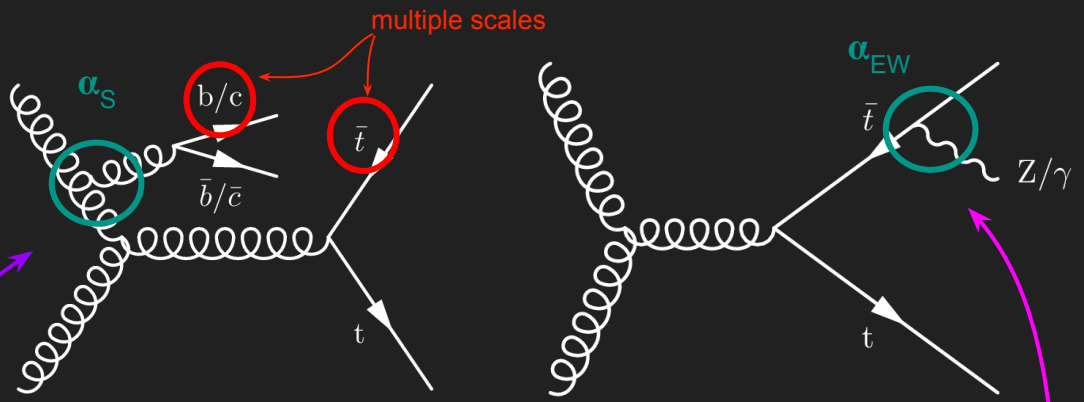
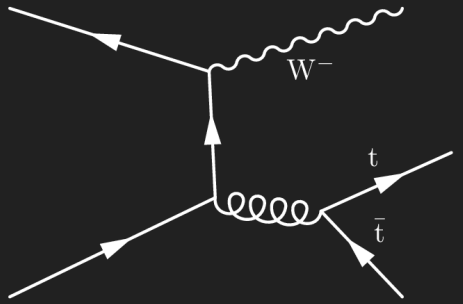
CMS Results on tt+X Production

Joshuha Thomas-Wilsker (IHEP)
On behalf of the CMS Collaboration
The 7th China LHC Physics Workshop

Introduction



No results shown



tt+X = Top pairs produced with additional bb/cc/Z/W/γ

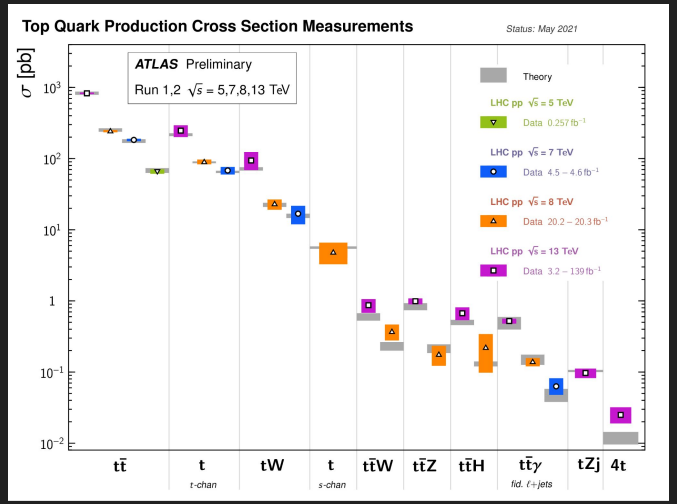
Probe of QCD and EW physics

Why?

- tt+HF: tough multi-scale modelling → invaluable to theorists
- t-Z / t-γ couplings play key role in several BSM scenarios

Entering precision measurement era:

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



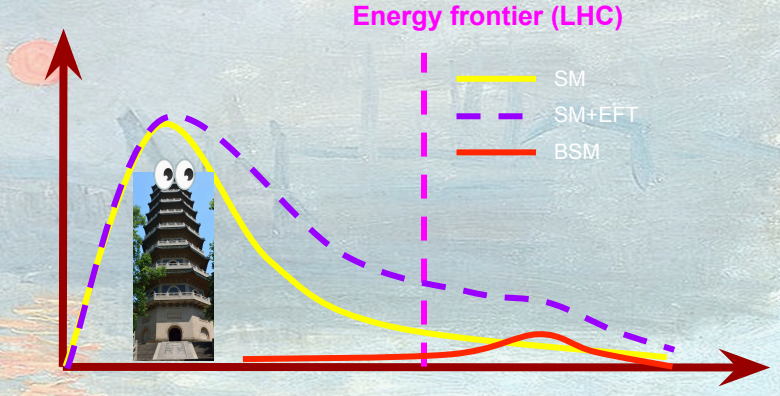
EFT *in Broad Strokes*

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

Construct effective lagrangian

Incorporates effects from new physics at higher scales

Constrain couplings/rare processes



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

Wilson Coefficients aka WCs

EFT operators: products and derivatives of SM fields

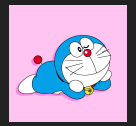
BSM effects: incorporated in momentum expansion

Overview

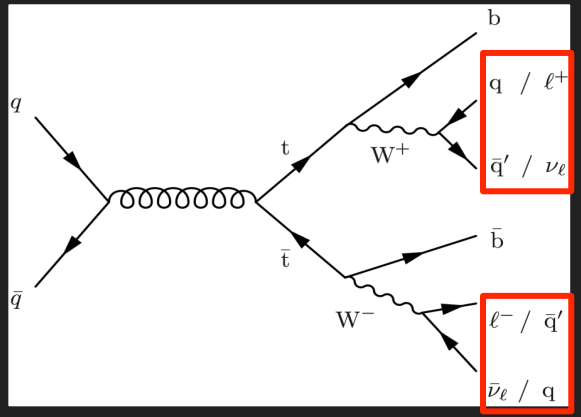
Measurement	Final state(s)	Int. Luminosity	Journal Ref.
tt+γ	Single lepton	137 fb^{-1}	arXiv:2107.01508
tt+γ	Dilepton	138 fb^{-1}	CMS-PAS-TOP-21-004
Direct EFT search in t(t)Z	3, 4 leptons	138 fb^{-1}	arXiv:2107.13896
tt+cc	Dilepton	41.5 fb^{-1}	arxiv:2012.09225

NEW

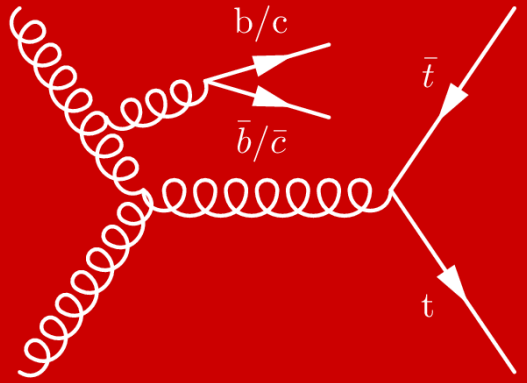
NEW



I'll add a few comments of my own

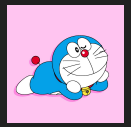


Dominant systematics: b-tagging,
JES, tt modelling



tt+cc

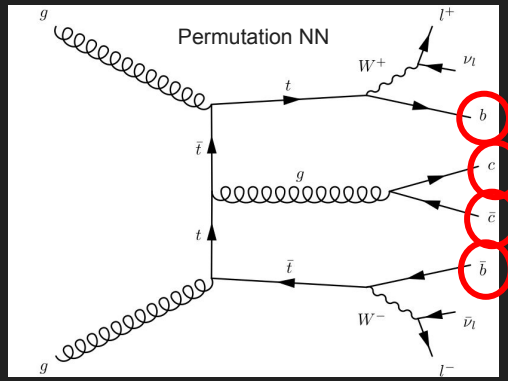
arxiv:2012.09225



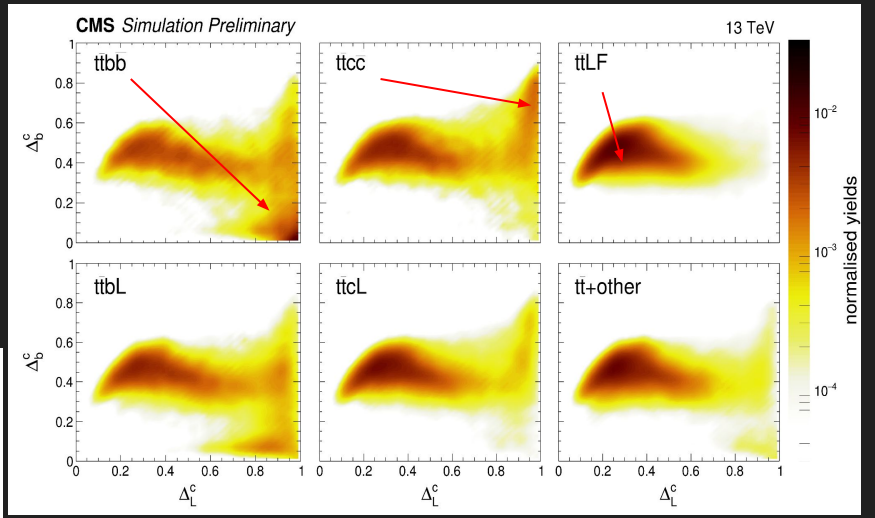
Incredible precision on subsidiary σ_{ttbb}^{fid} measurement!

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

Jet-parton assignment



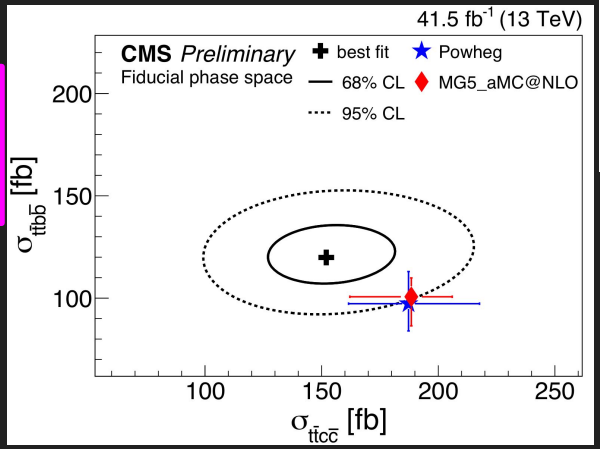
tt+cc vs bb & LF discriminators



19% precision on σ_{ttcc}^{fid}

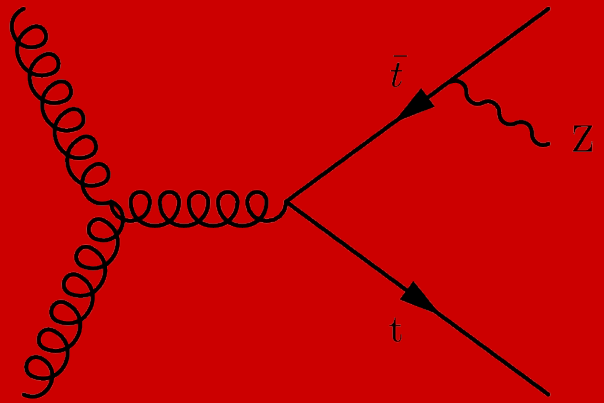
15% precision on σ_{ttbb}^{fid}

Over(under) prediction of ttcc(ttbb)



Fit 2D templates

Dominant systematics: non-prompt lepton bkgd estimate, theoretical



NEW

Direct EFT Search in t(t)Z

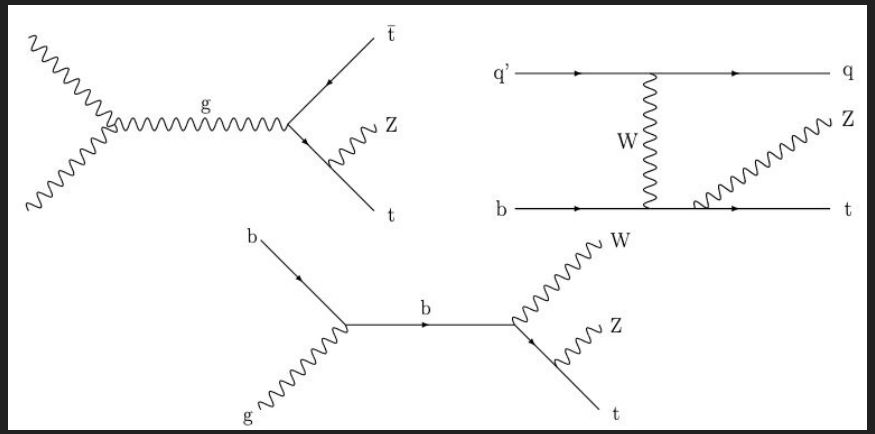
arXiv:2107.13896

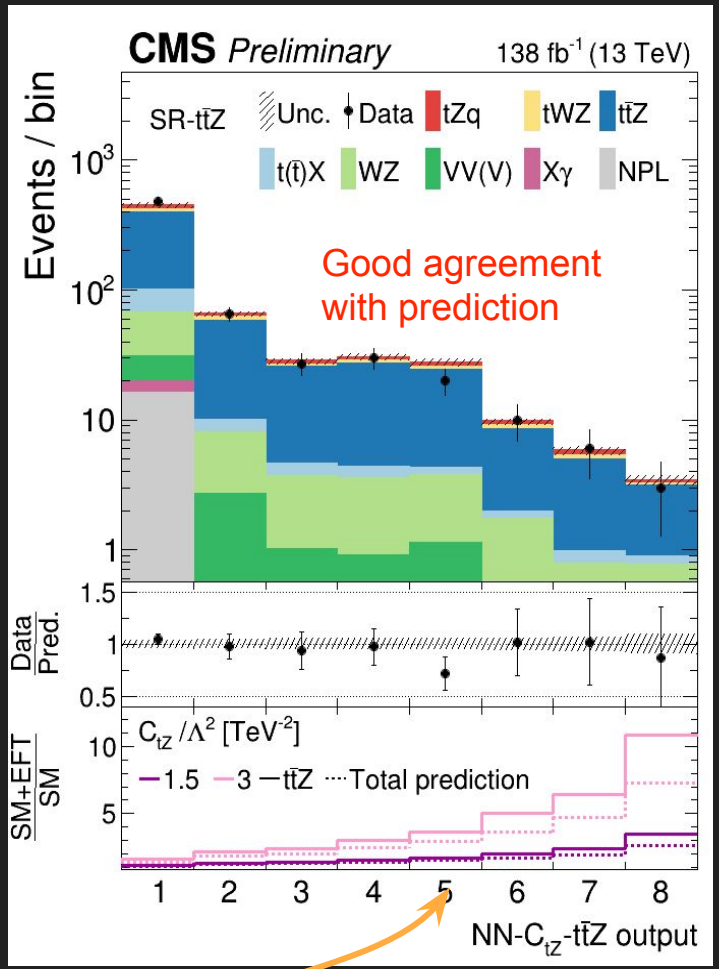
Direct EFT search in 3 & 4 lepton final states

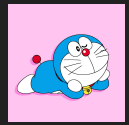
Target of t-Z interaction (least constrained by available data in top sector)

Pioneering work on EFT MVA techniques

Multiclass MVA (ttZ,tZq,other) + NNs target specific EFT effects!







Stronger anomalies = stronger response.

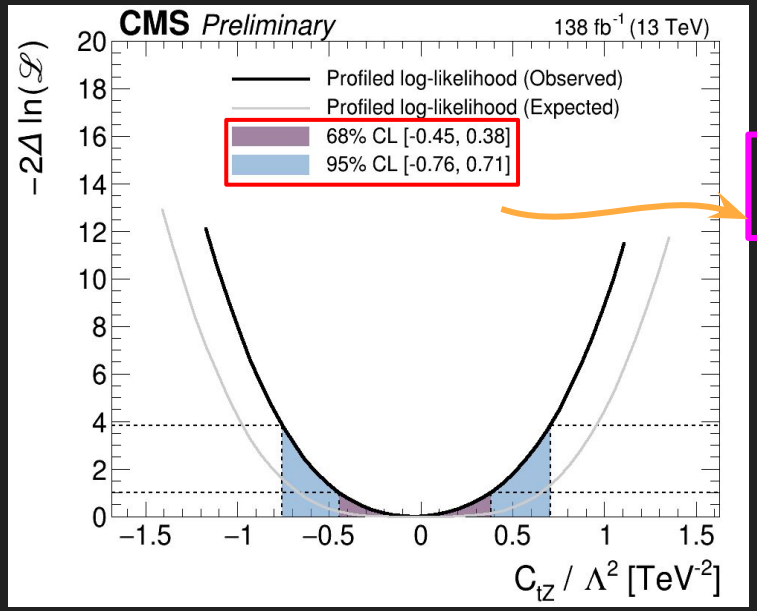
NEW

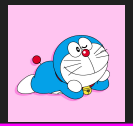
Direct EFT Search in t(t)Z

arXiv:2107.13896

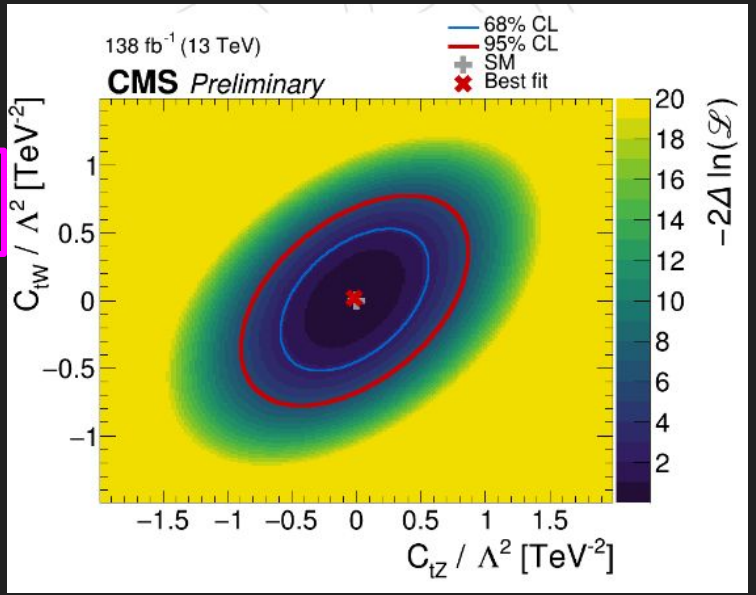
EFT NN distributions used as input to several fits in SR + CRs

Extract confidence intervals for 1, 2 or 5 WCs simultaneously



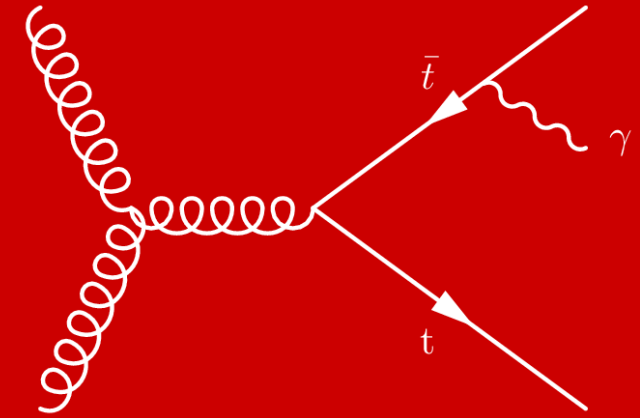


Large improvements due to machine learning methods!



Agreement with SM extremely good!

Dominant uncs: Signal/bkg modelling, photon ID



CMS: tt+γ (single lepton)

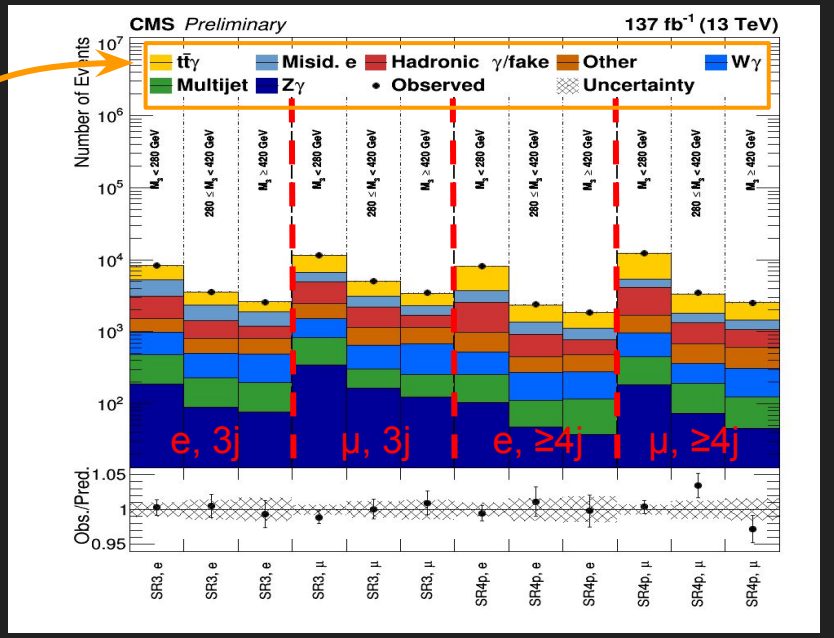
arXiv:2107.01508

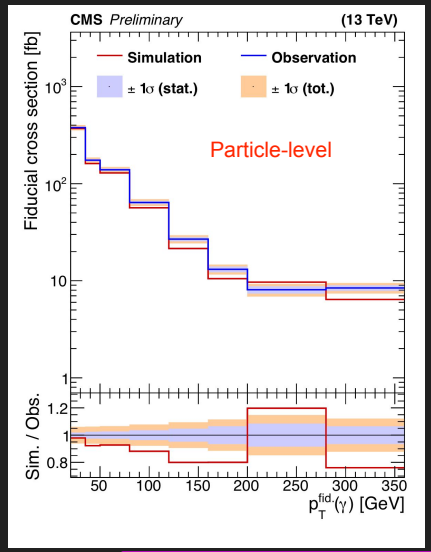
Use gen. matching to define prompt γ

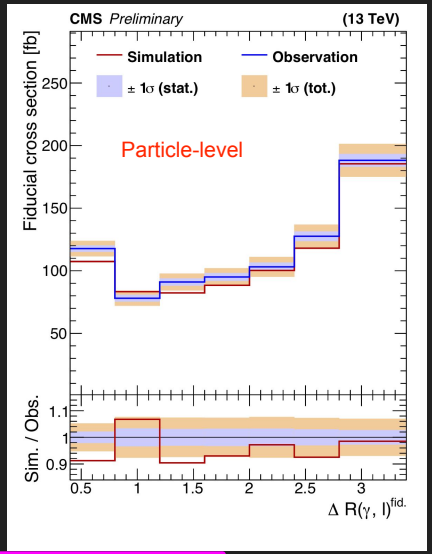
$$\sigma_{\text{incl}} = 800 \pm 46(\text{syst}) \pm 7(\text{stat})\text{fb}$$

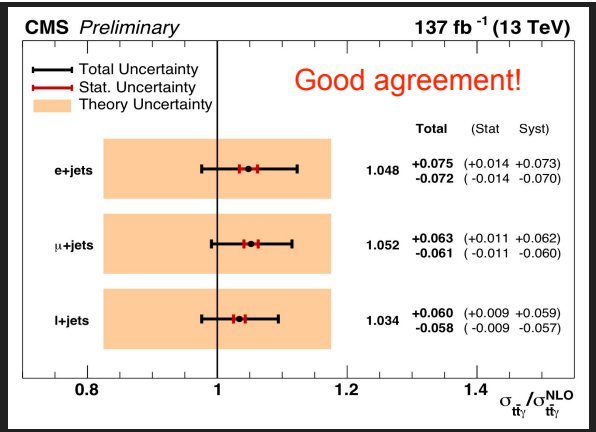
~6% precision.

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







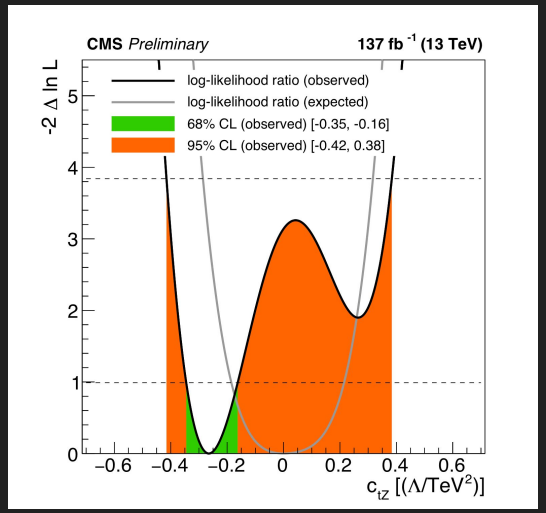


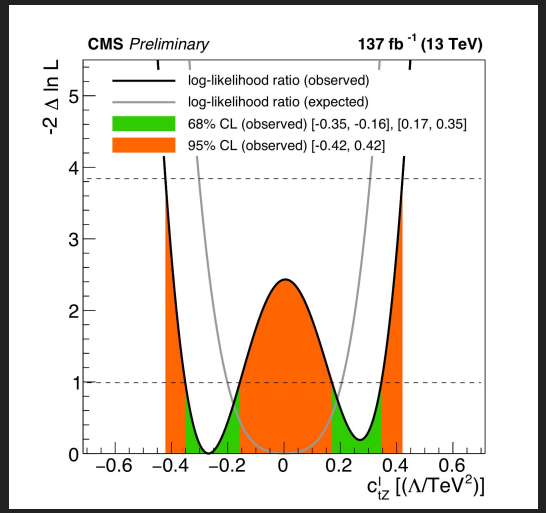
Shapes generally well described!

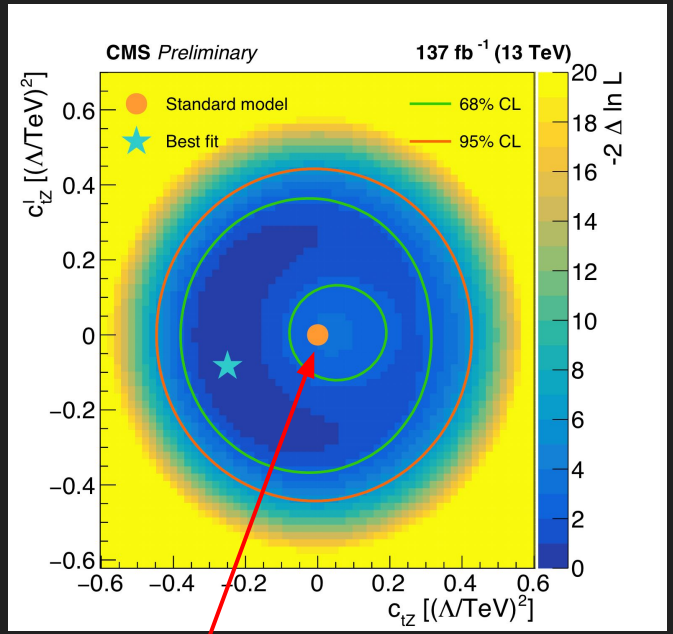
CMS: tt+γ (single lepton)

arXiv:2107.01508

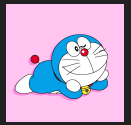
$p_T(\gamma)$ fit performed at BSM points defined by varied Wilson coefficients values







SM pred. Within 95% confidence interval of data.



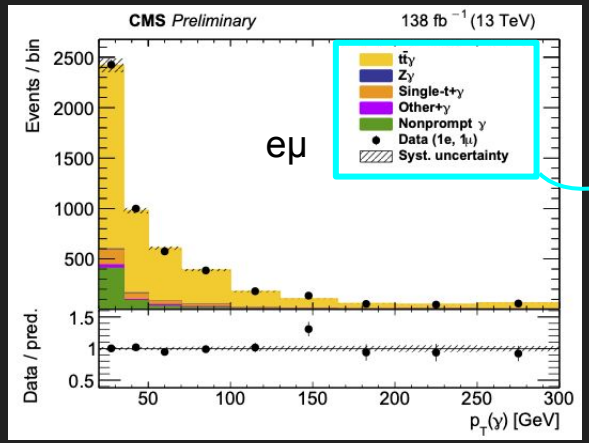
1D confidence intervals strongest individual measurement to date!

NEW

CMS: tt+γ (dilepton)

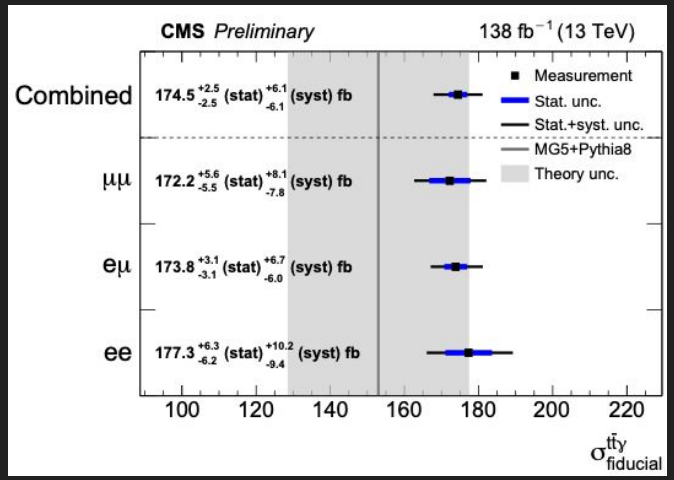
TOP-21-004

Inclusive

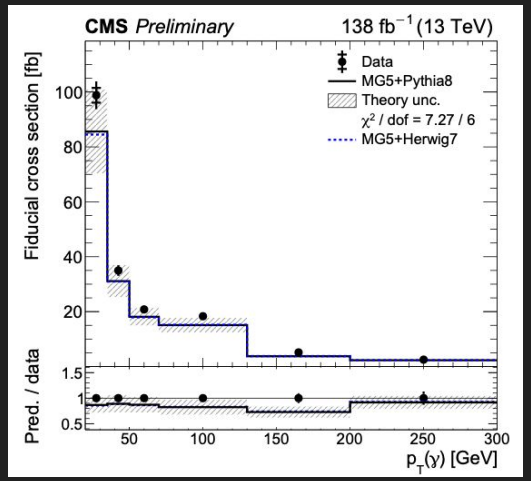


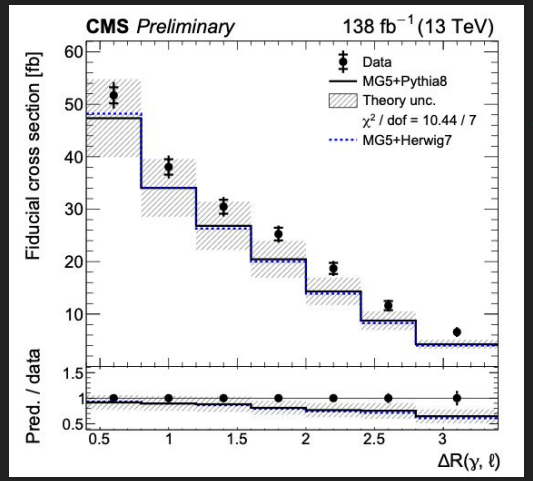
Use gen. matching to define prompt γ

fit



Differential





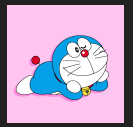
Comparison with 2 cross-section predictions (chi2 and theory unc. for pythia8)

Many more unfolded photon, lepton and jet kinematic distributions in paper

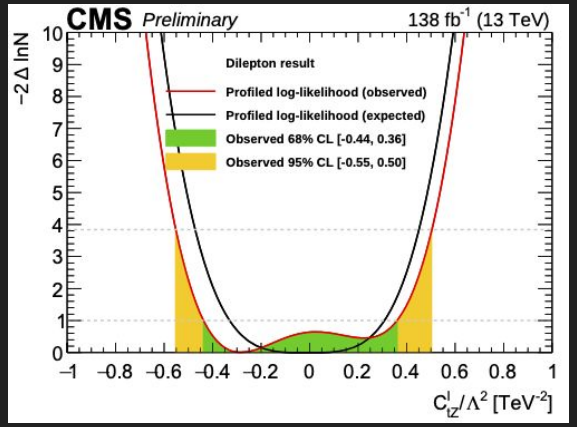
NEW

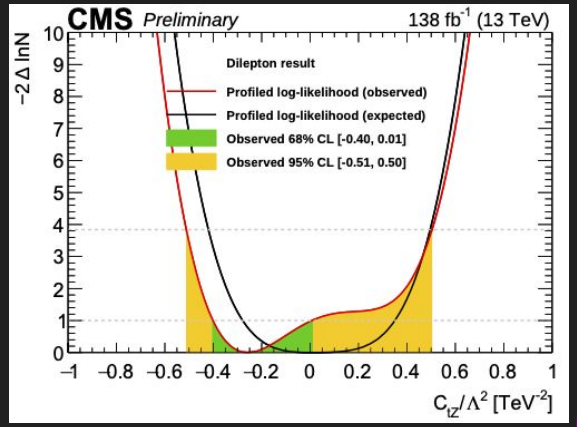
CMS: tt+γ (dilepton)

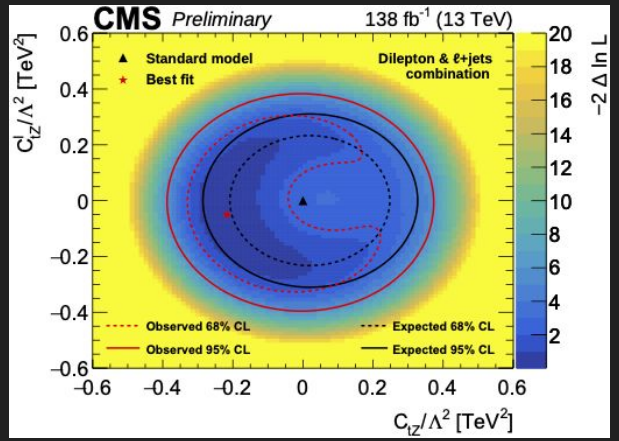
TOP-21-004



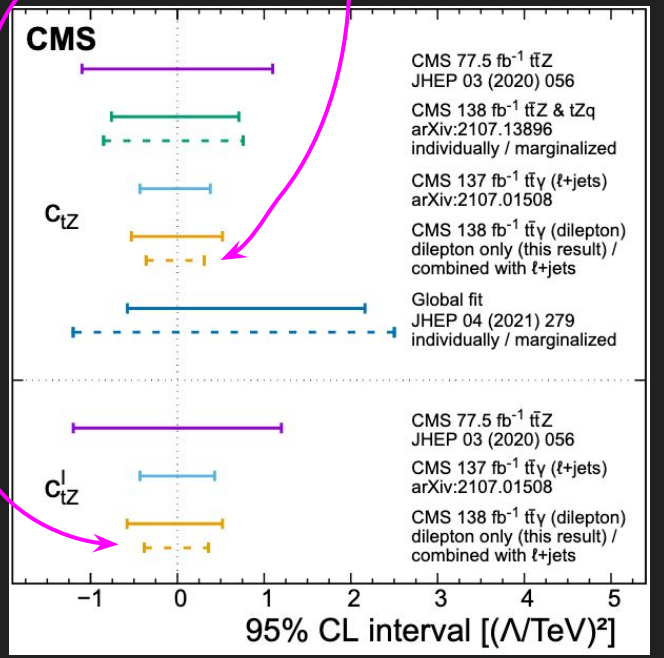
1D and 2D scans of negative LL value for two W.C's







Combination with l+jets = best limits to date!



Concluding Remarks

Excellent precision in XS measurements of tt+Z/γ/HF

Precise theory predictions / close collaboration between communities provides interesting comparison

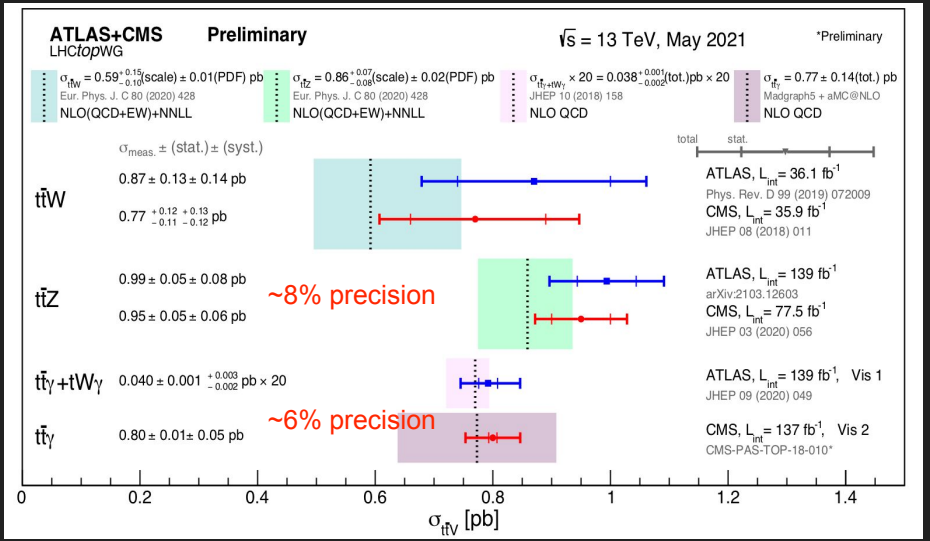
Small under-predictions in tt+X

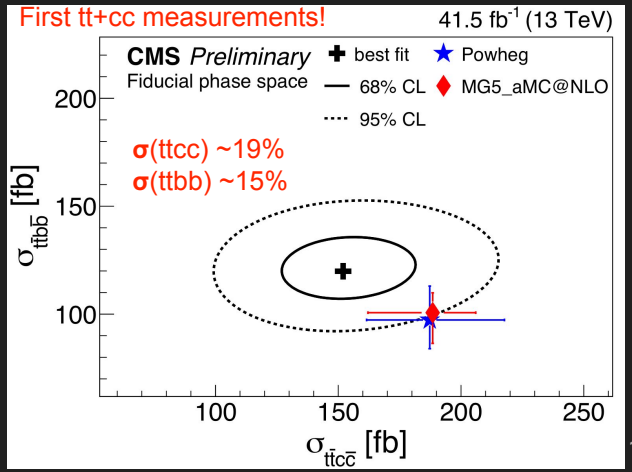
Unprecedented constraints on t-Z/γ WCs

Impressive progress in EFT searches using novel ML techniques

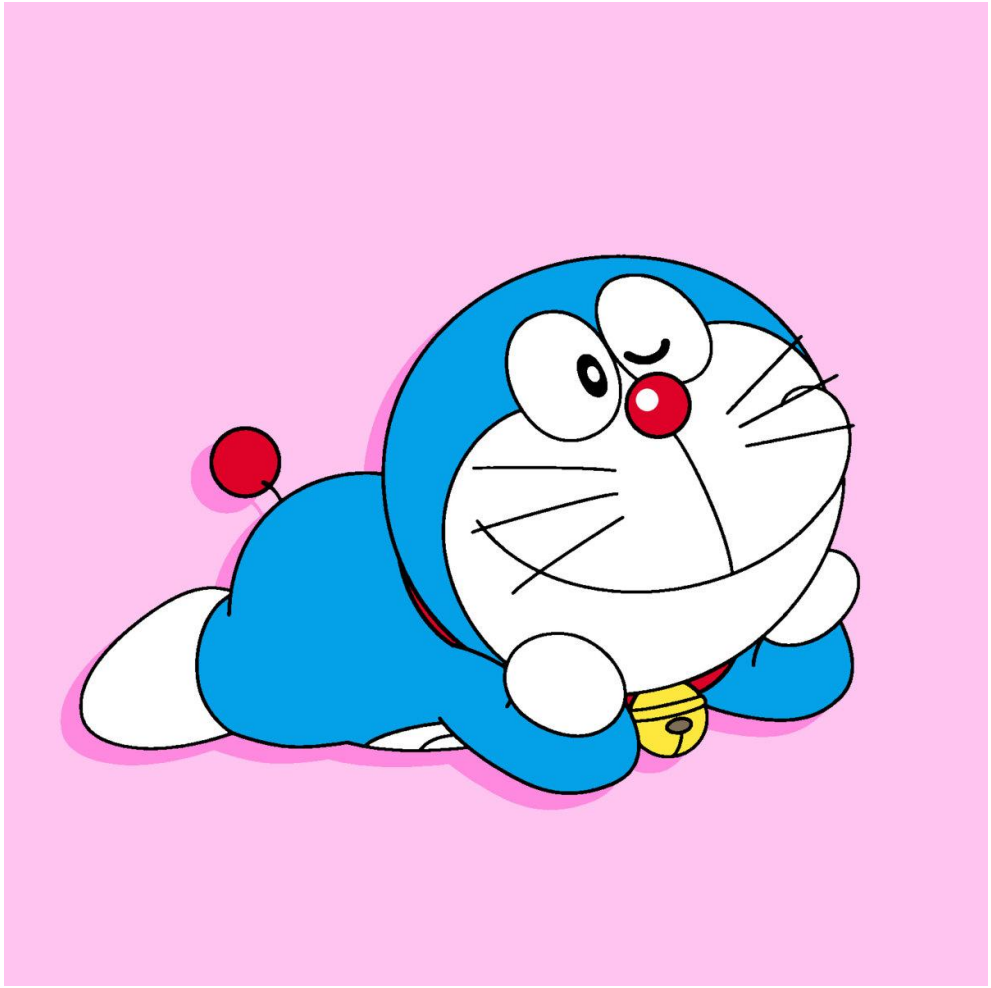
Standard model is holding up very well so far

Full run 2 updates with improved precision will help understand significance of minor tensions





Backup



ATLAS: Combined tt+γ & tWγ

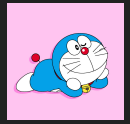
JHEP 09 (2020) 049

Absolute and normalised differential XS measurements in fiducial volume

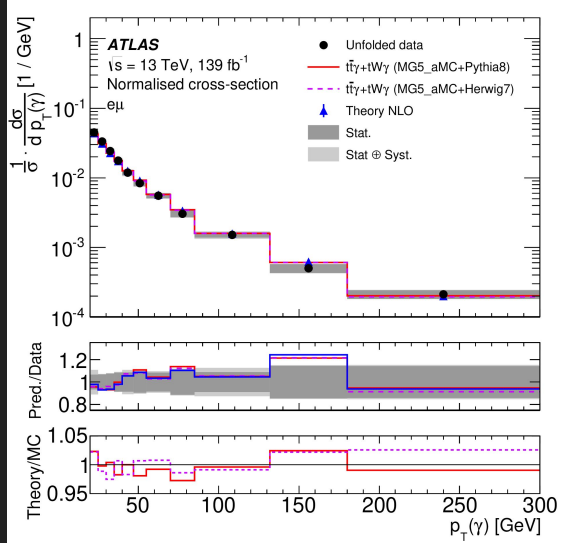
Several variables related to γ and lepton kinematics

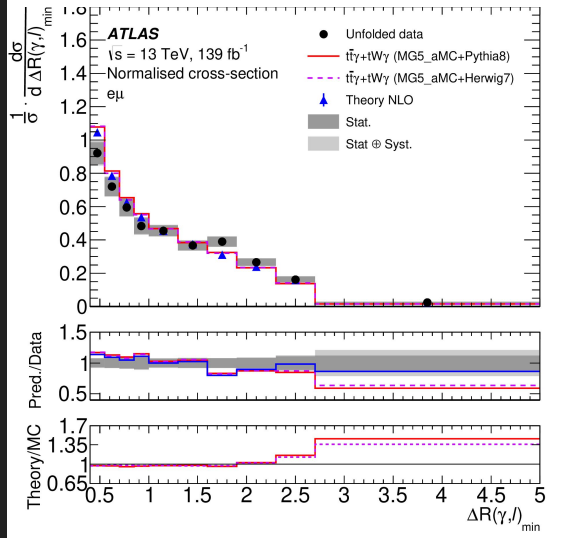
Shapes generally well described by MC and NLO theory

Imperfect description using LO MC in a few variables



Having a precise theory prediction is really beneficial!





tt+Z

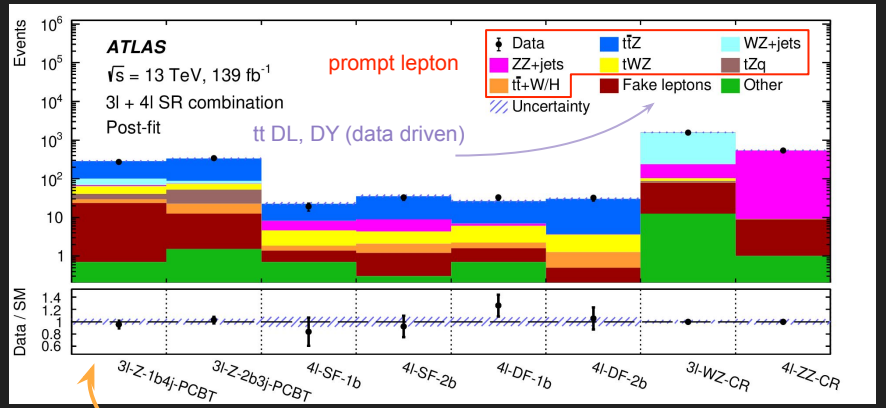
3, 4 lepton

ATLAS

arXiv:2103.12603

Fit 8 SR's+CR's

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



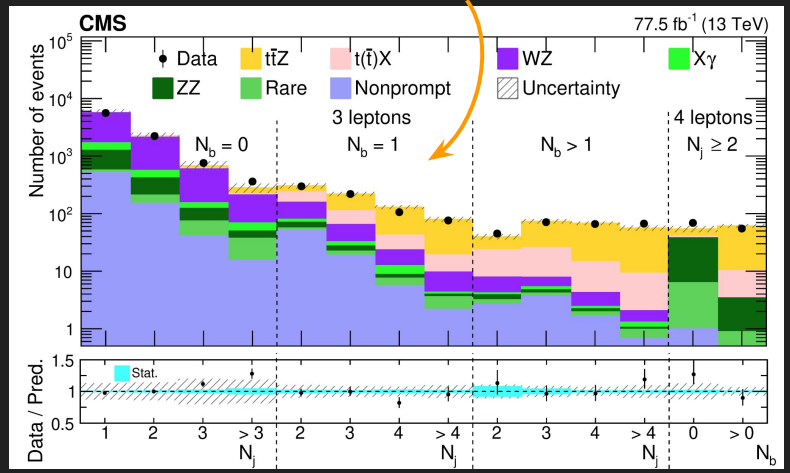
Events categorised according to # (b)jets and leptons.

CMS

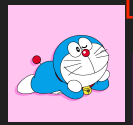
JHEP 03 (2020) 056

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!

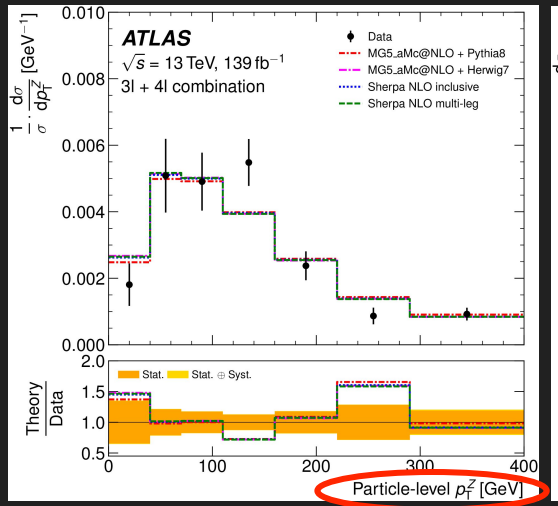
tt+Z

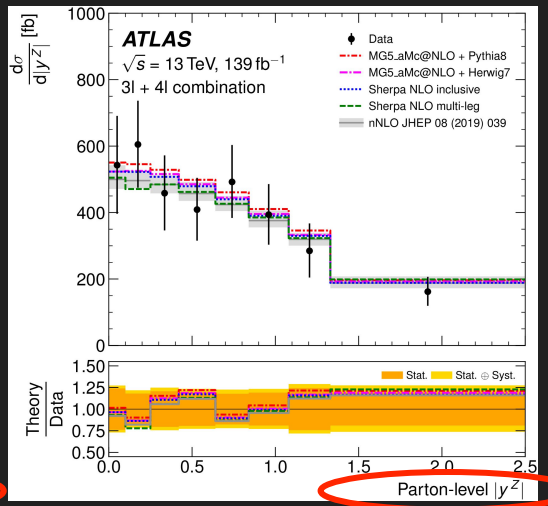
ATLAS

arXiv:2103.12603

Extensive study of several differential distributions.

Most distributions in good agreement with NLO/MC





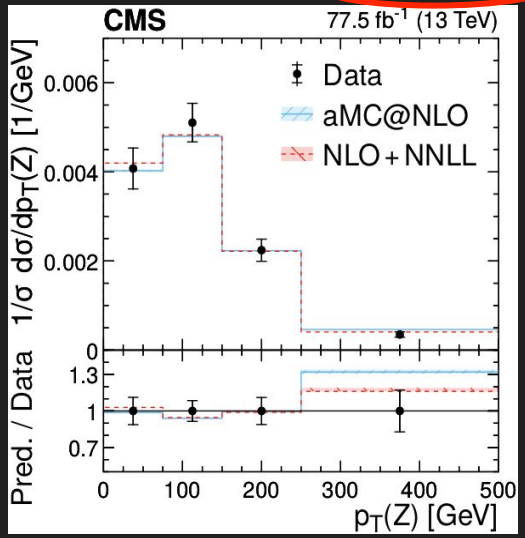
CMS

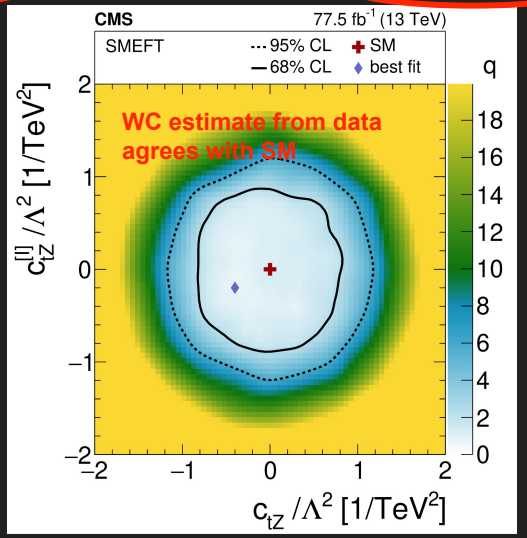
JHEP 03 (2020) 056

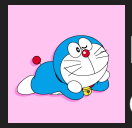
Differential XS of several observables

Good agreement w. NLO theory prediction and MC simulation

Provide CL intervals for WC's







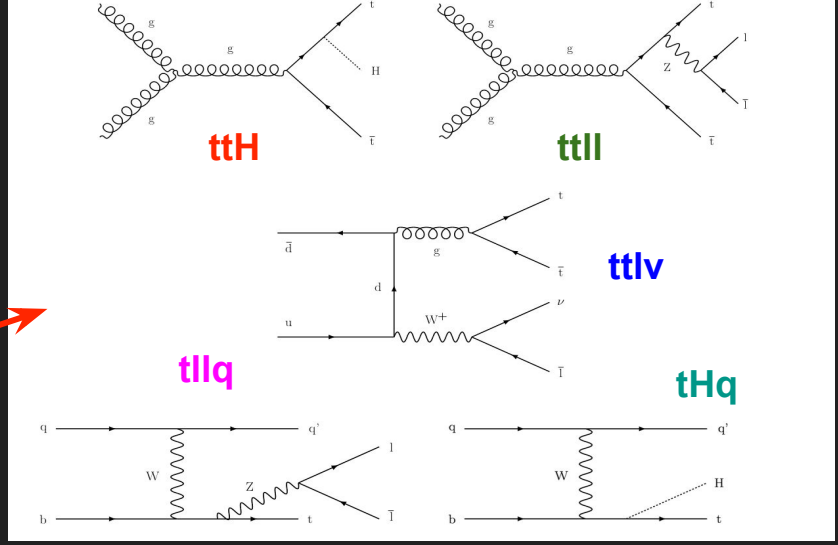
Both experiments statistically limited in differential XS.

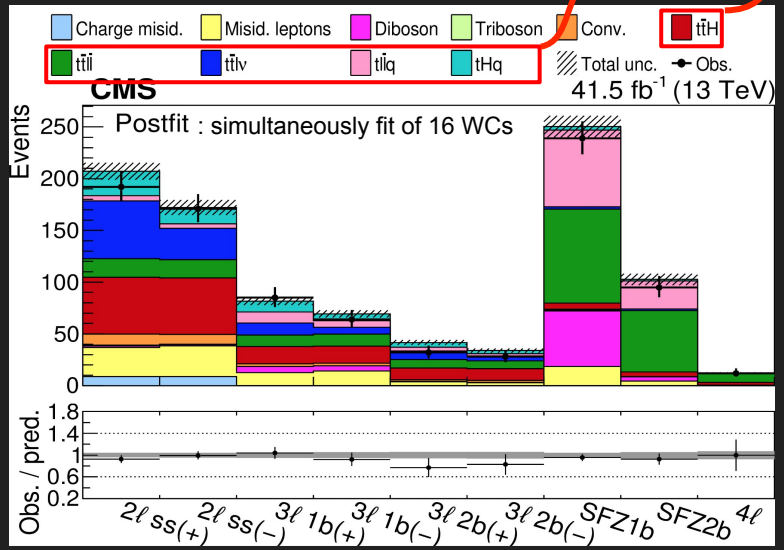
Direct EFT Search in t(t)X

JHEP 03 (2021) 095

‘Global’ approach to EFT targeting on multiple final states → 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 paramterised by Wilson coeff’s directly at detector level

Direct EFT Search in t(t)X

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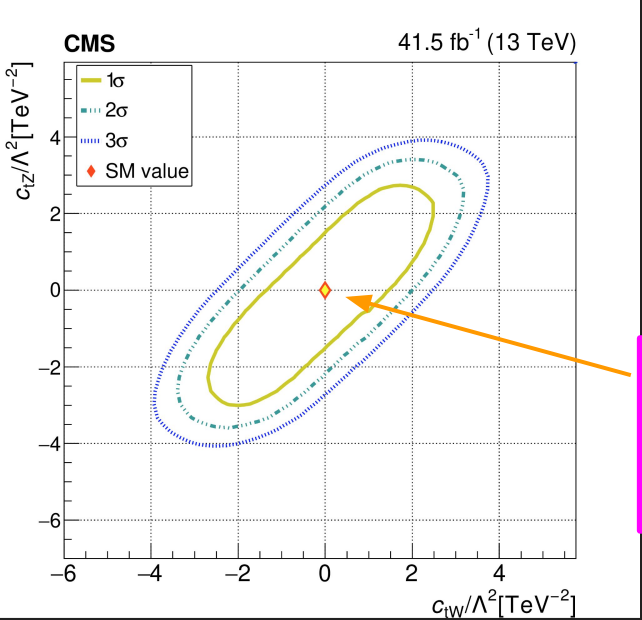
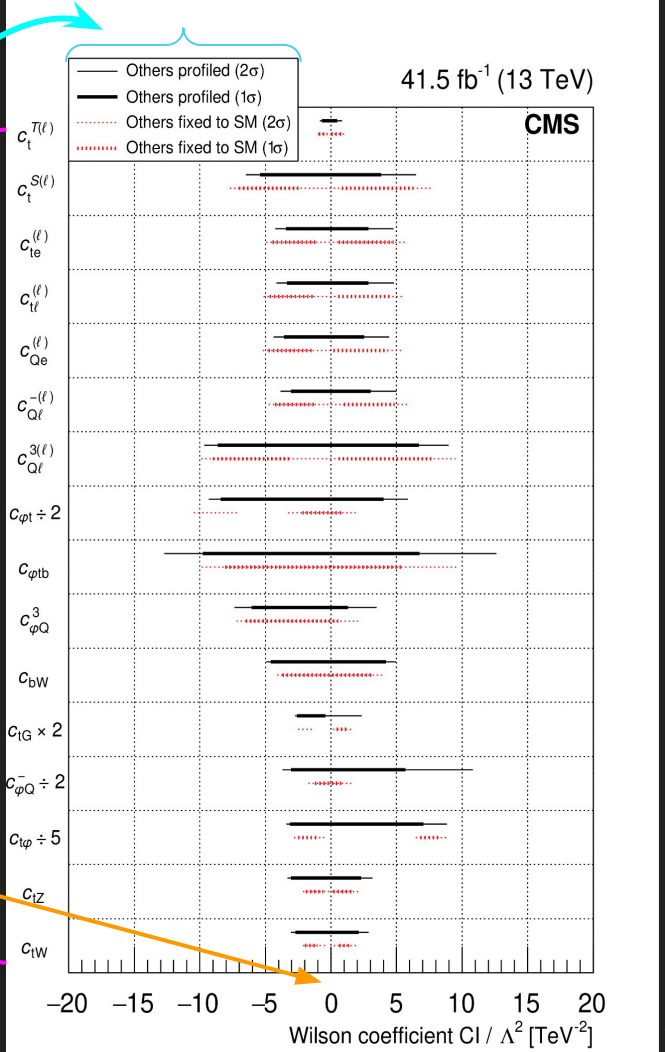
Profile likelihood fit of 35 independent categories.

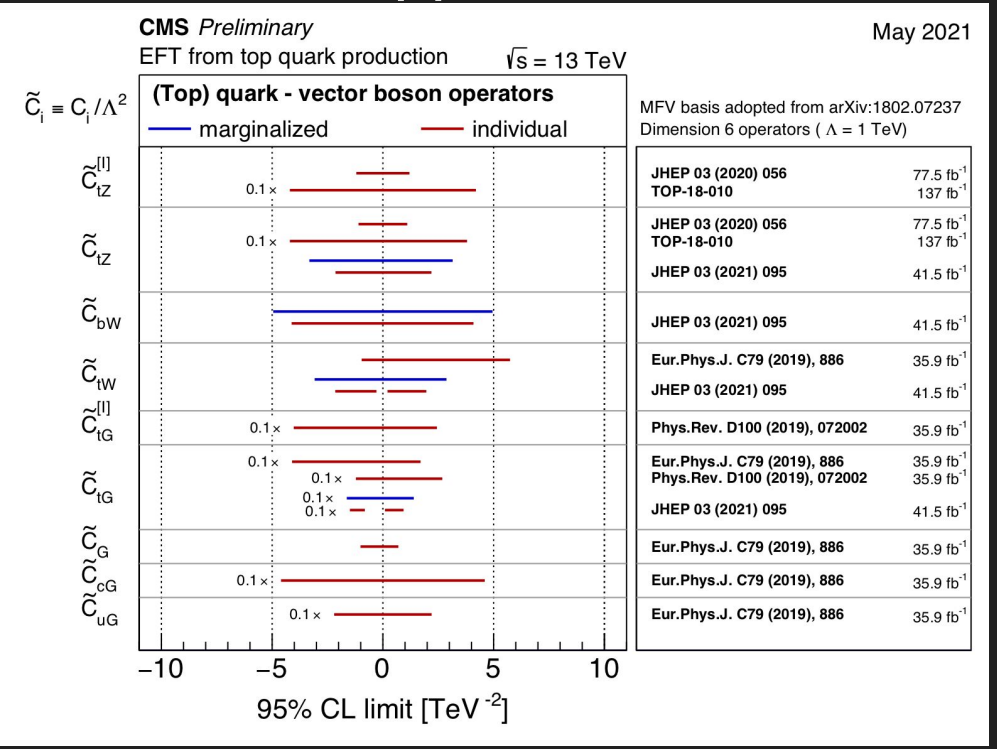
Fit 16 EFT operators, calculate confidence intervals in 2 scenarios.



SM points fall within 2σ in most cases.



Direct EFT approaches



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Top-21-001

Fit configuration	Region SR-tZq	SR-tt̄Z	SR-Others	SR-tt̄Z-4ℓ	CR WZ	CR ZZ
1D c_{tZ}	NN-c_{tZ}-tZq	NN-c_{tZ}-tt̄Z				
1D c_{tW}	NN-c_{tW}-tZq	NN-c_{tW}-tt̄Z				
1D $c^3_{\varphi Q}$	NN-$c^3_{\varphi Q}$-tZq	NN-$c^3_{\varphi Q}$-tt̄Z	m_T^W	Counting experiments		
1D $c^-_{\varphi Q}$	NN-SM (tZq node)	NN-SM (tt̄Z node)				
1D $c_{\varphi t}$	NN-SM (tZq node)	NN-SM (tt̄Z node)				
2D and 5D	NN-5D-tZq	NN-5D-tt̄Z				

	Other WCs fixed to SM		5D fit	
	Expected	Observed	Expected	Observed
WC / Λ^2 [TeV^{-2}]	95% CL confidence intervals			
c_{tZ}	$[-0.97, 0.96]$	$[-0.76, 0.71]$	$[-1.24, 1.17]$	$[-0.85, 0.76]$
c_{tW}	$[-0.76, 0.74]$	$[-0.52, 0.52]$	$[-0.96, 0.93]$	$[-0.69, 0.70]$
$c^3_{\varphi Q}$	$[-1.39, 1.25]$	$[-1.10, 1.41]$	$[-1.91, 1.36]$	$[-1.26, 1.43]$
$c^-_{\varphi Q}$	$[-2.86, 2.33]$	$[-3.00, 2.29]$	$[-6.06, 14.09]$	$[-7.09, 14.76]$
$c_{\varphi t}$	$[-3.70, 3.71]$	$[-21.65, -14.61] \cup [-2.06, 2.69]$	$[-16.18, 10.46]$	$[-19.15, 10.34]$

WC/Λ^2[TeV^{-2}]	2σ interval (others profiled)	2σ interval (others fixed to SM)
c_{tW}	$[-3.08, 2.87]$	$[-2.15, -0.29] \cup [0.21, 1.96]$
c_{tZ}	$[-3.32, 3.15]$	$[-2.14, 2.19]$
$c_{t\varphi}$	$[-16.98, 44.26]$	$[-14.12, -1.46] \cup [32.30, 44.48]$
$c^-_{\varphi Q}$	$[-7.59, 21.65]$	$[-3.45, 3.33]$
c_{tG}	$[-1.38, 1.18]$	$[-1.26, -0.69] \cup [0.08, 0.79]$
c_{bW}	$[-4.95, 4.95]$	$[-4.12, 4.09]$
$c^3_{\varphi Q}$	$[-7.37, 3.48]$	$[-7.21, 2.25]$
$c_{\varphi tb}$	$[-12.72, 12.63]$	$[-9.87, 9.67]$
$c_{\varphi t}$	$[-18.62, 12.31]$	$[-20.91, -14.10] \cup [-6.52, 4.24]$
$c^{3(\ell)}_{Q\ell}$	$[-9.67, 8.97]$	$[-9.91, 9.50]$
$c^{-(\ell)}_{Q\ell}$	$[-4.02, 4.99]$	$[-4.76, 5.83]$
$c^{(\ell)}_{Qe}$	$[-4.38, 4.59]$	$[-5.20, 5.36]$
$c^{(\ell)}_{t\ell}$	$[-4.29, 4.82]$	$[-5.15, 5.51]$
$c^{(\ell)}_{te}$	$[-4.24, 4.86]$	$[-4.97, 5.80]$
$c^{S(\ell)}_{t}$	$[-6.52, 6.52]$	$[-7.70, 7.70]$
$c^{T(\ell)}_{t}$	$[-0.84, 0.84]$	$[-1.01, 1.01]$

ATLAS: Combined tt+γ & tWγ

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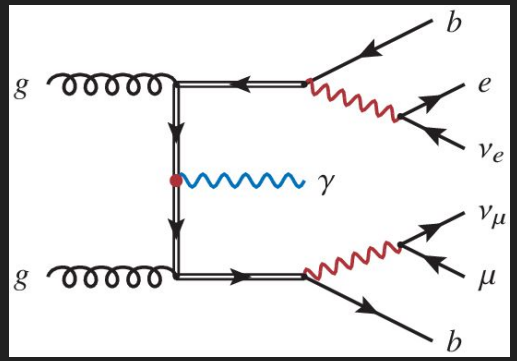

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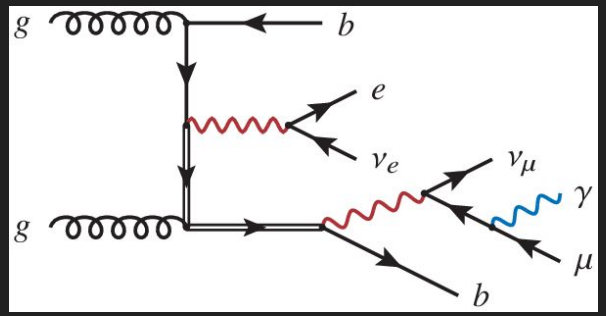
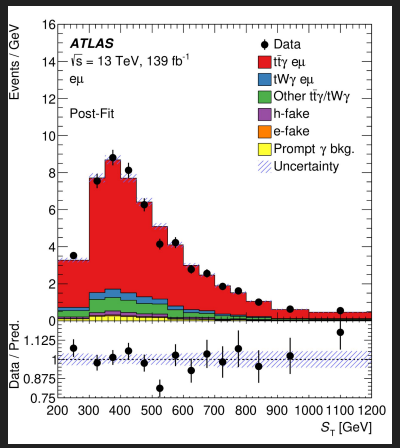


Fiducial XS measurement of ttγ and tWγ → compare w. recent theory prediction [1,2]

Parton-level selection mimics theory phase-space

OS eμ



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

~ 7% precision!

Measurement in good agreement with NLO theory pred:

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

CMS

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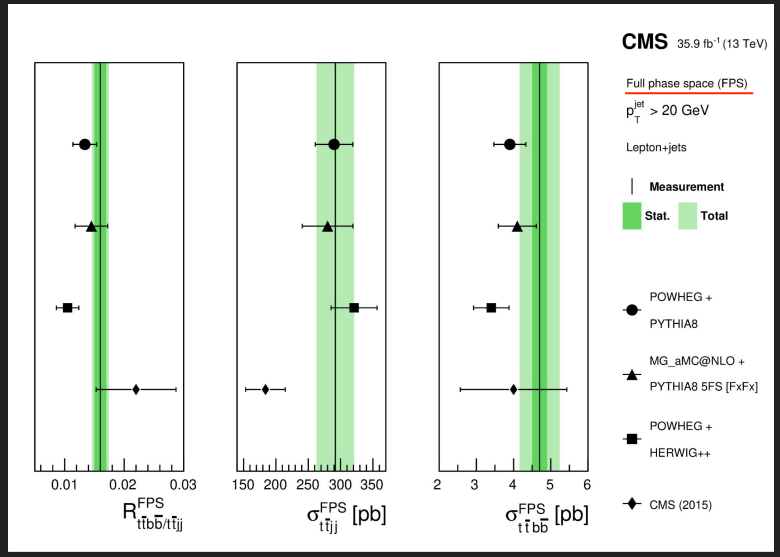
2L & l+jet final states

Fiducial XS precision in l+jets ~11%

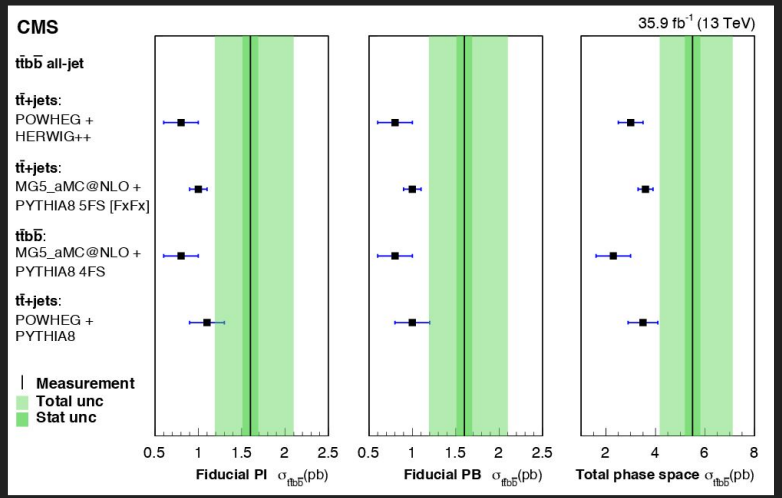


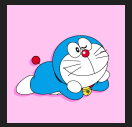
CMS

PLB 803 (2020) 135285

All-hadronic final state

Fiducial XS precision ~32%





XS higher in data than in predicted in MC

ATLAS

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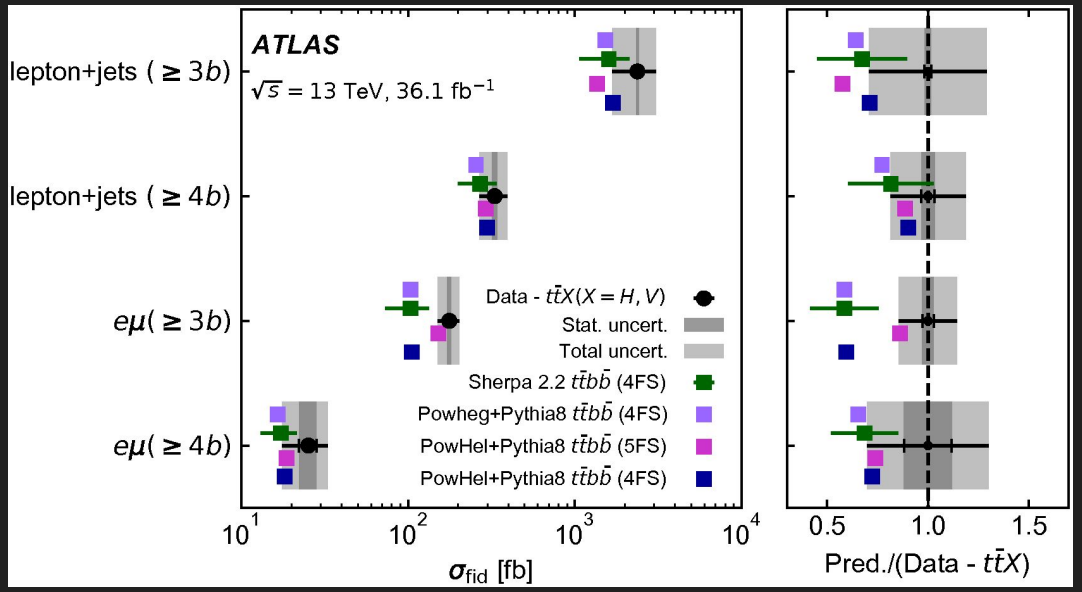
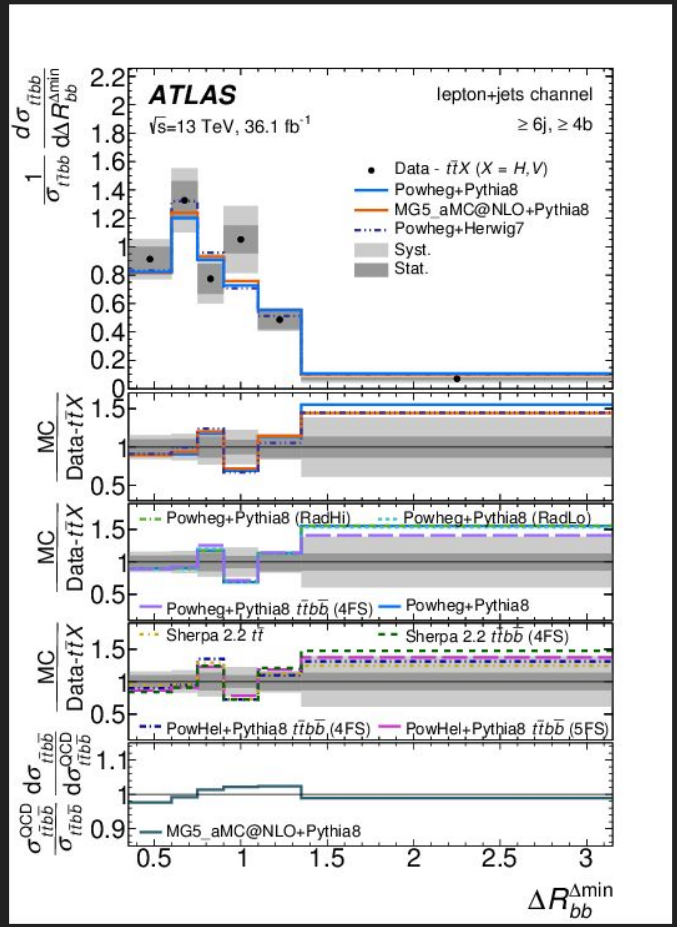
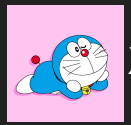
Fiducial XS measurement in eμ and l+jets

Precision in ≥3b eμ of 13%

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







XS in data higher than in prediction

tt+bb Summary