Helicity of the *W* Boson in Single-Lepton *ttbar* Events

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Users' Meeting

Overview

- Top Quark Properties + Helicity of the ***W*** Boson in Top Events
- Event topology and selections
- A new approach for measuring top quark properties
- Monte Carlo tests of the new approach
- F_0 measurement using Run I data: Final Result
- Conclusions

Top Quark Properties

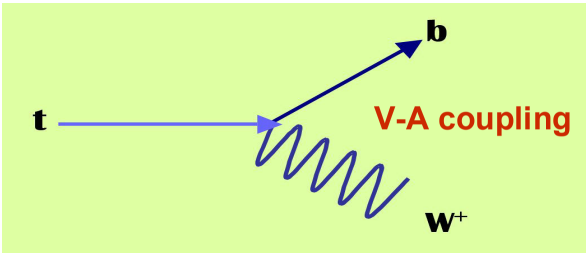
- **Top is very massive** => 40 times heavier than the next quark (***b***), making it the only fermion that decays to a real ***W***. It probes physics at a much higher energy scale than other fermions.

M_{top} **Experiment (Run I TeVatron)** = 178.0 ± 4.3 GeV

- **Top decays before hadronizing** => spin information is passed to its decay products. In contrast to lighter quarks, it is essentially free of complications associated with the strong interaction, and it is the only quark that does not form hadrons.

$\tau_{top} \sim 4 \times 10^{-25}$ sec

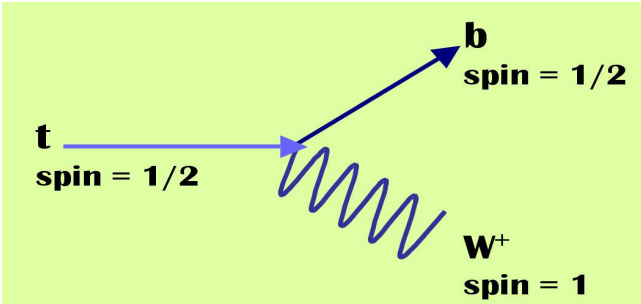
- **Within the Standard Model** => BR(***t***⇒***Wb***) @ 100%



- Are there **new interactions** at this high energy scale?

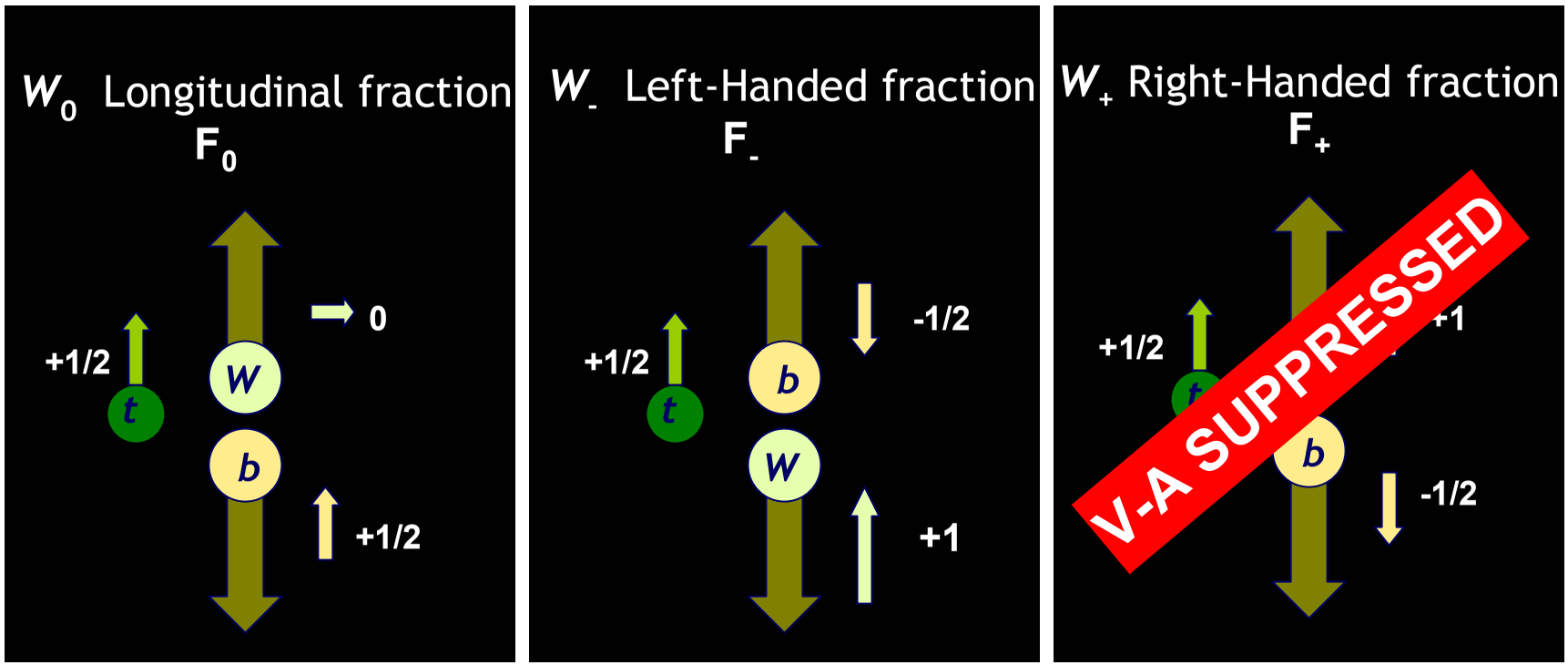
- Measuring the helicity of the ***W*** boson examines the nature of the ***tbW*** *vertex,* and provides a stringent test of Standard Model.

Helicity of the *W* Boson in $t\bar{t}$ Events



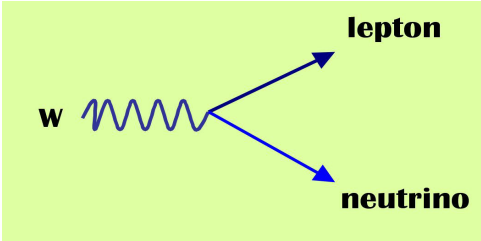
This analysis concentrates on the measurement of longitudinal *W* fraction F_0

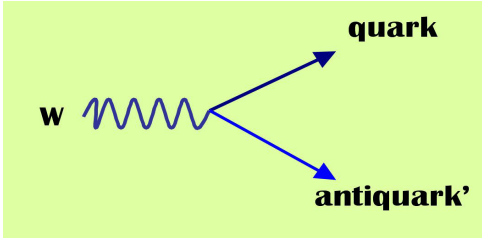
Therefore we have 3 possibilities:



Angular Distributions of Top Decay Products

- The decay products of the ***W*** contain information about the helicity of the ***W***, and therefore the ***tbW*** vertex





- The angular decay (or momentum distribution) of the decay products depends on the ***W*** helicity. This information is in the Matrix Element (**ME**):

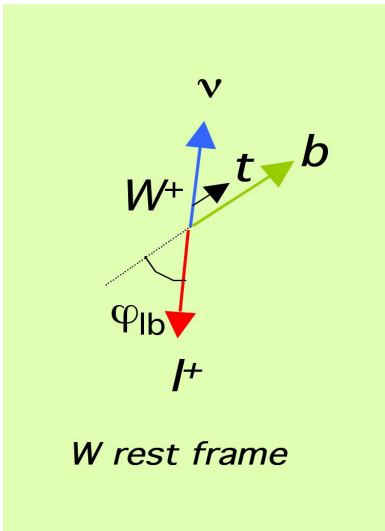
$$w(\cos\varphi_{l\bar{b}}) = F_- \cdot \frac{3}{8}(1-\cos\varphi_{l\bar{b}})^2 + F_0 \cdot \frac{3}{8}(1-\cos^2\varphi_{l\bar{b}}) + F_+ \cdot \frac{3}{8}(1+\cos\varphi_{l\bar{b}})^2$$

- In the Standard Model (with M_b=0),

$$F_- = \frac{2(M_W^2/M_t^2)}{1+2(M_W^2/M_t^2)} \qquad F_0 = \frac{1}{1+2(M_W^2/M_t^2)} \qquad F_+ \approx 0$$

and with M_{top} =175 GeV and M_W=80.4 GeV

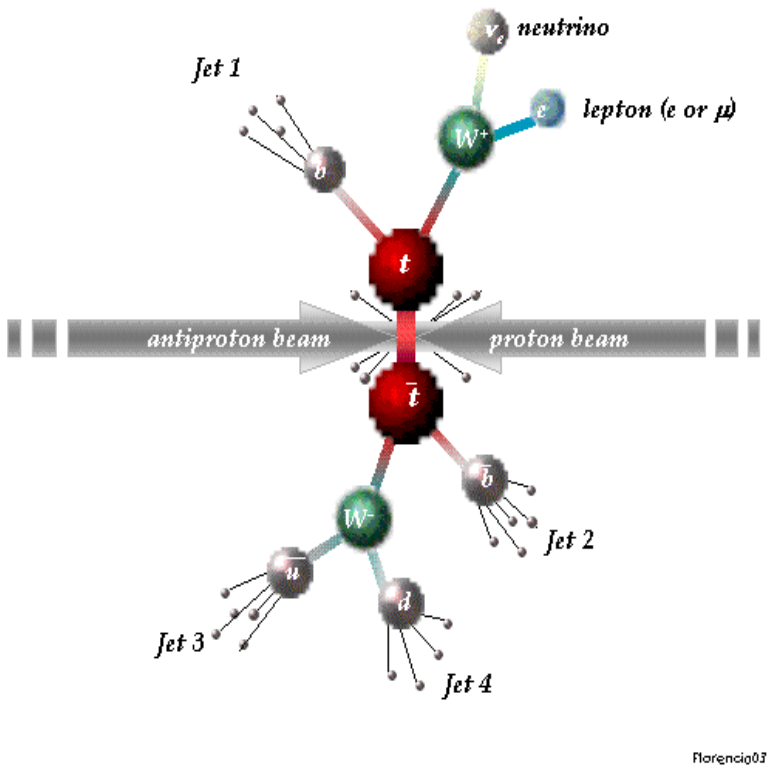
$$F_- \approx 0.3,\ F_0 \approx 0.7,\ F_+ \approx 0$$



Event Topology

- DØ Statistics Run I (125 pb^{-1} or ~500 ***ttbar*** events)
- In ppbar collisions @ $\sqrt{s}$ =1.8TeV top quarks are primarily **produced in pairs**
- **90% $q\bar{q}$->$t\bar{t}$, 10% gg->$t\bar{t}$**
- There are 3 main signatures that depend on the how the 2 ***W*** bosons decay:
  - Dilepton,
  - All-hadronic, and
  - **Lepton +Jets** topologies.

Single-Lepton $t\bar{t}$ Channel



- This analysis is based on the lepton+jets decay:
  - BR(***e***+jets,μ+jets) ~ 30%
  - many final particles
  - 12 permutations among jets

- We use both of the ***W*** bosons in each event to extract F_0

Lepton+Jets Selection

- **Lepton+Jets**
  - **Signal:** 1 high-P_T lepton, 4 jets, large missing-E_T
  - **Background:** ***W*** with associated production of jets and multijet production

- **Standard Selection:**
  - **Lepton:** E_T>20GeV, $|\eta^e|<2$, $|\eta^\mu|<1.7$
  - **Jets:** ≥4, E_T>15 GeV, $|\eta|<2$
  - **Missing-E_T** > 20 GeV
  - "E_T^W"> 60 GeV ; $|\eta_W|<2$

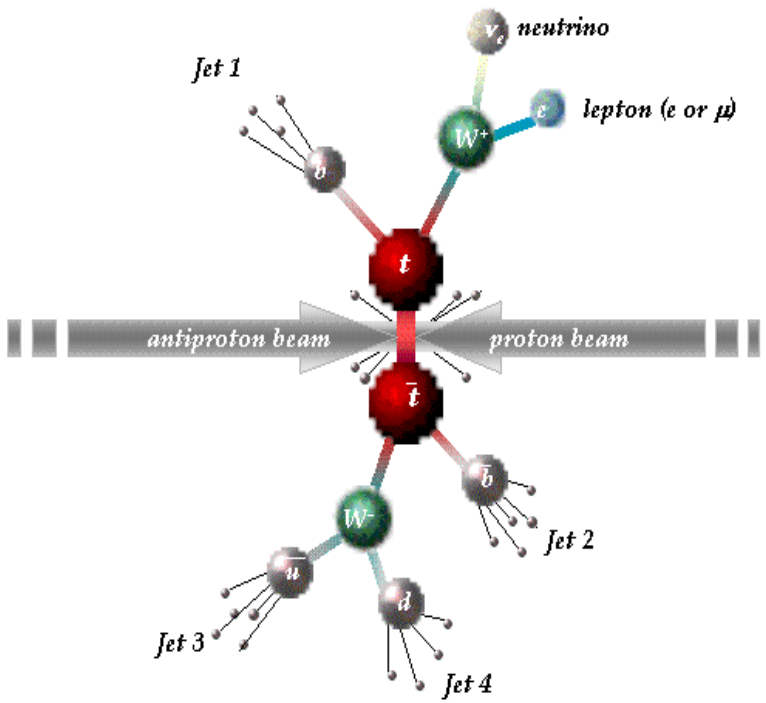
  91 events ***Ref. PRD 58 (1998), 052001***

- **Additional cuts for this analysis:**
  - 4 Jets only (Leading Order Matrix Element

    71 events
  - Background probability (to improve purity)

    22 events => 12 signal + 10 background

Single-Lepton $t\bar{t}$ Channel



In general …

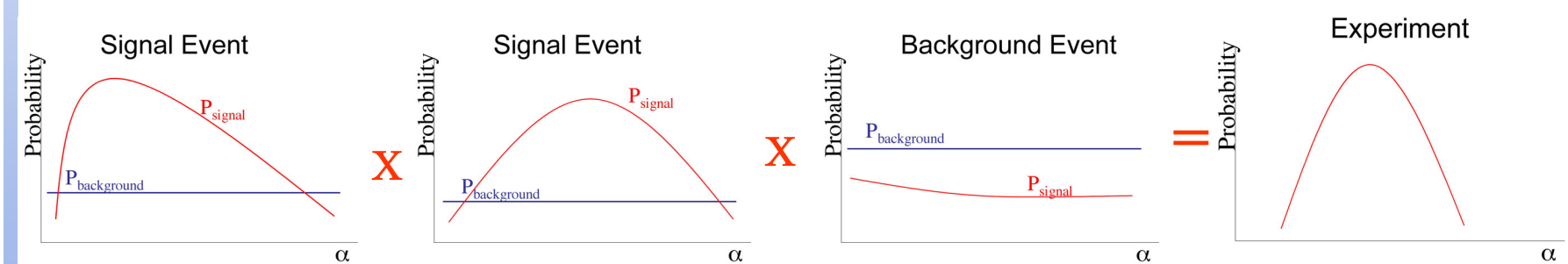
- …the best estimate of a **parameter (α)** is achieved by comparing the events in data with a probability from theory through maximizing a likelihood:

$$L(\alpha) = e^{-N\int \bar{p}(x;\alpha)\,dx} \prod_{i=1}^{N} \bar{P}(x_i;\alpha)$$

where ***x*** is a set of measured variables.

$$\bar{P}(x;c_1,c_2,\alpha) = c_1 P_{signal}(x;\alpha) + c_2 P_{background}(x)$$

- For example:



A new approach

- How can we calculate P_{signal} and $P_{background}$?
  - The standard model predicts these probabilities (**differential cross sections**) in terms of the parton-level quantities (four-vectors of all partons involved), *but we do not have access to parton-level quantities for events in our data sample, only to final jets, etc.*
  - We therefore integrate over everything we don't know. That is, sum over all the possible parton variables ***y*** that lead to the observed set of variables ***x***

dσ is the differential cross section

W(y,x) is the probability that a parton-level set of variables ***y*** will be measured as a set of observed variables ***x***

$$\bar{P}(x;\alpha) = \frac{1}{\sigma}\int d^n\sigma(y;\alpha)\underline{dq_1 dq_2 f(q_1) f(q_2)}W(x,y)$$

f(q) is the probability distribution than a parton will have a momentum fraction ***q***

- How can we take **detector effects** into account ?

$$\bar{P}_{measured}(x;\alpha) = Acc(x)\bar{P}_{production}(x;\alpha)$$

where ***Acc(x)*** include all conditions for accepting or rejecting an event

Transfer Functions

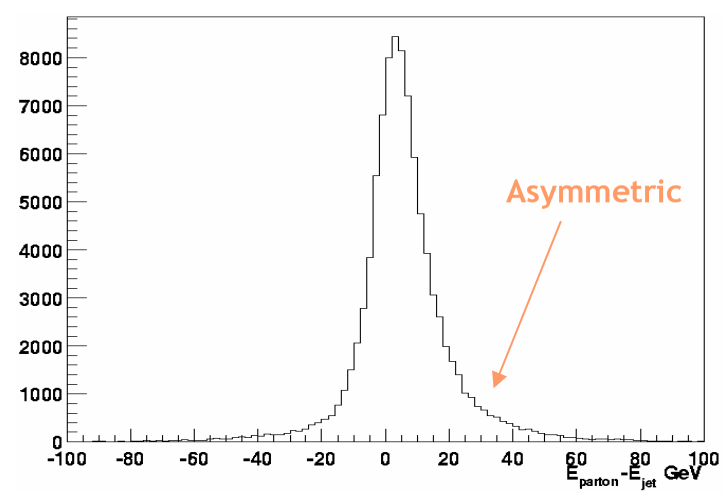
- ***W(x,y)*** probability of measuring ***x*** when ***y*** was produced (***x*** =jet, ***y*** =parton):

Energy of **electrons** is considered well measured

$$W(x,y) = \delta^3(p_e^y - p_e^x)\prod_{j=1}^{4} W_{jet}(E_j^y, E_j^x)\prod_{i=1}^{4}\delta^2(\Omega_i^y - \Omega_i^x)$$

And due to the excellent granularity of the DØ calorimeter, **all angles** are also considered well measured

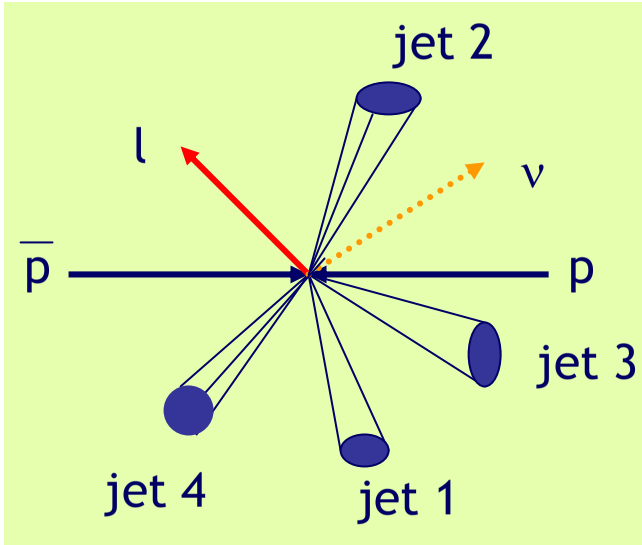
- ***W_{jet}(x,y)*** models the smearing in jet energies from effects of radiation, hadronization, measurement resolution, and jet reconstruction algorithm -- obtained from Monte Carlo studies
  - Correcting on average, and considering these distributions to be Gaussian, can underestimate the jet energy
  - Use 2 Gaussians, one to account for the peak and the other to fit the asymmetric tails
  - *b* and light quarks parameterizations



- Events with muons are integrated over their resolution

Probability that an event is signal

- 2(*in*) + 18(*final*) = **20 degrees of freedom**
- 3(**e**)+8(Ω1..Ω4)+3(P_{in}=P_{final})+1(E_{in}=E_{final}) = **15 constraints**
- 20 – 15 = **5 integrals** => we choose $\mathbf{M_{top}}$, $\mathbf{m_W}$ and jet energy of one of the jets from the ***W***, because $|M_{t\bar{t}}(\alpha)|^2$ is almost negligible, except near the peaks of the four Breit-Wigners within $|M_{t\bar{t}}(\alpha)|^2$



Sum over 12 combinations and all neutrino solutions

Top masses in the event

PDFs (CTEQ4)

Jet transfer functions

$$P_{t\bar{t}}(x,\alpha) = \frac{1}{12\sigma_{t\bar{t}}} \int d\rho_1 dm_1^2 dM_1^2 dm_2^2 dM_2^2 \sum_{comb,\nu} |M_{t\bar{t}}(\alpha)|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} \phi_6 W_{jet}(x,y)$$

Momentum of one of the W jets

W masses in the event

LO matrix element

Six-particle phase space

Probability that an event is background

- The background probability is defined **only** in terms of the main background (***W***+jets, 80%), which also proves to be an adequate representation of multijet background.

- The background probability for each event is calculated using ***W*+jets subroutines in VECBOS.**

- For each event:
  - Obtain a probability density from observed jet energies and transfer function. Same **transfer functions** for modeling the jet resolutions in ***W***+jets as for ttbar signal. **M** points selected randomly in ***W***+4jets multidimensional space:

$$P_{W+jets}(x) = \frac{1}{M} \sum_{k=1..M} P_{VECBOS}(y_k)$$

    - All permutations are considered.
    - All possible values of the **z component of the momentum of the neutrino**, constrained by the ***W*** mass.
    - ***W*** mass resolution is considered in integrating over the invariant ***W*** mass of the event.

  - We increase **M** until we get convergence.

Advantages of this Method

- Historically, **DØ** had large amount of background, no b-tagging, and poor statistics.
  - Need more events for angular distributions than for mass!

- The previously published measurement from CDF has an uncertainty of 0.39, which is larger than having no measurement at all (for parameter between 0 and 1).

Our approach:

- **Maximal use of statistical power => all variables are taken into account, a probability per event as a function of F_0, with well-measured events contributing sharper values of parameter, and all combinations of jets contribute to measurement.**

- **Maximal discrimination relative to background (using all the information).**

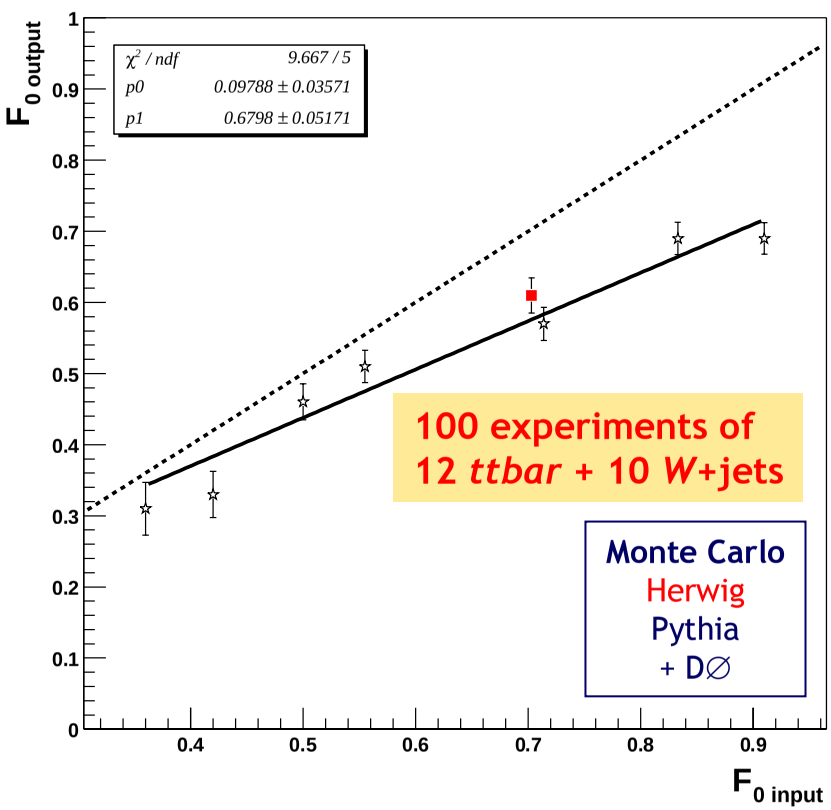
- **Physical boundaries are taken into account in a natural way.**

- **Both decay modes of *W* contribute to the measurement.**

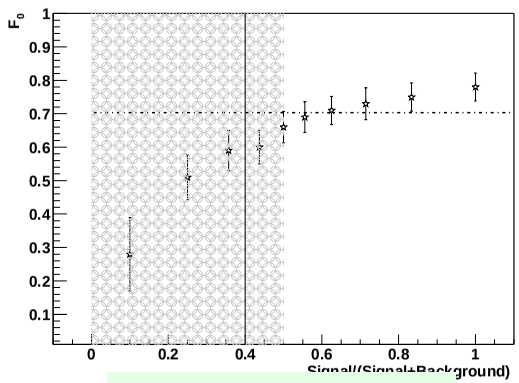
Despite that this is a harder analysis, it provides an unbiased and excellent way of extracting parameters in data.

Monte Carlo Tests

- Using different input values of $\mathbf{F_0}$, pseudo-experiments (ensembles) are used to determine output values of $\mathbf{F_0}$
- A response correction needs to be applied to the data



- Output F_0 is biased towards smaller values, as more background is introduced
- There is no bias at the parton-level for *ttbar* and ***W***+jets Monte Carlo events
  - Effect may originate from gluon radiation

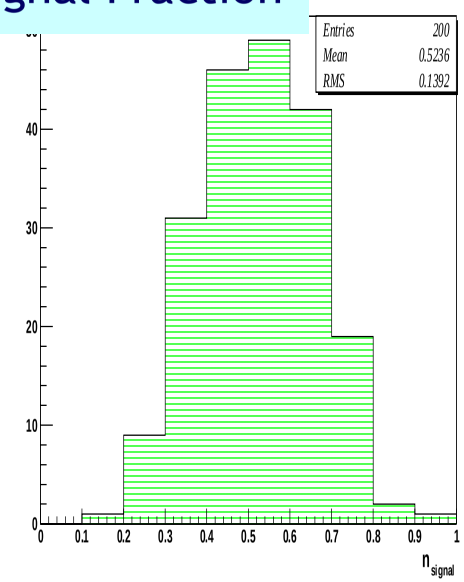


Full MC Simulation

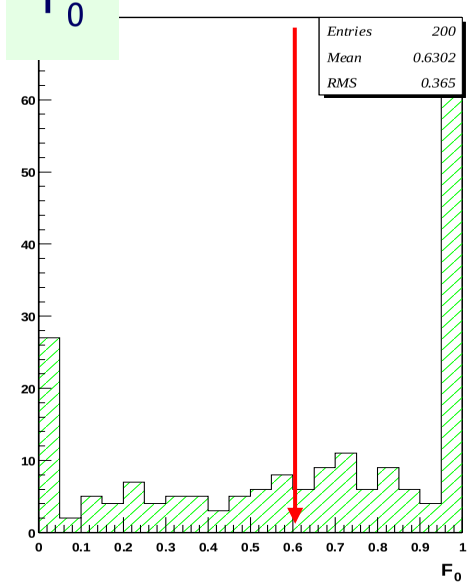
Ensemble

- 200 experiments of 12 $t\bar{t}$ (F_0=0.7) and 10 ***W***+jets events
- Distributions show most probable F_0, uncertainty in F_0, and number of signal events
- **Arrows show results from Run I data**
- Input F_0 is within 68.27% interval of the likelihood in 67% of the experiments
  - Reasonable definition for the uncertainty on F_0

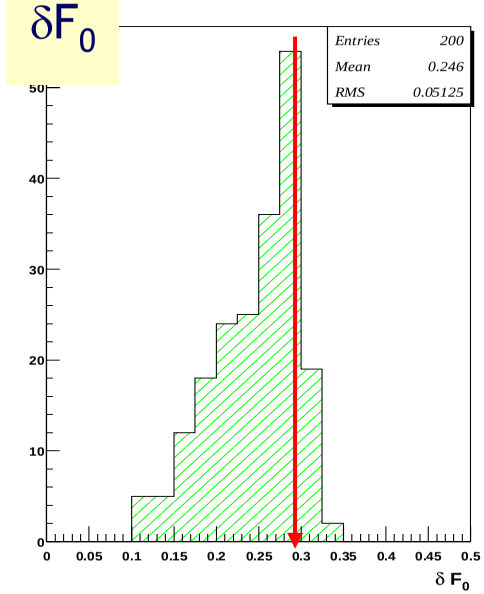
Signal Fraction



F_0



δF_0

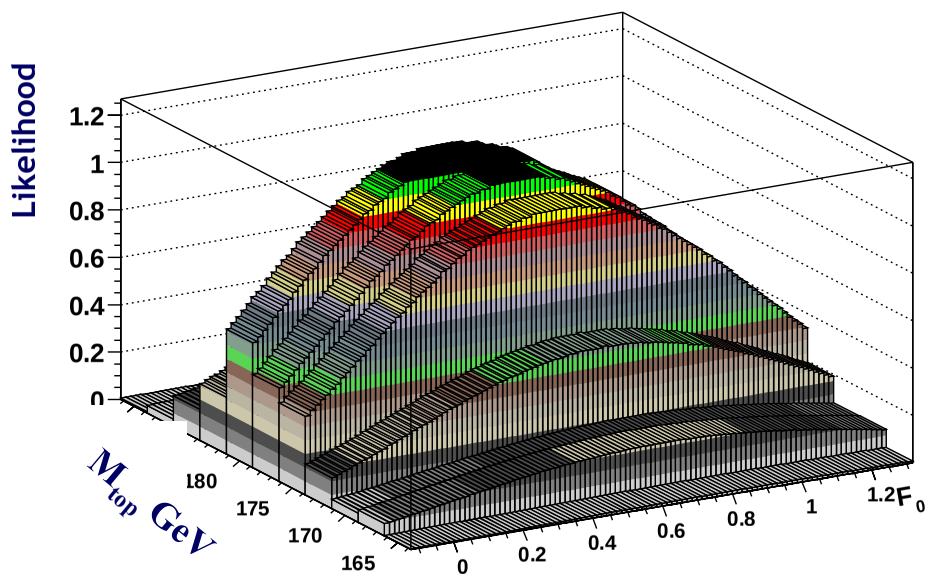


Results - Statistical Errors

- Assuming F_0= 0.7 (**SM**), **M_{top} is measured** to be 180.1 ± 3.6 GeV
- Assuming M_{top}=175 GeV, **F_0 is measured** to be 0.599 ± 0.302 (response correction applied)
- Uncertainty on the top mass translates into a systematic error on the measurement of F_0
- Integrate over M_{top}

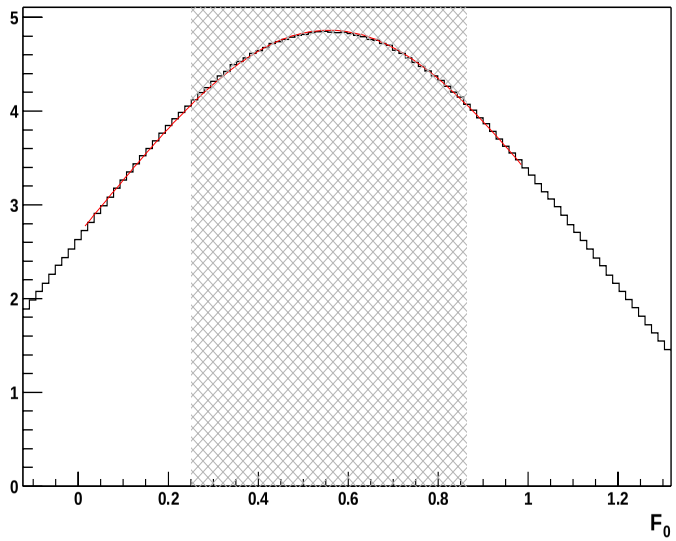
$$L(F_0) = \int L(M_{top}, F_0) dM_{top}$$

This method allow us to include the systematic uncertainty within the calculation - correct boundaries and correlations. Therefore, the uncertainties are estimated properly.



Results

After integration over $\mathbf{M_{top}}$



$$F_0 \pm \delta F_0(\text{Stat \& } M_{top}) = 0.558 \pm 0.306$$

	Statistics + M_{top} uncertainty	0.306
From data	Jet Energy Scale	0.014
From data	Parton Distribution Function	0.007
From data	Acceptance-Linearity Correction	0.021
From Monte Carlo	Background	0.010
From Monte Carlo	Signal Model	0.020
From Monte Carlo	Multiple Interactions	0.009
From Monte Carlo	ttbar Spin Correlations	0.008

Conclusions

- The helicity of the ***W*** boson offers a way to learn about the coupling of the top quark

- Using LO approximation and a parametrized showering for the jet resolutions, we calculate the event probabilities, and measure:

$$F_0 = 0.56 \pm 0.31$$

First F_0 measurement at **DØ** using 125pb^{-1}.

- We have a method that allows us to extract F_0 using **maximal information** in any event:
  - Correct permutation is always considered (along with the other eleven).
  - All features of individual events are included, thereby well measured events contribute more information than poorly measured events.
  - This method offers the possibility of improving the statistical error by using **both branches of W decay.**
  - Physical boundaries are taken into account naturally.
  - Natural way to include systematic uncertainties.
  - For higher statistics, one clearly needs to improve the calculation of the probabilities, but this method is a **logical way** to do the analysis.