TeVatron Results on Top Quark Physics

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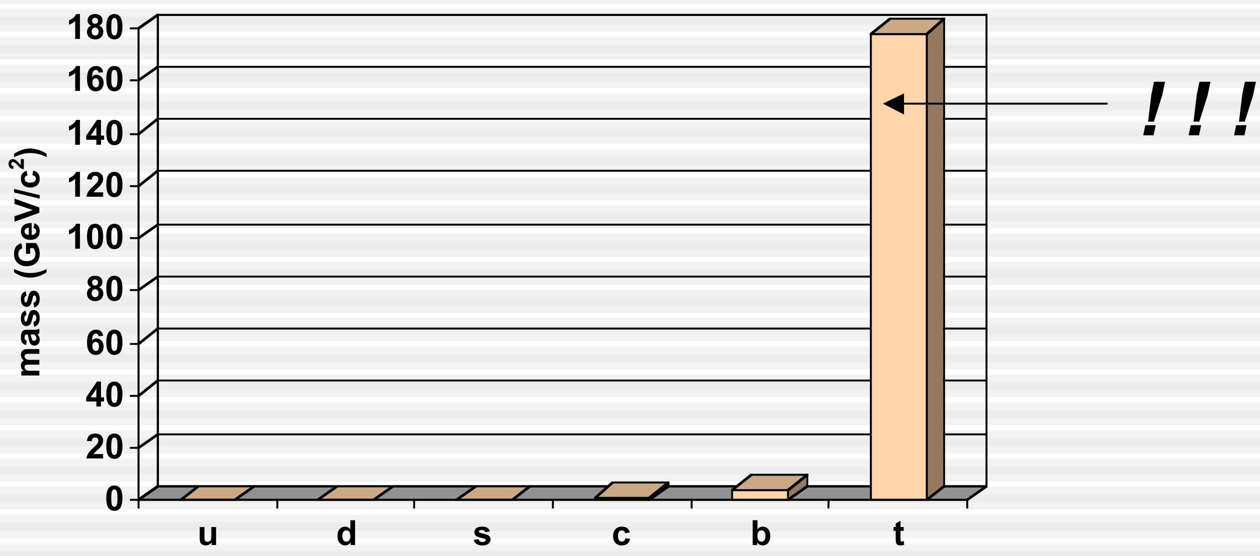
for the CDF and D0 Collaborations

PIC 2004

The Top Quark

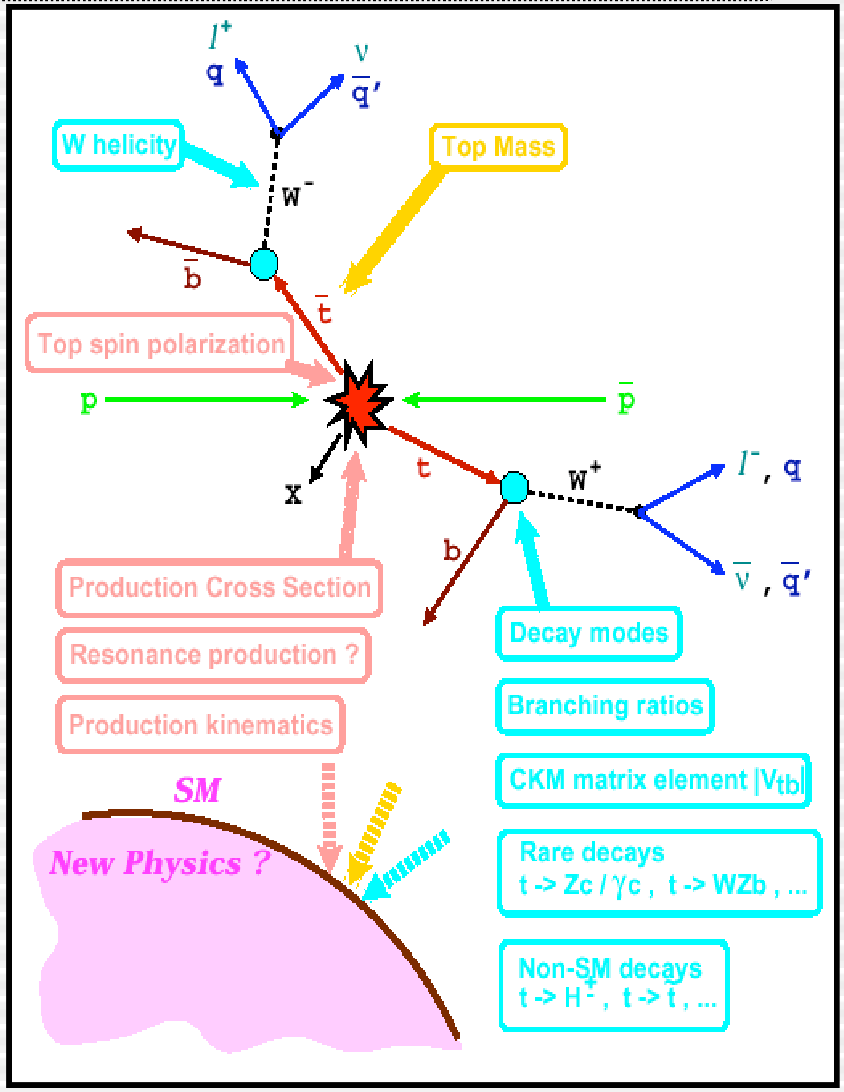
- Discovery of top in 1995 ushered in a new experimental program
  - Fully explore the properties of this newest particle
- ~100 pb^{-1} of Run I data left every analysis statistically challenged
- Top is intriguing enough to pursue aggressively at Run II

Favorite motivational plot….



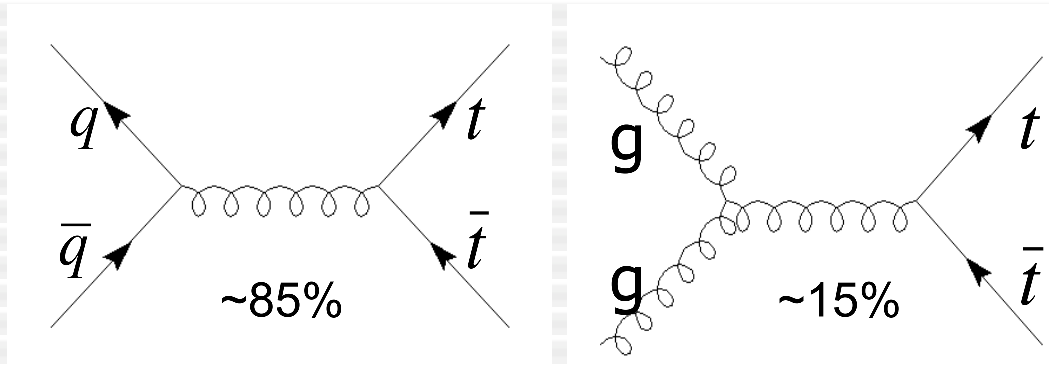
Top Quark Physics Opportunities

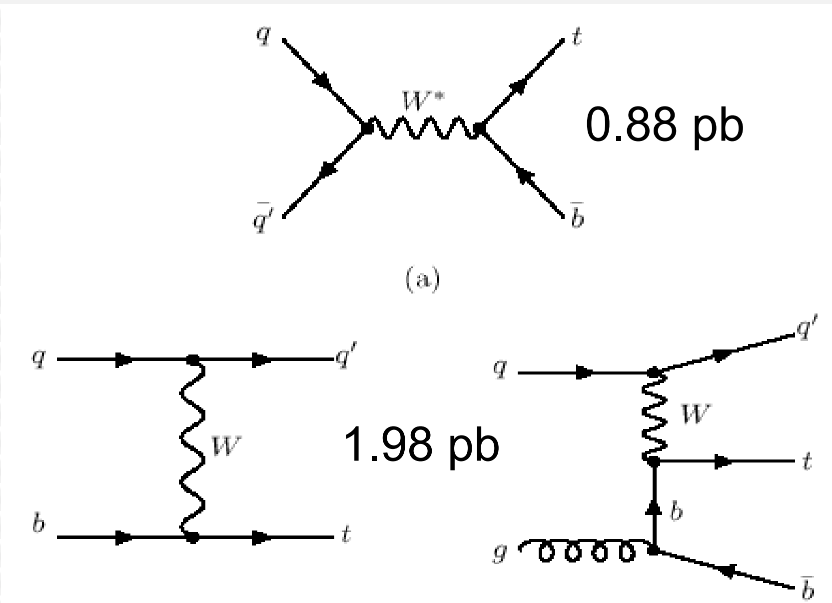
- A veritable cavalcade of interesting physics in the top sector
  - Studying EW interaction at high energy
  - Direct contact with V_{tb}
  - Unique opportunity to probe bare quark properties (spin? charge?)
- Top mass at EWSB scale (Yukawa coupling ~1)… what does this tell us?
  - Is top the gateway to new physics?



Top Production at the TeVatron

- Pair production
  - Main mode for top physics at Run II
  - σ=6.7 pb
    - ~30% increase w/r/t Run I

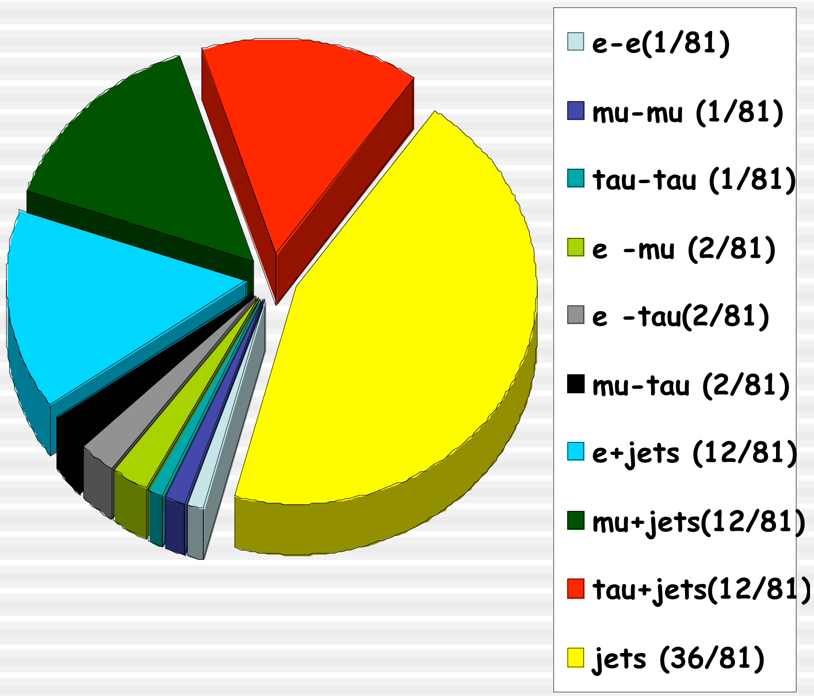




- Single top
  - Not yet observed
  - Slightly different final states than pair production
  - Larger background

Top Quark Decays

- ~100% t →Wb in SM
  (we'll be testing that…)
- Categorize final states according to decay of the W bosons



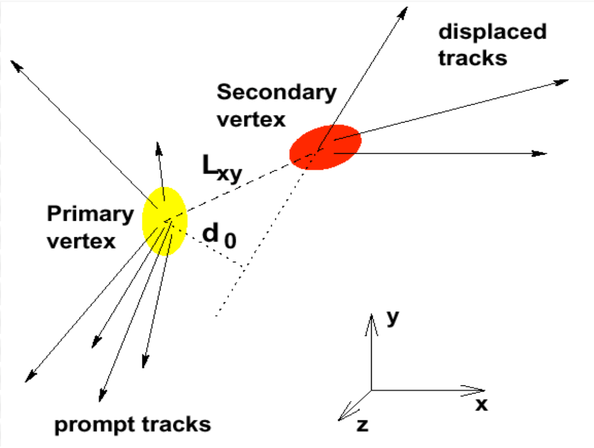
- "DILEPTON:" lνlνbb
  - Both W's decay to e, μ (maybe through a τ)
  - Clean sample even w/o b-tagging
  - Main BGs: DY, fake leptons, dibosons
- "LEPTON+JETS:" lνjjbb
  - Something of a "golden mode"
  - ~3x as much BR as dileptons, good purity after b-tagging
  - Main BG: W+jets
- "ALL JETS:" jjjjbb
  - Largest BR
  - Huge BG from QCD multijets
- These final states determine what you need to do top physics…

Experimental Tools for Top Physics

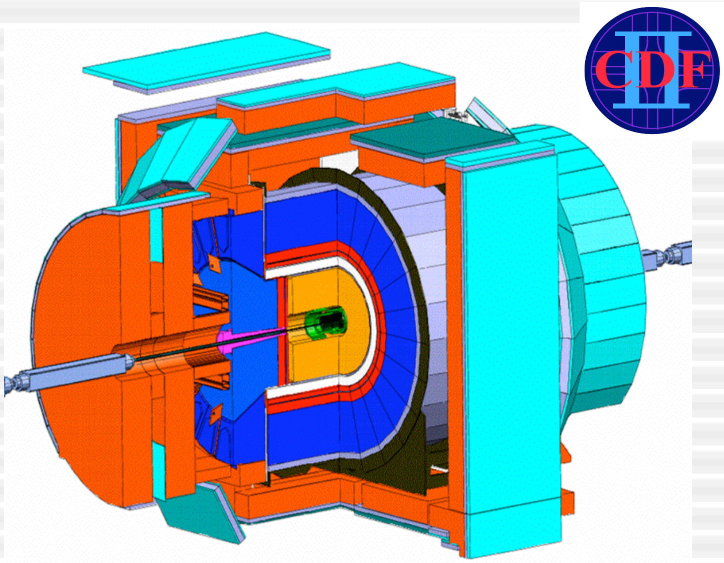
- MET measurement
  - Cleanly identify final states with neutrinos
- Jet E measurement
  - For good mass resol'n and accurate reconstr'n of kinematics
- Both require a well-calibrated calorimeter w/ as much of 4π as possible

- Lepton ID
  - Need EM calorimeters, muon chambers with as much coverage as possible
  - Z,J/$\psi \rightarrow$ll decays provide useful samples for ID efficiency calibration
  - ♣ Large jet samples to study fake rates

- Bottom-quark tagging
  - Exploit long lifetime of B hadrons
  - Requires precision tracking (Si microstrip detectors) with as much forward reach as possible



CDF and D0 in Run II



Run II upgrades

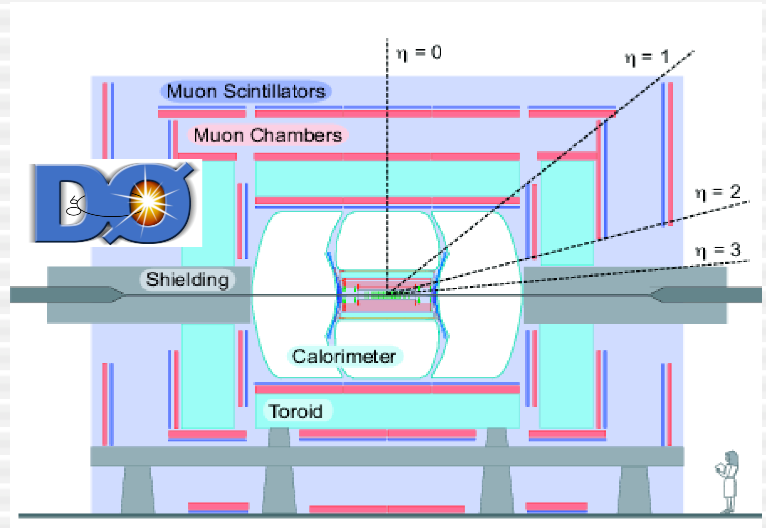
New Si, central tracking

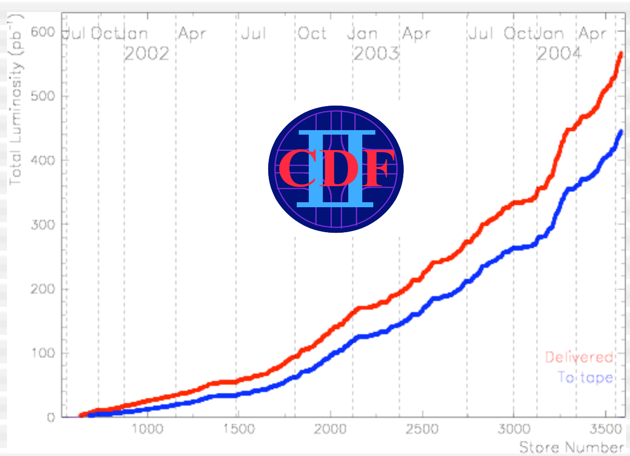
Forward muon systems

Trigger/DAQ

CDF: forward calorimeter

D0: new 2T magnet



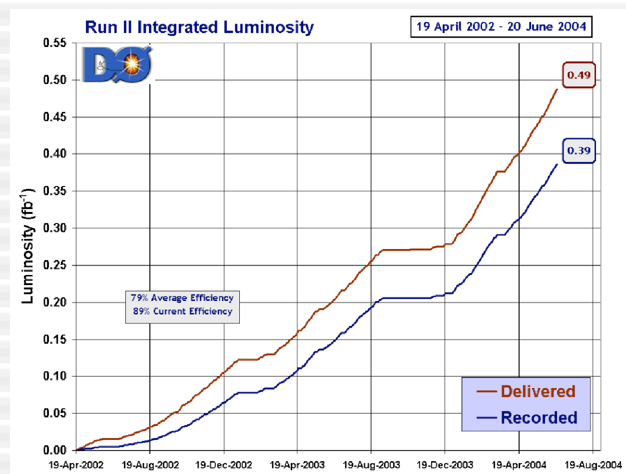


Data samples

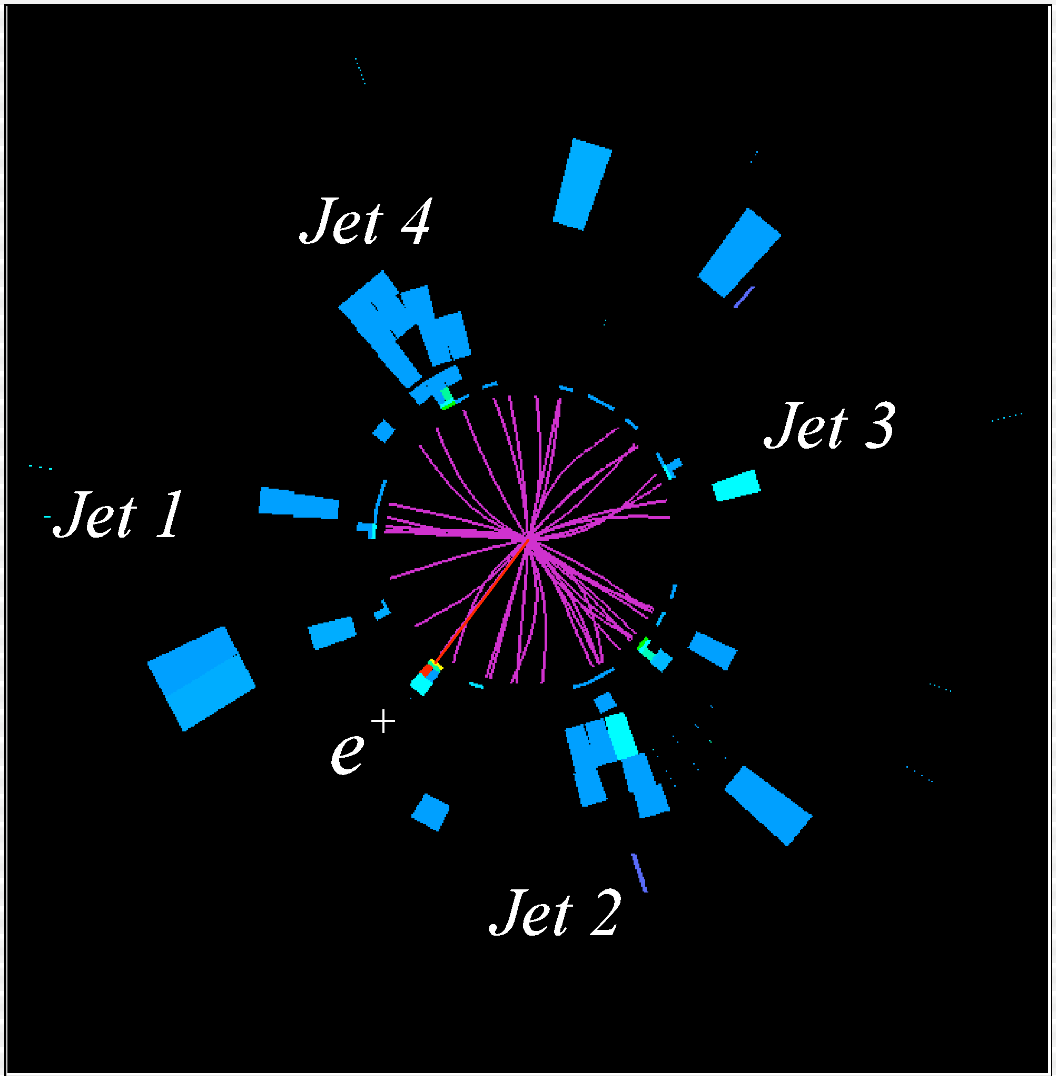
About 400 pb^{-1} in the can now

Results here cut off in SEP-2003

Varying data subsets for varying analyses; 150-200 pb^{-1}

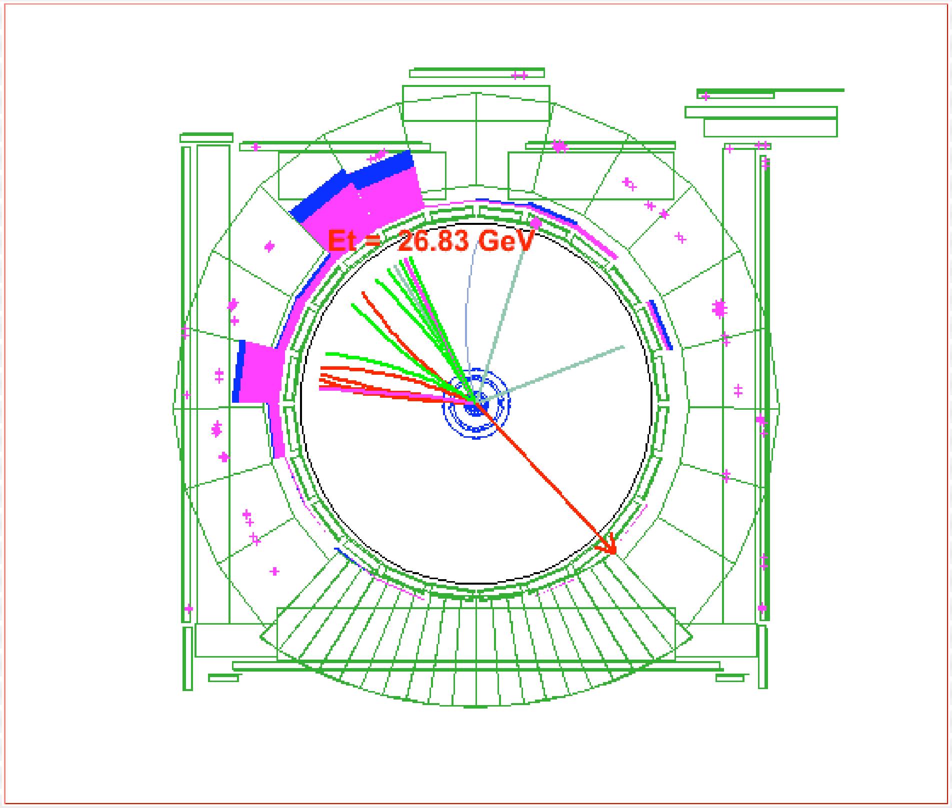


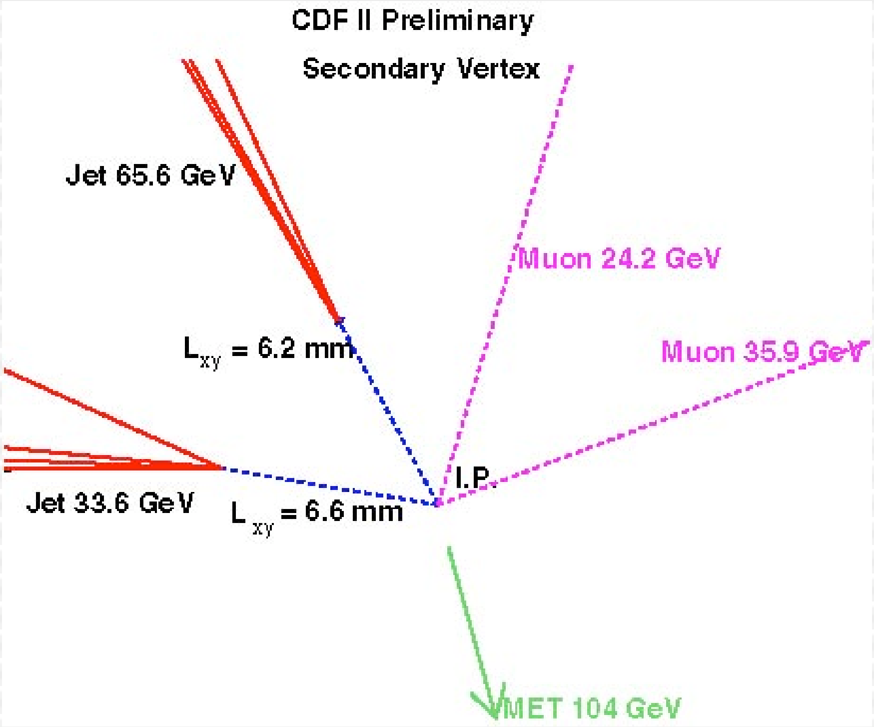
A lepton + jets event at D0



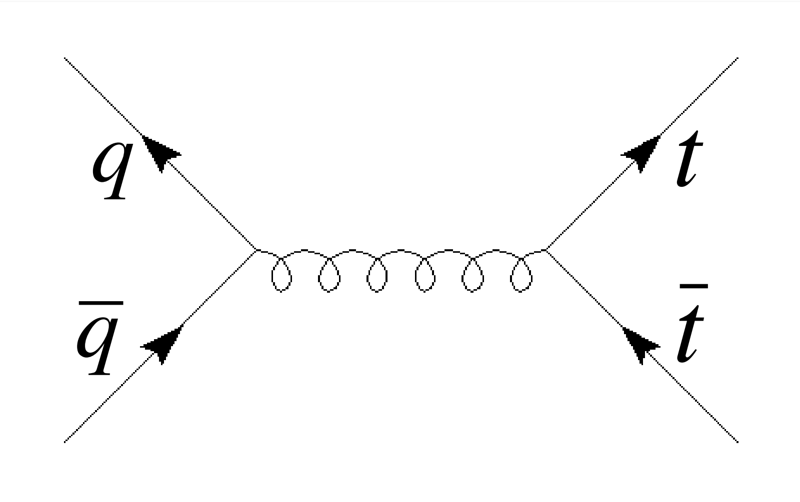
Not shown: MET (58 GeV)

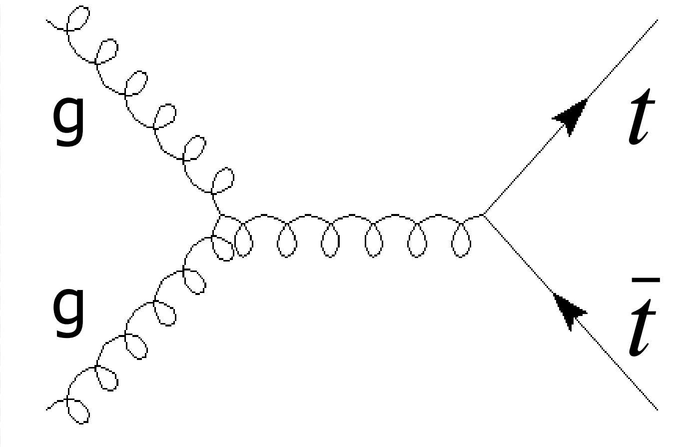
A dilepton event at CDF





Measuring the top pair cross section

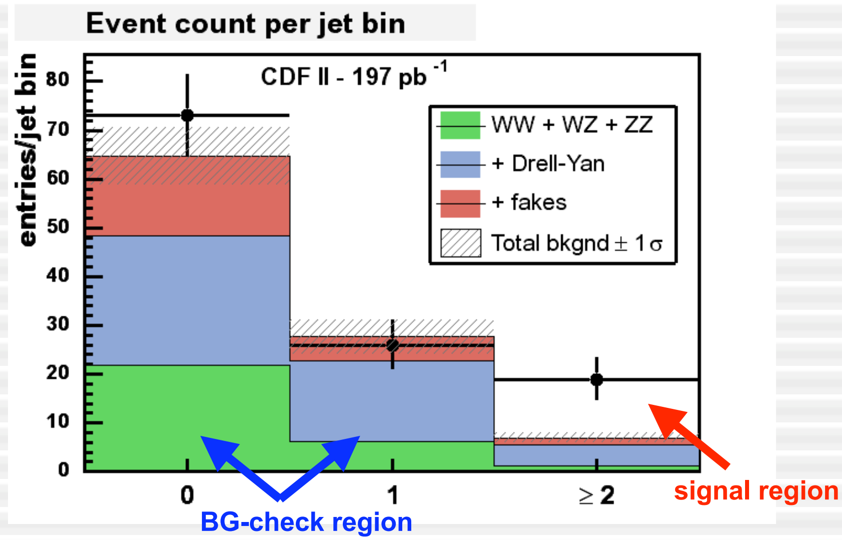




- First step in any top physics program
  - Establish baseline event selection for defining the top sample
  - Validate top analysis tools (b-tagging, lepton ID, etc.)
- Interesting measurement
  - Test SM: is tt produced via good old QCD? More exotic mechanism (e.g. heavy tt resonance)?
  - Is there anything "unknown" in there with top?

Top Pair Cross Section -- dileptons

- Basic selection: two leps (e, μ), two jets, large MET
  - Second lep can be loose -- - just an isolated track even!
- Main BGs are DY, dibosons, and j→lep fakes
- Counting experiment results:



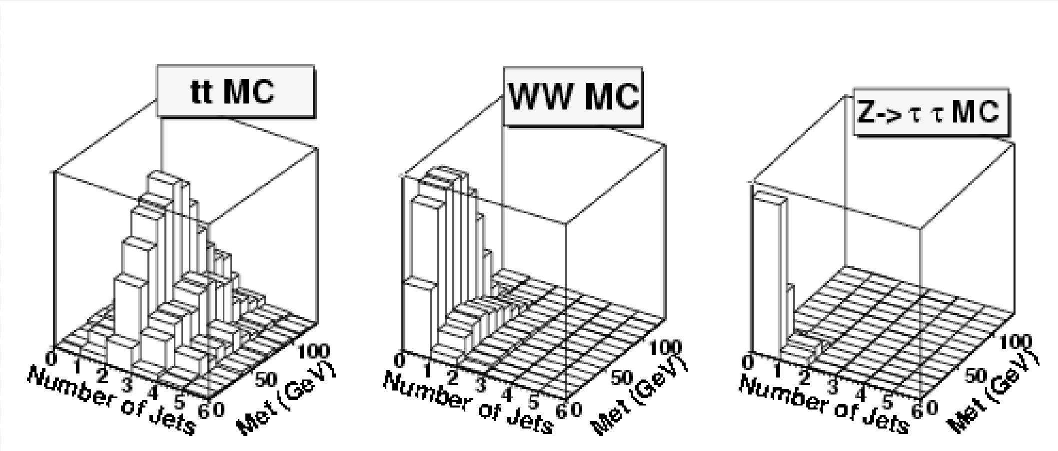
	CDF l+trk (197 pb^{-1})	CDF di-l (193 pb^{-1})	D0 di-l (140 pb^{-1})
Expected top+BG	18.4±2.5	10.9±1.4	10.8±0.8
Observed	19	13	17

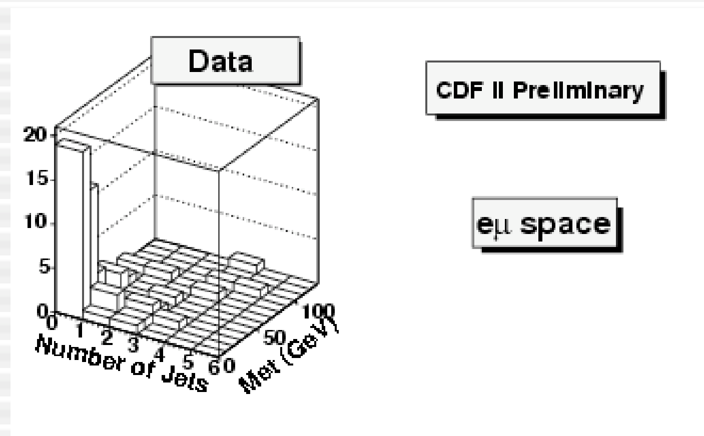
D0: $\sigma(t\bar{t}) = 14.3^{+5.1}_{-4.3}(stat)^{+2.6}_{-1.9}(syst) \pm 0.9(lum)$ pb

CDF: $\sigma(t\bar{t}) = 7.0^{+2.4}_{-2.1}(stat)^{+1.6}_{-1.1}(syst) \pm 0.4(lum)$ pb

Top Pair Cross Section -- inclusive dileptons

- New CDF technique to measure σ_{tt} in dileptons
- No cuts other than two-lep requirement
  - If same-flavor, Z→ee, μμ dominates --- require significant MET
- Fit data for tt, WW, Z→ττ contribution in 2D (MET,N_{jet}) plane





Result (~200 pb^{-1}):

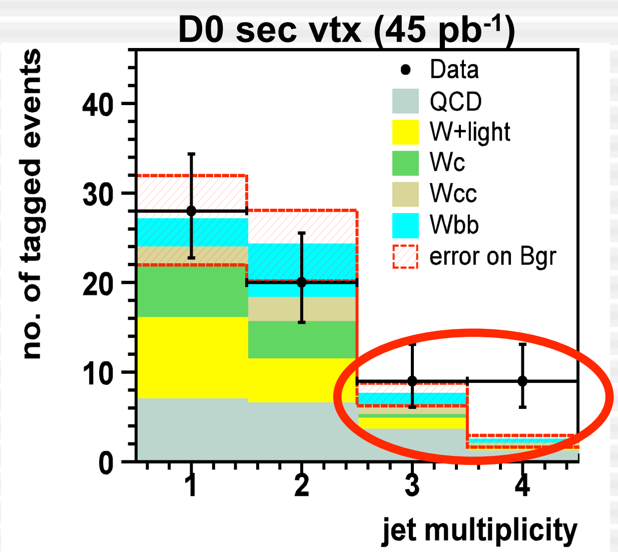
$$\sigma(t\bar{t}) = 8.6^{+2.5}_{-2.4}(stat) \pm 1.1(syst)\ \text{pb}$$

Significant improvement over counting expt!

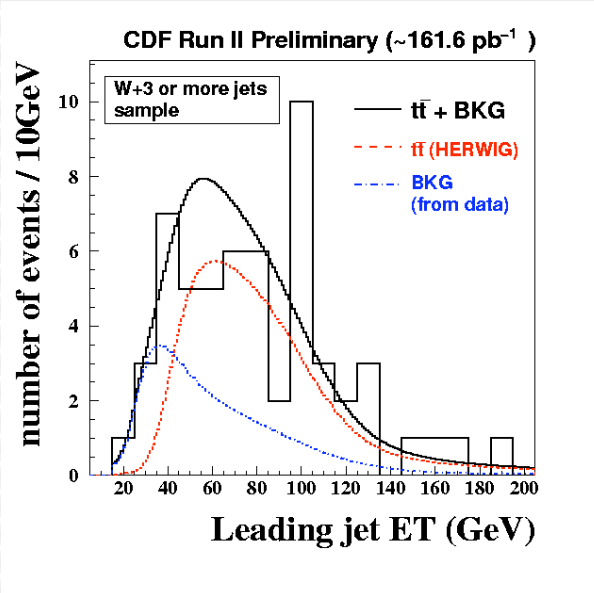
Top Pair Cross Section -- l+jets w/ b-tagging

- b quark ID separates top from dominant W+jets bkgd
  - Lifetime tag methods
    - Find displaced secondary vertex in jet
    - Find tracks with large impact parameters
  - Soft lepton tag methods
    - Find "soft" muons from semileptonic *B* decay
- Extract cross section from tagged event sample

Counting expt



Fit discriminant kinematic qty

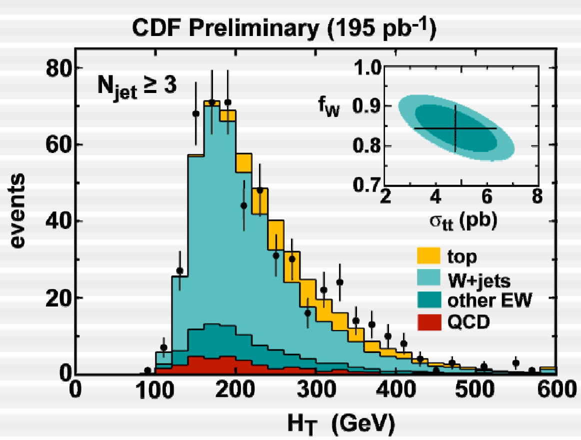


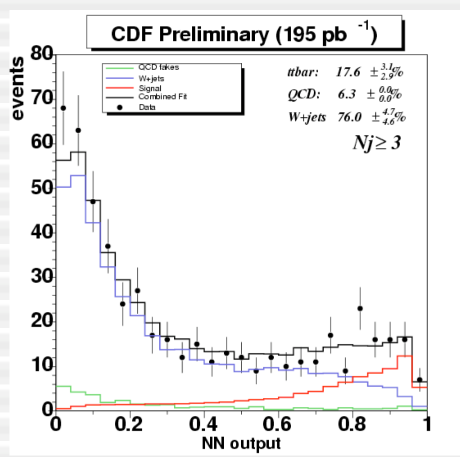
Top Pair Cross Section -- l+jets topological

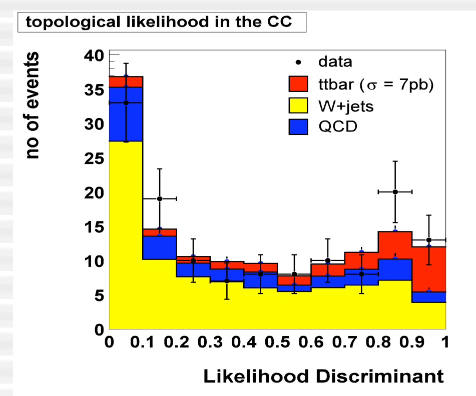
- Use higher-statistics “pre-tagged” W+jet data
- Exploit large top mass
  - Top decay products more energetic than generic W+jets

- Simple: fit a discriminant distribution for top, BG
  - H_T: scalar sum of jet E_T, lepton E_T, MET

- Advanced: fit a quantity (ANN, Lhood) composed of several discriminant distribs







D0 e+jets, 141 pb^{-1}

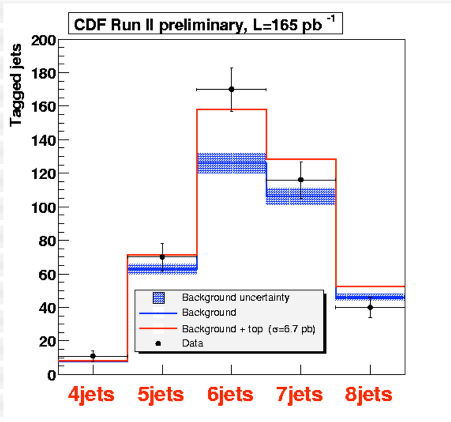
Top Pair Cross Section -- All-jet

- Challenging channel --- QCD multijet BG several orders of magnitude larger than top
- Exploit
  - Topological differences between top and BG (preselect top-like events)
  - b-content of top (requires good understanding of tagging rates for BG --- determine from data)

- D0: count single-tagged preselected events with high topo. ANN output

$$\sigma(t\bar{t}) = 7.7^{+3.4}_{-3.3}(stat)^{+4.7}_{-3.7}(syst)\ \text{pb}$$

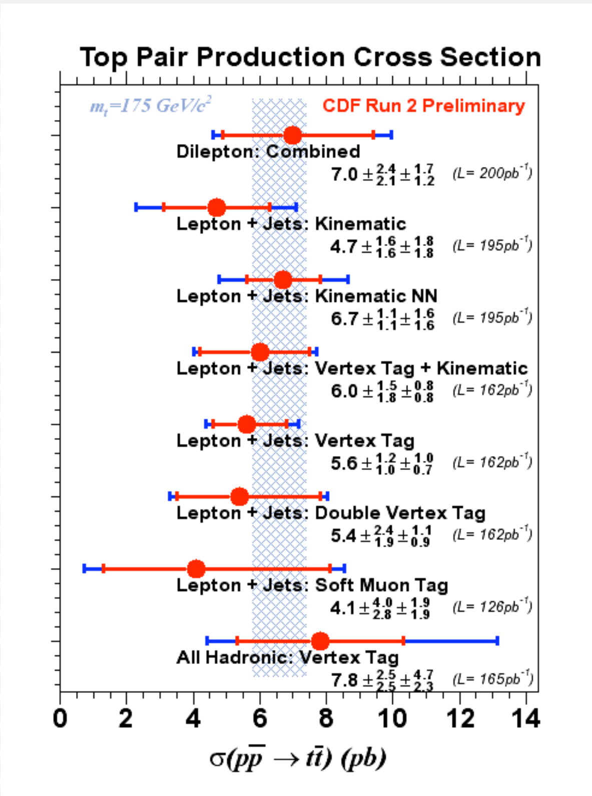
- CDF: count excess tags in preselected $N_{jet} \geq 6$ events

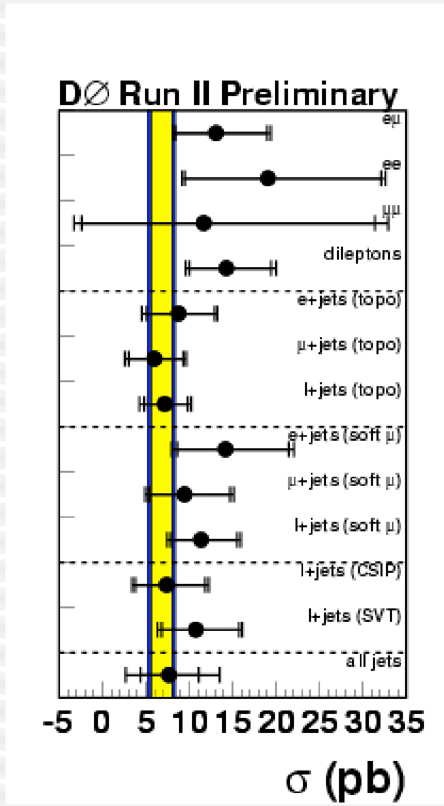


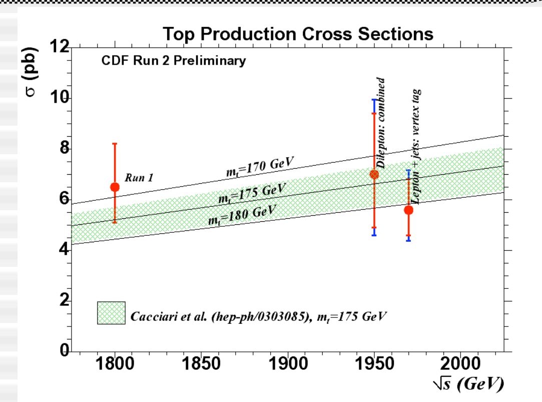
$$\sigma(t\bar{t}) = 7.8 \pm 2.5(stat)^{+4.7}_{-2.3}(syst)\ \text{pb}$$

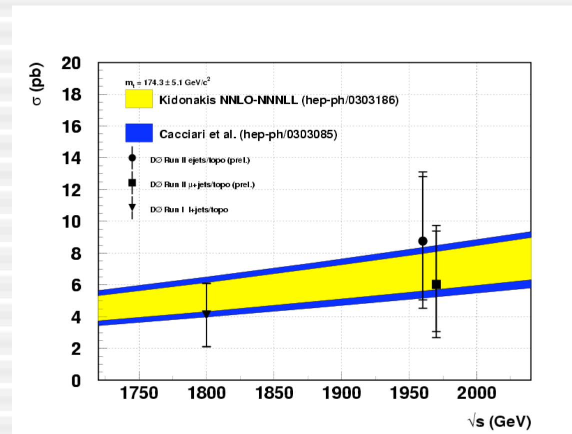
Top Pair Cross Section Summary

Observed cross sections consistent with each other…







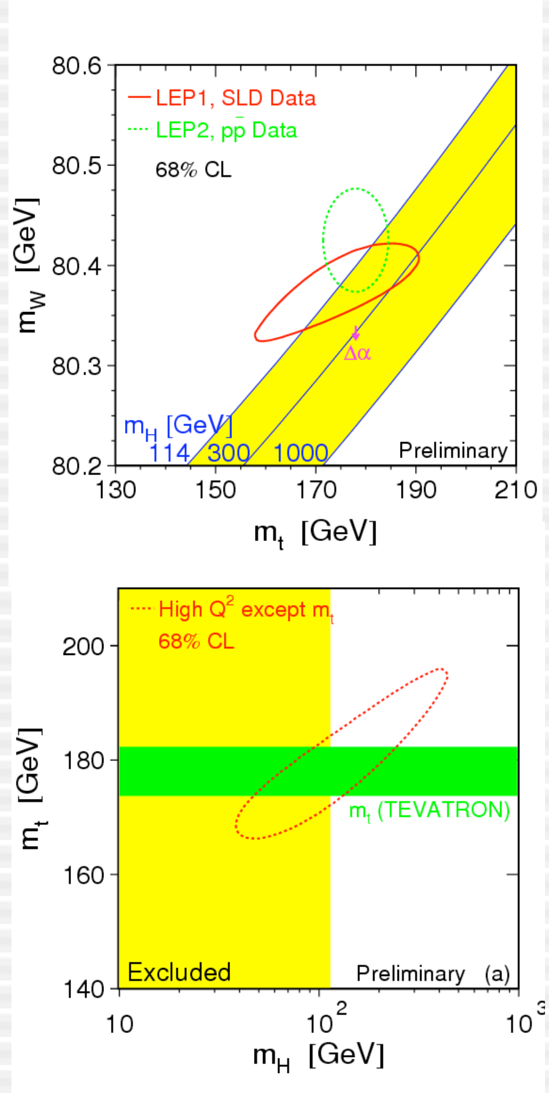


…and with the SM prediction for m_t=175 GeV/c²: $\sigma(t\bar{t}) = 6.7^{+0.7}_{-0.9}$ pb

Bonciani *et al.*, *Nucl. Phys.* **B529**, 424 (1998)
Kidonakis and Vogt, *Phys. Rev.* **D68**, 114014 (2003)

Measuring the top mass

- Large mass makes top intimately connected with the Higgs boson
- m_t combined with precision EW data constrains possible value of m_H
  - Ex: $\delta m_W^2 \propto (m_t^2, \log m_H)$
- Precision measurement of m_t allows us to squeeze the Higgs mass even further
  - Run II goal: Δm_t = 2--3 GeV/c^2



New Run I D0 Top Mass

Catch that article in *Nature* a few weeks ago? (**429**, pp. 638-642)

m_t = 180.1±3.6(stat)±3.9(syst) GeV/c^2

- Statistical uncertainty reduced from 5.6 to 3.6 GeV/c^2
  - Equivalent to a 2.4x larger dataset!
- Form an event-by-event likelihood vs. m_t:

“transfer function”

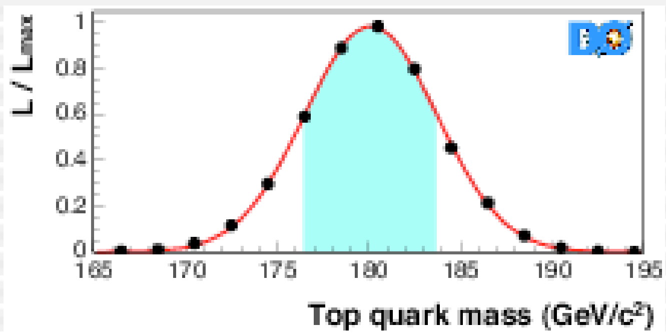
$$P(x,m_t) = \frac{1}{\sigma(m_t)} \int \underbrace{d\sigma(x,m_t)}_{\text{Phase space x LO ME for top or BG (W+4j)}} dq_1 dq_2 \underbrace{f(q_1) f(q_2)}_{\text{PDFs}} \underbrace{W(x,y)}_{\text{Probability for observable x given parton y}}$$

Phase space x LO ME for top or BG (W+4j)

PDFs

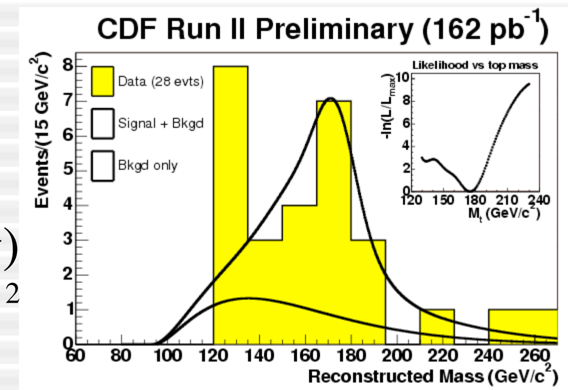
Probability for observable x given parton y (Ex: quark E_T → jet E_T)

- “Sharpness” of likelihood effectively weights each event
- Maximize joint likelihood to extract m_t



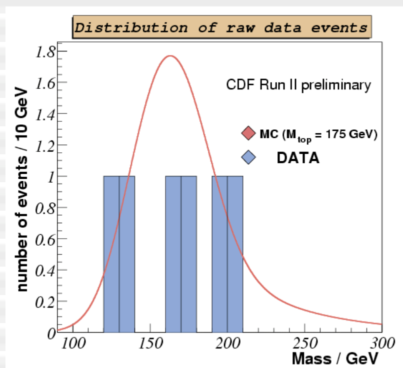
CDF Run II Top Mass Measurements

- Run-I-like “template” methods have been resurrected
  - Reconstruct one top mass per event
  - Compare resulting mass distribution with parameterized templates from simulated top of varying mass, form Lhood vs. m_t
  - Minimize -ln L to extract top mass



Dileptons:

$$m_t = 175.0^{+17.4}_{-16.9}(stat) \pm 8.4(syst)\ \mathrm{GeV}/c^2$$

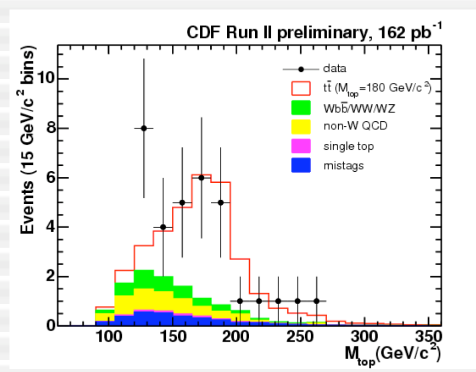


b-tagged l+jets:

$$m_t = 174.9^{+7.1}_{-7.7}(stat) \pm 6.5(syst)\ \mathrm{GeV}/c^2$$

•b-tagged l+jets w/ multivar templates:

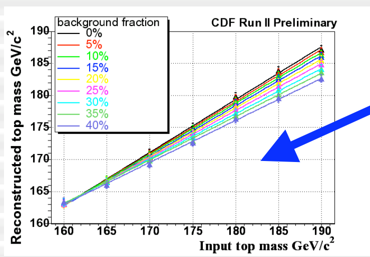
- •Uses reconstructed mass and jet E_T sum
- •Decrease sensitivity to BG
- •Weight events according to probability for chosen jet permutation to be correct



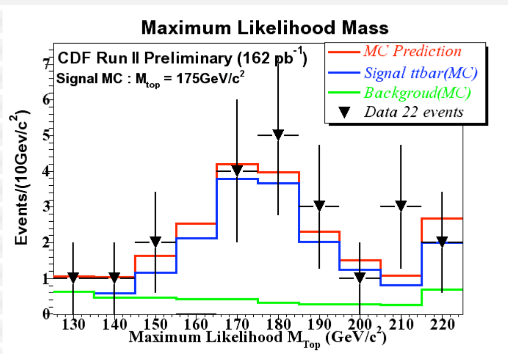
$$m_t = 179.6^{+6.4}_{-6.3}(stat) \pm 6.8(syst)\ \mathrm{GeV}/c^2$$

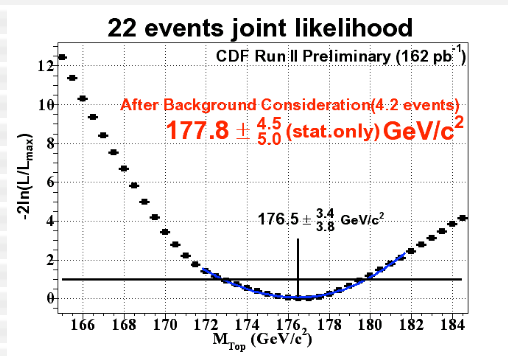
Run II Top Mass -- CDF DLM

- “Dynamical Likelihood Method” --- similar to new D0 method
  - Form event-by-event Lhood vs. m_t based on LO ME for tt→l+4j, transfer functions for quark E_T → jet E_T
  - Minimize -ln L (joint likelihood of event sample)
- No BG ME used, instead correct pull on m_t due to BG:



Mapping function: from measured mass to true mass for a given BG fraction (19% for b-tagged l+4j sample)



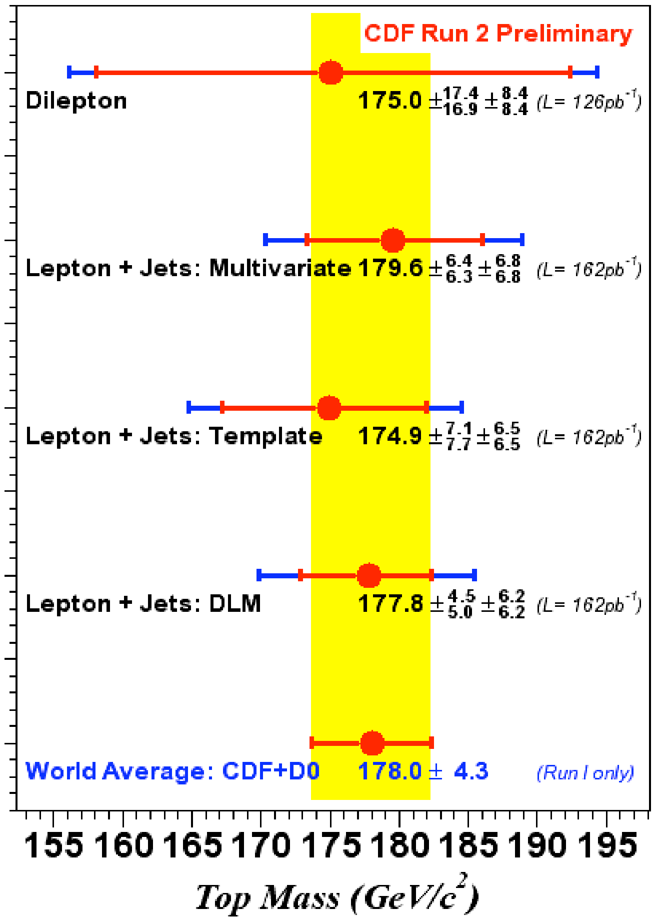


Result:

$$m_t = 177.8^{+4.5}_{-5.0}(stat) \pm 6.2(syst)\ \mathrm{GeV}/c^2$$

most precise Run II measurement

Top Mass Summary

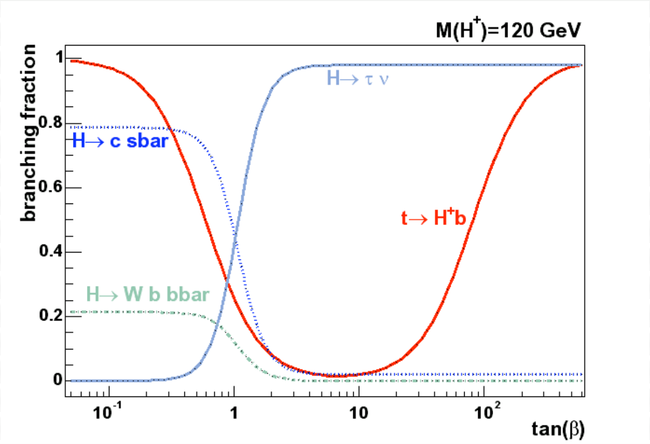


- New combined Run I mass
  - m_t=178.0 ± 4.3 GeV/c^2
    - was: 174.3 ± 5.1 GeV/c^2
  - Has implications for allowed Higgs mass --- see talk from S. Mattingly
- New mass measurement techniques being explored for Run II
  - Systematics (read: jet energy scale) quickly becoming limiting factor for individual results
    - *In situ* calibration with Z→bb? W→qq in double-tagged top events?

Top Branching Ratios -- $t \to \tau\nu b$

- Taus generally excluded from the dilepton / lepton +jets / all-jets triumvirate
- BR($\tau \to$hadrons) ≈ 65%
  - Difficult to distinguish from a low-multiplicity jet
- BUT, worth the challenge!
  - Leave no stone unturned
  - $t \to Wb \to \tau\nu b$ is all 3rd-generation --- good place for new physics to appear!

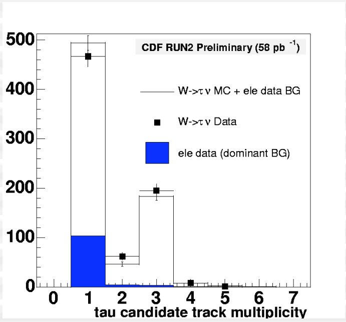
Ex: Charged Higgs



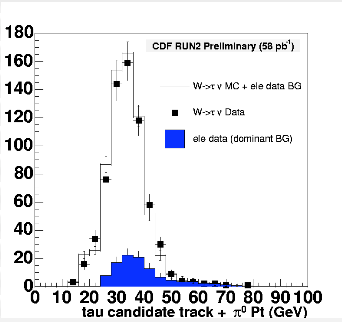
- Cleanest signature: $tt \to l\nu\tau_h\nu bb$ (dilepton-like)
- τ_h+jets: no results yet!

$t \to \tau\nu b$ in Dilepton Channel

- Select events with high-p_T e or μ, 2 jets, MET, and a τ
- τ ID mainly exploits tendency for taus to be more isolated than jets
  - Need to ensure that this is adequately modelled by simulation



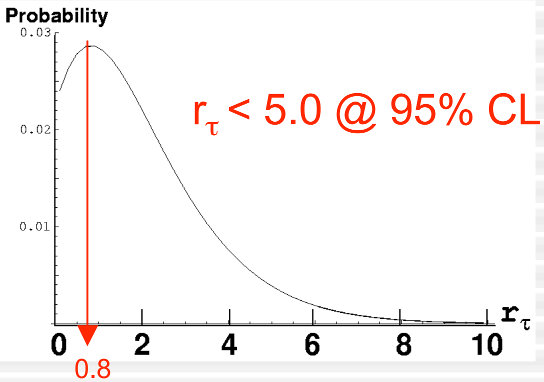
W→τν data and MC: good agreement in shape and norm.



Results:

	eτ	μτ
Total bkgd	0.77±0.18	0.53±0.11
tt (σ=6.7 pb)	0.59±0.11	0.47±0.08
Data (193 pb^{-1})	2	0

$$r_\tau = \frac{BR(t \to b\tau\nu)}{BR_{SM}(t \to b\tau\nu)}$$



Top Branching Ratios -- t→Xb

- Does top decay into something besides Wb?
  - Like Xb, where X→qq'? Or Yb, where Y→lν?
  - If so, then dilepton and l+jets cross sections will disagree
- Measure the ratio of cross sections $R_\sigma = \sigma_{ll}/\sigma_{lj}$
  - Assume efficiency for detecting X,Y decays the same as for W decays (*i.e.* similar masses), then

$$R_\sigma = \frac{1}{1 + \frac{1}{B}\frac{\beta}{1-\beta}}$$

or

$$R_\sigma = 1 + \frac{1}{(1-B)}\frac{\beta'}{(1-\beta')}$$

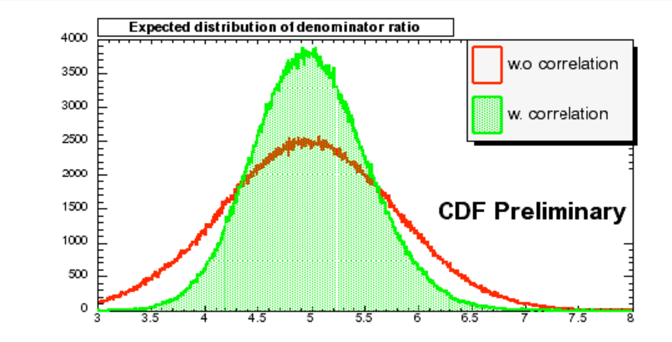
B=BR(W→hadrons)

β=BR(t→Xb)

β'=BR(t→Yb)

Many systematics cancel in ratio!

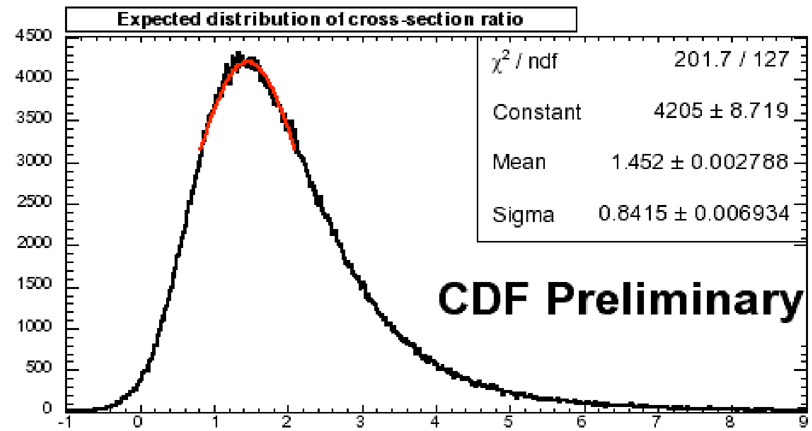
lj/ll acceptance ratio



- Lower limit on R_σ → upper limit on β
- Upper limit on R_σ → upper limit on β'
- SM: R_σ=1

R_σ Results

- Create ensemble of pseudoexpts w/ mean N_{obs} equal to the data
  - Note: these results based on earlier (smaller) datasets

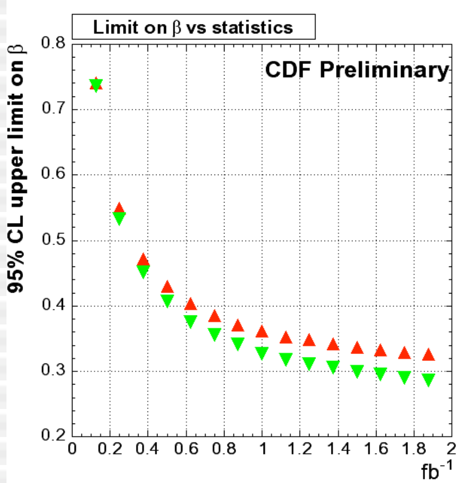


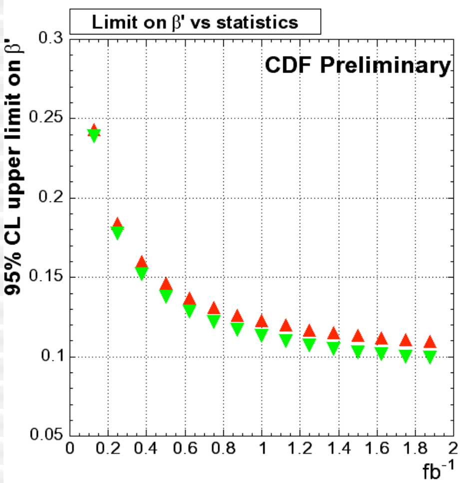
$$R_\sigma = 1.45^{+0.83}_{-0.55}$$

$\beta < 0.46$ @ 95% CL

$\beta' < 0.47$ @ 95% CL

Prospects (expected limits vs. luminosity):





Top Branching Ratios -- $t \rightarrow Wq_{light}$

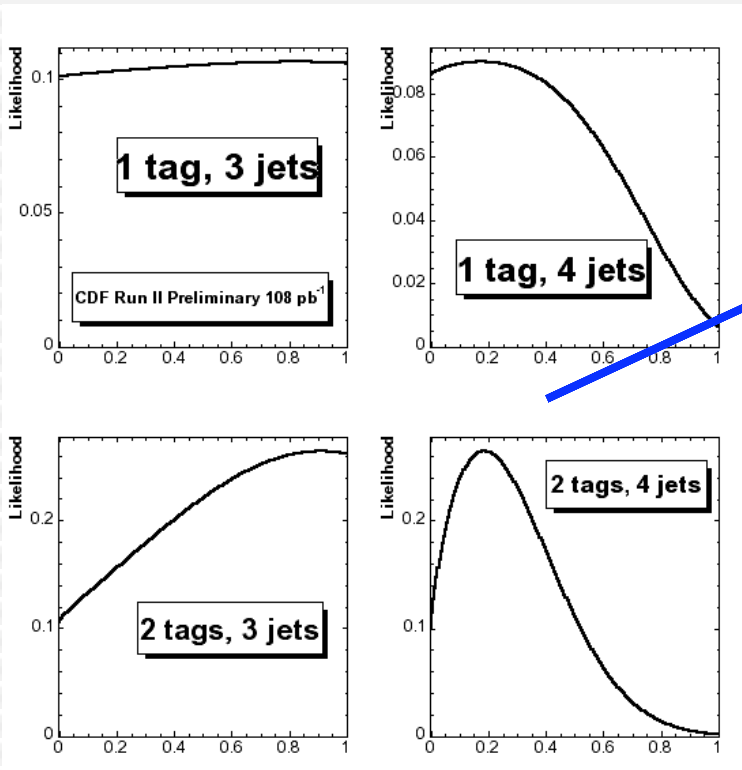
- Assuming three-generation CKM unitarity, $|V_{tb}|=0.999$
  - Implies $b = BR(t \rightarrow Wb)/BR(t \rightarrow Wq) > 0.998$
- Can measure "b" by checking the b-quark content of the top sample --- is it "polluted" with light quarks?
- If efficiency to tag a b-quark is ε_b (0.453 at CDF), then

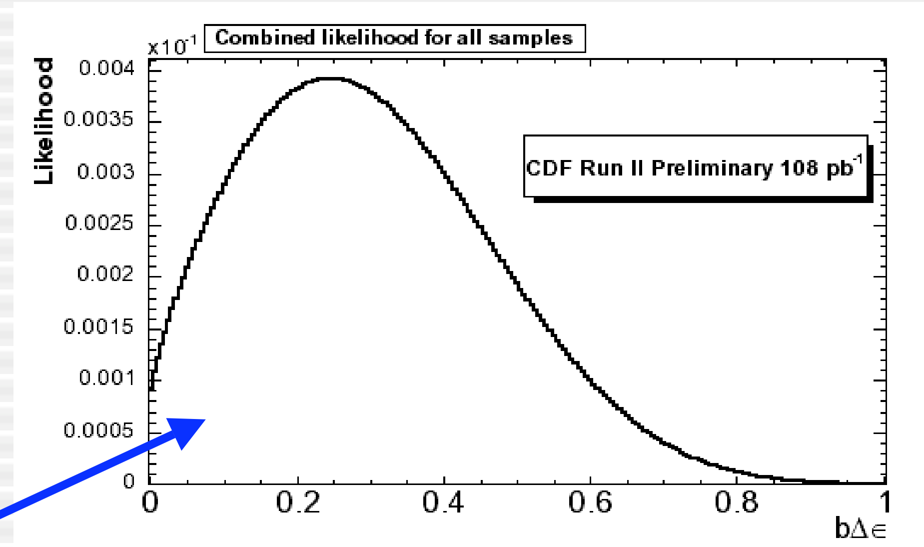
$\varepsilon_2=(b\varepsilon_b)^2$	"double-tagged"
$\varepsilon_1=2b\varepsilon_b(1-b\varepsilon_b)$	"single-tagged"
$\varepsilon_0=(1-b\varepsilon_b)^2$	"no-tag"

- Strategy: Take four subsamples of tt l+jets sample
  - 3 jets, single- and double-tagged
  - 4 jets, single- and double-tagged
- Form likelihood for observed number of events in each sample, maximize joint likelihood w/r/t $b\varepsilon_b$

b = BR(t→Wb)/BR(t→Wq) Results

Observed (BG)	3 jet	≥4 jet
1 tag	12 (10.0)	19 (4.1)
2 tag	2 (0.6)	2 (0.4)



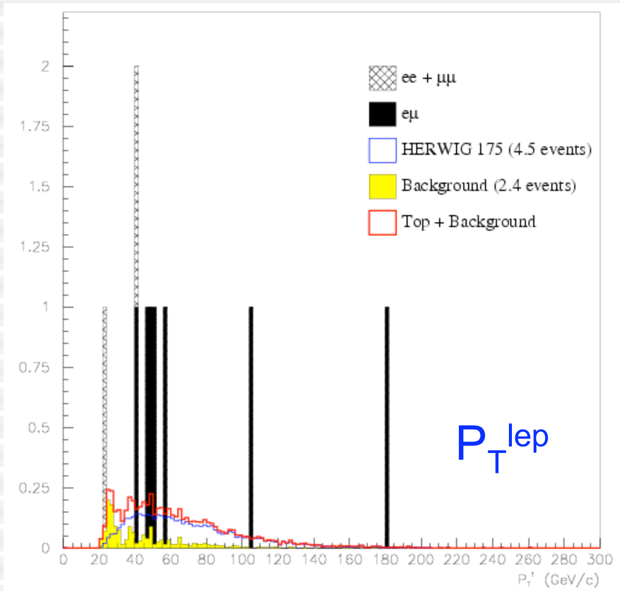


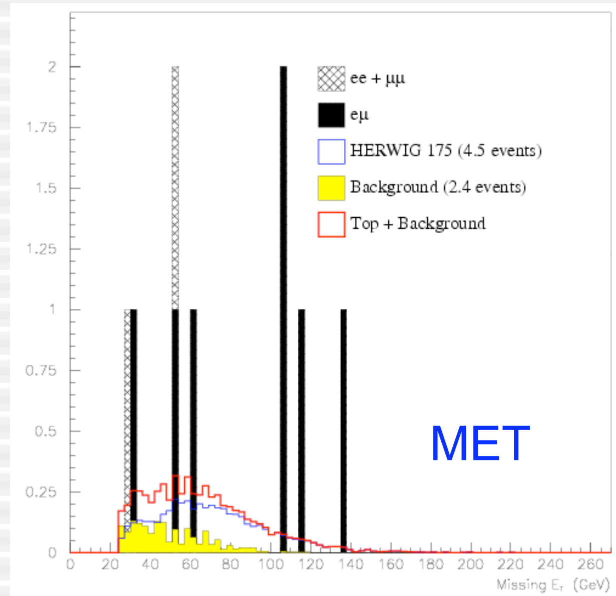
Dividing out ε_b,

$$b = 0.54^{+0.49}_{-0.39}$$

Immediate improvements: bringing in dilepton samples, no-tag samples

Top Dilepton Kinematics

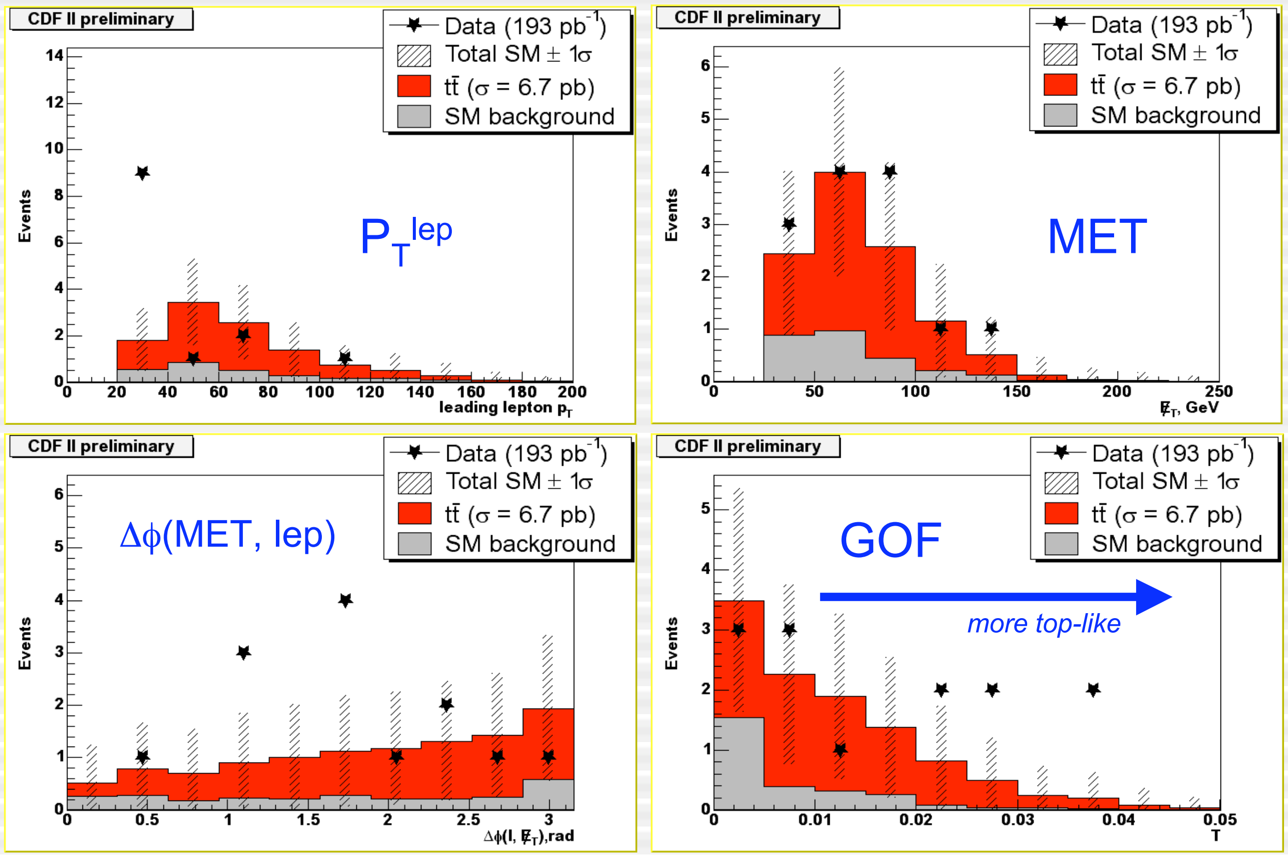




- Several events in Run I dilepton sample had large MET, lepton p_T --- not very compatible with top
- Suggestion that the events are better described by cascade decays of heavy squarks [Barnett and Hall, *Phys. Rev. Lett.* **77** 3506 (1996)]
- Develop search for this kind of anomaly in Run II
  - ♣ Stay general --- frame search as null-hypothesis test (SM = H_0)

Run II Dilepton Kinematics

Four kinematic variables chosen *a priori* to test against SM



•Probability of consistency w/ SM (based on KS probabilities) = 1.0-4.5%

•Low probability driven by excess of *low*-p_T leptons --- likely fluctuation of top

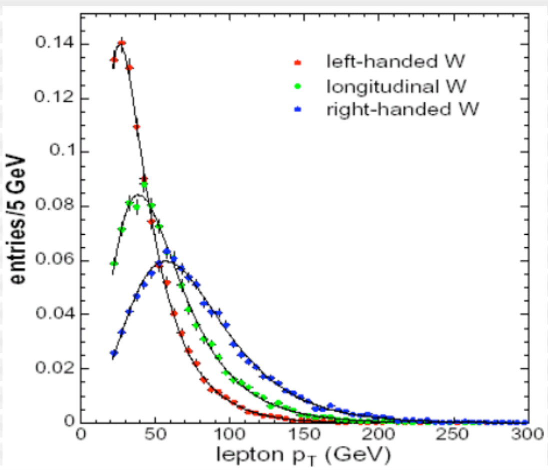
W Helicity in Top Decays

- Testing V-A in top decays
- Angular momentum conservation: top decays only into LH (negative-helicity) or longitudinally-polarized (0-helicity) W bosons

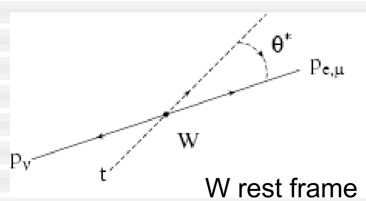
$$F_0 = \frac{\Gamma(t \to W_0 b)}{\Gamma(t \to W_0 b) + \Gamma(t \to W_T b)} = \frac{1}{1 + 2(m_W / m_t)^2} = 0.70$$

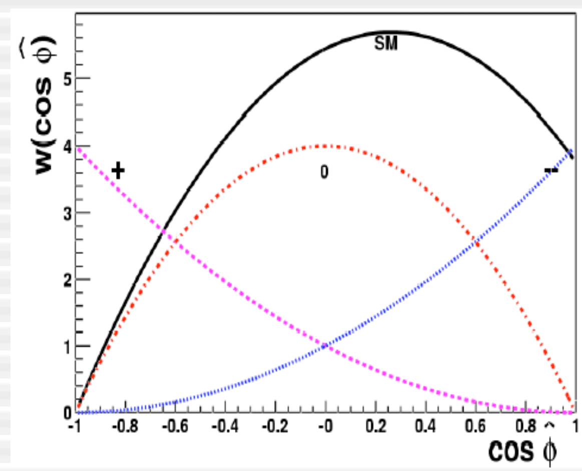
- Helicity of W manifests itself in decay product kinematics

Lepton p_T: lepton thrown anti-|| to W_{LH}, || to W_{RH}



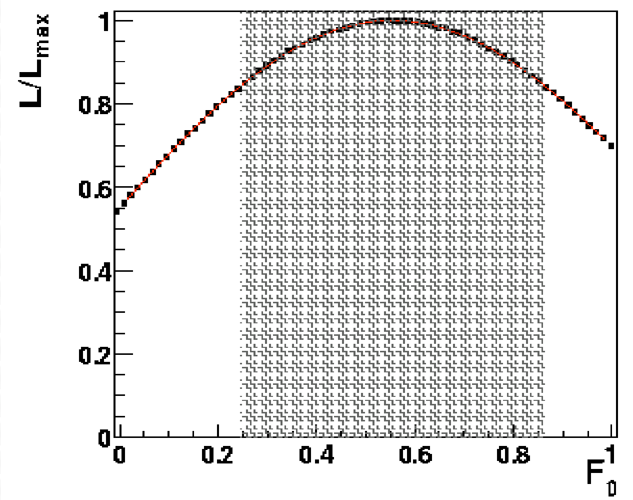
$\cos\theta^*$: different helicity amplitudes

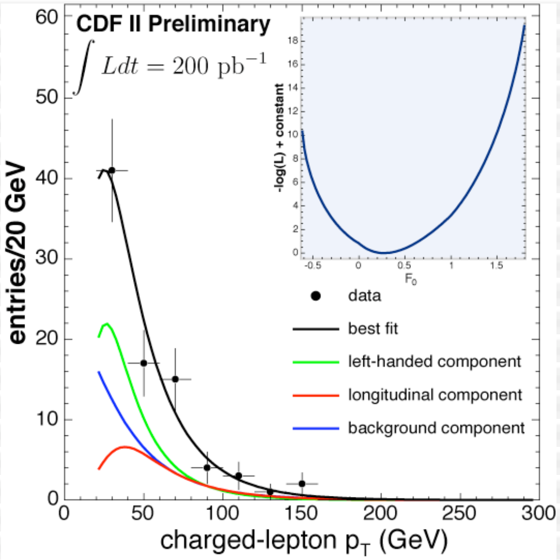




F_0 Results

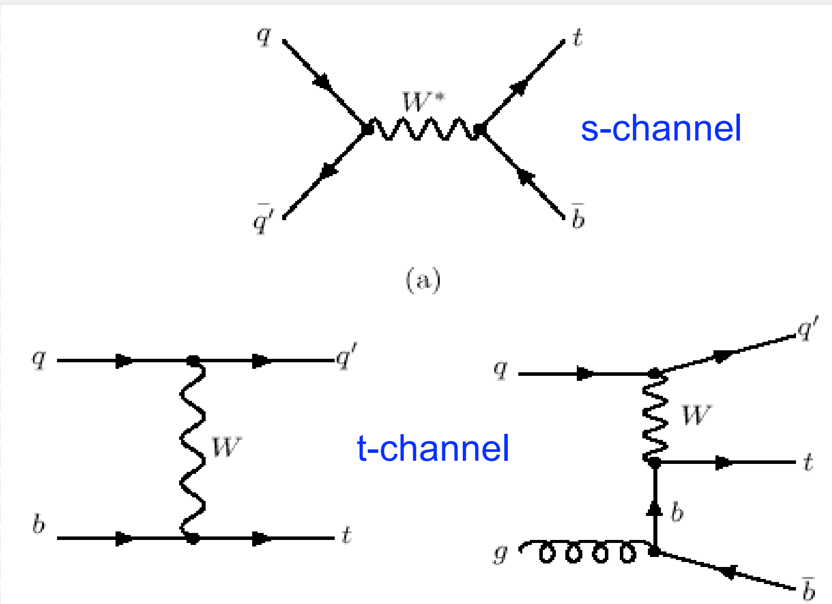
- New D0 l+jets result from Run I
- Use m_t technique
  - Event-by-event likelihood based on observables' consistency with ME
  - Maximize joint likelihood w/r/t F_0
- Result: $F_0=0.56\pm0.31$





- CDF result from Run II (l+jets and dilepton)
  - Fit lepton p_T spectrum for W_0 fraction
- Result: $F_0 = 0.27^{+0.35}_{-0.24}$
- Low-p_T lepton excess seen in dileptons pulls result down

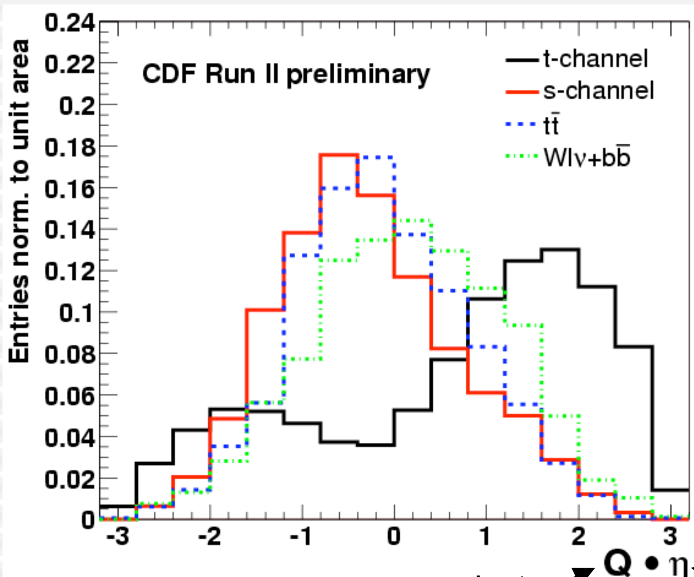
Search for Single Top Production



- Single top production is a direct probe of $|V_{tb}|^2$
- SM cross section too small to observe (for now) but could be increased by new physics (*e.g.* W', anomalous couplings)
- Signature is lepton, MET, 2 jets w/ at least one b-tag
  - Select events based on these requirements
  - Sandwiched between tt and a large non-top BG --- can't just do a counting expt

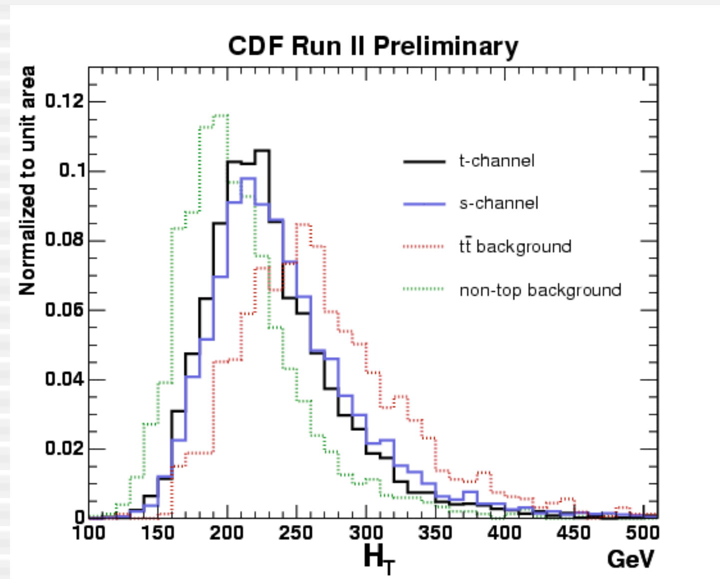
Single Top in Run II

MC templates



lepton

forward jet

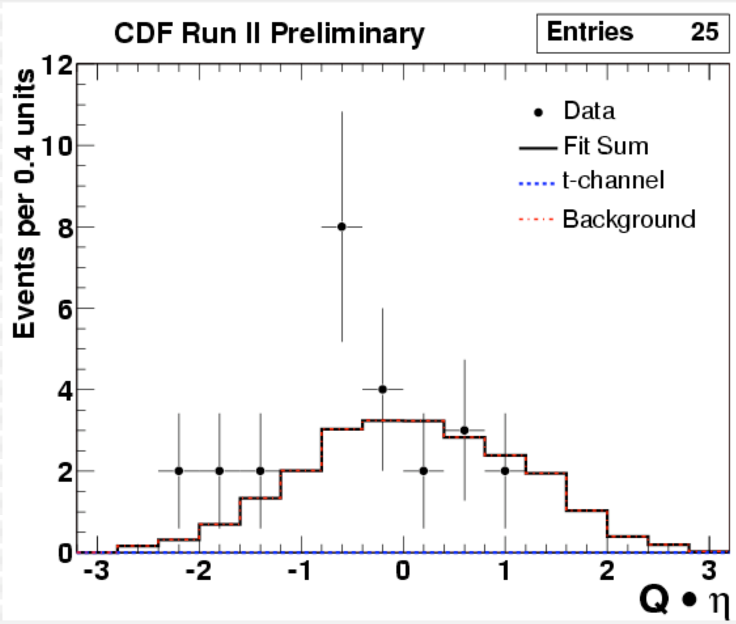


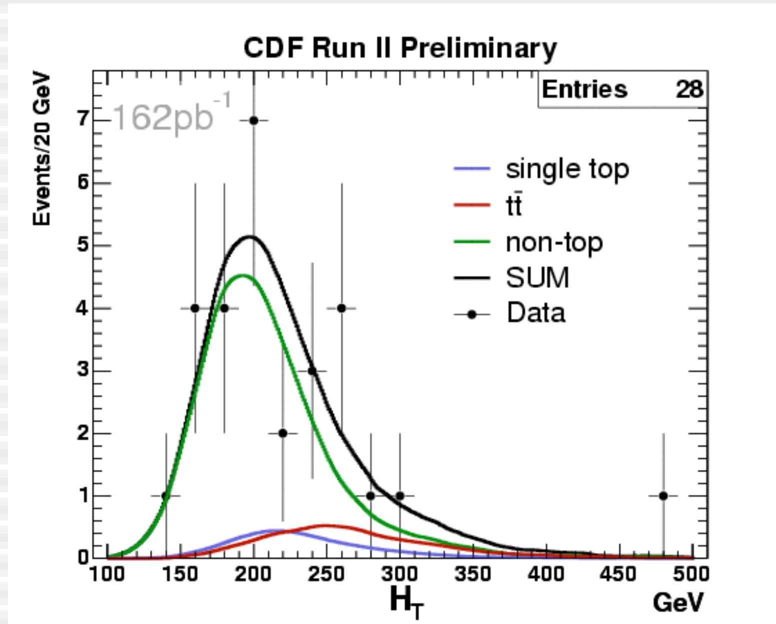
t-channel only: quark tends to follow proton direction, antiquark follows antiproton direction

Both channels: single top busier than non-top BG, but not as busy as tt

Fit data distributions for these components

Run II Single Top Fit Results





$\sigma_t < 8.5$ pb @ 95% CL

$\sigma_{t+s} < 13.7$ pb @ 95% CL

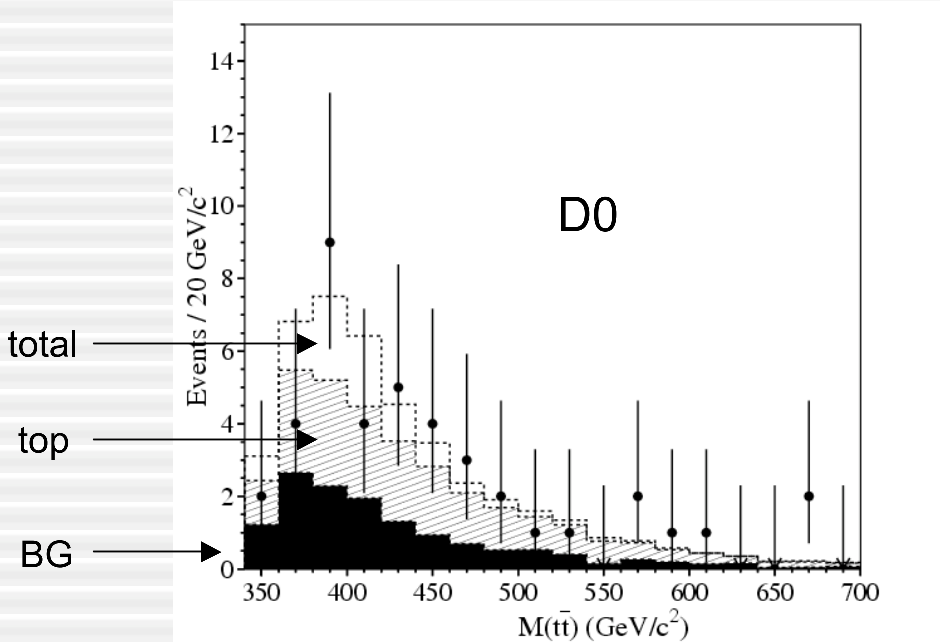
Will be reporting observations with 2 fb^{-1}…

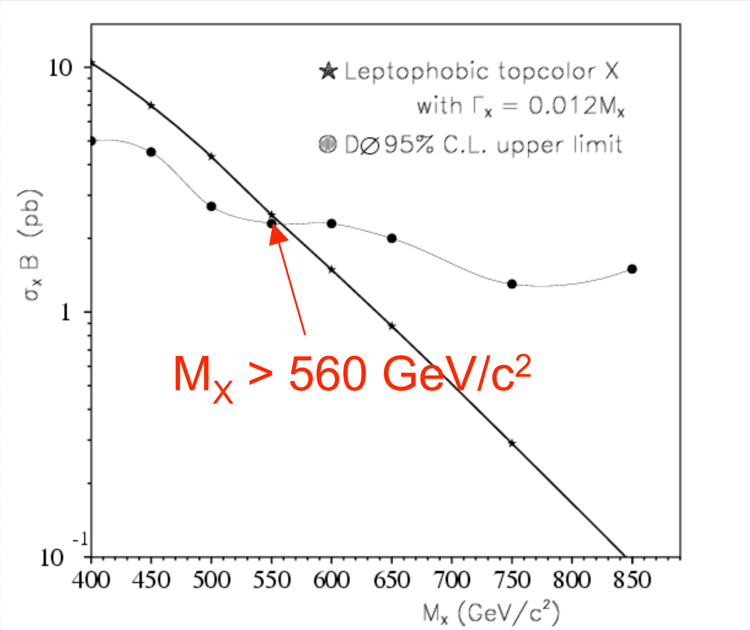
A Few Results from Run I

…all on deck for Run II…

Search for Narrow M_{tt} Resonances

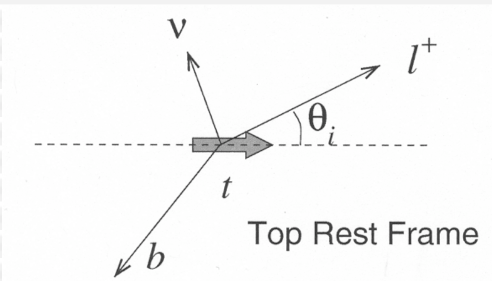
- No SM particle decays to tt
  - M_{tt} resonance = new physics
- Example model: topcolor-assisted technicolor (Harris, Hill, Parke, hep-ph/9911288)
  - Predicts leptophobic Z' w/ strong 3rd-gen coupling
- Assume a top mass and go bump hunting!

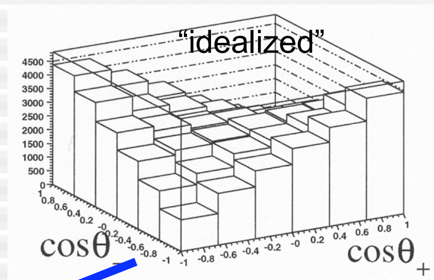




Spin Correlations in tt

- Particular choice of spin basis (“off-diagonal”) provides ~100% correlation between spin of t, tbar produced from qqbar annihilation
- Top decays before hadronization perturbs spin
  - $1/\Gamma_t << m_t/\Lambda^2_{QCD}$
  - Observation of correlations limits Γ_t, and therefore $|V_{tb}|$

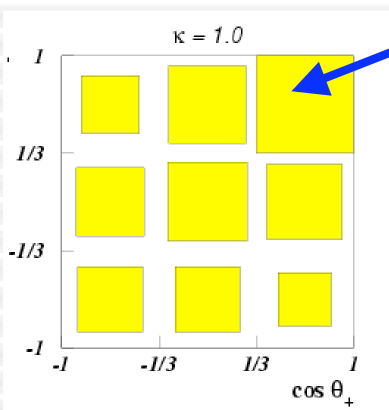




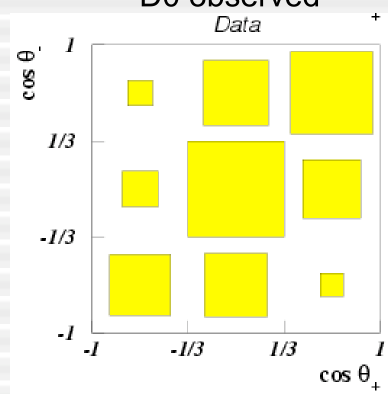
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1+\kappa\cos\theta_+\cos\theta_-}{4}$$

κ = 0.88 in SM

Detector effects, underconstrained kinematics….



D0 observed



κ > -0.28 @ 68%CL

Conclusions

- A full-fledged experimental top program is underway at the TeVatron
- Analyses have been re-established, and…
- Lots of progress in "taking them to the next level"
  - New techniques to better exploit the data
- Nothing unexpected about top turned up so far
  - Attacking from many sides, but need to squeeze harder with more data
- The top picture will get clearer and clearer in the coming years