Tevatron Top Physics

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(for the D0 and CDF collaborations)

LX1Vth Rencontres de Moriond – EWK – March 10, 2009

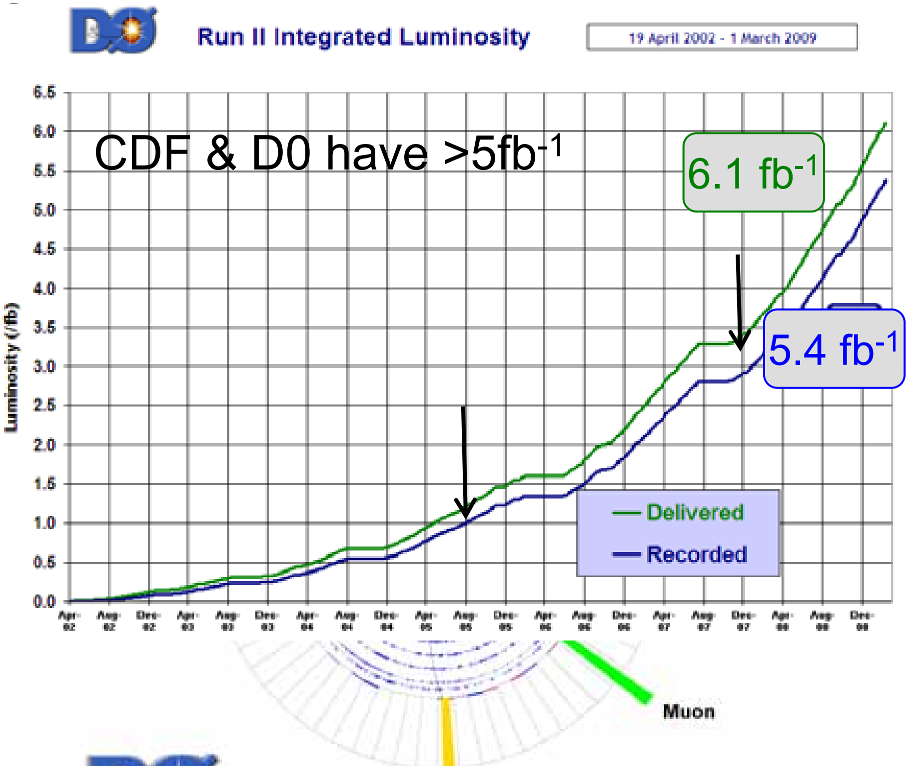
top at Fermilab

- 14 years ago…

…we observed a few handfuls of top quarks

…and celebrated at Moriond 1995

- Last week…
- today…



…we are performing detailed studies of 1000's of top decays

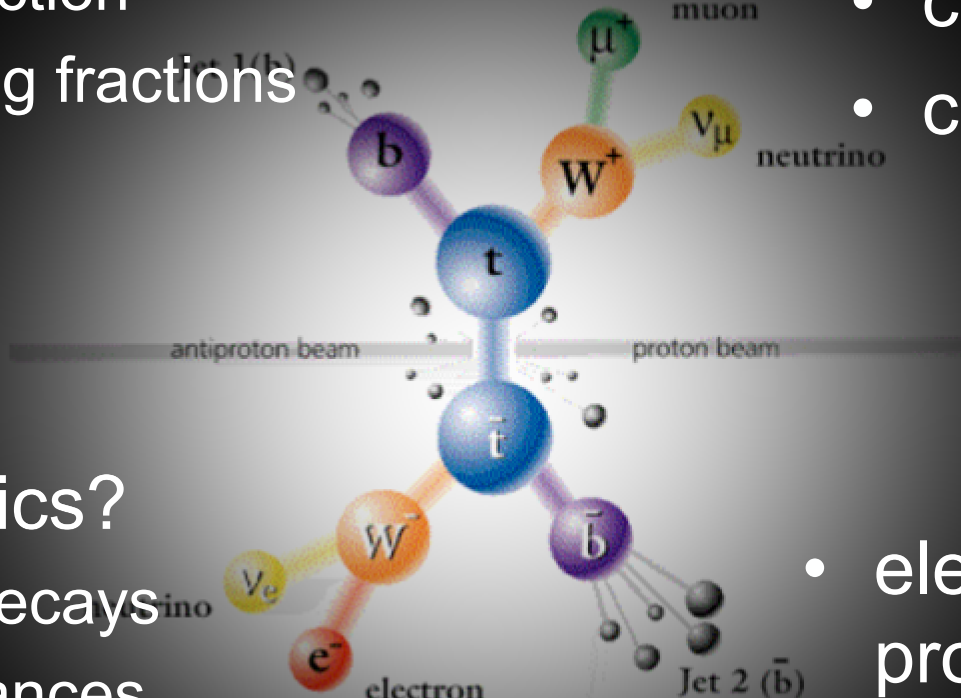
…time to celebrate again!

outline

- strong production
  - cross section
  - branching fractions

This talk

- mass
- couplings
- charge

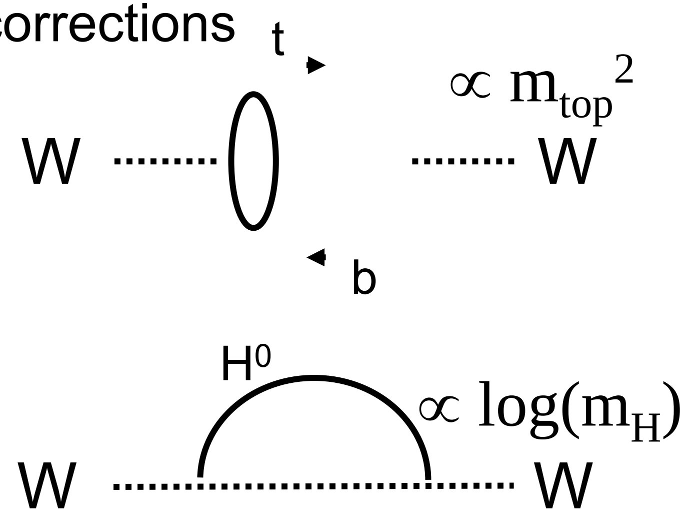


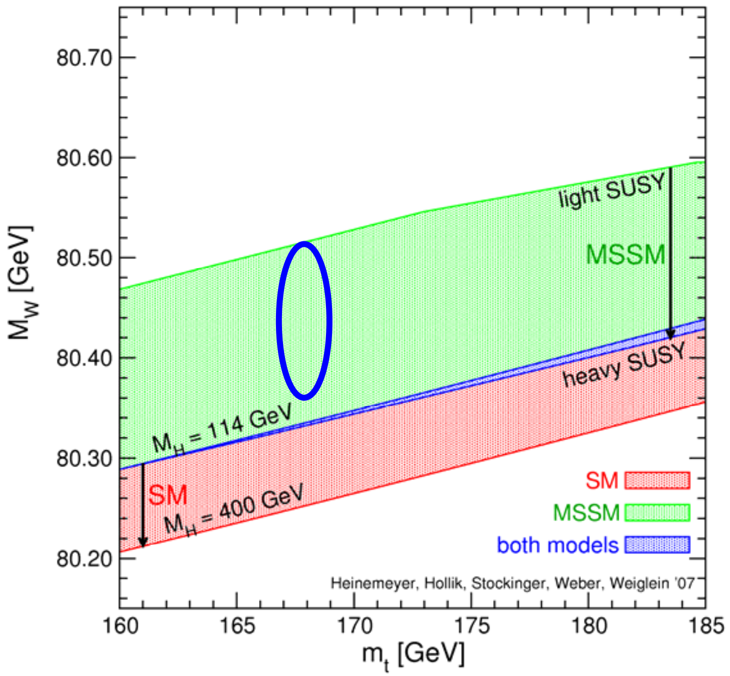
- new physics?
  - FCNC decays
  - tt resonances
  - tb resonances
  - H^+
  - ....

- electroweak production
  - $|V_{tb}|$

why is the top quark important?

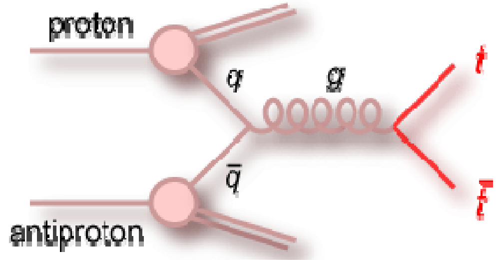
- most massive elementary particle
  - dominant contributor to radiative corrections





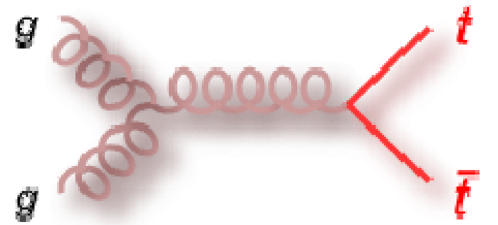
  - how is its mass generated?
    - topcolor?
  - does it couple to new physics?
    - massive G, heavy Z', H^+, …

top-antitop production



- strong interaction

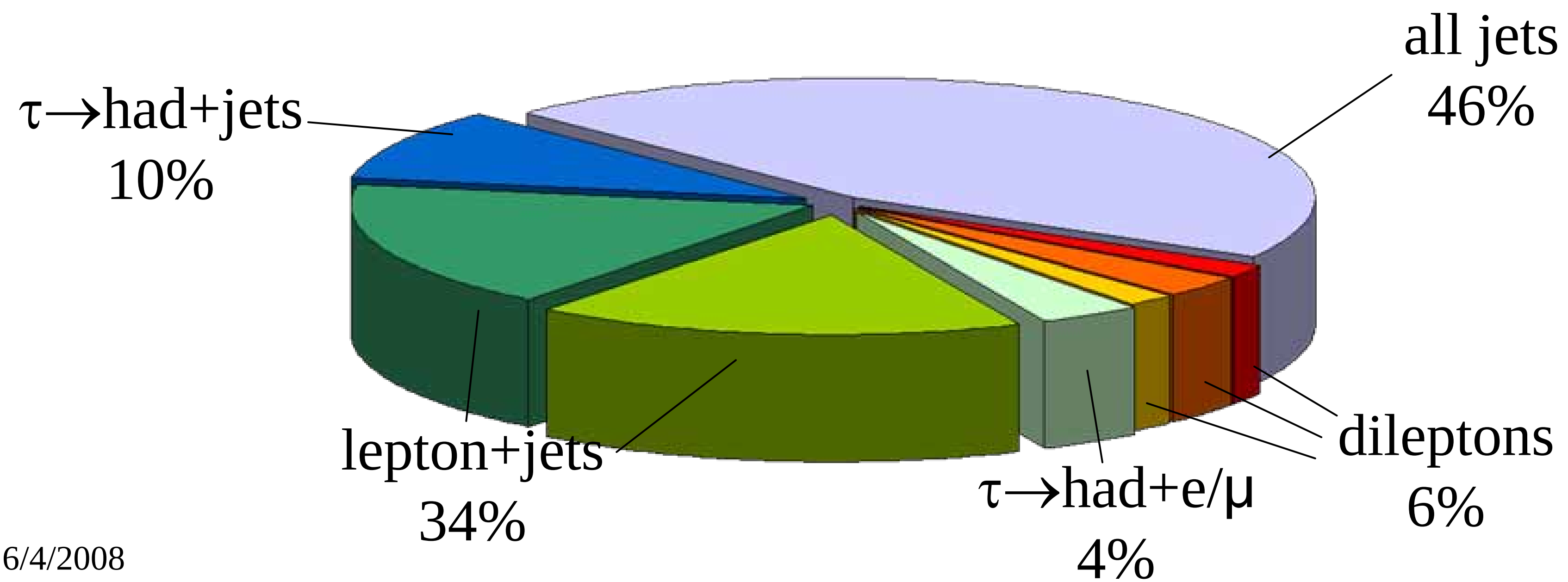
  → top-antitop pairs (σ = 7.6±0.6 pb)



- final state signatures for top-antitop pairs
- t→Wb with $B \approx 100\%$

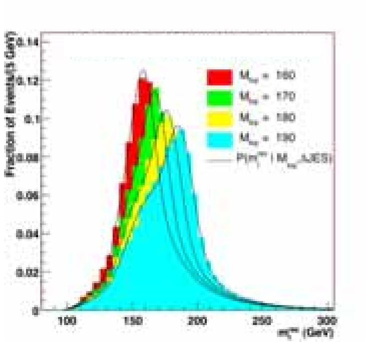
  →tagging b-jets important

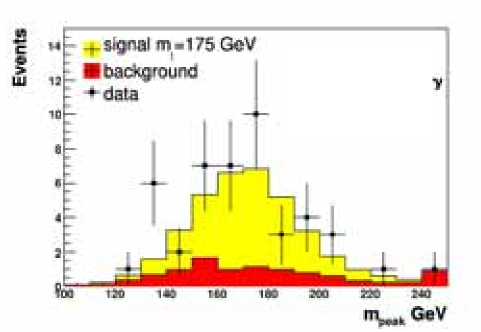
  – W→qq with $B \approx 67$ %; W→$\ell\nu$ with $B \approx 11\%$
  – τ→e$\nu\nu$/$\mu\nu\nu$ with $B \approx 17$ %

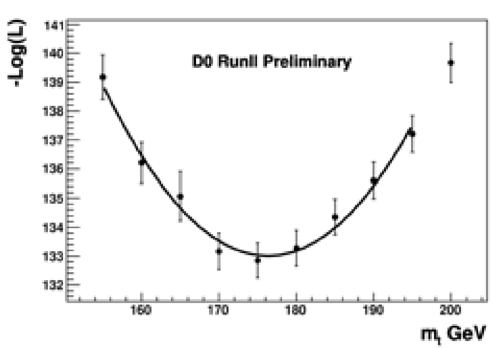


top mass measurement

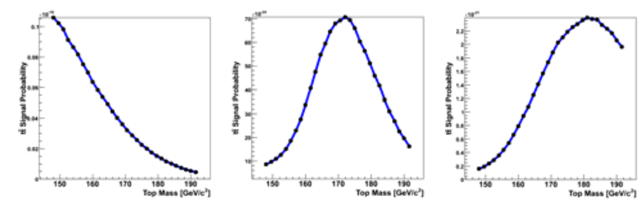
- template fits
  - mass estimator (eg best m_t from kinematic fitter)
  - fit probability density functions from simulated tt events and background to data



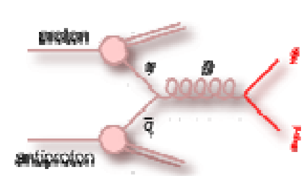


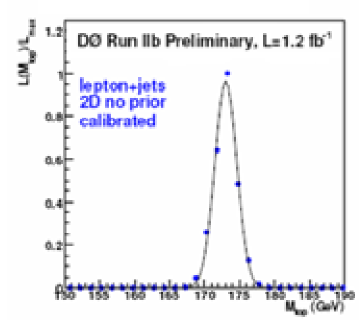


- event-by-event likelihood
  - for each event determine likelihood as a function of m_t (eg by integrating over LO matrix element)
  - extract mass from peak of joint likelihood



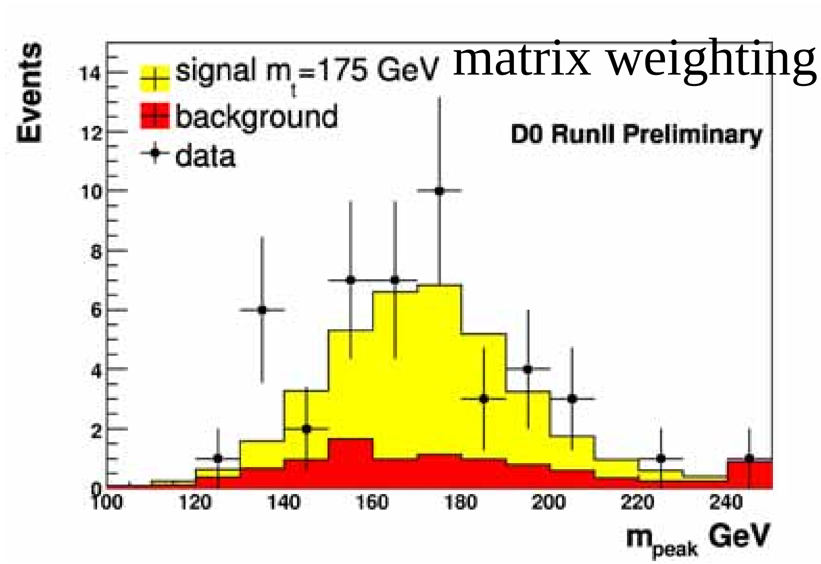
Event 1 Event 2 Event 3





dilepton channel

- D0 (1 fb^{-1})
- matrix weighting and neutrino weighting techniques
- compute weight curve as a function of top mass for each event
- template fit to mass distribution
- Combined measurement:

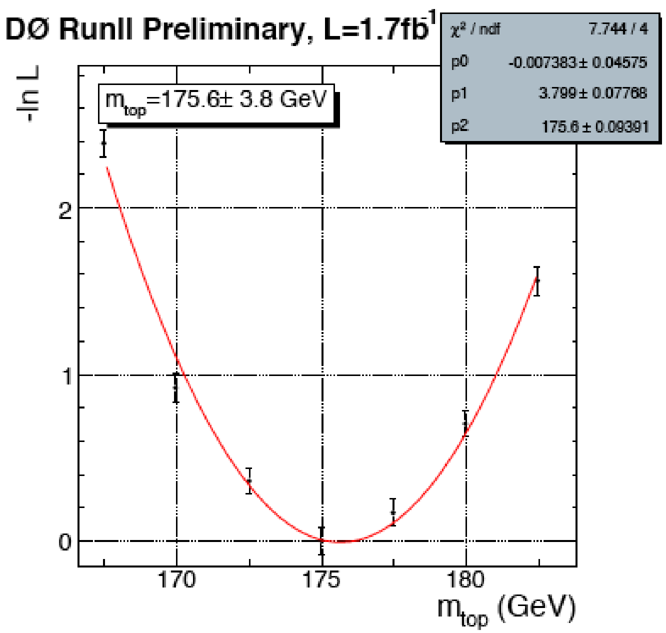


174.7±4.4(stat)±2.0(syst) GeV

Source of uncertainty	νWT_h [GeV]	MWT [GeV]
b fragmentation	0.4	0.4
Underlying events modeling	0.3	0.5
Extra jets modeling	0.1	0.3
Event generator	0.6	0.5
PDF variation	0.2	0.5
Background template shape	0.4	0.3
Jet energy scale	1.6	1.2
b/light response ratio	0.3	0.6
Sample dependent JES	0.4	0.1
Jet resolution	0.1	0.2
Muon/track resolution	0.1	0.2
Electron resolution	0.1	0.2
Jet identification	0.4	0.5
MC corrections	0.2	0.2
Background yield	0.0	0.1
Signal shape modeling	0.8	0.8
MC calibration	0.1	0.1
Total systematic uncertainty	2.1	2.0

dilepton channel

- D0 (2.8 fb^{-1})
  - compute event weight using LO matrix element
  - Use electron-muon events
  - Clean sample, little background

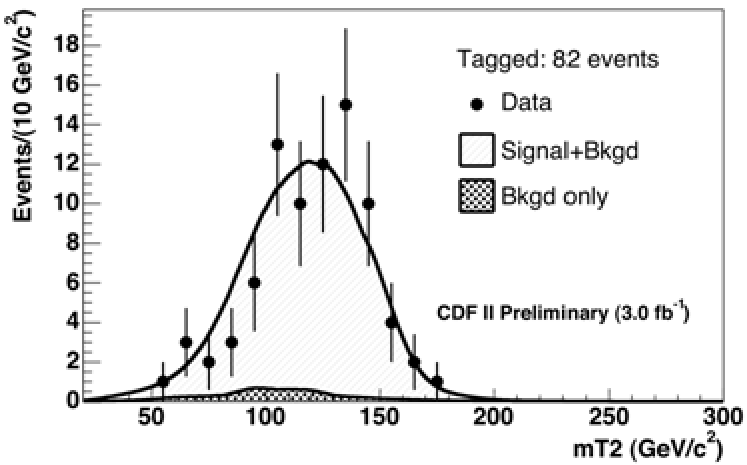


172.9±3.6(stat)±2.3(syst) GeV

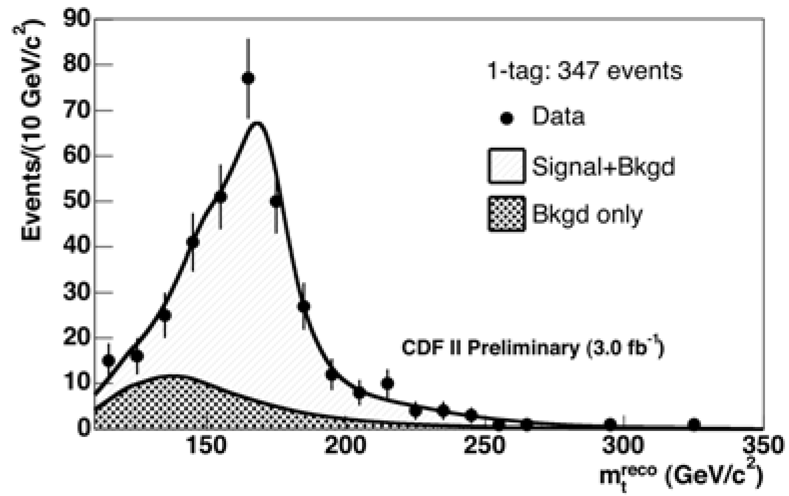
Uncertainty	$e\mu$ Run IIb [GeV]
JES up	-1.5
JES down	$+1.8$
b quark JES	$+1.4$
jet resolution up	-0.7
jet resolution down	$+0.7$
jssr shifting	$+0.1$
muon smearing up	-0.0
muon smearing down	$+0.3$
b quark fragmentation	± 0.3
PDF uncertainty up	-0.2
PDF uncertainty down	$+0.1$
fit uncertainty	± 0.4
signal modeling	± 0.4
background fraction up	-0.1
background fraction down	$+0.2$
TOTAL	$^{+2.5}_{-1.8}$

dilepton and lepton+jets channel

- CDF (3.0 fb^{-1}) dilepton
  - neutrino weighting technique
  - mT2: transverse mass of the two missing particle system
  - 2D template fit

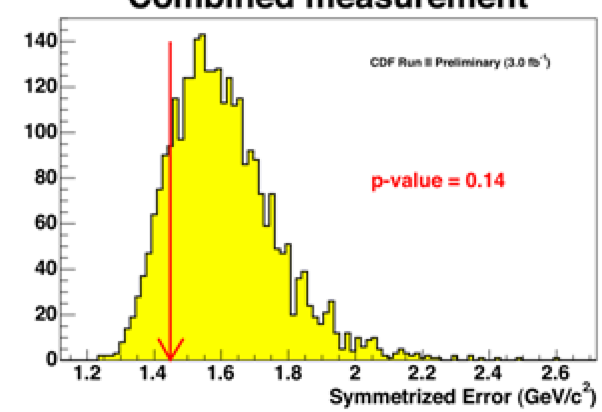


- Lepton+jets
  - 2D template fits for reconstructed top quark mass and the jet energy scale



m_{top} = 171.8 ± 1.5(stat⊕jes) ± 1.1(syst) GeV

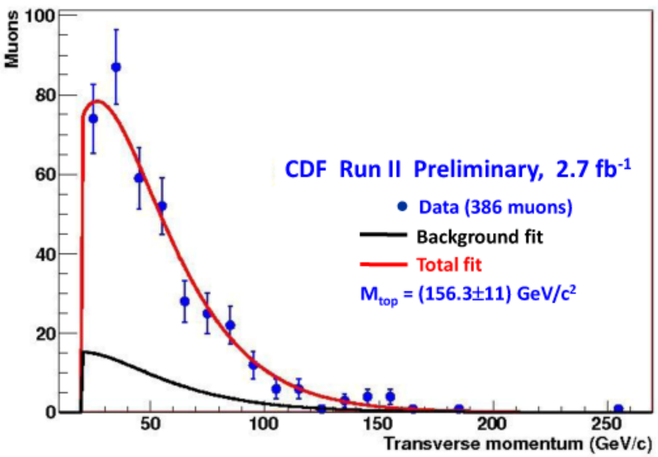
Combined measurement

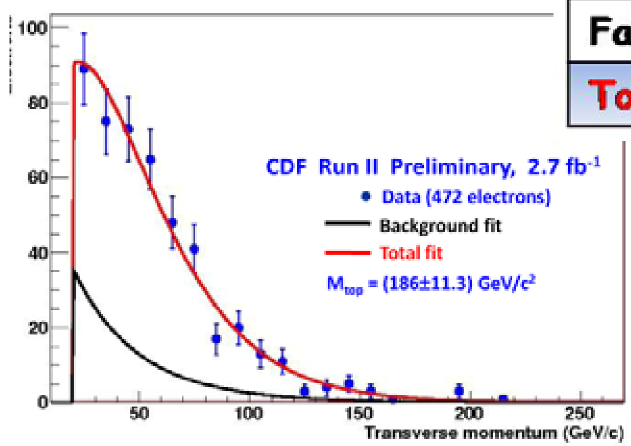


lepton+jets

- CDF (2.7 fb^{-1})
- Use either the pT spectrum of the leptons from top quark decays
- Generate templates for signal as a function of the top quark mass and the background
- method not sensitive to jet energy scale uncertainties.

Source	Top mass error (GeV/c^2)
MC statistics	±0.4
Global P_T scale	±0.1
Local P_T scale	±1.1
Generator	±1.4
IFSR	±1.4
PDF	±0.6
Q^2	±0.7
JES	±0.0
Pileup	±0.1
Fakes	±1.8
Total	±3.0



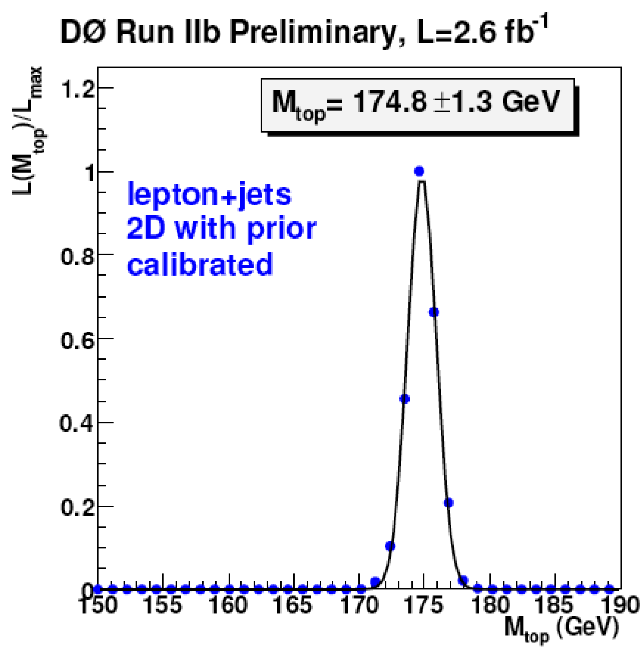


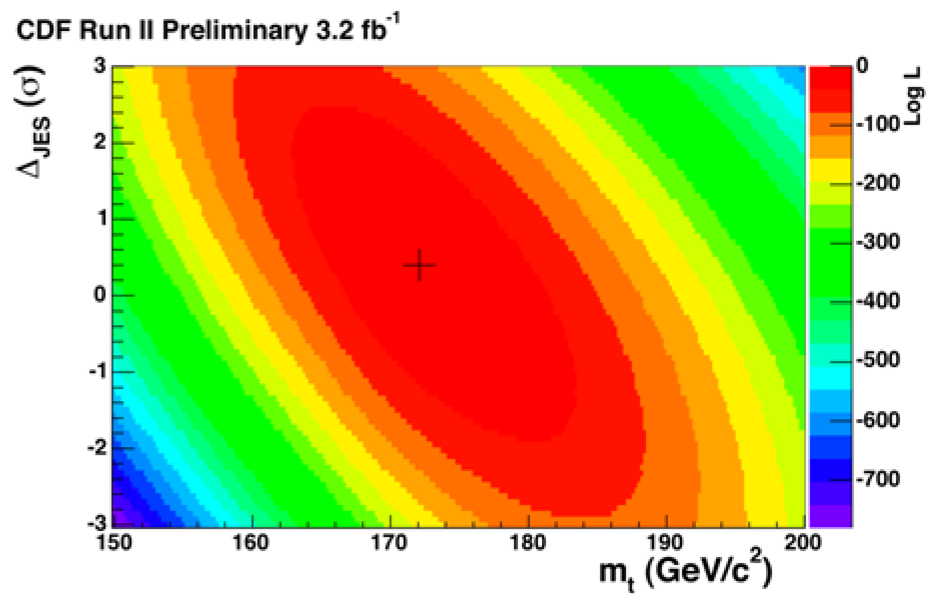
M_{top} = 172.1± 7.9(stat) ±3.0(syst) GeV

lepton+jets

best precision

- matrix element analysis
  - integrate over LO matrix element to get likelihood for event as a function of top quark mass
  - in situ jet energy calibration using $W \to qq$ decay
  - peak of joint likelihood = top quark mass





CDF: 172.1± 0.9(stat) ±0.7(jes)±1.1(syst) GeV (3.2 fb^{-1})

D0: 173.7±0.8(stat)±1.6(syst⊕jes) GeV (3.6 fb^{-1})

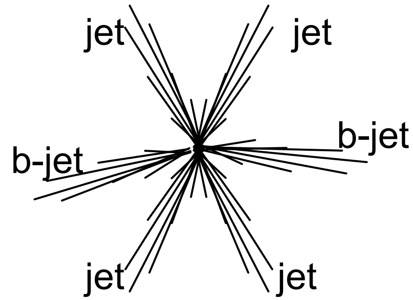
Lepton+jets systematics:

- D0 CDF

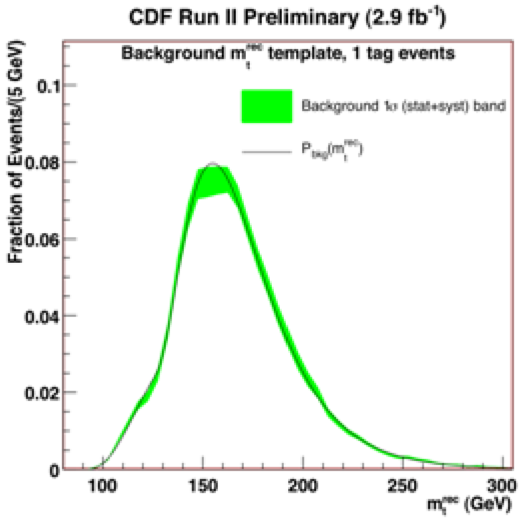
Source	Uncertainty (GeV)
Higher Order Effects	±0.25
ISR/FSR	±0.26
Hadronization and UE	±0.58
Color Reconnection	±0.50
PDF uncertainty	±0.24
Residual JES uncertainty	±0.21
Relative b/light response	±0.81
Sample-dependent JES	±0.56
Jet ID efficiency	±0.26
Jet energy resolution	±0.32
Plus a few smaller sys <0.2	
Total	±1.44

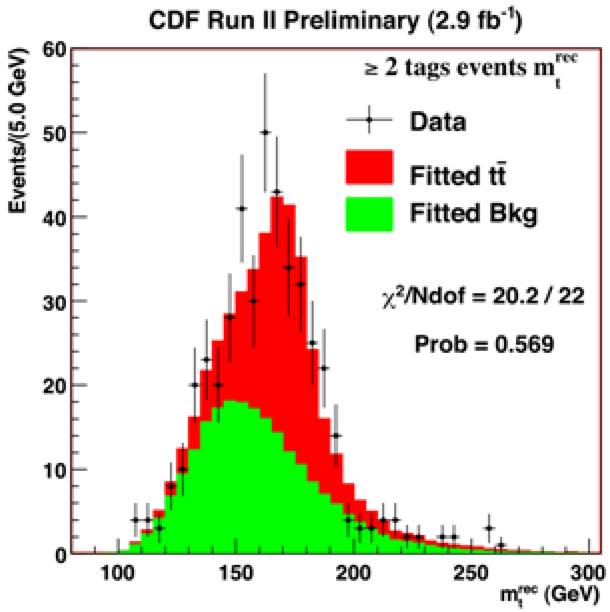
Systematic source	Systematic uncertainty (GeV)
Calibration	0.2
MC generator	0.5
ISR and FSR	0.3
Residual JES	0.5
b-JES	0.4
Lepton P_T	0.2
Multiple hadron interactions	0.1
PDFs	0.2
Background	0.5
Color reconnection	0.4
Total	1.1

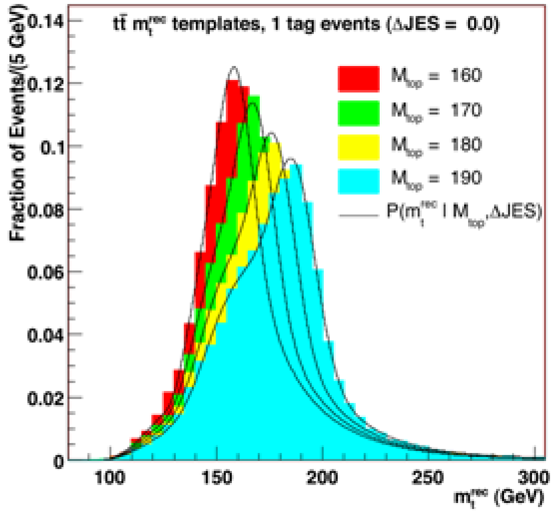
all jets (CDF)



- kinematic fitter
  - leading 6 jets
  - jj/jjj masses, jet p_Ts
- 2-dimensional template fit
  - top/W masses with smallest χ^2

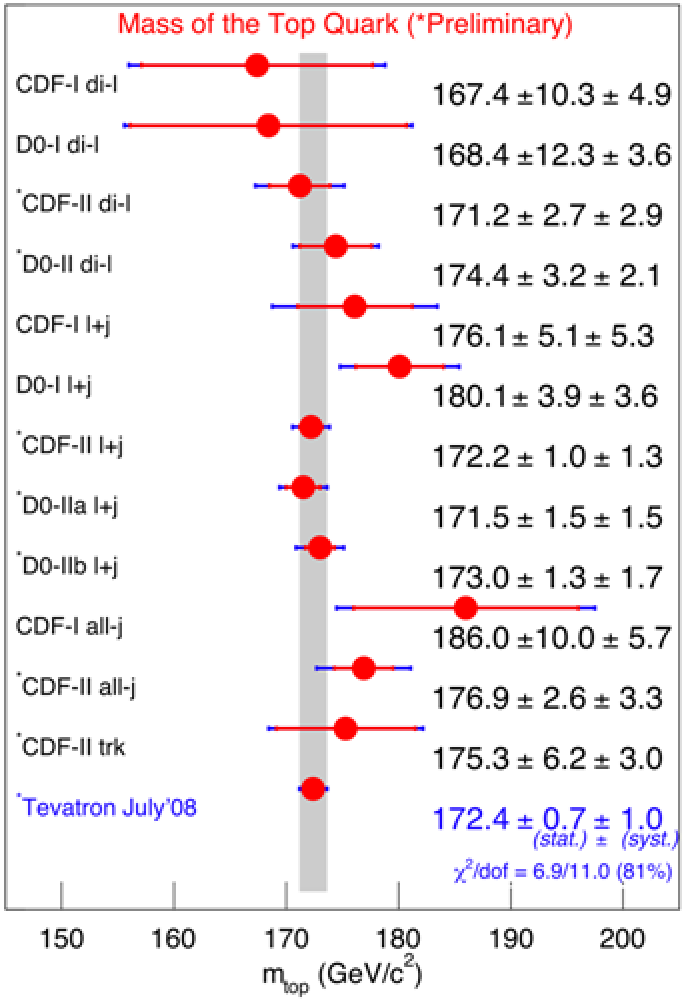






$$m_{top} = 174.8 \pm 2.4(\text{stat}\oplus\text{jes})\ ^{+1.2}_{-1.0}(\text{syst})\ \text{GeV}$$

Combination (as of summer 08)

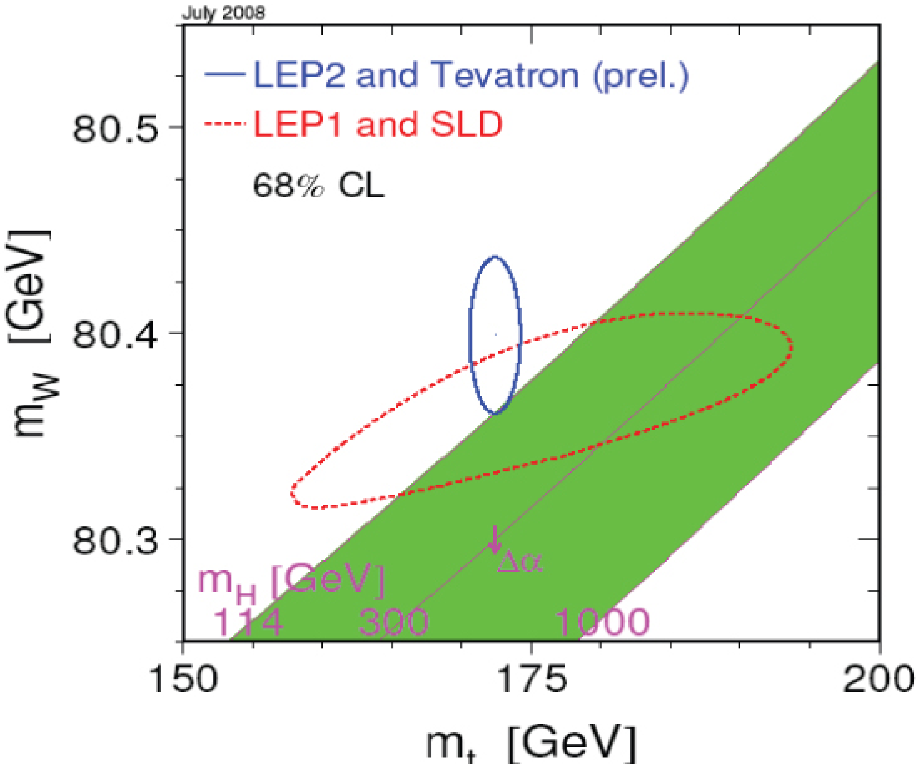


CDF winter'09

m_{top} = 172.6 ± 0.9(stat) ± 1.2(syst) GeV

D0 summer'08

m_{top} = 172.8 ± 0.9(stat) ± 1.3(syst) GeV



$\delta m/m < 1\%$

Run II goal: $\delta m \approx 1$ GeV

http://tevewwg.fnal.gov/top/

http://lepewwg.web.cern.ch/LEPEWWG/plots/summer2008/

top quark coupling

- if top plays a special role in ewk symmetry breaking its couplings to W bosons may differ from predictions
- modifications to top quark interactions, in particular with weak gauge bosons, could yield the first signs of new physics
- most general CP-conserving W-t-b vertex involves four couplings

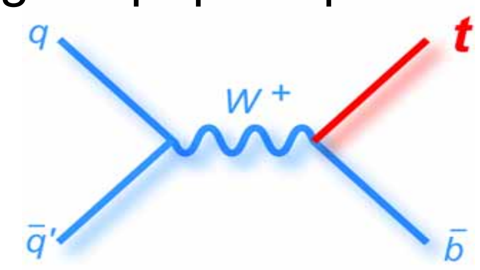
$$L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t$$

$+h.c.$

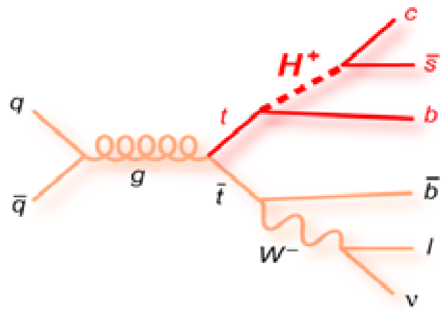
where, in the SM $f_1^L \approx 1,\ f_2^L = f_1^R = f_2^R = 0$

- probing tWb vertex:

Anomalous couplings in single top quark production and decay



W helicity In top pair decays



– Both measurements can be combined to fully specify the tbW vertex

W boson helicity from t→Wb decays in top pair production

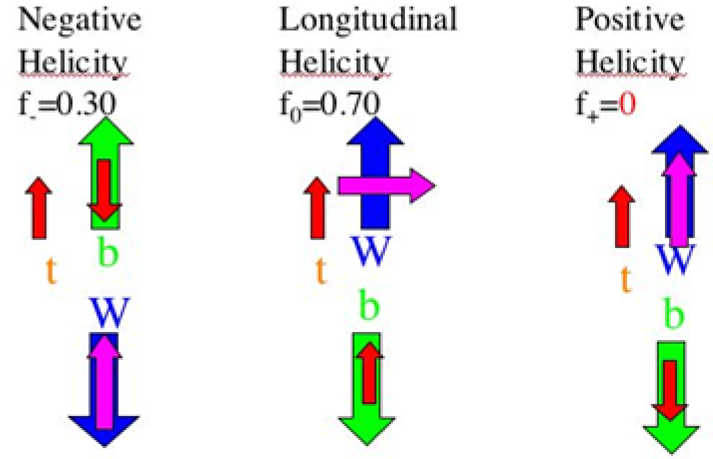
- sm predicts V-A coupling at Wtb
- □ helicity of W boson

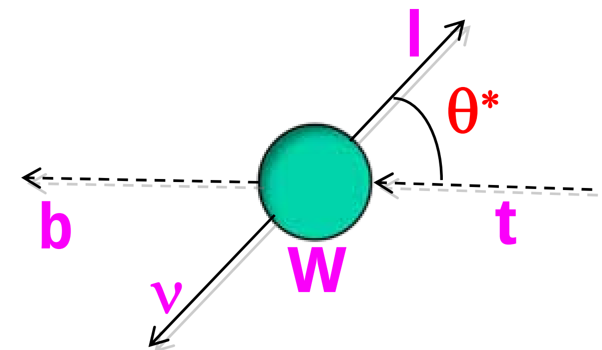
  $f_0 = 0.7$, $f_- = 0.3$, $f_+ = 0.0$

  (longitudinal, left-handed, right-handed)
- a different Lorentz structure of the t → Wb interaction would alter the fractions of W bosons produced in each polarization state.

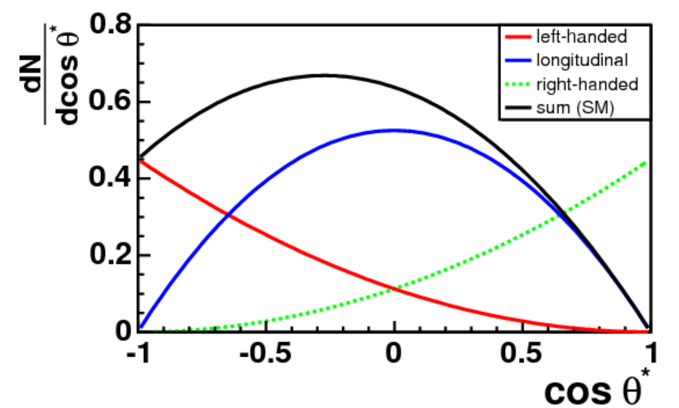
- model-independent measurement based on reconstruction of cosθ* distribution - angle between lepton and top in W rest frame
- distribution of cos θ* depends on the W boson helicity fractions

- Generate samples corresponding to each of the three W boson helicity states
  - by reweighting the generated cosθ* distributions
- Simultaneous measurement of f_0 and f_+
  - The negative helicity fraction f_- is then fixed by the requirement that $f_- + f_0 + f_+ = 1$



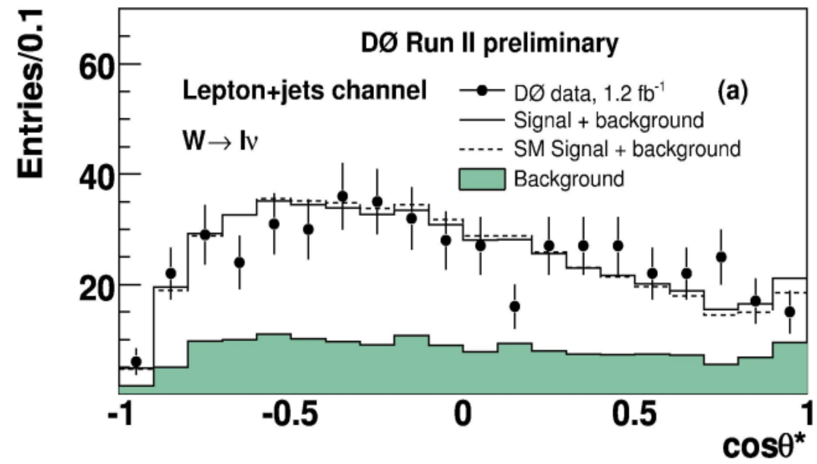


of cosθ* (angle between the momenta of the down-type fermion and the top quark in the W boson rest frame for each top



top quark coupling

- Use a maximum likelihood fit, for the data to be consistent with the sum of signal and background in the cosθ* distribution
- The fit parameters are the W helicity fractions f_0 and f_+



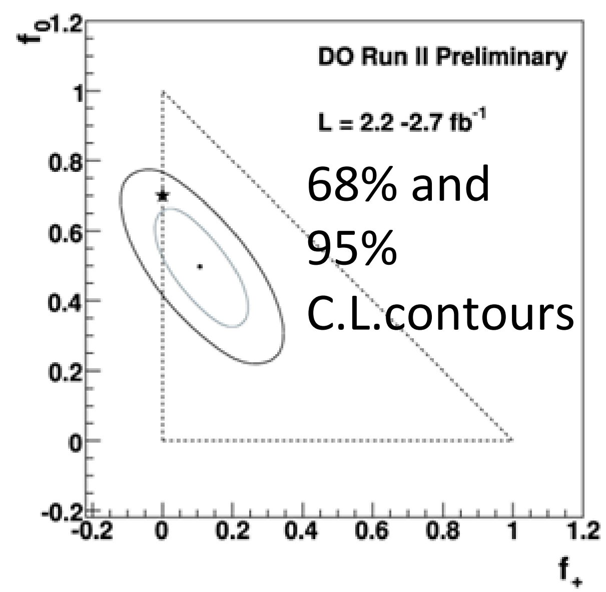
- A model-independent measurement of the helicity of W bosons

$$f_0 = 0.490 \pm 0.106\,(\text{stat.}) \pm 0.085\,(\text{syst.})$$
$$f_+ = 0.110 \pm 0.059\,(\text{stat.}) \pm 0.052\,(\text{syst.})$$

- if f_0 constrained to the standard model value

$$f_+ = 0.019 \pm 0.031\,(\text{stat.}) \pm 0.047\,(\text{syst.})$$

- This is the most precise such measurement



68% and 95% C.L.contours

top quark couplings

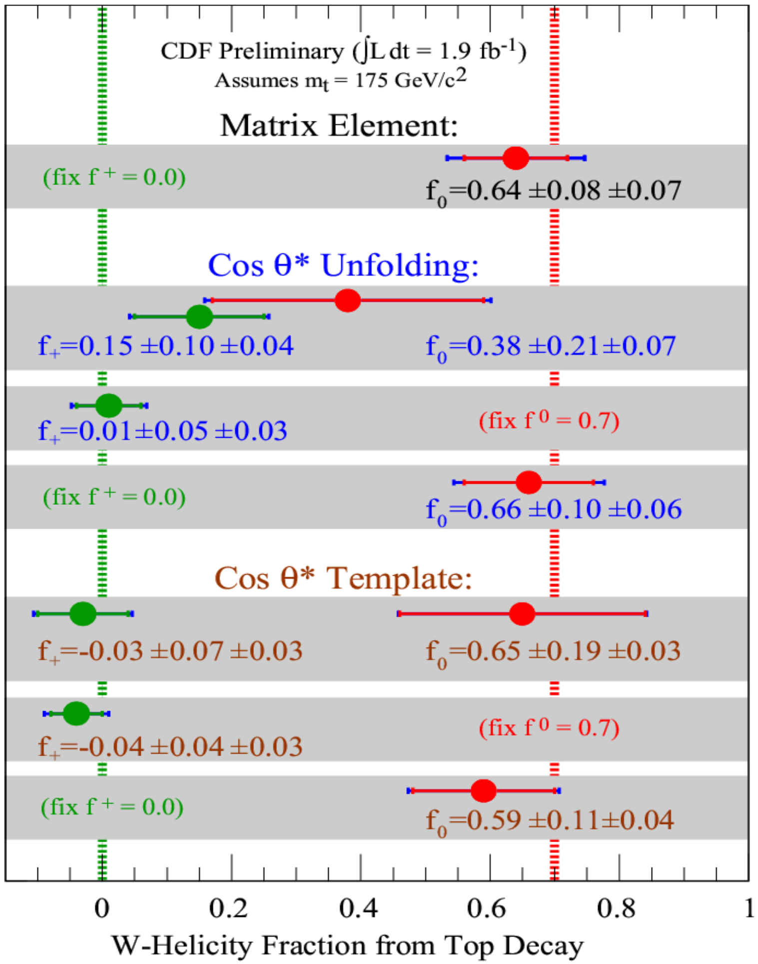
CDF used three approaches for this measurement

- Using the fully reconstructed decay chain
- Template method
- Using a matrix element based technique
  - Likelihood based on differential cross sections of signal and background
- Combining Cosθ* analyses:

  $f_0 = 0.66 \pm 0.16$

  $f_+ = -0.03 \pm 0.07$

CDF (1.9 fb^{-1})



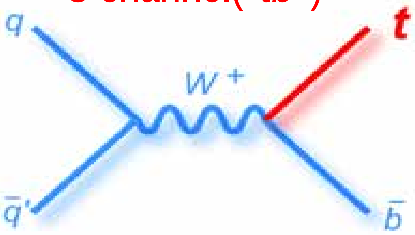
anomalous couplings in single top production

- Left & Right handed Vector and Tensor couplings

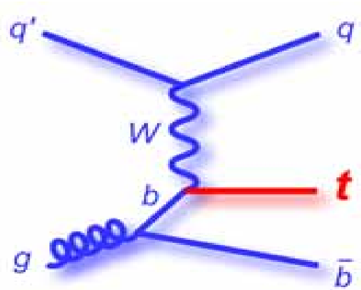
$$L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t$$

where, in the SM $f_1^L \approx 1,\ f_2^L = f_1^R = f_2^R = 0$ +*h.c.*

s-channel(“*tb*”)



t-channel(“*tqb*”)



- Two non –zero couplings at a time
  – Consider 3 scenarios
  – Simultaneous limit on two couplings

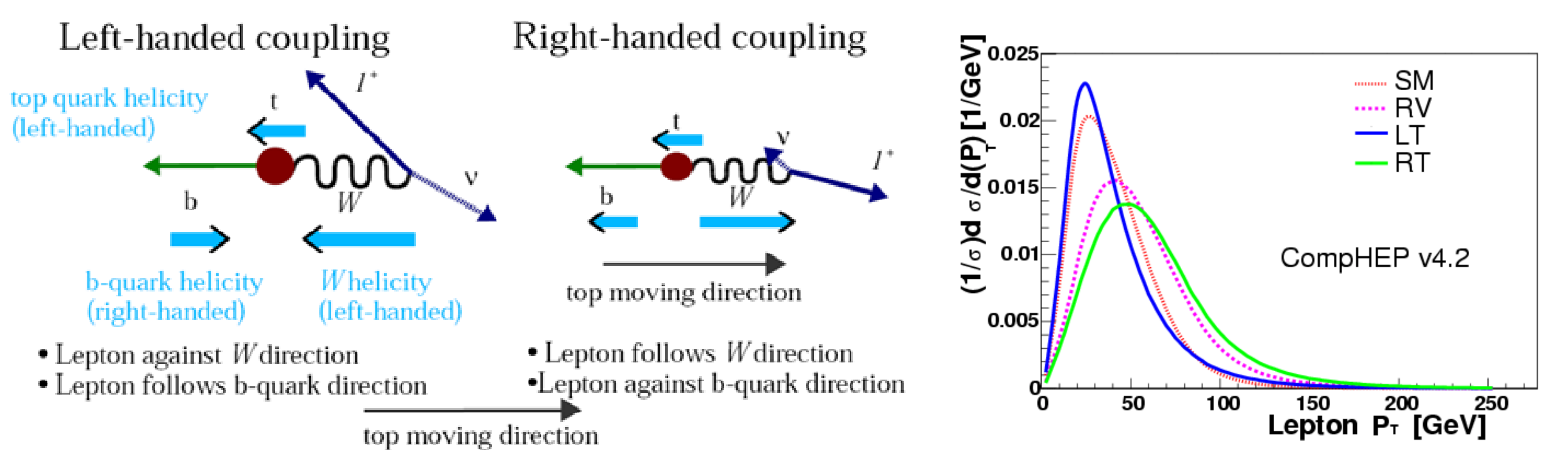
Only f_1^L, f_1^R non-zero

Only f_1^L, f_2^L non-zero

Only f_1^L, f_2^R non-zero

anomalous couplings vs SM

- presence of anomalous couplings changes the production cross-section, and kinematics and angular distributions



multivariate analysis

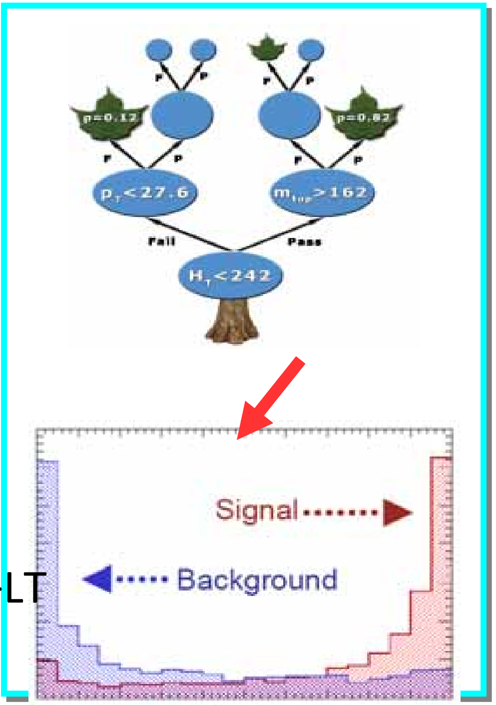
L = 1 fb^{-1}

- Use Boosted Decision Trees to discriminate signal from background
- For every analysis, train 2 signals against sum of backgrounds

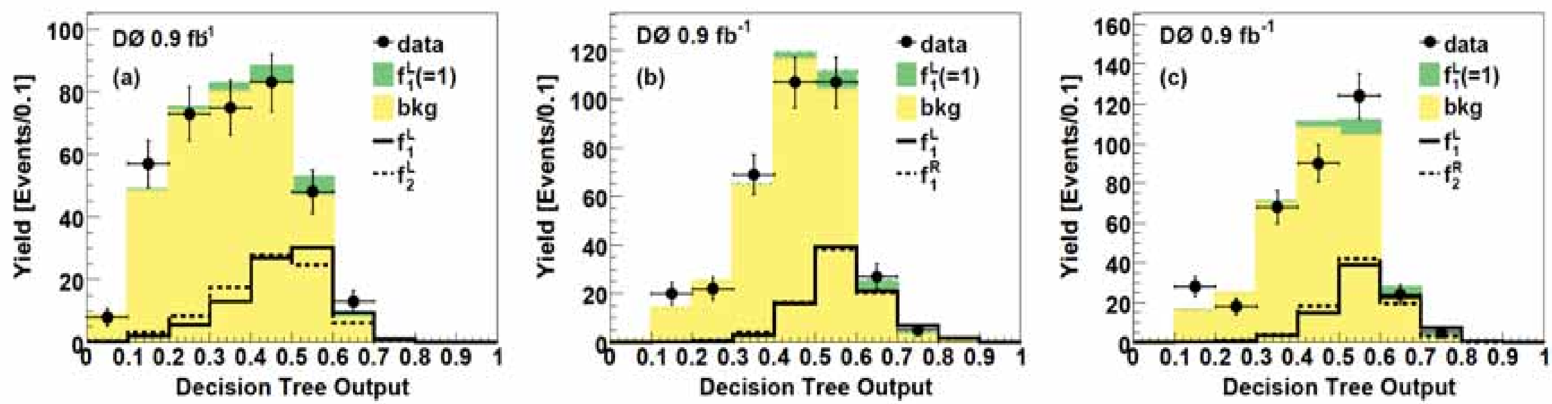
f_1^L, f_1^R scenario : (tb + tqb)LV + (tb + tqb)RV

f_1^L, f_2^L scenario : (tb + tqb)LV + (tb + tqb)LT + (tb + tqb)LV+LT

f_1^L, f_2^R scenario : (tb + tqb)LV + (tb + tqb)RT



f_1^L, f_2^L f_1^L, f_1^R f_1^L, f_2^R



Limit Setting

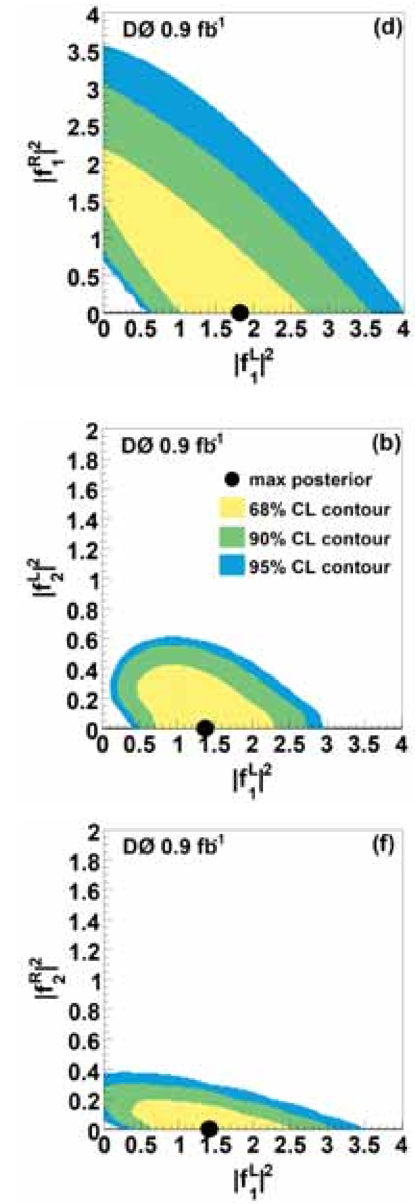
- Bayesian approach for limit setting
- Simultaneous limit setting for two signals by calculating 2 dimensional posterior probability density

Scenario	Cross Section	Coupling
(L_1, L_2)	$4.4^{+2.3}_{-2.5}$ pb	$\lvert f_1^L\rvert^2 = 1.4^{+0.6}_{-0.5}$
		$\lvert f_2^L\rvert^2 < 0.5$ at 95% C.L.
(L_1, R_1)	$5.2^{+2.6}_{-3.5}$ pb	$\lvert f_1^L\rvert^2 = 1.8^{+1.0}_{-1.3}$
		$\lvert f_1^R\rvert^2 < 2.5$ at 95% C.L.
(L_1, R_2)	$4.5^{+2.2}_{-2.2}$ pb	$\lvert f_1^L\rvert^2 = 1.4^{+0.9}_{-0.8}$
		$\lvert f_2^R\rvert^2 < 0.3$ at 95% C.L.

First experimental limits on tensor couplings!

(PRL 101, 221801 (2008))

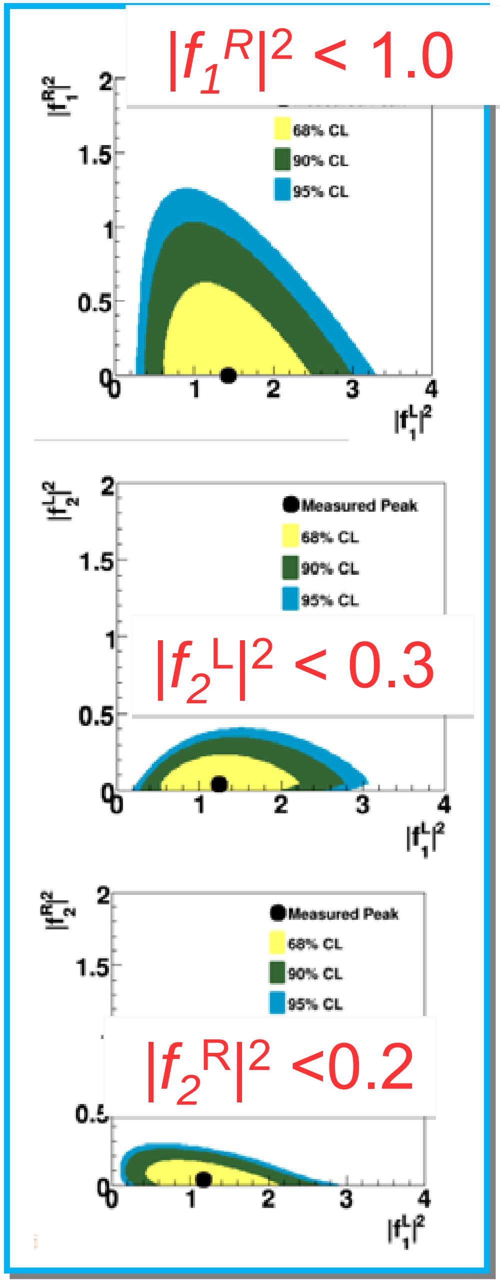
$L = 1\ fb^{-1}$



Combination

- W helicity measurement in top pair decays
- Anomalous couplings measurement in single top
- Bayesian analysis:
  - output of W helicity analysis forms input prior to single top anomalous couplings
- Observed posterior from data: single top and W helicity combined

$L = 1\ fb^{-1}$



conclusion

- top physics has come a long way since 1995
- Tevatron is still the only place to do it
- top quark mass measured to 0.8%
    - reaching uncertainties below 1 GeV
- Measurement of top properties and possible non-standard physics in t-W-b couplings are consistent with SM

http://www-d0.fnal.gov/Run2Physics/top/
http://www-cdf.fnal.gov/physics/new/top/top.html

thank you

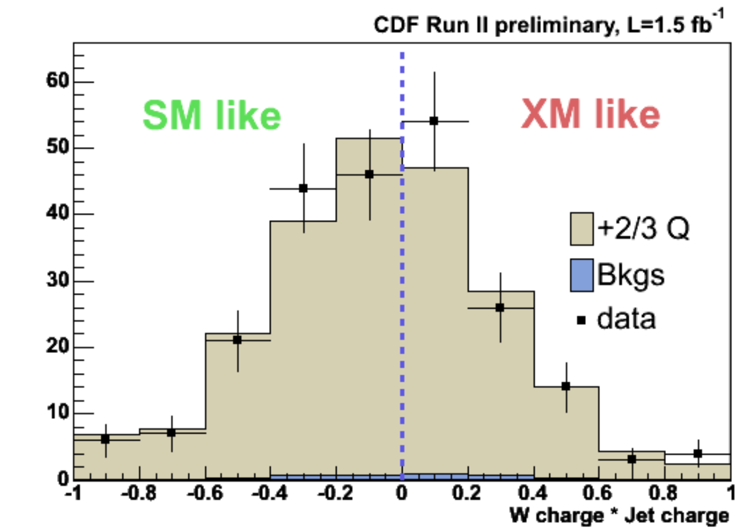
searches for non-standard physics

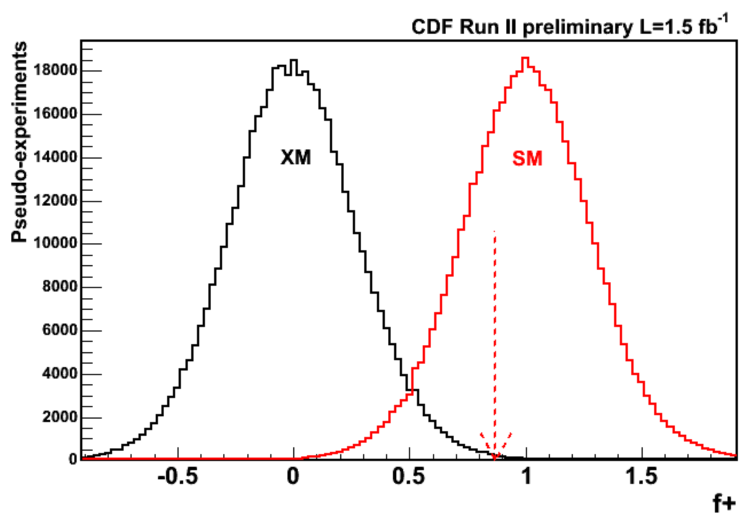
- quarks with charge 4/3e → disfavored
- FB ttbar asymmetry → consistent with sm
- 4th generation t' quarks → m > 284 GeV
- scalar top production →no evidence
- charged Higgs bosons → limits on $H^+ \rightarrow tb, t \rightarrow H^+b$
- tb resonances
- ttbar resonances
- FCNC decays of top quarks

Backup slides

top quark charge

- is it
  - $t \rightarrow W^+b$ (Q_{top} = 2/3 e)
  - $t \rightarrow W^-b$ (Q_{top} = -4/3 e)
- Exotic model
  - doublet (–1/3e,–4/3e) ?
  - D. Chang et al., PRD59 (1999) 091503
- D0 PRL 98, 041801 (2007)
  - 4/3e excluded at 92% CL
  - fraction of exotic quark pairs < 0.80 (90% CL)
- CDF result with 1.5/fb
  - p-value for SM: 0.31
  - exotic model XM excluded with 87% CL





systematic uncertainty

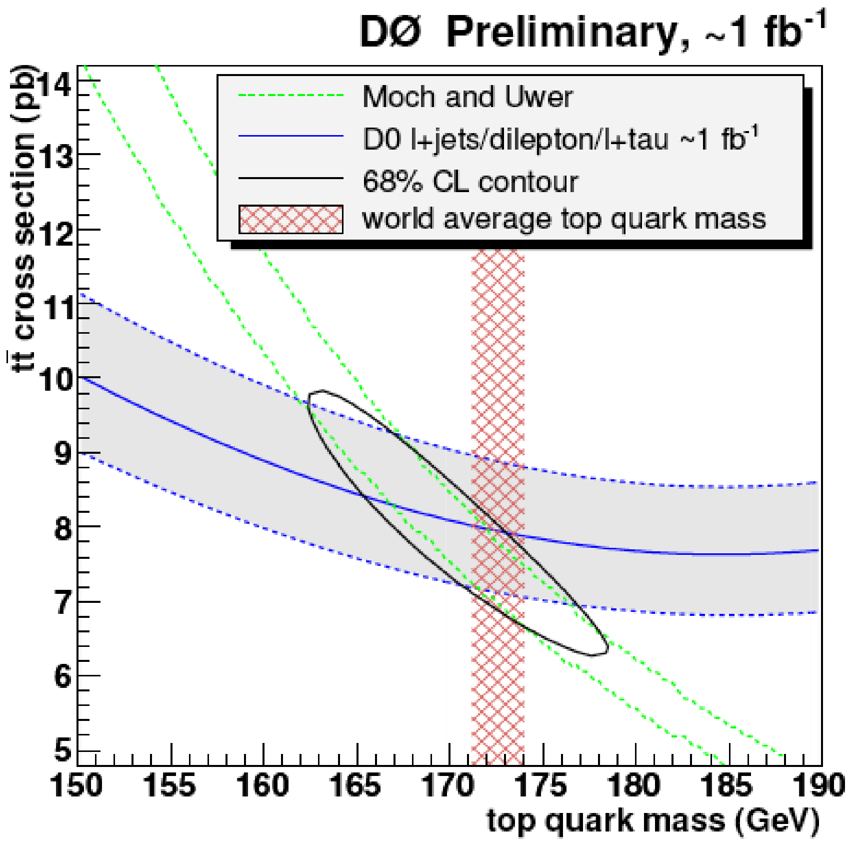
- CDF (3.0 fb^{-1})

Systematic (GeV/c^2)	Combined fit	L+J	DIL	DIL(mT2 only)
Residual JES	**0.68**	**0.66**	**3.04**	**2.58**
Generator	**0.74**	**0.72**	**0.46**	**0.22**
PDF	**0.19**	**0.17**	**0.48**	**0.47**
b jet energy scale	**0.17**	**0.18**	**0.21**	**0.21**
Background shape	**0.24**	**0.27**	**0.12**	**0.36**
gg-fusion fraction	**0.04**	**0.00**	**0.01**	**0.32**
ISR and FSR	**0.13**	**0.14**	**0.34**	**0.57**
MC statistics	**0.10**	**0.08**	**0.32**	**0.33**
Lepton energy scale	**0.03**	**0.06**	**0.28**	**0.56**
Pileup	**0.19**	**0.24**	**0.34**	**0.18**
Color reconnection	**0.34**	**0.38**	**0.55**	**0.68**
Total	**1.14**	**1.14**	**3.24**	**2.91**

Systematics from template method for L+J and DIL channel

Mass from cross section

- compare with theory
  - combine likelihood and b-tag cross section measurements in lepton+jets
  - dilepton cross section
  - lepton+tau cross section



m_{top} = 167.8 ± 5.7 GeV

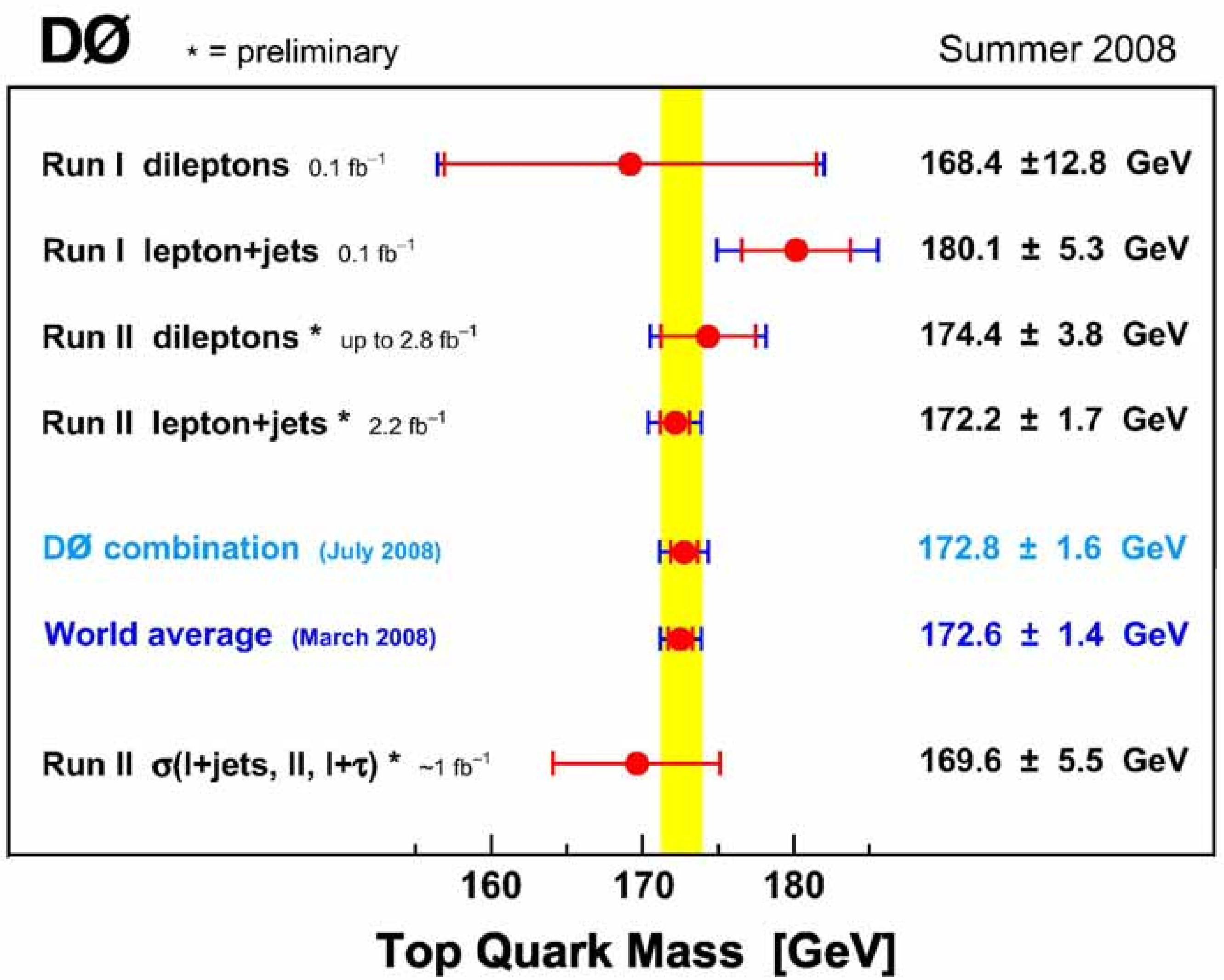
(NLO+NLL) Cacciari et al., *arXiv:*0804.2800)

= 169.6 $^{+5.4}_{-5.5}$ GeV

(NNLO approx) (Moch & Uwer, *arXiv:*0804.1476

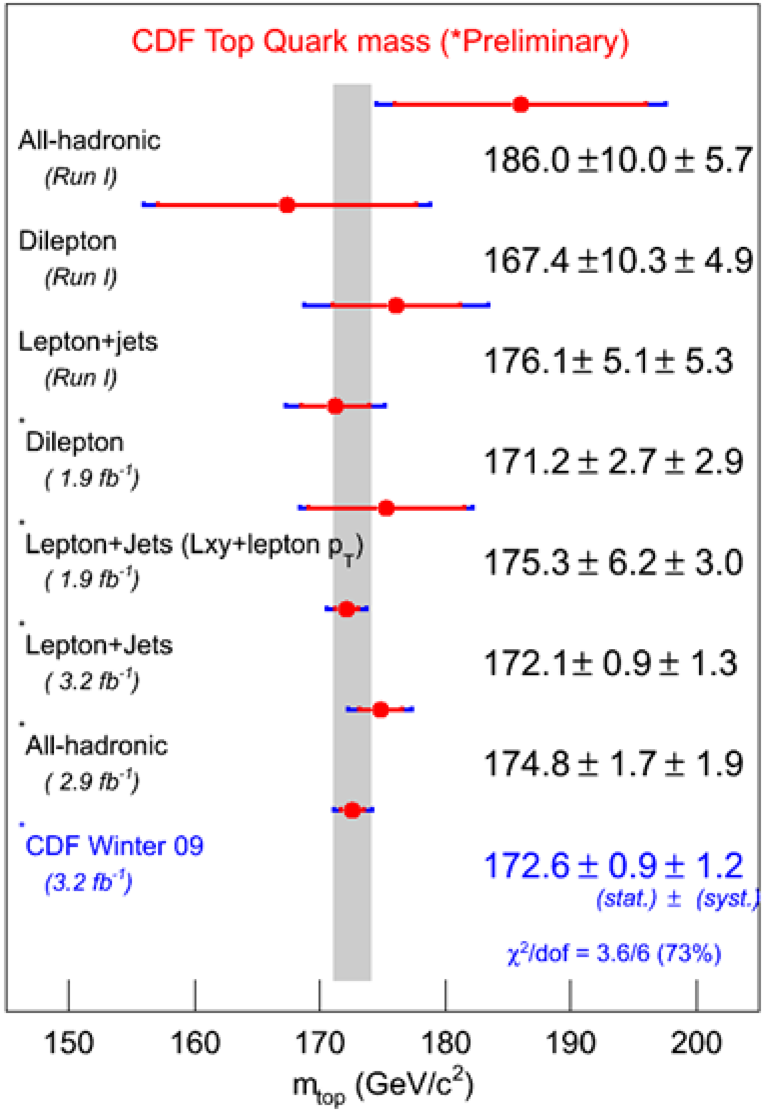
Combination

D0 (summer 08)



Combination

- CDF (winter 09)



Color Reconnection Systematic

- New models of Color Reconnection (CR) have been introduced in recent versions of PYTHIA starting with V6.3.
- In our analyses we have been using PYTHIA V6.2 (tune A).

- The latest version (PYTHIA V6.4) includes, in addition to a new model for color reconnection,new models for the parton shower,
Multiple Parton Interaction (MPI),
ISR and FSR, and the underlying event (UE).

The CDF and D0 collaborations work together on understanding the effects of these changes and on defining a common procedure to include them in the systematic uncertainties.

Tuning of PYTHIA V6.4 to data is in progress.
Tunes which include LEP data (called “pro”) are now available.
(see Perugia MC meeting, October 2008)

So far we have looked at two recent tunes: ACR(pro) and S0(pro).

Color Reconnection systematic (cont.)↰

Tune ACR(pro): includes only the new color reconnection model.

Tune S0(pro): uses new modeling for ISR/FSR, parton shower, MPI, UE and CR. For this tune, we have to investigate possible overlaps with the systematic uncertainties we are now using.

At this stage of our studies we evaluate the CR systematics using the ACR(pro) tune, that includes only changes in the CR model. We compare ACR(pro) to the A(pro) (tune A in V6.4) tune.

This has been done in the di-lepton, the lepton+jets and the all hadronic channels. The three mass shifts agree within statistics

☟M_{top} = M_{top}(A(pro))–M_{top}(ACR(pro)) = (0.4-0.5) ⌖ 0.3 GeV/c^2

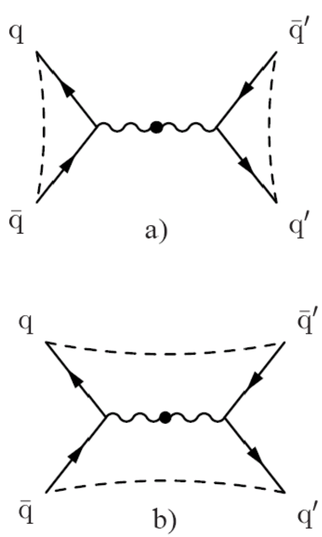
Work is in progress to compare jet shapes in PYTHIA V6.4 with data from various samples to isolate the effects of the new parton shower from the CR contribution.

Color Reconnection Systematic

Strong color correlations between the hard process and the underlying event are required by tune A and similar tunes. These effects are interpreted as sign for color reconnection.

The issue has been studied at LEP for the W mass measurement

LEP



CR effects on the M_W measurement at LEP contribute to systematics

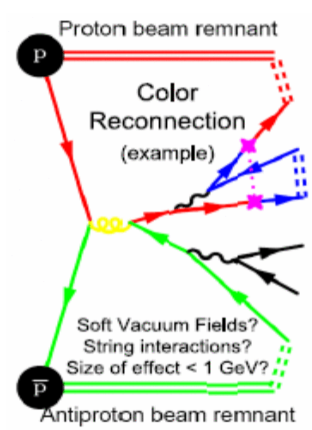
CR(sys) = 8 MeV

out of 22 MeV (total sys)

(LEPEWWG hep-ex/061203)

Tevatron

Preliminary MC studies have indicated possible contributions



to the top mass systematics of order

CR(sys)🕔 0.5 GeV

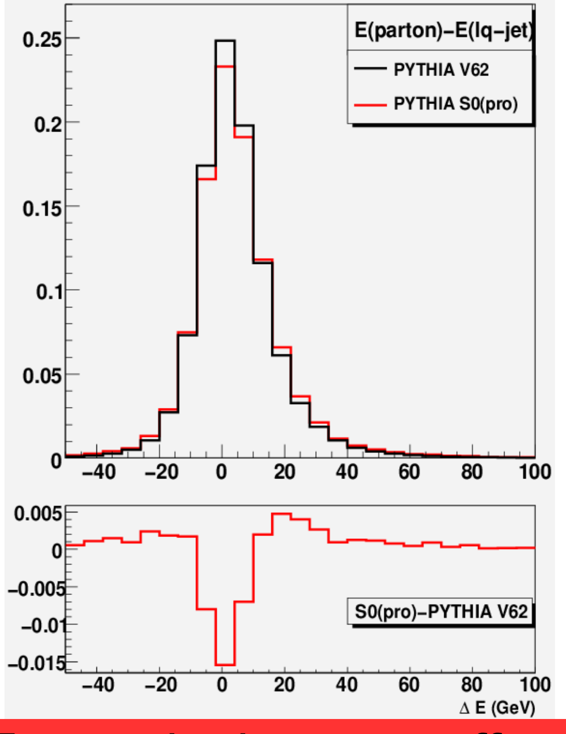
D. Wicke and P. Skands arXiv:0807.3248V1

Comparison of Different MC Versions

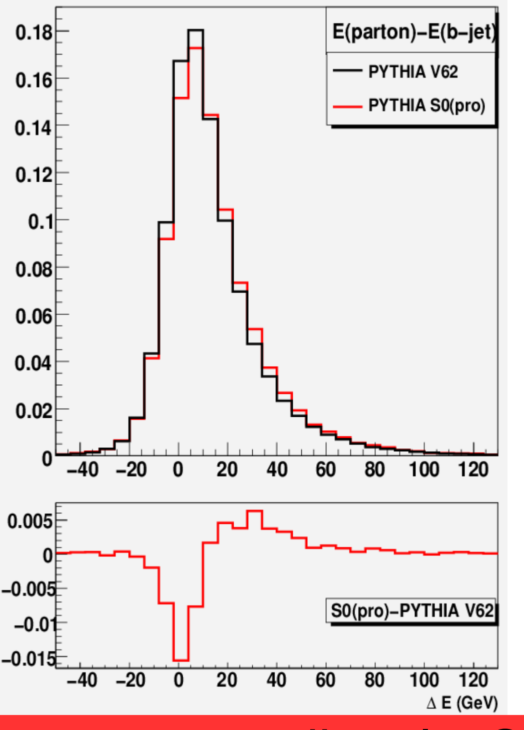
We have compared jet properties after generation + detector simulation.
Preliminary studies find the ACR(pro) jets agree with PYTHIA V6.2, but:

E (✋R=0.4 cone) S0 sample < E (✋R=0.4 cone) PYTHIA V6.2 sample

Light quark jets



b-quark jets



Jets in the S0(pro) sample are wider and shifted

S0(pro) -Nominal

✋ ☞ (cone)

GeV

W-jets -0.38 ± 0.15

b-jets -1.43 ± 0.15

Energy in the cone affects the top mass directly. Studies are ongoing