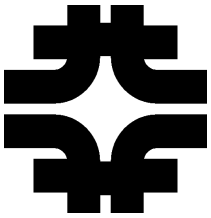

Top Quark Properties @ the TeVatron

Yvonne Peters

Newton International Fellow @

University of Manchester

On Behalf of the
CDF & DØ Collaborations

The Top Quark: Properties

What we know from SM prediction:

- Electric charge +2/3 e
- Short lifetime 0.5×10^{-24}s
- Width: ~1.4GeV
- Branching ratio: ~100% decay into W^+b
- Spin correlation of $t\bar{t}$
- Large coupling to Higgs

Free parameter in the SM:

- Top mass

What else can we learn using top events:

- CPT violation: Top-Antitop mass difference
- W helicity

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Charged Higgs search

Free parameter in the SM:

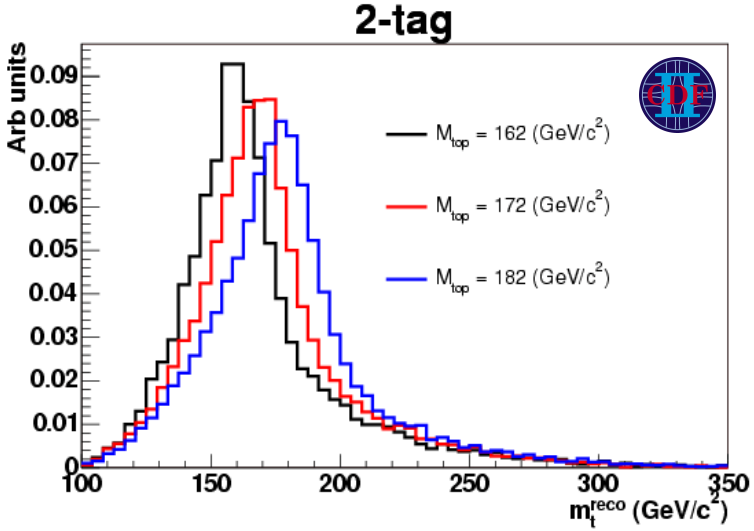
- Top mass

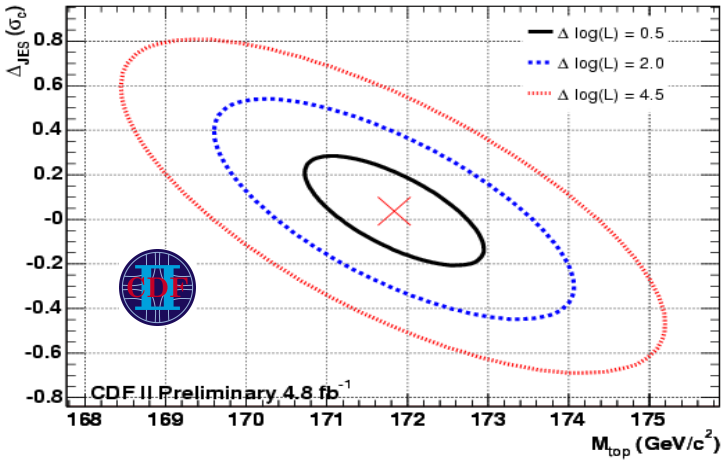
What else can we learn using top events:

- CPT violation: Top-Antitop mass difference
- W helicity

Top Quark Mass

- Motivation: Not predicted by the SM & constraint on Higgs!
- Template method:
  - Construct mass dependent template
  - Fit to data!





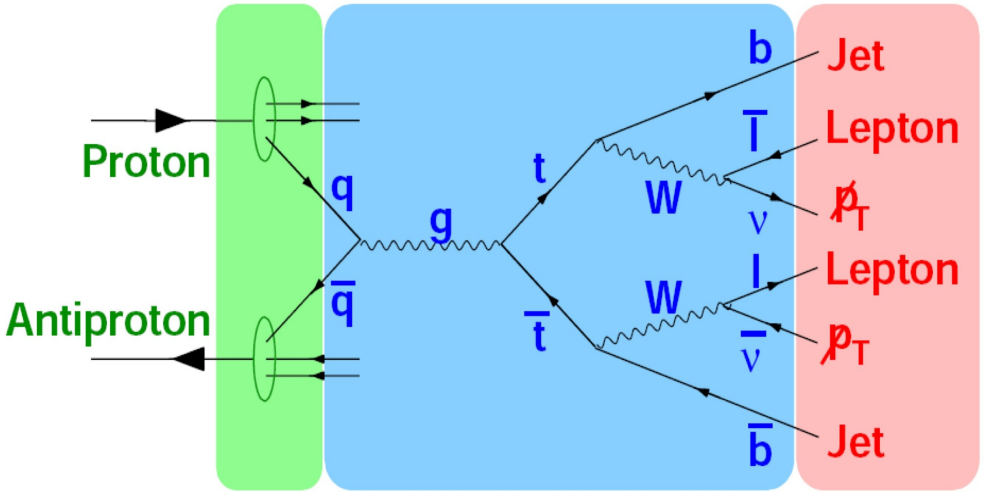
Take info from W mass to constrain jet energy scale

CDF: m_t=171.9±1.1(stat+JES)±0.9(syst)GeV (L=4.8 fb^{-1},l+jets & dilepton)

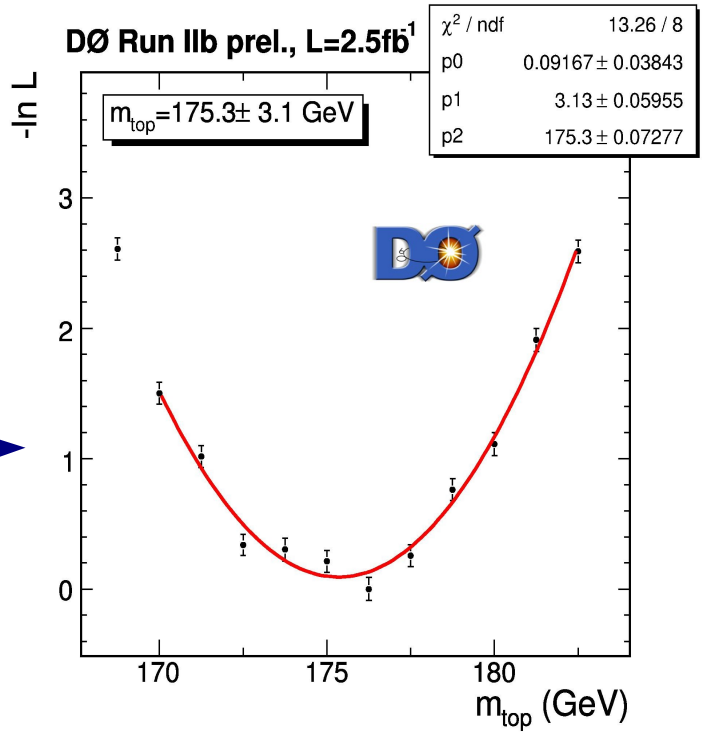
Top Quark Mass

- Matrix element method: use full kinematic info → Most precise method!
- For each event calculate probability that the top has a certain mass

$P_{sig}(x;m_t) \propto \int$ PDF x Matrix element x Transfer function



Likelihood fit of event probabilities



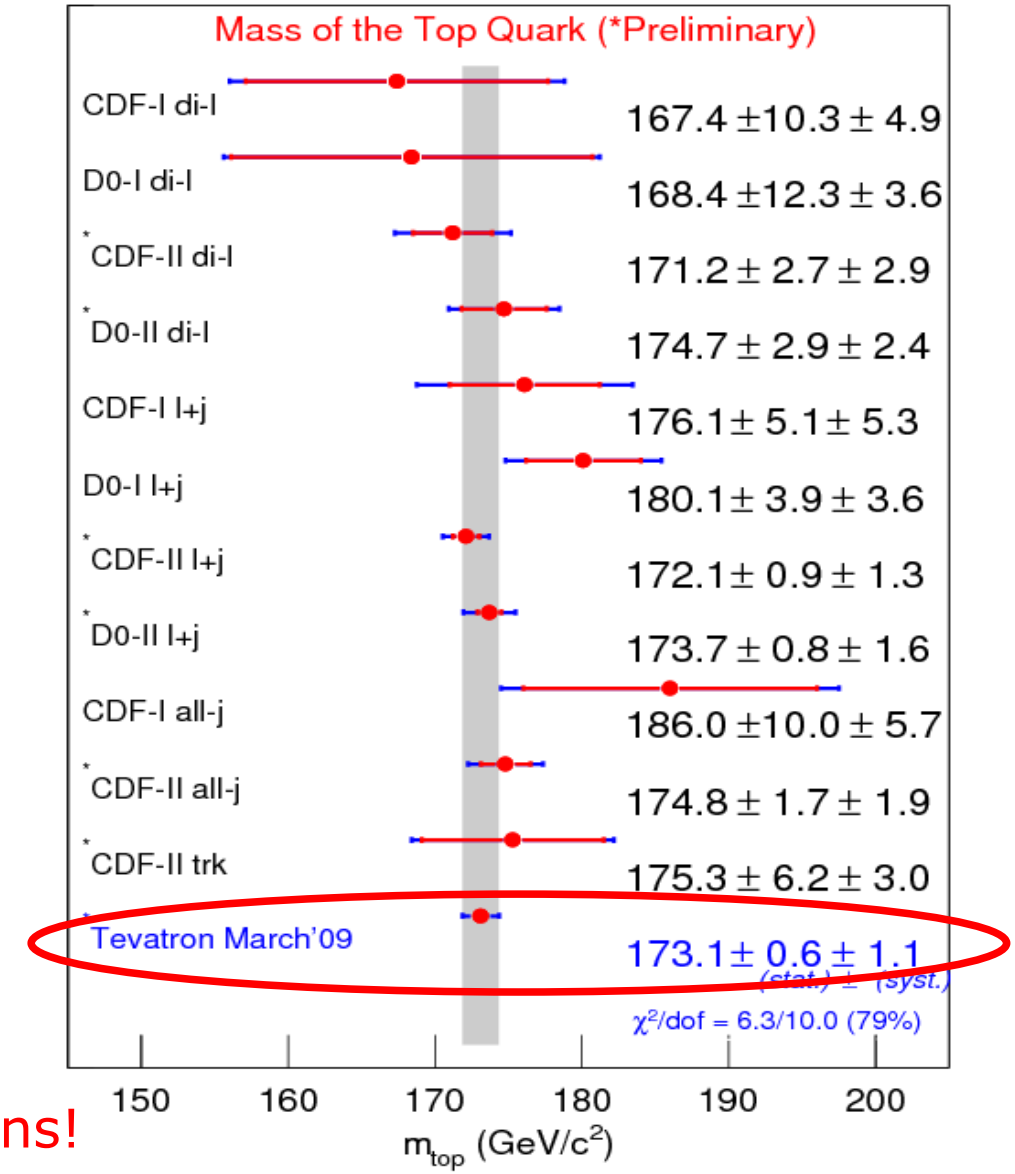
- l+jets: Simultaneously extract jet energy scale

D0: m_t = 173.7±1.3(stat+JES)±1.4(syst)GeV (L=3.6 fb^{-1}, l+jets)

CDF: m_t = 172.8±0.9(stat+JES)±0.8(syst)GeV (L=4.8 fb^{-1}, l+jets)

Top Quark Mass

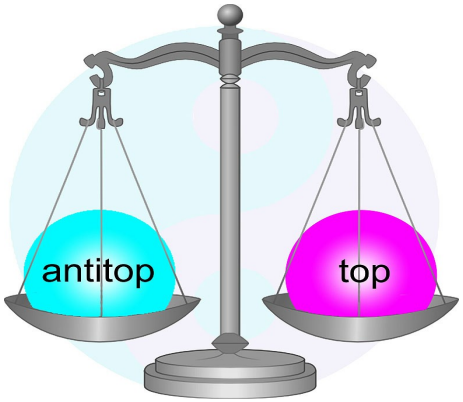
Combination!



0.75% relative uncertainty!
Exceeds Tevatron expectations!

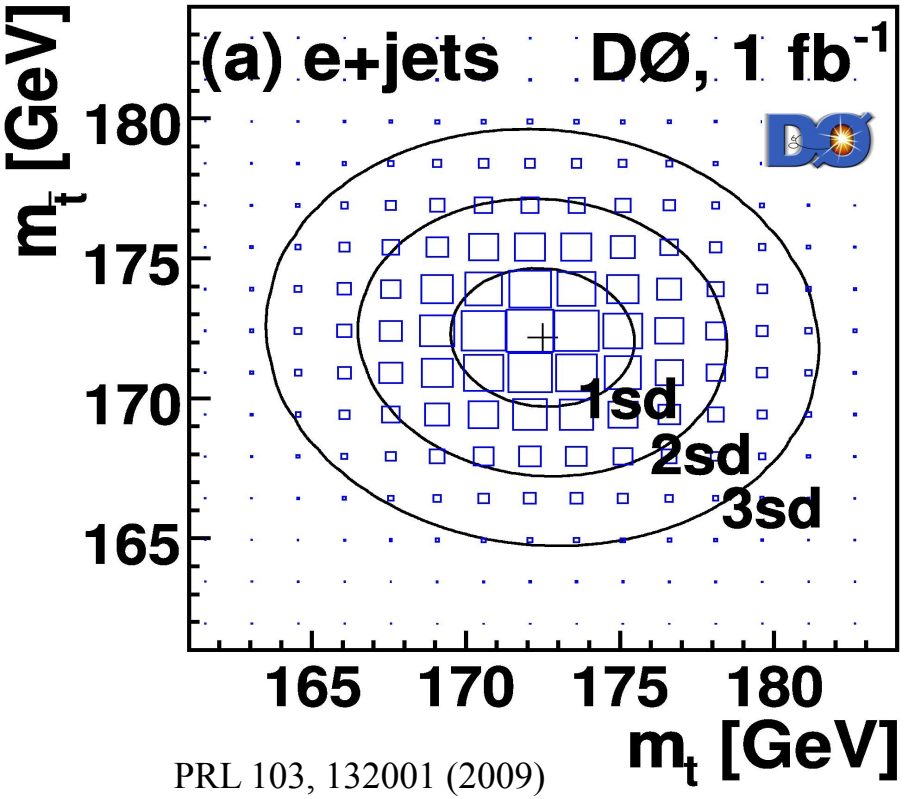
Top Mass Difference

- Are top and anti-top equally heavy?
  - If not: CPT violation!
- Using Matrix Element technique
  - $P_{sig}(x;m_t, m_{\bar{t}})$ instead of $P_{sig}(x;m_t)$



$m_t - m_{\bar{t}} = 3.8 \pm 3.7 \text{GeV}$

Featured in Nature & Physics Today!



PRL 103, 132001 (2009)

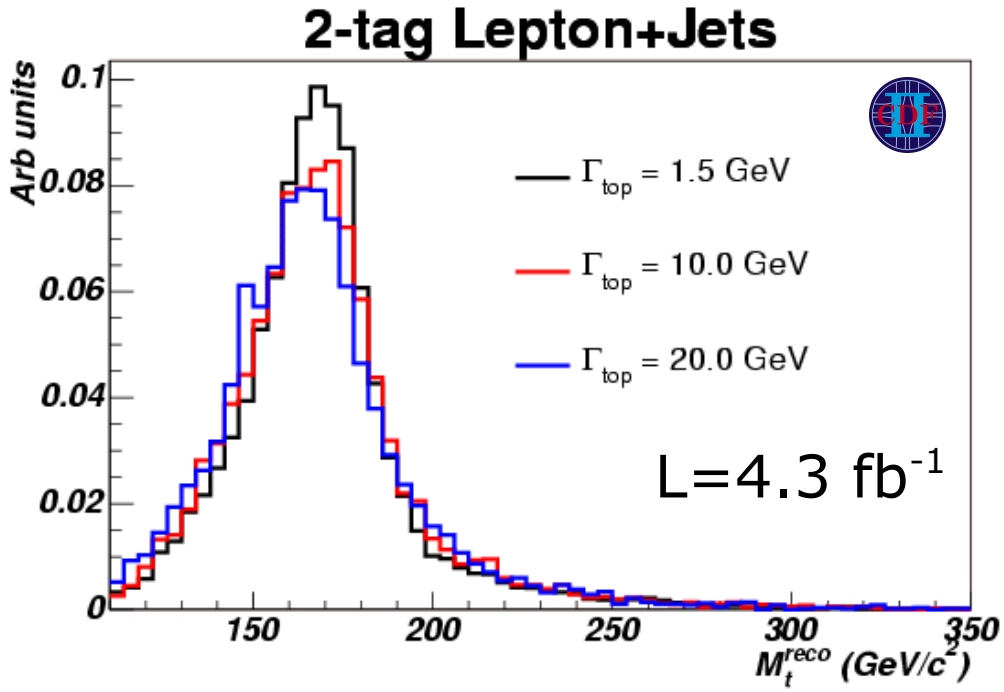
- Good agreement with the SM!
- First measurement of bare quark and anti-quark mass difference

Top Quark Width

- Top lifetime ~5×10^{-25}s
  => Top quark decay width is 1.4 GeV
- Top width determination using l+jets events
  - Reconstruct top mass
  - Use hadronic W mass for jet energy scale constraint
  - Fit template of reconstructed mass to data

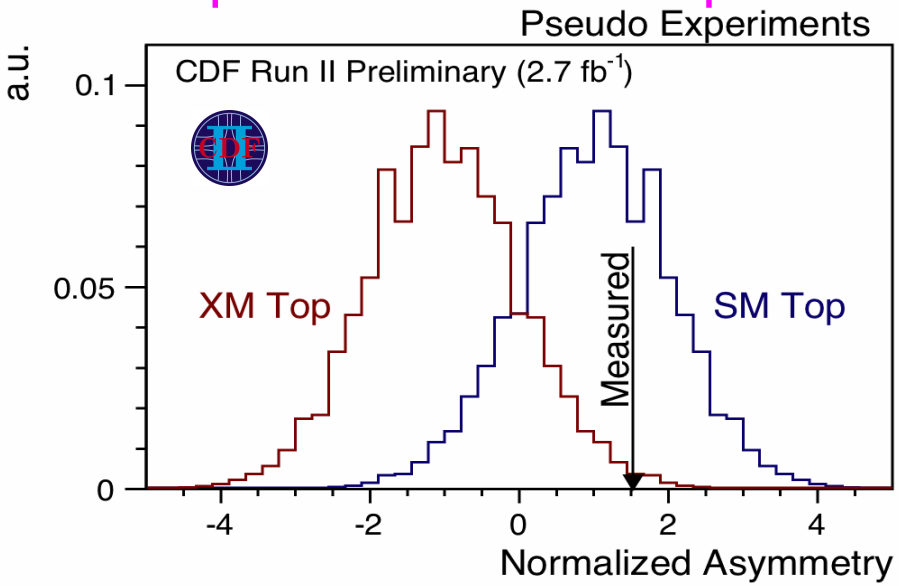
$0.4 < \Gamma < 4.4$ GeV @68% CL

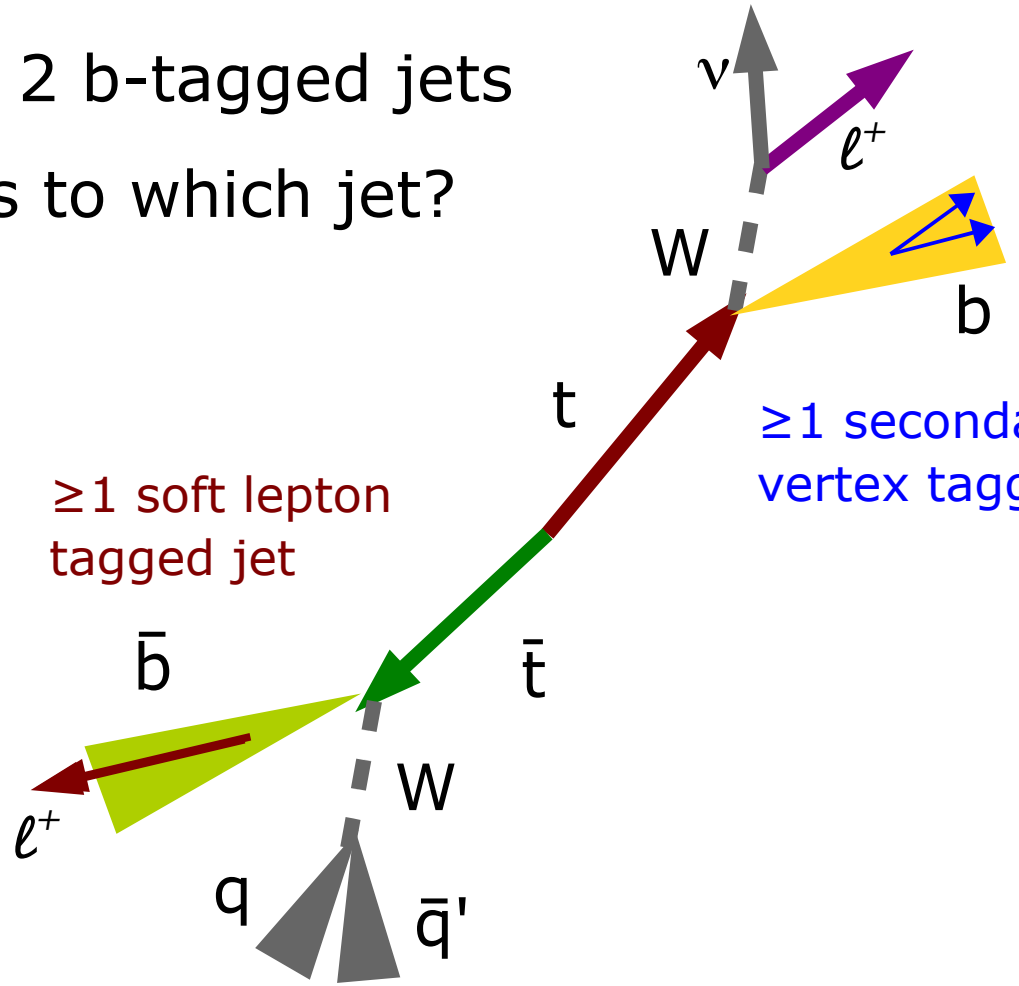
$\Gamma < 7.5$ GeV @95% CL



Top Quark Charge

- Exotic model with top charge -4/3 e could be possible (SM: +2/3e)
- Use l+jets events with at least 2 b-tagged jets
- Kinematic fit: Which W belongs to which jet?
- Determine top charge from
  - Lepton from W
  - Lepton from soft lepton tag

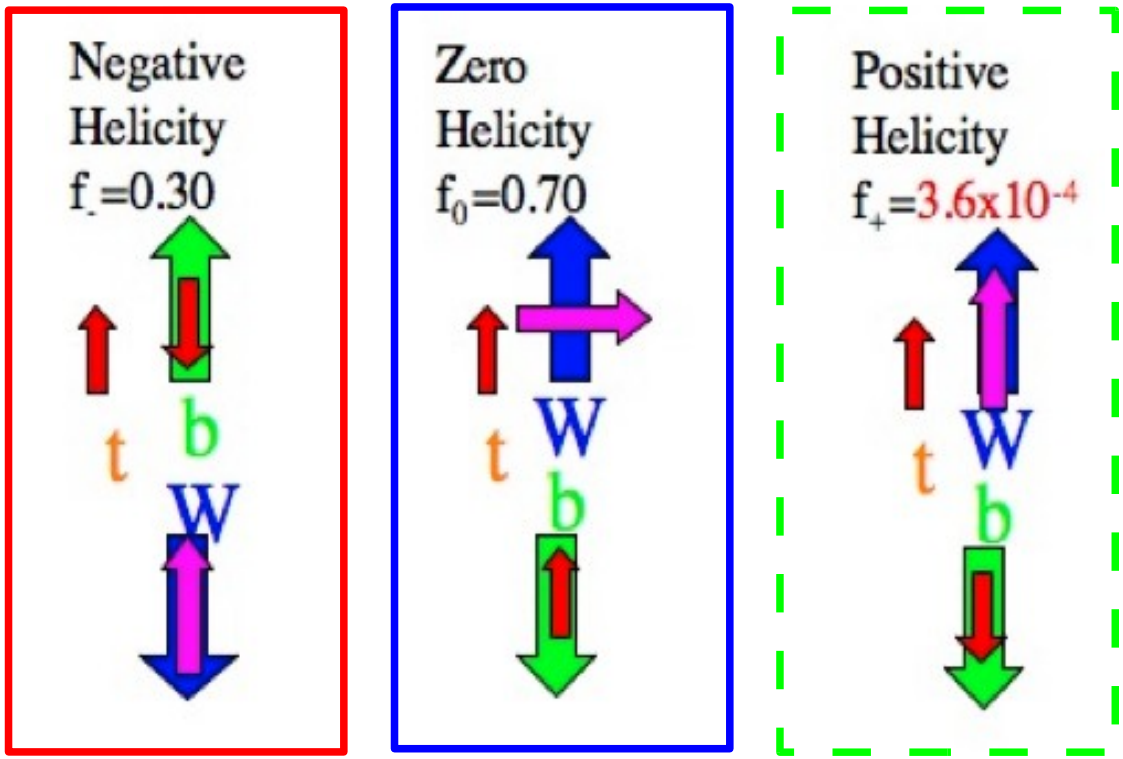


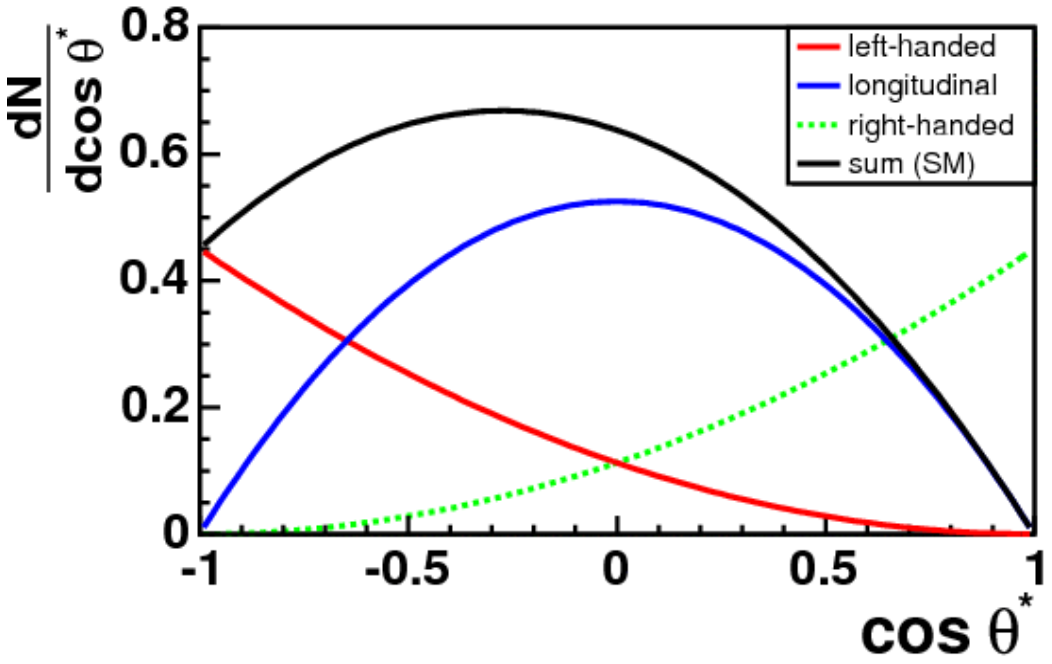


Exclude exotic top charge of -4/3 e with 95% CL!

W Helicity in Top Quark Decays

- Left handed coupling of W-boson to fermions:
  Not every combination of spin for W and b-quark is allowed



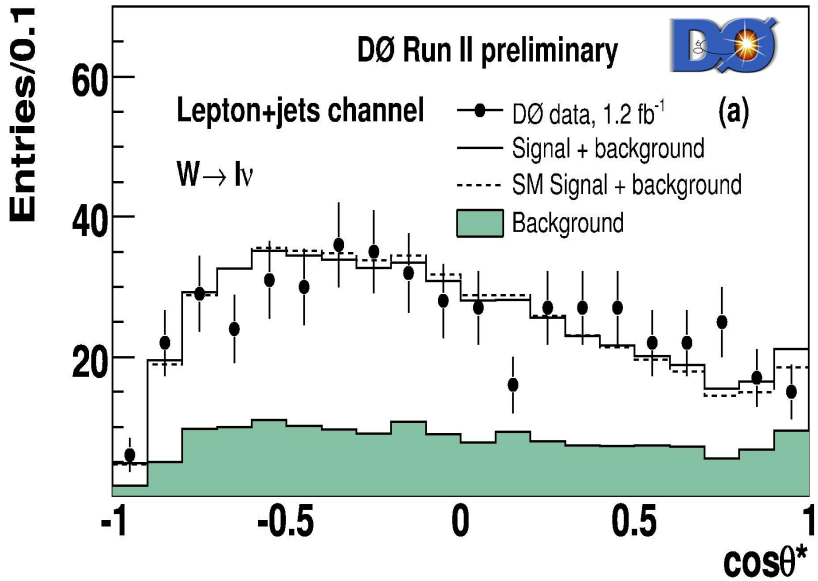


- Measure angle θ* between down-type decay product of W in W rest frame and W in top quark rest-frame

W Helicity in Top Quark Decays

Template method

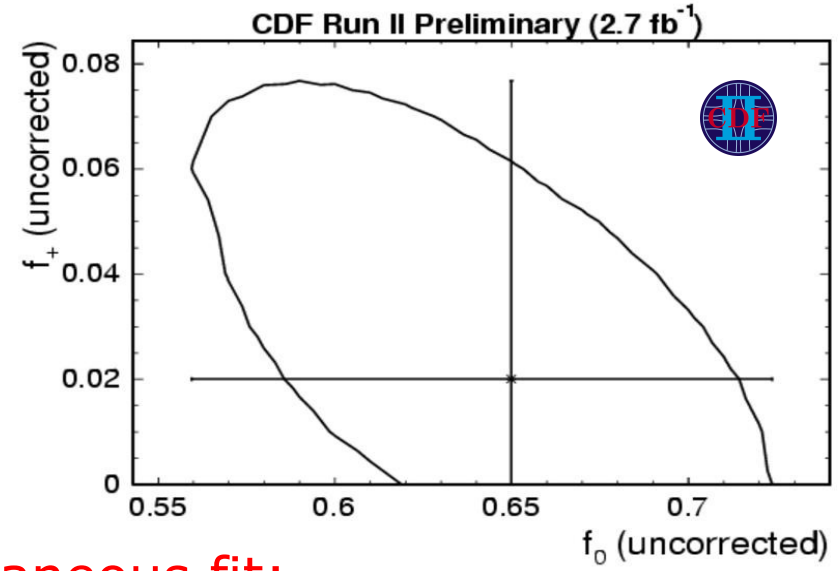
- Fit fraction of f_+, f_-, f_0 templates to data



L=2.7 fb^{-1}

Matrix element method

- Same method as for mass
- Replace top mass with f_0 & f_+



L=2.7 fb^{-1}

Model independent simultaneous fit:

f_0 = 0.49 ±0.11 (stat) ±0.09 (syst)

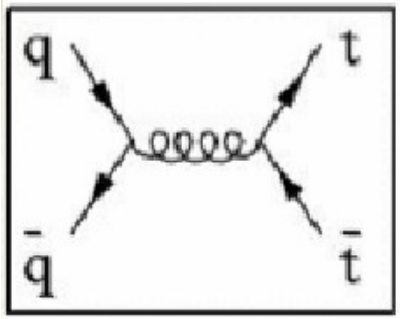
f_+ = 0.11 ±0.06 (stat) ±0.05 (syst)

f_0 = 0.88 ±0.11 (stat) ±0.06 (syst)

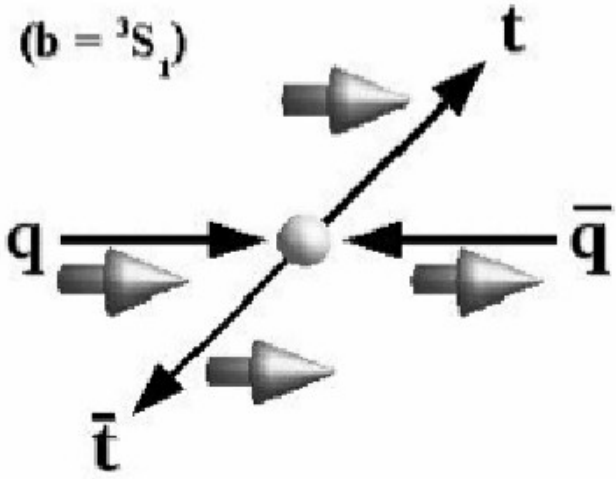
f_+ = -0.15 ±0.07 (stat) ±0.06 (syst)

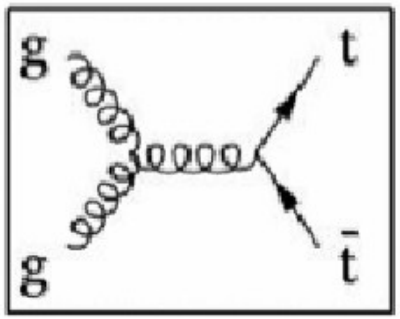
$t\bar{t}$ Spin Correlations

- Top quarks decay before fragmentation
  - Spin information is preserved
- Spin correlation depends on production mode

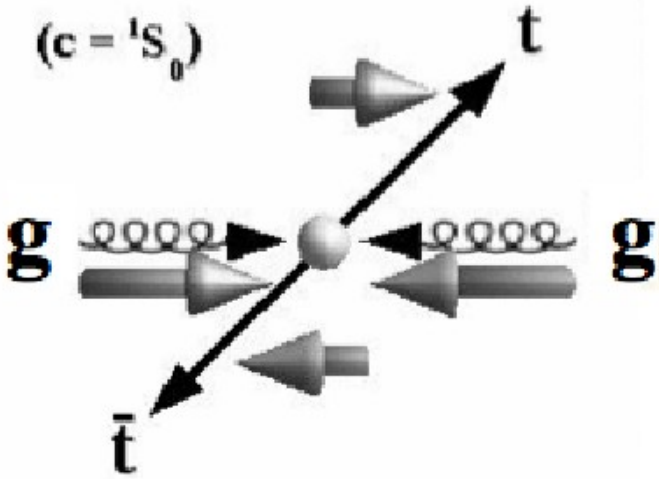


85%





15%



$t\bar{t}$ Spin Correlations

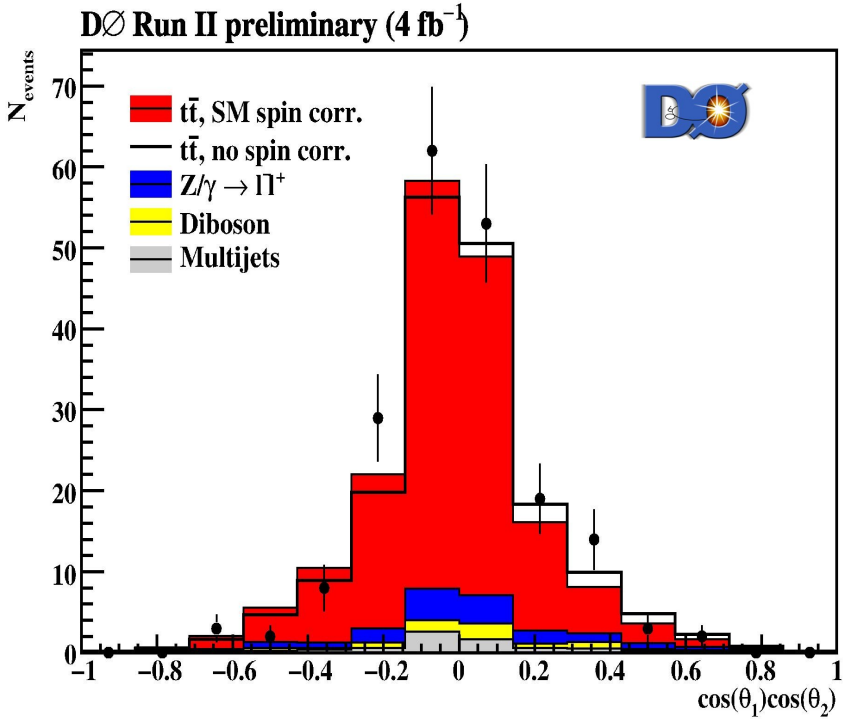
- Use the angles θ_1 (θ_2) of down-type fermion from W or top decay in top (antitop) rest-frame wrt. quantization axis:
  - top in $t\bar{t}$ rest-frame (helicity basis)
  - or beam axis (beam basis)
- Doubly differential cross section:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1 \, d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

depends on spin correlation strength C

$$C = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

Fit $\cos\theta_1$ $\cos\theta_2$



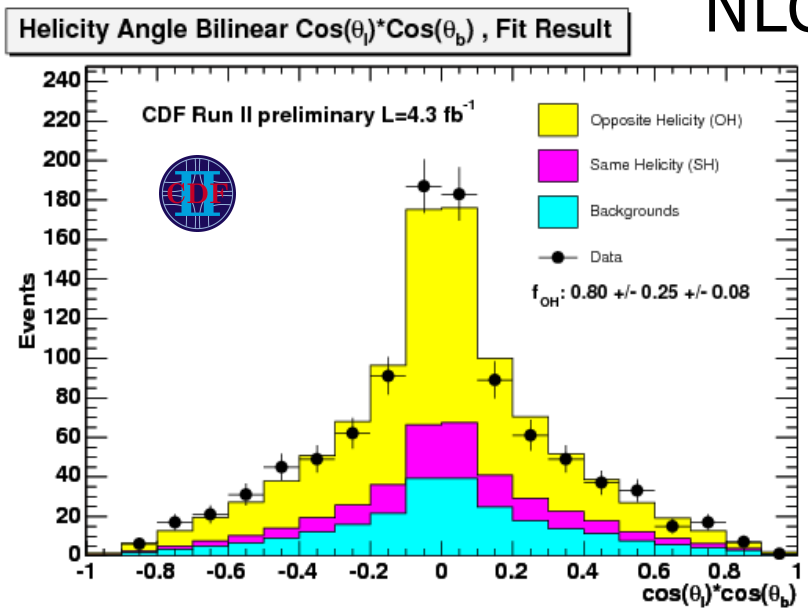
$t\bar{t}$ Spin Correlations

- Three first Run II spin correlation analyses since last summer!
- lepton+jets and dilepton results!

$$CDF: \quad C = 0.60 \pm 0.50(stat) \pm 0.16(syst)$$

NLO SM: 0.35

Bernreuther et. al, 04



Helicity basis

First extraction of $t\bar{t}$ spin correlation in l+jets!

$$CDF: \quad C = 0.32^{+0.55}_{-0.78}(stat+syst)$$

$$D0: \quad C = -0.17^{+0.65}_{-0.53}(stat+syst)$$

NLO SM: 0.78

Beam basis

In agreement with SM

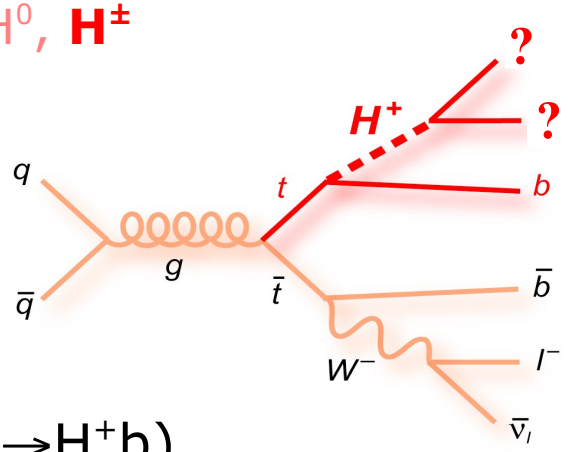
Still statistically dominated

First evidence soon?

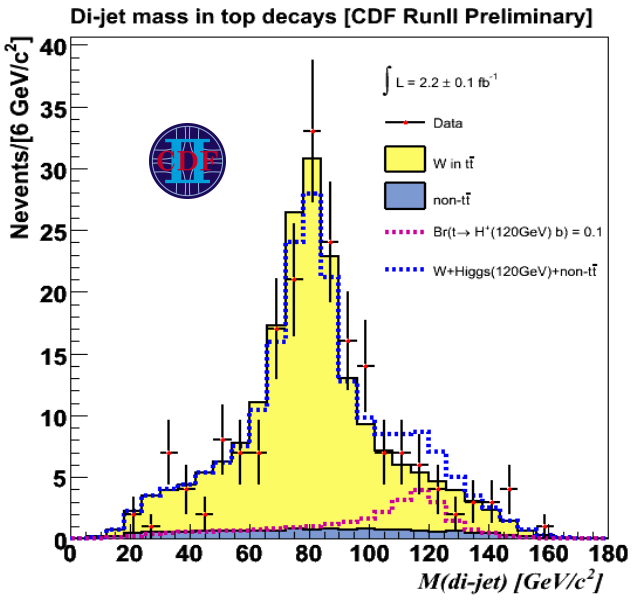
STAY TUNED!

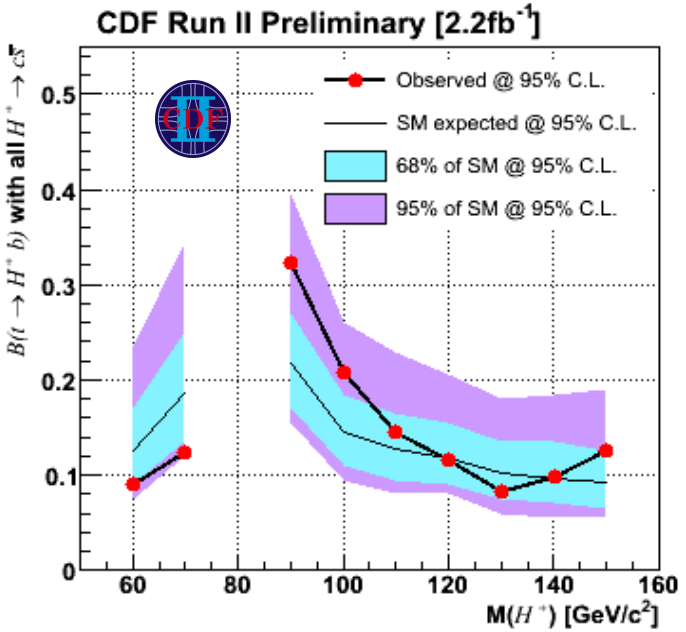
Charged Higgs

- Extended Higgs sector → Five physical Higgs Bosons: A^0, h^0, H^0, $\mathbf{H^\pm}$
  - Realized in MSSM
- $m_t > M_{H+}$: Decays $t \to W^+b$ and $t \to H^+b$ can compete
  Here: Searches considering $H^+ \to \tau\upsilon$, $c\bar{s}$ or W^+A !
- Strategy 1:
  Different behavior in same final state for increasing $B(t \to H^+b)$
- $B(H^+ \to c\bar{s}) = 100\%$: Reconstruct invariant mass of non-b-jets



  - M(di-jet) templates different for W & H^+



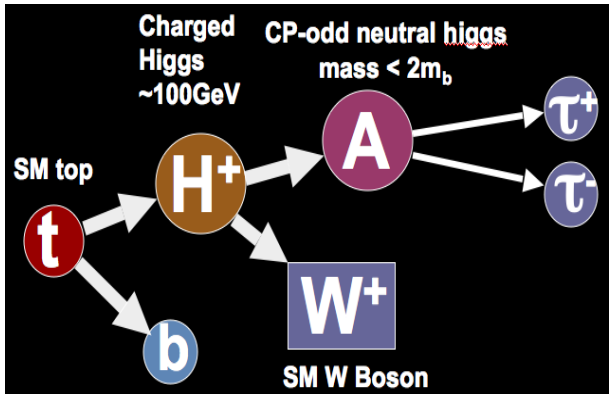


Most stringent limits for $H^+ \to c\bar{s}$

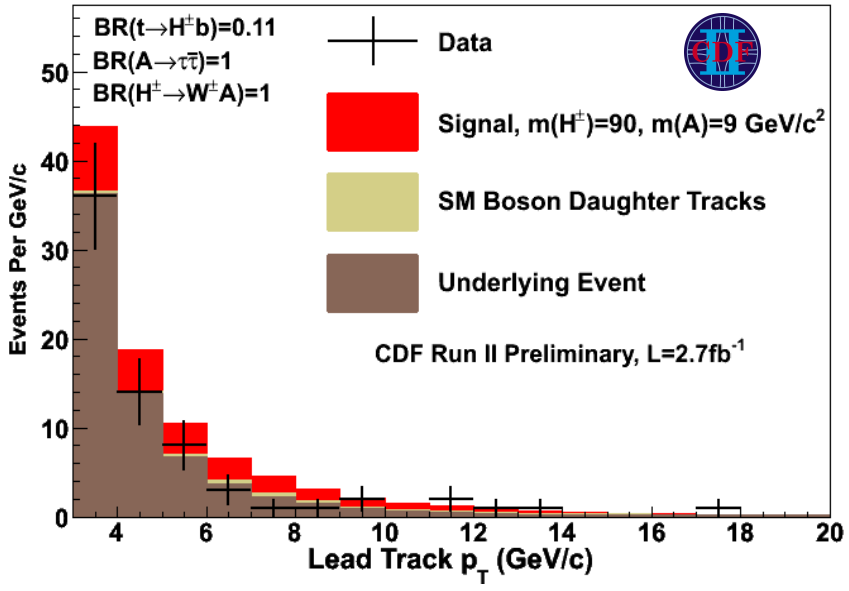
PRL 103 101803

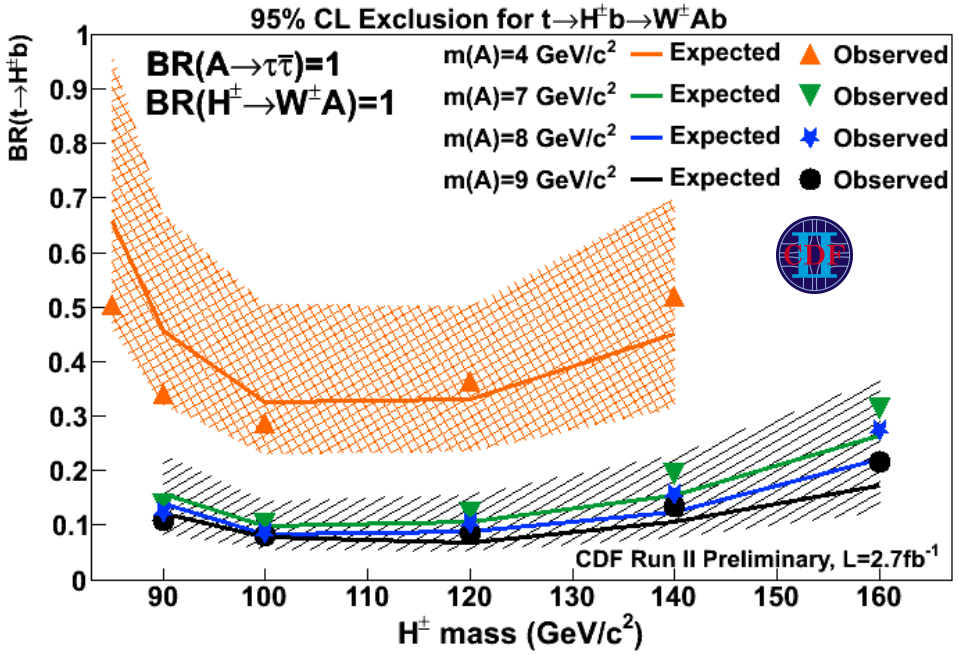
Charged Higgs

- nMSSM: allows neutral Higgs mass below LEP limits
- $B(H^+ \rightarrow W^+A)=100\%$: In nMSSM no limits existed for $H^+ \rightarrow W^+A$ when $m_A < 2m_b$



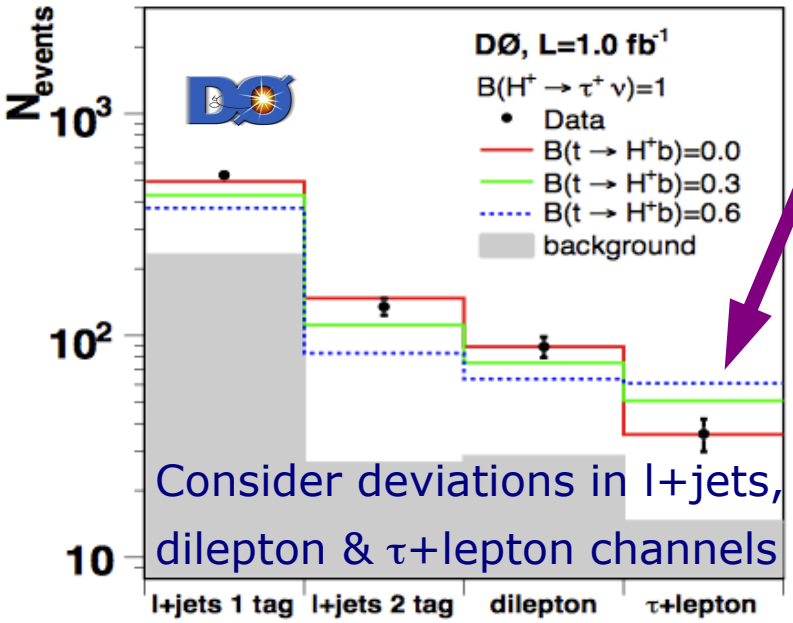
- Method:
  Look for low p_T isolated track created from τ decay





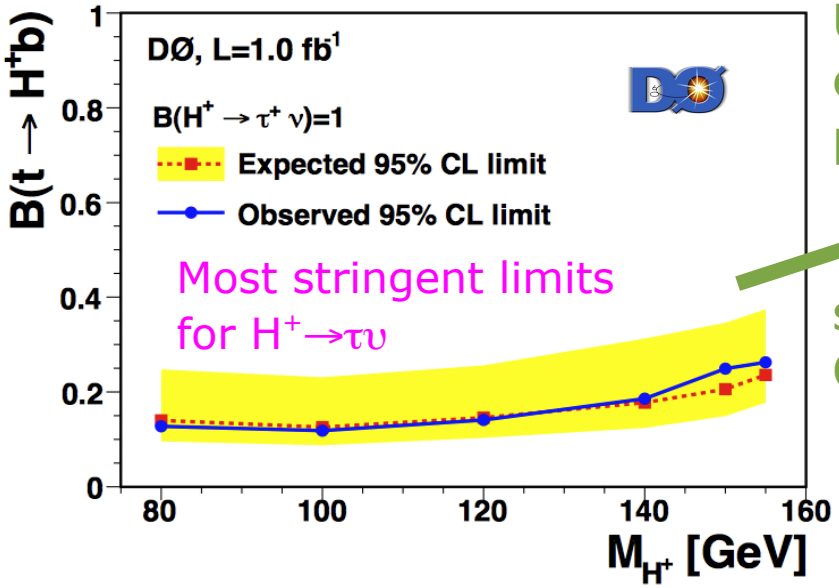
Most stringent limits for $H^+ \rightarrow W^+A$

Charged Higgs

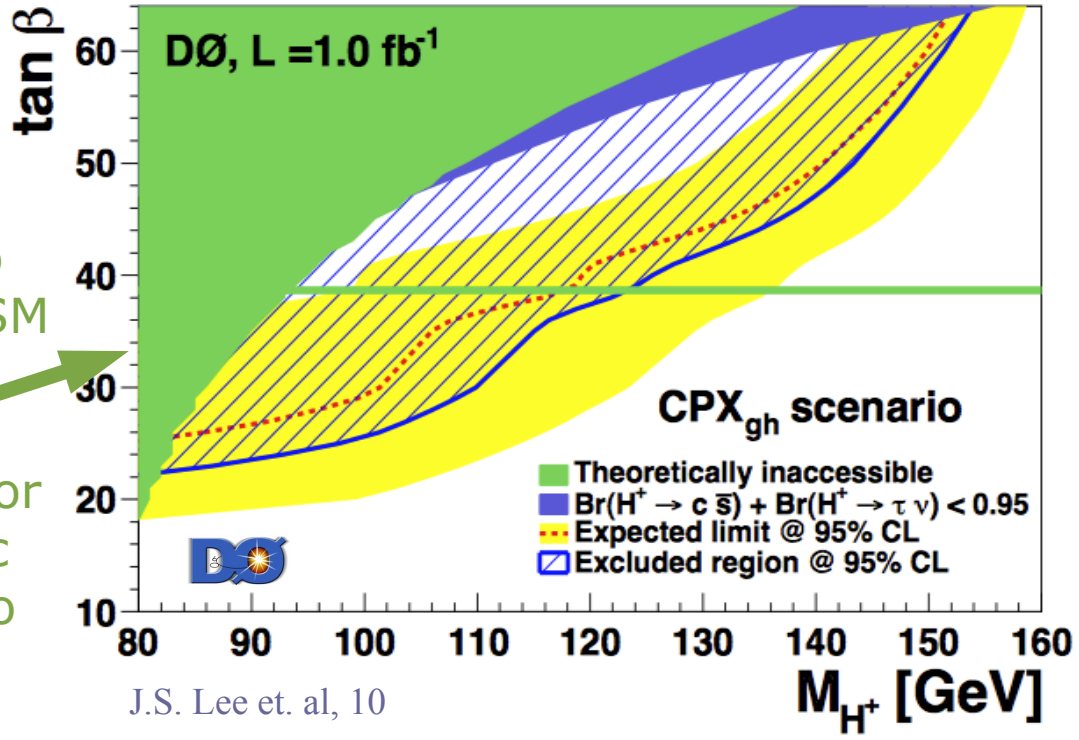


- Strategy 2: Different behavior in different final states for increasing B(t→ H⁺b)
- B(H⁺→cs̄)=100%, B(H⁺→τυ)=100% or B(H⁺→cs̄)+B(H⁺→τυ)=100%

PLB 682, 278 (2009)



Use limits to exclude MSSM parameter space for strangephilic CPX scenario



J.S. Lee et. al, 10

First limits from Tevatron on CP-violating model!

Summary

- Rich Top Quark program at the Tevatron!
  - Precision measurements (cross section, mass)
  - Many new properties analyzed for the first time (e. g. mass difference, $t\bar{t}$ helicity)
  - Sensitive searches, e. g. , t', charged Higgs

- Just an excerpt of results shown here – full beauty of top results at

D0: http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

CDF: http://www-cdf.fnal.gov/physics/new/top/top.html

- Great performance of the Tevatron
  - ~7fb^{-1} of data on tape per experiment!

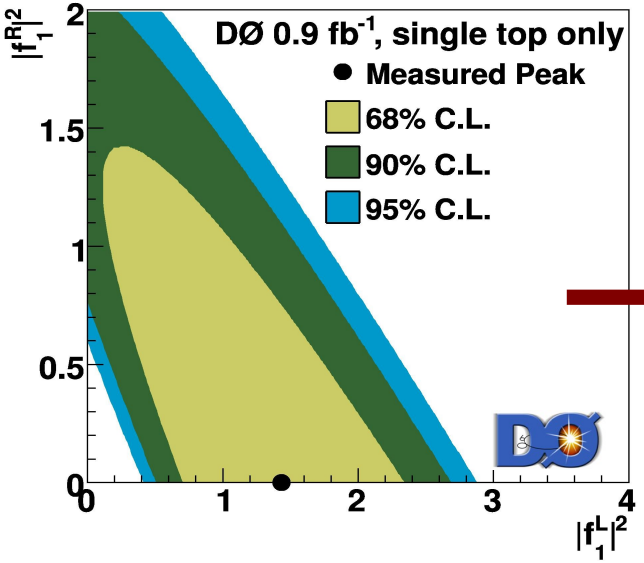
→ More data to analyse, more physics to explore!

BACKUP

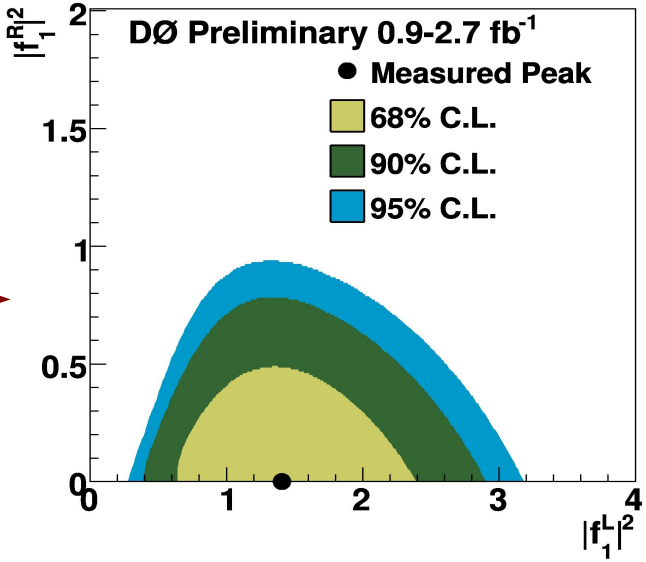
W helicity and anomalous couplings

- Form factors f_1^L, f_1^R, f_2^L, f_2^R: Can be extracted in single top channel
- Single top and W helicity measurement:
  - Usage of all applicable top quark measurements

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu V_{tb}(f_1^L P_L + f_1^R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu V_{tb}}{M_W}(f_2^L P_L + f_2^R P_R)tW_\mu^- + h.c.$$



Single top alone



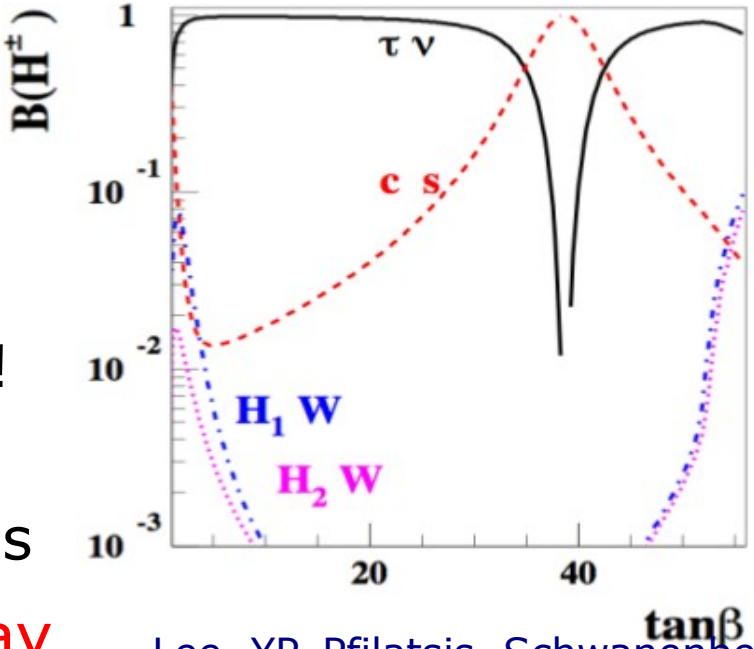
Single top and W helicity

Two Higgs Doublet Model (2HDM)

- Extension of the Standard Model with a second complex Doublet
  - Two vacuum expectation values v_1 and v_2
  - In total five physical Higgs Bosons: A^0, h^0, H^0, $\mathbf{H^{\pm}}$
- Higgs-Fermion couplings not fixed by the model – but requirement: Avoid FCNC
  - TYPE I: only one Higgs doublet couples to Fermions
  - TYPE II: one Higgs doublet couples to up-type Fermions, the other to down-type Fermions
  - Type III: both Higgs doublets couple to fermions
- MSSM: Type II 2HDM needs to be realized
  - Leading order: independent parameters: m_A and $\tan(\beta)=v_1/v_2$

Strangephilic CPX Benchmark Scenario

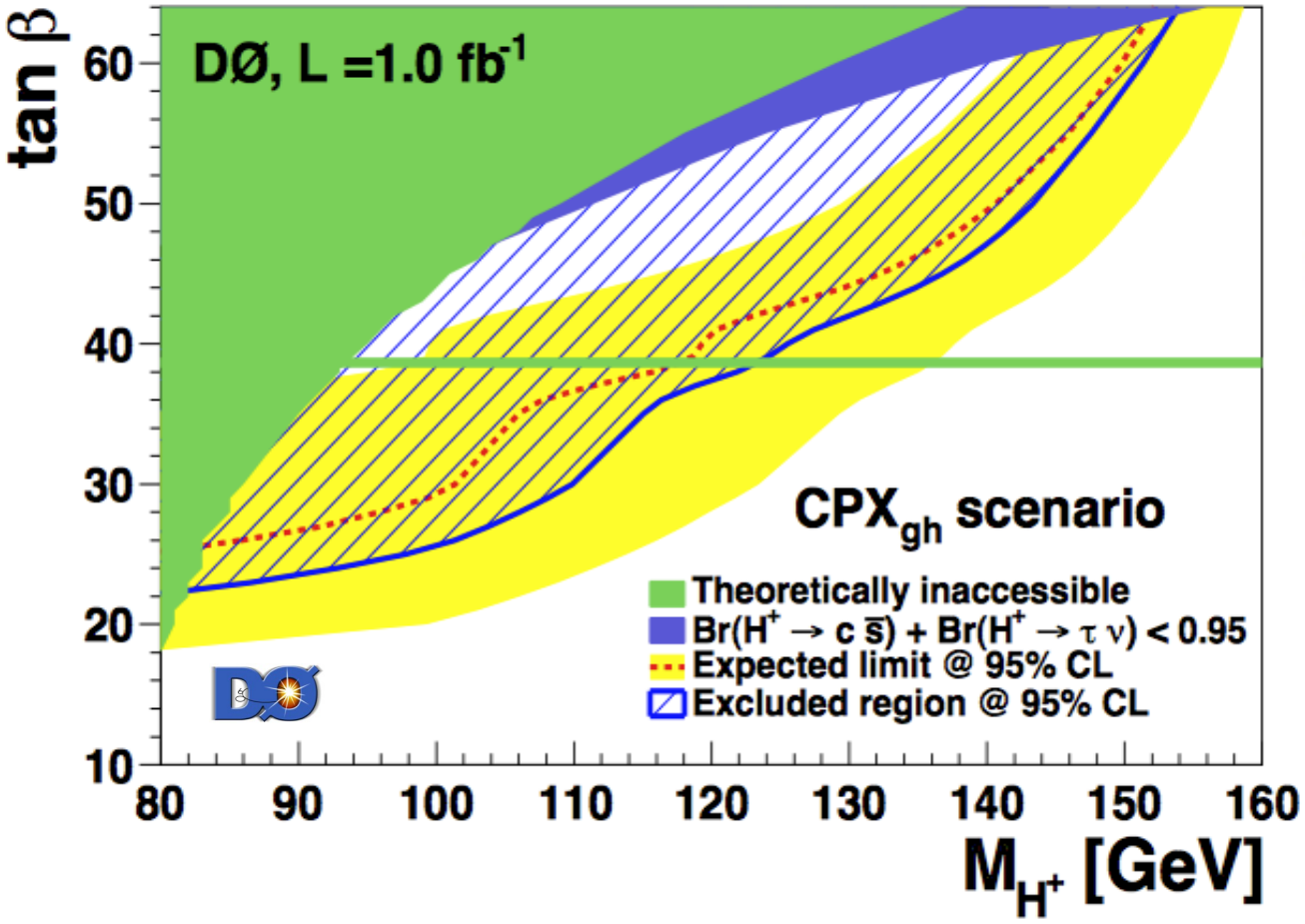
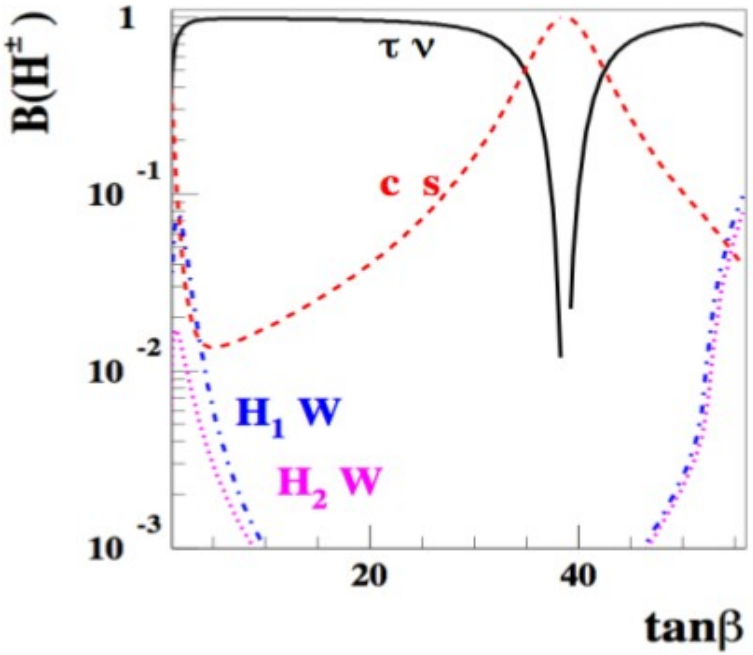
- Use the limits on the top to charged Higgs branching ratio to exclude MSSM parameter space
  - Example: strangephilic CPX scenario
- Hierarchy between first two and third generation introduced
  - Enhanced s-quark Yukawa coupling
- Neutral Higgs:
  Higher branching ratio $h \to s\bar{s}$
  - Attention Higgs hunters: Hard to identify!
    - None of current Tevatron Higgs searches would see strangephilic Higgs
- Charged Higgs: Increased $\tau\nu$ and $c\bar{s}$ decay



Lee, YP, Pfilatsis, Schwanenberger
arxiv:0909.1749[hep-ph]

Strangephilic CPX Benchmark Scenario

- With presented limits: Sensitive to strangephilic model
- Assume: $B(H^+ \to c\bar{s}) + B(H^+ \to \tau\nu) = 100\%$



First limits from Tevatron on CP-violating model!