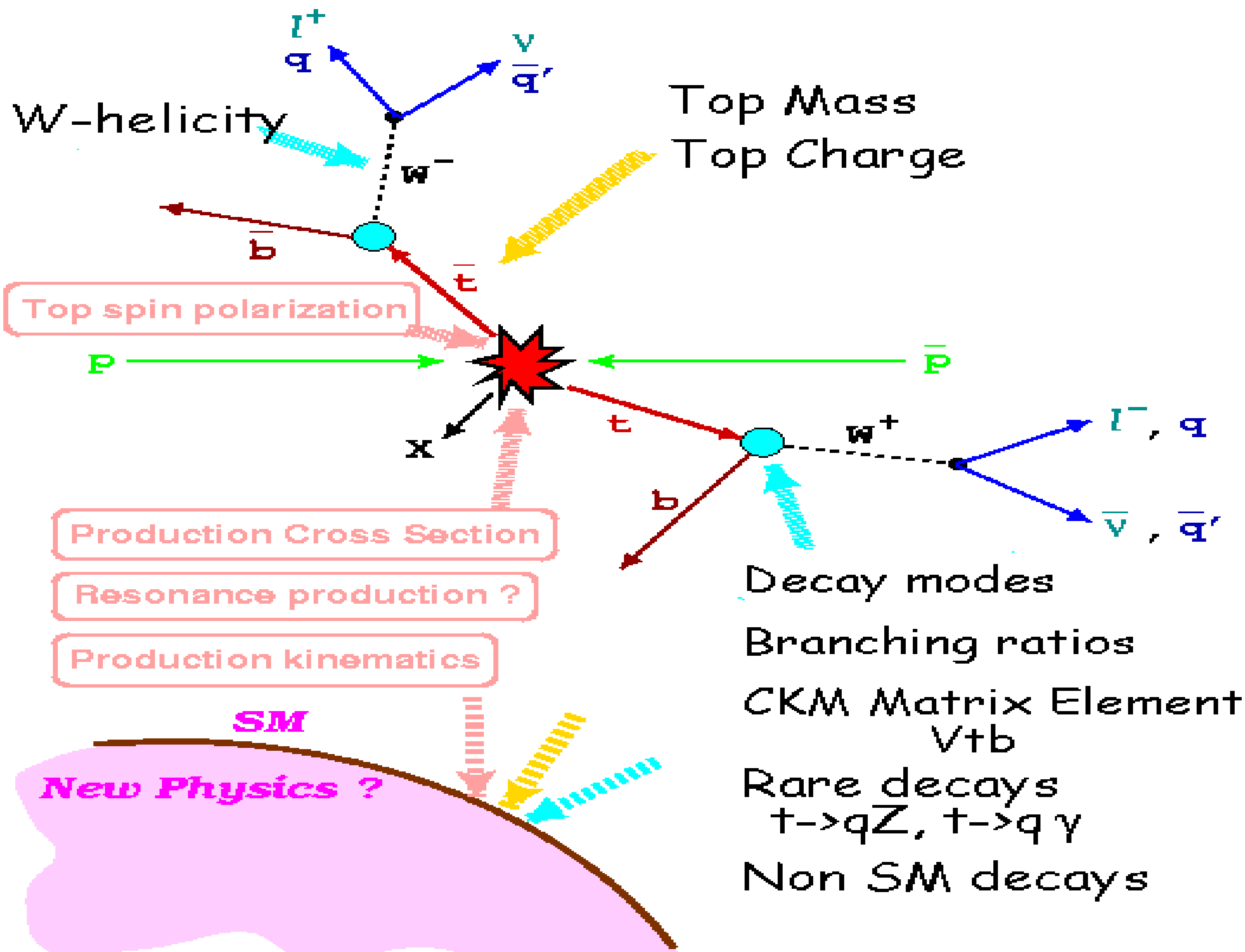
Properties of the Top Quark
XXXII SLAC Summer Institute



Stockholm University - C. Clement - on behalf of CDF and D0 Collaborations

INTRODUCTION

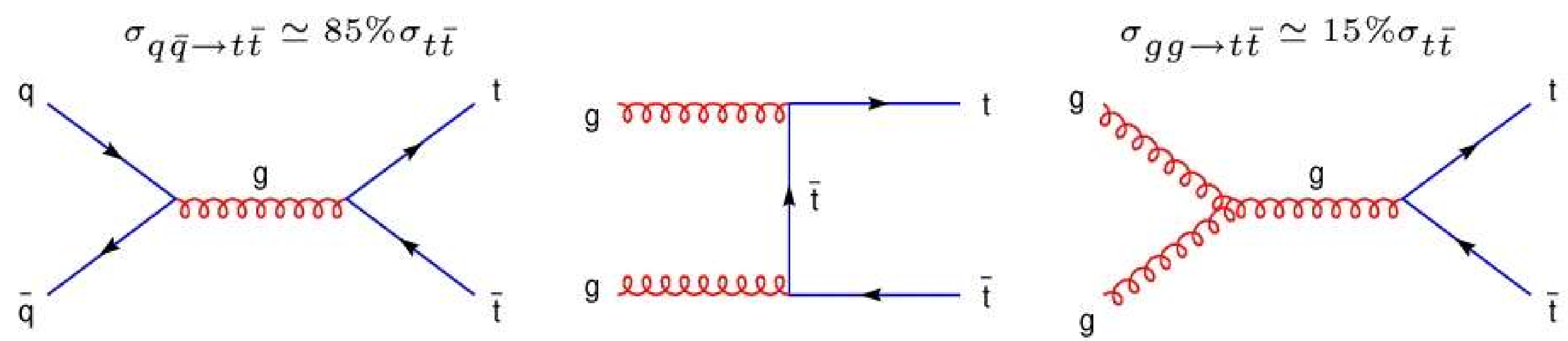
- The top quark was discovered by the CDF and D0 collaborations at Fermilab in 1995, after 15 years of search by many experiments.
- Its mass was measured as well as several of its properties but with large uncertainties.
- RunII of Tevatron is producing significantly larger data sets.
- The properties of the top quark can be measured now with greater accuracy. Some properties have not been measured at all in Run I.
- Is the particle observed at 175GeV/c^2 the Standard Model top quark or

  Is there anything exotic about the top quark?
- There is actually something special about the top quark:

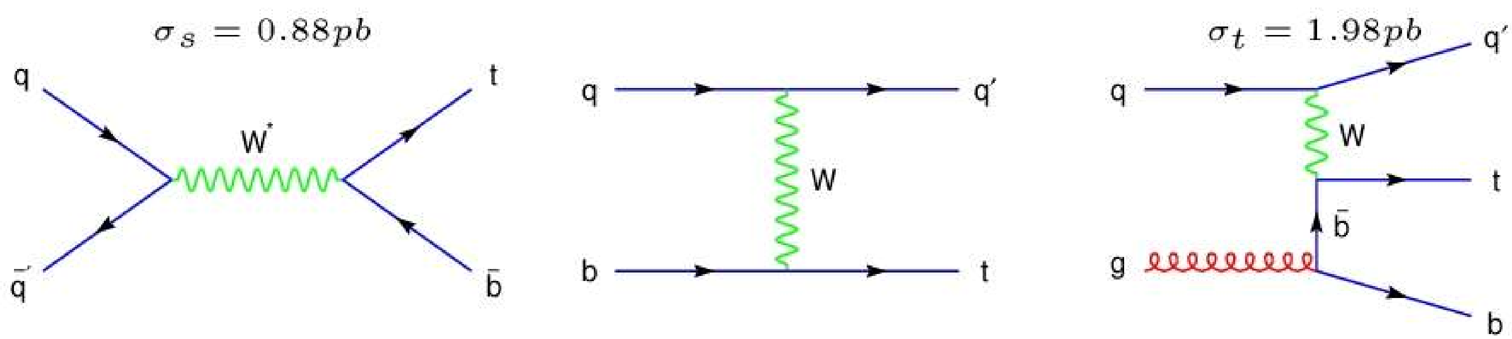
  its high mass (0.5/1.5/4.5/175 GeV for the 4 heaviest quarks....)

Top Quark Production

- At Tevatron top quarks are mostly produced in pairs via strong interaction:



- Single top production is also allowed via the weak interaction



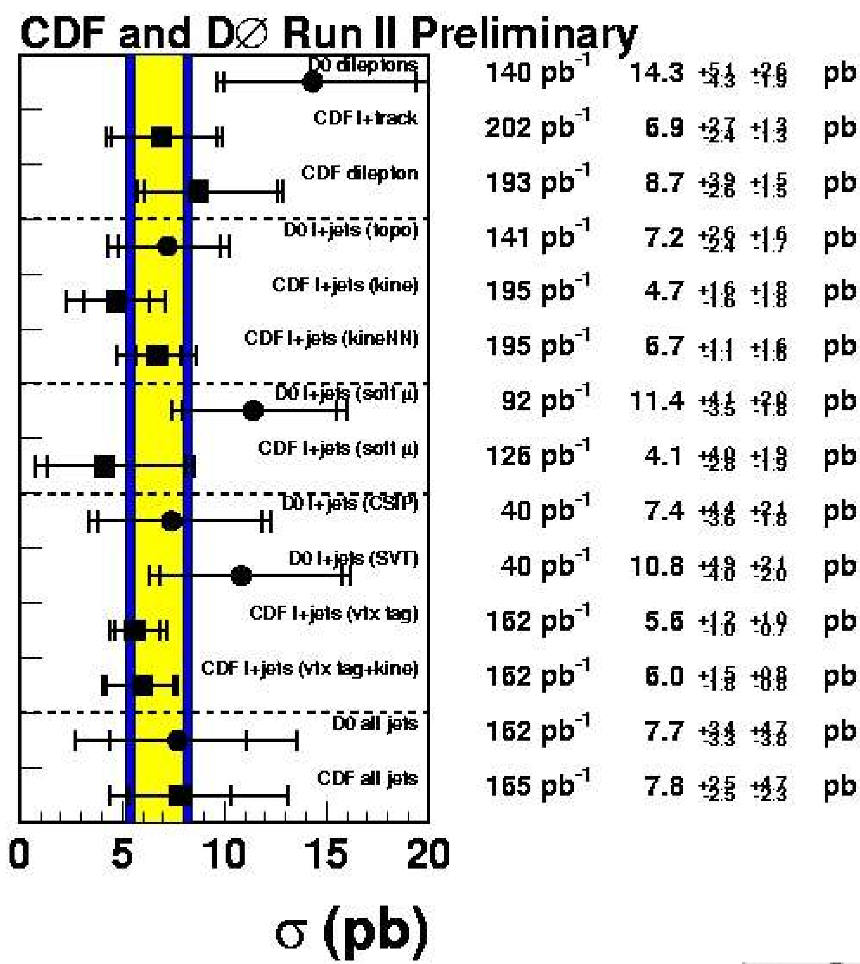
- Single top production has not been observed yet, mainly due to much larger backgrounds than top quark pair production.

The **top production cross section** can be theoretically derived from:

the top mass, PDFs and QCD.

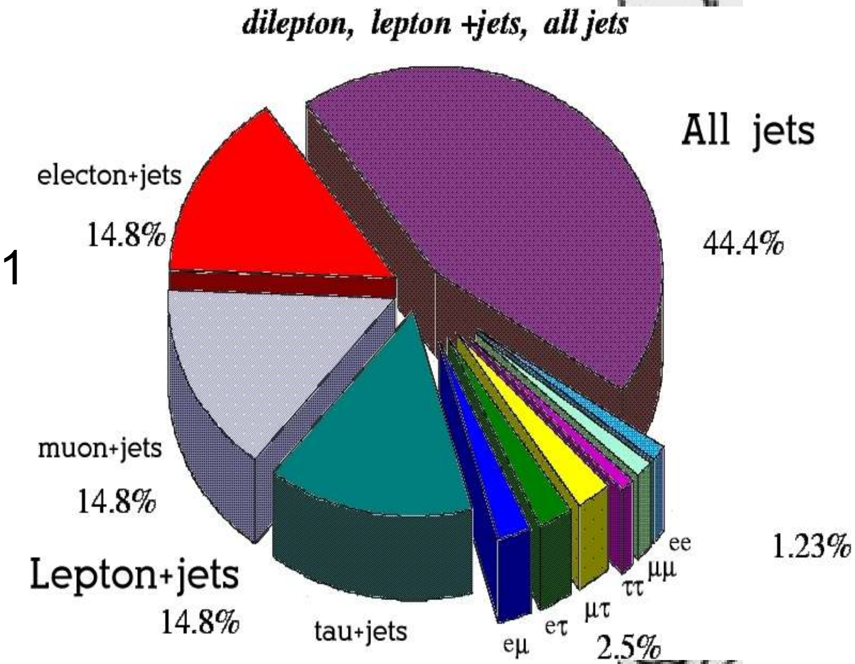
Cross section measurements also rely on the assumption that 100% of the top quarks decay into Wb

- Cross section is sensitive to
  - Non-W top quark decays
  - Small value of the CKM matrix element Vtb,
  - New production mechanism ie additional source of top quarks beyond the standard model



Top Quark Decays

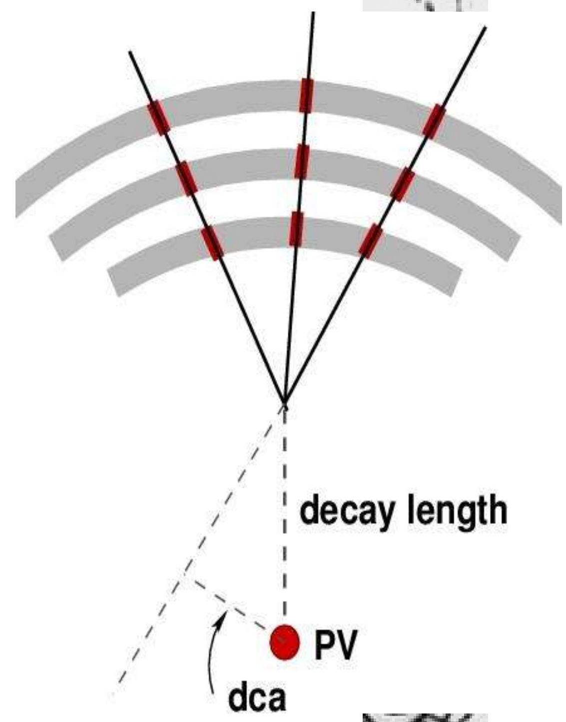
- Within the Standard Model the top quark decays into a real W boson and a b-quark $t \rightarrow Wb$.
- <u>This makes two assumptions</u>
  - There are no "non-W" top decays
  - The CKM matrix element $|V_{tb}|$ is close to 1



- The CKM matrix tells us what decay to expect. But we cannot predict its elements except using unitarity, the assumption of 3 quark families and the already measured matrix elements.
- The Vtb, Vts, Vtd coefficients are not measured directly but are derived from other matrix elements using the above assumptions.
- With these assumptions $|V_{tb}|$ is very close to unity with the corrolary that $B(t\rightarrow Wb)/B(t\rightarrow Wq) = |V_{tb}|^2/(|V_{td}|^2+|V_{ts}|^2+|V_{td}|^2) = 1$

MEASURING B(t→Wb)/B(t→Wq)

- CDF and D0 are equipped with silicon tracking devices that allow to "tag" a jet coming from the hadronization of a b-quark
- Uses the long lifetime of b-mesons.
- The ratio of top events with 1 and 2 b-tagged jets is determined entirely by:
  - the probability to find a b-tagged jet from t→Wb
  - The ratio B(t→Wb)/B(t→Wq)



- CDF looks at the ratio of single to double b-tagged top events on 108pb^{-1} of data and finds in RunII $B(t\to Wb) = 0.54^{+0.49}_{-0.39}$

  A D0 measurement of this ratio is also in the pipeline.

  In RunI B(t→Wb) was measured using SLT and dilepton, $|Vtb|=0.97^{+0.16}_{-0.12}$

NON-W TOP QUARK DECAYS

All top quark properties are measured in events with a pair of top quarks. This is our available top sample.

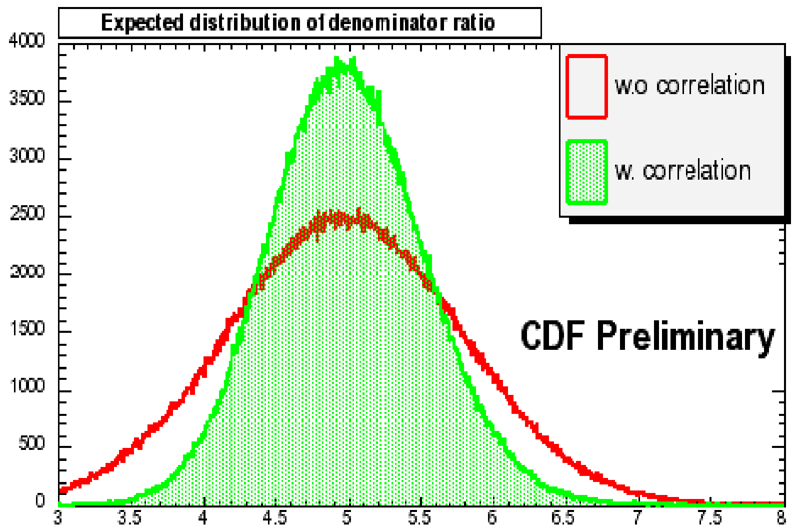
- If top decays exclusively to W bosons then the fraction of final states with 1, resp. 2 leptons is determined by the well known W branching fractions.
- Ratio of single to dilepton top decays would be sensitive to the presence of for ex $t \rightarrow H^{+}b$
-

CDF has measured the ratio R of single to dilepton with 125pb^{-1}

It is potentially a more precise measurement than the cross section itself if one makes sure that some uncertainties cancel out.

The Stamdard Model predicts R = 1

CDF result: $R_{?} = 1.45^{+0.83}_{-0.55}$



Ratio of single to dilepton acceptance

RARE DECAYS

- The Standard Model predicts very small rates for FCNC decays of the top quark such as $t \to q\,Z$ and $t \to q\,\gamma$
- Any observation of these processes would be clear evidence of new physics

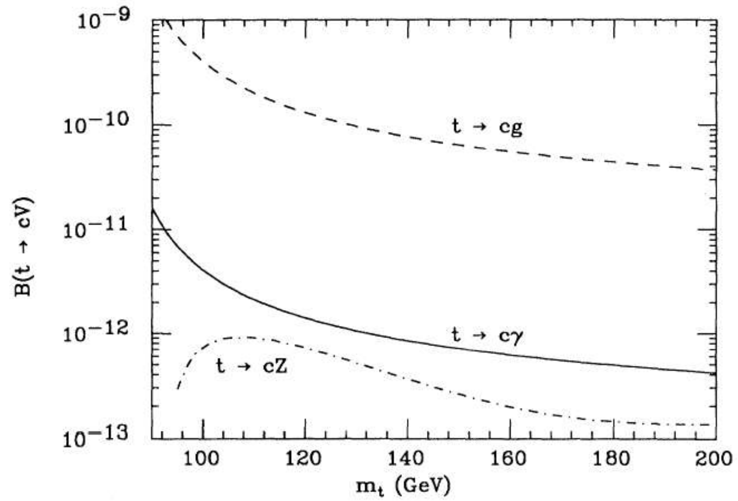


FIG. 2. $B(t \to cV)$ as a function of m_t in the SM. The dashed curve denotes the process $t \to cg$, the solid curve $t \to c\gamma$, and the dashed-dotted curve $t \to cZ$.

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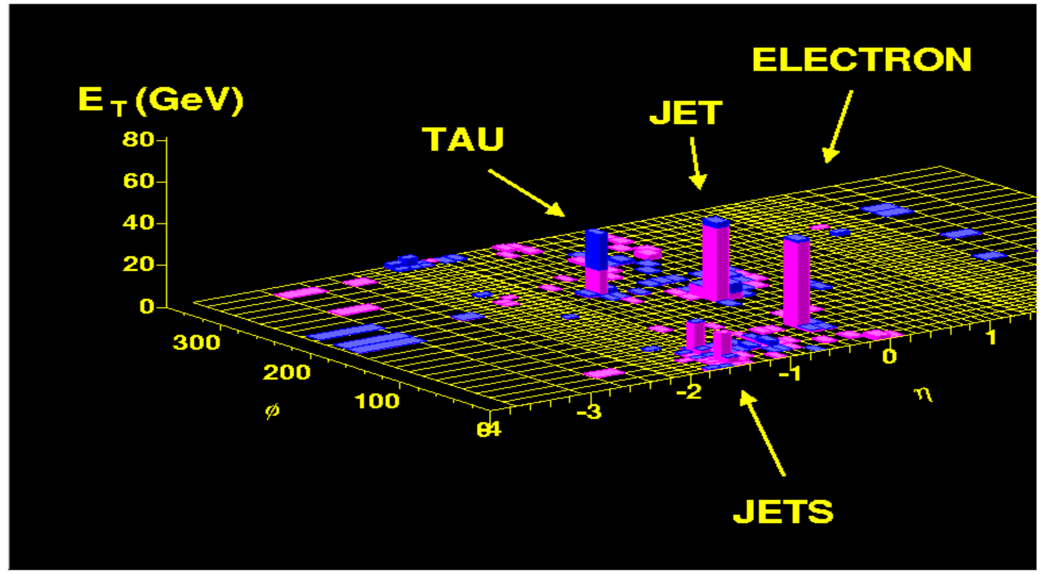
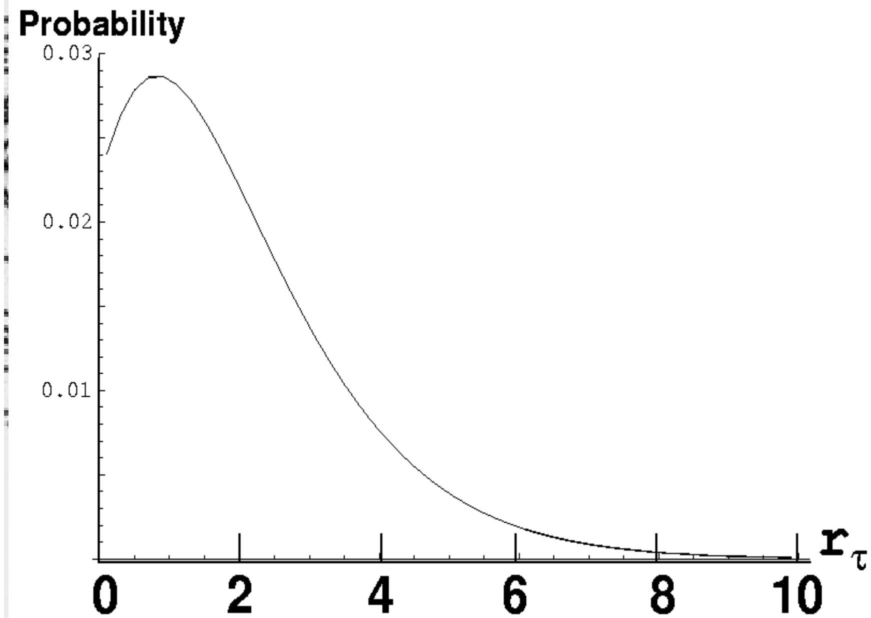
- Using Run I data CDF has derived limits on $t \to q\,\gamma$ and $t \to q\,Z$ processes
- For the $t \to q\,\gamma$ final states where the W decays leptonically are looked for. Signature: missing E_T, γ, lepton and 2 jets
- For the $t \to qZ$ final states where the W decays hadronically are considered. Signature: 2 leptons and 4 jets
- $B(t \to q\,\gamma) < 3.2\%$ at 95% CL and $B(t \to q\,Z) < 33\%$ at 95% CL ($\sim 110\,pb^{-1}$)

- Test of lepton universality,
- Search for new physics (2 Higgs doublet models...)
- In MSSM with high tan β, $t \rightarrow H^+b$ may dominate over t– Wb





For high tan β $H^+ \rightarrow \tau^+\nu$ is dominant

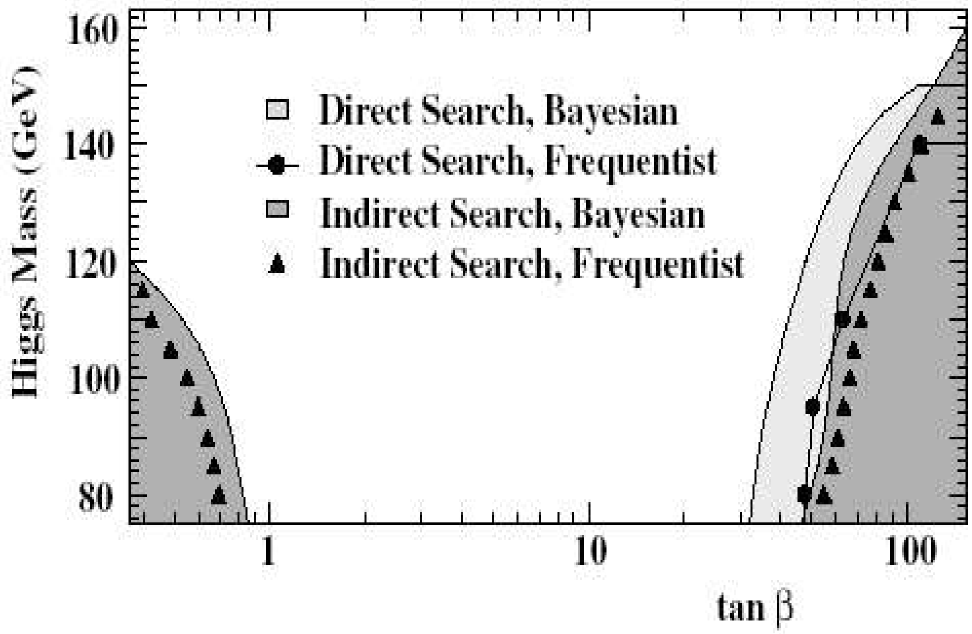
Standard model decay of top

$tt \rightarrow W^+W^-bb \rightarrow \tau^+ \tau^-$ b b+missing E_T

CDF RunII looks for events where one τ decays leptonically and the other hadronically and place an upper limit on the ratio of observed $t \rightarrow \tau$ over the number of predicted $t \rightarrow \tau$

$r(\tau) = B(t \rightarrow \tau;\ \text{observed})/B(t \rightarrow \tau;\ \text{SM}) < 5.0$ @ 95% C.L. ($193\,pb^{-1}$)

In RunI CDF and D0 searched for charged Higgs in decays of the top quarks



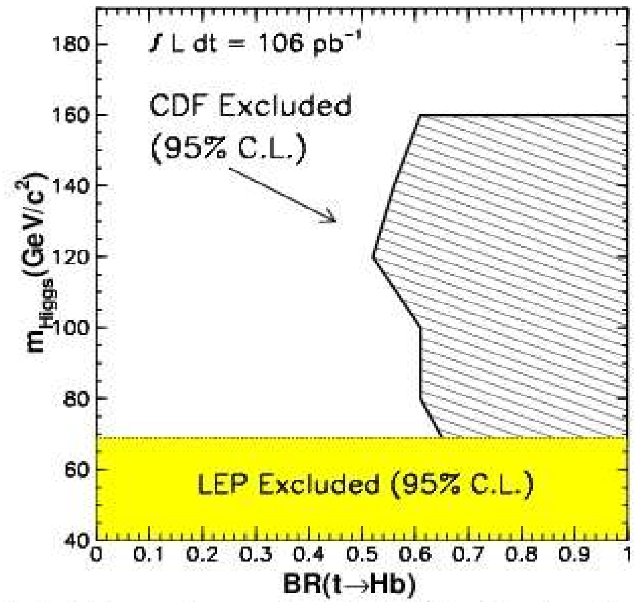
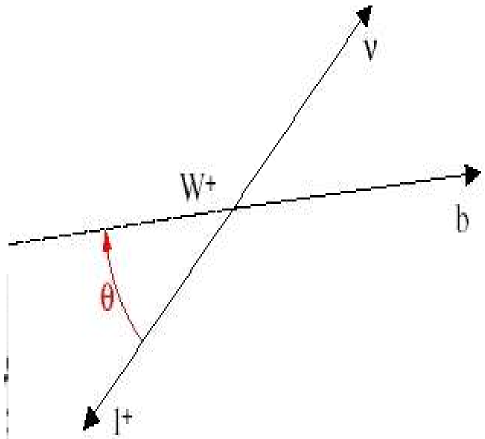


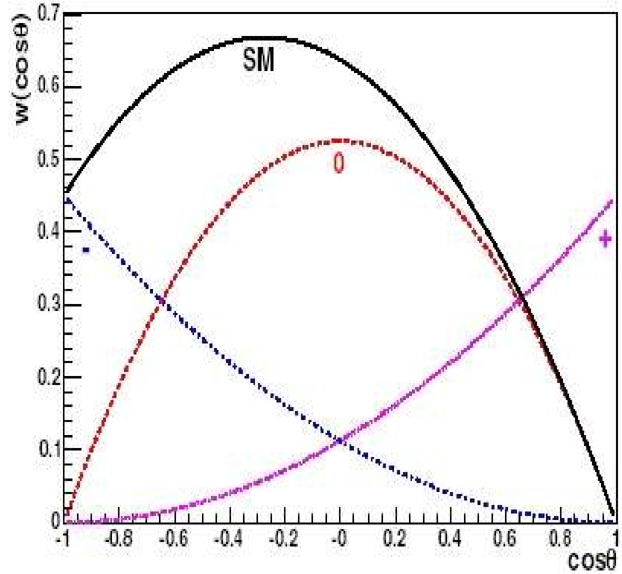
FIG. 6. The region excluded at 95% C.L. for charged Higgs production versus the branching ratio for top decay into H^+b.

D0 Collaboration, Phys. Rev. Lett. **88**, 151803

CDF Collaboration, Phys. Rev. D**62** 012004

W Helicity in Top Decays





In the Standard model the decay of the top quark is described by the V-A charged current interaction.

Only left-handed W_- and longitudinal W_+ may be produced

Given the mass of the W boson and top quark the fraction F_0 of longitudinally polarized W is predicted to be ~0.70, while F_- should be ~0.30

Any V+A structure of the interaction would yield $F_+ \neq 0$ and $F_- < 0.3$

If θ is the angle between the lepton and the direction of flight of the W in the W-rest frame then cos θ allows to discriminate between the various polarizations.

<u>Method:</u> fit cos θ templates obtained for left-handed, right-handed and longitudinally polarized W bosons to the observed distribution of cos θ

LEPTON P_T SPECTRA AND W-HELICITY

The lepton from W_- is emitted antiparallel to the W boost

The lepton from W_0 is emitted perpendicular to the W boost

=> The W_0 lepton will have harder pT spectrum than in W_-

This method is used in the CDF analysis of Run II data.

The results at 200pb^{-1} are

<u>l+jets</u>

F_0 = 0.88+0.12-0.47 or

F_0 >0.24 @ 95%C.L.

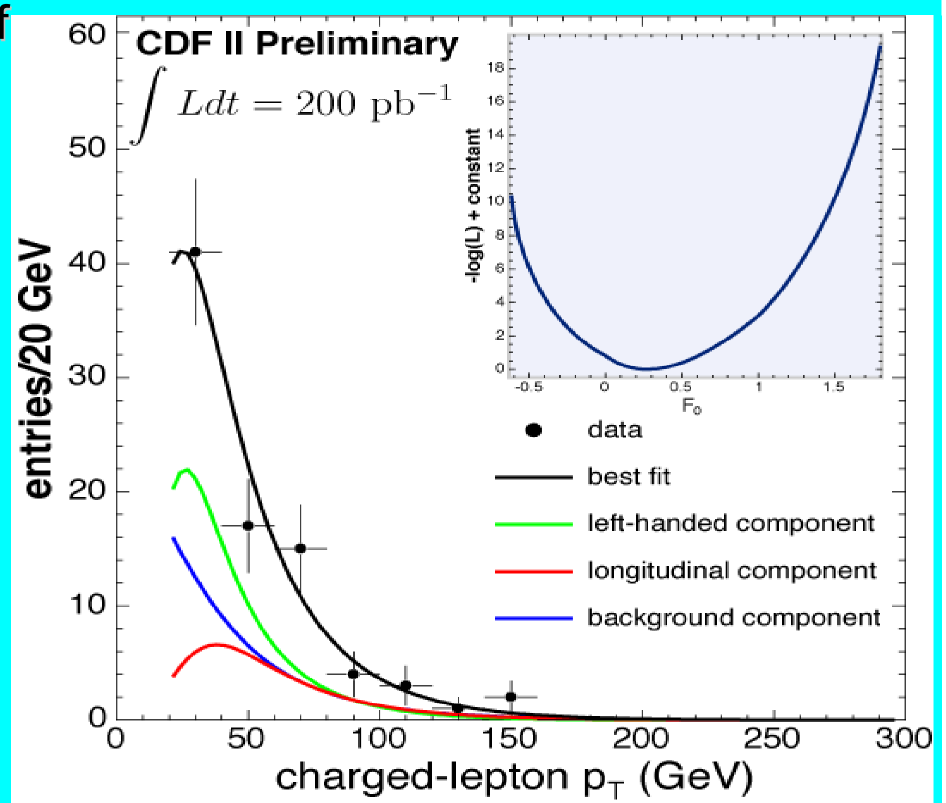
<u>Dilepton sample</u>

F_0 < 0.52 @ 95%

<u>Combined</u>

F_0=0.27 +0.35 -0.24 (stat.+syst),

F_0 < 0.88 @ 95% CL



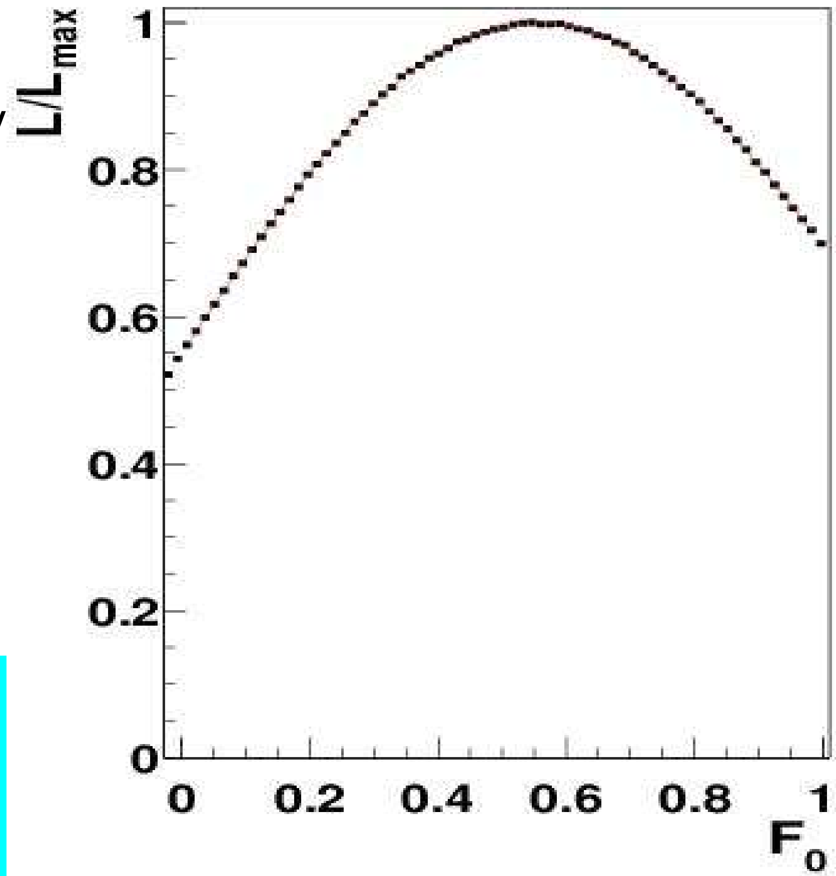
W Helicity and Matrix Element Method

- Use the probability density function for observing a given set of observables in ttbar events for a given value of F_0.
- The probability density function is dependent upon the fraction of longitudinally polarized W bosons.
- The probability density is given by the matrix element of the ttbar process, parton distribution functions and phase space.

- The chosen observables are
  - **the 2 top quark invariant masses,**
  - **the 2 W bosons invariant masses,**
  - **the energy of one of the quark from W decay.**

- This method is applied to the lepton+jets channels, where at least four jets are present in the final state: 12 combinations.

- Take all combinations and weight them with their probability to occur, the probability being given by the probability density function described above.
- Weight also events w.r.t. to how well measured they are.
- Similar technique provided the best top mass measurement so far.



likelihood as function of F_0

Only 22 events after all selections

<u>D0 RunI result</u>

F_0= 0.56+/-0.31(stat+m_{top})+/-0.07(syst)

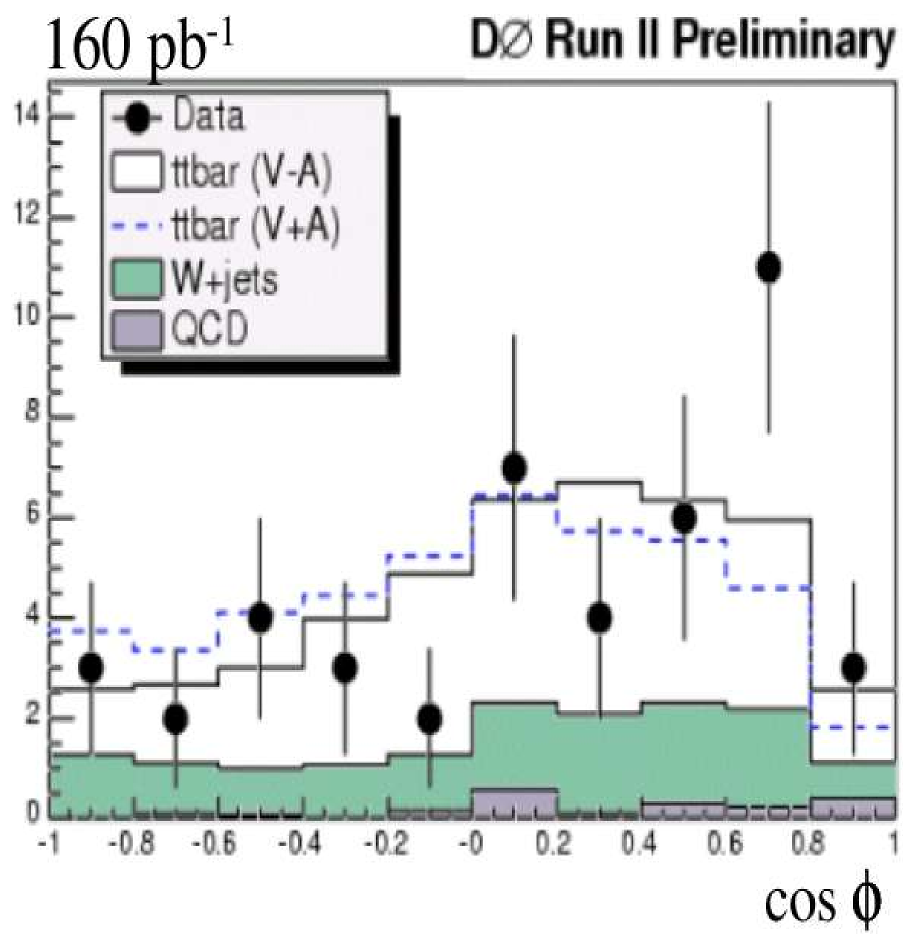
(hep-ex/0404040)

<u>CDF RunI result</u>

F_0 = 0.91+/-0.39 (stat+syst)

W HELICITY WITH COS Θ TEMPLATES

- D0 RunII W helicity analyses
  - Use l+jet channels
  - One topological analysis
  - One b-tagging analysis
  - Will be combined
  - Fit templates of cos θ for various F_+ while F_0 is kept fixed to its standard model value.
  - Fit both F_+ and background fraction.
  - Results for ICHEP



SPIN CORRELATIONS

The top quark decays as a free quark, since its lifetime is ~ 5.10^{-25} s

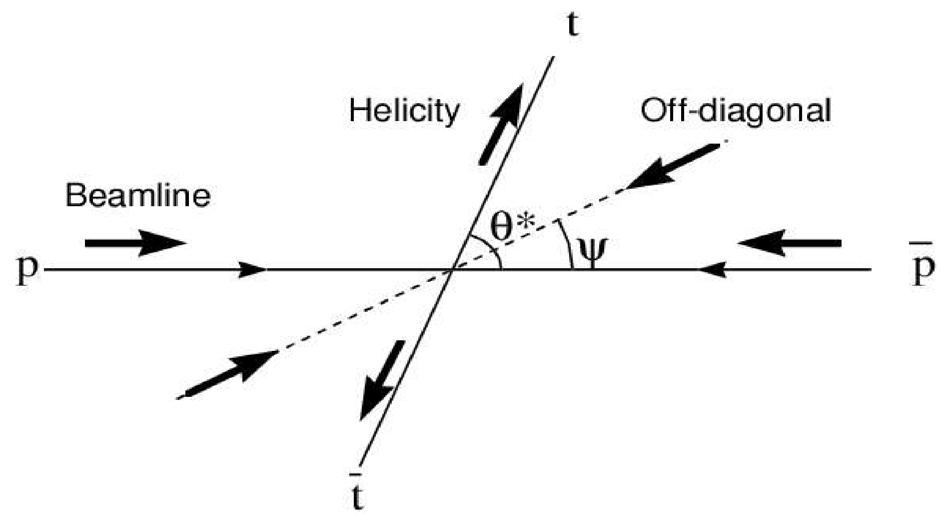
<u>The top quark decays before it hadronizes.</u>

For all other quarks the spin information of the initial quark is lost due to the hadronization.

The pairs of top quarks produced at Tevatron are unpolarized but the spin of the two top quarks are correlated.

The spin is transmitted into the daughter particles of the top quarks.

A measurement of the correlation and its consistency with the Standard model is a is a test of the production mechanism.



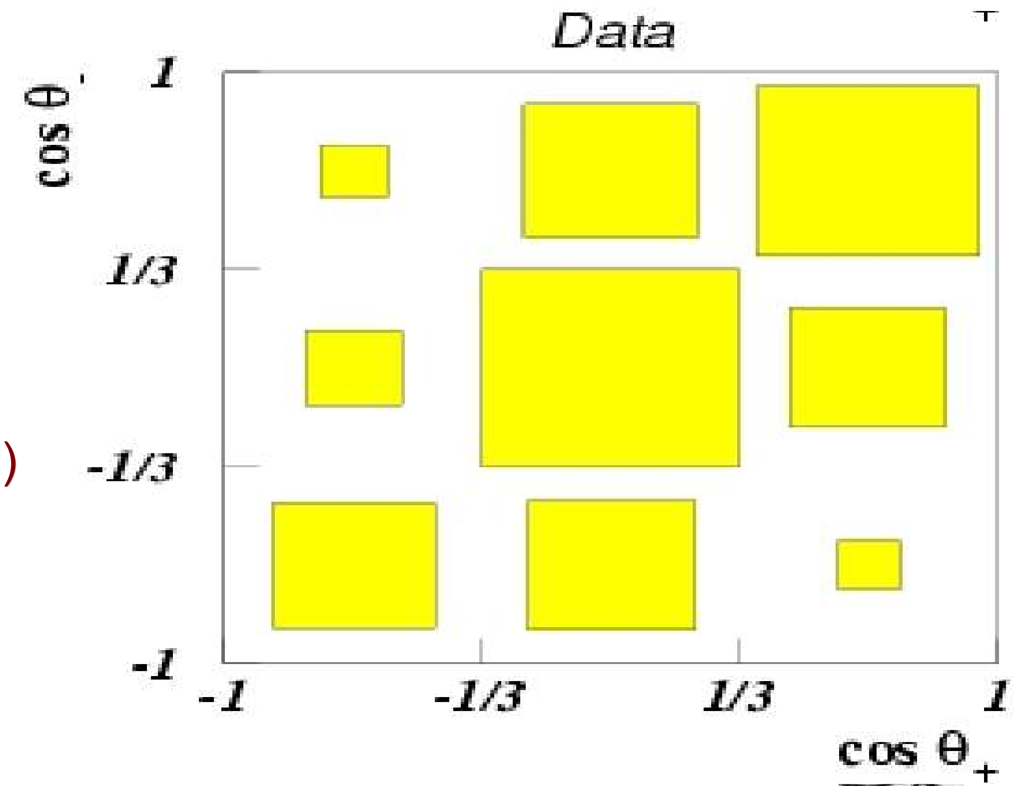
The sensitivity is highest when the daughters are **charged leptons or down-type** quark. D0 makes use of dilepton final states. Choose the “off-diagonal” basis.

D0 makes use of dilepton final states.

Chose the “off-diagonal” basis along which like-spin rate vanishes.

$\tan\psi = \beta^2 \sin\theta^* \cos\theta^* / (1 - \beta^2 \sin^2\theta^*)$

In this basis the standard model predicts $\kappa = 0.88$



3C fit with top mass and weight each the 4 neutrino solutions.

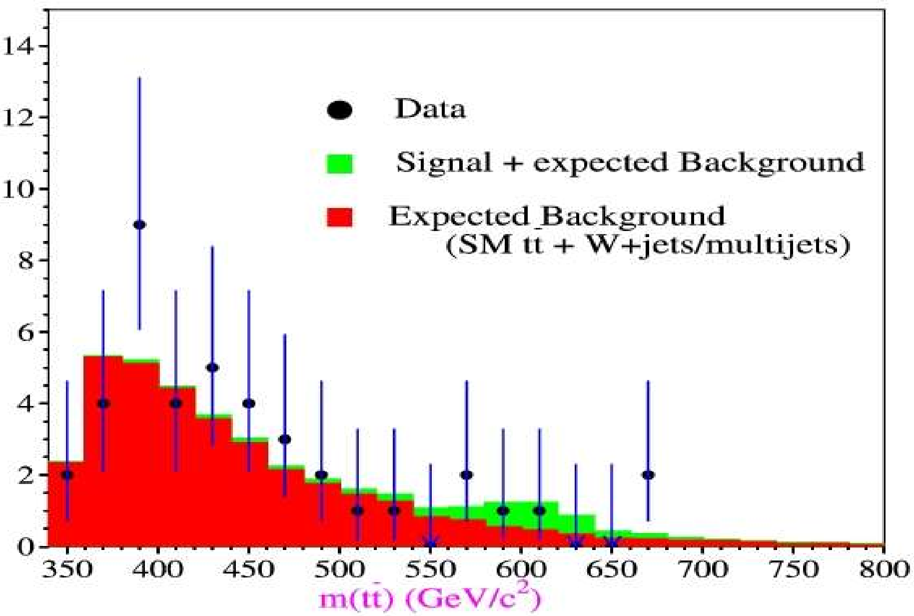
Binned likelihood fit to the observed distribution of ($\cos\theta^+$, $\cos\theta^-$)

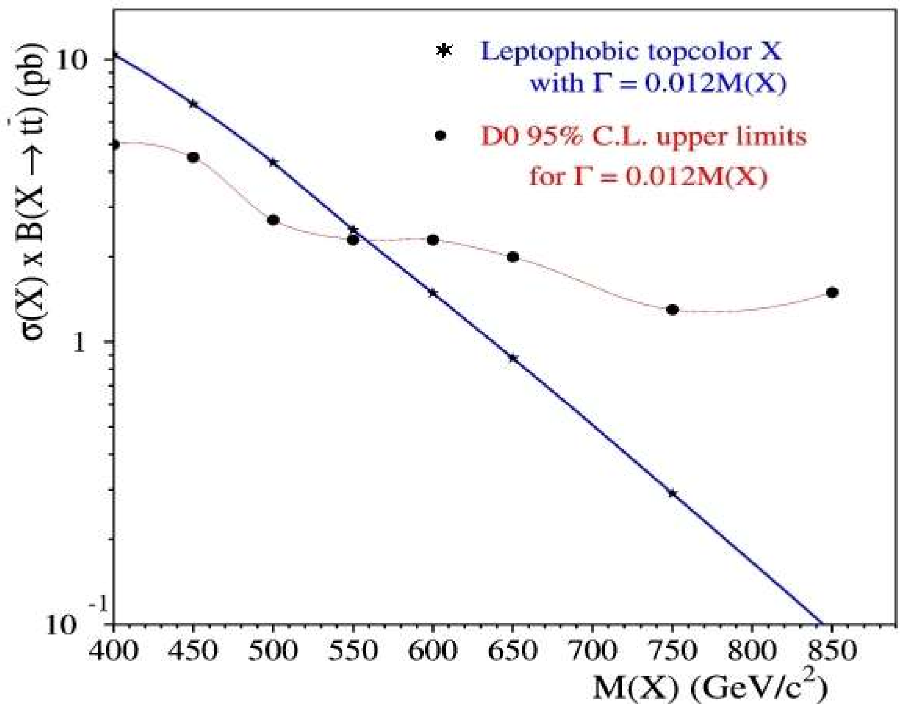
D0 measured κ using 125pb^{-1} of data from Run I.

$\kappa > -0.28$ @ 68%C.L.

Search for Top-anti-top Resonances

- Search for a narrow resonance in the invariant mass distribution of top pairs
- D0 uses its lepton+jets sample from RunI ($130pb^{-1}$)
- Combine topological and SLT analyses.





Search that is sensitive to X->tt, Z'->tt

Results

D0 M_x >560GeV/c^2 (accepted PRL)

CDF M_x>480GeV/c2 PRL85,256,2000

EXPECTATIONS FROM RUN II OF TEVATRON

- Tevatron is doing well, expect 4-7pb^{-1} from RunII
- Assume 2fb^{-1} and combine CDF and D0
- Expected precision on
  - Cross section ~ 9%
  - Single top cross section ~20%
  - $\sigma(ll)/\sigma(l+jets)$ ~12%
  - |Vtb| from B(t->Wb)/B(t->Wq) > 0.25
  - |Vtb| from single top ~12%
  - Γ_t from single top 25%
  - B(t->γq) <2.10^{-3}
  - B(t->Zq) < 0.02
  - Helicity fractions F^0 and F^+ with precisions of 0.09 and 0.03

Conclusion

- After pioneering measurements, precision measurements of the top quark properties are ramping up,
- This is made possible thanks to the upgraded Tevatron and the large amount of new data
- Advance techniques are in place to provide enhanced results.
- Very interesting period since the top quark might be coupled to new physics in many ways
- Number of properties not mentionned in this talk such as measurements of the top charge, width, anomalous kinematic,...
- Lots of new results are in the pipeline both from CDF and D0 which are pending collaboration approvals...