of Electron (J.J.Thompson)

Symmetries

1995 - Discovery of t-quark (CDF and DØ)



Classification

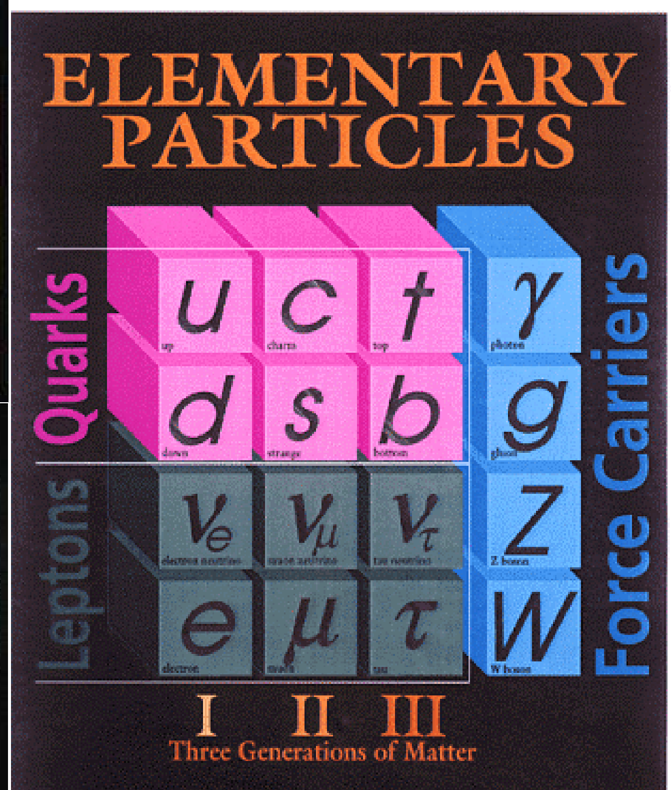
FERMIONS — matter constituents, spin = 1/2, 3/2, 5/2,...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c²	Electric charge	Flavor	Approx. Mass GeV/c²	Electric charge
ν_e electron neutrino	$<7\times10^{-9}$	0	u up	0.005	2/3
e electron	0.000511	-1	d down	0.01	-1/3
ν_μ muon neutrino	<0.0003	0	c charm	1.5	2/3
μ muon	0.106	-1	s strange	0.2	-1/3
ν_τ tau neutrino	<0.03	0	t top (initial evidence)	170	2/3
τ tau	1.7771	-1	b bottom	4.7	-1/3

BOSONS — force carriers, spin = 0, 1, 2,...

Unified Electroweak spin = 1	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.22	-1
W^+	80.22	+1
Z^0	91.187	0

Strong or color spin = 1	Mass GeV/c²	Electric charge
g gluon	0	0



Symmetries and Invariants

Symmetries → Groups → Transformations (e.g., SO(3) - three-dimensional rotations)

Noether's Theorem:

If the Lagrangian is invariant under certain one-parameter transformation, there exists a conserved quantity associated with the generator of this transformation (true for forces which can be described via potential).

Examples:

1) Laws of physics do not depend on time, hence energy is conserved

2) Laws of physics do not depend on the position in space, hence momentum is conserved

3) Gauge invariance: Lagrangian is invariant under gauge transformations

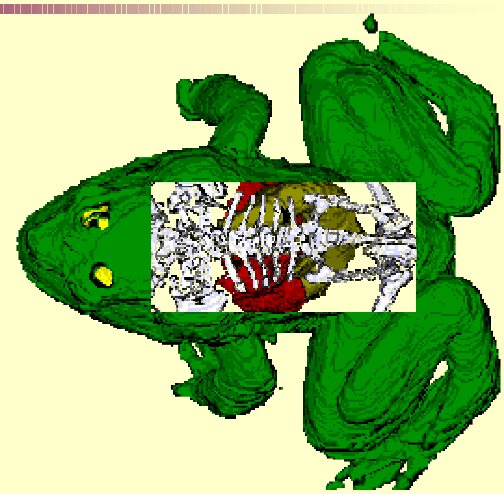
$$A_\nu \to A_\nu - \frac{1}{e}\frac{\partial\Lambda(x^\nu)}{\partial x^\nu}, \varphi \to \varphi \cdot e^{i\Lambda(x^\nu)}$$

ergo, electric charge is conserved

Symmetries → Invariance → Conservation Laws

Approximate and Broken Symmetries

Approximate symmetry of a frog



Some symmetries are only APPROXIMATE:
$H = S + B$, where S is an EXACT symmetry under certain group G, and B is a small term for which symmetry is broken, i.e. it is invariant only under a subgroup H $\rightarrow$ PERTURBATION THEORY

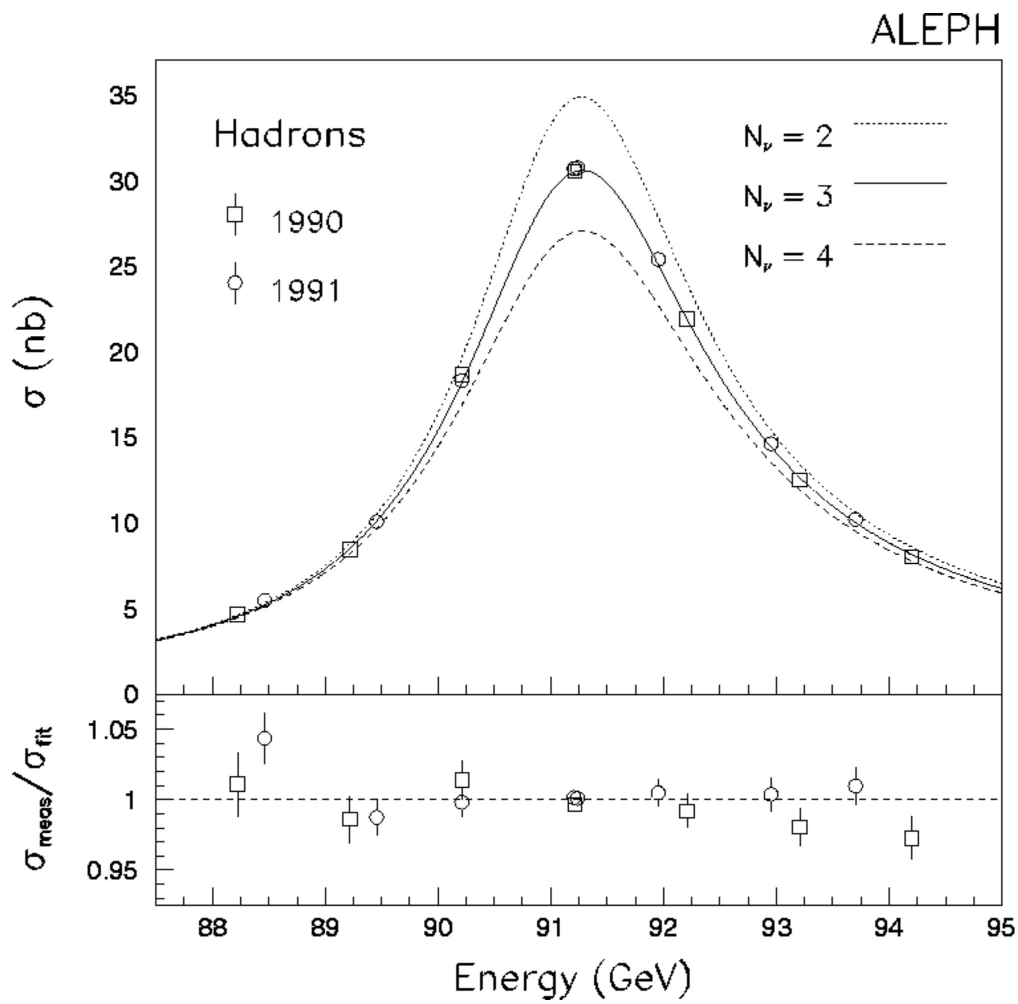
If Lagrangian is symmetric under certain group G, but the ground state is not →
SPONTANEOUS SYMMETRY BREAKING

If the ground state is symmetric under a subgroup H, generators of H become massless fields, whereas remaining generators of G become massive fields:
e.g. SU(2)×U(1) (Standard Model) → massless photon and massive W and Z particles (Higgs mechanism)

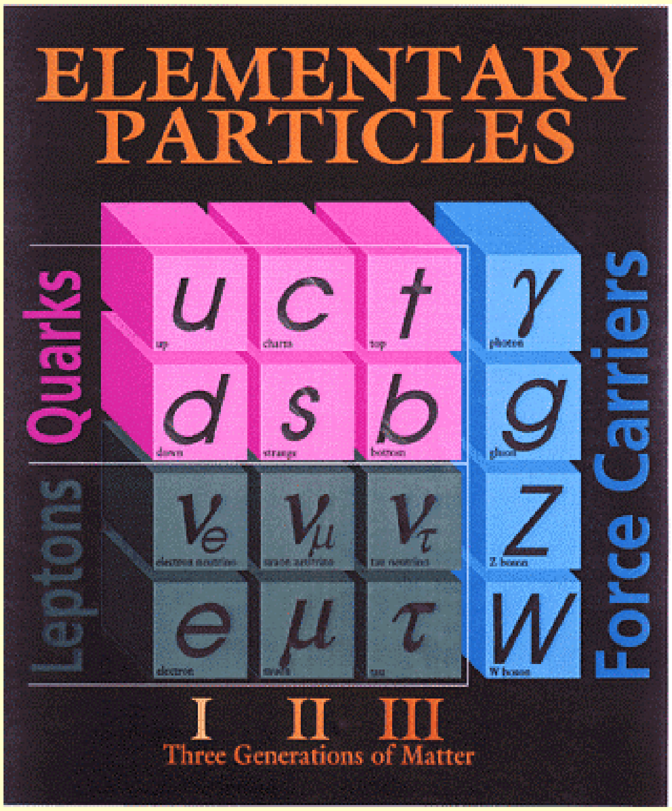
Number of Quark and Lepton Generations

We know that there are THREE generations of quarks and leptons (at least the light ones). We do not know why…

$$N_\nu = 2.989 \pm 0.012 \,\text{(LEP combined)}$$



Mysterious Symmetry of Generations



3 COLORS

u +2/3	**u** +2/3	**u** +2/3
d -1/3	**d** -1/3	**d** -1/3

e -1
ν_e 0

Colorless

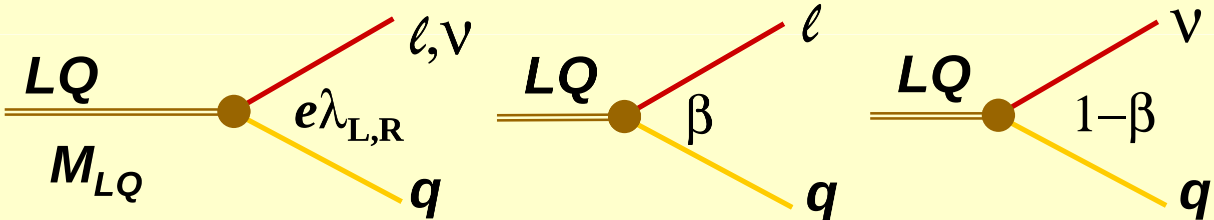
$\Sigma Q = 0$!

One of the ways to solve the mystery of generations is to introduce the LEPTOQUARKS - exotics objects which have properties of both leptons and quarks and let them know of each other's presence via e-q-LQ interaction

First introduced by J.C.Pati and A.Salam in 1973 (SU(4) model), these particles became popular in many extensions of the SM, especially in Grand Unified Theories and composite models

LQ Phenomenology

- LQ come in 3 generations and are coupled to both leptons and quarks and carry SU(3) color, fractional electrical charge, baryon (B) and lepton (L) numbers
- LQ interactions are entirely fixed by the effective Lagrangian $SU(3)_C \times SU(2)_L \times U(1)_Y$ assuming baryon/lepton number conservation, EGI, renormalizability, and chiral couplings:



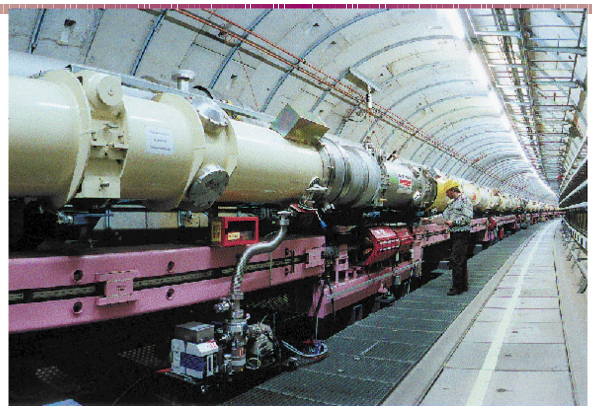
- BR into charged leptons β can be 0, 1/2, or 1 only, if no extra fermions are added to the model
- LQ can have spin 0 (scalar) or 1 (vector)
- LQ interactions can be classified by the fermion number ($F=3B+L$): $\mathcal{L} = \mathcal{L}_{F=-2} + \mathcal{L}_{F=0}$
  - S-type scalar LQ have F= -2 (3 singlets and 1 triplet)
  - R-type scalar LQ have F=0 (3 doublets)
  - V-type vector LQ have F= -2 (3 doublets)
  - U-type vector LQ have F=0 (3 singlets and 1 triplet)

Low Energy Limits

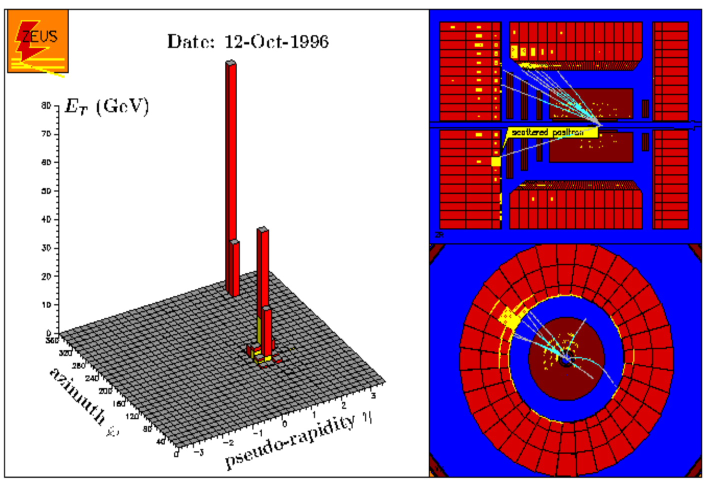
- Intergenerational mixing of LQ is severely restricted by FCNC data and other low energy phenomena:
  - $K \to \pi e^+ e^-, \pi\mu^+\mu^-$ ($\bar{s}d\ell\bar{\ell}$ vertex)
  - $B \to \ell\bar{\ell}X$
  - $K \to \mu e$ decay would receive a large contribution from LQ coupled to the first and second families
- Chirality of the couplings is ensured from tight limits on the $\pi \to e\bar{\nu}$ decay and from g_μ-2 measurements
- Limits on the LQ mass from low energy data (atomic parity violation, quark-lepton universality, etc.):
  - $M_{LQ}/\lambda > 500\text{-}2000$ GeV
- Previous HERA measurements:
  - $M_{LQ} > 230\text{-}250$ GeV for $\lambda = 1$
- LEP searches for $Z \to \mathrm{LQ}\,\overline{\mathrm{LQ}}$ set coupling-independent mass limits (as long as couplings are strong enough to ensure short LQ lifetime):
  - $M_{LQ} > 44$ GeV

Why Is (Was) It So Exciting?

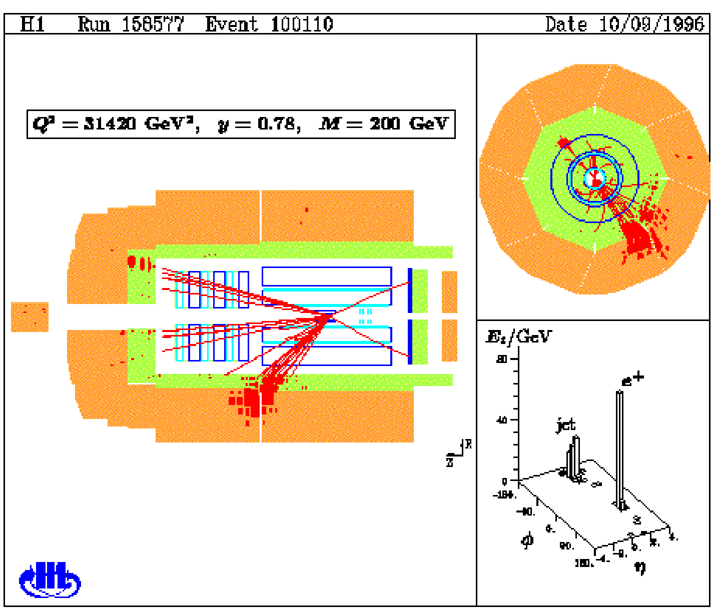
HERA at DESY (Hamburg)



High Q^2 events in 20 pb^{-1} of e^+p data



ZEUS: 4 events (SM: 0.9)



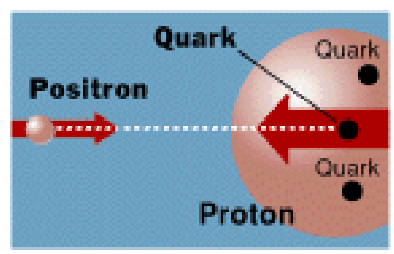
H1: 7 events (SM: 1.0)

New York Times February 25, 1997

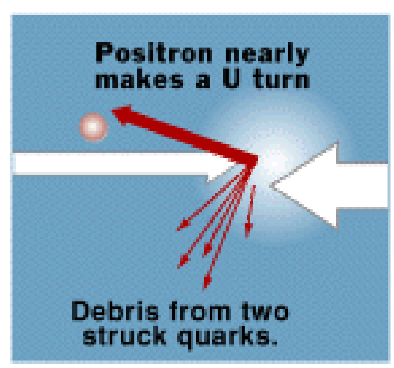
Footprints of a Leptoquark?

At the DESY accelerator in Hamburg, Germany a positron (the electron's antimatter counterpart) collides with a quark. In a few spectacular collisions, the positron nearly makes a U turn. One possible explanation is the momentary creation of a strange new particle called a leptoquark.

Positron and a quark inside a proton are accelerated close to the speed of light and then collided



The high-energy positron nearly reverses direction, possible evidence of a leptoquark.

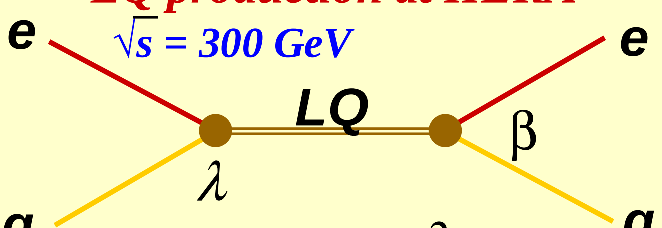


LQ Production at HERA

- ***Both H1** [Z.Phys. **C74**, 191 (1997)] **and ZEUS** [Z.Phys. **C74**, 207 (1997)] **have recently reported high-Q^2 event excess, which could be explained by the production of the first generation scalar LQ with the mass of around 200 GeV (vector LQ's were already excluded up to much higher mass by DØ)***

LQ production at HERA

$\sqrt{s}$ = 300 GeV



$$\sigma \propto \beta\,(\lambda \mathbf{e})^2/4\pi$$

λ=1: *EM coupling*

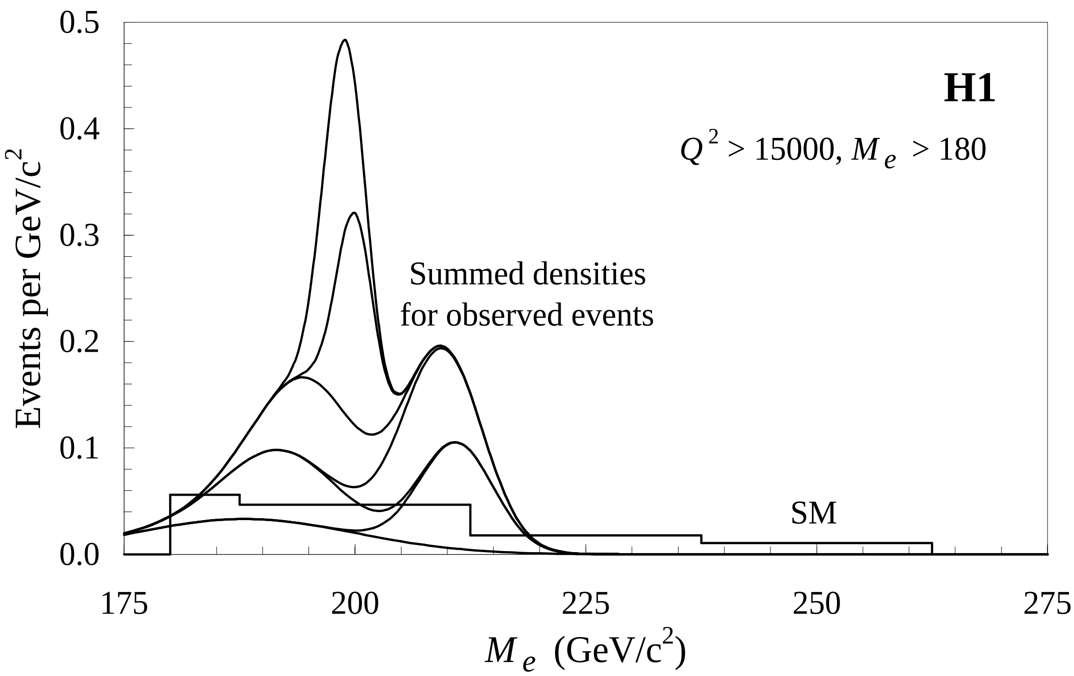
20 pb^{-1} e^+p data:
H1 - 7 events (1.0 bck.)
ZEUS - 4 events (0.9 bck.)
1 pb^{-1} e^-p data:
no excess reported

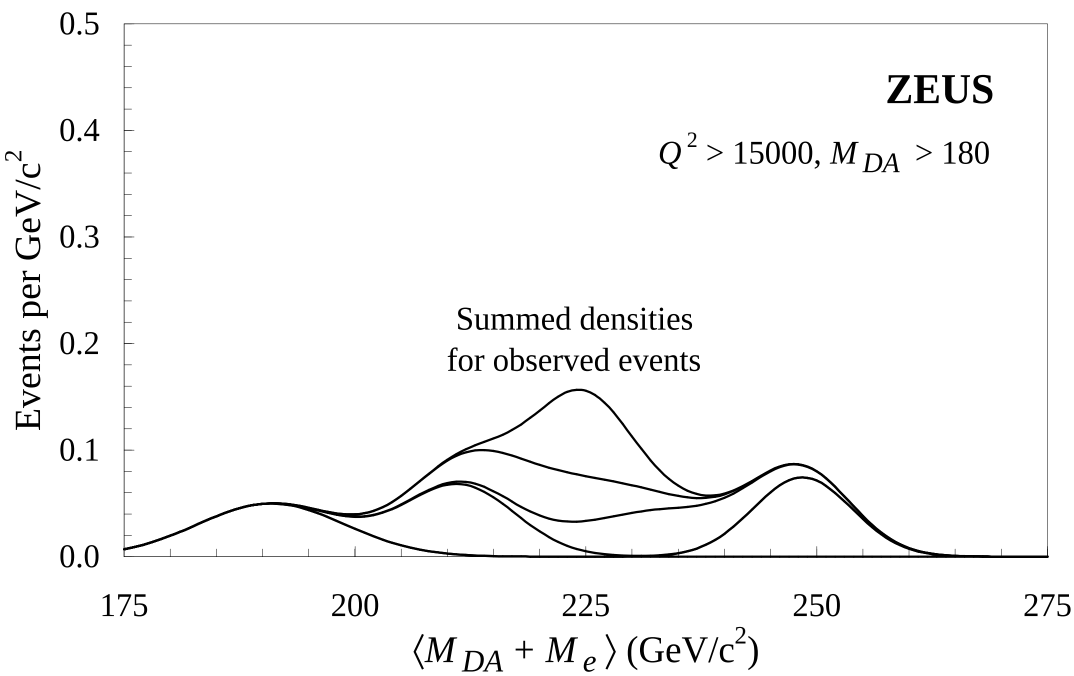
S-type LQ have much higher production rate in e^-p collisions, so HERA data can be explained within the LQ framework only by R-type LQ with q = 5/3. There are two such LQ and both have β = 1. HERA data requires λ = 0.04–0.10.

There is no way to explain HERA data with $\beta \neq 1$ LQ without pushing experimental constraints or adding new terms to the Lagrangian (such as additional fermions). Some attempts to do so appeared recently [J.Hewett,T.Rizzo - hep-ph/9708419; Babu, Kolda, March-Russell - hep-ph/9705414].

Are They Consistent With Each Other?

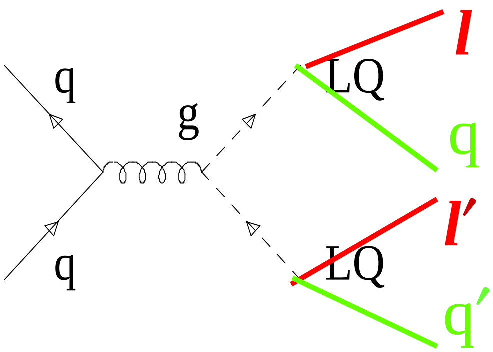
[M.Strovink, DØ]





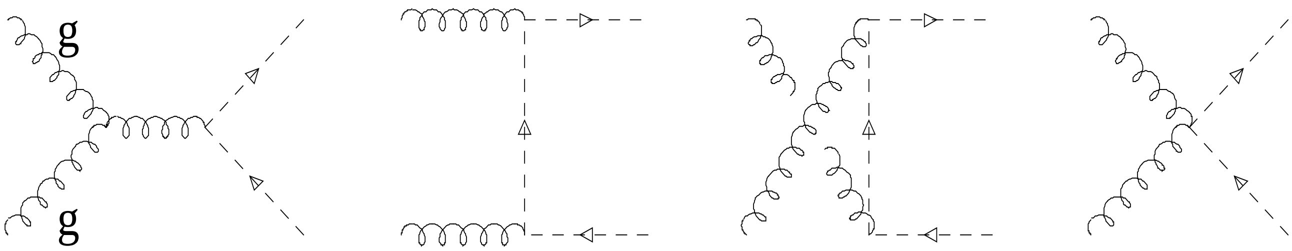
LQ Production at the Tevatron

- *At the Tevatron leptoquark pair production via gluon splitting (strong interaction) dominates*



eejj, eνjj or ννjj channels
Major backgrounds: W/Z+jj, QCD and $t\bar{t}$ production

$$\beta \equiv B(LQ \to l^{\pm}q)$$

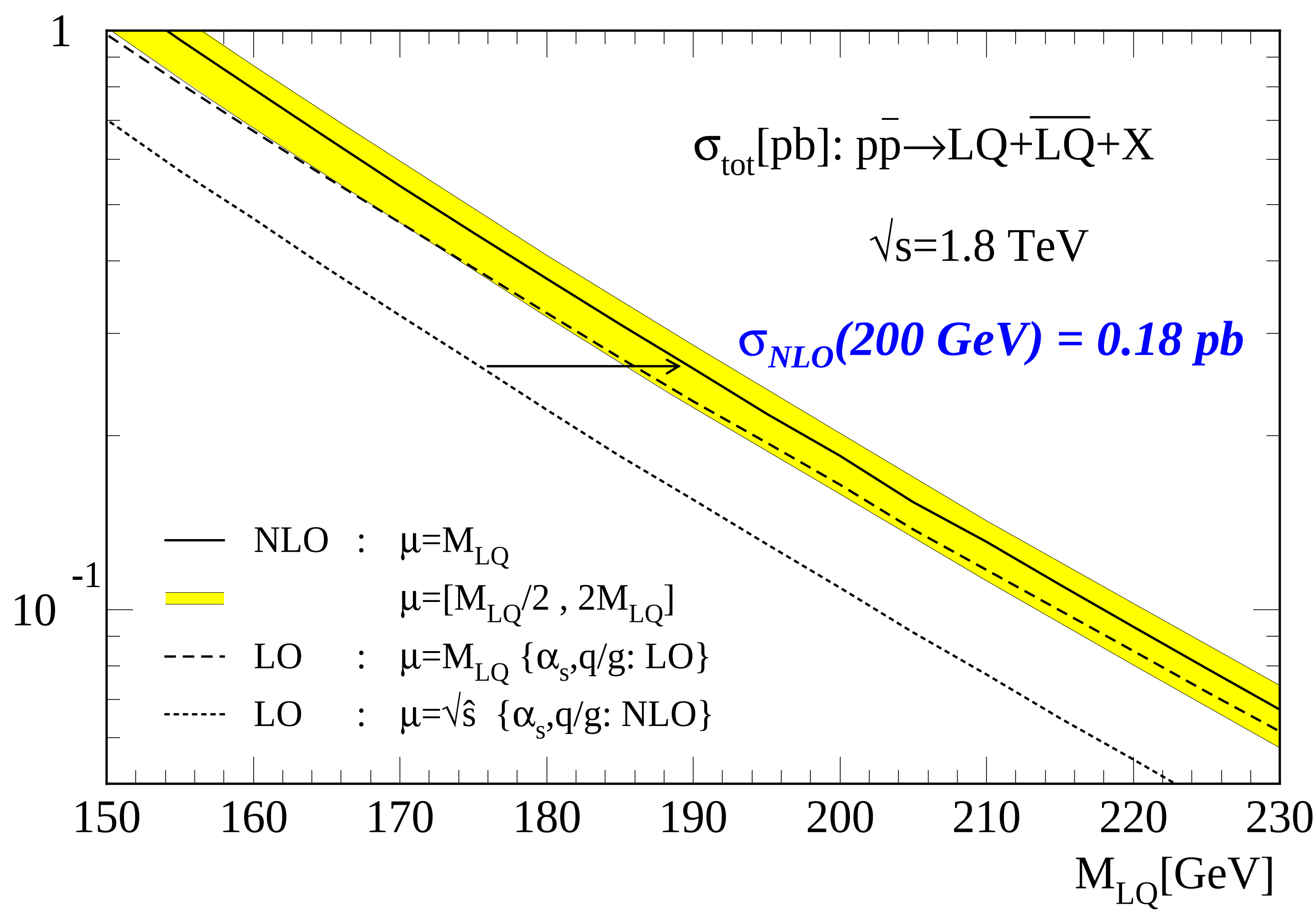


- *Pair production is insensitive to the value of λ since it enters only in the LQ lifetime and for $\lambda > 10^{-12}$ LQ decay within a collider detector*
- *It depends only on* β ($\propto \beta^2$ *for eejj,* $\propto 2\beta(1-\beta)$ *for eνjj and* $\propto (1-\beta)^2$ *for ννjj)*
- *It has very little model dependence (such as p.d.f. choice, etc.) similar to top pair production*

Next-to-Leading Order Theory

NLO theory – calculate ~100 additional diagrams to include $O(\alpha_s^3)$ effects

M.Krämer, T.Plehn, M.Spira, and P.M.Zerwas,
Phys.Rev.Lett. **79**, 341 (1997)



Review of Published Tevatron Limits

Limits on First Generation LQ Mass

CDF

eejj

PR D48, 3939 (1993): 113 GeV for $\beta = 1$ (LO)
80 GeV for $\beta = 1/2$ (LO)

DØ

eejj
eνjj

PRL 72, 965 (1994): 130 GeV for $\beta = 1$ (LO)
116 GeV for $\beta = 1/2$ (LO)

Limits on Second Generation LQ Mass

CDF

$\mu\mu$jj

PRL 75, 1012 (1995): 131 GeV for $\beta = 1$ (LO)
96 GeV for $\beta = 1/2$ (LO)

DØ

$\mu\mu$jj
$\mu\nu$jj

PRL 75, 3618 (1995): 119 GeV for $\beta = 1$ (LO)
97 GeV for $\beta = 1/2$ (LO)

Limits on Third Generation LQ Mass

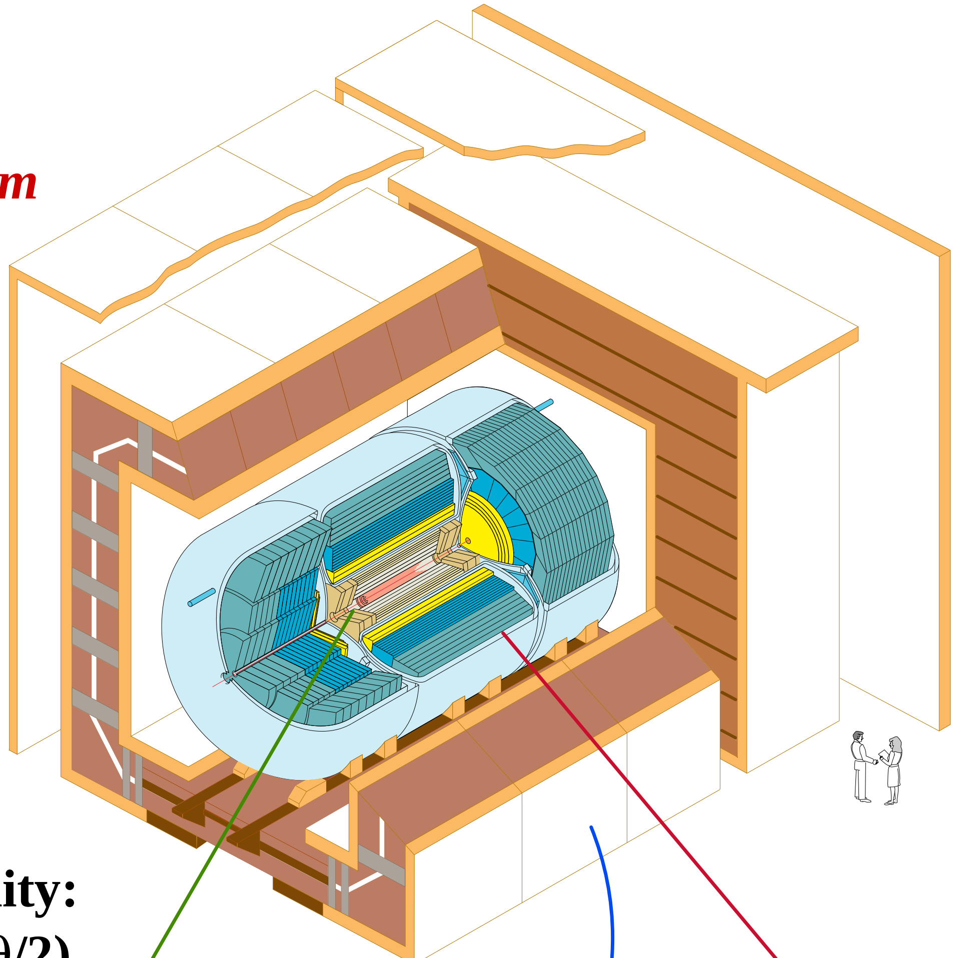
CDF

$\tau\tau$jj

PRL 78, 2906 (1997): 99 GeV for $\beta = 1$ (NLO)
vector (Y-M) LQ: 225 GeV for $\beta = 1$ (NLO)

DØ Detector

3 Level Trigger System



Pseudorapidity:

$\eta = -\ln \tan(\theta/2)$

DØ Detector

TRACKING

$\sigma(\text{vertex}) = 6$ mm
$\sigma(r\phi) = 60\ \mu$m (VTX)
$= 180\ \mu$m (CDC)
$= 200\ \mu$m (FDC)

MUON

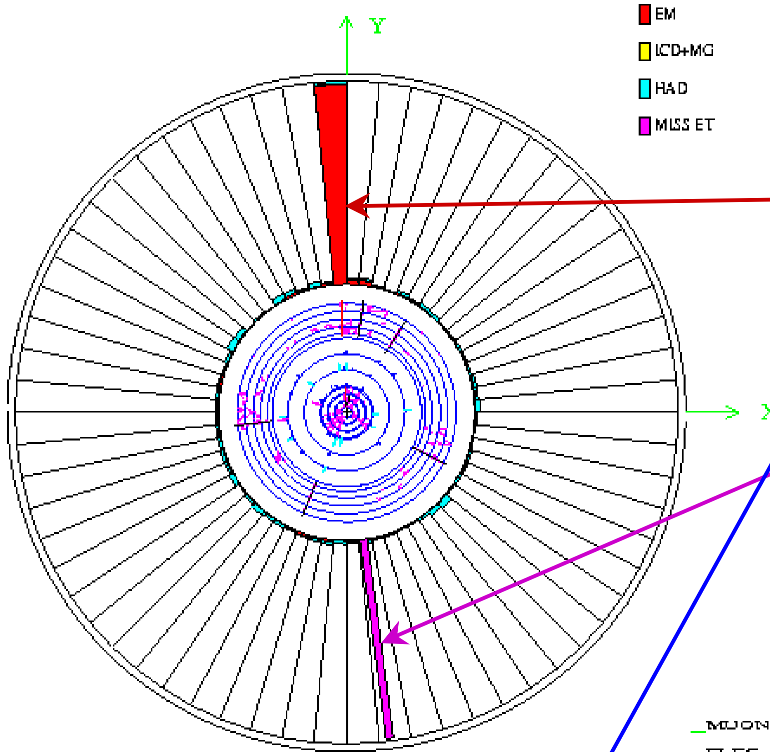
$|\eta| < 3.3$

$$\frac{\delta p}{p} = 0.2 \oplus .003p$$

CALORIMETRY

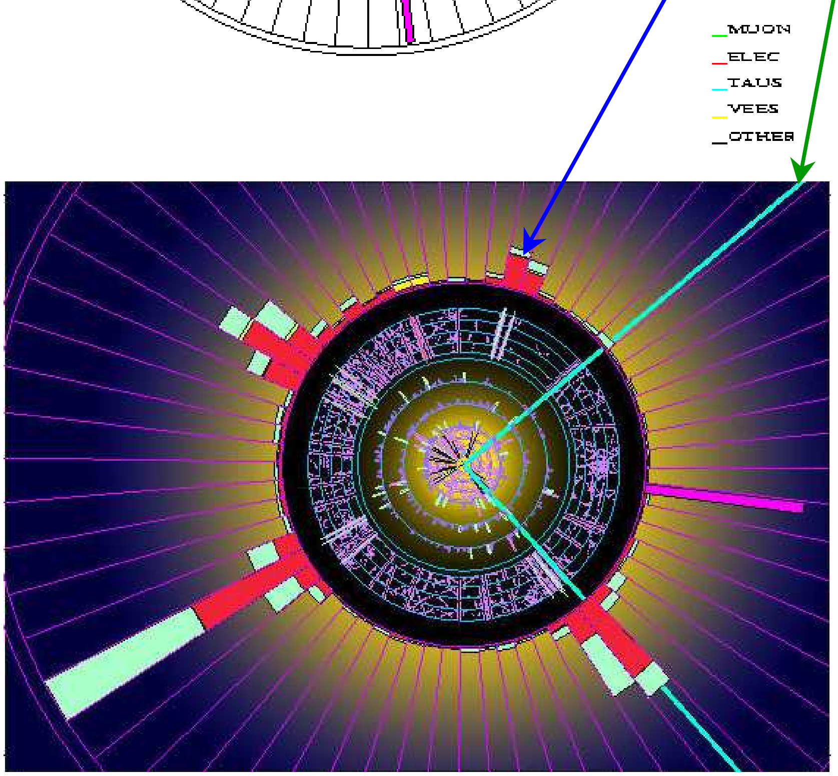
$|\eta| < 4$
$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
$\sigma(\text{EM}) = 15\% / \sqrt{E}$
$\sigma(\text{HAD}) = 50\% / \sqrt{E}$

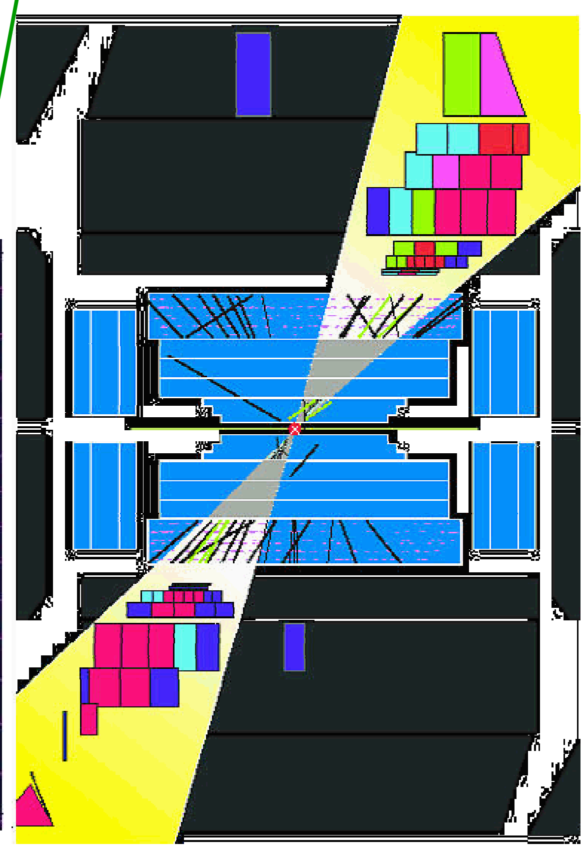
Particle Identification



DØ is perfectly suited for identification of:

- *Electrons/Photons*
- *Jets*
- *Muons*
- *Neutrinos (Missing Transverse Energy)*





Signal & Background Samples

- **Signal:**

  ISAJET v7.22 + GEANT Detector Simulation

  50-260 GeV; ≈5000 events per mass point

  PYTHIA, 200 GeV; 2000 events (cross checks)

- **Z+jets and Drell-Yan+jets Background:**

  ISAJET v7.22 + GEANT Detector Simulation (1M events)

- **W+jets Background:**

  VECBOS + ISAJET v7.22 + GEANT Detector Simulation (230K events)

- **Top Quark Background:**

  HERWIG + ISAJET v7.22 + GEANT Detector Simulation (M_t = 170 GeV, 300K $\ell\ell'$ + jets and 80K ℓ + jets events)

- **QCD Background:**

  Data collected with a jjj trigger in 1994-1995 (360K events, 1pb^{-1})

Search for LQ at DØ: Optimization Strategy

HERA

Leptoquarks?

↓

Improved Particle ID

Very loose cuts

↓

Random Grid Searches
Neural Nets

Advanced Multivariate Techniques

Apriori optimization

Discovery:
optimize
$S/\sqrt{B}$

Limit:
optimize
S for B $\approx$ 0.4
0 events (70%)

↓

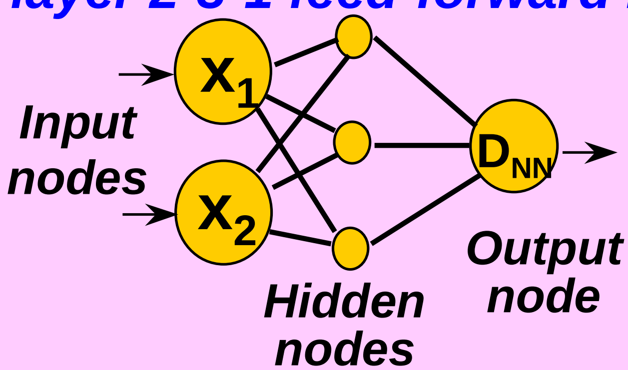
Multiple Cross Checks

Random Grid and Neural Net Searches

Random Grid Search:

Use kinematic parameters of MC events for signal and MC or data events for backgrounds in order to find the optimal cuts

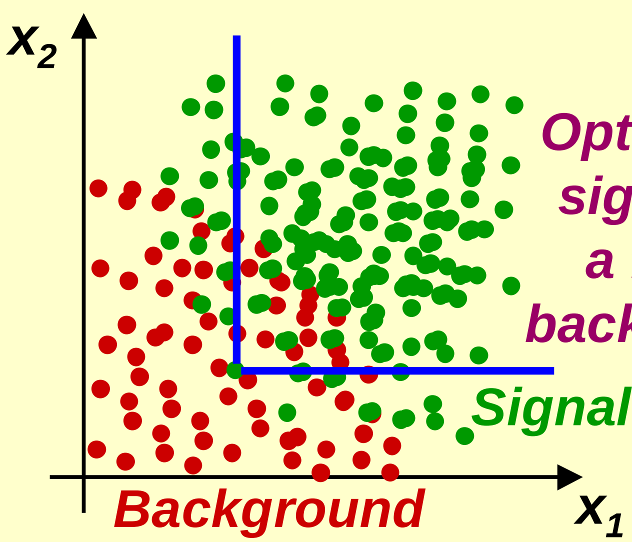
3 layer 2-3-1 feed-forward NN



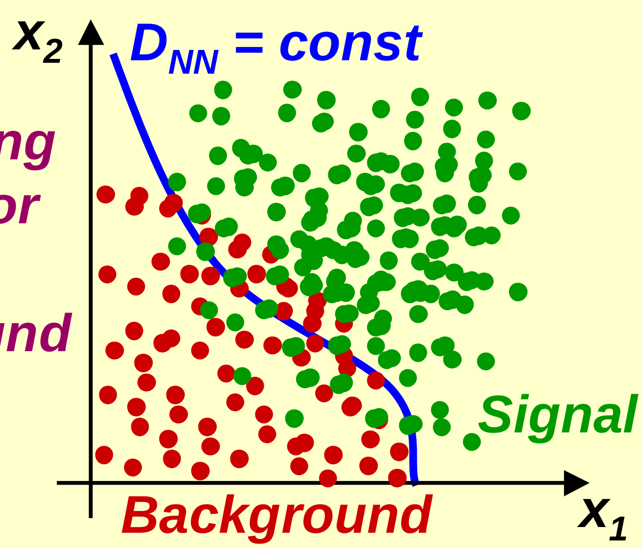
Neural Net Search:

Train the net on a mixture of signal and background, so that $D_{NN} \approx 1$ for signal and $D_{NN} \approx 0$ for background

Random Grid Search



Neural Net Search



Optimizing signal for a fixed background

Simpler cut, lower S/B

Sophisticated cut, best possible S/B

Data Selection in ee+jets channel

- Entire Run I statistics (123 pb^{-1})

  EM trigger; >99% efficient for offline cuts

- Electrons:

$E_T^e > 20$ GeV; $|\eta_e| < 1.1$ (CC) or $1.5 < |\eta_e| < 2.5$ (EC)

Significant EM fraction

- "Loose":

  Good energy isolation
  Cluster shape typical for the EM object

- "Tight":

  Matching track
  Combined tracking-TRD-calorimeter info (electron likelihood) consistent with electron

N.B. twice the QCD background rejection compared to standard ID

- Require exactly 2 electrons; at least 1 "tight"
- Jets (R = 0.7 cone algorithm; 2 or more):

$E_T^j > 15$ GeV; $|\eta^j| < 2.5$

Data Selection in ee+jets channel (cont'd)

- **General:**

M_{ee} far from the Z-peak

(not in the 82-100 GeV window)

Electrons well separated from jets

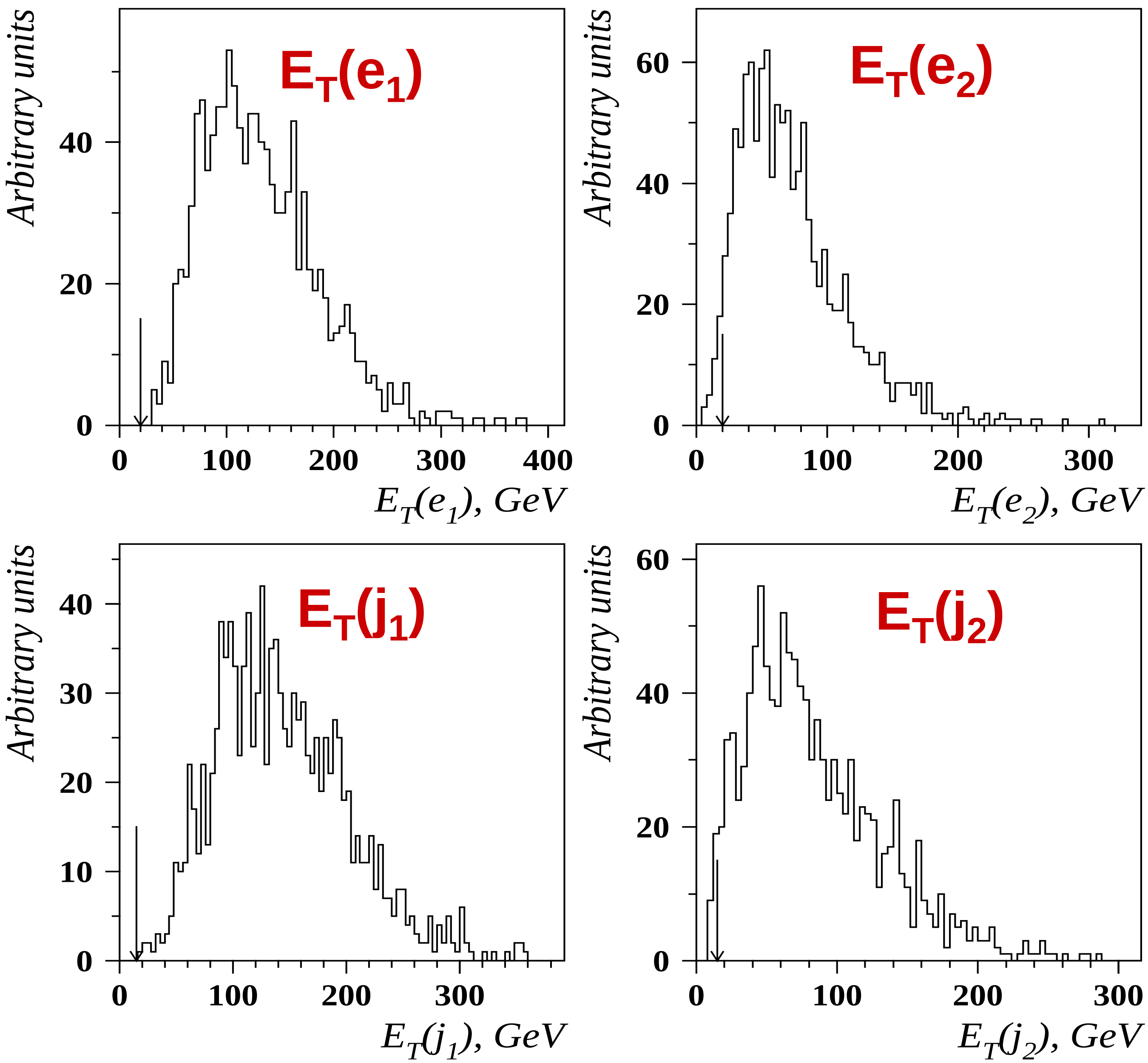
($\Delta R^{ej} > 0.7$)

- **Base sample: 101 events**

Cut	Events
Preselection	9,451
Two EM objects	4,967
EM in CC/EC, $E_T > 20$ GeV	3,880
2 or more jets, $E_T > 15$ GeV	2,918
$\Delta R^{ej} > 0.7$	2,496
$M_{ee} > 100$ GeV or $M_{ee} < 82$ GeV	1,802
At least one "tight" electron	225
"Loose" ID	101

Kinematic Properties of LQ decay

LQ Kinematic properties (M_{LQ} = 225 GeV)



Random Grid Searches

- *Test various combinations of individual object parameters and global parameters of the event*
- *Fix optimal set of cuts and apply it to the data*

A number of variables were tried:

- **Energy variables:**

  $S_T = \Sigma E_T^e + \Sigma E_T^j$ - scalar E_T

  $S_T^{12} = \Sigma E_T^e + E_T^{j1} + E_T^{j2}$ - scalar E_T^{12}

  $S = \Sigma E^e + \Sigma E^j$

  $H_T^e = \Sigma E_T^e$, H_T^j, H_T^{j12}, H_T^{j123}

- **Event shape variables:**

  Centrality = S_T/S, Aplanarity

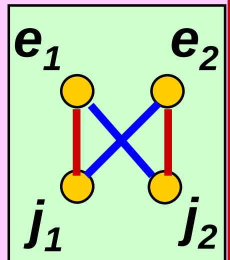
  Sphericity, Jet Clustering (η_{RMS})

- **Invariant mass variables:**

  M_{ee}, pair ej-masses ($M^{e_a j_b}$)

- **Mass difference variables:**

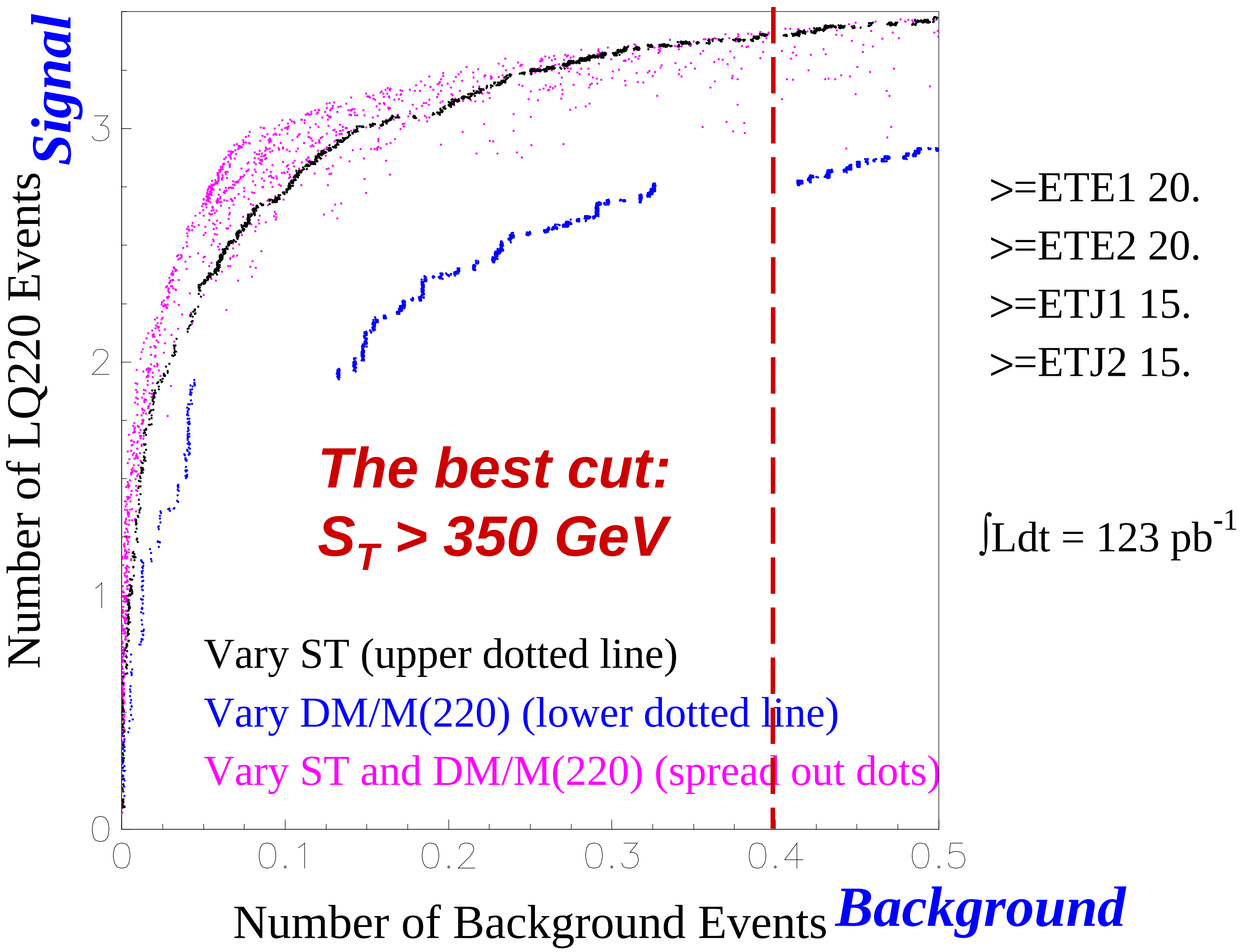
  $\delta M_{min}/M_{LQ}$, $\delta M_{min}/\langle M\rangle$, $\delta M_{min}/\sqrt{\langle M\rangle}$



$M_{e1j2} = M_{e2j1}$
or
$M_{e1j1} = M_{e2j2}$

Optimal Cuts

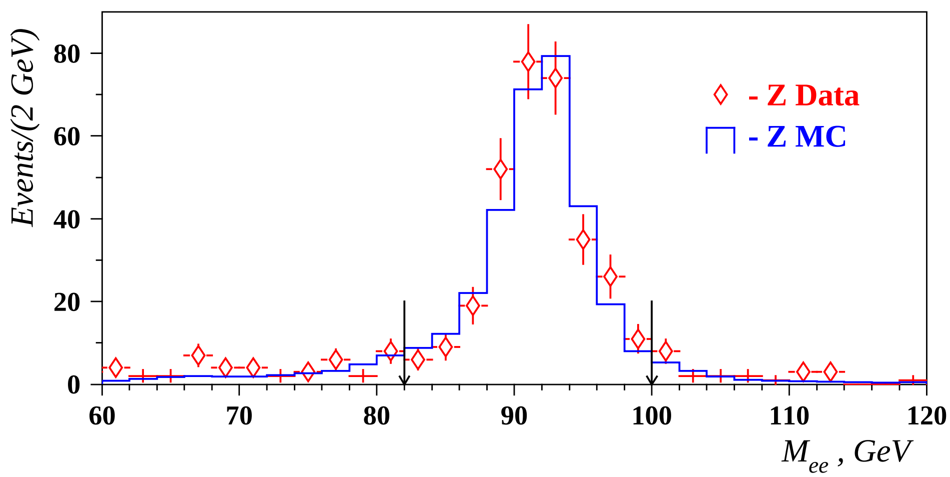
About 50 different combinations of variables were tried. The S_T was shown to be the single most effective variable for backgrounds of about 0.4 events

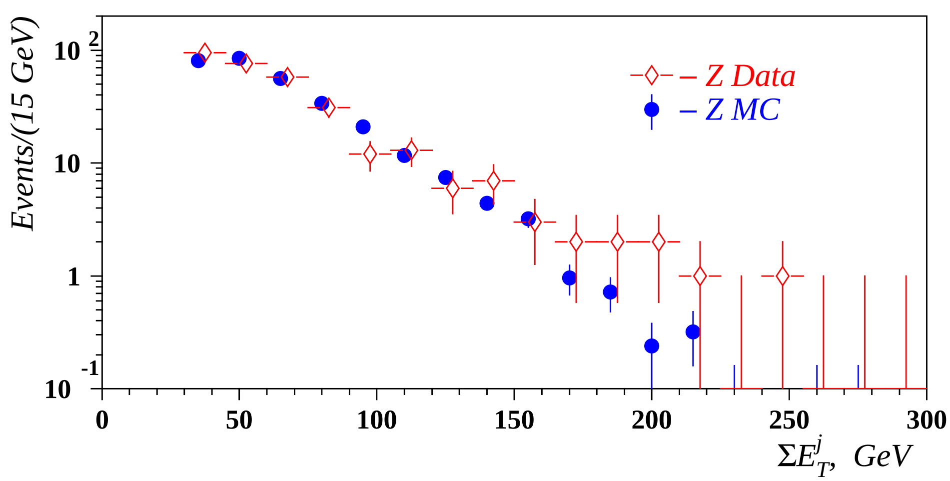


The S_T cut is about 20% more efficient for the signal compared to the $\delta M_{min}/M_{LQ}$ cut

Drell-Yan Background

- *Normalize integral under the Z-peak to the observed number of Z+2j events*
- *Calculate the background outside the Z-window*





ΣE_T^j

Associated jet production regime equivalent to S_T >350 GeV cut for D-Y background (dominated by high masses) is understood

D-Y Background:

67 ± 13 events for S_T > 0 GeV

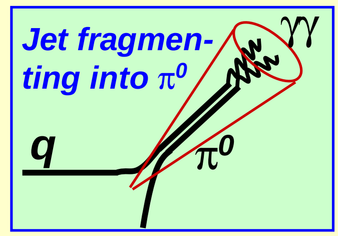
0.18 ± 0.04 events for S_T > 350 GeV

(error dominated by jet energy scale)

QCD Background

- ***Determine jet faking electron probabilities (including direct photons)***

  Compare number of jets in QCD 3j sample with the number of 2j+e events



  $P(j \rightarrow \text{“tight”}) = (3.5 \pm 0.4)\times 10^{-4}$

  $P(j \rightarrow \text{“loose”}) = (1.3 \pm 0.1)\times 10^{-3}$

  (error covers slight η and E_T^e variations)

- ***Calculate the QCD background***

  Two methods:

  - *Start with 4j sample and apply faking probabilities twice*
  - *Start with 3j+e sample and apply faking probabilities once*

  Excellent agreement; use the first method for the final numbers due to a better statistics at high S_T

QCD Background:

24 ± 4 events for $S_T > 0$ GeV

0.16 ± 0.02 events for $S_T > 350$ GeV

(error dominated by $P(j \rightarrow e)$ uncertainties)

Top Background

- *Apply all signal cuts to the $t\bar{t} \to \ell\ell' +$ jets MC (includes τ-decaying into electrons)*
- *Count the number of events which pass*
- *Calculate background using the top production cross section measured by DØ:*

$$\sigma(p\bar{p} \to t\bar{t}) = (5.5 \pm 1.8)\ pb$$

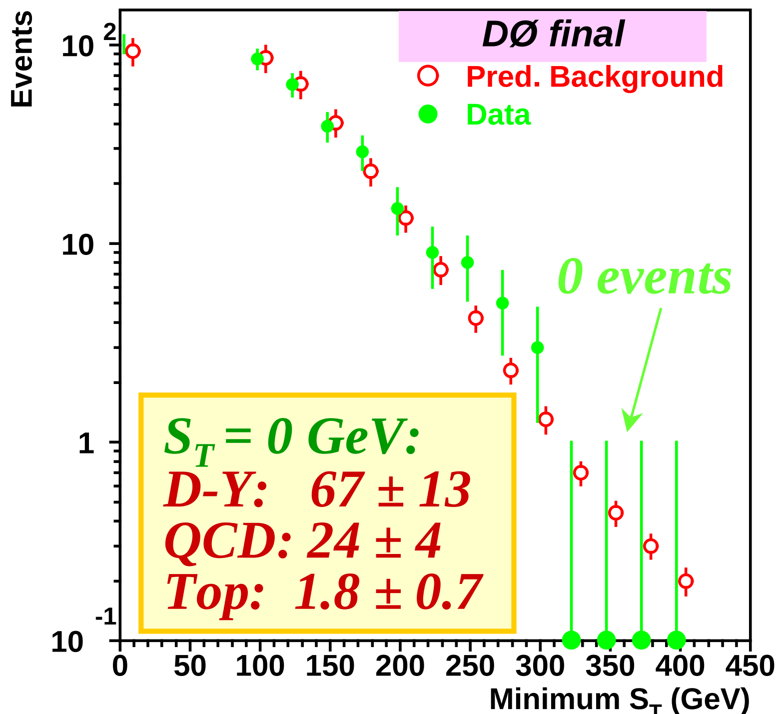
and theoretical branching ratio

$$B(t\bar{t} \to \ell\ell' + jets) = 0.0685$$

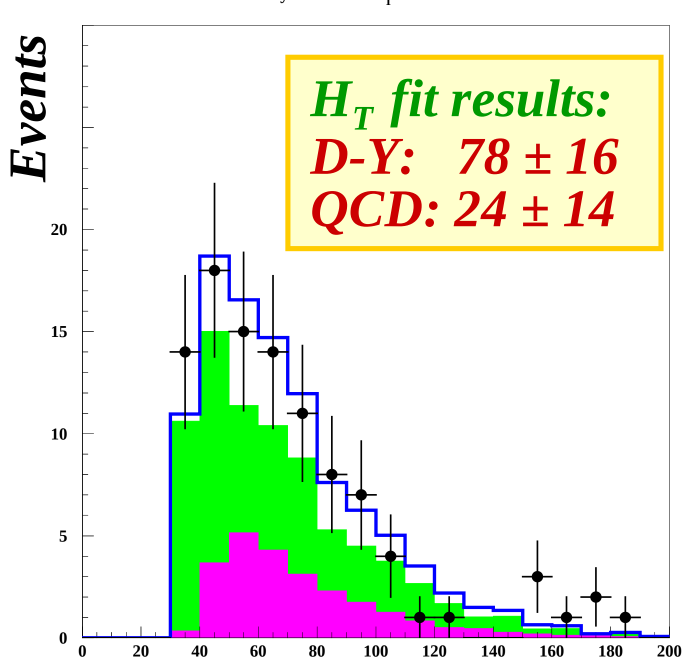
- *Studied a possibility to apply a missing E_T cut to reduce top background, but ended up not applying it since the top background is already small*

Top Background:
1.8 ± 0.7 events for $S_T > 0$ GeV
0.11 ± 0.04 events for $S_T > 350$ GeV
(error dominated by uncertainty in the cross section)

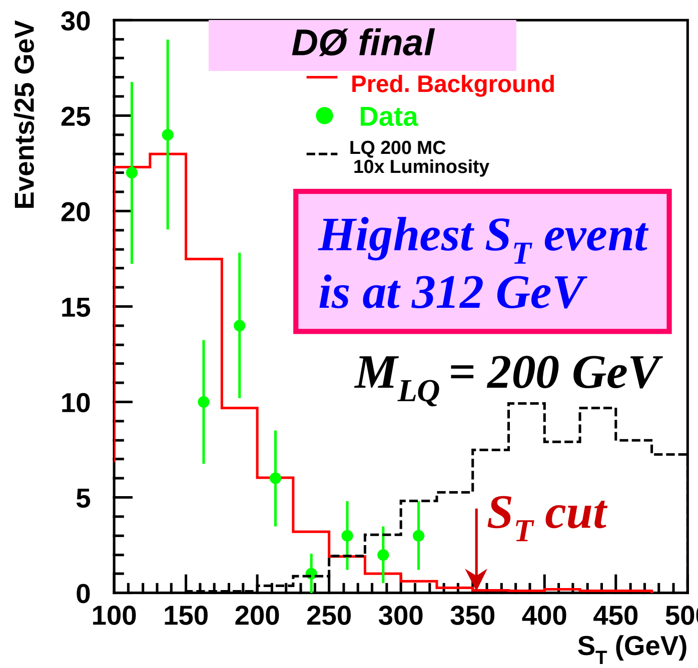
Data vs. Background



S_T Cut (GeV)	Background prediction	Data
0	93 ± 14	101
100	86 ± 13	85
150	41 ± 6	39
200	13 ± 2	15
250	4.2 ± 0.6	8
300	1.4 ± 0.2	3
350	0.44 ± 0.06	0
400	0.20 ± 0.03	0

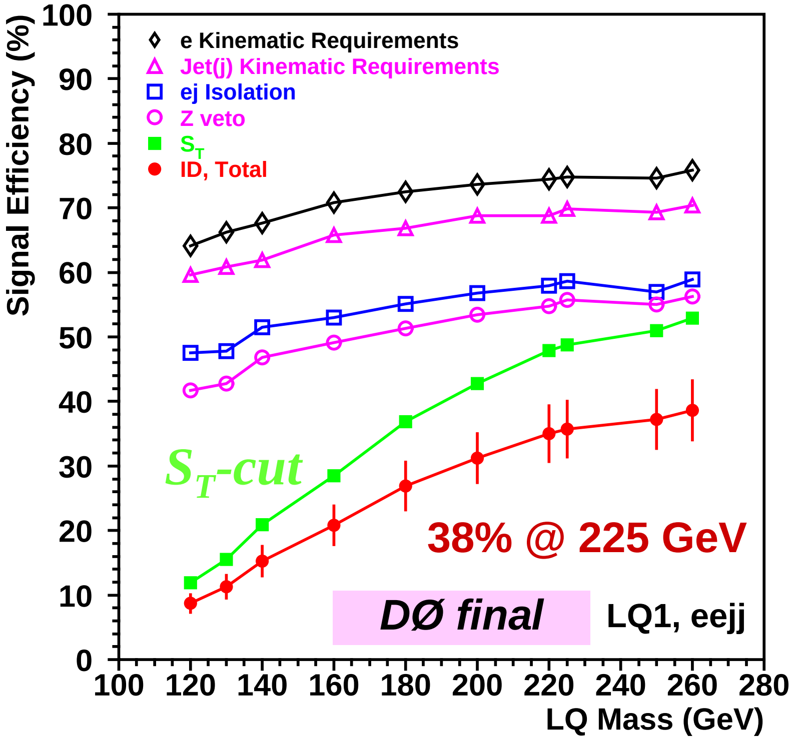


$$H_T = \Sigma E_T^j$$



Acceptance, Efficiency and Systematics

The kinematical/geometrical acceptance is calculated from the LQ MC samples and further corrected for particle ID efficiency as measured with the Z data



Signal Systematics

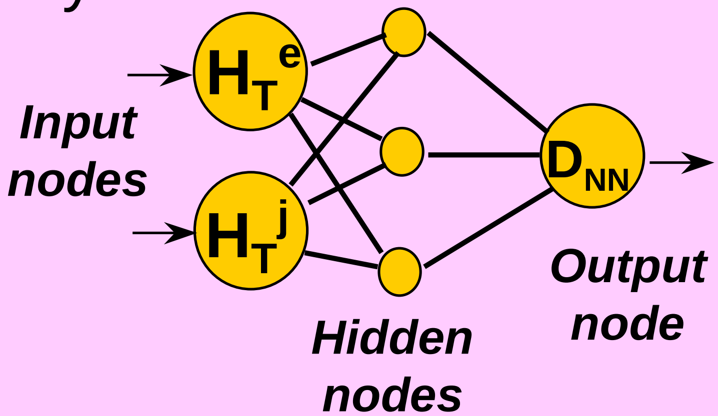
Source of error	*Error*
Particle ID	*5%*
Smearing in the Detector	*3%*
Jet Energy Scale	*2% (260 GeV)* *11% (120 GeV)*
Gluon Radiation	*7%*
PDF and Q^2	*7%*
MC Statistics	*2%*
Luminosity	*5%*
Total	*13% (260 GeV)* *16% (120 GeV)*

Background Systematics

Background	*Systematics*
Drell-Yan	*20% (jet energy scale)*
QCD	*15% (E_T and η dependencies)*
Top	*38% (top cross section)*

Neural Network Analysis

3 layer 2-3-1 feed-forward NN



$H_T^e = \Sigma E_T^e$

$H_T^j = \Sigma E_T^j$

Training:

Signal: LQ(200 GeV) MC

Mixture of QCD, D-Y and Top backgrounds

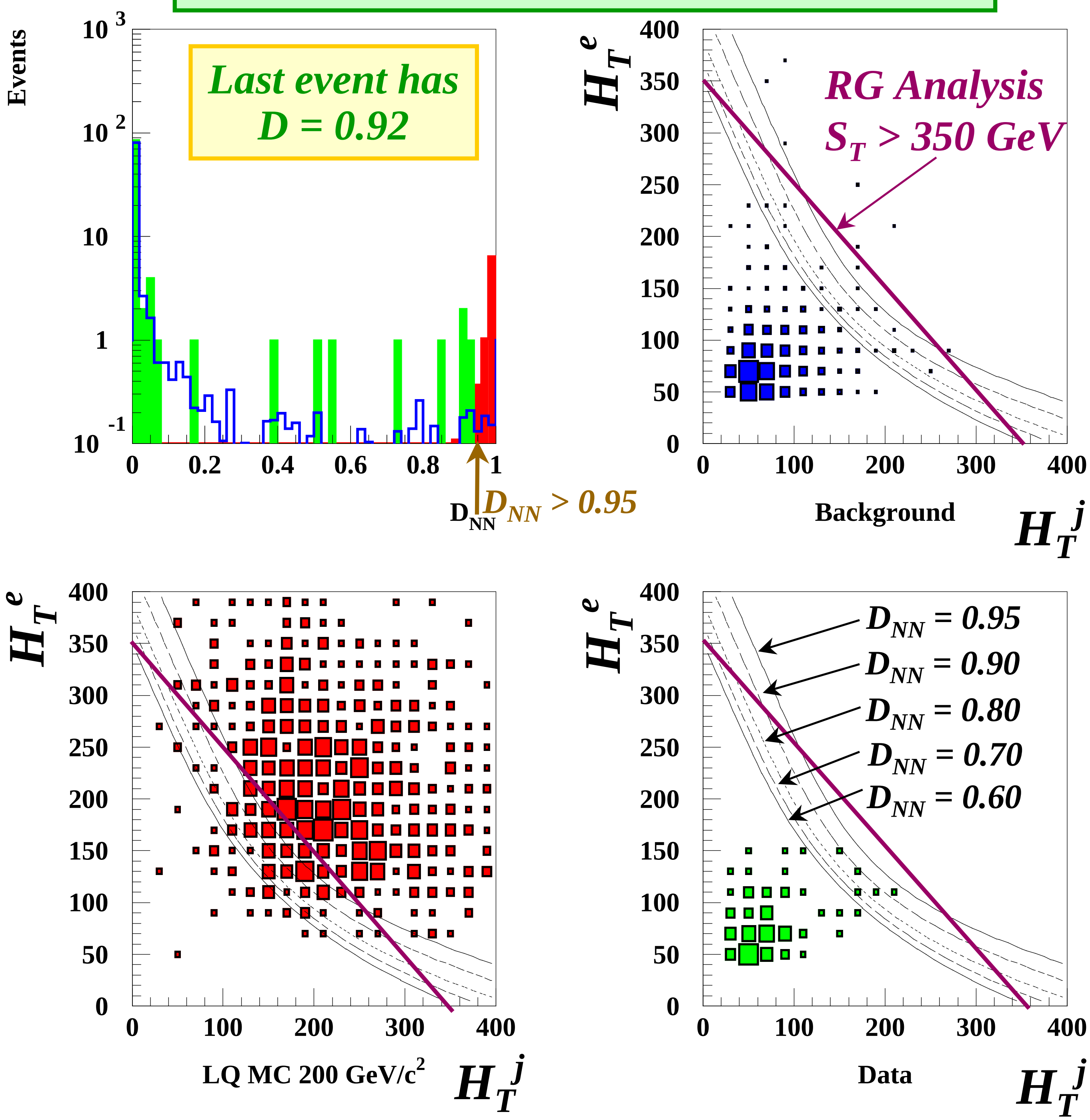
Output:

NN discriminant $0 < D_{NN} < 1$ maximized for the signal

The $D_{NN} > 0.95$ cut corresponds to similar to the RG analysis background. Overall efficiency is slightly better than that of the RG analysis. Both analyses are highly correlated with each other and result in essentially the same LQ mass limits

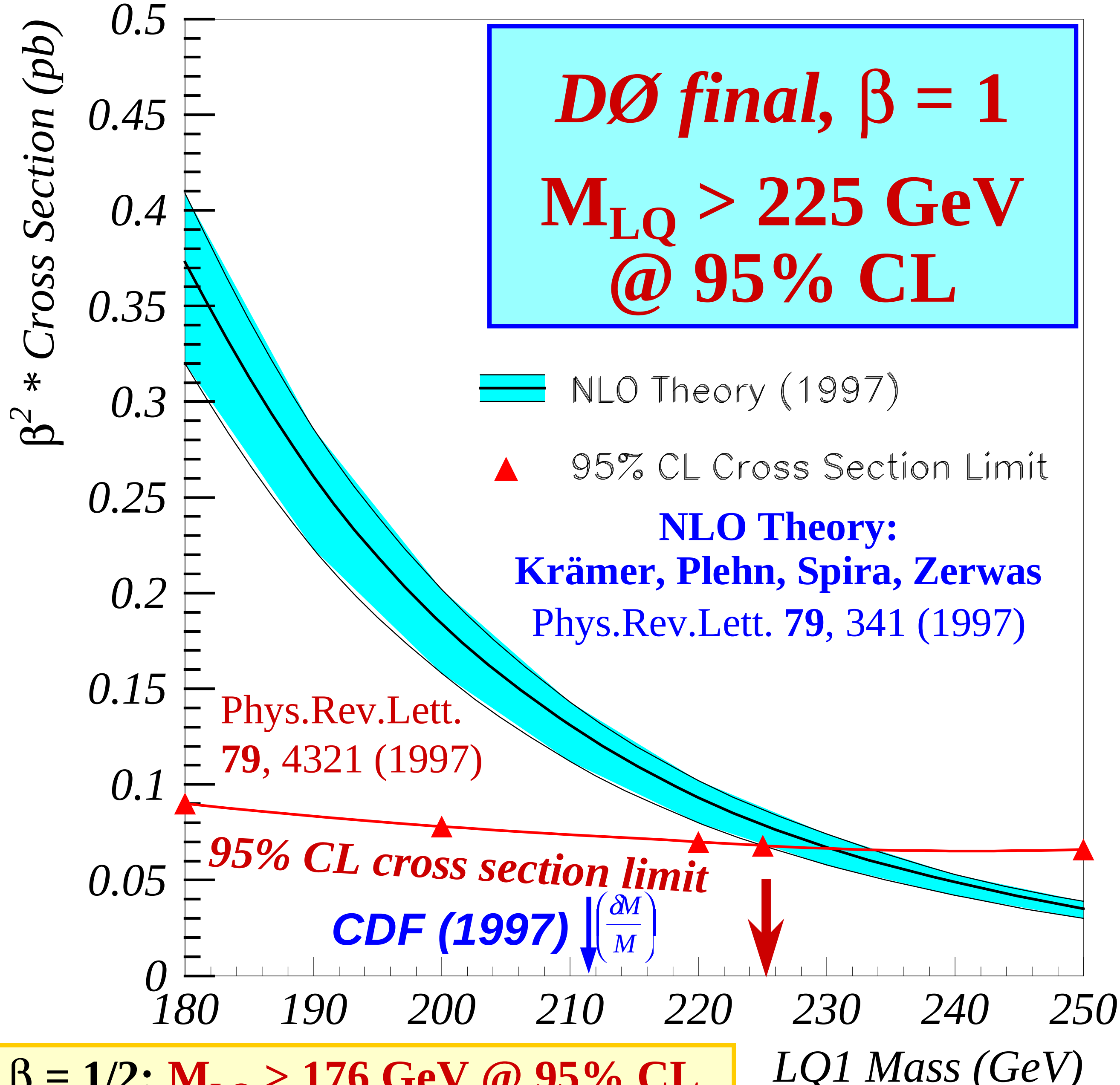
Neural Network Analysis

Results of the NN-based optimization



Limits on the First Generation LQ

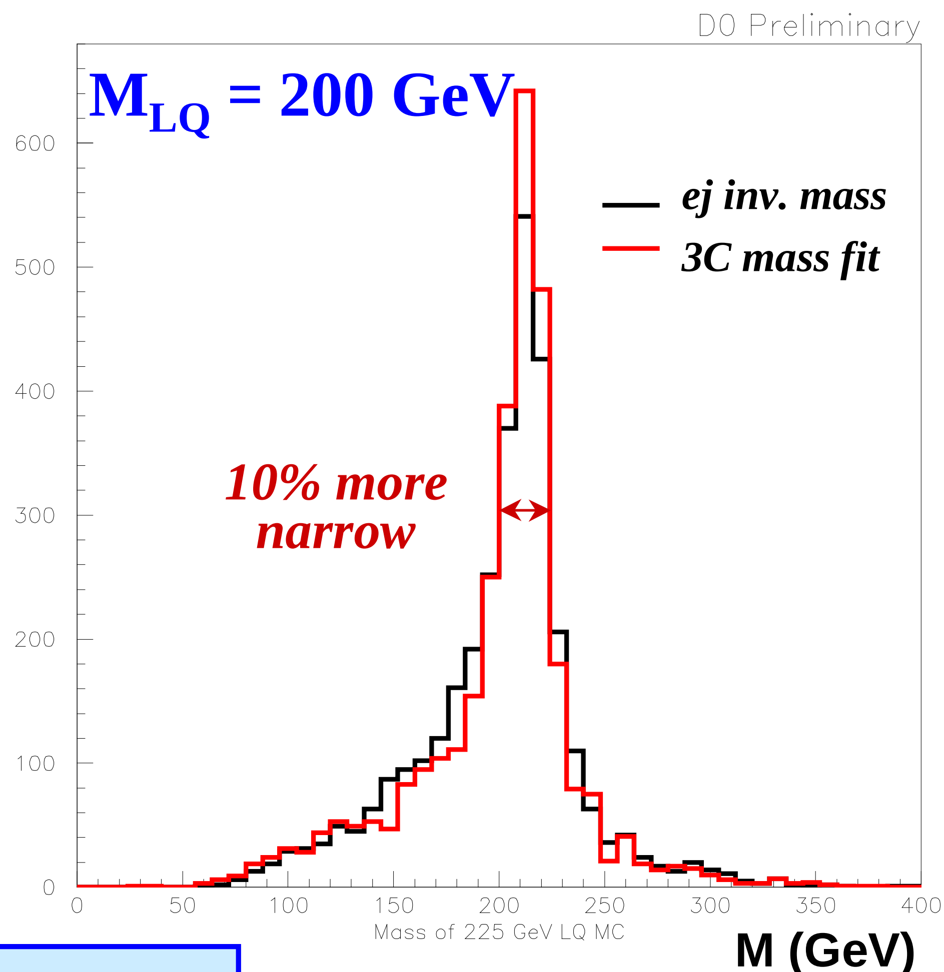
- *No background subtraction (limits are independent of the background and its uncertainty) - PDG method*
- *Account for systematic uncertainty on the signal*



$\beta = 1/2$: $M_{LQ} > 176$ GeV @ 95% CL

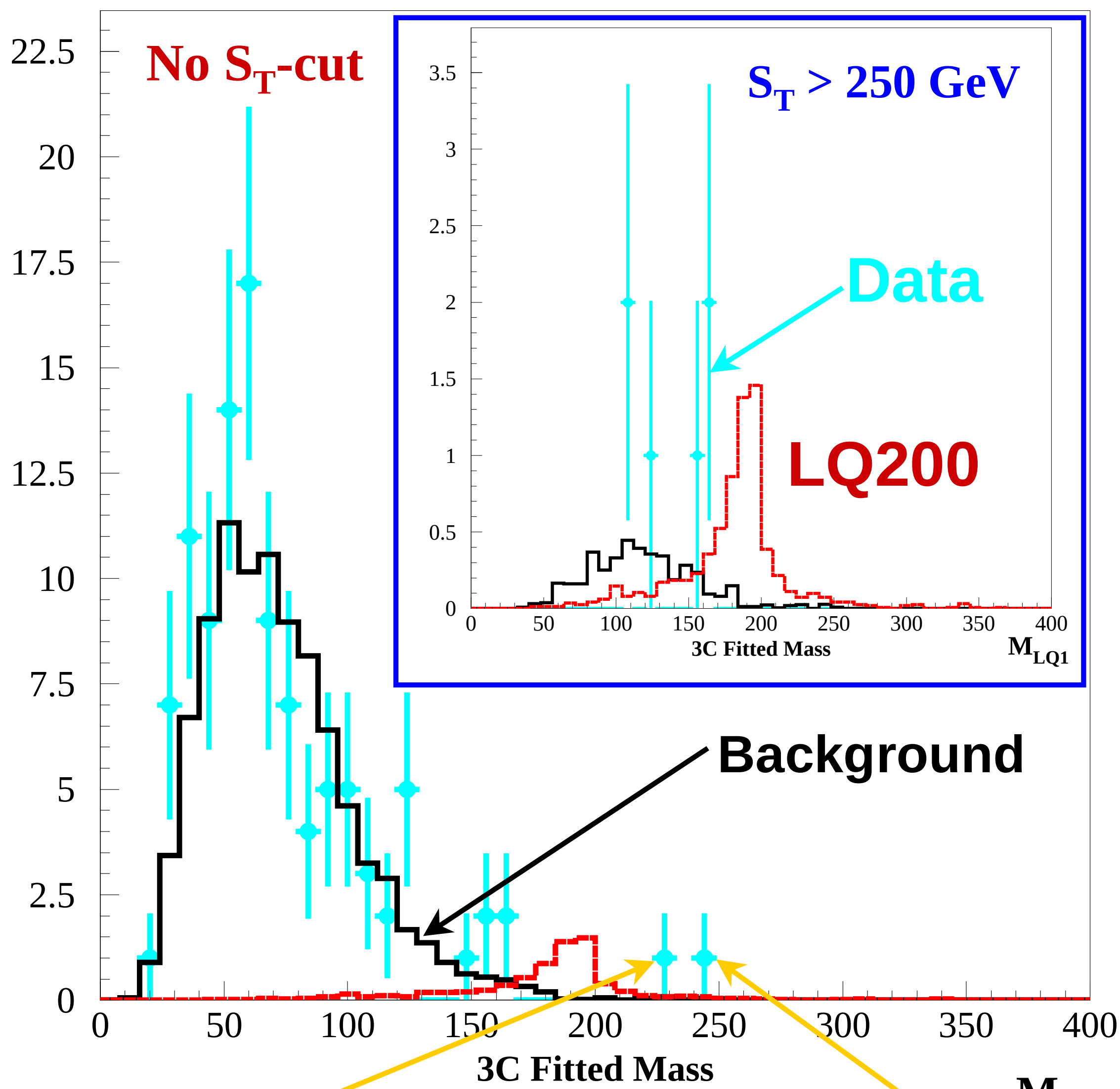
Mass Fit

- *Full-fledged kinematic fitter KFIT (based on SQUAW by O.Dahl) balancing all objects in the event (e, j, unclustered energy)*
- *3C-fitter: fits to the LQ-pair hypothesis with equal mass constraint. Lowest χ^2 solution is kept. Resolution is 10% better than that for pure kinematial calculations.*



Also tried 2C-fitter

3C-fit Mass Spectra



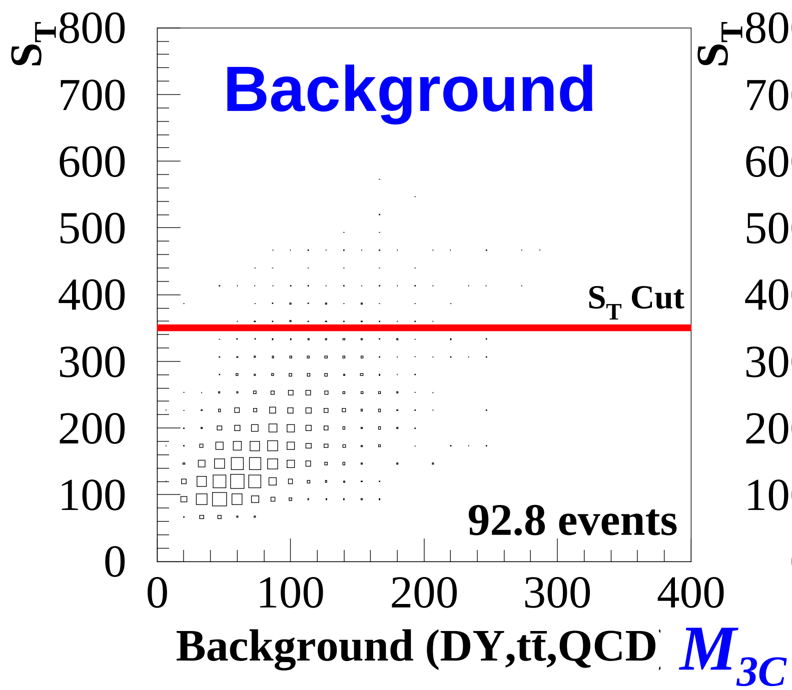
Run 63057, Event 1782

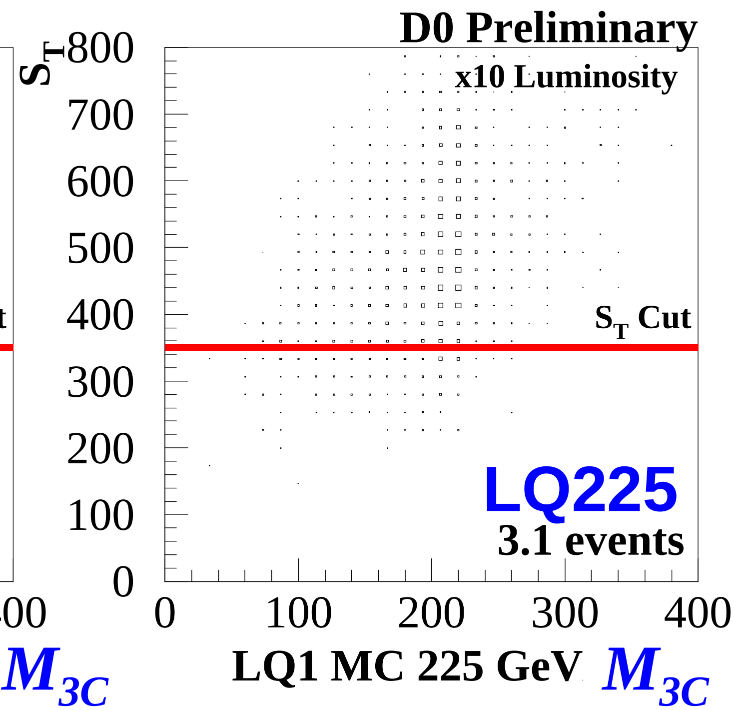
S_T = 121.2 GeV
E_T^{e1} = 29.0 GeV
E_T^{e2} = 25.7 GeV
E_T^{j1} = 36.3 GeV
E_T^{j2} = 30.2 GeV
M_{ee} = 55.3 GeV
M_{3C} = 244.9 GeV
M_{2C} = 269.7/232.7 GeV

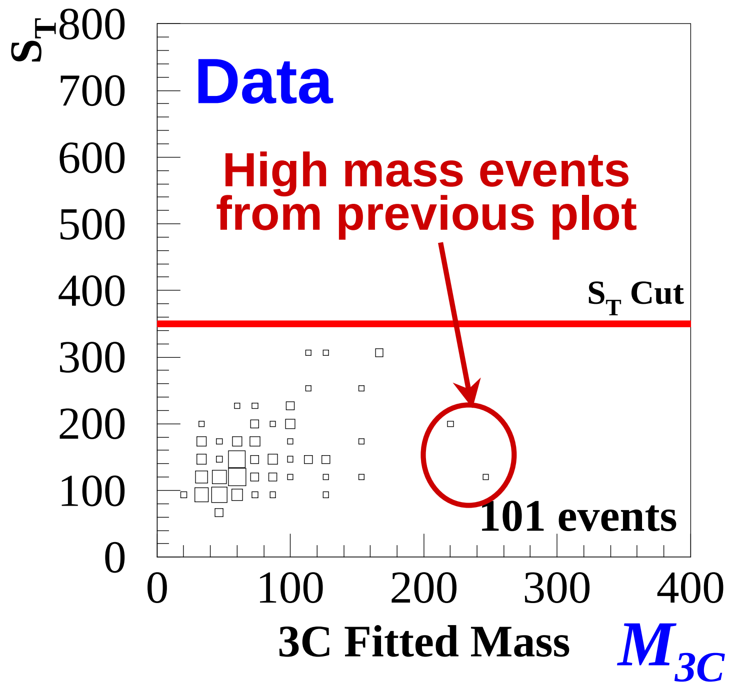
Run 90498, Event 13191

S_T = 210.5 GeV
E_T^{e1} = 70.5 GeV
E_T^{e2} = 54.6 GeV
E_T^{j1} = 53.5 GeV
E_T^{j2} = 31.8 GeV
M_{ee} = 129.2 GeV
M_{3C} = 224.7 GeV
M_{2C} = 246.7/217.3 GeV

S_T versus 3C-fit Mass





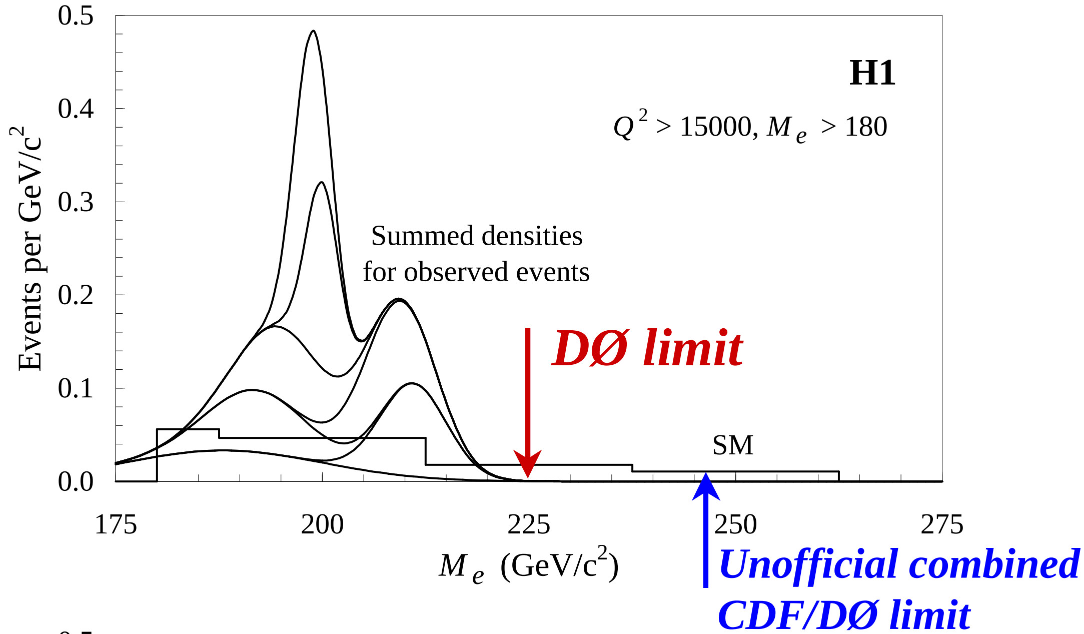


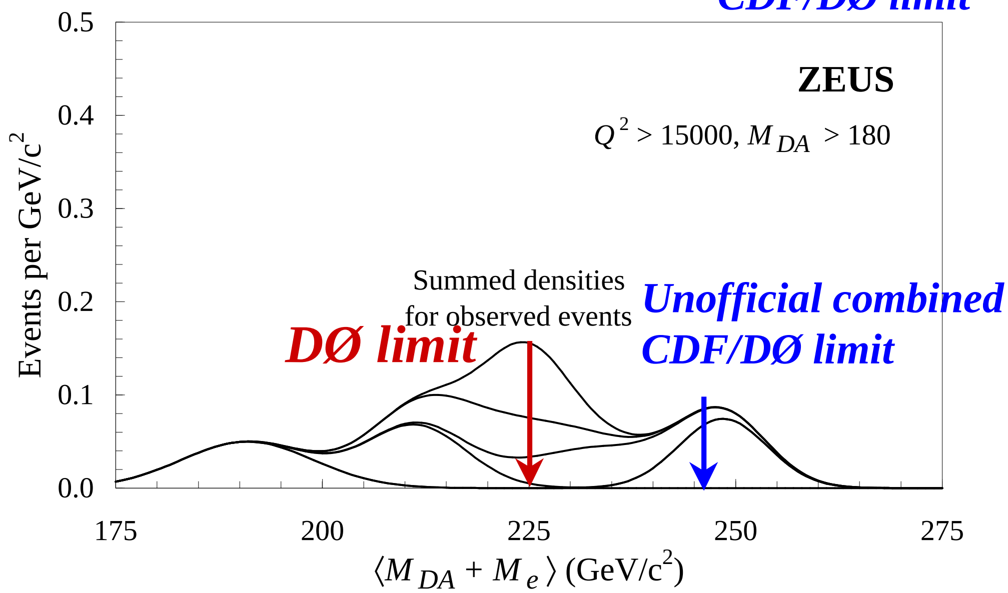
Two events with high mass seen in the 1-dimensional plot are nothing like the LQ signal

No evidences for the LQ signal are seen in the mass analysis as well

DØ on HERA Excess

New DØ result is a single most sensitive search for the β=1 1st generation LQ. It rules out an interpretation of the HERA high Q^2 event excess with 1st generation LQ within general LQ models w/o extra fermions or intergenerational mixing





Data Selection in $e\nu$+jets channel

- **Entire Run I statistics (115 pb^{-1})**

  EM [+$\not{E}_T$ [+ jets]] triggers; >99% efficient for offline cuts

- **Electron:**

  $E_T^e > 20$ GeV; $|\eta_e| < 1.1$ (CC) or $1.5 < |\eta_e| < 2.5$ (EC)

  - *Significant EM fraction*
  - *Matching track*
  - *Combined tracking-TRD-calorimeter info (electron likelihood) consistent with electron*

- **Jets (R = 0.7 cone algorithm; 2 or more):**

  $E_T^j > 20$ GeV; $|\eta^j| < 2.5$

- **General:**

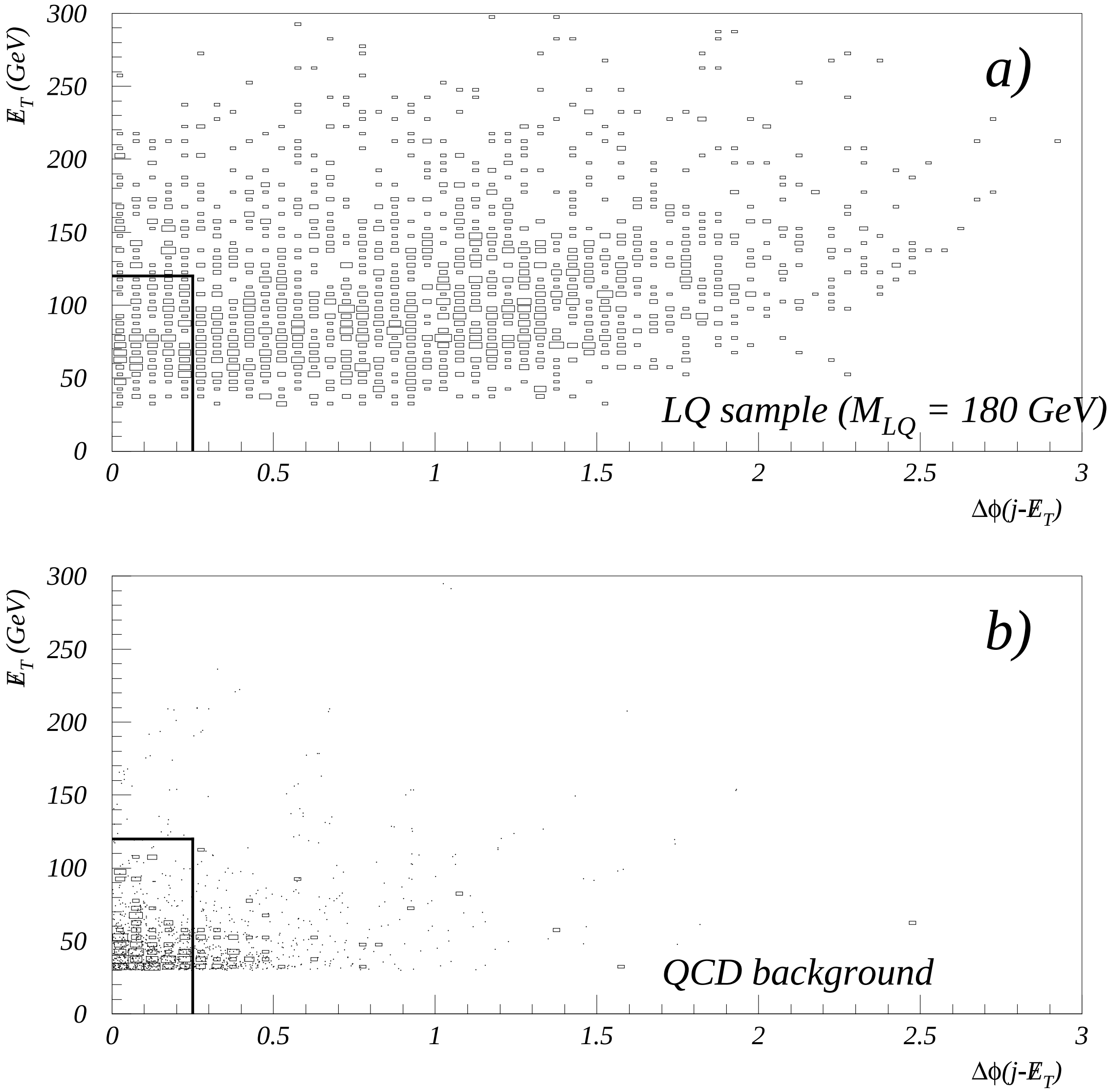
  Muon veto (reduces top background)

Data Selection in eν+jets channel (cont'd)

- **Missing Transverse Energy:**

  $\not{E}_T > 30$ GeV

  $\min(\Delta\phi(j,\not{E}_T)) > 0.25$ for $\not{E}_T < 120$ GeV

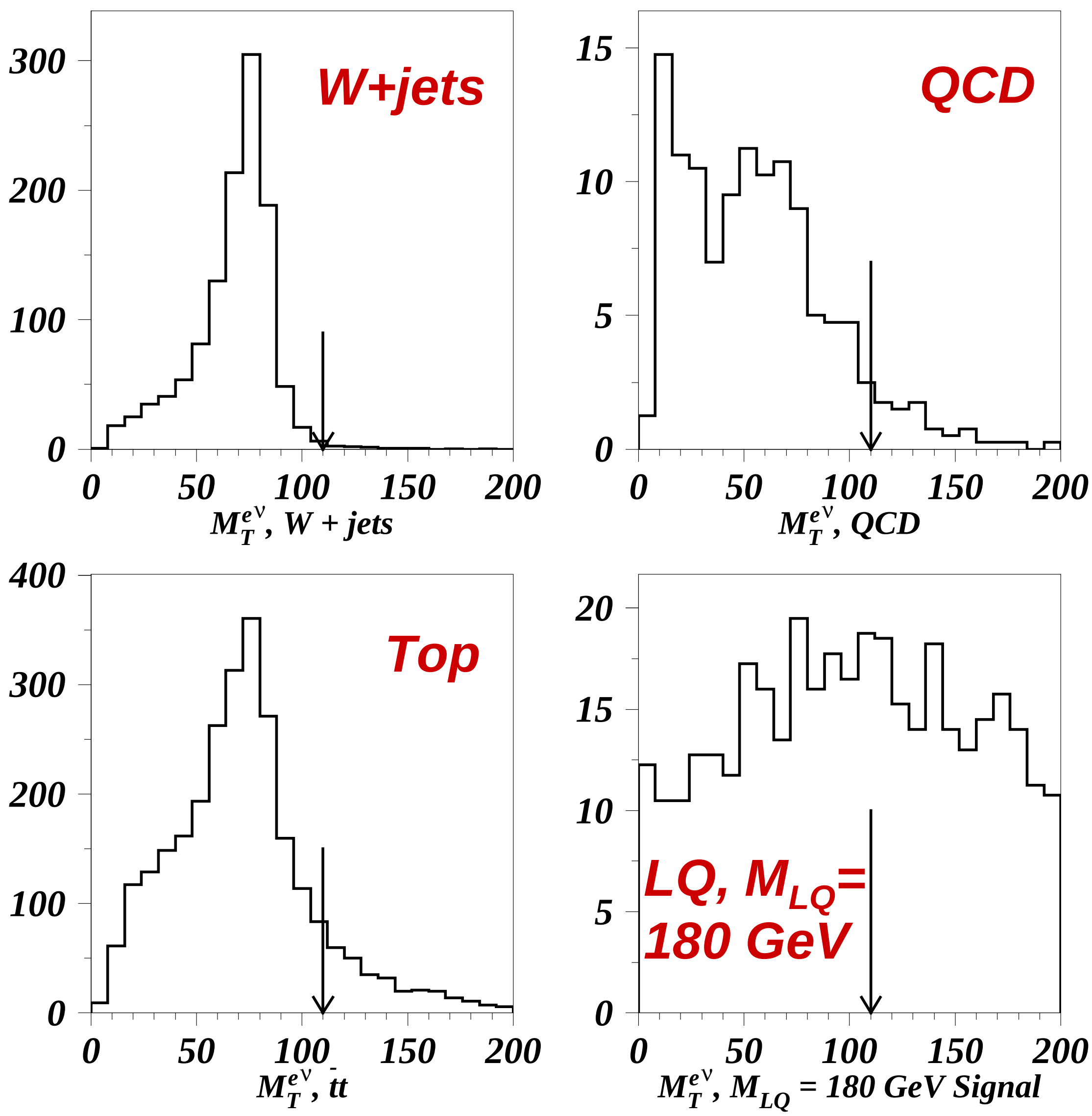


Data Selection in $e\nu$+jets channel (cont'd)

- **General:**

  $M_T(e\nu) > 110$ GeV (suppresses W+jets background)

$M_T^{e\nu}$ for Background and Signal Samples



Data Selection in $e\nu$+jets channel (cont'd)

- *Base sample: 14 events*

Cut	*Events*
Preselection	*95,383*
One EM object	*22,649*
EM in CC/EC, $E_T > 20$ GeV	*18,683*
2 or more jets, $E_T > 20$ GeV	*8,925*
Electron ID	*3,091*
Muon veto	*2,963*
$\not{E}_T$-cuts	*1,094*
$M_T(e\nu) > 110$ GeV	*14*

Total Background:
17.8 ± 2.1 events (see below)

QCD Background

- ***Use jet faking electron probability from the ee+jets analysis :***

  $$P(j \to \text{electron}) = (3.5 \pm 0.4) \times 10^{-4}$$

  (error covers slight η and E_T^e variations)

- ***Calculate the QCD background***
  - *Select single interaction events to ensure correct vertex (important for $\not{E}_T$)*
  - *Start with 3j+$\not{E}_T$ sample with all other cuts applied and multiply the number of combinations passing jet and electron fiducial cuts by electron faking probability*
  - *Correct for single interaction requirement inefficiency (50% ± 5%)*

QCD Background:

75 ± 15 events before $M_T(e\nu)$ cut

4.1 ± 0.9 events in the base sample

(error dominated by $P(j \to e)$ uncertainties)

Top Background

- Apply all signal cuts to the $t\bar{t} \to \ell + jets$ MC (includes dilepton contribution)
- Correct for muon veto (suppression factor of 1.9 ± 0.1)
- Count the number of events which pass
- Calculate background using the top production cross section measured by DØ:

$$\sigma(p\bar{p} \to t\bar{t}) = (5.5 \pm 1.8)\ pb$$

and theoretical branching ratio

$$B(t\bar{t} \to \ell + jets) = 0.456$$

Top Background:

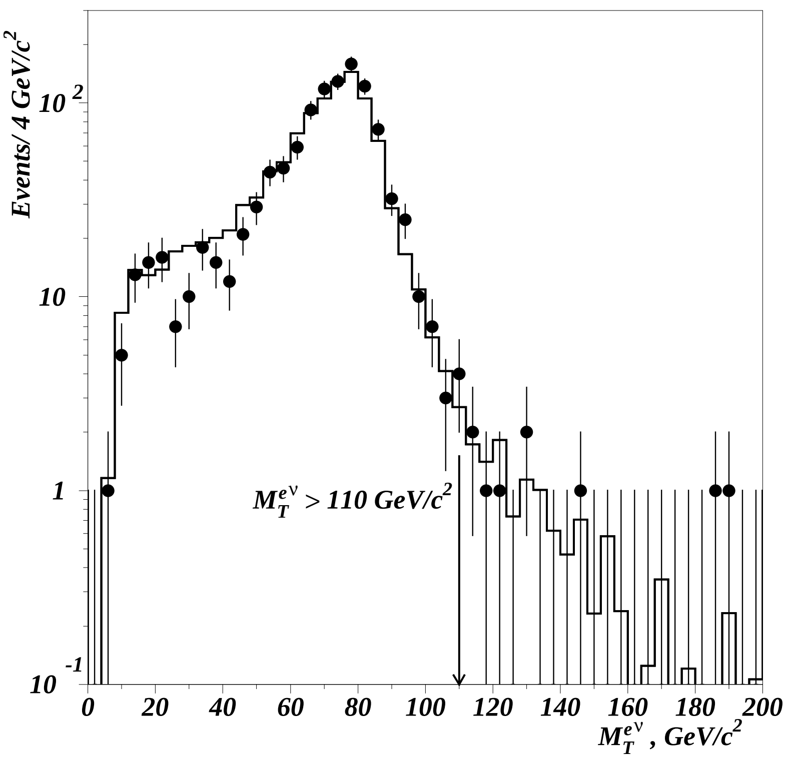
12 ± 4 events before $M_T(e\nu)$ cut

2.0 ± 0.7 events in the base sample

(error dominated by uncertainty in the cross section)

W+jets Background

- **Normalize the W+jets MC sample with all cuts except for $M_T(e\nu)$ applied and the estimated QCD and $t\bar{t}$ backgrounds added to the data for $M_T(e\nu)$ < 110 GeV**



W+jets Background:

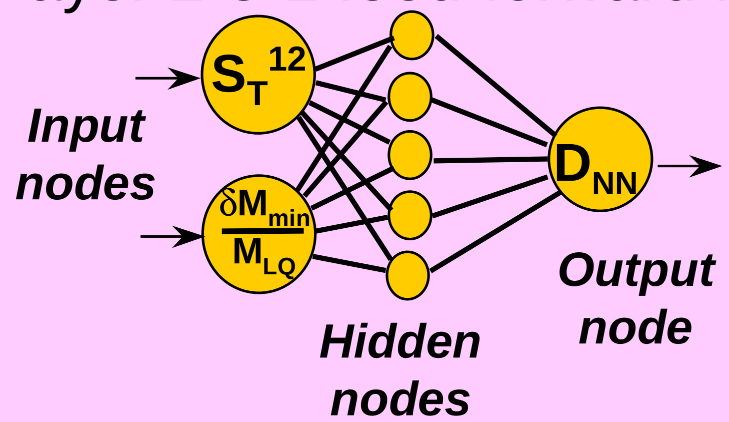
1010 ± 70 events before $M_T(e\nu)$ cut

11.7 ± 1.8 events in the base sample

(error dominated by the uncertainties in jet energy scale and MC statistics)

Neural Network Analysis

3 layer 2-5-1 feed-forward NN



M_{LQ} =
140 GeV
160 GeV
180 GeV
200 GeV
220 GeV

$$S_T^{12} = E_T^e + \not{E}_T + E_T^{j1} + E_T^{j2}$$

Reduced gluon radiation systematics

$$\delta M_{min}/M_{LQ} = \min(|M_{ej} - M_{LQ}|)/M_{LQ}$$

Essential against the $t\bar{t}$ background

Training:

Signal: LQ(M_{LQ}) MC

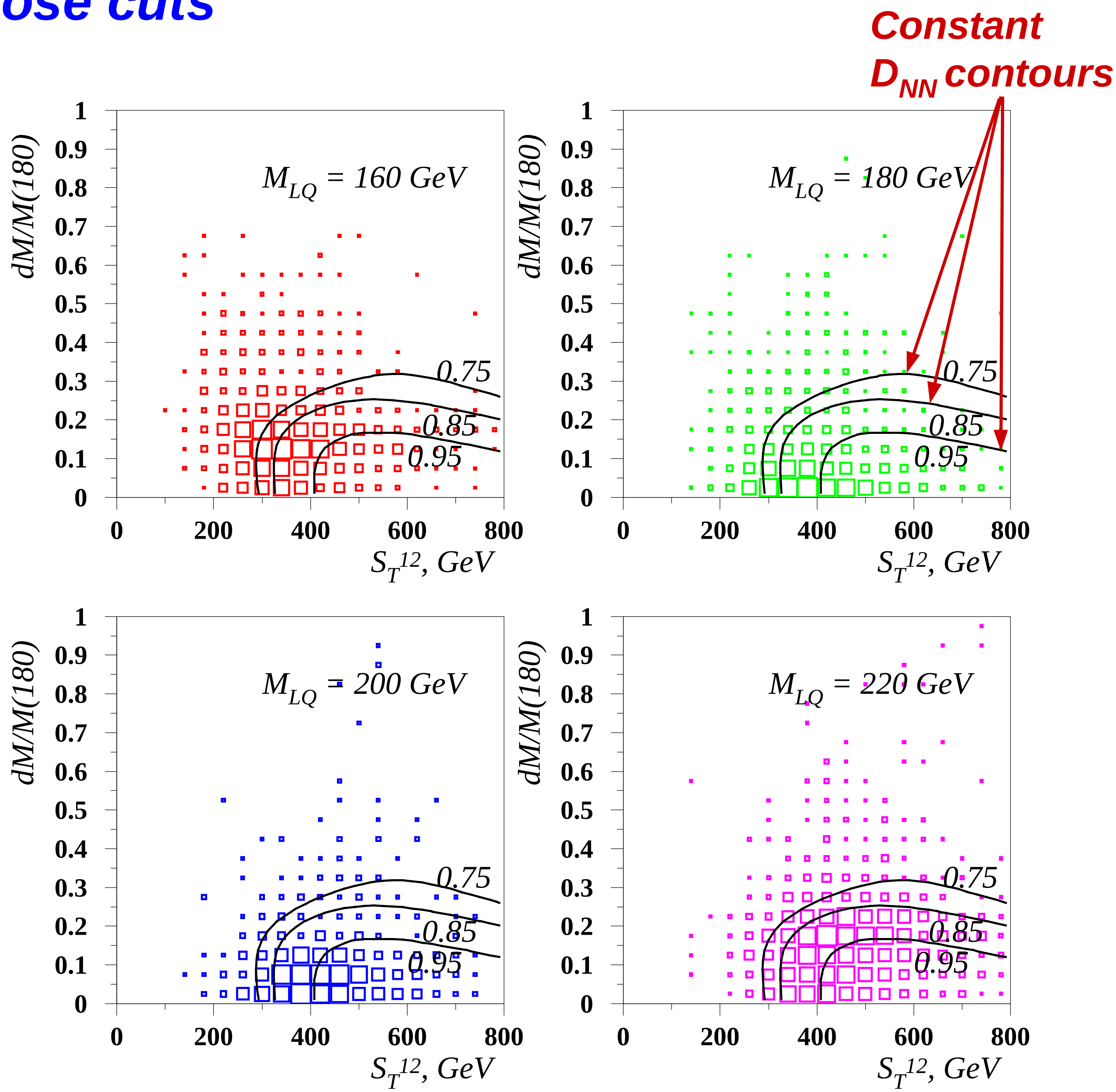
Mixture of QCD, W+jets and Top backgrounds

Output:
NN discriminant 0 < D_{NN} < 1 maximized for the signal

For M_{LQ} < 120 GeV where top background is not an issue used straight ee+jets-like S_T^{12} > 400 GeV cut:

NN Optimization, M_{LQ} = 180 GeV

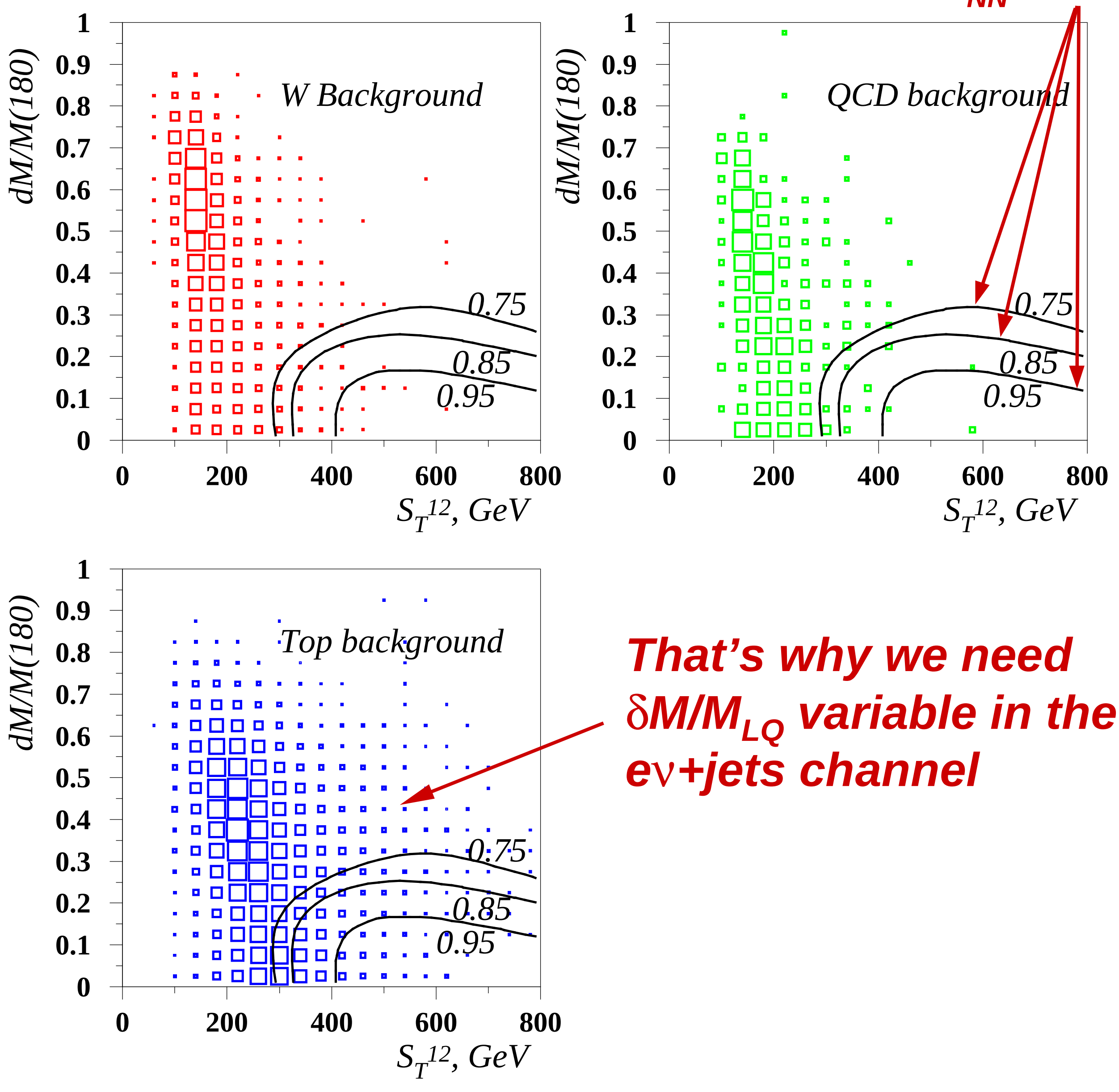
Constant D_{NN} contours for the signal, loose cuts



NN Optimization, M_{LQ} = 180 GeV

Constant D_{NN} contours for backgrounds, loose cuts

Constant D_{NN} contours

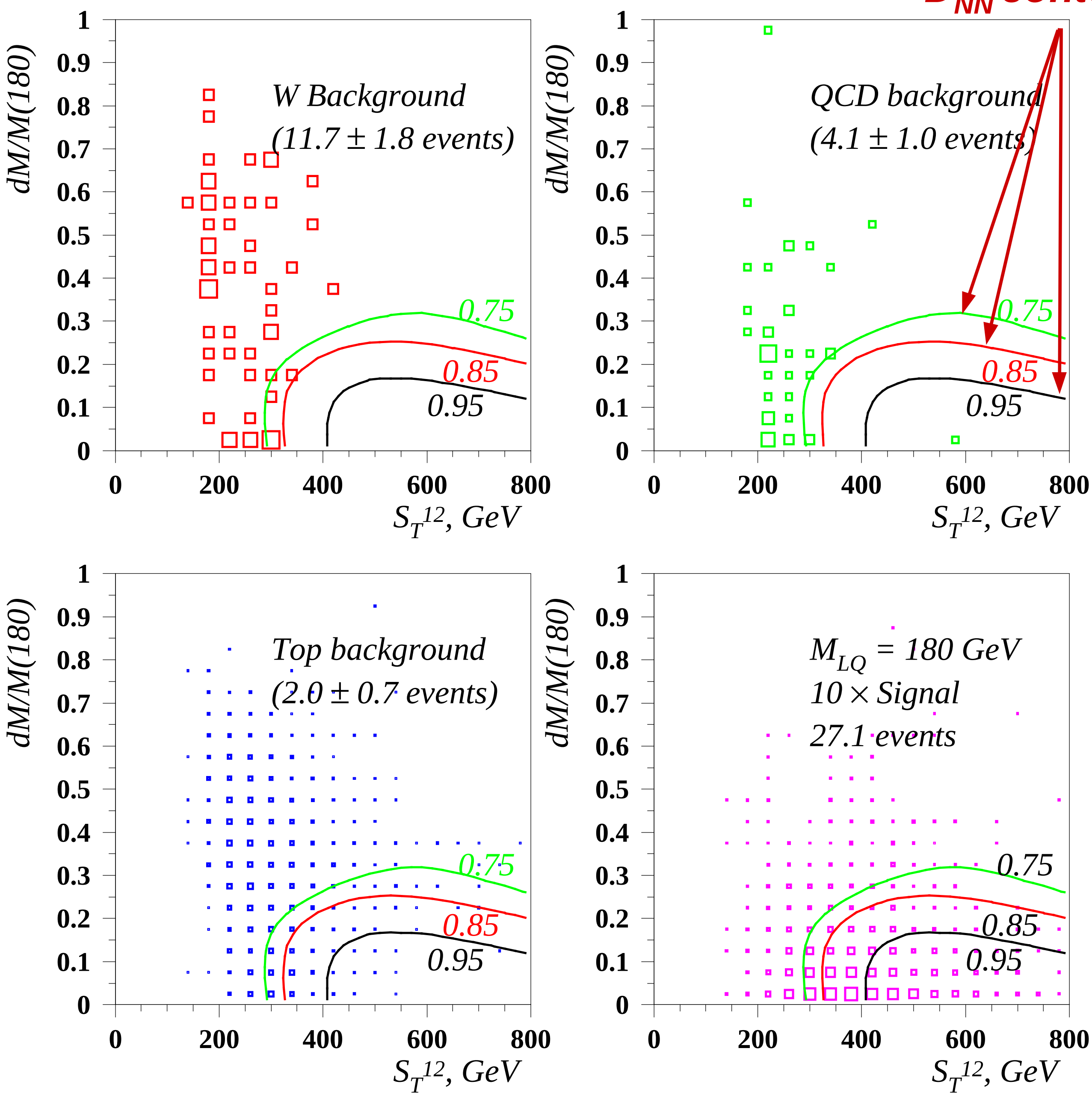


That's why we need $\delta M/M_{LQ}$ variable in the eν+jets channel

NN Optimization, M_{LQ} = 180 GeV

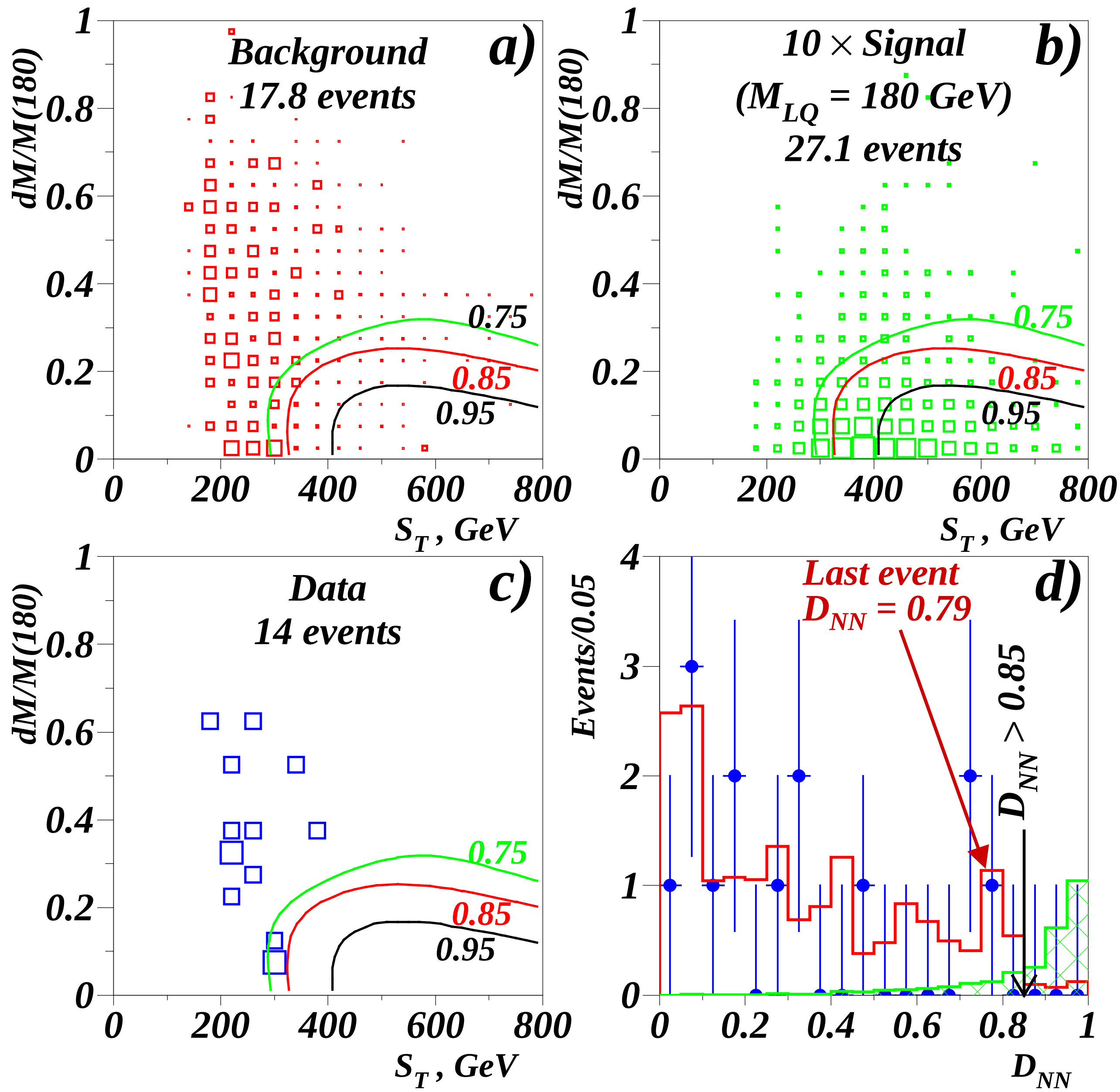
Constant D_{NN} contours for backgrounds, base sample cuts

Constant D_{NN} contours



NN Results
M_{LQ} = 180 GeV

Background for D_{NN} > 0.85 cut is 0.29 ± 0.25 events



Data are consistent with the background hypothesis

Background and efficiency

We vary the D_{NN}-cut (in 0.05 steps) and S_T^{12}-cut (in 50 GeV steps) and fix it to give the background value closest to the desired level of 0.4 events (with the background uncertainties taken into account). As a result, no events pass the chosen cut for any of the networks or S_T^{12} cut.

Background and efficiency

M_{LQ} (GeV)	Background prediction	Signal efficiency
80	0.60 ± 0.27	0.003 ± 0.001
100	0.60 ± 0.27	0.012 ± 0.002
120	0.60 ± 0.27	0.025 ± 0.003
140	0.54 ± 0.25	0.067 ± 0.010
160	0.61 ± 0.27	0.109 ± 0.012
180	0.29 ± 0.25	0.147 ± 0.012
200	0.43 ± 0.27	0.194 ± 0.017
220	0.41 ± 0.27	0.215 ± 0.017

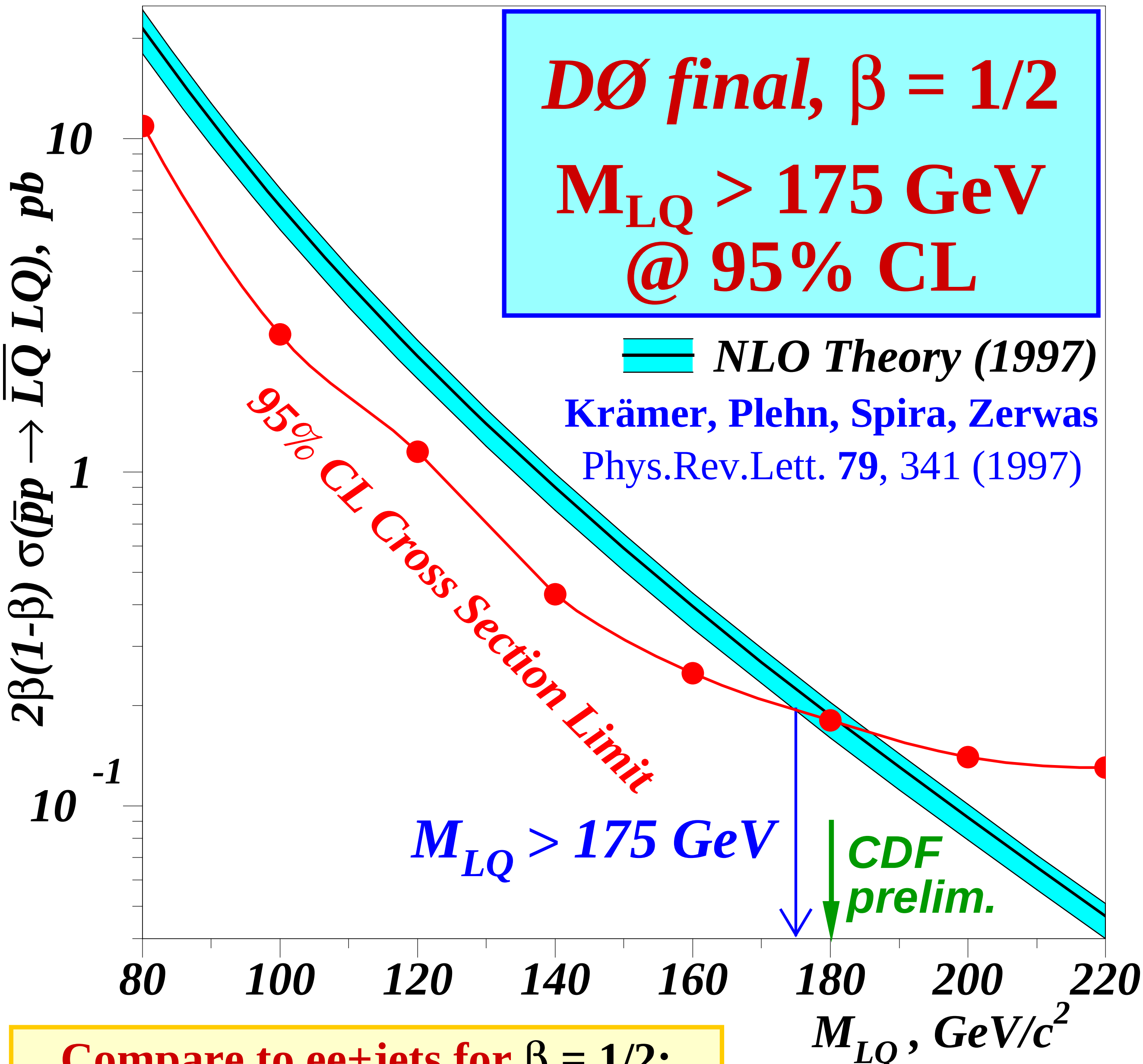
Signal Systematics

Source of error	Error
Particle ID	5%
Smearing in the Detector	3%
Jet Energy Scale	2% -10%
Gluon Radiation	4%
PDF and Q^2	5%
MC Statistics	3-25%
Luminosity	5%
Total	8%-25

Data are consistent with the background hypothesis; no evidences for leptoquarks are found

Mass Limits in eν+jets channel

Fermilab-Pub-97/344-E, submitted to PRL



Compare to ee+jets for β = 1/2: M_{LQ} > 176 GeV @ 95% CL

Data Selection in $\not{E}_T$+jets channel

- *Use our published analysis [PRL **76**, 2222 (1996)]: search for stop pair production in*

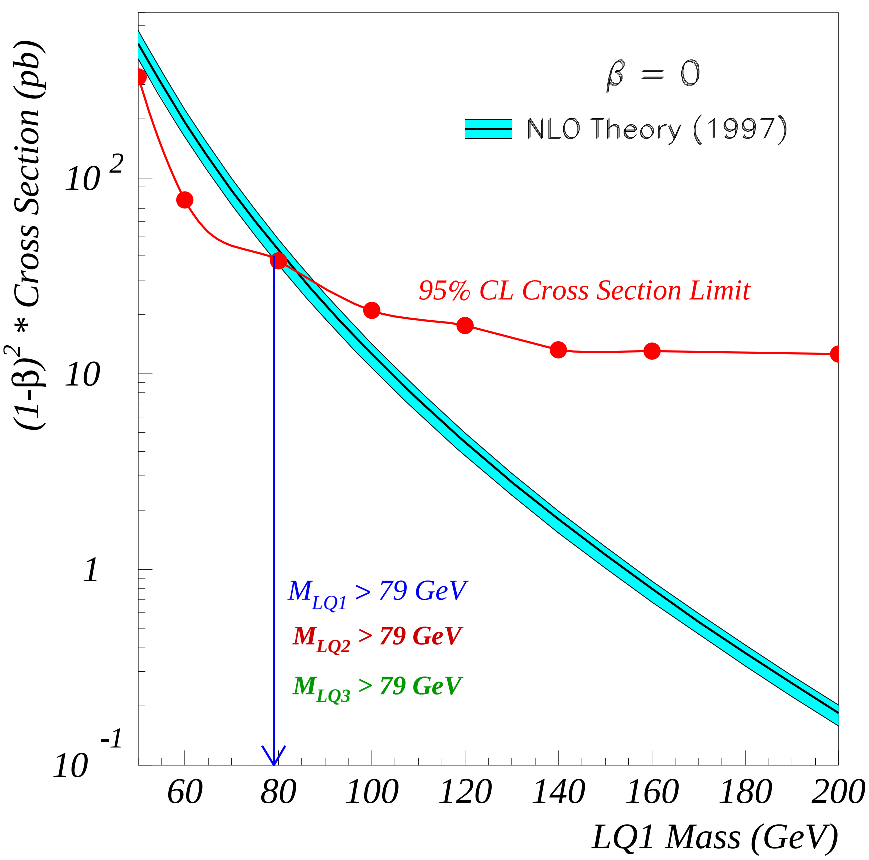
$$p\bar{p} \to \tilde{t}_1\bar{\tilde{t}}_1 + X \to c\chi_1^0 c\chi_1^0 + X \to \not{E}_T + jets$$

- *This analysis is not optimized for LQ searches; it also uses only a small fraction of available statistics; still it is useful to extend LQ mass limits to β=0*
- *Data set:*
  - **7.4 pb^{-1}, collected with $\not{E}_T$ trigger in the 1992-1994 run**
- *Selection Cuts:*
  - **$\not{E}_T$ > 40 GeV, E_T^j > 30 GeV**
  - **$90^o < \Delta\phi(j_1,j_2) < 165^o$**
  - **$10^o < \Delta\phi(j_{1,2},\not{E}_T) < 125^o$; $10^o < \Delta\phi(j_{>2},\not{E}_T)$**
  - **electron/muon veto**
- *Observed 3 candidate events*

Results in $\not{E}_T$+jets channel

- **Backgrounds:**
  - W(eν,μν,τν)+jets ***(2.98 ± 1.14 events)***
  - Z(μμ,ττ) [+jets] ***(0.51 ± 0.27 events)***
  - ***Total: 3.49 ± 1.17 events***
- **Signal efficiency:**

From: 0.45% ± 0.10% + 0.00% - 0.05% (M_{LQ}=50 GeV)
To: 6.36% ± 0.35% + 0.04% - 0.06% (M_{LQ}=200 GeV)



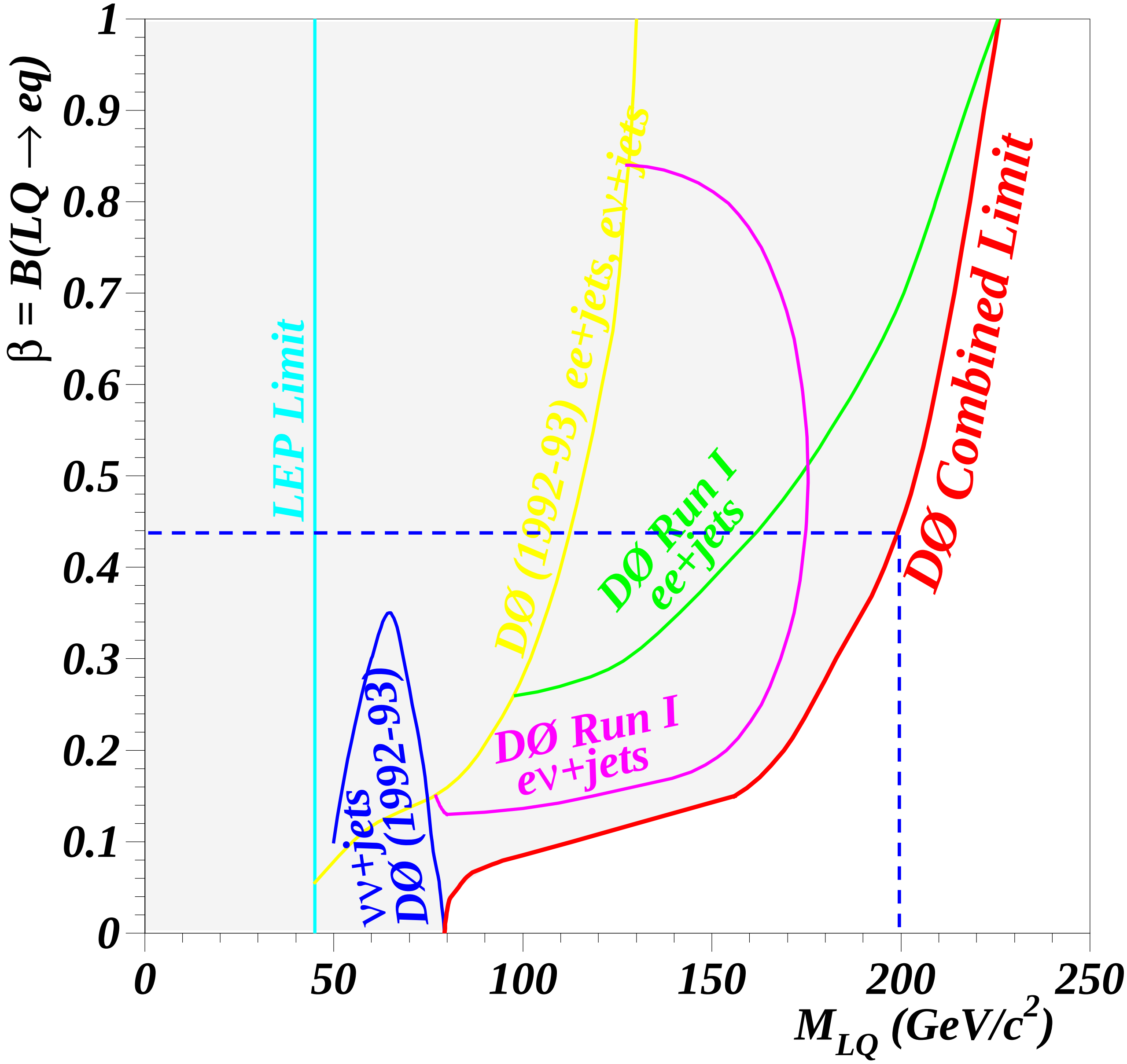
DØ final, β = 0
M_{LQ} > 79 GeV @ 95% CL

Unique measurement sensitive to β = 0; generation-independent

Combined Limits on First Generation LQ

First Generation Scalar Leptoquarks are excluded by DØ at 95% CL for β > 0.4. This closes HERA LQ saga.

For $\beta = 1.0$, $M_{SLQ} > 225$ GeV

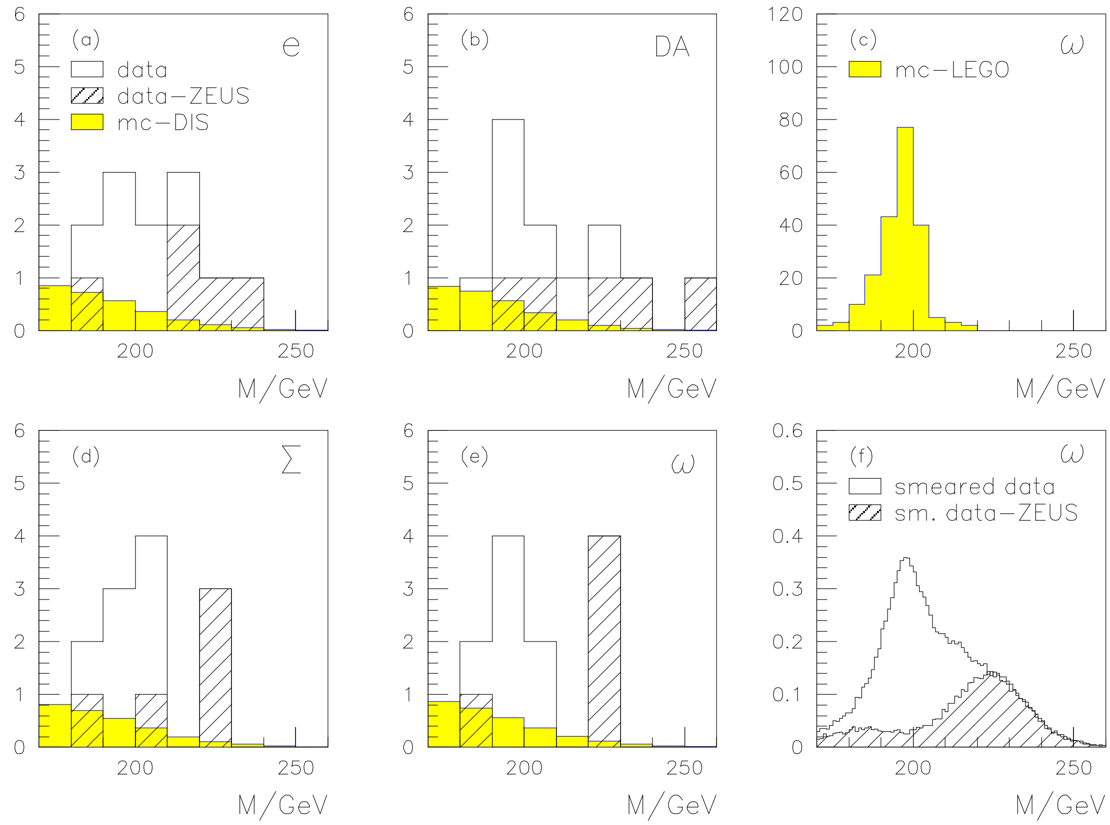


For $\beta = 0.5$, $M_{SLQ} > 204$ GeV

The Aftershock

- *After analyzing 1997 data set the significance of HERA excess did not improve. In fact, 1997 data alone does not exhibit any significant excess of high Q^2 events*
- *Joint analysis of the H1/ZEUS data does not support an explanation of the HERA results with a single narrow resonance:*

[U.Bassler, G.Bernardi, *Z.Phys.* ***C76****, 223 (1997)]*



Search for Second Generation LQ

μμjj channel

Data: 1994-1996 Tevatron run (94.4 pb^{-1})

Event Selection:

2 isolated muons:
$p_T^{\mu} > 15$ GeV, $|\eta^{\mu}| < 1.0$,
$\Delta R(\mu,j) > 0.5$

2 jets: $E_T^{j} > 15$ GeV, $|\eta^{j}| < 2.5$

$\Delta\phi(\mu 1,\mu 2) < 160^{o}$ if
$|\eta_{\mu 1} + \eta_{\mu 2}| < 0.5$

$M_{\mu\mu} > 10$ GeV

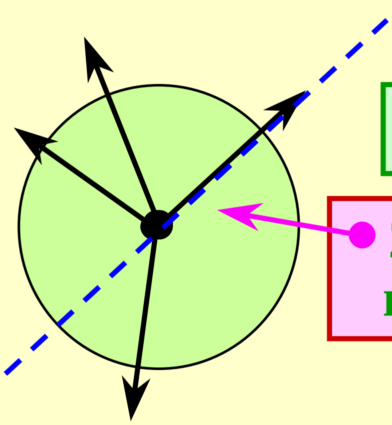
$H_T^{j} > 100$ GeV

Z-kinematic fit $P(\chi^2) < 1\%$

Standard $t\bar{t} \rightarrow$ dimuon selection

2 muons and 2 leading jets are not in the same ϕ-hemicylinder

Top rejection

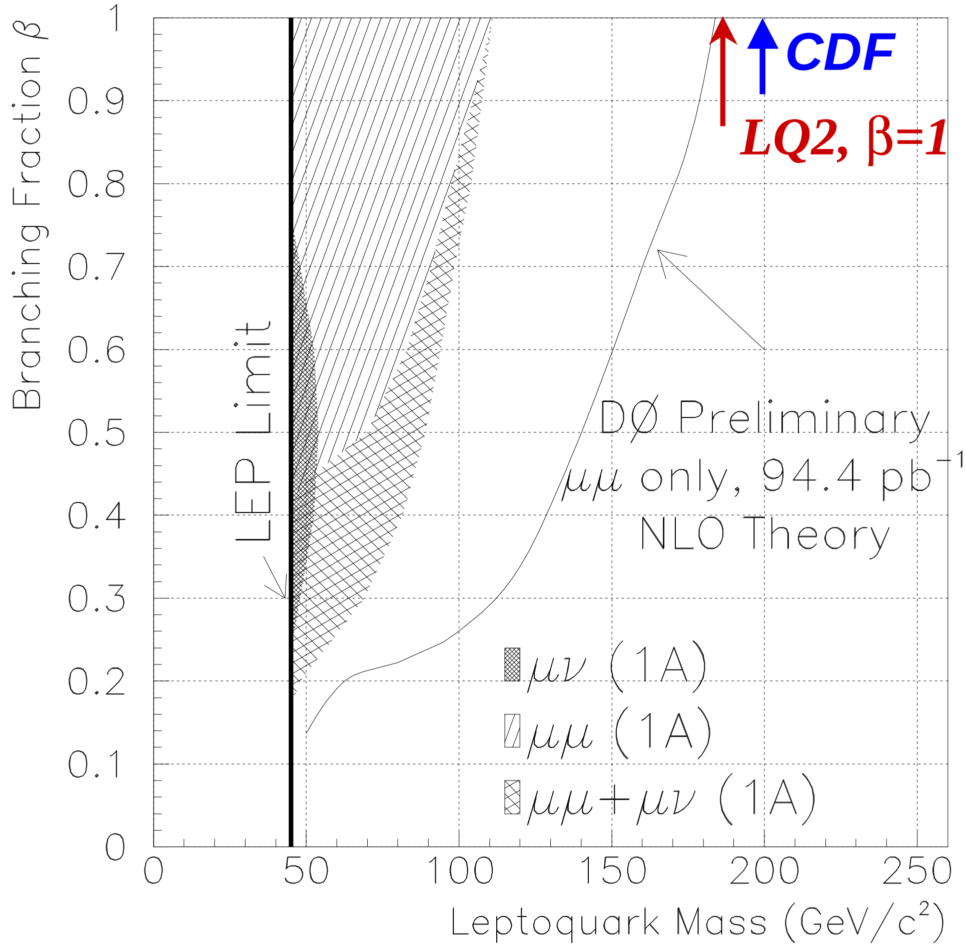


0 events survive

Second Generation LQ Mass Limits

Run 1 Data Sample (94.4 pb^{-1})
Data: 0 events, Exp. Bkgd: 0.9 ± 0.2 events

M_{LQ2} > 184 GeV @ 95% CL for β = 1



NLO Theory: Krämer, Plehn, Spira, Zerwas
Phys.Rev.Lett. **79**, 341 (1997)

Search for Third Generation LQ

q = 1/3 third generation LQ
$\nu\bar{\nu}b\bar{b}$ channel

- $\nu\bar{\nu} \Rightarrow \not{E}_T > 35$ *GeV*
- *2 jets, at least 1 with muon tag*
  - *untagged,* $E_T^j > 25$ *GeV*
  - *tagged,* $E_T^j > 10$ *GeV*
- *topological cuts*

Efficiency = 1.9% (M_{LQ3} = 100 GeV)
(3-5% at higher LQ3 masses)

Major Backgrounds:
$t\bar{t}$, W/Z+2j, QCD multijets

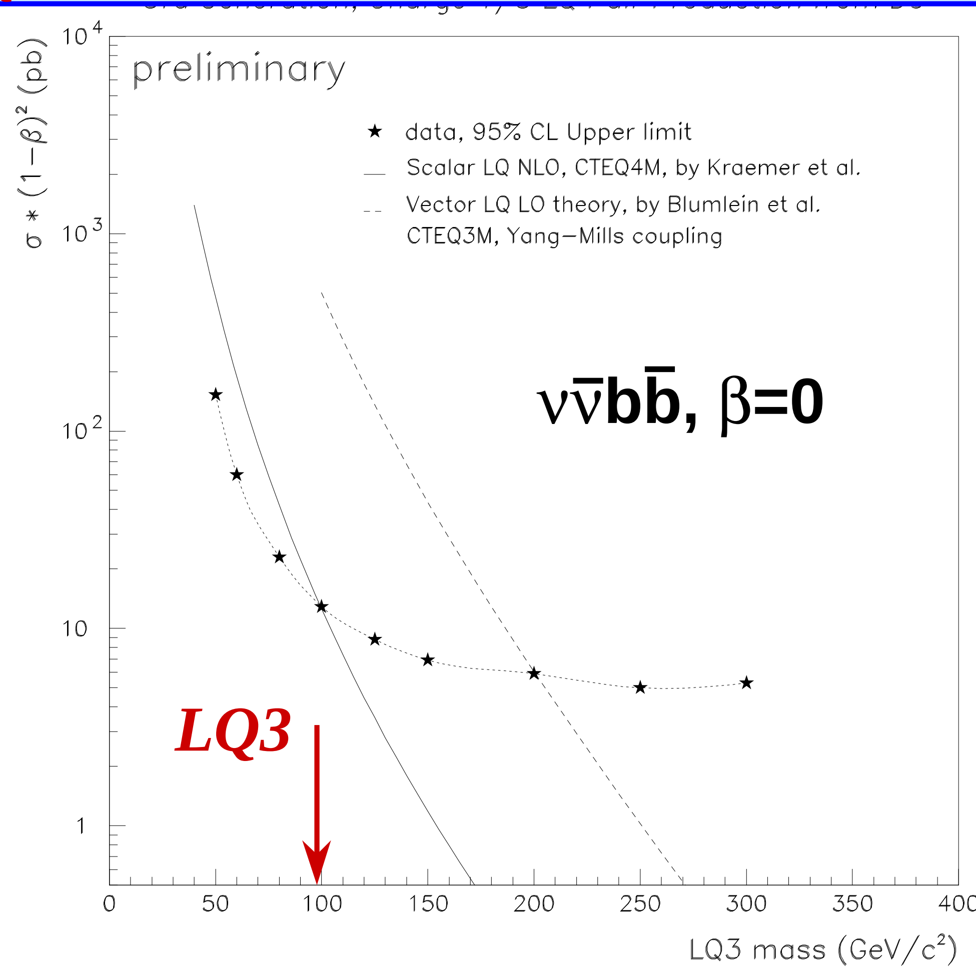
Third Generation LQ Mass Limits

Run 1 Data Sample

Data: 2 events, Exp. Bkgd: 3.1± 0.9 events

M_{LQ3} > 98 GeV @ 95% CL for β = 0, q = 1/3

M_{VLQ3} > 201 GeV @ 95% CL for β = 0, q = 1/3



NLO Theory: Krämer, Plehn, Spira, Zerwas

Phys.Rev.Lett. **79**, 341 (1997)

Conclusions

- *The DØ Collaboration has performed a search for scalar LQ and set the following 95% CL lower LQ mass limits based on the NLO theory:*
  - **First Generation:**
    - $\beta = 1$ **225 GeV**
    - $\beta = 1/2$ **204 GeV**
    - $\beta = 0$ **79 GeV**
  - **Second Generation:**
    - $\beta = 1$ **184 GeV**
    - $\beta = 1/2$ **140 GeV**
    - $\beta = 0$ **79 GeV**
  - **Third Generation:**
    - $\beta = 0$ **98 GeV**

all limits are given @ 95% CL

- *Our search for first generation LQ is the single most sensitive Yukawa-coupling-independent measurement. It rules out at 95% CL an interpretation of the HERA data with LQ with masses below 200 GeV and $\beta > 0.4$. This excludes a very broad class of models.*
- *Combined Tevatron results are expected to yield even higher mass limits on the LQ*

A Final Touch

New York Times, February 25, 1997

NEW YORK TIMES SCIENCE TUESDAY, FEBRUARY 25, 1997

Surprising New Particle Appears, Or on the Other Hand, ~~Maybe~~ Not

By DAVID KESTENBAUM

Physicists in Germany may have detected a bizarre hybrid particle called a leptoquark that, if it turns out to be real, could topple the reigning scientific model of how the world is put together.

For two decades, particle physicists have sorted the smallest, apparently indivisible subatomic particles into two exclusive categories, quarks and leptons. Quarks are what protons and neutrons are made of. Leptons are particles like electrons and neutrinos. Together, leptons and quarks make up the atoms that form all of the material world.

The leptoquark — half lepton, half quark — has lived for almost two decades only in the dreams and equations of theoretical physicists as an object that would overturn the Standard Model, a theory that has been dominant for so long that a generation of physicists has known nothing else. The Standard Theory does not predict leptoquarks, but tracks of a leptoquark may now have been seen in a German accelerator.

"A leptoquark would have such enormous consequences for our understanding of physics that I don't dare to dream of it," said Dr. Ralph Eichler, a physicist at the Institut für Teilchenthysik in Switzerland and a spokesman for one of two international teams that reported the leptoquark results on Wednesday at the accelerator, the Deutsches Elektronen-Synchrotron in Hamburg, Germany. Their results were submitted for publication yesterday.

But the DESY physicists are wary of claiming too much. "What we're seeing might just be a random fluctuation," said Dr. Allen Caldwell, a physicist at Columbia University who is the spokesman for the other team, "like getting seven heads in a row when flipping a coin."

The new results, the teams say, could also be evidence for new particles within the quarks, an equally exciting possibility. Dr. Guido Altarelli, a physicist at the CERN laboratory in Switzerland, said the data could also be interpreted as evidence for an even heavier particle, a leptoquark or something else not yet seen.

The Standard Model describes the world from the ground up, from the architecture of atoms to the reactions that power the sun. Although it does not include gravity, it is the closest thing physicists have to a "theory of everything."

"I'm positive the Standard Model is incomplete," said Dr. Joseph Lykken, a physicist at Fermilab in Batavia, Ill., in an interview. "It just leaves too many questions unanswered. I expect we will find a crack in it sometime this decade."

A new particle like the leptoquark would be such a crack. Leptoquarks arise, Dr. Lykken said, in theories that try to unite leptons and quarks into a larger, simpler structure. The Standard Model will not fall so much as it will be consumed by a more complete theory, he predicted.

"If the leptoquark is real," Dr. Lykken said, "it will really be a shock to the whole community."

At the DESY accelerator, a ring of magnets accelerates protons and positrons (the electron's antimatter counterpart) to close to light speed and has them collide. The DESY instrument, the only proton-positron collider in the world, is ideal for making leptoquarks, if they exist.

In most collisions, the positron bounces off the quarks within the proton, which breaks up to form a shower of other particles. The two research teams, which include collaborating groups from 19 countries, monitor the collisions at different points around the four-mile ring, each using a house-sized particle detector weighing thousands of tons. After examining the data from millions of collisions over the last few years, the teams found that some positrons had emerged at surprisingly high energies, a greater number than predicted by the Standard Model. In these events, Dr. Caldwell said, the positron "almost makes a U-turn."

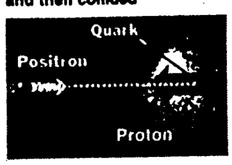
One explanation for that would be the momentary formation of a leptoquark, surviving only a fraction of a second before decaying back into a positron and a quark. Because there were only about 10 of these collisions, the teams said it was impossible to draw definite conclusions about what they might be. The odds that those collisions were produced them by chance, they said, is only about 1 in 200, but this is still well short of the 1-in-10,000 standard usually required to establish firmly that a new particle has been detected.

The two DESY research teams analyzed their data in isolation and did not compare their results until last week, and they were excited to find that they had a lot in common. If the presence of a leptoquark is established, it would be the heaviest subatomic particle yet observed, weighing almost as much as a lead atom. Previous searches had not observed any but could have missed one this heavy. But DESY physicists are choosing their words cautiously, saying leptoquarks are only one possible explanation. DESY will begin collecting more data in March.

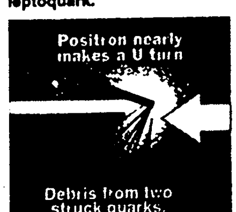
Footprints of a Leptoquark?

At the DESY accelerator in Hamburg, Germany a positron (the electron's antimatter counterpart) collides with a quark. In a few spectacular collisions, the positron nearly makes a U turn. One possible explanation is the momentary creation of a strange new particle called a leptoquark.

Positron and a quark inside a proton are accelerated close to the speed of light and then collided



The high-energy positron nearly reverses direction, possible evidence of a leptoquark.



Source: DESY

The New York Times

Elsevier

...uman chromosomes.

...ler University who re-...hed a paper on this phe-... human cells, said that ...are constantly moving ...forth between states." ...ate between growing and ...in a dynamic equilib-...le Lange said. ...riety of species use the ...anism, said Dr. Thomas ...Nobel Prize-winning cell ...the University of Colora-...r, who published a paper ...telomere length regula-...st. "The story is consis-...id. ...il leaves the question ...omeres have any use oth-... buffer zones. Dr. Black-...n answer was imminent, ...ers, she said, are about to ...pers showing that telo-...ssential for nuclear divi-...ocess of pulling apart the ...es when cells divide. So, ...e telomere story may not ...le one of a few years ago ...ifically, it is a lot more