Top Pair Production and Properties at the Tevatron

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On Behalf of the CDF and D0 Collaborations

Rencontres de Moriond, Electroweak Session
March 4, 2013

- Since top discovery, nearly 20 years of top properties studies
- With full Tevatron data set, era of precision measurements reached
- Too many topics to cover
- Only show new results since Moriond 2012:
  - Mass (TeV combo)
  - Differential cross section (CDF)
  - Dilepton A_{FB} (D0)
  - Single lepton A_{FB} (CDF)
  - W Helicity (TeV combo and CDF)
  - Branching ratio (CDF)
  - Intrinsic width (CDF)
  - Lorentz invariance (D0)

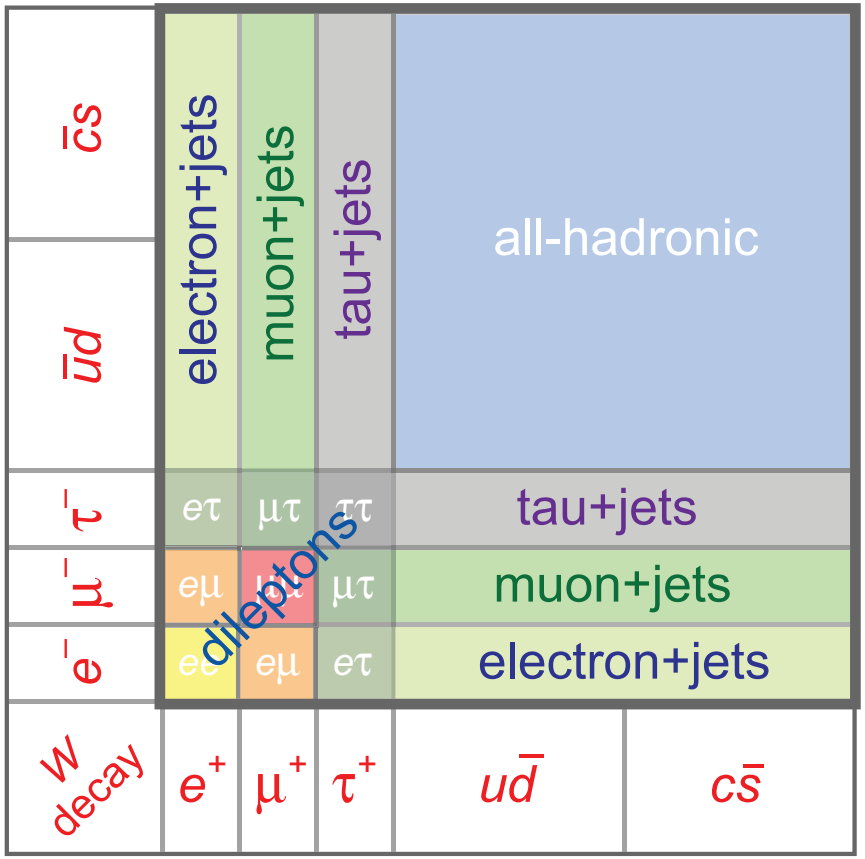


The "Top" of the Alps

Results found at:

- `http://www-cdf.fnal.gov/physics/new/top/top.html`
- `http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html`

Top Pair Decay Channels



- Top quark decays to W boson and bottom quark nearly 100 % of the time
- Look for at least two hadron jets, employ b-identification algorithms (b-tagging)
- Additionally look for W decay products:

Dilepton Both Ws decay leptonically:

$$b\bar{b}\ell\ell\nu\nu$$

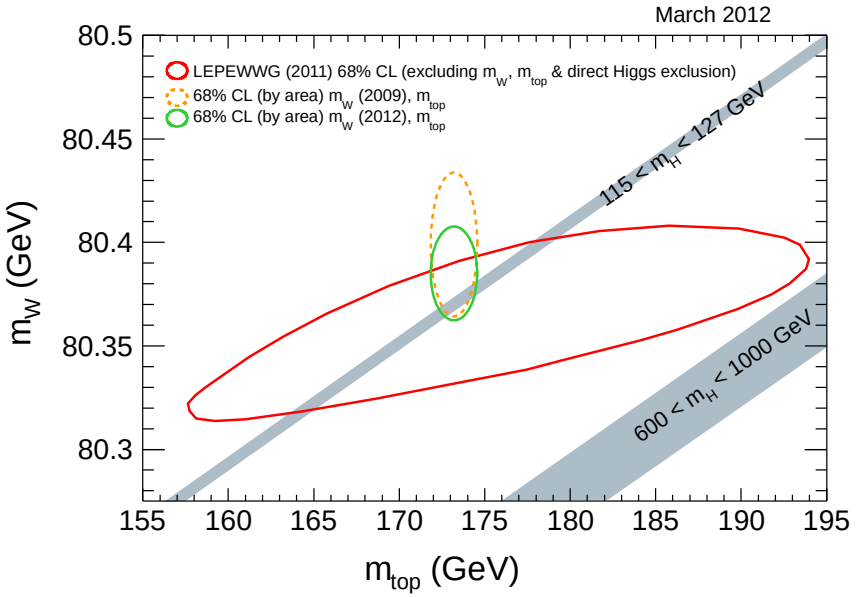
Lepton+jets One W decays leptonically:

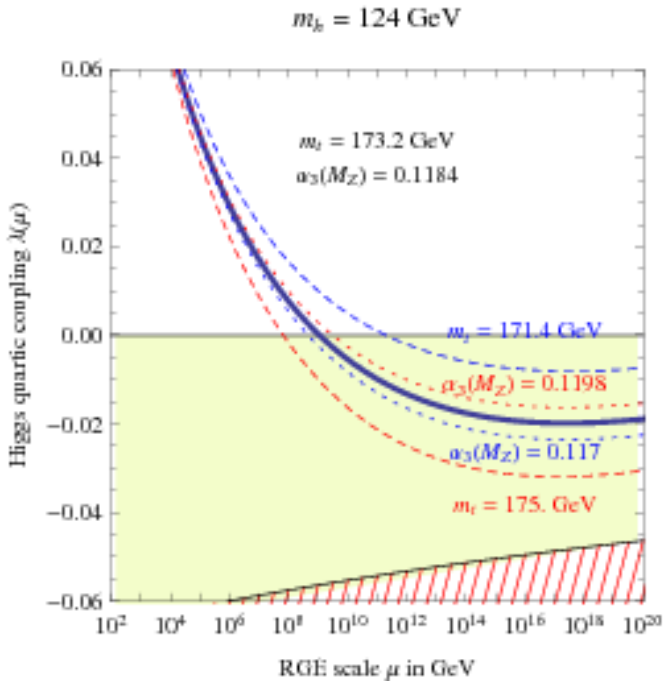
$$b\bar{b}q\bar{q}\ell\nu$$

All-hadronic Both Ws decay hadronically:

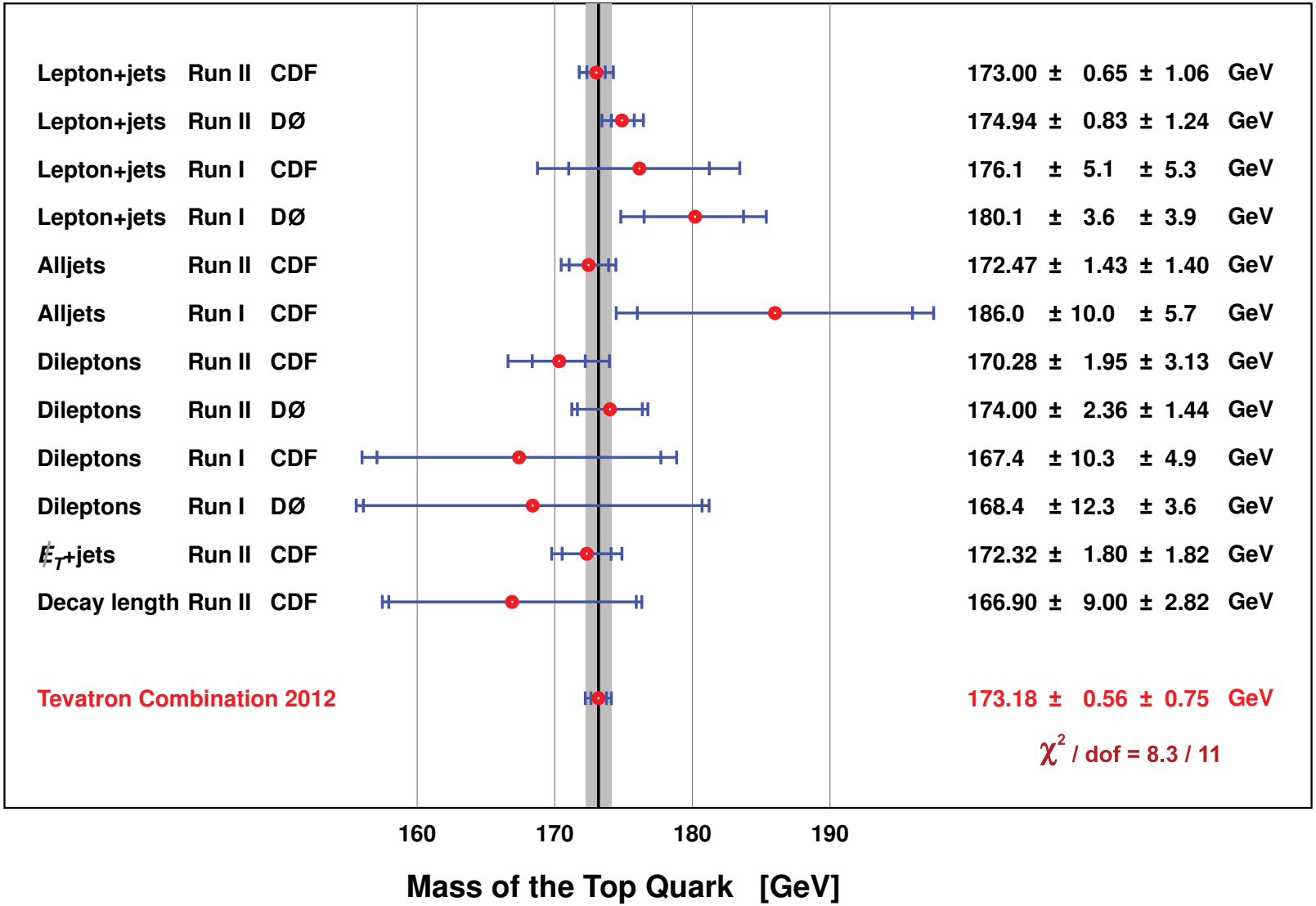
$$b\bar{b}q\bar{q}q\bar{q}$$

- Top mass is important input to global electroweak fits
- Given mass of SM scalar, vacuum stability very sensitive to m_t
- Many analyses, Tevatron combination summer 2012
- Most sensitive analyses are lepton+jets from both D0 (PRD 84 032004 (2011)) and CDF (PRL 109 152003 (2012))
- Long exceeded pre-Run II sensitivity projections
- Many clever tricks to improve sensitivity, such as *in situ* systematic uncertainty constraints





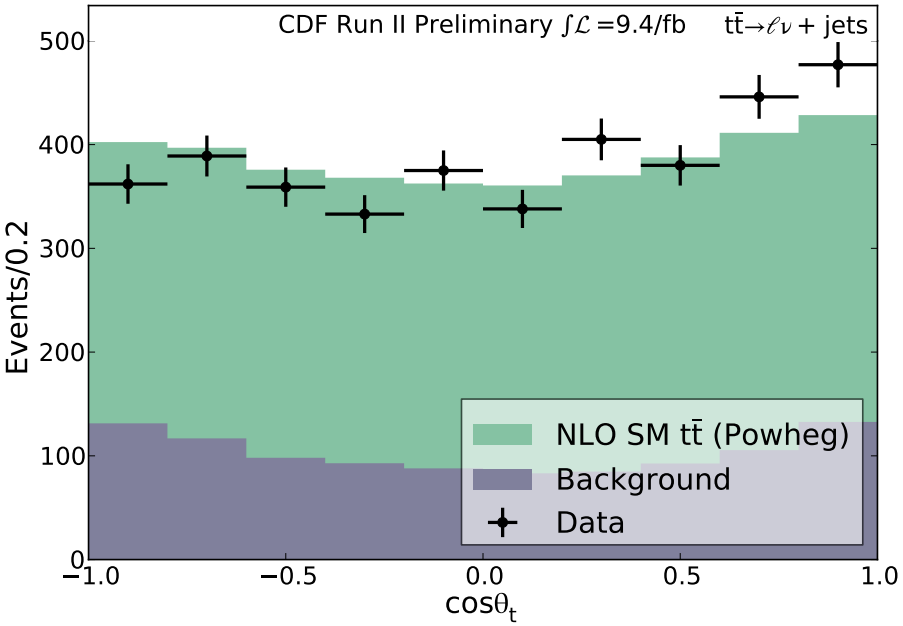
$(173.18 \pm 0.94)\,\mathrm{GeV}/c^2$: $\sim 0.5\,\%$ precision!



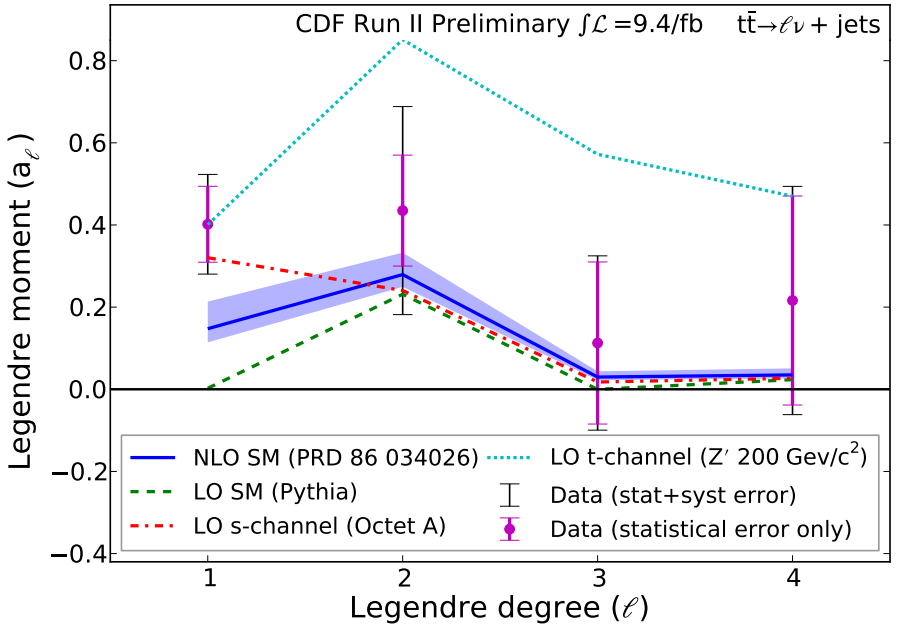
- Top A_{FB} is a simple statement about the production angle

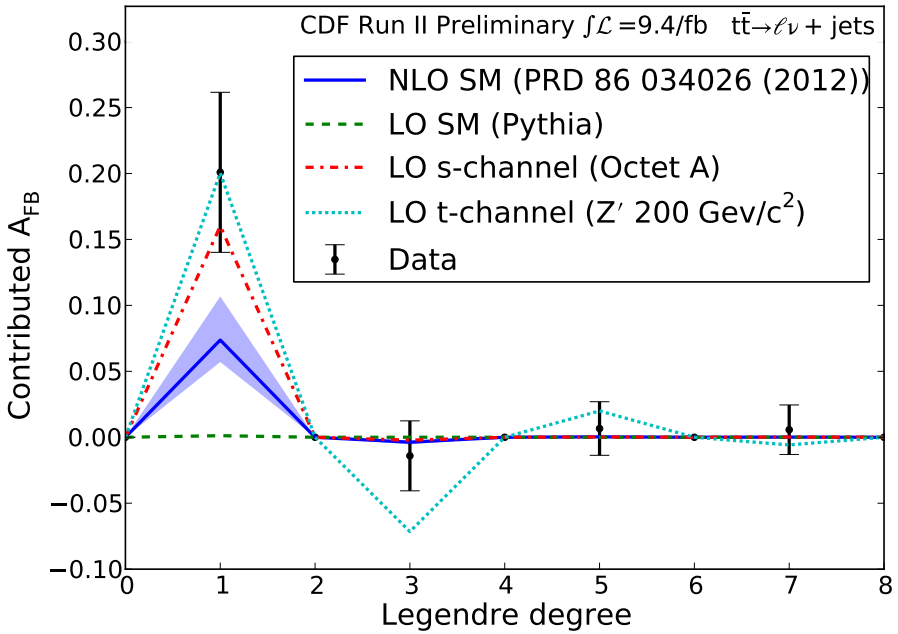
  $\cos\theta_t$ Angle between top momentum and proton momentum in $t\bar{t}$ center-of-mass frame

- Just two bins, forward and backward
- Shape of differential cross section has more information
- What component(s) of shape explains A_{FB}?
- How to describe shape?
- Project onto Legendre polynomials:
  $\frac{d\sigma}{d\cos\theta_t} = \sum_\ell a_\ell P_\ell(\cos\theta_t)$
- Measure moments: $a_1 - a_8$



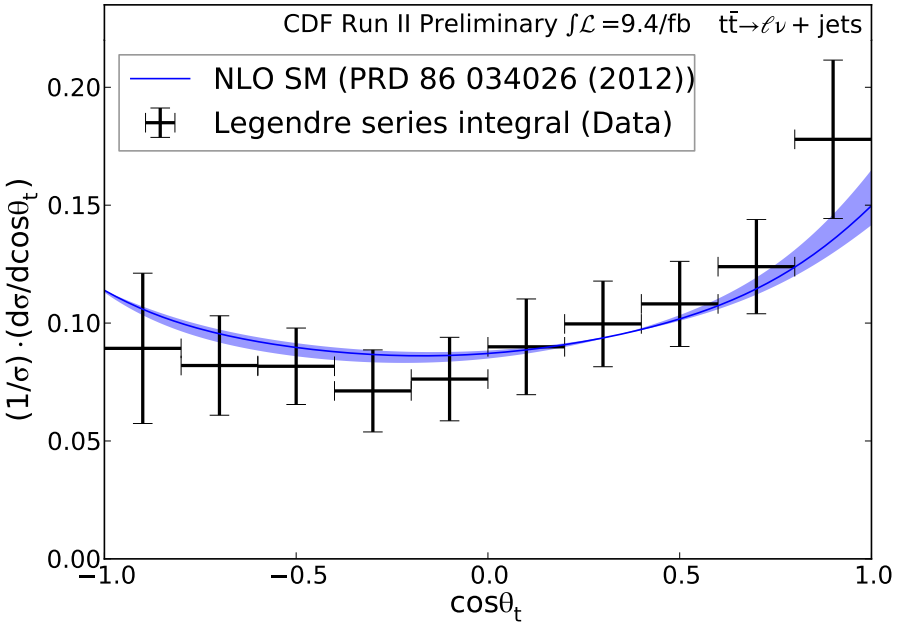
ℓ	$P_\ell(x)$
0	1
1	x
2	$\frac{1}{2}(3x^2-1)$
3	$\frac{1}{2}(5x^3-3x)$
4	$\frac{1}{8}(35x^4-30x^2+3)$
5	$\frac{1}{8}(63x^5-70x^3+15x)$

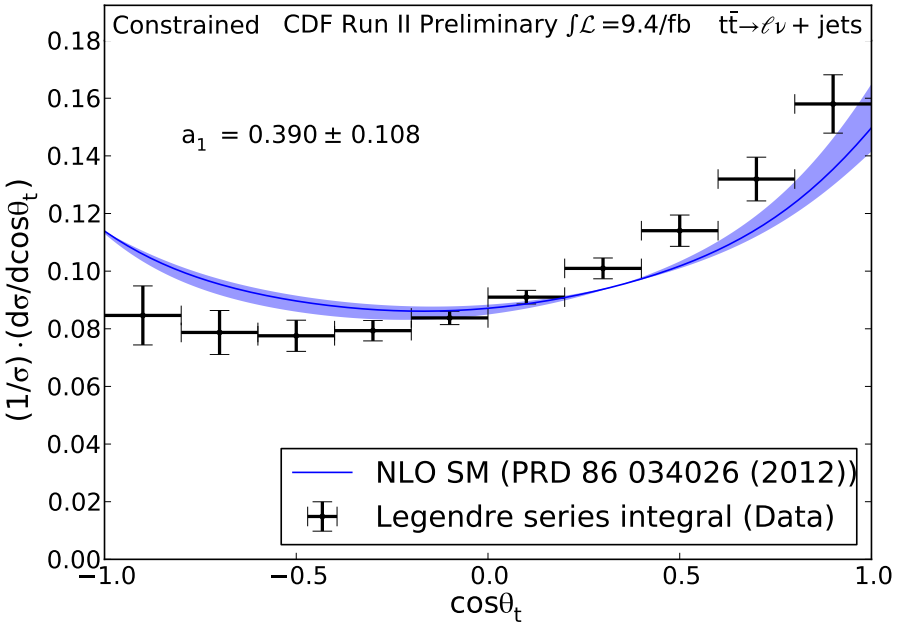




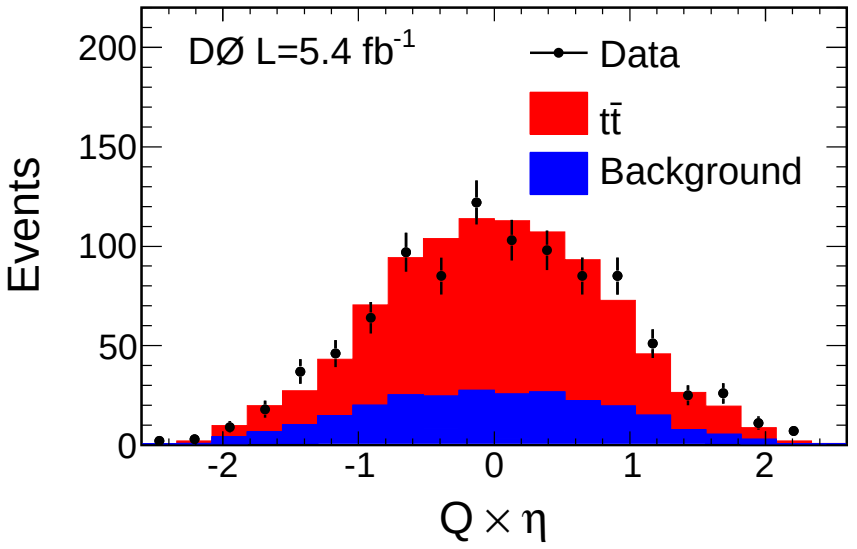
- After correcting to parton level, good agreement with NLO SM prediction except first moment
- We see an excess linear term, $a_1 \cos\theta_t$, in the cross section
- Linear term coefficient 3.3σ from zero (LO SM), 2.1σ from NLO SM
- Also compare benchmark new physics models (s- and t-channel) to parton level data
- A_{FB} contributed by each measured consistent with zero, except first moment
- Excess first moment sufficient to explain excess A_{FB}

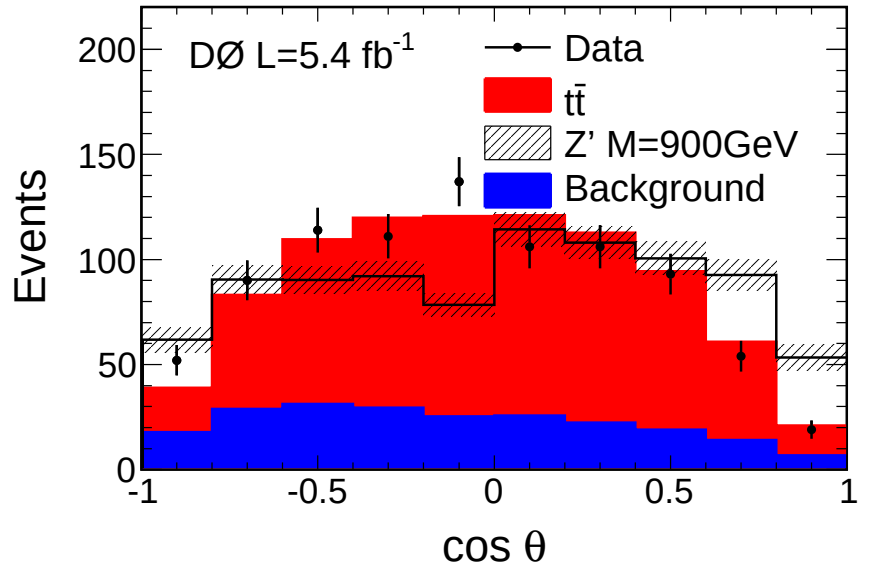
- Legendre moments difficult to visualize
- Integrate Legendre series over bins to get more traditional view
- Large uncertainties from coherent fluctuations
- Damp these by assuming NLO SM ($\pm$ scale) correct for all but first moment
- Combine assumption with data using BLUE method
- 10 % more precise a_1, but more model dependent
- NB: Any prediction can be compared to our data using covariance (see backup)

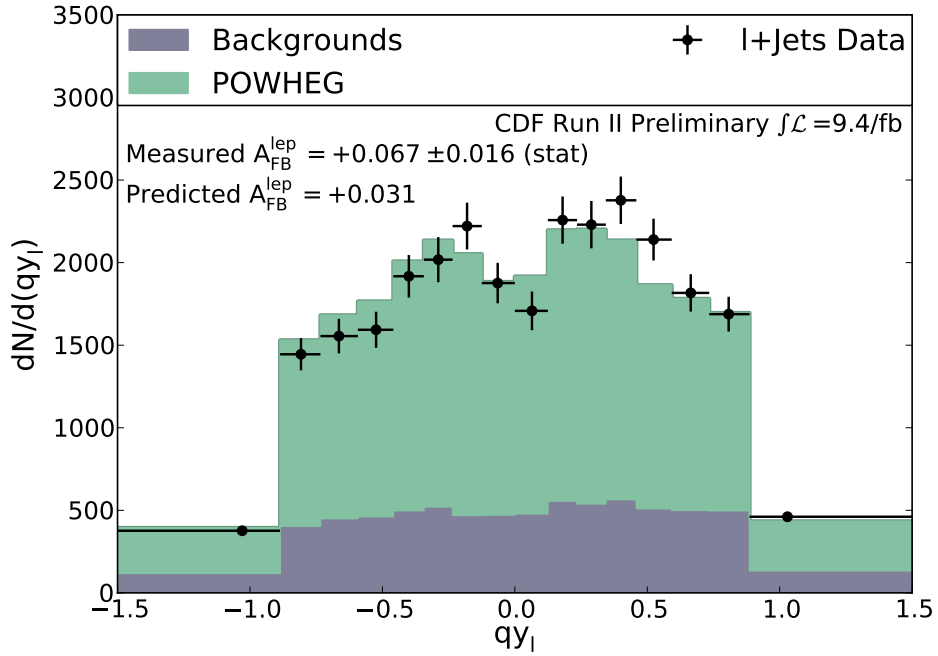


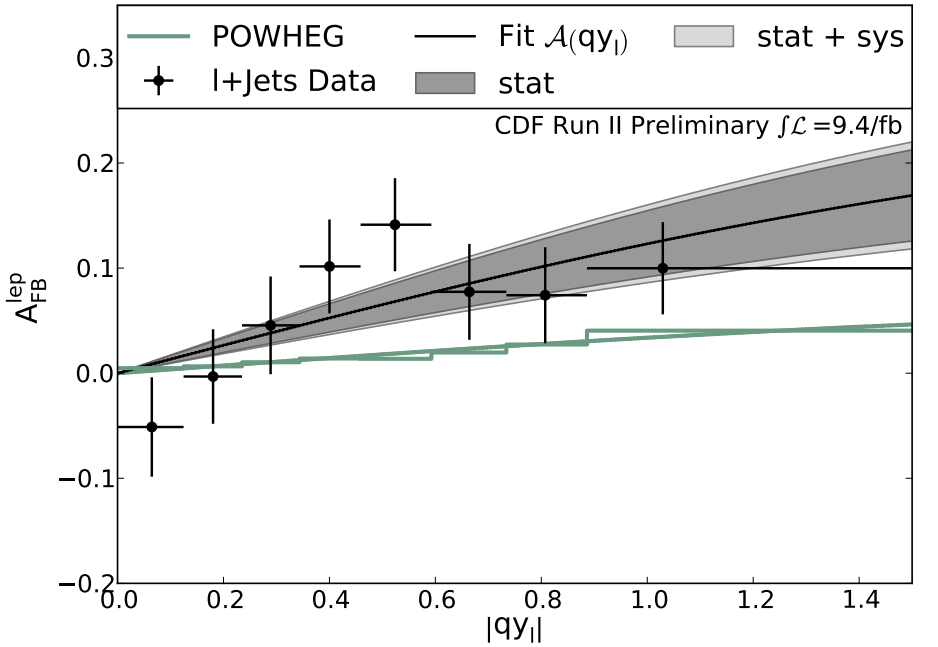


- D0 dilepton, 5.4/fb
- Study only the two charged leptons in the lab frame
- Define asymmetry, $A_{FB}^{\ell} = \frac{N(q_\ell \eta_\ell > 0) - N(q_\ell \eta_\ell > 0)}{N(q_\ell \eta_\ell > 0) + N(q_\ell \eta_\ell > 0)}$
- Correct for acceptance to get parton-level result, $A_{FB}^{\ell} = 0.058 \pm 0.053$
- MC@NLO: $A_{FB}^{\ell} = 0.047 \pm 0.001$
- Combine with A_{FB}^{ℓ} from lepton+jets: $A_{FB}^{\ell} = 0.118 \pm 0.032$
- Also study top-quark polarization via lepton helicity angle
- Consistent with SM polarization

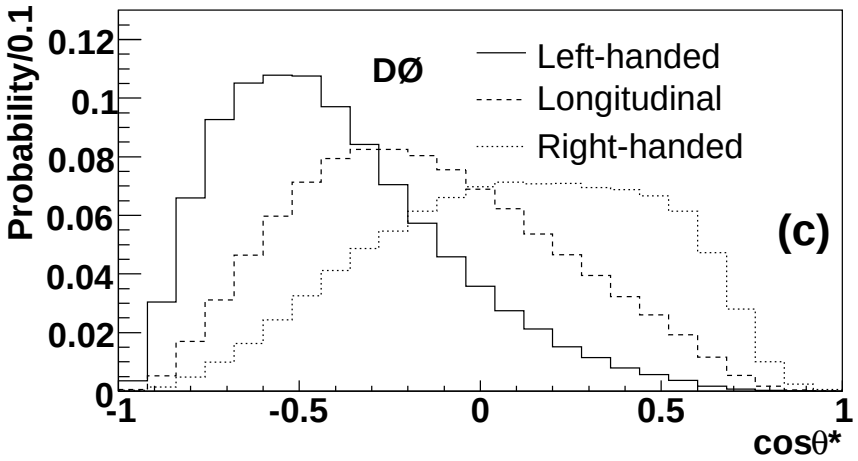


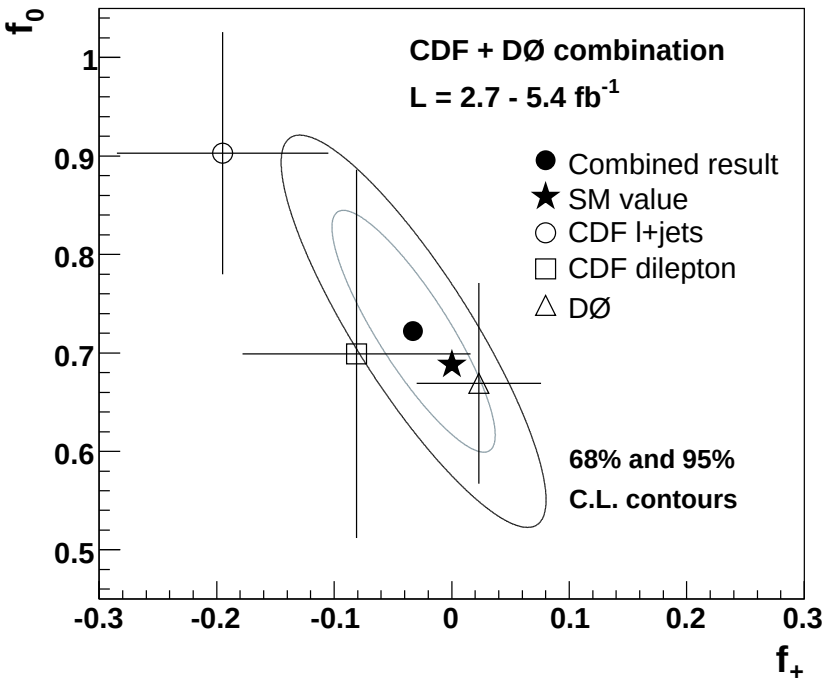






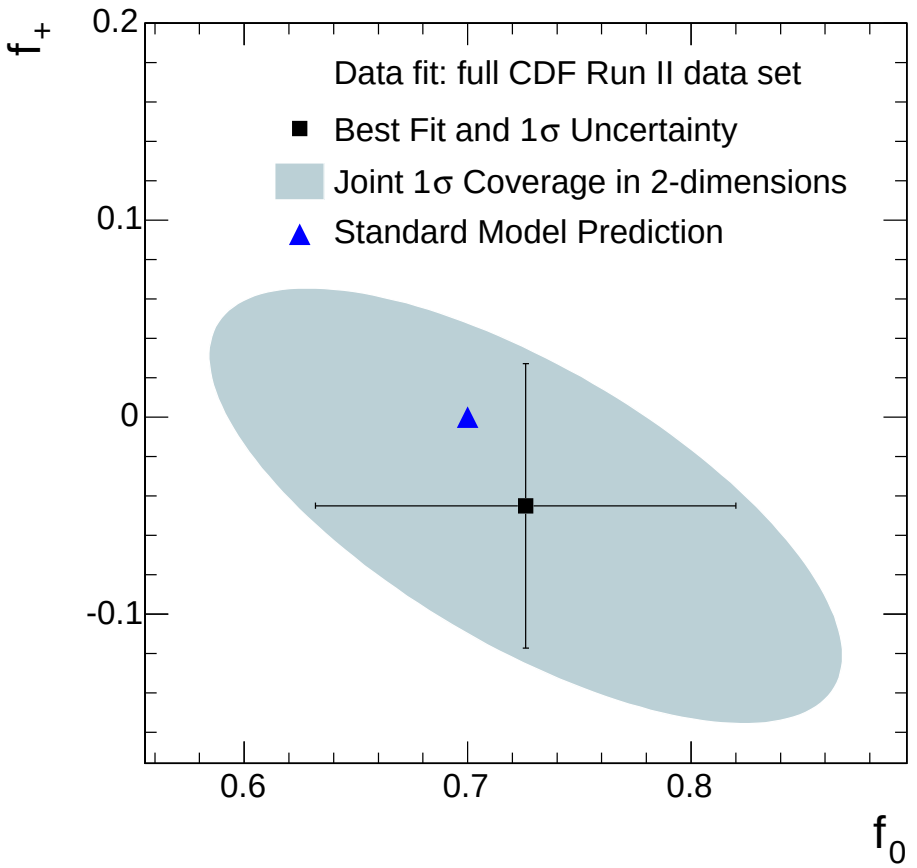
- CDF lepton+jets, 9.4/fb
- Similar idea: lab-frame $q_\ell \eta_\ell$
- Insensitive to biases from top reconstruction procedure
- After acceptance correction, fit to model $A^\ell_{\rm FB}(|\eta_\ell|) = a \tanh\left(\frac{1}{2} q_\ell \eta_\ell\right)$
- Extrapolate into unmeasured region
- Extract parton-level $A^\ell_{\rm FB}$
- NLO SM calc by Bernreuther and Si (PRD 86 034026): $A^\ell_{\rm FB} = 0.036 \pm 0.002$
- Given observed $t\bar{t}$ $A_{\rm FB}$, expect $A^\ell_{\rm FB} \sim 0.076$
- Observe $A^\ell_{\rm FB} = 0.094^{+0.032}_{-0.029}$
- Consistent w/D0: $A^\ell_{\rm FB} = 0.12 \pm 0.03$



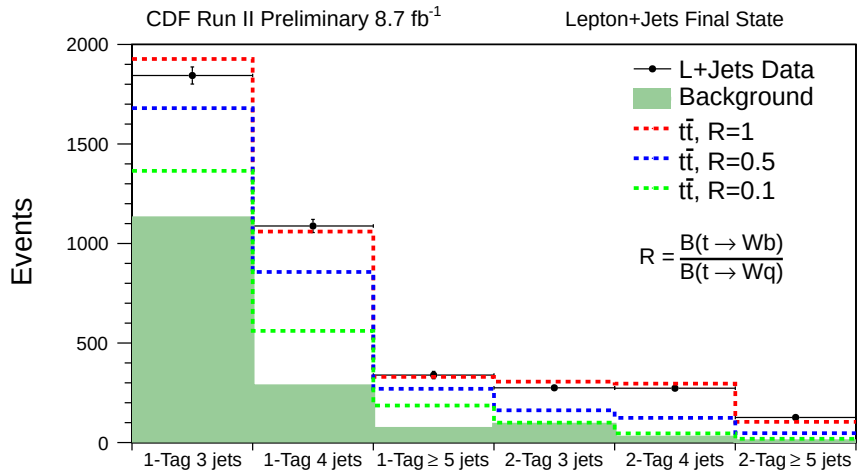


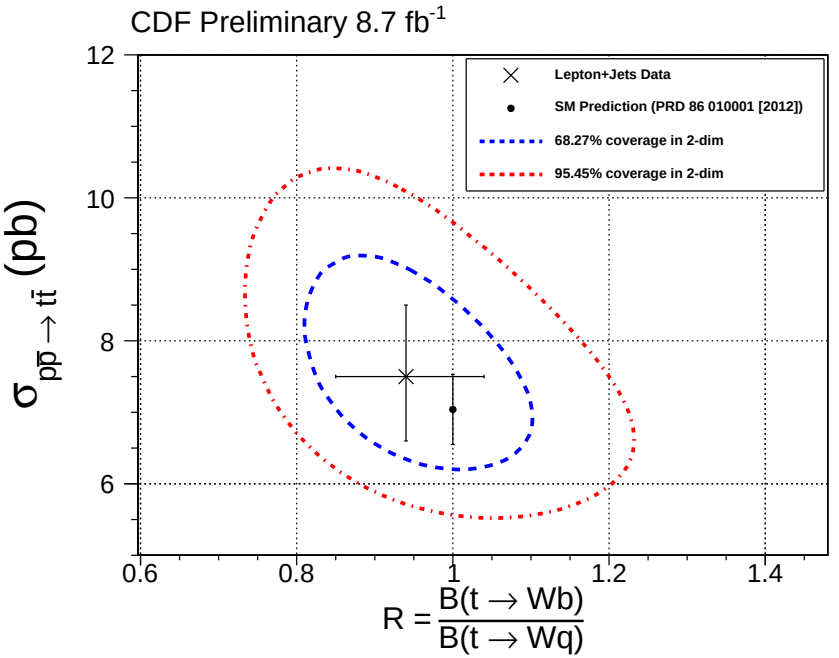
- Helicity fractions of W bosons from top decay
- Test $V-A$ structure and (indirectly) EWSB
- Expect $\sim$ zero right-handed W bosons (f_+)
- $f_- + f_0 + f_+ = 1$
- CDF lepton+jets uses matrix element method
- CDF and D0 dilepton use fits to $\cos\theta^*$ distribution
- Tevatron combination May 2012
- $f_+ = -0.033 \pm 0.046$
- $f_0 = 0.722 \pm 0.081$
- Compatible with SM prediction

- CDF lepton+jets update to full data set, 8.7/fb
- Matrix element method
- Compute probability for each event, given:
  - Signal purity, $t\bar{t}$ vs W+jets
  - Longitudinal polarization f_0
  - Right-handed polarization f_+
- Negative log-likelihood from per-event probabilities
- Minimize to find best-fit f_0, f_+ and 1σ variations
- $f_+ = -0.045 \pm 0.072$
- $f_0 = 0.726 \pm 0.094$
- Again, compatible with SM



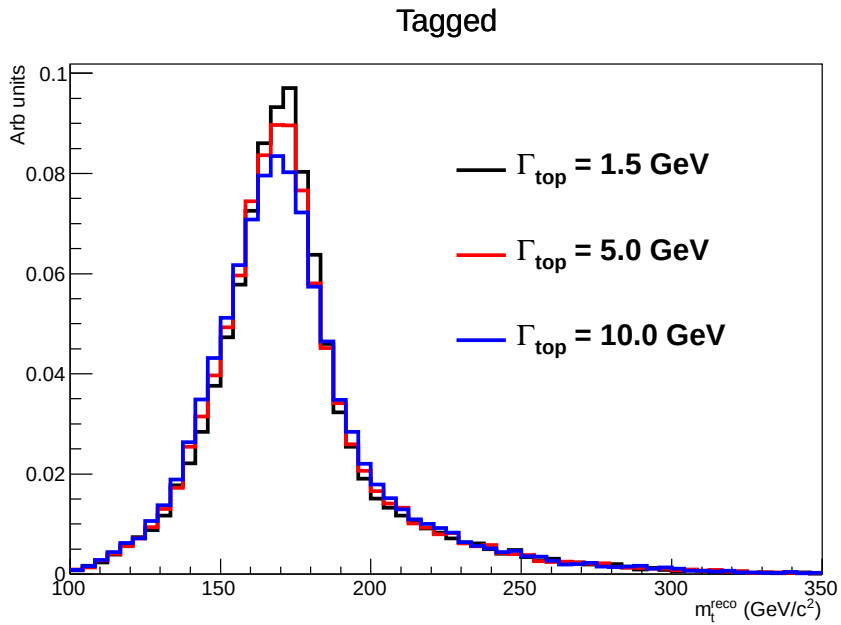
This measurement of f_0 almost as precise as combination

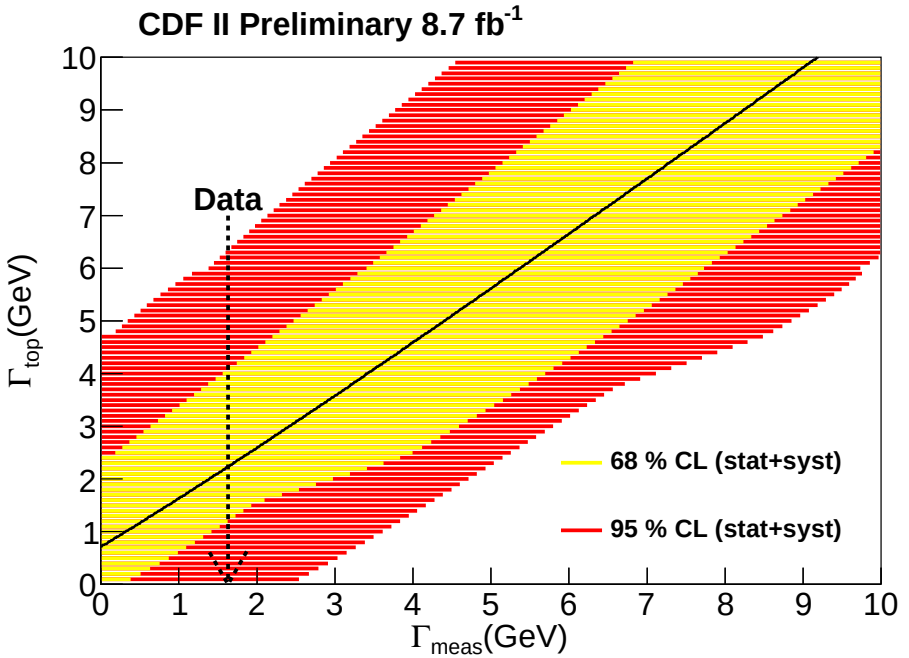


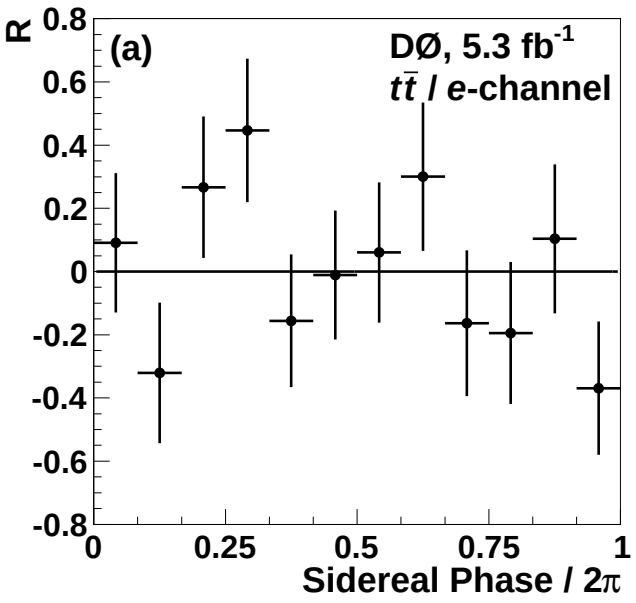


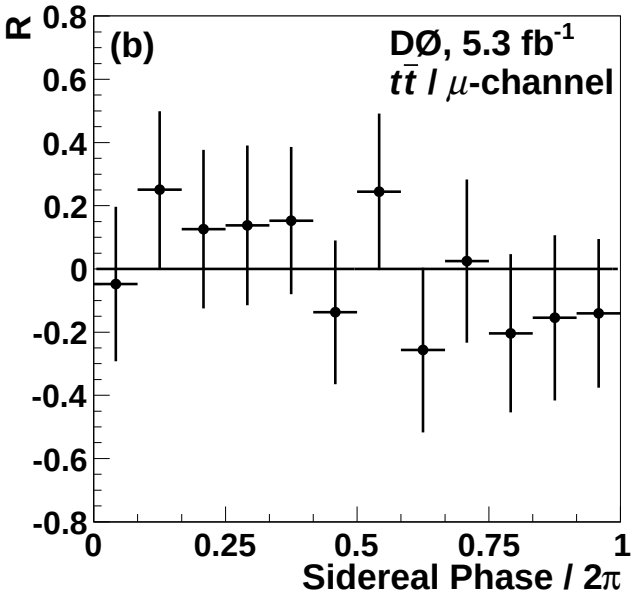
- Ratio of branching fractions, $R = \mathcal{BR}(t \to Wb)/\mathcal{BR}(t \to Wq)$
- Related to CKM element, $R = |V_{tb}|^2 / (|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2)$
- CDF lepton+jets, 8.7/fb
- Changes in R affect jet and b-tagged jet multiplicity
- Likelihood fit to jet/b-tag multiplicity
- Simultaneously minimize for both R and total cross section
- $\sigma_{t\bar{t}} = (7.5 \pm 1.0)$ pb
- $R = 0.94 \pm 0.09$
- $|V_{tb}|^2 = 0.97 \pm 0.05$

- Intrinsic decay width of top, related to R
- SM predicts $\Gamma_t = 1.25\,\mathrm{GeV}/c^2$
- Test for invisible decays
- D0 also measures R and the top width, see talk by Aran Garcia-Bellido
- CDF lepton+jets, 8.7/fb
- Reconstruct top mass from kinematic constraints: $m_W = 80.4\,\mathrm{GeV}/c^2$ and $m_t(1) = m_t(2)$
- Use Feldman-Cousins method to extract intrinsic Γ_t from width of reconstructed top mass distribution
- $\Gamma_t = 2.21^{+1.84}_{-1.11}\mathrm{GeV}/c^2$









- D0 lepton+jets, 5.3/fb
- PRD 58 116002 (1998) adds Lorentz violating terms to the Standard Model Lagrangian
- Earth is a rotating reference frame with a repetition period of one sidereal day
- Lorentz violation predicts dependence of $t\bar{t}$ cross section on time of day
- $R + 1$ is ratio of observed cross section to SM cross section
- Expect $R = 0$ for no Lorentz Violation, sinusoidal variation if Lorentz Violation
- Einstein wins again

- We are fully exploiting the unique Tevatron dataset
- Top quark studies are firmly into the precision realm
- Top may still be the gateway to new physics
- Still more interesting studies to come in the future

Many thanks to the audience and the organizers!

BACKUP

Total covariance matrix

The covariance matrix describing the uncertainty of our measurement of $\frac{d\sigma}{d\cos\theta_t}$. Likelihood is very Gaussian. Inverting this matrix induces a χ^2 goodness-of-fit statistic with 8 degrees of freedom. Can be used for likelihood fits to our result.

CDF Run II Preliminary $\int \mathcal{L} = 9.4\,\text{fb}^{-1}$

	1	2	3	4
1	1.47×10^{-2}	-7.60×10^{-4}	1.14×10^{-2}	-2.95×10^{-3}
2	-7.60×10^{-4}	6.41×10^{-2}	8.96×10^{-3}	3.29×10^{-2}
3	1.14×10^{-2}	8.96×10^{-3}	4.50×10^{-2}	-8.18×10^{-5}
4	-2.95×10^{-3}	3.29×10^{-2}	-8.18×10^{-5}	7.72×10^{-2}
5	6.86×10^{-3}	-3.70×10^{-3}	2.72×10^{-2}	-7.32×10^{-4}
6	-1.73×10^{-3}	4.12×10^{-3}	-4.88×10^{-3}	4.00×10^{-2}
7	2.01×10^{-3}	1.05×10^{-2}	1.36×10^{-2}	5.49×10^{-3}
8	-7.34×10^{-3}	-4.69×10^{-2}	-1.33×10^{-2}	1.13×10^{-2}

	5	6	7	8
1	6.86×10^{-3}	-1.73×10^{-3}	2.01×10^{-3}	-7.34×10^{-3}
2	-3.70×10^{-3}	4.12×10^{-3}	1.05×10^{-2}	-4.69×10^{-2}
3	2.72×10^{-2}	-4.88×10^{-3}	1.36×10^{-2}	-1.33×10^{-2}
4	-7.32×10^{-4}	4.00×10^{-2}	5.49×10^{-3}	1.13×10^{-2}
5	1.06×10^{-1}	2.31×10^{-3}	4.85×10^{-2}	1.13×10^{-2}
6	2.31×10^{-3}	1.63×10^{-1}	1.42×10^{-2}	8.81×10^{-2}
7	4.85×10^{-2}	1.42×10^{-2}	2.32×10^{-1}	-5.45×10^{-3}
8	1.13×10^{-2}	8.81×10^{-2}	-5.45×10^{-3}	4.17×10^{-1}

$\cos\theta_t$ backup plots

