Precise measurements of the top mass and direct measurement of the mass difference between top and antitop quarks at DØ

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1. Introduction
2. Neutrino and Matrix Weighting
   - $\ell\ell+$jets final state
3. Matrix Element method
   - $\ell\ell+$jets final state
   - $\ell+$jets final state
4. Combination of DØ results
5. Top/antitop mass difference
6. Summary

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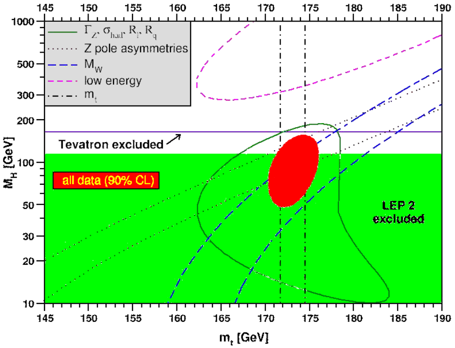
The top quark

- top mass is a free parameter of the Standard Model
- it is an important parameter for the evaluation of the loop corrections to *W* boson mass and a constraining parameter for *H* boson mass *(left)*
- top is the only quark that can be measured free rather than in a bound state: it decays before it can hadronize



*90% CL limits on SM Higgs boson mass from measurements, as function of m_t [Erler, PRD **81**, 051301 (2010)]*

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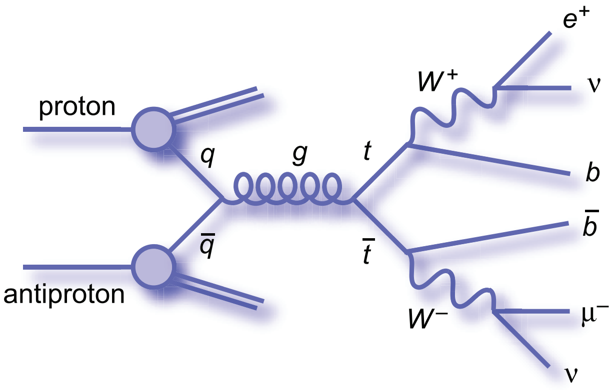
$\ell\ell+$jets final state



Events selection outline:

- two isolated leptons (ee, $e\mu$ or $\mu\mu$) with opposite charge
- at least 2 reconstructed jets
- signal purities of $80 - 85\%$ (ee and $e\mu$) and 60% ($e\mu$) are achieved

Neutrino weight

Our final state is not fully reconstructed:

- 6 final state particles of known mass ⇒ *18 unknown*
- energy and direction of b, $\bar{b}$, e and μ are measured ⇒ *6 left*
- W mass ($m(\ell\nu) = M_W$), same top mass ($m_t = m_{\bar{t}}$) ⇒ *3 left*:
  two neutrino unknown (e.g. η_ν and $\eta_{\bar{\nu}}$), plus the top mass M_t

We define a «weight» to quantify the agreement of the missing energy $\vec{\not{E}}_T^{\text{calc}}$ calculated from event kinematics with the measured one, $\vec{\not{E}}_T^{\text{obs}}$:

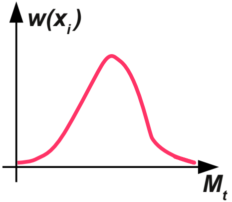
$$w\left(\eta_\nu, \eta_{\bar{\nu}}, M_t\right) = \exp\left[-\left(\frac{\not{E}_x^{\text{obs}} - \not{E}_x^{\text{calc}}}{\sqrt{2}\,\sigma_x^u}\right)^2\right] \exp\left[-\left(\frac{\not{E}_y^{\text{obs}} - \not{E}_y^{\text{calc}}}{\sqrt{2}\,\sigma_y^u}\right)^2\right]$$

including $\not{E}_T$ resolution $\sigma_{x/y}^u$. The dependency on $\eta_{\nu/\bar{\nu}}$ is resolved by convolving the weight with the distributions $\rho\left(\eta_{\nu/\bar{\nu}}\right)$ predicted for $t\bar{t}$:

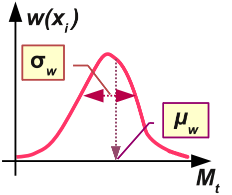
$$w\left(M_t\right) = \int w\left(\eta_\nu, \eta_{\bar{\nu}}, M_t\right) \rho\left(\eta_\nu\right) \rho\left(\eta_{\bar{\nu}}\right)\, \mathrm{d}\eta_\nu\, \mathrm{d}\eta_{\bar{\nu}}$$

Templates method with weights (I): building templates

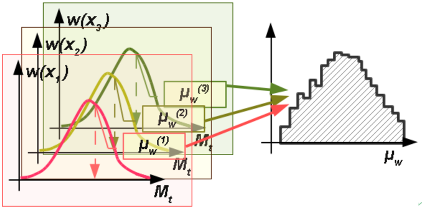
1. assign to each event the weigth w as function of the top mass M_t assumed to compute the event kinematics)



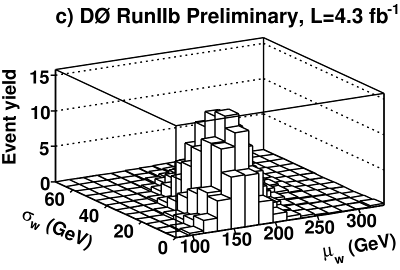
2. for each event, extract from its weight the values of the average μ_W and its RMS σ_W; they don't depend explicitly on M_t anymore

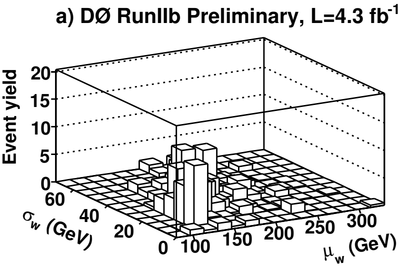


3. merge μ_W and σ_W from all the events in the sample into a 2D template h_{sample}; for signal samples, it will depend on the sample top mass m_t: $h_{\text{sig}}(m_t)$



Templates method with weights (II): mass extraction

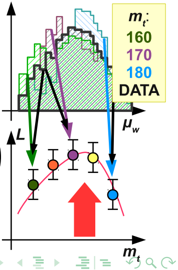




Signal template (top mass 175 GeV/c^2*) and all backgrounds template*

4. compute a likelihood for the N events in data to follow signal (with different m_t) + background templates:

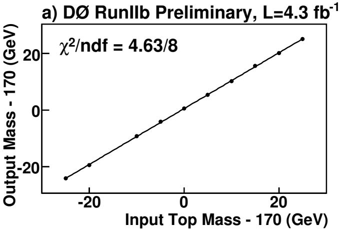
$$L(m_t) = \prod_{i=1}^{N} f\, h_{\mathrm{sig}}\left(\mu_W^{(i)}, \sigma_W^{(i)}; m_t\right) + (1-f)\; h_{\mathrm{bck}}\left(\mu_W^{(i)}, \sigma_W^{(i)}\right)$$



5. maximize the likelihood to find the best m_t estimator

Calibration

- our mass estimator is biases due to the chosen approximations, selection etc.
- a calibration is performed to correct for these biases
- “pseudo-datasets” are built from simulated events, using a known value of the top mass and sample composition
- the very same analysis procedure for measured data is then applied on them too
- calibration is based on the average and RMS of the results, for each input top mass



Measurement in $e\mu$ + jets by Neutrino Weighting

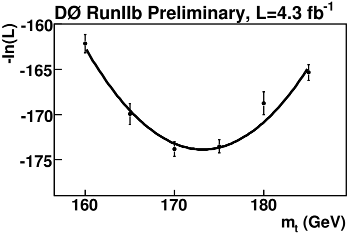
The 202 events selected in $e\mu$ final state from 4.3 fb^{-1} of DØ data yield to

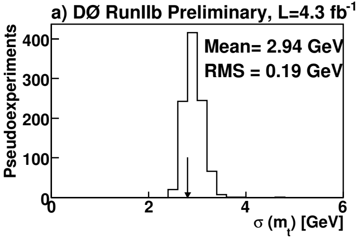
$$m_t = 172.7 \pm 2.8(\text{stat}) \pm 2.1(\text{syst})\ \text{GeV}/c^2$$

Main systematic uncertainties (GeV/c^2):

Jet Energy Scale	1.4
b/light jet response	0.8
Signal modelling	1.0

Conference note DØ 6104-CONF





Combined result for 5.3 fb^{-1}:

$$m_t = 173.3 \pm 2.4(\text{stat}) \pm 2.1(\text{syst})\ \text{GeV}/c^2$$

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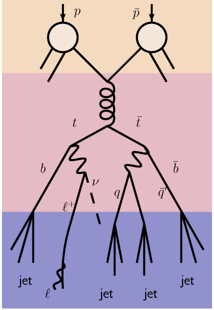
Matrix Element method (I): process probability

At the core of the Matrix Element method there is the probability of measuring an event from a certain process, which can depend on the parameters we want to measure, e.g. the top mass m_t:

$$P(x, m_t) = \frac{1}{\sigma(m_t)} \int \sum_{\text{flavours}} f(q_1)\, f(q_2)\, \sigma(y, m_t)\, \mathcal{W}(x, y)\; dq_1\, dq_2\; dy$$



- the probability $f(q_{1/2})$ of having a specific initial state (Parton Distribution Functions)
- the scattering matrix element $\mathcal{M}$ for a final-state parton configuration "y" (including 4-momenta of all the 6 final state particles)
- the probability $\mathcal{W}$ of reconstructing the scattering final state "y" as our measured jets/lepton objects "x" (transfer functions)

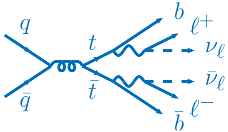
Matrix Element method (II): event probability

Prob. to observe an event x (including the detector acceptance $A(x)$):

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

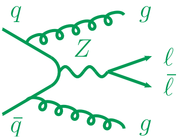
The processes are mixed by a fraction f (a free parameter).

Signal



P_{sig} depends on the top mass m_t. Its $\mathcal{M}\left(q_1 q_2 \to t\bar{t}\right)$ is computed analytically at Leading Order.

Background



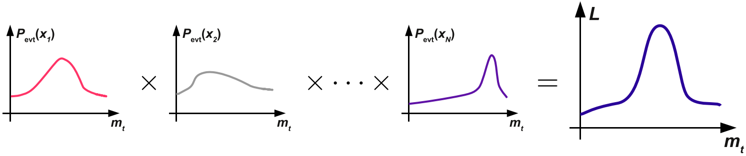
We pick a process from the largest background, $Z + 2$ jets. The $\mathcal{M}(q_1 q_2 \to Z + 2\,\text{jets})$ is computed using VECBOS (LO).

For $e\mu$ + jets final state, we use $Z \to \tau^+\tau^- \to e\mu + 4\nu$ and an additional transfer function connecting τ with e/μ from its decay.

Matrix Element method (III): sample probability

Probabilities from all the events are combined in the likelihood to measure our actual data sample, as function of our parameters:

$L(m_t, \ldots) =$

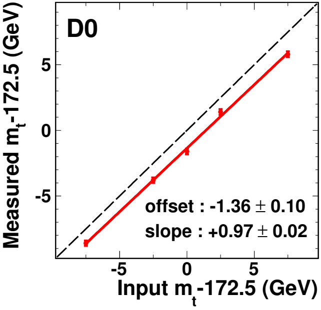


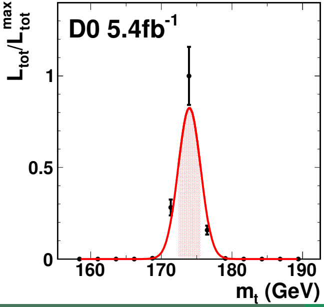
$$\Downarrow$$

$$L\left(\{x_i\}\,; f, m_t\right) = \prod_i P_{\text{evt}}\left(x_i; f, m_t\right)$$

- the likelihood is evaluated numerically using tens of hypotheses for the top mass m_t and the signal fraction f
- *maximization* of L provides estimators of the two parameters
- a calibration of L point by point corrects for biases

Measurement in $\ell\ell +$ jets by Matrix Element





The analysis of 5.4 fb^{-1} of DØ data (using 73, 266 and 140 events from *ee*, $e\mu$ and $\mu\mu$ final states) yields:

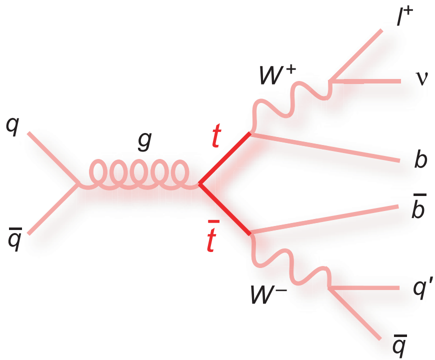
$m_t = 174.0 \pm 1.8(\text{stat}) \pm 2.4(\text{syst})$ GeV/c^2

Dominant systematic uncertainties (GeV/c^2):

Jet Energy Scale	1.5
b/light jet response	1.6
Signal modelling	0.8

Accepted by PRL (arXiv:1105.0320 [hep-ex])

$\ell +$ jets final state



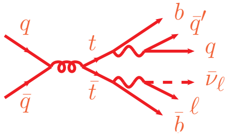
Events selection outline:

- only one isolated electron/muon
- exactly 4 reconstructed jets
- at least one jet identified as coming from a *b* quark
- purities of $\approx$ 70% ($e +$ 4 jets) and $\approx$ 75% ($\mu +$ 4 jets) are achieved

Matrix Element method for $\ell +$ jets final state

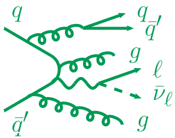
The Matrix Element method applied on the $\ell +$ jets final state shares many of the features used for the $\ell\ell +$ jets.

Signal



P_{sig} depends on the top mass m_t. Its $\mathcal{M}\left(q_1 q_2 \to t\bar{t}\right)$ is computed analytically at Leading Order.

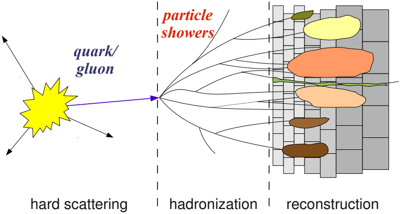
Background



We pick the process from the largest background, $W + 4$ jets. Its $\mathcal{M}\left(q_1 q_2 \to W + 4\,\text{jets}\right)$ is computed using VECBOS (LO).

The main difference in the *method* is the use of an additional free parameter, k_{JES}, representing a residual Jet Energy Scale correction specific to this data sample.

Matrix Element method: *in situ* JES



- Jet Energy Scale: detected energy $E_{\mathrm{raw}} \Rightarrow$ estimated jet energy E_x
- transfer functions: particle jet energy $E_x \Rightarrow$ parton energy E_y

Additional free parameter: global residual JES shift k_{JES}

- can compensate a global residual bias of JES
- affects directly the jet transfer functions
- is strongly constrained by the presence of $W \to q\bar{q}'$ in the signal

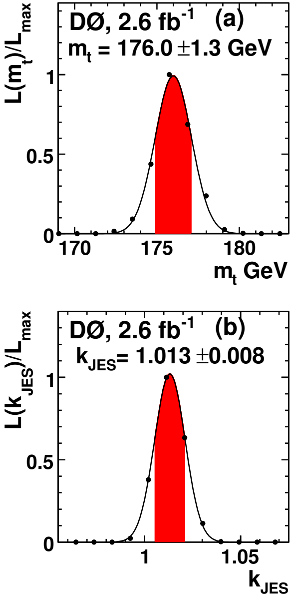
Measurement in $\ell+$jets by Matrix Element

The analysis of 2.6 fb^{-1} of DØ data (using 312 $e+$jets and 303 $\mu+$jets events) yields:

$m_t = 176.0 \pm 1.3(\text{stat+JES}) \pm 1.0(\text{syst})\,\text{GeV}/c^2$
with $k_{\text{JES}} = 1.013 \pm 0.008$.

Dominant systematic uncertainties (GeV/c^2):

Signal modelling	± 0.74
Jet energy resolution	± 0.32
Data – MC jet response	± 0.28
Jet ID efficiency	± 0.26



Combined result for 3.6 fb^{-1} DØ data:

$m_t = 174.9 \pm 1.1(\text{stat+JES}) \pm 1.0(\text{syst})\,\text{GeV}/c^2$

Accepted by PRD (arXiv:1105.6287 [hep-ex])

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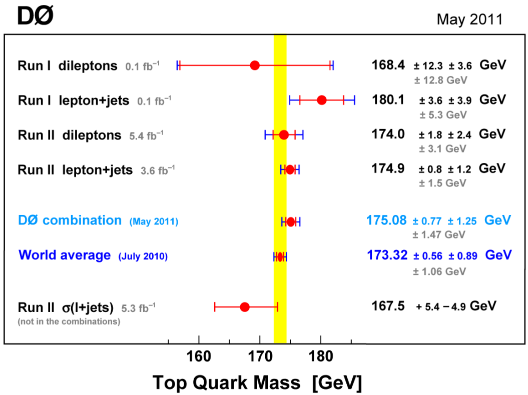
Combination of top mass measurements by DØ



DØ has combined the results from lepton+jet, di-lepton and lepton+track analyses from Tevatron RunI and RunII up to 5.4 fb^{-1} of data.
The *Best Linear Unbiased Estimator* technique has been used in order to take into account the correlations between the different measurements.

DØ top quark mass combination:

$$m_t = 175.08 \pm 0.77(\text{stat}) \pm 1.25(\text{syst})\ \text{GeV}/c^2$$

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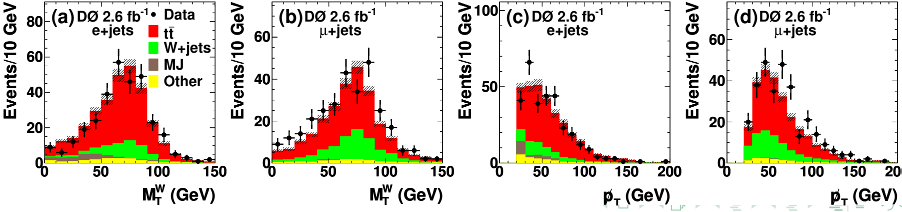
Top/antitop mass difference

- Lorentz-invariant local quantum field theories (including the Standard Model) are invariant for *CPT* transformations
- as a consequence, particles and antiparticles *must* have the same mass
- this has been confirmed for charged leptons, protons etc.
- quarks can't be tested directly because they immediately hadronize
- the unique exception is the quark top

DØ employs the Matrix Element method to measure the difference between top and antitop quarks.

Top/antitop mass difference: method

- the analysis method is based on the $\ell +$jets mass measurement, with which it shares the event selection
- a custom version of the PYTHIA generator is used, which allows different masses for t and $\bar{t}$ (the other masses are not changed)
- the parameters of the event probabilities are the two masses: $P_{\rm evt}\,(m_t, m_{\bar{t}}, f)$
- in the likelihood the two parameters are "rotated" to the difference and mean value: $L\,(\Delta m, m_{\rm top}, f)$
- no JES global shift parameter is used



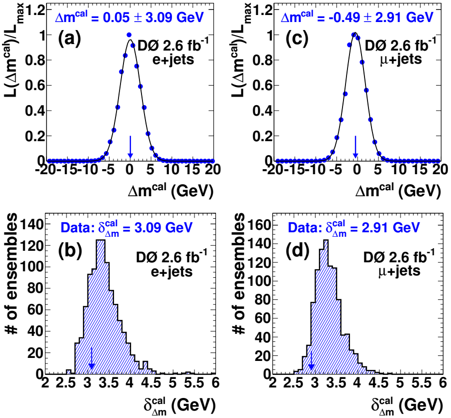
Measurement of top/antitop mass difference

The $m_t - m_{\bar{t}}$ difference extracted from 2.6 fb^{-1} of DØ data is:

$-0.2 \pm 2.1(\text{stat}) \pm 0.5(\text{syst})\ \text{GeV}/c^2$

Main syst. uncertainties (GeV/c^2):

Jet energy resolution	0.30
Response between b and $\bar{b}$	0.23
Calibration of the method	0.18
Jet Energy Scale	0.15



Combination with the previous DØ result: (3.6 fb^{-1} overall)

$$m_t - m_{\bar{t}} = 0.84 \pm 1.81(\text{stat}) \pm 0.48(\text{syst})\ \text{GeV}/c^2$$

Submitted to PRD (arXiv:1106.2063 [hep-ex])

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Summary

- the mass of the quark top is an important parameter for many theories and predictions
- the precision achieved by DØ alone is better than 1%
- the measurements in the various final states are consistent
- the precision of the measurement is now *limited by systematic uncertainties* (already with half the Tevatron data)
- DØ has also an *indirect top mass measurement from production cross section* (described by Christian Schwanenberger this morning)

Picture: Dean Validis

Backup

Integration variables

Count of degrees of freedom:

	$\ell +$ jets	ee + jets	$e\mu$ + jets	$\mu\mu$ + jets
initial and final state	8×4			
known particle masses	1×8	1×8		
detected η and φ	2×5	2×4		
four-momentum conservation	4	4		
narrow width approximation	no	2		
detected electron energy	no	2	1	0
final degrees of freedom	10	8	9	10

Integration variables:

$\ell +$ jets : $m_{W_1}, m_{W_2}, m_{t_1}, m_{\bar{t}}, E_\ell, \vec{p}_{Tq_1}, \vec{p}_{Tq_2}$

ee + jets : $p_{b_1}, p_{b_2}, m_{W_1}, m_{W_2}, \vec{p}_{T\nu_1} - \vec{p}_{T\nu_2}, \vec{p}_{Tt\bar{t}}$

$e\mu$ + jets : as ee + jets, plus p_μ

$\mu\mu$ + jets : as ee + jets, plus p_{μ_1} and p_{μ_2}

Complete systematic uncertainties for $\ell +$ jets

Signal modelling	± 0.74
Choice of PDF	± 0.24
Background modelling	± 0.16
Jet energy resolution	± 0.32
Data – MC jet response	± 0.28
Jet ID efficiency	± 0.26
Residual jet energy scale	± 0.21
Lepton momentum scale	± 0.17
Calibration	± 0.20
Multijet contamination	± 0.14
Signal fraction	± 0.10
Total	± 1.02
Statistical	$\pm$
JES (*in situ*)	$\pm$

Systematic uncertainty from jet flavour

The dominant uncertainty on the $\ell +$ jets analysis with Matrix Element method *was* from the diffent calorimeter response to jets from gluons, light and *b* quarks, ± 0.98 GeV/c^2.

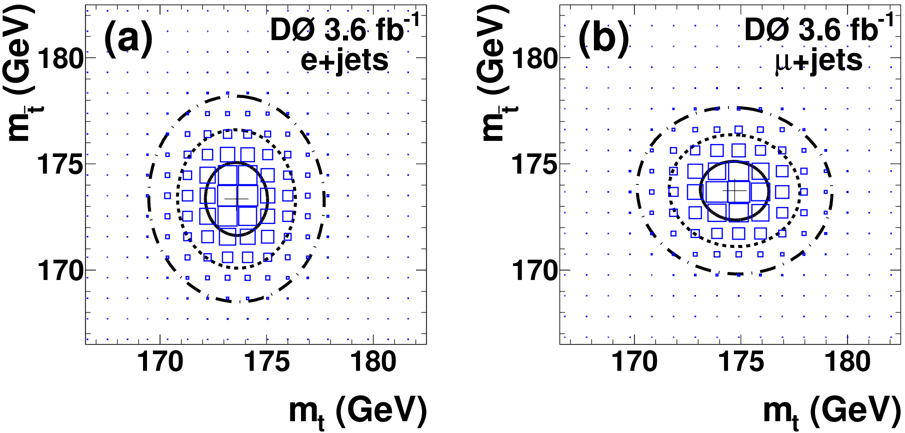
- every particle in a (simulated) jet contributes to its energy according to its "single particle response"
- detector simulation was used to estimate them (no results from test beam are availabe for DØ calorimeter), leading to biases
- jet energy scale corrects this on average, *ignoring jet composition*
- now the parameters of single particle responses are tuned to reproduce the jet response from data, removing the bias
- simulated jets are corrected accordingly
- the systematic uncertainty has dropped to 0.28 GeV/c^2

Back to the $\ell +$ jets ME results

Top/antitop mass correlation

We can write our likelihood as $L(m_t, m_{\bar{t}})$ instead than $L(\Delta m, m_{top})$:

e + jets $\qquad$ μ + jets:



$\rho = -0.02$ $\qquad$ $\rho = -0.01$