Top-Quark Physics at the Tevatron

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U.S. DEPARTMENT OF ENERGY

Fermilab

Why Study the Top Quark?

- Fundamental constituent of the Standard Model (SM)

$$\textbf{quarks} \quad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\textbf{leptons} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

- Relatively unexplored… first observed in 1995

Why Study the Top Quark?

- Unlike its fellow quarks… it's very heavy

$$M_t \sim \text{Au atom} >> M_{b,c,s,u,d}$$

- Consequently
  - t --> Wb decay kinematically allowed
  - Decays before it hadronizes
  - Can study properties of the bare quark

- Since mechanism for EWSB couples to mass, top quarks may be good place to look for evidence of New Physics

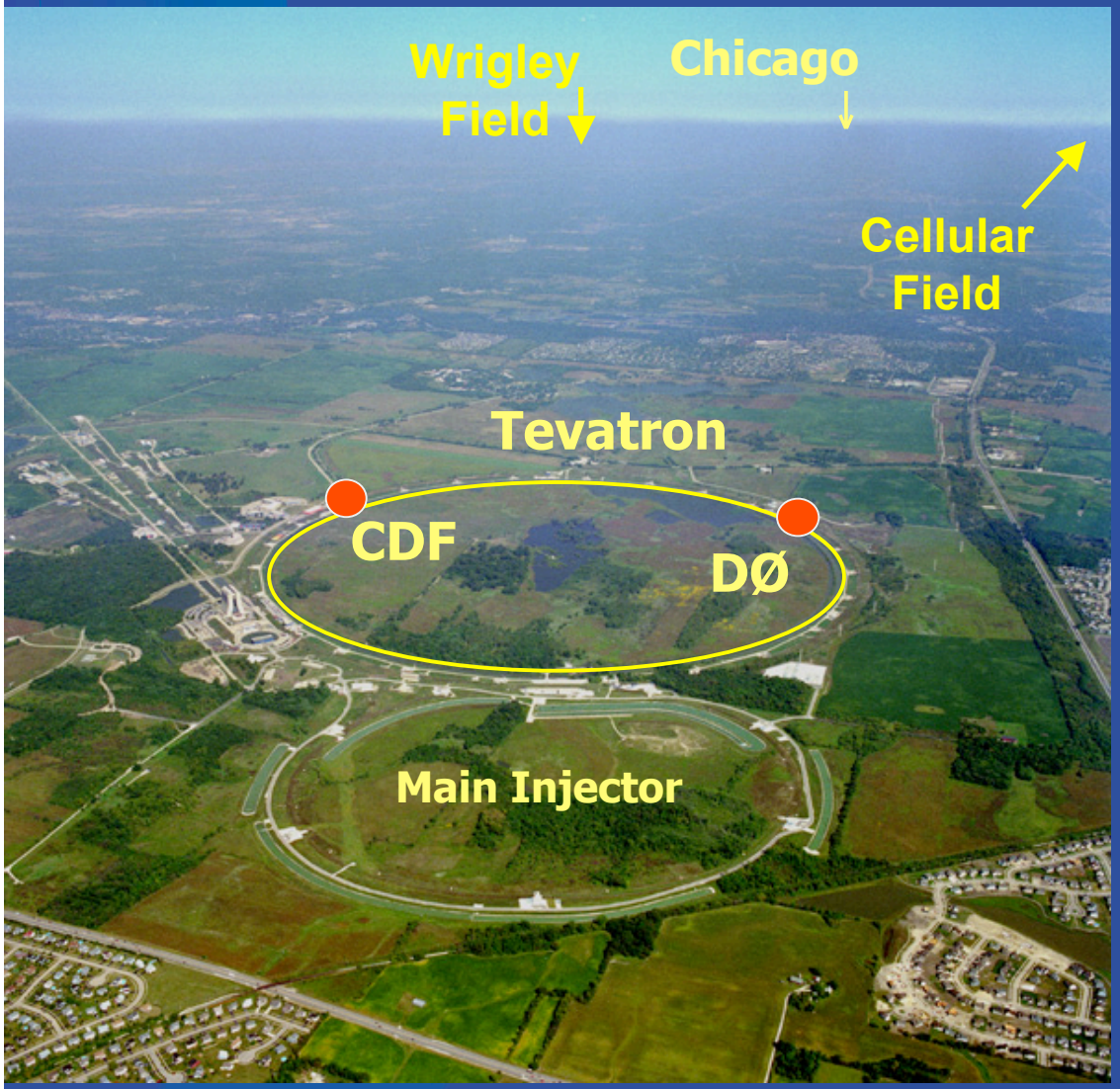
Physics using Top Quarks

- New Physics contributions
  - might affect top-quark **production**
  - might affect top-quark **decay**
  - might affect top-quark **properties**
  - might “contaminate” top-quark event samples
- Tevatron program explores all these possibilities

Physics using Top Quarks

- Exploring top-quark **production**
  - Single top production cross section
  - t-tbar pair production cross section
  - Forward-backward asymmetries
- Exploring top-quark **decay**
  - Helicity fractions of W-bosons from top decay
  - Limits on generic tWb couplings
- Exploring top-quark **properties**
  - Mass
- Exploring the tops for **direct evidence of NP**
  - Resonant t-tbar production, decays to H^+, t' or squarks hiding in t-tbar sample

Fermilab Tevatron

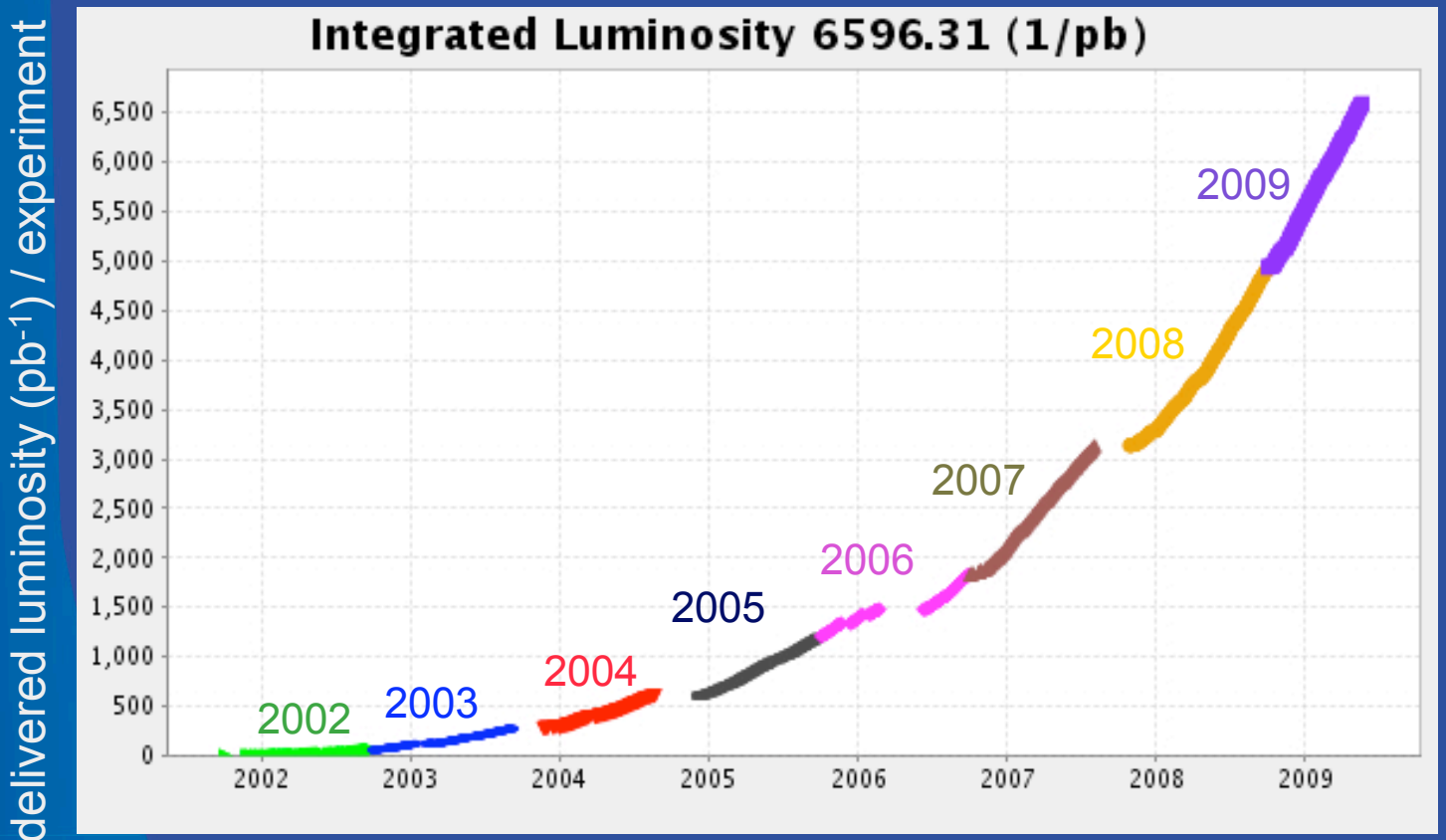


- $p\bar{p}$ collider E_{cm}=2 TeV
  (Only place that makes top)
- Run I 1990-1995
  (110 pb^{-1} / experiment)
- Run II 2001-2010
  (~9000 pb^{-1} / exp expected)
- Performing excellently

Tevatron Run I

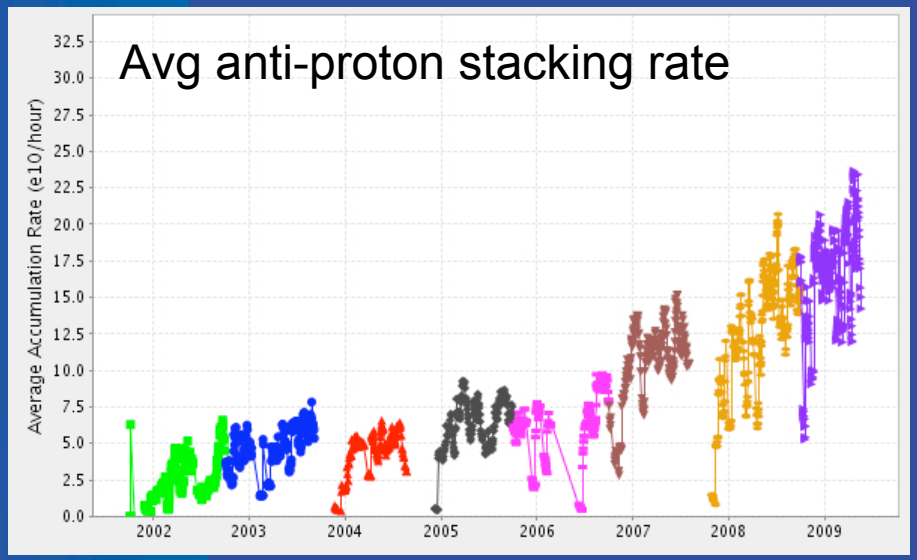
- Top Quark discovered in 1995
- CDF and D0 experiments
  - Each uncovered ~20 top quark events in 60 pb^{-1}
- With full Run 1 dataset
  - ~35 top quark events /exp
  - Afforded first glimpse
- These days, we reproduce Run 1 about every 2 weeks

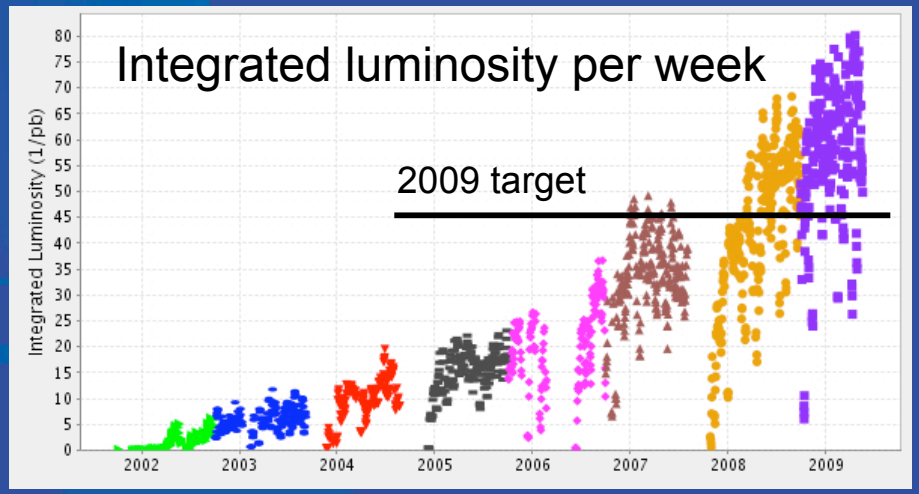
Tevatron Run II Performance



- Doubled data set each year for four years
- Expect 1500-2000 pb^{-1} per year in >2008

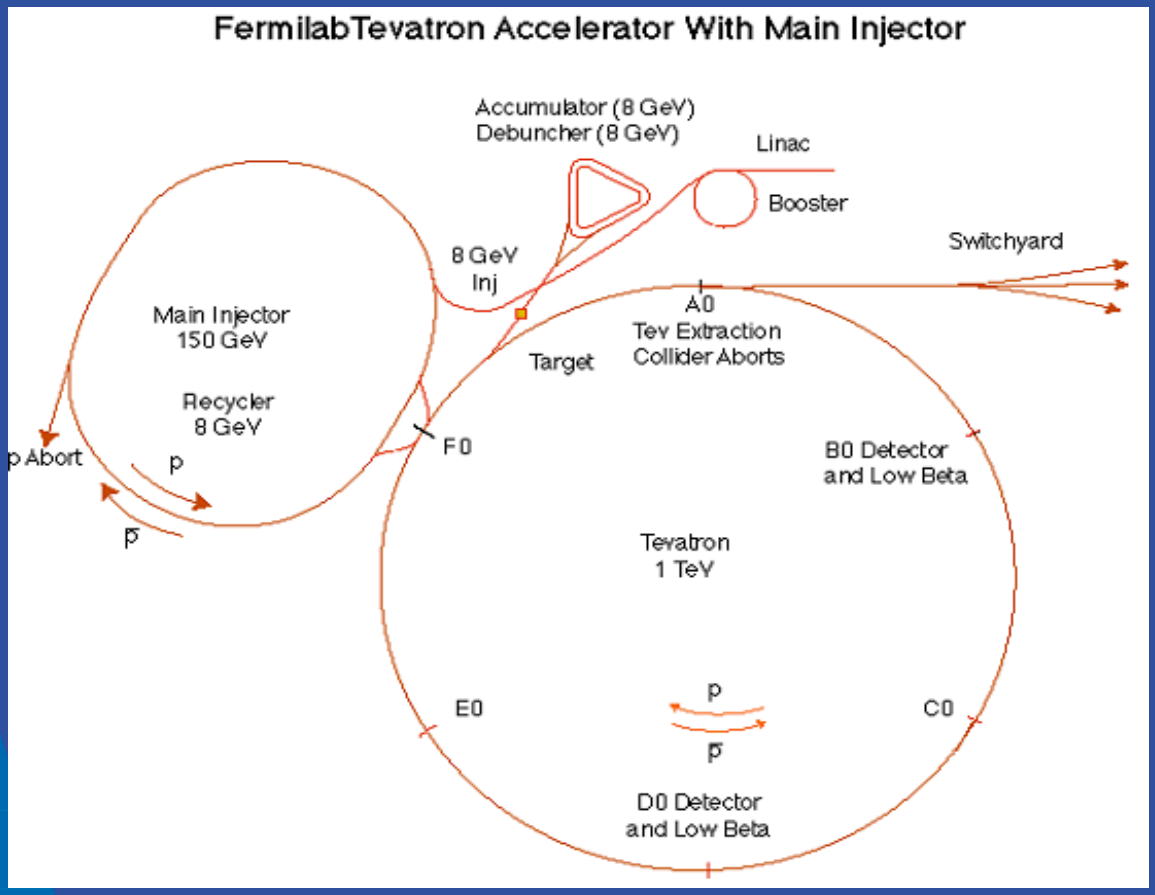
Tevatron Performance





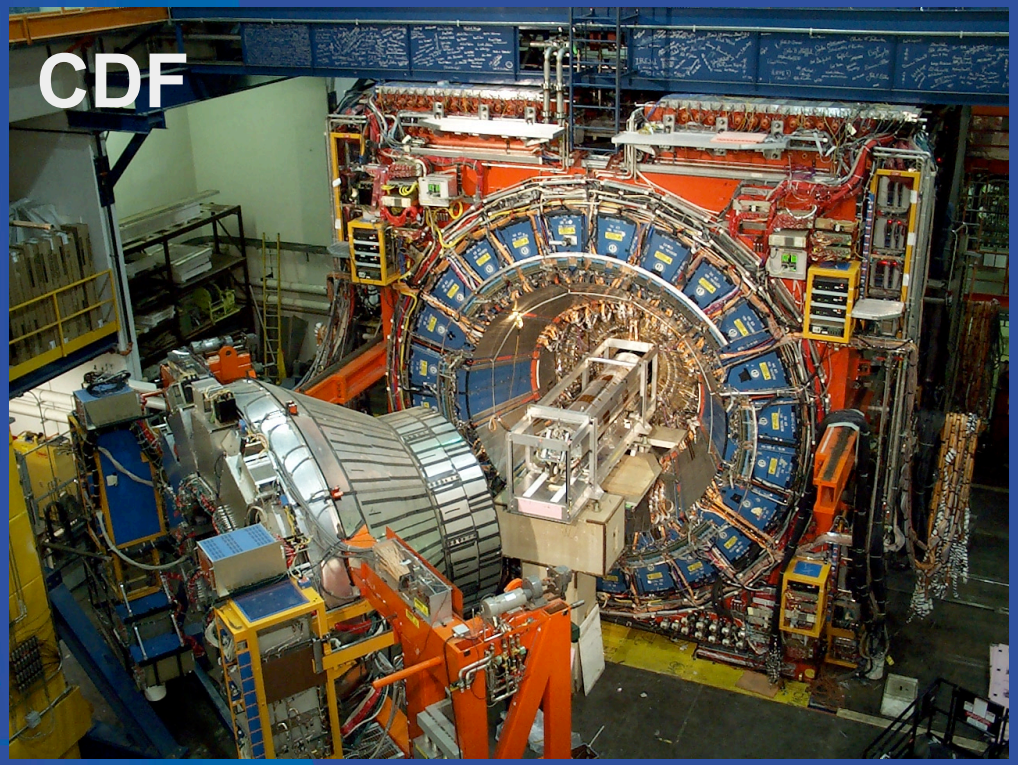
- Anti-Protons
  - Doubled stacking rate over last two years
  - No longer limiting factor
- Complex up time
  - 20 years old
  - Exceeding original design specs by x300
  - Requires constant vigilance

Tevatron Accelerator Complex



- Need entire accelerator complex working well in order to deliver high luminosity stores consistently

Tevatron Experiments

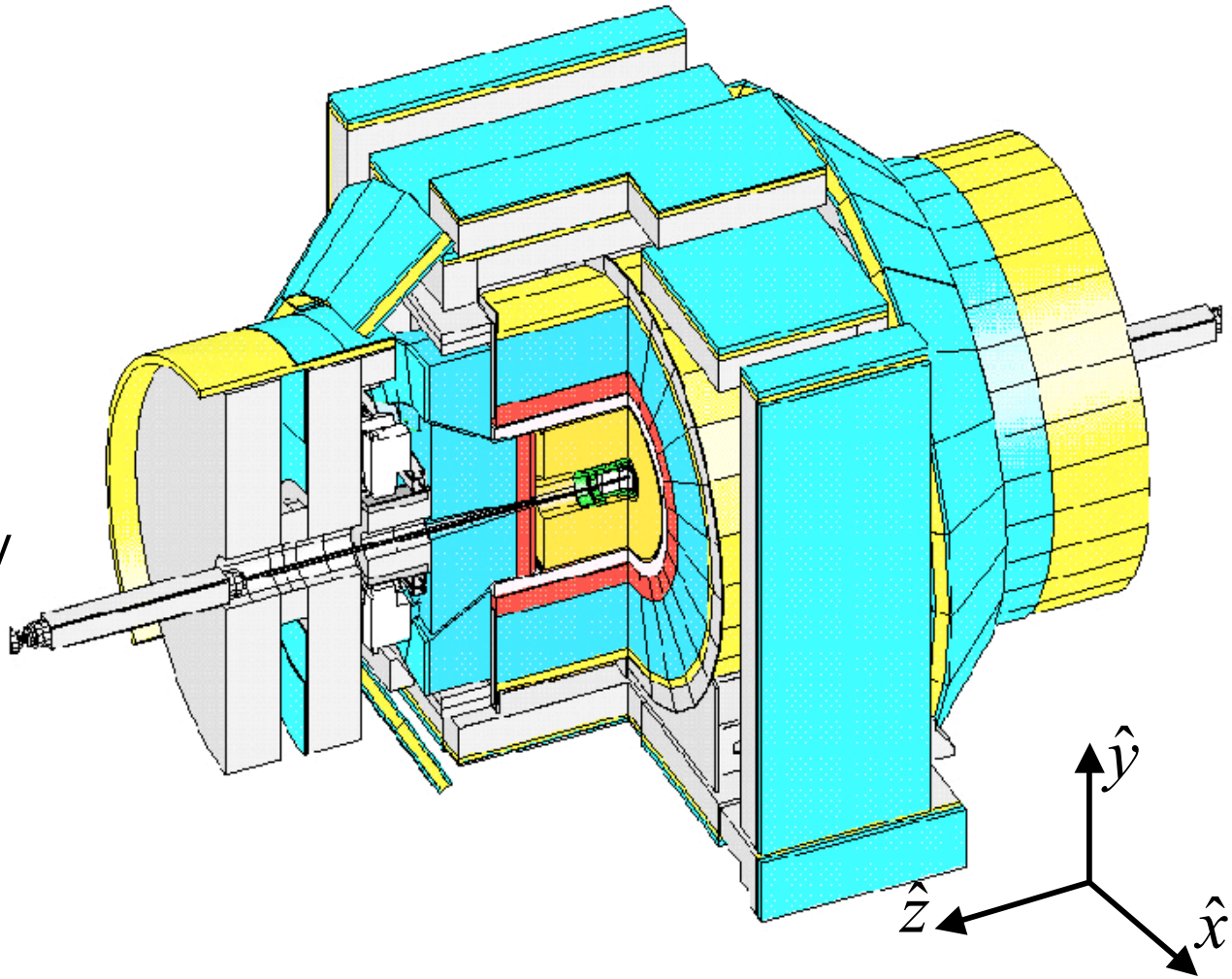


- Two Experiments: CDF and D0
  - Multipurpose collider detectors
  - Large international collaborations, 600+ members each

CDF detector

Features:

- Silicon tracking for precision vertexing
- Large radius drift chamber (r=1.4m)
- 1.4 T solenoid
- Projective calorimetry ($|\eta| < 3.5$)
- Muon chambers ($|\eta| < 1.0$)
- Particle identification
- Silicon Vertex Trigger

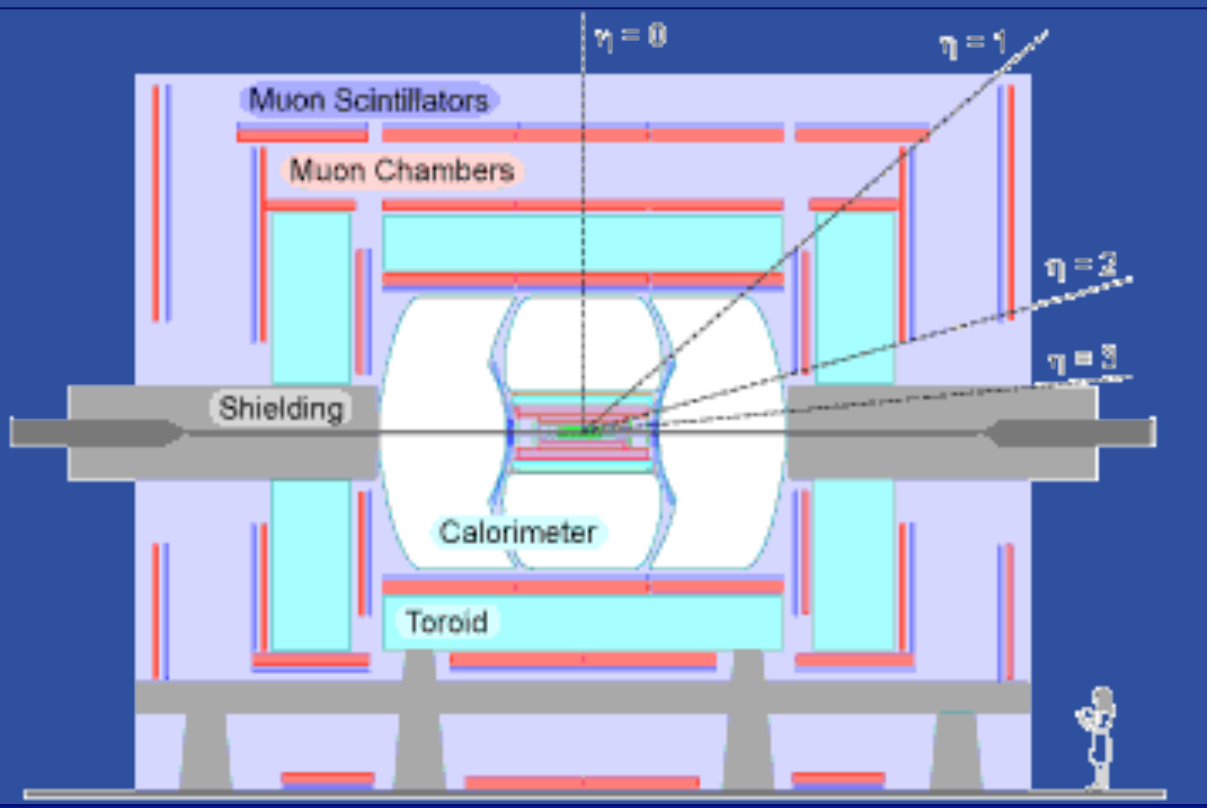


$$\eta = -\ln(\tan(\theta/2))$$

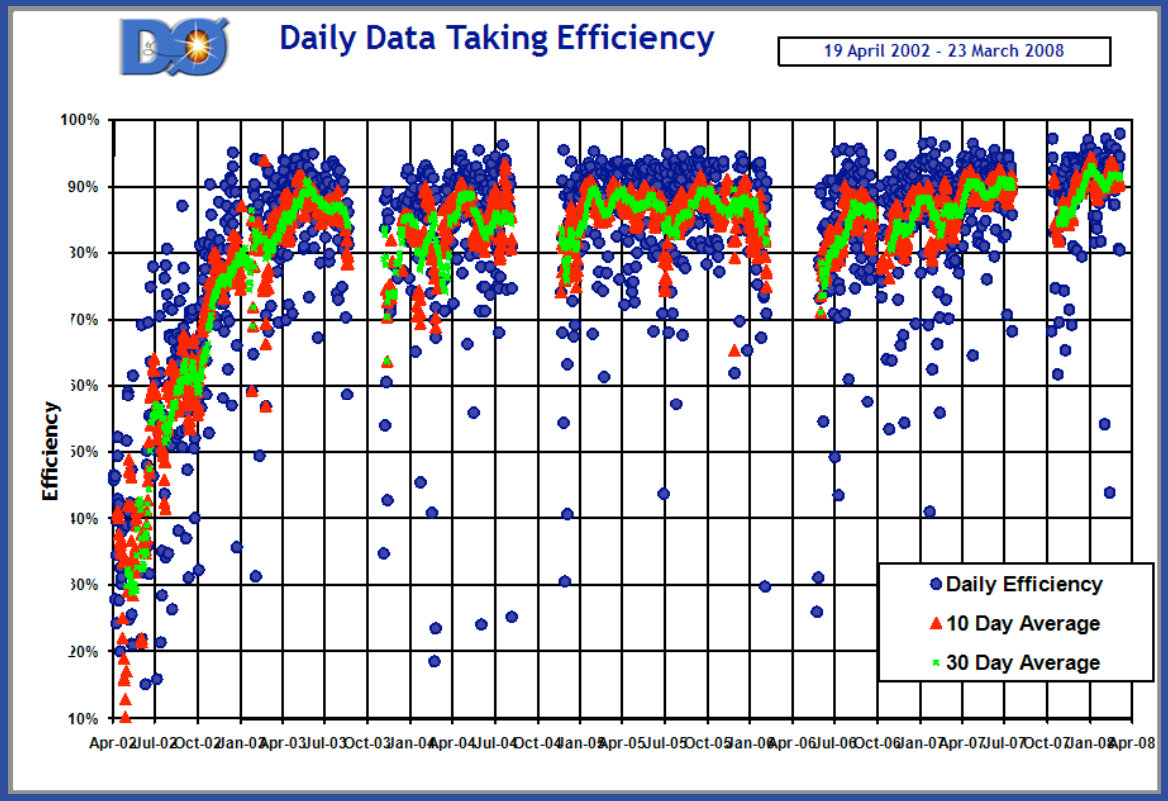
DZero (D0) Detector

Features:

- Silicon tracking for precision vertexing
- Outer fiber tracker (r=0.5m)
- 2.0 T solenoid
- Hermetic calorimetry ($|\eta| < 4$)
- Muon chambers ($|\eta| < 2.0$)
- New trigger and more silicon in Summer 2006 (Run2b)



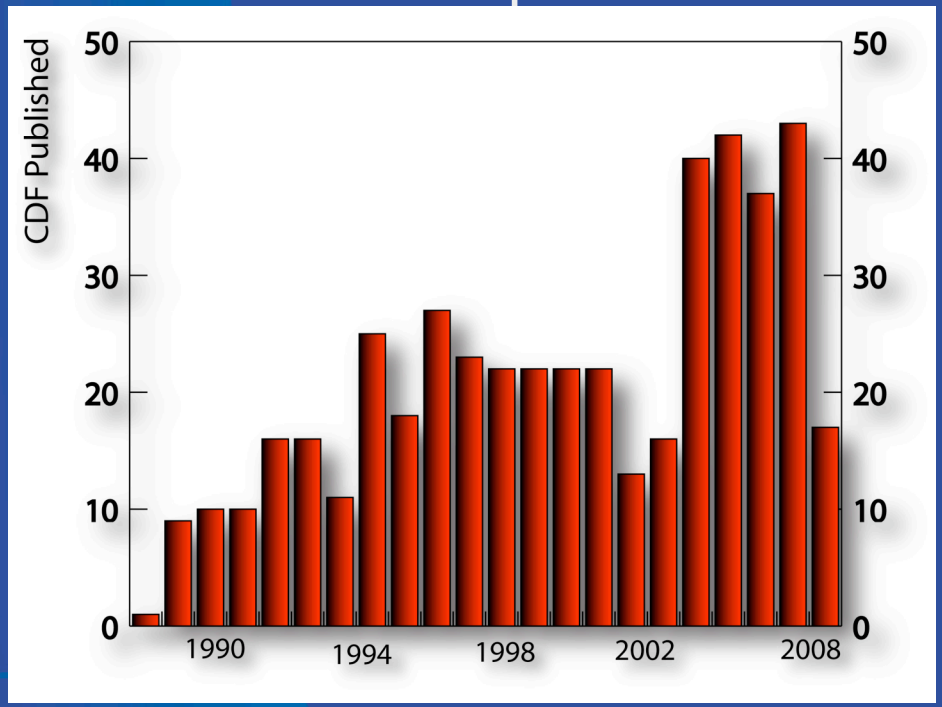
Detector Performance



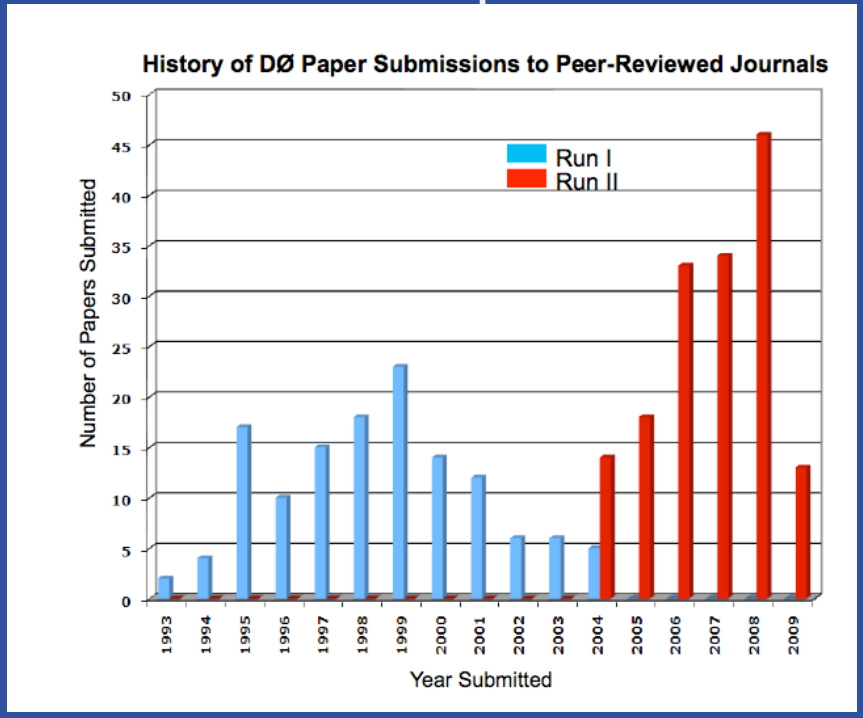
- CDF&D0: Stable operations since 2002
- Experiments keeping-up with luminosity
- No known problems for foreseeable future

Physics Productivity

CDF Papers

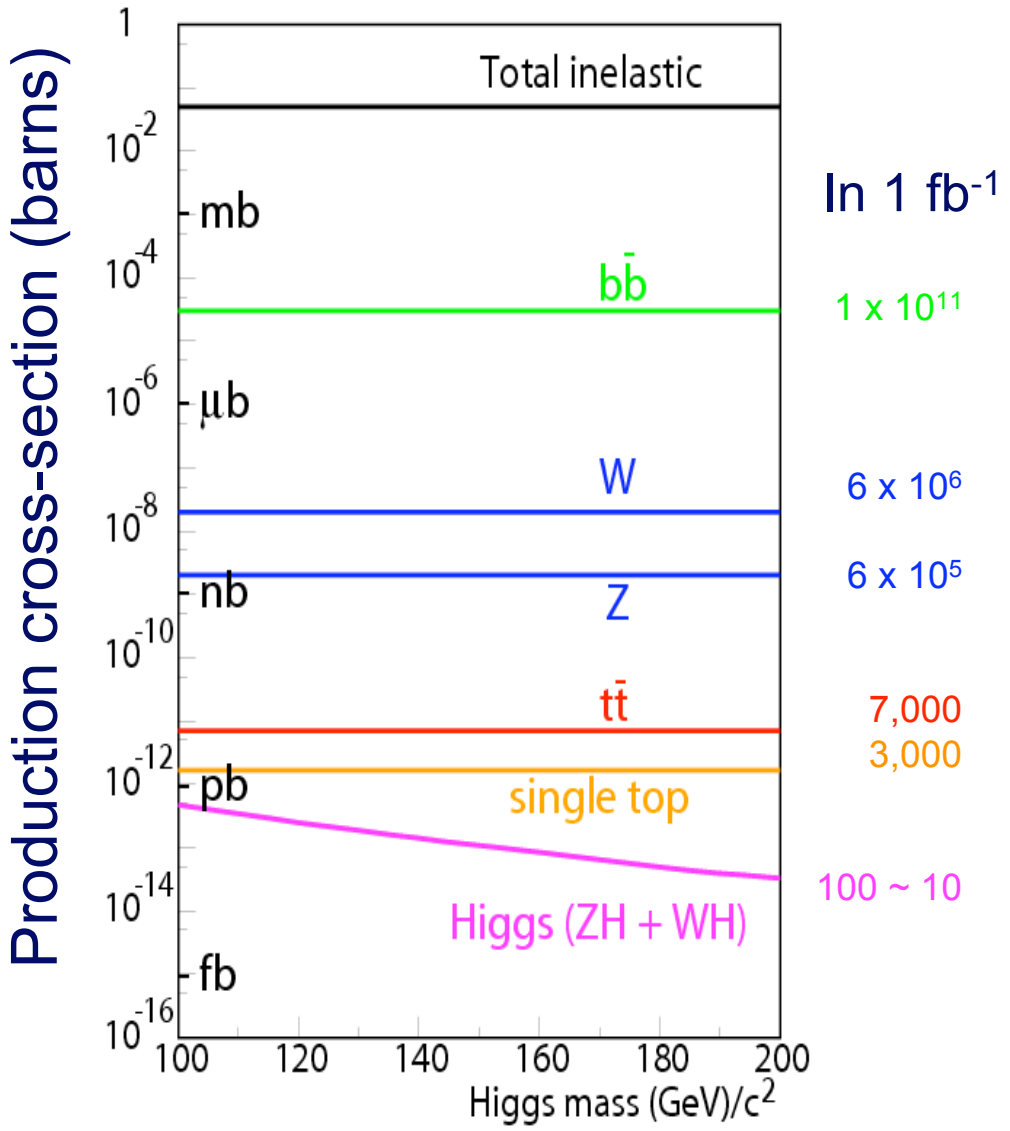


D0 Papers



- A Tevatron Publication every 5 days
- CDF and D0 each publishing ~35 papers / year

Physics Program

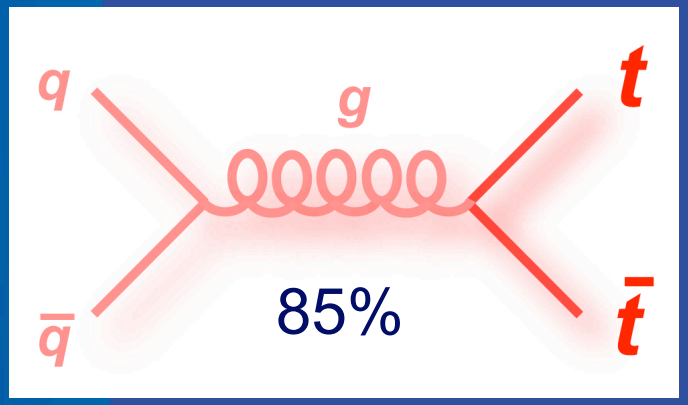


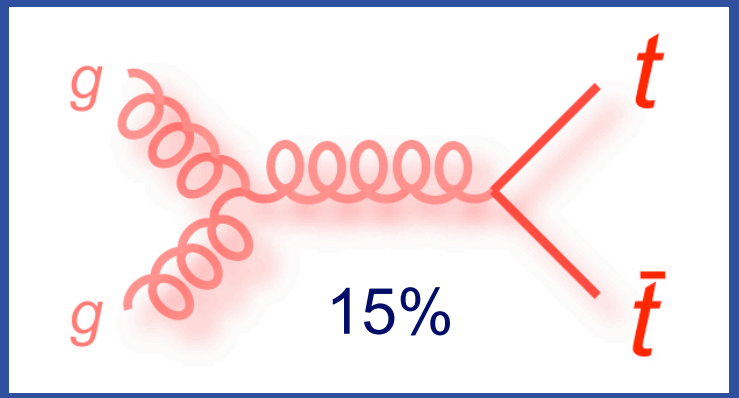
- Tevatron the only place that makes top… but top not the only thing it makes!

- QCD
- Heavy Flavor
- Electroweak
- Top Quarks
- New Phenomena

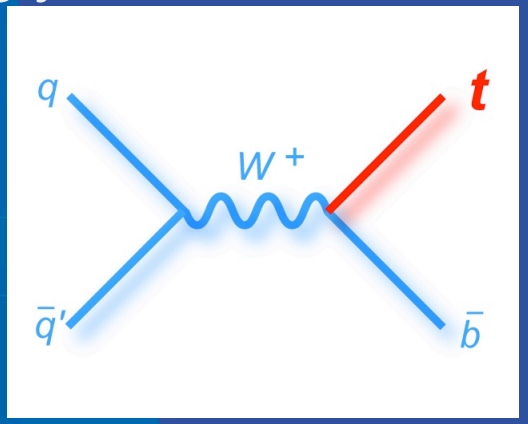
Top Quark Production

- In top+anti-top (ttbar) pairs via strong interactions:

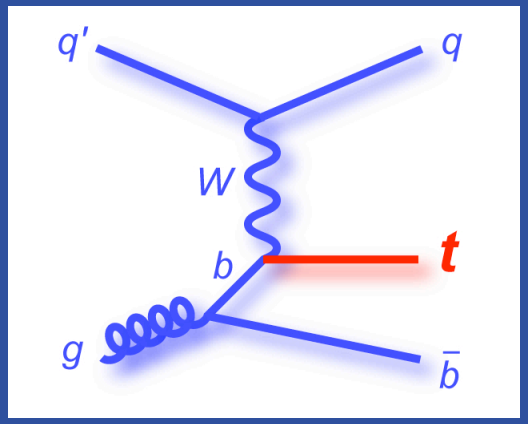




- Singly via electroweak interactions:



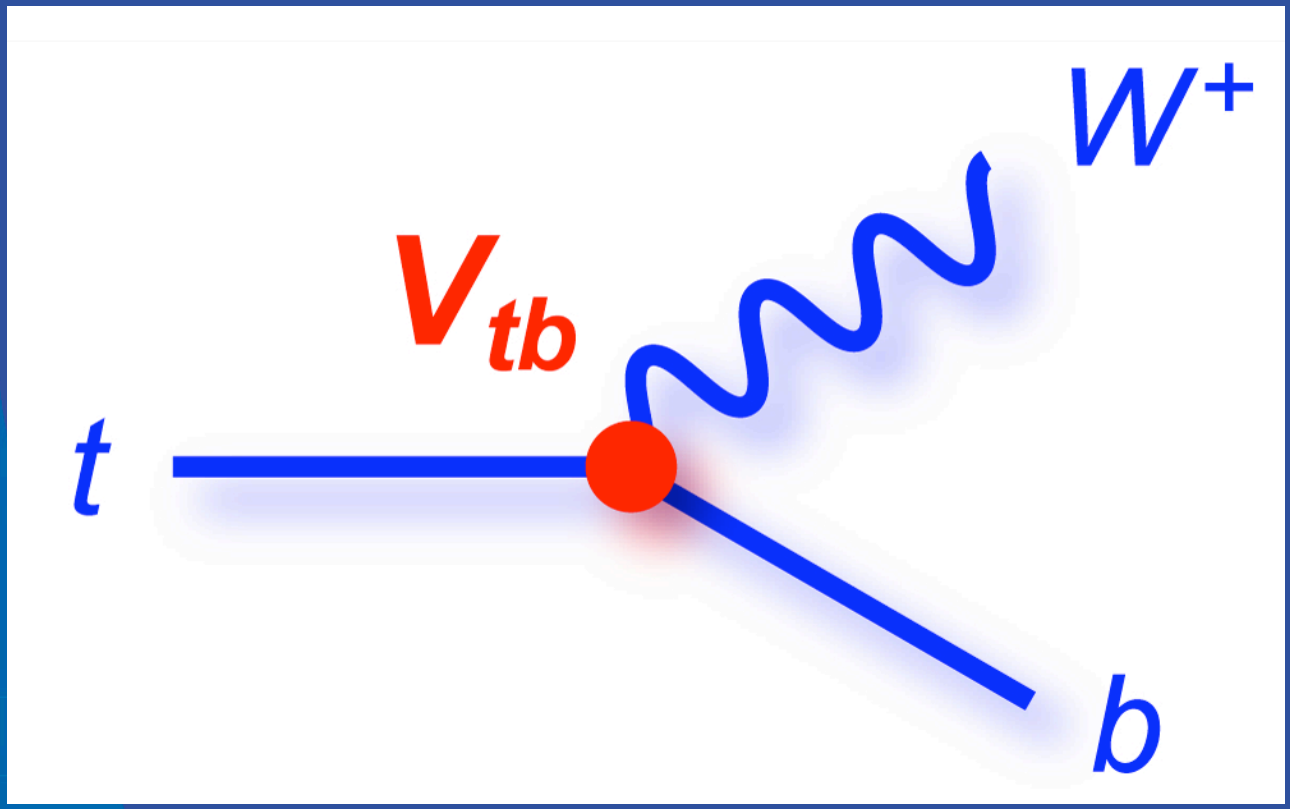
33%



67%

Top Quark Decay

- Since $M_t > M_W + M_b$ and $V_{tb} >> V_{ts}, V_{td}\ldots$



BR(t-->Wb)~100%

Decay Final States

Dictated by W-decays

- For t-tbar Pair events
  - Dilepton (DIL): $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow \ell\nu\,\ell\nu\,b\bar{b}$ (10%)
  - Lepton+jets (LJT): $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow \ell\nu\,q\bar{q}'\,b\bar{b}$ (44%)
  - All jets (AJT): $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow q\bar{q}'\,q\bar{q}'\,b\bar{b}$ (46%)

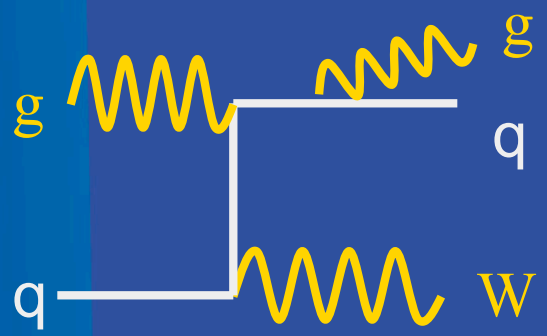
- For Single top events
  - s-channel: $tb \rightarrow W^+b\,\bar{b} \rightarrow \ell\nu\,b\,\bar{b}$ (11%)
  - t-channel: $tq(\bar{b}) \rightarrow W^+b\,q(\bar{b}) \rightarrow \ell\nu\,b\,q(\bar{b})$ (22%)

(overwhelming background prevents using hadronic W decays for single top)

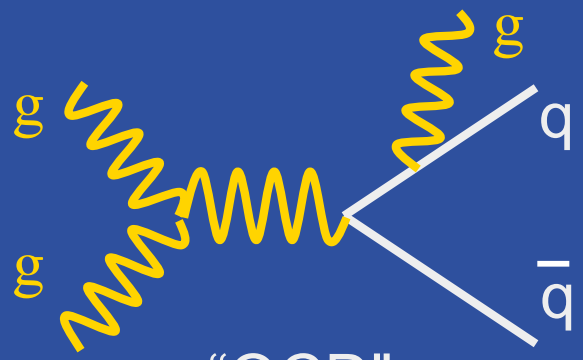
Experimental signatures

- For t-tbar Pair events
  - DIL: 2 energetic leptons + 2 b-jets + missing E (νs)
  - LJT: 1 energetic lepton + 2 b-jets + 2 jets + missing E
  - AJT: 2 b-jets + 4 other jets
- For Single top events
  - s : 1 energetic lepton + 2 b-jets + missing E
  - t : 1 energetic lepton + 1 b-jet + 1 other jet + missing E
- B-jet identification ("b-tagging") crucial
  - Exploits long lifetime of b quark and the precision vertexing capabilities from the silicon trackers

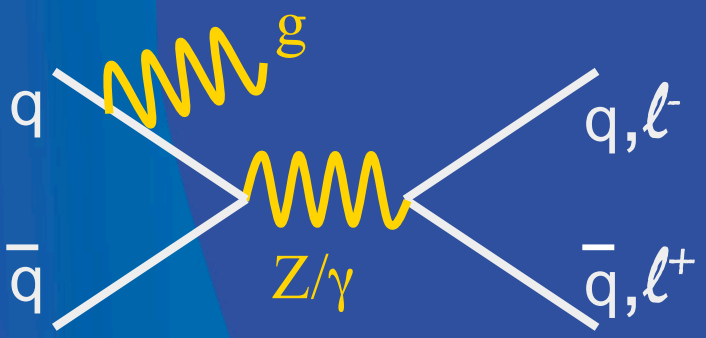
Backgrounds to Top



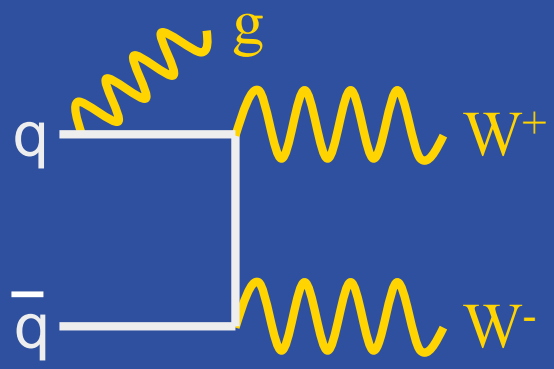
"W+jets"



"QCD"



"Drell-Yan"



"Diboson"

- Compared to top events, the backgrounds
  - Have fewer jets and almost no b-jets; are less energetic

t-tbar Pair vs Single Top Production

- Cross section:

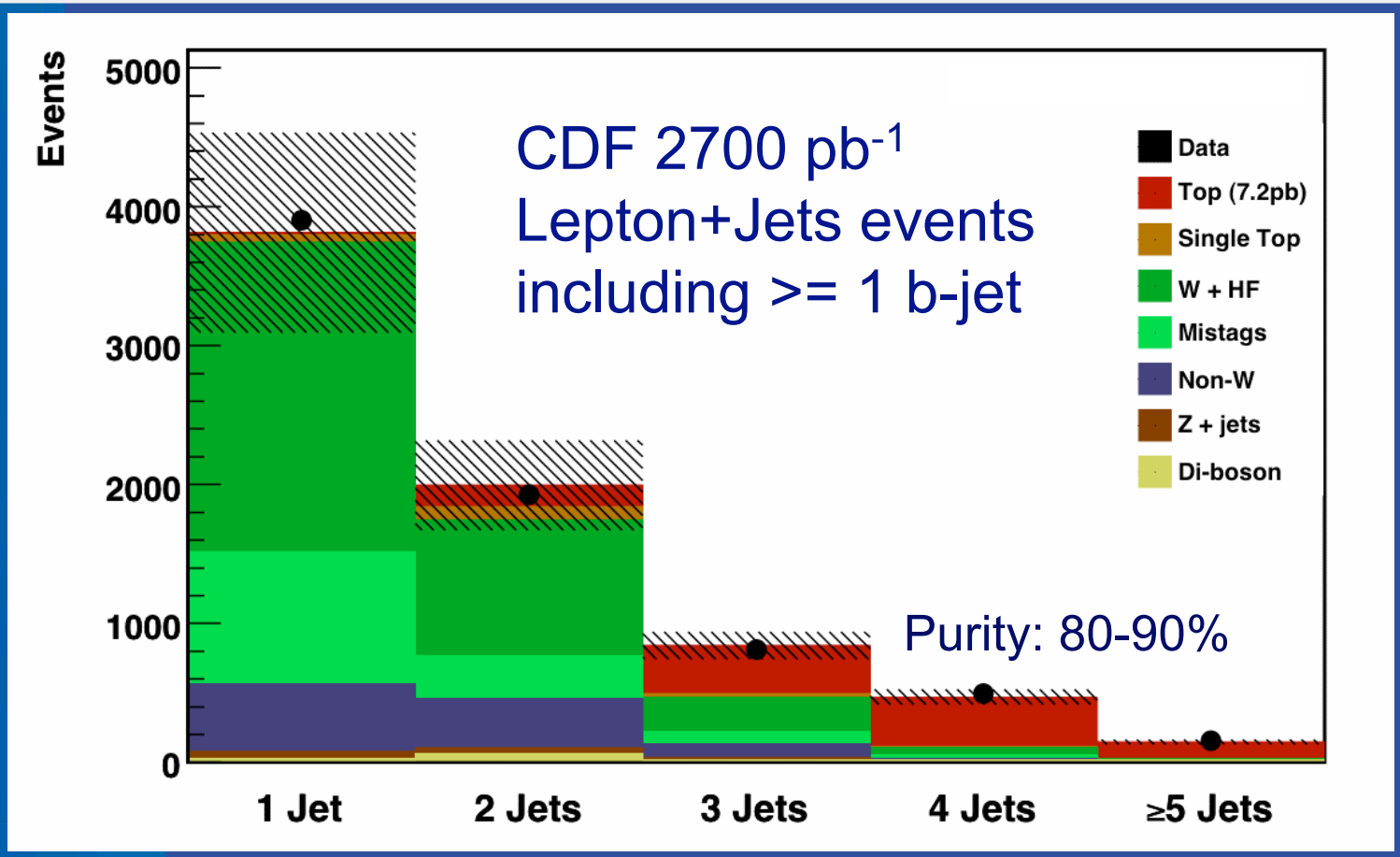
σ(t-tbar)~7pb σ(single-t)~3pb

- Experimental signature for t-tbar more striking
  - t-tbar Pair: 2 W bosons, 2 high energy b-jets
  - Single-top: 1 W boson, 1 high energy b-jet, 1 other jet

- Most the present measurements use t-tbar events

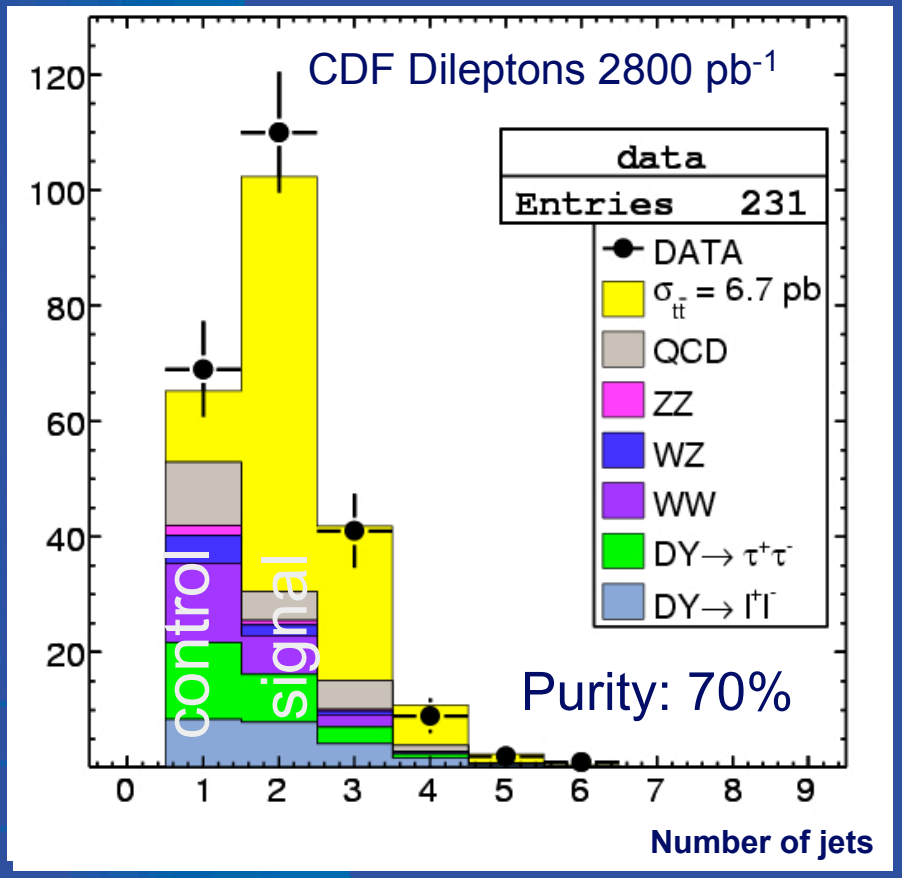
Exploring Top-Quark Production

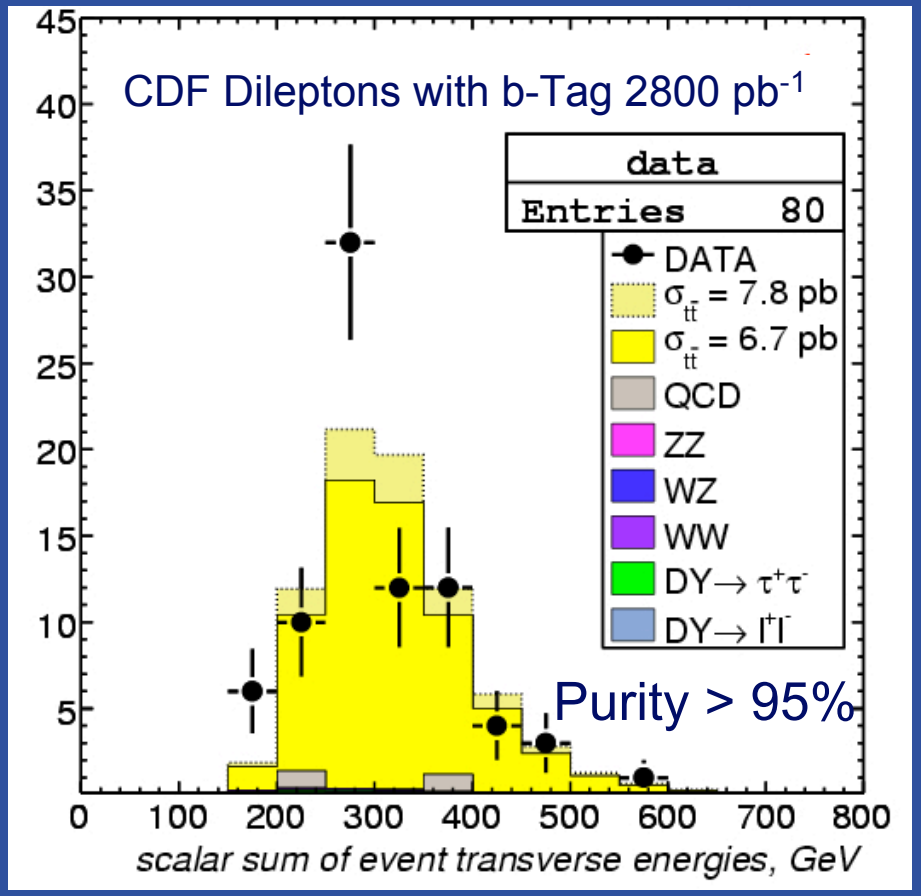
σ(t-tbar) using LJT channel



- Sample composition well understood

σ(t-tbar) using DIL channel

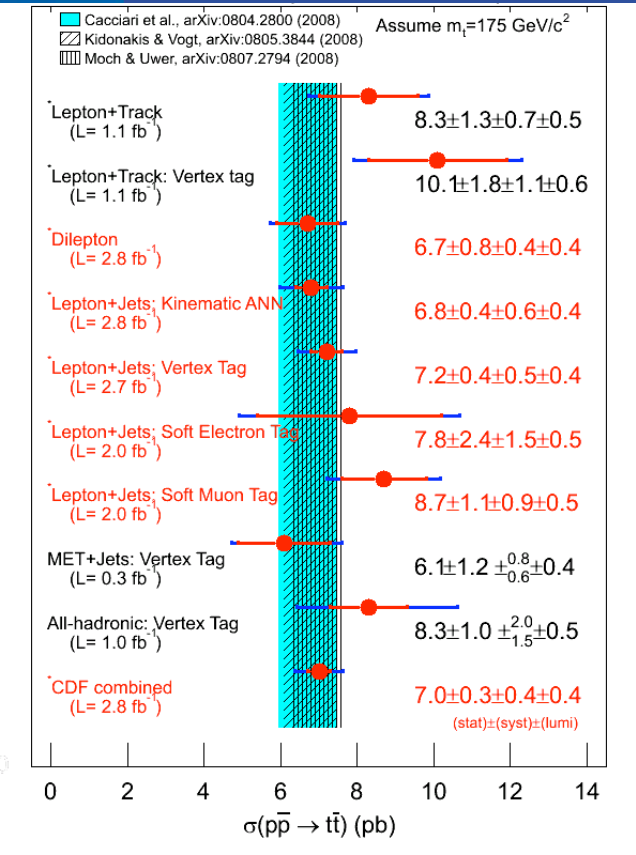




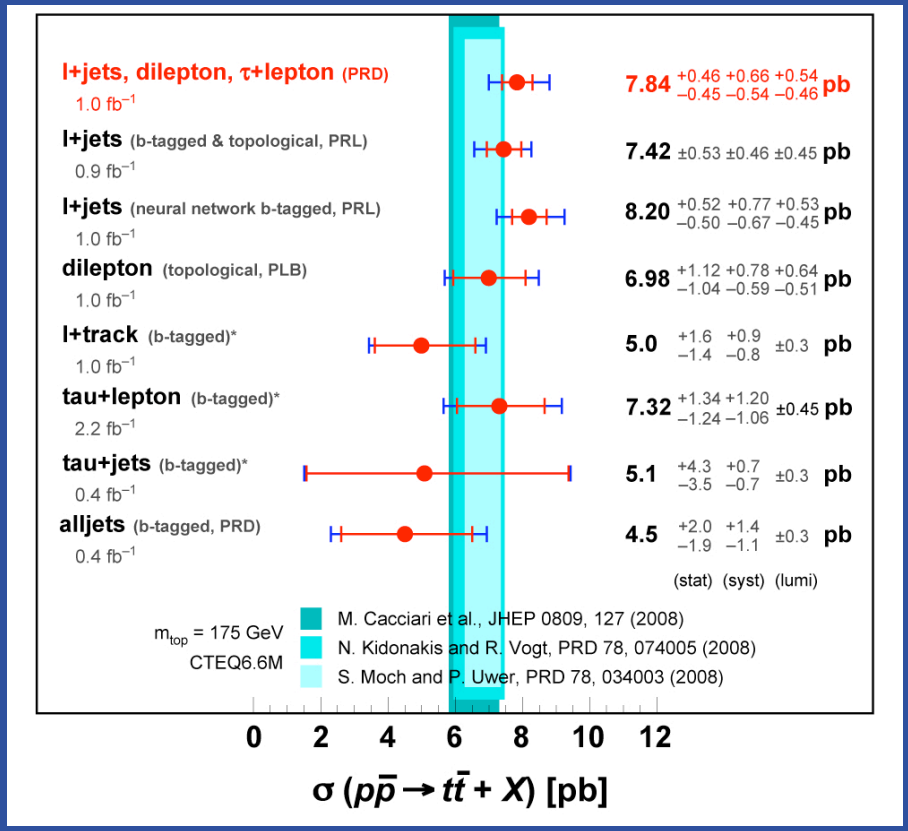
- Sample composition well understood

σ(t-tbar) Results

CDF Results



D0 Results



- Consistent across channels, methods, CDF/D0

σ(t-tbar) Results

- In combination

$$\sigma\left(p\bar{p} \rightarrow t\bar{t}\right) = 7.0 \pm 0.3 \pm 0.4 \pm 0.4 \text{ pb}$$

(sta) (sys) (lum)

- Experiment: $\Delta\sigma/\sigma$ ~ 9% Theory: $\Delta\sigma/\sigma$ ~ 11%

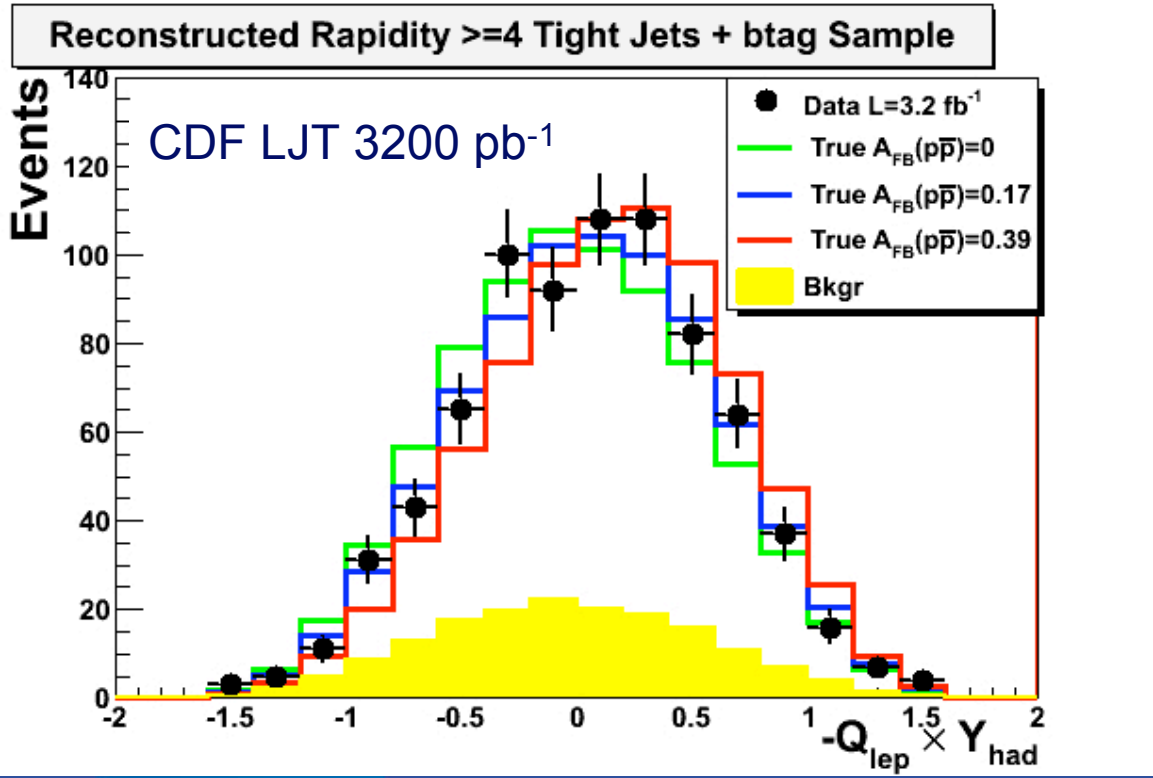
- Dominant experimental uncertainties:

  b-tag acceptance, luminosity, W+bjet background

  - Measuring relative to σ(Z) reduces $\Delta\sigma/\sigma$~8%
  - Limited improvement expected with additional data

Forward Backward Asymmetry

- At NLO in QCD a small asymmetry arises in proton-antiproton production of t-tbar pairs
  - New Physics contributions can significantly increase it



Theory:

$$A_{FB}^{p\bar{p}} = (5 \pm 2)\%$$

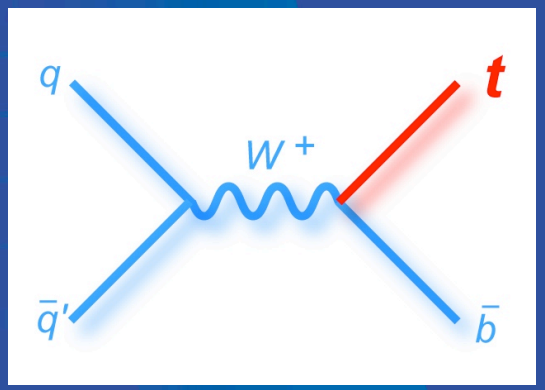
Experiment:

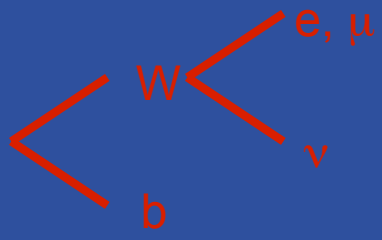
$$A_{FB}^{p\bar{p}} = (19.3 \pm 6.5_{stat} \pm 2.4_{syst})\%$$

Consistent with the Standard Model

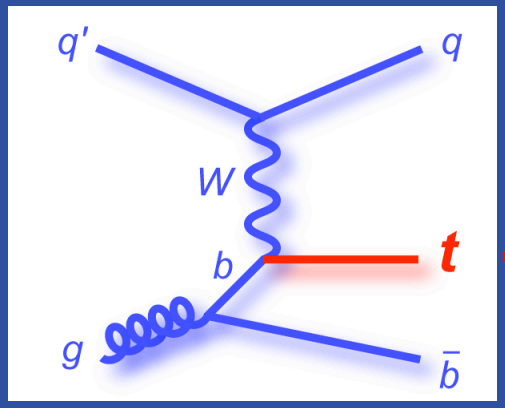
Single Top Production

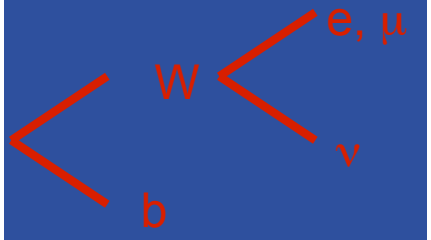
- Electroweak production of top quarks
  - Depending on M_t and E_{cm} could have been dominant
  - Offers direct, model-independent probe of V_{tb}
- Experimental signature is very challenging
  - 1 energetic lepton, 1 b-jet, 1 other jet, missing E (ν)





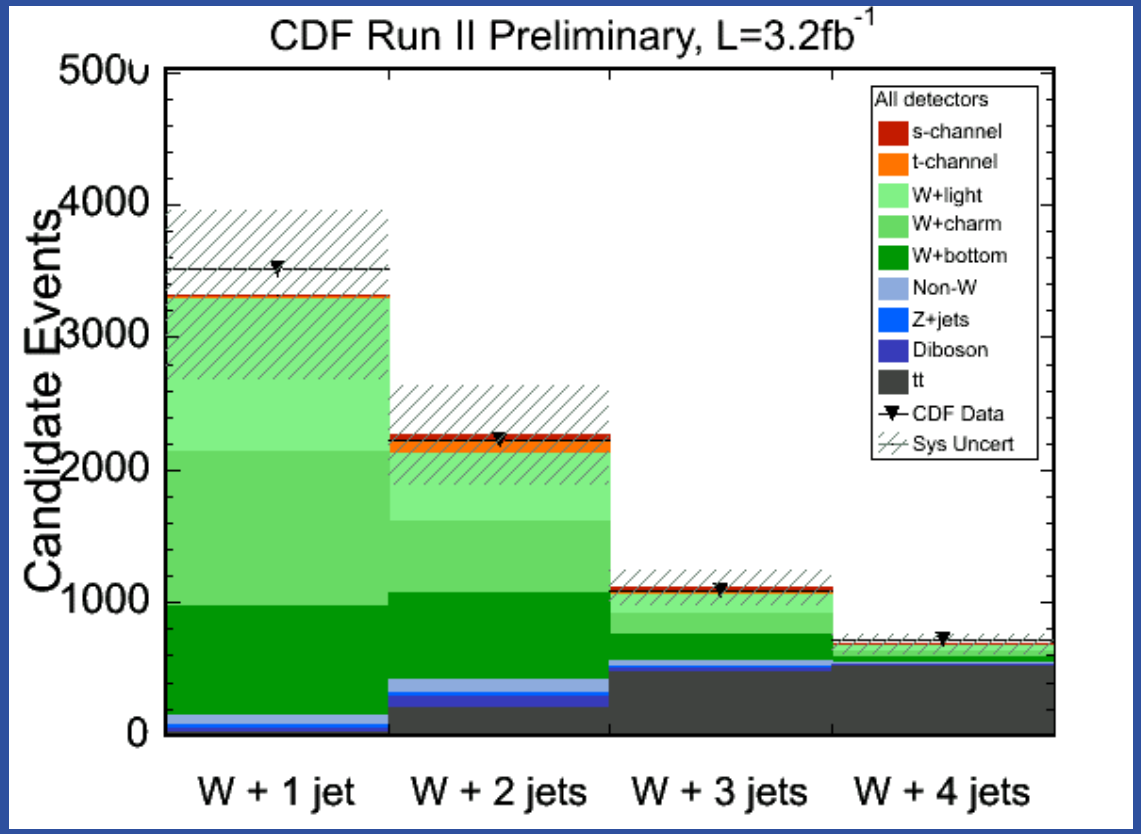
s-channel (tb)





t-channel (tqb)

Single Top Production



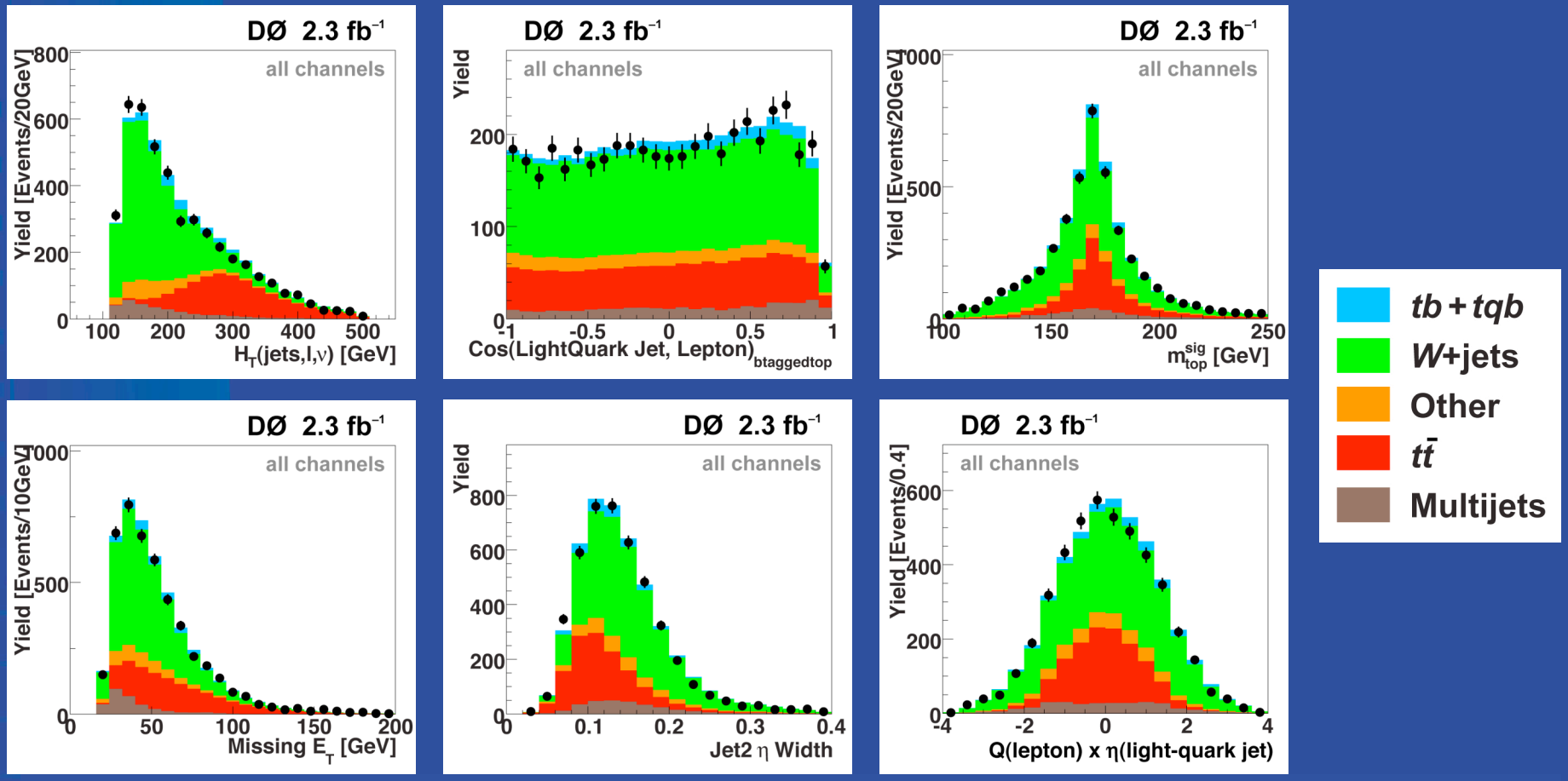
- $N_{single\text{-}top} < \Delta Bgd(syst)$
  - Counting experiment won't work
  - Requires more sophisticated techniques

Single Top Production

- Multiple Multivariate (MV) algorithms employed
  - Neural Networks, Boosted Decision Trees, Matrix Element Discriminates, Likelihood Ratios, …
  - Comparison offers consistency cross-check
  - Combination offers improved sensitivity
- MV Techniques in a nutshell
  - Identify a set of input variables, each offering some discrimination of signal from background
  - Model those distributions separately for signal events and background events
  - Using the collection of S and B distributions, train your MV algorithm to preferentially identify signal events

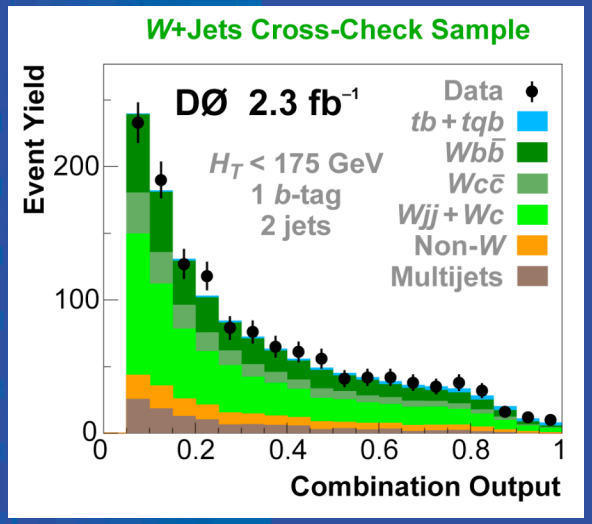
    e.g. by exploiting correlations in the multidimensional space

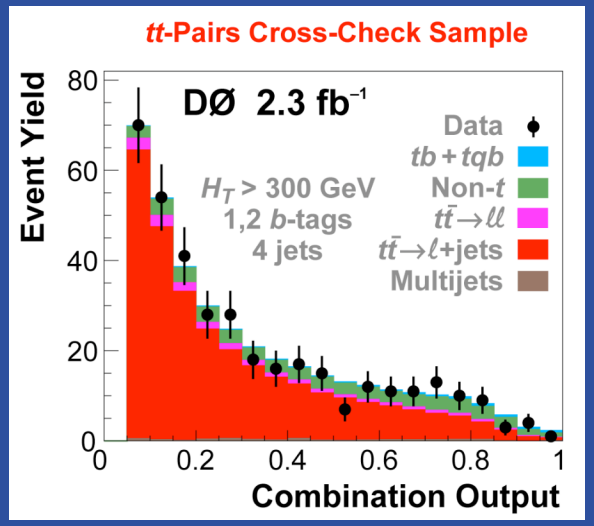
Single Top Production

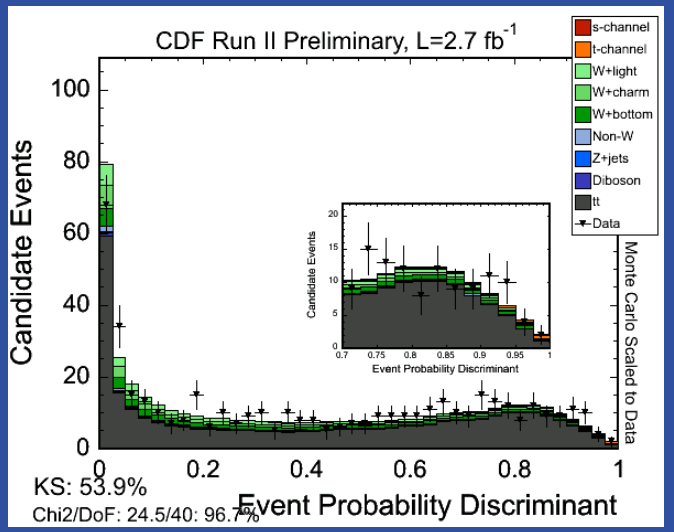


- Validation of Background modeling important
  - Compare background model to background-dominated data control samples for **each input distribution**

Single Top Production

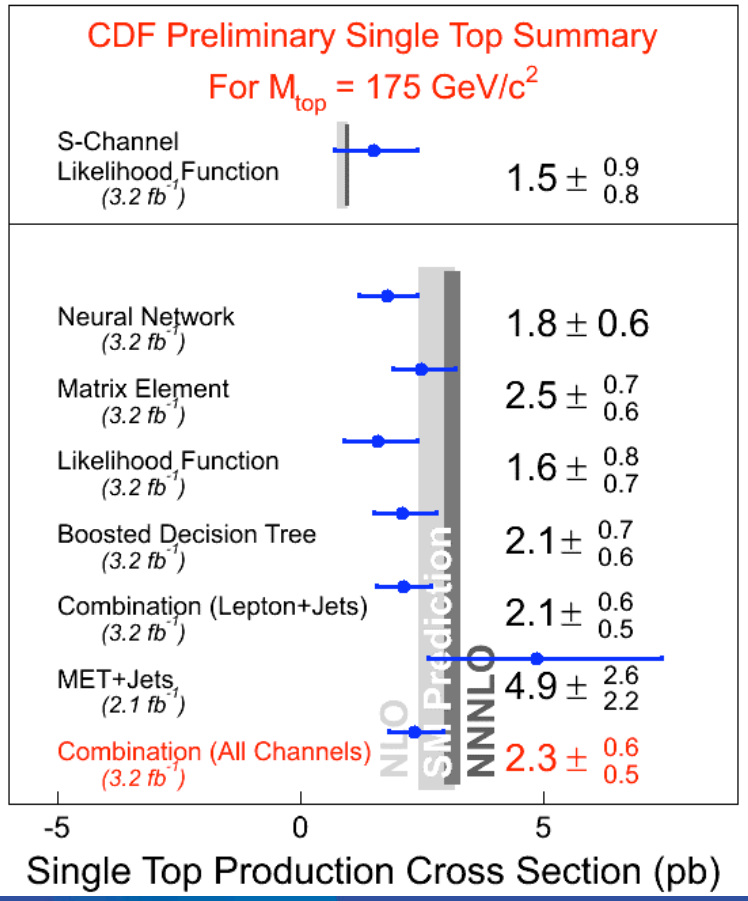


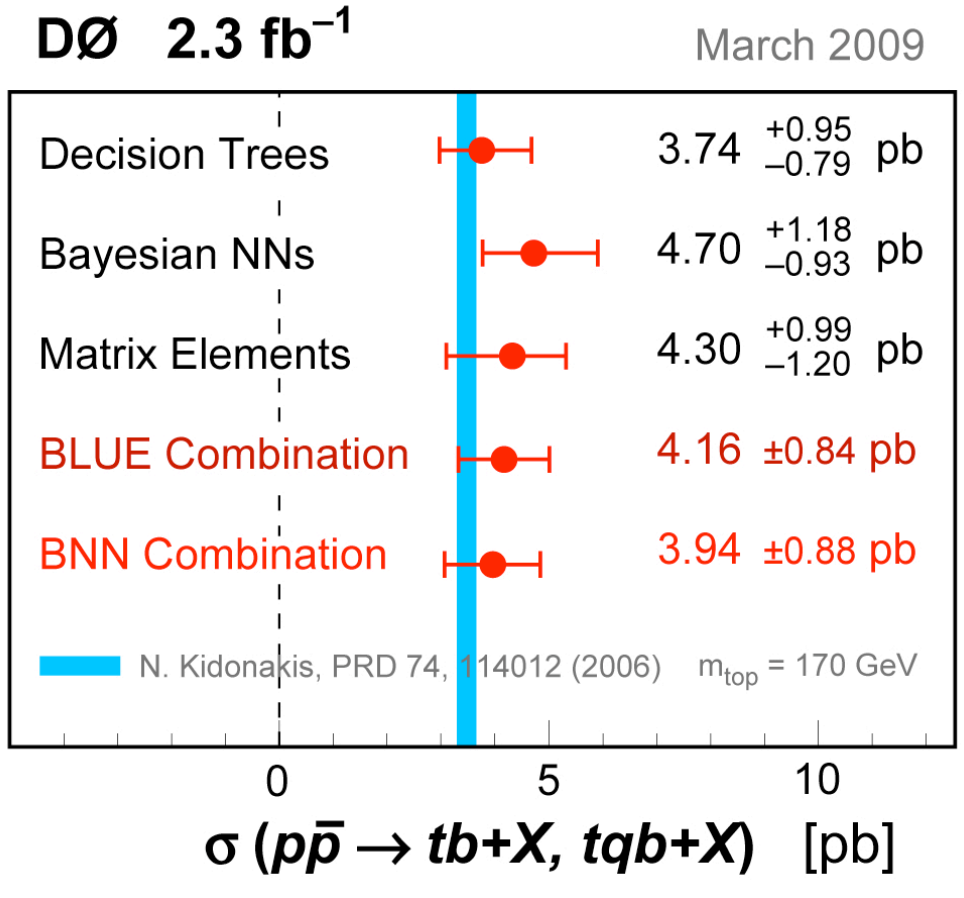




- Validation of Background modeling important
  - Compare background model to background-dominated data control samples for each **MV output distribution**
- For Discrepancies either re-weight model to reproduce data or inflate systematics to cover difference between data-model

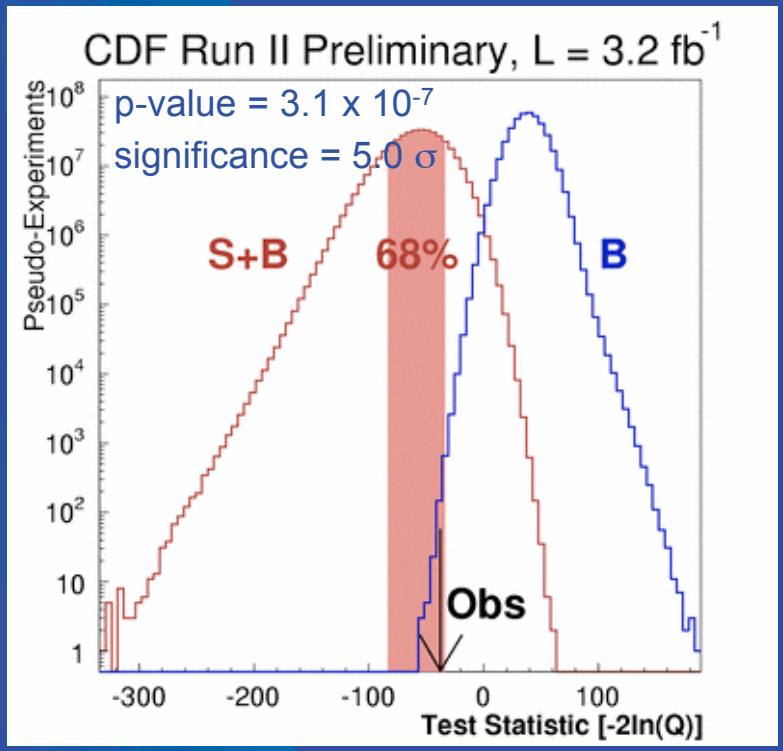
Single Top Production

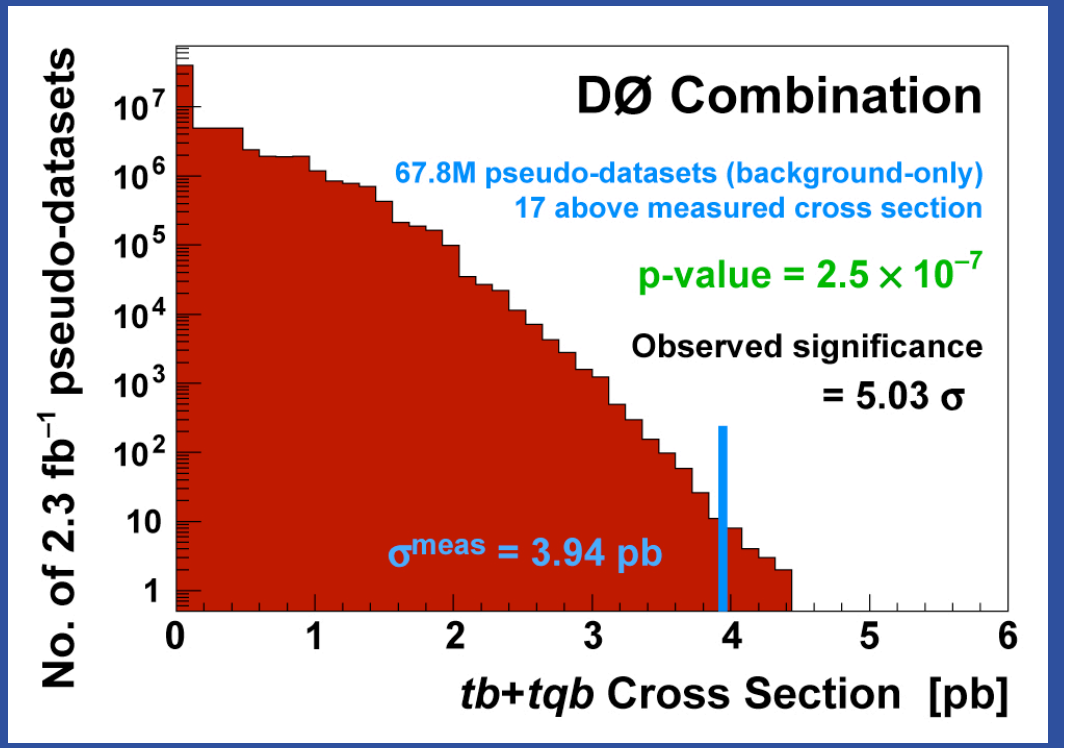




- The various MV methods give consistent results

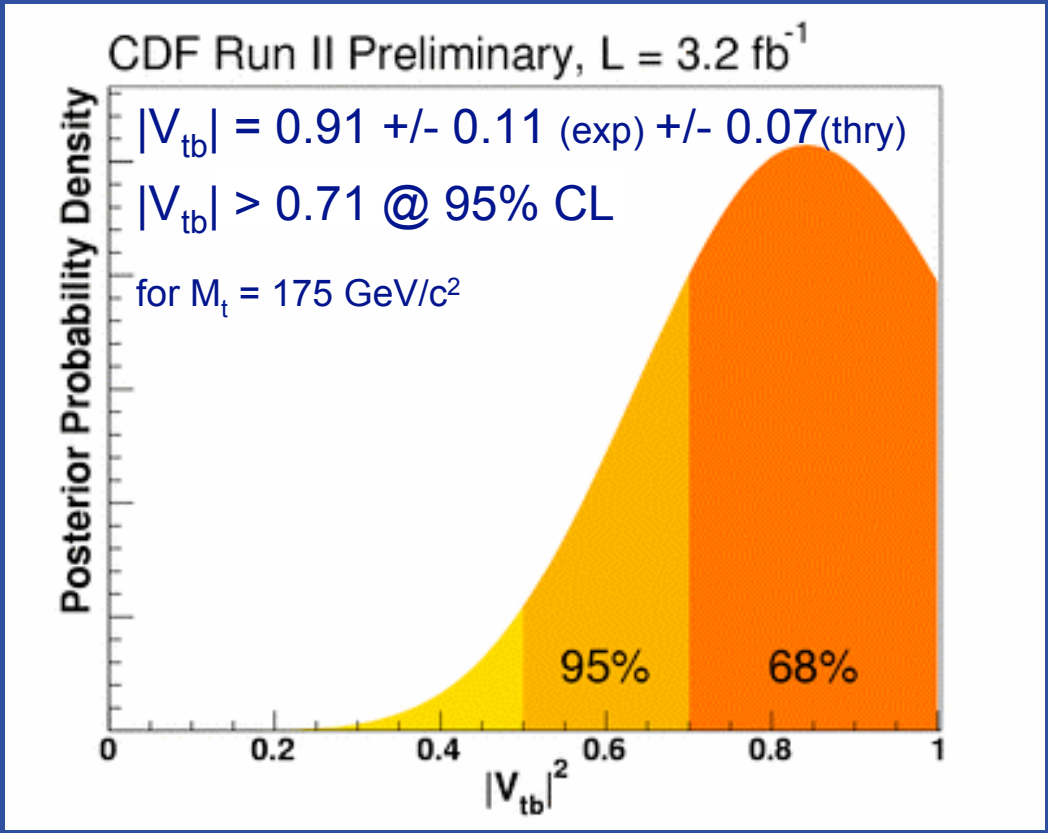
Single Top Quark Production





- Combined to give best sensitivity
  - CDF and D0 both report >5σ observation Mar-2009

Single Top Quark Production



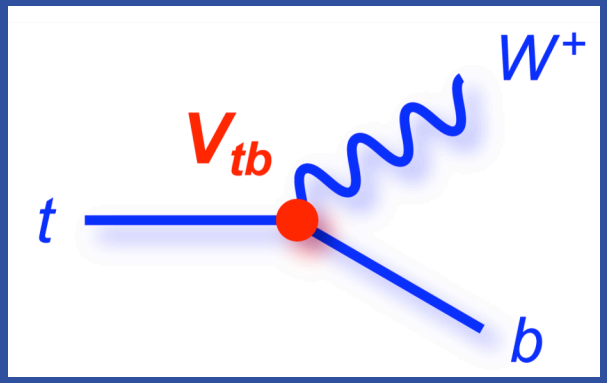
(D0 has very similar result with similar sensitivity)

- Best model-independent determinations of V_{tb}

Exploring Top-Quark Decay

Probing the tWb Vertex

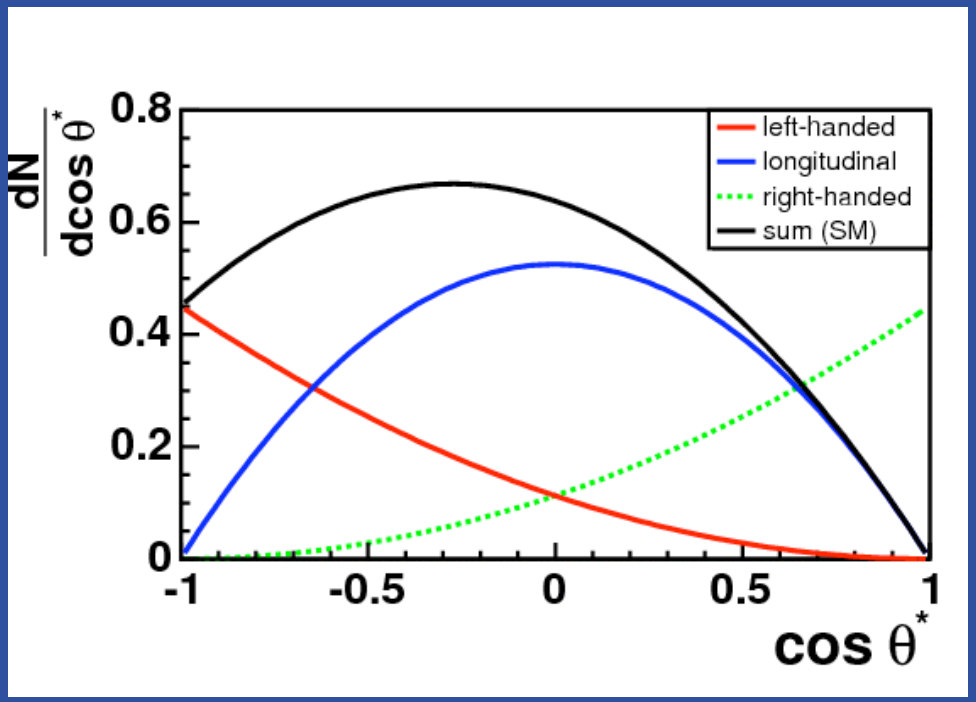
- Top-quark decays afford a direct probe of the tWb vertex (at large q^2)



- In Standard Model helicity of W-boson specified
  - Longitudinal fraction (f_0) ~ M_t^3 = 0.7
  - Left-handed fraction (f_-) ~ M_t = 0.3
  - Right-handed fraction (f_+) supressed ~ 10^{-4}

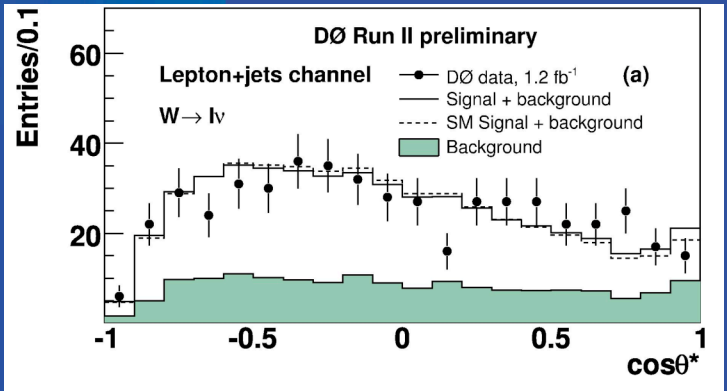
W-boson Helicity Fractions

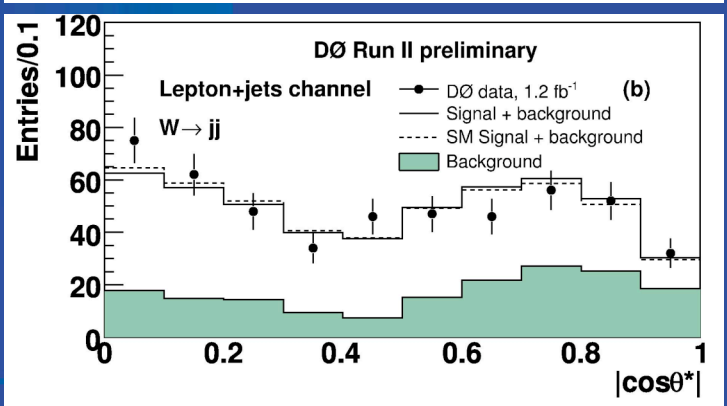
- Can measure (f_0,f_-,f_+) using the cosθ^* distribution

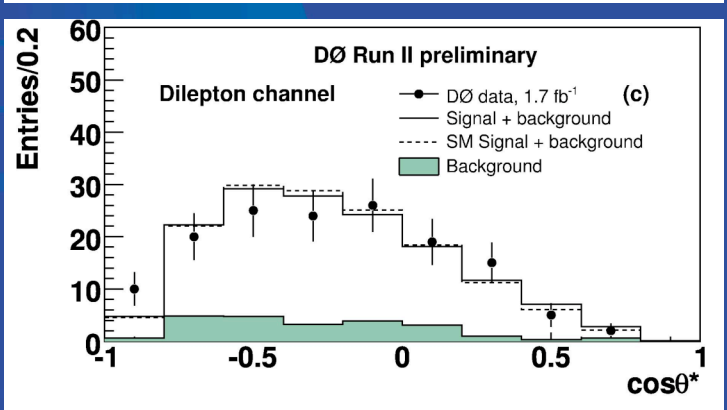


cosθ^* == angle between lepton (from W-->lv) and b quark in W rest frame

W-boson Helicity Fractions







- D0 LJT+DIL 1200 pb^{-1}

$$f_0 = 0.49 \pm 0.11 \pm 0.09$$

sta sys

$$f_+ = 0.11 \pm 0.06 \pm 0.05$$

sta sys

- CDF LJT 2000 pb^{-1}

$$f_0 = 0.62 \pm 0.10 \pm 0.05$$

sta sys

$$f_+ = -0.04 \pm 0.04 \pm 0.03$$

sta sys

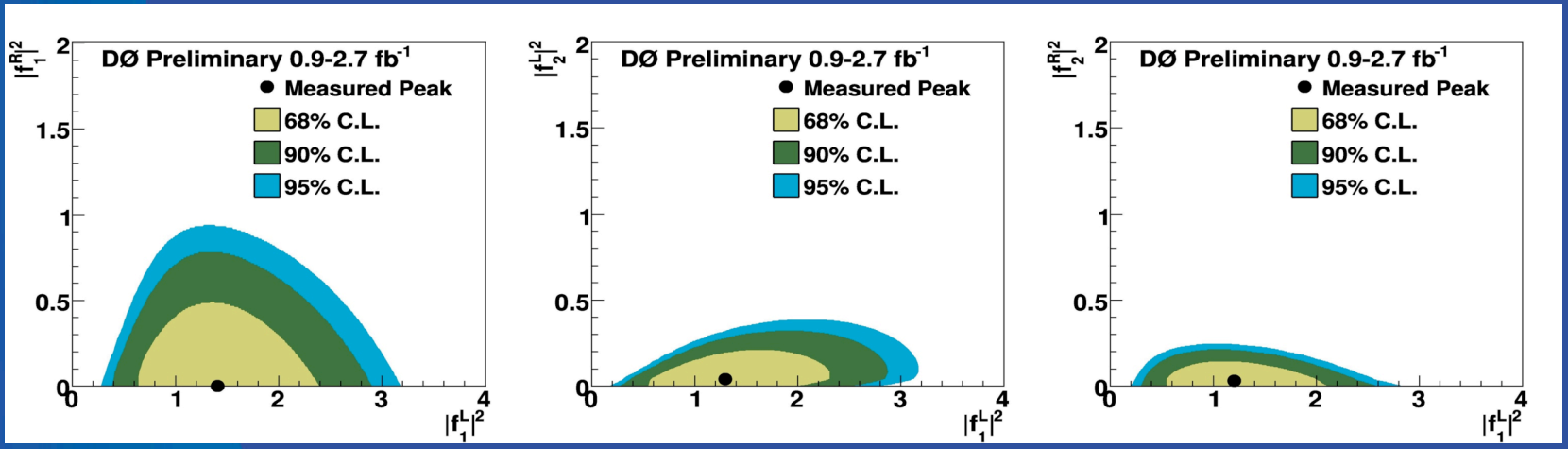
Consistent with the Standard Model

Generic tWb Couplings

- Use (f_0,f_-,f_+) to constrain generic tWb couplings

$$L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t$$

Standard Model: $f_1^L = 1$, $f_1^R = f_2^L = f_2^R = 0$



LJT+DIL+Single-Top

$$\left|f_1^R\right|^2 < 0.72$$

for $\left|f_1^L\right|^2 = 1$ $\quad \left|f_2^L\right|^2 < 0.19$ @ 95% CL

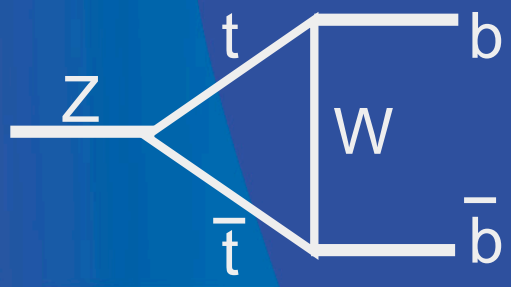
$$\left|f_2^L\right|^2 < 0.20$$

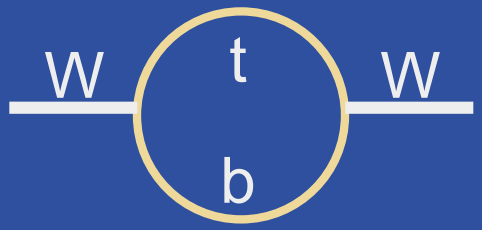
Consistent with Standard Model

Exploring Top-Quark Properties

Top-Quark Mass

- M_t is a fundamental parameter of the Standard Model
- Since M_t is large, quantum loops involving top quarks are important to include when calculating precision observables (e.g. $\sin\theta_W^2$, R_b, M_W, …)



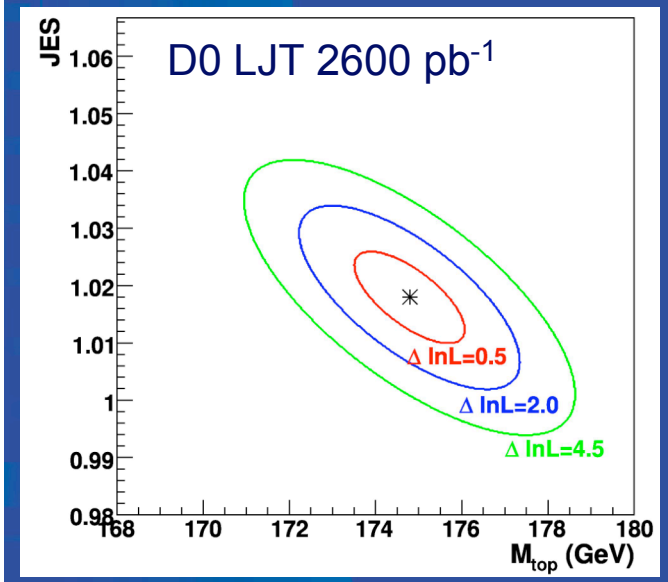


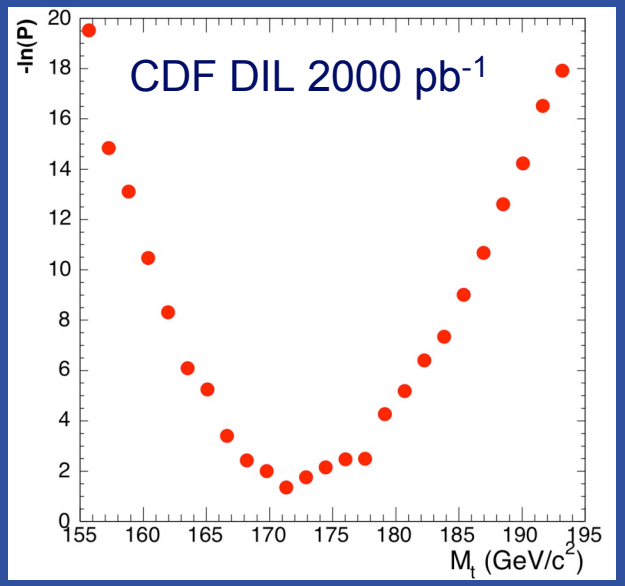
- Within SM, particularly important to help constrain M_H

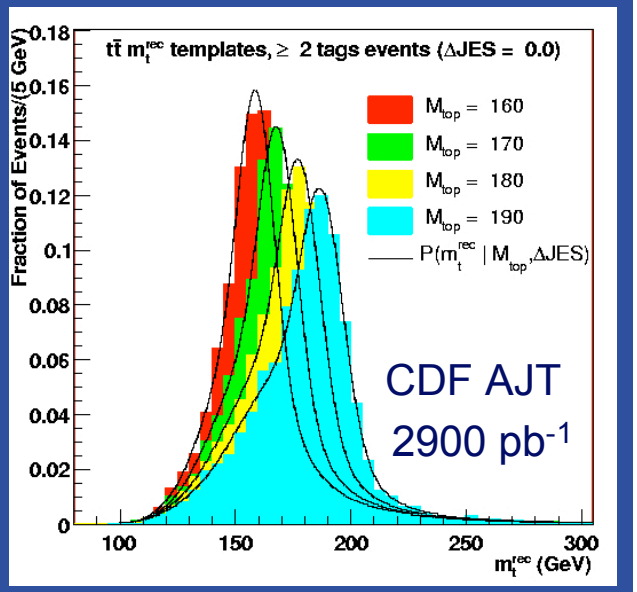
Top-Quark Mass

- M_t important for any model endeavoring to describe particle physics
  - In MSSM at tree level: $M_h < M_Z$ (very excluded)
    w/ M_t loop corrections: $M_h < 135$ GeV/c^2
  - M_t impacts soft-SUSY breaking phenomenology
  - M_t plays critical role in verifying gauge unification through Renormalization Group Equations
- Precision M_t crucial to understanding underlying theory of particle physics whether SM or SUSY or …

Top-Quark Mass

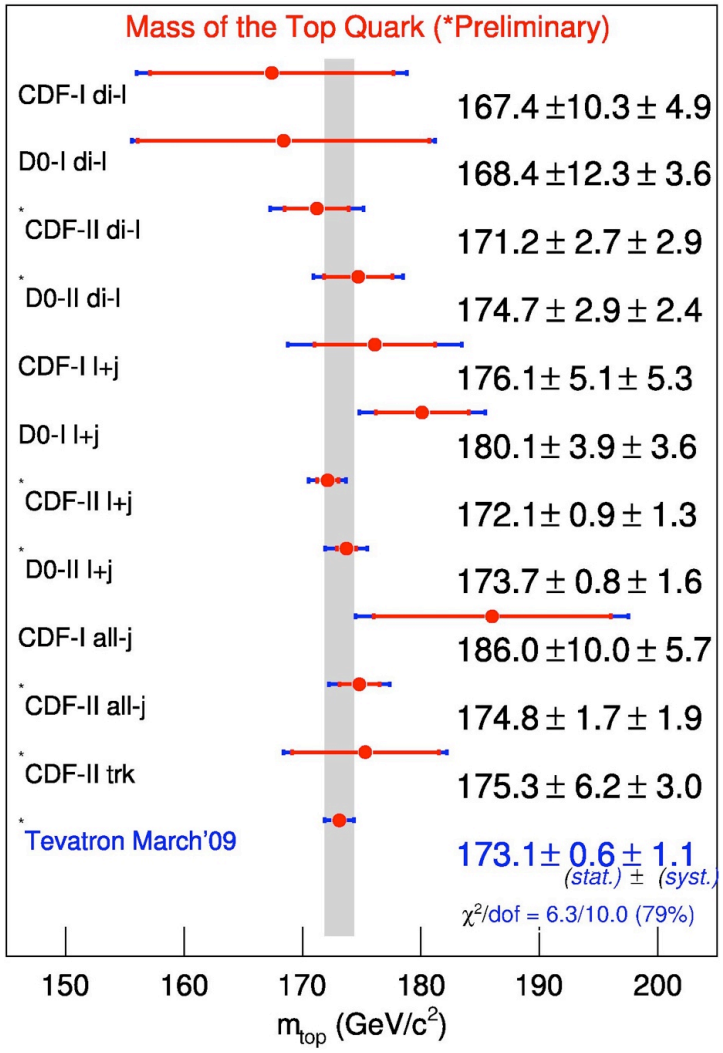






- Results in all channels (LJT, DIL, AJT)

Top-Quark Mass



- Consistent across channels and methods
- Tevatron combination

$$M_t^{world} = 173.1 \pm 0.6 \pm 1.1\ GeV/c^2$$

(sta) (sys)

  - ΔM_t(total) = 1.3 GeV/c^2 (relative precision 0.8%)
  - Have surpassed Run II goal by a factor of >2

Top Quark Mass

Source	ΔM_t (GeV/c^2)
jet energy scale:	0.73
* t-tbar modeling:	0.71
background:	0.26
lepton energy scale:	0.11
miscellaneous:	0.18
Systematic:	1.07
Statistical:	0.65

- Some of the systematic uncertainties actually limited by statistics of calibration control samples

* Includes ISR, FSR, and Color Reconnection modeling uncertainties

Top Quark Mass

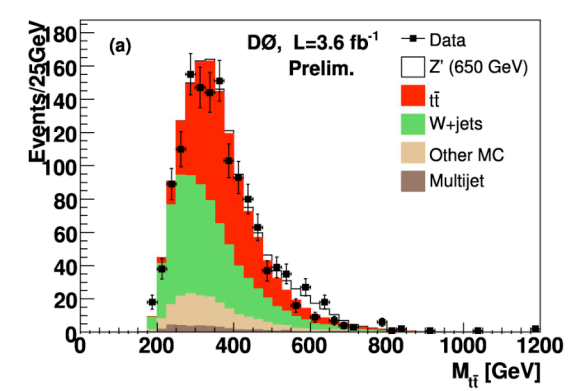
$$\Delta M_t^{\text{world}} = 0.81 \pm 0.71 \pm 0.65\ \text{GeV}/c^2$$

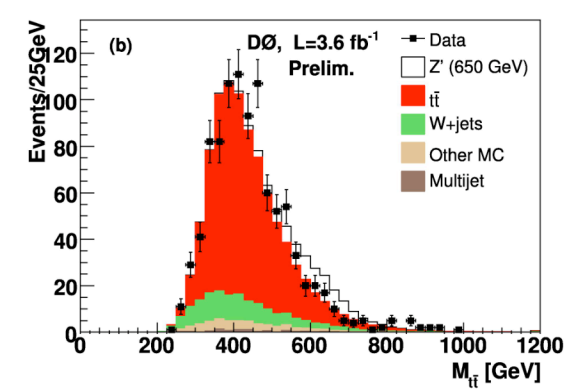
experimental t-tbar modeling other

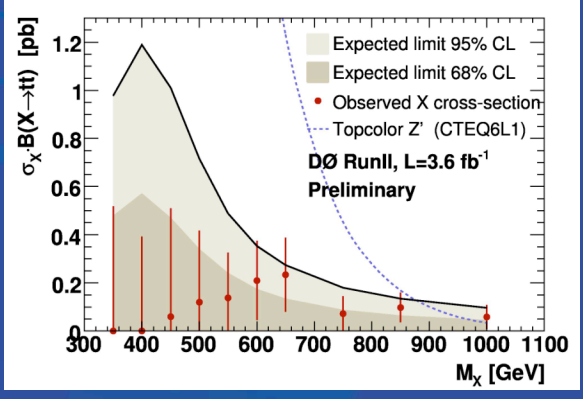
- Uncertainty dominated by sources which should continue scale with the statistics of the sample
- With full Run II data set could reach a total uncertainty of $\Delta M_t \sim 1\ \text{GeV}/c^2$

Exploring Top-Quark Events for Direct Evidence of New Physics

New Physics in Top-Quark Production



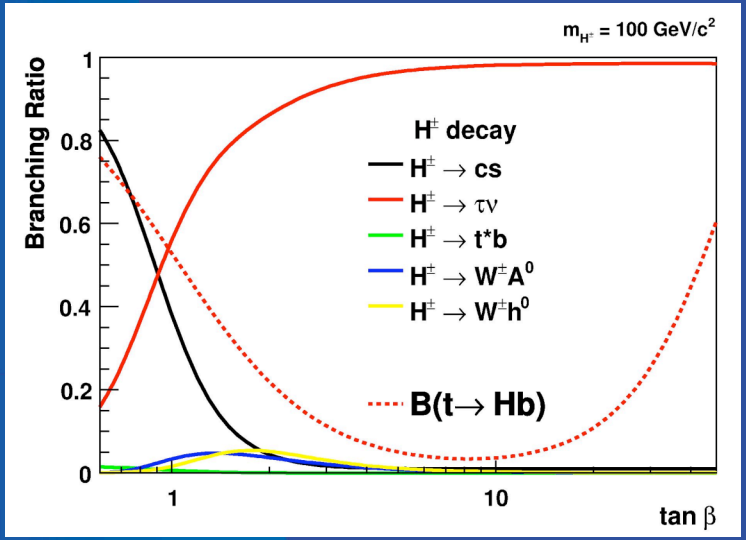


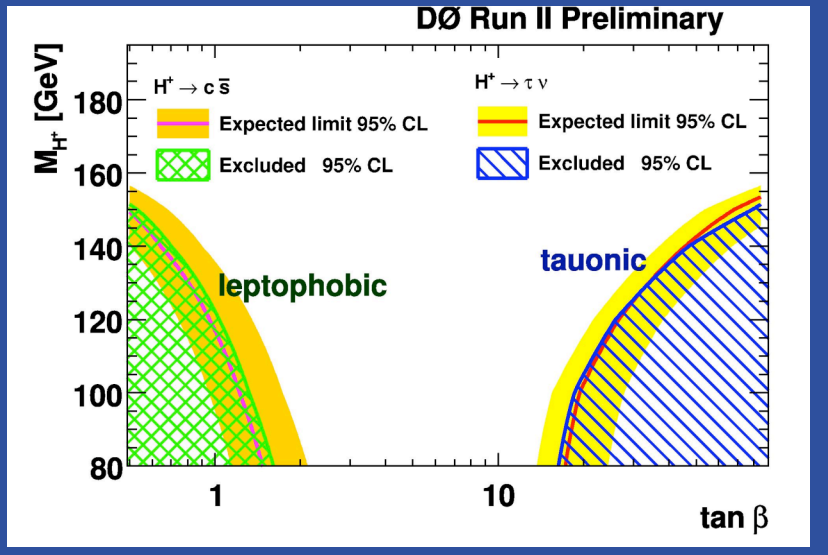


- Resonant Production of t-tbar
  - Can arise in some New Physics models e.g. heavy Z'
- Final state still t-tbar, but M_{tt} would exhibit a resonance
- Use LJT channel
  - Good S/B
  - Good M_{tt} resolution
- $M_{Z'} > 820$ GeV/c^2 @ 95% CL

New Physics in Top Quark Decay

- If kinematics allowed, t --> H^+b happens in SUSY
  - $H^+ \to c\bar{s}$ or $H^+ \to \tau\nu$
  - Branching ratio depends on tanβ, model parameters
  - Would alter the observed ratio of LJT:DIL:AJT

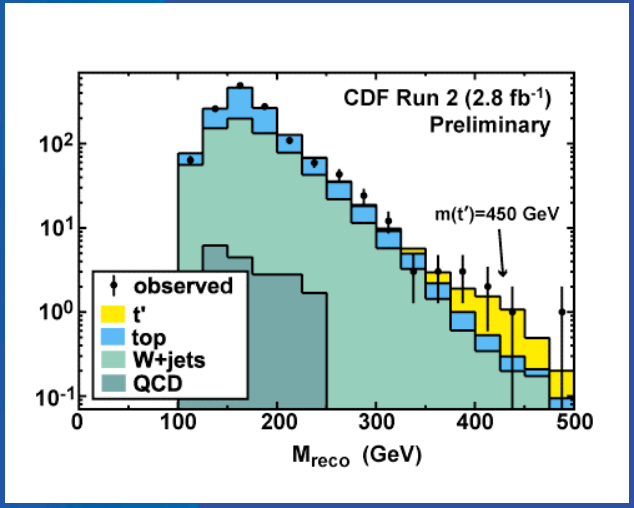


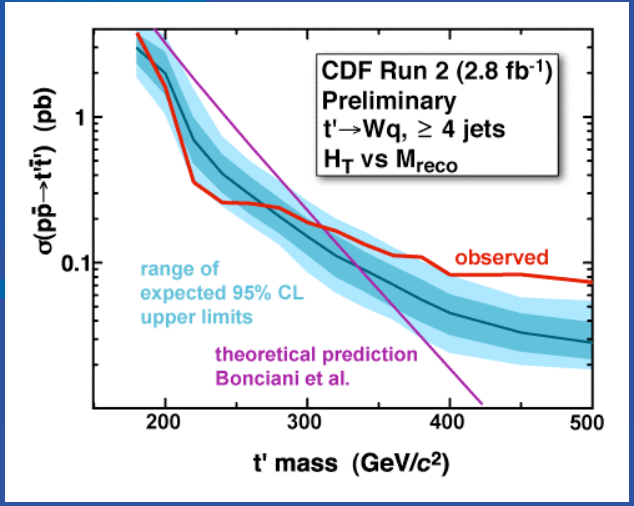


New Physics that Looks like Top

Heavy t' in LJT

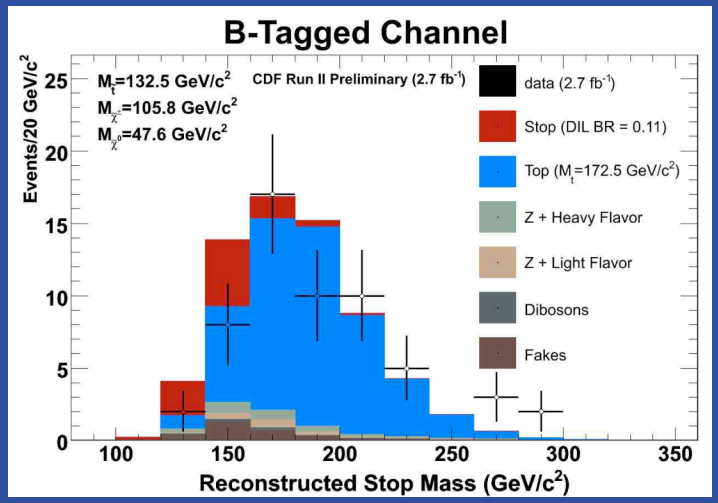
t' --> Wq

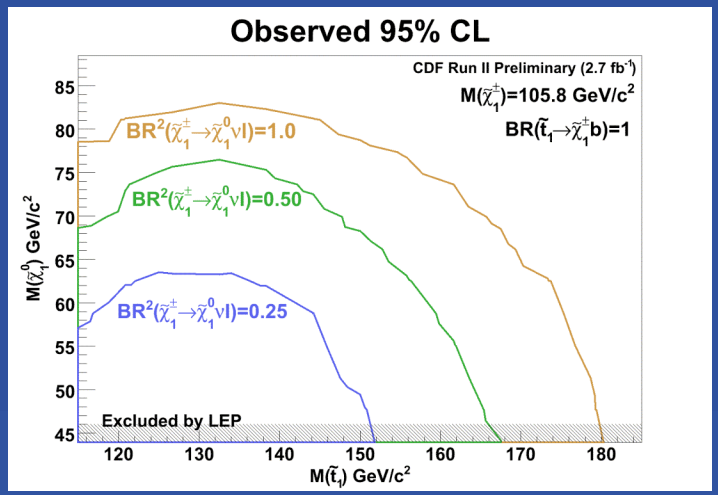




top squarks in DIL

$\tilde{t}$ --> $b\chi^{+}$-->$b\chi^{0}l\nu$





Top Quark Physics Results

Apologies for my many omissions.

For a full listing of results go to:

http://www-cdf.fnal.gov/physics/new/top/top.html

and

http://www-d0.fnal.gov/Run2Physics/WWW/results/top.htm

Conclusions

- In Run I, Tevatron discovered the top quark with tens of events
- In Run II, Tevatron pioneering full program of top-quark physics with thousands of events
  - Exploring top-quark **Production**, **Decay**, **Properties**
  - Exploring top-quark sample for **New Physics**
  - So Far, **Consistent with the Standard Model**
- Most measurements statistics limited
  - Results shown used 2-3 fb^{-1}
  - Each experiment will collect ~8 fb^{-1} by end 2010
  - Significant improvements expected