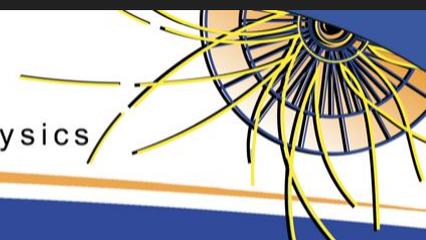


D. Longpers - LHCaE 2021



LHCP2021

The Ninth Annual Conference on Large Hadron Collider Physics



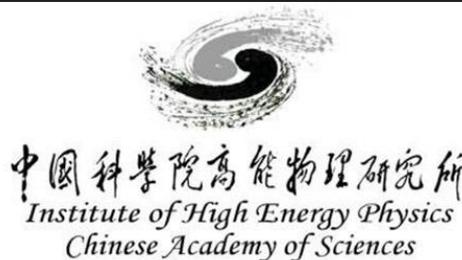
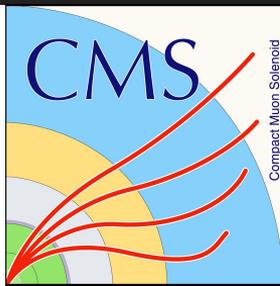
7-12 June 2021 ~~Paris (France), Sorbonne Université~~ (IN2P3/CNRS, IRFU/CEA)

Results on $tt+X$ Production

Joshuha Thomas-Wilsker (IHEP)

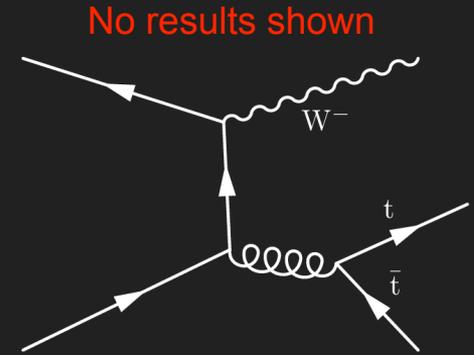
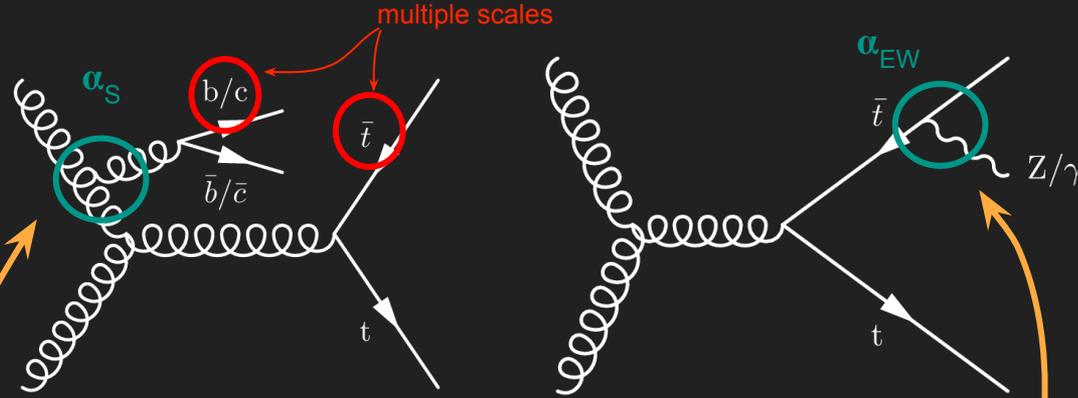
On behalf of the ATLAS and CMS Collaborations

9th Edition of the Large Hadron Collider Physics Conference



Introduction

$X \neq H$ or $t\bar{t}$. More details on these and results presented here in [Monday](#) and [Wednesday](#) sessions.



Top pairs produced with additional $X = HF/Z/W/\gamma$

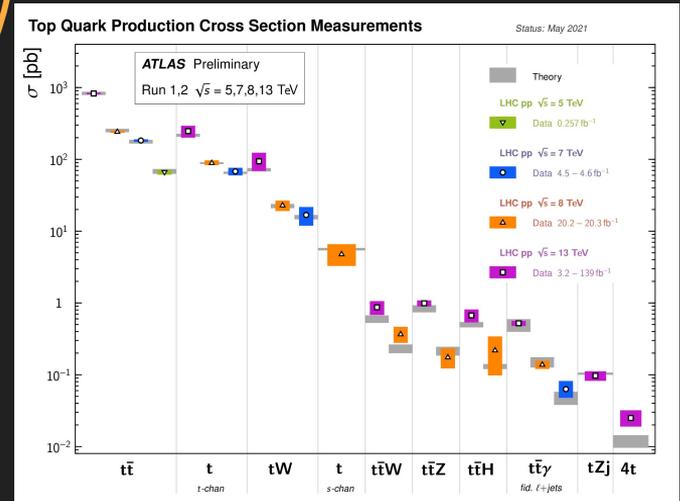
Probe of QCD and EW physics

$t\bar{t}+HF$: difficult multi-scale modelling challenge

$t-Z / t-\gamma$ couplings play key role in several BSM scenarios

Entering precision measurement era:

- Differential comparisons with latest theory predictions
- Effective field theory (EFT) interpretations \rightarrow anomalous couplings



EFT in Broad Strokes

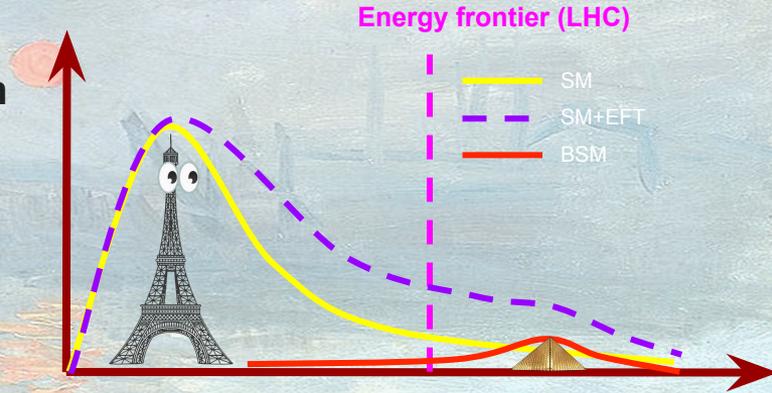
Treat the SM as a low-energy approximation of a more fundamental theory

Construct effective lagrangian incorporating effects from new physics at higher scales

Constrain couplings/rare processes

Topical talks on experimental approaches to EFT in Top sector by *Laura Barranco Navarro & Juan Gonzalez*

Dedicated EFT session on Wednesday



Wilson Coefficients aka WCs

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{\mathbf{d}, \mathbf{i}} \frac{c_{\mathbf{i}}^{\mathbf{d}}}{\Lambda^{\mathbf{d}-4}} \mathcal{O}_{\mathbf{i}}^{\mathbf{d}}$$

EFT operators: products and derivatives of SM fields

BSM effects: incorporated in momentum expansion

Overview



I'm here if Josh forgets to say something!



= since LHCP 2020

Measurement	Final state(s)	Experiment	Int. Luminosity	Journal Ref.
 tt+ γ	Single lepton	CMS	137 fb ⁻¹	CMS-PAS-TOP-18-010
 tt+ γ +tW γ	e, μ	ATLAS	139 fb ⁻¹	JHEP 09 (2020) 049
 tt+Z	3, 4 leptons	CMS	77.5 fb ⁻¹	JHEP 03 (2020) 056
 tt+Z	3, 4 leptons	ATLAS	139 fb ⁻¹	arXiv:2103.12603 Submitted to EPJC
 Direct EFT search in t(t)X	Dilepton (SS), 3, 4 leptons	CMS	41.5 fb ⁻¹	JHEP 03 (2021) 095
 Direct EFT search in t(t)Z	3, 4 leptons	CMS	138 fb ⁻¹	CMS-PAS-TOP-21-001
 tt+bb	Dilepton, single lepton	ATLAS	36.1 fb ⁻¹	JHEP 04 (2019) 046
tt+bb	Dilepton, single lepton	CMS	35.9 fb ⁻¹	JHEP 07 (2020) 125
tt+bb	Fully hadronic	CMS	35.9 fb ⁻¹	PLB 803 (2020) 135285
tt+cc	Dilepton	CMS	41.5 fb ⁻¹	arxiv:2012.09225 Submitted to PLB

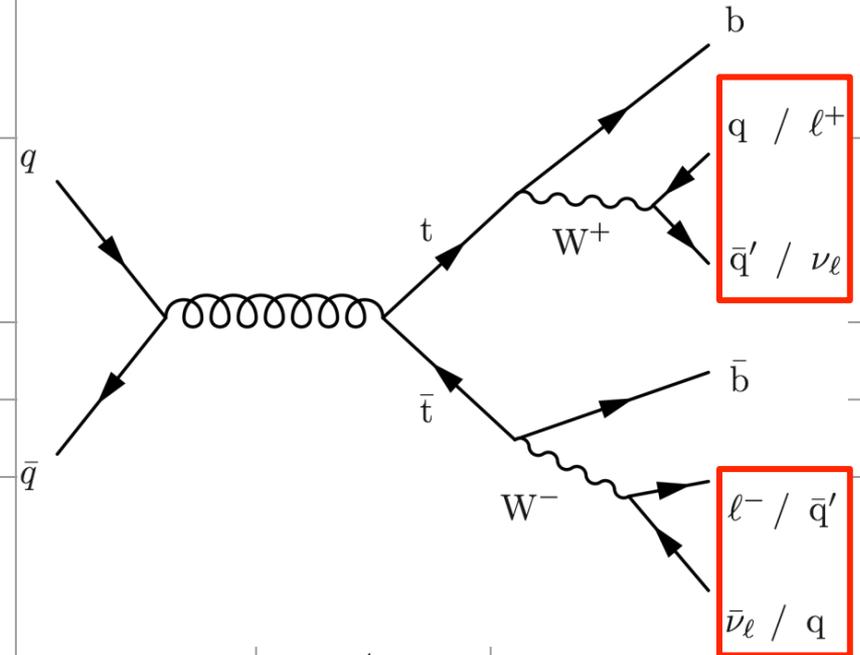
Overview

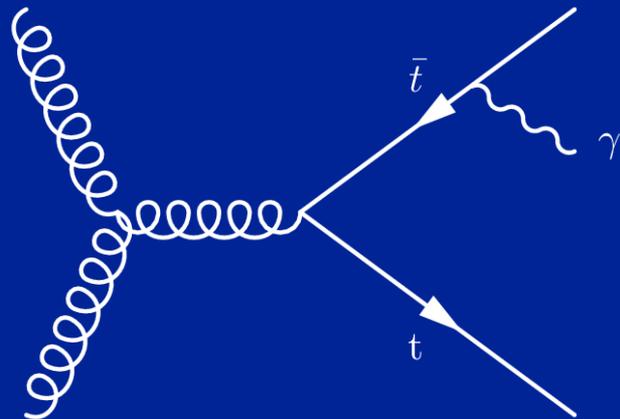


I'm here if Josh forgets to say something!

 = since LHCP 2020

Measurement	Final state(s)	Experiment	Int. Luminosity	Journal Ref.
$tt+\gamma$	Single lepton			
$tt+\gamma+tW\gamma$	e, μ			
$tt+Z$	3, 4 leptons			
$tt+Z$	3, 4 leptons			
Direct EFT search in $t(t)X$	Dilepton (SS), 3, 4 leptons			
Direct EFT search in $t(t)Z$	3, 4 leptons			
$tt+bb$	Dilepton, single lepton			
$tt+bb$	Dilepton, single lepton			
$tt+bb$	Fully hadronic	CMS	35.9 fb^{-1}	PLB 803 (2020) 135285
$tt+cc$	Dilepton	CMS	41.5 fb^{-1}	arxiv:2012.09225 Submitted to PLB





Dominant uncs: Signal/bkg
modelling, JES, photon ID, (ATLAS
definition of $tW\gamma$ @ parton level)

CMS: $t\bar{t} + \gamma$

CMS-PAS-TOP-18-010

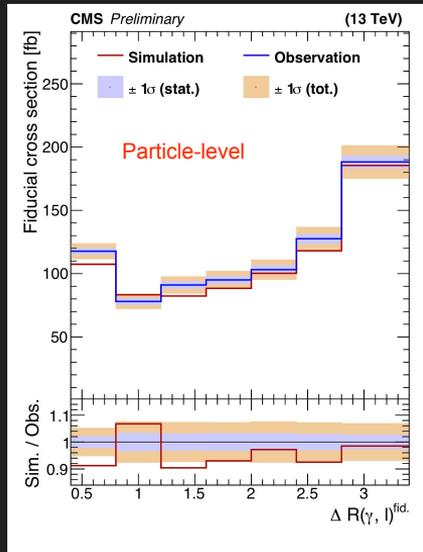
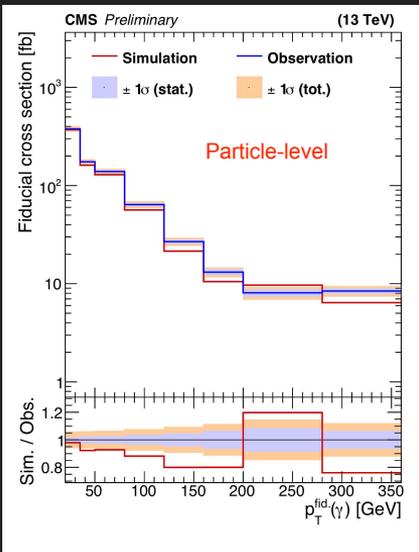
Single lepton

$$\sigma_{\text{incl}} = 800 \pm 46(\text{syst}) \pm 7(\text{stat})\text{fb}$$

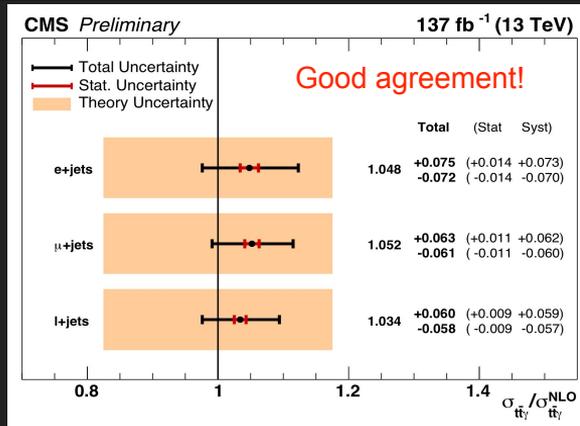
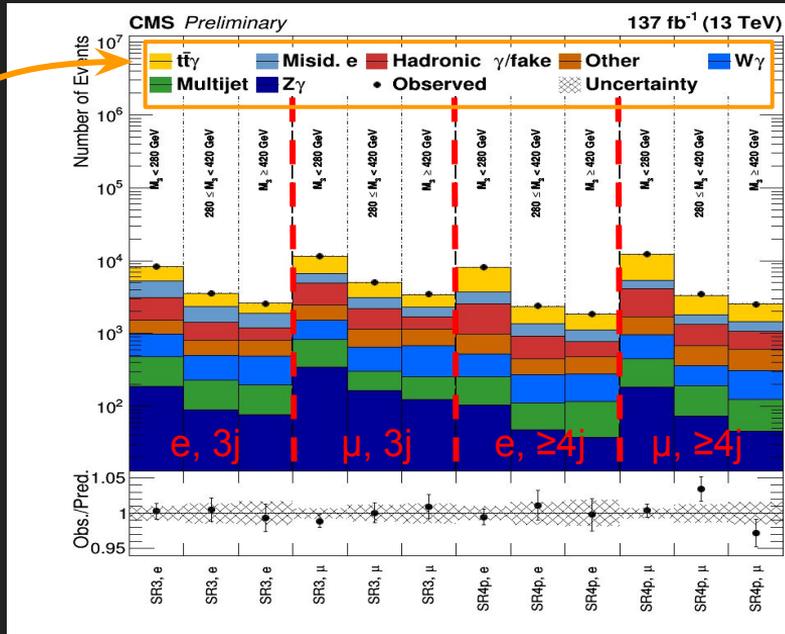
~6% precision.

$$\sigma_{\text{incl}}^{\text{NLO}} = 770 \pm 140(\text{tot})\text{fb}$$

Grouped via gen. matching of γ

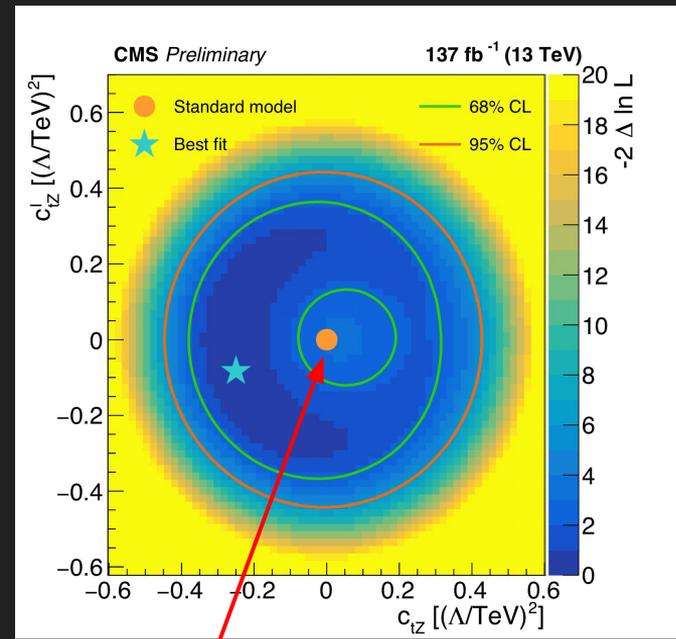
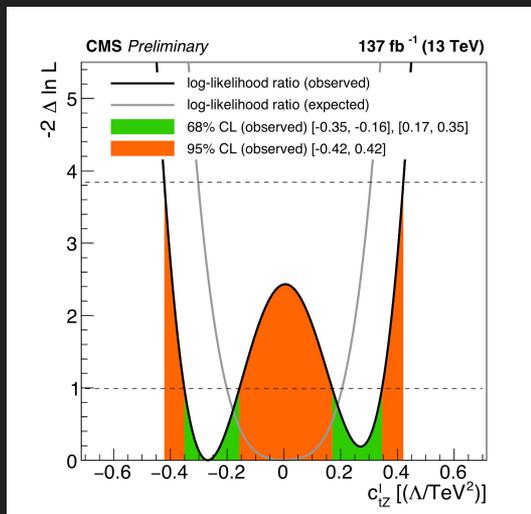
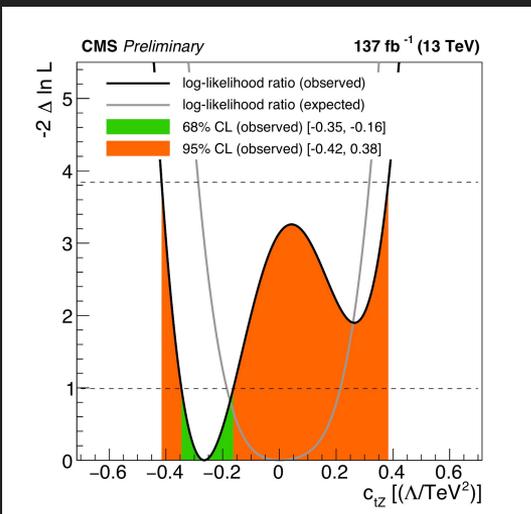


Shapes generally well described!





$p_T(\gamma)$ fit performed at BSM points defined by varied Wilson coefficients values



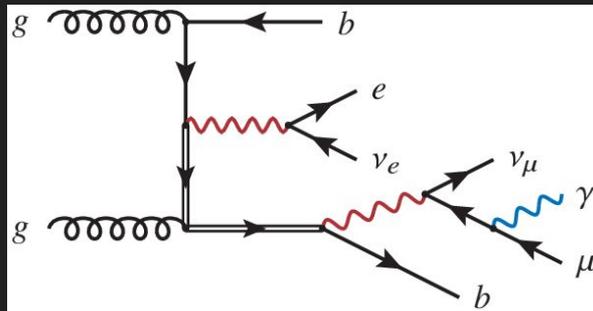
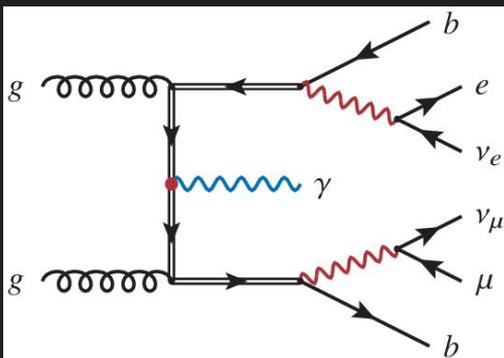
SM pred. Within 95% confidence interval of data.



1D confidence intervals on targeted WCs strongest to date!

ATLAS: Combined $t\bar{t}+\gamma$ & $tW\gamma$

JHEP 09 (2020) 049

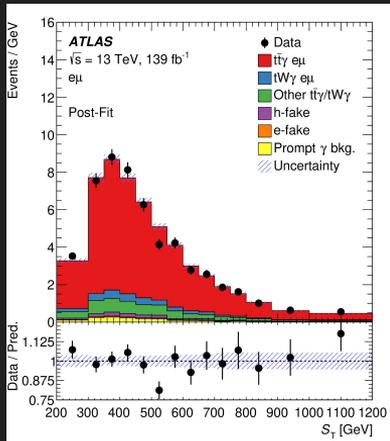


Fiducial XS measurement of $t\bar{t}\gamma$ and $tW\gamma \rightarrow$ compare w. recent theory prediction [1,2]

Parton-level selection mimics theory phase-space

OS $e\mu$

$$\sigma_{\text{fid}} = 39.6_{-2.2}^{+2.6}(\text{syst}) \pm 0.8(\text{stat})\text{fb}$$



~ 7% precision!

Measurement in good agreement with NLO theory pred:

$$\sigma_{\text{fid}}^{\text{NLO}} = 38.5_{-2.18}^{+0.56}(\text{scale})_{-1.18}^{+1.04}(\text{PDF})\text{fb}$$

ATLAS: Combined $t\bar{t}+\gamma$ & $tW\gamma$

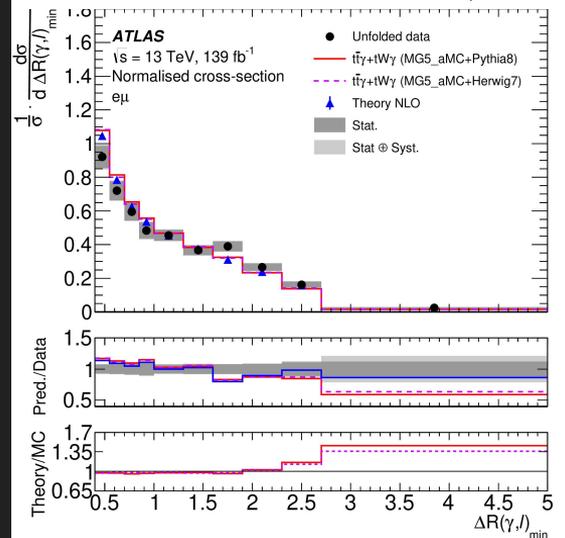
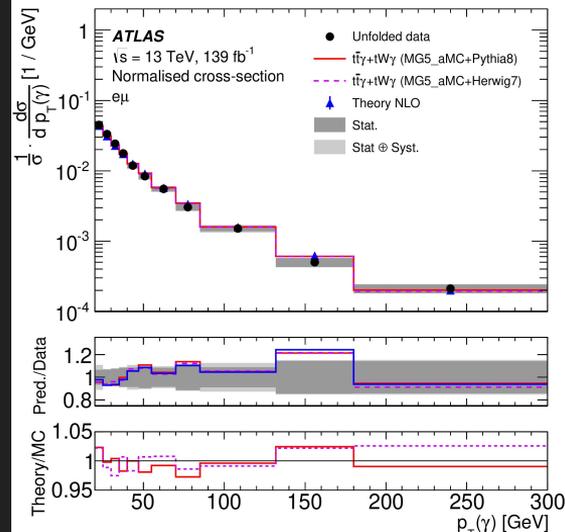
JHEP 09 (2020) 049

Absolute and normalised differential XS measurements in fiducial volume

Several variables related to γ and lepton kinematics

Shapes generally well described by MC and NLO theory

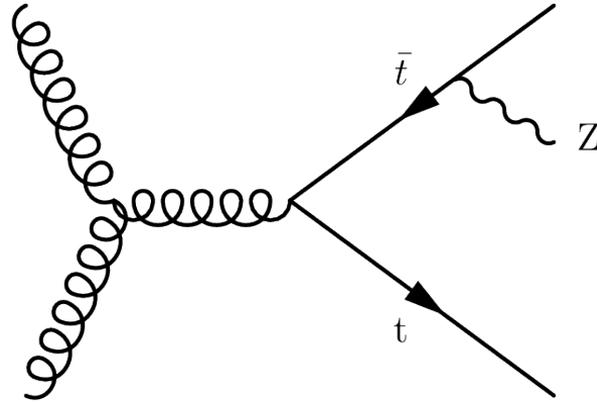
Imperfect description using LO MC in a few variables



Having a precise theory prediction is really beneficial!



Dominant systematics: Signal/bkg modelling, b-tagging, lepton ID.



tt+Z
3, 4 lepton

ATLAS

[arXiv:2103.12603](https://arxiv.org/abs/2103.12603)

Fit 8 SR's+CR's

$$\sigma^{\text{incl.}} = 0.99 \pm 0.08(\text{syst.}) \pm 0.05(\text{stat.})\text{pb}$$

CMS

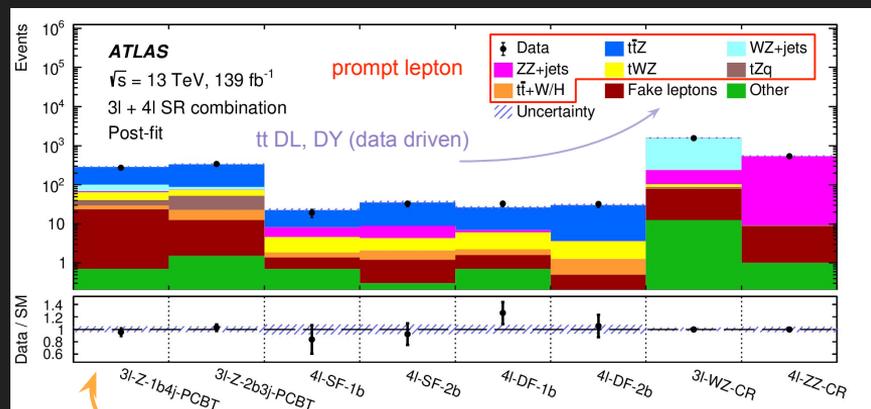
[JHEP 03 \(2020\) 056](https://arxiv.org/abs/2003.056)

Fit 14 SR's+CR's.

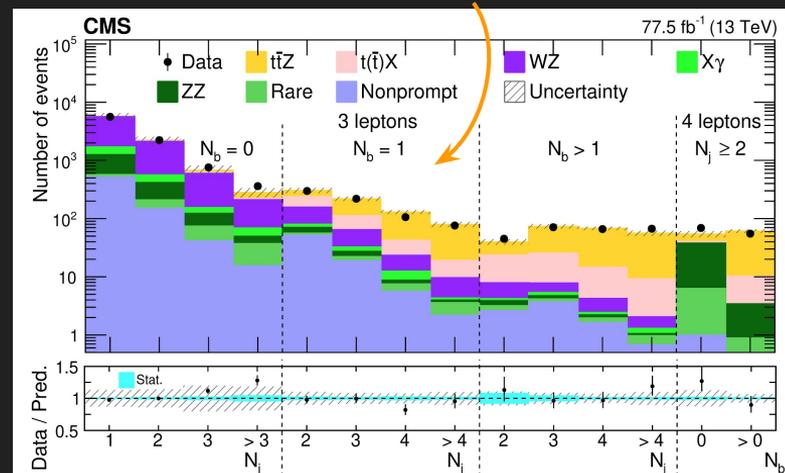
$$\sigma^{\text{incl.}} = 0.95 \pm 0.06(\text{syst}) \pm 0.05(\text{stat})\text{pb}$$

[1] $\sigma^{\text{NLO (QCD+EW)+NNLL}} = 0.86^{+0.07}_{-0.08}(\text{scale}) \pm 0.02(\text{pdf})\text{pb}$

Good agreement. ~ Same 8-9% in theory and measurements!



Events categorised according to # (b)jets and leptons.



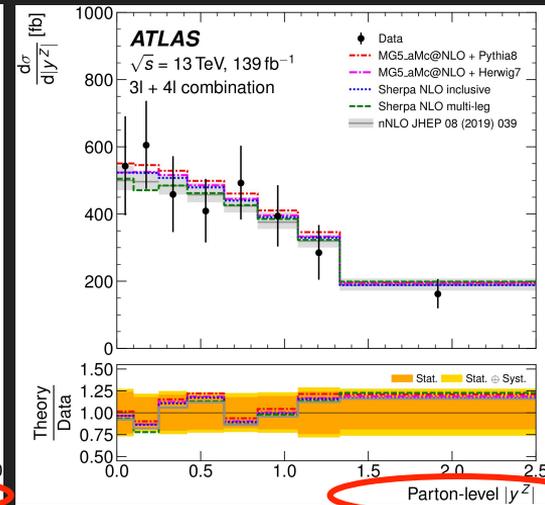
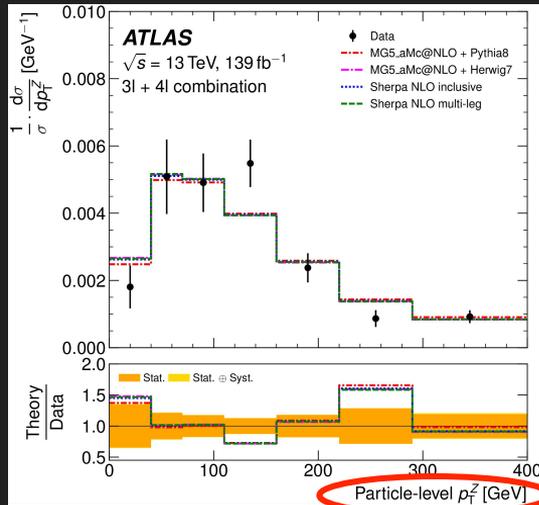
tt+Z

ATLAS

[arXiv:2103.12603](https://arxiv.org/abs/2103.12603)

Extensive study of several differential distributions.

Most distributions in good agreement with NLO/MC



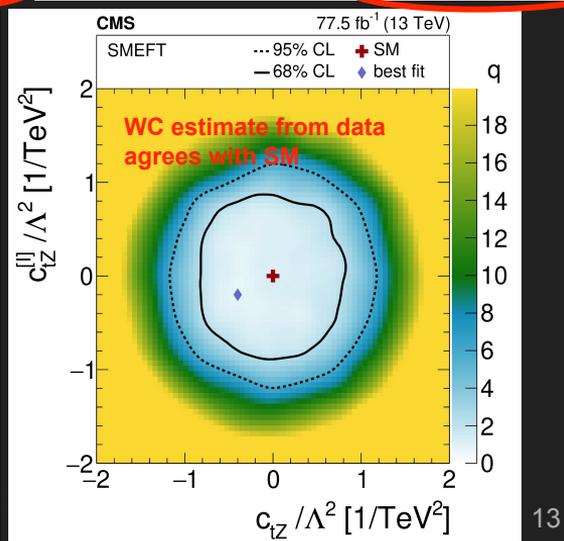
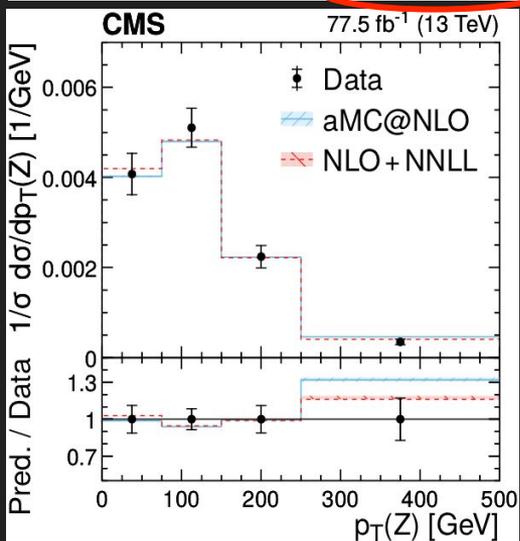
CMS

[JHEP 03 \(2020\) 056](https://arxiv.org/abs/2003.056)

Differential XS of several observables

Good agreement w. NLO theory prediction and MC simulation

Provide CL intervals for WC's



Both experiments statistically limited in differential XS.



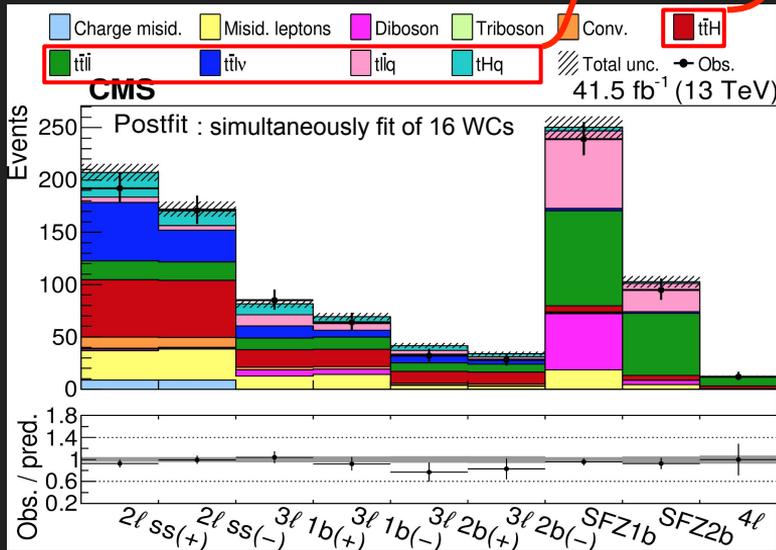
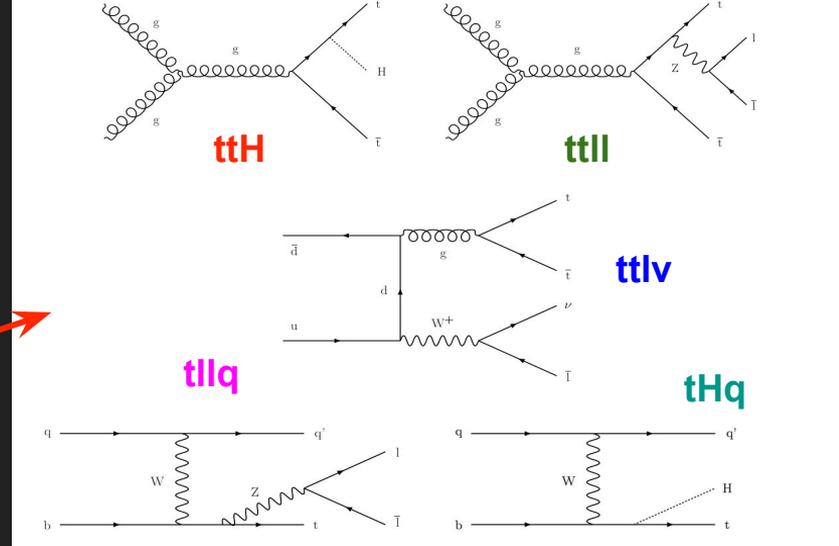


Direct EFT Search in $t(t)X$

JHEP 03 (2021) 095

‘Global’ approach to EFT targeting on multiple final states \rightarrow sensitive to many EFT operators

Multilepton events categorised based on: # and charge sum of leptons, # b-jets, # jets



Accounts for SM/BSM interference and interplay between new physics operators

Event weights parameterised by Wilson coeff's directly at detector level

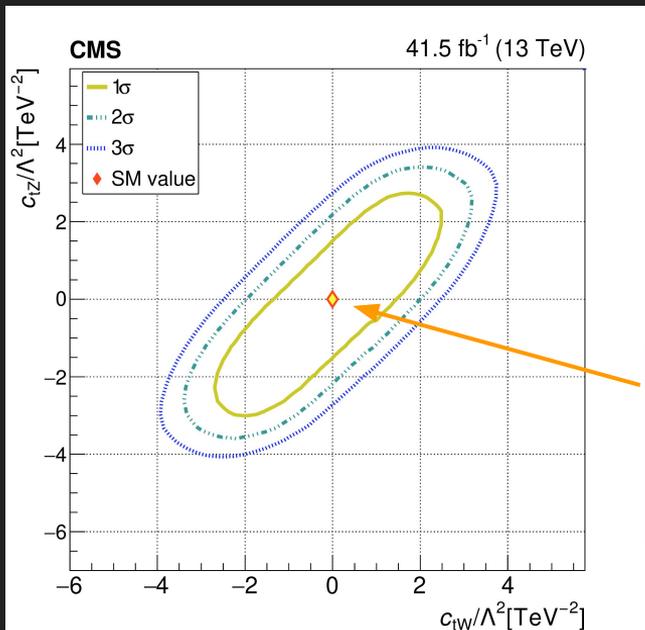


Direct EFT Search in $t(t)X$

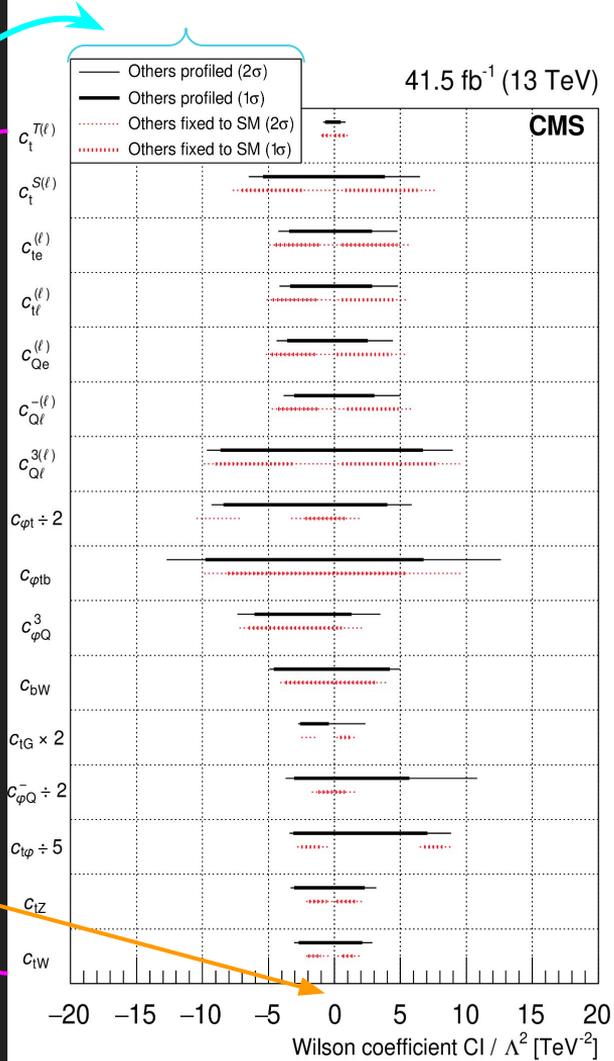
JHEP 03 (2021) 095

Profile likelihood fit of 35 independent categories.

Fit 16 EFT operators, calculate confidence intervals in 2 scenarios.



SM points fall within 2σ in most cases.



NEW

Direct EFT Search in $t(t)Z$

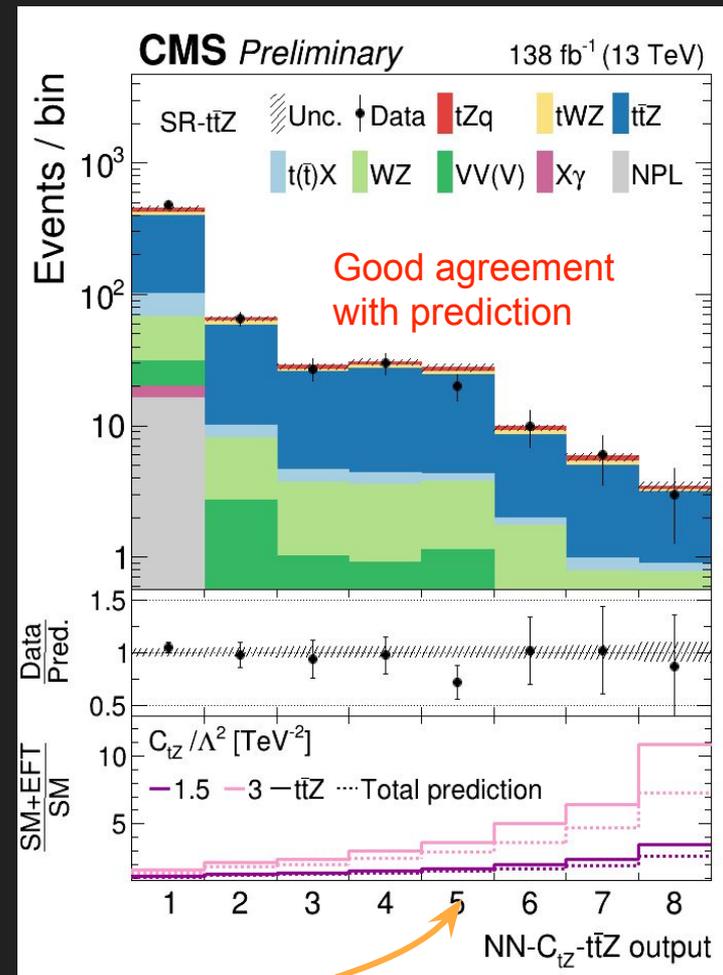
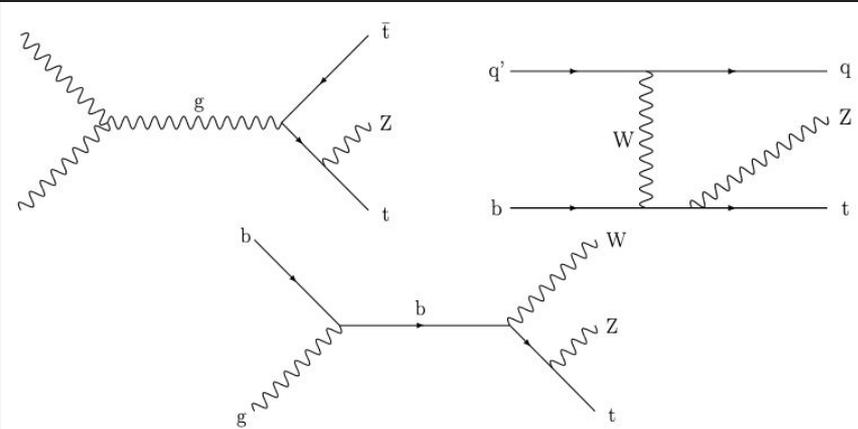
CMS-PAS-TOP-21-001

Refined iteration of direct EFT search method in 3 & 4 lepton final states

Target of t - Z interaction (least constrained by available data in top sector)

Pioneering work on EFT MVA techniques

Multiclass MVA ($t\bar{t}Z$, tZq , other) + NNs target specific EFT effects!



Stronger anomalies = stronger response.

NEW

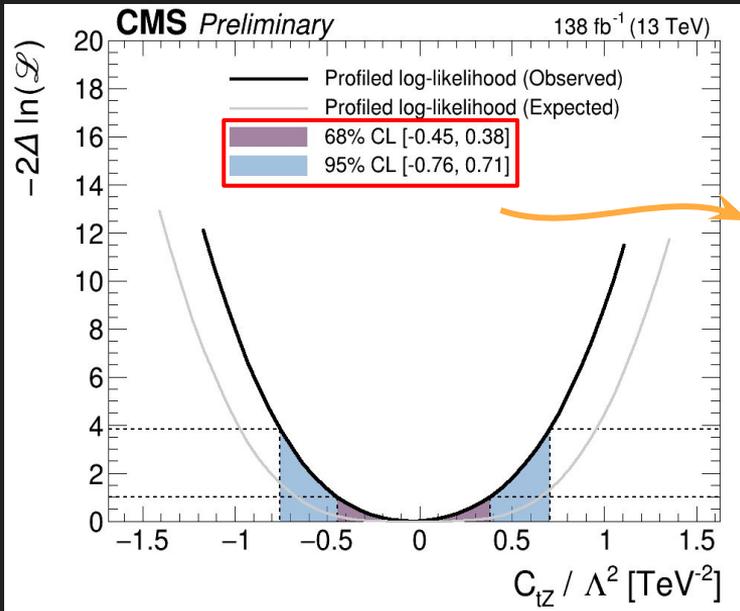
Direct EFT Search in $t(t)Z$

[CMS-PAS-TOP-21-001](#)

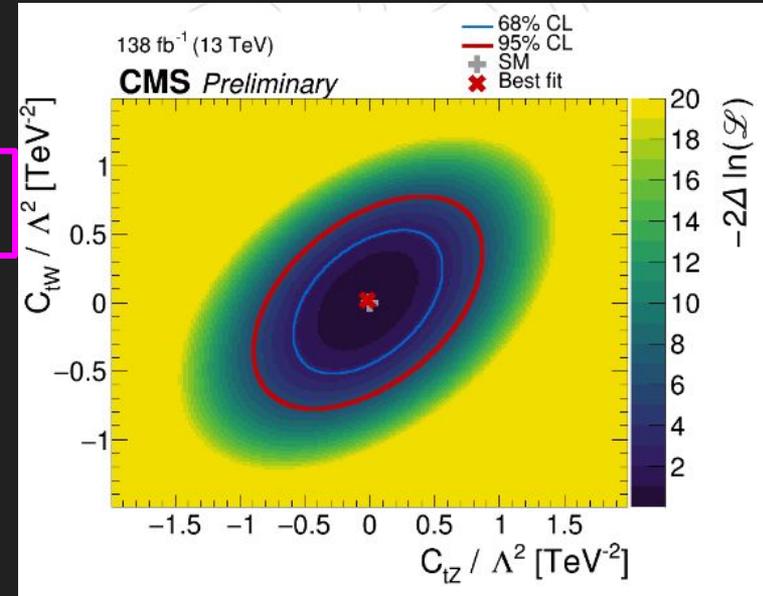
EFT NN distributions used as input to several fits in SR + CRs

Extract confidence intervals for 1, 2 or 5 WCs simultaneously

Dominant unc: from non-prompt lepton background estimation and theory uncertainties

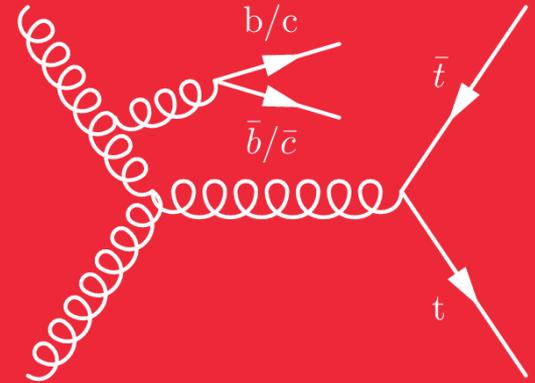


Large improvements due to machine learning methods!



Agreement with SM extremely good!

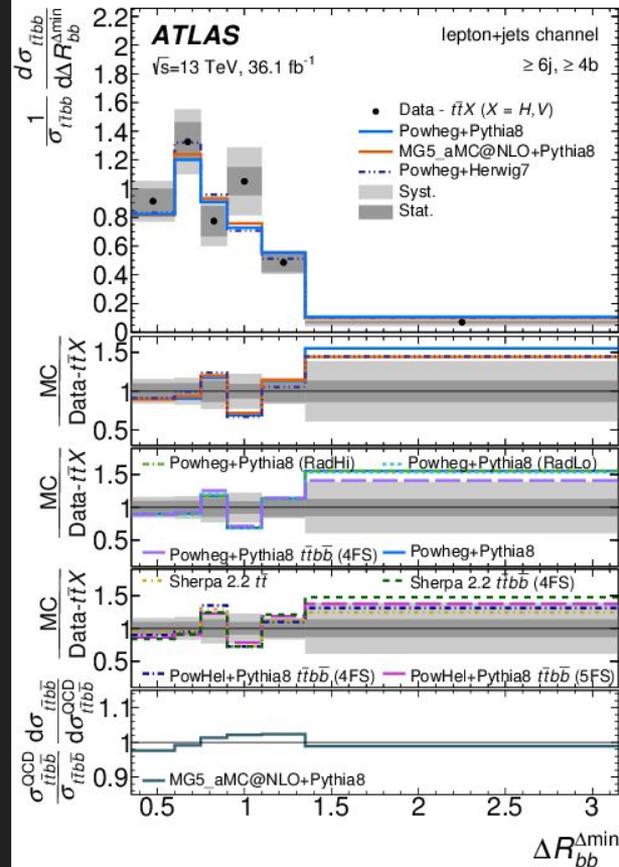
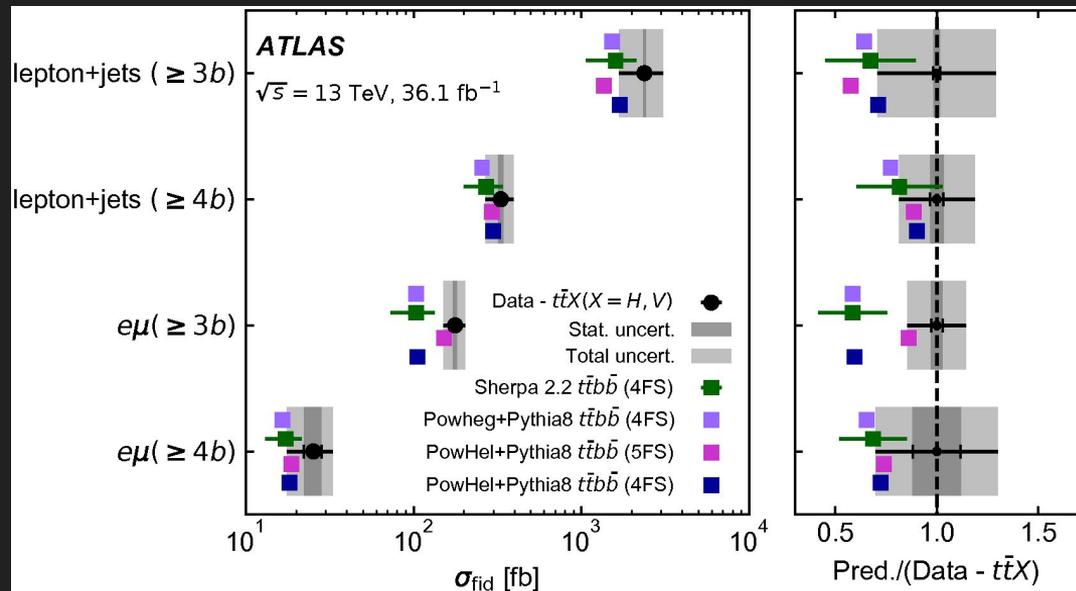
Dominant systematics from
b-tagging, JES, tt modelling.



Fiducial XS measurement in $e\mu$ and $l+jets$

Precision in $\geq 3b$ $e\mu$ of 13%

Emphasis on differential measurements of observables sensitive to the QCD modelling of additional jets



XS in data higher than in prediction

CMS

JHEP 07 (2020) 125

2L & l+jet final states

Fiducial XS precision in l+jets ~11%

CMS

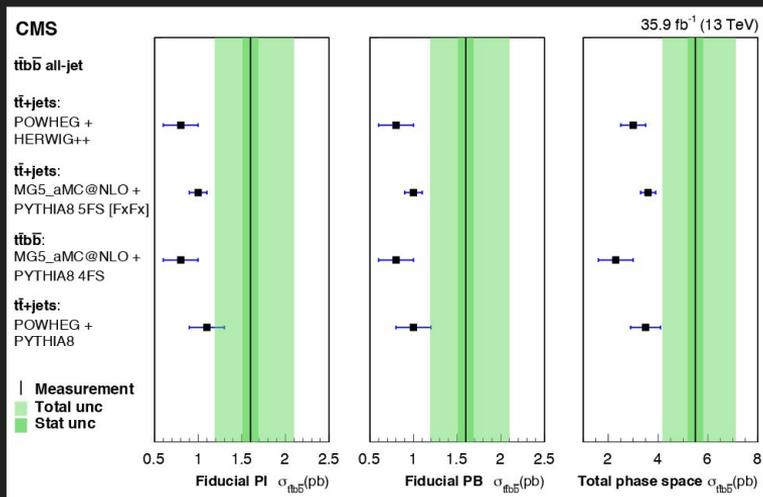
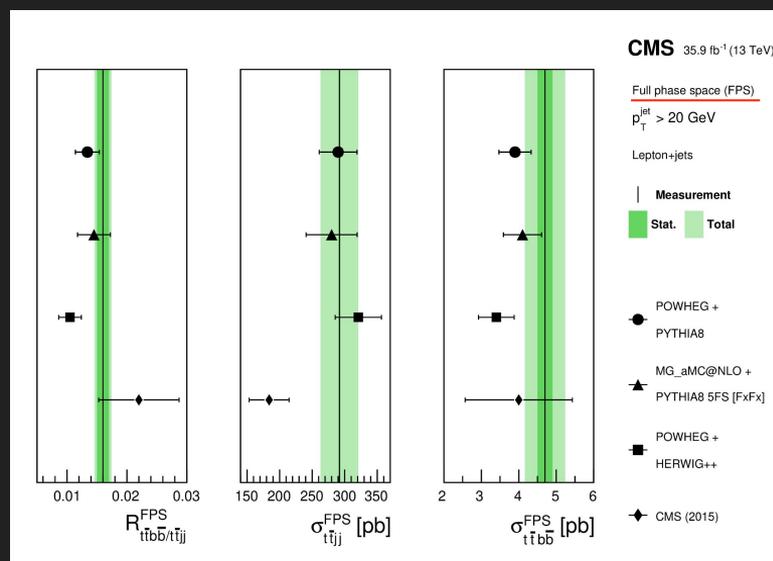
PLB 803 (2020) 135285

All-hadronic final state

Fiducial XS precision ~32%



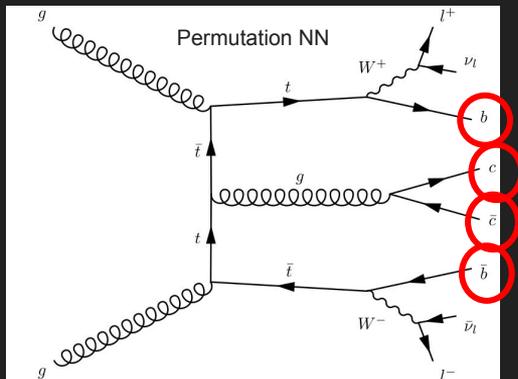
XS higher in data than in predicted in MC



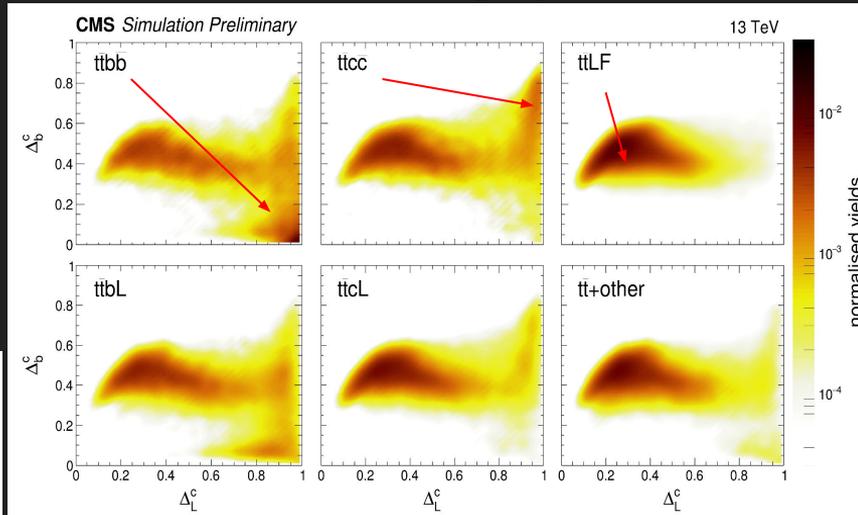


First measurement of σ_{ttcc} in dilepton channel along with σ_{ttbb} , σ_{ttLF} and $R(\sigma_{ttcc/bb}/\sigma_{ttjj})$

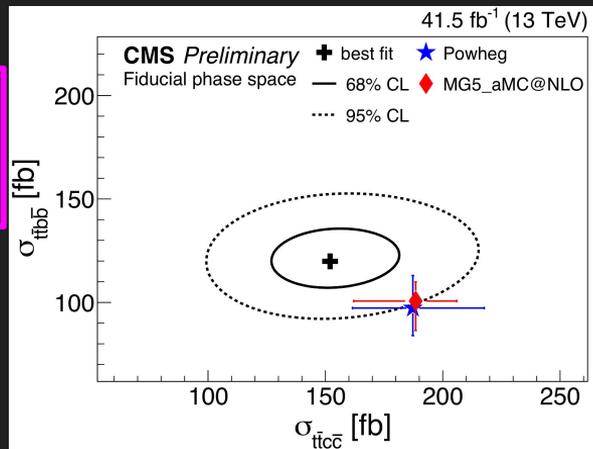
Assigns jet origin



Discern tt+cc from bb & light processes



Fit 2D templates



19% precision on σ_{ttcc}^{fid}

15% precision on σ_{ttbb}^{fid}

Over(under)prediction of $ttcc(ttbb)$

Concluding Remarks

Excellent precision in XS measurements of $t\bar{t}+Z/\gamma/HF$

Small under-prediction in $t\bar{t}+Z/\gamma/b\bar{b}$

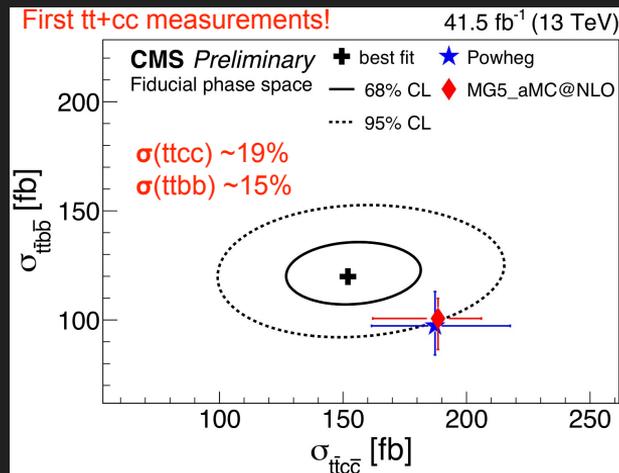
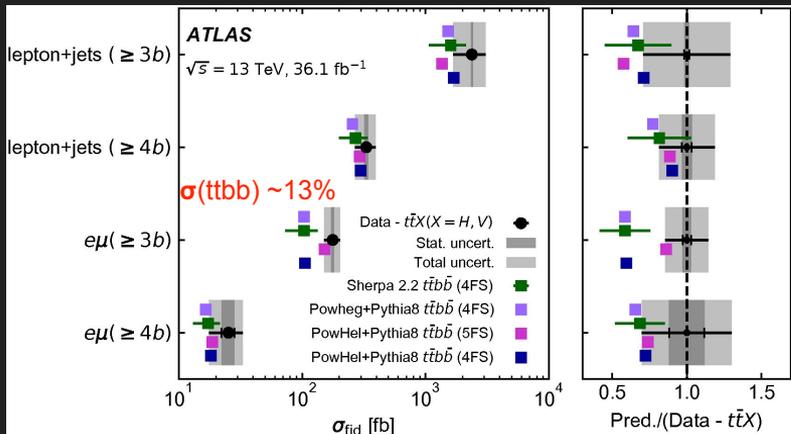
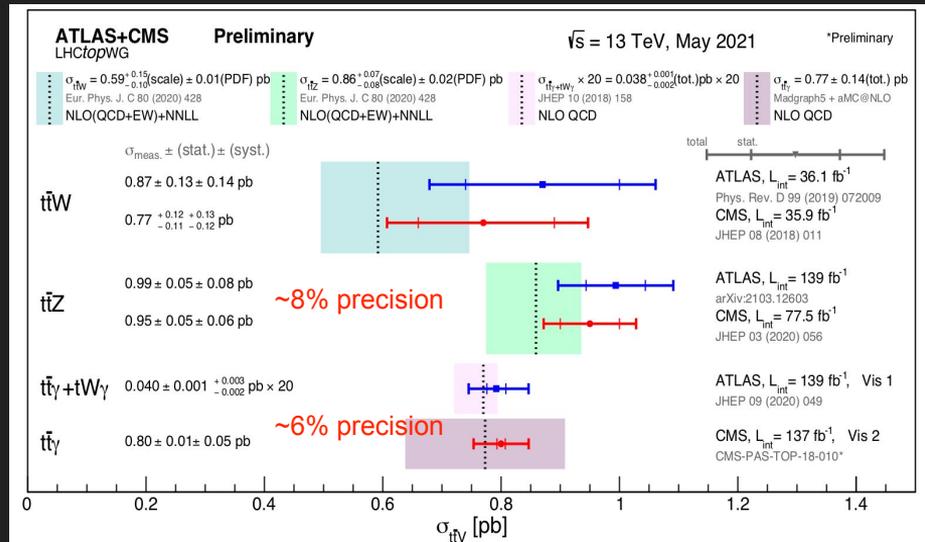
Unprecedented constraints on $t\text{-}Z/\gamma$ WCs

Global approach to EFT provides competitive WC constraints. Improvements from novel ML techniques

Standard model is holding up very well so far

Several full run 2 results to come

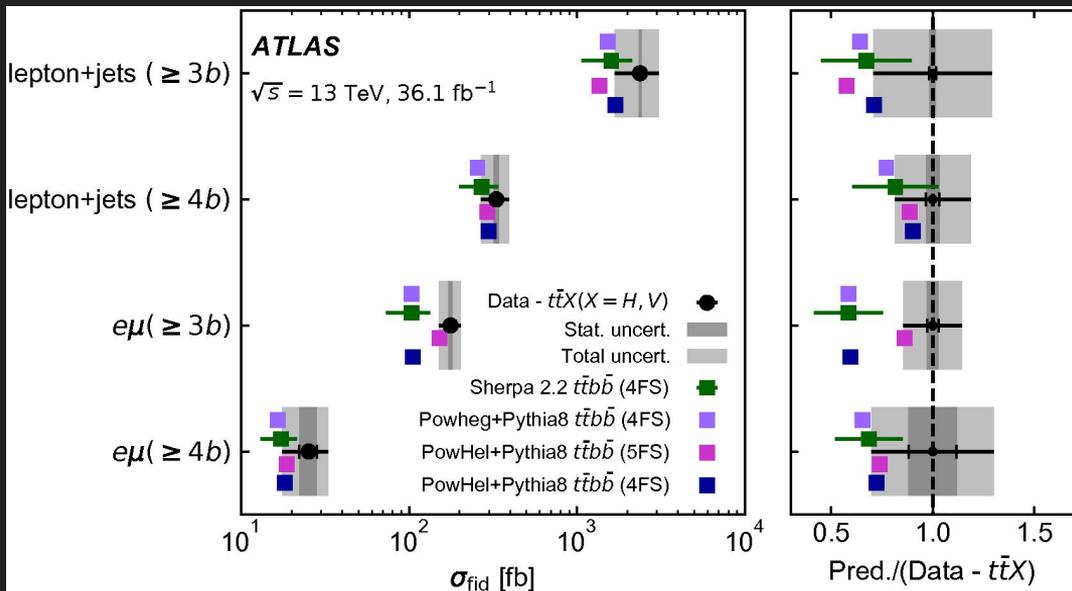
Precise theory predictions and close collaboration between communities pays off



Backup



tt+bb Summary



CMS Preliminary

