Associated top quark production: pp → t(t)+X where X = cc, bb, j, jj in ATLAS and CMS

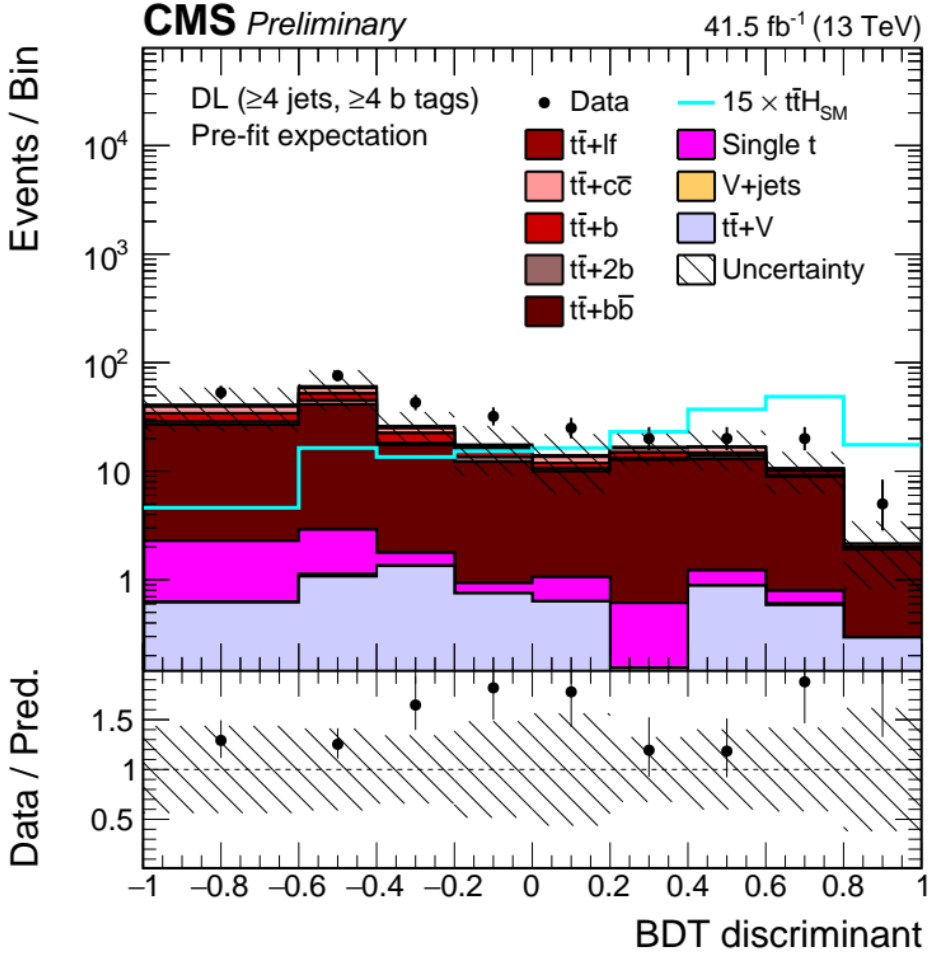
Andrej Saibel on behalf of the ATLAS and CMS collaborations
TOP Conference 2021, 14. September

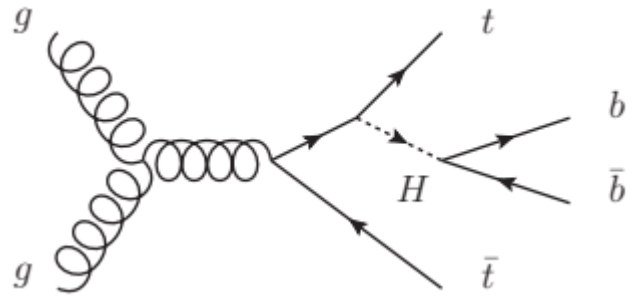
HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

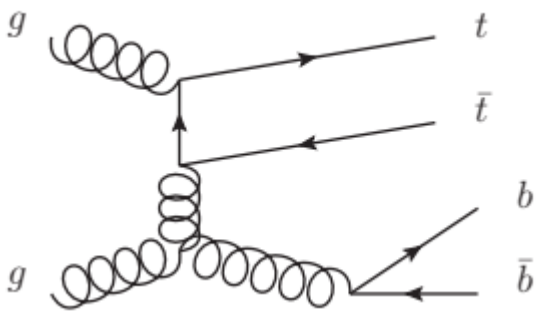
DESY.

Introduction

CMS-PAS-HIG-18-030



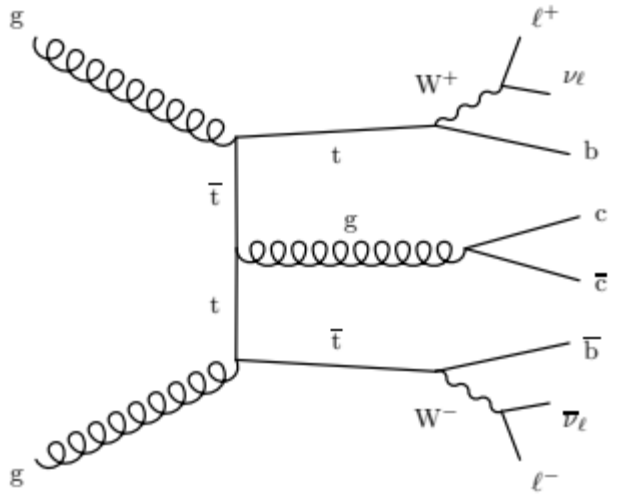




- **<u>tt+jets as background</u>**
  - Dominant background for ttH and ttV processes
  - **<u>σ(tt+jets) >> σ(ttH, ttV)</u>**
  - High jet multiplicity in final state
    - Simple reconstruction often not possible (combinatorics)
    - Multivariate methods highly dependent on modeling
- **<u>tt+heavy flavor as signal</u>**
  - Four massive quarks in final state
  - Scale uncertainty: > 30% at next-to-leading order
  - Discrepancies in tt + b-jets modeling observed
    - e.g. Yellow Report 4

$t\bar{t}+b\bar{b}$ and $t\bar{t}+c\bar{c}$ Measurements at 13 TeV

- **Motivation**
  - Test of QCD
  - Understanding of multi-scale processes
  - Background modeling for SM and BSM processes
- **Important systematic uncertainties**
  - Jet flavor identification, Jet Energy Scale, ME scale, ME-PS matching, statistical uncertainty



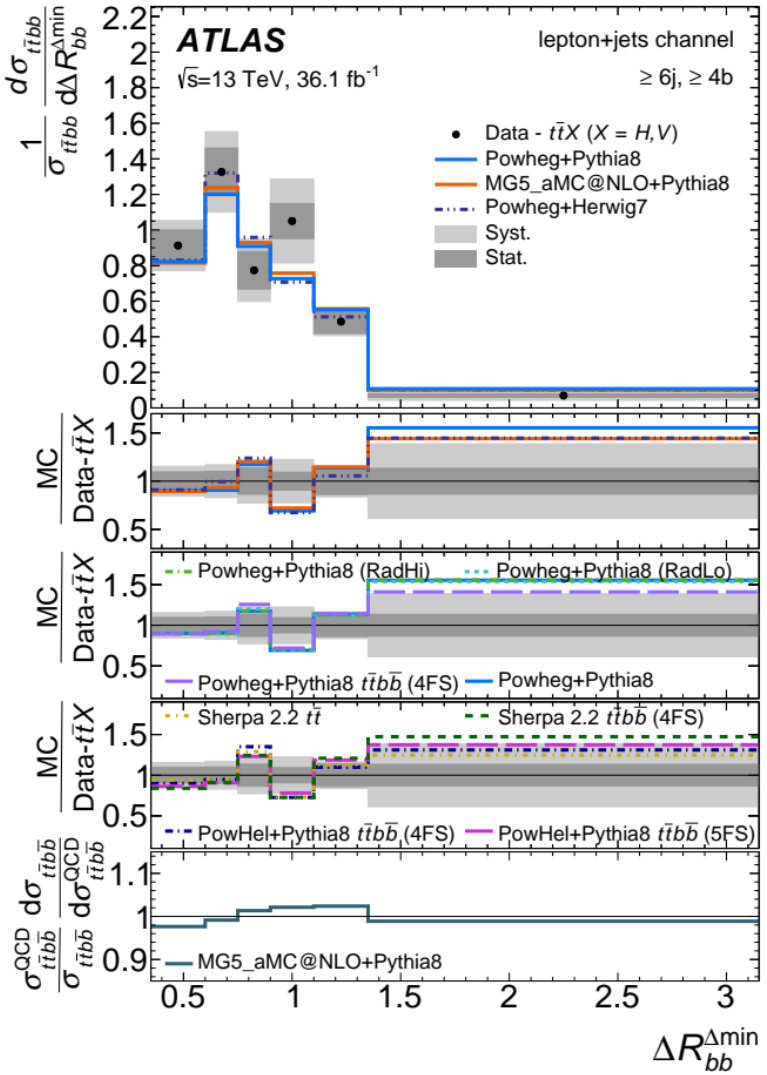
ATLAS Measurement	CMS Measurements

• tt+bb 2l and l+jets (36.1 fb^{-1}) JHEP 04 (2019) 046
  • Inclusive and differential fiducial cross sections
	• tt+bb 2l and l+jets 35.9 fb^{-1} JHEP 07 (2020) 125
	• tt+bb all-jet 35.9 fb^{-1} PLB 803 (2020) 135285
	• First **tt+cc** measurement PLB. 820 (2021) 136565
	  • 41.5 fb^{-1}

ATLAS Measurement of σ(tt̄+bb̄)

JHEP 04 (2019) 046

L = 36.1 pb^{-1}



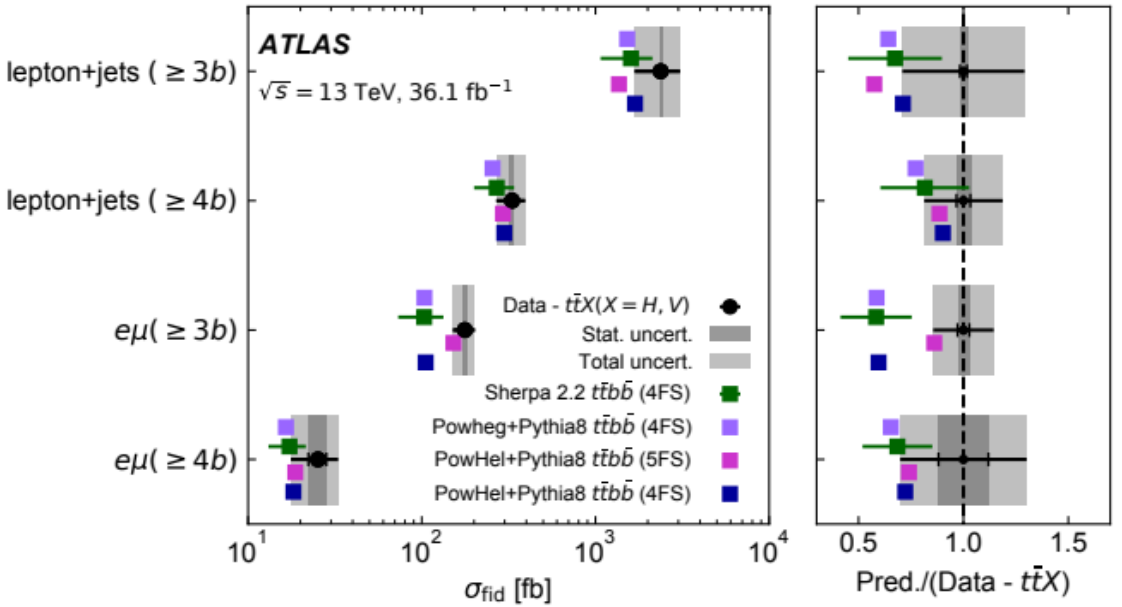
Inclusive and differential σ(tt̄+bb̄) measurement in fiducial phase space eμ and l+jets channels

Inclusive σ(tt̄+bb̄)

- Non-tt̄ backgrounds estimated from MC
- Template fit to b tag distribution →**tt̄+bb̄,tt̄+cc̄,tt̄+lf**
- tt̄H(bb̄) and tt̄V(bb̄) treated as signal and subtracted after fit

Normalized differential σ(tt̄+bb̄)

- Particle level measurements of b tagged jet distributions
- No jet origin assignment
- Overall agreement of shapes between measurement and predictions



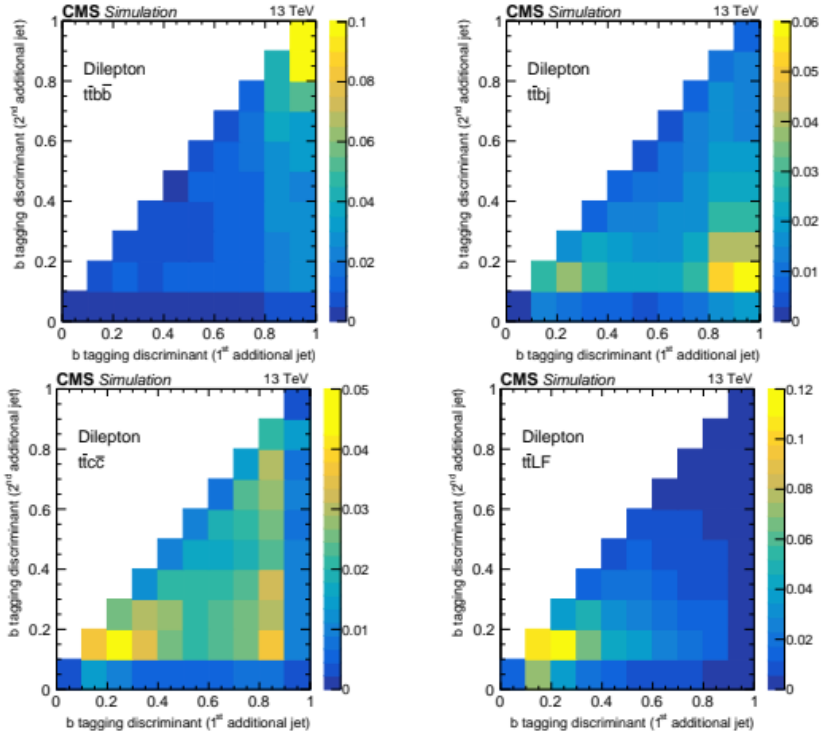
Precision:
13-17%

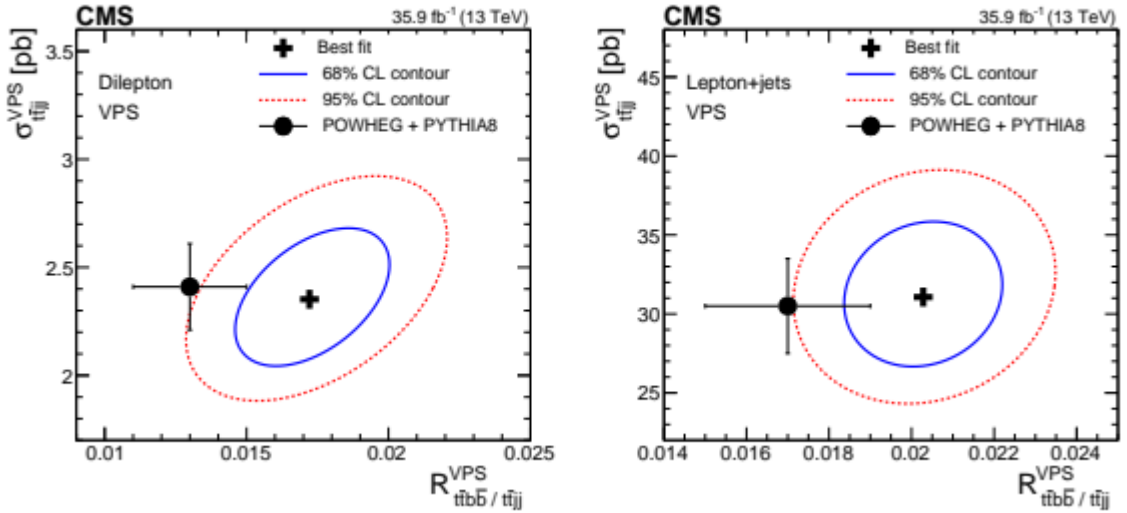
Measurement of σ(tt̄+bb̄) 2l and l+jets

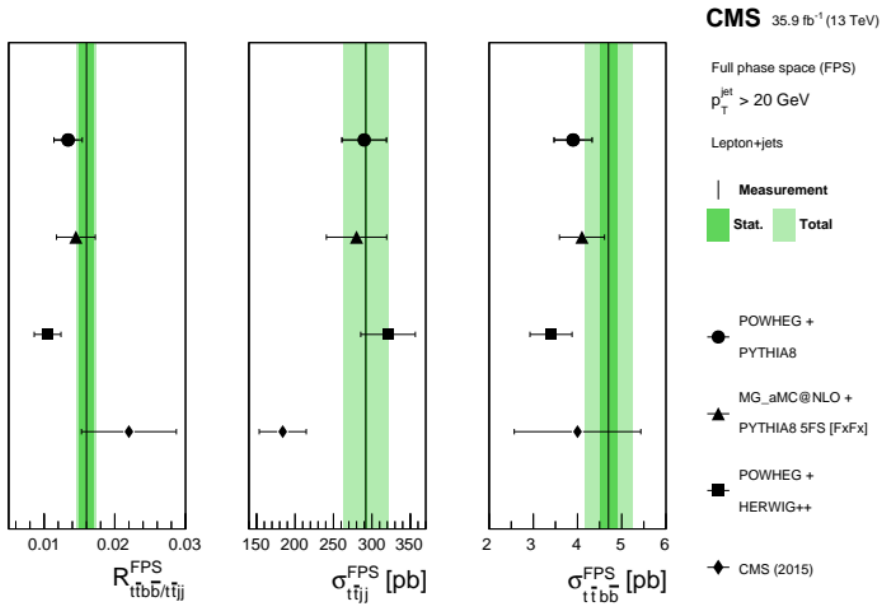
JHEP 07 (2020) 125

L = 35.9 fb^{-1}

- Fiducial and full phase spaces
- **σ(tt̄+bb)** extracted from **R(tt̄+bb/tt̄+jj)**
  - Ratio reduces systematic uncertainties
- **Jet origin assignment** (jets from top/additional jets)
  - **2l channel:** 3rd and 4th highest jet b tag value
  - **l+jets channel:** kinematic fit
- **Likelihood fit** to highest vs 2nd highest b tag scores of additional jets







Precision:
12-13%

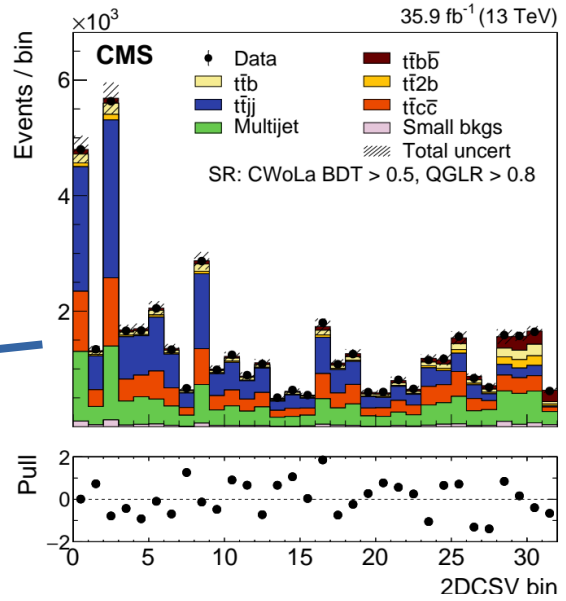
Deviation:
1-2σ

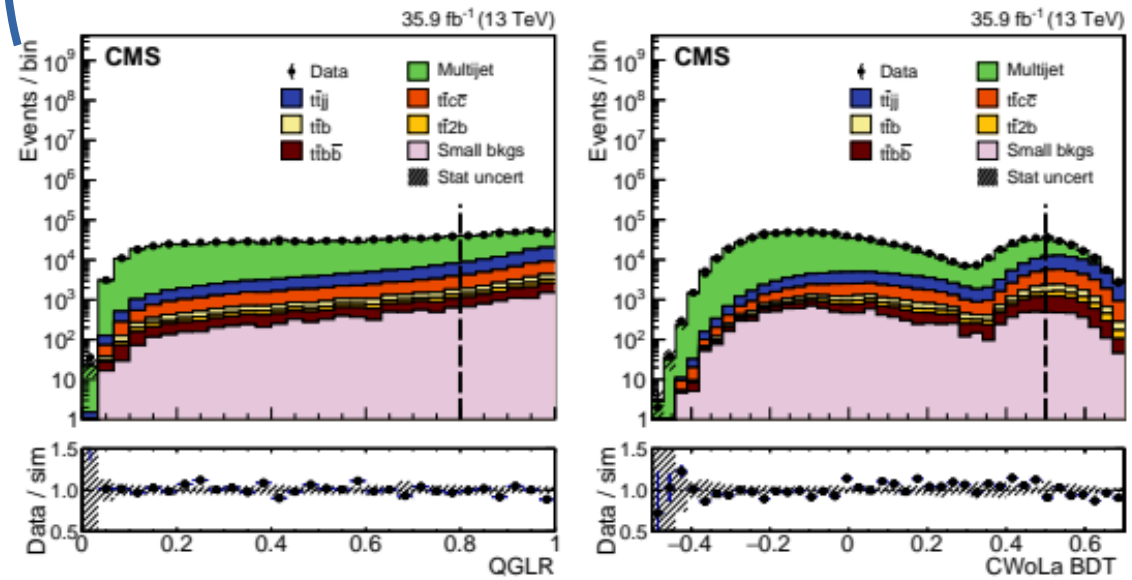
Measurement of σ(tt̄+bb̄) All-Jets

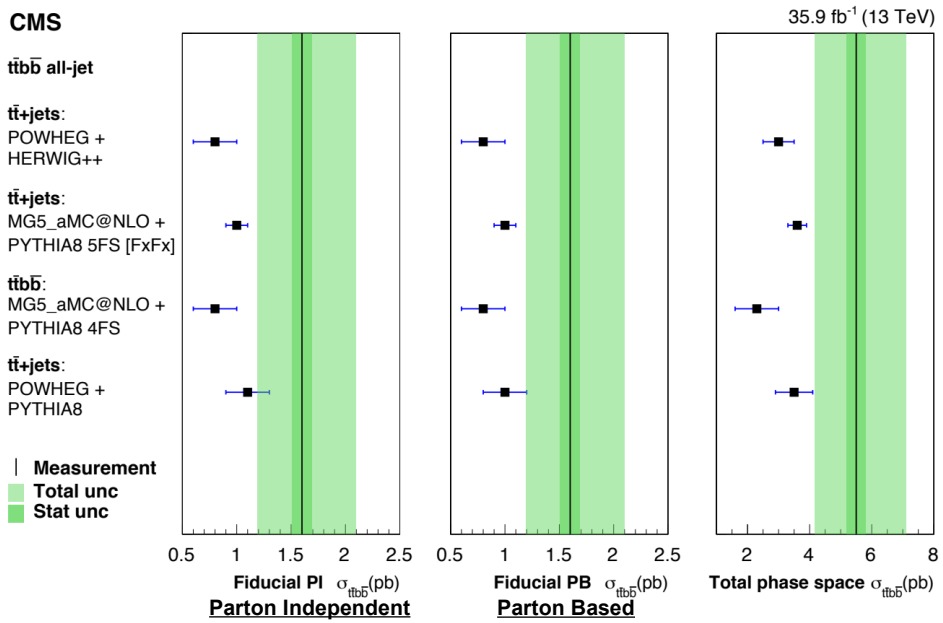
PLB 803 (2020) 135285

L = 35.9 fb^{-1}

- **Challenging due to**
  - High jet mutiplicity, large QCD multi-jet background
- **Advantages of all-jets channel**
  - Large branching ratio, reconstructable final state
- **Multivariate Analysis Techniques**
  - Quark-Gluon-Likelihood, tt̄ and QCD multi-jet separation
  - Jet origin assignment with BDT
- **Likelihood fit to 2D CSV (enrolled)**
  - Highest and 2nd highest b tag score of additional jets
  - QCD background estimation from control region (CR 1-3)







Precision:
23-28%

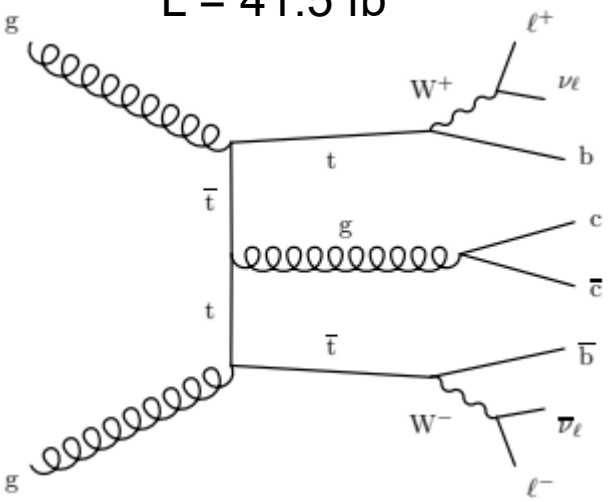
Deviation:
1-2σ

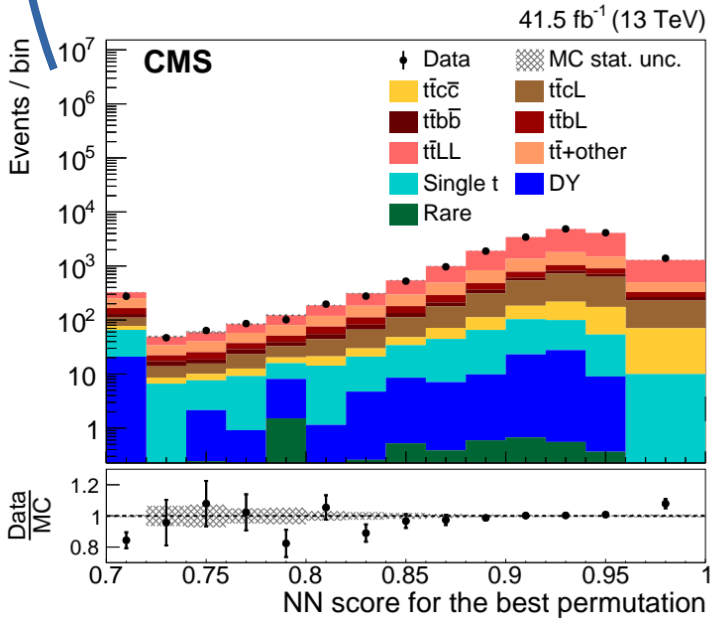
Inclusive σ(tt̄+cc̄) Measurement (2l)

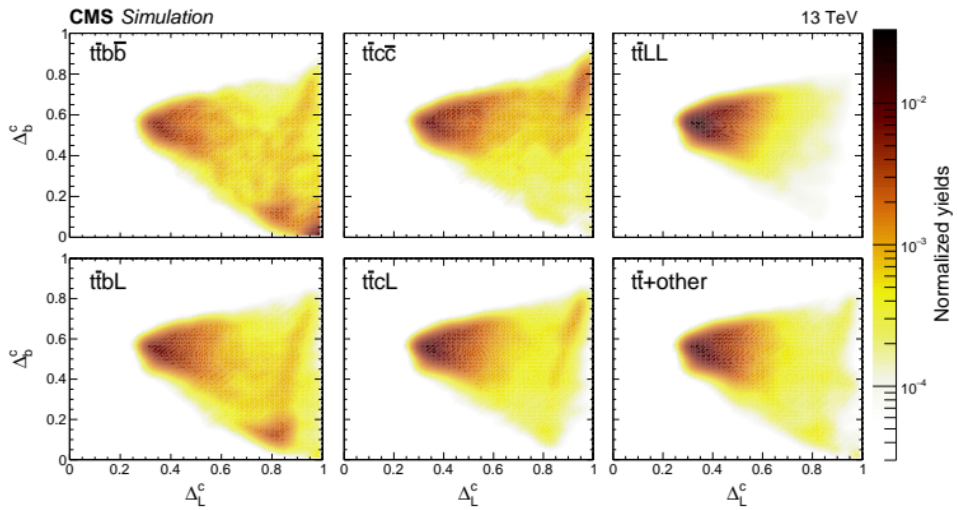
PLB. 820 (2021) 136565

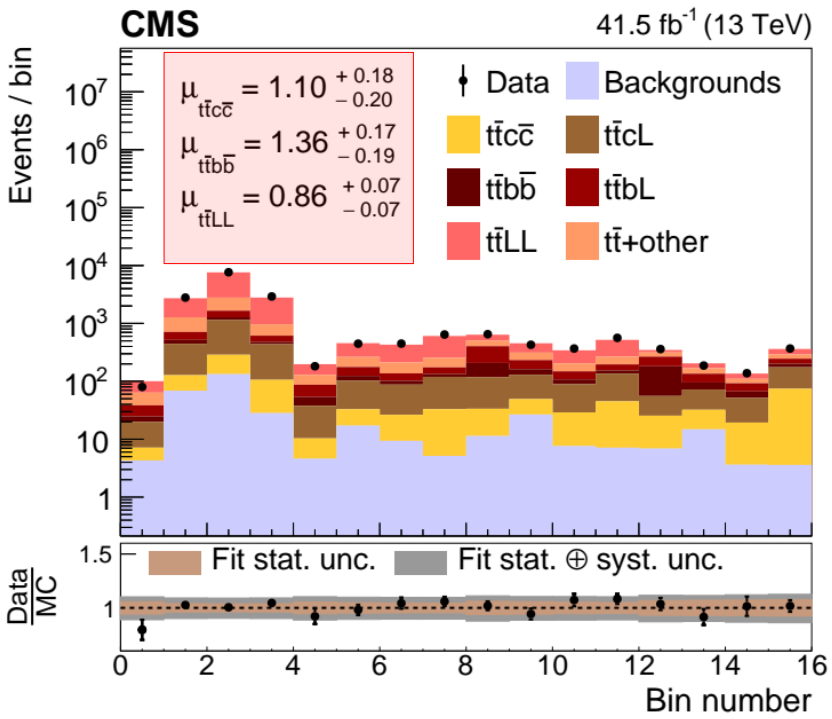
L = 41.5 fb^{-1}

- Measurement of **σ(tt̄+bb̄), σ(tt̄+cc̄), σ(tt̄+ll)**
  - First measurement of σ(tt̄+cc̄)
- Challenging c-jet identification → DeepCSV CMS-PAS-BTV-20-001
- Using Neural Network for jet origin assignment
- Multi-class NN for tt+bb, tt+cc, tt+lf separation
- Likelihood fit to enrolled NN response
- **All results compatible with prediction in 1-2σ**
  - Powheg+Pythia8 normalized to NNLO+NNLL

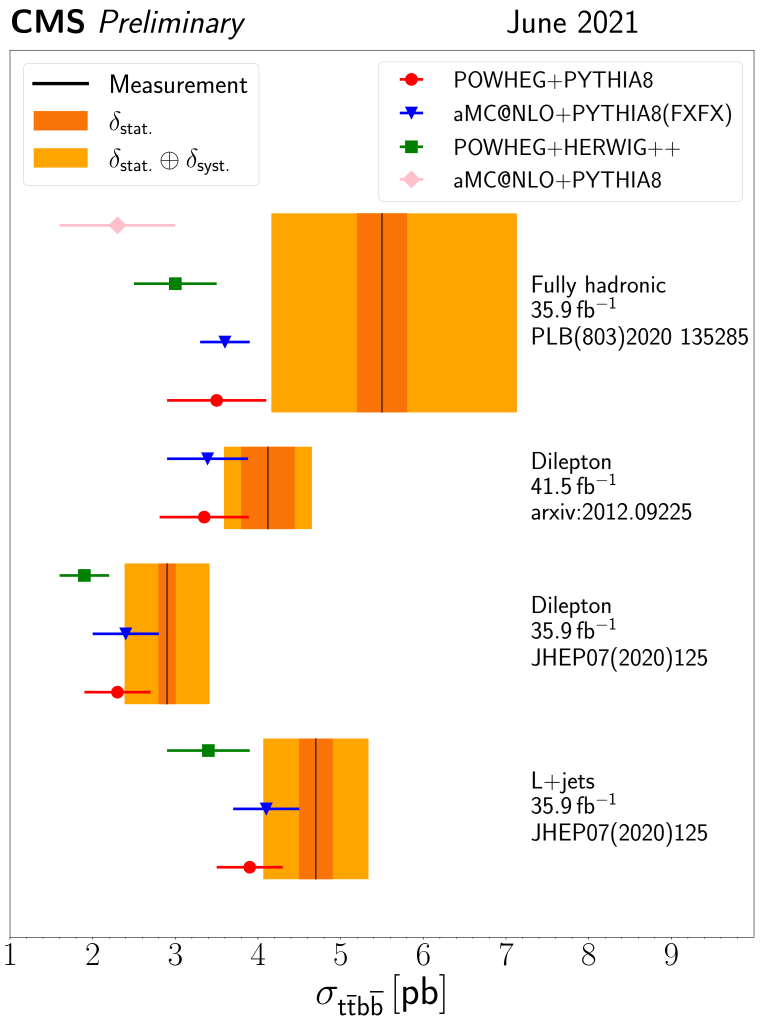




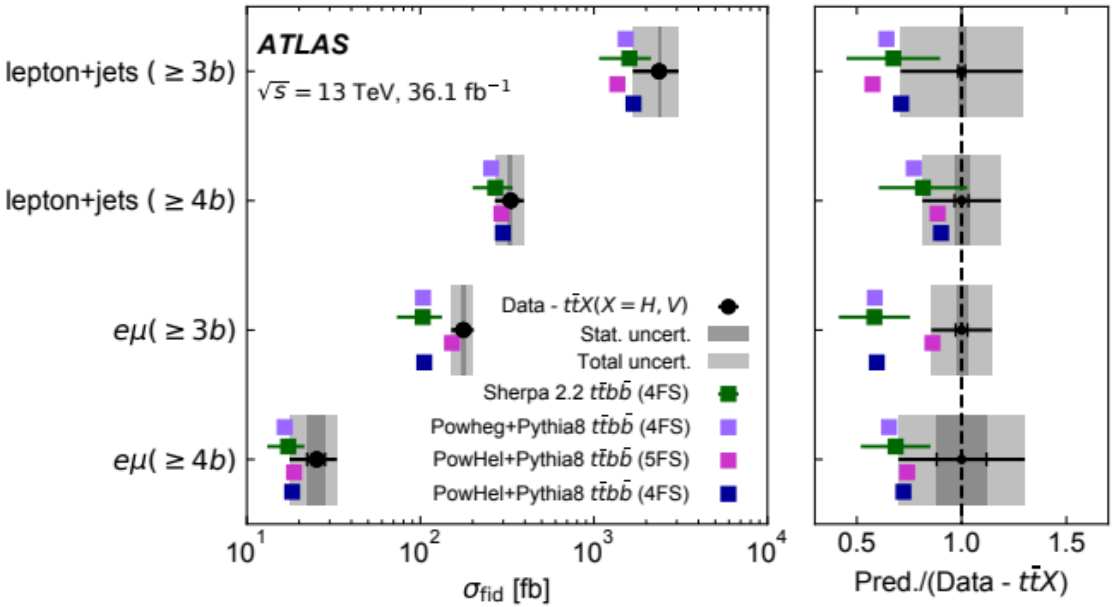




Status of $t\bar{t}+b\bar{b}$ measurements



- $\sigma(t\bar{t}+b\bar{b})$ measured in all decay channels
- Fiducial and full phase spaces
- Measured cross sections in agreement across decay channels
- Simulations consistently underpredict data
  - Simulation scaled to NNLO+NNLL $t\bar{t}$ cross section
- 2l, l+jets measurements are more precise than the predictions



Summary

- Presented **$t\bar{t}$+X ($b\bar{b}$, $c\bar{c}$, jj)** measurements from the ATLAS and CMS collaboration
  - Analyses show consistent results across all channels and phase spaces
  - Underprediction of 1-2σ by all MC simulations
  - First measurement of $\sigma(t\bar{t}+c\bar{c})$ in agreement with prediction
- **Prospects for full Run II (137 fb^{-1}):**
  - More precise total and differential cross section measurements

Thank you for your attention!

BACKUP

ATLAS Measurement of σ(tt̄+bb̄)

Source	Fiducial cross-section phase space $e\mu$		lepton + jets	
	$\geq 3b$ unc. [%]	$\geq 4b$ unc. [%]	$\geq 5j, \geq 3b$ unc. [%]	$\geq 6j, \geq 4b$ unc. [%]
Data statistics	2.7	9.0	1.7	3.0
Luminosity	2.1	2.1	2.3	2.3
Jet	2.6	4.3	3.6	7.2
b-tagging	4.5	5.2	17	8.6
Lepton	0.9	0.8	0.8	0.9
Pile-up	2.1	3.5	1.6	1.3
$t\bar{t}c$ fit variation	5.9	11	-	-
Non-$t\bar{t}$ bkg	0.8	2.0	1.7	1.8
Detector+background total syst.	8.5	14	18	12
Parton shower	9.0	6.5	12	6.3
Generator	0.2	18	16	8.7
ISR/FSR	4.0	3.9	6.2	2.9
PDF	0.6	0.4	0.3	0.1
$t\bar{t}V/t\bar{t}H$	0.7	1.4	2.2	0.3
MC sample statistics	1.8	5.3	1.2	4.3
$t\bar{t}$ modelling total syst.	10	20	21	12
Total syst.	13	24	28	17
Total	13	26	28	17

	$e\mu$ [fb] $\geq 3b$	$e\mu$ [fb] $\geq 4b$	lepton + jets [fb] $\geq 5j, \geq 3b$	lepton + jets [fb] $\geq 6j, \geq 4b$
Measured	181 ± 5 (stat) ± 24 (syst)	27 ± 3 (stat) ± 7 (syst)	2450 ± 40 (stat) ± 690 (syst)	359 ± 11 (stat) ± 61 (syst)
$t\bar{t}X(X = H, V)$ MC	4	2	80	28
Measured − $t\bar{t}X$	177	25	2370	331
SHERPA 2.2 $t\bar{t}b\bar{b}$ (4FS)	103 ± 30	17.3 ± 4.2	1600 ± 530	270 ± 70
POWHEG+PYTHIA 8 $t\bar{t}b\bar{b}$ (4FS)	104	16.5	1520	260
POWHEL+PYTHIA 8 $t\bar{t}b\bar{b}$ (5FS)	152	18.7	1360	290
POWHEL+PYTHIA 8 $t\bar{t}b\bar{b}$ (4FS)	105	18.2	1690	300

Measurement of σ(tt̄+bb̄) 2l and l+jets

Source	$R^{VPS}_{t\bar{t}b\bar{b}/t\bar{t}jj}$ [%]		$\sigma^{VPS}_{t\bar{t}jj}$ [%]	
	Dilepton	Lepton+jets	Dilepton	Lepton+jets
Lepton uncertainties				
Trigger	<0.1	0.2	1.0	0.5
Lepton identification	0.6	0.2	1.1	1.3
Lepton energy scale	—	<0.1	—	0.1
Jet uncertainties				
Jet energy resolution (JER)	0.4	0.3	0.3	0.7
Jet energy scale (JES)	1.5	1.2	2.9	3.6
b tagging uncertainties				
c-flavor btag (lin.)	2.2	2.0	1.0	0.3
c-flavor btag (quad.)	0.7	1.2	0.3	0.2
Heavy-flavor btag	4.0	0.1	0.5	0.9
Heavy-flavor btag (lin.)	0.9	0.4	1.5	0.5
Heavy-flavor btag (quad.)	2.0	0.3	1.5	0.8
Light-flavor btag	4.9	0.9	5.5	4.9
Light-flavor btag (lin.)	0.1	0.2	0.3	1.1
Light-flavor btag (quad.)	0.7	0.7	0.1	1.4
Theoretical uncertainties				
Initial-state radiation (ISR)	1.0	2.2	2.5	1.2
Final-state radiation (FSR)	0.8	0.7	2.5	5.9
ME-PS matching	0.5	<0.1	1.8	1.9
Underlying event tune (UE)	1.5	1.5	0.4	1.4
μ_F/μ_R scales (ME)	0.1	0.4	0.1	1.4
top-p_T	0.2	0.4	1.6	0.3
Ratio $R^{MC}_{t\bar{t}bj/t\bar{t}b\bar{b}}$	1.4	0.2	1.3	0.7
Other uncertainties				
Pileup	0.7	0.2	1.3	0.1
Backgrounds	0.3	2.0	0.7	1.2
Simulated sample size	1.5	2.8	0.1	2.2
Luminosity	0.2	0.5	2.6	3.1
Total	8.0	5.5	8.8	10.0

	$R_{t\bar{t}b\bar{b}/t\bar{t}jj}$	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}$ [pb]
Dilepton channel (VPS)			
POWHEG + PYTHIA8	0.013 ± 0.002	2.41 ± 0.21	0.032 ± 0.004
Measurement	$0.017 \pm 0.001 \pm 0.001$	$2.36 \pm 0.02 \pm 0.20$	$0.040 \pm 0.002 \pm 0.005$
Dilepton channel (FPS)			
POWHEG + PYTHIA8	0.014 ± 0.003	163 ± 21	2.3 ± 0.4
MG_aMC@NLO + PYTHIA8 5FS [FxFx]	0.015 ± 0.003	159 ± 25	2.4 ± 0.4
POWHEG + HERWIG++	0.011 ± 0.002	170 ± 25	1.9 ± 0.3
Measurement	$0.018 \pm 0.001 \pm 0.002$	$159 \pm 1 \pm 15$	$2.9 \pm 0.1 \pm 0.5$
Lepton+jets channel (VPS)			
POWHEG + PYTHIA8	0.017 ± 0.002	30.5 ± 3.0	0.52 ± 0.06
Measurement	$0.020 \pm 0.001 \pm 0.001$	$31.0 \pm 0.2 \pm 2.9$	$0.62 \pm 0.03 \pm 0.07$
Lepton+jets channel (FPS)			
POWHEG + PYTHIA8	0.013 ± 0.002	290 ± 29	3.9 ± 0.4
MG_aMC@NLO + PYTHIA8 5FS [FxFx]	0.014 ± 0.003	280 ± 40	4.1 ± 0.4
POWHEG + HERWIG++	0.011 ± 0.002	321 ± 36	3.4 ± 0.5
Measurement	$0.016 \pm 0.001 \pm 0.001$	$292 \pm 1 \pm 29$	$4.7 \pm 0.2 \pm 0.6$

Measurement of σ(tt̄+bb̄) All-Jets

Source	FPS PI (%)	FPS PB (%)
Simulated sample size	$^{+15}_{-11}$	$^{+15}_{-11}$
Quark-gluon likelihood	$^{+13}_{-8}$	$^{+13}_{-8}$
b tagging of b quark	±10	±10
JES and JER	$^{+5.1}_{-5.2}$	$^{+5.0}_{-5.4}$
Integrated luminosity	$^{+2.8}_{-2.2}$	$^{+2.4}_{-2.2}$
Trigger efficiency	$^{+2.6}_{-2.1}$	$^{+2.5}_{-2.2}$
Pileup	$^{+2.3}_{-2.0}$	$^{+2.2}_{-1.9}$
μ_R and μ_F scales	$^{+13}_{-9}$	$^{+13}_{-9}$
Parton shower scale	$^{+11}_{-8}$	$^{+11}_{-8}$
UE tune	$^{+9.0}_{-5.3}$	$^{+9.0}_{-5.2}$
Colour reconnection	±7.2	±7.1
Shower matching (h_{damp})	$^{+4.3}_{-2.8}$	$^{+3.8}_{-2.7}$
tt̄cc̄ normalization	$^{+3.2}_{-4.4}$	$^{+2.9}_{-4.5}$
Modelling of p_T of top quark	±2.5	±2.4
PDFs	$^{+2.2}_{-2.0}$	$^{+2.2}_{-2.0}$
Total	$^{+28}_{-23}$	$^{+28}_{-23}$

	FPS PI (pb)	FPS PB (pb)	TPS (pb)
Measurement	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$5.5 \pm 0.3^{+1.6}_{-1.3}$
POWHEG (tt̄)	1.1 ± 0.2	1.0 ± 0.2	3.5 ± 0.6
POWHEG (tt̄) + HERWIG++	0.8 ± 0.2	0.8 ± 0.2	3.0 ± 0.5
MADGRAPH5_aMC@NLO (4FS tt̄bb̄)	0.8 ± 0.2	0.8 ± 0.2	2.3 ± 0.7
MADGRAPH5_aMC@NLO (5FS tt̄+jets, FxFx)	1.0 ± 0.1	1.0 ± 0.1	3.6 ± 0.3

Inclusive σ(tt̄+cc̄) Measurement (2l)

Sources	Systematic uncertainty (%)				
	$\Delta\sigma_{t\bar{t}c\bar{c}}$	$\Delta\sigma_{t\bar{t}b\bar{b}}$	$\Delta\sigma_{t\bar{t}LL}$	ΔR_c	ΔR_b
Jet energy scale	4.0	3.2	4.7	2.8	2.1
Jet energy resolution	2.3	1.0	0.9	2.5	1.3
c tagging calibration	7.0	3.2	2.5	7.3	3.5
Lepton identification and isolation	0.8	1.0	1.3	0.6	0.3
Trigger	2.0	2.0	2.0	< 0.1	< 0.1
Pileup	0.3	0.2	0.3	0.5	< 0.1
Total integrated luminosity	2.3	2.4	2.3	< 0.1	< 0.1
μ_R and μ_F scales in ME	3.3	6.2	2.1	3.8	6.8
PS scale	0.4	1.6	0.3	0.5	1.6
PDF	0.3	0.1	0.1	0.2	0.1
ME-PS matching	7.1	5.7	3.5	2.6	1.5
Underlying event	1.9	2.3	1.1	0.5	0.9
b fragmentation	0.4	1.9	0.8	0.3	2.4
c fragmentation	4.6	< 0.1	< 0.1	3.9	0.7
$t\bar{t}bL(cL)/t\bar{t}b\bar{b}(c\bar{c})$ and $t\bar{t}$+other/$t\bar{t}LL$	2.4	1.8	1.1	1.8	1.5
Efficiency (theoretical)	2.4	2.1	2.0	< 0.1	< 0.1
Simulated sample size	3.2	2.6	1.1	3.1	2.5
Background normalization	0.5	0.7	0.6	0.1	0.1
Total	13.7	11.4	8.2	10.9	9.2

	Result	POWHEG	MADGRAPH5_aMC@NLO
	Fiducial phase space		
$\sigma_{t\bar{t}c\bar{c}}$ [pb]	$0.207 \pm 0.025 \pm 0.027$	0.187 ± 0.038	0.189 ± 0.032
$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$0.132 \pm 0.010 \pm 0.015$	0.097 ± 0.021	0.101 ± 0.023
$\sigma_{t\bar{t}LL}$ [pb]	$5.15 \pm 0.12 \pm 0.41$	5.95 ± 1.02	6.32 ± 0.94
R_c [%]	$3.01 \pm 0.34 \pm 0.31$	2.53 ± 0.18	2.43 ± 0.17
R_b [%]	$1.93 \pm 0.15 \pm 0.18$	1.31 ± 0.12	1.30 ± 0.16
	Full phase space		
$\sigma_{t\bar{t}c\bar{c}}$ [pb]	$10.1 \pm 1.2 \pm 1.4$	9.1 ± 1.8	8.9 ± 1.5
$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$4.54 \pm 0.35 \pm 0.56$	3.34 ± 0.72	3.39 ± 0.66
$\sigma_{t\bar{t}LL}$ [pb]	$220 \pm 5 \pm 19$	255 ± 43	261 ± 37
R_c [%]	$3.36 \pm 0.38 \pm 0.34$	2.81 ± 0.20	2.72 ± 0.19
R_b [%]	$1.51 \pm 0.11 \pm 0.16$	1.03 ± 0.08	1.03 ± 0.09