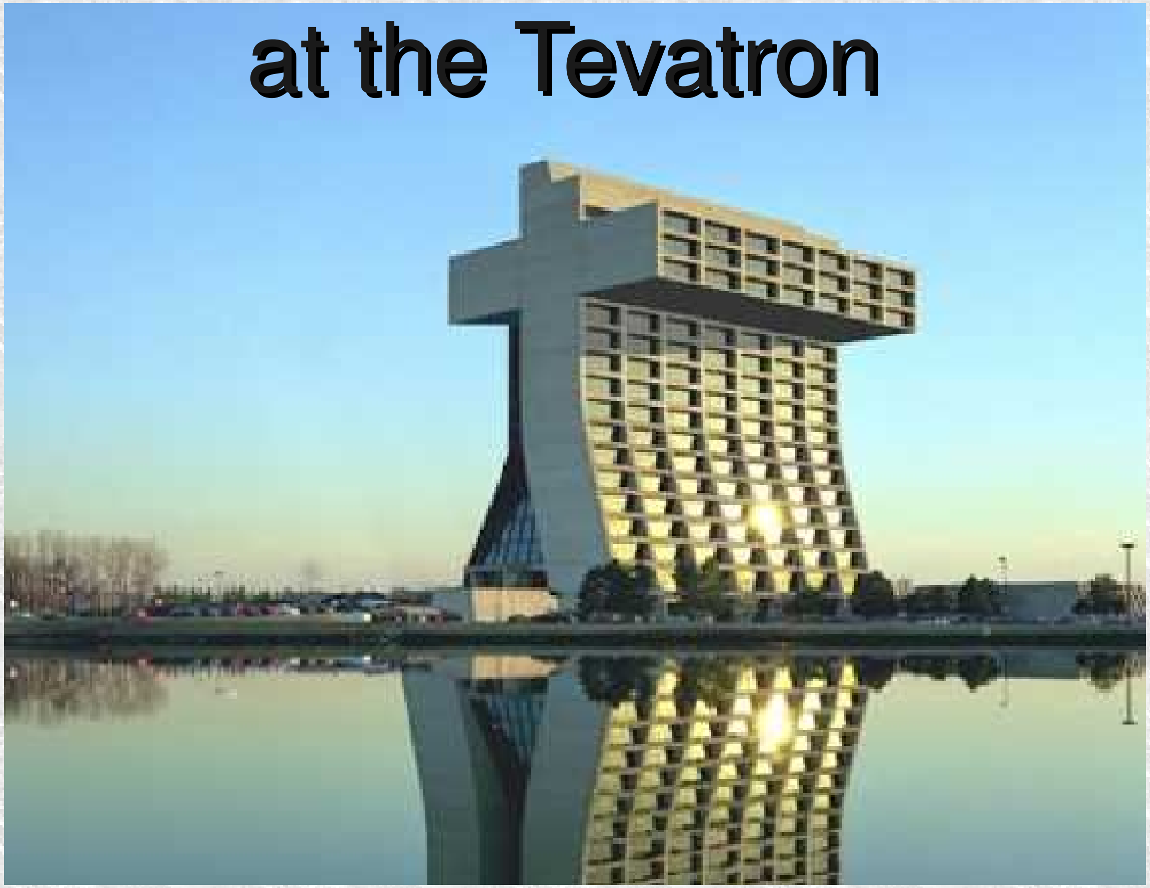
Top Quark Physics at the Tevatron



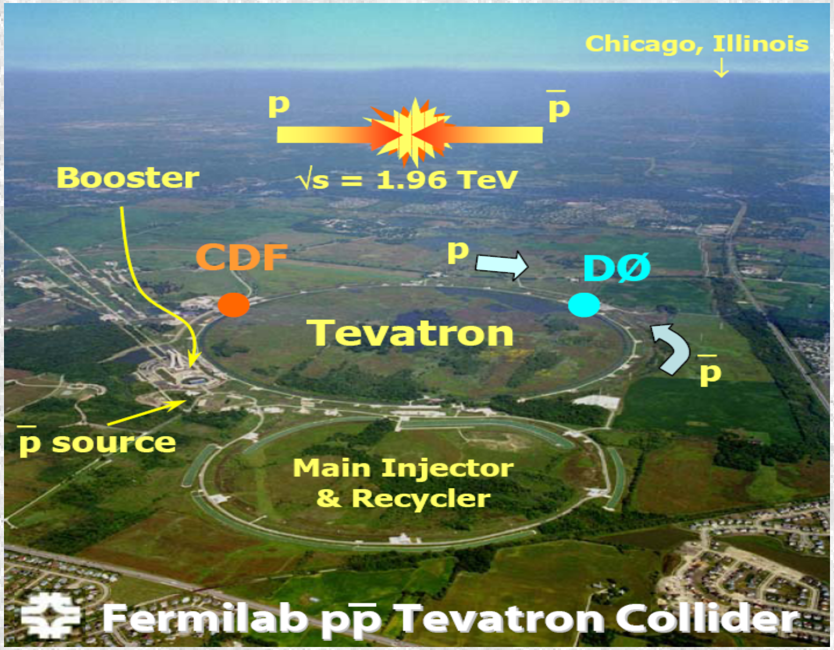
Maxim Perfilov

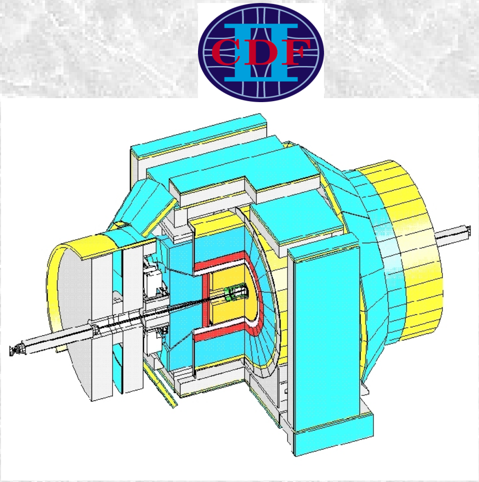
on behalf of

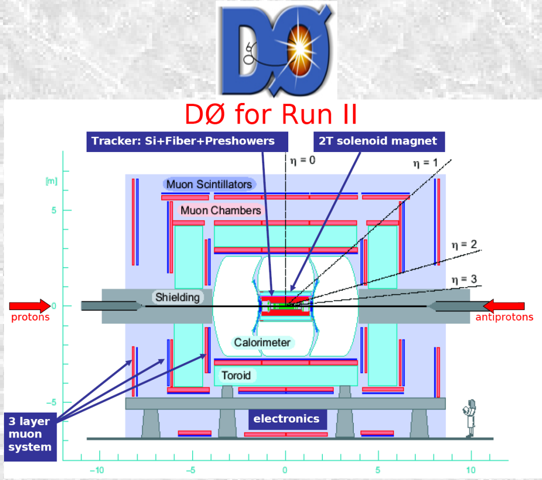
CDF and D0 collaborations

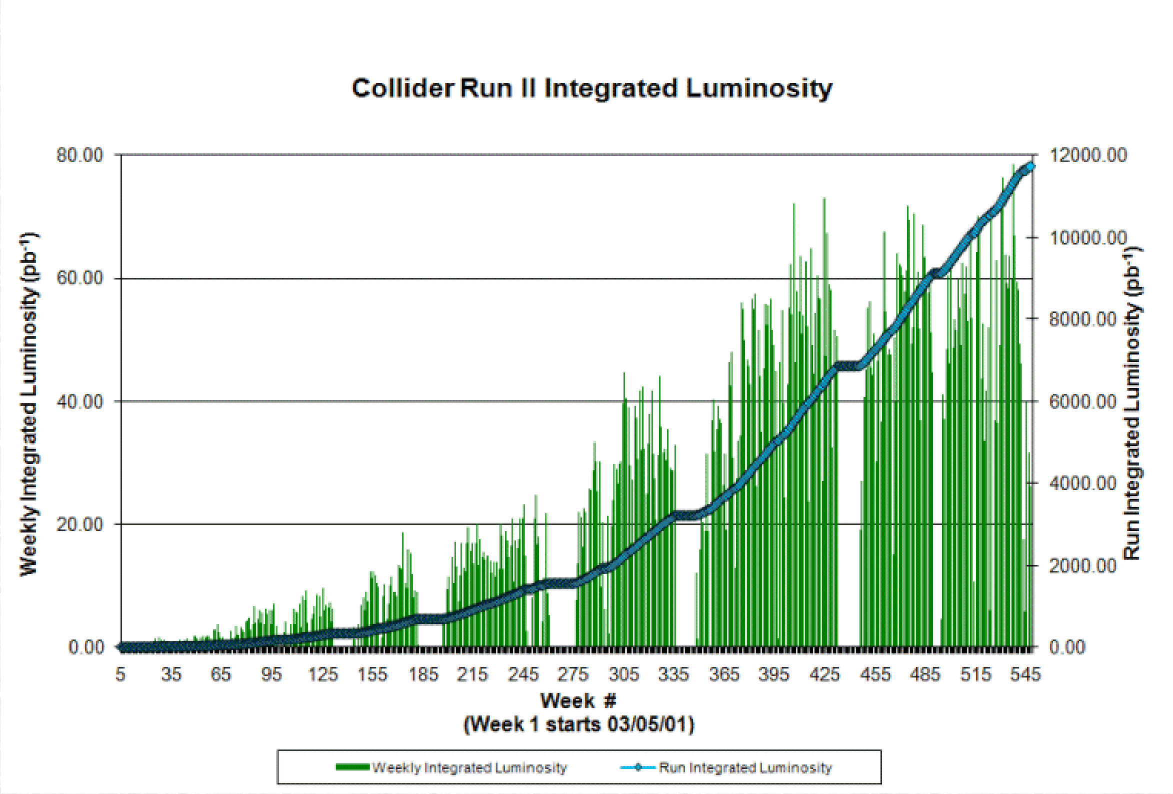
QFTHEP-2011

Tevatron









- Maximum instantaneous luminocity ~$4*10^{32}sm^{-2}sec^{-1}$
- 396 ns between bunches
- We'll have more than $10fb^{-1}$

Run II:

March, 1st, 2001 -

September, 30th, 2011 :(

A few words about Top Quark:

- The heaviest (and the point-like) quark:

Mtop = 173.2 ± 0.9 GeV
(Tevatron 2011 July combination)

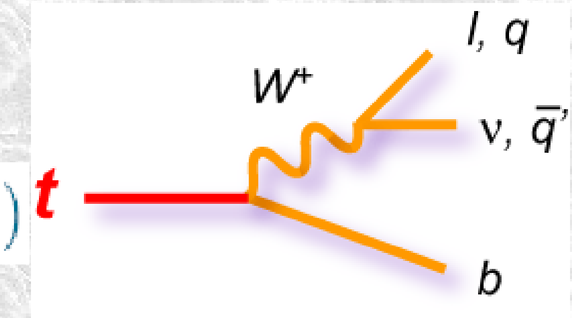
  - has a mass on the same order as the EW symmetry breaking scale

- Top Quark decays before hadronization

$$\tau_{\mathrm{top}} = 4 \cdot 10^{-25}\,\mathrm{sec}\ ,\ \tau_{\mathrm{hadr}} = 3.3 \cdot 10^{-24}\,\mathrm{sec}$$

- Top Quark decays through ONE decay channel

$$t \rightarrow bW^{+},\ \mathrm{BR}(t \rightarrow \mathrm{other}) \leq \mathcal{O}(10^{-3})$$



  - spin information of the Wtb vertex

- Many of the SM extensions explain the large Top mass by allowing the Top to participate in new dynamics

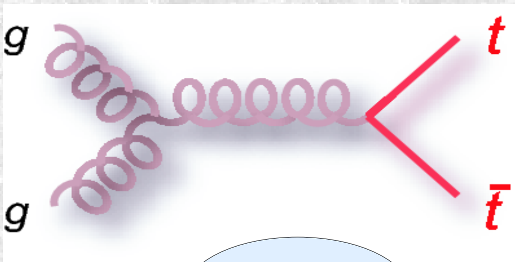
- Top Quark is the good candidate to test the SM

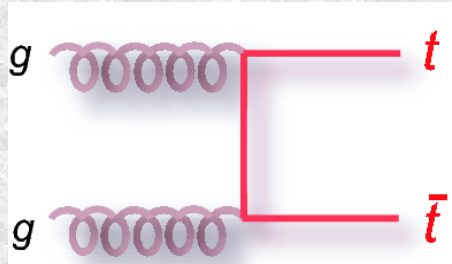
  - and search for the possible deviations from the SM

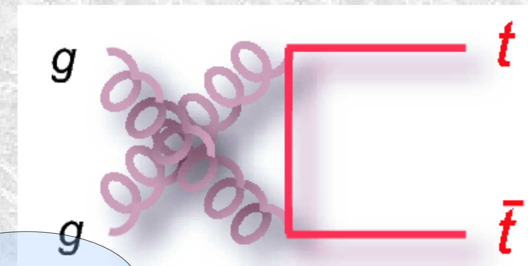
The main Top Quark production processes at Tevatron:

- Pair production: cross sections

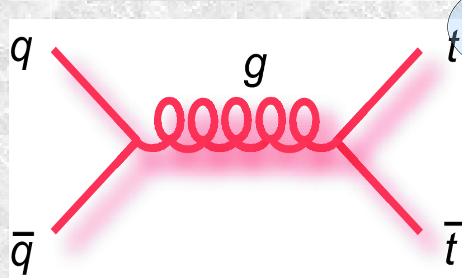
Top mass: **175 GeV**







~85%

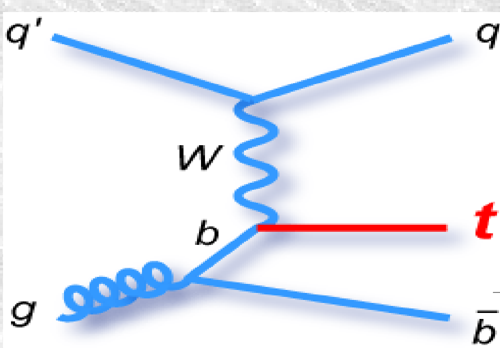


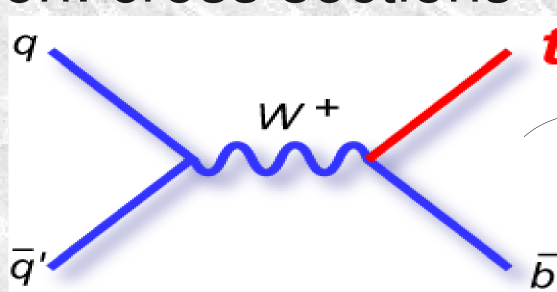
~15%

(Moch and Uwer)

6.90 +0.44 −0.62 pb

- Single Top production: cross sections





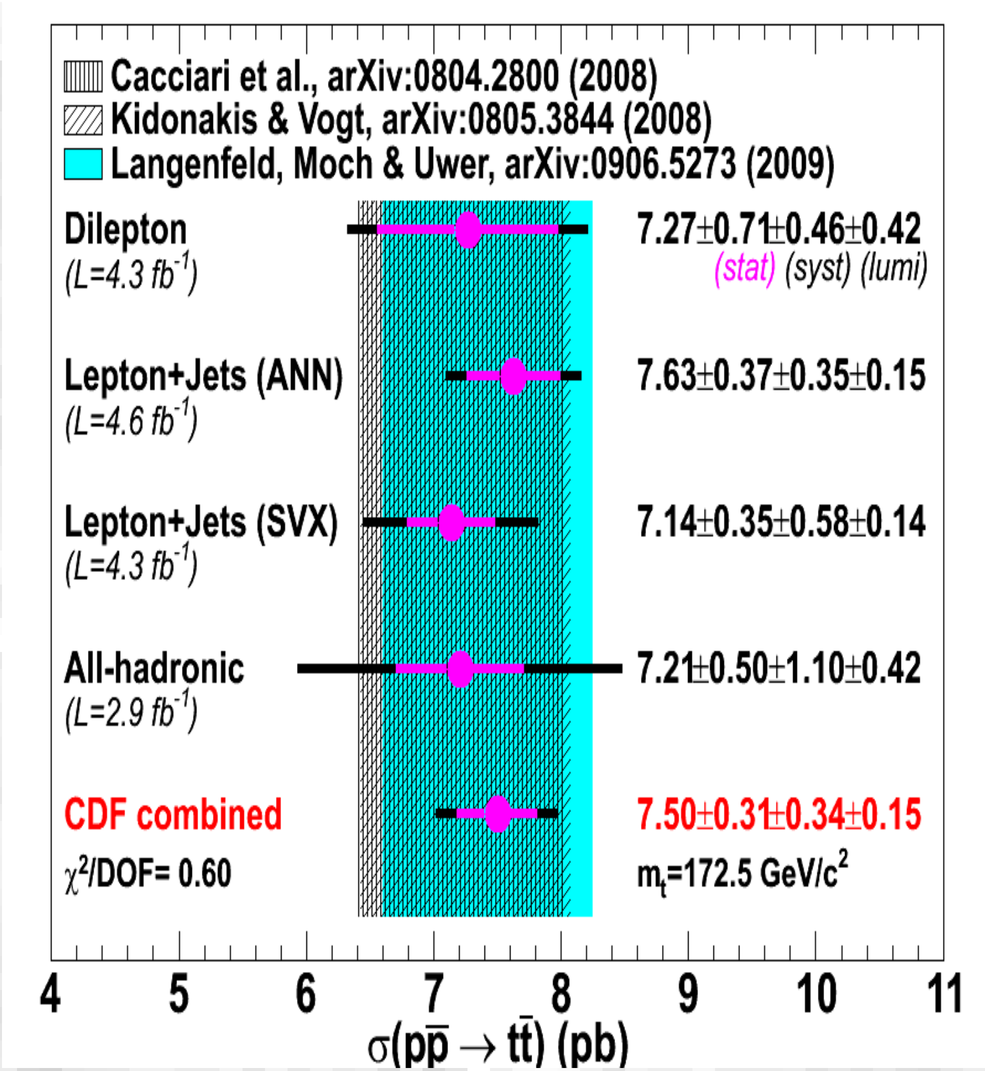
s-channel tb — 0.98 ± 0.04 pb

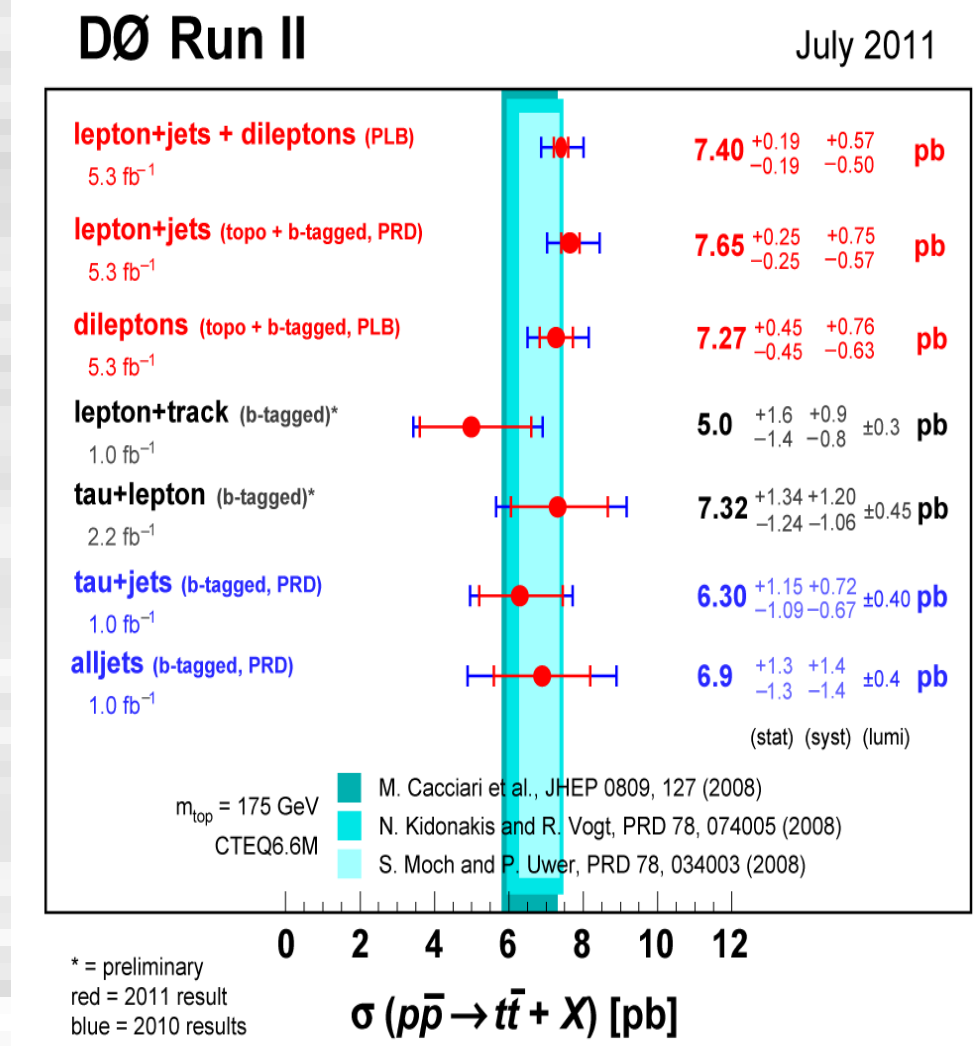
t-channel tqb — 2.16 ± 0.12 pb

(Kidonakis)

Double Top Production

- *Cross section measurement*
- *Top Quark mass measurement*
- *Top Quark Width measurement*
- *Spin correlations*
- *Forward-Backward Charge Asymmetry*
- *Heavy Top Quark search*





7.5 + 0.31 - 0.34 | **Double Top CS** | 7.56 + 0.63 – 0.56

- CS are in agreement in different channels

Top Quark Mass

- Why is it necessary to measure the top quark mass?

  - free parameter in SM

  - constrain the SM Higgs mass and W boson mass

  - check the consistency of SM (if Higgs will be found)

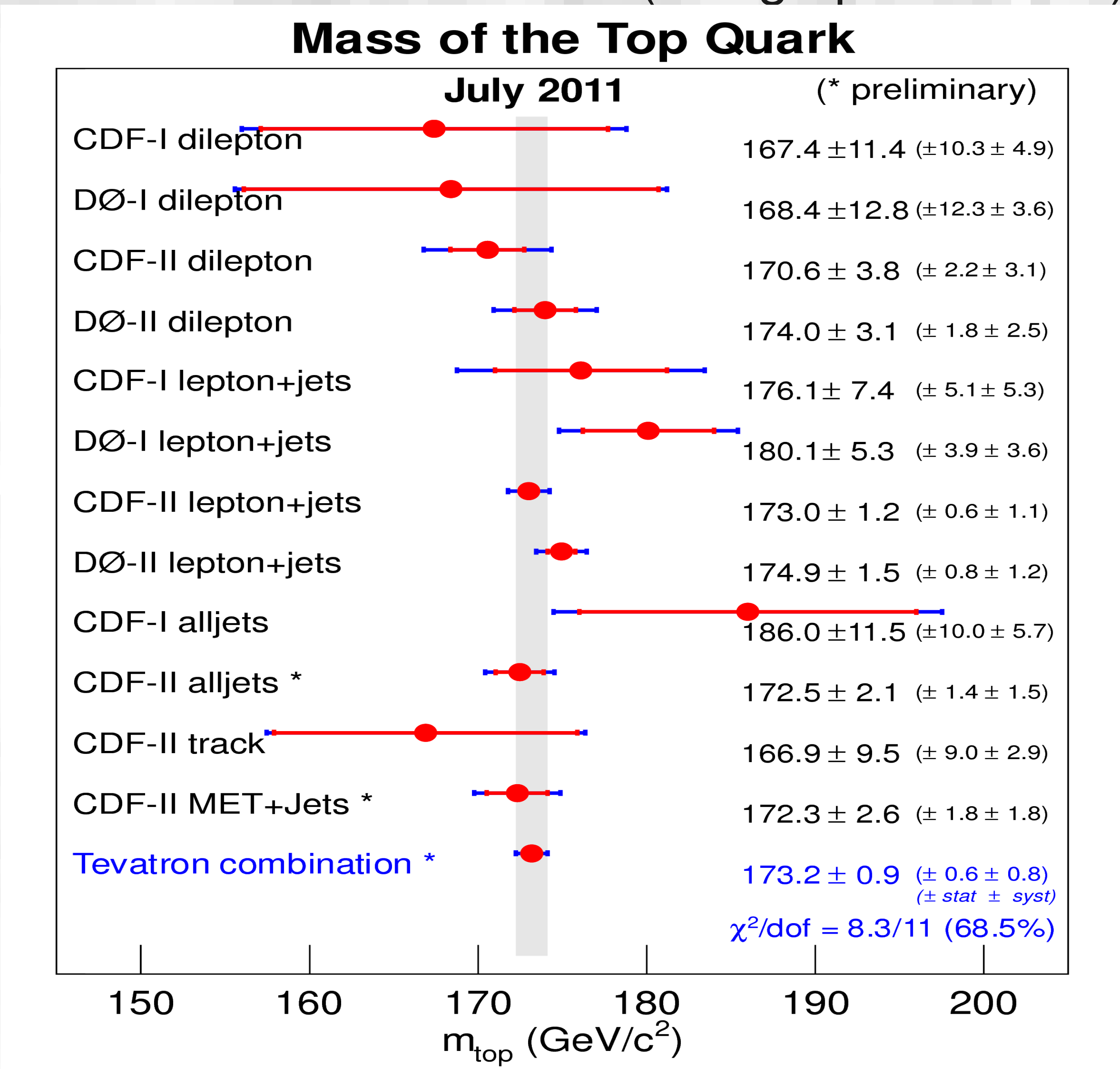
- Two main methods to measure the top quark mass at Tevatron

  - Template method: compare distribution of an observable in data with MC templates generated with different masses

  - Matrix element method:: calculate event-by-event likelihood function, vs generated top mass using convolution of the LO matrix element and the detector resolution function

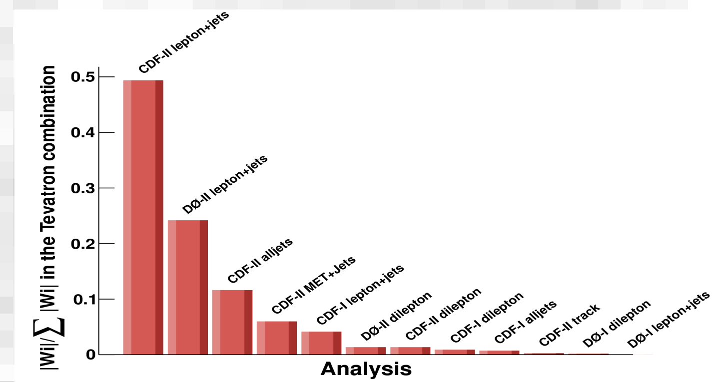
Top Physics at Tevatron: Top quark mass

- Tevatron combination (using up to 5.8 fb^{-1}):



M_{top}=173.2+/-0.9 GeV

(PDG: M_{top}=172.9)



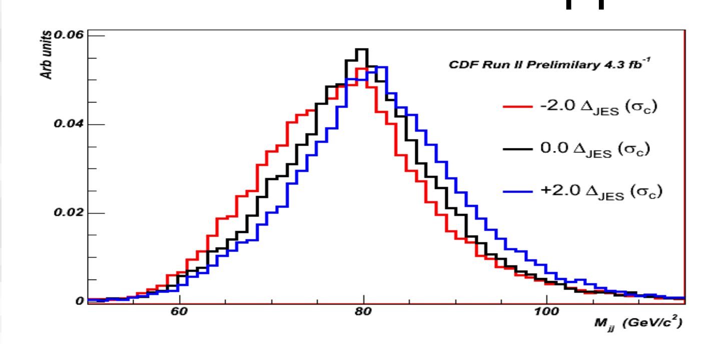
Each analysis weights

Top Quark Width

- CDF, lepton+jets channel, 4.3fb^{-1}

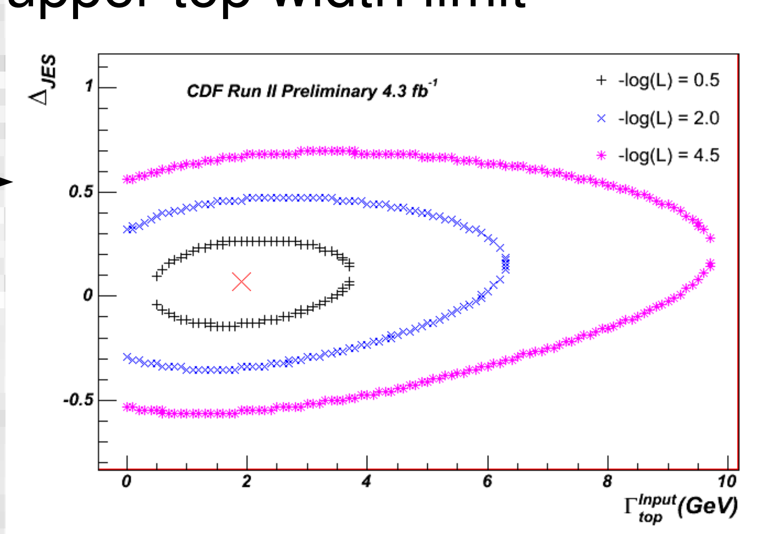
$$\Gamma_t^0 = |V_{tb}|^2 G_F m_t^3 / (8\pi\sqrt{2})$$

- Reconstructed Mt and MW for each event are compared with templates of different top widths, M_t set to be 172.5 in MC
- Feldman-Cousins approach to establish the upper top width limit

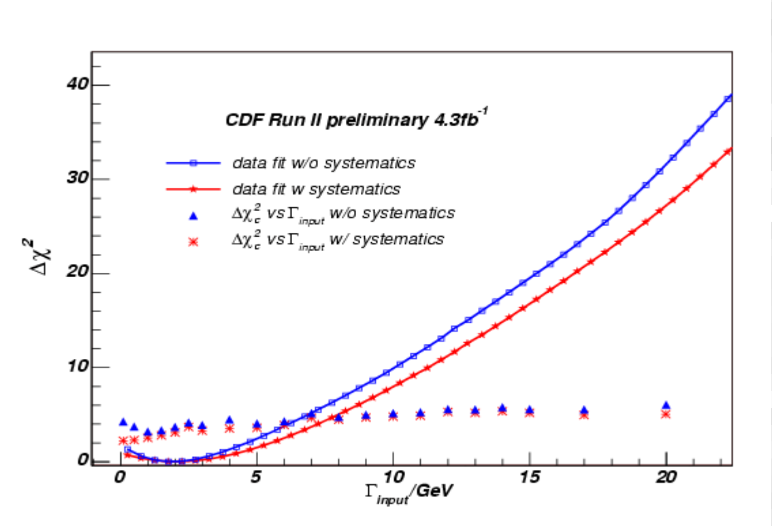


Mjj for 1 b-tag sample

intermediate analysis plots



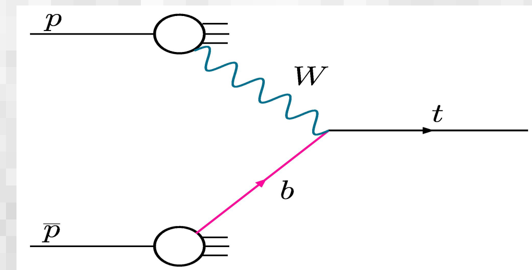
The best fit picture

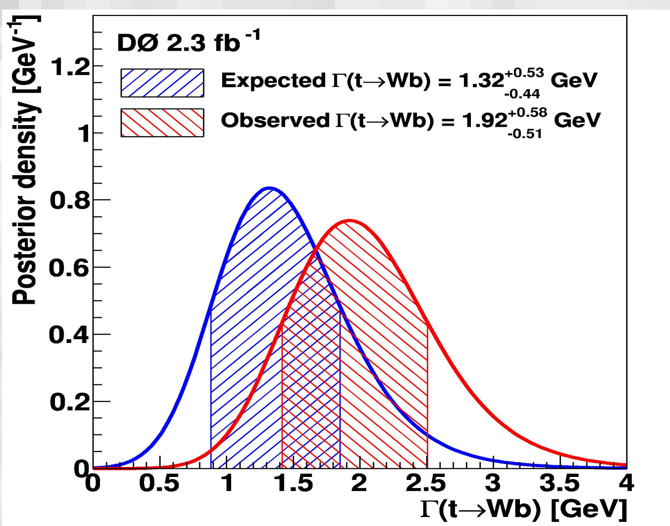


From the interception of the overlapped plots sets the upper limit of top quark width

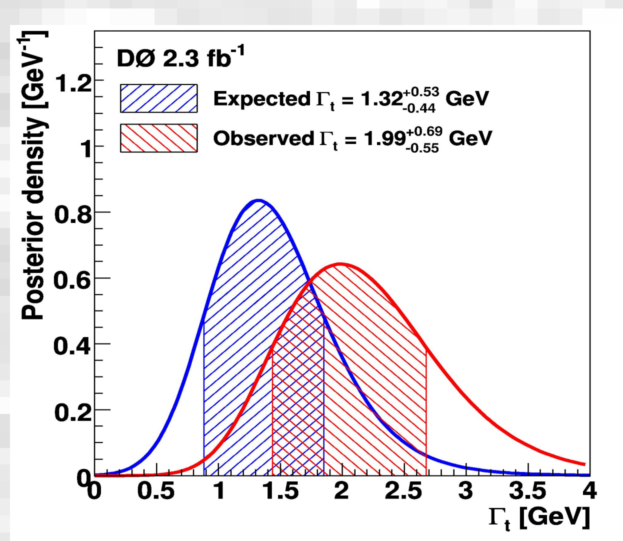
$$\Gamma_{top} < 7.6\ \mathrm{GeV\ at\ 95\ CL}$$
$$(\tau_{top} > 8.7 \cdot 10^{-26}\ \mathrm{sec}),$$
$$0.3 < \Gamma_{top} < 4.4\ \mathrm{GeV\ at\ 68\ CL}$$

- D0, 2.3fb^{-1}, indirect search
- Extract the value of the top quark width from the partial decay Γ(t->Wb) measured using the t-channel CS for single top production and from the branching fraction B(t->Wb) measured in tT





Probability density for partial width

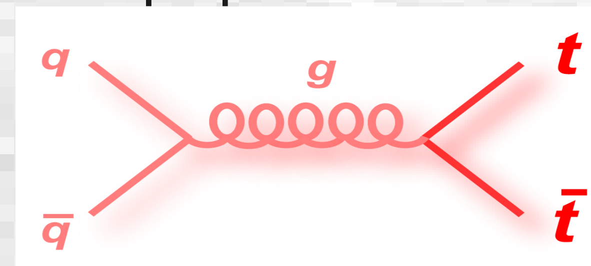


Probability density for total width

$$\Gamma_{top} = 1.99^{+0.69}_{-0.55}\,\mathrm{GeV}$$
$$\left(\tau_{top} > 3.3^{+1.3}_{-0.9} \cdot 10^{-25}\,\mathrm{sec}\right),$$
$$|V_{tb'}| < 0.63$$

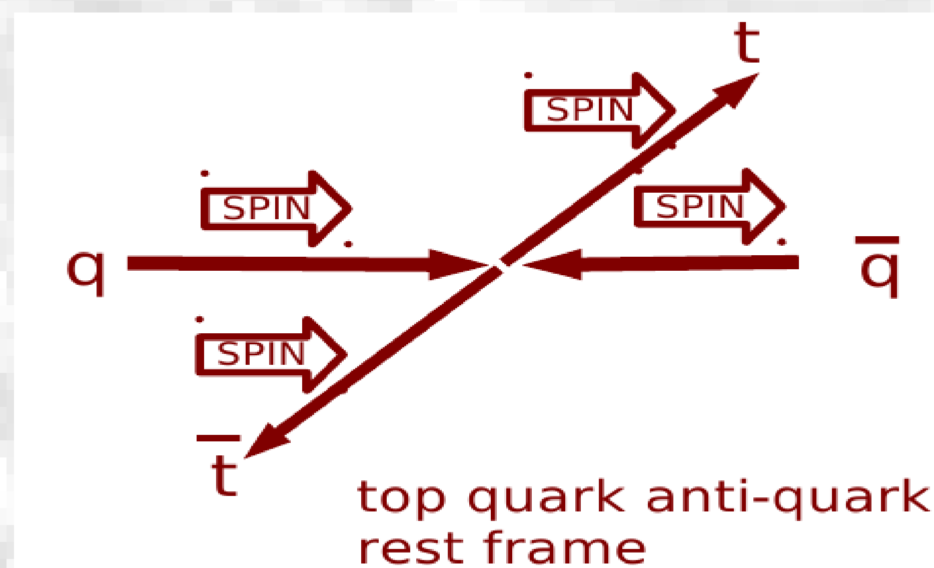
Spin Correlations

- Correlation between the spins of top and antitop quarks
- Top quark decays before hadronization
  - *top quark spin information transmitted to its decay products*

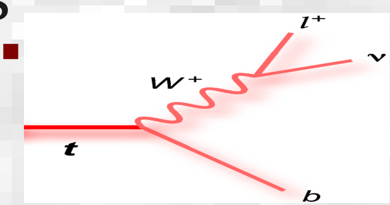


Dominant process, so S=1 in SM

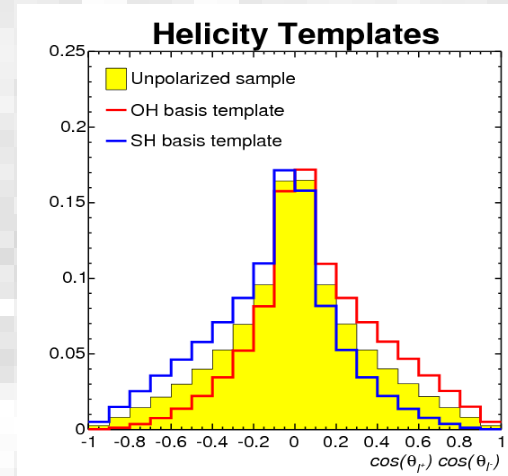
- Spin correlation value may be affected by the non SM scenario
- Two method for spin correlation measurement
  - *angular distribution templates*
  - *matrix element method*



Top Physics at Tevatron: Spin correlations



- CDF, 5.3fb^{-1}, lepton+jets, template method
- MC samples which are correspond to 4 possible ttbar helicity states
  - templates were created by combining (LR, RL) and (LL, RR) samples (OH and SH samples)
  - beamline basis templates
- Fitting method is a binned likelihood fit to the data, using three separate templates
  - the SH, OH and BckgrH templates



Distribution of cosine product variable

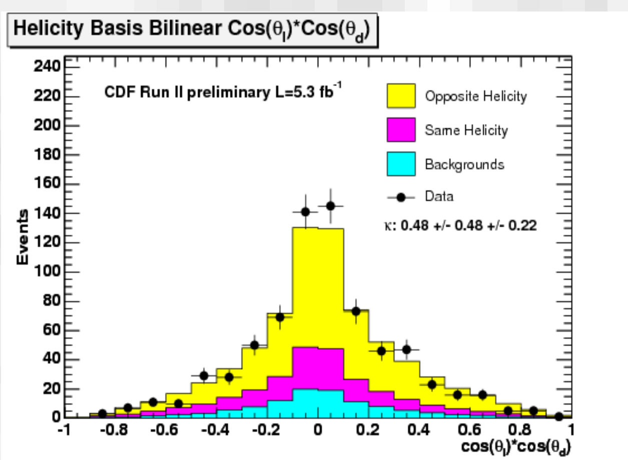
Results

in helicity basis: $\mathbf{F_{OH} = 0.74 \pm 0.24stat \pm 0.11syst}$

$\mathbf{K_{Helicity} = 0.48 \pm 0.48stat \pm 0.22\ syst}$

In beamline basis: $\mathbf{F_{SH} = 0.86 \pm 0.32stat \pm 0.13syst}$

$\mathbf{K_{Beam} = 0.72 \pm 0.64stat \pm 0.26\ syst}$



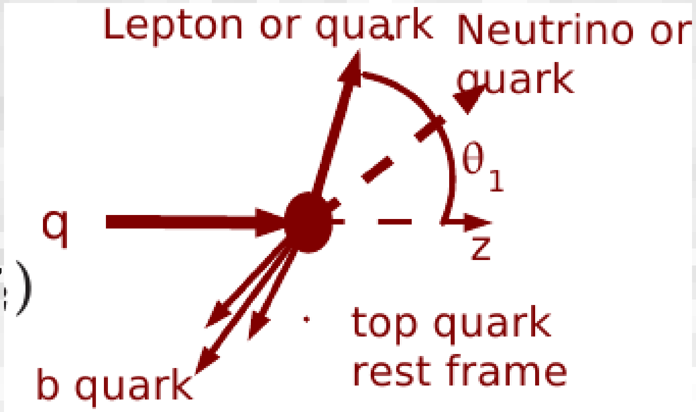
Helicity basis distribution of the cos(θlep)cos(θdown) where OH fraction in signal is 0.74

Top Physics at Tevatron: Spin correlations

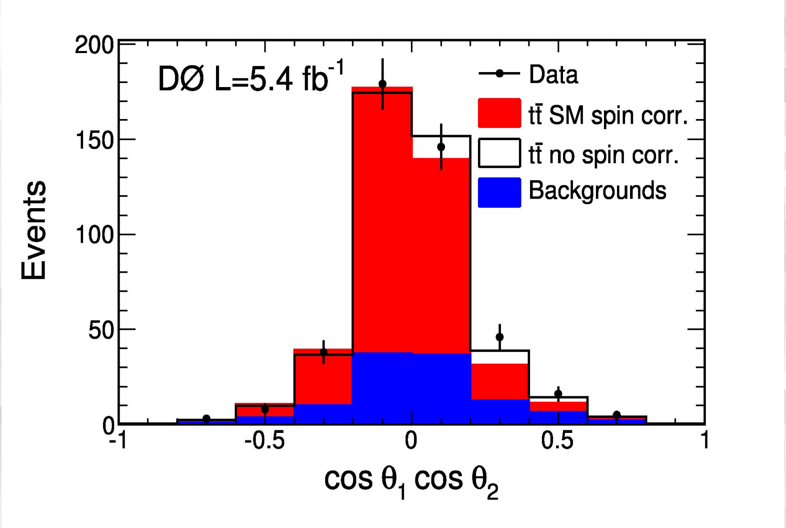
- D0, 5.4fb^{-1}, tT, dilepton final state
- related to the $|V_{tb}|$ without assumptions about number of quark generations
- tT spin correlation strength C is obtained from:

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

(NLO QCD predictions: C = 0.777)



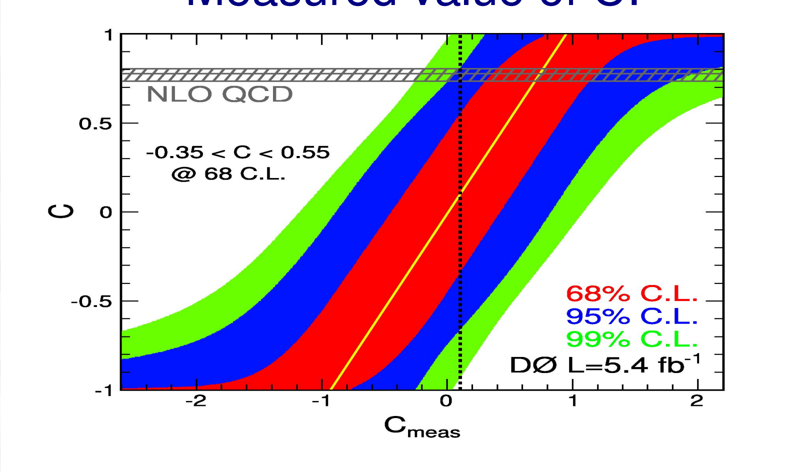
- MC samples with/without correlations



The distribution for the entire sample. The summed tT signal, incl. NLO QCD spin correlation and all bckgrds are compared to data

- Binned maximum likelihood fit

Measured value of C:

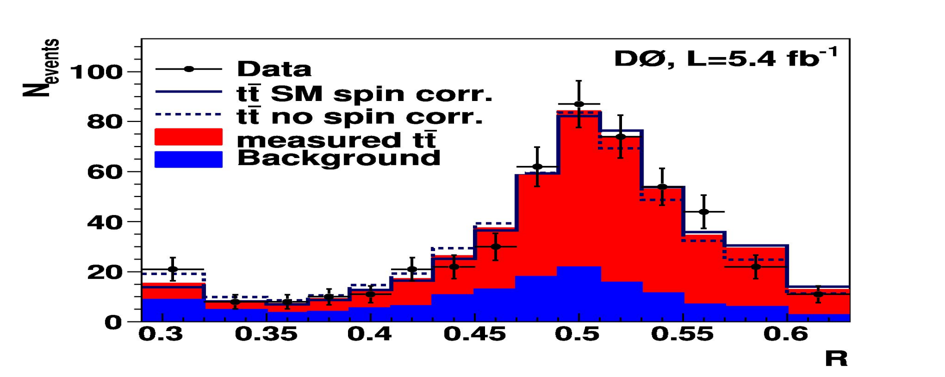


Results:

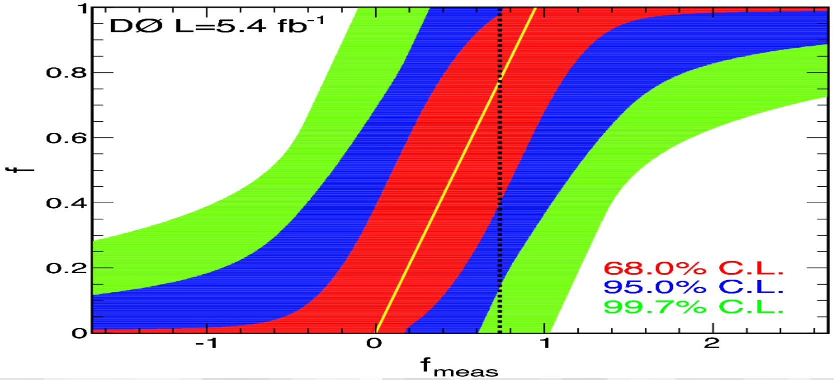
$$C = 0.10^{+0.45}_{-0.45}\ (\text{stat+syst})$$

Top Physics at Tevatron: Spin correlations, ME approach

- D0, 5.4fb^{-1}, tT, dilepton final state
- Hypothesis that the spins of tT are uncorrelated
- Matrix-element-based approach
  - exploring the full matrix elements in LO QCD
- Define descriminator $$R = \frac{P(H=1)}{P(H=0)+P(H=1)}$$
- Result on template fit: f=0.74+0.40-0.41 (stat+syst)
  - corresponds to C=0.57 +/- 0.31 (stat+syst)



The predicted discriminant distribution R for the combined dilepton sample for the fitted cross section of tT sample compared to data



Different CL bands of **f** as **f**$_{meas}$ from likelihood fits to MC events. Vertical line corresponds to f=0.74

Forward-Backward Charge Asymmetry

- QCD predicts that top quark-antiquark production in quark and antiquark collisions is forward-backward symmetric at LO

  - possible asymmetry appears at higher order

- Asymmetry is such that top quark is preferentially emitted in the direction of the incoming light quark

  - antitop follows the direction of incoming antiquark

- asymmetry is a sensitive variable to test the new physics contribution

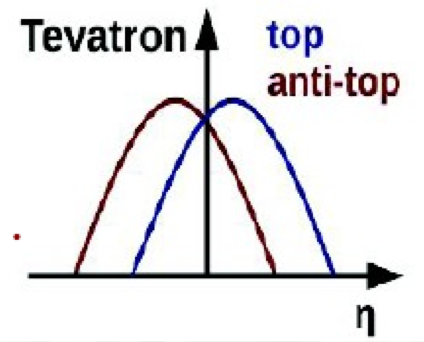
- A charge asymmetry can be observed as forward-backward asymmetry defined as:

$$A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}$$

$$\Delta y = y_t - y_{\bar{t}}$$

N- number of events

y - rapidities



SM predicts: A_{FB}= 0.06+/-0.01

Top Physics at Tevatron: FB charge asymmetry

- CDF, 5.3fb^{-1}, tT, combined result from lepton+jets and dilepton

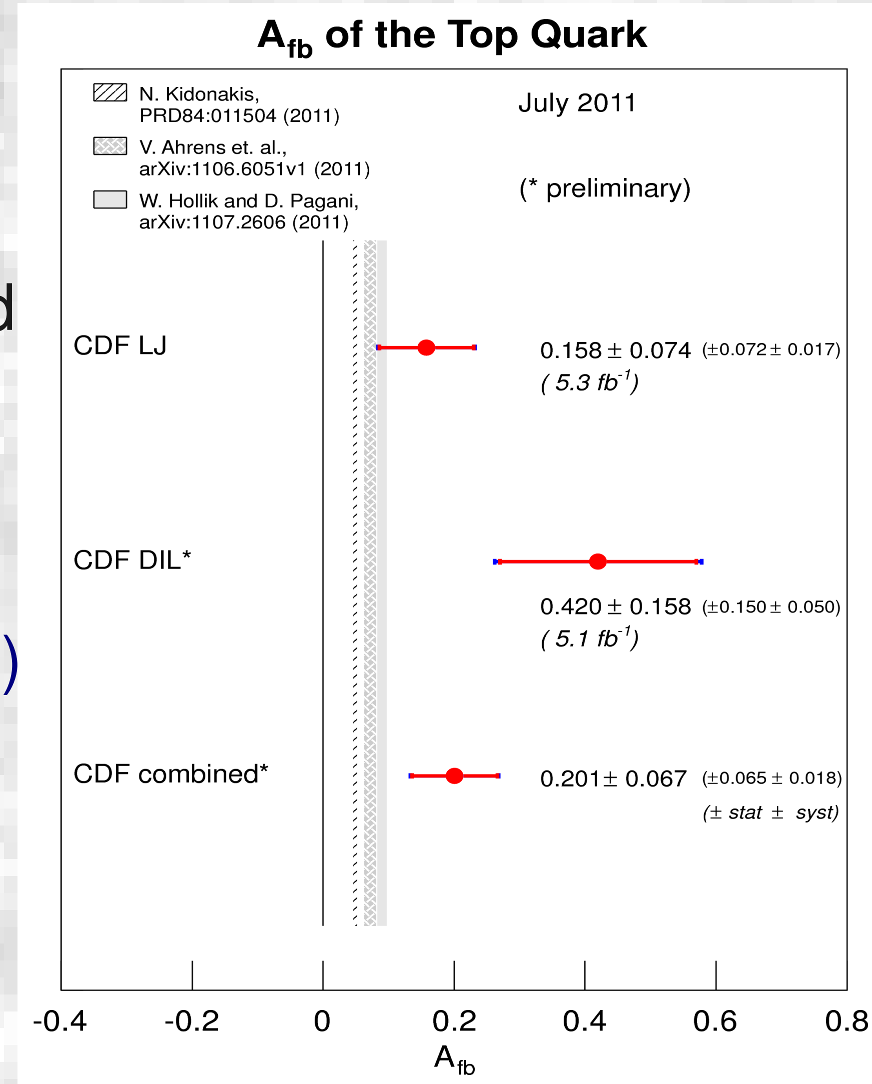
	L+J	DIL
A_{fb}	$0.158 \pm 0.072_{stat} \pm 0.017_{sys}$	$0.42 \pm 0.15_{stat} \pm 0.05_{sys}$

- Method: from the measured value and its uncertainty the effective numbers of events in the forward and backward directions can be estimated

- Results:

  A_{FB} = 0.201+/-0.065+/-0.018 (stat+syst)

  about 3 sigma away from no assymmetry

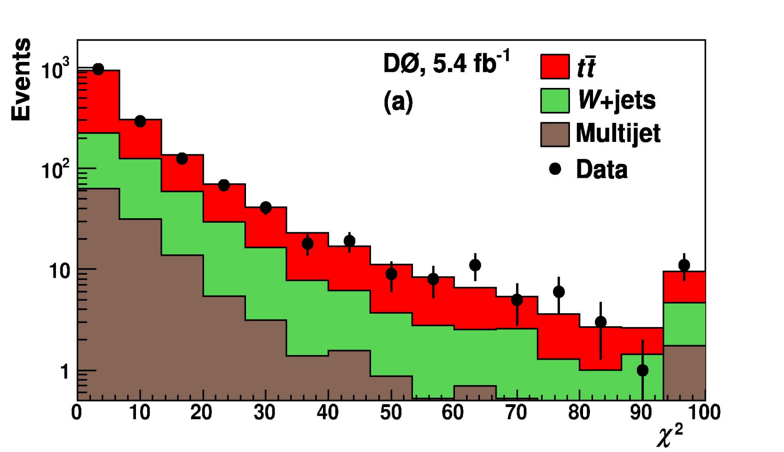


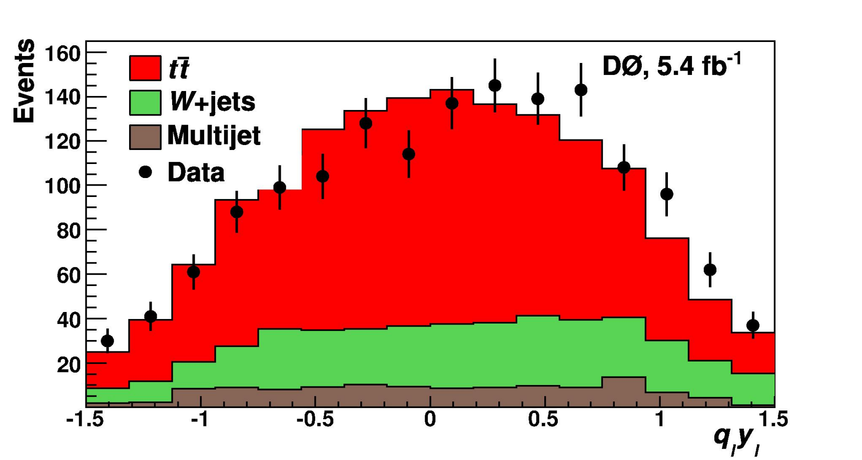
Top Physics at Tevatron: FB charge asymmetry

- D0, 5.4fb^{-1}, tT, lepton + jets
- Employ a kinematic fitting technique to fully reconstruct the tT events

  - the energies and angles of the detected objects are varied and the most likely jet-parton assignment is identified by minimizing a chi^2 function based on the experimental resolution

  - good agreement between data and simulation





The reconstructed charge-signed Lepton rapidity

- Results: A_{FB}= 9.2+/-3.7 %

  (theory: A_{FB}= 2.4+/-0.7 %);

  A_{FB}^{lept}= 14.2+/-3.8 %

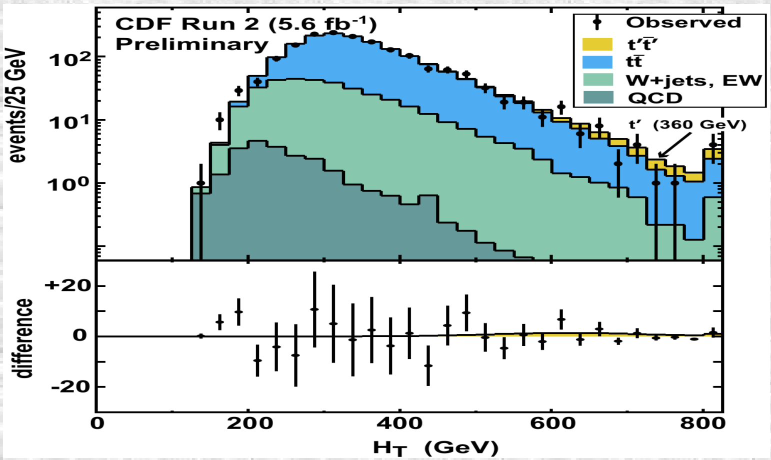
  (theory: A_{FB}^{lept}= 0.8+/-0.6 %)

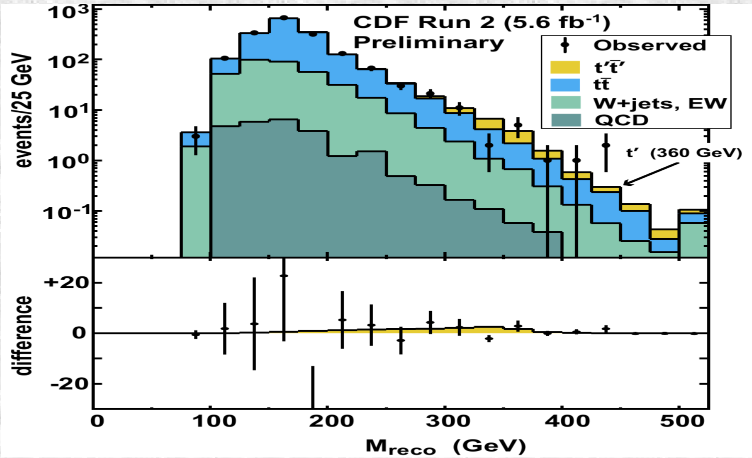
  - disagree with theory predictions with discrepancy above three SD

Heavy top (t') quark search

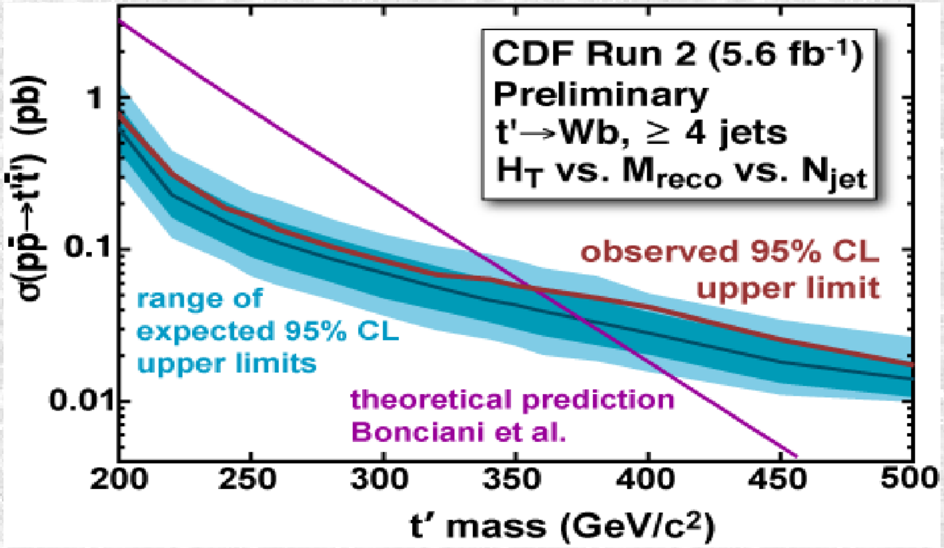
- CDF, 5.6fb^{-1}, lepton plus jets, t'T' production

  - t' is pair-produced strongly, M(t')>M(t), decays promptly to Wb final states





Distributions of HT and Mreco showing expected signal contribution for a t' mass of 360 GeV.



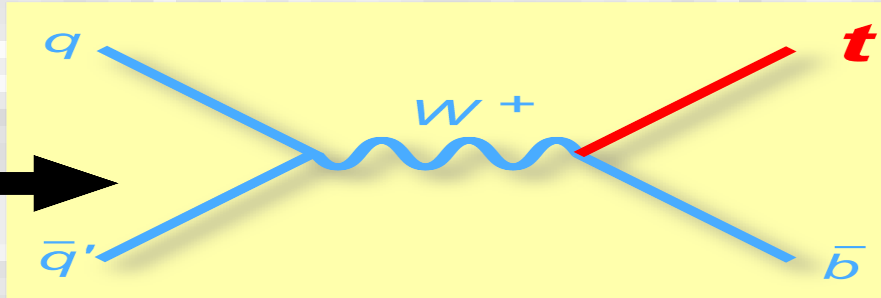
- exclude the standard model forth-generation t'-quark with mass below 358 GeV

Single Top Production

- *Single Top production Cross Section*
- *Beyond-the-SM physics related to Single Top*

Single Top Quark Production

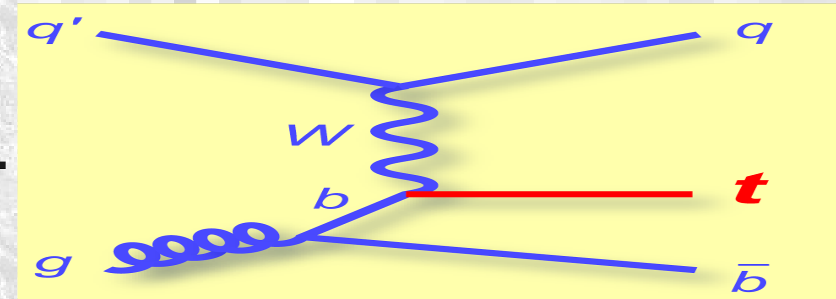
p, $\bar{p}$ →



s-channel

$\sigma^{NNLO} = 1.12 \pm 0.04$ pb

+



t-channel

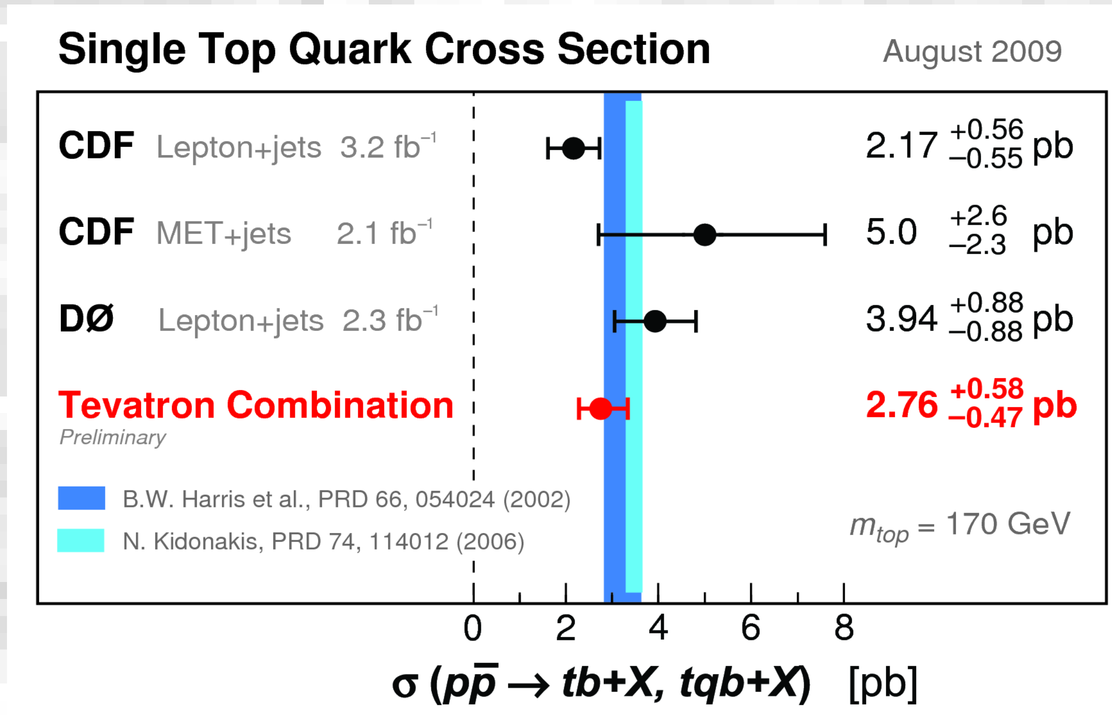
$\sigma^{NNLO} = 2.34 \pm 0.012$ pb

- Observation of the Single Top Quark Production (2009) :

D0 & CDF combination

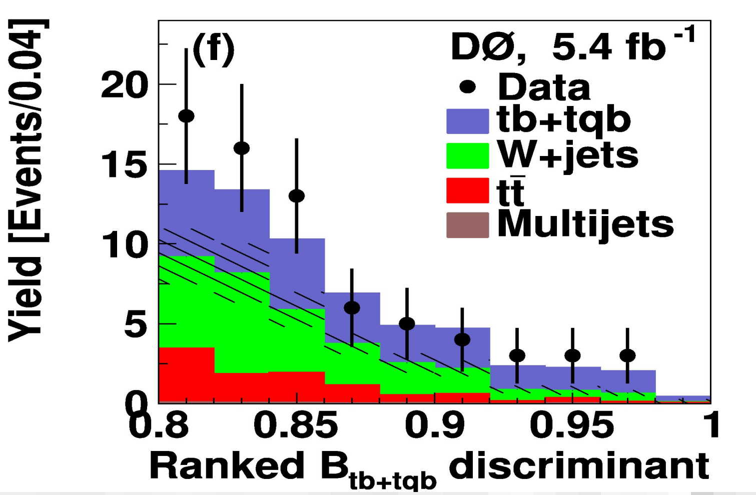
$\sigma\ (tb+tqb) = 2.76^{+0.58}_{-0.47}$ pb

$|V_{tb}| = 0.88 \pm 0.07$

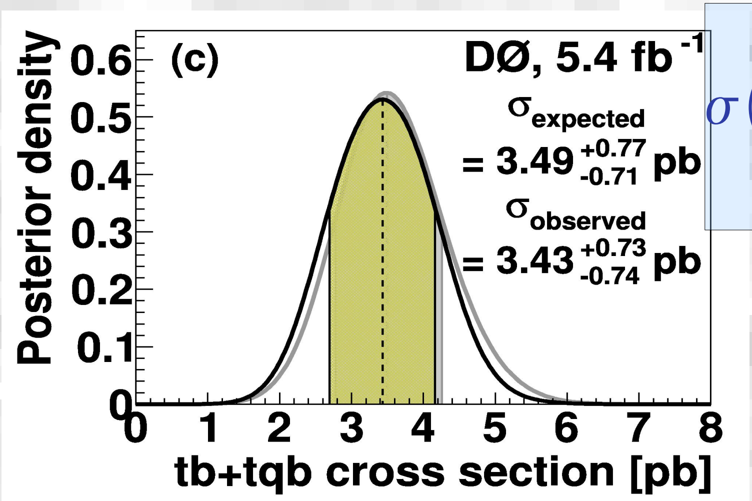


- D0, 5.4fb^{-1}, single top, lepton + jets
- An improved measurement of the production rate of *tb* and *tqb*
- *CompHEP-based MC generator*
- *Three different MVA techniques*

  - boosted desicion trees, Baesian neural networks, neuroevolution of augmented topologies (NEAT); each method defines the discriminant



Distribution of the discriminant for the signal region



Posterior probability density for tb+tqb production

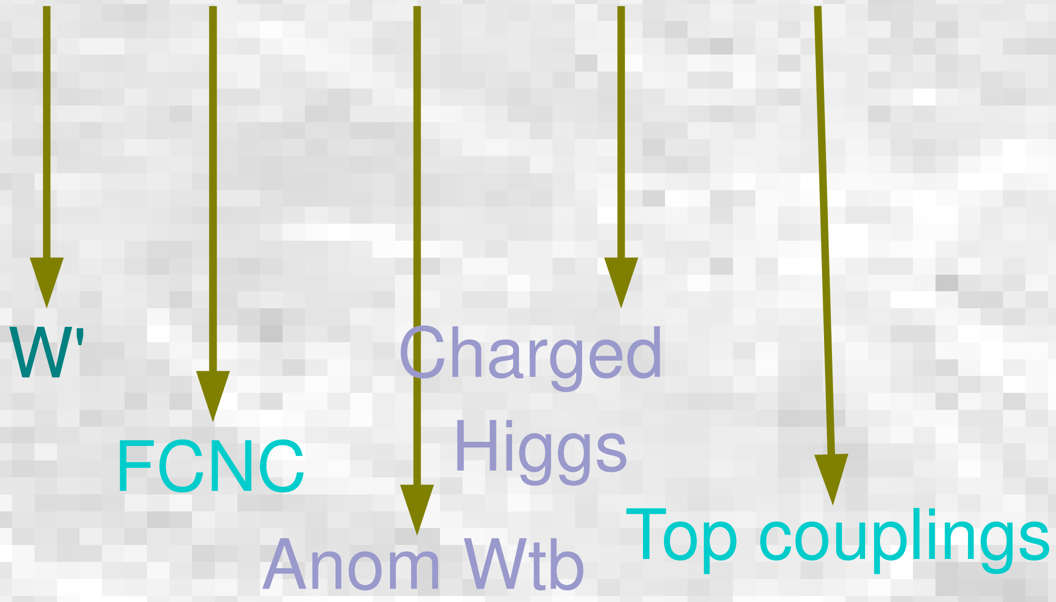
D0 results

$\sigma(tb+tqb) = 3.43^{+0.73}_{-0.74}$ pb

$|V_{tb}| > 0.79$

CS was extracted without any assumption on the tb production rate

BSM physics related to Single Top

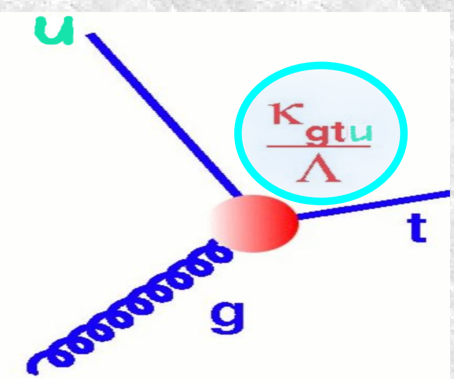


Flavor Changing Neutral Currents (FCNC)

- change the flavour of the quarks without changing the charge
- SM: absent on the tree level but do occur at higher order in perturbation theory through loop diagrams
- can be realized in extensions of the SM

	SM	two-Higgs	SUSY
$B(t \to cg)$	$5 \cdot 10^{-11}$	10^{-6}	10^{-3}
$B(t \to c\gamma)$	$5 \cdot 10^{-13}$	10^{-6}	10^{-5}
$B(t \to cZ)$	$\sim 10^{-13}$	10^{-9}	10^{-4}

- Tevatron: FCNC via gluons

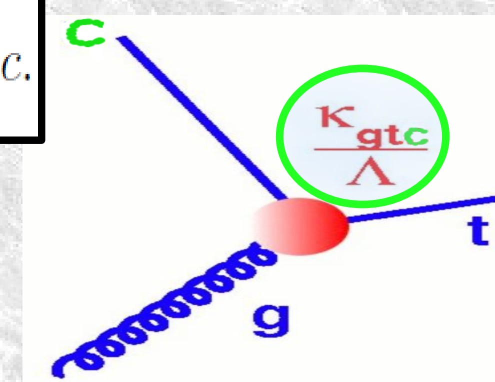


$$g_s \frac{\kappa_{tug}}{\Lambda} \bar{u}\, \sigma^{\mu\nu} \frac{\lambda^a}{2} t\, G^a_{\mu\nu} + g_s \frac{\kappa_{tcg}}{\Lambda} \bar{c}\, \sigma^{\mu\nu} \frac{\lambda^a}{2} t\, G^a_{\mu\nu} + h.c.$$

G: gauge field tensor of gluon

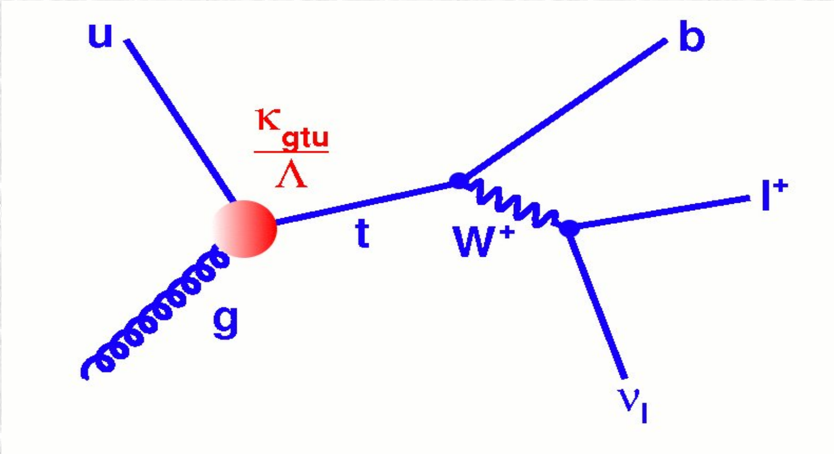
κ: strength of *tug* or *tcg* couplings

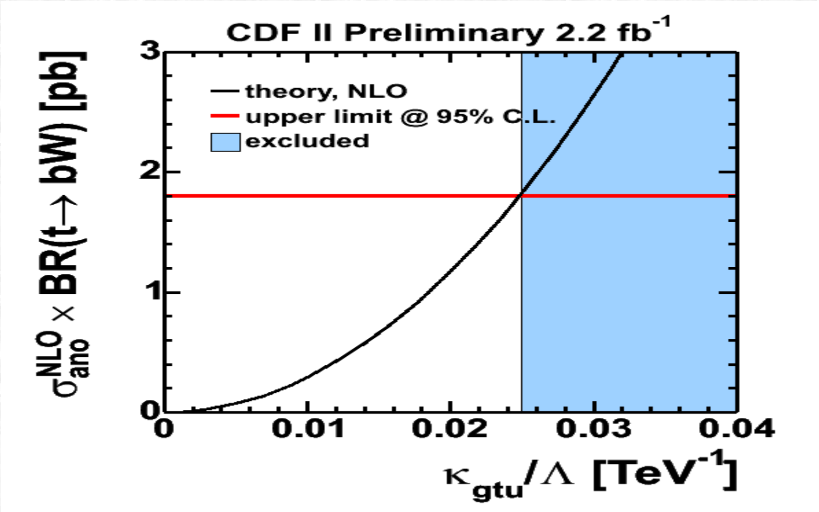
Λ: scale of new physics

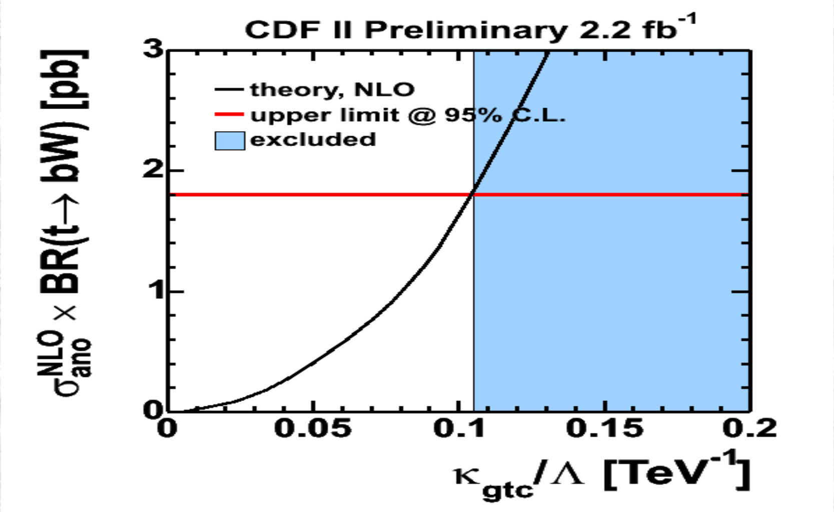


Anomalous Top Quark Production: FCNC at CDF

- $\mathbf{2.2\,fb^{-1}}$ (Phys. Rev. Lett. 102, 151801 (2009))
- the first one at the Tevatron searching for 2->1 process
- $\mathbf{u(c)+g \rightarrow t \rightarrow Wb \rightarrow l\,\nu\, b}$ topology
- apply NN





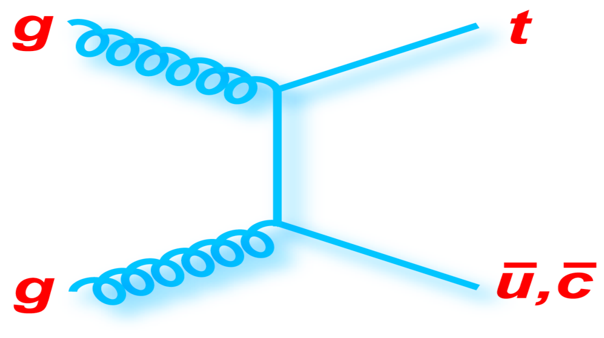


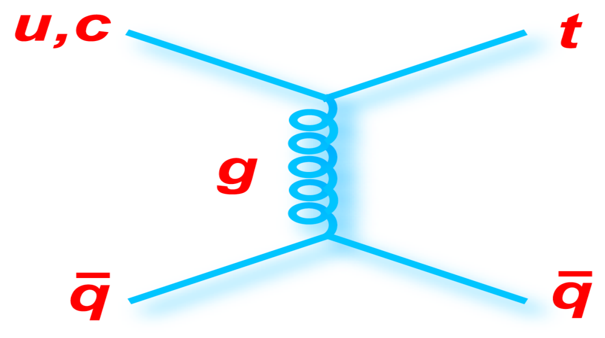
$$\kappa_{tug}/\Lambda < 0.018 \text{ TeV}^{-1} \text{ assuming } \kappa_{tcg} = 0$$

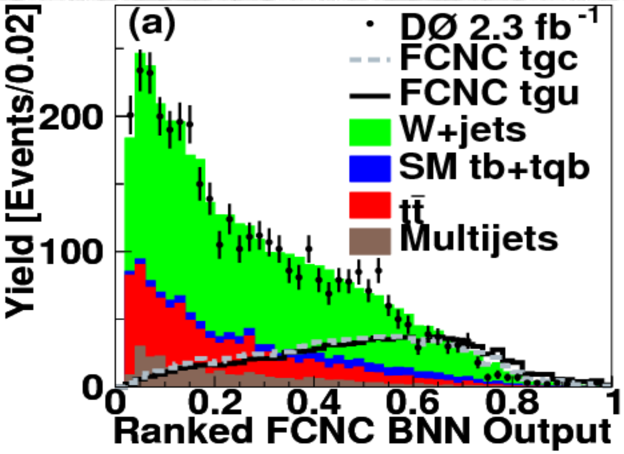
$$\kappa_{tcg}/\Lambda < 0.069 \text{ TeV}^{-1} \text{ assuming } \kappa_{tug} = 0$$

Anomalous Top Quark Production: FCNC at D0

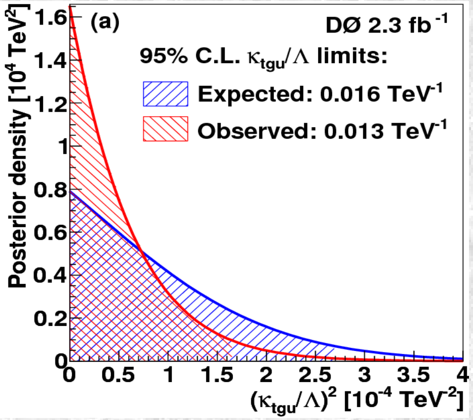
- $2.3\,\text{fb}^{-1}$ (Phys. Lett. B 693, 81 (2010))
- lepton + jets topology
- 2 set of signal events:
- NN applied:

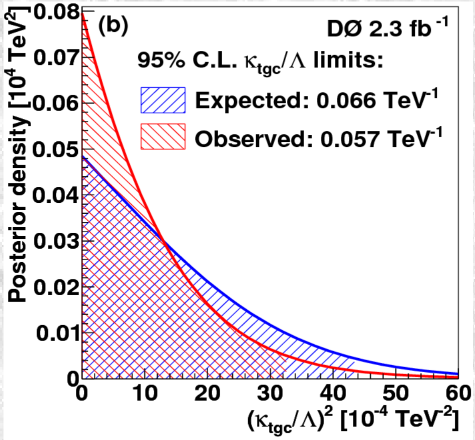






latest Tevatron FCNC results:





	tgu	tgc
Cross section	0.20 pb	0.27 pb
κ_{tgf}/Λ	$0.013\ \text{TeV}^{-1}$	$0.057\ \text{TeV}^{-1}$
$\mathcal{B}(t \to qg)$	2.0×10^{-4}	3.9×10^{-3}

W' search

Effective lagrangian of W' interaction to fermions in model-independent form:

$$L=\frac{V_{q_i q_j}}{2\sqrt{2}} g_W \bar{q}_i \gamma_\mu [a^R_{q_i q_j}(1+\gamma_5)+a^L_{q_i q_j}(1-\gamma_5)] W' q_j + H.C.$$

$a^R_{q_i q_j}, a^L_{q_i q_j}$ - *left and right couplings of W' to fermions*

$g_W=\frac{e}{\sin(\theta)}$ - *Standard Model weak coupling constant*

$V_{q_i q_j}$ - *Standard Model CKM matrix element*

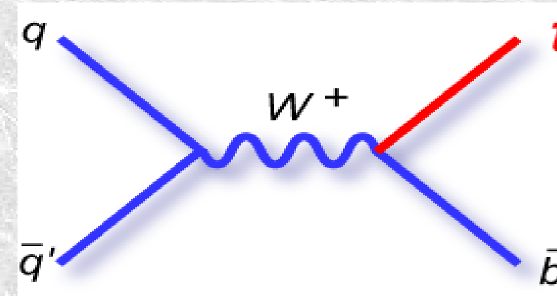
- Different scenarios of W' interaction to fermions:

Left-Handed W' (SM-like couplings)	Right-Handed W'	Mixed case
$a^L_{q_i q_j}=1, a^R_{q_i q_j}=0$	$a^L_{q_i q_j}=0, a^R_{q_i q_j}=1$	$a^L_{q_i q_j}=1, a^R_{q_i q_j}=1$

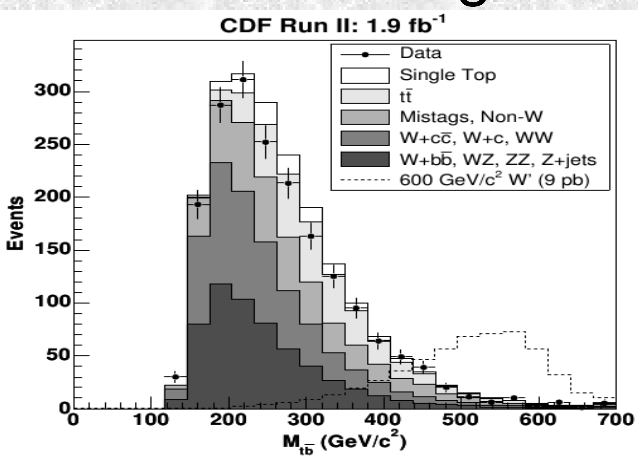
$$M_{W'} > M_{\nu_R} ; M_{W'} < M_{\nu_R}$$

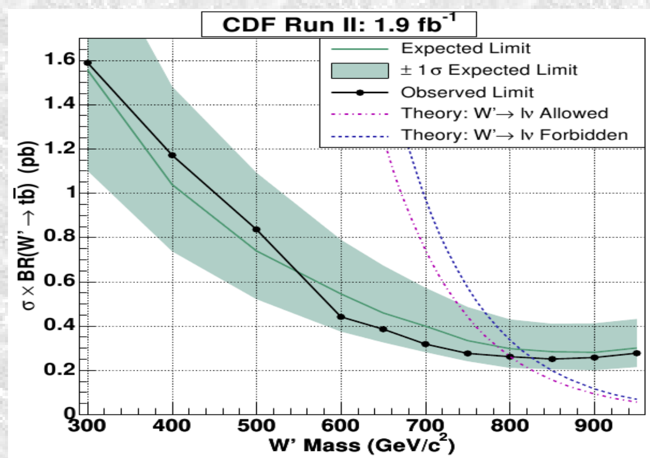
Anomalous Top Quark Production: W' at CDF

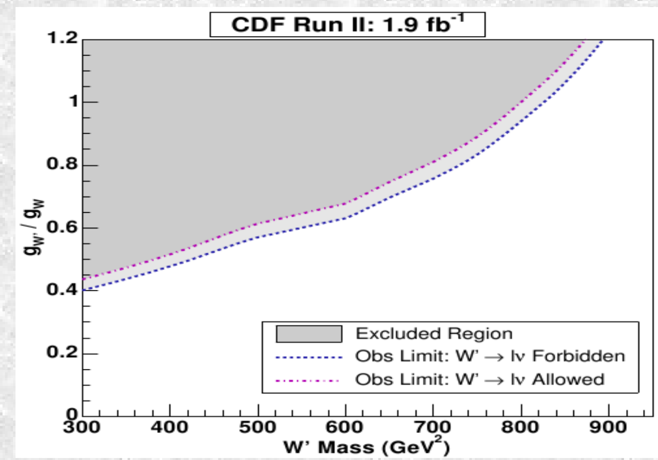
- **1.9 fb^{-1}** W'-like Resonances in the tb Decay Channel
- modeled the Right-handed W'
- $W' \to tb \to Wbb \to l\nu jj$ (W+jets) topology
- many features from the single top analysis



- search for right-handed W' in the s-channel







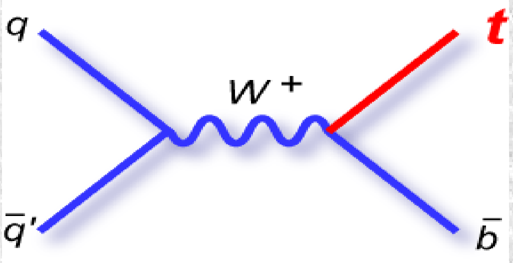
- CDF results: - limits on masses of $M_{W'} > 800\,\mathrm{GeV}/c^2$ $M_{W'} > M_{\nu_R}$

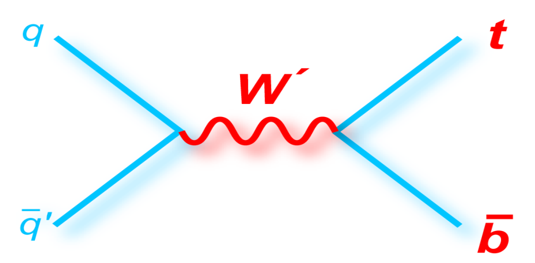
  right W' with SM-like couplings: $M_{W'} > 825\,\mathrm{GeV}/c^2$ $M_{W'} < M_{\nu_R}$

  and on the strength of W' couplings

Top Physics at Tevatron: W'

- D0 results: 2.3fb^{-1} PLB 699, 145 (2011)

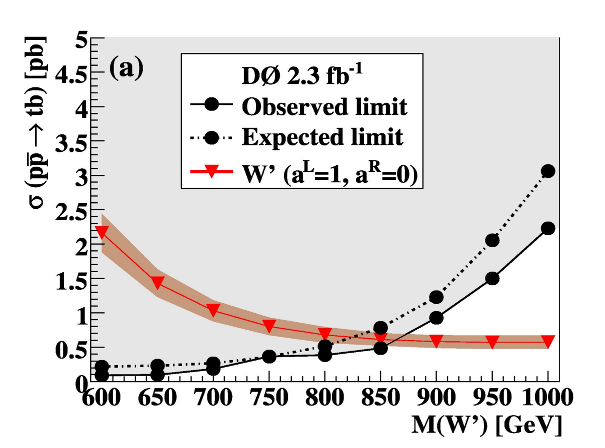


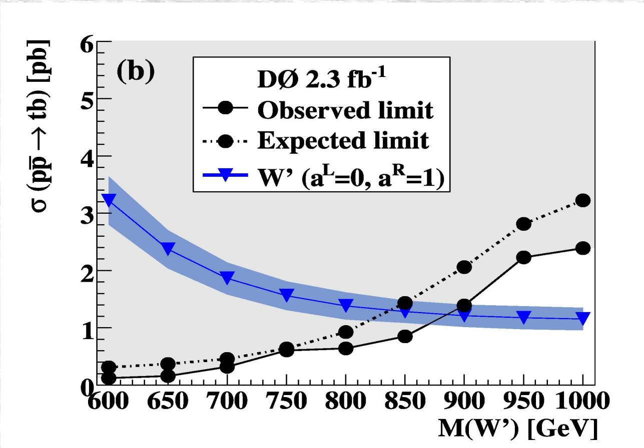


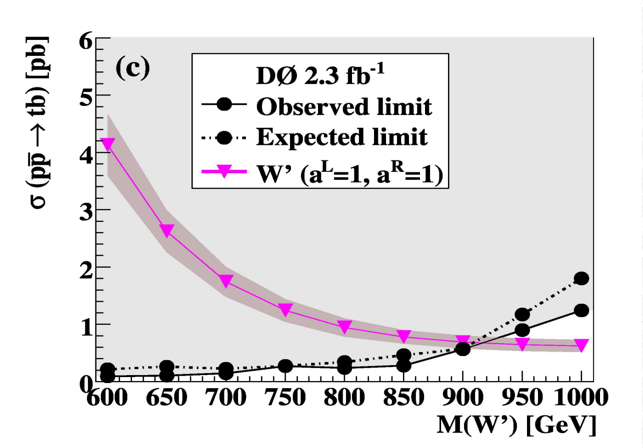
- three scenarios of W' interaction

to fermions: 1) SM + left-handed W' , 2) purely right-handed W', 3) mixed case

- Interference of W and W'







Newest Tevatron results:

M(W′(left) → lν,qq) > 863 GeV

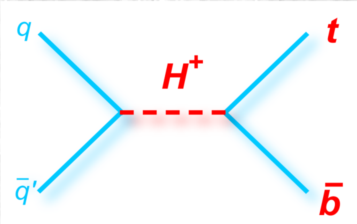
M(W′(right) → lν,qq) > 885 GeV

M(W′(left,right) → lν,qq) > 916 GeV

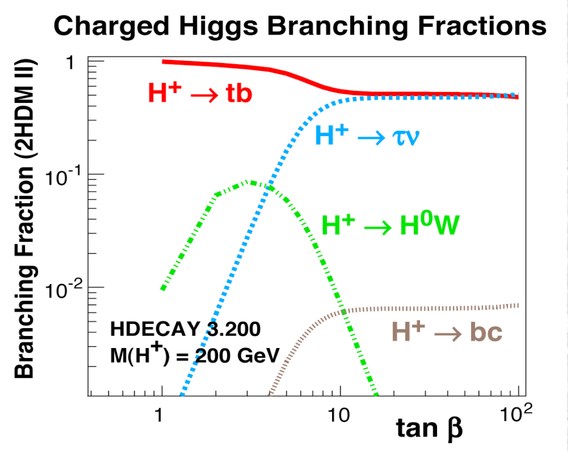
M(W′(right) → qq) > 890 GeV at 95% CL

Charged Scalar Search

- S-channel production of Charged Scalar

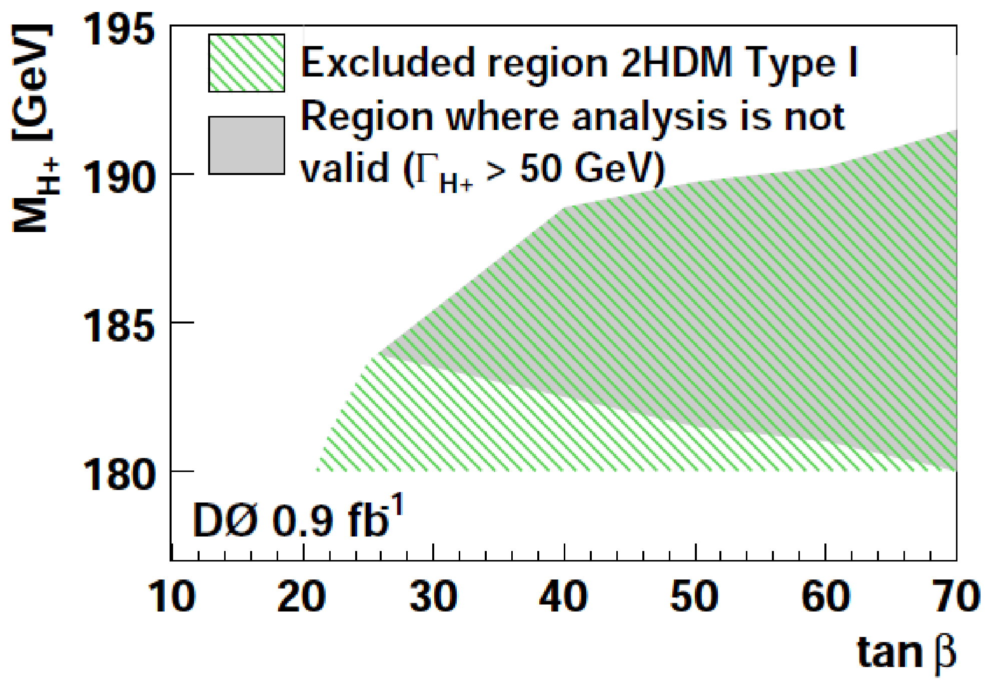


$$\mathcal{L} = H^+ \bar{q}_i \left[g_L^{ij} \left(\frac{1-\gamma^5}{2} \right) + g_R^{ij} \left(\frac{1+\gamma^5}{2} \right) \right] q_j$$



- D0, 0.9 fb^{-1} Phys. Rev. Lett. 102, 191802 (2009)
- Various types of 2HDM are distinguished by their strategy for avoiding FCNC

M_{H+} (GeV)	$\tan\beta < 0.1$	$\tan\beta = 1$	$\tan\beta = 5$	$\tan\beta > 10$
180	12.9 (11.4)	14.3 (12.2)	13.7 (11.7)	13.7 (12.2)
200	[5.9 (9.6)]	6.3 (9.9)	6.5 (10.0)	6.5 (10.0)
220	[2.9 (4.2)]	3.0 (4.4)	3.0 (4.5)	3.0 (4.5)
240	[2.3 (3.1)]	2.4 (3.3)	2.6 (3.5)	2.6 (3.5)
260	[3.0 (2.8)]	3.0 (2.9)	3.0 (3.0)	3.0 (3.0)
280	[4.0 (2.6)]	4.2 (2.7)	4.5 (2.9)	4.5 (2.9)
300	[4.5 (2.4)]	4.7 (2.4)	4.9 (2.5)	4.9 (2.5)

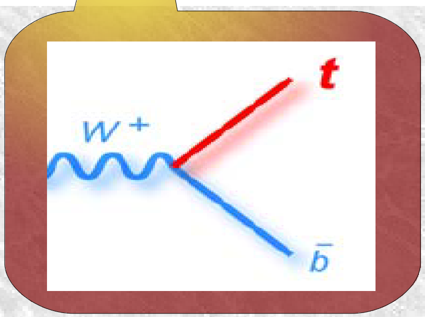


Anomalous Wtb Couplings Search

- Effective Lagrangian in model-independent form:

vector left and right couplings

$$\mathcal{L}_{tbW} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t + h.c.$$

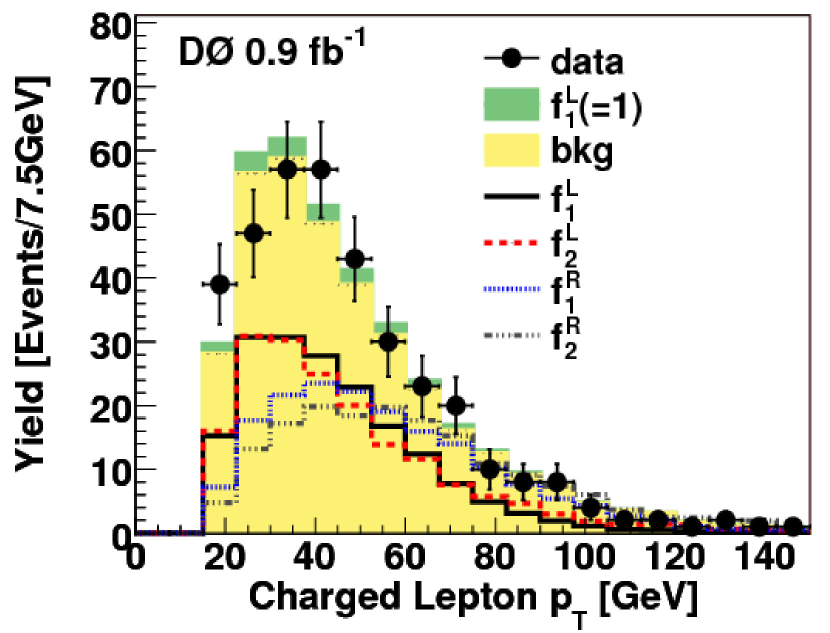


tensor left and right couplings

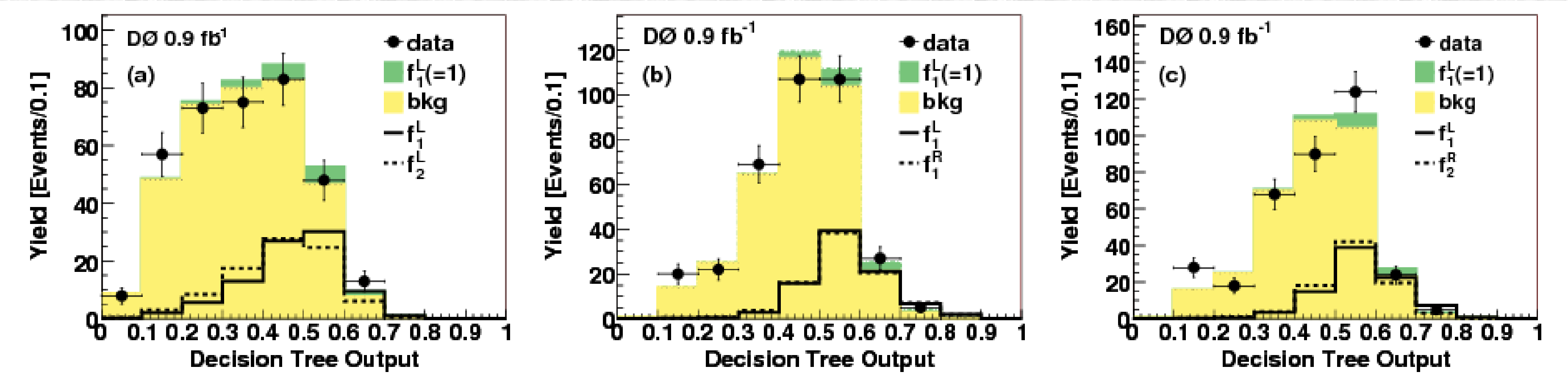
$$P_{L,R} = 1/2 \cdot (1 \mp \gamma_5) \quad , \quad \sigma^{\mu\nu} = i/2 [\gamma^\mu, \gamma^\nu]$$

Top Physics at Tevatron: AnomWtb

- **$0.9\ \mathrm{fb}^{-1}$**, Phys. Rev. Lett. 101, 221801 (2008)
- look at two couplings at a time and assume that the others are negligible
- consider three cases
  - allow the left-handed vector coupling and any one of the others to be non-zero
- use boosted decision trees to discriminate between signal and background
  - different composition of the signal samples for each scenario
- The same variables as for D0 single top observation paper
  - plus lepton Pt (helps to distinguish the signals for the different couplings)



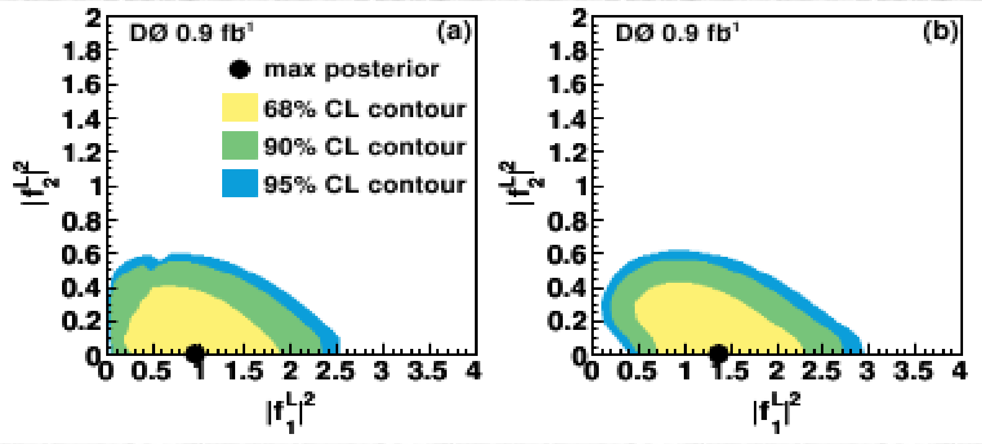
Top Physics at Tevatron: AnomWtb in D0



Representative output distributions for the data and the sum of SM signal and bckgrds

- compute 95% C.L. upper limits on anomalous couplings

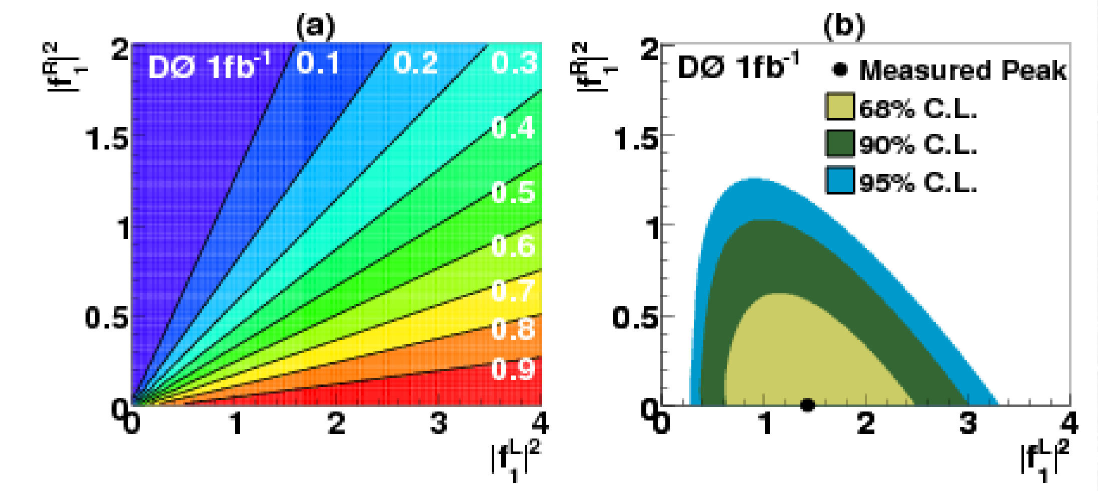
Scenario	Cross section	Coupling
(L_1, L_2)	$4.4^{+2.3}_{-2.5}$ pb	$\lvert f_1^L\rvert^2 = 1.4^{+0.6}_{-0.5}$
		$\lvert f_2^L\rvert^2 < 0.5$ at 95% C.L.
(L_1, R_1)	$5.2^{+2.6}_{-3.5}$ pb	$\lvert f_1^L\rvert^2 = 1.8^{+1.0}_{-1.3}$
		$\lvert f_1^R\rvert^2 < 2.5$ at 95% C.L.
(L_1, R_2)	$4.5^{+2.2}_{-2.2}$ pb	$\lvert f_1^L\rvert^2 = 1.4^{+0.9}_{-0.8}$
		$\lvert f_2^R\rvert^2 < 0.3$ at 95% C.L.



Plots of the 2D posterior probability density for left-vector and left-tenzor couplings

Top Physics at Tevatron: anomalous top couplings

- **0.9 fb^{-1}** Phys.Rev.Lett.102:092002,2009.
- combination of the D0 results for W helicity fractions in tT events with information about single-top quark production
- investigate one pair of couplings at a time - the others have SM values



W helicity prior (a) and final posterior density (b)
For right- vs left-handed vector coupling

- 95% C.L. combined limits on anomalous couplings

Scenario	Coupling	Coupling limit if $f_1^L = 1$
(L_1, R_1)	$\|f_1^L\|^2 = 1.27^{+0.57}_{-0.48}$	
	$\|f_1^R\|^2 < 0.95$	$\|f_1^R\|^2 < 1.01$
(L_1, L_2)	$\|f_1^L\|^2 = 1.27^{+0.60}_{-0.48}$	
	$\|f_2^L\|^2 < 0.32$	$\|f_2^L\|^2 < 0.28$
(L_1, R_2)	$\|f_1^L\|^2 = 1.04^{+0.55}_{-0.49}$	
	$\|f_2^R\|^2 < 0.23$	$\|f_2^R\|^2 < 0.23$

Top Physics at the Tevatron: Conclusion

- Tevatron performed many possible measurements of top quark parameters
- Tevatron demonstrates a good agreement with SM predictions

  - FB asymmetry

- Tevatron searches for anomalous Top production:

  - the limits on the anomalous cross sections, W' mass, FCNC couplings, AnomWtb couplings, t' mass.

- we expect more analyses in the nearest future statistic.
- details of all analyses listed here are available at the common pages:

CDF results

D0 results

- Results from Tevatron: double top production

Double top production cross section:

CS (tT) = 7.5 + 0.31 - 0.34 pb

Top quark mass: M_{top}=173.2+/-0.9 GeV

Top quark width: Γ_{top}<7.6 GeV

Spin correlation:

in helicity basis: F_{OH} = 0.74 ± 0.24stat ± 0.11syst

$K_{Helicity}$ = 0.48 ± 0.48stat ± 0.22 syst

in beamline basis: F_{SH} = 0.86 ± 0.32stat ± 0.13syst

K_{Beam} = 0.72 ± 0.64stat ± 0.26 syst

Forward-Backward asymmetry:

A_{FB}= 0.201+/-0.065+/-0.018 (stat+syst)

- Results from Tevatron: single top production

Single top production cross section:

CS (tb+tqb) = 3.43 + 0.73 - 0.74 pb

FCNC parameters: $K^u/L < 0.013$, $K^c/L < 0.057$

Mass of W' : M(W′(left) → lν,qq) > 863 GeV

M(W′(right) → lν,qq) > 885 GeV

M(W′(left,right) → lν,qq) > 916 GeV

M(W′(right) → qq) > 890 GeV

Wtb vertex parameters:

$$|f_1^R|^2 < 1.01$$

$$|f_2^L|^2 < 0.28$$

$$|f_2^R|^2 < 0.23$$


Thank You!!!
QFTHEP-2011