W Boson Polarization in Top Quark Decay at CDF II

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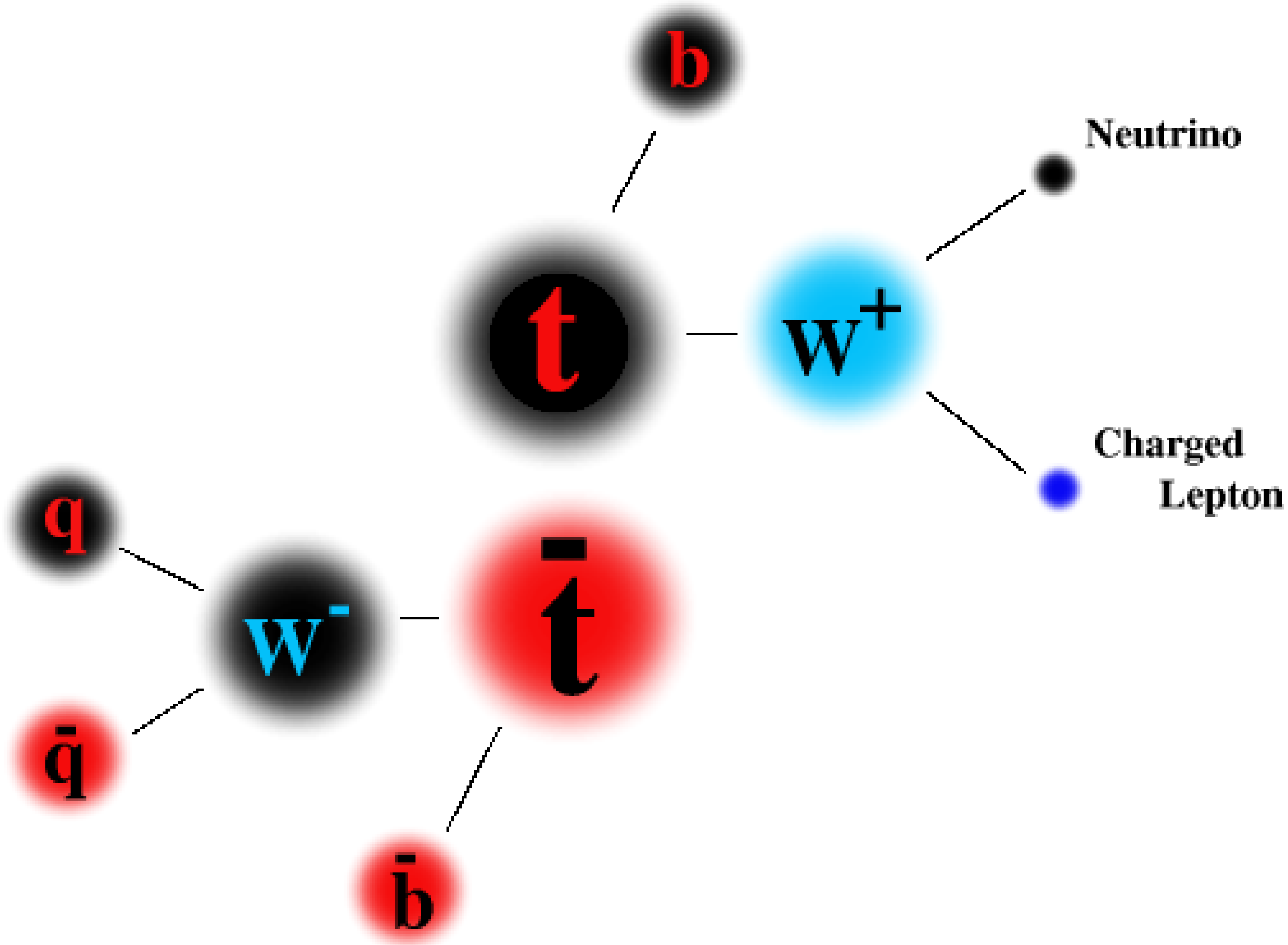
What Can We Learn?

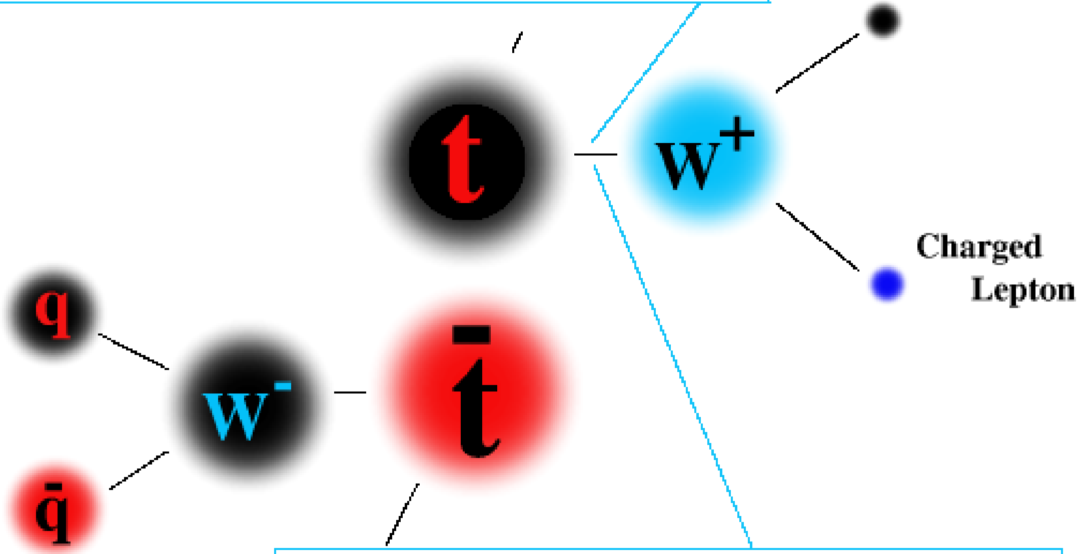
- According to the Standard Model, the top quark will decay to a W boson and a b quark nearly 100% of the time (Think CKM Matrix).



What Can We Learn?

- Standard Model gives specific predictions for fractions of longitudinal and transverse W bosons in top decay ($m_t = 175$ GeV/c^2).
- Testing the weak decay of the top quark (Expected to be purely $V - A$)
- Higgs Mechanism gives rise to the longitudinal polarization state of the W

$$BR(t \rightarrow W_{\lambda=-1} b) = \frac{2M_W^2}{m_t^2 + 2M_W^2} \simeq 0.30$$



$$BR(t \rightarrow W_{\lambda=0} b) = \frac{m_t^2}{m_t^2 + 2M_W^2} \simeq 0.70$$

What do you mean by "W polarization"?

- Helicity is the projection of spin along the direction of motion
  - This is defined by the helicity operator: $\vec{\sigma} \cdot \hat{p}$
  - The helicity values for the W left and right-handed ($\vec{\epsilon}_L$ and $\vec{\epsilon}_R$) polarization states are then -1 and $+1$, respectively
    - ▷ Transverse W
  - Assume that the direction of motion is $\hat{z}$, then a W with a polarization of $\vec{\epsilon}_z$ has helicity 0
    - ▷ Longitudinal W
- Squares of the various helicity amplitudes
  - These are well-known:

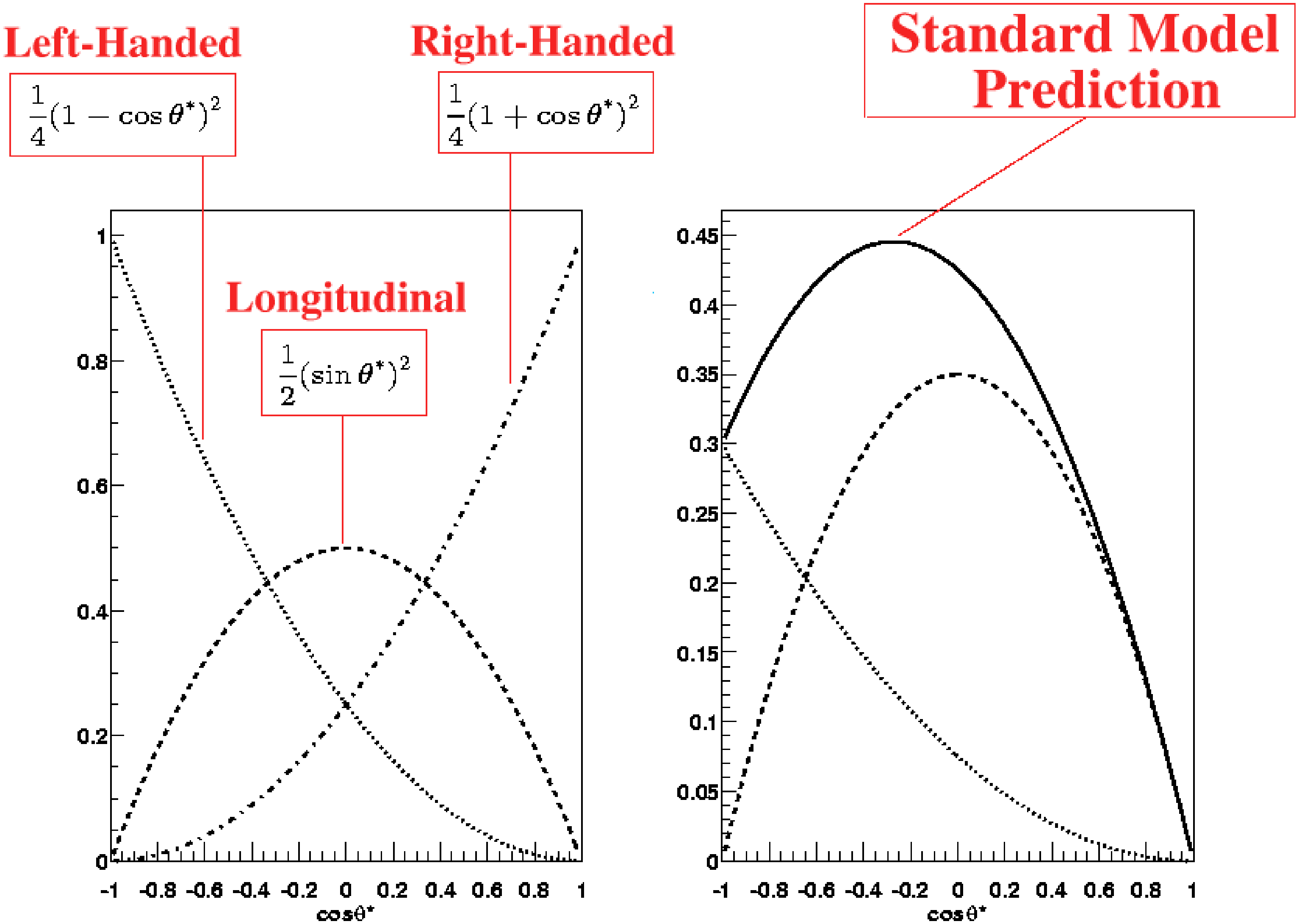
$$|\mathcal{M}(W^+_{\lambda=-1})|^2 = |\mathcal{M}(W^-_{\lambda=+1})|^2 = \frac{1}{4}(1 - \cos\theta^*)^2$$

$$|\mathcal{M}(W^+_{\lambda=+1})|^2 = |\mathcal{M}(W^-_{\lambda=-1})|^2 = \frac{1}{4}(1 + \cos\theta^*)^2$$

$$|\mathcal{M}(W^+_{\lambda=0})|^2 = |\mathcal{M}(W^-_{\lambda=0})|^2 = \frac{1}{2}(\sin\theta^*)^2$$

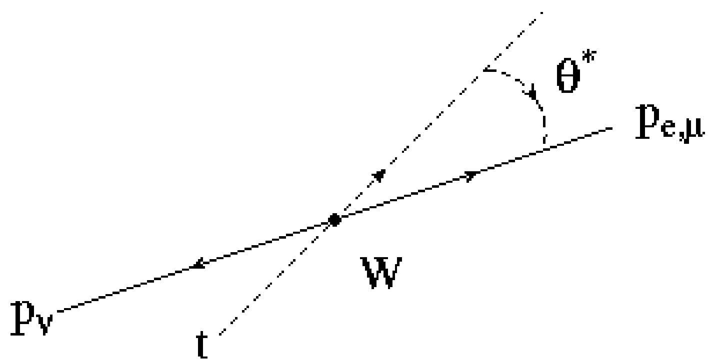
The $\cos\theta^*$ distributions

- The $\cos\theta^*$ distribution is very distinct for each helicity.



Technique for measuring W polarization

- Use the $\cos\theta^*$ distribution to make the measurement, since it is distinct for each helicity
  - Angle θ^* is defined as the angle between charged-lepton momentum in W rest-frame and the W momentum in the top rest-frame:



- What data samples can we use to make this measurement?
  - We can use the dilepton sample
    - ▷ $t\bar{t}$ events where both W bosons decay to e and/or μ
  - We can also use the lepton+jets sample
    - ▷ $t\bar{t}$ events where only one W decays to e or μ
  - Extremely difficult to use the all-hadronic sample for this analysis
    - ▷ We need the charges of the daughter quarks!

Extracting $\cos\theta^*$ from the Data

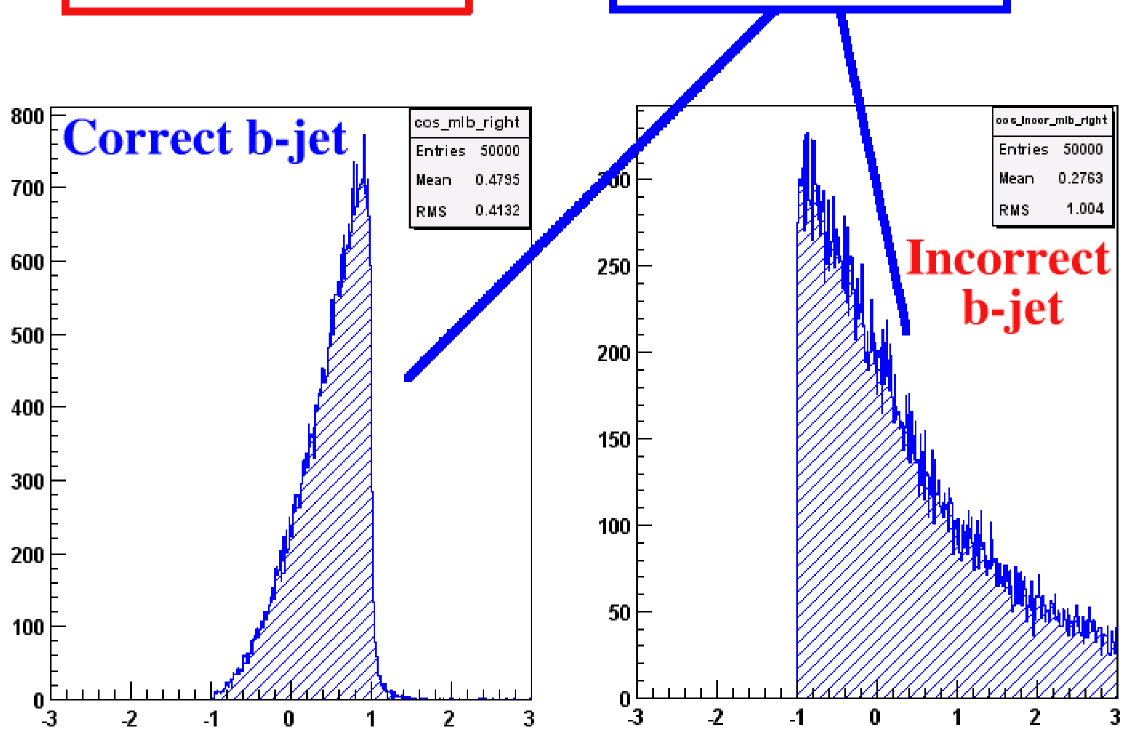
- Difficult to determine $\cos\theta^*$ explicitly in the data
  - We can not reliably reconstruct the top and W rest-frames
  - Use m_{lb} approximation instead (invariant mass of lepton and b)
  - Choosing the correct b is important (wrong $b \Rightarrow$ decrease in sensitivity)

Exact

$$\cos\theta^* = \frac{(\vec{p}_l)_W \cdot (\vec{p}_W)_t}{|(\vec{p}_l)_W||(\vec{p}_W)_t|}$$

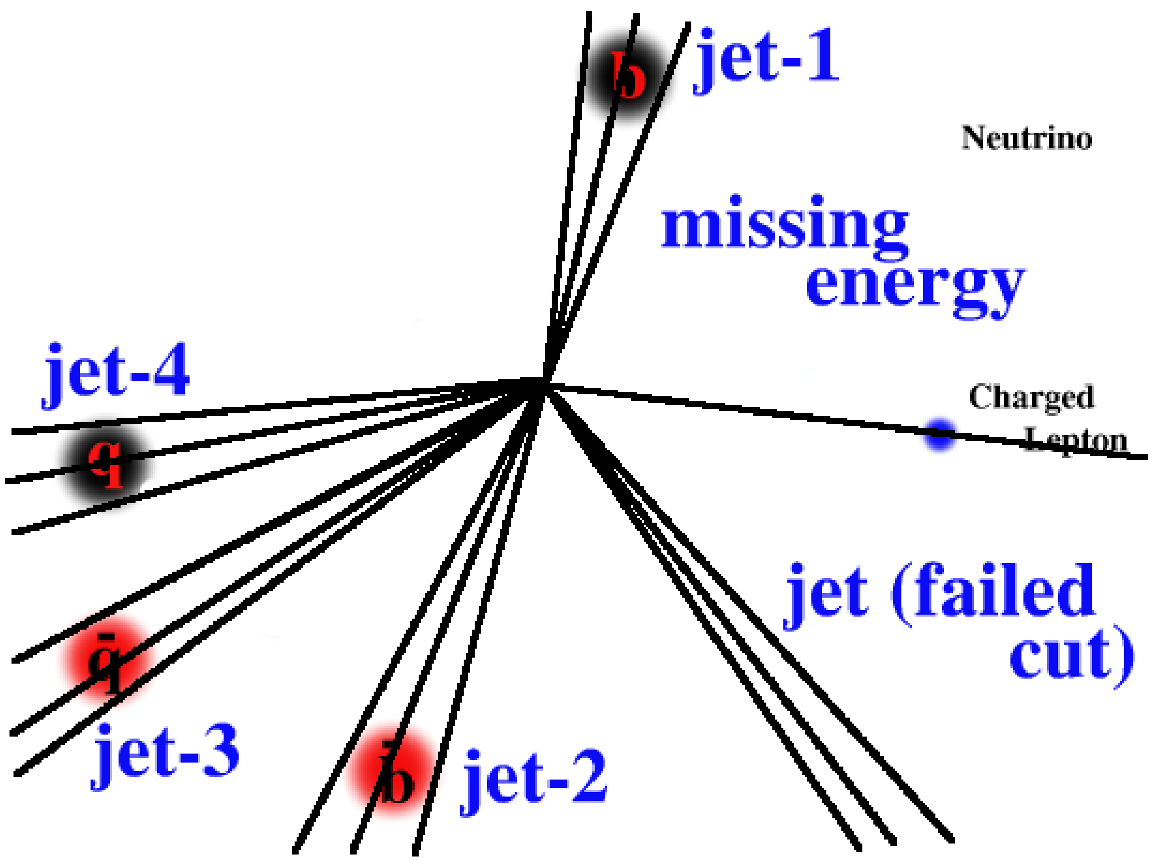
Approximation

$$\cos\theta^* \simeq \frac{2m_{lb}^2}{m_t^2 - M_W^2} - 1$$



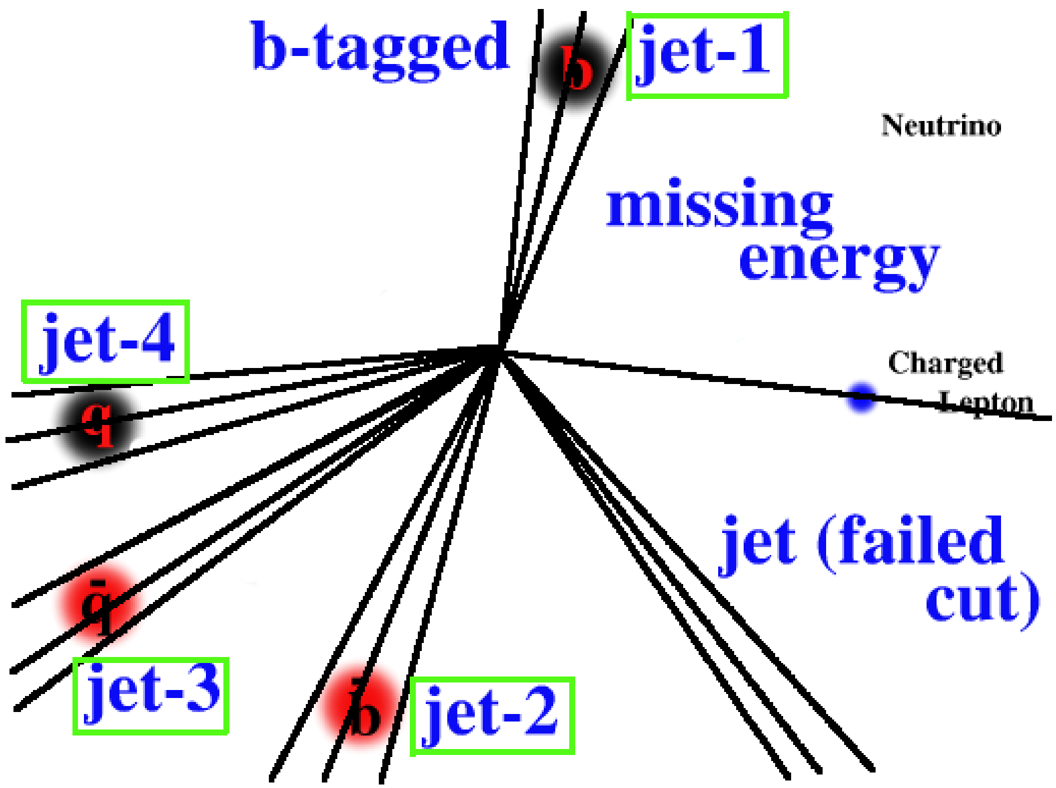
Choosing the correct b Jet

- We use top mass-fitting to choose the correct b-jet (full reconstruction)
  - Currently this is only being done in the Lepton+Jets channel
  - This fit is done 24 times for each event (24 χ^2 values)
    - ▷ 12 ways to assign the four leading jets to the four partons in $t\bar{t}$ decay
    - ▷ $\times 2$ for ambiguity in neutrino longitudinal momentum



Choosing the correct b Jet

- By definition, the Lepton+Jets dataset includes at least one "b-tagged" jet
  - Throw away fits where a tagged jet was assigned to the hadronicly-decaying W
  - Require $\chi^2 < 20$ for the fit (help reduce background, increase fraction of time fitter assigns the correct b-jet)
  - Jet assigned by the fitter to be the leptonic-b in the event is used in the m_{lb} approximation for $\cos\theta^*$



A binned likelihood fitter

- We use a binned likelihood fitter to measure the longitudinal fraction, F_0

$$\mathcal{L} = \frac{1}{\sqrt{2\pi\sigma_{bm}^2}} \cdot e^{-\frac{(F_B - f_{bm})^2}{2\sigma_{bm}^2}} \prod_{i=1}^{N_b} \frac{\mu_i^{x_i} e^{-\mu_i}}{x_i!}$$

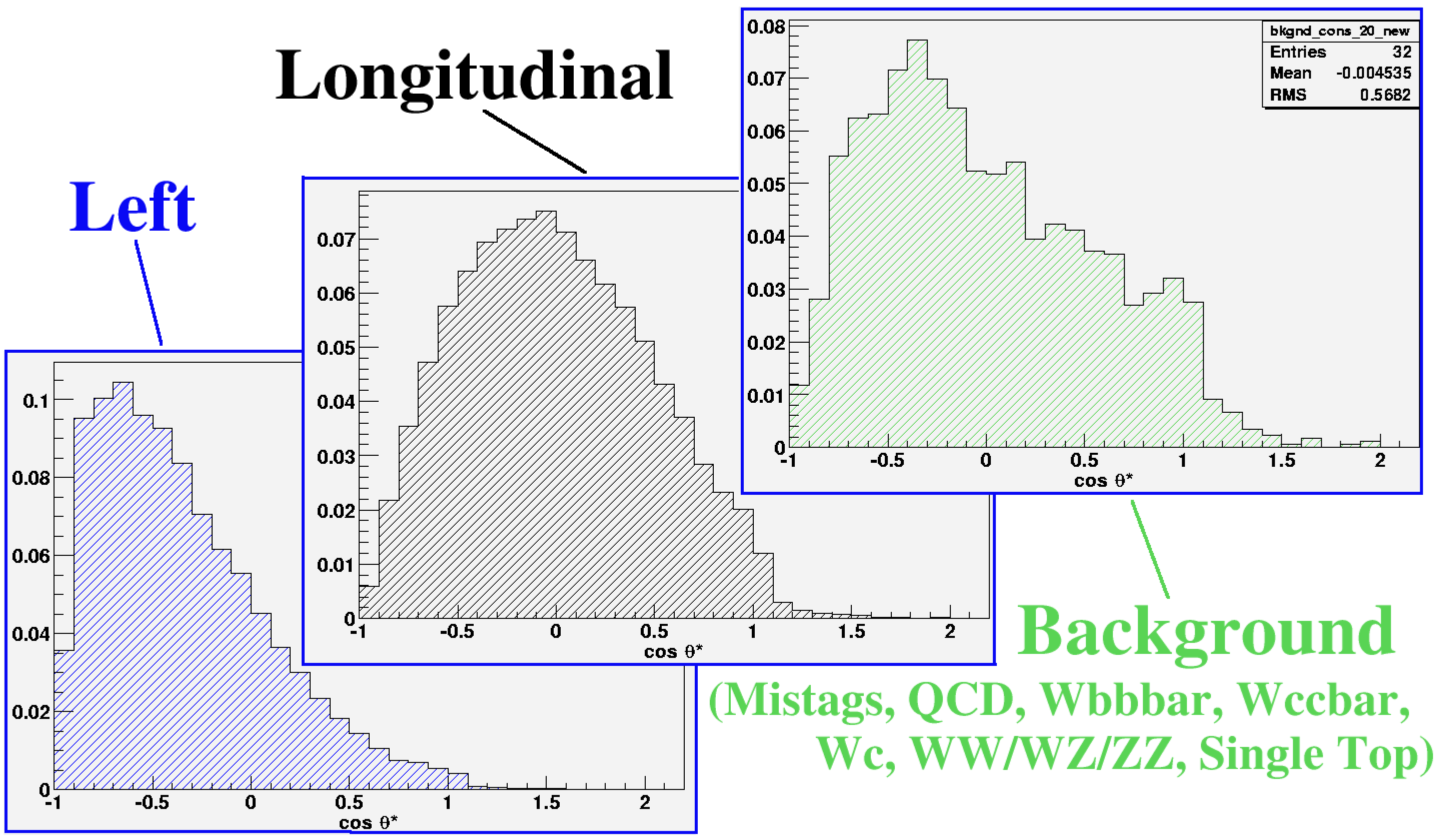
- Where i is the index over bins, N_b is the total number of bins
- F_B is the fraction of background events measured by the fitter, f_{bm} and σ_{bm} are the estimated fraction of background events and the error on that estimation
- x_i is the number of data events in bin i, μ_i is the prediction in bin i, given by:

$$\mu_i = N_e \cdot (F_B T_{B,i} + (1 - F_B) F_0^{obs}(F_0) T_{0,i} + (1 - F_B)(1 - F_0^{obs}(F_0)) T_{L,i})$$

- N_e is the total number of events, T_B is the background template, T_0 and T_L are the longitudinal, left-handed signal templatess, F_0^{obs} is the longitudinal fraction after we correct for the acceptance bias.
- Due to the angular distributions for each of the helicity values, charged leptons from left-handed W decays go preferentially backwards in the W rest frame

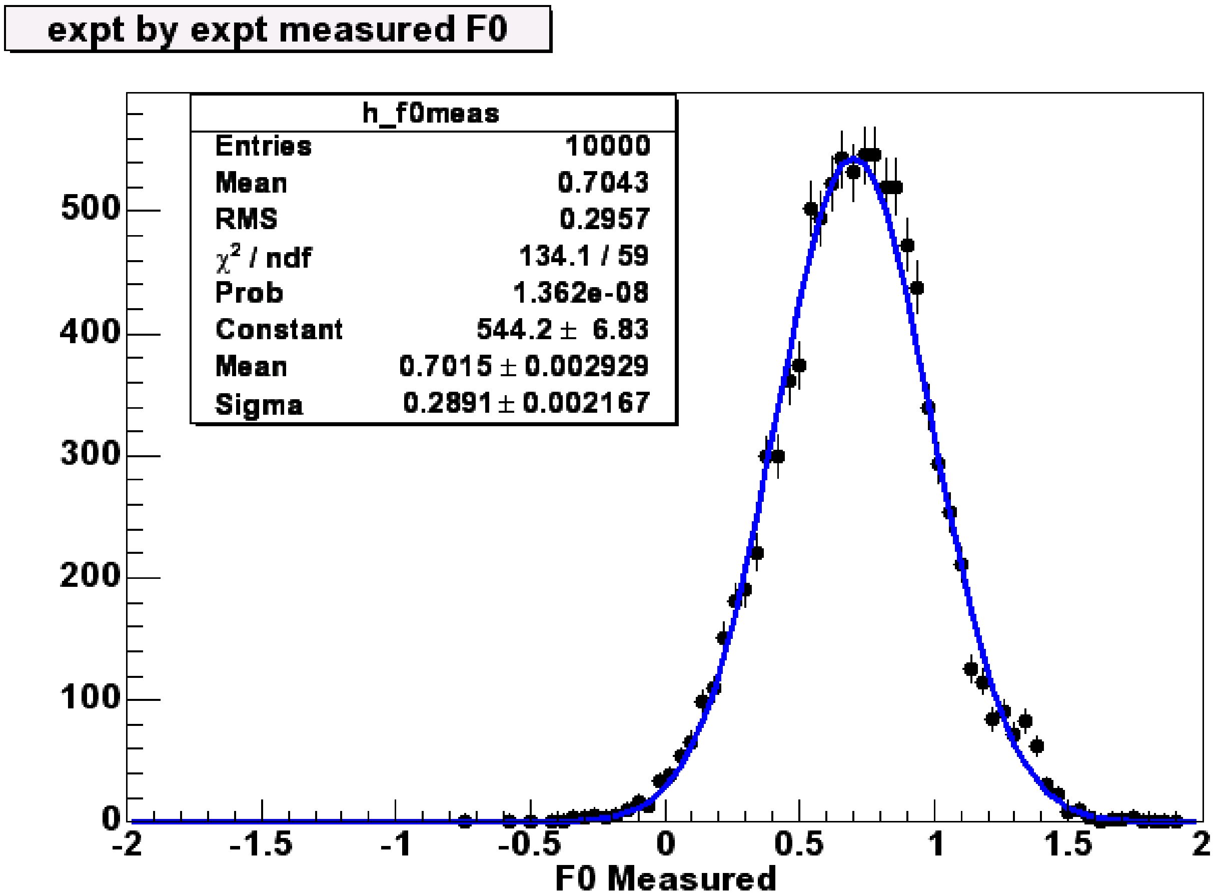
Template shapes

- Our signal templates are created with `MadEvent` $t\bar{t}$ Monte Carlo where the helicity of one W boson is fixed
  - Thanks to Tim Stelzer and Fabio Maltoni
  - Different left-handed, longitudinal and background templates were created using events which passed our selection criteria



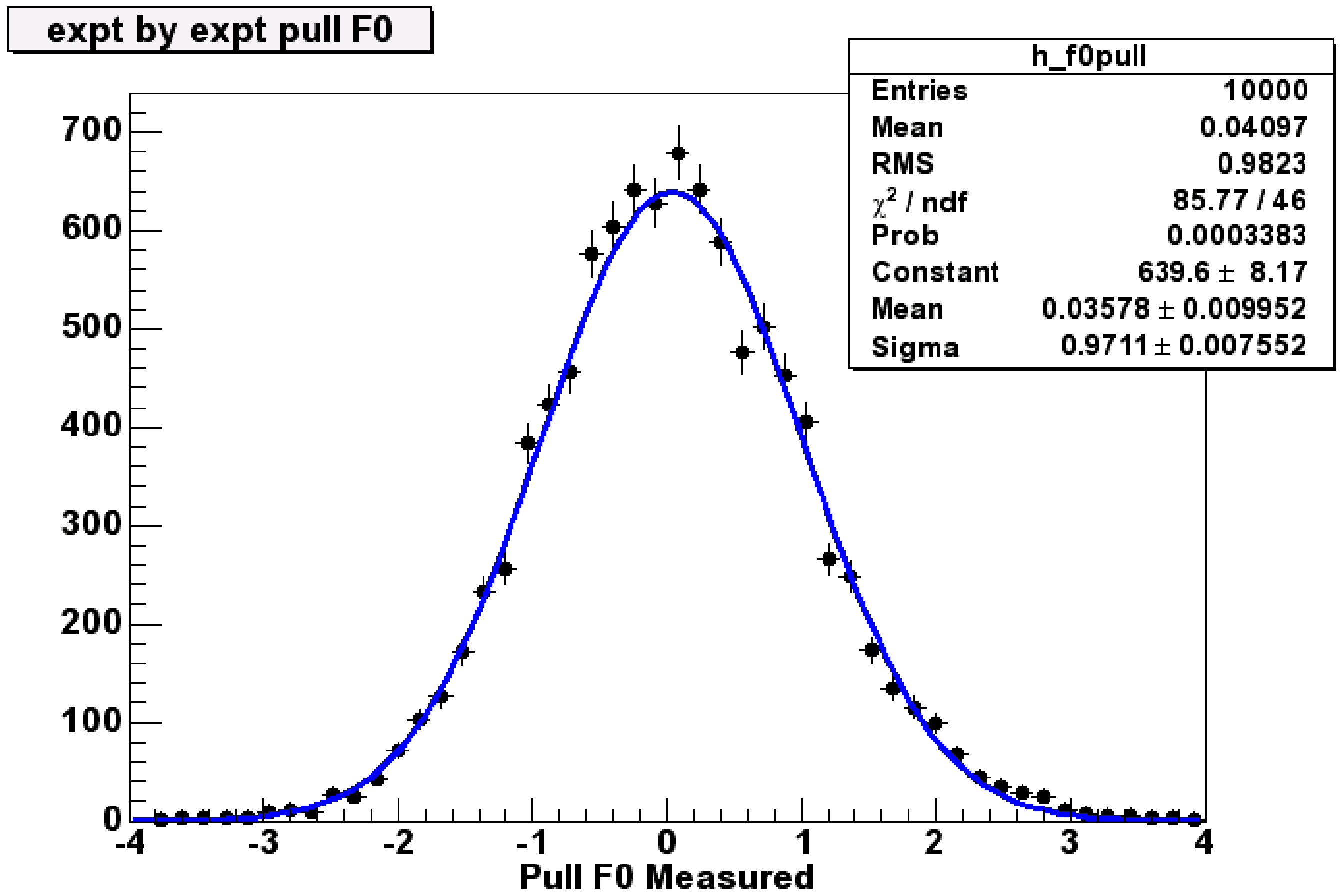
Sensitivity Study Results

- Values for F_0 measured by the fitter for 10k pseudo-experiments (used SM $F_0 = 0.70$) assuming a dataset of 162 pb^{-1}
- For this series of pseudo-experiments shown, mean value is $F_0 = 0.70 \pm 0.29$.
- F_0 is permitted to venture into the non-physical region.



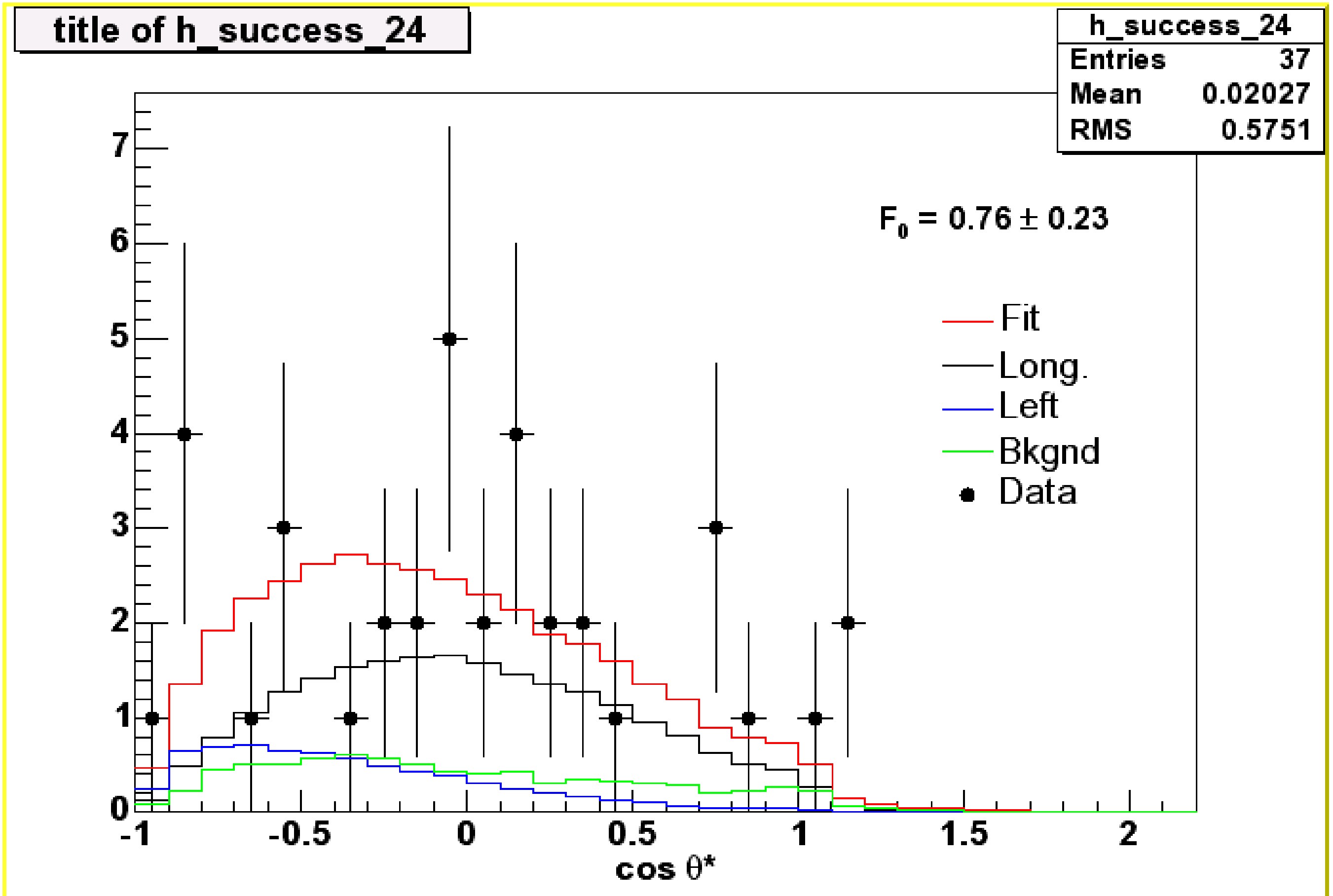
Sensitivity Study Results: Pulls

- We examined the pulls to check for the accuracy of F_0 measured.
- Pull $\equiv (F_0^{meas} - F_0^{actual})/\delta F_0^{meas}$
- Mean $\sim 0,\ \sigma \sim 1$
- Our results are un-biased and the errors are accurate



Sensitivity Study: Fit results for a pseudo-experiment

- Fit results for one pseudo-experiment ($\chi^2 < 20$).



Conclusions

- We have a method for measuring W boson polarization in top quark decay using lepton angular distributions
- From pseudo-experiments we estimate a statistical uncertainty on F_0 of ± 0.29 in 162 pb^{-1} using this method
- We have already investigated many systematics:
  - Top Mass Uncertainty
  - Jet Energy Scale
  - Background Shape
  - ISR/FSR
  - PDFs
  - MC statistics (signal)
  - Acceptance Correction Error
  - b-tagging
- Expect to see a measurement in the data in a couple of weeks...