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:

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

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

- Tests of Electroweak theory
- Non-SM production or decay:

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

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

Predominantly Pair Produced

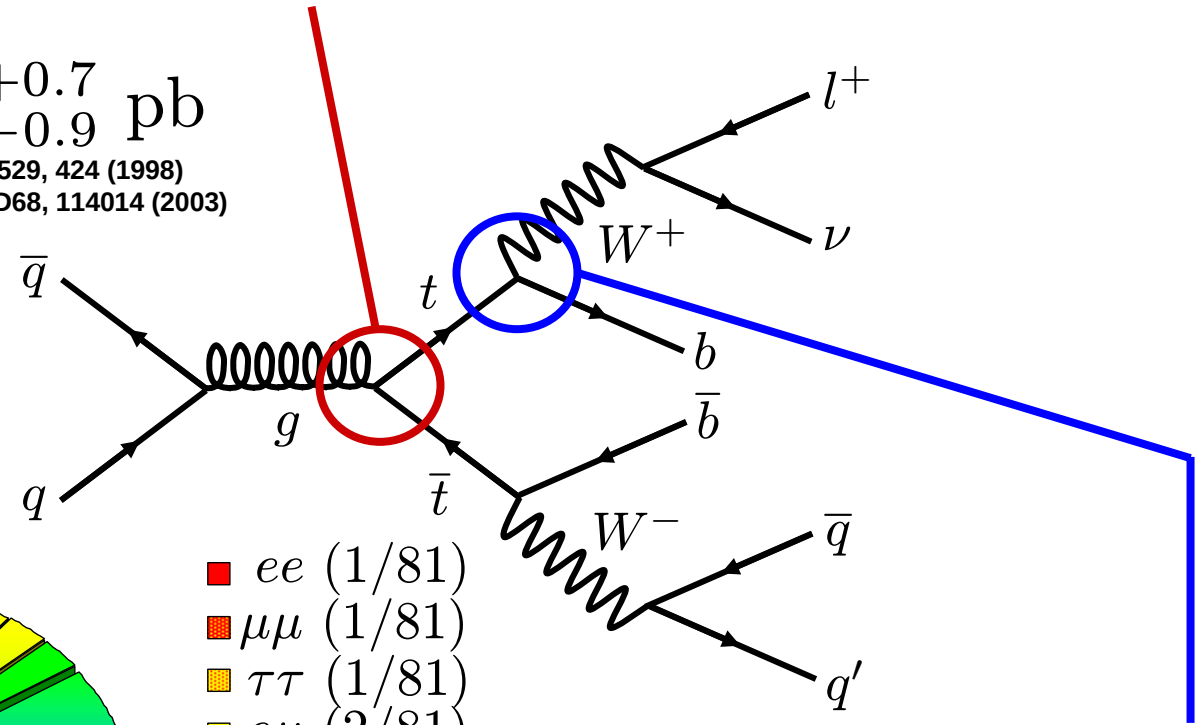
$$\sigma_{t\bar{t}} = 6.7^{+0.7}_{-0.9}\ \mathrm{pb}$$

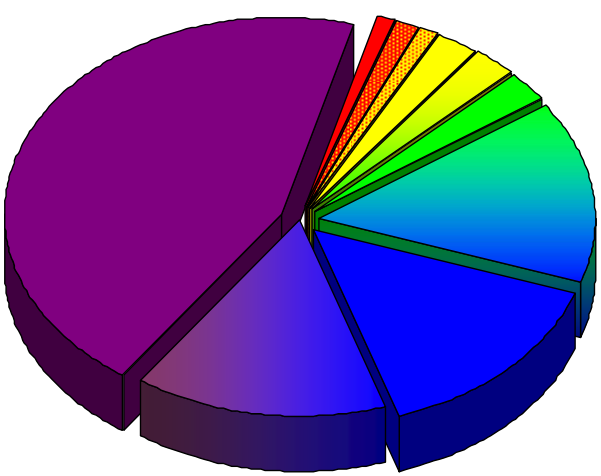
Bonciani et al., Nucl. Phys. B529, 424 (1998)
Kidonakis and Vogt, Phys. Rev. D68, 114014 (2003)

For $\sqrt{s} = 1.96$ TeV

$q\bar{q} \to t\bar{t} \ \sim 90\%$

$gg \to t\bar{t} \ \sim 10\%$



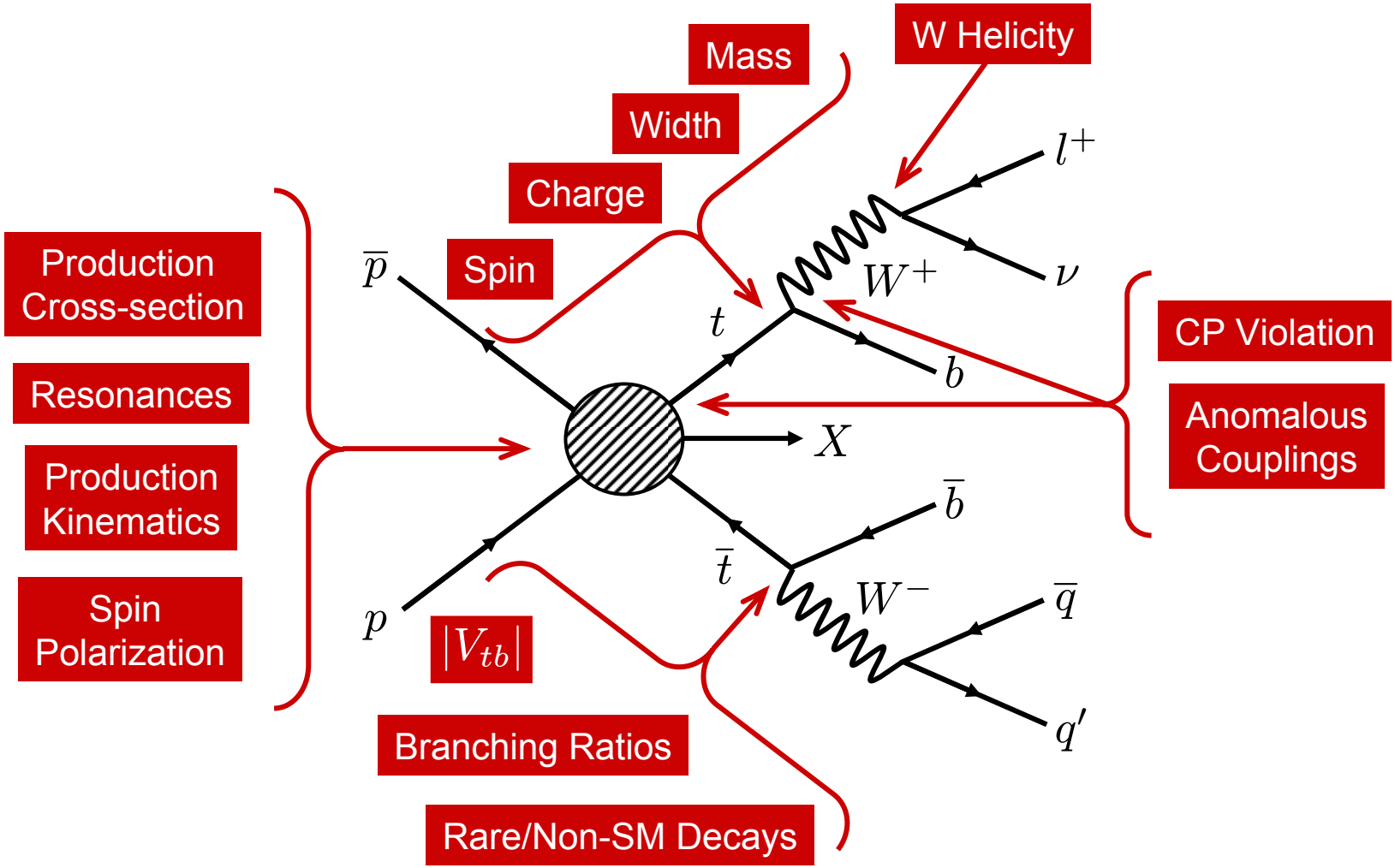


- ee (1/81)
- $\mu\mu$ (1/81)
- $\tau\tau$ (1/81)
- $e\mu$ (2/81)
- $e\tau$ (2/81)
- $\mu\tau$ (2/81)
- $e+$jets (12/81)
- $\mu+$jets (12/81)
- $\tau+$jets (12/81)
- jets (36/81)

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

Final State	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…



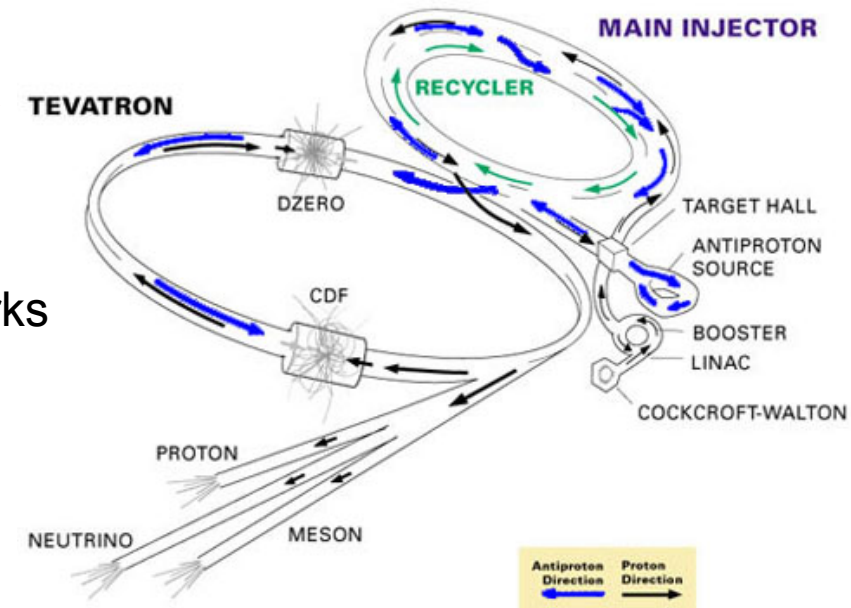
…can only be explored at the Fermilab Tevatron*

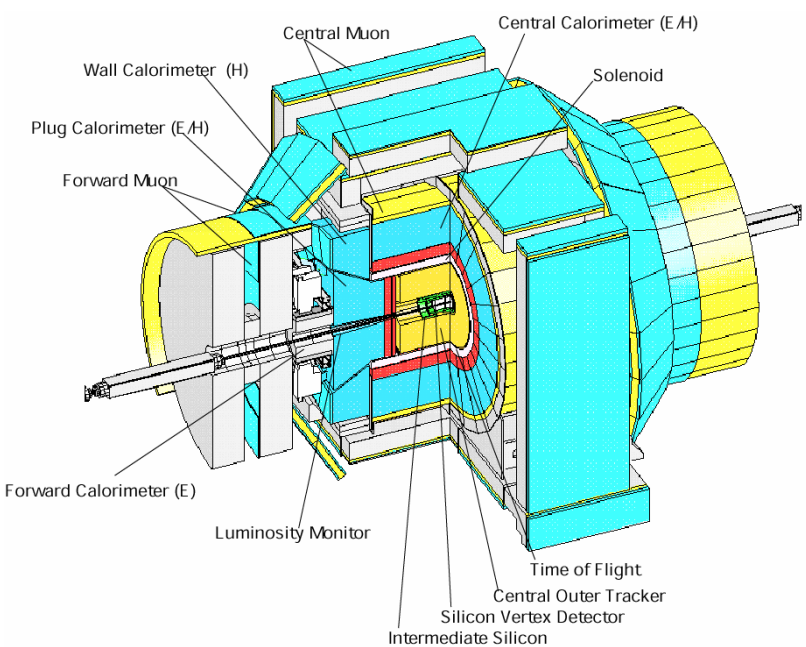
*Until the LHC turn-on

The Tevatron and CDF

Great for producing top quarks!

- Proton-antiproton collider at Fermilab
- $\sqrt{s} = 1.96\ \mathrm{TeV}$
- Only facility in the world producing top quarks
- One collision every 396 ns
- Routine shots of $1 \times 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$





Well suited for detecting them!

- CDF is a general purpose solenoidal detector
- Great for reconstructing top events
- Silicon detector for secondary verticies
- Precision charged particle tracking
- Fast projective calorimetry
- Fine muon resolution

Detecting the Top Quark

Top events are spherical and central

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

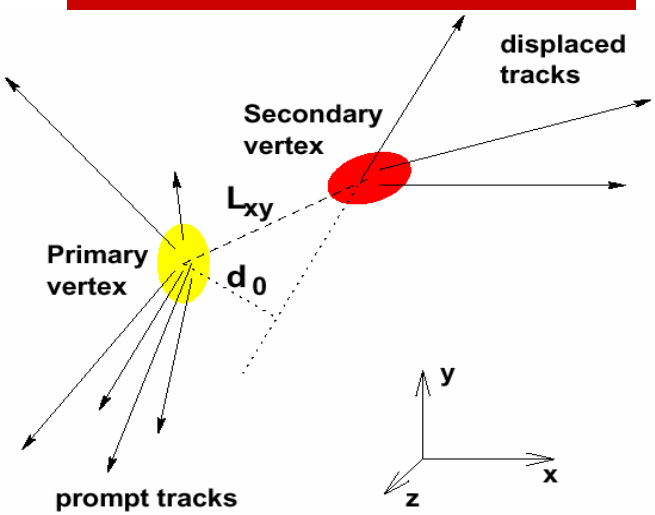
Expect two b-quark jets with high E_T

- 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



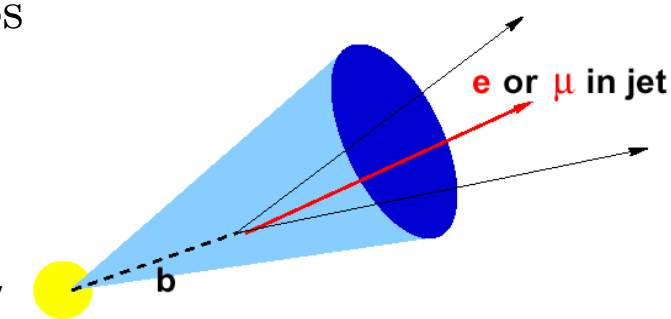
B hadrons are short lived $\tau_b \simeq 1.5$ ps

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

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%)

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 top physics as well as PBSM

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
- Measurement could reveal PBSM

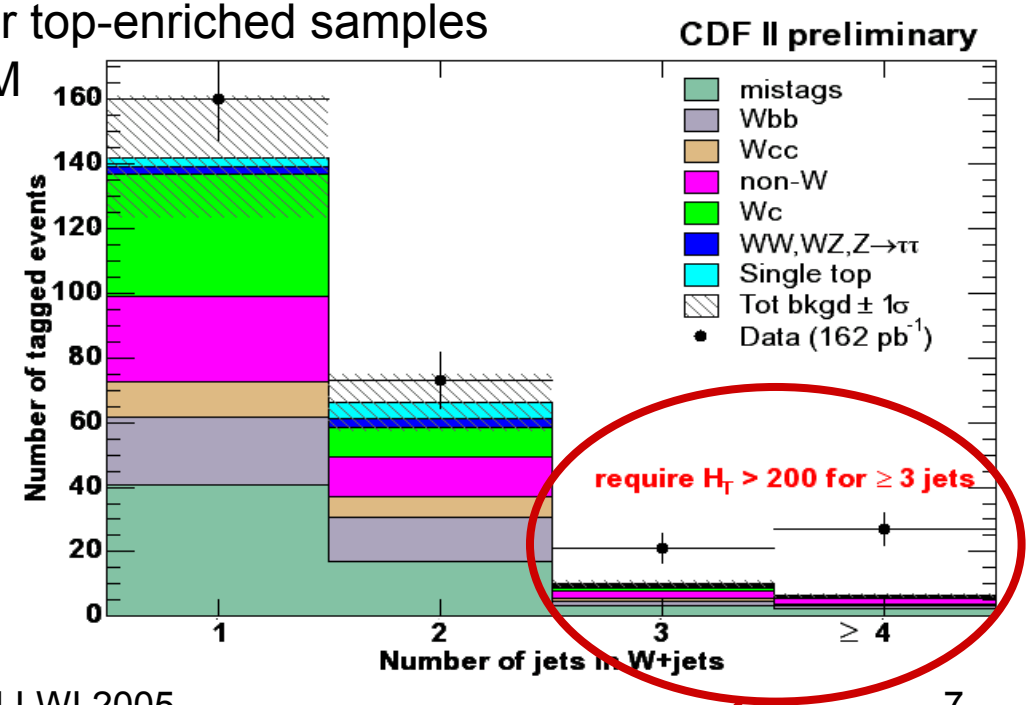
Total number of events observed

Number of background events

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

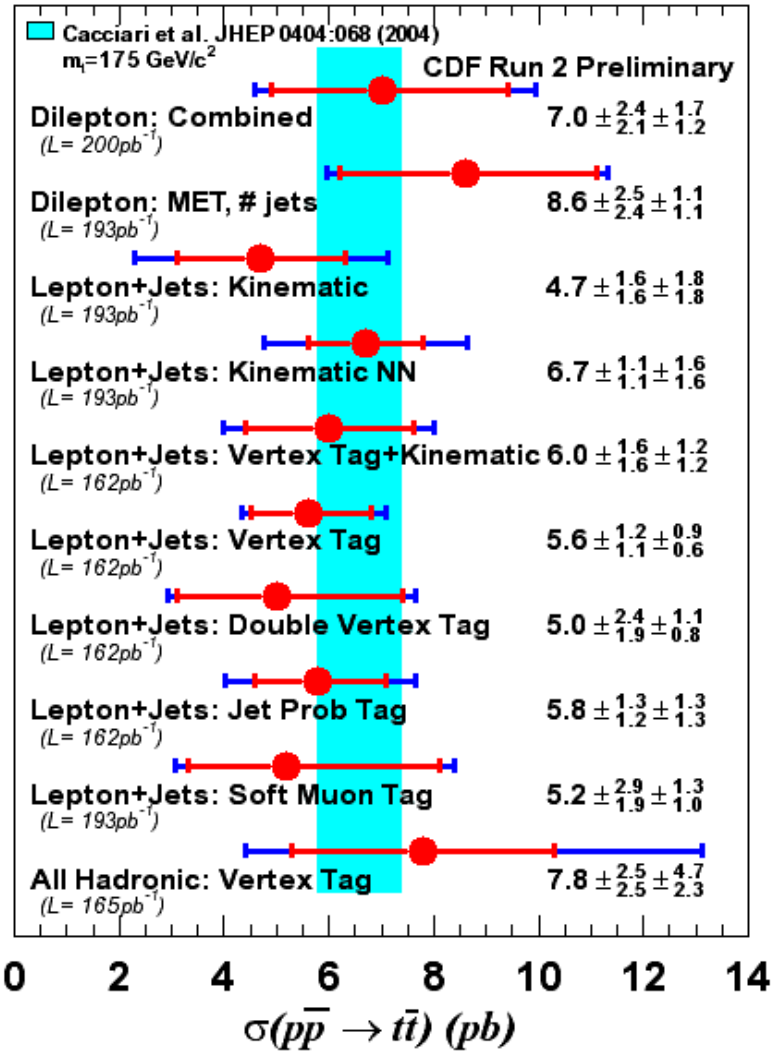
Efficiency as measured In data and Monte Carlo

Integrated Luminosity



Lepton-plus-jets top quark signal region

Results for top pair-production cross-section measurements:



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

Datasets
- Dilepton
- Lepton+Jets
- All-Hadronic

Top Mass Measurements (Three Methods)

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 with other SM parameters:

$$\delta M_W \propto M_t^2 \qquad \delta M_W \propto \ln M_H$$

Precise mass measurement puts constraints on the Higgs

Mass template method:

- Balance the event transverse momentum
- Constrain invariant masses: $m_{l\nu} = m_W$, $m_{jj} = m_W$
- Fit mass distbn to templates $m_{t,1} = m_{t,2}$

Dynamic Likelihood Method:

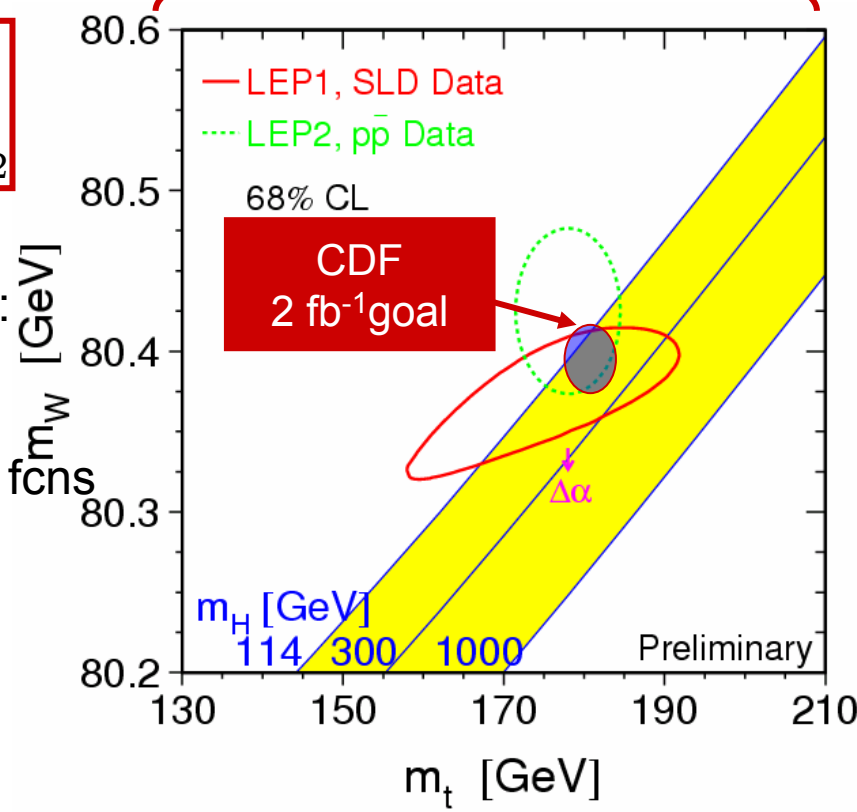
- Obtain mass by maximizing the likelihood:

$$\prod_i \mathcal{L}^i(m_t)$$

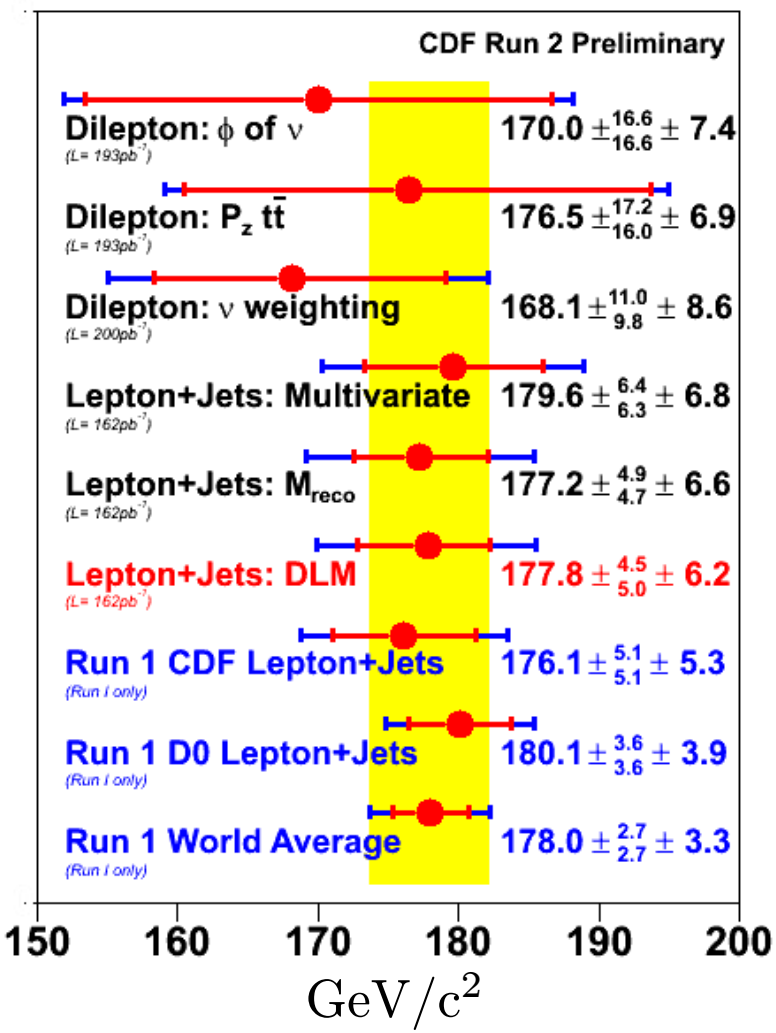
- Contains PDFs, matrix elements, transfer fcns

Multivariate method:

- Uses three sets of signal templates:
  - Correct parton assignments
  - Incorrect parton assignments
  - Wrong jets selected
- Weight the signal templates accordingly



Results for top mass measurements:



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

Datasets
- Dilepton
- Lepton+Jets
- Run I Results

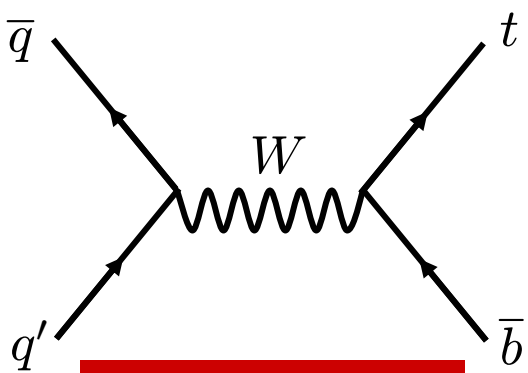
Single Top Quark Production

Single top production via Electroweak processes is possible

- A great opportunity to study the CCWI 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

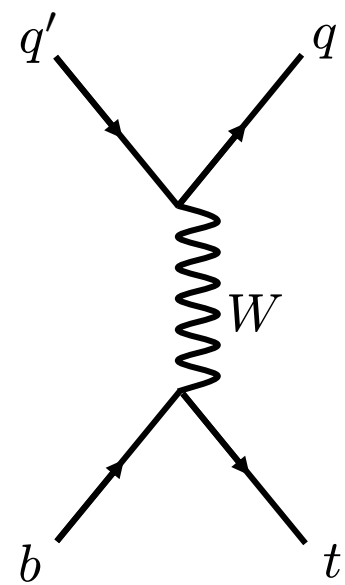
Search for these processes at the Tevatron

Forget about this until the LHC



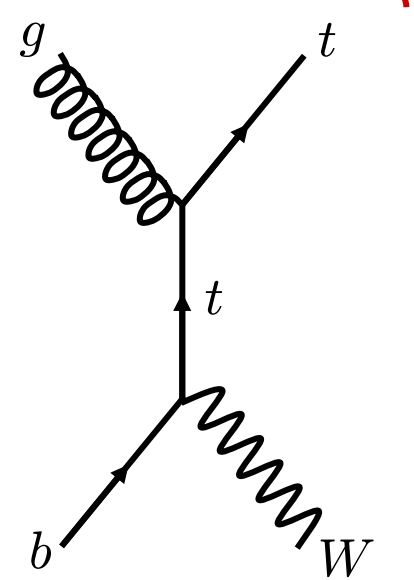
s-channel production

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



t-channel production

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



associated production

$\sigma \sim$ tiny @ Tevatron

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

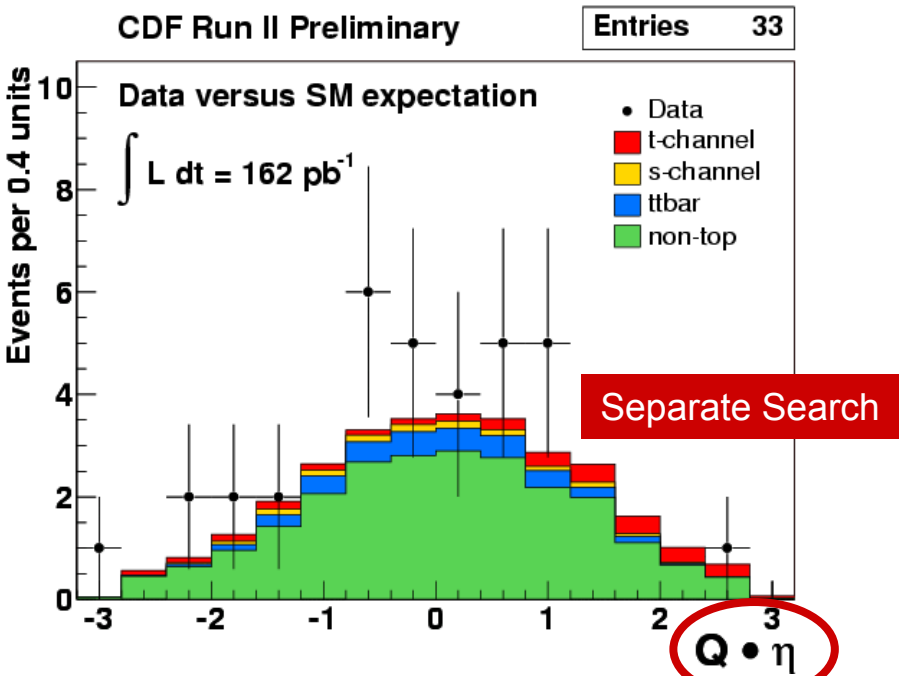
Strategy for finding single top:

- 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 $W \to e\nu, \mu\nu$

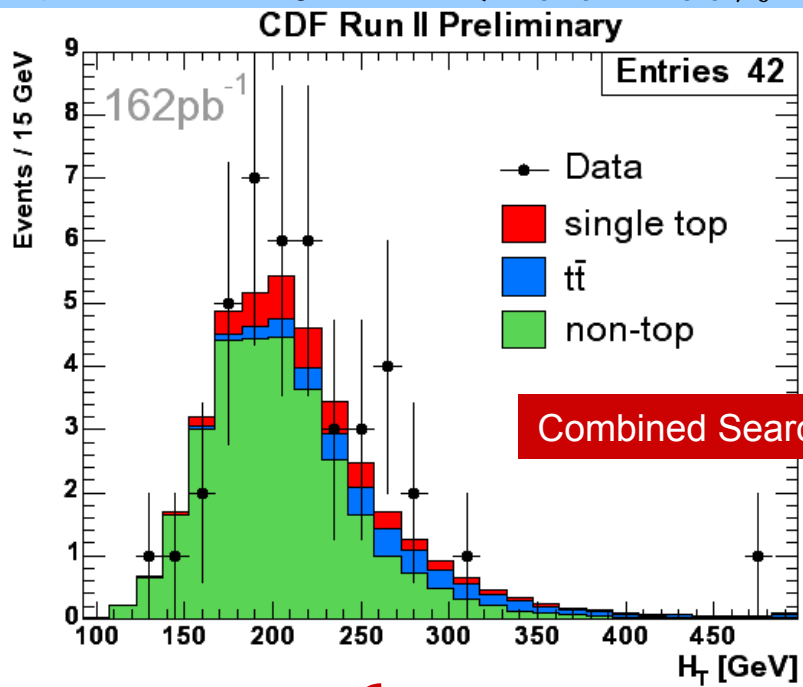
Conduct two analyses

- Combined search using H_T distribution (for single top discovery)
- Separate channel searches
  - To reveal new physics
  - Use $Q \times \eta$ distribution

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



Separate Search



Combined Search

Charge of lepton, η of light-quark jet

Datasets { Lepton+Jets

W Helicity from Top Decay

W boson has three helicity states:

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

Suppressed in the SM

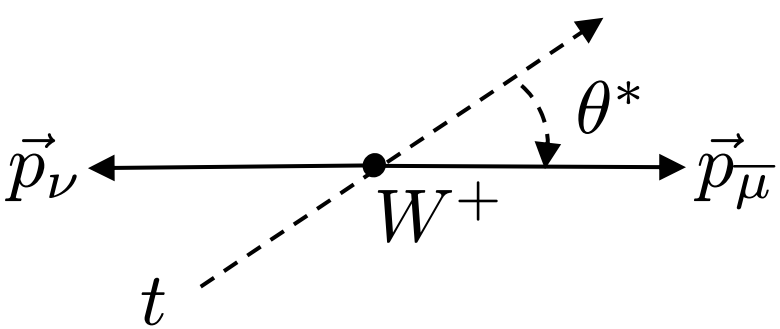
By measuring the fraction of longitudinal Ws we are:

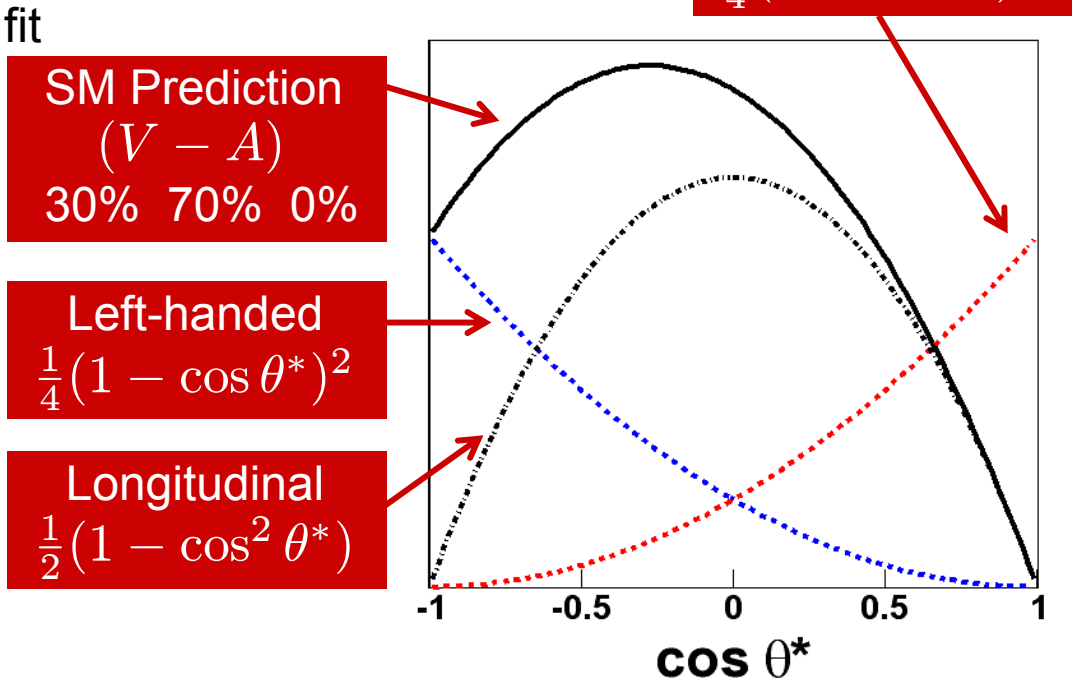
- Testing a Standard Model prediction: $F_0 = 0.7$
- Probing the tWb vertex, believed to be $(V-A)$
- Could provide insight into the nature of EWSB

Distributions for each helicity state are very distinct:

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

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





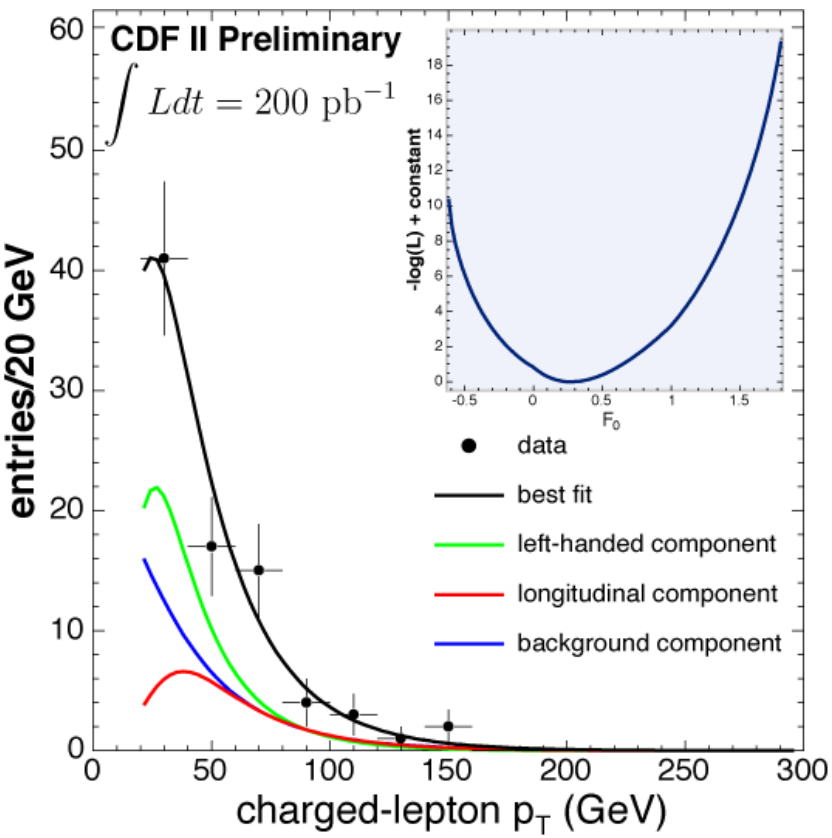
Results for measuring the Longitudinal Fraction:

Lepton p_T Method

Sample: Dilepton and Lepton + Jets

Result:

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

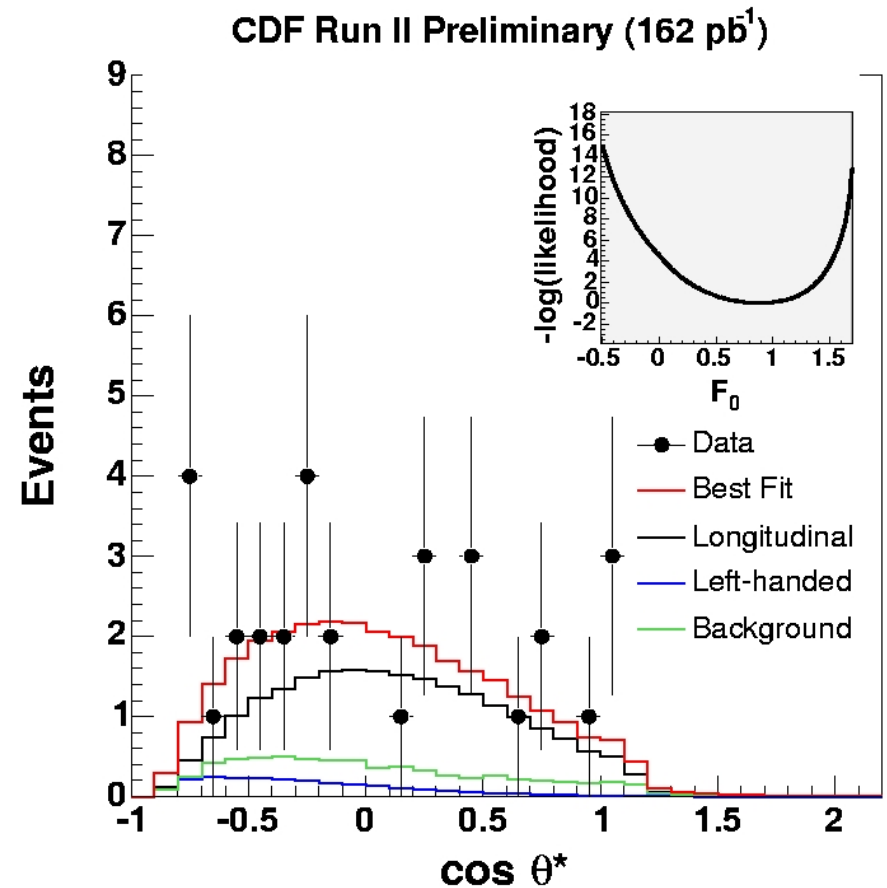


$\cos\theta^*$ Method

Sample: Lepton + Jets

Result:

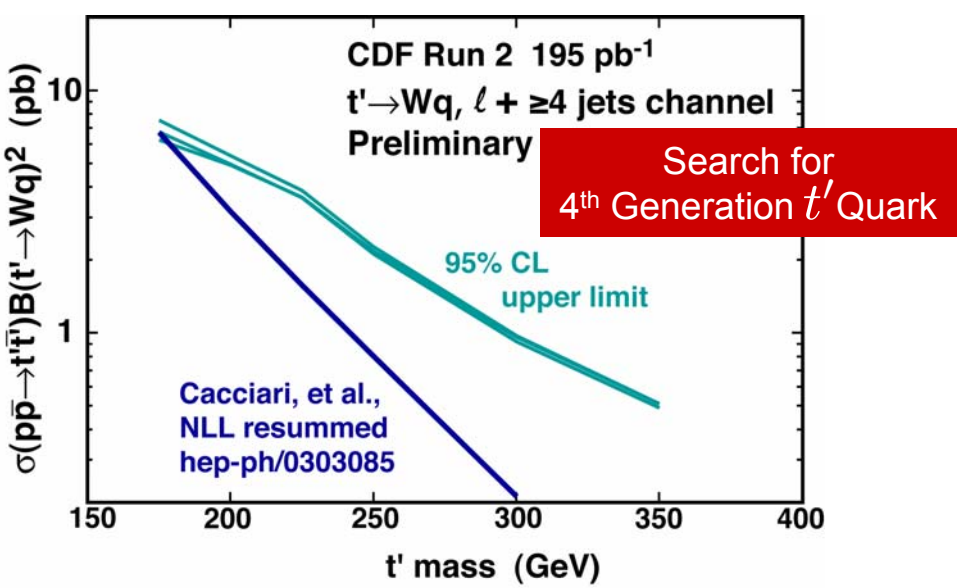
$$F_0 = 0.89^{+0.30}_{-0.34}\ (\text{stat.}) \pm 0.17\ (\text{syst.})$$

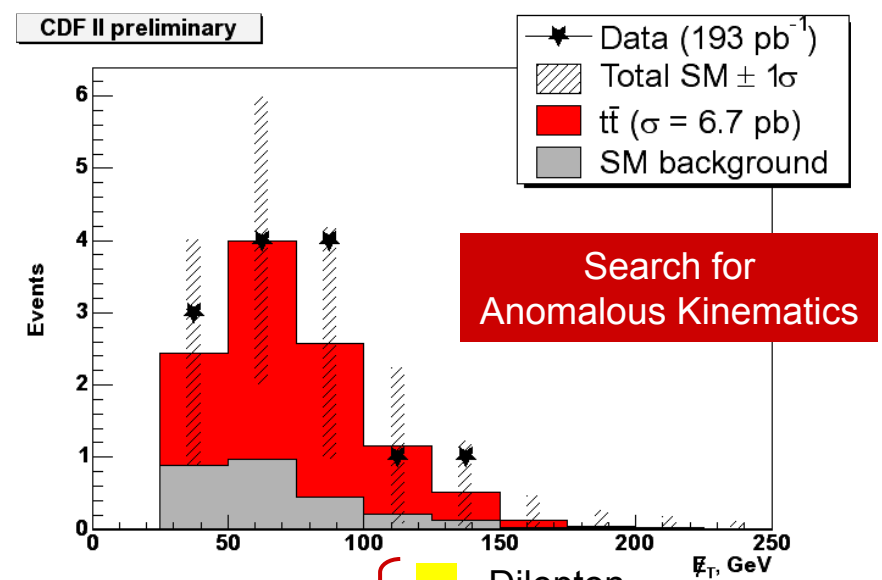


Datasets { Dilepton, Lepton+Jets

Other Top Quark Property Measurements

Measurement	$\int \mathcal{L}\, dt$ [pb^{-1}]	Result
W Helicity F_+	109	$F_+ < 0.18$ @ 95% CL
Search for Anomalous Kinematics	193	Prob. 1-4.5% Consistent with SM
$BR(t \to \tau\nu b)/BR_{\rm SM}(t \to \tau\nu b)$	193	< 5.0 @ 95% CL
Search for 4th generation t' Quark	195	Set Limits
$BR(t \to Wb)/BR(t \to Wq)$	162	$1.11^{+0.21}_{-0.19}$ (stat. + syst.)
$\sigma_{\rm dilepton}/\sigma_{\rm lepton+jets}$	126	$1.45^{+0.83}_{-0.55}$ (stat. + syst.)
Search for H^+ in t decays	193	$BR(t \to Hb) < 0.7$ @ 95% CL





Datasets
- Dilepton
- Lepton+Jets
- Run I Results

Summary/Conclusions

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
- 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 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
- **"Measurement of the W Boson Polarization in Top Decay at CDF at S**(1/2) = 1.8-TeV,"** hep-ex/0411070
- **"Search for Anomalous Kinematics in t anti-t Dilepton Events at CDF II,"** hep-ex/0412042

When Trish discovers Ned works exclusively with top quarks, she will be putty in his hands.