Top quark mass and coupling measurements at the ATLAS and CMS experiments

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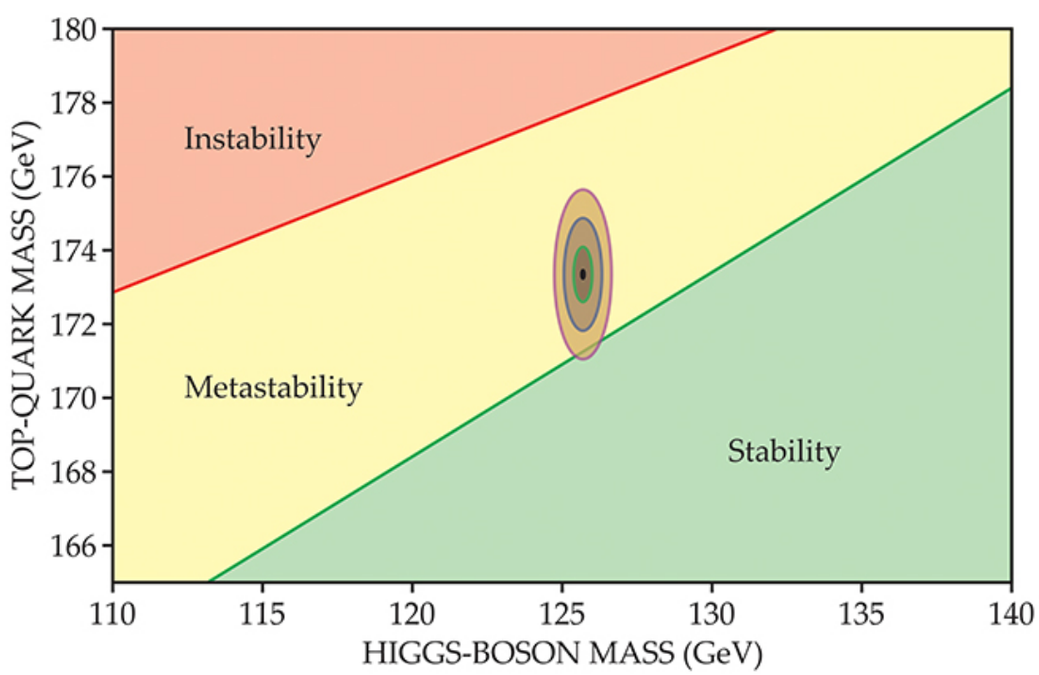
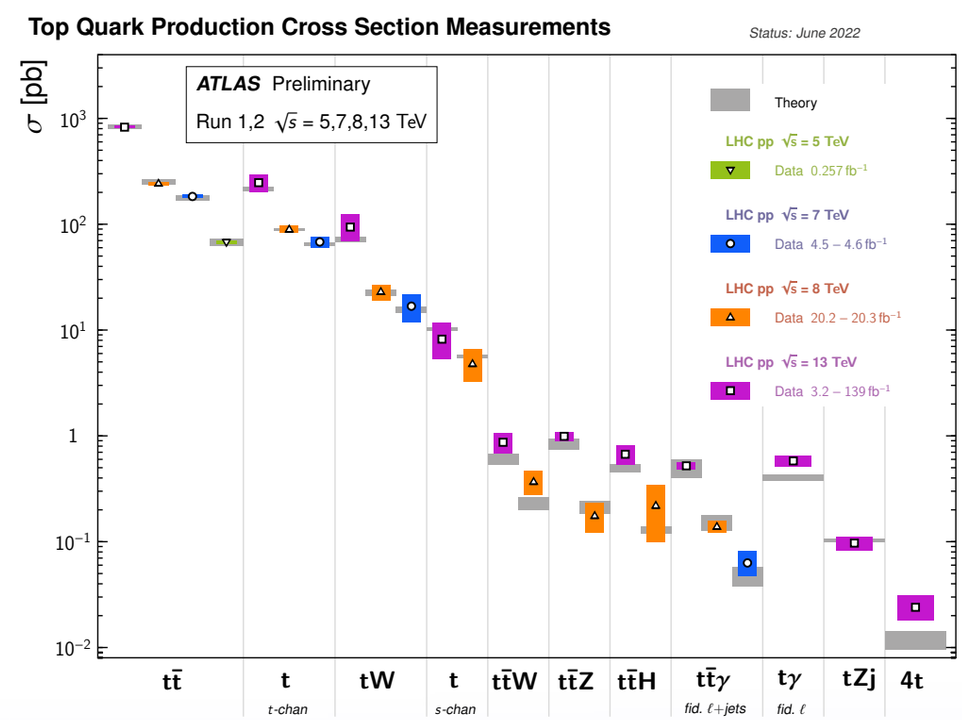
Introduction

- The properties of the top quark are of major importance to check the predictions of the SM and to allow sensitive tests for physics beyond the SM (BSM).
  - The mass of the top quark (m_{top}) can be measured with high precision by LHC experiments (ATLAS & CMS) ⇒ particularly interesting, as it can affect e.g. the vacuum stability of the universe (together with the Higgs mass).
  - Also the couplings of the top quark (e.g. to vector bosons or the Higgs) can be assessed by the measurement of "rare" SM processes, such as $t+X$ or $t\bar{t}+X$.
- Will present some of the most recent and relevant results released by ATLAS and CMS in the last year ⇒ full list can be found here (ATLAS) and here (CMS).



JHEP 09 (2014) 182



ATL-PHYS-PUB-2022-031

ATLAS

Top quark mass from template fit

Top quark mass from template fit:

- Different ways to extract the top quark mass from ATLAS/CMS data.
- Standard (most common) approach is to use "MC template fits".
  - Likelihood- or MVA-based reconstruction of top quark (or full event) kinematics.
  - Using one- or more-dimensional template functions which are sensitive to top quark mass
  - Fit to data (with m_{top} as free parameter) to extract best result.
- Several results released by ATLAS and CMS using $\sqrt{s}$ = 7, 8 and 13 TeV data in different final states ⇒ published also combination of 7+8 TeV results:
  - ATLAS ⇒ ***EPJC 79 (2019) 290***
  - CMS ⇒ ***Phys. Rev. D 93 (2016) 072004***

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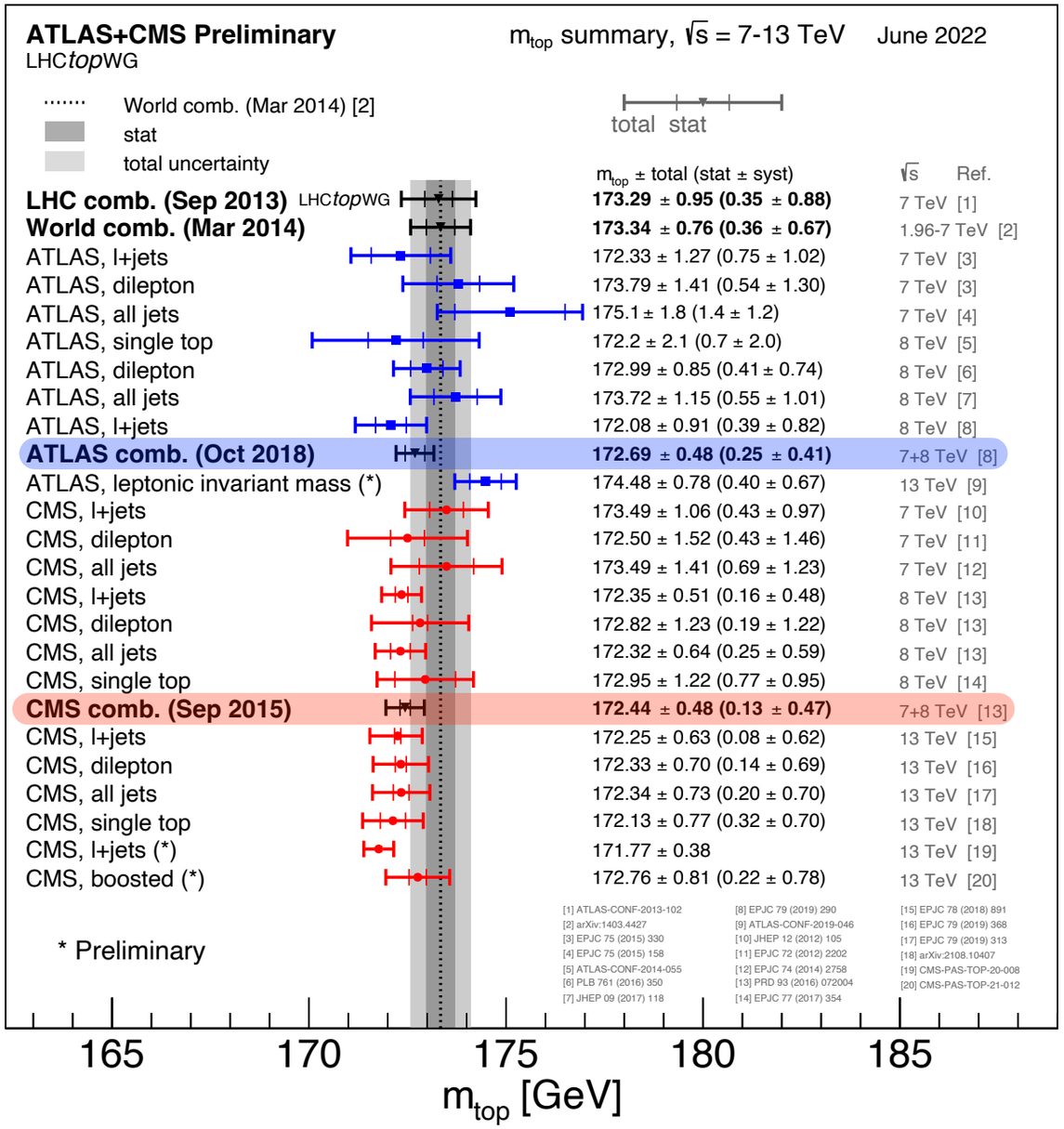
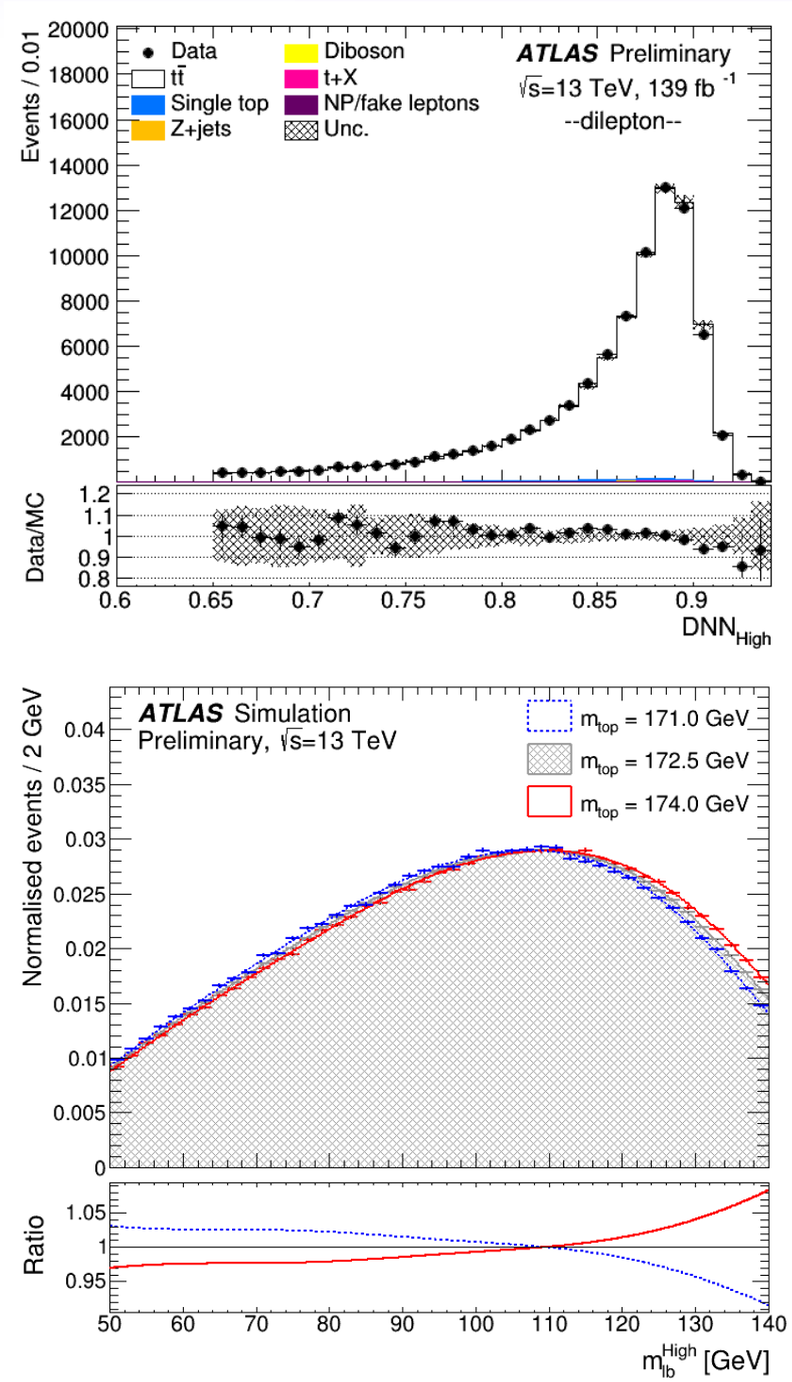


ATLAS/CMS results for direct top quark mass measurements (June 2022)

Top mass from template fit: Measurement

- Latest ATLAS measurement: top quark mass from template fit in di-lepton final states, using the full Run 2 data (139 fb^{-1}) ⇒ ***ATLAS-CONF-2022-058***.
  - Selecting two opposite-sign (OS) leptons (electrons/muons) with Z-veto and two b-tagged jets ⇒ signal region enriched with $t\bar{t}$ events.
  - Event reconstruction: assign leptons to their corresponding b-jets (top decay products) via a deep neural network (DNN) ⇒ select permutation with highest DNN score.
  - Variable used for fit ⇒ invariant mass of lepton/b-jet pair with largest p_T: m_{lb}^{High}
  - Optimising phase space (DNN > 0.65, p_T^{lb} > 160 GeV, max. p_T^{b}) to reduce uncertainty.
  - Using MC templates with different assumptions on m_{top} ⇒ unbinned likelihood fit to data on m_{lb}^{High} distribution (50 GeV < m_{lb}^{High} < 140 GeV) to extract best m_{top}.



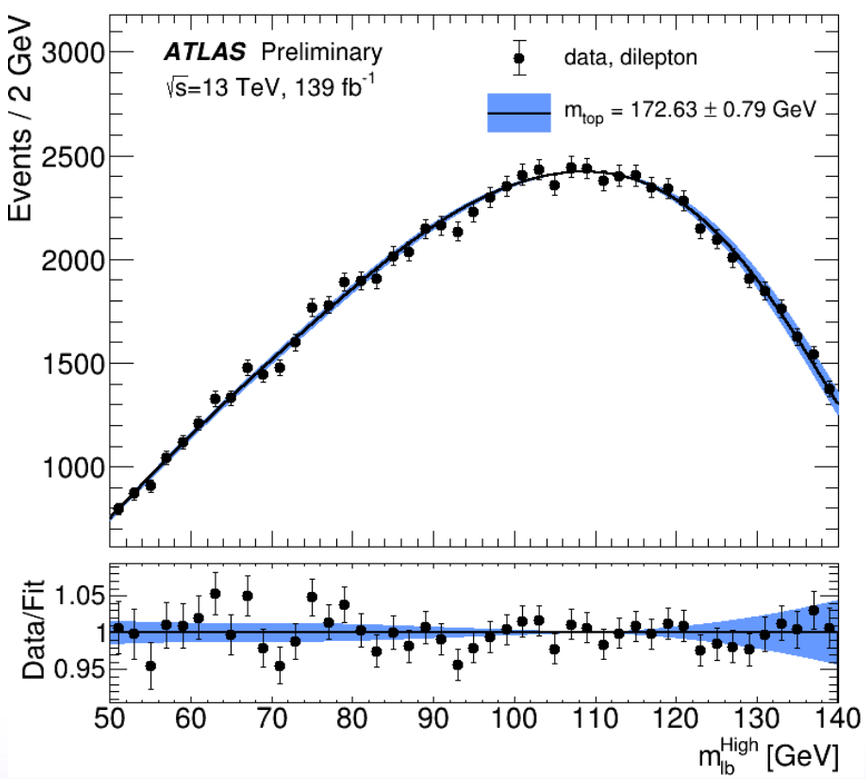
DNN after final selection (top), MC templates for m_{lb}^{High} for different m_{top} values (bottom)

Top mass from template fit: Results

- Best fit value of top quark mass:

$$m_{\text{top}}^{\text{dilep}} = 172.63 \pm 0.20\ (\text{stat.}) \pm 0.67\ (\text{syst.}) \pm 0.37\ (\text{recoil})\ \text{GeV}$$

  - Dominant systematic uncertainties: Jet energy scale (JES), MC modelling uncertainties of $t\bar{t}$ signal (e.g. matrix-element matching or colour-reconnection model).
  - Improved precision with respect to equivalent result at 8 TeV ⇒ ***Phys. Lett. B 761 (2016) 350***.
  - New extra uncertainty on m_{top} is considered to account for gluon-recoil scheme used in PYTHIA8 (against W boson or b-quark).



m_{lb}^{High} distribution in data with best fit

ATLAS-CONF-2022-058

	m_{top} [GeV]
Result	172.63
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.35 ± 0.07
Parton shower and hadronisation	0.08 ± 0.05
Initial- and final-state QCD radiation	0.20 ± 0.02
Underlying event	0.06 ± 0.10
Colour reconnection	0.29 ± 0.07
Parton distribution function	0.02 ± 0.00
Single top modelling	0.03 ± 0.01
Background normalisation	0.01 ± 0.02
Jet energy scale	0.38 ± 0.02
b-jet energy scale	0.14 ± 0.02
Jet energy resolution	0.05 ± 0.02
Jet vertex tagging	0.01 ± 0.01
b-tagging	0.04 ± 0.01
Leptons	0.12 ± 0.02
Pile-up	0.06 ± 0.01
Recoil effect	0.37 ± 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)	0.79 ± 0.06

Breakdown of systematic uncertainties

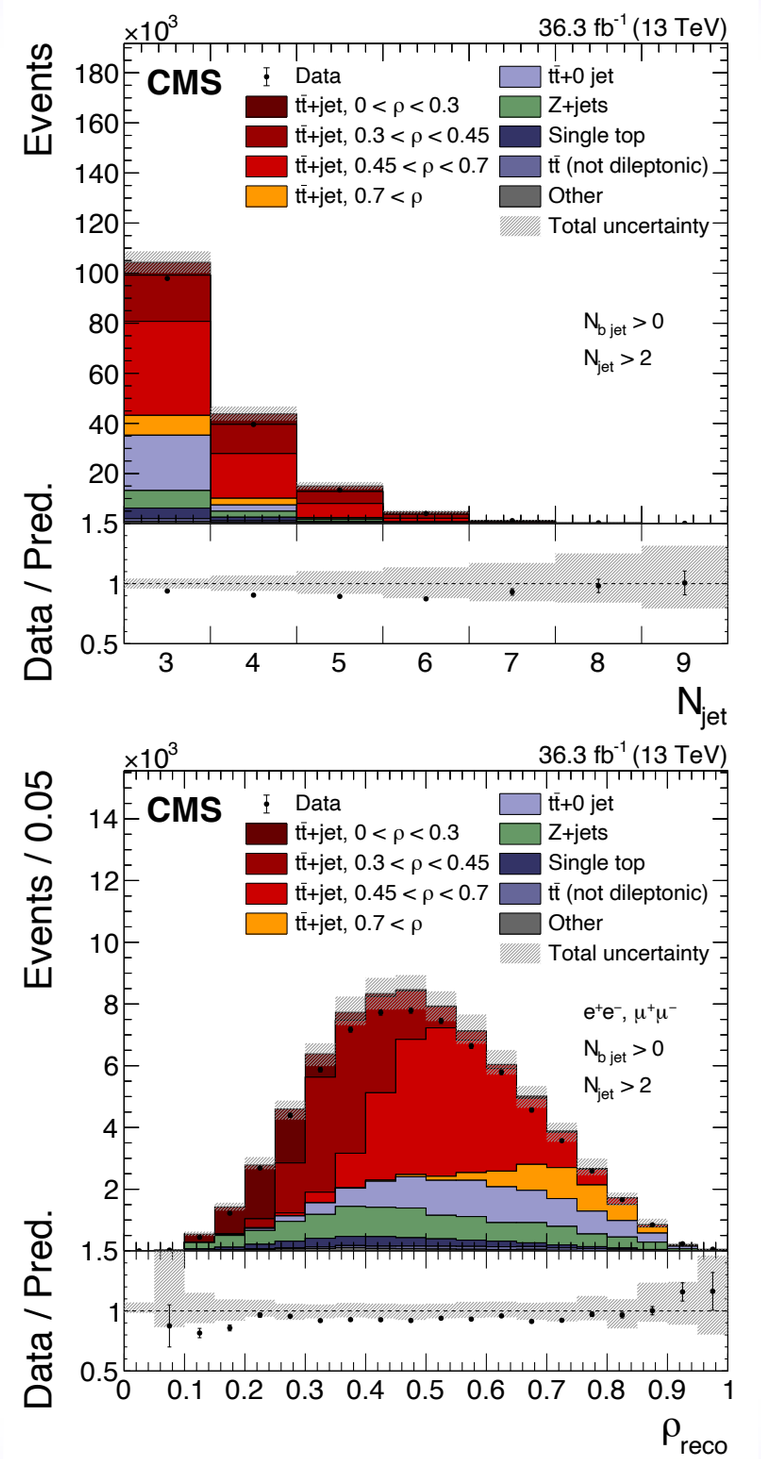
CMS

Top quark mass from $t\bar{t}$+jets cross section

Top quark mass from $t\bar{t}$+jets cross section:

- An alternative way to measure the top quark mass is to extract it from inclusive (or differential) cross-section measurements.
- Using differential measurement of di-leptonic $t\bar{t}$+jets cross section in 2015/16 data (36 fb^{-1}) ⇒ ***arXiv:2207.02270***.
  - Select events with two OS leptons and at least one jet (b-jet) ⇒ region enriched in $t\bar{t}$+jets.
  - Measurement binned in $\rho = 2 \times m_0/m_{t\bar{t}+\text{jets}}$ (m_0 = 170 GeV), which is sensitive to the pole mass of the top quark: $m_{\text{top}}^{\text{pole}}$ ⇒ ***EPJC 77 (2017) 794***.
  - The ρ variable is built by reconstructing the $t\bar{t}$ system and the kinematics of the single top quarks analytically and input their solutions (together with basic kinematic quantities) to a NN.
  - Use another NN-based event classification to separate targeted process ($t\bar{t}$+jets) from main backgrounds (Z+jets and $t\bar{t}$+0 jets).

arXiv:2207.02270



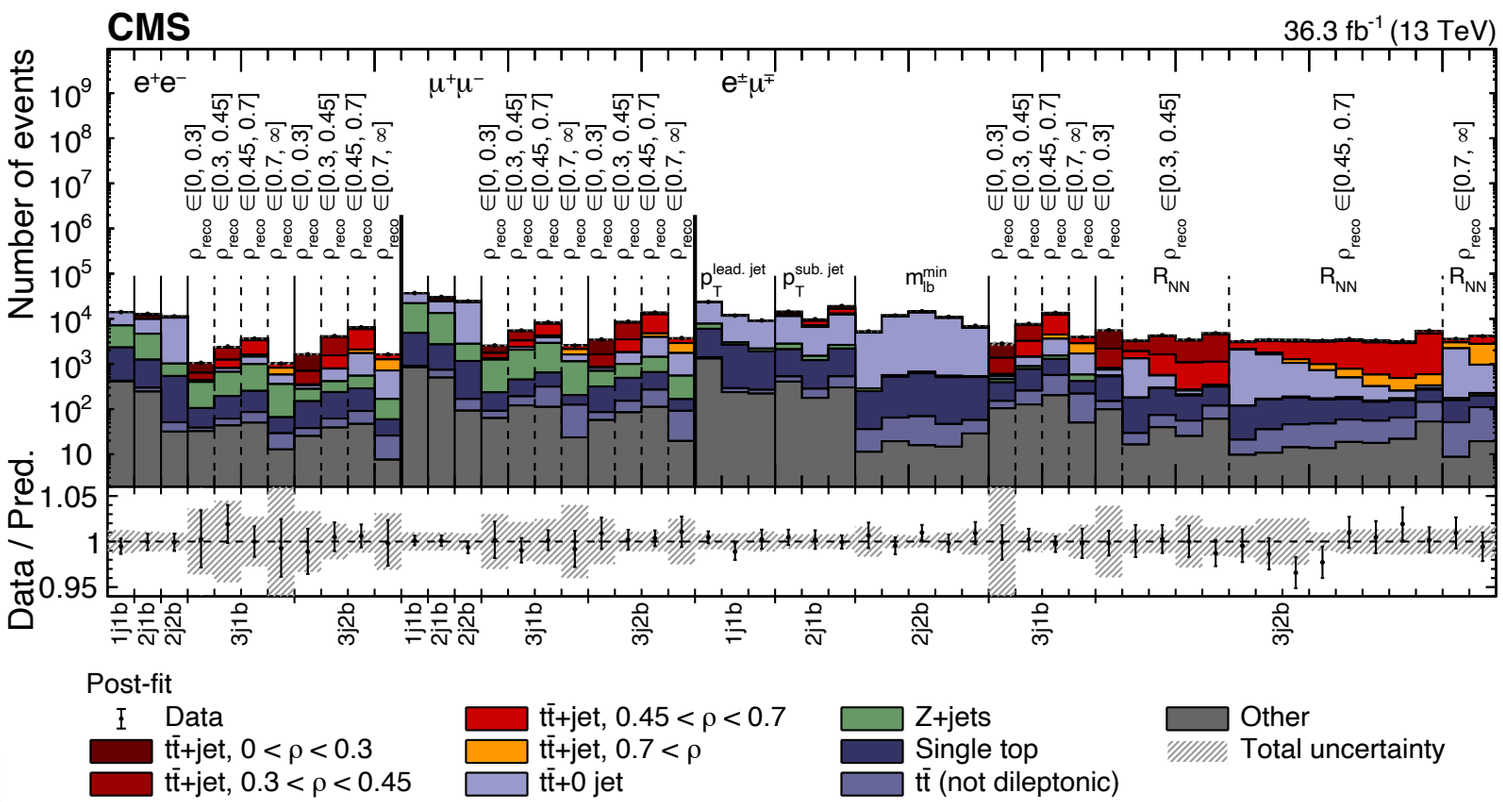
N_{jet} (top) and ρ (bottom) distributions

Top mass from diff. x-sec: Measurement

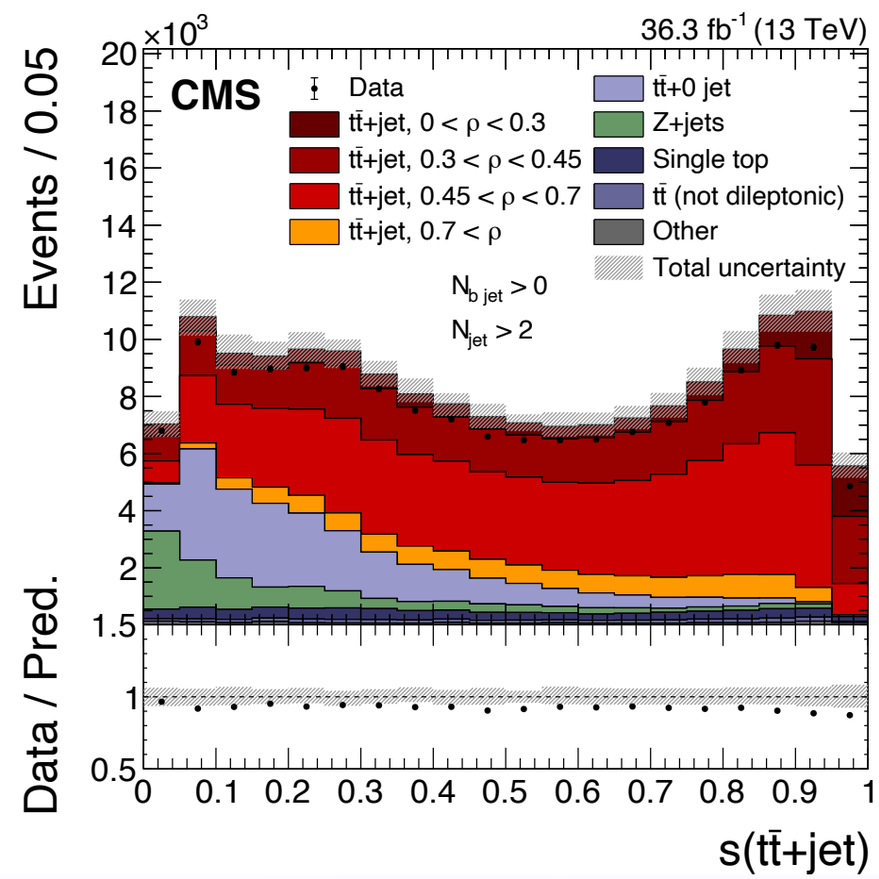
- Simultaneous profile-likelihood fit is performed on combined signal+background NN response: $R_{NN} = s(t\bar{t}\text{+jets}) / [s(Z\text{+jets}) + s(t\bar{t}\text{+0 jets})]$ in **four** different ρ bins.
  - Also $t\bar{t}$+jets depleted regions included in the fit (constraining uncertainties on main backgrounds).
- The ρ distributions are unfolded to parton level.
  - Absolute and normalised differential $t\bar{t}$+jets cross sections.

	Reconstructed ρ, $N_{jet} \geq 3$				No reconstructed ρ	
	$\rho < 0.3$	$0.3 < \rho < 0.45$	$0.45 < \rho < 0.7$	$\rho > 0.7$	$N_{jet} = 1$	$N_{jet} = 2$
$N_{b\,jet} = 1$	R_{NN}	R_{NN}	R_{NN}	R_{NN}	$p_T^{leading\ jet}$	$p_T^{subleading\ jet}$
$N_{b\,jet} \geq 2$	R_{NN}	R_{NN}	R_{NN}	R_{NN}	—	$m_{\ell b}^{min}$

arXiv:2207.02270



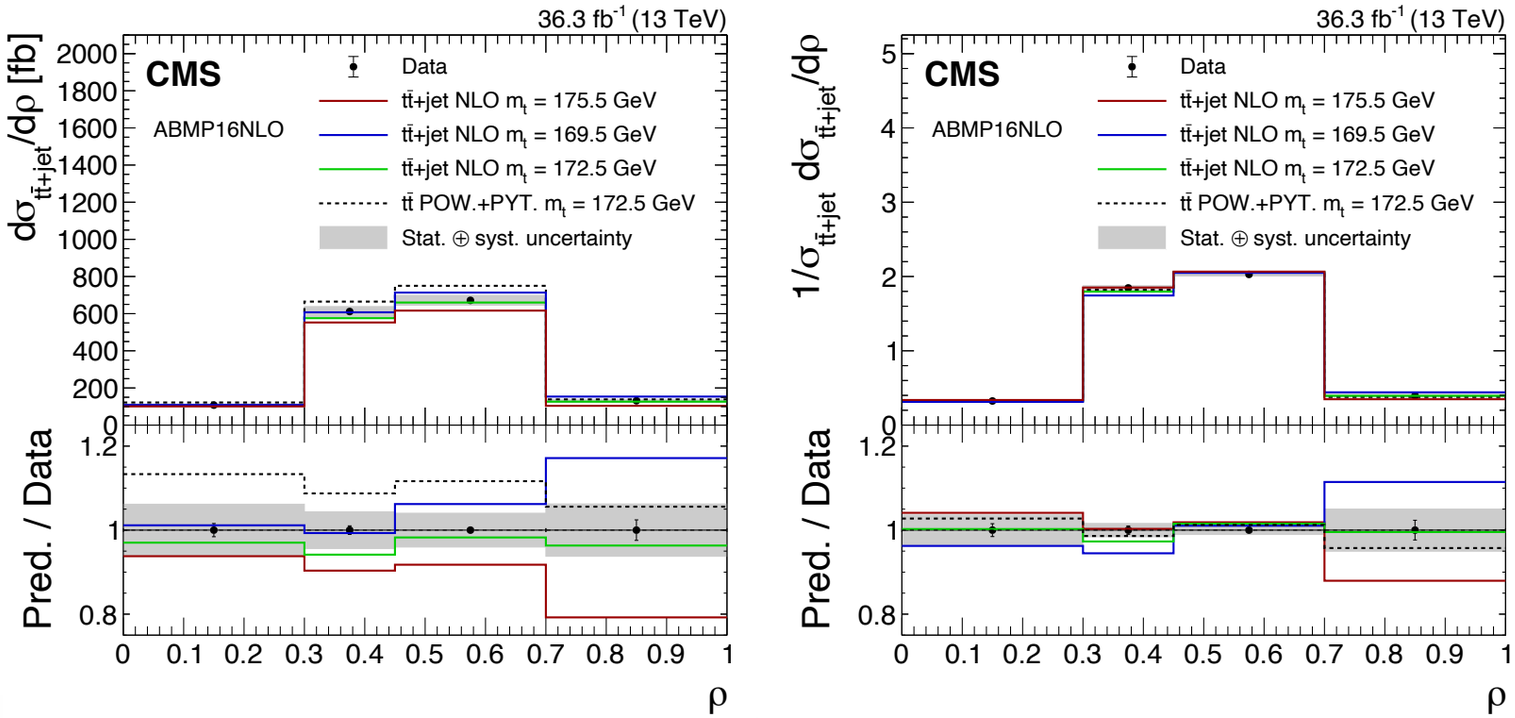
Data and background event yields for the regions included in the fit



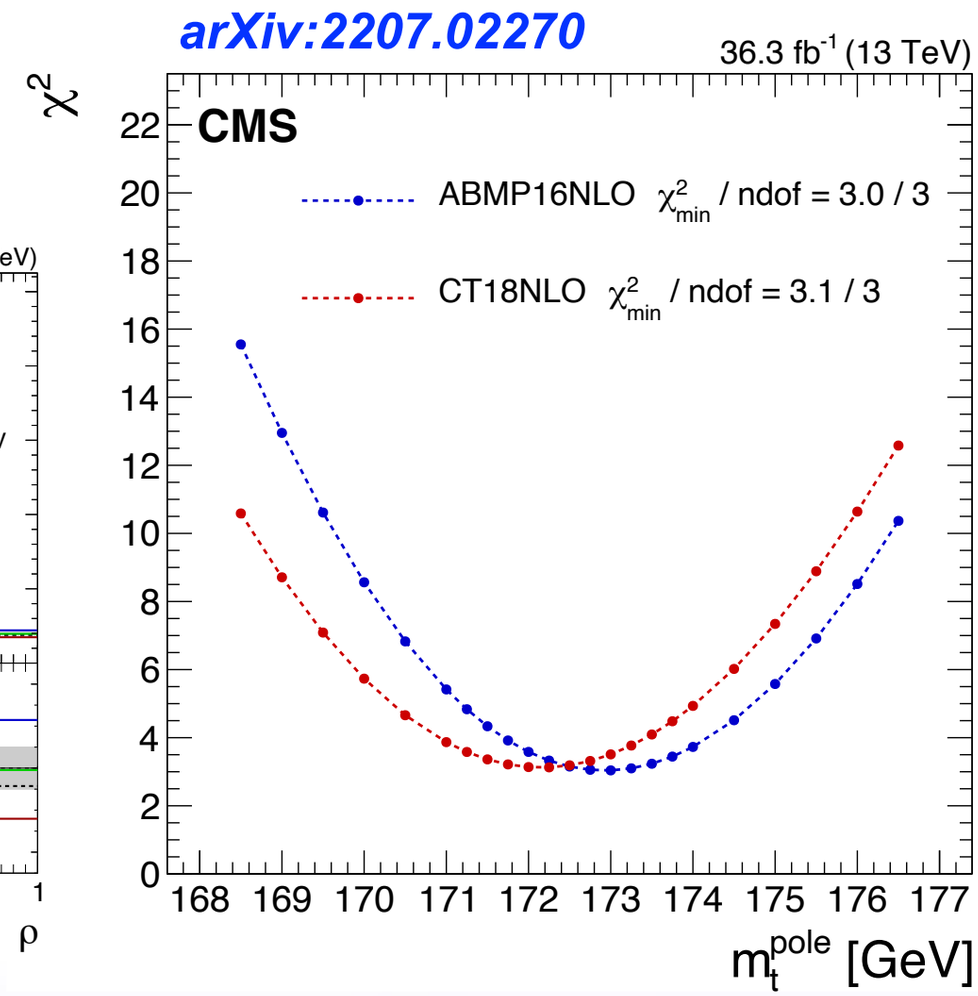
NN output for $t\bar{t}$+jets

Top mass from diff. x-sec: Results

- Top quark pole mass is extracted from χ^2 minimisation between the unfolded normalised differential cross section and theoretical $t\bar{t}$+jets MC predictions at NLO (using two different input PDF sets).
  - $m_{\text{top}}^{\text{pole}} = 172.94 \pm 1.27\,(\text{fit})\,^{+0.51}_{-0.43}\,(\text{scale})\,\text{GeV}$ ➡ ABMP16NLO
  - $m_{\text{top}}^{\text{pole}} = 172.16 \pm 1.35\,(\text{fit})\,^{+0.50}_{-0.40}\,(\text{scale})\,\text{GeV}$ ➡ CT18NLO
- Dominant systematic uncertainties: MC scale variations (μ_R, μ_F), JES and background normalisations.



Absolute (left) and normalised (right) differential $t\bar{t}$+jets cross sections for data and different NLO predictions

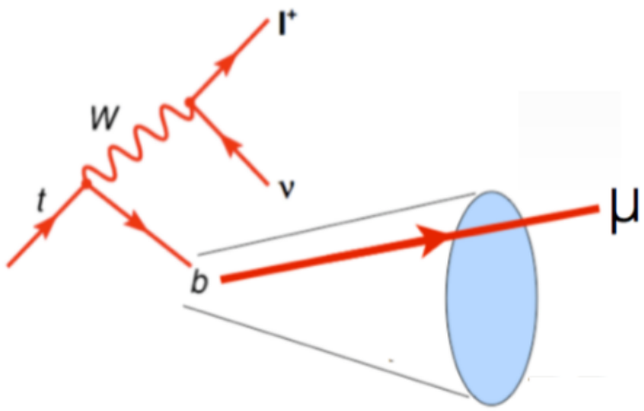


χ^2 distributions vs. top mass

ATLAS

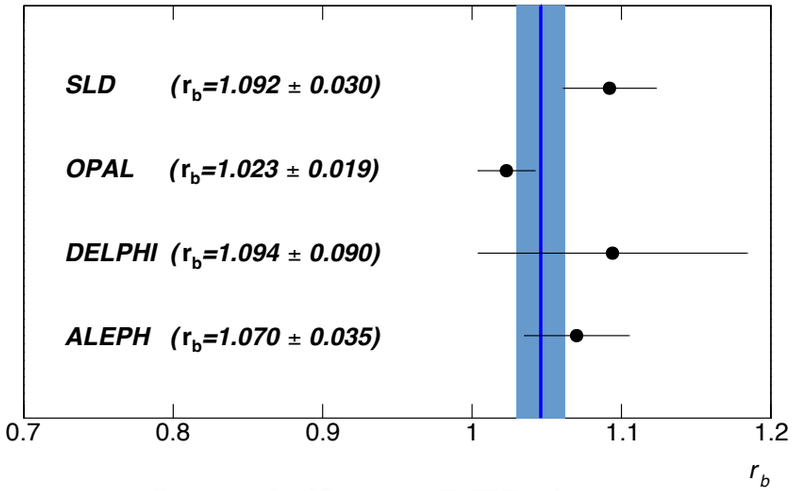
Top quark mass using "soft muon tags"

Top quark mass using soft muon tags (SMT):



- Measurement of m_{top} with 2015/16 data in l+jet events.
  - One lepton (electron/muon) from a W boson and a jet containing a "soft muon" ($p_{\text{T}} > 8$ GeV) originating from a b-hadron decay (SM-tagged jet).
- Binned likelihood fit on $m_{l\mu}$ (invariant mass between lepton from W and muon from SMT-jet) to extract m_{top}.
- Requirement on angular separation ($\Delta R_{l,\mu} < 2$) between W-lepton and SMT-muon increases probability that they originate from the same top quark ⇒ **83%** in OS events.
- Momentum transfer between b-quarks and b-hadrons (b-fragmentation) is modelled differently for different MC generators.
  - Nominal $t\bar{t}$ MC simulation (POWHEG + PYTHIA8) uses Lund-Bowler parametrisation ⇒ derive custom MC tune (with optimised r_b parameter) with data from LEP & SLAC experiments.

$$f(z) = \frac{1}{z^{1+br_b m_b^2}}(1-z)^a \exp(-b\, m_{\text{T}}^2/z)$$



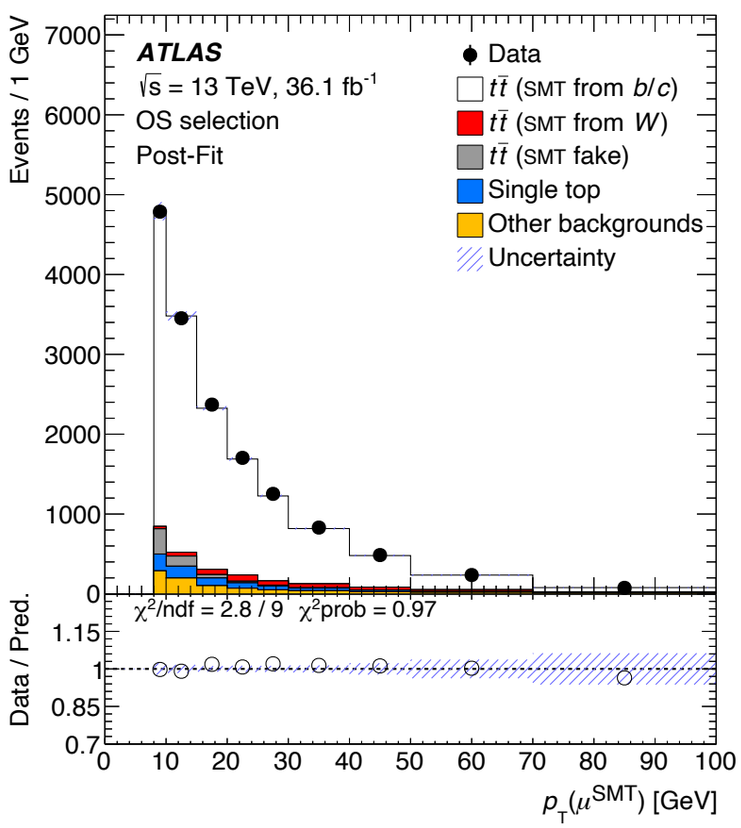
r_b from different LEP datasets

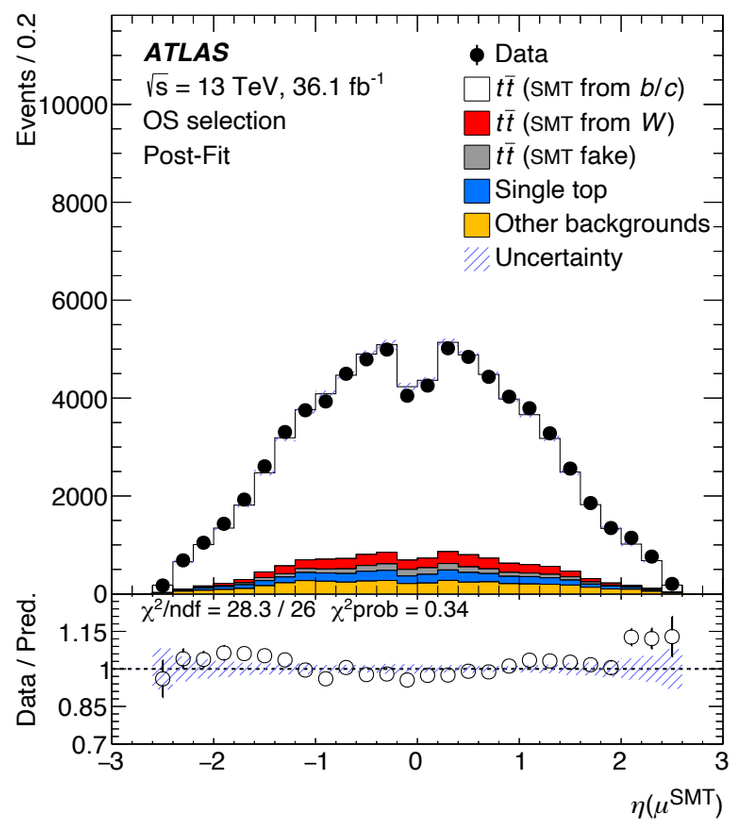
arXiv:2209.00583

SMT top mass: Fit setup

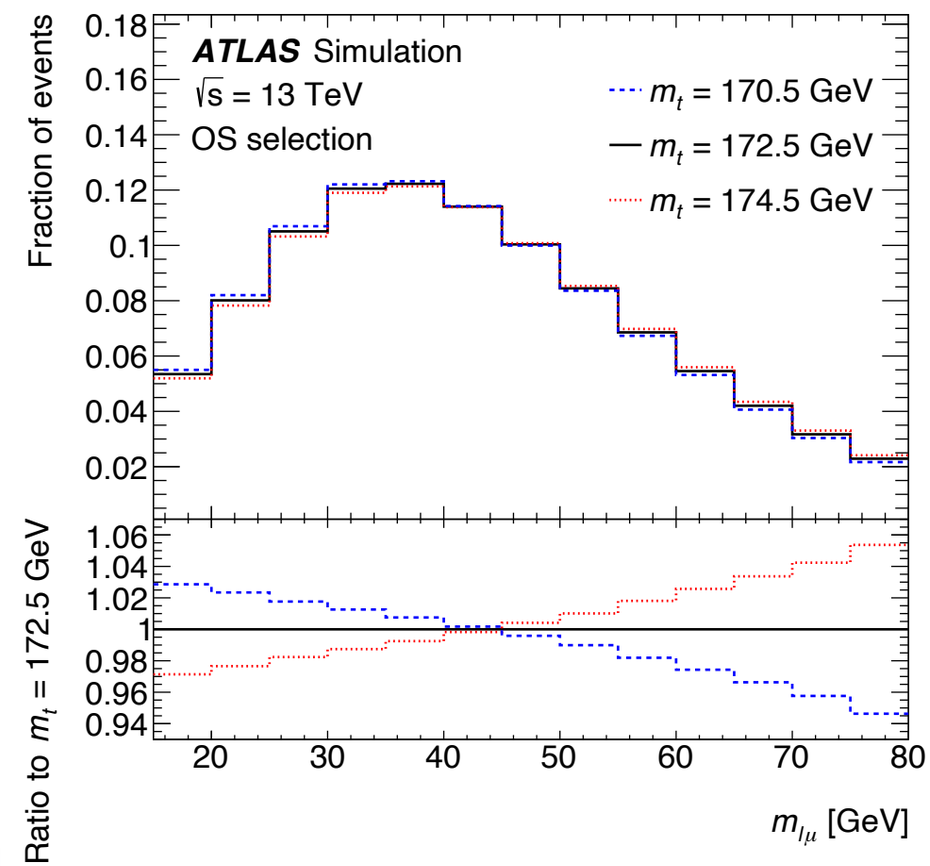
- Apply selection to obtain region enriched in $t\bar{t}$ events (> 90%) containing at least one SMT-jet.
- Distribution of $m_{l\mu}$ depends on simulated top quark mass.
  - Perform binned likelihood MC template fit to data on $m_{l\mu}$ ⇒ MC templates featuring different top masses.
  - Fit performed in most sensitive range (15 GeV < $m_{l\mu}$ < 80 GeV) and simultaneously in OS and SS events ⇒ consistent results for OS and SS final states.

arXiv:2209.00583





Pre-fit distributions of p_T (left) and η (right) of SMT muon



$m_{l\mu}$ for tt MC with different m_{top}

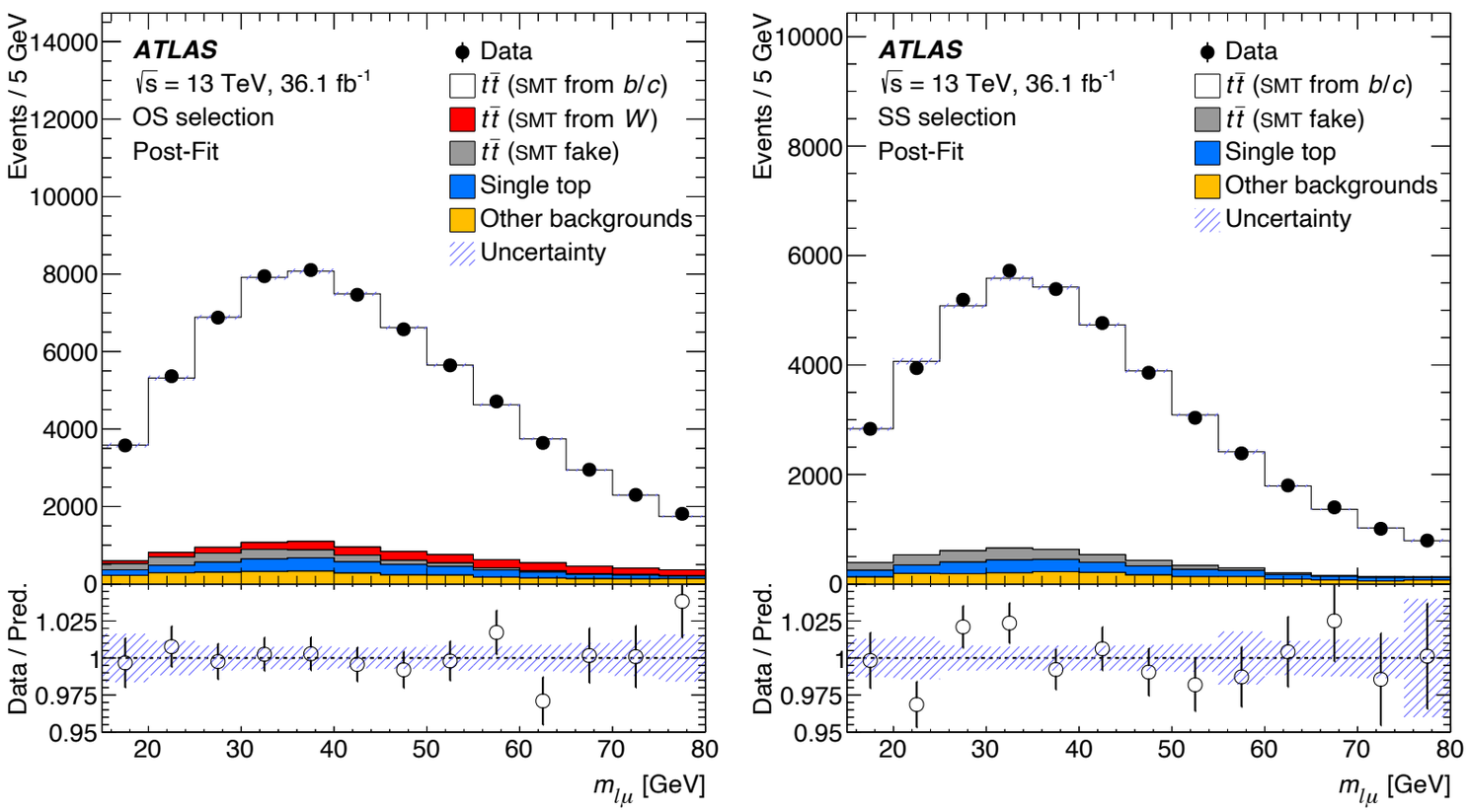
SMT top mass: Results

- Best fit value of top quark mass:

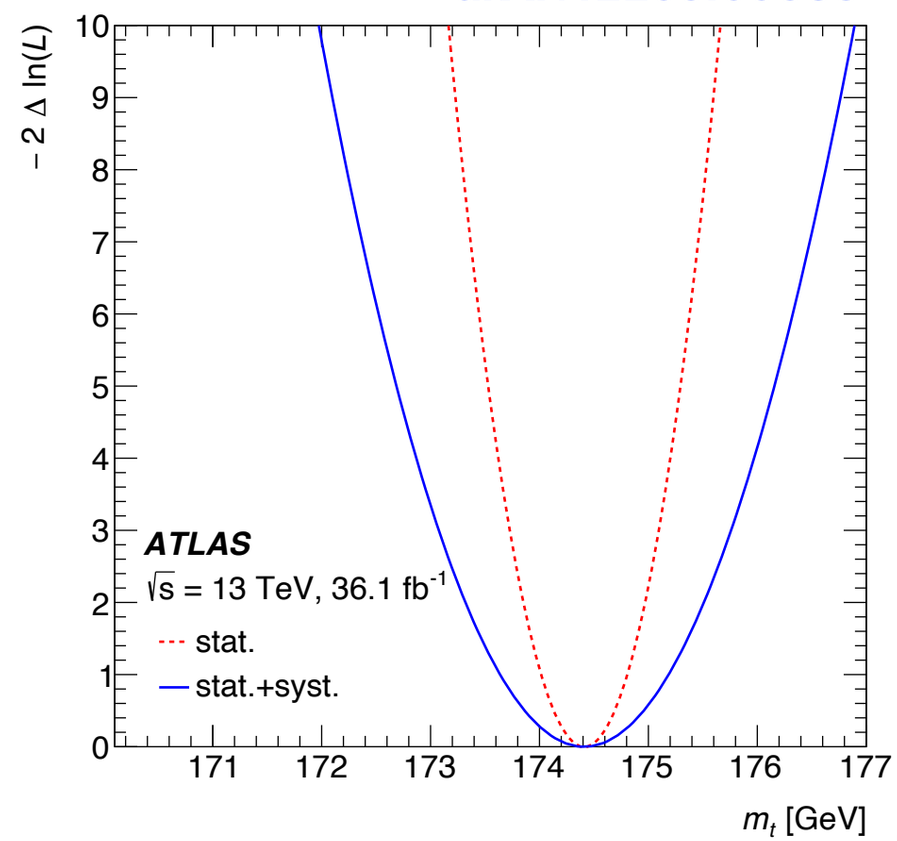
  $m_{\text{top}} = 174.41 \pm 0.39\ (\text{stat.}) \pm 0.66\ (\text{syst.})\ \text{GeV} \pm 0.25\ (\text{recoil})\ \text{GeV}$

- Dominant systematic uncertainties: branching ratios of *b/c*-hadrons to muons, modelling of initial-state QCD radiation and *b*-fragmentation function (choice of r_b parameter).
  - Also here, new extra uncertainty to account for PYTHIA8 gluon-recoil scheme.

arXiv:2209.00583



Post-fit $m_{l\mu}$ distributions in OS (left) and SS (right) regions



Likelihood scan of m_{top}

CMS

Top quark mass using profile likelihood fit

Top quark mass using profile-likelihood fit:

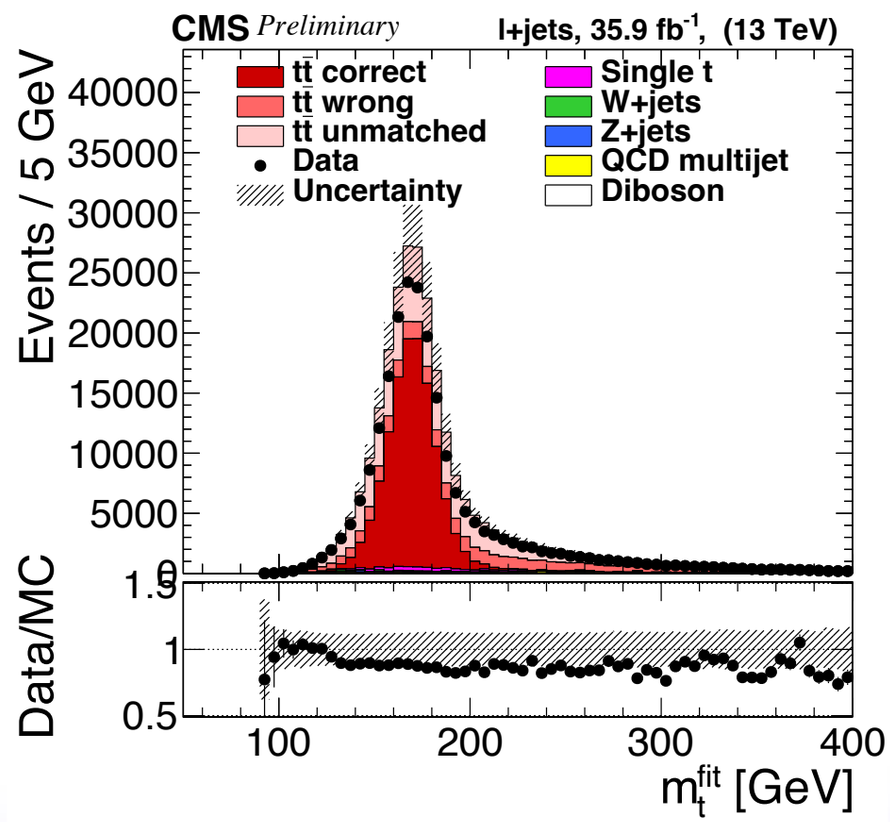
- Measurement of top quark mass with 2015/16 data in events with one lepton and ≥ 4 jets.
- Extraction of m_{top} from a likelihood fit to data on the (assumed) $t\bar{t}$ decay products.
  - Kinematic quantities of input objects (leptons, jets, $E_{\text{T}}^{\text{miss}}$) are checked against $t\bar{t}$ hypothesis via a χ^2 minimisation and goodness-of-fit requirement ($P_{\text{gof}} \geq 0.2$) $\Rightarrow$ most compatible objects are associated with $t\bar{t}$ decay products.
  - Build up to five different observables (■) from input objects, which enter likelihood function $\boldsymbol{\lambda(m_{\text{t}})}$ to extract top mass.

CMS-PAS-TOP-20-008

$$\lambda(m_{\text{t}}, \vec{\theta}, \vec{\beta}, \vec{\omega}|\text{data}) = \left(\prod_i \lambda_i(m_{\text{t}}, \vec{\theta}, \vec{\beta}, \vec{\omega}|x_i) P(\vec{\beta}) P(\vec{\omega})\right) \left(\prod_l P(\theta_l)\right)$$

histogram observable	histogram category	set label 1D	2D	3D	4D	5D
$m_{\text{t}}^{\text{fit}}$	$P_{\text{gof}} \geq 0.2$	x	x	x	x	x
$m_{\text{W}}^{\text{reco}}$	$P_{\text{gof}} \geq 0.2$		x	x	x	x
$m_{\ell\text{b}}^{\text{reco}}$	$P_{\text{gof}} < 0.2$			x	x	x
$m_{\ell\text{b}}^{\text{reco}} / m_{\text{t}}^{\text{fit}}$	$P_{\text{gof}} \geq 0.2$				x	x
$R_{\text{bq}}^{\text{reco}}$	$P_{\text{gof}} \geq 0.2$					x

Likelihood function and input observables

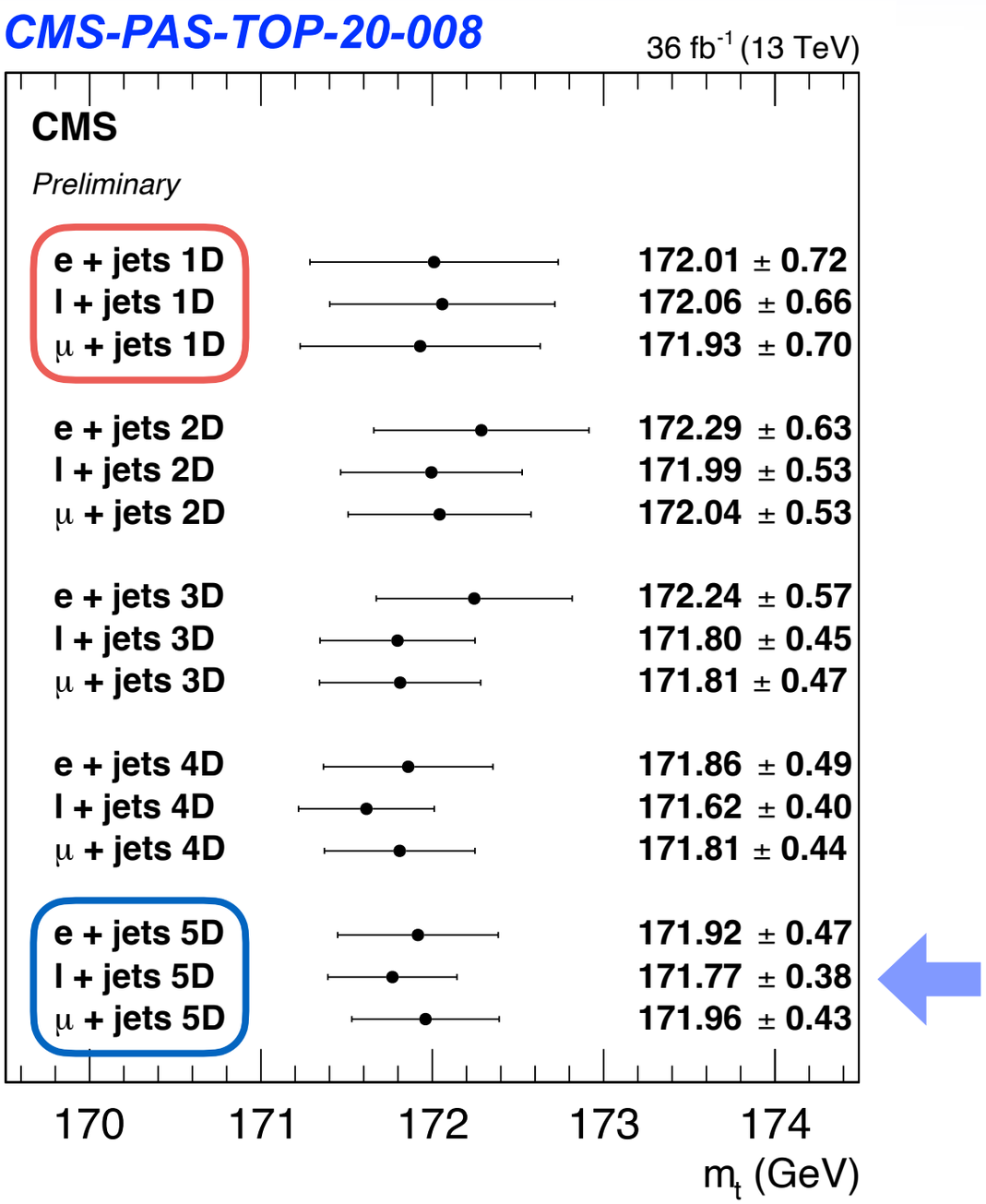


Reconstructed top quark mass

Likelihood top mass: Results

- Results obtained separately for different lepton flavours $l = (e/\mu)$ and numbers of observables included in the likelihood function (1 → 5).
  - Consistent results for electrons/muons.
  - Number of included observables improves precision of extracted top mass.
- Most precise result (with $e+\mu$ and 5 observables):

  $m_{\text{top}} = 171.77 \pm 0.04\ (\text{stat.}) \pm 0.38\ (\text{syst.})\ \text{GeV}$
- Pseudo-experiments used to validate statistical model (e.g. measured mass is not biased by different input m_t^{MC} used in MC).
- Dominant uncertainties: jet-fragmentation, FSR modelling in PS and colour reconnection.
  - Some large uncertainties can be constrained by the observables entering the fit (e.g. JER by width of m_W^{reco} distribution).
  - Improved precision with respect to other top mass measurements in similar regions.



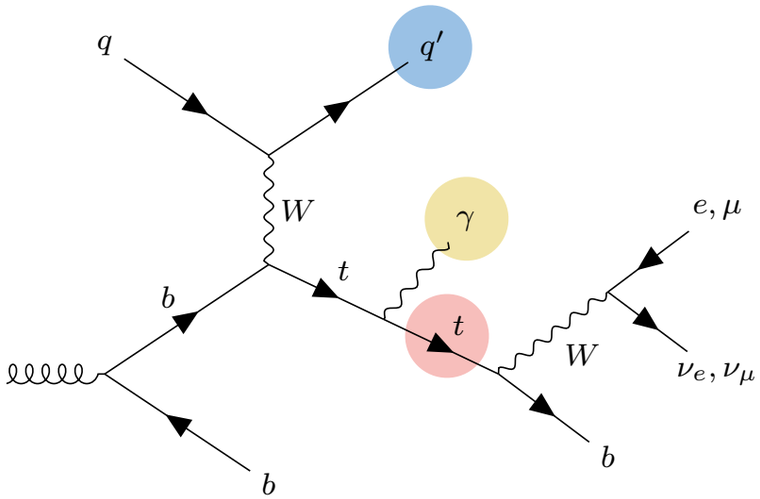
Top mass results for different lepton flavours and numbers of input observables

ATLAS

Observation of single top production in association with a photon

Single-top production in association a photon:

- Rare SM process ⇒ predicted cross section of around 400 fb.
- Evidence has already been reported by CMS using 2015/16 data ⇒ ***Phys. Rev. Lett. 121 (2018) 221802***.
- ATLAS analysis uses the full Run 2 data ⇒ define signal regions with one lepton, one photon and a *b*-jet.
  - Sensitive to *t*-channel single-top quark production (with leptonic top-decay) in association with a radiated photon and an extra parton in the final state ($tq\gamma$).
- Signal regions subdivided by presence of "forward jet" ($2.5 < |\eta_{\text{jet}}| < 4.5$): **0 fj** ($N_{\text{fwd-jet}} = 0$) and **≥ 1 fj** ($N_{\text{fwd-jet}} \geq 1$) ⇒ use NN to further separate $tq\gamma$ from background.
- Main irreducible SM backgrounds: $t\bar{t}\gamma$ and $W\gamma$ ⇒ obtain normalisations factors from data using $t\bar{t}\gamma$ and $W\gamma$ control regions:
  - Defined by *b*-jet requirements ⇒ one extra *b*-jet for $t\bar{t}\gamma$ and *b*-jet veto for $W\gamma$.
- Fake-photon contamination (mostly di-leptonic $t\bar{t}$ with $e \rightarrow \gamma$).
  - Estimated from MC, but correction factors to account for different $e \rightarrow \gamma$ probabilities are applied ⇒ estimated from $Z \rightarrow e\gamma$ events.

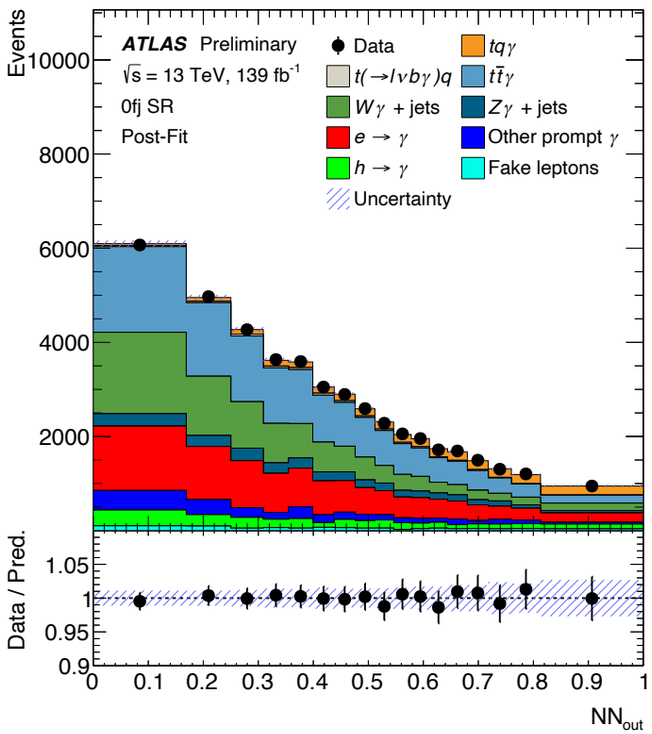


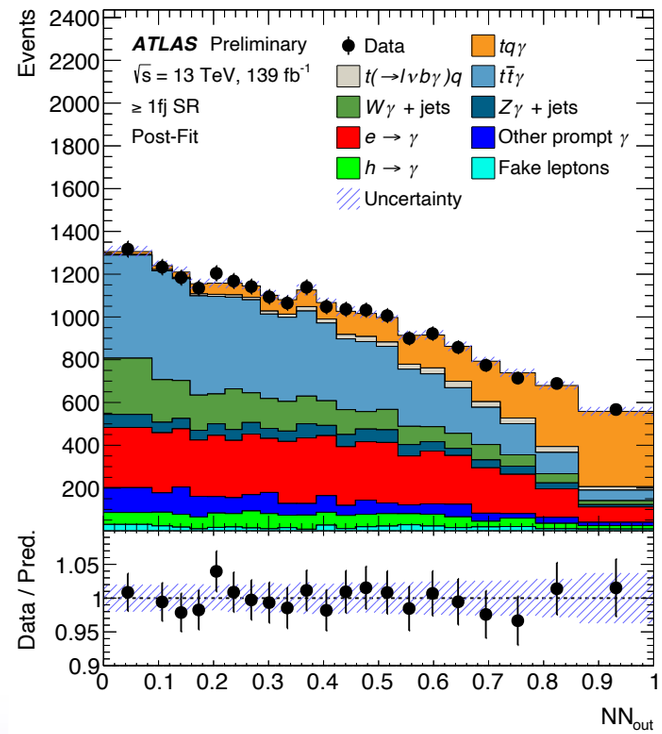
ATLAS-CONF-2022-013

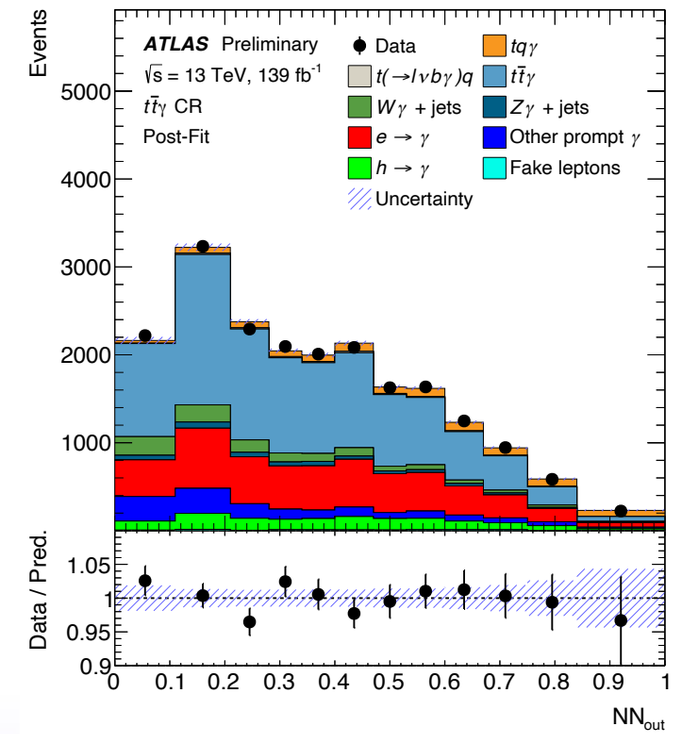
Single top+photon: Results

- Perform simultaneous likelihood fit to NN score in all regions (unbinned in $W\gamma$ control region).
  - Observed significance of the $tq\gamma$ process: **9.1σ** (6.7σ expected) ⇒ **discovery!**
- Correct results to particle/parton level in fiducial volumes close to signal regions ⇒ compare to theoretical MC predictions in these regions.
  - $\sigma_{tq\gamma} \times \mathscr{B}(t \to \ell\nu b) = 580 \pm 19\,(\text{stat.}) \pm 63\,(\text{syst.})\,\text{fb} \quad \Rightarrow \quad \sigma_{\text{MC}} = 406\,^{+25}_{-32}\,\text{fb}$
  - $\sigma_{tq\gamma} \times \mathscr{B}(t \to \ell\nu b) + \sigma_{t(\to\ell\nu b\gamma)q} = 287 \pm 8\,(\text{stat.}) \pm 31\,(\text{syst.})\,\text{fb} \quad \Rightarrow \quad \sigma_{\text{MC}} = 207\,^{+26}_{-11}\,\text{fb}$
- Dominant systematic uncertainties: $t\bar{t}$ and $t\bar{t}\gamma$ modelling, as well as limited MC statistics for minor SM backgrounds.

ATLAS-CONF-2022-013







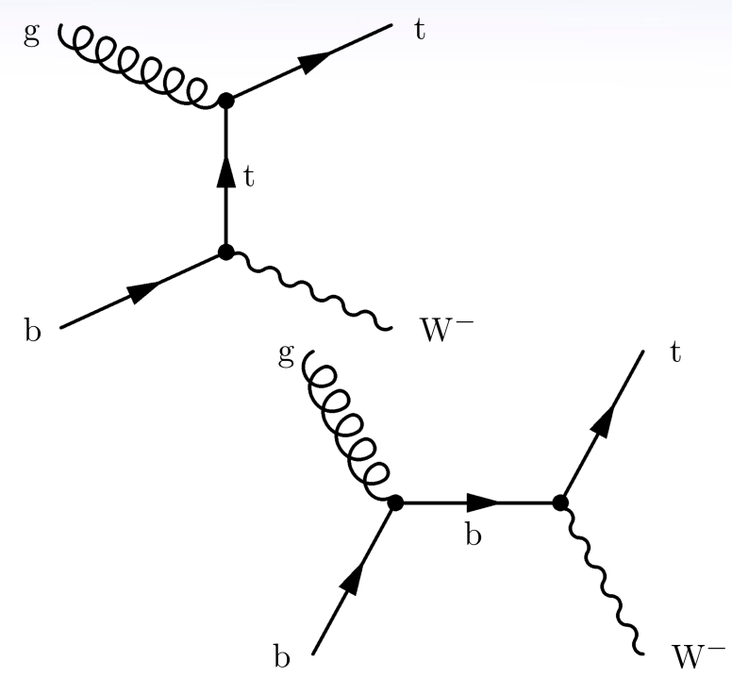
NN score in signal region with 0fj (left), ≥ 1fj (middle) and control region for $t\bar{t}\gamma$ background (right)

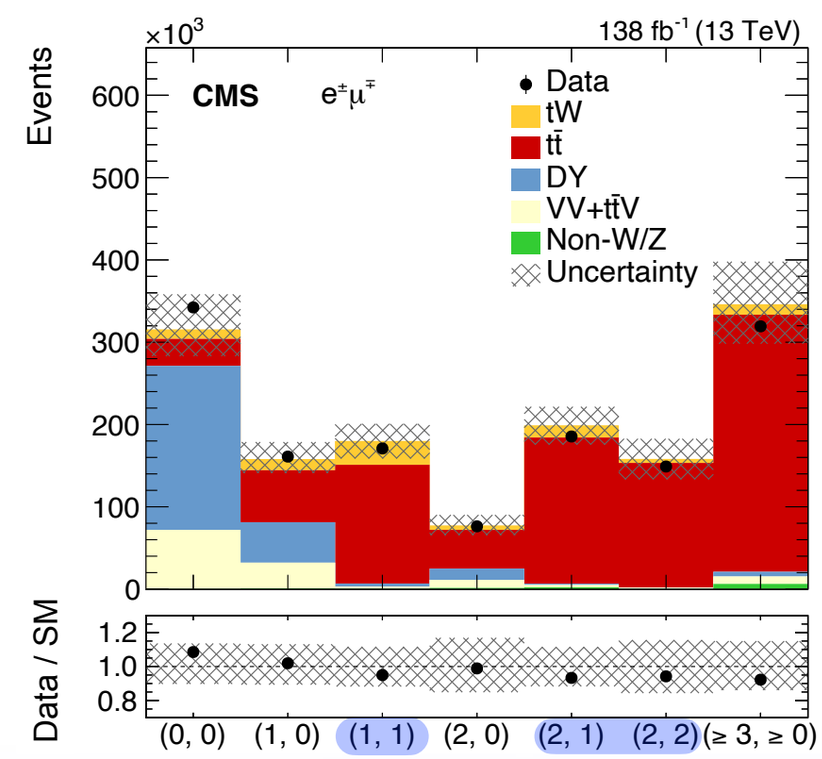
CMS

Measurement of single top production in association with a W boson

Single-top in association with a W boson:

- LO production of tW in s- and t-channel ⇒ predicted SM cross section of around 72 pb.
- Inclusive measurements already done by ATLAS and CMS with 2015/16 data in di-lepton channel.
  - Especially challenging due to large $t\bar{t}$ background (**> 80%**).
- First differential measurement by ATLAS with 2015/16 data ⇒ ***Eur. Phys. J. C 78 (2018) 186***.
- CMS analysis performed differential measurement using full Run 2 data (together with updated inclusive measurement) ⇒ ***arXiv:2208.00924***.
- Selecting OS $e\mu$ events ⇒ subdivide channel according to jet and b-jet multiplicities.
  - Regions with notable tW contribution (***1j1b***, ***2j1b***, ***2j2b***) used for inclusive measurement (only $1j1b$ for differential results).
  - Use two BDTs for $1j1b$ and $2j1b$ to separate tW from $t\bar{t}$ background in these regions.



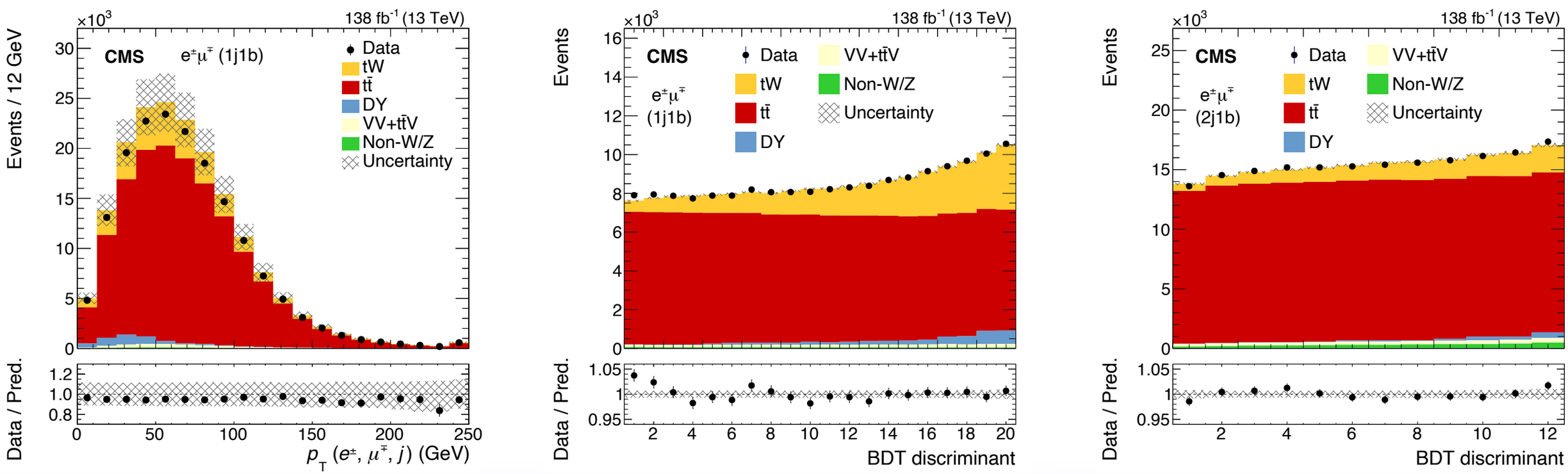


Event yields in OS $e\mu$ (by N_{jet} and $N_{b\text{-jet}}$)

tW cross section: Inclusive measurement

- Most discriminating variables in BDTs:
  - $1j1b$: combined momentum/centrality/mass of di-lepton/jet system (e, μ, j).
  - $2j1b$: angular separation between leptons and jets.
- Perform binned likelihood fit on BDT scores in $1j1b$ and $2j1b$ regions (and on sub-leading jet in to $2j2b$ to constrain JES) to extract cross section:
  - $\sigma_{tW} = 79.2 \pm 0.9\,(\text{stat.})\,^{+7.7}_{-8.0}\,(\text{syst.})\ \pm 1.2\,(\text{lumi})\,\text{pb} \qquad \sigma_{tW}^{\text{SM}} = 71.7 \pm 3.8\,(\text{scale} + \text{PDF})\,\text{pb}.$
- Dominant uncertainties: JES, background normalisations and MC modelling uncertainties of tW signal (μ_R, μ_F, FSR).

arXiv:2208.00924



$p_T(e,\mu,j)$ in $1j1b$ (left) and BDT score in $1j1b$ (middle) and $2j1b$ (right)

tW cross section: Differential measurements

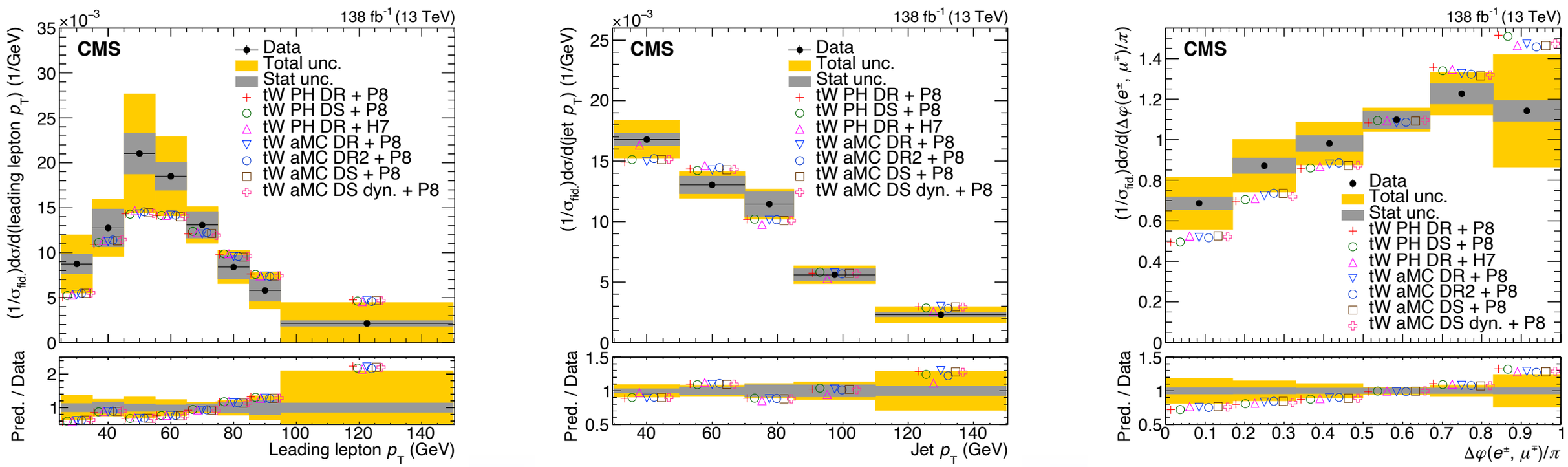
- Unfold distributions to particle level in fiducial volume close to $1b1j$ region.
  - Normalised differential cross sections in six observables (■) which are sensitive to BSM effects and/or differences among tW MC generators.

p-values for different tW MC settings

Variable	PH DR + P8	PH DS + P8	PH DR + H7
Leading lepton p_T	0.02	0.01	0.03
Jet p_T	0.14	0.27	0.01
$\Delta\varphi(e^{\pm},\mu^{\mp})/\pi$	0.26	0.29	0.32
$p_z(e^{\pm},\mu^{\mp},j)$	0.70	0.77	0.82
$m_T(e^{\pm},\mu^{\mp},j,\vec{p}_T^{miss})$	0.54	0.60	0.59
$m(e^{\pm},\mu^{\mp},j)$	0.03	0.02	0.28

- Evaluating compatibility between unfolded data and theoretical predictions by computing p-values for different tW MC generators or generator-settings (e.g. DS vs. DR).

arXiv:2208.00924



Normalised differential cross sections of leading lepton/jet p_T (left/middle) and $\Delta\varphi$ between e and μ (right)

Summary

- Presented some of the most recent ATLAS and CMS results on measurements of the top quark mass and top+X processes ⇒ most results released in 2022.

ATLAS

- Top mass from template fit

  ⇒ ***ATLAS-CONF-2022-058***

- Top mass using soft muon tags

  ⇒ ***arXiv:2209.00583***

- Observation of $t+\gamma$ production

  ⇒ ***ATLAS-CONF-2022-013***

CMS

- Top mass from $t\bar{t}$+jets x-sec.

  ⇒ ***arXiv:2207.02270***

- Top mass from likelihood fit

  ⇒ ***CMS-PAS-TOP-20-008***

- Measurement of tW x-sec.

  ⇒ ***arXiv:2208.00924***

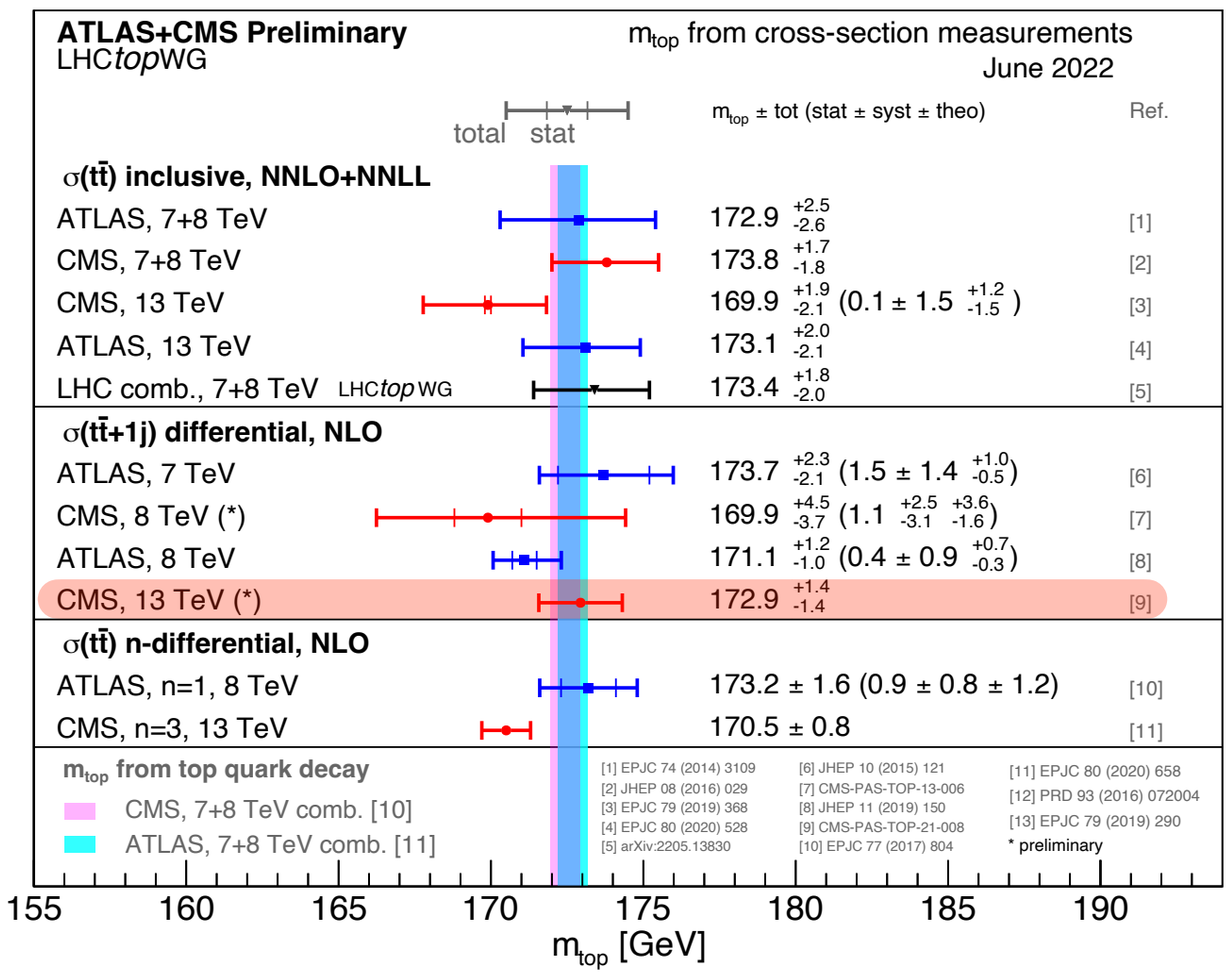
- Further interesting results on top physics in can be found on the "Top Public Results" webpages of the ATLAS and CMS collaborations.

Thanks a lot for your attention!

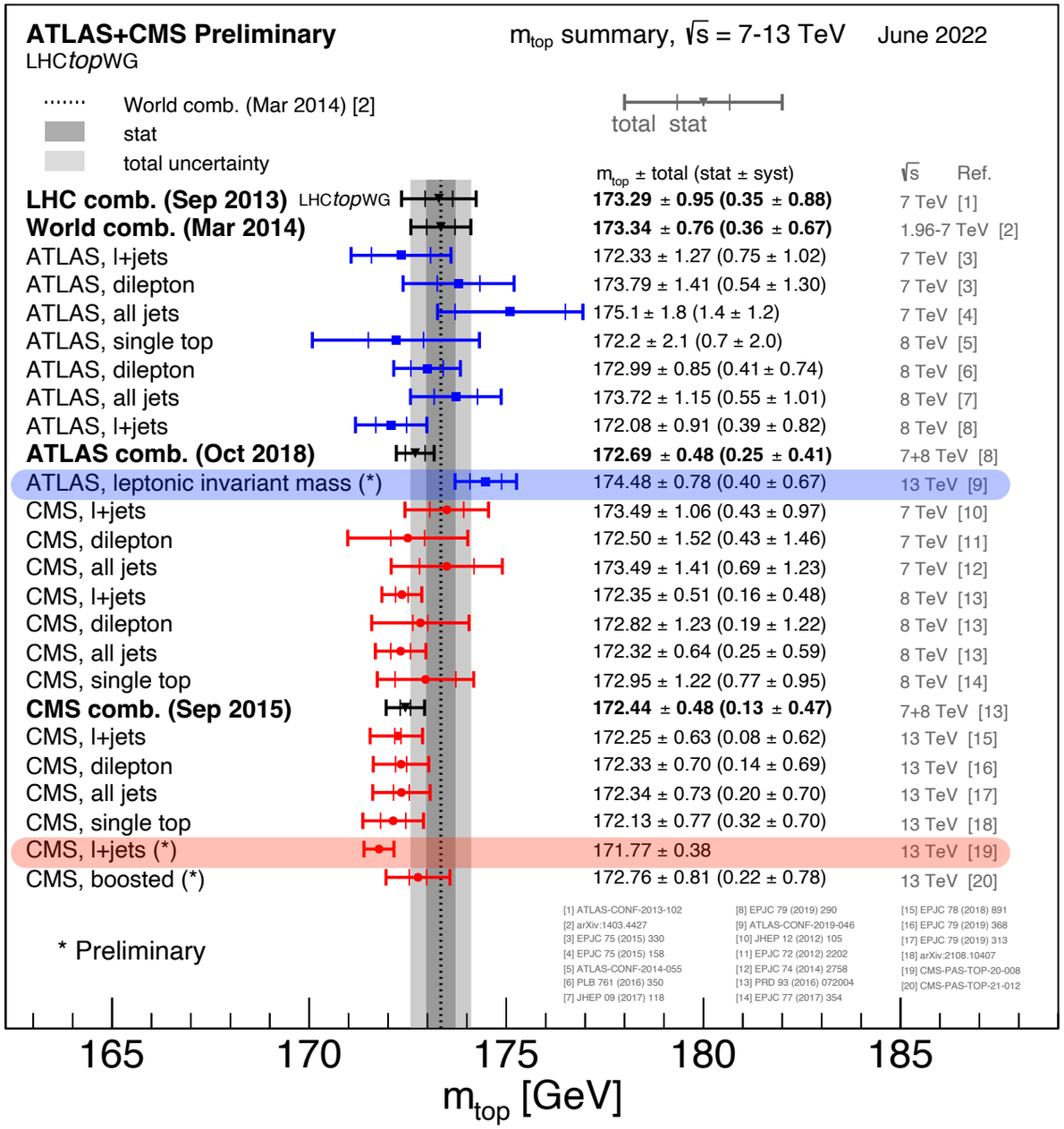
Backup

ATLAS/CMS summary plots: Top mass

- ATLAS/CMS summary plots of top mass measurements (June 2022) ⇒ presented results are highlighted.
  - Results extracted from cross sections (left) and from direct top mass measurements (right).



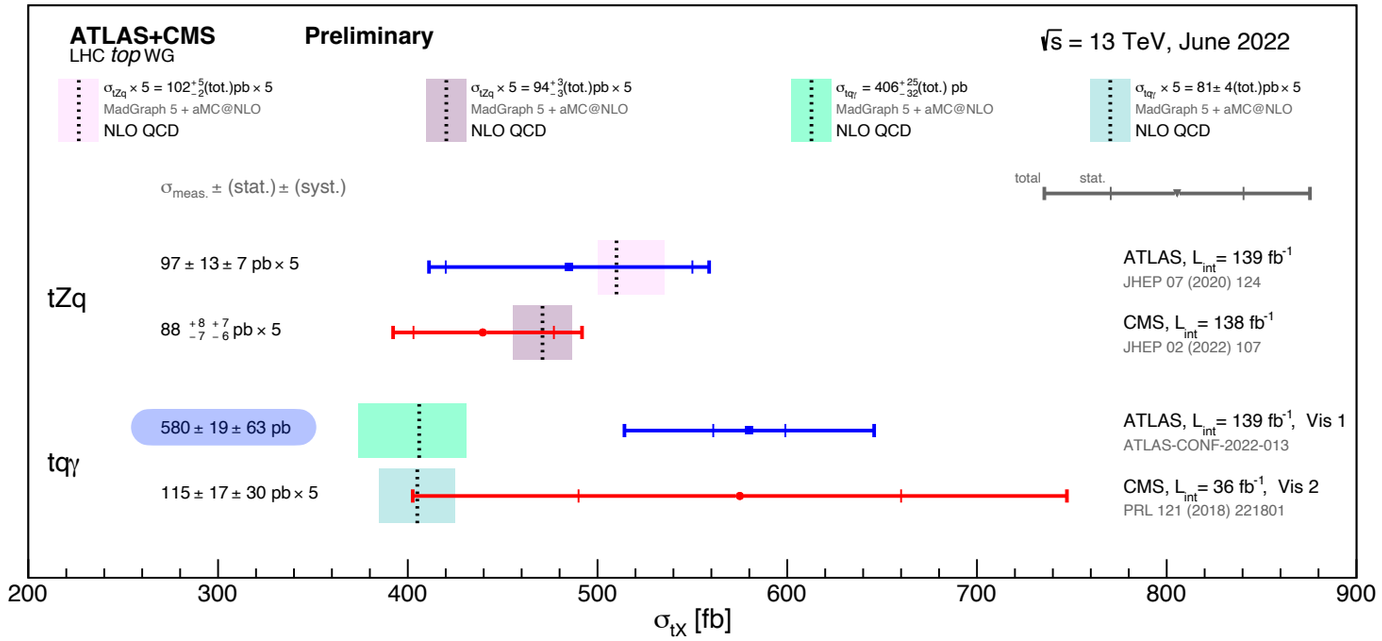
ATL-PHYS-PUB-2022-032

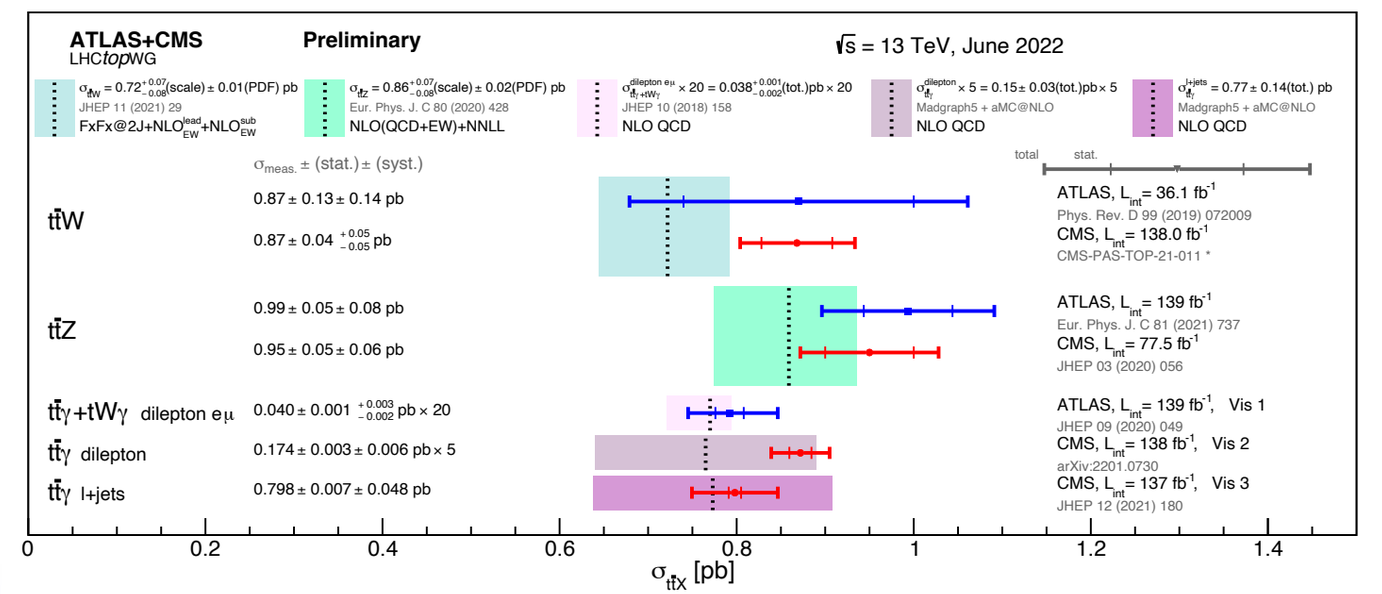


ATLAS/CMS summary plots: Top+X cross sections

- ATLAS/CMS summary plots of $t+X$ (top) and $t\bar{t}+X$ (bottom) cross sections (June 2022) ⇒ presented results are highlighted.

ATL-PHYS-PUB-2022-030

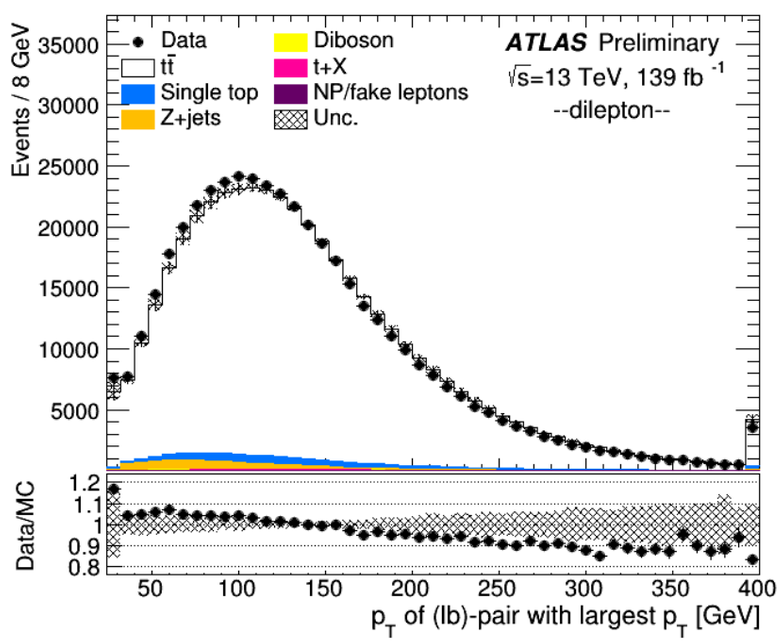




Top mass from template fit

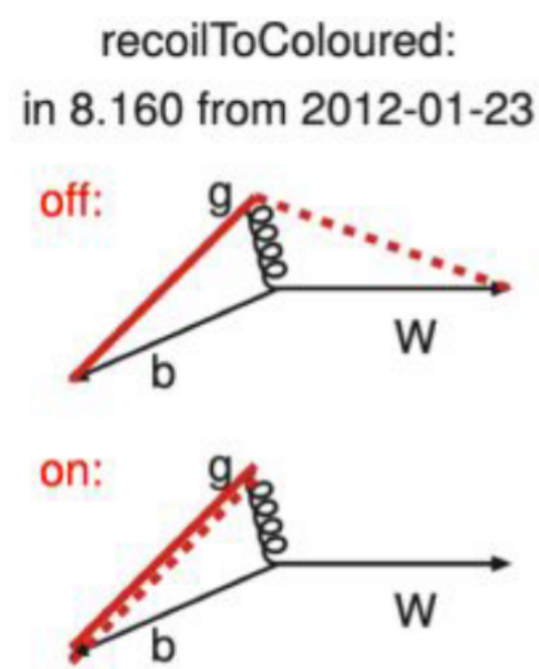
- Top: Data and MC event yields after the final signal region selection.
- Bottom: Lepton/b-jet pair with largest p_T.

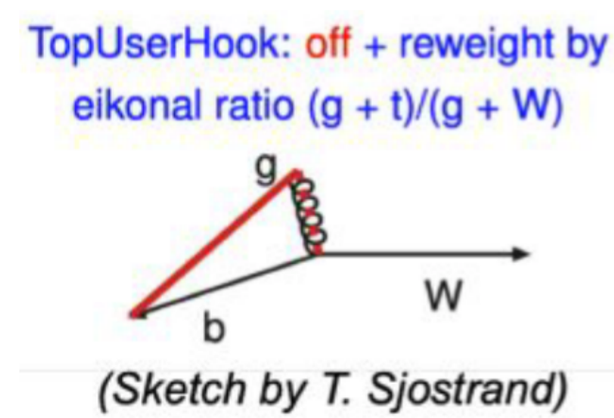
Data	83785
$t\bar{t}$ signal	90800 ± 5800
Single-top-quark signal	1144 ± 74
Z+jets	122 ± 49
Diboson	4.1 ± 2.2
$t\bar{t}+V$, tWZ, tZq	270 ± 41
$t\bar{t}+H$	86.9 ± 8.8
NP/fake leptons	100 ± 100
Signal+background	92500 ± 5800
Expected background fraction	0.006 ± 0.001
Data/(Signal + background)	0.905 ± 0.058



ATLAS-CONF-2022-058

- Recoil uncertainty: nominal setting in PYTHIA8 is to let gluon recoil against b-quark ⇒ new option since PYTHIA8.2 to let it recoil against the W boson ⇒ see ***arXiv:1410.3012***.
  - Changes e.g. in jet p_T and b-fragmentation function ⇒ significant effect on top mass.
  - Open discussion about optimal settings ⇒ so far used as an extra uncertainty on gluon emission in $t \to Wb$.



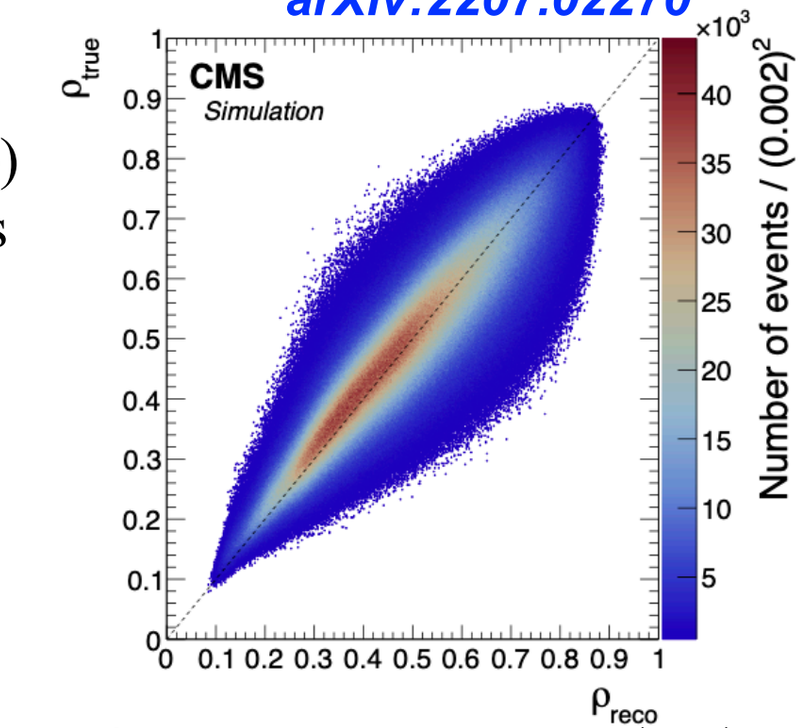


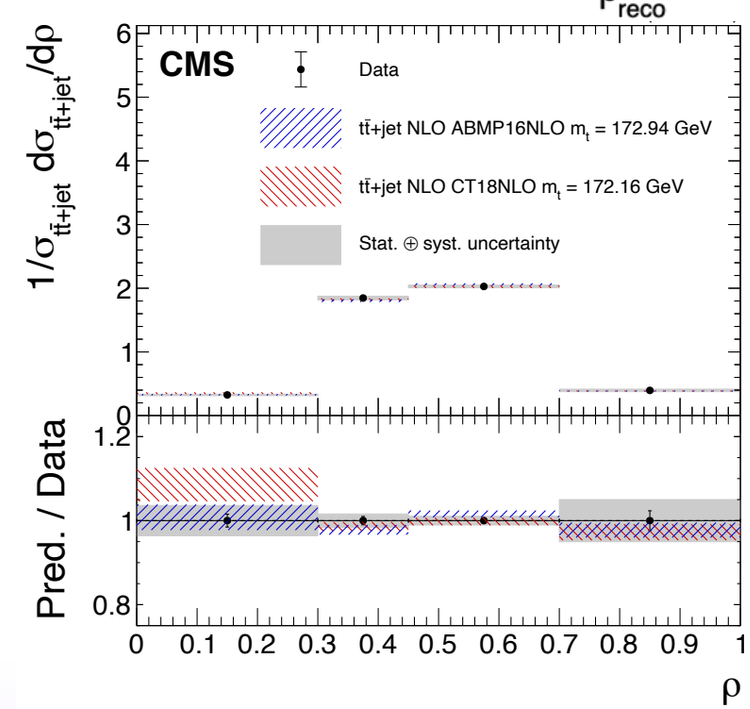
Top mass from diff. x-sec

- Left: Table with the most relevant uncertainties affecting the differential measurement.
- Right: Migration between truth-level and reconstructed ρ (top) and unfolded data vs. the two different $t\bar{t}$+jets MC predictions (with m_{top} fixed to their post-fit values).

Uncertainty Source	$\Delta\sigma^1_{t\bar{t}+\text{jet}}$ [%]	$\Delta\sigma^2_{t\bar{t}+\text{jet}}$ [%]	$\Delta\sigma^3_{t\bar{t}+\text{jet}}$ [%]	$\Delta\sigma^4_{t\bar{t}+\text{jet}}$ [%]
Experimental				
Muon identification	0.3	0.2	0.2	0.5
Muon energy scale and resolution	0.2	≤0.1	≤0.1	0.2
Electron identification	0.3	0.2	0.2	0.5
Electron energy scale and resolution	0.1	≤0.1	0.1	0.3
Jet energy scale	1.0	0.5	0.5	1.3
Jet energy resolution	0.3	0.3	0.5	0.2
Jet identification	0.2	0.4	0.4	1.1
p_T^{miss}	≤0.1	≤0.1	≤0.1	≤0.1
b jet identification	0.3	0.1	0.1	0.2
Trigger efficiency	0.3	0.3	0.3	0.6
Total	2.1	1.6	1.7	2.9
Background normalization				
$t\bar{t}$+0 jet	≤0.1	0.1	0.1	0.4
Z+jets	0.4	0.2	0.2	0.6
Single top quark	0.2	0.1	0.1	0.2
Total	0.8	0.4	0.3	0.7
Modeling				
Z+jets ME scale	0.2	0.1	0.1	0.3
Single top quark ME/FSR/ISR scales	1.0	0.2	0.1	0.2
$t\bar{t}$ PDF	0.1	≤0.1	≤0.1	0.1
$t\bar{t}$ ME scale	0.7	0.1	0.2	0.6
$t\bar{t}$ ISR scale	0.1	0.1	0.1	0.1
$t\bar{t}$ FSR scale	0.2	0.2	0.3	0.4
$t\bar{t}$ top quark p_T	0.7	0.5	0.2	0.6
b fragmentation	0.2	0.1	0.2	0.2
Color reconnection	0.2	≤0.1	0.2	≤0.1
$t\bar{t}$ matching scale	0.1	0.2	≤0.1	0.1
Underlying-event tune	0.1	≤0.1	0.1	≤0.1
Total	1.8	0.8	0.5	1.2
Integrated luminosity	0.3	0.3	0.3	0.6
m_t^{MC}	0.1	≤0.1	0.3	0.1
Finite size of simulated samples	1.1	0.5	0.4	1.5
Total systematic	6.0	4.3	4.0	5.7
Statistical	1.6	1.0	0.8	2.4
Total	6.2	4.4	4.0	6.2

arXiv:2207.02270



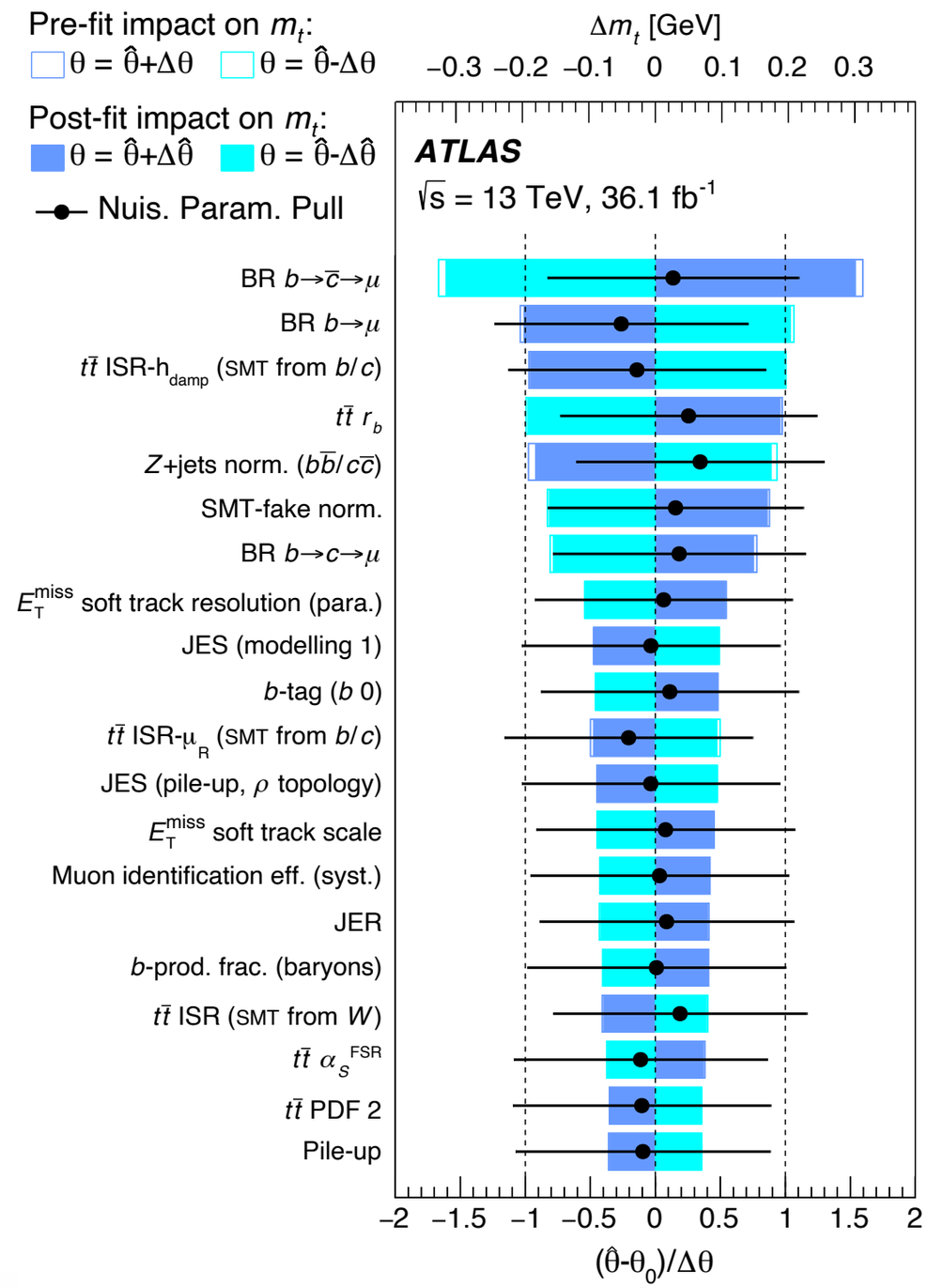


SMT top mass

- Left: Event yields in the signal region, separated by OS and SS final states.
- Right: Fit-impact (and pulls) of largest systematic uncertainties.

arXiv:2209.00583

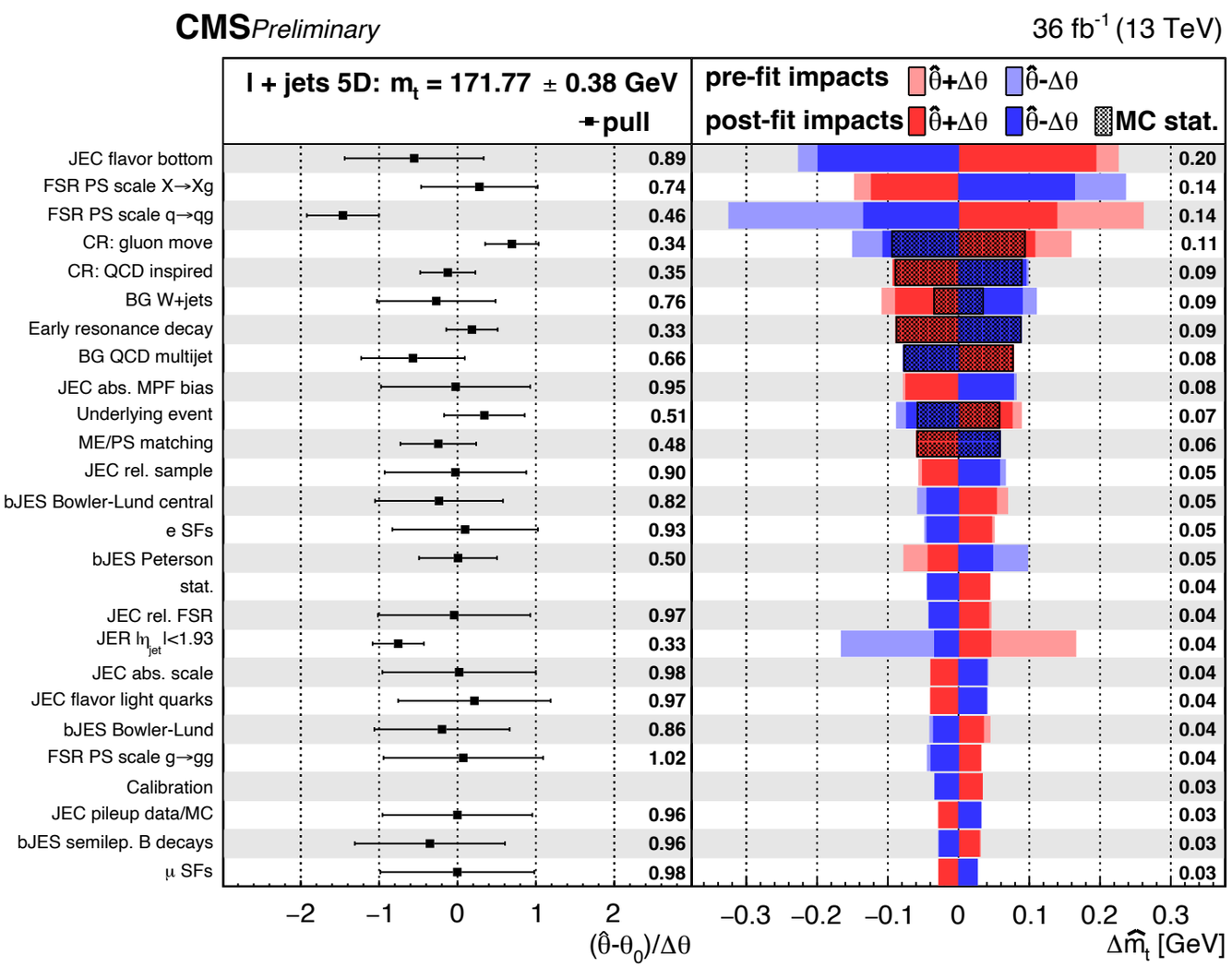
Process	Yield (OS)	Yield (SS)
$t\bar{t}$ (SMT from b- or c-hadron)	55 700 ± 3400	34 800 ± 2300
$t\bar{t}$ (SMT from $W \to \mu\nu$)	2190 ± 310	4.9 ± 3.6
$t\bar{t}$ (SMT fake)	1490 ± 210	1240 ± 170
Single top t-channel	770 ± 70	490 ± 40
Single top s-channel	63 ± 6	49 ± 4
Single top Wt channel	1840 ± 140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

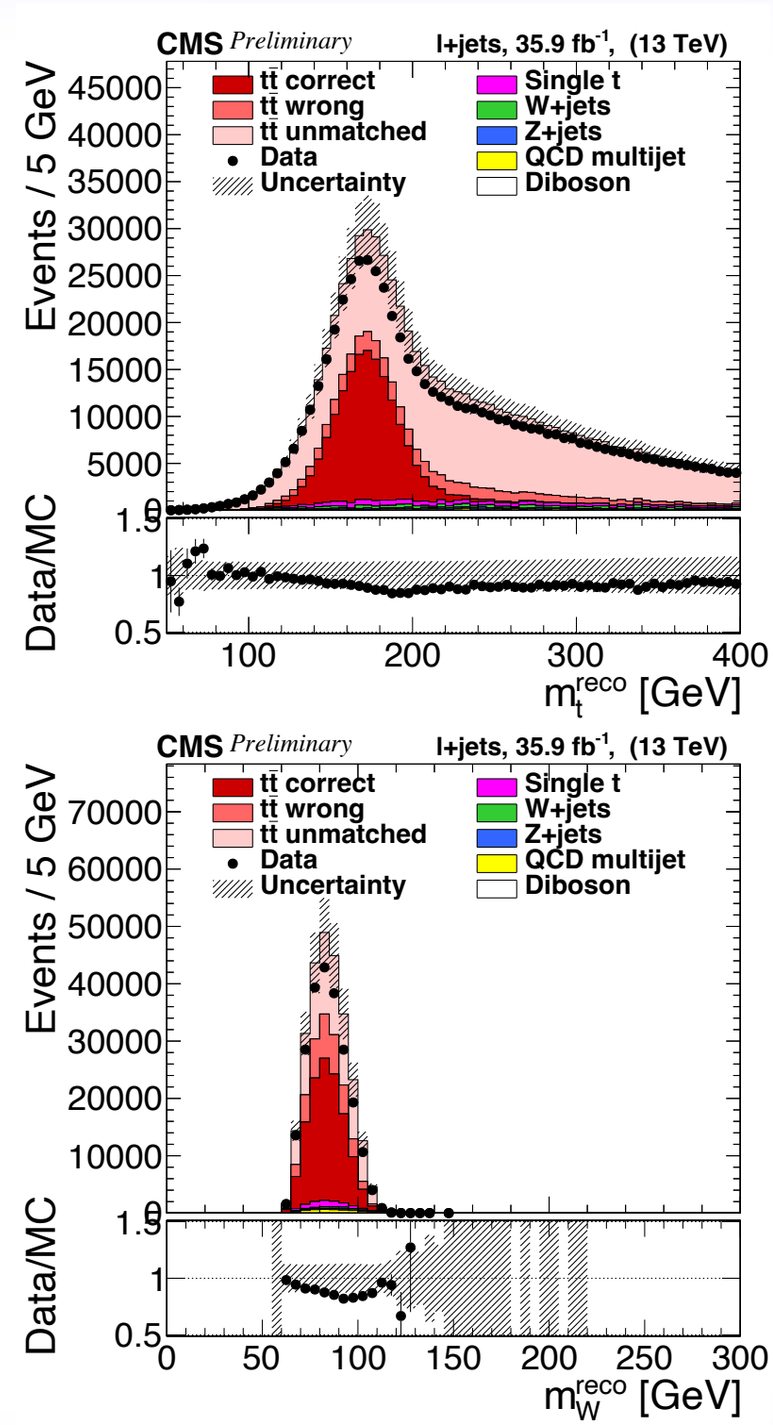


Likelihood top mass

- Left: Fit-impact (and pulls) of largest systematic uncertainties.
- Right: Pre-fit reconstructed top mass without P_{gof} requirement (top) and reconstructed mass of W boson (bottom).

CMS-PAS-TOP-20-008





Single top+photon

- Expected and observed post-fit event yields (top) and systematic uncertainties (bottom) of $tq\gamma$ analysis.
  - Left: particle-level results.
  - Right: parton-level results.

Uncertainty	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modelling	±5.7%
Background MC statistics	±3.5%
$t\bar{t}$ modelling	±3.1%
$tq\gamma$ MC statistics	±3.1%
$t\,(\to \ell\nu b\gamma)\,q$ modelling	±2.2%
$tq\gamma$ modelling	±2.0%
Additional background uncertainties	±1.9%
$t\,(\to \ell\nu b\gamma)\,q$ MC statistics	±0.3%
Lepton fakes	±2.4%
$h \to \gamma$ photon fakes	±2.2%
$e \to \gamma$ photon fakes	±0.6%
Luminosity	±2.2%
Pileup	±1.3%
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±3.9%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.6%
Total systematic uncertainty	±11.0%

Uncertainty	$\Delta\sigma/\sigma$
$t\bar{t}\gamma$ modelling	±5.6%
Background MC statistics	±3.5%
$t\bar{t}$ modelling	±3.4%
$tq\gamma$ MC statistics	±3.4%
$t\,(\to \ell\nu b\gamma)\,q$ modelling	±1.9%
Additional background uncertainties	±1.9%
$tq\gamma$ modelling	±1.8%
$t\,(\to \ell\nu b\gamma)\,q$ MC statistics	±0.3%
Lepton fakes	±2.2%
$h \to \gamma$ photon fakes	±2.2%
$e \to \gamma$ photon fakes	±0.6%
Luminosity	±2.2%
Pileup	±1.2%
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	±4.0%
Photons	±2.5%
Leptons	±0.9%
b-tagging	±0.8%
Total systematic uncertainty	±10.9%

ATLAS-CONF-2022-013

	≥ 1fj SR	0fj SR	$t\bar{t}\gamma$ CR	$W\gamma$ CR
$tq\gamma$	2340 ± 250	2430 ± 310	880 ± 120	1250 ± 140
$t\,(\to \ell\nu b\gamma)\,q$	480 ± 160	660 ± 210	170 ± 60	320 ± 120
$t\bar{t}\gamma$ (production)	3100 ± 400	4700 ± 700	4200 ± 600	2670 ± 350
$t\bar{t}\gamma$ (radiative decay)	3700 ± 600	9100 ± 1300	5600 ± 600	4200 ± 900
$W\gamma$+jets	2500 ± 400	9400 ± 1300	1060 ± 190	31 800 ± 3000
$Z\gamma$+jets	990 ± 310	2800 ± 800	440 ± 150	7900 ± 2400
$e \to \gamma$ fake photons	5200 ± 500	10 400 ± 800	4900 ± 400	5500 ± 500
$h \to \gamma$ fake photons	1200 ± 400	2700 ± 800	1400 ± 500	2600 ± 800
Other prompt γ	1380 ± 350	2600 ± 900	1400 ± 400	4100 ± 500
Fake leptons	350 ± 170	900 ± 500	100 ± 50	3300 ± 1600
Total	21 250 ± 150	45 720 ± 240	20 180 ± 150	63 590 ± 320
Data	21 227	45 723	20 194	63 592

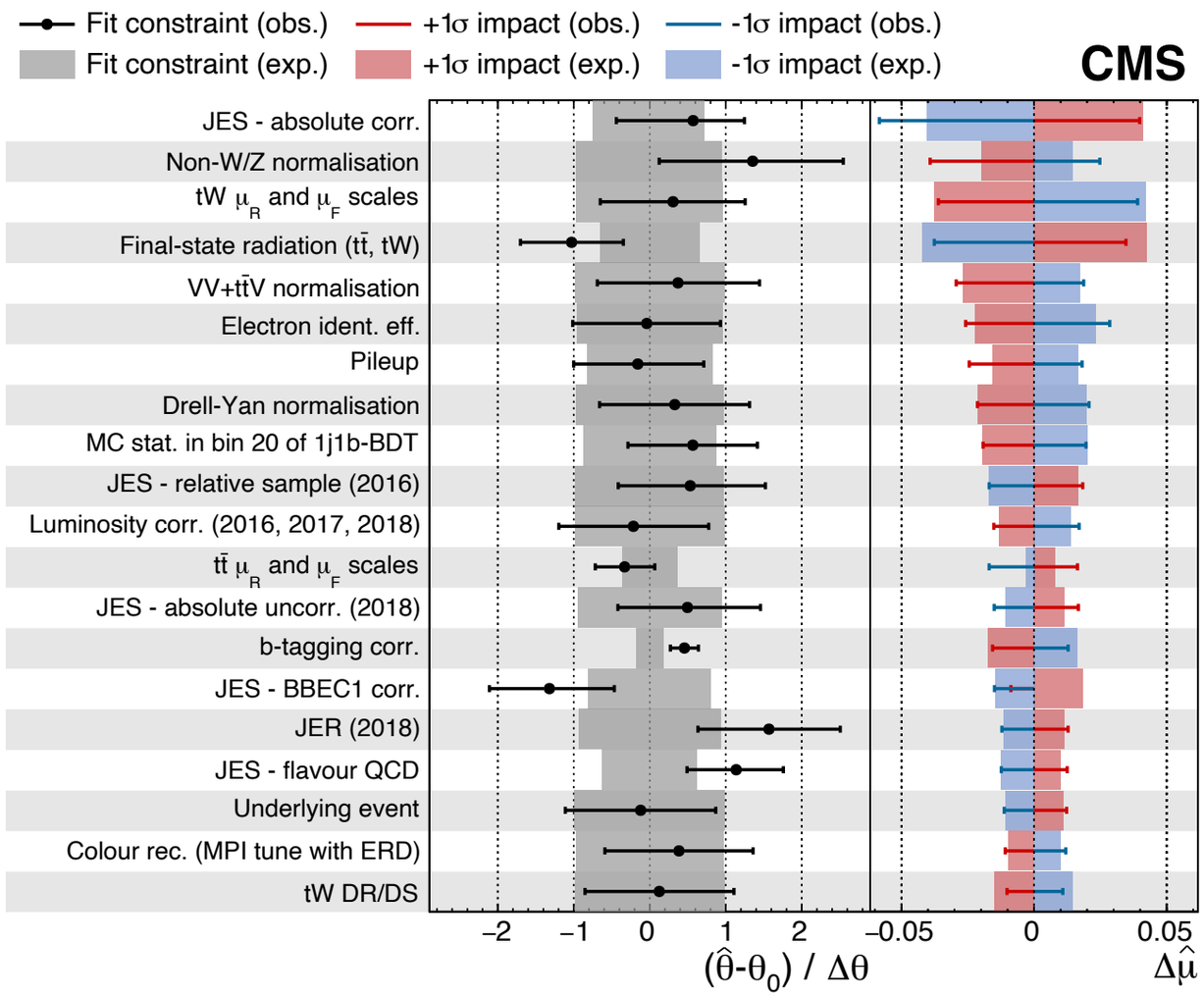
	≥ 1fj SR	0fj SR	$t\bar{t}\gamma$ CR	$W\gamma$ CR
$tq\gamma$	2390 ± 260	2480 ± 320	890 ± 120	1280 ± 150
$t\,(\to \ell\nu b\gamma)\,q$	360 ± 150	460 ± 240	120 ± 50	230 ± 110
$t\bar{t}\gamma$ (production)	3100 ± 400	4800 ± 700	4300 ± 600	2720 ± 350
$t\bar{t}\gamma$ (radiative decay)	3800 ± 600	9300 ± 1400	5700 ± 600	4300 ± 900
$W\gamma$+jets	2500 ± 400	9300 ± 1300	1050 ± 190	31 900 ± 3000
$Z\gamma$+jets	990 ± 310	2800 ± 800	440 ± 150	7900 ± 2400
$e \to \gamma$ fake photons	5200 ± 500	10 300 ± 800	4800 ± 400	5400 ± 500
$h \to \gamma$ fake photons	1100 ± 400	2700 ± 800	1300 ± 500	2500 ± 800
Other prompt γ	1360 ± 350	2600 ± 900	1400 ± 400	4100 ± 500
Fake leptons	350 ± 170	900 ± 400	100 ± 50	3300 ± 1600
Total	21 250 ± 150	45 720 ± 240	20 180 ± 140	63 590 ± 310
Data	21 227	45 723	20 194	63 592

tW cross section: Inclusive measurement

- Left: Data/MC event yields in the three regions ($1j1b$, $2j1b$, $2j2b$) used for inclusive measurement.
- Right: Fit-impact (and pulls) of largest systematic uncertainties for inclusive measurement.

arXiv:2208.00924

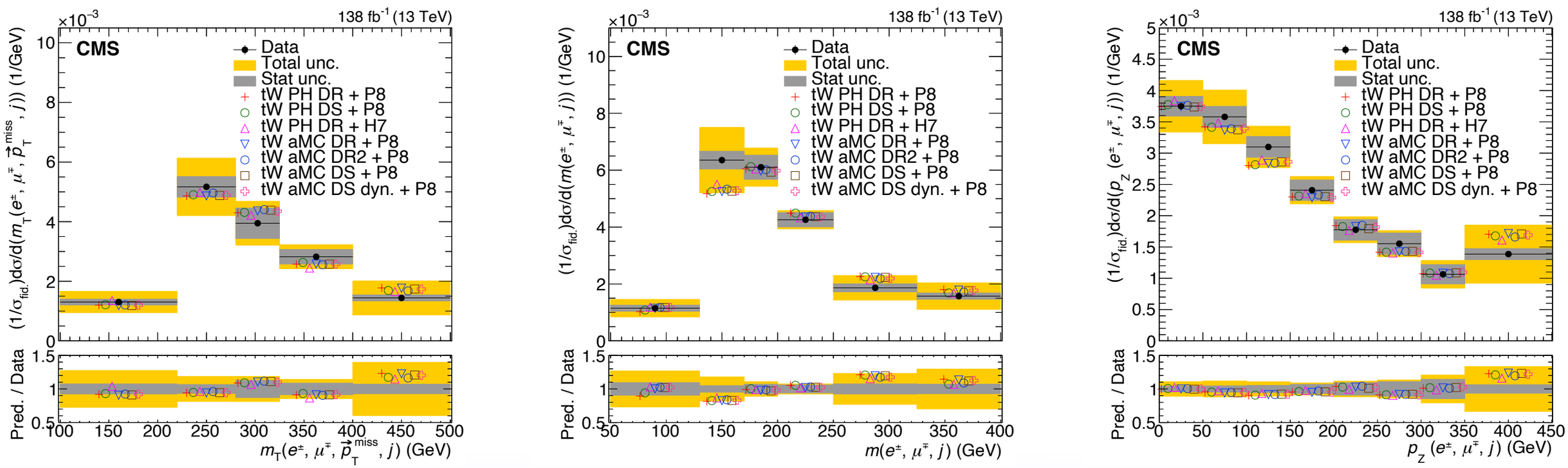
Process	1j1b	2j1b	2j2b
tW	$31\,600 \pm 600$	$16\,600 \pm 500$	$5\,500 \pm 200$
$t\bar{t}$	$131\,200 \pm 500$	$160\,300 \pm 600$	$141\,100 \pm 400$
Drell–Yan	$3\,990 \pm 190$	$1\,630 \pm 100$	260 ± 20
VV+$t\bar{t}$V	$2\,800 \pm 300$	$3\,300 \pm 500$	$1\,700 \pm 400$
Non-W/Z	$1\,140 \pm 150$	$3\,700 \pm 700$	470 ± 120
Total	$170\,800 \pm 300$	$185\,400 \pm 400$	$149\,100 \pm 300$
Data	$170\,900 \pm 400$	$185\,400 \pm 400$	$148\,900 \pm 400$



tW cross section: Differential measurements

- Top: Definition of the fiducial volume used for the unfolding (left). *p*-value compatibility test for further alternative *tW* MC generators (right).
- Bottom: Differential cross-section measurements for m_T, m and p_Z of the (e, μ, j) system.

Number of leptons	≥ 2
Leading lepton p_T	>25 GeV
Invariant mass of all dilepton pairs	>20 GeV
Number of jets	1
Number of loose jets	0
Number of b jets	1

Variable	aMC DR + P8	aMC DR2 + P8	aMC DS + P8	aMC DS dyn. + P8
Leading lepton p_T	0.05	0.04	0.03	0.07
Jet p_T	0.15	0.11	0.14	0.12
$\Delta\varphi(e^{\pm}, \mu^{\mp})/\pi$	0.33	0.40	0.37	0.32
$p_z(e^{\pm}, \mu^{\mp}, j)$	0.76	0.86	0.84	0.82
$m_T(e^{\pm}, \mu^{\mp}, j, \vec{p}_T^{miss})$	0.49	0.51	0.48	0.52
$m(e^{\pm}, \mu^{\mp}, j)$	0.09	0.12	0.10	0.14

arXiv:2208.00924