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Top Pair Spin Correlations at the Tevatron

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Part 1 - Introduction

Part 2 - Measurement

Part 3 - Results

The Top Quark

Mass = 173.1±1.3 GeV

100% decay to Wb

Heaviest SM particle

Lifetime ≈ 5×10^{-25} seconds

Strong coupling to Higgs and new physics

Decays before hadronising

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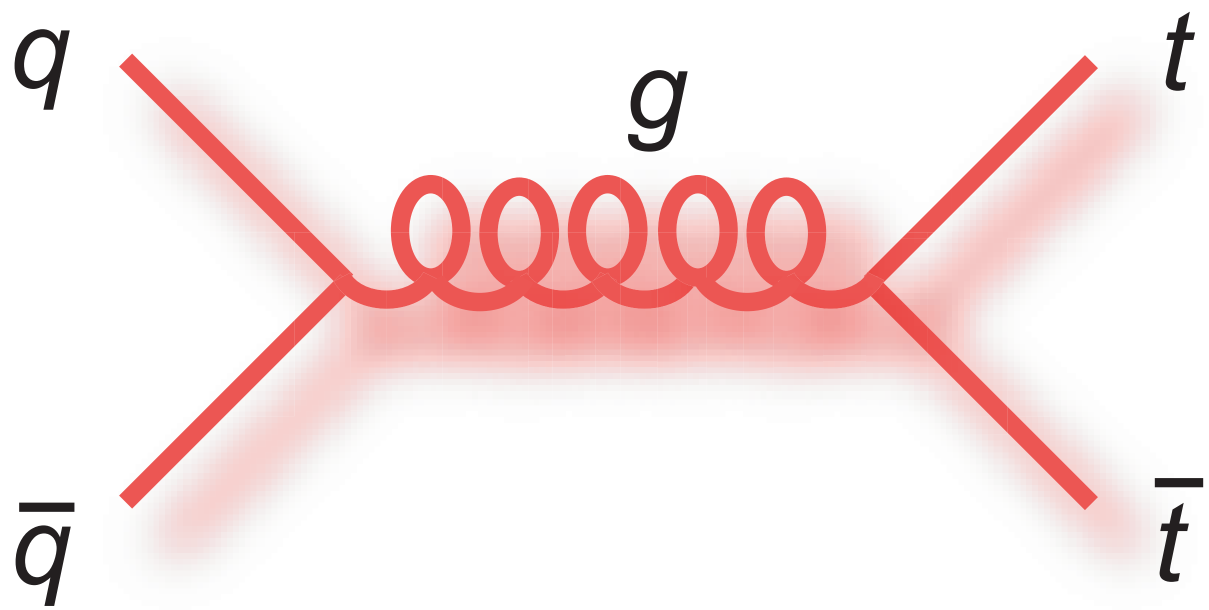
Why Spin Correlation Is Interesting?

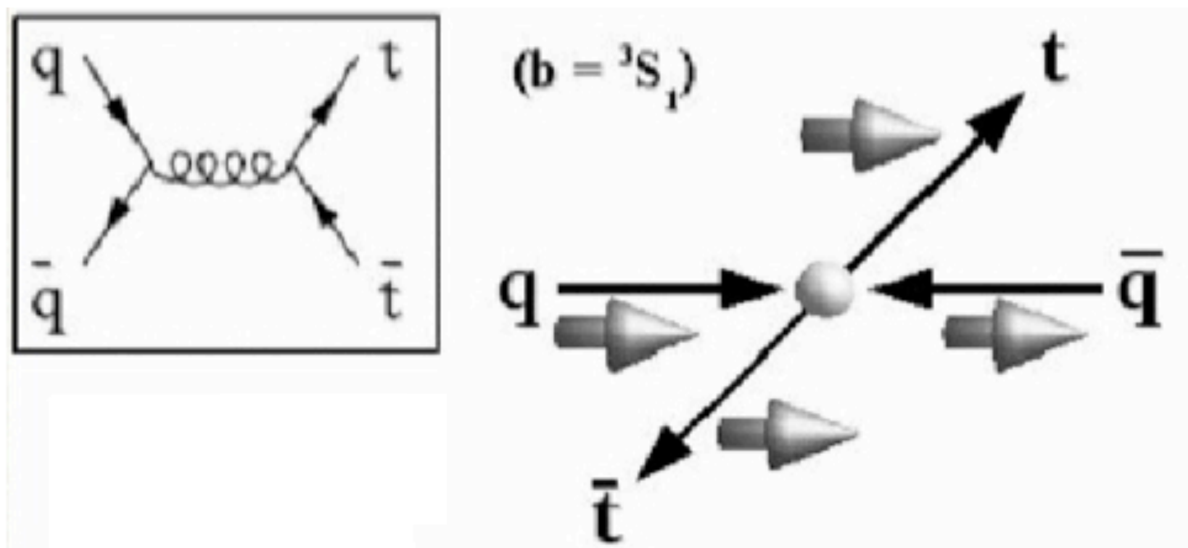
- Tests whole chain from production to decay.
- Only in top production can we see QCD correlating the spins during production.
  - Can not reliably predict this for b quarks which form hadrons!
- Predictions of QCD and EW theory aspects can be experimentally verified.
- Observing Spin Correlations would place an upper limit on top quark lifetime.

Top Production



- SM cross section ≈ 8pb, dominated by quark antiquark fusion.
- QCD dynamics cause top quark spins to be correlated.
- Can be modified by Z', KK gluons, ... decaying to tops.

Spin Correlations in Production



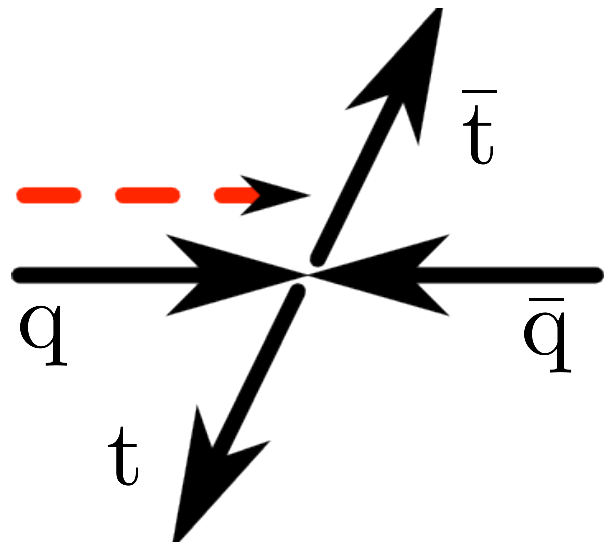
$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\downarrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\downarrow\uparrow} + N_{\uparrow\downarrow}}$$

- Strength of correlation, ***A***, depends on spin quantisation axis.

Spin Quantisation Axes

- To measure the direction in which a spin vector is pointing we need a quantisation axis.
- Three choices at the Tevatron: beamline, helicity and off-diagonal.

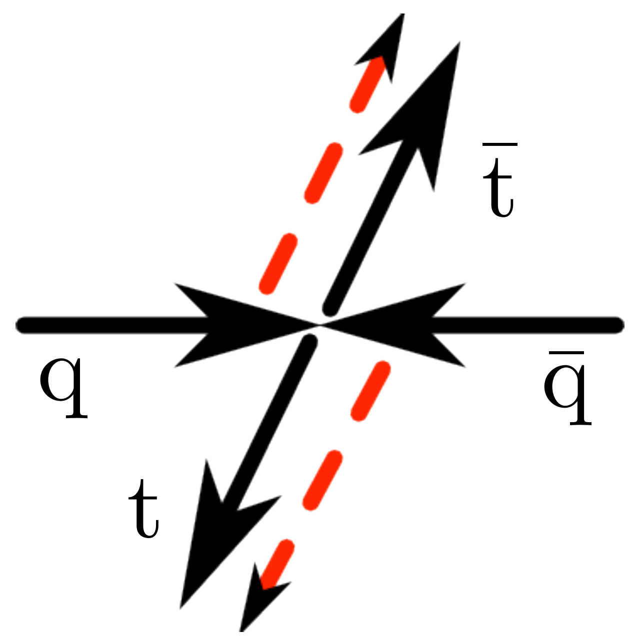
Beamline



- Use direction of one of the colliding hadrons in the top-antitop zero momentum frame.
- Simple to construct, optimal for top pairs produced at threshold.
- (almost) highest correlation, A=0.777 @NLO.

Bernreuther, Brandenburger, Si and Uwer et al., Nucl. Phys. B 690, 81 (2004)

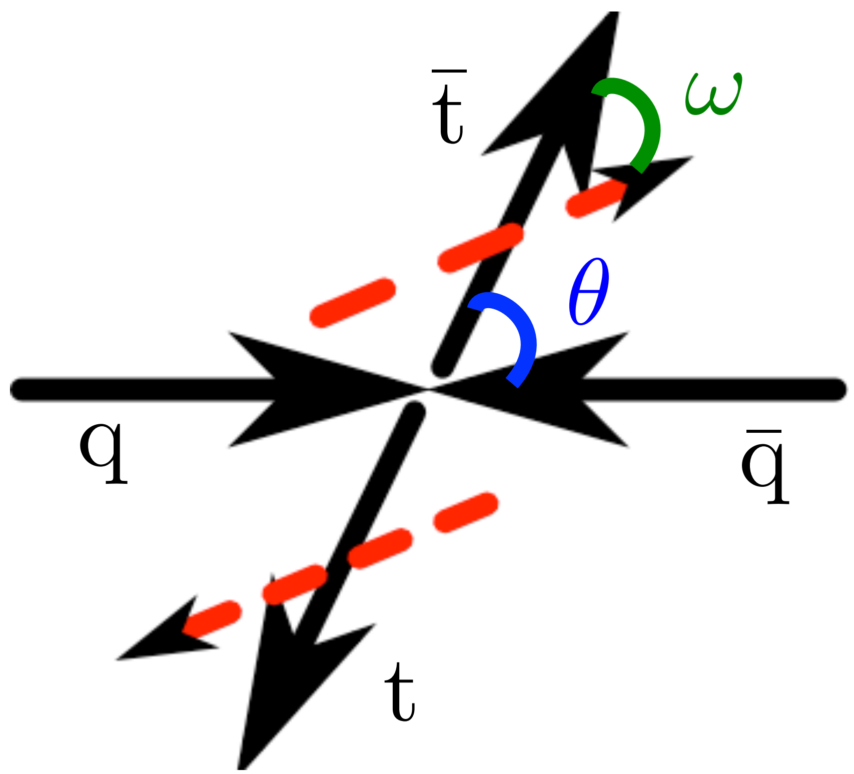
Helicity



- Use direction of (anti)top quark in the top-antitop zero momentum frame to quantise (anti)top quark spin.
- Smaller correlation strength, A=-0.352 @NLO.

Bernreuther, Brandenburger, Si and Uwer et al., Nucl. Phys. B 690, 81 (2004)

Off-Diagonal



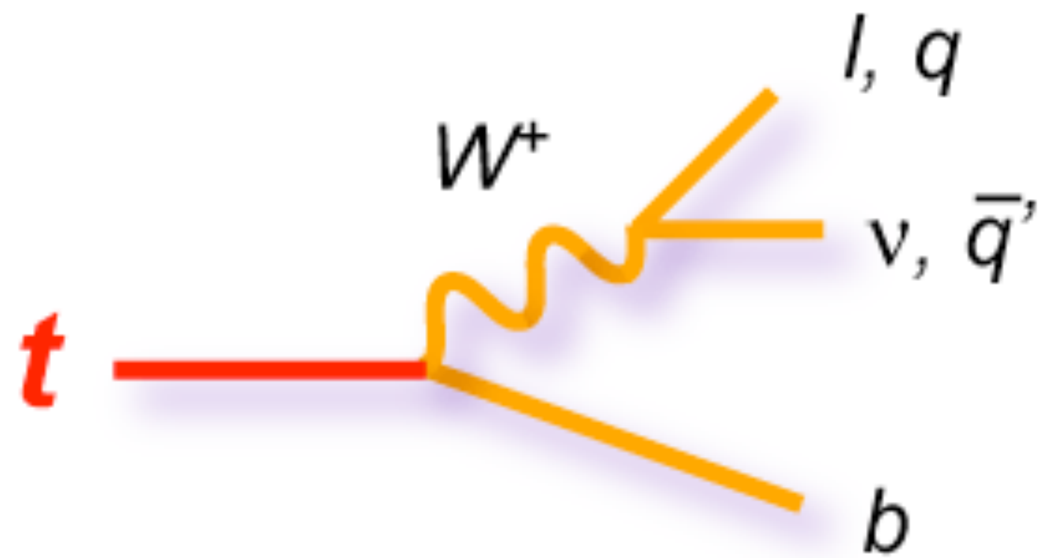
- Interpolates between beamline and helicity basis.

$$\tan\omega = \sqrt{1-\beta^2}\,\tan\theta$$

- Gets the top pairs produced above threshold.
- Slightly higher correlation, A=0.782 @NLO.

Bernreuther, Brandenburger, Si and Uwer et al., Nucl. Phys. B 690, 81 (2004)

Top Decay



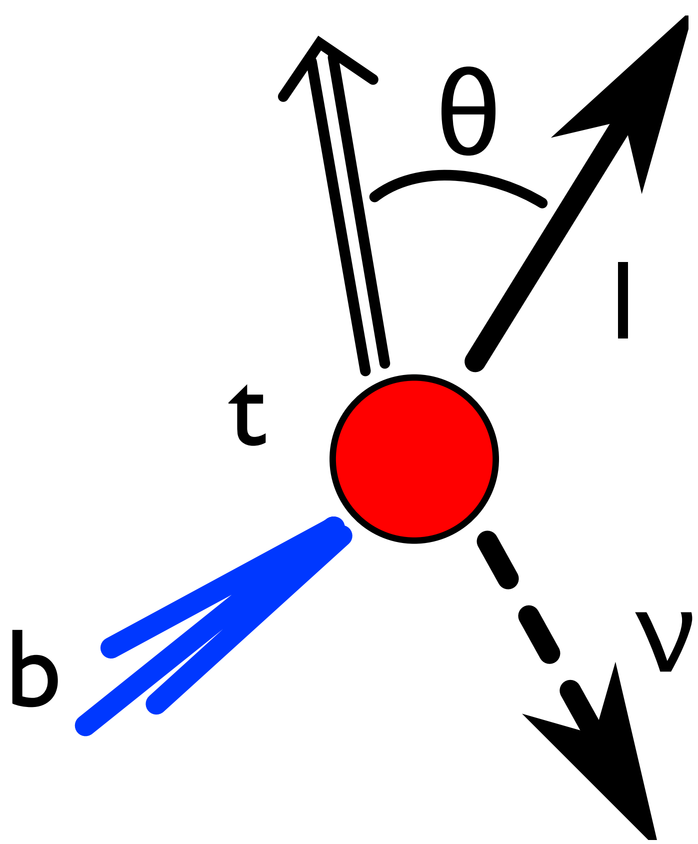
- Decays before it hadronises
  ⇒ spin information preserved in decay products

- Decays to charged Higgs (spin 0)?

- MSSM might modify the Wtb vertex.

Analysing the Top Spin

- Information about direction of top spin is passed on to its decay products.



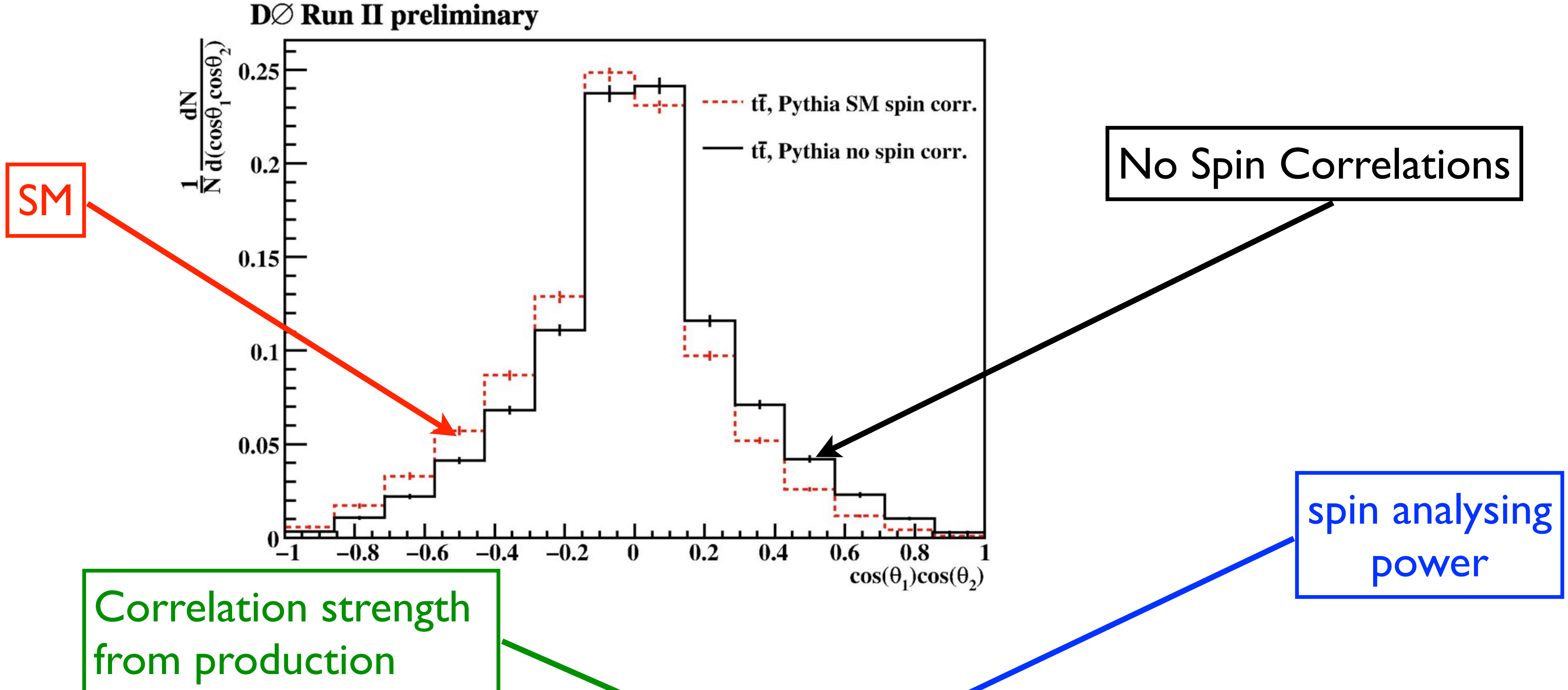
spin analysing power

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i} = \frac{1}{2}(1 + \alpha_i \cdot \cos\theta_i)$$

Spin analysing power for lepton and down type quark α=1, for b quarks α=-0.41.

Use lepton or down type quark!

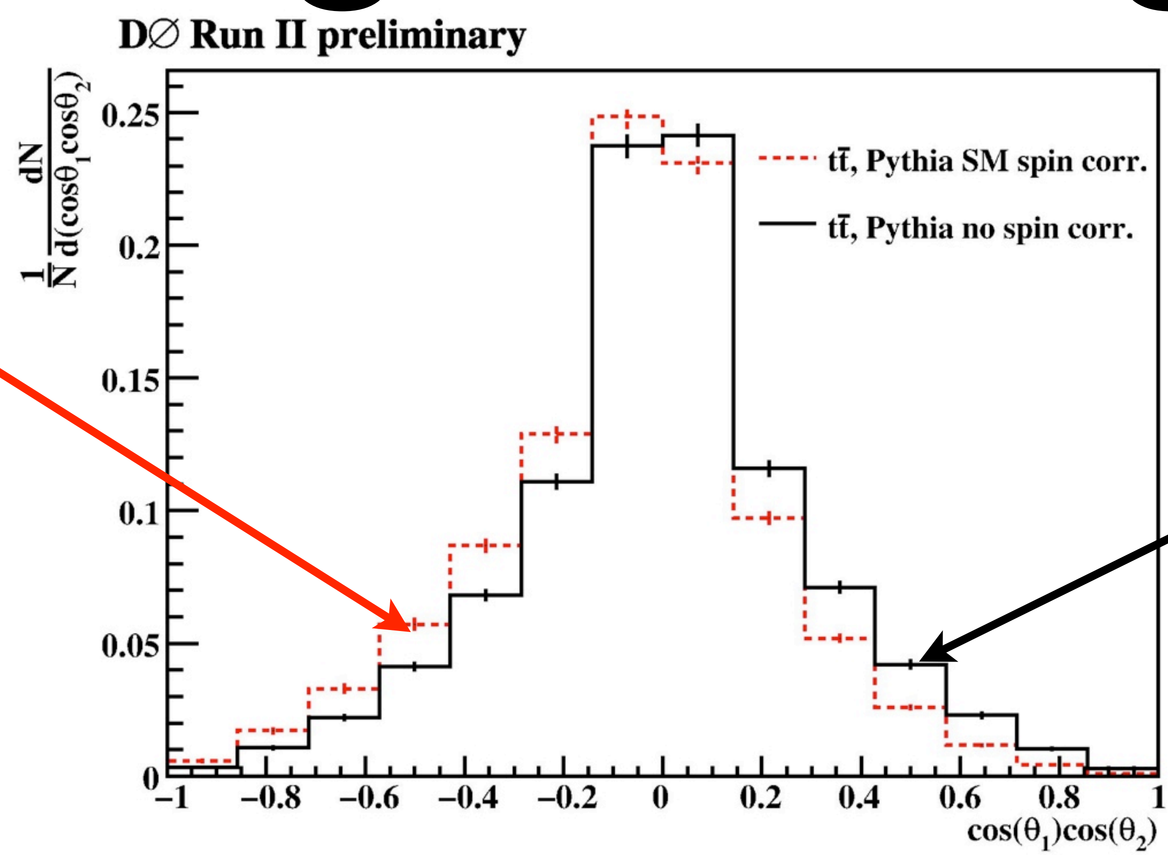
Putting it All Together



$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos(\theta_1)\mathrm{d}\cos(\theta_2)} = \frac{1}{4}(1 - A\alpha_1\alpha_2\cos(\theta_1)\cos(\theta_2))$$

- To see the correlations look at combinations of decay products from top and anti top quark.
- This is a tough measurement to make!

Putting it All Together



SM

No Spin Correlations

Combined correlation strength

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos(\theta_1)d\cos(\theta_2)} = \frac{1}{4}(1 - \overbrace{A\alpha_1\alpha_2}^{=C}\cos(\theta_1)\cos(\theta_2))$$

- To see the correlations look at combinations of decay products from top and anti top quark.
- This is a tough measurement to make!

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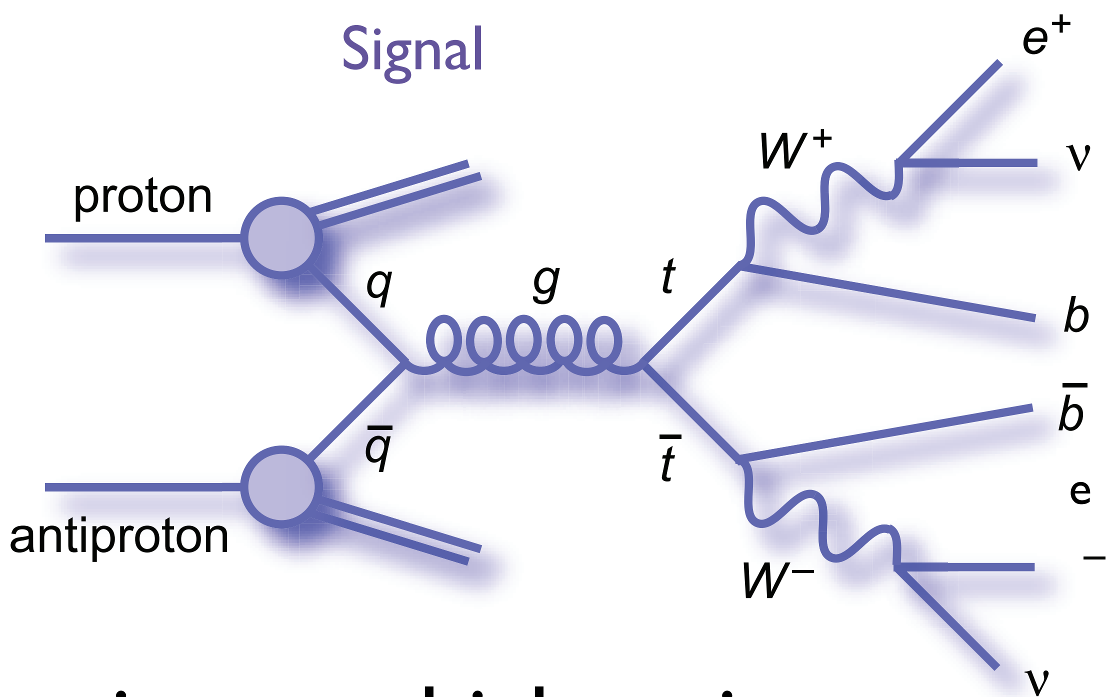
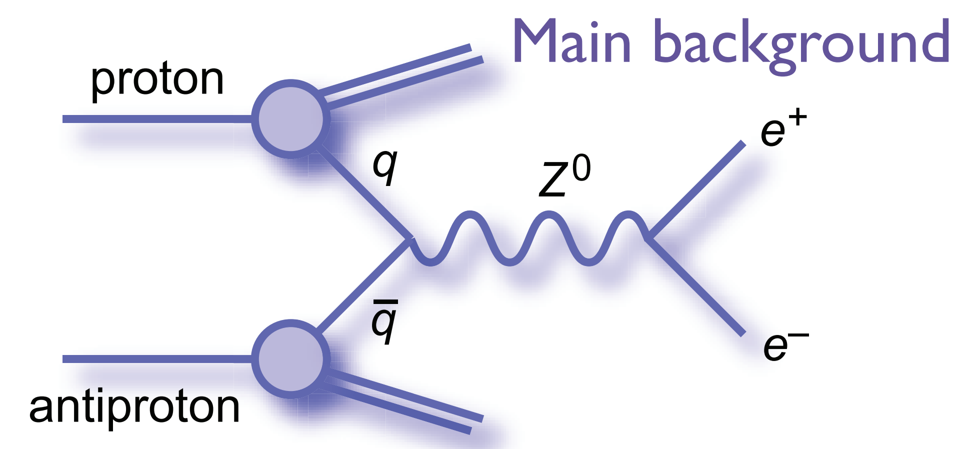
Dilepton





- Require two high p_T jets.
- Advantage: Small backgrounds!
- Advantage: No ambiguities in finding down type objects.
- Disadvantage: Two neutrinos in the final state.

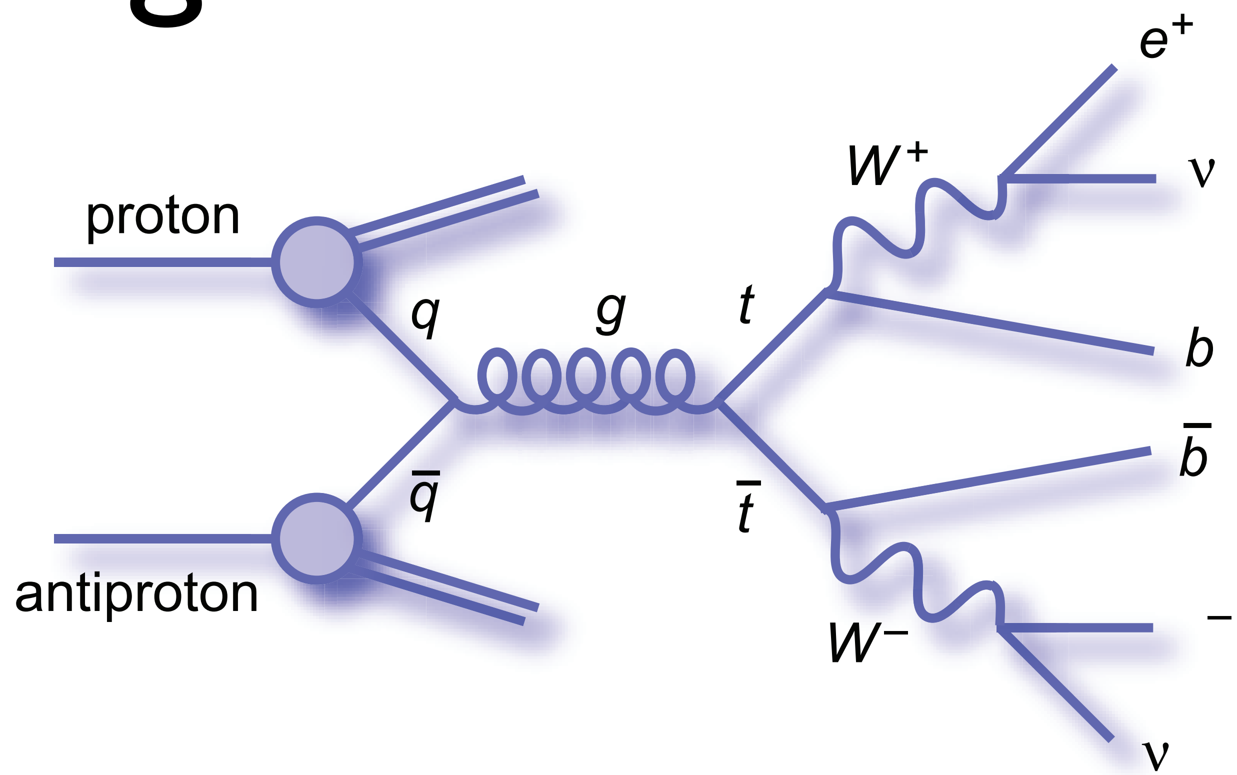
DØ using up to $4.1 fb^{-1}$

	ee	eμ	μμ
Background	3.4	24.3	5.4
Signal	11.5	140	8.3
Data	17	168	13

CDF using $2.8 fb^{-1}$

	All
Background	75
Signal	130
Data	195

Dealing With Two Neutrinos

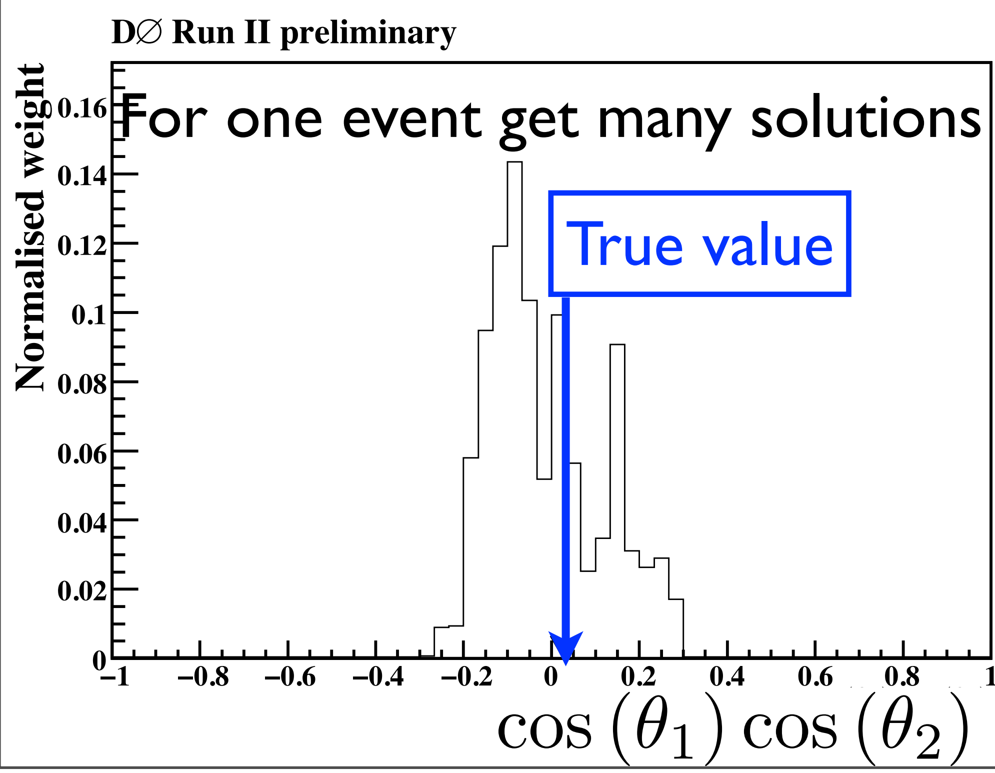


- Using sum of neutrino momenta $\not{E}_T^x$, $\not{E}_T^y$, assuming M_{top} and M_W the kinematics can be solved.
- The equations are quartic so one can get up to four solutions per event, additionally the jet assignment is unknown.
- Therefore up to eight solutions per event!

Neutrino Weighting

- At DØ the "Neutrino weighting" technique is used.
- Do not use $\not{E}_T^x$ and $\not{E}_T^y$ to solve kinematics.
- Instead test several assumptions for neutrino and antineutrino η.
- Weighted by agreement with missing transverse energy:

$$w = \exp\left(-\frac{(\not{E}_T^x - \nu_x - \bar{\nu}_x)^2}{\sigma^2}\right) \times \exp\left(-\frac{(\not{E}_T^y - \nu_y - \bar{\nu}_y)^2}{\sigma^2}\right)$$



Use weighted mean as estimator for $\cos\theta_1 \cos\theta_2$

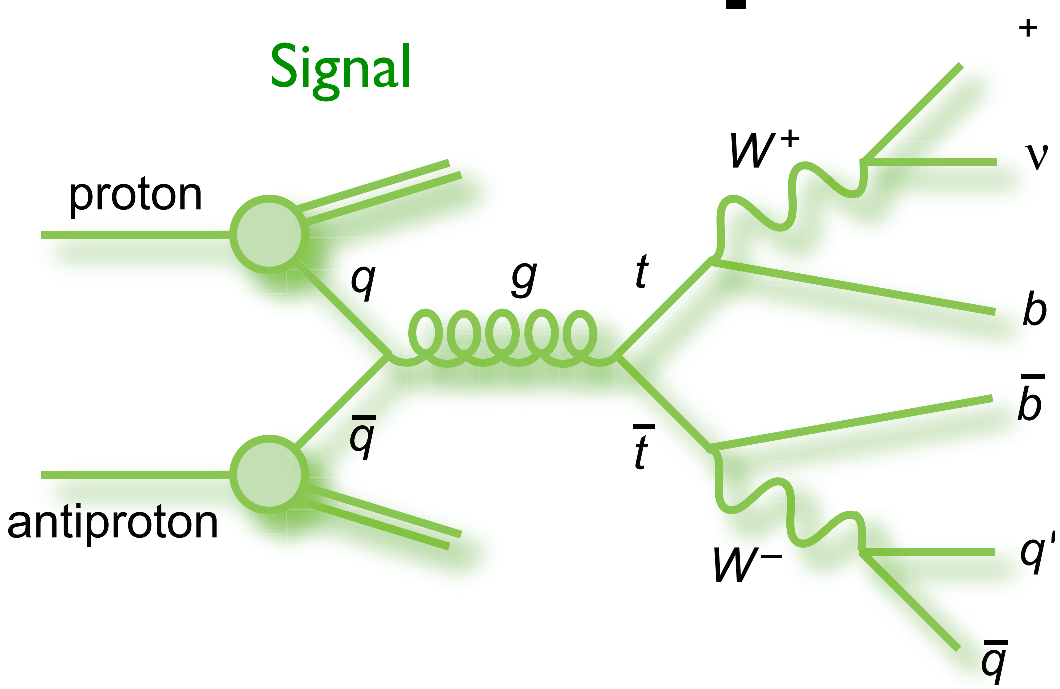
Dealing With Two Neutrinos

- Alternative approach used at CDF.
- Likelihood fit for neutrino and b jet momenta.
- Solve jet-lepton assignment problem by choosing combination with largest likelihood.

$$\mathcal{L}\left(\vec{p}_{\nu}, \vec{p}_{\bar{\nu}}, E_{b}^{\mathrm{guess}}, E_{\bar{b}}^{\mathrm{guess}}\right) = P\left(p_{z}^{t\bar{t}}\right) P\left(p_{T}^{t\bar{t}}\right) P\left(M_{t\bar{t}}\right) \times$$
$$\frac{1}{\sigma_b} \exp\left[-\frac{1}{2}\left\{\frac{E_b^{\mathrm{meas}} - E_b^{\mathrm{guess}}}{\sigma_b}\right\}^2\right] \times \frac{1}{\sigma_{\bar{b}}} \exp\left[-\frac{1}{2}\left\{\frac{E_{\bar{b}}^{\mathrm{meas}} - E_{\bar{b}}^{\mathrm{guess}}}{\sigma_{\bar{b}}}\right\}^2\right] \times$$
$$\frac{1}{\sigma_x^{\mathrm{MET}}} \exp\left[-\frac{1}{2}\left\{\frac{\not{E}_x^{\mathrm{meas}} - \not{E}_x^{\mathrm{guess}}}{\sigma_x^{\mathrm{MET}}}\right\}^2\right] \times \frac{1}{\sigma_y^{\mathrm{MET}}} \exp\left[-\frac{1}{2}\left\{\frac{\not{E}_y^{\mathrm{meas}} - \not{E}_y^{\mathrm{guess}}}{\sigma_y^{\mathrm{MET}}}\right\}^2\right]$$

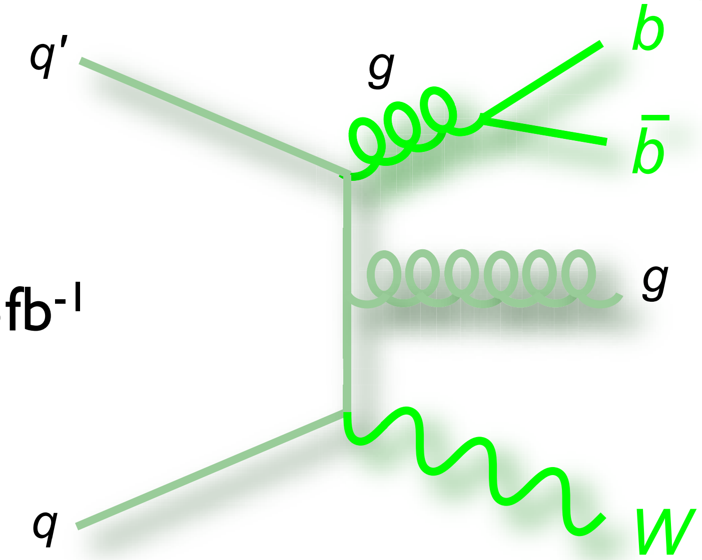
Lepton plus Jets

Signal



Main background

using 4.3fb^{-1}



- 1001 events of which 786 are signal.
- Advantage: High statistics!
- Disadvantage: Having to pick down type quark.

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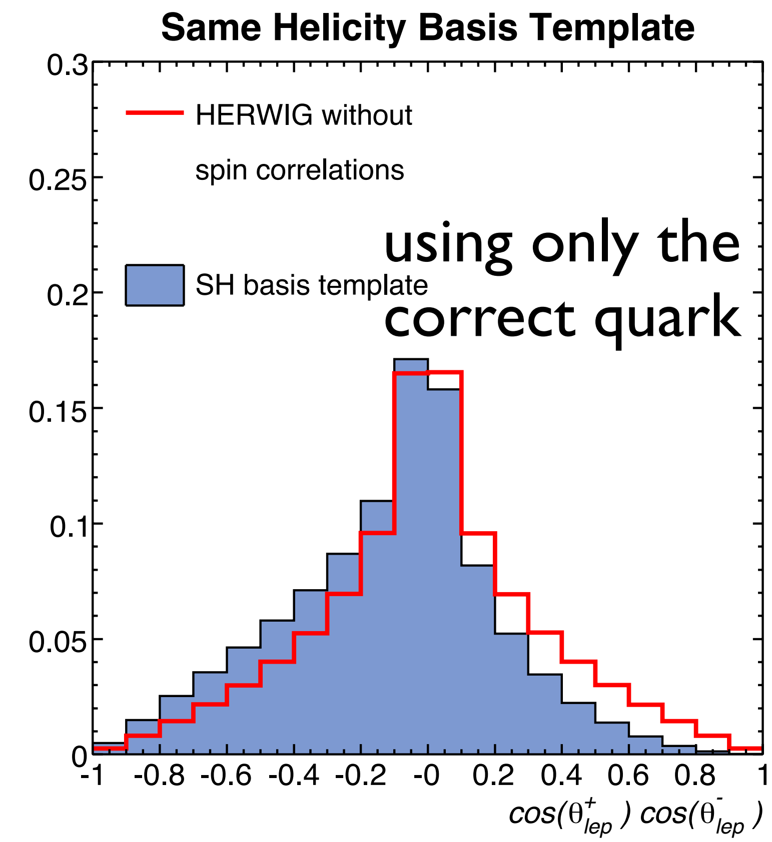
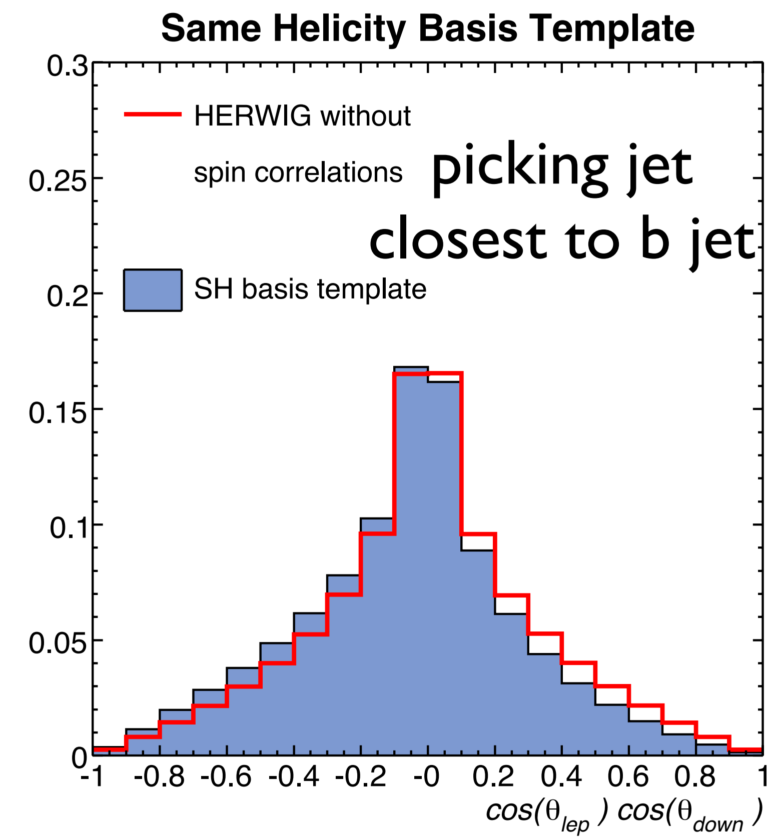
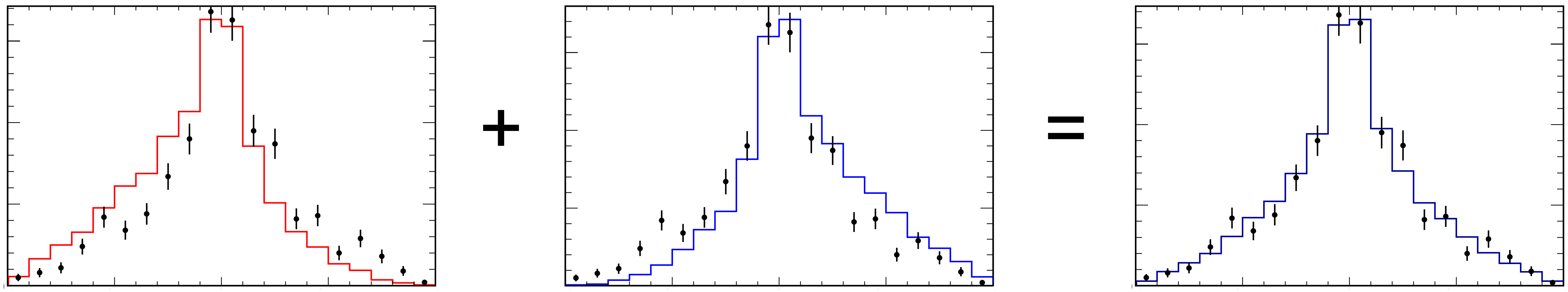
Event Reconstruction

- Pick jet closest to b jet in W boson rest frame as down type quark.
  - ≈ 60% chance of getting it right.
- Reconstruction of kinematics not as difficult as in dilepton, there is only one neutrino.
- Kinematics are solved using a constrained χ^2 fitter.
- Measuring the top quark helicity fraction, but equivalent to a spin correlations measurement.





Template Fits



- As distributions are distorted by selection and acceptance cuts ⇒ template fits.

- Make template for backgrounds and different values of spin correlation strength.

- Fit several distributions simultaneously to take advantage of all the information.

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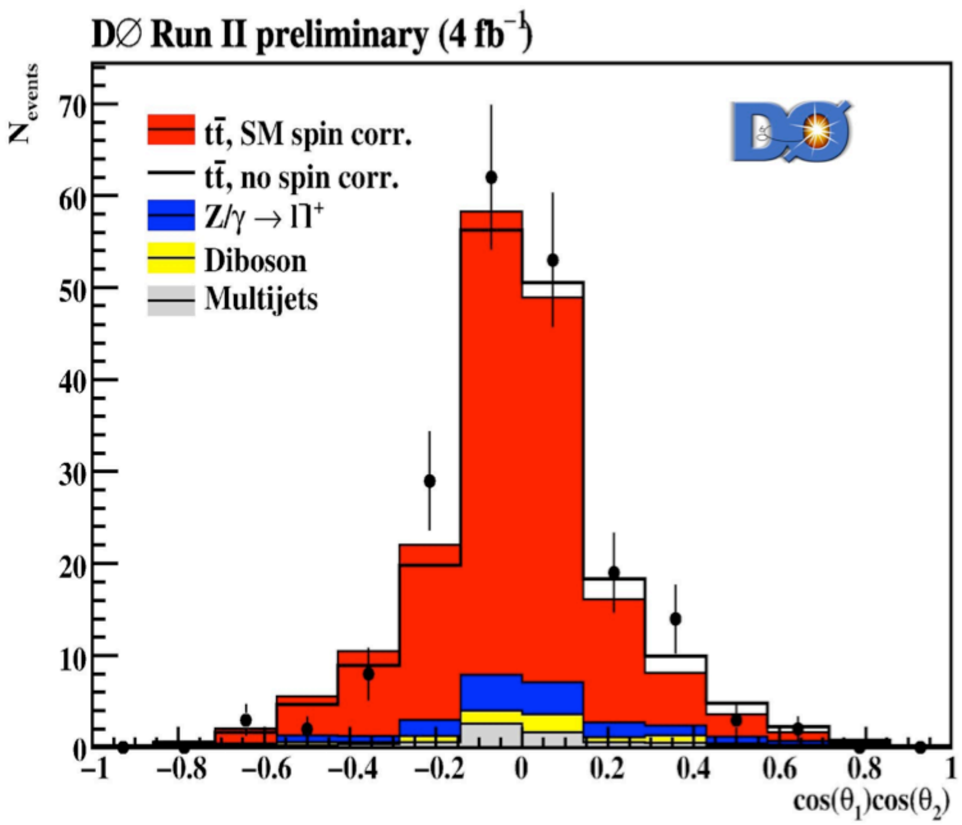
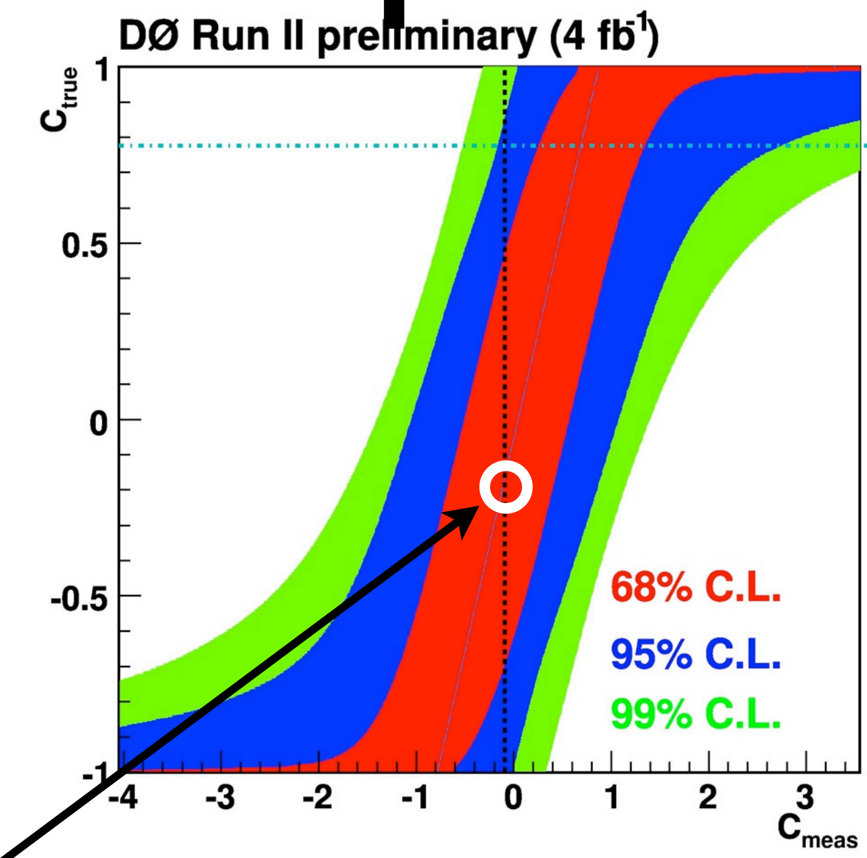
Results in Dilepton



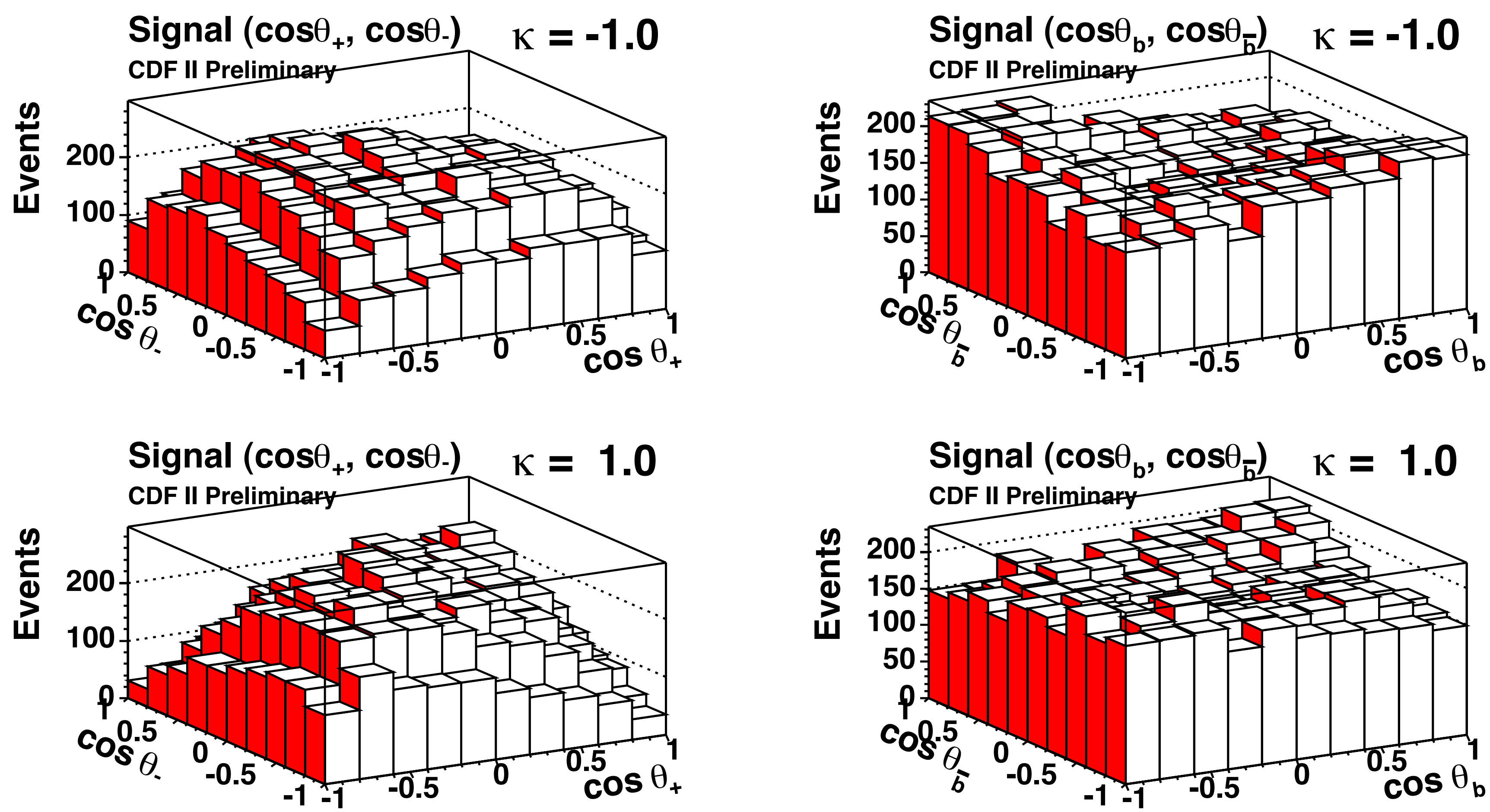


$$C = -0.17^{+0.65}_{-0.53}(\mathrm{stat} + \mathrm{syst})$$

SM beamline basis C=0.777

- Uses angles of the two leptons.
- Fit for fraction of no spin and SM spin contribution.
- Use Feldman-Cousins prescription for limit setting.

Results in Dilepton



- Using 2D templates for both lepton and b jet angles.
- Fit analytic functions to histograms and perform unbinned likelihood fit for C.

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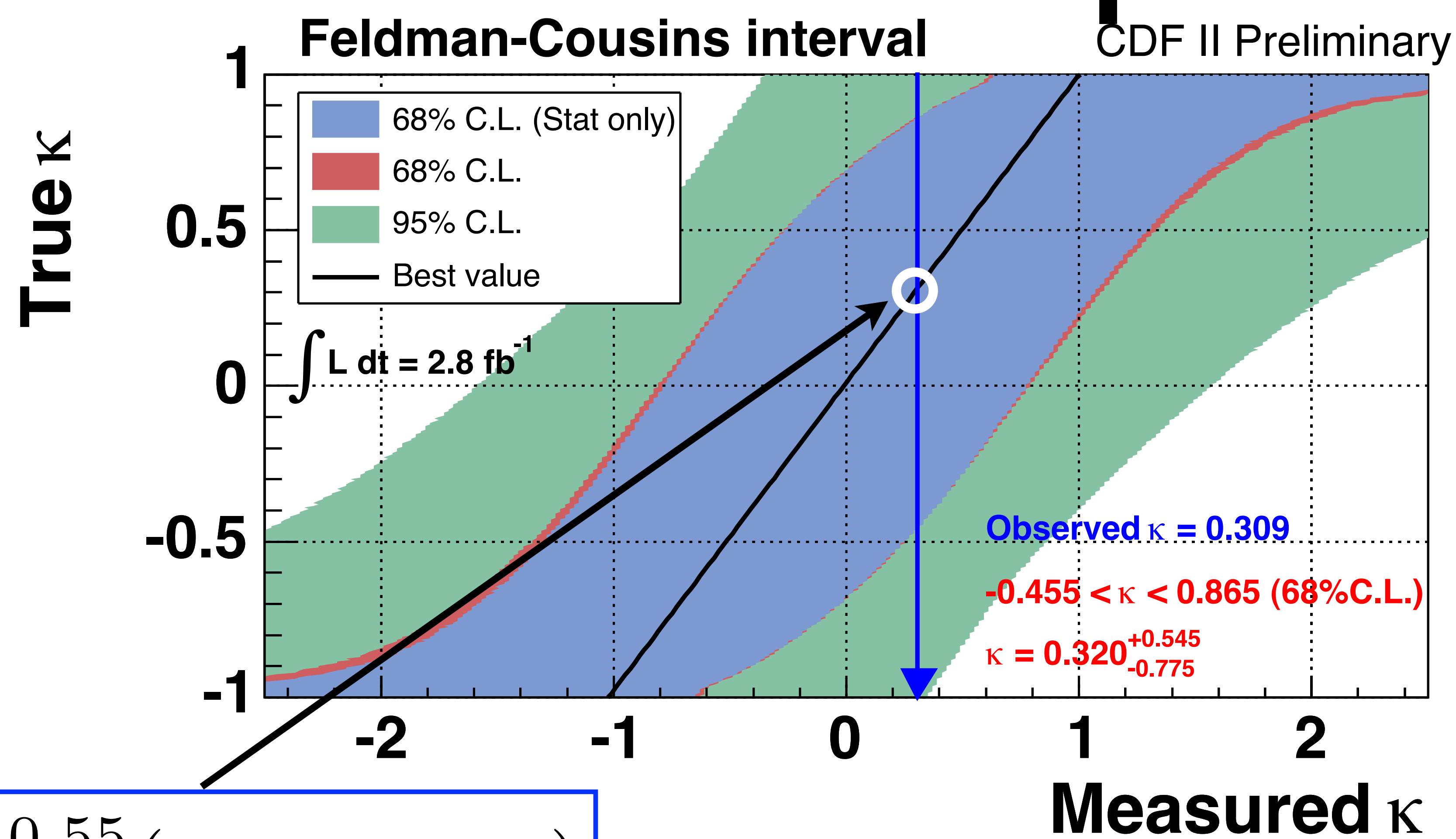
Results in Dilepton

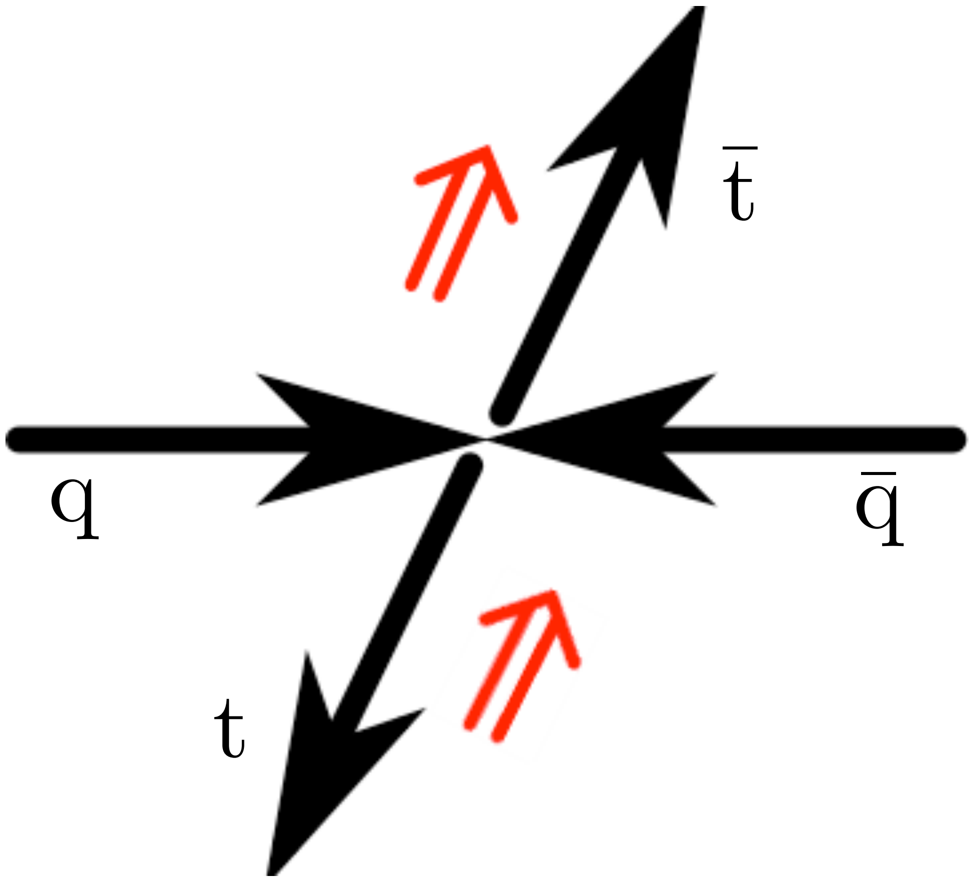


$$C = 0.32^{+0.55}_{-0.78}(\text{stat} + \text{syst})$$

SM off-diagonal basis C=0.782

- Using 2D templates for both lepton and b jet angles.
- Fit analytic functions to histograms and perform unbinned likelihood fit for C.

Results in Lepton + Jets

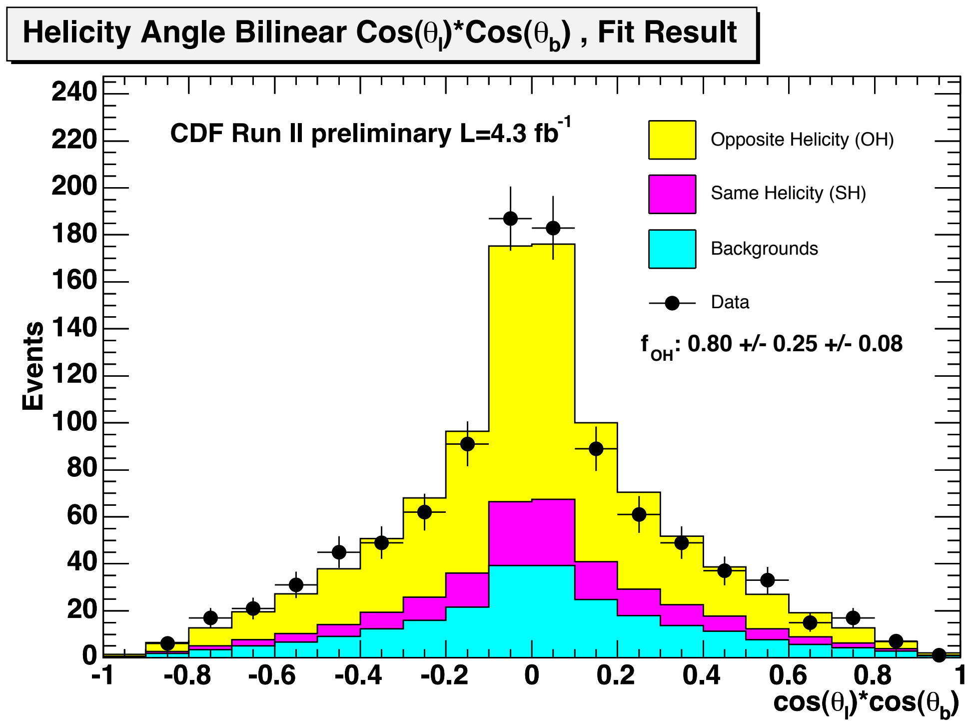


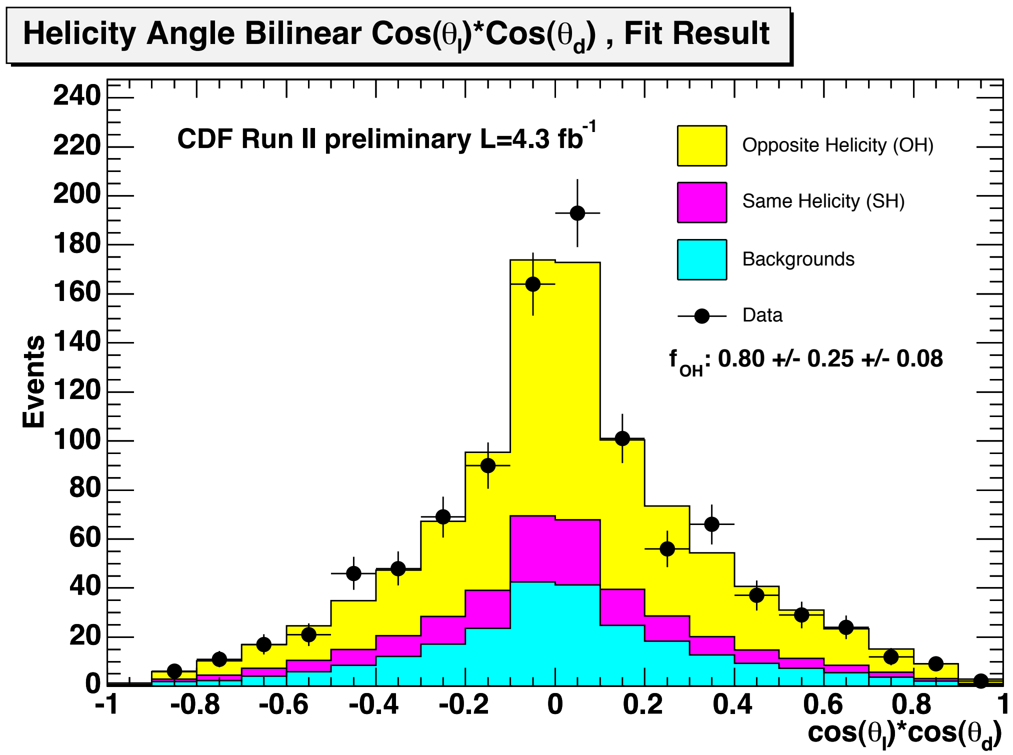
$$f_0 = \frac{\sigma\left(\bar{t}_R t_L\right) + \sigma\left(\bar{t}_L t_R\right)}{\sigma\left(\bar{t}_R t_R + \bar{t}_L t_L + \bar{t}_R t_L + \bar{t}_L t_R\right)}$$

- Opposite helicity states dominate at low β.
- Use templates for same and opposite helicity states.
- Helicity fraction easily translated: $C = 2f_0 - 1$

S. Willenbrock, Phys. Lett. B374, 169 (1996)

Results in Lepton + Jets





$$f_0 = 0.80 \pm 0.25(\text{stat}) \pm 0.08(\text{syst})$$
$$C = 0.60 \pm 0.50(\text{stat}) \pm 0.16(\text{syst})$$

SM helicity basis C=0.4

- Opposite helicity states dominate at low β.
- Use templates for same and opposite helicity states.
- Helicity fraction easily translated: $C = 2f_0 - 1$

Systematic Uncertainties

- Statistics, statistics, statistics.
- Largest systematic is ≈ 0.2.
  - A factor of 2.5 smaller than statistical uncertainty of 0.5.
- Main uncertainties come from:
  - PDF set used for generation,
  - assumed top mass during reconstruction,
  - jet energy scale,
  - and signal and background modelling.

Conclusions

- Top quarks are unique, we can use their decay products to analyse their spin.
- Three measurements since summer 2009!
    - Before only one Run1 measurement with six events.
- Measurements so far compatible with SM.
- Tevatron has delivered 7fb^{-1} by now, expect updates soon!
- Planning a combination of Tevatron results.