Top Quark Properties

results and ongoing analyses at the Tevatron

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QCD and High Energy Interactions
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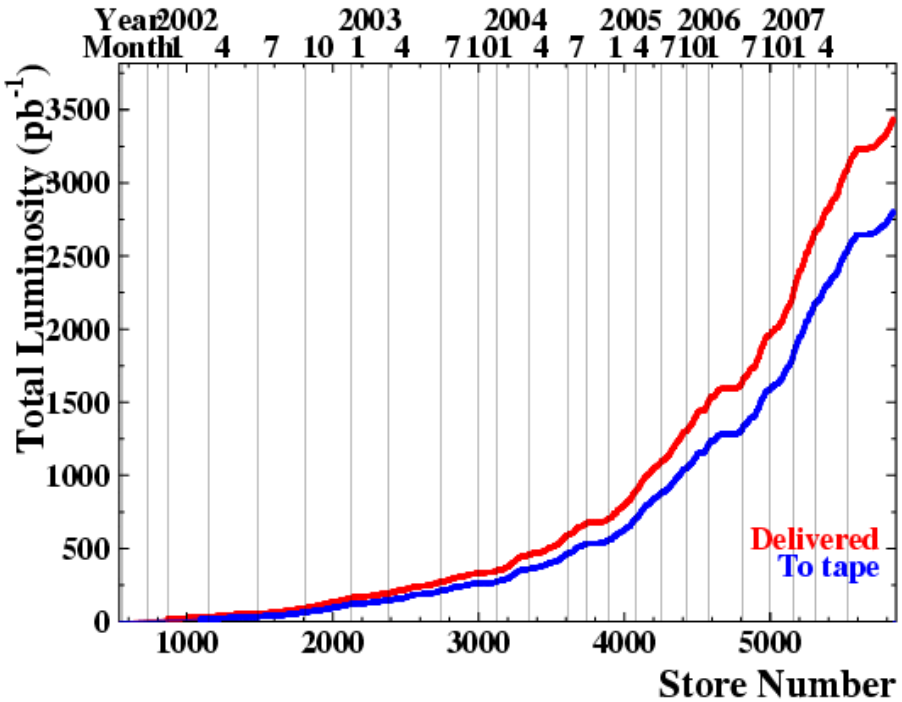
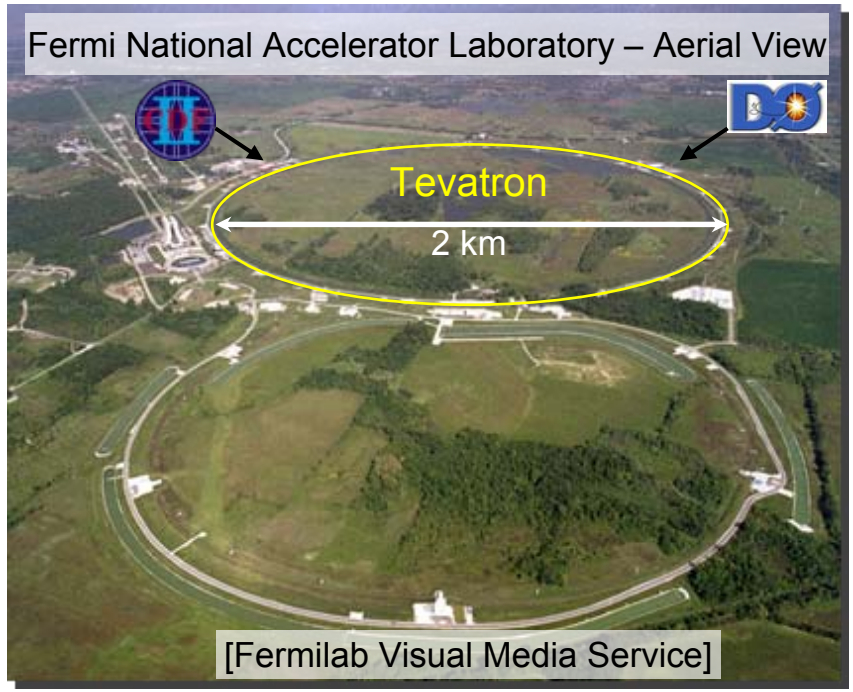
Fermilab and The Tevatron

- **F.N.A.L. (1967)**
  - Large number of H.E.P. projects
- **Tevatron Run II (2001–2009):**
  - Proton-antiproton collider
  - Two multi-purpose experiments: CDF & DØ

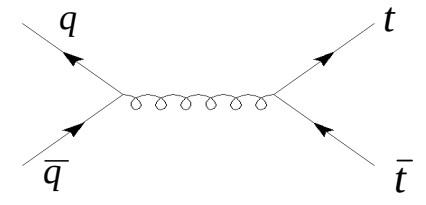




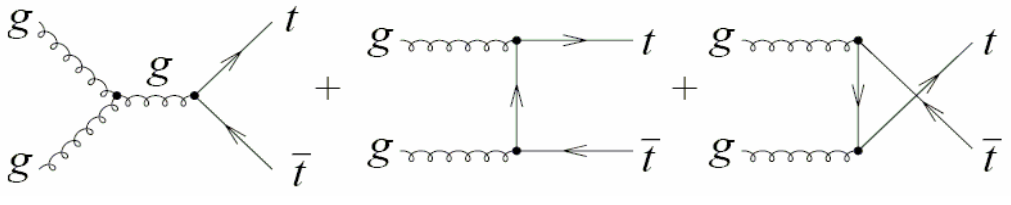
- **Proton-antiproton collider**
  - $\sqrt{s}$ = 1.96 TeV, 36×36 bunches
  - Record instant. peak luminosity 292 $\mu b^{-1}\ s^{-1}$ ($1\ \mu b^{-1}\ s^{-1} \equiv 10^{-30}\ cm^{-2}\ s^{-1}$)
  - Expect 6–8 fb^{-1} by end of Run II

Top Pair Production at the Tevatron

- produced in pairs **via the strong interactions.**



~85%

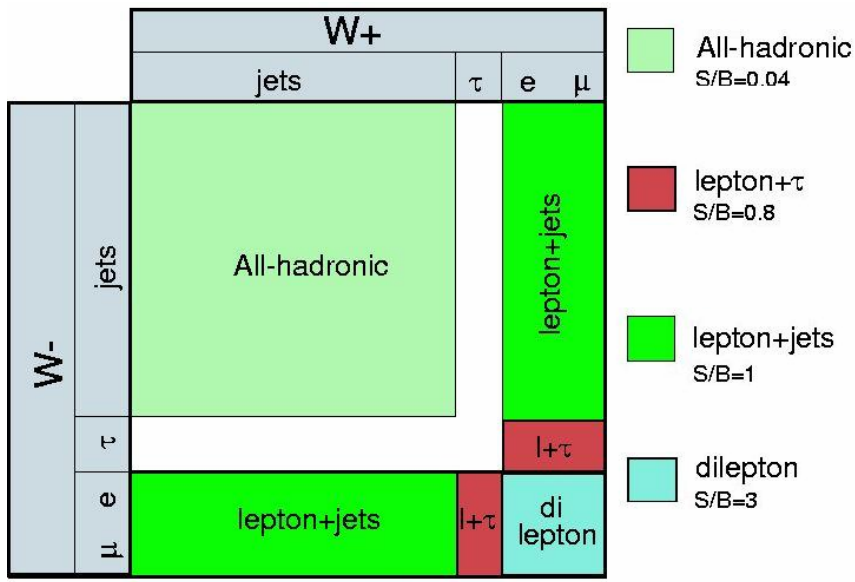


~15%

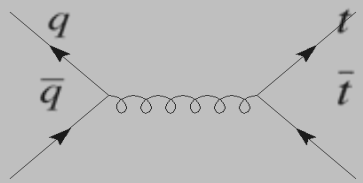
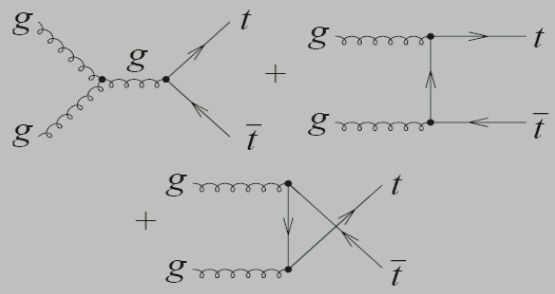
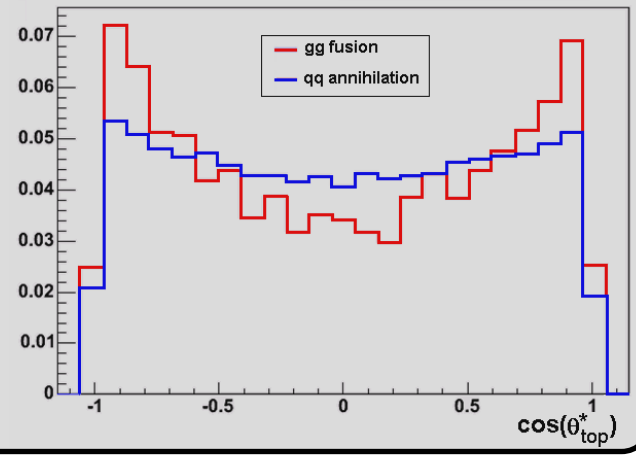
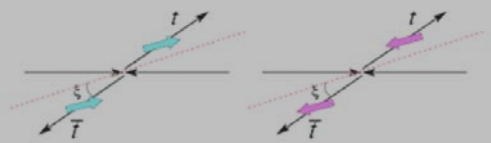
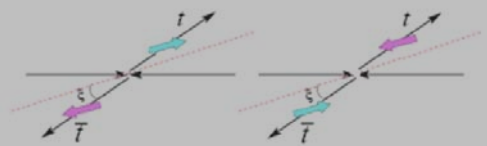
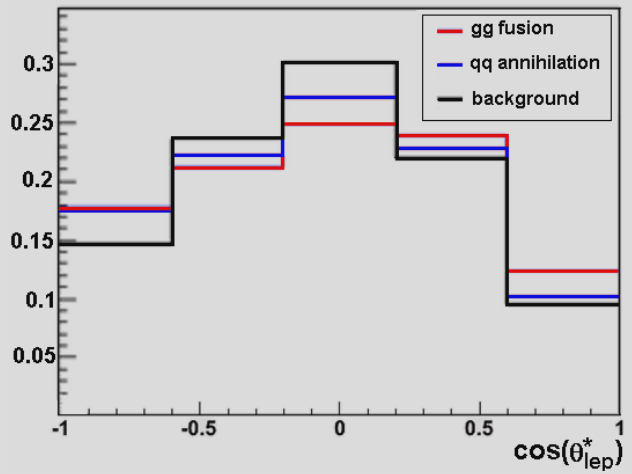
$$\sigma(\bar{p}p \to t\bar{t} \,@\, M_{top} = 172 GeV) \approx 7.3 \pm 0.9 \text{ pb}$$

one top pair event every 10^{10} inelastic collisions

- In the SM, BR(t→W⁺b) >0.99 @95%CL
- Final state is given by W⁺ and W⁻ decays
  - **All Hadronic** channel ($tt \to bqq'bqq$)
    - Large BR, small S/B
  - **Lepton (e,μ)+Jets** channel ($tt \to bl\nu bqq'$)
    - Second large BR, good S/B
    - overconstrained kinematics
  - **Dilepton** channel : ($tt \to bl\nu bl\nu$)
    - BR is ¼ of L+Jets, cleanest channel
    - underconstrained kinematics
  - **Lepton + Had. Tau** channel($tt \to blvb\tau_h\nu$)
    - Very small BR, S/B~1



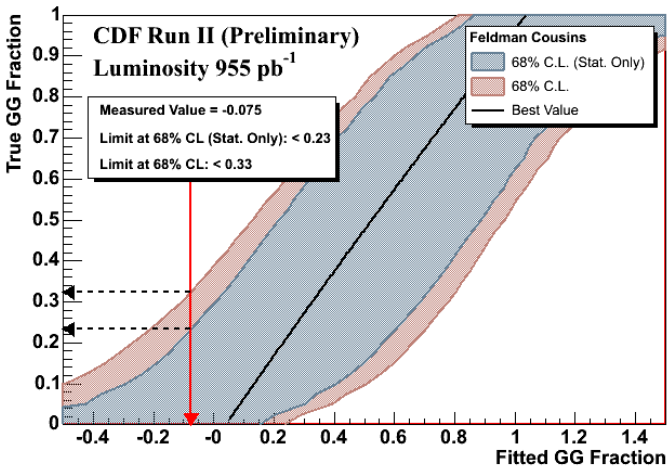
Top production: Intro

	qq annihilation	gg fusion	
Production	 Tops are central	 Tops are forward	
Decay	 like spins	 Unlike spins	

Top production: Two approaches

- **Measurement**
  - Find the production ratio (F_{gg}) of the gg-produced to $p\bar{p}$-produced tt events:

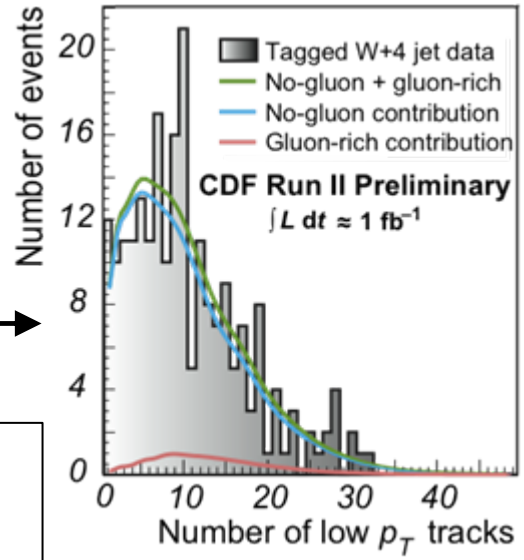
$$F_{GG} = \frac{\sigma(gg \to t\bar{t})}{\sigma(p\bar{p} \to t\bar{t})}$$



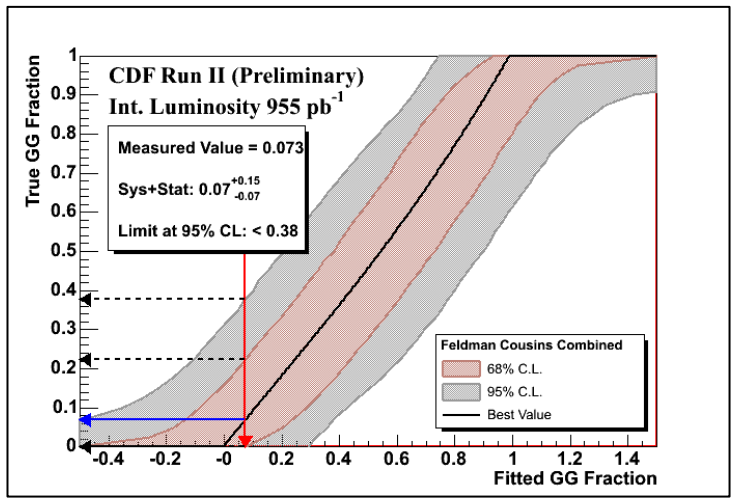
Two strategies

1. **Analyze the kinematic information**

2. **Take advantage of the fact that gluon radiate more**



Combination



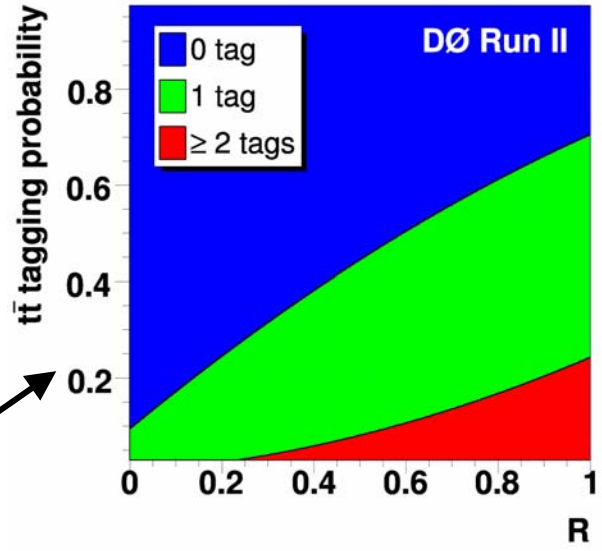
Combined result: $F_{GG} < 0.38$ @ 95% C.L.

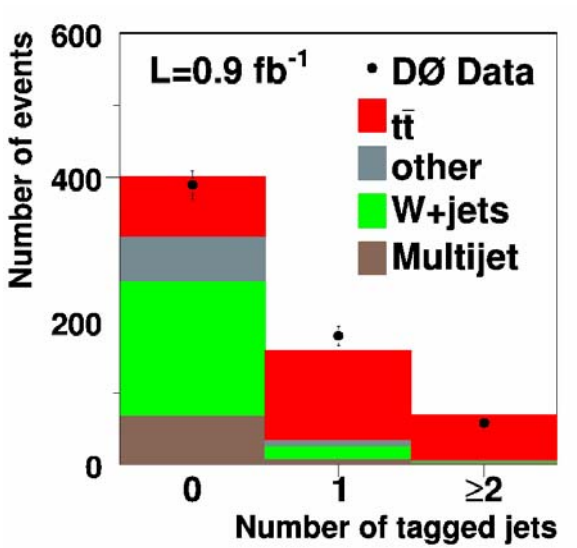
Measurement of BR(t→Wb)/BR(t→Wq)

- Ratio of top branching ratios

$$R \equiv \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

- Measurement
  - Fraction of b-tagged $t\bar{t}$ events depends strongly on R and ε_b
  - Measurement simultaneous with $\sigma_{t\bar{t}}$
  - Fitting to data results:





$$R = 0.97^{+0.09}_{-0.08}\ (\text{stat} + \text{syst})$$

$$\sigma_{t\bar{t}} = 8.18^{+0.9}_{-0.84}\,(\text{stat} + \text{syst}) \pm 0.5\,(\text{lumi})\ \text{pb}$$

$$R > 0.79\ @\ 95\%\ \text{C.L.}$$

$$|V_{tb}| > 0.89\ @\ 95\%\ \text{C.L.}$$

Best direct limits to date!

Top Charge: 2/3e or –4/3e?

- **Standard Model:** Q_{top} **= 2/3 e**
- **Exotic model: part of doublet (–1/3e,–4/3e) ?**
  See [D. Chang et al., Phys. Rev. D59 (1999) 091503] for details

- **Use L+Jets and Dilepton channels**
  - Counting Experiment : find number of pairs SM like (W^+b) and exotic like (W-b)

- **Direct measurement:**
  1. Determine W charge
  2. Correct pairing of W and b jet
  3. Determine flavor of b-quark: "Jet Charge" (calibrated with dijet data)

Two measurements per event in both channels

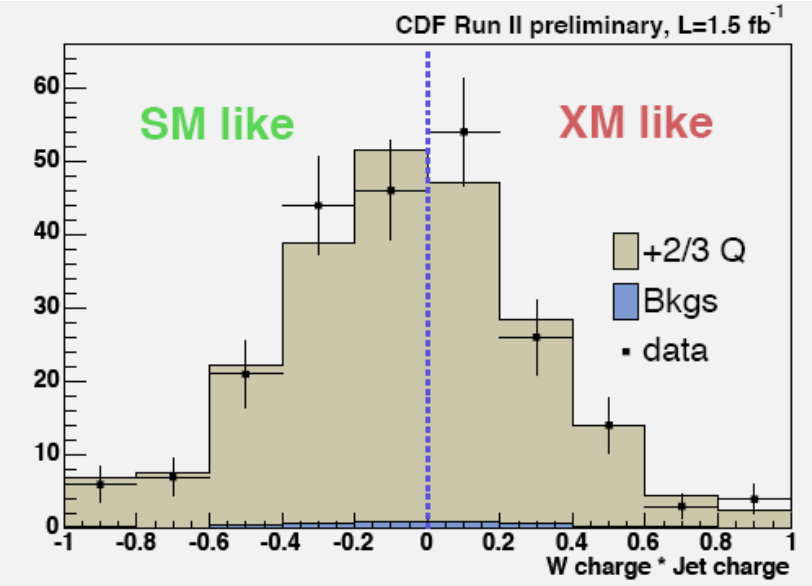
Flavor of b-quark:

- **Use "Jet Charge"**

$$\mathrm{JetQ} = \frac{\sum_{\text{tracks}} \left(\vec{p}_{\text{track}} \cdot \vec{p}_{\text{jet}}\right)^{0.5} \cdot Q_{\text{track}}}{\sum_{\text{tracks}} \left(\vec{p}_{\text{track}} \cdot \vec{p}_{\text{jet}}\right)^{0.5}}$$

- Calibrated with dijet data

Top Charge: 2/3e or –4/3e?



- **Counting experiment:**
  - Both Lepton+Jets & Dilepton datasets
  - 62 Standard Model-like events
  - 48 exotic model-like events

Statistical Treatment: Hypothesis Test

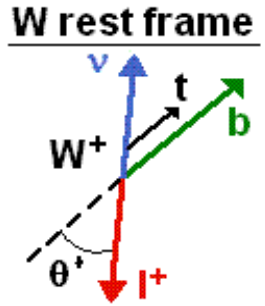
- Null hypothesis: SM is correct
- Decide *a priori*: probability of incorrectly rejecting SM: α = 0.01
- If nature followed exotic model: 87% of all measurements would return p-values below 0.01 under SM hypothesis
- Measured p-value: 0.35, i.e. larger than α
  → data consistent with SM
  → exotic model excluded at 87% C.L.

P-value: Probability that measurement results in the measured value or worse, given a hypothesis.

W helicity from t→Wb decays

- **Examines the nature of the tWb vertex**
  - Stringent test of Standard Model and its **V-A** type of interaction.

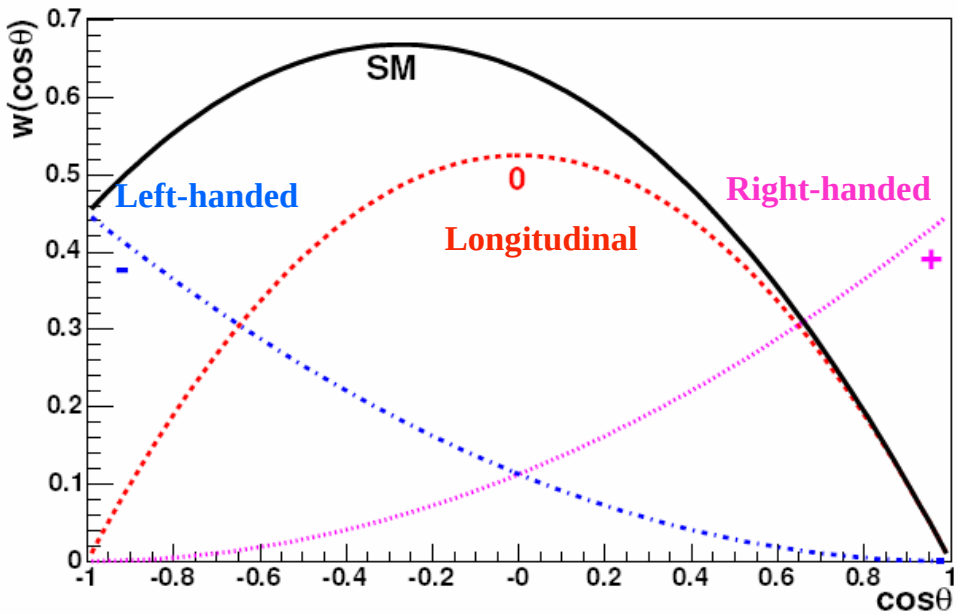
- **In general, the θ^* distribution of top decays in the W rest frame is**



$$w(\cos\theta^*) = f_- \cdot \frac{3}{8}(1-\cos\theta^*)^2 + f_0 \cdot \frac{3}{4}(1-\cos^2\theta^*) + f_+ \cdot \frac{3}{8}(1+\cos\theta^*)^2$$

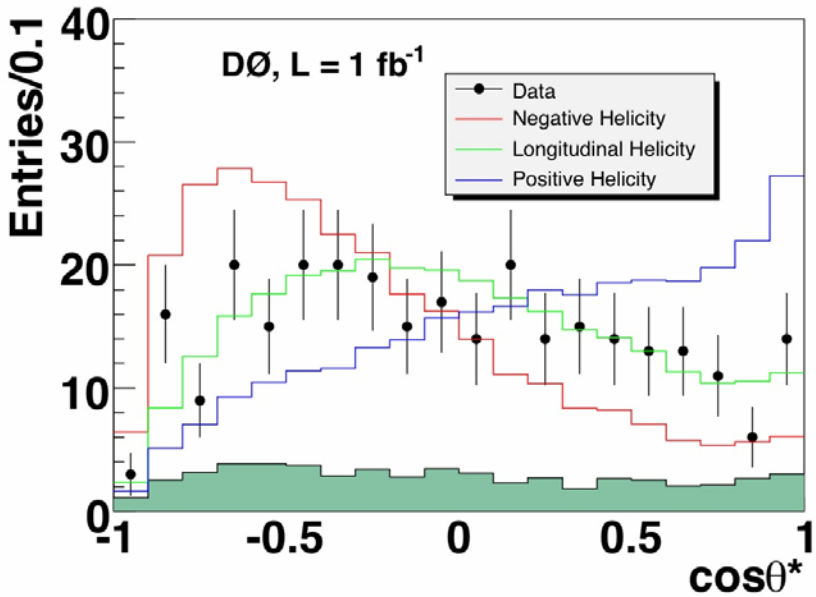
$$f_- + f_0 + f_+ = 1$$

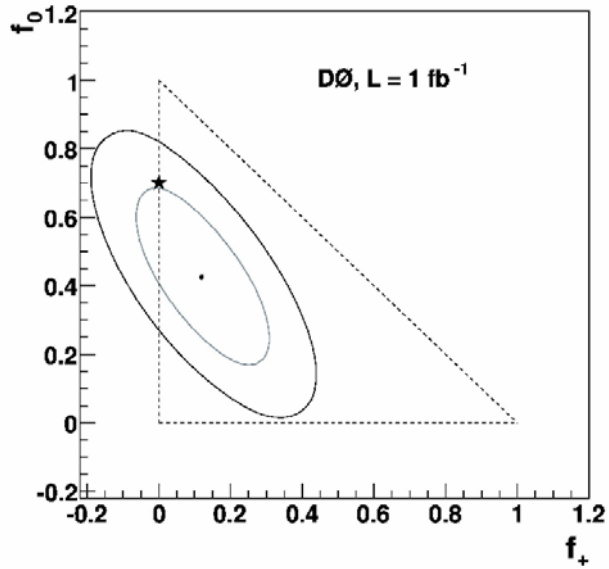
- **In the Standard Model** :$f_- = 0.3$, $f_0 = 0.7$, $f_+ \approx 0$



W helicity from t→Wb decays

- Template fits for f_0, f_+ and f_-
- Take advantage of lepton+jet and Dilepton channels: 1 fb^{-1}





- Simultaneous fit to f_0 and f_+

$$f_0 = 0.425 \pm 0.166(\text{stat}) \pm 0.102(\text{syst})$$
$$f_+ = 0.119 \pm 0.090(\text{stat}) \pm 0.053(\text{syst})$$

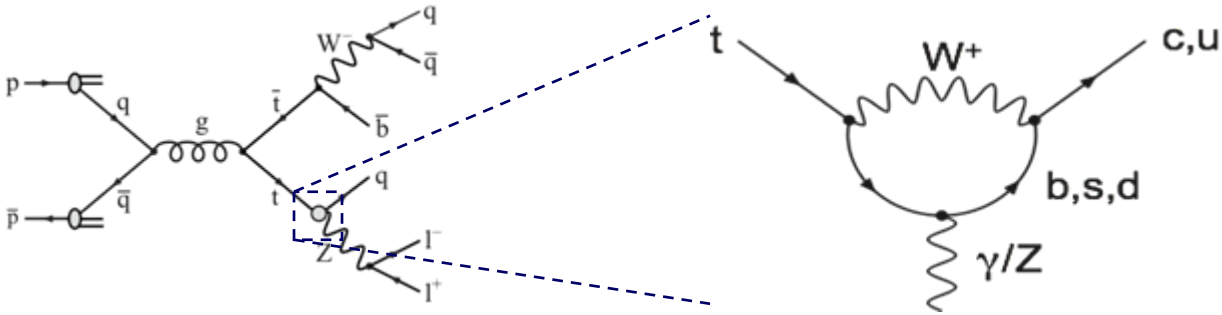
- Fit to f_0 (f_+) assuming SM f_+ (f_0)

$$f_0 = 0.619 \pm 0.090(\text{stat}) \pm 0.052(\text{syst})$$
$$f_+ = -0.002 \pm 0.047(\text{stat}) \pm 0.047(\text{syst})$$
$$(f_+ < 0.13 \ @ \ 95\% \ \text{C.L.})$$

Best results to date

Flavor Changing Neutral Currents

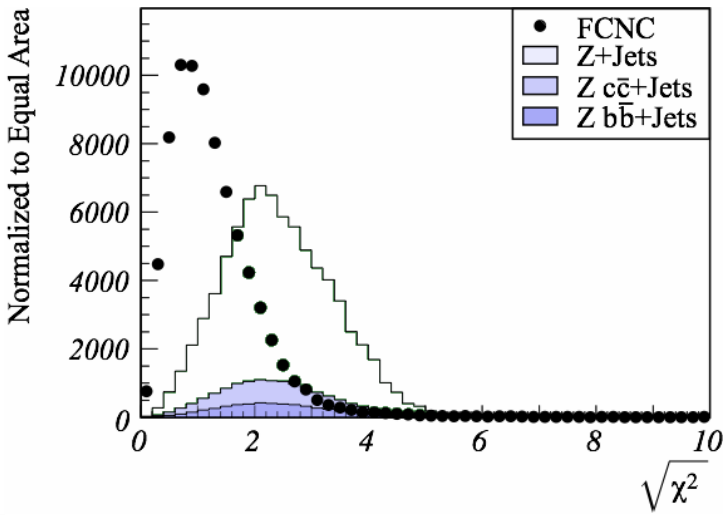
- **No Flavor Changing Neutral Currents (FCNC) at tree level in the SM.**

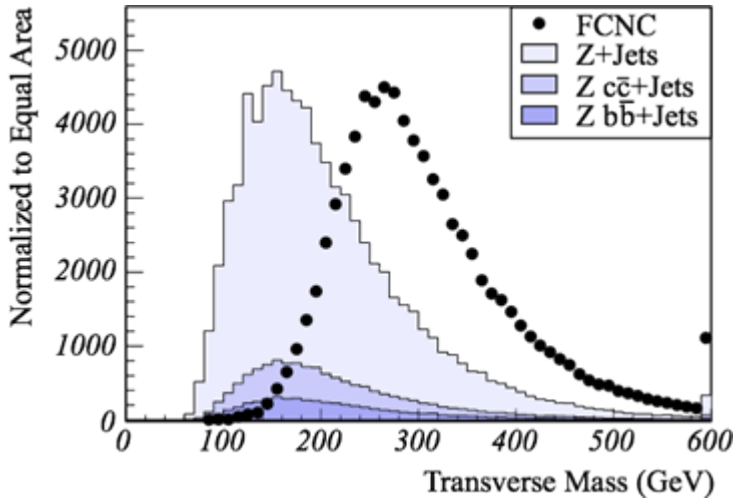


Allowed at higher orders, but heavily suppressed (GIM, small CKM elements)

Beyond SM models predict branching ratios up to O(10^{-2})…

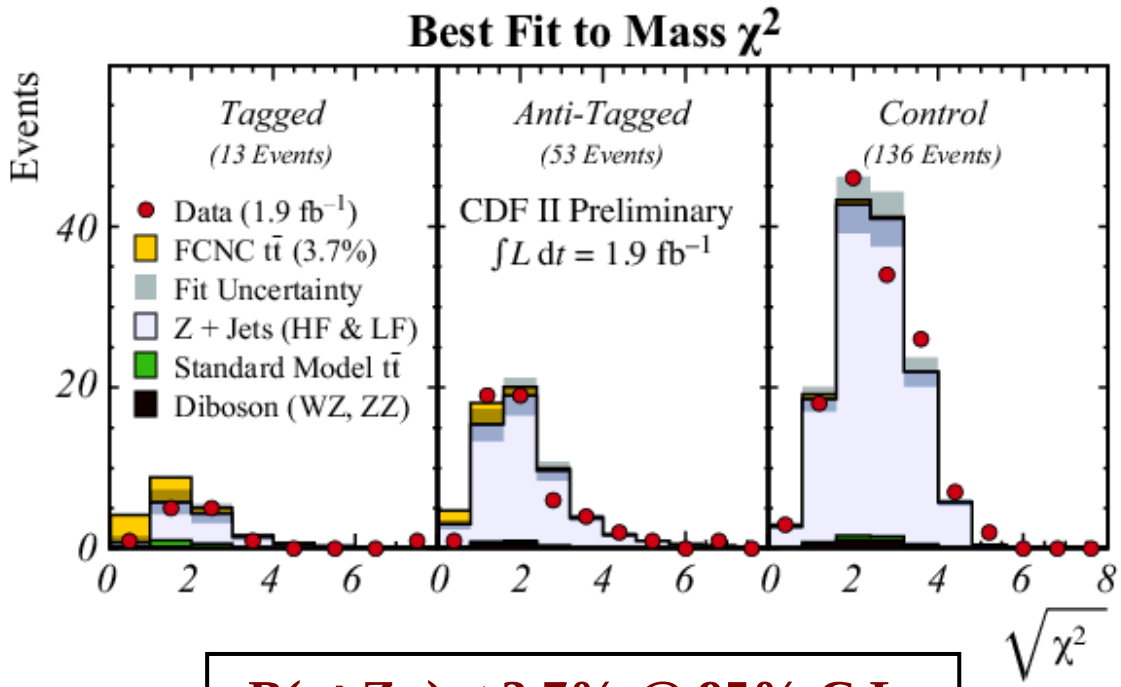
- **Search in the Z+4 jets channel. Handles:**
  - **Kinematic χ2:**
  - **Transverse mass:**





Top FCNC Search: Results

- **Events separated in three categories:**
  - Tagged, anti-tagged and control region



B(t→Zq) < 3.7% @ 95% C.L.

World's best limit. Improved previous limit (13.7% @ L3) by a factor of 3.5

Forward-Backward Charge assmetry

- **Arises at higher than tree level order (see PRD 59, 054017)**
  - Reconstruct the $t\bar{t}$ decay chain and get the top rapidities y_t and $y_{\bar{t}}$

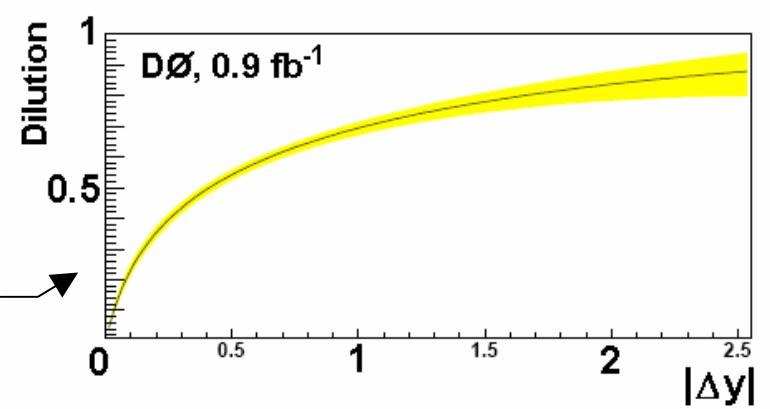
$$A_{fb} = \frac{N_f - N_b}{N_f - N_b}$$

N_f (N_B) = # of $t\bar{t}$ events with positive (negative) $\Delta y = y_t - y_{\bar{t}}$

- **Using 0.9 fb^{-1}, Lepton+jets channel**

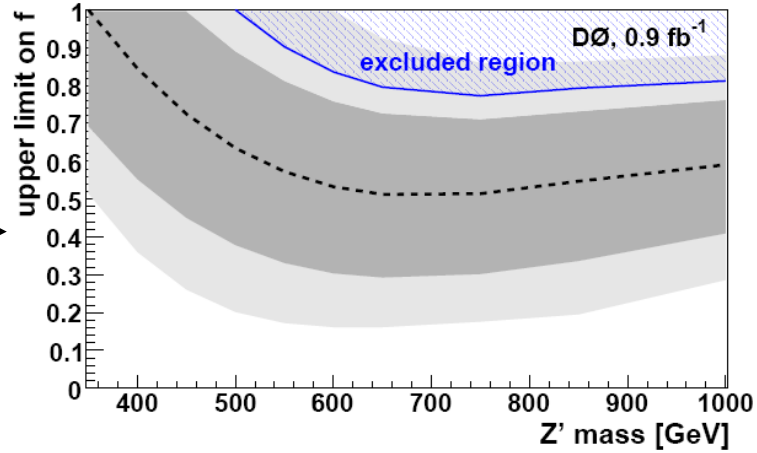
$$A_{fb}^{obs} = 0.12 \pm 0.08\,(stat) \pm 0.01\,(syst)$$

  - For a model's prediction of $|\Delta y|$ distribution dilution function is used to go to the particle level



- **Sensitive probe for new physics**
  - Example: limits on Z' based on charge asymmetry

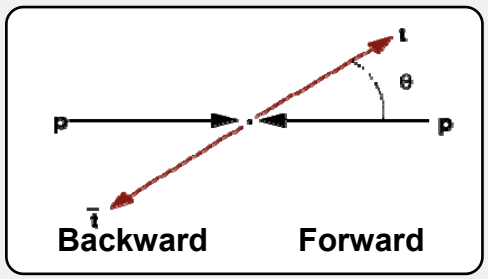
$$f = \frac{\sigma(p\bar{p} \to Z' \to t\bar{t})}{\sigma(p\bar{p} \to t\bar{t})}$$



Top Properties: Other Measurements

Forward–Backward asymmetry

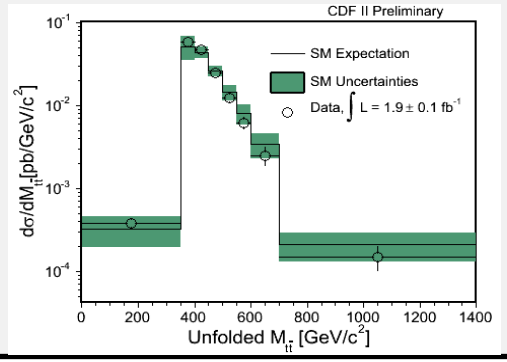
$$A_{fb} = \frac{N_{(-Q_\ell)\cdot Cos\Theta>0} - N_{(-Q_\ell)\cdot Cos\Theta<0}}{N_{(-Q_\ell)\cdot Cos\Theta>0} + N_{(-Q_\ell)\cdot Cos\Theta<0}}$$



Is the Top really the Standard Model Top?

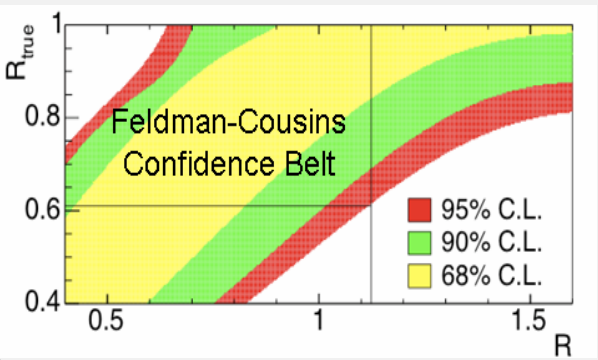
Differential cross section

$$\frac{d\sigma^i}{dM_{t\bar{t}}} = \frac{N_i - N_i^{bkg}}{\mathcal{A}_i \int \mathcal{L}\Delta^i_{M_{t\bar{t}}}}$$

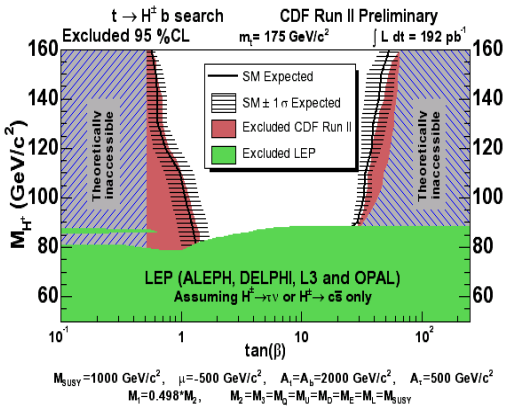


Measurement of |Vtb|

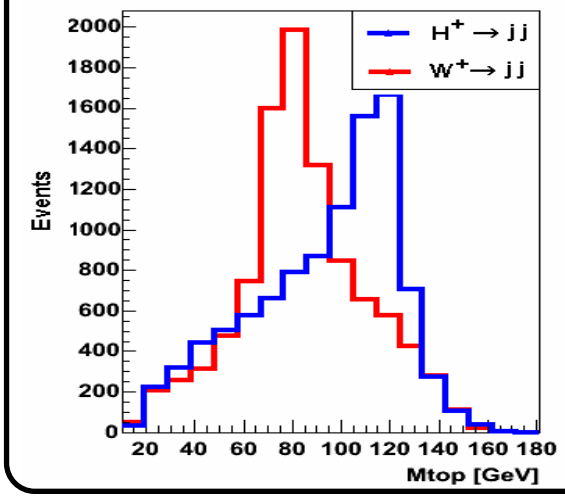
$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$



Search for Charged Higgs Limits on B(t→H⁺b)



Limits on BR(t→H⁺b), H⁺→cs̄



Conclusions

- **CDF and D0 are seriously focused on exhaustive measurements of top properties**

- **Many more analyses ongoing**
  - B(t→H^+b), with H^+ decaying to specific channels
  - Top Spin correlations
  - Search for t'→Wq
  - and more…

- **Exciting times :**
  - Analyses are very mature
  - Much more data on tape

- **Uncertainties are beginning to shrink…**

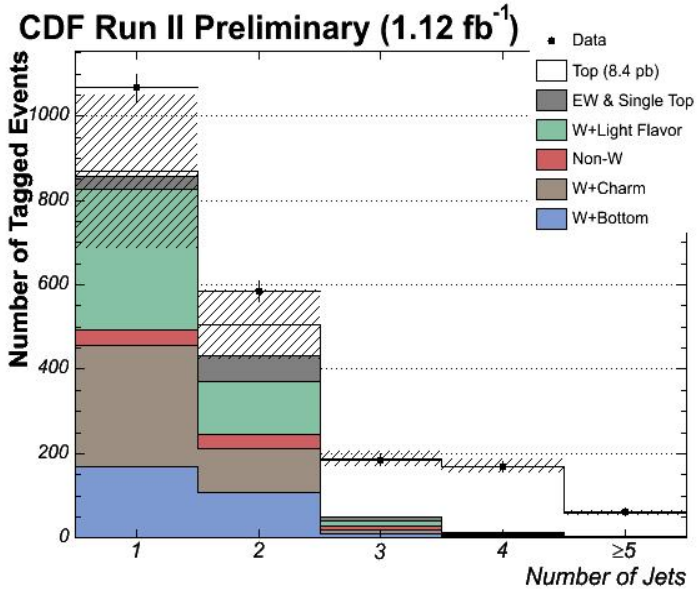
More and more we are putting the SM to the test

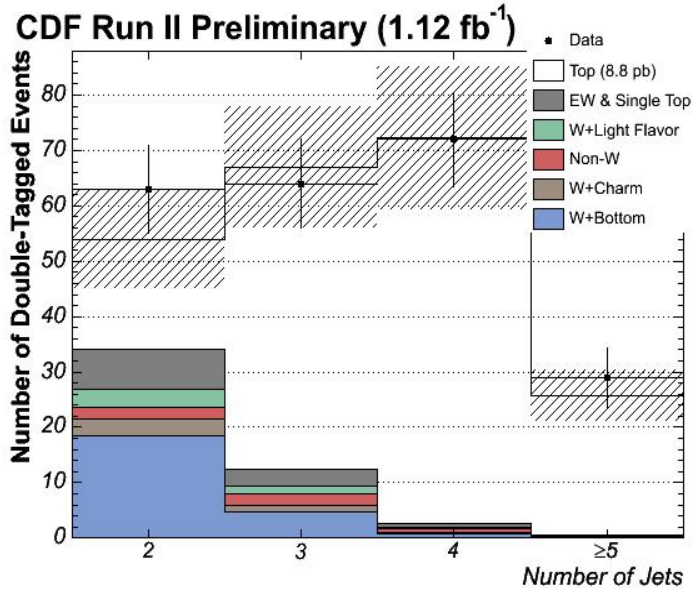
Chapter

Backup slides

Top Cross Section Results

- **Measure the cross section**
  - Assume $t\bar{t}$ production cross section, $\sigma_{t\bar{t}}$
  - Get backgrounds from using $\sigma_{t\bar{t}}$
  - Measure a new $\sigma_{t\bar{t}}$ and iterate until convergence





- **After statistical treatment to consider the iterative process**
  - ≥1 tight tag: σ=8.4 ± 0.6(stat) ± 0.9(syst) pb,
  - ≥2 tight tag: σ=8.8 ± 0.8(stat) ± 0.8(syst) pb,

Baseline for Top Properties analyses

Top Charge: 2/3e or –4/3e?

- **Standard Model:** Q_{top} **= 2/3 e**
- **Exotic model: part of doublet (–1/3e,–4/3e) ?**
  See [D. Chang et al., Phys. Rev. D59 (1999) 091503] for details
- **Use L+Jets and Dilepton channels**
  - Counting Experiment : find number of pairs SM like (W^+b) and exotic like (W-b)
- **Direct measurement:**
  1. Determine W charge
  2. Correct pairing of W and b jet
  3. Determine flavor of b-quark: "Jet Charge" (calibrated with dijet data)

Two measurements per event in both channels

Flavor of b-quark:

- **Use "Jet Charge"**

$$\mathrm{JetQ} = \frac{\sum_{\text{tracks}} \left(\vec{p}_{\text{track}} \cdot \vec{p}_{\text{jet}}\right)^{0.5} \cdot Q_{\text{track}}}{\sum_{\text{tracks}} \left(\vec{p}_{\text{track}} \cdot \vec{p}_{\text{jet}}\right)^{0.5}}$$

- Calibrated with dijet data

Top Lifetime

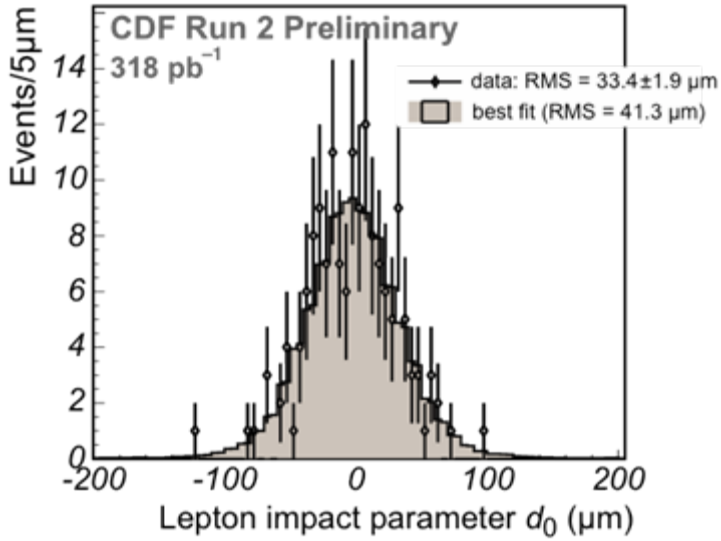
- **Top lifetime in the Standard Model**
  - Expected lifetime: < 10^{-24} s
  - Constrained by unitarity of CKM matrix, but no direct measurements so far

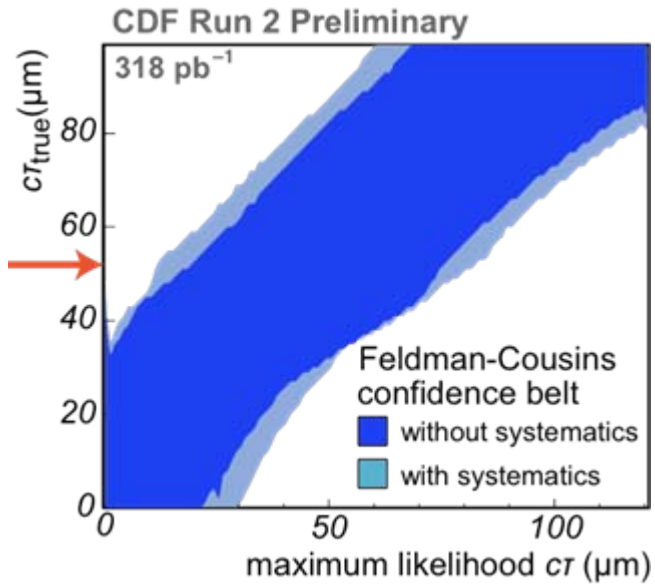
- **First direct measurement at CDF**
  - 318 pb^{-1}, Lepton+Jets sample
  - Measure lepton impact parameter d0
  - Calibrate impact parameter resolution in data with leptons from γ*/Z decays
  - Create templates for signal & background

- **Results:**
  - Maximum likelihood: cτ = 0 μm
  - Feldman-Cousins limit including systematics:

cτ < 52.5 μm at 95%C.L.

[CDF Public Note 8104]

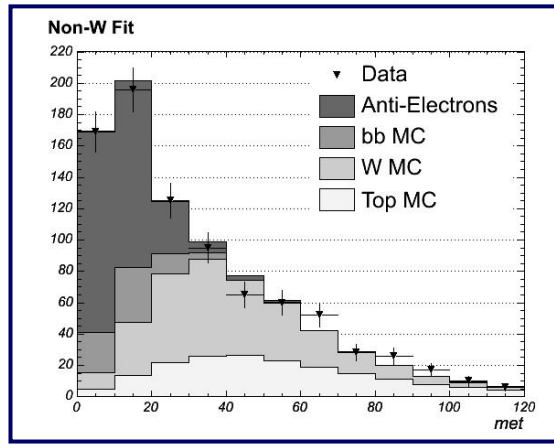




Lepton+Jets Sample composition

- **Cross section requires understanding of all processes in sample**

- **Sample-composition estimator**
  - Performed in a jet-bin basis
  - Based on the pretag data
  - Predicts sample composition in the tagged sample



- **Components in pretag data:**
  - $t\bar{t}$
  - WW,WZ,ZZ,Z/$\gamma \rightarrow \tau\tau$
  - single top

  } Production cross section relatively well known

  - non-W

  } Handle on these processes: MET

  - W+jets (W+HF, W+LF)

  } Theoretical cross section with large corrections