Determination of Electroweak Parameters

Seminar 'Particle Physics at the LHC'

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Contents

Introduction

- el.weak interaction: unification of electromagnetism (γ) and weak interaction (Fermi / V-A theory / $W^{\pm}$)
- structure: $SU(2)_L \times U(1)_Y$ (fields: W_1, W_2, W_3, B)
- predicts additional particle (Z^0) $\rightarrow$ first evidence in bubble chamber at CERN ($\bar{\nu}_\mu e^-$ scattering, 1973)
- discovery of Higgs boson ($\rightarrow m_H$) allows for constistency check.

Introduction

- experimental fact: m_Z well known (LEP), $m_Z = 91\ 188 \pm 2$ MeV [3]
- relations in el. weak theory (Born level):

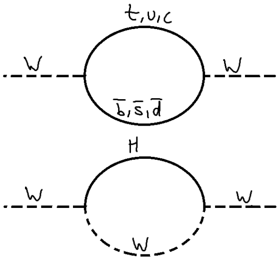
$$e = g \sin\theta_W = g' \cos\theta_W, \quad m_W = m_Z \cos\theta_W,$$

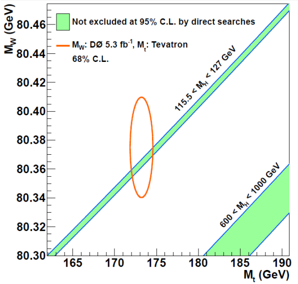
$$G_F = \frac{\sqrt{2} g^2}{8 {m_W}^2}, \quad \alpha = \frac{e^2}{4\pi}, \quad m_H = v\sqrt{2\lambda} = \frac{\sqrt{8\lambda} m_W}{g}$$

$\Rightarrow$ 4 independent parameters

Introduction

- additional relations by higher orders:





$\rightarrow$ contributions to m_W: $\sim (m_u - m_d)^2$ and $\sim \log m_H / m_W$ respectively.

- significant contribution from m_t
- additional contributions from new particles (SUSY)

Template Method

create simulations (distributions) for multiple values of physics parameter m in observable d ($p_T, m_T, E_T^{\text{miss}}, ...$)

$\Downarrow$

interpolate between samples with continuous function (fitting, determine arbitrary parameters p_j), axis: m, d

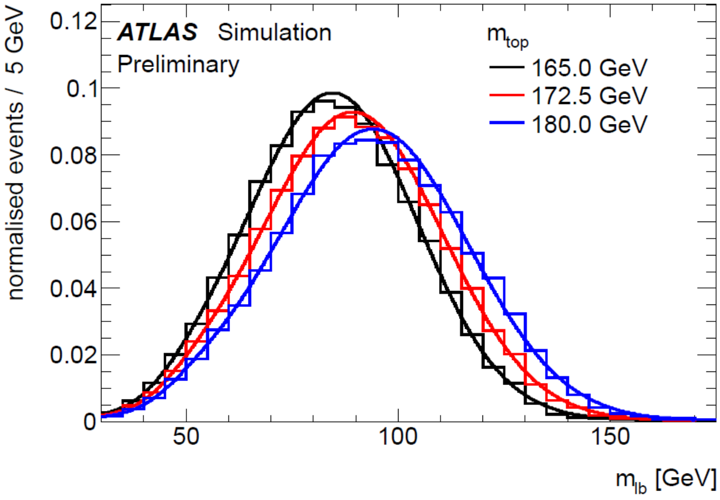
$f(m, d, p_j)$

$\Downarrow$

fit function to data with fixed p_j, determine m

$f(m, d, p_j)$

Template Method



Mass of the W Boson

- main production channel: $q\bar{q}' \to W + X$ (X=hadr. recoil, gluon ISR)
- decay channel for measurement: $W \to \ell\nu,\ \ell = e, \mu$ (low background, BR $\approx$ 22%)
- m_W measurement via kinematic distributions
- so far: only Tevatron results ($\sqrt{s} = 1.96$ TeV, $\sim 2 - 5\ \mathrm{fb}^{-1}$, $p\bar{p}$)

Mass of the W Boson - Variables

frequently used variables:

- transverse momentum $p_T^\ell = p^\ell \cdot \cos\theta$
- transverse mass (for $W \to e\nu$):

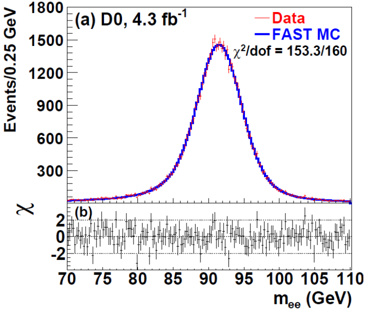
$$m_T = \sqrt{2 p_T^e p_T^\nu (1 - \cos\Delta\phi)}$$

- missing transverse momentum / energy:

$$p_T^{\text{miss}} = E_T^{\text{miss}} = \left| \sum_{i \in \text{event}} \vec{p}_T^{\,i} \right| = p_T^\nu$$

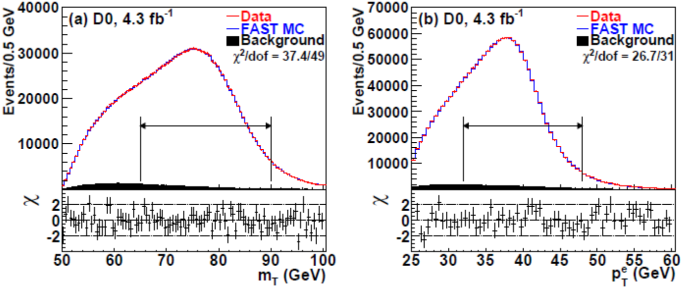
Mass of the W Boson @ D0 (2012)

- Z boson mass for calibration of el.mag.-calorimeter and hard.-calorimeter, only $W \to e\nu$ for measurement
- el.mag.-calorimeter: $E^{\text{meas}} = \alpha E^{\text{true}} + \beta \to$ fit of m_{ee}, E_e, ϕ_{ee} for $Z \to ee$ events
- hadr.-cal.: use projection of $\vec{p}_T^{ee} + \vec{u}_T$ (u_T = E-deposits w/o p_T^{ee}) onto axis $\vec{e}^{\ell_1} + \vec{e}^{\ell_2}$



Mass of the W Boson @ D0 (2012)

- event requirements: high $p_T^e, E_T^{\text{miss}} > 25$ GeV, small (hadronic) recoil (< 15 GeV), $m_T \in (50, 200)$ GeV
- template method with $d = m_T, p_T^e, E_T^{\text{miss}}$



- combined result: $m_W = 80.367 \pm 0.013 \pm 0.022$ GeV [1]

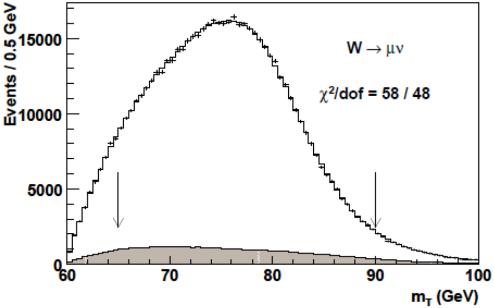
Mass of the W Bosons @ D0 (2012)

TABLE II: Systematic uncertainties of the M_W measurement.

Source	ΔM_W (MeV) m_T	p_T^e	$\not{E}_T$
Electron energy calibration	16	17	16
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	5	6	14
Electron efficiencies	1	3	5
Backgrounds	2	2	2
Experimental subtotal	18	20	24
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
Production subtotal	13	14	17
Total	22	24	29

Mass of the W Boson @ CDF (2013)

- momentum scale calibration: $J/\psi, \Upsilon \rightarrow \mu\mu$, compair simulation + data
- energy scale: use E/p peak in $Z \rightarrow ee$ (S_E extracted through likelihood fit)
- $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ used, same kinematic variables as D0



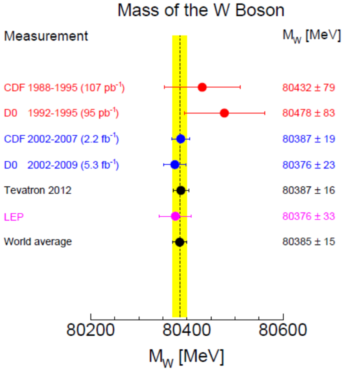
Mass of the W Boson @ CDF (2013)

m_T fit uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	0	0	0
Lepton tower removal	2	3	2
Recoil scale	5	5	5
Recoil resolution	7	7	7
Backgrounds	3	4	0
PDFs	10	10	10
W boson p_T	3	3	3
Photon radiation	4	4	4
Statistical	16	19	0
Total	23	26	15

result: $m_W = 80.387 \pm 0.012 \pm 0.015$ GeV [2] ($2.2\ \text{fb}^{-1}$)

Mass of the W Boson @ Tevatron (2013)

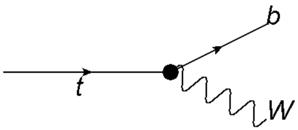
- combination→ account for correlations (collider, simulation software, calibration method,...)

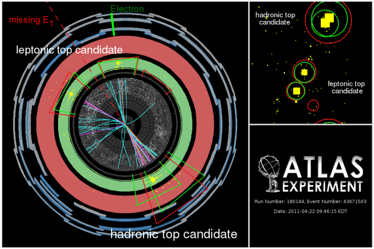


Introduction
Template Method
Mass of the W Boson
Mass of the top Quark
Test of the Standard Model

Mass of the top Quark

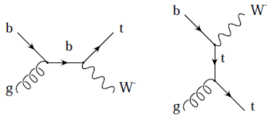
- decay mainly via $t \rightarrow bW$
- analysis channels ($t\bar{t}$): di lep ($WW \rightarrow \ell\nu\ell'\nu'$, BR = 4%), lep+jets ($WW \rightarrow \ell\nu q\bar{q}'$, BR = 29%), all jets (BR = 45 %)
- event selection via *b-tagging*, ATLAS: neural-net using topology of t decay (efficiency: $\sim 70\%$ of b-jets, $\sim 1/130$ light quark jets)





Mass of the top Quark (Dileptonic, ATLAS)

- $\sqrt{s} = 7$ TeV, $4.7\ \text{fb}^{-1}$
- requirements: $= 2$ b-tagged jets, high E_T^{miss}, $= 2$ op. charge leptons, ≥ 2 central jets with $p_T > 25$ GeV
- main backgrounds: single t via Wt production, $Z \rightarrow \ell^+\ell^-$



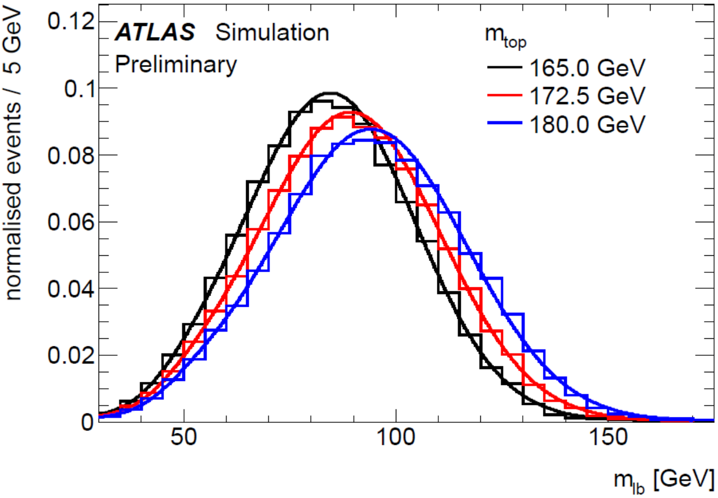
- strict selection → background is small
- method: template method

Mass of the top Quark (Dileptonic, ATLAS)

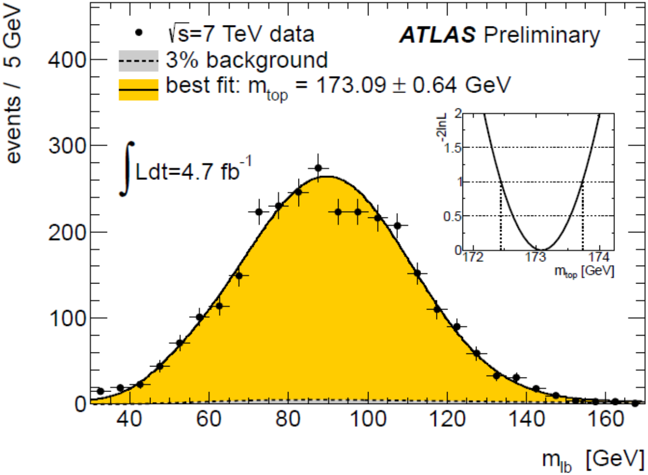
kinematic variable $m_{\ell b}$:

- two possible combintions of $\ell + b$ per event
- two invariant masses per combination → calculate average
- $m_{\ell b}$ is the lower avg. inv. mass

Mass of the top Quark (Dileptonic, ATLAS)



Mass of the top Quark (Dileptonic, ATLAS)



Mass of the top Quark (Dileptonic, ATLAS)

Description	Value [GeV]
Measured value	173.09
Statistical uncertainty	0.64
Method calibration	0.07
Signal MC generator	0.20
Hadronisation	0.44
Underlying event	0.42
Colour reconnection	0.29
ISR/FSR	0.37
Proton PDF	0.12
Background	0.14
Jet energy scale	0.89
b-jet energy scale	0.71
b-tagging efficiency and mistag rate	0.46
Jet energy resolution	0.21
Missing transverse momentum	0.05
Pile-up	0.01
Electron uncertainties	0.11
Muon uncertainties	0.05
Total systematic uncertainty	1.50
Total uncertainty	1.63

Table 2: The measured value of m_{top} and the contributions of the various sources detailed in the text to the total systematic uncertainty.

Mass of the top Quark (lep+jets, ATLAS)

- $\sqrt{s} = 7$ TeV, $1.04\ \text{fb}^{-1}$
- requirements: 2 b-jets, ≥ 4 central jets with $p_T > 25$ GeV, $= 1$ lepton, $E_T^{\text{miss}} > 20$ GeV
- most precise channel, advantages compared to

dilep	full reconstruction (only 1 ν)
all jets	easier matching

- two subanalyses

Mass of the top Quark (lep+jets, ATLAS): 1d

1d-analysis:

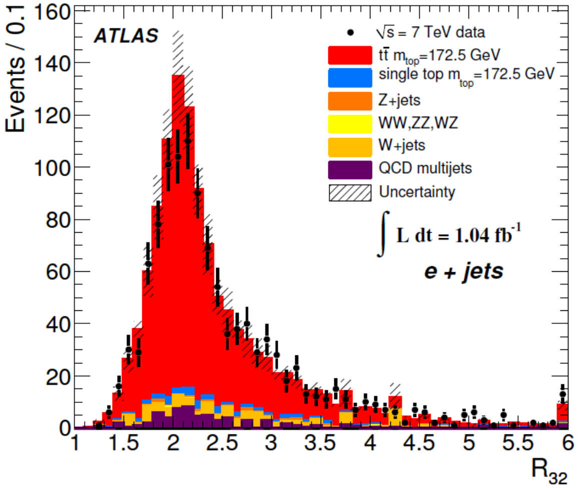
- variable (for $t \to bW,\ W \to$ had):

$$R_{32} \equiv \frac{m_{\text{top}}^{\text{reco}}}{m_W^{\text{reco}}}$$

$\to$ cancellation of uncertainties

- selection of jets via kinematic likelihood fit

Mass of the top Quark (lep+jets, ATLAS): 1d



Mass of the top Quark (lep+jets, ATLAS): 2d

2d-analysis:

- fitting probability density functions in $(m_{\text{top}}^{\text{reco}}, m_W^{\text{reco}})$ plane to data
- use known m_W and Γ_W for $m_{\text{top}}^{\text{reco}}$ reconstruction
- free fit parameters: $m_t, JSF, n_{\text{bkg}} \rightarrow$ "in situ jet scaling" $\Rightarrow$ shifting syst. $\rightarrow$ stat. uncertainty

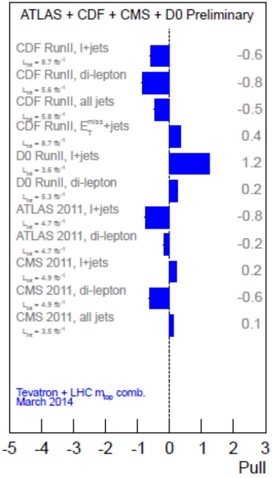
Mass of the top Quark (lep+jets, ATLAS)

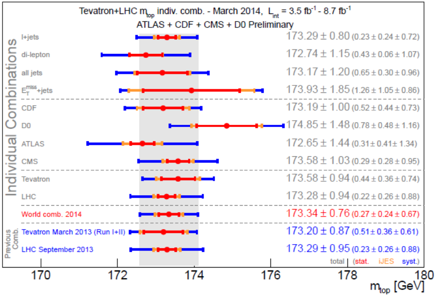
results:

$m_{t,1d} = 174.4 \pm 0.9 \pm 2.5$ GeV, $m_{t,2d} = 174.5 \pm 0.6 \pm 2.3$ GeV [5]

	1d-analysis		2d-analysis		Combinations		Correlation
	e+jets	μ+jets	e+jets	μ+jets	1d	2d	ρ
Measured value of m_{top}	172.93	175.54	174.30	175.01	174.35	174.53	
Data statistics	1.46	1.13	0.83	0.74	0.91	0.61	
Jet energy scale factor	na	na	0.59	0.51	na	0.43	0
Method calibration	0.07	< 0.05	0.10	< 0.05	< 0.05	0.07	0
Signal MC generator	0.81	0.69	0.39	0.22	0.74	0.33	1
Hadronisation	0.33	0.52	0.20	0.06	0.43	0.15	1
Pileup	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	1
Underlying event	0.06	0.10	0.42	0.96	0.08	0.59	1
Colour reconnection	0.47	0.74	0.32	1.04	0.62	0.55	1
ISR and FSR (signal only)	1.45	1.40	1.04	0.95	1.42	1.01	1
Proton PDF	0.22	0.09	0.10	0.10	0.15	0.10	1
W+jets background normalisation	0.16	0.19	0.34	0.44	0.18	0.37	1
W+jets background shape	0.11	0.18	0.07	0.22	0.15	0.12	1
QCD multijet background normalisation	0.07	< 0.05	0.25	0.33	< 0.05	0.20	(1)
QCD multijet background shape	0.14	0.12	0.38	0.30	0.09	0.27	(1)
Jet energy scale	1.21	1.25	0.63	0.71	1.23	0.66	1
b-jet energy scale	1.09	1.21	1.61	1.53	1.16	1.58	1
b-tagging efficiency and mistag rate	0.21	0.13	0.31	0.26	0.17	0.29	1
Jet energy resolution	0.34	0.38	0.07	0.07	0.36	0.07	1
Jet reconstruction efficiency	0.08	0.11	< 0.05	< 0.05	0.10	< 0.05	1
Missing transverse momentum	< 0.05	< 0.05	0.12	0.16	< 0.05	0.13	1
Total systematic uncertainty	2.46	2.56	2.31	2.57	2.50	2.31	
Total uncertainty	2.86	2.80	2.46	2.68	2.66	2.39	

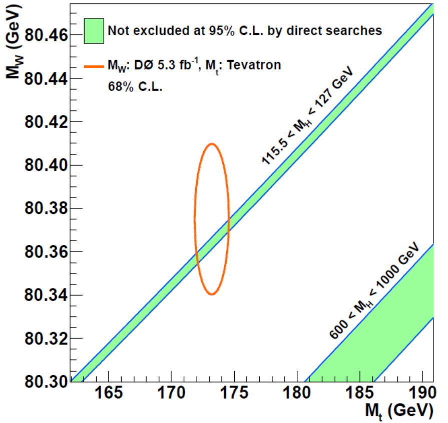
stat. correlation 1d$\leftrightarrow$ 2d : $< 50\%$ (different jet triplet selection + m_{top} estimator) consistent results:





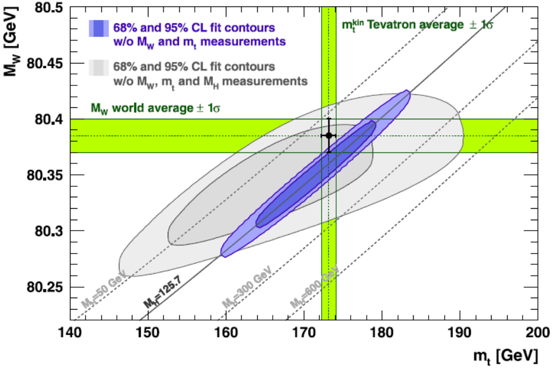
Test of the Standard Model

- m_W and m_t give constraints on m_H before summer 2012:



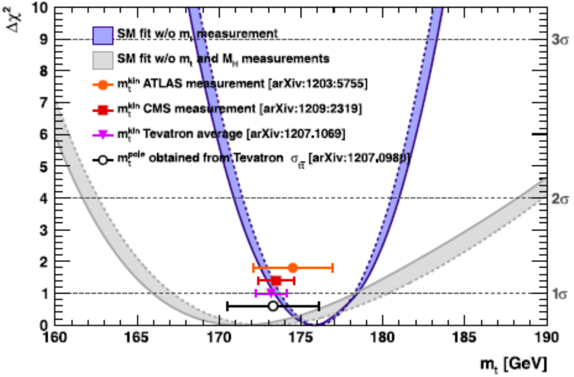
Test of the Standard Model

and after:

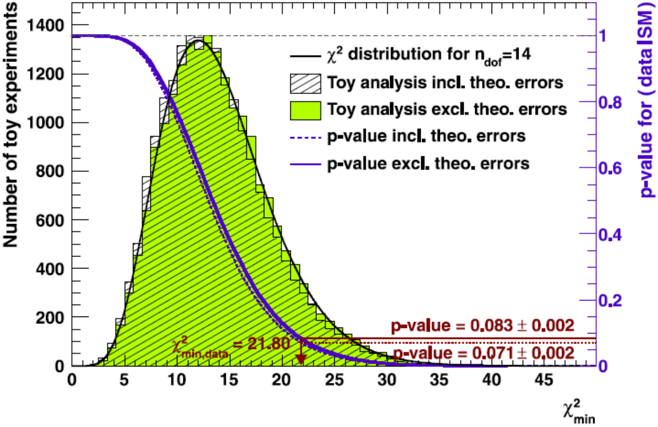


shifted focus: prediction of m_H → testing consistency of SM → σ_{m_w} is limiting!

Test of the Standard Model

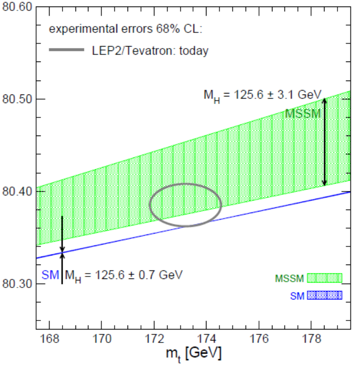


Test of the Standard Model



Test of the Standard Model - new physics?

for light ($m_H = 125.6\ \mathrm{GeV}$) CP even Higgs boson (MSSM: 5 Higgs bosons)



→ σ_{m_w} is limiting!

Summary

- W-mass: 80385 ± 15 MeV (syst. limited!)
- top-mass: 173340 ± 760 MeV (syst. limited!)
- standard model compatible with measurements ($p \approx 8\%$)
- exclusions/hints on new physics limited by m_W precision

Thanks for your attention!

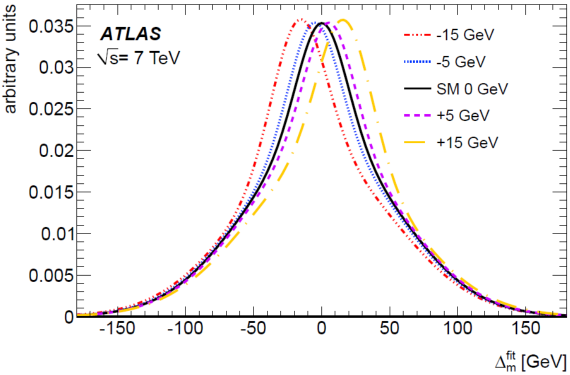
Questions? Remarks?

backup

top-Mass ($\Delta m_{t,\bar{t}}$)

- CPT invariance requires $\Delta m = m_t - m_{\bar{t}} = 0$
- ATLAS: $\sqrt{s} = 7\ \mathrm{TeV}, 4.7\ \mathrm{fb}^{-1}$, template method, variable
$$\Delta_m^{\mathrm{fit}} = q_\ell \cdot \left(m_{b\ell\nu}^{\mathrm{fit}} - m_{bjj}^{\mathrm{fit}} \right)$$
$\rightarrow$ cancellation of systematic uncertainties. Result: $\Delta m = 0.67 \pm 0.61 \pm 0.41$ [8]
- other results (from [8]):
  - CDF: $\Delta m = 3.3 \pm 1.4 \pm 1.0\ \mathrm{GeV}$
  - D0 : $\Delta m = 0.8 \pm 1.8 \pm 0.5\ \mathrm{GeV}$
  - CMS: $\Delta m = -0.44 \pm 0.46 \pm 0.27\ \mathrm{GeV}$
- $\Rightarrow$ compatible with $\Delta m = 0$

top-Mass ($\Delta m_{t,\bar{t}}$)



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