Top quark mass determination at Hadron Colliders

(a short report)

Workshop on Top physics at the LC 2015

Valencia, 30th June 2015

Adrián Irles

1) Motivation.

2) Direct top quark mass measurements.

+ interpretation.

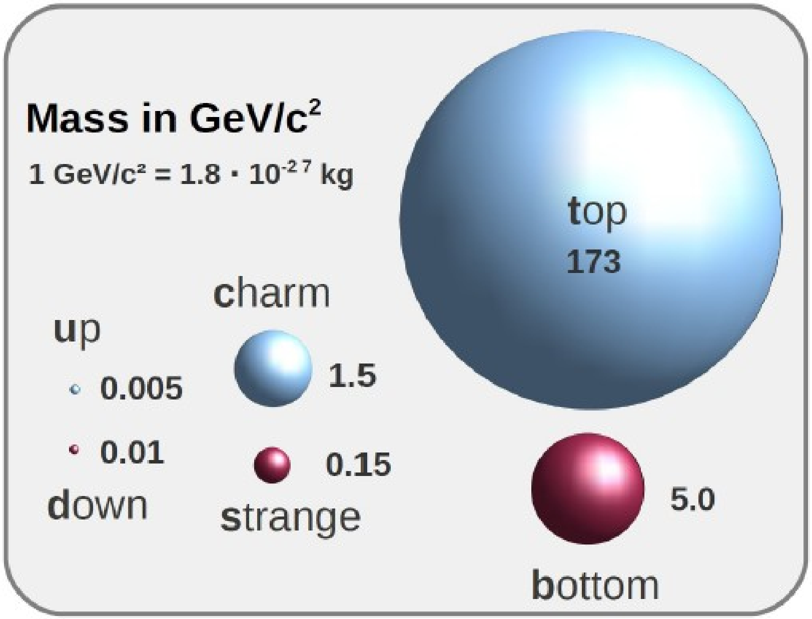
3) Top quark mass determination from NLO observables.

4) Summary

What is not in the slides:

- *many of the measurements (just a personal selection)*
- *top quark mass schemes definitions (see A. Hoang & P. Marquard talks)*

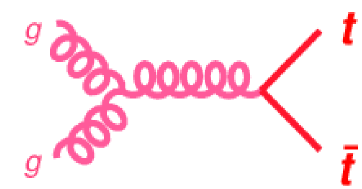
The heaviest elementary particle discovered so far



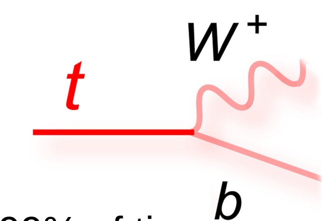
A peculiar quark

Discovered in 1995, only observed in two colliders.

Mainly produced in pairs



Decays before hadronizing

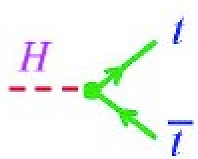


~99% of times

m_t ~ 173 GeV:

→ Fundamental parameter of the Standard Model (SM)

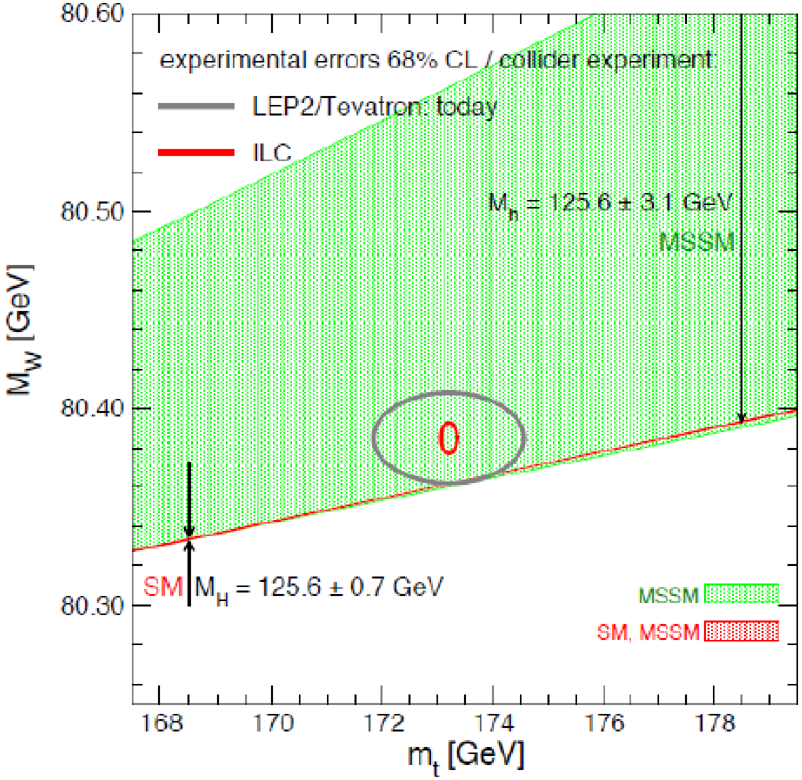
→ Important for precise tests of the SM



$$y_t = \frac{\sqrt{2}}{v} m_t = 2^{3/4} G_F^{1/2} m_t = 1 \qquad (0.995)$$

→ Test of new physics scenarios.

Consistency of the SM and BSM

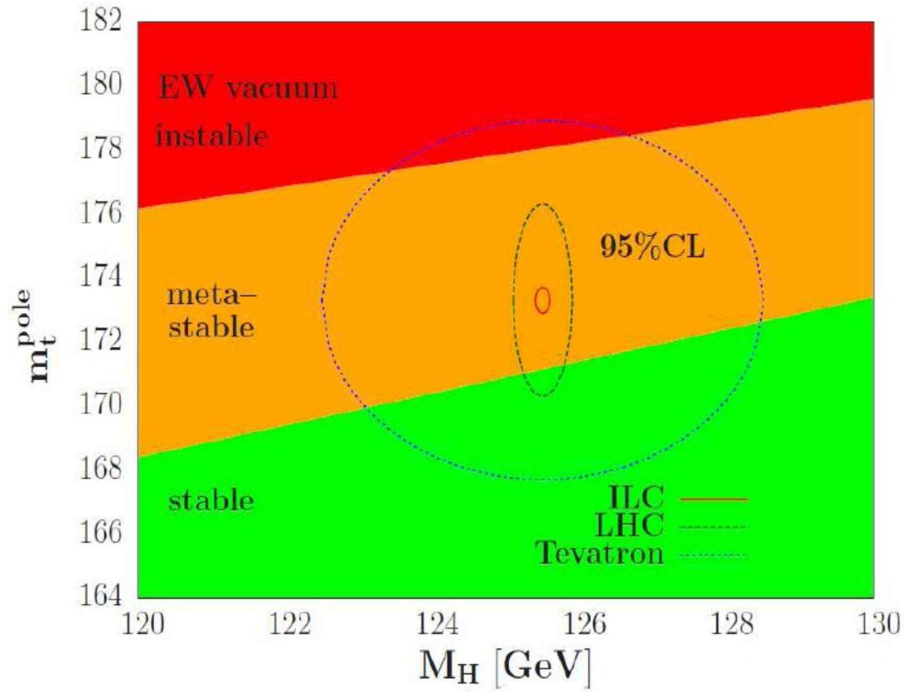


[Heinemeyer et al updated to summer 2014]

Enter in all loop corrections (reduce parametric uncertainty)

$$M_W = M_W^{LO} + \Delta r_{top} + \Delta r_H$$

SM Vacuum stability



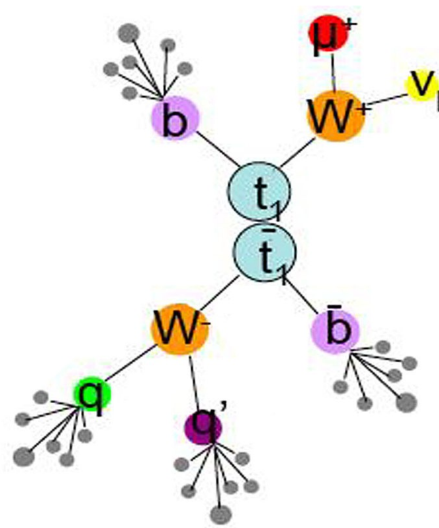
$$M_H > 129.6\ \text{GeV} + 2.0\left(m_t^{pole} - 173.34\ \text{GeV}\right) - 0.5\ \text{GeV}\,\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \pm 0.3\ \text{GeV}$$

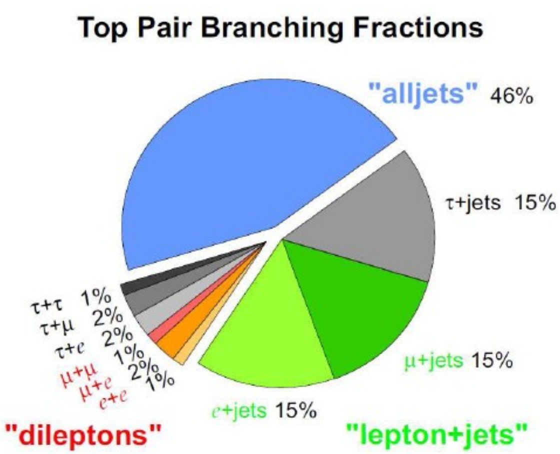
[Degrassi, Di Vita, Elias-Miro,Spinosa,Giudici ’12, Alekhin, Djouadi, Moch ’12]

Strong dependence with the Higgs and top-quark mass.

Assumption: no New Physics up to the Planck scale

Inferring the top quark mass from the kinematic properties of its decay products.





Matrix Element method (ME):

Calculates event probability densities from differential cross sections and detector resolutions.

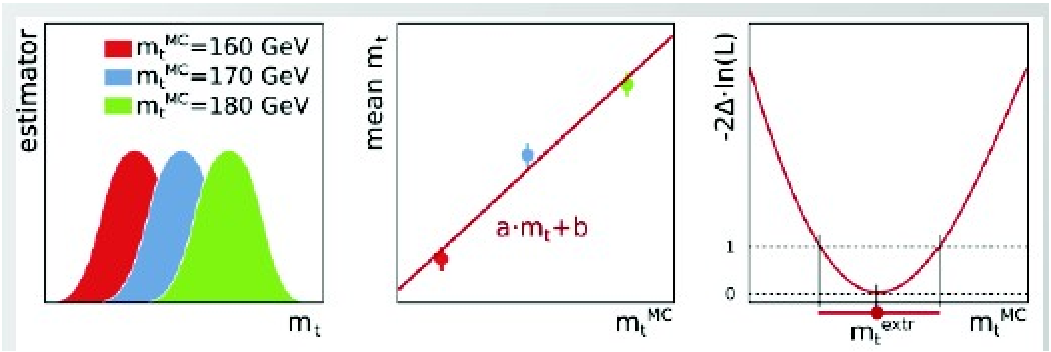
- Maximizes the statistical information.
- Current implementations at LO.

Ideogram method:

Event likelihood function to test compability of event kinematics with the decay hypothesis convoluted with detector resolutions.

Template method:

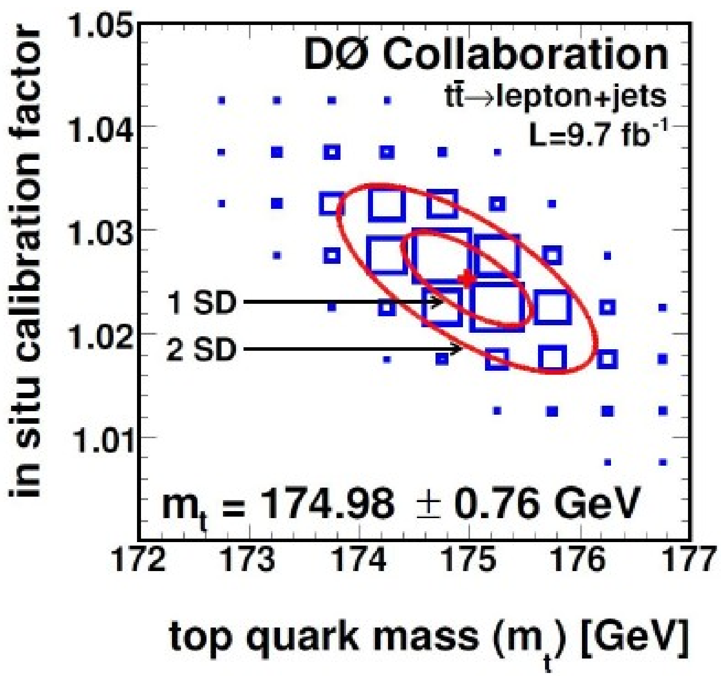
Compare histograms in data to simulations.



These methods measure the kinematic MC mass

Most precise measurement at Tevatron

$$P(x, m_t) = \frac{1}{\sigma(m_t)} \int \sum \underbrace{d\sigma(y, m_t)}_{\text{LO ME}}\, dq_1 dq_2\, \underbrace{f(q_1) f(q_2)}_{\text{PDFs}}\, \underbrace{W(y, x, k_{\text{JES}})}_{\text{Transfer function}}$$



Simultaneous fit of $\mathbf{m_t}$ and $\mathbf{k_{JES}}$ *(global factor for the Jet Energy Scale -JES-, used for in situ calibration using the hadronic W decay)*

Improvements:

- *Full Run II data → statistics*
- *Improved objects ID (e, mu, b)*
- *Faster method that allowed dramatic increase in MC statistics*

Typical statistical uncertainty:

~0.25 GeV → ~ 0.01 – 0.05 GeV

$$m_t^{MC} = 174.98 \pm 0.58\,(stat + JES) \pm 0.49\,(syst)\,GeV$$

$$m_t^{MC} = 174.98 \pm 0.76\,GeV$$

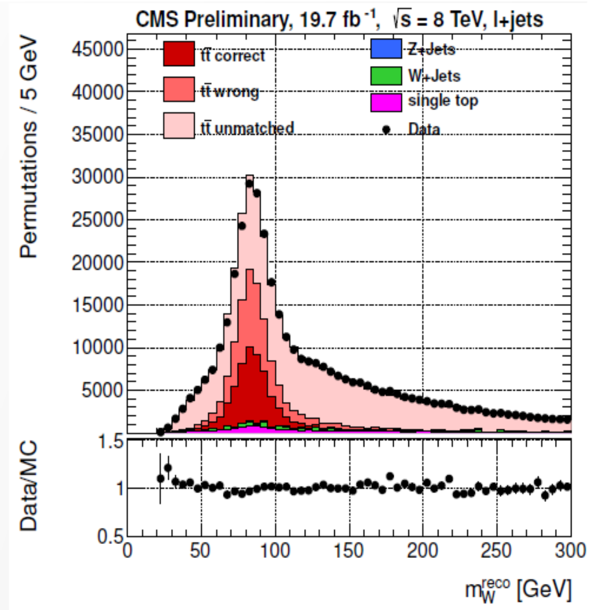
Larger unc:

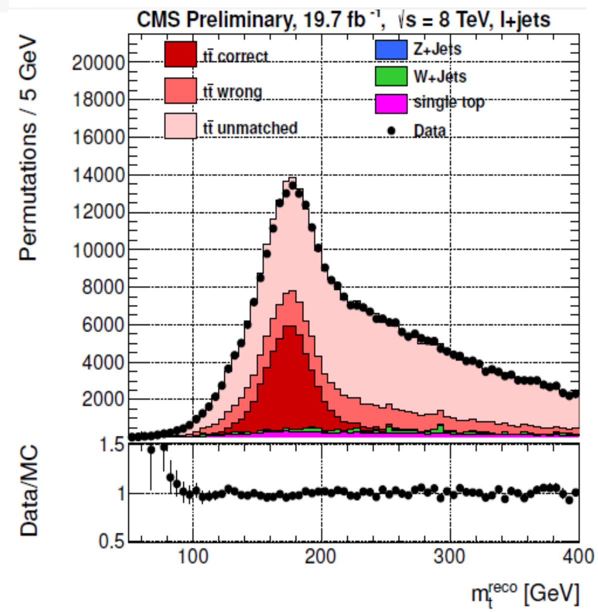
Had. and UE → 0.26 GeV

Residual JES → 0.21 GeV

PRL [arxiv:1405:1756]

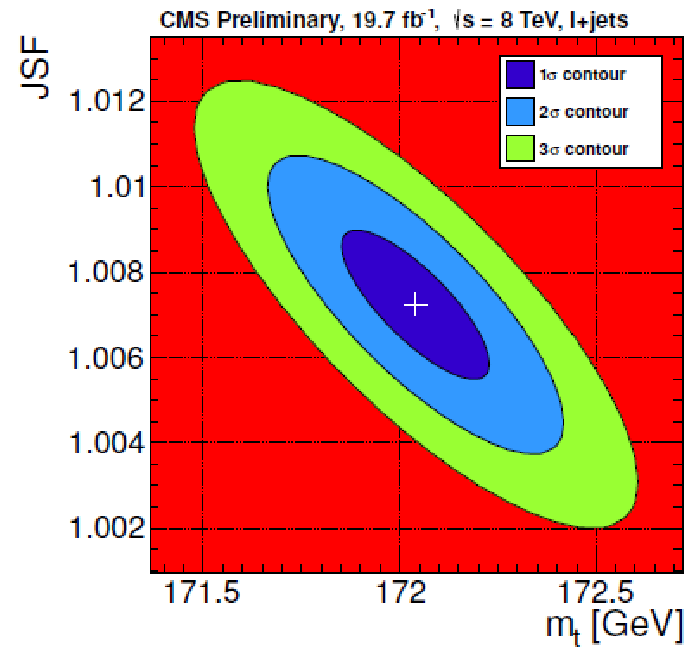
Single most precise measurement!!





Most precise measurement at the LHC

CMS, lepton+jets, using 8 TeV data.
Ideogram method using all permutations.
Estimators: $\mathbf{m_t}$ and $\mathbf{m_W}$.
Simultaneous fit of $\mathbf{m_t}$ and **JSF**



$$m_t^{MC} = 172.04 \pm 0.19\,(stat + JSF) \pm 0.75\,(syst)\,GeV$$

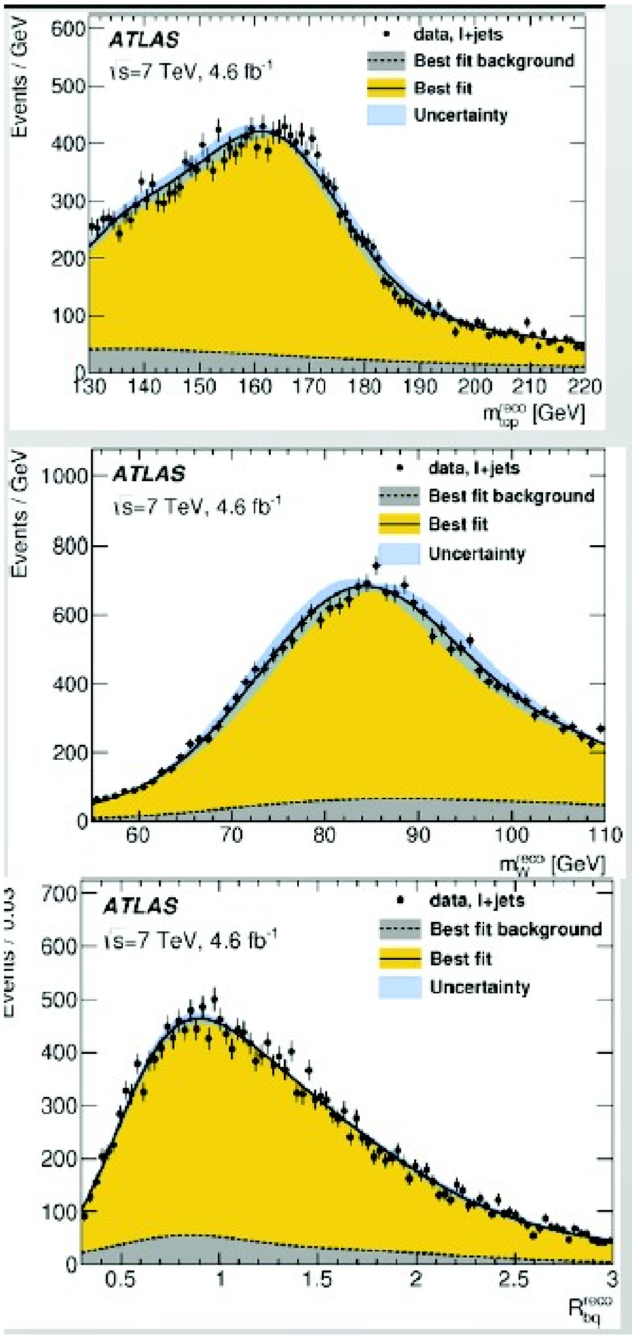
$$m_t^{MC} = 172.04 \pm 0.77\,GeV$$

Larger unc:

Flavour JSF → ***0.41 GeV***
JES → ***0.26 GeV***
Pile-up → ***0.27 GeV***

JHEP 12 (2012) 105, CMS PAS-TOP-14-001

Direct top quark mass measurements: Template Method



Most precise measurement at the ATLAS experiment

lepton+jets channel, using 7 TeV data.
3D fit of $\mathbf{m_t}$, **JES and bJSF.**

m_t^{reco}

m_W^{reco}

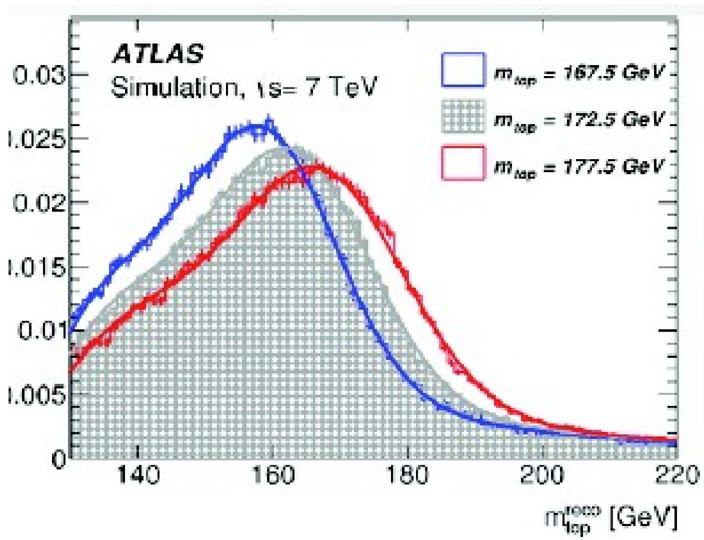
R_{bq}^{reco}

$$R_{\text{lb}}^{\text{reco,2b}} = \frac{p_T^{b_{\text{had}}} + p_T^{b_{\text{lep}}}}{p_T^{W_{\text{jet}_1}} + p_T^{W_{\text{jet}_2}}},$$

$$R_{\text{lb}}^{\text{reco,1b}} = \frac{p_T^{b_{\text{tag}}}}{(p_T^{W_{\text{jet}_1}} + p_T^{W_{\text{jet}_2}})/2}$$

arXiv:1503.05427

Uncertainties on JES and bJES and hadronization are reduced.



Larger unc:

JES → ***0.51 GeV***
Btag → ***0.50 GeV***
ISR/FSR → ***0.32 GeV***

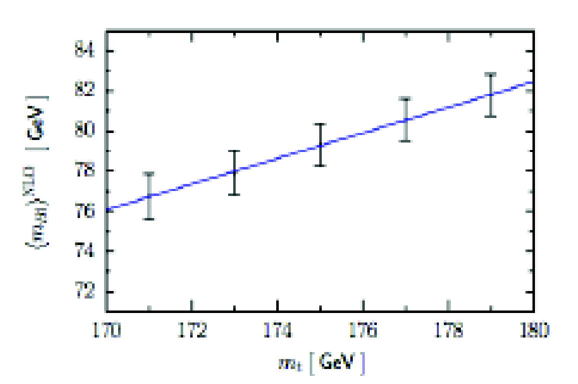
$$m_t^{MC} = 172.33 \pm 0.75\,(stat + JSF + bJSF) \pm 1.02\,(syst)\,GeV$$

$$m_t^{MC} = 172.33 \pm 1.27\,GeV$$

Top quark mass extraction from lepton+b-jet invariant mass

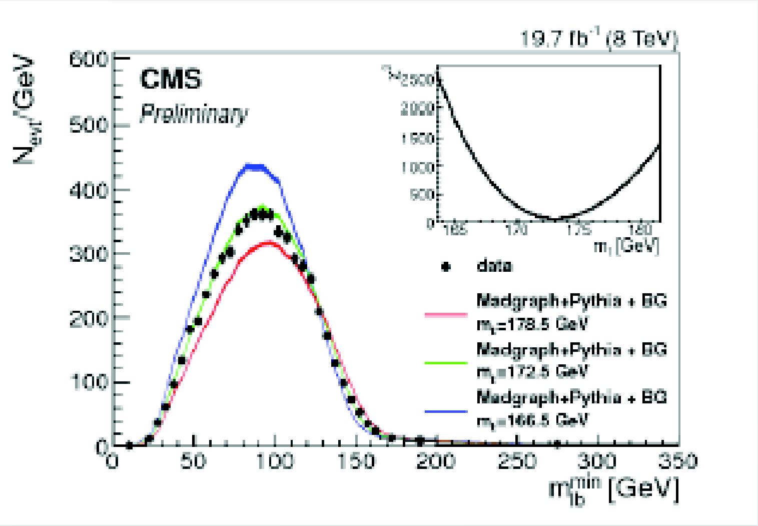
- CMS @ 8 TeV using di-lepton channel (μe) :

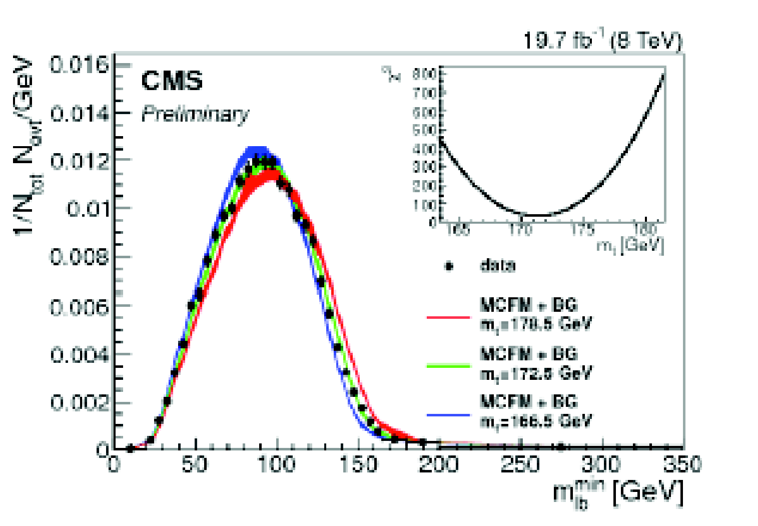
CMS PAS-TOP-14-014



S. Biswas, K. Melnikhov, M. Schulze, JHEP 1008 (2010) 048

$\langle M_{B\ell} \rangle$ at NLO accuracy in QCD





- Theoretical predictions are forward-folded through the detector

- MadGraph fit to m_{lb}^{reco} (rate and shape)

$$m_{t,8TeV}^{shape} = 172.3 \pm 0.3(stat) \pm 1.3(syst) GeV$$

- MCFM@NLO fit to m_{lb}^{reco} (NLO production, LO decay, shape)

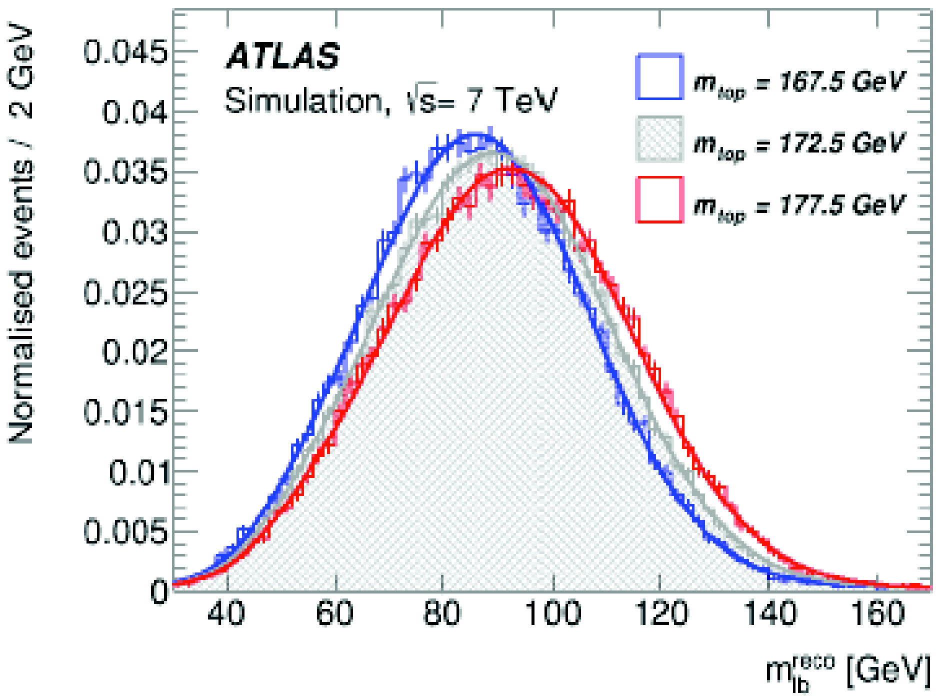
$$m_{t,8TeV}^{shape} = 171.4 \pm 0.4(stat) \pm 1.0(syst) GeV$$

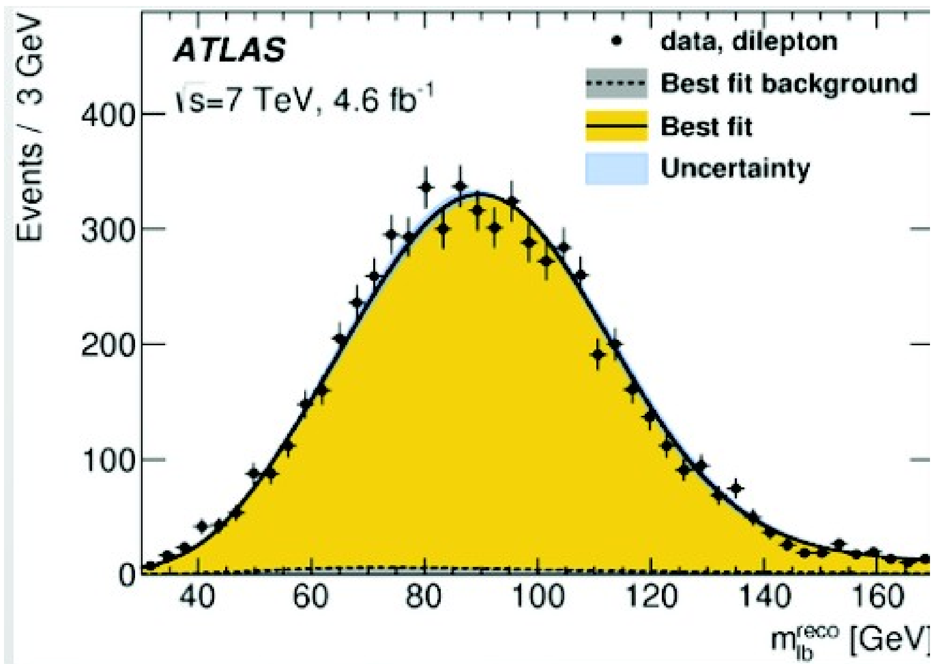
- Main uncertainties: $\sigma(\mu_{R/F})$=0.51 GeV; σ(b-frag)=0.40 GeV

ATLAS measurement using dilepton channel

arXiv:1503.05427

dilepton channel, using 7 TeV data.
Template method fitting the $\mathbf{m_{lb}^{reco}}$ distribution (lepton + b-jet invariant mass)
Compared with simulations at NLO(production) with LO decay

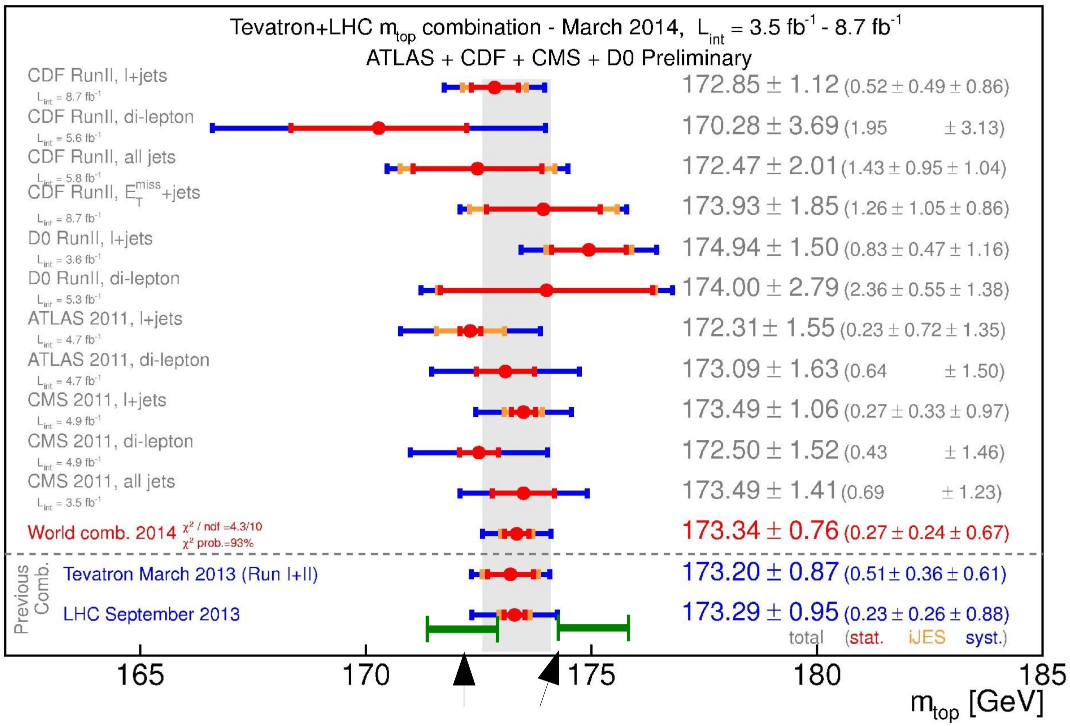




$$m_t^{MC} = 173.79 \pm 0.54\,(stat) \pm 1.30\,(syst)\,GeV$$
$$m_t^{MC} = 173.79 \pm 1.41\,GeV$$

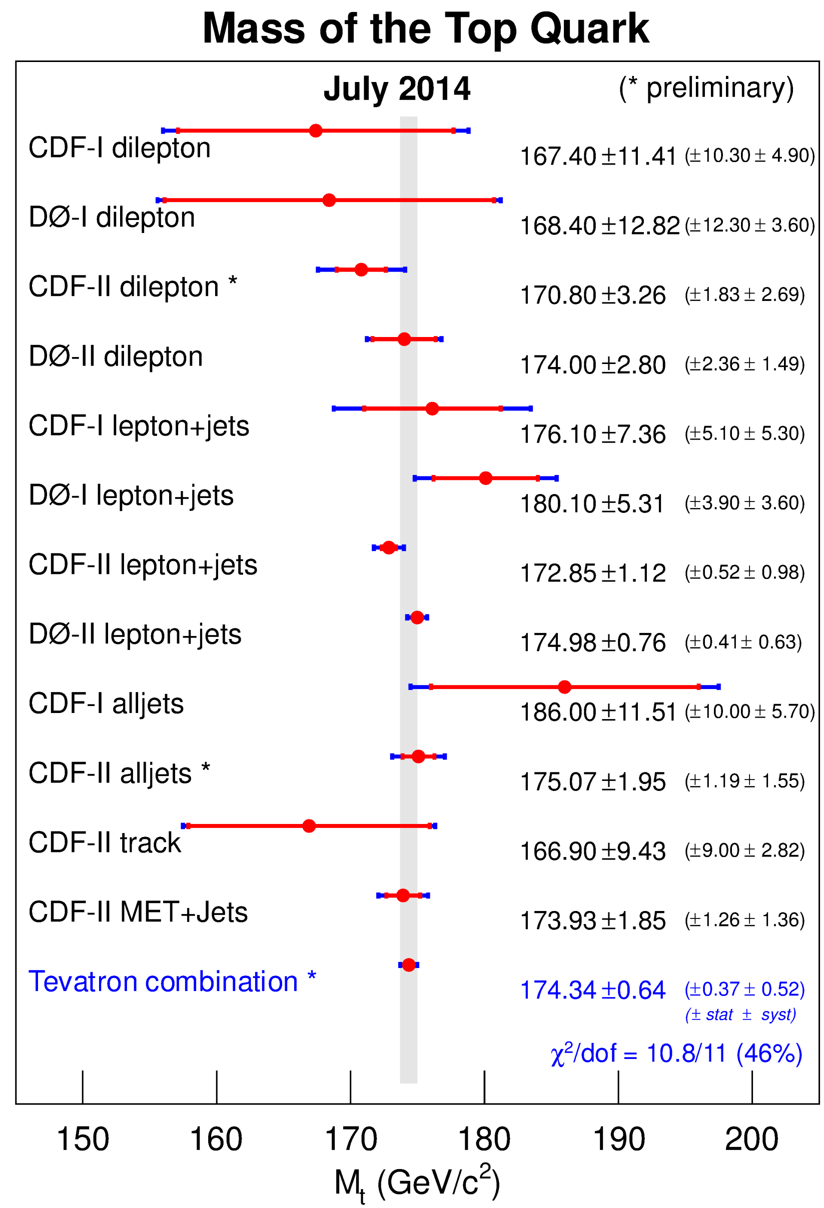
Larger unc:
JES → ***0.75 GeV***
Btag → ***0.68 GeV***
ISR/FSR → ***0.53 GeV***

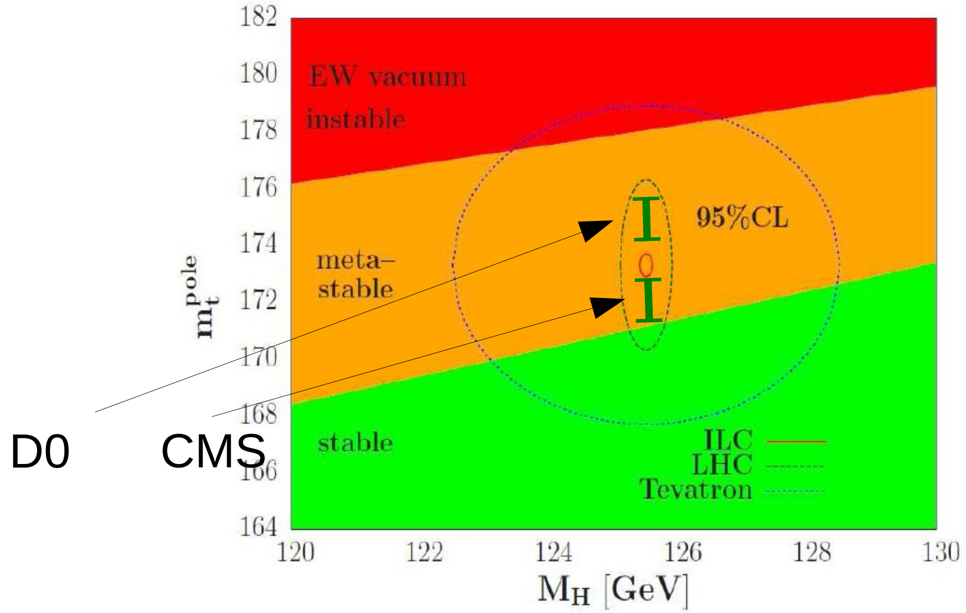
Direct Top quark mass measurements: summary

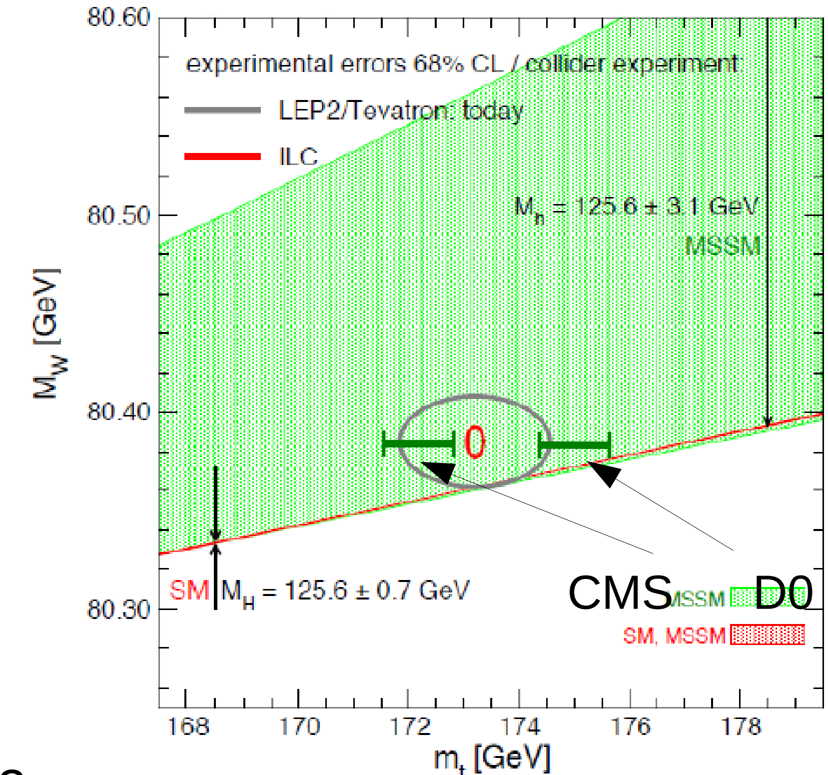


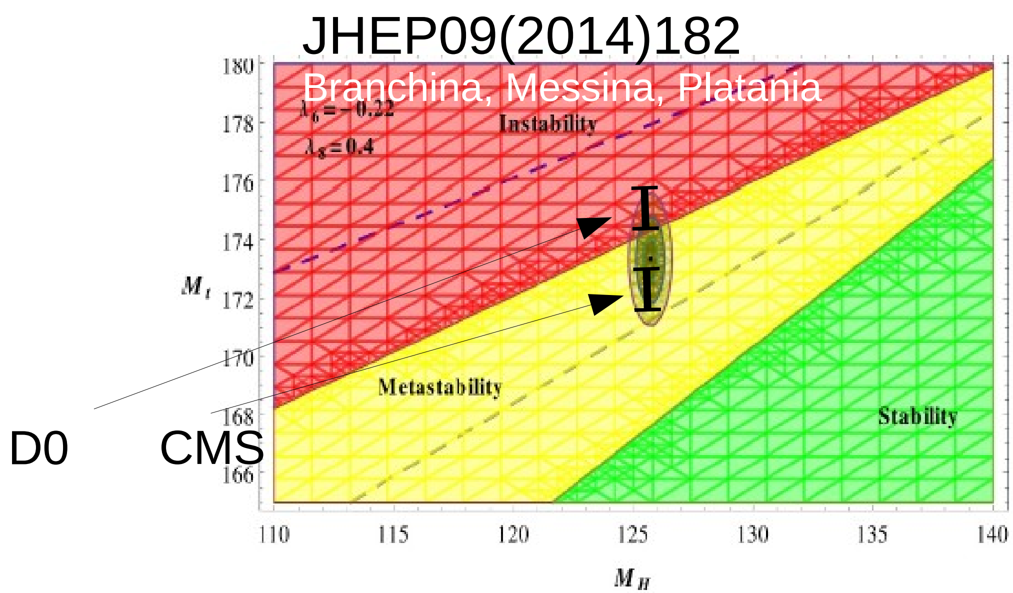
CMS D0

Most precise individual measurements (not included in the comb.)

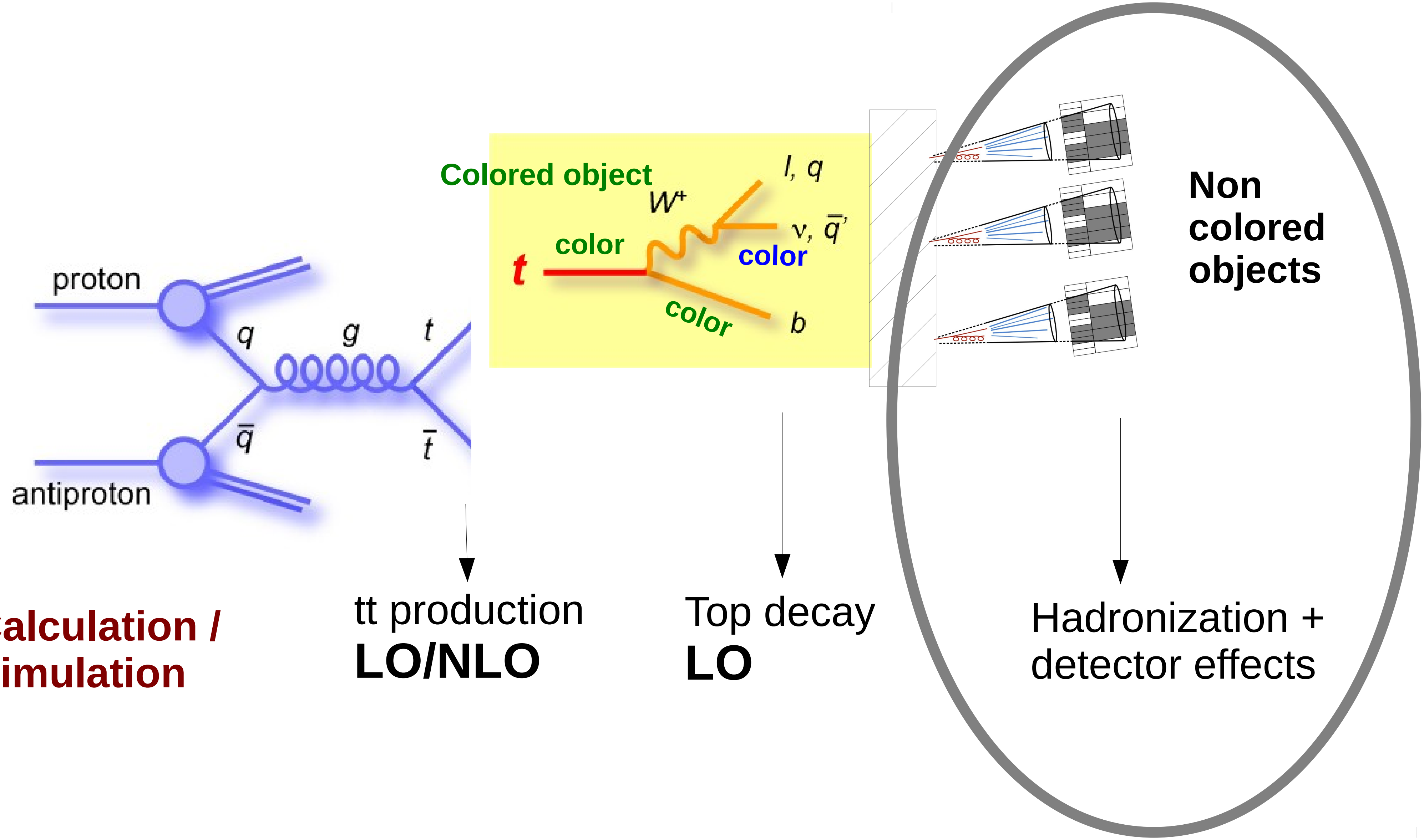








$V(\phi) = \lambda\phi^4/4 + \lambda_6\phi^6/(6M_P^2) + \lambda_8\phi^8/(8M_P^4)$



Calculation / Simulation

tt production
LO/NLO

Top decay
LO

Hadronization + detector effects

Direct Top quark mass measurements: interpretation

The world combination achieves an improvement of the total m_{top} uncertainty of 28% relative to the most precise single input measurement [16] and ≈ 13% relative to the previous most precise combination [6]. The total uncertainty of the combination is 0.76 GeV, and is currently dominated by systematic uncertainties due to jet calibration and modelling of the $t\bar{t}$ events. Given the current experimental uncertainty on m_{top}, clarifying the relation between the top quark mass implemented in the MC and the formal top quark pole mass demands further theoretical investigations. The dependence of the result on the correlation assumptions between mea-

LHC/Tevatron NOTE

ATLAS-CONF-2014-008
CDF Note 11071
CMS PAS TOP-13-014
D0 Note 6416

There is no well defined prescription that relates $\mathbf{m_t^{MC}}$ and $\mathbf{m_t^{pole}}$

Is the same MC mass for both colliders? And for the four experiments?

Current estimation of the uncertainty ~O(1) GeV

Current precision in $\mathbf{m_t^{MC}}$ ~ 0.7 GeV

- S. Moch et al., arXiv:1405.4781,
- ATLAS, CDF, CMS and D0 Collaborations, arXiv:1403.4427,
- A. H. Hoang and I. W. Stewart, 500 Nouvo Cimento B123 (2008) 1092–1100,
- A. Buckley et al., arXiv:1101.2599
- A. H. Hoang, arXiv:1412.3649.

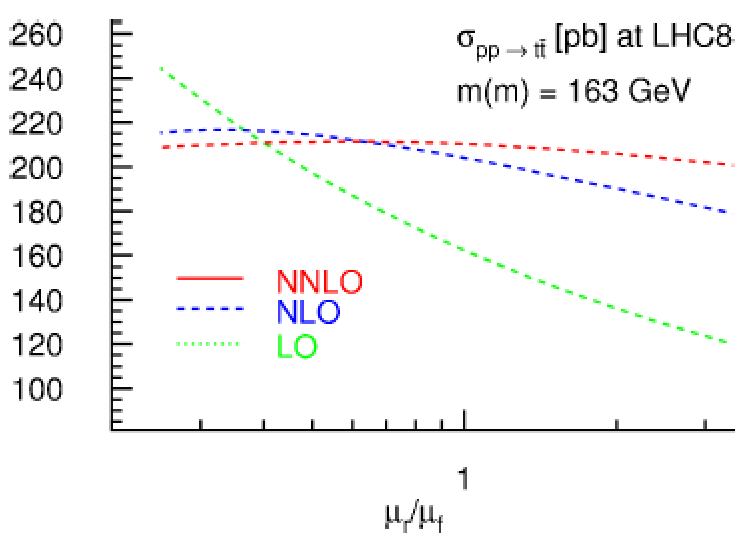
Requirements for a precise top quark mass determination

1) Define an observable which should show **good sensitivity** $\frac{\Delta O}{O} \leftrightarrow \frac{\Delta m_t}{m_t}$

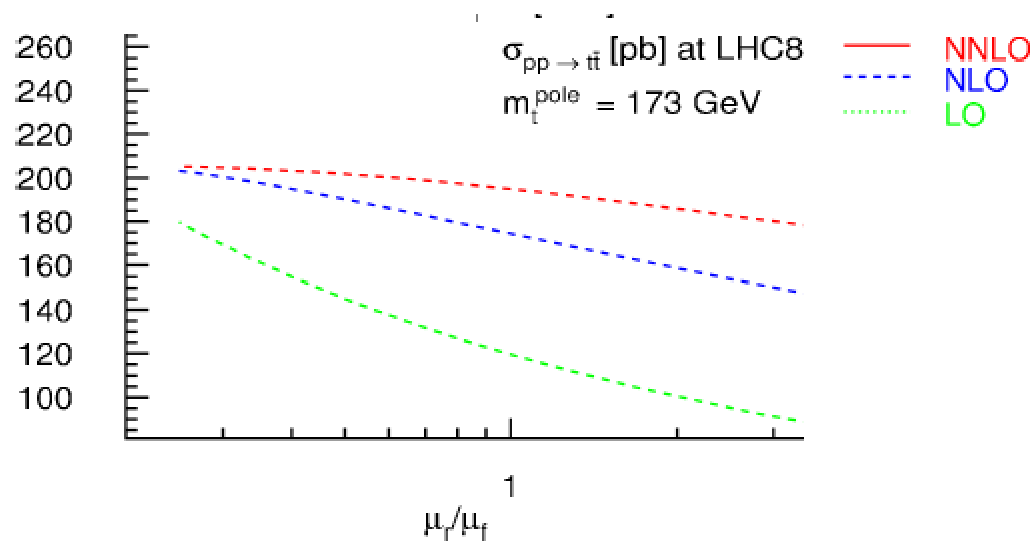
2) Small theoretical uncertainties.

3) Well defined **mass scheme** → **NLO calculations!**

4) Measured observables are corrected to the parton level where they are compared with calculations



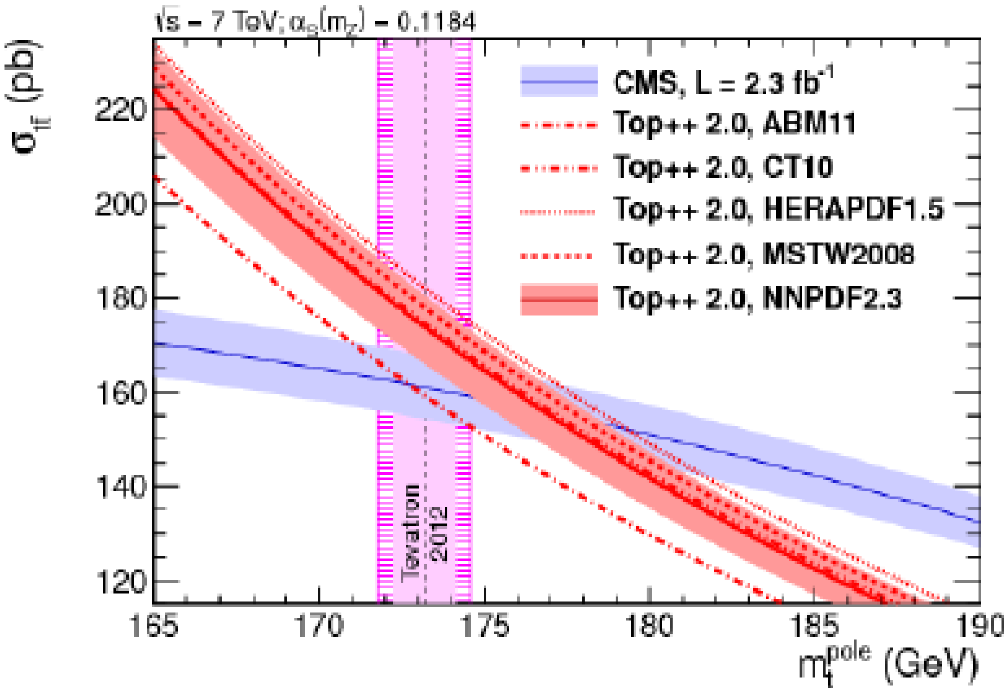
P. Uwer,
La Thuile, Feb. 2013



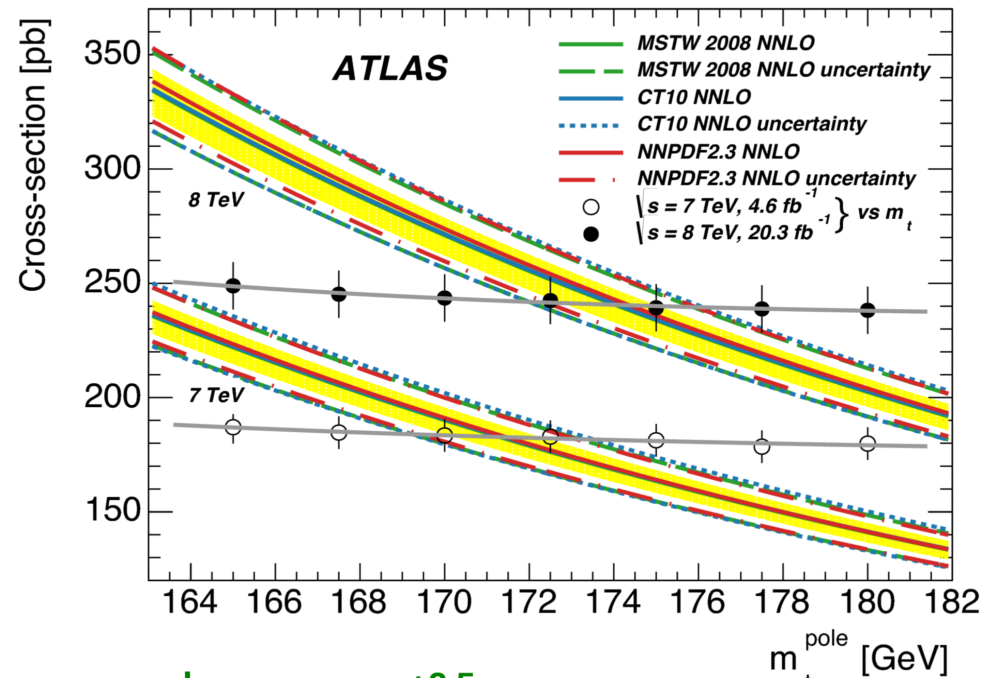
Langenfeld, Moch, Uwer PRD 80, 054009 (2009)

Czakon, Fiedler, Mitov hep-ph/1303.6254

Top quark pole mass extraction from inclusive cross section



$m_t^{pole} = 176.7^{+3.0}_{-2.8}$ GeV CMS, Phys. Lett B 728 (2014) 496



$m_t^{pole} = 172.9^{+2.5}_{-2.6}$ GeV ATLAS, Eur. Phys. J. C74 (2014) 3109

- Dilepton channel
- MC simulations are used to correct for event efficiency selection and acceptance
- $\mathbf{m_t^{pole}}$ inferred from the inclusive $t\bar{t}$ cross section at NNLO(+NNLL).
- “Limited” theoretical sensitivity: $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \approx -5\, \Delta m_t/m_t$

Larger unc:

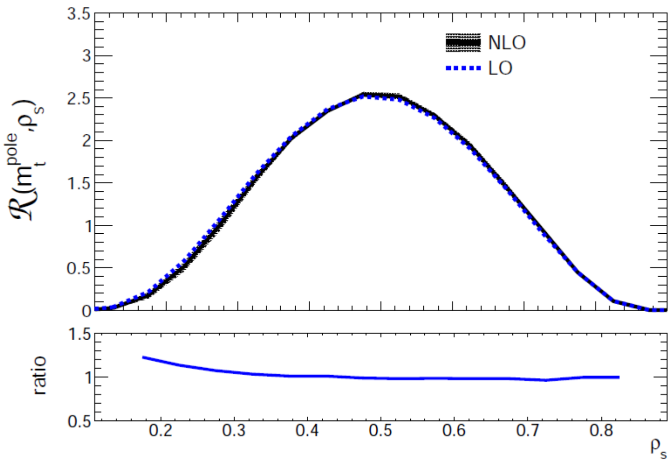
PDF	→ ***~1.5 GeV***
Scale	→ ***~1.0. GeV***
Lum.	→ ***~0.7 GeV***

***Top quark pole mass** determination from the jet rates*

$$\mathcal{R}(m_t^{\text{pole}},\rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}},\rho_s), \quad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}$$

m_0=170 GeV

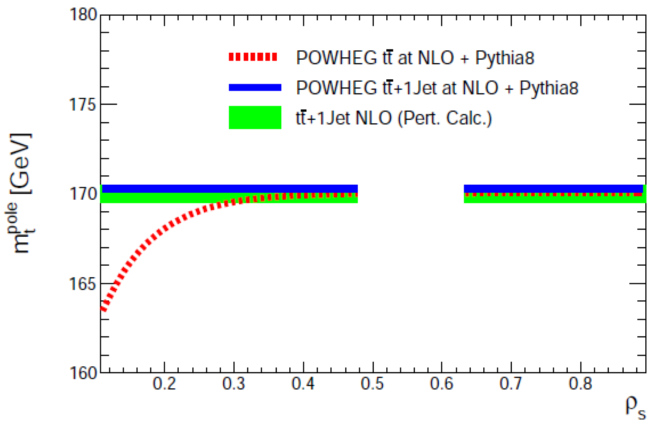
- **$t\bar{t}$+1-jet**
  The production of extra gluons(quarks) depend on the top-quark mass



- **differential**
  Mass dependence enchanced in certain regions of the phase space

- **normalized**
  Cancelation and reduction of systematic uncertainties (theoretical and experimental)

NLO → small corrections

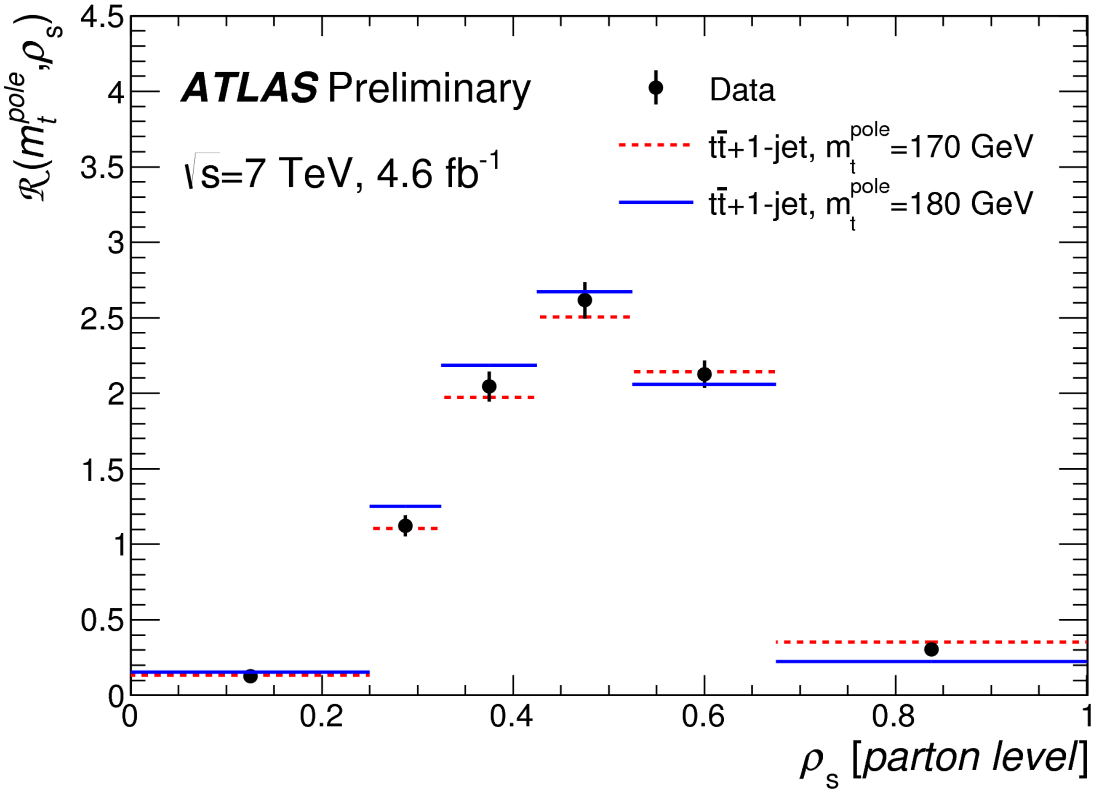


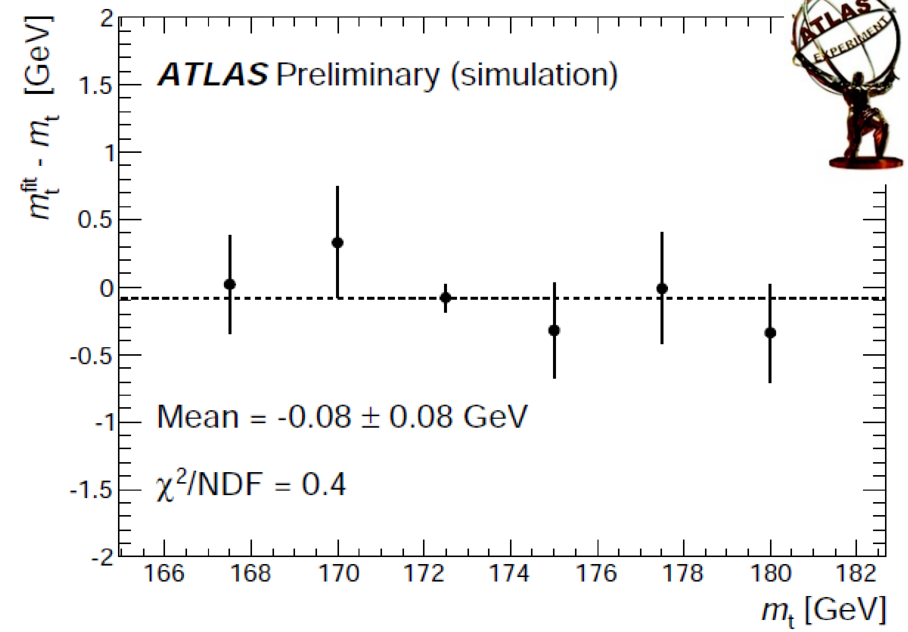
- **Large event rates at LHC ~ 30% of the inclusive cross section**

- **NLO & NLO+PS corrections available.**

Eur.Phys.J. C73 (2013) 2438
Alioli, Fernández, Fuster, A.I., Moch, Uwer, Vos

Top quark pole mass *determination from the jet rates*





$m_t^{pole} = 173.7^{+2.3}_{-2.1}$ GeV

ATLAS CONF 2014-053

- ATLAS 7 TeV, semileptonic decay

- MC simulations are used to correct to parton level for event efficiency selection and acceptance

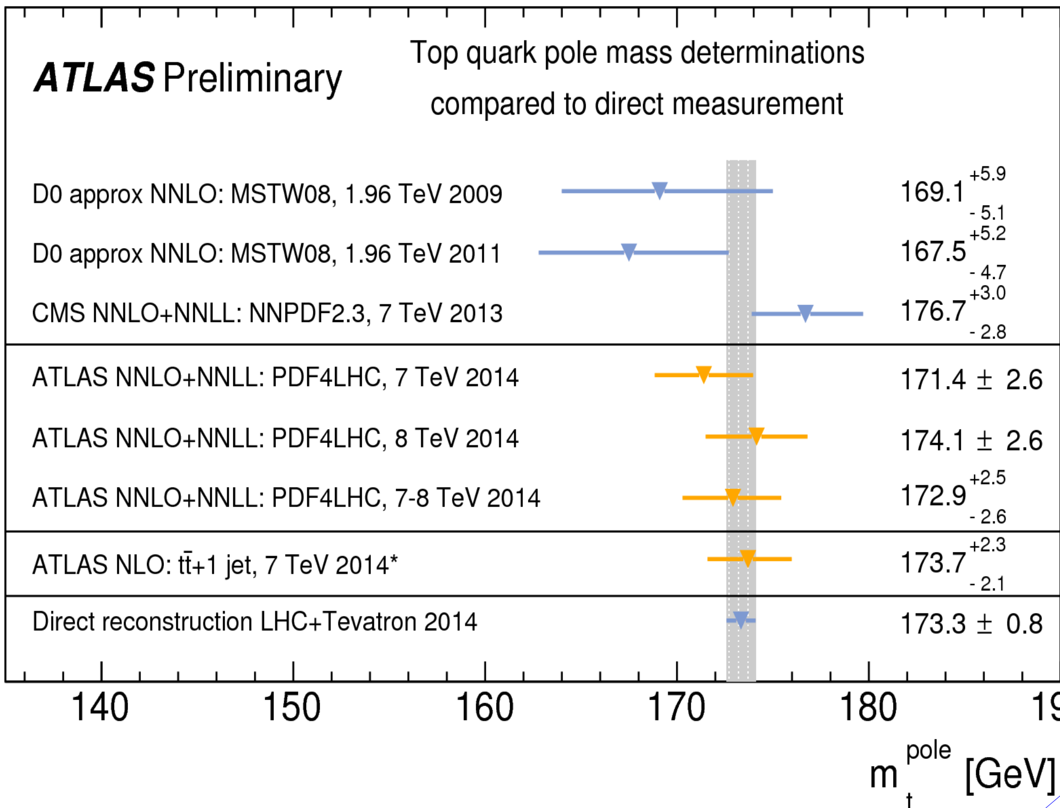
- $\mathbf{m_t^{pole}}$ inferred from the $t\bar{t}$+1Jet cross section at NLO(+PS) with pT(Jet)>50 GeV.

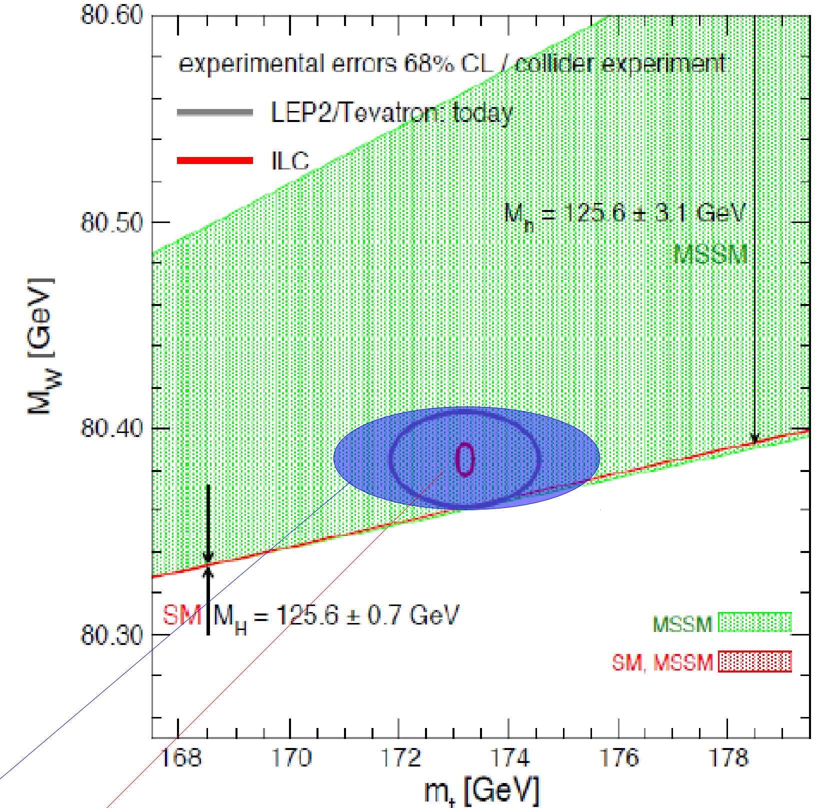
- No dependence on the MC mass used in the correction procedure

Larger unc:

JES → ***0.94 GeV***
ISR/FSR → ***0.72. GeV***
Scale → ***0.93 GeV***

Top quark pole mass determination: summary





[Heinemeyer et al updated to summer 2014] **+ “non authorised” ellipses**

Best top-quark pole mass measurement so far.

ILC prospects

- **Precise top quark mass** determinations are mandatory to **test and probe the SM** and BSM.

- Current direct top quark **kinematic mass** determinations reach **precisions better than 0.5%**...
  - What is its **interpretation**?
  - What is the **theoretical uncertainty** associated to this interpretations?

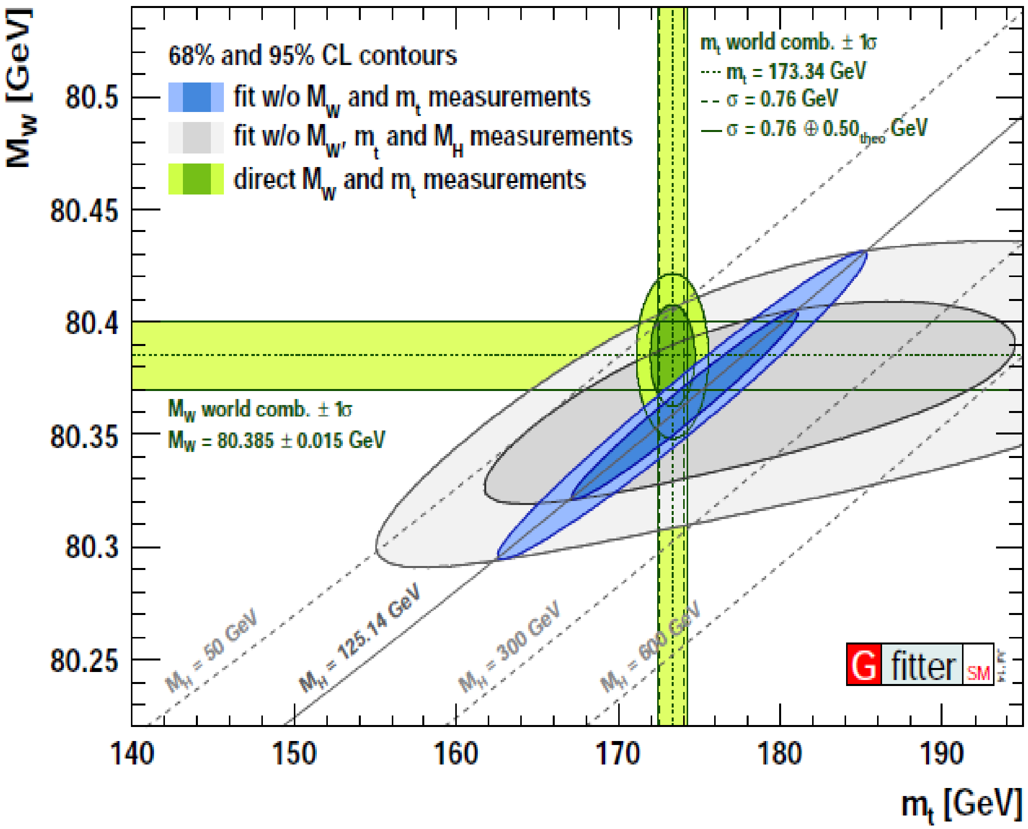
- **Unambiguosly scheme defined top quark mass determinations** need to compare measurements with **NLO calculations**.
  - Theoretical uncertainties of the order of 1-1.8 GeV
  - Traditionally, less precise (experimentally) methods.
  - Last results show great advances in the increase of experimental precision of these methods.

Thanks to J. Fuster, A. Jung, M. Vos and many others for interesting discussions and the slides that I've borrow from them

Back up slides

The top-quark mass: why so important?

SM consistency



Enter in all loop corrections (reduce parametric uncertainty)

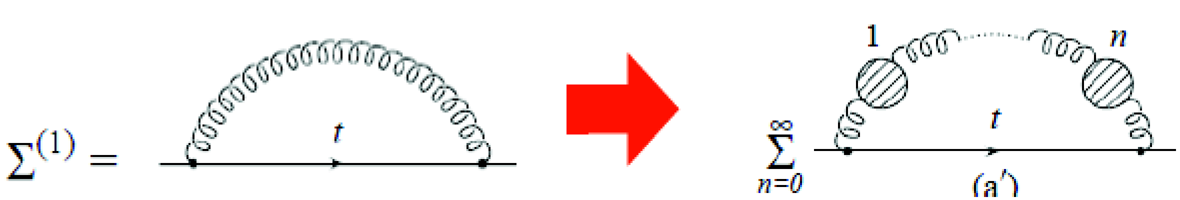
Relation H, W, t mass → EW fit (SM and BSM)

$$M_W = M_W^{LO} + \Delta r_{top} + \Delta r_H$$

$$\Delta r_{top} \simeq -\frac{3 G_F m_t^2}{8\sqrt{2}\pi^2} \frac{1}{\tan\theta_W}$$

$$\Delta r_H \simeq \frac{11 G_F M_Z^2 \cos\theta_W}{24\sqrt{2}\pi^2} \ln \frac{M_H^2}{M_Z}$$

Mass scheme

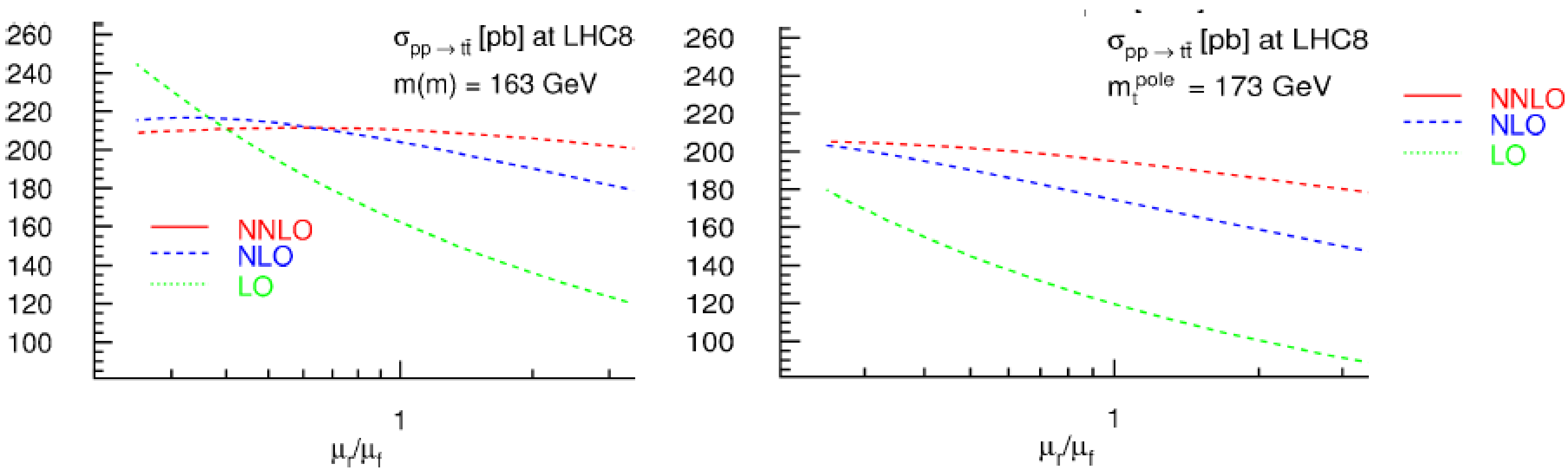


$$\frac{16 m_R}{3\beta_0}\sum_{n=0}^{\infty} c_n a^{n+1}$$

$$c_n \stackrel{n\to\infty}{\longrightarrow} e^{-C/2} 2^n n!$$

[Bigi, Shifman, Uraltsev, Vainshtein 94 Beneke, Braun,94 Smith, Willenbrock 97]

Pole mass has an intrinsic ambiguity of the order of Λ_{QCD}



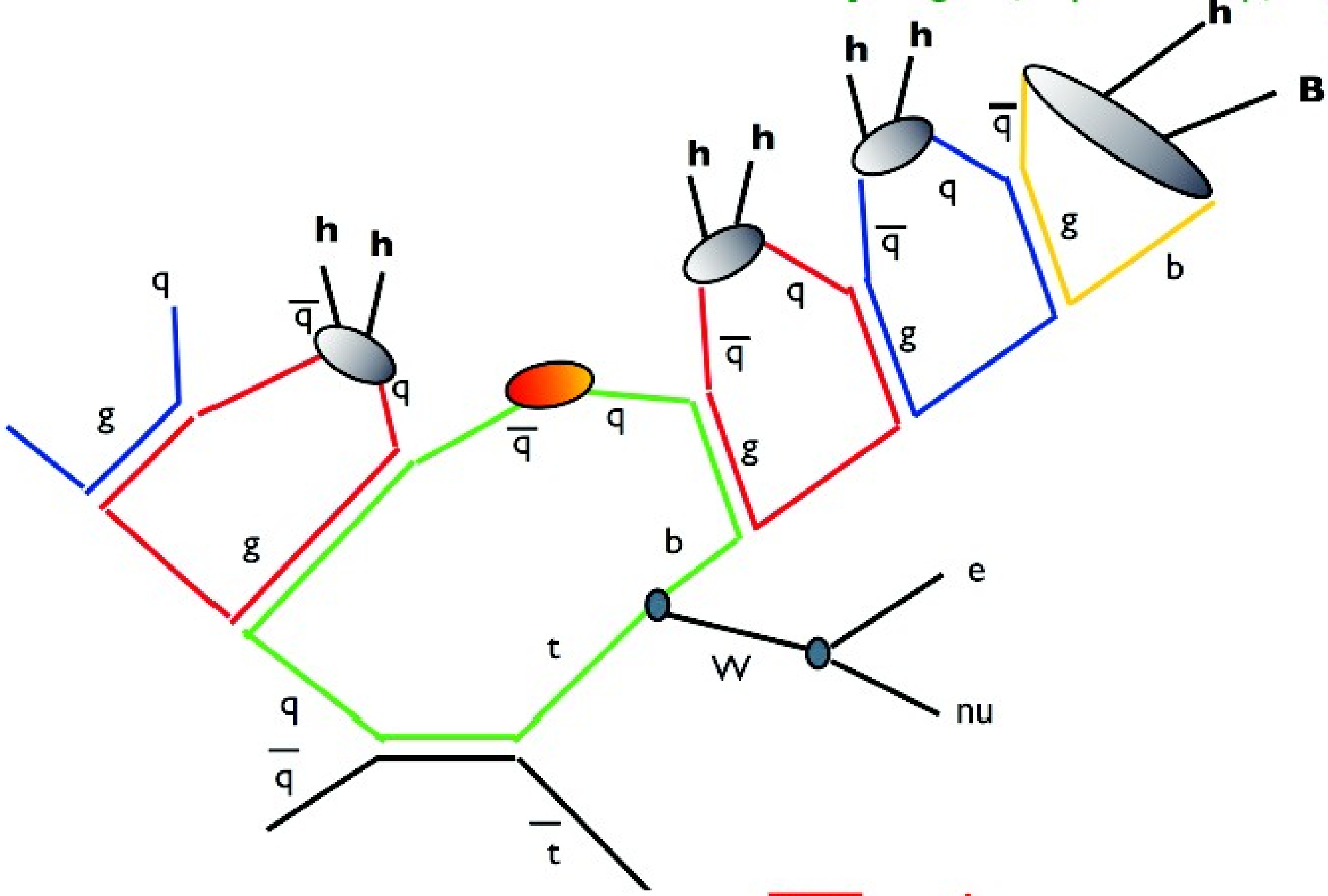
Running mass definition provides better perturbative stability (tt)

Langenfeld, Moch, Uwer PRD 80, 054009 (2009)

Czakon, Fiedler, Mitov hep-ph/1303.6254

What is it measured?

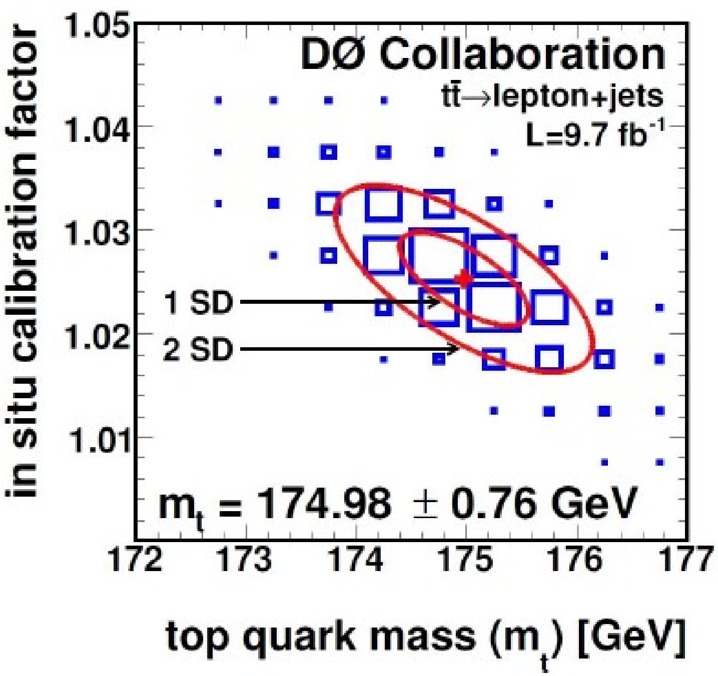
[Mangano, Top workshop, July 2012, CERN]



$$p_t \neq p_W + \sum_i p^i_{\text{had}}$$

Direct top quark mass measurements: Matrix Element

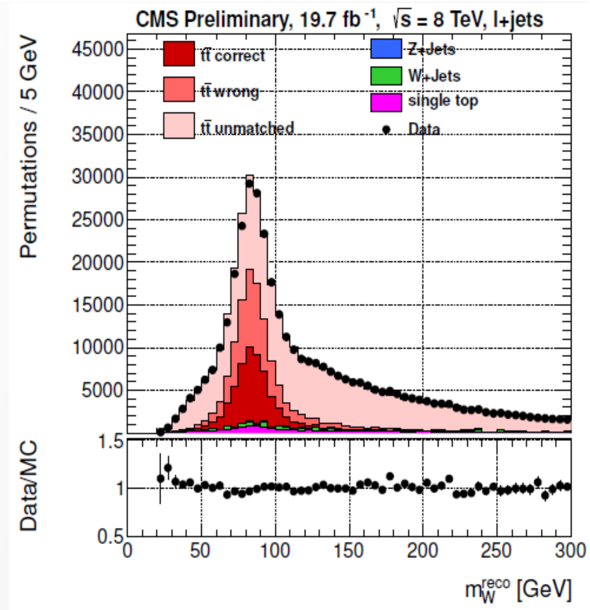
Most precise measurement at Tevatron

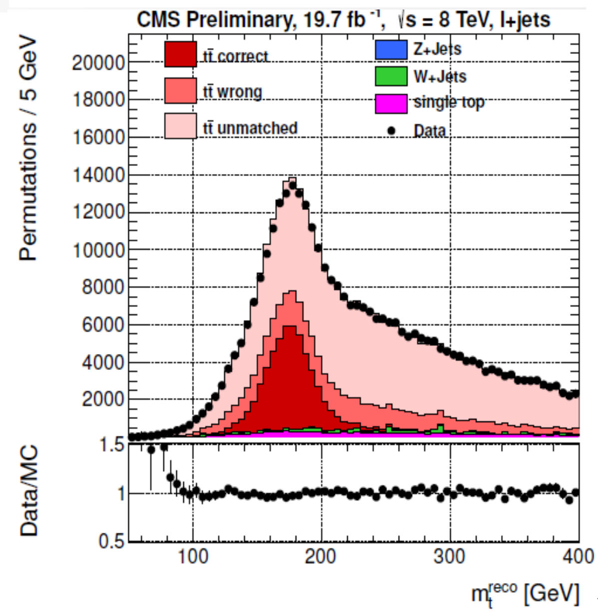


Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher order corrections	+0.15
Initial/final state radiation	±0.09
Hadronization and UE	+0.26
Color reconnection	+0.10
Multiple $p\bar{p}$ interactions	−0.06
Heavy flavor scale factor	±0.06
b-jet modeling	+0.09
PDF uncertainty	±0.11
Detector modeling:	
Residual jet energy scale	±0.21
Flavor-dependent response to jets	±0.16
b tagging	±0.10
Trigger	±0.01
Lepton momentum scale	±0.01
Jet energy resolution	±0.07
Jet ID efficiency	−0.01
Method:	
Modeling of multijet events	+0.04
Signal fraction	±0.08
MC calibration	±0.07
Total systematic uncertainty	±0.49
Total statistical uncertainty	±0.58
Total uncertainty	±0.76

TABLE I: Summary of uncertainties on the measured top quark mass. The signs indicate the direction of the change in m_t when replacing the default by the alternative model.

PRL [arxiv:1405:1756]





Most precise measurement at the LHC

Table 1: List of systematic uncertainties for the combined fit to the entire lepton+jets data set.

	δm_t^{2D} (GeV)	δJSF	δm_t^{1D} (GeV)
Experimental uncertainties			
Fit calibration	0.10	0.001	0.06
p_T- and η-dependent JES	0.18	0.007	1.17
Lepton energy scale	0.03	<0.001	0.03
MET	0.09	0.001	0.01
Jet energy resolution	0.26	0.004	0.07
b tagging	0.02	<0.001	0.01
Pileup	0.27	0.005	0.17
Non-$t\bar{t}$ background	0.11	0.001	0.01
Modeling of hadronization			
Flavor-dependent JSF	0.41	0.004	0.32
b fragmentation	0.06	0.001	0.04
Semi-leptonic B hadron decays	0.16	<0.001	0.15
Modeling of the hard scattering process			
PDF	0.09	0.001	0.05
Renormalization and factorization scales	0.12±0.13	0.004±0.001	0.25±0.08
ME-PS matching threshold	0.15±0.13	0.003±0.001	0.07±0.08
ME generator	0.23±0.14	0.003±0.001	0.20±0.08
Modeling of non-perturbative QCD			
Underlying event	0.14±0.17	0.002±0.002	0.06±0.10
Color reconnection modeling	0.08±0.15	0.002±0.001	0.07±0.09
Total	0.75	0.012	1.29

$$m_t^{MC} = 172.04 \pm 0.19\,(stat + JSF) \pm 0.75\,(syst)\,GeV$$

$$m_t^{MC} = 172.04 \pm 0.77\,GeV$$

JHEP 12 (2012) 105, CMS PAS-TOP-14-001

	$t\bar{t} \to$ lepton+jets			$t\bar{t} \to$ dilepton	Combination	
	$m_{\rm top}^{\ell+\rm jets}$ [GeV]	JSF	bJSF	$m_{\rm top}^{\rm dil}$ [GeV]	$m_{\rm top}^{\rm comb}$ [GeV]	ρ
Results	172.33	1.019	1.003	173.79	172.99	
Statistics	0.75	0.003	0.008	0.54	0.48	0
– Stat. comp. ($m_{\rm top}$)	*0.23*	*n/a*	*n/a*	*0.54*		
– Stat. comp. (JSF)	*0.25*	*0.003*	*n/a*	*n/a*		
– Stat. comp. (bJSF)	*0.67*	*0.000*	*0.008*	*n/a*		
Method	0.11 ± 0.10	0.001	0.001	0.09 ± 0.07	0.07	0
Signal MC	0.22 ± 0.21	0.004	0.002	0.26 ± 0.16	0.24	+1.00
Hadronisation	0.18 ± 0.12	0.007	0.013	0.53 ± 0.09	0.34	+1.00
ISR/FSR	0.32 ± 0.06	0.017	0.007	0.47 ± 0.05	0.04	−1.00
Underlying event	0.15 ± 0.07	0.001	0.003	0.05 ± 0.05	0.06	−1.00
Colour reconnection	0.11 ± 0.07	0.001	0.002	0.14 ± 0.05	0.01	−1.00
PDF	0.25 ± 0.00	0.001	0.002	0.11 ± 0.00	0.17	+0.57
W/Z+jets norm	0.02 ± 0.00	0.000	0.000	0.01 ± 0.00	0.02	+1.00
W/Z+jets shape	0.29 ± 0.00	0.000	0.004	0.00 ± 0.00	0.16	0
NP/fake-lepton norm.	0.10 ± 0.00	0.000	0.001	0.04 ± 0.00	0.07	+1.00
NP/fake-lepton shape	0.05 ± 0.00	0.000	0.001	0.01 ± 0.00	0.03	+0.23
Jet energy scale	0.58 ± 0.11	0.018	0.009	0.75 ± 0.08	0.41	−0.23
b-jet energy scale	0.06 ± 0.03	0.000	0.010	0.68 ± 0.02	0.34	+1.00
Jet resolution	0.22 ± 0.11	0.007	0.001	0.19 ± 0.04	0.03	−1.00
Jet efficiency	0.12 ± 0.00	0.000	0.002	0.07 ± 0.00	0.10	+1.00
Jet vertex fraction	0.01 ± 0.00	0.000	0.000	0.00 ± 0.00	0.00	−1.00
b-tagging	0.50 ± 0.00	0.001	0.007	0.07 ± 0.00	0.25	−0.77
$E_{\rm T}^{\rm miss}$	0.15 ± 0.04	0.000	0.001	0.04 ± 0.03	0.08	−0.15
Leptons	0.04 ± 0.00	0.001	0.001	0.13 ± 0.00	0.05	−0.34
Pile-up	0.02 ± 0.01	0.000	0.000	0.01 ± 0.00	0.01	0
Total	1.27 ± 0.33	0.027	0.024	1.41 ± 0.24	0.91	−0.07

Table 3: The measured values of $m_{\rm top}$ and the contributions of various sources to the uncertainty in the $t\bar{t} \to$ lepton+jets and the $t\bar{t} \to$ dilepton analyses. The corresponding uncertainties in the measured values of the JSF and bJSF are also shown for the $t\bar{t} \to$ lepton+jets analysis. The statistical uncertainties associated with these values are typically 0.001 or smaller. The result of the $m_{\rm top}$ combination is shown in the rightmost columns, together with the correlation (ρ) within each uncertainty group as described in Sect. 8. The symbol n/a stands for not applicable. Values quoted as 0.00 are smaller than 0.005. Finally, the last line refers to the sum in quadrature of the statistical and systematic uncertainty components.

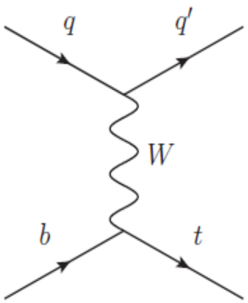
Alternative measurements

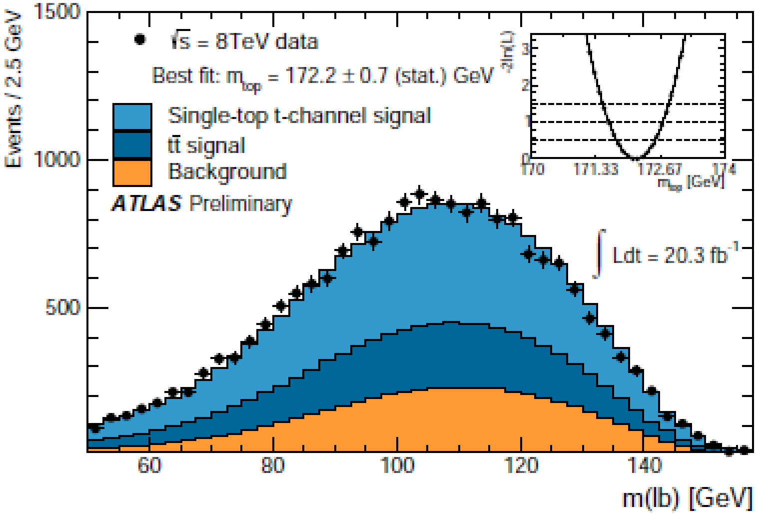
Using single-top events
(t-channel)

dominant systematic uncertainties:

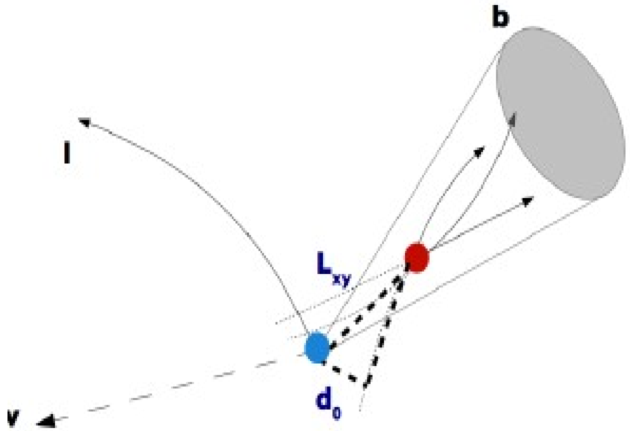
▷ JES (1.5 GeV)
▷ (t-channel) hadronisation (0.7 GeV)
▷ background (0.6 GeV)

ATLAS-CONF-2014-055





B-hadron Lifetime / lepton pT



Phys.Rev.D81 032002 (2010)

$m_t = 170.7 \pm 6.3\,(\mathrm{stat.}) \pm 2.6\,(\mathrm{syst.})\,\mathrm{GeV}$

Simultaneous fit to both kin. distributions **CDF**

CMS PAS TOP-12-030

$m_t = 173.5 \pm 1.5\,(\mathrm{stat.}) \pm 1.3\,(\mathrm{syst.}) \pm 2.6\,(p_T^{\mathrm{top}})\,\mathrm{GeV}$

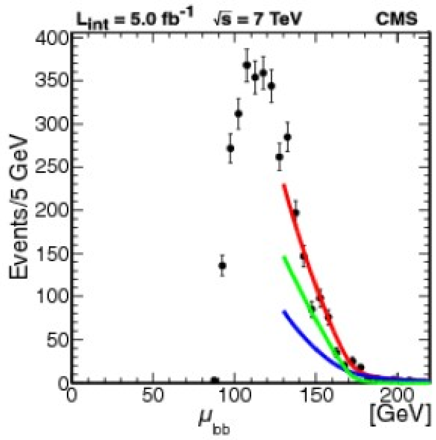
▷ dominant sources of systematic uncertainty:

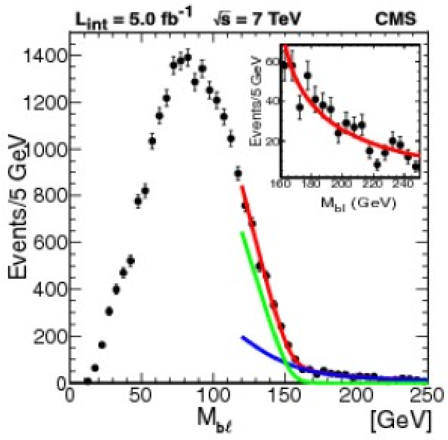
▷ top p_T modelling
▷ background in ℓ + jets
▷ hadronisation model

Fit to median Lxy **CMS**

S. Adomeit Top14

Kinematic endopoints

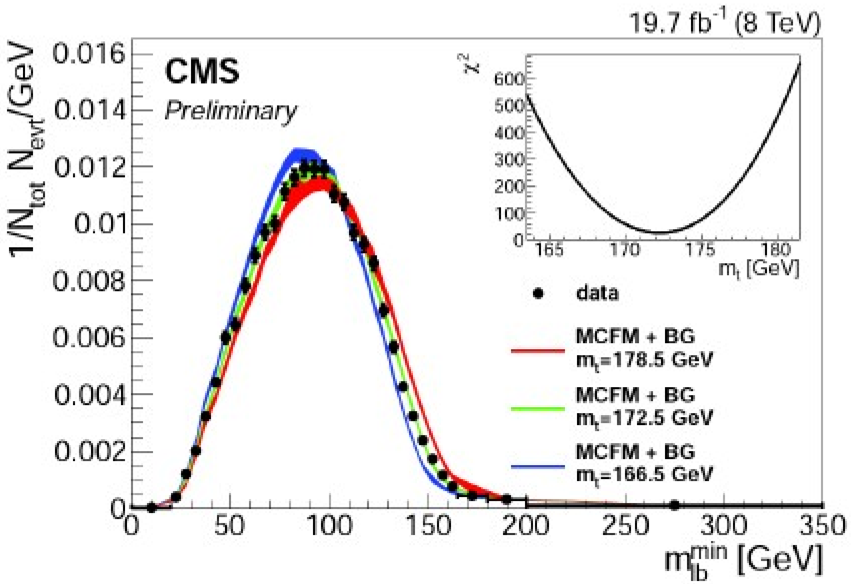




$m_t = 173.9 \pm 0.9\,(\text{stat.})^{+1.7}_{-2.2}\,(\text{syst.})\ \text{GeV}$

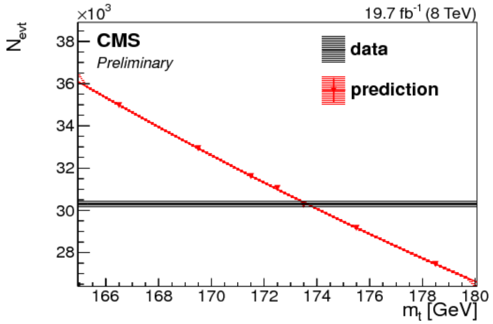
Eur. Phys. J. C 73 (2013) 2494

Mlb and forward folding



$\vec{x}_{reco} = \mathcal{L}\ \mathcal{M}^{resp}\vec{x}_{pred}$ $m_t = 171.4^{+1.0}_{-1.1}$ GeV

From the rate $m_t = 173.7^{+3.5}_{-3.4}$ GeV



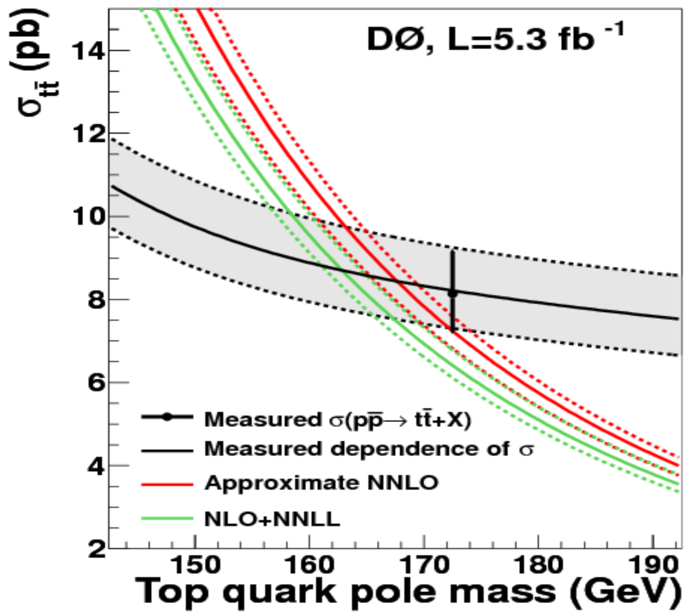
CMS PAS TOP-14-014

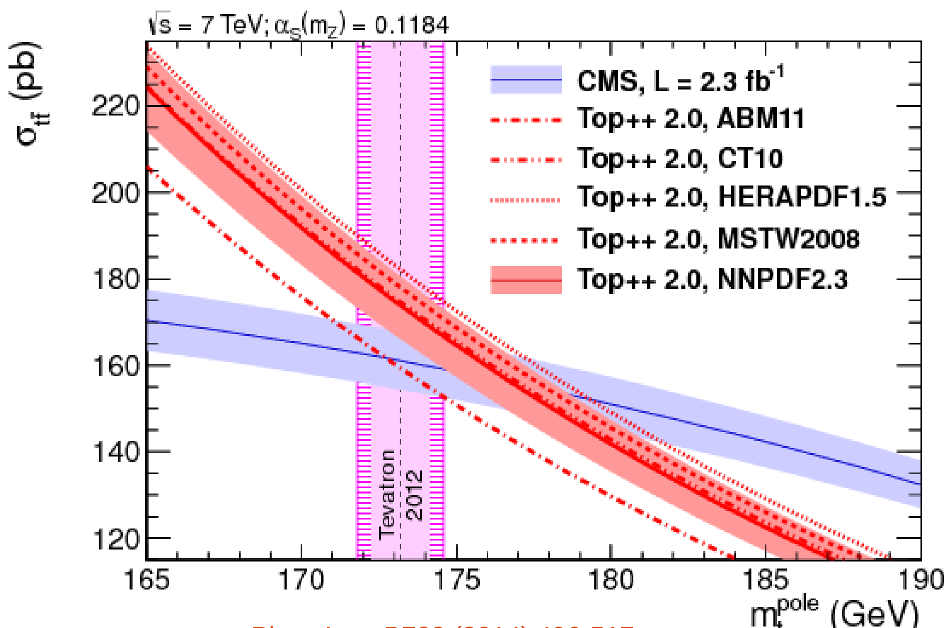
S. Adomeit Top14

Mt from cross section

Langenfeld U Moch S and Uwer P 2009

Ahrens et al 2010





Phys. Lett. B728 (2014) 496-517

$\sqrt{s}$ Uncertainty (inclusive $\sigma_{t\bar{t}}$)	 $\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	7 TeV $\Delta C_b/C_b$ (%)	 $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics			1.69
$t\bar{t}$ modelling	0.71	−0.72	1.43
Parton distribution functions	1.03	-	1.04
QCD scale choice	0.30	-	0.30
Single-top modelling	-	-	0.34
Single-top/$t\bar{t}$ interference	-	-	0.22
Single-top Wt cross-section	-	-	0.72
Diboson modelling	-	-	0.12
Diboson cross-sections	-	-	0.03
Z+jets extrapolation	-	-	0.05
Electron energy scale/resolution	0.19	−0.00	0.22
Electron identification	0.12	0.00	0.13
Muon momentum scale/resolution	0.12	0.00	0.14
Muon identification	0.27	0.00	0.30
Lepton isolation	0.74	-	0.74
Lepton trigger	0.15	−0.02	0.19
Jet energy scale	0.22	0.06	0.27
Jet energy resolution	−0.16	0.08	0.30
Jet reconstruction/vertex fraction	0.00	0.00	0.06
b-tagging	-	0.18	0.41
Misidentified leptons	-	-	0.41
Analysis systematics ($\sigma_{t\bar{t}}$)	1.56	0.75	2.27
Integrated luminosity	-	-	1.98
LHC beam energy	-	-	1.79
Total uncertainty ($\sigma_{t\bar{t}}$)	1.56	0.75	3.89

Eur.Phys.J. C74 (2014) 3109

The R observable: calculations

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s), \quad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}$$

m_0=170 GeV

Calculations:

- Fixed NLO calculations
  (Dittmaier et al arXiv:0810.0452)
- Mass scheme fixed
  (pole mass)

	$\sigma_{t\bar{t}+1\text{-jet}}$ [pb] $p_T(jet) > 50\,\text{GeV}, \lvert\eta(jet)\rvert < 2.5$	
m_t^{pole} [GeV]	LO	NLO
160	66.727(5)	60.04(8)
165	57.615(4)	52.25(9)
170	$49.910(3)^{+30}_{-17}$	$45.45(6)^{+1}_{-6}$
172.5	$46.508(3)^{+28}_{-15}$	$42.37(6)^{+1}_{-6}$
175	45.372(3)	39.46(6)
180	37.800(2)	34.73(5)

Pole mass scheme chosen, small NLO corrections

Off shell corrections to ttbar production.

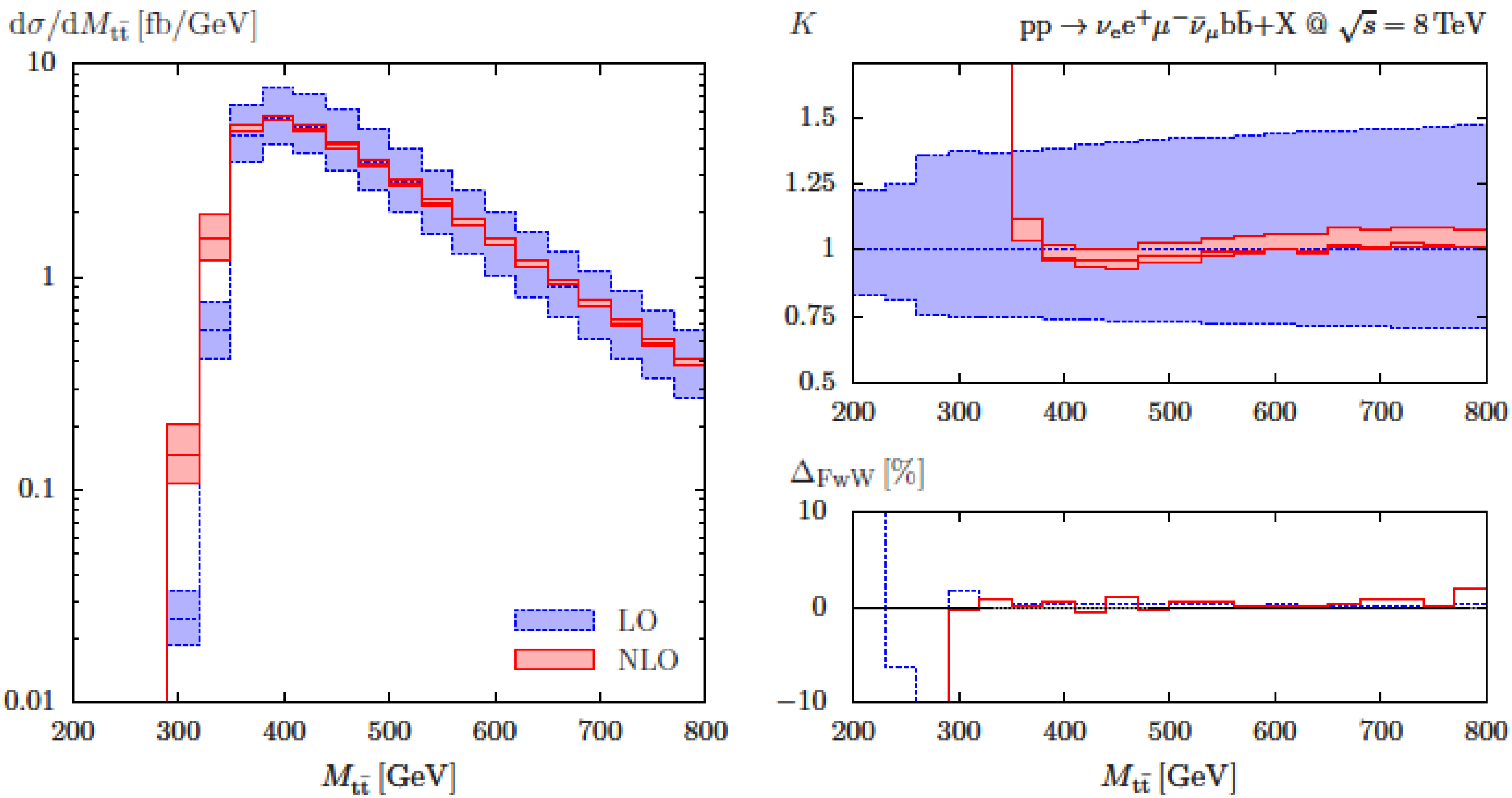


Figure 20: Distribution in the invariant mass of the $t\bar{t}$ pair with standard cuts for the LHC at $\sqrt{s} = 8\,\text{TeV}$ for dynamical scale $\mu_0 = E_T/2$.

arXiv:1207.5018v2