



Top quark cross section & properties

S. Greder,
on behalf of the D0 Collaboration

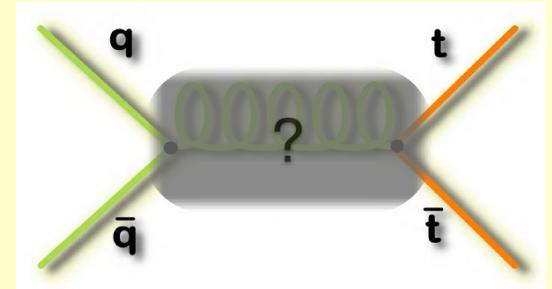


Outline

- Introduction
- TeVatron and D0 detector
- Top-antitop cross-sections
- W helicity & W-t-b coupling
- Spin correlations
- Conclusion

Why measuring top cross sections ?

- Test pQCD, SM.
- Probe of the new production mechanism (e.g. resonance production)
 - *cross-check results in as many channels as possible*
 - *Look for consistency, constrain non-standard contributions (e.g look at ratios, see Yvonne's talk)*
- Define well understood samples for *properties measurements*
- Dominant background to Higgs/SUSY searches
- Extract *top pole mass* from x-section

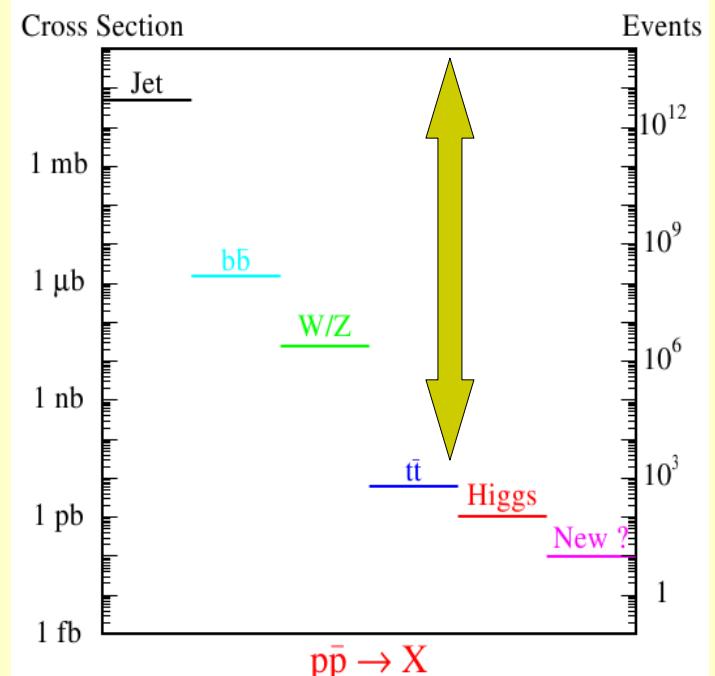
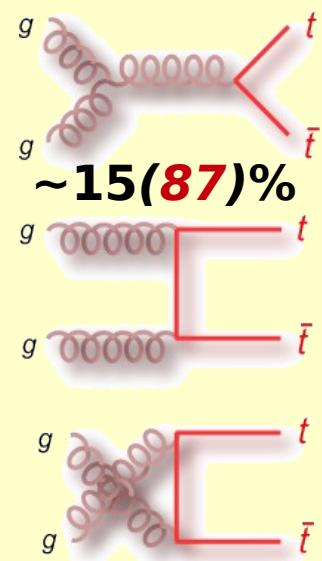
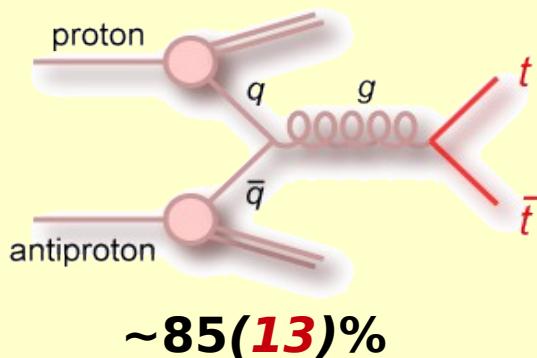




Top quark production

TeVatron (LHC)

Strong production:



- See Reinhard's talk for EW production
- - *N. Kidonakis and R. Vogt*, arXiv:hep-ph/0805.3844, PRD 78, 074005 (2008):
NLO + NNLO soft gluon correction, $\sigma = 7.27+0.76-0.85 \text{ pb}$, $m_t = 172.5 \text{ GeV}$
- *S. Moch and P. Uwer*, arXive:hep-ph/0804.1476, PRD 78, 034003 (2008):
NNLO (approx), $\sigma = 7.45+0.50-0.70 \text{ pb}$, $m_t = 172.5 \text{ GeV}$
- *M. Cacciari, S. Frixione, M. M. Mangano, P. Nason and G. Ridolfi*, arXiv:hep-ph/0804.2800, JHEP 09, 127 (2008):
NLO + next-to-leading threshold logarithm correction, $\sigma = 7.14+0.76-0.86 \text{ pb}$, $m_t = 172.5 \text{ GeV}$

↳ Errors ~7-10%

↳ In RunII, most of errors are **systematic-limited** (*JES, luminosity, ...*)

(RunI, $\sqrt{s} = 1.8 \text{ TeV}$, $L \sim 100 \text{ pb}^{-1}$: $\Delta \sigma_{tt} / \sigma_{tt} \sim 25\%$).



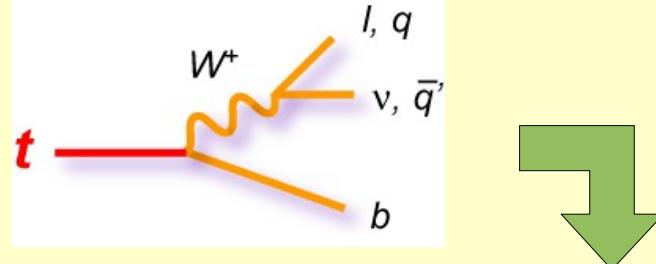
Top quark decays

Properties

- $m_t \gg m_W + m_b$ & 3 generations CKM

$|V_{tb}| = 0.9990-0.9992$ (@ 90% C.L)

↳ $B(t \rightarrow Wb) \sim 100\%$

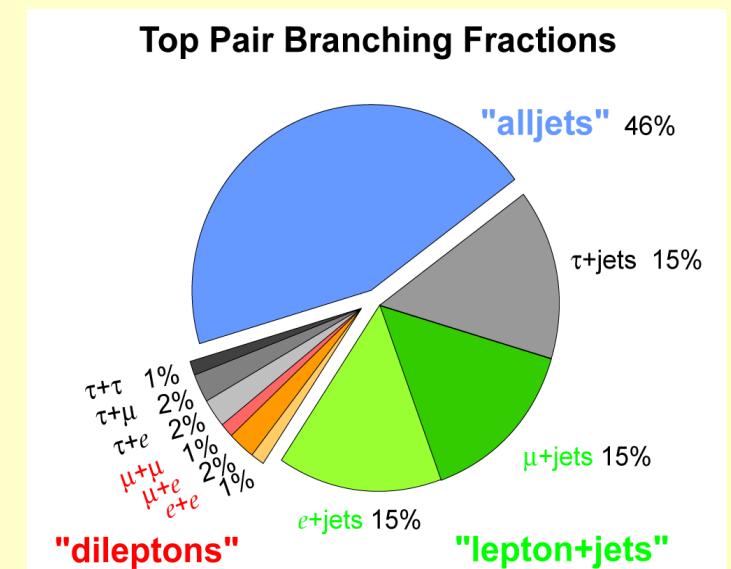
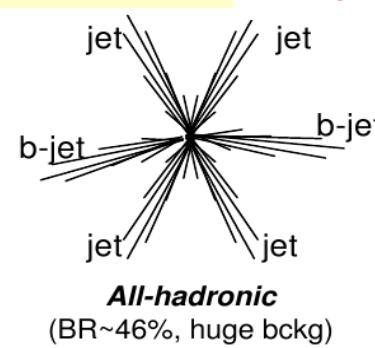
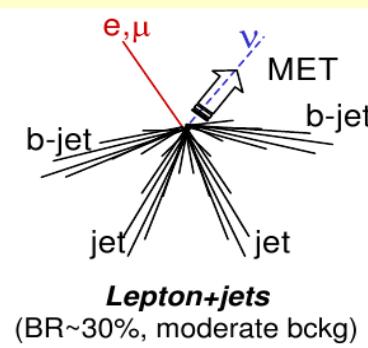
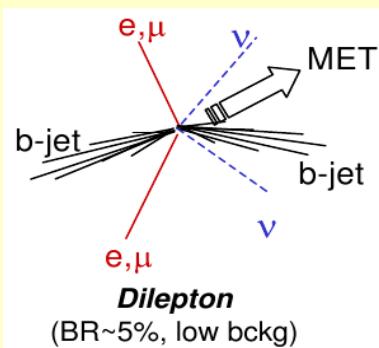


- $\Gamma_t \sim 1.4 \text{ GeV} \Rightarrow \Gamma_t \gg \Lambda_{\text{QCD}}$

↳ *top spin ~fully transferred to decay products*

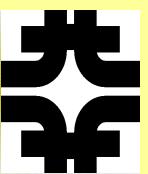
Final states

- Efficient triggering system (QCD is $\sim 10^9$)
- Multipurpose detector

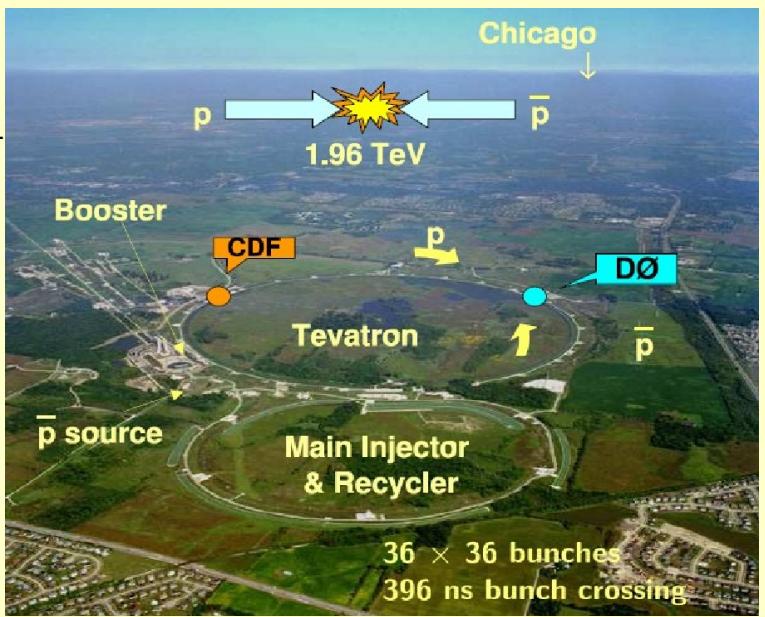
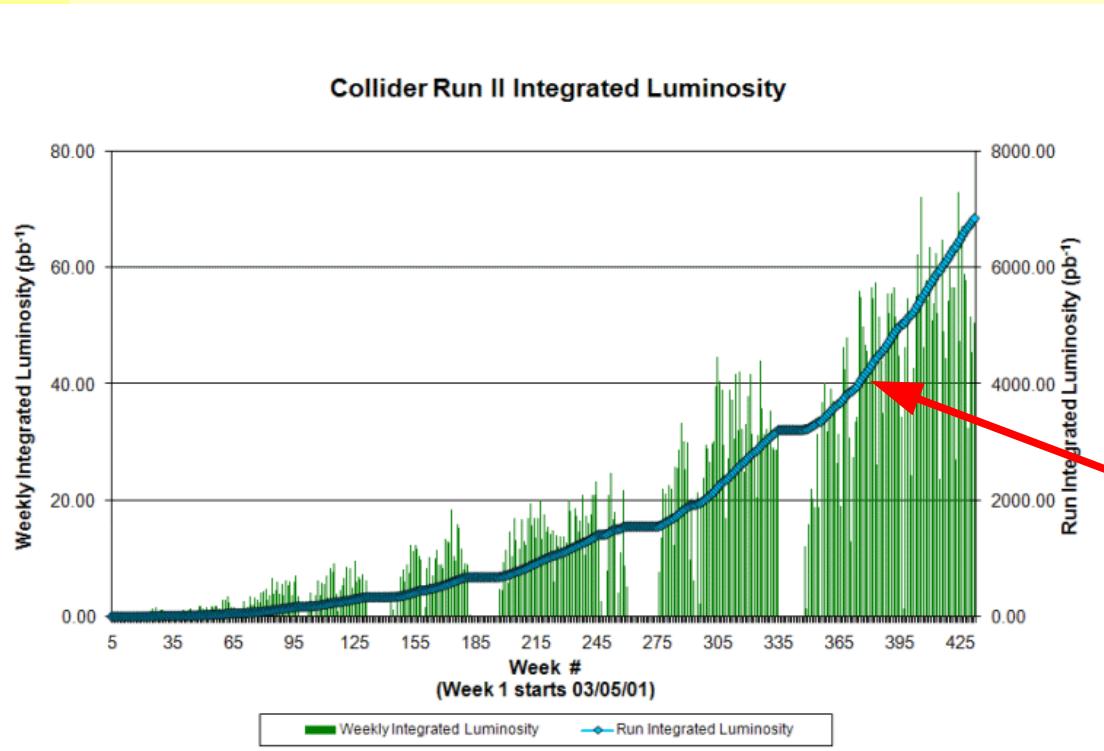




TeVatron



- Proton / anti-proton collider @ 1.96 TeV
- RunI 1995: top discovery, RunII, started 2001
- Excellent / stable performance
- Peak luminosity $> 3.5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- $6.7 / 6 \text{ fb}^{-1}$ per experiment delivered/recorded



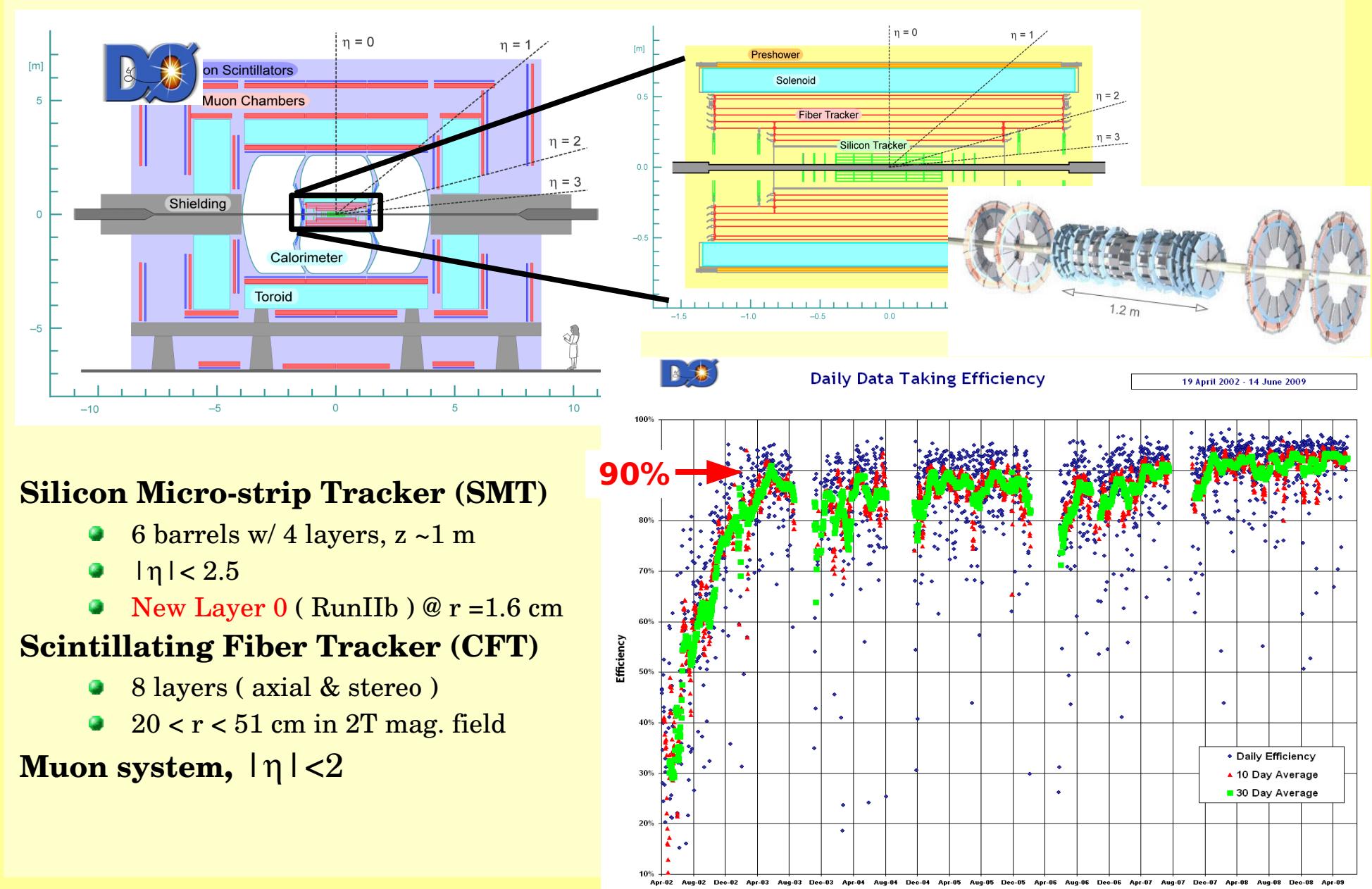
TeVatron @ $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$: 7kEvts/year
(*LHC @ $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$:* 8MEvts/year !)

4 fb^{-1} , top pairs:

- ~15k (alljets)
- ~ 9k (e, mu+jets)
- ~ 3k (dileptons, incl. tau)



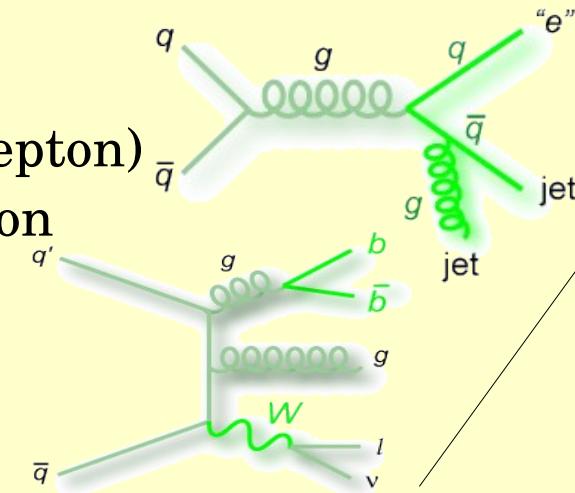
DØ detector



Top x-sections: lepton+jets

- **Topology**

- 1 high p_T *isolated* lepton (e,μ)
- + ≥ 3 jets, $p_T > 40/20/20$ GeV
- + MET $> 20(25)$ GeV + $\Delta\phi(\text{MET}, \text{lept.})$



- **Background**

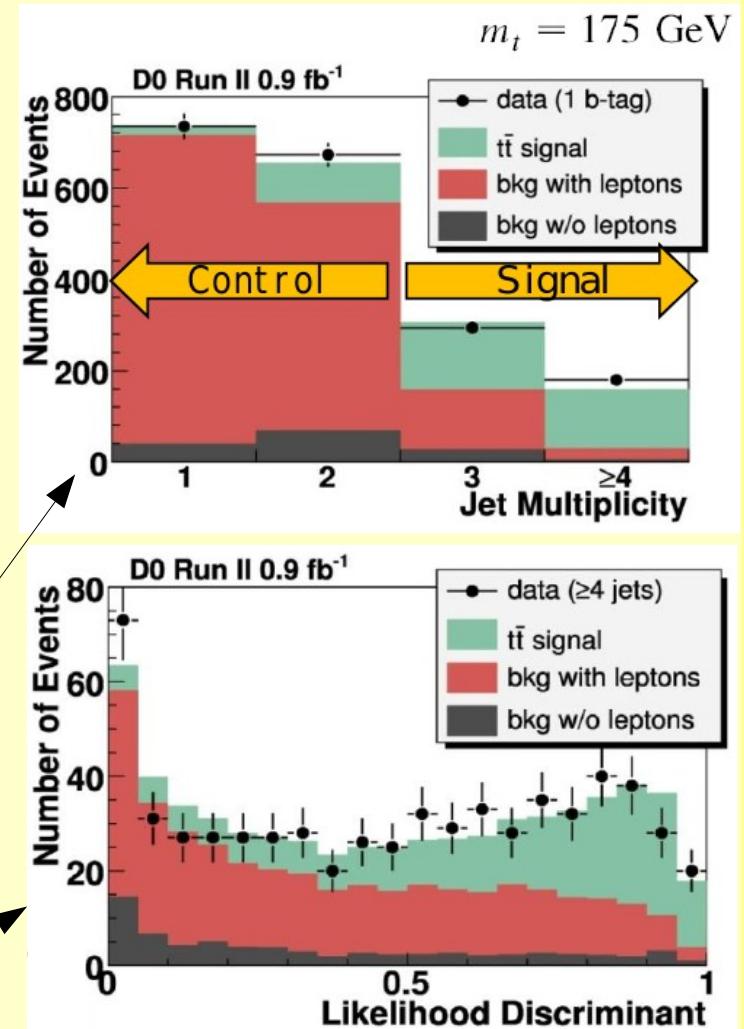
Multijet (fake lepton)
W/Z+jets, diboson

- **With b-tagging**

counting exp.; max. LLH fit to #events
 $\geq 3,4$ jets with 1,2 b-tag(s)

- **Topological**

max. LLH fit to discriminant
combining topological inputs events w/ $\geq 3,4$ jets





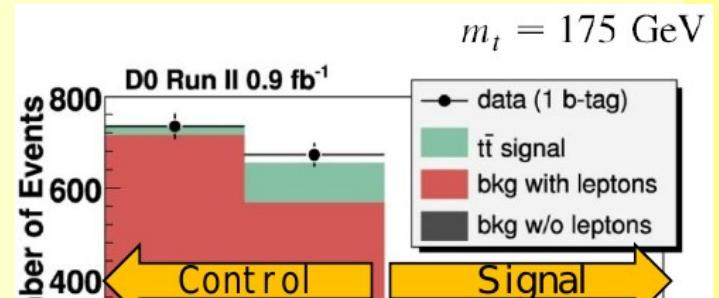
Top x-sections: lepton+jets

- **Topology**

1 high p_T *isolated* lepton(e, μ)

≥ 3 jets, $p_T > 40, 20$ GeV

MET $> 20(25)$ GeV + $\Delta\phi(\text{MET}, \text{lent.})$



Results ($m_t = 175$ GeV):

With b-tagging: $\sigma_{t\bar{t}} = 8.05 \pm 0.54 \text{ (stat.)} \pm 0.70 \text{ (syst.)} \pm 0.49 \text{ (lumi.) pb}$

Topological: $\sigma_{t\bar{t}} = 6.62 \pm 0.78 \text{ (stat.)} \pm 0.36 \text{ (syst.)} \pm 0.40 \text{ (lumi.) pb}$

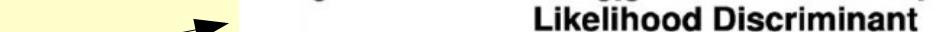
Combined: $\sigma_{t\bar{t}} = 7.42 \pm 0.53 \text{ (stat.)} \pm 0.46 \text{ (syst.)} \pm 0.45 \text{ (lumi.) pb}$

$\geq 3, 4$ jets with 1, 2 b-tag(s)

- **Topological**

max. LLH fit to LLH discriminant

using topological inputs events w/ $\geq 3, 4$ jets



Top x-sections: dileptons & $\tau+\text{lepton}$

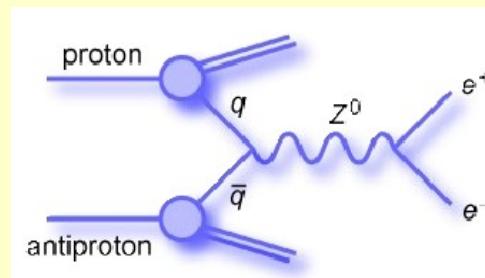
- **Topology**

- **dileptons:**

- 2 high p_T *isolated & opposite charge*
 leptons (e, μ) + ≥ 2 jets $p_T > 30, 20$ GeV
 + MET > 45 GeV + $\Delta\phi(\text{MET}, \text{lept.})$
 + dilepton inv. mass + topological cuts

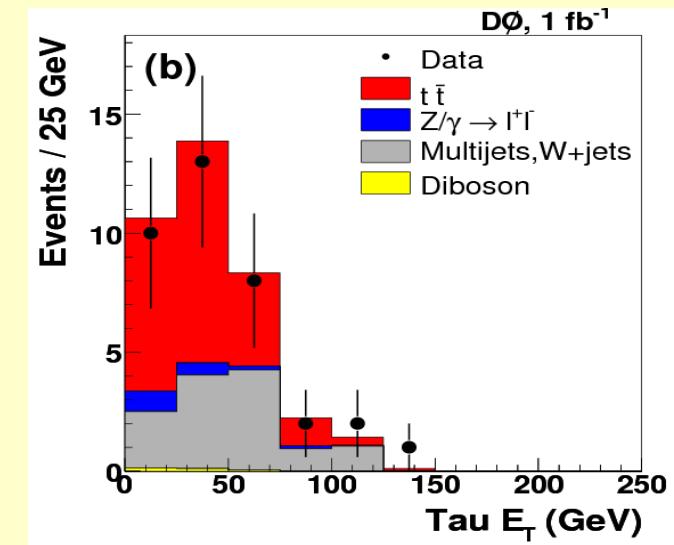
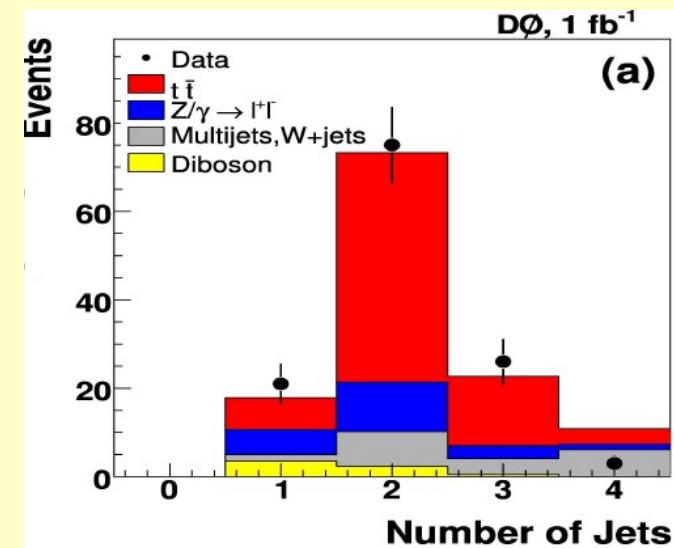
- **$\tau + \text{lepton}$:**

- 1 high p_T lep. + *1 hadronic opp. charge τ*
 + MET > 15 GeV + $\Delta\phi(\text{MET}, \text{lept.})$
 + 1 b-tag jet



- **Backgrounds**

- Multijet (fake lepton + heavy flavour)
- $Z/\gamma \rightarrow ll$, $Z/\gamma \rightarrow \tau\tau$, $W/Z+jets$, dibosons



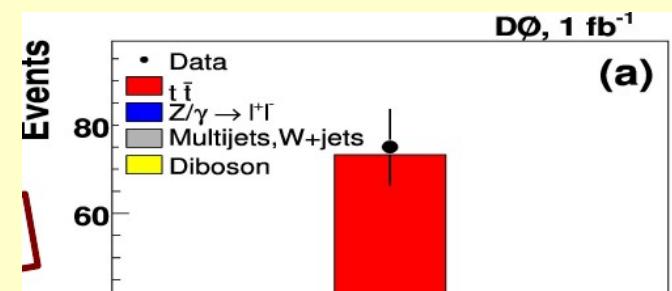
Top x-sections: dileptons & tau+lepton

- **Topology**

dileptons (1fb⁻¹):

2 high p_T *isolated & opposite charge*

Leptons (e, μ) + > 2 jets, $p_T > 20$ GeV



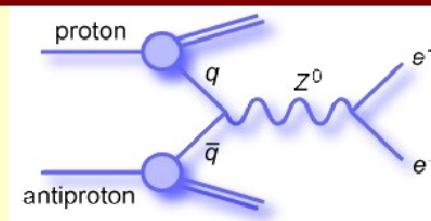
Results ($m_t = 175$ GeV):

dileptons:

$$\sigma_{t\bar{t}} = 7.5^{+1.0}_{-1.0} (\text{stat})^{+0.7}_{-0.6} (\text{syst})^{+0.6}_{-0.5} (\text{lumi}) \text{ pb}$$

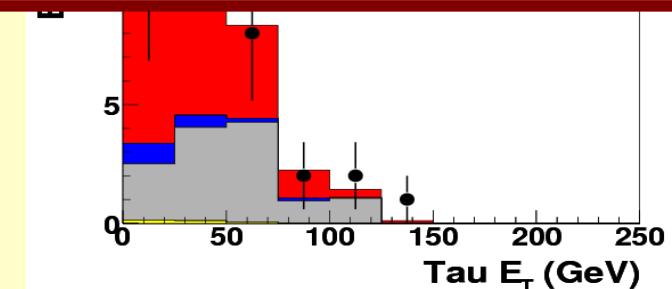
tau+lepton:

$$\sigma(t\bar{t}) = 7.32^{+1.34}_{-1.24} (\text{stat})^{+1.20}_{-1.06} (\text{syst}) \pm 0.45 (\text{lumi}) \text{ pb}$$



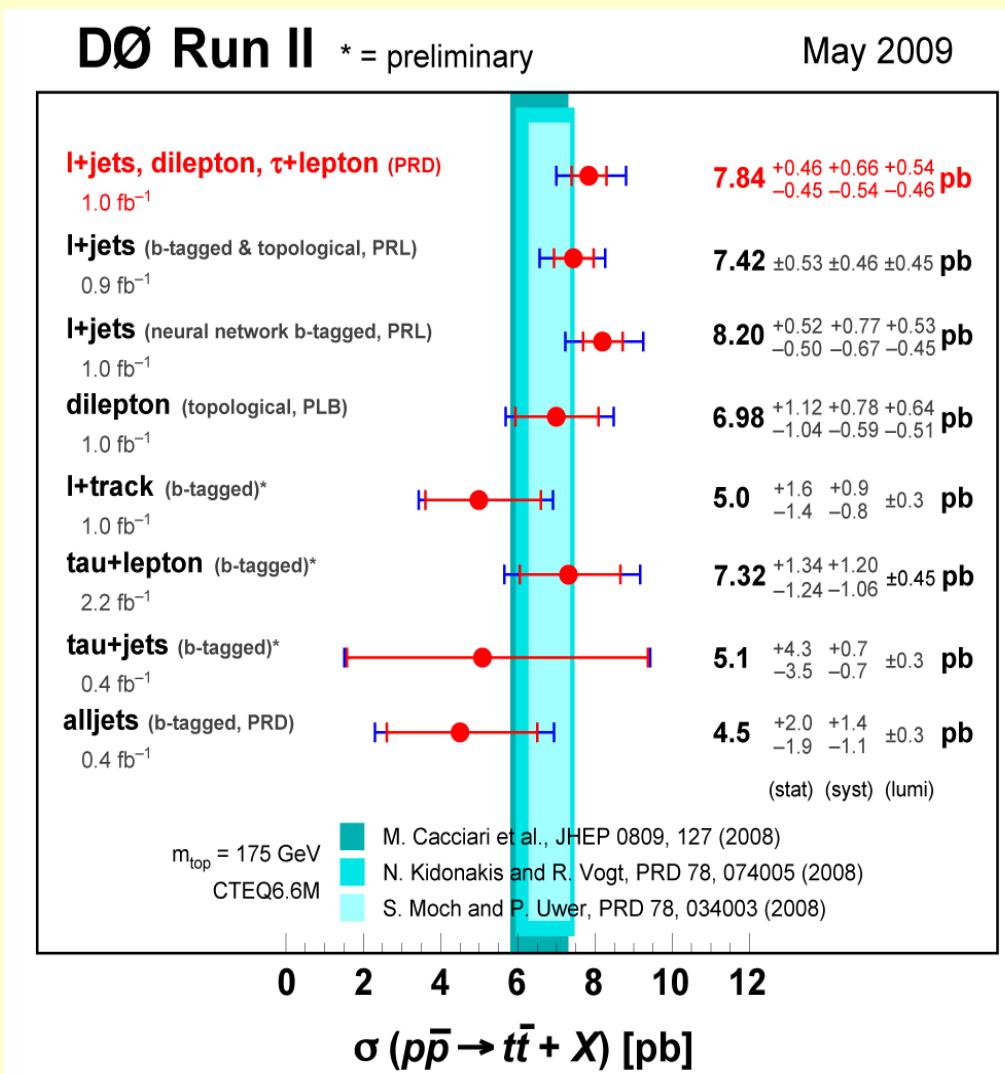
- **Backgrounds**

- Multijet (fake lepton + heavy flavour)
- Z/γ → ττ, W/Z+jets, diboson



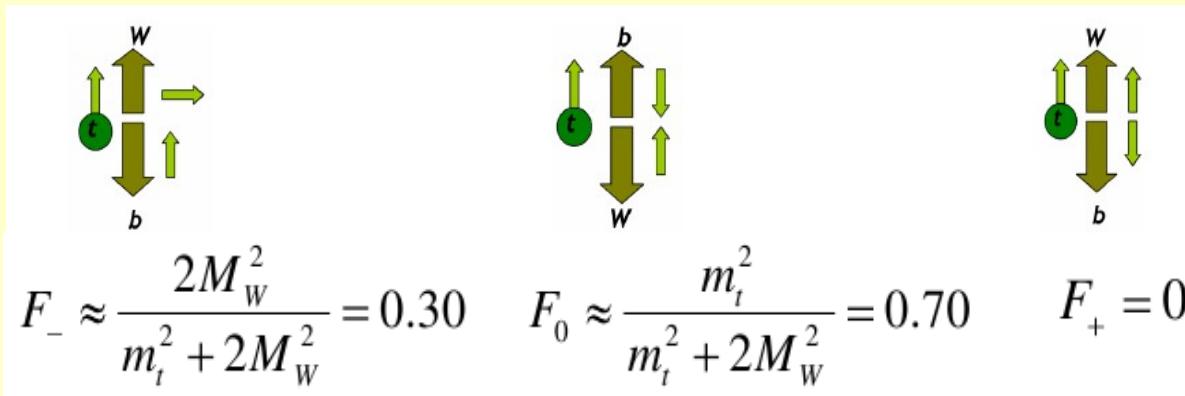
Overview of top x-sections

- Self-consistent measurement across channels (*shown here for $m_t = 175 \text{ GeV}$*)
All agree with SM!
- Single measurement:
 $\Delta\sigma_{tt}/\sigma_{tt} \sim 11\%$! (l+jets),
 limited by systematic errors
- On-going D0/CDF effort
 for x-sections combinations,
 common systematic defs., ...
- Non-standard decay modes
 can be tested through e.g
x-sections ratios
 (see Yvonne's talk)

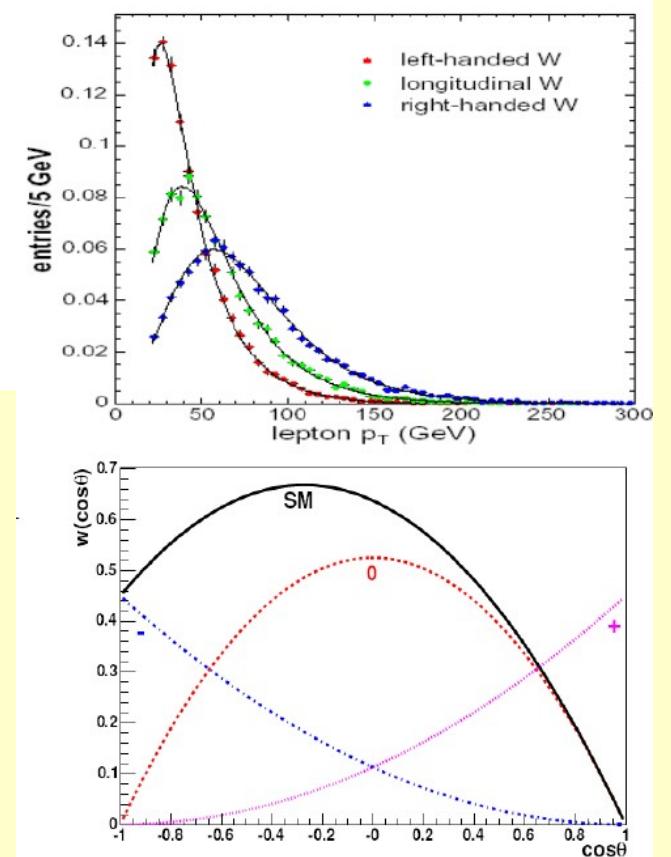


W helicity in top decays

- Investigate structure of t-W-b interaction
- Reminder:** SM only left-handed particles couple to W (*V-A coupling*).
Possible W helicity configurations:

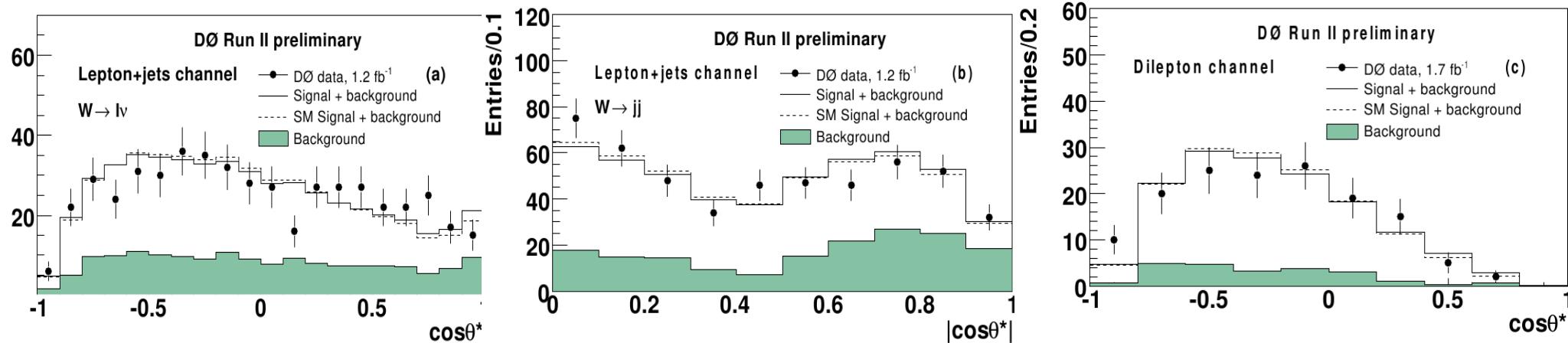


- Lepton kinematic* sensitive to W helicity:
 - Lepton p_T
 - θ^* : angle between lepton / W in W rest frame / top rest frame
- ↳ samples: lepton+jets and dileptons



W helicity in top decays

- Compare *templates* for left, right and longitudinal polarizations



Results:

- Model independent analysis (f_0 and f_+ are varied ind.)

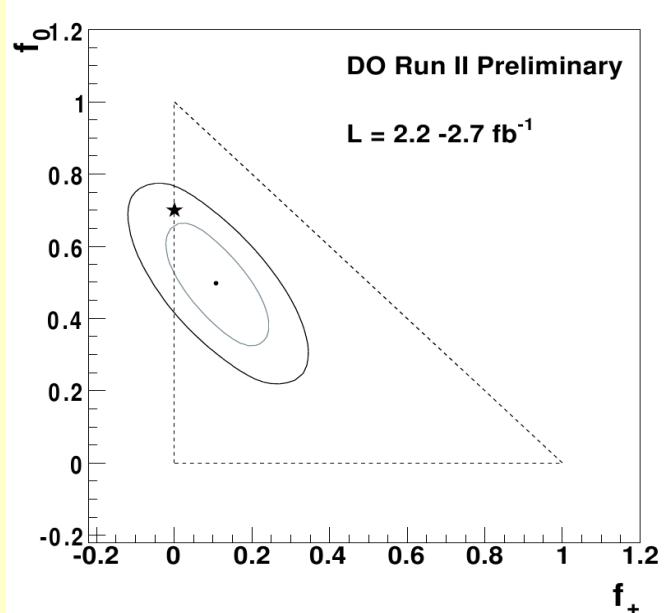
$$f_0 = 0.490 \pm 0.106 \text{ (stat.)} \pm 0.085 \text{ (syst.)}$$

$$f_+ = 0.110 \pm 0.059 \text{ (stat.)} \pm 0.052 \text{ (syst.)}$$

23% consistency with SM values:

$$f_0 = 0.697 \text{ and } f_+ = 3.6 \times 10^{-4}$$

- Systematic dominated by *signal/bkgd models*





Anomalous couplings

Phenomenology

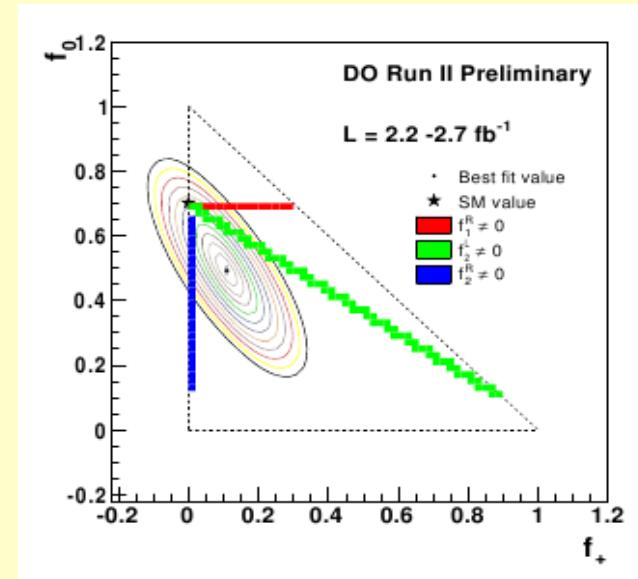
- Can affect many observables
 - top-antitop / single-top x-sections, spin correlations, *angular/kinematic distributions of decay products, ...*
- Additional couplings
 - left/right vector $f_1^{L/R}$, tensor $f_2^{L/R}$:

$$\begin{aligned}\mathcal{L} = & -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_1^L P_L + f_1^R P_R) t W_\mu^- \\ & - \frac{g}{\sqrt{2}} \bar{b} \frac{i \sigma^{\mu\nu} q_\nu V_{tb}}{M_W} (f_2^L P_L + f_2^R P_R) t W_\mu^- + \text{H.c.}\end{aligned}$$

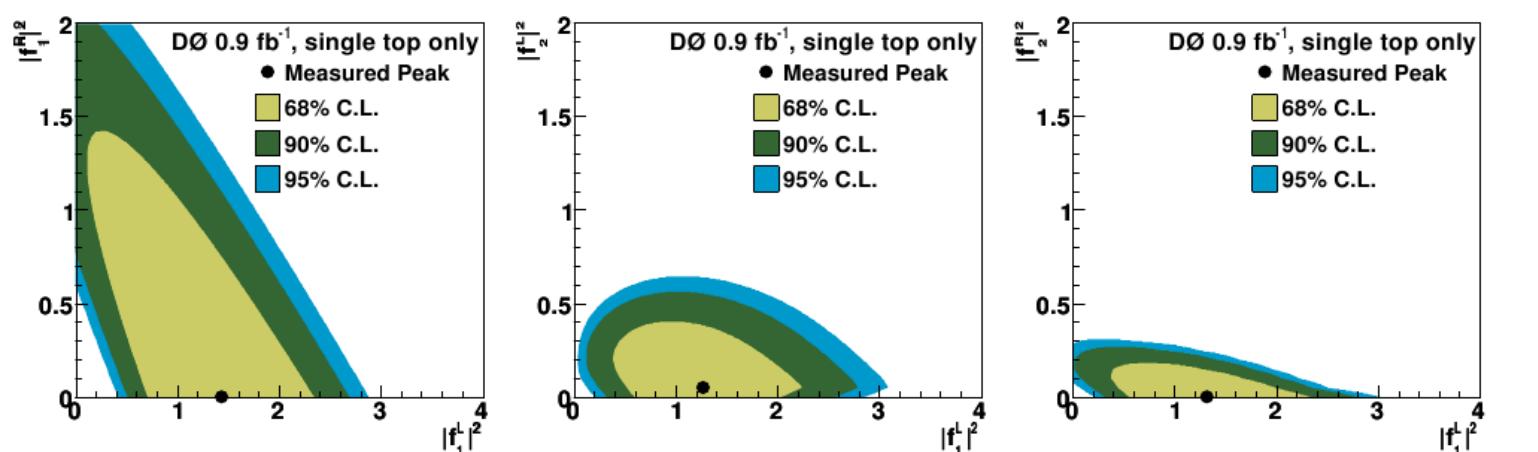
Anomalous couplings

- Use information from W helicity (*see previous slides*) and *single-top*:
 - Single-top sample: 0.9 fb^{-1}
 - Decision trees trained for 3 different anomalous couplings scenarios
 - Phys. Rev. Lett. 102, 092002 (2009)

Results



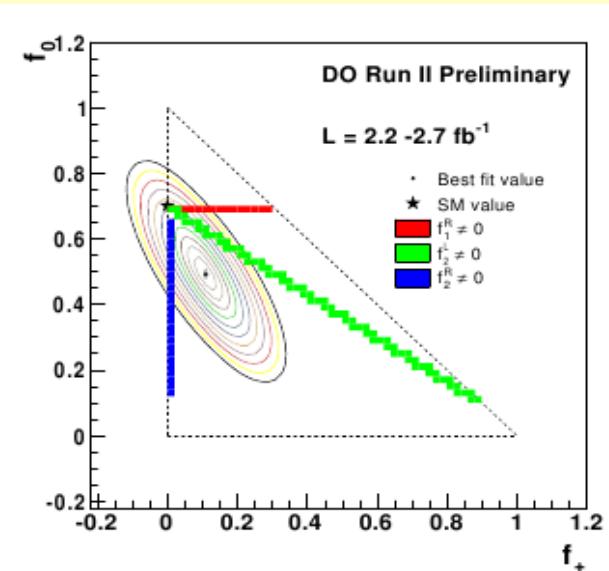
Good agreement with expected SM values: $f_1^L = 0$, $f_1^R = f_2^{L/R} = 0$



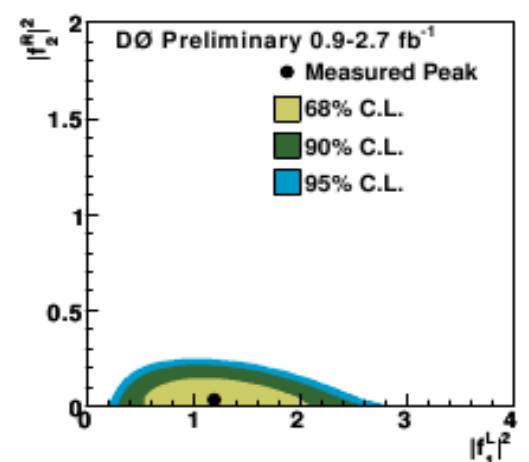
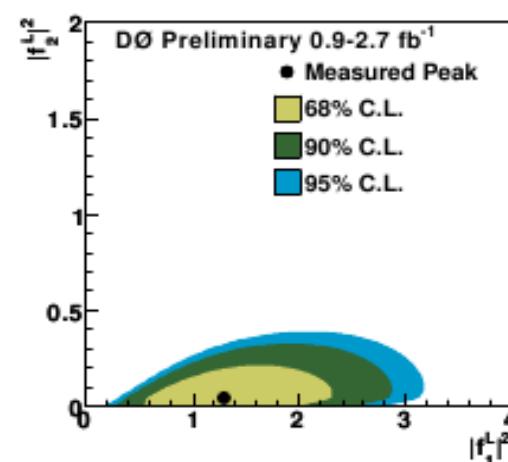
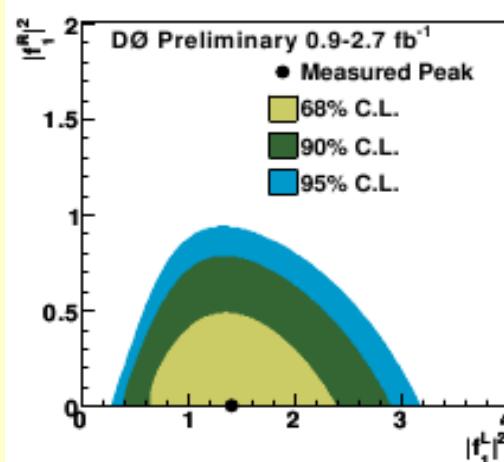
Anomalous couplings

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Results



Good agreement with expected SM values: $f_1^L = 1$, $f_1^R = f_2^{L/R} = 0$



Top-antitop spin correlations

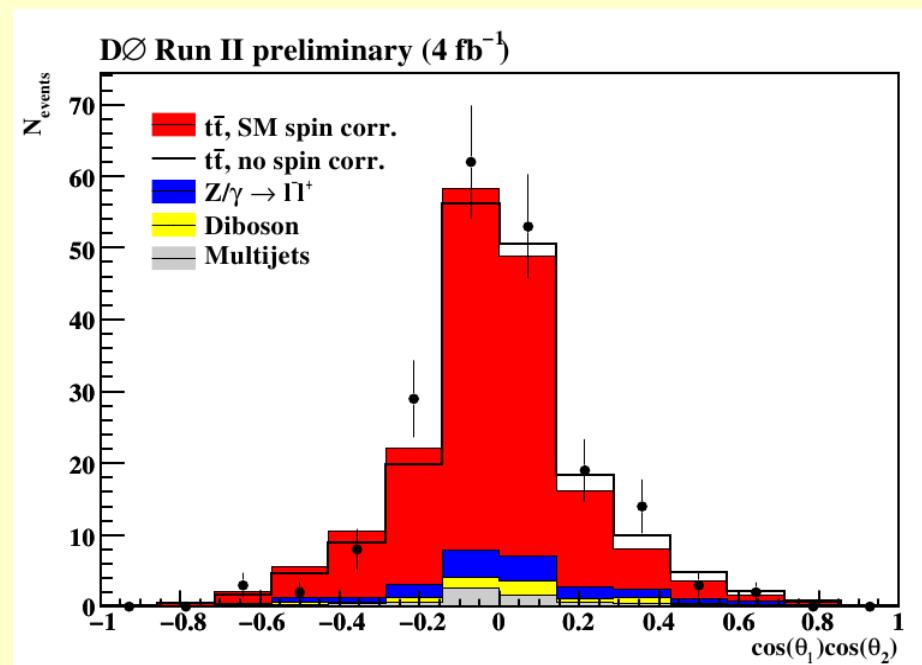
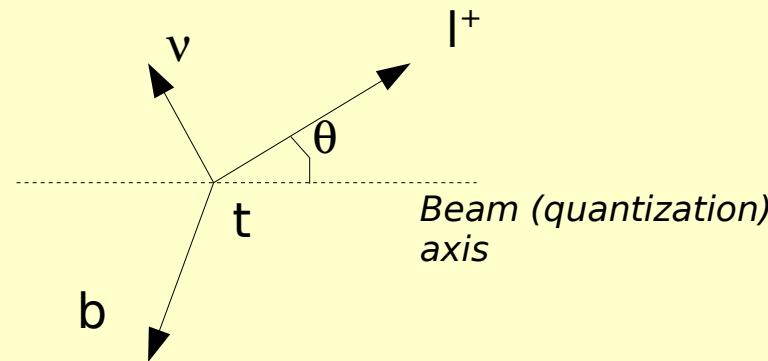
! NEW !

- $\Gamma_t \sim 1.4 \text{ GeV} \Rightarrow \Gamma_t \gg \Lambda_{\text{QCD}}$
 \hookrightarrow top spin ~fully transferred to decay products
- Dilepton channels (4.2 fb^{-1}): ee, $\mu\mu$, e μ and measure decay products (l^+, l^-) angular corr. C:

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

coefficient	LO	NLO
C	0.928	0.777

- C is a free parameter and $\theta_{1,2}$: angles between leptons flight directions / beam in *top rest frame*:



! NEW !

- **Results:**

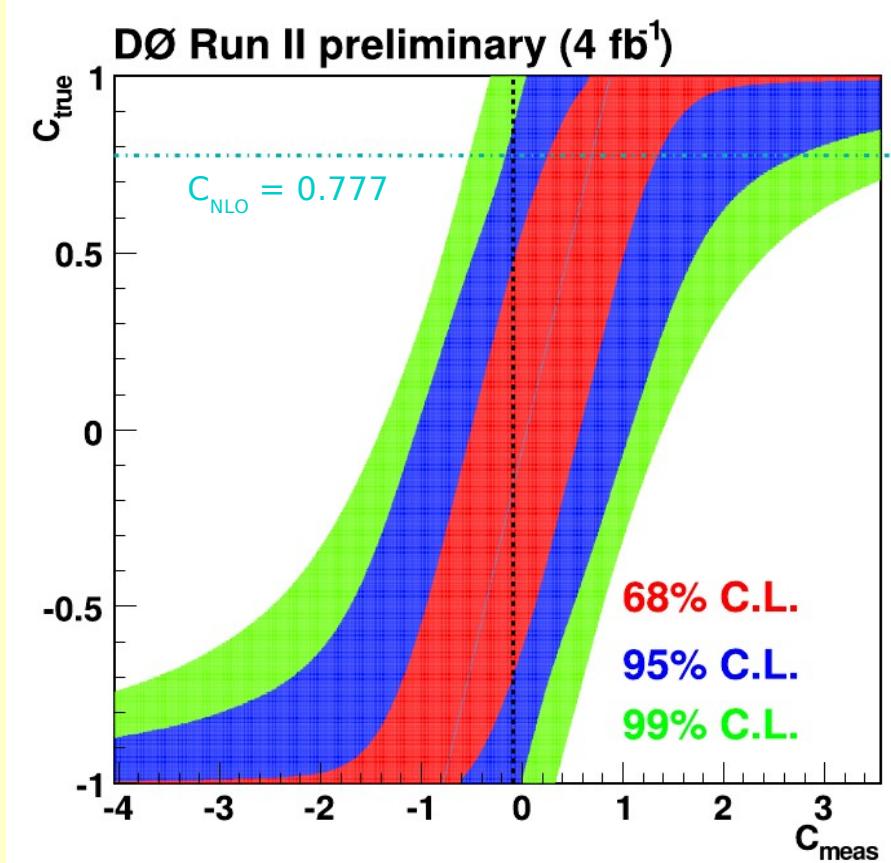
$$C = -0.17^{+0.64}_{-0.53} \text{ (stat + syst)}$$

coefficient	LO	NLO
C	0.928	0.777

- **Errors:**

- Dominated by stat. ($\sim +/- 0.5$)
- Syst.: top mass, signal modeling

Source	ΔC
Statistical only	+0.503 -0.510
Signal modeling ALPGEN	+0.197 -0.120
Signal modeling MC@NLO	+0.107 -0.085
Top Mass	+0.215 -0.223
Jet energy scale	+0.012 -0.022
Jet energy resolution	+0.000 -0.030
Monte Carlo background x-section	+0.008 -0.008
Monte Carlo signal & bkg branching ratio	+0.002 -0.002
Monte Carlo bkg scale factors	+0.000 -0.000
Monte Carlo statistics	+0.010 -0.010
$t\bar{t}$ cross section error	+0.008 -0.005
Luminosity	+0.002 -0.002
Total systematic	+0.312 -0.270





Conclusion

- Various top-antitop final states under investigation
 - l+jets, dileptons, tau+leptons
 - Allows to test different SM facets (*x-section consistencies, ratios, ...*)
- Experimental cross-section measurements **are reaching current NNLO calculation uncertainties (~10%)**
- **t-W-b interaction** scrutinized through W helicity & single-top kinematic
- First measurement of **top-antitop spin correlation since RunI !**
- On-going effort to combine D0 and CDF results

*Not full data used yet, **keep tuned !***

- **For more information see:**

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



Back-up



X-section combination

TABLE I: Expected numbers of background and signal events for $\sigma_{t\bar{t}} = 8.18 \text{ pb}$, observed numbers of data events and measured $\sigma_{t\bar{t}}$ at top mass of 170 GeV. Quoted uncertainties include both statistical and systematic uncertainties, added in quadrature.

Channel	Luminosity(pb^{-1})	$W+\text{jets}$	$Z+\text{jets}$	Multijet	Other bkg	$t\bar{t}$	Total	Observed	$\sigma_{t\bar{t}}$ (pb)
$e+\text{jets}$ (3 jets, 1 b tag)	1038	$53.4^{+6.0}_{-6.0}$	$6.0^{+1.2}_{-1.2}$	$31.5^{+3.5}_{-3.5}$	$11.4^{+1.5}_{-1.4}$	$81.7^{+6.4}_{-6.7}$	$184.0^{+9.0}_{-9.2}$	183	$8.06^{+1.89}_{-1.71}$
$\mu+\text{jets}$ (3 jets, 1 b tag)	996	$59.2^{+5.5}_{-5.6}$	$6.5^{+1.3}_{-1.3}$	$9.7^{+2.8}_{-2.8}$	$9.5^{+1.2}_{-1.2}$	$59.0^{+5.7}_{-5.6}$	$143.9^{+8.1}_{-8.1}$	133	$6.43^{+2.22}_{-2.01}$
$e+\text{jets}$ (3 jets, ≥ 2 b tags)	1038	$5.0^{+0.8}_{-0.8}$	$0.6^{+0.2}_{-0.2}$	$2.7^{+0.3}_{-0.3}$	$2.4^{+0.4}_{-0.4}$	$30.7^{+3.9}_{-3.9}$	$41.5^{+4.7}_{-4.6}$	40	$7.78^{+2.41}_{-2.01}$
$\mu+\text{jets}$ (3 jets, ≥ 2 b tags)	996	$5.8^{+0.9}_{-0.9}$	$0.7^{+0.2}_{-0.2}$	$1.0^{+0.3}_{-0.3}$	$2.1^{+0.3}_{-0.3}$	$23.8^{+3.4}_{-3.2}$	$33.5^{+4.1}_{-3.9}$	31	$7.29^{+2.73}_{-2.25}$
$e+\text{jets}$ (≥ 4 jets, 1 b tag)	1038	$8.5^{+2.7}_{-2.7}$	$2.2^{+0.5}_{-0.5}$	$7.9^{+1.0}_{-1.0}$	$3.0^{+0.5}_{-0.5}$	$81.6^{+8.7}_{-9.1}$	$103.3^{+7.3}_{-7.6}$	113	$9.38^{+1.82}_{-1.52}$
$\mu+\text{jets}$ (≥ 4 jets, 1 b tag)	996	$13.6^{+2.6}_{-2.7}$	$2.5^{+0.7}_{-0.6}$	$0.0^{+0.0}_{-0.0}$	$2.4^{+0.4}_{-0.4}$	$65.9^{+6.9}_{-7.2}$	$84.3^{+5.9}_{-6.3}$	99	$10.44^{+2.11}_{-1.76}$
$e+\text{jets}$ (≥ 4 jets, ≥ 2 b tags)	1038	$1.0^{+0.3}_{-0.3}$	$0.2^{+0.1}_{-0.1}$	$1.1^{+0.1}_{-0.1}$	$0.9^{+0.2}_{-0.2}$	$41.7^{+6.0}_{-6.0}$	$44.9^{+6.0}_{-6.0}$	30	$5.12^{+1.59}_{-1.28}$
$\mu+\text{jets}$ (≥ 4 jets, ≥ 2 b tags)	996	$1.5^{+0.4}_{-0.4}$	$0.3^{+0.1}_{-0.1}$	$0.0^{+0.0}_{-0.0}$	$0.7^{+0.1}_{-0.1}$	$35.6^{+5.0}_{-5.1}$	$38.2^{+5.1}_{-5.2}$	34	$7.60^{+2.11}_{-1.70}$
ee	1074		$2.3^{+0.5}_{-0.5}$	$0.6^{+0.4}_{-0.4}$	$0.5^{+0.1}_{-0.1}$	$11.6^{+1.2}_{-1.2}$	$15.0^{+1.5}_{-1.5}$	17	$9.61^{+3.47}_{-2.84}$
$e\mu$ (1 jet)	1070		$5.5^{+0.7}_{-0.8}$	$0.9^{+0.3}_{-0.2}$	$3.1^{+0.7}_{-0.7}$	$8.9^{+1.4}_{-1.4}$	$18.4^{+1.9}_{-1.9}$	21	$10.61^{+5.33}_{-4.23}$
$e\mu$ (≥ 2 jets)	1070		$5.4^{+0.9}_{-1.0}$	$2.6^{+0.6}_{-0.5}$	$1.4^{+0.4}_{-0.4}$	$36.4^{+3.6}_{-3.6}$	$45.8^{+4.5}_{-4.5}$	39	$6.66^{+1.81}_{-1.52}$
$\mu\mu$	1009		$5.6^{+1.1}_{-1.2}$	$0.2^{+0.2}_{-0.2}$	$0.6^{+0.1}_{-0.1}$	$9.1^{+1.0}_{-1.0}$	$15.4^{+1.8}_{-1.9}$	12	$5.08^{+3.82}_{-3.06}$
τe	1038	$0.6^{+0.0}_{-0.1}$	$0.6^{+0.1}_{-0.1}$	$3.0^{+1.7}_{-1.7}$	$0.2^{+0.1}_{-0.1}$	$10.7^{+1.3}_{-1.3}$	$15.0^{+2.2}_{-2.2}$	16	$8.94^{+4.03}_{-3.32}$
$\tau\mu$	996	$0.8^{+0.1}_{-0.2}$	$1.2^{+0.3}_{-0.3}$	$8.0^{+2.8}_{-2.8}$	$0.2^{+0.0}_{-0.0}$	$12.6^{+1.4}_{-1.4}$	$22.7^{+3.2}_{-3.2}$	20	$6.40^{+3.88}_{-3.43}$



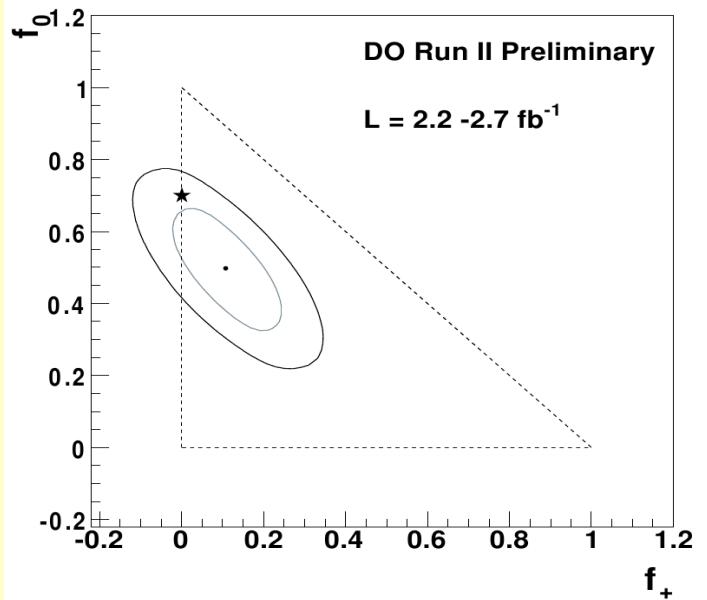
W helicity in top decays

Results:

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

23% consistency with SM values:

$$f_0 = 0.697 \text{ and } f_+ = 3.6 \times 10^{-4}$$



Source	Uncertainty (f_0)	Uncertainty (f_+)
Top mass	0.009	0.016
Jet reconstruction eff.	0.018	0.009
Jet energy calibration	0.029	0.019
Jet energy resolution	0.023	0.008
$t\bar{t}$ model	0.055	0.028
Background model	0.039	0.026
Template statistics	0.028	0.014
Total	0.085	0.052