Search for 3rd Generation Vector Leptoquarks in Run II at CDF

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For the CDF Collaboration

DPF + JPS
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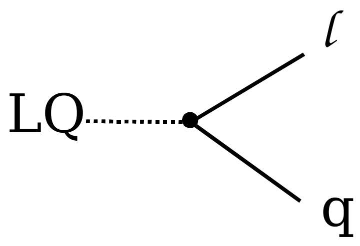
Motivation

- Symmetry between quark and lepton sectors suggests a possible link at higher energy scales (e.g. > m_{top})

- Theoretical particle which couples to *quarks* and *leptons*



- Carries baryon and lepton quantum numbers
- Fractional charge
- Color-triplet boson

- Two possible spin structures:

  Spin 0 (scalar): couplings are fixed and decays are isotropic

  * Spin 1 (vector): anomalous magnetic and electric quadrupole moments *

- Appears in several beyond-the-Standard-Model theories:

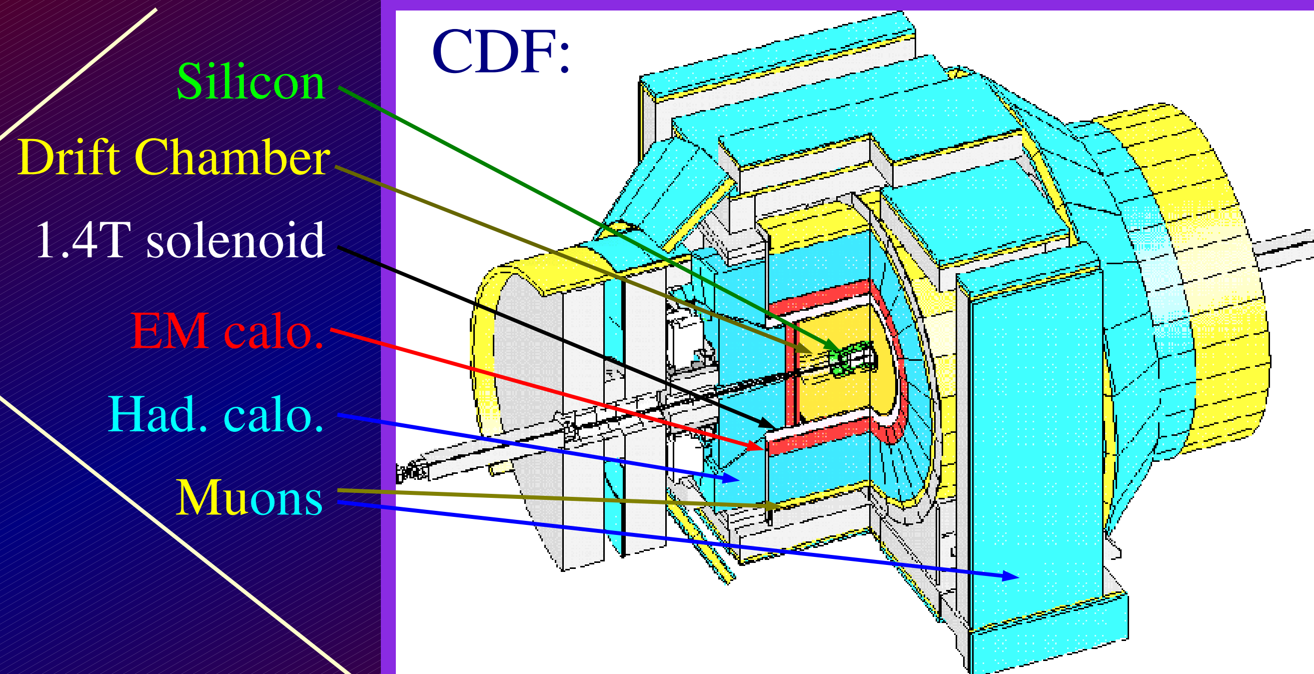
  SU(5) GUT, Superstrings, SU(4) Pati-Salam, Composite, Technicolor

Production at the Tevatron

Fermilab Tevatron:

$\sqrt{s} = 1.96$ TeV

CDF:



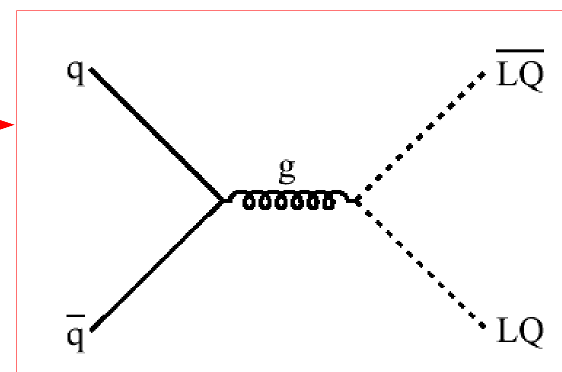
- Pair production:
  - quark/anti-quark annihilation

    $q\bar{q} \rightarrow LQ\,\overline{LQ}$

    dominant

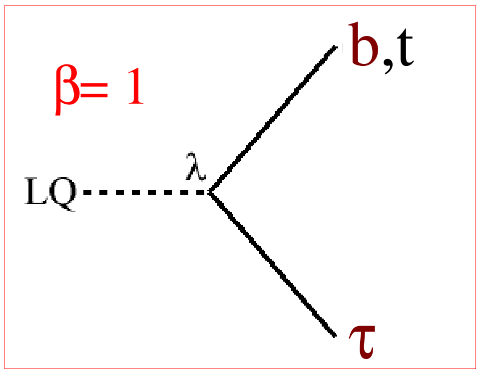
  - gluon fusion

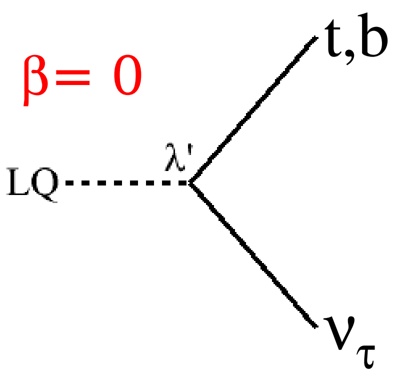
    $gg \rightarrow LQ\,\overline{LQ}$



Decay

- 3^{rd} generation decays:
  - lack of FCNC suggests decay remains within generation
  - Define: $\beta = Br(LQ \rightarrow \ell q)$



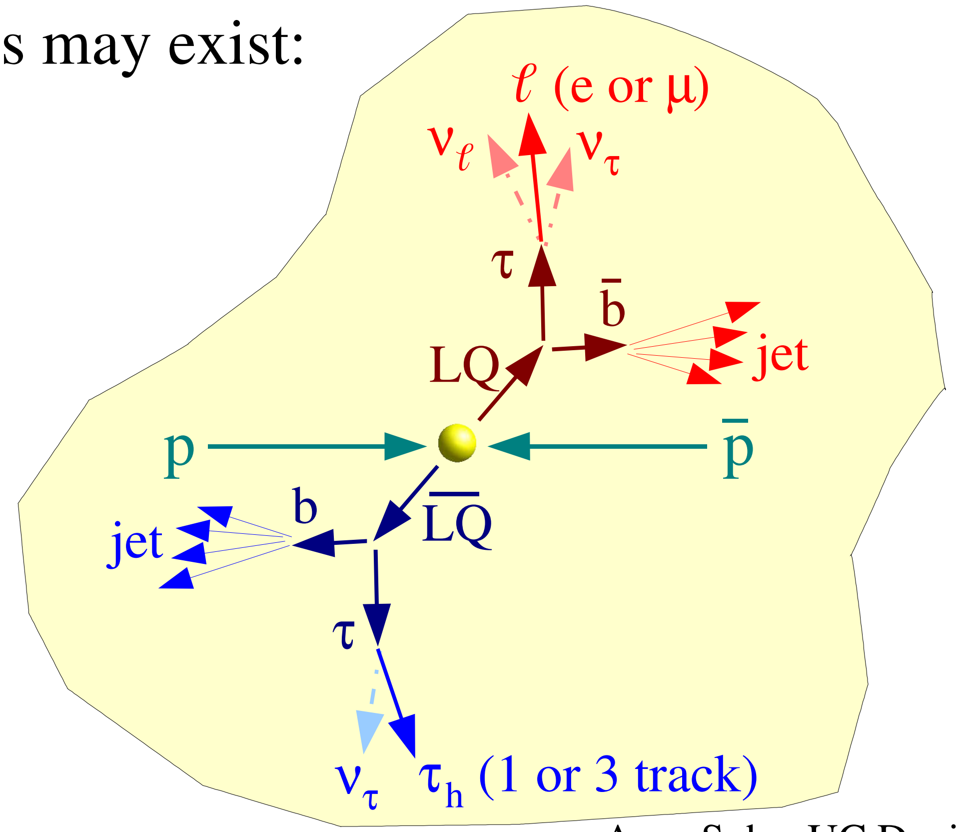


- Various species of vector (spin=1) LQs may exist:

E.g., subset with β= 1

LQ3 →	$\tau\, t$	$\tau\, \bar{t}$	$\tau\, b$	$\tau\, \bar{b}$
charge=	-1/3	-5/3	-4/3	-2/3

- Considering $\tau_{e,\mu}\tau_h\, bb$
  - Signature: $e,\mu + \tau_h + 2$ jets
  - Use a Lepton+Track trigger:
    - $\tau_{e,\mu}$ is triggered as lepton
    - τ_h is triggered as track



Existing Limits

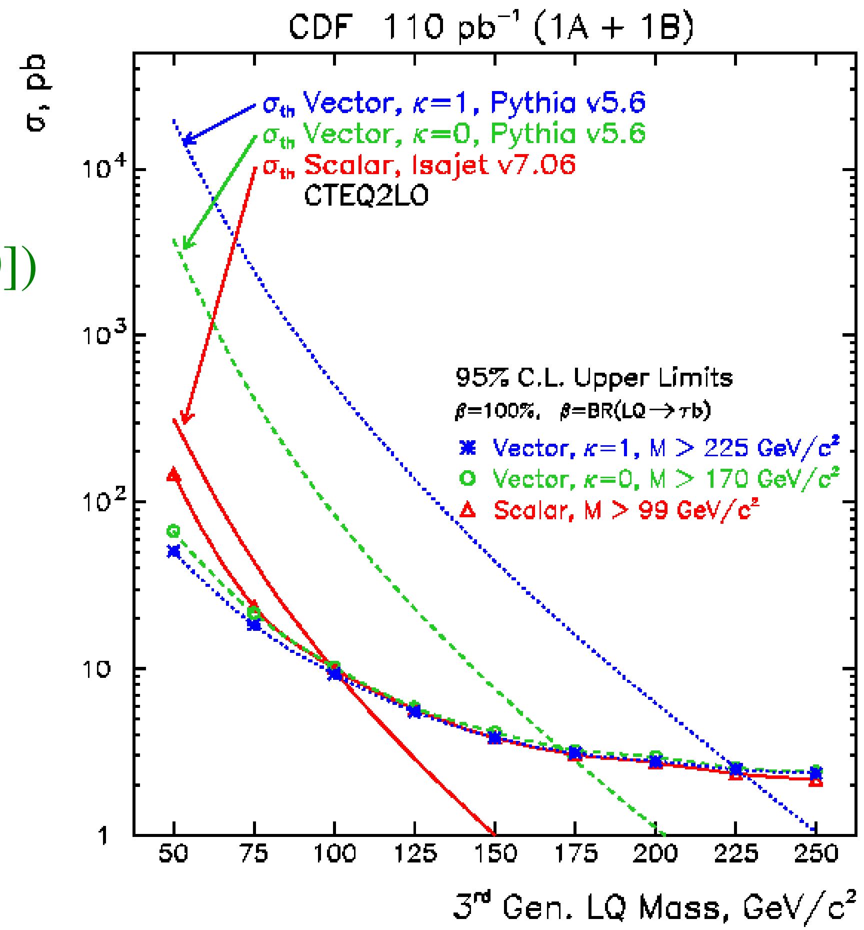
- CDF Run I limits (110 pb^{-1}) →
  - Assume Br(LQ3 → τb) = 100%

    $m_{VLQ3} > 225$ GeV/c^2 (Yang-Mills [κ=1])

    $m_{VLQ3} > 170$ GeV/c^2 (Minimal Coupling [κ=0])

    $m_{SLQ3} > 99$ GeV/c^2

    [F. Abe *et al*., Phys Rev Lett **78,** 2906 (1997)]



- D0 Run I limits
  - Assume Br(LQ3 → ν_τb) = 100%

    $m_{VLQ3} > 216$ GeV/c^2 (Yang-Mills)

    $m_{VLQ3} > 148$ GeV/c^2 (Minimal Coupling)

    [B. Abbott *et al*., Phys Rev Lett **81**, 38 (1998)]

- Related CDF Run II limit (322 pb^{-1})
  - From an R-parity violating stop search

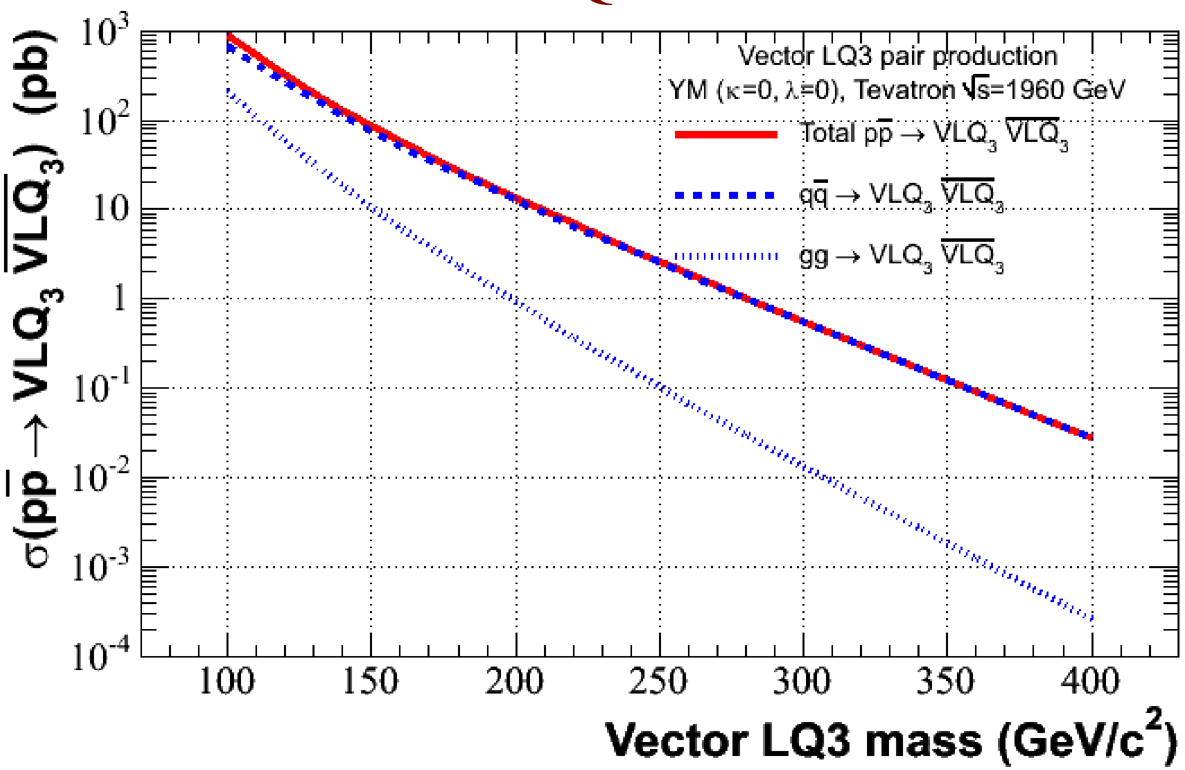
    $m_{SLQ3} > 155$ GeV/c^2

Data & VLQ3 Simulation

- Data
  - 322 pb^{-1}, at $\sqrt{s}$ = 1.96 TeV
  - Lepton+Track trigger

- Signal MC
  - VLQ3 added to GRACE (amplitude calculations)
    + GR@PPA (computations of primary hadron interactions)
    + PYTHIA (decay, fragmentation, and showering)
    + GEANT (full CDF simulation)

New VLQ3 Simulation



- Calculates helicity amplitudes for LQ pair production and carries through to taus

- Flexible: Can model other LQ generations, and decays to other final states

Backgrounds

Source	Comments

- Physics backgrounds (yielding lepton, τ_h, + 2 jets)

- $t\bar{t}$	$t\bar{t} \to WbWb \to \ell\nu b\ \tau_h\nu b$
- $Z^0/\gamma^* \to \tau\tau$	+ jets in the event

- Faking backgrounds (≥1 object is misidentified)

- $t\bar{t}$	$t\bar{t} \to WbWb \to \ell\nu b\ qqb$, and jet fakes a τ_h
- $Z^0/\gamma^* \to e\, e$ or $\mu\,\mu$	+ jets in the event, ... e, μ, or 3rd jet fakes a τ_h
- W+jets	$W \to \ell\nu$ and 3rd jet fakes a τ_h
- WW, WZ, ZZ	negligible

Evaluated using MC simulation

- multi-jet QCD	jets fake e/μ+ τ_h --- evaluated by extrapolating from non-isolated lepton region to isolated region
- γ+jets	photon conversions

Evaluated using data

Event Selection

Lepton

e (E_T>10 GeV)
or μ (p_T>10 GeV/c)
separated from jet

Hadronic Tau

τ_h (E_T>15 GeV)
separated from jet

Event Selection

Opposite sign charge ($Q(e/\mu)*Q(\tau_h) = -1$)

Conversion removal and cosmic removal

Drell Yan removal using mass window cut (veto if $76 < M < 106$ GeV/c^2)

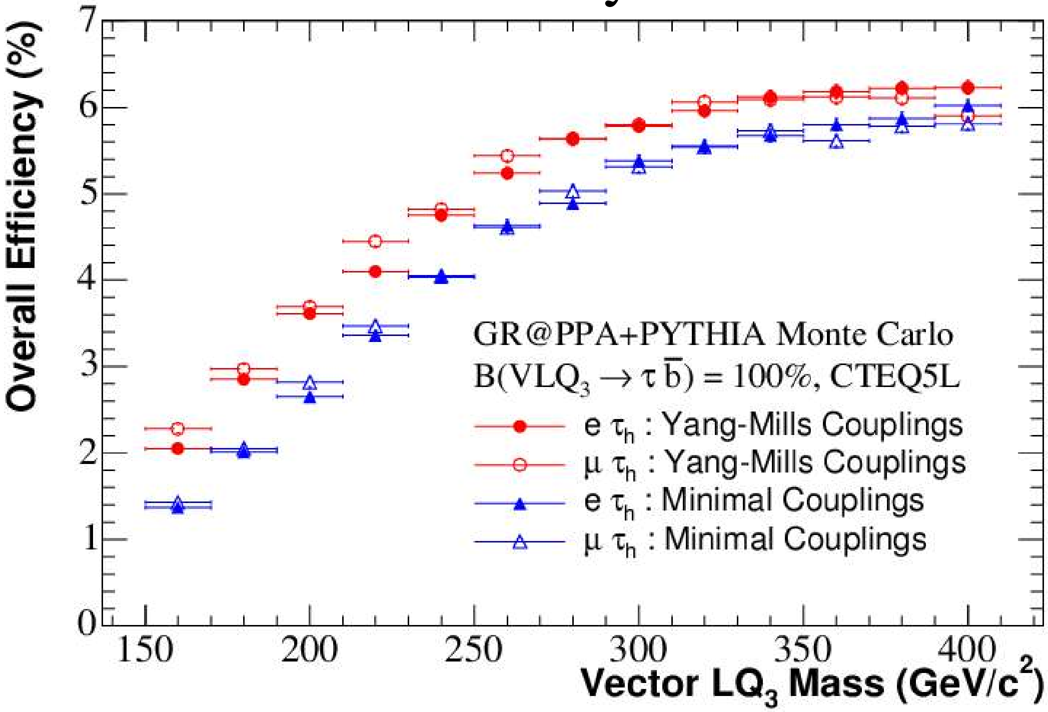
$\not{E}_T > 10$ GeV

$H_T = E_T(\text{lepton}) + E_T(\tau_h) + \not{E}_T + \sum E_T(\text{jets}) > 400$ GeV
(optimized for $m_{VLQ3} = 300$ GeV/c^2 ... but still sensitive to 200 GeV/c^2)

$N_{jets} \geq 2$ (jet $E_T > 15$ GeV)

Efficiencies

- Full selection efficiency as a function of mass



Includes:

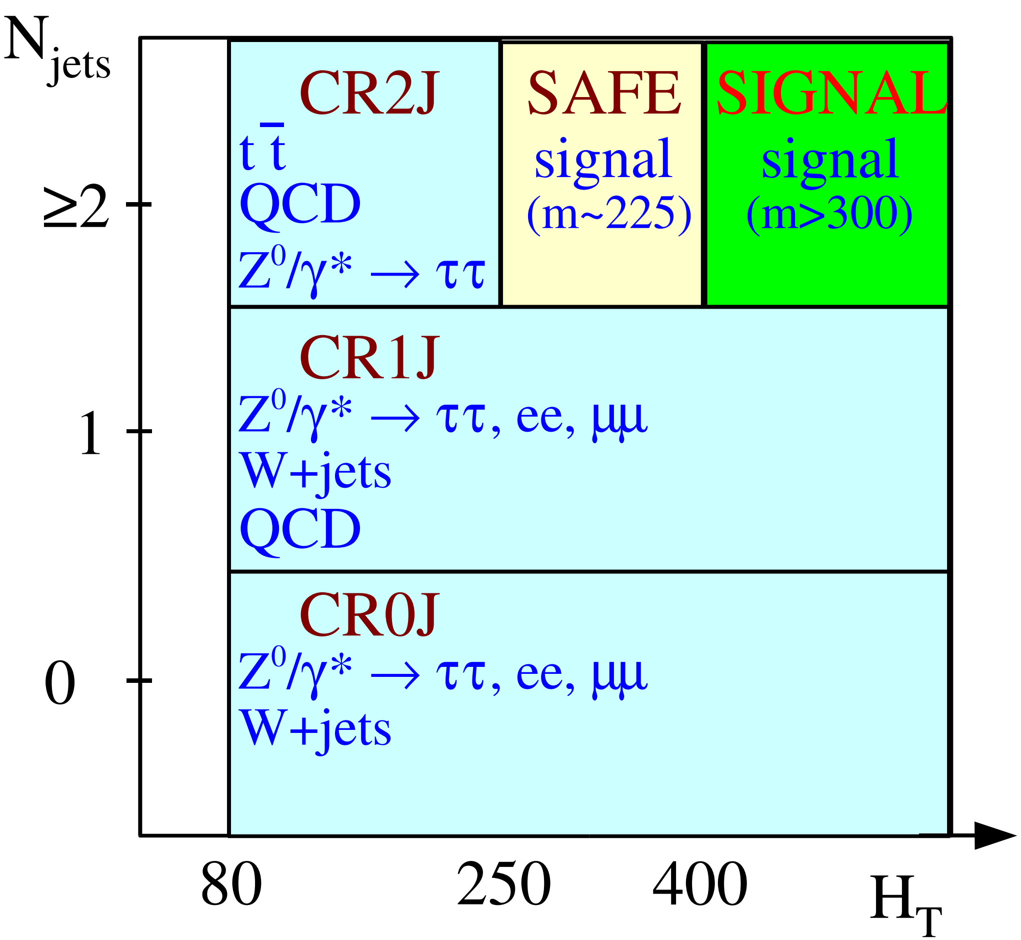
- "Particle Selection"
  - triggers
  - acceptance
  - particle ID
  - particle isolation and separations
- Event level requirements

- Efficiencies

Requirement	$e\tau_h$ Efficiency (%)	$\mu\tau_h(\lvert\eta_\mu\rvert < 0.6)$ Efficiency (%)	$\mu\tau_h(0.6 < \lvert\eta_\mu\rvert < 1.0)$ Efficiency (%)
Particle Selection	7.52 ± 0.08	5.17 ± 0.07	1.84 ± 0.04
Event Selection	81.73 ± 0.19	87.37 ± 0.25	85.83 ± 0.36
Total	6.14 ± 0.07	4.52 ± 0.07	1.58 ± 0.04

Signal and Control Regions

- Define 3 control regions, 1 safety region, and 1 signal region

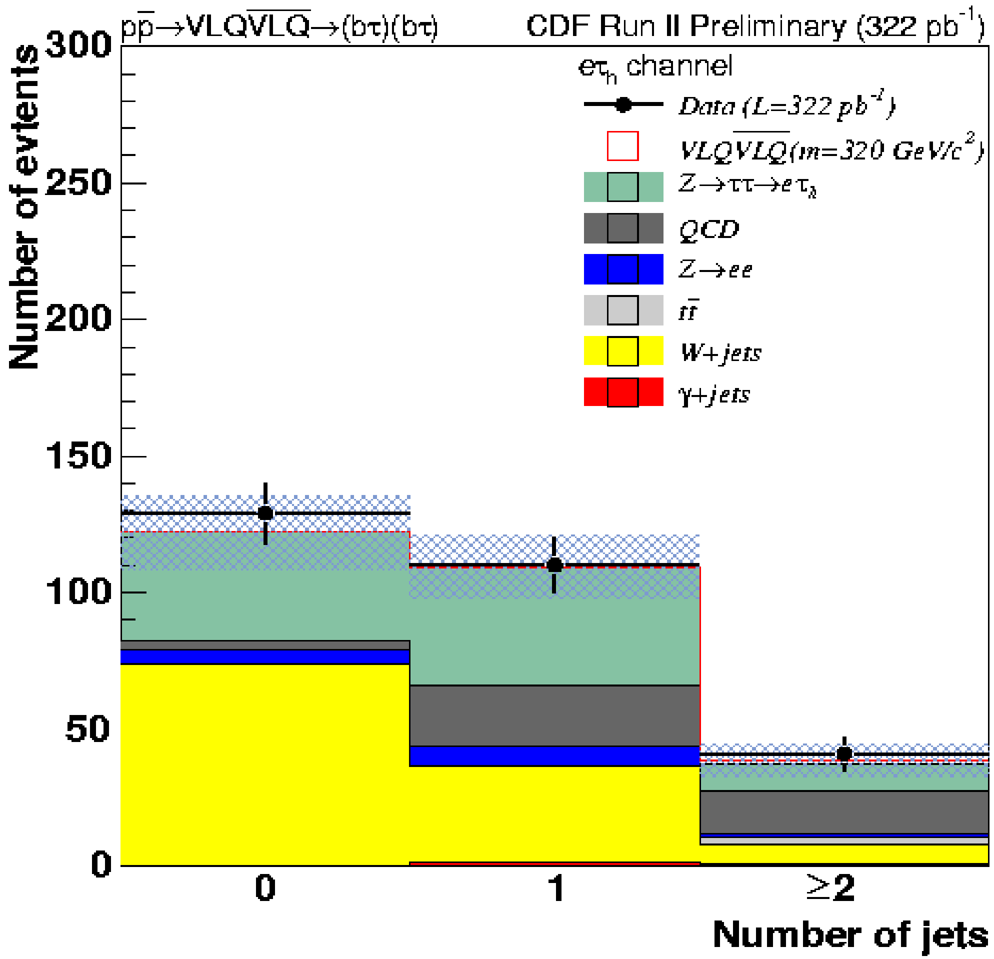


- $H_T > 250$ GeV is sensitive to existing limit ($m_{VLQ3} > 225$ GeV/c^2)
- Perform optimized search with highest mass reach by using simultaneous fit to SAFE region and SIGNAL region
- SAFE and SIGNAL regions left "closed" until selection and validation finalized

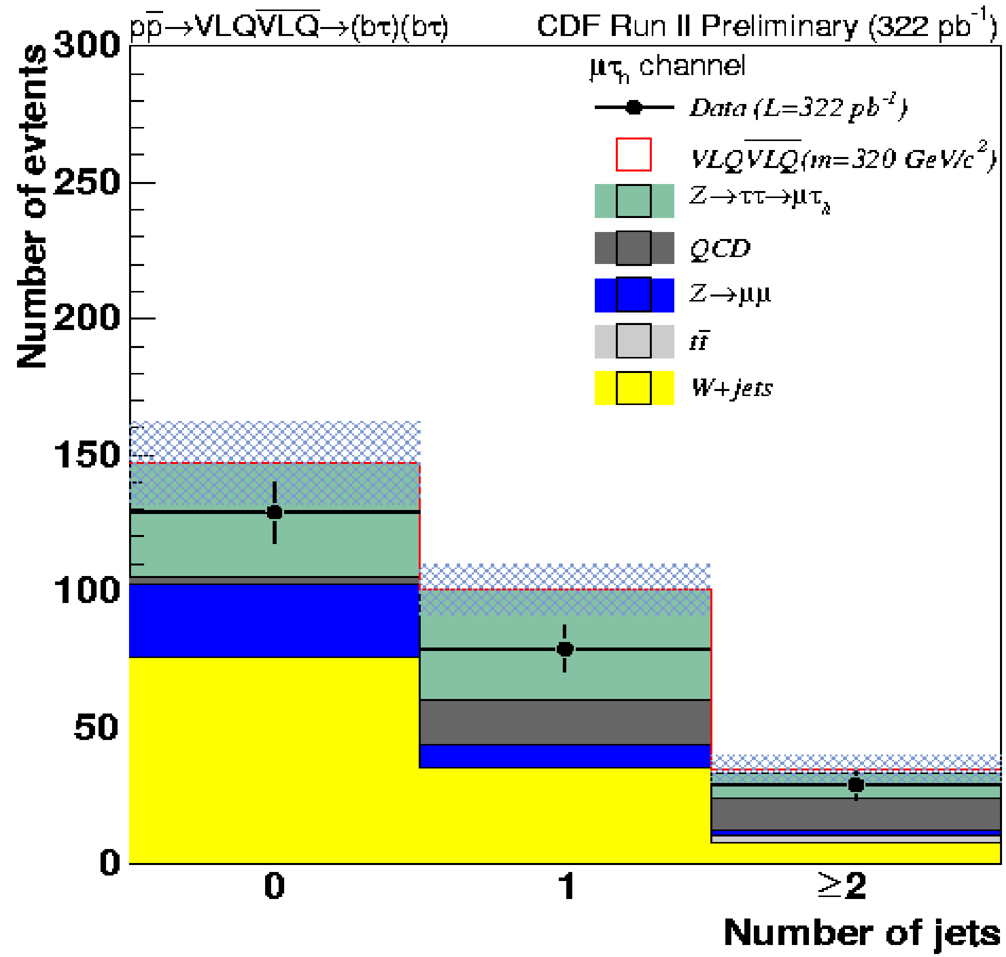
Validation Using Control Regions

- Control and signal region plots of jet multiplicity
- Hatched region is uncertainty on summation of backgrounds

$e\tau_h$ channel



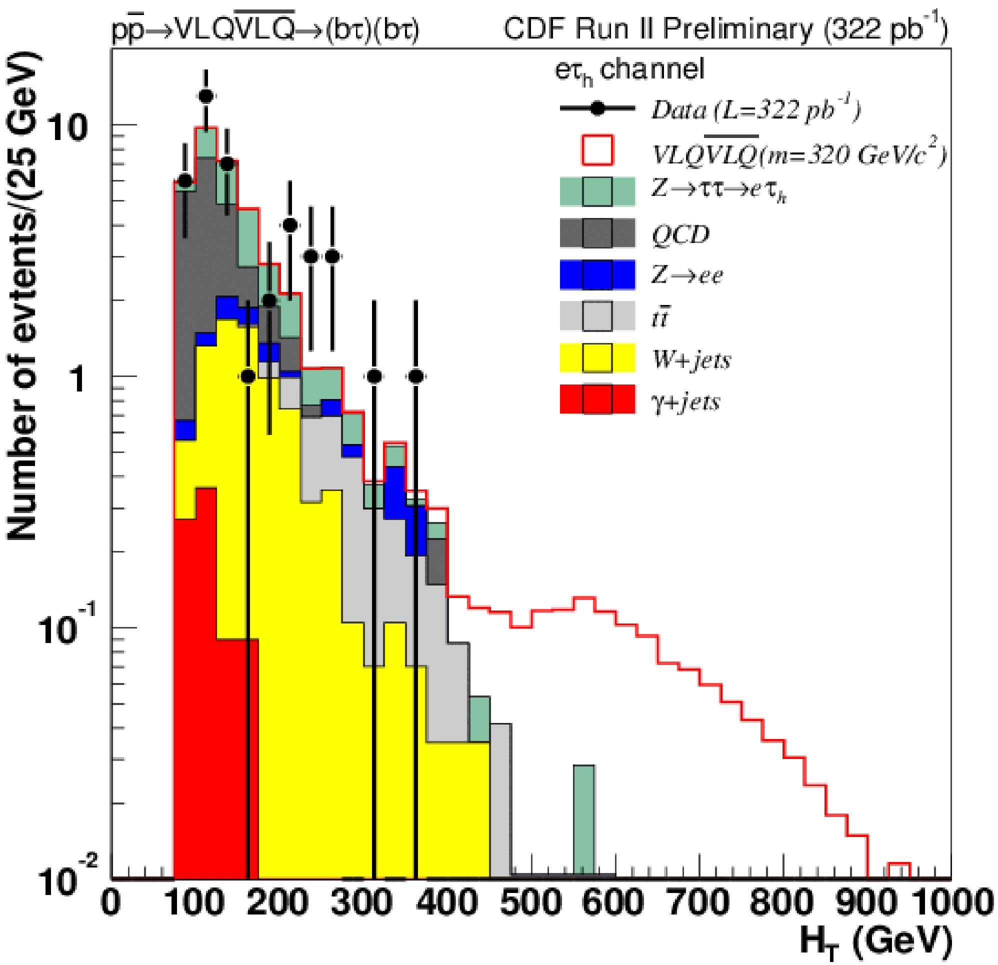
$\mu\tau_h$ channel



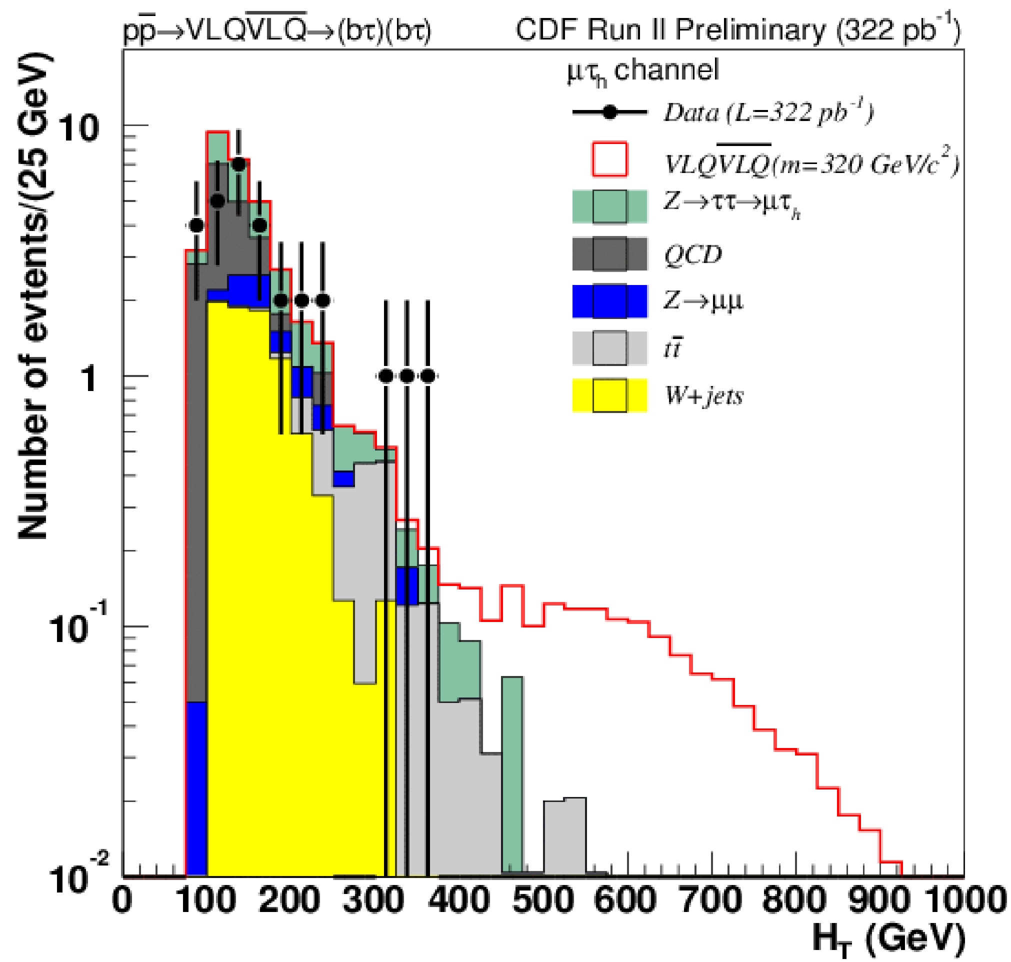
H_T for Control and Signal Regions

- H_T for individual backgrounds and example signal at m_{VLQ3}=320 GeV/c^2
- For all H_T > 80 GeV, and $N_{jets} \geq 2$

$e\tau_h$ channel



$\mu\tau_h$ channel



Systematics

- Systematic uncertainties on signal, for m_{VLQ3} = 160, 260, 360 GeV/c^2

$e\tau_h$ channel

Systematics (%) for $e\tau_h$ Channel			
	m_{LQ3}		
Source	160	260	360
PDF	2.4	1.1	0.7
ISR	3.6	3.6	3.6
FSR	3.7	3.7	3.7
Jet Scale	7.5	2.8	0.9
$\not\!\!E_T$	0.1	0.1	0.1
Acceptance	1.7	1.7	1.7
Lepton ID	1.0	1.0	1.0
Tau ID	3.0	3.0	3.0
Isolation	3.0	3.0	3.0
Total	10.5	7.6	7.1

$\mu\tau_h$ channel

Systematics (%) for $\mu\tau_h$ Channel			
	m_{LQ3}		
Source	160	260	360
PDF	2.7	1.0	0.5
ISR	3.7	3.7	3.7
FSR	3.6	3.6	3.6
Jet Scale	6.9	2.7	0.8
$\not\!\!E_T$	0.0	0.1	0.0
Acceptance	1.0	1.0	1.0
Lepton ID	3.0	3.0	3.0
Tau ID	3.0	3.0	3.0
Isolation	3.0	3.0	3.0
Total	10.4	7.9	7.5

- Additional systematics include 6% for luminosity, + background systematics

Event Yields

- Expected number of background events in each region, and observed number of events in data

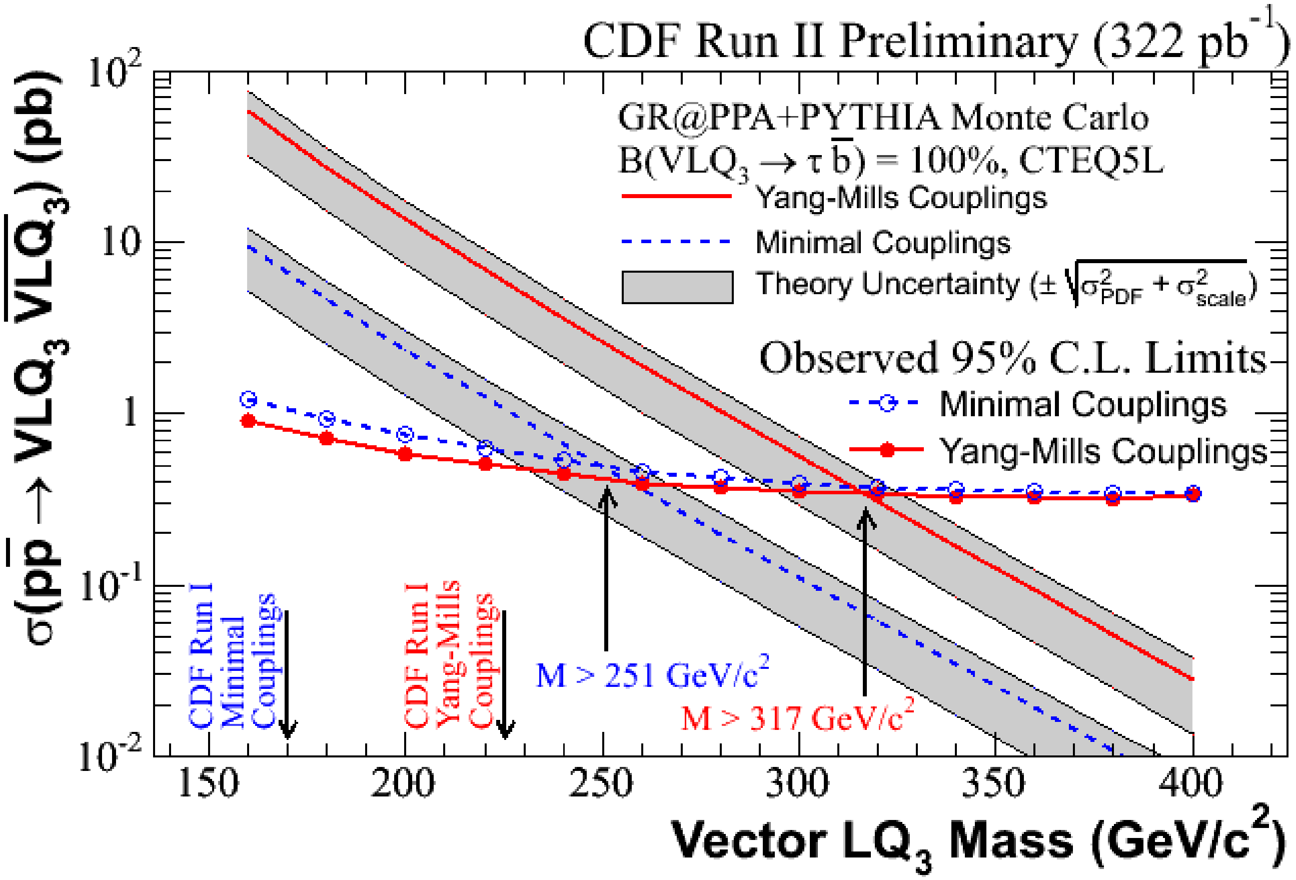
$e\tau_h$ channel

	CR0J	CR1J	CR2J	SAFE	SIGNAL
Background	$122.08^{+2.14}_{-2.14} \pm 11.31$	$109.23^{+2.35}_{-2.35} \pm 9.27$	$33.39^{+1.40}_{-1.39} \pm 4.80$	$3.28^{+0.40}_{-0.27} \pm 0.52$	$0.25^{+0.21}_{-0.06} \pm 0.05$
Data	129	110	36	5	0

$\mu\tau_h$ channel

	CR0J	CR1J	CR2J	SAFE	SIGNAL
Background	$147.13^{+2.62}_{-2.62} \pm 12.29$	$100.46^{+2.51}_{-2.51} \pm 6.74$	$30.58^{+1.62}_{-1.62} \pm 3.83$	$2.25^{+0.32}_{-0.20} \pm 0.32$	$0.24^{+0.22}_{-0.05} \pm 0.05$
Data	129	79	26	3	0

Cross Section and Mass Limits



- Likelihood fit uses results from both $e\tau_h$ and $\mu\tau_h$ channels
- Includes correlations among systematics
- 95% C.L limits

	Minimal Couplings	Yang-Mills Couplings
Nominal:	σ < 493 fb, M > 251 GeV/c^2	σ < 344 fb, M > 317 GeV/c^2
-1σTheory:	σ < 610 fb, M > 223 GeV/c^2	σ < 360 fb, M > 294 GeV/c^2

Conclusions

- Searched for the pair production and decay of third generation vector leptoquarks in 322 pb^{-1} of Run II CDF data, in the di-tau di-jet channel

- Leptoquarks remain undiscovered, but ...

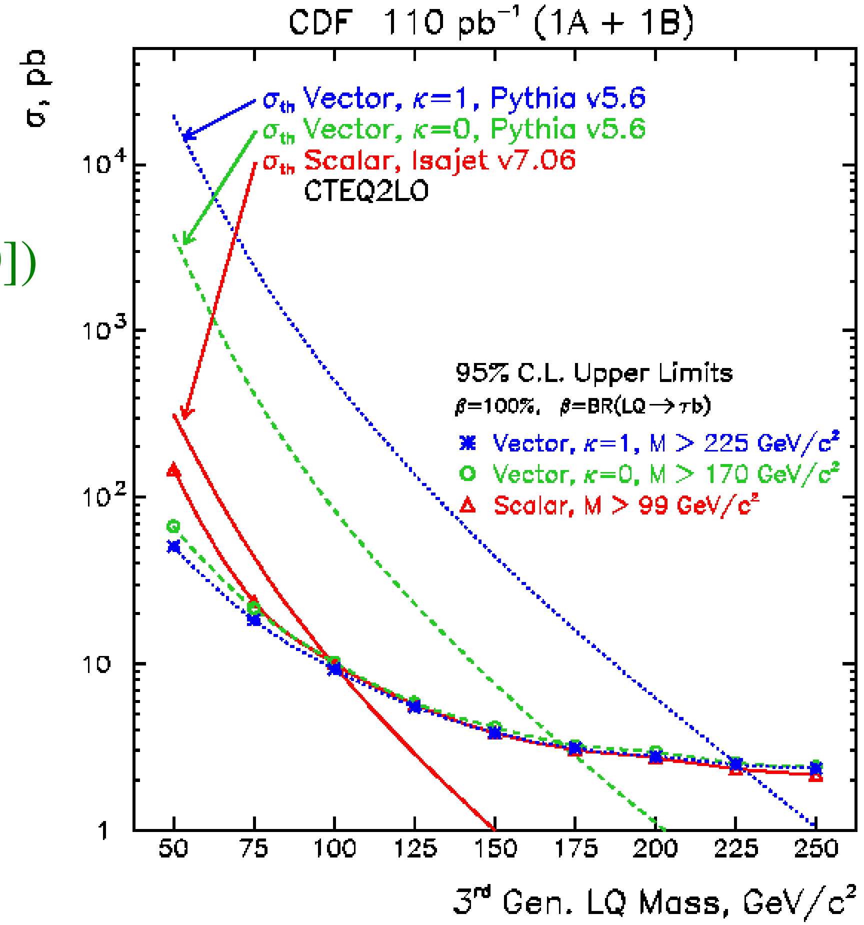
- Placed the world's strongest 95% C.L. limits on the cross section and mass for two models:

	Minimal Couplings	Yang-Mills Couplings
Nominal:	$\sigma < 493$ fb, $M > 251$ GeV/c^2	$\sigma < 344$ fb, $M > 317$ GeV/c^2
-1σTheory:	$\sigma < 610$ fb, $M > 223$ GeV/c^2	$\sigma < 360$ fb, $M > 294$ GeV/c^2

Backup →

Existing Limits

- CDF Run I limits (110 pb^{-1}) →
  - Assume Br(LQ3 → τb) = 100%
    - $m_{VLQ3} > 225$ GeV/c^2 (Yang-Mills [κ=1])
    - $m_{VLQ3} > 170$ GeV/c^2 (Minimal Coupling [κ=0])
    - $m_{SLQ3} > 99$ GeV/c^2
    - [F. Abe *et al.*, Phys Rev Lett **78,** 2906 (1997)]

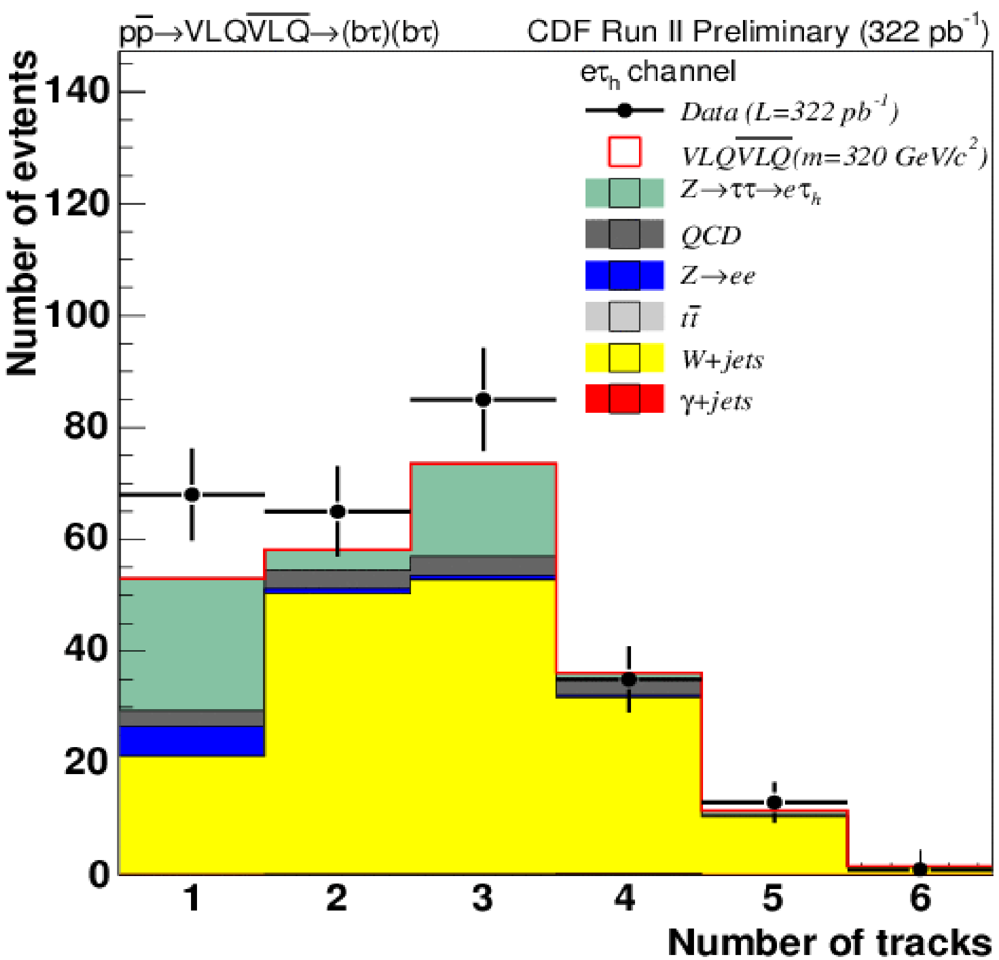


- D0 Run I limits
  - Assume Br(LQ3 → ν_τb) = 100%
    - $m_{VLQ3} > 216$ GeV/c^2 (Yang-Mills)
    - $m_{VLQ3} > 148$ GeV/c^2 (Minimal Coupling)
    - [B. Abbott *et al.*, Phys Rev Lett **81**, 38 (1998)]
- OPAL at LEP II
  - $m_{VLQ3} > 101$ GeV/c^2
- H1 at HERA
  - $m_{VLQ3} > 198$ GeV/c^2 (but allowing lepton flavor violation)
- Related CDF Run II limit (322 pb^{-1})
  - From an R-parity violating stop search
    - $m_{SLQ3} > 155$ GeV/c^2

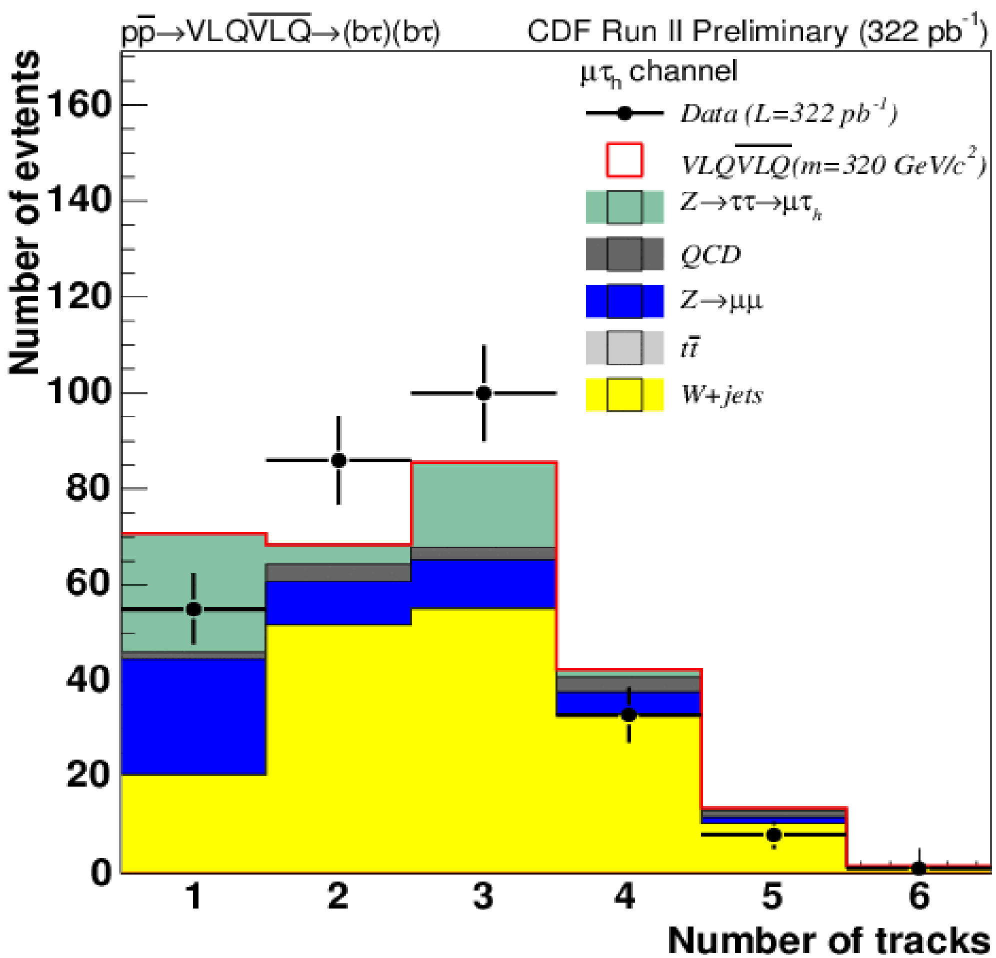
Validation Using Control Regions (II)

- Number of tau prongs in CR0J control region
- N_{prongs}= 1, 3 used for measurement, N_{prongs}= 2, ≥4 also serve as control

$e\tau_h$ channel



$\mu\tau_h$ channel



Event Yields: $e\tau_h$ Channel

- Expected number of events, by category and summed, in each region, and observed number of events in data

$e\tau_h$ channel

	CR0J	CR1J	CR2J	SAFE	SIGNAL
Backgrounds:					
$Z^0 \to \tau\tau \to e\tau_h$	$39.86^{+0.85}_{-0.85} \pm 3.22$	$43.02^{+0.88}_{-0.88} \pm 3.80$	$9.09^{+0.41}_{-0.41} \pm 1.06$	$0.67^{+0.11}_{-0.11} \pm 0.15$	$0.04^{+0.04}_{-0.02} \pm 0.00$
$Z^0 \to ee$	$5.45^{+0.55}_{-0.55} \pm 1.12$	$6.62^{+0.61}_{-0.61} \pm 1.47$	$1.22^{+0.26}_{-0.26} \pm 0.33$	$0.45^{+0.19}_{-0.13} \pm 0.10$	$0.00^{+0.06}_{-0.00} \pm 0.00$
QCD	$2.83^{+0.47}_{-0.47} \pm 0.32$	$22.66^{+1.32}_{-1.32} \pm 5.63$	$15.23^{+1.08}_{-1.08} \pm 3.85$	$0.08^{+0.12}_{-0.05} \pm 0.00$	$0.00^{+0.08}_{-0.00} \pm 0.00$
$t\bar{t}$	$0.01^{+0.01}_{-0.0} \pm 0.01$	$0.30^{+0.06}_{-0.06} \pm 0.07$	$0.81^{+0.09}_{-0.09} \pm 0.22$	$1.35^{+0.12}_{-0.12} \pm 0.39$	$0.15^{+0.04}_{-0.04} \pm 0.04$
$W(e+\nu)+\text{jets}$	$53.06^{+1.13}_{-1.13} \pm 9.82$	$20.29^{+0.79}_{-0.79} \pm 4.87$	$3.51^{+0.35}_{-0.35} \pm 1.72$	$0.60^{+0.15}_{-0.15} \pm 0.29$	$0.07^{+0.07}_{-0.04} \pm 0.03$
$W(\tau+\nu)+\text{jets}$	$20.68^{+1.43}_{-1.43} \pm 4.43$	$14.90^{+1.37}_{-1.37} \pm 3.73$	$2.87^{+0.64}_{-0.64} \pm 1.99$	$0.14^{+0.23}_{-0.09} \pm 0.08$	$0.00^{+0.14}_{-0.00} \pm 0.00$
$\gamma+\text{jets}$	$0.18^{+0.18}_{-0.09} \pm 0.00$	$1.44^{+0.36}_{-0.36} \pm 0.29$	$0.66^{+0.07}_{-0.00} \pm 0.18$	$0.00^{+0.09}_{-0.00} \pm 0.00$	$0.00^{+0.09}_{-0.00} \pm 0.00$
Total Background	$122.08^{+2.14}_{-2.14} \pm 11.31$	$109.23^{+2.35}_{-2.35} \pm 9.27$	$33.39^{+1.40}_{-1.39} \pm 4.80$	$3.28^{+0.40}_{-0.27} \pm 0.52$	$0.25^{+0.21}_{-0.06} \pm 0.05$
Data	129	110	36	5	0

Event Yields: $\mu\tau_h$ Channel

- Expected number of events, by category and summed, in each region, and observed number of events in data

$\mu\tau_h$ channel

	CR0J	CR1J	CR2J	SAFE	SIGNAL
Backgrounds:					
$Z^0 \to \tau\tau \to \mu\tau_h$	$42.03^{+0.87}_{-0.87} \pm 2.91$	$40.10^{+0.85}_{-0.85} \pm 2.22$	$8.34^{+0.39}_{-0.39} \pm 0.70$	$0.59^{+0.10}_{-0.10} \pm 0.06$	$0.09^{+0.05}_{-0.03} \pm 0.03$
$Z^0 \to \mu\mu$	$27.06^{+1.19}_{-1.19} \pm 8.45$	$8.39^{+0.66}_{-0.66} \pm 2.74$	$2.20^{+0.34}_{-0.34} \pm 0.73$	$0.10^{+0.10}_{-0.05} \pm 0.04$	$0.00^{+0.05}_{-0.00} \pm 0.00$
QCD	$2.30^{+0.56}_{-0.56} \pm 0.39$	$16.54^{+1.50}_{-1.50} \pm 2.91$	$11.58^{+1.25}_{-1.25} \pm 2.05$	$0.00^{+0.13}_{-0.00} \pm 0.00$	$0.00^{+0.13}_{-0.00} \pm 0.00$
$t\bar{t}$	$0.04^{+0.03}_{-0.02} \pm 0.00$	$0.32^{+0.06}_{-0.06} \pm 0.07$	$0.67^{+0.08}_{-0.08} \pm 0.13$	$1.24^{+0.11}_{-0.11} \pm 0.29$	$0.15^{+0.04}_{-0.04} \pm 0.05$
$W(\mu+\nu)+\text{jets}$	$56.60^{+1.59}_{-1.59} \pm 7.98$	$21.99^{+1.12}_{-1.12} \pm 4.23$	$4.36^{+0.53}_{-0.53} \pm 1.74$	$0.31^{+0.18}_{-0.11} \pm 0.11$	$0.00^{+0.06}_{-0.00} \pm 0.00$
$W(\tau+\nu)+\text{jets}$	$19.11^{+1.37}_{-1.37} \pm 2.71$	$13.13^{+1.28}_{-1.28} \pm 2.56$	$3.44^{+0.70}_{-0.70} \pm 2.53$	$0.00^{+0.14}_{-0.00} \pm 0.00$	$0.00^{+0.14}_{-0.00} \pm 0.00$
Total Background	$147.13^{+2.62}_{-2.62} \pm 12.29$	$100.46^{+2.51}_{-2.51} \pm 6.74$	$30.58^{+1.62}_{-1.62} \pm 3.83$	$2.25^{+0.32}_{-0.20} \pm 0.32$	$0.24^{+0.22}_{-0.05} \pm 0.05$
Data	129	79	26	3	0