Searches for vector-like quarks, leptoquarks and quirks at DØ

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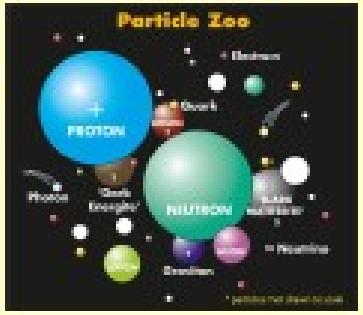
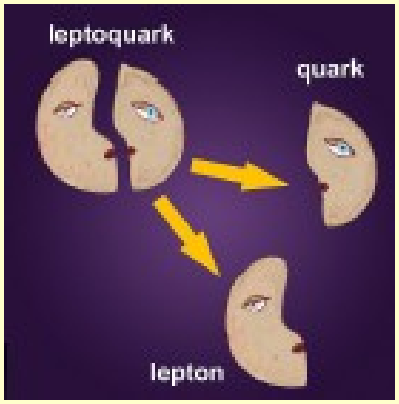
on behalf of the

collaboration

Outline

- Leptoquarks
- Vector-like quarks
- Quirks



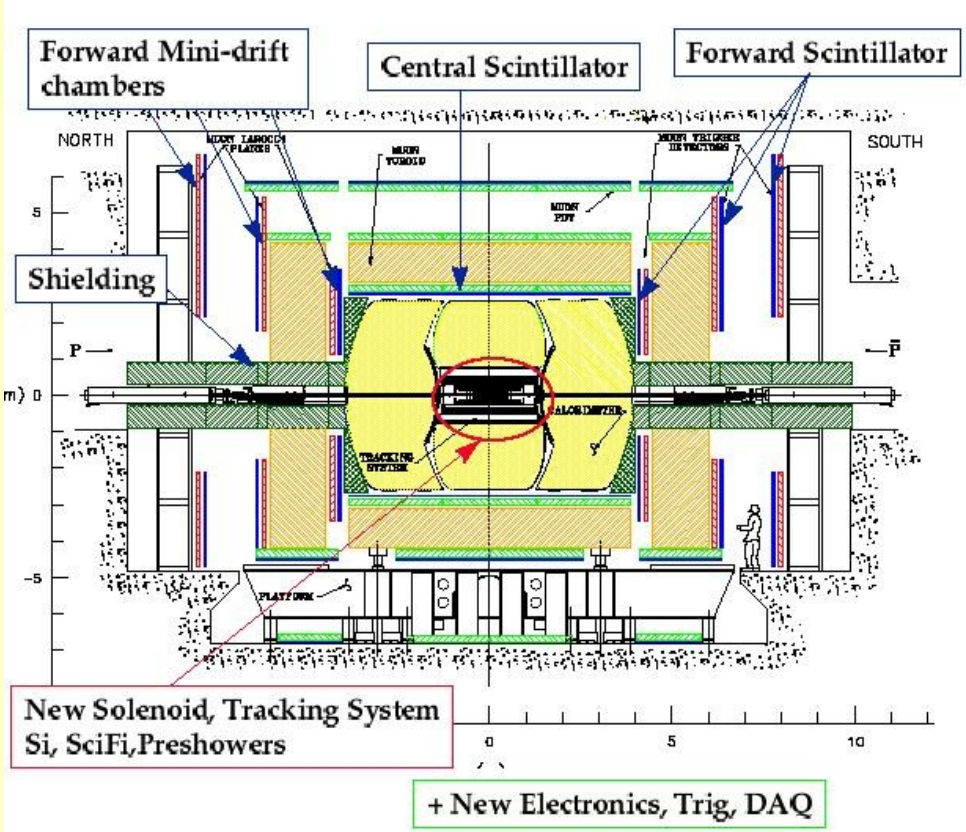


Motivation

- Standard model is believed to be low energy effective theory
  - There are evidences of physics beyond SM
- Many additional models are proposed
- DØ performed extensive search for new particles and models over the years

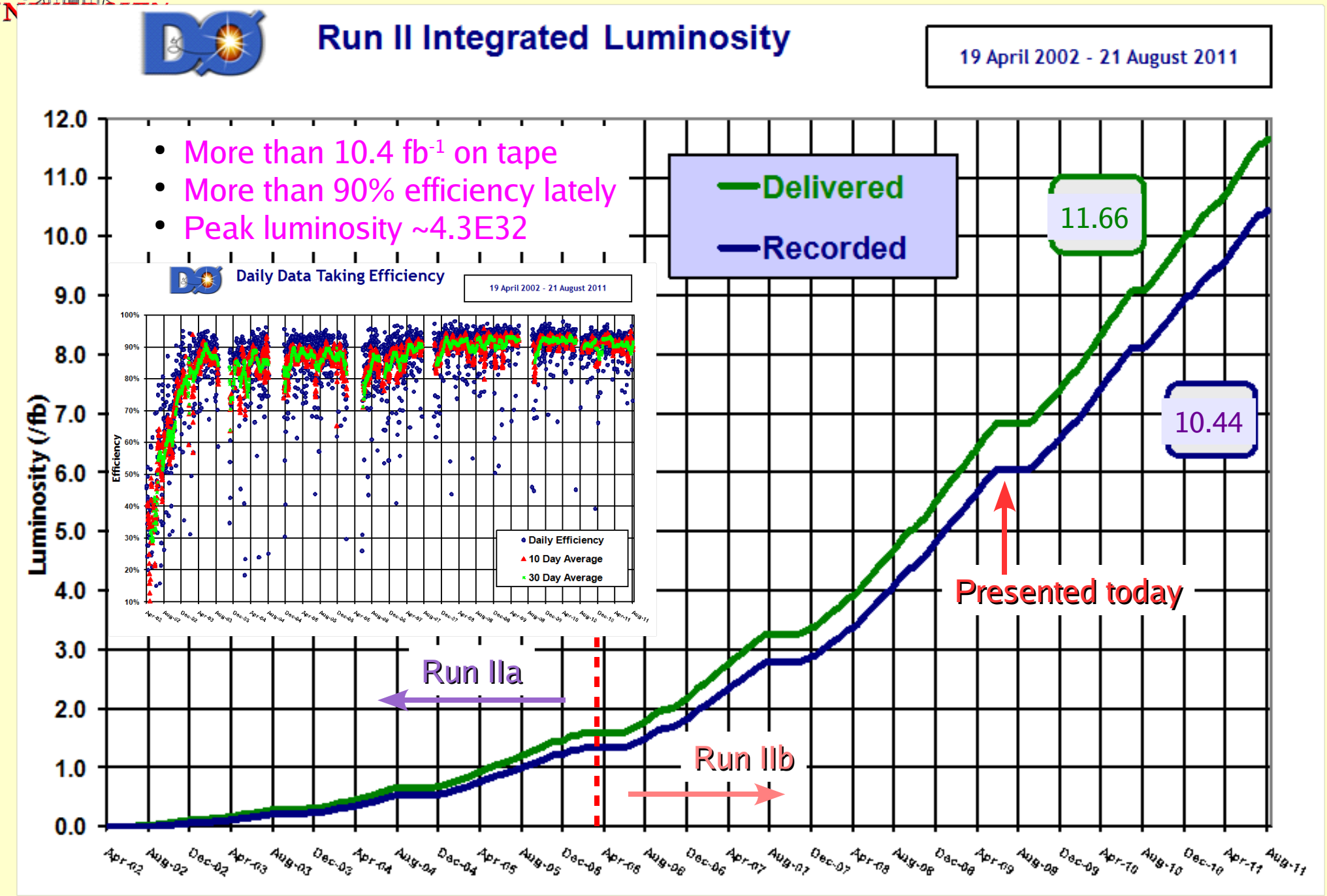
DØ experiment in Run II

- Multipurpose detector:
  - Central tracking system embedded in a solenoid magnetic field:
    - Silicon vertex detector (SMT)
    - Central Fiber tracker (CFT)
  - Preshowers
  - Electromagnetic and hadronic calorimeters
  - Muon system



Angular coverage	$\lvert\eta\rvert$
Muon ID	~2
Tracking	~2.5
EM / Jet ID	~4

Data taking


Run II Integrated Luminosity
19 April 2002 - 21 August 2011
More than 10.4 fb-1 on tape
More than 90% efficiency lately
Peak luminosity ~4.3E32
Daily Data Taking Efficiency
19 April 2002 - 21 August 2011
Efficiency
Daily Efficiency
10 Day Average
30 Day Average
Delivered
Recorded
11.66
10.44
Presented today
Run IIa
Run IIb
Luminosity (/fb)

Leptoquarks

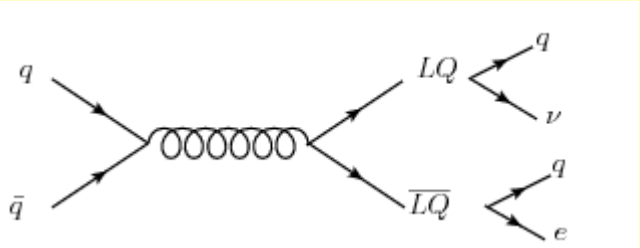
Motivation

- Leptoquark (LQ) is predicted by many extensions of the Standard Model (GUT, technicolor, SUSY, etc.)
  - LQ can be a mediating boson, allowing interaction between leptons and quarks
    - In the SM, leptons and quarks do not directly interact
  - Can be scalar or vector field
    - has three generations
  - Short-lived and decays to a lepton and a quark

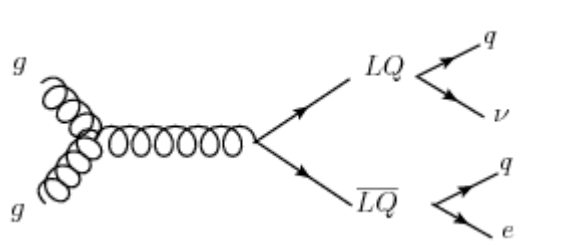
Introduction

- LQ can be produced singly or in pairs
- Produced via quark-antiquark annihilation or gluon-gluon fusion:

q + q → LQ + LQ



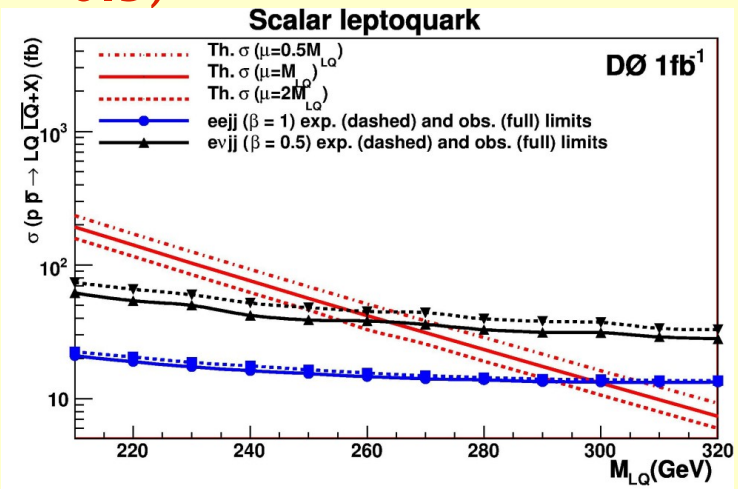
g + g → LQ + LQ

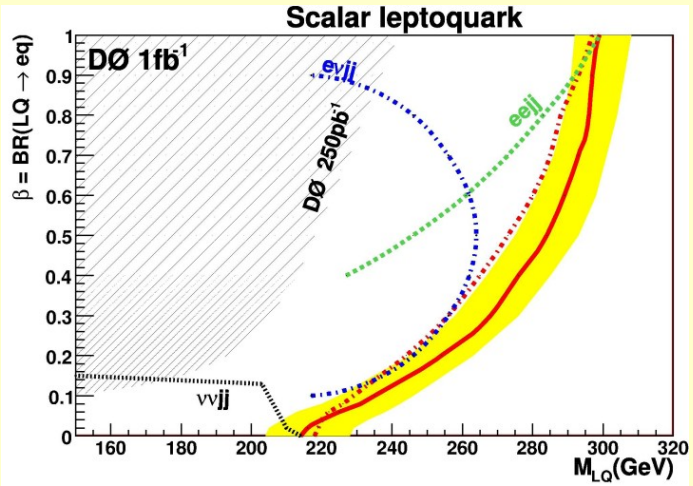


- Assume no intergenerational mixing
  - search for the first generation
- LQ pair decays to 1 of 3 final states: eqeq, eqνq, and νqνq.
  - Define branching ratio β = Br(LQ → e + q), then probability of LQ pair decaying to eqνq is 2β(1 - β)
- Cross section times branching ratio is maximized for β = 0.5

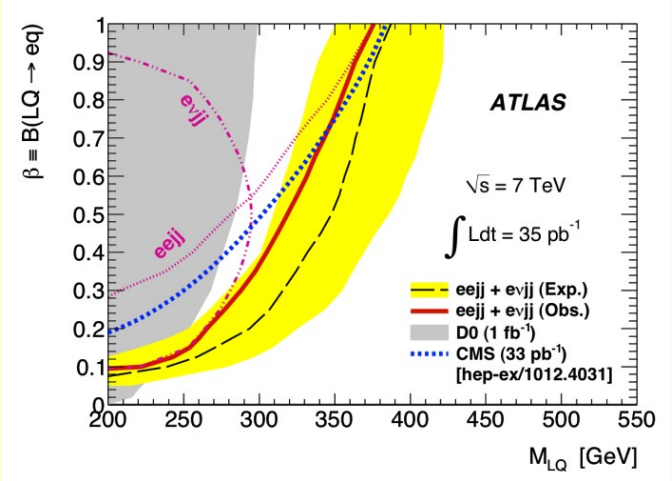
Previous results

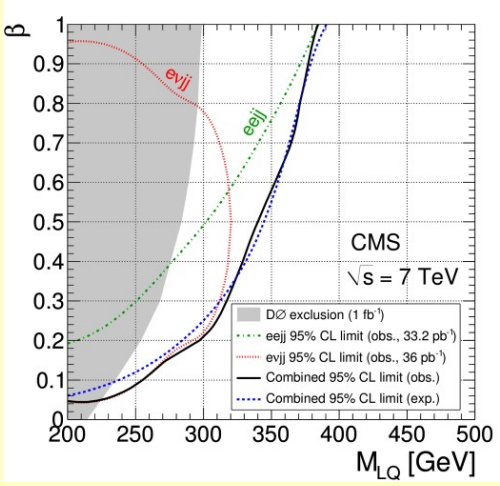
- Previous published DØ result puts lower limit on a scalar LQ mass at 264 GeV in ejνj channel, and 284 GeV when combined with ejej and νjνj (β = 0.5)





- ATLAS and CMS released their first searches this year excluding mass of 319 and 340 GeV at β = 0.5 (combined ejνj and ejej channels)





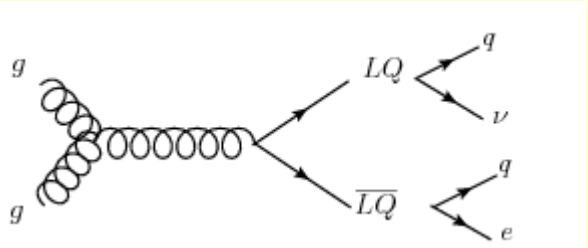
Data and backgrounds

- Data – 5.4 fb^{-1} collected with DØ between 2002 and 2009
- SM backgrounds:
  - modeled with MC:
    - W/Z+jets, tt, single top, diboson (WW, WZ and ZZ)
    - Normalized to the (N)NLO
  - Multijet (MJ) background estimated from data
- Leptoquark signal normalized to NLO

TABLE I: Scalar LQ pair production cross sections, calculated at NLO, for different m_{LQ}.

m_{LQ} (GeV)	200	210	220	230	240	250	260	270
σ (fb)	270	190	140	100	76	56	42	31
m_{LQ} (GeV)	280	290	300	310	320	340	360	
σ (fb)	23	17	13	10	7.4	4.2	2.4	

Signal reconstruction



- Channel LQLQ → eqνq;
  - explored ways to pair jets and e/ν coming from the same LQ
- Two possible combinations: [(j1,e),(j2,ν)] and [(j1,ν),(j2,e)]
  1. matching by minimizing differences in p_T from the combination of (jet,e) and (jet,ν)
  2. reconstruct LQ from both combinations, and pick the combination such that Δφ(LQ1,LQ2) is closest to π
  3. matching by minimizing Δφ between the decay products of LQs
  4. matching by minimizing the differences in m_T reconstructed from (jet,e) and (jet,ν), since the LQs are produced with the same mass

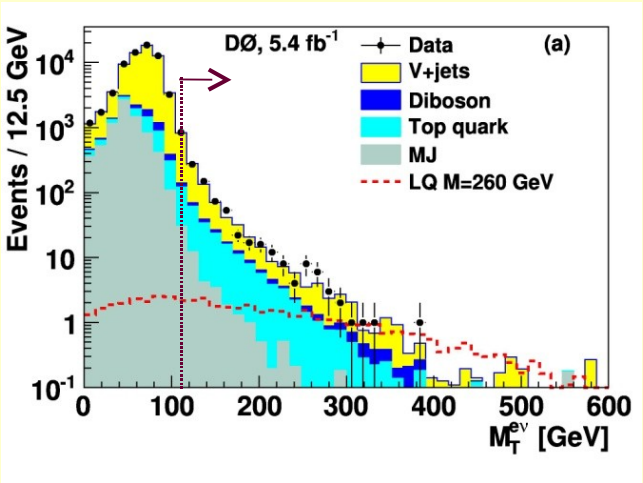
Success rate:

m_{LQ} (GeV)	200	240	280
p_T	0.46	0.47	0.47
$\Delta\varphi(LQ_1,LQ_2)$	0.61	0.59	0.58
Δφ(dec. products)	0.48	0.47	0.45
$m_{T1}=m_{T2}$	0.77	0.75	0.74

Selection

- Few very simple cuts to achieve higher sensitivity
- Preselection: 1 electron with p_T > 15 GeV, MET > 15 GeV, at least 2 jets with p_T > 20 GeV,
  MJ cleaning cut: MET/50 + m_T(e, MET)/70 >= 1

	Data	Total BG	LQ (m=260 GeV)
Preselection	65992	65703.4 ± 5957.5	50.4 ± 6.8
m_T (e,MET) > 110 GeV	990	986.3 ± 81.6	33.5 ± 4.6
$\Sigma(m_{LQ})$ > 350 GeV	64	54.5 ± 4.1	27.3 ± 3.7
Σp_T(rec. objects) > 450 GeV	15	14.8 ± 1.1	24.4 ± 3.3



Selection

- Few very simple cuts to achieve higher sensitivity
- $\Sigma(m_{LQ}) = m_{ej}+m^{vis}_{\nu j}$, $m^{vis}_{\nu j}$ is mass of jet and visible part of neutrino, i.e. $\nu^{vis} = (MET_x, MET_y, 0, MET)$

	Data	Total BG	LQ (m=260 GeV)
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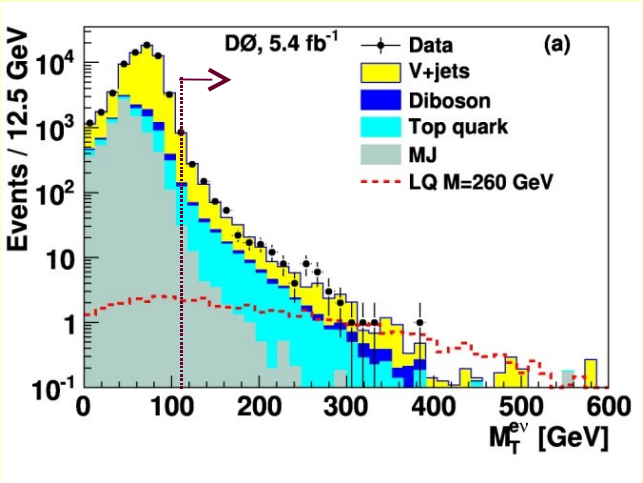

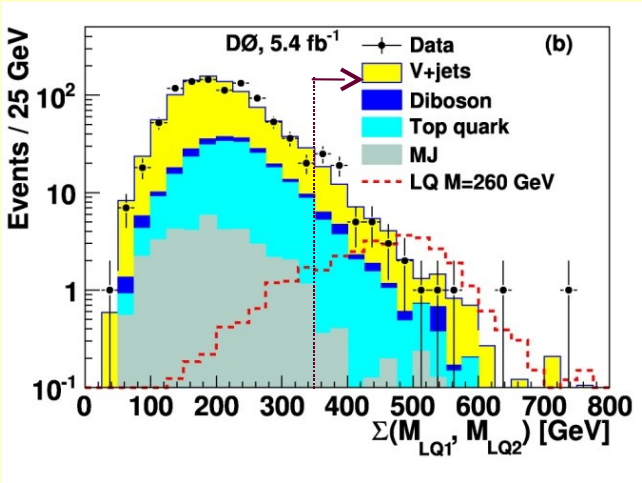

Selection

- Few very simple cuts to achieve higher sensitivity
- $S_T = \Sigma p_T(\text{rec. objects}) = p_T(e)+MET+p_T(jet_1)+p_T(jet_2)$

	Data	Total BG	LQ (m=260 GeV)
Preselection	65992	65703.4 ± 5957.5	50.4 ± 6.8
m_T (e,MET) > 110 GeV	990	986.3 ± 81.6	33.5 ± 4.6
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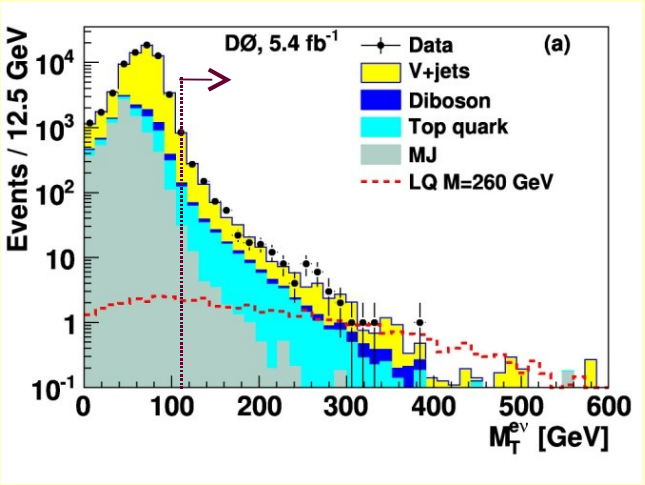
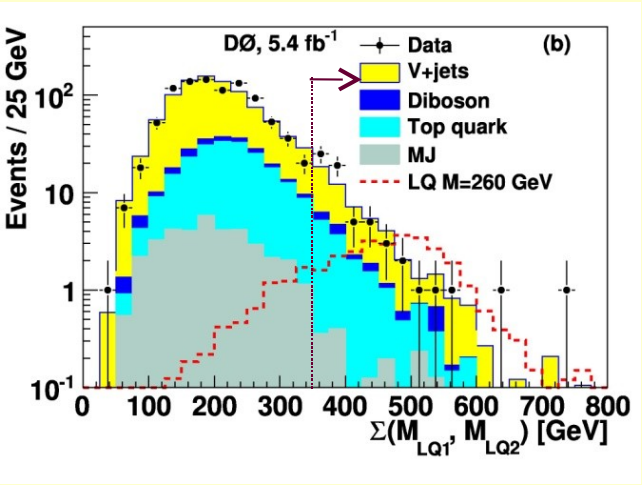
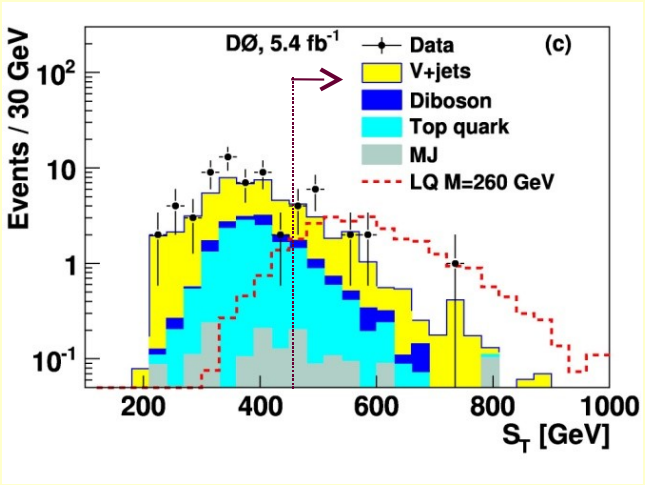


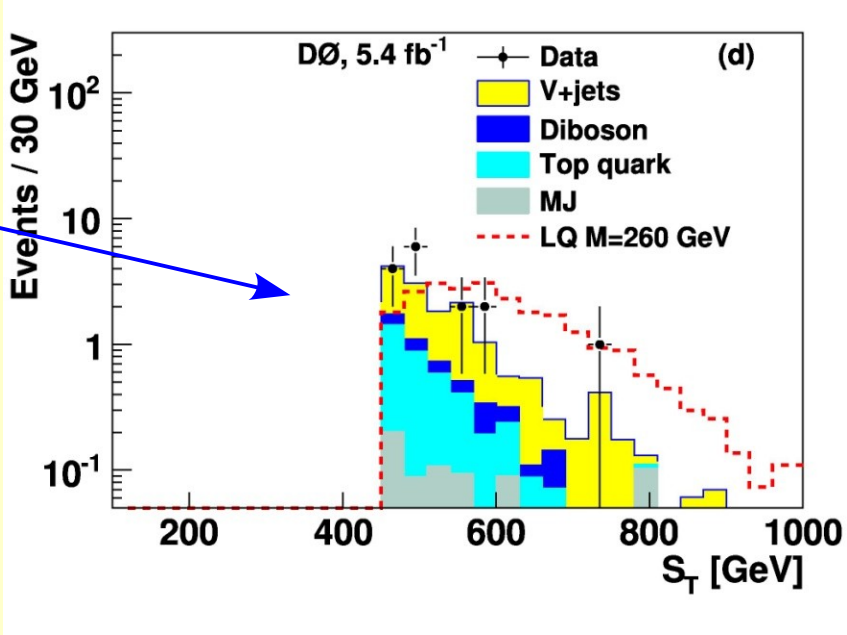


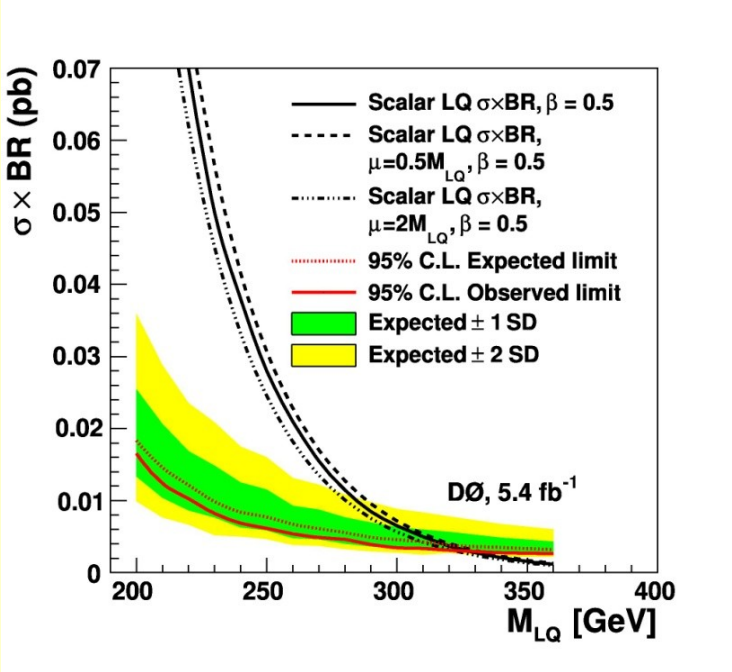


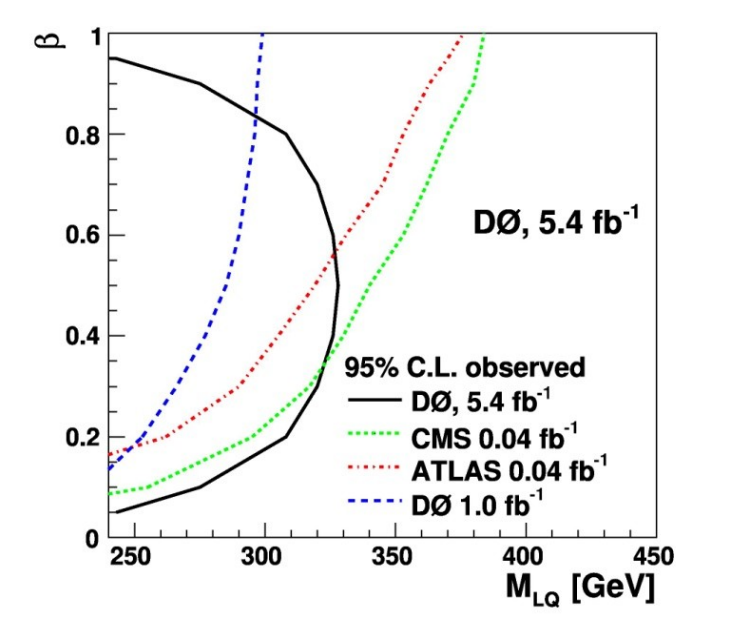
Result

arXiv:1107.1849 [hep-ex]

- S_T after final cut used to search for signal
- No excess in data ⇒ limits set
  - For β=0.5 LQ with mass below 326 GeV is excluded
  - Below β=0.3 we set the best limits







Vector-like quarks

Motivation

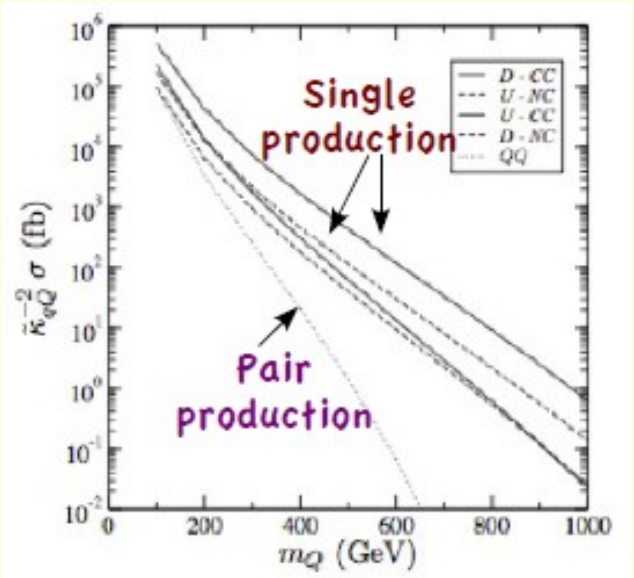
- Many new theories predict vector-like quarks:
  - Little Higgs
  - Warped extra dimensions
  - Universal extra dimensions => lowest KK excitation of SM fermions comprises a vector-like 4th generation
- Vector-like quarks are:
  - Fermions despite the name
  - Their left- and right-handed components transform in the same way under $SU(3)xSU(2)_L xU(1)$

Introduction

- Vector-like quarks can be produced via strong or electroweak interaction

Pair production

Single production



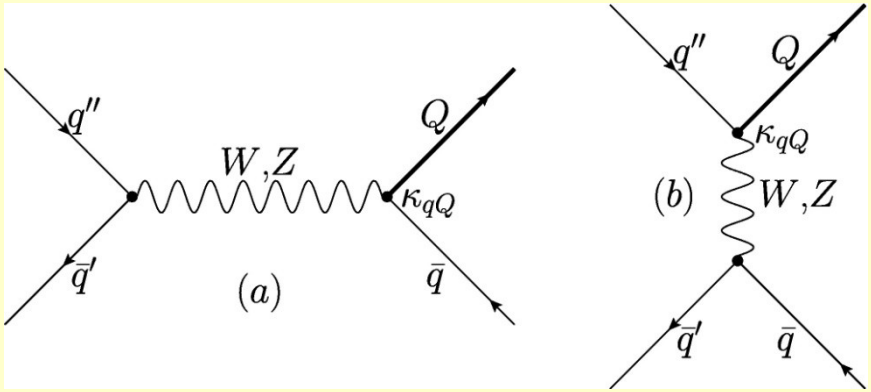
- In some scenarios (e.g. warped extra dimensions), corrections to SM quark couplings due to mixing with vector-like quarks can cancel.
- No constraints from precision EW measurements
- Single weak production is possible at the Tevatron

$$\kappa_{qQ} = \frac{v}{m_Q}\tilde{\kappa}_{qQ}$$

VEV

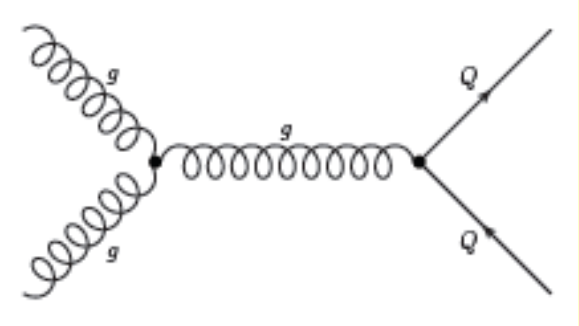
Coupling strength

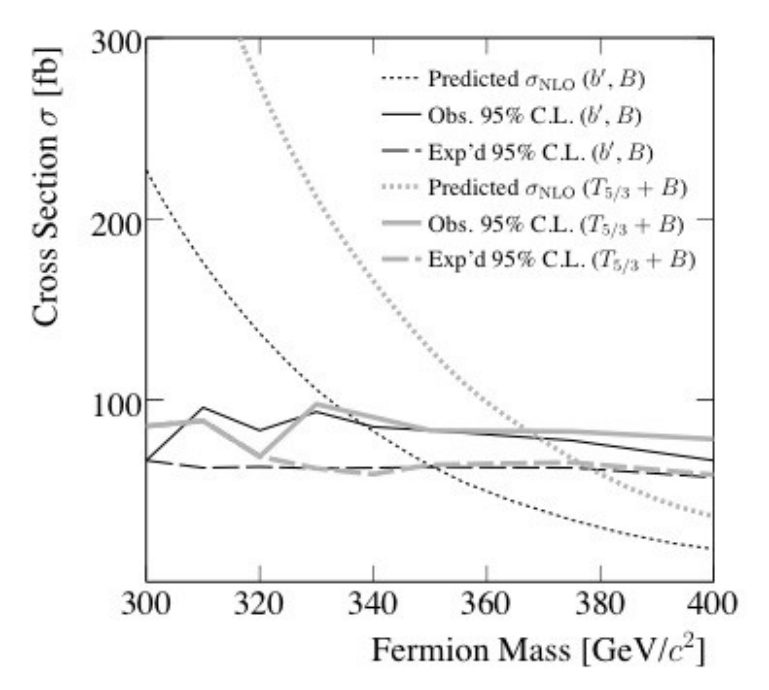
Heavy quark mass



Previous result

- Search for pair-produced heavy quarks: heavily constrained by the kinematic reach of the Tevatron
- CDF: m_Q > 338 GeV at 95% C.L. (PRL 104, 091801 (2010))

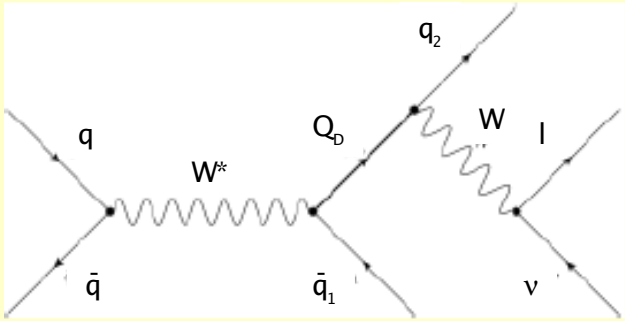


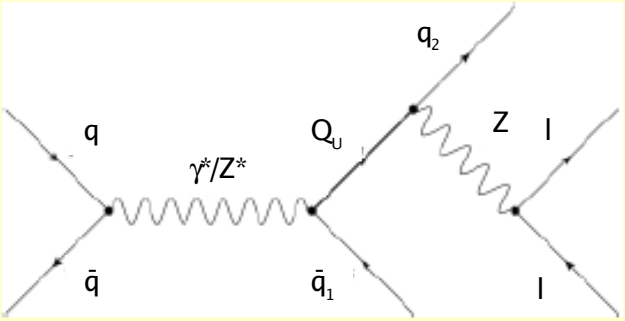


Vector-like quark signatures

- Vector-like quark can decay to W+q and to Z+q
- We assume $\tilde{\kappa}_{uD} = 1, \tilde{\kappa}_{uU} = \sqrt{2}, \tilde{\kappa}_{dU} = \tilde{\kappa}_{dD} = 0,$

  i.e. BR($Q_D \rightarrow Wq$) = BR($Q_U \rightarrow Zq$) = 100%





- One isolated lepton, p_T>15 GeV, missing E_T>15 GeV, and at least two jets, p_T > 20 GeV
- Main background W+jets

- Two isolated leptons, p_T>15 GeV from a Z boson, 70<M_{ll}<110 GeV, and at least two jets p_T>20 GeV; no MET, i.e. < 50 GeV
- Main background Z+jets

- Other backgrounds tt, single top, diboson (WW, WZ, ZZ) and instrumental multijet background
- Data – 5.4 fb^{-1} collected with DØ between 2002 and 2009

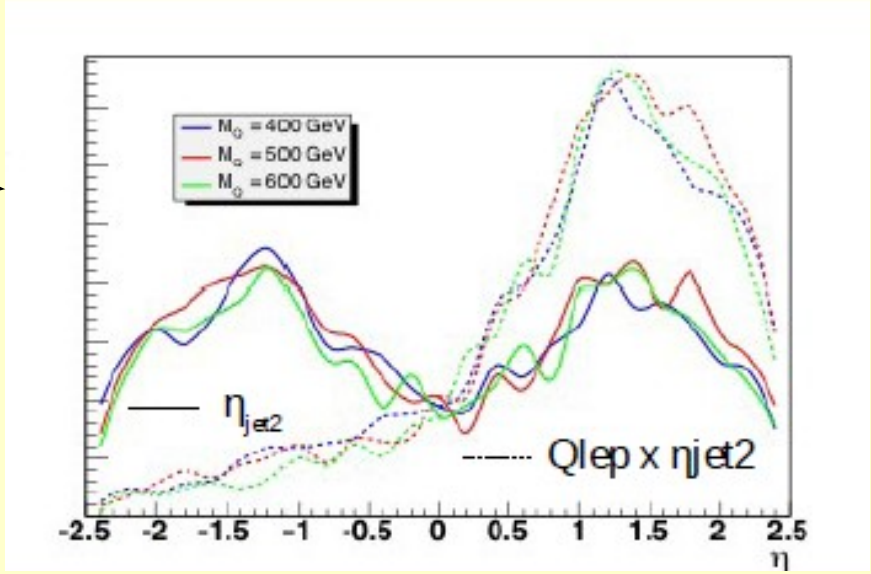
Final selection

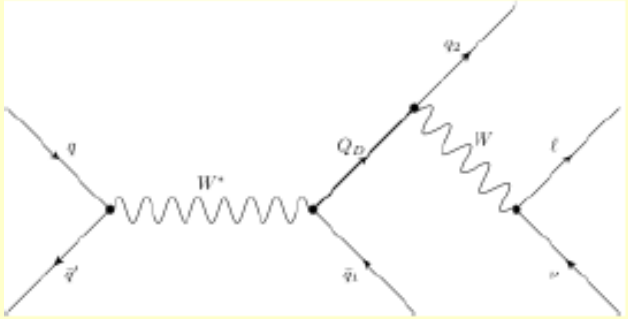
- Single lepton channel:
  - Lepton $p_T > 50$ GeV
  - Leading jet $p_T > 100$ GeV
  - $\Delta\phi$(lep,MET) < 2.0
  - $M_{TR} < 150$ GeV
  - MET > 40(50) GeV
  - $Q_{lep} \times \eta_{jet2} > 0$

- Dilepton channel:
  - Z->ll p_T>100 GeV
  - Leading jet p_T>100 GeV
  - $\Delta R(l,l)<2.0$

- 2nd jet in Qq->Wqq signal comes from SM quark produced in association with vector quark => forward, relatively soft

- Direction of 2nd jet is correlated with production of VQ/anti-VQ, and therefore correlated with the sign of the lepton in W decay mode

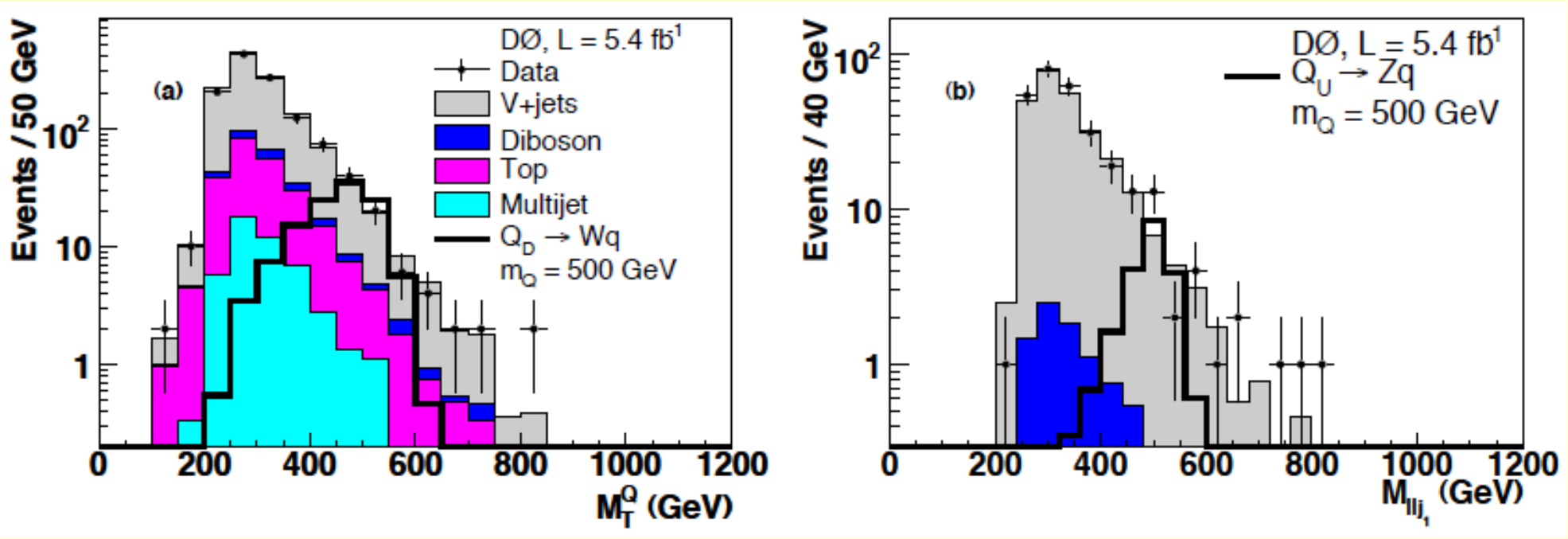




Result

- W+q
- m_T(l+ν+lead jet) used to search for a signal

- Z+q
- $m(l_1+l_2+\text{lead jet})$ used to search for a signal

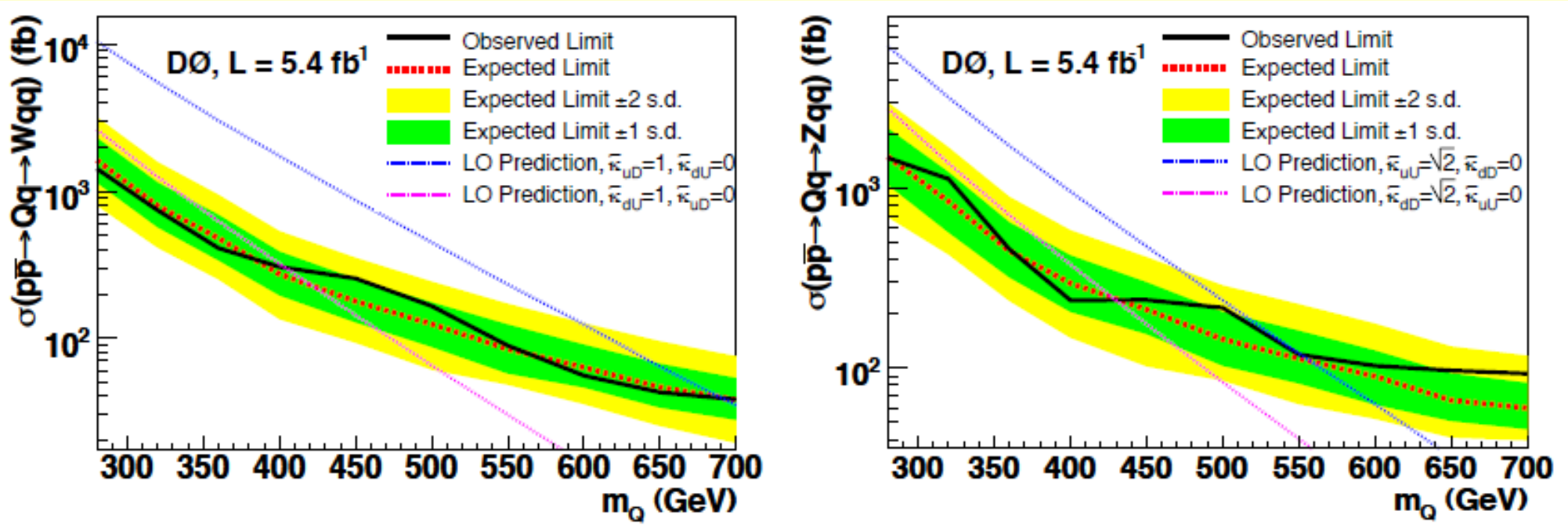


- No significant excess
- Limits are set on production cross sections

Limit

Phys.Rev.Lett.106:081801,2011

- W+q
- Z+q



- For $\tilde{\kappa}_{uD}=1, \tilde{\kappa}_{uU}=\sqrt{2}, \tilde{\kappa}_{dQ}=0$
  - m_Q > 693 GeV for Q → Wq, m_Q > 551 GeV for Q → Zq
- For $\tilde{\kappa}_{dU}=1, \tilde{\kappa}_{dD}=\sqrt{2}, \tilde{\kappa}_{uQ}=0$
  - m_Q > 403 GeV for Q → Wq, m_Q > 430 GeV for Q → Zq

Quirks

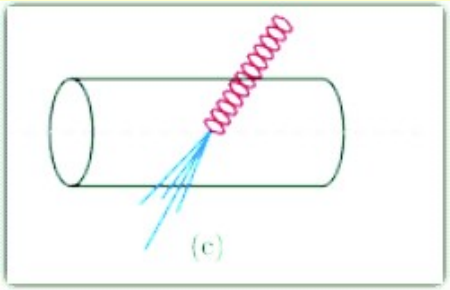
Motivation

- Possible minimal extension of the standard model includes an addition of a new unbroken SU(N) gauge group new fermions, quirks, in the fundamental representation
  - Two parameters:
    - the new fermion mass m_Q
    - strength of new SU(N) gauge coupling, infracolor, is defined through scale Λ where it becomes strong
- If quirks carry SM charges, they can be pair-produced at colliders
- Phenomenology in a case of $\Lambda \ll m_Q \simeq$ 0.1-1 TeV recently studied
- $\Gamma_{break} \sim \exp(-m_Q^2/\Lambda^2) \Rightarrow$ Infracolor strings are stable

Motivation

- Quirk-antiquirk pair stays connected by the infracolor string like a rubber band that can stretch to macroscopic length

$$L \simeq \frac{m_Q}{\Lambda} \simeq 1\,\mu m \left(\frac{m_Q}{100} GeV\right)\left(\frac{\Lambda}{100} keV\right)^{-2}$$



- We consider a case where quirks have electric charge, no strong color charge, 10 keV < Λ < 1 MeV, and 60 GeV < m_Q < 1 TeV.

  ⇒ Decay length of many centimeters

  ⇒ String size that is too small to be resolved in a detector, but large compared to atomic scales

  - for m_Q = 100 GeV the corresponding string size is less than 100 μm, which is comparable to the resolution of the DØ tracking system.

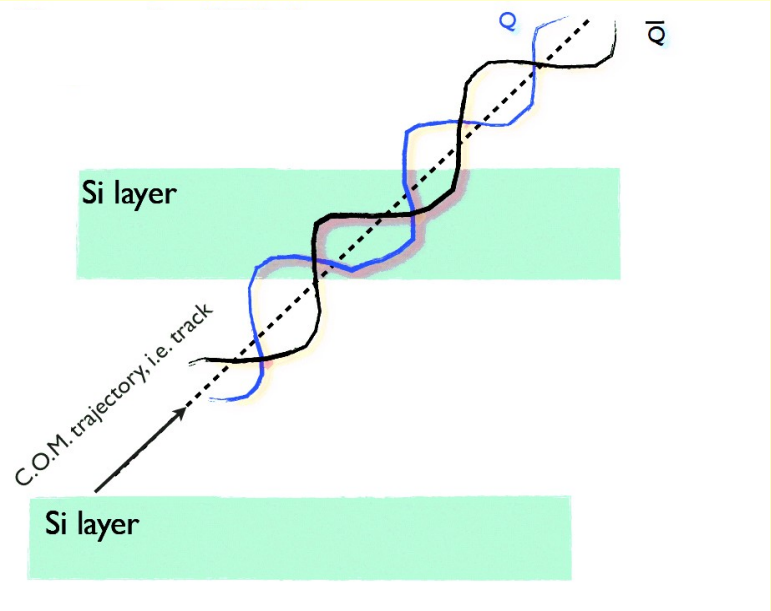
Signature

- Experimental signature:
  - Quirk-antiquirk pair will be reconstructed in the detector as a single highly ionizing track
  - The net charge of the string is zero ⇒ the track will be straight ⇒ a pair of quirks will look like a single massive slow moving particle
    - (1) High transverse momentum track with a large ionization-energy loss rate dE/dx
  - High ET jets from initial state radiation
    - (2) Jet to trigger events
  - (3) Missing transverse energy (MET) aligned with the track

Event selection

- High transverse momentum track with a large ionization-energy loss rate dE/dx:
  - $p_T > 40$ GeV
  - $|\eta_{SMT}| < 1.6$
  - N of SMT hits ≥ 4; N of CFT hits ≥ 12
  - Isolation: No additional tracks with summed $p_T > 2.5$ GeV in a cone $\Delta R<0.5$ around track
- Jet to trigger events
  - $p_T^{lead} > 75$ GeV, $|\eta| < 1.6$
  - No additional jet with $p_T > 25$ GeV
- Missing transverse energy (MET) aligned with the track
  - MET > 50 GeV (muons p_T not included)

Signal reconstruction



- In addition to position, the SMT detector provides a measurement of ionization energy with a dynamic range up to ~1.4 MeV per strip
- the quirk-antiquirk pair follow a trajectory which is a classical superposition of the motion of the center of mass (c.o.m.) of the quirk-antiquirk system and the motion of the quirk (or the antiquirk) in the c.o.m. frame
  - to compute dE/dx of a di-quirk system we integrate energy deposited by each quirk along its trajectory and normalize sum of both contributions by the displacement of c.o.m.
  - to simulate effect of detector resolution and noise we smear this dE/dx with width of dE/dx for muons in data.
  - optimal dE/dx cut depends on mQ

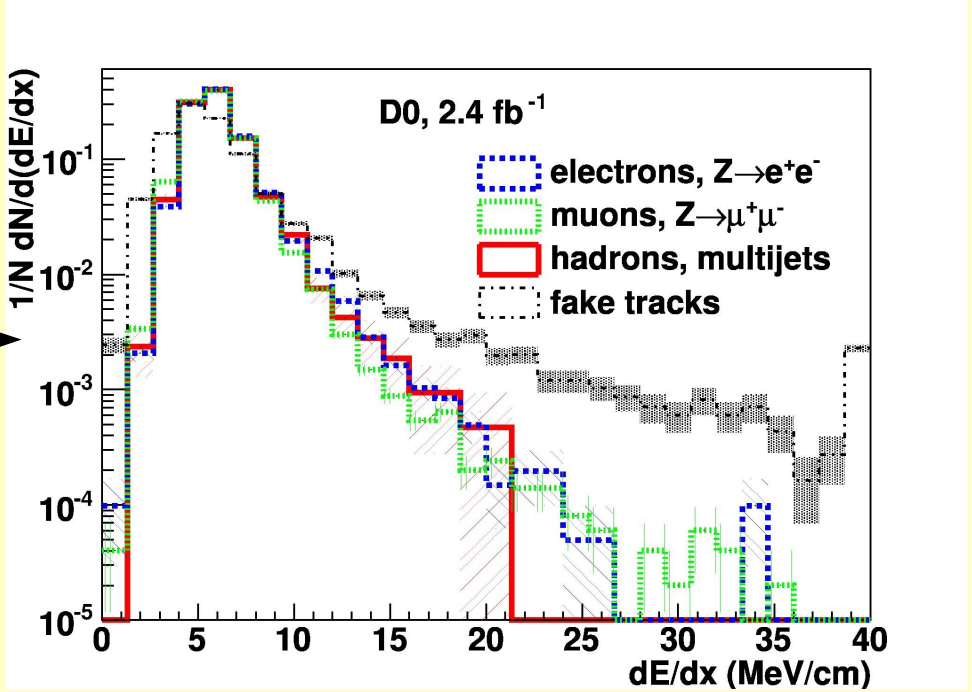
Data and background

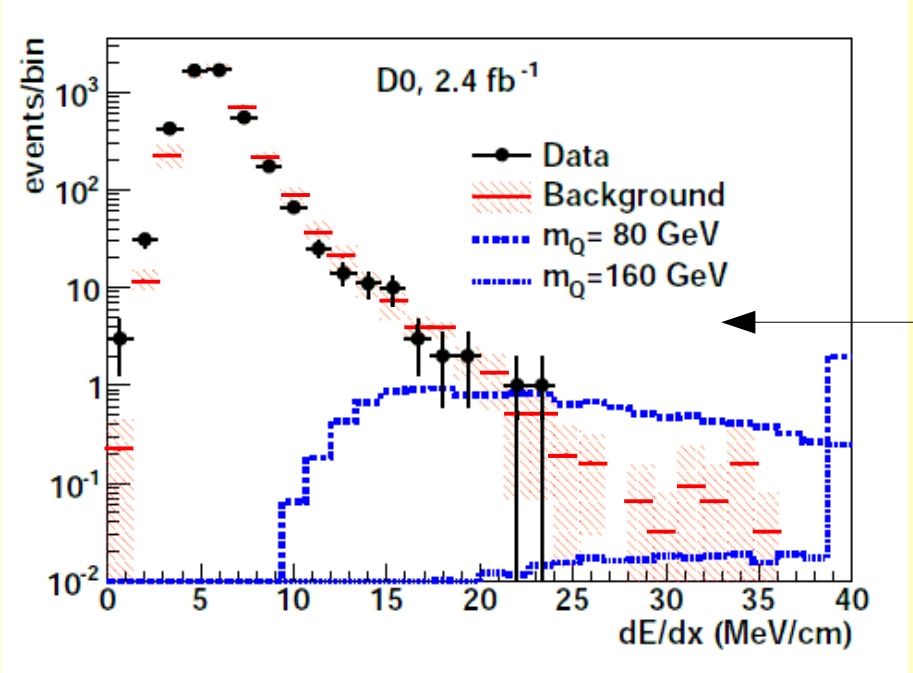
- Data is 2.4 fb^{-1} collected with DØ

- Backgrounds determined from data:
  - Electrons and Muons: W+jet
    - From $Z \rightarrow ee$($Z \rightarrow \mu\mu$) events: at least one lepton to have a track that passes selection criterion and an invariant mass of two leptons to be consistent with Z boson
  - Hadrons
    - Tracks with p_T>40 GeV found inside jets
    - From the same primary vertex $|Z_{jet} - Z_{track}| < 1$ cm
  - Fake Tracks
    - Tracks found in the vicinity of a jet (ΔR <0.5)
    - Same track selection criteria except $N_{CFT} \leq 1$

Selection

- Electron/muon: track from lepton, obtained from Z→ee(μμ)
- hadrons: tracks found in the vicinity of jets
- fake tracks: no hits in CFT, crossing angles are wrong, thus wider dE/dx

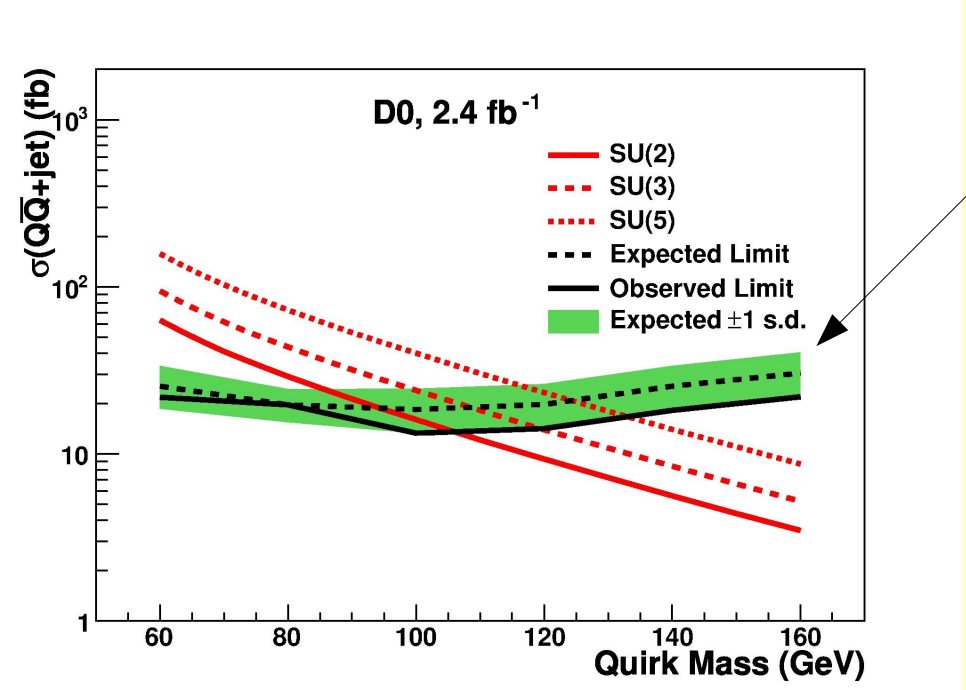




- No excess of highly ionizing tracks above SM expectations
  - Proceed to set limits

Results

- The dE/dx cut is optimized to achieve the lowest 95% C.L. expected limit for each quirk mass.



- No excess of highly ionizing tracks
- Exclude charged quirks of mass up to 107 GeV, 119 GeV, and 133 GeV at the 95% C.L. with strong dynamics scale Λ in the range from 10 keV to 1 MeV for SU(2), SU(3), and SU(5) gauge sectors

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Summary

- Tevatron is running well and reliably and we are thankful to accelerator people that made it all happen – delivered more than 11 fb^{-1}.
- DØ has been searching for new physics signals over many years and produced dozens of papers
- LHC has started and surpassed many of our results
  - It used Tevatron experiences in the best possible way
- We present results on the search for the first generation scalar LQ pair production in $e\nu jj$ final state
  - We exclude scalar LQ with mass below 326 GeV for β=0.5
- We also searched for the heavy vector-like quark
  - We set the most stringent limits to date on the production of the heavy vector-like quark
- Quirks:
  - The first limits on quirk-antiquirk production

Results: http://www-d0.fnal.gov/d0_publications/d0_pubs_list_runII_bytopic.html#np

Backup

LQ systematics

- Flat:
  - Production cross sections: on W/Z+jets (6%), ttbar (7%), diboson (10%) and signal (10%)
  - Multijet production (QCD): 20%
  - Luminosity: 6.1%
  - Lepton ID and trigger: Combined 4%
- Shape:
  - Jet energy scale (JES)
  - Jet energy resolution (JER)
  - Jet ID and reconstruction efficiency
  - PDF (signal only)
  - Jet pT missmodeling (W+jets only)

Systematic Uncertainties

dominant sources

Source	Single Lepton Channel	Dilepton Channel
Integrated lumi	6.1%	--
Global MC norm.	--	5%
V+jets modeling	15%	
top x-section	9%	
W/Z+jets x-section	4%	
diboson x-section	4%	
lepton ID	3%	--
Trigger	1% (electron) 4% (muon)	--
Jet energy scale	1-5%*	3%
Jet energy resolution	1-5%*	2%
Jet ID efficiency	1-5%*	3%
Jet vertex confirmation	1-5%*	--
high-p_T muon modeling	3-5%*	--
QCD modeling	6.5% (electron) 30% (muon)	100%

*: shape-dependent systematic uncertainty

13

23/02/11