Measurement of top pair spin correlation using CDF Run II lepton+jets data

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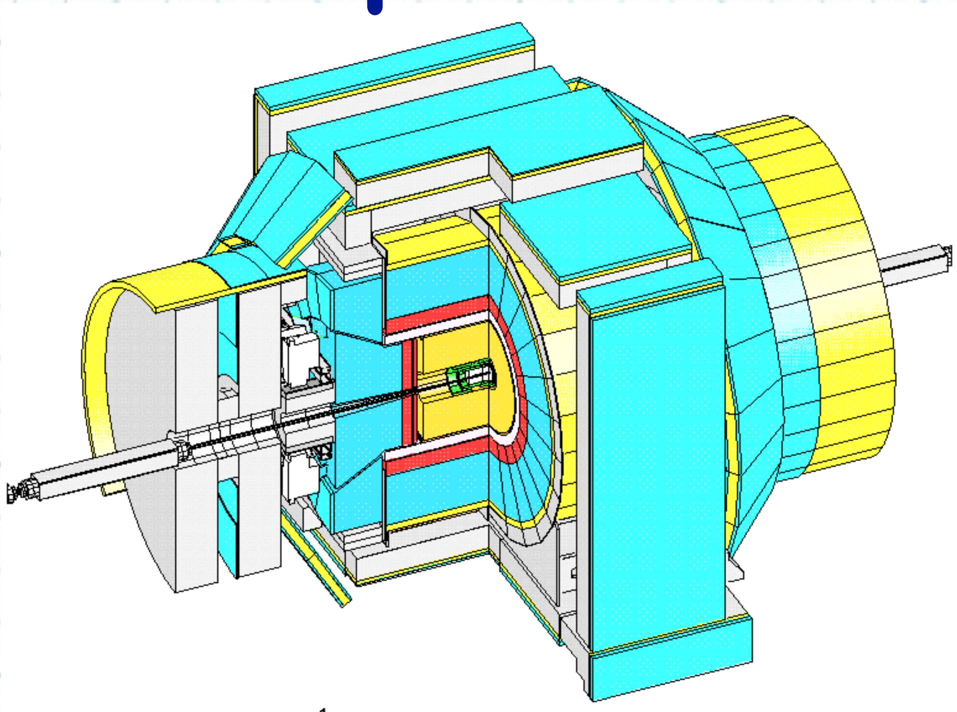
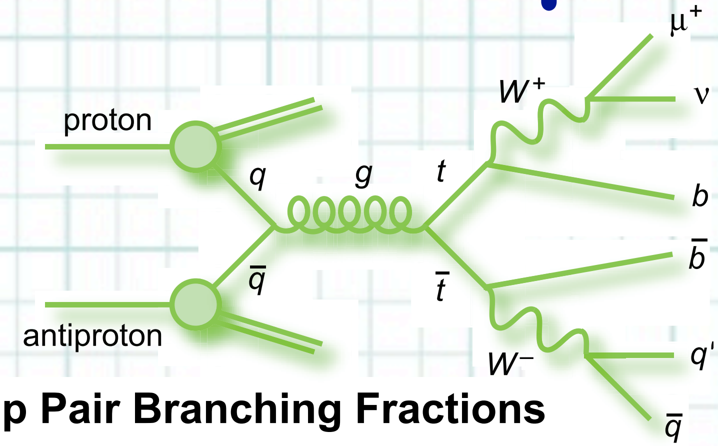
Introduction

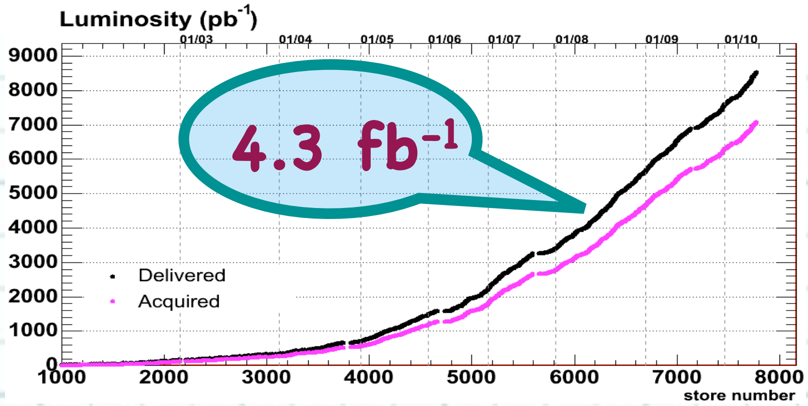
- Top pairs produced through a spin 1 gluon. Conservation of angular momentum implies:
  - top pairs from qqbar annihilation tend to be produced in unlike helicity states
  - gluon fusion prefers like-helicity tops
- Top pairs @Tevatron produced mostly (85%) by qqbar annihilation hence creating polarized tops !

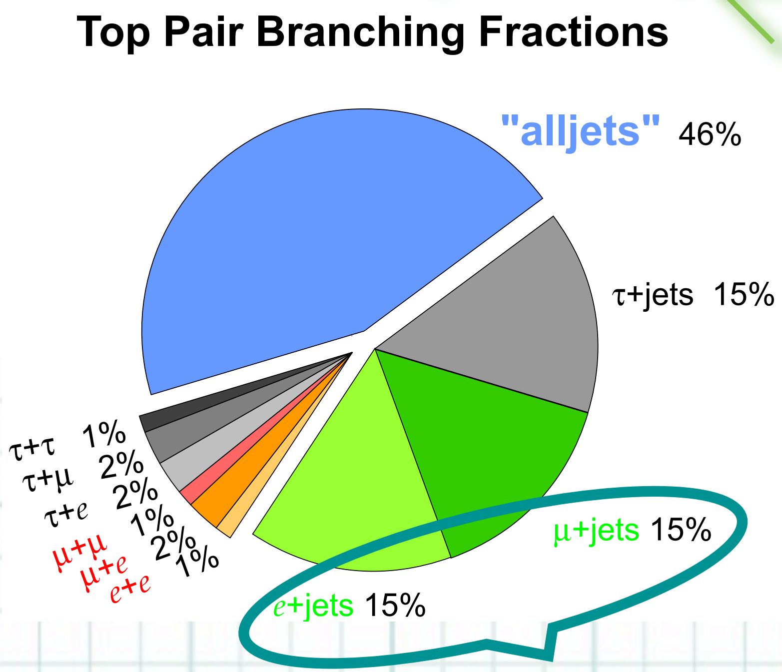
- A light quark always undergoes hadronization into meson or baryon on the time scale of $m_q/\Lambda^2_{QCD} = 3\times10^{-24}$ s
- Top quark is very heavy with $m_t = 173$ GeV/c^2 and narrow $\Gamma \approx 1.4$ GeV so lifetime 4×10^{-25} s short, so no hadronization
- Tops spin information passed on to decay products !

Experimental Setup









30% lepton+jets

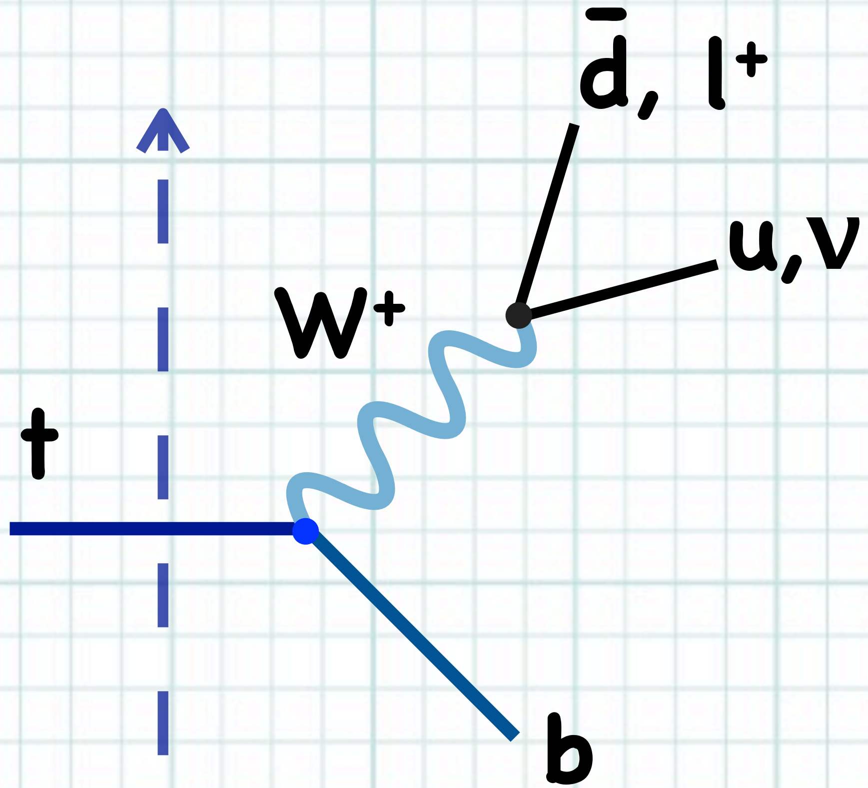
Polarization in Top Decay

Look at angles θ_i between top spin axis and momenta of decay partons in parent top rest frame

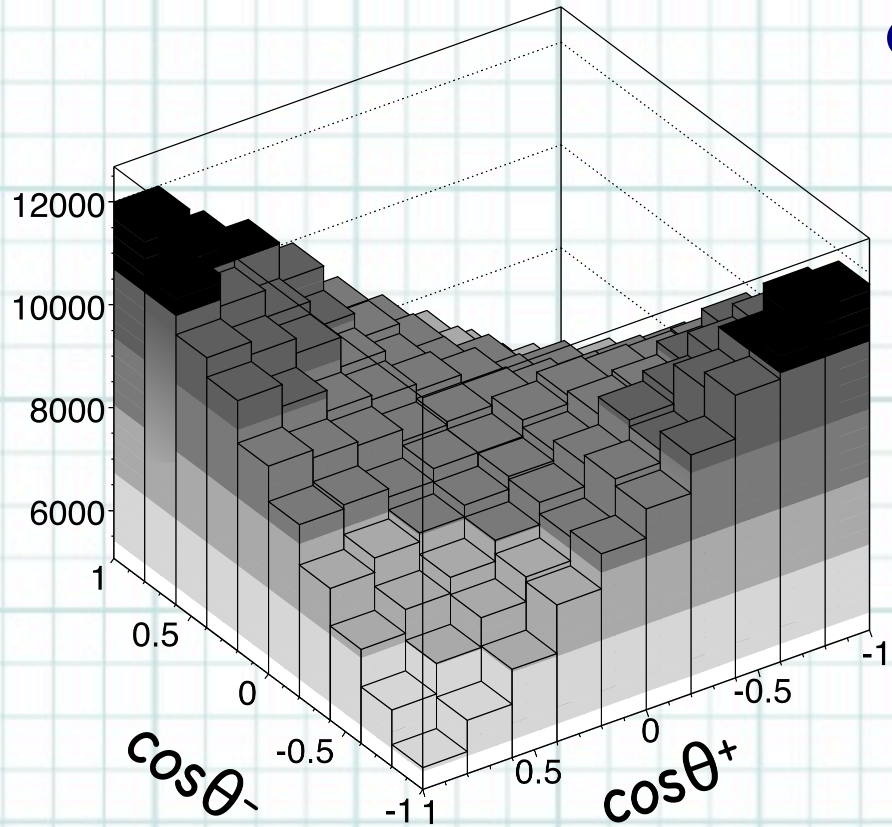
$$f(\cos\theta_i) = \frac{1}{2}(1 \pm \alpha_i \cdot \cos\theta_i)$$

- α_l = 1.0 for leptons and down-quarks - best analyzer!
- α_b = -0.41 for b-jets
- α_ν = -0.31 for neutrino and up

Use positive sign for right-handed top t_R and negative for left-handed top t_L (reverse for antitop)



Correlation Coefficient



- For certain choices of spin quantization axis we have

$$\frac{1}{\sigma}\frac{d^2\sigma}{d(\cos\theta_i^+)d(\cos\theta_j^-)} =$$

$$= \frac{1-\kappa\alpha_i\alpha_j\cos\theta_i^+\cos\theta_j^-}{4}$$

where κ is the spin correlation coefficient

$$\kappa = \frac{[\sigma(\bar{t}_R t_L)+\sigma(\bar{t}_L t_R)]-[\sigma(\bar{t}_R t_R)+\sigma(\bar{t}_L t_L)]}{\sigma(\bar{t}_R t_R)+\sigma(\bar{t}_L t_L)+\sigma(\bar{t}_R t_L)+\sigma(\bar{t}_L t_R)}$$

Analysis Approach

- Assuming P-conservation

$$\sigma(\bar{t}_R t_L) = \sigma(\bar{t}_L t_R) = \sigma_o$$

- Assuming CP-conservation

$$\sigma(\bar{t}_R t_R) = \sigma(\bar{t}_L t_L) = \sigma_s$$

then spin correlation is the difference between opposite helicity top pair fraction and same helicity top pair fraction

$$\kappa = \frac{\sigma_o - \sigma_s}{\sigma_o + \sigma_s} = f_o - f_s$$

- We always assume

$$f_o + f_s = 1$$

- We are measuring

$$f_o = N_o / N$$

- We choose "helicity basis" for which top polarization axis is the direction of top in top pair rest frame

- Theoretical prediction

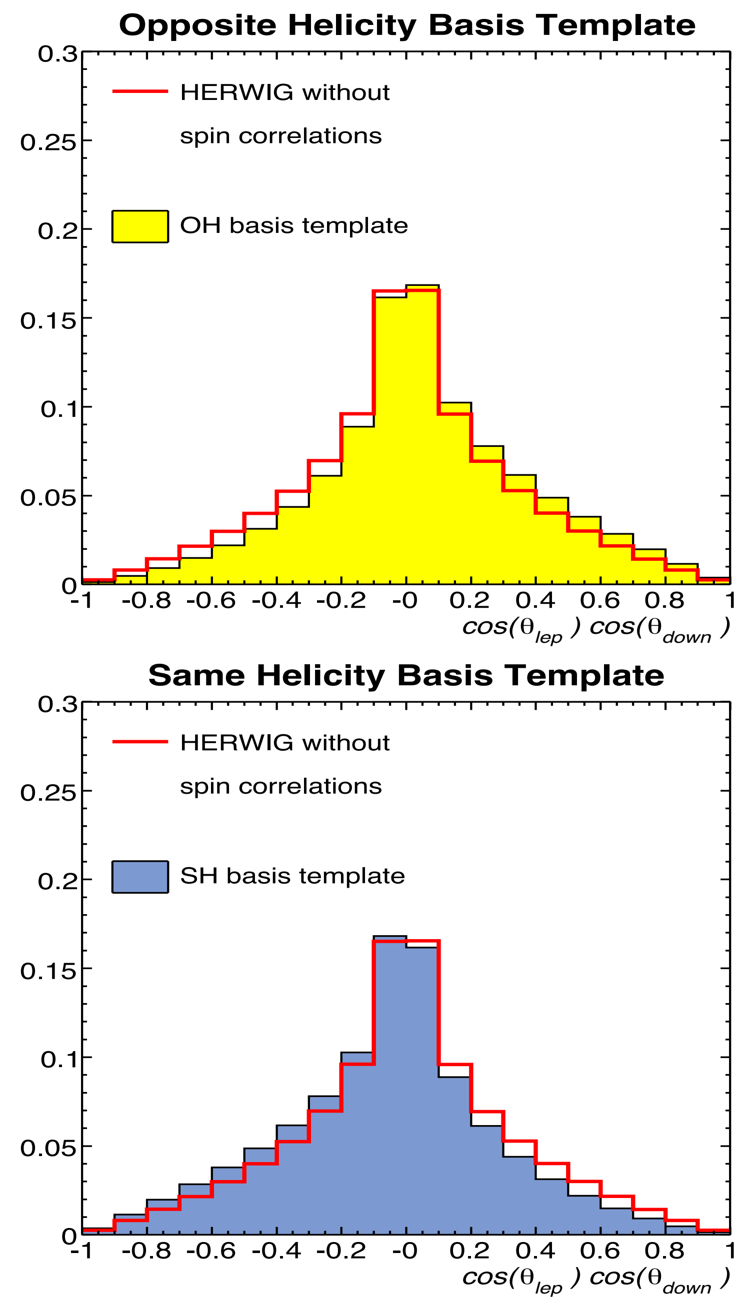
$$f_o = 0.67 \quad \kappa_{hel} = 0.34$$

Method

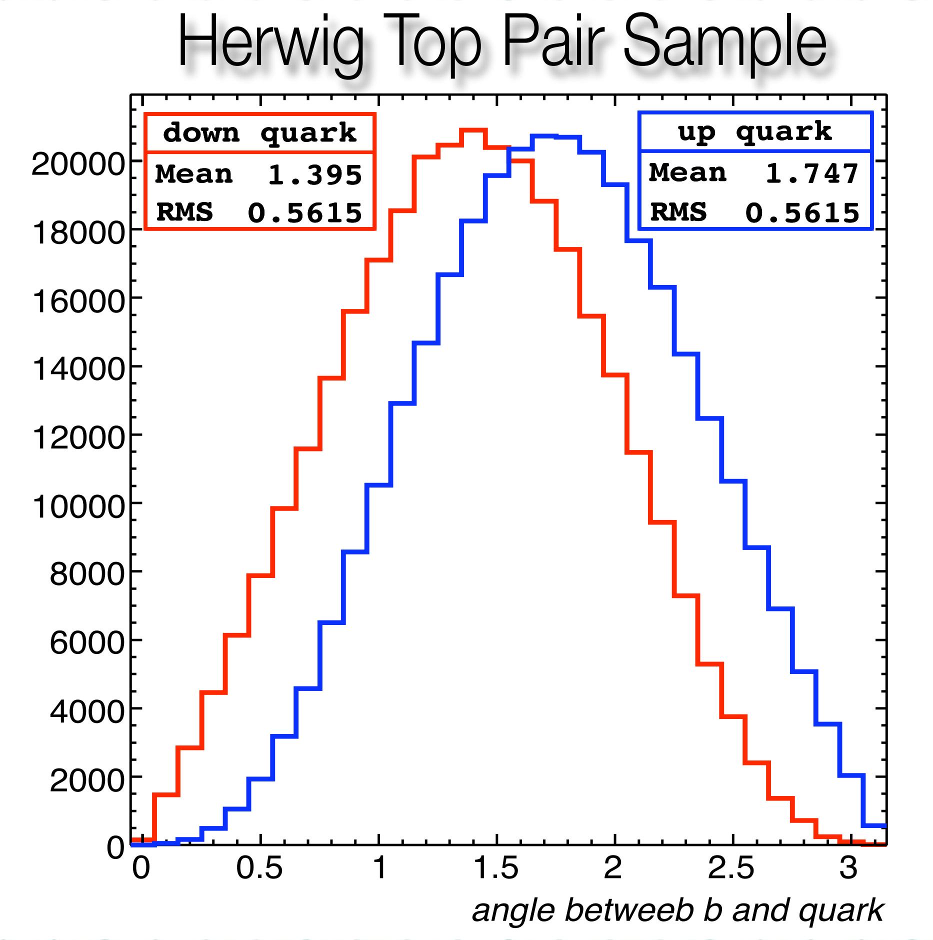
- Construct two signal models for the opposite helicity (OH) and the same helicity (SH) tops
- Use binned likelihood fit to sensitive bi-linear statistics in order to extract top pair helicity fraction f_o
- Sensitive bi-linears form 2D distribution

$$\cos\theta_{\mathrm{lep}} \cdot \cos\theta_{\mathrm{d}}$$

$$\cos\theta_{\mathrm{lep}} \cdot \cos\theta_{\mathrm{b.had}}$$



Determining d-Quark



- Analysis uses down quark helicity angle - need to distinguish down from up
- Once jets from W are identified, choose the jet that is closest to the b jet, in the W rest frame, as the down

  G. Mahlon and S. Parke, Phys Lett. **B 411** (1997) 173

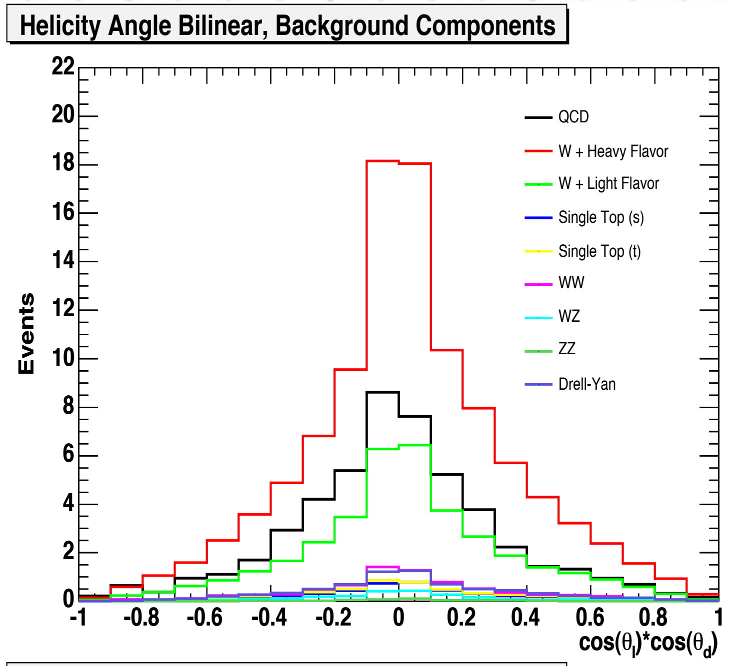
- Correctly identifies the down at a rate of about 60%

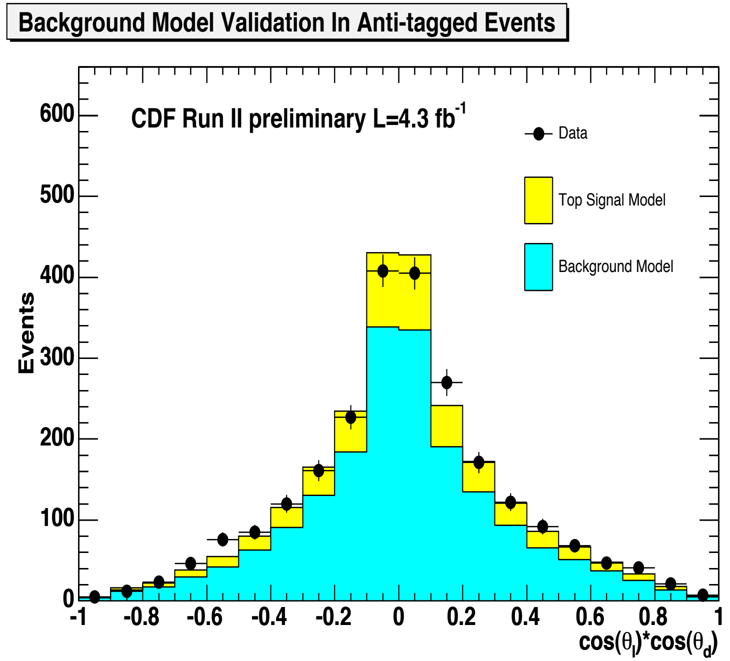
Event Selection and Reconstruction

- We select top pairs in the lepton plus jets decay channel:
  - one lepton with $|\eta|<1$ and $p_T>20$ GeV/c
  - large missing transverse energy MET>20 GeV
  - at least 4 jets with $|\eta|<2$ and $E_T>20$ GeV, one jet must be b-tagged
- Found 1001 candidate events in 4.3 fb^{-1} of CDF data
- Kinematics of lepton plus jets events is well constrained and fully reconstructable
- Out of all possible permutations of jet assignments we chose combination with lowest χ^2
- For mass constraints we use values m_t = 172.5 GeV/c^2 and m_W = 80.4 GeV/c^2
- We assign jets correctly in about 40% of reconstructed events

Backgrounds

- Background prediction is 215±48 events
- Largest components are W + heavy flavor jets and QCD
- Validate background shape using untagged ("anti-tag") sample
- Background shape used as a template in our final fit





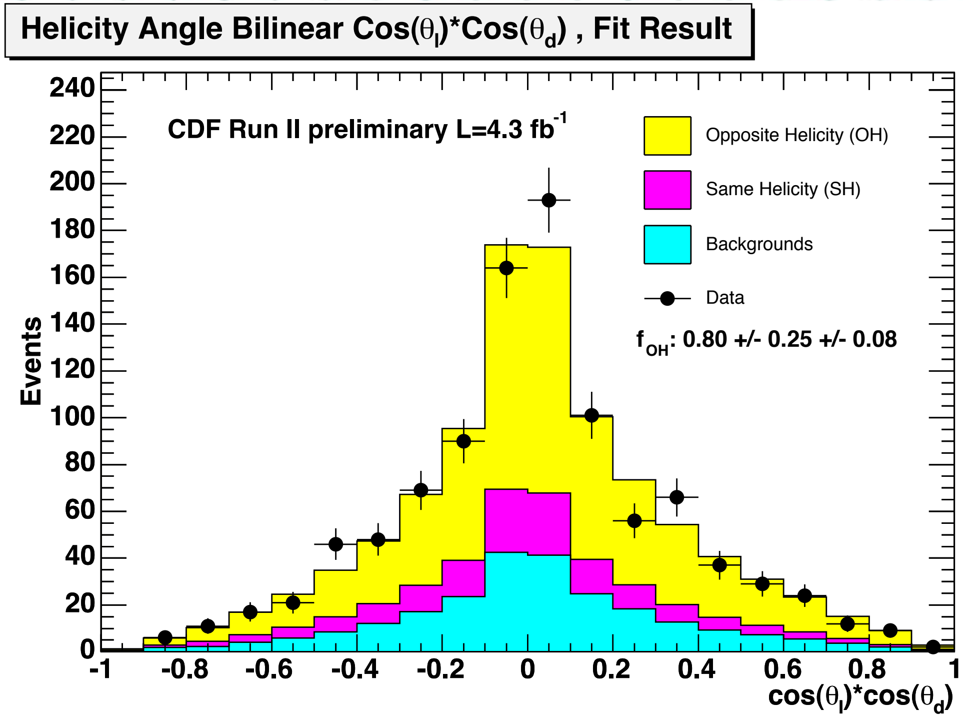
Uncertainty Analysis

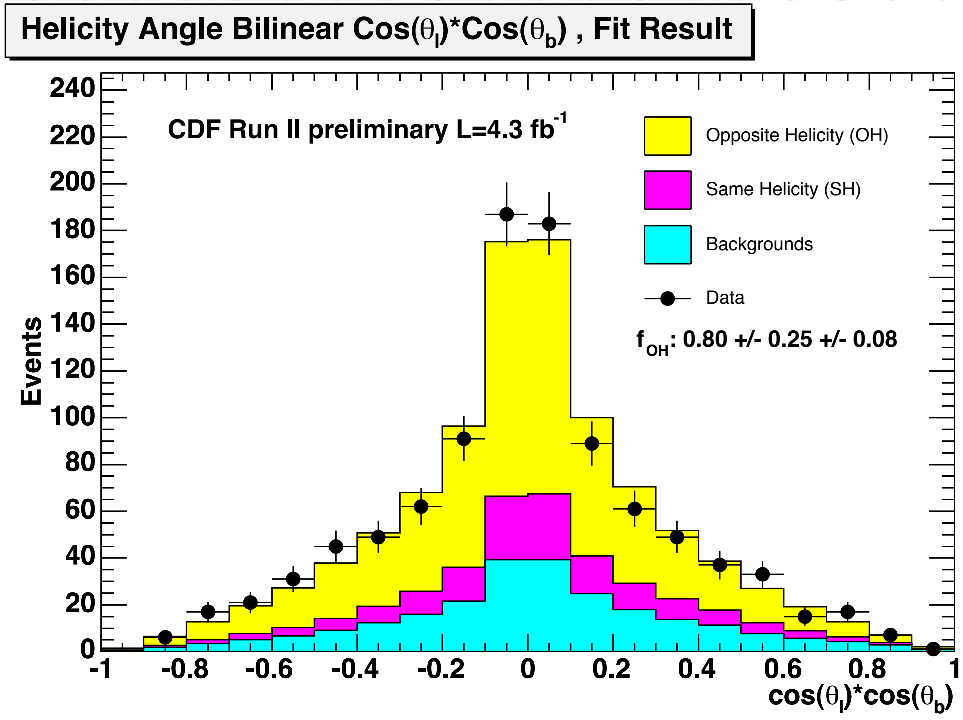
- Binned likelihood fit with signal SH, OH, and background templates
  - background template Gaussian-constrained to prediction
  - helicity fractions f_0 and allowed to float freely
- For nominal signal expected statistical uncertainty is **0.23**
- Other uncertainties evaluated by replacing nominal signal or background templates with systematics models

Source	Uncertainty
Bias Around Null	0.060
JES	0.042
ISR/FSR	0.030
Color Reconnection	0.009
PDF	0.007
Parton Shower	0.006
Background Shape	0.023
Total	0.083

Results with 4.3 fb^{-1}

$$f_o = 0.80 \pm 0.25_{stat} \pm 0.08_{syst}$$





$$K = 0.60 \pm 0.50_{stat} \pm 0.16_{syst}$$

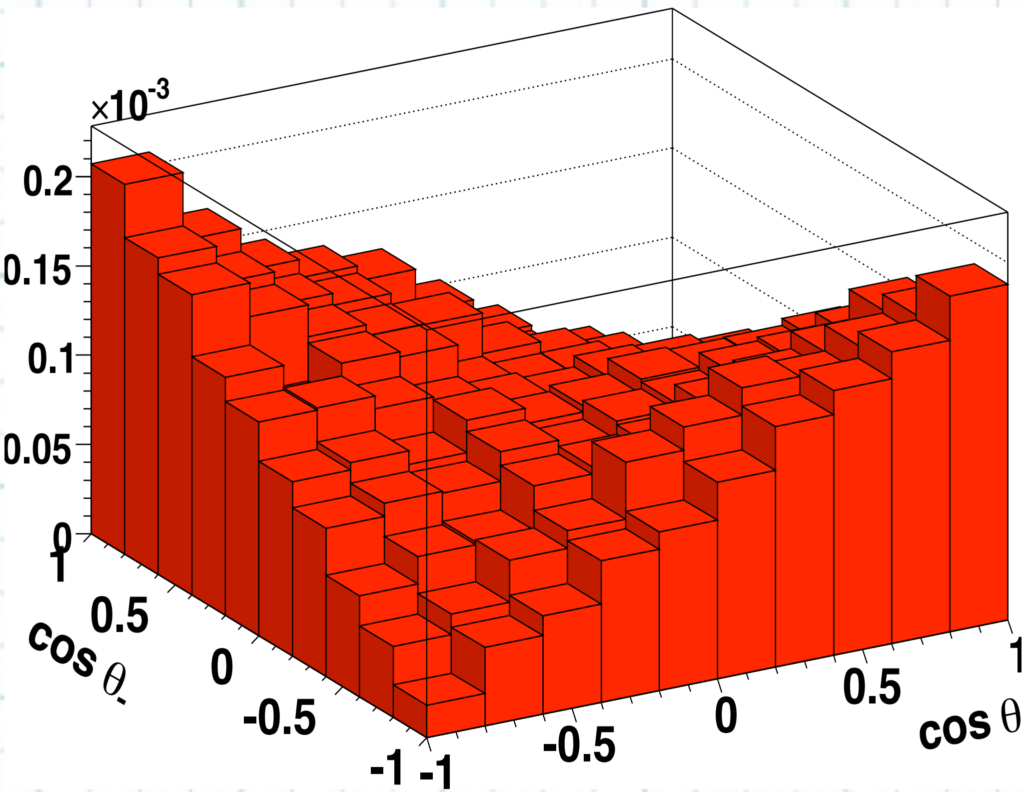
Summary and Outlook

- We have made the first measurement of the top pair spin correlation in the lepton + jets channel
  - fully reconstructable events
  - high statistics
  - rely on W helicity property in top decay to identify down type quark
- Future plans include
  - improve the precision of the result
  - try similar measurement in the beam basis

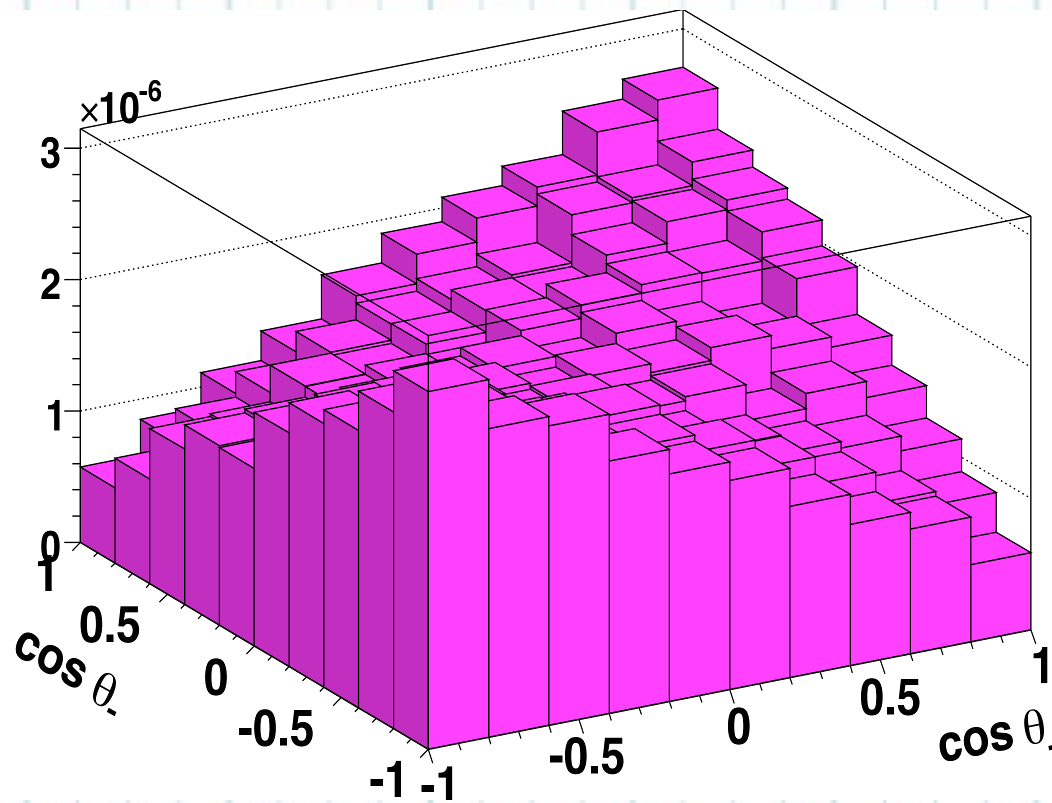
Backup Slides

BSM Top Scenarios

top pairs mediated by J=0



top pairs mediated by J=2



R. Frederix, F. Maltoni arXiv:0712.2355