





Treatment of top-quark backgrounds in extreme phase spaces in ATLAS and CMS

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- The top quark plays an important role in searches for physics beyond the SM, both as dominant background and as key signature for signal
- Main focus: **treatment of the top quark background** in BSM searches (high- p_T and/or large multiplicity regimes)
 - cover new (mostly **data-driven**) techniques for $t\bar{t}$ estimation used in Exotics, SUSY, HDBS and B2G analyses
 - and when the top background is taken from MC: summary and discussion concerning the “**top p_T reweighting**”

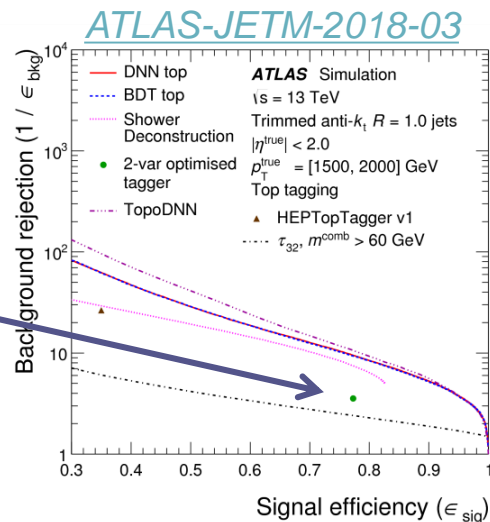
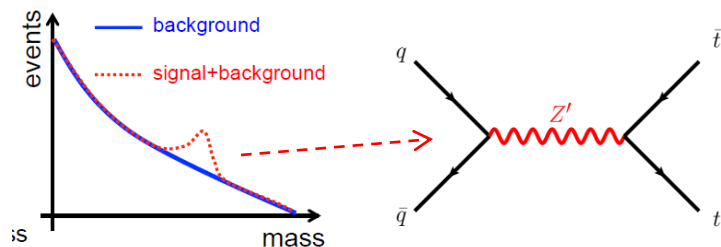
- Full list of results from BSM searches from both  and  Collaborations:

- **ATLAS:** [Exotics](#), [SUSY](#), [Higgs and Diboson searches](#)
- **CMS:** [Exotica](#), [SUSY](#), [Beyond 2 Generations](#)
- Apologies if your preferred search is not included due to lack of time

- Search for $t\bar{t}$ resonances in fully hadronic states

- First analysis in ATLAS using the new high level DNN top-tagger with several jet-moment observables related to substructure variables

- Large improvement: 4 times better bkg rejection



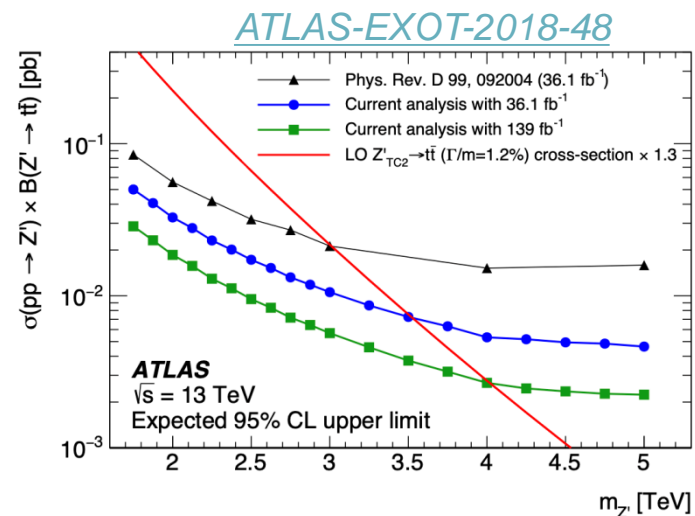
- Background spectrum **derived from data** by fitting a smoothly falling function to the $m(t\bar{t})$ distributions

$$F(x) = p_0(1 - x)^{p_1} x^{p_2 + p_3 \log(x) + p_4 \log(x)^2}$$

- functional form determined using combinations of data and simulated events

- Wilk's test used to determine the optimal number of parameters to describe the function: most optimal with three shape parameters

- spurious signal studies by performing S+B fits constructed under a background-only hypothesis



- 95 % C.L. exclusion of Z' with masses up to **3.9 TeV** (width = 1%)

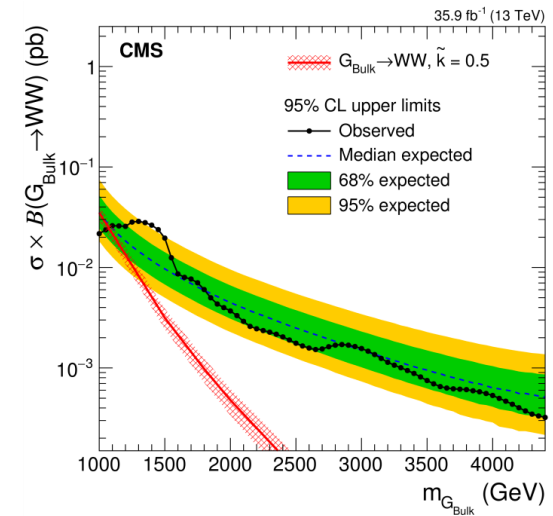
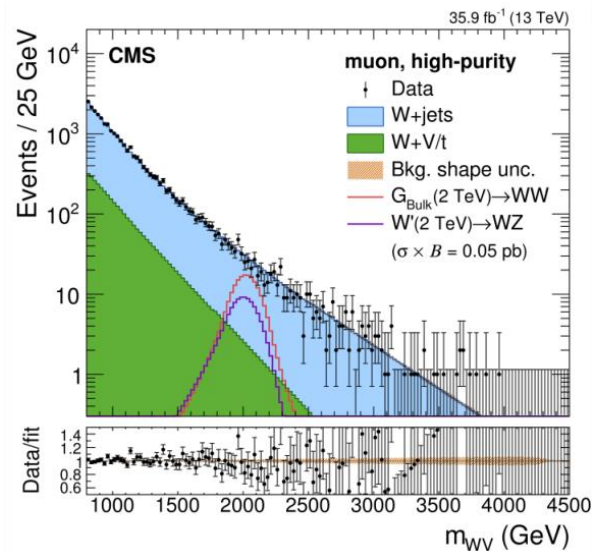
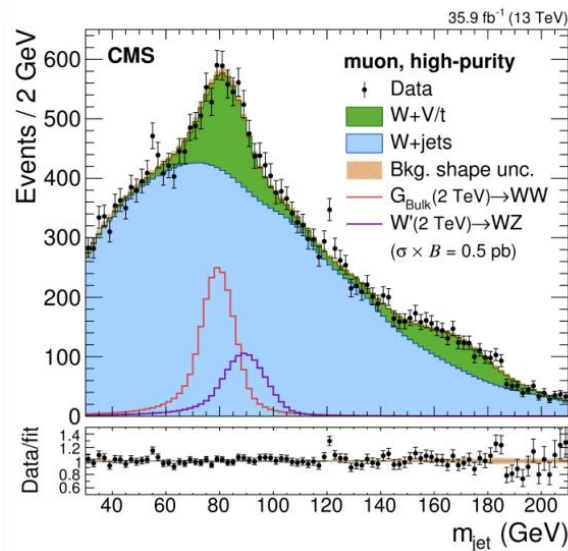
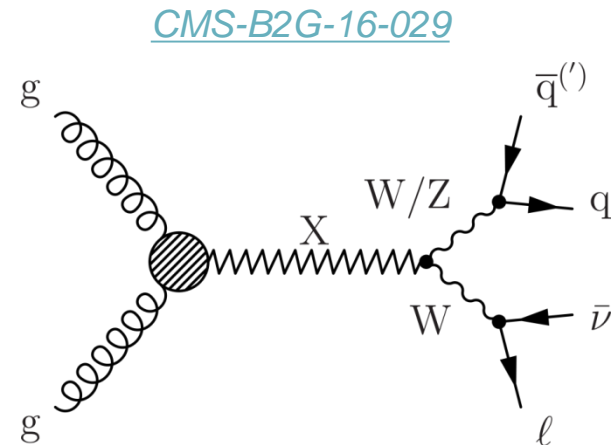
- Search for heavy resonance X decaying to a pair of vector bosons (WW or WZ) in the lepton plus merged jet final state

- $W \rightarrow e$ (or μ) ν , while the other $W,Z \rightarrow qq'$ reconstructed as 1 large- R jet using jet substructure

- Novel 2D simultaneous maximum likelihood (m.l.) fit on $m(WV)$ and $m(V\text{-jet})$: SM bkg **estimated from data**

- 2D conditional templates populated from simulation before detector simulation

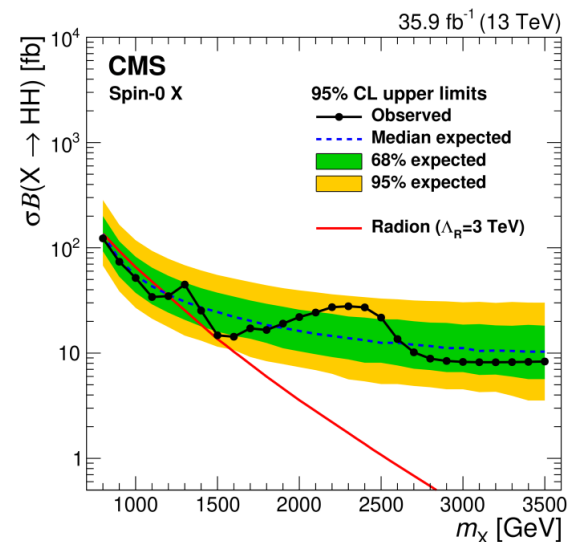
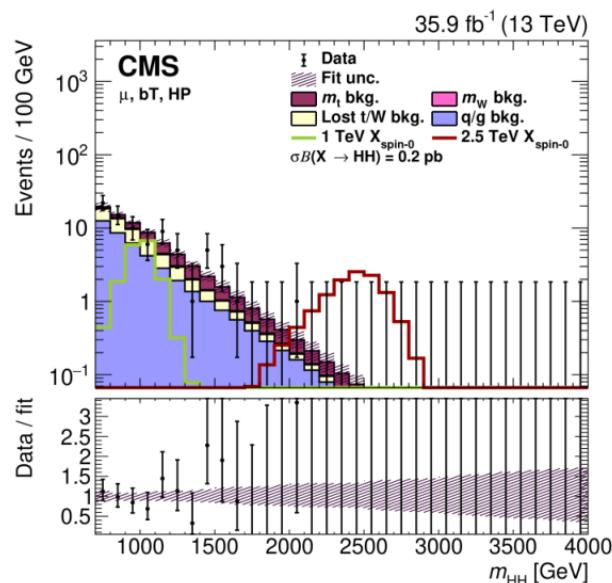
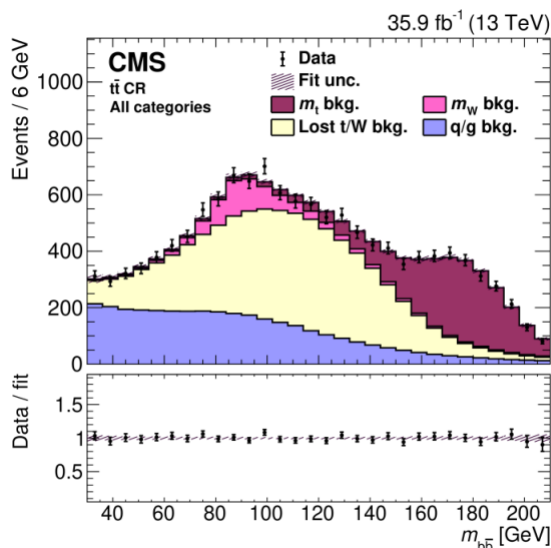
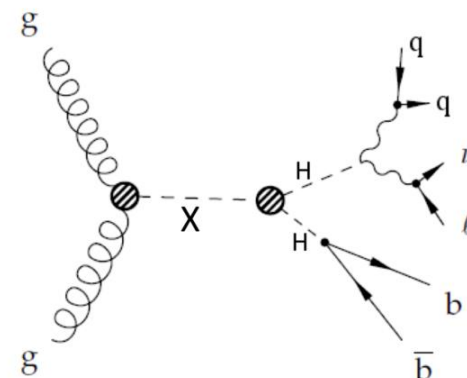
- scale and resolution model derived as function of gen. jet p_T ; templates populated as sums of 2D Gaussians – similar to kernel estimation



- W' HVT model B: excl. up to 3 TeV
- Graviton ($k=0.5$) excl. up to 1 TeV

- Search for heavy resonance X decaying to a pair of Higgs bosons ($HH \rightarrow bb WW$)
 - 1 lepton + MET + 1 large-R b-jet + 1 large-R jet
- Signal and SM bkg simultaneously estimated using **maximum likelihood fit to data** in the 12 event categories to 2D distributions of $m(bb)$ and $m(HH)$ mass plane
- All bgds defined in 4 generator level categories (number of gen. level quarks) with distinct $m(bb)$ shapes
 - bkg. templates modeled as conditional probabilities of $m(bb)$ as function of $m(HH)$ using kernel estimation (KDE)

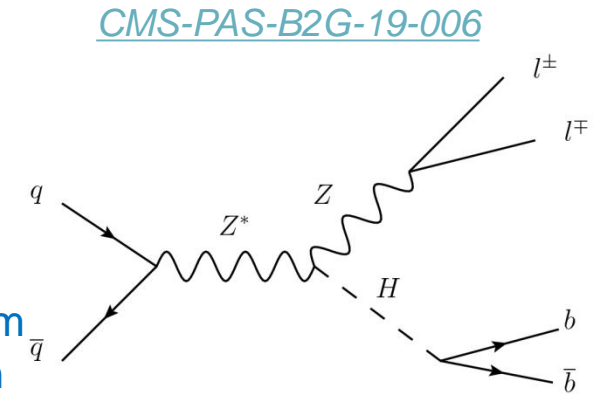
CMS-B2G-18-008



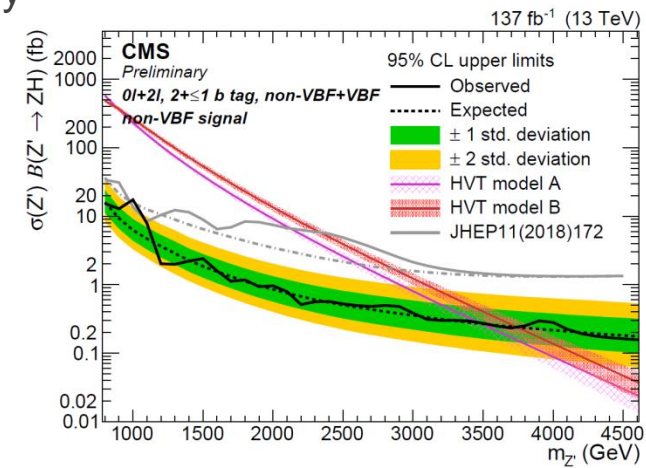
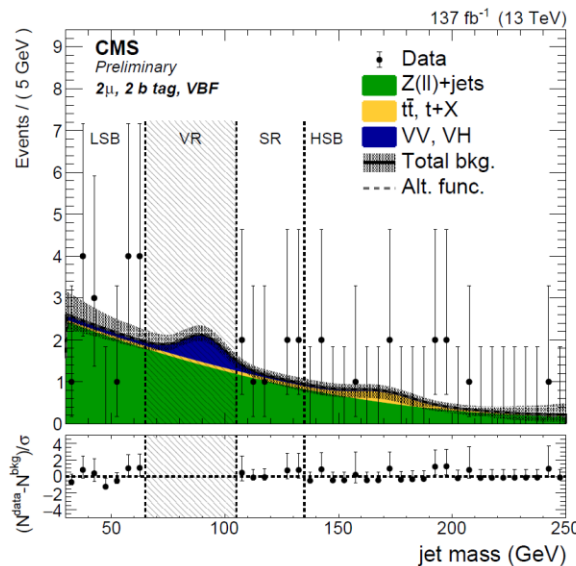
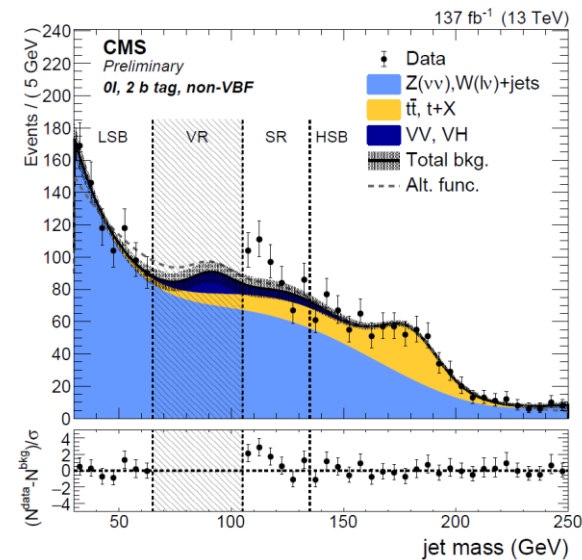
- obs. limit for spin-0 (8.3-123 fb) and spin-2 resonances (7.8-103 fb) for mass ranged of **3.5 - 0.8 TeV**



- Search for spin-1 resonance Z' decaying into a Z and H(125) bosons with $Z \rightarrow 2e, 2\mu, 2\nu$ and $H \rightarrow bb'$
- Higgs boson reconstructed as jet with substructure
- 0 lepton (large MET) and 2 lepton channels, for the first time including VBF production (forward jets)
- $m(Z')$ or $m_T(Z')$ distributions **estimated from data** in CRs from the sidebands (SB) of the Higgs candidate jet mass distribution



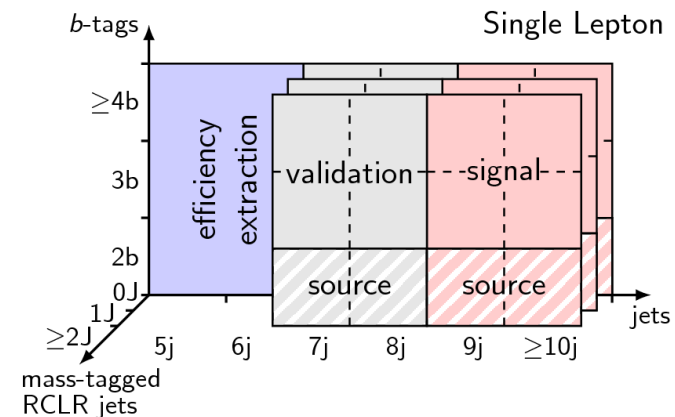
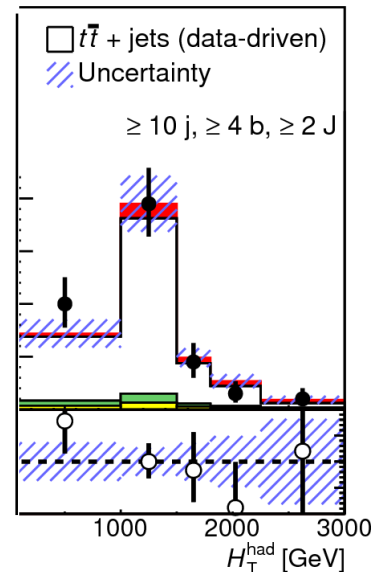
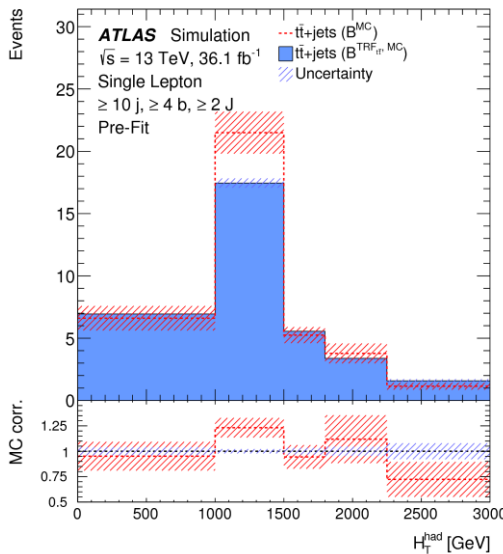
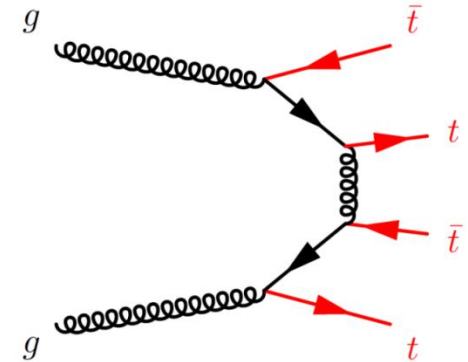
- extrapolated to SRs through analytical functions derived from simulation
- number of parameters for the fit to data is determined by a Fisher F-test



- Z' HVT model A (B):
excl. up to 3.5 (3.7) TeV

- Search for extremely rare 4 tops in 1L / 2OSL
 - highest sensitivity categories in 1L (2OSL) require at least 10 (8) jets, 4 b-tagged jets and 2 (1) reclustered jets
- **Data-driven** method to estimate $t\bar{t}$ +jets background
 - assume that the probability of b-tagging a jet in $t\bar{t}$ +jets event is essentially independent of the number of additional jets;
 - b-tagging efficiencies (ϵ_j) extracted as a function of jet p_T and the $\min\Delta R$ for the given jet wrt. to all other jets, multiplied by N_j

ATLAS-EXOT-2017-11



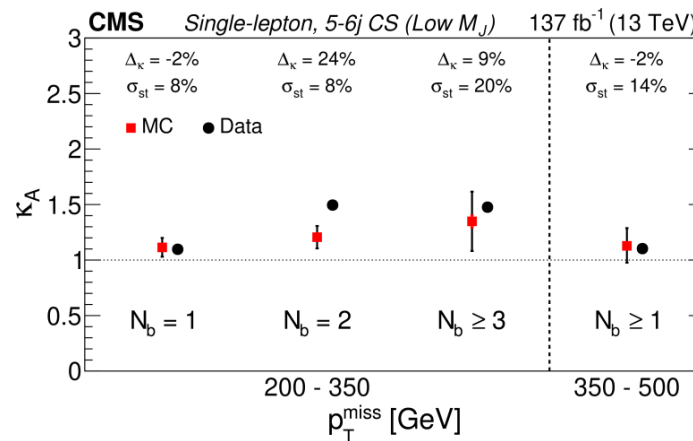
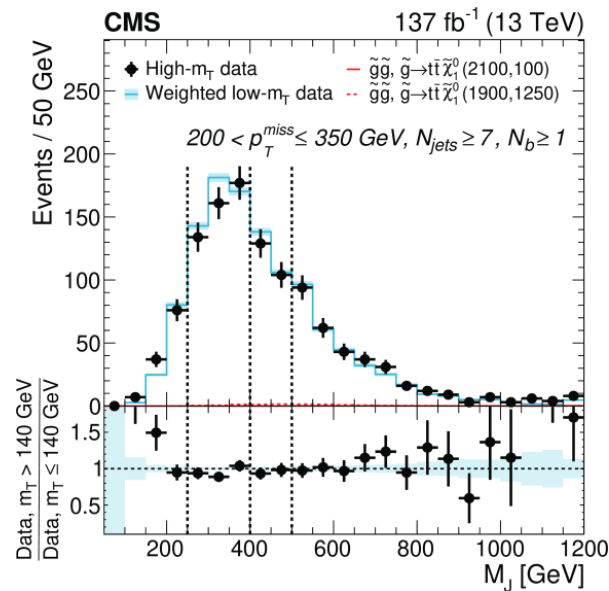
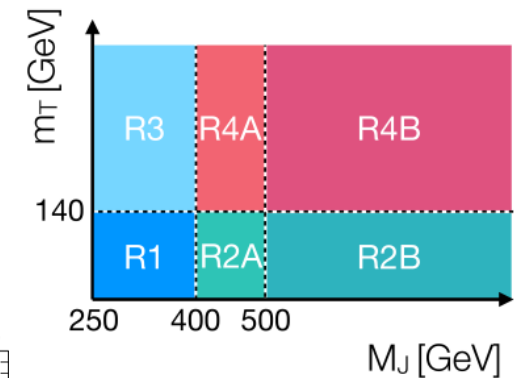
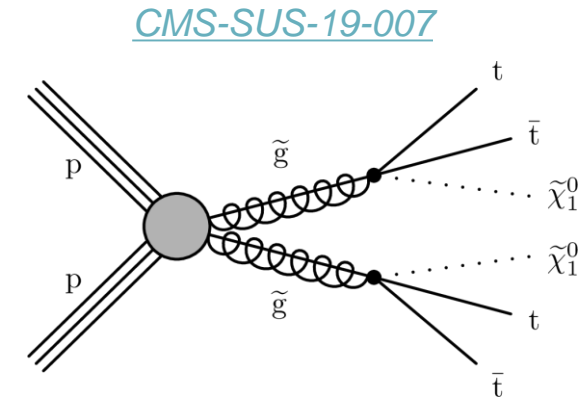
- Obs. (exp.) limits (95 % C.L.) of **5.1 (3.6) x SM**
- Limits on 4 tops via EFT



Search for SUSY in 1L and multiple jets

- signal regions categories based on N-jets, N-bjets, MET and sum of masses of large-R jets (NJ)
- Dominant $t\bar{t}$ bkg estimated with modified **ABCD** method in two uncorrelated planes of MJ and transverse mass m_T
 - each event in low- m_T data (R2A or R2B) is weighted with a k factor

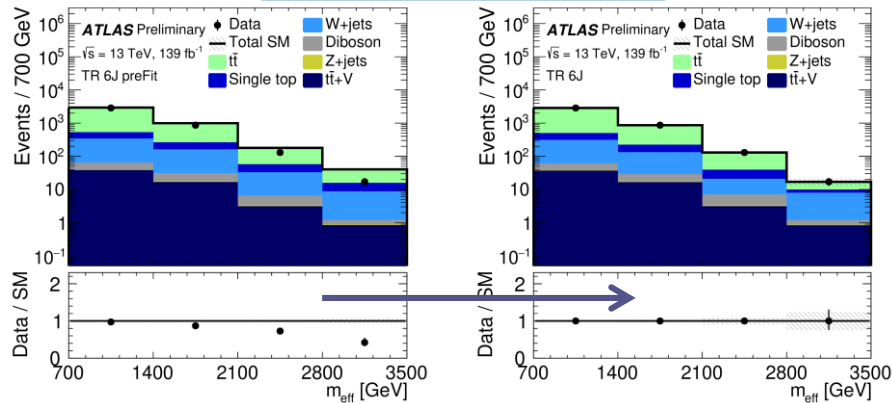
$$\kappa_A = \frac{N_{R4A}^{MC,bkg} / N_{R3}^{MC,bkg}}{N_{R2A}^{MC,bkg} / N_{R1}^{MC,bkg}'}$$
 - the total low- m_T yield is normalized to the total high- m_T yield in data



- excluded gluino masses up to **2150 GeV** for neutralino mass up to **700 GeV**

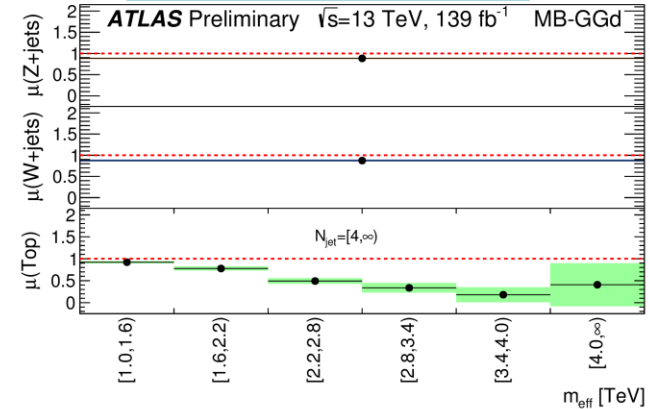
- mismodelling in $M(\text{eff})$: different top norm. parameters for each bin in the fit

ATLAS-CONF-2020-047



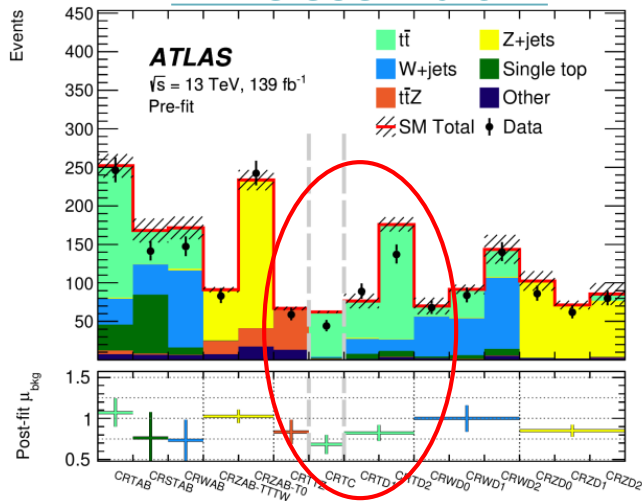
- fitted norm. factors away from 1: simulated top MC generally harder kinematics

ATLAS-CONF-2019-040



- Several SUSY scenarios searches use high-pT jets originating from ISR to improve sensitivity; norm. factors are <1 by 1-2 sigma: mismodelling in the ISR system in $t\bar{t}b\bar{a}$

ATLAS-SUSY-2018-12



	tN_med	tN_high	tN_diag_low	tN_diag_high	bffN_btag	brfN_softb	DM
$t\bar{t}$ NF	$0.98^{+0.14}_{-0.12}$	0.90 ± 0.12	$0.88^{+0.13}_{-0.12}$	$0.73^{+0.14}_{-0.13}$	$0.80^{+0.09}_{-0.08}$	0.68 ± 0.10	$1.12^{+0.15}_{-0.13}$
$t\bar{t}V$ NF	$0.95^{+0.22}_{-0.20}$	0.92 ± 0.17	-	-	-	-	$1.18^{+0.20}_{-0.18}$
Single-top NF	$0.11^{+0.26}_{-0.11}$	$0.12^{+0.22}_{-0.12}$	-	-	-	-	-
W+jets NF	$0.96^{+0.25}_{-0.23}$	0.86 ± 0.17	-	-	0.83 ± 0.28	$1.04^{+0.22}_{-0.20}$	-

ATLAS-CONF-2020-003

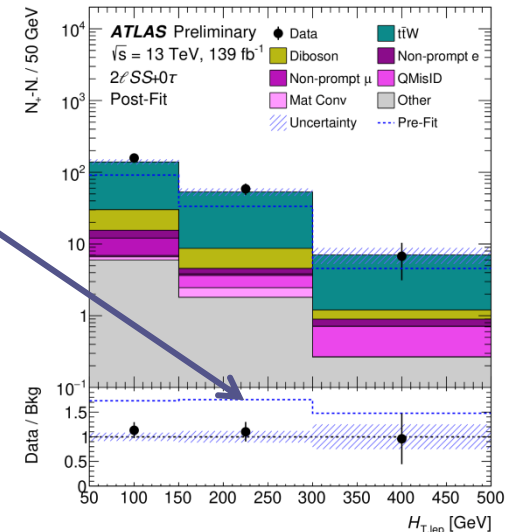
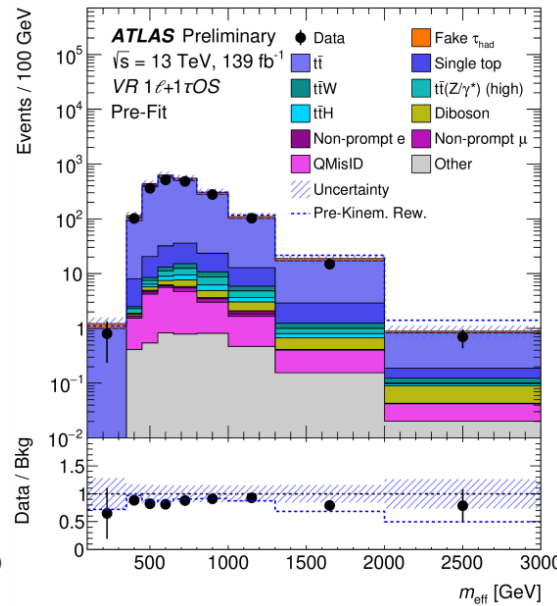
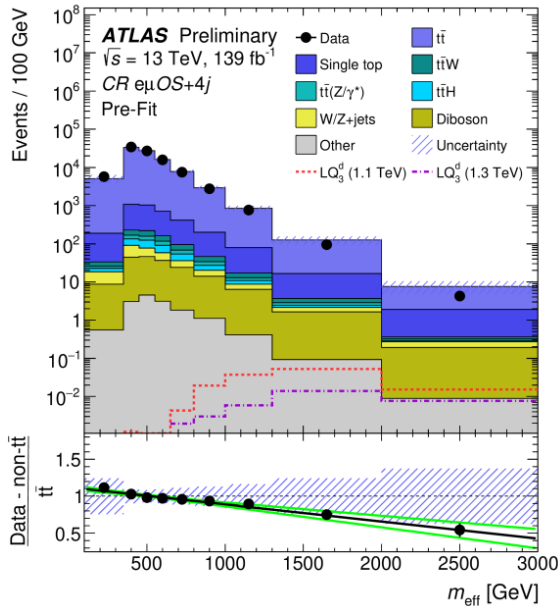
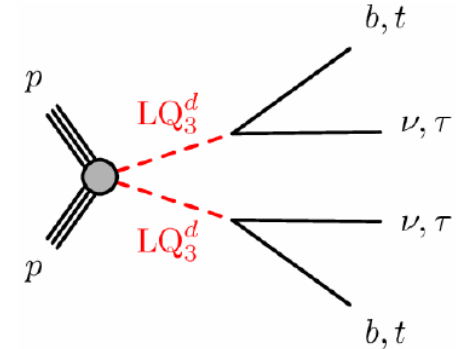
• Search for pair production of leptoquarks (LQ) decaying each in a top and tau-lepton

- ≥ 1 e/μ + ≥ 1 $\tau(\text{had})$ + ≥ 2 jets (1 b-jet)
- Five final states, defined by the multiplicity and lepton flavour: 15 CRs, 6 VRs and 7 SRs

• **ttbar from MC:** kinematic reweighting as function of number of jets (nJ) and $M(\text{eff})$ derived in control region

- correction factors (derived in OS $e\mu$): ~ 0.4 for 3 TeV (nJ=4) difference in the slope derived in 1L1 τ VR - systematic
- ttW verified in 2LSS + 0 τ : norm. factor 1.78 ± 0.15

ATLAS-CONF-2020-029



- Excluded LQs decaying exclusively into tt up to 1.43 TeV

and references therein, and Refs. [53–55]). The modeling of SM tt production in POWHEG is known to predict a harder p_T spectrum of the top quarks than observed in the data. An empirical reweighting for top quark pairs based on the p_T spectrum of generator-level top quarks is applied to obtain a better agreement with the measured differential $t\bar{t}$ cross section [56, 57].

terms, with Top++2.0 [33–39]. A correction depending on the top-quark p_T value is applied to account for shape effects due to NNLO QCD and NLO EW corrections according to Ref. [40]. The cross sections for

Differential measurements of $\sigma_{t\bar{t}}$ at $\sqrt{s} = 13$ TeV have demonstrated that the p_T distribution of the top quark is softer than predicted by the POWHEG simulation [67–69]. An additional uncertainty, referred to as “Top quark p_T ”, is estimated by reweighting the simulation. This


reweighting of the $t\bar{t}$ simulation has been applied to match the predictions to the data [42, 43]. The correction is applied as a function of the transverse momenta of the parton-level top quark and antiquark after initial- and final-state radiation. Specifically for this result, additional ded-

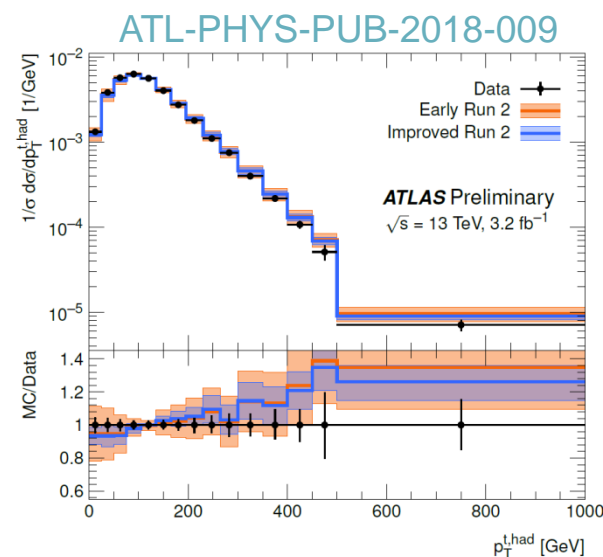
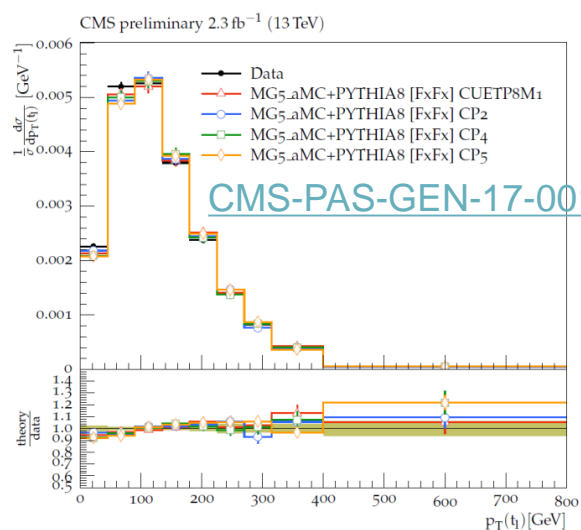
jets events, including those with no additional jets. In previous studies, better agreement between data and prediction was observed, particularly for the top quark p_T distribution, when comparing to NNLO calculations [77]. These small improvements to the modelling are incorporated by reweighting all $t\bar{t}$ samples to match their top quark p_T distribution to that predicted at NNLO accuracy in QCD [78, 79].

tively [22, 23]. In order to better describe the transverse momenta (p_T) distribution of the top quark in $t\bar{t}$ events, the top quark transverse momentum spectrum simulated with POWHEG is reweighted to match the differential top quark p_T distribution at NNLO QCD accuracy and including EW corrections calculated in Ref. [24]. The other SM background contributions from

The level of agreement between data and prediction for the lepton p_T and the leading jet p_T improves if the top-quark p_T distribution in the nominal $t\bar{t}$ simulation is corrected to match the top-quark p_T calculated at NNLO in QCD with NLO electroweak corrections [73]. In this analysis, the full difference between the

and many others. . .

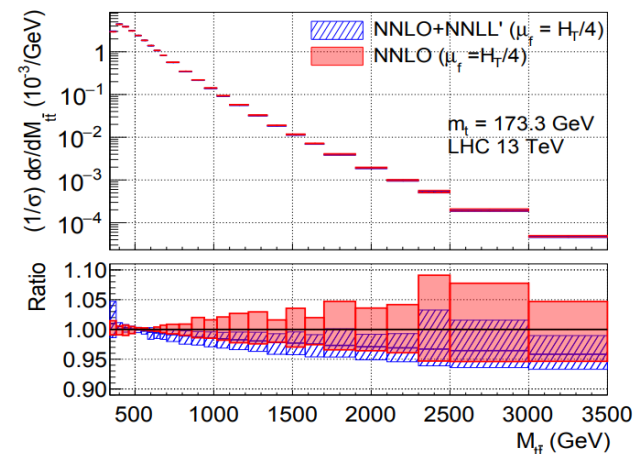
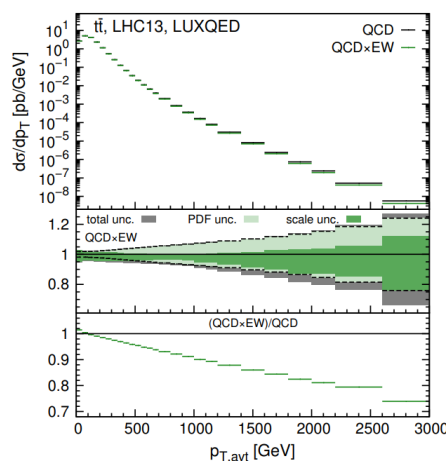
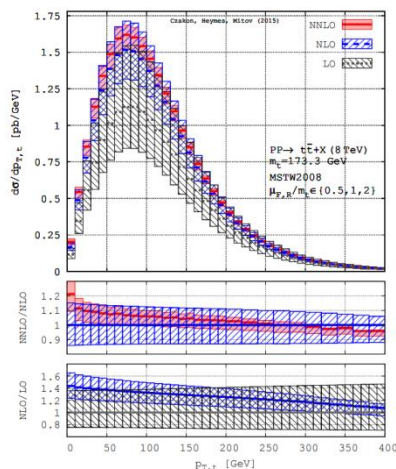
- For full story of the top pT since 2013, see ‘back in time’  in the back-up
- As a summary:
 - general trend of the NLO predictions to overestimate the data at high pT(top)
 - same trends seen in resolved and boosted, consistent among experiments



- Things to have in mind:
 - largely affect searches using simple variables such as HT or M(eff)
 - it's one of the main uncertainty if used in precise measurements
 - previously shown data-driven methods are a potential way around it

- Approaches taken up to now:

- reweight parton-level kinematics (usually top and anti-top pT) to the best available fixed-order prediction



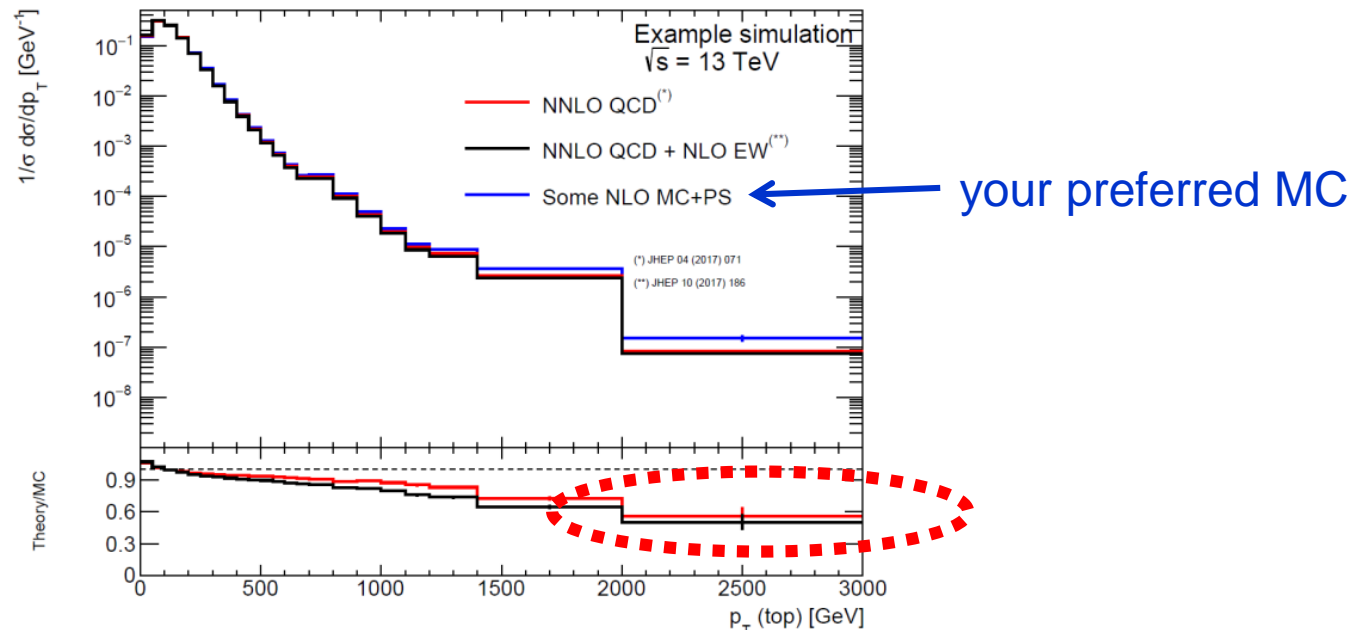
➤ In the last years, several high-order predictions available^(*)

- M. Czakon et al., [Phys. Rev. Lett. 116, 082003 \(2016\)](#), NNLO QCD
- M. Czakon et al., [JHEP 10 \(2017\) 186](#), NNLO QCD + NLO EW
- M. Czakon et al., [JHEP 1805 \(2018\) 149](#), NNLO+NNLL' (boosted)
- C. Gütschow et al., [Eur. Phys. J. C 78 \(2018\) 4, 317](#), MEPS@NLO QCD+EW
- M. Czakon et al., [arXiv:1901.04442](#), NNLO+EW vs. MEPS@NLO
- S. Catani et al, [JHEP 07 \(2019\) 100](#), NNLO, MATRIX
- M. Czakon et al., [Chin. Phys. C 44 \(2020\) 8, 083104](#), NNLO+NNLL'
- N. Kidonakis, [Phys. Rev. D 101, 074006 \(2020\)](#), aN³LO
- S. Catani et al, [arXiv:2005.00557](#), NNLO in MS scheme

(*) this is a non-comprehensive list

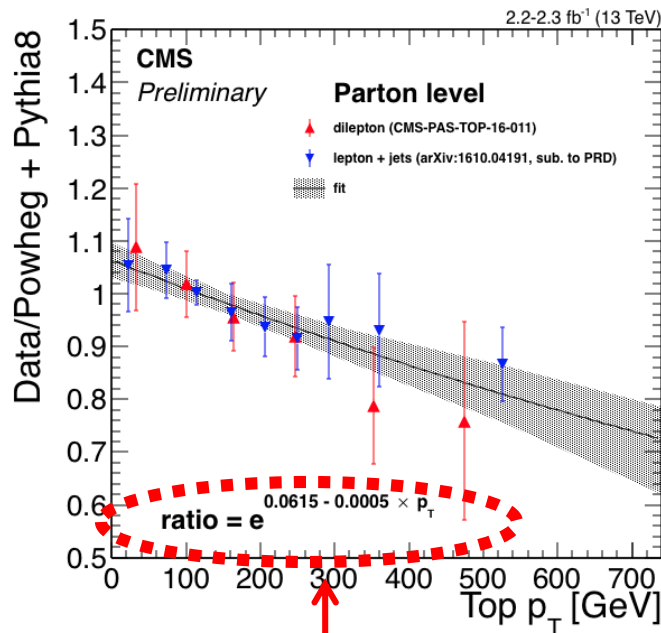
- Approaches taken up to now:

- reweight parton-level kinematics (usually top and anti-top pT) to the best available fixed-order prediction
 - take the top pT distribution from your preferred calculation; extract from your MC sample (without selection) the (anti) top p_T histogram with the same binning (use “last top” in MC record, that is after radiation and before decay)
 - get the ratio between the two histograms, use this ratio to assign to each MC event a weight; use this reweighted distribution as **nominal** (CMS) or as **systematic** (ATLAS) uncertainty

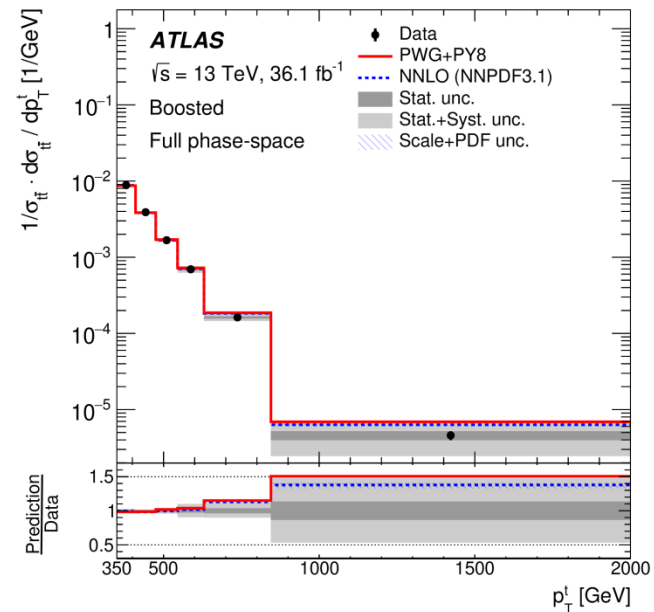


- Approaches taken up to now:
 - reweight parton-level kinematics to differential cross-section measurements
 - used by CMS mainly in measurements as the top p_T range of the diff. measurements currently are dominated by uncert. in the tails: not recommended for analyses dealing with the tail of the distribution (searches)

CMS Top Summary



the reweighting function

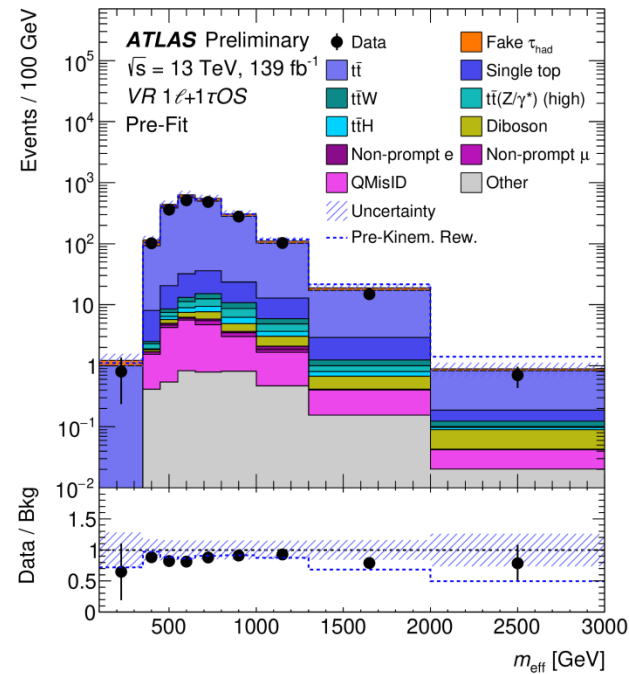
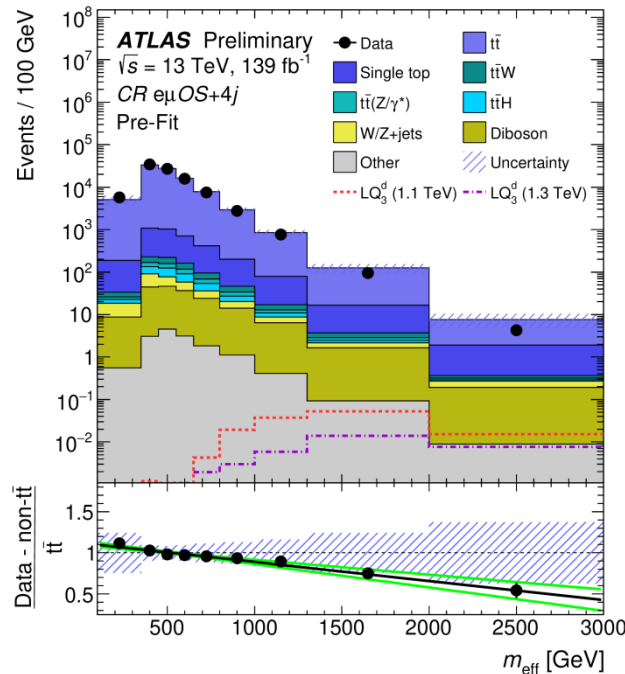


- Approaches taken up to now:

- derive ad-hoc reweightings to data in control regions using particular reconstructed distributions

➤ often used in ATLAS BSM searches, but what if we cannot define such a signal-free CR?

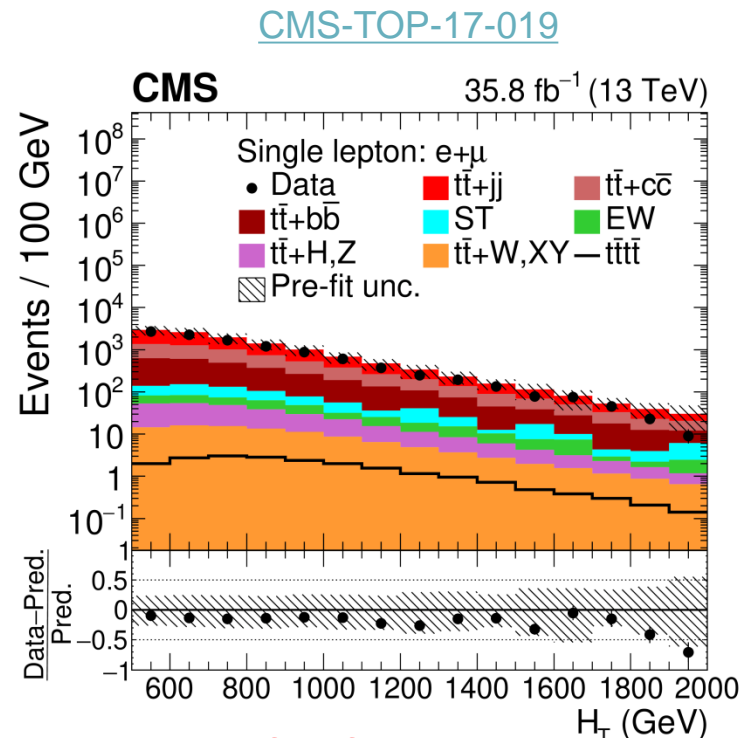
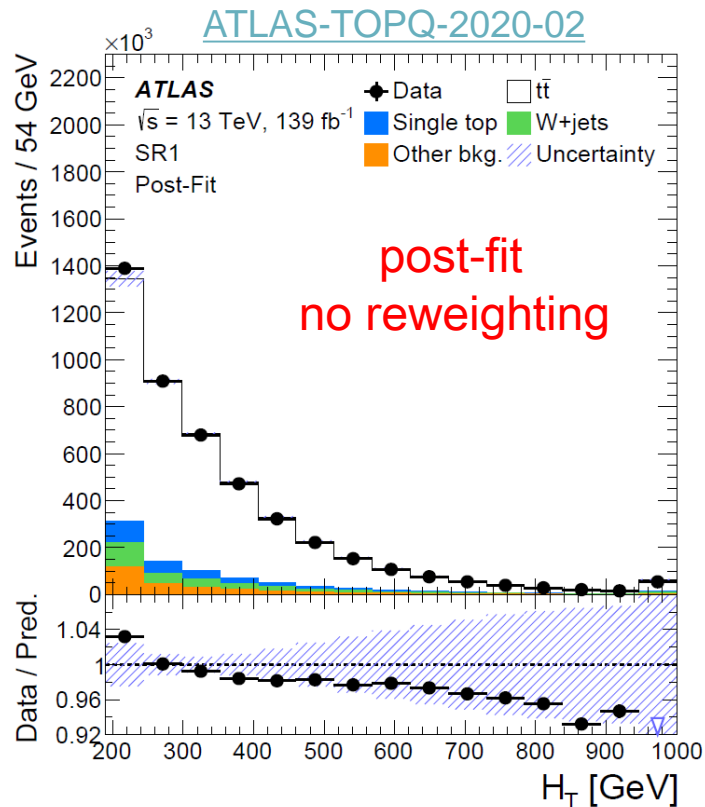
ATLAS-CONF-2020-029



- Approaches taken up to now:







- not to reweight (ATLAS), since the comparison of different MC predictions, when turned into systematic uncertainties, can (at least partially) cover the mismodelling

➤ with the precision we have (from data) and we want (in precise measurements), we cannot anymore ignore this issue



pre-fit after reweighting:
much better initial data/MC

- In both ATLAS and CMS, the treatment changes **depending on the use case**, i.e. correcting effs. or acceptance in ttbar measurements, BSM searches, etc.
- If applied in BSM searches, usually CMS corrects to the top pT to NNLO QCD + NLO EW correction by default, while ATLAS considers it as a systematic uncert.
- Recent examples^(*) of top pT reweightings and associated uncertainties:

Results	Reweighting to	Uncertainty (shape)
 ttH ML (CMS-HIG-19-008)	NNLO QCD + NLO EW	Difference between weighted and un-weighted scenarios
 tt cross-section (ATLAS-TOPQ-2020-02)	NNLO QCD + NLO EW	symmetrised full difference between on and off
 Vector-like quarks (ATLAS-EXOT-2016-13)	NNLO QCD	full difference between applying and not applying
 tt resonances (CMS-B2G-17-017)	function derived from data (p. 15)	symmetrised difference between on and off
 SM 4 tops (CMS-TOP-17-019)	function derived from differential measurements	function variation within a ± 1 sigma
 Heavy H to ttbar (CMS-HIG-17-027)	function derived from differential measurements	varying the two parameters of the function

(*) this is a non-comprehensive list

- Commonly raised points concerning the reweighting to fixed-order:
 - the latest NNLO calculations recommend different functional forms for the renormalisation and factorisation scales for different observables
 - PDFs, top mass, scale variations and scale choices not always easily available in theory predictions, nor match ATLAS/CMS settings
- given that the baseline Powheg V2 ttbar MC in ATLAS and CMS uses the same fact. and ren. scales ($\sqrt{m^2+p_T^2}$), having calculations with the same scale for all variables would be helpful
- having calculations with the same choices would help the Collaborations to apply the correction in a consistent way where needed (e.g. ATLAS/CMS uses top mass of 172.5 GeV in Powheg, while theory uses 173.3 GeV as input parameters for the calculation)

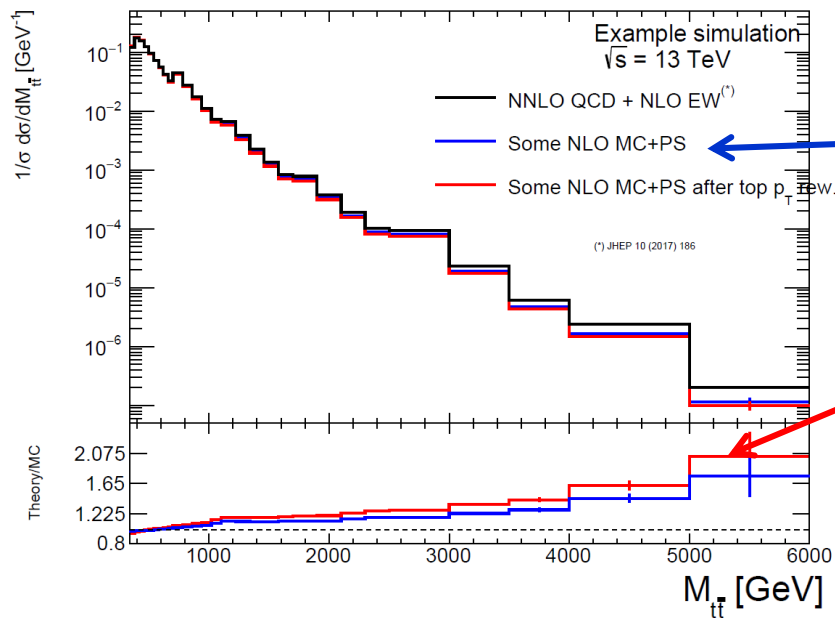
$$\mu = \frac{m_{T,t}}{2} \text{ for the } p_{T,t} \text{ distribution,} \quad \text{JHEP10(2017)186} \quad (2.3)$$

$$\mu = \frac{m_{T,\bar{t}}}{2} \text{ for the } p_{T,\bar{t}} \text{ distribution,} \quad (2.4)$$

$$\mu = \frac{H_T}{4} = \frac{1}{4} (m_{T,t} + m_{T,\bar{t}}) \text{ for all other distributions,} \quad (2.5)$$

where $m_{T,t} \equiv \sqrt{m_t^2 + p_{T,t}^2}$ and $m_{T,\bar{t}} \equiv \sqrt{m_t^2 + p_{T,\bar{t}}^2}$ are the transverse masses of the top

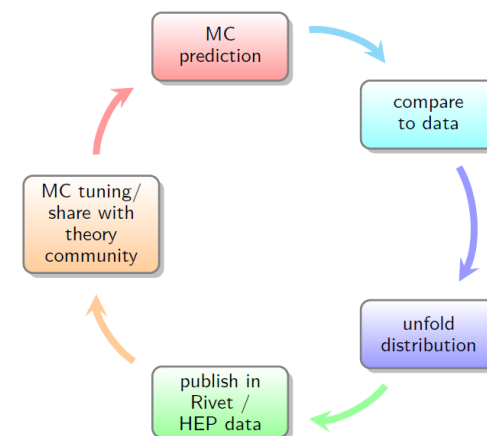
- Commonly raised points concerning the reweighting to fixed-order:
 - top pT gets corrected, but what about other (partially correlated) variables, e.g. ttbar mass?
- usually analysers monitor the change in agreement between data and reweighted MC in other distributions (especially ttbar mass) and make sure that the reweighting does not spoil the agreement
- we **do** have NNLO QCD and NLO EW predictions for top pT and ttbar-system mass



after top p_T rew.
moves away from
prediction

- Commonly raised points concerning the reweighting to fixed-order:
 - top pT gets corrected, but what about other (partially correlated) variables, e.g. ttbar mass?
 - usually analysers monitor the change in agreement between data and reweighted MC in other distributions (especially ttbar mass) and make sure that the reweighting does not spoil the agreement
 - we **do** have NNLO QCD and NLO EW predictions for top pT and ttbar-system mass
 - thus, we could do a **2-D** pT(top) and m(ttbar) reweighting
 - or we can reweight the different distributions iteratively and repeat the procedure recursively (2 x 2) – which would give us a MC prediction which matches both top pT and ttbar mass NNLO predictions (can get further refined using other variables and become 3x3...)
 - yet, any reweighting is imperfect until we know the full kinematic dependence in the full phase space → NNLO MC + PS...

- Many novel data-driven background (ttbar) estimation methods: really large amount of efforts by the Exotics, SUSY, B2G and Higgs communities
 - Allow to search for NP in extreme phase-spaces without dealing with top pT and other mismodellings (or lack of stats in the tails)
- Yet, top quark pT mismodelling is still one of the main issues with the current dataset
- Both ATLAS and CMS have a broad (multi-dimensional) differential measurements and MC tuning programs: the only way to solve this issue is to continue these efforts
 - MC tuning may improve the agreement, but if the discrepancy is really due to missing QCD and EW corrections, forcing the MC parameters to bring the top pT distribution in agreement with data is likely to break the agreement in other distributions



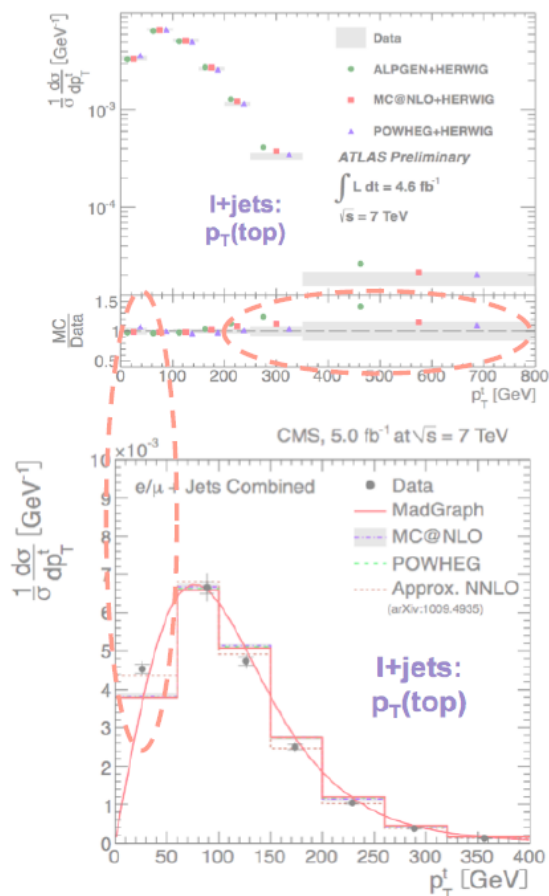
- Meanwhile, refined approaches to the “top pT reweighting” are possible
- Inputs from the theory community would be vital, as well as novel calculations and access to tools to perform NNLO computations
- Thanks to all my colleagues from ATLAS and CMS who helped in preparing the talk, and you for the attention!

BACK-UP

TOP 2013: both ATLAS and CMS begin to see softer top p_T in data

Differential Cross Sections: $p_{T,t}$, m_{tt}

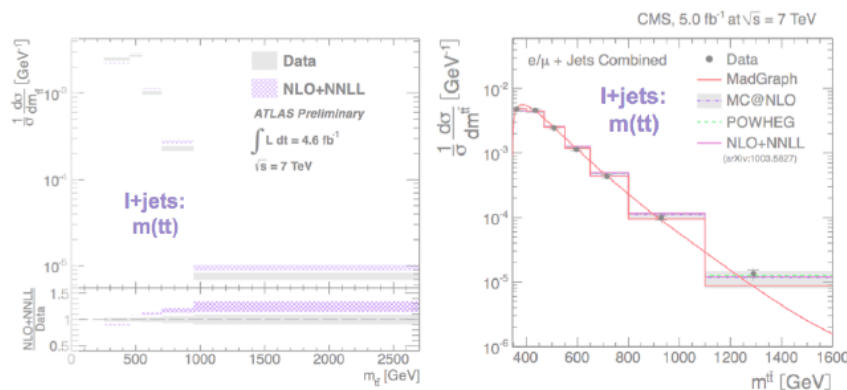
M. Aldaya



- Top p_T : in general softer spectrum in data than predicted by MCs.

Some tension between ATLAS and CMS in the first bin affects conclusion on agreement with NLO+NNLL prediction.

- Partonic level defined in the same way?
 Non-perturbative corrections missing?



- m_{tt} : very sensitive to PDFs but also to NP. Beware of EW effects not accounted for!
- Somewhat contradictory conclusions by ATLAS and CMS regarding agreement with NLO+NNLL.

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2013: CMS 'short-term solution': propose to use top p_T reweighting

Measurement of the top quark mass using the B-hadron lifetime technique

[CMS PAS TOP-12-030](#)

The CMS Collaboration

an assumption on the mass hypothesis is made. The top p_T spectrum from simulation, assuming $m_t=172.5$ GeV, is compared to one observed in data [35–37]. The simulated top p_T spectrum is then **re-weighted** to the unfolded top p_T spectrum observed in data. The difference in \widehat{L}_{xy} due to the re-weighting is interpreted as the uncertainty on m_t due to a potential mis-modeling of the top quark p_T distribution.

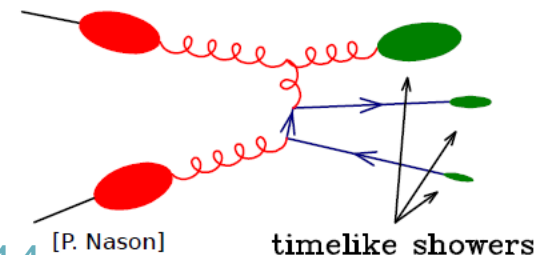
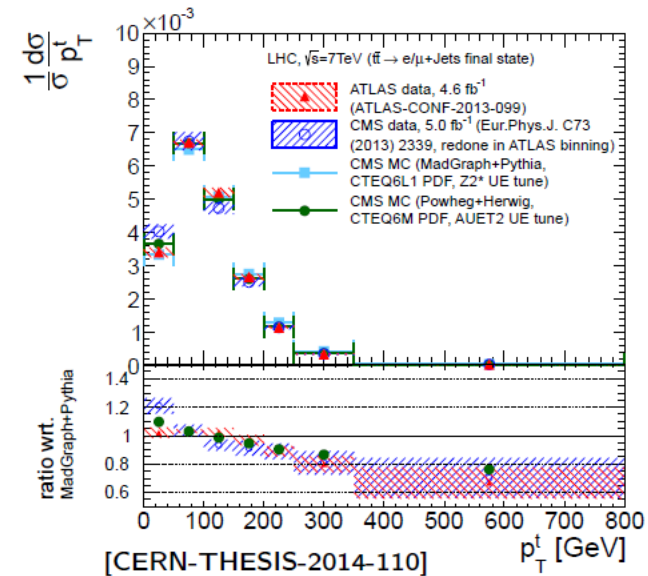
Source	Δm_t [GeV]		
	μ +jets	e +jets	$e\mu$
Top quark p_T modeling	3.27 ± 0.48	3.07 ± 0.45	2.36 ± 0.35

At present, this measurement of m_t is strongly limited by the systematic uncertainty on the top quark transverse momentum spectrum **which makes further studies necessary**. In general,

TOP 2014: further differential results about the top p_T mismodelling appear

$t\bar{t}$ top-quark p_T (mis)modeling

- **CMS** sees softer top p_T in data, agreement with **ATLAS** at high p_T
- Powheg+Herwig6 seems to agree with data, rescaling of t, \bar{t}, j momenta to give virtuality to extra jet [P. Nason, <https://indico.cern.ch/event/301787>]
- Different reshuffling schemes implemented in Herwig++ 2.7.1
- Pythia8: dipole-recoil vs. global recoil
- NNLO might be able to resolve
- **CMS** short-term solution: uncertainty from top p_T reweighting (similar approach at **D0** for $t\bar{t}$ p_T)

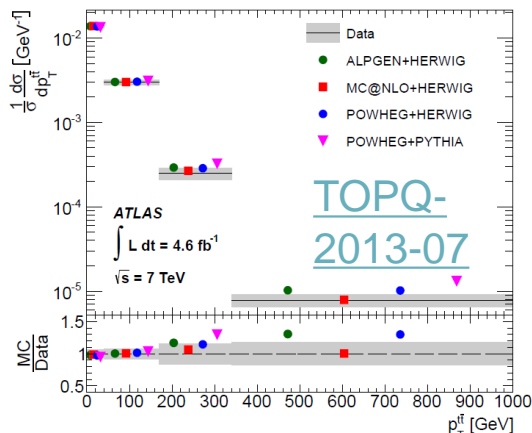
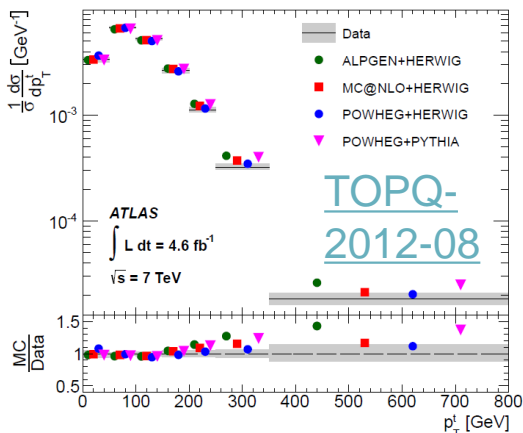


[slides at Top 2014](#)

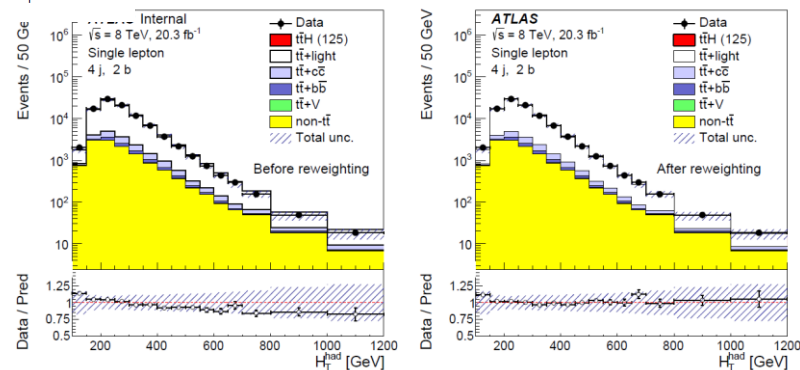
2014: ATLAS uses the top p_T reweighting as well (+ $t\bar{t}$ p_T reweighting)

Since the best possible modelling of the $t\bar{t}$ +jets background is a key aspect of this analysis, a correction is applied to simulated $t\bar{t}$ events in POWHEG+PYTHIA based on the ratio of measured differential cross sections at $\sqrt{s} = 7$ TeV between data and the simulation as a function of top quark p_T and $t\bar{t}$ system p_T [54]. This significantly improves the agreement between simulation and data in the total number of jets (driven mostly by $t\bar{t}$ system p_T reweighting) and jet p_T (driven mostly by the top quark p_T reweighting). This reweighting is applied to all $t\bar{t}$ +jets events, including the $t\bar{t}$ +HF component. The

ATLAS-CONF-2014-011



CERN-THESIS-2016-089

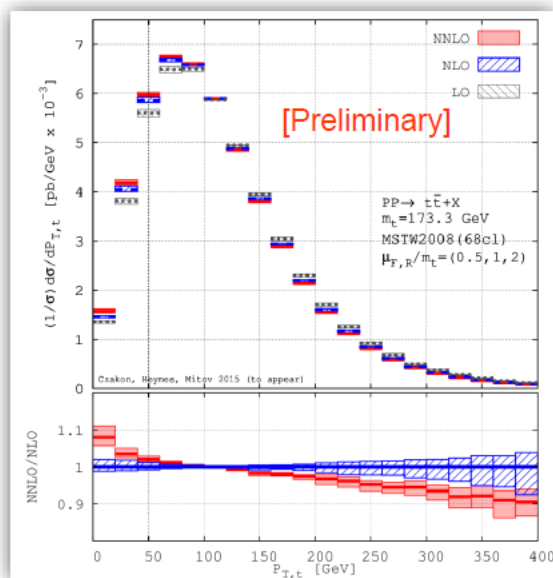


TOP 2015: both ATLAS and CMS see the slope in top p_T

Top p_T modeling: the verdict

→ Heymes

Really NEW (yesterday!):



Full NNLO/NLO k-factor
vs top p_T : a slope!

- Full NNLO correction “confirms” observed slope, in direction closer to the data

- Use k-factors to reweight NLO+PS MCs ?

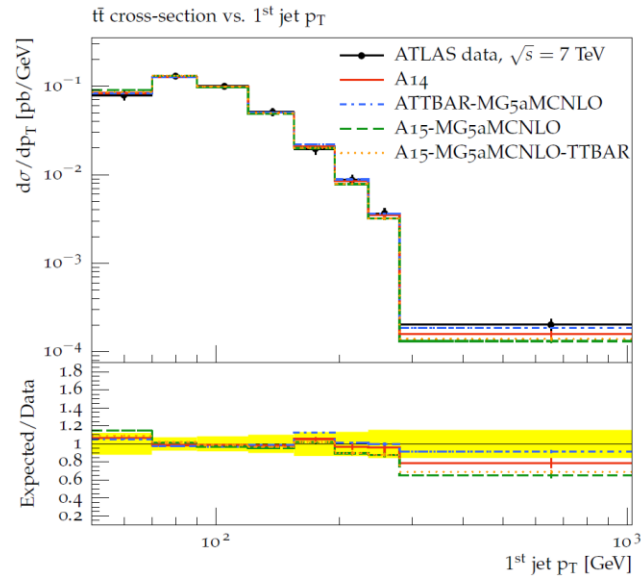
- Ultimately NNLO+PS would be great 😊

→ Great to see this dialogue between LHC precision measurements and state-of-the-art theory calculations

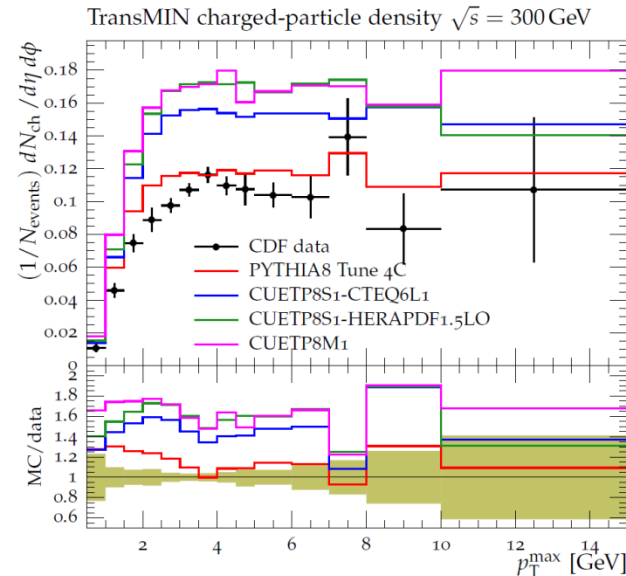
→ Important step forward in our understanding of Top production !!

2015: MC tuning efforts ramp up both in ATLAS and CMS

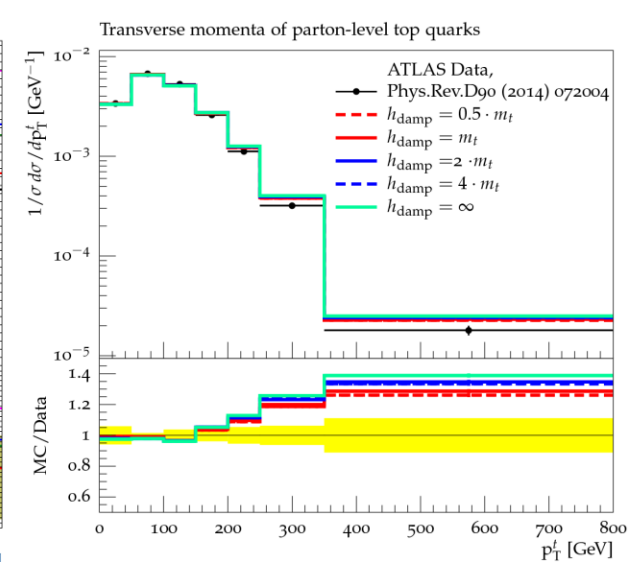
ATL-PHYS-PUB-2015-048



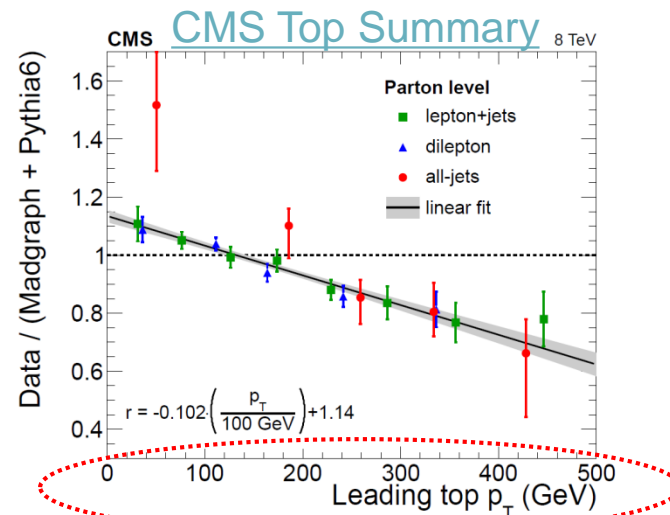
CMS-GEN-14-001



ATL-PHYS-PUB-2015-002



slope seen in all decay channels



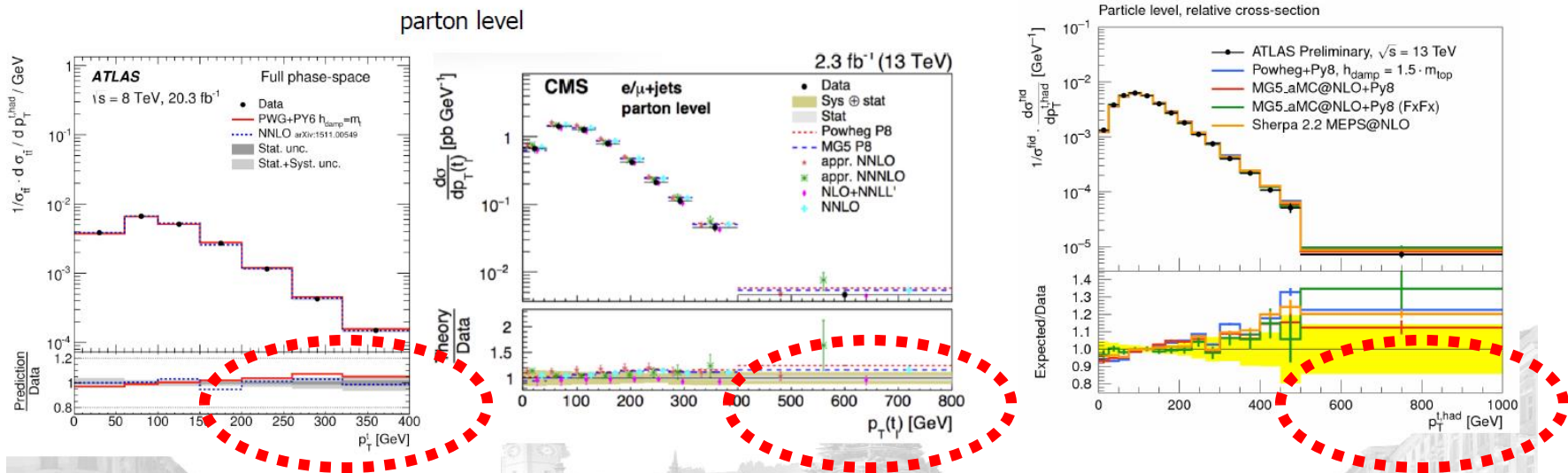
TOP 2016: many differential measurements confirm the findings



The top Pt modeling story

S. Henkelmann

- slope in the top pt distribution: data softer than MC predictions
 - largely improved by NNLO computations
 - modern NLO+PS MC can also cope for part of the discrepancy



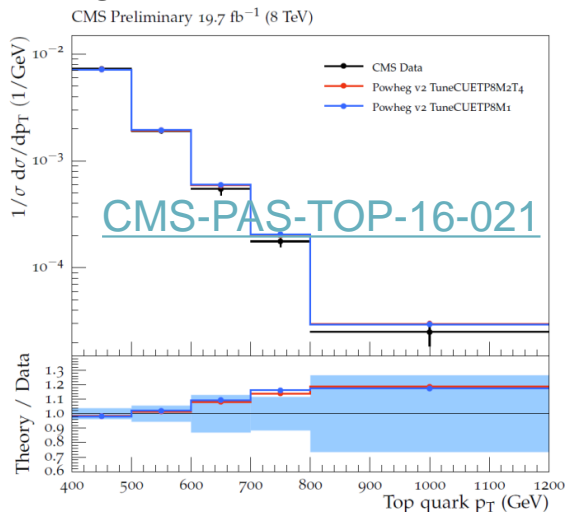
Frédéric Déliot, Top2016, 23-SEP-16

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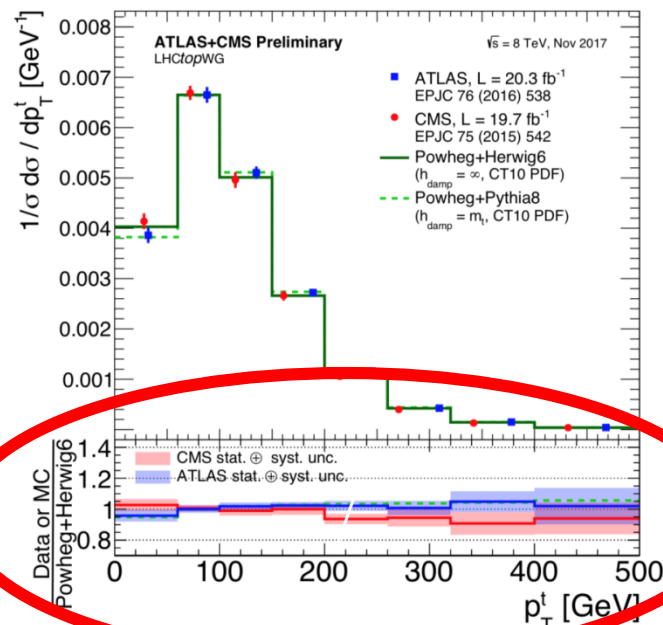
[slides as TOP 2016](#)

TOP 2017: top quark modelling and tuning from ATLAS and CMS

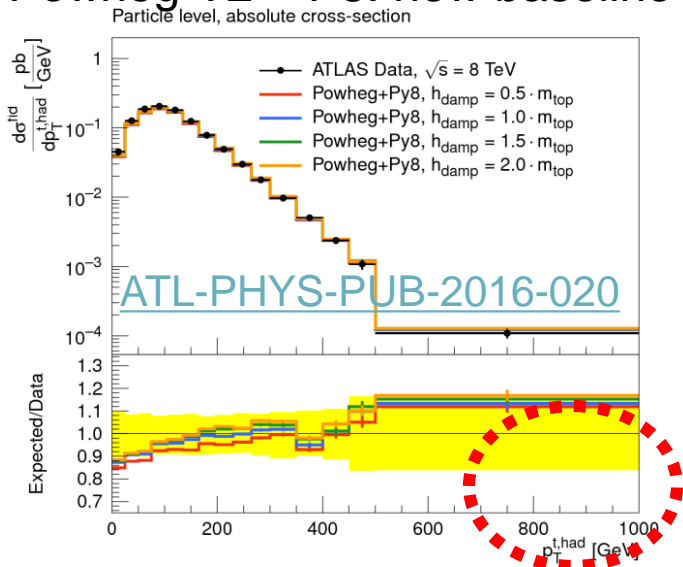
Powheg V2 as baseline, new CMS tune



LHCTopWGSummaryPlots



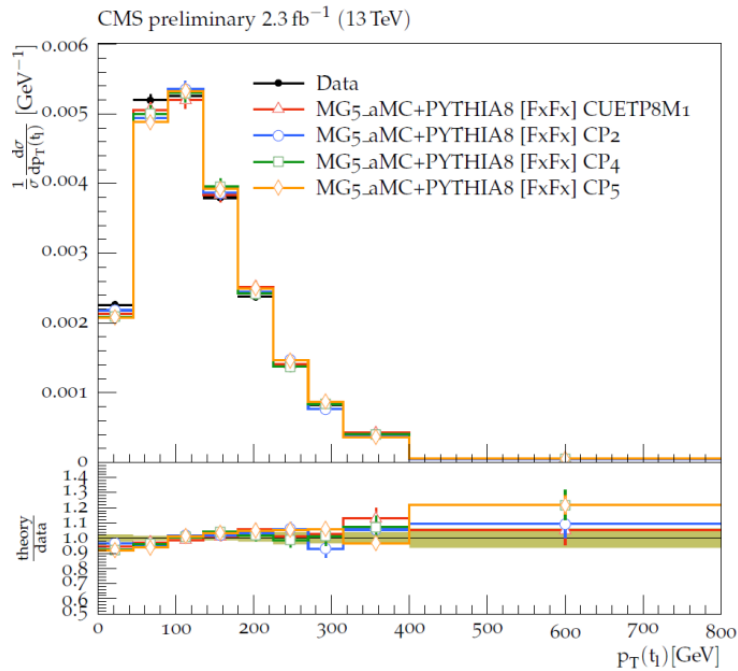
Powheg V2 + P8: new baseline in ATLAS



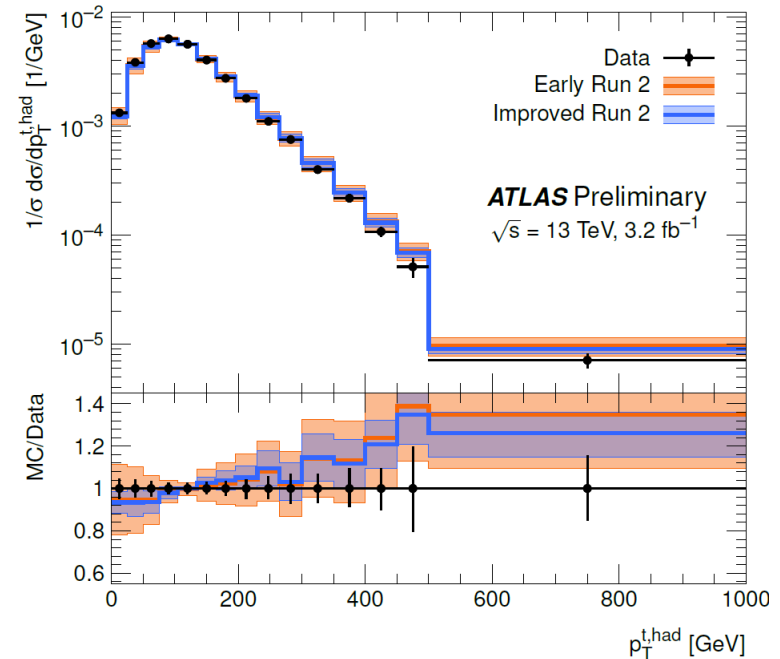
comparisons between ATLAS and CMS

TOP 2018: improvements in modelling ongoing, still not perfect

CMS-PAS-GEN-17-001

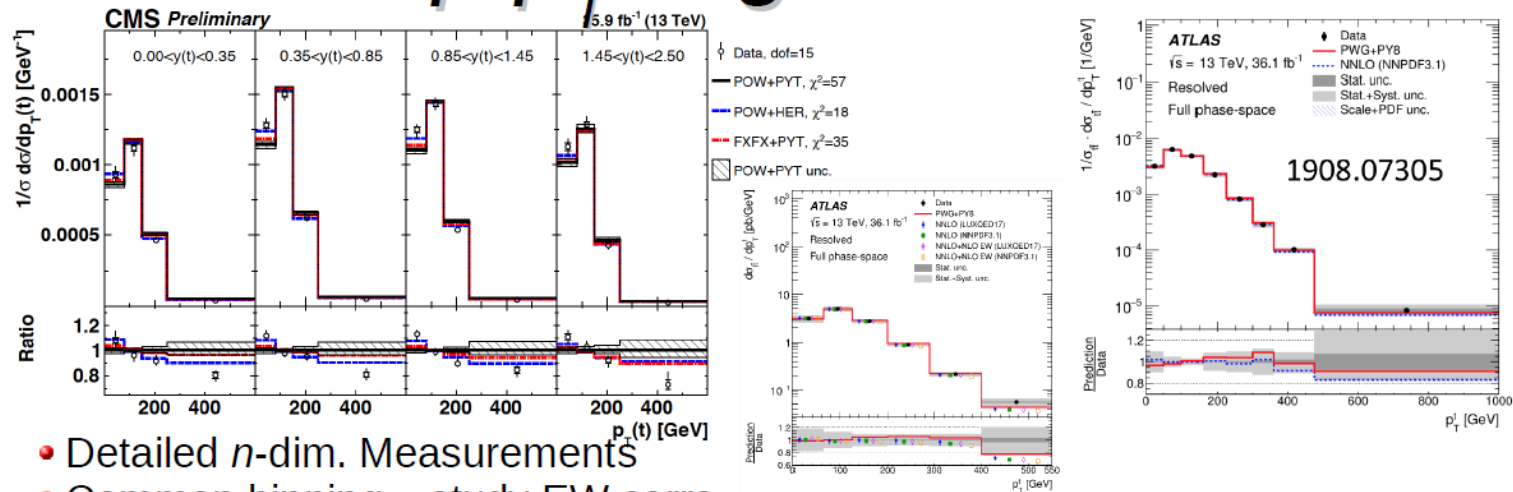


ATL-PHYS-PUB-2018-009



Precise predictions in top-quark physics must take into account both QCD and EW effects in order to correctly identify possible BSM effects.

TOP 2019: more and more precise differential measurements

The top p_T saga...continued Boisvert

- Detailed n -dim. Measurements
- Common binning – study EW corr.

- Slopes in 13 TeV ATLAS & CMS data
- Large systematic uncertainty – further understanding, common procedure ?
- To be continued in LHCTopWG context...
- Theory can help: experiments are eager to use an “NNLO MC”

