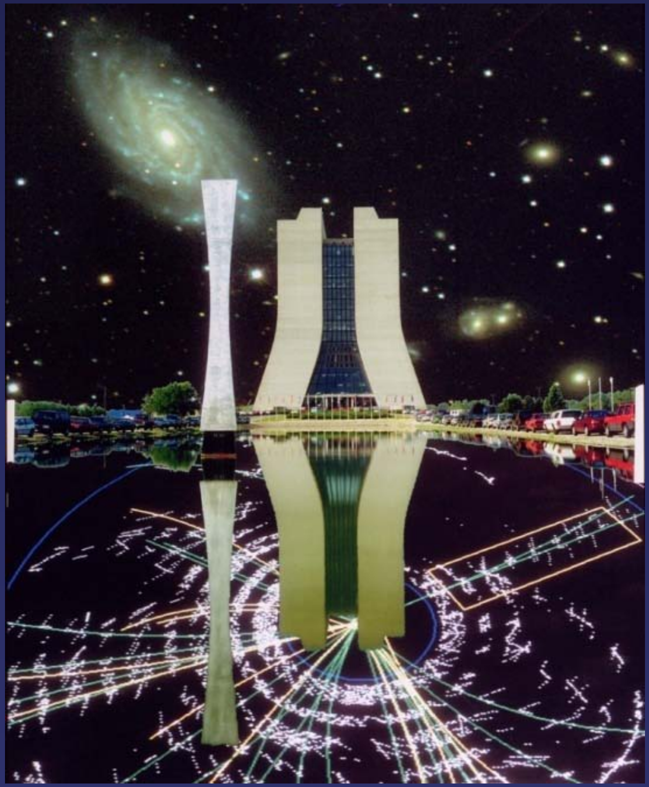
The Top Quark as a Window to New Physics at D∅



Shabnam Jabeen
Boston University

For the D0 Collaboration

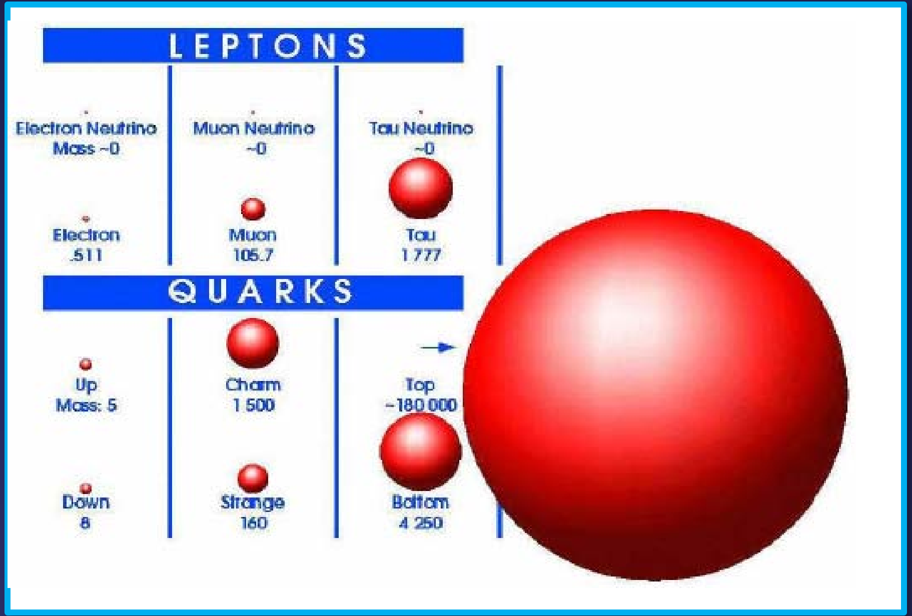
Fermilab Wine & Cheese Seminar
12 December 2008

Why Look at The Top Quark

- Was discovered at Fermilab in1995
- The heaviest known fundamental particle
  - m_t = 172.4   1.4 GeV (~1% precision)

    Close to a gold atom
- $\tau = 5\ \ 10^{-25}$ s $<< \Lambda_{QCD}^{-1}$

  Decays before hadronization

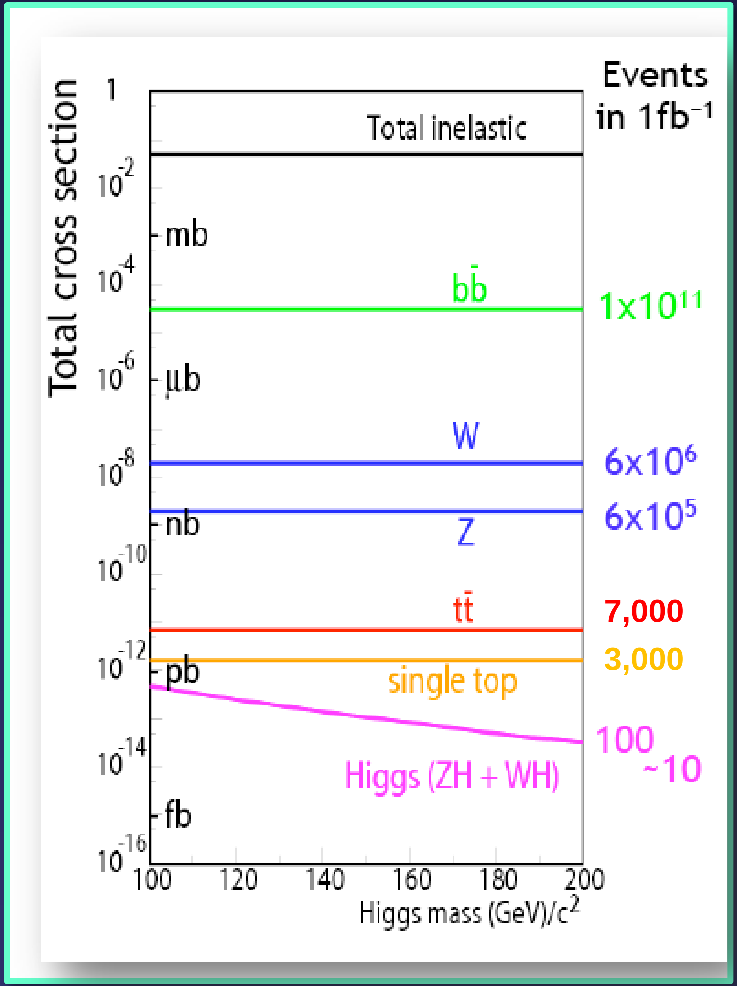


- Mass close to scale of electroweak symmetry breaking
  - Only quark for which coupling to Higgs is significant
  - May shed light on EWSB mechanism
- Top quark plays special role in many of the new physics models

Why Keep Looking at the Top?

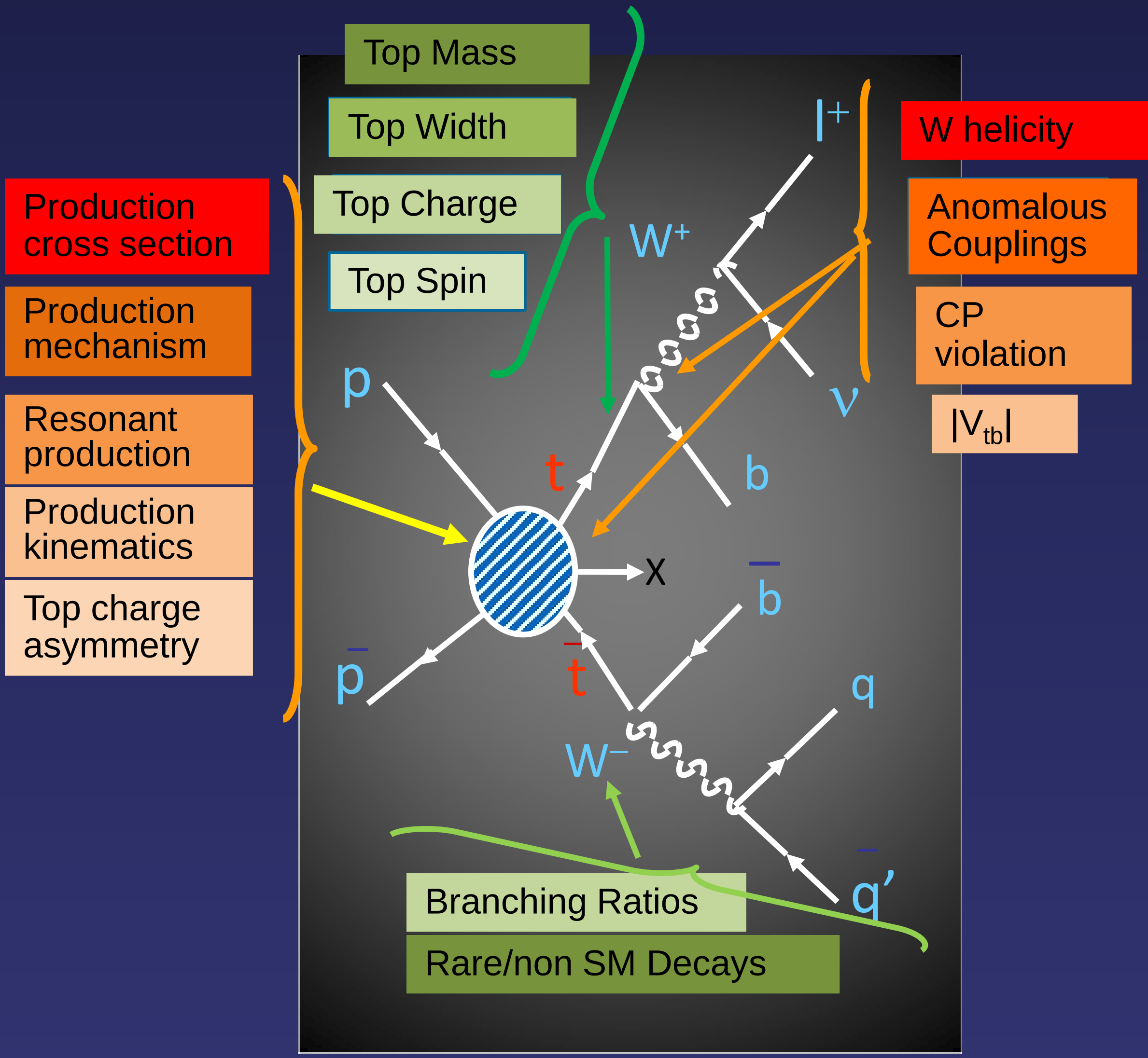
- Tevatron is the only place (so far) where top quarks can be produced
- Even more than a decade after its discovery, our sample consists of ~ 1000 top quark events
  - Many of the measurements of top quark properties are still statistics limited

Lot of room for surprises!



What Should we Know about the Top?

Everything!



Questions we can answer

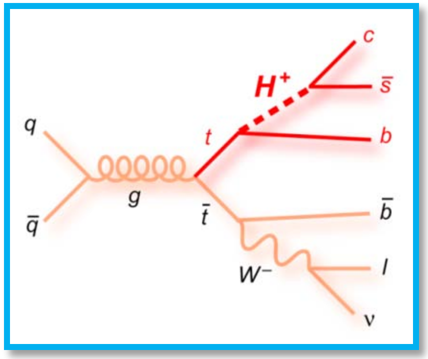
- Higgs boson mass?
- Charged Higgs bosons?
- New massive particles?
- Measurements that can only be made here (e.g charge assymetry)
- Do all quarks have the expected couplings?

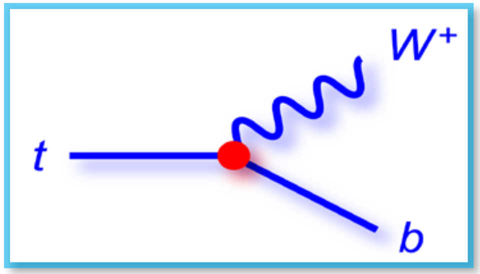
….. and many more, including

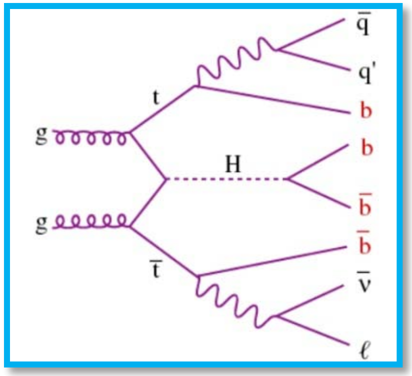
- Unknown unknowns??

Looking for New Physics

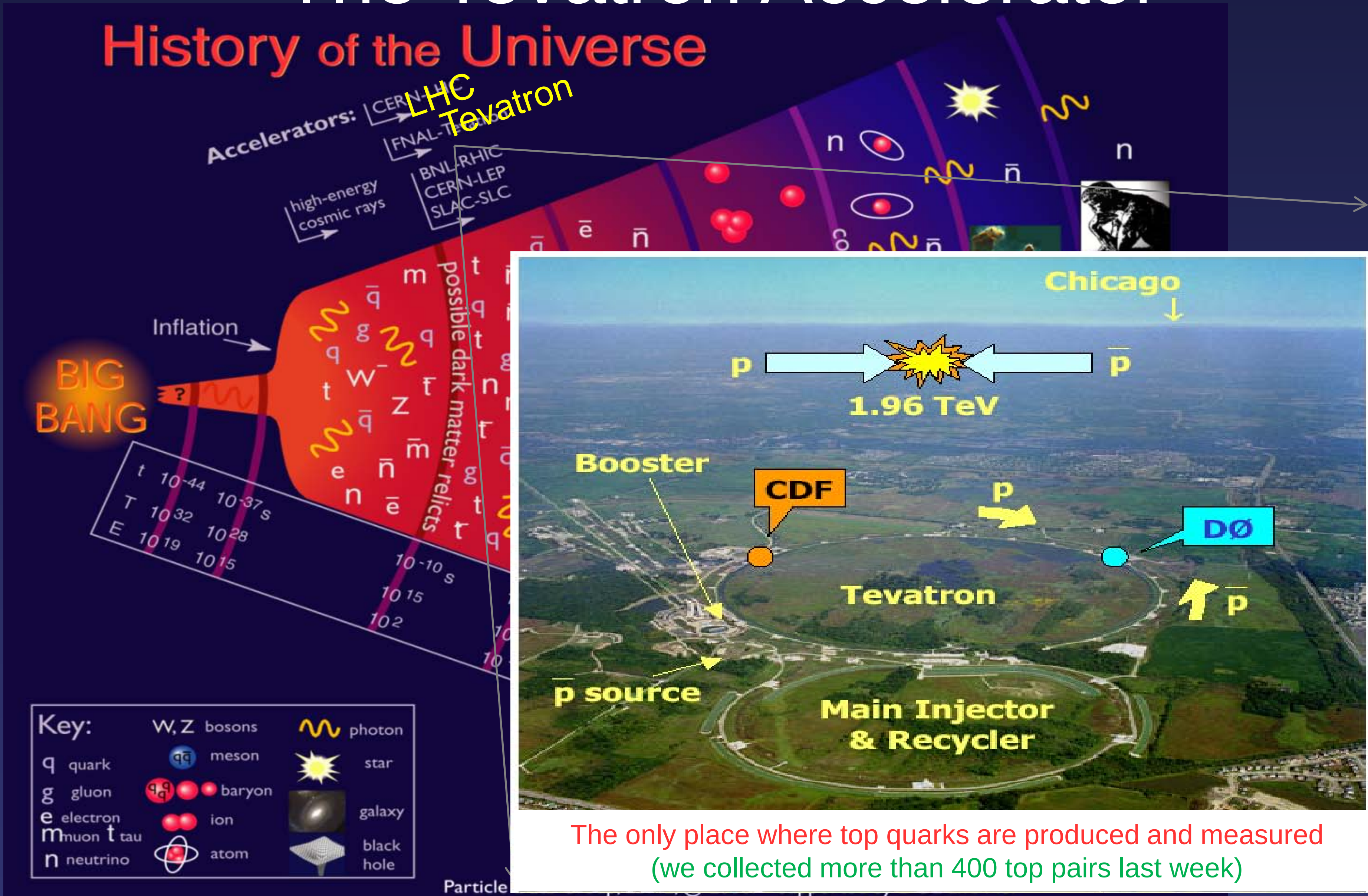
- New particles in top decay?
- Intercation of top quark with weak gauge bosn
  - Measurement of W helicity and
  - Anomalous Wtb couplings
  - Combination of these two measurements
- Particles produced in association with top





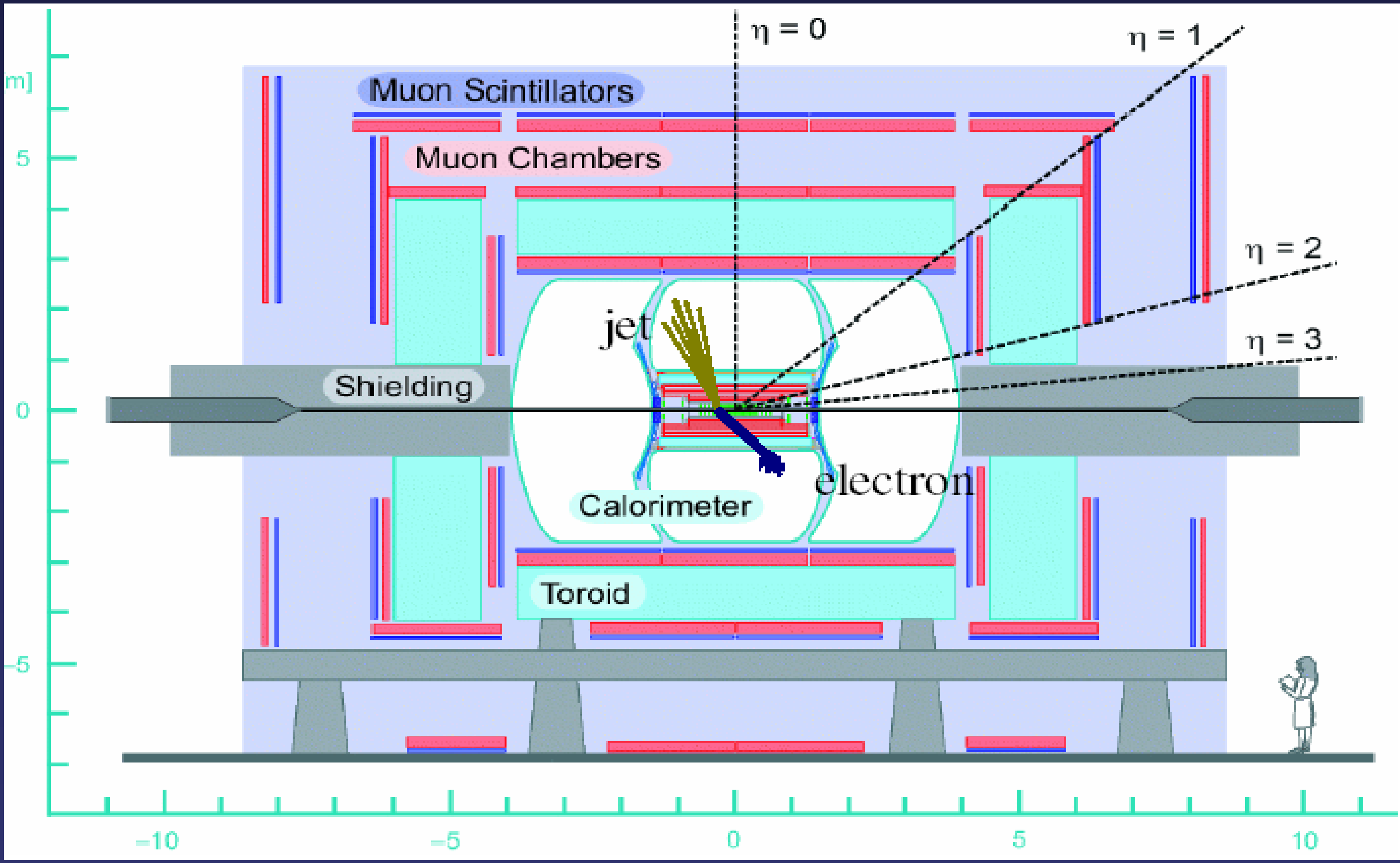


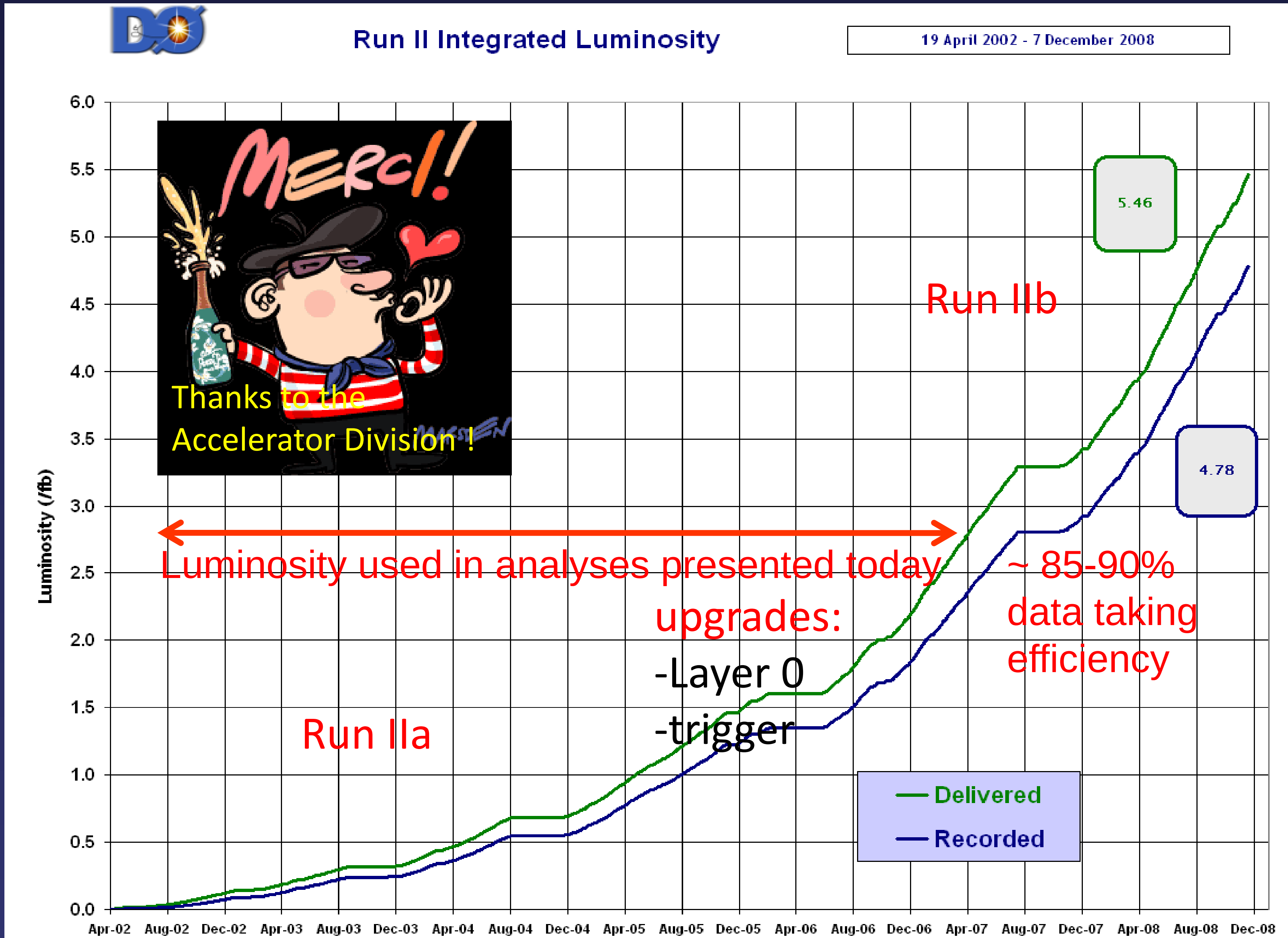
The Tevatron Accelerator



The only place where top quarks are produced and measured
(we collected more than 400 top pairs last week)

The DØ Detector

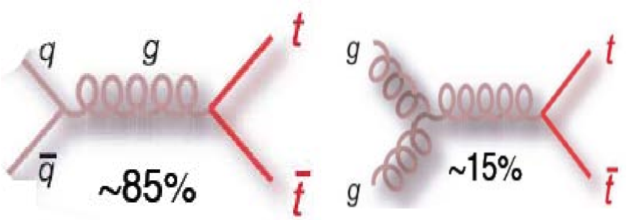



Run II Integrated Luminosity
19 April 2002 - 7 December 2008
Luminosity (/fb)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Apr-02 Aug-02 Dec-02 Apr-03 Aug-03 Dec-03 Apr-04 Aug-04 Dec-04 Apr-05 Aug-05 Dec-05 Apr-06 Aug-06 Dec-06 Apr-07 Aug-07 Dec-07 Apr-08 Aug-08 Dec-08
MERCI!
Thanks to the
Accelerator Division !
Run IIb
5.46
4.78
Luminosity used in analyses presented today
~ 85-90%
data taking
efficiency
upgrades:
-Layer 0
-trigger
Run IIa
Delivered
Recorded

Production

Top quark pair production

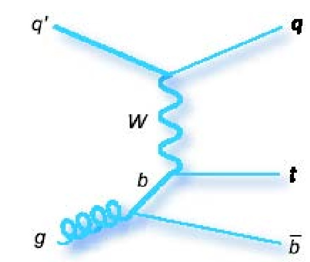
σ_{tt} ~7 pb



Single Top quark production

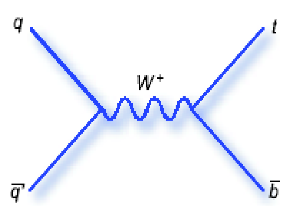
***t*-channel**

σ ~2 pb



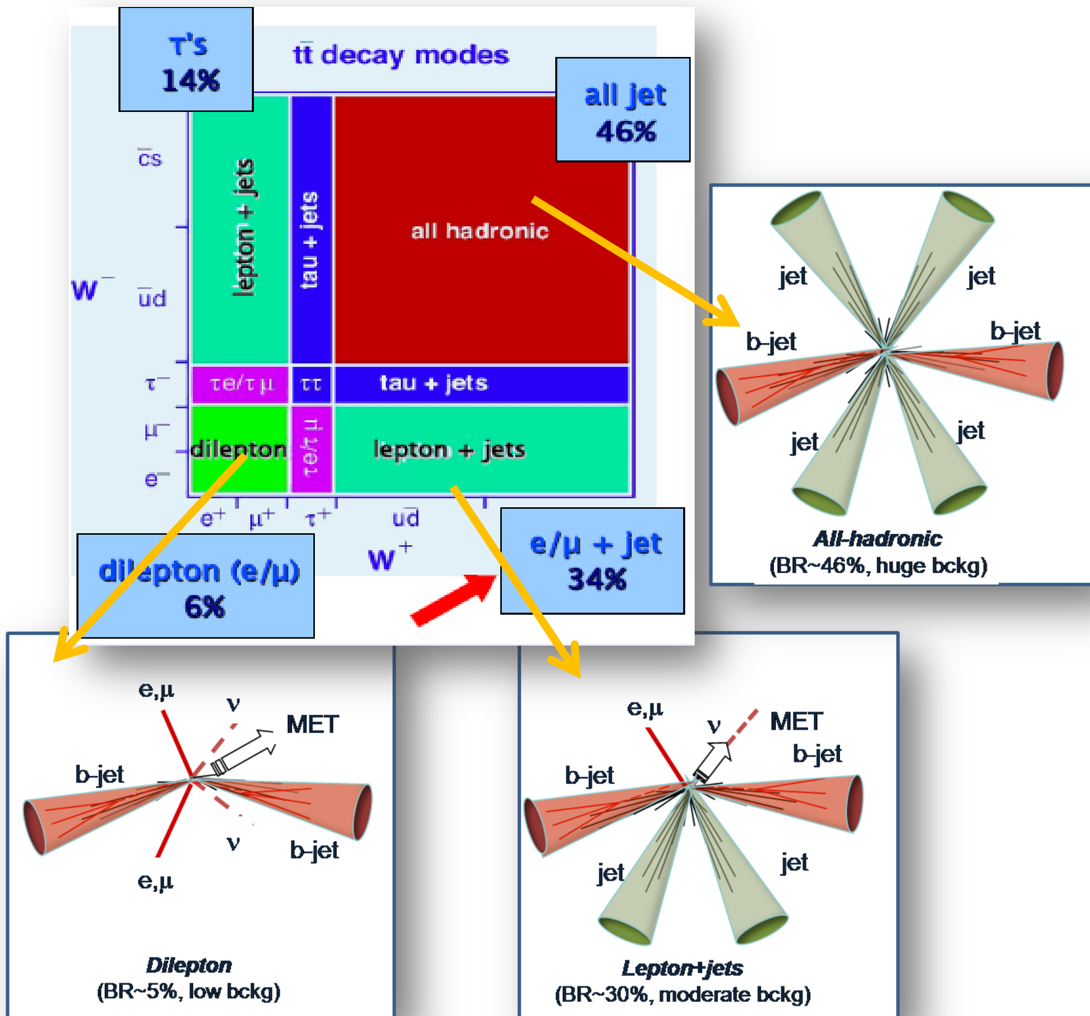
***s*-channel**

σ ~1 pb



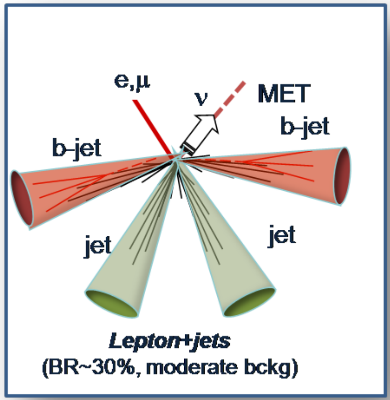
Decay

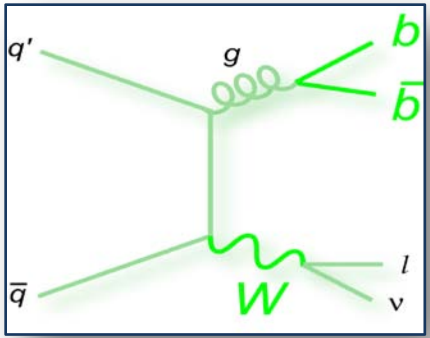
Within Standard Model t→Wb ~ 100%

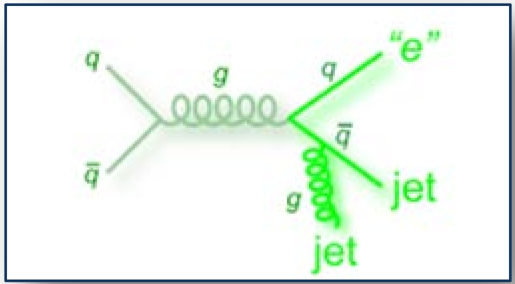


- Dominant Backgrounds
  - Dominant backgrounds arise from W+jets and multijet production (ℓ+jets channel) and Z+jets WW+jets (dilepton channel)
  - When searching for new physics in top sector, SM top quark production itself becomes the dominant background

- Signal and Background Modeling
  - The SM top pair samples are generated with ALPGEN for the matrix elements and parton showers followed by PYTHIA for the hadronization
  - Single top quarks production is modeled using SINGLETOP based on COMPHEP
  - Other backgrounds are also modeled using ALPGEN or PYTHIA except multijet background which is determined from data







General Selection

- Consider a combination of l+jets, dilepton and l+tau final states for top quark decays
  - All channels are constructed to be orthogonal
- single top selection is generally more relaxed compared to top pair selection
- Since top quark decay final states include b jets and most of the background doesn't we make use of b-tagging algorithm to further reduce our background contributions

Selection in l+jets channel

$e: \quad p_T > 20\ GeV, |\eta| < 1.1$

$\mu: \quad p_T > 20\ GeV, |\eta| < 2.0$

Missing E_T:

$e: \ > 20\ GeV; \quad \mu: > 25\ GeV$

Jets :

$\geq 3\ jets$

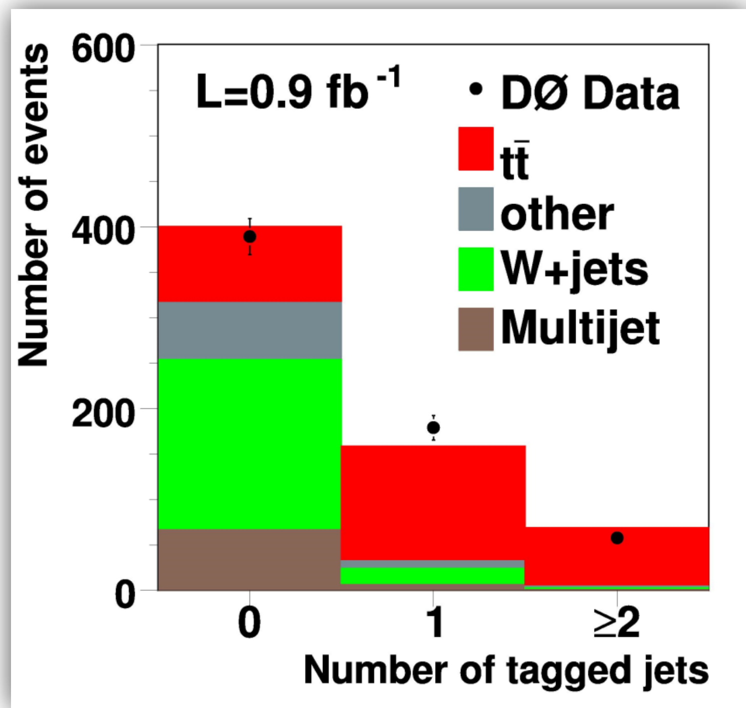
$p_T > 20\, GeV, |\eta| < 2.5$

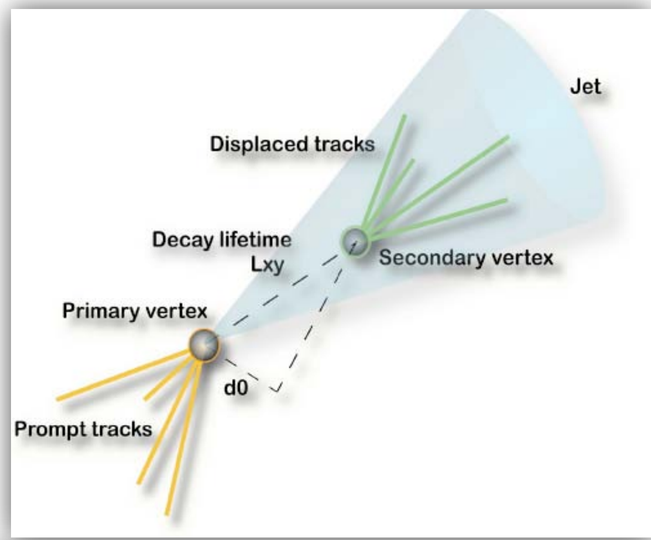
$p_{T,1} > 40\, GeV$

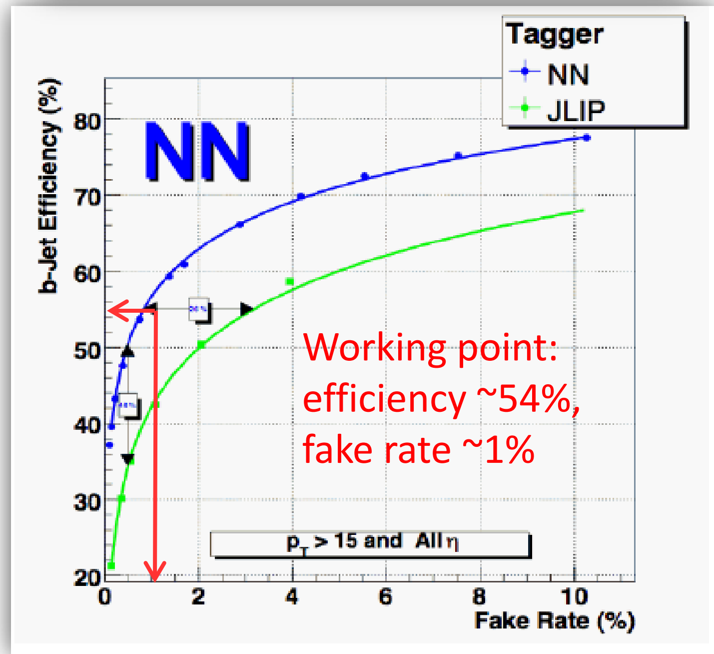
B-jet identification

(aka b-tagging)

- *B*-hadron lifetime $\tau \sim 1$ ps
  - *B*-hadron travels $L_{xy} \sim 1$ mm before decay
- Combine properties of reconstructed secondary vertices and displaced tracks in 7-variable network

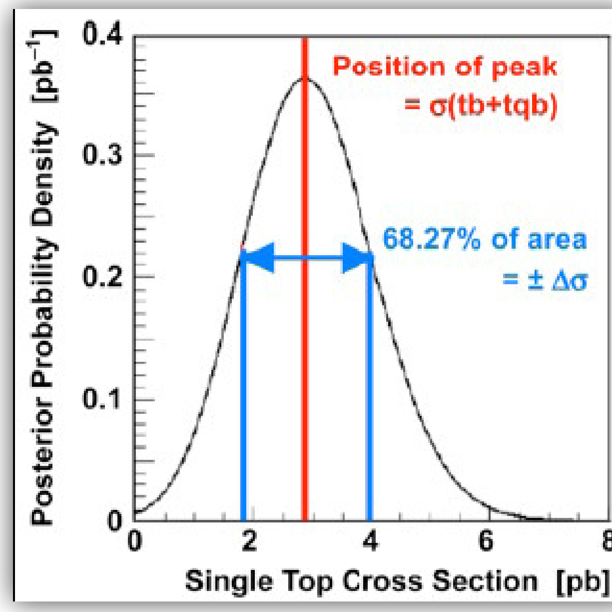


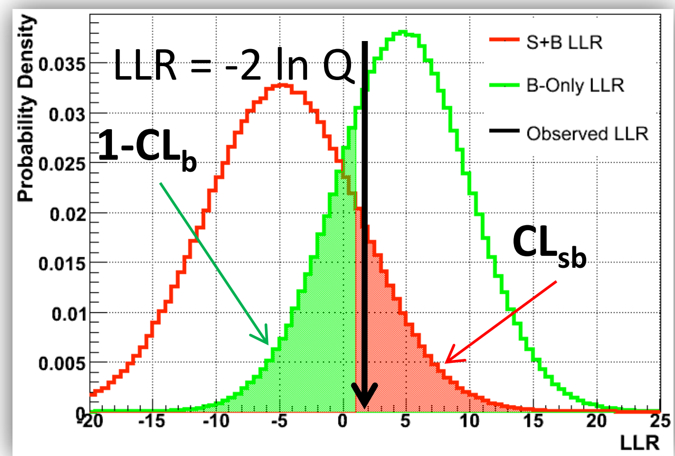




Limit Setting

- When we don't see hints of new physics we set limits
- Various methods in use
  - Bayesian : perform binned likelihood fits of signal + background to data. Compute posterior probability density using Bayes' theorem
  - Modified Frequentist : Background only (b) and signal plus background (s+b) hypotheses are compared to data using Poisson likelihoods
  - Feldman and Cousin
- In all these methods all systematics, their correlations and any effects on shapes are properly taken into account
- Since signal to background ratio is different in different in samples with different jet and tag multiplicities , keeping them separate in limit calculations improves sensitivity

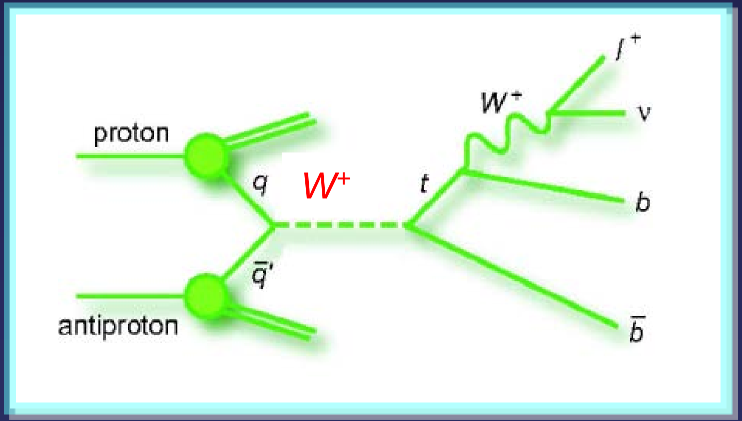




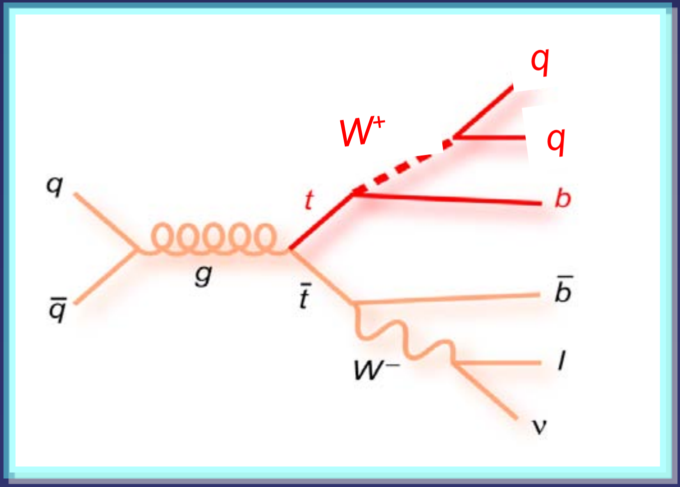
$$Q(m_H) = \frac{L_{s+b}}{L_b}$$

Searching for Charged Higgs

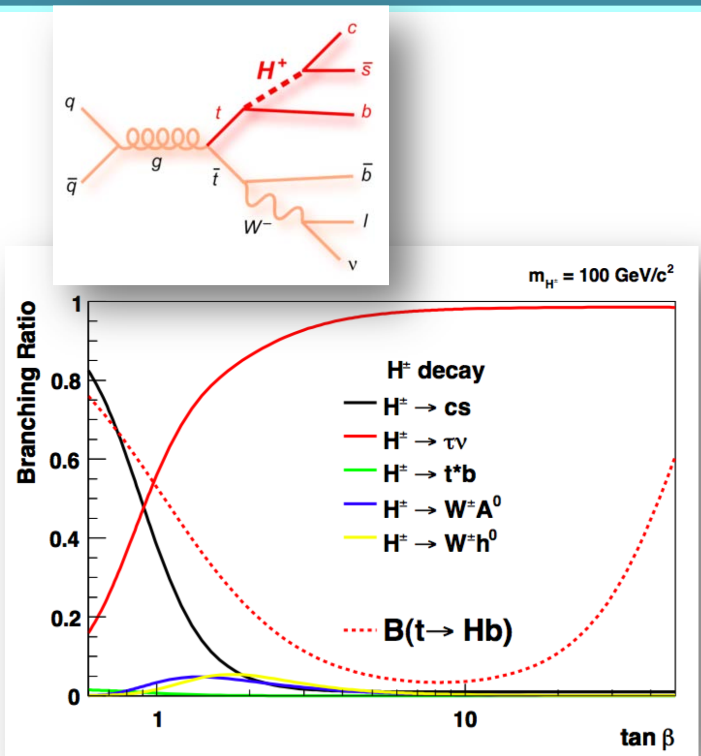
- No “charged” Higgs boson in the standard model
- Many extensions of the SM, (e.g Supersymmetry) require the existence of an additional Higgs doublet Such models predict additional physical Higgs particles, including two charged Higgs bosons $H^{\pm}$
- Heavy H
  - If sufficiently heavy, charged Higgs can decay into top quark
  - $m_t < m_H$ => $H^+ \rightarrow tb$
  - Measure $\sigma(pp \rightarrow H^+)*Br(H^+ \rightarrow tb)$ in single top quark production channels
  - (FERMILAB-PUB-08/229-E, *Submitted to PRL)*



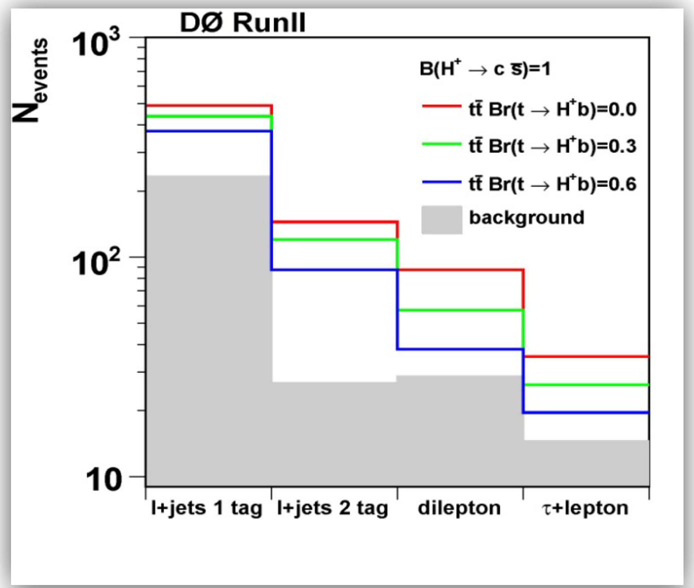
- Light H
  - If sufficiently light, top quark can decay into charged Higgs
  - $m_t > m_H$ => $t \rightarrow H^+ b$
  - Measure $\sigma(pp \rightarrow H^+)*Br(H^+ \rightarrow tb$ in top quark pair production channels

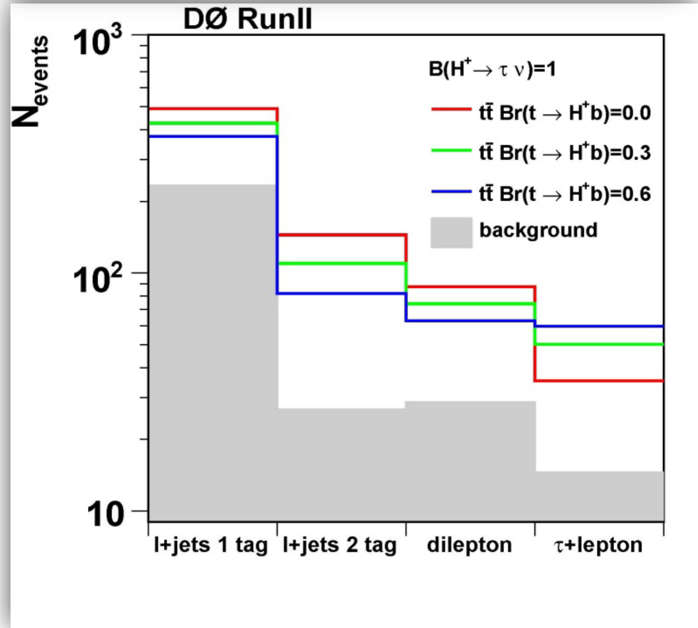


Tau Loving or Leptophobic?

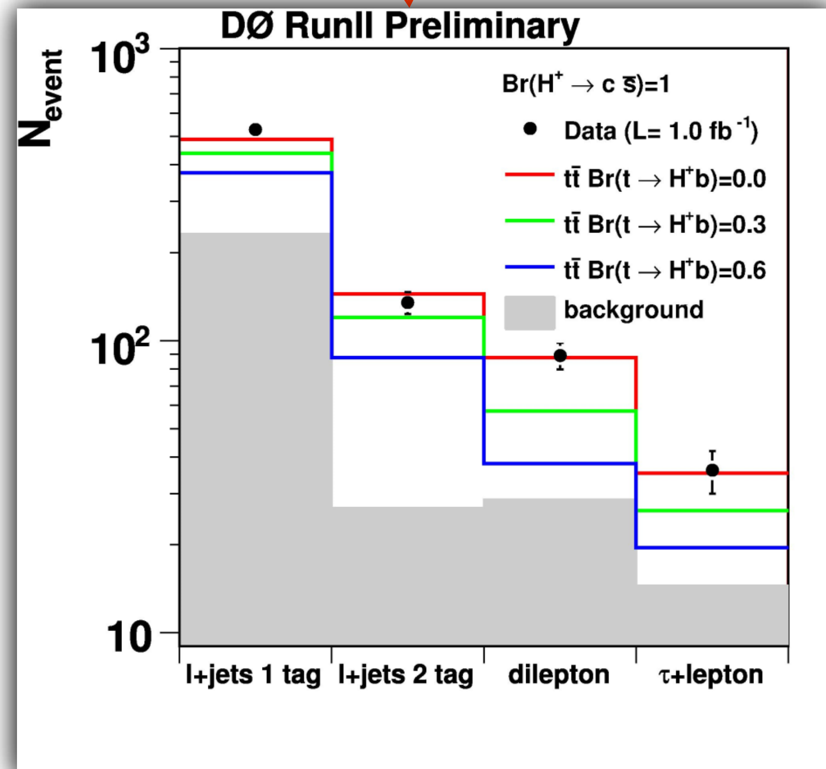


The presence of a charged Higgs boson can significantly modify the expected number of events in different final states

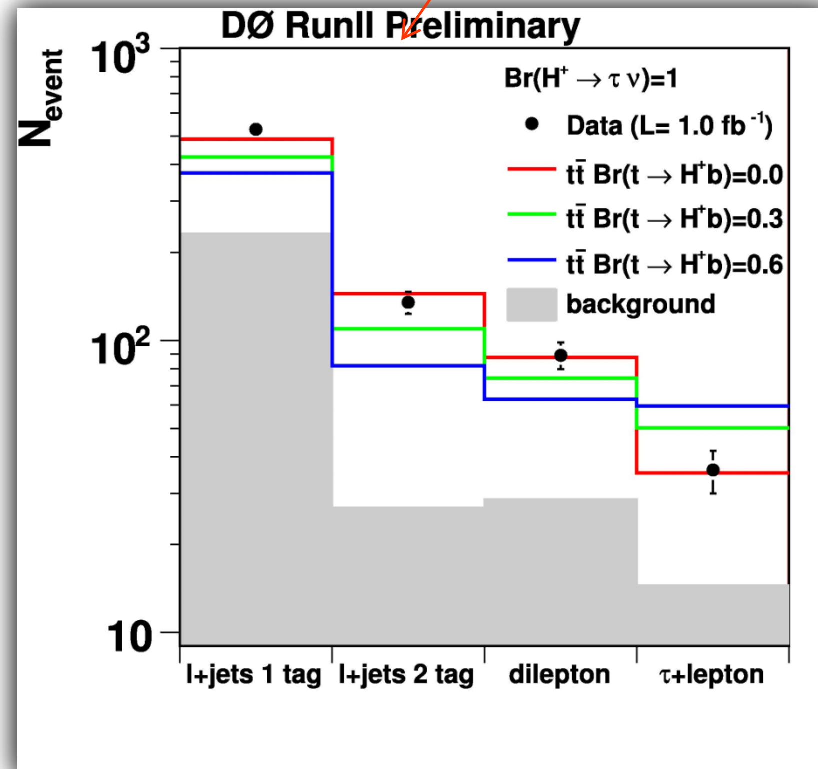




leptophobic charged Higgs



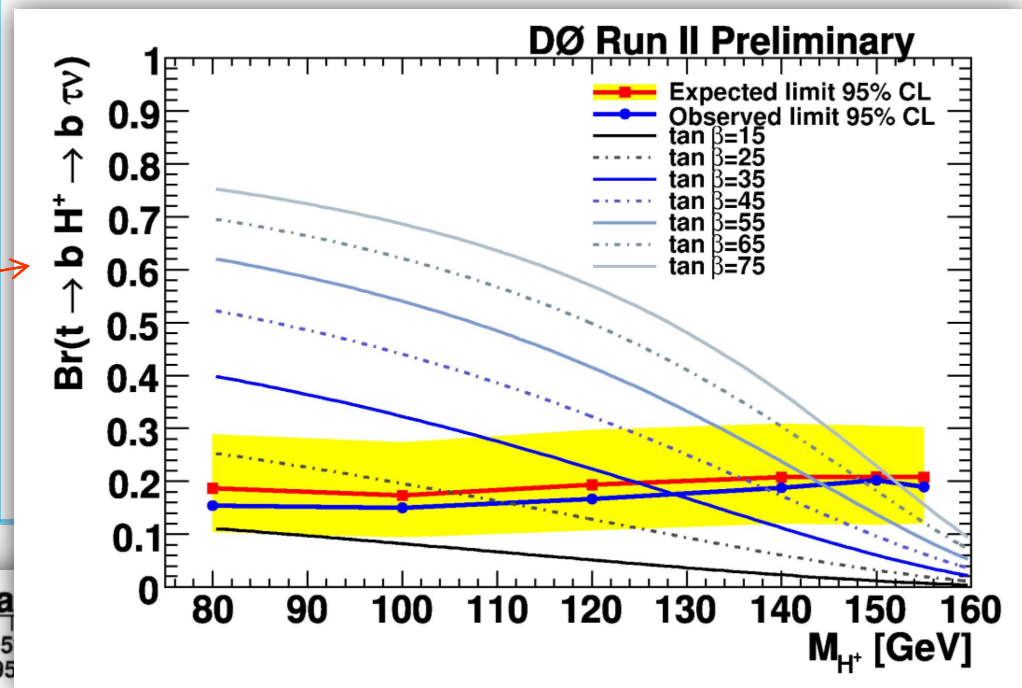
tauonic charged Higgs



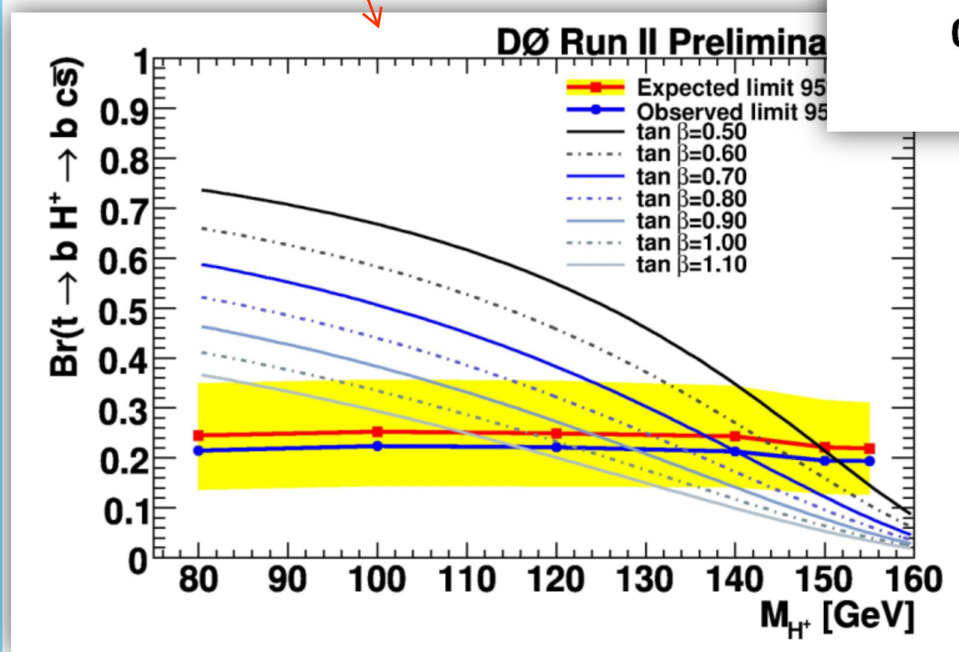
Data is consistent with the SM

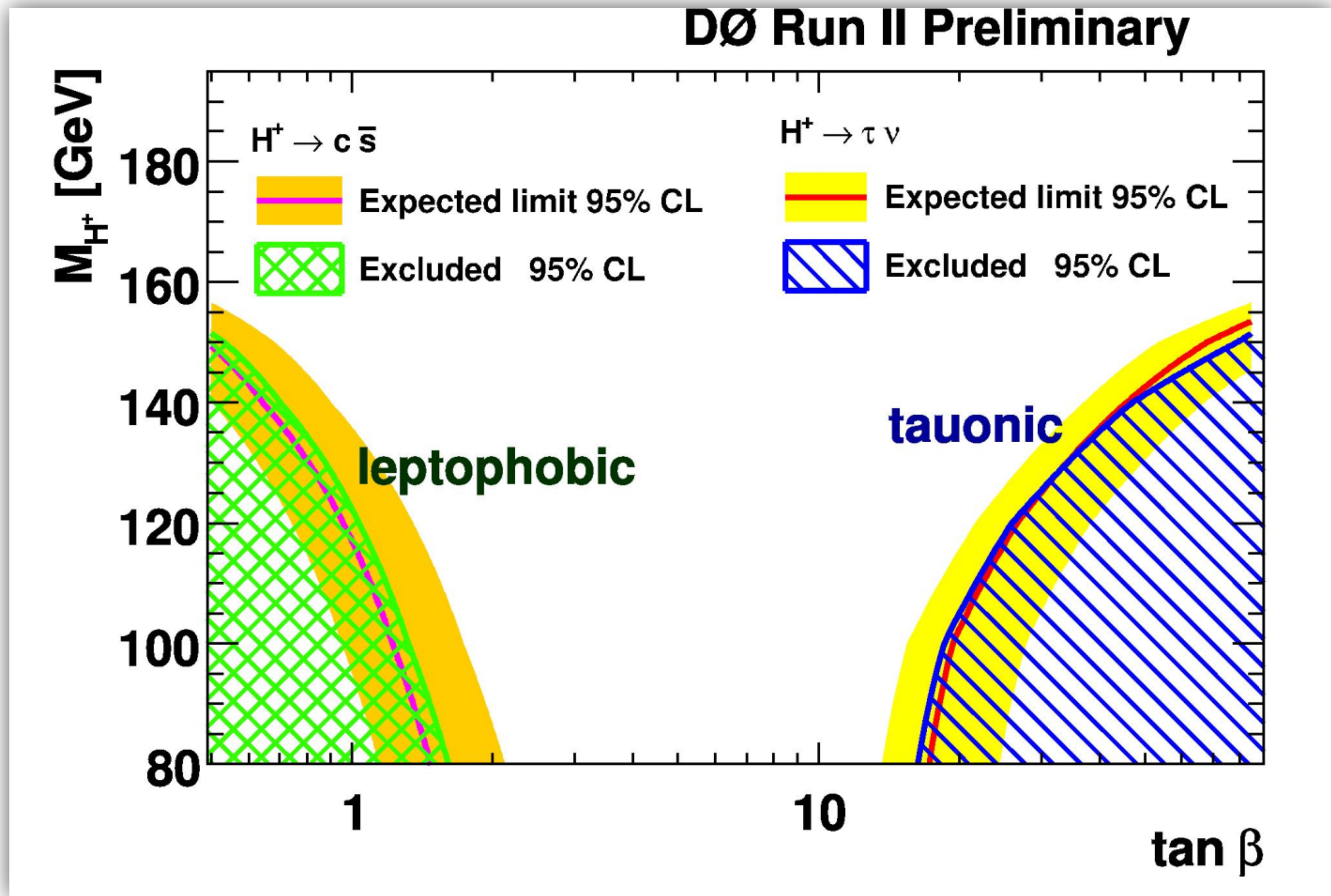
Results

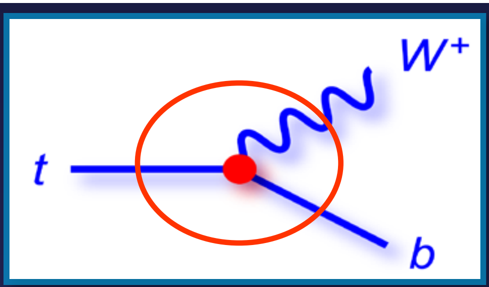
tauonic charged Higgs



leptophobic charged Higgs




DØ Run II Preliminary
M_{H^+} [GeV]
180
160
140
120
100
80
1
10
tan β
$H^+ \to c\bar{s}$
Expected limit 95% CL
Excluded 95% CL
$H^+ \to \tau\nu$
Expected limit 95% CL
Excluded 95% CL
leptophobic
tauonic



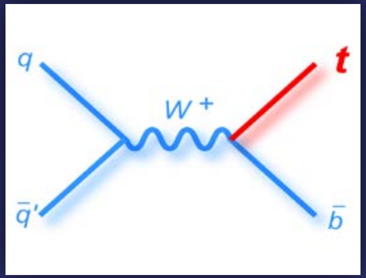
- Modifications to top quark interactions, in particular with weak gauge bosons, could yield the first signs of new physics
- Most general CP-conserving Wtb vertex up to mass dimension 5 involves four couplings

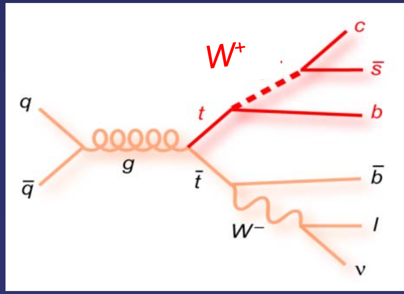
$$L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t + h.c.$$

where, in the SM $f_1^L \approx 1,\ f_2^L = f_1^R = f_2^R = 0$

- Probing tWb vertex:
  - Anomalous couplings in single top quark production and decay →
  - W helicity In top pair decays →
  - Both measurements can be combined to fully specify the tbW vertex

  (C.-R.Chen, F. Larios, and C.-P. Yuan, Phys. Lett. B 631, 126 (2005))

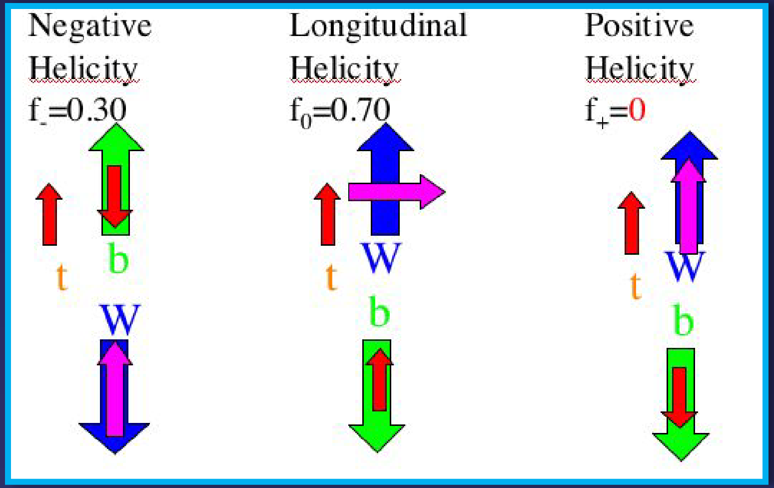




Model-independent measurement of the W boson helicity from t→Wb decays in top pair production

In the SM, the top quark decays via the V −A charged-current interaction, almost always to a W boson and a b quark

A different Lorentz structure of the t → Wb interaction would alter the fractions of W bosons produced in each polarization state from the SM



1fb^{-1} W helicity measurement was presented at a W&C on Nov 9, 2007 by Erich Varnes.

Analysis Strategy

- Model-independent measurement based on reconstruction of cosθ* distribution
- Distribution of cos θ* depends on the W boson helicity fractions

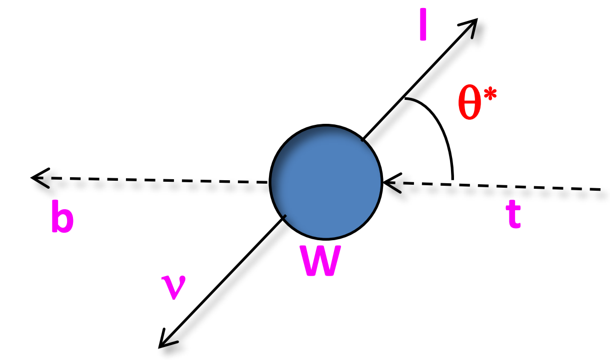
$$\omega(c) \propto 2(1-c^2)f_0 + (1-c)^2 f_- + (1+c)^2 f_+$$

where c = cos θ*

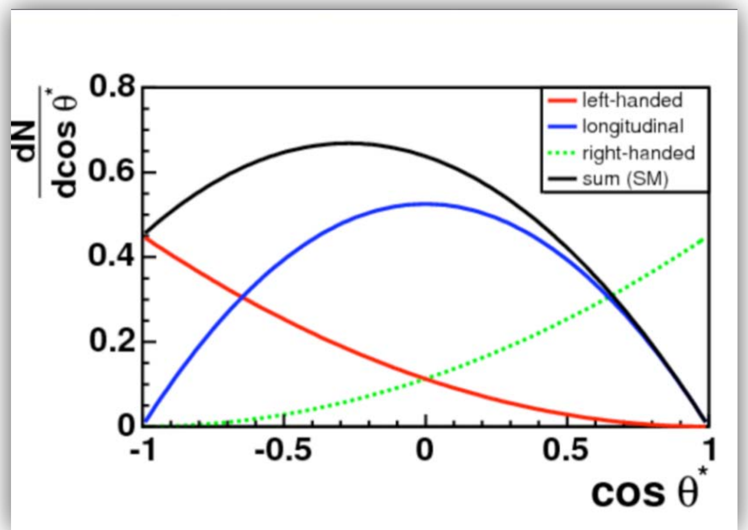
- In the selected events, the four-momenta of the top quark and the W boson are reconstructed
- Using these four-momenta, cos θ * is calculated

- We generate samples corresponding to each of the three W boson helicity states by reweighting the generated cosθ* distributions
- Simultaneous measurement of f_0 and f_+

(the negative helicity fraction f_- is then fixed by the requirement that $f_- + f_0 + f_+ = 1$)



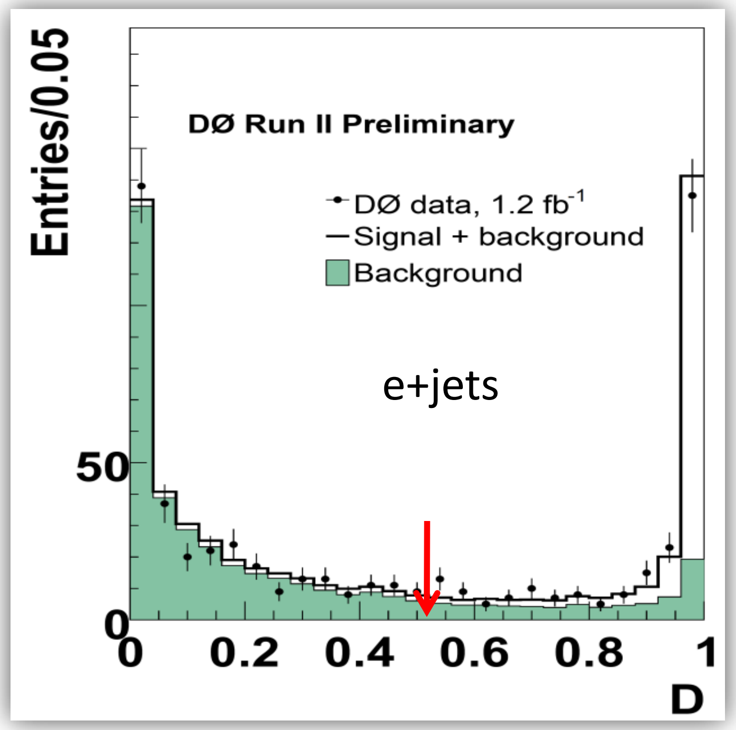
of cosθ* (angle between the momenta of the down-type fermion and the top quark in the W boson rest frame for each top quark decay.)



Event Selection

- Apply basic selection
  - 1.2 fb^{-1} in lepton+jets channel
  - 1.7 fb^{-1} in dilepton channel
  - Measurement is then combined with published 1 fb^{-1} measurement (also l+jets and dileptons)
- Further enhance signal purity by using a multivariate discriminant

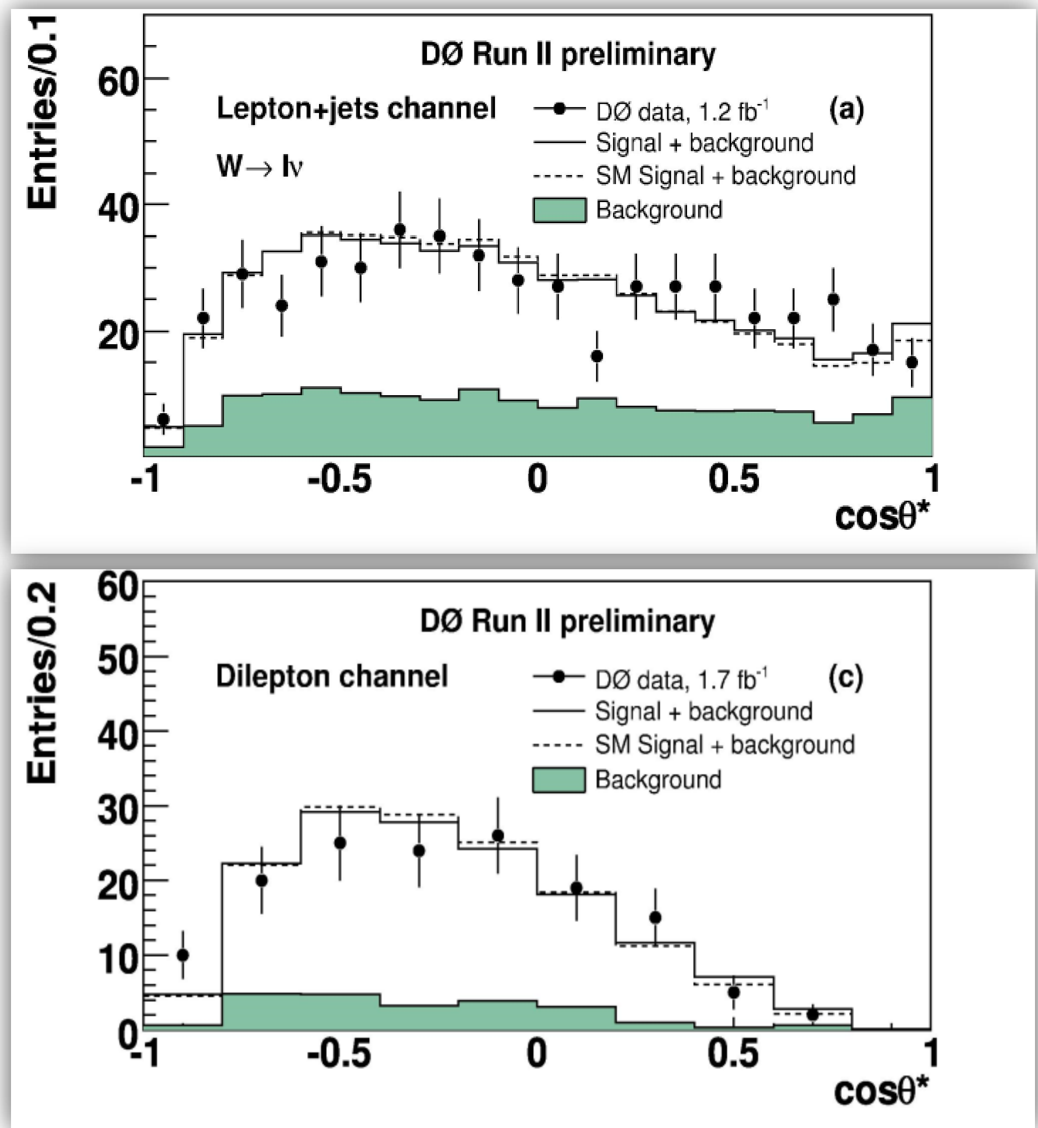
	μ+jets	e+jets
Best cut on D	>0.2	> 0.5
Data	247	251
ttbar	162.7±5.1	171.3±4.2
W+jets	75.6±4.7	55.2±3.4
Multijet	5±2.2	35.5±2.9
Expected Total	243.3±7.3	262.0±6.1



Choice of variables and discriminant cut is based on expected precision for the W boson helicity

Measuring W Boson Helicity

- cosθ* distributions for events after the cut on D
- Use a maximum likelihood fit, for the data to be consistent with the sum of signal and background in the cosθ* distribution
- The fit parameters are the W helicity fractions f_0 and f_+
- Get the W helicity fractions from the best fit



Results

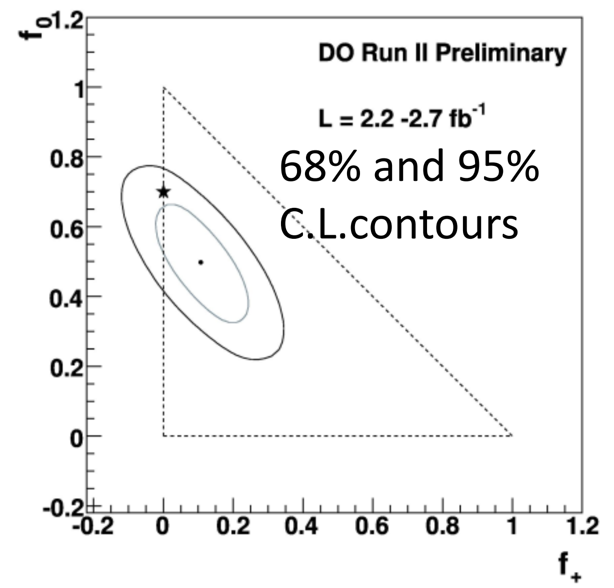
- A model-independent measurement of the helicity of W bosons in top pair production

$$
\begin{aligned}
f_0 &= 0.490 \pm 0.106\,(\text{stat.}) \pm 0.085\,(\text{syst.}) \\
f_+ &= 0.110 \pm 0.059\,(\text{stat.}) \pm 0.052\,(\text{syst.})
\end{aligned}
$$

- if f_0 constrained to the standard model value

$$f_+ = 0.019 \pm 0.031\,(\text{stat.}) \pm 0.047\,(\text{syst.})$$

This is <u>the</u> most precise such measurement



Main source uncertainties

Source	f_+	f_0
ttbar Modeling	0.028	0.055
Back. Modeling	0.026	0.039
Jet Energy Scale	0.019	0.029

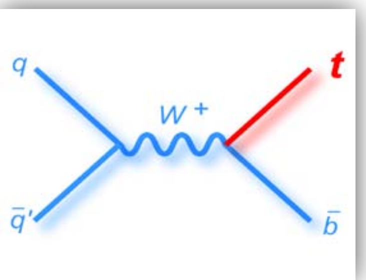
Anomalous couplings in Single top Production

- Most general CP-conserving Wtb vertex up to mass dimension 5 involves four couplings
- Left and Right handed Vector(1) couplings
- Left and Right handed Tensor(2) couplings

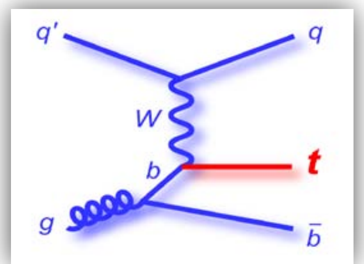
$$L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t + h.c.$$

where, in the SM $f_1^L \approx 1,\ f_2^L = f_1^R = f_2^R = 0$

s-channel("*tb*")



t-channel("*tqb*")



Search strategy:

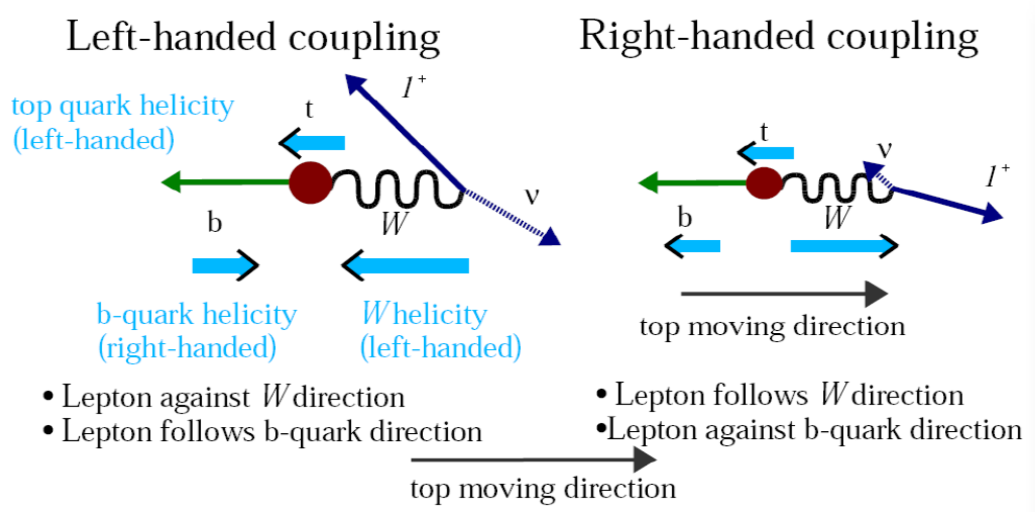
- Two non –zero couplings at a time
  - Consider 3 scenarios
  - Simultaneous limit on two couplings

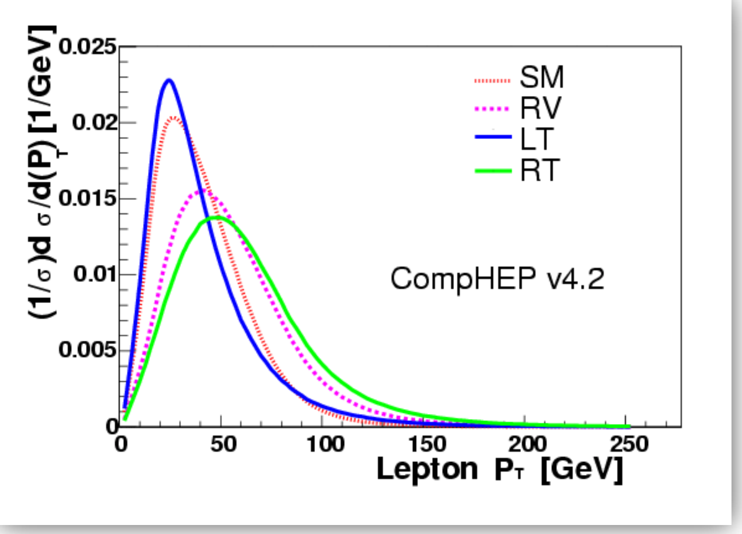
Only f_1^L, f_1^R non-zero

Only f_1^L, f_2^L non-zero

Only f_1^L, f_2^R non-zero

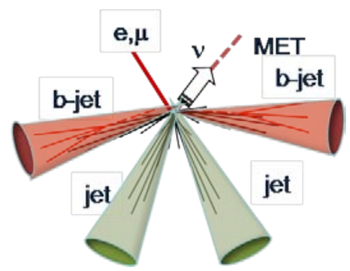
SM vs Anomalous Couplings





Presence of anomalous couplings changes the production cross-section, and kinematics and angular distributions

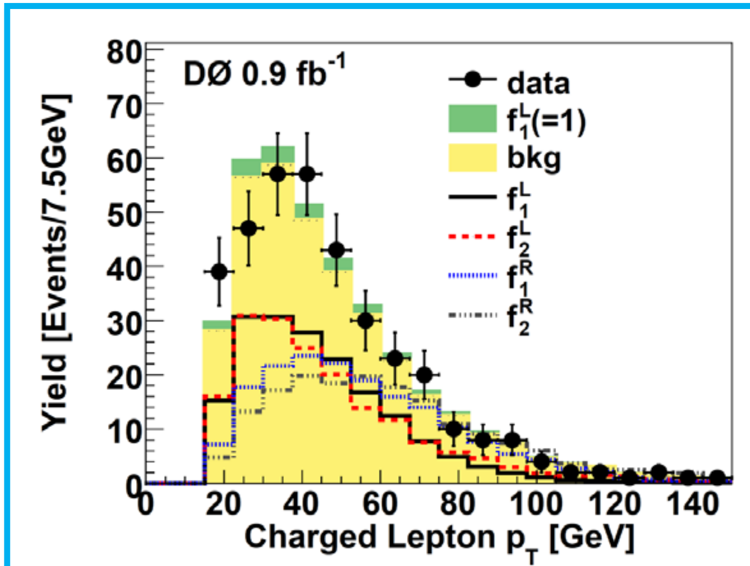
Event Selection



e :	$p_T > 15\,GeV, \lvert\eta\rvert < 1.1$	
μ :	$p_T > 18\,GeV, \lvert\eta\rvert < 2.0$	
Missing E_T	$15 < MET < 200\,GeV$	
Jets	$2-4, p_T > 15\,GeV, \lvert\eta\rvert < 3.0$	
	$p_{T,1} > 25\,GeV, \lvert\eta\rvert < 2.5$	
	$p_{T,2} > 20\,GeV$	
B − jet	1 or 2	

Lepton+jets channel only

- Acceptances for anomalous production are very similar to the SM single top (~ 3%)
- Single top signal is smaller than total background uncertainty
- Counting events or using separation power of a single variable is not a sensitive enough method



- Data is described by the model reasonably well

Main sources of uncertanities

Source	value
ttbar Modeling	18%
W+jets Modeling	18-28%
Jet Energy Scale	1-20%
B-tagging	2-16%

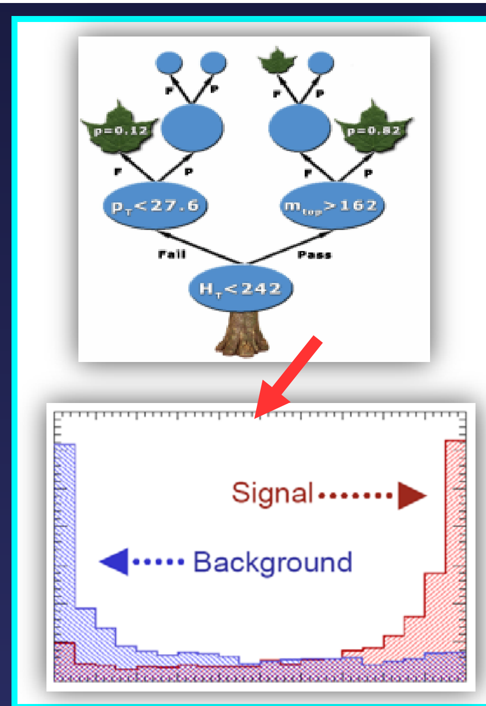
Multivariate Analysis

- Use Boosted Decision Trees to discriminate signal from background
- For every analysis, train 2 signals against sum of backgrounds

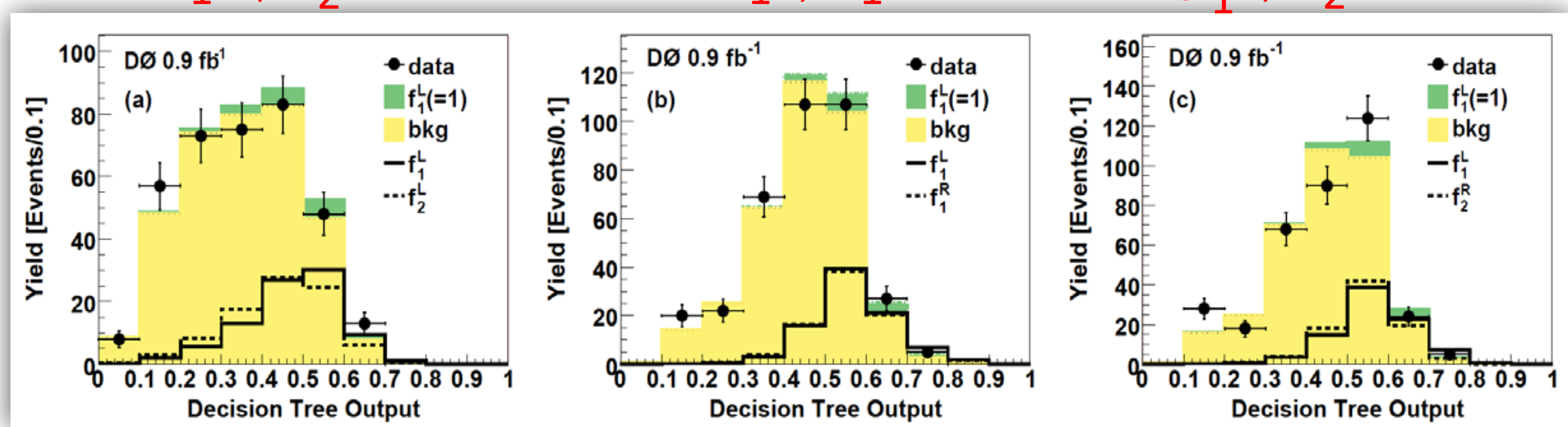
f_1^L, f_1^R scenario : (tb + tqb)LV + (tb + tqb)RV

f_1^L, f_2^L scenario : (tb + tqb)LV + (tb + tqb)LT + (tb + tqb)LV+LT

f_1^L, f_2^R scenario : (tb + tqb)LV + (tb + tqb)RT



f_1^L, f_2^L f_1^L, f_1^R f_1^L, f_2^R



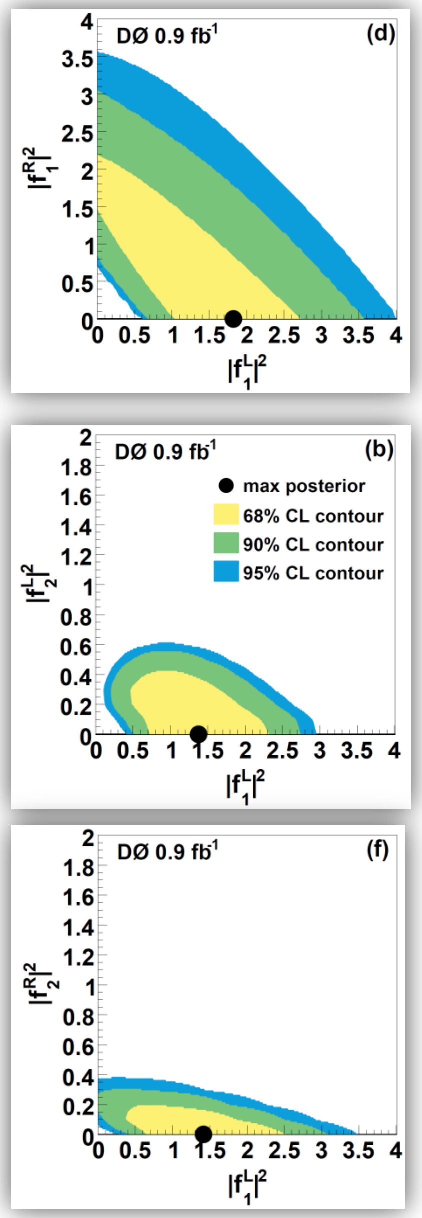
Limit Setting

- Bayesian approach for limit setting

- Simultaneous limit setting for two signals by calculating 2 dimensional posterior probability density

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.

First experimental limits on tensor couplings!
(PRL 101, 221801 (2008))



Combining W Helicity and Anom. Wtb Couplings

- General Analysis of Single Top Production and W Helicity in Top Decay
  Ren, Larios, and C. P. Yuan (PLB 631, 126 (2005))

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

$+h.c.$

where, in the SM $f_1^L \approx 1,\ f_2^L = f_1^R = f_2^R = 0$

- Combine W helicity measurement in top pair decays (PRL 100 , 062004 (2008))
  with
- Anomalous couplings measurement in single top (PRL 101, 221801 (2008))

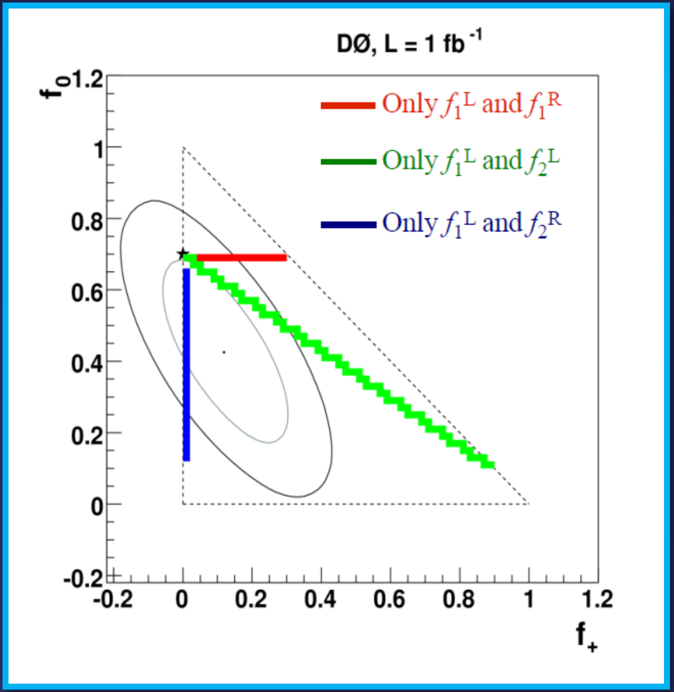
$$f_{0,\text{meas}} - f_0\left(f_1^L, f_2^L, f_1^R, f_2^R\right)$$
$$f_{+,\text{meas}} - f_+\left(f_1^L, f_2^L, f_1^R, f_2^R\right)$$
$$\Delta\sigma_{\text{s, meas}} - \Delta\sigma_{\text{s}}\left(f_1^L, f_2^L, f_1^R, f_2^R\right)$$
$$\Delta\sigma_{\text{t, meas}} - \Delta\sigma_{\text{t}}\left(f_1^L, f_2^L, f_1^R, f_2^R\right)$$

Analysis Strategy

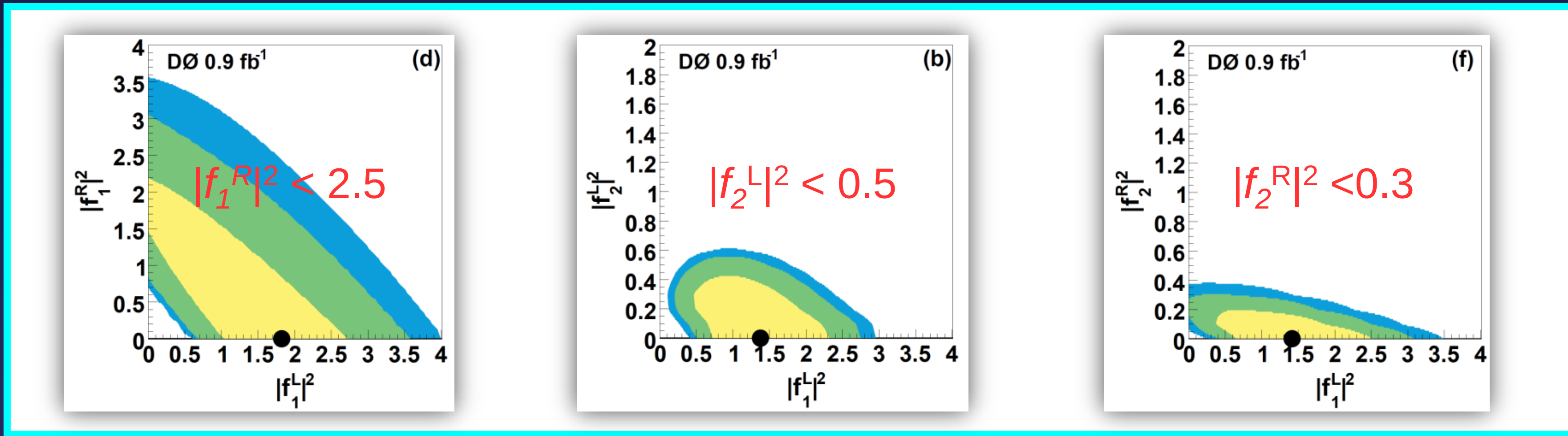
- W helicity
  - Lepton+jets and di-lepton channels
  - Same cuts as W Helicity PRL ($1 fb^{-1}$)
- Single top anomalous couplings
  - Same cuts as anomalous coupling PRL ($1 fb^{-1}$)
  - 2-jet and 3-jet events only

    Remove 4-jet events from analysis to keep orthogonality
- Combination
  - Bayesian analysis, output of W helicity analysis forms input prior to single top anomalous couplings
  - Include all W helicity systematics and all single top systematics

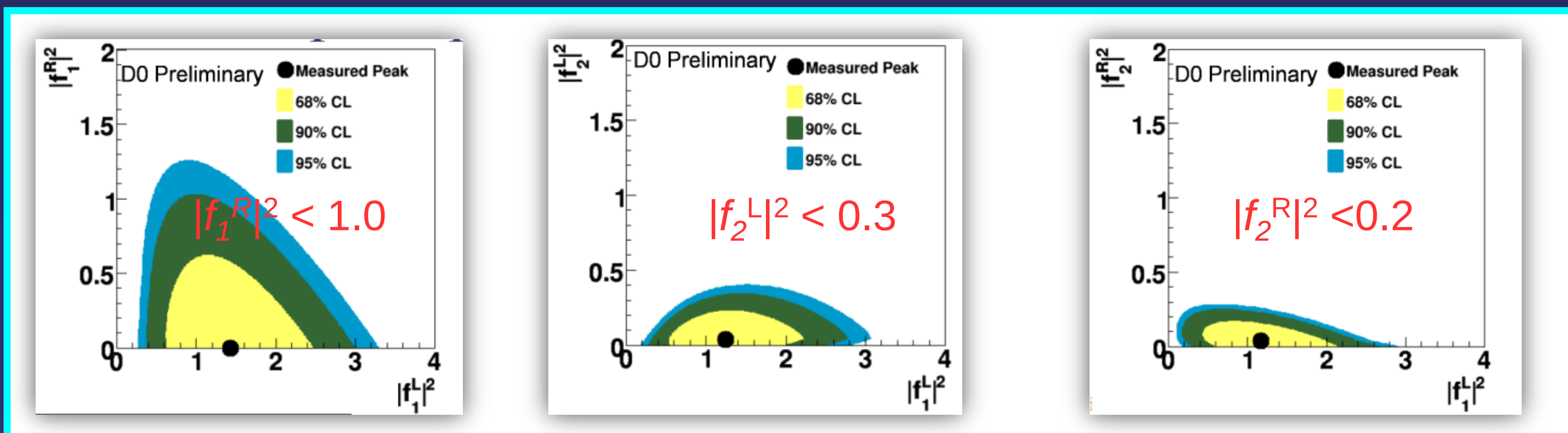
    Take all correlations of systematic uncertainties into account.



Observed posterior from the data for single top

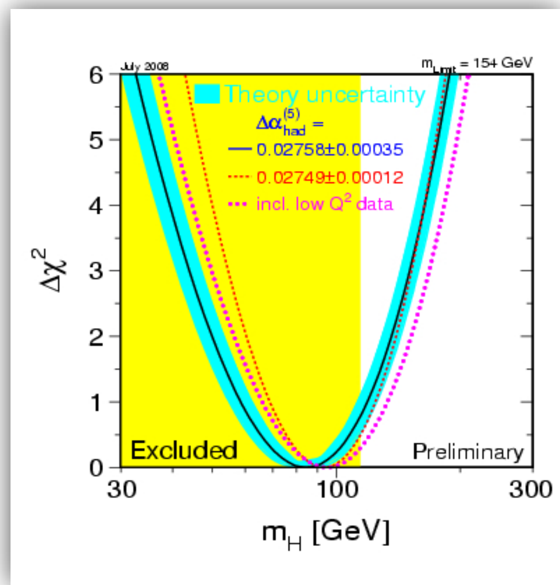


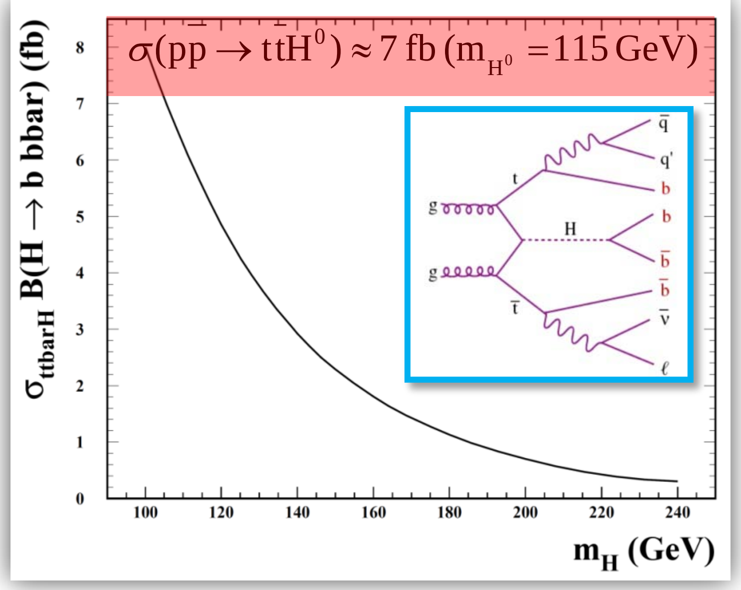
Observed posterior from the data for single top and W helicity combined



ttH Production at DØ

- Contributes to overall sensitivity (at low masses)
- Spectacular signature
- This is the first time we are looking at 5 jets with 3 or more b-jets separately events
- Could be enhanced in BSM scenarios such as 2HDMs (MSSM)
- Any new physics (e.g. G' --> t' t' H) could show up independent from SM associated Higgs production





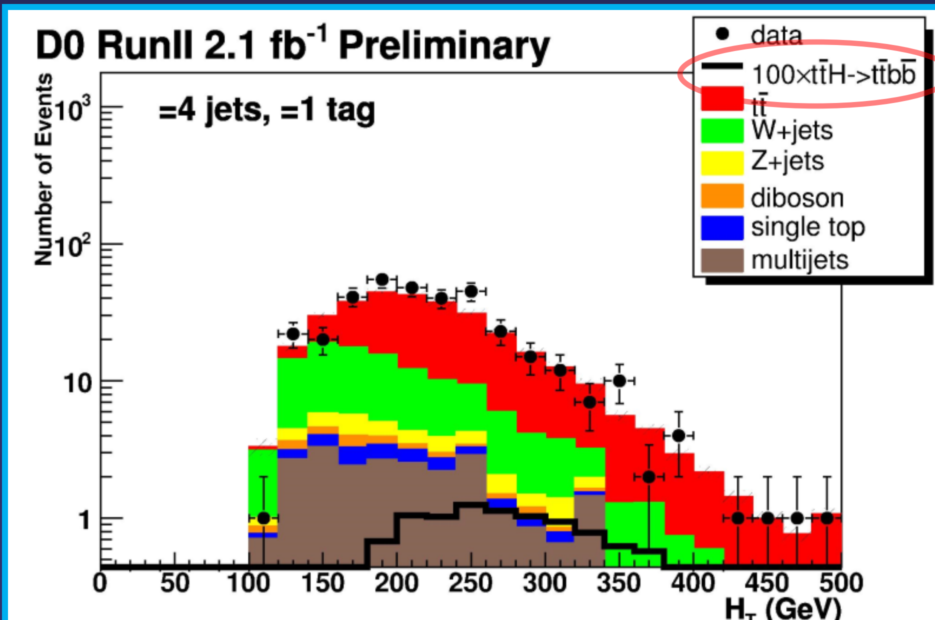
Event Selection

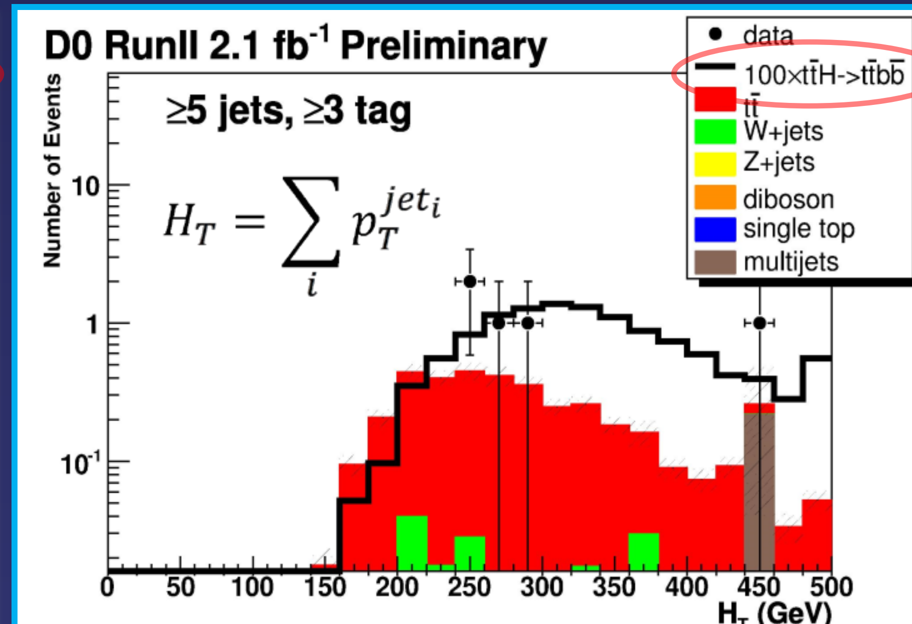
we use differences in final state, number of jets, number b-jets and kinematical difference to separate signal from background:

	e+jets					
	4j1t	4j2t	4j3t	5j1t	5j2t	5j3t
Signal	0.0675	0.0684	0.0318	0.0765	0.0882	0.0669
$t\bar{t}$	110 ± 0.6	60.5 ± 0.4	5.98 ± 0.12	25.5 ± 0.3	15.0 ± 0.2	1.97 ± 0.07
non-$t\bar{t}$ Bkg	67.2 ± 2.9	8.96 ± 0.97	0.35 ± 0.14	12.9 ± 1.3	2.52 ± 0.62	0.31 ± 0.22
sum Bkg	177 ± 3.0	69.5 ± 1.1	6.32 ± 0.18	38.4 ± 1.4	17.6 ± 0.7	2.28 ± 0.23
Observed	179	57	10	42	22	3

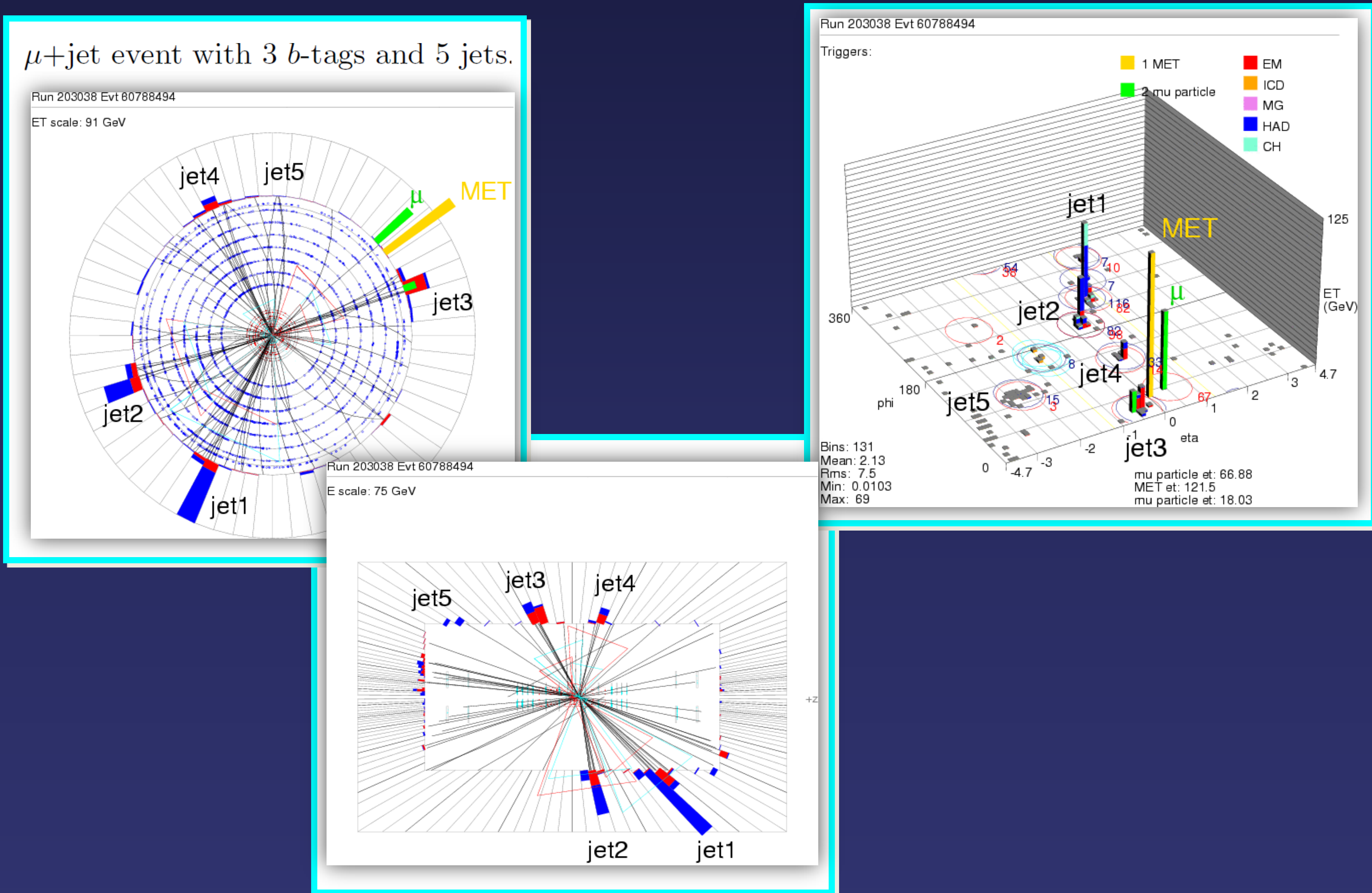
Systematic Uncertainties

Source	Values
W Backgnd Modeling	15.0%
Uncertainty on tt	10.0%
Uncertainty on ttbb	50.0%



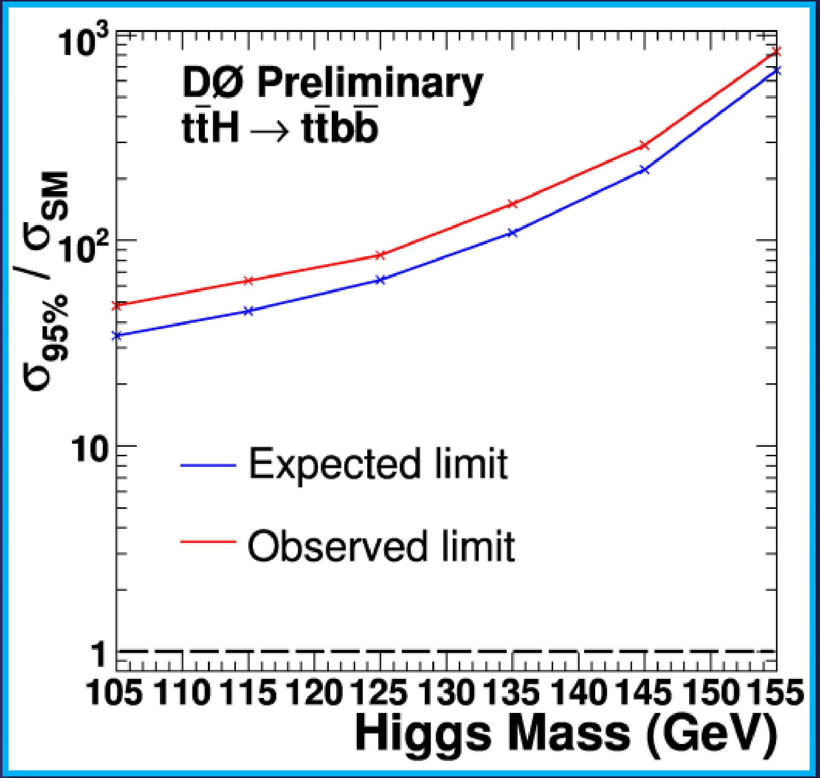


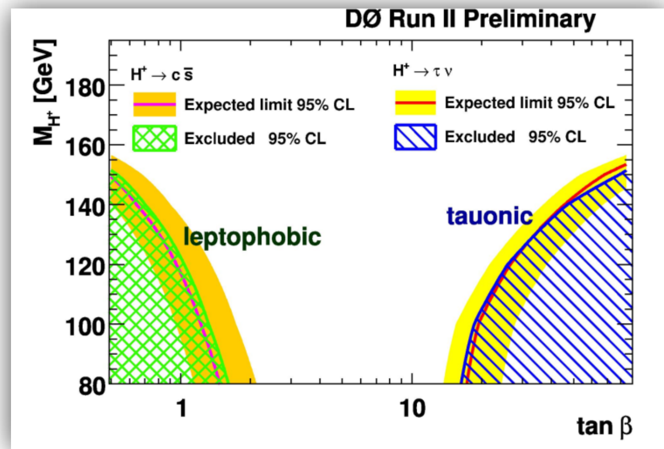
Sheer Beauty

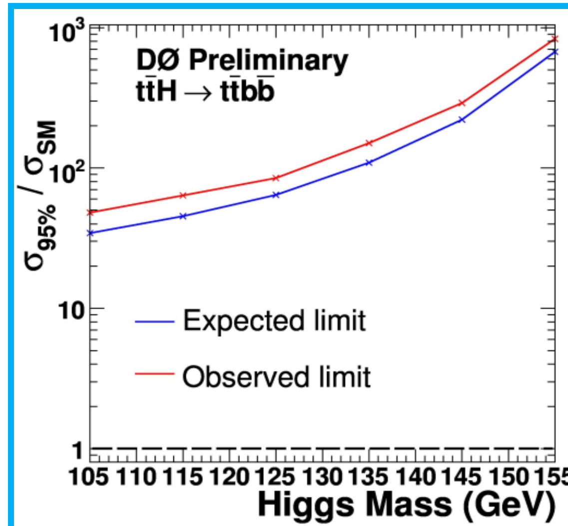


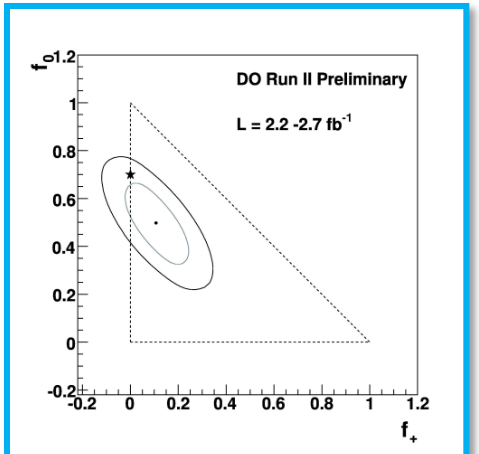
Results

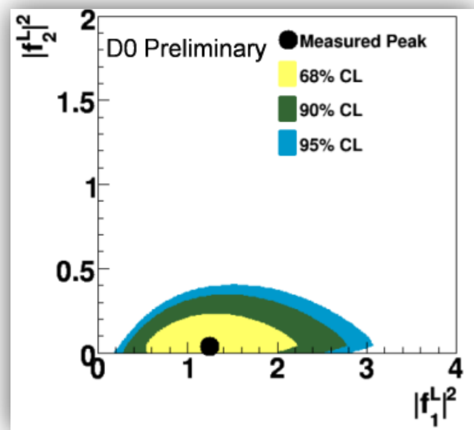
- Set 95% CL upper limit on the ttH cross section times branching ratio
- Limits strongly depend on the mass of the Higgs boson
- Improvement from ratio of 60 to 35 for Higgs mass of 105 GeV with increase in data from 0.9 fb^{-1} to 2.1fb^{-1} (expected improvement is √2)

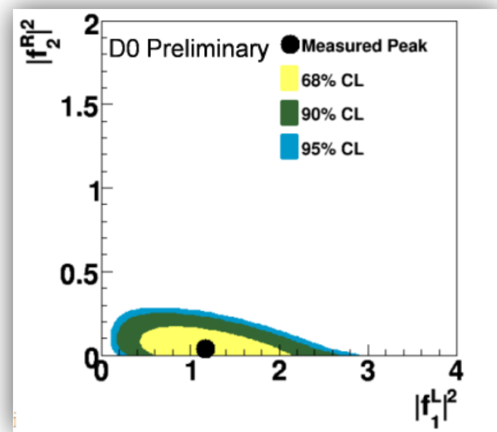



DØ Run II Preliminary
M_{H^+} [GeV]
$H^+ \to c\bar{s}$
Expected limit 95% CL
Excluded 95% CL
$H^+ \to \tau\nu$
Expected limit 95% CL
Excluded 95% CL
leptophobic
tauonic
tan β
180
160
140
120
100
80
1
10


DØ Preliminary
$t\bar{t}H \to t\bar{t}b\bar{b}$
$\sigma_{95\%} / \sigma_{SM}$
Expected limit
Observed limit
Higgs Mass (GeV)
10^3
10^2
10
1
105 110 115 120 125 130 135 140 145 150 155


DO Run II Preliminary
L = 2.2 -2.7 fb^{-1}
f_0
f_+
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.2 0 0.2 0.4 0.6 0.8 1 1.2


D0 Preliminary
Measured Peak
68% CL
90% CL
95% CL
$|f_2^L|^2$
$|f_1^L|^2$
2
1.5
1
0.5
0
0 1 2 3 4


D0 Preliminary
Measured Peak
68% CL
90% CL
95% CL
$|f_2^R|^2$
$|f_1^L|^2$
2
1.5
1
0.5
0
0 1 2 3 4

Conclusions/Outlook

- Top quark provides a window to new physics

- The high statistics samples available at the Tevatron not only allows to carry out a program of precision measurements such as cross section and top mass, but also
- Sensitively probe for new physics in the top sector

- So far we have not seen any significant deviations from the SM perdcitions but…
  - We still have to analyze a large chunk of available data (increasing every day)
  - We have not explored all possible scenarios
  - Analysis techniques keep getting better and better

Looking at the Physics program both at D0 and CDF,

I am confident that If there is new physics hiding in our data,

It will not be able to hide much longer