Precision top measurements – lessons learned and future prospects

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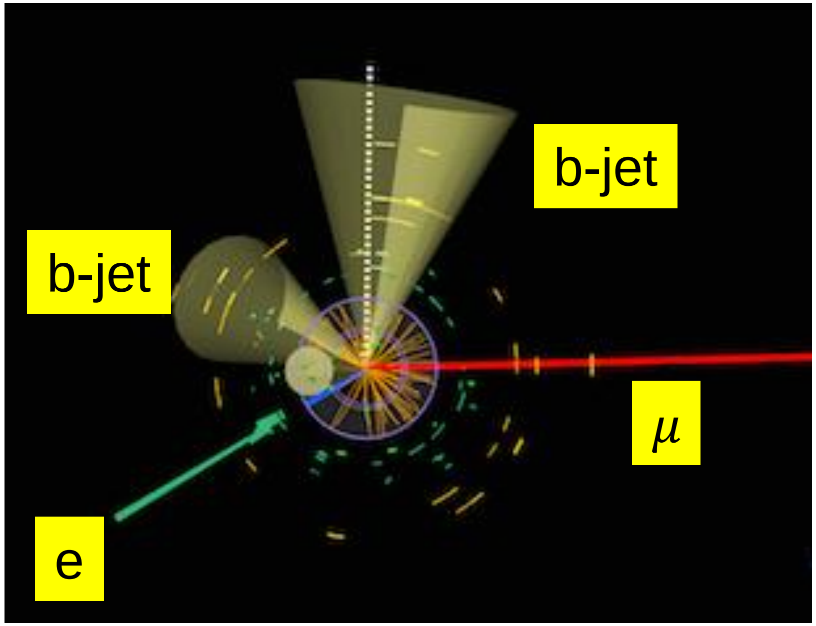
LHC precision programme, Benasque, Spain, 2/10/2022

- Some topics in LHC top quark physics
  - Introduction
  - Top cross-section measurements and their applications
  - Measurements of the top quark mass
    - Direct, indirect, limitations
  - Top Monte Carlo modelling
  - Rare top processes – ttW



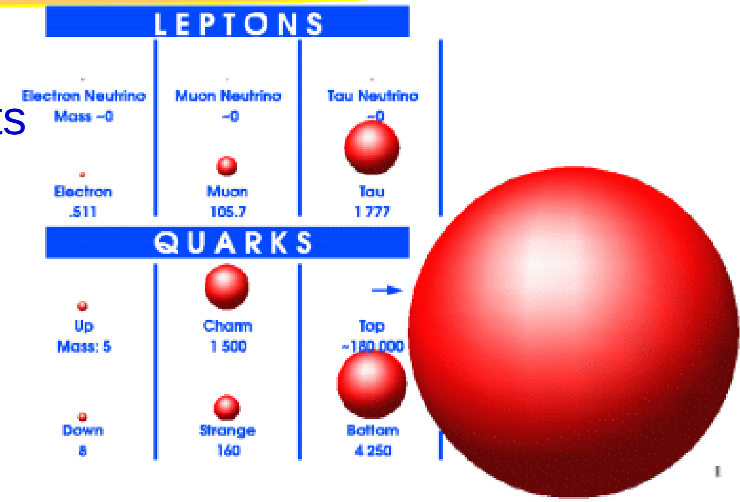
- More information:
  - ATLAS TopPublicResults
  - CMS: PhysicsResultsTOP

Introduction

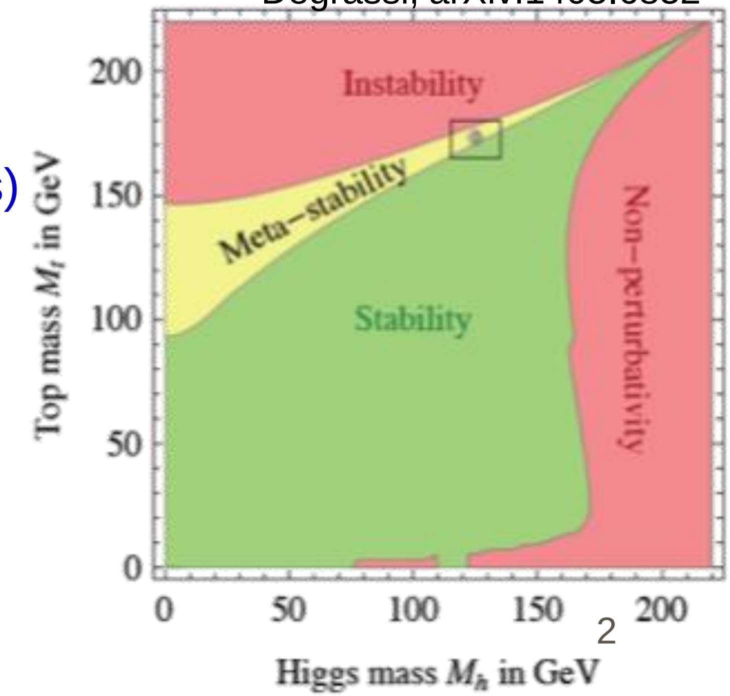
- Why is top quark physics interesting?
  - Top quark fits into the 3-generations of quark doublets
- But it is very heavy – 40x bottom quark
  - Same mass scale as W, Z and Higgs bosons – connection to EW symmetry breaking?
  - Now we know m_H=125 GeV, top Yukawa coupling is almost exactly 1… coincidence?

$$y_t = \sqrt{2}m_t/v \simeq 1$$

    - SM could be valid up to Plank scale, meta-stable?
- Top decays quickly, as a bare quark: $t\rightarrow Wb$
  - Lifetime of ~10^{-25} s too short to form hadrons (10^{-24} s)
    - Also shorter than spin de-correlation time (10^{-21} s)
- Heaviest particle in SM, copiously produced
  - Cross-section 0.2-1 nb at LHC energies (7-14 TeV)
  - Laboratory for QCD studies at highest energies
  - Important background and/or decay mode for BSM searches involving new heavy states



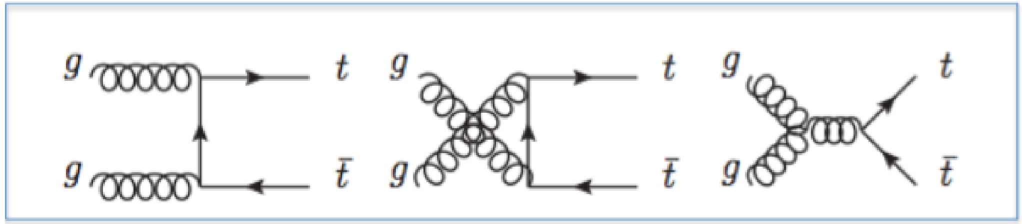
Degrassi, arXiv:1405.6852



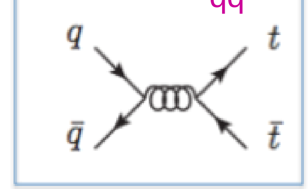
Top production at LHC

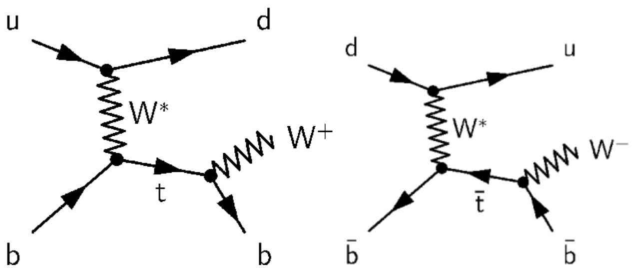
- Top quarks are copiously produced at LHC – some leading-order diagrams

Top-pair:
$\sigma_{tt} \approx$ 830 pb @ 13 TeV
gg fusion dominant

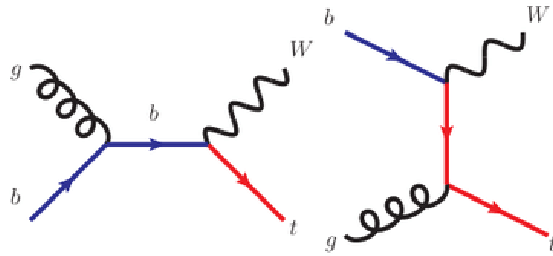


f_{qq}~11%

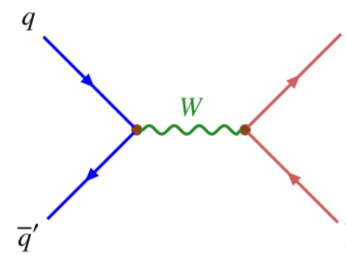




t-channel: $\sigma_{tq+t\sim q} \approx$ 220 pb



Wt: $\sigma_{Wt} \approx$ 79 pb



s-channel: $\sigma_s \approx$ 10 pb

  - Top-pair+X associated production (X=W,Z,H) with cross-sections ~1pb
- Top quarks decay t→Wb, → lνb or qqb
  - Final states include leptons, missing transverse energy, b-tagged jets and jets
- Top pair-production can be selected with high purity, especially in dilepton
  - But only ~2% produce the 'golden' eμ final state, so l+jets events also useful
- Cross-sections for single-top channels are much smaller
  - Rely on final states with leptons (t→lνb), and need multivariate techniques

The LHC top quark factory

- Numbers of top events produced at LHC
  - #events before reco-efi at $\sqrt{s}$=13 TeV for 140 fb^{-1} (Run2) and 3000 fb^{-1} (HL-LHC)
  - Theoretical predictions with scale, PDF and m_t (±1 GeV) uncertainties (%)

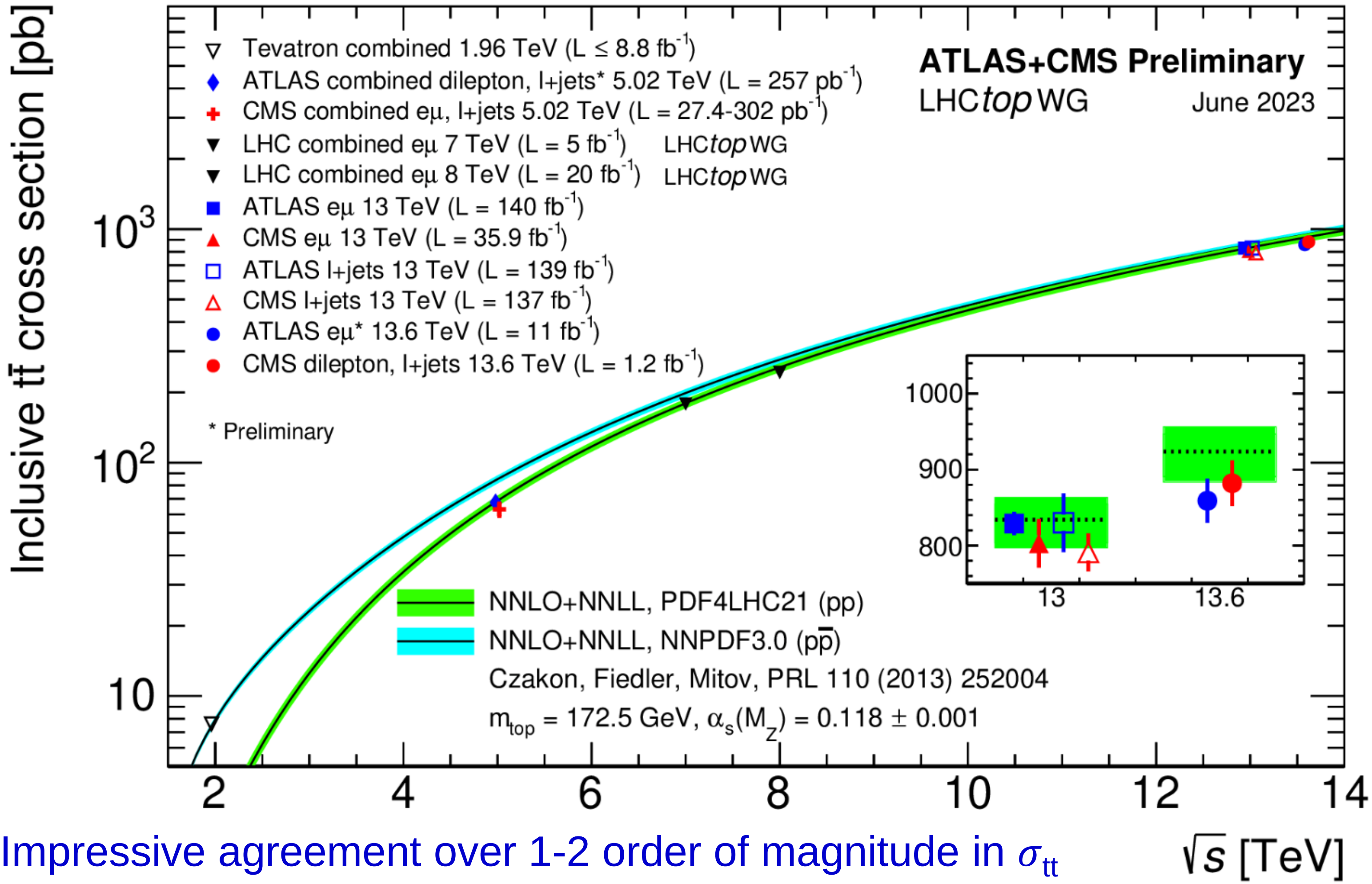
l=e+μ

Process	σ (pb)	Channel	BR	Run-2	HL-LHC	scale	PDF	m_t
tt	834	eμ	0.023	3M	60M	3.0	2.5	2.8
tt	834	l+jets	0.029	34M	730M			
t-chan	220	l+jets	0.22	7M	140M	1.0	1.2	0.8
Wt	79.3	eμ	0.023	0.3M	6M	2.3	2.8	1.5
ttW	0.72	W→l	0.22	20k	0.5M	10	1.0	
ttZ	0.86	Z→ll	0.07	10k	200k	9.2	3.2	
ttH	0.51	all	1	70k	1.5M	9.2	3.6	
4-top	0.012	all	1	1.7k	36k	10		

- Inclusive processes selected with 1 or 2 leptons
  - Millions of events (before reco. efficiency) already at Run2 – how to exploit at HL-LHC?
- More complex processes (e.g. ttH, 4-top) exploit many final states
  - 2 (SS) leptons, 3 leptons, large jet/b-jet multiplicity
  - Including acceptance/efficiency and backgrounds, 4-tops just reached 5σ at Run-2

Inclusive top-pair production

- Comparison of measurements to NNLO+NNLL calculation



- Impressive agreement over 1-2 order of magnitude in σ_{tt}
  - At 13 TeV, expt. unc. of 1.8% (ATLAS eμ+b-jets) c.f. ~4% for pred. with PDF4LHC21

Precision of inclusive ttbar measurements

- Uncertainties (%) on most precise dilepton / l+jets measurements at 13 TeV
  - Approximate breakdown in categories (approximate for profile likelihood fits)

Collab.	Chan	L(fb^{-1})	Stat.	tt model	Det	Bkgd	Lumi	Total	Ref
ATLAS	eμ	140	0.15	1.0	0.8	0.8	0.9	1.8	JHEP 07 (2023) 141
CMS	ll	35.9	0.2	2.3	2.1	1.5	2.5	4.0	EPJC 79 (2019) 368
ATLAS	l+jets	139	0.05	4.2	3.1	1.7	1.7	4.6	PLB 810 (2020) 135797
CMS	l+jets	2.2	0.2	1.7	2.3	1.9	2.3	3.8	JHEP 09 (2017) 051

- Most precise result from ATLAS eμ + b-jet analysis with full data sample
  - Simple event counting of 1b/2b events to calibrate b-tagged jet efi. in situ.
  - tt modelling uncertainties from leptonic acceptance (e.g. PDF, top quark p_T)
    - Background uncertainties dominated by Wt x-sec and tt/Wt interference
  - Detector uncertainties dominated by lepton efi., calibrated in-situ and in Z→ll
  - Benefits from final ATLAS Run-2 luminosity uncertainty of 0.83%
  - Challenging to reduce this further (better top-pair and background modelling?)
- Profile likelihoods on multiple distributions (esp l+jets) are less precise ...

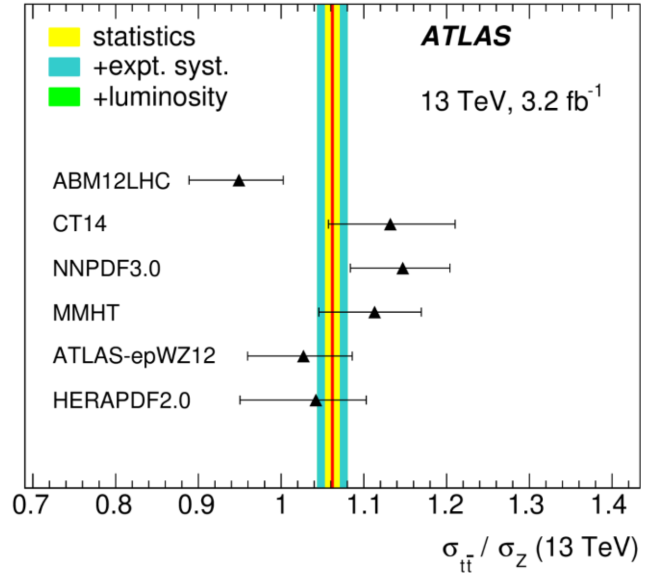
tt/Z cross-section ratios

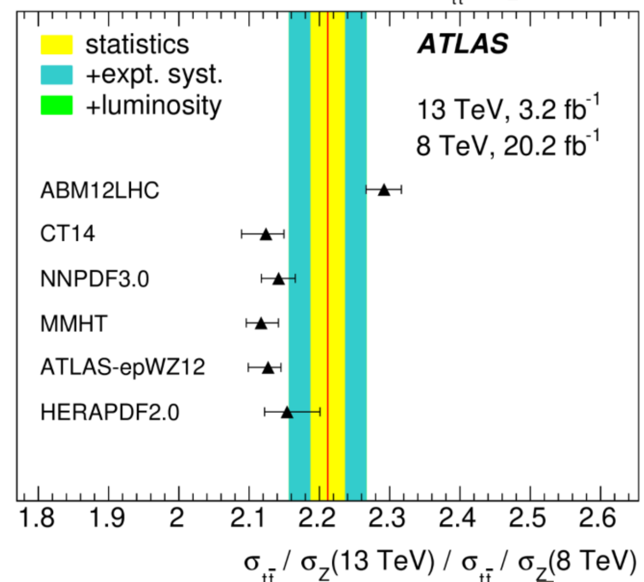
- Ratios of tt/Z cross-sections are useful — Mangano, Rojo
  - E.g. PDF constraints, BSM tests, JHEP 08 (2012) 010
  - Luminosity and lepton efi. systematics cancel

$$R_{t\bar{t}/Z} = \frac{\sigma_{t\bar{t}}}{0.5\left(\sigma_{Z\to ee} + \sigma_{Z\to\mu\mu}\right)}$$

- Exploited by ATLAS in JHEP 02 (2017) 117
  - Updated ratios with better σ_{tt} in EPJC 80 (2020) 528

$\sqrt{s}$ value [TeV]	$t\bar{t}/Z$ cross-section ratio	CT14 prediction
13	$1.062 \pm 0.009 \pm 0.016 \pm 0.002\ (0.018)$ 1.7%	$1.132^{+0.078}_{-0.075}$ 6.9%
$\sqrt{s}$ values [TeV]	$t\bar{t}/Z$ cross-section double ratio	
13/7	$2.617 \pm 0.049 \pm 0.060 \pm 0.007\ (0.078)$ 2.9%	$2.691^{+0.045}_{-0.058}$ 1.9%
13/8	$2.212 \pm 0.024 \pm 0.049 \pm 0.006\ (0.055)$ 2.5%	$2.124^{+0.026}_{-0.035}$ 1.4%

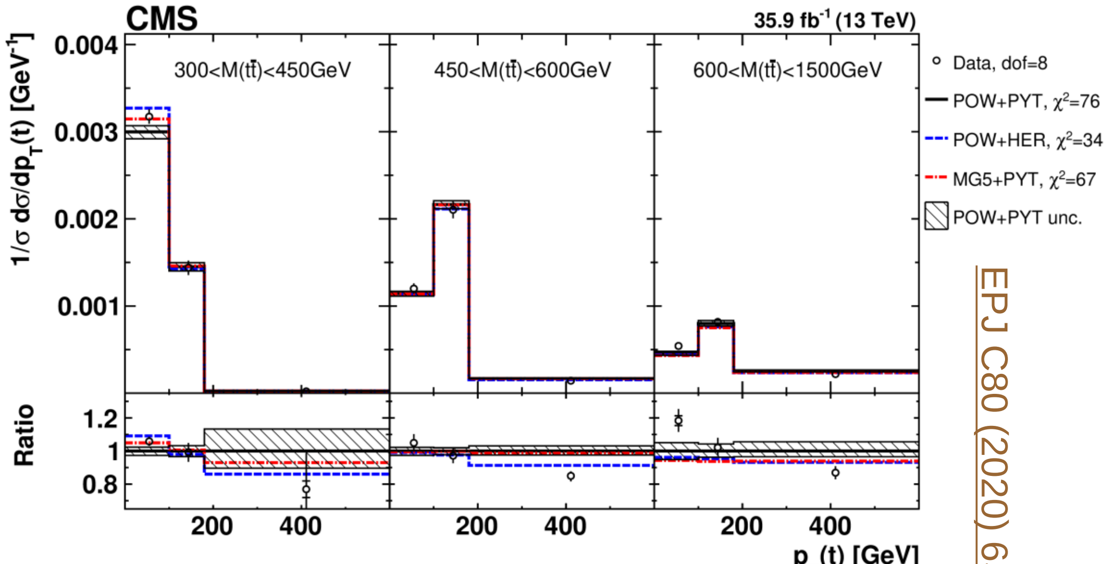




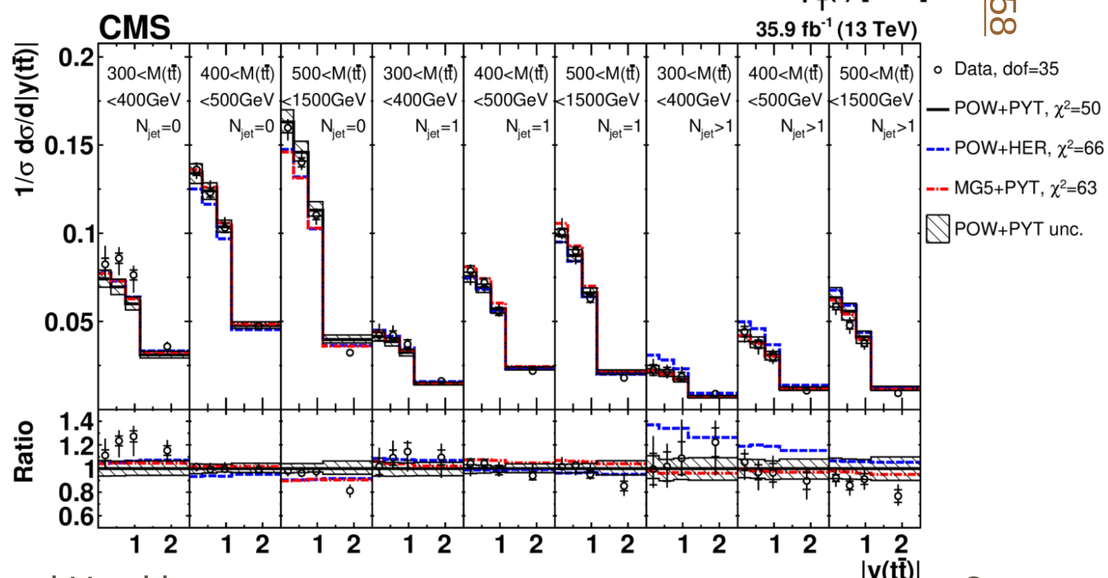
  - tt/Z ratio sensitive to gluon vs quark PDF
  - Double ratio reduces PDF, scale and m_t prediction unc.
    - At expense of larger experimental unc. from Run 1 data
  - Single ratio not yet measured with full Run 2 data

tt differential measurements

- Differential measurements attempt to reconstruct parton kinematics
  - Dilepton final state gives easier access to tt+N jets, harder tt reco^n
  - Uncertainties 5-10% up to 20%
- Normalised 1D/2D/3D x-secs compared to various NLO+PS MC
  - Default simulation tunes do not usually describe all features
    - Could be improved with tuning?



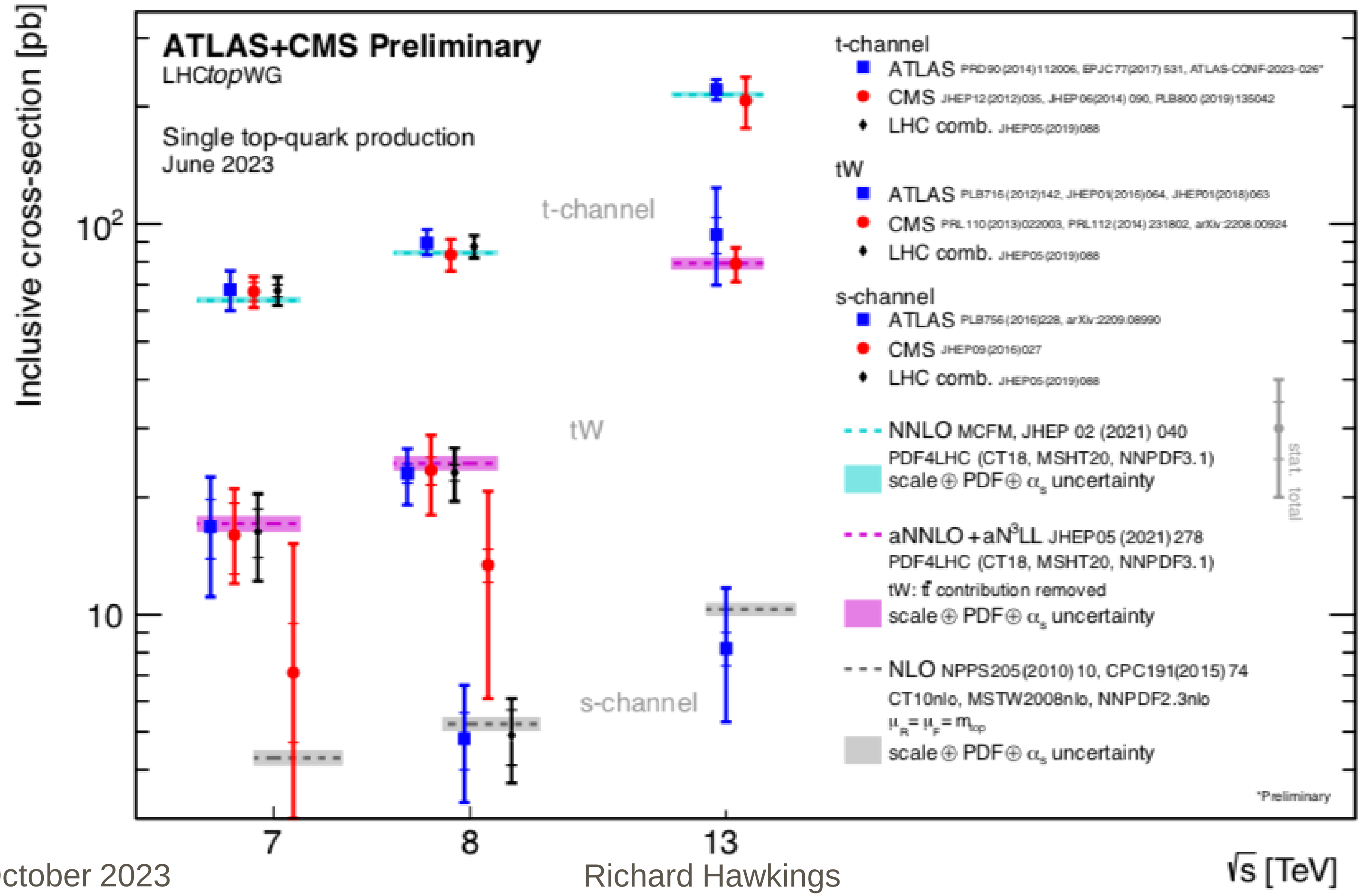
EPJ C80 (2020) 658



Cross section variables	dof	χ^2 'POW+PYT'	χ^2 'POW+HER'	χ^2 'MG5+PYT'
$[y(\mathrm{t}), p_\mathrm{T}(\mathrm{t})]$	15	57	18	35
$[M(\mathrm{t\bar{t}}), y(\mathrm{t})]$	15	26	18	36
$[M(\mathrm{t\bar{t}}), y(\mathrm{t\bar{t}})]$	15	28	17	23
$[M(\mathrm{t\bar{t}}), \Delta\eta(\mathrm{t},\mathrm{\bar{t}})]$	11	66	68	124
$[M(\mathrm{t\bar{t}}), \Delta\phi(\mathrm{t},\mathrm{\bar{t}})]$	15	14	18	10
$[M(\mathrm{t\bar{t}}), p_\mathrm{T}(\mathrm{t\bar{t}})]$	15	21	22	29
$[M(\mathrm{t\bar{t}}), p_\mathrm{T}(\mathrm{t})]$	15	77	34	68
$[N_\mathrm{jet}^{0,1+}, M(\mathrm{t\bar{t}}), y(\mathrm{t\bar{t}})]$	23	34	31	34
$[N_\mathrm{jet}^{0,1,2+}, M(\mathrm{t\bar{t}}), y(\mathrm{t\bar{t}})]$	35	50	66	63

Single top measurements

- t-channel and Wt reach uncertainties of 5-10%, good agreement with pred^{n}
  - Much larger uncertainties for s-channel (smaller x-sec and larger background)



ATLAS t-channel measurement at 13 TeV

- Final state with t→blν plus forward spectator jet from t-channel process
  - Significant background from tt and W+jets, reduced with kinematics-based NN
- Simultaneous measurement of t (with l^+) and anti-t (with l^-) production
  - Results: $\sigma(tq) = 137 \pm 8\,\text{pb}$ and $\sigma(\bar{t}q) = 84^{+6}_{-5}\,\text{pb}.$ (~6%, c.f. 1.6, 2% pred^{n})
  - Systematics dominated by signal modelling and jet calibration
  - Ratio R_t=σ(tq)/σ(t~q) measured to be $1.636^{+0.0036}_{-0.0034}$ (~2%)
    - Result sensitive to differences in u and d quark PDFs – moderate discrimination
  - Total t-channel x-sec is also sensitive to V_{tb}; $|V_{tb}|$>0.95

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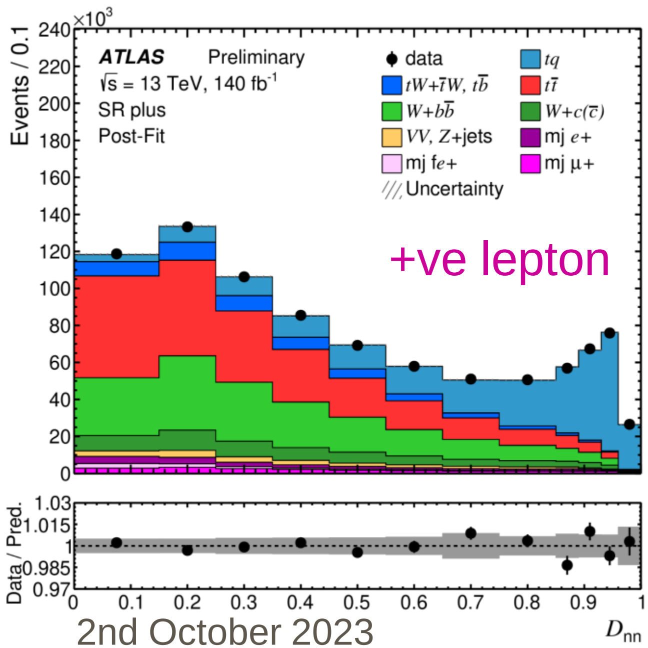
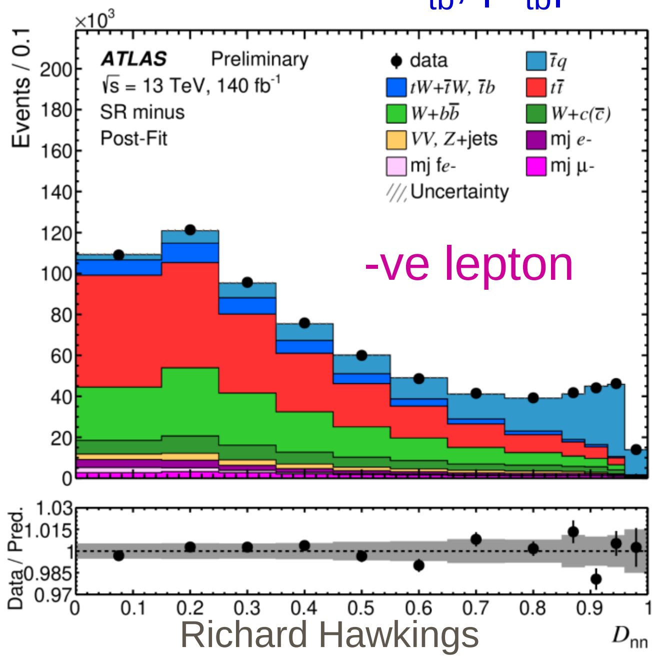
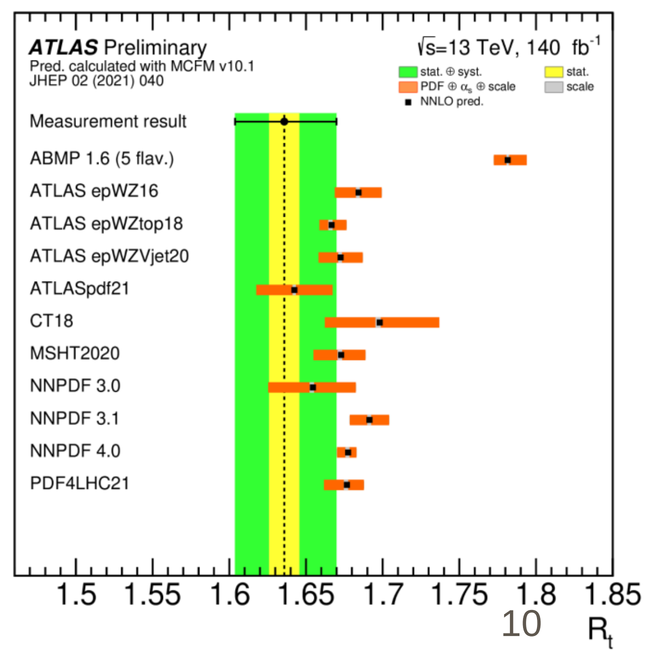




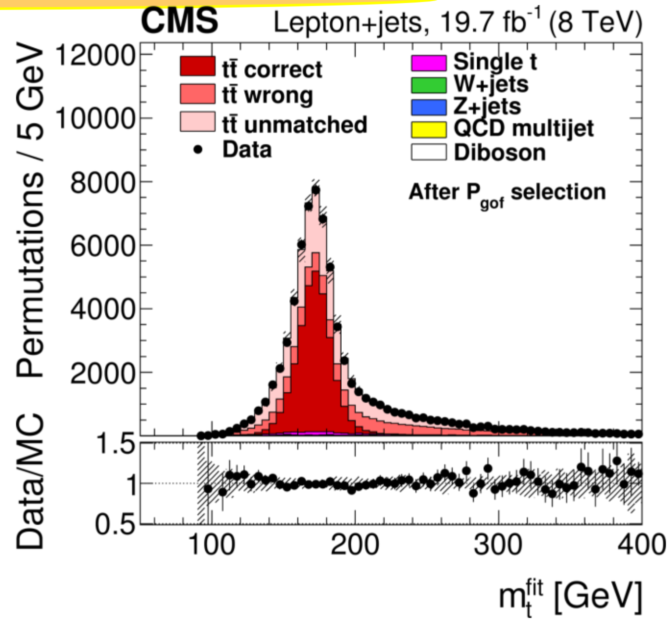


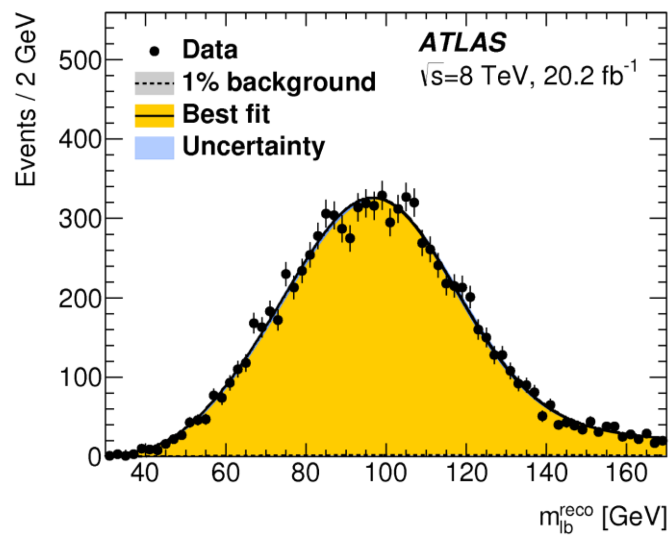
The top quark mass – introduction

- A fundamental SM parameter – precise measurement is a key LHC goal
  - Needed for the precision electroweak fit
    - Loop corrections to W mass lead to 1 MeV uncertainty in m_W for 100 MeV in m_t
  - Requires m_t in a well-defined scheme, typically the pole mass m_t^{pole}
- Experimental measurements fall into two types:
- Measurements from the decay products, reconstructing $m=\sqrt{(E^2-p^2)}$
  - Complex observables, cannot be related to m_t in a well-defined scheme
    - Effectively a measurement of the mass parameter in an MC generator, m_t^{MC}
  - Expect m_t^{MC} to be within ~0.5 GeV of m_t^{pole} (e.g. see A. Hoang, 2004.12915)
- Measurements in well-defined mass schemes, typically from cross-sections
  - σ_{tt}, or differential cross-sections with enhanced sensitivity to m_t
  - Typically have a greater sensitivity to top production modelling (e.g. PDFs, p_T(t))
- In both cases, systematic uncertainties are often already dominant
  - Experiments exploring various ways to reduce modelling uncertainties directly using the data, or by making optimised selections

Direct measurements at Run-1

- Fit per-event m_t from leptons, jets (and E_T^{miss})
  - In l+jets channel, kinematic fit can fully reconstruct event to find best m_t hypothesis
    - Ambiguities in jet assignment need to be resolved
    - Reconstructed m_W from W→qq used to constrain (light) jet energy scale in-situ
  - Dilepton events are under-constrained (2 ν)
    - Use analytical matrix reweighting or fit to partially reconstructed observables (m_{bl}, m_{T2})
  - All-hadronic channel also exploited, less precise
- In all cases, ME+PS Monte Carlo is used to 'calibrate' observables
  - Fits to to MC templates with different m_t assumptions ⟹ measuring the 'MC mass'
    - Expected to be within ~0.5 GeV of the pole mass or the MSR(1 GeV) mass
    - Uncertainty **not** included in experimental results





Run-1 top mass combination

- New combination of all Run-1 measurements

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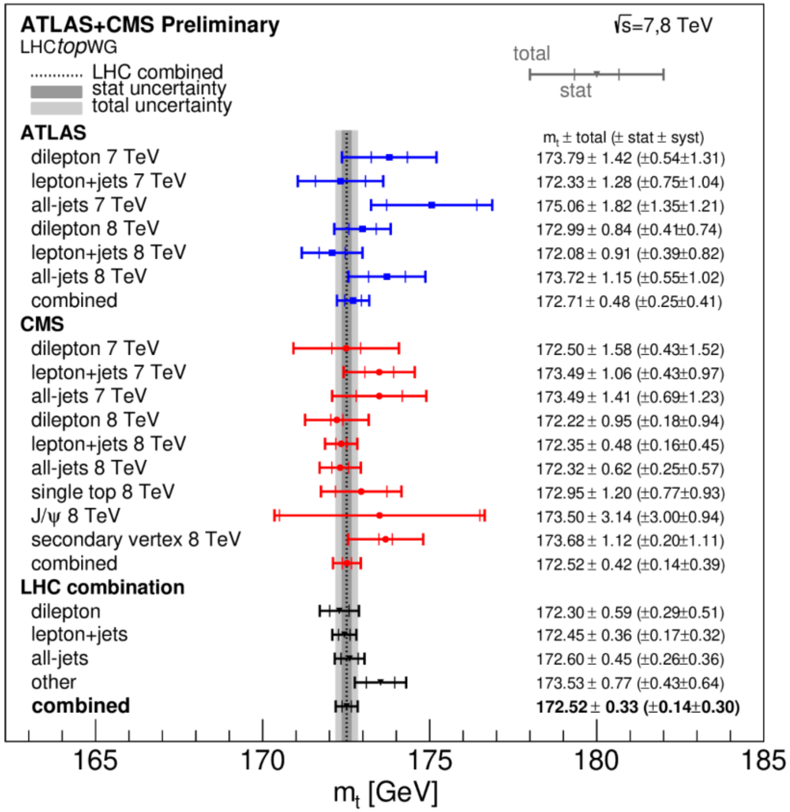
CMS-PAS-TOP-22-001
CERN-LPCC-2023-02



$$m_t = 172.52 \pm 0.14\,(\text{stat}) \pm 0.30\,(\text{syst})\ \text{GeV}$$

- Excellent χ^2 compatibility of 91%
- Already systematics dominated – how to improve?
  - Largest contrib^{n}s from JES, b-tagging, tt modelling

size of systematic ↑

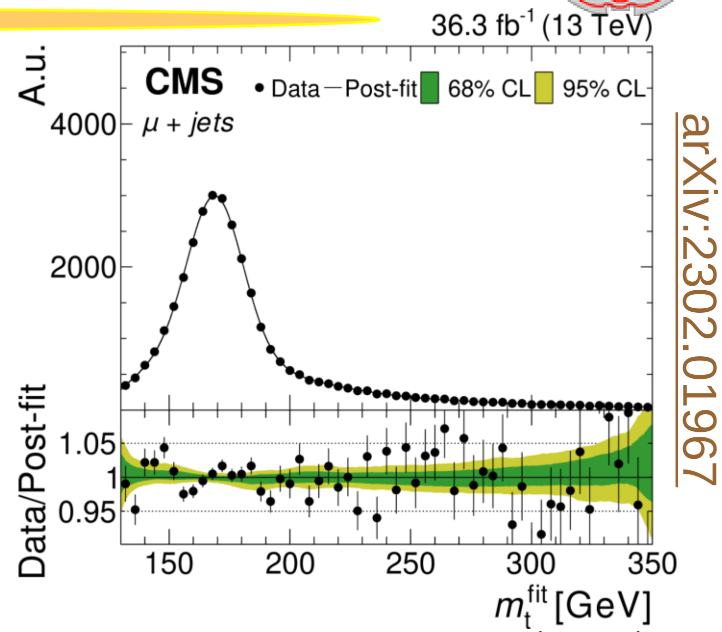
Uncertainty category	Uncertainty impact [GeV] LHC	ATLAS	CMS
LHC b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
LHC JES 1	0.08	0.18	0.06
LHC JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS B hadron BR	0.07	—	0.12
LHC radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
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
LHC g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
LHC l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
LHC JES 3	0.02	0.07	0.01
LHC 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 systematics	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42

Run 2 m_t measurement – CMS l+jets

- Reanalysis of 2015-16 l+jets data
  - New mass extraction with profile likelihood fit
    - Improvements in b-tagging, MC tune, ..
- Kinematic fit χ^2 used to pick best jet combination
  - Recon. m_W, m_{lb}/m_t, $R_{lb}=(p_T^{b1}+p_T^{b2})/(p_T^{q1}+p_T^{q2})$ used as additional observables to constrain systematics
  - m_{lb} in events without good kinematic fit also used
- '5D' fit with all variables gives very precise result

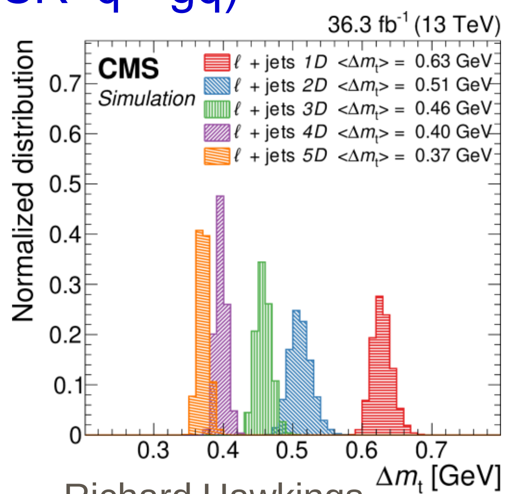
$$m_t^{5D} = 171.77 \pm 0.37\,\text{GeV}$$ (stat. 0.04 GeV)

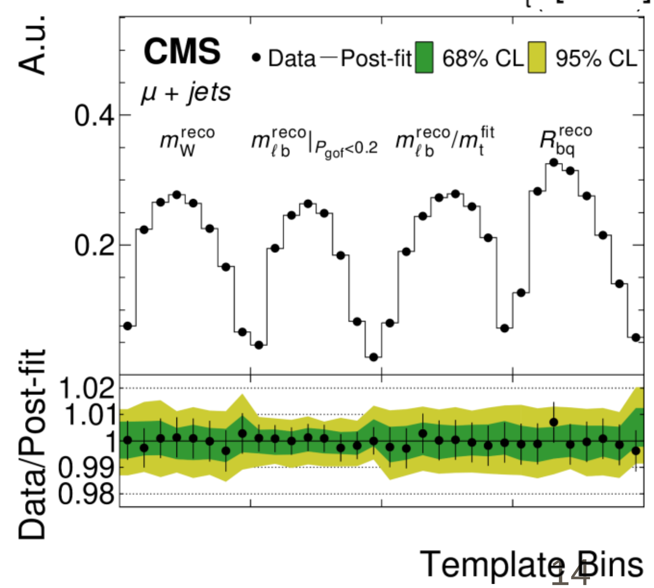
  - Good description of data, but strong constraints of some modelling systs (e.g. FSR q→gq)



arXiv:2302.01967

Observable	Histogram Category	Set label 1D	2D	3D	4D	5D
m_t^{fit}	$P_{gof} > 0.2$	×	×	×	×	×
m_W^{reco}	$P_{gof} > 0.2$		×	×	×	×
$m_{\ell b}^{reco}$	$P_{gof} < 0.2$			×	×	×
$m_{\ell b}^{reco}/m_t^{fit}$	$P_{gof} > 0.2$				×	×
R_{bq}^{reco}	$P_{gof} > 0.2$					×



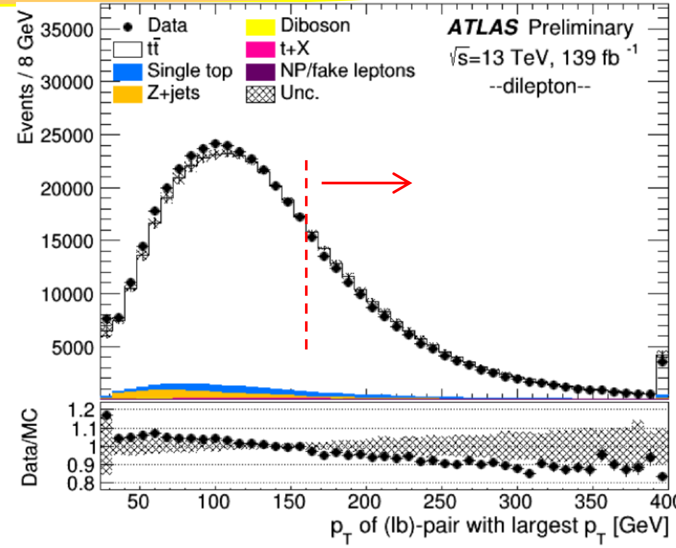


Run 2 m_t measurement – ATLAS dilepton

- Strategy improved wrt. Run 1 measurements
  - DNN algorithm to pick correct lb-lb pairing, based on event kinematics
    - Efficiency of 88% with purity of 79%
  - Cut on DNN and on p_T(lb)>160 GeV to reduce signal modelling and jet systematics
    - Keeps 20% of sample, exploiting Run-2 statistics
- Template fit performed to m_{lb} of selected pair
  - Modelling systematics considered by changing the model in pseudo data, no likelihood profiling

$$m_{top}^{dilepton} = 172.21 \pm 0.20\,(\text{stat}) \pm 0.67\,(\text{syst}) \pm 0.39\,(\text{recoil})\ \text{GeV}.$$

  - Result has similar precision to 8 TeV analysis
    - Dominant errors from choice of matrix element, colour reconnection (new models), jet energy scale
  - 'Recoil' error from t→Wbg decay in Pythia8
    - Subsequent gluons recoil against b (default) or top (alternative, more consistent)
    - No dedicated recoil-to-top tune – conservative?



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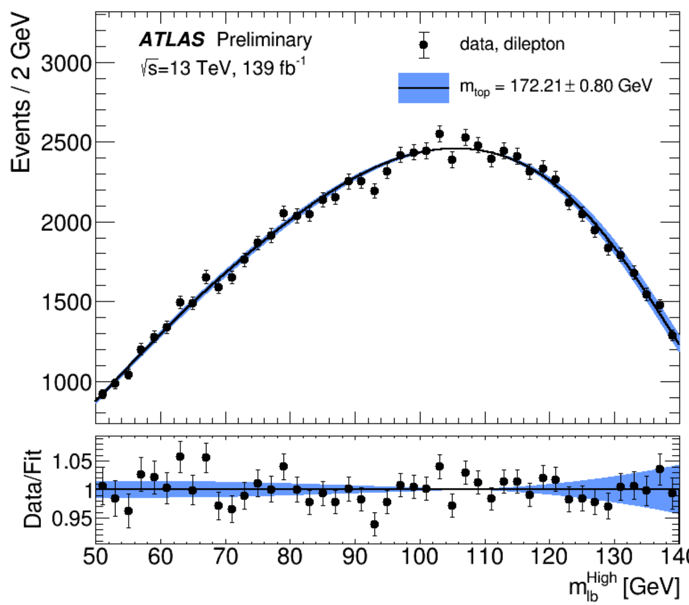


Top mass Run-2 uncertainty comparisons

CMS l+jets

	δm_t [GeV] previous 2D	2D	5D
Experimental uncertainties			
Method calibration	0.05	0.02	0.02
JEC	0.18	0.32	0.16
– Intercalibration	0.04	0.10	0.04
– MPFInSitu	0.07	0.15	0.07
– Uncorrelated	0.16	0.21	0.10
Jet energy resolution	0.12	0.12	0.05
b tagging	0.03	0.01	0.03
Lepton SFs and mom. scale		0.00	0.03
Pileup	0.05	0.00	0.03
Background	0.02	0.12	0.15
Modeling uncertainties			
JEC flavor	0.39	0.30	0.20
b-jet modeling	0.12	0.15	0.11
PDF	0.02	0.00	0.01
Ren. and fact. scales	0.01	0.03	0.02
ME/PS matching	0.07	0.06	0.07
ISR PS scale	0.07	0.01	0.01
FSR PS scale	0.13	0.37	0.21
Top quark p_T	0.01	0.06	0.00
Underlying event	0.07	0.09	0.04
Early resonance decays	0.07	0.13	0.09
CR modeling	0.31	0.15	0.15
Statistical	0.08	0.05	0.04
Total	0.63	0.52	0.37

ATLAS dilepton

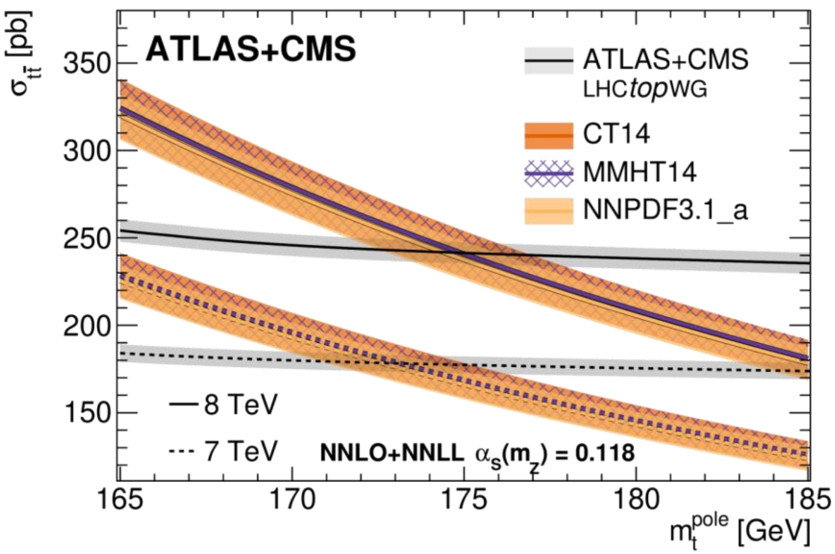
	m_{top} [GeV]
Result	172.21
Statistics	0.20
Method	0.05 ± 0.04
Matrix-element matching	0.40 ± 0.06
Parton shower and hadronisation	0.05 ± 0.05
Initial- and final-state QCD radiation	0.17 ± 0.02
Underlying event	0.02 ± 0.10
Colour reconnection	0.27 ± 0.07
Parton distribution function	0.03 ± 0.00
Single 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

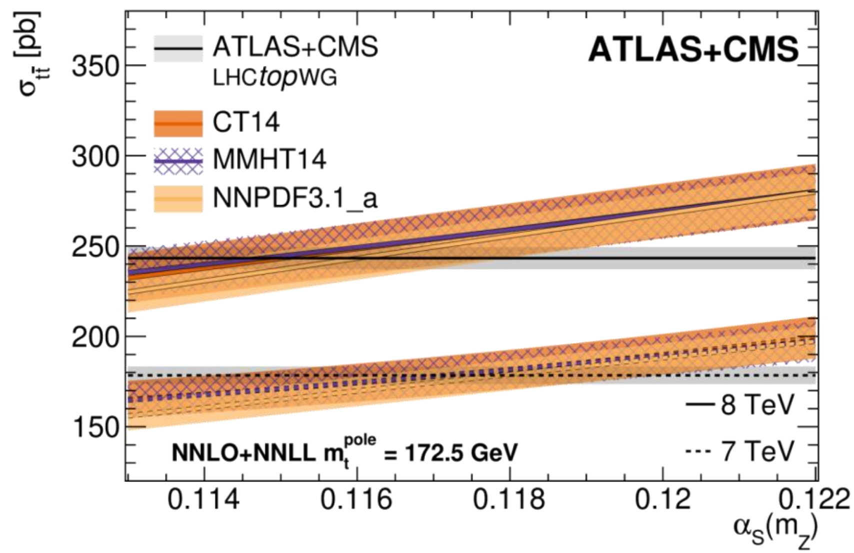
- Largest CMS uncertainties from jet calibration, FSR, colour reconnection
- Largest ATLAS uncertainties from ME matching (different generators), jet calibration, colour reconnection and top decay recoil matching (not in CMS)

- Need to reduce 0.5 GeV ‘MC mass interpretation’ uncertainty to make use of future data – new ideas?

Extraction of m_t and α_S from tt cross-section

- Measured σ_{tt} can be used to extract pole mass m_t^{pole}, assuming a value of α_S
  - Or vice versa – assume m_t^{pole} and extract α_S
  - σ_{tt} results depend on assumed MC mass as acceptance/kinematics depend on m_t
    - Have to assume m_t^{pole} and m_t^{MC} are equal within a few GeV





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- Using combination of ATLAS+CMS dilepton results at 7 or 8 TeV (±2.7% or 2.5%)
- Simultaneous χ^2 fits to 7+8 TeV σ_{tt}
  - Precision of ~2 GeV on m_t^{pole}, limited by PDF and scale uncertainties on pred^n
  - Most precise α_S extraction from top events

PDF set	m_t^{pole} ($\alpha_s = 0.118 \pm 0.001$)	$\alpha_s(m_Z)$ ($m_t = 172.5 \pm 1.0$ GeV)
CT14	$174.0^{+2.3}_{-2.3}$ GeV	$0.1161^{+0.0030}_{-0.0033}$
MMHT2014	$174.0^{+2.1}_{-2.3}$ GeV	$0.1160^{+0.0031}_{-0.0030}$
NNPDF3.1_a	$173.4^{+1.8}_{-2.0}$ GeV	$0.1170^{+0.0021}_{-0.0018}$

Measurements from ttbar+1 jet

- Extract m_t^{pole} from diff-xsec in ttbar+1 jet events

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \cdot \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s} \qquad \rho_s = \frac{2m_0}{m_{t\bar{t}+1\text{-jet}}}$$

Sensitivity at $\rho \to 1$ threshold

  - 1/N $d\sigma/d\rho$ unfolded to parton level and compared to fixed-order QCD predictions
- CMS 13 TeV analysis with ML and profile LH
  - ML-based regression to reconstruct ρ_{reco}
  - Profile likelihood to extract parton-level $d\sigma/d\rho$ in four bins, all expt. uncertainties profiled (inc. m_t^{MC})
  - Comparison to prediction with specific PDF

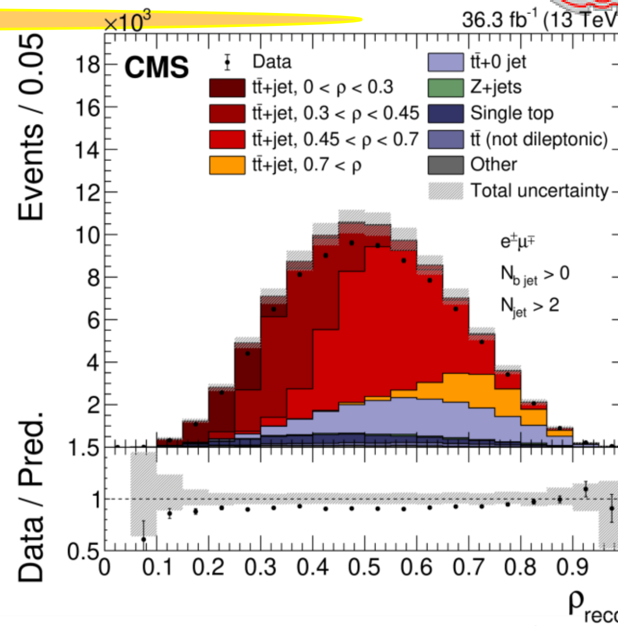
$$m_t^{\text{pole}} = 172.93 \pm 1.26\,(\text{fit})\,^{+0.51}_{-0.43}\,(\text{scale})\,\text{GeV}$$

(ABMP16NLO)

  - ~0.5 GeV uncertainty from QCD scales in pred^n
    - Uncertainties from AMBP16NLO included in ‘fit’ uncertainty, result with CT18NLO shifts by -0.8 GeV
  - ATLAS 8 TeV result with simpler unfolding

$$m_t^{\text{pole}} = 171.1 \pm 0.4\,(\text{stat}) \pm 0.9\,(\text{syst})\,^{+0.7}_{-0.3}\,(\text{theo})\,\text{GeV}$$

    - Measurements do not yet break the 1 GeV barrier



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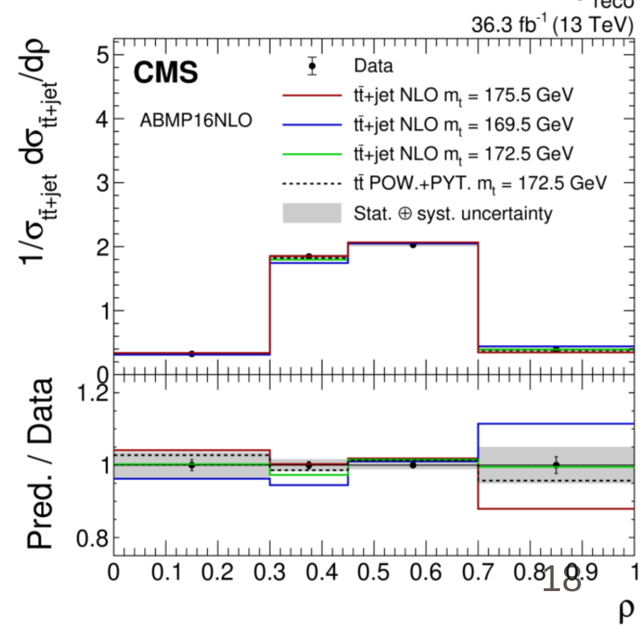
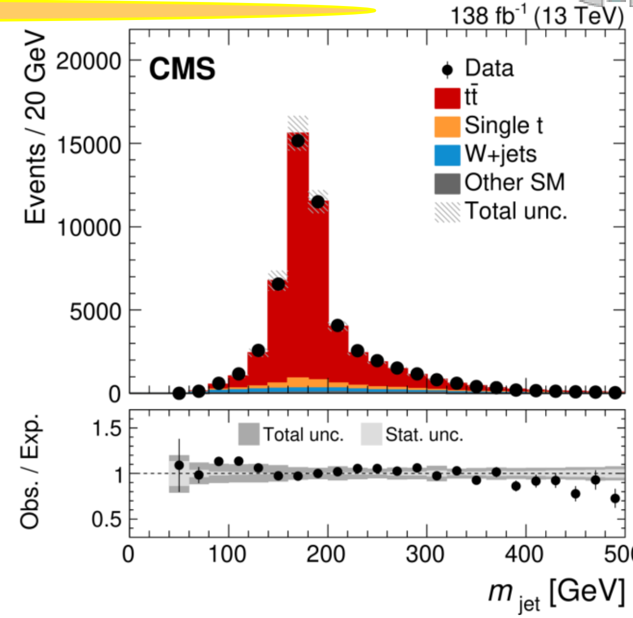


Boosted jet measurements

- Differential x-sec vs jet mass in boosted tt events
  - Select $t\rightarrow bW\rightarrow bqq$ in large-radius jet with p_T>400 GeV
  - Unfold jet mass to particle level, hope to eventually compare to analytic calculations in pQCD
    - For now, compare to predictions of NLO+PS MC
- CMS analysis using l+jets events in Run 2 data
  - Reconstruct large-radius jet with XCone algorithm
    - Also reconstruct 3 sub-jets (bqq)
    - Untagged subjets ($W\rightarrow qq$) used to calibrate mass scale
    - Jet substructure (τ_{32} in R=0.8 anti-k_T jets) used to tune FSR
  - Unfolded distribution fitted to Powheg+Pythia8 pred^n

$$m_t = 173.06 \pm 0.24\,(\text{stat}) \pm 0.61\,(\text{exp}) \pm 0.47\,(\text{model}) \pm 0.23\,(\text{theo})\ \text{GeV}$$

  - Dominant systematic uncertainties from jet mass scale and energy resolution – different to other techniques
- ATLAS explored use of boosted jet mass to 'calibrate' m_t^{MC} in topologies with p_T>750 GeV
  - Real data studies will benefit from HL-LHC statistics



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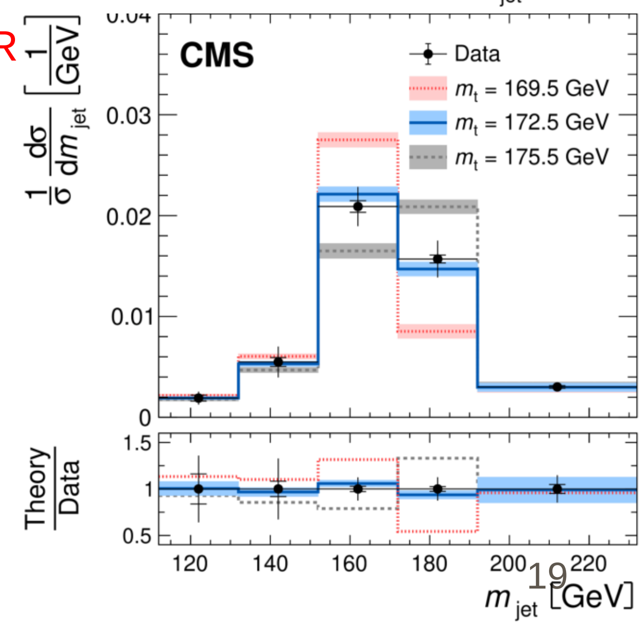


Other m_t measurements from cross-sections

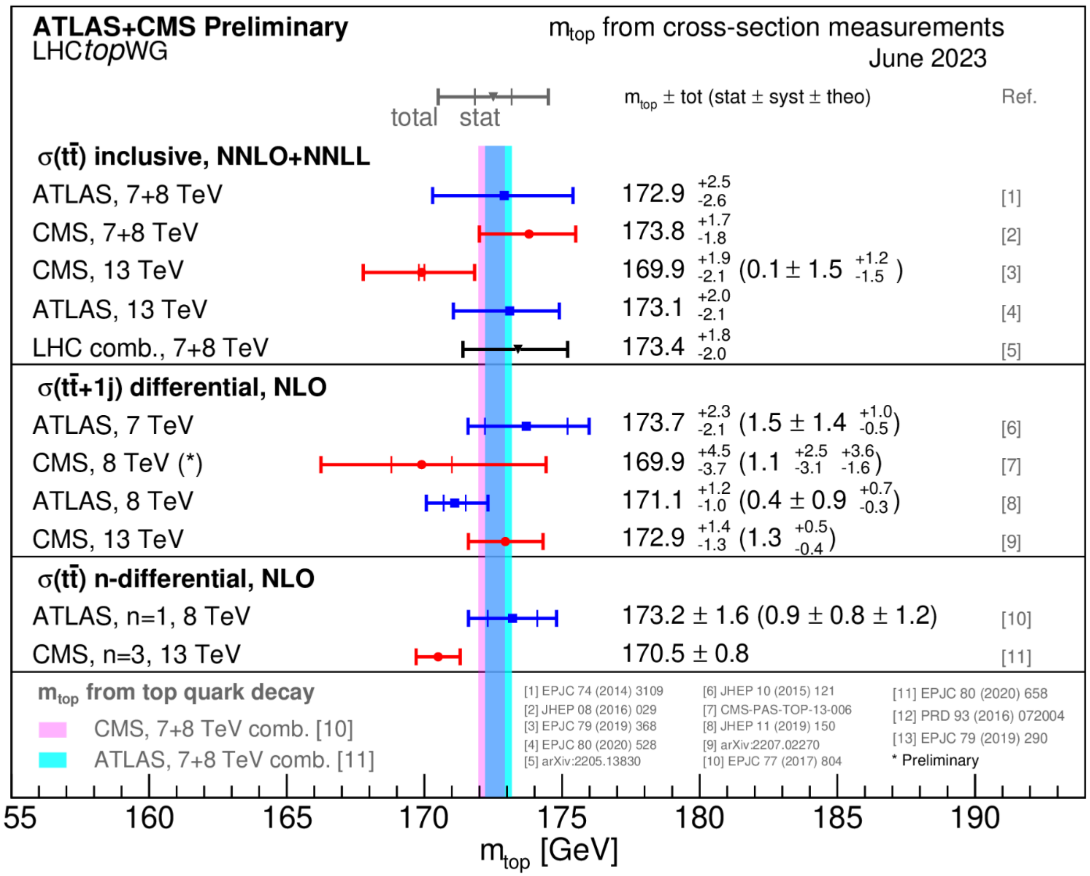
- NLO fixed-order fits to m_t^{pole} +PDFs using differential distributions
  - Eight lepton distributions
    - ATLAS using 8 TeV data

$$m_t^{\mathrm{pole}} = 173.2 \pm 0.9 \pm 0.8 \pm 1.2\,\mathrm{GeV}$$

- Simultaneous extraction of PDFs, m_t^{pole} and α_S from CMS-3D diff^n

$$m_\mathrm{t}^{\mathrm{pole}} = 170.5 \pm 0.8\,\mathrm{GeV}$$

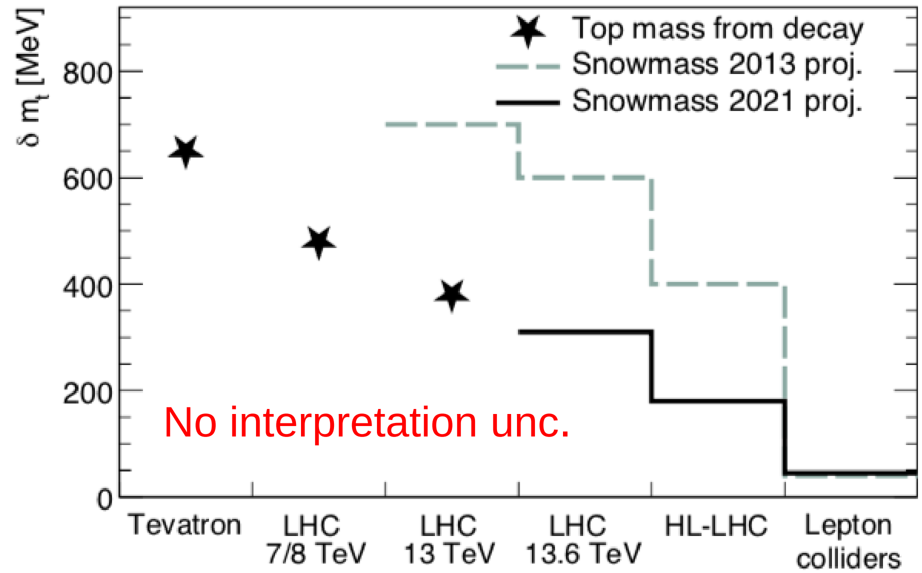
    - Missing ~+1 GeV threshold corr^n ?
- Uncertainties of ~2 GeV from inclusive x-secs, ~1 GeV from diff.
  - Not yet 'competitive' with direct measurements at or below 0.5 GeV
  - Cannot yet probe the compatibility of m_t^{MC} and m_t^{pole} (or m_t^{MSbar})
    - Reduction of systematics, new ideas as well as new data needed



Future top mass precision

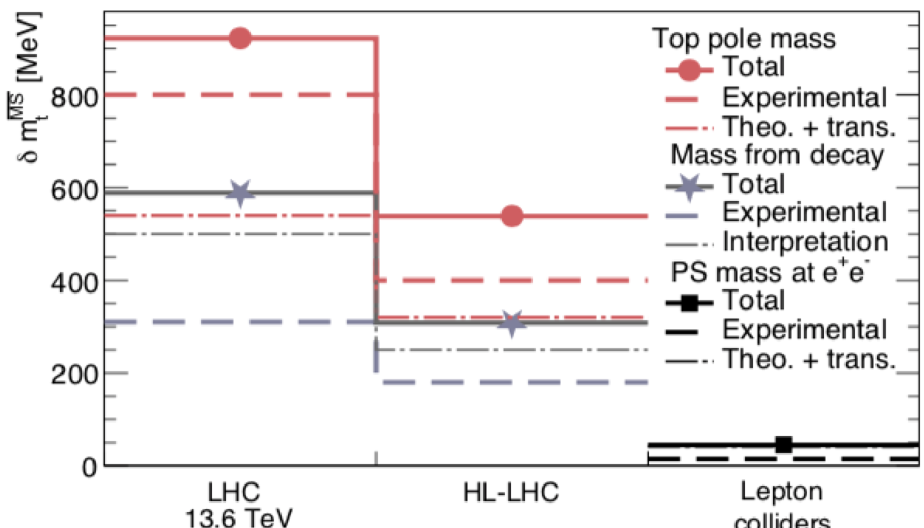
- Projections in Snowmass 2021 report
  - Direct measurements from decay, not including MC mass interpretation unc.

δm_t^{MC} [MeV]	Tevatron	LHC					HL-LHC
		Run 1		Run 2		Run 3	
		ATLAS	CMS	ATLAS	CMS		
$\sqrt{s}$ [TeV]	1.96	7,8	7,8	13	13	13.6	14
$\mathcal{L}$[fb^{-1}]	9.7	5, 20	5, 20	36	36	300	3,000
Statistical uncert.	350	250	130	400	40	40	20
Systematic uncert.	540	410	470	670	380	300	170
Total uncert.	650	480	480	780	380	310	170



  - Pole mass measurements from production
    - Assuming combination of tt and ttj, and reductions in PDF unc. from top results

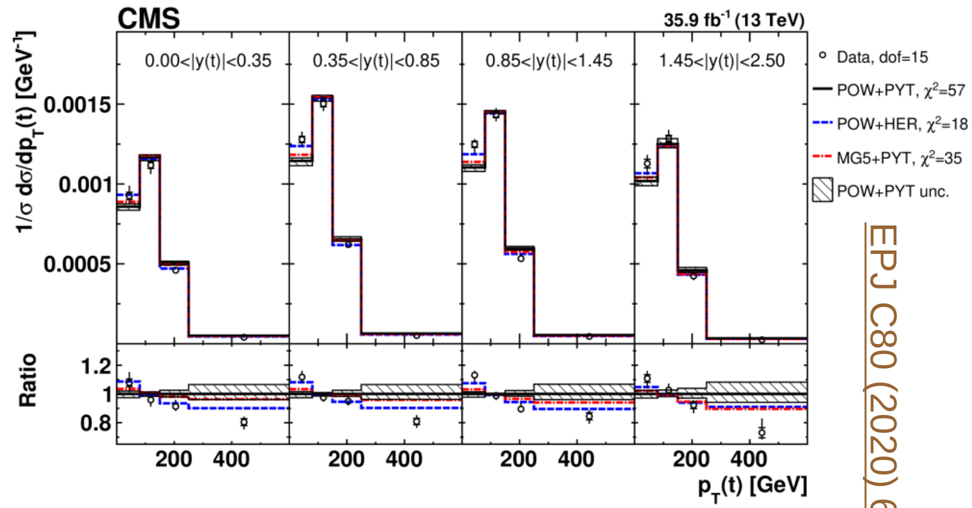
δm_t^{pole} [GeV]	Tevatron	LHC Run 1	LHC Run 2	LHC Run 3	HL-LHC
$\sqrt{s}$ [TeV]	1.96	7/8	13	13.6	14
$\mathcal{L}$[fb^{-1}]	10	20	140	300	3,000
Experimental uncertainty	2.2	1.0	1.3	0.8	0.4
Theoretical uncertainty	1.4	0.7	0.5	0.5	0.25
Total uncertainty	2.5	1.2	1.4	0.9	0.5



  - Future focus on m_t^{MSbar} rather than m_t^{pole} ?
    - Easier to relate to m_t^{MC} with NLL showers?
  - Potential for ~0.3/0.5 GeV from decay/prod

Monte Carlo developments

- Full exploitation of present and future top samples needs improved MC, e.g.
  - Modelling of t and tt p_T distributions
    - Currently using ad-hoc reweighting schemes to NNLO predictions
    - Future move to MiNNLOPS samples?
- Ad-hoc 2-point systematic comparisons
  - Powheg+{PY8,HW7}, Powheg vs MG5
  - Trend towards full set of uncertainties in one generator, better for profile likelihoods
    - Does this capture all the uncertainties?
- tt vs. Wt interference in dilepton events
  - Traditional diagram removal vs. diagram subtraction is limiting in some analyses
  - Alternative DR-DS schemes
  - Deployment of 'bb4l' in PowhegBox
    - bb4l often closer to DS scheme



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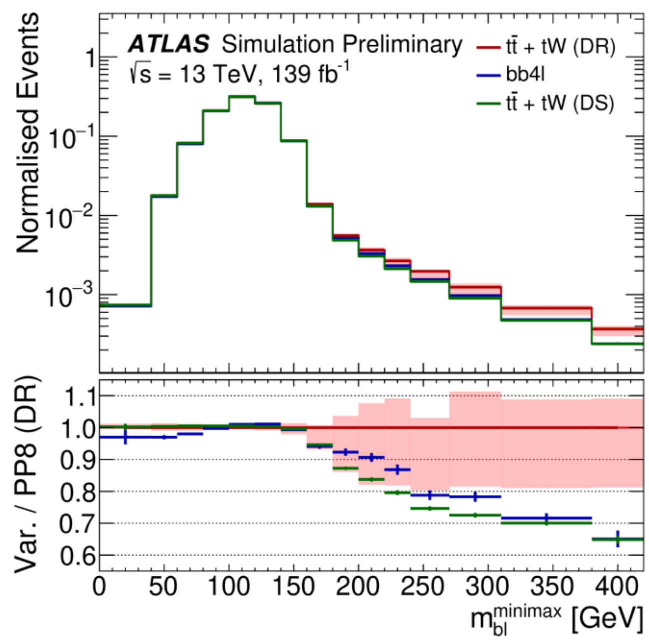

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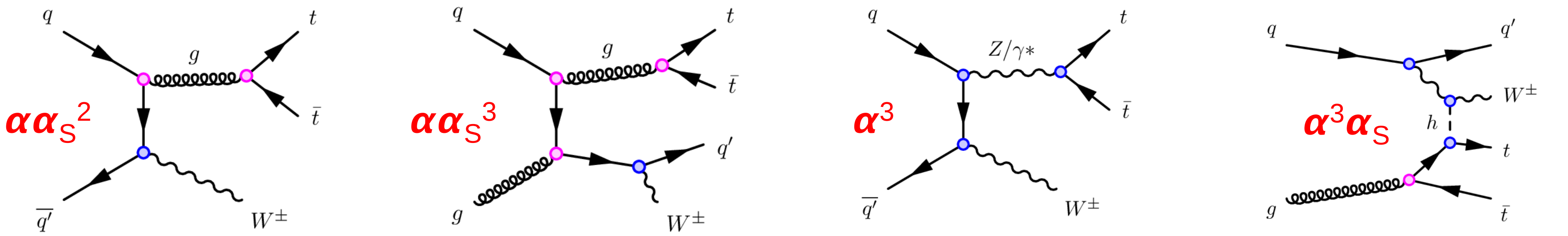
Top-pair + X: ttW production

- tt+W/Z/H a main focus of the Run 2 (and Run 3) physics programme
  - ttW is one of the most complex: SS-lepton pair background to ttH, tttt, BSM



  - Prediction increased recently by ~20%, including NLO QCD corr^n for ttW+2 partons
- Experimental signature: 2 SS leptons or 3 leptons, with multiple (b) jets
  - Significant cross-contamination between ttW, ttZ and ttH
    - Dedicated normalisation control regions

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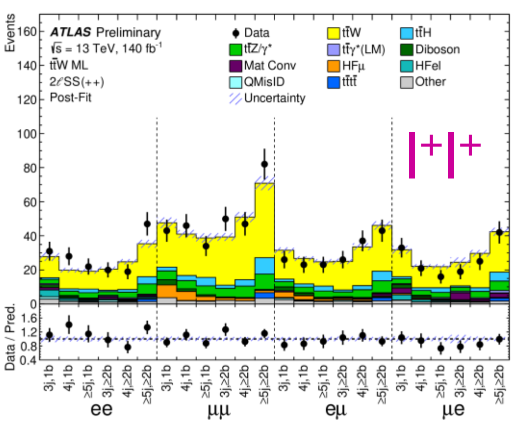
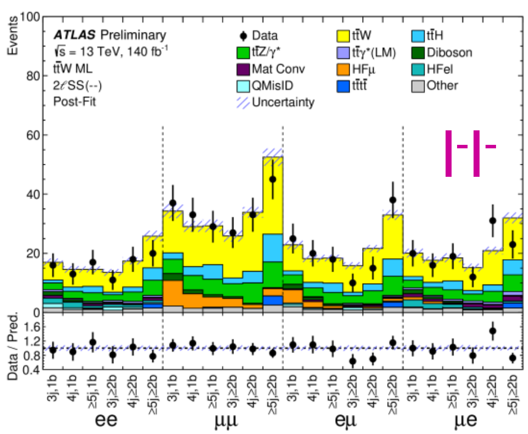
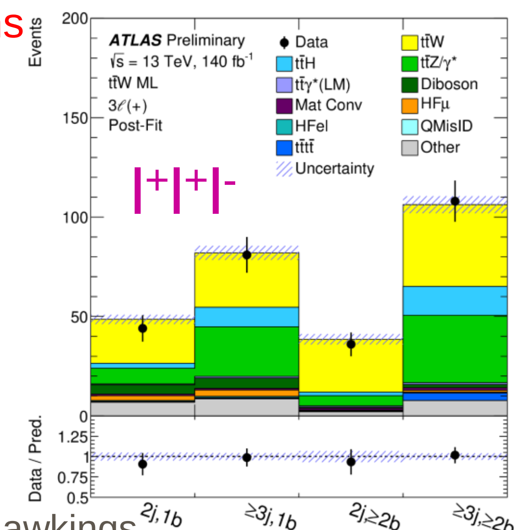
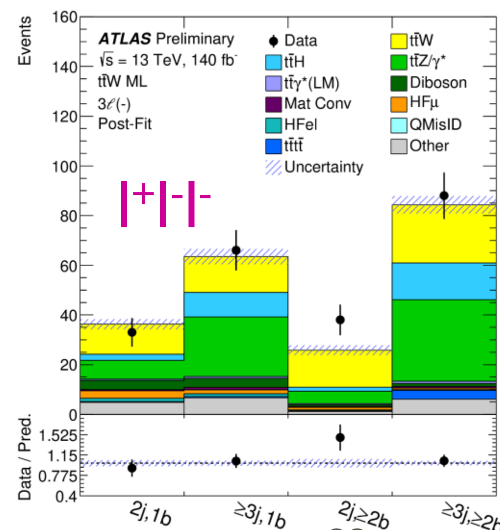


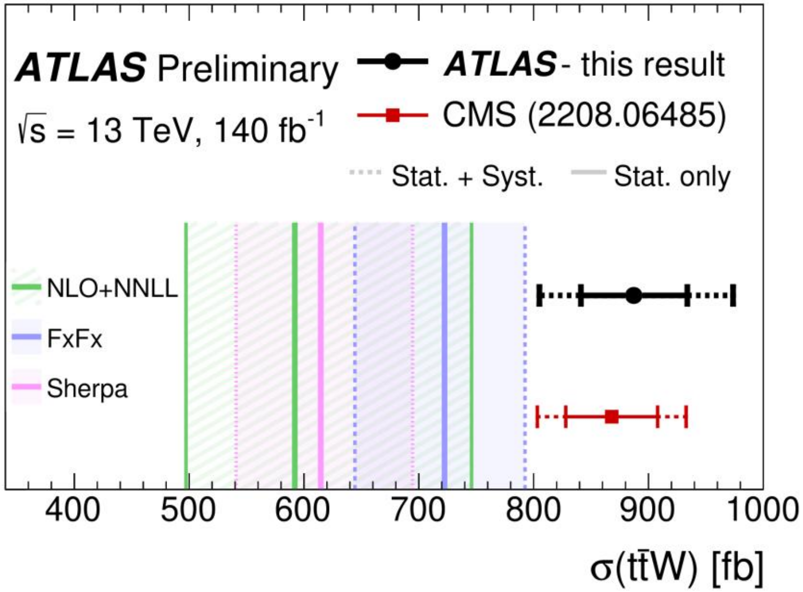


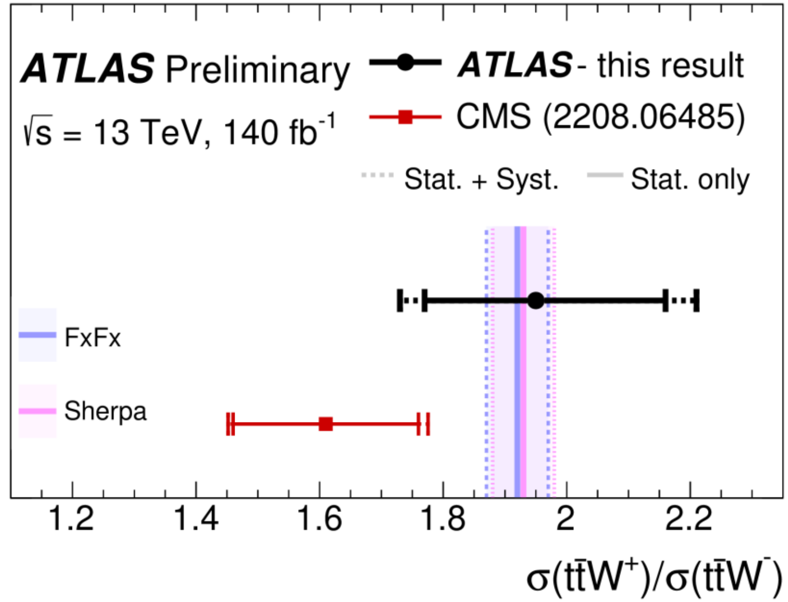




ttW results

- Measure ttW inclusively and separately for W^+ and W^- charge states





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  - Both experiments (still) see a larger x-sec than predictions, reached ~10% unc.
    - Measurements of ttW^+/ttW^- ratio show less tension – excess in both signs
- With O(1000) candidates, can start to study differential distributions
  - E.g. vs. N_{jet}, H_T, ΔR(l-jet), $\Delta\phi$(ll), m(jet,jet)
  - Normalised differential distributions generally agree well with predictions
- Understanding will profit from Run3/4 data + MC developments (NNLO)

Conclusions

- LHC top physics has reached maturity with Run 1+2 data
  - Very large samples (millions of events), many analyses limited by systematics
- Top cross-section measurements
  - Inclusive tt reached 2% precision, many differential measurements below 5%
  - Challenges theory, NLO+PS no longer adequate to describe the data
    - Need to move to higher precision to fully exploit this data (e.g. for PDFs, α_S, m_t)
  - Single-top less precise, interesting for PDFs, $|V_{tb}|$ and EFT/BSM constraints
- Top mass measurements are also systematics limited
  - Direct measurements below 0.5 GeV uncertainty
    - Hitting the 0.5 GeV ambiguity on $m_t^{MC} \approx m_t^{pole}$; can this be improved?
  - Production-based measurements at ~1 GeV, limited by modelling/theory
  - New ideas needed – boosted measurements look promising (statistics?)
- Many pressing issues in MC modelling of top processes – ideas to improve
- Rate top processes (ttW, ttZ, ttH, 4-tops) all observed and being studied
  - Challenging experimentally and theoretically – e.g. persistent ttW excess
- Eagerly awaiting Run3 and Run4 results, and corresponding theory advances

Backup slides

- Backup slides

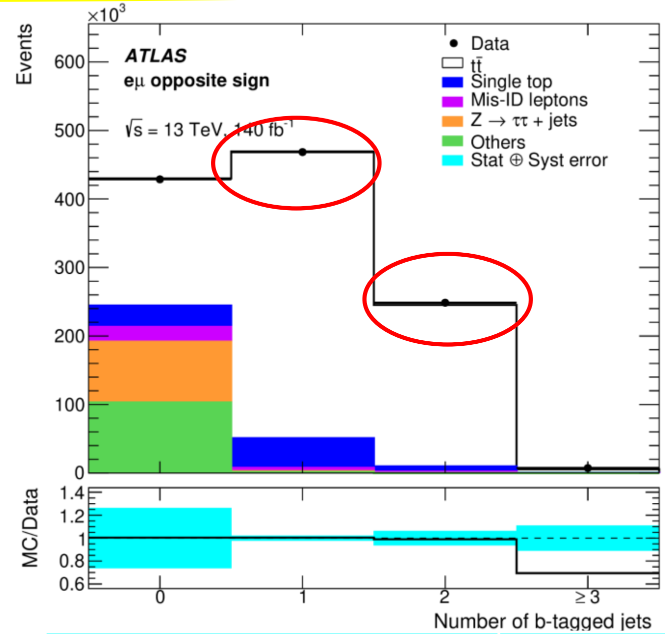
Double-tagging in eμ events at 13 TeV

- Count $e^{\pm}\mu^{\mp}$ events with 1 or 2 b-tagged jets
  - Assume top quarks decay independently
  - Fit $\sigma_{t\bar{t}}$ and probability ε_b to select and b-tag jet:

$$N_1 = L\sigma_{t\bar{t}}\, \epsilon_{e\mu} 2\epsilon_b (1 - C_b\epsilon_b) + N_1^{\rm bkg}$$

$$N_2 = L\sigma_{t\bar{t}}\, \epsilon_{e\mu} C_b {\epsilon_b}^2 + N_2^{\rm bkg}$$

  - $\varepsilon_{e\mu}$ is efficiency to to select the two leptons
  - 1/2 b-tag regions 88/96% pure in top-pair events



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- Method minimises uncertainties due to top-pair modelling, jets and background
  - Remaining uncertainty dominated by luminosity and top-pair modelling (eμ acceptance)

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

  - Precise result can be used to measure m_t^{pole} and constrain PDFs via ratios σ_{tt}/σ_Z

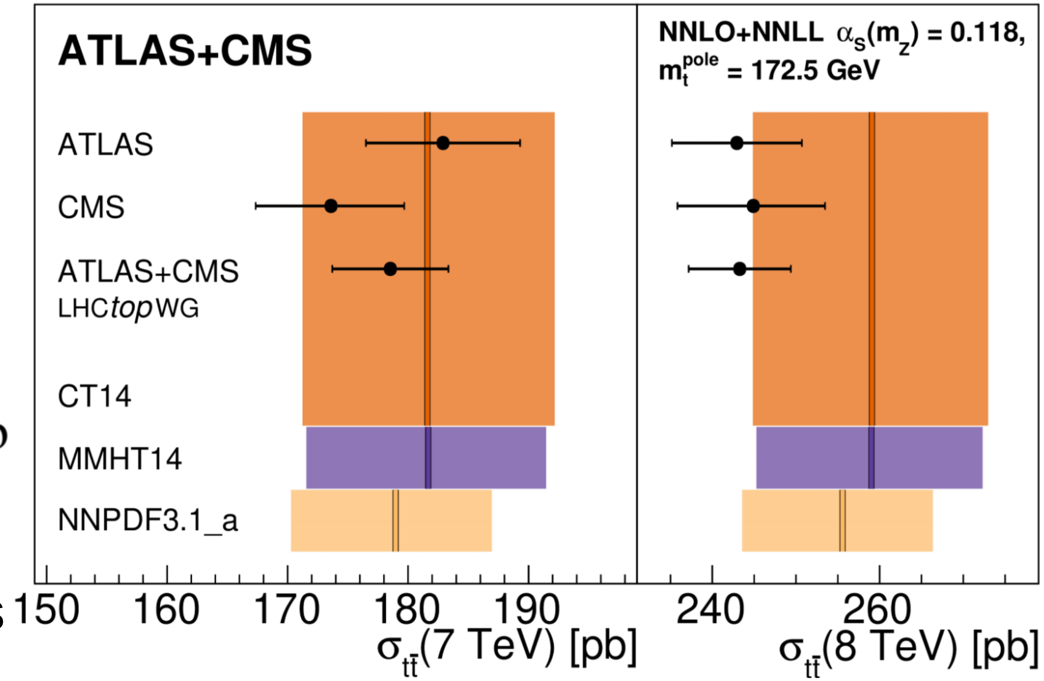
Category	Uncertainty (%)
Statistics	0.4
Top-pair modelling	1.0
Leptons	0.8
Jets / b-tagging	0.1
Backgrounds	0.8
Luminosity/beam energy	1.0
Total	**1.8**

ATLAS+CMS top-pair combination at 7+8 TeV

- Legacy eμ results from ATLAS+CMS at √s=7, 8 TeV have been combined
  - ATLAS measurements used simple tag-counting
  - CMS used profile likelihood fit inducing post-fit correlations between systematics
- Combination of all data at 7+8 TeV using χ^2 minimisation with Convino tool
  - Careful accounting of correlations between experiments and beam energies
- Total uncertainties:

arXiv:2205.13830

Uncert. (%)	σ_{tt}(7 Tev)	σ_{tt}(8 Tev)
ATLAS	3.5	3.2
CMS	$^{+3.6}_{-3.5}$	$^{+3.7}_{-3.5}$
Comb^n	$^{+2.7}_{-2.6}$	$^{+2.5}_{-2.4}$



  - 25/28% better c.f. most precise input

$$\sigma_{t\bar{t}}\ (\sqrt{s} = 7\,\text{TeV}\ ) \quad = \quad 178.5 \pm 4.7\ \text{pb}$$
$$\sigma_{t\bar{t}}\ (\sqrt{s} = 8\,\text{TeV}\ ) \quad = \quad 243.3^{+6.0}_{-5.9}\ \text{pb},$$

- Results compatible with recent PDFs