# Measurements of the top quark mass and decay width with the D0 detector

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***08/12/2011***

# Top quark in The Standard Model

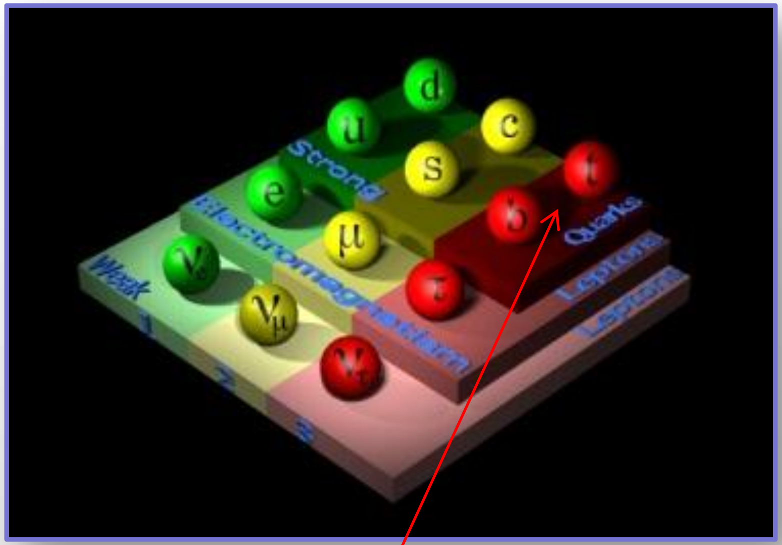
Top quark prominent facts:

- Heaviest known elementary particle – about 175 GeV
- short lifetime – $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s – decays before hadronizing
- Yukawa coupling to the Higgs boson is close to 1 (0.996 ± 0.0006)

Prominent role :

- Provides an indirect constraint on the Higgs mass and other particles through loop corrections
- Can help in testing CPT invariance by measuring $m_{top} - m_{antitop}$
- Can be an indicator of New Physics

Fermions in The Standard Model




**Top quark** is of particular importance for testing SM and searching for New Physics

⇨ It is important to measure top quark properties precisely!

# Measuring of top quark mass and width at D0

- Mass
  - Matrix Element method
    - Neutrino Weighting method
  - *dilepton* and *lepton + jets* channels
- Mass difference ($m_{top}$ - $m_{antitop}$)
  - Matrix Element method
  - *lepton + jets* channel

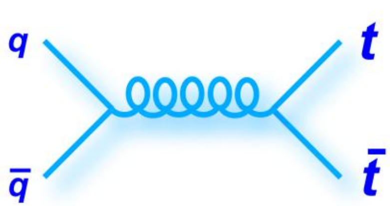
in double top production mode

- Width
  - Indirect measurement
    - single top t-channel cross section combined with measured branching ratio

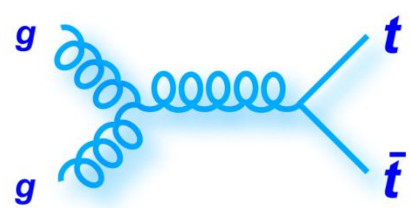
in single top production mode

# $t\bar{t}$ production and decay

- Production: double-top mode




~85%




~15%

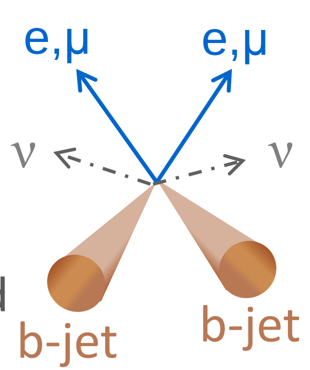
σ ≈ 7 pb
@ 2 TeV

ATLAS and CMS: quark-antiquark annihilation -15%, gluon fusion 85%

- Decay: in SM t→Wb almost 100%. Dilepton (WW → llνν), Lepton + jets (WW → lνqq)

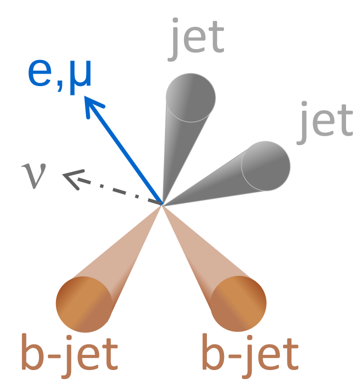
*Dilepton*

Br ~ 5%,
Low
background




*Lepton + jets*

Br ~ 30%,
Moderate
background



# Matrix Element Method

- Probability to observe $t\bar{t}$ event with kinematic quantities x measured in the detector is given

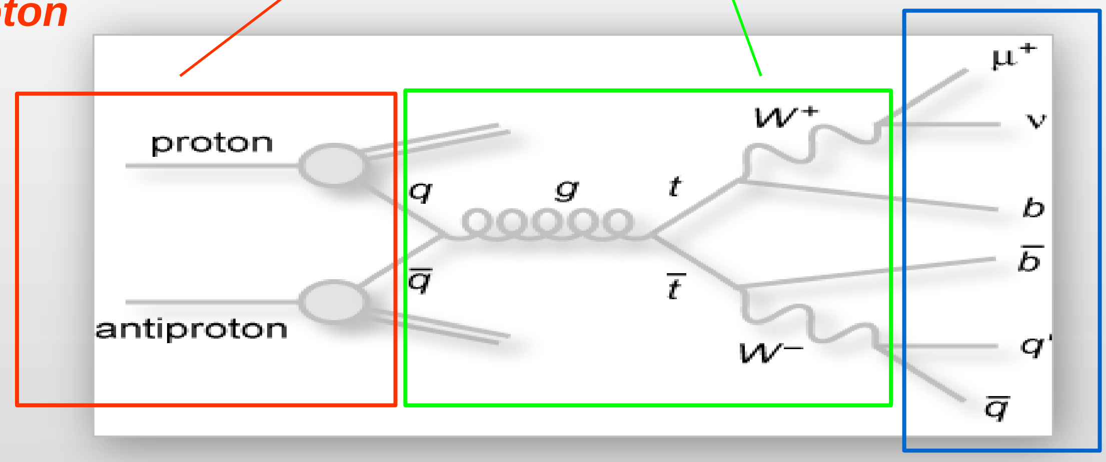
$$P_{sig}(x,\alpha) = \frac{1}{\sigma(\alpha)}\int \sum_{flavors} dq_1 dq_2 f(q_1) f(q_2) d\sigma(y,\alpha) W(x,y)$$

where α – parameter, for e.g. $m_{top}$

*PDF for finding a parton in proton/antiproton*

*Partonic x-sec*

*Transfer function*




- *Transfer function* – probability for partonic state y *to* be measured as x
  - Determined from Monte Carlo, tuned to match resolutions observed in data
- *Partonic x-sec* – cross section calculated to LO

# Matrix Element Method

- Compute $P_{sig}$ for ttbar and similarly $P_{bkg}$ background
- Assign probability $P_{evt}$ to each event

$$P_{evt} = A(x)\left[f P_{sig} + (1-f) P_{bkg}\right]$$

*A(x) – accounts for efficiencies and acceptance*

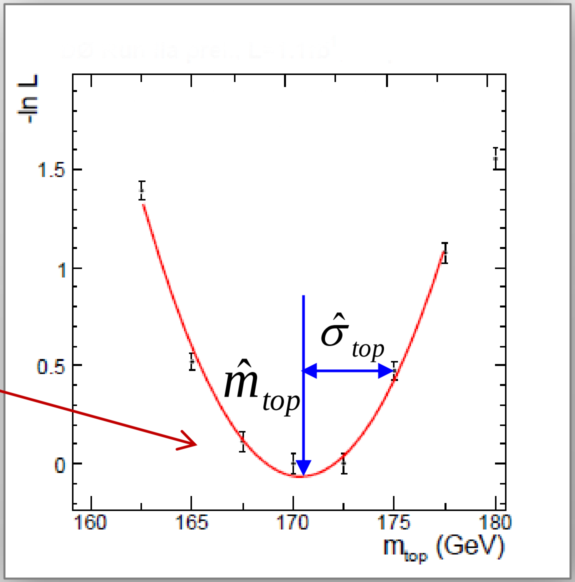
*f – fraction of signal*

*$P_{sig}$, $P_{bkg}$ – probabilities for the event to be signal or background*

- Combined likelihood function for N events

$$L(\tilde{x}) = \prod_{i=1}^{N} P_{evt}(x_i)$$

- Top quark mass is extracted from likelihood fit
- Perform ensemble tests to ensure the correct mass extraction and for method calibration



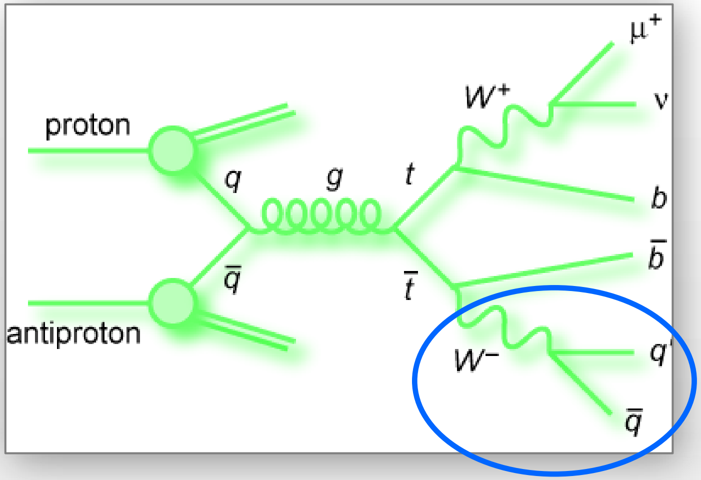
# *Lepton + jets* mass measurement

Integrated luminosity is 3.6 $fb^{-1}$

Event selection:

- Exactly 4 jets - leading $p_t$ >40 GeV, other $p_T$ > 20 GeV , at least 1 identified b-jet
- Lepton $p_T$ > 20 GeV
- Missing $E_T$ > 20 GeV (e+jets), 25 GeV (μ+jets)

Lepton + jets event diagram




- Use ME method to find top quark mass
  - measure $m_{top}$ and $k_{JES}$ simultaneously
- Dominant background is W + jets

W decays into 2 jets. Allows to **additionally calibrate** jets energy

- 2 quarks are from W and form jets
  - can calibrate jet energy by constraining invariant mass to $M_W$=80.4 GeV

# Flavor dependent correction

- Brings the simulation of jet response into agreement with Data
  - jets from different partons have different jet response
- Flavor dependent correction is based on Single Particle responses
  - correct b independently from light jets
  - b/light systematic has been significantly reduced → Data-MC jet response difference systematic
- Discrepancy in energy between Data and MC

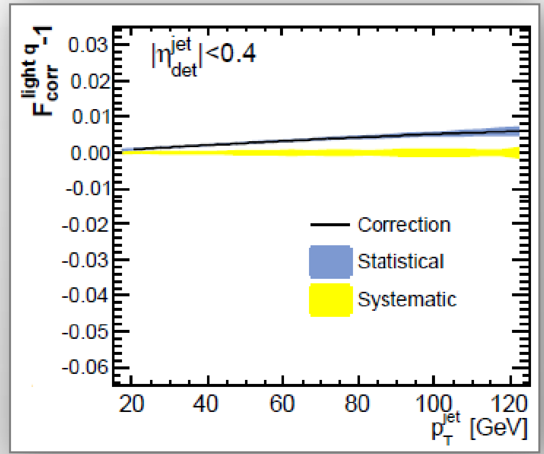
$$\mathcal{D} = \frac{\sum E_i \cdot R_i^{\rm Data}}{\sum E_i \cdot R_i^{\rm MC}},$$

$E_i$, $R_i$ – single particle energy and response

- Define correction factor for jet of flavor **β**

$$F^{\beta}_{\rm corr} = \mathcal{D}^{\beta} / \langle \mathcal{D}^{\gamma+\rm jet} \rangle$$

flavor-averaged in γ+jets events




($F_{corr}$-1) for light jets in |η|<1.4

- Correct jet energies based on their flavor

⇨ Systematical uncertainty is significantly reduced!

# *Lepton + jets* results

Top quark mass measurement in lepton + jets final states:

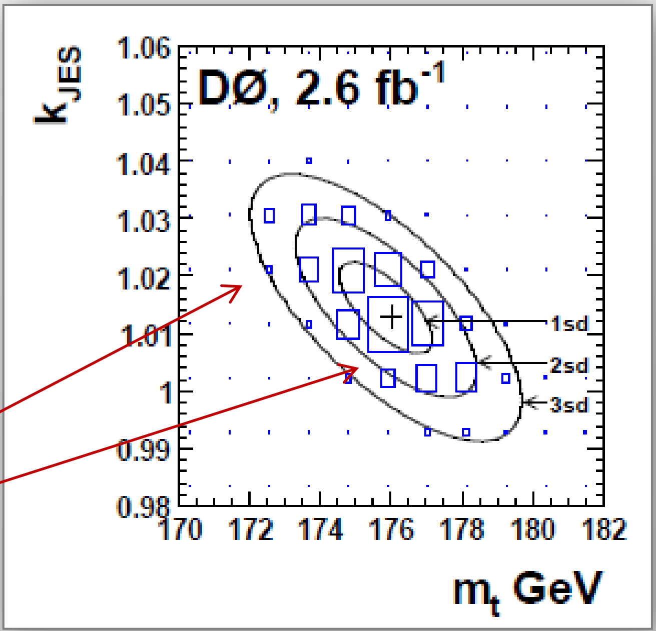
$m_{top}$ = 176.0 ± 1.0 (stat.) ± 0.8 (jes.) ± 1.0 (syst.) GeV
$m_{top}$ = 176.0 ± 1.6 GeV ,

L = 3.6 $fb^{-1}$

D0 most precise top quark single mass measurement

- in-situ calibration
- flavor dependent correction
  ($k_{JES}$ = 1.013 ± 0.008)

Fitted contours of equal probability




2D likelihood in $m_{top}$ and $k_{JES}$

# Lepton + jets systematic uncertainties

Largest systematic – Hadronization and UE

- derived by comparing modeling hadronization and underlying events in PYTHIA and HERWIG. Being improved.

Major systematic improvement - Data-MC jet response

- reduces b/light systematic that was 0.83 GeV

Table IV. Summary of systematic uncertainties.

| Source | Uncertainty (GeV) |
|---|---|
| *Modeling of production:* | |
| *Modeling of signal:* | |
| Higher-order effects | ±0.25 |
| ISR/FSR | ±0.26 |
| Hadronization and UE | ±0.58 |
| Color reconnection | ±0.28 |
| Multiple $p\bar{p}$ interactions | ±0.07 |
| Modeling of background | ±0.16 |
| $W$+jets heavy-flavor scale factor | ±0.07 |
| Modeling of $b$ jets | ±0.09 |
| Choice of PDF | ±0.24 |
| *Modeling of detector:* | |
| Residual jet energy scale | ±0.21 |
| Data-MC jet response difference | ±0.28 |
| $b$-tagging efficiency | ±0.08 |
| Trigger efficiency | ±0.01 |
| Lepton momentum scale | ±0.17 |
| Jet energy resolution | ±0.32 |
| Jet ID efficiency | ±0.26 |
| *Method:* | |
| Multijet contamination | ±0.14 |
| Signal fraction | ±0.10 |
| MC calibration | ±0.20 |
| Total | ±1.02 |

# *Dilepton* mass measurement

Integrated luminosity is 5.4 $fb^{-1}$

Event selection:

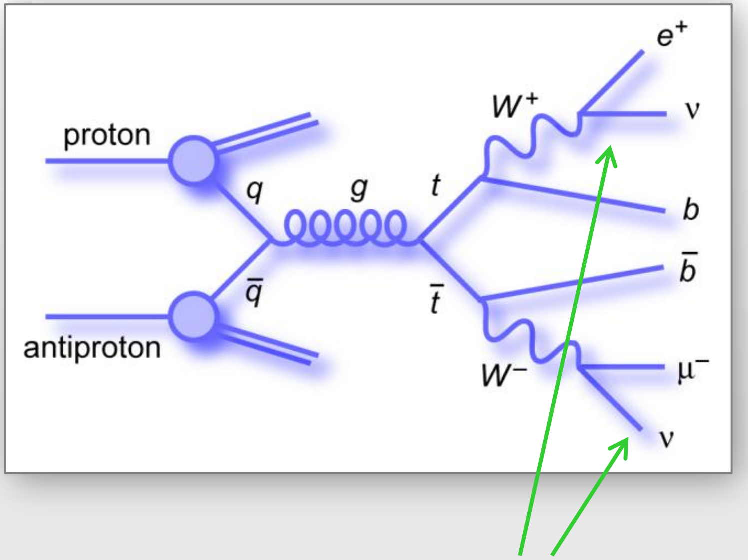
- Exactly 2 oppositely charged, isolated leptons $p_T$ > 15 GeV
- At least 2 jets – |η|<2.5, leading $p_t$ >20 GeV
- Additional topological cuts against Z+jets background

- Use ME method to find top quark mass
- Dominant background is Z + jets

Mass measurement result:

$m_{top}$ = 174.01 ± 1.8 (stat.) ± 2.4 (syst.) GeV

Dilepton event diagram




Full kinematic reconstruction is impossible. One degree of freedom is missing.

# *Dilepton* systematic uncertainties

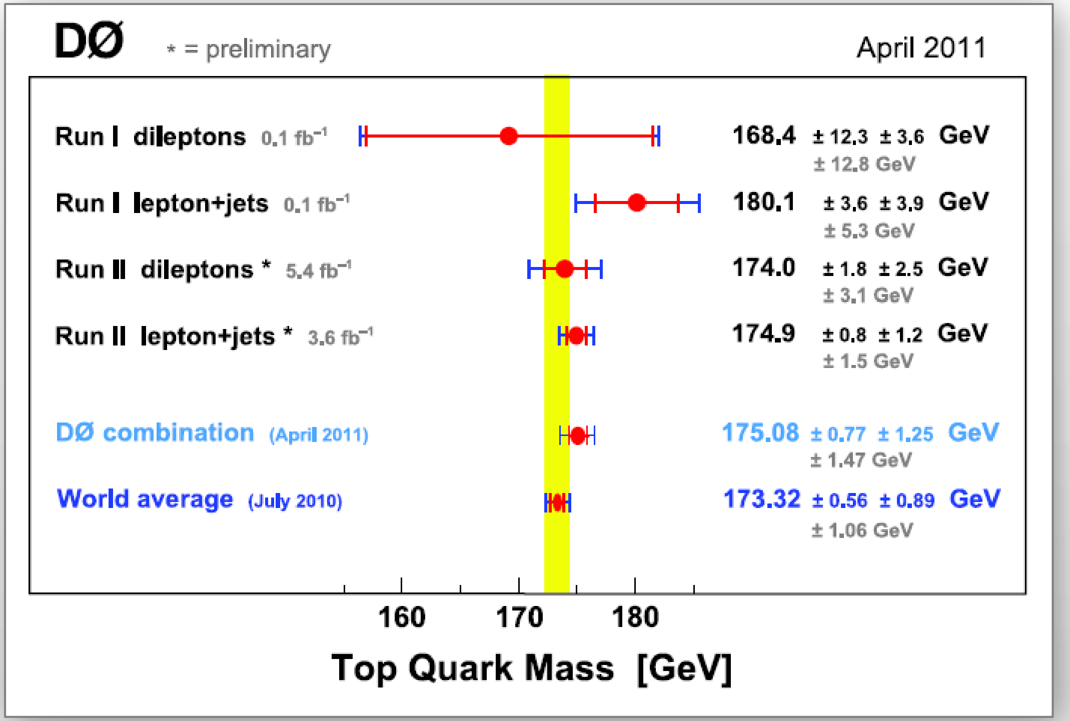
Largest systematics – b/light jet response and JES

- jes cannot be constrained by W mass as in lepton + jets case
- flavor dependent correction is not used here

| Source | Uncertainty (GeV) |
|---|---|
| *Detector modeling:* | |
| $b$/light jet response | $\pm 1.6$ |
| JES | $\pm 1.5$ |
| Jet resolution | $\pm 0.3$ |
| Muon resolution | $\pm 0.2$ |
| Electron $p_T$ scale | $\pm 0.4$ |
| Muon $p_T$ scale | $\pm 0.2$ |
| ISR/FSR | $\pm 0.2$ |
| *Signal modeling:* | |
| Higher order and hadronization | $\pm 0.7$ |
| Color reconnection | $\pm 0.1$ |
| $b$-quark modeling | $\pm 0.4$ |
| PDF uncertainty | $\pm 0.1$ |
| *Method:* | |
| MC calibration | $\pm 0.1$ |
| Signal fraction | $\pm 0.5$ |
| Total | $\pm 2.4$ |

# D0 mass combination

- Results in different channels are in agreement
- World average $m_{top}$ is known better than 1% for the first time




Combined mass measurement for D0 and Tevatron

Combined D0 *lepton + jets* and *dilepton* result from Run I and Run II

$m_{top}$ = 175.1 ± 0.8 (stat.) ± 1.3 (syst.) GeV
or $m_{top}$ = 175.1 ± 1.5 (stat.+ syst.) GeV

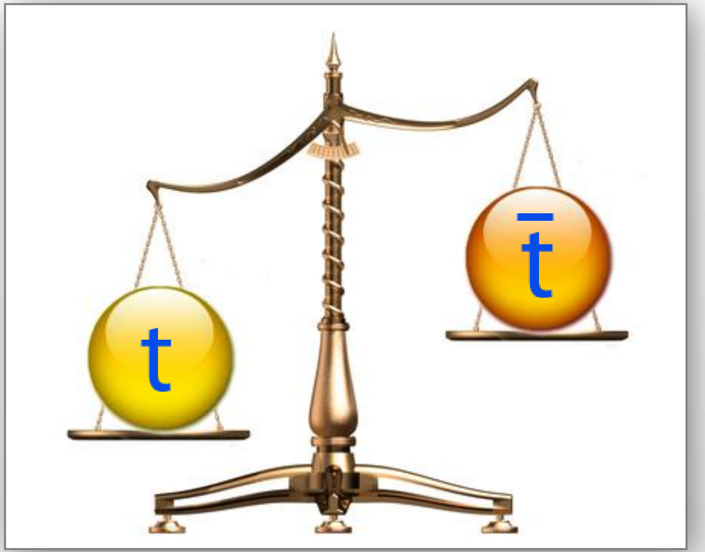
*D0 top quark mass relative uncertainty is **0.84%***

# Top quark mass difference

- Top quark mass measurements assume $m_{top} = m_{antitop}$

- Mass difference would mean violation of CPT invariance

- Top quark decays before hadronization → allows to measure directly quark-antiquark mass difference




Is $m_{top} = m_{antitop}$ actually?

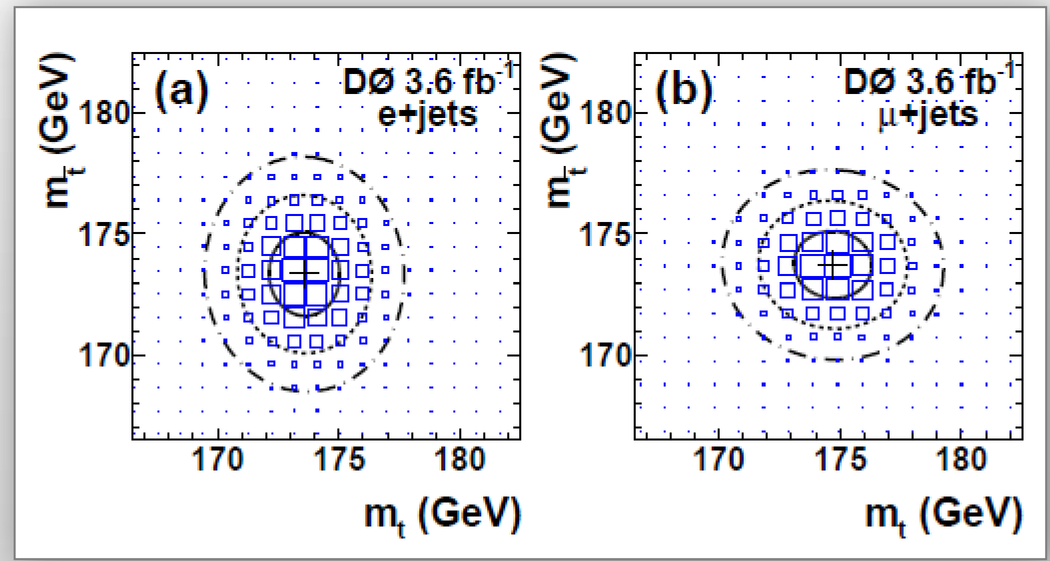
- Integrated luminosity is 3.6 $fb^{-1}$
- Based on ME method in *lepton + jets* channel
  - measure $m_{top}$ and $m_{anti\text{-}top}$ directly and independently
  - two dimensional likelihood becomes $L(m_{top}, JES) \rightarrow L(m_{top}, m_{antitop})$

# Mass difference result

- Combined result for mass difference $\Delta m$:

$$\Delta m = 0.8 \pm 1.8\ (\text{stat.}) \pm 0.5\ (\text{syst.})\ \text{GeV}$$

- Agrees with no mass difference at the level of ≈ 1%




Fitted contours of equal probability in 2D likelihood

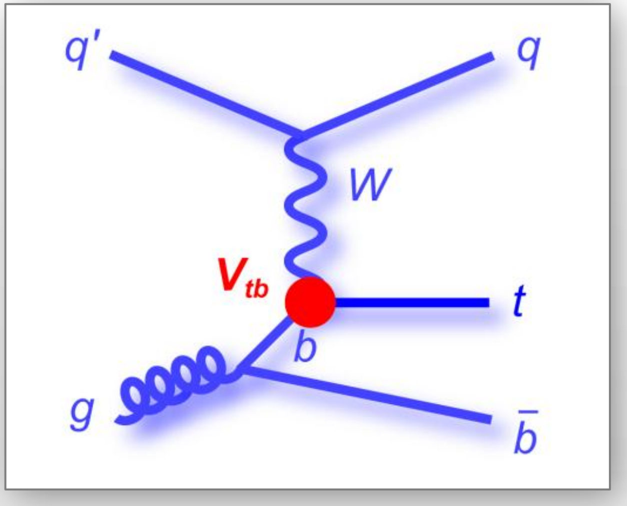
Systematic uncertainties

| Source | Uncertainty on $\Delta m$ (GeV) |
|---|---|
| Modeling of detector: | |
| Jet energy scale | 0.15 |
| Remaining jet energy scale | 0.05 |
| Response to $b$ and light quarks | 0.09 |
| Response to $b$ and $\bar{b}$ quarks | 0.23 |
| Response to $c$ and $\bar{c}$ quarks | 0.11 |
| Jet identification efficiency | 0.03 |
| Jet energy resolution | 0.30 |
| Determination of lepton charge | 0.01 |
| ME method: | |
| Signal fraction | 0.04 |
| Background from multijet events | 0.04 |
| Calibration of the ME method | 0.18 |
| Total | 0.47 |

Major additional systematic uncertainty – **asymmetry in response to quark antiquark**

# Top quark width

- Direct measurement – less sensitive
  - determines the width $\Gamma_t$ from top quark mass spectrum
  - $\Gamma_t < 7.6$ GeV (95% C.L., L=4.5 $fb^{-1}$) by CDF collaboration
- Indirect measurement – more precise
  - extracts width from single top t-channel cross-section measurement and branching fraction from ttbar




Single top production diagram

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

- assumes coupling is the same for production and decay

# Top quark width results

Derive the width using Bayesian statistical approach

Result for top quark width and lifetime:

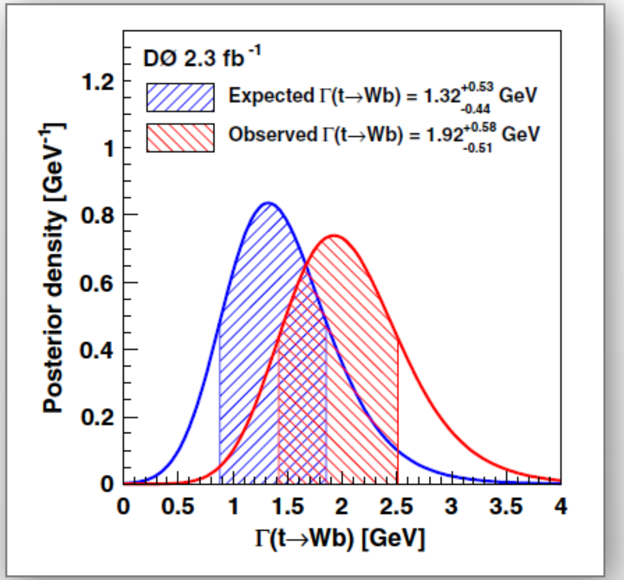
$\Gamma_t > 1.21$ GeV at 95% C.L.
$\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s

L = 2.3 $fb^{-1}$

The width result is consistent with SM prediction $\Gamma_t^{SM} = 1.26$ GeV ($m_{top}$ = 170 GeV)

New physics – can set a limit on high mass 4th generation b' quark

- $|V_{tb'}| < 0.63$ at 95% C.L.




Partial width probability density distribution
(expected and observed)

# Conclusion

- Mass difference for top-antitop – no CPT violation evidence
- Indirect width measurement gives more sensitive result than direct measurement but somewhat model dependent (SM)
- Mass measurement (combined result) – less than 1% error

$m_{top}$ = 175.1 ± 0.8 (stat.) ± 1.3 (syst.) GeV
$m_{top}$ = 175.1 ± 1.5 (stat.+ syst.) GeV