Challenges in top-mass determination at LHC

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1. **Introduction**
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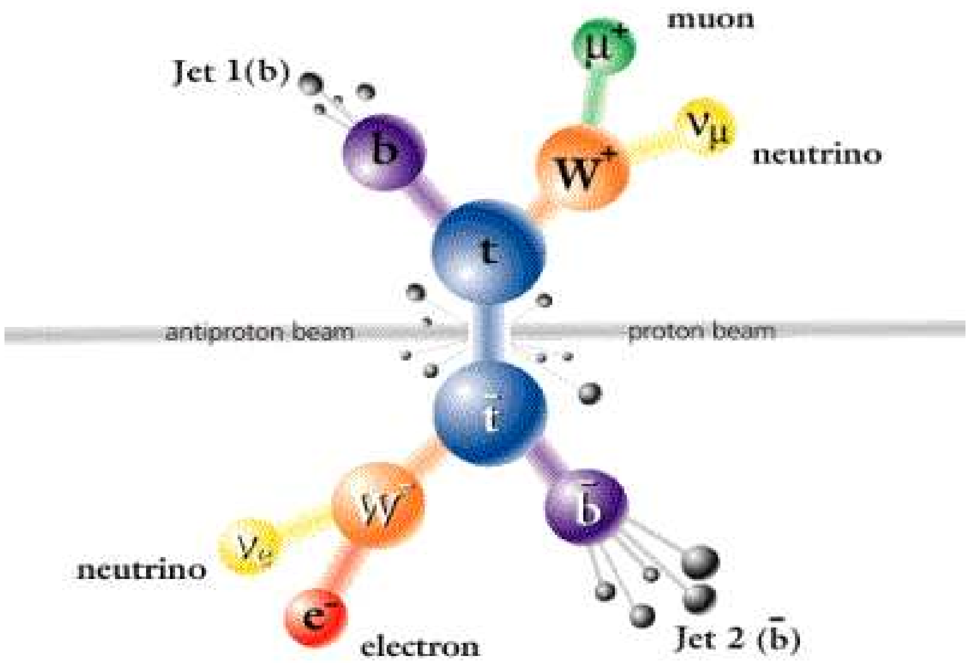
G.C. and ATLAS Collaboration, JHEP 06 (2023) 019

Special thanks to L. Cerrito, U. De Santis, M. Pinamonti and M. Vanadia (ATLAS Tor Vergata)

The top quark was discovered in 1995 by CDF and D0 experiments at Tevatron (FNAL)



$Q = (2/3)\,e$, $T_3 = +1/2$, phenomenology driven by its large mass: $m_t \simeq 173$ GeV

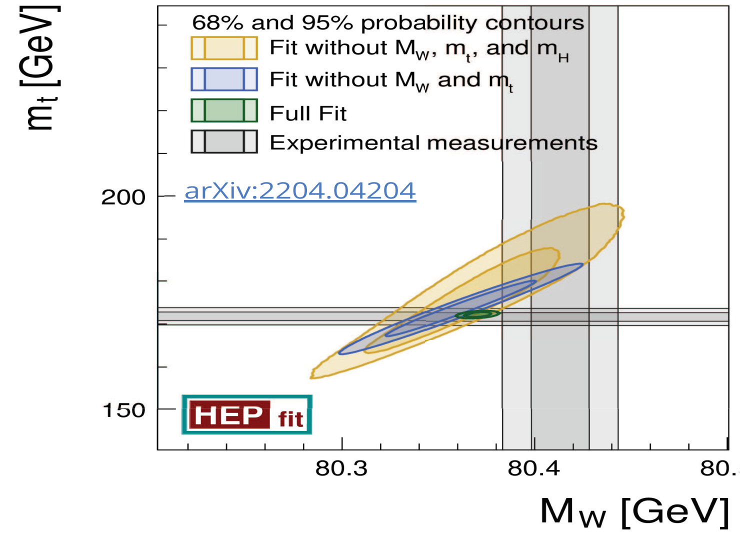
Large width $\Gamma_t \simeq 1.326\ \mathrm{GeV} \Rightarrow \tau_t \simeq 0.5 \times 10^{-24}\ \mathrm{s}$ (PDG'24)

The top quark decays before forming any T-hadron or $t\bar{t}$ resonance

Being $m_t \sim m_H$, the top Yukawa coupling is the only of order 1

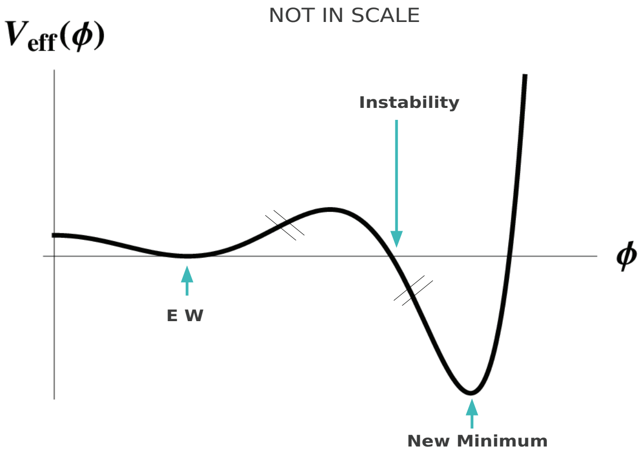
Processes with top quarks are background for many New Physics searches

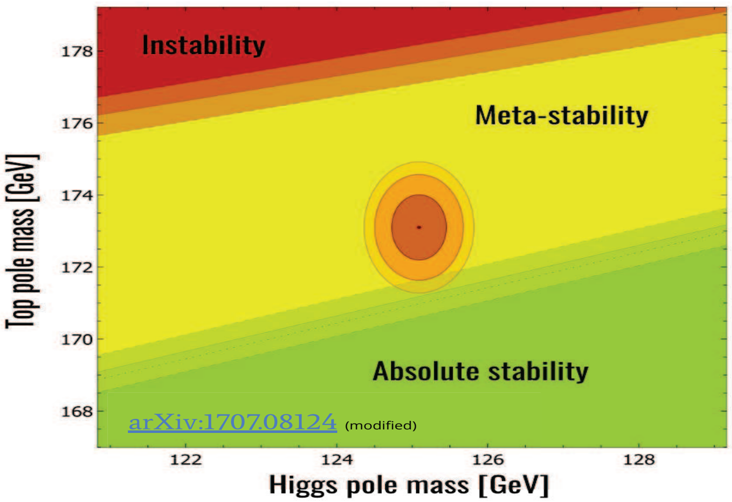
The top quark mass plays a crucial role in the electroweak symmetry breaking



Stability of SM vacuum depends on m_t and m_H (G.Degrassi et al, JHEP'12, A.Andreassen et al, PRD'18)

$$V_{RG}(\phi) \simeq \frac{1}{2} m^2(\Lambda)\phi^2(\Lambda) + \frac{1}{4}\lambda^4(\Lambda)\phi^4(\Lambda)\ ,\ \phi \sim \Lambda \gg v$$

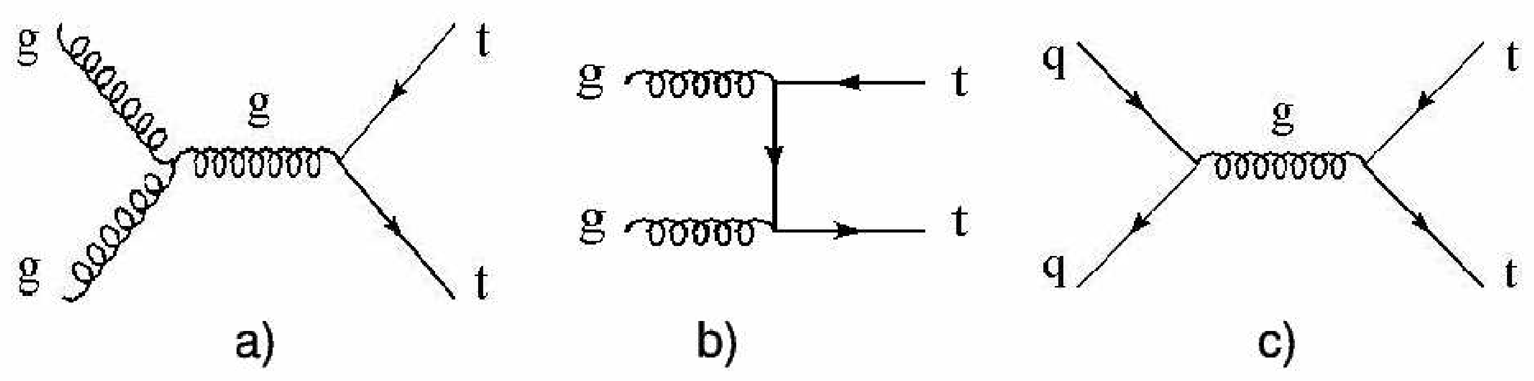




Stability: $V_{\mathrm{eff}}(v) < V_{\mathrm{eff}}(v')$; Instability: $V_{\mathrm{eff}}(v) > V_{\mathrm{eff}}(v')$; Metastability: $\tau > T_U$

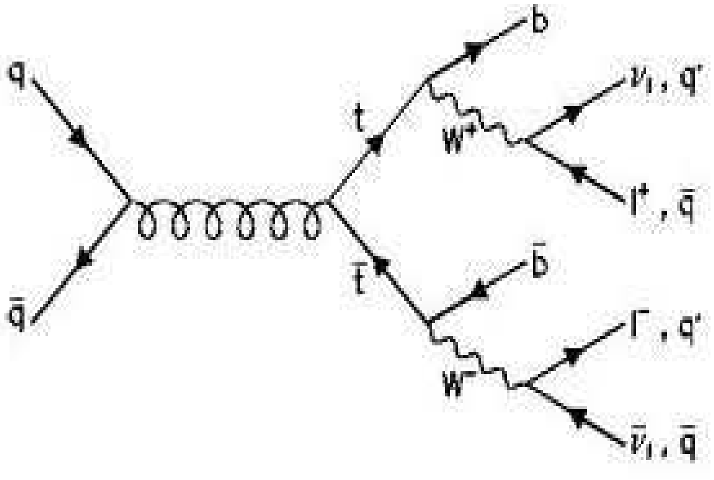
Top mass world average as pole mass in determination of Yukawa coupling

Top production and decay at hadron colliders ($t\bar{t}$ pairs)



Production via strong interaction (mainly $q\bar{q}$ at Tevatron, gg at LHC): LO is $\mathcal{O}(\alpha_S^2)\ldots$

Top decays via $t \to bW$ with $\mathrm{BR} \simeq 1$



Final states as all-leptons, lepton+jets or all-jets according to W decays

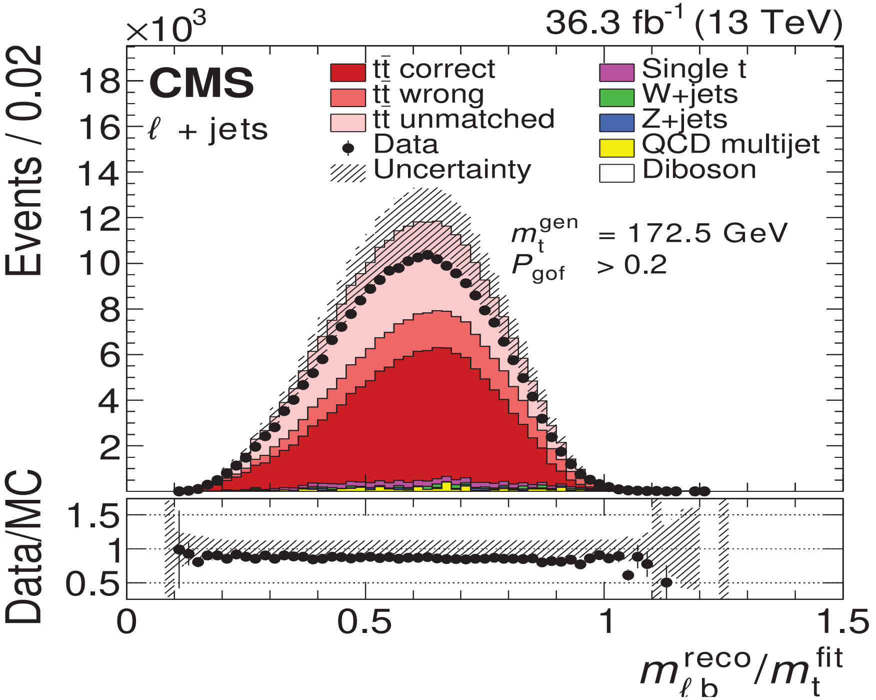
Mass measurements compare data with theory: m_t parameter in the theoretical prediction

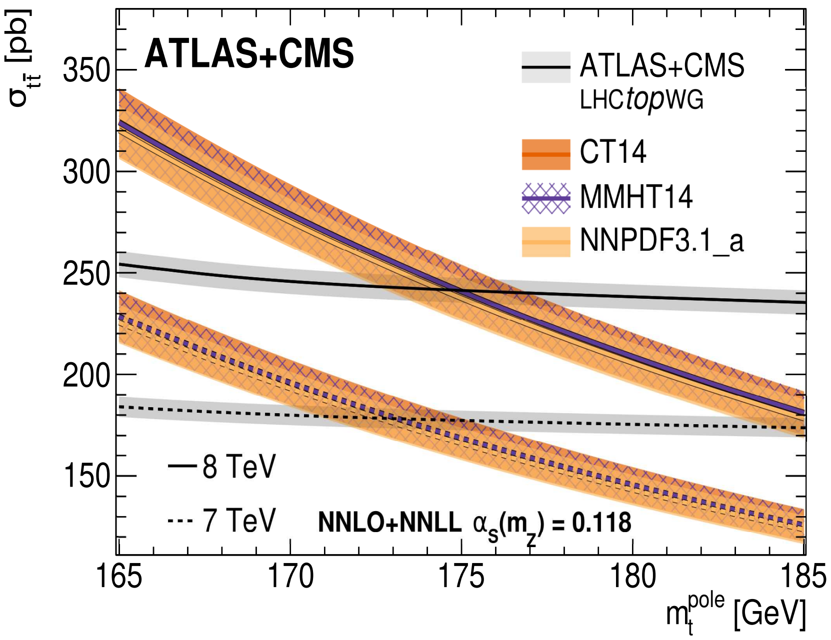
Direct top mass measurements based on reconstruction of top decays under the assumption that the final state is $WbWb$ and the W mass is fixed

Data confronted with Monte Carlo templates and m_t is the value minimizing the χ^2

m_t is the parameter in the event generator, often called 'Monte Carlo' mass

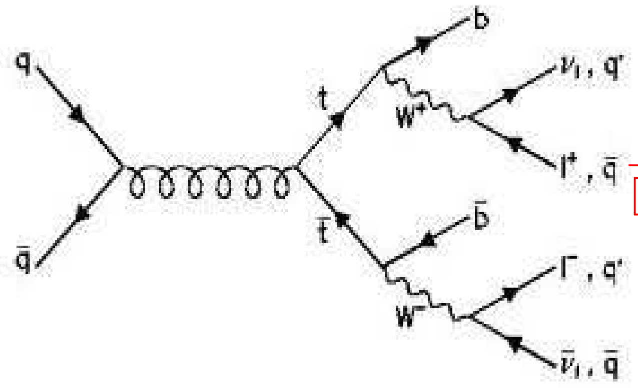
Alternative top mass measurements from other observables depending on (pole, $\overline{\rm MS}$) m_t, e.g., $\sigma(t\bar t) = \alpha_S^2\sigma_0(m_t) + \alpha_S^3\sigma_1(m_t) + \alpha_S^4\sigma_2(m_t) + \dots$





Longstanding debate on m_t interpretation in direct measurements (G.C., Front.in Phys.'19)

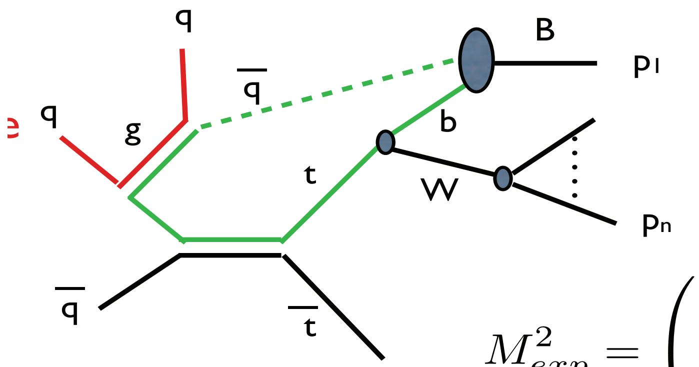
Measured mass must be close to $m_{\rm pole}$: top-decay kinematics is driven by $m_{\rm pole}$



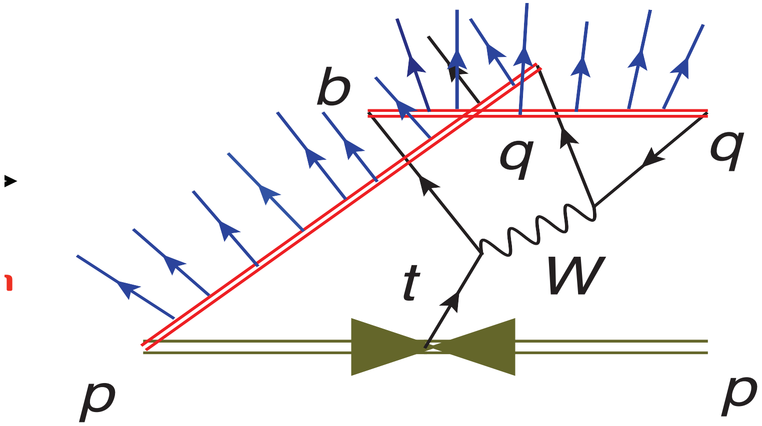
$$\frac{1}{[(p_W+p_b)^2-m_t^2]^2+m_t^2\Gamma_t^2}\sim\frac{1}{\pi}\,\delta[(p_W+p_b)^2-m_t^2]\ \text{for}\ \Gamma_t\ll m_t$$

Reconstructed mass $p^2=(p_{b-{\rm jet}}+p_\nu+p_\ell)^2$ (with cuts on jets and leptons) with on-shell tops should be close to the pole mass, up to widths, NP and higher-order corrections

Colour-reconnection effects can spoil this picture



$$M^2_{exp}=\left(\sum_{i=1,\ldots,n}p_i\right)^2$$

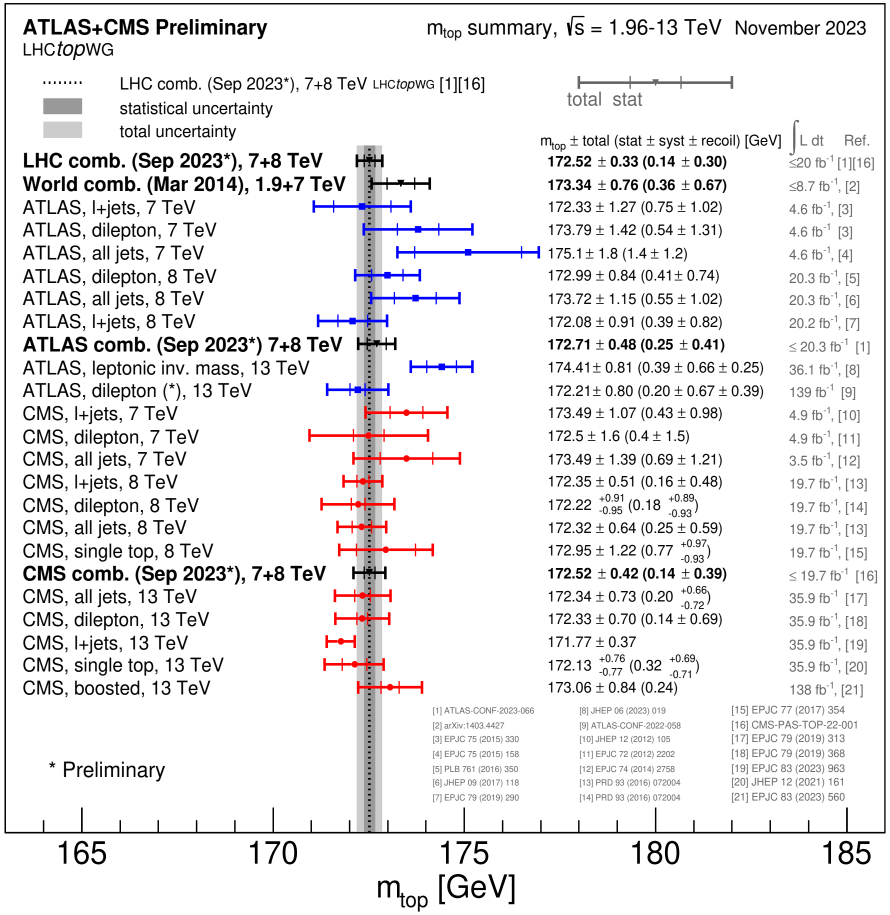


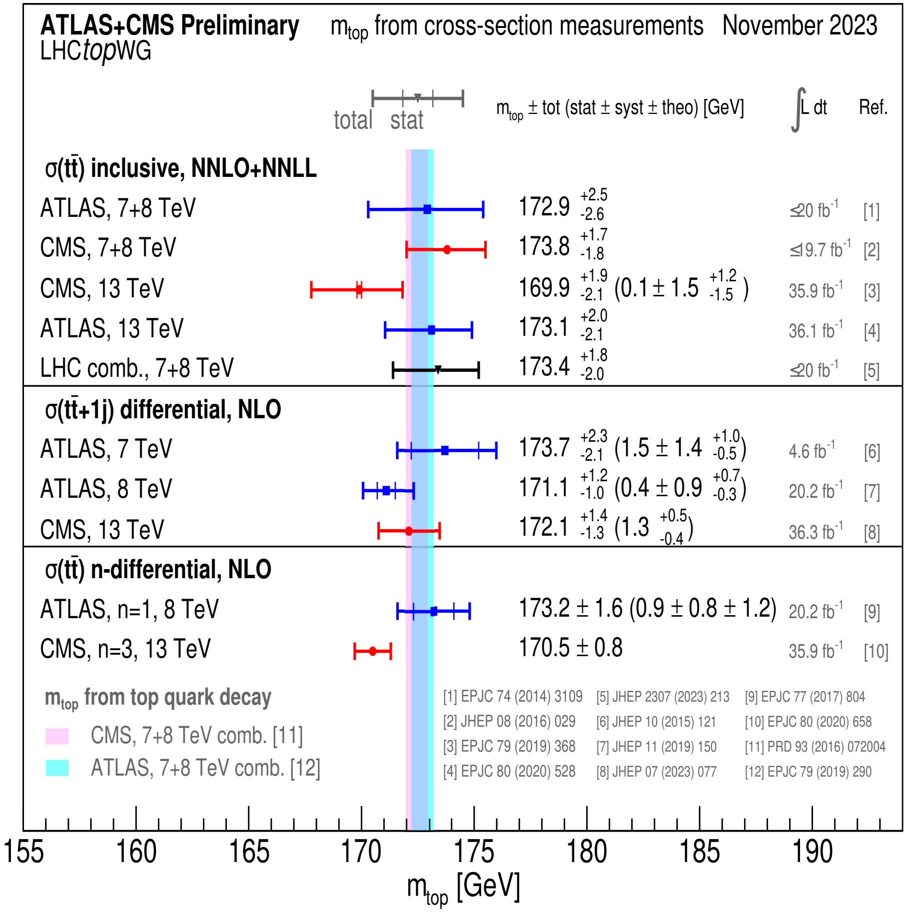
Left: M.L.Mangano, TOP 2013 workshop, Right: S.Argyropoulos, LNF'15 workshop

Much work within SCET and standard QCD: shift with respect to the pole mass about a few hundreds MeV

Summary of mass measurements (M.Myllymaki, talk at TOP 2023)

Left: direct measurements Right: alternative measurements

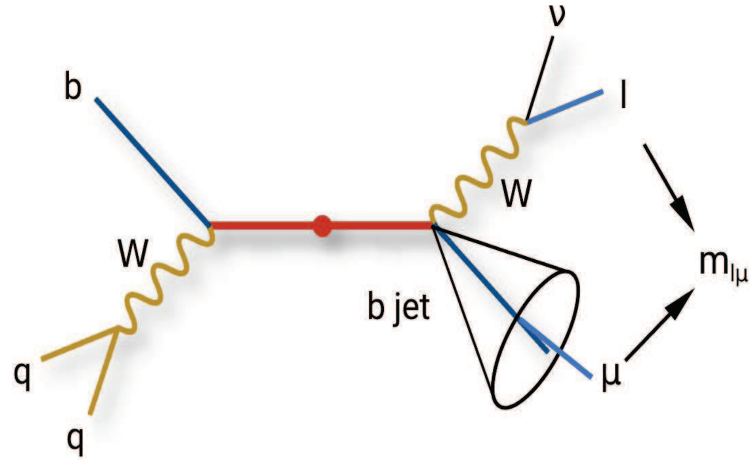




$$m_t^{\text{TeV+LHC}} = [173.34 \pm 0.27(\text{stat}) \pm 0.71(\text{syst})]$$ GeV (World average, 1403.4427)

World average based on direct measurements, not combined with alternative ones

Soft-muon tagging (SMT): $m_{l\mu}$ in $l+$ jets (similar to CDF and CMS with $t \to B \to J/\psi$)

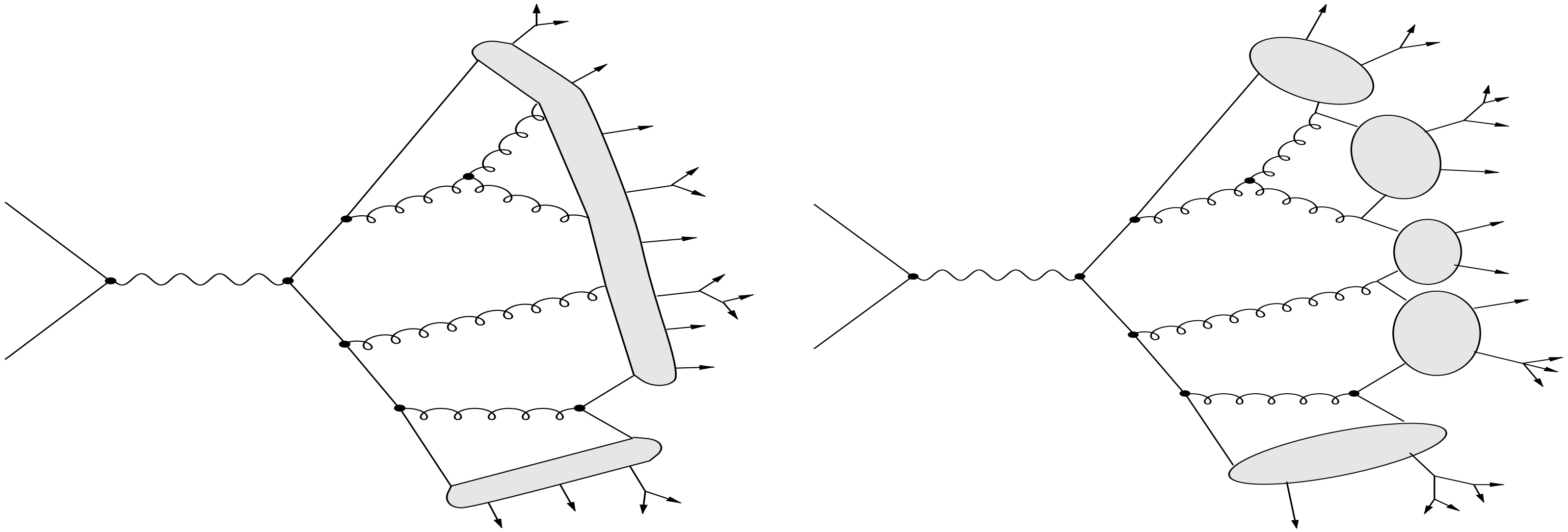


Primary leptons: $p_{T,l} > 27$ GeV, $|\eta_l| < 2.47$, $\Delta R_{ll} > 0.4$; anti-k_T jets with $p_{T,j} > 25$ GeV, $|\eta_j| < 2.5$, $\Delta R_{jj} > 0.2$, $\Delta R_{jl} > 0.4$; SMT: $p_{T,\mu} > 8$ GeV, $\Delta R_{j,\mu} < 0.2$

Advantages: leptonic, mild sensitivity to jet calibration/uncertainty and production

Drawback: major dependence on treatment of b-quark fragmentation $b \to B$

Analysis uses POWHEG+PYTHIA (default, left) and +HERWIG (MC uncertainty, right)

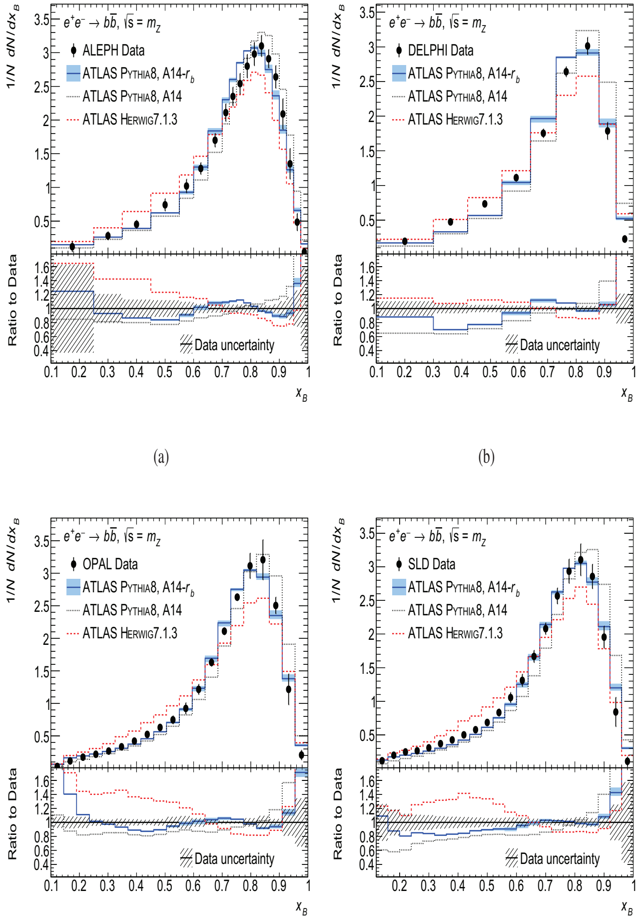


Bottom fragmentation in top decays: universality from e^+e^- to pp (true in full QCD)

b-fragmentation through Lund–Bowler function ($z = 2p_B \cdot p_Z / m_Z^2 \simeq E_B/E_b$):

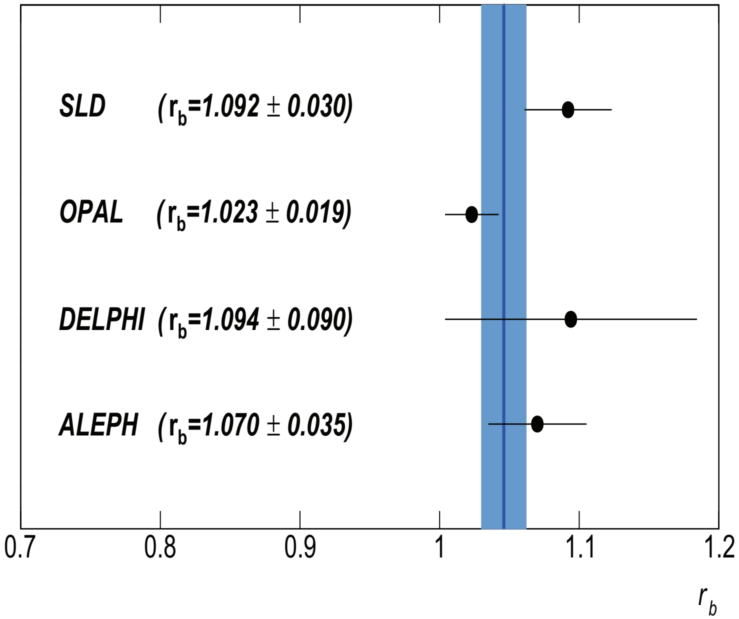
$$f(z) = \frac{1}{z^{1+br_b m_b^2}}(1-z)^a \exp(-bm_T^2/z)$$

a and b tuned to light and heavy-flavour data, refitting r_b in A14 ATLAS tuning



(a) (b)

Experiment	r_b	χ^2/ndf
ALEPH	1.070 ± 0.035	21/18
DELPHI	1.094 ± 0.030	73/8
OPAL	1.023 ± 0.019	18/19
SLD	1.092 ± 0.018	58/21



Overall result, global χ^2 with uncorrelated experiments: $r_b = 1.05 \pm 0.02$ (A14-r_b)

Rescaling b- and c-hadron production fractions and BRs into muons

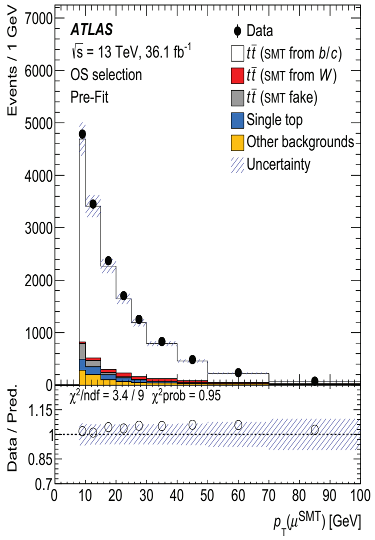
Hadron	PDG	POWHEG+PYTHIA8	Scale Factor
B^0	0.404 ± 0.006	0.429	0.941 ± 0.014
B^+	0.404 ± 0.006	0.429	0.942 ± 0.014
B_s^0	0.103 ± 0.005	0.095	1.088 ± 0.052
b-baryon	0.088 ± 0.012	0.047	1.87 ± 0.26
D^+	0.226 ± 0.008	0.290	0.780 ± 0.027
D^0	0.564 ± 0.015	0.553	1.020 ± 0.027
D_s^0	0.080 ± 0.005	0.093	0.857 ± 0.054
c-baryon	0.109 ± 0.009	0.038	2.90 ± 0.24

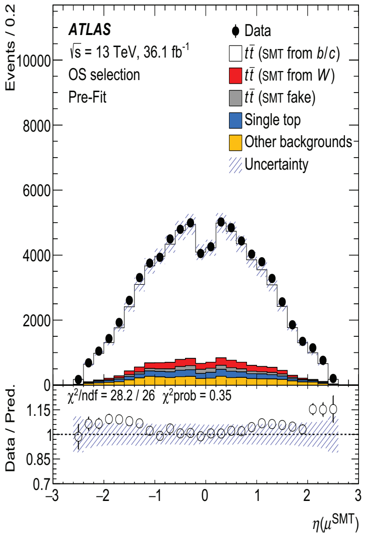
Hadronic Decay Mode	PDG	POWHEG PYTHIA8+EVTGEN	Scale Factor
$b \to \mu$	$0.1095^{+0.0029}_{-0.0025}$	0.106	$1.032^{+0.0027}_{-0.0023}$
$b \to \tau$	0.0042 ±0.0004	0.0064	0.661 ±0.062
$b \to c \to \mu$	0.0802 ±0.0019	0.085	0.946 ±0.022
$b \to \bar{c} \to \mu$	0.016 ±0.003	0.018	0.89 ±0.17
$c \to \mu$	0.082 ±0.005	0.084	0.976 ±0.059

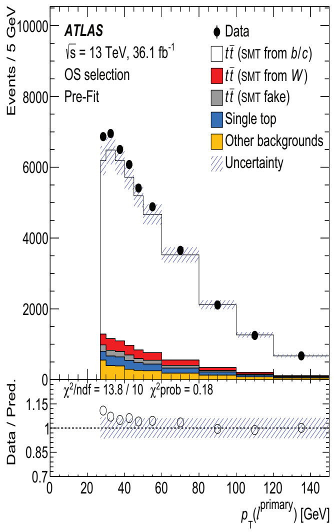
Event yields with $15\ \text{GeV} < m_{l\mu} < 80\ \text{GeV}$ and fractions of events with a SMT

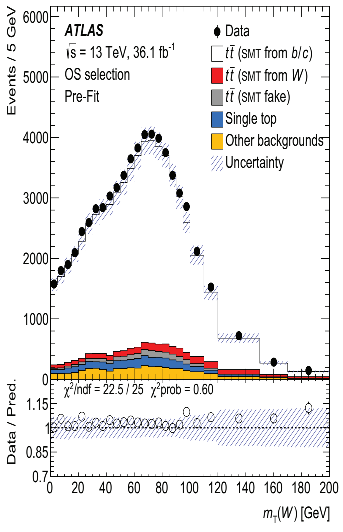
Process	Yield (OS)	Yield (SS)
$t\bar{t}$ (SMT from b- or c-hadron)	55 700 ± 3400	34 800 ± 2300
$t\bar{t}$ (SMT from $W \to \mu\nu$)	2190 ± 310	4.9 ± 3.6
$t\bar{t}$ (SMT fake)	1490 ± 210	1240 ± 170
Single top t-channel	770 ± 70	490 ± 40
Single top s-channel	63 ± 6	49 ± 4
Single top Wt channel	1840 ± 140	1260 ± 100
W+jets	1600 ± 400	1080 ± 240
Z+light jets	210 ± 80	15 ± 6
Z+HF jets	550 ± 180	310 ± 100
Diboson	17.2 ± 2.9	6.3 ± 1.4
Multijet	530 ± 140	480 ± 130
Total Expected	65 000 ± 4000	39 700 ± 2500
Data	66 891	42 087

	OS [%]	SS [%]
Processes involving a μ from a t or $\bar{t}$		
$t \to B \to \mu$	73.6	51.2
$t \to B \to D \to \mu$	16.7	44.2
$t \to B \to \tau \to \mu$	2.0	1.3
$t \to B \to D \to \tau \to \mu$	0.8	0.8
Processes involving a μ not from a t or $\bar{t}$		
$B \to \mu$	0.6	0.9
$D \to \mu$	5.8	1.4
Other ($\tau \to \mu$)	0.5	0.1

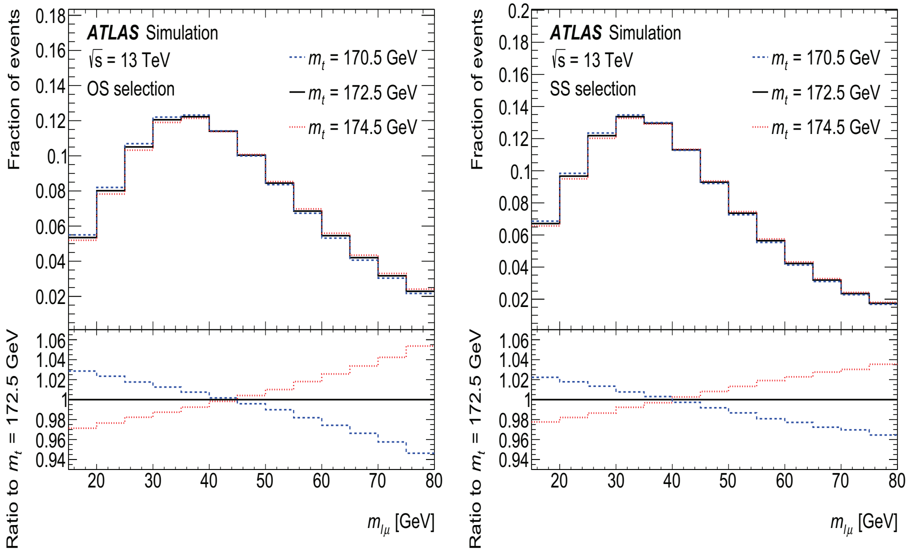


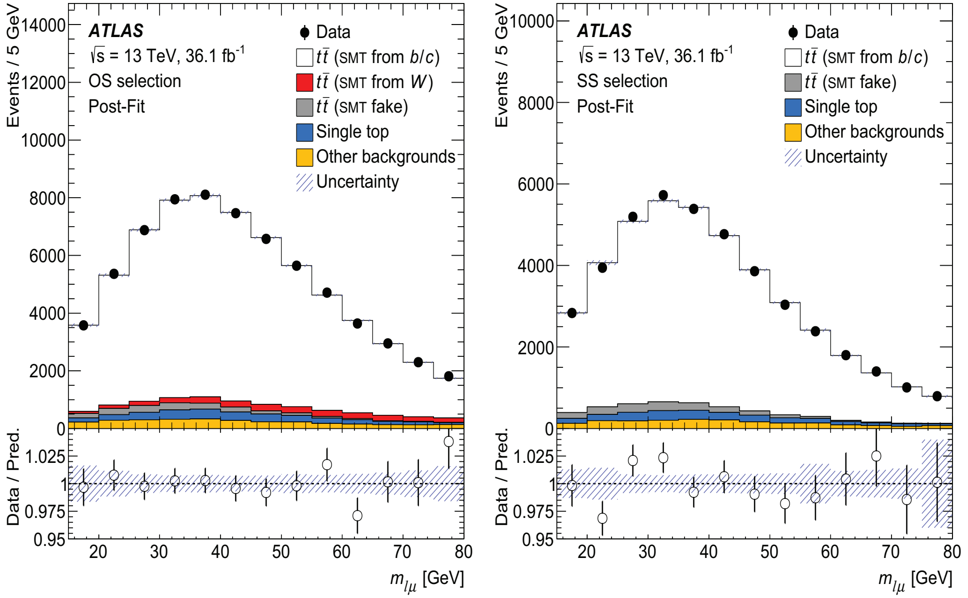






Extraction of the top-quark mass $\sqrt{s} = 13\ \text{TeV},\ \mathcal{L} = 36.1\ \text{fb}^{-1}$





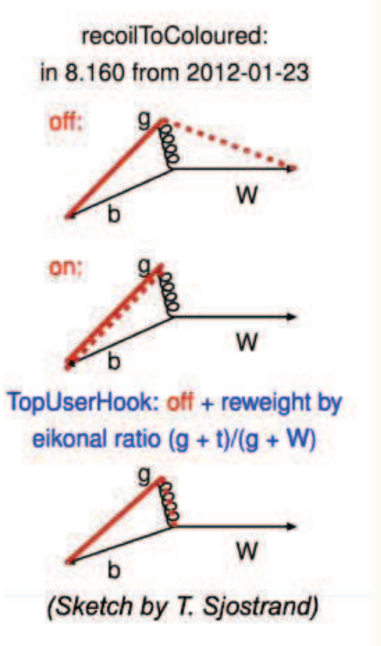
Best-fit result: $m_t = 174.41 \pm 0.39(\text{stat.}) \pm 0.66(\text{syst.}) \pm 0.25(\text{recoil})$

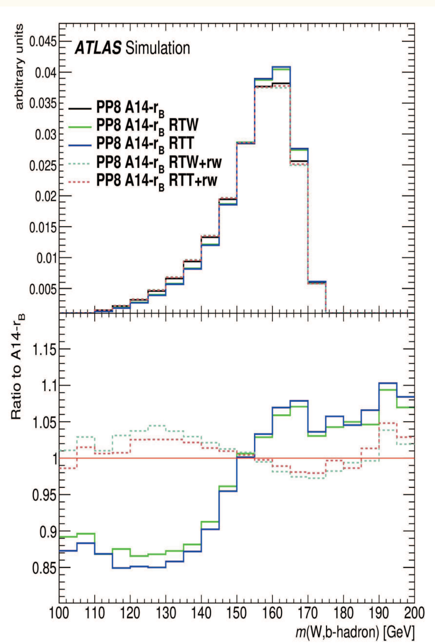
Most precise single measurement by ATLAS and more precise than similar techniques

Summary of uncertainties

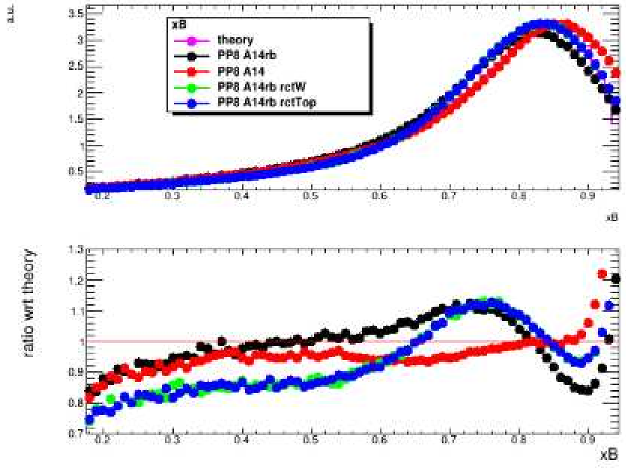
Source	Unc. on m_t [GeV]	Stat. precision [GeV]
Statistical and datasets		
Data statistics	0.39	
Signal and background model statistics	0.17	
Luminosity	< 0.01	±0.01
Pile-up	0.07	±0.03
Modelling of signal processes		
Monte Carlo event generator	0.04	±0.06
b, c-hadron production fractions	0.11	±0.01
b, c-hadron decay BRs	0.40	±0.01
b-quark fragmentation r_b	0.19	±0.06
Parton shower α_S^{FSR}	0.07	±0.04
Parton shower and hadronisation model	0.06	±0.07
Initial-state QCD radiation	0.23	±0.08
Colour reconnection	< 0.01	±0.02
Choice of PDFs	0.07	±0.01
Modelling of background processes		
Soft muon fake	0.16	±0.03
Multijet	0.07	±0.02
Single top	0.01	±0.01
W/Z+jets	0.17	±0.01
Detector response		
Leptons	0.12	±0.01
Jet energy scale	0.13	±0.02
Soft muon jet p_T calibration	< 0.01	±0.01
Jet energy resolution	0.08	±0.07
b-tagging	0.10	±0.01
Missing transverse momentum	0.15	±0.01
Total stat. and syst. uncertainties (excluding recoil)	0.77	±0.03
Recoil uncertainty	0.25	
Total uncertainty	0.81	

Specific to this analysis: gluon-recoil uncertainty in first emission off top decays



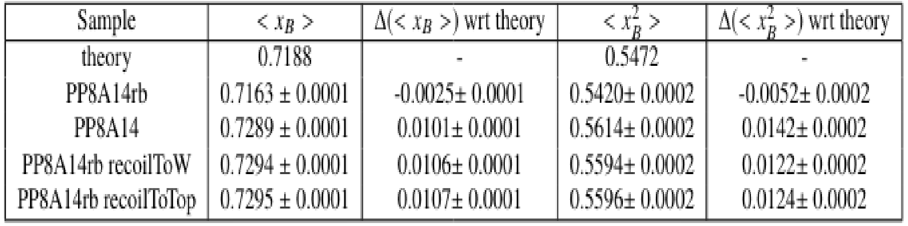


Recoil-to-b: best agreement with NLO+NLL resummation of x_B (G.C.,Cacciari, Mitov, JHEP'02)



(a)

Figure 194: Comparison of x_B distributions for theoretical prediction based on NLO+NLL resummations and that of PP8 smaples with different recoil strategies. The theoretical calculations are performed for m_{top} = 175 GeV, while the PP8 MC samples are for m_{top} = 172.5 GeV, but x_B is independent from m_{top}.



Sample	$< x_B >$	$\Delta(< x_B >)$ wrt theory	$< x_B^2 >$	$\Delta(< x_B^2 >)$ wrt theory
theory	0.7188	-	0.5472	-
PP8A14rb	0.7163 ± 0.0001	-0.0025± 0.0001	0.5420± 0.0002	-0.0052± 0.0002
PP8A14	0.7289 ± 0.0001	0.0101± 0.0001	0.5614± 0.0002	0.0142± 0.0002
PP8A14rb recoilToW	0.7294 ± 0.0001	0.0106± 0.0001	0.5594± 0.0002	0.0122± 0.0002
PP8A14rb recoilToTop	0.7295 ± 0.0001	0.0107± 0.0001	0.5596± 0.0002	0.0124± 0.0002

Table 61: Average x_B (i.e. the second Mellin moment) for NLO+NLL predictions and for different PP8 settings in the 0.18-0.94 range. The third Mellin moment is also shown.

Conclusions

Top-quark mass is a fundamental SM parameter

Direct and alternative methods to measure to mass at LHC

Ongoing debate on the interpretation of m_t in terms of field-theory definitions

Novel ATLAS analysis on top-mass measurement based on soft-muon tagging

Leptonic final states minimize jet uncertainty, while contribution from b fragmentation

Final result $m_t = 174.41 \pm 0.81$ GeV most precise single measurement by ATLAS

Smaller uncertainty than companion measurements using fully leptonic final states (e.g. from J/ψ)

Extension to full Run II data and Run III

Use of updated codes and fragmentation models to improve $t\bar{t}$ production and decay modelling

Phenomenology work on fragmentation functions (hadronization models) according to resummed calculations and Monte Carlo generators and comparison with data