Top properties from DØ

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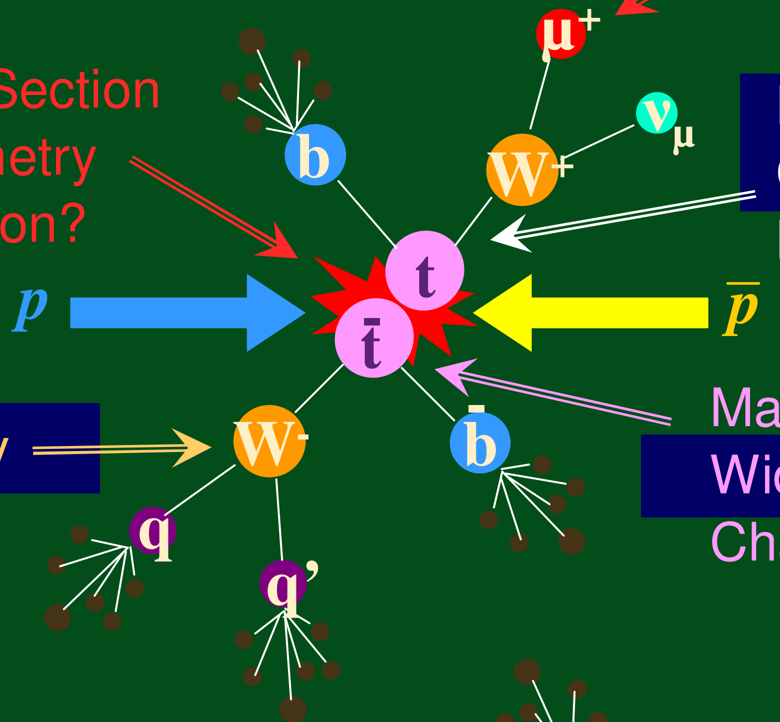
Top Quark Measurements at DØ

Top Pair Production

Production Cross Section
Production Asymmetry
Resonant Production?

Spin correlations

Branching Ratios:
CKM matrix, R_b
Non SM decays

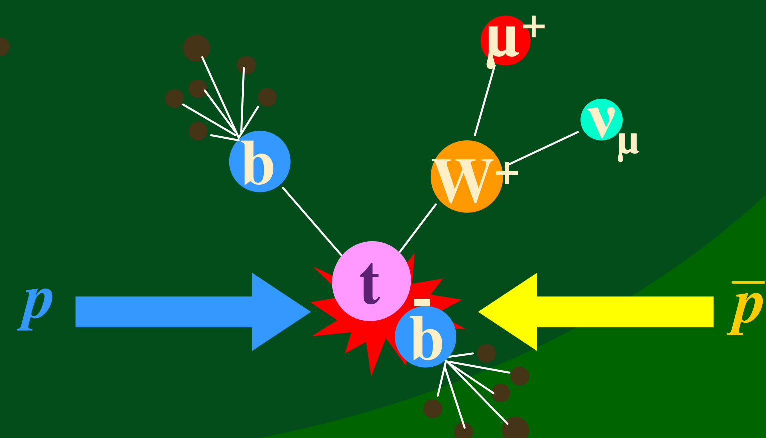


W Helicity

Mass, mass difference
Width
Charge

Single Top Production

Production Cross Section
Anomalous Couplings
W' Search



Search for $\tilde{t}_1$ Pair Production

A model-independent measurement of

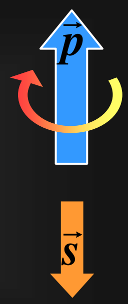
W helicity

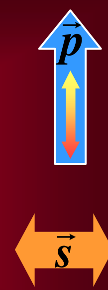
in top decays

W helicity

So far measurements support the SM prediction: f($t \to Wb$) = ~100%
Breaking it down by W helicity states:

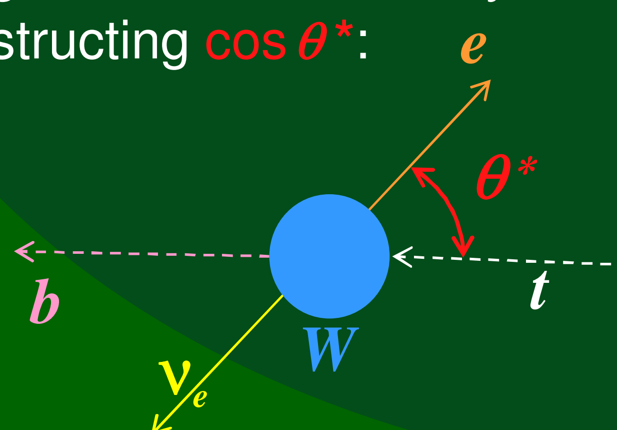
Left handed	Longitudinal	Right handed
$\lambda=-1$	$\lambda=0$	$\lambda=1$
$f_- = \frac{\Gamma(t \to W_- b)}{\Gamma(t \to Wb)}$	$f_0 = \frac{\Gamma(t \to W_0 b)}{\Gamma(t \to Wb)}$	$f_+ = \frac{\Gamma(t \to W_+ b)}{\Gamma(t \to Wb)}$
SM: 30.3%	SM: 69.6%	SM: 0.1%

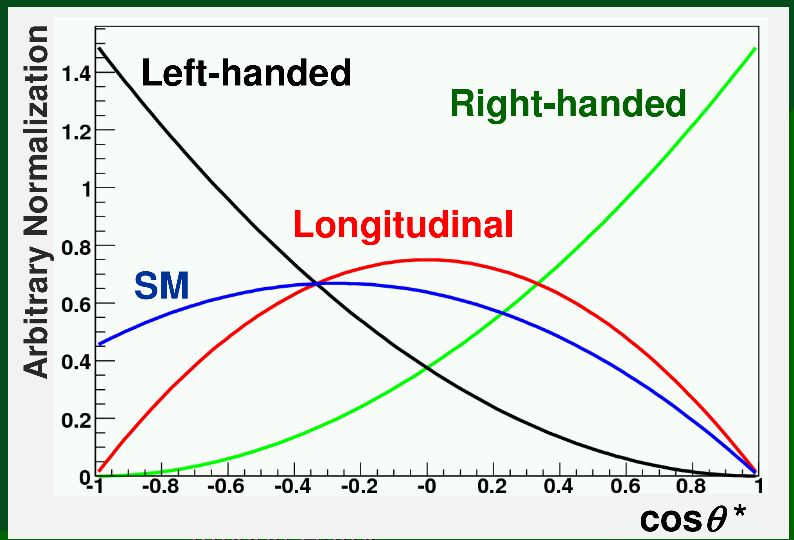




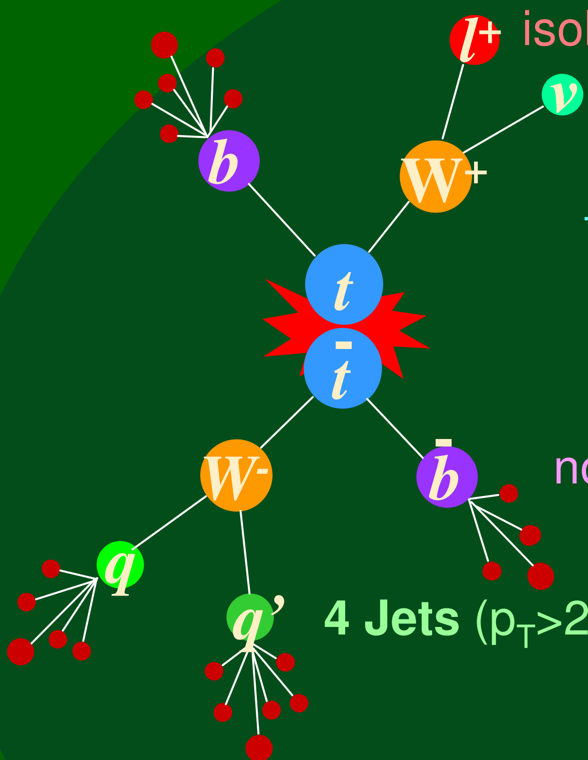
SM uncertainties << Experimental uncertainties → can't constrain SM parameters
Firm SM prediction, in particular: tiny f_+ → looking for new physics

Distinguish between helicity states by reconstructing $\cos\theta^*$:





l+jets sample



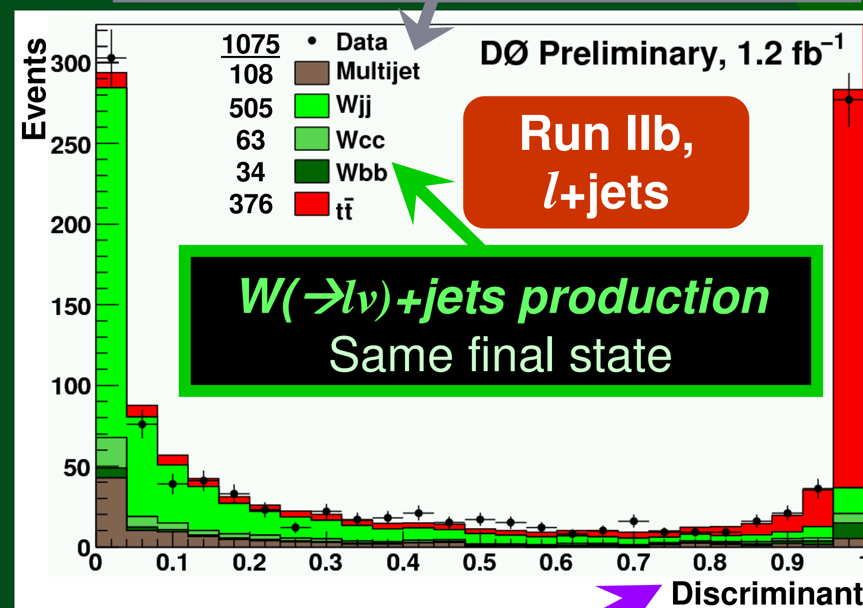
isolated, p_T>20 GeV, |η|<1.1(e)/2.0(μ)

MET>20GeV, triangle cut on ΔΦ(l,MET)

note any b-tags

4 Jets (p_T>20 GeV, |η|<2.5)

Multijet production
Estimated from data with leptons that almost pass our ID



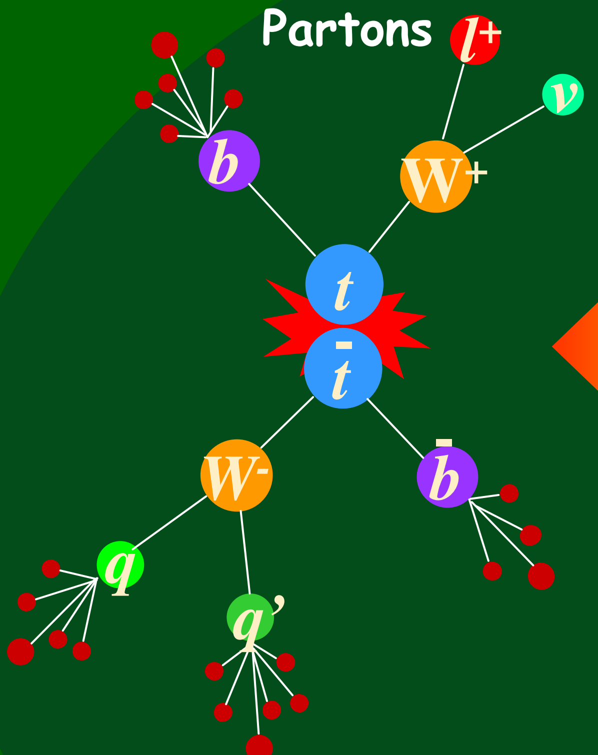
Run IIb, l+jets

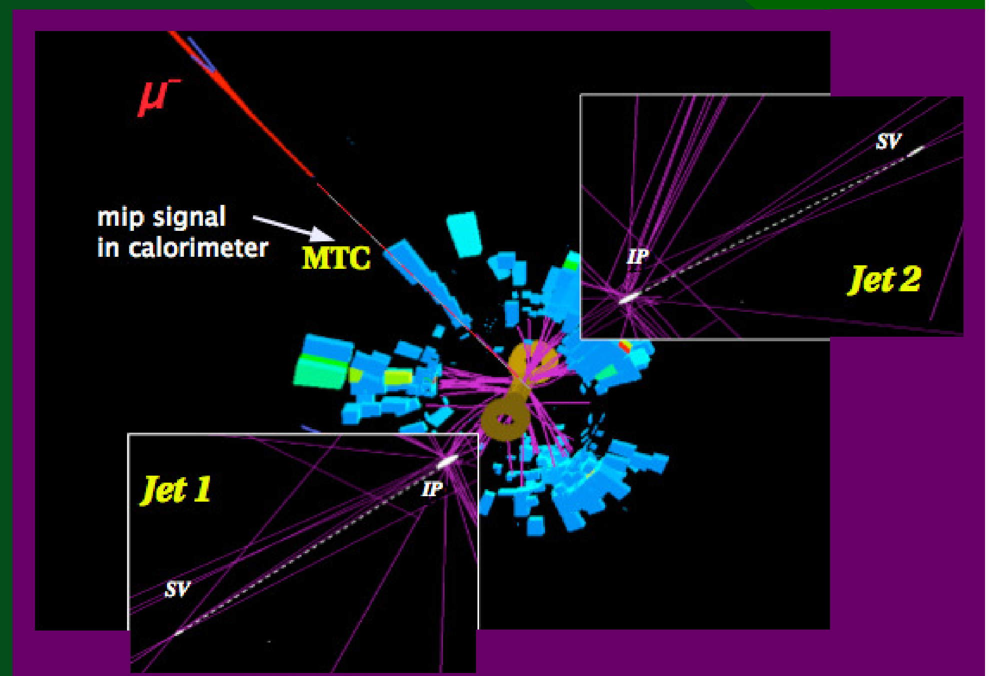
W(→lν)+jets production
Same final state

- Signal and W+jets templates from MC.
  - Matched ALPGEN + Pythia
  - V+A and V-A signal MC reweighted to yield desired cos θ* distributions
  - Data and MC are compared in control samples; corrections applied for residual discrepancies
- Their amounts from fit to data sample.

Discriminant
Combines kinematic and b-ID information
Chose variables that:
- discriminate between signal and W+jets
- are well modeled
- are weakly correlated with cos θ*

l+jets reconstruction





Parton-level ⟷ Particle-level ⟷ Detector-level

QCD Simulation

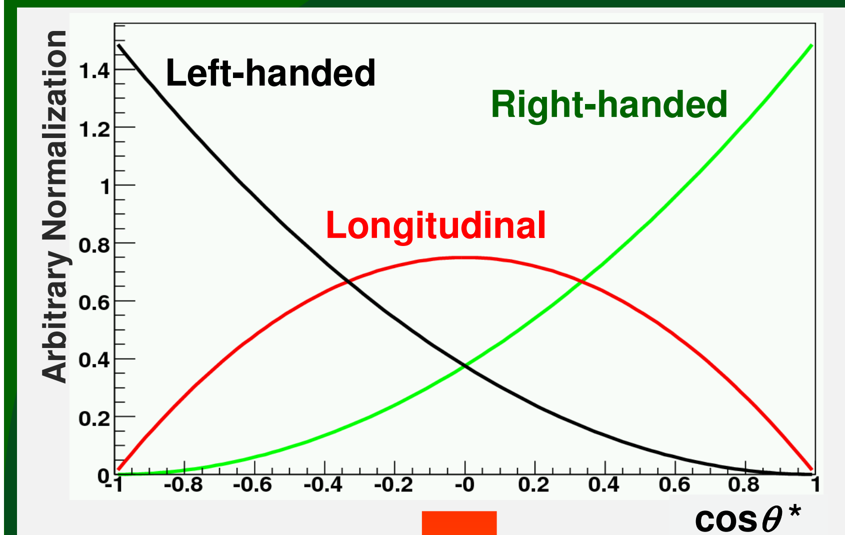
Experimental resolutions & *b*-ID probabilities

- fit partons to the measured objects, minimizing a χ^2
- Constraints: $m_{t1} = m_{t2} = 172.5$ GeV; $m_{W1} = m_{W2} = 80.4$ GeV
- Do the fit for every combination of assigning a jet to a parton

W helicity

l+jets reconstruction results

Parton level

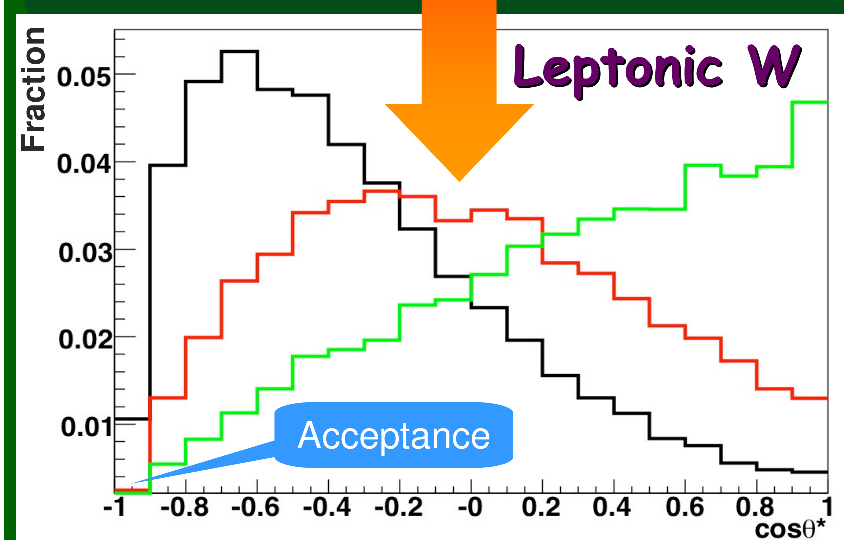


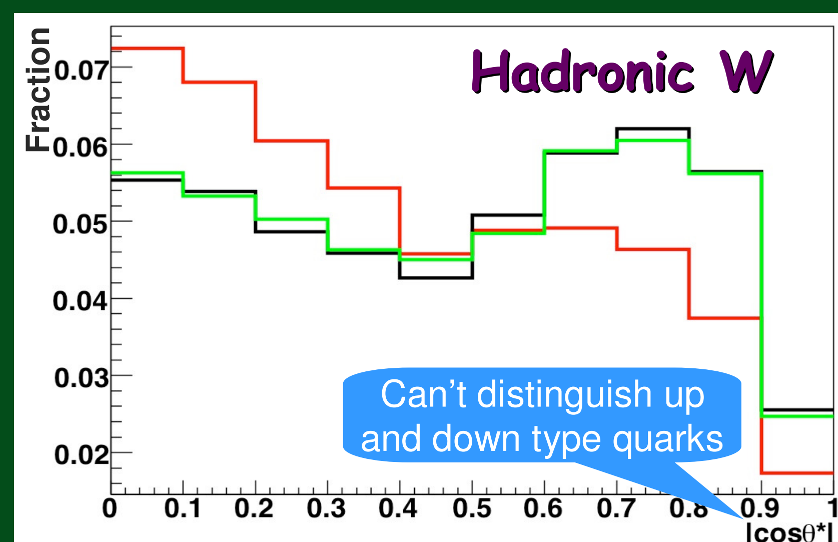
Excellent cos θ* reconstruction!

Fitting f_0, and f_+ *rather than V-A vs. V+A*

→ Can also use the hadronic W to fit f_0

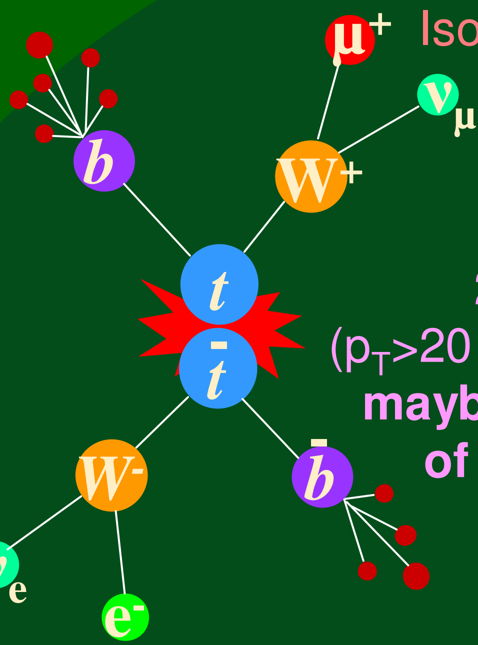
Reconstructed





$e\mu$ sample

Isolated μ, p_T>15 GeV, |η|<2.0



2 Jets

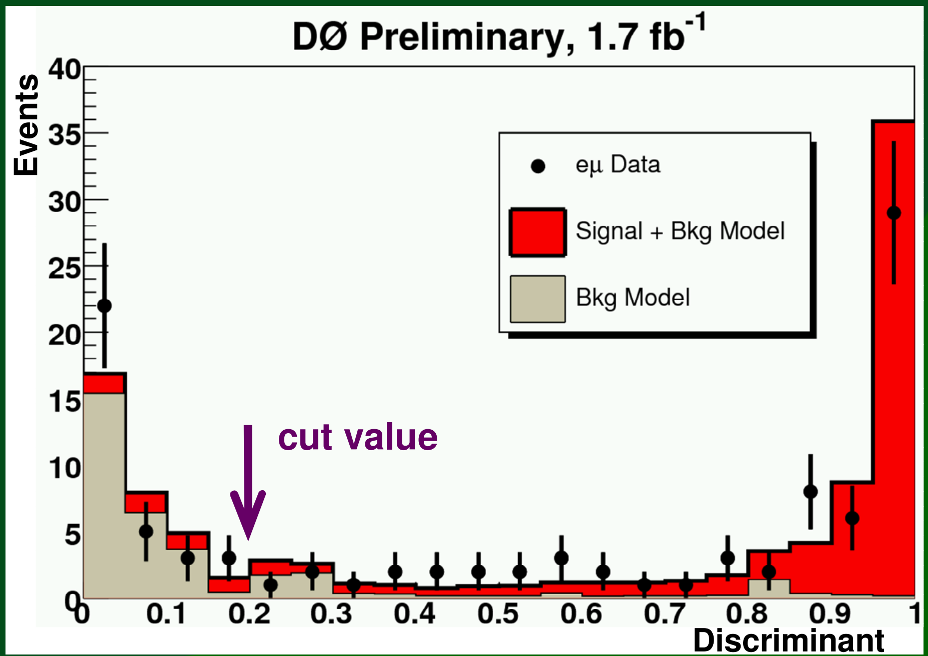
(p_T>20 GeV, |η|<2.5)

maybe a couple of b-tags…

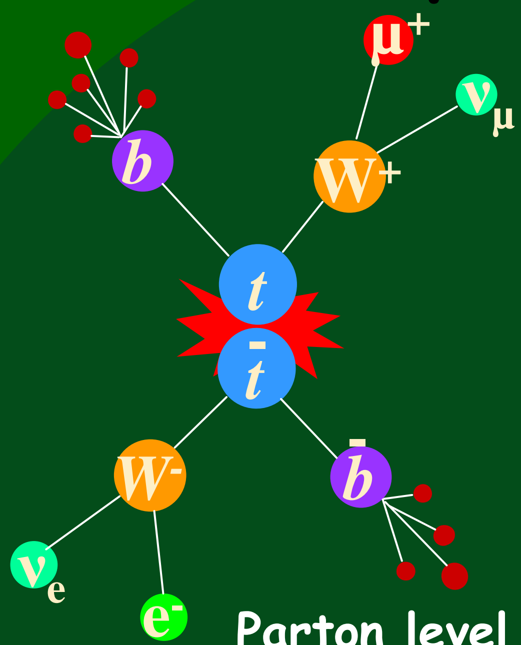
Isolated e, p_T>15 GeV,
|η|<1.1 / 1.5<|η|<2.5

A strong experimental signature
→ no MET requirements
→ looser lepton ID requirements

Discriminant construction and fit procedures similar to those in l+jets



$e\mu$ reconstruction

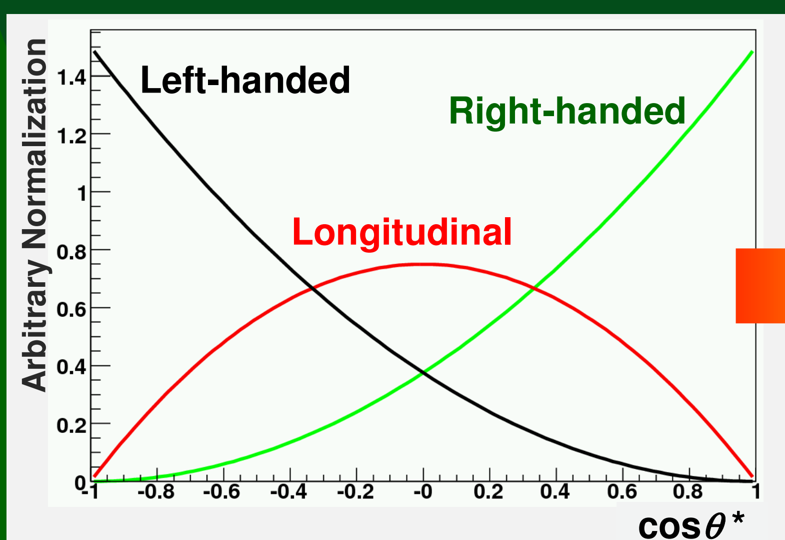


With two νs, reconstruction is harder.

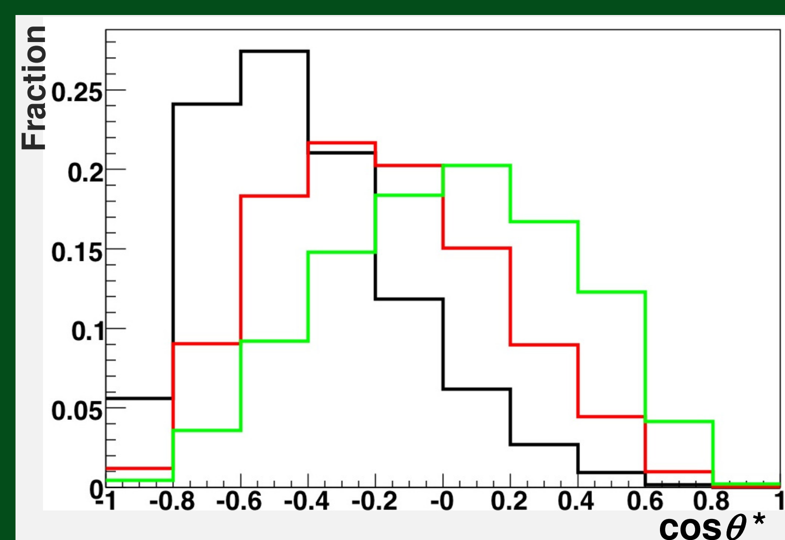
"***resolution sampling***"

- smear objects within their resolution
  - 500 times per event
- for each b-jet & l combination and smearing, solve algebraically for $\cos\theta^*$
  - use the 2 MET components + 4 mass constraints
  - 0-8 solutions
- average all solutions

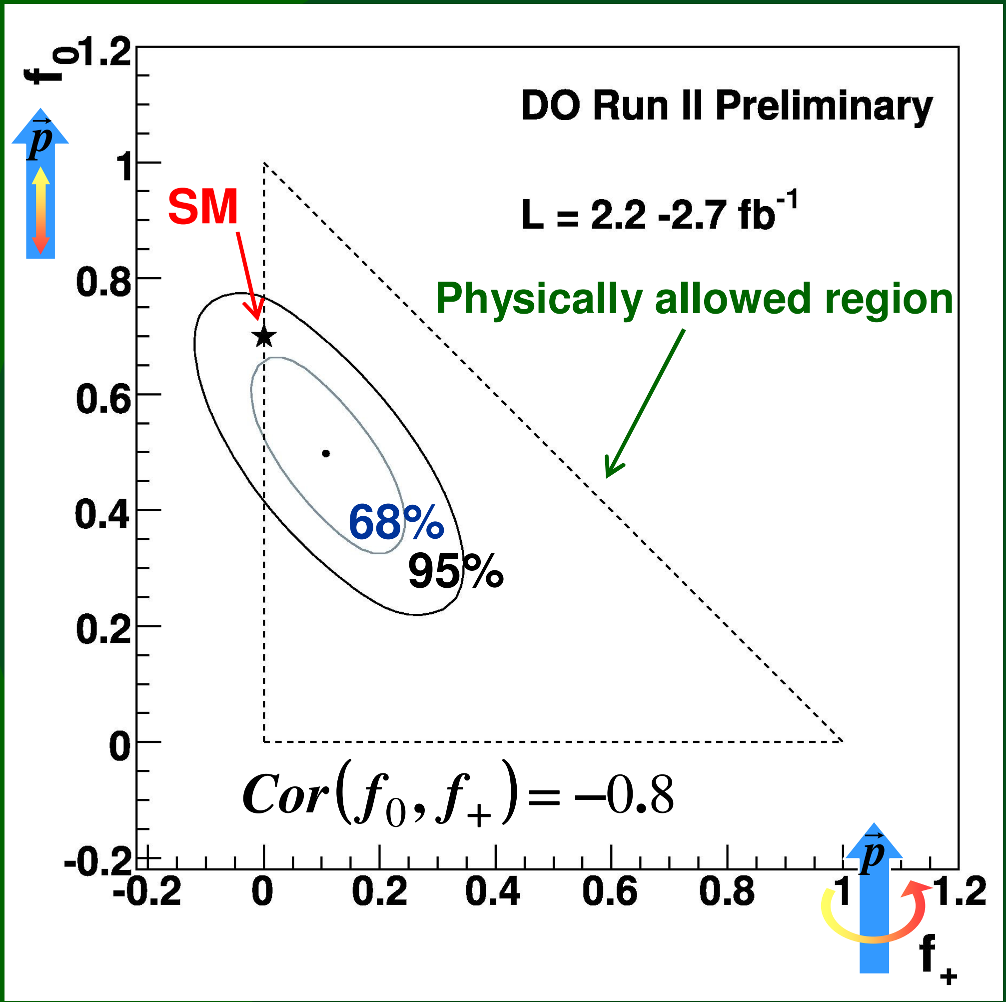
Parton level



Reconstructed



Results



Consistencies

- first 1fb^{-1} vs. newer data: 49%
- e+jets vs. μ+jets: 12%
- l+jets vs. di-lepton: 1.6%
- data vs. SM: 23%

Dominant systematics

- Signal modeling
  - underlying event
  - additional collisions
  - MC generator
- Background modeling
  - shape and yield in low discriminant sample

Longitudinal: f_0 = 0.490 ± 0.106(stat.) ± 0.085(syst.)

Right handed: f_+ = 0.110 ± 0.059(stat.) ± 0.052(syst.)

Combine W helicity + previous single top result (“evidence” using only 1fb^{-1}) into:

Measurement of anomalous top quark couplings

Anomalous coupling

Can combine the W helicity and single-top production rates (separated for s and t channels) to fully specify the Wtb vertex [Chen, Larios, and Yuan, Phys. Lett. B 631, 126 (2005)]

DØ published a variation on this idea [Phys. Rev. Lett. 102, 092002 (2009)] as follows:

Start with the most general CP-conserving Wtb vertex up to mass dimension 5:

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

SM has: $f_1^L \approx 1,\ f_2^L = f_1^R = f_2^R = 0$

Statistics are low

→ Need some assumptions:

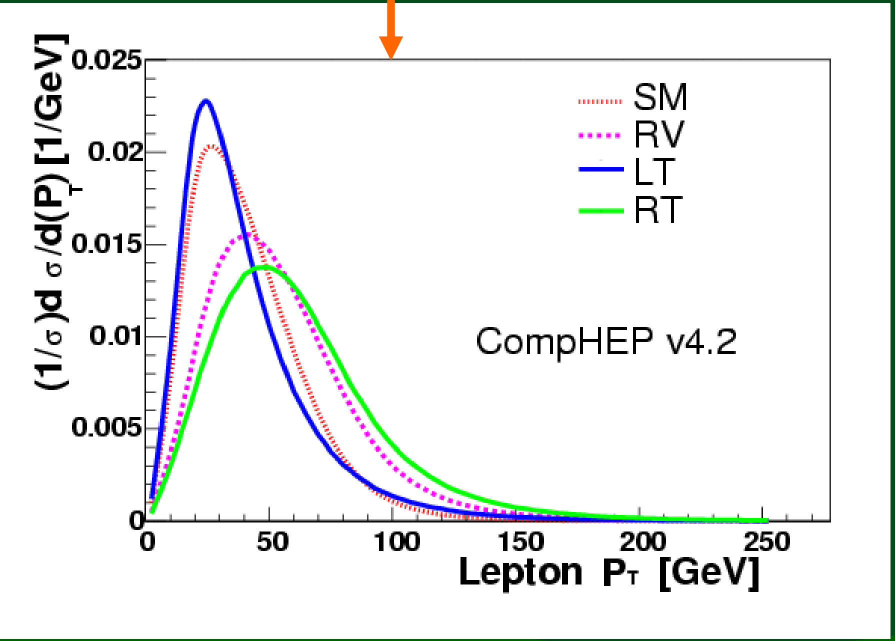
- real couplings (CP-conserving)
- Wtb dominates single top production and decay
- only one non-SM coupling at a time → three scenarios
  - only f_1^L, and f_1^R non-zero (interference taken into account)
  - only f_1^L, and f_2^L non-zero
  - only f_1^L, and f_2^R non-zero

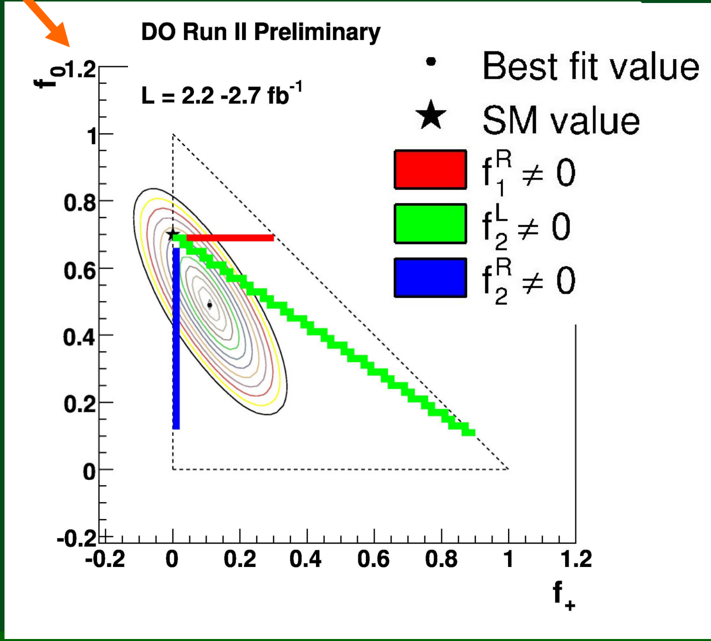
Inputs

Modify single-top measurement to use only 2 & 3 jet events
→ independent data sets

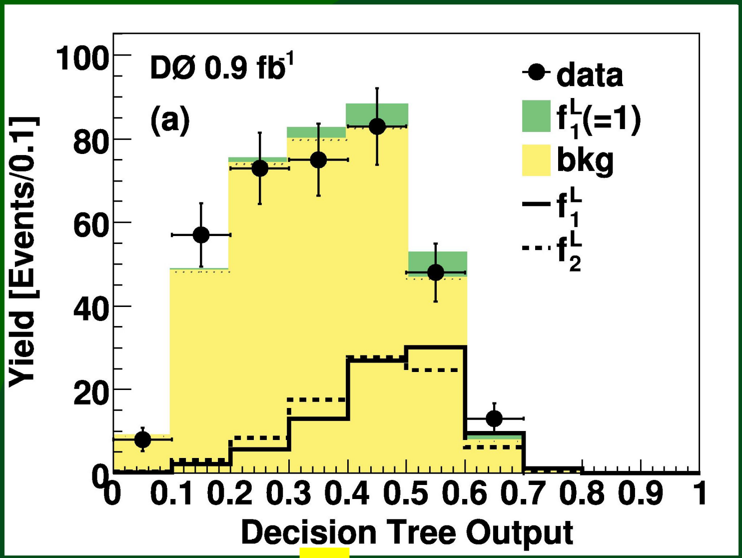
Modify W helicity measurement to fit templates as function of f_1^L, f_2^L, f_1^R, and f_2^R, instead of f_0 and f_+

Cross-sections, kinematics, and angular distributions change



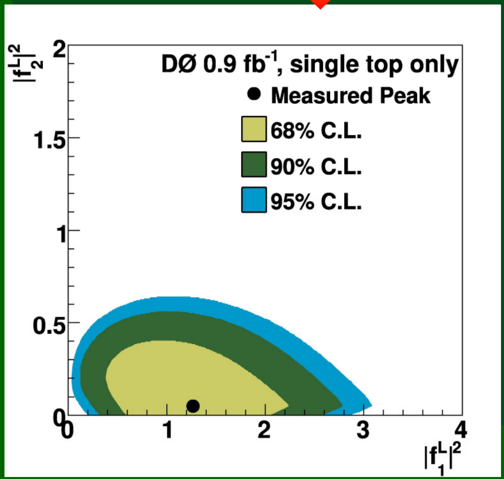


For each scenario



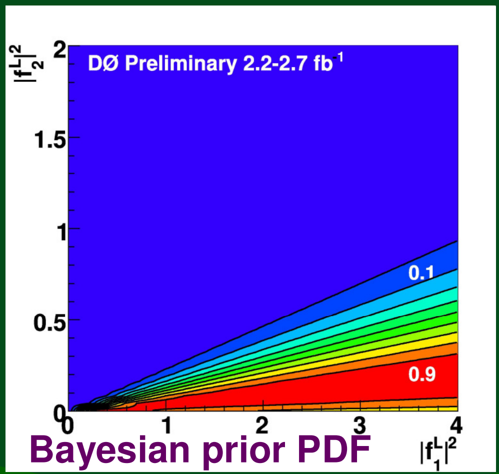
Train boosted decision tree to distinguish signal ($f_1^L = f_X = 1$) from background

- "Only" 4 samples, not dividing by N_{jet}
- single top only a "3σ" effect in these samples
  → very little separation



+

W helicity result constrains ratio of couplings



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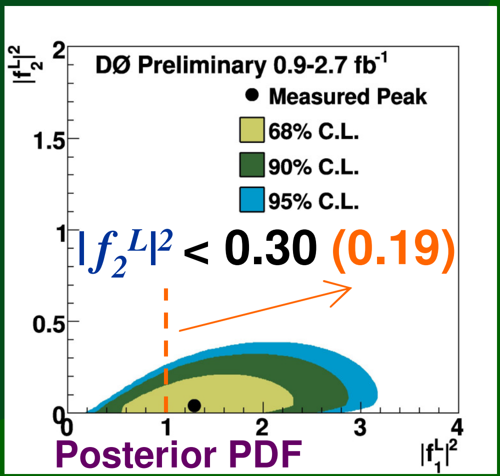
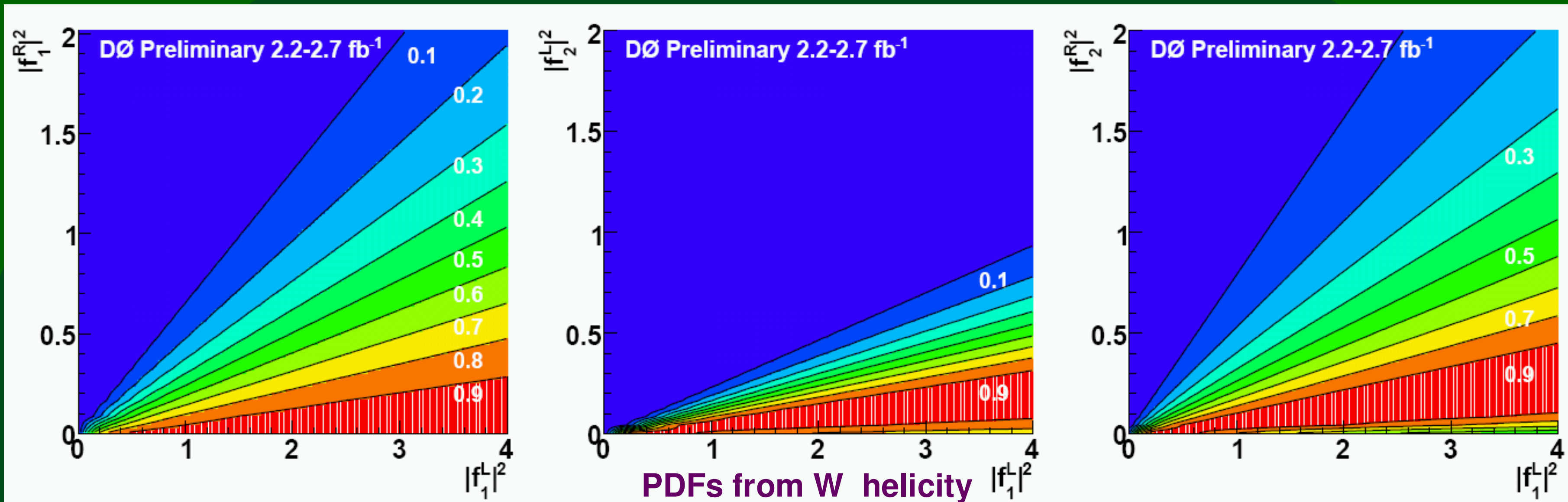
Bayesian combination

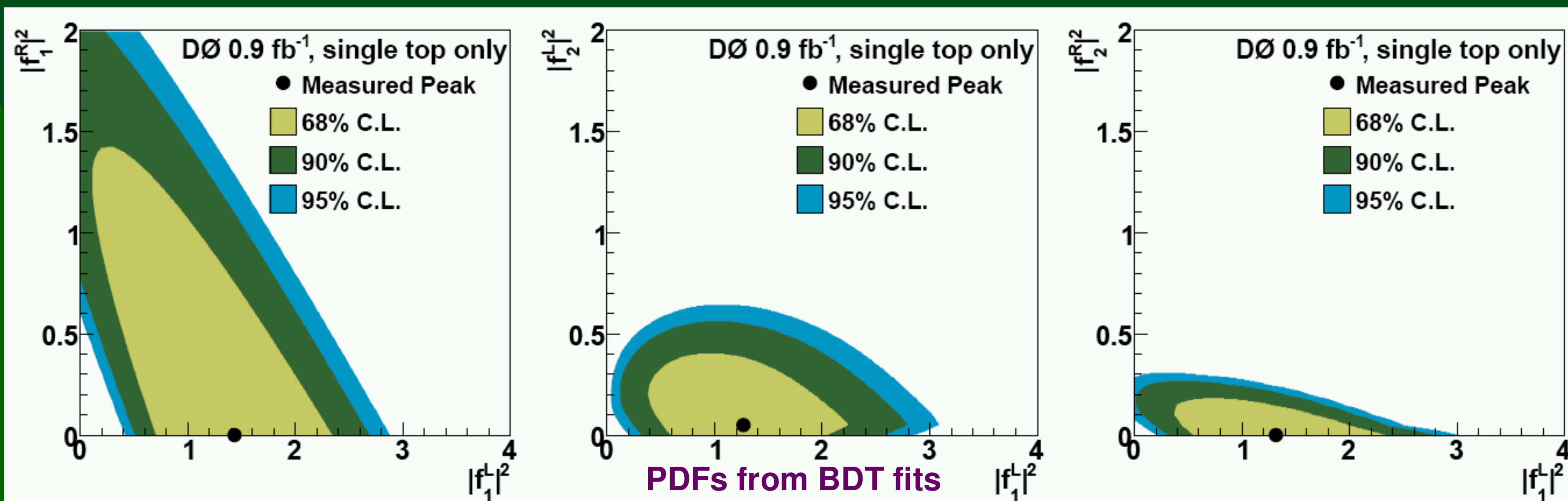


Anomalous f

Results - separate

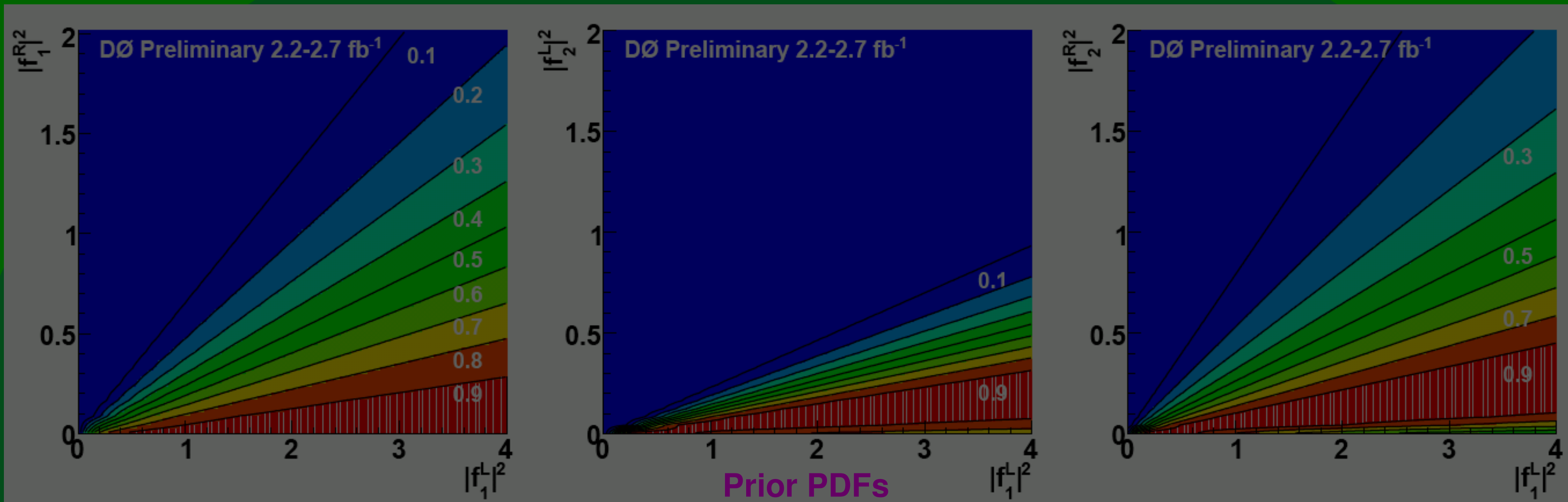


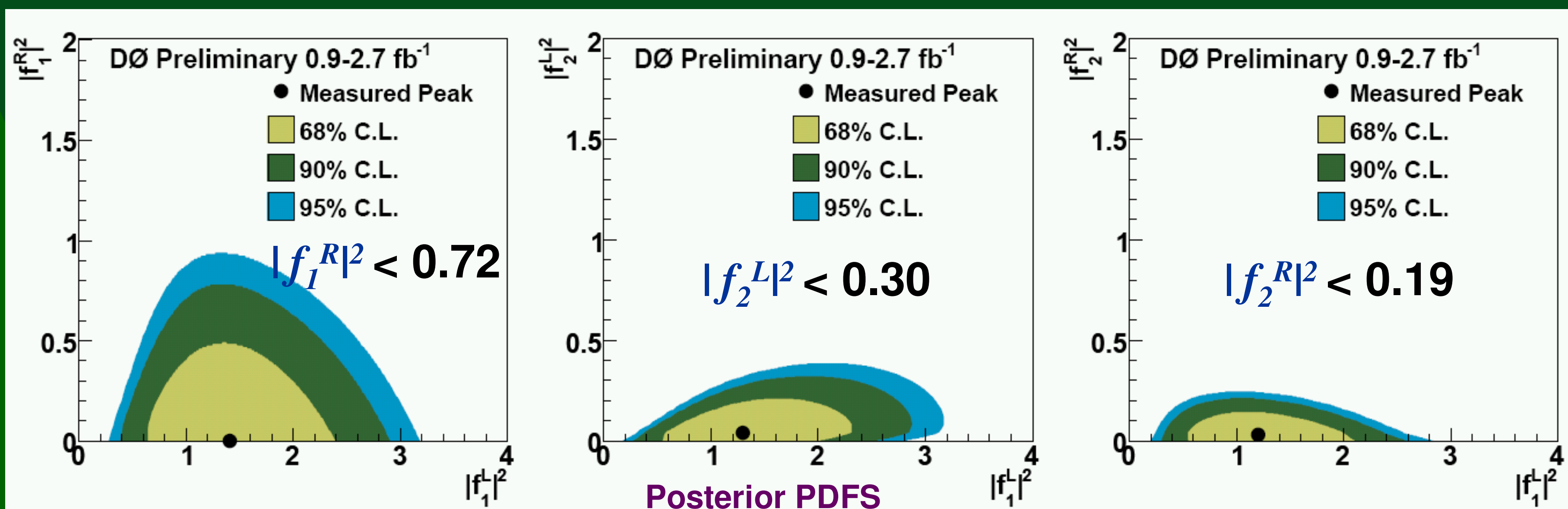
PDFs from W helicity



PDFs from BDT fits

Results – combined





A brief reminder of:

Simultaneous Measurement of the Ratio *$B(t\rightarrow Wb)/B(t\rightarrow Wq)$* *and the* Top Quark Pair Production Cross Section

or for short…

PRL **100**, 192003 (2008)

A brief reminder of:

R_b

PRL **100**, 192003 (2008)

Observable & method

$$R_b = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|Vtb|^2}{|Vtd|^2 + |Vts|^2 + |Vtb|^2}$$

Standard model

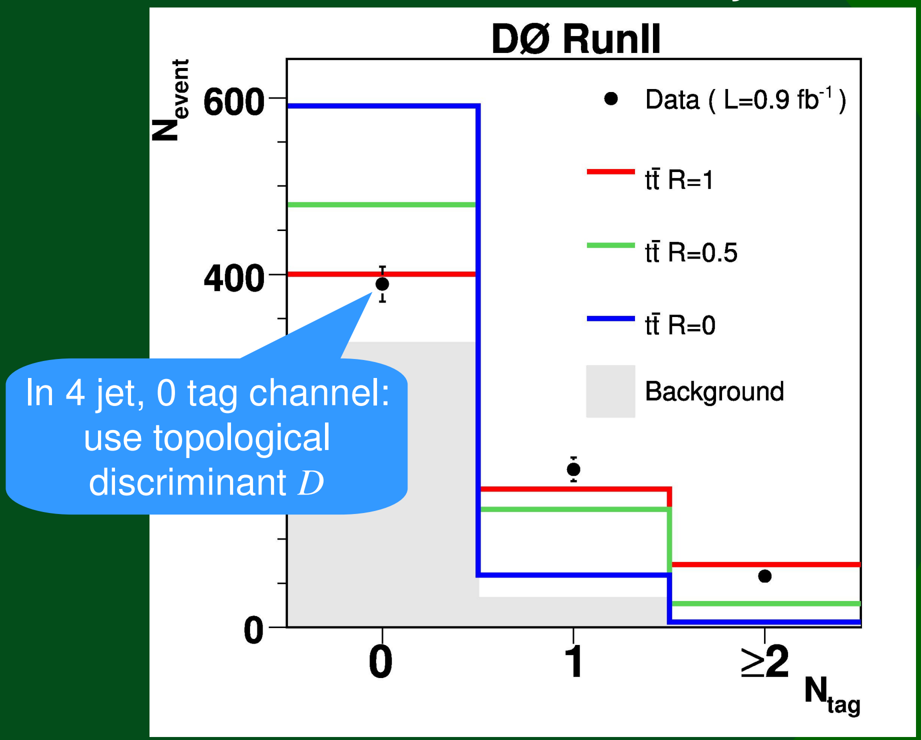
- 3 quark generations
- Unitary CKM matrix

$R_b \approx 1$

New physics can break either premise

$R_b \neq 1$

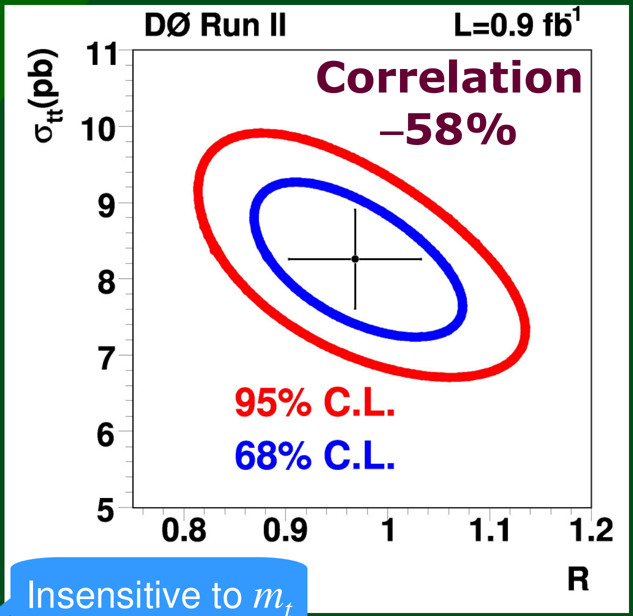
- l+jets channel
- Events with 3 or 4-or-more jets



- Simultaneous fit of σ & R_b
- Poisson likelihood in N_{tag} & D bins
- Systematic effects described with nuisance parameters (profile likelihood)

Results

From fit



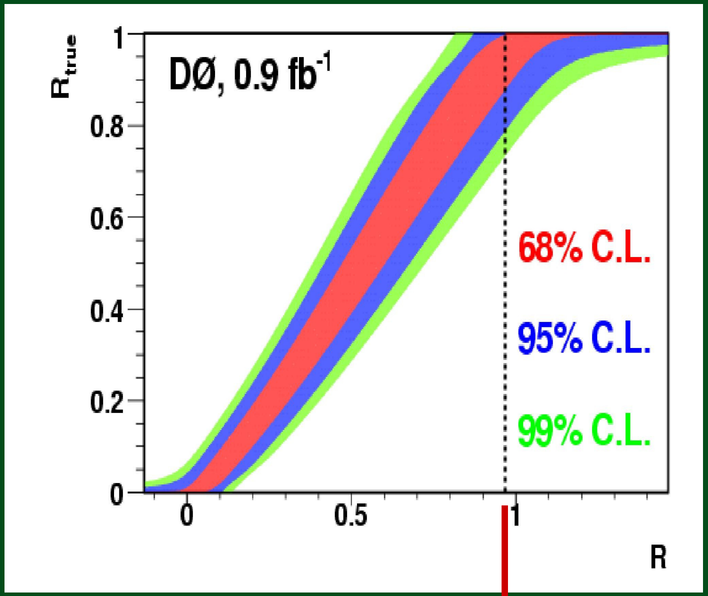
Insensitive to m_t

$$R_b = 0.97^{+0.09}_{-0.08}\,(\text{stat}+\text{syst})$$

For m_t=175 GeV:

$$\sigma_{t\bar{t}} = 8.18^{+0.90}_{-0.84}\,(\text{stat}+\text{syst})$$
$$\pm 0.50\,(\text{lumi})\ \text{pb}$$

Ensemble testing to find limits:



$R_b > 0.88$ @ 68% C.L.

$R_b > 0.79$ @ 95% C.L.

Combine R_b + single top production in *t*-channel into:

Width

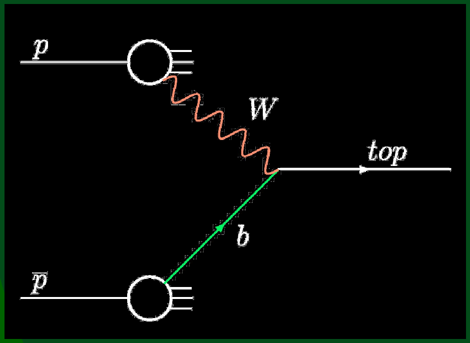
Measuring the top width

Standard model

Γ_t=1.3GeV (for m_t=170GeV)

→ Difficult to measure directly
(but see CDF talk)

Indirect measurement:



Can combine the R_b and single-top t-channel cross section σ_{tbqX} to extract $\Gamma(t\to Wb)$ [C.-P. Yuan, e.g. arXiv:hep-ph/9604434]

- "effective W approximation" → The Wtb vertex factorizes

→ σ_{tbqX} proportional to $\Gamma(t\to Wb)$ even in the presence of anomalous Wtb coupling

Assuming the above production mechanism

- no FCNC production
- |Vtd|, |Vts| small

BSM production with similar kinematics (e.g. right-handed vector coupling) also fine

$$\Gamma_t = \frac{\Gamma(t\to Wb)}{\mathrm{B}(t\to Wb)}$$

$$\mathrm{R}_b = \frac{\mathrm{B}(t\to Wb)}{\mathrm{B}(t\to Wq)}$$

Assume:

$$\mathrm{B}\,(t\to Wq) = 1$$

Method

Reinterpret the t-channel cross section measurement as:

$$\sigma \mathrm{B} = \sigma_{tbqX} \cdot \mathrm{B}\left(t \to Wb\right) = 3.14^{+0.94}_{-0.80}\ \mathrm{pb}$$

Wtb also effects the decay

Yielding: $$\Gamma\left(t \to Wb\right) = \frac{\sigma \mathrm{B}}{\mathrm{B}(t \to Wb)} \frac{\Gamma(t \to Wb)_{SM}}{\sigma_{tbqX,SM}}$$

Both calculated at (pure) NLO QCD

and: $$\Gamma_t = \frac{\frac{\sigma \mathrm{B}}{\mathrm{B}(t \to Wb)} \frac{\Gamma(t \to Wb)_{SM}}{\sigma_{tbqX,SM}}}{\mathrm{B}(t \to Wb)}$$

Redo the statistical analysis of t-channel x-section measurement

- same selections, 24 channels, same discriminants, etc. (see A. Heinson's talk)
- extracting the widths instead of σ
- priors flat in the widths
- *and….*

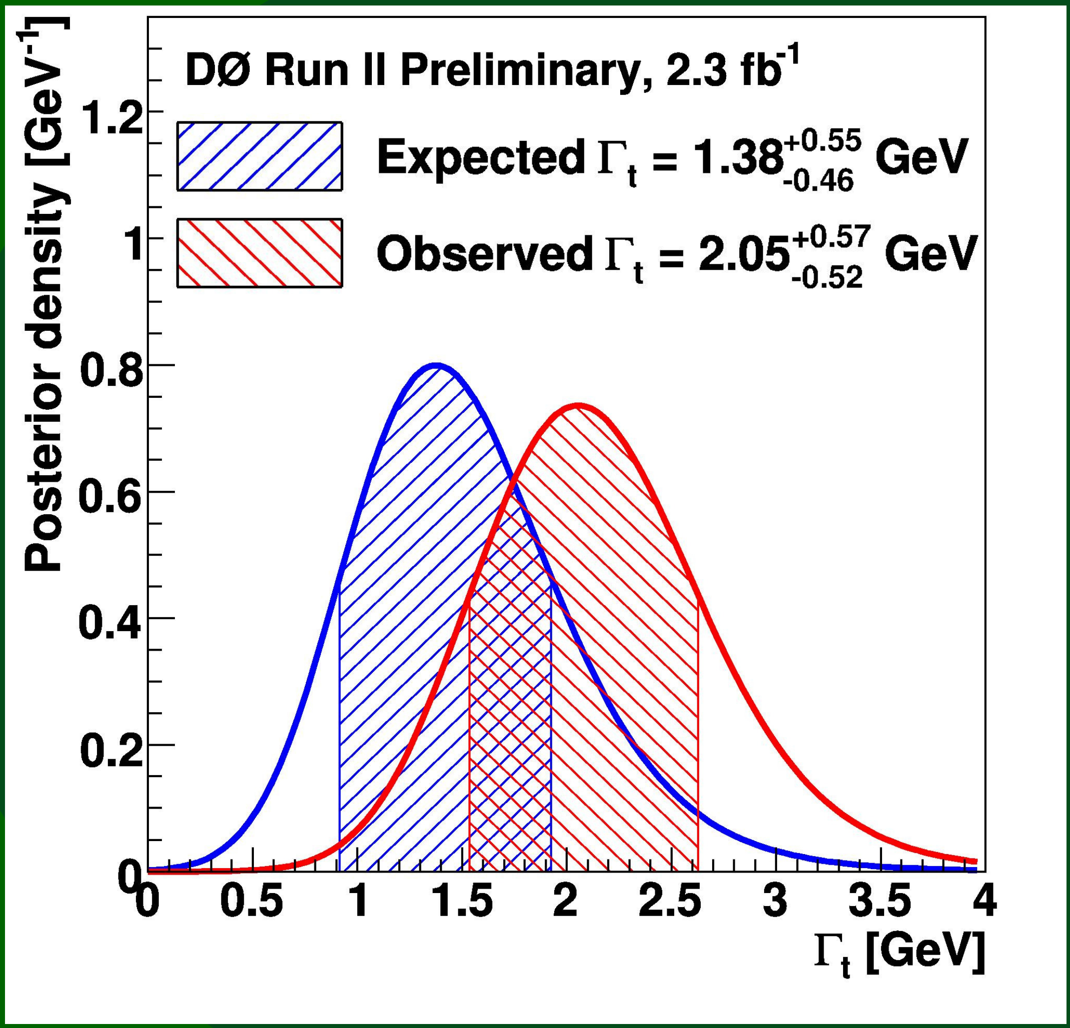
Input systematics

…and…

- systematic uncertainties from both analyses combined in 8 categories
  - each category treated as either fully correlated or uncorrelated

	Relative Systematic Uncertainties		
Sources	**t-channel**	**R measurement**	**Correlations**
Components for Normalization			
Luminosity	6.1%	0.0%	
Single top signal modeling	3.5–13.6%	0.0%	
Top pair production signal modeling	—	1.0%	X
Other background from MC	15.1%	0.6%	X
Detector modeling	7.1%	0.1%	X
Components for Normalization and Shape			
Background from data	13.7–54%	1.7%	X
b-tagging	2–30%	6.3%	X
Jet Energy Scale	0.1–13.1%	0.0%	

Results



An *indirect* measurement

Assumptions:

- No FCNC production
- |Vtd|, |Vts| small
- $\mathrm{B}(t \to Wq) = 1$

All supported by experiment!

Most precise measurement

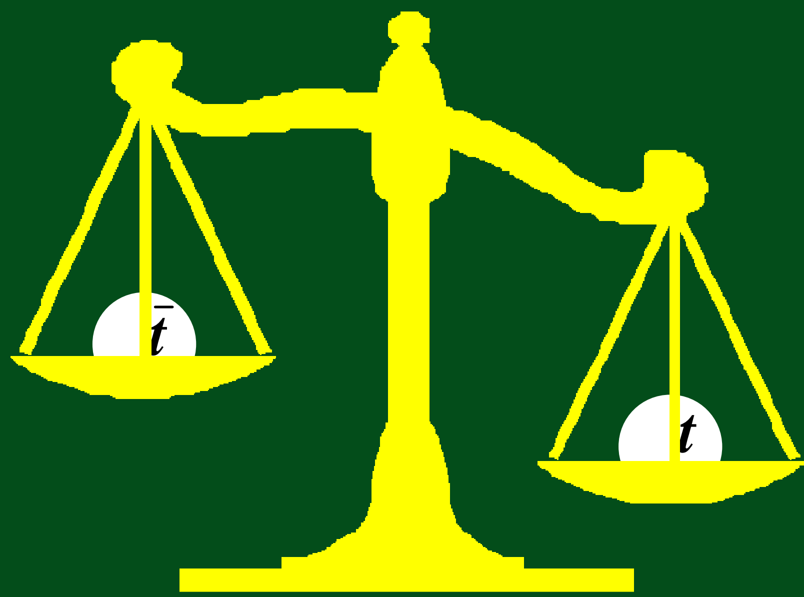
That is: $\tau_t = \left(3.2^{+1.1}_{-0.7}\right) \cdot 10^{-25}\ \mathrm{s}$

Direct measurement of the mass difference between top and antitop quarks

Mass difference

- CPT theorem → particle and antiparticle masses are the same
- QCD confinement → quark masses are not directly accessible
- …except for the top mass: $\tau_t \approx 3\times10^{-25}\,\text{sec} < \frac{1}{\Lambda_{QCD}} \approx 3\times10^{-24}\,\text{sec}$

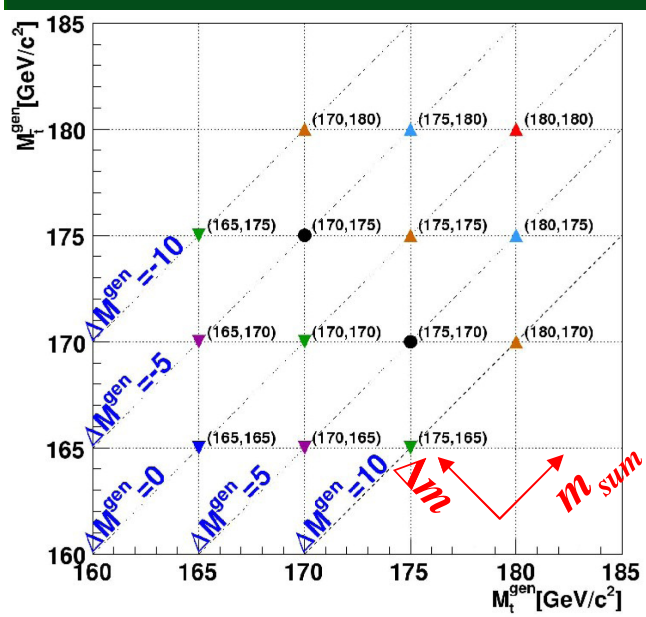
Taken from the previous result ☺



PRL **103**, 132001 (2009), featured in Nature and Physics Today.

Method

- A variation of the DØ l+jets matrix-element mass measurement with ~1 fb^{-1} (PRL 101, 182001 (2008), see O. Brandt's talk)
- Separate the top quark from the top antiquark by lepton charge
  - solenoid and toroid polarities routinely reversed
  - unfortunately (?) can't switch detector to anti-matter
    - arguably the trickiest experimental aspect - $\bar{b}JES$ vs. $bJES$ studied in data and MC (K^+ vs K^- interact with matter differently)



Δm enters:

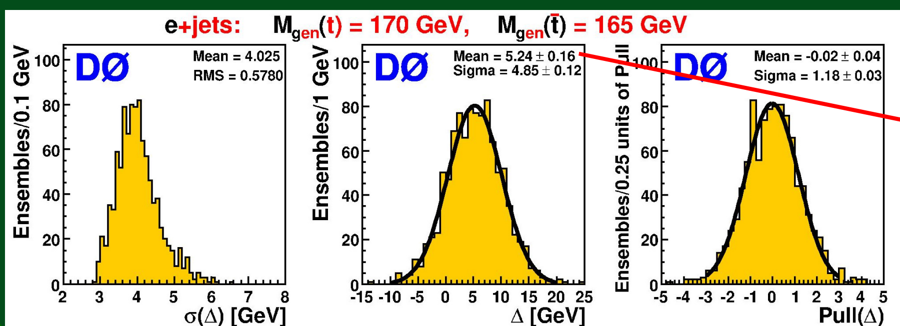
- the matrix elements
  - almost a trivial change
- the MC
  - modified Pythia to generate events with $m_t \neq m_t$
- the acceptance (taken from the MC)

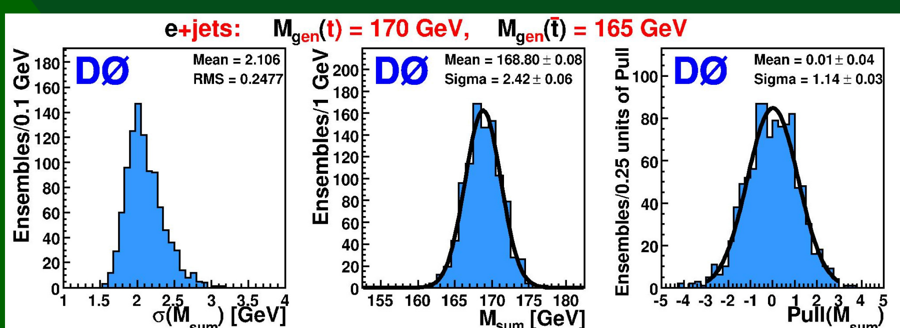
Calibration

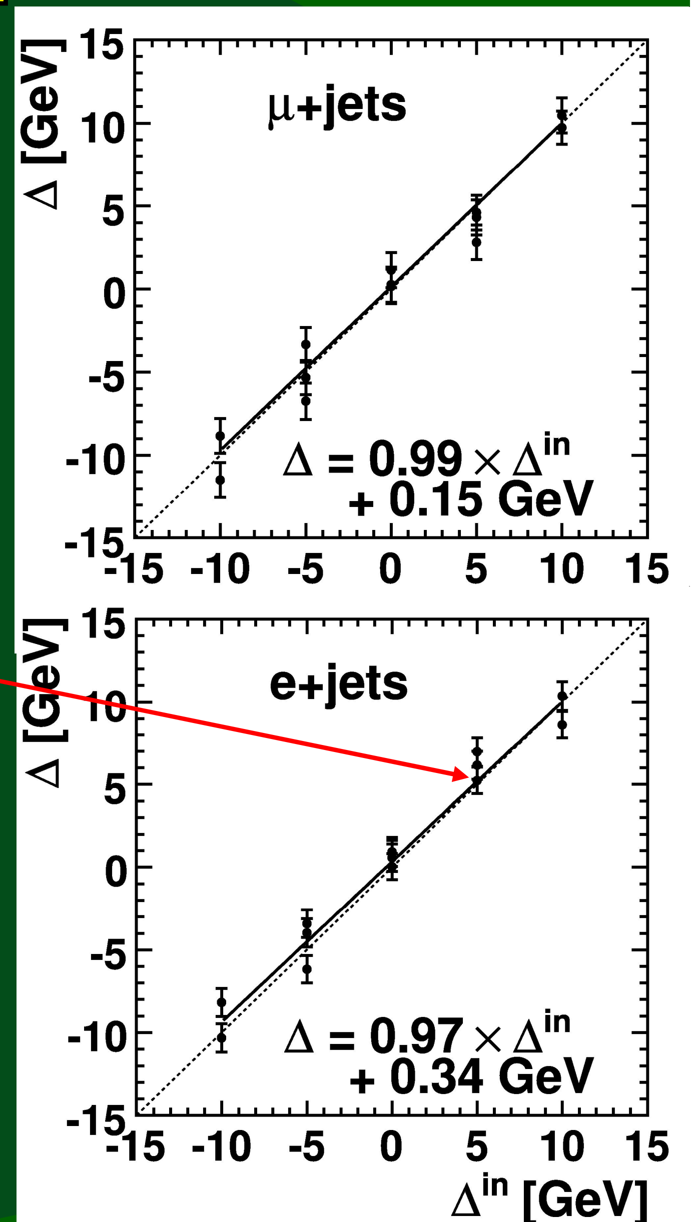
8 Calibrations:

- ***e*** +jets and ***μ***+jets calibrated separately
- m_{sum} and Δ
- values and uncertainties (jargon: means and pulls)

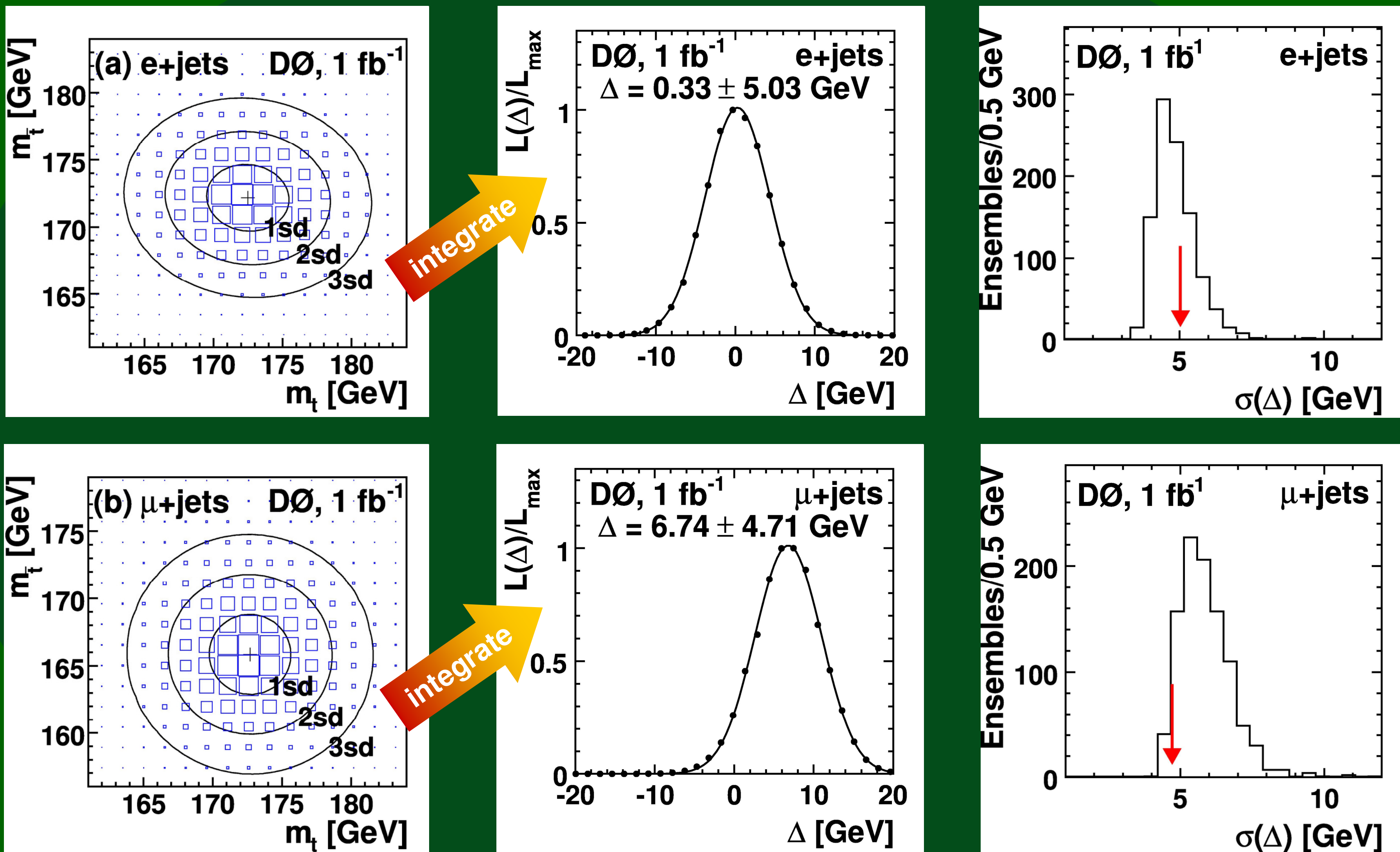
From ensemble tests w. the modified Pythia







Results



$$m_t - m_{\bar{t}} = 3.8 \pm 3.7\text{GeV}$$ (includes 1.2GeV from systematic uncertainties)

Summary & outlook

Model-independent measurement of W helicity:

- Longitudinal: f_0 = 0.490 ± 0.106(stat.) ± 0.085(syst.)
- Right handed: f_+ = 0.110 ± 0.059(stat.) ± 0.052(syst.)

New top property measurements possible by using both the electroweak single top production and the strong top pair production

- constraints on anomalous Wtb coupling
- $\Gamma_t = 2.05^{+0.57}_{-0.52}\,\mathrm{GeV}$

First direct measurement of quark antiquark mass difference:

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

More top property measurements to come this summer

Back up slides

Anomalous coupling

Can combine the W helicity and single-top production rates (separated for s and t channels) to fully specify the Wtb vertex [Chen, Larios, and Yuan, Phys. Lett. B 631, 126 (2005)]

DØ published a variation on this idea [Phys. Rev. Lett. 102, 092002 (2009)] as follows:

Start with the most general CP-conserving Wtb vertex up to mass dimension 5:

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

SM has: $f_1^L \approx 1, f_2^L = f_1^R = f_2^R = 0$

$$L_{tWb} = \frac{g}{\sqrt{2}} W^-_\mu \bar{b} \circ^\mu \left(f_1^L P_L + f_1^R P_R\right)$$

Statistics are low

→ Need some assumptions:

- real couplings (CP-conserving)
- Wtb dominates single top production and decay

} As in V_{tb} measurement

- only one non-SM coupling at a time → three scenarios
  - only f_1^L, and f_1^R non-zero (interfe
  - only f_1^L, and f_2^L non-zero
  - only f_1^L, and f_2^R non-zero

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

$$P_R\big) t - \frac{g}{\sqrt{2} M_W} \partial_\nu$$

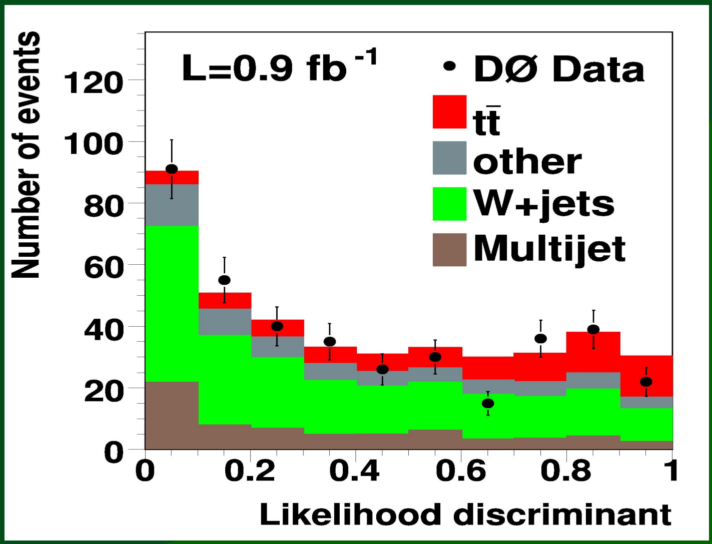
R_b discriminant

- e+jets: the leading jet pT , the maximum DR between two of the four leading jets, A(aplanarity), C(surface area), and D(volume) from the momentum tensor
- mu+jets: A, D, HT(4 jets+muon), pT3+pT4, MT(jets), M(3jets)/M(4jets+l+MET)

$$D=\frac{\prod_i S_i}{\prod_i S_i+\prod_i B_i}$$

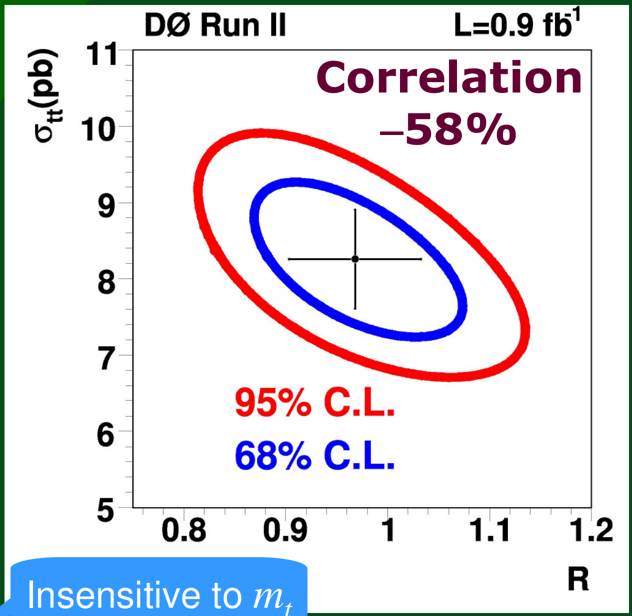
Probability density functions

S – ttbar, *B*– W+jets



Results

From fit



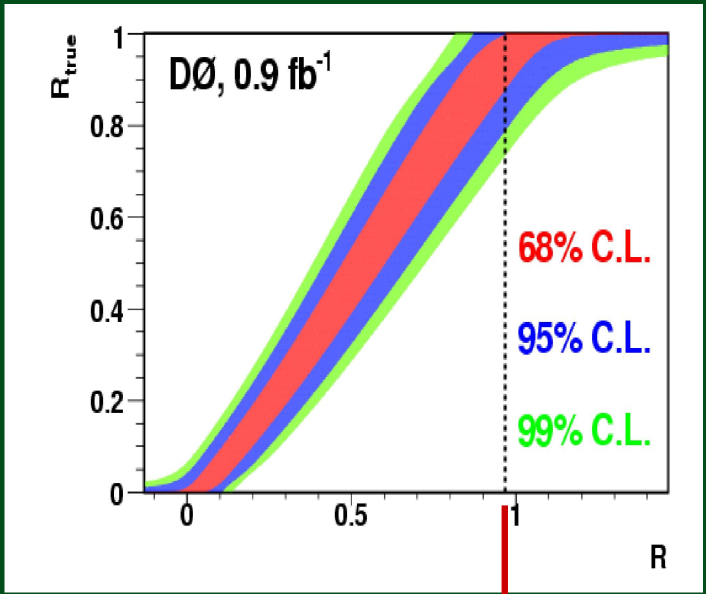
Insensitive to m_t

$$R_b = 0.97^{+0.09}_{-0.08}\,(\text{stat} + \text{syst})$$

For m_t=175 GeV:

$$\sigma_{t\bar{t}} = 8.18^{+0.90}_{-0.84}\,(\text{stat} + \text{syst})$$
$$\S\, 0.50\,(\text{lumi})\ \text{pb}$$

Ensemble testing to find limits:

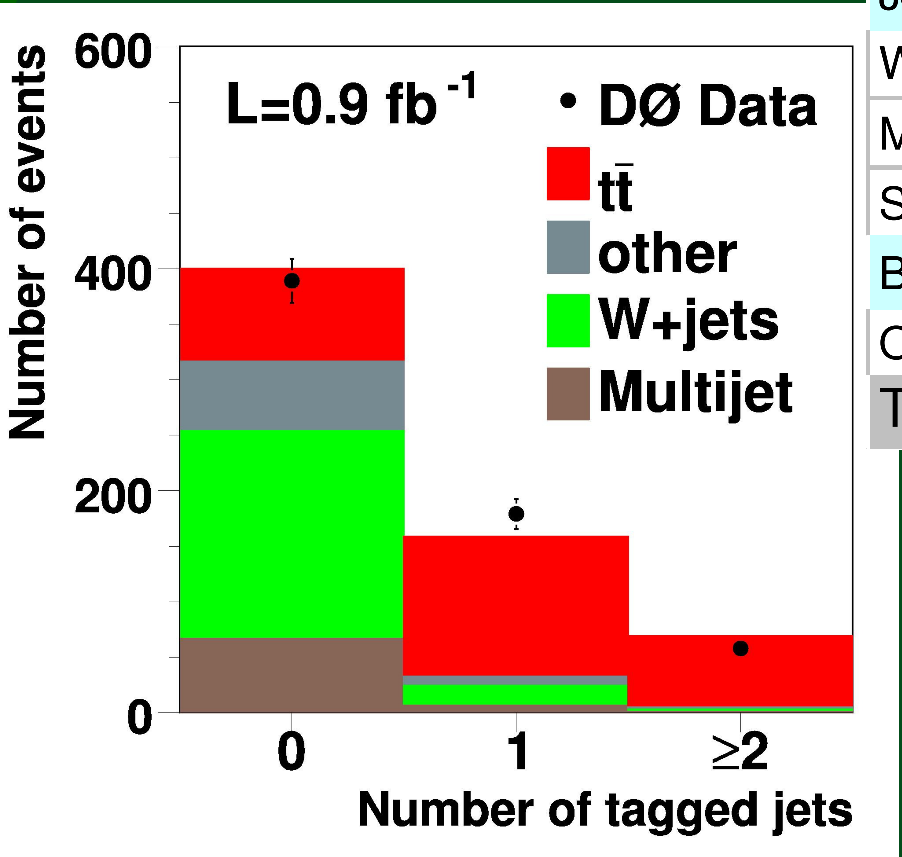


$R_b > 0.88$ @ 68% C.L.

$R_b > 0.79$ @ 95% C.L.

More on R_b

- Text



Source	δσ(pb)	δR
Statistical	+0.67-0.64	+0.067-0.065
Lepton identification	+0.32-0.27	n/a
Jet energy calibration	+0.32-0.23	n/a
W+jets background	+0.21-0.23	n/a
Multijet background	±0.17	±0.016
Signal model	+0.12-0.25	n/a
B-tagging	+0.10-0.09	+0.059-0.047
Other	+0.24-0.13	+0.015-0.014
Total	+0.90-0.84	+0.092-0.083

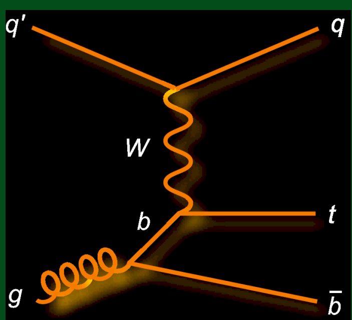
Measuring the top width

Standard model

Γ_t=1.3GeV (for m_t=170GeV)

Difficult to measure directly
(but see CDF talk)

Indirect measurement:



Can combine the R_b and single-top t-channel cross section to extract $\Gamma(t\to Wb)$ [C.-P. Yuan, e.g. arXiv:hep-ph/9604434]

- "effective W approximation" → The Wtb vertex factorizes

→ σ_{tbqX} proportional to $\Gamma(t\to Wb)$ even in the presence of anomalous Wtb coupling

Assuming the above production mechanism

- no FCNC
- |Vtd|, |Vts| small

```
$\Gamma_t=\frac{\Gamma\left
(t\to Wb\right)}{{\rm
B}\left(t\to Wb\right)}
```

$$R_b = \frac{B(t\to Wb)}{B(t\to Wq)}$$

Assume:

$$B\left(t\to Wq\right) = 1$$

Method

Reinterpret the t-channel cross section measurement as:

$$\sigma \mathrm{B} = \sigma_{tbqX} \cdot \mathrm{B}\left(t \to Wb\right) = 3.14^{+0.94}_{-0.80}\,\mathrm{pb}$$

Wtb also effects
the decay

Yielding: $$\Gamma\left(t \to Wb\right) = \frac{\sigma \mathrm{B}}{\mathrm{B}(t \to Wb)} \frac{\Gamma(t \to Wb)_{SM}}{\sigma_{tbqX,SM}}$$

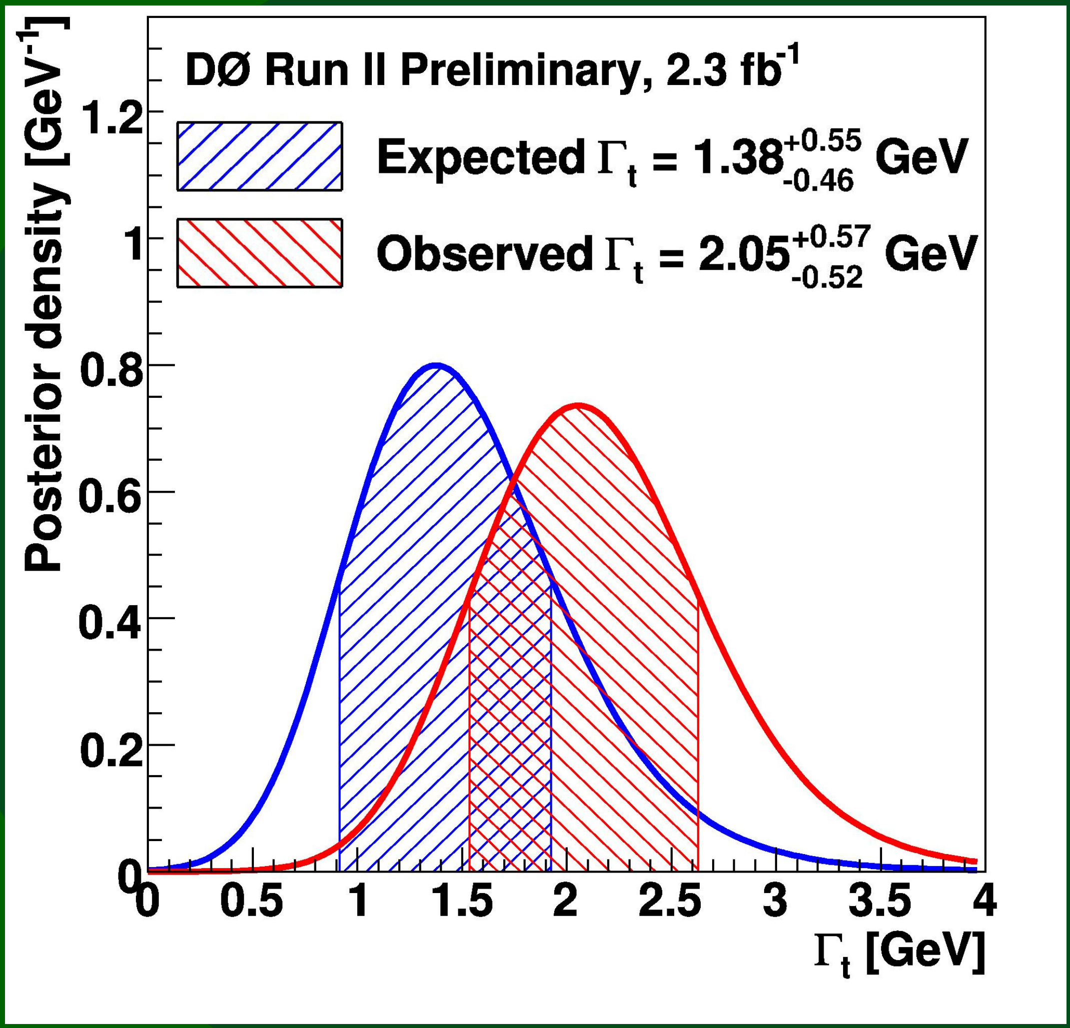
and: $$\Gamma_t = \frac{\frac{\sigma \mathrm{B}}{\mathrm{B}(t \to Wb)} \frac{\Gamma(t \to Wb)_{SM}}{\sigma_{tbqX,SM}}}{\mathrm{B}(t \to Wb)}$$

Both calculated at
(pure) NLO QCD

Redo the statistical analysis of t-channel x-section measurement

- same selections, 24 channels, same discriminants, etc. (see A. Heinson's talk)
- extracting the widths instead of σ
- priors flat in the widths
- *and….*

Results



An *indirect* measurement

Assumptions:

- No FCNC production
- |Vtd|, |Vts| small
- $\mathrm{B}\left(t \rightarrow Wq\right) = 1$

All supported by experiment!

Most precise measurement

That is: $\tau_t = \left(3.2^{+1.1}_{-0.7}\right) \cdot 10^{-25}\,\mathrm{s}$

Top width systematics

Relative Systematic Uncertainties

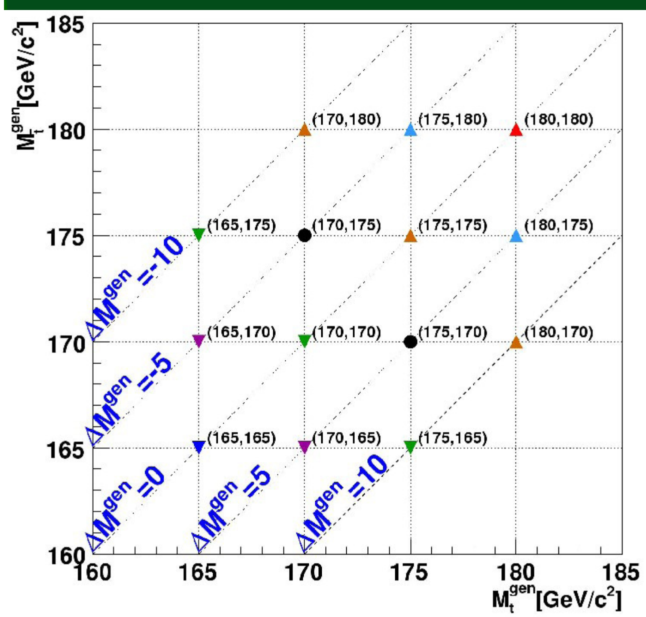
Sources	t-channel	R measurement	Correlations
Components for Normalization			
Luminosity	6.1%	0.0%	
Single top signal modeling	3.5–13.6%	0.0%	
Top pair production signal modeling	—	1.0%	X
Other background from MC	15.1%	0.6%	X
Detector modeling	7.1%	0.1%	X
Components for Normalization and Shape			
Background from data	13.7–54%	1.7%	X
b-tagging	2–30%	6.3%	X
Jet Energy Scale	0.1–13.1%	0.0%	

$$\Gamma_t = 2.05^{+0.57}_{-0.52}\ \mathrm{GeV}$$

$$\Gamma\left(t \to Wb\right) = 1.90^{+0.58}_{-0.48}\ \mathrm{GeV}$$

Method

- A variation of the DØ l+jets matrix-element mass measurement with ~1 fb^{-1} (PRL 101, 182001 (2008), see O. Brandt's talk)
- Separate the top quark from the top antiquark by lepton charge
  - solenoid and toroid polarities routinely reversed
  - unfortunately (?) can't switch detector to anti-matter
    - arguably the trickiest experimental aspect - $\bar{b}JES$ vs. $bJES$ studied in data and MC (K^+ vs K^- interact with matter differently)



Δm enters:

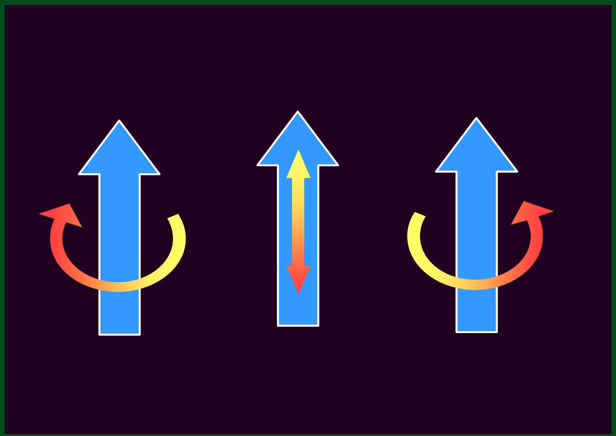
- the matrix elements (incl. decay terms)
- the acceptance, and
- the MC
  - modified Pythia to generate events with $m_t \neq m_{\bar{t}}$

2D likelihood in $m_t \; \& \; m_{\bar{t}}$ → integrate → 1D likelihood in $\Delta = m_t - m_{\bar{t}}$ or m_{sum}

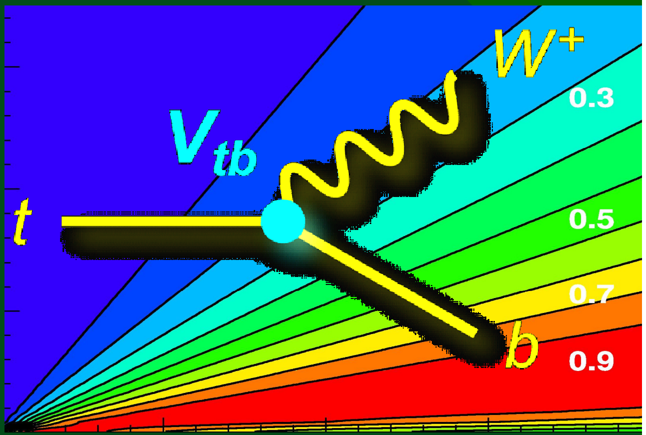
Outline

top quark @ DØ

W helicity



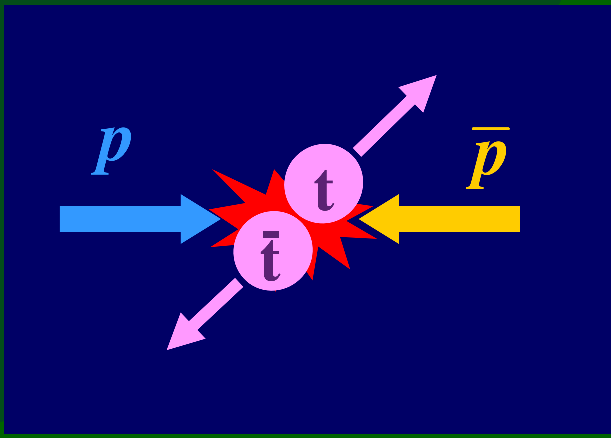
Wtb structure



R_b

Width

Not ready



Delta m systematics

Source	Uncertainty (GeV)
Physics modeling	
Signal	±0.85
PDF uncertainty	±0.26
Background modeling	±0.03
Heavy flavor scale factor	±0.07
b fragmentation	±0.12
Detector modeling:	
b/light response ratio	±0.04
Jet identification	±0.16
Jet resolution	±0.39
Trigger	±0.09
Overall jet energy scale	±0.08
Residual jet energy scale	±0.07
Muon resolution	±0.09
Wrong charge leptons	±0.07
Asymmetry in $b\bar{b}$ response	±0.42
Method:	
MC calibration	±0.25
b-tagging efficiency	±0.25
Multijet contamination	±0.40
Signal fraction	±0.10
Total (in quadrature)	±1.22

Delta m in matrix elements

$$\frac{d\hat{\sigma}}{dt}(q\overline{q} \to t\overline{t}) = \frac{4\pi\alpha_s^2}{9\hat{s}^4}\left[(m_1^2 - \hat{t})^2 + (m_2^2 - \hat{u})^2 + 2m_1 m_2 \hat{s}\right]$$

$$|\mathscr{M}|^2 = \frac{g_s^4}{9} F\overline{F} \frac{2}{s}\left[(E_1 - p_1\cos\theta)^2 + (E_2 + p_2\cos\theta)^2 + 2m_1 m_2\right]$$

Decay terms (F) take into account the corresponding mass