# Top Properties at Tevatron with the CDF Detector

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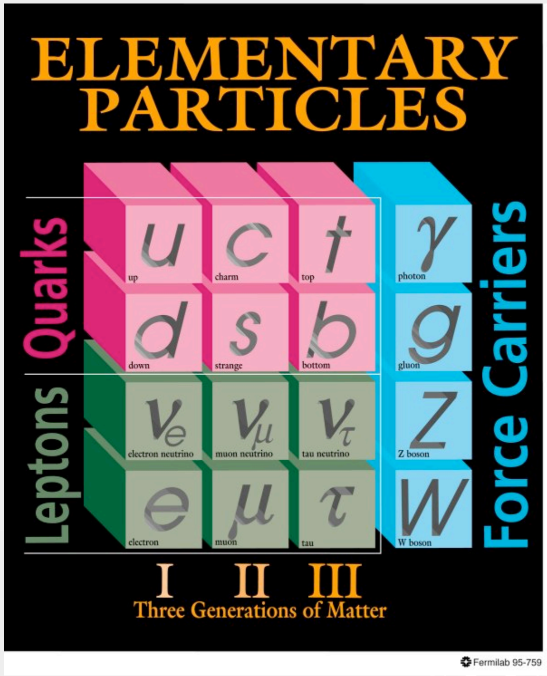
# Outline

- Introduction
- Exploring top properties
  - Forward-backward asymmetry
  - ttbar differential cross section $d\sigma/dM_{ttbar}$
  - W-polarization from top decay
  - Single top polarization
  - Top-quark width
  - Top-quark charge
- Summary and prospects

# Top Quark Physics

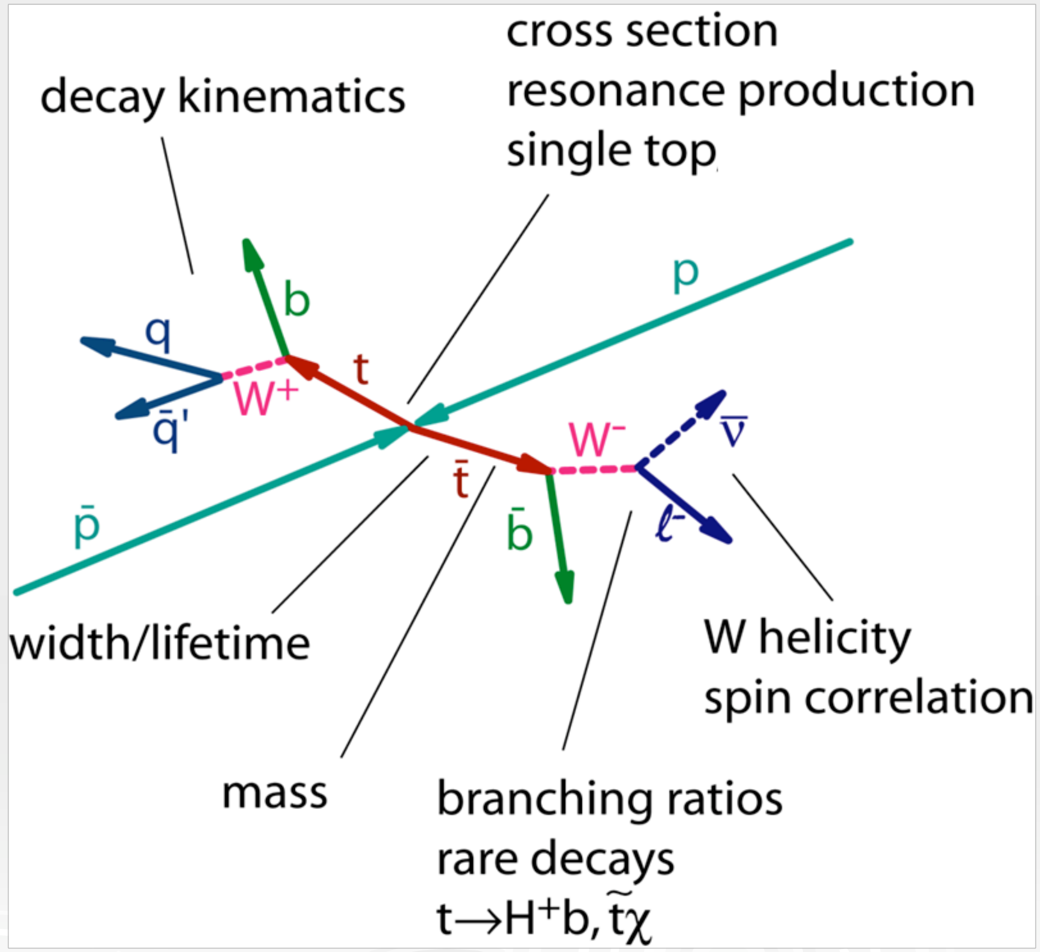
- Existence required by the SM
  - Spin 1/2 fermion, charge +2/3, weak-isospin partner of the bottom quark
- Discovered in 1995 at Tevatron
- Mass surprisingly large ⇒ ~40x heavier than the bottom quark
  - Only SM fermion with mass at the EW scale
- Top decays before hadronization: $\Gamma \sim 1.4$ GeV $\gg \Lambda_{QCD}$
  - Provide an unique opportunity to study a "bare" quark



# Why Study Top Properties?

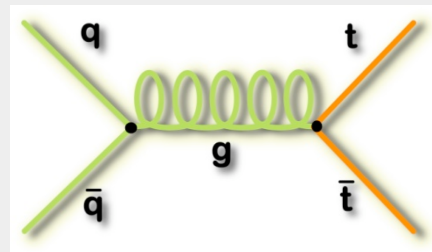
Try to address some of the questions:

- Why is top so heavy ?
- Is top related to the EWSB mechanism?
- Is it the SM top?
- Search for beyond SM physics
  - Does top decay into new particles?
  - Couple via new interactions?

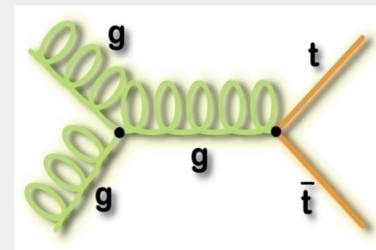


# Top Quark Production at Tevatron

- Predominantly pair produced via strong interaction
  - $\sigma_{tt} = 7.45^{+0.72}_{-0.63}$ pb
  for $m_{top}$=172.5 GeV/$c^2$ (Nucl. Phys. Proc. Suppl. 183, 75 (2008))

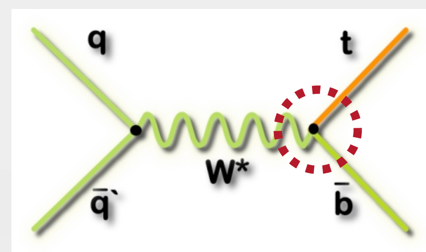


~85% from qq→tt

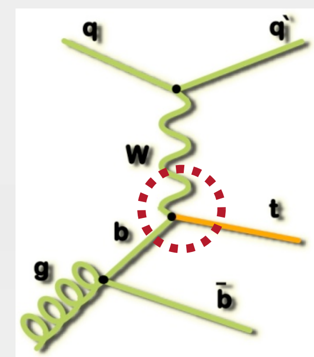


~15% from gg→tt

- EW single top production
  - $\sigma_{s\text{-channel}}$ =0.88 ± 0.11 pb
  - $\sigma_{t\text{-channel}}$ =1.98 ± 0.25 pb
  for $m_{top}$ = 175 GeV/$c^2$ (PRD 70, 114012 (2004))



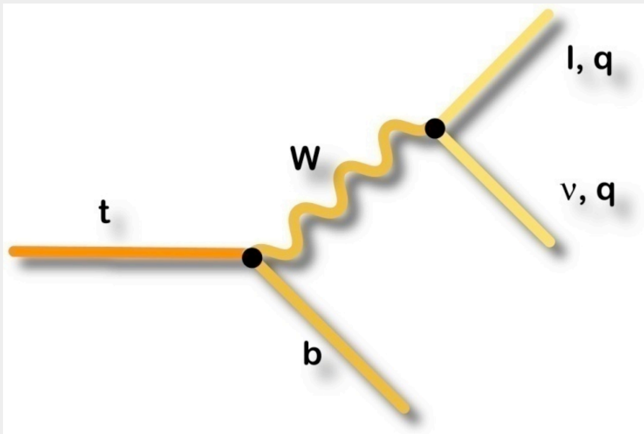
**s-channel**

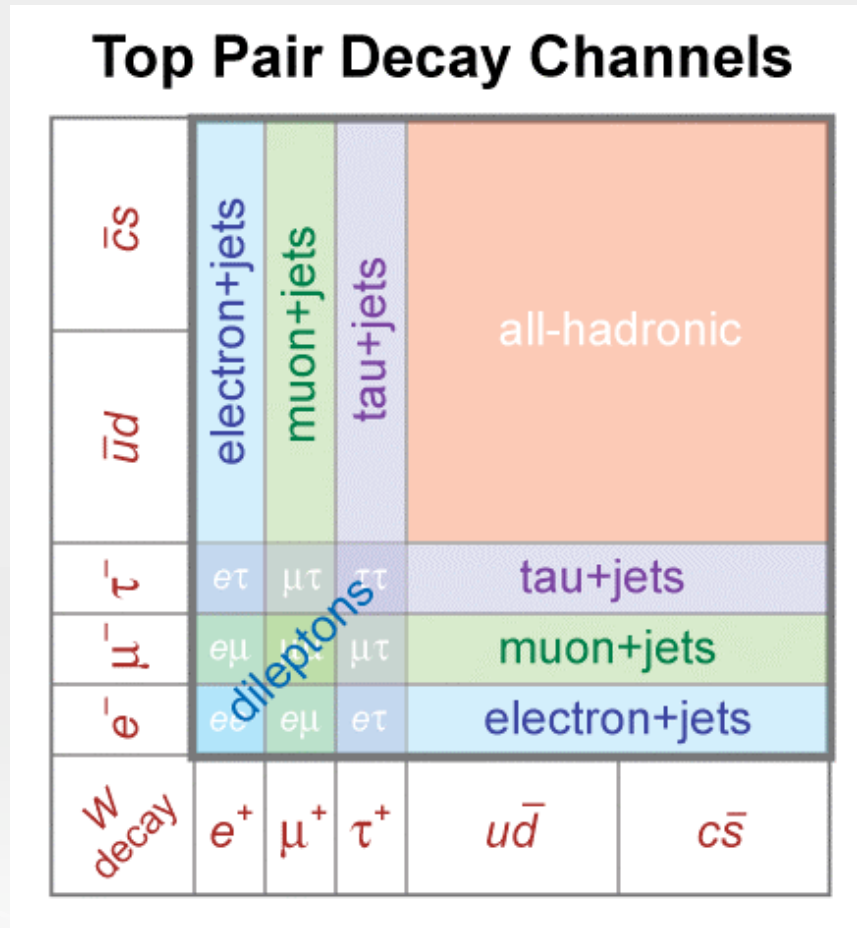


**t-channel**

Rare at Tevatron: One top pair (ttbar) per 10 billion inelastic collisions

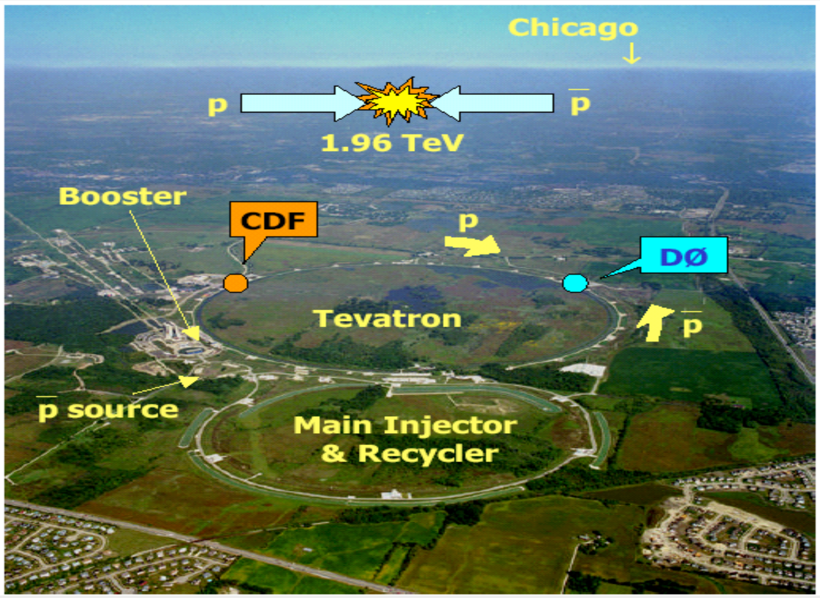
# Top Quark Decay

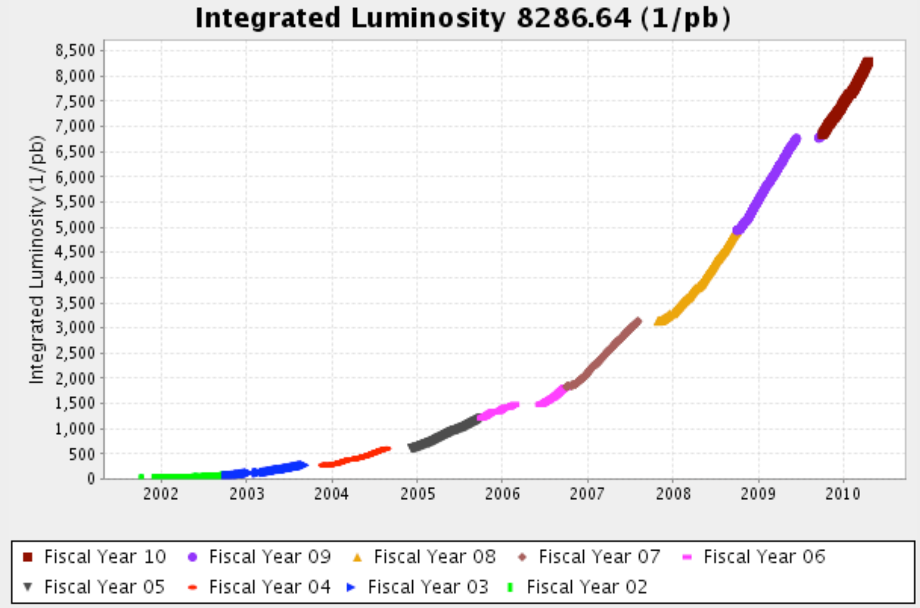


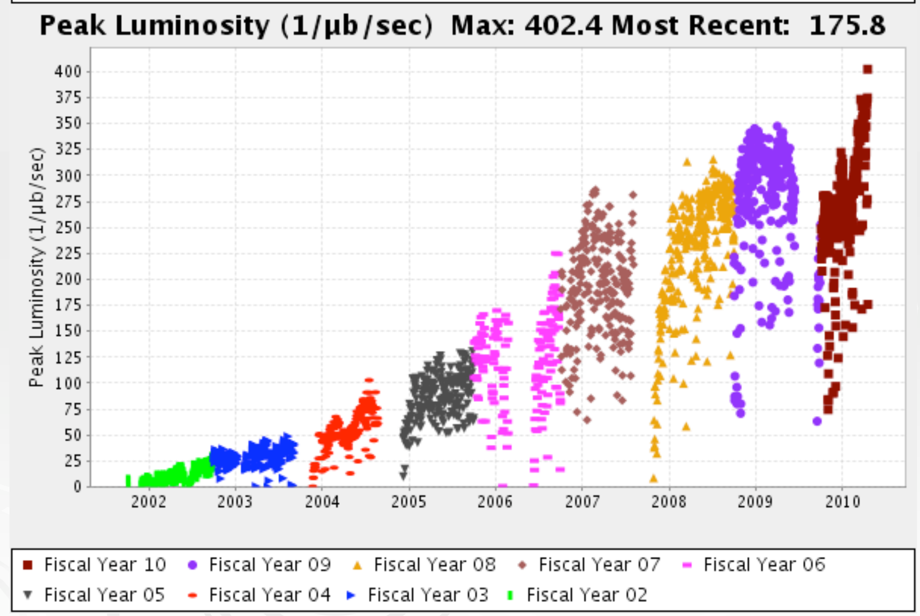




- In the SM: Br(t →Wb) ~ 100%
- Decay channels classified by W decays
- Top pair decay channels (*l=e,μ*)
  - Dilepton (DIL): *lνlνbb (5%)*
  - Lepton+jets : *lνqqbb (30%)*
  - All-hadronic: *qqqqbb (45%)*

# Tevatron Run II



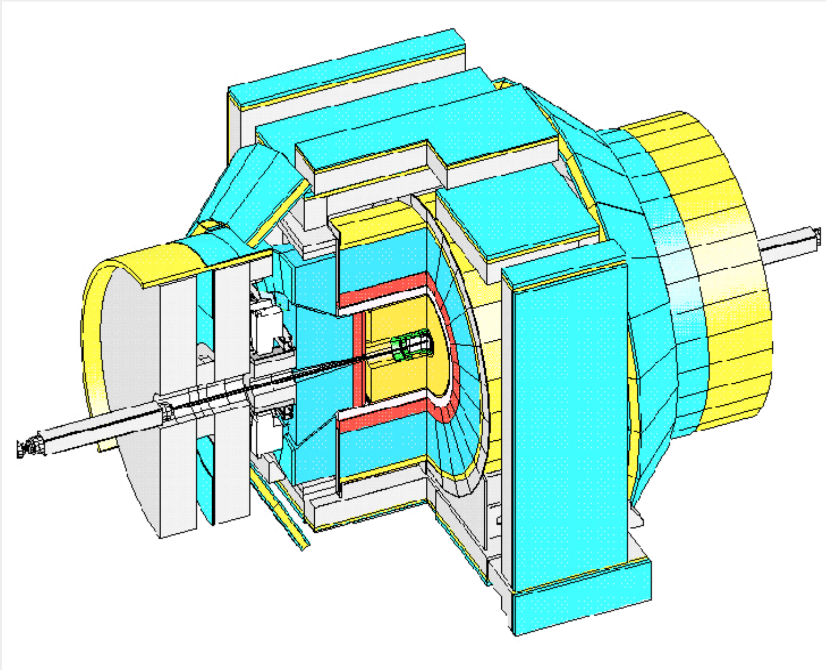

**Tevatron Run II**

**Proton-antiproton collider (2001-2011)**

$\sqrt{s}$ = 1.96 TeV

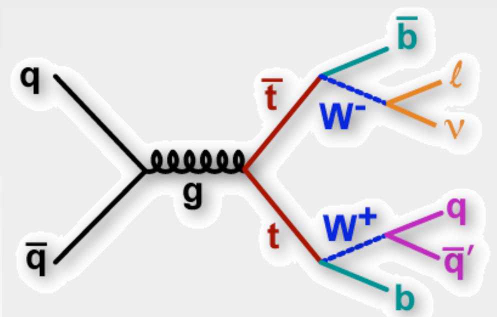
- Total integrated luminosity delivered : ~8 $fb^{-1}$
  - ~7 $fb^{-1}$ recorded per experiment
  - Results presented in this talk uses up to 4.3 $fb^{-1}$

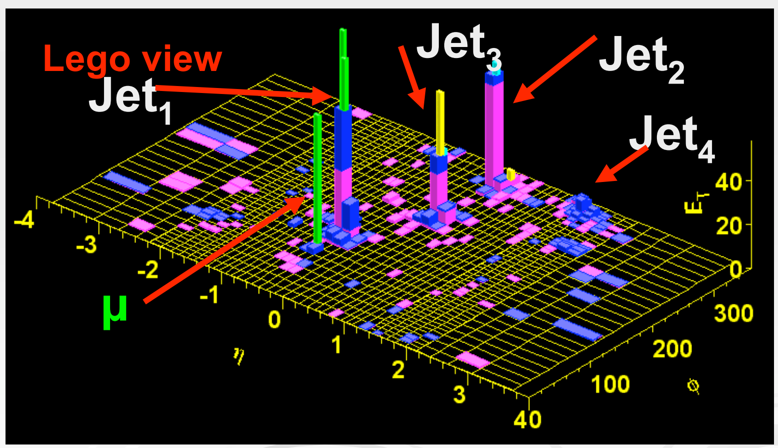
# The CDF Detector

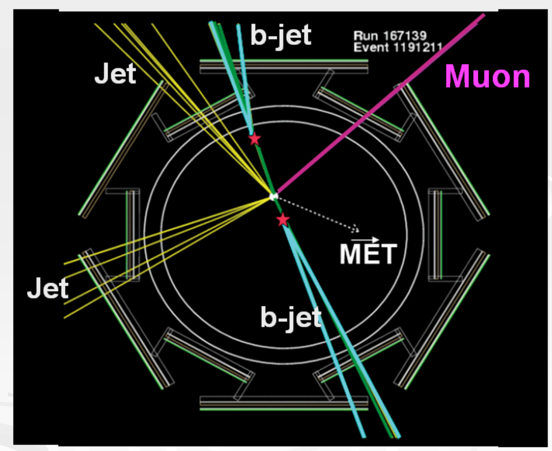


- Silicon tracking
- Large radius drift chamber (r=1.4m)
- 1.4 T solenoid
- Projective calorimetry (|η| < 3.5)
- Muon chambers (|η| < 1.0)
- Particle identification
- Silicon Vertex Trigger

***All crucial for top physics!***



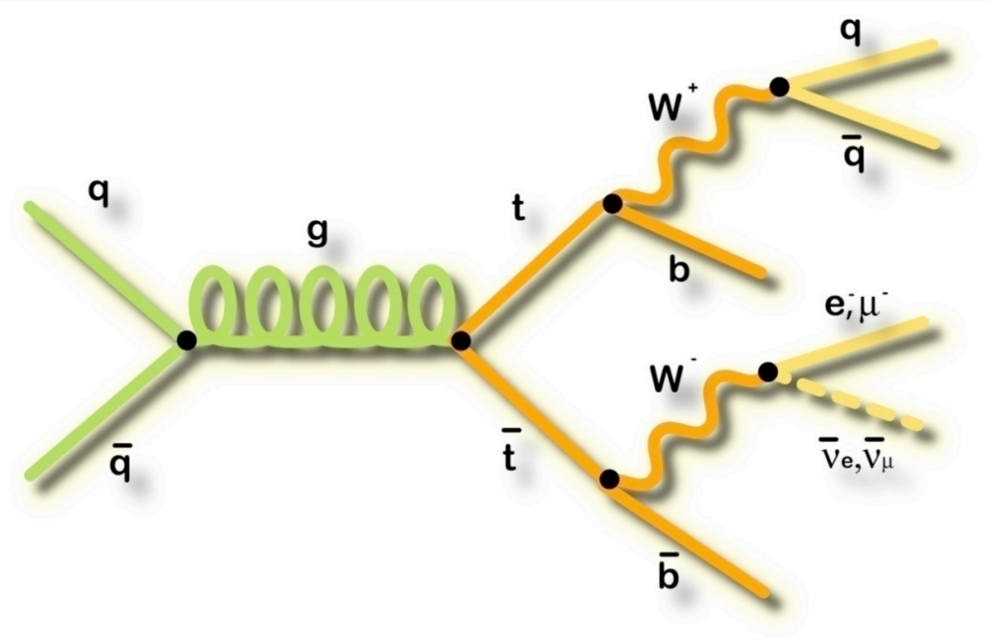



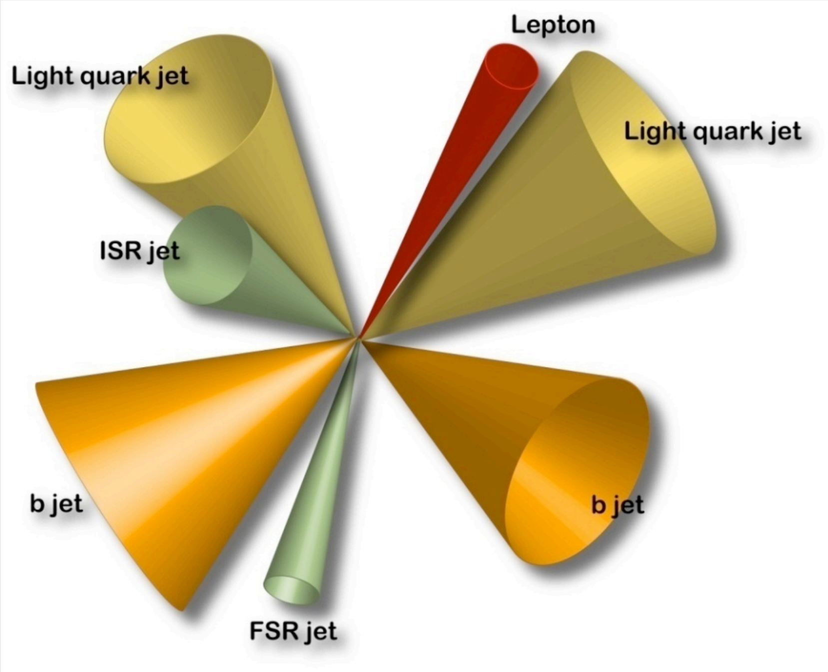
# Other Talks Covering Top Physics at CDF

- *ttbar cross section measurements at Tevatron*
  - *F. DELIOT, 31 May 2010*
- *Top mass measurements at the Tevatron*
  - *O. BRANDT, 01 June 2010*
- *Multivariate analysis techniques: the Tevatron experience*
  - *F. CANELLI, 01 June 2010*
- *Observation of single top at Tevatron with the CDF detector*
  - *J. LUECK, 01 June 2010*
- *V+jets at Tevatron*
  - *L. CERRITO, 02 June 2010*
- *Spin correlations at Tevatron*
  - *T. HEAD, 03 June 2010*
- *New Physics searches in top events at Tevatron*
  - *P. SINERVO, 03 June 2010*

# Experimental Challenges




Final State from Leading Order Diagram

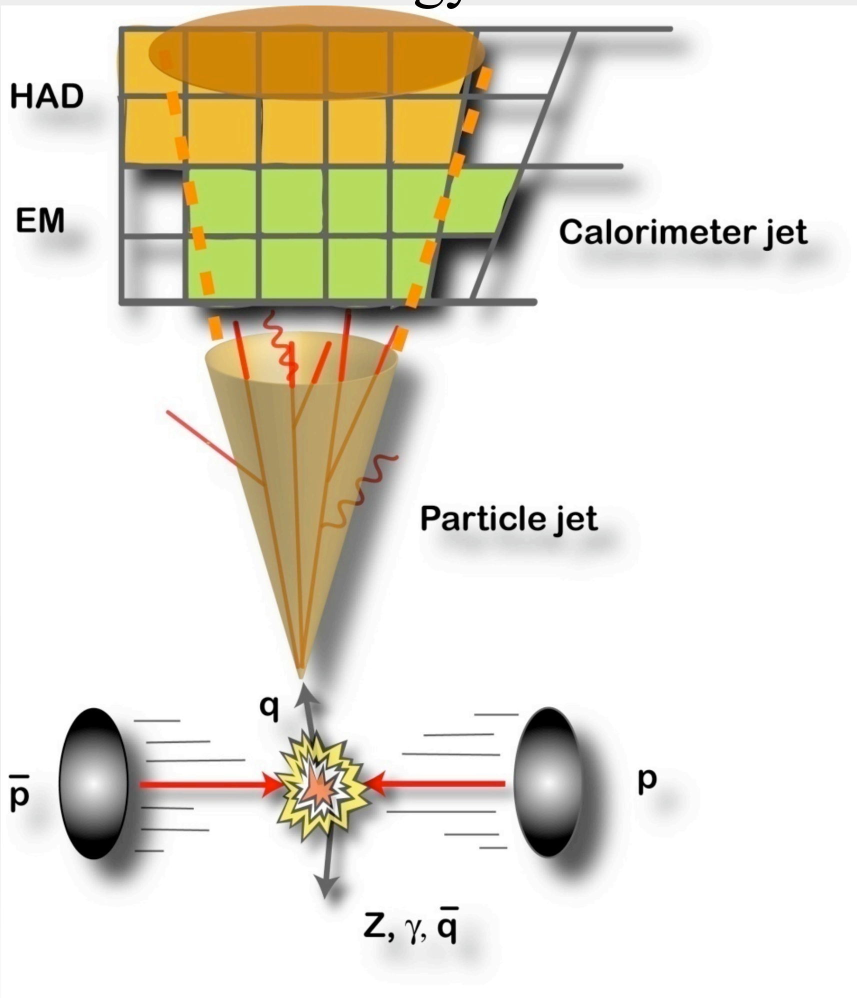



What we measure

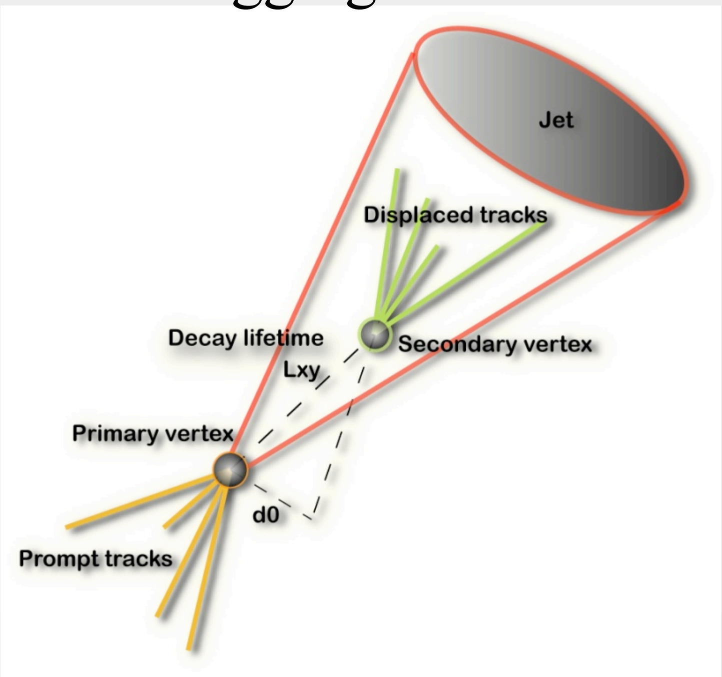
- Combinatorial background and jet-parton assignment
  - Dilepton (DIL): 2 combinations
  - Lepton+Jets: 12 (0 b tag), 6 (1 b tag), and 2 (2 b tags)
  - All hadronic: 90 combinations (0 b tag), 30 (1 btag), 6 (2 btags)

# Experimental Challenges (Cont')

Jet Energy Scale

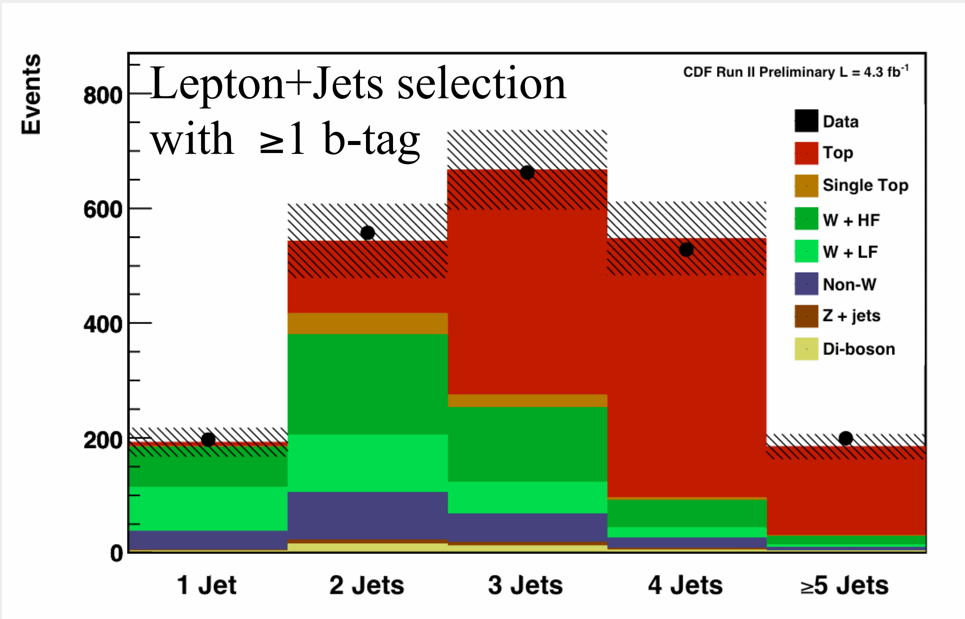


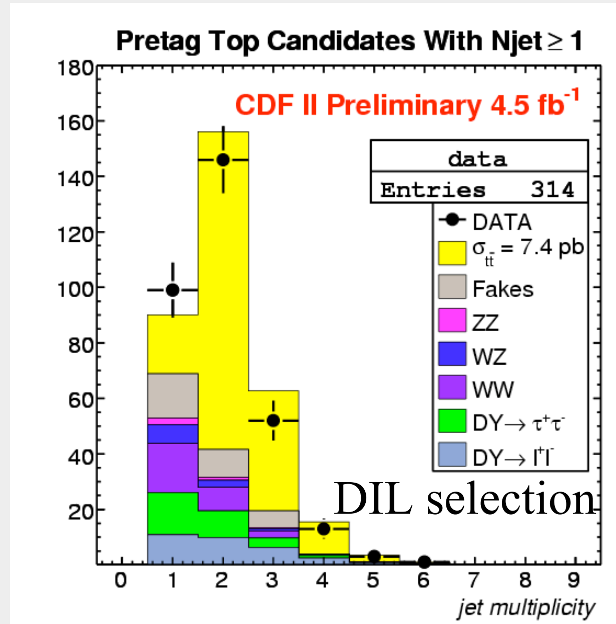

b-tagging




And more: background and signal modeling, background estimation, etc.

# Sample Composition




Sample composition based on ttbar cross section measurement

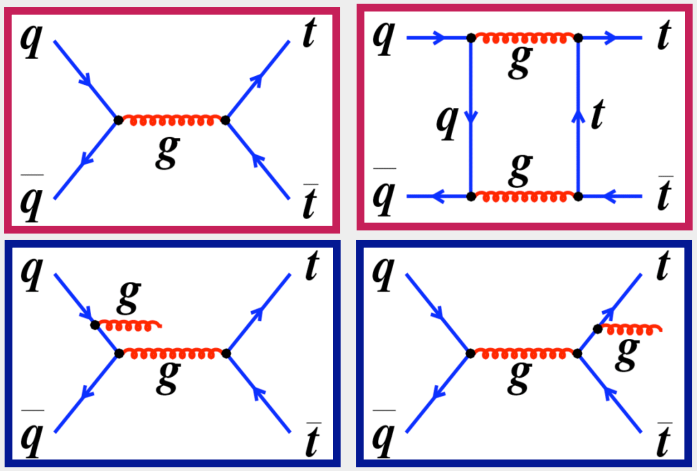
| S/B at CDF | Dilepton (≥2 jets) | Lepton+Jets (≥4 jets) | All-hadronic (6-8 jets, after NN Selection) |
|---|---|---|---|
| 0 b-tag | 1:1 | ~1:4 | ~1:20 |
| 1 b-tag | 20:1 | 4:1 | 1:4 |
| 2 b-tags | | 20:1 | 1:1 |

Most top properties analyses use relatively clean event sample

# Analyses

# Forward Backward Asymmetry ($A_{fb}$) in Top Pair Production

- Asymmetry caused by interference of ME amplitudes for same final state




- The SM prediction:
  - In ppbar frame: $A_{fb}^{ppbar} = 0.05 \pm 0.015$ (QCD at NLO)
- Can be significantly enhanced in different BSM models:
  - Z'-like states with parity violating coupling (PLB 387, 113 (1996)), theories with chiral color (PLB 190, 157 (1987), PLB 200, 211(1988))

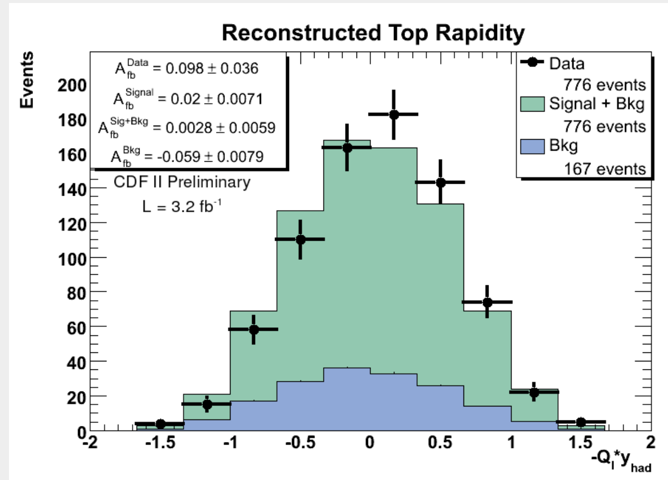
PRL 101, 202001, 2009 **3.2 fb$^{-1}$**

# Forward Backward Asymmetry ($A_{fb}$) in Top Pair Production

- Use Lepton+Jets channel
- $A_{fb}$ measured in the ppbar rest frame

$$A_{fb}^{t\bar{t}} = \frac{N(-Q.Y_{had} > 0) - N(-Q.Y_{had} < 0)}{N(-Q.Y_{had} > 0) + N(-Q.Y_{had} < 0)}$$

*$Y_{had}$ = rapidity of hadronically decaying top*
*Q = lepton charge from leptonically decaying system*




- Apply matrix unfolding to go from reconstructed to parton level
  - Correct for smearing and acceptance effects

$$N_{Corr} = A^{-1}.S^{-1}.N_{bkg-sub}\,,\quad S_{ij} = N^{ij}_{reco}/N^{i}_{gen}\,,\quad A_{ij} = N^{i}_{sel}/N^{i}_{gen}$$

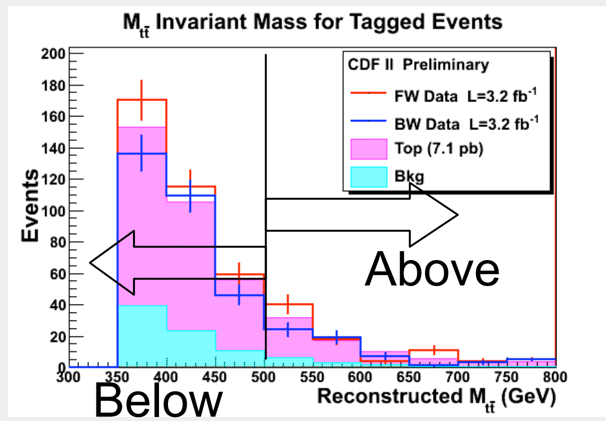
**$A_{fb}$ = 0.193 ± 0.065 (stat) ± 0.024 (syst)**

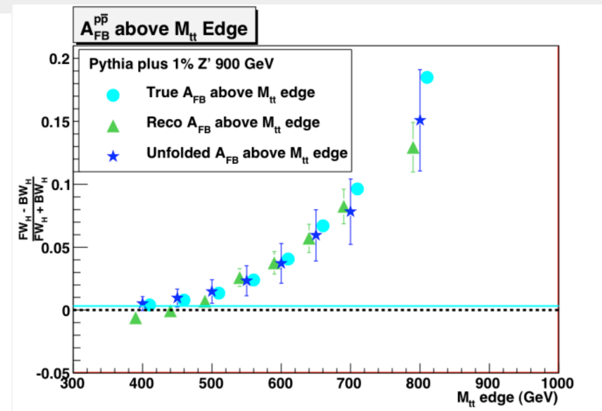
SM prediction $A_{fb}^{ppbar}$ = 0.05 ± 0.015

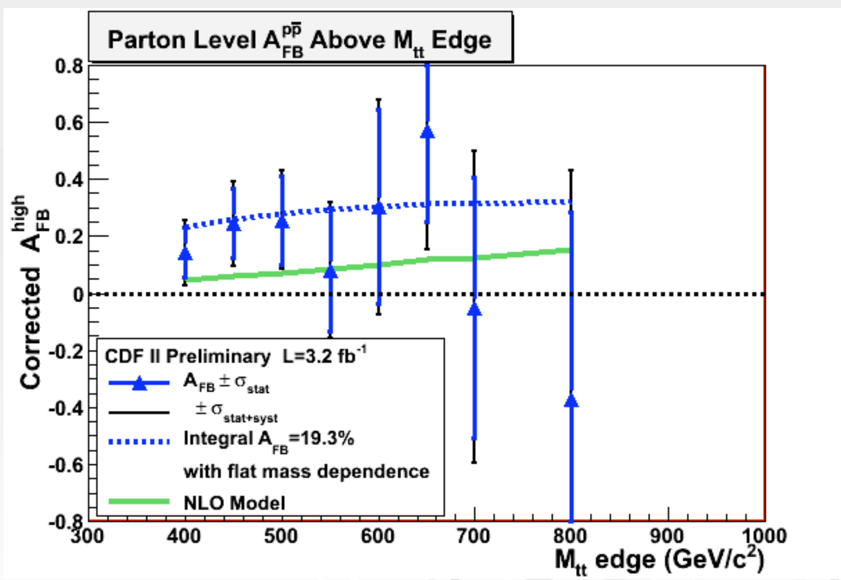
3.2 fb$^{-1}$

# $A_{fb}$ Dependence on the Invariant Mass of ttbar

- Scan for $A_{fb}$ above and below 8 different $M_{tt}$ thresholds
- Sensitive to new physics effect



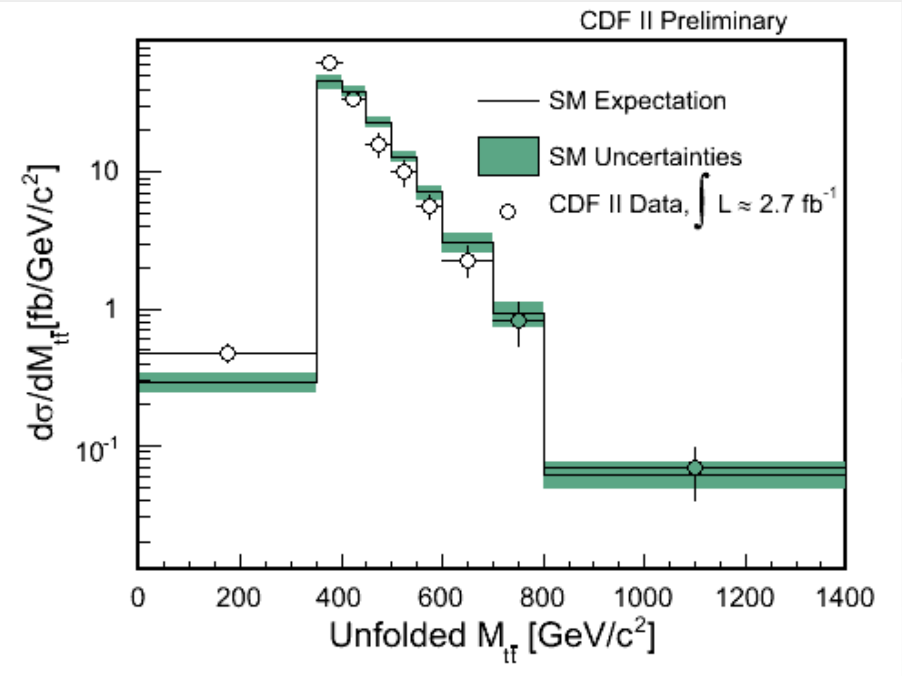

Consistent with the SM

2.7 $fb^{-1}$

# Measurement of the ttbar Differential Cross Section $d\sigma/dM_{ttbar}$

- In BSM models new gauge interactions can produce massive particles which may strongly couple to top quark (PRD 49, 4454 (1994), hep-ph/07122355V1)
  - Can produce resonances in the ttbar invariant mass ($M_{ttbar}$) distribution
  - Or may interfere with the SM and modify the shape of $M_{ttbar}$

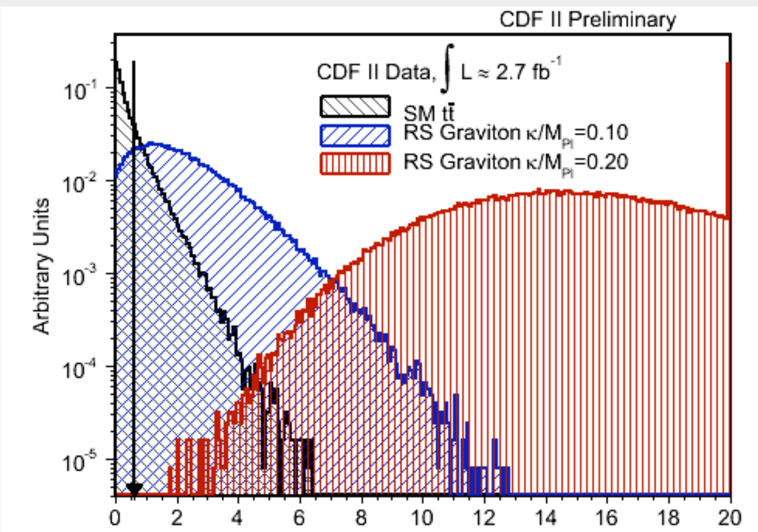
- Measure top pair cross-section in bins of $M_{ttbar}$ for Lepton+Jets events
  - Determine $\Delta_{JES}$ by fitting the dijet distribution
  - Correct the reconstructed invariant mass distribution back to true distribution
    - Use singular-value decomposition (SVD) unfolding (A. Hocker and V. Kartvelishivili, hep-ph/9509397)



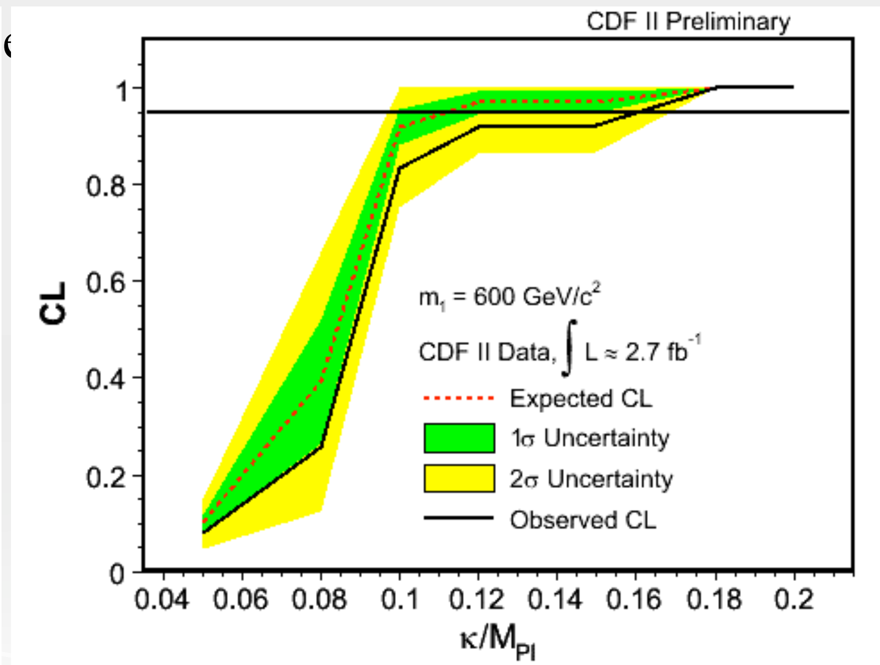
# $d\sigma/dM_{ttbar}$ (Cont')

**2.7 fb$^{-1}$**

- Check consistency with the SM using the Anderson-Darling statistic
  - Put emphasis on the tail of the distribution
  - No evidence of non-SM physics in the $M_{ttbar}$ distribution
- Set limits on the ratio $\kappa/M_{Pl}$ for gravitons which decay to top quarks in the Randall-Sundrum model

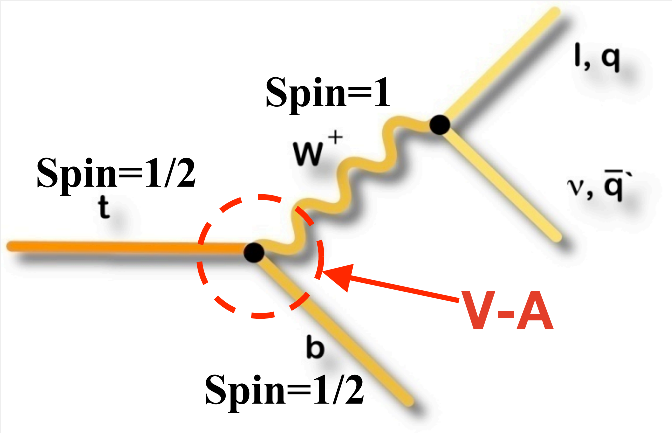


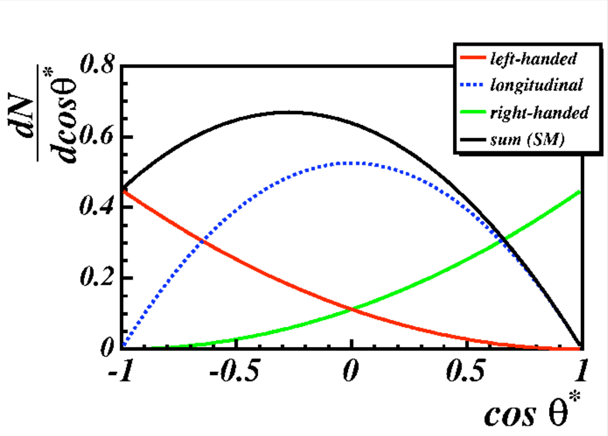

The distribution of the Anderson-Darling statistic




**Exclude $\kappa/M_{Pl} > 0.16$ at the 95% CL**

# tbW coupling

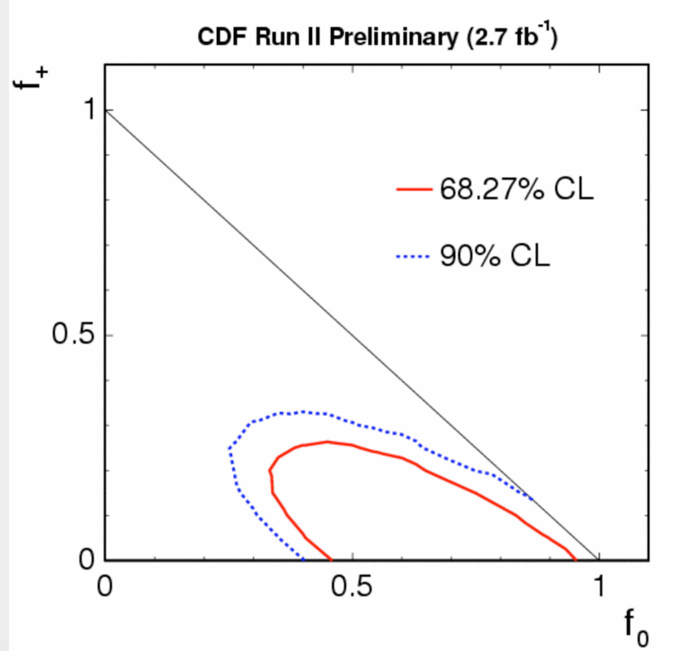



- The SM top decays via EW interaction: Br(t→bW)~100%
  - Top decays as a bare quark ⇒ spin info transferred to final states
- V-A coupling in the SM ⇒
  - longitudinal fraction $f_0$ ~70%
  - left-handed fraction $f_-$ ~30%
  - right-handed fraction $f_+$ ~0%
- The SM prediction modified in various new physics models
- W-helicity fractions are sensitive to non-SM tWb couplings
- Use cosθ* : Angle between lepton (down-type quark) in W rest frame and the momentum of the W in the top-quark rest frame

# Results

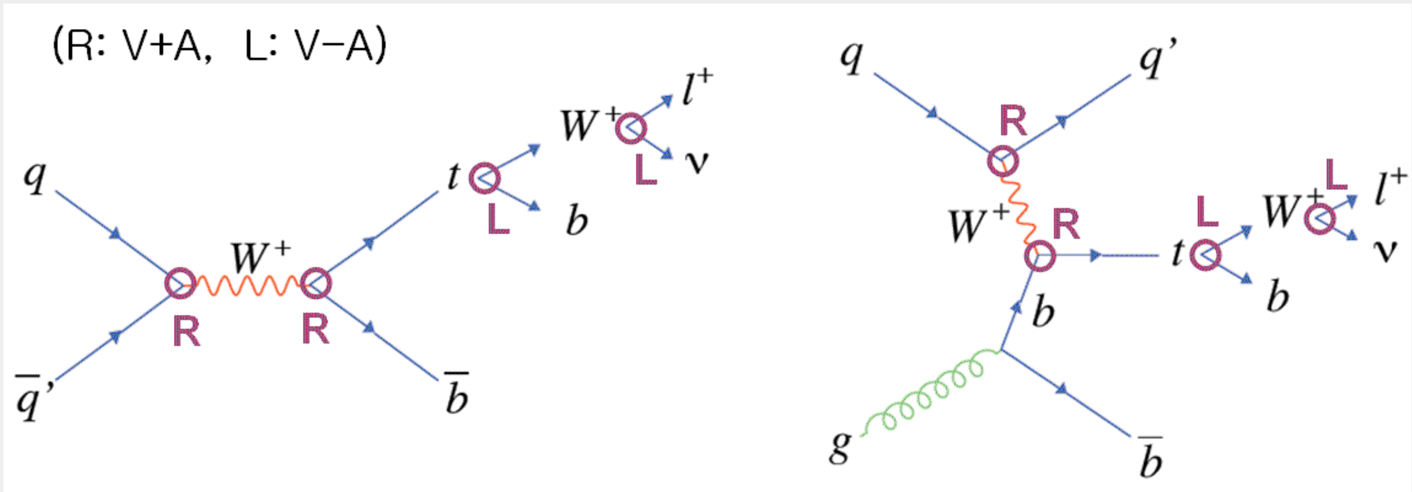
- Use event-by-event probability densities based on matrix elements of ttbar and dominant background (W+jets)
- Simultaneous measurement:
  - $f_0 = 0.88 \pm 0.11$ (stat) $\pm 0.06$ (sys)
  - $f_+ = -0.15 \pm 0.07$ (stat) $\pm 0.06$ (syst)
- Model dependent measurements:
  - $f_0 = 0.70 \pm 0.07$ (stat) $\pm 0.04$(stat) constraining $f_+=0.0$
  - $f_+ = -0.01 \pm 0.02$ (stat) $\pm 0.05$ (syst), constraining $f_0=0.7$
    - Upper limit at 95% CL : $f_+<0.12$
- Most precise measurement of $f_0$ so far
  - Will be systematically limited with full Tevatron dataset and current understanding of systematic uncertainties




FC Contours include stat+syst uncertainties

*Accepted for PRL publication FERMILAB-PUB-10-041-E, arXiv:1003.0224v1 [hep-ex]*

# Single-Top Polarization



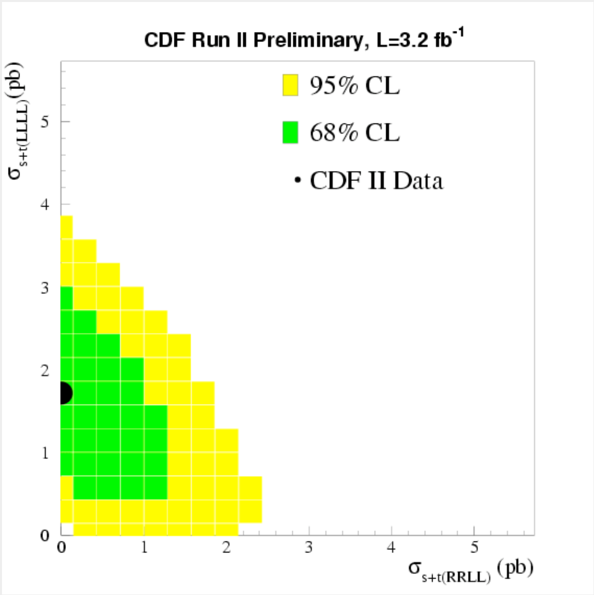

- In the SM expected to be produced 100% polarized along d-type quark axis
- Test model where top is produced with opposite polarization, but decay according to SM
- Compute two likelihood function for SM-like and exotic model (XM) like scenarios
    - Use likelihood discriminant method used for single top observation

# Single-Top Polarization (Cont')

- Divide the samples in two subsets:
  - $\cos\theta_{ij}>0$ (SM like) and
  - $\cos\theta_{ij}<0$ (XM like)

*$\cos\theta_{ij}$ :the angle between lepton and down-type quark*

- Measure two cross sections as independently as possible




**Cross Section Measurment**

$$\boldsymbol{\sigma_{SM(V-A)} = 1.72\ \text{pb}\ ,\quad \sigma_{Exotic(V+A)} = 0\ \text{pb}}$$

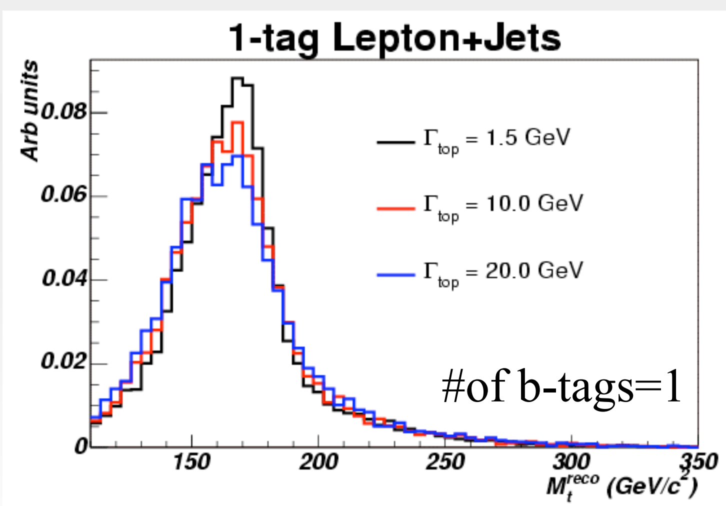
(2.864pb "SM prediction" : hep-ph/0207055 B.W.Harris at al. )

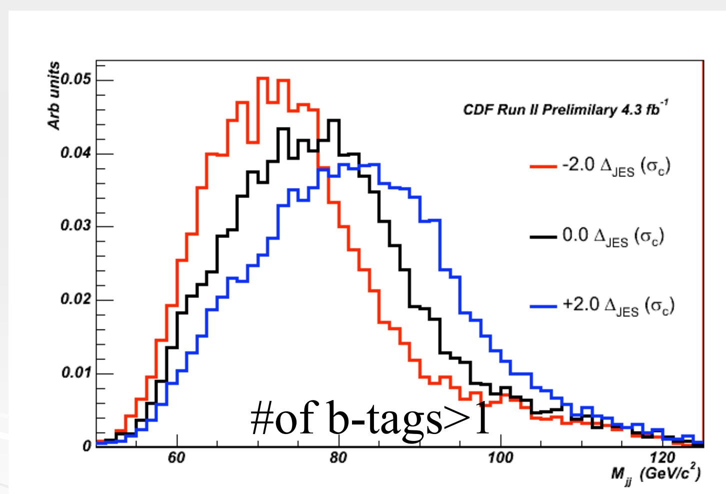
$$polarization = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -1^{+1.5}_{-0}$$

# Top Quark Width

4.3 $fb^{-1}$

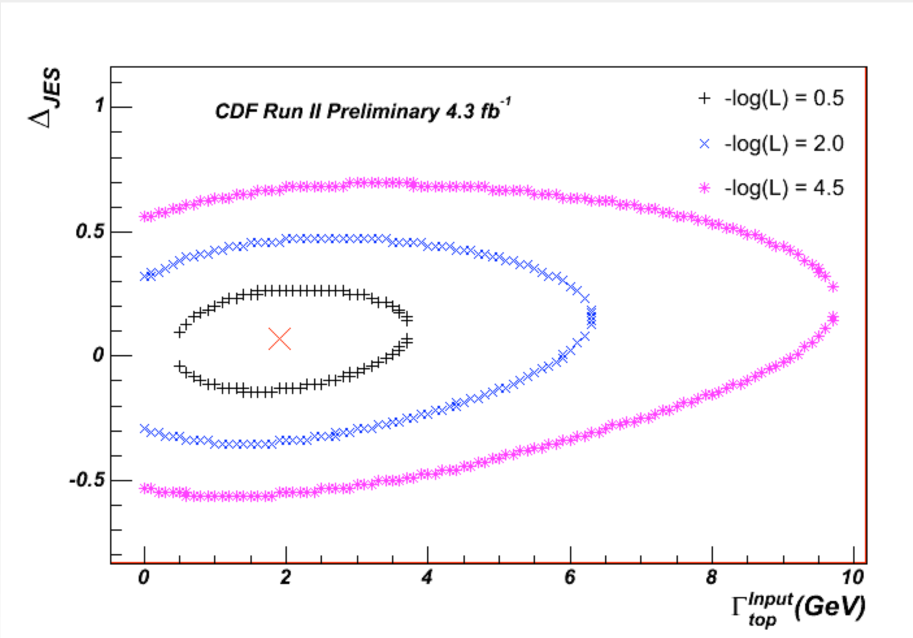
- In the SM top decay width ~1.4 GeV, at NLO for $m_{top}$=172.5 GeV/$c^2$
- Deviation from SM prediction may indicate significant decays of $t \to bH^+$ or $t \to dW^+$, $t \to sW^+$
- Previous upper limit $\Gamma_t$ < 13.1 GeV at 95% CL (PRL 102, 042001(2009))
- Use lepton+jets channel: template based on 2D distributions
  - $M_t^{reco}$ : reconstructed top mass
  - $m_{jj}$ : invariant mass of the jets from the hadronically decaying W



# Top Quark Width (cont')

- Liklihood fit to data
  - $\Gamma_{top}=1.9^{+1.9}_{-1.5}$ GeV and $\Delta_{JES}=0.07^{+0.2}_{-0.2}$
- Apply Feldman-Cousins construction to build 95% confidence interval
- Upper limit $\Gamma_{top}$ < 7.5 GeV at 95% CL
  - Central limit at 68% CL: 0.4 GeV < $\Gamma_{top}$ < 4.4 GeV
  - A lower limit on the top quark lifetime > 8.7 $\times 10^{-26}$ s



# Top Charge

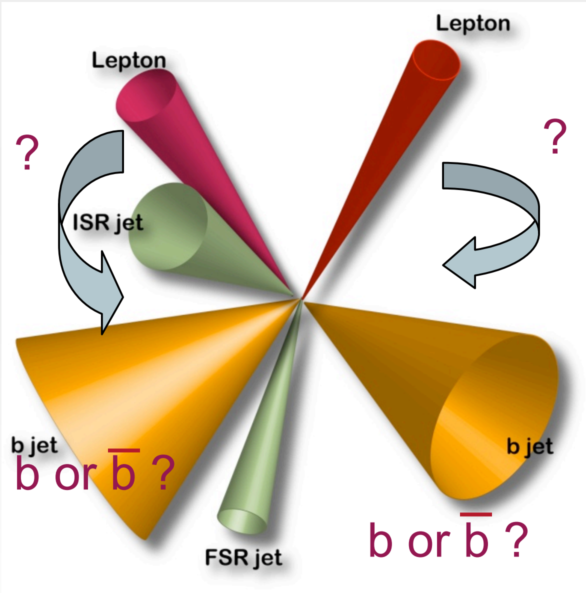
2.7 $fb^{-1}$

- Is the observed particle with mass ~172.5 GeV really the SM top?
  - The SM predicts top charge of 2e/3
- Other top physics measurements DO NOT check the flavor of the b-jet
  - Ambiguity in W and b-jet pairing $\Rightarrow$ 2e/3 or -4e/3 ?
- There is a BSM theory that predicts an exotic particle with charge -4e/3 and the same other properties as "top" (D.Chang et al. PRD 59, 09153(99)):
- Discriminate between 2e/3 (SM-like) and -4e/3 (Exotic Model-like) scenarios

Pairing of W and b-jet

W charge : use lepton charge

Flavor of b




Use Lepton+Jets channel

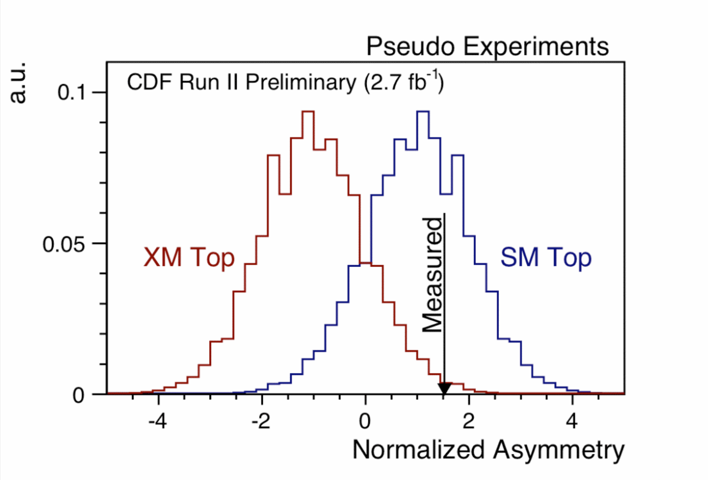
- b-jet flavor using soft lepton tag
- Require two b tagged jets per event , one SECVTX and the other one SLT
- Reconstruct event with kinematic fitter to determine W and b-jet pairing

# Top Charge (Cont')

2.7 fb$^{-1}$

- Use normalized asymmetry as test statistics

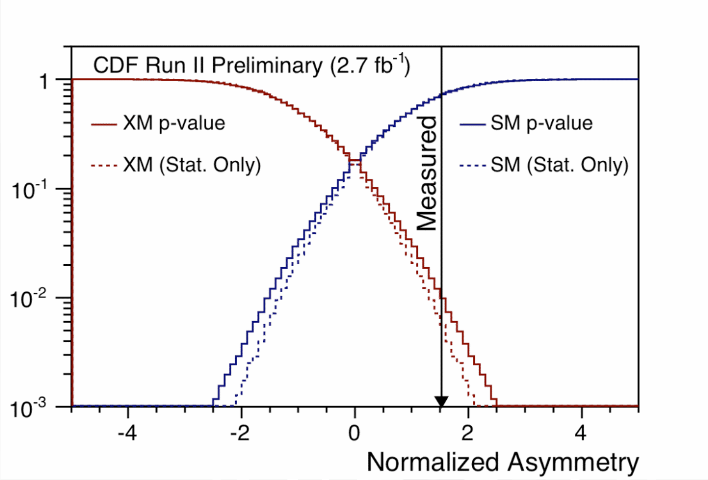
$$A \equiv \frac{1}{D_S}\frac{N_{SM} - N_{XM} - \langle B \rangle D_B}{N_{SM} + N_{XM} - \langle B \rangle}$$




- 29 Standard Model-like (SM) and 16 Exotic Model-like (XM) pairs in data
- Calculate two P-values assuming SM and XM. P-values compared with a-priori type-I error rates
  - For exclusion of XM use 5%.
  - For exclusion of the SM use 0.27% (3 σ) and 5.7·10-5% (5 σ),for evidence and exclusion.
- Result:

Measure XM p-value of 0.0094, and the SM p-value of 0.69.

Exclude charge -4e/3 hypothesis at 95% CL



# Summary and Outlook

- Recent top properties results from CDF are shown
  - All the measurements are consistent with the SM prediction so far
- All the top properties measurement presented here are currently statistics limited
  - ~1K reconstructed ttbar events in ~4 $fb^{-1}$ of dataset
- Results will be updated with 6-8 $fb^{-1}$data soon
  - Plan to combine with D0 measurement
  - Combination based on 6-8 $fb^{-1}$ data results will make some of the properties measurements systematically limited
- LHC is expected to deliver ~100-200 $pb^{-1}$ by end of 2010
  - CDF is expected to have 8.5 $fb^{-1}$ recorded by that time
  - The Tevatron will offer the world's largest ttbar sample for analyses
- For some of the properties measurements: Tevatron combination based on full dataset will become systematically limited
  - More effort on understanding the systematic effects in future
- Tevatron's top physics program and understanding of systematic effects will continue to play a significant role for years to come

# Backup Slides

# Kinematical Reconstruction of Lepton+Jets

- Minimize a $\chi^2$ describing the over constrained kinematics of Lepton+Jets channel

Constraints on measured Lepton and Jet momenta

Constraints on un-clustered Energy

$$\chi^2 = \sum_{i=\ell,4\,jets} \frac{\left(p_T^{i,fit} - p_T^{i,meas}\right)^2}{\sigma_i^2} + \sum_{j=x,y} \frac{\left(U_j^{fit} - U_j^{meas}\right)^2}{\sigma_j^2}$$
$$+ \frac{\left(M_{jj} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(M_{\ell\nu} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(M_{bjj} - m_t^{reco}\right)^2}{\Gamma_t^2} + \frac{\left(M_{b\ell\nu} - m_t^{reco}\right)^2}{\Gamma_t^2}$$

W Mass Constraints

Top mass Constraints

- Select one permutation based on $\chi^2$:
  - Require consistency with identified b-jet assignments

# Kinematical Reconstruction of Dilepton : Spin Correlation

- Two neutrinos in the final state
  - Six unknown variables and six constraints
- Define a likelihood

$$\mathcal{L}\left(\vec{p}_\nu, \vec{p}_{\bar{\nu}}, E_b^{\text{guess}}, E_{\bar{b}}^{\text{guess}}\right) = P\left(p_z^{t\bar{t}}\right) P\left(p_T^{t\bar{t}}\right) P\left(M_{t\bar{t}}\right) \times$$

$$\frac{1}{\sigma_b} \exp\left[-\frac{1}{2}\left\{\frac{E_b^{\text{meas}} - E_b^{\text{guess}}}{\sigma_b}\right\}^2\right] \times \frac{1}{\sigma_{\bar{b}}} \exp\left[-\frac{1}{2}\left\{\frac{E_{\bar{b}}^{\text{meas}} - E_{\bar{b}}^{\text{guess}}}{\sigma_{\bar{b}}}\right\}^2\right] \times$$

$$\frac{1}{\sigma_x^{\text{MET}}} \exp\left[-\frac{1}{2}\left\{\frac{\not{E}_x^{\text{meas}} - \not{E}_x^{\text{guess}}}{\sigma_x^{\text{MET}}}\right\}^2\right] \times \frac{1}{\sigma_y^{\text{MET}}} \exp\left[-\frac{1}{2}\left\{\frac{\not{E}_y^{\text{meas}} - \not{E}_y^{\text{guess}}}{\sigma_y^{\text{MET}}}\right\}^2\right]$$

- Choose the combination with maximum likelihood value

# Event-by-Event Likelihood : W Polarization from Top Decay

- Use probability densities based on matrix elements of signal (ttbar) and dominant background (W+jets)
- Construct probability density for each event and multiply all the event probabilities to obtain likelihood

$$L(C_s, f_0, f_+) = \prod_{i=1}^{N_{events}} C_s \frac{P_{signal,i}(x; f_0, f_+)}{\langle Acc_{sig}(x; f_0, f_+)\rangle} + (1 - C_s)\frac{P_{bkg,i}}{\langle Acc_{bkg}(x)\rangle}$$

$$P_{signal}(x; f_0, f_+) = \sum_{perm.} \int \frac{d\sigma(y; f_0, f_+)}{dy} W(x, y) dq_1 dq_2 f(q_1) f(q_2)$$

- **dσ** is the differential ttbar cross section
- *W(x,y)* models detector resolution effects
  - Relates a set of observable x to corresponding parton level quantities y
- **f(q)** is from the parton distribution function

# Spin Correlation

- SM ttbar produces a characteristic spin correlation
- Can be modified by new production mechanisms such as Z' bosons or Kaluza-Klein gluons
- Observed though correlations between the flight directions of the decay products
- Choose an optimal quantization basis
- Measure correlation co-efficient κ
- Two spin correlation measurements:
- Lepton+jets channel
  - Use helicity  basis
- Dilepton channel
  - Use off-diagonal basis

4.3 fb$^{-1}$

# Spin Correlation : Lepton+Jets

- Spin correlation described by four helicity states
- In ttbar rest frame same spin (S = 1) ⇒ opposite helicity
- Measure opposite helicty fraction $f_o$ and extract κ

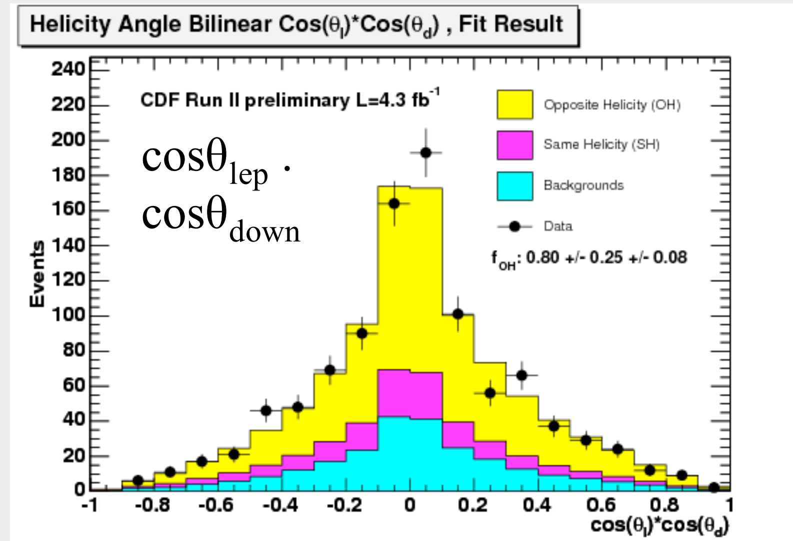
$$f_o = \frac{\sigma(\bar{t}_R t_L) + \sigma(\bar{t}_L t_R)}{\sigma(\bar{t}_R t_R + \bar{t}_L t_L + \bar{t}_R t_L + \bar{t}_L t_R)} = \frac{N_o}{N_o + N_s}$$

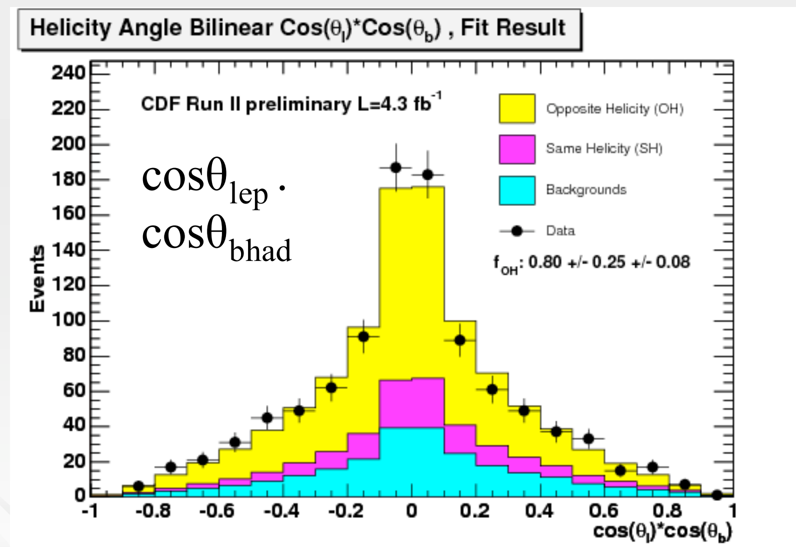
$$\kappa = \frac{[\sigma(\bar{t}_R t_L) + \sigma(\bar{t}_L t_R)] - [\sigma(\bar{t}_R t_R) + \sigma(\bar{t}_L t_L)]}{\sigma(\bar{t}_R t_R) + \sigma(\bar{t}_L t_L) + \sigma(\bar{t}_R t_L) + \sigma(\bar{t}_L t_R)} = \frac{N_o - N_s}{N_o + N_s}$$

- Use the helicity angles of the lepton $\theta_{lep}$, and the d-quark $\theta_{down}$ and b-quark $\theta_{bhad}$ from hadronically decaying top
  - *θ: angle between the decay product momentum in the top rest frame and the top quark momentum in the ttbar rest frame*

# Spin Correlation : Lepton+Jets (Cont')

- Identifying down quark
  - Jet closest to the b jet in W rest frame is the d-jet ~60% of the time
- Likelihood fit to data based on 2D templates $\cos\theta_{lep} \cos\theta_{down}$ vs. $\cos\theta_{lep}\cos\theta_{bhad}$




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

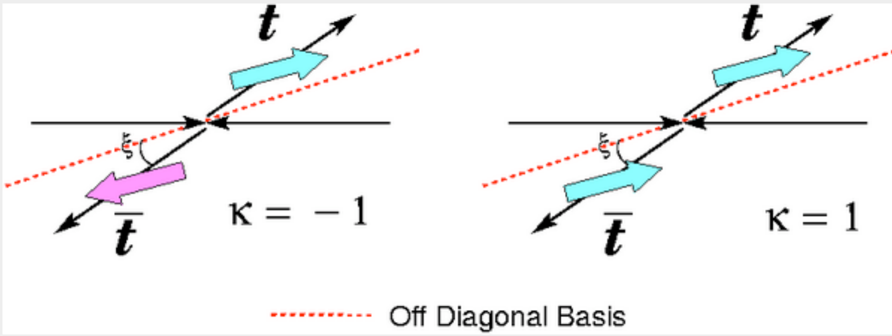
Converting to κ

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

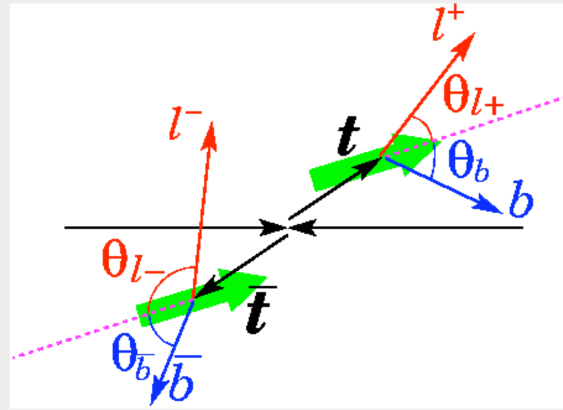
SM prediction : κ = ~0.4

2.8 fb$^{-1}$

# Spin Correlations : Dilepton




$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1+\kappa\cos\theta_+\cos\theta_-}{4}$$




- Use off-diagonal basis : tan ξ ≡sqrt(1-$\beta^2$) tan θ*. In ttbar frame: β ≡ top velocity and θ*≡ top flight direction w.r.t. proton direction.
- Templates: angular distribution of ( cos $\theta_{l+}$, cos θ $_{l-}$ ) and (cos$\theta_b$, cos $\theta_{bbar}$)

-0.455< κ <0.865 at 68% C.L.
$\kappa = 0.320^{+0.545}_{-0.775}$ for $M_t$ = 175 GeV/$c^2$

SM prediction : κ = ~0.8