Measurement of top quark properties at Tevatron

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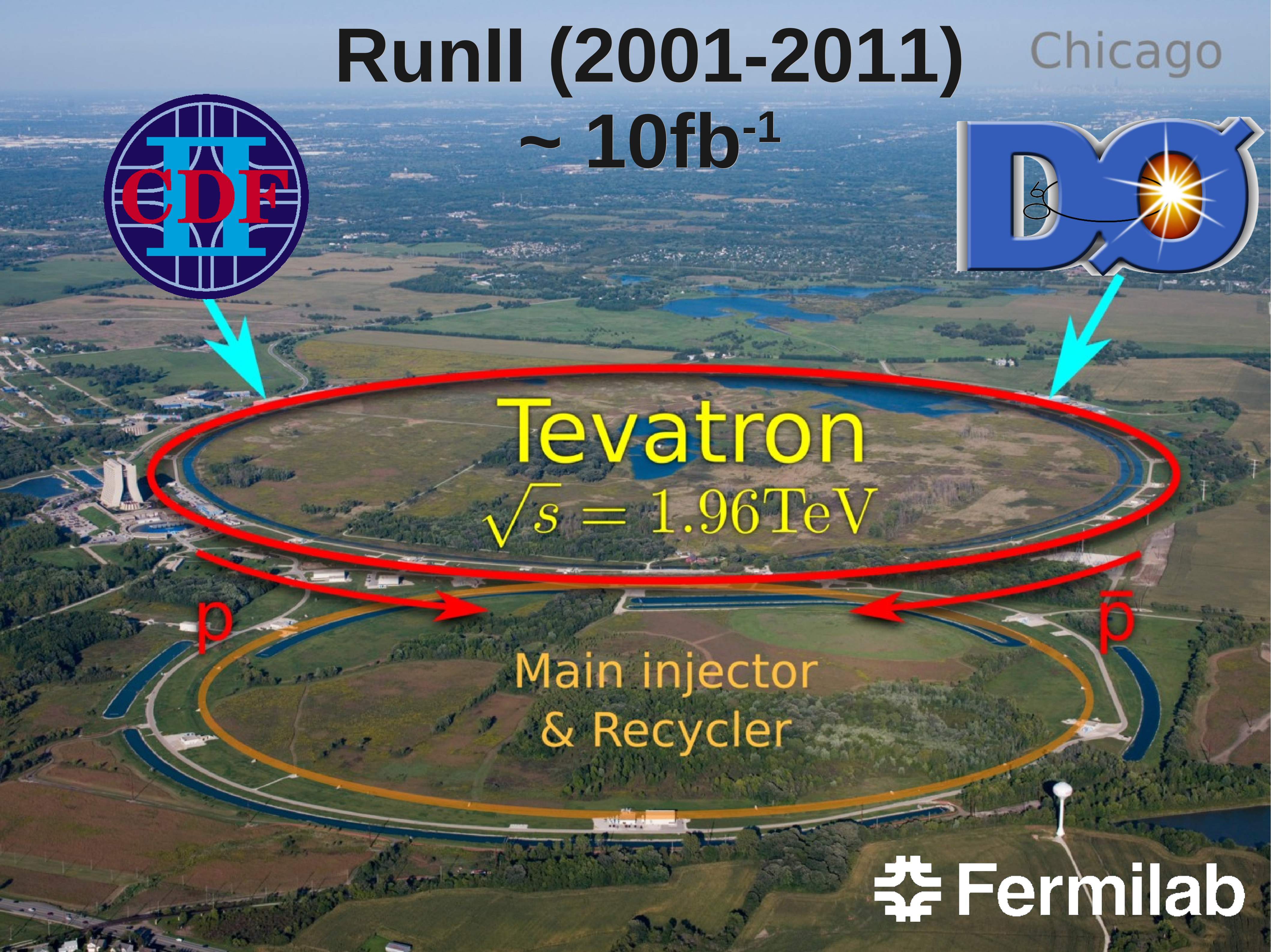
Heavy Quarks and Leptons
June 11 – 15, 2012

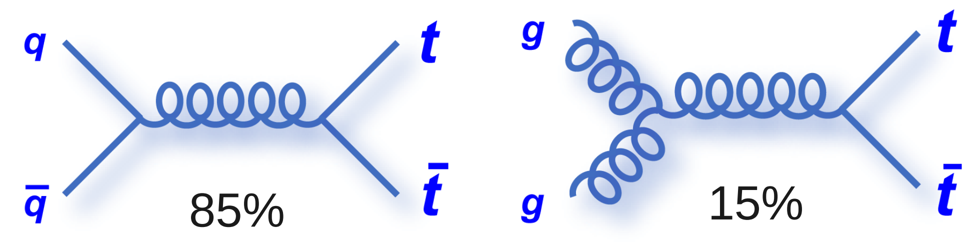
Outline

- Top quark mass measurements
- Top and antitop mass difference
- Top width & lifetime
- Spin correlations in top antitop events
- W helicity


RunII (2001-2011)
~ 10fb-1
Chicago
CDF II
DØ
Tevatron
$\sqrt{s} = 1.96\mathrm{TeV}$
p
p̄
Main injector
& Recycler
Fermilab

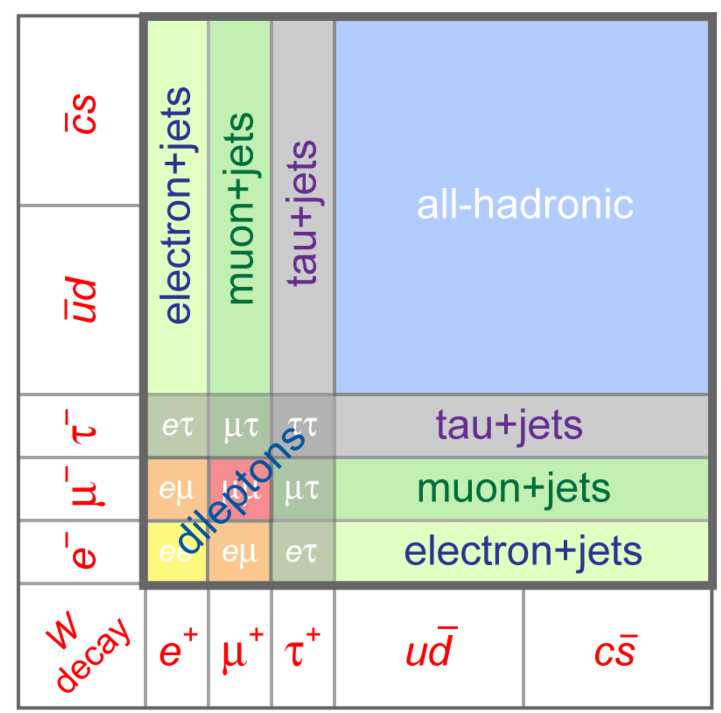
Top quark

- High mass and short lifetime
  - good for measuring properties
  - sensitive to physics beyond SM



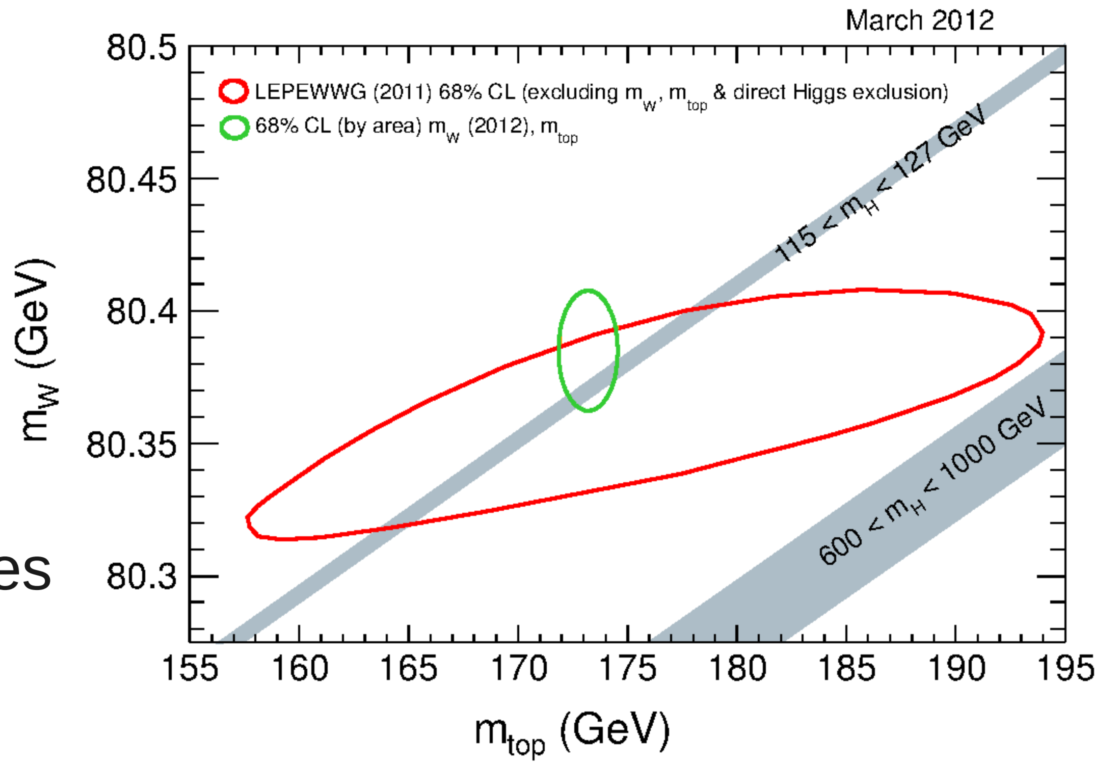
- Almost 10fb^{-1} data
  - thousands of events
  - precision measurement of top properties
- SM top quark → Wb ≈ 100%
  - different final states given by W decay
    - l+jets ~ 30%
    - dilepton ~ 5%
    - all-jets ~ 46%
    - tau

Top Pair Decay Channels



Top mass

- Free parameter in SM
- With W-boson mass constraints on the SM Higgs
- Two main methods
  - template method – compare distribution of an observable in data with MC s+b templates for different masses
  - matrix element method (ME)
    - calculate per event signal & background probabilities for given top mass using convolution of leading order matrix element and transfer function that describes detector resolution
    - only main backgrounds (ME requires significant CPU time)
    - ensemble tests + calibration (using only LO approximation)
- Reduce JES uncertainty by in situ calibration using W boson mass

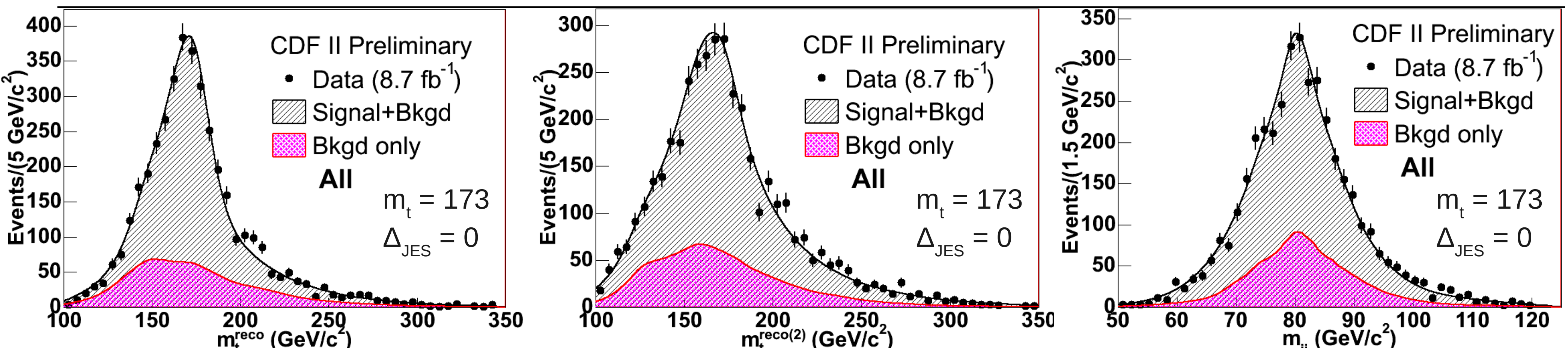


Mass in l+jets channel

all data

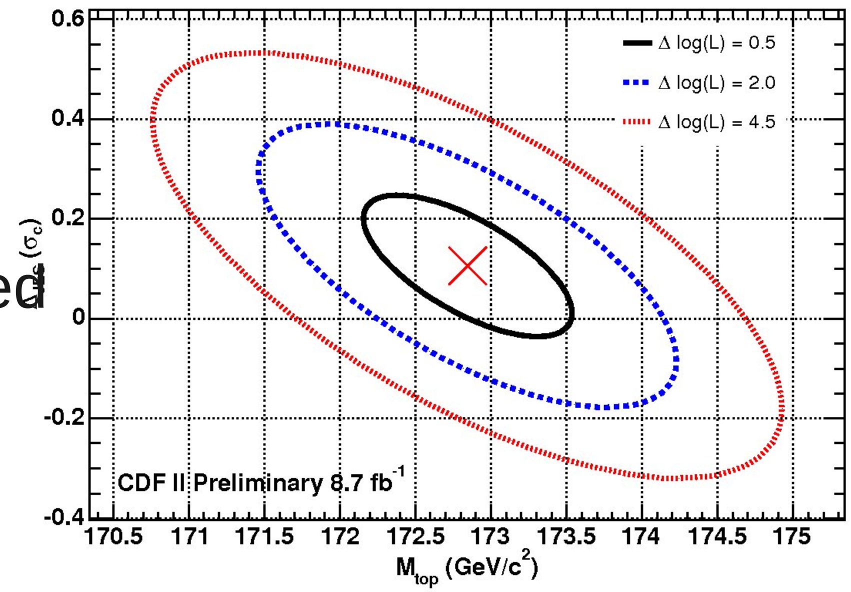
- Template method with full CDF RunII dataset 8.7fb^{-1}
- Minimize χ^2 to kinematics of the $t\bar{t}$ system
- Templates (m_t^{reco}, $m_t^{reco(2)}$, m_{jj}) for signal and background
  - $m_t \times \Delta_{JES}$ grid, for 0,1,2 b tagged jets and 4 or >4 jets
- Maximum likelihood – product of per event probabilities
  - product over all categories, quadratic fit on ($m_t \times \Delta_{JES}$ grid)

	0-tag	1-tagL	1-tagT	2-tagL	2-tagT
W+jets,QCD,...	963.5±229.3	234.7±61.1	144.0±40.9	19.9±5.5	13.8±4.2
$t\bar{t}$	644.8±86.3	695.0±86.7	867.3±107.6	192.3±29.7	303.7±46.6
Observed Events	1627	882	997	208	275



Mass in l+jets channel

- Jet Energy Scale dominant systematic
  - in-situ – only global scale of JES
  - special JES for jet from b quark
  - NN to improve calorimeter energy based on momentum provided by tracker
- Systematically dominated
- Most precise single method



172.85 ±0.71(stat) ±0.84(syst) GeV/c^2
172.85 ±1.10 GeV/c^2 (precision ±0.64%)

CDF Note 10761 (2012)

CDF II Preliminary 8.7 fb^{-1}

Systematic	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

- Matrix element method used by DØ on 3.6fb^{-1}
  - flavor dependent jet energy scale

174.94 ±0.83(stat) ±0.78(JES) ±0.96(syst) GeV/c^2
174.94 ±1.49 GeV/c^2 (precision ±0.85%)

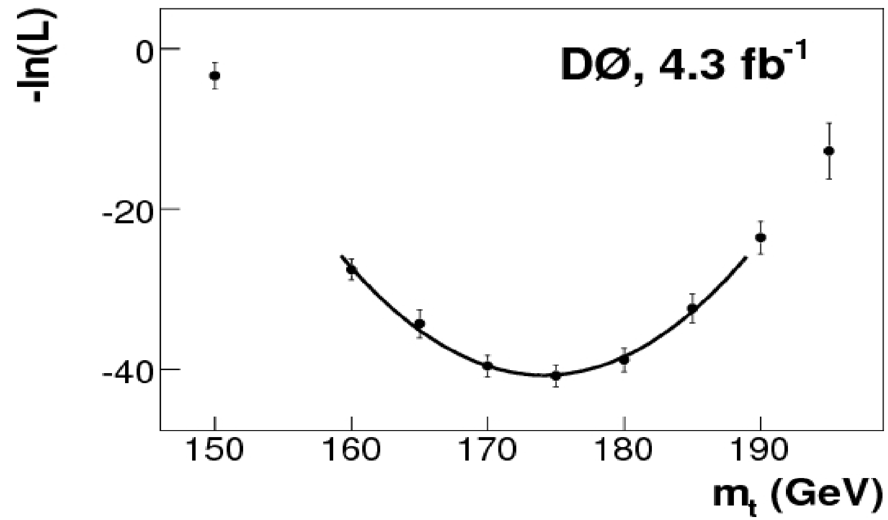
PRD 84, 032004 (2011)

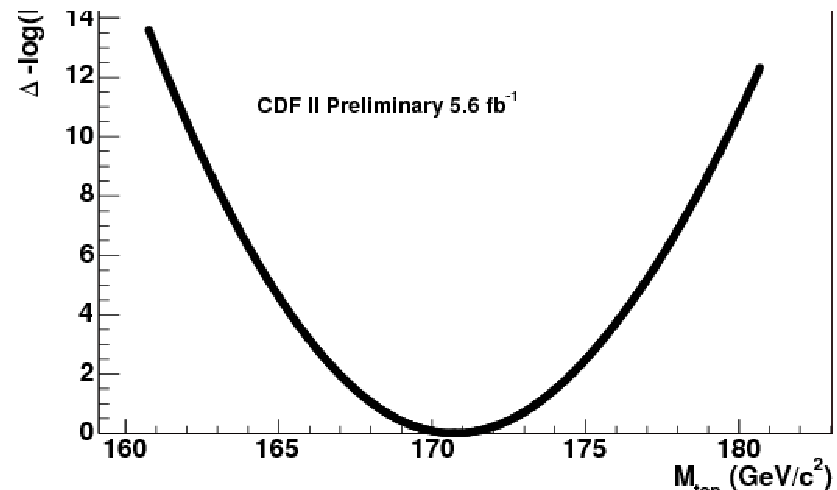
Mass in dilepton channel

- Neutrino weighting, 5.3fb^{-1}
  - kinematically underconstrainted
    - can't use in situ calibration
    - using the one from l+jets
    - integration over η distribution of both neutrinos → kinematics solutions + weight (MET)
  - independently ee, eμ, μμ
  - JES still main systematic uncertainty
  - most precise in dilepton (stat. limited)

174.0 ±2.4 (stat) ±1.4 (syst) GeV/c^2
174.0 ±2.8 GeV/c^2 (precision ±1.6%)

submitted to PRL (2012), arXive 1201.5172





- Matrix Element, 5.4fb^{-1}

173.3 ±1.8(stat) ±2.4(syst) GeV/c^2
173.3 ±3.0 GeV/c^2 (precision ±1.8%)

PRL 107, 082004 (2011)

- Neutrino weighting, 5.3fb^{-1}

170.3 ±2.0(stat) ±3.1(syst) GeV/c^2
170.3 ±3.7 GeV/c^2 (precision ±2.2%)

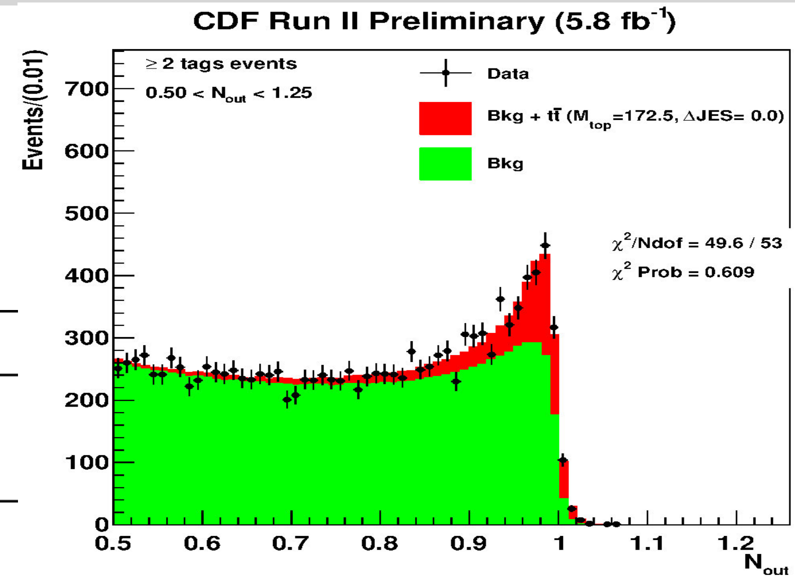
PRL 107, 082004 (2011)

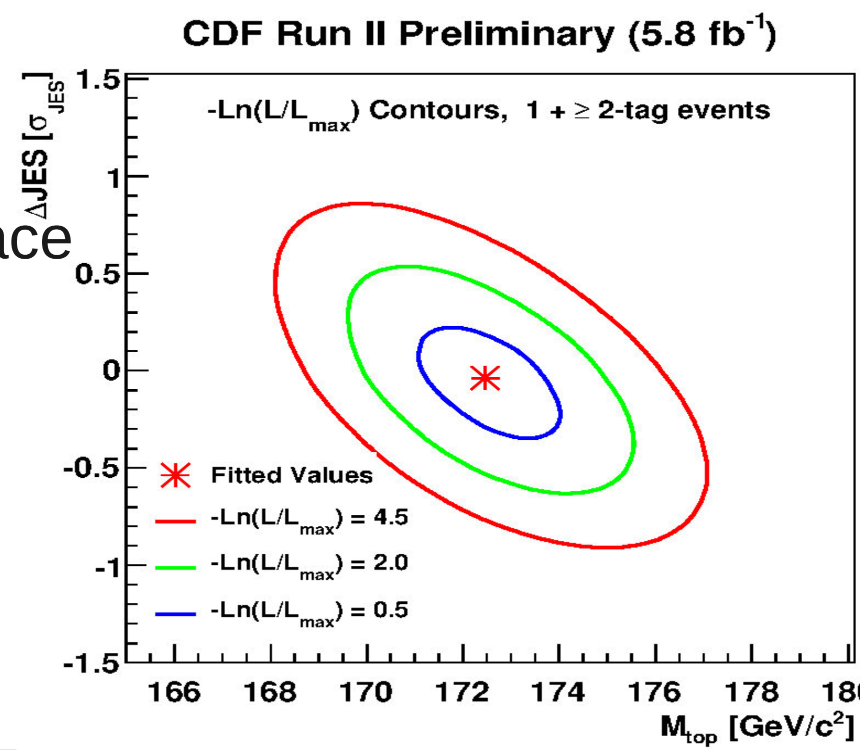
Mass in all-jets channel

- Template method with in situ JES, 5.8fb^{-1}
  - 6-8 jets (consider leading 6)
  - NN to select signal

b-tagging	Signal	Background	Observed
1-tag	1712 ± 77	604 ± 50	2256
$\geq$2-tags	305 ± 22	316 ± 26	600

  - combinations (1 btag 30, 2 btags 6, ≥2 btags 18)
- Data driven background
  - QCD can't reliably model this phasespace
  - based on tag rate parametrization
- Systematic dominated s+b modeling





172.5 ±1.4(stat) ±1.4(syst) GeV/c^2
172.5 ±2.0 GeV/c^2 (precision ±1.1%)

CDF Note 10456 (2011)

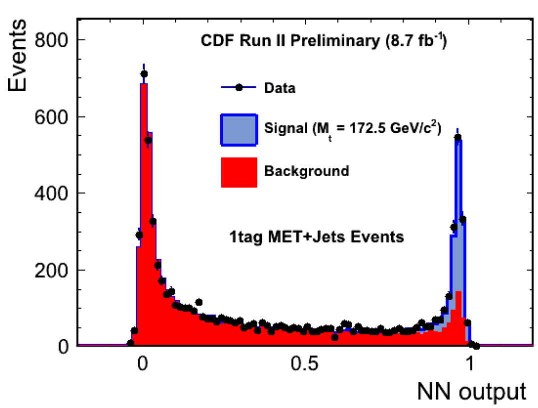
Mass in MET + jets channel

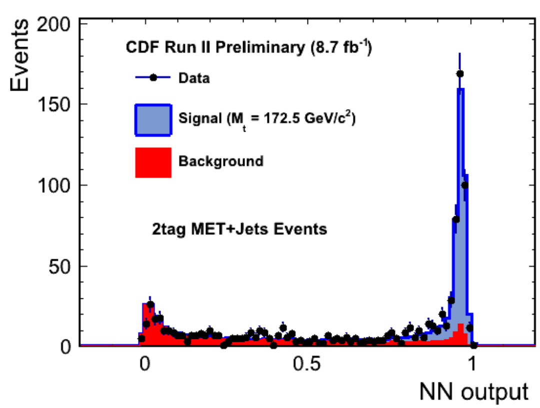
all data

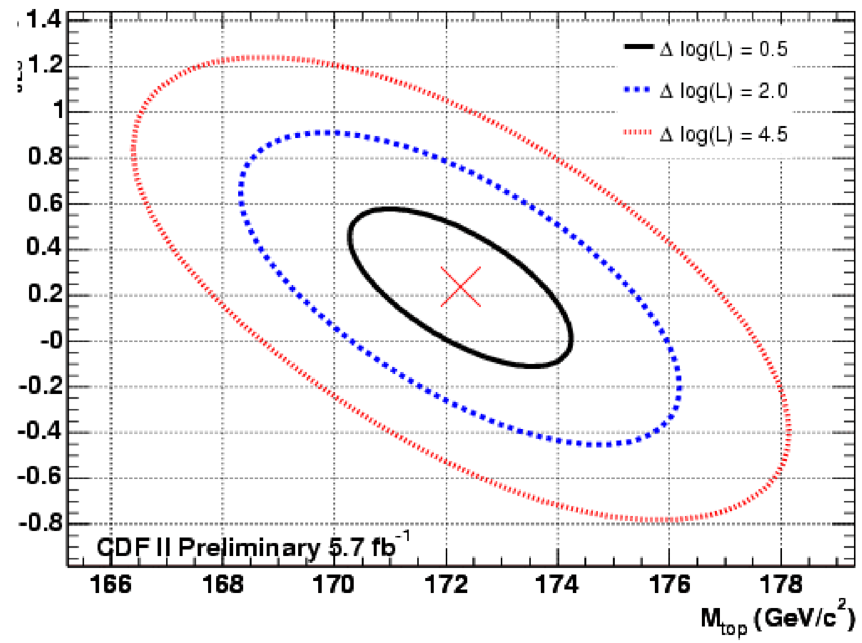
- Template method with full CDF RunII dataset 8.7fb^{-1}
  - same approach as in l+jets
- Catching all events missed in channels with MET

b-tagging	Signal	Background	Total Expected	Observed
1tag	1228.1±144.2	713.3±61.3	1941.4±156.7	2102
2tag	552.5±73.3	168.6±43.9	721.1±85.4	775

- Data driven background (similar to alljet)
- NN trained to get cleaner signal



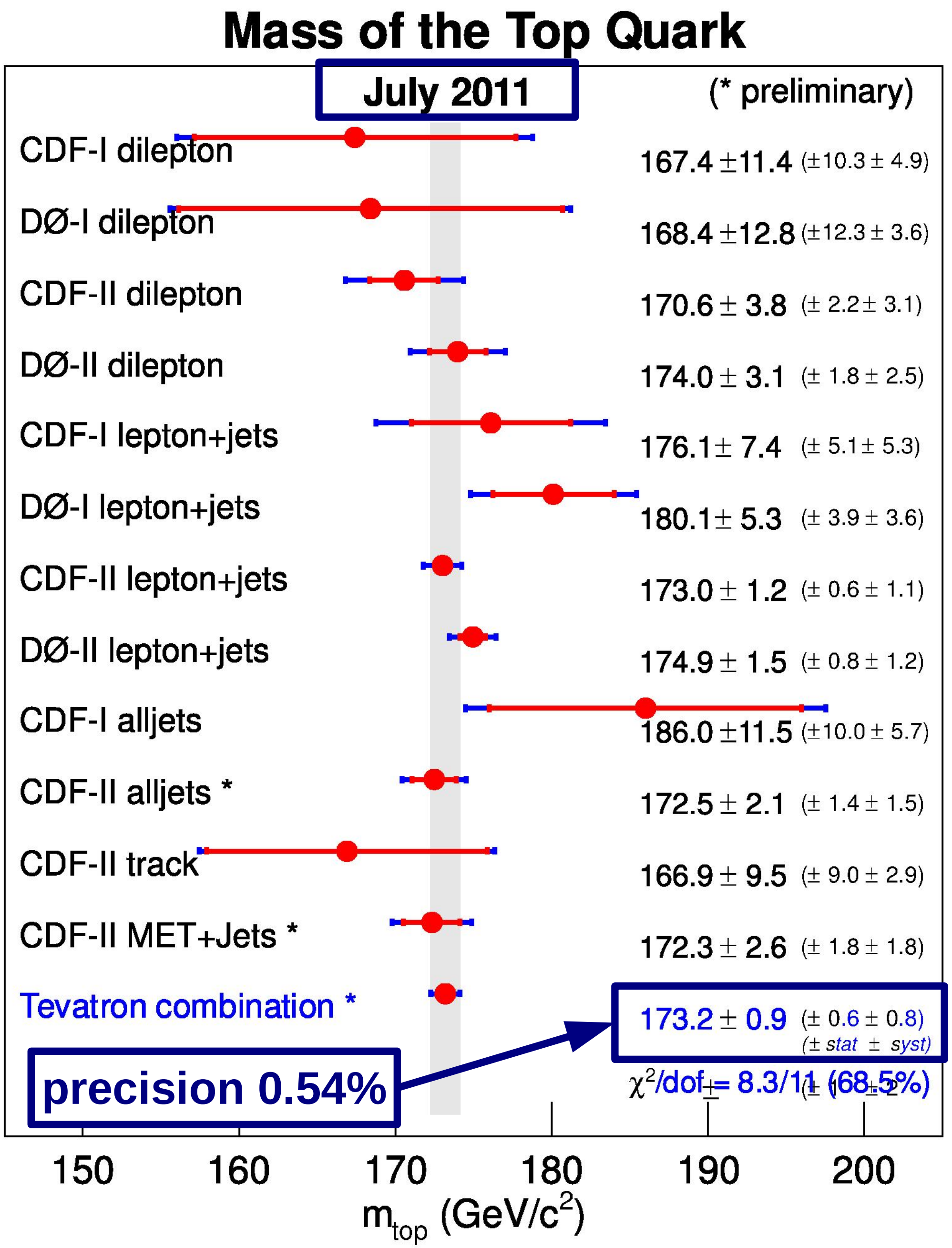




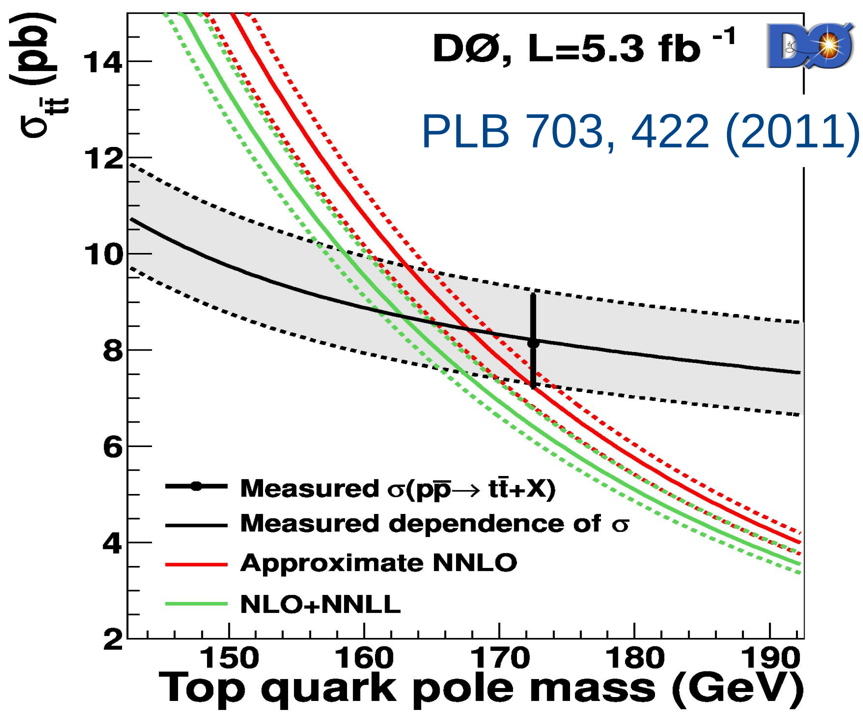
171.3 ±1.4(stat) ±0.9(syst) GeV/c^2
171.3 ±1.7 GeV/c^2 (precision ±1.4%)

???? web X pdf res. ???? CDF Note 10810 (2012)

Tevatron top mass combination



- Up to 5.8fb-1, arXiv:1107.5255
  - with all data measurement of the mass approaching 1 GeV uncertainty
- Top mass definition (comes from MC templates, calibration)
  - mass from cross section

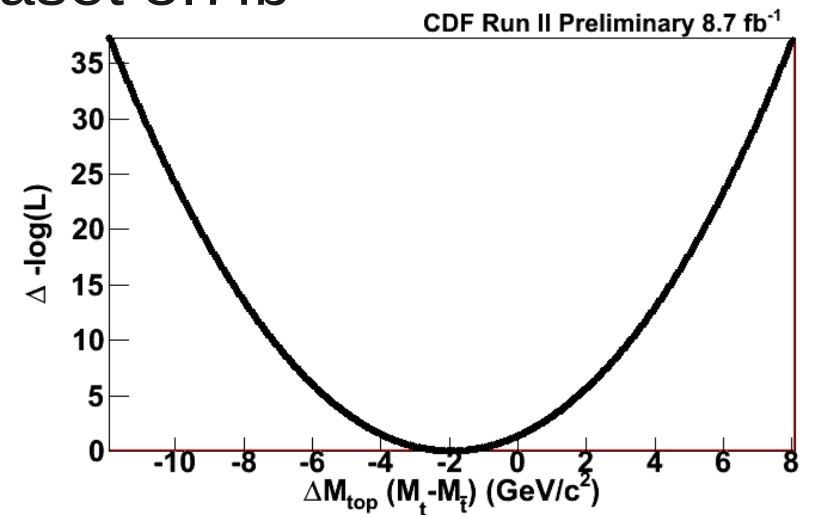


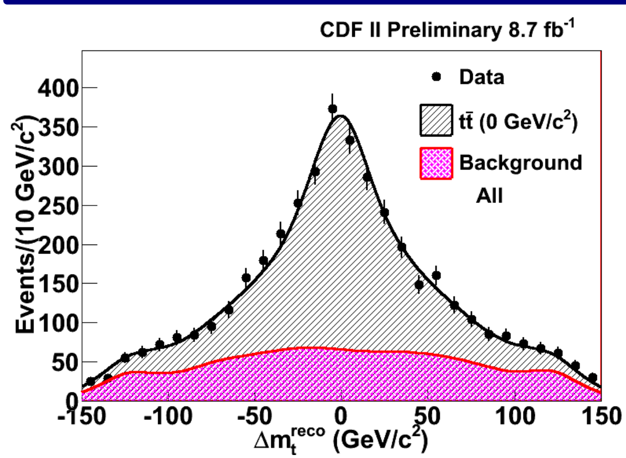
Mass difference

all data

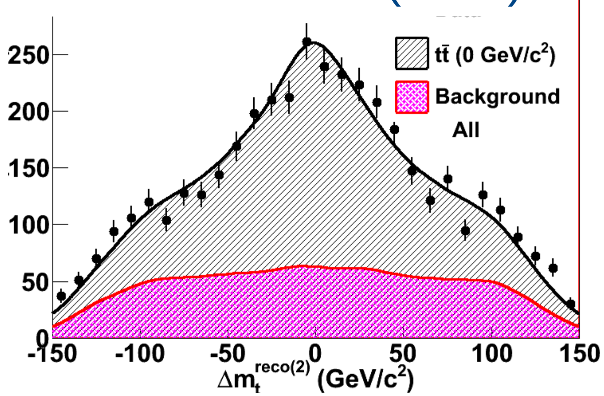
- Template method with full CDF RunII dataset 8.7fb^{-1}
  - look for difference top-antitop mass
  - check of CPT invariance in top sector
  - same procedure l+jets mass, but $m_t \neq m_{\bar{t}}$
  - in agreement with SM (no difference)

ΔM_{top} = -1.95 ± 1.11(stat) ± 0.59(syst) GeV/c^2





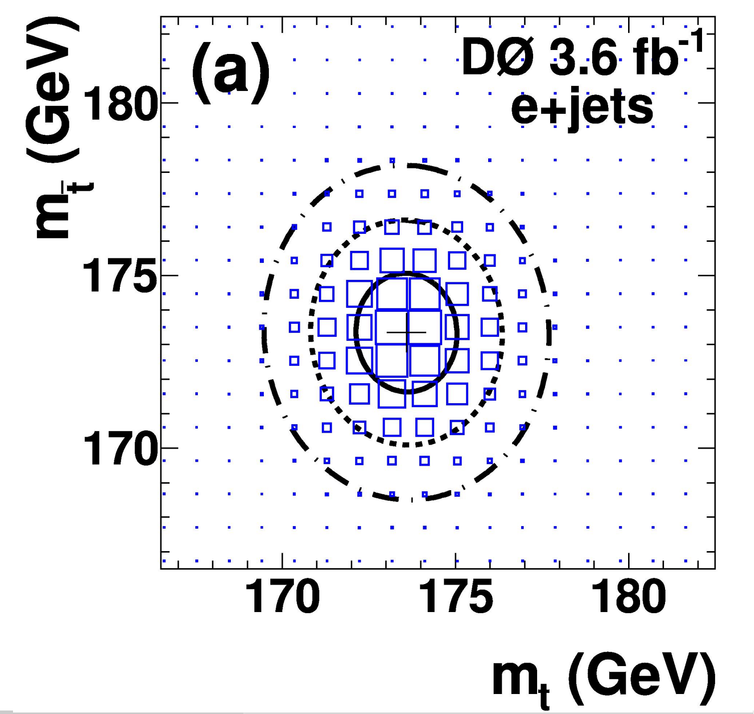
CDF Note 10777 (2012)



- Matrix element method, 3.6fb^{-1}

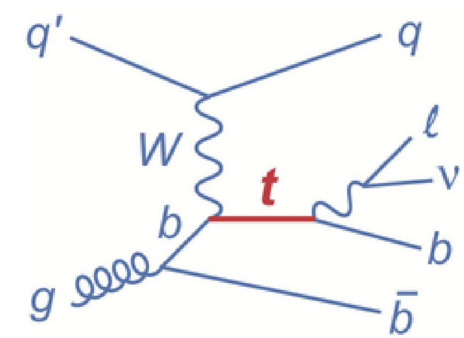
ΔM_{top} = -0.8 ± 1.8(stat) ± 0.5(syst) GeV/c^2

PRD 84, 052005 (2011)



Top quark width

- Indirect measurement from single top quark t-channel cross section and ratio $B(t\to Wb)/B(t\to Wq)$



$R = B(t\to Wb)/B(t\to Wq) = 0.90\pm0.04$
$|V_{tb}| = 0.95\pm0.02$

PRL, 121802 (2011)

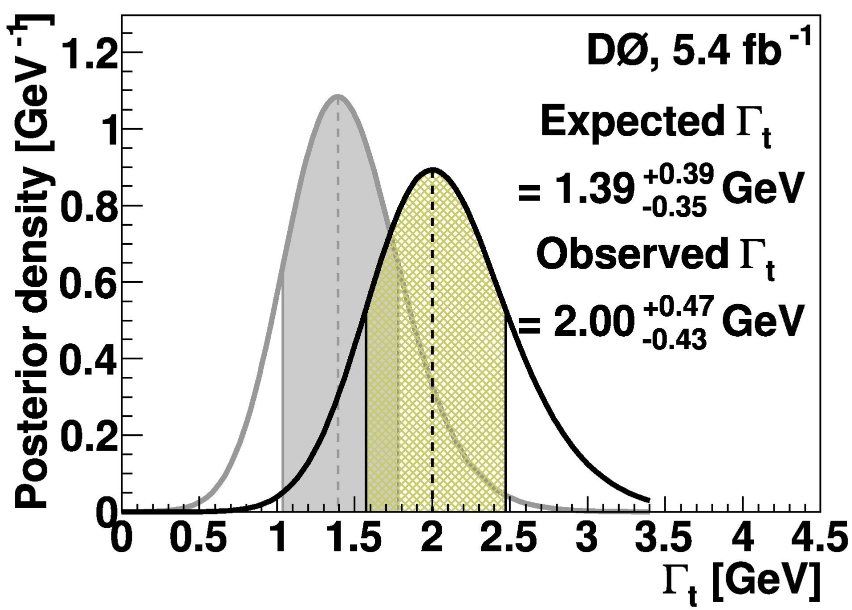
$$\Gamma_p \equiv \Gamma(t\to Wb) \approx \sigma^{meas}_{t-channel}$$

$$\Gamma_t = \frac{\Gamma_p}{\mathcal{B}(t\to Wb)} = \frac{\sigma^{meas}_{t-channel}\Gamma(t\to Wb)^{SM}}{\mathcal{B}(t\to Wb)\sigma^{SM}_{t-channel}}$$

– NLO prediction $\Gamma_t = 1.33$ GeV

$\Gamma_t = 2.00^{+0.47}_{-0.43}$ GeV
$\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25}$ (h/Γ_t)

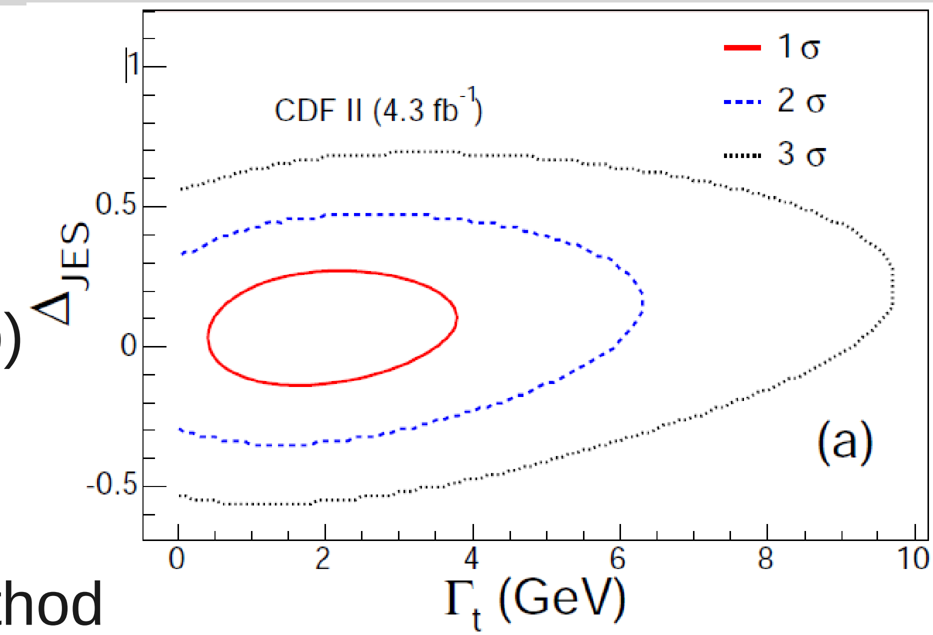
PRD 85, 091104 (2012)



– hadronization time scale 3.3×10^{-24}s => top quark decay before hadronization

Top quark width

- Direct measurement in l+jets, 4.3fb^{-1}
  - template method with different top quark Γ_t and in situ JES
  - subsamples with 1,2 b-tags (diff. s+b)
  - comparing s + b probability density
    - unbinned maximum likelihood
  - limits on Γ_t via Feldman-Cousins method



Γ_t < 7.6 GeV @ 95% CL
0.3 < Γ_t < 4.4 GeV @ 68% CL

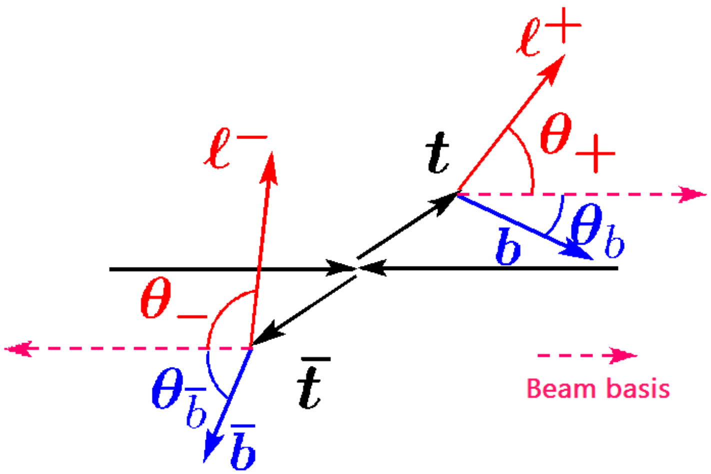
PRL 105, 232003 (2010)

Spin correlations

- SM predict top quark polarized
  - polarization of top quark spin observed through correlations between flight directions of decay products
  - $t\bar{t}$ correlation spin strength C [-1, 1]

$$\frac{1}{\sigma_{t\bar{t}}}\frac{d^2\sigma_{t\bar{t}}}{d\cos\theta_+ d\cos\theta_-} = \frac{1 + C\cos\theta_+\cos\theta_-}{4}$$

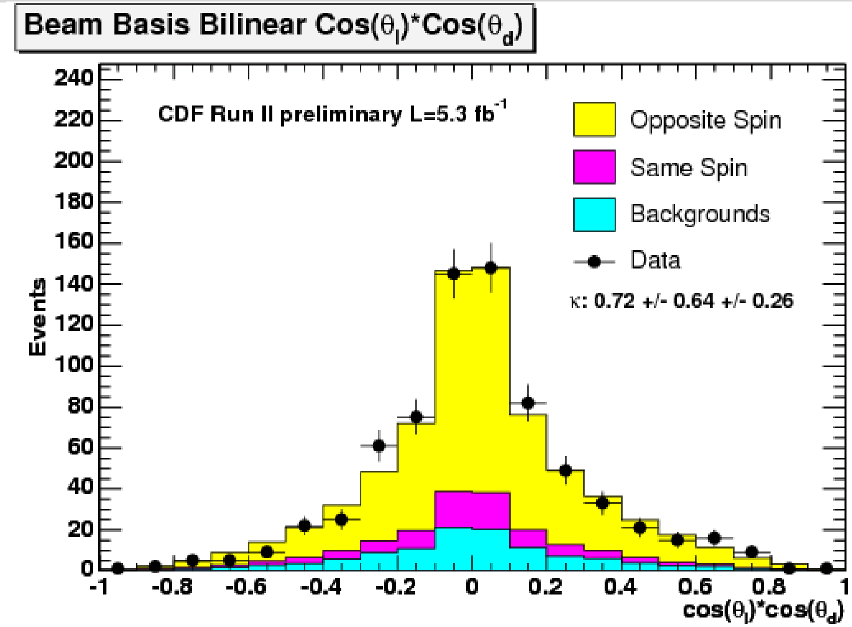
  - SM predicts C = $0.777^{+0.027}_{-0.042}$ (beam basis)
    - sensitive to non-SM



$$C = \frac{N_{\parallel} - N_{\nparallel}}{N_{\parallel} + N_{\nparallel}}$$

Spin correlations – template methods

- Using templates for $\cos\theta_{-}\cos\theta_{+}$
- Binned maximum likelihood for C_{meas}
- Statistically limited
- Consistent with SM



C = 0.04 ±0.56(stat+syst), dilepton, 5.1fb^{-1}

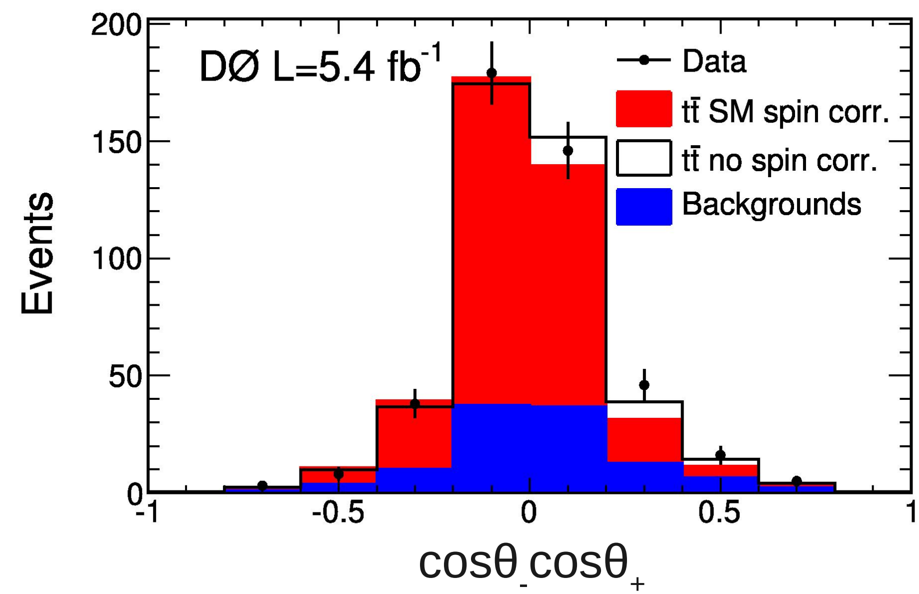
CDF Note 10719 (2011)

C = 0.72 ±0.69(stat+syst), l+jets, 5.3fb^{-1}

CDF Note 10211 (2011)

C = 0.10 ±0.45(stat+syst), l+jets, 5.3fb^{-1}

PLB 702, 16 (2011)

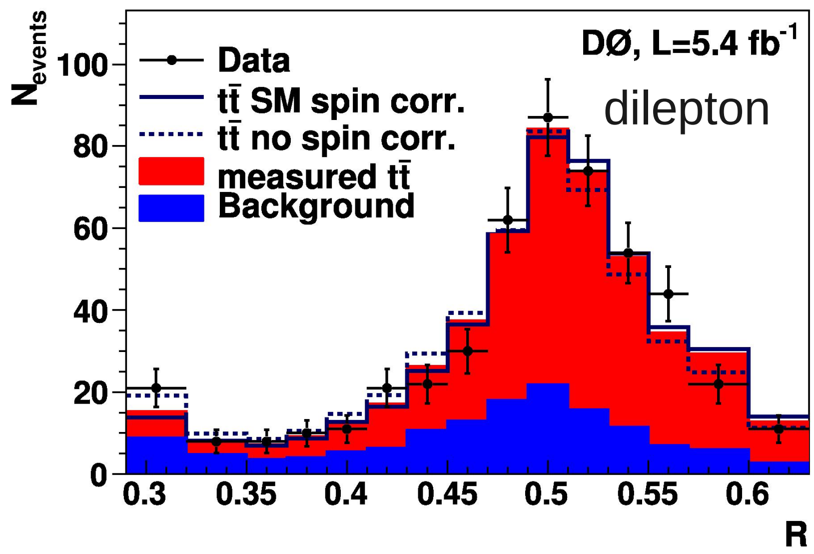


Spin correlations – ME

- ME for hypothesis with (H=c) and without (H=u) spin correlations

$$R = \frac{P_{sig}(x, H=c)}{P_{sig}(x, H=u) + P_{sig}(x, H=c)}$$

  - distributions of R for $t\bar{t}$ MC (c/u)



- Better sensitivity

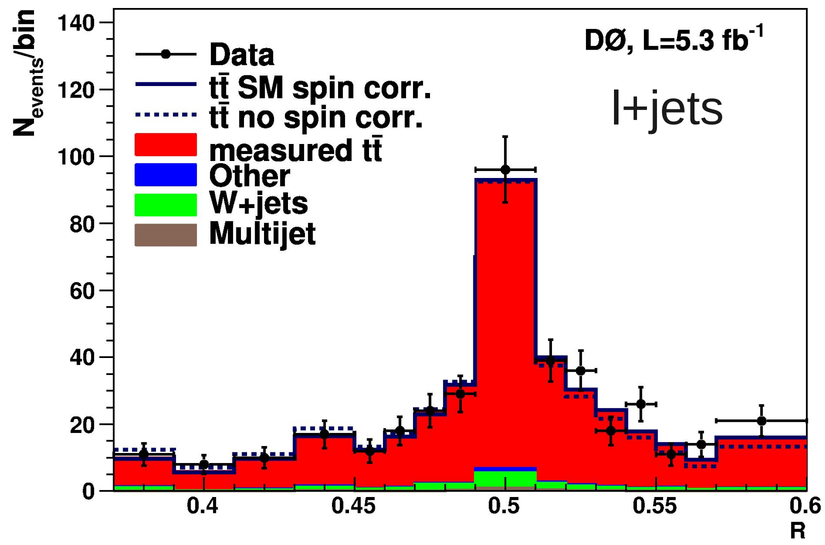
C = 0.57 ±0.31(stat+syst), dilepton, 5.4fb^{-1}

PRL 107, 031001 (2011)

C = 0.89 ±0.33(stat+syst), l+jets, 5.3fb^{-1}

Combined l+jets + dilepton:
C = 0.66 ±0.23(stat+syst)
C > 0.26 @ 95% CL
C > 0.041 @ 99.7% CL

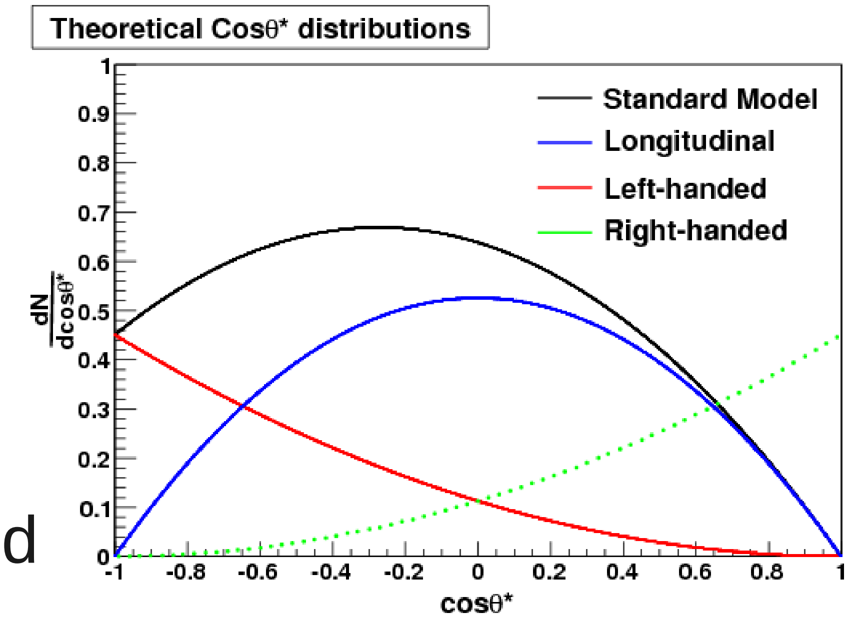
PRL 108, 032004 (2012)



- First evidence of non-zero SM spin correlation at 3.1 standard deviations

W boson helicity

- Measured in t→Wb (~ 100%)
- three possible helicity states
  - Longitudinal (f_0), left (f_-) and right (f_+) handed
  - angular distribution of decay products in W rest frame
- in SM right-handed strongly suppressed
  - V – A interaction
  - fraction of f_0, f_+ and f_- depends on m_t, m_W
  - deviation would provide evidence BSM
    - non-SM contribution
    - difference in V – A structure of tWb vertex
- Measurement doesn't rely on SM constraints
  - simultaneous measurement of f_0, f_+



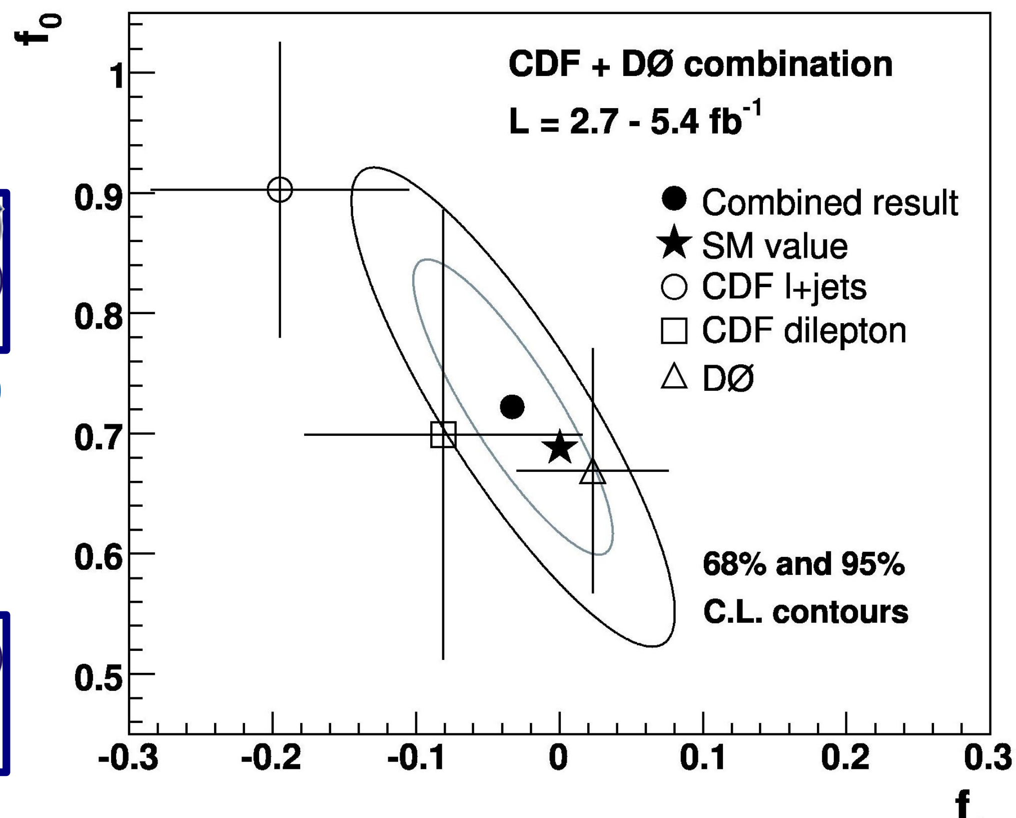
Standard model:
f_0 = 69.6%
f_- = 30.3%
f_+ = 0.1%

W boson helicity combination

- Combination of three published results
  - DØ, 5.4fb^{-1}, l+jets and dilepton, binned Poisson likelihood — PRD 83, 032009 (2011)
  - CDF, 5.1fb^{-1}, dilepton, template method — CDF Note 10543 (2011)
  - CDF, 2.7fb^{-1}, l+jets, matrix element method — PRL 105, 042002 (2010)
- First combination, improved sensitivity by factor ~ 2
- Systematic uncertainties
  - signal modeling (LO x NLO)

f_0 = 0.722±0.062(stat)±0.052(syst)
f_+ = -0.033±0.034(stat)±0.031(syst)

PRL 107, 031001 (2011)



- Matrix element, l+jets, 8.7fb^{-1}

f_0 = 0.726±0.066(stat)±0.067(syst)
f_+ = -0.025±0.024(stat)±0.040(syst)

all data

CDF Note 10855 (2012)

Conclusions

- Tevatron is making legacy measurement
  - several measurements use all RunII data
  - mass measured with precision 0.54%
    - final combination not yet done
    - improvements requires better understanding of systematic uncertainties
- Some measurements are complementary to LHC (e.g. spin correlations)
- A lot of top quark properties have been measured and tested to SM predictions

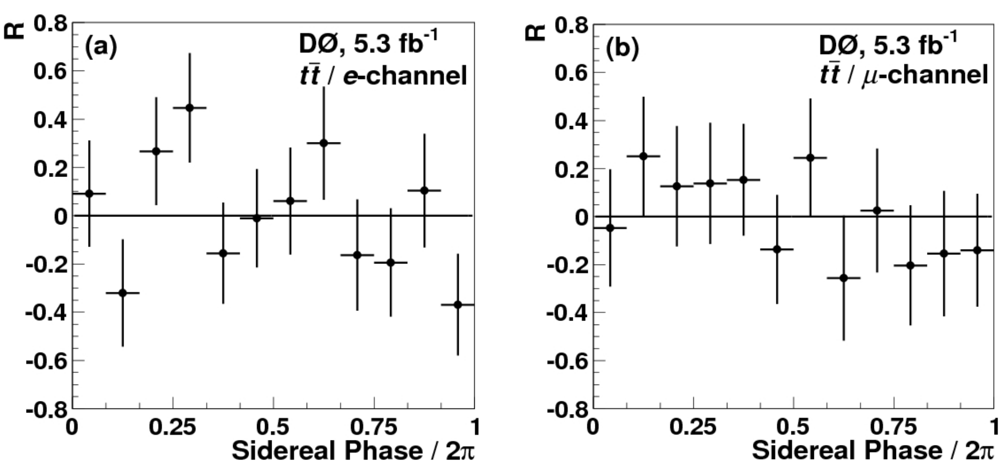
Backup

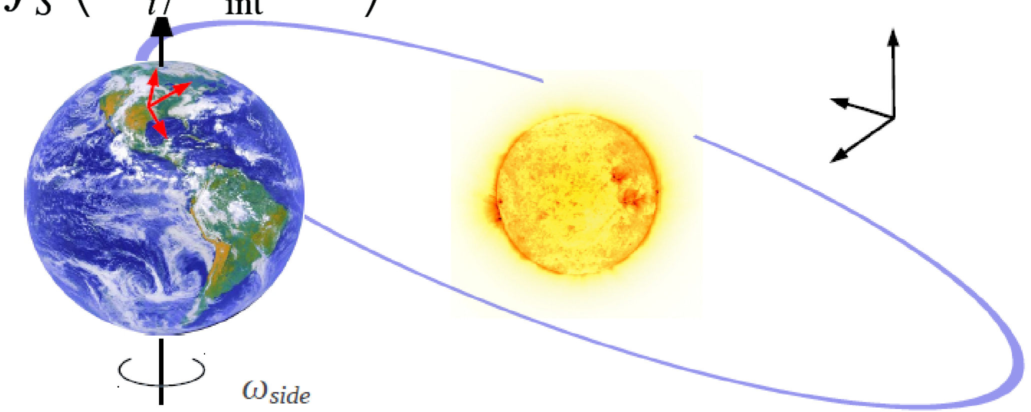
Search for LIV in top sector

- No limits on violation of Lorentz invariance exist in top quark sector
- Look for periodic oscillation in the number of ttbar events observed in the Earth-based detector as a function of sidereal time
- The relevant time scale is the sidereal day (1 day)
- $\sigma_t \approx \sigma_{ave}\,(1 + f_{SME}(t))$
- Look at distribution $N_i \approx N_{tot}\,(L_i / L_{tot})\,(1 + f_S f_{SME}\,(\Phi_i))$ (f_S – average fraction of signal events in data)
- To simplify fitting f_{SME}, define $R_i \equiv \frac{1}{f_S}\left(\frac{N_i/N_{tot}}{L_i/L_{\text{int}}} - 1\right)$

No signs for LIV in top sector

FERMILAB-PUB-12-085-E
Accepted in PRL





$$c_{L(R)}^{\text{Apparatus}} = \hat{\mathrm{R}}\,(\omega_{side}\,t)_{(\text{Sun}\rightarrow\text{Apparatus})}\, c_{L(R)}^{\text{Sun}}$$