Top Physics Results at CDF

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Motivations for studying the top quark

Most recently discovered quark, but the least well understood

- Discovered by CDF and D-Zero in 1995
- Heaviest known fundamental particle ($178\ \mathrm{GeV/c^2}$)
- Decays before it hadronizes due to its yactosecond lifetime:

Close to the mass of a gold nucleus!

$$\tau_{top} \sim 0.4 \times 10^{-24}\ \mathrm{s} \qquad 1/\Lambda_{QCD} \sim 10^{-24}\ \mathrm{s}$$

Hints of an intimate relationship between top and EWSB

- Top mass is close to the scale of EWSB
- Higgs is most strongly coupled to the top quark:

$$\text{Top-Higgs Yukawa coupling} \simeq 1$$

Top may be sensitive to Physics Beyond the Standard Model

- Studying top tests Electroweak theory
- We can look for non-SM production or decay modes:

$$X \to t\bar{t} \qquad t \to Xb$$

Top is a background for many discovery channels

- Top events are backgrounds for low mass Higgs searches $HW,\ HZ\ \ (H \to b\bar{b})$

Top Production & Decay Modes

$\sim 0.3\ \text{events}/\text{pb}^{-1}$

Finding top is like panning for gold!

Predominantly Pair Produced

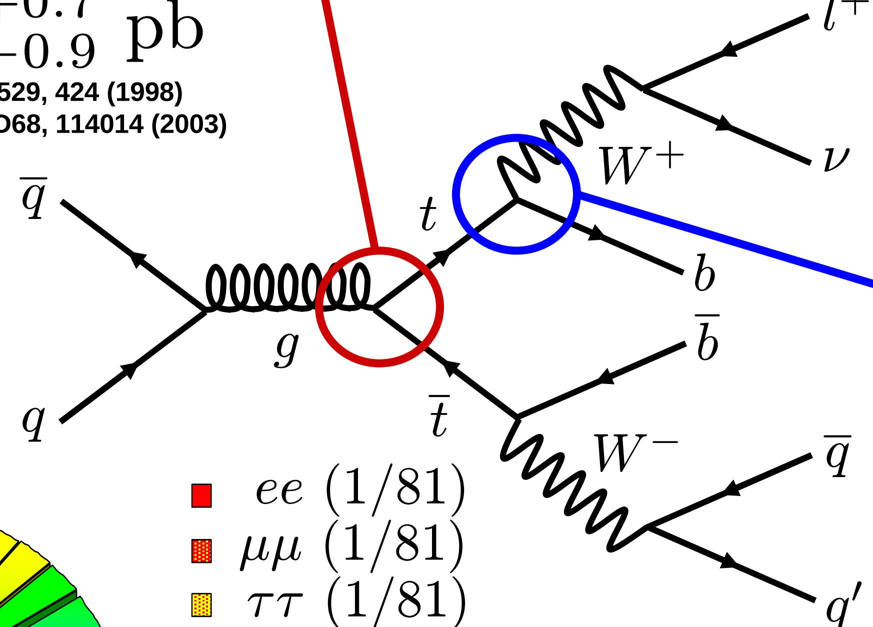
$$\sigma_{t\bar{t}} = 6.7^{+0.7}_{-0.9}\ \text{pb}$$

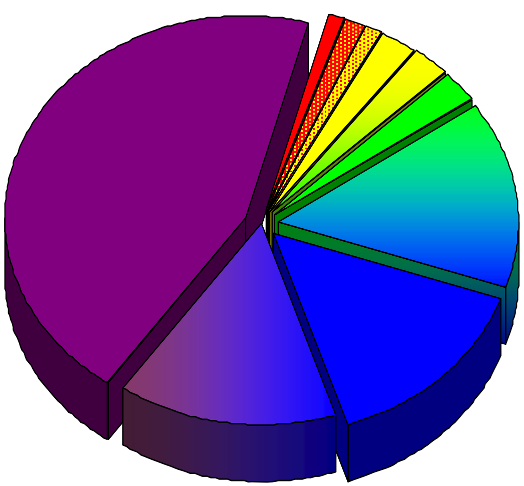
Bonciani et al., Nucl. Phys. B529, 424 (1998)
Kidonakis and Vogt, Phys. Rev. D68, 114014 (2003)

For $\sqrt{s} = 1.96$ TeV

$q\bar{q} \to t\bar{t} \ \sim 85\%$

$gg \to t\bar{t} \ \sim 15\%$



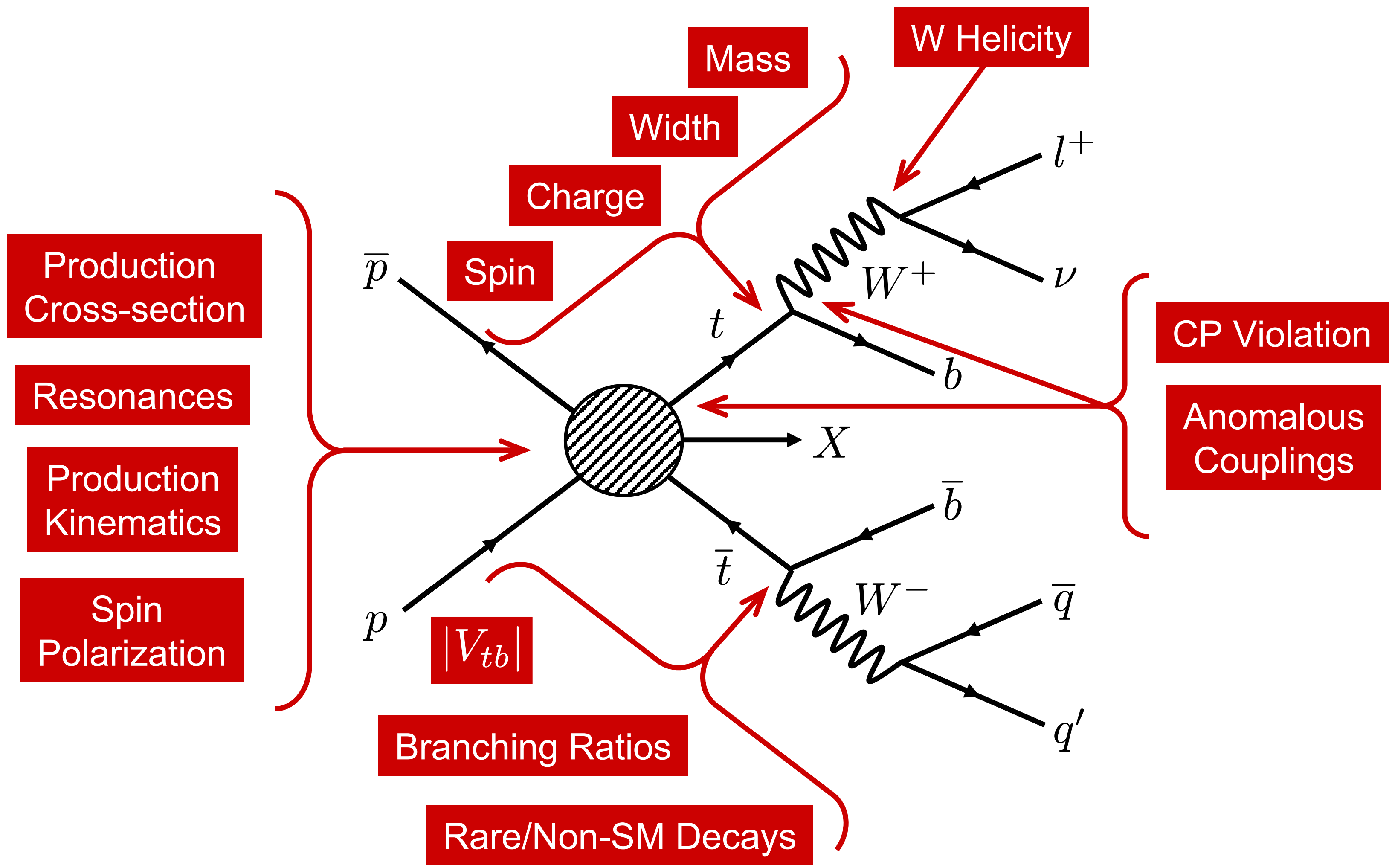


- ee (1/81)
- $\mu\mu$ (1/81)
- $\tau\tau$ (1/81)
- $e\mu$ (2/81)
- $e\tau$ (2/81)
- $\mu\tau$ (2/81)
- $e +$ jets (12/81)
- $\mu +$ jets (12/81)
- $\tau +$ jets (12/81)
- jets (36/81)

$t \to W^+ b$ Nearly 100%

Final State	Ideal Dataset
$l\nu\ l\nu\ bb$	Dilepton
$l\nu\ qq\ bb$	Lepton + Jets
$qq\ qq\ bb$	All-Hadronic

The burgeoning field of top quark physics…



…can only be explored at the Fermilab Tevatron*

*Until the LHC turn-on

Detecting the Top Quark

At the Tevatron top events are spherical and central

- Very massive quarks, created almost at rest in lab-frame

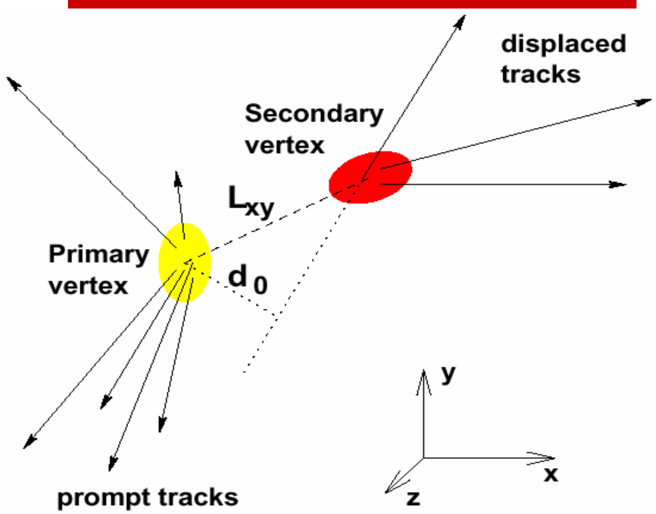
Expect two b-quark jets with high E_T

- Identified with a displaced secondary vertex relative to the primary vertex

Additional light quarks or leptons from W decays

- Significant missing transverse energy from undetected neutrino

Displaced Track Vertex Tagging



B hadrons are short lived

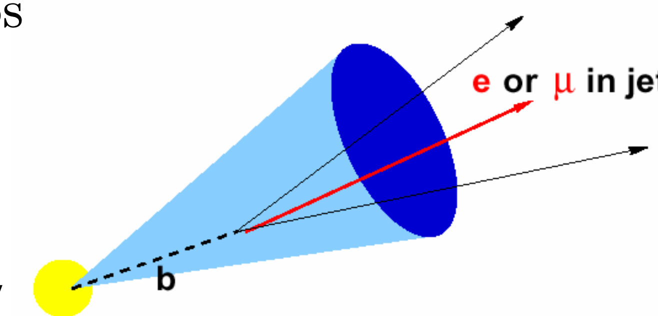
$$\tau_b \simeq 1.5 \text{ ps}$$

$$c\tau_b \simeq 450 \ \mu\text{m}$$

B "tagging" improves S:B

They may decay semileptonically

Soft Lepton Tagging



- $b \to \ell \nu c$ (BR $\sim$ 20%)
- $b \to c \to \ell \nu s$ (BR $\sim$ 20%)

Displaced Track Vertex Tagging		Soft Lepton Tagging
55%	Top Event Tagging Efficiency	15%
0.5%	False Tag Rate (QCD jets)	3.6%

Top Cross-section Measurements

Events triggered on one high p_T lepton or multiple jets

- Further event selection is optimized for finding top as well as new physics

We define some event samples by counting leptons and jets

- "Dilepton" two charged leptons and ≥ 2 jets
- "Lepton-plus-jets" one charged lepton and ≥ 3 jets
- "All-hadronic" ≥ 6 jets

Cross-section meas. is essentially a counting experiment

- Cross-section results validate our top-enriched samples
- Could reveal new physics

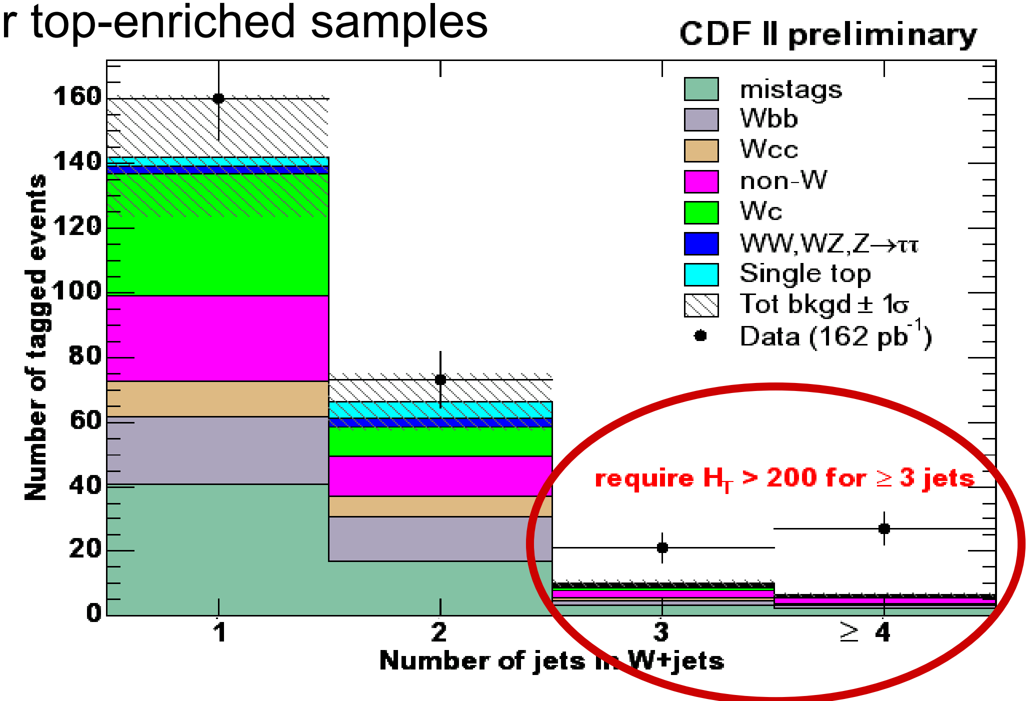
Total number of events observed

Number of background events

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bkg}}{\epsilon \int \mathcal{L} dt}$$

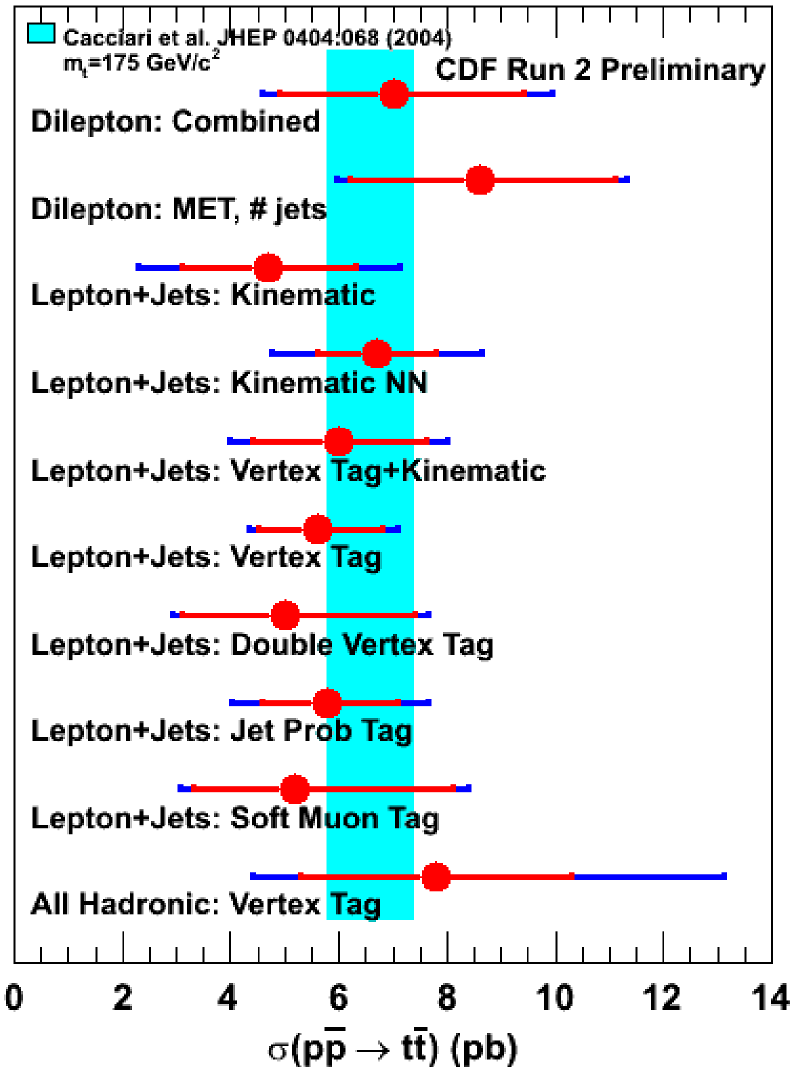
Efficiency includes geometric and kinematic acceptance

Integrated Luminosity



Lepton-plus-jets top quark signal region

Results for top pair-production cross-section measurements:



$\sigma_{t\bar{t}}$ [pb]	$\int \mathcal{L}\, dt$ [pb^{-1}]
$7.0^{+2.7}_{-2.3}$ (stat.) $^{+1.5}_{-1.4}$ (syst.)	200
$8.6^{+2.5}_{-2.4}$ (stat.) ± 1.1 (syst.)	200
4.7 ± 1.6 (stat.) ± 1.8 (syst.)	193
6.7 ± 1.1 (stat.) ± 1.6 (syst.)	193
6.0 ± 1.6 (stat.) ± 1.2 (syst.)	162
$5.6^{+1.2}_{-1.1}$ (stat.) $^{+0.9}_{-0.6}$ (syst.)	162
$5.0^{+2.4}_{-1.9}$ (stat.) $^{+1.1}_{-0.8}$ (syst.)	162
$5.8^{+1.3}_{-1.2}$ (stat.) ± 1.3 (syst.)	162
$5.2^{+2.9}_{-1.9}$ (stat.) $^{+1.3}_{-1.0}$ (syst.)	193
7.8 ± 2.5 (stat.) $^{+4.7}_{-2.3}$ (syst.)	165

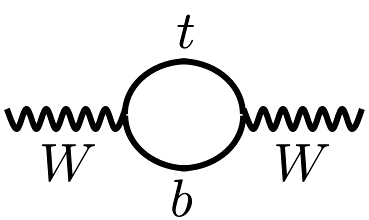
Datasets:
- Dilepton
- Lepton+Jets
- All-Hadronic

Top Mass Measurements

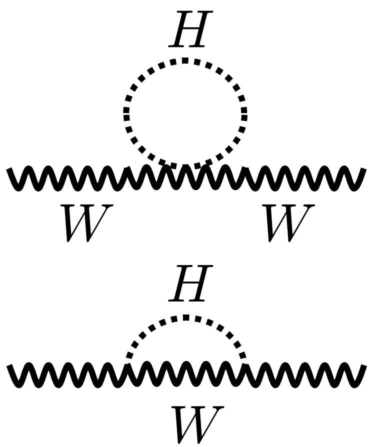
The top mass is a fundamental parameter of the SM

- The mass of this fermion is close to the scale of EWSB
- Top mass is correlated to other SM parameters:

$\propto M_t^2$

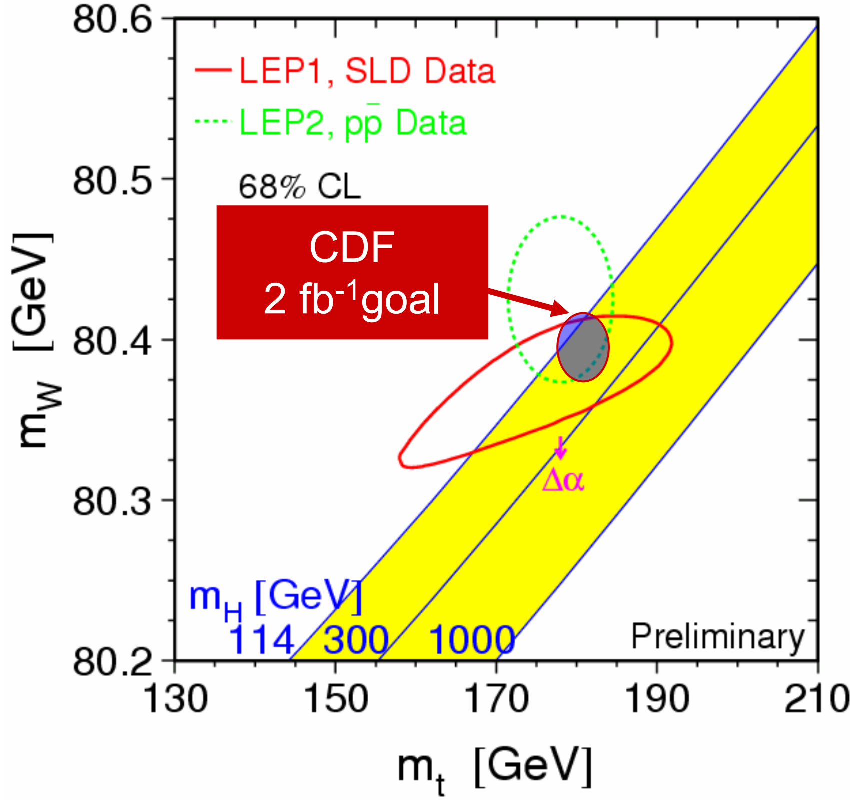


$\propto \ln(\frac{M_H}{M_W})$



Precise mass measurement puts constraints on the Higgs

Top mass correlated to other SM parameters via electroweak radiative corrections



- CDF Run II Goal is $\delta m_t \sim$ 2-3 $\mathrm{GeV/c^2}$
- This yields $\delta m_H / m_H \sim 35\%$ (indirect)

Dynamic Likelihood Method

This technique yields CDF's best top mass measurement to date

- Why are the matrix element methods (like CDF DLM and D0 MEM) so powerful?

Canonical template methods
Cross-section used as a *prior* probability

Initial state configuration $p\bar{p}$ → Cross-section $\sigma_{t\bar{t}}(m_{top})$ → Probability for measured final state $b\bar{b}l\nu jj$

Newer matrix element methods
Cross-section used as a *posterior* probability

Likelihood of a final state for a given m_{top} ← Cross-section $\sigma_{t\bar{t}}(m_{top}|x_i)$ ← Measured final state $b\bar{b}l\nu jj$

CDF uses the following likelihood for the i[th] event:

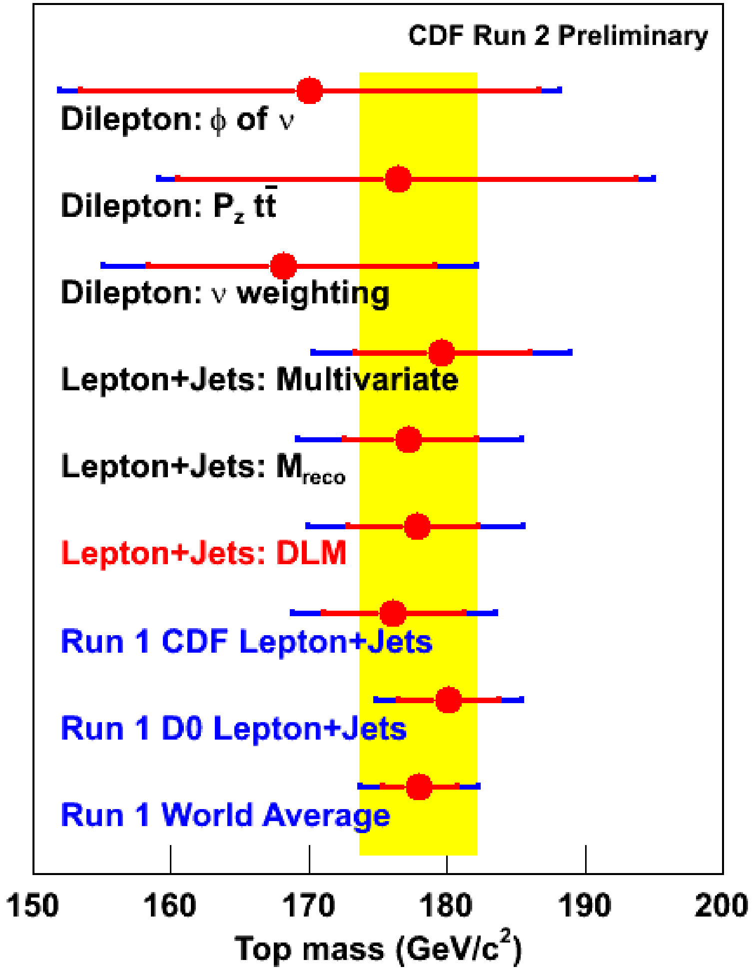
$$\mathcal{L}^i(m_{top}) = \sum_{comb}\sum_{nsol}\int \frac{2\pi^4}{flux}\mathcal{F}(z_a, z_b) f(p_T)|\mathcal{M}|^2 w(\mathbf{x},\mathbf{y};m_{top})d\mathbf{x}$$

- $\sum_{comb}\sum_{nsol}$: Sums over jet-parton assignments and neutrino solutions
- $\mathcal{F}(z_a, z_b)$: PDFs
- $f(p_T)$: Probability for the p_T of the $t\bar{t}$ system
- $|\mathcal{M}|^2$: LO matrix element of $t\bar{t}$ process
- $w(\mathbf{x},\mathbf{y};m_{top})$: Transfer function. Go back to the partons from jets. x (partons) ↔ y (observables)

Minimize this likelihood to extract the top mass:

$$\Lambda(m_{top}) = -2\ln\left(\prod_{event}\mathcal{L}^i(m_{top})\right)$$

Results for top quark mass measurements:



m_t [GeV/c^2]	$\int \mathcal{L}\, dt$ [pb^{-1}]
170.0 ± 16.6 (stat.) ± 7.4 (syst.)	193
$176.5^{+17.2}_{-16.0}$ (stat.) ± 6.9 (syst.)	193
$168.1^{+11.0}_{-9.8}$ (stat.) ± 8.6 (syst.)	200
$179.6^{+6.4}_{-6.3}$ (stat.) ± 6.8 (syst.)	162
$177.2^{+4.9}_{-4.7}$ (stat.) ± 6.6 (syst.)	162
$177.8^{+4.5}_{-5.0}$ (stat.) ± 6.2 (syst.)	162
176.1 ± 5.1 (stat.) ± 5.3 (syst.)	~ 110
180.1 ± 3.6 (stat.) ± 3.9 (syst.)	~ 110
178.0 ± 2.7 (stat.) ± 3.3 (syst.)	

Datasets:
- Dilepton
- Lepton+Jets
- Run I Results

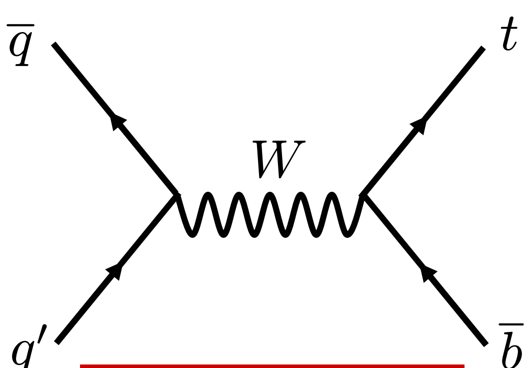
Single Top Quark Production

Single top production via Electroweak processes is possible

- A great opportunity to study the charged-current weak interaction of the top quark
- Cross-section proportional to CKM matrix element $|V_{tb}|^2$ (direct measurement)
- Production channels sensitive to new physics:
  - High-mass W', Kaluza-Klein modes of the W, anomalous couplings, FCNCs

Search for these processes at the Tevatron

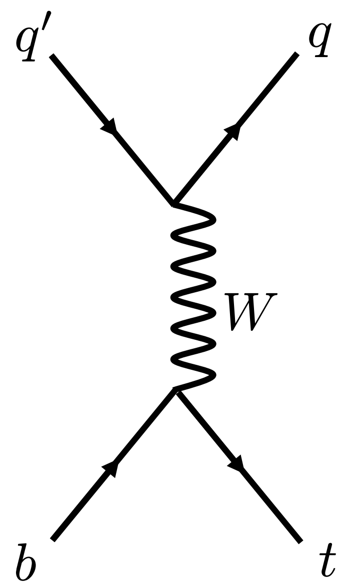
Possible at the LHC



s-channel production

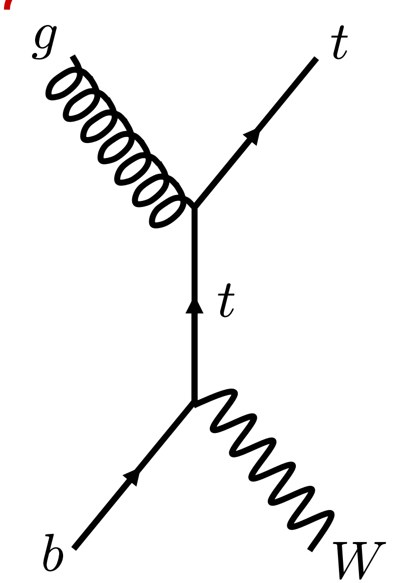
$\sigma_{\text{NLO}} = 0.88$ pb

B.W. Harris et al., Phys. Rev. D66, 054024 (2002)
Z. Sullivan, Phys. Rev. D70, 114012 (2004)



t-channel production

$\sigma_{\text{NLO}} = 1.98$ pb



associated production

$\sigma \sim$ tiny @ Tevatron

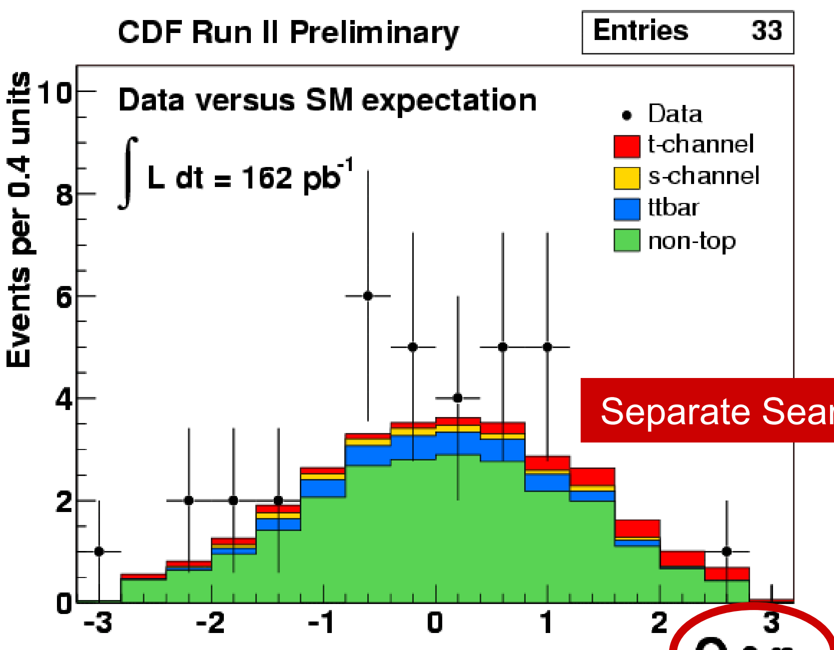
Strategy for finding single top:

- Search for W decay products plus 2 or 3 jets (one of which is a b jet)
- Suppress multi-jet QCD background by only selecting $W \to e\nu, \mu\nu$

Conduct two analyses

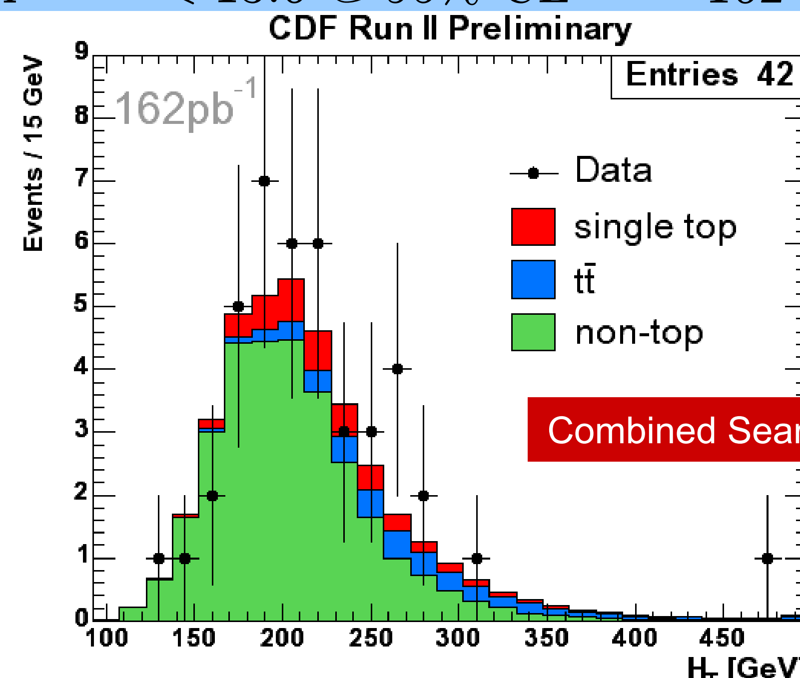
- Combined search using H_T distbn (for single top discovery and to measure $|V_{tb}|$)
- Separate channel searches
  - To reveal new physics
  - Use $Q \times \eta$ distribution

Measurement	σ_t [pb]	$\int \mathcal{L}\, dt$ [pb^{-1}]
Combined Search	< 17.8 @ 95% CL	162
t-channel	< 10.1 @ 95% CL	162
s-channel	< 13.6 @ 95% CL	162



Separate Search

Charge of lepton, η of light-quark jet



Combined Search

Datasets: Lepton+Jets

W Helicity from Top Decay

W boson has three helicity states:

- "Left-handed", "Longitudinal", "Right-handed" — Suppressed in the SM
- Top quark decay is the most significant source of Longitudinal Ws.

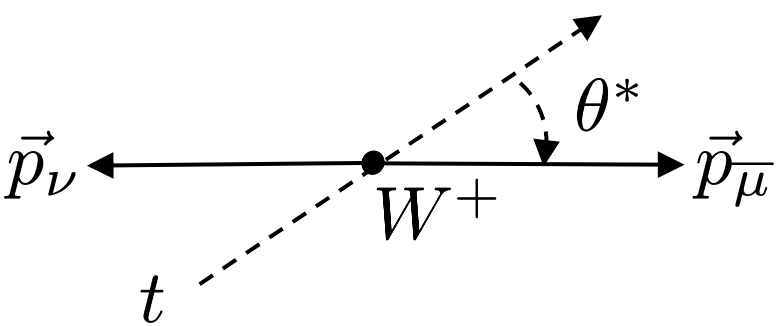
By measuring the fraction of longitudinal Ws we are:

- Testing a Standard Model prediction: $F_0 = 0.7$
- Probing the tWb vertex, believed to be $(V - A)$
- Could provide insight into the nature of EWSB

Distributions for each helicity state are very distinct:

- Create templates, do likelihood fit
- $\cos\theta^*$ and Lepton p_T methods

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

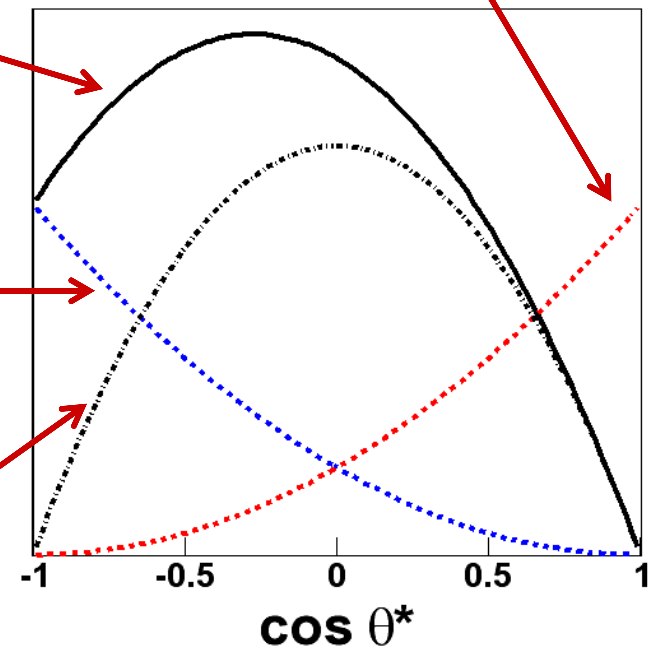


SM Prediction
$(V - A)$
30% 70% 0%

Left-handed
$\frac{1}{4}(1 - \cos\theta^*)^2$

Longitudinal
$\frac{1}{2}(1 - \cos^2\theta^*)$

Right-handed
$\frac{1}{4}(1 + \cos\theta^*)^2$



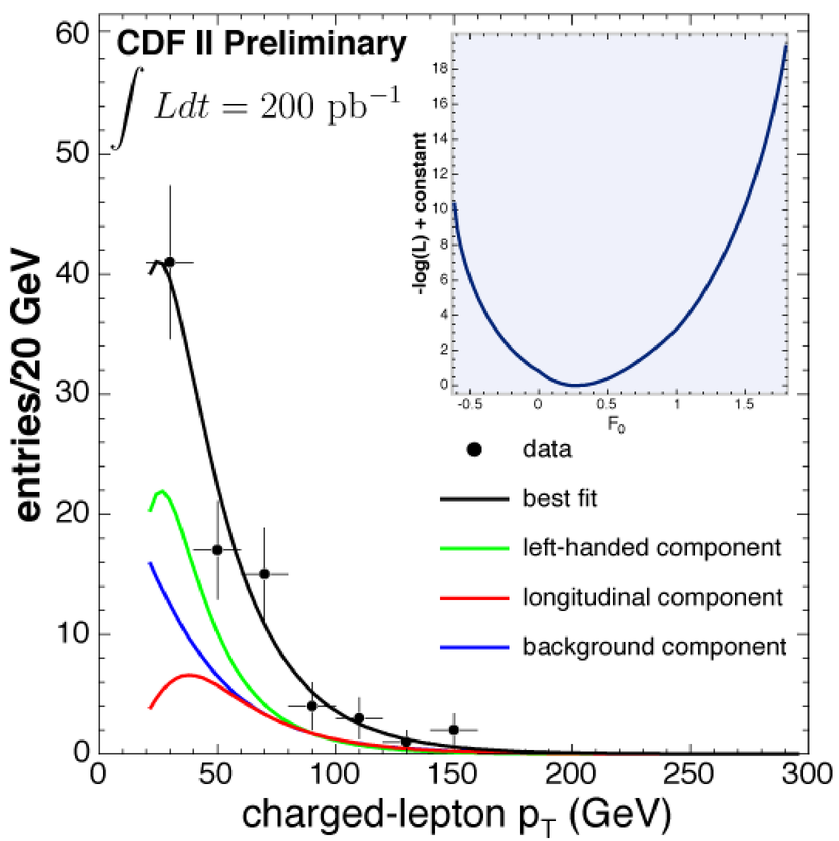
Results for measuring the Longitudinal Fraction:

Lepton p_T Method

Sample: Dilepton and Lepton + Jets

$$F_0 = 0.27^{+0.35}_{-0.21}\ (\text{stat.}) \pm 0.17\ (\text{syst.})$$

$$F_0 < 0.88\ @\ 95\%\ \text{CL}$$

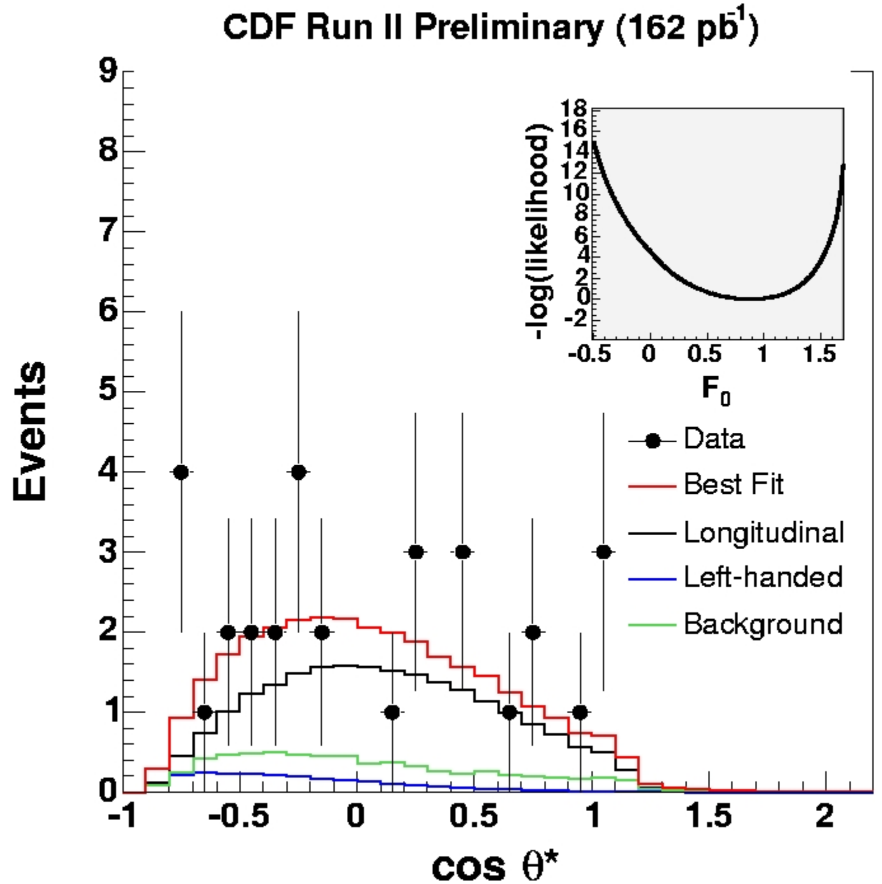


$\cos\theta^*$ Method

Sample: Lepton + Jets

$$F_0 = 0.89^{+0.30}_{-0.34}\ (\text{stat.}) \pm 0.17\ (\text{syst.})$$

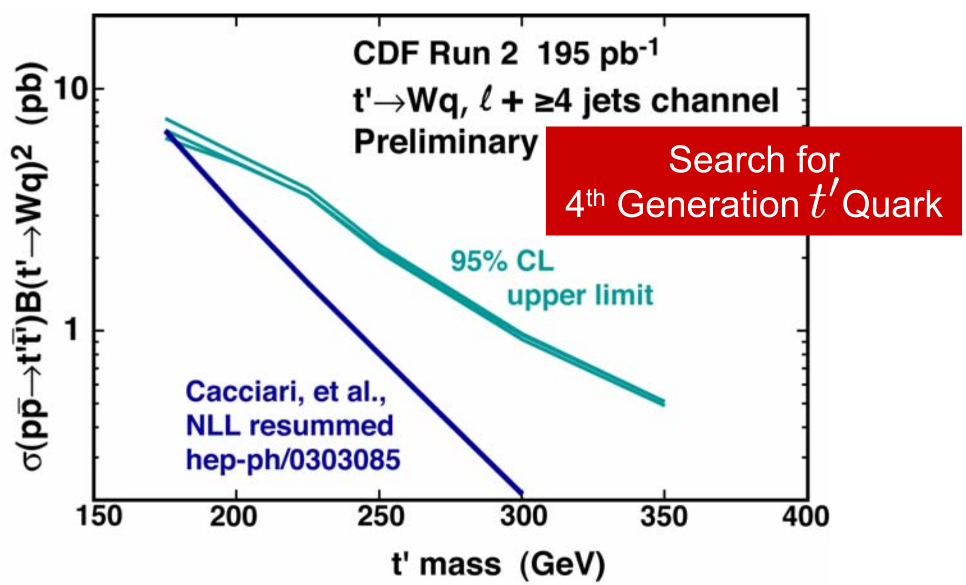
$$F_0 > 0.25\ @\ 95\%\ \text{CL}$$

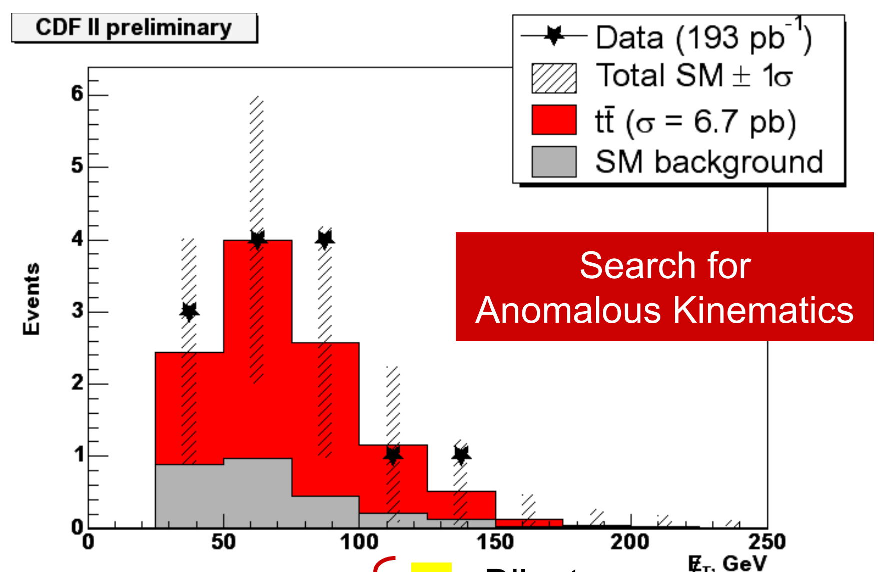


Datasets: Dilepton (yellow); Lepton+Jets (blue)

Other Top Quark Property Measurements

Measurement	Result	$\int \mathcal{L}\, dt$ [pb^{-1}]
W Helicity F_+	$F_+ < 0.18$ @ 95% CL	109
Search for Anomalous Kinematics	Consistent with SM	193
$BR(t \to \tau\nu b)/BR_{\mathrm{SM}}(t \to \tau\nu b)$	< 5.0 @ 95% CL	193
Search for 4^{th} generation t' Quark	Set Limits	195
$BR(t \to Wb)/BR(t \to Wq)$	> 0.62 @ 95% CL	162
$\sigma_{\mathrm{dilepton}}/\sigma_{\mathrm{lepton+jets}}$	$1.45^{+0.83}_{-0.55}$ (stat. + syst.)	126
Search for H^+ in t decays	$BR(t \to Hb) < 0.7$ @ 95% CL	193





Datasets
- Dilepton
- Lepton+Jets
- Run I Results

Summary and Outlook

Experimental top quark physics still in its infancy

- No unexpected physics results observed yet
- Still many opportunities for discovery at CDF

CDF is doubling its dataset each year

- Current measurements will continue to improve
  - Reduction in statistical uncertainty, top mass JES systematic uncertainty
- Many new measurements and techniques are in the works:
  - Top resonances, fraction right-handed Ws, neural-network techniques

Many top physics results CDF recently published or submitted:

- **"Measurement of the t anti-t Production Cross Section in p anti-p Collisions at S**(1/2) = 1.96-TeV Using Dilepton Events," Phys. Rev. Lett 93, 142001 (2004)**
- **"Search for Electroweak Single Top Quark Production in p anti-p Collisions at S**(1/2) = 1.96-TeV," Phys. Rev. D 71, 012005 (2005)**
- **"Measurement of the W Boson Polarization in Top Decay at CDF at S**(1/2) = 1.8-TeV," Phys. Rev. D 71, 031101(R) (2005)**
- **"Measurement of the t anti-t Production Cross Section in p anti-p Collisions at S**(1/2) = 1.96-TeV Using Kinematic Fitting of B-Tagged Lepton + Jet Events," hep-ex/0409029**
- **"Measurement of the t anti-t Production Cross Section in p anti-p Collisions at S**(1/2) = 1.96-TeV Using Lepton + Jets Events with Secondary Vertex B-Tagging," hep-ex/0410041**
- **"Search for Anomalous Kinematics in t anti-t Dilepton Events at CDF II," hep-ex/0412042**