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

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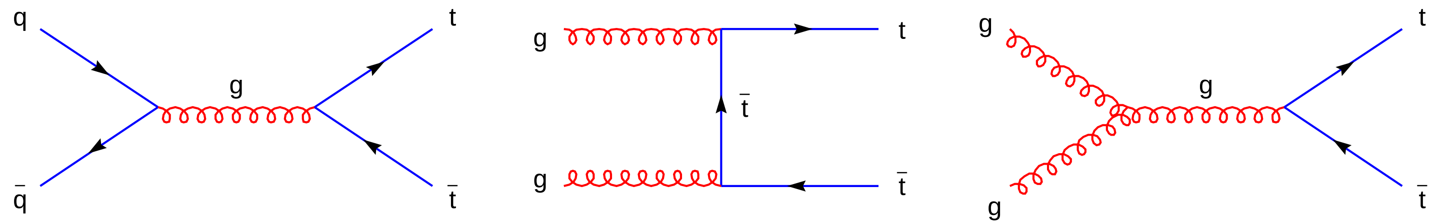
on behalf of the CDF and DØ collaborations

Top quark properties overview

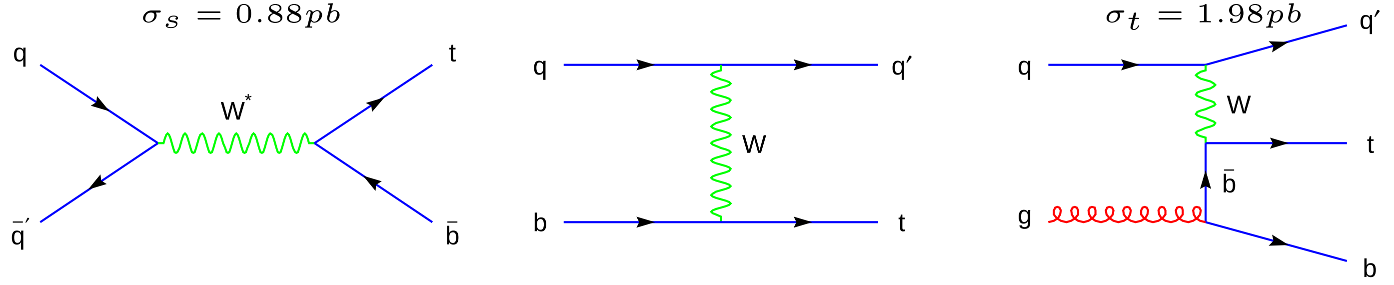
- Heaviest known particle: $m_t = 178.0 \pm 4.3\,\mathrm{GeV}/c^2$
  - Sensitive probe for new physics, FCNCs?
  - $m_t \sim v/\sqrt{2}$, $\lambda_t \sim 1$ Related to EWSB?
- Decays as a free quark: $\tau_t = 5 \times 10^{-25}\, s \ll \Lambda_{QCD}^{-1}$
  - Spin information is passed to its decay products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

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



Single top production offers direct access to V_{tb}

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



$\mathcal{B}(t \to Wb)$ measurement

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

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

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

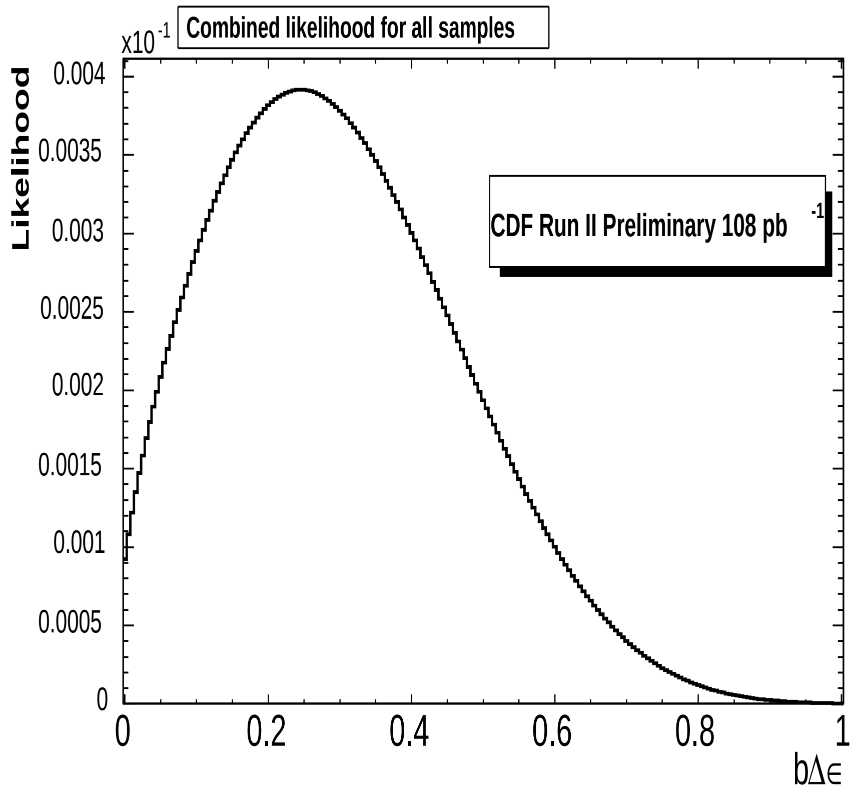
- Always measure the product bε. Assume ε and extract b

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

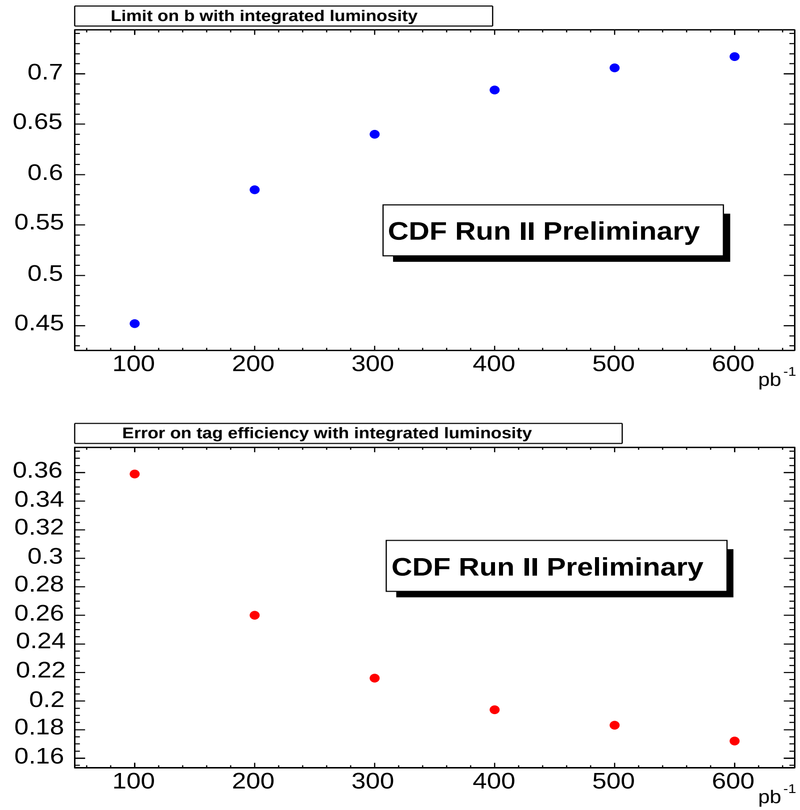
	3-jet	$\geq$ 4-jet
1-tag events	12	19
2-tag events	2	2

- Main backgrounds are $Wb\bar{b}$, mistags, single top $s-$channel and diboson
- Use likelihood to obtain bε 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 ε



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

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

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

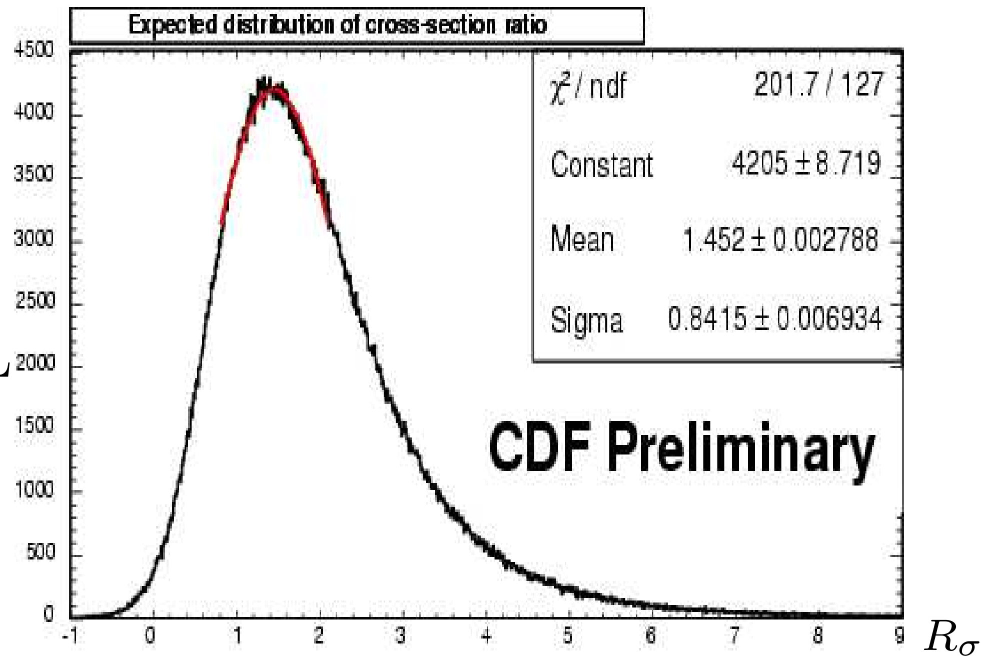
Ratio of dilepton to ℓ+jets cross sections

- $\sigma_{t\bar{t}\to\ell\ell}$ 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 σ (i.e. PDF's, m_t)
- Create probability distribution for R_σ

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

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

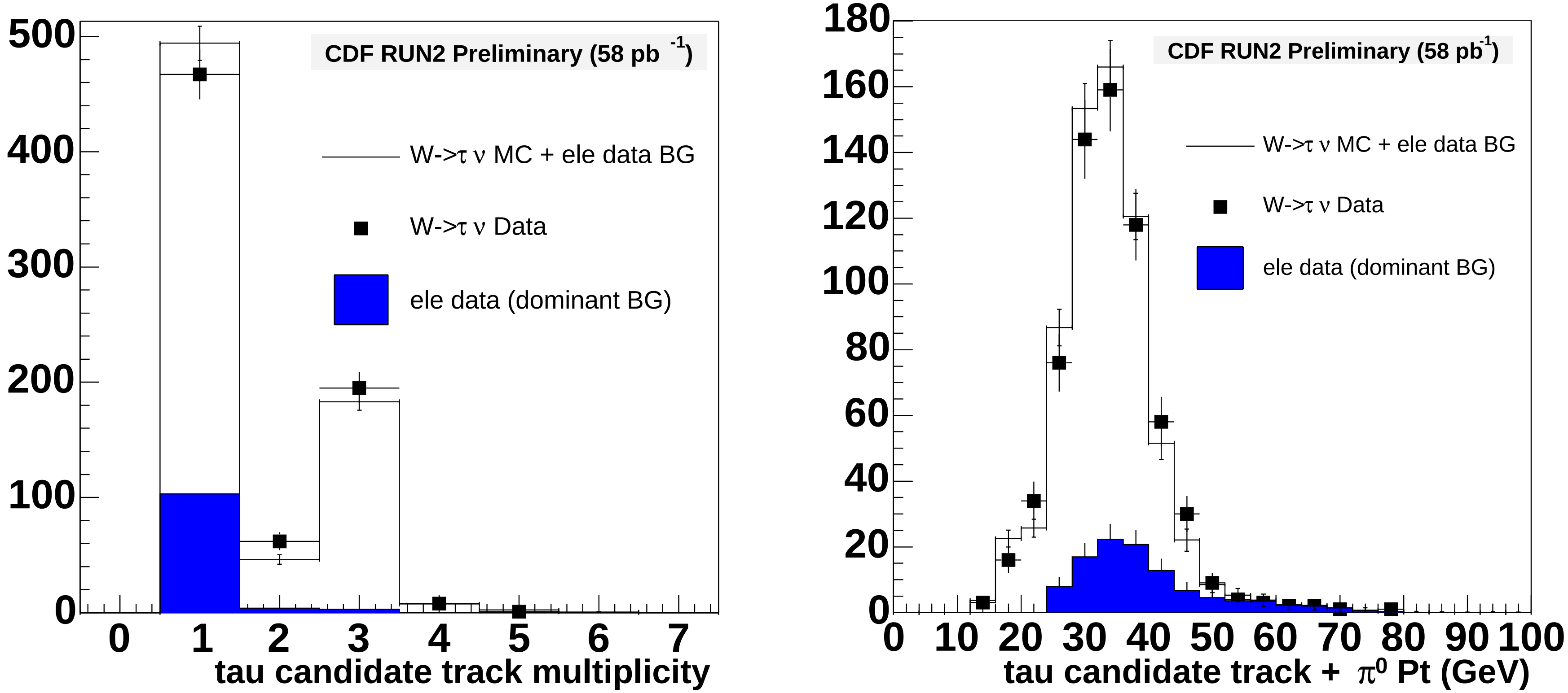
$0.46 < R_\sigma < 4.45$ @ 95%C.L



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

- Test of lepton universality, search for new physics (2HDM: $t \to H^+ b \to \tau^+ \nu b$)
- In MSSM with high $\tan\beta$, $t \to H^+ b$ may dominate over $t \to W^+ b$
- Look for excess over the SM: $t\bar{t} \to W^+ W^- b\bar{b} \to \tau^+ \tau^- b\bar{b} + \not{E}_T$
- One of the taus decays leptonically and the other hadronically

- τ ID is crucial: CDF used $58\,\mathrm{pb}^{-1}$ of $W \to \tau\nu$ data and Pythia MC



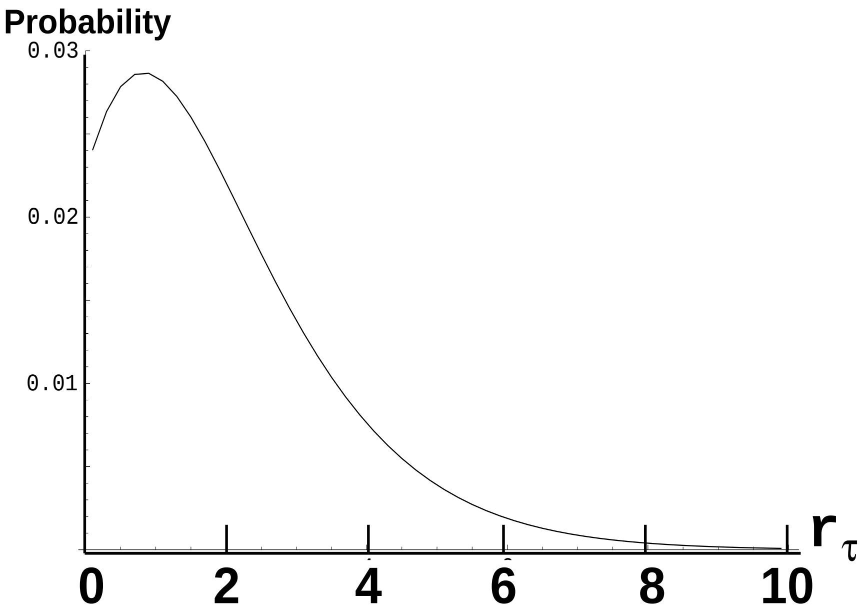
CDF rate of top decays to $\tau\nu b$: results

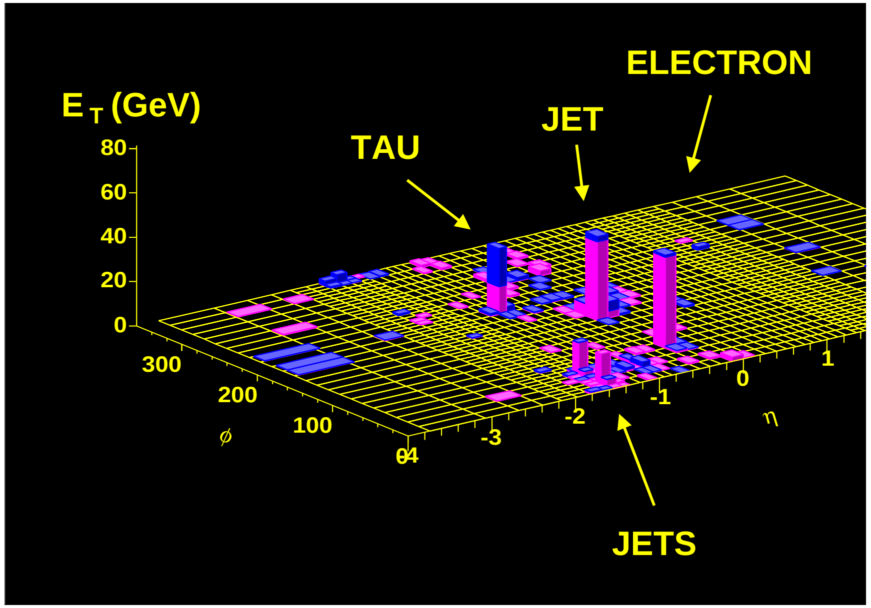
- In dilepton sample with e or μ and $\tau \to$hadrons ($193\,\text{pb}^{-1}$)
- Largest background is jets faking taus
- Major uncertainties: MC $t\bar{t}$ acceptance (generator, ISR, FSR) and τ ID

Expect 2.3 events, Observe: 2 events

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

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

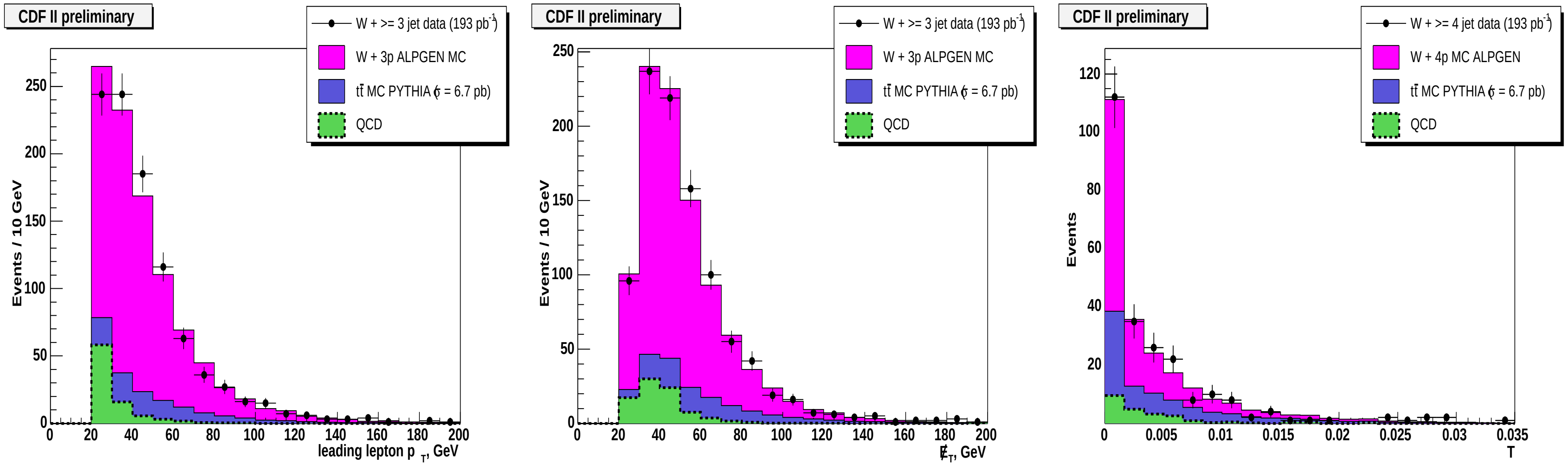




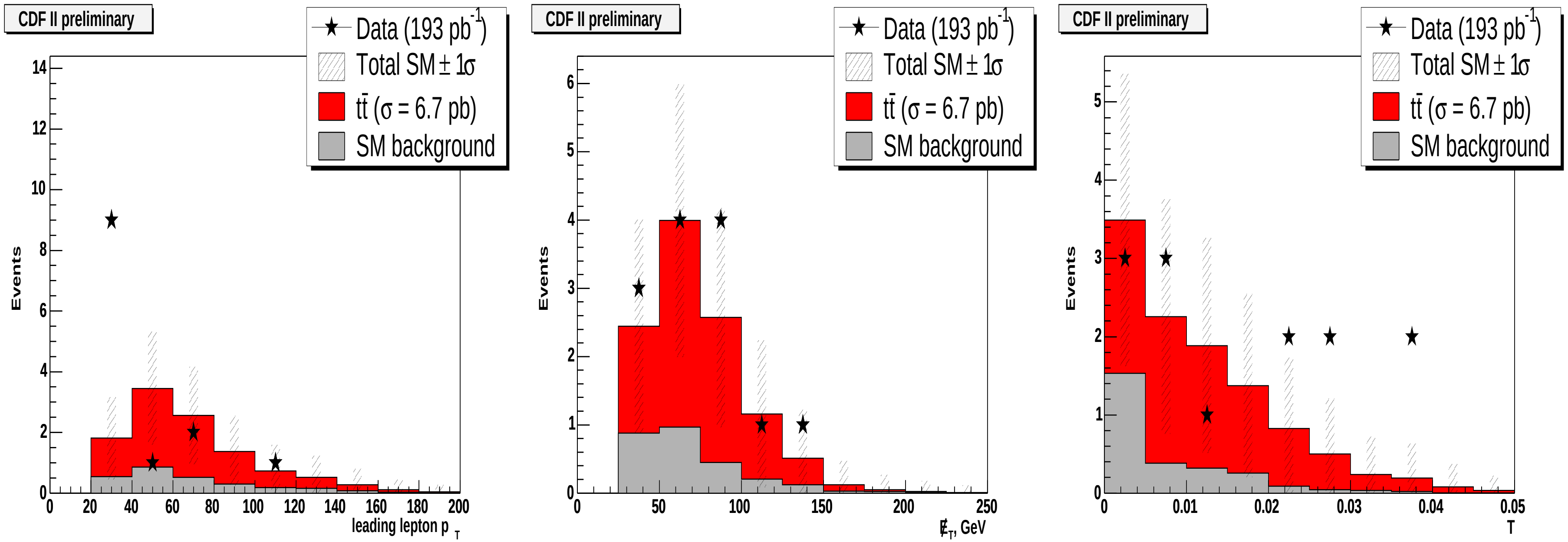
CDF search for anomalous kinematics

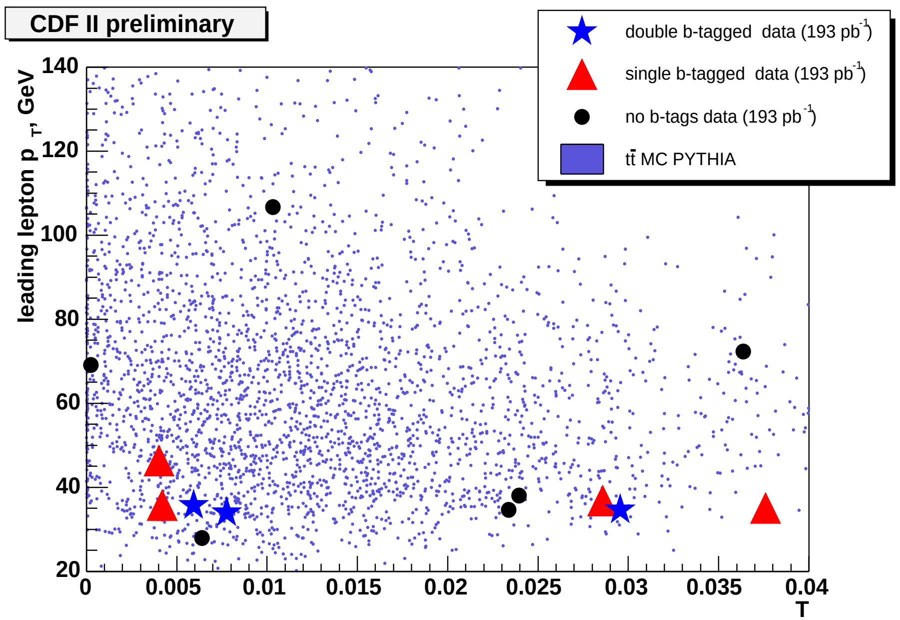
- Models beyond the SM predict anomalous top p_{T} spectra
- Same analysis as $\sigma_{\ell\ell}$ measurement (hep-ex/0404036) with $193\,\mathrm{pb}^{-1}$
- New technique to isolate subsets of sample which reveal the largest discrepancy looking at four variables: high $\not{E}_{\mathrm{T}}$, lepton p_{T}, $\Delta\phi(\ell, \not{E}_{\mathrm{T}})$ or consistency with $\ell\ell$ topology: $T = \int \exp\left[-\left(\vec{\not{E}}_{\mathrm{T}}^{\,SM} - \vec{\not{E}}_{\mathrm{T}}^{\,obs} \right)^2 / 2\sigma_{\not{E}_{\mathrm{T}}} \right] d\vec{\not{E}}_{\mathrm{T}}^{\,SM}$
- 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



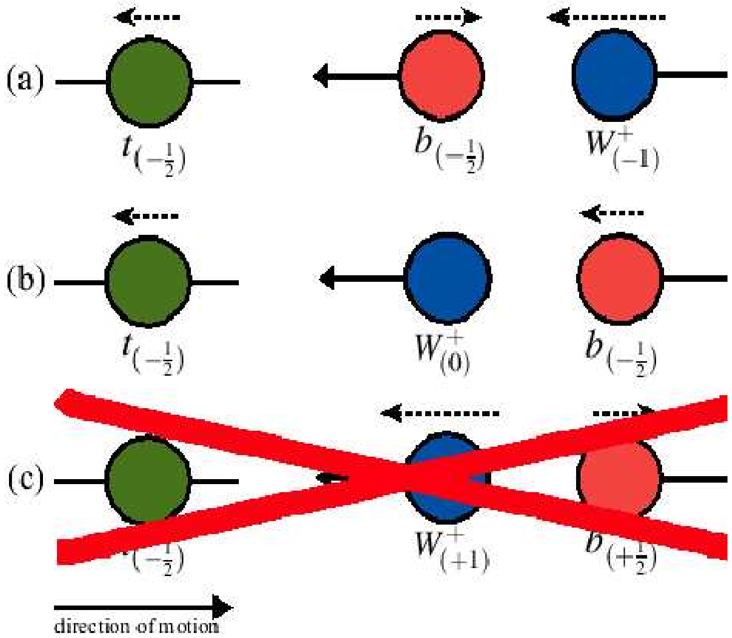


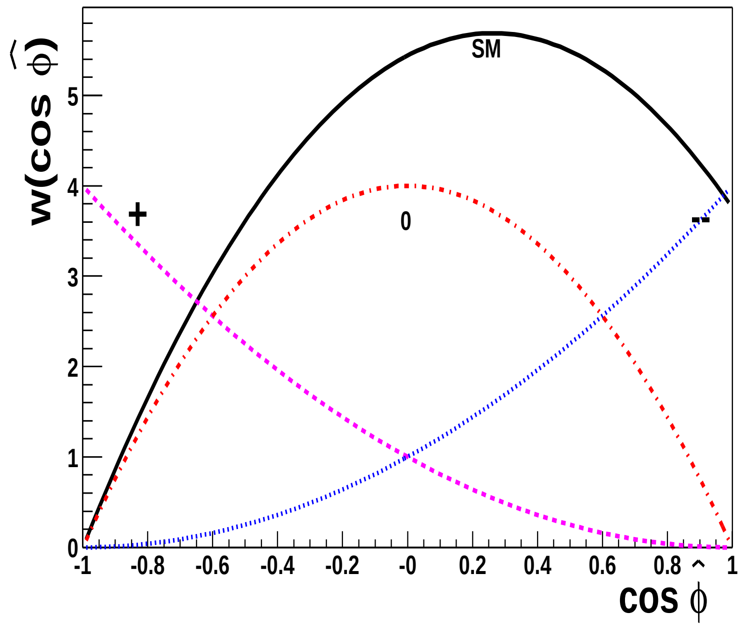
Consistency with the SM for the whole dilepton sample:

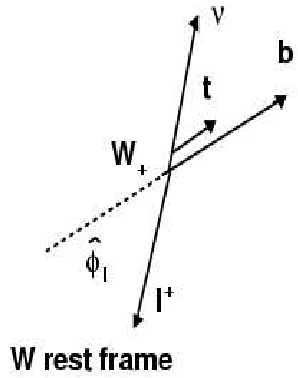
P-value = 1.0 – 4.5%

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



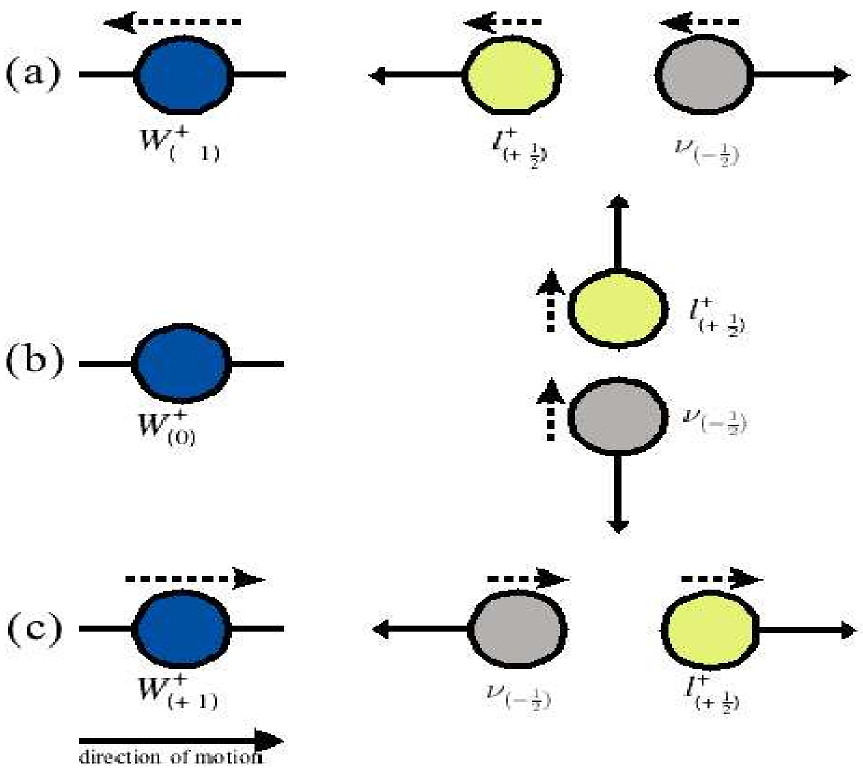


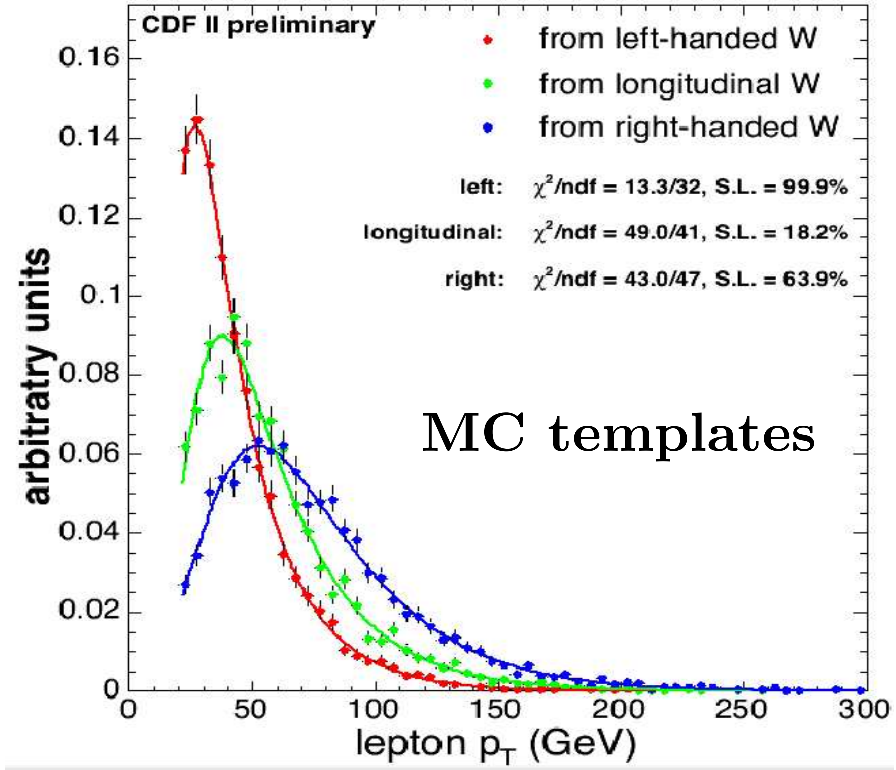


- ★ In the SM only left-handed W_- and longitudinal W_0 may be produced
- ★ W_0 fraction: $\boxed{F_0 = \frac{\Gamma(W_0)}{\Gamma(W_0)+\Gamma(W_T)} = \frac{1}{1+2(M_W/M_t)^2} \simeq 0.7} \Rightarrow F_- \simeq 0.3$
- ★ Any V+A structure in the dynamics would yield $F_+ \neq 0$ and $F_- \leq 0.3$
- ★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

  ϕ: angle between the ℓ 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 ℓ p_T spectra

CDF W helicity measurement

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

sample	dilepton	ℓ+jets	total
# leptons	26	57	83

- Construct likelihood function with the PDFs of p_{T} of leptons from background and signal for different helicities:

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

β: background fraction

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

N: number of reconstructed leptons

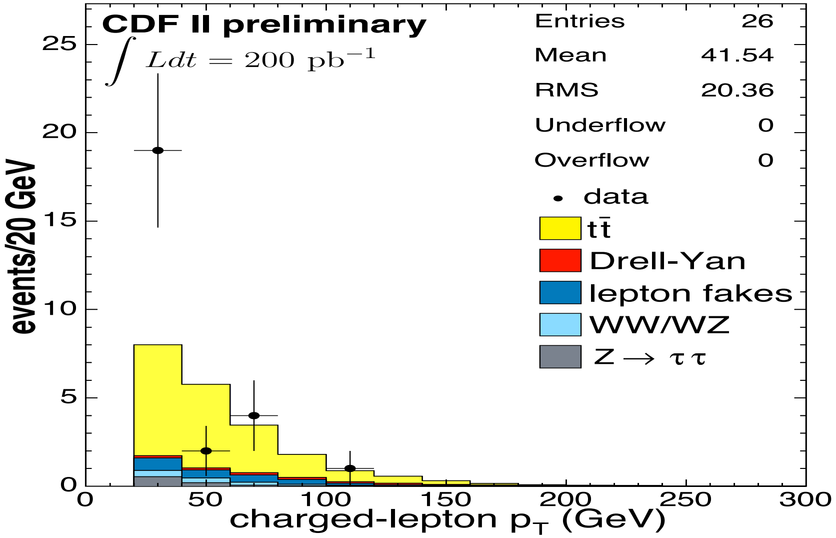
$P(x_i,\text{bkg})$: PDF of charged ℓ with $p_{\text{T}} = x_i$ due to background process

$P(x_i,h)$: PDF of charged ℓ with $p_{\text{T}} = x_i$ from W with helicity h

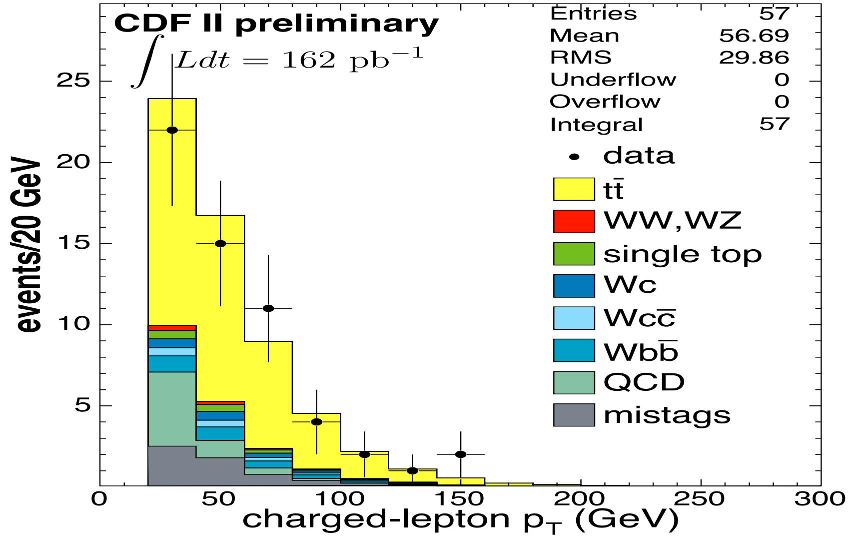
- Major systematic uncertainties: top mass and background normalization

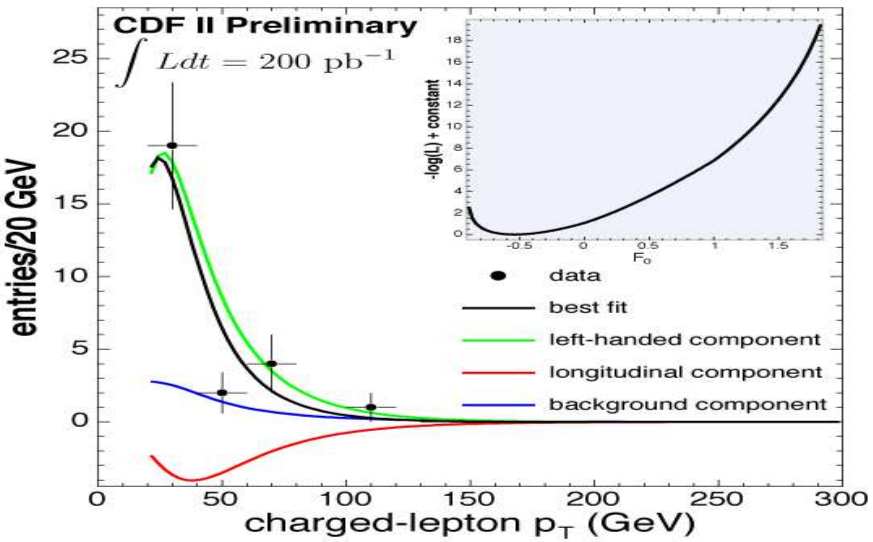
CDF W helicity measurement: distributions

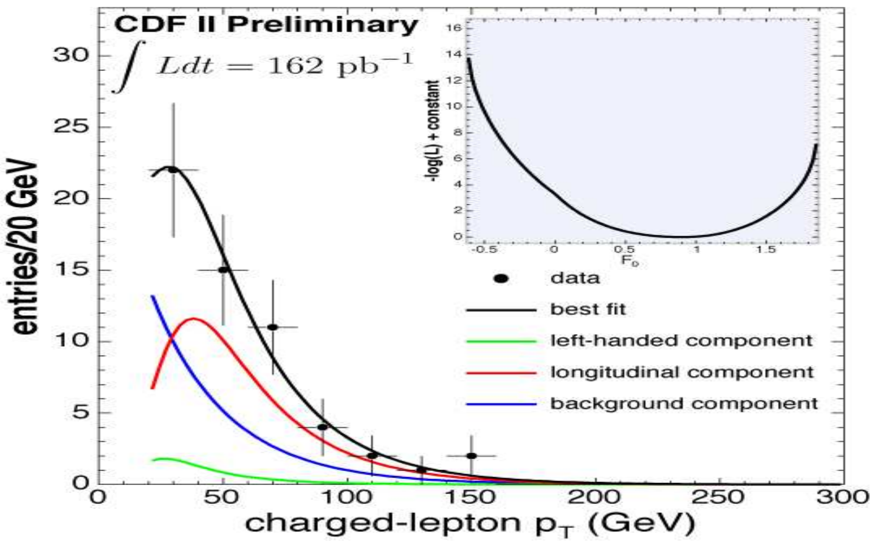
dilepton



ℓ+jets







$\hat{F}_0 = -0.54$

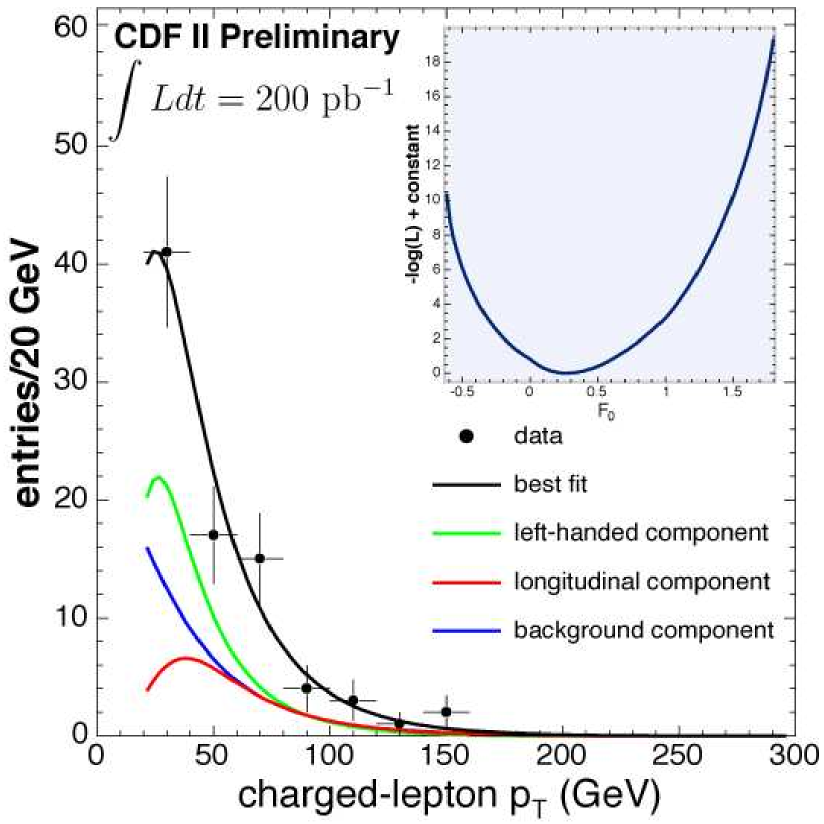
$F_0 < 0.52$ @ 95%C.L.

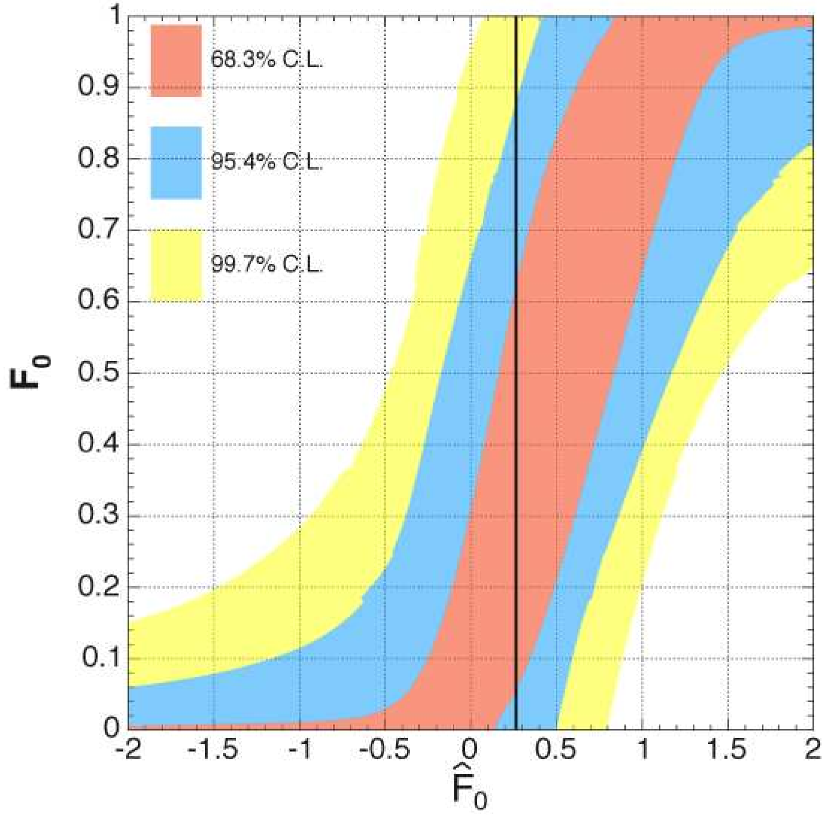
$F_0 = 0.88^{+0.12}_{-0.47}$

$F_0 < 0.88$ @ 95%C.L.

CDF W helicity measurement: results

Combining the samples:





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

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

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

W helicity: Matrix Element Method

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

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

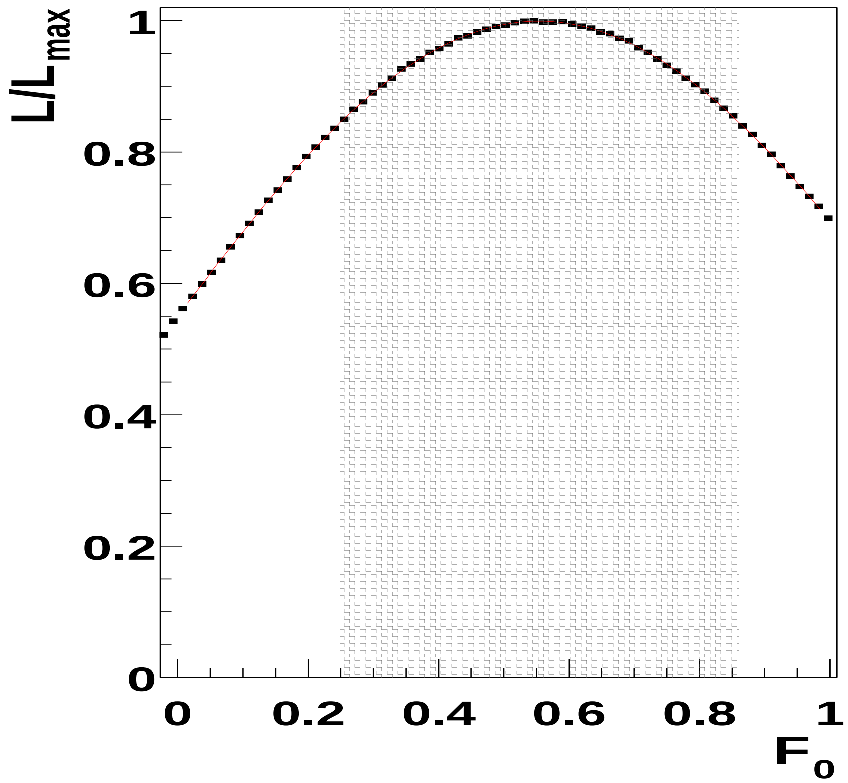
- x set of reconstructed variables measured in the detector
- α parameter to estimate, for the helicity calculation $\alpha = F_0$
- $d^n\sigma$ differential cross section (L0 matrix element $\rightarrow$ cut on $\mathrm{N_{jets}}$=4)
- $f(q)$ parton distribution function
- $W(x,y)$ transfer function: 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 ℓ+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

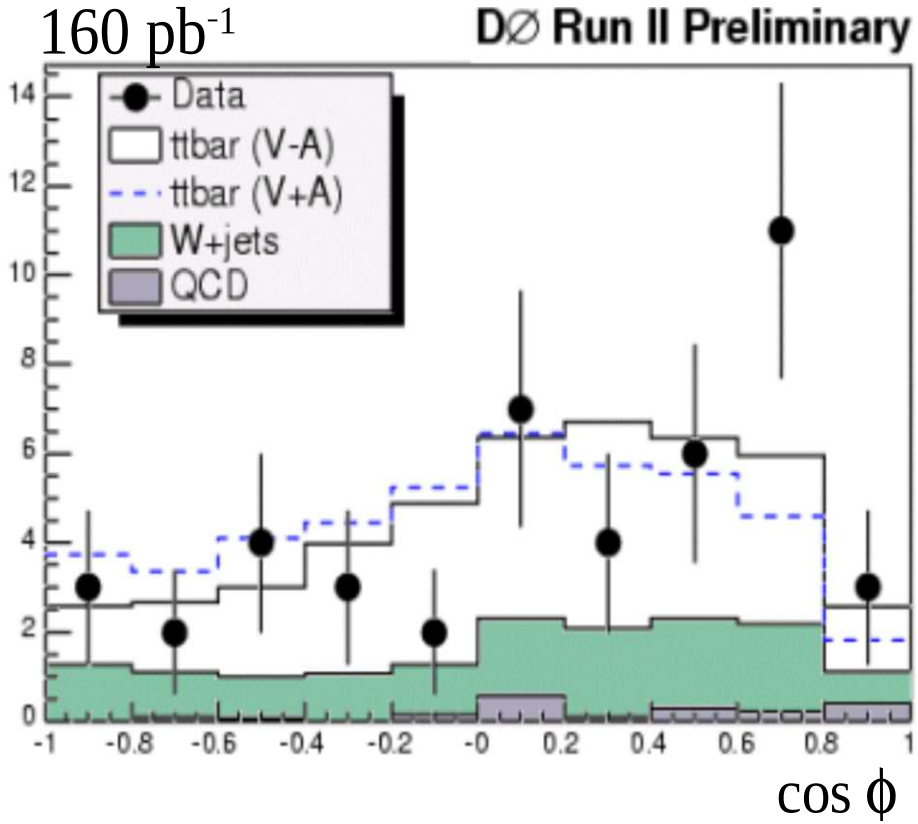
$\mathbf{F_0 = 0.56 \pm 0.31}(\mathrm{stat} + \mathrm{m_t}) \pm \mathbf{0.07}(\mathbf{syst})$ (submitted to PRL, hep-ex/0404040)

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

DØ Run II W helicity analysis overview

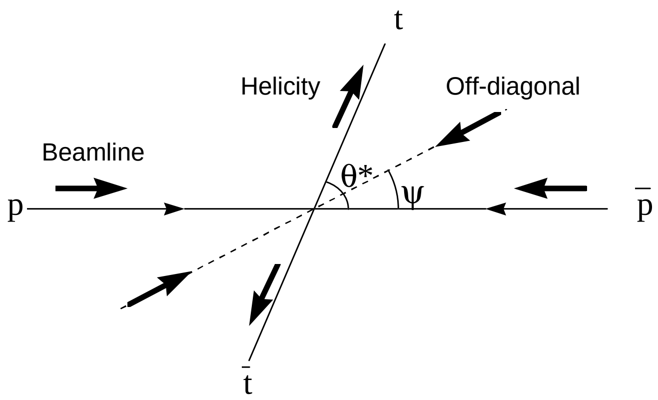
- Using ℓ+jets sample ($160\,\mathrm{pb}^{-1}$)
- Developing two parallel analysis: topological selection / b-tagging and then event kinematic fitting
- The data is fitted to $\cos\phi$ templates for various F_+ fixing $F_0 = 0.7$
- Simultaneous determination of F_+ and S/B ratios

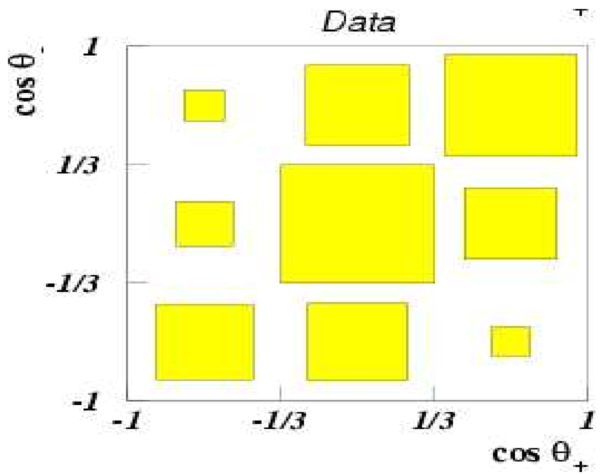
Working on optimization and combination of analyses
Expect results for ICHEP



DØ Run I spin correlations

- Confirm that top decays before spin flips, lower limit on $\tau_t \Rightarrow$ lower limit on Γ_t
- Non standard EW interactions may manifest in decay product anomalies
- Dilepton analysis ($125\,\mathrm{pb}^{-1}$) 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 + $m_t = 175\,\mathrm{GeV}/c^2$ 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 ℓ+jets sample ($130\,\mathrm{pb}^{-1}$) and analysis
- ✶ Perform 3C kinematic fit over two orthogonal analyses: topological cuts and soft muon tagging

A total of 41 events:

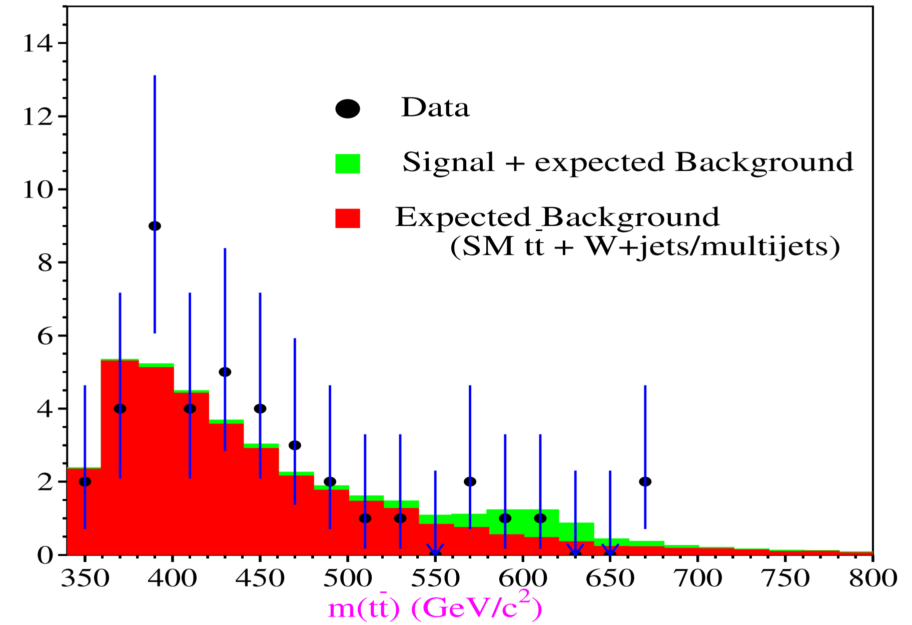
e+jets	μ+jets	e+jets/SLT	μ+jets/SLT
16	21	1	3

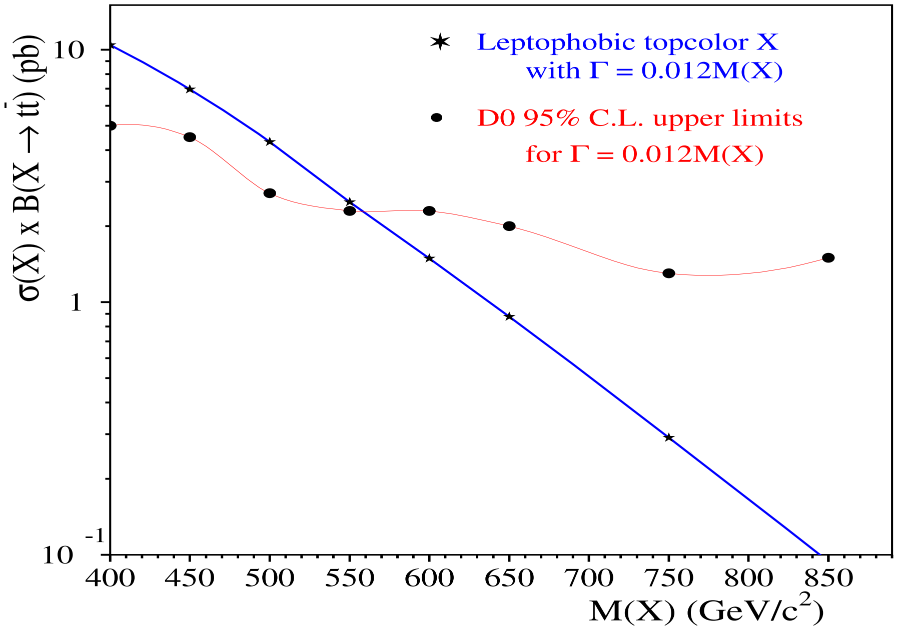
- ✶ Main systematic uncertainites: MC acceptance (ISR/FSR, PDF) and Jet Energy Scale

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 ± 3.2	23.7 ± 11.6	15.4 ± 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



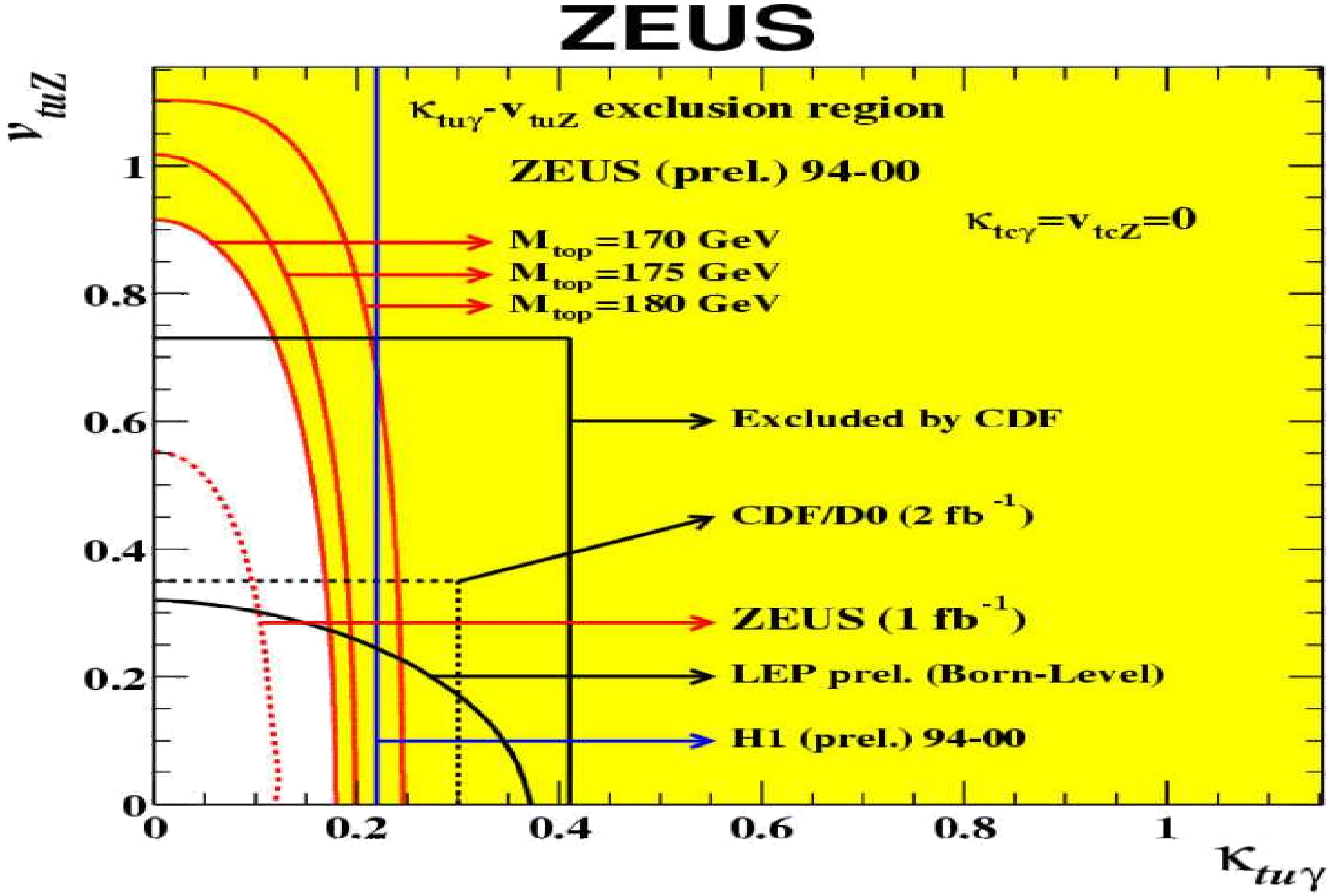


Assuming $\Gamma_X = 0.012 M_X, m_t = 175\,\text{GeV}/c^2$ and flat priors, exclude narrow leptophobic X boson: $\mathbf{M_X > 560\,GeV/c^2}$ (accepted by PRL, hep-ex/0307079)

$\mathbf{M_X > 480\,GeV/c^2}$ (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	σ single top	20%
$R = \frac{\mathcal{B}(t\to Wb)}{\mathcal{B}(t\to Wq)}$	4.5%	Γ_t from single top	25%
$\lvert V_{tb}\rvert$ from R	> 0.25	$\lvert V_{tb}\rvert$ from single top	12%
$\mathcal{B}(t \to \gamma q)$	2×10^{-3}	$\mathcal{B}(t \to qZ)$	0.02