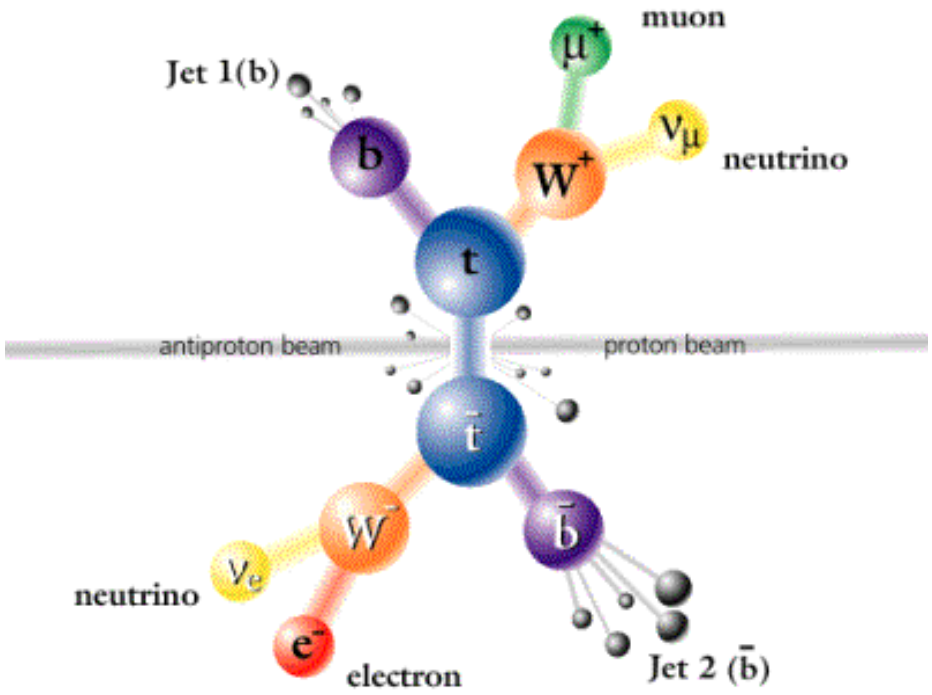
W Helicity in Top Quark Decays at the CDF



Markus Klute

Massachusetts Institute of Technology

For the CDF Collaboration

Fermilab Wine & Cheese Seminar

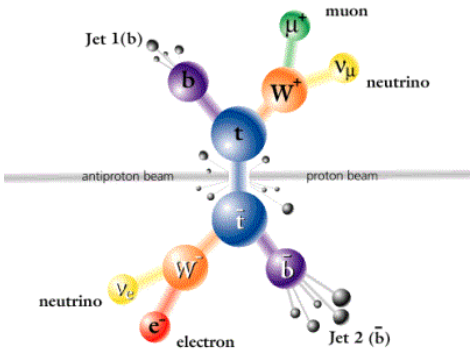
Hot Wine & CheeseTopics

Soccer World Cup in Germany

Weddings, Honeymoons, etc.

Thanks for your wishes, cards and gifts.

W Helicity in Top Quark Decays



Outline:

Brief History of Top Quark Physics

W Helicity in Top Quark Decays
- theory
- methods
- new CDF results

Summary

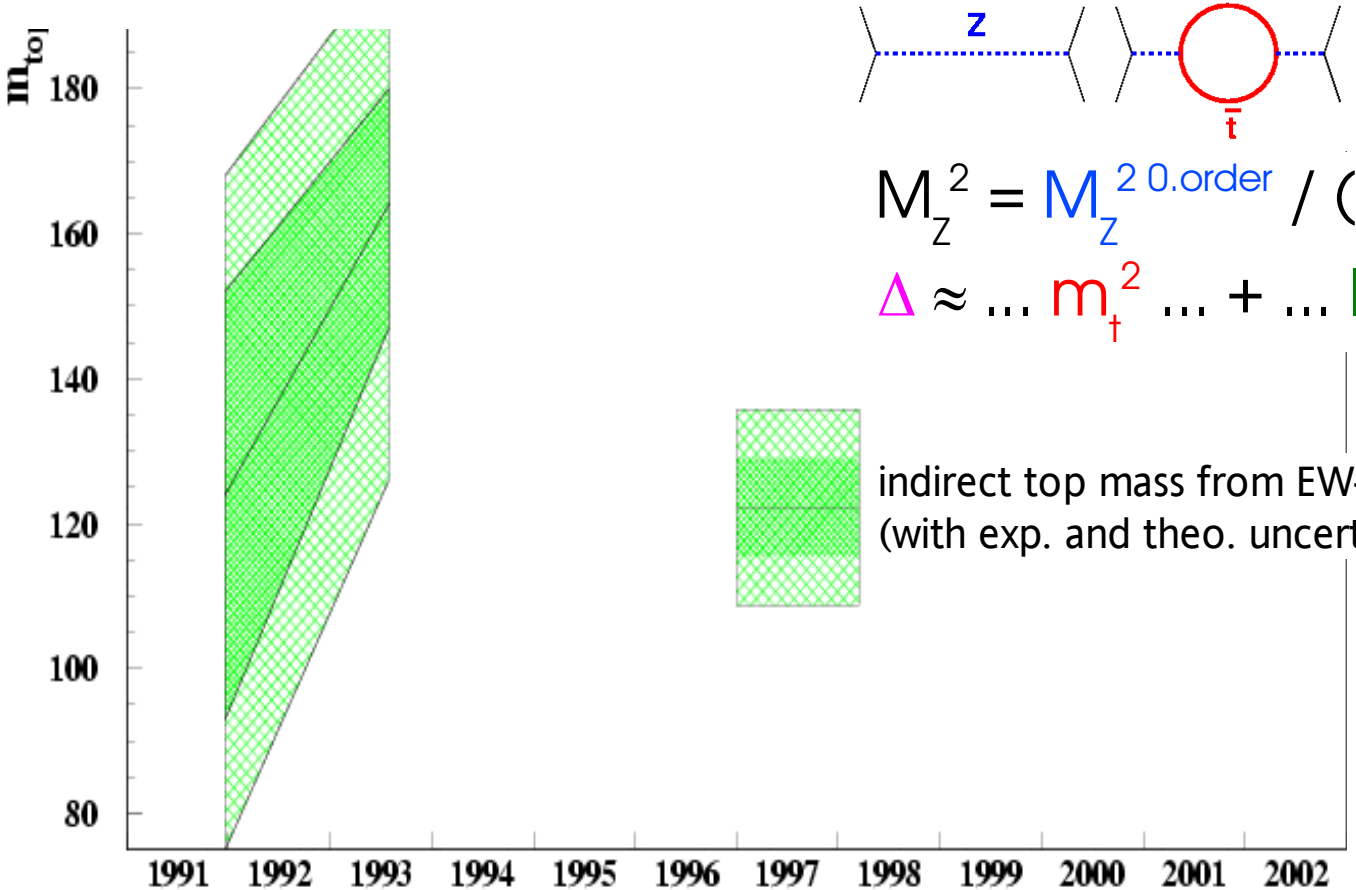
Long History of Top

* 1979-1990 (PETRA, TRISTAN, SLC/LEP): $e^+e^- \rightarrow$ ttbar bound states

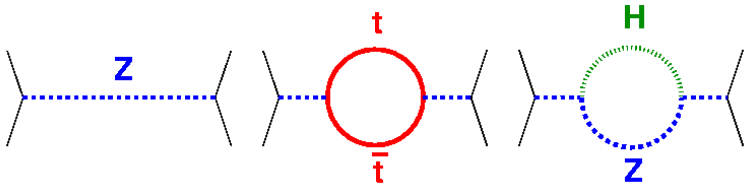
  $m_{top} > 45.8$ GeV

* 1990-1991 (SppS, Tevatron): $W \rightarrow tb$ decays

  $m_{top} > 77$ GeV



indirect top mass from EW-fit.
(with exp. and theo. uncertainties)



$$M_Z^2 = M_Z^{2\ 0.order} / (1 - \Delta)$$

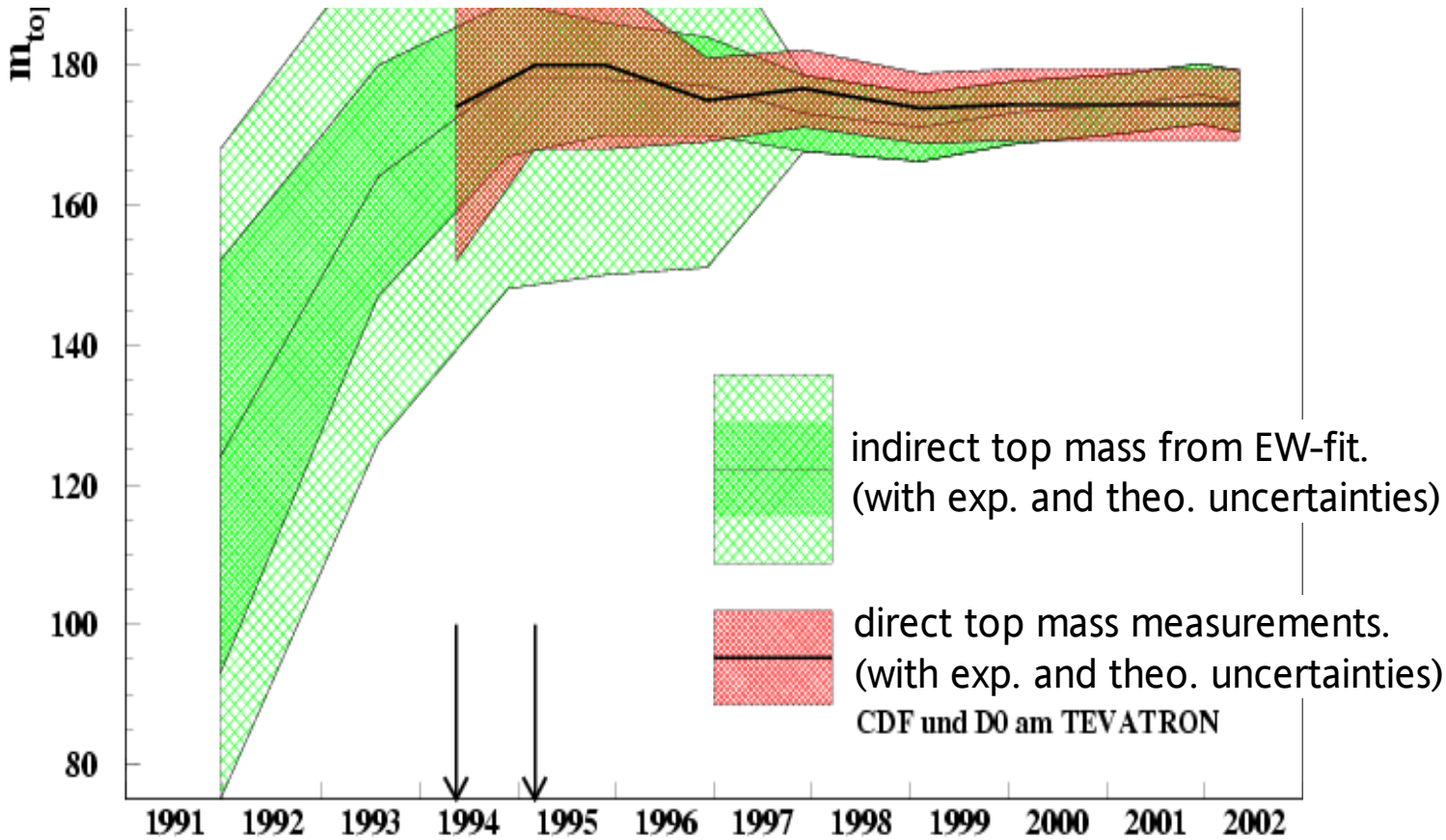
$$\Delta \approx \ldots m_t^2 \ldots + \ldots \ln m_h \ldots$$

Long History of Top Physics

* 1992 (Tevatron): t → Wb decays

  $m_{top} > 91$ GeV

* 1995 (Tevatron): discovery by CDF and D0



Long History of Top Physics

* 2005 (Tevatron): big celebration of a successful physics program !!!

Discovery of the top completed the quark sector of the Standard Model.

in '06: Top Mass = 172.3 ±2.3 GeV

Top very interesting:

- large mass $m_{top} \sim 175$ GeV

  (Yukawa coupling ~ 1)

- short lifetime $\tau \sim 0.5 \cdot 10^{-24}$ s

  (study bare quark / spin preserved)

- sensitive to physics beyond the SM.

Tevatron Run I: Top Quark Discovery

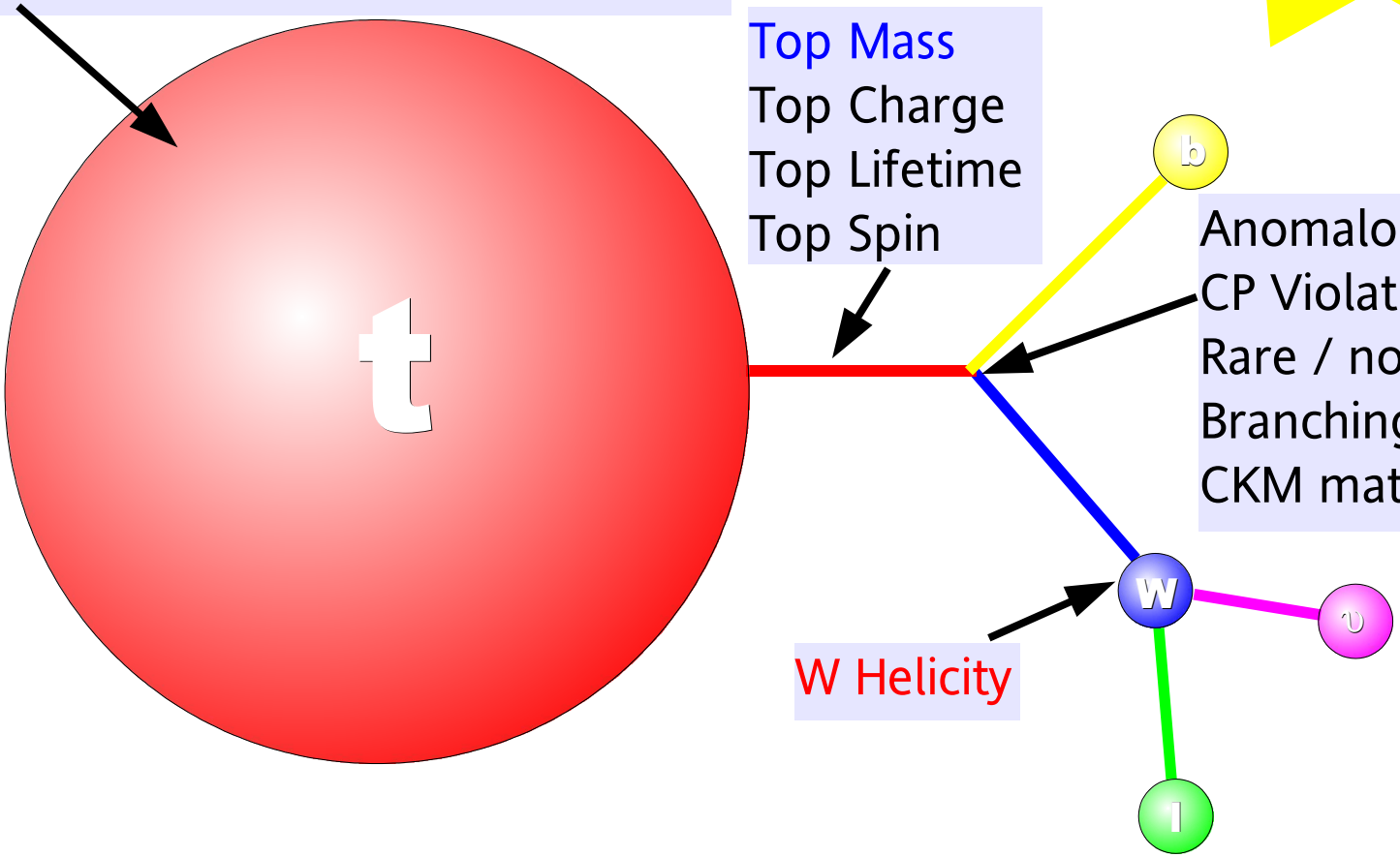
Tevatron Run II: High Precision Tests ...

Top Quark Physics at CDF

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

Top Physics
is very rich

Top Mass
Top Charge
Top Lifetime
Top Spin



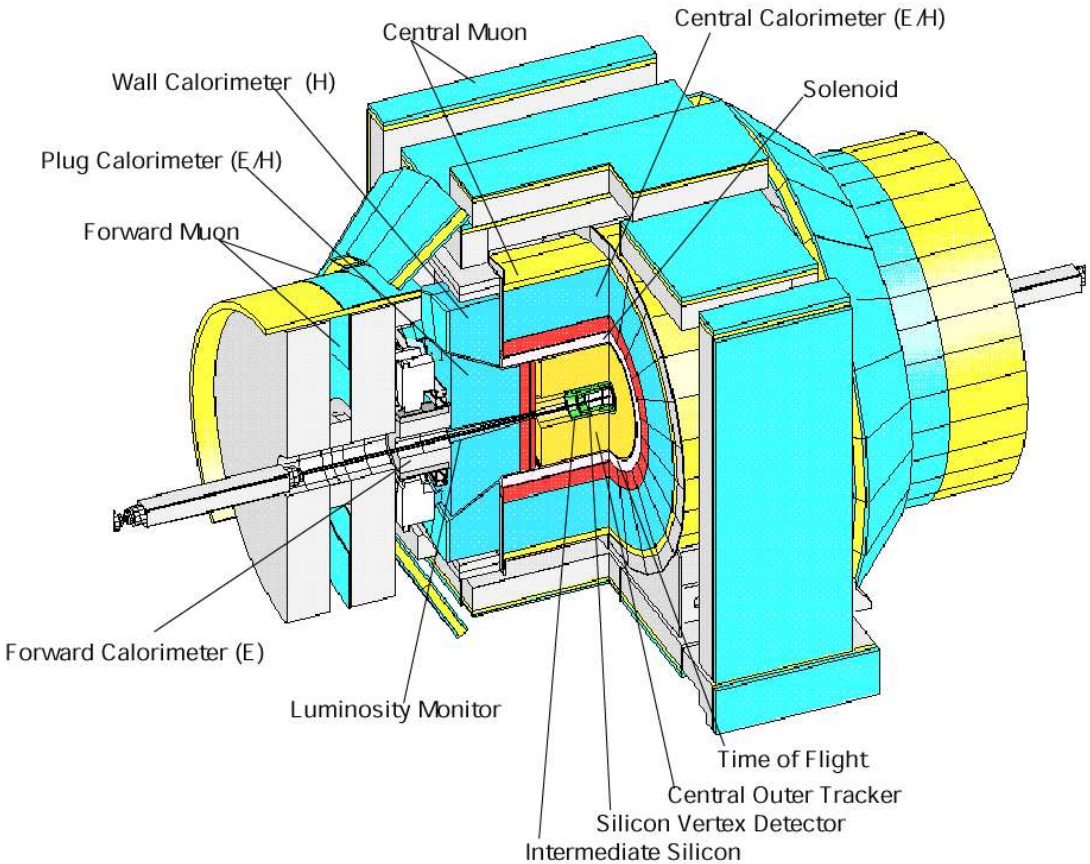
Anomalous Couplings
CP Violation
Rare / non-SM Decays
Branching Fractions
CKM matrix element $|V_{tb}|$

W Helicity

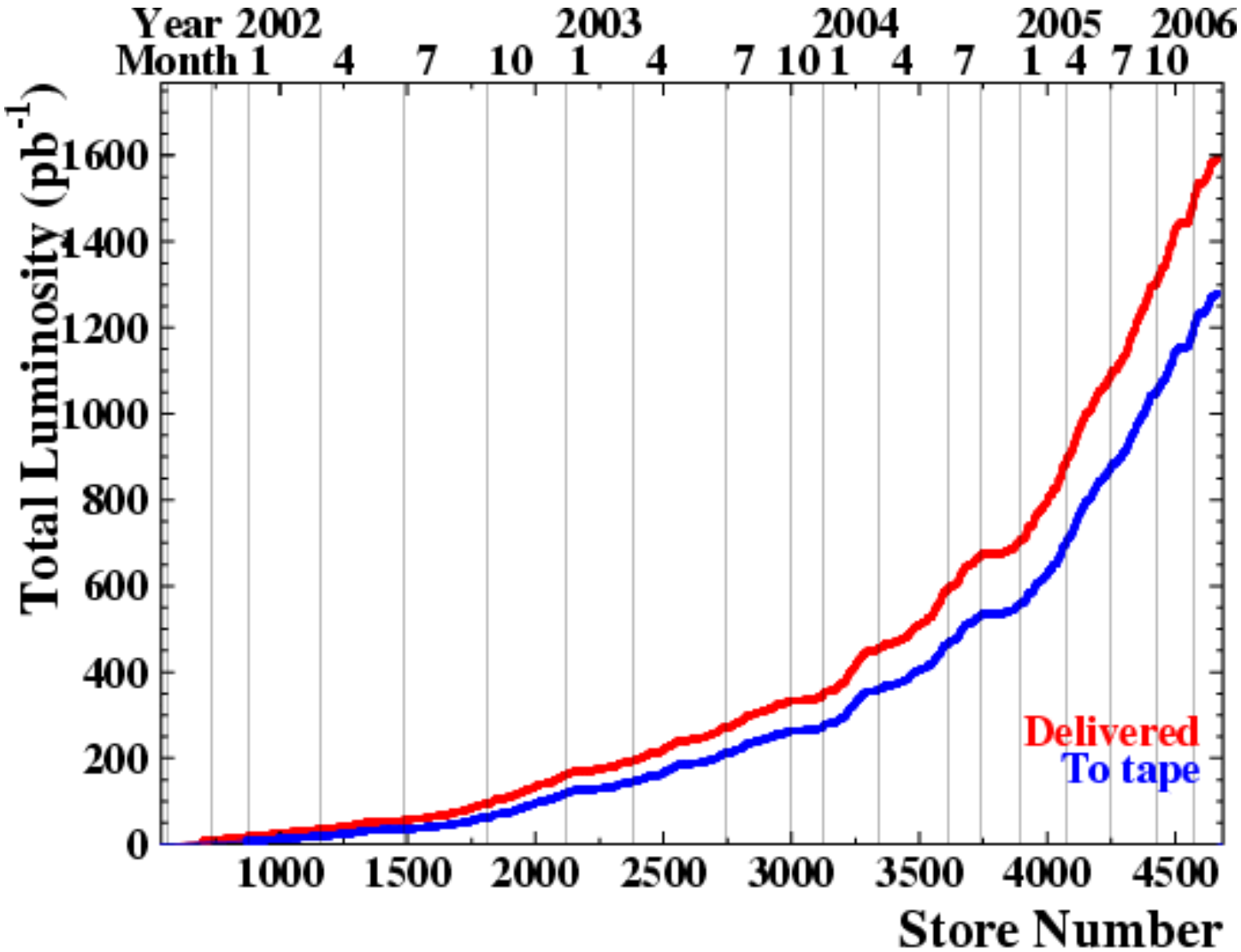
The Run II CDF Detector

like most collider detectors:
- inner silicon tracking
- tracking chamber
- solenoid
- em and had calorimeters
- muon detectors

upgrades in 2005/2006:
- ensure high quality and efficient data taking with highest luminosities



Tevatron Luminosity



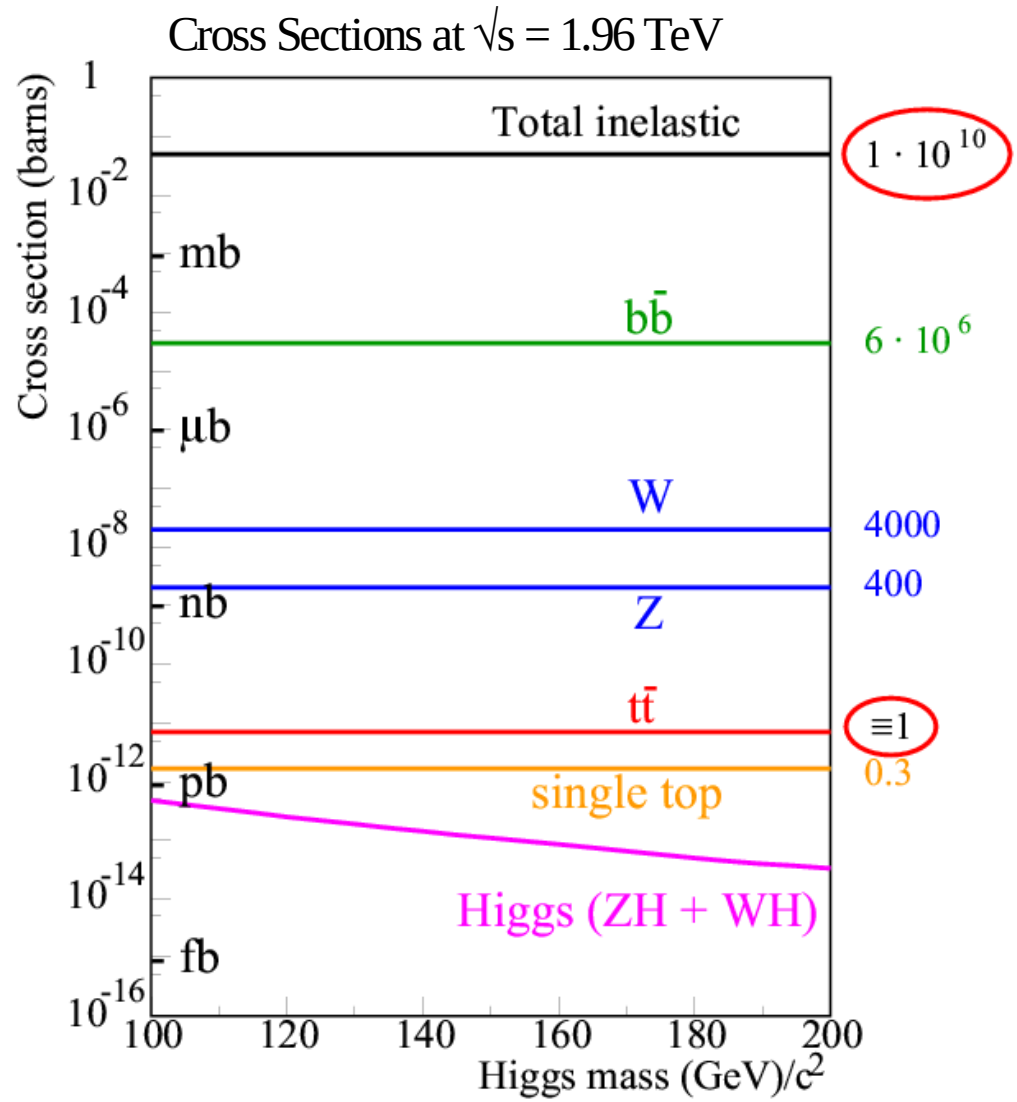
This talk will show results with up to 955pb^{-1} int. luminosity.

High p_T Physics at the Tevatron

top event:
- 1 in 10 Billion

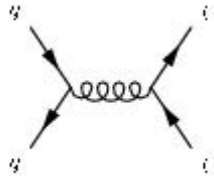
name of the game:
- reduce and understand backgrounds

tools, i.e.:
- trigger and identify leptons
- b jet tagging

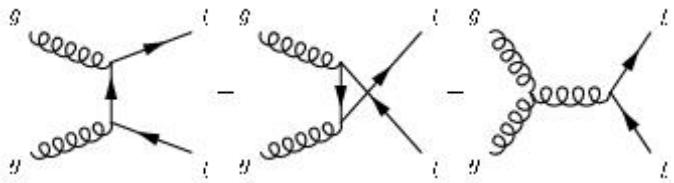


Production and Decay Modes

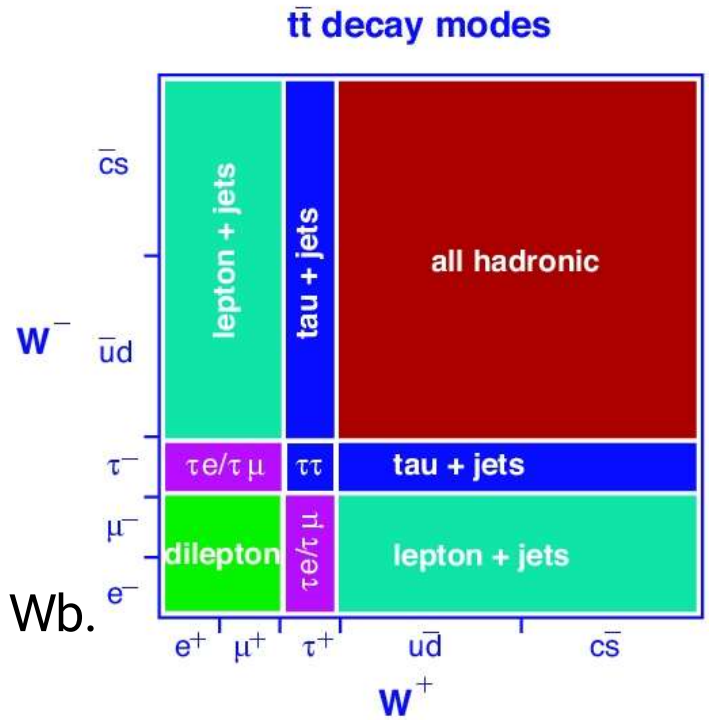
- up to now, top only observed in pairs.



qq ~ 85 %



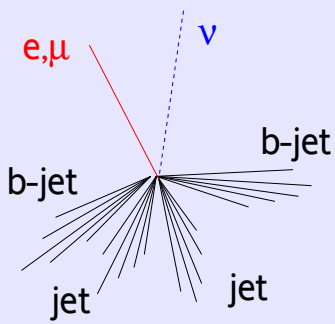
gg ~ 15 %



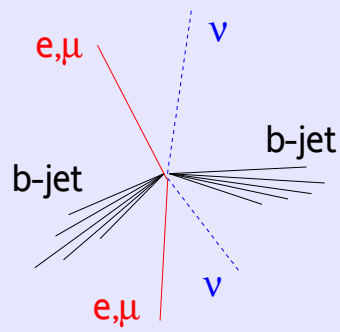
- according to the SM, top (almost) always decays to Wb.

- top pair event classification:

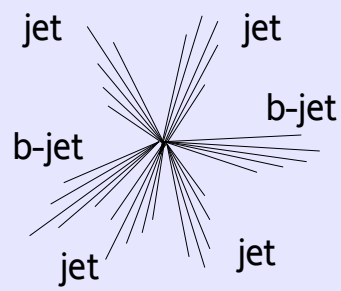
Lepton+jets
(BR~30%, moderate bgd)



Di-lepton
(BR~5%, moderate bgd)



All-hadronic
(BR~46%, huge bgd)



Top Pair Cross Section at CDF

- important for all top quark measurements.

- different sensitivity and challenges in each decay channel.

- only lepton+jets and dilepton channels considered for W helicity measurements.
  + high purity
  + lepton provides W helicity information

- top pair cross section measurement:

$$\sigma_{t\bar{t}} = \frac{N_{\text{observed}} - N_{\text{background}}}{A \cdot \varepsilon \cdot \int \mathscr{L}\, dt}$$

Top Pair Cross Section at CDF

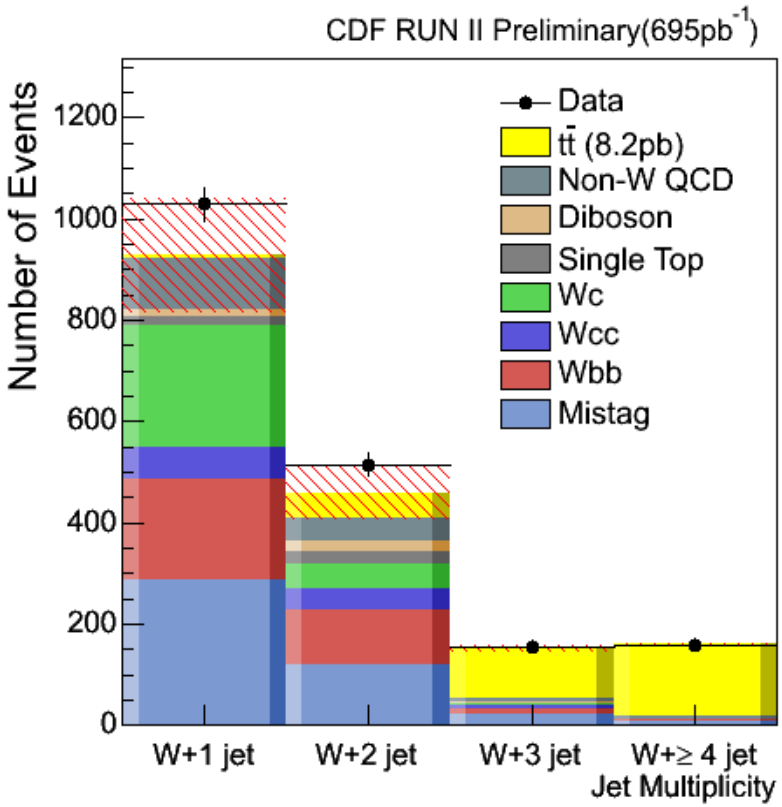
Lepton+jets channel with b jet tagging:

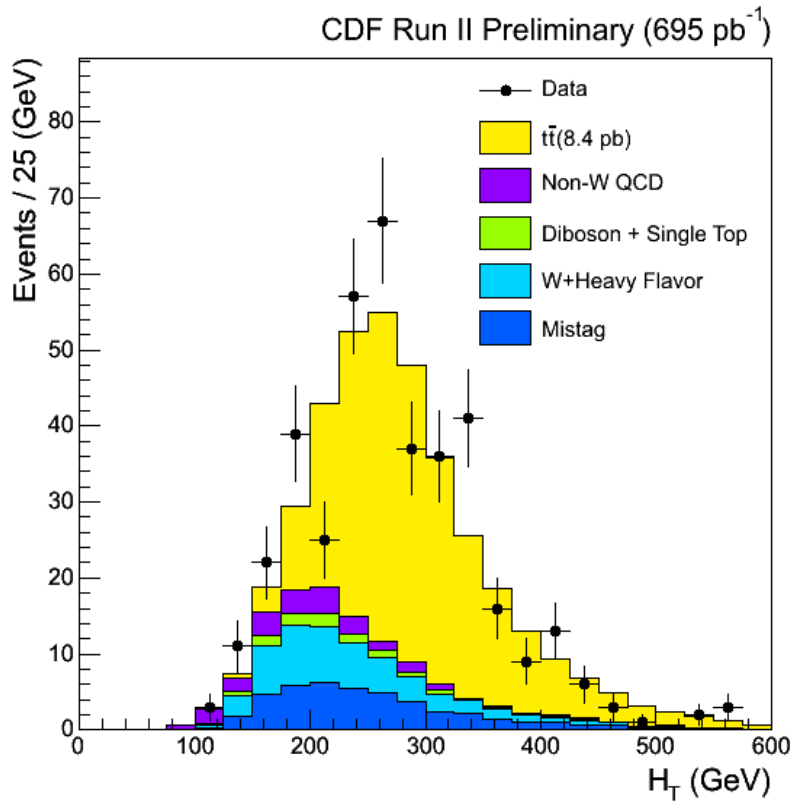
- high p_T lepton (e, μ)
- missing transverse energy
- 3 or more jets (at least one b tag)
- H_T > 200 GeV
- W + jets is dominant background

for m_{top} = 175 GeV:

$$\sigma_{tt} = 8.2 \pm 0.6\,(stat.) \pm 1.0\,(syst.)\ pb$$

$$\sigma_{tt} = 6.7 \pm 0.8\ pb\,(theory)$$





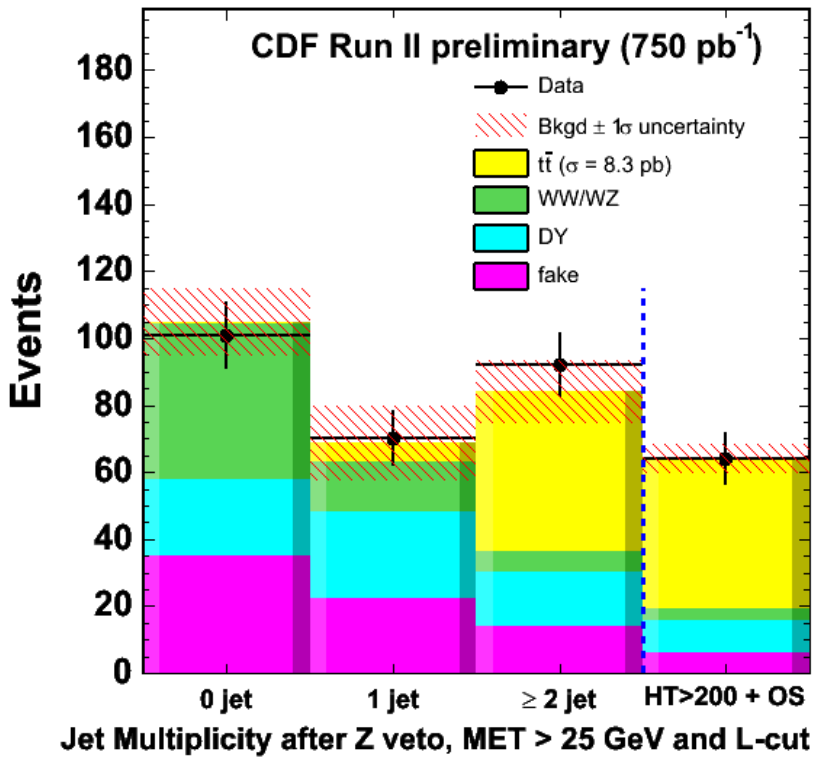
Top Pair Cross Section at CDF

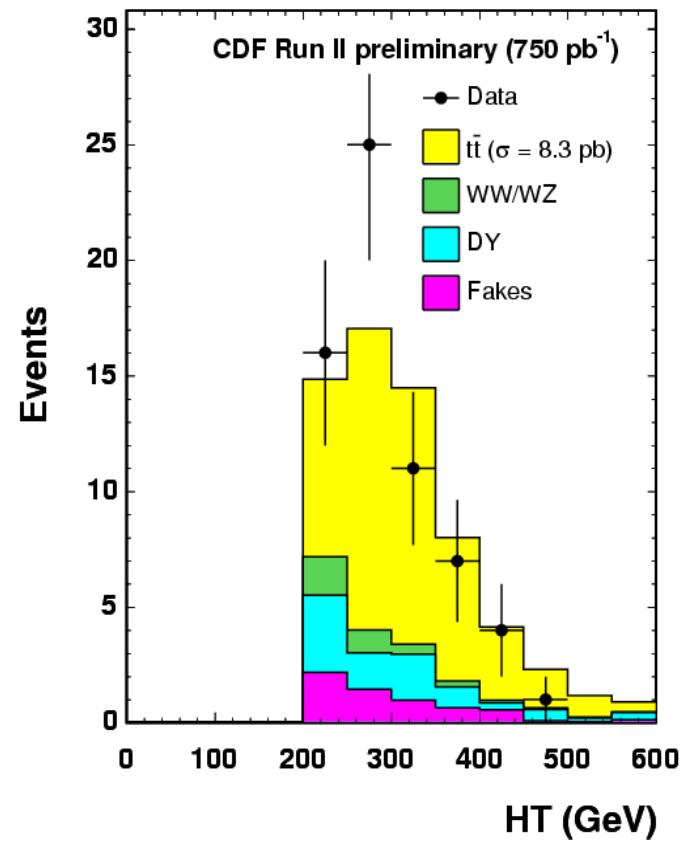
Dilepton channel:

- two high p_T lepton (e, μ)
- missing transverse energy
- 2 or more jets
- H_T > 200 GeV

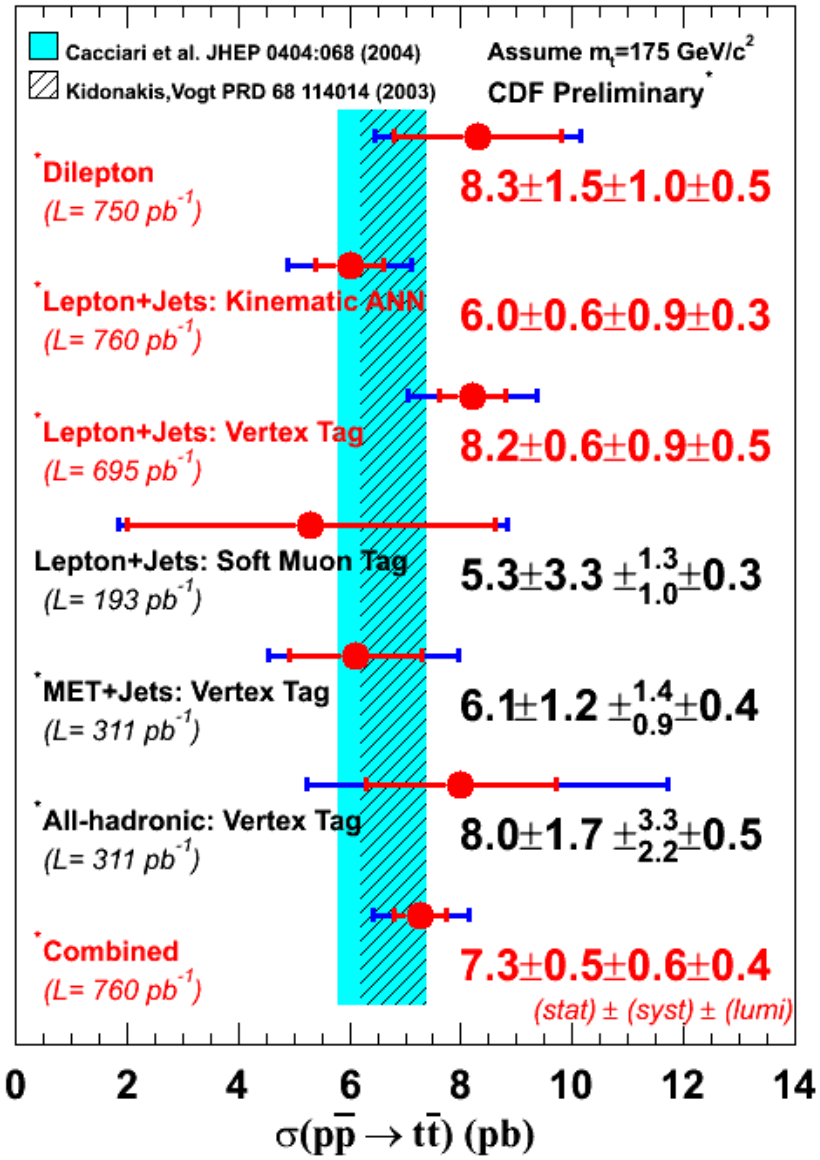
for m_{top} = 175 GeV:

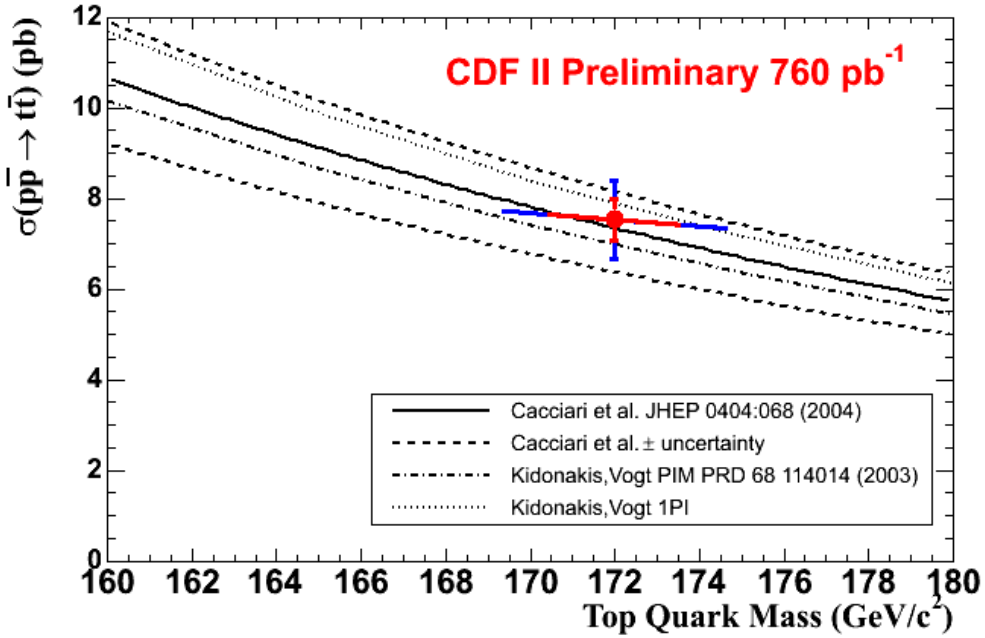
$$\sigma_{tt} = 8.3 \pm 1.5\,(stat.) \pm 1.1\,(syst.)\ pb$$





Top Pair Cross Section at CDF





Top Cross Section Summary:

- top pair data set well understood.
- everything is consistent with the SM.
- starting point for the W helicity measurement.

Outline

Brief History of Top Quark Physics

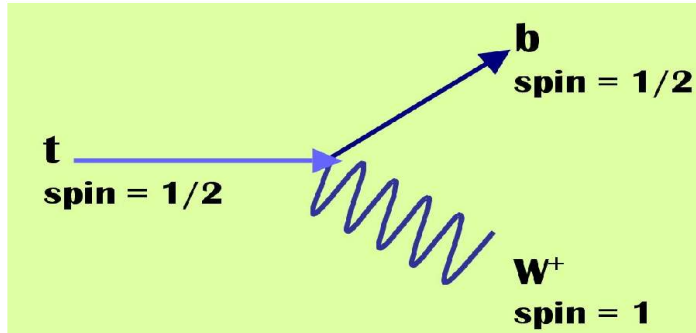
W Helicity in Top Quark Decays
- theory
- methods
- new CDF results

Summary

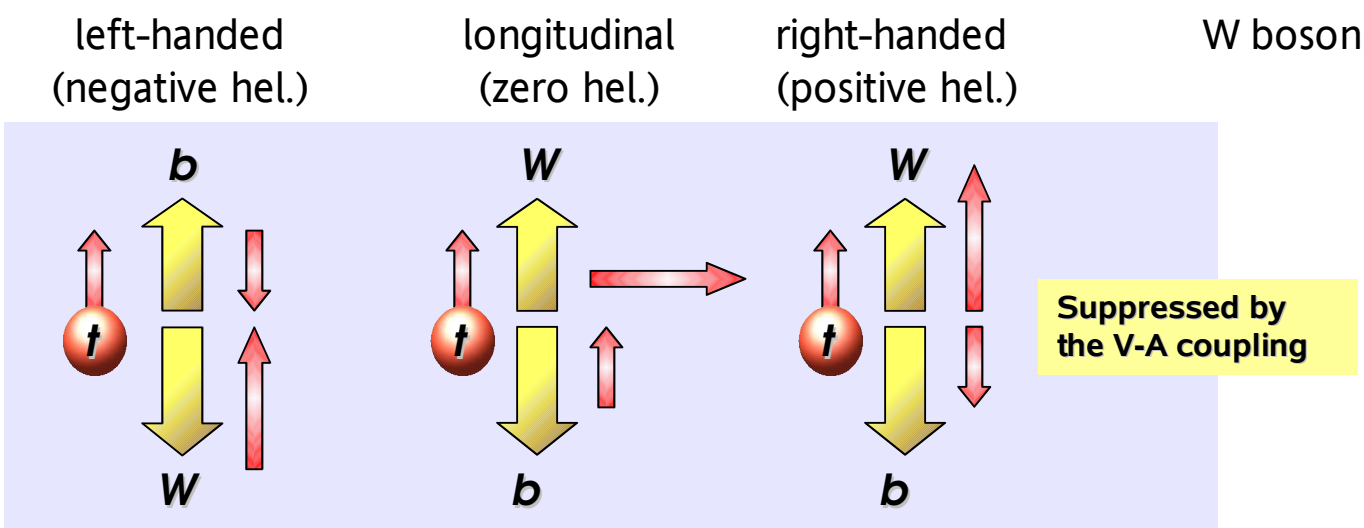
W Helicity in Top Quark Decays

SM Top decays via weak interaction
→ V-A coupling like all other quarks:

$$\frac{-i\,g}{2\sqrt{2}}\,\bar{t}\,\gamma^{\mu}\left(1-\gamma^{5}\right)V_{tb}\,b\,W_{\mu}$$

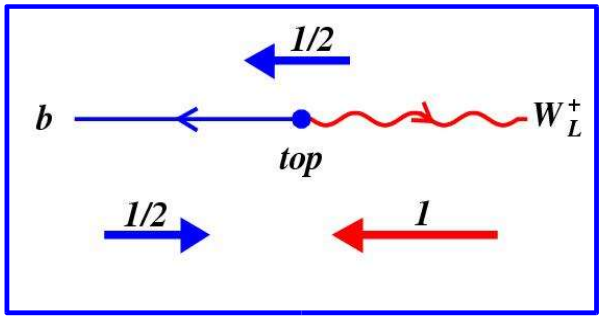


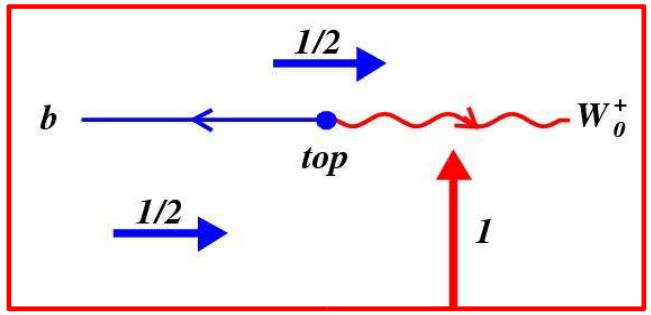
H = J • P

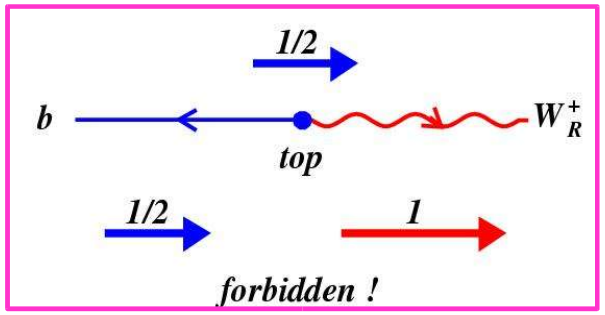


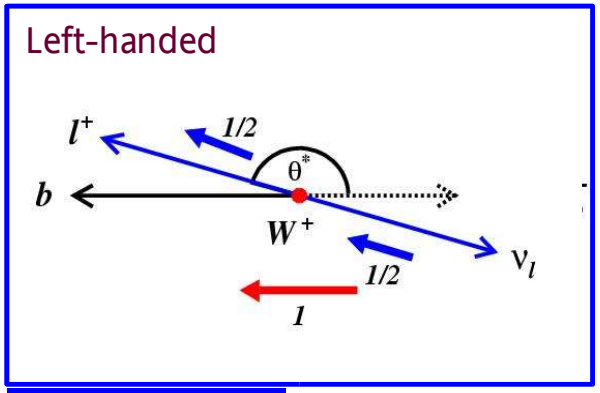
Is the top decay vertex consistent with the SM ?

W Helicity in Top Quark Decays

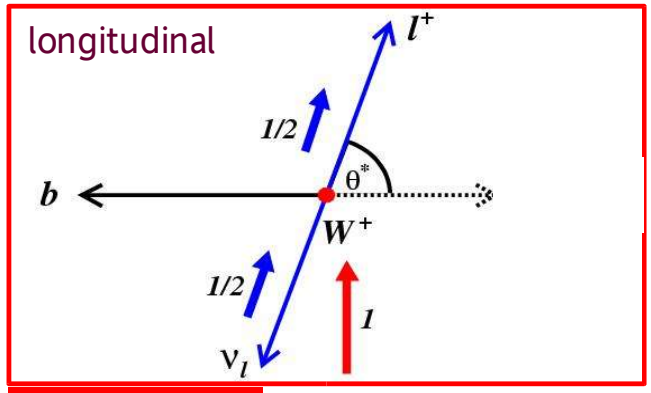




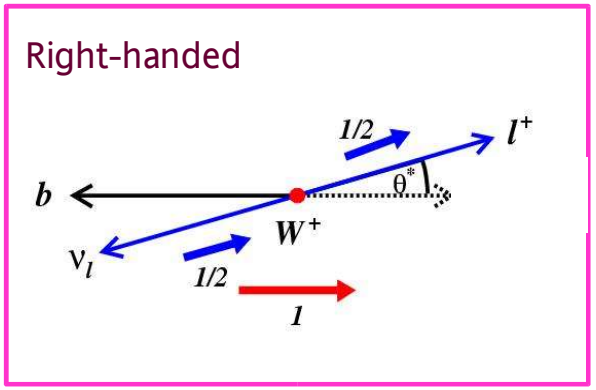




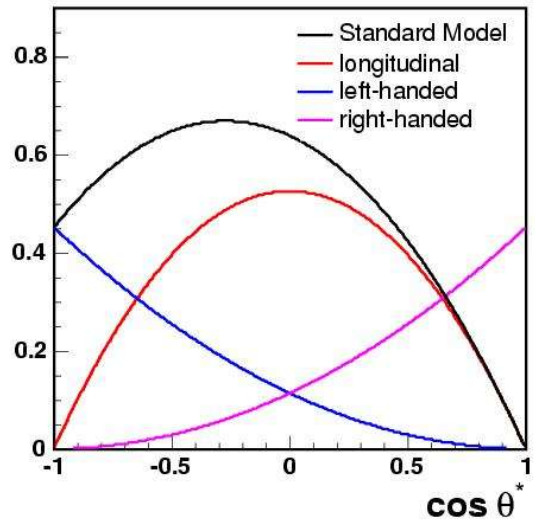
$\sim(1 - \cos\theta^*)^2$



$\sim(1 - \cos^2\theta^*)$



$\sim(1 + \cos\theta^*)^2$

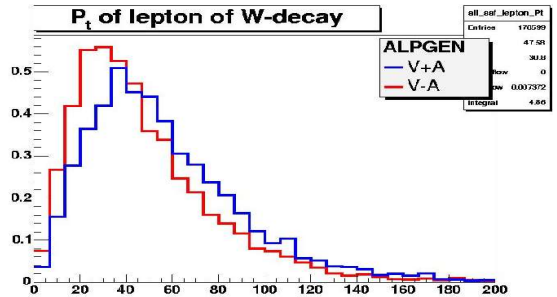


$$\cos(\theta^*) = \frac{p_l \cdot p_b - E_l \cdot E_b}{|p_e||p_b|}$$

How Can We Measure the W Helicity ?

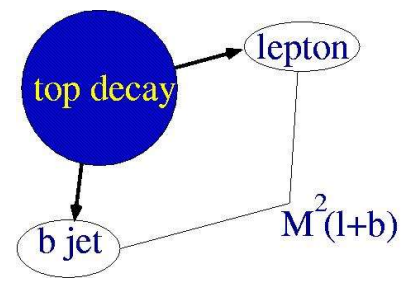
Senisitive observables to W helicity:

- lepton p_T
  + use all leptons

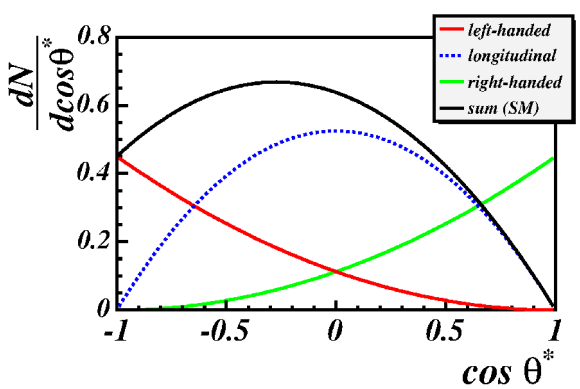


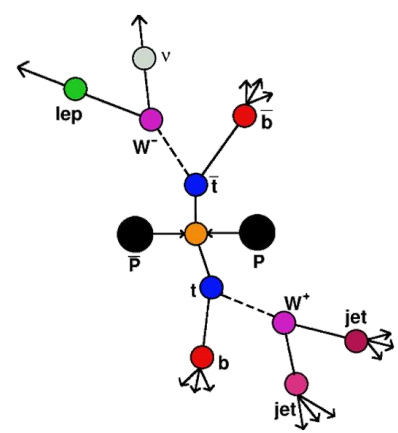
- l-b invariant mass
  + use all lepton-b-combinations

$$m_{\ell b}^2 = \frac{1}{2}(m_{\text{top}}^2 - m_{\text{W}}^2)(1 + cos(\theta^*))$$



- cos θ*
  + fully reconstruct the events





- matrix element approach (only used by D0 in RunI)

complexity

How Can We Measure the W Helicity ?

... expressing the result:

f_0 := fraction of top decays to longitudinally polarised W bosons

$f_0^{SM} = 70.3 \pm 1.2\%$ (at m_{top} = 175 GeV)
measured by fixing $f_+ = 0$.

f_+ := fraction of top decays to right-handed W bosons.
f_{V+A} := V+A current in top decays ($f_{V+A} = f_+ / 0.3$).
measured by fixing $f_0 = 70.3\%$.

$f_+^{SM} \approx 3.6 \times 10^{-4}$ (surpressed by a factor $(m_b / m_{top})^2$).

Previous Measurements

Period	Sensitive variable	Meas. quantity	Decay channel	N_{jets}	$\mathcal{L}$ $[pb^{-1}]$
Run I	p_T^ℓ	F_0, F_+	Lepton+Jets	≥ 3	106
			Dilepton	≥ 2	106
	$M_{\ell b}^2$	f_{V+A}	Lepton+Jets	≥ 3	109
			Dilepton	≥ 2	109
		Comb.: $F_+ = -0.02 \pm 0.11$; p_T^ℓ: $F_0 = 0.91 \pm 0.39$			
Early Run II	p_T^ℓ	F_0, F_+	Lepton+Jets	≥ 3	162
			Dilepton	≥ 2	193
	$\frac{2M_{\ell b}^2}{m_t^2 - M_W^2} - 1 \approx \cos\theta^*$	F_0, F_+	Lepton+Jets	≥ 3	162
		Comb.: $F_0 = 0.74^{+0.22}_{-0.34}$, $F_+ = 0.00^{+0.20}_{-0.19}$			

Consistent with SM:

- top decay is of V-A nature

Large uncertainties.

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- new CDF results

Summary

new CDF results:

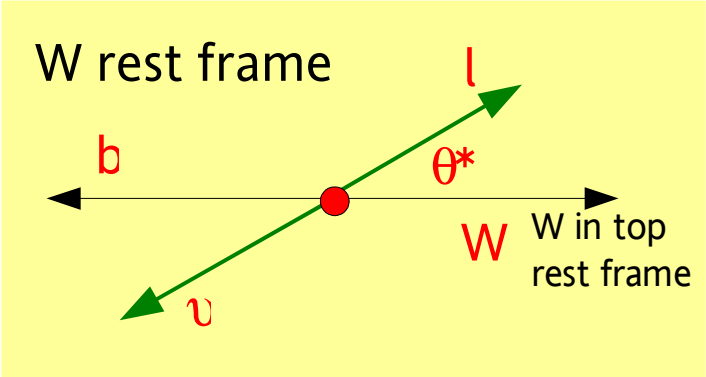
method:	$\cos\theta^*$
luminosity:	955 pb^{-1}
channel:	$l+ \geq 4$ jets (≥ 1 b tag)

method:	$\cos\theta^*$
luminosity:	320 pb^{-1}
channel:	$l+ \geq 4$ jets (≥ 1 b tag)

method:	m_{lb}^2
luminosity:	750 pb^{-1}
channel:	$l+ \geq 3$ jets (≥ 1 b tag) dilepton

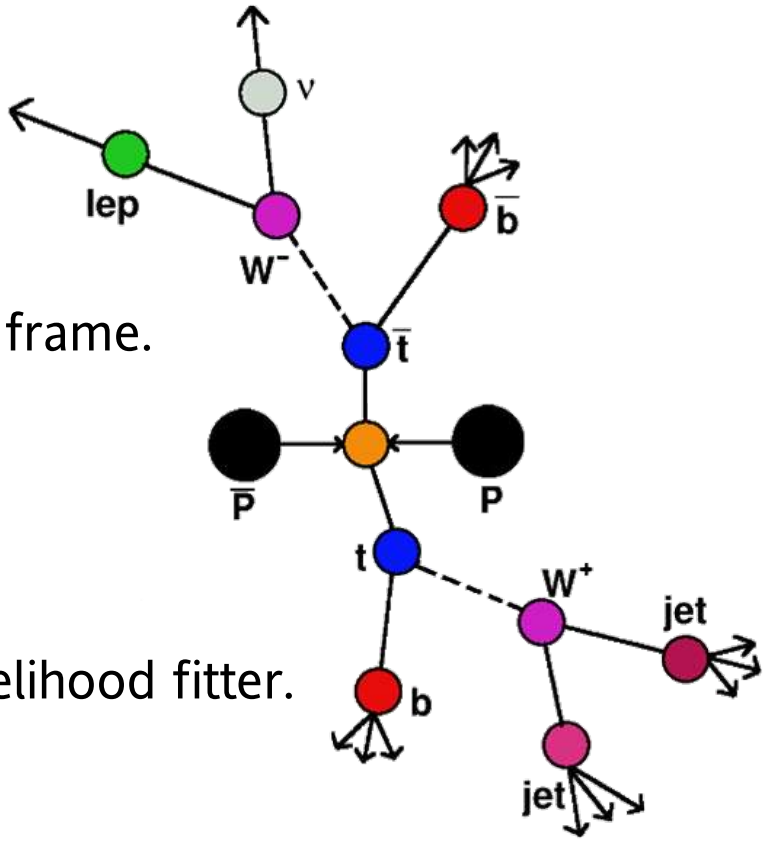
W Helicity in Top Quark Decays at the CDF

measurement using cos θ* in 955pb^{-1}.



analysis strategy:

- select candidate sample and evaluate backgrounds.
  * lepton+ ≥4 jets with b-tag and H_T cut.
- fully reconstruct ttbar event using a kinematic fitter.
  (used for template top mass analysis)
- extract cos θ* by boosting lepton and top into W rest frame.
- create templates for signal with f_0 =1, f_- =1 and f_+ =1
  and for background.
- fit templates to extract f_0, f_- and f_+ with unbinned likelihood fitter.
- correct for acceptance effects.



W Helicity in Top Quark Decays at the CDF

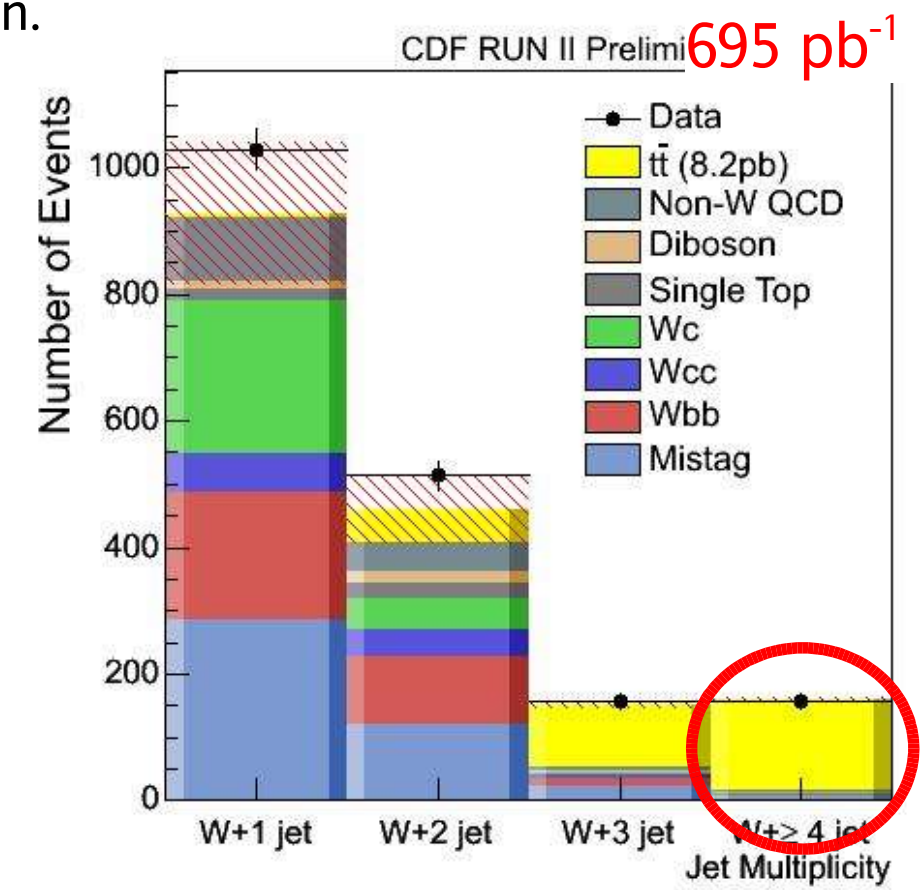
measurement using cos θ* in 955pb^{-1}.

Data	220	
Total Bgd	22.8 ± 2.5	90% signal fraction.

(very clean top pair sample)

695pb-1 cross section result scaled to 1fb^{-1} :

process	events	bkg fraction	sample fraction
Mistag	9.0 ± 1.4	38%	4.2%
W+hf	6.4 ± 1.9	30%	3.3%
Single top	0.5 ± 0.2	2%	0.3%
Diboson	1.4 ± 0.3	6%	0.6%
QCD	5.5 ± 1.1	24%	2.6%



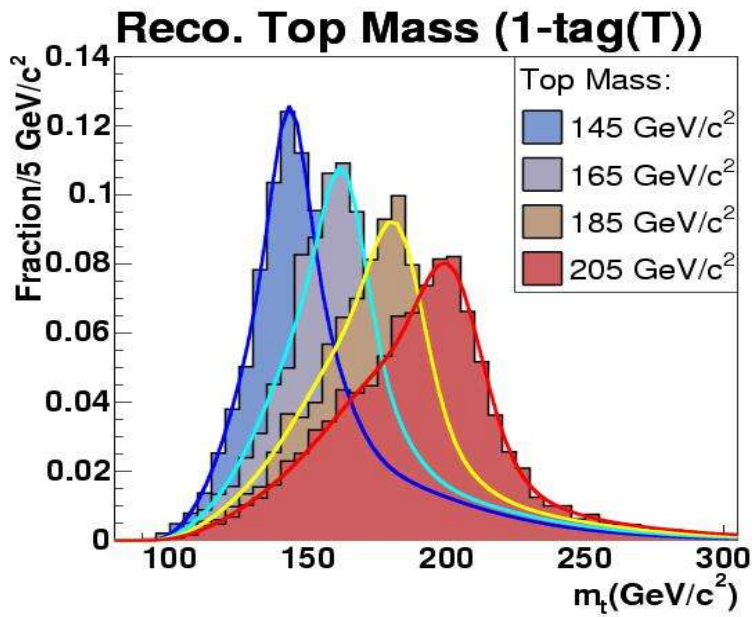
W Helicity in Top Quark Decays at the CDF

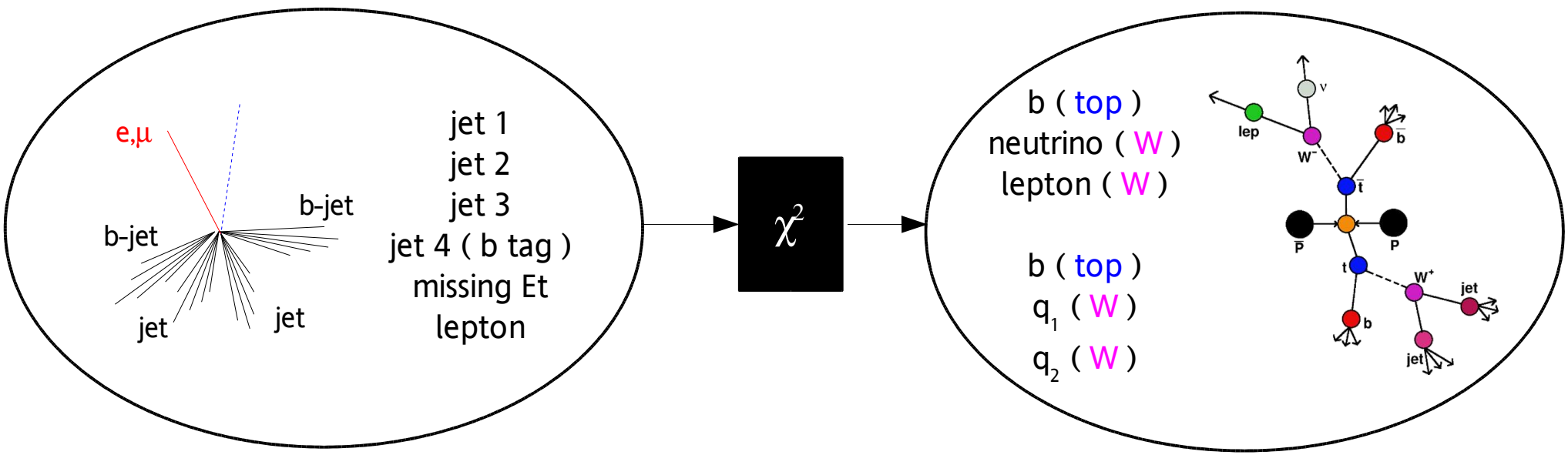
measurement using cos θ* in 955pb^{-1}.

- ttbar event reconstruction.
  (used for top mass analysis)

- find the correct assignment between reconstructed objects and partons.

– χ^2 kinematic fitter used to select the most likely combination.



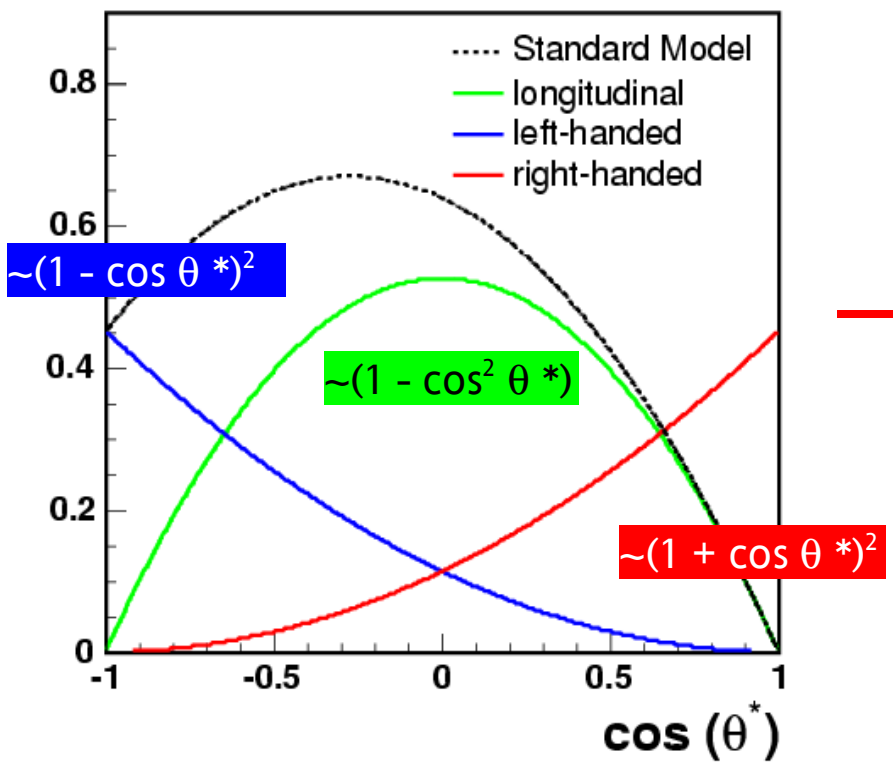


extract cos θ* by boosting lepton and top into W rest frame.

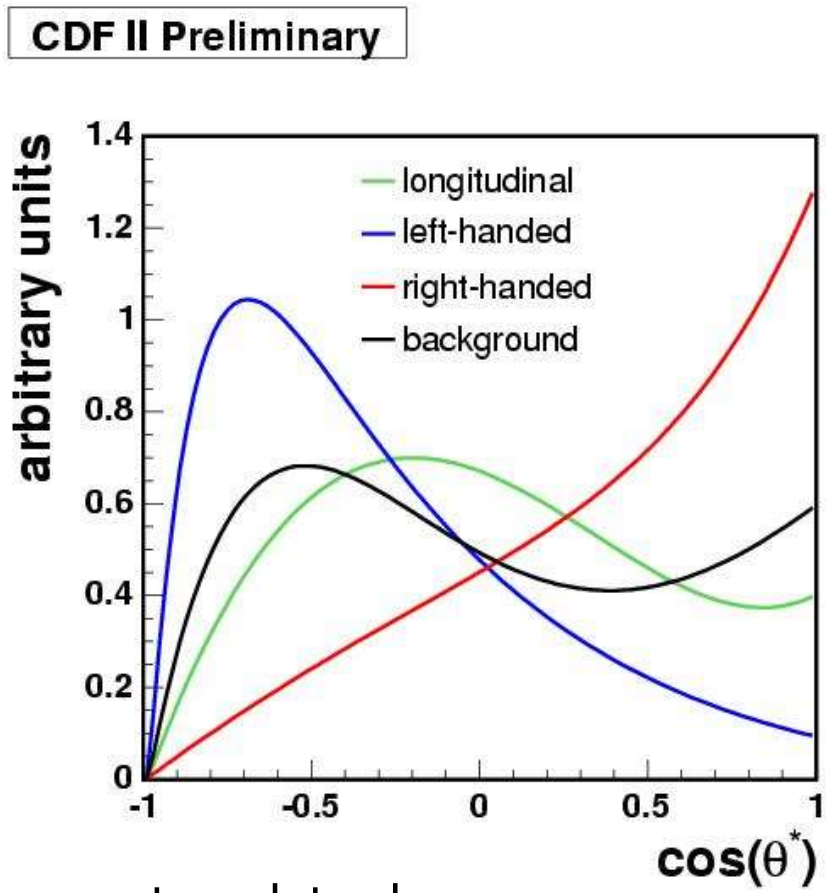
W Helicity in Top Quark Decays at the CDF

measurement using cos θ* in 955pb^{-1}.

- generate Monte Carlos samples for signal with f_0 =1, f_- =1 and f_+ =1 and for background.
- generate and parametrised templates



theoretical distributions



template shape

W Helicity in Top Quark Decays at the CDF

measurement using cos θ* in 955pb^{-1}.

- extract F_0 or F_+ and background fraction with unbinned likelihood fitter

$$L = G(b \mid \mu_b, \sigma_b) \cdot P(s+b \mid \mu_s + \mu_b) \cdot \prod_{i=1}^{N_s} (f_b\, p_b(\cos\theta^*) + (1-f_b)\, p_s(\cos\theta^*))$$

Gauss constraint for external background estimate.

Poisson fluctuate signal+background.

background fraction.

background shape information.

signal shape information.

signal shape information:

$$p_s = F_0 \cdot p_0 + F_+ \cdot p_+ + (1 - F_0 - F_+) \cdot p_-$$

longitudinal

right-handed

left-handed

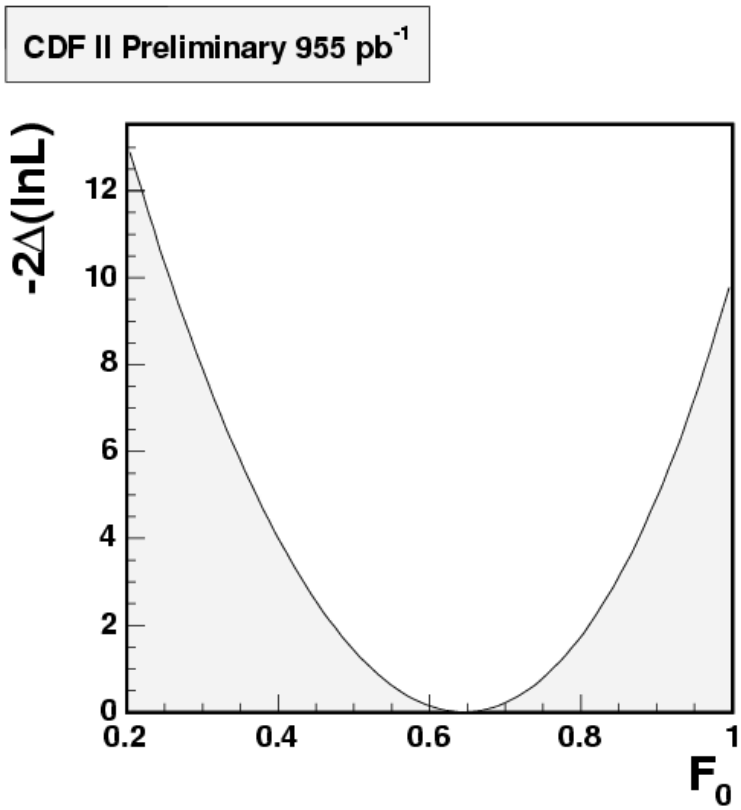
- extract two results by fitting for:
  - F_0 while $F_+ = 0$ and
  - F_+ while F_0 is fixed to SM value @175GeV

W Helicity in Top Quark Decays at the CDF

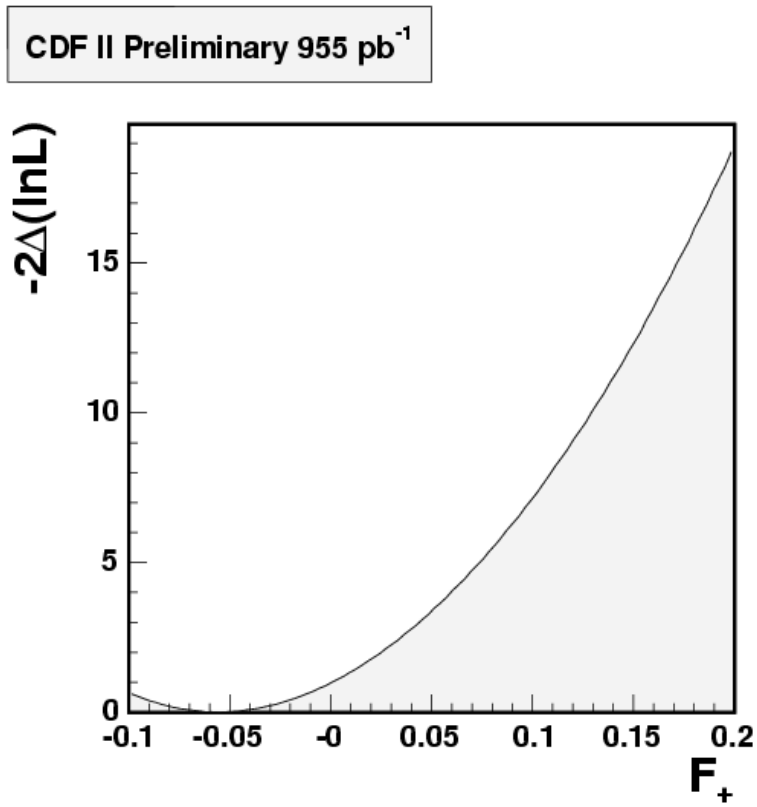
measurement using cos θ* in 955pb^{-1}.

Likelihood curves:

for longitudinal fraction



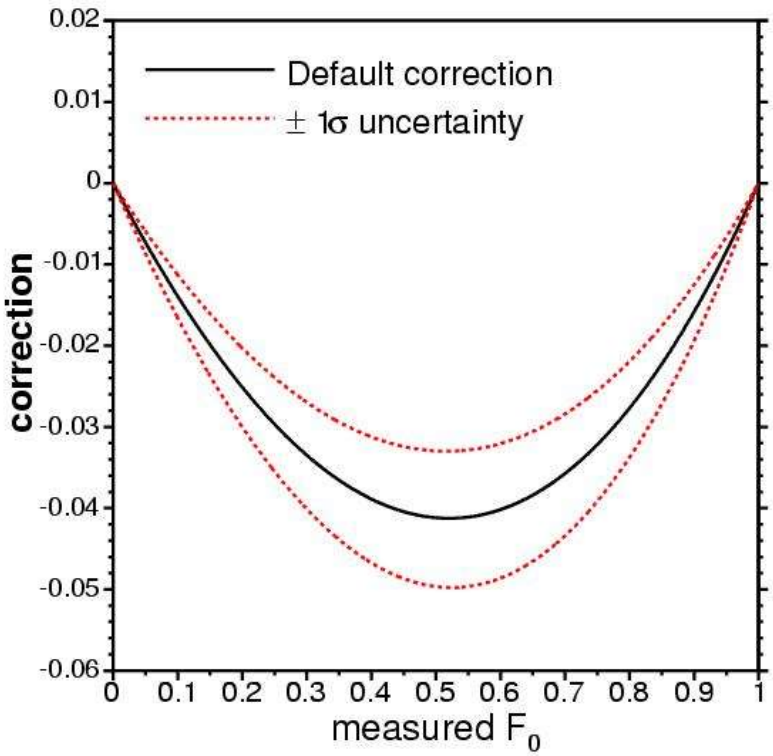
for right-handed fraction

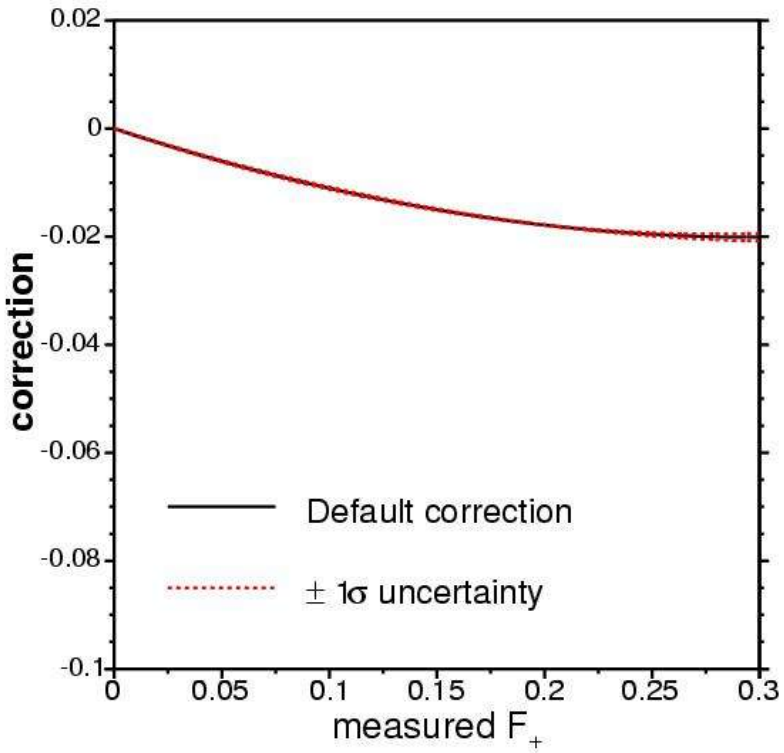


W Helicity in Top Quark Decays at the CDF

- we measure F_0 and F_+ in selected sample and have to correct for acceptance effects, i.e. selection efficiencies for $f_0=1$, $f_-=1$ and $f_+=1$ samples.

f := corrected value; F := measured value
f = F + correction

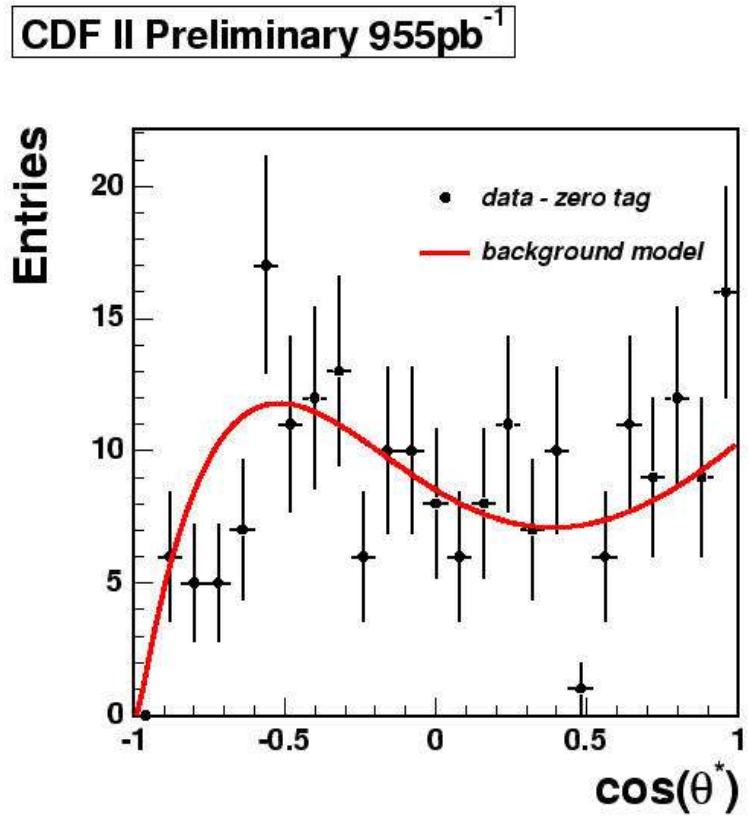




W Helicity in Top Quark Decays at the CDF

- systematic uncertainties.

Source	δf_0	δf_+
Bkg model	±0.038	±0.017
JES	±0.013	±0.010
Signal model	±0.020	±0.010
PDF	±0.009	±0.006
ISR/FSR	±0.010	±0.005
MC statistics	±0.020	±0.010
Int. luminosity	±0.007	±0.002
Method	±0.010	±0.010
Total	±0.053	±0.027



Background model cross check.

- analysis statistically limited.

expected stat. uncertainty $\delta f_0 = 0.12$ & $\delta f_+ = 0.06$

W Helicity in Top Quark Decays at the CDF

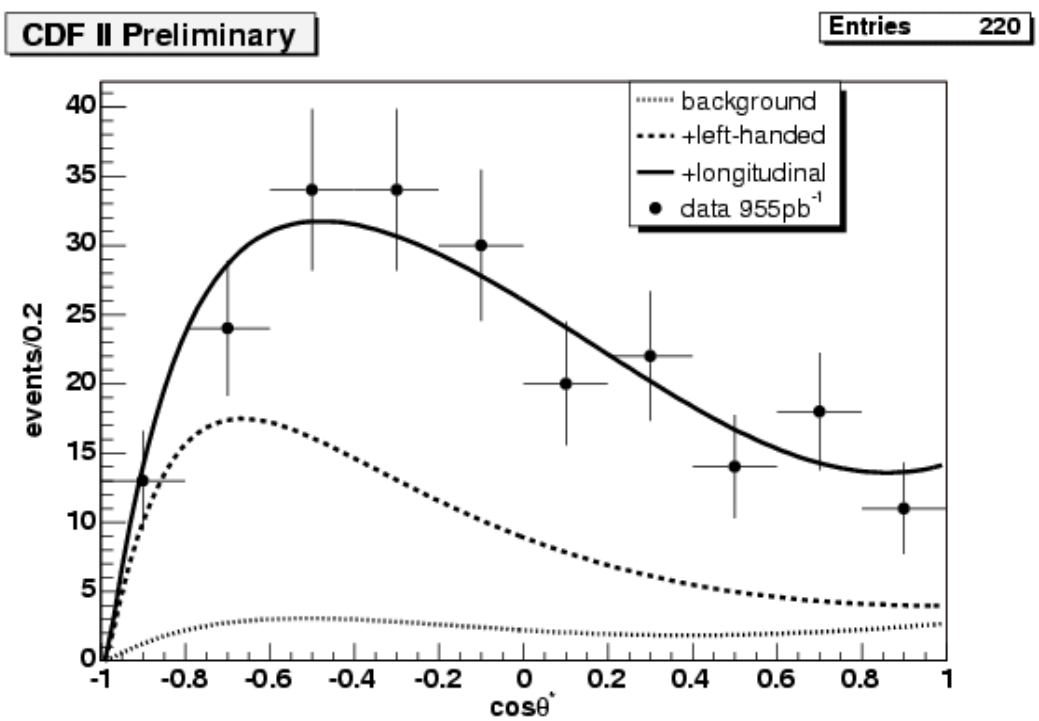
measurement using cos θ* in 955pb^{-1}.

Fitting the data:

expected stat. uncertainty $\delta f_0 = 0.12$ & $\delta f_+ = 0.06$

$f_0 = 0.61 \pm 0.12$ (stat.) ± 0.06 (syst), $f_+ = 0$ fixed

$f_+ = -0.06 \pm 0.06$ (stat.) ± 0.03 (syst), f_0 fixed to SM value @175GeV



Consistent with SM:

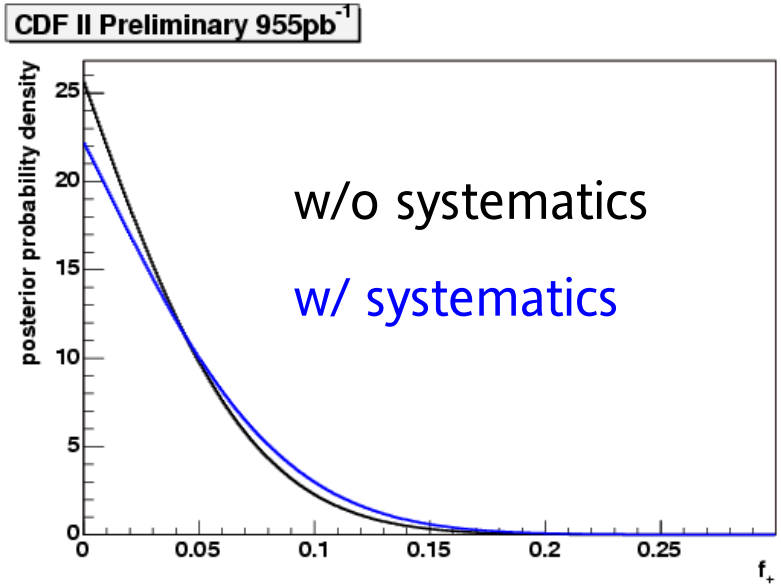
- top decay is of V-A nature.

W Helicity in Top Quark Decays at the CDF

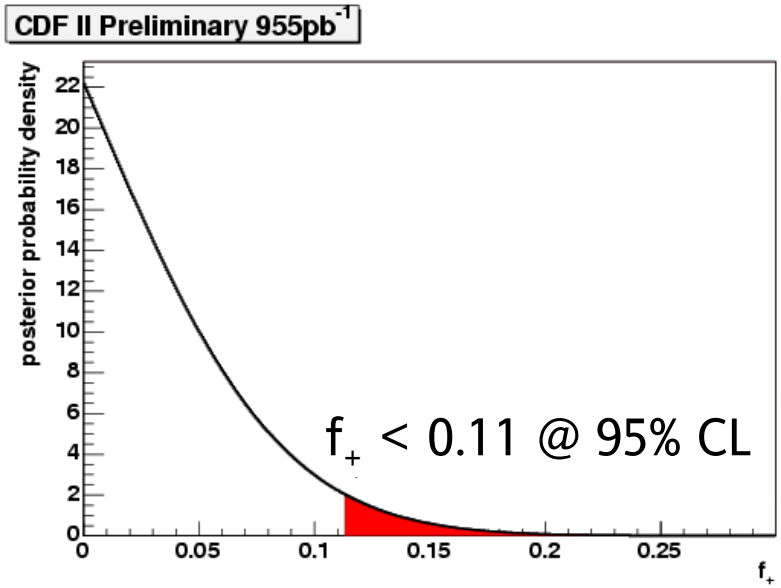
Upper limit on f_+:

Bayesian method for setting a
95% confidence limit.

- model systematic uncertainty with gaussian
with $\mu = 0$, $\sigma = 0.027$.
- convolute with likelihood.



- multiply likelihood curve by prior in
physical region (0-1).
- integrate out to 95% area.



W Helicity in Top Quark Decays at the CDF

measurement using cos θ* in 955pb^{-1}.

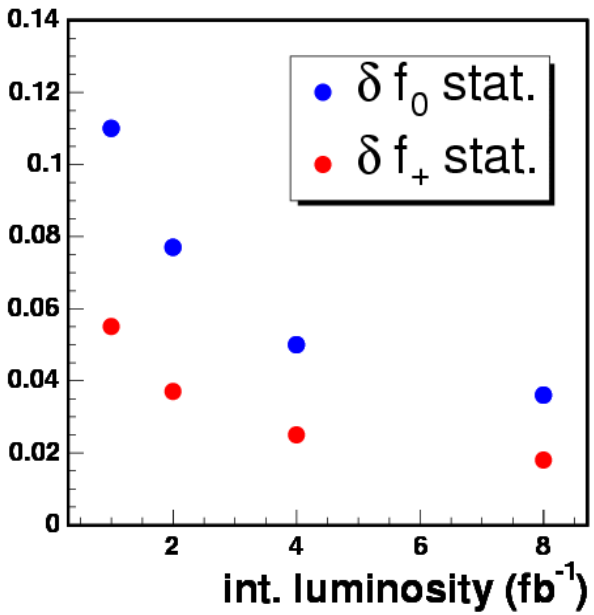
results:

$f_0 = 0.61 \pm 0.12 \pm 0.06$, $f_+ = 0$ fixed

$f_+ = -0.06 \pm 0.06 \pm 0.03$, f_0 fixed to SM value @175GeV

$f_+ < 0.11$ @ 95% C.L (including systematics)

projection of exp. stat. uncertainty



to come for this summer:

- improved method
- f_0, f_+ combined fit (unique)

Outline

Brief History of Top Quark Physics

W Helicity in Top Quark Decays
- theory
- methods
- new CDF results

Summary

new CDF results:

method:	$\cos\theta^*$
luminosity:	955 pb^{-1}
channel:	$l+ \geq 4$ jets (≥ 1 b tag)

method:	$\cos\theta^*$
luminosity:	320 pb^{-1}
channel:	$l+ \geq 4$ jets (≥ 1 b tag)

method:	m_{lb}^2
luminosity:	750 pb^{-1}
channel:	$l+ \geq 3$ jets (≥ 1 b tag) dilepton

W Helicity in Top Quark Decays at the CDF

measurement using cos θ^* in 320 pb^{-1}

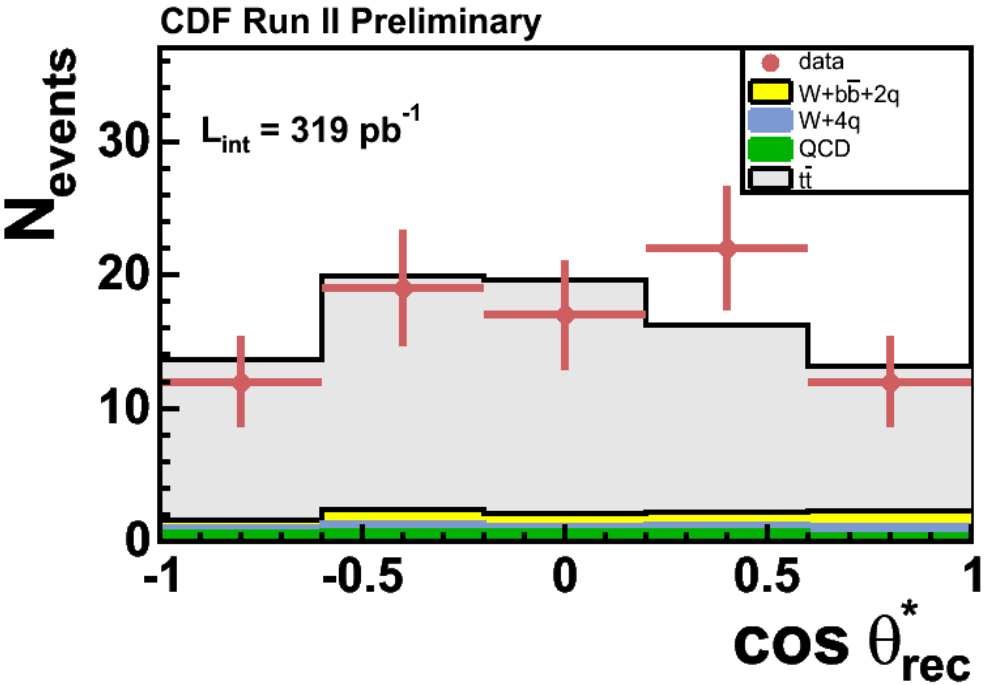
similar to previous measurement

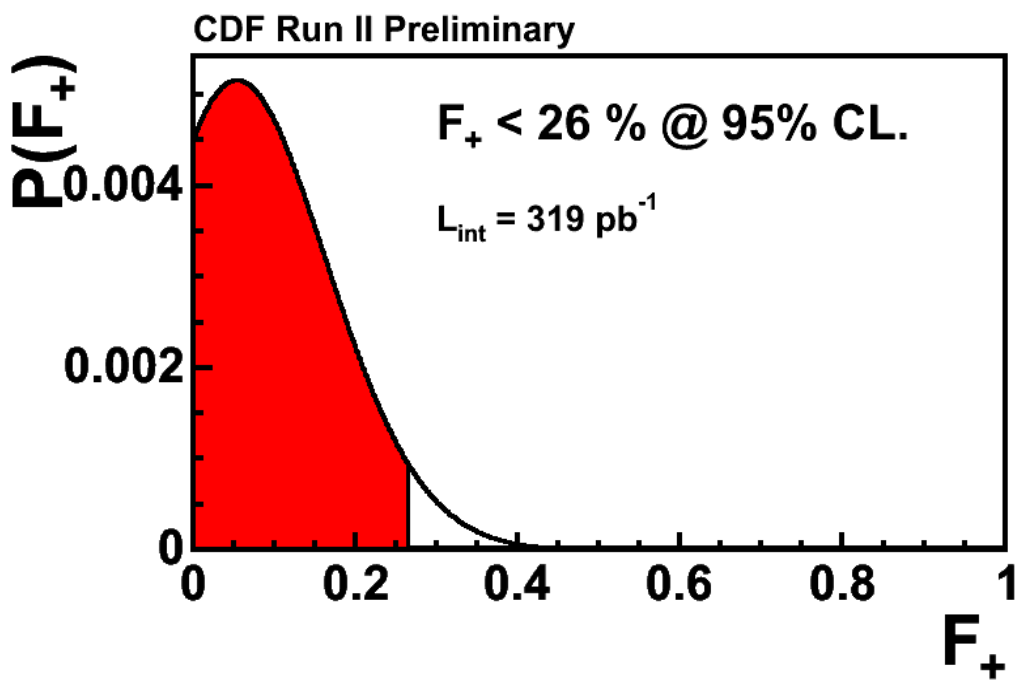
main differences:

1. method	2. method
templates extracted from MC samples.	templates extracted from theoretical cos θ^* distributions corrected for detector effects.
unbinned likelihood	binned likelihood

W Helicity in Top Quark Decays at the CDF

measurement using cos θ* in 320 pb^{-1} (82 candidate events)





Result:

$f_0 = 0.85^{+0.15}_{-0.22} \pm 0.06$, $f_+ = 0$ fixed

$f_+ = 0.05^{+0.11}_{-0.05} \pm 0.03$, f_0 fixed to SM value @175 GeV

$f_+ < 0.26$ @ 95% C.L (currently being updated with 1fb^{-1})

similar sensitivity and cross check for previous analysis!

Consistent with SM:

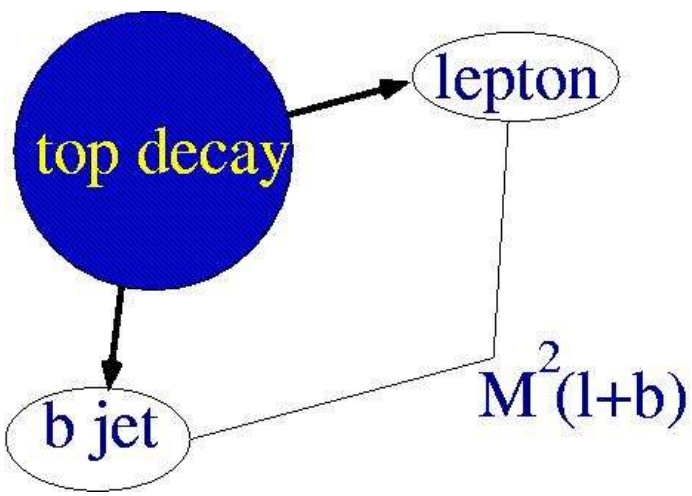
- top decay is of V-A nature.

Outline

Brief History of Top Quark Physics

W Helicity in Top Quark Decays
- theory
- methods
- new CDF results

Summary



new CDF results:

method:	cos θ*
luminosity:	955 pb^{-1}
channel:	l+ ≥ 4 jets (≥1 b tag)

method:	cos θ*
luminosity:	320 pb^{-1}
channel:	l+ ≥ 4 jets (≥1 b tag)

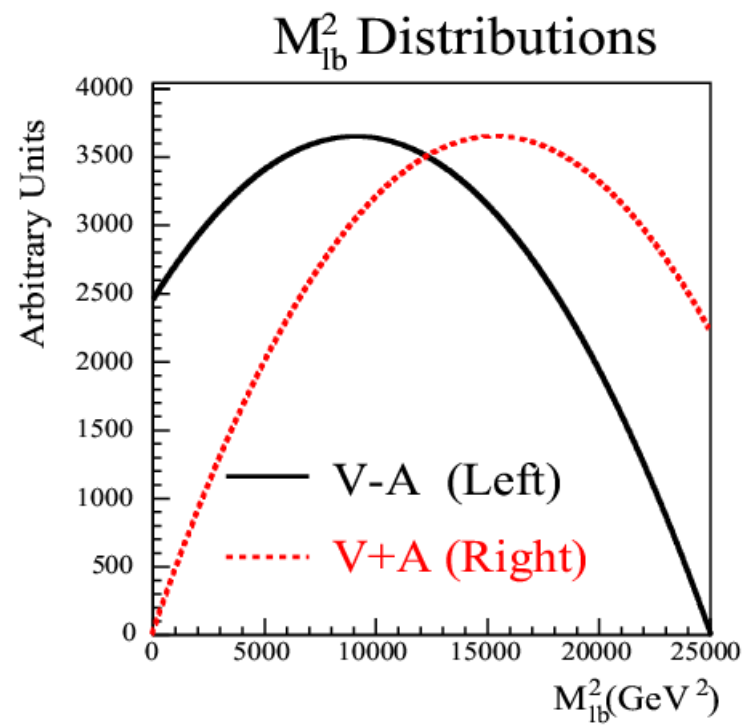
method:	m_{lb}^2
luminosity:	750 pb^{-1}
channel:	l+ ≥ 3 jets (≥1 b tag) dilepton

W Helicity in Top Quark Decays at the CDF

measurement using m_{lb}^2 in 750 pb^{-1}

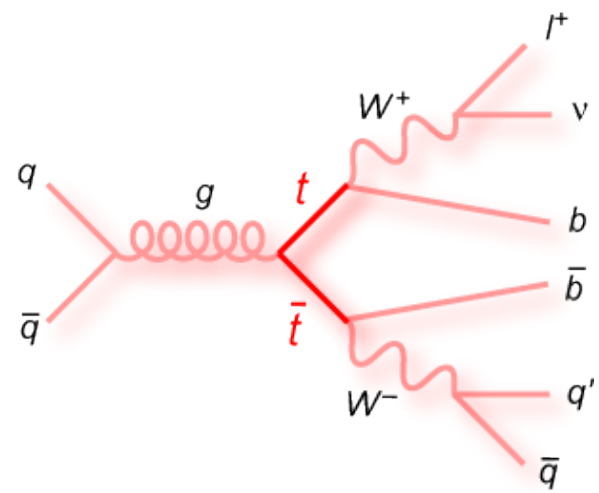
analysis strategy:

- use 3 data samples
  - a) lepton + ≥3 jets with single b tag
    - 304 evts in 695pb^{-1}, 108.4 bkg.
  - b) lepton + ≥3 jets with double b tag
    - 75 evts in 695pb^{-1}, 9.1 bkg.
  - c) dilepton
    - 64 evts in 750pb^{-1}, 19.9 bkg.



- use invariant mass of lepton and b jet, with m_b=0,

$$m_{\ell b}^2 = \frac{1}{2}(m_{\mathrm{top}}^2 - m_{\mathrm{W}}^2)(1 + cos(\theta^*))$$



No kinematic fitter needed in this analysis.

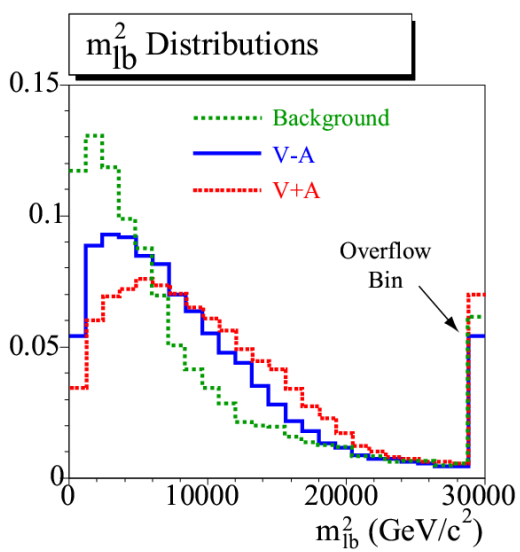
- which l-b-combination to pick?

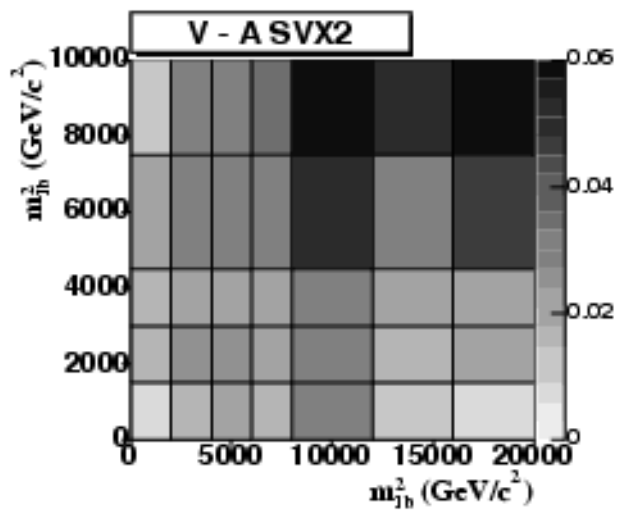
- use binned likelihood to extract f_{V+A} (= f_+ / 0.3) in data.

W Helicity in Top Quark Decays at the CDF

- which l-b-combination to pick?

- with one lepton and one b tagged jet, it is clear what invariant mass to use.
- with one lepton and two b tagged jets, there are two choices:
  - a) lepton with leading b jet $\rightarrow$ x axis.
  - b) lepton with second b jet $\rightarrow$ y axis.
- with two leptons and two jets, there are 4 choices:
  - * same description as above, but two entries per event.
- use variable bin sizes to account for differences in histogram occupancies.





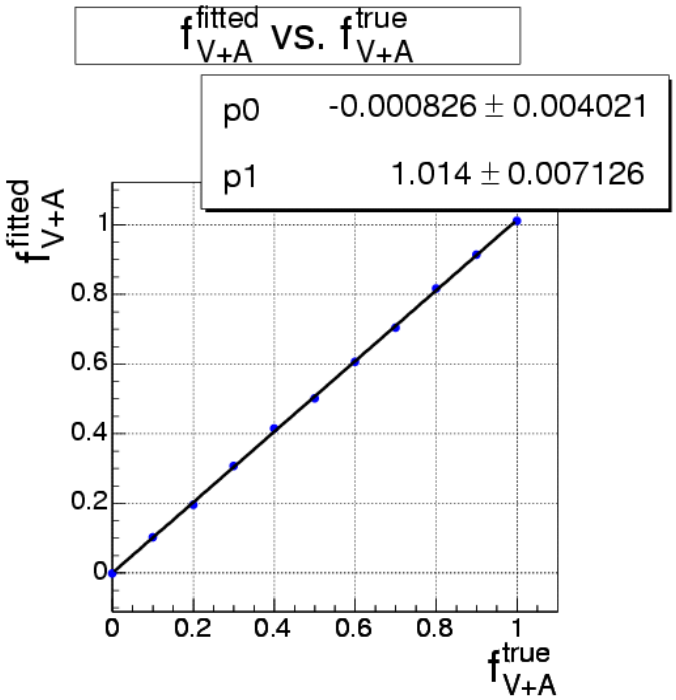
W Helicity in Top Quark Decays at the CDF

- systematic uncertainties on f_{V+A}

Source	Uncertainty
Jet Energy Scale	0.10
Background modelling	0.04
MC statistics	0.04
b-tagging	0.02
ISR/FSR	0.02
Minimum bias	0.02
Generator	0.01
PDF's	0.01
Total	0.12

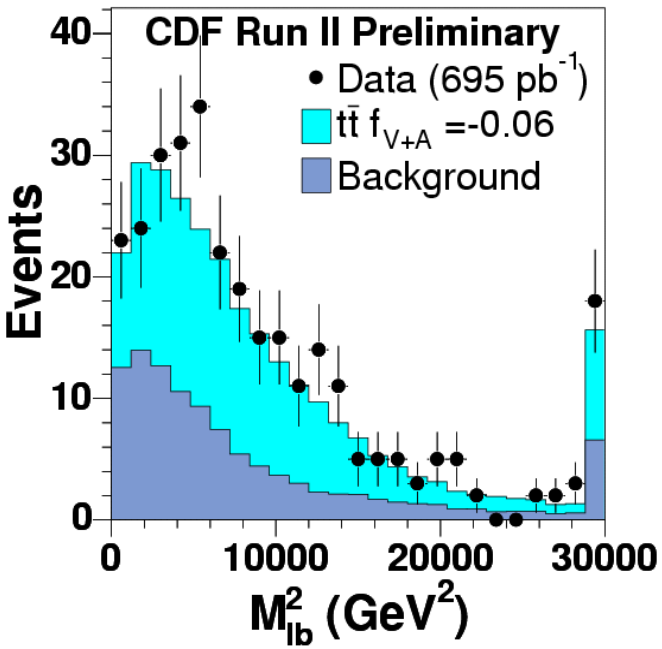
- total systematic uncertainties on $\delta f_+ = 0.036$.

- linearity checks with pseudo-experiments.

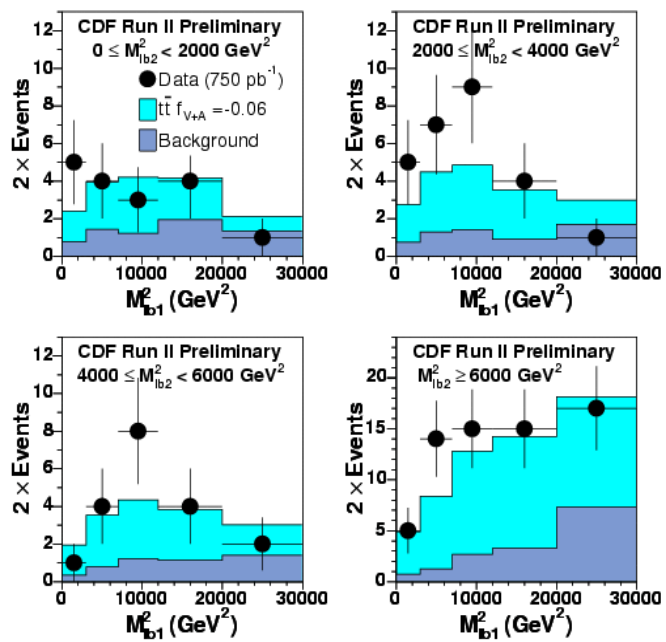


W Helicity in Top Quark Decays at the CDF

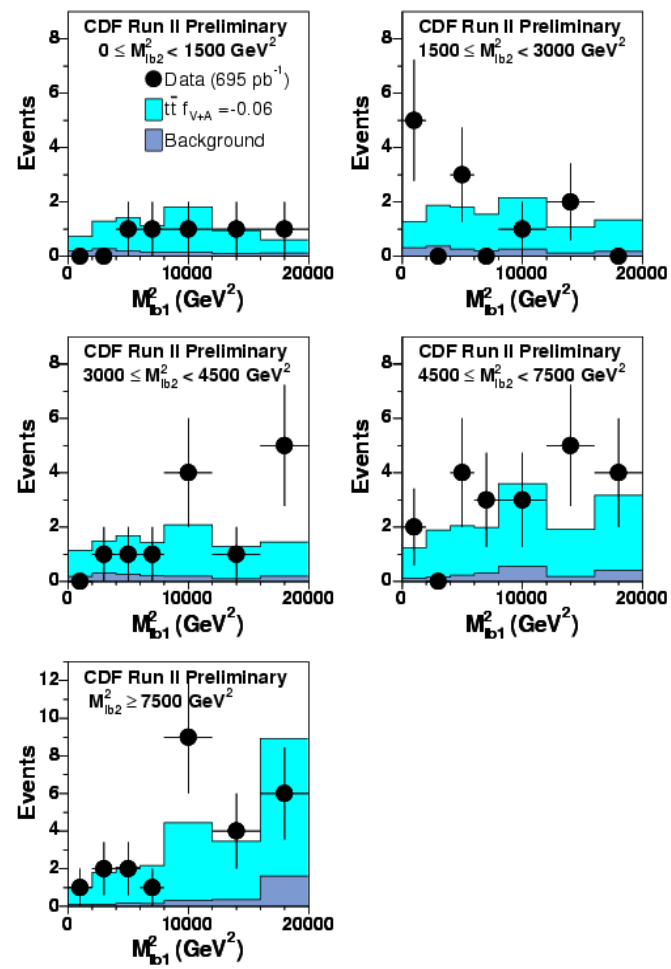
lepton+jets sample with 1 b tagged jet



lepton+jets sample with 2 b tagged jet



dilepton sample

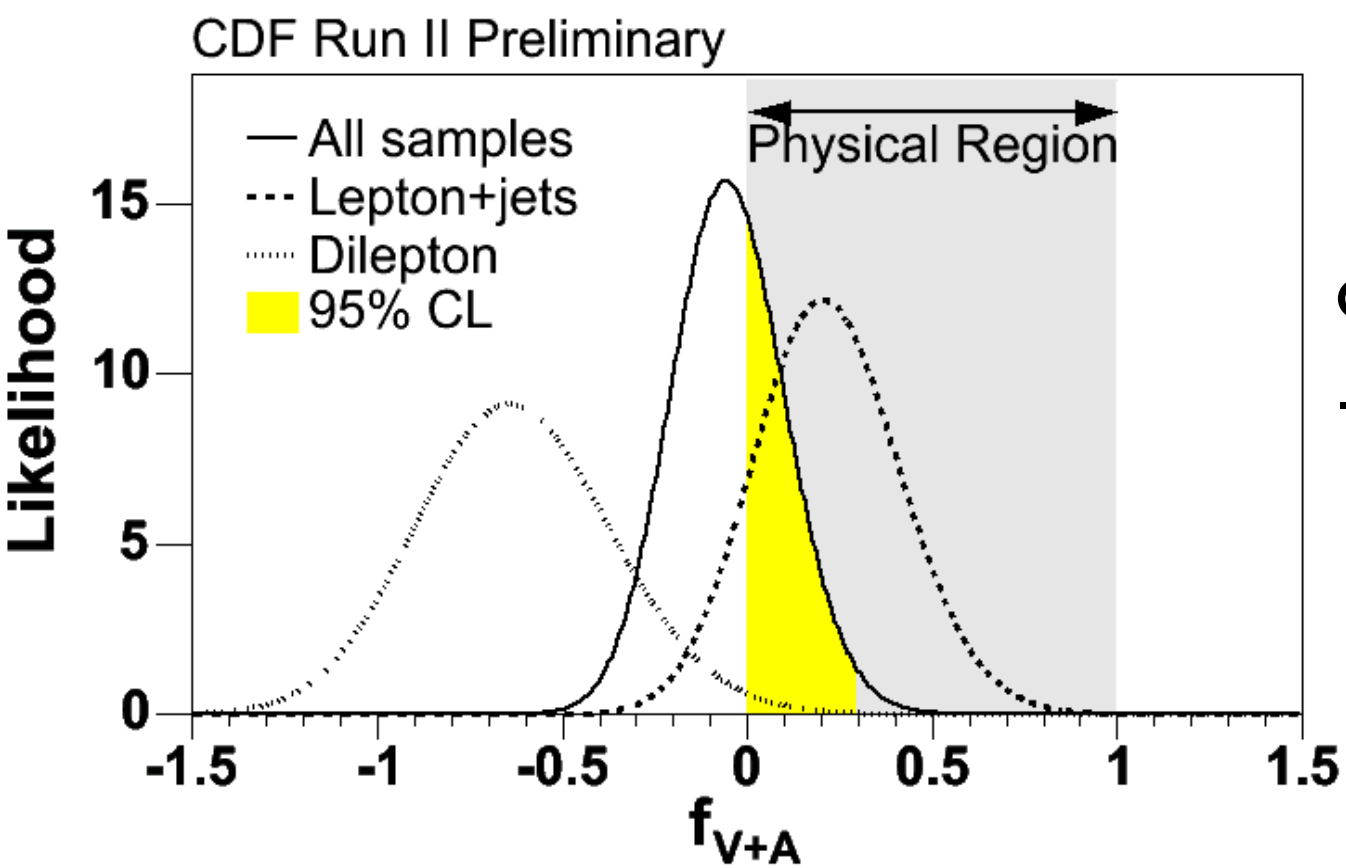


W Helicity in Top Quark Decays at the CDF

measurement using m_{lb}^2 in 750 pb^{-1}

result: $f_{v+A} = -0.06 \pm 0.25$ or $f_+ = -0.02 \pm 0.08$

$f_{v+A} < 0.29$ @ 95% C.L $f_+ < 0.10$ @ 95% C.L



Consistent with SM:

- top decay is of V-A nature.

W Helicity in Top Quark Decays at the CDF

Comparison of methods for f_+ and assuming $700pb^{-1}$:

method	m_{lb}^2	$\cos\theta^*$
expected 95% CL	0.12	0.14
expected statistical	0.072	0.063
total systematic	0.036	0.027
jet energy scale	0.033	0.010
background	0.014	0.017

+ two methods using different data sample
+ similar sensitivity
+ leading sources for systematic uncertainty differ

- detailed comparisons of the sensitivity and a combination are work in progress.

More Results: Soccer World Cup in Germany

¼ final

Ger – Arg
5 – 3

Ita – Ukr
2 – 0
65min

Eng – Por
07/01 10am CT

Bra – Fra
07/01 2pm CT

½ final

Ger – ?
07/04 2pm CT

? – ?
07/05 2pm CT

final

? – ?
07/09 1pm CT

3rd place
? – ?
07/08 2pm CT

More data is needed for final conclusions.

Learn about "Angstgegner, Poldi, Flügelflitzer and
So ein Tag so wunderschön wieder heute … " after the talk.

Summary

- discussed briefly the history of top physics.

- top physics is offering exiting opportunities to test the SM and beyond.

- we have collected a large top event sample with $1fb^{-1}$
  and more and more data is coming.

- CDF has measured W helicity fractions in top decays
  with different methods and in different data samples.

Summary

- latest CDF results:

$f_0 = 0.61 \pm 0.12$ (stat.) ± 0.06 (syst.), $f_+ = 0$ fixed with $\cos\theta^*$ in $955 pb^{-1}$.

$f_+ < 0.11$ @ 95% C.L, f_0 fixed to SM value @175GeV with $\cos\theta^*$ in $955 pb^{-1}$.

$f_+ < 0.10$ @ 95% C.L, f_0 fixed to SM value @175GeV with m_{lb}^2 in $750 pb^{-1}$.

Uncertainty reduced by a factor of ~2 compared to previous CDF results.

- all results are statistically limited

- results are consistent with SM predictions: top decay is of V-A nature.

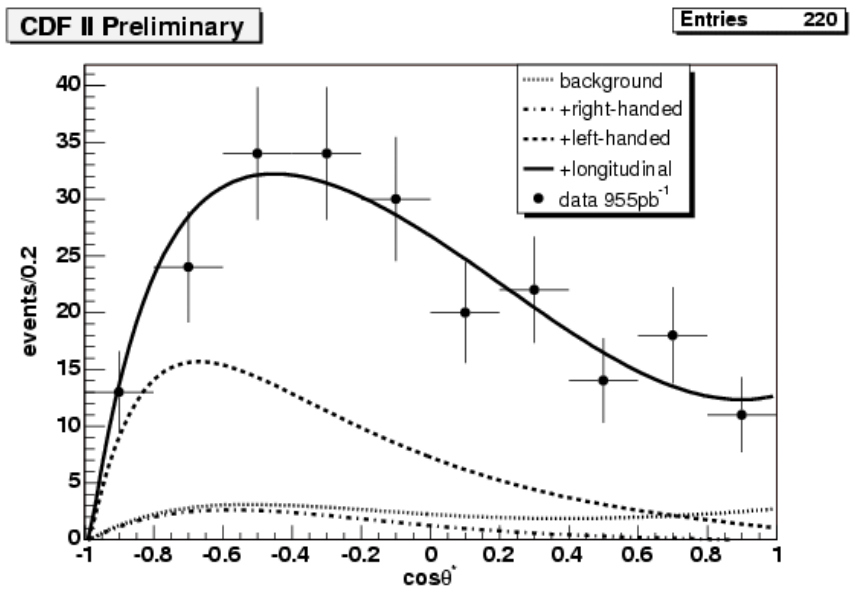
- in the pipeline:

  * combined f_0 and f_+ fits.

  * improvements in analysis technics and combination of results.

  * many more top property results with $1 fb^{-1}$

back up slide



MC input	Fits
(f_0,f_+)	(f_0,f_+)
(0.3,0.0)	(0.31 0.03, fixed)
(0.5,0.0)	(0.51 0.03, fixed)
(0.7,0.0)	(0.71 0.03, fixed)
(0.9,0.0)	(0.90 0.03, fixed)
(0.7,0.0)	(fixed, 0.00 0.01)
(0.7,0.1)	(fixed, 0.10 0.01)
(0.7,0.2)	(fixed, 0.20 0.01)