
# Top-Quark Measurements at CDF with the Full Run II Data Sample

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For the CDF Collaboration

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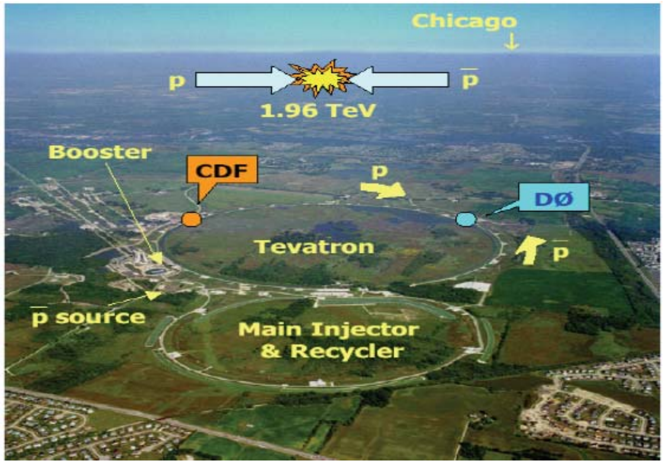
# Top Quark and the Tevatron

- Top is the heaviest known particle
  - Mass ≈172.5 GeV/$c^2$
- Fermilab Tevatron
  - Sqrt(s)=1.96 TeV
  - Just completed data taking phase
  - Collected 8.7 $fb^{-1}$ of data useful for these analyses
  - Top-pair cross section ≈7.5 pb
  - Single top cross section ≈3.1 pb
- Show some of the results from the full (or nearly full) Run II Data sample



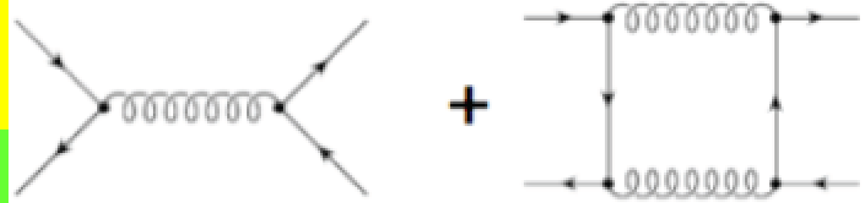
# Outline:
# Mass, Properties and Cross Sections

- Top Properties
  - Forward-Backward Asymmetry: $A_{FB}$
  - Ratio of Branching Ratios: $\frac{Br(t \to Wb)}{Br(t \to Wq)}$ and $|V_{tb}|$
  - Single Top: Cross sections and $|V_{tb}|$
  - W-Helicity in Top Decays
- Top Mass
  - $M_{top}$ in Lepton+Jets
  - Top-antitop Mass Difference
  - $M_{top}$ in Met+Jets
- Conclusions

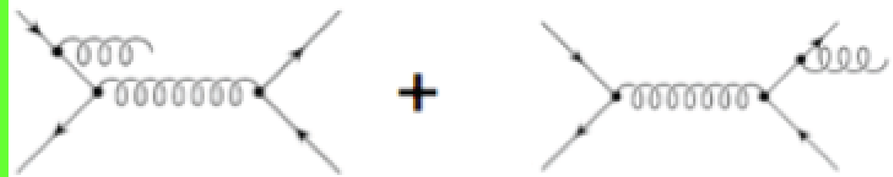
# $A_{FB}$ in the Standard Model

- Standard Model has no Forward-Backward asymmetry for top pair production at LO
- NLO has interference terms that give a small asymmetry
- Some uncertainty regarding theory predictions
  - Use POWHEG central value and a 26% correction for EWK contributions

Born + Box Interference
Positive Contribution to $A_{FB}$



ISR/FSR Interference
Negative Contribution to $A_{FB}$



$$A_{FB}^{NLO} = 6.6\%$$

*POWHEG*: JHEP **0709**, 126 (2007)

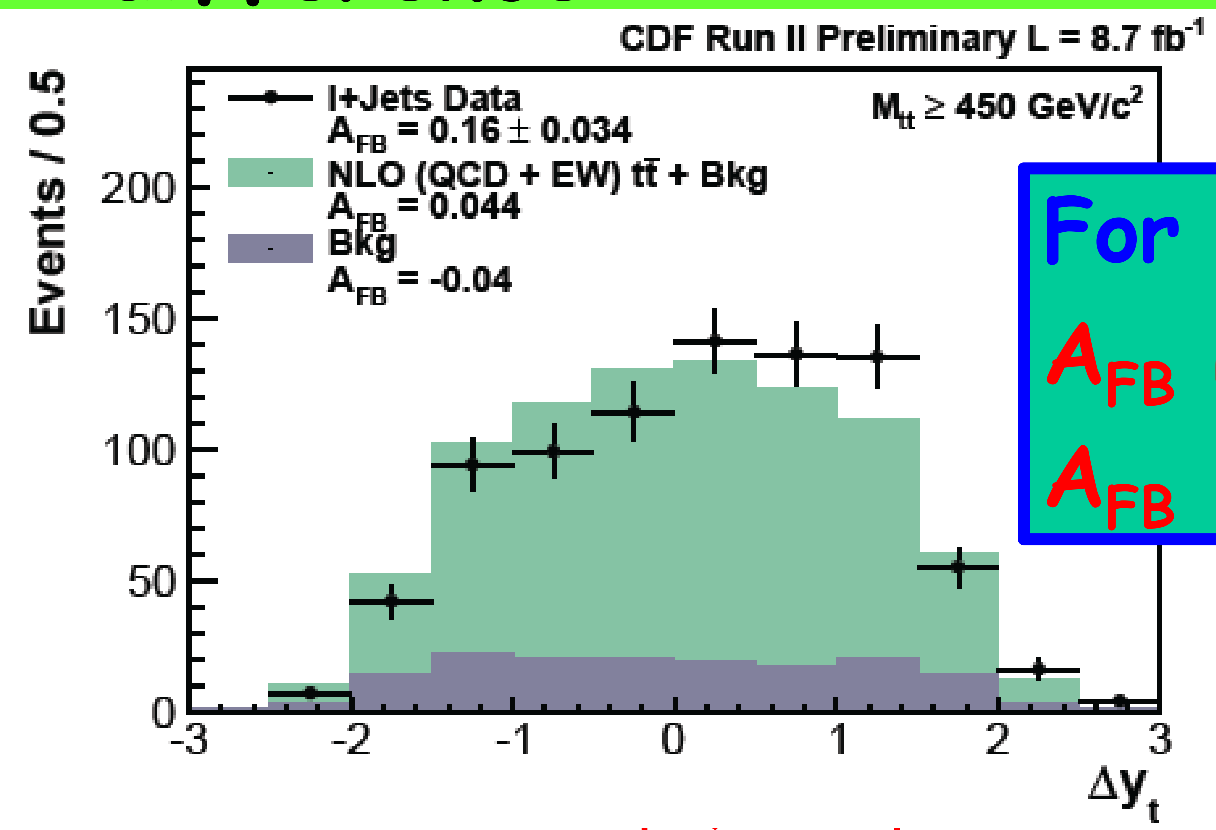
*EW Corrections*: Phys. Rev. D 84, 093003 (2011); JHEP **1201**, 063 (2012); arXiv:1201.3926[hep-ph]

CDF Public Notes

- CDFNote 10774: Lepton+Jets
- CDFNote 10807: Differential Measurements

# $A_{FB}$ in Lepton+Jets Events

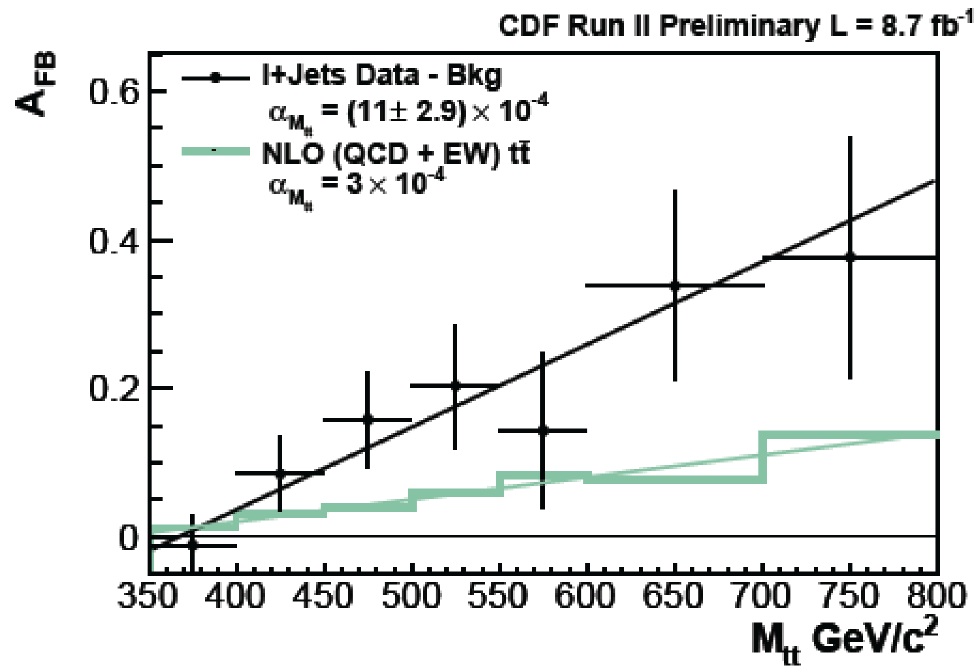
- Have measured an $A_{FB}$ that is $3\sigma$ from zero and larger than SM predictions
- $A_{FB}$ Depends on Mass of the $t\bar{t}$ system
- $A_{FB}$ Depends on the top rapidity difference

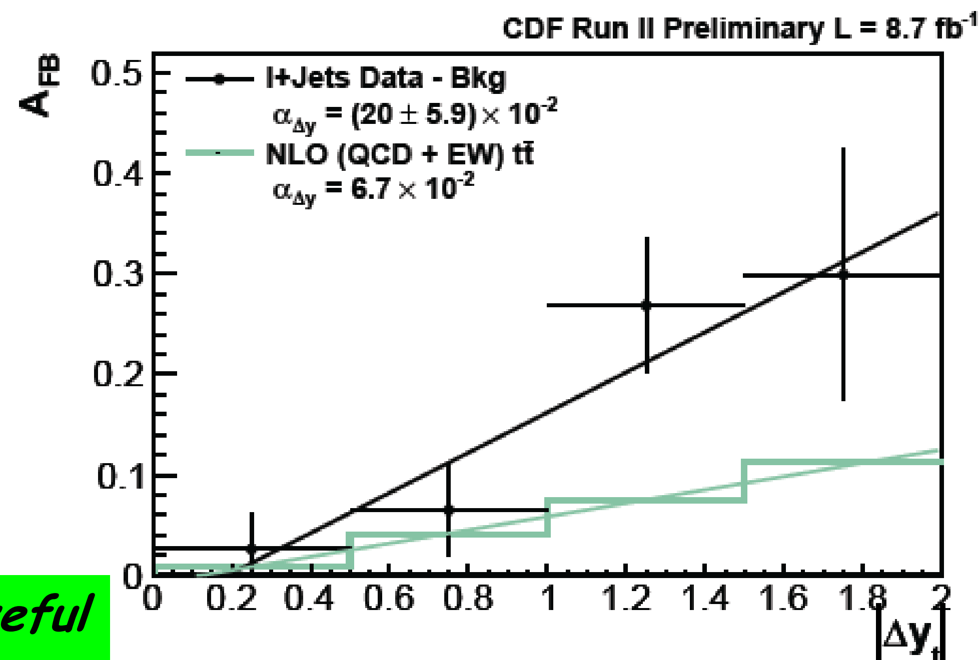



For $M_{t\bar{t}}$>450 GeV/$c^2$ find
$A_{FB}$ Pred = 4.4%
$A_{FB}$ Data = (16.0±3.4)%

# Asymmetry vs. $M_{tt}$ and $|\Delta Y|$

- With the full dataset we can look at the differential $A_{FB}$ as a function of $M_{t\bar{t}}$ and $|\Delta Y|$ after background subtraction
- SM predicts both to be roughly linear
  - Observe a linear dependence in the data
  - Slopes are 3$\sigma$ from zero and inconsistent with SM predicted slopes
  - *p*-values less than 1% from SM

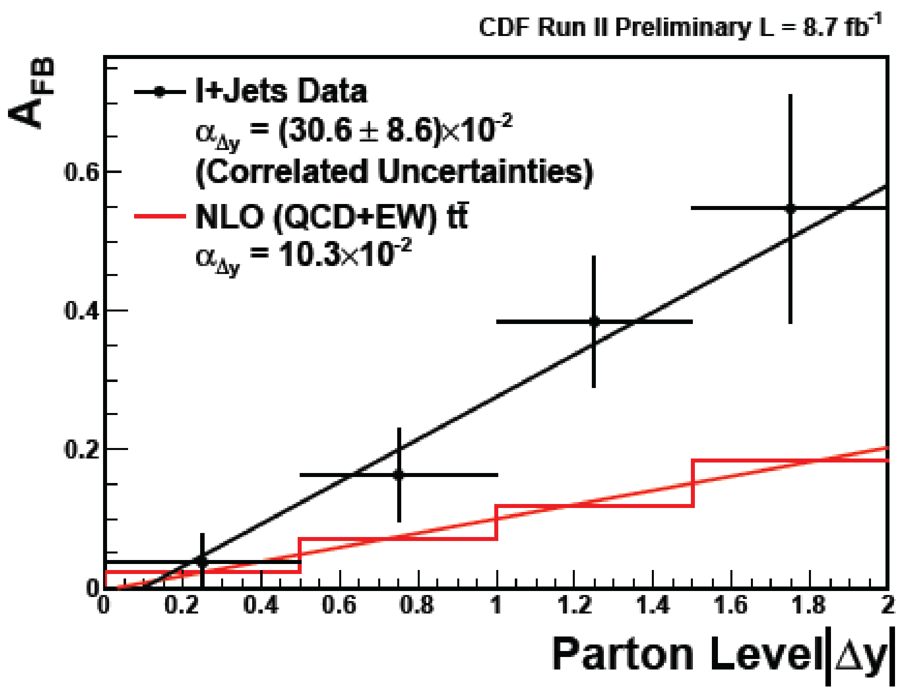


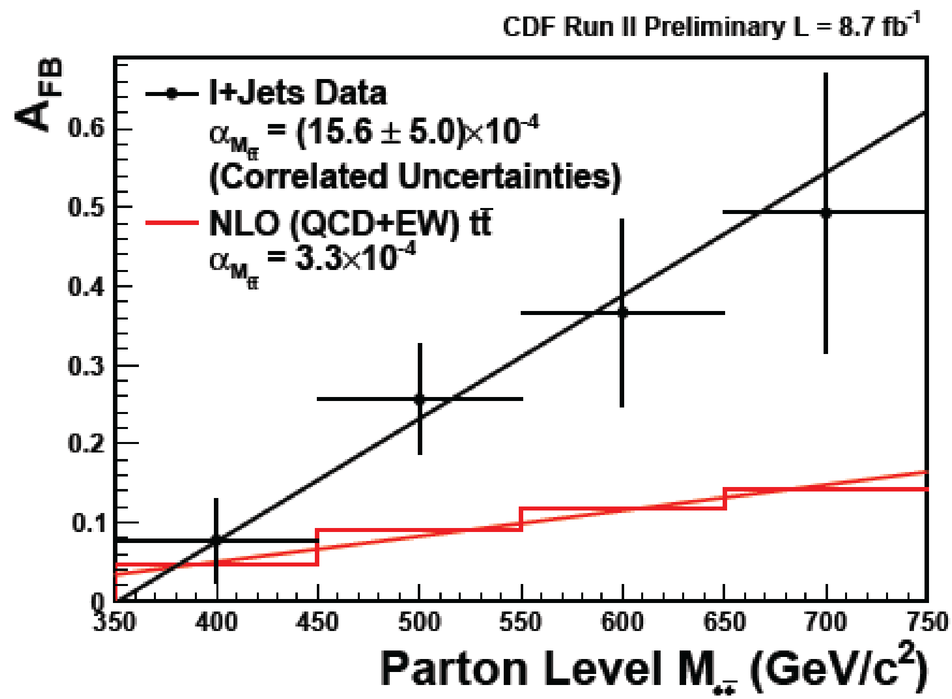




*Can the numerical values of these slopes be useful to model builders?*

# Asymmetries at the Parton Level

Can unfold data to get back to the parton level to get to a "true" $A_{FB}$




| slope parameter $\alpha$ | $A_{FB}$ vs $M_{t\bar{t}}$ | $A_{FB}$ vs $\Delta y$ |
|---|---|---|
| DATA | $(15.6 \pm 5.0) \times 10^{-4}$ | $(30.6 \pm 8.6) \times 10^{-2}$ |
| SM | $3.3 \times 10^{-4}$ | $10.3 \times 10^{-2}$ |

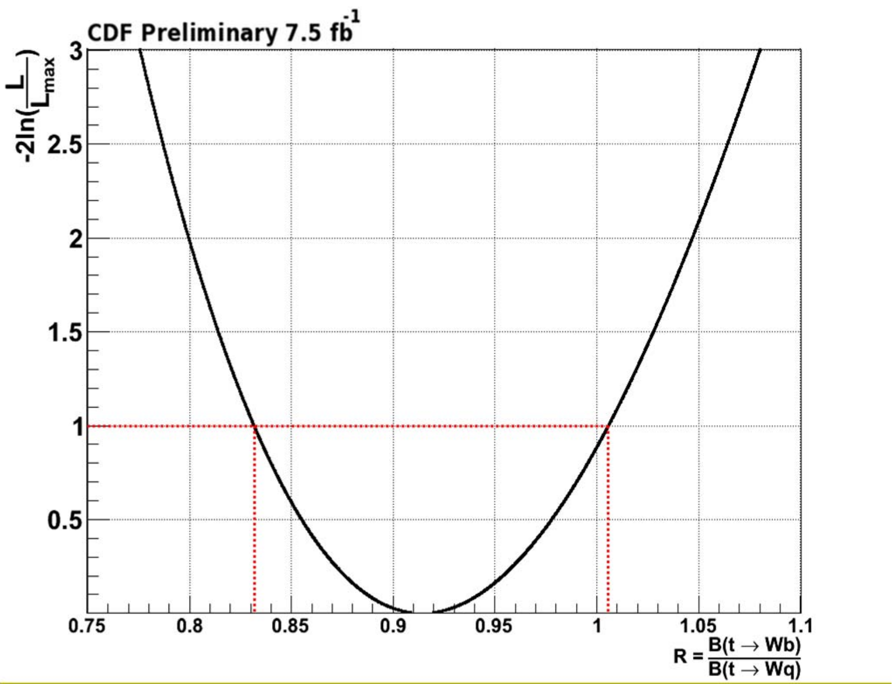
Again, linear relationships with slopes that are 3σ from zero and inconsistent with SM predicted slopes

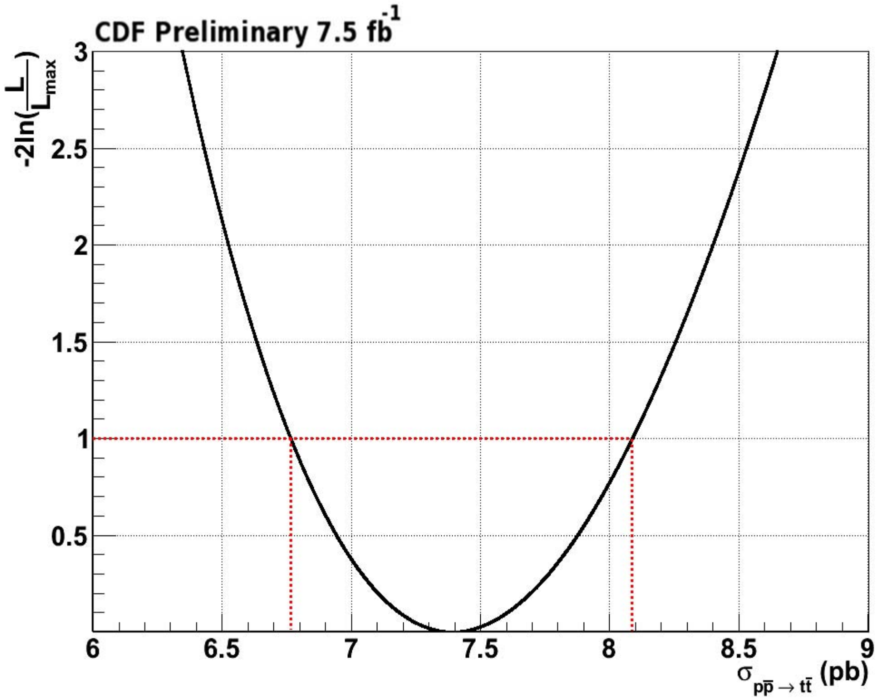
# Ratio of Branching Ratios

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

- SM: $R$ =1 constrained by CKM unitarity. $R$<1 could indicate new physics
- Drop R=1 assumption and Measure R simultaneously with the $t\bar{t}$ cross section
- Expect 2 $b$'s in each $t\bar{t}$ event if BR(t→Wb)=100%
  - Tagging efficiency determines number of Lepton+Jets events with 0, 1, or 2 tagged jets in 3, 4 or ≥5 Jet samples
- Derive $|V_{tb}|$ from result (assuming a unitary 3×3 CKM matrix)

# Top Cross Section, Branching Fraction and $|V_{tb}|$



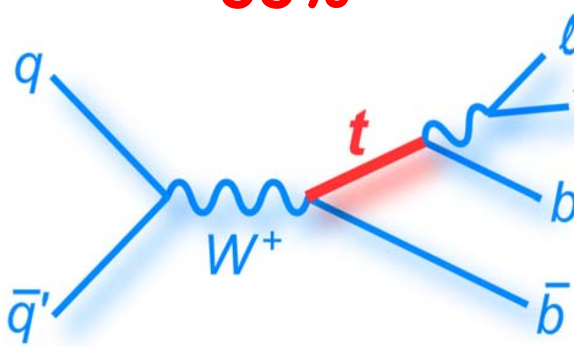

| | |
|---|---|
| $\sigma_{p\bar{p}\to t\bar{t}}(pb)$ | $7.4 \pm 1.1$ |
| $R$ | $0.91 \pm 0.09$ |
| $\lvert V_{tb} \rvert$ | $0.95 \pm 0.05$ |

**Systematics included in the fit:**

- Tag efficiency
- Selection efficiency
- Background normalization
- Luminosity

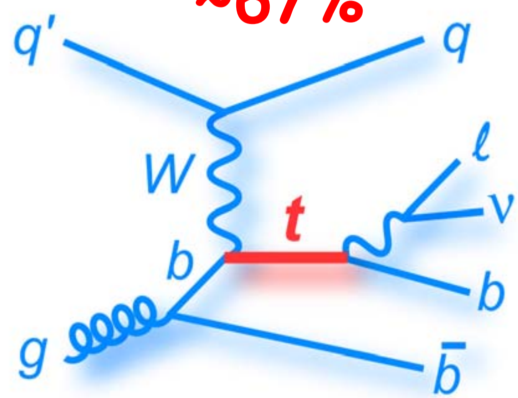
# Single Top Quark Production

~33%



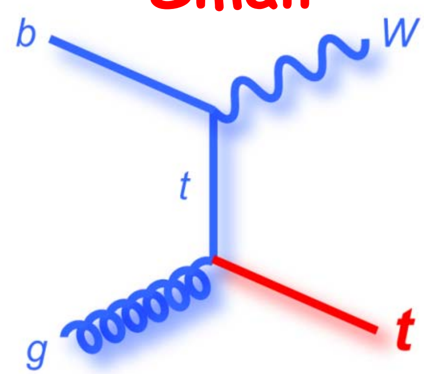

s-channel production

~67%




t-channel production

Small



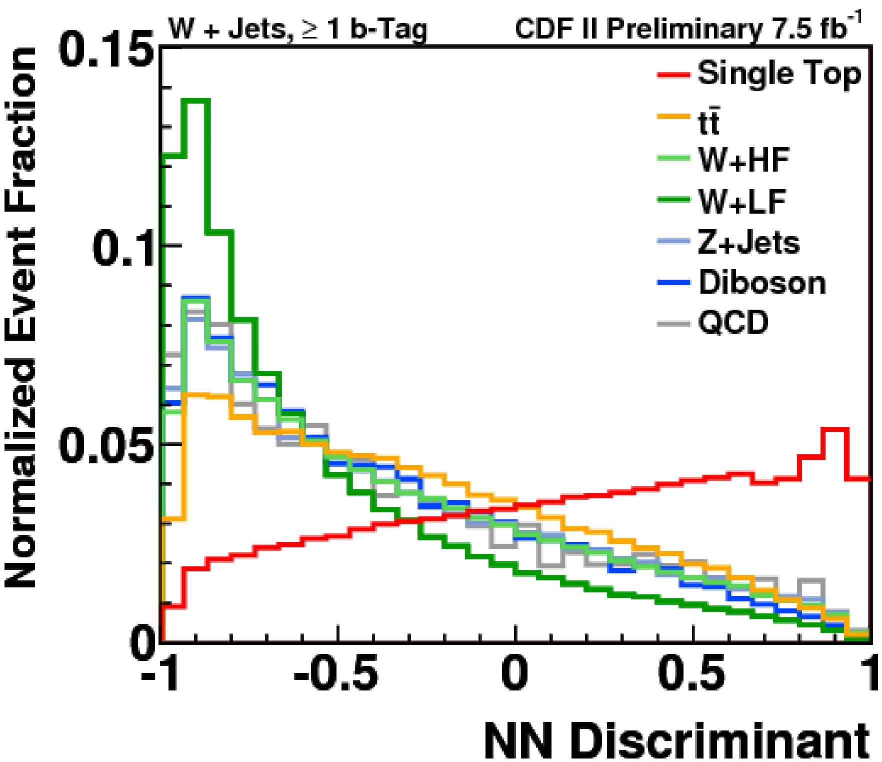

Associated Wt production

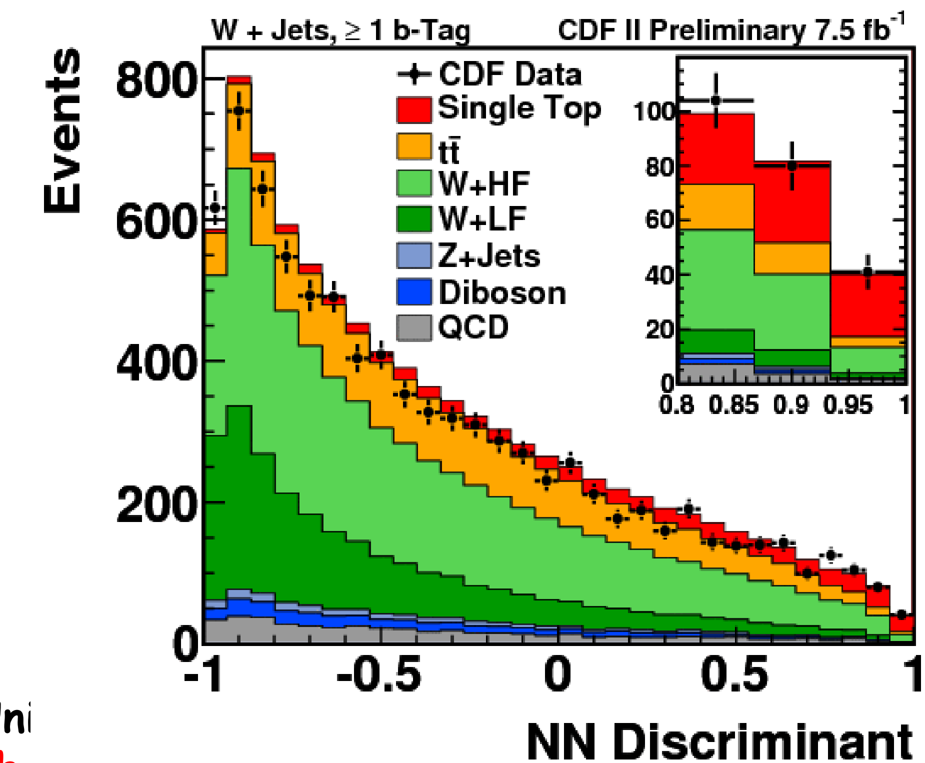
- **Motivation:**
  - Measure $\sigma_{s+t}$ as well as $\sigma_s$ and $\sigma_t$ simultaneously
  - Gives a measure of $|V_{tb}|$
  - Sensitive to New Physics (FCNC, W'…) and CP violation

CDF Public Note 10793

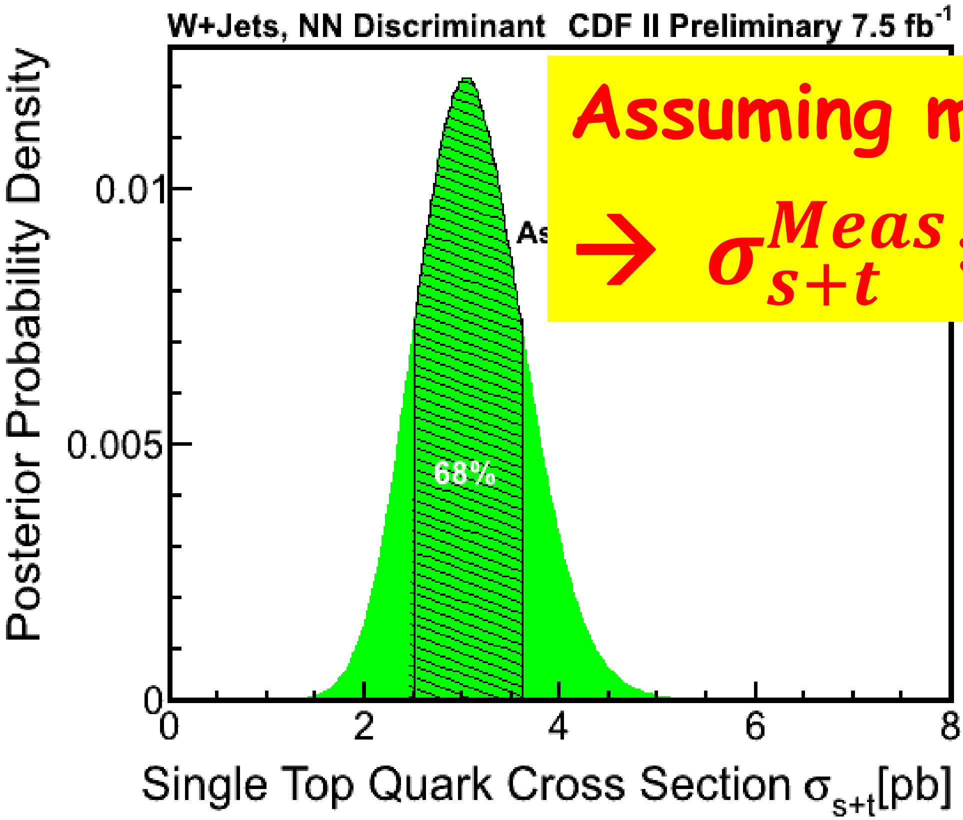
# Data and Neural Net Analysis

- Large backgrounds in the Lepton+Jets+Met with a *b*-tag
- Use Neural Nets for *s* and *t*-channel separately and to separate the different signals from backgrounds



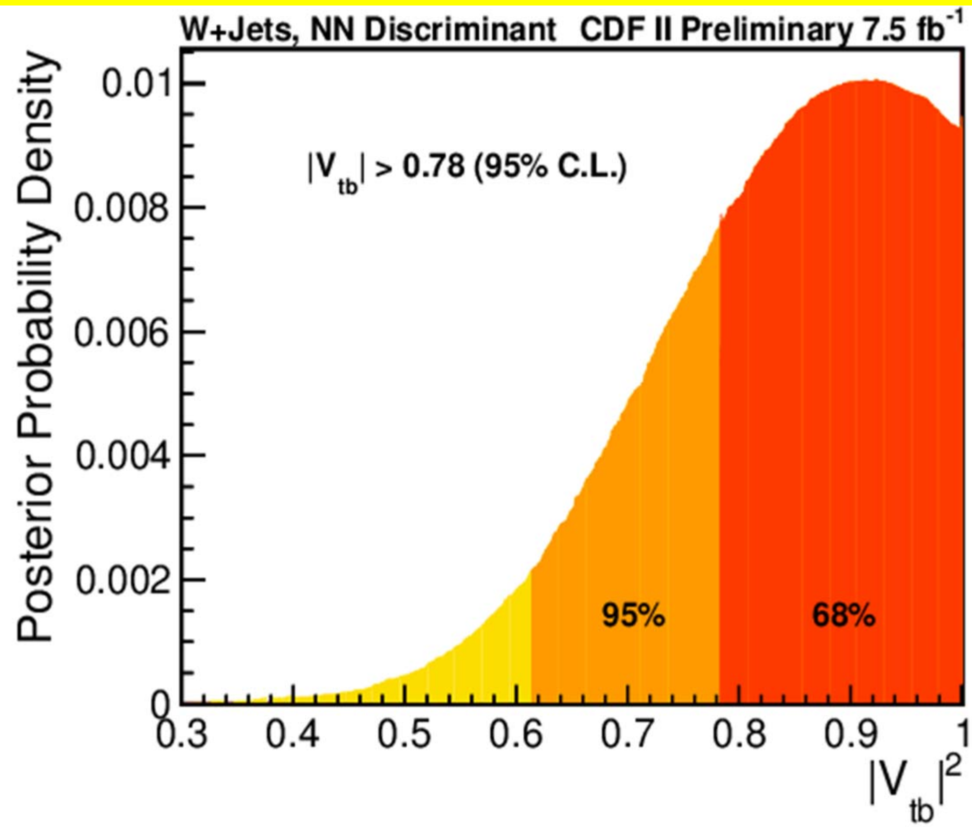



# Total Cross Section and $|V_{tb}|$




**Assuming $m_{top}$ = 172.5 Gev/c$^2$**

**→ $\sigma_{s+t}^{Meas} = 3.04^{+0.57}_{-0.53}$ pb**

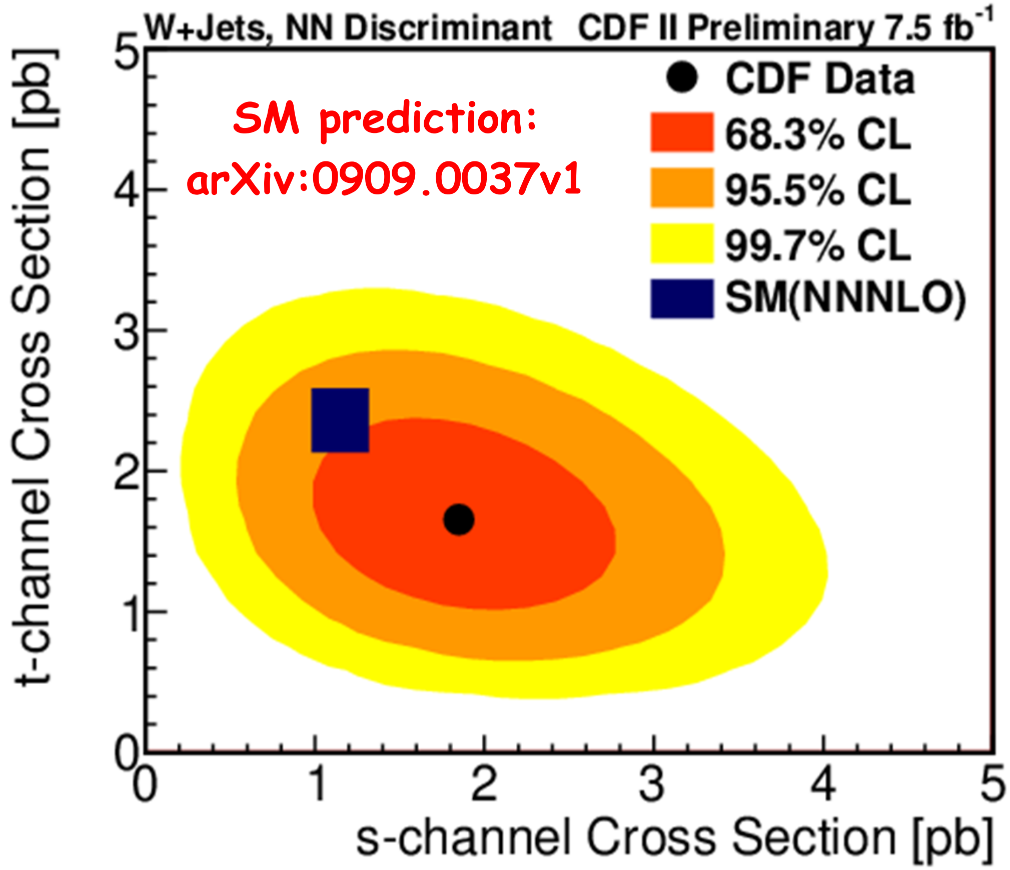



$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb,SM}|^2$$

**Set limit: $|V_{tb}|$ > 0.78 at 95% CL**

**Extracted $|V_{tb}|$ = $0.92^{+0.10}_{-0.08}$ (stat.+sys.) ± 0.05(theory)**

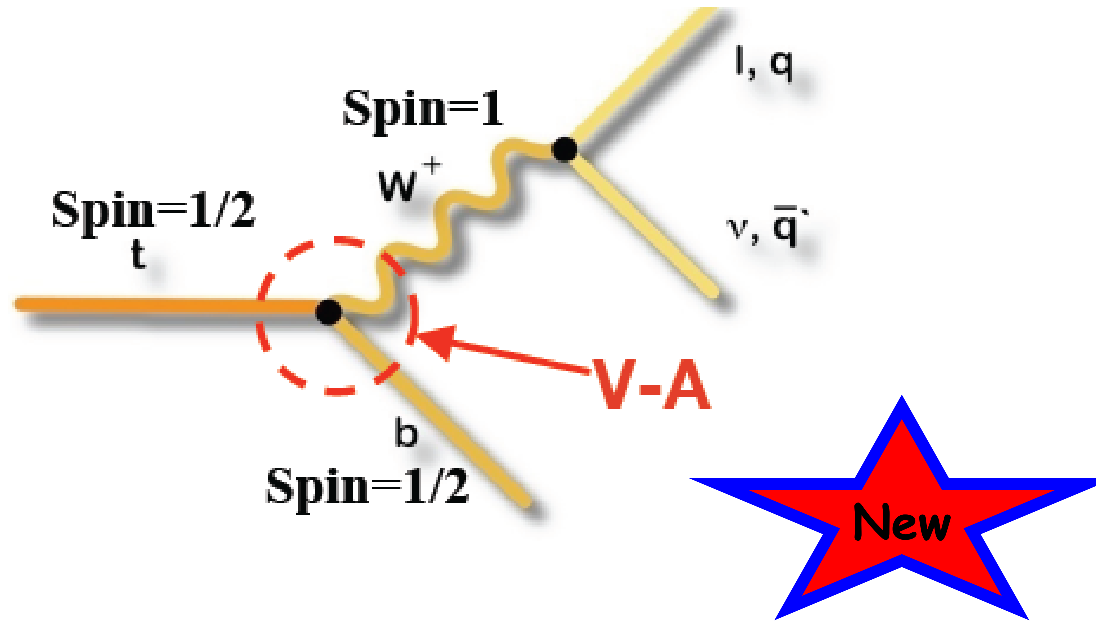
# Simultaneous $\sigma_t$ and $\sigma_s$ Measurement

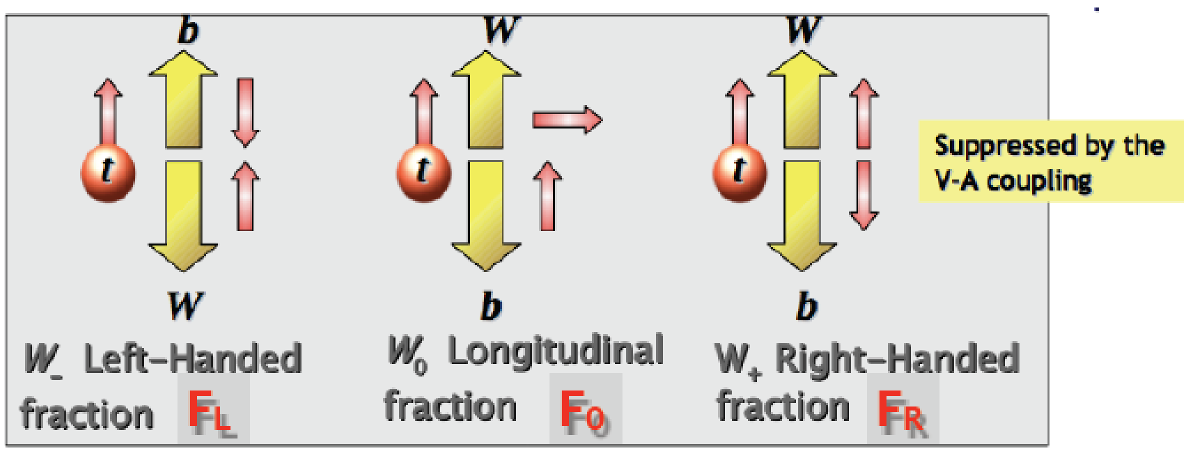



| Measured Cross Section | SM Prediction |
|---|---|
| $\sigma_s = 1.81^{+0.63}_{-0.58}$ pb | $\sigma_s = 1.05 \pm 0.07$ pb |
| $\sigma_t = 1.49^{+0.47}_{-0.42}$ pb | $\sigma_t = 2.10 \pm 0.19$ pb |
| | $\sigma_{wt} = 0.22 \pm 0.08$ pb |

# W Helicity in Top Quark Decays

- Since the top decays as a bare quark it's spin information is transferred into it's final state
- Sensitive to non-SM tWb couplings

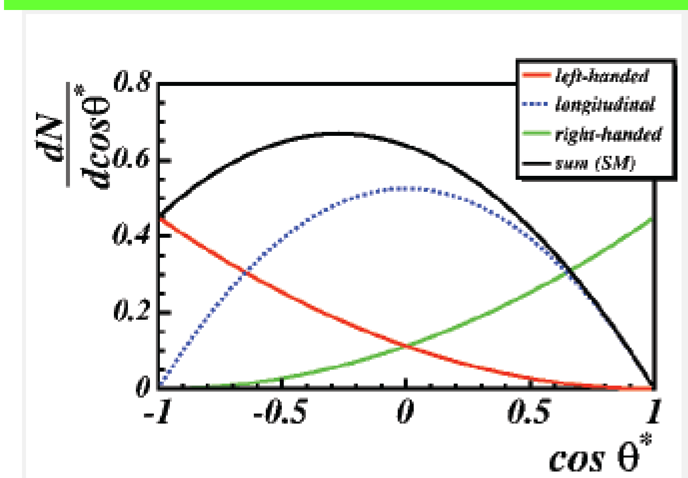


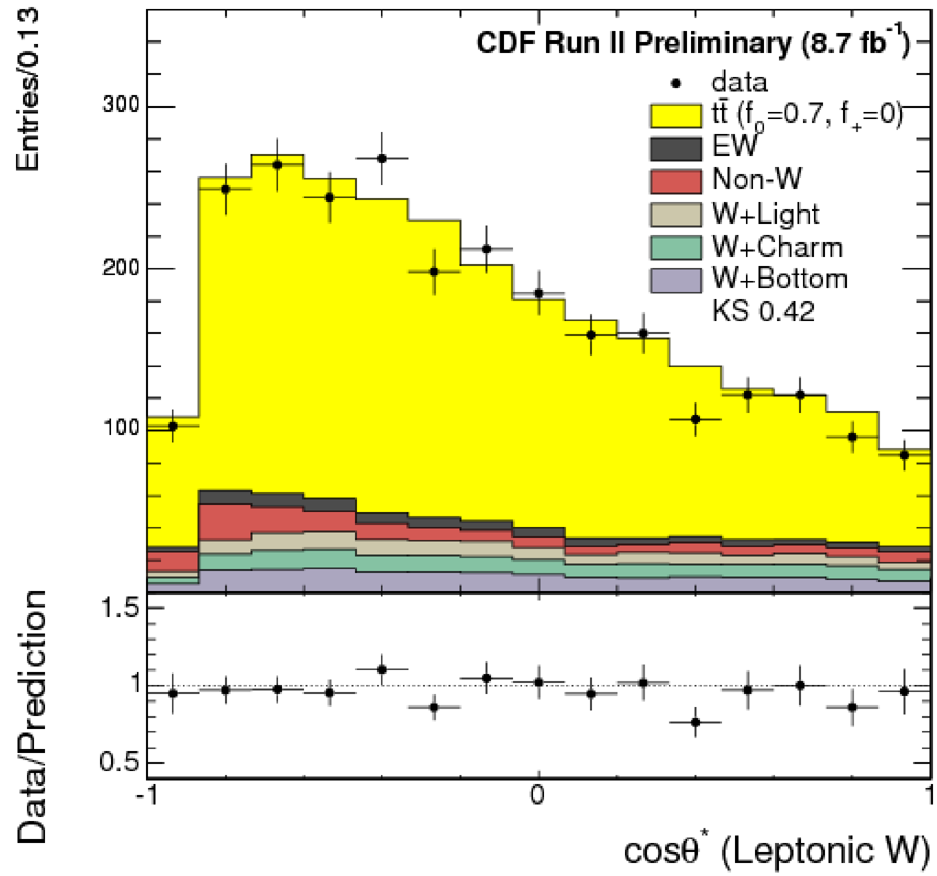



# Simultaneous Measurement of the Longitudinal and Right-Handed Helicity

Use Matrix Element Techniques in Lepton+Jets events

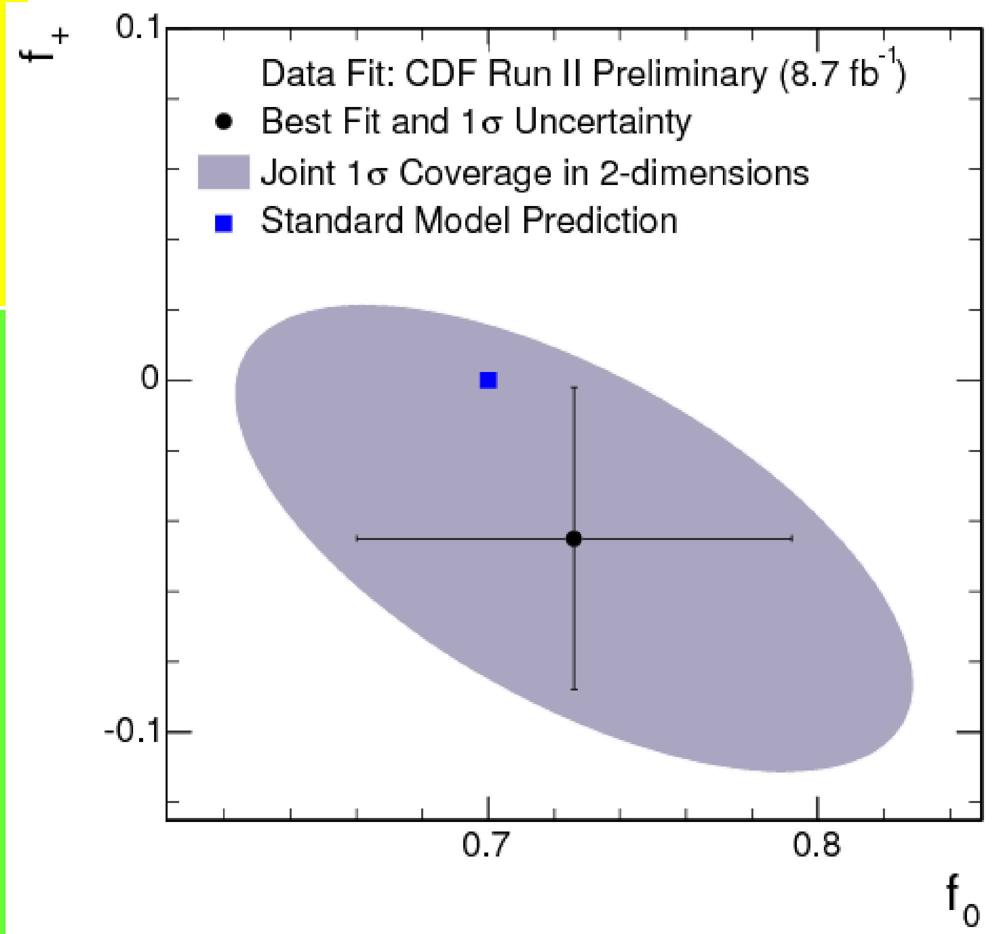
Consider Cosθ* which is the angle between the lepton in the W rest frame and the momentum of the W in the top quark rest frame



# W Helicity in Top Decays

**Report both the uncertainties on each value as well as the joint coverage in 2-dim**

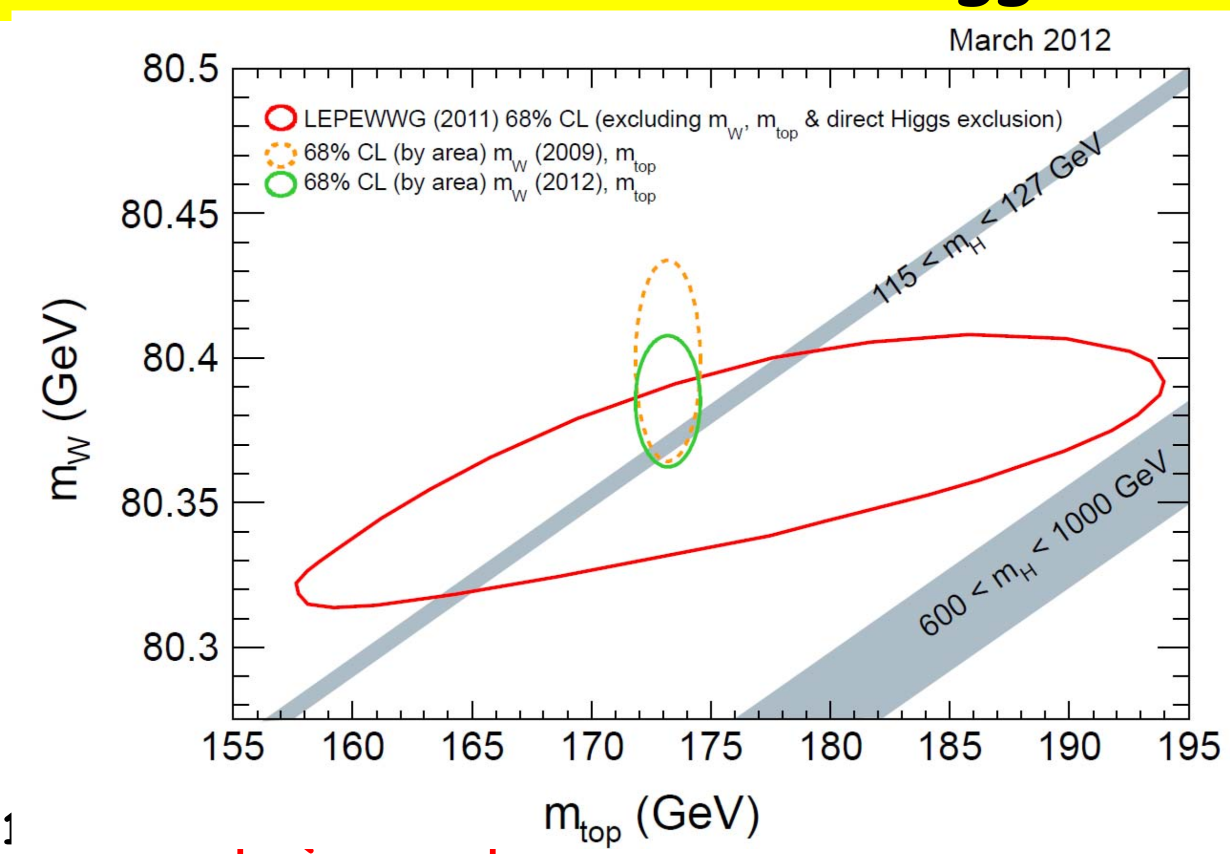



| Parameter | Measured Value | Standard Model Value |
|---|---|---|
| Longitudinal (fix $f_+$=0) | $f_0 = (72.6 \pm 6.6(stat) \pm 6.7\ (sys))\%$ | $f_0 = 69.6\%$ |
| Right-Handed (fix $f_0$=0.7) | $f_+ = (-2.5 \pm 2.4(stat) \pm 4.0\ (sys))\%$ | $f_+ = 0.1\%$ |

CDF Public Note 10855

# Top Quark Mass

- The top quark mass is a fundamental parameter of the Standard Model
- Affects predictions via radiative corrections
- When combined with the W mass places important constraints on the Higgs Mass

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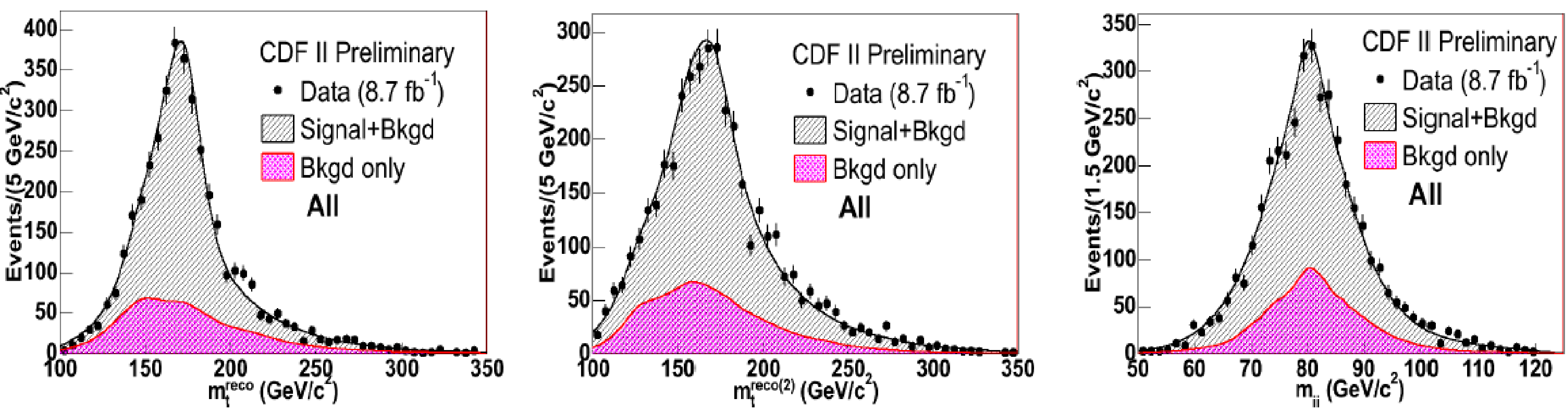
# Top Mass: Lepton+Jets

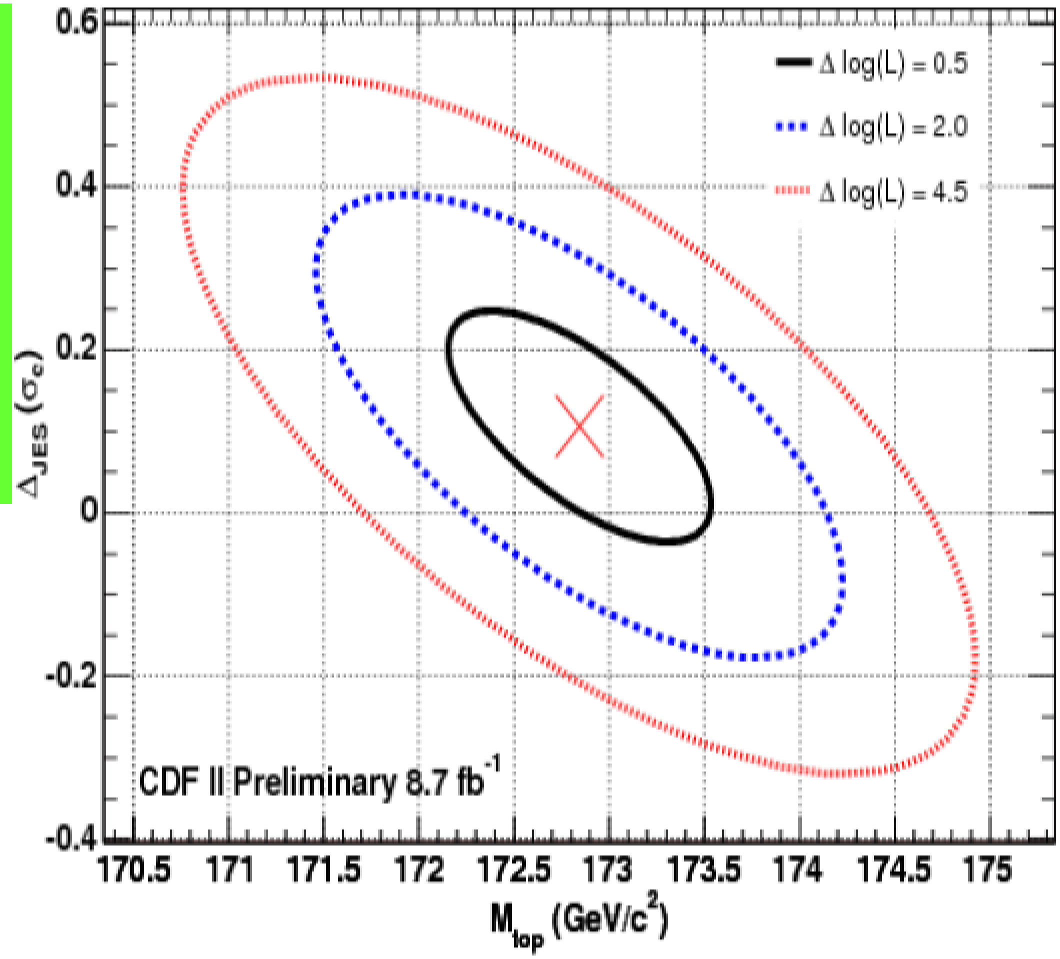
- Template methods with a kernel density estimator
- Reconstruct the likelihood as a product of per-event probabilities in the 0-tag, 1 tag and 2-tag samples
- Model both right and "wrong" combination distributions as part of the method



# Top Mass: Lepton+Jets

The dominant systematic is the Jet Energy Scale include it directly

Statistical Uncertainty now better than systematic uncertainty




CDF II Preliminary 8.7 $\text{fb}^{-1}$

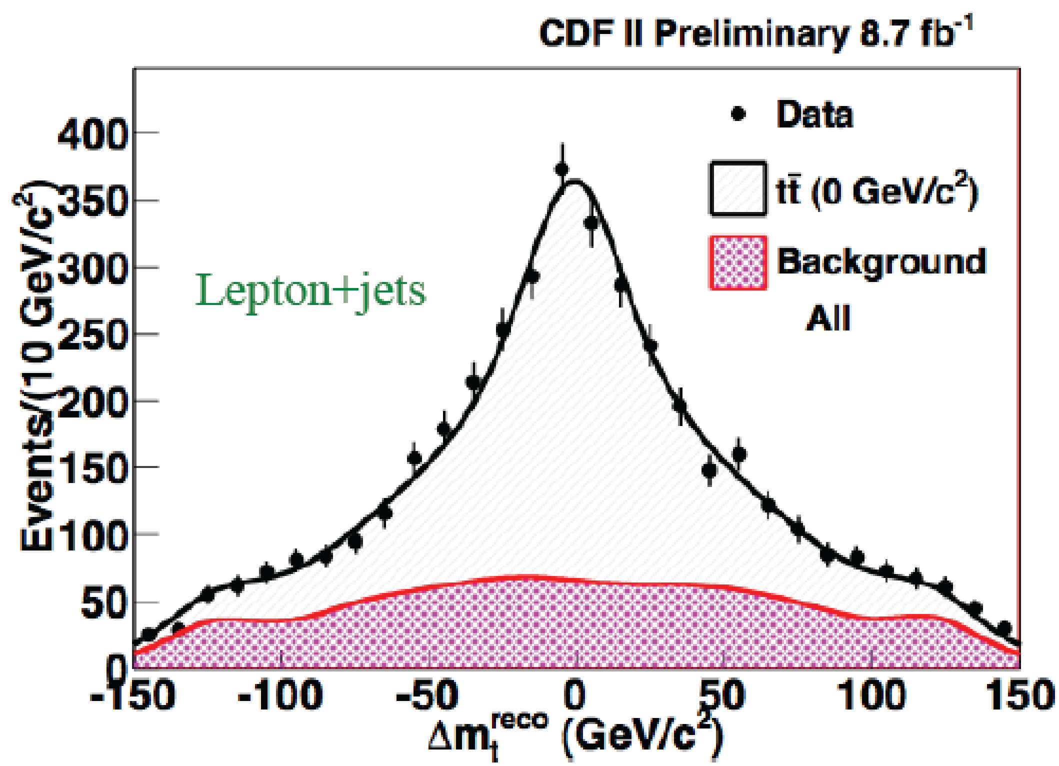
| Systematic | $\text{GeV/c}^2$ |
|---|---|
| Residual JES | 0.52 |
| Generator | 0.56 |
| Next Leading Order | 0.09 |
| PDFs | 0.08 |
| b jet energy | 0.10 |
| b tagging efficiency | 0.03 |
| Background shape | 0.20 |
| gg fraction | 0.03 |
| Radiation | 0.06 |
| MC statistics | 0.05 |
| Lepton energy | 0.03 |
| MHI | 0.07 |
| Color Reconnection | 0.21 |
| Total systematic | 0.84 |

172.85 ± 0.71 (stat) ± 0.84 (syst) GeV
172.85 ± 1.10 GeV ( precision: 0.6%)

Most sensitive single method of measuring to mass

# $\Delta M_{Top}$

- Look for a difference between the measured top mass and the antitop mass
- Powerful test of CPT violation
- Use the same procedure as in the previous top quark mass measurement where we assumed $M_{top} = M_{antitop}$, but remove this requirement and allow both to float independently in the fitting




Top quark only quark that decays before hadronizing, giving the possibility for a clean test

CDF Public Note 10777

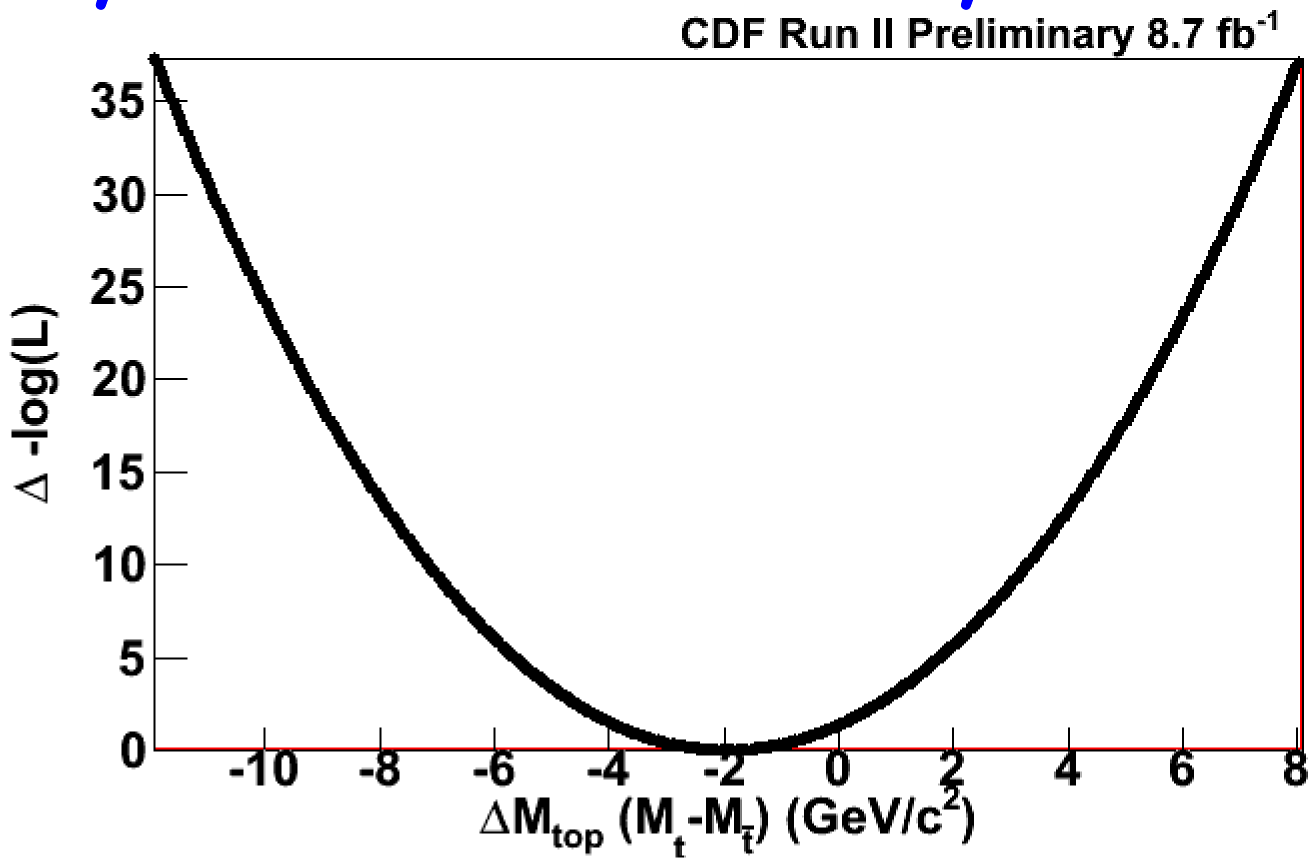
# $\Delta M_{Top}$

**Many Jet Energy systematics uncertainties cancel**

**Result dominated by Statistical Uncertainty**

CDF II Preliminary 8.7 $fb^{-1}$

| Systematic | GeV/$c^2$ |
|---|---|
| Signal Modeling | 0.14 |
| Parton Showering | 0.17 |
| Next Leading Order | 0.16 |
| Jet energy scale | 0.07 |
| Parton Distribution Functions | 0.12 |
| $b$ jet energy | 0.05 |
| $b/\bar{b}$ asymmetry | 0.38 |
| Background shape | 0.20 |
| gg fraction | 0.05 |
| Radiation | 0.10 |
| MC statistics | 0.07 |
| Lepton energy | 0.06 |
| MHI | 0.05 |
| Color Reconnection | 0.23 |
| Total systematic | 0.59 |



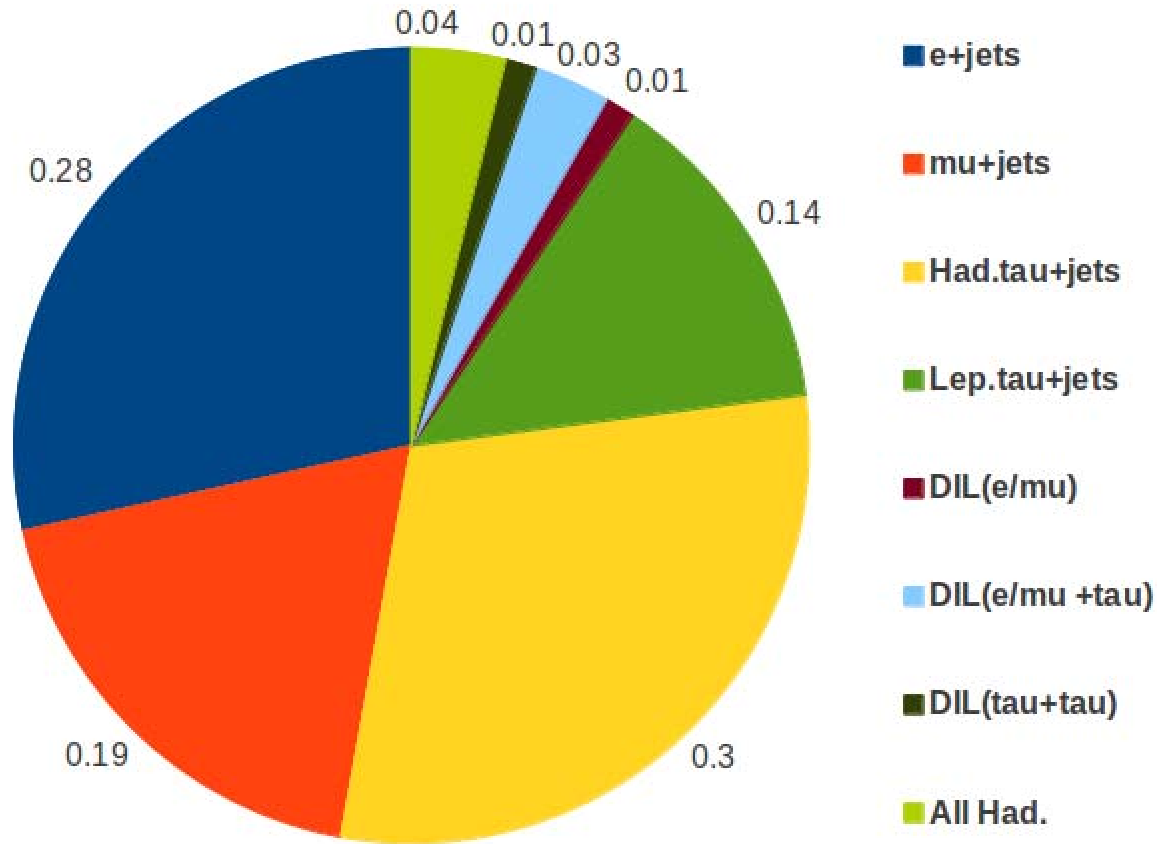

$$\Delta M_{top} = -1.95 \pm 1.11\,(\text{stat}) \pm 0.59\,(\text{sys})\ \text{GeV}/c^2$$

$$= -1.95 \pm 1.26\ \text{GeV}/c^2$$

# Top Mass: Met+Jets

New

- While many measurements of top pairs have come in the lepton+Jets, dilepton, and all-hadronic modes, many more $t\bar{t}$ events show up in our data
- Identify many of them using a "catch-all" analysis which looks for events with Met+Jets where one or more of the jets is *b*-tagged
- Many are from lost leptons or hadronic tau decays



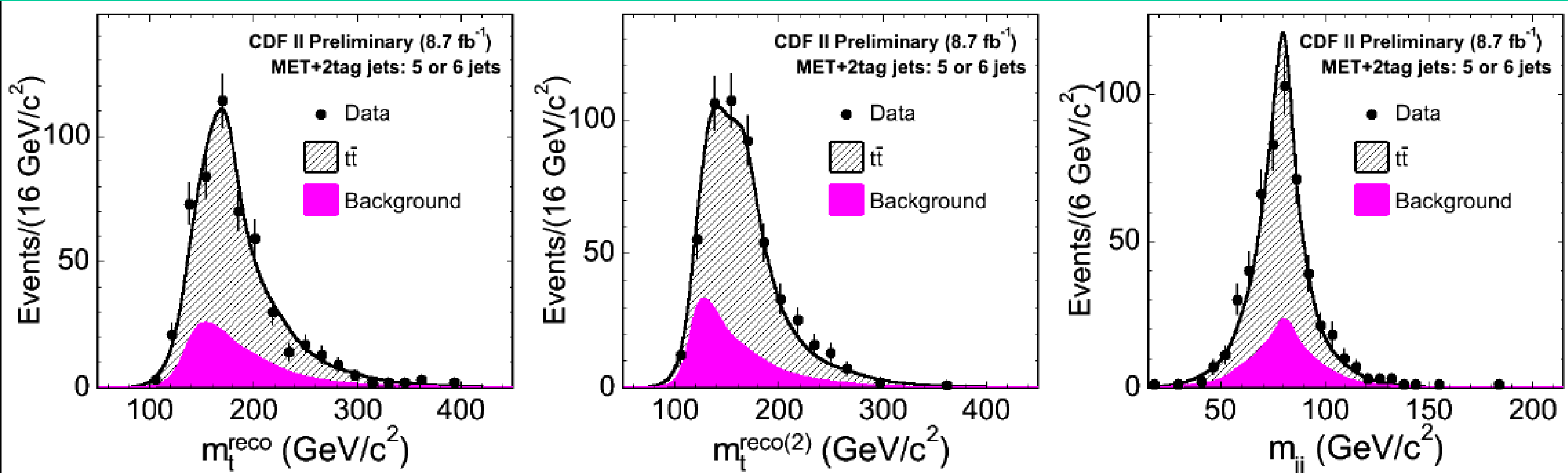

CDF Public Note 10810

# Top Mass: Met+Jets

- Pick up more than 1,500 top candidate events
- Fairly clean sample
- Allows for a strong mass measurement

CDF II Preliminary 8.7 $fb^{-1}$

| b-tagging | jet-multiplicity | $t\bar{t}$ | Background | Total Expected | Observed |
|---|---|---|---|---|---|
| 1tag | 4 jets | $427 \pm 50$ | $262 \pm 22$ | $690 \pm 55$ | 761 |
| | 5 or 6 jets | $801 \pm 70$ | $450 \pm 29$ | $1251 \pm 76$ | 1341 |
| 2tag | 4 jets | $179 \pm 23$ | $43 \pm 11$ | $222 \pm 26$ | 225 |
| | 5 or 6 jets | $373 \pm 37$ | $125 \pm 23$ | $498 \pm 44$ | 550 |

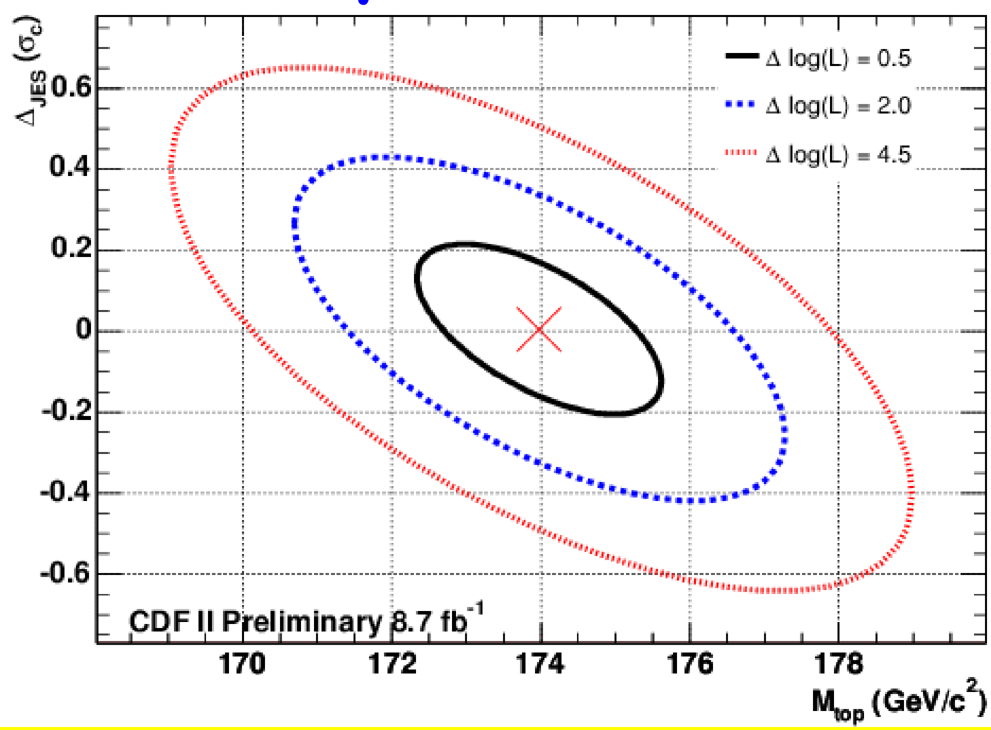


# Top Mass: Met+Jets

- Use many of the same techniques as the Lepton+Jets measurement
- Systematics dominated by the jet energy scale, overall measurement dominated by statistics

CDF II Preliminary 8.7 $fb^{-1}$

| Systematic ($GeV/c^2$) | $\Delta M_{top}$ |
|---|---|
| Residual JES | 0.44 |
| Generator | 0.36 |
| PDFs | 0.16 |
| b jet energy | 0.19 |
| Background | 0.15 |
| gg fraction | 0.27 |
| Radiation | 0.28 |
| Trigger simulation | 0.13 |
| Multiple Hadron Interaction | 0.18 |
| Color Reconnection | 0.28 |
| Calibration | 0.21 |
| Total Effect | 0.87 |




$M_{top}$ = 173.9 ± 1.6(stat.+JES) ± 0.9(syst.) $GeV/c^2$

= 173.9 ± 1.9 $GeV/c^2$

# Conclusions

- Measurements of the top quark continue to be a priority for the community
  - $A_{FB}$ different than the SM predictions in interesting ways
- The Tevatron legacy measurements continue to be some of the most precise results in the world
  - Individual mass measurements approaching 1 GeV each
- Many new results including $A_{FB}$, mass and cross sections in the dilepton final state coming soon

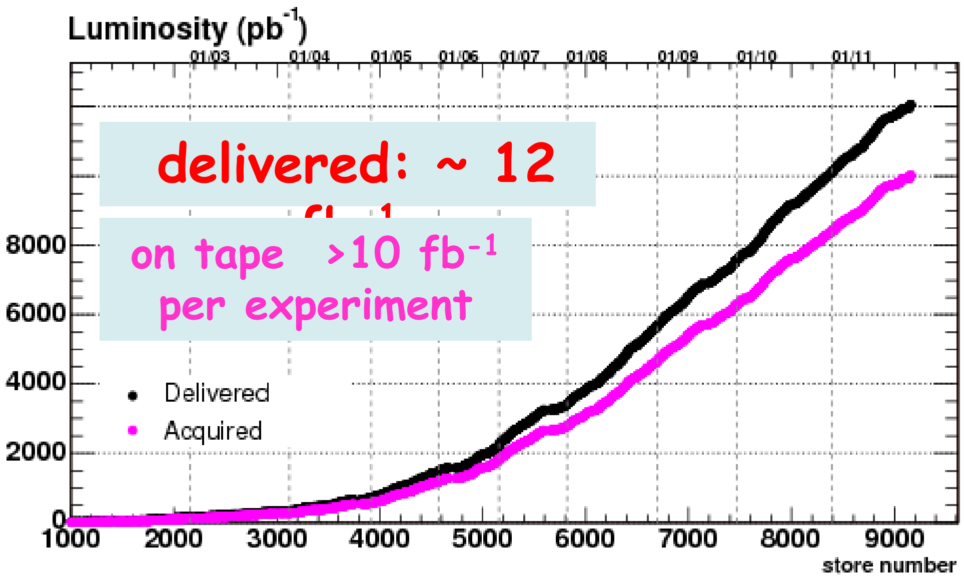

It's an exciting time as we move from the data taking phase to the analysis-only phase at the Tevatron

# Backups

# Abstract

The top-quark, discovered at the Tevatron almost two decades ago, is the heaviest elementary particle known today. Its large mass and short life time make it an ideal probe for studies of the standard model and searches for new physics. These are still intensively pursued with the full CDF Run II data sample. We present recent high-precision measurements of the forward-backward asymmetry in top pair production; of cross sections for top pair production differential in the production angle; of the single top production cross section in the s- and t-channel separately; of the top mass and of the mass difference between the top and anti-top quarks; of the top decay branching ratio into a W boson and a bottom quark; and of the helicity states of the W boson in top pair decays.

# Basic Top Stuff




Results shown in the following based on datasets up to 8.7 $fb^{-1}$

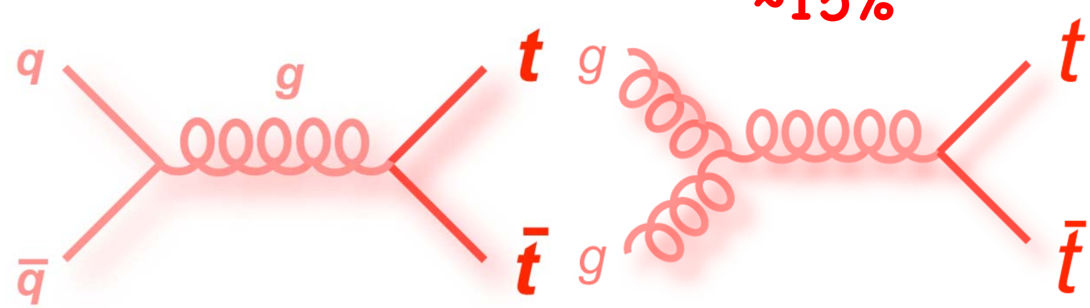
- QCD pair production

  $\sigma_{SM} = 7.46^{+0.48}_{-0.67}$ pb

  (for $m_{Top}$= 172.5 GeV)

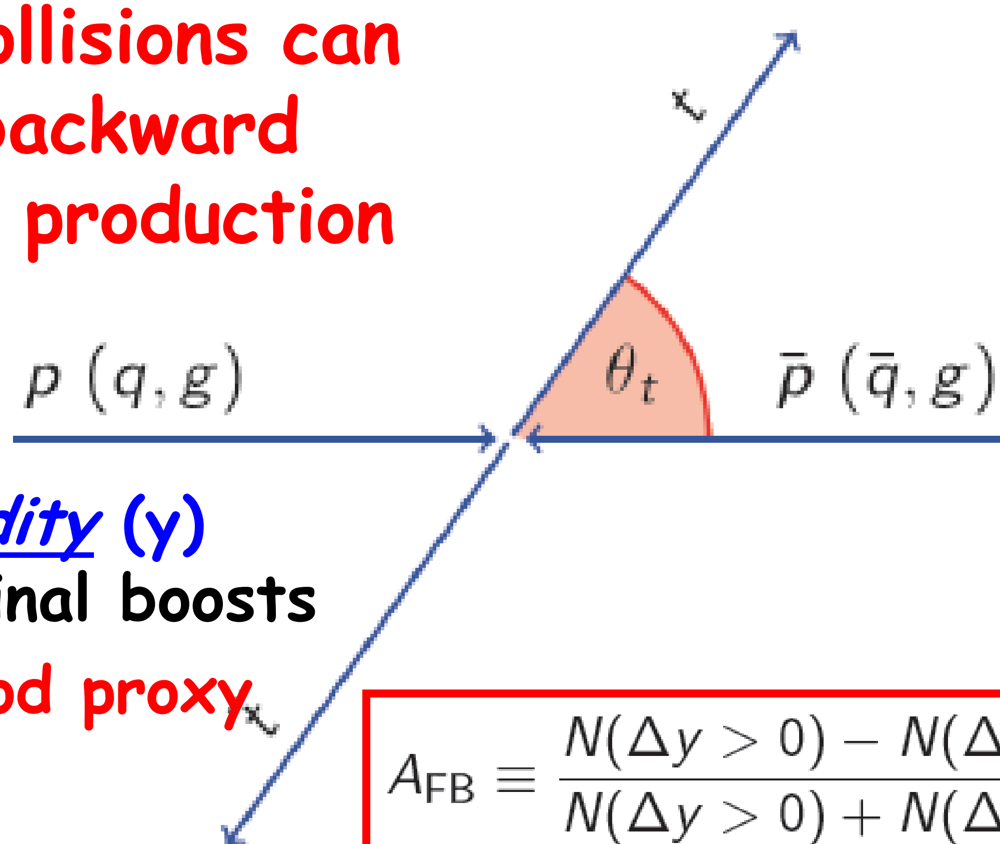
PRD 78, 034003 (2008)

~85% ~15%



# What are $A_{FB}$ and $\Delta Y$?

In proton-antiproton collisions can measure the forward-backward asymmetry ($A_{FB}$) in the production angle




Transform from $\Theta_t$ to *rapidity* (y)

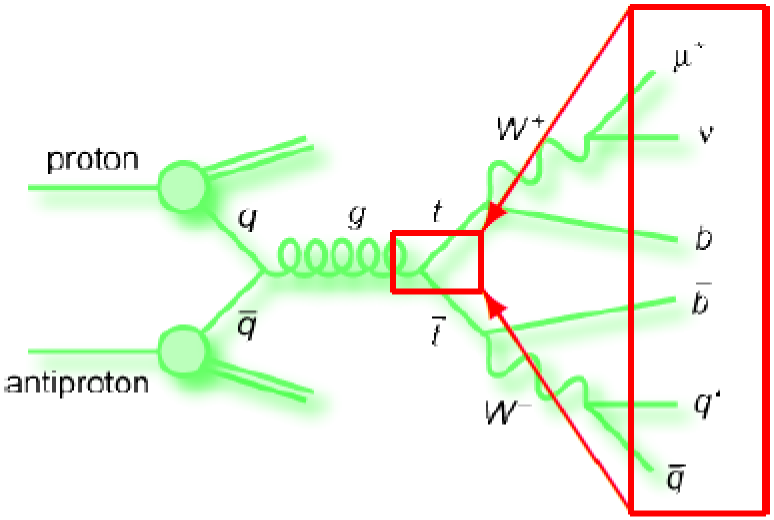
Invariant under longitudinal boosts

Rapidity difference is a good proxy for production angle

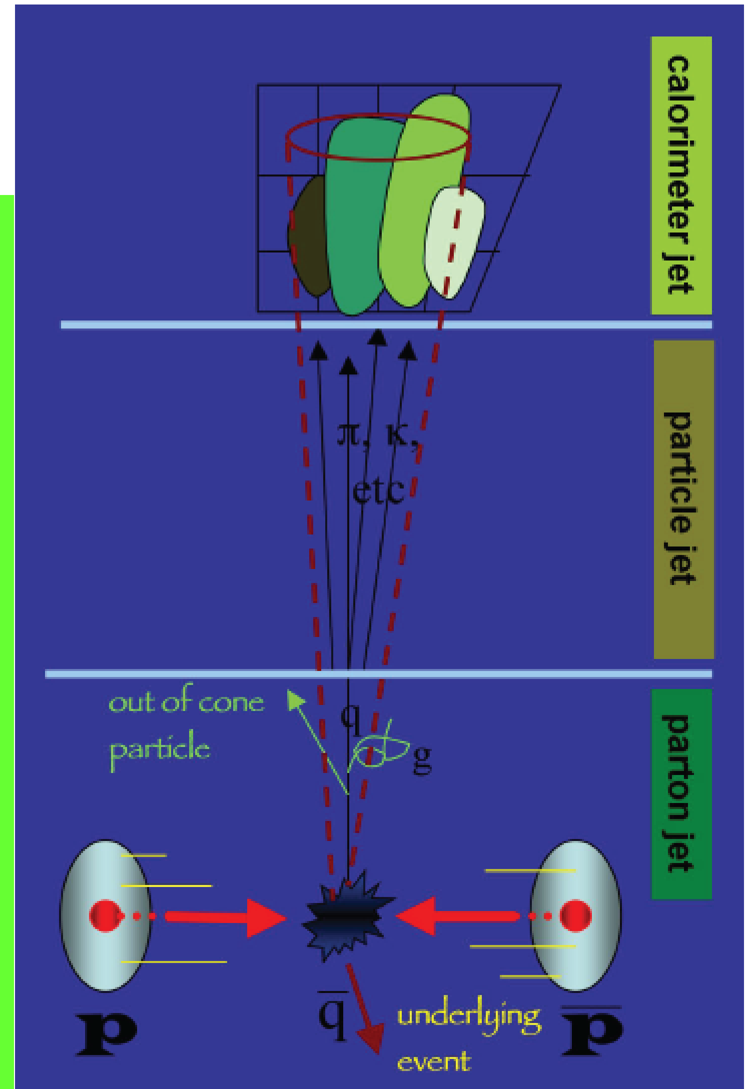
$$A_{FB} \equiv \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$\text{Measure } \Delta y = y_t - y_{\bar{t}}, \text{ where } y = \frac{1}{2} ln\left(\frac{E+p_z}{E-p_z}\right)$$

Note: y doesn't have the usual geometric angle many of us are used to.
At hadron colliders we usually use pseudo-rapidity which assumes m=0
→ Here *E* and *p* not close to equal because of the top mass



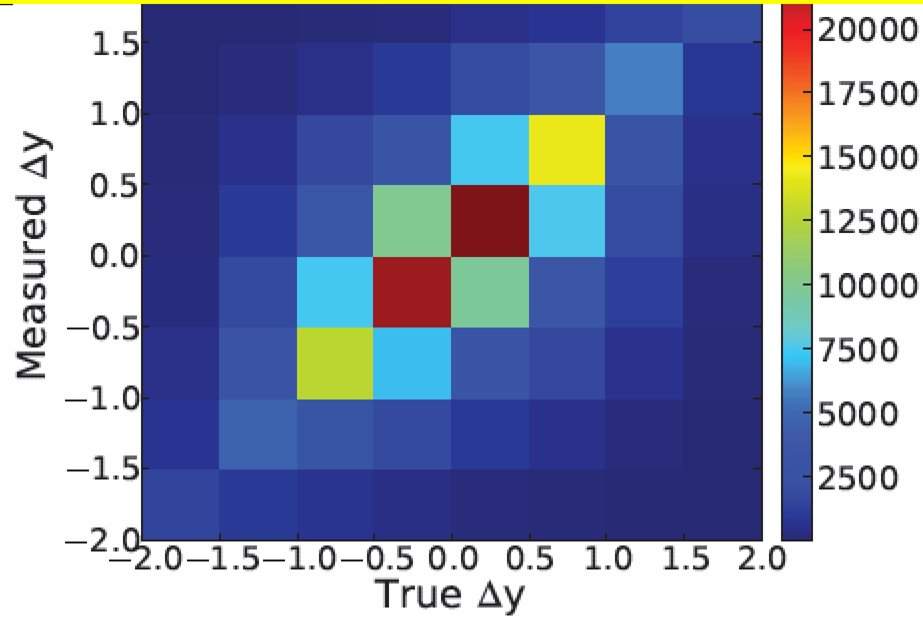

# Working our back to Parton Level $A_{FB}$

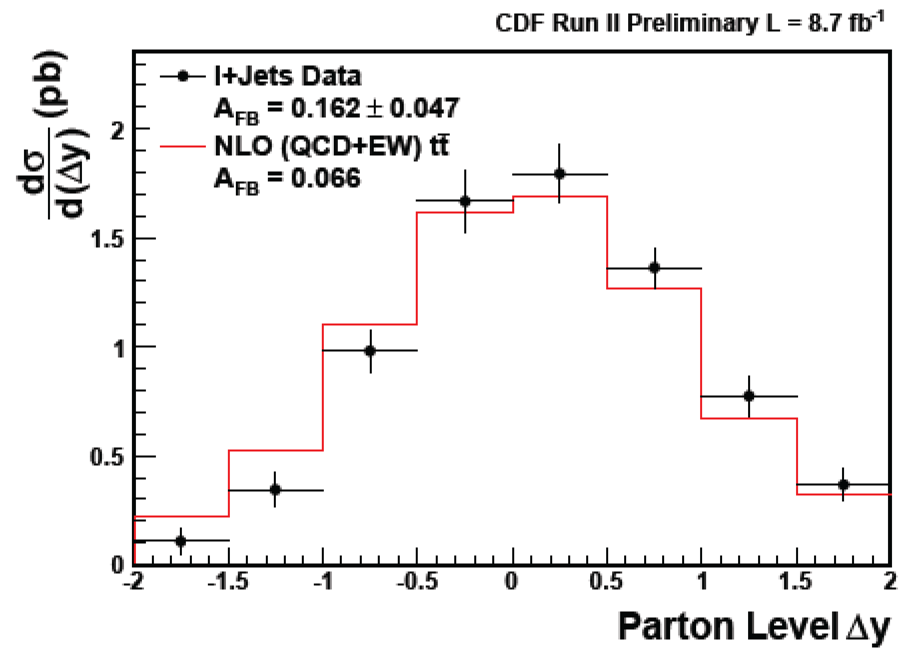



- Correct for
  - Finite Detector resolution
  - Smearing from incorrect reconstruction
  - Selection Cuts
  - Geometry
  - Trigger
  - Statistics
- Acceptance correction bin-by-bin of MC truth before and after selection

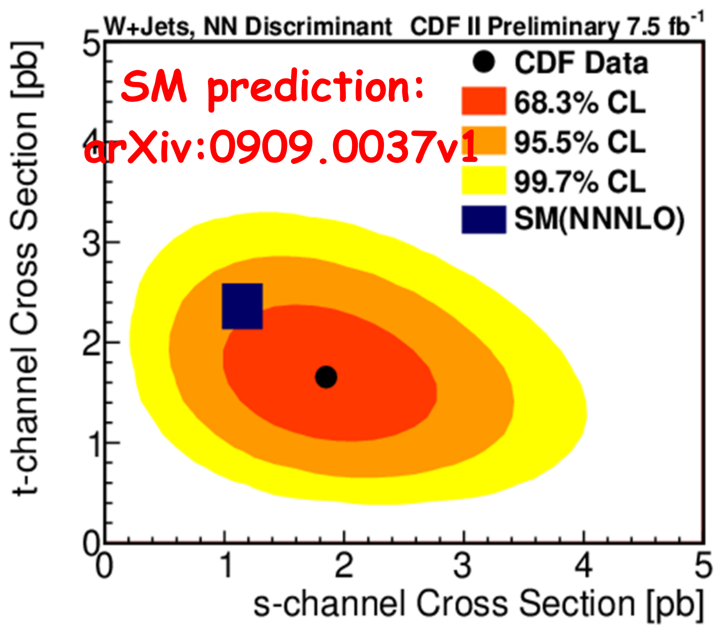
# A Full Correction Matrix Method

- Estimate detector response matrix $S$ from Monte Carlo
- Linear equation for corrected data $\vec{x}$ from data $\vec{b}$: $S\vec{x} = \vec{b}$
- Inverse problem is ill-conditioned
- Can only be solved in least squares sense ($\min \left| S\vec{x} - \vec{b} \right|^2$)
- Even then, solution grossly magnifies statistical imprecision
- Use technique from math. stats.: Tikhonov regularization (Höcker and Kartvelishvili 1995)
- Expect true parton level distribution to be smooth
    - Many sources of systematic uncerta
    - Statistical uncertainty dominates systematic uncertainty



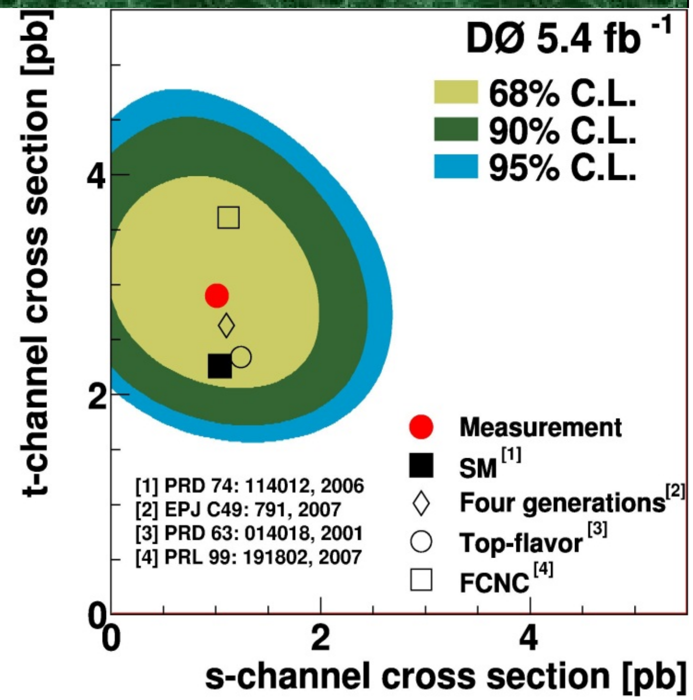



# Single Top Stuff




- Measured cross section:
  - $\sigma_s = 1.81^{+0.63}_{-0.58}$ pb
  - $\sigma_t = 1.49^{+0.47}_{-0.42}$ pb
- SM Prediction:
  - $\sigma_s^{SM} = 1.05 \pm 0.07$ pb
  - $\sigma_t^{SM} = 2.10 \pm 0.19$ pb
  - $\sigma_{wt}^{SM} = 0.22 \pm 0.08$ pb (Effect negligible)

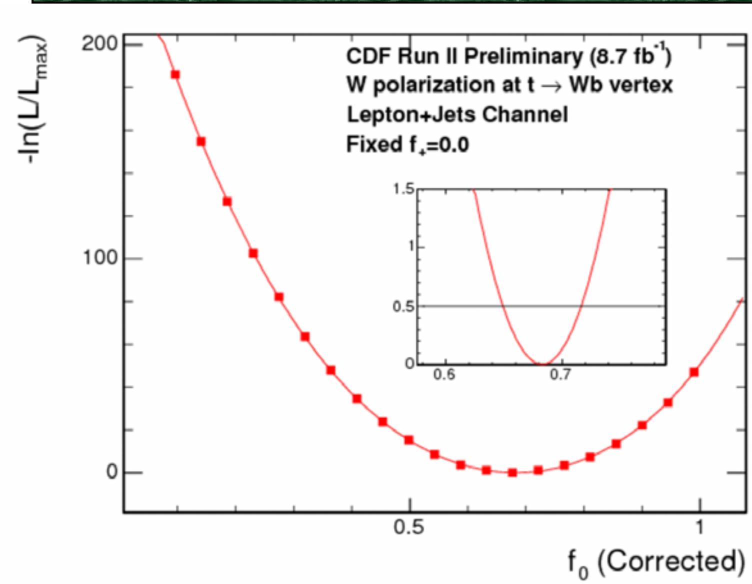
(± ~33%)

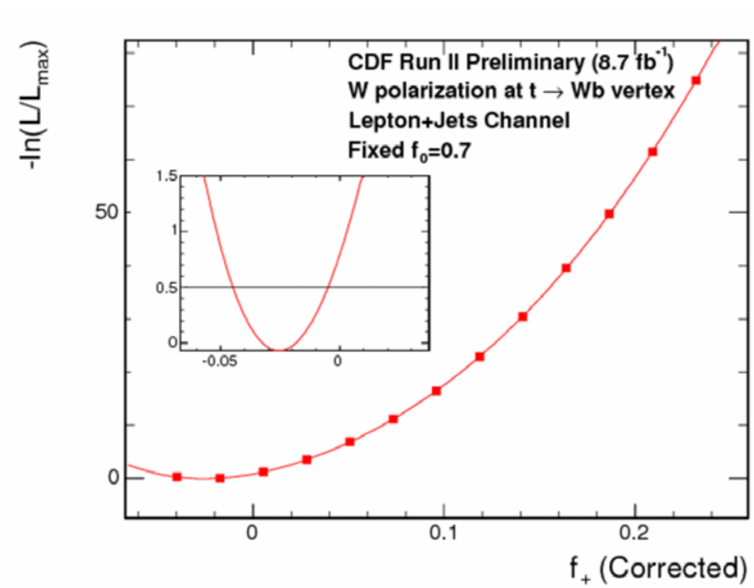


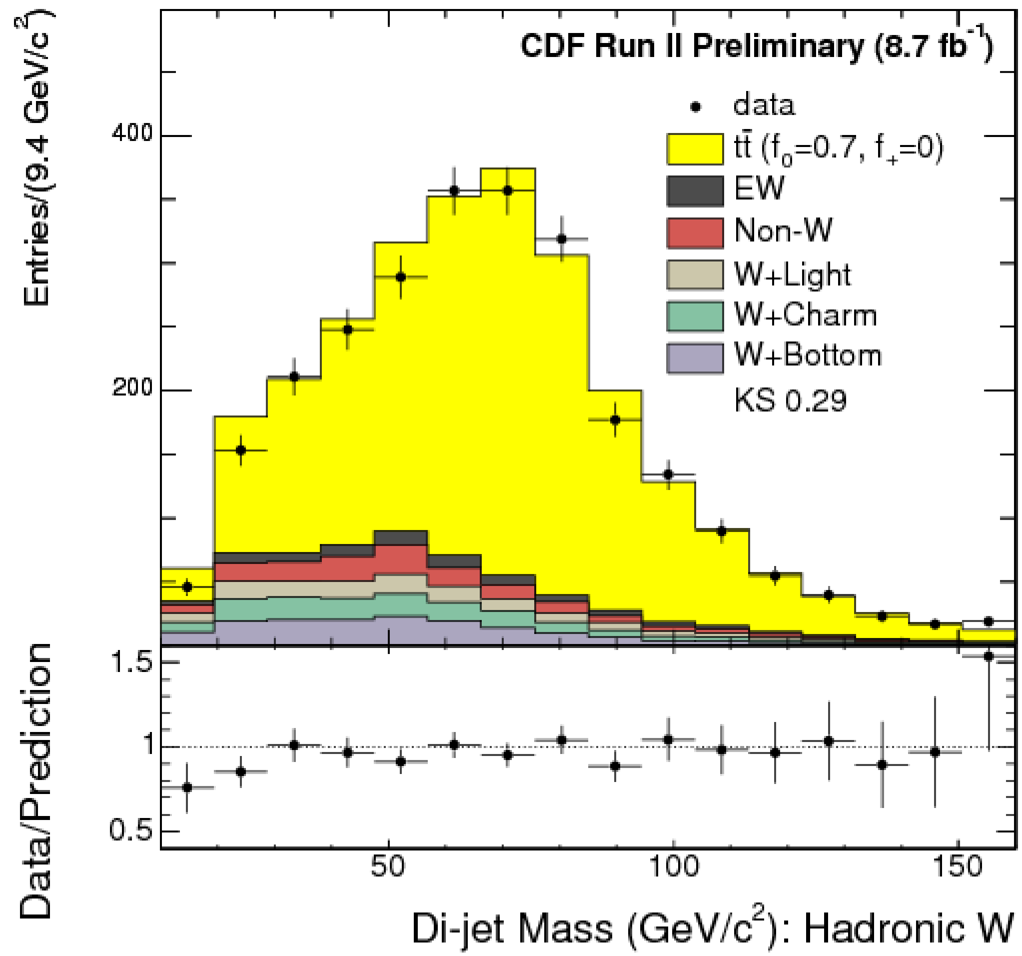

- Measured cross section:
  - $\sigma_s = 0.98 \pm 0.63$ pb
  - $\sigma_t = 2.90 \pm 0.59$ pb
- SM Prediction:
  - $\sigma_s^{SM} = 1.04 \pm 0.04$ pb
  - $\sigma_t^{SM} = 2.26 \pm 0.12$ pb

(± 20%)

# W Helicity Backups

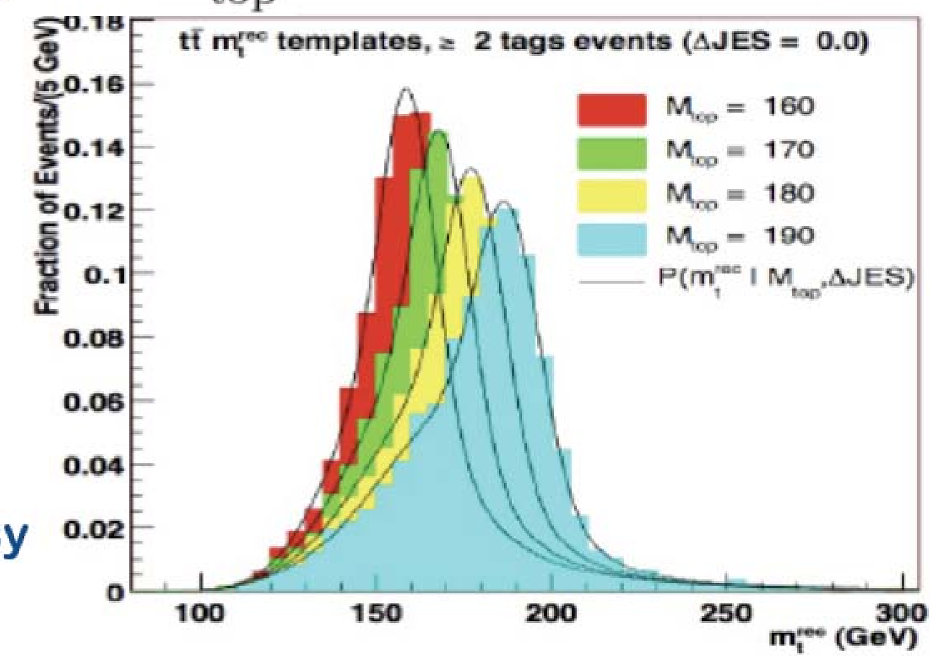


# Top Mass Stuff

- The measurements shown today are based on:
  - Template method
  - Matrix Element method
- Template method:
  - Pick a set of variables $x$ sensitive to $m_{\text{top}}$
  - Create "templates" = distributions of $x$ using MC:
    - for signal: $x = x(m_{\text{top}})$, e.g. $x = m_{\text{top}}^{\text{reco}}$
    - for background
  - Maximise the likelihood of their consistence with the data
  - → Advantages:
    - few assumptions
    - fairly straight forward
    - combination of channels easy



# More Top Mass Stuff

- The measurements shown today are based on:
  - Template method
  - Matrix Element method
- Matrix Element method:
  - Calculate p.d.f. on an event-by-event basis:

$$P_{\rm evt}(x, m_{\rm top}) \propto f P_{\rm sig}(x, m_{\rm top}) + (1-f) P_{\rm bgr}(x)$$

  - The clue:

$$P_{\rm sig}(x, m_{\rm top}) \equiv \frac{1}{\sigma_{t\bar{t}}(m_{\rm top})} \int W(x,y) d\sigma_{t\bar{t}}(y, m_{\rm top})$$

$$\propto |\mathcal{M}|^2(y, m_{\rm top})$$

    - For each event, we calculate $P_{\rm sig}(x, m_{\rm top})$ based on its consistency to come from $t\bar{t}$ production, depending on $m_{\rm top}$
    - Use Transfer Functions $W(x,y)$ to map parton level quantities $y$ to reco level quantities $x$.
  - → Maximal use of stat. information on event-by-event basis!
    - *(Disadvantage: high computational demand)*

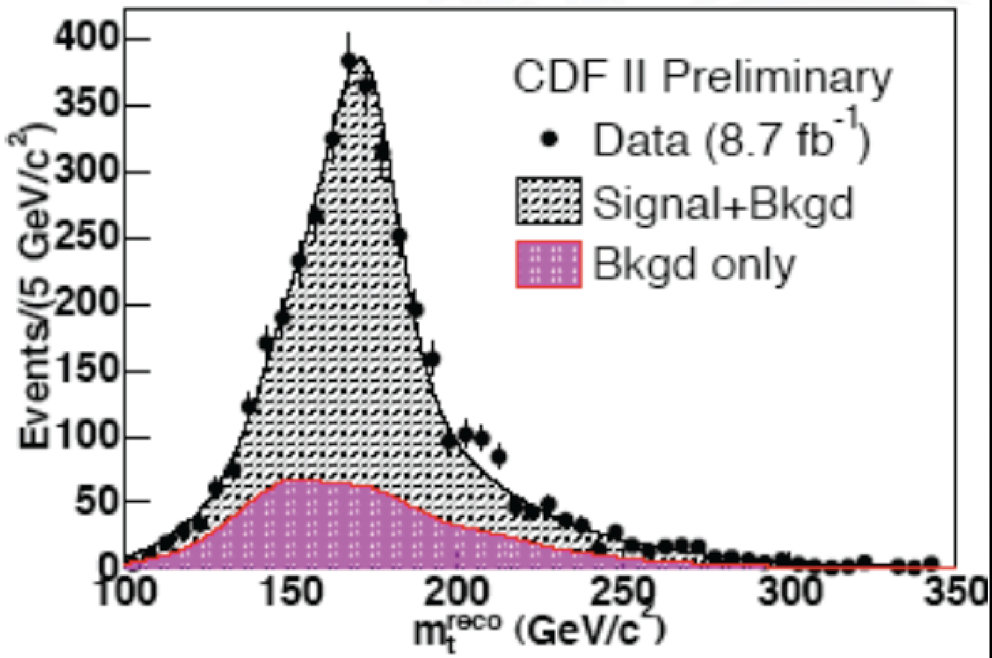
# Top Mass Stuff: Lepton+Jets

- Template method in lepton+jets final states, CDF (8.7 fb$^{-1}$)
  - Reconstruct the event kinematics by minimising:

$$\chi^2 = \Sigma_{i=\ell,4jets}\frac{(p_T^{i,fit}-p_T^{i,meas})^2}{\sigma_i^2}+\Sigma_{j=x,y}\frac{(U_j^{fit}-U_j^{meas})^2}{\sigma_j^2}$$

$$+\underbrace{\frac{(M_{jj}-M_W)^2}{\Gamma_W^2}}_{\text{JES constraint}}+\underbrace{\frac{(M_{\ell\nu}-M_W)^2}{\Gamma_W^2}}_{\text{MET constraint}}+\underbrace{\frac{(M_{bjj}-m_t^{\mathrm{reco}})^2}{\Gamma_t^2}+\frac{(M_{b\ell\nu}-m_t^{\mathrm{reco}})^2}{\Gamma_t^2}}_{m_{top}\text{ extraction}}$$

  - Consider jet-parton assignments consistent with b-tagging
  - Form templates from:
    - $\mathrm{m}_t^{\mathrm{reco}}$ : best jet-parton ass't
    - $m_t^{\mathrm{reco(2)}}$: second-best ass't
    - $m_{\mathrm{jj}}$ : dijet invariant mass




*CDF Conf-Note 10761 (2012)*

# R Measurements

## Ratio of branching fractions R

in the SM the ratio $R = \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$ is constrained

by CKM unitarity to be R=1 → R < 1 could indicate new physics

measure R simultaneously with the ttbar cross section
dropping the assumption R=1

**CDF 7.5 fb$^{-1}$ (l+jets)**

$$\sigma_{t\bar{t}} = 7.4 \pm 1.1 \quad \text{pb}$$
$$R = 0.91 \pm 0.09$$
$$|V_{tb}| = 0.95 \pm 0.05$$

stat +syst uncertainties

**D0 5.4 fb$^{-1}$ (dilepton & l+jets)**

$$\sigma_{t\bar{t}} = 7.74^{+0.67}_{-0.57} \quad \text{pb}$$
$$R = 0.90 \pm 0.04$$
$$|V_{tb}| = 0.95 \pm 0.02$$
$$|V_{tb}| > 0.88 \quad @\, 99.7\%\ \text{CL}$$

stat +syst uncertainties

PRL 107, 121802 (2011)

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# Single Top Stuff

- Train the NN with 11~14 variables in four channels (2, 3 jets with 1, 2 b-tags)
- Train for s-channel in 2 jet 2 b-tags, train for t-channel in the rest channels
- Train the NN with systematic mixed samples for better uncertainty constraint (~3% improvement expected)

- Main analysis channel: Lepton+Jets
  - Only one isolated lepton
  - Large missing Et from neutrino
  - At least 2 jets
  - At least one of the jets is b-tagged

- Background rejection:
  - CDF: Veto QCD, Dilepton, Z and Cosmic
- Still large backgrounds share similar final state after the background rejection.