Measurements of Top Quark Properties at Run II of the Tevatron

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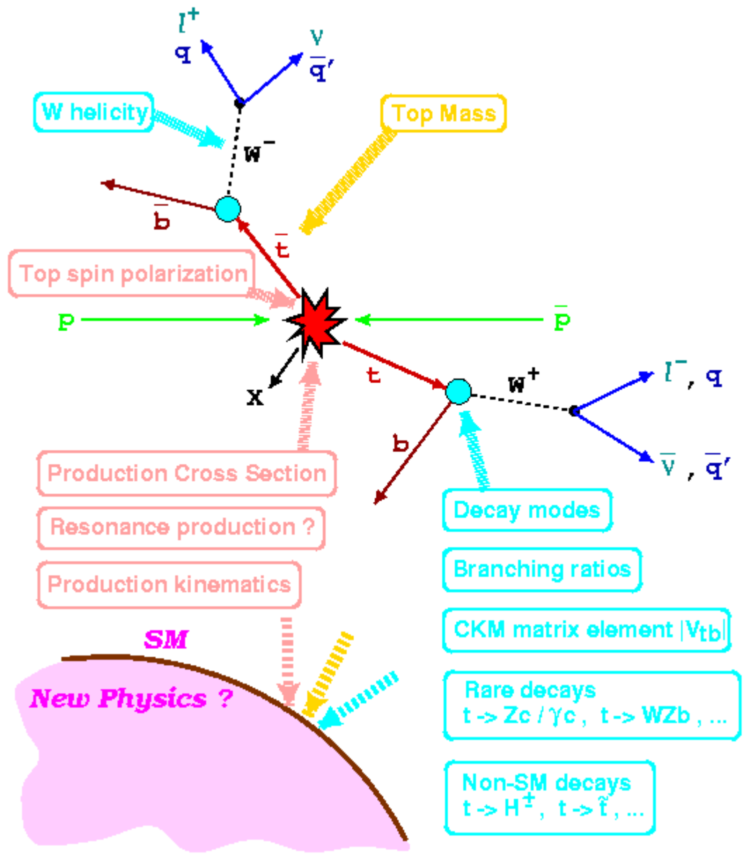
Introduction

- The top quark was discovered with a sample of ~50 pb^{-1} of Run I data
  - Found to be massive -- Yukawa coupling of order unity
- With the larger Run II sample we can explore:
  - is top quark production and decay according to SM?
  - is there an exotic component to the "top" sample?
- In particular, we measure
  - the *W* boson helicity
  - the top quark charge
  - top quark branching ratios
- Results shown in this talk are obtained from ~few hundred pb^{-1}



Common Factors

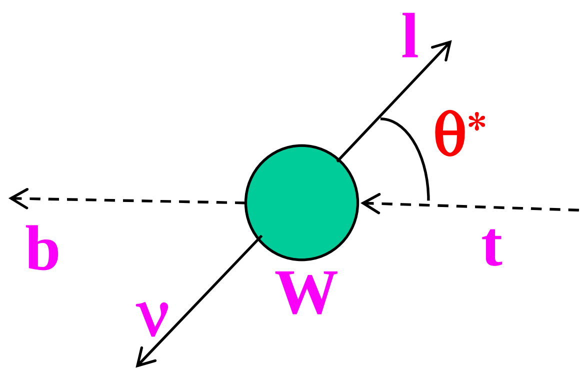
- All top measurements so far are based upon pair-produced top quarks
  - single top production has not yet been observed
- Measurements of top quark properties generally build upon well-understood event selection criteria
  - i.e. those established by cross-section measurement
- All measurements so far are based upon decay channels with at least one lepton in the final state
- Searches for one aspect of non-SM behavior generally assume all *other* top quark properties are SM
- Measured mass and cross section may be used as inputs

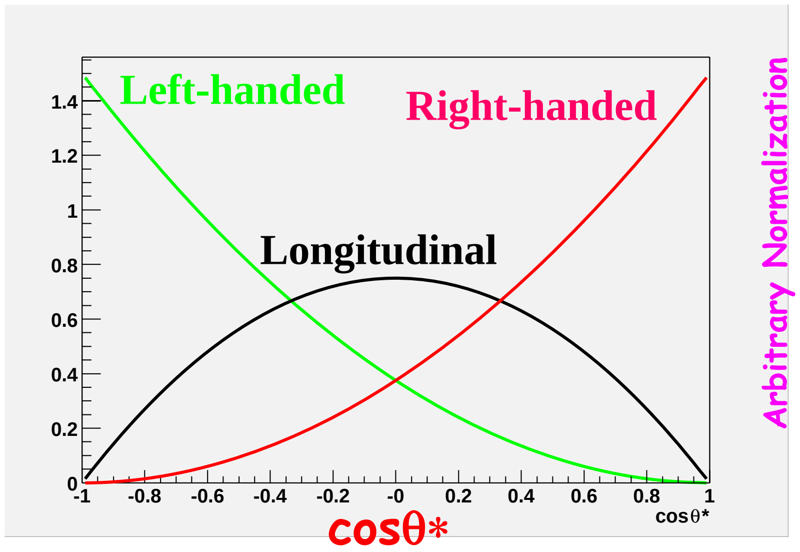
W Helicity: Motivation and Observables

The Standard Model predicts the helicity of the W boson from top quark decay

~70% longitudinal
~30% left-handed
~0% right-handed

- The helicity can be found from the distribution of θ^*, defined as:





and also from the charged lepton p_T in the lab frame

Decay Channels

- Each leptonically-decaying top gives information about the *W* helicity
  - using hadronic decays would require distinguishing jets from up-type and down-type quarks
- Each lepton + jets event provides one measurement, while dilepton events provide two
  - dilepton events play a larger role in *W* helicity than they do in other top properties measurements
- Initial measurements were performed using Run I data:

CDF: $f_+ < 0.18$ @95% CL (Feldman-Cousins)

[Lepton plus jets and dilepton] Phys. Rev. D71, 031101(R) (2005)

DØ: $f_o = 0.56 \pm 0.31$ (stat. + syst.)

[Lepton plus jets] Phys. Lett. B **617**, 1 (2005)

Measuring $\cos\theta^*$

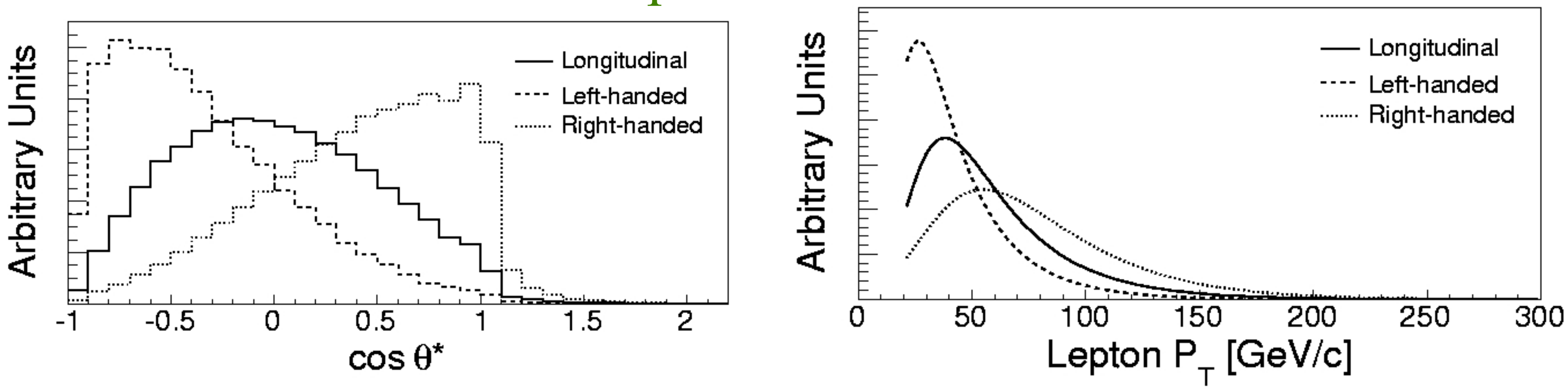
- One needs to find the "right" jet to associate with each charged lepton
  - done with a kinematic constrained fit to the $t\bar{t}$ hypothesis, with top mass fixed (to 175 GeV)
  - all jet permutations are considered, and one with the lowest χ^2 is taken
- Once the leptonic b jet has been selected, one can either
  - boost to W boson rest frame and calculate $\cos\theta^*$ directly (DØ) or
  - use the approximation:

$$\cos\theta^* \approx \frac{2m_{\ell b}^2}{m_t^2 - M_W^2} - 1 \quad \text{(CDF)}$$

Comparing the Observables

- $\cos\theta^*$ has larger correlation with W helicity than does lepton p_T:

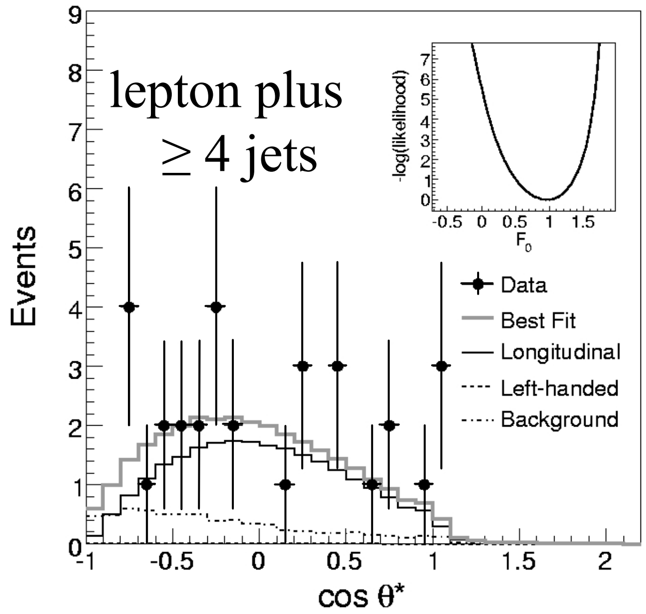
MC templates from CDF



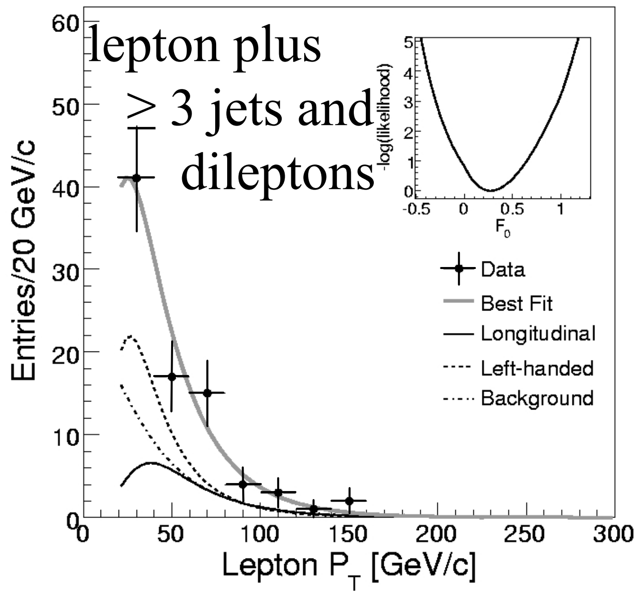
- But lepton p_T has smaller systematics
  - e.g. no first-order dependence on jet energy calibration
  - can also be used for events where kinematic fit is not possible
- Currently, we're statistics-dominated, so $\cos\theta^*$ is used by both CDF and DØ in lepton + ≥4 jets events
  - CDF also performs a lepton + ≥3 jets analysis using lepton p_T
  - Both CDF and DØ use lepton p_T in dilepton channel

CDF *W* Helicity Measurements

- From ~200pb^{-1}, CDF finds: hep-ex/0511023; submitted to PRL



$$f_o = 0.99^{+0.29}_{-0.35}\,(\text{stat.}) \pm 0.19\,(\text{syst.})$$



$$f_o = 0.31^{+0.37}_{-0.23}\,(\text{stat.}) \pm 0.17\,(\text{syst.})$$

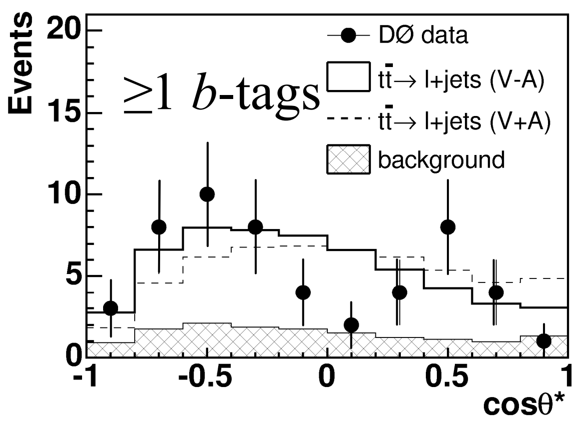
- Combining these results gives:

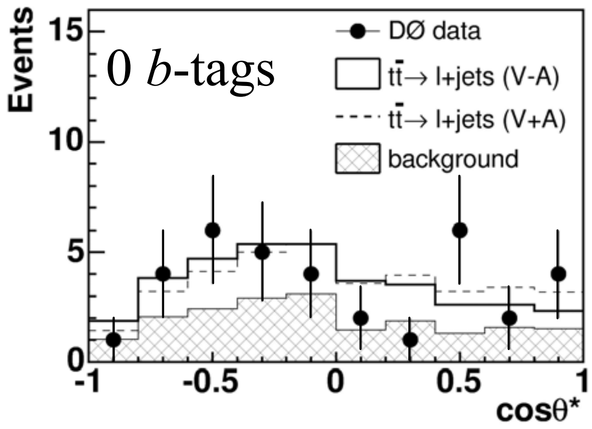
$$f_o = 0.70^{+0.22}_{-0.34}\,(\text{stat.+syst.})$$

$$f_+ = 0.00^{+0.20}_{-0.19}\,(\text{stat.+syst.}); < 0.27 \text{ @95\% CL}$$

DØ *W* Helicity Measurements

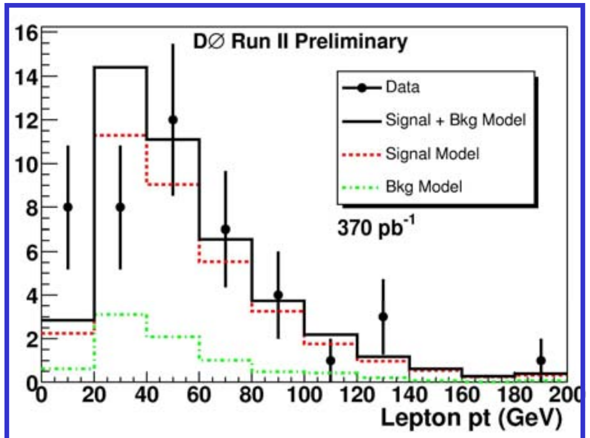
- Using ~230pb^{-1} (lepton plus jets) and ~370pb^{-1} (dilepton):





$$f_+ = 0.00 \pm 0.13 \text{ (stat.)} \pm 0.07 \text{ (syst.)}$$

Phys. Rev. D **72** 011104 (2005)



$$f_+ = 0.13 \pm 0.20 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$$

- Combination gives:

$$f_+ = 0.04 \pm 0.11 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$$

$$< 0.25 \text{ @95\% CL (Bayesian)}$$

$$[\text{Preliminary}]$$

Systematic Effects

- With ~10^2 $t\bar{t}$ events, most properties measurements are currently statistics-dominated
  – but reducing systematics will be crucial in LHC era
- Here's how systematics impact the present W helicity analyses (average between CDF and DØ):

Source	$\delta(\cos\theta^*)$	$\delta(\text{lepton } p_T)$
Jet energy	0.04	0.0005
Top mass	0.04	0.05
Background model	0.04	0.05
Signal model	0.02	0.04

None of these will scale simply with $1/\sqrt{L}$

Top Quark Decay Branching Ratio

- In the SM, top must decay weakly
- Further, given unitarity of the CKM matrix, the BR to *Wb* is nearly 100%:

$$R \equiv \frac{BR(t \to Wb)}{BR(t \to Wq)} = \left|V_{tb}^2\right| > 0.998 @ 90\%\mathrm{CL}$$

- *b* jets are identified using finite *b* lifetime
- Probability to observe *n* (=0,1,2) tagged jets in an event is:

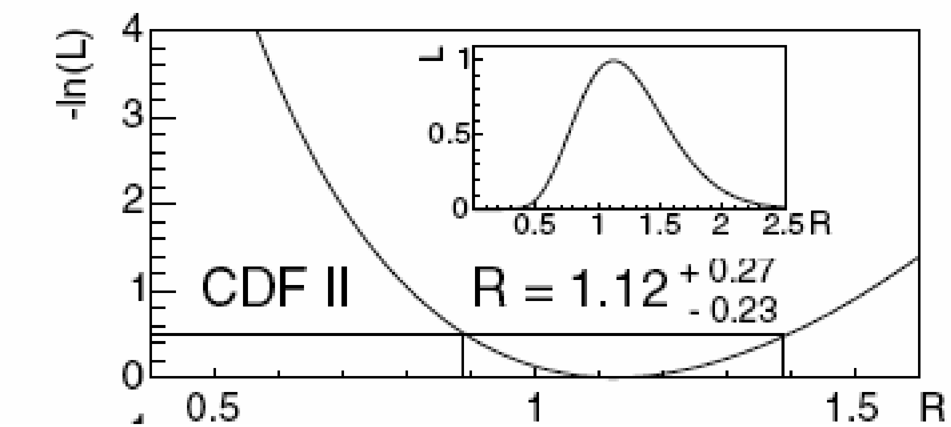
$$P_n(t\bar{t}) = R^2 P_n(t\bar{t} \to b\bar{b} + X)$$
$$+2R(1-R)P_n(t\bar{t} \to q_l\bar{b} + X)$$
$$+(1-R^2)P_n(t\bar{t} \to q_l\bar{q}_l + X)$$

These depend on *b* and q_l tagging efficiencies

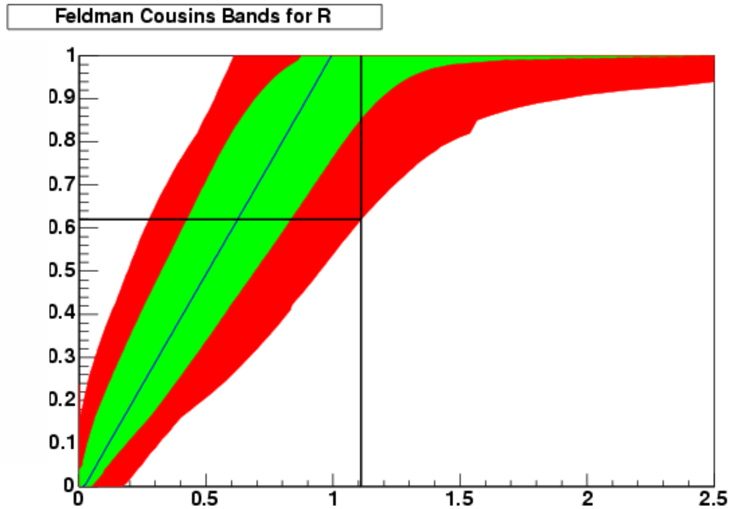
CDF Measurement of *R*

- Distribution of *b*-tags in 160 pb^{-1}:

	Lepton + jets			Dilepton		
	0 tags	1 tag	≥2 tags	0 tags	1 tag	≥2 tags
Expected *S+B*	80.4 ± 5.2	21.5 ± 4.1	5.0 ± 1.4	6.1 ± 0.4	4.0 ± 0.2	0.9 ± 0.2
Observed	79	23	5	5	4	2



$$R = 1.12^{+0.21}_{-0.19}\ (\text{stat.})\ ^{+0.17}_{-0.13}(\text{syst.})$$



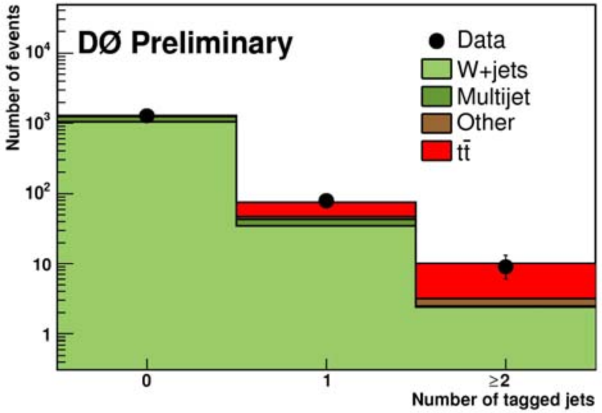
$$R > 0.61\ @95\%\ \text{CL}$$

Phys. Rev. Lett. **95**, 102002

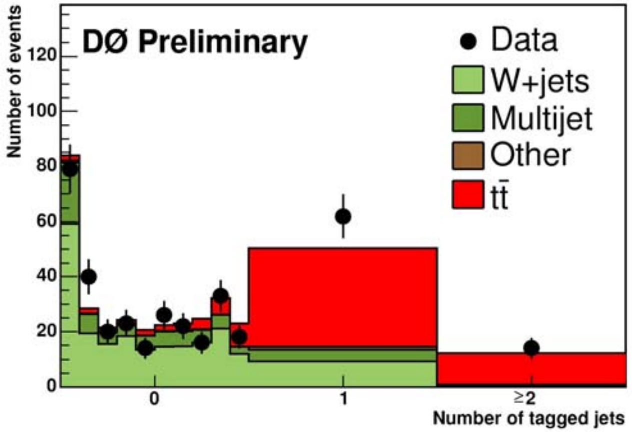
DØ Measurement of *R*

- Distribution of *b*-tags in 230 pb^{-1} of lepton + jets data:

Lepton + 3 jets



Lepton + ≥4 jets

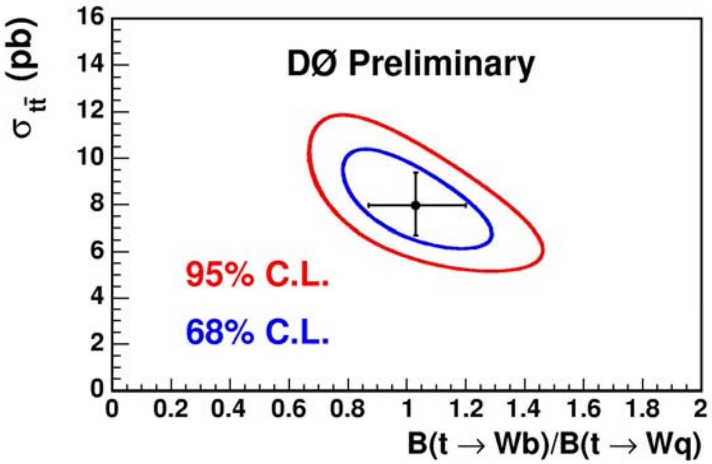


Fitting overall normalization and tag distribution allows extraction of both $\sigma_{t\bar{t}}$ and *R*:

$$\sigma_{t\bar{t}} = 7.9^{+1.7}_{-1.5}\ (\text{stat.+syst.}) \pm 0.5\ (\text{lumi.})\ \text{pb}$$

$$R = 1.03^{+0.19}_{-0.17}\,(\text{stat.+syst.})$$

$$R > 0.64\ \text{@95\% CL (Bayesian)}$$

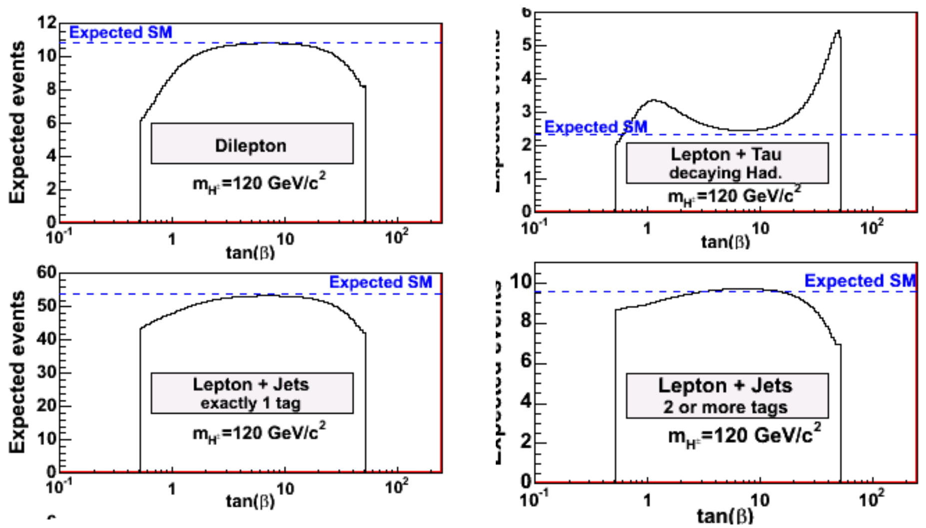


Preliminary

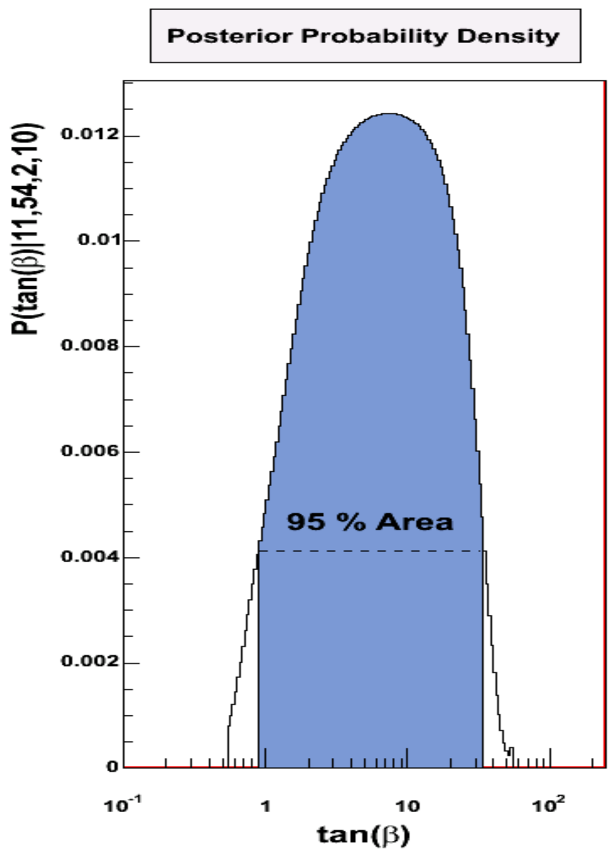
Branching Ratio to Charged Higgs

- In extensions to SM, top may have additional decay channel to $H^{+}b$

- Final state particle content would be altered by H^{+} decays
  - essentially resulting in an excess of τ's and a deficit in other channels:



If data agrees with SM:

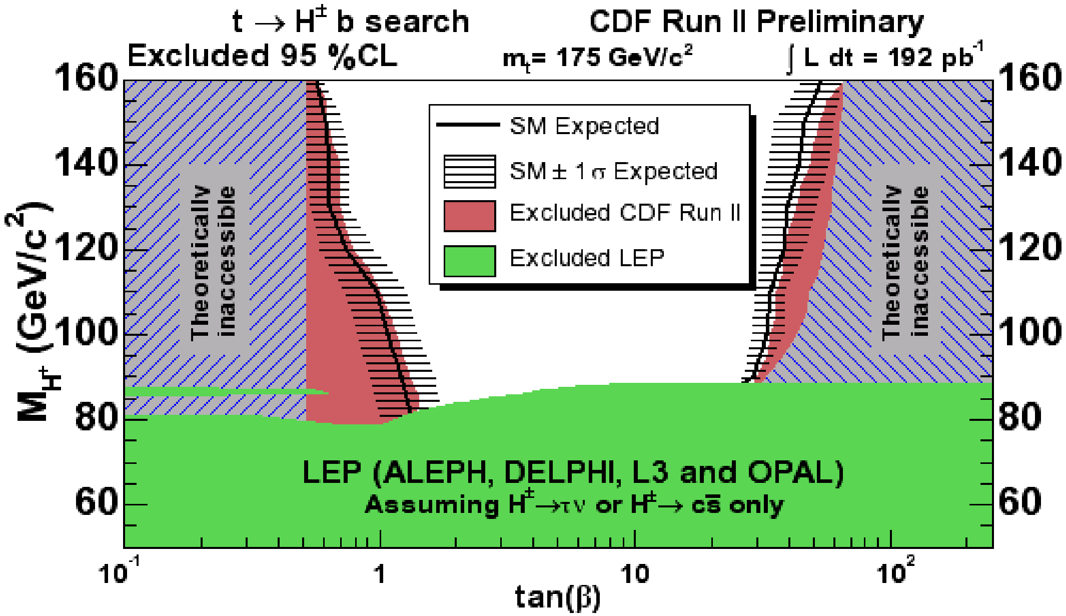


Results

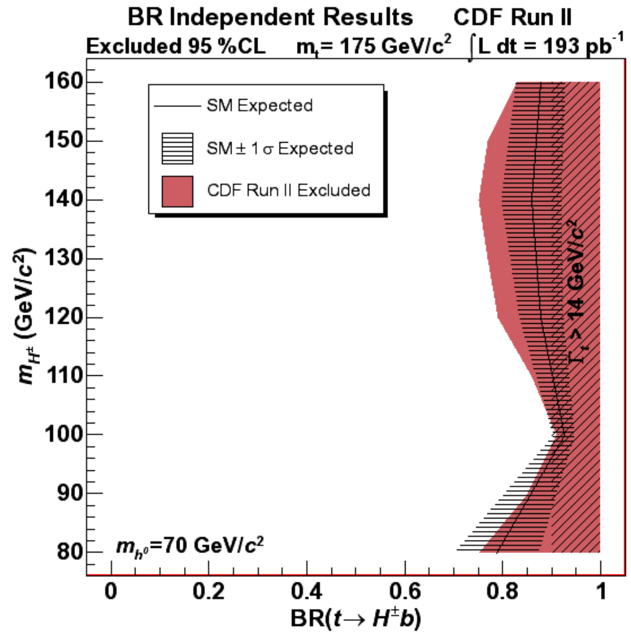
hep-ex/0510065
Accepted by PRL

- The data is consistent with SM prediction

Implications for MSSM:



Limit without assumption on H^+ decay BR:



M_{SUSY} =1000 GeV/c^2, μ=-500 GeV/c^2, A_t=A_b=2000 GeV/c^2, A_τ=500 GeV/c^2

M_1=0.498*M_2, M_2=M_3=M_Q=M_U=M_D=M_E=M_L=M_{SUSY}

Top Quark Charge

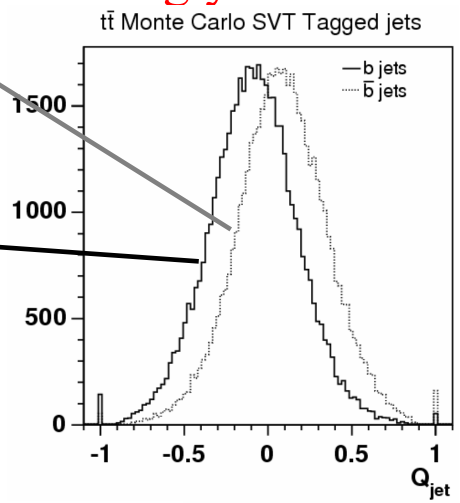
- The SM top quark charge is +2/3
- In some models there is an exotic quark (t'') that appears top-like but has a charge of -4/3
  - i.e. decay is $t'' \to W^- b$ rather than $t \to W^+ b$
  - the "real" top quark in this model is too massive to have been observed
- Can measure the charge by summing the charge of final-state lepton with that of "correct" *b* jet
  - in lepton plus jets events, use constrained kinematic fit to decide which *b* jet is correct
  - *b* jet charge measured by p_T-weighted sum of track charge within jet cone
- To enhance S/B and reduce combinatorics, two *b*-tagged jets are required

Top Charge Results

- Jet charge measurement is correlated with *b* flavor
  - but not strongly!

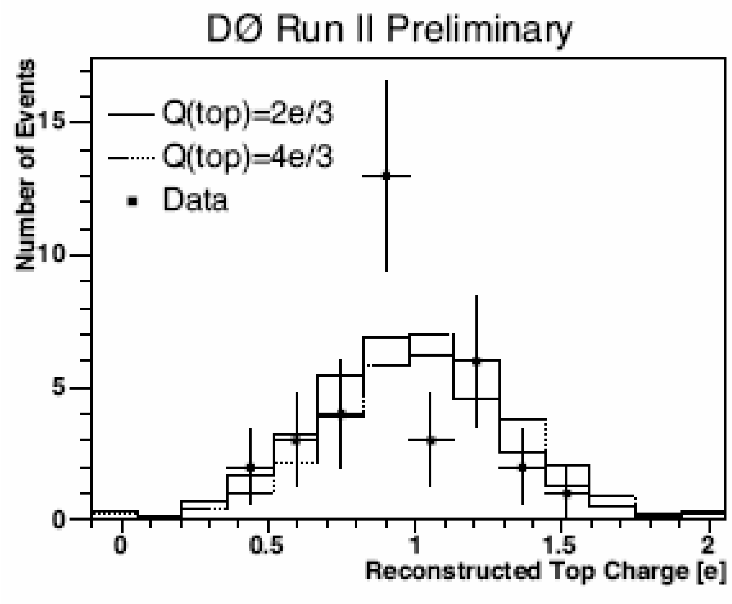
MC $\bar{b}$ jets

MC b jets



- Performance is calibrated using $b\bar{b}$ data
  - corrected for kinematic differences between $b\bar{b}$ and $t\bar{t}$

- Data favors $Q = +2/3$: (370 pb^{-1})



-4/3 hypothesis ruled out at 94% CL using likelihood ratio

Summary

- We are entering the era of precision measurements of the nature of the top quark
- Techniques have been fully developed for measuring the top quark decay structure, branching ratios and charge
- Initial measurements show no deviation from SM
- Due to excellent (and improving) Tevatron luminosity, our sample is growing rapidly
  - the fb^{-1} era begins this year!
- At the Tevatron, many results will improve simply due to increased statistics
  - controlling systematics well enough to take advantage of LHC-era statistics will be a major challenge