Measurement of the *W* Boson Helicity in Top Quark Decays at DØ

Fermilab Joint Experimental-Theoretical Seminar

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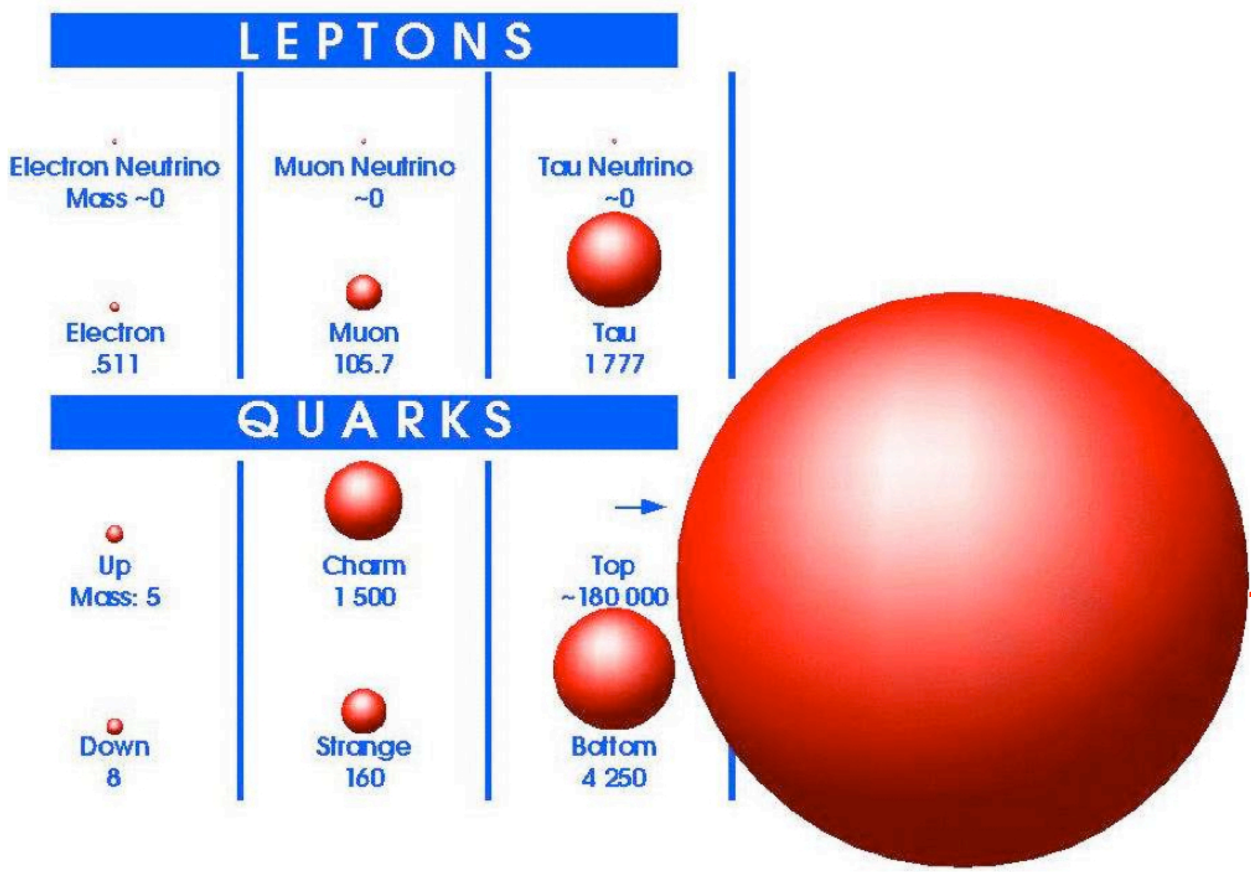
Outline

- Introduction
- Event selection
- Kinematic reconstruction
- Extracting the W boson helicity fractions
- Systematic uncertainties
- Result
- Conclusion

- The Standard Model describes the following set of fermions:



What's special about this one?

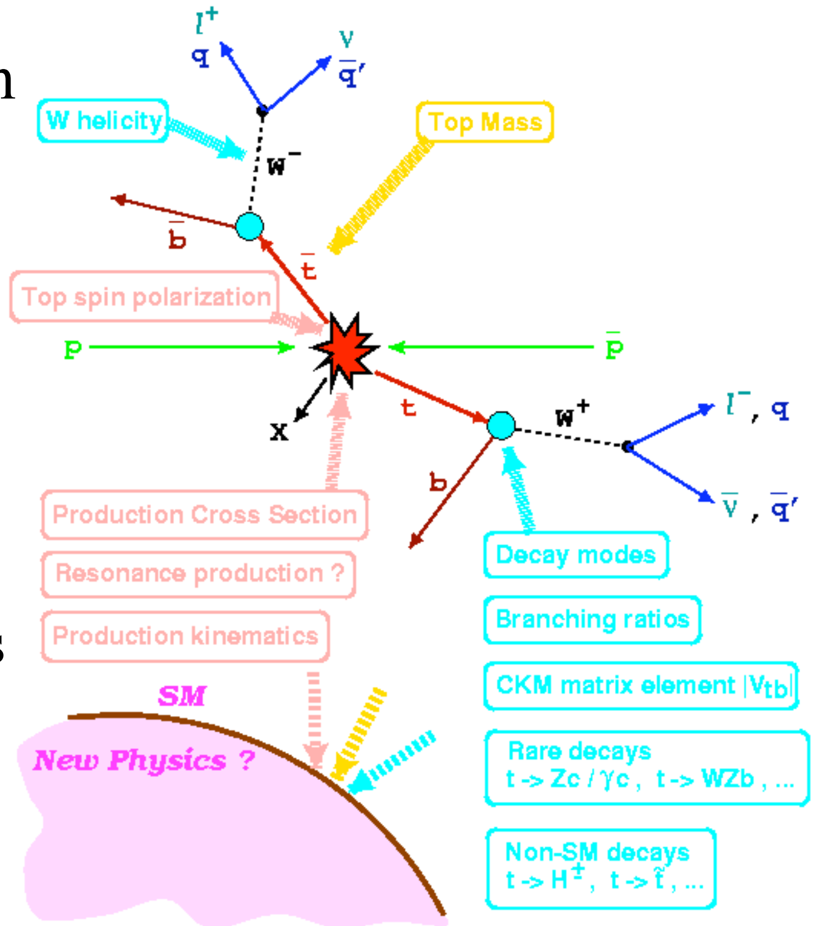
Unique features of the top quark

- It's the most recently-discovered quark (1995 at Fermilab)
  - world sample is ~10^3 $t\bar{t}$ pairs, all from the Tevatron
  - we have ~unlimited statistics for all the other quarks
- It's the only quark that doesn't form a hadron before it decays
  - we have experimental access to the "bare" properties of the quark
- Both of the above statements are true for the same reason:
  - it's by far the most massive quark!
- The top's coupling to the Higgs is ~1
  - the other fermions have "unnaturally" small couplings
  - special role for the top in electroweak symmetry breaking?

Important to investigate coupling to gauge bosons

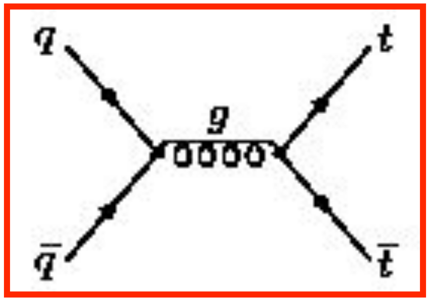
The Top Quark in Run II

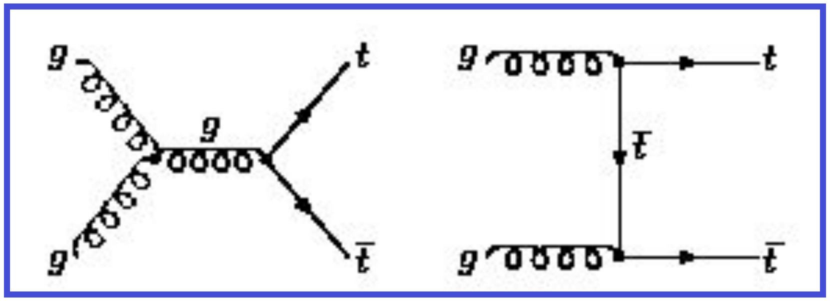
- Improving our understanding of the top quark is one of the primary goals for Run II
- With the larger Run II sample we can explore:
  - Is top quark production and decay according to SM?
  - Is there an exotic component to the "top" sample?
- We have now measured
  - The $t\bar{t}$ and single-top cross sections
  - The top quark mass
  - The top quark charge
  - The *W* boson helicity



$t\bar{t}$ production and decay at the Tevatron

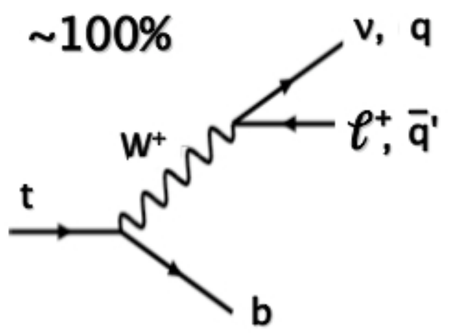
- Top quark pairs produced via $q\bar{q}$ annihilation (85%) or gluon fusion (15%)

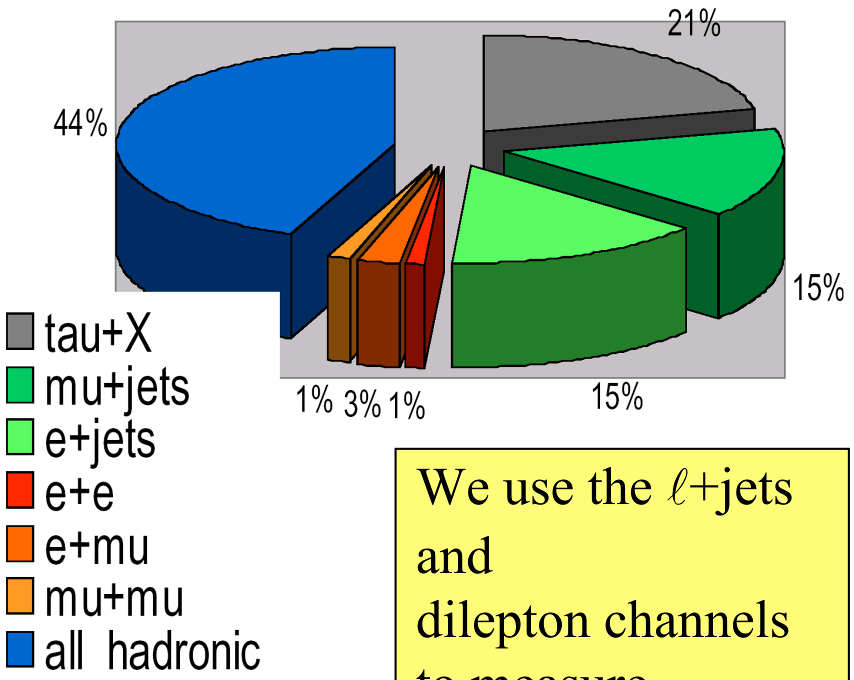




$\sigma_{t\bar{t}} \approx 7$ pb

- Decay:



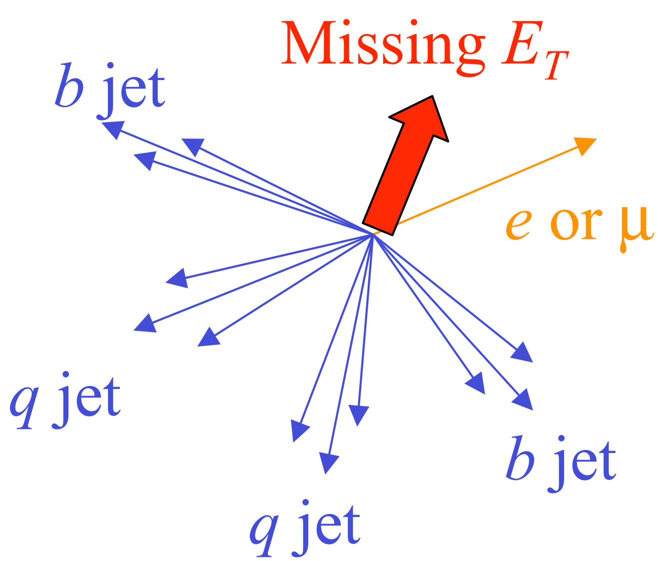


We use the ℓ+jets and dilepton channels to measure W boson helicity

Experimental signatures

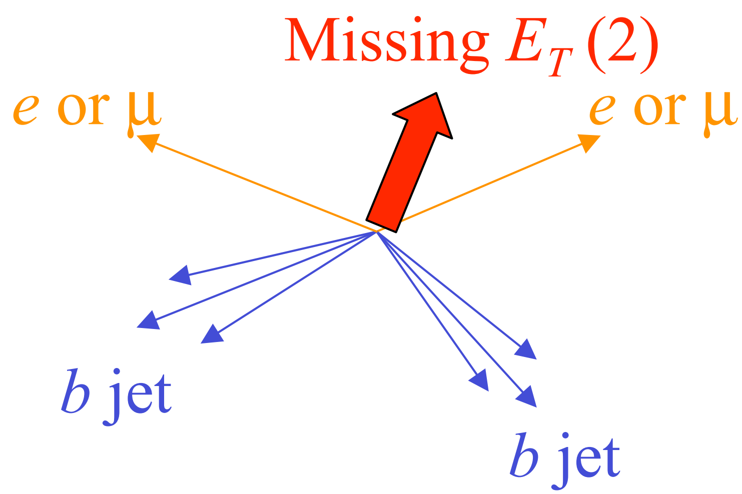
ℓ + jets:

$t\bar{t} \rightarrow WbWb \rightarrow \ell\nu bbjj$



Dilepton:

$t\bar{t} \rightarrow WbWb \rightarrow \ell\ell'\nu\nu'bb$



Backgrounds

- Two classes of background:

1. Instrumental
   - e.g. hadronic jet appears to be a lepton

Normalization and kinematics from data control samples

2. Physics
   - same final-state objects as in $t\bar{t}$ events

Examples:

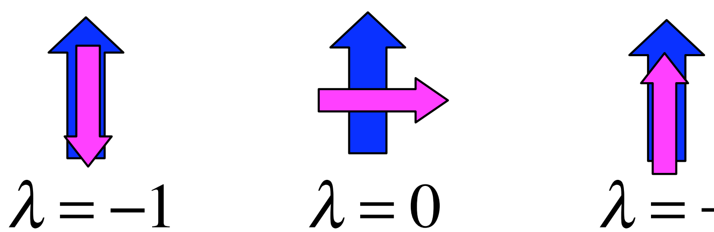
$$W+\geq 4\,\text{jets} \rightarrow \ell\nu + \geq 4\,\text{jets}$$

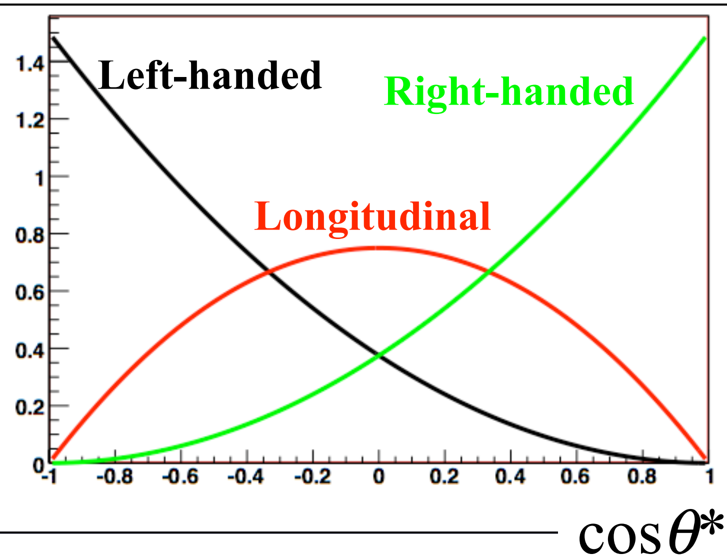
$$Z+\geq 2\,\text{jets} \rightarrow \tau\tau + \geq 2\,\text{jets} \rightarrow \ell\nu\ell'\nu' + \geq 2\,\text{jets}$$

Kinematics from Monte Carlo

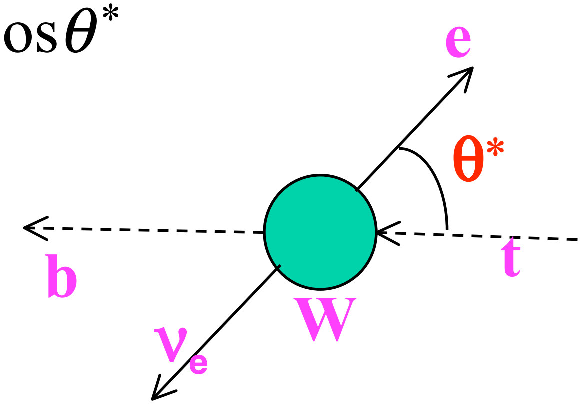
W boson helicity

W boson has three possible helicity states:





Can distinguish in top decays using lepton p_T or (better) $\cos\theta^*$



We measure the helicity fractions:

$$f_o = \Gamma\left(t \to W_0 b\right) / \Gamma\left(t \to Wb\right)$$

$$f_+ = \Gamma\left(t \to W_+ b\right) / \Gamma\left(t \to Wb\right)$$

$$f_- = 1 - f_o - f_+$$

W boson helicity in the Standard Model

- The Standard Model Lagrangian for top quark decay is:

$$L_{tWb} = \frac{g}{2\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu V_{tb} (1 - \gamma_5) t$$

  - predicts the *W* boson helicity fractions: $m_t = 172.5$ GeV

Longitudinal: $f_0 = \frac{m_t^2}{m_t^2 + 2M_W^2} + O\left(\frac{m_b}{m_t}\right)^2 \approx 0.70$

Right-handed: $f_+ \sim \left(\frac{m_b}{m_t}\right)^2 \approx 3.6 \times 10^{-4}$

Left-handed: $f_- = 1 - f_0 + O\left(\frac{m_b}{m_t}\right)^2 \approx 0.30$

Motivation

- Uncertainties in the SM prediction are far smaller than the precision we can achieve experimentally
- Any significant deviation from the SM values would be a clear signature of new physics

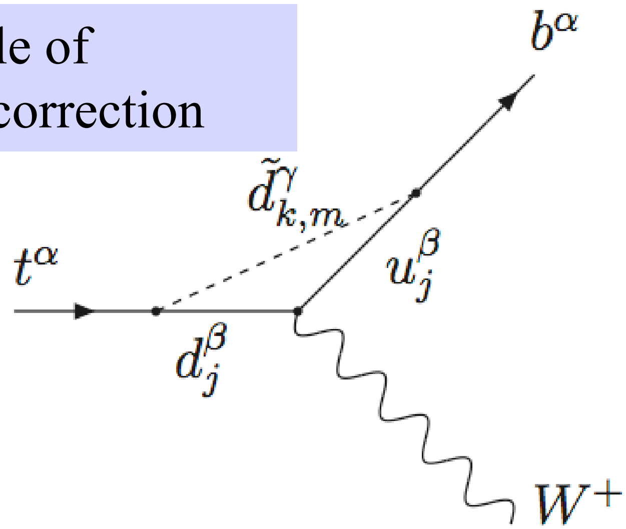
We're using the top quark to search for new phenomena

New phenomena?

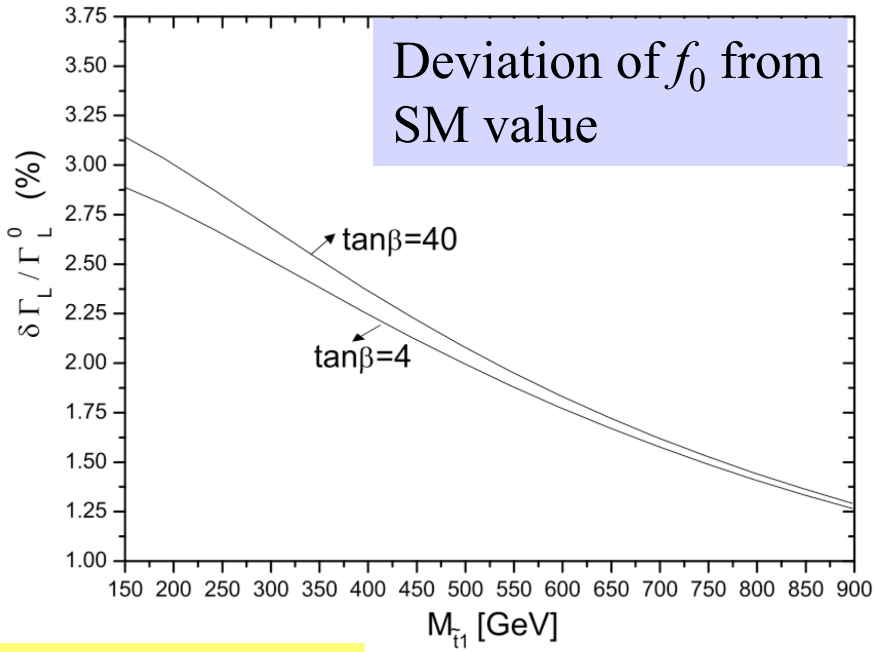
- For example, *W* helicity fractions are altered in *R*-parity violating SUSY models:

Y. M. Nie, C. S. Li, Q. Li, J. J. Liu and J. Zhao, Phys.Rev.D71:074018, 2005.

Example of vertex correction



Deviation of f_0 from SM value



Corrections are ~few %

New phenomena?

- Look at general effective Lagrangian for *tWb*:

$$L_{tWb} = \frac{g}{2\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L (1-\gamma_5) + f_1^R (1+\gamma_5) \right) t$$
$$- \frac{g}{2\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L (1-\gamma_5) + f_2^R (1+\gamma_5) \right) t$$

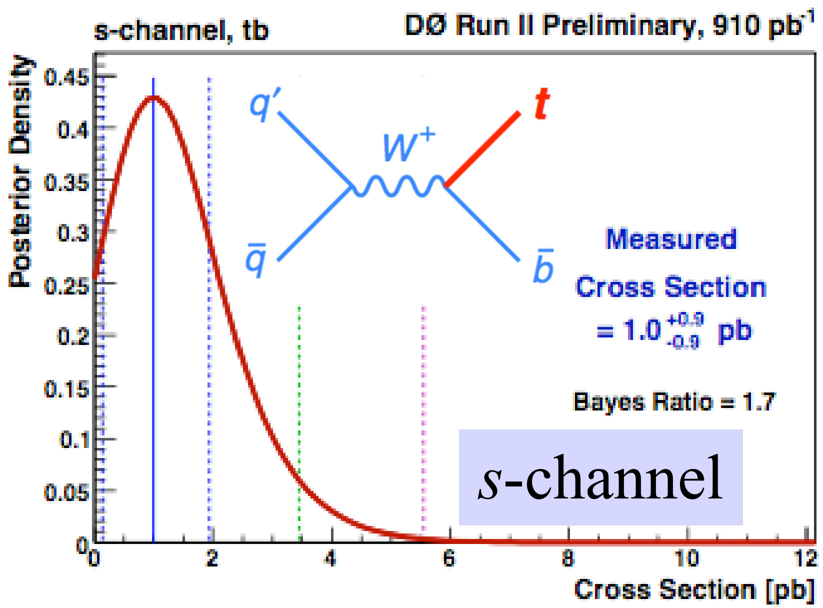
form factors

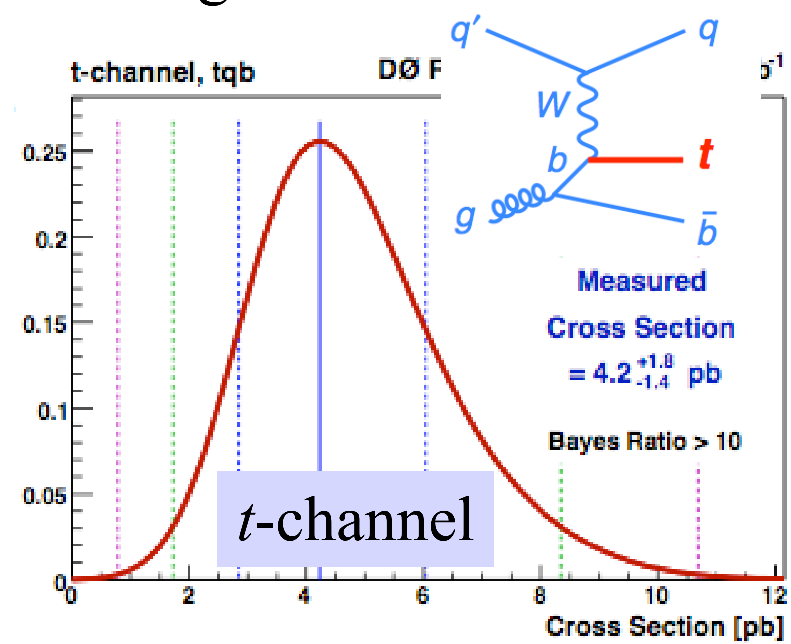
C.-R.Chen, F. Larios, and C.-P. Yuan, Phys. Lett. B **631**, 126 (2005).

- In SM, $f_1^L = V_{tb} \approx 1$, others are 0

New phenomena?

- With four measurements, one can specify all form factors
- Single-top production cross sections give two:





- The *W* helicity fractions give another two

We can start to place model-independent constraints on top quark couplings

Overview of analysis

Identify data sample

Model signal and background events

Select events

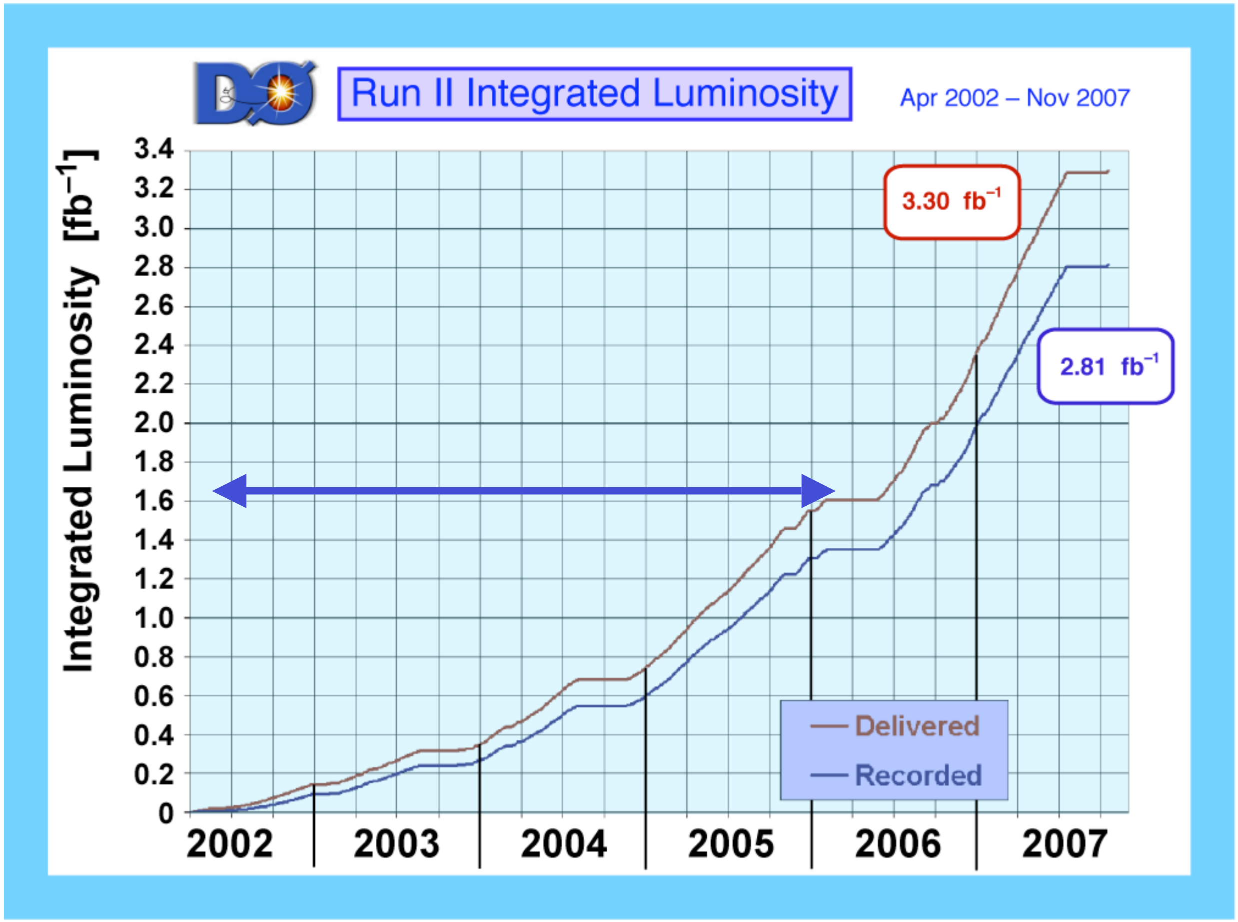
Reconstruct $\cos\theta^*$ for selected events

Measure W helicity fractions

Evaluate systematic uncertainties

Data sample

- We use data from the RunII period (2002 - 2006):



- About 1fb^{-1} of data used
- Much more on tape, but not trivial to add due to change in detector
- Coming soon…

Monte Carlo

- ALPGEN v2 is used to model $t\bar{t}$, W +jets, and Z+jets events
  - PYTHIA used for hadronization
  - includes MLM matching to properly account for sources of jets
  - can produce any linear combination of V-A and V+A top quark decays
  - we include correct fraction of b and c jets in W, Z + jets samples
- PYTHIA is used for other physics backgrounds (i.e. dibosons)
- All samples are passed through GEANT simulation
  - reconstructed with same algorithms as data

Data and MC are compared in control samples; corrections applied for residual discrepancies

Overview of analysis

Identify data sample

Model signal and background events

Select events

~90% of the analysis

Reconstruct $\cos\theta^*$ for selected events

Measure W helicity fractions

Evaluate systematic uncertainties

Event Selection

- Divided into two logical steps:

1. Preselection
   - require jets and leptons expected in $t\bar{t}$ events
     - use well-understood selection criteria to identify each object

   Can be common to many analyses

2. Final selection
   - optimized according to needs of analysis
   - we use a multivariate discriminant
     - combines both kinematic and *b* ID information

Preselection

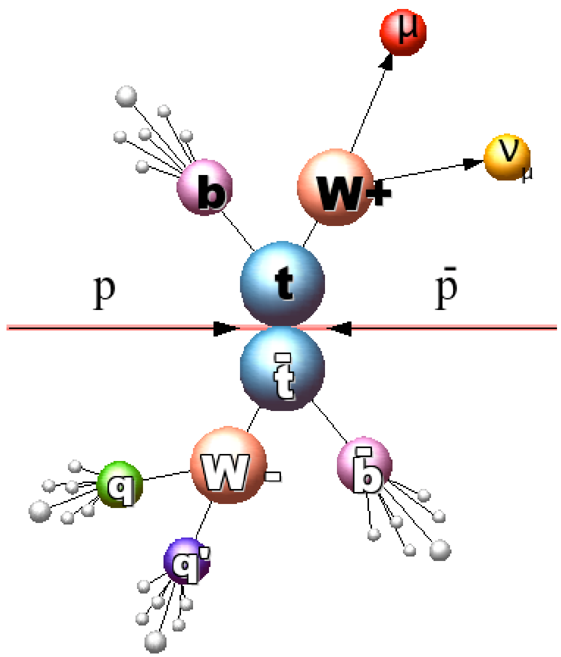
- First apply data quality, event vertex, lepton and jet ID requirements
  - standardized for many DØ analyses
- Then apply kinematic cuts:

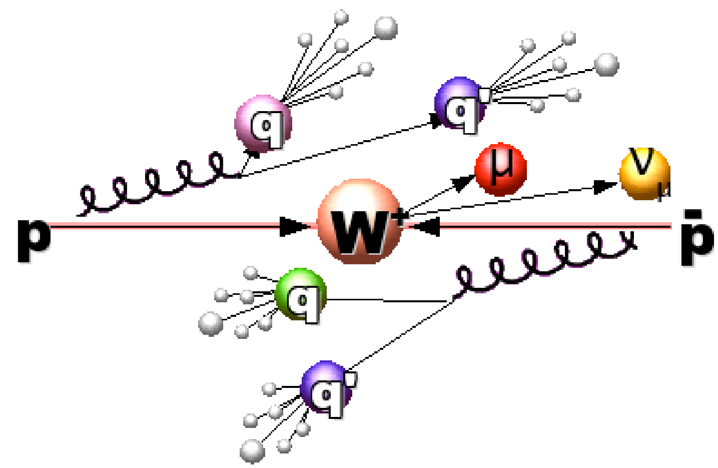
	ℓ+jets	Dilepton
Leptons (e or μ)	One with $p_T > 20$ GeV $\lvert\eta_e\rvert < 1.1$ $\lvert\eta_\mu\rvert < 2.0$	Two with $p_T > 15$ GeV $\lvert\eta_e\rvert < 1.1$ or $1.5 < \lvert\eta_e\rvert < 2.5$ $\lvert\eta_\mu\rvert < 2.0$
Jets	≥ 4 $p_T > 20$ GeV $\lvert\eta\rvert < 2.5$	≥ 2 $p_T > 20$ GeV $\lvert\eta\rvert < 2.5$
Missing E_T	> 20 GeV	No cut

Final Selection

- Consider a large set of variables that distinguish signal from background:

Signal tends to have higher-p_T jets distributed uniformly in $\eta\!-\!\phi$ space

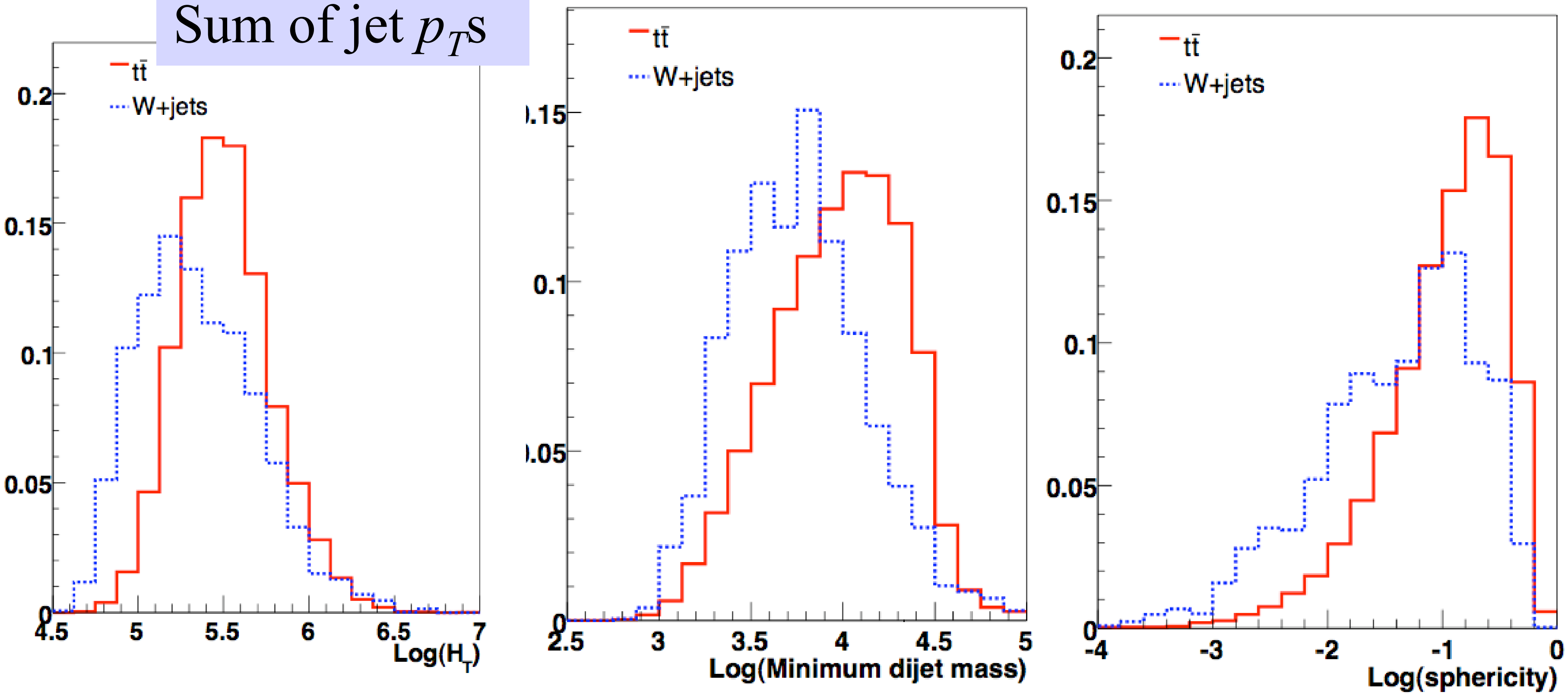




- Many kinematic variables are sensitive to these differences
- Jet flavor is also very different in signal and background…

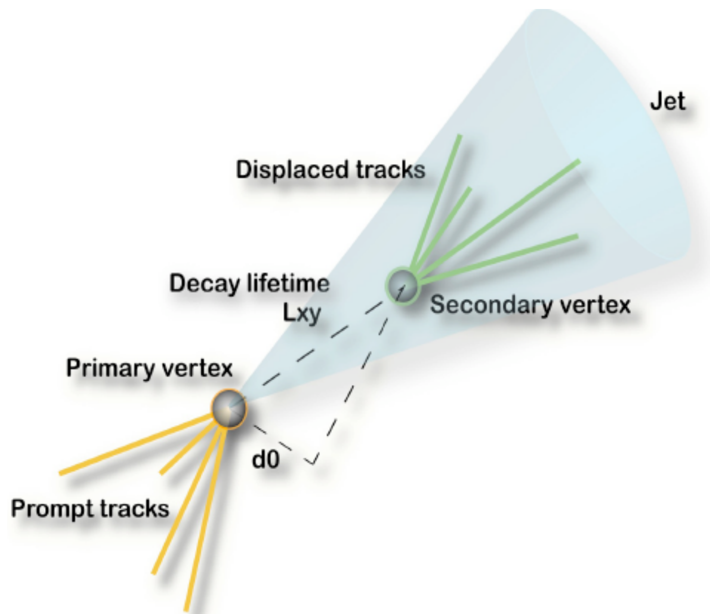
Some of the variables

Sum of jet p_Ts



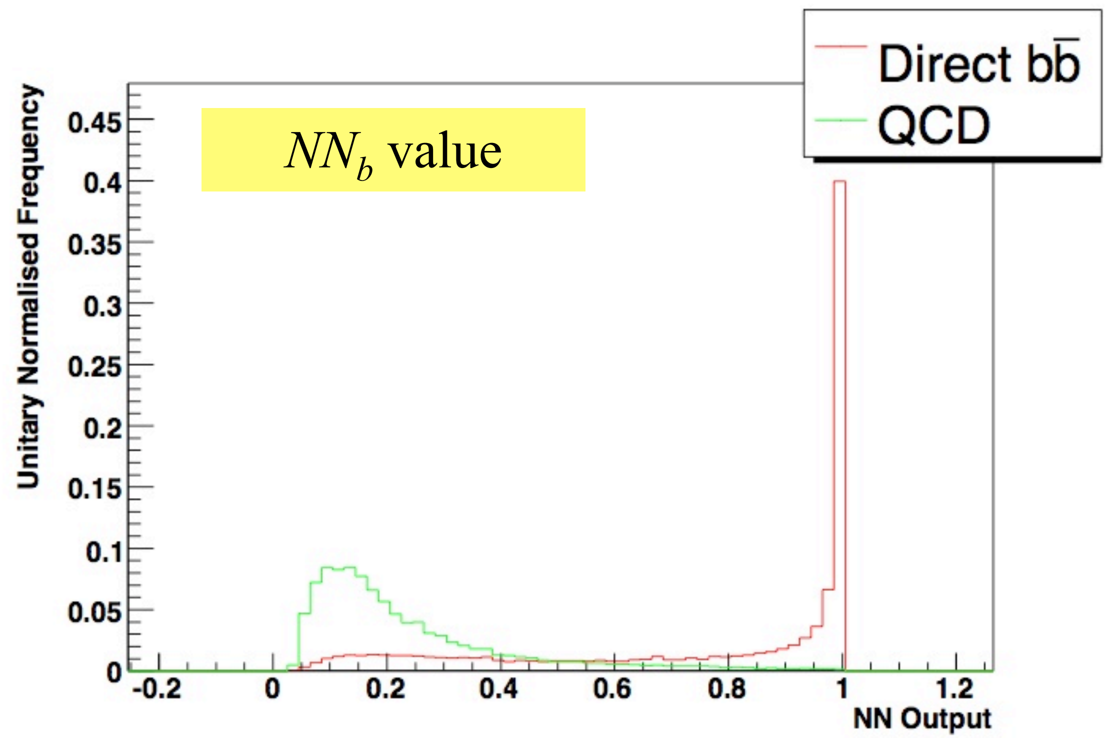
Combine several variables into a discriminant *D*

Using jet lifetime information



Combine several track and secondary vertex quantities in neural net

NN_b value



NN_b variable

- The NN_b variable is a complex quantity depending on details of the track reconstruction
  - and there are known differences between our data and the Monte Carlo
- Many analysis apply a cut on NN_b
  - jets passing the cut are called "*b*-tagged"
  - corrections applied for differences between data and MC tag rates
- But we use the *distribution* of NN_b

Higher efficiency than requiring a *b* tag
Better S/B than ignoring jet flavor

Data/MC differences included in systematic

Discriminant

- Information from multiple variables is combined in a likelihood discriminant:

Set of measured values

$$D(\mathbf{x}) = \frac{P_{\text{sig}}(\mathbf{x})}{P_{\text{sig}}(\mathbf{x}) + P_{\text{bkg}}(\mathbf{x})}$$

$$P_{\text{sig}}(\mathbf{x}) = \prod_{i=1}^{N_{\text{var}}} p_{\text{sig},i}(x_i) \qquad P_{\text{bkg}}(\mathbf{x}) = \prod_{i=1}^{N_{\text{var}}} p_{\text{bkg},i}(x_i)$$

signal and background pdfs

Result is near one for signal, near zero for background

Optimization of final selection

- Two questions remain:

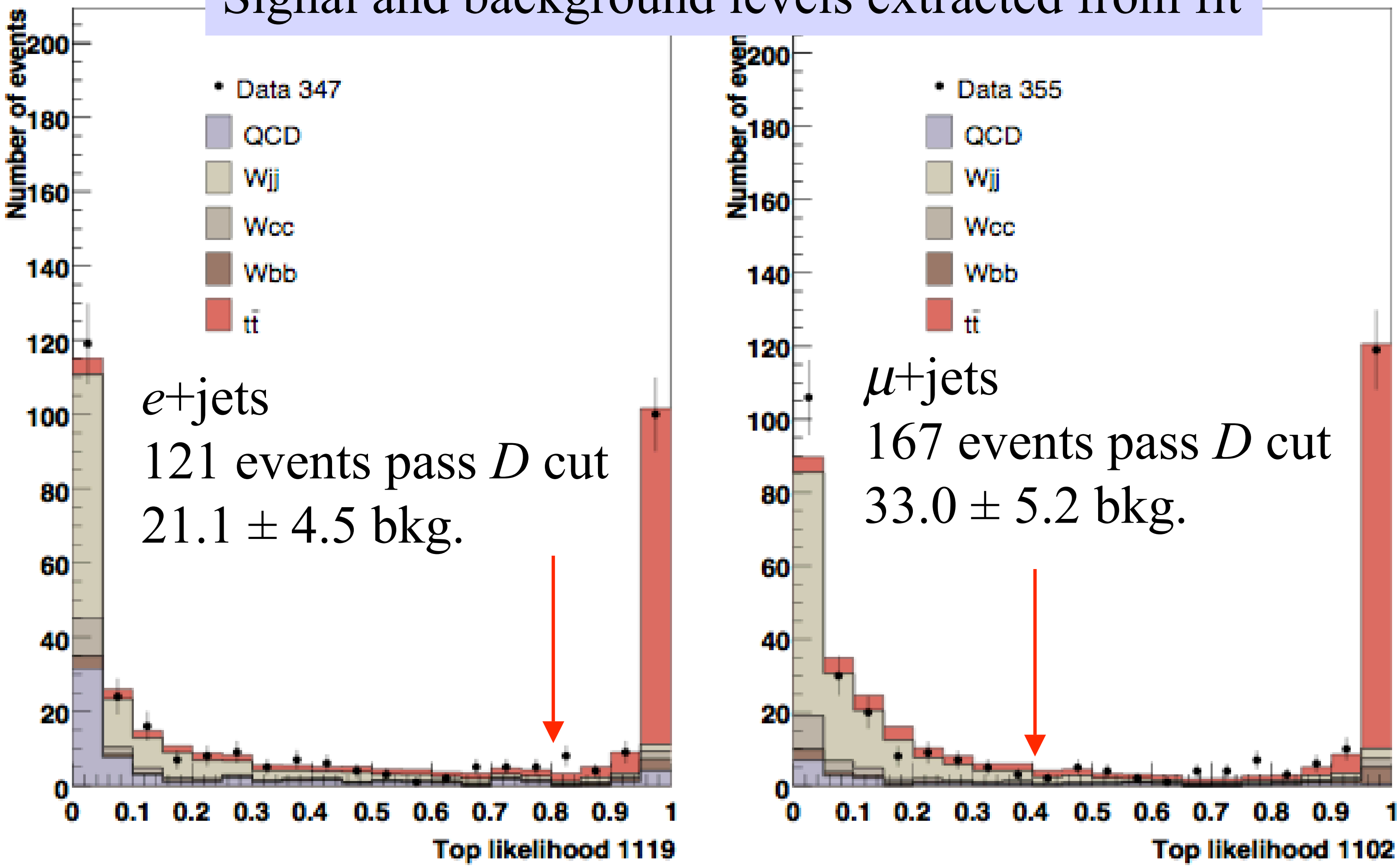
1. What is the best set of variables to use?
   - having too many correlated variables can reduce separation power
2. Where should we place the cut on *D*?

- We answer these with a “brute force” approach in Monte Carlo
  - consider every combination of input variables
  - choose the combination that separates signal and background best
  - then step over the range to find the best cut

N.B. optimization is done before looking at data!

Optimized D (ℓ+jets)

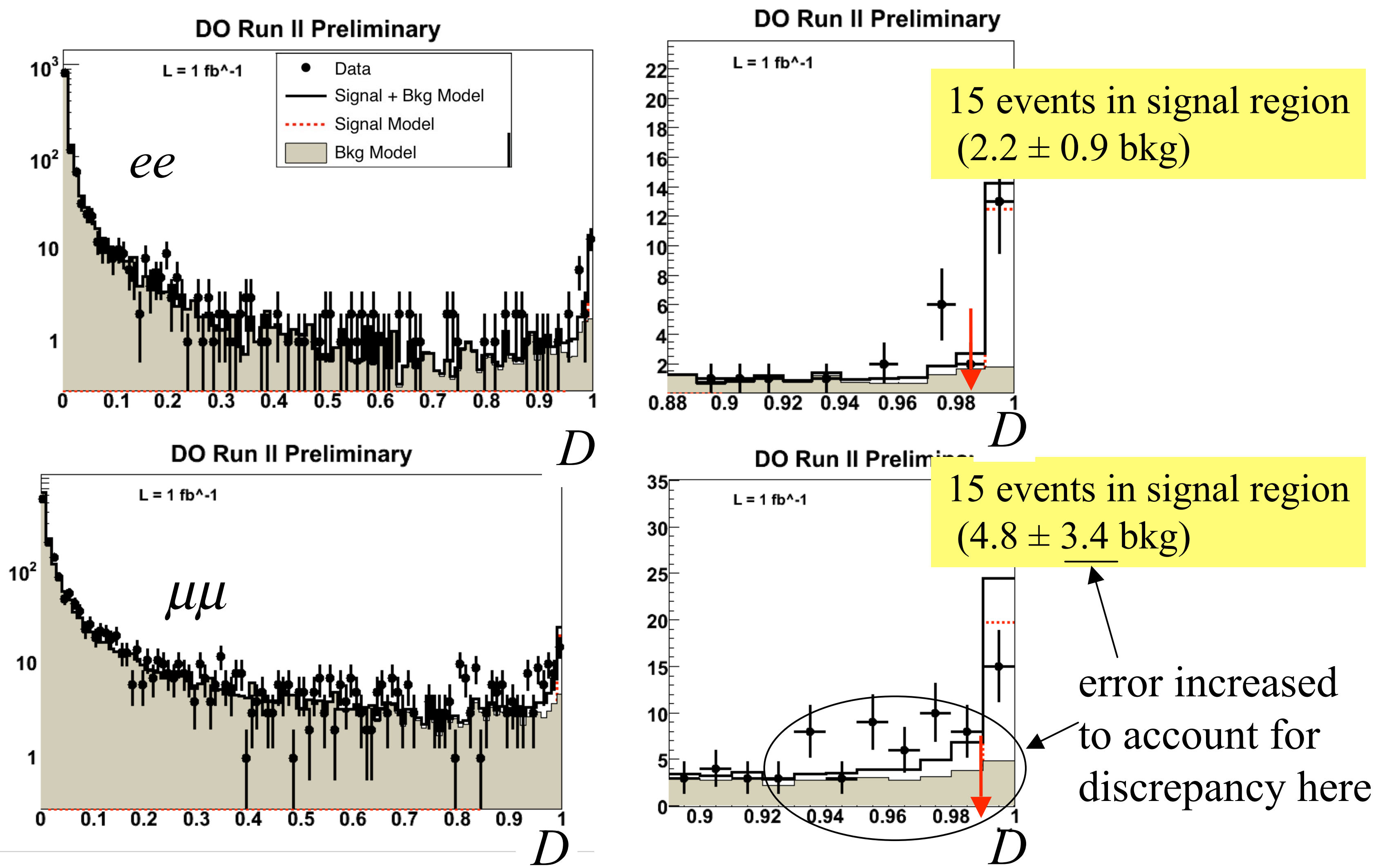
Signal and background levels extracted from fit



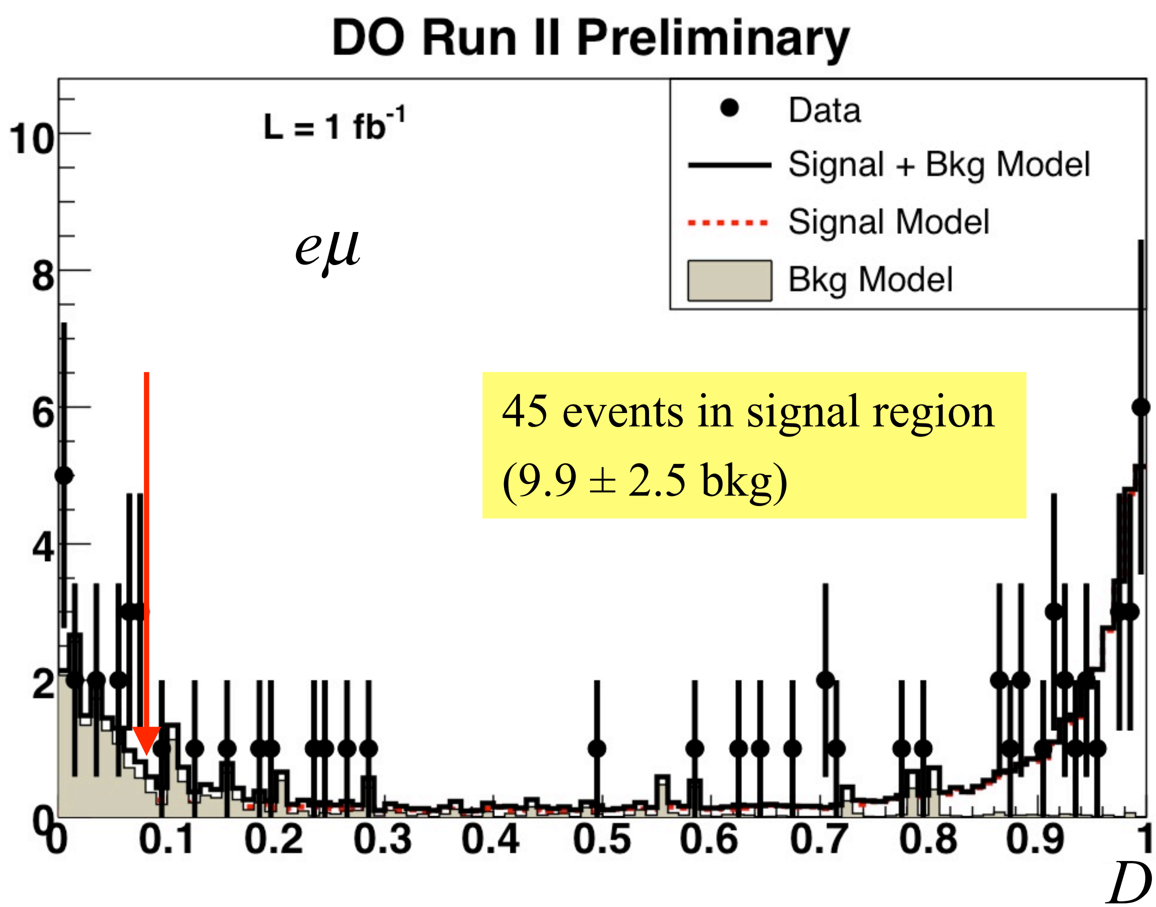
e+jets
121 events pass *D* cut
21.1 ± 4.5 bkg.

μ+jets
167 events pass *D* cut
33.0 ± 5.2 bkg.

Optimized *D* (dilepton)



Optimized *D* (dilepton)



Final Data Sample

	e+jets	μ+jets	$e\mu$	ee	$\mu\mu$
Purity in preselected sample	0.38	0.44	0.67	0.014	0.024
Cut on D	0.80	0.40	0.08	0.986	0.990
Background after cut	21.1 ± 4.5	33.0 ± 5.2	9.9 ± 2.5	2.2 ± 0.9	4.8 ± 3.4
Data after cut	121	167	45	15	15

So we have a high-purity top quark sample--
now the fun part can begin!

Overview of analysis

Identify data sample

Model signal and background events

Select events

Reconstruct $\cos\theta^*$ for selected events

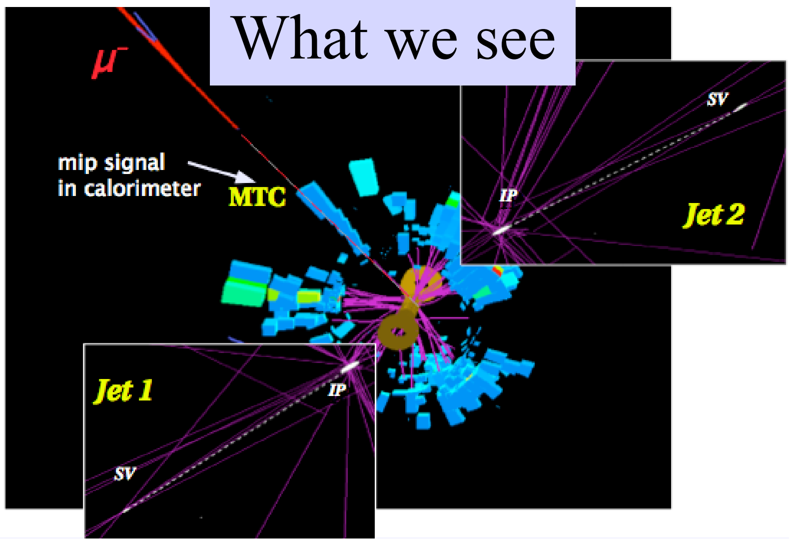
Measure W helicity fractions

Evaluate systematic uncertainties

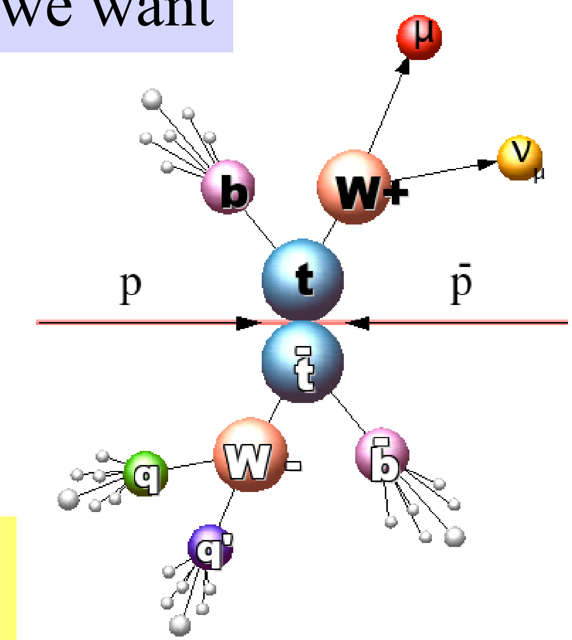
Reconstructing $\cos\theta^*$

- We do not directly observe $\cos\theta^*$
  - Rather, we see a collection of jets, leptons, and missing E_T
- There is a good chance these objects came from $t\bar{t}$, but…

What we see



What we want

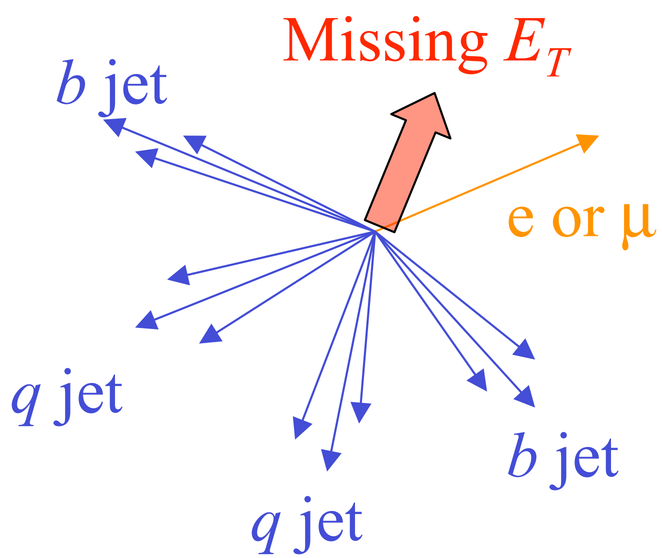


We make use of techniques developed for measuring the top quark mass

Reconstructing $\cos\theta^*$

- In ℓ+ jets channel, have:

- Observables:



- Unseen:
  - p of the neutrino (3)

- Constraints:
  - Conservation of p_T (2)
  - $m_{t1} = m_{t2} = 172.5$ GeV (2)
  - $M_{W1} = M_{W2} = 80.4$ GeV (2)

Can do a 3C kinematic fit

Reconstructing $\cos\theta^*$

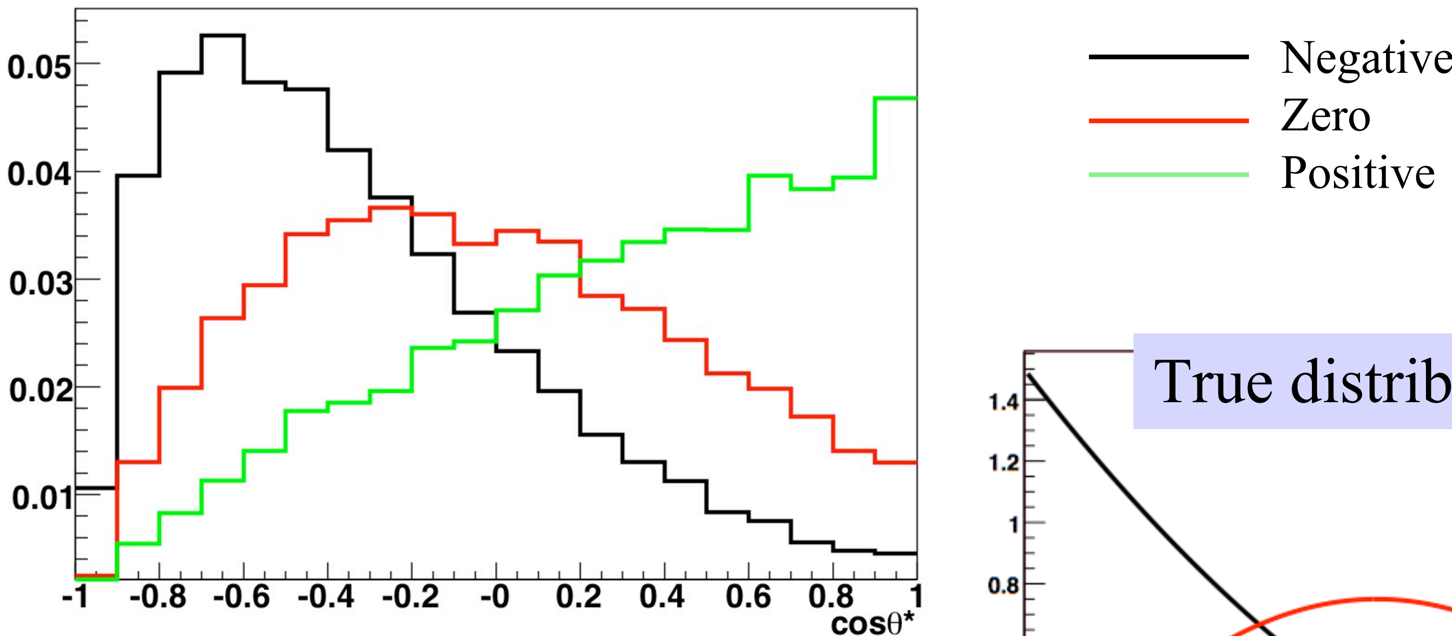
- Still have to choose assignment of jets to initial partons
  - if only four highest-p_T jets are considered, have 12 combinations
- Decide among them using

1. Kinematics
   - χ^2 probability from kinematic fit
2. *b*-tag information
   - information from each jet is passed through a neural network
   - larger output value → more likely to be a *b* jet
   - find probability of four NN_b values with assumed partons

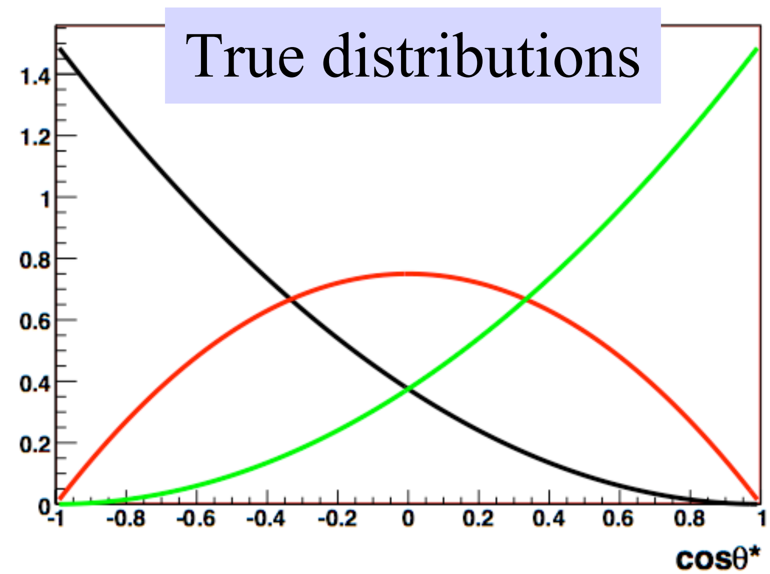
- Choose combination with highest joint kinematic/NN_b probability

Example of reconstructed cosθ^*

- *e*+jets channel, *W* decays leptonically

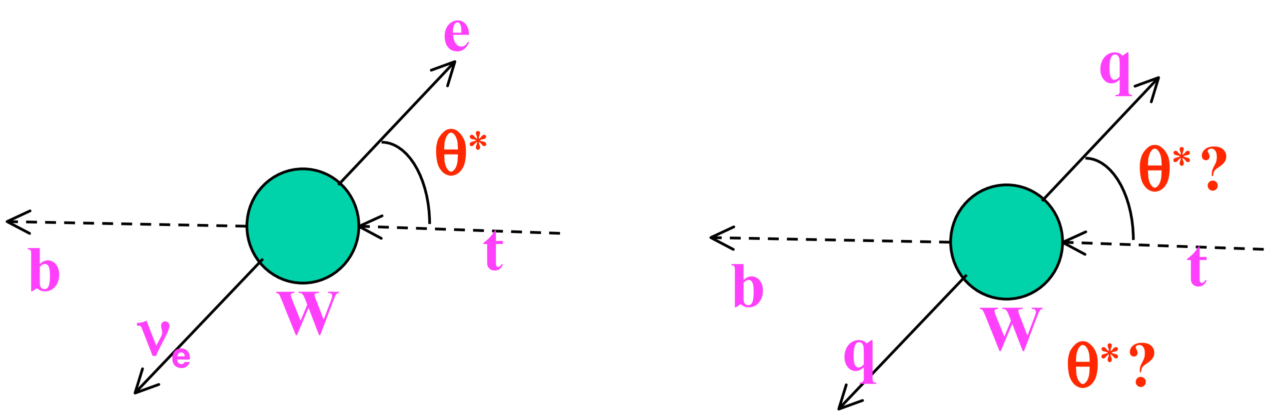


Substantial distortions due to acceptance and resolution



Using hadronic W decays

- Previous W helicity measurements used only the leptonic W decays
  - since it's much easier to determine $\cos\theta^*$ for these:



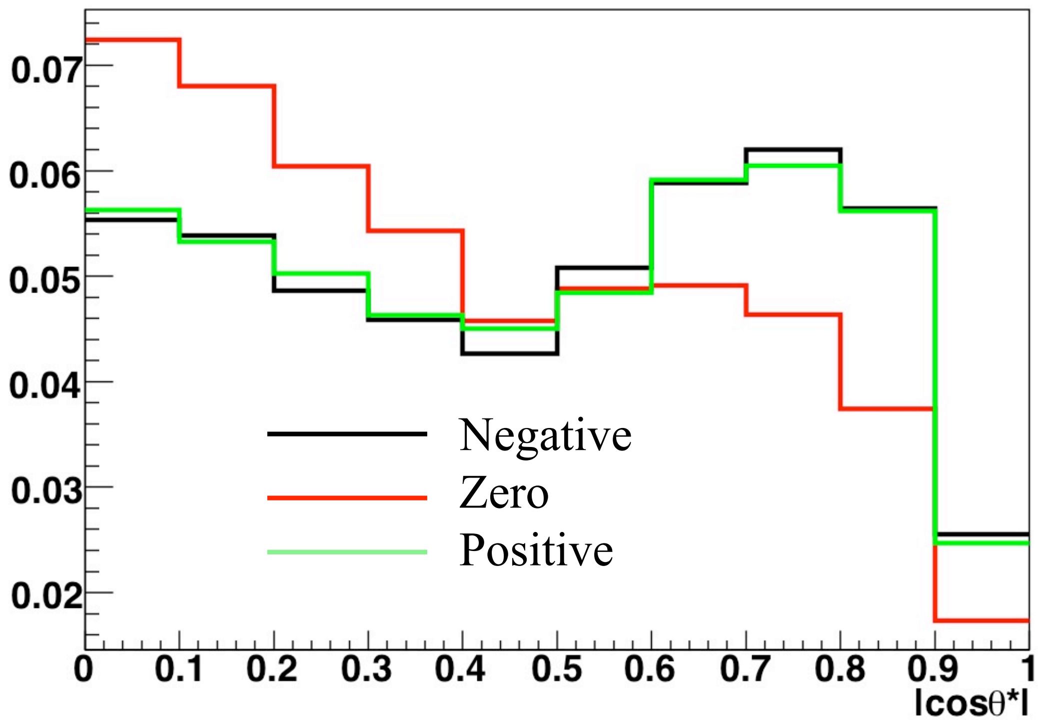
We choose randomly -- sign ambiguity in $\cos\theta^*$

- But, longitudinal W's have a different distribution in $|\cos\theta^*|$ than right- or left-handed W's do

Can improve precision in model-independent fit by using these decays

Example of reconstructed $\cos\theta^*$

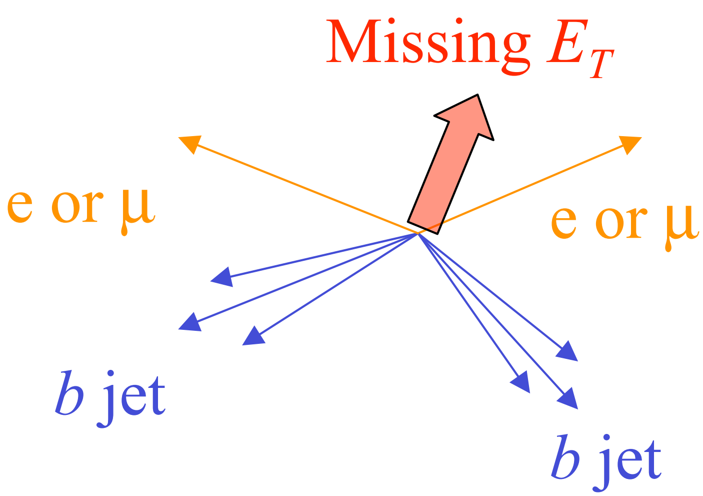
- e+jets channel, W decays hadronically



Reconstructing $\cos\theta^*$

- Dilepton events are more challenging:

- Observables:



- Unseen:
  - *p* of the neutrinos (6)

- Constraints:
  - $\vec{E}_T = \vec{p}_T(\nu)$ (2)
  - $m_{t1} = m_{t2} = 172.5$ GeV (2)
  - $M_{W1} = M_{W2} = 80.4$ GeV (2)

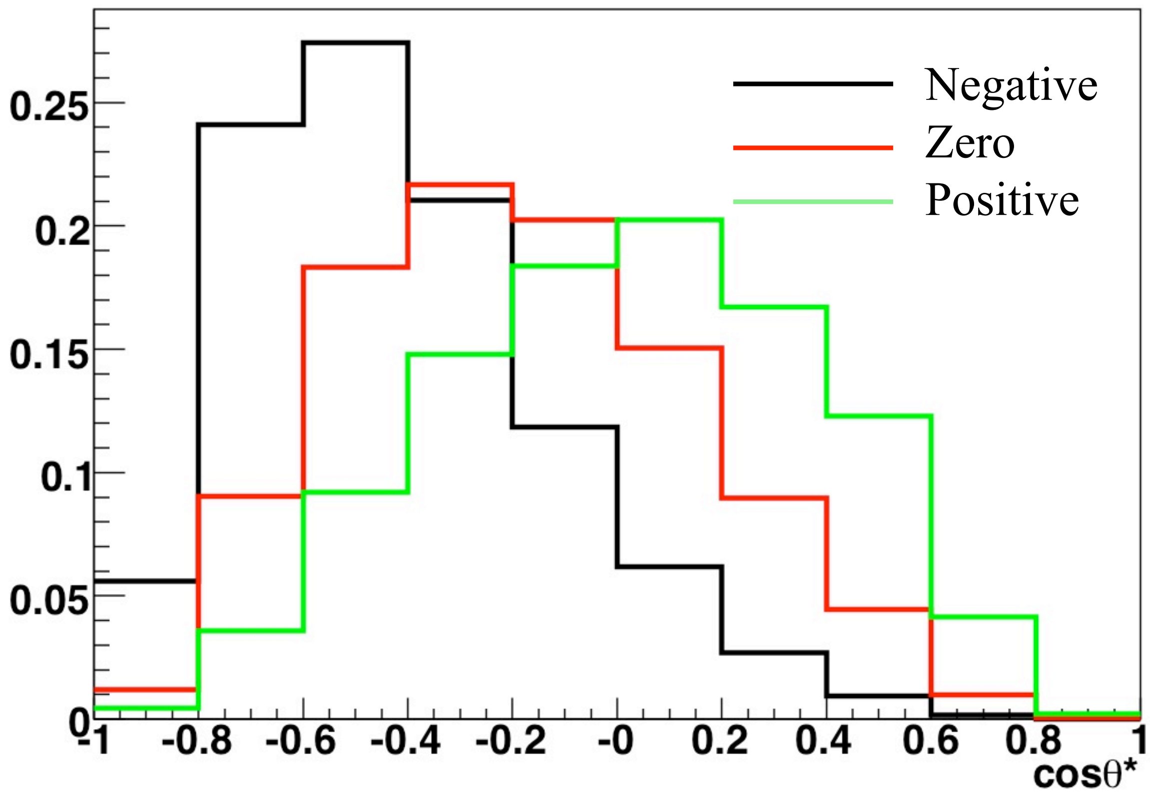
0C “fit” -- really means an algebraic solution

Reconstructing $\cos\theta^*$

- For some events, there is no solution to the kinematic equations
  - observed energies are not parton energies!
  - so, smear measured jet and lepton energies according to resolution many times, and try to find solution each time
    - i.e. explore the parton kinematics consistent with the observed energies
- Four-fold solution ambiguity
- Two-fold ambiguity in pairing jets and leptons
  - no kinematic χ^2 to help out
  - and both jets are presumably *b*'s, so NN_b doesn't provide any information either
- Average over all solutions to find $\cos\theta^*$

Example of reconstructed cosθ^*

- $e\mu$ channel; two entries per event



Overview of analysis

Identify data sample

Model signal and background events

Select events

Reconstruct $\cos\theta^*$ for selected events

Measure W helicity fractions

Evaluate systematic uncertainties

Maximum Likelihood Fit

- Now we have the data, and the templates for signal and background
  - All that's left is to fit to find the helicity fractions
- We use a binned Poisson fit:

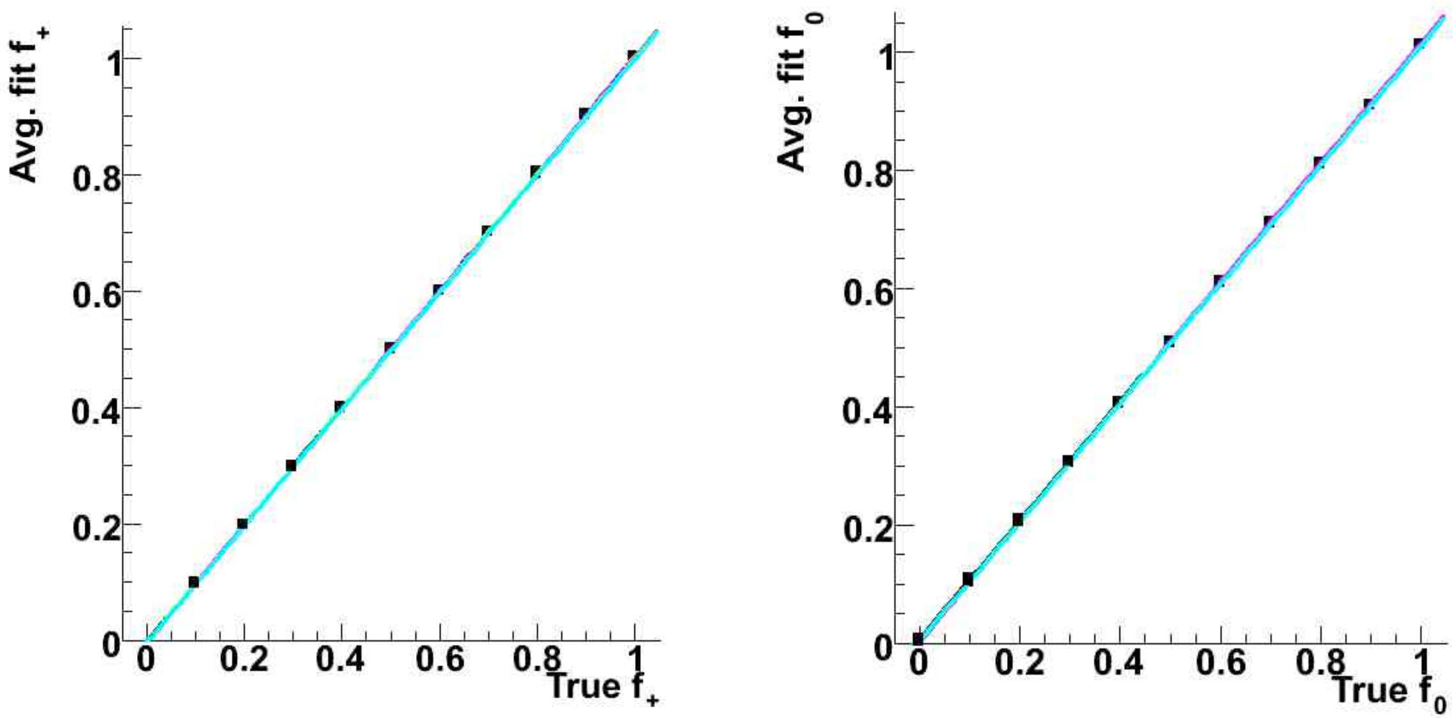
$$L = \prod_{i=1}^{N_{\text{chan}}} \prod_{j=1}^{N_{\text{bkg},i}} \exp\left[\frac{\left(n_{\text{bkg},ij} - \overline{n_{\text{bkg},ij}} \right)^2}{2\sigma^2_{\text{bkg},ij}} \right] \prod_{k=1}^{N_{\text{bins},i}} P\left(d_{ik}, n_{ik}\right)$$

Quantities in green are fit parameters

$$n_{ik} = n_{s,i}\left(f_o p_{o,ik} + f_+ p_{+,ik} + \left(1 - f_o - f_+\right) p_{-,ik} \right) + \sum_{j=1}^{N_{\text{bkg}}} n_{b,ij} p_{b,ijk}$$

Ensemble Tests

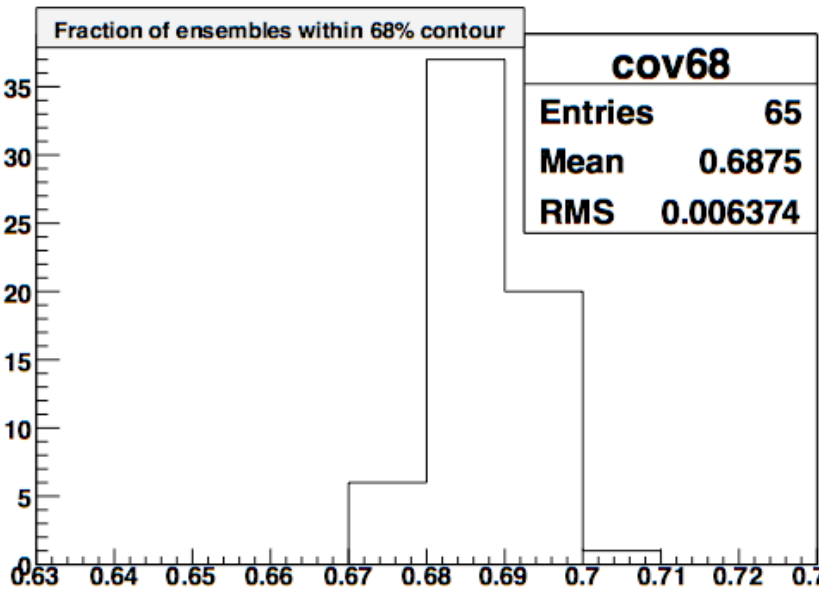
- Fit many simulated data sets, spanning the range of possible *W* helicity fractions

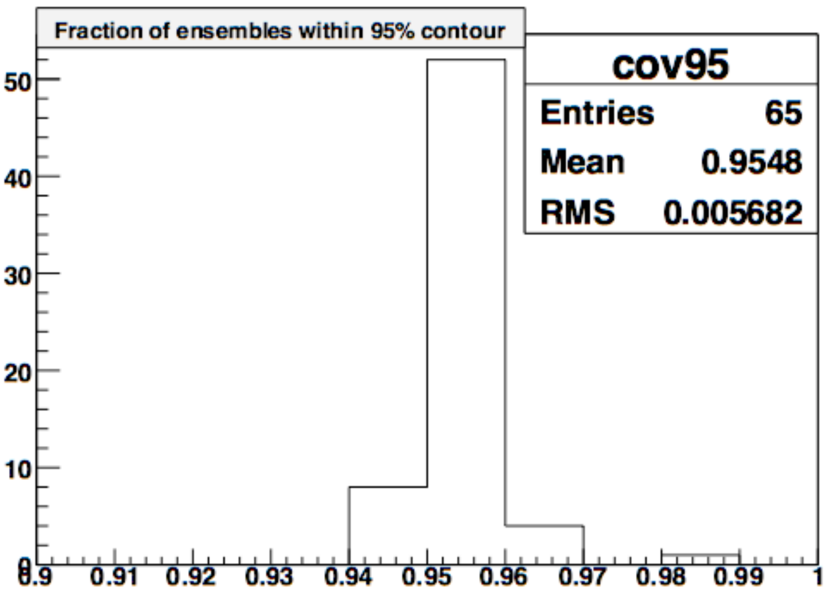


Small deviations taken as systematic uncertainty

Ensemble Tests

- Also test coverage
  - i.e. how often are the true values in the expected C.L. region?





Ensemble tests are also used to assess systematic uncertainties

Systematics on f_o and f_+

- Though statistics-limited, we account for several systematic effects:

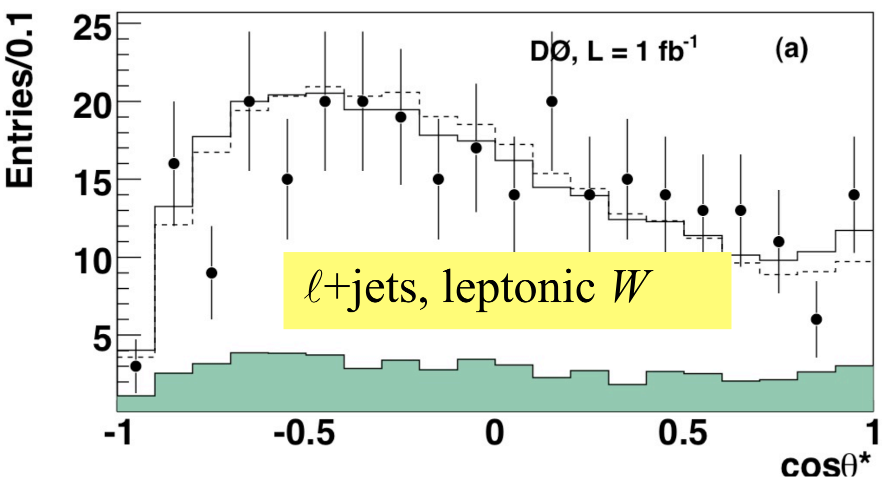
- top quark mass
  - 172.5 ± 2.3 GeV
- jet energy calibration and resolution
- signal model
  - Alpgen vs. Pythia
  - TuneA vs. tuneDW
  - one PV only vs. all PV's
- heavy flavor fraction in bkg.
  - ±20% variation
- NN_b variable
- Template statistics
- Parton distribution functions
- Jet ID efficiency
- Background model
- b fragmentation

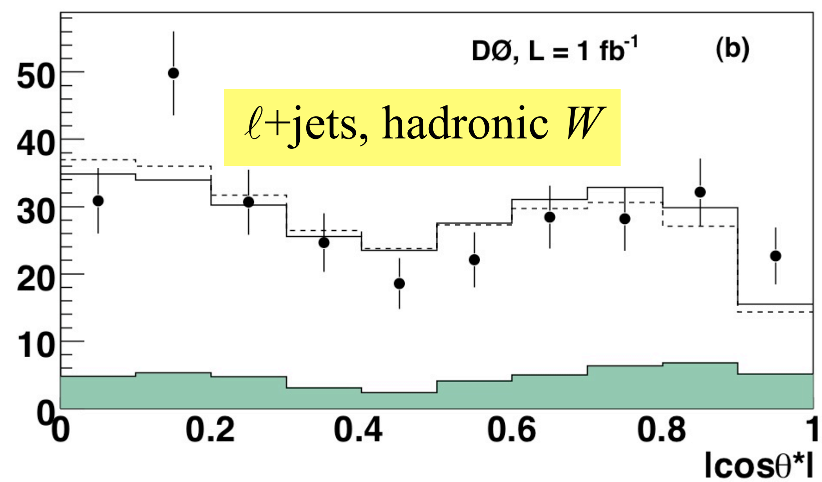
Systematic uncertainties

Source	$\delta(f_+)$	$\delta(f_0)$
Top mass	0.014	0.015
Signal model	0.032	0.059
Jet energy calibration	0.021	0.016
jet energy resolution	0.003	0.003
Heavy flavor content	0.004	0.006
Bkg model	0.023	0.053
Template stats	0.031	0.053
Analysis consistency	0.002	0.006
Jet identification	0.013	0.029
B fragmentation	0.007	0.019
PDF	0.002	0.003
Modeling of NN_b	0.002	0.005
Total	0.058	0.104

Fit to data

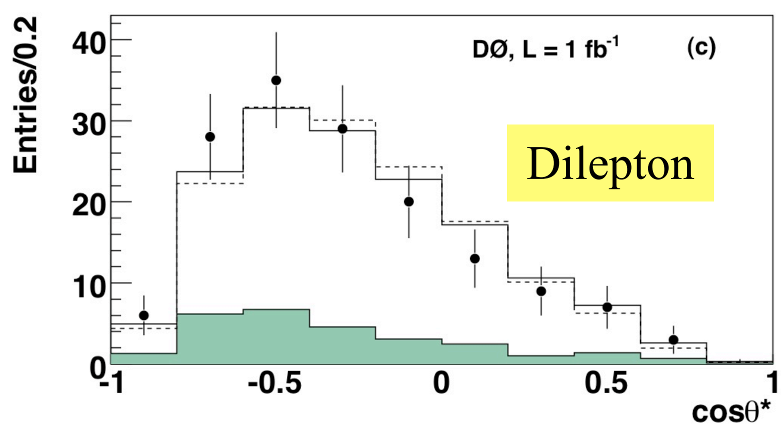
- Comparing the global best-fit model to data in the dilepton and ℓ+jets channels:





Best-fit model

SM

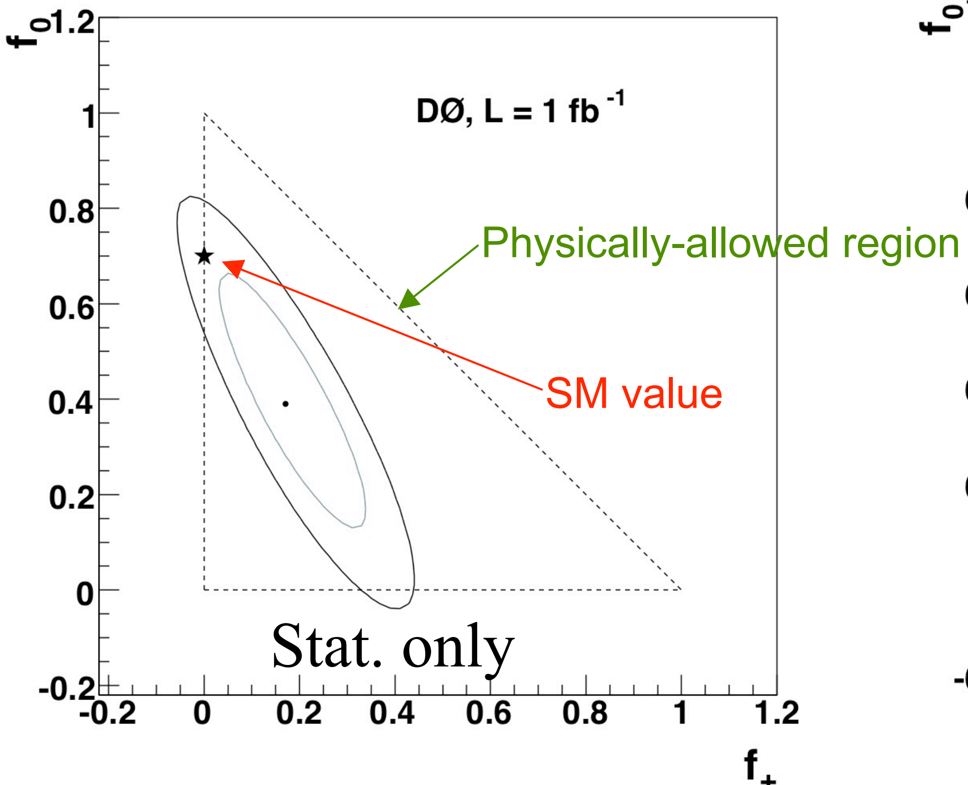


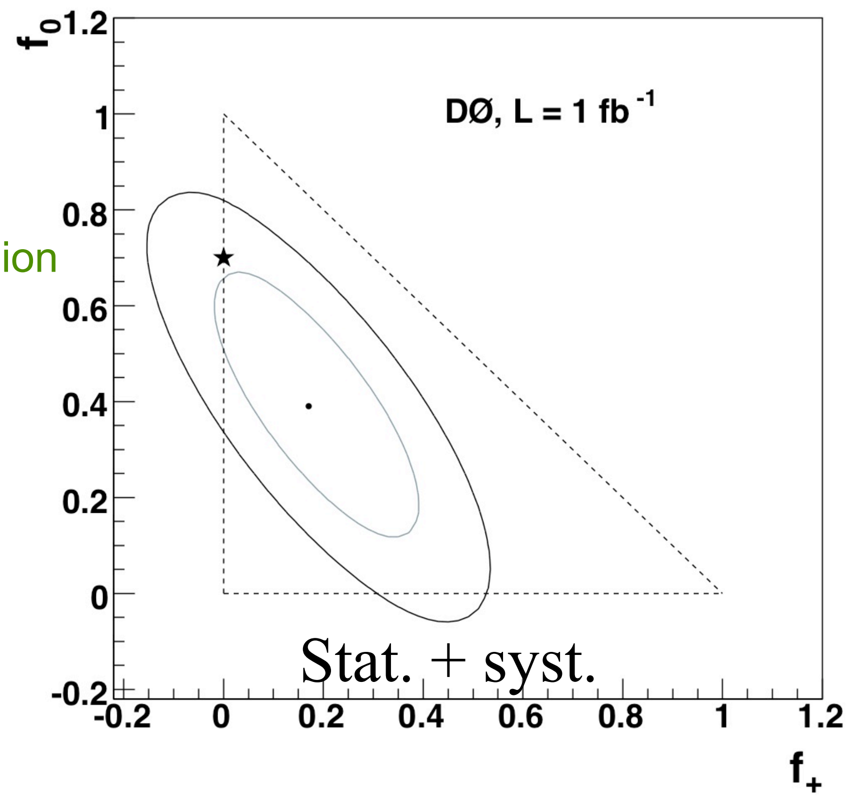
Plots for illustration only

We fit each decay channel separately

Result of fit to data

- 68% and 95% C.L. contours:





$$f_o = 0.390 \pm 0.177 \text{ (stat.) } \pm 0.104 \text{ (syst.)}$$
$$f_+ = 0.171 \pm 0.102 \text{ (stat.) } \pm 0.058 \text{ (syst.)}$$

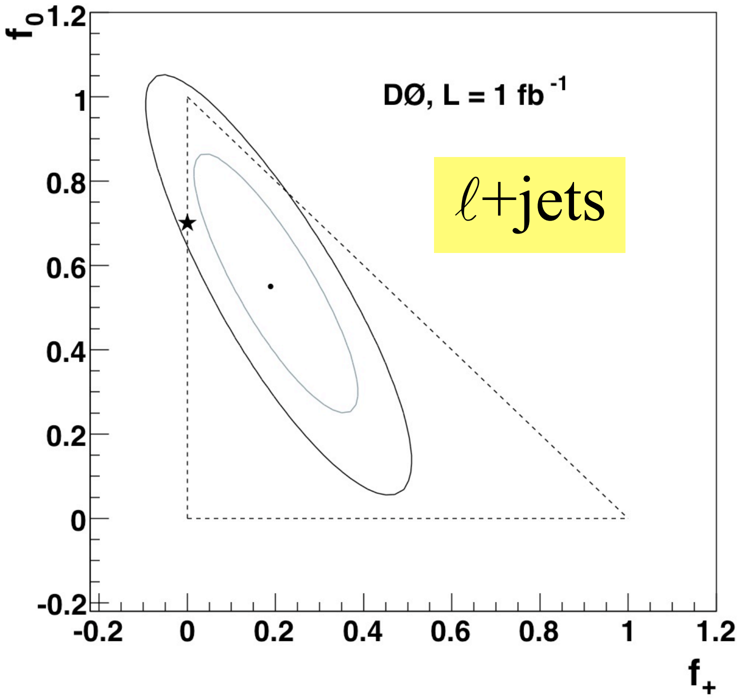
correlation: -0.87

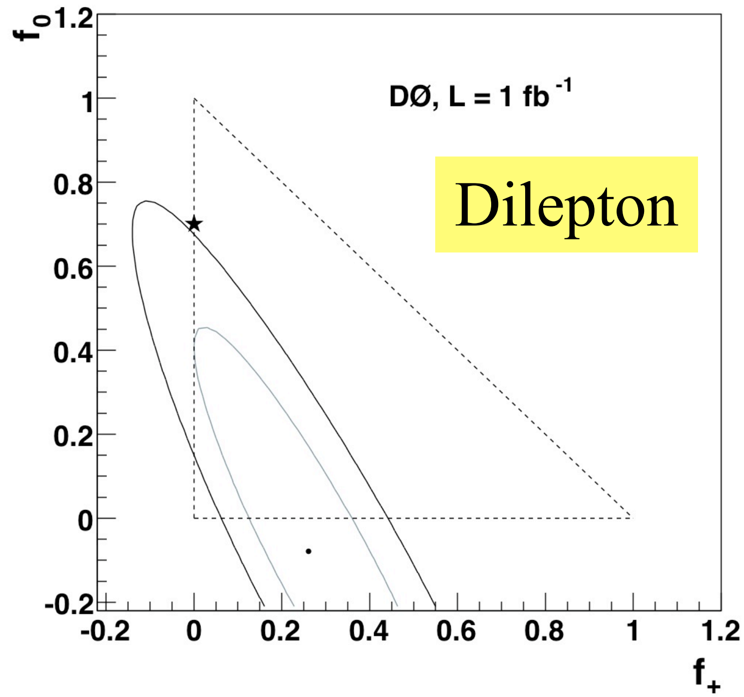
Significance of discrepancy with SM

- Considering statistics only, 21% chance of observing a greater $\Delta\ln L$ for a 2D fit
- Account for systematics by MC smearing of L distribution by δf_+(syst.) and δf_o(syst.)
- After this smearing, 27% chance of observing a greater $\Delta\ln L$ for a 2D fit

SM is alive and well!
…but we're eager to analyze more data

Subchannels





$$f_o = 0.550 \pm 0.205 \text{ (stat.)}$$
$$f_+ = 0.189 \pm 0.124 \text{ (stat.)}$$

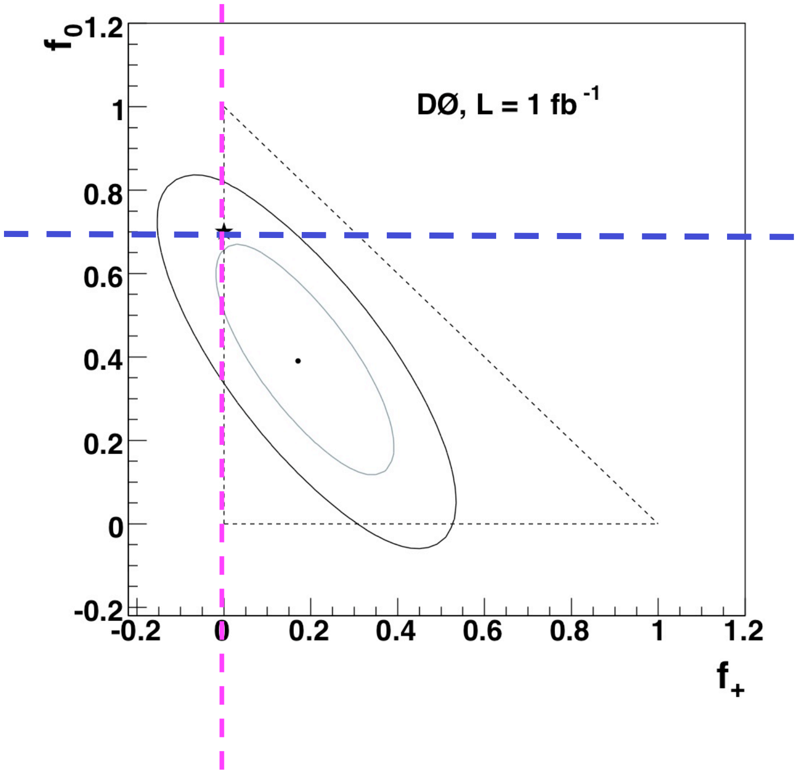
$$f_o = -0.079 \pm 0.357 \text{ (stat.)}$$
$$f_+ = 0.261 \pm 0.193 \text{ (stat.)}$$

- 2.1σ discrepancy (including uncorrelated systematics)

Slices

- Also of interest to look at one helicity fraction at a time
  - with other fixed to SM value

$$f_+ = 0.018 \pm 0.048\ (\text{stat.}) \pm 0.070\ (\text{syst.})$$

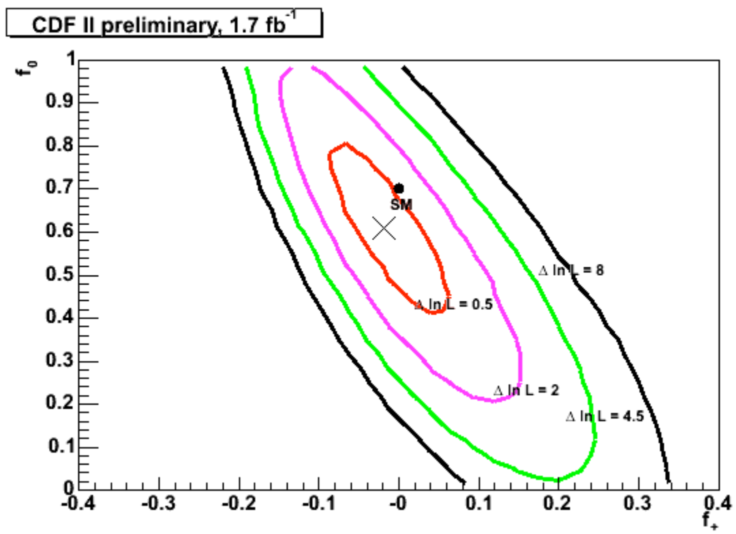


Note that discrepancy with SM is obscured!

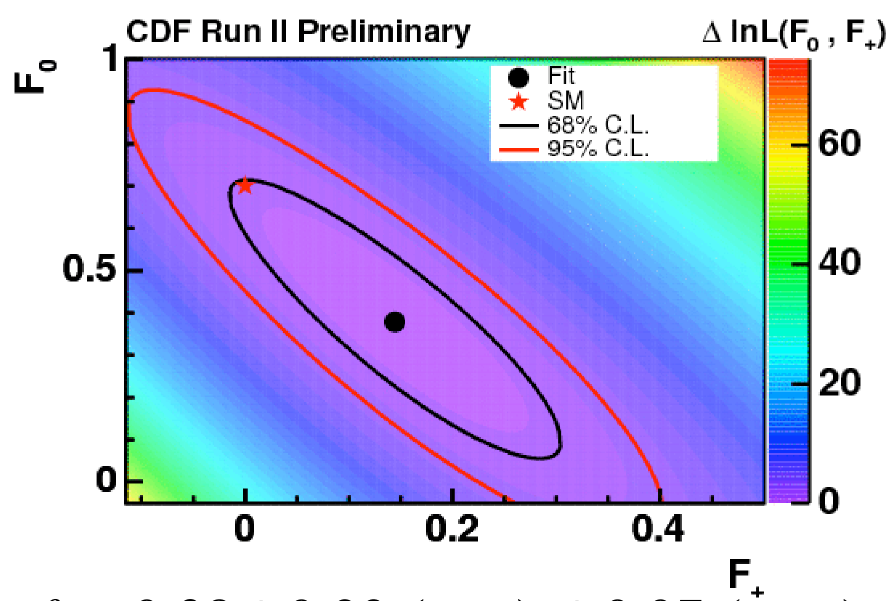
$$f_o = 0.653 \pm 0.086\ (\text{stat.}) \pm 0.047\ (\text{syst.})$$

Results from CDF

- CDF has presented two preliminary model-independent *W* helicity measurements
  - Both used 1.7 fb^{-1}, ℓ+jets channel only (and leptonic *W* decays only)



$$f_o = 0.61 \pm 0.20 \text{ (stat.) } \pm 0.03 \text{ (syst.)}$$
$$f_+ = -0.02 \pm 0.08 \text{ (stat.) } \pm 0.03 \text{ (syst.)}$$



$$f_o = 0.38 \pm 0.22 \text{ (stat.) } \pm 0.07 \text{ (syst.)}$$
$$f_+ = 0.15 \pm 0.10 \text{ (stat.) } \pm 0.04 \text{ (syst.)}$$

Prospects for the future

- Still much room for improvement
  - additional statistics will help!
  - many of the large systematics will scale statistically
  - total error should drop by more than x2
- At LHC, systematics will dominate the measurement
  - probably means lepton p_T will be the measurement variable
  - precision of 1-2% attainable with ~10fb^{-1}

Tevatron combination should be pursued!

Sufficient precision to constrain beyond-SM models

Summary

- A model-independent measurement of the *W* boson helicity yields:

$$f_o = 0.390 \pm 0.177 \text{ (stat.) } \pm 0.104 \text{ (syst.)}$$

$$f_+ = 0.171 \pm 0.102 \text{ (stat.) } \pm 0.058 \text{ (syst.)}$$

- FERMILAB-PUB-07-588-E; submitted to PRL; preprint at arXiv:0711.0032
- Improvements w.r.t. previous measurements:
  - better event selection
  - fitting two helicity fractions simultaneously
  - using hadronic *W* decays

Consistent with SM -- but still plenty of room for new physics to appear in the future

Backup Slides

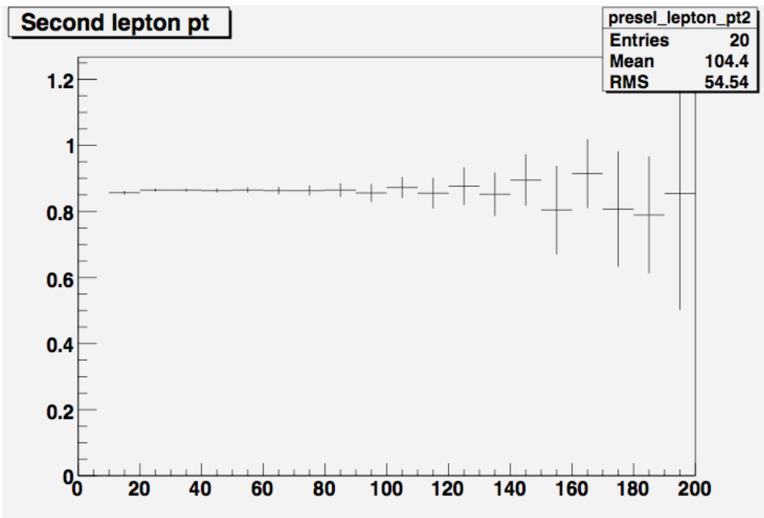
Optimal Selection

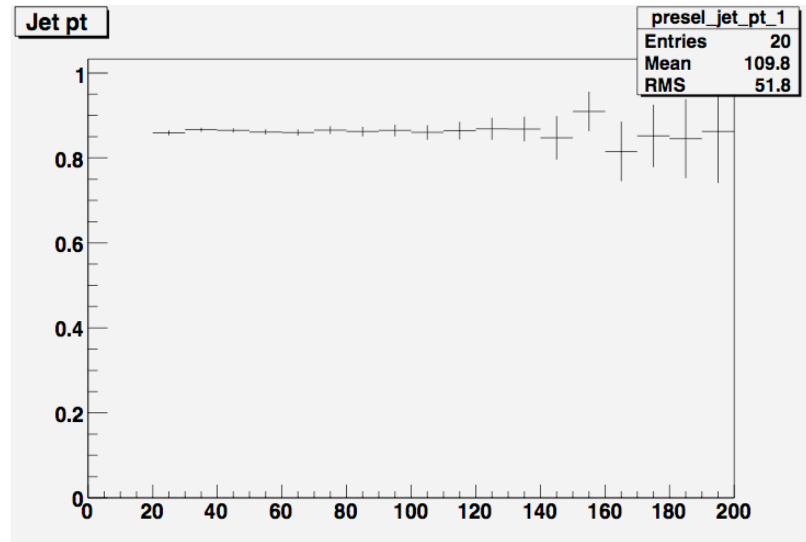
- The best selection found uses:
  - aplanarity, sphericity, ktmin', missing Et, maximum NN *b* value, dilepton mass
- Optimal cut is at 0.986
- Efficiencies and resulting sample (expected):

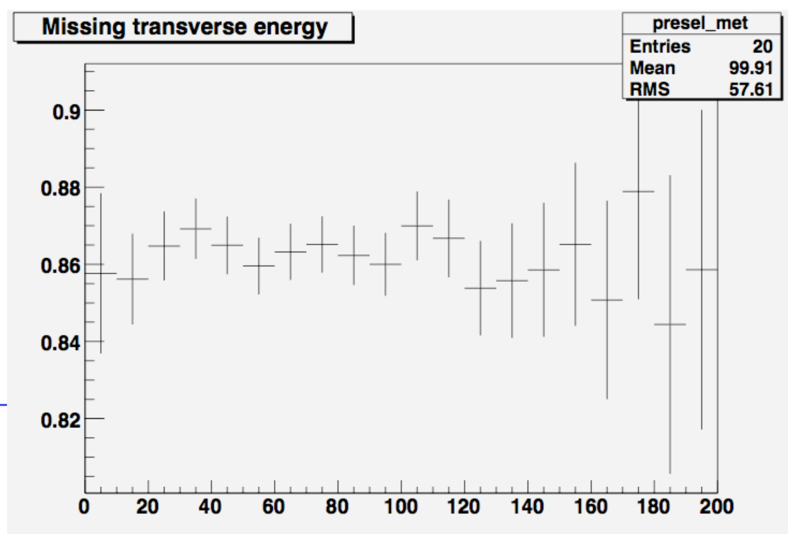
Sample	Eff.	Nevents	Eff (reweighted)	Nevents (reweighted)
ttbar	0.719	14.7		
$Z \rightarrow ee$	8.3 x 10^{-4}	0.98		
$Z \rightarrow \tau\tau$	0.070	0.44		
WW	0.142	0.18		
WZ	0.009	0.06		
ZZ	0.008	0.11		
Fake	0.009	0.35		
Tot. bkg	0.0017	2.11	0.0025	3.0

- 49% more ttbar, 29% less bkg than Moriond xsec selection

- Does removing the trigger requirement mess up the kinematic distributions?
  - take ratio of MC events with/without trigger weights:







N.B. This isn't the whole answer! Also need to look at data for things like odd bumps in jet p_T specta (control plots are in note)

Optimal emu Selection

- Optimal cut is at 0.08
- Efficiencies and resulting sample:

Sample	Eff.	Nevents
ttbar	0.964	38.4
$Z \rightarrow \tau\tau$	0.41	4.8
WW	0.56	1.4
Fake	0.60	2.0
Tot. bkg	0.47	8.2

- 29% more ttbar, 66% more bkg than Moriond xsec selection

Optimal Selection

- The best selection found uses:
  - aplanarity, sphericity, h, min. dijet mass, Z fit chisq, maximum NN *b* value, dilepton mass
- Optimal cut is at 0.990
- Efficiencies and resulting sample (expected):

Sample	Eff.	Nevents	Eff (reweighted)	Nevents (reweighted)
ttbar	0.47	9.9		
$Z \rightarrow \mu\mu$	1.9×10^{-3}	2.53		
$Z \rightarrow \tau\tau$	0.052	0.42		
WW	0.029	0.057		
WZ	2.9×10^{-3}	0.030		
ZZ	8.2×10^{-3}	0.16		
Fake	0.079	0.61		
Tot. bkg	0.0028	3.81	0.0031	4.22

- 71% more ttbar, 7% more bkg than Moriond xsec selection

Forming the cosθ* templates

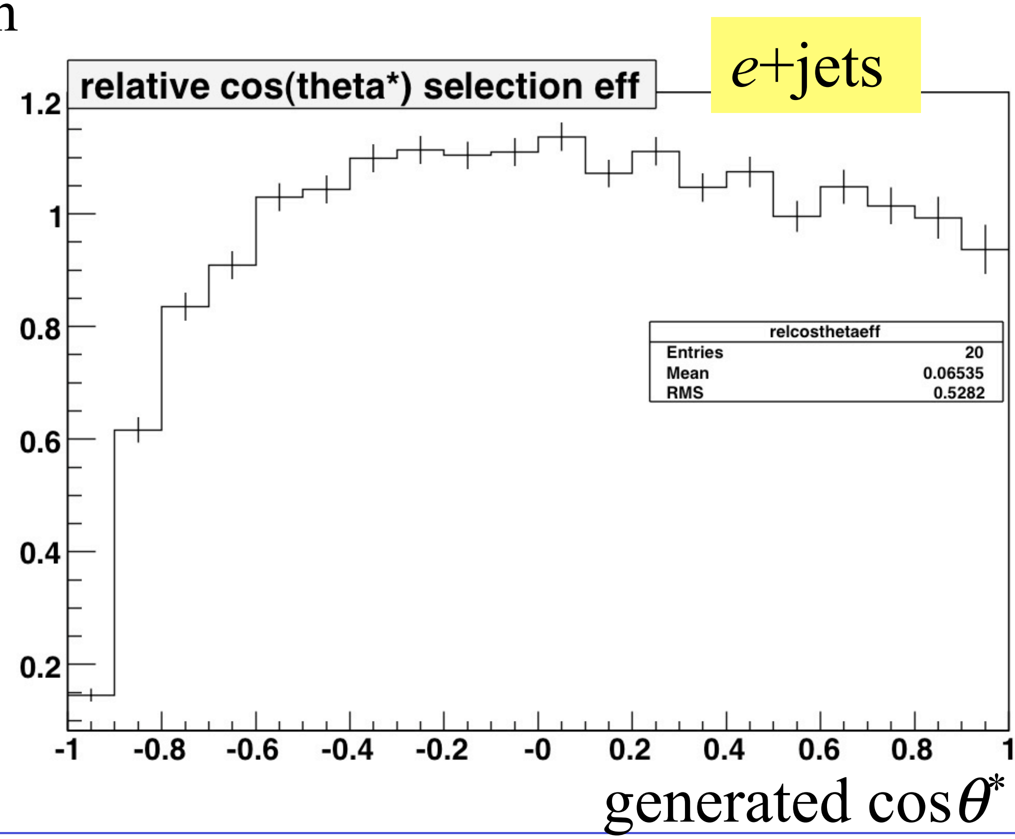
- Want templates corresponding to a given *W* helicity state
- But Alpgen doesn't give us that…
  - so, we form templates from the *V*-*A* and *V*+*A* samples
- Reweight Alpgen events based on:

1. Selection efficiency as a function of generated cosθ^*
2. Distribution of reconstructed cosθ^* for each value of generated cosθ^*

With these inputs, we can construct template of reconstructed cosθ^* for any generated distribution

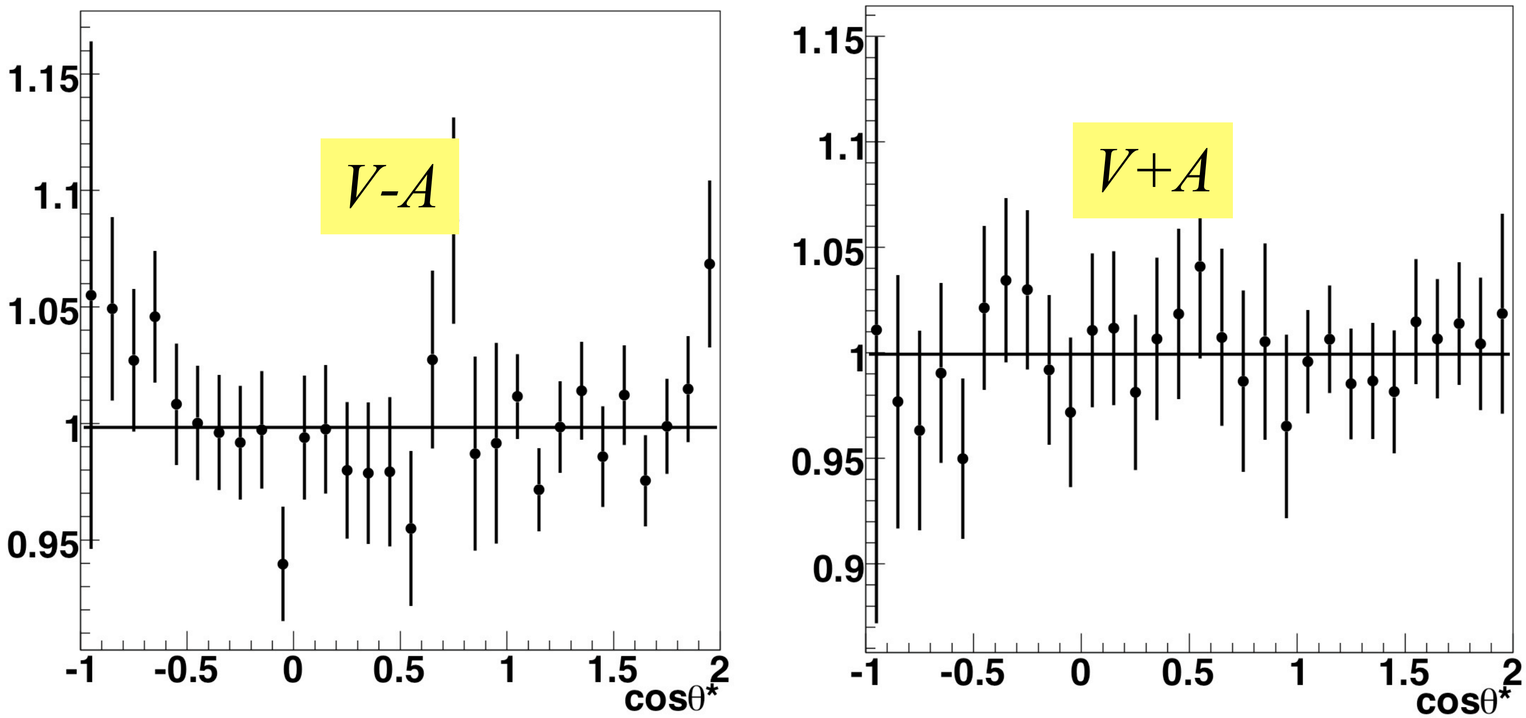
Relative Selection Efficiency

- Biggest "shaping factor" is lepton pt cut, which disfavors small $\cos\theta^*$
  - since that means that lepton is emitted opposite W boson momentum



Cross-check of templates

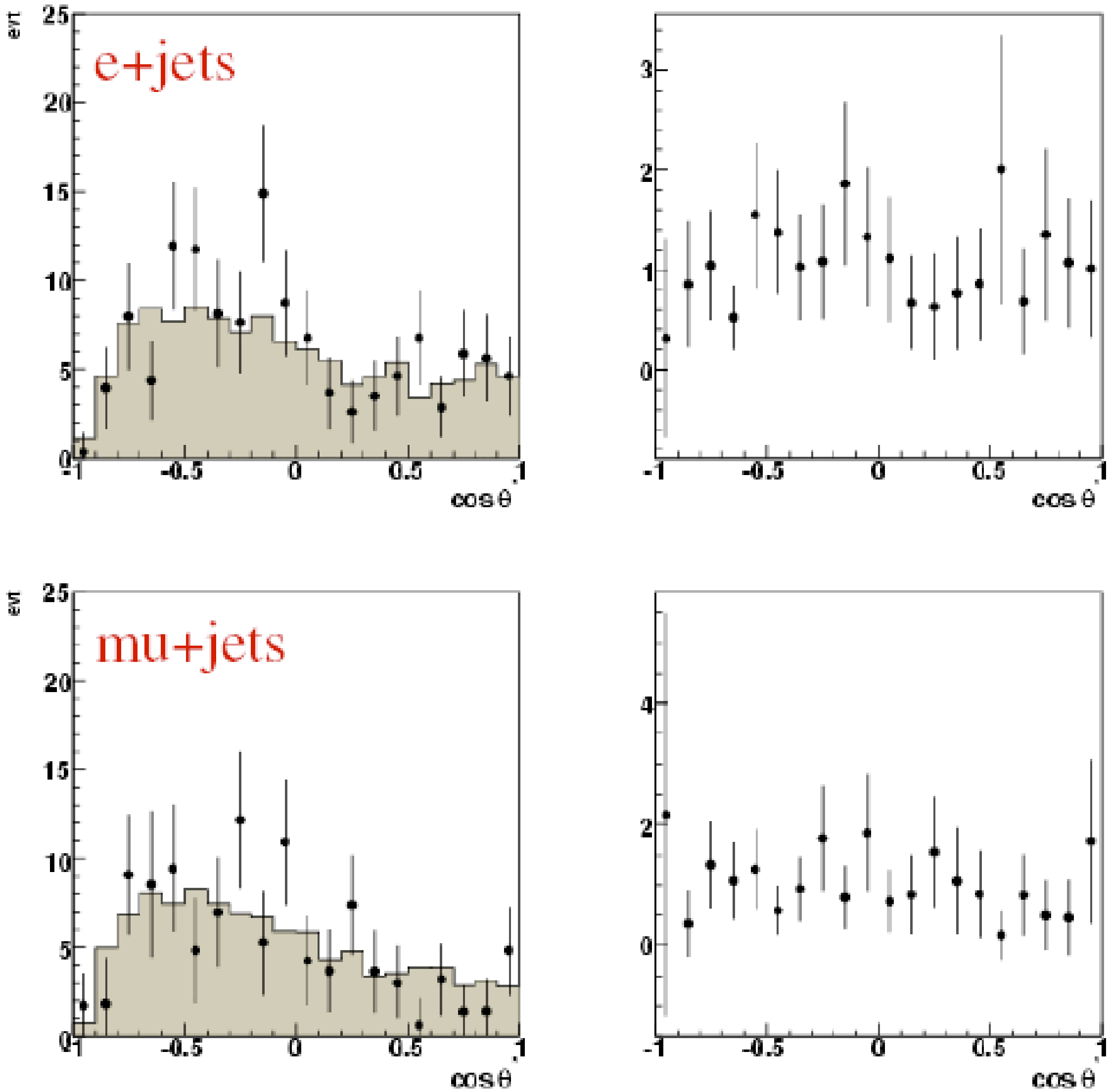
- Combine pure *W* helicity state templates in ratio expected for *V-A* and *V+A* couplings, and compare to *V-A* and *V+A* directly from MC
  - plots show ratio of combined pure helicity templates over direct from MC:



Background Model Uncertainty

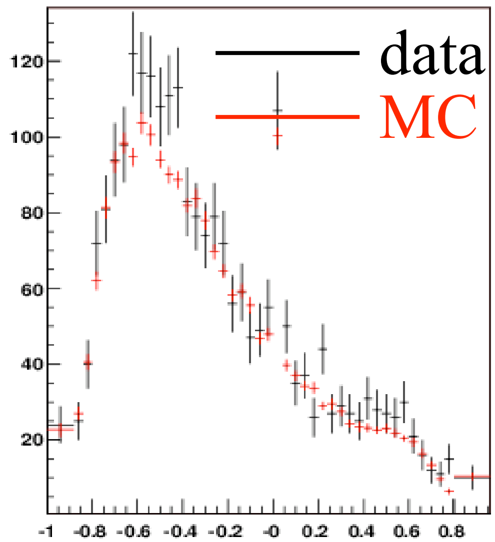
- Strategy:
  - select events with low L_t values (low enough that ttbar contribution is negligible)
  - compare data and MC $\cos(\theta^*)$ distributions
  - form alternate background model by reweighting events by data/MC ratio
  - propagate to systematic error via ensemble tests
  - Exception: not enough bkg statistics to do this for $e\mu$
    - take the "worst case" from ee, $\mu\mu$

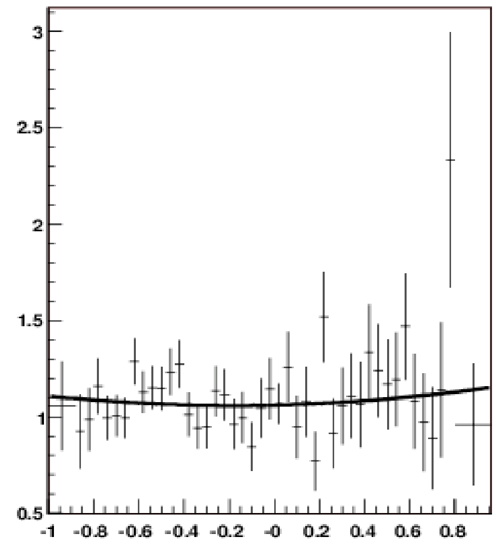
Background Model (l+jets)



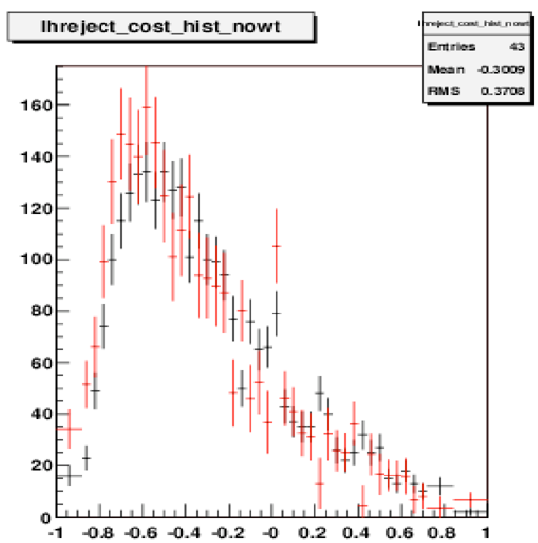
Background Model (dilepton)

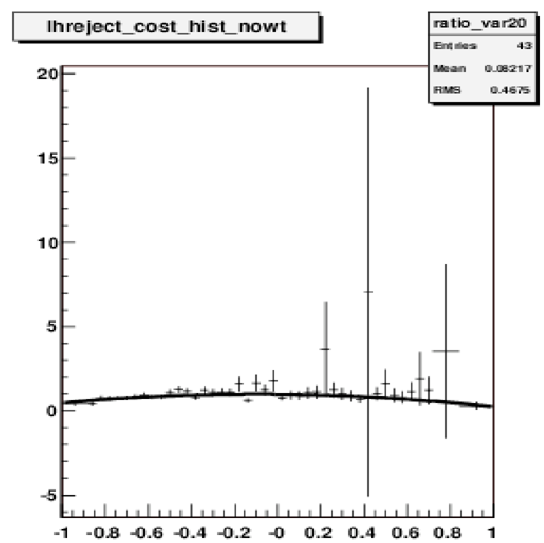
ee





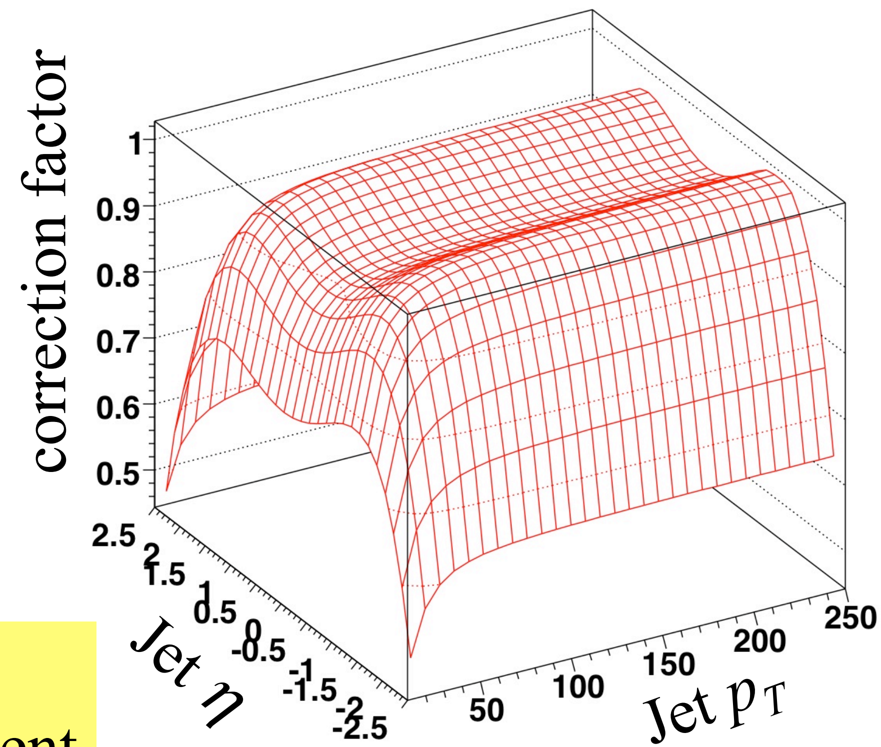
μμ





Systematic from NN_b

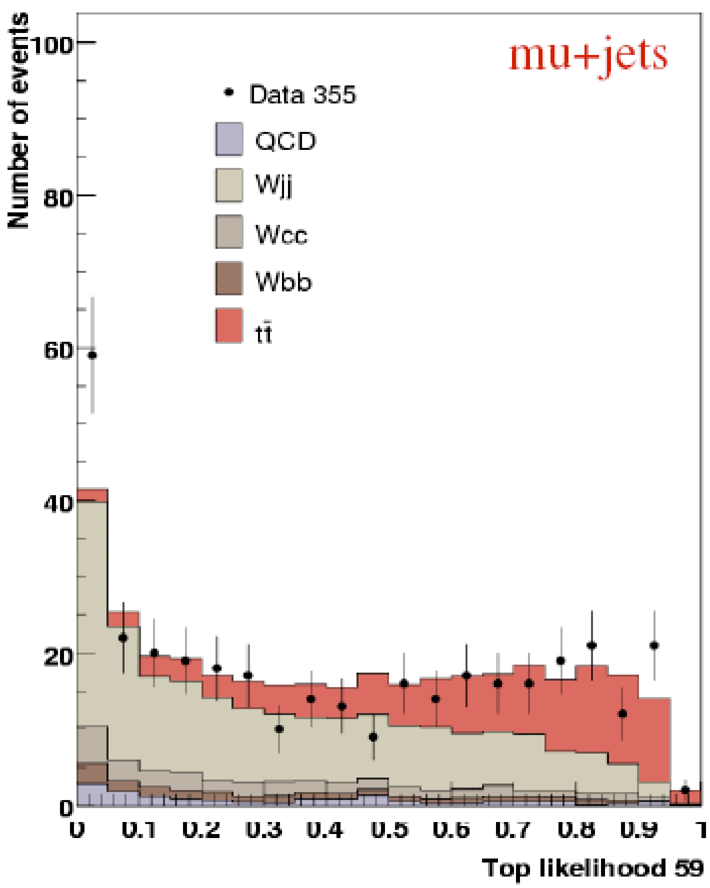
- DØ declares a jet to be "taggable" if it contains at least two tracks
  - with at least one silicon hit on each
- We measure the taggability rate in data and MC
- Correct for differences by declaring a fraction of the taggable MC jets untaggable
  - means setting NN_b to 0

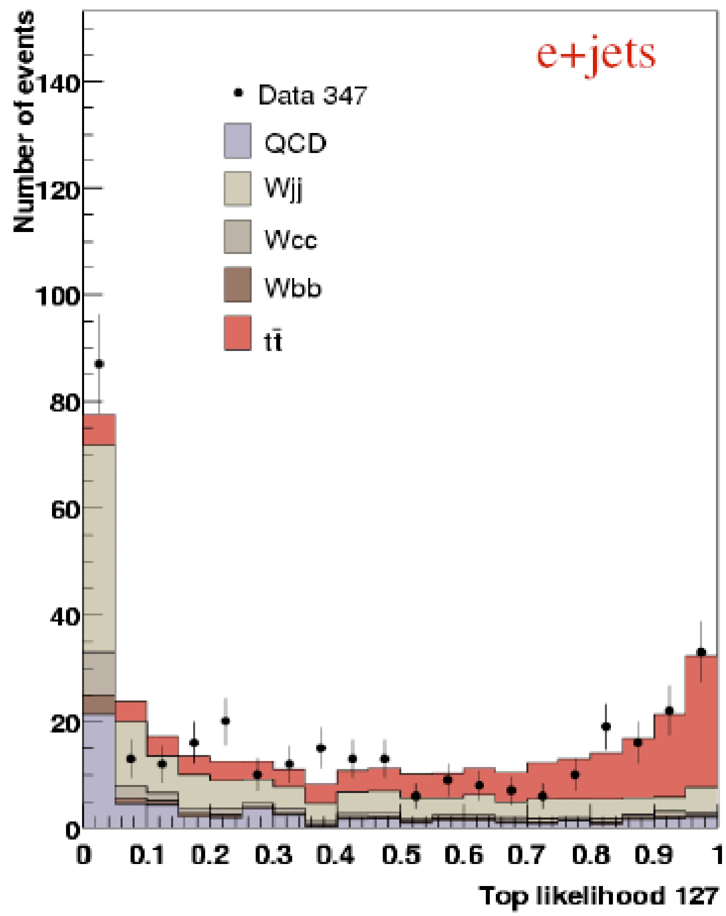


This accounts for one source of data/MC disagreement

Systematic from NN_b

- First, calculate D without NN_b included:

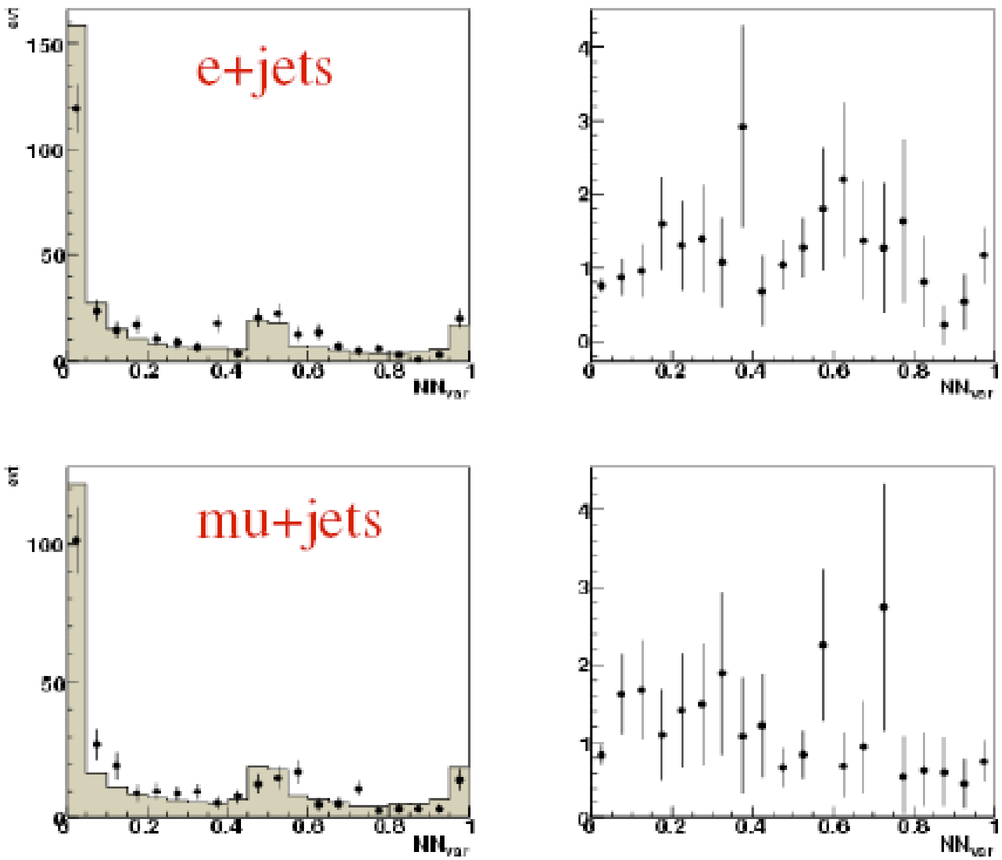




- Refit data to determine signal and background levels

Systematic from NN_b

- Use signal/background levels from fit to unbiased D to compare NN_b variable in data to MC:

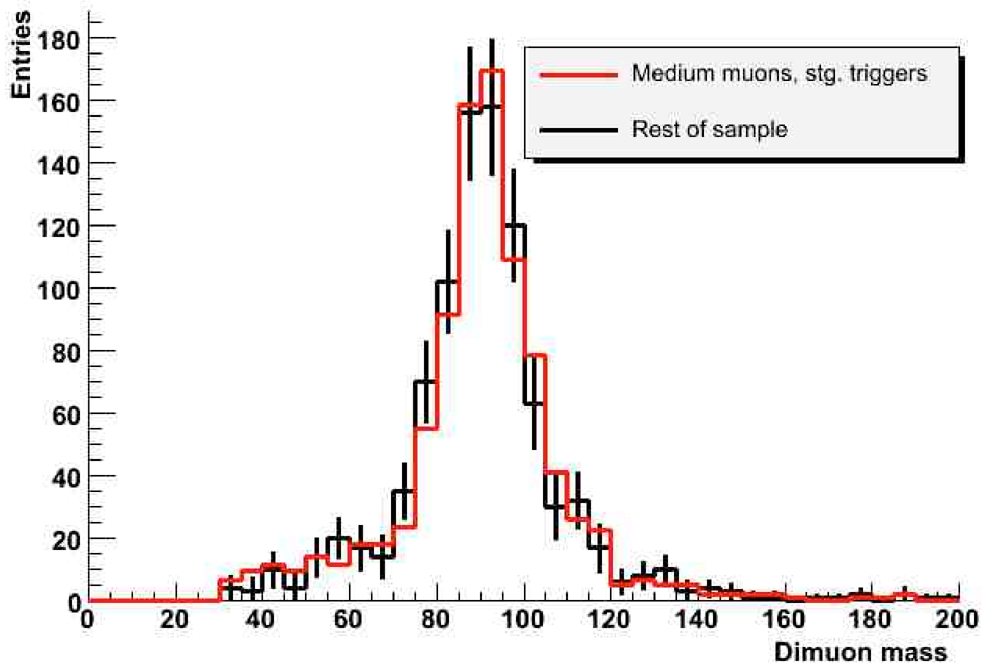


- Reweight MC events by data/MC ratio
- Re-evaluate eff. for background to pass standard D cut
- propagate difference to systematic with ensemble tests

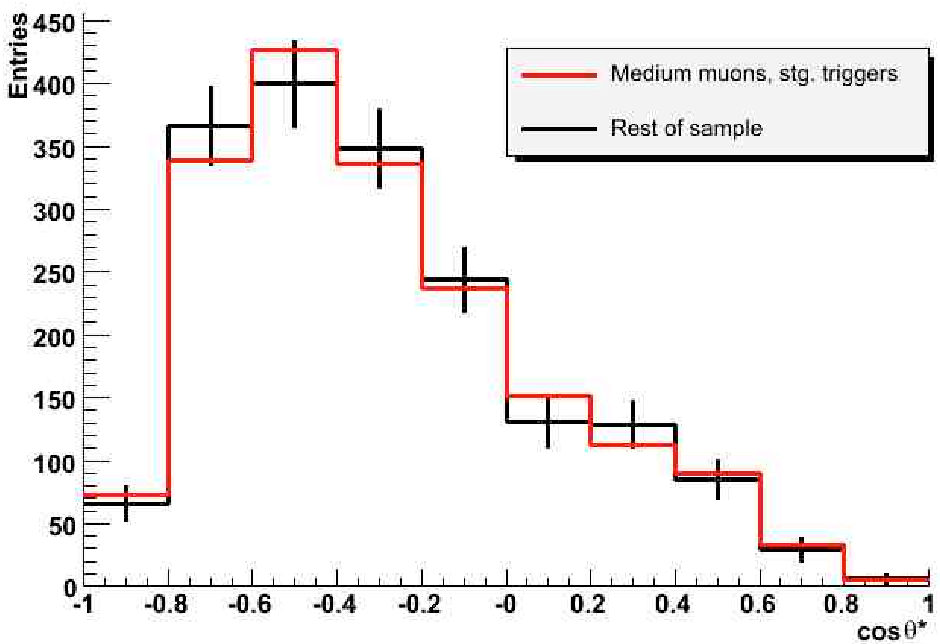
Loosened Cuts

- Cuts were loosened from the Winter '07 cross section preselection in the following ways:
  - change requirement on local muons from medium Nseg = 3 to loose
    - regain bottom hole
    - isolation criteria unchanged
  - reduce electron lhood8 cut from 0.85 to 0.20
  - remove trigger requirement in eμ and μμ channels

- Does the combination of looser muon ID and no trigger requirement let in a lot of junk?
  - No indication of that:



- Is the $\cos\theta^*$ distribution altered by the trigger and/or lepton ID requirements?
- No evidence of that, either:



Final dilepton selection

1. Use "l+jets" style multivariate likelihood to separate signal from background
2. All combinations of variables, and all cuts on the resulting likelihoods, are considered in choosing the optimal selection
   - in *ee* and μμ "alternate" MC sample created by reweighting events according to data/MC differences in variables used in L_t
   - figure of merit to optimize:

$$FOM = \frac{N_{sig}}{\sqrt{\sigma^2_{sig,stat} + \sigma^2_{bkg,stat} + \sigma^2_{bkg,syst}}} = \frac{N_{sig}}{\sqrt{N_{sig} + N_{bkg} + \sigma^2_{bkg,syst}}}$$

   - to protect against fluctuations, half the MC sample is used for optimizing, and the other half for calculating efficiency

Final Data Sample

	e+jets	μ+jets	$e\mu$	ee	$\mu\mu$
Variables used in D	$C, S, A, H_T, h, k'_{T\min}, NN_b$	$C, S, H_T, k_{T\min}, NN_b$	$C, S, H_T, h, m_{jj}, k_{T\min}, NN_b$	$A, S, h, E_T k_{T\min}, NN_b, m_{\ell\ell}$	
Purity in preselected sample	0.38	0.44	0.67	0.014	0.024
Cut on D	0.80	0.40	0.08	0.986	0.990
Background after cut	21.1 ± 4.5	33.0 ± 5.2	9.9 ± 2.5	2.2 ± 0.9	4.8 ± 3.4
Data after cut	121	167	45	15	15

So we have a high-purity top quark sample--
now the fun part can begin!