What we know about top

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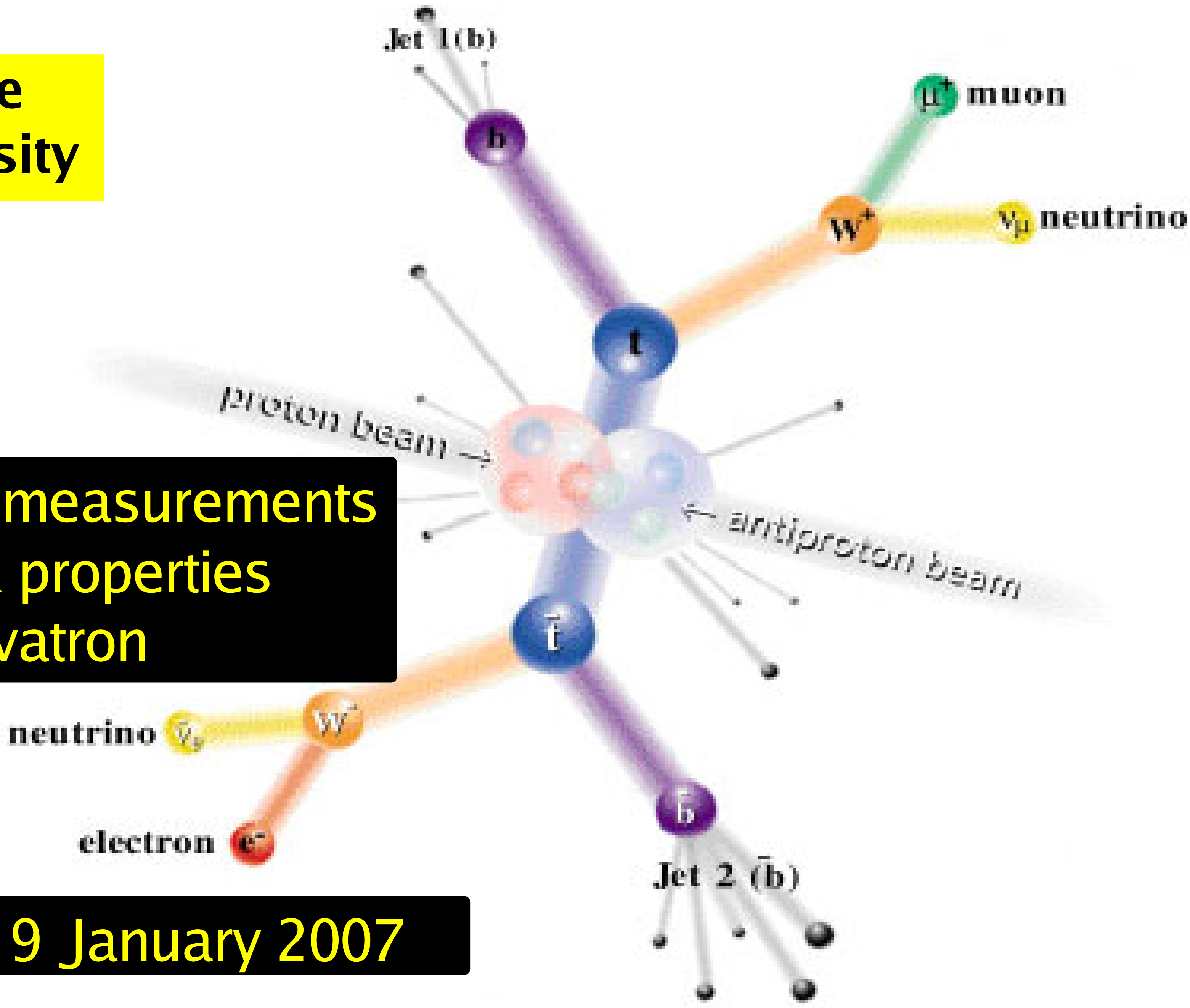
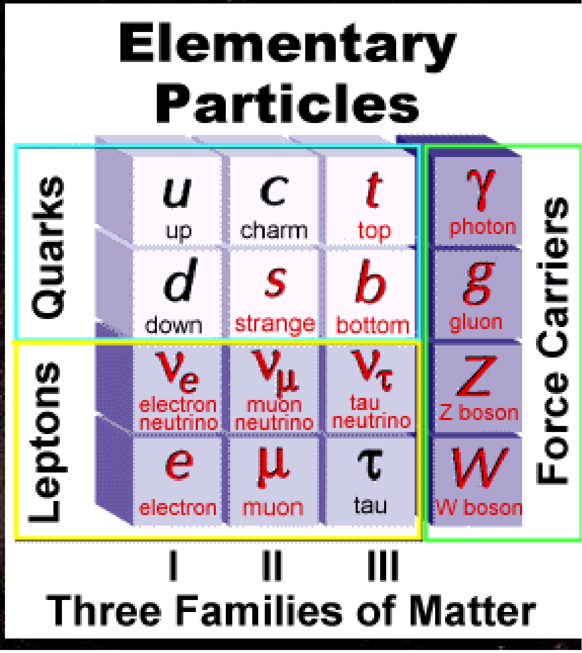
A survey of measurements of top-quark properties from the Tevatron

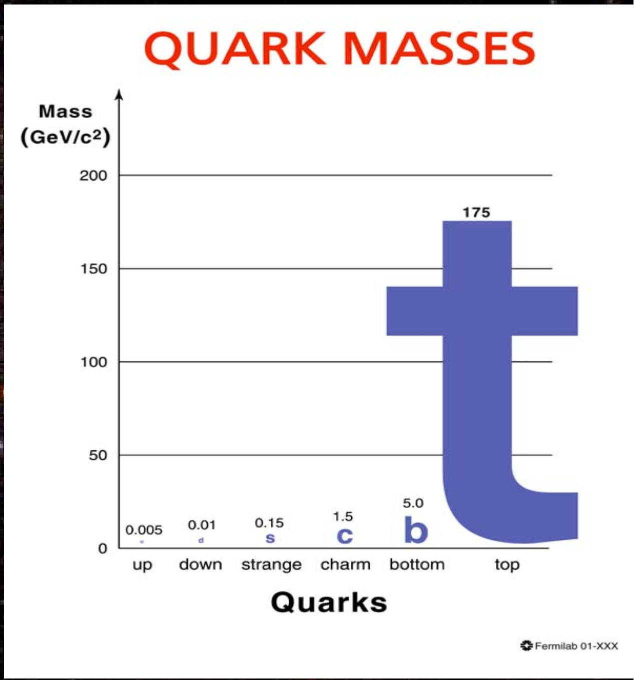


Aspen, CO, 9 January 2007

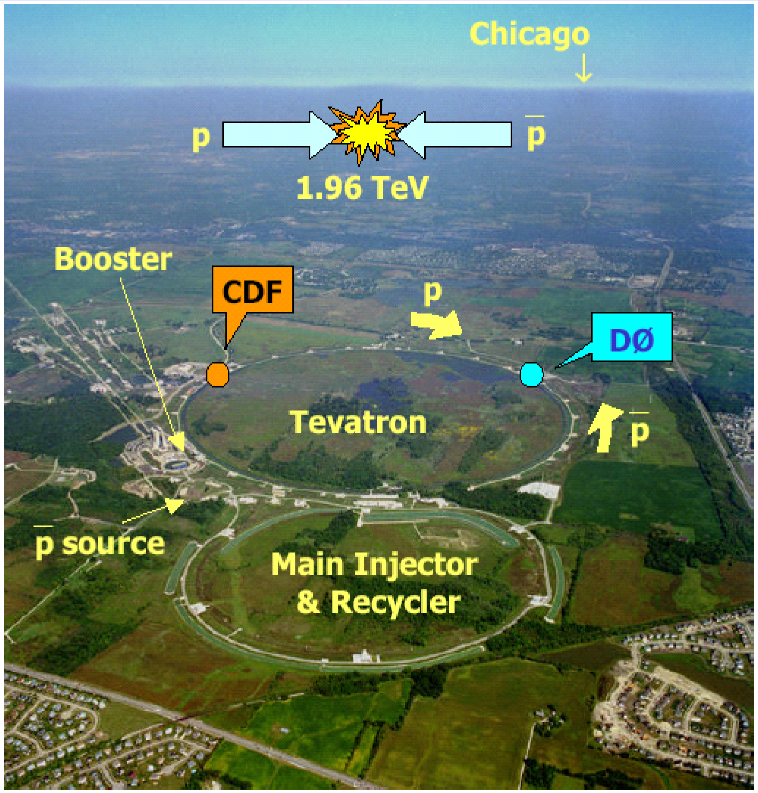
The big picture

- We now know a lot about the top quark:
  - It completes the 3 generations of quarks
  - Its mass is 171.4 GeV/c^2 to ~1.2%
  - Many other properties with increasing precision
- But there remain open questions:
  - Why did the universe settle for this "picture" ~10^{-32}s after the Big Bang ?
  - Why is top so heavy ?
  - Is there a close connection between the top quark and mass generation itself (and EWSB) ?
  - Can it lead us to new symmetries of the Universe ?
- A better understanding of the properties of the top quark could shed some light on such questions
- And the Tevatron is the only place for these studies for a couple more years still !

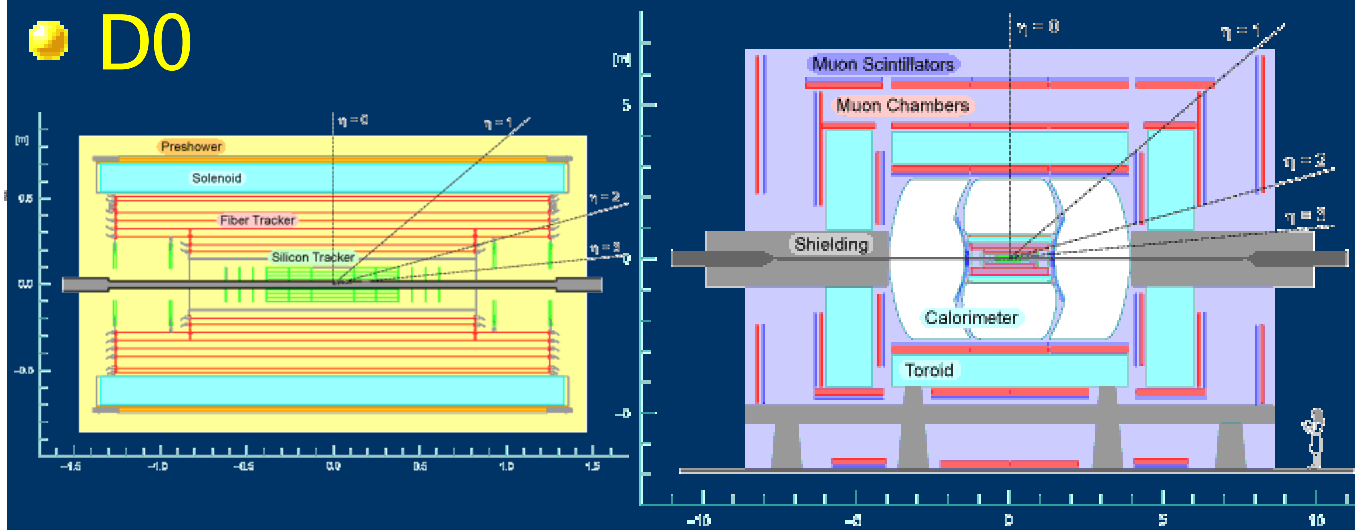




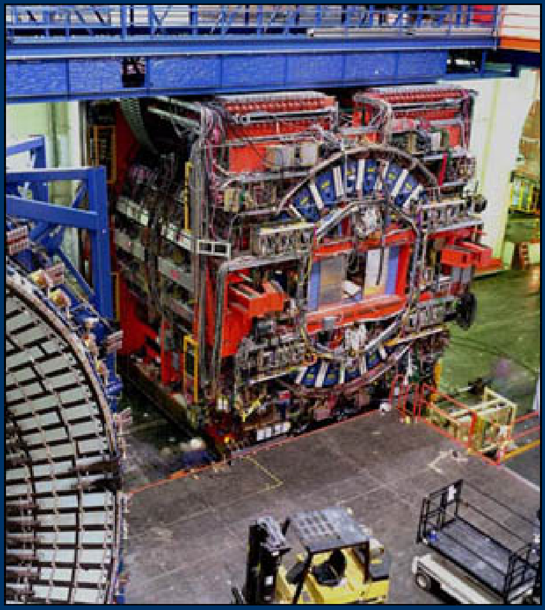
Experimental Apparatus and datasets



- D0



- CDF



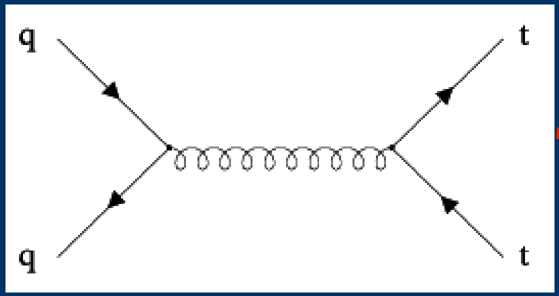
Both detectors are general purpose:
- Precision tracking
- Calorimetry
- Muon systems

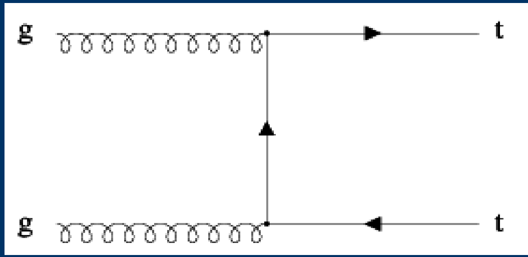
- Tevatron:
  - 980 GeV beam energies
  - ~1.5fb^{-1} recorded/expt
  - Expect 6-8fb^{-1} by 2009

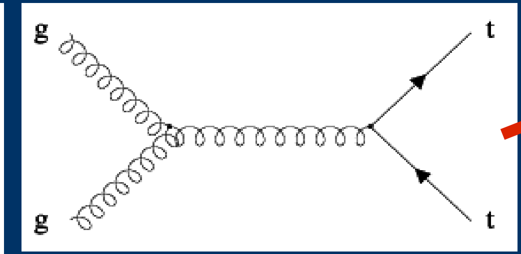
Results presented use between 200pb^{-1} and 1fb^{-1} of Tevatron Run 2 data

Top quark production at the Tevatron

- In pairs via the strong interaction



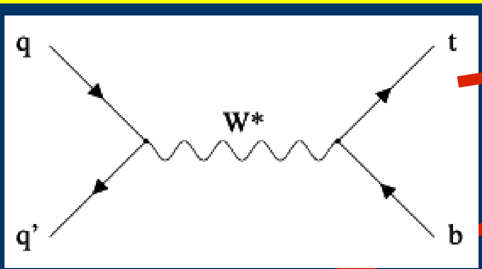


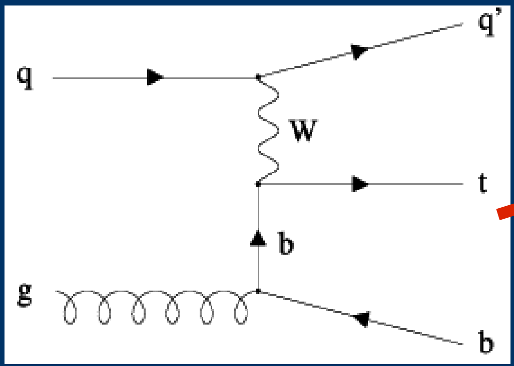


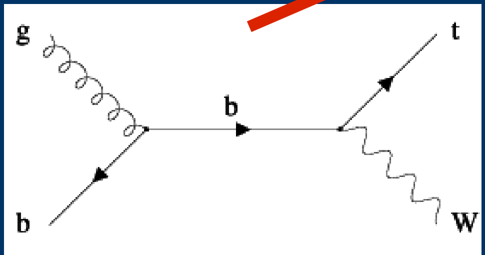
Production Cross Section	
Tevatron (2 TeV)	LHC (14 TeV)
85%	5%
15%	95%
6.7 pb	800 pb

in 1 fb^{-1} about 7000 $t\bar{t}$ events produced (assumes m_{top} = 175 GeV)

- Singly via the electroweak interaction



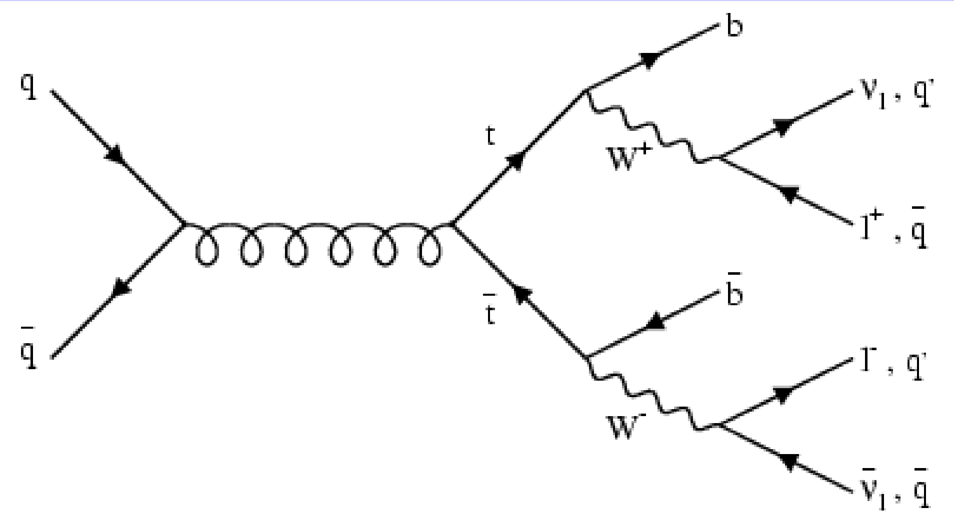




2.1 pb	10.2 pb
0.88 pb	245 pb
0.12 pb	62 pb

- Total single top production cross-section about 3 pb
- See talk by Y. Caudou

Top quark decay



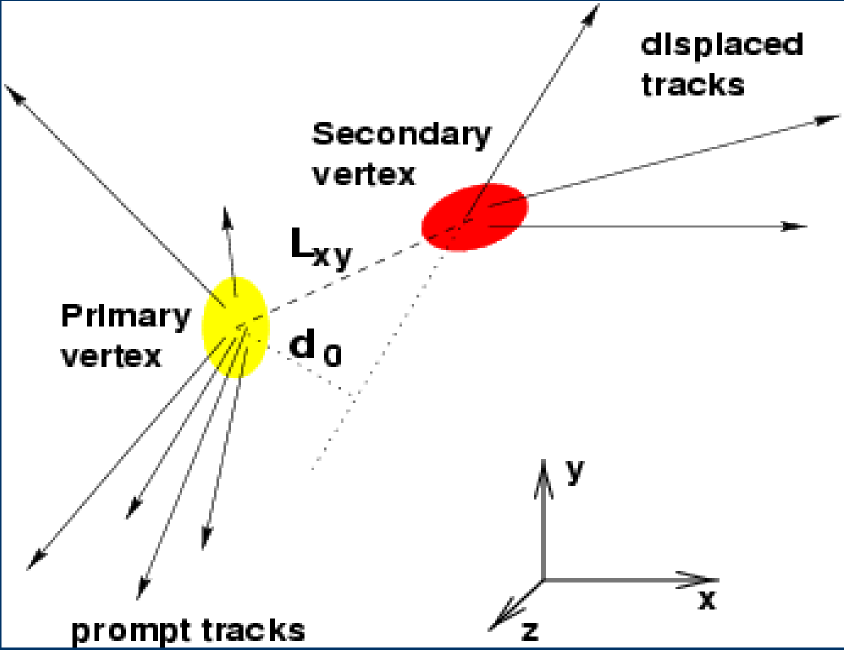
- The SM $t \rightarrow Wb$ decay has $\tau \sim 10^{-25}$s
  - No time to form bound states !

BR($W \rightarrow l\,\nu$) = 3/9
BR($W \rightarrow qq'$) = 6/9

- <u>Measurements are made using distinct decay channels</u>
  - **Dilepton** → 2 high-P_T *e*'s or μ's, 2 high-E_T jets, large missing E_T ($\not{E}_T$)
    → Branching Ratio(BR) = 5%
  - **Tau-Dilepton** → 1 high-P_T *e* or μ, 1 high-E_T τ, 2 high-E_T jets, large $\not{E}_T$
    → BR = 5%
  - **Lepton (or tau) + jets** → 1 high-P_T *e*, μ (or τ), 4 jets (2 b's), large $\not{E}_T$
    → BR = 30% (15%)
  - **All-hadronic** → 6 jets (2 b's)
    → BR = 45%

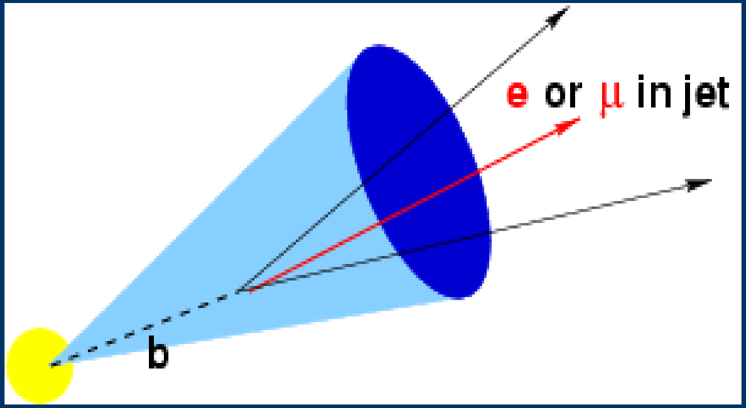
Identifying b-quarks helps reduce backgrounds (crucial for many top analyses)

Measure secondary vertex:
B's travel ~3 mm before decay



- $t\bar{t}$ event b-tag efficiency ~55%
- False tag rate ~0.5%
- Relies heavily on excellent performance and understanding of the silicon tracker

Identify low-P_T muon in jet:
BR($b \rightarrow l\,\nu\,c$) ~ 20%

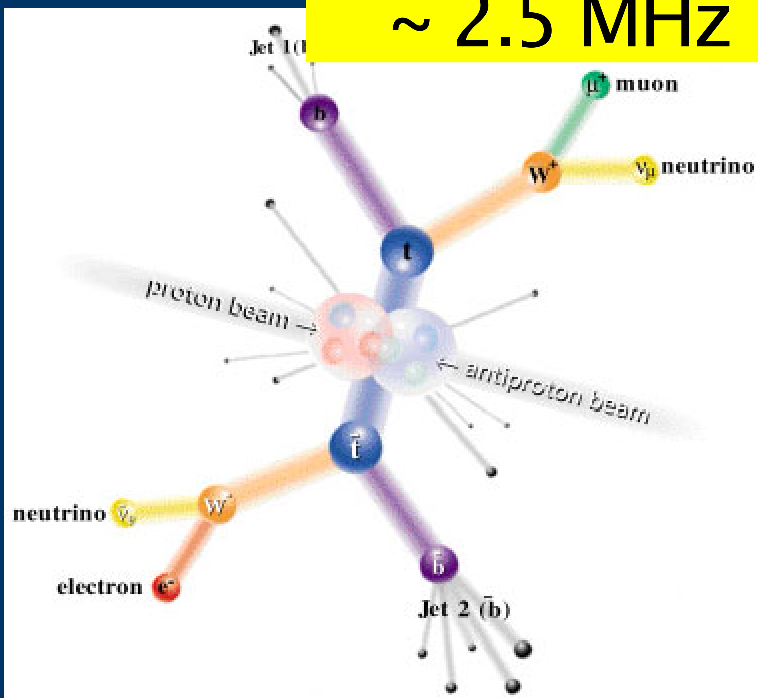


- $t\bar{t}$ event b-tag efficiency ~15%
- False tag rate ~4%

Other algorithms also used and being developed for greater efficiency

Extracting the Physics from Collisions

Collision rate
~ 2.5 MHz



3 Tiered Trigger Systems to select "interesting" events

E.g. about 1 in 10^{10} collisions produces a top quark event:

- dilepton and lepton+jet data samples trigger on high-P_T leptons
- all-hadronic channel uses a multi-jet trigger

Events written to tape at ~100 Hz

Top quark samples

In 1 fb^{-1} of integrated luminosity:

7000 tt events produced

BR + trigger →

200 dilepton
1000 lepton + jets
2000 all-hadronic

event selection →

50	dilepton	S/B ~ 2:1
200	lepton + jets (with b-tag)	S/B ~ 3:1
300	all-hadronic (with b-tag)	S/B ~ 1:5

Main backgrounds

W+jets, WW, WZ, DY

mistag, W+hf, VV, non-W

QCD multijets

To first order these are the samples of top events with which we make measurements

Measurements

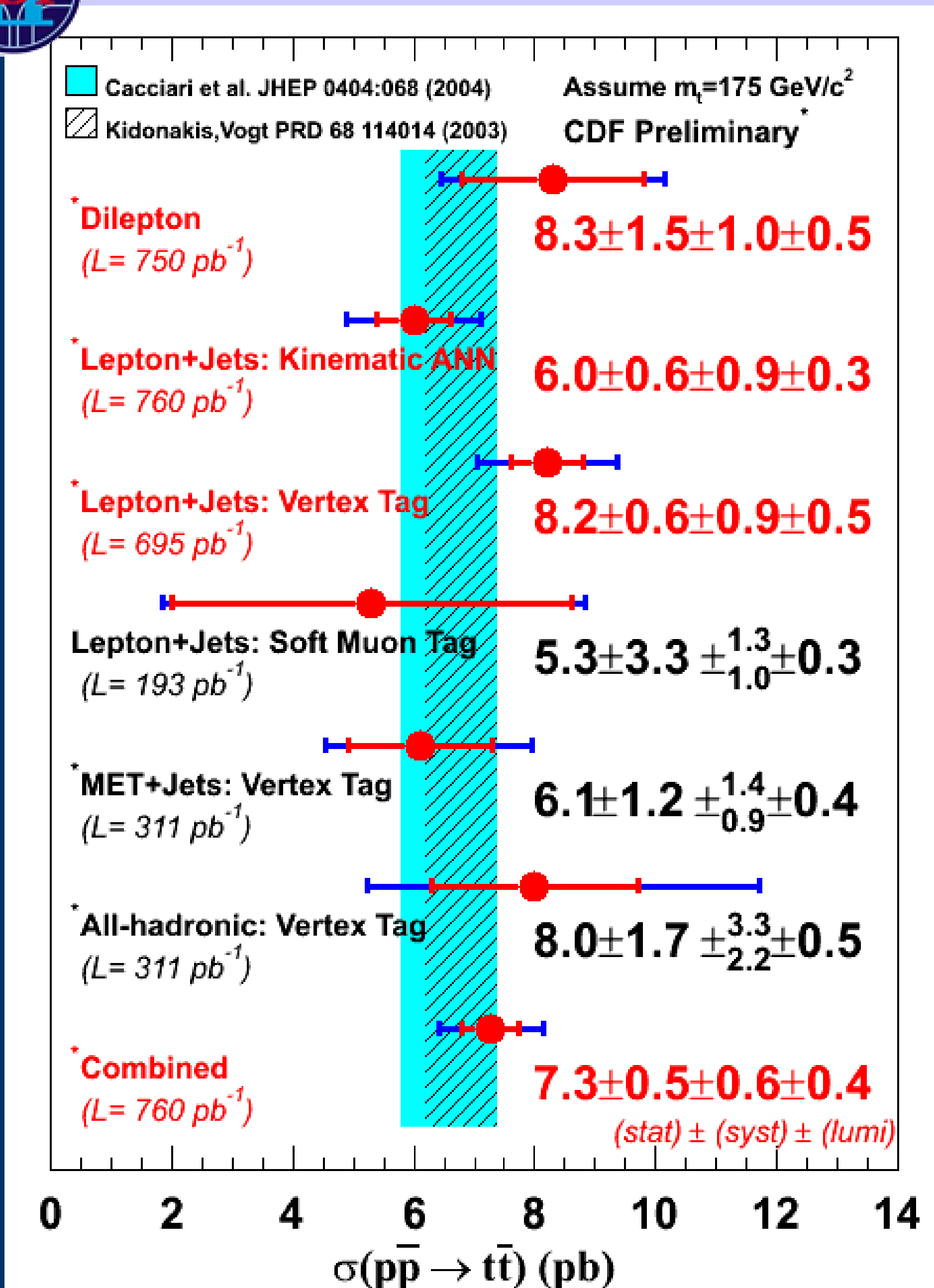
- Top quark production
  - **Cross sections**
  - **Production mechanism**
  - Resonance production (see talk by R. Erbacher)
  - Single top production (see talk by Y. Coadou)
- Top quark decay
  - **Lifetime**
  - **Branching fractions**
  - **W helicity**
  - Rare decays (see talk by R. Erbacher)
- Top quark characteristics
  - **Charge**
  - Spin
  - Mass (see talk by R. Wallny)

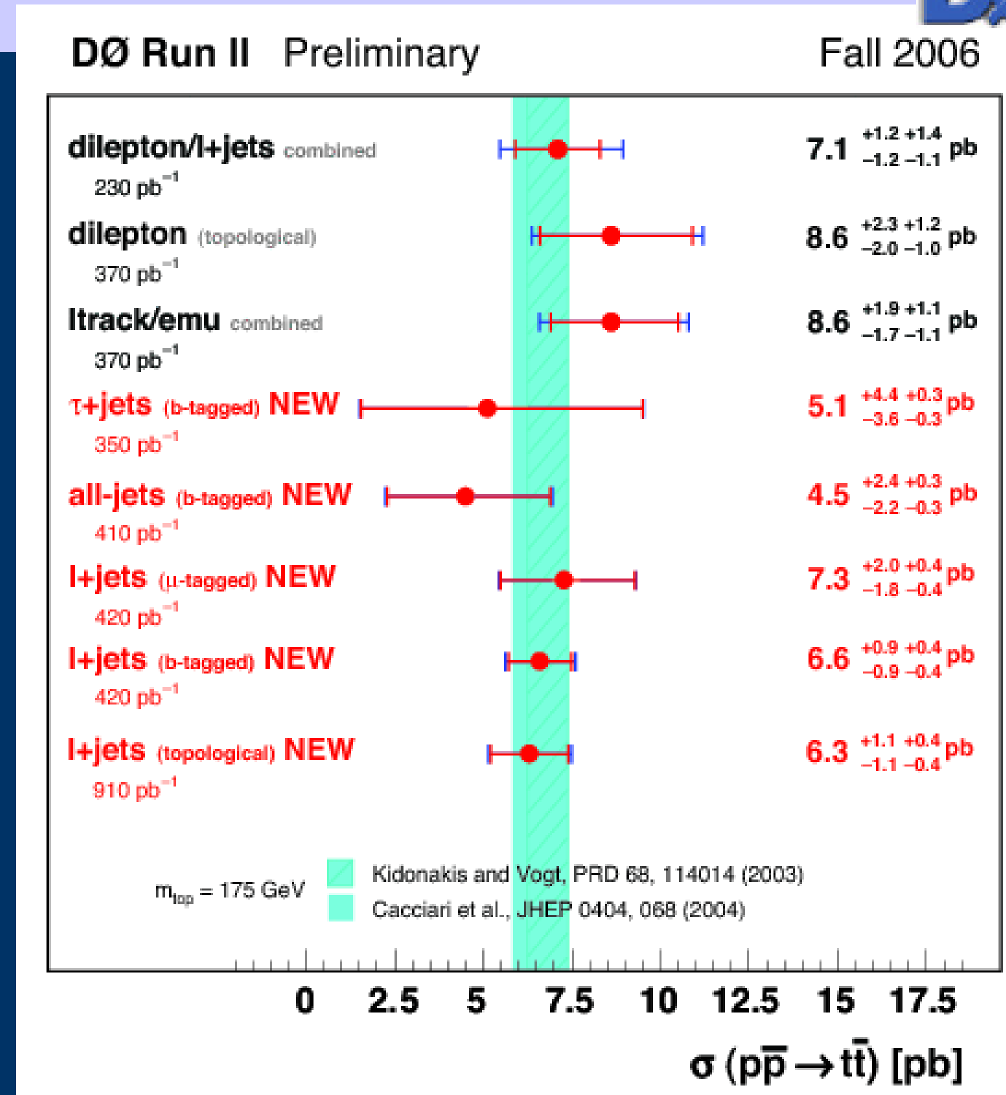
Production cross sections of top quark pairs

- Tests QCD in very high Q^2 regime
- Measurements across all decay channels and topologies have different sensitivities to new physics possibilities
- Provides important sample composition for all other top property measurements

$$\sigma(p\bar{p} \rightarrow t\bar{t}) = \frac{N_{observed} - N_{background}}{A_{tot} \int L\, dt}$$

Top cross section measurements

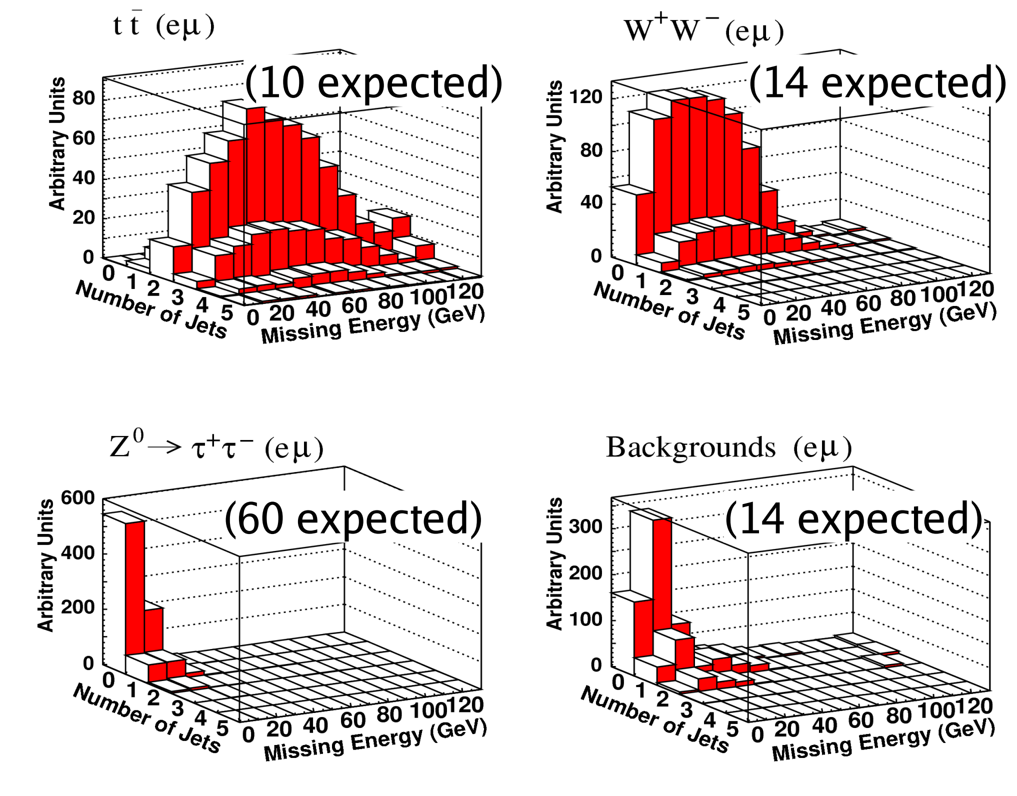




- Many analyses across all decay channels
- No surprises yet !

Global technique to extract dilepton cross sections

(hep-ex/ 0612058)



- Likelihood fit performed on the data to SM templates in the missing-E_T – N_{jet} space:
  - σ(tt), σ(WW), σ(Z → ττ) float
  - Extract tt, WW, and Z → ττ cross sections **simultaneously**
- Provides different test of the SM than single cross section measurements
- Utilizes full statistical power of the data
- Results:

Process	$e\mu$	$ee+\mu\mu+e\mu$
$\sigma(t\bar{t})$	$9.3^{+3.1\ +0.7}_{-2.6\ -0.2}$ pb	$8.5^{+2.6\ +0.7}_{-2.2\ -0.3}$ pb
$\sigma(W^+W^-)$	$11.4^{+5.2\ +0.5}_{-4.3\ -0.1}$ pb	$16.3^{+5.1\ +0.8}_{-4.4\ -0.2}$ pb
$\sigma(Z^0\to\tau^+\tau^-)$	$291^{+50\ +6}_{-46\ -3}$ pb	-

SM prediction

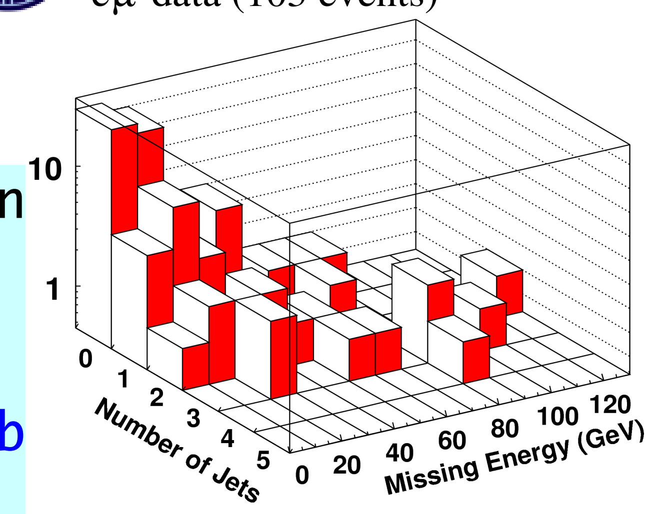
6.7 ± 0.9 pb

12.4 ± 0.8 pb

251 ± 5 pb

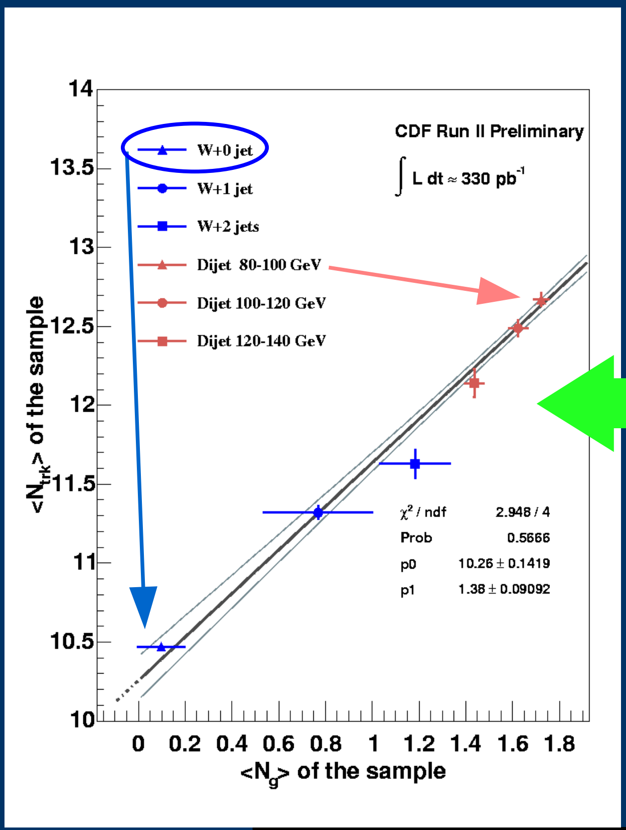
preliminary 360 pb^{-1}

eμ data (103 events)

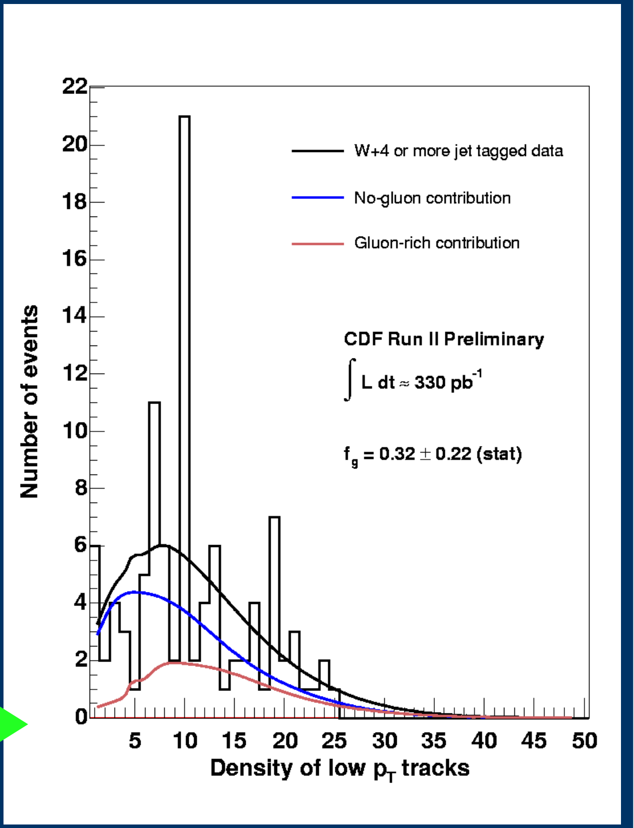


Top pair production mechanism

- $gg \to tt$ versus $qq \to tt$: tests pQCD and sensitive to new production mechanisms
- Discrimination is tough, but can use # of tracks in underlying event:
  - gg initial state tends to have greater underlying event activity

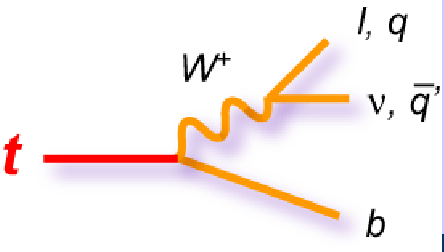


- Use # low p_T tracks in event as discriminator (0.3 – 3 GeV)
- Calibrate $<N_{trk}>$ vs. $<N_g>$ correlation using W+jets and dijet data
- Fit W+jets(b-tagged) data to gluon-rich and no-gluon $<N_{trk}>$ templates



$$\frac{\sigma(gg \to tt)}{\sigma(qq \to tt)} = 0.25 \pm 0.24(\text{stat}) \pm 0.10(\text{syst})$$

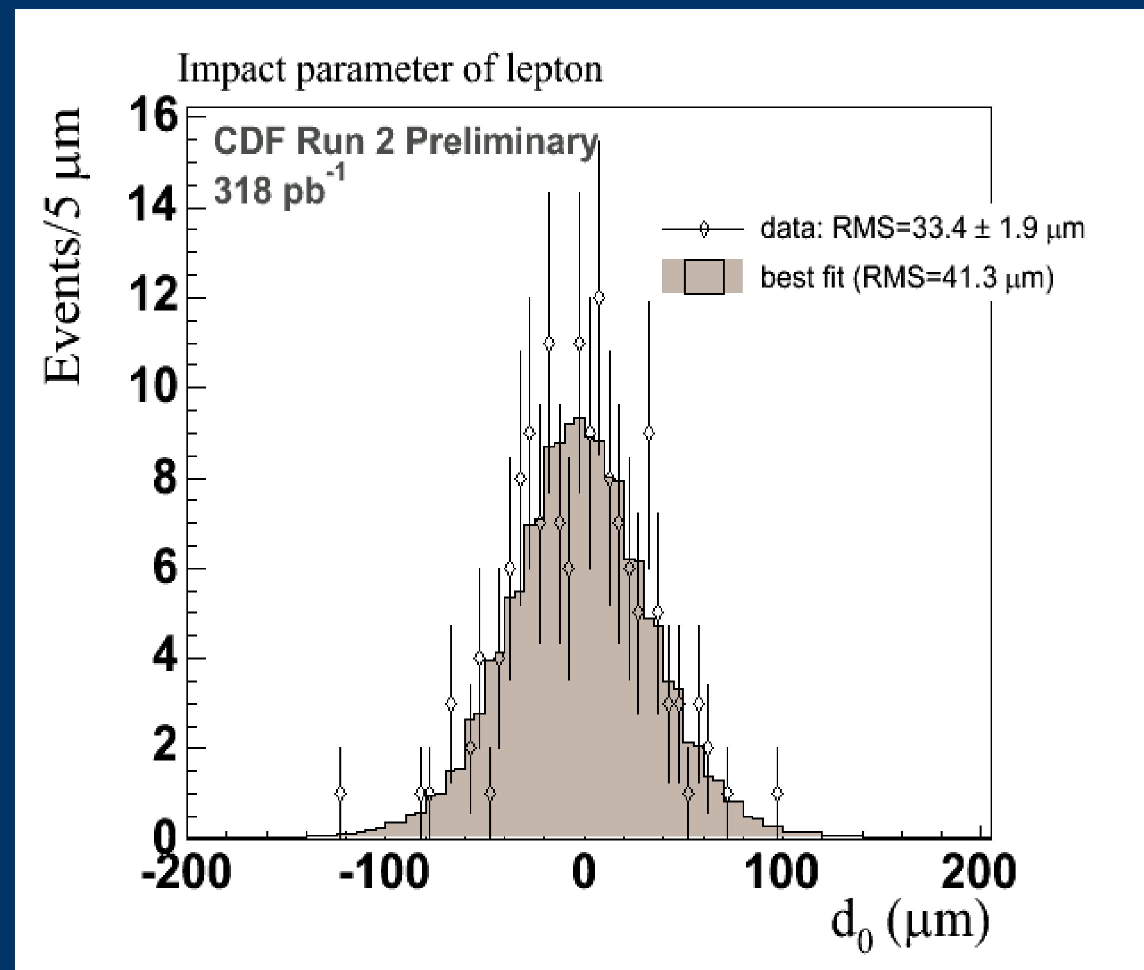
(SM predicts 0.18)



Top quark decay: lifetime

- Under the SM assumption of a V-A tWb coupling, and $|V_{tb}| \sim 1$, the partial width for $t \rightarrow Wb$ is $\Gamma \sim 1.5$ GeV giving $\tau \sim 10^{-25}$s ($c\tau \sim 10^{-10}\mu$m)
- Deviations from these assumptions can give very different predictions
- Using lepton + 3-jet data:
  - require 1 b-tag
  - measure impact parameter (d_0) of lepton tracks
  - determine resolution from lepton trigger data
- Obtain:

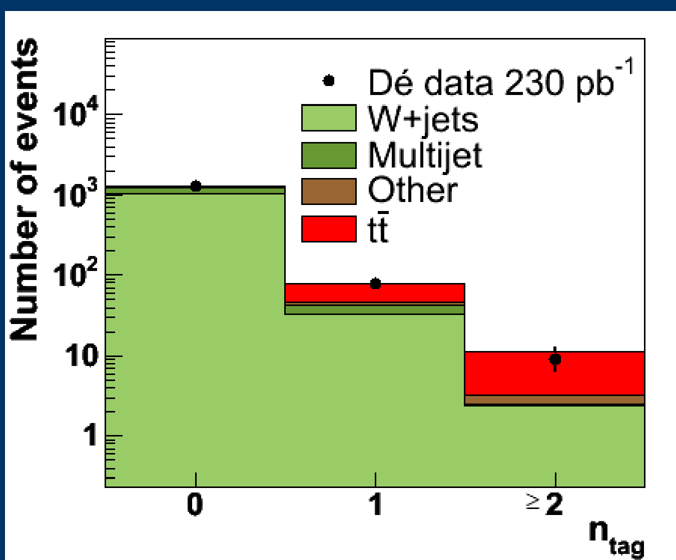
  $c\tau < 52.5\ \mu$m (95% CL)



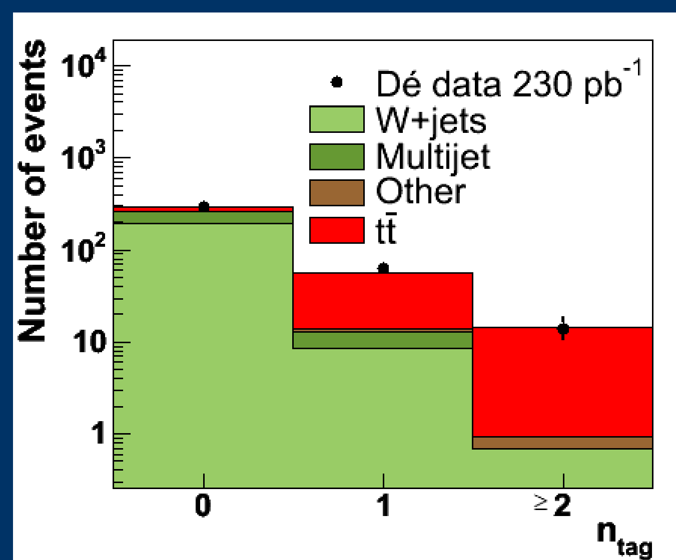
Top quark decay: Branching Fractions

(hep-ex/ 0503002)

- In the SM, $R = BR(t \rightarrow Wb) / BR(t \rightarrow Wq) = 0.998 \sim |V_{tb}|^2$
- R determines the fraction of tt events with 0, 1 and 2 b-jets
- Use this to extract R from fits to the 0, 1 and 2 b-tagged samples



lepton + 3-jet sample



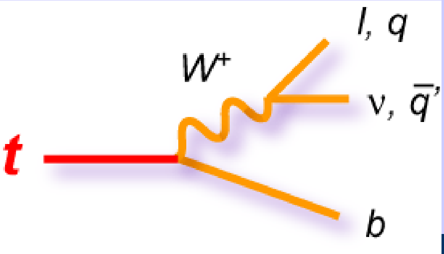
lepton + >3-jet sample

$R = 1.03^{+0.19}_{-0.17}$

$R > 0.61$ @ 95% CL

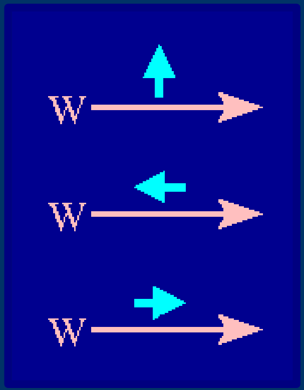
$|V_{tb}| > 0.78$ @ 95% CL

Still need a lot more data to really test the SM, but a nice technique for doing so



Top quark decay: W helicity

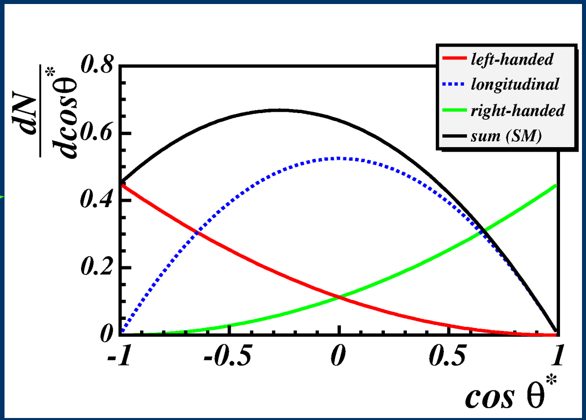
- The helicity of the W can be:
  - Longitudinal (fraction F_0)
  - Right-handed (fraction F_-)
  - Left-handed (fraction F_+)

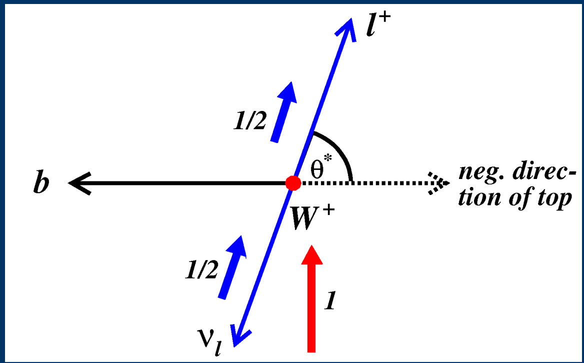


- The V-A character of the decay $\Rightarrow$ $F_0 = 0.70$, $F_- = 0.30$, $F_+ = 0$

  (if the decay vertex was V+A then $F_0 = 0.70$, $F_- = 0$, $F_+ = 0.30$)

- The W helicity fractions can be measured using variables sensitive to the angular distributions of the W decay products:
  - Lepton p_T
  - M_{lb}^2
  - $\cos(\theta^*)$

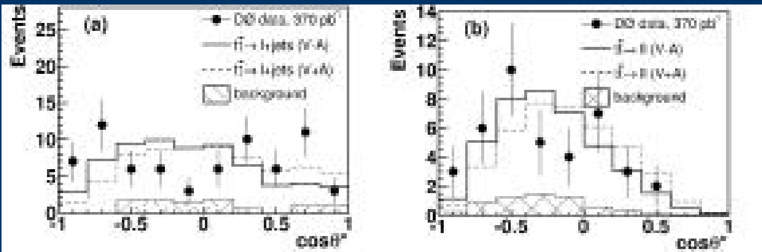




W helicity measurements

- Using cos(θ*) :

DØ (370pb^{-1}, dil and lepton + jets)

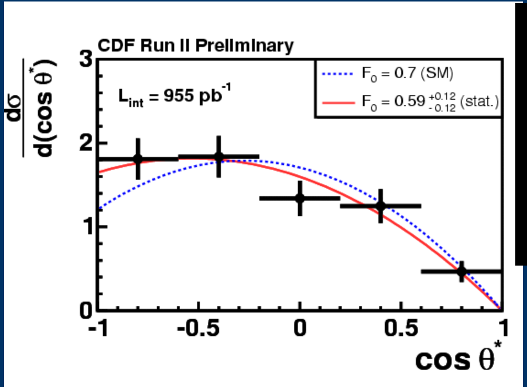


(hep-ex/ 0609045)

$F_+ = 0.06 \pm 0.10$

$F_+ < 0.23$ @ 95% CL

CDF (1 fb^{-1}, lepton + jets)



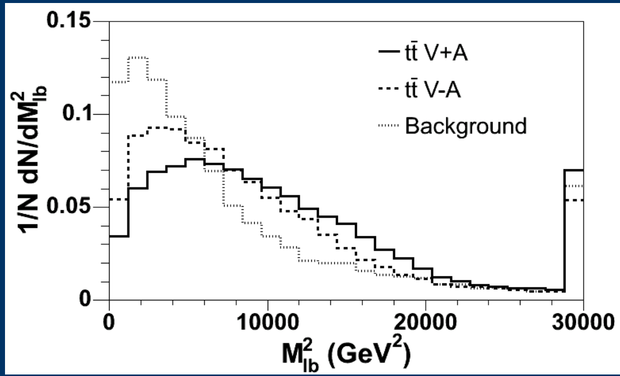
$F_0 = 0.59 \pm 0.12 \pm 0.07$

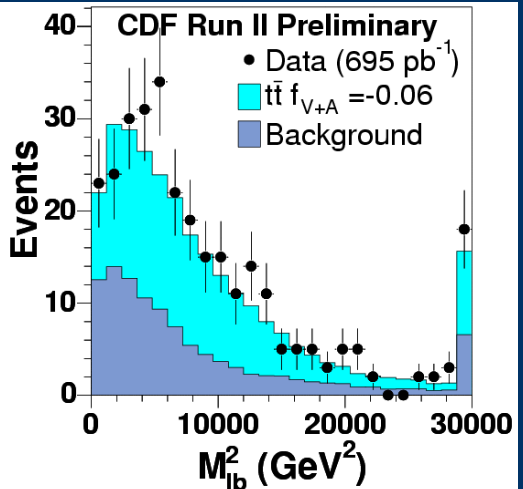
$F_+ = -0.03 \pm 0.07$

$F_+ < 0.1$ @ 95% CL

(hep-ex/ 0612011)

- Using M_{lb}^2 (700pb^{-1}, dilepton and lepton + jets): (hep-ex/ 0608062)





$F_+ = 0.02 \pm 0.07$

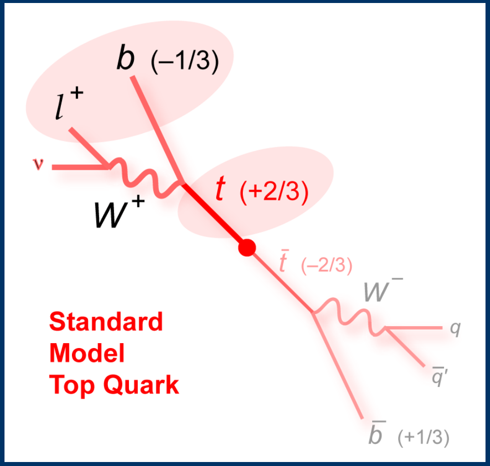
$F_+ < 0.09$ @ 95% CL

Within large errors, consistency observed with SM.
New analyses underway.

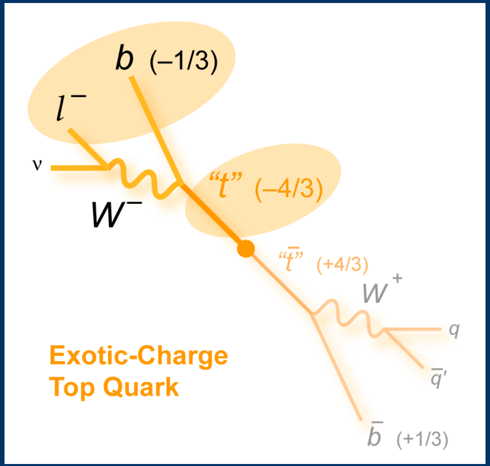
Top Quark charge

(hep-ex/ 0608044)

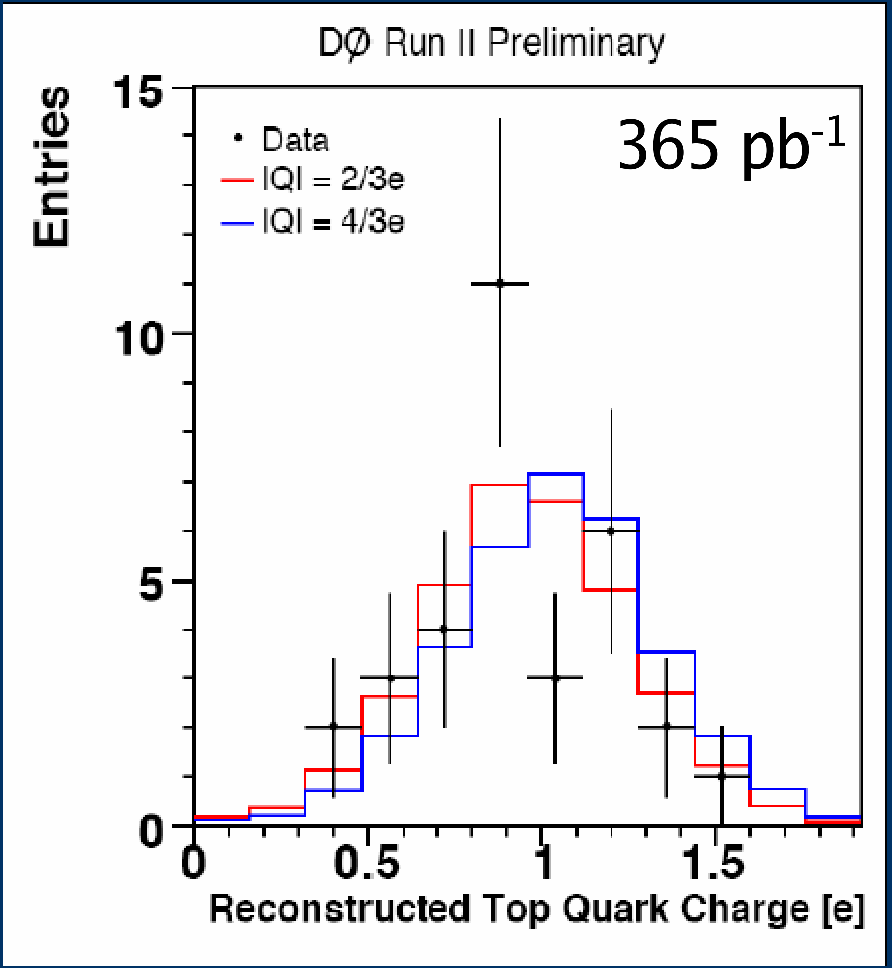
- In the SM top is +2/3 partner to the -1/3 bottom
- But how do we know that this is what we've been measuring ?
- For example:



or

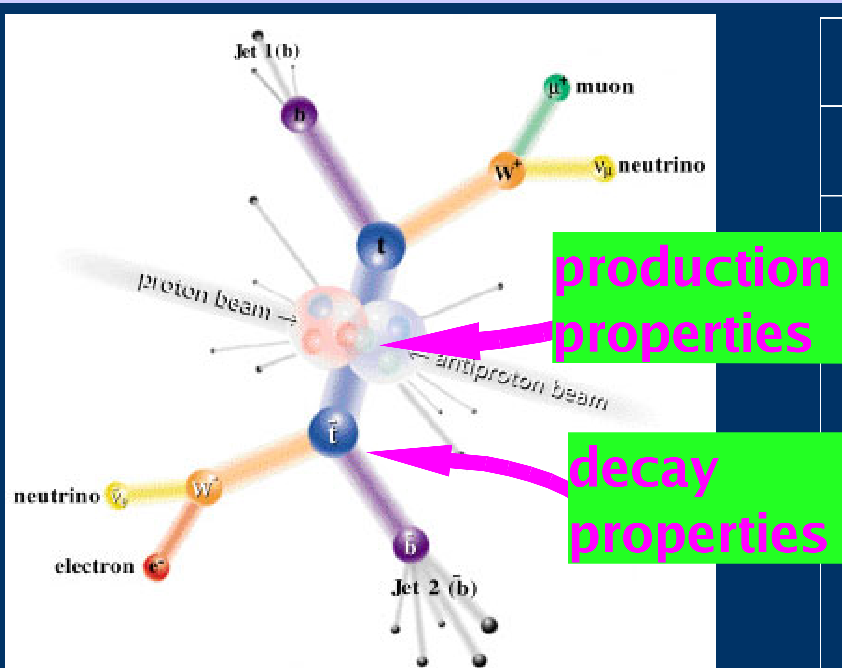


?



- In lepton + 4-jet sample:
  - require 2 b-tags
  - use a jet-charge algorithm to discriminate between b and bbar
  - pair to charged lepton to infer Q_{top}
- **Q_{top} = 4/3e excluded at 94% CL**

Summary of our knowledge of top



	Measurement	SM prediction
M_{top} (Tevatron combined) (GeV/c^2)	171.4 ± 2.1 GeV	171.7 GeV
σ_{tt} (CDF combined)	7.3 ± 0.9 pb	6.7 ± 0.9 pb
$\sigma(gg \to tt) / \sigma(gg + qq \to tt)$	0.25 ± 0.26	0.18
$c\tau_{top}$	< 53.5 μm (95% CL)	10^{-10} μm
$BR(t \to Wb) / BR(t \to Wq)$	> 0.61 (95% CL)	0.998
F_0	0.59 ± 0.14	0.75
F_+	< 0.09 (95% CL)	0
charge	Not 4/3 @ 94% CL	2/3
spin		½

Aside from the top mass, the precision on all other measurements is still relatively poor (the next best being σ_{tt} at ~12%)

Closing remarks

- The Tevatron is currently running very well and making important strides in precision top quark measurements
- By the end of Run 2 (~6 fb^{-1})
  - Mass measured to <1% precision (further constraining Higgs sector)
  - Cross-sections to be measured to ~7%
  - All other top properties to better precision, not just due to more data, but also greater effort to optimally utilize the data and control systematic uncertainties
- The LHC will take over where the Tevatron leaves off, with its comparatively huge *top* samples available....(at LHC design luminosity of $10^{33} cm^{-2} s^{-1}$, 1 day at LHC ≡ 3 years at Tevatron!)
- ***Top* may be getting on in years, but it remains our most mysterious particle, and a greater understanding of it could lead to what lies beyond the SM**