Recent highlights of top-quark cross section and properties measurements with the ATLAS detector at the LHC

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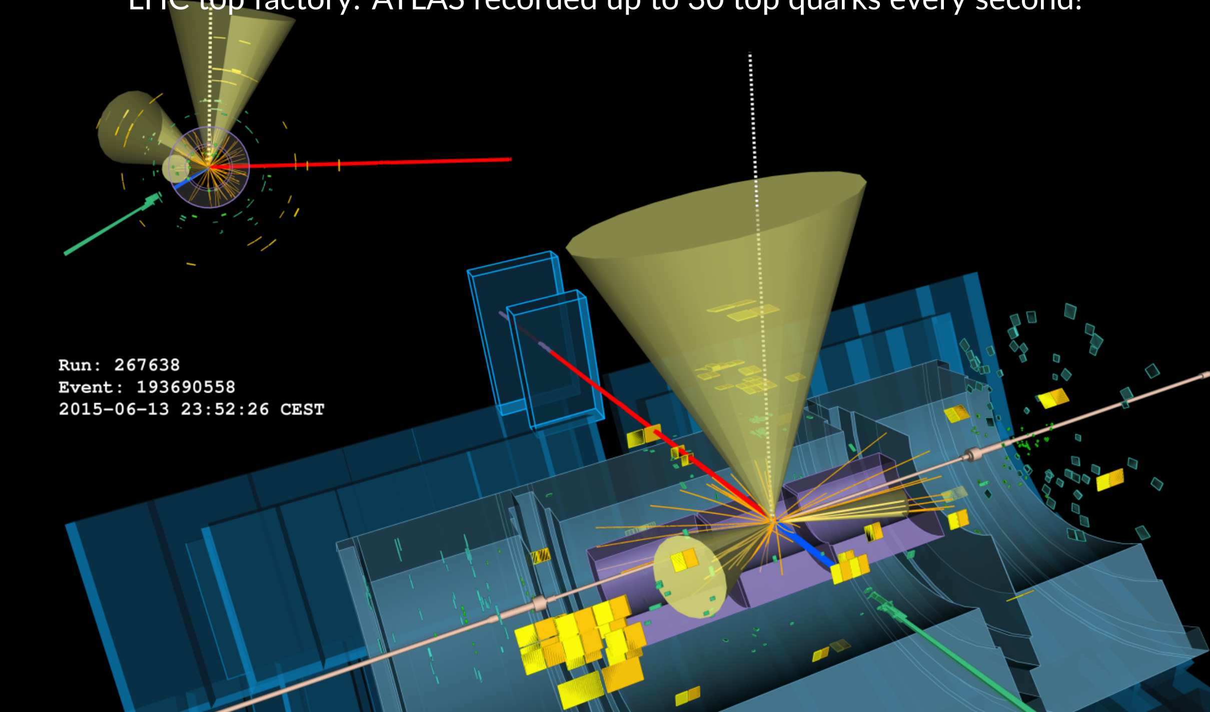
on behalf of the ATLAS collaboration

Lake Louise Winter Institute · Lake Louise, Canada · 20 February 2024

Link to this talk

LHC top factory: ATLAS recorded up to 30 top quarks every second!



Why the top quark fascinates us

From Higgs discovery to Higgs precision measurements: the top quark holds the key thanks to large mass $\rightarrow$ strong coupling to Higgs: $y_{\mathrm{t}} = \sqrt{2}\, m_{\mathrm{t}}/v \approx 1$

Pseudo-bare quark:
short lifetime ($\sim 10^{-25}$ s) $\ll$ hadronisation shrouds quantum numbers ($\sim 10^{-24}$ s)
$\ll$ spin decorrelation ($\sim 10^{-21}$ s)

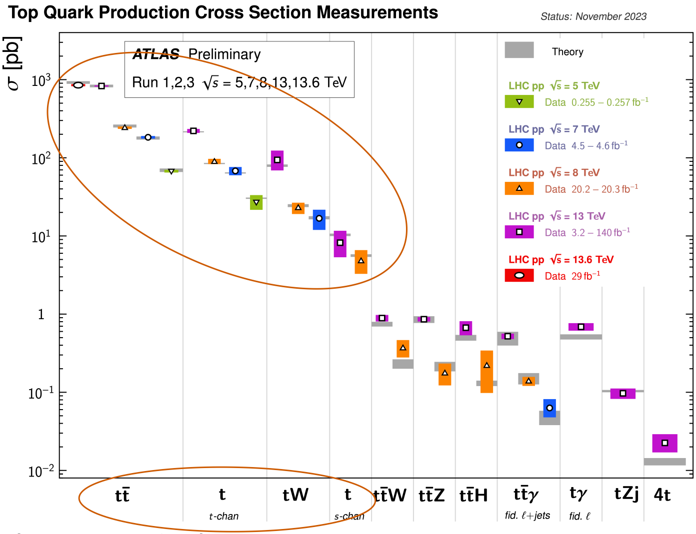
Dominant production modes at LHC: $\mathrm{t\bar{t}}$, then electroweak single top

$\mathrm{t\bar{t}}$ as background to countless searches and measurements

- Need good modelling
- Also differential & in extreme phase space

Most results based on 140 fb^{-1} of 13 TeV collisions

Top production cross sections



Processes span 5 orders of magnitude

Large top mass $\rightarrow$ very $\sqrt{s}$-dependent

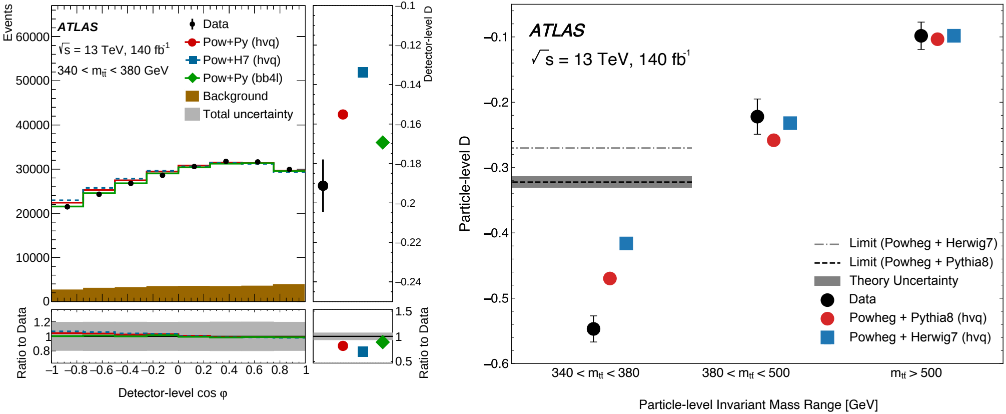
I focus on $t\bar{t}$ and single top (in precision phase) — next talk by Sahal on $t(\bar{t}) + X$

ATL-PHYS-PUB-2023-038

$t\bar{t}$ quantum entanglement

New lab for observing quantum effects (with relativistic effects) Eur. Phys. J. Plus (2021) 136:907; Quantum 6, 820 (2022)

Pseudo-bare quark! $\rightarrow$ entanglement expected in $t\bar{t}$ near threshold
Angle between charged leptons from top/antitop decay $\rightarrow$ entanglement marker D



$D = -0.547 \pm 0.002$ (stat) ± 0.021 (syst) for $340 < m_{t\bar{t}} < 380$ GeV, $>5\sigma$ away from no-entang. scenario
Observation: first in quark pair & highest energy

2311.07288 $\rightarrow$ Nature, 13 TeV, 140 fb^{-1}

Ultimate precision: top mass combination with CMS

Key SM parameter: Higgs coupling, consistency fits

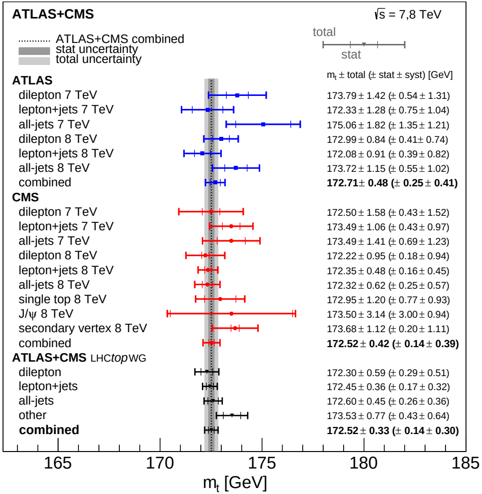
BLUE combination of 15 Run-1 measurements

- Datasets (assumed) statistically uncorrelated
- Challenge: how to correlate systematics between experiments?
- Classify sources as strongly/partially/un·correlated ($\rho = 0.85/0.5/0$)

$m_t = 172.52 \pm 0.14$ (stat) ± 0.30 (syst) GeV
Total uncertainty ± 0.33 GeV $\to$ 0.2%!

Most precise m_t ever reported by experiments;
$\sim$same precision as PDG world average! (for now)

More details in AJ's talk!

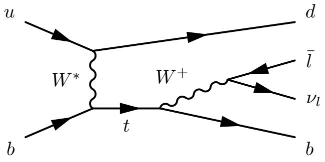


2402.08713, 7 TeV, $\leq$5 fb^{-1} and 8 TeV, $\leq$20 fb^{-1}, physics briefing

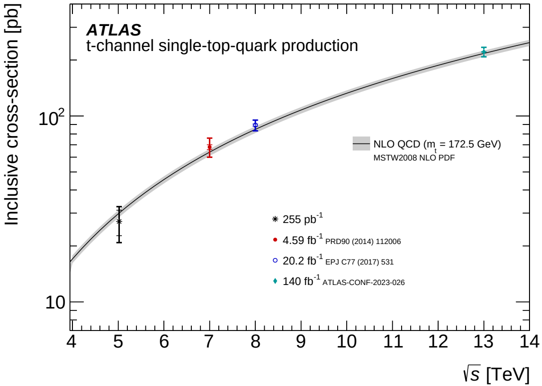
Single-top t-channel

Higher-order QCD, CKM matrix ($|V_{tb}|$, unitarity), PDFs

5 vs. 13 TeV: different backgrounds & instrumental uncertainties
Total cross sections agree well with (N)NLO QCD



Lepton, E_T^{miss}, b-jet, light jet



13 TeV:

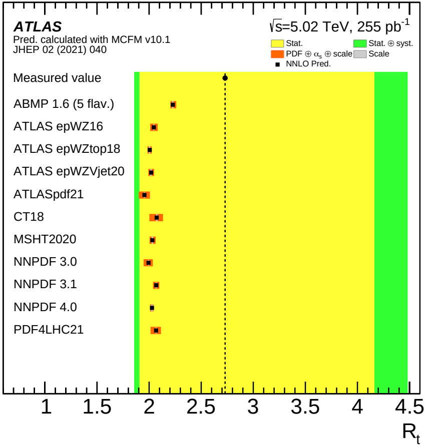
- SMEFT coefficient $C_{qQ}^{(1,3)} \in [-0.25, 0.12]$ (95% CL), competitive with global fits
  $O_{qQ}^{(1,3)} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{Q}\gamma^\mu \tau^I Q)$
- $f_{LV} \cdot |V_{tb}| = 1.016 \pm 0.031$ is 30% more precise than previous best JHEP 05 (2019) 088
- Assuming SM, $|V_{tb}| > 0.95$ (95% CL)

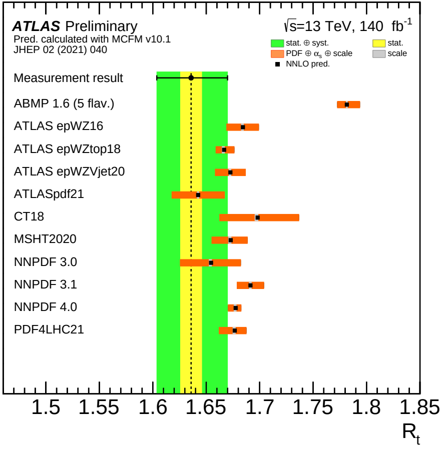
2310.01518 → PLB, 5.02 TeV, 255 pb^{-1}; CONF-2023-026, 13 TeV, 140 fb^{-1}

Single-top *t*-channel

Higher-order QCD, CKM matrix ($|V_{tb}|$, unitarity), PDFs

Very sensitive to PDF: R_t = top/antitop
Comparison to NNLO QCD:





Constraining power in future PDF fits!

2310.01518 → PLB, 5.02 TeV, 255 pb^{-1}; CONF-2023-026, 13 TeV, 140 fb^{-1}

Ultimate precision: total $t\bar{t}$ cross section @ 13 TeV

Important SM "integration" test: sensitivity to BSM and QCD predictions (also $t\bar{t}$ as background!)

Dilepton channel:

$$\sigma_{t\bar{t}} = 829 \pm 1\ \text{(stat)} \pm 13\ \text{(syst)} \pm 8\ \text{(lumi)} \pm 2\ \text{(beam) pb}$$

Total uncertainty $\pm$15 pb $\rightarrow$ 1.8%! (fiducial measurement even at 1.6%!)

Benefits from:

- ATLAS' record 0.83% luminosity uncertainty Eur. Phys. J. C 83 (2023) 982 (down from 1.7%) $\rightarrow$ massive impact!
- More and more precise understanding & calibration of detector (lepton and b-tagging efficiencies, jet energy scale, ...)

Agrees well with NNLO+NNLL calculation:

$$\sigma_{t\bar{t},\ \text{pred}} = 832^{+20}_{-29}(\text{scale})^{+23}_{-23}(m_t)^{+35}_{-35}(\text{PDF} + \alpha_s)\ \text{pb}$$

LHC & ATLAS reach precisions beyond what was expected at a hadron collider!

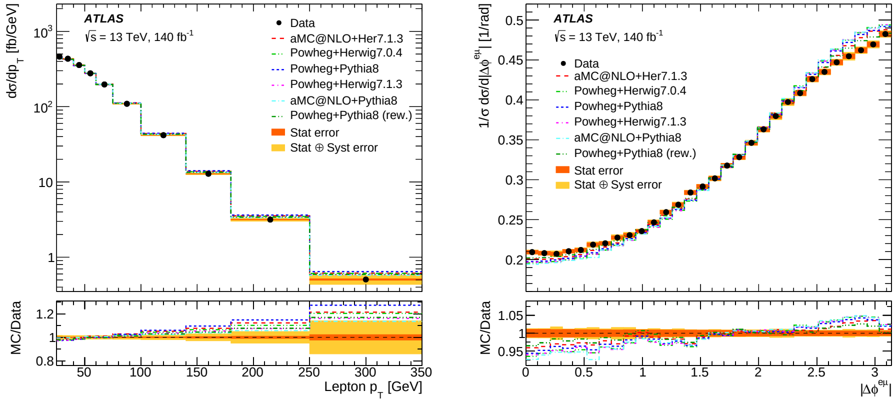
JHEP 07 (2023) 141, 13 TeV, 140 fb^{-1}, physics briefing

Going differential: $t\bar{t}$ distributions

Understand and refine theoretical modelling (signal, background)

Dilepton channel, fiducial, particle-level

Also double-differential (very important for understanding modelling, but hard to parse → HepData!)



Discrepancies: all generators predict harder lepton p_T spectrum, larger lepton–lepton angle $\Delta\phi^{e\mu}$

No generator predicts all distributions within their uncertainties

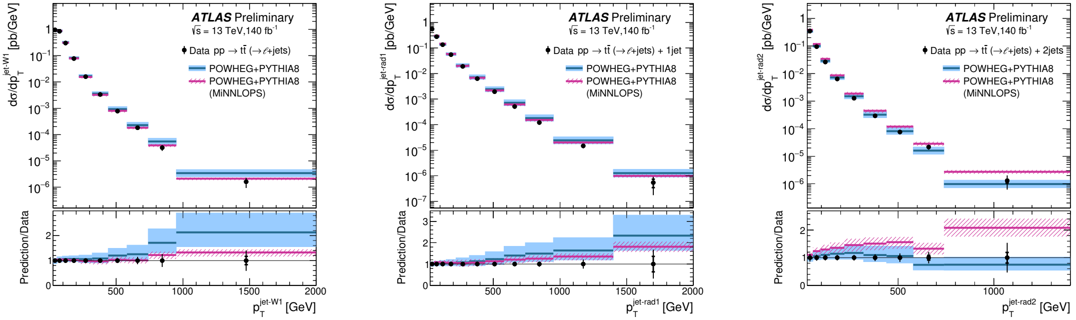
JHEP 07 (2023) 141, 13 TeV, 140 fb^{-1}

Going differential: $t\bar{t}$ + jets distributions

Understand and refine theoretical modelling (signal, background)

Lepton + jets channel, fiducial, particle-level

Lots of novel distributions — now here are some good old jet p_T's:



$d\sigma/dp_T^{\text{jet-rad1}}$: six orders of magnitude, 20% precision above 1 TeV (!)
Requires excellent detector performance & calibration... and lots of data

First-ever ATLAS comparison to $\text{MiNNLO}_{\text{PS}}$ 1908.06987
NNLO vs. NLO: better description of Born-level and first extra jet, but overpredicts rate of second extra jets!

CONF-2023-068, 13 TeV, 140 fb^{-1}

Fast action: $t\bar{t}$ at 13.6 TeV

Tests scaling with $\sqrt{s}$, upgraded detector and reconstruction software

Dilepton channel

$\sigma_{t\bar{t}} = 850 \pm 3$ (stat) ± 18 (syst) ± 20 (lumi) pb

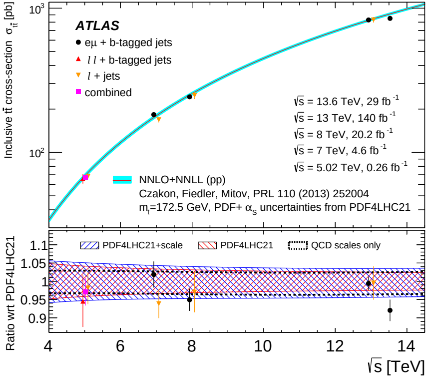
Predicted 12% larger than at 13 TeV, but observed 1.5σ below prediction

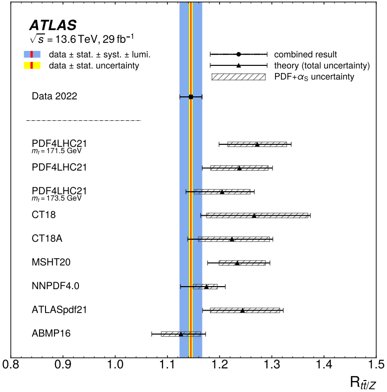
Cross-section ratio $t\bar{t}$ / Z sensitive to gluon-to-quark PDF ratio

Uncertainties cancel partially

$R_{t\bar{t}/Z} = 1.145 \pm 0.003$ (stat) ± 0.021 (syst) ± 0.002 (lumi)

$R_{t\bar{t}/Z}$ prediction is NNLO + NLO-EW





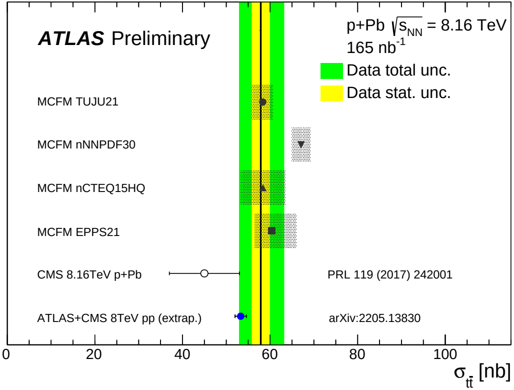
Phys. Lett. B 848 (2024) 138376, 13.6 TeV, 29 fb^{-1}

Heavy ions: observation of $t\bar{t}$ in p+Pb

Provides information on nPDFs (important e.g. for extracting quark-gluon plasma properties)

Already observed by CMS in lepton + jets channel Phys. Rev. Lett. 119 (2017) 242001
ATLAS adds dilepton channel and halves cross section uncertainty (CMS 18%, ATLAS 9%)

$\sigma_{t\bar{t}} = 57.9 \pm 2.0\text{ (stat) }^{+4.9}_{-4.5}\text{ (syst) nb}$ ($\mathcal{O}(200)\times$ larger than in 8 TeV pp; $A_{\text{Pb}} \sim 200$)



Good agreement with NNLO predictions (various nPDFs) and other measurements

CONF-2023-063, 8.16 TeV per nucleon, 165 nb^{-1}, physics briefing

Takeaways

Top quark is key for understanding SM & Higgs
and major background in countless searches

ATLAS is going broader and deeper

Precision:

- mass (0.2%)
- total cross section (1.8%)
- quantum entanglement observed

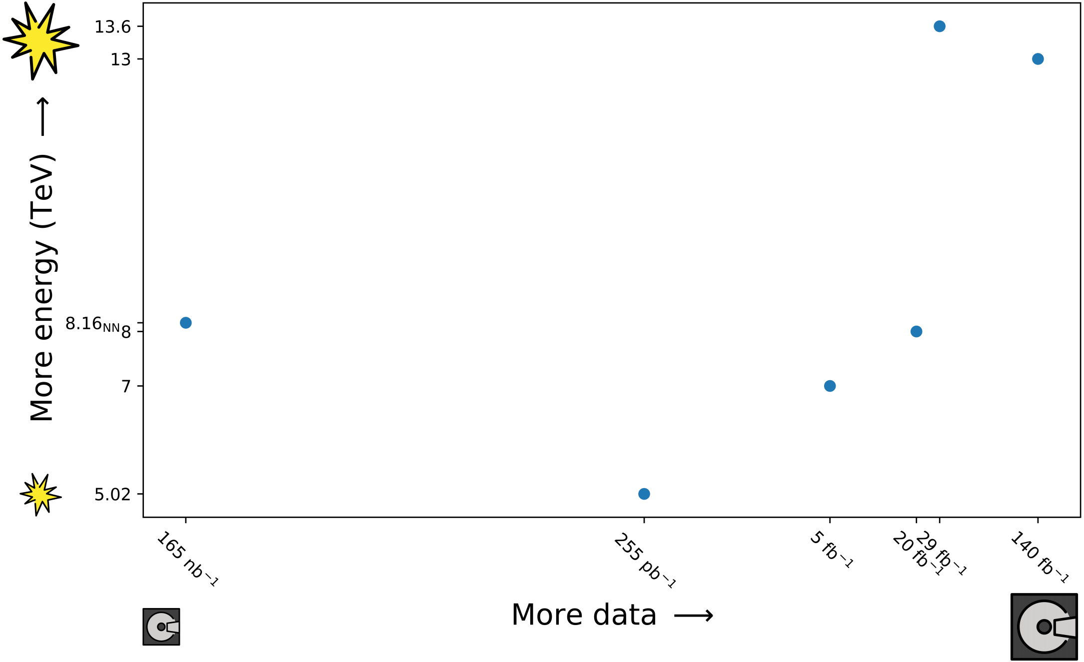
Frontiers probed:

- heavy ion collisions
- record $\sqrt{s}$
- TeV-scale jets
- boosted tops ($\rightarrow$ Jon's talk)

Many new & precise differential cross sections reveal discrepancies w.r.t. predictions

Backup

Datasets shown today

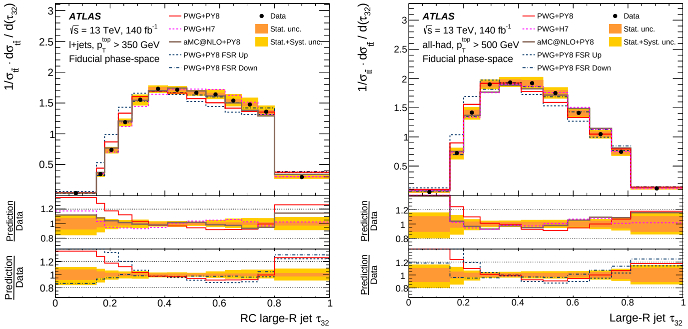


Looking inside: $t\bar{t}$ jet substructure (Jon's talk)

High-p_T ('boosted') top quarks: decay products collimated into a single large-R jet
Measure jet substructure in $R = 1.0$ top jets

QCD test, BSM sensitivity, understand substructure-based top taggers

Generalised angularities (p_T dispersion, Les Houches angularity); energy correlation functions; N-subjettiness — also vs. m_t and $p_{T,t}$
Some described well/poorly → very interesting info for QCD pheno & MC development!

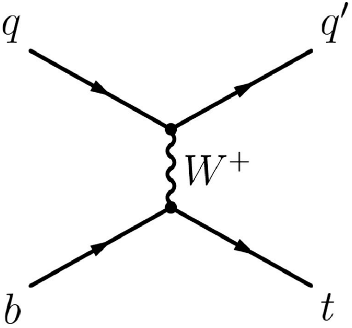


more 3-prong-like ⟷ more 2-prong-like   more 3-prong-like ⟷ more 2-prong-like

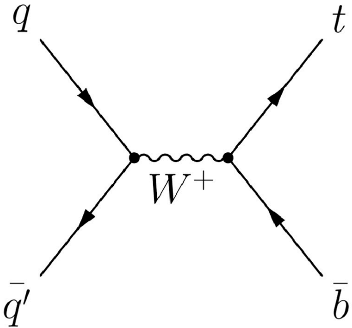
Nominal τ_{32} prediction too 3-prong-like

2312.03797 → Phys. Rev. D, 13 TeV, 140 fb^{-1}

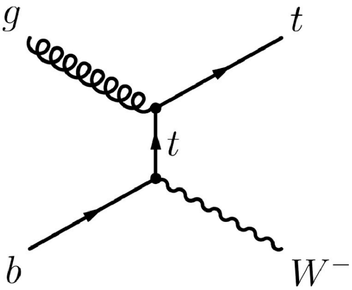
Single-top modes



“*t* channel”

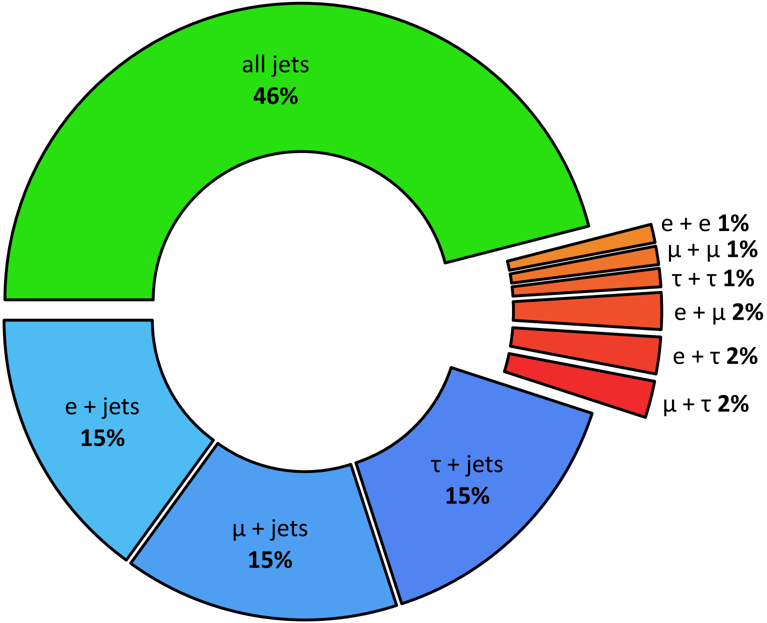


“*s* channel”

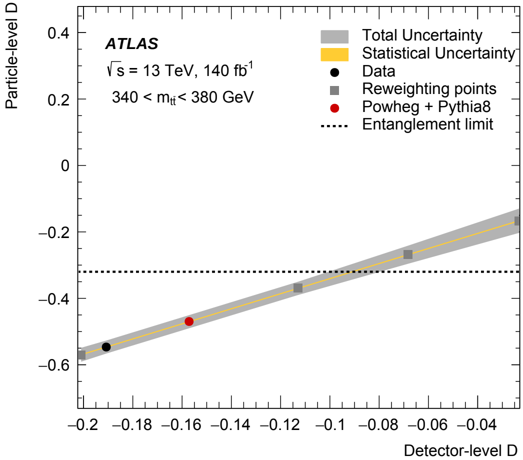


“tW”

$t\bar{t}$ final state fractions



Entanglement marker calibration



At parton-level:

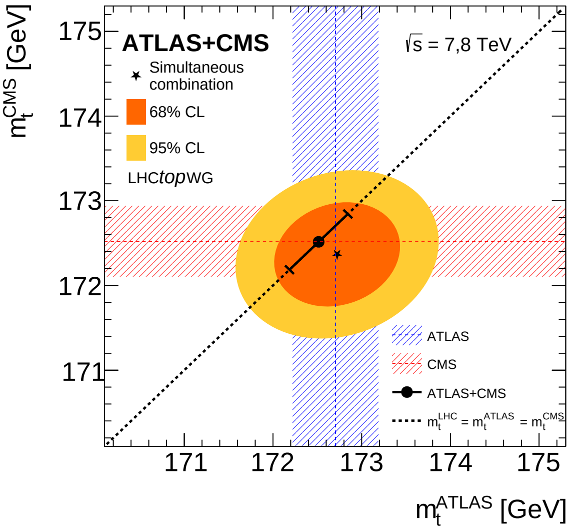
1. Fit $m_{t\bar{t}}$ dependence of D: $D_\Omega\left(m_{t\bar{t}}\right) = x_0 + x_1 \cdot m_{t\bar{t}}^{-1} + x_2 \cdot m_{t\bar{t}}^{-2} + x_3 \cdot m_{t\bar{t}}^{-3}$
2. Reweight each event by $w = \frac{1 - D_\Omega(m_{t\bar{t}}) \cdot X \cdot \cos\varphi}{1 - D_\Omega(m_{t\bar{t}}) \cdot \cos\varphi}$ with X the desired reweighting scale
3. Interpolate linearly between reweighting points to get full calibration curve

Mass combination: systematics and correlations

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

Mass combination: consistency between ATLAS & CMS



"Simultaneous" = separate m_t parameter per experiment
Good agreement with having one m_t parameter $\rightarrow$ good!

$t\bar{t}$ cross section with dilepton events: systematics

Source of uncertainty	$\Delta\sigma^{\mathrm{fid}}_{t\bar{t}}/\sigma^{\mathrm{fid}}_{t\bar{t}}$ [%]	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%]
Data statistics	0.15	0.15
MC statistics	0.04	0.04
Matrix element	0.12	0.16
h_{damp} variation	0.01	0.01
Parton shower	0.08	0.22
$t\bar{t}$ + heavy flavour	0.34	0.34
Top p_{T} reweighting	0.19	0.58
Parton distribution functions	0.04	0.43
Initial-state radiation	0.11	0.37
Final-state radiation	0.29	0.35
Electron energy scale	0.10	0.10
Electron efficiency	0.37	0.37
Electron isolation (in situ)	0.51	0.51
Muon momentum scale	0.13	0.13
Muon reconstruction efficiency	0.35	0.35
Muon isolation (in situ)	0.33	0.33
Lepton trigger efficiency	0.05	0.05
Vertex association efficiency	0.03	0.03
Jet energy scale & resolution	0.10	0.10
b-tagging efficiency	0.07	0.07
$t\bar{t}/Wt$ interference	0.37	0.37
Wt cross-section	0.52	0.52
Diboson background	0.34	0.34
$t\bar{t}V$ and $t\bar{t}H$	0.03	0.03
$Z+$jets background	0.05	0.05
Misidentified leptons	0.32	0.32
Beam energy	0.23	0.23
Luminosity	0.93	0.93
Total uncertainty	1.6	1.8