Top Quark Physics at Tevatron

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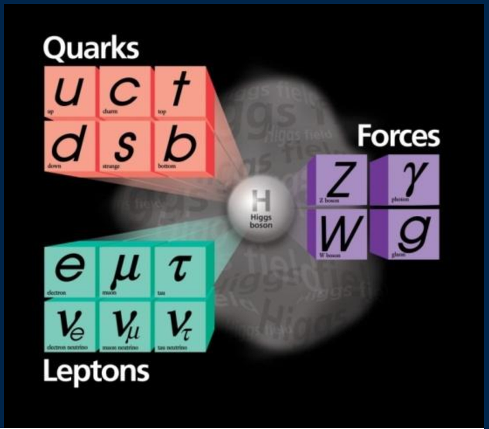
Outline

- Introduction
- Exploring top properties
  - Top quark production
  - Top quark mass
  - Other top properties
  - Search for beyond the Standard Model (SM) physics
- Summary and prospects

The Top Quark

- Existence required by the SM
  - Spin 1/2, charge +2/3, weak-isospin partner of the bottom quark
- Discovered in 1995 at Tevatron
- Mass ~173.3 GeV/c^2
  - Only SM fermion with mass at the EW scale
- Top decays before hadronization: $\Gamma \sim 1.4$ GeV $\gg \Lambda_{QCD}$
  - Provide an unique opportunity to study a "bare" quark



Today's "Top" Story

SPECIAL EDITION

IS IT THE TOP QUARK? YES!!!

CDF

"The discovery of the top quark is a great achievement for the collaborations."

- John Peoples, Fermilab Director 1989-1999

"Last April, CDF announced the first direct experimental evidence for the top quark, but at that time we stopped short of claiming a discovery. Now, the analysis of about three times as much data confirms our previous evidence and establishes the discovery of the top quark."

- Bill Carithers, CDF

Scientists at CDF (top) and DZero (bottom) simultaneously push the buttons on their computers to submit two research papers to Physical Review Letters on Friday, February 24, 1995 at 11 a.m. The papers described the observation of top quarks produced in the Tevatron.

DZero

"This monster, compared with all the other quarks, is like a big cowbird's egg in a nest of little sparrow eggs. It's so peculiar it must hold clues to some important new physics."

- Paul Grannis, DZero

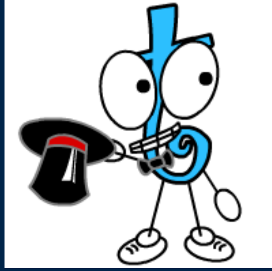
"We're so elated by the discovery of the top quark that we haven't yet begun to sift all the data, but this particle is so astonishingly heavy that its decay may give us hints of a lot of other things, perhaps even of supersymmetric particles."

- Boaz Klima, DZero

"This discovery serves as a powerful validation of federal support for science. Using one of the world's most powerful research tools, scientists at Fermilab have made yet another major contribution to human understanding of the fundamentals of the universe."

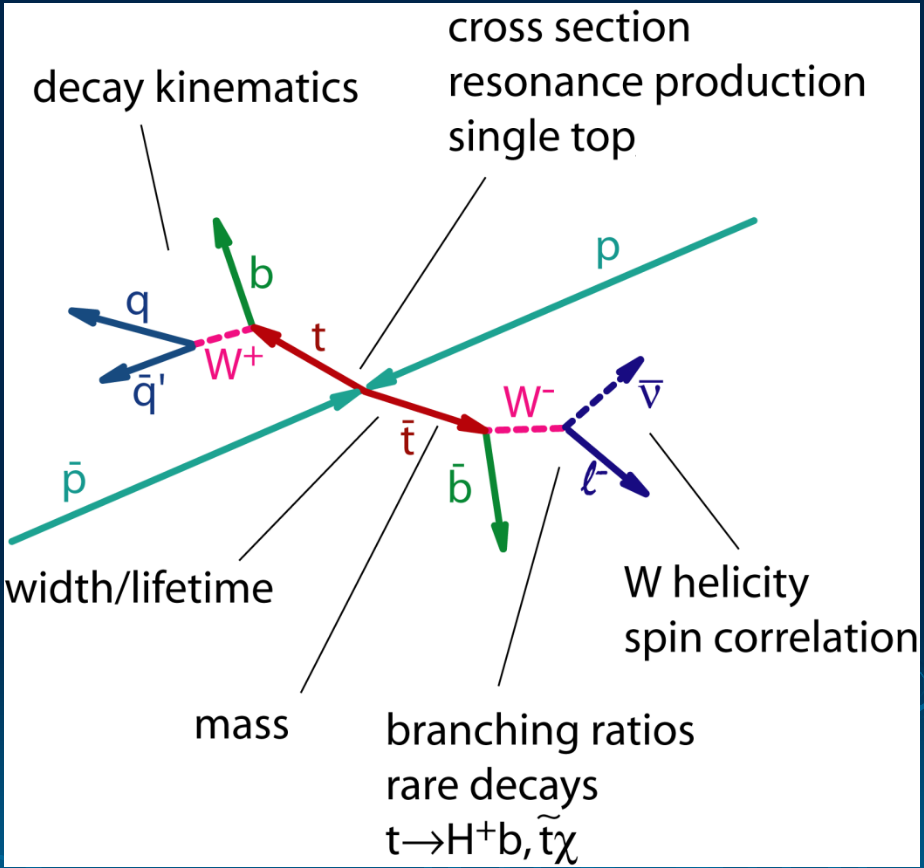
- Hazel R. O'Leary, Secretary of Energy 1993-1997

Why Study Top Quarks?



Try to address some of the questions:

- Why is top so heavy ?
- Is top related to the EWSB mechanism?
- Is it the SM top?
- Search for beyond SM physics
  - Does top decay into new particles?
  - Couple via new interactions?

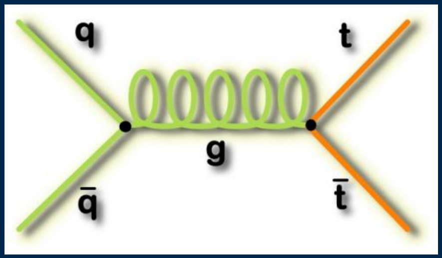


Top Quark Production at Tevatron

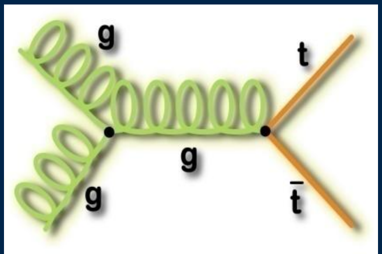
- Predominantly pair produced via strong interaction
  - $\sigma_{tt} = 7.45^{+0.72}_{-0.63}$ pb

  for m_{top}=172.5 GeV/c^2

  (Nucl. Phys. Proc. Suppl. 183, 75 (2008))



~85% from qq→ttbar



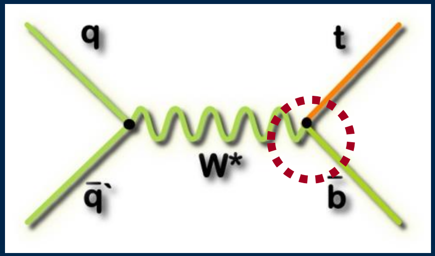
~15% from gg→ttbar

Top Quark Pair Production

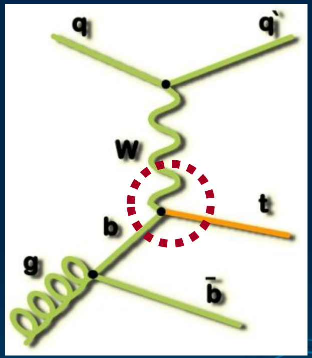
- EW single top production
  - $\sigma_{s\text{-}channel}$ =0.88 ± 0.11 pb
  - $\sigma_{t\text{-}channel}$ =1.98 ± 0.25 pb

  for m_{top} = 175 GeV/c^2

  (PRD 70, 114012 (2004))



s-channel

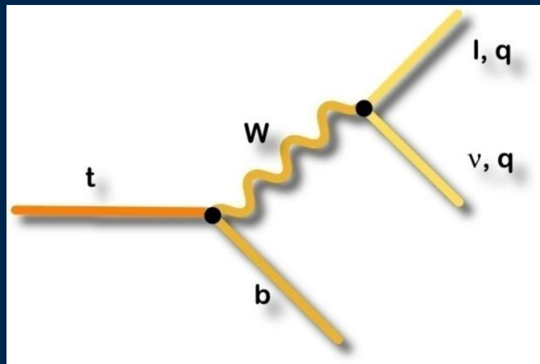


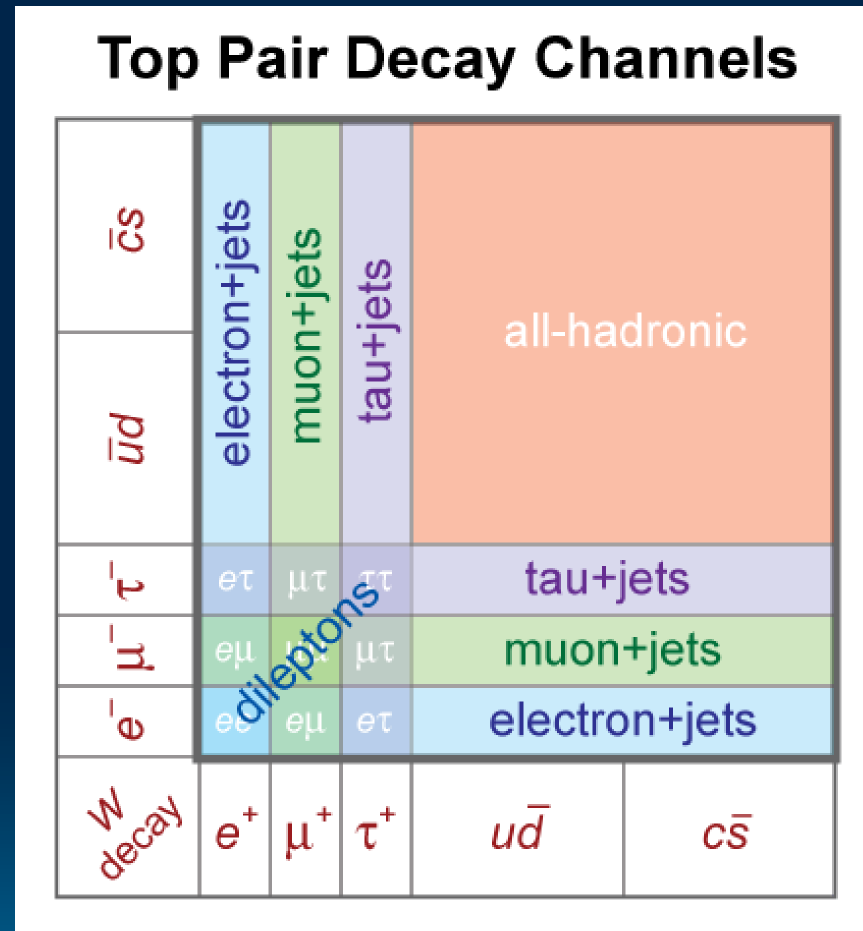
t-channel

EW Single Top Production

Rare at Tevatron: One top pair (ttbar) per 10 billion inelastic collisions

Top Quark Decay

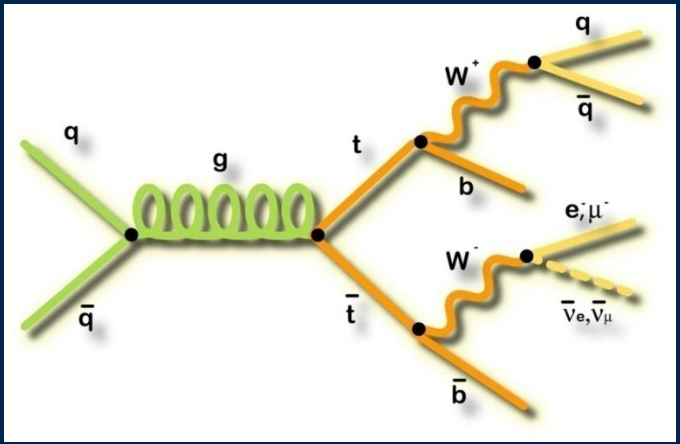




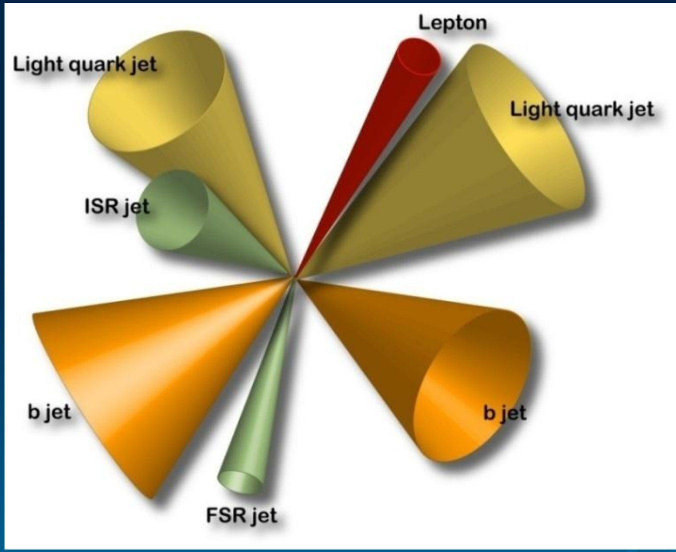
- In the SM Br(t $\rightarrow$Wb) ~ 100%
- Top pair decay channels
  - Dilepton : *l νl νbb*
  - Lepton+jets : *l νqqbb*
  - All-hadronic: *qqqqbb*
- Single top decay channels
  - s-channel: *l νbb*
  - t-channel: *l νbq(b)*

(overwhelming background in hadronic W decays for single top)

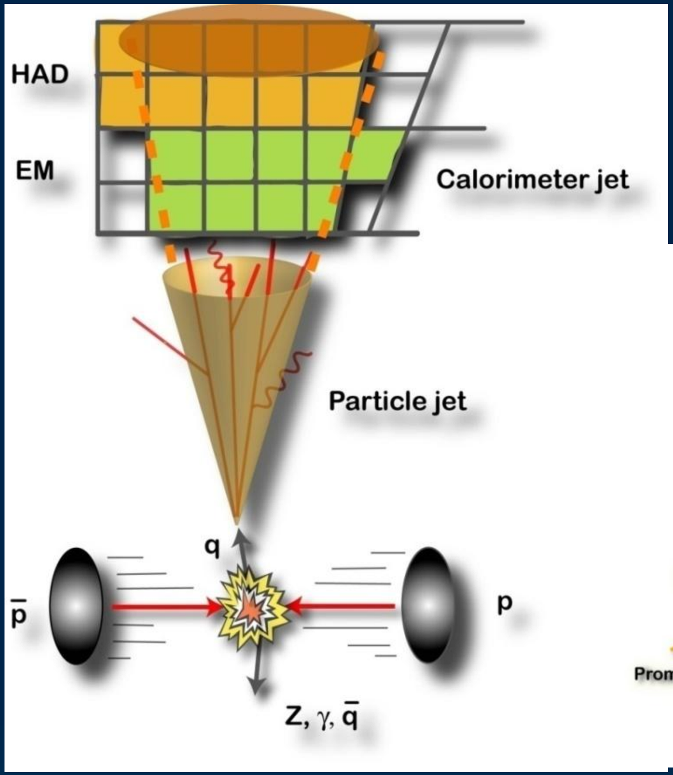
Experimental Essentials



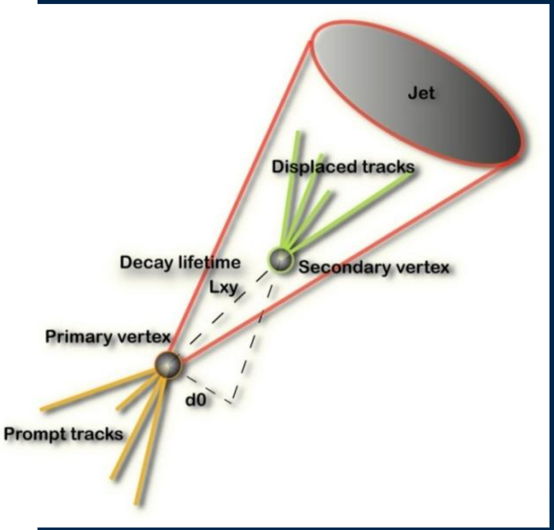
Final State from LO Diagram



What we measure



Jet Energy Scale



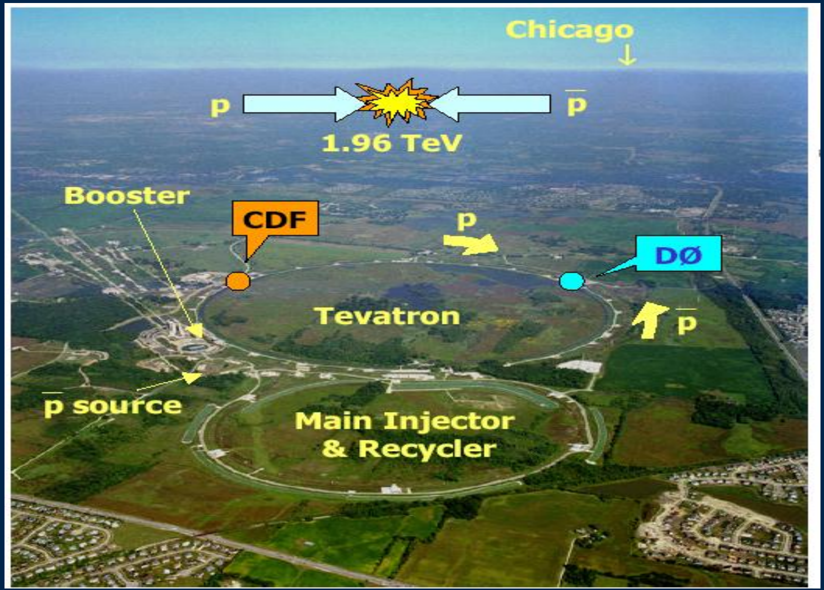
b-tagging

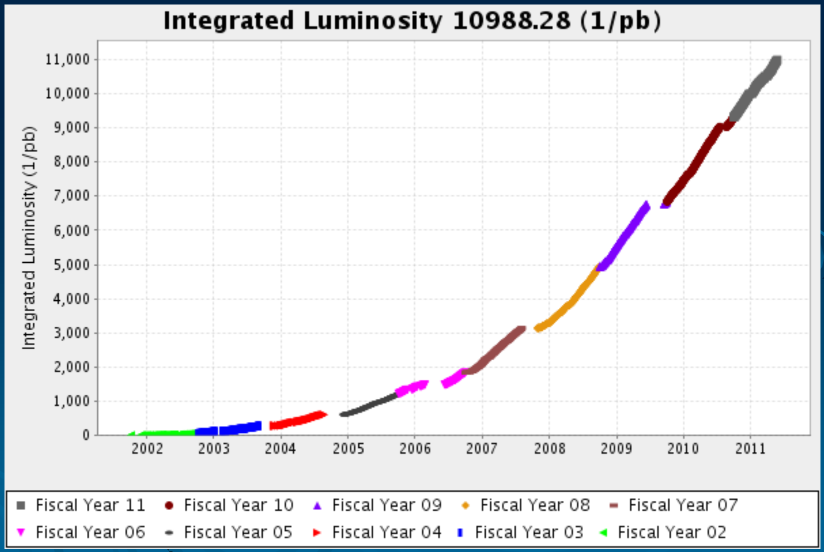
- And more: background and signal modeling, background estimation, jet-parton assignment, combinatorics etc.

Data Sample

- Tevatron Run II (2001-2011) : $\sqrt{s}$ = 1.96 TeV
- Total integrated luminosity delivered ~11 fb^{-1}
  - ~9 fb^{-1} recorded per experiment
- Results presented with ≤6 fb^{-1}
- Estimated ttbar signal events (S) and signal-to-background (S/B) events in 6 fb^{-1} data

Lepton+Jets : e/μ+≥4 jets, ≥1 b-tag S ~1600, S/B ~ 3:1
Dilepton : 2 e/μ + ≥2 jets, ≥0 b-tag S ~280, S/B ~ 2:1
All hadronic : 6-8 jets , ≥1 b-tag, NN selection, S~1800, S/B ~ 1:4





Top Physics at Tevatron

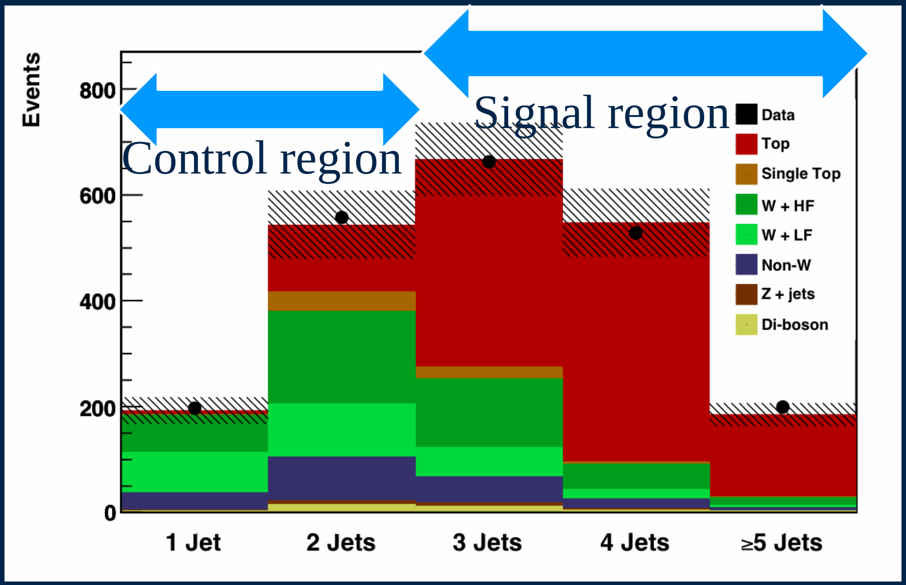
Robust program of top quark measurements

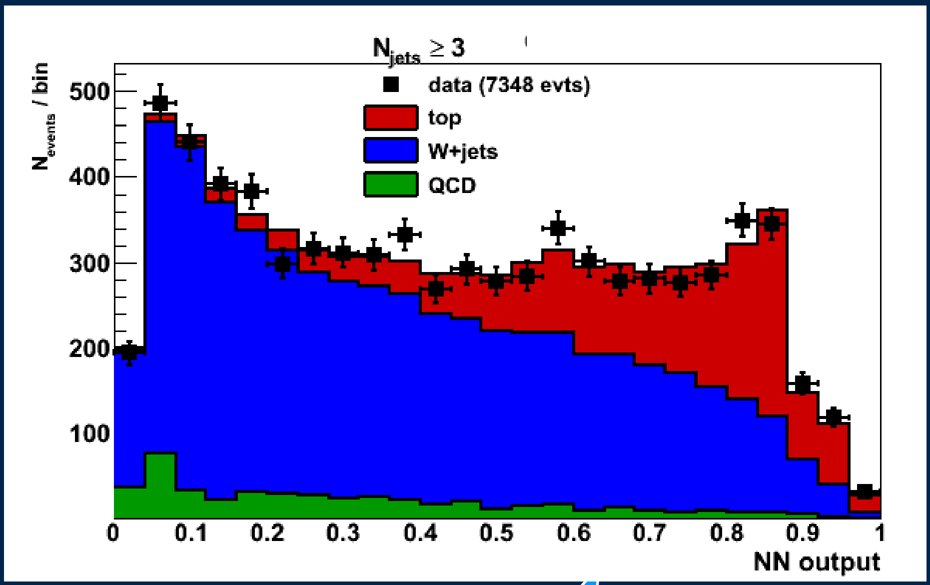
- Many measurements in all the different channels → consistency
- Different methods of extraction with different sensitivity → confidence
- Combine all channels and all methods → precision

Top Pair Production Cross-Section

- Tests QCD in very high Q^2 regime.
- Compare measured cross sections among various ttbar final states
    - Anomalies in the tt rate would indicate the presence of non-QCD production channels: for example resonant state $X \rightarrow$ ttbar
- Provides important sample composition for all other top property measurements.

ttbar Cross Section : Lepton+Jets





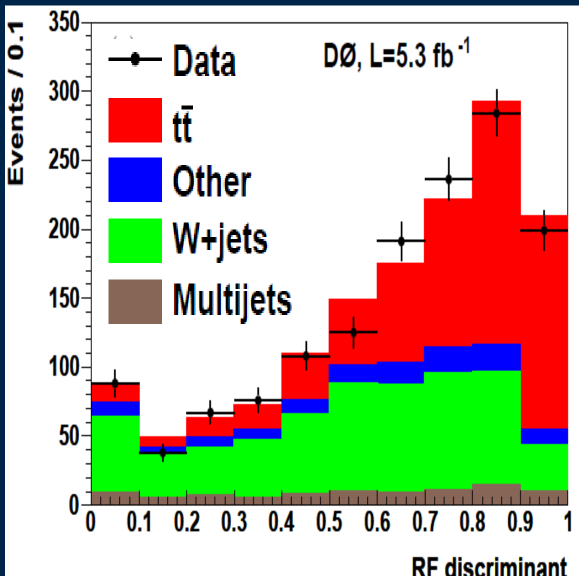
- Two complimentary methods
  - Requiring ≥1 b-tag
  - A topological method using pre-tag (≥0 b-tag)
- Normalizing with respect to Z/γ* cross section
  - Reduce uncertainty from luminosity determination

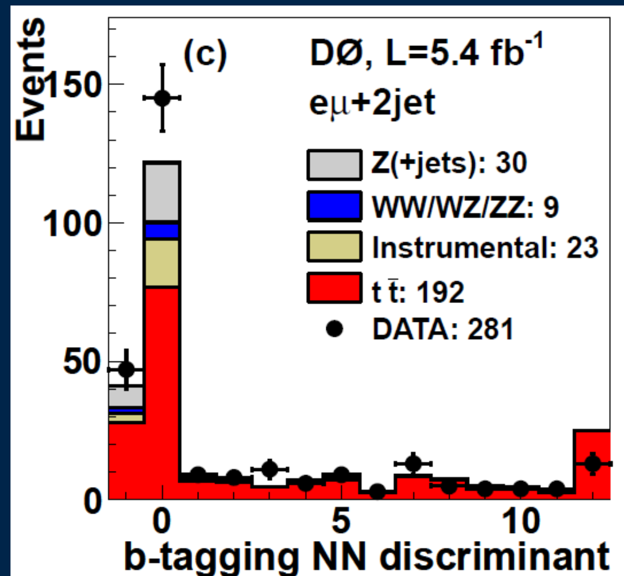
Most Precise
$\Delta\sigma/\sigma$ = 6.7%

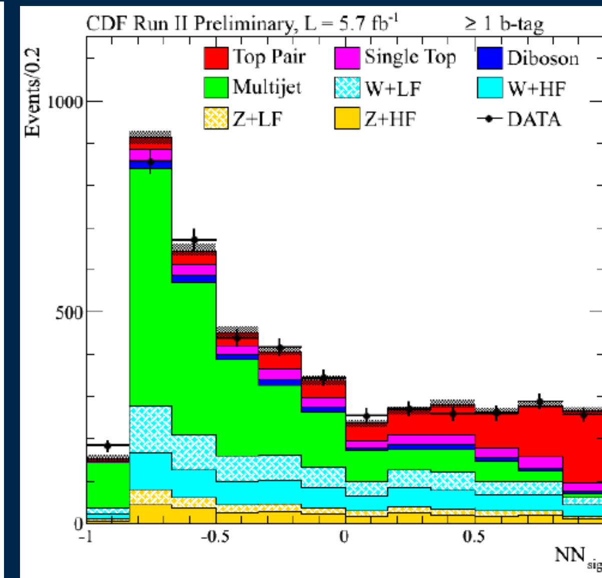
σ_{ttbar} = 7.70 ± 0.52 pb, for m_{top} = 172.5 GeV/c^2

Tom Schwarz's talk on June 1

Recent Results : σ_{ttbar}







- D0, leptpn+jets: based on kinematics of ttbar and b-tagging.

$$\sigma_{ttbar} = 7.78\ ^{+0.77}_{-0.64}\ \text{pb},\ \Delta\sigma/\sigma = 9\%$$

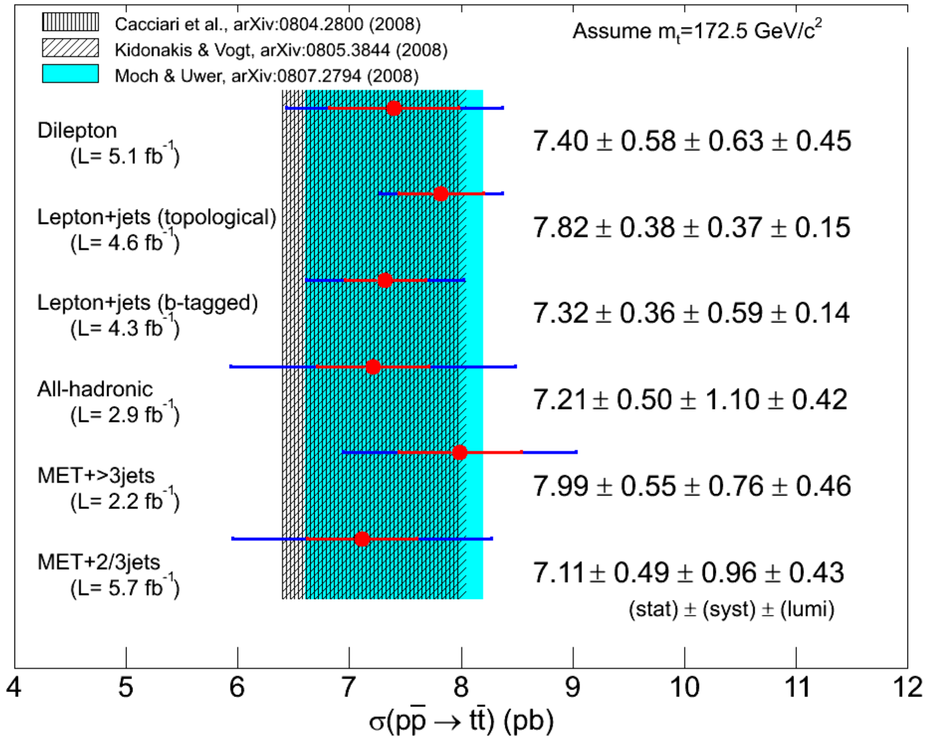
- D0, dilepton: Fit the b-tagging NN output, most precise in dilepton channel

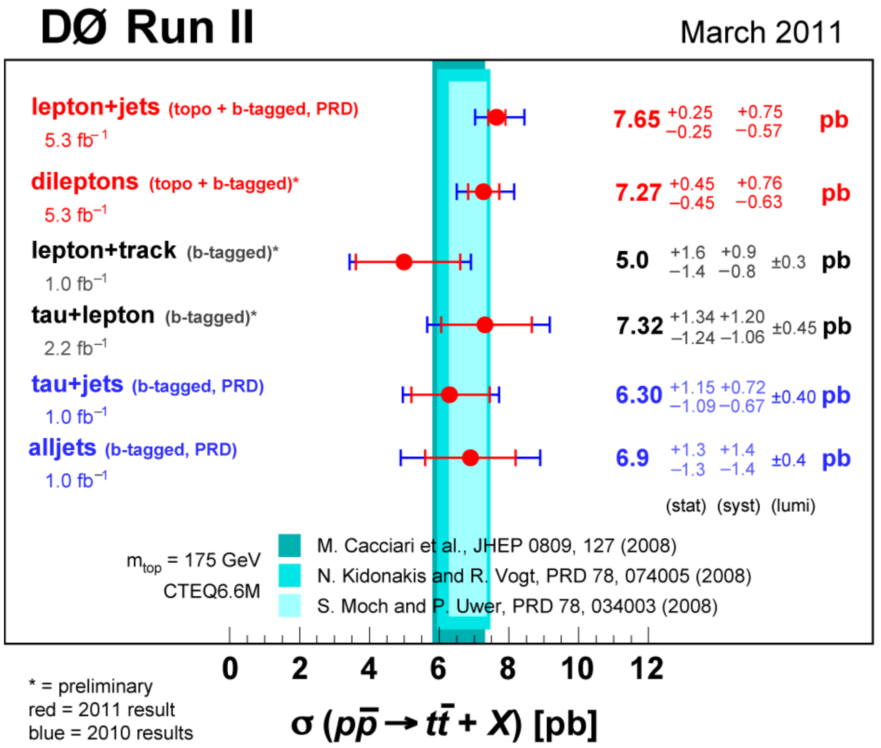
$$\sigma_{ttbar} = 7.36\ ^{+0.90}_{-0.79}\ \text{pb},\ \Delta\sigma/\sigma = 11\text{-}12\%$$

- CDF, MET+jets: Use MET and jets to select event, veto lepton. Background to Higgs searches in the low mass region

$$\sigma_{ttbar} = 7.12\ ^{+1.20}_{-1.12}\ (\text{stat + syst})\ \text{pb}$$

ttbar Cross Section Results

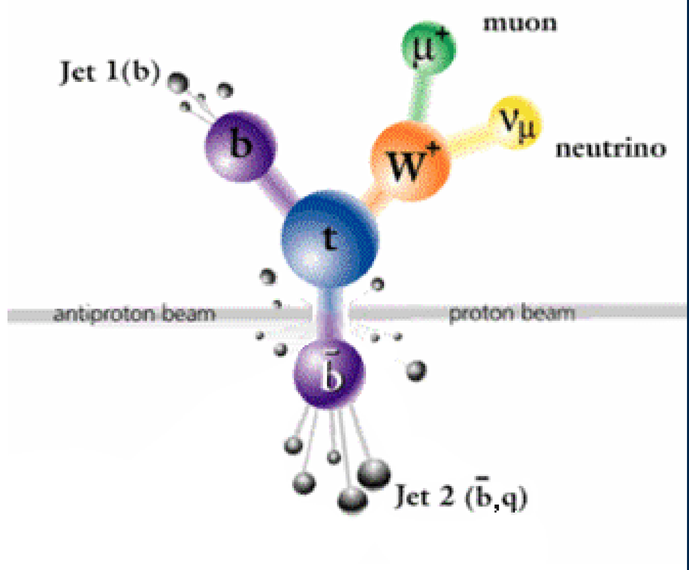


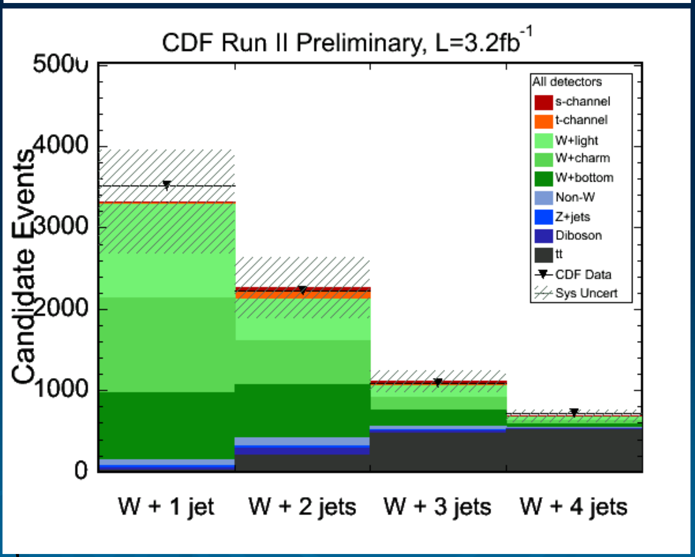


- Consistent among channels, methods and experiments
- Uncertainties comparable to the theoretical uncertainty
- Most sensitive measurements limited by systematic uncertainties

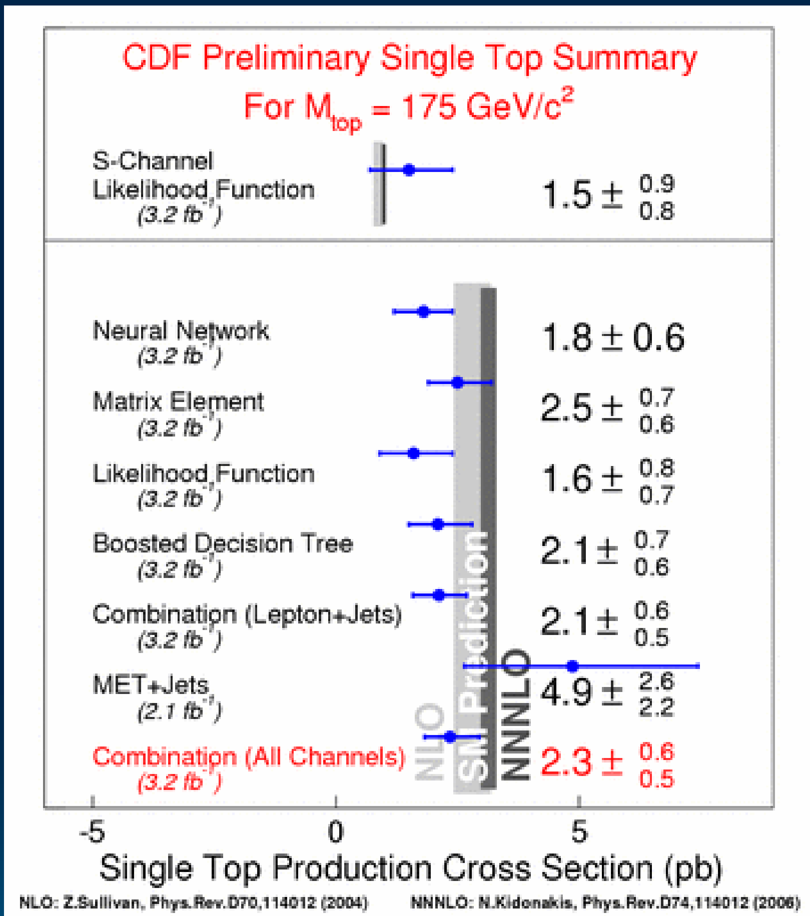
EW Single Top Production

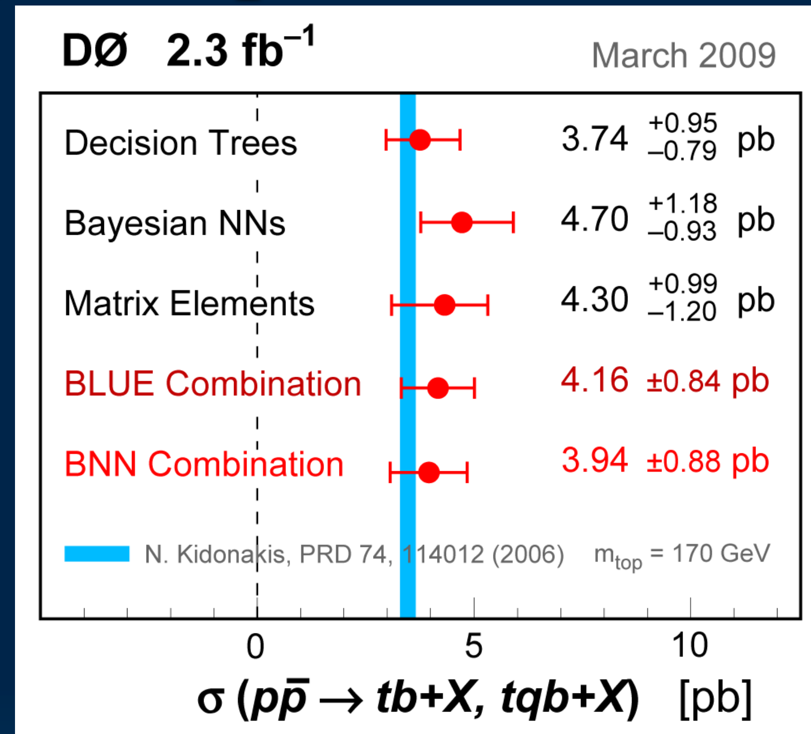
- Direct measurement of V_{tb}
- Produced ~100% polarized top
  - Can be used to test the V-A structure of the top EW interaction
- Sensitive to beyond SM physics
  - t-channel: 4th family, FCNC
  - s-channel: W', H^+
- Experimental signatures:
  - One high P_T isolated e or μ
  - Large missing transverse energy
  - ≥ 2 jets (≥ 1 b-tag)
- Suffers from large amount of W+jets backgrounds
  - No single variable provide significant signal-background separation





Observation of Single Top Production





First observation by CDF and D0 in March 2009 (PRL 103, 092002 (2009), PRL 103 092001 (2009))

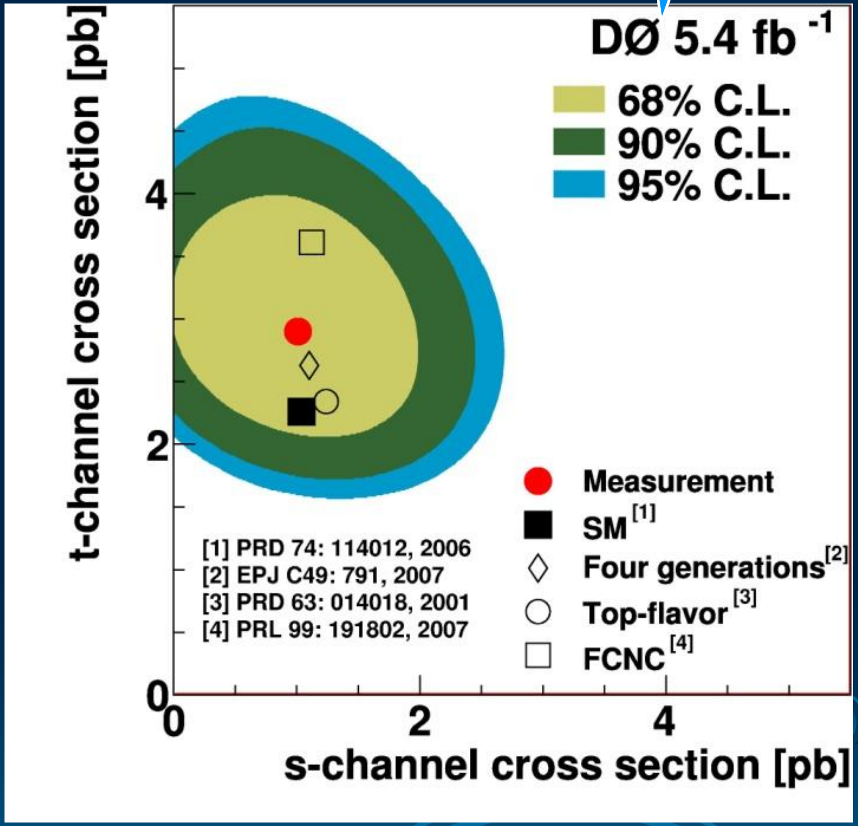
Tevatron combination: $\sigma_{s+t} = 2.76^{+0.58}_{-0.47}$ pb
$|V_{tb}|$ = 0.88 0.07, $|V_{tb}|$ > 0.77 at 95% CL

Single Top Production

NEW

- D0 measurement uses:
  - Boosted decision trees
  - Bayesian NNs and
  - Neuroevolution of augmented topologies ⇒ new method
- Measurement of s-channel and t-channel cross-sections from 2D fit
- D0 Result (5.4 fb^{-1}):

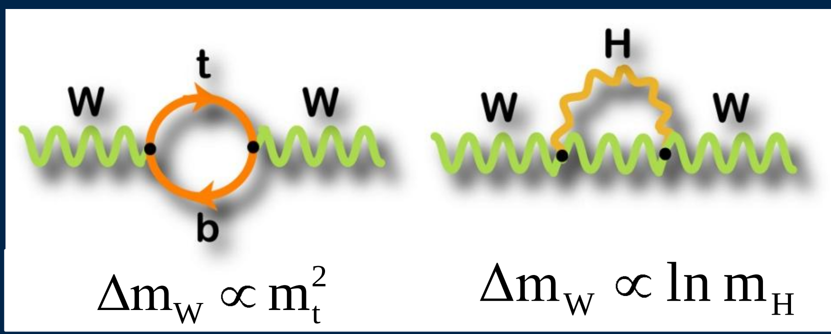
$\sigma_t = 2.90$ 0.59 pb
(5.5σ significance)
$\sigma_s = 0.98$ 0.63 pb



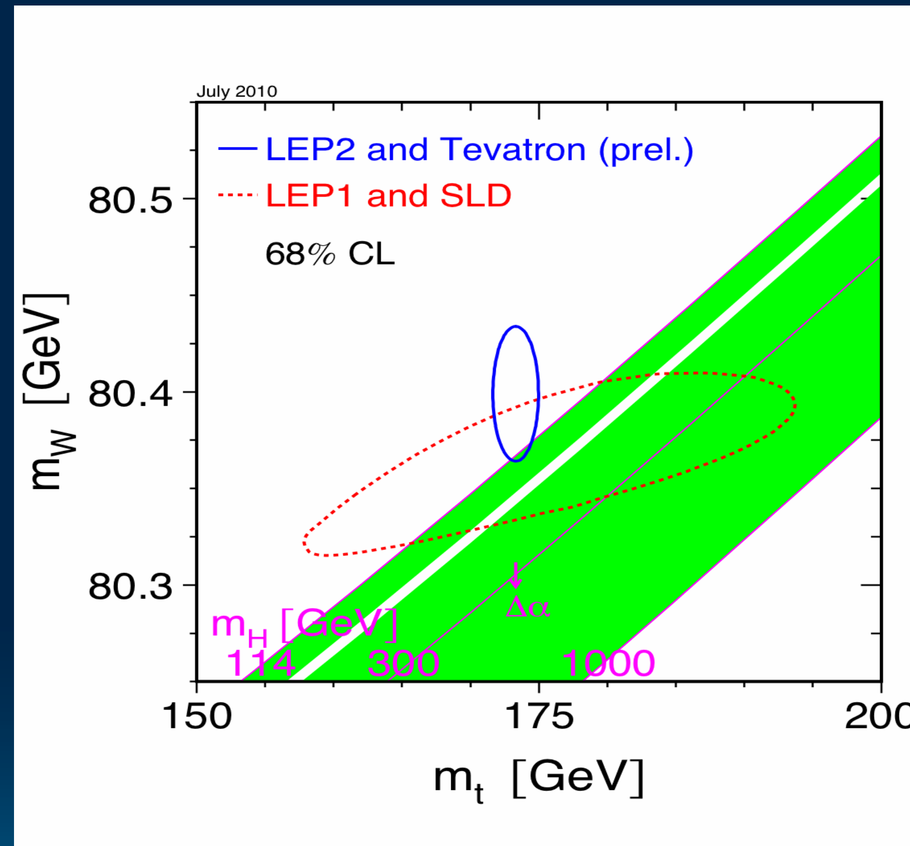
J. Joshi's talk at New Perspective 2011

Top Quark Mass

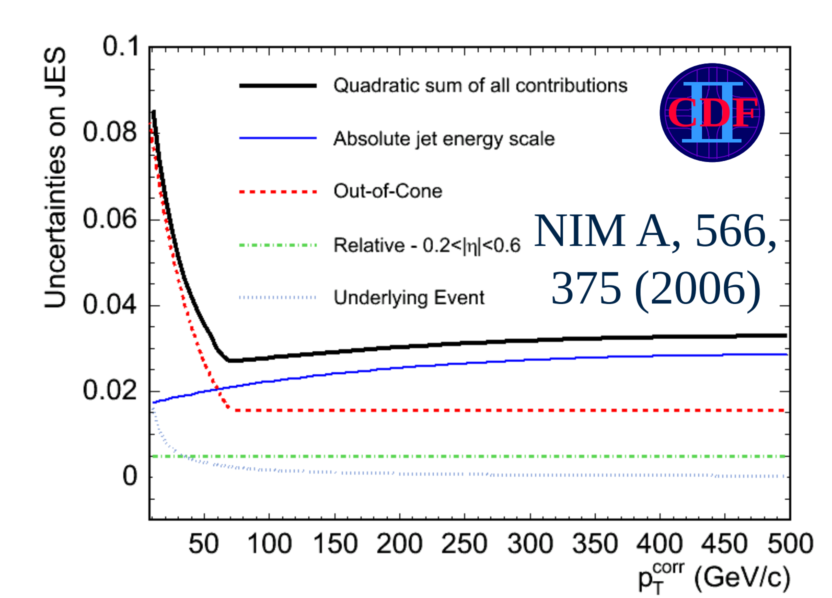
- Related to SM observables and parameters through loop diagrams
- Consistency checks of SM parameters

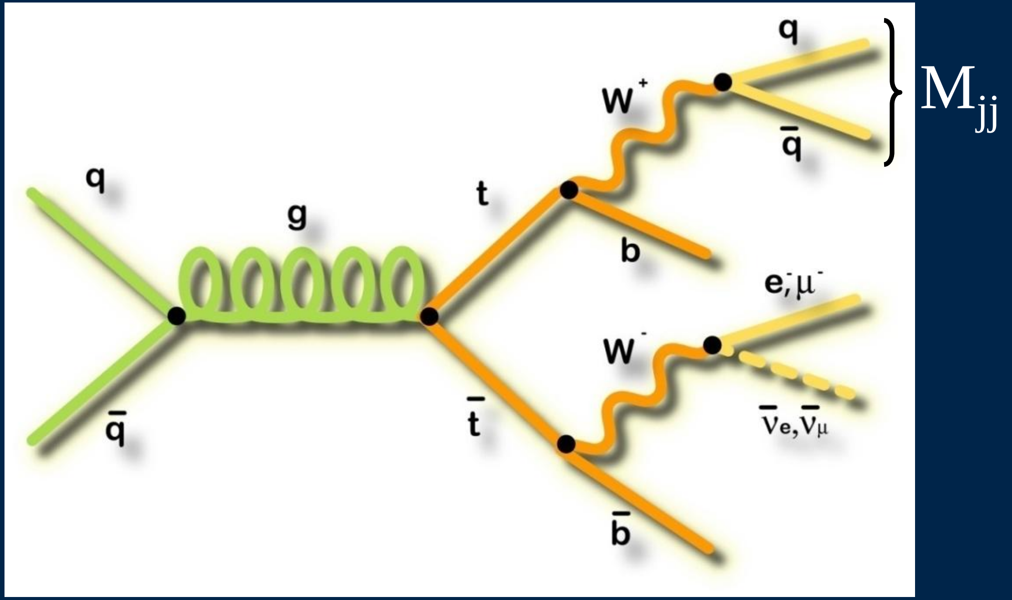


- Precision measurements of the m_t (and m_W) allow prediction of the m_H
- Constraint on Higgs mass can point to physics beyond the standard model



Jet Energy Scale Uncertainty

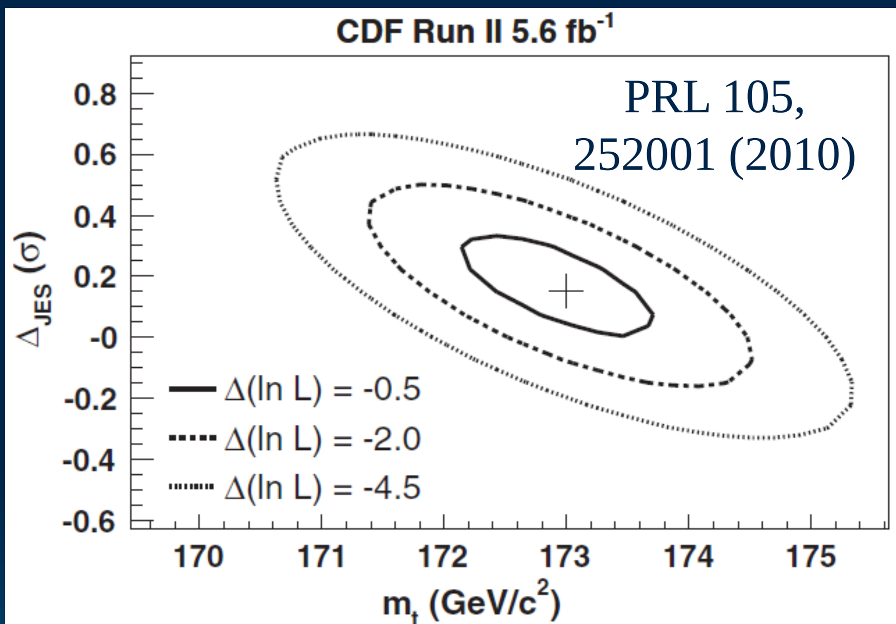


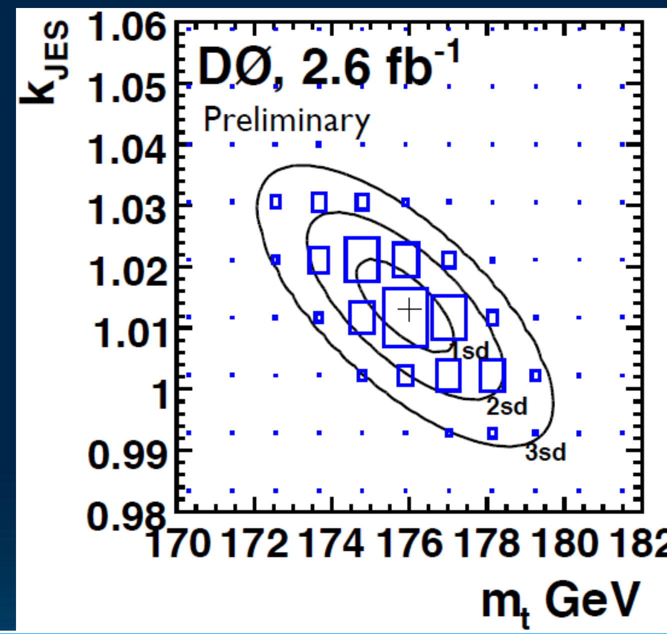


- Uncertainty on JES ⇒ About 3% systematic uncertainty on m_t measurement when convoluted with ttbar p_T spectrum
- In-situ JES measurement for lepton+jets and all-hadronic channels
  - Constrain the invariant mass (M_{jj}) of the non-b-tagged jets to be 80.4 GeV/c^2

Top Mass : Lepton+Jets Channel

- Use event-by-event likelihood based on leading order ttbar differential cross section.
  - *Most precise top mass measurements from single channels*

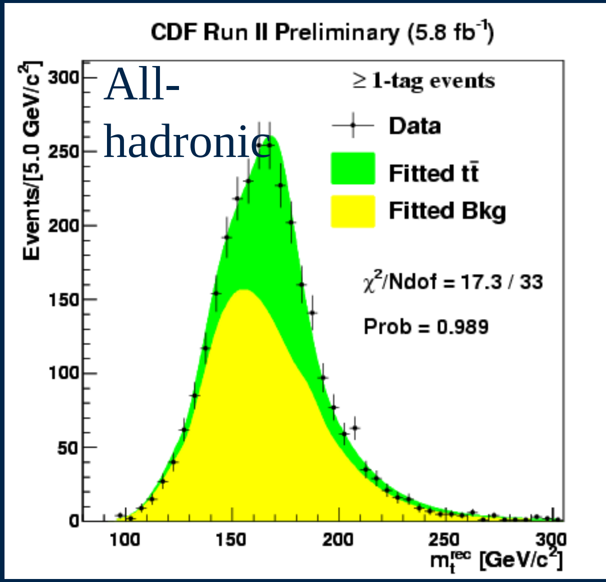


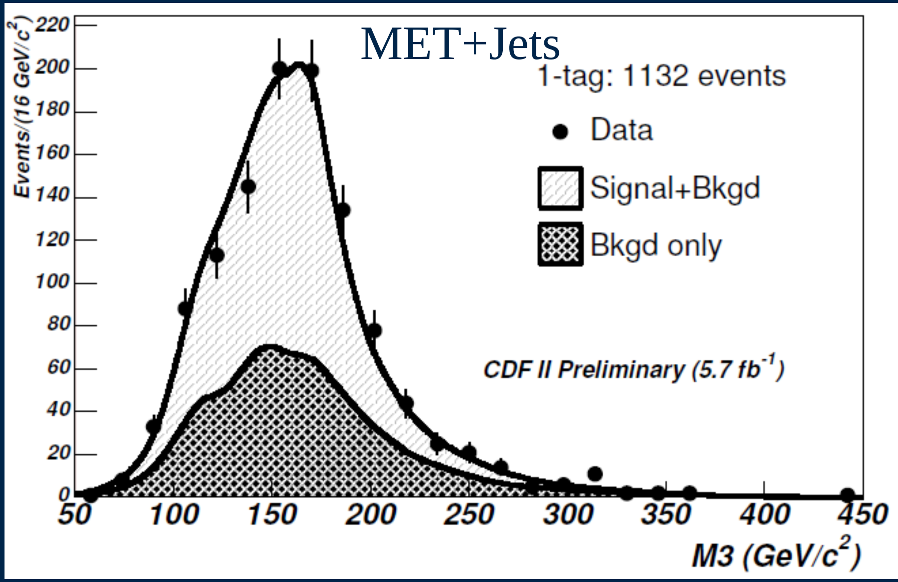


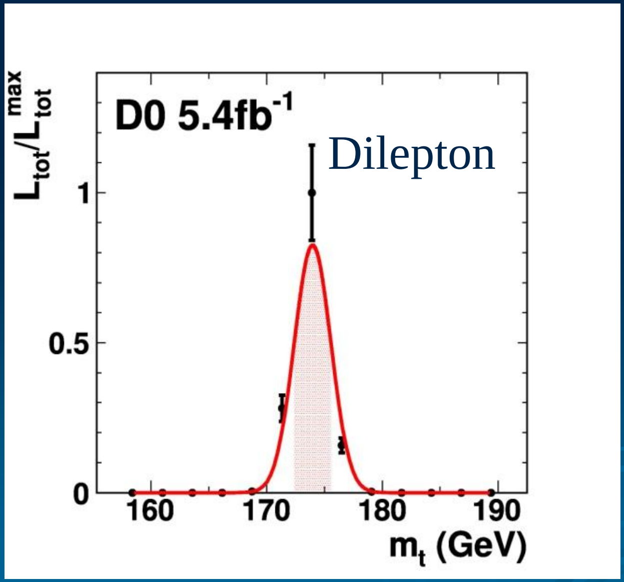
m_{top} = 173.0 ± 0.7 (stat) ± 0.6 (JES) ±0.9 (syst) GeV/c^2
Δm_{top}=1.2 GeV/c^2

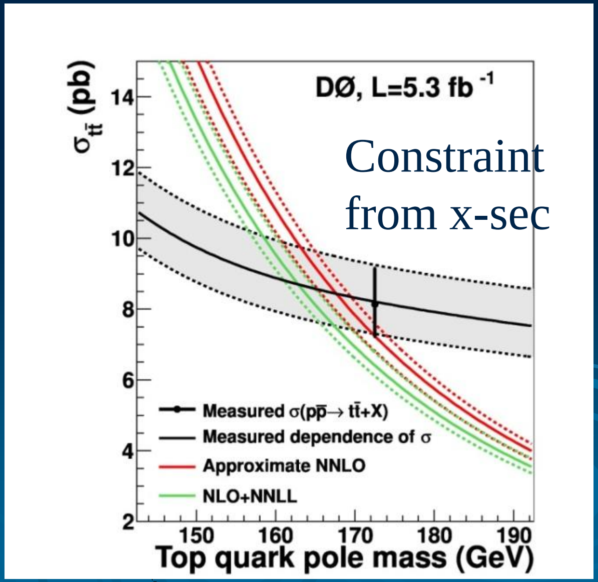
m_{top} with 3.6 fb^{-1} D0 data:
174.9   0.8(stat)   1.3(syst+JES) GeV/c^2

Resent Results : Top Mass

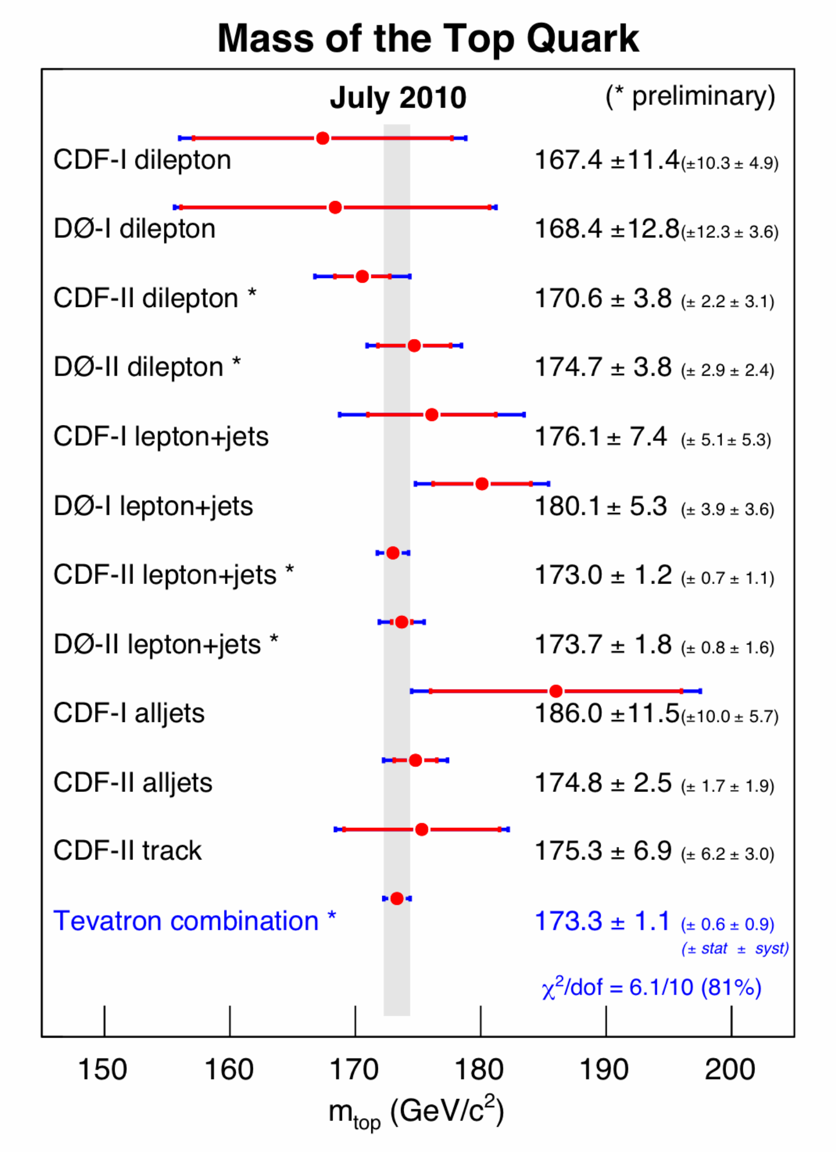








Top Mass : Combination



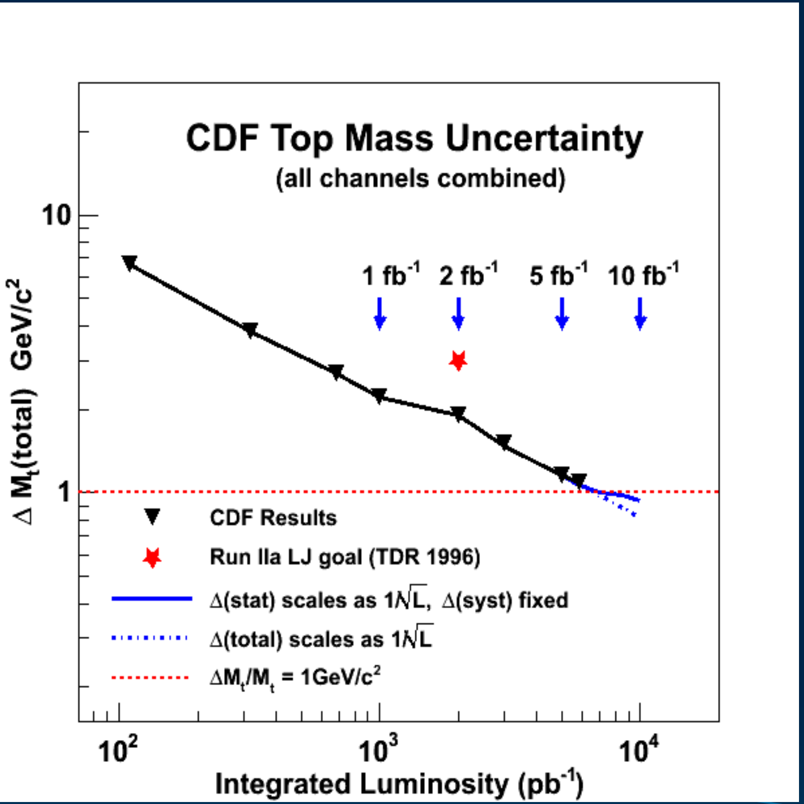
- Combine Run I measurements with most recent Run II measurements
  - Take into account the statistical and systematic uncertainties and their correlations (NIM A270 (1988) 110, NIM A500 (2003) 391)
- Combined top mass

  173.3 ± 1.1 GeV/c^2

  $\chi 2$/ndof 6.1/10 $\Rightarrow$ 81% prob
  - Good agreement among all input measurements
- Top mass known with relative precision of 0.61%

Uncertainties on Measured Top Mass

Source	ΔM_t (GeV/c^2)
jet energy scale:	0.61
* ttbar modeling:	0.59
background:	0.23
lepton energy scale:	0.10
miscellaneous:	0.14
Systematic:	0.89
Statistical:	0.56



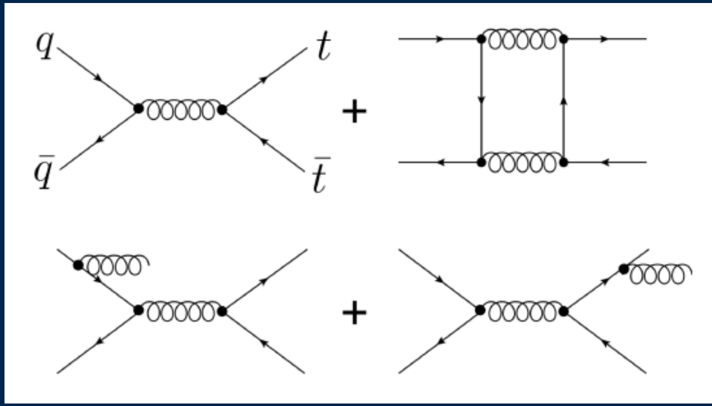
- Several sources of uncertainties should continue scale with the statistics of the sample
  - Example: stat component of uncertainty from JES ±0.46 GeV/c^2
- With full Run II data set could reach Δm_t below ~1 GeV/c^2

TOP QUARK PROPERTIES

Forward Backward Asymmetry in Top Pair Production

- Asymmetry caused by interference of ME amplitudes for same final state
- Significantly enhanced in BSM models: Z'-like states with parity violating coupling , theories with chiral color
- The SM prediction (QCD at NLO) :

$$A^{ttbar} = 0.058 \pm 0.009$$



$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

Δy $t\bar{t}$ rapidity difference: $y_t - y_{\bar{t}}$

- Look at A^{ttbar} dependence on the invariant mass of ttbar
  - Sensitive to new physics effect

Tom Schwarz's talk on June 1

A^{ttbar} (cont')

- CDF analyses corrects for acceptance and smearing effects
- CDF Lepton+Jets (5.3 fb^{-1})

$$A^{ttbar} = 0.158 \pm 0.075 \ \ (stat + syst)$$

$$A^{ttbar} (M^{ttbar} > 450\ GeV/c^2) = 0.475 \quad 0.114$$

3.4σ above the SM prediction in high M^{ttbar} region

- CDF Dilepton (5.1 fb^{-1})

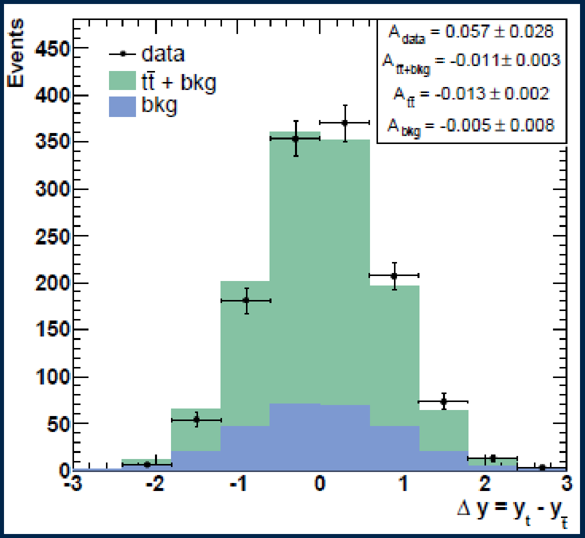
$$A^{ttbar} = 0.42 \quad 0.15\ (stat) \quad 0.05\ (syst)$$

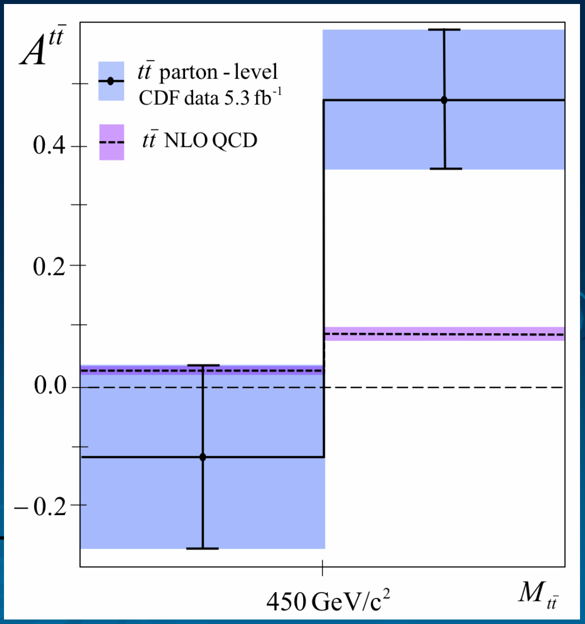
2.3 σ from the SM prediction

- D0 lepton+jets uncorrected (4.3 fb^{-1})

$$A^{ttbar} = (8 \quad 4\ (stat) \quad 1\ (syst))\%$$

1% expected from NLO MC before correction

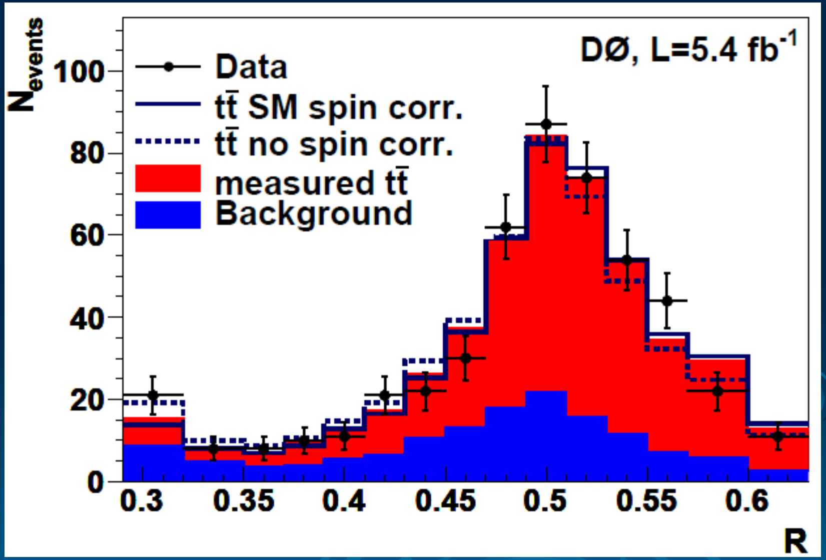




ttbar Spin Correlations

- Top production has a characteristic spin correlation. New production mechanisms (Z', KK) can modify it
- D0 analysis: dilepton channel using a matrix-element approach
  - Distinguish "H = c" (hypothesis of SM-like correlated top spins) from "H = u" (hypothesis of uncorrelated top spins)

$$R = \frac{P_{\mathrm{sgn}}(H=c)}{P_{\mathrm{sgn}}(H=u) + P_{\mathrm{sgn}}(H=c)}$$



- **Fraction of events with "H=c"**

$f_{meas} = 0.74^{+0.40}_{-0.41}$ (stat+syst)

- **Exclude "H=u" at 97.7% C.L.**
- **Correlation coefficient**

$C_{meas} = 0.57 \quad 0.31$

(*SM Prediction: C=0.78*)

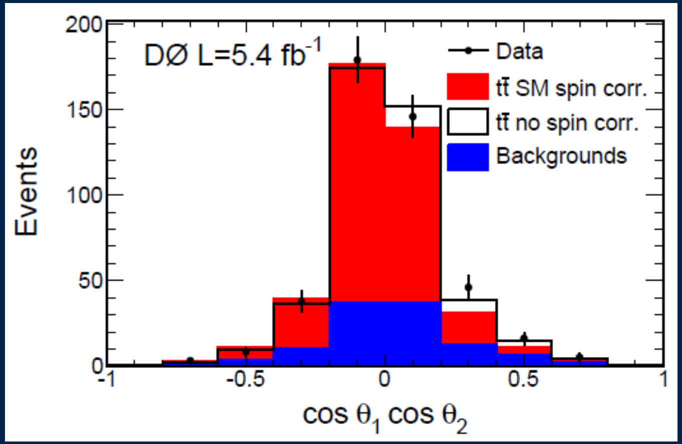
See T. Head's talk at New Perspective 2011

ttbar Spin Correlations (Cont')

- D0 measurement (dilepton)
  - Decay products *(l^+,l^-)* angular correlation coefficient C

C = 0.10 ± 0.45 (stat+syst)

SM Prediction: C=0.78

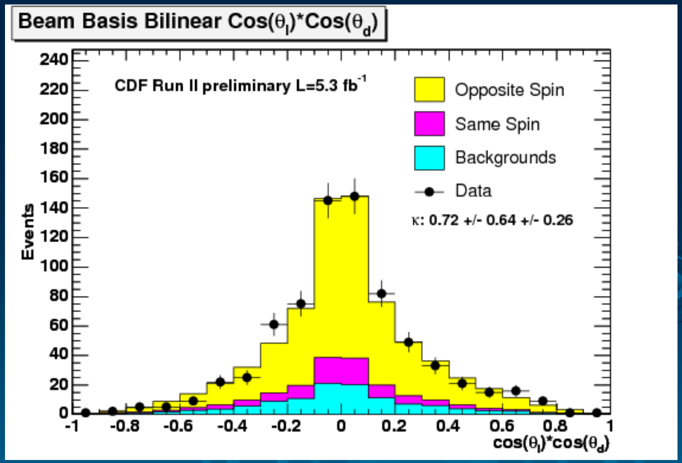


- CDF measurement (lepton+jets)
  - Use both helicity and beam-line basis

$$\kappa_{helicity} = 0.48 \quad 0.48_{stat} \quad 0.22_{syst}$$

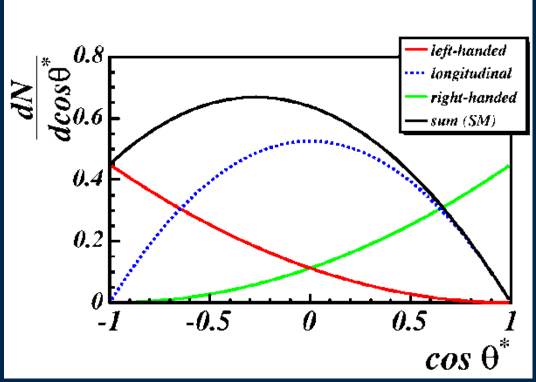
$$\kappa_{beam} = 0.72 \quad 0.64_{stat} \quad 0.26_{syst}$$

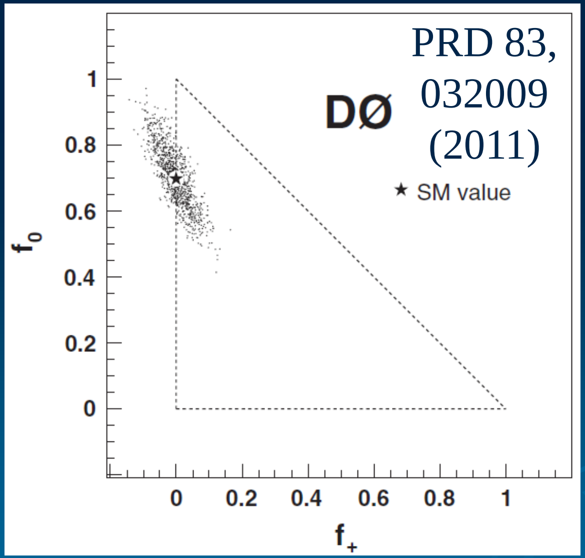
SM prediction: $\kappa_{helicity}$ = 0.35 and κ_{beam} = 0.77



Polarization of W from Top Decay

- V-A coupling in the SM
  - longitudinal fraction f_0 ~70%
  - left-handed fraction f_- ~30%
  - right-handed fraction f_+ ~0%
- Sensitive to non-SM tWb coupling
- Use θ*: Angle between lepton (down-type quark) in W rest frame and the momentum of the W in the top rest frame





Simultaneous measurement of f_0 and f_+

- **D0 (lepton+jets and dilepton, 5.4 fb^{-1}):**
  - **$f_0 = 0.669 \pm 0.078$ (stat) ± 0.065 (syst)**
  - **$f_+ = 0.023 \pm 0.041$ (stat) ± 0.034 (syst)**
- **CDF (dilepton, 5.1 fb^{-1})**
  - **$f_0 = 0.722 \pm 0.179$ (stat) ± 0.065 (syst)**
  - **$f_+ = -0.088 \pm 0.088$ (stat) ± 0.032 (syst)**

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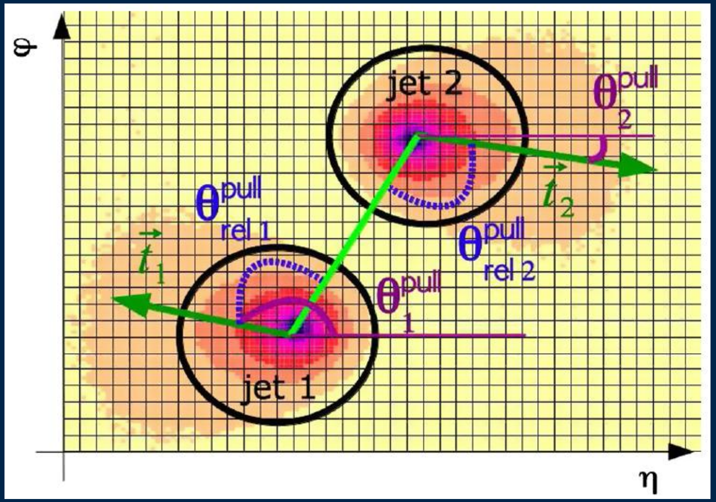
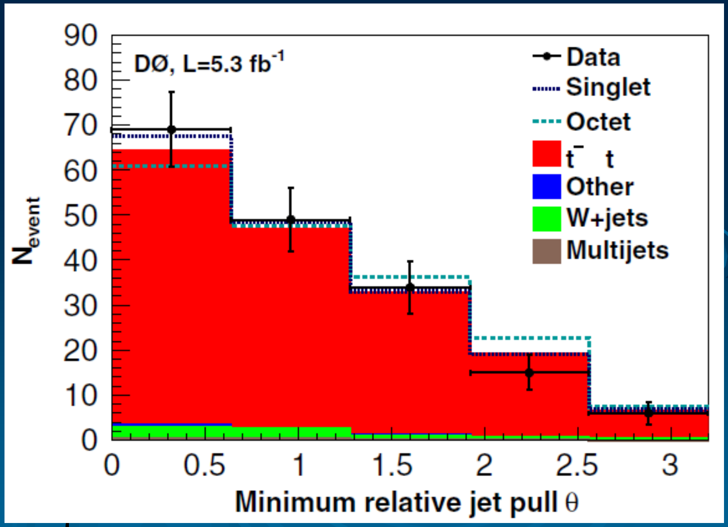
Color Flow In Top Decays

- Using color connections between jets to separate different processes. Example:
  - H→bb : two b quarks color connected to each other ⇒ color singlet
  - g→bb: b quarks color connected to beam remnants ⇒ color octet
- Measure "jet pull": related to the jet energy pattern in the η-ϕ plane
- Verify color-flow simulation and jet pull reconstruction using lepton+jets
  - Two jets from W decay ⇒ color singlet
- W(singlet)/W(all) =

$$f_{singlet} = 0.56 \pm 0.42 \text{ (stat + syst)}$$

(SM ratio for ttbar = 1)





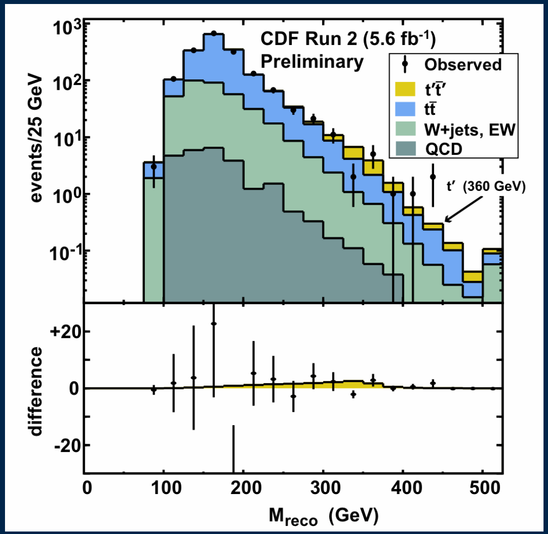
SEARCH FOR NEW PHYSICS

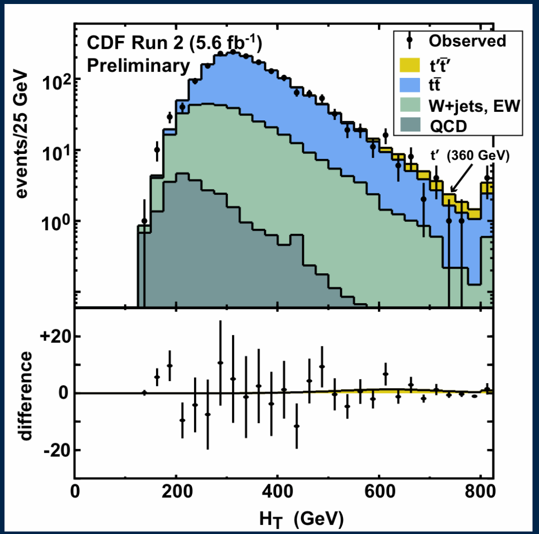
t' search

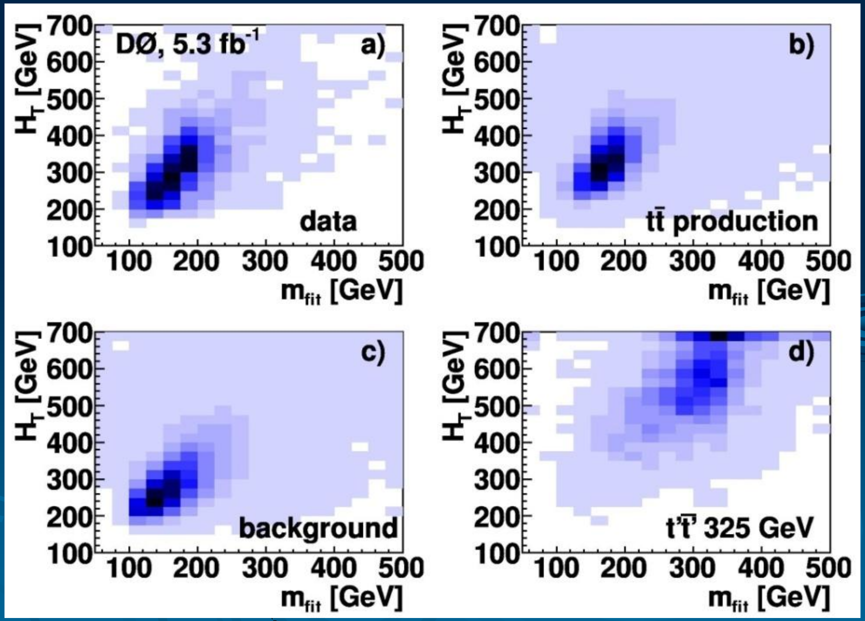
- Motivated in various BSM: Little Higgs model with t-parity, "Beautiful Mirrors" model
- EWK precision data don't exclude fourth generation
- Two-variable search using e/μ+ ≥4 jets events:
  - Reconstructed top mass
  - H_T (total transverse energy)
- CDF searches for t'→Wb
  - Exclude $M_{t'}$< 358 GeV at 95% CL

(D. Cox's talk at New Perspective 2011)

- D0 searches for t'→Wq
  - Exclude $M_{t'}$ < 285 GeV at 95% CL





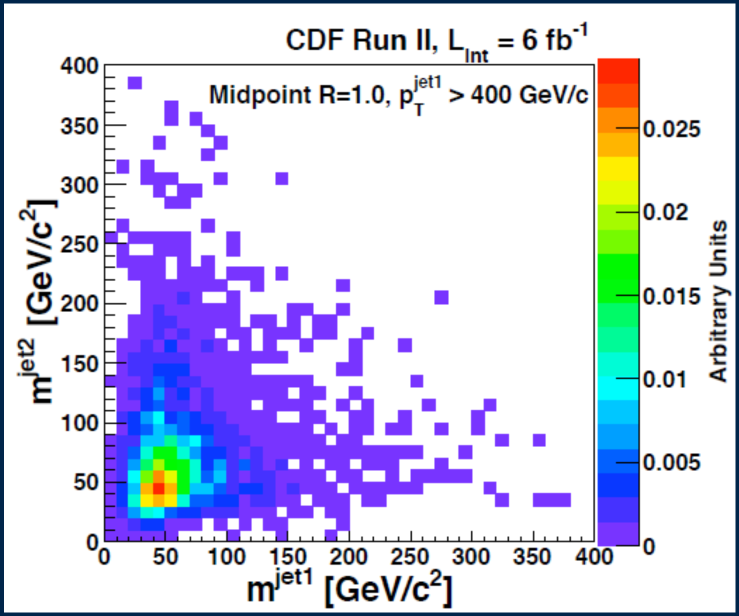


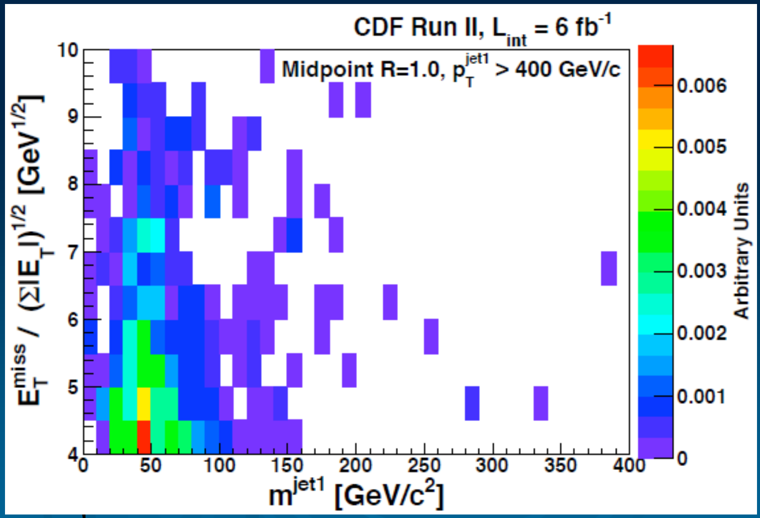
Search for Boosted Top Quarks

- Probe NLO QCD
  - Search for possible new physics
- Require two massive jets or one massive jet with large missing E_T
- 58 candidate events
  - Exp. bkg. of 44±8 (stat) ±13 (syst)
- Boosted SM ttbat cross section < 40 fb^{-1} @ 95% CL

  (for ≥ 1 jet with pT>400 GeV/c)
- Cross section for a pair of massive objects with masses near the top mass < 20 fb^{-1} @ 95% CL

  (for ≥1 jet with pT > 400 GeV/c)





Summary

- Top quark properties are currently being studied at Tevatron
  - Most precise ttbar cross-section and top mass measurements are already systematically limited
  - Study other properties of top quark, search for new physics
    - Almost all the measurements are statistically limited
- Almost twice the data sample already available
  - Stay tuned for the updates and new results
- LHC will have a much larger top sample in future
  - Understanding of systematic uncertainties would be crucial

Tevatron's top physics program and understanding of systematic effects will continue to play a significant role for years to come

More Top Physics Results From Tevatron

Apologies for my many omissions.

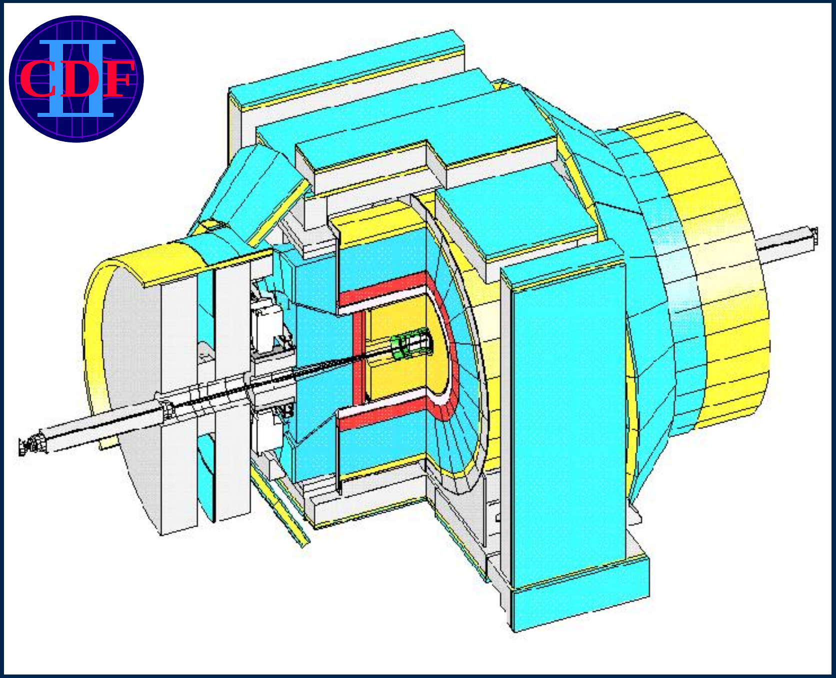
For a full listing of results go to:

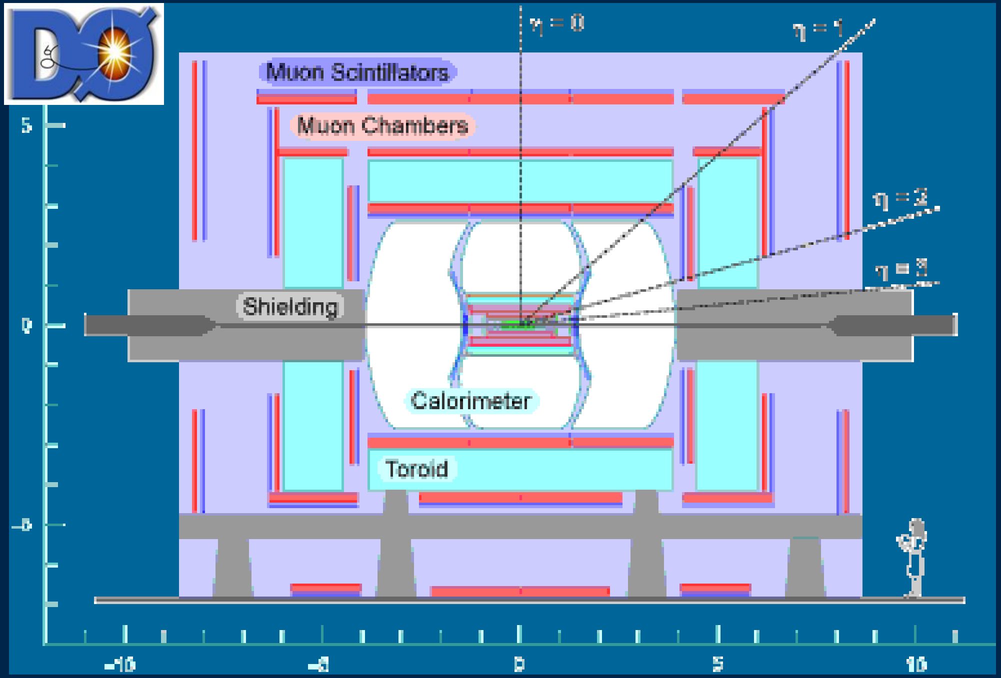
http://www-cdf.fnal.gov/physics/new/top/top.html

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

BACKUP

The CDF and D0 Detectors





- Silicon tracking
- Large radius drift chamber (r=1.4m)
- 1.4 T solenoid
- Projective calorimetry (|η| < 3.5)
- Muon chambers (|η| < 1.0)

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

All crucial for top physics!

Experimental Essentials

- Sample composition : Signal to background ratio (S/B)

S/B	Dilepton (≥2 jets)	Lepton+Jets (≥4 jets)	All-hadronic (6-8 jets, after NN Selection)
0 b-tag	2:1	~1:4	~1:20
1 b-tag	20:1	3:1	1:4
2 b-tags		20:1	1:1

  - Lepton+Jets : Golden channel for most top-properties measurements

- Jet-parton assignment : Combinatorial background
  - Dilepton: 2 combinations
  - Lepton+Jets: 12 (0 b-tag), 6 (1 b-tag), and 2 (2 b-tags) combinations
  - All hadronic: 90 combinations (0 b-tag), 30 (1 b-tag), 6 (2 b-tags)

ttbar Spin Correlations : Dilepton

- D0 measures decay products (l^+,l^-) angular correlation coefficient C

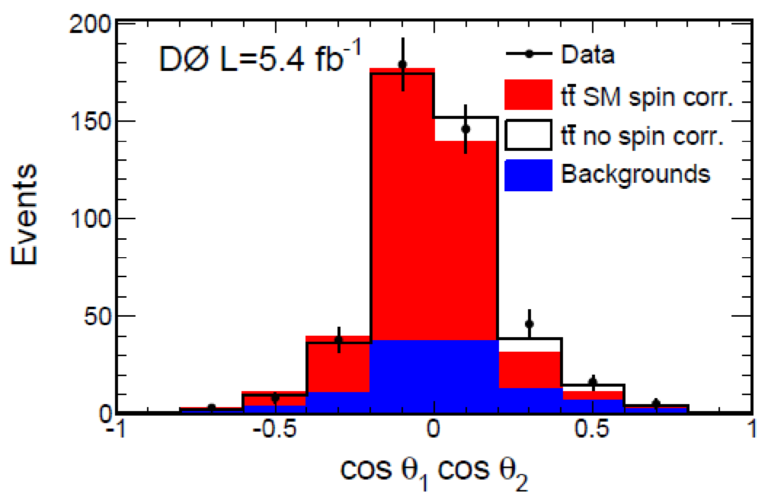
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

- θ_1 (θ_2): angle between the flight direction of l^+ (l^-) and direction of flight of one of the colliding hadrons in the ttbar rest frame
- D0 result:

$$C = 0.10^{+0.45}_{-0.45}\ (\text{stat+syst})$$

- SM Prediction at NLO:

$$C = 0.777^{+0.027}_{-0.042}$$



Bound on C: [−0.66, 0.81] at 95% CL

ttbar Spin Correlations : Lepton+Jets

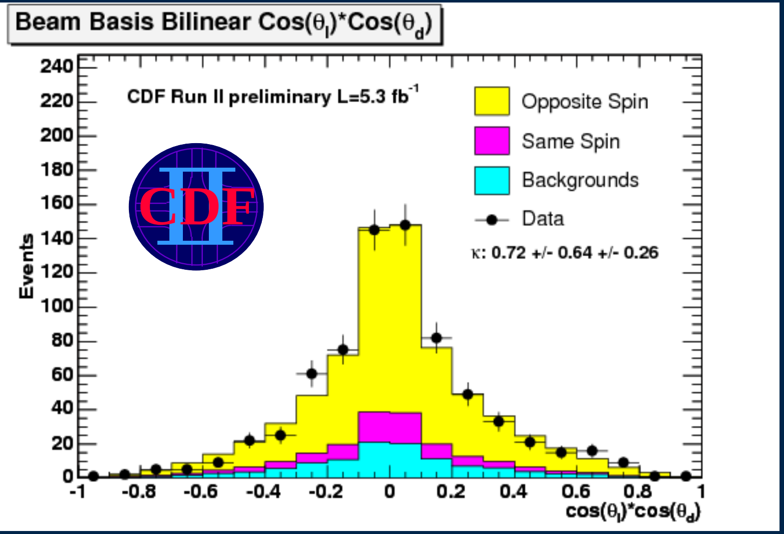
- Use the decay angles of the lepton (θ_l), the d-quark (θ_d), and the b-quark which comes from the hadronically decaying top (θ_b)
- Decay angles defined in two basis
  - *Helicity (Beam-line) basis: the angle between the decay product momentum in the top rest frame and the top quark momentum (the direction of the beamline) in the ttbar rest frame*
- Obtain spin correlation coefficient κ from fit to 2D distributions

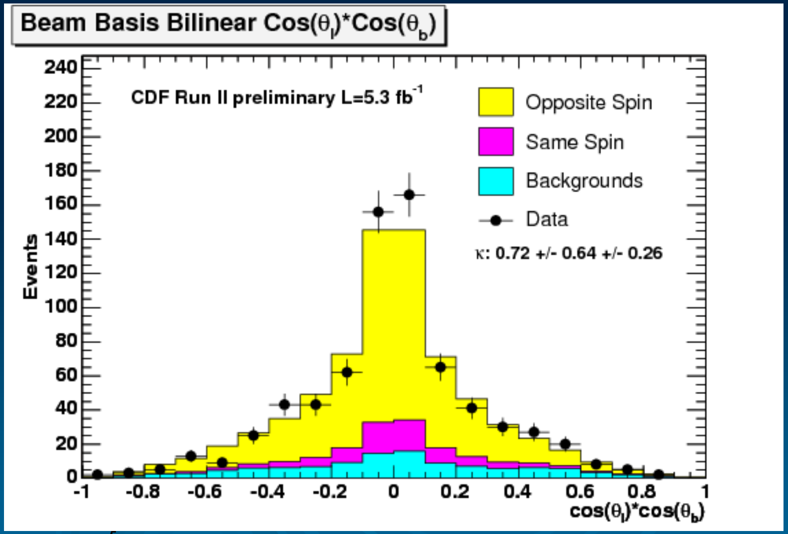
$$\kappa_{helicity} = 0.48 \quad 0.48_{stat} \quad 0.22_{sys}$$

$$\kappa_{beam} = 0.72 \quad 0.64_{stat} \quad 0.26_{syst}$$

SM prediction at NLO:

$\kappa_{helicity} = 0.35$ *and* $\kappa_{beam} = 0.77$





Kinematical Reconstruction of Lepton+Jets

- Minimize a χ^2 describing the over constrained kinematics of Lepton+Jets channel

Constraints on measured Lepton and Jet momenta

Constraints on un-clustered Energy

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

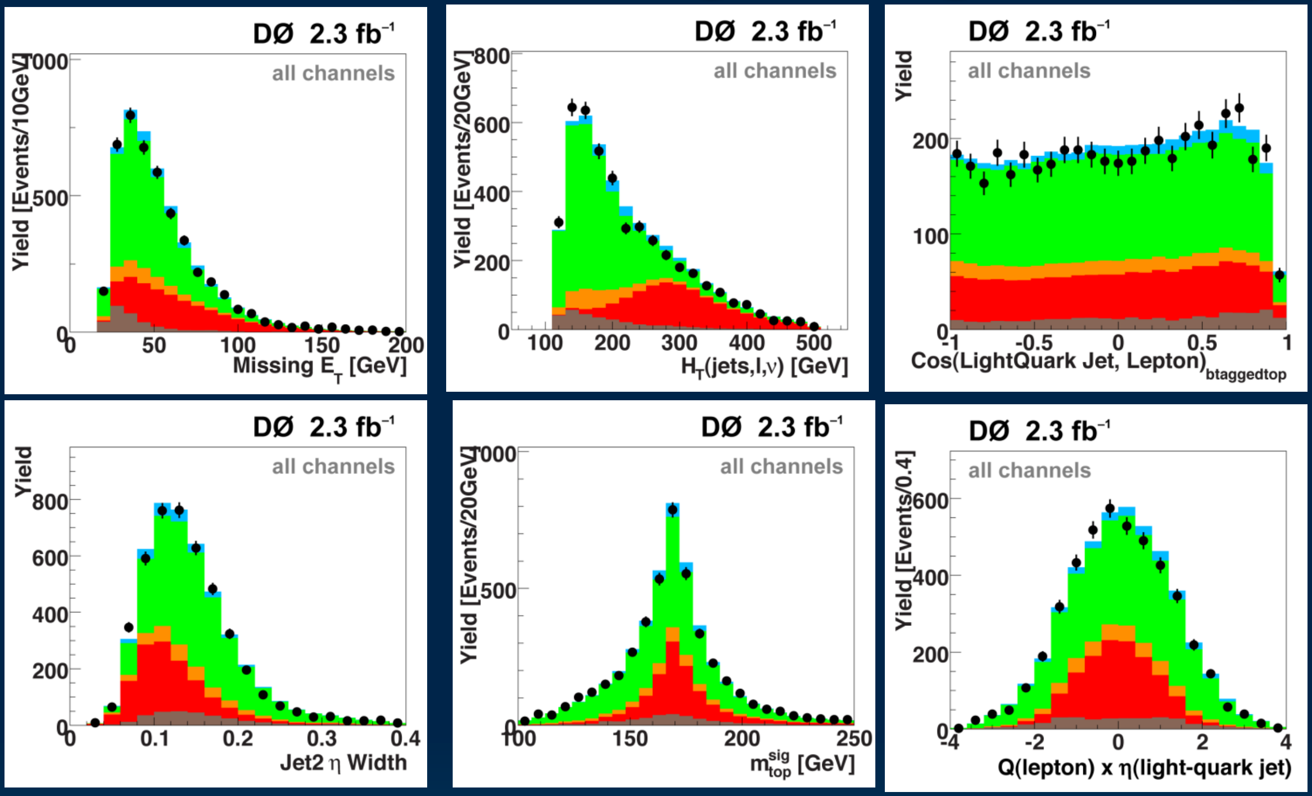
$$+ \frac{\left(M_{jj} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(M_{\ell\nu} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(M_{bjj} - m_t^{reco}\right)^2}{\Gamma_t^2} + \frac{\left(M_{b\ell\nu} - m_t^{reco}\right)^2}{\Gamma_t^2}$$

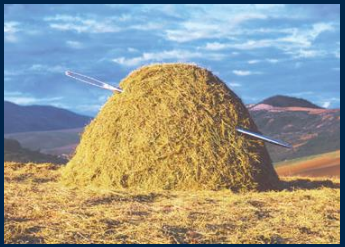
W Mass Constraints

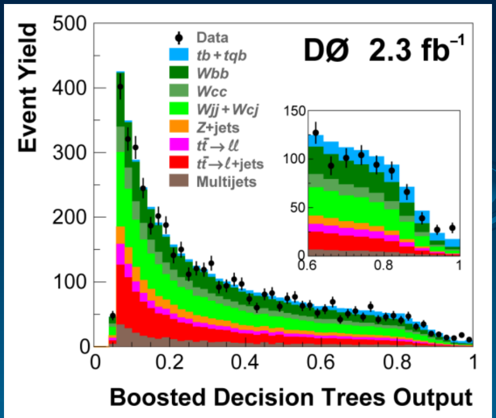
Top mass Constraints

- Select one permutation based on χ^2:
  - Require consistency with identified b-jet assignments

Extracting Single Top Signal







- No single variable provide significant signal-background separation
- Perform multivariate analysis ⇒ take advantage of small signal background separation in many variables