Highlights on top quark properties and mass measurements with the ATLAS detector

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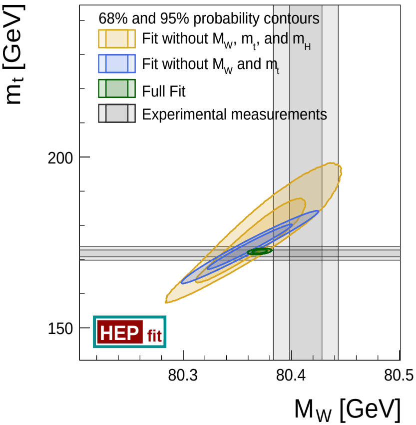
Contents

Leveraging top production @LHC

New ideas and pushing rare processes frontier is possible @LHC:

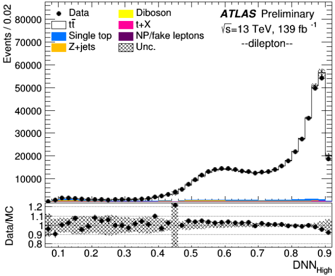
- LHC is a $t\bar{t}$ factory, $\sigma(t\bar{t}) \approx 830$ pb at $\sqrt{s} = 13$ TeV, ATLAS has collected about 116M $t\bar{t}$ events
- in this presentation:
  - improving top mass measurements as the first step
    - using the dilepton channel at $\sqrt{s} = 13$ TeV (ATLAS-CONF-2022-058)
    - using the leptonic invariant mass at $\sqrt{s} = 13$ TeV (JHEP 06 (2023) 019)
    - combination of ATLAS and CMS measurements at $\sqrt{s} = 7$ and 8 TeV (Phys. Rev. Lett. 132 (2024) 261902)
  - study the fundamental properties of quantum mechanics
    - observation of quantum entanglement in $t\bar{t}$ (arXiV:2311.07288, accepted by Nature)

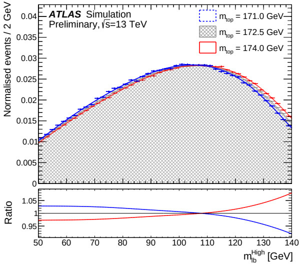
Why measure M_t



arXiV:2204.04204

- precise measurement needed to check the consistency of the SM and restrict BSM
  - mass measurements helps to restrict the parameters space of BSM models.
  - Yukawa coupling ≈ 1 to Higgs: the top and Higgs masses play a important role in the EW vacuum stability.
- strong $t\bar{t}$ cross section dependence on top mass, important background in Higgs measurements and NP searches
- LHC is producing large amount of top quarks, multiple measurements are possible
- combinations could improve precision, very promising result from ATLAS+CMS



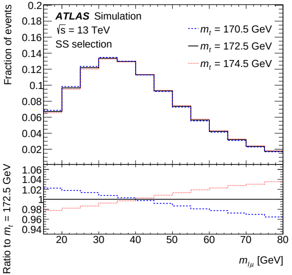


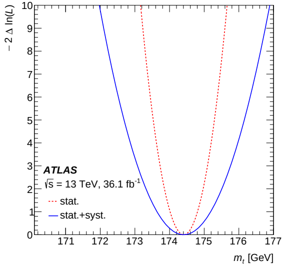
- uses invariant mass $m_{\ell b}^{High}$ of the selected ℓb pair with the larger $p_{\mathrm{T}\ell \mathrm{b}}$ per event, more precise then using both pairs
- ML algorithm to pick the best combination of ℓ and b-tagged jets, fully connected DNN with three hidden layers
- training on p_{T} and η of each ℓb pair, angular distance between paired ℓ and b as well as p_{T} and η of individual ℓ and b, and also m_{bb}
- data with 139 fb^{-1} at $\sqrt{s}$=13 TeV
- main systematics uncertainties comes from matrix element matching, jet energy scale and recoil effect (which is quoted separately)
- unbinned maximum-likelihood fit to data

ATLAS-CONF-2022-058

Result: $\mathrm{m_{top}} = 172.21 \pm 0.20(\mathrm{stat}) \pm 0.67(\mathrm{syst}) \pm 0.39(\mathrm{recoil})$ GeV

Top mass from soft muon tag





- event selection designed to collect $\ell\nu bjj'\bar{b}$ final states, and maximize the fraction of events where ℓ from the W and b-initiated jet with the muon from semileptonic decay come from the same top
- leptonic-only, invariant mass reconstruction of $m_{\ell\mu}$, lepton from W and soft μ from a b-hadron
  - smaller sensitivity to the jet energy scale and resolution
  - less sensitivity to top-quark production modeling than previously showed measurement
- data with 36.1 fb^{-1} at $\sqrt{s}$=13 TeV
- binned-template profile likelihood fit used to find best value for m_t, systematics included as Gaussian-constrained nuisance parameters

JHEP 06 (2023) 019

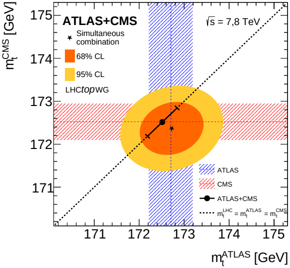
Result: $m_{top} = 174.41 \pm 0.39(\text{stat}) \pm 0.66(\text{syst}) \pm 0.25(\text{recoil})$ GeV

Top mass from soft muon tag

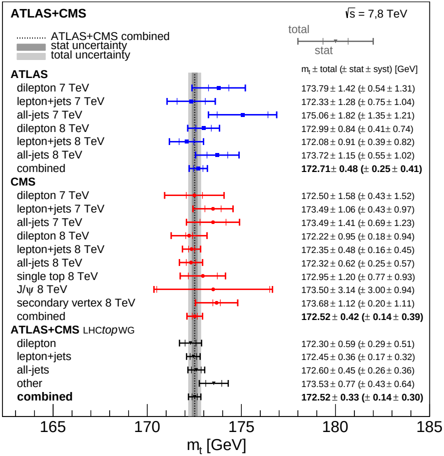
Source	Unc. on m_t [GeV]	Stat. precision [GeV]
Statistical and datasets		
Data statistics	0.39	
Signal and background model statistics	0.17	
Luminosity	< 0.01	± 0.01
Pile-up	0.07	± 0.03
Modelling of signal processes		
Monte Carlo event generator	0.04	± 0.06
b, c-hadron production fractions	0.11	± 0.01
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	

- systematics ranking, grouped per source
- leading ones are due to the modeling of the top-quark pair production and modeling of the b-quark fragmentation and decay
- jet energy calibration uncertainty is sub-dominant
- nearly all of the main uncertainties are largely uncorrelated with those dominant in previous lepton+jets ATLAS measurements

Top mass ATLAS+CMS combination



See [Matteo's talk] for the details



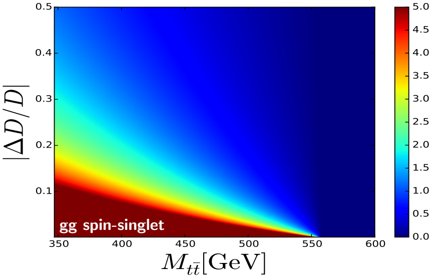
- using BLUE [1], calculate or estimate the correlation between measurements, BLUE then calculates the corresponding uncertainty on the physics parameter
- ATLAS inputs 6 measurements, CMS the same channels plus single top, J/ψ and secondary vertex at 8TeV
- to see compatibility run "simultaneous" BLUE with two m_{top} parameters, m_{top}^{ATLAS} and m_{top}^{CMS}, excellent agreement, see above
- **resulting precision is below 2 per mil**

[1] Nucl. Inst. and Meth. A 270 (1988) 110

Result: $m_{top} = 172.52 \pm 0.14(\text{stat}) \pm 0.30(\text{syst})$ GeV Phys. Rev. Lett. 132 (2024) 261902

Quantum entanglement at ATLAS

- Eur. Phys. J. Plus (2021) 136 → first analysis of top quark pair production from the quantum information point of view, gg→$t\bar{t}$ spin singlet state at threshold (80% of produced pairs)
- t lifetime shorter than hadronization and spin decorrelation time, spin info preserved in t→Wb, for W→ $\ell\nu$ spin info carried by ℓ

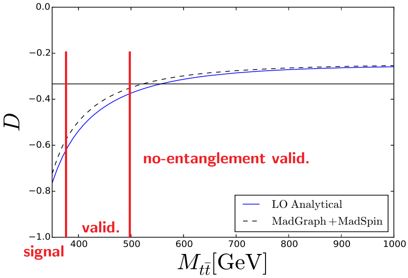


- $\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_1\mathrm{d}\Omega_2} = \frac{1}{4\pi^2}(1 + \alpha_2 \mathbf{B}_1 \cdot \hat{\ell}_1 + \alpha_2 \mathbf{B}_2 \cdot \hat{\ell}_2 + \alpha_1\alpha_2 \hat{\ell}_1 \mathbb{C} \hat{\ell}_2)$
- $\mathbf{B} \simeq 0$ because most $t\bar{t}$ produced via QCD on LHC
- $\mathrm{Tr}[\mathbb{C}] < -1$ Peres-Horodecki criterion
- $\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$
- $D = \frac{\mathrm{Tr}\mathbb{C}}{3} \Rightarrow D < -\frac{1}{3}$

Quantum entanglement at ATLAS

- entanglement marker $D = -3 \cdot \langle \cos\varphi \rangle$, with φ angle between ℓ from $t\bar{t}$ in rest frame:
  - $t\bar{t}$ boosted to its rest frame
  - each $t \to \ell \nu b$ boosted into its rest frame
- measurement performed on stable particle level
- requires full event reconstruction

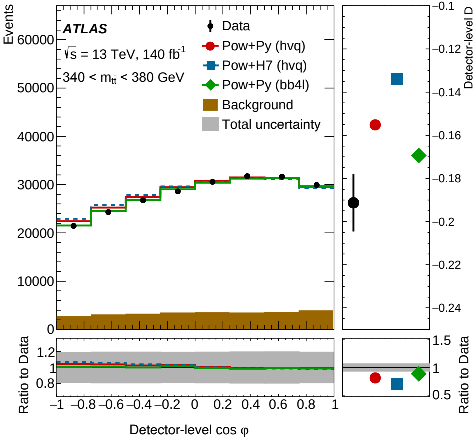
Eur. Phys. J. Plus (2021) 136



- partition events into three selections:
  - **340 $< M_{t\bar{t}} <$ 380: entanglement signal region**
  - 380 $< M_{t\bar{t}} <$ 500: validation region (dilution from mis-reconstruction)
  - 500 $< M_{t\bar{t}}$: **no-entanglement** validation region

Quantum entanglement at ATLAS

- dilepton $e\mu$ channel with ≥ 1 b-jet, 140 fb^{-1} at $\sqrt{s} = 13$ TeV
- very clean channel, 90 % purity
- ν reconstructed based on kinematic constraints on top and W mass
- D distorted by detector response
  - calibration curve approach, derive true D vs detector-level D
  - systematics with their own curves, quadratic envelope
  - event-by-event reweighting, cos φ distributions for various D
  - background cos φ estimate based on MC
    - tW, VV, $t\bar{t}W$
    - data-driven normalization of non-prompt leptons from samesign $e\mu$ events



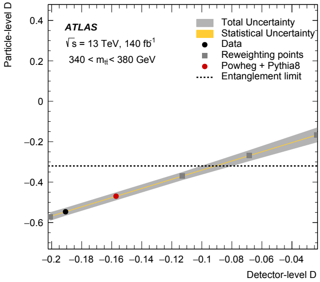
Quantum entanglement at ATLAS

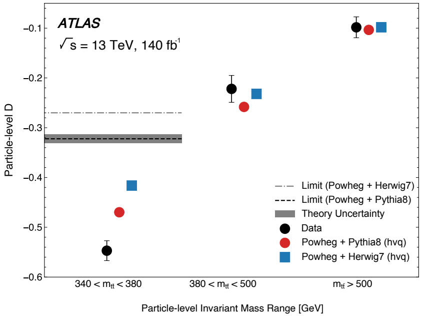
- Calculated detector-level D from data and corrected using calibration curve
- D_{obs} = **-0.547 ± 0.002 (stat.) ± 0.021 (syst.)**
- D_{exp} = **-0.470 ± 0.002 (stat.) ± 0.018 (syst.)**

  arXiV: 2311.07288, accepted by Nature
- **observation of quantum entanglement with $>5\sigma$ significance**

  CERN physics briefing

  CERN Courier article
- good agreement between measured and predicted D in validation regions
- measurement dominated by systematic uncertainties, mainly signal modeling
- paves the way for future measurements of quantum information at the LHC





Conclusions

ATLAS benefits from large top samples provided by LHC during Run-2 and study fundamental SM properties:

- **top mass measurements in different channels, with increasing precision**
- **combination with CMS results brings the most precise top mass result to date**
- **first observation of quantum entanglement in "bare" quarks, at highest energy so far**

Backup

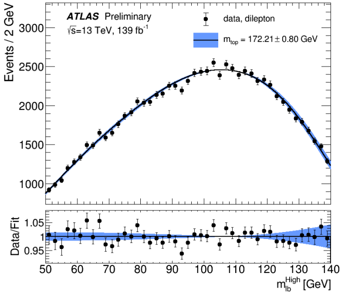
Top mass from dilepton channel

recoil effects in top-quark decays

- PYTHIA 8 used in this analysis recoils subsequent gluons against b-quark by default
- too small out-of-cone radiation, affects b-jets shape, too narrow reconstructed top-mass distribution
- recent setup allows the top quark to be the recoiler for the gluon radiation
- recoil-to-top likely overestimates the effect, no dedicated tune has been performed yet
- the full difference between the mass values extracted from pseudo-data using these two settings is used as an additional uncertainty

Top mass from dilepton channel

parametrisation (two Gauss and cosine) of template distributions of $m_{\ell b}^{High}$ with linear dependence of parameters on m_{top}, with very good description (χ^2/ndf $= 1.01$ and $P(\chi, \mathrm{ndf}) = 0.44$)

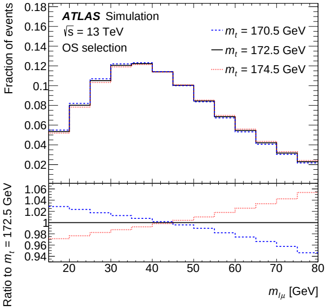


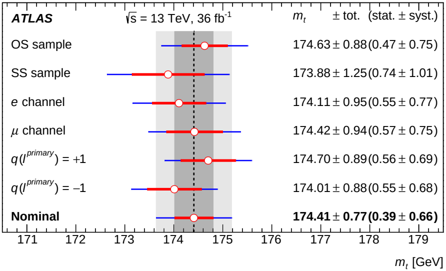
Data	86811
$t\bar{t}$ signal	94000 ± 5800
Single-top-quark signal	1167 ± 75
Z+jets	131 ± 52
Diboson	4.7 ± 2.4
$t\bar{t}+V$, tWZ, tZq	301 ± 46
$t\bar{t}+H$	97.0 ± 9.8
NP/fake leptons	110 ± 110
Signal+background	95800 ± 5800
Expected background fraction	0.006 ± 0.001
Data/(Signal + background)	0.906 ± 0.058

Top mass from dilepton channel

	m_{top} [GeV]
Result	172.21
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.40 ± 0.06
Parton shower and hadronisation	0.05 ± 0.05
Initial- and final-state QCD radiation	0.17 ± 0.02
Underlying event	0.02 ± 0.10
Colour reconnection	0.27 ± 0.07
Parton distribution function	0.03 ± 0.00
Single top modelling	0.01 ± 0.01
Background normalisation	0.03 ± 0.02
Jet energy scale	0.37 ± 0.02
b-jet energy scale	0.12 ± 0.02
Jet energy resolution	0.13 ± 0.02
Jet vertex tagging	0.01 ± 0.01
b-tagging	0.04 ± 0.01
Leptons	0.11 ± 0.02
Pile-up	0.06 ± 0.01
Recoil effect	0.39 ± 0.09
Total systematic uncertainty (without recoil)	0.67 ± 0.05
Total systematic uncertainty (with recoil)	0.77 ± 0.06
Total uncertainty (without recoil)	0.70 ± 0.05
Total uncertainty (with recoil)	0.80 ± 0.06

Top mass from soft muon tag





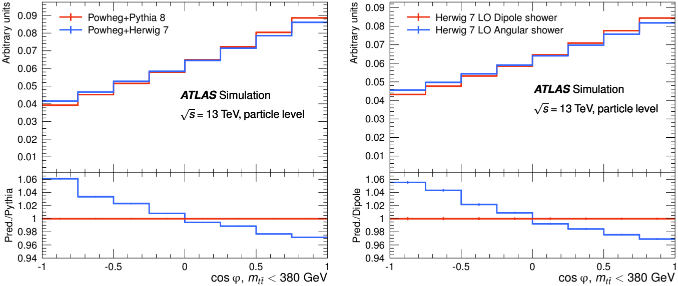
Process	Yield (OS)	Yield (SS)
$t\bar{t}$ (SMT from b- or c-hadron)	55 700 ± 3400	34 800 ± 2300
$t\bar{t}$ (SMT from $W \to \mu\nu$)	2190 ± 310	4.9 ± 3.6
$t\bar{t}$ (SMT fake)	1490 ± 210	1240 ± 170
Single top t-channel	770 ± 70	490 ± 40
Single top s-channel	63 ± 6	49 ± 4
Single top Wt channel	1840 ± 140	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

Top mass ATLAS+CMS combination

Uncertainty category	ρ	Scan range	$\Delta m_t/2$ [MeV]	$\Delta\sigma_{m_t}/2$ [MeV]
JES 1	0	—	—	—
JES 2	0	[−0.25, +0.25]	8	7
JES 3	0.5	[+0.25, +0.75]	1	<1
b-JES	0.85	[+0.5, +1]	26	5
g-JES	0.85	[+0.5, +1]	2	<1
l-JES	0	[−0.25, +0.25]	1	<1
CMS JES 1	—	—	—	—
JER	0	[−0.25, +0.25]	5	1
Leptons	0	[−0.25, +0.25]	2	2
b tagging	0.5	[+0.25, +0.75]	1	1
p_T^{miss}	0	[−0.25, +0.25]	<1	<1
Pileup	0.85	[+0.5, +1]	2	<1
Trigger	0	[−0.25, +0.25]	<1	<1
ME generator	0.5	[+0.25, +0.75]	<1	4
QCD radiation	0.5	[+0.25, +0.75]	7	1
Hadronization	0.5	[+0.25, +0.75]	1	<1
CMS b hadron $\mathcal{B}$	—	—	—	—
Color reconnection	0.5	[+0.25, +0.75]	3	1
Underlying event	0.5	[+0.25, +0.75]	1	<1
PDF	0.85	[+0.5, +1]	1	<1
CMS top quark p_T	—	—	—	—
Background (data)	0	[−0.25, +0.25]	8	2
Background (MC)	0.85	[+0.5, +1]	2	<1
Method	0	—	—	—
Other	0	—	—	—

Uncertainty category	Uncertainty impact [GeV]		
	LHC	ATLAS	CMS
b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
JES 1	0.08	0.18	0.06
JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS b hadron $\mathcal{B}$	0.07	—	0.12
QCD radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
CMS top quark p_T	0.05	—	0.07
Background (data)	0.05	0.04	0.06
Color reconnection	0.04	0.08	0.03
Underlying event	0.04	0.03	0.05
g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
JES 3	0.02	0.07	0.01
Hadronization	0.02	0.01	0.01
p_T^{miss}	0.02	0.04	0.01
PDF	0.02	0.06	<0.01
Trigger	0.01	0.01	0.01
Total systematic	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42

Quantum entanglement at ATLAS



Source of uncertainty	$\Delta D_{\text{observed}}(D = -0.547)$	ΔD [%]	$\Delta D_{\text{expected}}(D = -0.470)$	ΔD [%]
Signal modeling	0.017	3.2	0.015	3.2
Electrons	0.002	0.4	0.002	0.4
Muons	0.001	0.1	0.001	0.1
Jets	0.004	0.7	0.004	0.8
b-tagging	0.002	0.4	0.002	0.4
Pile-up	< 0.001	< 0.1	< 0.001	< 0.1
$E_{\text{T}}^{\text{miss}}$	0.002	0.3	0.002	0.4
Backgrounds	0.010	1.8	0.009	1.8
Total statistical uncertainty	0.002	0.3	0.002	0.4
Total systematic uncertainty	0.021	3.8	0.018	3.9
Total uncertainty	0.021	3.8	0.018	3.9

Systematic uncertainty source	Relative size (for SM D value)
Top-quark decay	1.6%
Parton distribution function	1.2%
Recoil scheme	1.1%
Final-state radiation	1.1%
Scale uncertainties	1.1%
NNLO reweighting	1.1%
pThard setting	0.8%
Top-quark mass	0.7%
Initial-state radiation	0.2%
Parton shower and hadronization	0.2%
h_{damp} setting	0.1%