Top Quark Properties results and ongoing analyses at CDF

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on behalf of the CDF collaboration

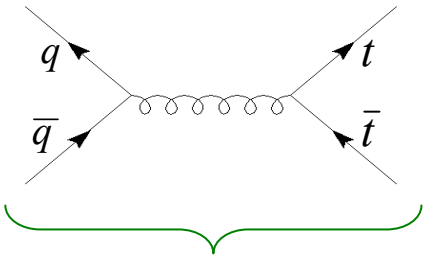
Fermilab's Tevatron

- Currently the highest energy particle accelerator in the World
  - Proton-antiprotons beam
- 2 multi-purpose detectors
  - D∅ and CDF
- Run I (1992-1996)
  - $\sqrt{s}$ = 1.8 TeV
  - Discover top quark in 1995!
  - Integrated luminosity 120 pb^{-1}
- Run II (2001-present)
  - $\sqrt{s}$ = 1.96 TeV
  - Integrated luminosity by April, 05:
    - Analyzed up to ~350 pb^{-1}
    - In tape ~600pb^{-1}

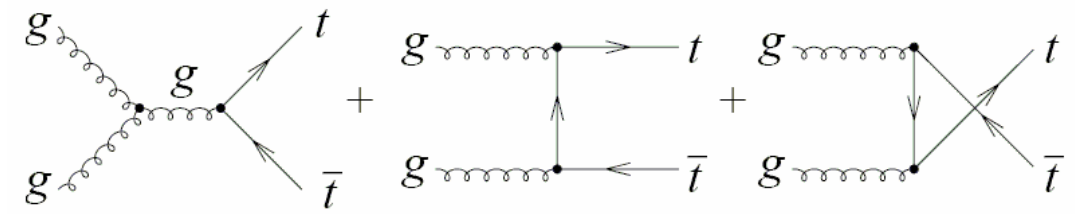
This talk about CDF
Collider **D**etector at **F**ermilab

Top Quark Production at the Tevatron

- **produced in pairs** via the strong interactions.



~85%

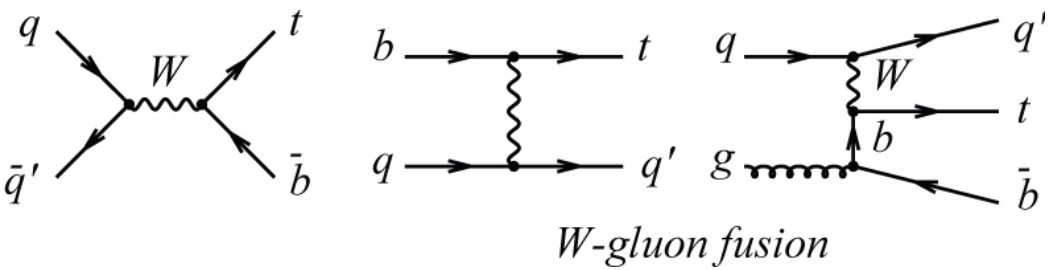


~15%

$$\sigma(\bar{p}p \to t\bar{t} \,@\, M_{top} = 175 GeV) \approx 6.7 \text{ pb}$$

one top pair event every 10^{10} inelastic collisions

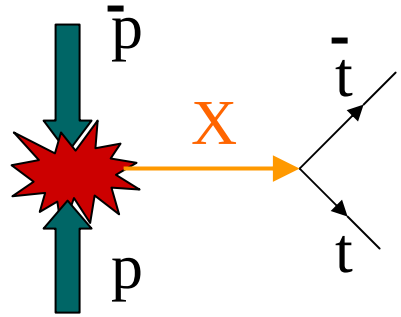
- **single produced,** in association with other particles



W-gluon fusion

$$\sigma(\bar{p}p \to t + X \,@\, M_{top} = 175 GeV) \approx 3 \text{ pb}$$

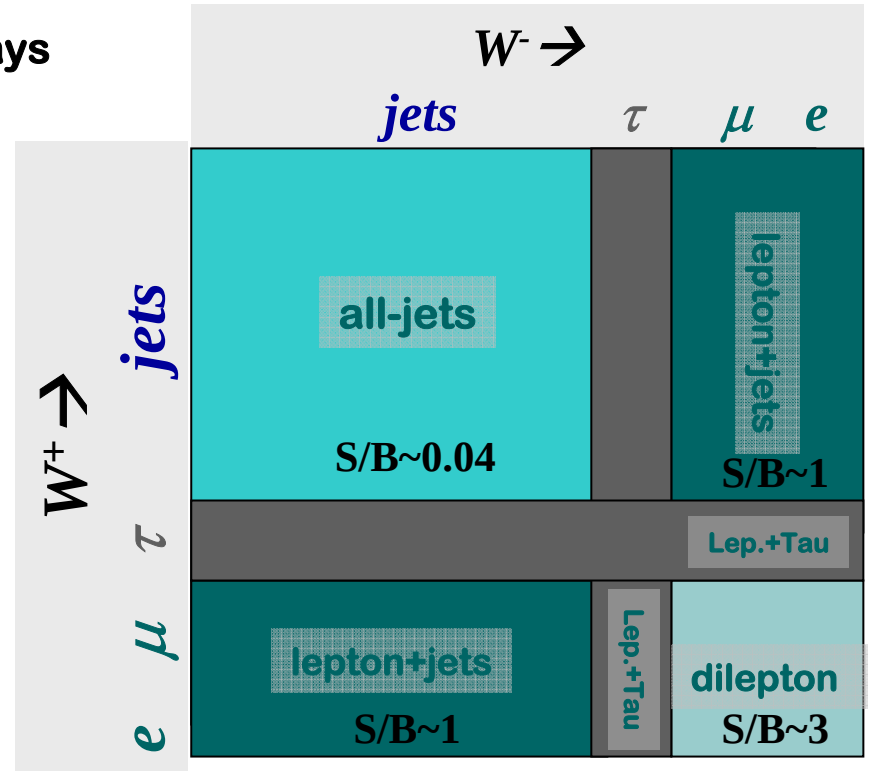
- **Through resonances ??**



- **Topcolor-assisted Technicolor**

ttbar final states

- In the SM the BR(t→Wb) >0.99 @95%CL
- Final state is given by W^+ and W^- decays
  - All Hadronic channel
    - Large BR
    - Small S/B
  - Lepton (e,μ) + Jets channel
    - Second large BR
    - Good S/B
    - overconstrained kinematics
  - Dilepton channel
    - BR is ¼ of L+Jets
    - cleanest channel
    - underconstrained kinematics
  - Lepton + Hadronic Tau channel
    - Very small BR
    - S/B~1
- Production cross section measured in all these channels
  - (See Petra Merkel's talk, tomorrow)



Can we measure BR(t→Wb) ?

Measurement of BR(t→Wb)/BR(t→Wq)

- **Indirect measurement using the CKM matrix :**
  - Elements $|V_{ub}|$ and $|V_{cb}|$ are measured from the decay of B mesons to be very small.
  - Assuming unitarity and only three generations $|V_{tb}|$ is expected to be 0.998@90 %CL
- **With top quarks at hand we can measure it directly :**
  - we measure R, defined as

$$R \equiv \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} \qquad \text{where } q = \{d, s, b\}$$

  - Use the ability to identify jets with a distinguished secondary vertex associated with the b parton .
    - The number of b-tagged jets depends strongly on R and ε_b
  - We classify the ttbar sample based on the number of b-tagged jets
    - The relative rates of events with 0/1/2 b-tags is very sensitive to R

Measurement of BR(t→Wb)/BR(t→Wq)

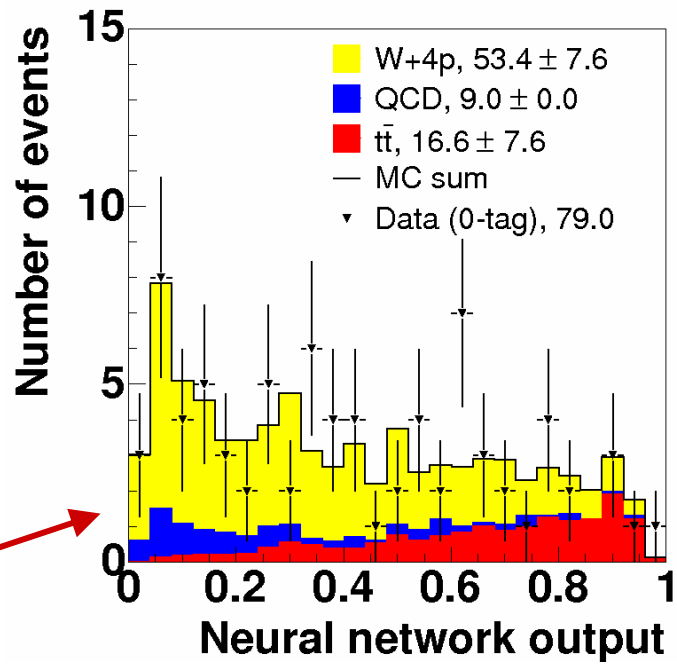
- Use the **Lepton+Jets** and **Dilepton** samples.
  - Total integrated luminosity of 162 pb^{-1}

- **Lepton+Jets** sample requires:
  - Isolated lepton (e,μ) with E_T>20 GeV
  - ME_T>20 GeV
  - at least 4 jets with E_T>15 GeV

- **Dilepton** sample requires :
  - At least two leptons (ee, μμ, eμ) E_T>20 GeV
  - ME_T>20 GeV
  - at least two jets with E_T>15 GeV.

- Classify **both** samples based on the number of 0/1/2 b-tagged jets

- Estimate the background contribution to each of the six sub-samples
  - MC and data driven
  - Background in the Lepton+Jet with 0-tags obtained using NN techniques.

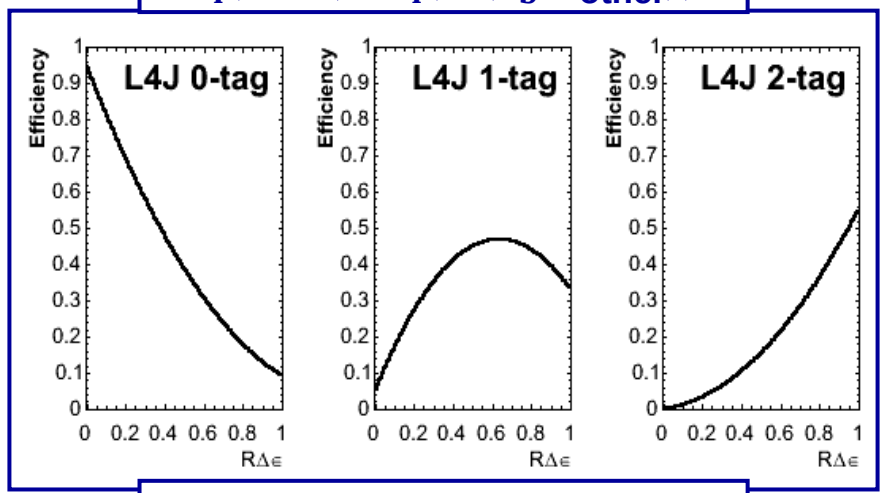


Measurement of BR(t→Wb)/BR(t→Wq)

- In the Dilepton and Lepton+Jets samples analyze the relative number of events with different multiplicity of secondary vertexes, ***i***.

$$N_i^{\exp} = N_{inc}^{t\bar{t}} \cdot \varepsilon_i(R) + N_i^b$$

$\varepsilon_i(R\Delta\varepsilon)=\varepsilon_i(R(\varepsilon_b-\varepsilon_{other}))$



$\varepsilon_b \sim 0.44$, $\varepsilon_{other} \sim 0.04$

- We could assume the production cross section to estimate $N_{inc}^{t\bar{t}}$ and compare different tag bins.

- ***Instead,*** we take the approach of normalizing to the measured cross section

$$N_{inc}^{t\bar{t}} = \sum_i N_i^{obs} - N_i^b$$

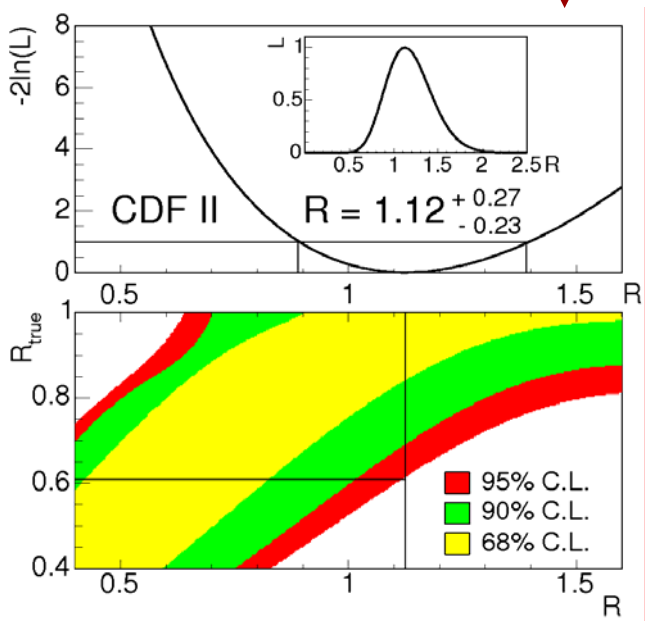
Measurement of BR(t→Wb)/BR(t→Wq)

Lepton + Jets (L+J)	0-tag	1-tag	2-tag
ϵ_i $(R=1)$	0.45 ± 0.03	0.43 ± 0.02	0.12 ± 0.02
ANN background	62.4 ± 9.0	5.8 ± 5.2	$0.1^{+1.0}_{-0.1}$
a priori background		4.2 ± 0.7	0.2 ± 0.1
Total expected	80.4 ± 5.2	21.5 ± 4.1	5.0 ± 1.4
Observed	79	23	5
Dileptons (DIL)	**0-tag**	**1-tag**	**2-tag**
ϵ_i $(R=1)$	0.47 ± 0.03	0.43 ± 0.02	0.10 ± 0.02
a priori background	2.0 ± 0.6	0.2 ± 0.1	< 0.01
Total expected	6.1 ± 0.4	4.0 ± 0.2	0.9 ± 0.2
Observed	5	4	2

Obtain expected events as a function of R

$$N_i^{exp} = N_{inc}^{t\bar{t}} \cdot \epsilon_i(R) + N_i^b$$
$$N_{inc}^{t\bar{t}} = \sum_i (N_i^{obs} - N_i^b)$$

Compare to observed and Maximize the likelihood



Measure R :

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

Set F-C lower limit :

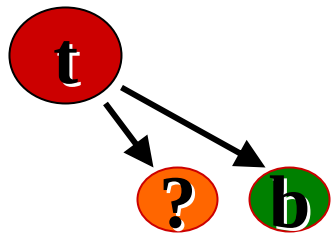
R>0.61 at 95%CL

|Vtb| > 0.79 at 95%CL
(assuming unitarity)

➲ **Mild excess in double b-tags sample drives the R value above 1**

What the results of R implies ?

- **The R result is consistent with the SM.**
- **This means that the top decays to a b quark most of the time, as expected.**



- **But, is ? always a W+ ?**

What the results of R implies ?

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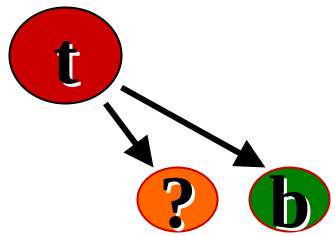


- **But, is ? always a W+ ?**

- **Could ? be sometimes an H^+ ?**

Measurement of BR(t→H±b)

Charged Higgs bosons appear in the context of 2HDM's, like MSSM.

- E.S.B → 5 Higgs bosons; 3 neutral (h^0, H^0, A^0) and 2 charged ($H^\pm$)

  Many new decay channels :

  - $h^0, H^0 \rightarrow bb, \tau\tau, gg, W^+W^-, ZZ, cc$
  - $A \rightarrow bb, \tau\tau, gg, Zh^0$
  - $H^+ \rightarrow t^*b, \tau+\nu, cs, W^+h^0, W^+A$, etc

This analysis assumes H+ may decay to any of these

- The presence of an H+ would affect the relative number of events in each top decay channel, according to its decay. For example :
  - If **H+→τν**, number of events in the **Lepton+Tau** sample would show an excess.
  - If **H+→cs**, number of events in the **Dilepton** and **Lepton+Jets** would show a deficit.

- Top and Higgs BR's unknown. MSSM can predicted them for specific benchmark parameters.

Measurement of BR(t→H±b)

- For each top quark we have 5 possible decay modes
  - t→Wb
  - t→H⁺b→t*b̄b→W⁺bb̄b
  - t→H⁺b→cs̄b
  - t→H⁺b→τνb
  - t→H⁺b→W⁺h⁰b→W⁺bb̄b
- Use the **Dilepton, Lepton+Jets** (1 and 2 or more tags) and **Lepton+TauH** (generically XSA)
- The number of expected candidates N^{exp} is

$$N_{XSA}^{\exp} = N_{XSA}^{back} + \sigma\, \varepsilon_{tt,XSA} \int Ldt \longrightarrow \sim 191\ pb^{-1}$$

from XS meas.

$\sigma^{theo} = (6.7 \pm 0.7)pb$ (hep-ph 0303085)

$$\varepsilon_{tt,XSA} = \sum_{i,j=1}^{5} B_i B_j\ \varepsilon_{i,j\ XSA}\left(wTop, wHiggs, m_{H^\pm}, m_{h^0}\right)$$

from MC

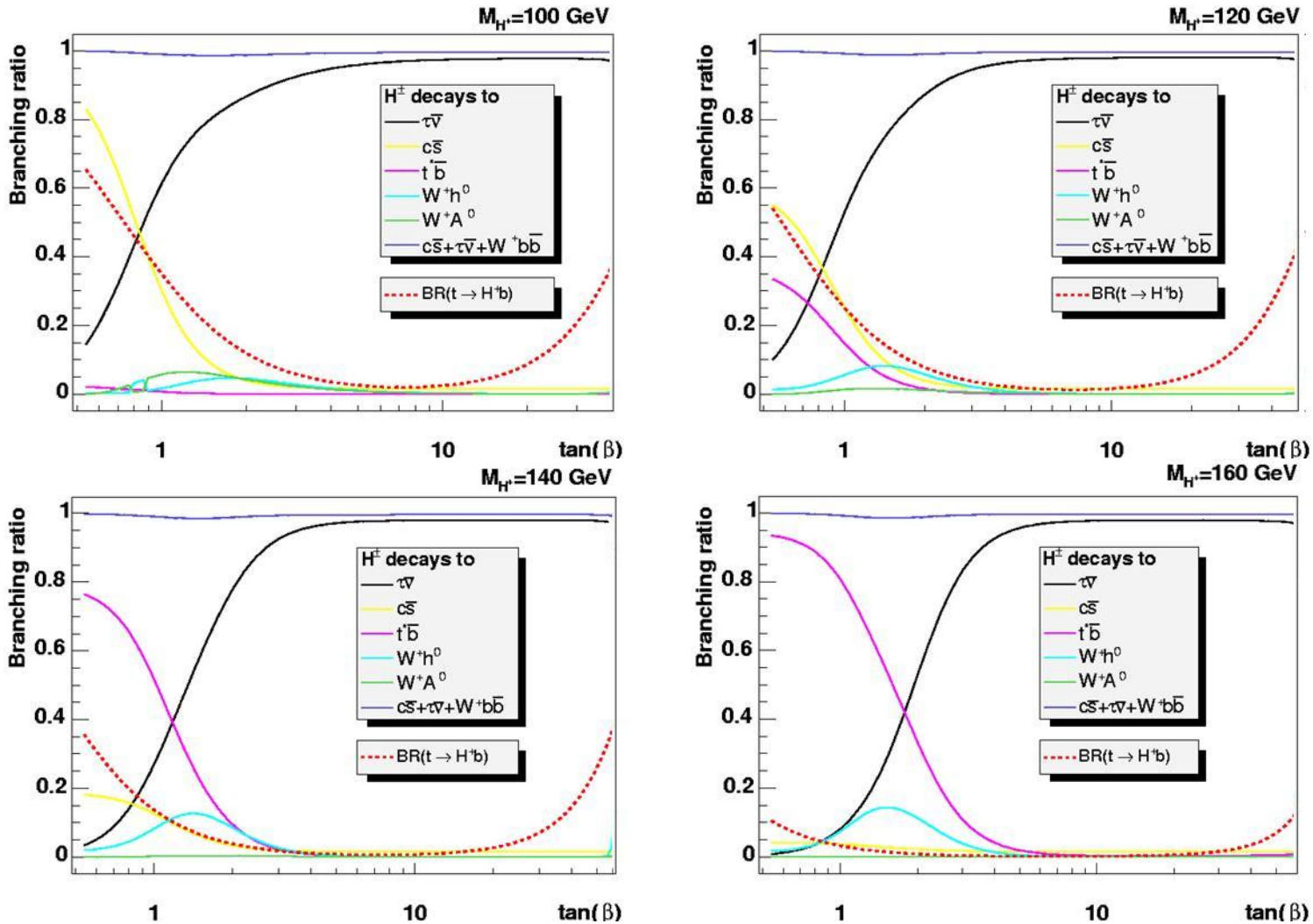
Branching fractions of each decay mode

- Need to know the BR's to compute the efficiency

- Given {BR's} compare N^{obs} to N^{exp} for each cross section measurement
  - Use a likelihood in the parameter of interest

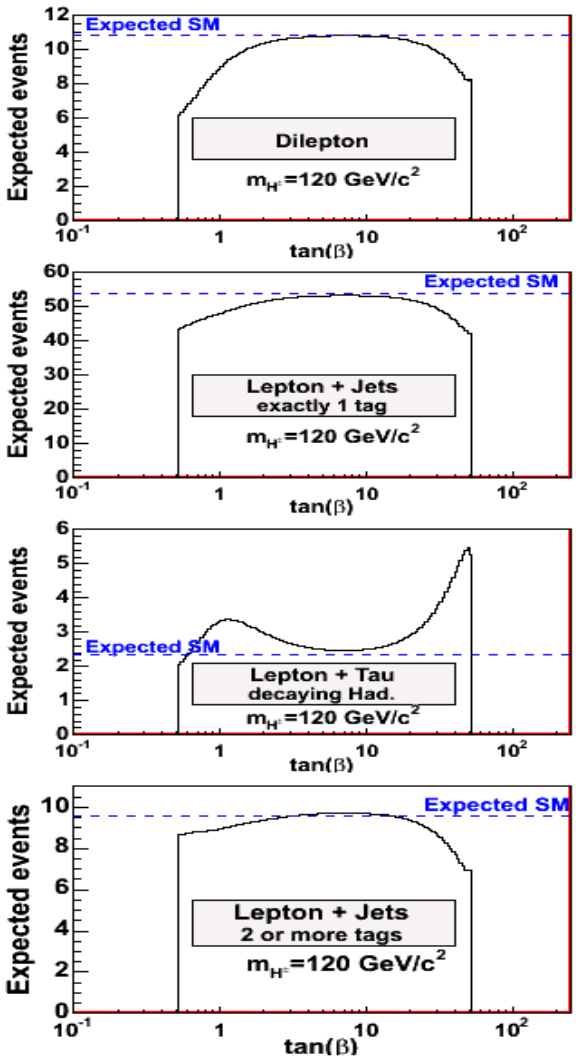
Measurement of BR(t→H±b)

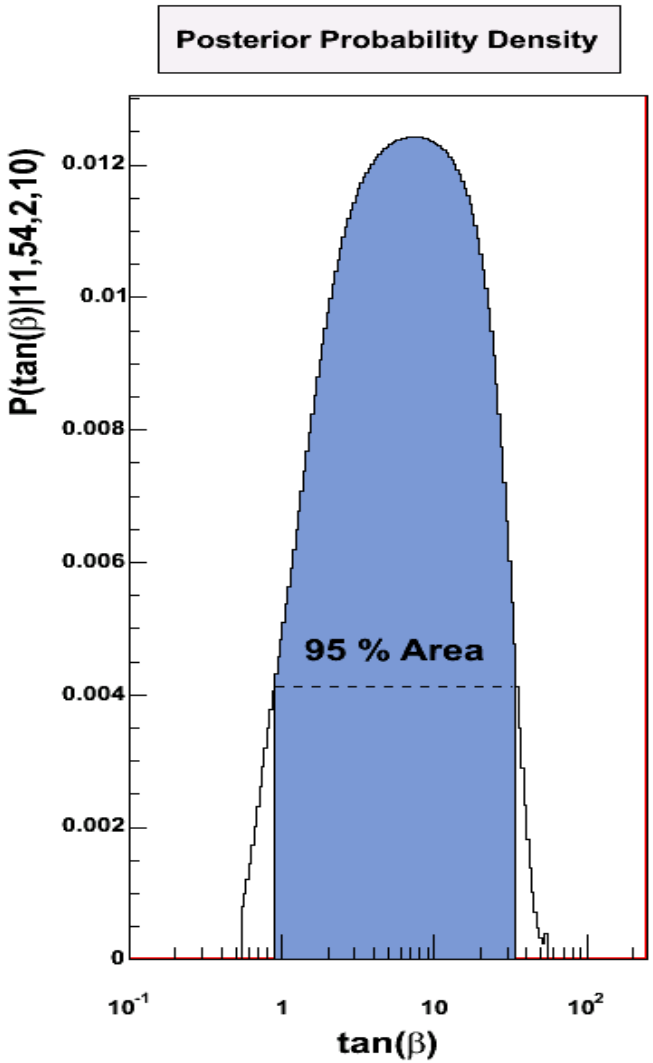
- Using CPsuperH (hep-ph/0307373) to predict the BRs
  - Full QCD, SUSY-EW and SUSY-QCD corrections included



Measurement of BR(t→H±b)

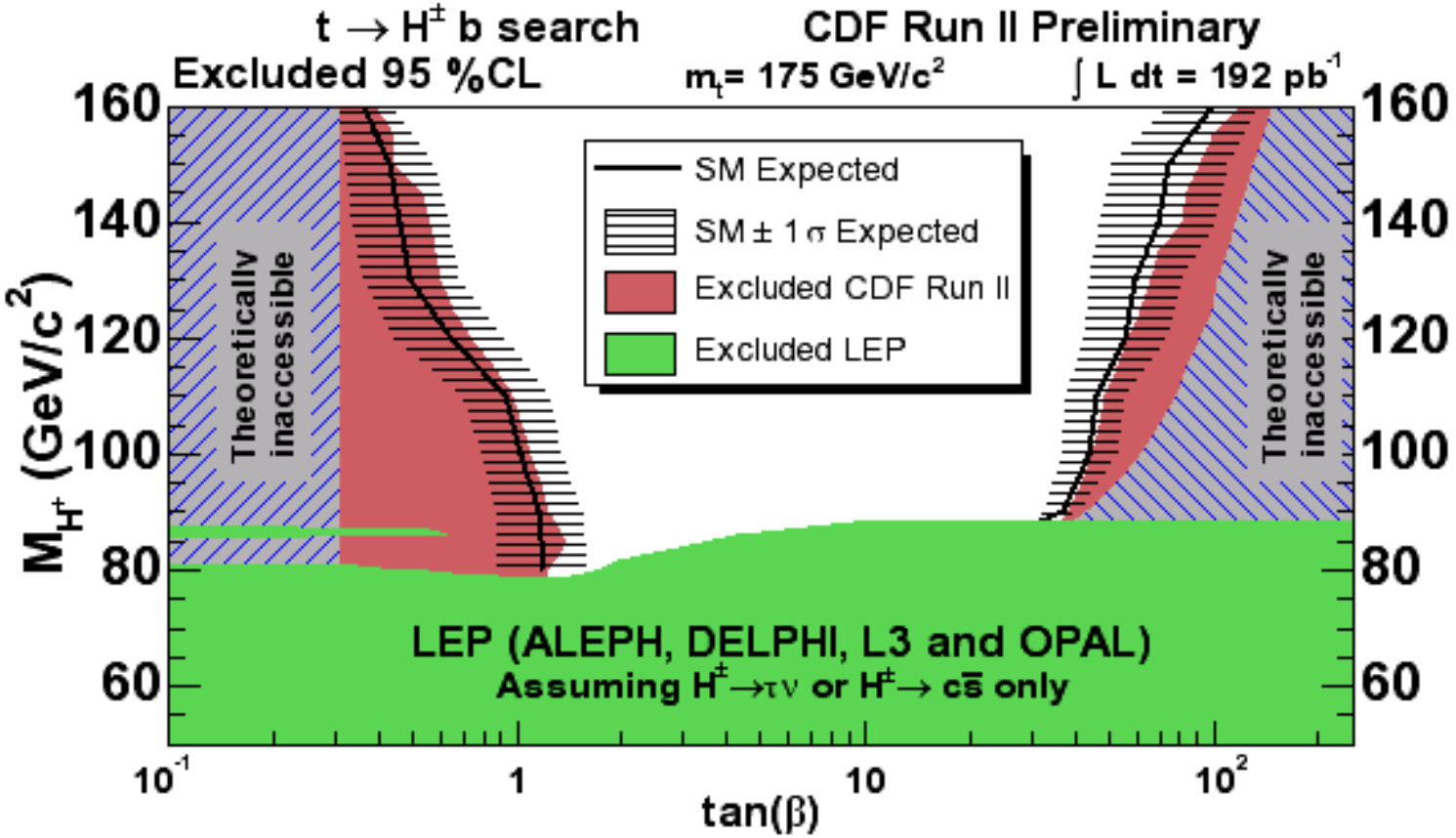
- Expected Events as a function of tan(β) . Integrated luminosity 191 pb^{-1}





Measurement of BR(t→H±b)

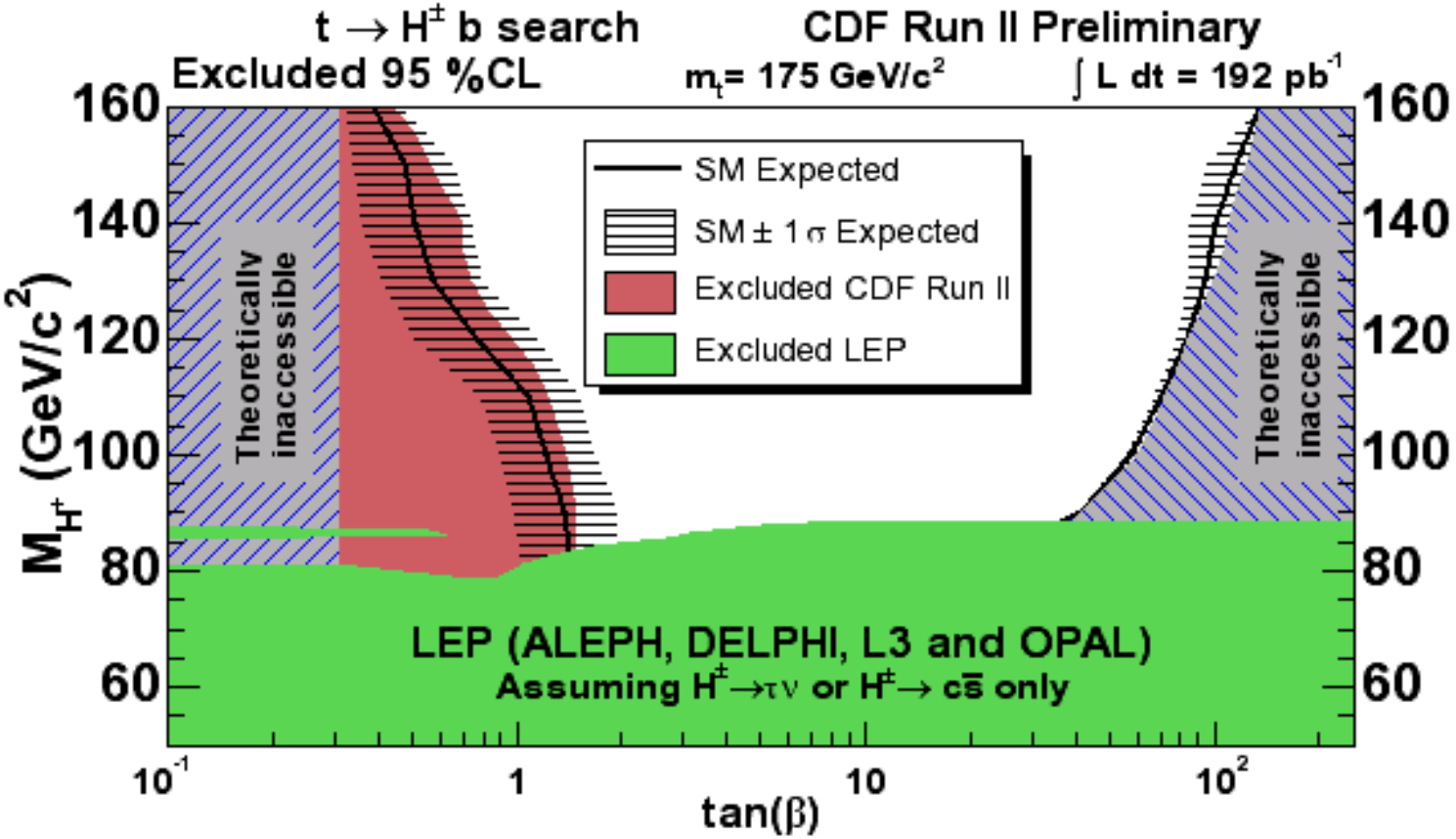
- BR's predicted by MSSM in Minimal Stop Mixing scenario



M_{SUSY}=800 GeV/c^2, μ=-200 GeV/c^2, $A_t=A_b=\mu/\tan(\beta)$, A_τ=500 GeV/c^2
$M_1=0.498*M_2$, $M_2=M_3=M_Q=M_U=M_D=M_E=M_L=M_{SUSY}$

Measurement of BR(t→H±b)

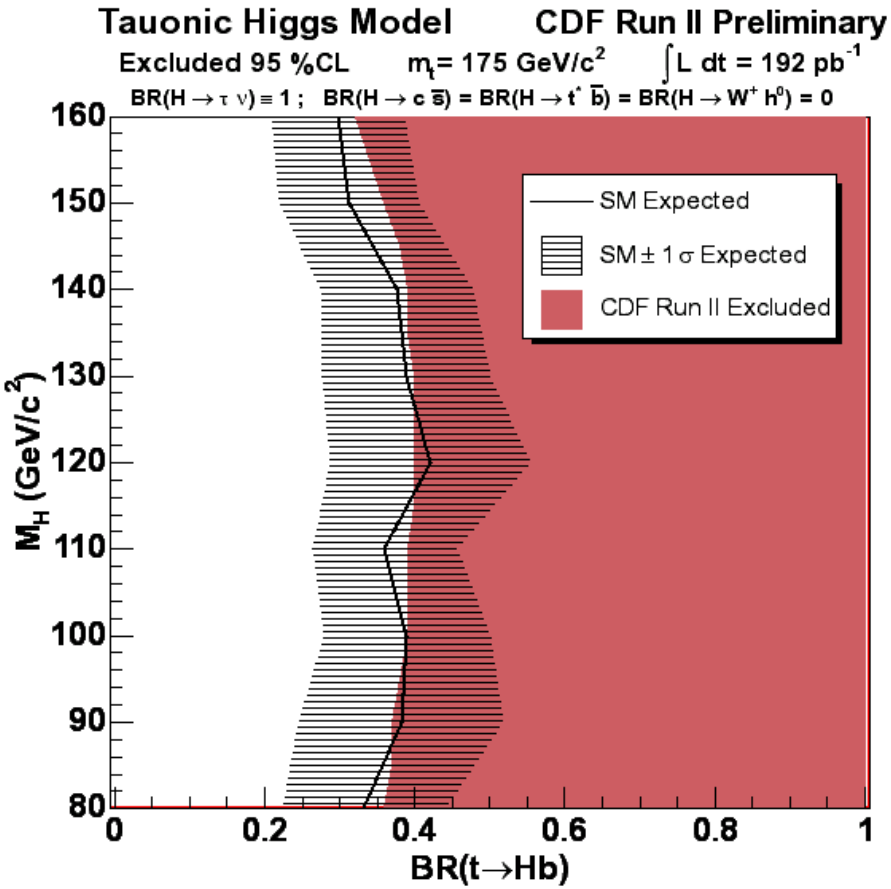
- BR's predicted by MSSM in another benchmark scenario



M_{SUSY}=1000 GeV/c^2, μ=500 GeV/c^2, $A_t=A_b$=2800 GeV/c^2, A_τ=500 GeV/c^2
$M_1=0.498*M_2$, $M_2=M_3=M_Q=M_U=M_D=M_E=M_L=M_{SUSY}$

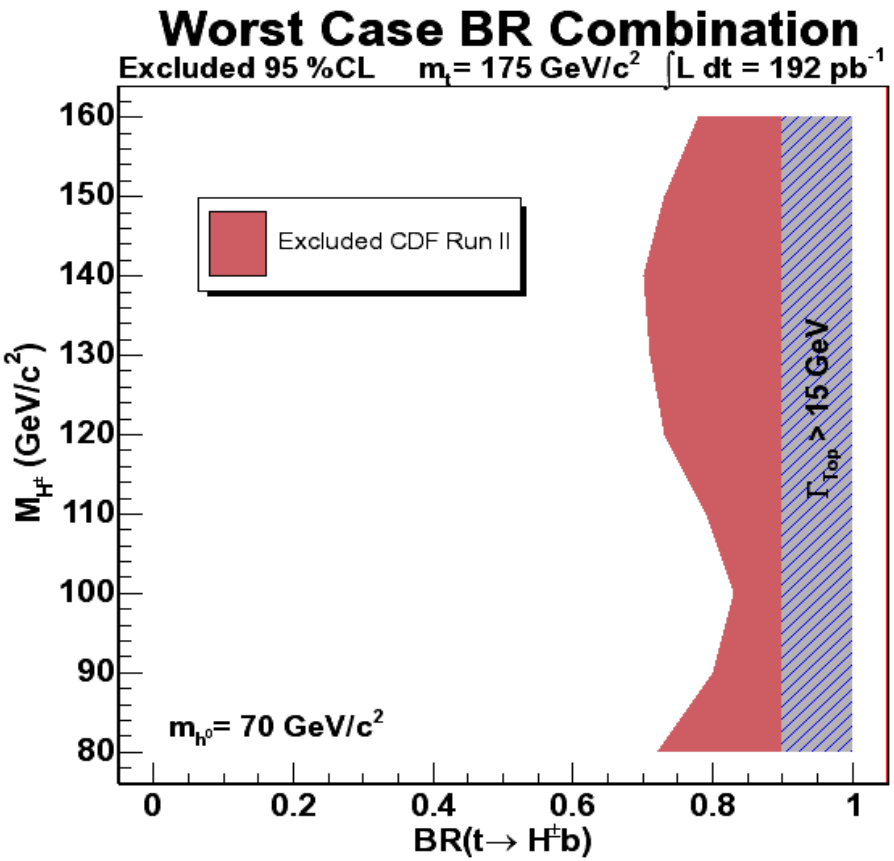
Measurement of BR(t→H±b)

- Assuming H+→τν only



- BR(t→H+b)<0.4@95%CL, 80<mH<160 GeV

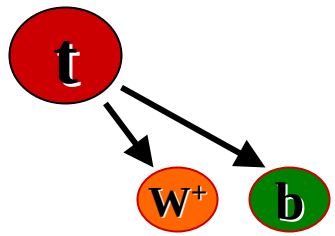
- Worst case of all possible BR's combinations



- BR(t→H+b)<0.85@95%CL,80<mH<160 GeV

What these results implies ?

- Results are, within reach, consistent with the SM.
  - Assume then that $t \rightarrow W^+b$

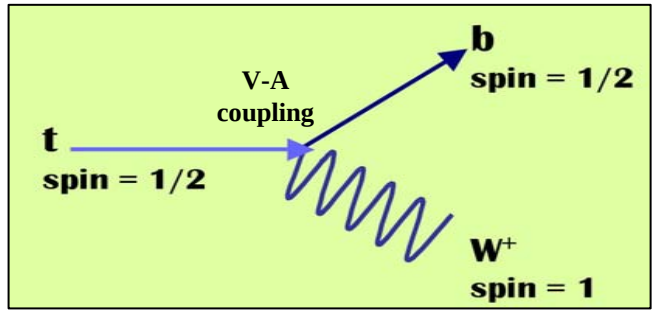


- But, is the nature of the tWb vertex as expected?

W helicity from t→Wb decays

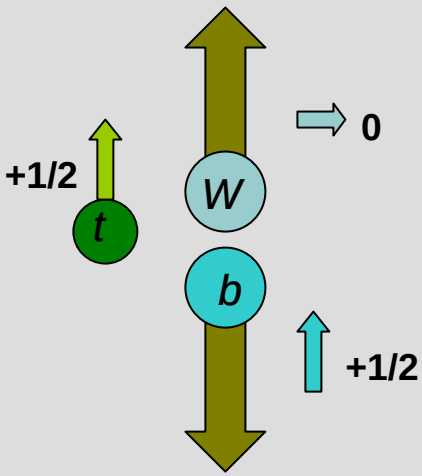
- **Examines the nature of the tWb vertex,** probing the structure of weak interactions at energy scales near EWSB

- **Stringent test of SM** and its V-A type of interaction.

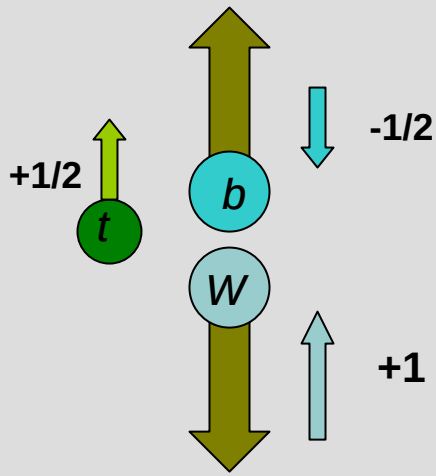


V-A Suppressed

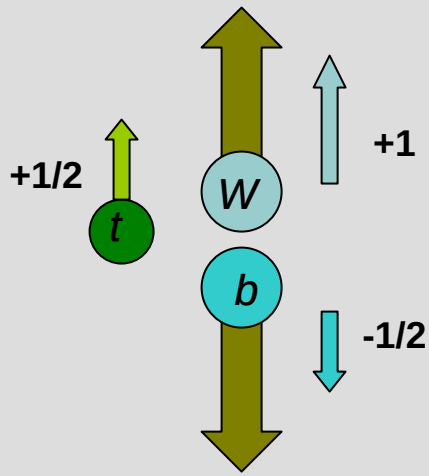
W_0 Longitudinal fraction
F_0



W_- Left-Handed fraction
F_-



W_+ Right-Handed fraction
F_+

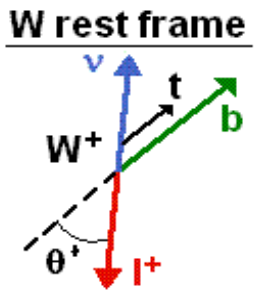


W helicity from t→Wb decays

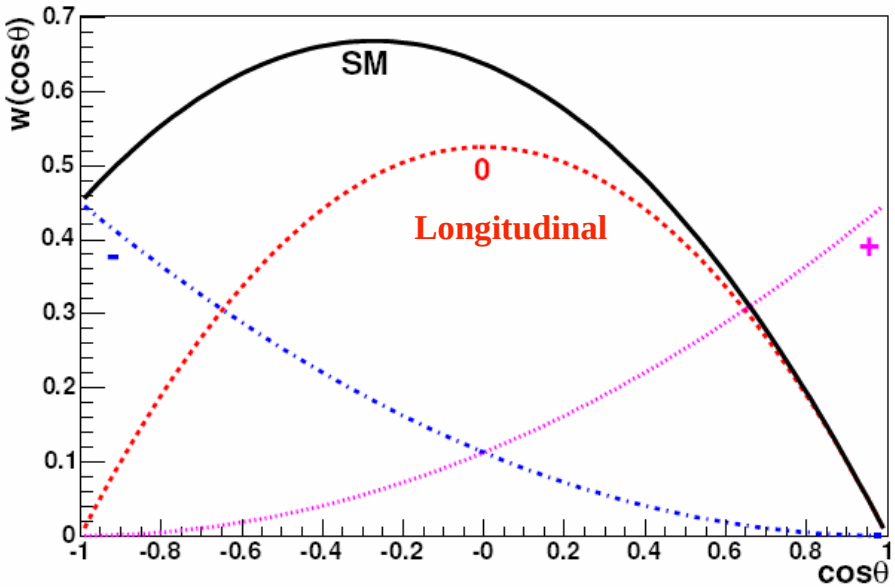
- In general, the θ^* distribution of top decays in the W rest frame is

$$w(\cos\theta^*) = F_- \cdot \frac{3}{8}(1-\cos\theta^*)^2 + F_0 \cdot \frac{3}{4}(1-\cos^2\theta^*) + F_+ \cdot \frac{3}{8}(1+\cos\theta^*)^2$$

where $F_- + F_0 + F_+ \equiv 1$



- In the Standard Model : $F_- = 0.3$ $F_0 = 0.7$ $F_+ \approx 0$ (exact when $m_b = 0$)



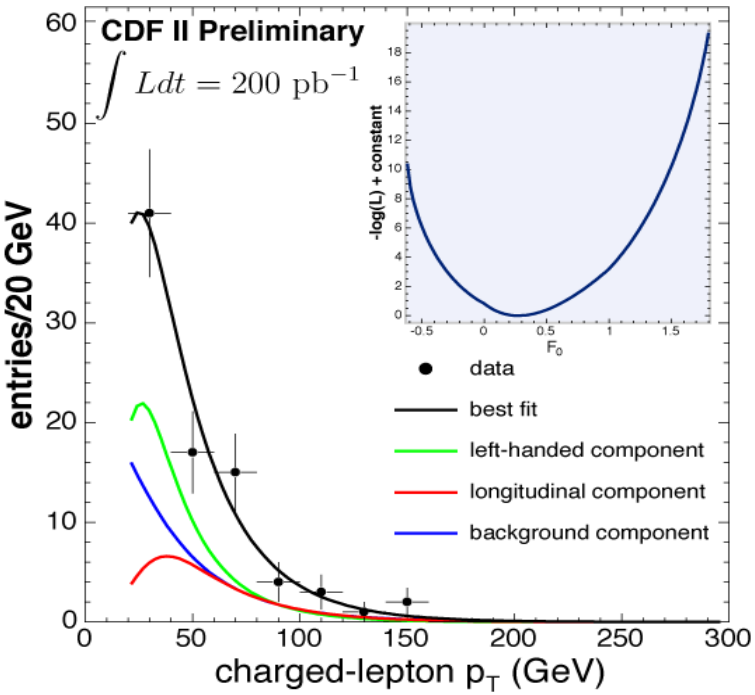
Left-handed

Right-handed

- The different W helicities result in different P_T spectrums
  - left-handed: leptons are emitted opposite to W boson (softer lepton P_T)
  - longitudinal: leptons are emitted perpendicular to the W (harder lepton P_T)
  - right-handed: leptons are emitted parallel to W boson (hardest lepton P_T)

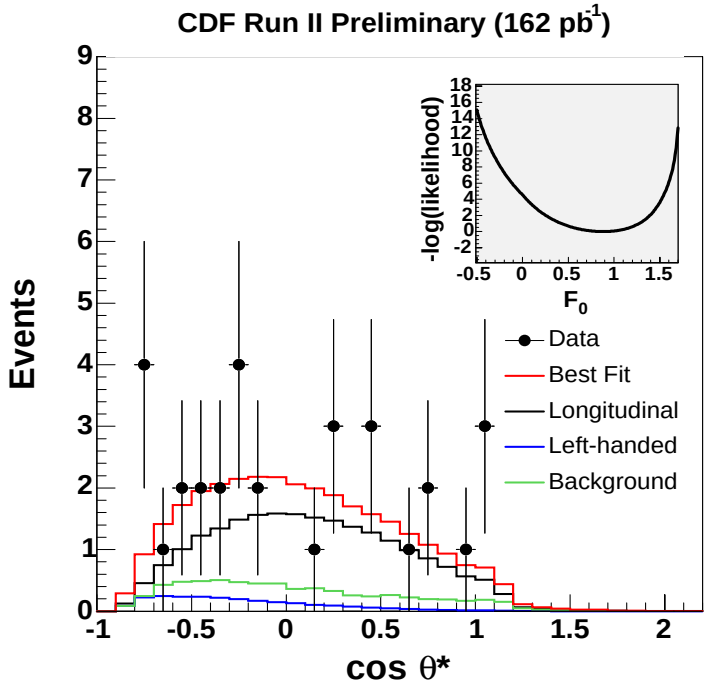
W helicity : Longitudinal Fraction

- Both analyses assume F_+=0 and are dominated by statistical uncertainties
- Likelihood analysis of P_T spectrum
- Combined lepton+jet and dilepton samples: **57+13 events**



$$F_0 = 0.27 \pm^{0.35}_{0.21} (stat + syst)$$
$$F_0 < 0.88 @ 95\% CL$$

- Likelihood analysis of $\cos(\theta^*) \cong \frac{2m_{lb}^2}{m_t^2 - m_W^2} - 1$
- Lepton+jets : **31 events**
- Use mass fitter to select the

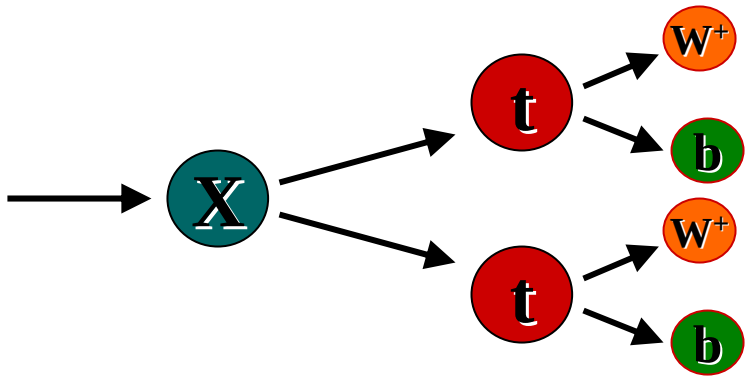


$$F_0 = 0.89 \pm^{0.30}_{0.34} (stat) \pm 0.17 (syst)$$
$$F_0 > 0.25 @ 95\% CL$$

- Mild Excess in the low Pt region
- Right Handed Fraction: measurement ongoing at CDF. **(Run 1 F_+<0.18 @95%)**

What about production ?

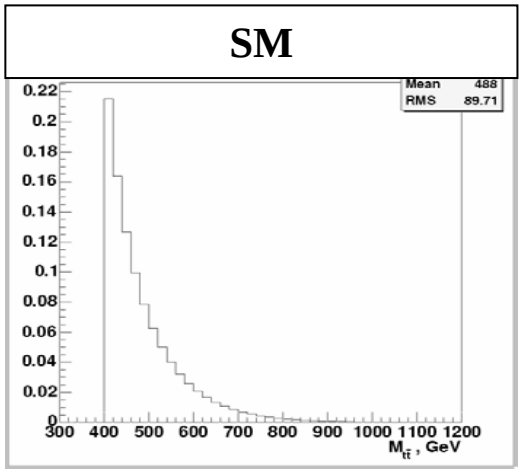
- We know that, within errors,:
  - The top decays mostly to b
  - The top decays mostly to W+
  - The nature of the tWb vertex is what's expected.

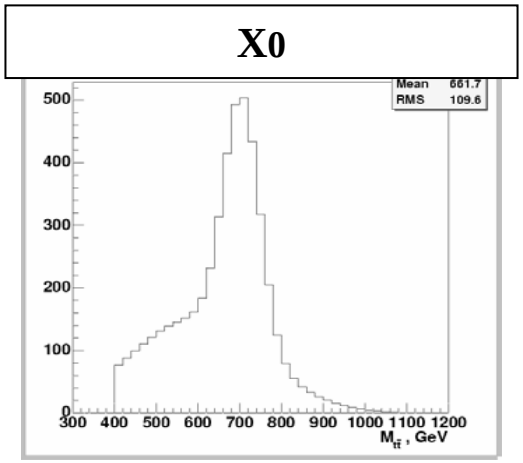


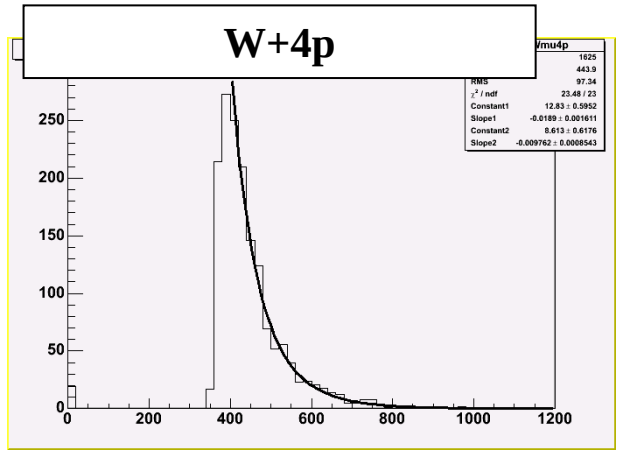
- Are some top pairs coming from a resonance?

Search for ttbar resonances

- **Template method : 3 templates for modeling data: X_0, tt, W+4p**



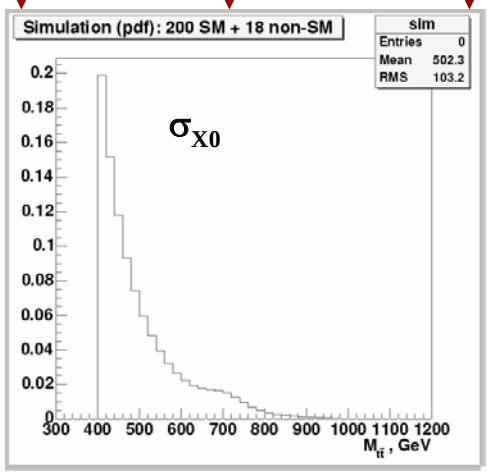




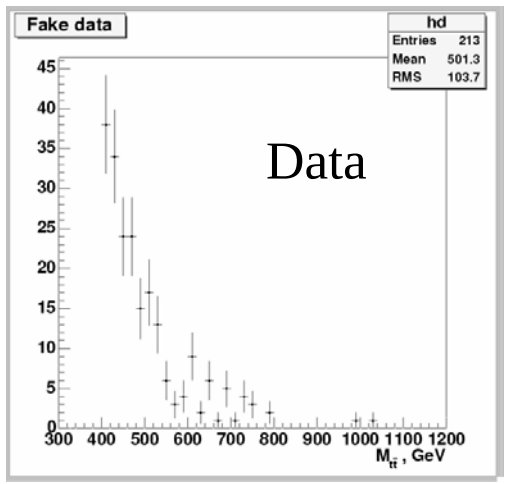
$N_{tt}(\sigma_{tt}=6.7pb)$

$N_{x0}(\sigma_{X0})$

$N_w=N_{tot}-N_{tt}-N_{x0}$



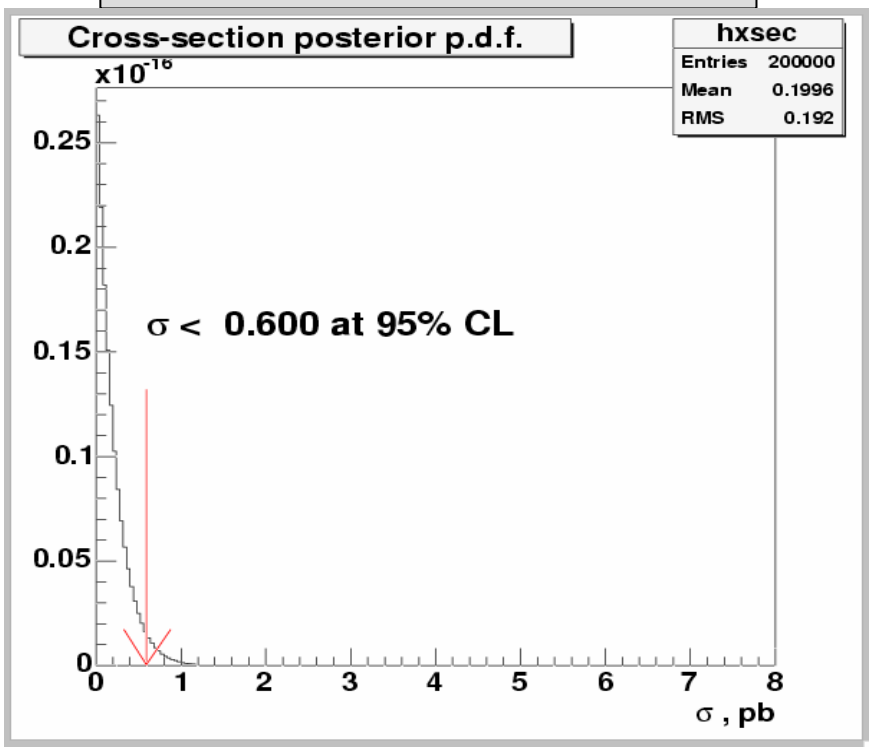
Compare to data and get $P(\sigma_{x0})$



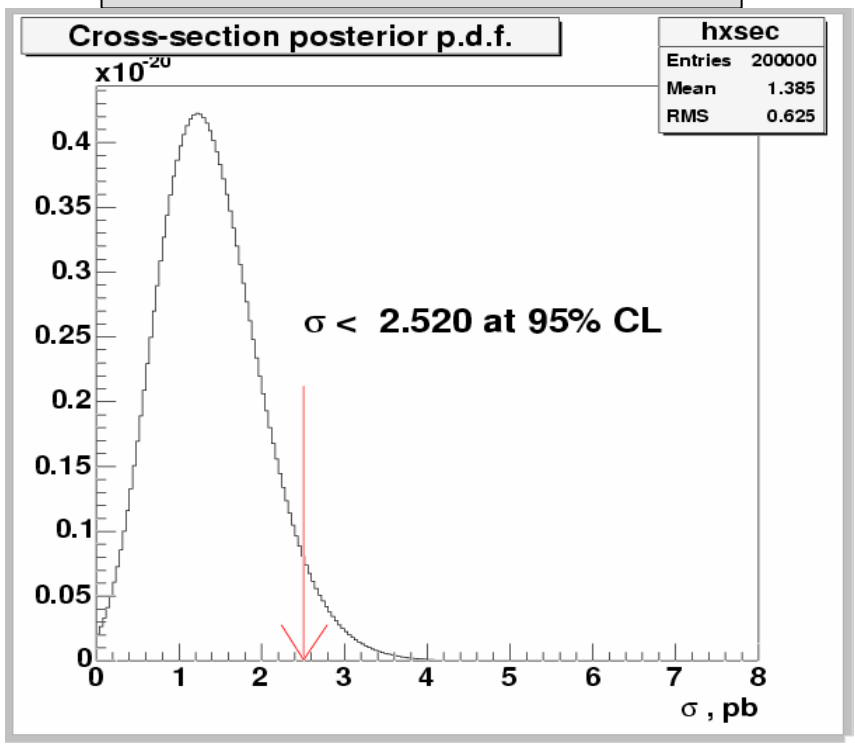
ttbar resonances: Sensitivity

- Expected posterior p.d.f. for a 700 GeV resonance

If there is none (i.e. SM only)



If there is 9% X_0 + SM



Work in progress. Stay tuned for incoming results.

What else ?

- We know that:
  - Top is produced in ttbar pairs (and possibly singly too)
  - The top decays mostly to b
  - The top decays mostly to W+
  - The nature of the tWb vertex is what's expected.

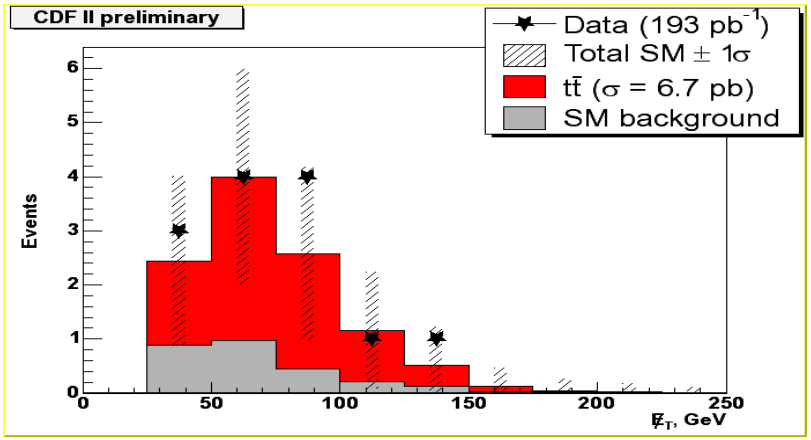
- Is anything beyond SM in our top sample?

SM Kinematic Test

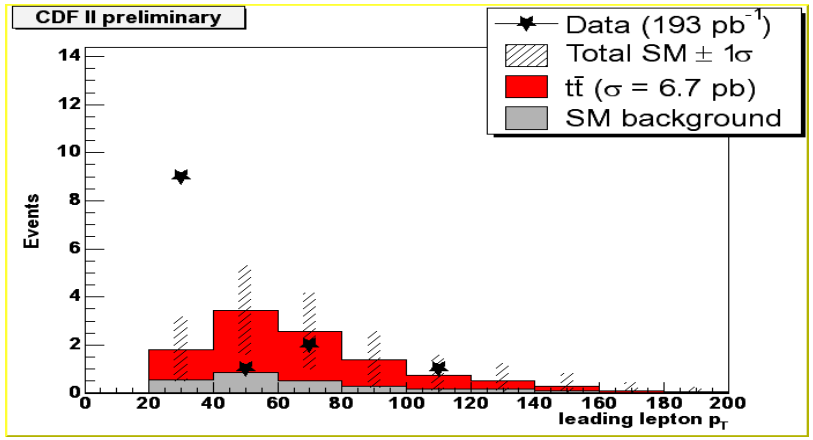
- Run 1 saw an excess of large ME_T and lepton P_T
  - PRL 77 3506 (1996) proposed that squarks around 300 GeV show better agreement to data
- Run 2 : Work in the **Dilepton** sample
- Choose *a priori* a set of variables with potential sensitivity to new physics
  - ME_T
  - Angle(ME_T, Leading Lepton)
  - Leading lepton P_T
  - "Topness" (based on kinematical fit)
- Perform Kolmogorov-Smirnov consistency test between data and MC
- Select the subset of events with the most non-SM features

SM Kinematic Test

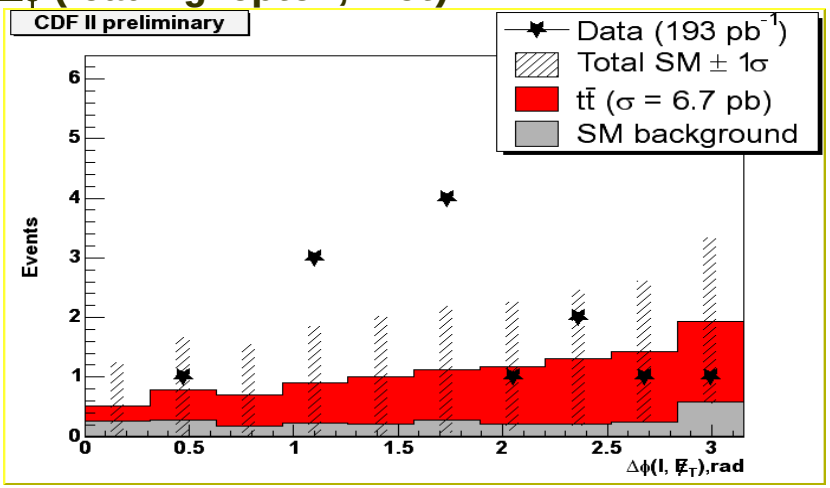
Missing E_T



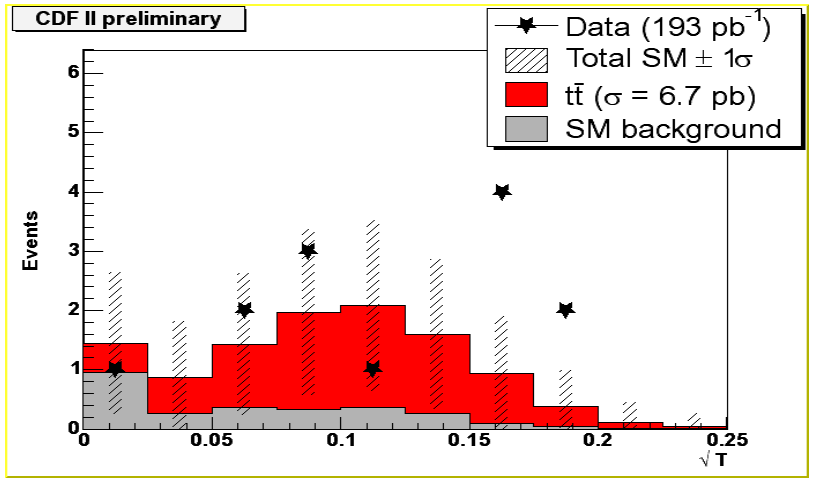
Leading lepton p_T



$\Delta\phi$ (leading lepton, met)



"topness" = ttbar decay goodness-of-fit



➲ **Overall agreement of 1.0-4.5% mainly due to an excess at low lepton P_T**

Conclusions

- CDF is seriously focused on exhaustive measurements of top properties
- Many more analyses ongoing
  - FCNC t→Zc
  - Top Spin correlations
  - Search for t'→Wq
  - Top charge measurements
  - and more…
- Exciting times :
  - Analyses are very mature
  - Much more data on tape
- Uncertainties are beginning to shrink

➲More and more we are putting the SM to the test!