HADRON COLLIDER PHYSICS

East Lansing, Michigan, June 15, 2004

# Top quark properties at the Tevatron

## Summary

- Branching ratios and tests of the SM
- Searches for non-standard top decays
- Anomalous kinematics
- W helicity and spin correlations
- Resonance production
- Conclusions and outlook

UNIVERSITY OF WASHINGTON

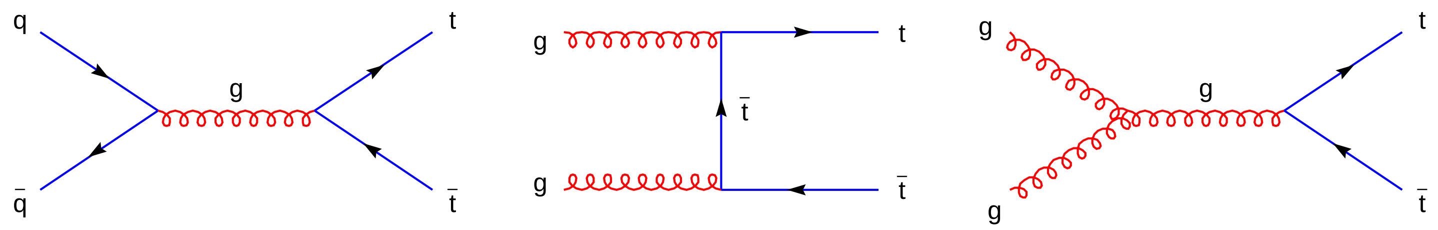
Arán García-Bellido

on behalf of the CDF and DØ collaborations

# Top quark properties overview

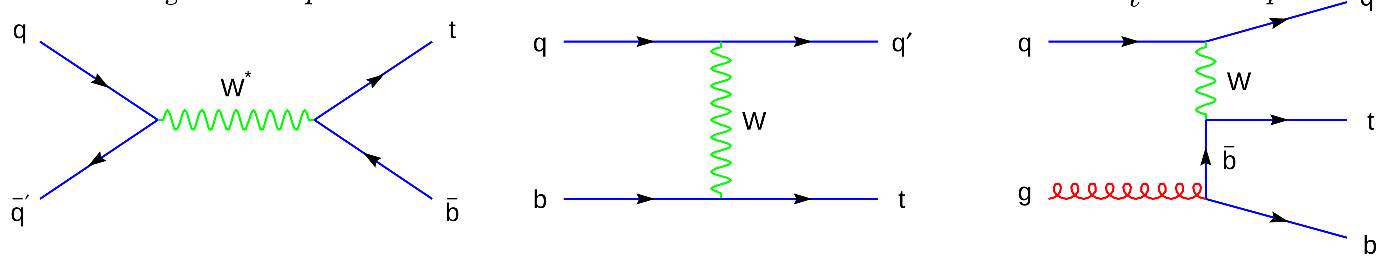
- Heaviest known particle: $m_t = 178.0 \pm 4.3\,\mathrm{GeV}/c^2$
  - Sensitive probe for new physics, FCNCs?
  - $m_t \sim v/\sqrt{2}$, $\lambda_t \sim 1$ Related to EWSB?
- Decays as a free quark: $\tau_t = 5 \times 10^{-25}\,s \ll \Lambda_{QCD}^{-1}$
  - Spin information is passed to its decay products
  - Test $V - A$ structure of the SM
- We have not yet measured its spin, charge or width

$\sigma_{q\bar{q}\to t\bar{t}} \simeq 85\% \sigma_{t\bar{t}}$ $\qquad$ $\sigma_{gg\to t\bar{t}} \simeq 15\% \sigma_{t\bar{t}}$




Single top production offers direct access to $V_{tb}$

$\sigma_s = 0.88pb$ $\qquad$ $\sigma_t = 1.98pb$



# $\mathcal{B}(t \rightarrow Wb)$ measurement

- $R = \frac{\mathcal{B}(t\rightarrow Wb)}{\mathcal{B}(t\rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{ts}|^2+|V_{td}|^2+|V_{tb}|^2} \simeq 1$ in the SM
- Test assumption $\mathcal{B}(t \rightarrow Wb) = 1$, provide indirect measurement on $|V_{tb}|$
- Ratio of single to double-tagged events is sensitive to b=$\mathcal{B}(t \rightarrow Wb)$ and $\varepsilon$=tagging efficiency:

$$N_0 \propto (1 - \mathrm{b}\varepsilon)^2,\ N_1 \propto 2\mathrm{b}\varepsilon(1 - \mathrm{b}\varepsilon) \text{ and } N_2 \propto (\mathrm{b}\varepsilon)^2$$

$$\boxed{\mathrm{b}\varepsilon = \frac{2}{N_1/N_2+2} = \frac{1}{2N_0/N_1+1}}$$

- Always measure the product b$\varepsilon$. Assume $\varepsilon$ and extract b

---

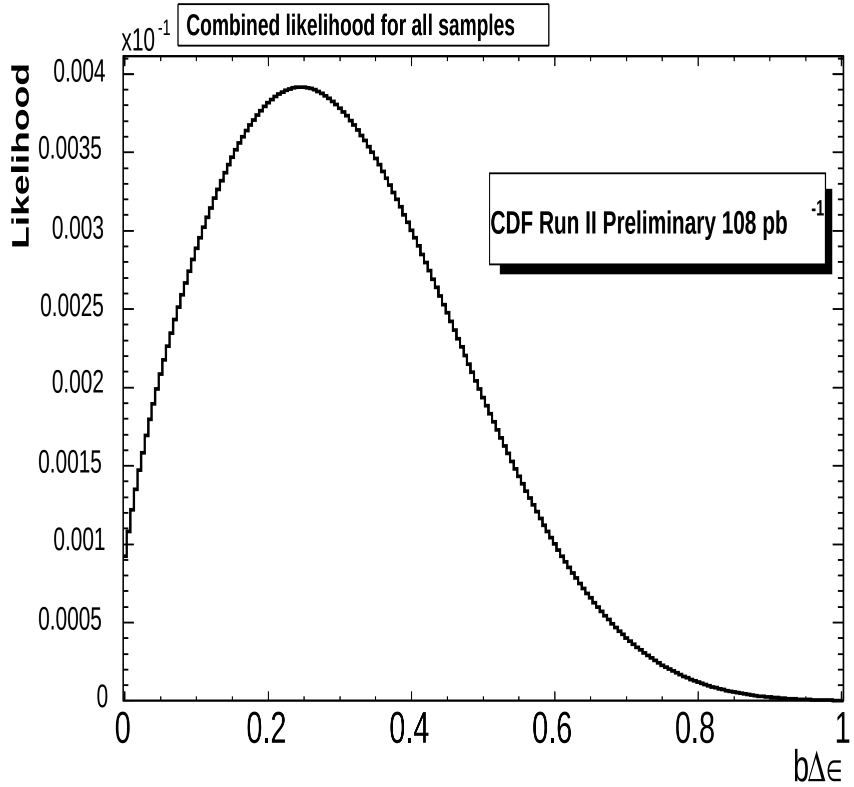
- CDF uses $\ell$+jets sample ($108\,\mathrm{pb}^{-1}$) and SVX tagging:

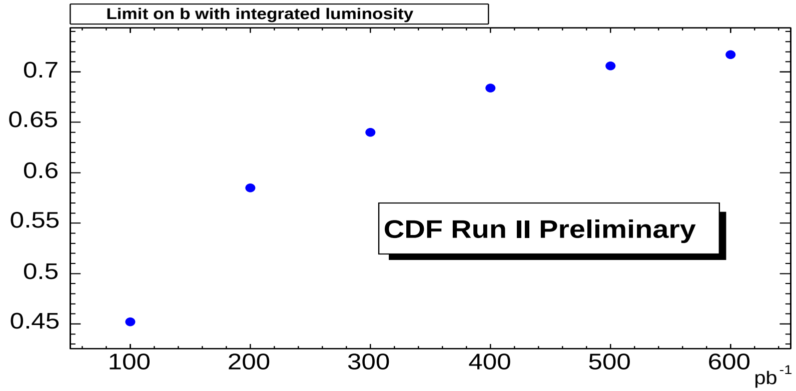
| | 3-jet | $\geq$ 4-jet |
|---|---|---|
| 1-tag events | 12 | 19 |
| 2-tag events | 2 | 2 |

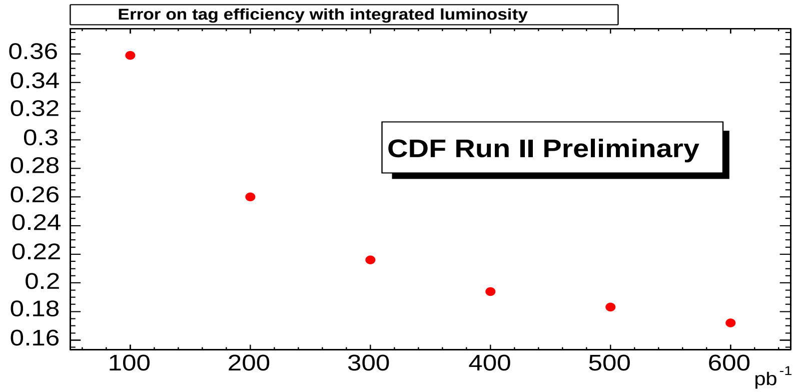
- Main backgrounds are $Wb\bar{b}$, mistags, single top $s-$channel and diboson
- Use likelihood to obtain b$\varepsilon$ most consistent with single and double-tagged events in data. Total number of $t\bar{t}$ also fitted.

# CDF $\mathcal{B}(t \to Wb)$ results

Expected lower limit on b and expected precision on $\varepsilon$




Most likely value: $b\varepsilon = 0.25^{+0.22}_{-0.18} \Rightarrow$ $\mathbf{b = 0.54^{+0.49}_{-0.39}}$ $\Rightarrow b > 0.12$ @ 95%C.L.

Assume $\varepsilon = 0.45 \pm 0.045$ from measurements in calibration samples

CDF Run I: $b = 0.94^{+0.31}_{-0.24} \Rightarrow V_{tb} = 0.97^{+0.16}_{-0.12}$

# Ratio of dilepton to $\ell$+jets cross sections

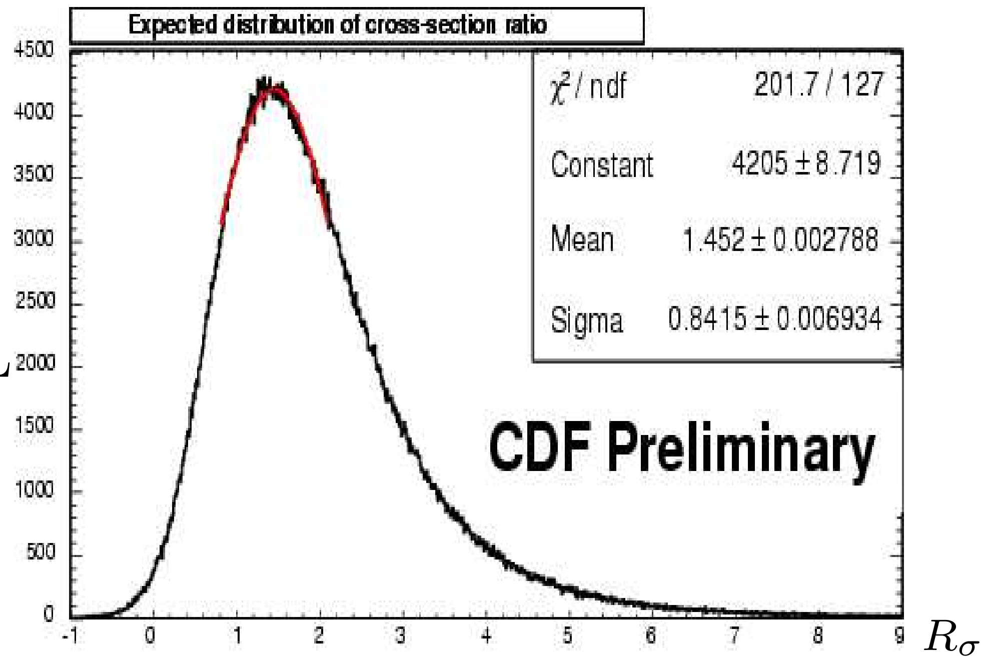
- $\sigma_{t\bar{t}\to\ell\ell}$ should be equal to $\sigma_{t\bar{t}\to\ell+\text{jets}}$ if $\mathcal{B}(t \to Wb) = 100\%$
- Therefore $R_\sigma = \frac{\sigma_{\ell\ell}}{\sigma_{\ell+\text{jets}}} = 1$ in the SM
  Any deviation would imply non-zero $\mathcal{B}(t \to Xb)$: sensitive to non-SM decays of top
- By taking the ratio: cancel systematic uncertainities, independent of theoretical $\sigma$ (i.e. PDF's, m$_t$)
- Create probability distribution for $R_\sigma$

---

- CDF results using dilepton and $\ell$+jets samples (126 and 108 pb$^{-1}$):

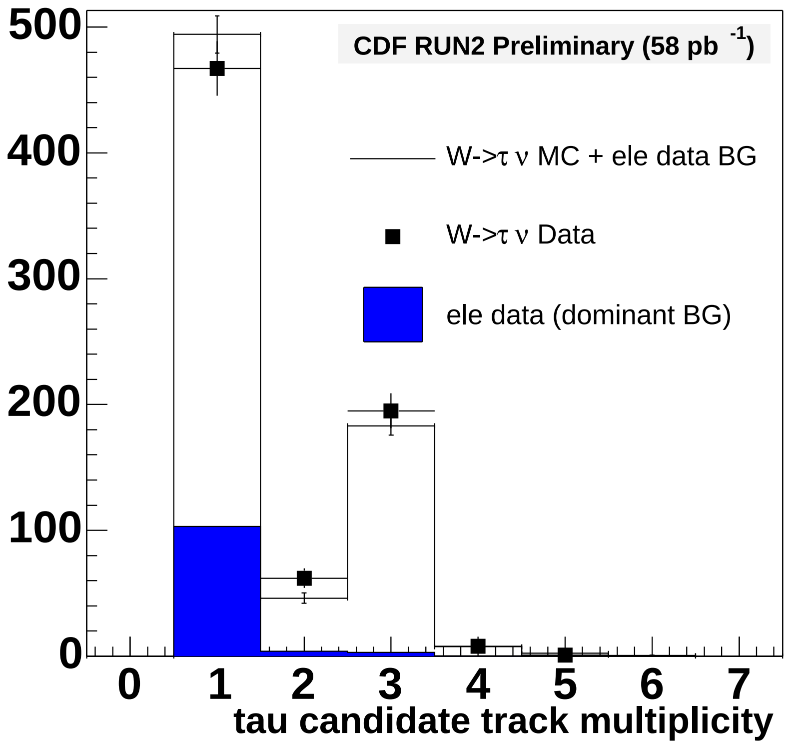
$$\mathbf{R_\sigma = 1.45^{+0.83}_{-0.55}}$$

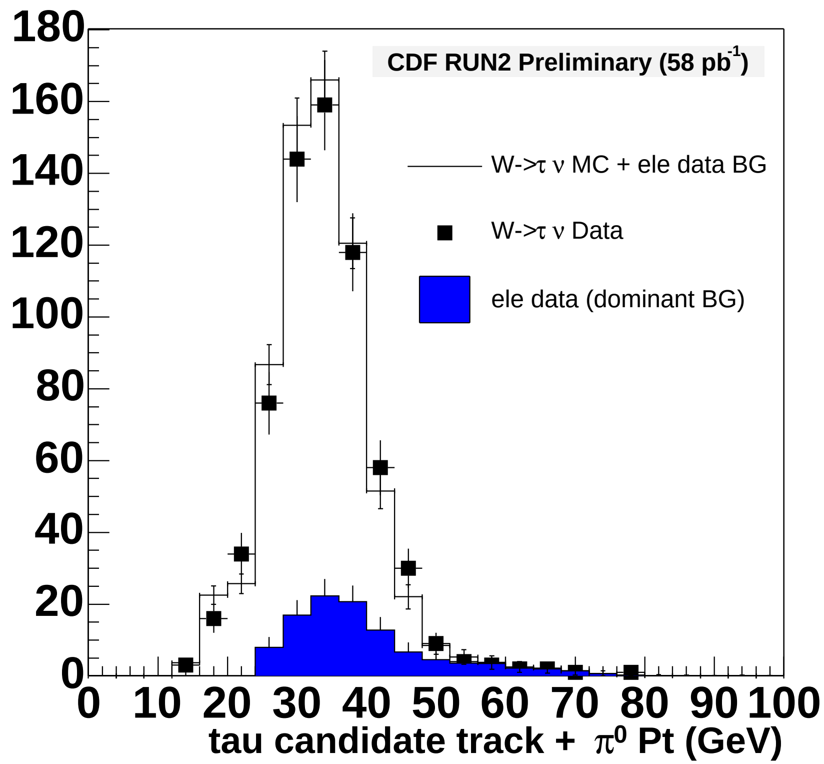
$$0.46 < R_\sigma < 4.45 \text{ @ } 95\%\text{C.L}$$



# Rate of top decays to $\tau\nu b$

- Search for new physics ($H^{\pm}$) and test of lepton universality
- $\tau$ ID is crucial: CDF used $58\,pb^{-1}$ of $W \to \tau\nu$ data and Pythia MC



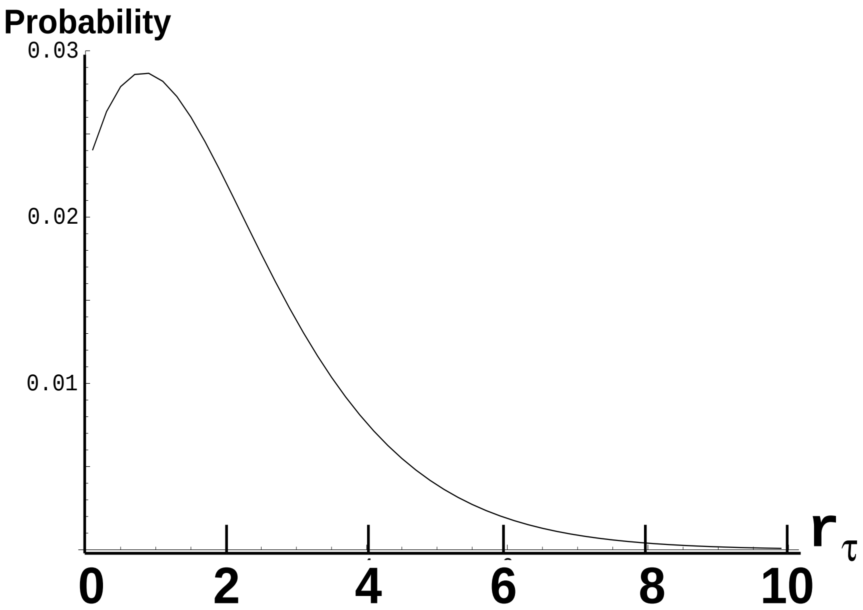
# CDF rate of top decays to $\tau\nu b$: results

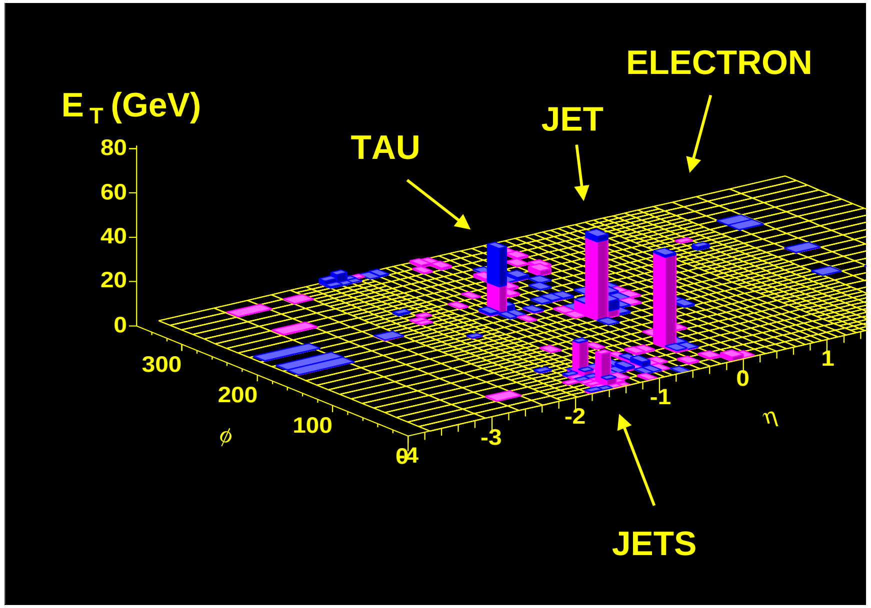
- In dilepton sample with e or $\mu$ and $\tau \rightarrow$hadrons ($193\,\mathrm{pb}^{-1}$)
- Largest background is jets faking taus
- Major uncertainties: MC $t\bar{t}$ acceptance (generator, ISR, FSR) and $\tau$ ID

Expect 2.3 events, Observe: 2 events

Most likely value: $r(\tau) = 0.8$ (SM expectation: $r(\tau) = 1$)

Set limit: $\mathbf{r}(\tau) = \frac{\mathcal{B}_{\mathrm{meas}}(\mathbf{t}\rightarrow\tau\nu\mathbf{b})}{\mathcal{B}_{\mathrm{SM}}(\mathbf{t}\rightarrow\tau\nu\mathbf{b})} < \mathbf{5}$ **@ 95% C.L.**

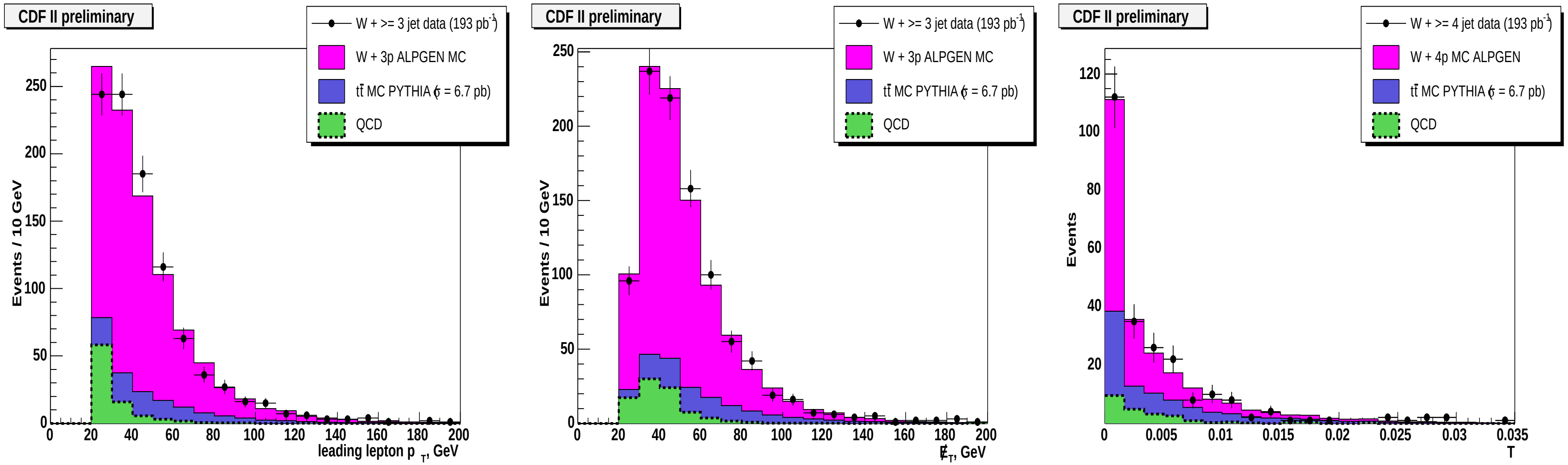


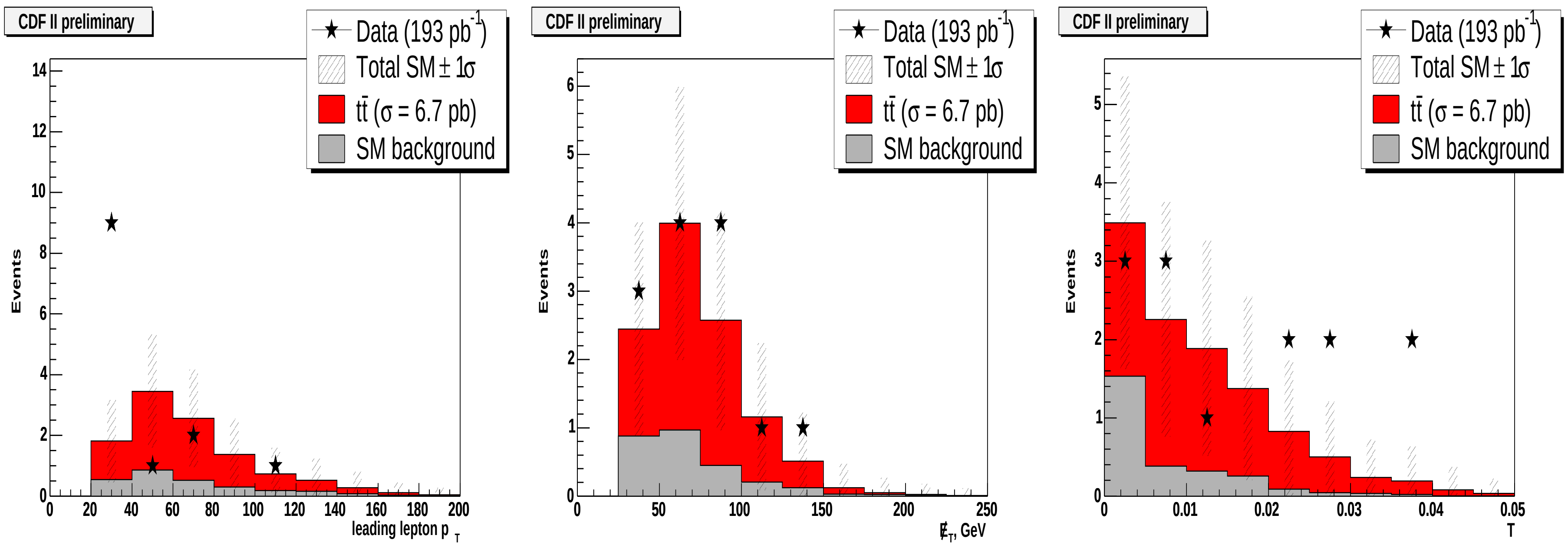
# CDF search for anomalous kinematics

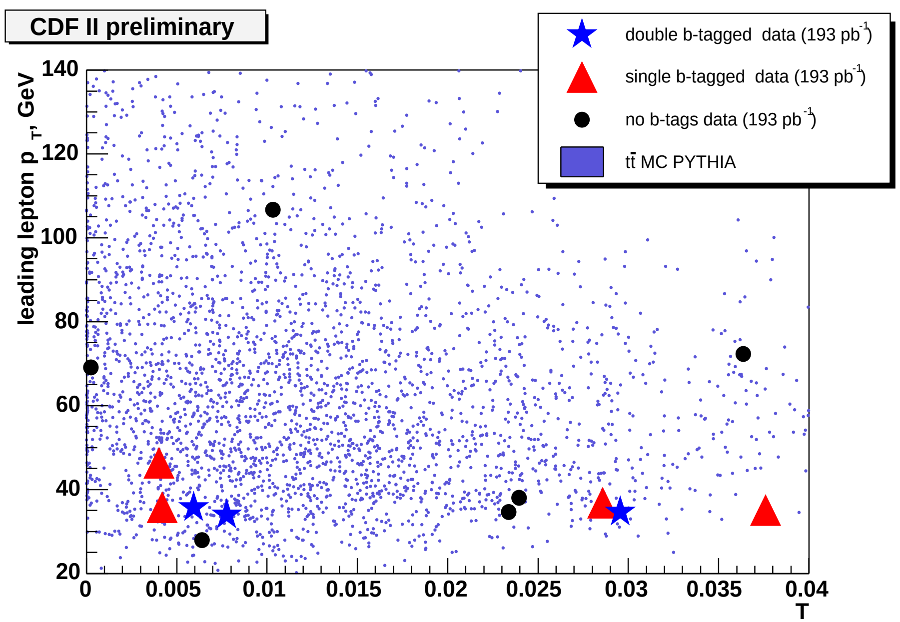
- Models beyond the SM predict anomalous top $p_T$ spectra
- Same analysis as $\sigma_{\ell\ell}$ measurement (hep-ex/0404036) with 193 pb$^{-1}$
- New technique to isolate subsets of sample which reveal the largest discrepancy looking at four variables: high $\not{E}_T$, lepton $p_T$, $\Delta\phi(\ell, \not{E}_T)$ or consistency with $\ell\ell$ topology: $T = \int \exp\left[-\left(\vec{\not{E}}_T^{\,SM} - \vec{\not{E}}_T^{\,obs}\right)^2 / 2\sigma_{\not{E}_T}\right] d\vec{\not{E}}_T^{\,SM}$
- Algorithm loops over different subsamples and creates a multi-variate KS test shape to compare to the SM distribution
- Extract significance of discrepancy (P-value) by pseudoexperiments

Control sample for simulation of kinematics: $W+ \geq 3$jets and $W + 4$jets samples



# CDF search for anomalous kinematics: results



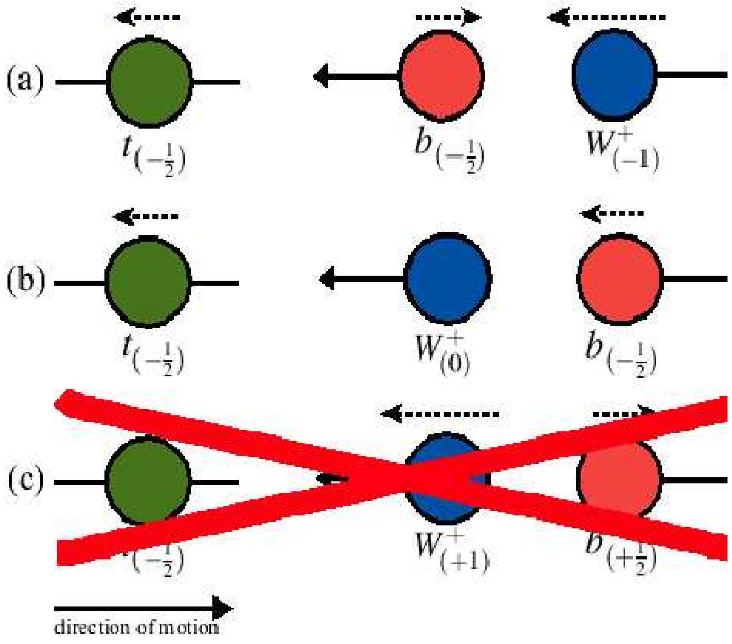



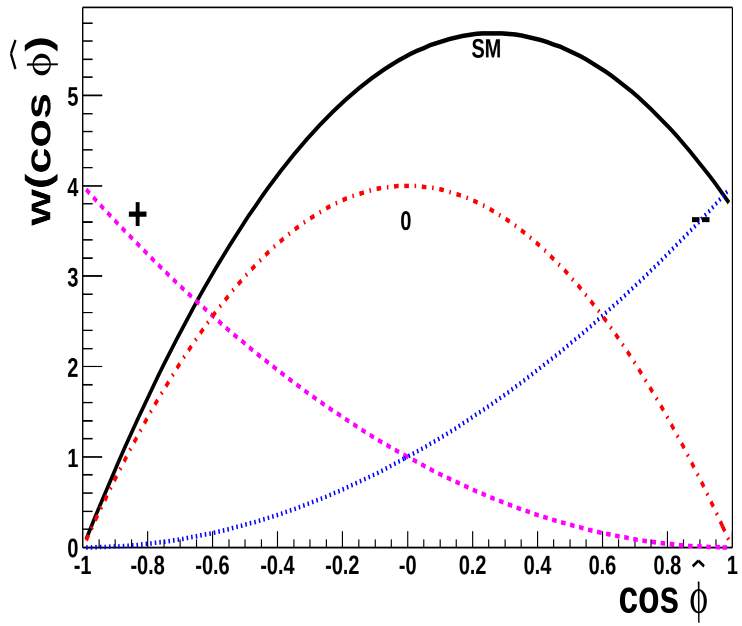

Consistency with the SM for the whole dilepton sample:

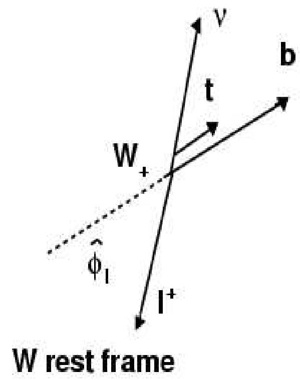
**P-value = 1.0 – 4.5%**

The discrepancy arises from an excess of events with low $p_T$ leptons compared to SM expectation

# Helicity of W in $t\bar{t}$ events



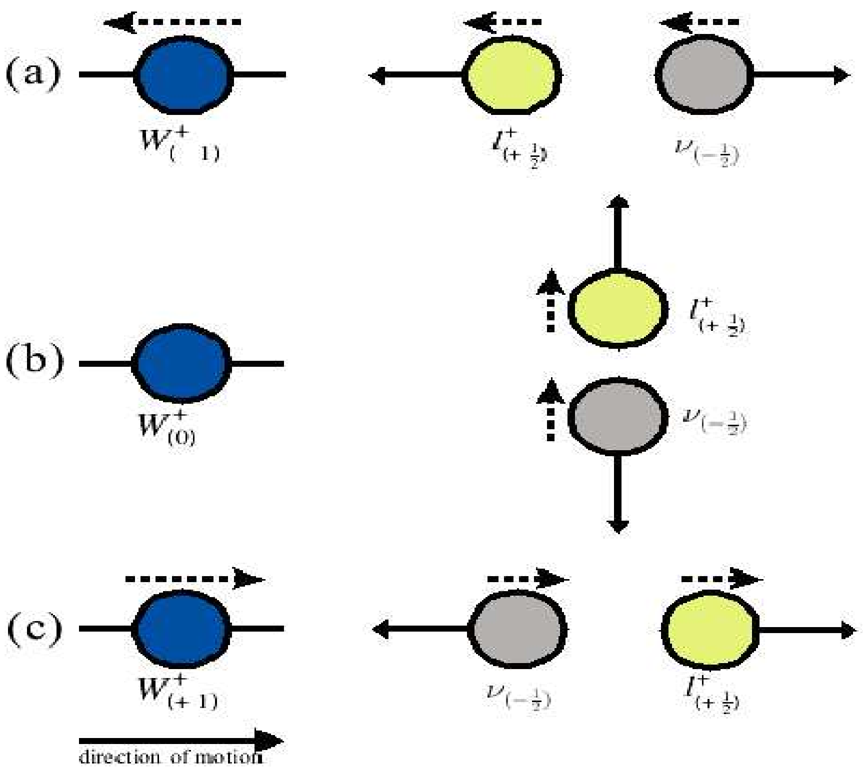



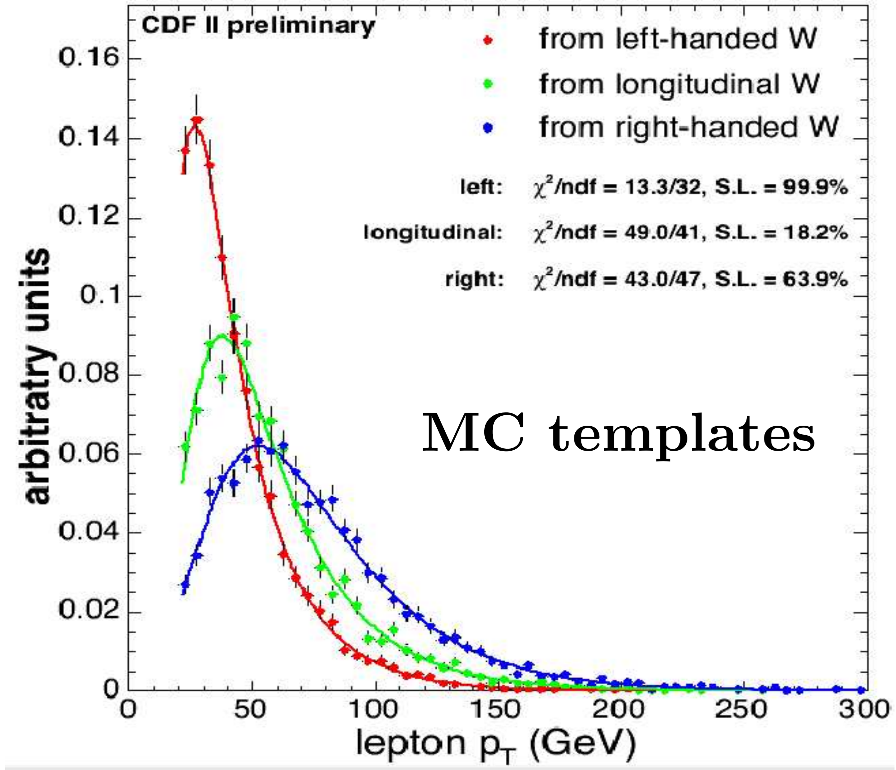




- In the SM only left-handed $W_-$ and longitudinal $W_0$ may be produced
- $W_0$ fraction: $F_0 = \frac{\Gamma(W_0)}{\Gamma(W_0)+\Gamma(W_T)} = \frac{1}{1+2(M_W/M_t)^2} \simeq 0.7$ $\Rightarrow F_- \simeq 0.3$
- Any V+A structure in the dynamics would yield $F_+ \neq 0$ and $F_- \leq 0.3$
- We can estimate the helicity content by fitting templates of $\cos\phi$

  $\phi$: angle between the $\ell$ and the $b$ in W rest frame

# Lepton $p_T$ spectra for different W helicities




- The $W_-$ lepton is emitted antiparallel to the W boost
- The $W_0$ lepton is emitted perpendicular to the W boost
- $W_0$ lepton spectrum is harder than $W_-$
- We can estimate the helicity content of $t\bar{t}$ samples by analyzing their $\ell$ $p_T$ spectra

# CDF W helicity measurement

- Use dilepton and $\ell$+jets samples: 162-192 $\mathrm{pb}^{-1}$
- Analysis with Secondary Vertex Tagger:

| sample | dilepton | $\ell$+jets | total |
|---|---|---|---|
| # leptons | 26 | 57 | 83 |

- Construct likelihood function with the PDFs of $p_T$ of leptons from background and signal for different helicities:

$$L = G(\beta;\mu,\sigma)\prod_{i=1}^{N}\left(\beta P(x_i,\mathrm{bkg}) + (1-\beta)[F_0 P(x_i;0) + (1-F_0)P(x_i;-1)]\right)$$

$\beta$: background fraction

$G(\beta;\mu,\sigma)$: Gaussian constrain on $\beta$ with $\mu\pm\sigma$ prior estimate

$N$: number of reconstructed leptons

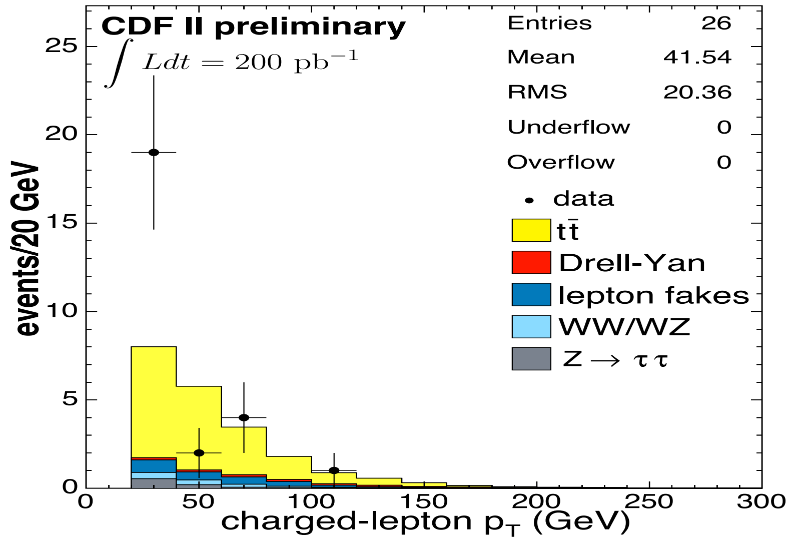
$P(x_i,\mathrm{bkg})$: PDF of charged $\ell$ with $p_T = x_i$ due to background process

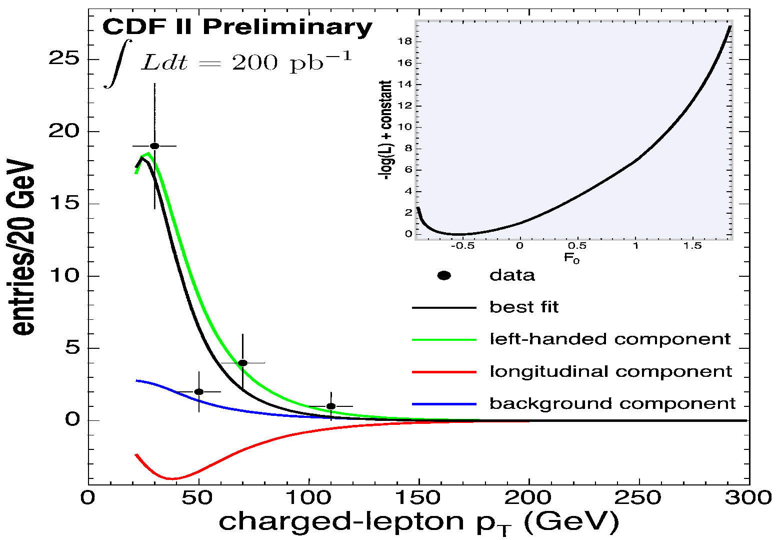
$P(x_i,h)$: PDF of charged $\ell$ with $p_T = x_i$ from W with helicity $h$

- Major systematic uncertainties: top mass and background normalization

# CDF W helicity measurement: distributions

## dilepton

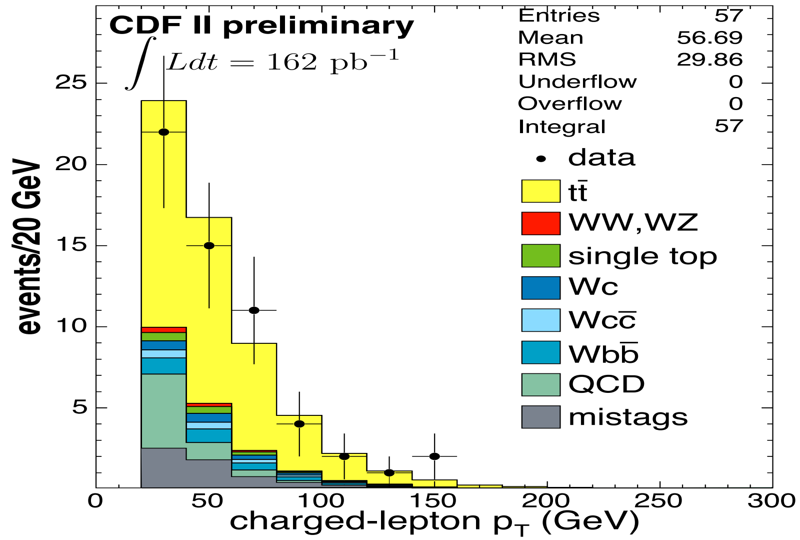


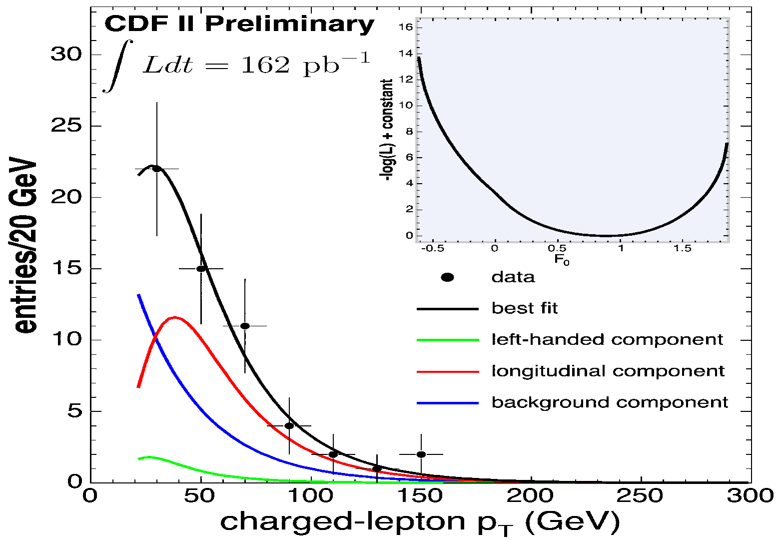




$$\hat{F}_0 = -0.54$$

$$F_0 < 0.52 \text{ @ } 95\%\text{C.L.}$$

## $\ell$+jets



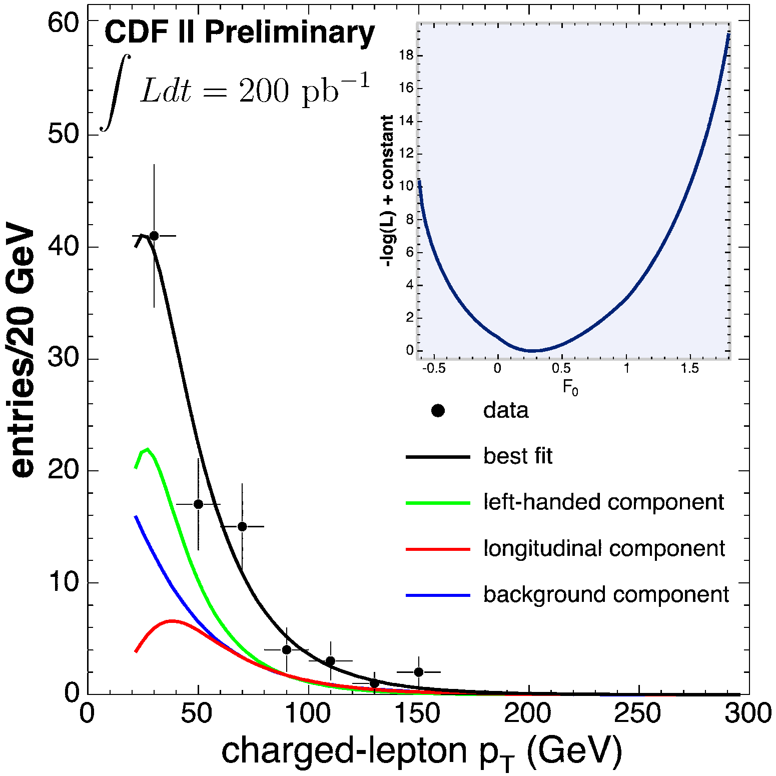



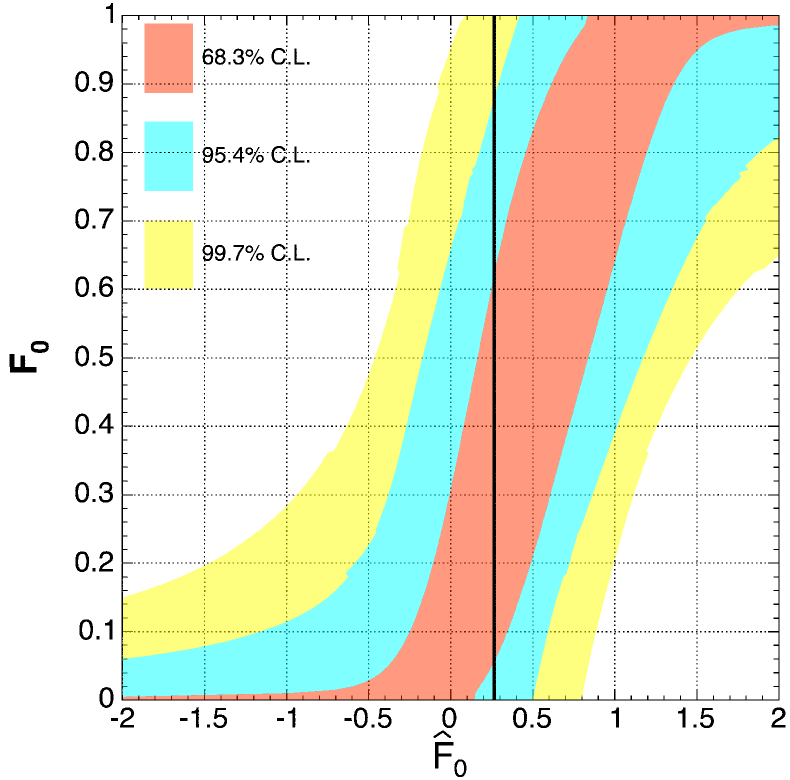

$$F_0 = 0.88^{+0.12}_{-0.47}$$

$$F_0 < 0.88 \text{ @ } 95\%\text{C.L.}$$

# CDF W helicity measurement: results

Combining the samples:




$$\mathbf{F_0 = 0.27^{+0.35}_{-0.21}}\,(\text{stat} + \text{syst})$$

$$\mathbf{F_0 < 0.88\ @\ 95\%}\text{C.L.}$$

- ★ The data distribution for dileptons is softer than any signal or background component → the longitudinal component is forced negative
- ★ $2\sigma$ level discrepancy for $F_0$ in the dilepton channel
- ★ The combined result is compatible with the SM at $1\sigma$

# W helicity: Matrix Element Method

Likelihood method to extract top properties with maximal use of statistical information:

$$P(x;\alpha) = Acc(x) \times \frac{1}{\sigma} \int d^n\sigma(y;\alpha) dq_1 dq_2 f(q_1) f(q_2) W(x,y)$$

- $x$ set of reconstructed variables measured in the detector
- $\alpha$ parameter to estimate, for the helicity calculation $\alpha = F_0$
- $d^n\sigma$ differential cross section (L0 matrix element $\rightarrow$ cut on $\mathrm{N_{jets}}$=4)
- $f(q)$ parton distribution function
- $W(x,y)$ transfer function: probability that a parton level set of variables $y$ appears as $x$ in the detector
- Integrate over all possible set of parton variables $y$ to observe $x$

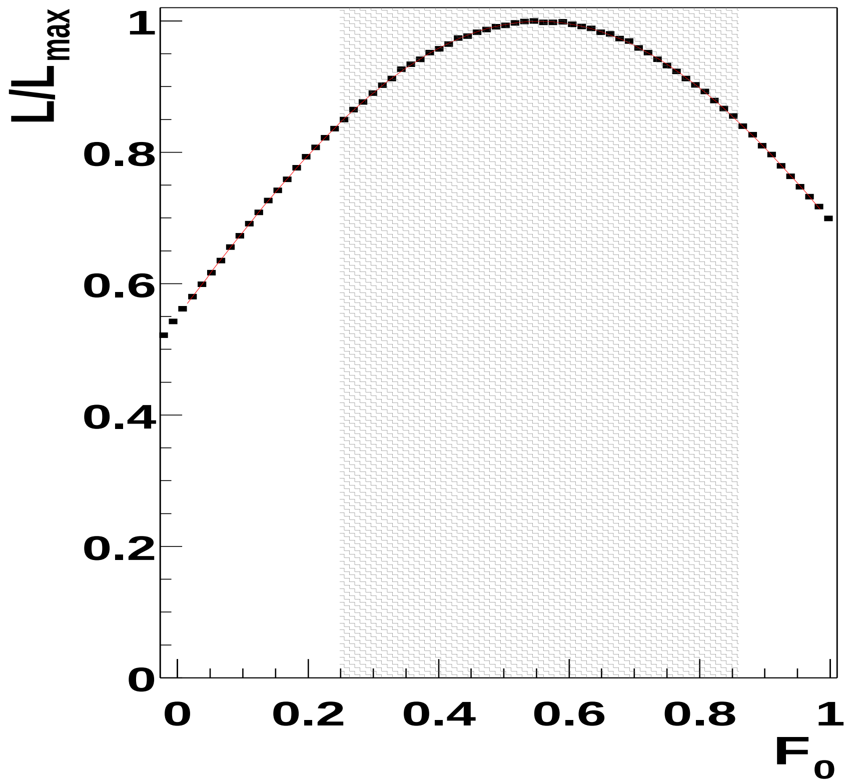
$$-\ln L(\alpha) = -\sum_{i=1}^{N} \ln \left[c_1 P_{t\bar{t}}(x_i;\alpha) + c_2 P_{\mathrm{bkg}}(x_i)\right] + N \int Acc(x) \left[c_1 P_{t\bar{t}}(x;\alpha) + c_2 P_{\mathrm{bkg}}(x)\right] dx$$

Obtain best values of $F_0$ and the signal and background fractions ($c_1$ and $c_2$) by minimizing $-\ln L(F_0)$

# DØ Run I W helicity measurement

Based on the Matrix Element $\ell$+jets mass analysis of Run I data ($125\,\mathrm{pb}^{-1}$)

- Include all 12 possible combinations of jets plus all possible neutrino $p_z$ to form the top
- Construct background and signal probabilities for each event
- Well measured events contribute more information than poorly measured events
- Better discrimination between signal and background:
  better mass measurement to date!




- Statistics limited:
  only 22 events after final selection!
- Integrate over $m_t$ to account for uncertainty

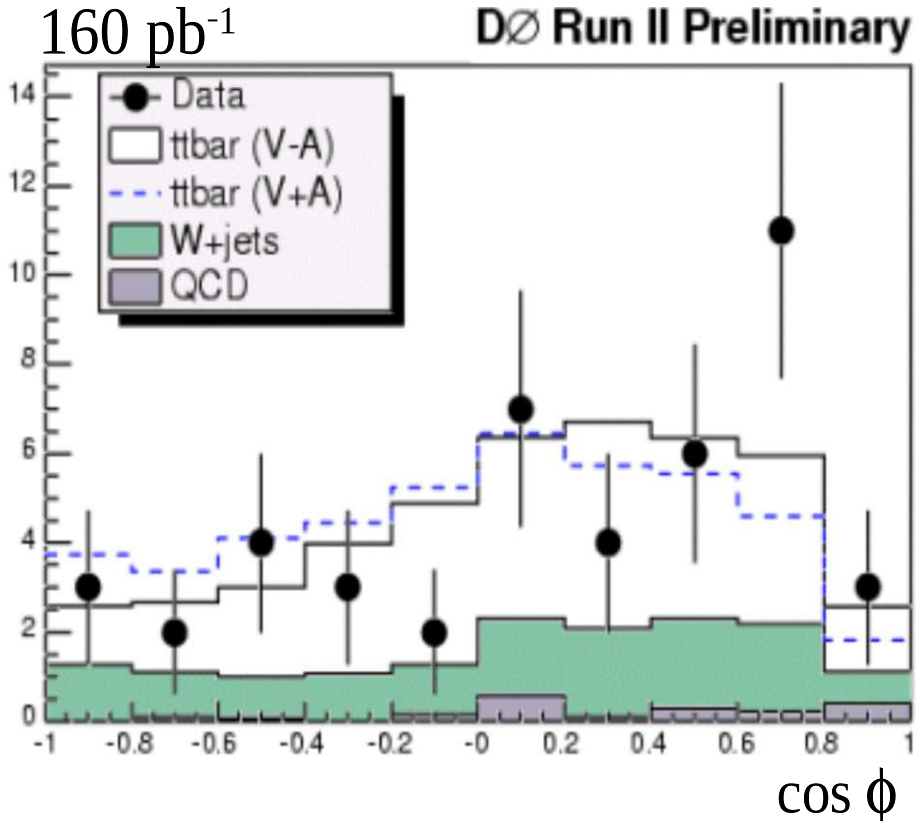
$\mathbf{F_0 = 0.56 \pm 0.31(\mathrm{stat} + m_t) \pm 0.07(syst)}$ (submitted to PRL, hep-ex/0404040)

$\mathbf{F_0 = 0.91 \pm 0.39(\mathrm{stat} + \mathrm{syst})}$ (CDF Run I Result)

# DØ Run II W helicity analysis overview

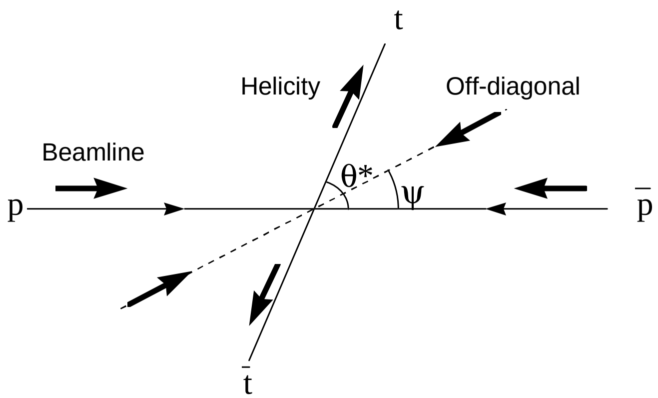
- Using $\ell$+jets sample (160 pb$^{-1}$)
- Developing two parallel analysis: topological selection / $b$-tagging and then event kinematic fitting
- The data is fitted to $\cos\phi$ templates for various $F_+$ fixing $F_0 = 0.7$
- Simultaneous determination of $F_+$ and S/B ratios

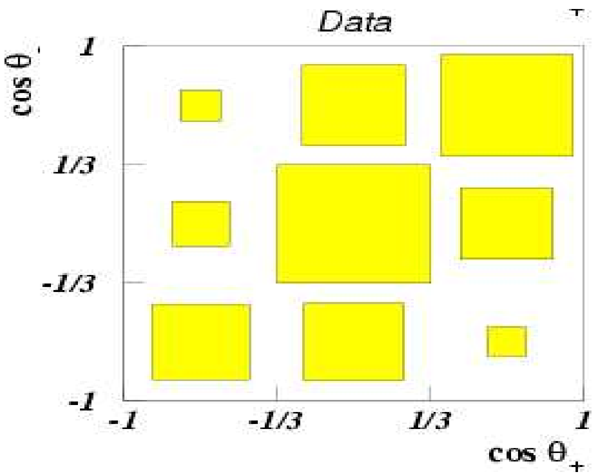
Working on optimization and combination of analyses
Expect results for ICHEP



# DØ Run I spin correlations

- ✶ Confirm that top decays before spin flips, lower limit on $\tau_t \Rightarrow$ lower limit on $\Gamma_t$
- ✶ Non standard EW interactions may manifest in decay product anomalies
- ✶ Dilepton analysis ($125\,\text{pb}^{-1}$) Phys. Rev. Lett. 85, 256, 2000
- ✶ At the Tevatron, the better spin-basis is the "off-diagonal", where like-spin rate vanishes to LO: defined by $\tan\psi = \frac{\beta^2 \sin\theta^* \cos\theta^*}{1-\beta^2 \sin^2\theta^*}$
- ✶ 3C fit + $m_t = 175\,\text{GeV}/c^2$ and weight each of the four neutrino solutions, use two-dimensional binned likelihood $(\cos\theta_+, \cos\theta_-)$




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

**$\kappa > -0.28$ @ 68%C.L.** (SM: $\kappa = 0.88$)

# DØ Run I search for $t\bar{t}$ resonances

- Technicolor may provide another EWSB mechanism
- Look for narrow resonances (compared to detector resolution) of a heavy top quark condensate $X \to t\bar{t}$ or $Z' \to t\bar{t}$
- Use Run I mass $\ell$+jets sample ($130\,\text{pb}^{-1}$) and analysis
- Perform 3C kinematic fit over two orthogonal analyses: topological cuts and soft muon tagging

A total of 41 events:

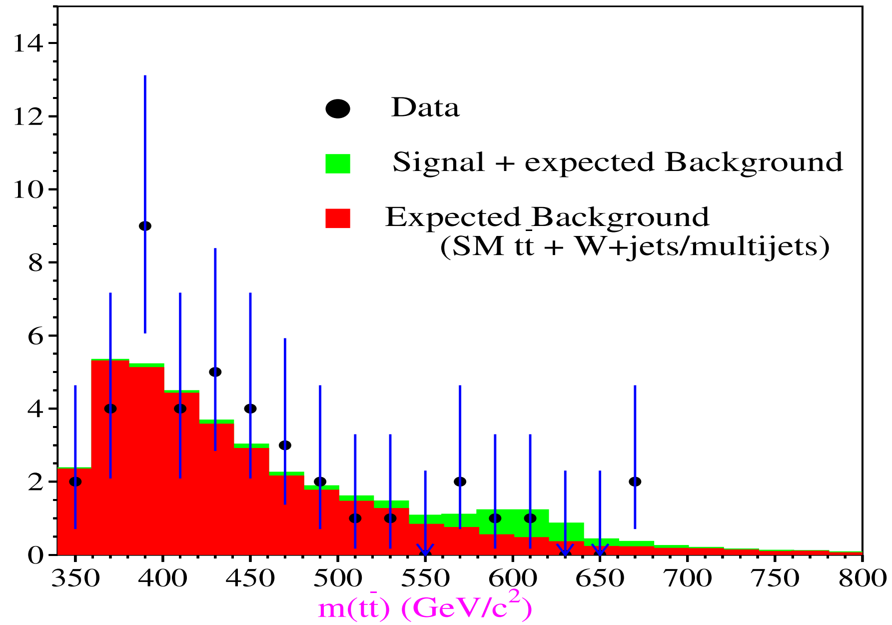
| e+jets | $\mu$+jets | e+jets/SLT | $\mu$+jets/SLT |
|---|---|---|---|
| 16 | 21 | 1 | 3 |

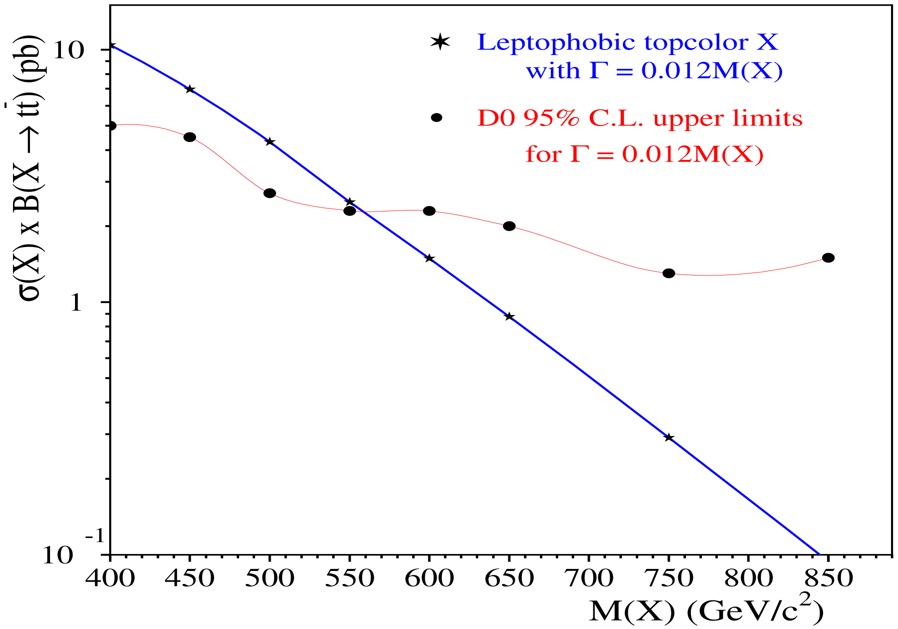
- Main systematic uncertainites: MC acceptance (ISR/FSR, PDF) and Jet Energy Scale

# DØ Run I search for $t\bar{t}$ resonances: results

| data | $X \to t\bar{t}$ | SM $t\bar{t}$ | W+jets & QCD |
|---|---|---|---|
| 41 | $4.2 \pm 3.2$ | $23.7 \pm 11.6$ | $15.4 \pm 10.6$ |

Set limit with Bayesian statistics: fit data $m_{t\bar{t}}$ distribution to weighted sum of three distributions $X \to t\bar{t}$, SM $t\bar{t}$ and W+jets & QCD



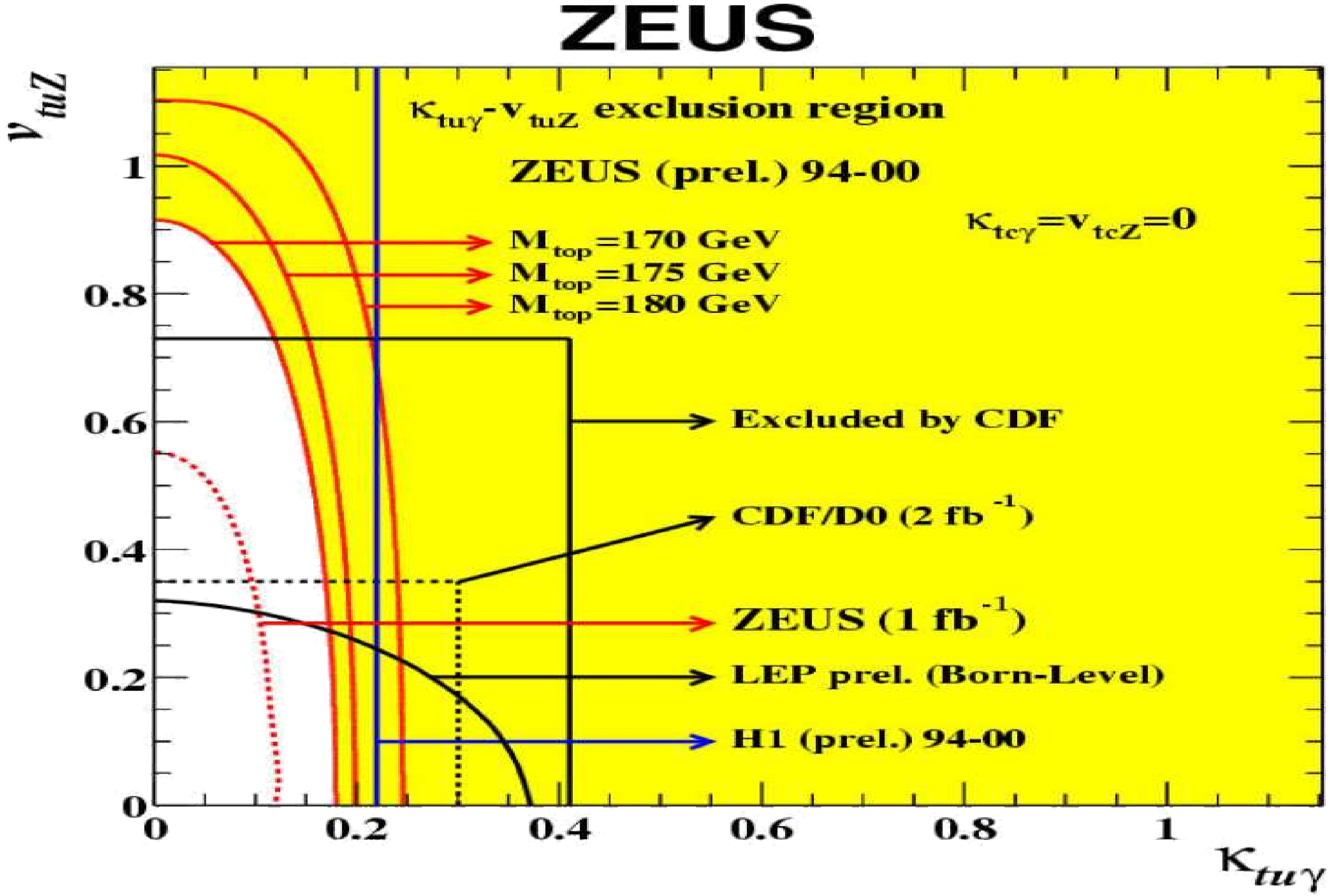




Assuming $\Gamma_X = 0.012 M_X, m_t = 175\,\text{GeV}/c^2$ and flat priors, exclude narrow leptophobic X boson: $\mathbf{M_X > 560\,GeV/c^2}$ (accepted by PRL, hep-ex/0307079)

$\mathbf{M_X > 480\,GeV/c^2}$ (CDF Run I: PRL 85, 256, 2000)

# Anomalous couplings

- New physics may appear in altered rates of FCNC
- At the Tevatron, can look for $t \to qZ$ and $t \to q\gamma$ where $q = u, c$ are expected to be extremely rare
- Study the decay instead of the production, normalize to $N_{t\bar{t}}$ produced



# Conclusions and outlook

- The Tevatron is performing very well, providing lots of new data
- Top quark physics is an excellent probe of the SM and a window beyond
- First Run II results with similar or exceeding luminosity to Run I
- Very sophisticated new analysis techniques are in place, ready to crunch more data and surpass Run I sensitivity
- Many exciting physics results from top properties!

CDF and DØ combined expected precisions for 2 $fb^{-1}$:

| | | | |
|---|---|---|---|
| W helicity $F_0,\ F_+$ | 0.09, 0.03 | $\sigma$ single top | 20% |
| $R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)}$ | 4.5% | $\Gamma_t$ from single top | 25% |
| $\lvert V_{tb} \rvert$ from R | $> 0.25$ | $\lvert V_{tb} \rvert$ from single top | 12% |
| $\mathcal{B}(t \to \gamma q)$ | $2 \times 10^{-3}$ | $\mathcal{B}(t \to qZ)$ | 0.02 |