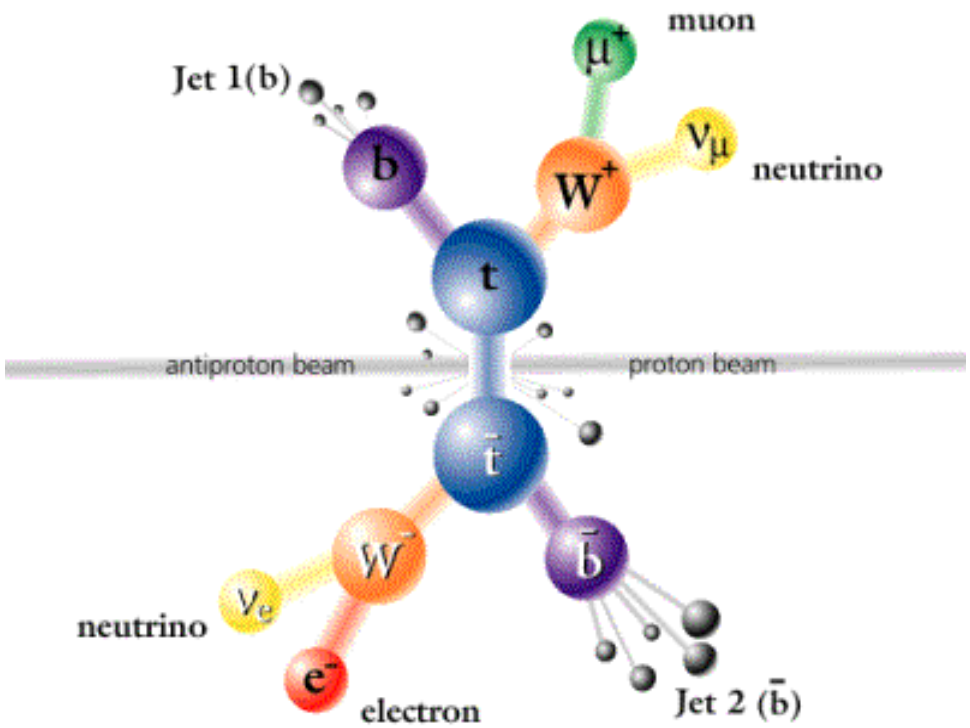
Top Quark Properties at the Tevatron



Markus Klute

Massachusetts Institute of Technology

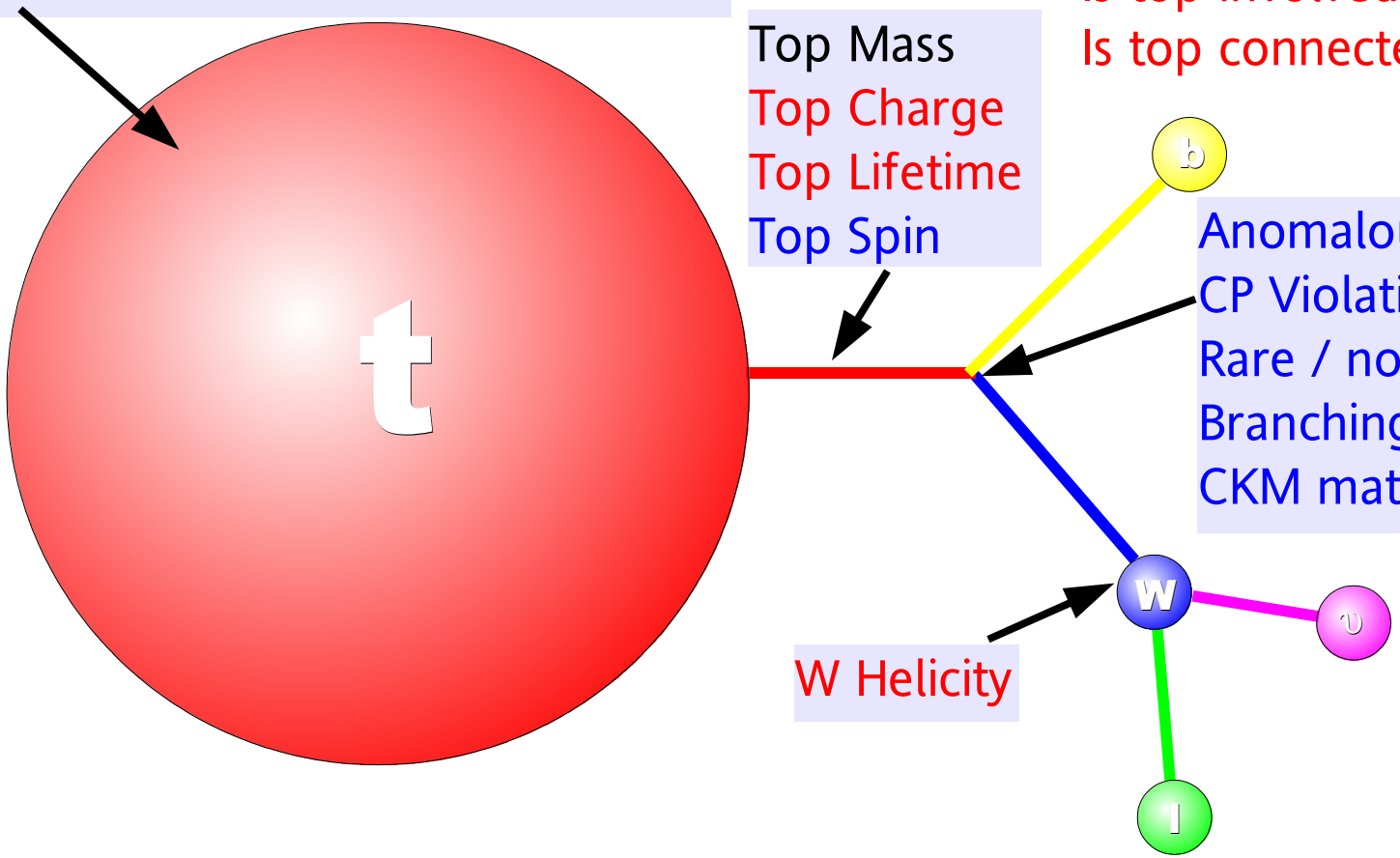
For the CDF and D0 Collaborations

Rencontres de Moriond EWK 2006

Top Quark Physics

Production Cross-Section
Production Kinematics
Spin Polarization
Production via interm. Resonances
t' Production

Tevatron Run I: top quark discovery
Tevatron Run II: high precision tests ...
Why is top so heavy ?
Is top/third generation special ?
Is top involved in EWSB ?
Is top connected to new physics ?



Top Mass
Top Charge
Top Lifetime
Top Spin

Anomalous Couplings
CP Violation
Rare / non-SM Decays
Branching Fractions
CKM matrix element $|V_{tb}|$

W Helicity

Very rich Top Physics program at the Tevatron.

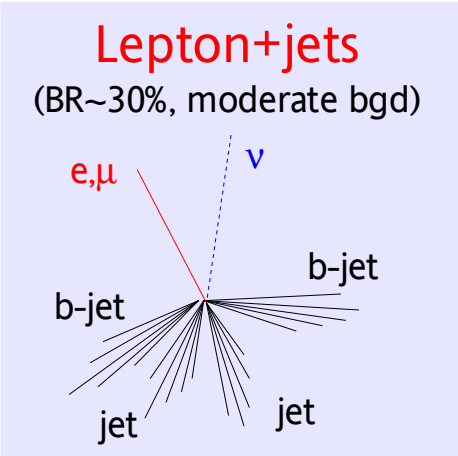
Top Quark Sample

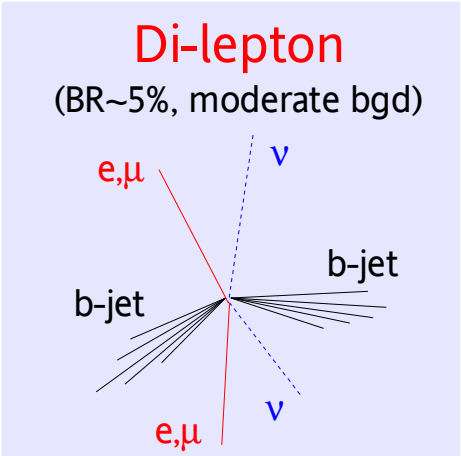
- all top measurements (so far) are based on pair-produced top quarks.

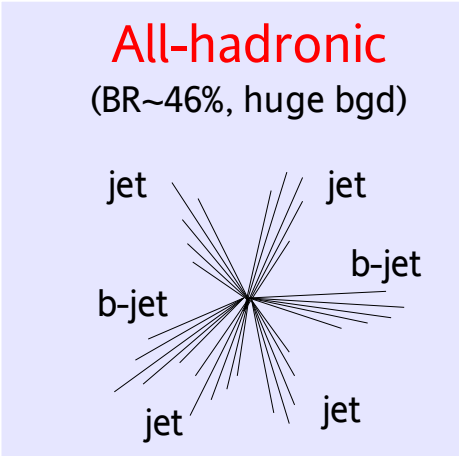
- all top property measurements are limited by statistics.

- all top property measurements are based on final states with at least one lepton.

- typical final state signatures in top pair production:







- analysed sample sizes vary from 150-700pb^{-1}.

- number of candidate events used for top property measurements
  presented here vary from 17 (lepton+jets with 2 b-tags)
  to several hundred candidate events (lepton+jets with 0 b-tag).

Roadmap

- The Tevatron
- CDF and D0 Detectors
- Top Mass Measurements
- Top Production at the Tevatron
- Single Top Searches

Covered in previous talks:

Top Mass from D0: A. Garcia-Bellido
Top Mass from CDF: E. Brubaker
Xsec and Single Top: M. Kopal

- Anomalous Top Pair Production
  * via intermediate Resonances
  * by a long-lived Particle
  * 4th Generation Quarks

- Top Charge

- W-helicity in Top Quark Decays

- Other Top Properties Measurements

- Summary

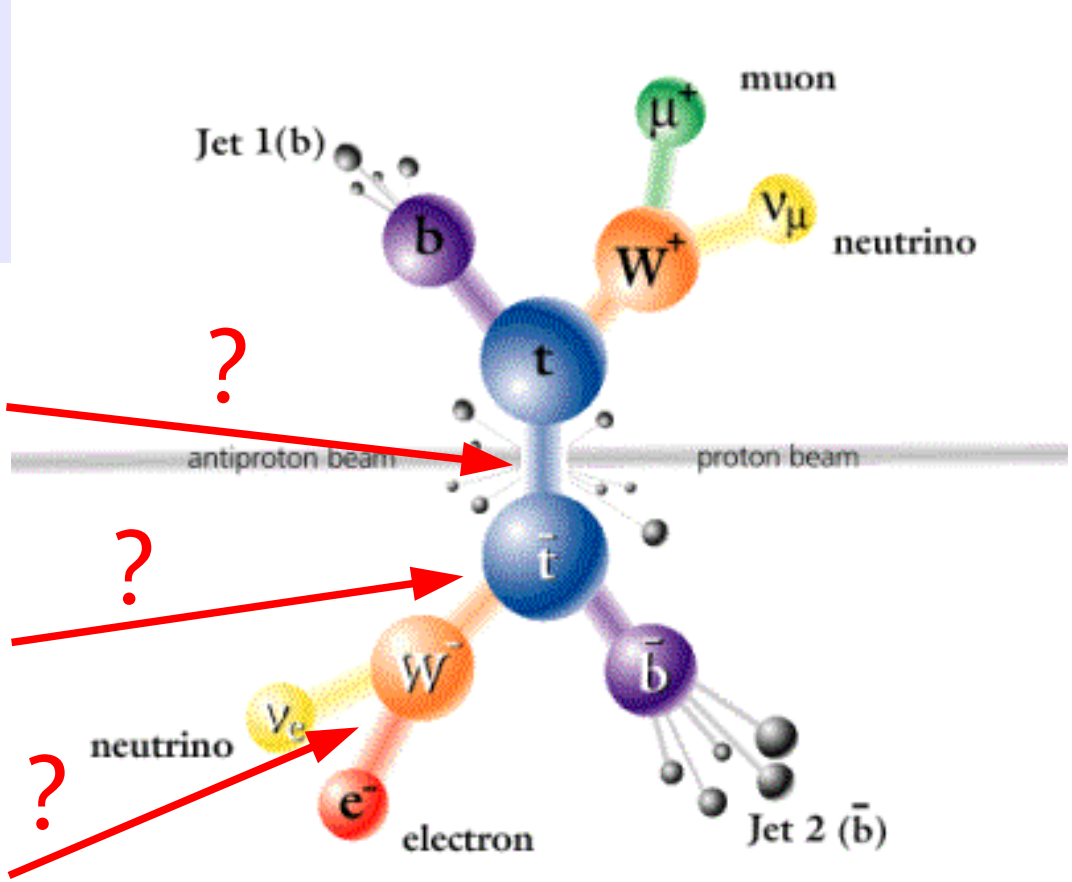
Anomalous $t\bar{t}$ Production

Large number of Standard Model extentions suggest anomalous $t\bar{t}$ – production:

- heavy 4th generation quark (He et al, hep-ph/0102144)
- beautiful mirrors (Wagner et al, hep-ph/0109097)
- exotic quark (hep-ph/98050131)
- 2 Higgs Doublet models
- Z' production
- ...

We try to find answers to questions like:

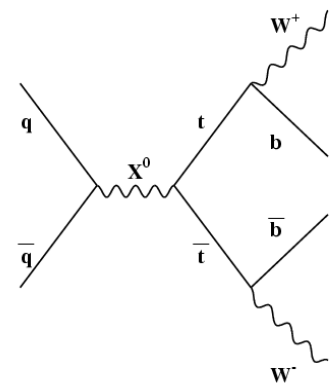
- does something new produce top pairs ?
- can we find something new with large mass and top properties ?
- does the top quark decay into something new ?

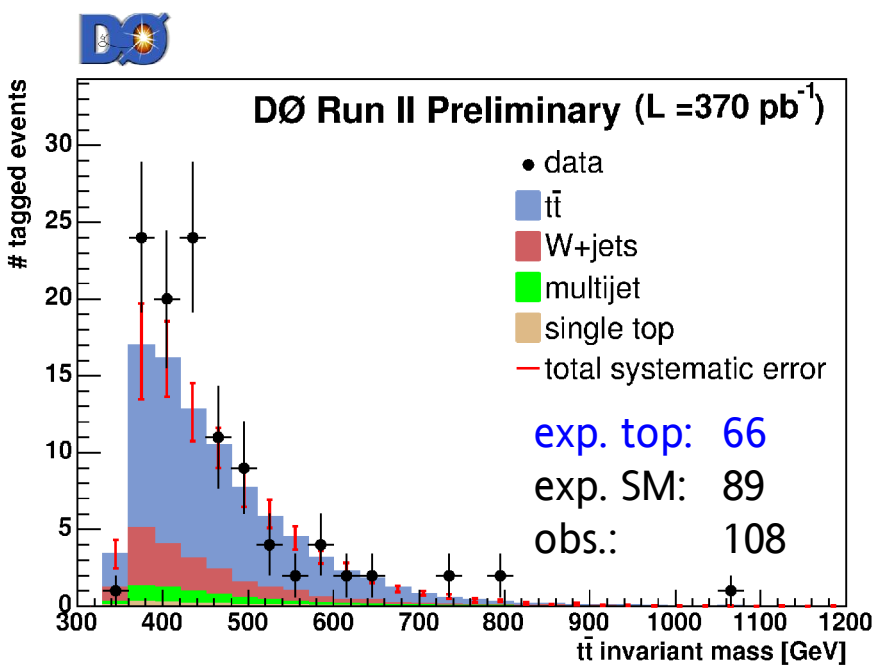


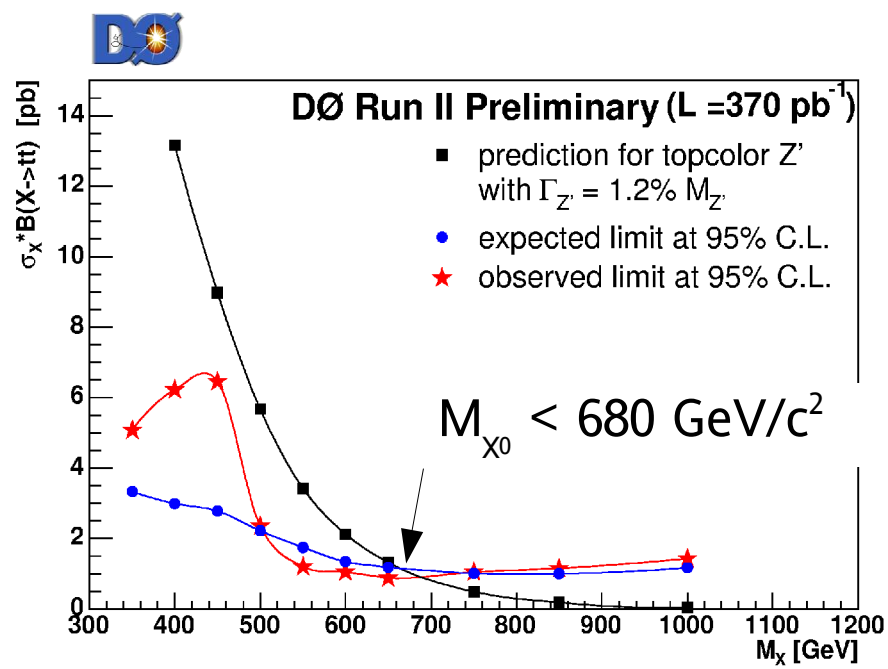
Search for Top Production via intermediate Resonances (I)

Does something new produce top pairs (at D0) ?

- lepton+≥4 jets with ≥1 b-tag in 370pb^{-1}.
- kinematic fit to ttbar hypothesis.
- fix SM ttbar production to expected rate (6.7pb).
- no significant excess observed.
- derive limit on σ_X x BR($X \rightarrow t\bar{t}$).
- interpret in terms of mass limit in possible model,
  e.g. topcolor assisted technicolor Z' (hep-ph/9911288)



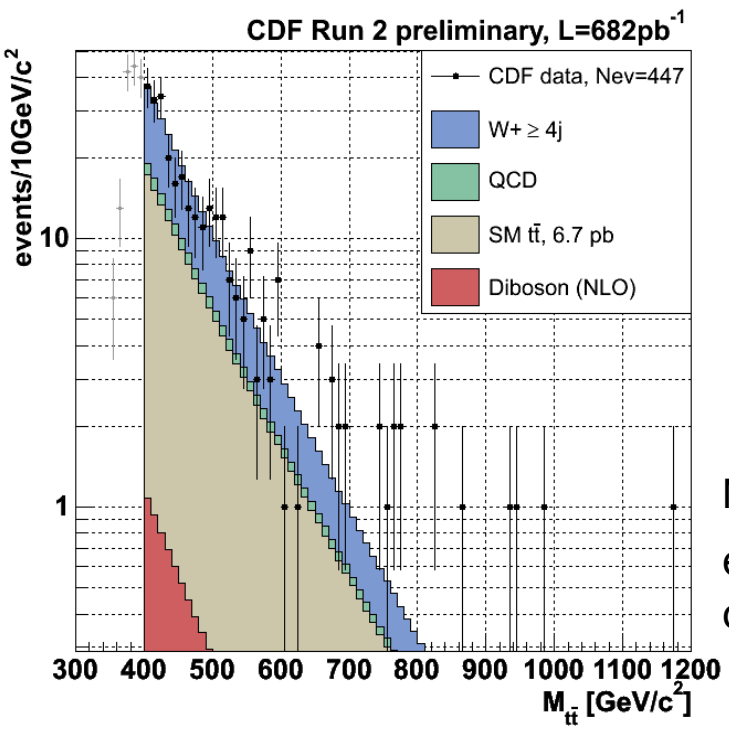




Search for Top Production via intermediate Resonances (II)

Does something new produce top pairs (at CDF) ?

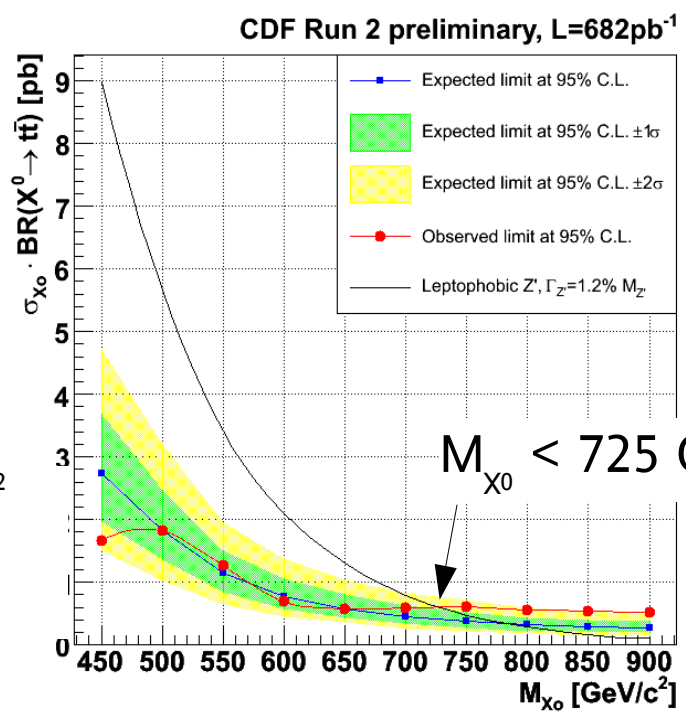
- lepton+≥4 jets (no b-tagging) in 680pb^{-1}.
- use matrix element technique to increase sensitivity.
- fix SM ttbar, diboson, QCD to expected rates.
- assume everything else is W+jets.
- no significant excess observed.



M_{X0} > 400 GeV/c^2

exp. top: 141

obs.: 302

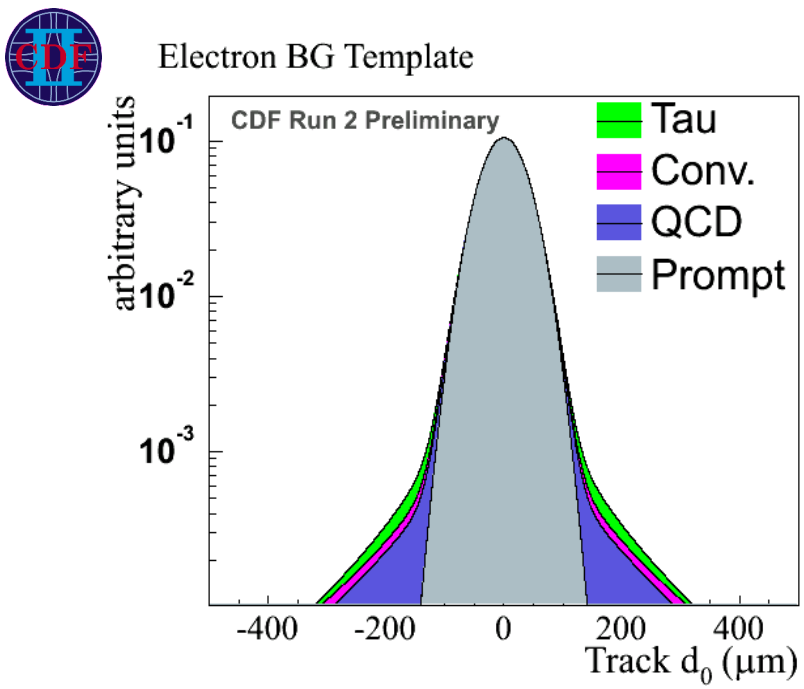


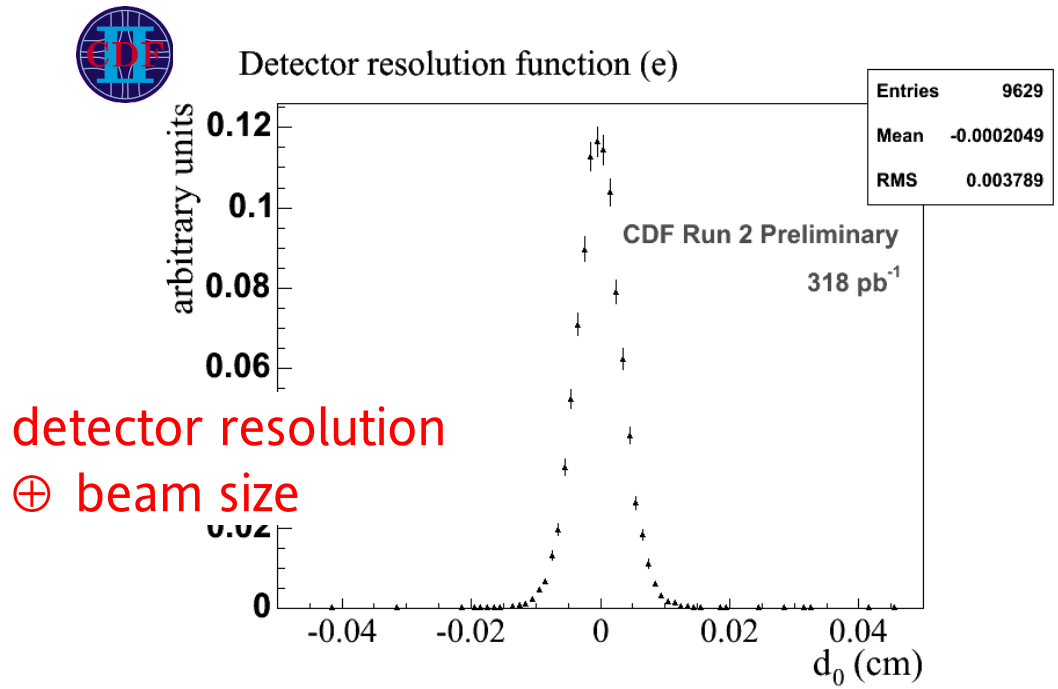
M_{X0} < 725 GeV/c^2

Top Quark Lifetime (I)

Does something new decay into top quarks ? A long-lived particle ?

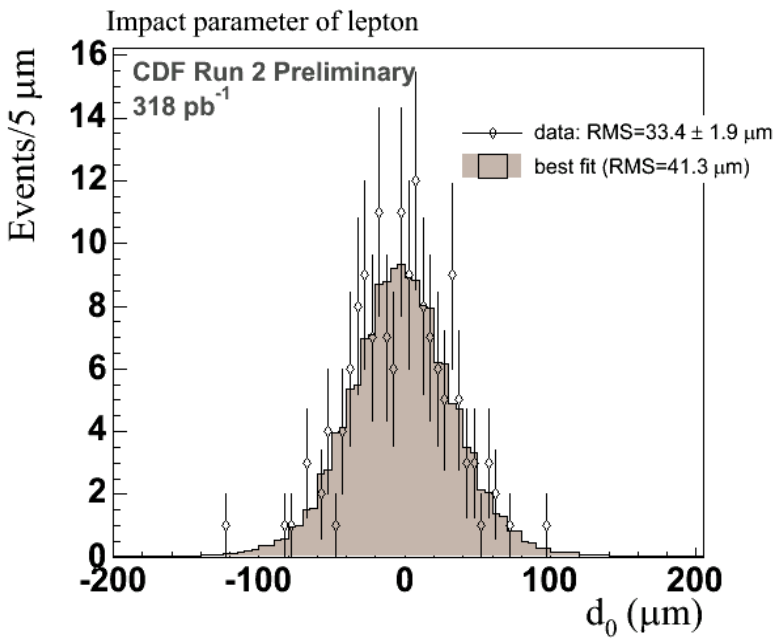
- first direct limit on the lifetime of the top quark.
- top quark lifetime in Standard Model ~ 10^{-24}s ($c\tau = 3\times10^{-10}\mu m$)
- search for anomalous top production by a new, long-lived particle.
- lepton+≥3 jets with ≥1 b-tag in 318 pb^{-1}
  - 97 e candidates
  - 60 μ candidates
- measure the impact parameter d0 for lepton tracks.
- use max. likelihood method with templates of arbitrary lifetime.

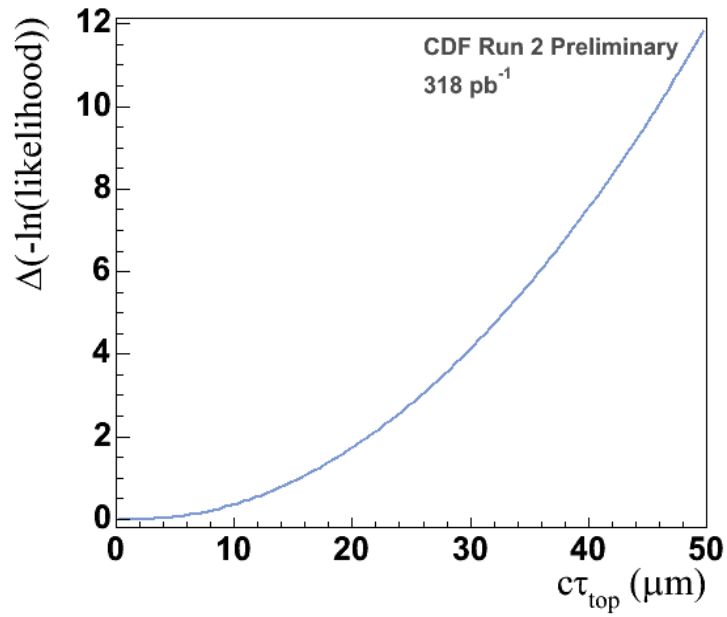


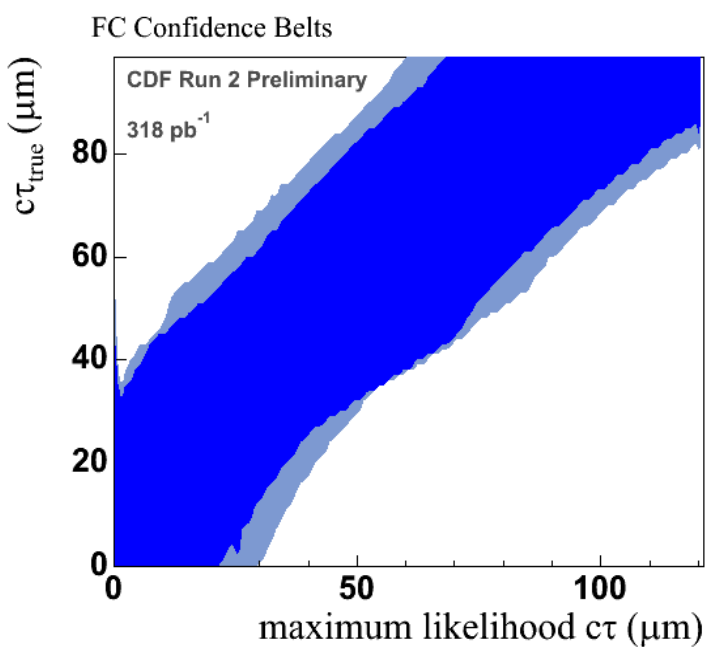


detector resolution
⊕ beam size

Top Quark Lifetime (II)







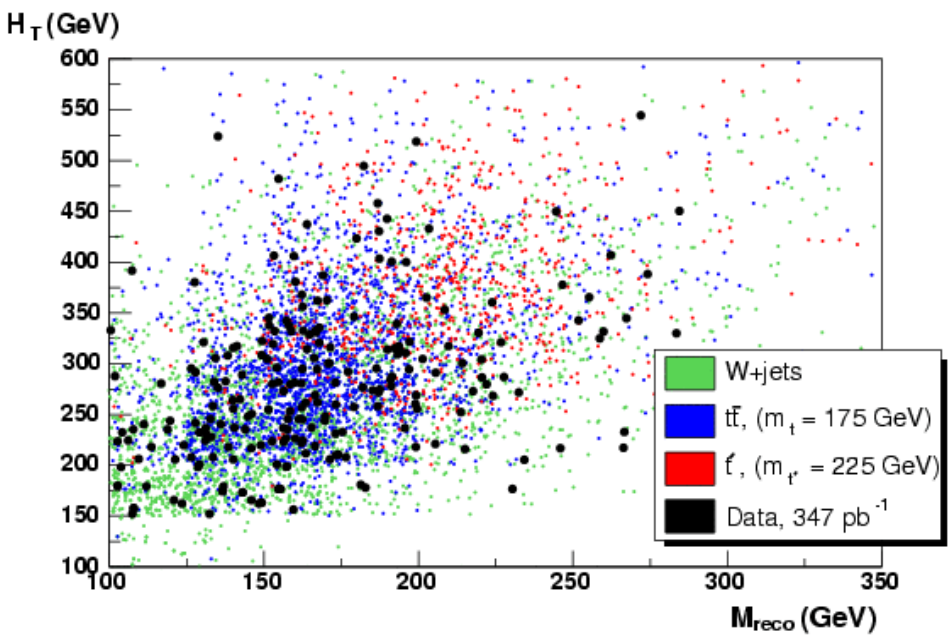
- best fit yields $c\tau = 0\ \mu m$
- extract limit on top quark lifetime
  $c\tau < 53\ \mu m$ @ 95% CL.

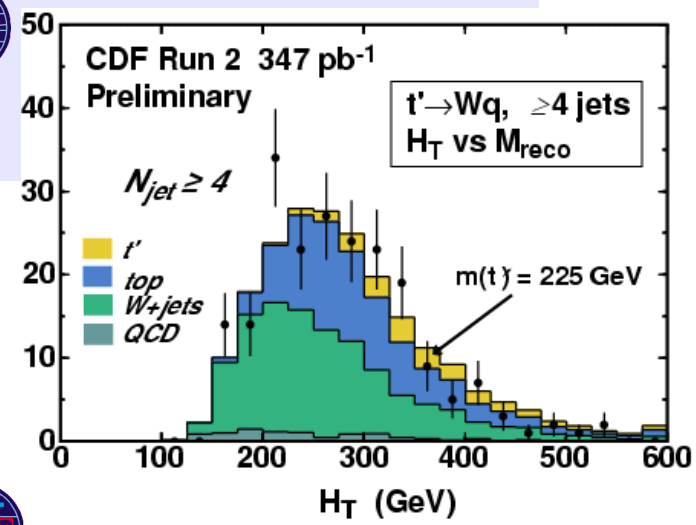
Top' Quark Search (I)

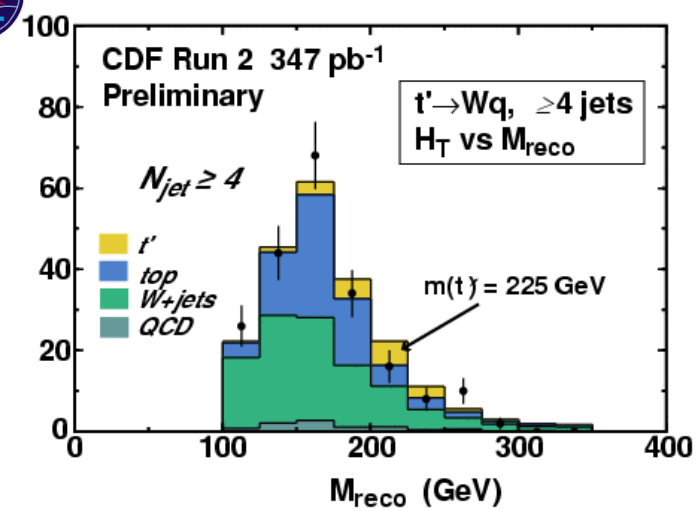
Can we find something new with large mass and top properties?

Heavy quarks (4th generation) t' → Wq exist in various extensions of the SM.

- search for t' → Wq in lepton + jets + missing E_T events (CDF, 347pb^{-1})
- try to remain model independent
- reconstruct t' candidate mass
- fit templates in (H_T, $M_{t'}$)



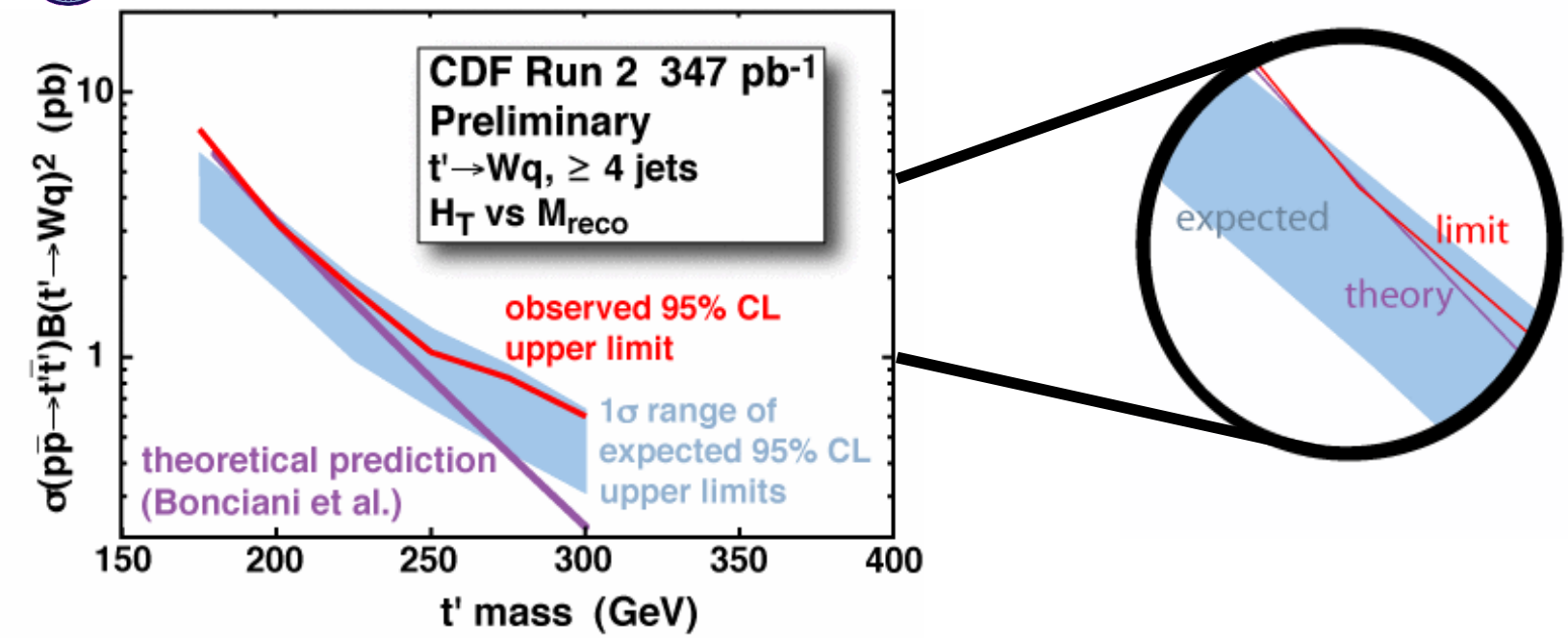




- no evidence for t' in 347pb^{-1}

Top' Quark Search (II)

t' cross section limit.



translate cross section limit into a t' prime mass limit of

196 – 207 GeV/c^2 @ 95 CL

for a true top mass of 175 GeV/c^2.

expect m(t') > 300 GeV/c^2 with 2fb^{-1} unless ...

Roadmap

- The Tevatron
- CDF and D0 Detectors
- Top Mass Measurements
- Top Production at the Tevatron
- Single Top Searches

} Covered in previous talks:

- Anomalous Top Pair Production
  * via intermediate Resonances
  * by a long-lived Particle
  * 4th Generation Quarks

} Covered in this talk ...
no evidence for new physics.

- Top Charge

- W-helicity in Top Quark Decays

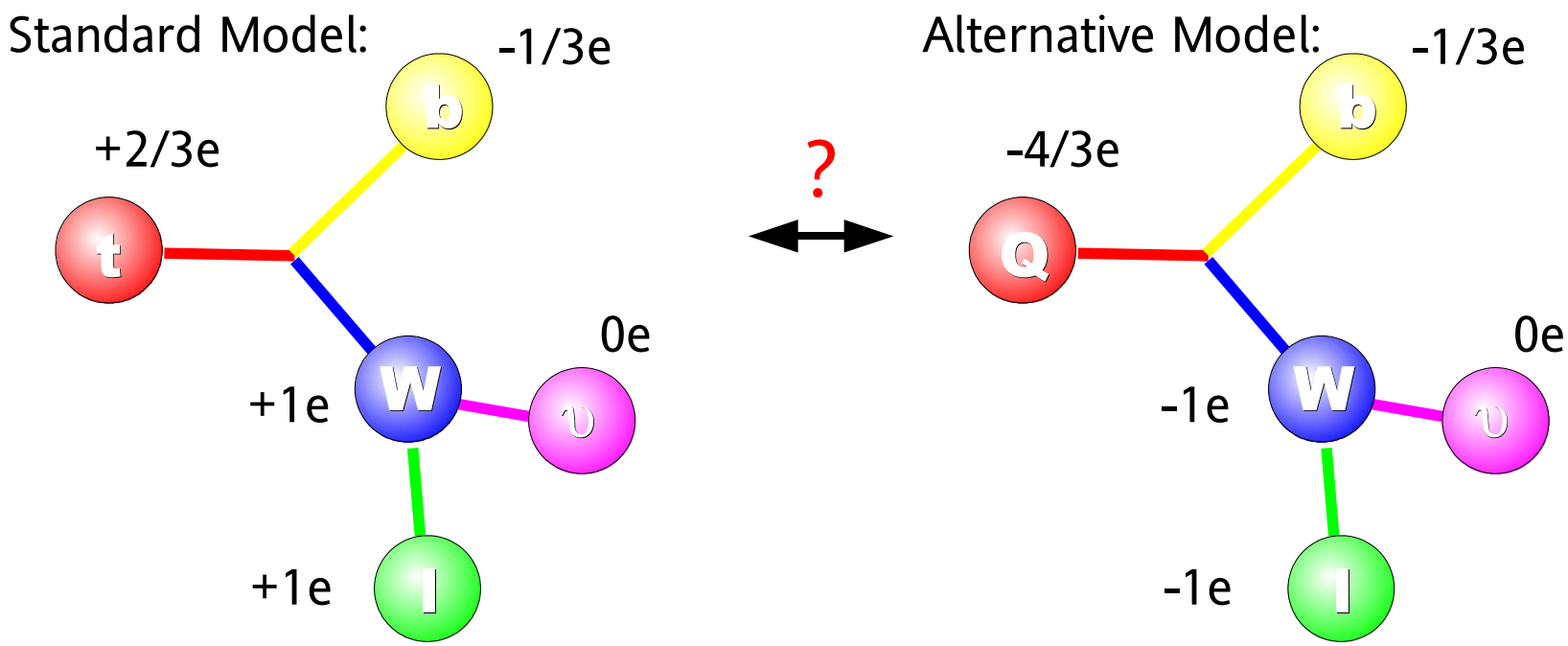
- Other Top Properties Measurements

- Summary

Top Quark Charge (I)

SM: Top Charge +2/3e
Other Models predict -4/3e

Strategy:
- measure $\sigma(t + \gamma)$ (@ LHC)
- b-jet charge (here)



Analysis Strategy at D0:

a) associate lepton and b quark to top quark
   use a kinematic fit for ttbar hypothesis

b) determine charge of the b-jet
   p_T weighted sum of charged tracks associated to a b-jet.

e.g.: exotic 4th generation + Higgs triplet.
D. Chang et al. Phys Rev D59, 09153 (1999)

Current cross section measurements would not contradict two possible top quark charges.

Top Quark Charge (II)

Very first measurement of one of the most fundamental top properties:

D0 RunII (365pb^{-1})

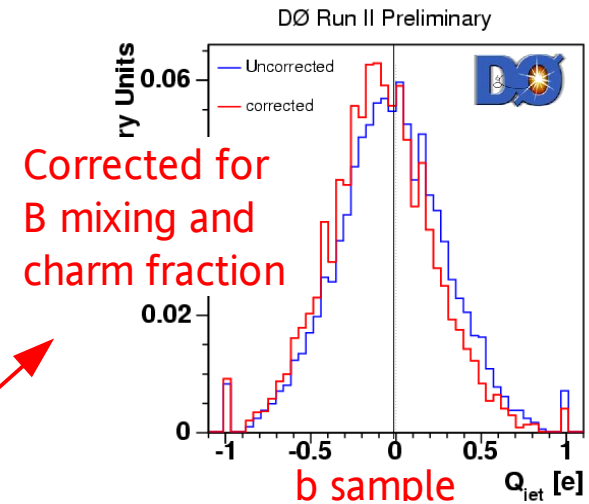
- 17 candidate events with two tagged b-jets, lepton, missing E_T, ≥ 4 jets.
- two entries per event for top and anti-top.
- discriminate b and bbar with track charge algorithm,

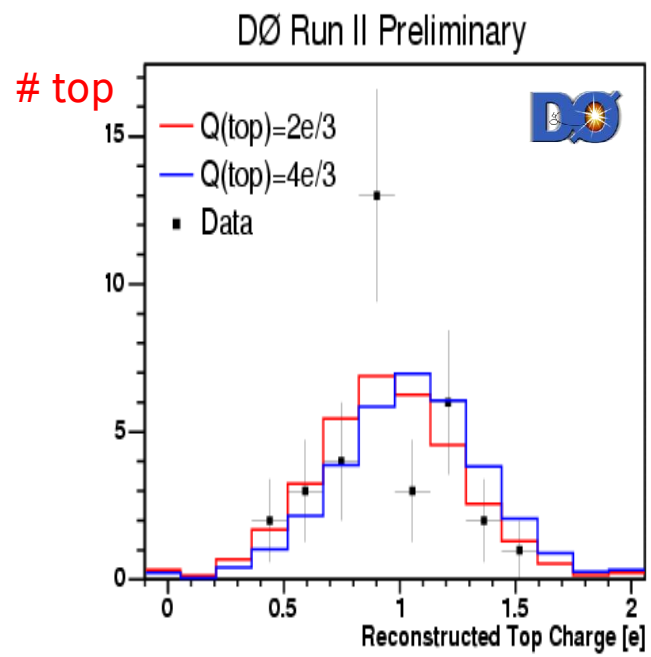
$$q_{jet} = \frac{\Sigma_i q_i p_{Ti}^{0.6}}{\Sigma_i p_{Ti}^{0.6}}$$, pT > 0.5 GeV & $\Delta R < 0.5$.

- calibrate Monte Carlo with data using two jet heavy flavor sample with opposite jet tagged with μ flavor.

- excluded the hypothesis of an exotic quark with charge = -4/3 e at 94% confidence level.

- CDF result with 1fb^{-1} coming ...

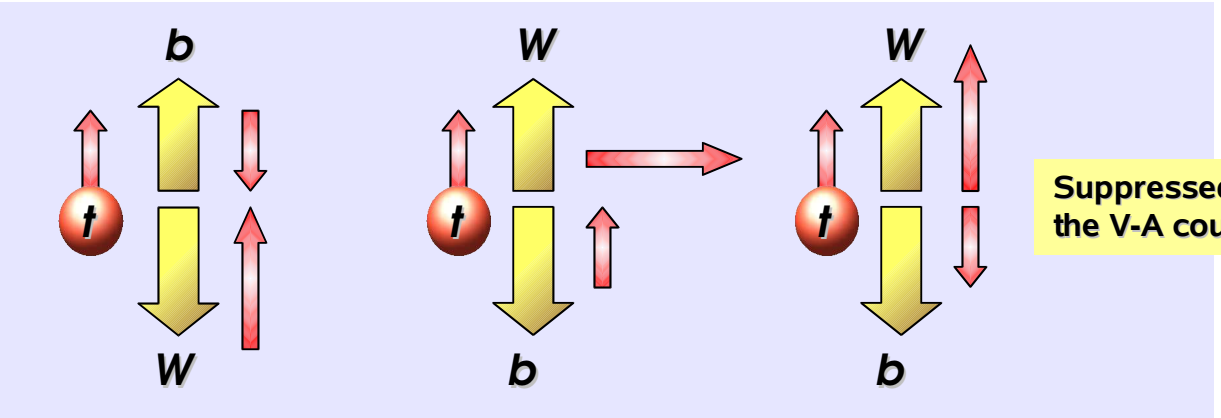




Helicity of the W (I)

Top decays via weak interaction → V-A coupling like all other quarks: $\frac{-ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}(1-\gamma^{5})V_{tb}bW_{\mu}$

W helicity manifests itself in decay product kinematics.

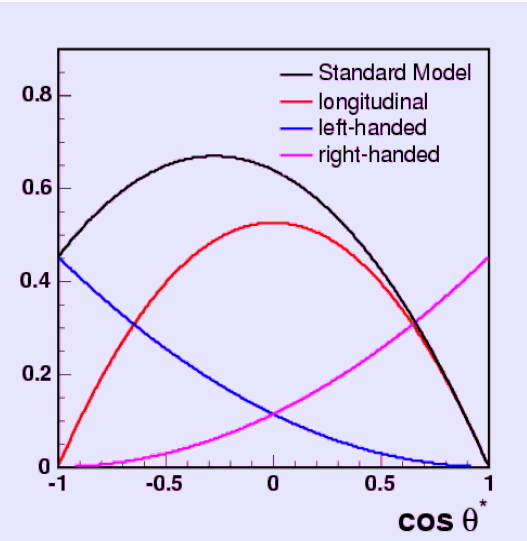


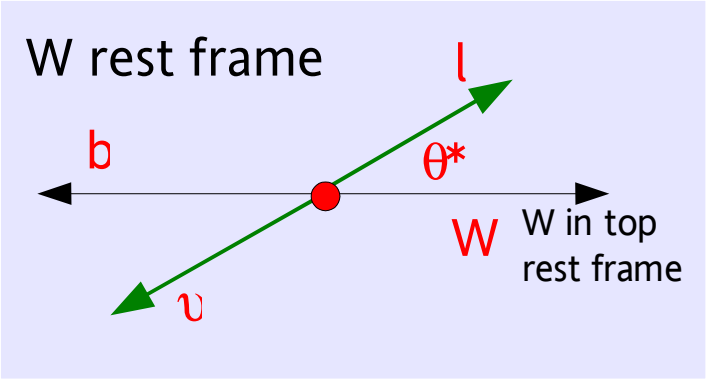
F_- : left-handed fraction

F_0 : longitudinal fraction

F_+ : right-handed fraction

$$F_- = \frac{2\frac{m_W^2}{M_{top}^2}}{1+2\frac{m_W^2}{M_{top}^2}} \approx 0.30 \qquad F_0 = \frac{1}{1+2\frac{m_W^2}{M_{top}^2}} \approx 0.70 \qquad F_+ \propto (m_b/m_t)^2 \approx 0$$





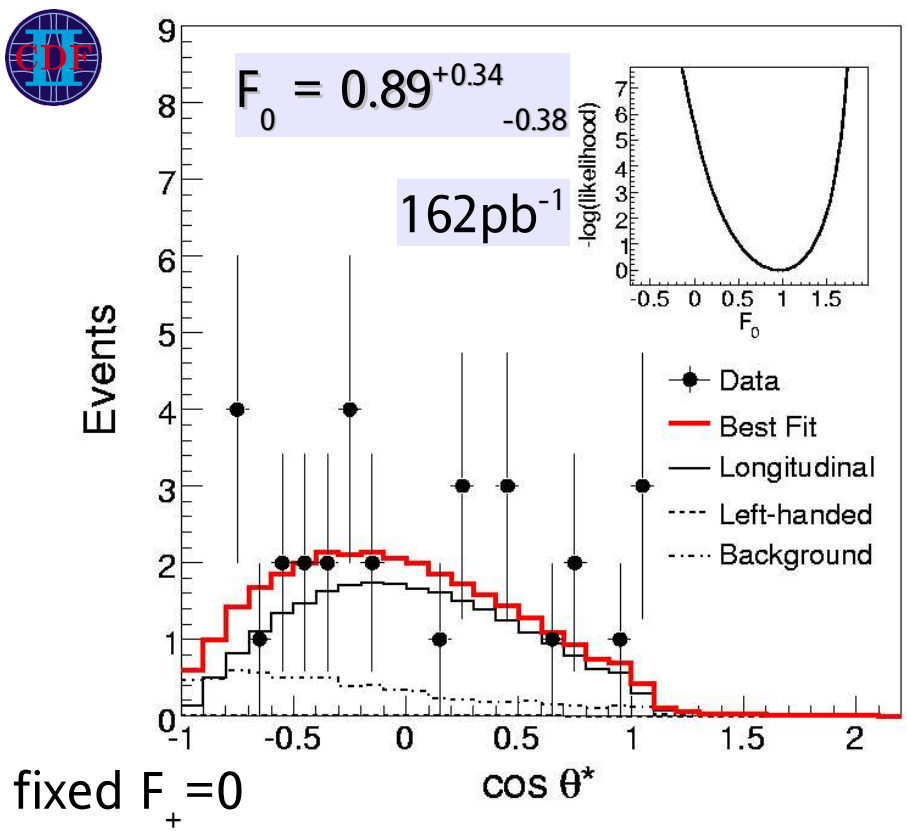
$$w(\cos\theta) = F_- \cdot \frac{3}{8}(1-\cos\theta)^2 + F_0 \cdot \frac{3}{4}(1-\cos^2\theta) + F_+ \cdot \frac{3}{8}(1+\cos\theta)^2$$

Helicity of the W (II)

cosθ* (m_{lb}) method:

- lepton+jets with 1b-tag sample
- full event reconstruction
- approximation for cosθ*

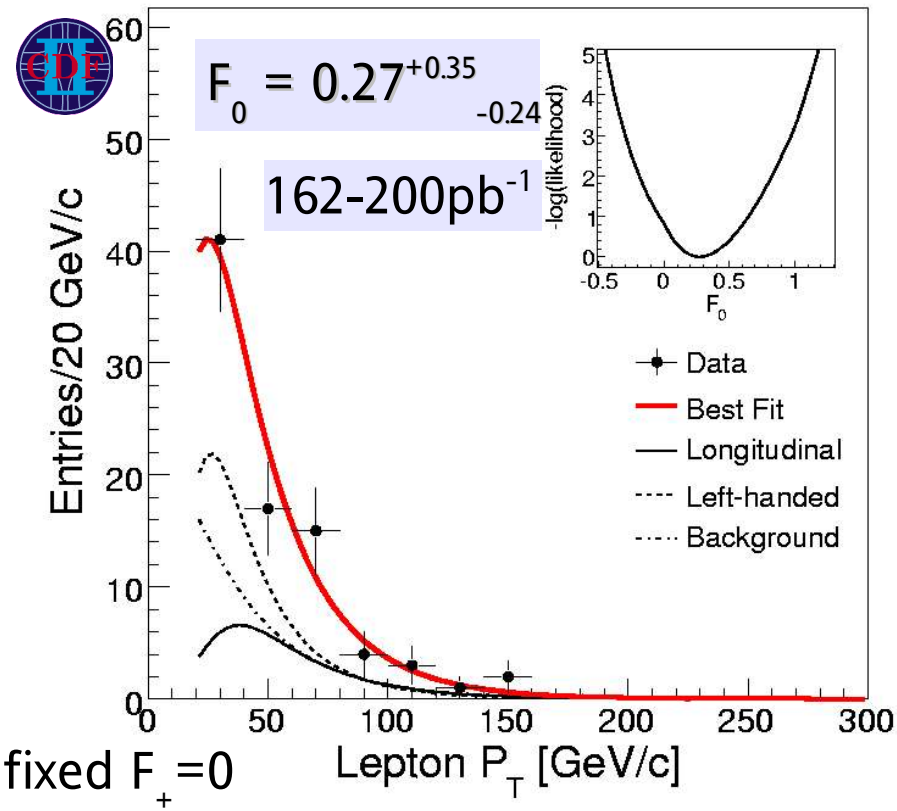
$$\cos\theta^* = \frac{2\, m_{lb}^2}{m_t^2 - m_W^2} - 1$$



fixed F_+=0

charged lepton p_T method:

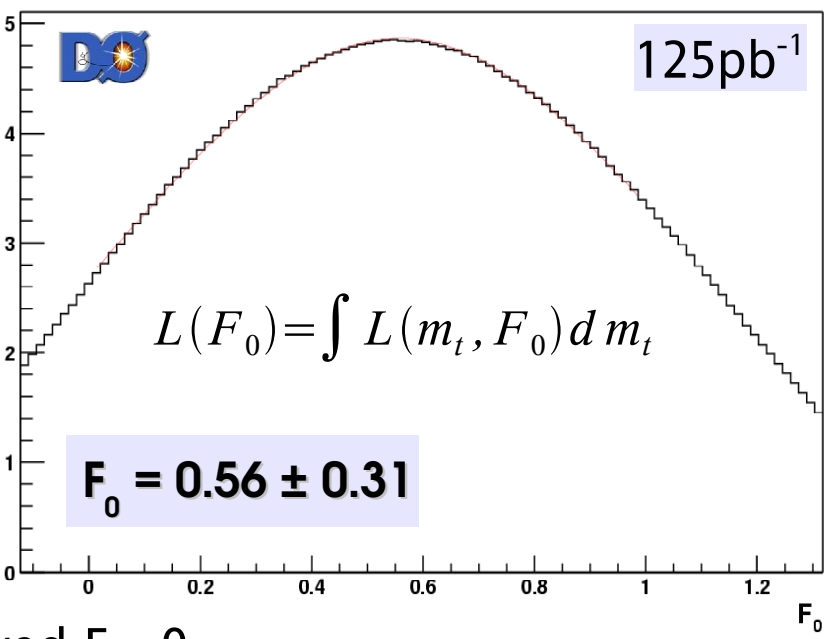
- left-handed W lepton p_T soft
- longitudinal W lepton p_T harder
- lepton+jets with 1, 2btags and dilepton sample.



fixed F_+=0

Helicity of the W (III)

matrix element method:
- a la D0 Run-I m_t measurement
- lepton+jets sample (Run-I)
- increase statistical precision



fixed F_+=0

Our knowledge on F_0:

D0 RunI	125pb^{-1}	$F_0=0.56 \pm 0.32$
CDF RunII	200pb^{-1}	$F_0=0.74^{+0.22}_{-0.34}$

... no deviation from the SM predicition.

CDF & D0 will update with 1fb^{-1} this Summer.

So far, fixed F_+=0 and fitted F_0.

Next slide, fix F_0=0.7 and fit F_+.

Eventually, do simultaneous fit for F_0 and F_+.

Helicity of the W (IV)

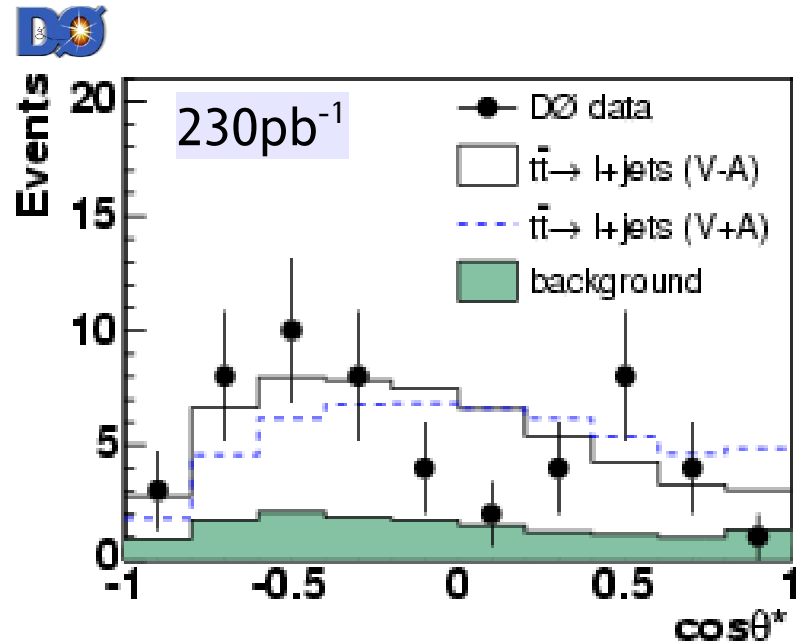
Observation of positive helicity ($F_+ > 0$) would indicate V+A coupling.

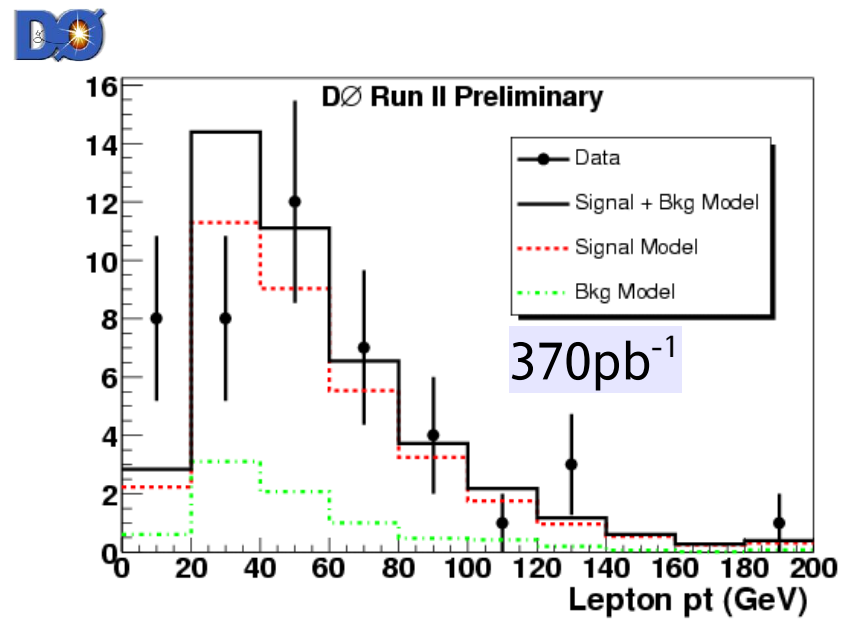
D0 measurements:

a) lepton+jets with topological + b-tag selection used $\cos\theta^*$ method.

b) dilepton selection used charged lepton p_T method.

- $F_+^{comb} = 0.04 \pm 0.11(\text{stat.}) \pm 0.06\ (\text{syst.})$





Our knowledge on F_+:

CDF RunI	110pb^{-1}	$F_+ < 0.18$	@ 95%CL
CDF RunII	200pb^{-1}	$F_+ < 0.27$	@ 95%CL
D0 RunII	230-370pb^{-1}	$F_+ < 0.25$	@ 95%CL

... no deviation from the SM predicition.

Summary (I)

Table of Top Property Results:

Measurement	Best Results	Dataset
Mass	172.0 +/- 2.7 GeV/c^2	680pb^{-1}
Cross Section	7.3 +/- 1.1 pb	760pb^{-1}
W Helicity	F_0 = 0.74+0.22-0.34	162pb^{-1}
W Helicity	F_+ < 0.18 @ 95%CL	109pb^{-1}
Top Charge	rule out +4/3 model @ 94%CL	365pb^{-1}
Resonance Searches	M_{x0} < 765 GeV/c^2	682pb^{-1}
Top Lifetime	$c\tau$ < 52 μm @ 95%CL	318pb^{-1}
4th Generation t' Quark	196 < M(t') < 207 GeV/c^2 @ 95%CL	347pb^{-1}
Charged Higgs Searches	Limits on BR(t->H+b)	194pb^{-1}
Anomalous Kinematics	no high p_T excess	194pb^{-1}
BR(t->Wb) / BR (t->Wq)	> 0.61 @ 95%CL	230pb^{-1}
Single Top	s-channel: σ (tb) < 5.0 pb	370pb^{-1}
Single Top	t-channel: σ (tqb) < 4.4 pb	370pb^{-1}
Spin Correlation	κ > -0.25	125pb^{-1}
...	...	...

Limited by statistics!

Summary (II)

The Top Quark is unique among the six quarks.

The Tevatron has a very rich top physics program:
mass, production (strong & weak), decays, width, charge, spin, couplings, ..., window into new physics.

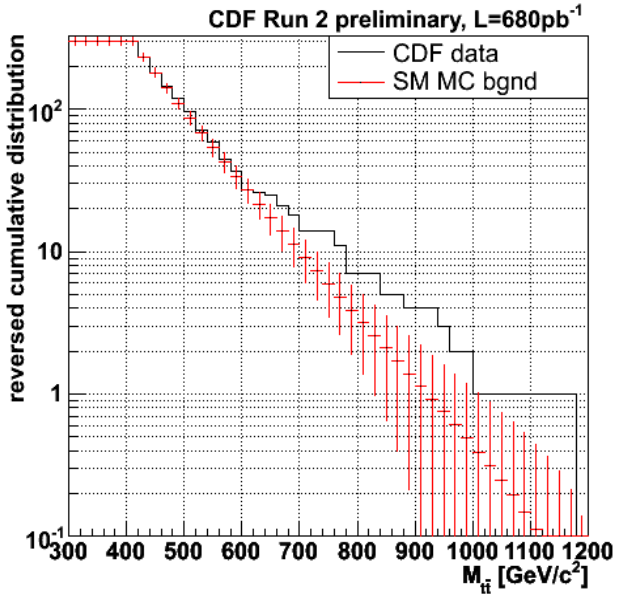
We will study the Top Quark and its role in Nature with unprecedented precision.

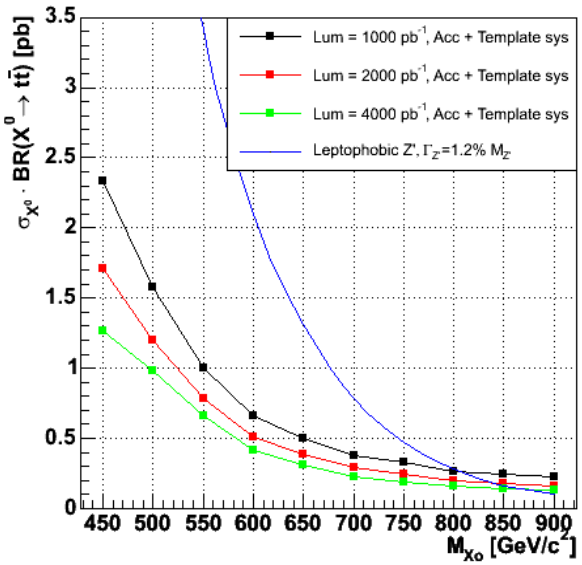
So far, observed Top Quark is consistent with Standard Model.

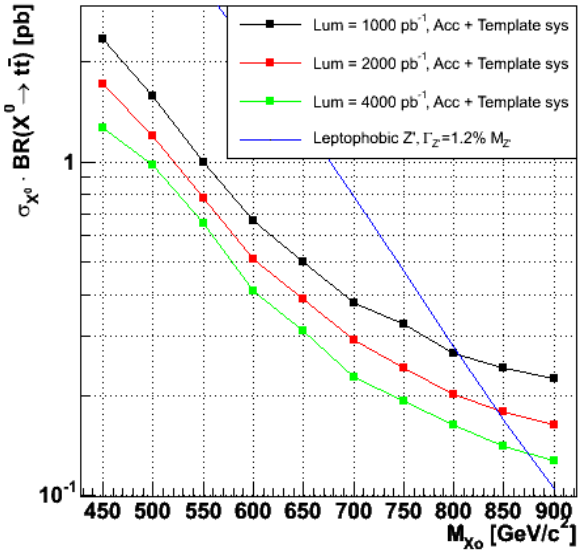
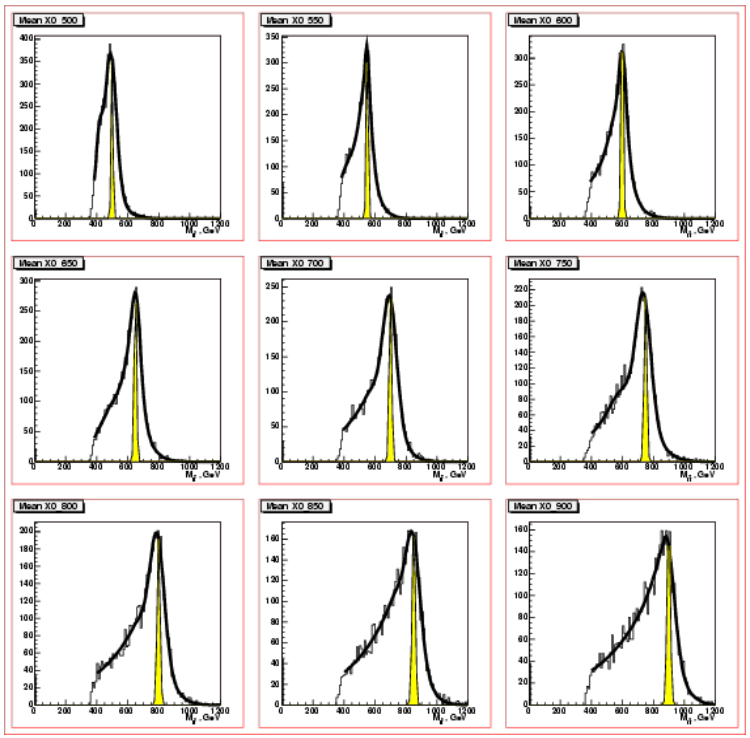
Open question:
Does physics beyond the Standard Model hide in large Top Quark samples collected at the Tevatron?

Expect results with $1 fb^{-1}$ datasets from CDF and D0 in Summer 2006.

Backup


CDF Run 2 preliminary, L=680pb^{-1}
CDF data
SM MC bgnd
reversed cumulative distribution
$M_{t\bar{t}}$ [GeV/c^2]


Lum = 1000 pb^{-1}, Acc + Template sys
Lum = 2000 pb^{-1}, Acc + Template sys
Lum = 4000 pb^{-1}, Acc + Template sys
Leptophobic Z', $\Gamma_{Z'}$=1.2% $M_{Z'}$
$\sigma_{X^0} \cdot BR(X^0 \to t\bar{t})$ [pb]
M_{X_0} [GeV/c^2]


Lum = 1000 pb^{-1}, Acc + Template sys
Lum = 2000 pb^{-1}, Acc + Template sys
Lum = 4000 pb^{-1}, Acc + Template sys
Leptophobic Z', $\Gamma_{Z'}$=1.2% $M_{Z'}$
$\sigma_{X^0} \cdot BR(X^0 \to t\bar{t})$ [pb]
M_{X_0} [GeV/c^2]