Search for Leptoquarks and 4th Generation Quarks at CDF

Aron Soha

(University of California at Davis)

For the CDF Collaboration

July 21, 2005

EPS HEP2005, Lisboa

Outline

- Leptoquarks
  - Motivation
  - Production and decay
  - 1st and 2nd generation leptoquarks
  - 3rd Generation vector leptoquarks

- 4th generation quarks
  - Search for b'
  - Search for t'

Leptoquark 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
  - Color-triplet boson with fractional charge
  - Two possible spin structures:
    Spin 0 (scalar): couplings are fixed and decays are isotropic
    Spin 1 (vector): anomalous magnetic and electric quadrupole moments

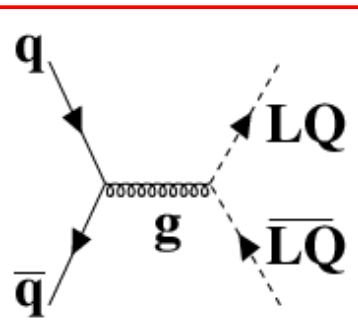
- Appears in several beyond-the-Standard-Model theories:
  SU(5) GUT, Superstrings, SU(4) Pati-Salam, Composite, Technicolor

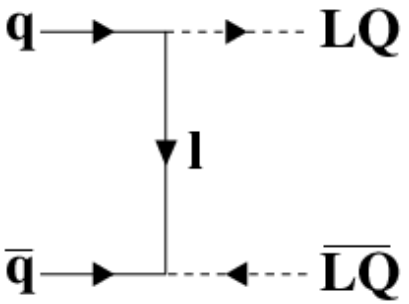
Leptoquark Production at the Tevatron

- Pair production: quark/anti-quark annihilation and gluon fusion
- For scalar case, cross-section depends only on mass

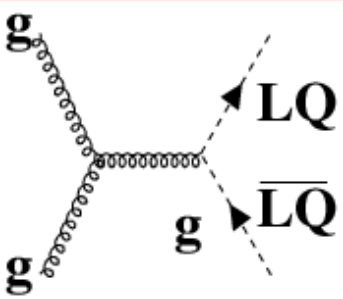
$q\bar{q} \rightarrow LQ\ \overline{LQ}$

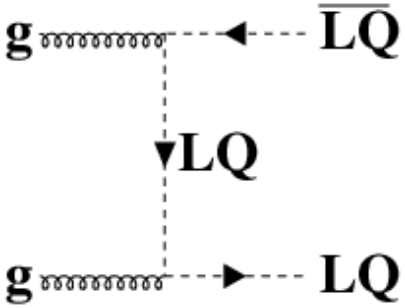
dominant

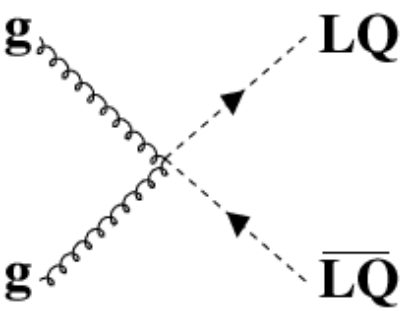


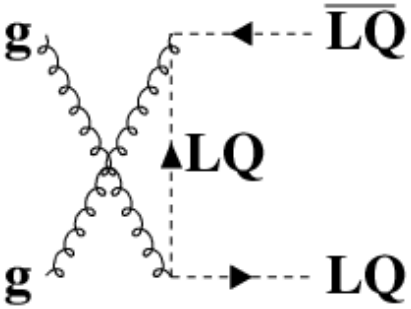


$gg \rightarrow LQ\ \overline{LQ}$









Leptoquark Decays

- Lack of FCNC suggests decays remain within generation
  - Therefore, 1st, 2nd, and, 3rd generation leptoquarks (LQ1, LQ3, LQ3)
- Define $\beta = \mathrm{Br}(LQ \rightarrow lq)$

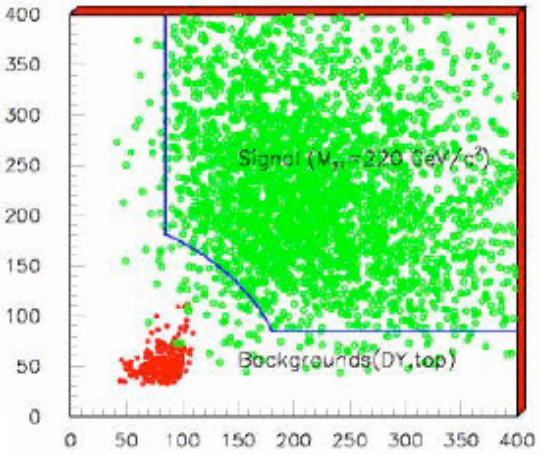
Generation			$\beta = 1.0$	$\beta = 0.5$	$\beta = 0.0$
1st	LQ1 $\overline{\mathrm{LQ1}}$	$\rightarrow$	$e^- e^+ q\bar{q}$	$e^{\pm}\nu_e q_i q_j$	$\nu_e \nu_e q_i q_j$
2nd	LQ2 $\overline{\mathrm{LQ2}}$	$\rightarrow$	$\mu^- \mu^+ q\bar{q}$	$\mu^{\pm}\nu_\mu q_i q_j$	$\nu_\mu \nu_\mu q_i q_j$
3rd	LQ3 $\overline{\mathrm{LQ3}}$	$\rightarrow$	$\tau^- \tau^+ q\bar{q}$	$\tau^{\pm}\nu_\tau q_i q_j$	$\nu_\tau \nu_\tau q_i q_j$

- This talk includes results from all three generations
  - Individual channels ($\beta = 0.0, 0.5, 1.0$)
  - Combined searches within 1st and 2nd generations using $0.0 < \beta < 1.0$

LQ1 in eeqq Channel

- Signature and selection:
  - 2 isolated ele with E_T>25 GeV
    Veto: 76 < M_{ee} < 110 GeV/c^2
  - 2 isolated jets
    E_T>30 GeV and E_T>15 GeV

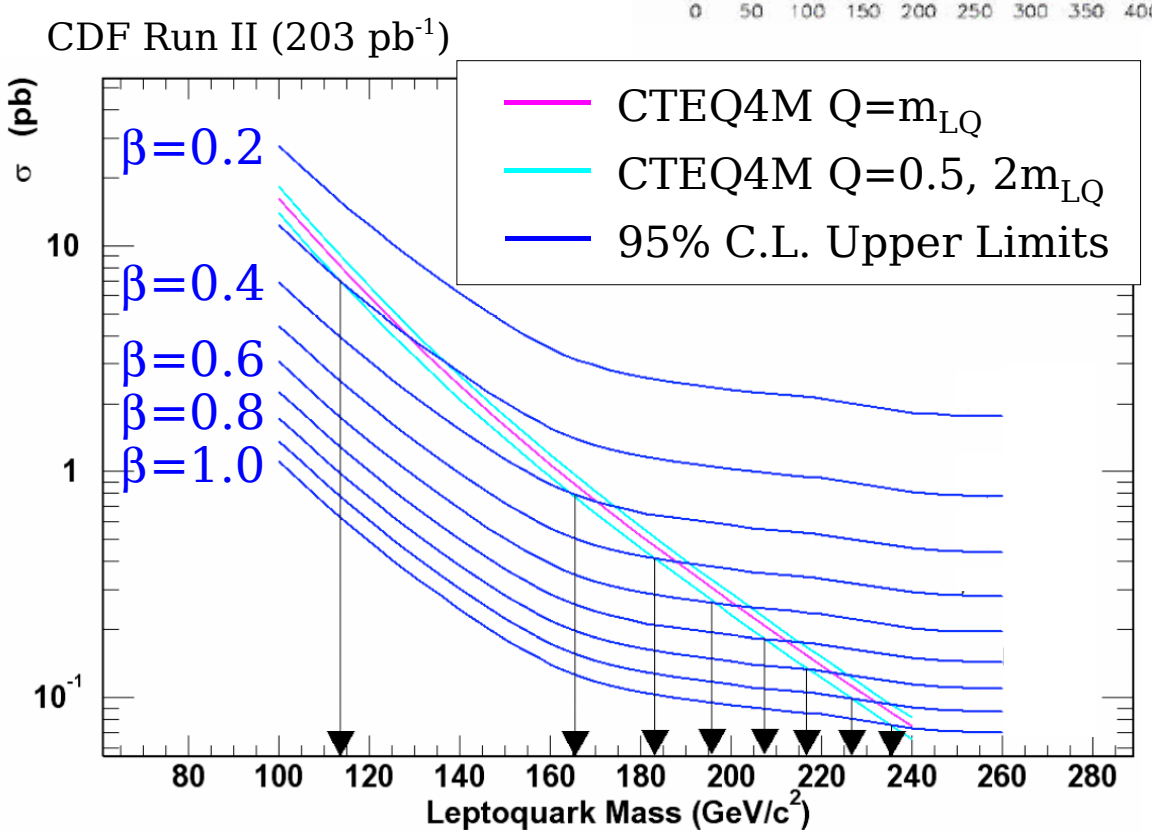
$E_T(j_1) + E_T(j_2)$
vs
$E_T(e_1) + E_T(e_2)$



- Acceptance = 32-43%
- Backgrounds:

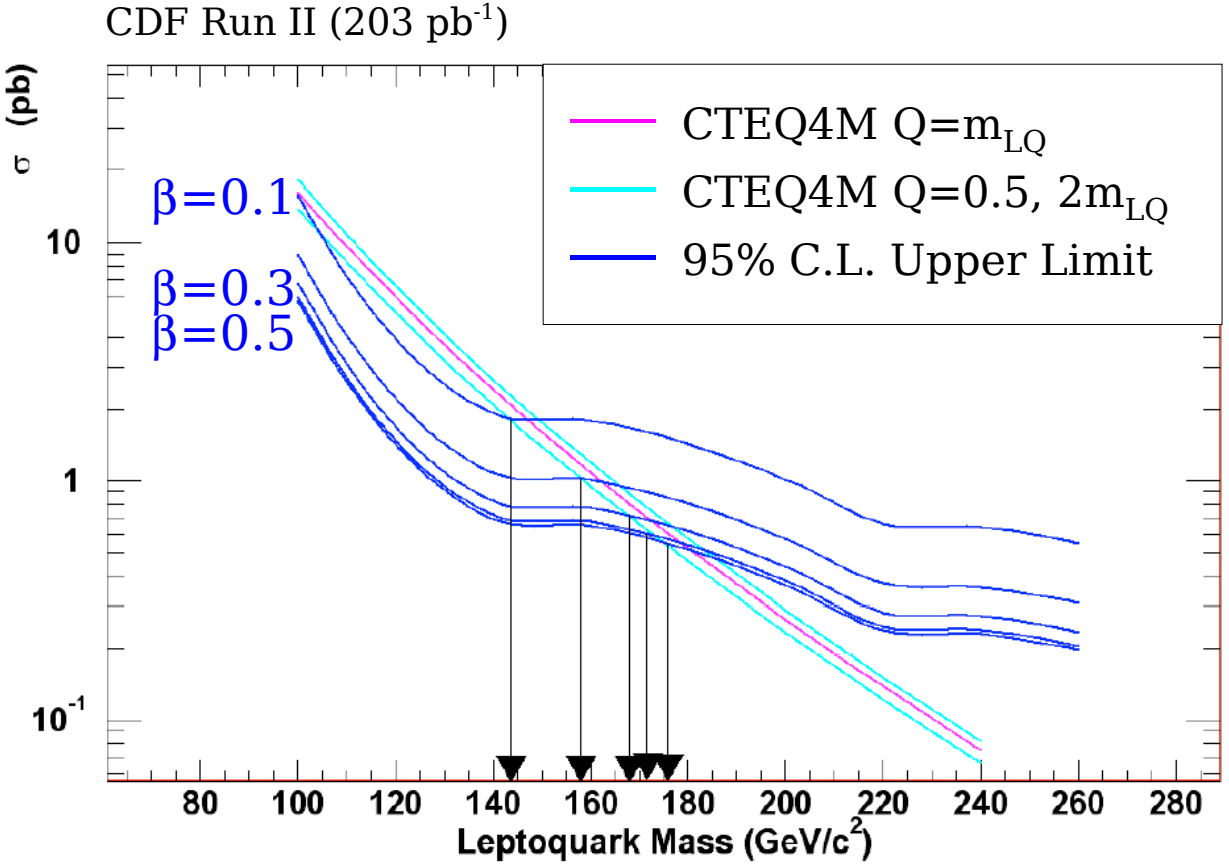
source	events
Z + 2 jets:	1.89 ±0.44
Top Dilepton:	0.35 ±0.03
Fakes:	3.96 ±2.01
Total Bkg:	6.24 ±2.16
Data:	4

- Optimized for β = 1.0
- Mass limit (95% C.L.)
  m_{LQ1} > 235 GeV/c^2



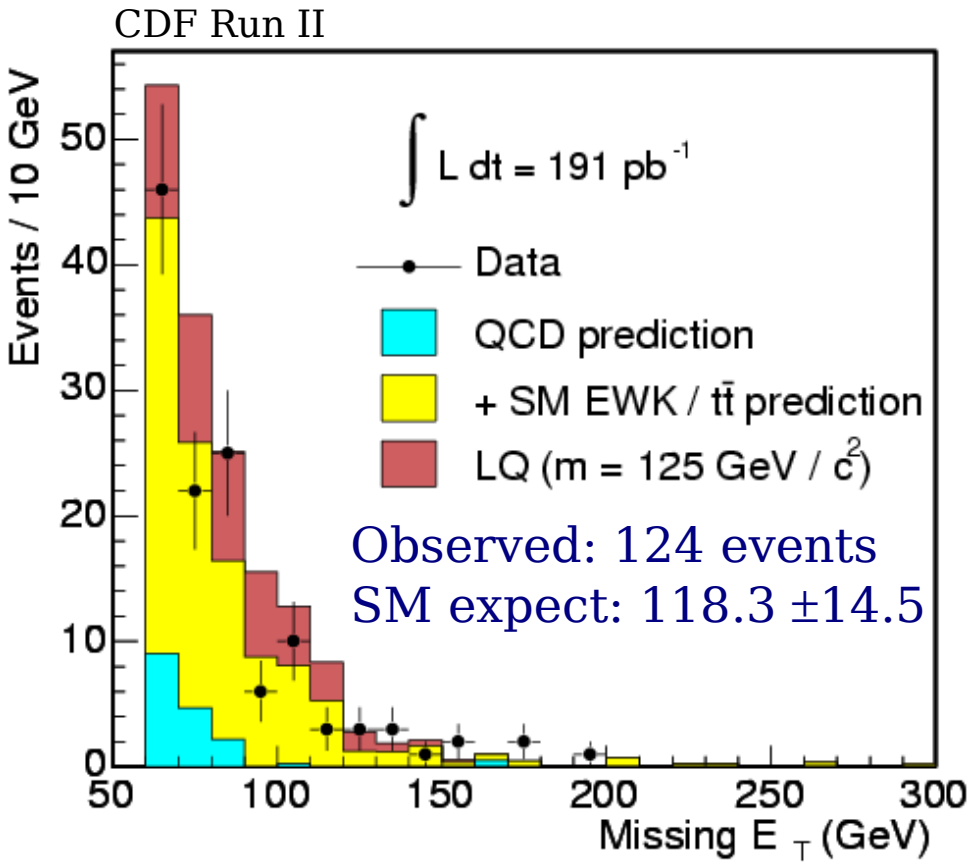
LQ1 in evqq Channel

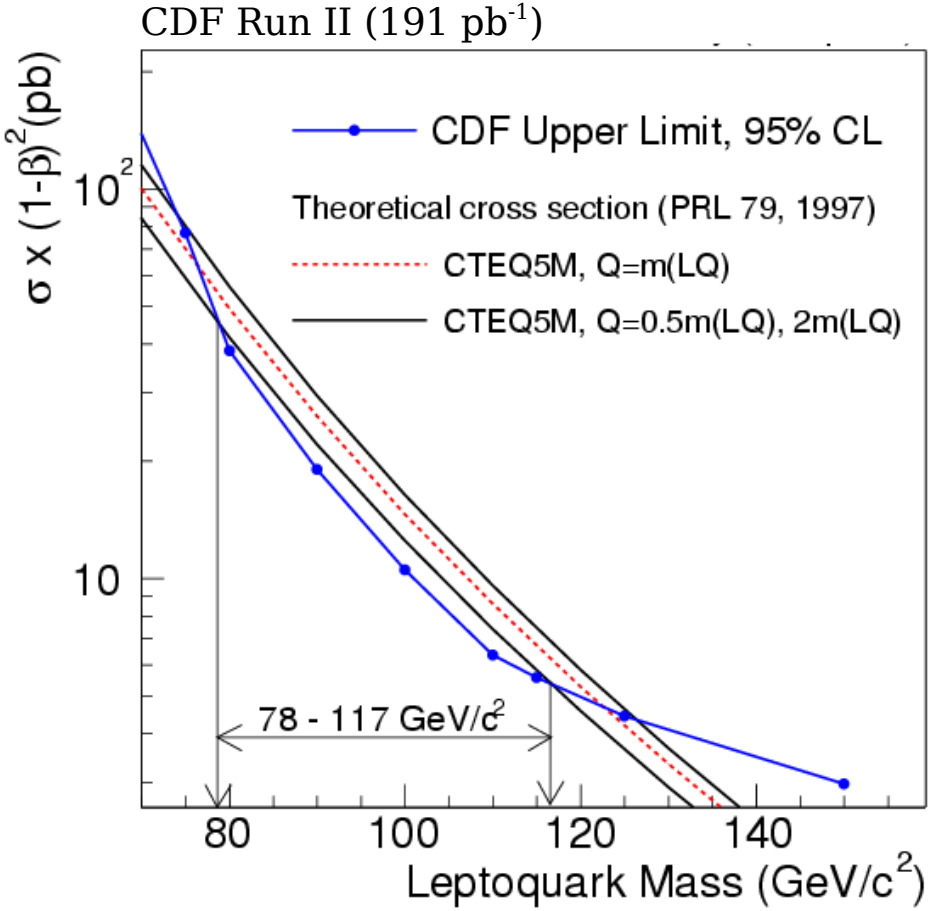
- Signature: 1 isolated electron and 2 isolated jets
  - 1 ele with E_T>25 GeV
  - $\not\!\!E_T$>60 GeV
  - 2 jets with E_T>30 GeV
  - No 2nd electron candidate
  - $\Delta\phi(\not\!\!E_T\text{-jet}_i) > 10^O$
  - $E_T(j_1) + E_T(j_2) > 80$ GeV
  - $M_T(e\nu) > 120$ GeV/c^2 (fights W+2jets bkgd)
- Requirements to match expected m_{LQ}
  - jet+$\not\!\!E_T$ transverse mass
  - e+jet invariant mass
  - 3σ "window" cuts defined from simulation
- Acceptance = 2-25%
- Optimized for β = 0.5
- Mass limit (95% C.L.)
  $m_{LQ1} > 176$ GeV/c^2



LQ1 in ννqq Channel

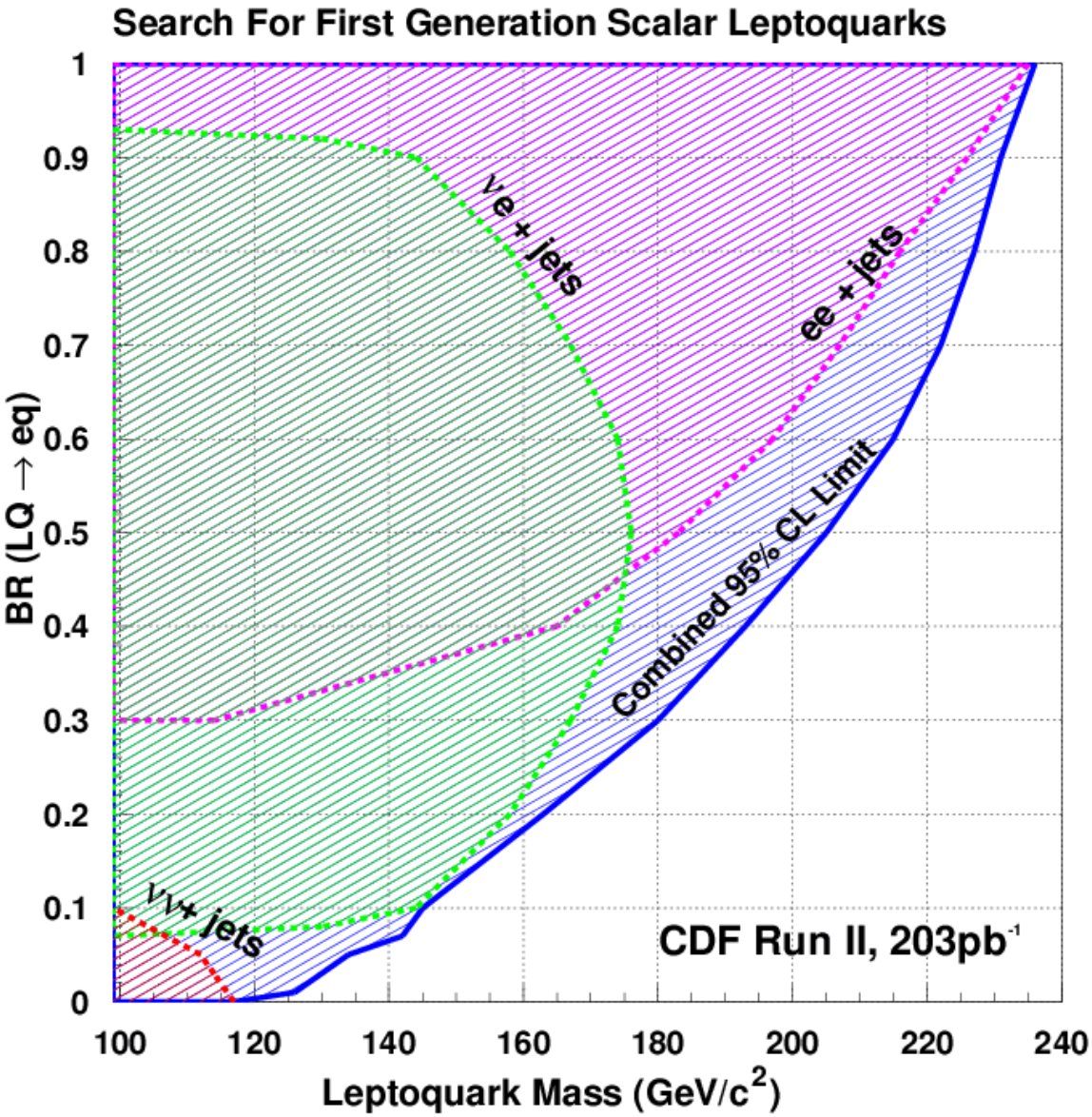
- Signature: Missing E_T and isolated jets
  - $\not\!\!E_T$ > 60 GeV
  - No e or μ candidates
  - 2 jets (E_T>40, E_T>25 GeV)
  - $80^O < \Delta\phi(jet_1\text{-}jet_2) < 165^O$
- Excluded mass interval 78-117 GeV/c^2 with 95% C.L.





Combined LQ1 Mass Limits

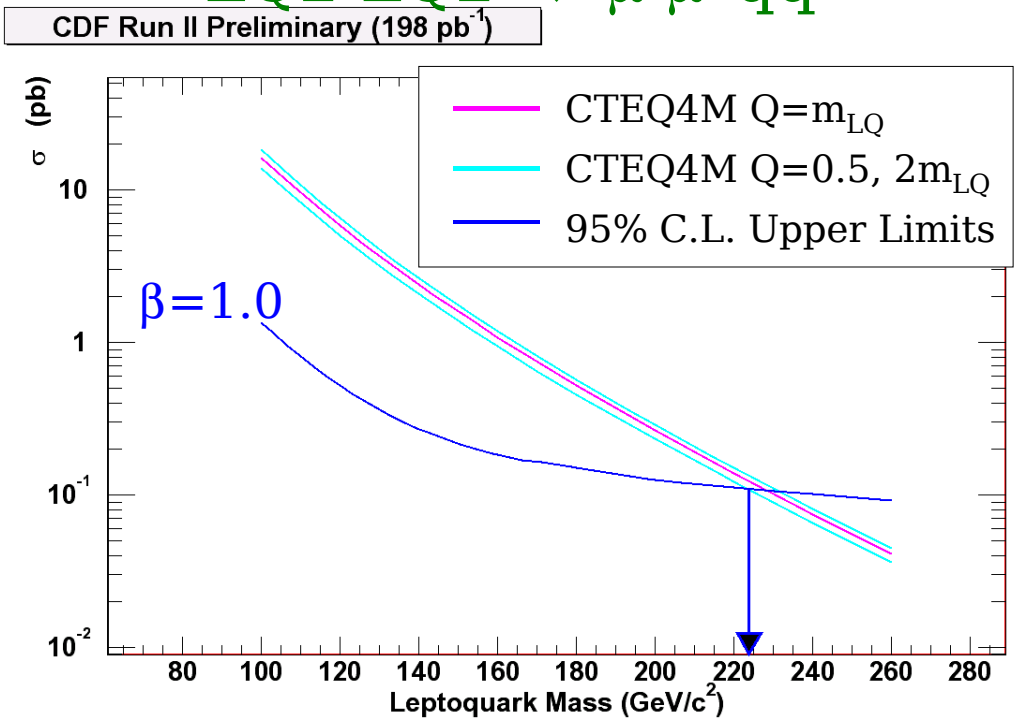
- Mass limit for a range of $\beta = \mathrm{Br}(\mathrm{LQ} \rightarrow \mathrm{lq})$
- Bayesian approach
  - Product likelihood formed from individual channel likelihoods
  - 10k pseudo-experiments at each mass point
  - Signal and bkgd yields are smeared by uncertainties
  - Correlations in channel selections taken into account for acceptance uncertainties



LQ2 in μμqq and μνqq

- Signature and selection are similar to 1st gen (e ↔ μ)

$LQ2\,\overline{LQ2} \rightarrow \mu^-\mu^+ q\bar{q}$



- Optimized for β = 0.5

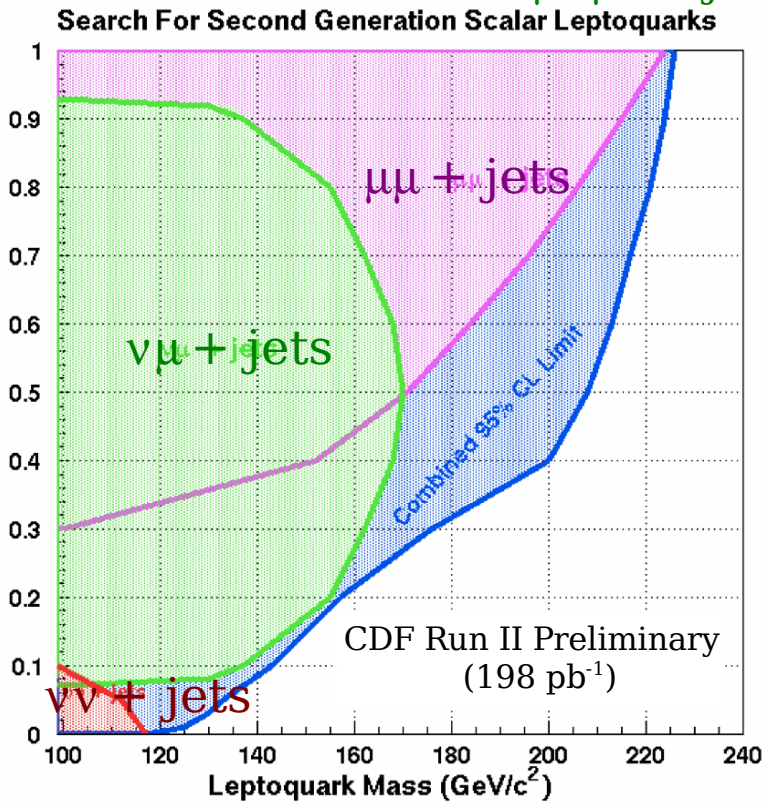
  $m_{LQ2} > 224$ GeV/c^2 (95% C.L.)

$LQ2\,\overline{LQ2} \rightarrow \mu^{\pm}\nu_\mu q_i q_j$

- Optimized for β = 0.5

  $m_{LQ2} > 170$ GeV/c^2 (95% C.L.)

- Combined LQ2 (including $\nu_\mu\nu_\mu q_i q_j$):



Vector LQ3 in $\tau\tau qq$

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

  E.g., subset with
  β = Br(LQ→lq) = 1.0

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

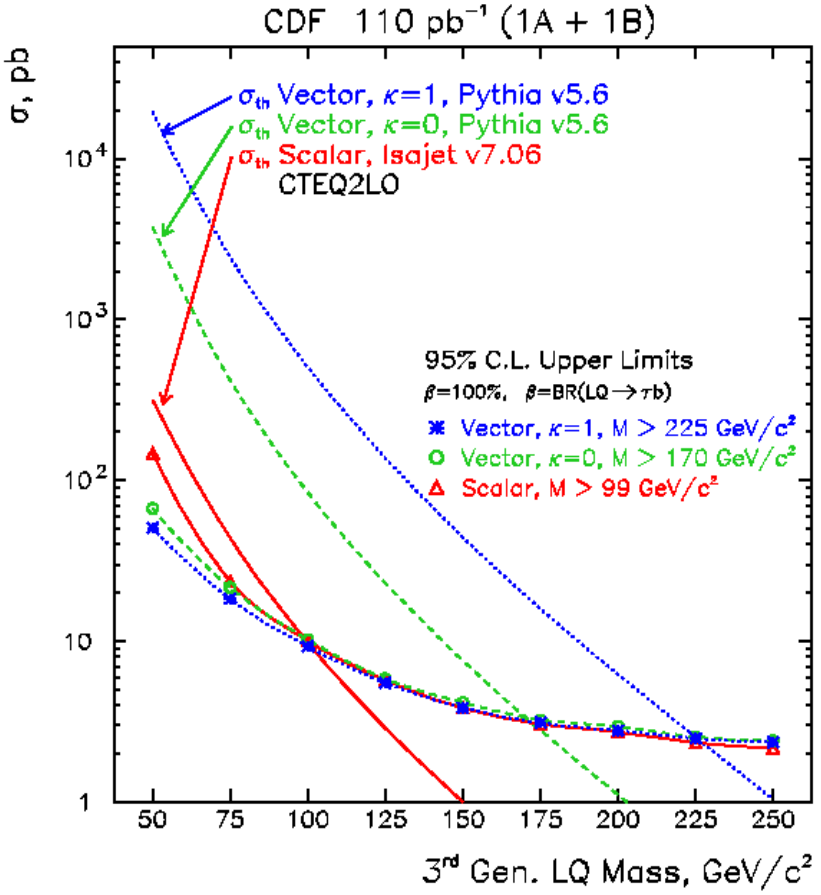
- Considering $\tau_e \tau_h$ bb and $\tau_\mu \tau_h$ bb (46% of total $\tau\tau$ combos)

- Signature and selection:
  - 1 isolated e with E_T>10 GeV or μ with p_T>10 GeV/c
  - 1 τ_h with p_T>15 GeV/c (seeded by isolated track)
  - 2 jets with E_T>15 GeV

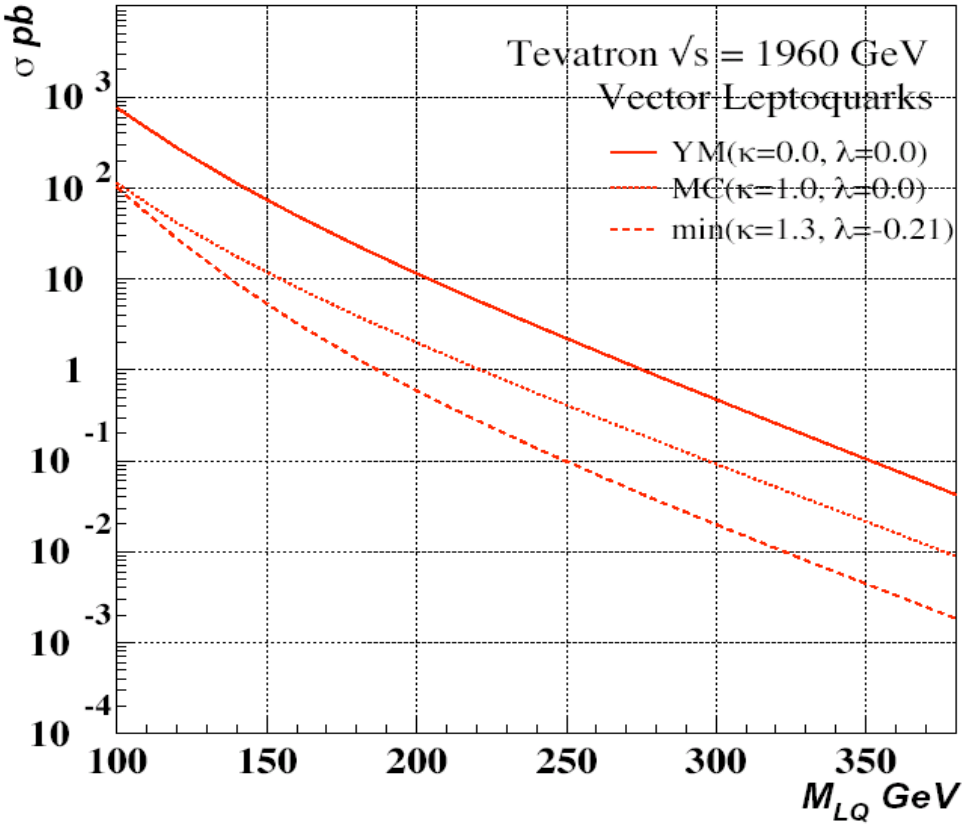
- New MC tools developed to calculate helicity amplitudes
  - VLQ3 added to GRACE matrix element generator

Vector LQ3 in $\tau\tau qq$

- CDF runI limit
  $m_{VLQ3} > 225$ GeV/c^2



- "Expect" ~3 signal events in 319 pb^{-1}, with a limit of roughly $m_{VLQ3} > 320$ GeV/c^2

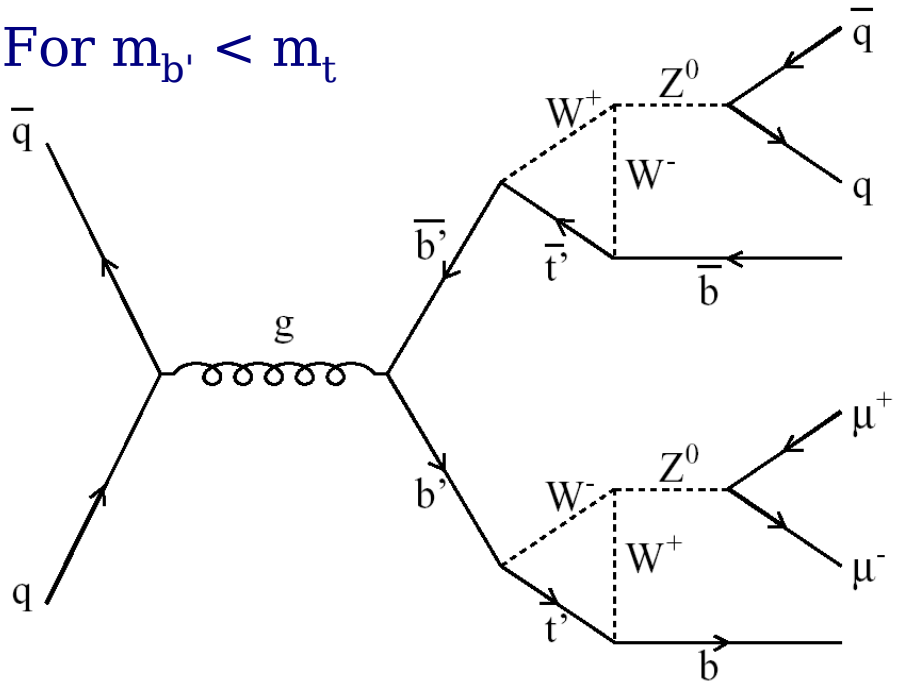


- Scalar LQ3 has same signature as R-parity violating SUSY top
  CDF search using 200 pb^{-1}: $m_{SLQ3} > 129$ GeV/c^2

4th Generation Quark: b'

- Search for long-lived particle (b') that decays to Z^0
  - Find vertex of $Z^0 \rightarrow \mu^-\mu^+$ and study decay length
  - Keep this search inclusive by just looking for one displaced Z^0
    - E.g. Could also be a neutralino in a gauge-mediated SUSY model where the gravitino is the LSP

- For $m_{b'} < m_t$



- 2 muons with $p_T > 20$ GeV/c
- $81 < m_{\mu\mu} < 101$ GeV/c^2

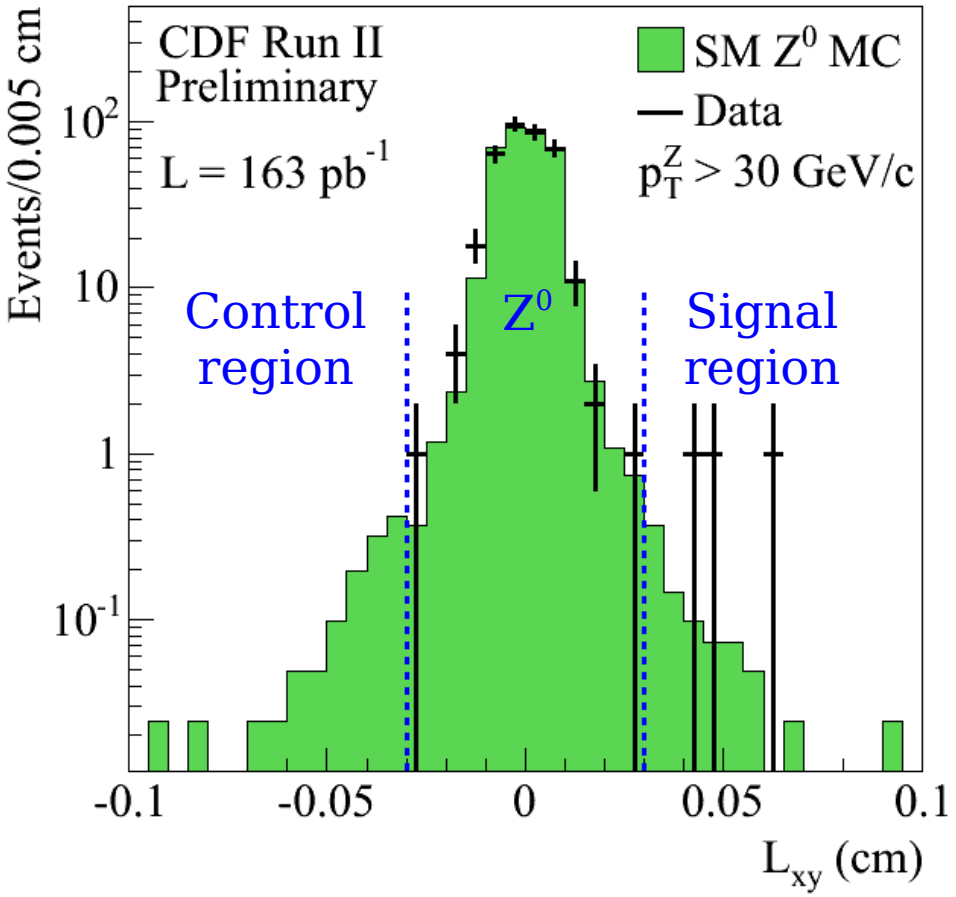
Main backgrounds:
- SM Z^0 (mis-reconstructed μ track)
- Semileptonic B-decays

Require $\Delta\phi < 175^0$
- In back-to-back events, a small mis-measurement of impact parameter can lead to large measure of L_{xy} (distance from beam in transverse plane)
- Rejects 99.8% of large L_{xy} bkgd
- Keeps boosted signal-like Z^0s

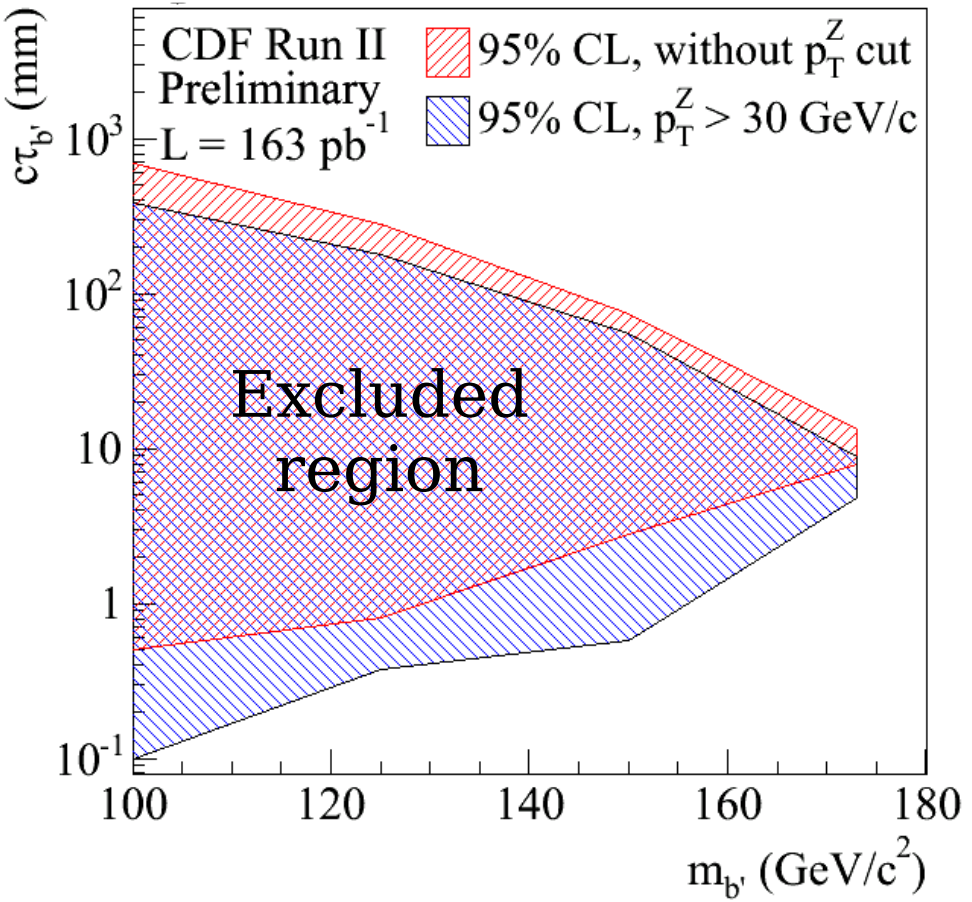
Look with and without $P_T(Z^0) > 30$
- Model favors high p_T

b'

- Number of events is consistent with background
- Always just one of the two tracks has large impact parameter



- Exclusion region based on b' model & leading order PYTHIA



4^{th} Generation Quark: t'

- Would be consistent with EWK data, and a heavy Higgs
  (He, Polonsky, Su: hep-ph0102144)
- Where to look:

  Natural: $t' \to Wb'$, as long as $m_{t'} > m_W + m_{b'}$

  However, precision EWK suggests $m_{t'}$ and $m_{b'}$ may be similar

  So, $t' \to$ Wb, Ws, Wd (singly, doubly, triply Cabibbo suppressed)
- Signature:

  $p\bar{p} \to t'\bar{t}' \to Wq\ W\bar{q} \to l\nu\bar{q}$ e/μ (p_T>20), $\not{E}_T$>20, jet (E_T>15)

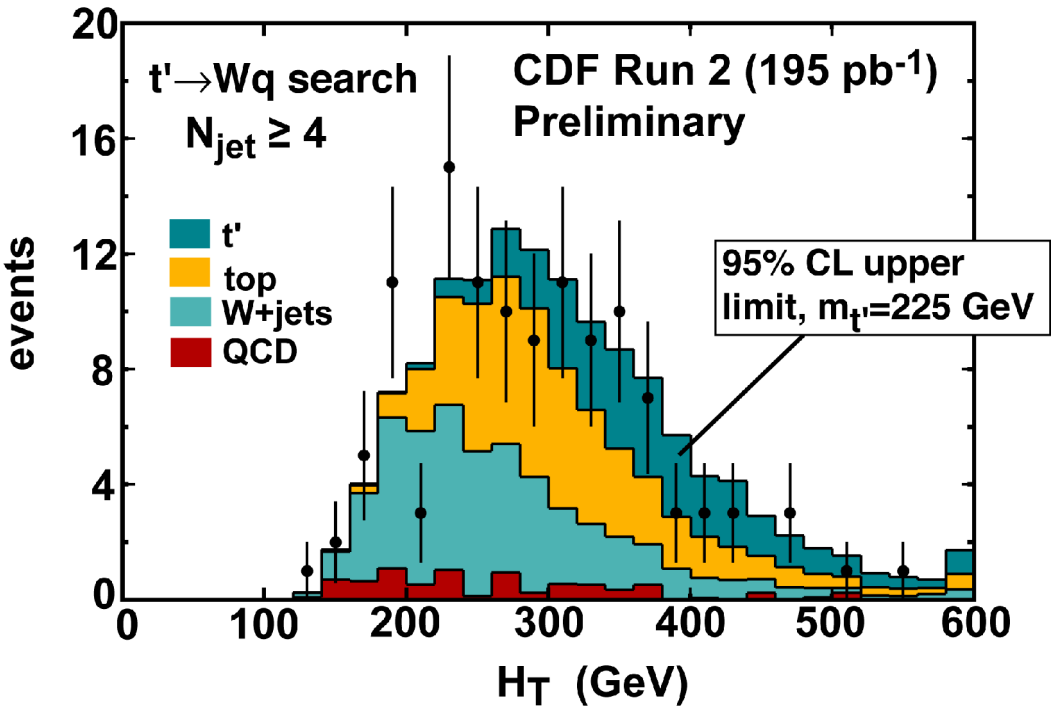
  $\hookrightarrow q\bar{q}q$ 3 jets (E_T>15)
- Strategy:
  - No b-tagging, to keep sensitivity to $t' \to$ Ws and $t' \to$ Wd
  - Use kinematic quantity, H_T, to separate signal from background

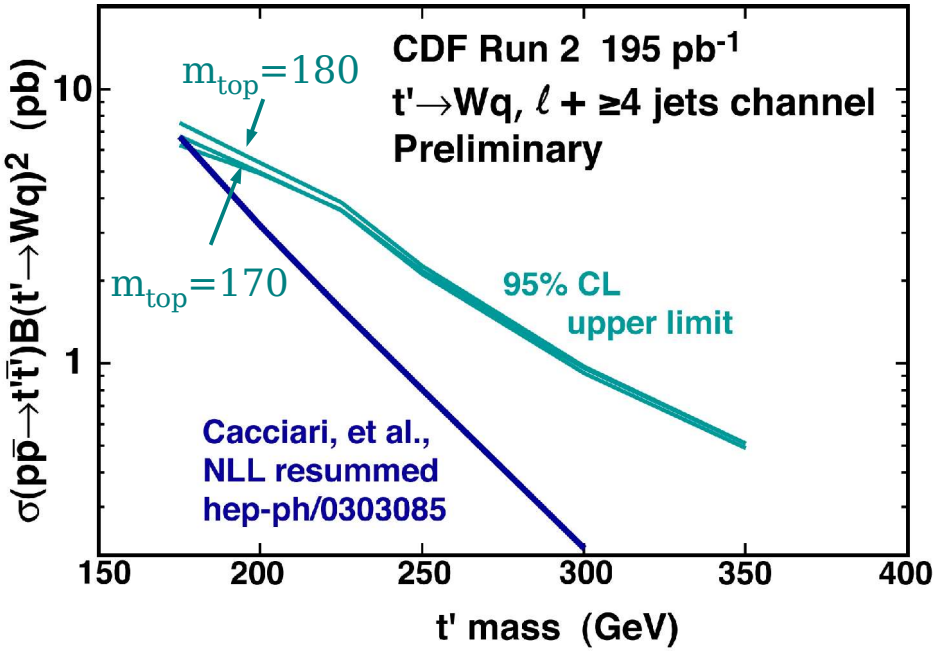
    H_T = E_T(lepton) + missing E_T + E_T(jets) [scalar sum]
  - Fit data for backgrounds (including $t\bar{t}$) and signal ($t'\bar{t}'$)

    Extract a 95% C.L. limit on $\sigma(t'\bar{t}')$x$Br(t' \to Wq)^2$

t'

- Perform maximum likelihood (L) fit to H_T
- Map out L as a function of $\sigma(t'\bar{t}')xBr(t'\rightarrow Wq)^2$ and integrate to find 95% CL limit
- H_T shown for $m_{t'} = 225$ GeV/c^2
- Repeat for different masses
- Data prefers no t' contribution





Small variation with assumed top mass

Conclusions

- Broad program of searches for leptoquarks and 4th gen. quarks
- Leptoquarks: 95% C.L. Limits (GeV/c^2)

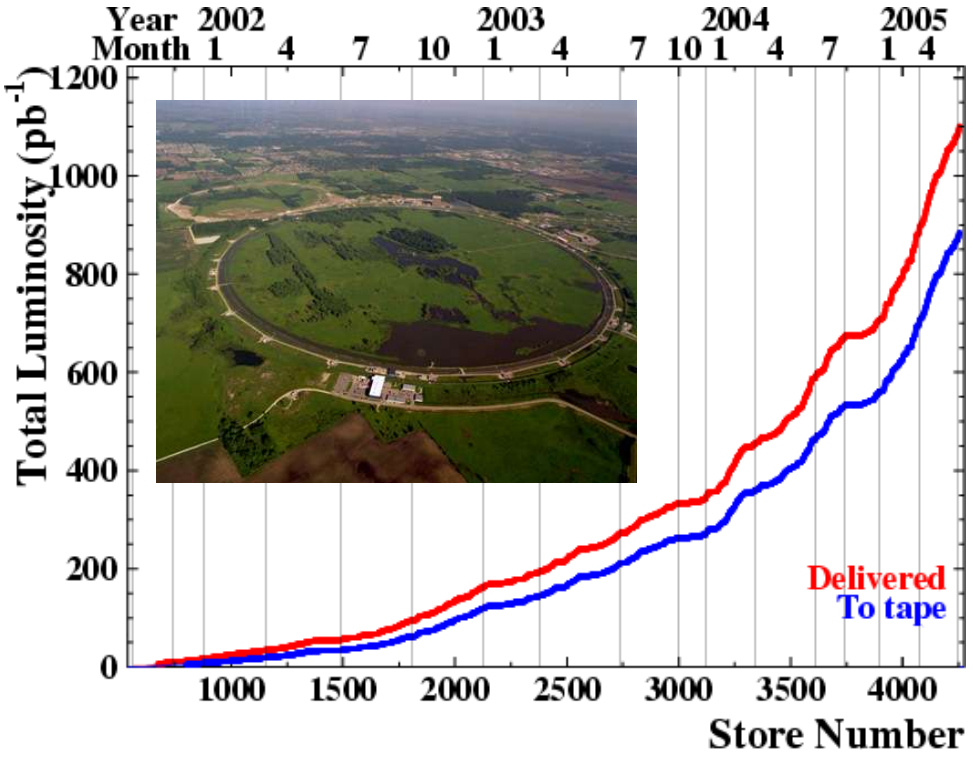
LQ1	$e^-e^+q\bar{q}$	$m_{LQ1} > 235$	Combined to give limits as function of β
	$e^{\pm}\nu_e q_i q_j$	$m_{LQ1} > 176$	
	$\nu_e\nu_e q_i q_j$	$m_{LQ1} < 78$ or $m_{LQ1} > 117$	
LQ2	$\mu^-\mu^+q\bar{q}$	$m_{LQ2} > 224$	Combined (with $\nu_\mu\nu_\mu q_i q_j$) to give limits as function of β
	$\mu^{\pm}\nu_\mu q_i q_j$	$m_{LQ2} > 170$	
LQ3	$\tau^-\tau^+q\bar{q}$	In progress	

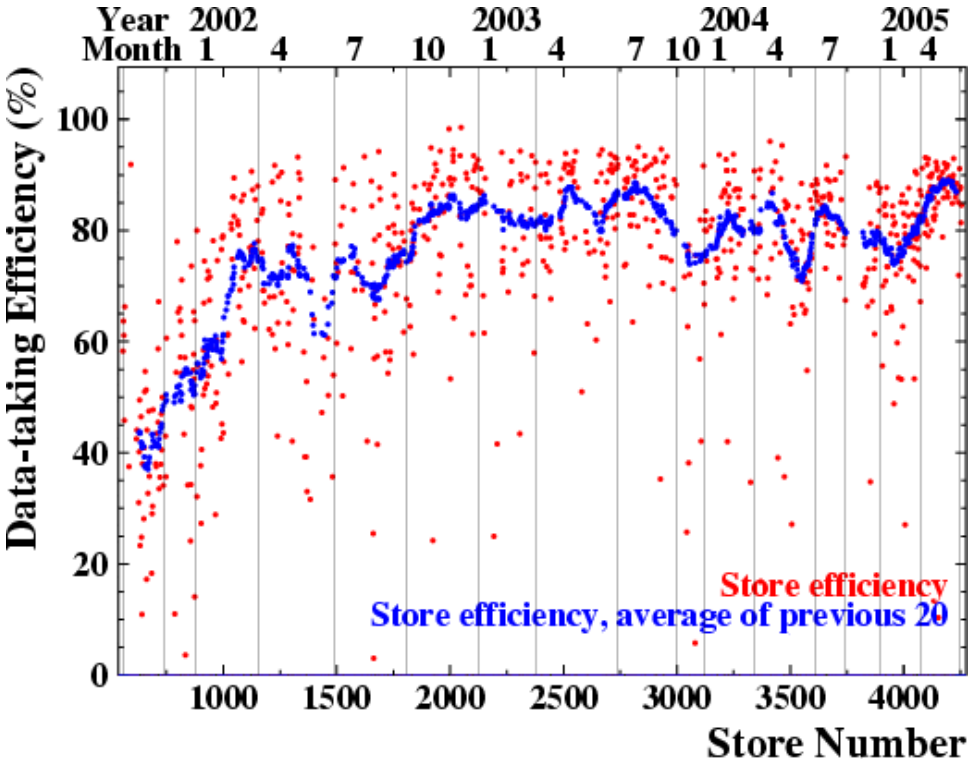
- b' 4 generation quark
  - Exclusion region: decay length vs mass
  - For example, for $c\tau = 10$ mm, $m_{b'} > 173$ GeV/c^2
- t' 4 generation quark
  - Cross-section x branching ratio limits as function of mass
- Improvements and updates coming soon!

Backup Slides

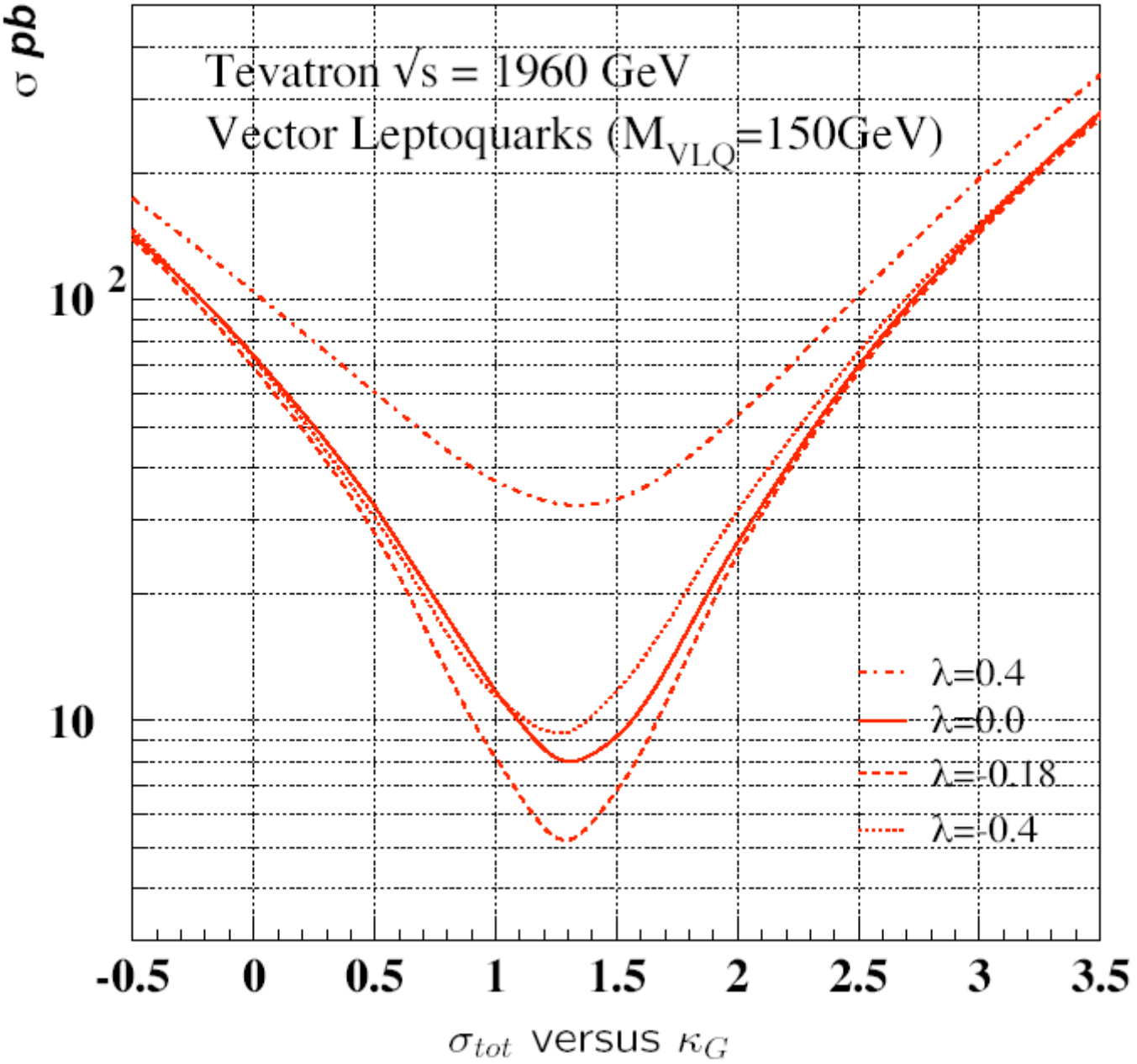
CDF at the Tevatron

- The runII Tevatron at Fermilab has delivered > 1.1 fb^{-1}
- CDF has recorded > 880 pb^{-1} (efficiency has climbed to ~90%)





VLQ3: Anomalous Coupling

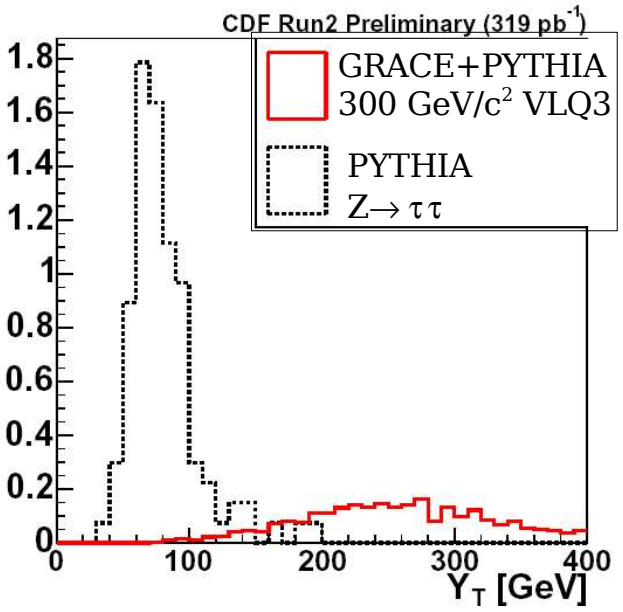


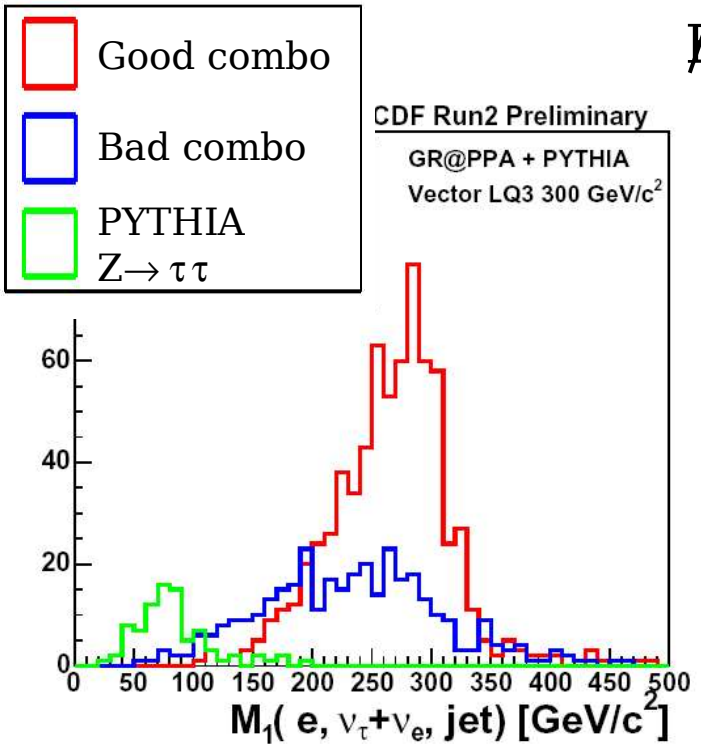
Vector LQ3 in $\tau\tau qq$

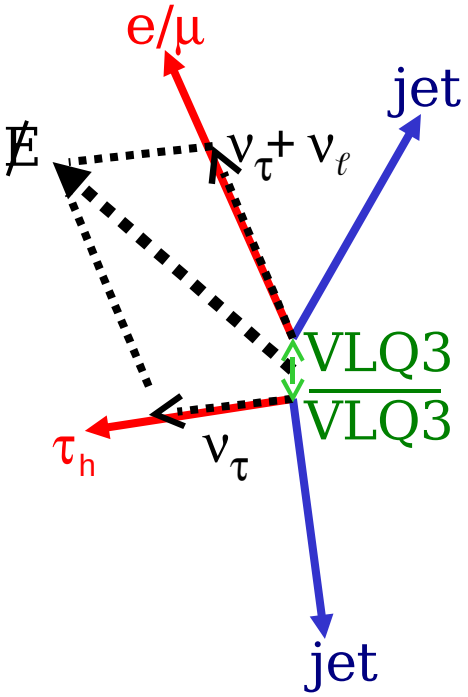
- Signal/Background (mostly $Z \rightarrow \tau\tau$) separation:

$Y_T = p_T(e/\mu) + p_T(\tau_h) + \not{E}_T$ - or -

Mass reconstruction, where missing energy is split between e/μ and τ_h

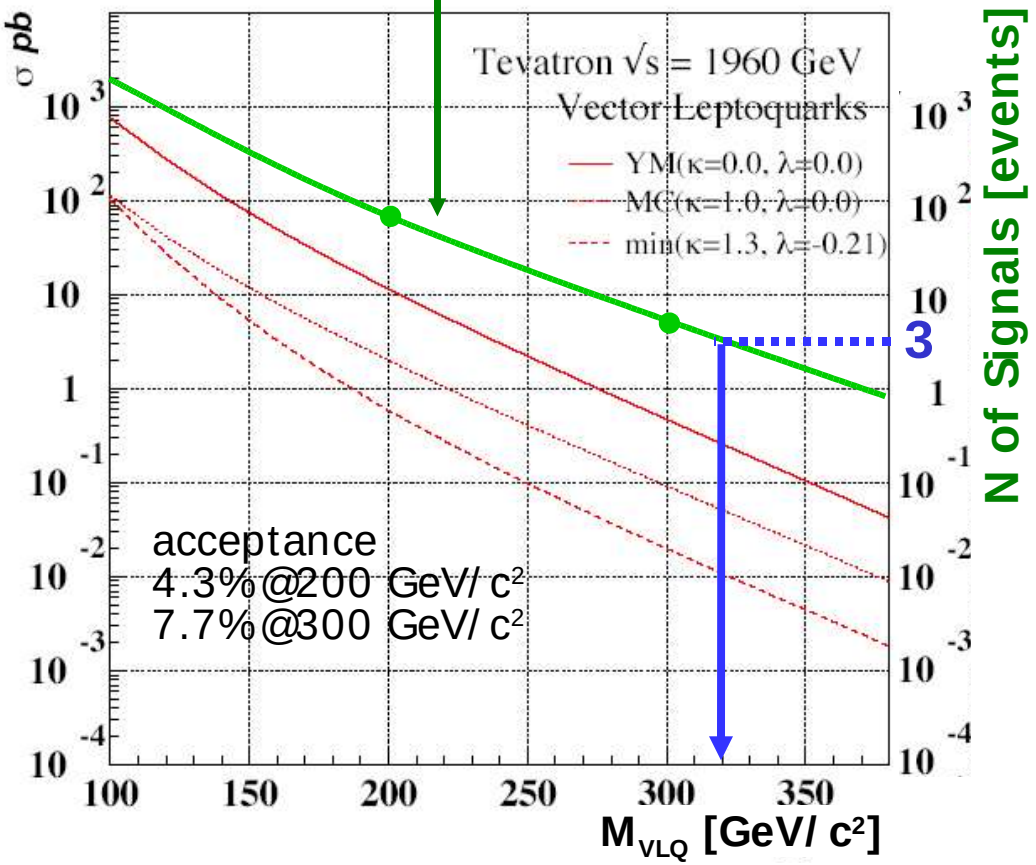




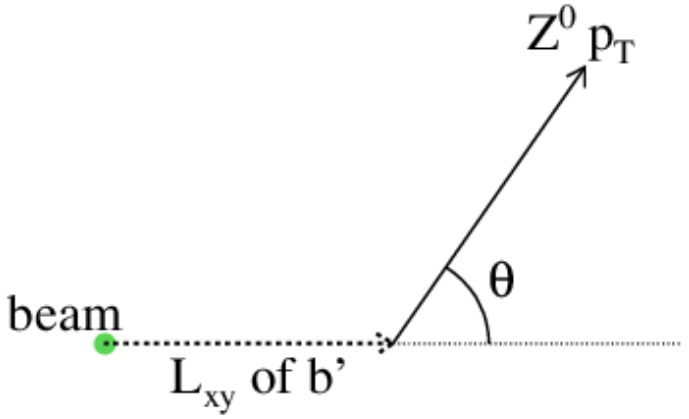


VLQ3: Expected Events

Expected number of signal events in 319 pb^{-1}



b': Definition of L_{xy}



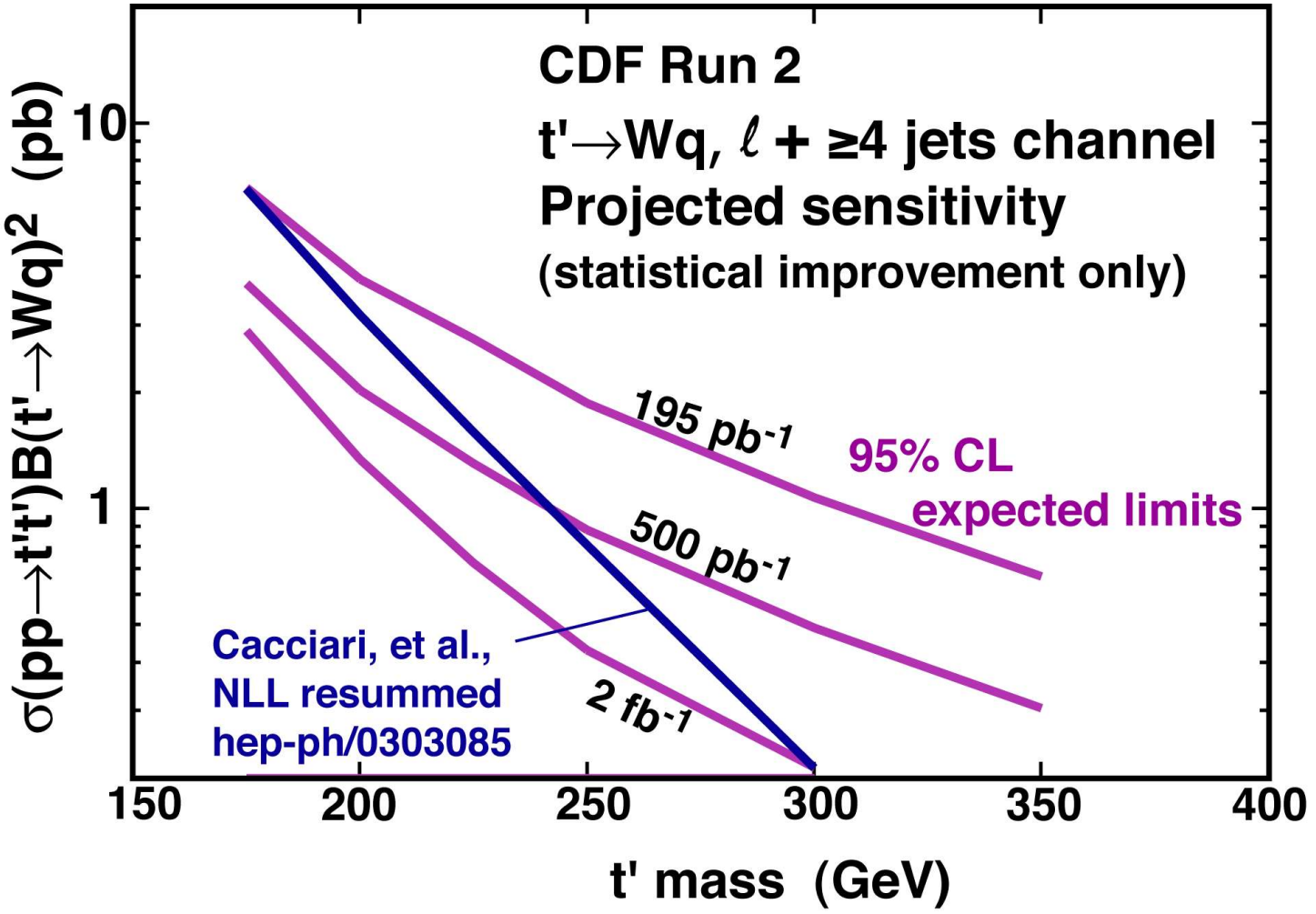
If $\theta < 90^0$, $L_{xy} > 0$

Otherwise, $L_{xy} < 0$

- Positive L_{xy}: Z^0 p_T is in direction of displacement
- Negative L_{xy}: Z^0 p_T is opposite to direction of displacement

- Motivation for this definition:
  - Signal would be toward positive L_{xy}
  - Tracking mis-measurements, which give the largest background, are symmetric in the sign of L_{xy}

t': Projected Limits



- This assumes no improvement in systematic uncertainties