tt+heavy flavor measurements at the LHC

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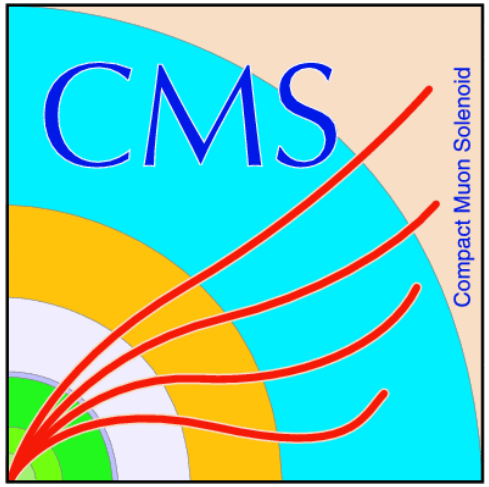
on behalf of the ATLAS and CMS collaboration



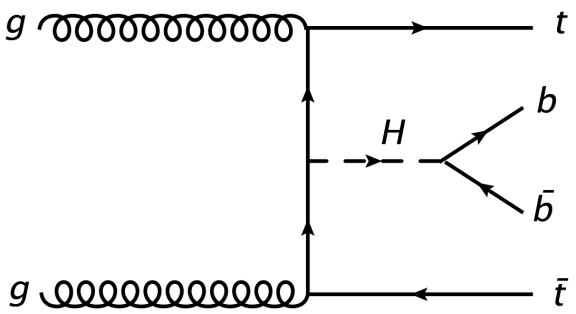
Outline

- Motivation
- Fiducial and full cross-section measurements at 8 TeV and 13 TeV
- ttbb/ttjj ratio measurements at 8 and 13 TeV
- Differential cross-section measurements at 8 TeV
- Conclusion

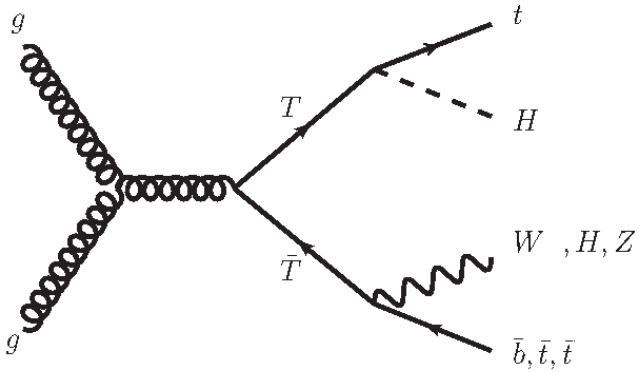
tt+HF measurement: motivation

- tt+Heavy Flavor main background to many SM and BSM searches at the LHC
- ttbb, but also ttb, ttcc, ttc

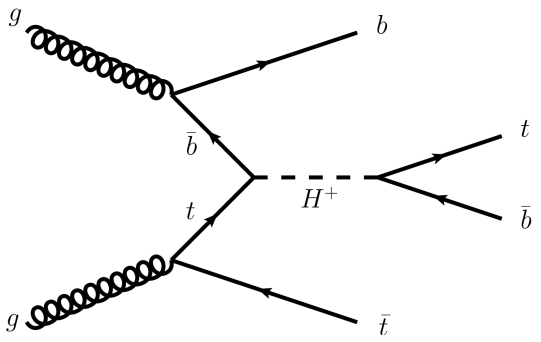
ttH(bb)



VLQ



$H^+ \rightarrow tb$



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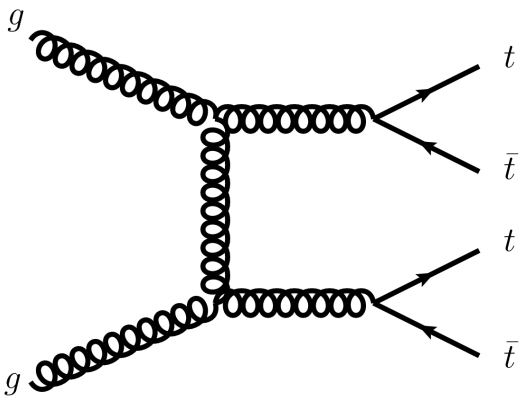
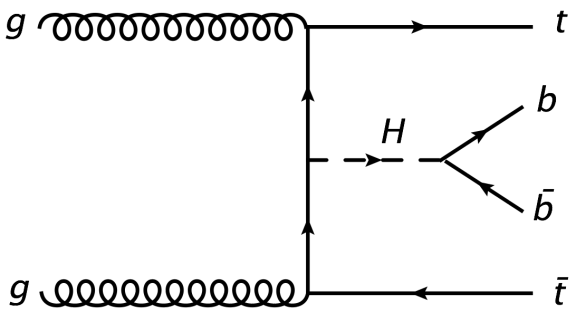


tt+HF measurement: motivation

- In ttH(bb) analysis, tt+HF cross-section and modelling are dominant systematic uncertainties:

ttH(bb)



Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	+0.53	−0.53
Jet flavour tagging	+0.26	−0.26
$t\bar{t}H$ modelling	+0.32	−0.20
Background model statistics	+0.25	−0.25
$t\bar{t}+\geq 1c$ modelling	+0.24	−0.23
Jet energy scale and resolution	+0.19	−0.19
$t\bar{t}$+light modelling	+0.19	−0.18
Other background modelling	+0.18	−0.18
Jet-vertex association, pileup modelling	+0.12	−0.12
Luminosity	+0.12	−0.12
$t\bar{t}Z$ modelling	+0.06	−0.06
Light lepton (e,μ) ID, isolation, trigger	+0.05	−0.05
Total systematic uncertainty	+0.90	−0.75
$t\bar{t}+\geq 1b$ normalisation	+0.34	−0.34
$t\bar{t}+\geq 1c$ normalisation	+0.14	−0.14
Statistical uncertainty	+0.49	−0.49
Total uncertainty	+1.02	−0.89

ATLAS, 1-lepton, 13 TeV
ATLAS-CONF-2016-080

- Much more details in next talk on ttH(bb)

tt+HF production and QCD prediction

- Cross-sections computed at NLO with massive b-quarks

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PLB 734 (2014) 210

	ttb	ttbb	ttbb($m_{bb} > 100$)
σ_{LO}[fb]	$2644^{+71\%+14\%}_{-38\%-11\%}$	$463.3^{+66\%+15\%}_{-36\%-12\%}$	$123.4^{+63\%+17\%}_{-35\%-13\%}$
σ_{NLO}[fb]	$3296^{+34\%+5.6\%}_{-25\%-4.2\%}$	$560^{+29\%+5.4\%}_{-24\%-4.8\%}$	$141.8^{+26\%+6.5\%}_{-22\%-4.6\%}$
σ_{NLO}/σ_{LO}	1.25	1.21	1.15
σ_{MC}[fb]	$3313^{+32\%+3.9\%}_{-25\%-2.9\%}$	$600^{+24\%+2.0\%}_{-22\%-2.1\%}$	$181.0^{+20\%+8.1\%}_{-20\%-6.0\%}$
σ_{MC}/σ_{NLO}	1.01	1.07	1.28
σ^{2b}_{MC}[fb]	3299	552	146
$\sigma^{2b}_{MC}/\sigma_{NLO}$	1.00	0.99	1.03

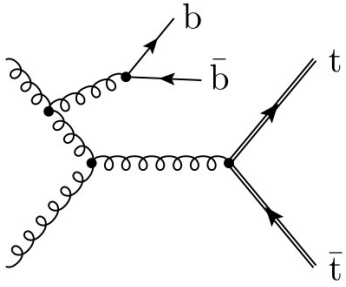
Nb of parton-level b-jets with p T > 25 GeV and | η(b) | < 2.5

- At 8 TeV, xs(ttbb) = 600 fb (for pT(b) > 25 GeV, |eta(b) < 2.5)
- NLO scale uncertainties at the level of 25% ~ 150 fb
- To be compared to ttH(bb) total cross-section:
  → 130 fb * 58% = 74 fb

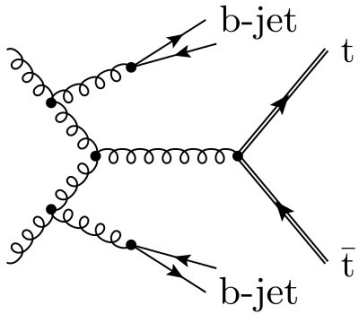
tt+HF production and QCD prediction

ttbb diagrams at tree level:

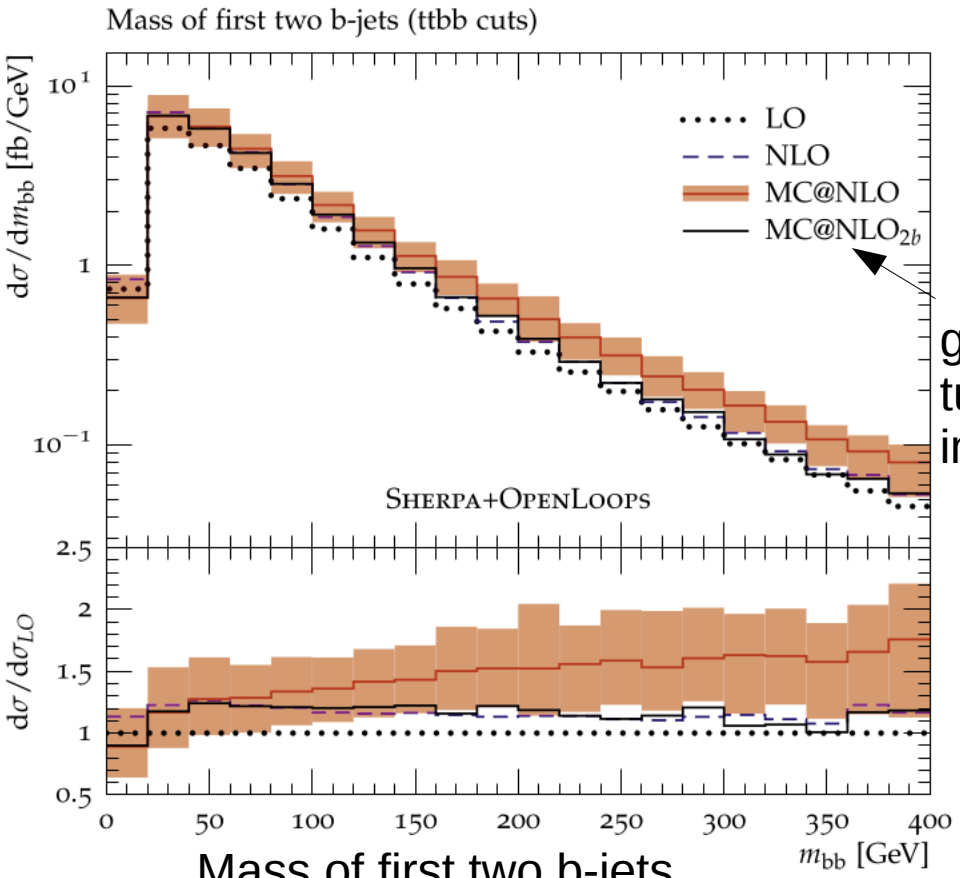
* High-mass gluon splitting → two b-jets:



* Low-mass gluon splitting → two b-jets each containing two b-hadrons: only one of the two is NLO!



The 2nd gluon splitting comes from parton shower



g→bb turned off in shower

Mass of first two b-jets (not from top)

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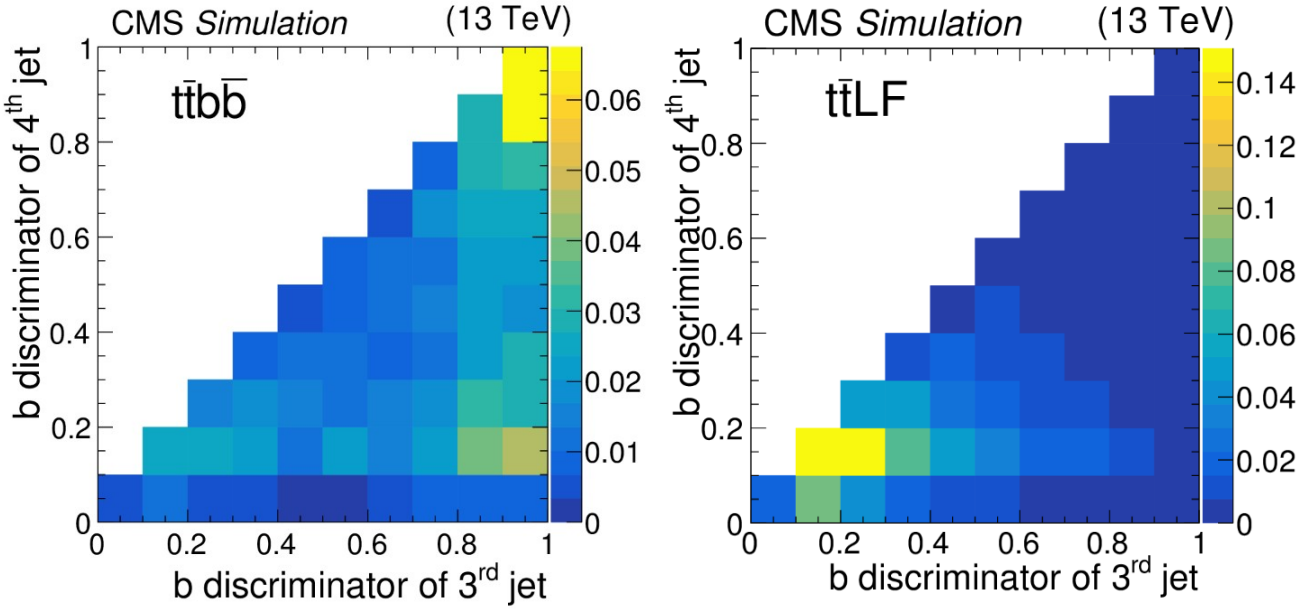
tt+HF measurements: overview of current results

- Measurements of:
  - → ttb and ttbb fiducial or full cross-section
  - → ttbb/ttjj cross-section ratio
  - → ttbb differential cross-section of kinematic variables
- 13 TeV results:
  - → CMS dilepton (fid. ttbb, ttbb/ttjj ratio) Phys. Lett. B (2017)
- 8 TeV results:
  - → ATLAS dilepton and 1-lepton (fid. ttb, ttbb, and ttbb/ttjj ratio) Eur. Phys. J. C76 (2016) 11
  - → CMS dilepton (fid. ttbb and ttbb/ttjj ratio) Phys. Lett. B 746 (2015) 132
  - → CMS 1-lepton (fid. ttbb and ttbb/ttjj ratio) CMS-PAS-TOP-13-016
  - → CMS dilepton (differential cross-sections) Eur. Phys. J. C 76 (2016) 379

ttb and ttbb fiducial and full cross-sections: analysis techniques

- Both experiments use the same strategy:
  - → Start from pure ttbar sample (1-lepton or dilepton channel) with two b-tags
  - → Fit b-tagging discriminant of additional jets to extract different tt+jets components: ttbb, ttb, ttc, tt+light

CMS, 13 TeV
Dilepton channel
Phys. Lett. B (2017)



- One exception: ATLAS measurement of ttbb using a very tight selection to isolate pure ttbb sample → cut-and-count

Event selection (dilepton channel) ATLAS-CMS comparison

CMS 13 TeV

- Two OS leptons (e or μ)
  - → pT > 20 GeV, |eta| < 2.4
- At least 4 jets anti-kt R = 0.4
  - → pT > 30 GeV, |eta| < 2.4
  - → at least 2 b-tags (60-70%)
- m(ll) > 12 GeV
- missing ET > 30 GeV and |m(ll) – m(Z)| > 15 GeV (same-flavor channels only)

CMS 8 TeV

- Same except jet |eta|<2.5 and R = 0.5

ATLAS 8 TeV

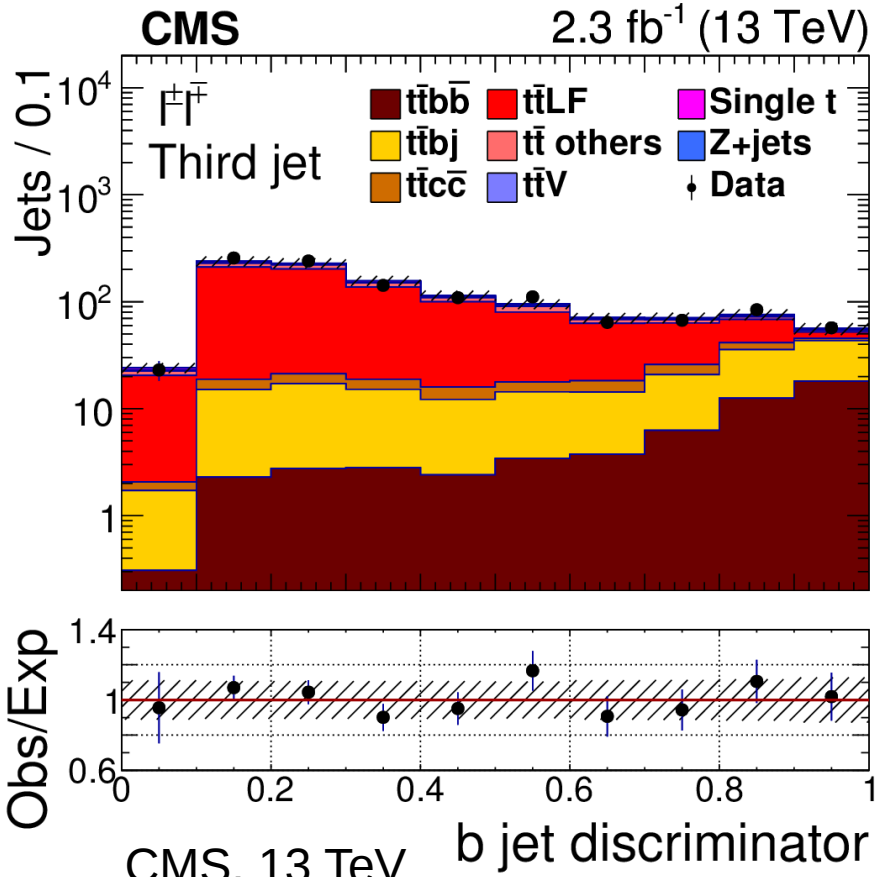
- Two OS leptons (e or μ)
  - → pT > 25 GeV, |eta| < 2.5
- At least 3 jets anti-kt R = 0.4
  - → pT > 25 GeV, |eta| < 2.5
  - → at least 2 b-tags (80%)
- m(ll) > 15 GeV
- No cut on missing ET
- |m(ll) – m(Z)| > 10 GeV (same-flavor channels only)

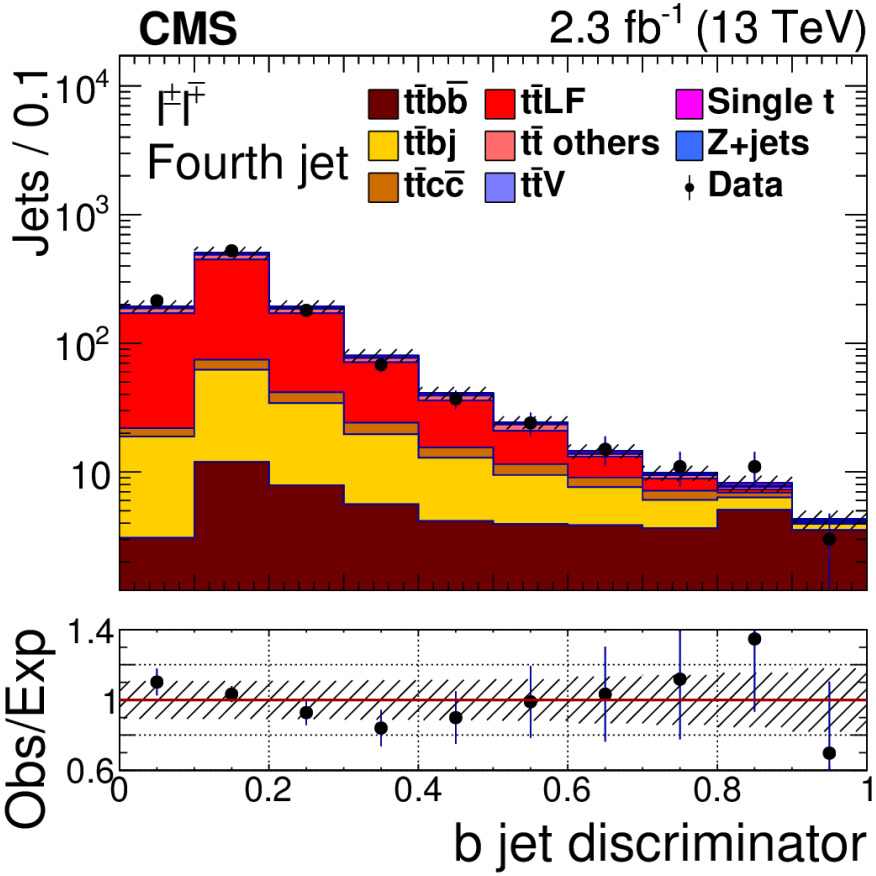
Fiducial region definition at particle level

- Fiducial region chosen as close as possible to reconstructed event selection (to minimize model-dependence)
- Fiducial cuts applied to Monte Carlo at particle level
- Lepton cuts identical to event selection
- Particle jets anti-kt R = 0.4 (except CMS 8 TeV: R = 0.5)
  - → pT > 20 GeV (lowered from 25 (ATLAS) or 30 (CMS) due to large jet energy resolution, |eta| < 2.5
  - → Dilepton ttb: at least 3 jets and three b-jets. ttbb: at least 4 jets and 4 b-jets
- b-jets: ghost-matching of b hadrons with particle-jets
  - → ATLAS: pT(B) > 5 GeV
- ATLAS and CMS: fiducial definitions almost identical

ttbb dilepton CMS 13 TeV measurements

- Fit b-tag discriminant of jets with 3rd and 4th highest discr.





CMS, 13 TeV
Dilepton channel

Phys. Lett. B (2017)

ttbb dilepton CMS 13 TeV measurements: Systematics

Syst. for visible xs (pT > 20 GeV)

Jet energy scale and res.

b-tag calibrations do not cancel in ratio

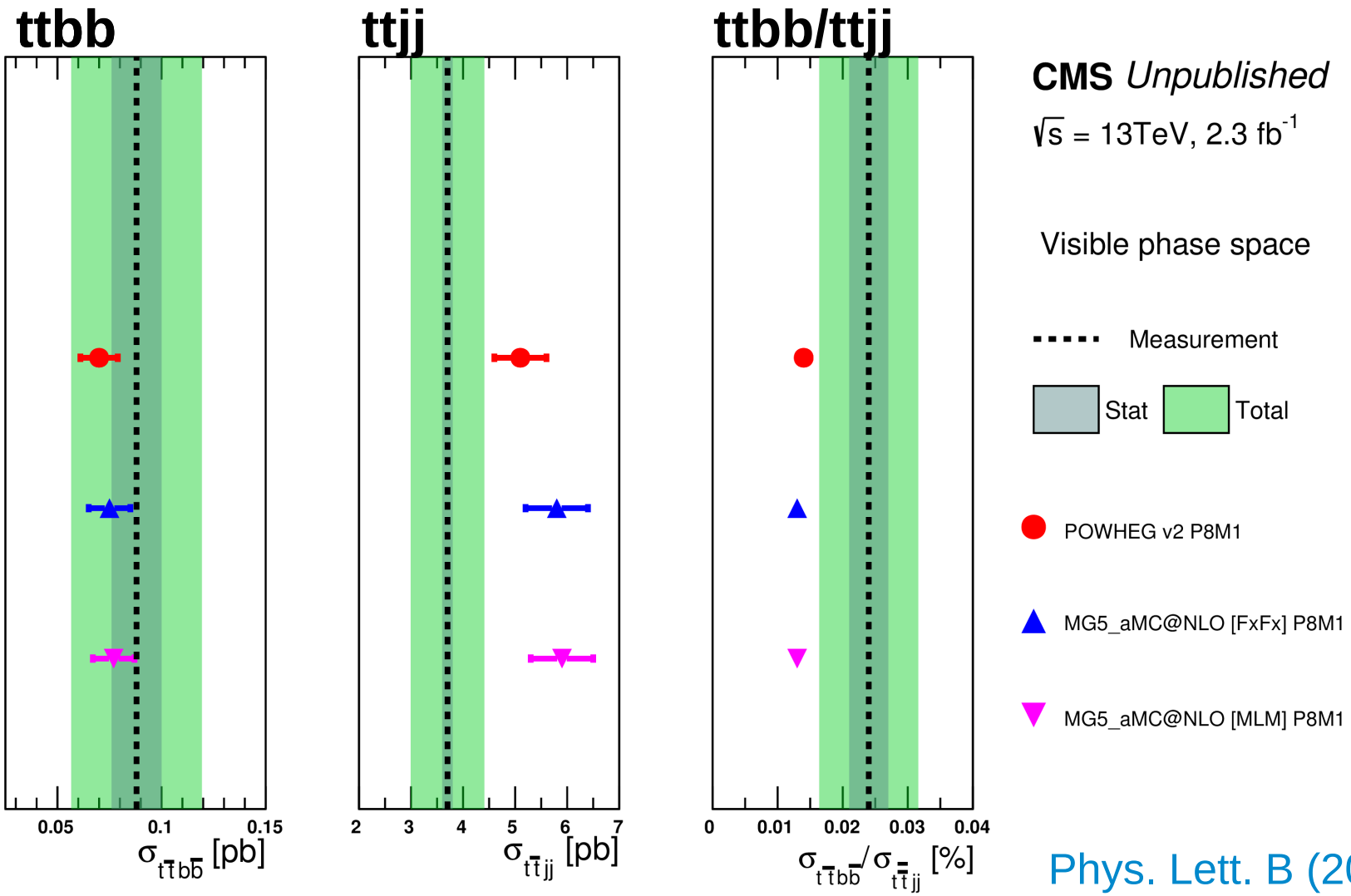
ttbar modelling (other than tt+HF)

cancel (mostly) in the ratio

Source	$\sigma_{t\bar{t}b\bar{b}}$	$\sigma_{t\bar{t}jj}$	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Pileup	0.4	<0.1	0.4
JES & JER	7.8	7.4	2.6
b tag (b quark flavour)	19	4.7	19
b tag (c quark flavour)	14	1.3	14
b tag (light flavour)	14	9.8	9.7
Ratio of $t\bar{t}b\bar{b}$ and $t\bar{t}bj$	2.6	0.5	2.6
Background modelling	3.8	3.5	1.6
$t\bar{t}c\bar{c}$ fraction in the fit	5.2	1.9	4.8
Lepton trigger/identification	3.0	3.0	0
MC generator	9.4	6.2	3.0
μ_F and μ_R scale	2.0	2.0	1.0
scale in PS	13	9.9	10
PDFs	0.5	0.5	<0.1
Efficiency ($t\bar{t}c\bar{c}$ fraction)	0	1.3	1.3
Jet multiplicity modelling	5.0	5.0	5.0
Top quark p_T modelling	0.8	0.3	0.5
Simulation (statistical)	1.5	1.5	1.5
Integrated Luminosity	2.3	2.3	0
Total uncertainty	34	19	28

Total: 34% for ttbb
28% for ratio

ttbb dilepton CMS 13 TeV measurements: Results



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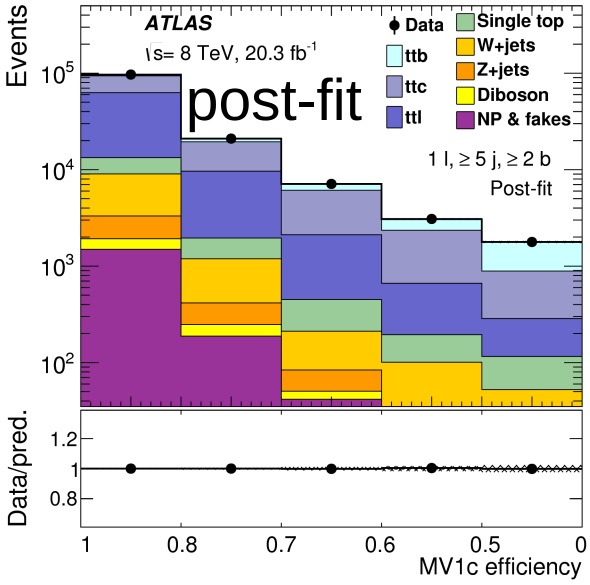
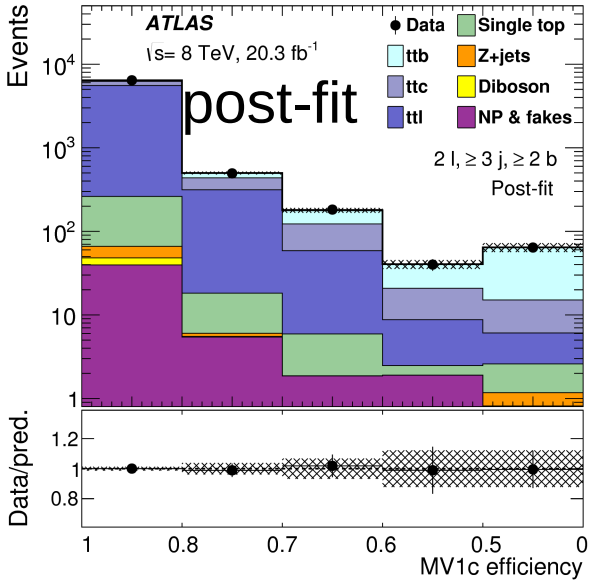
ttb and ttbb ATLAS 8 TeV measurements: fit-based analysis

- Separate measurements of ttb and ttbb:
  - → For ttb, fit only 3rd highest b-tag discriminant
- ATLAS uses only 5 bins corresponding to 4 calibrated working points: 80%, 70%, 60%, 50%

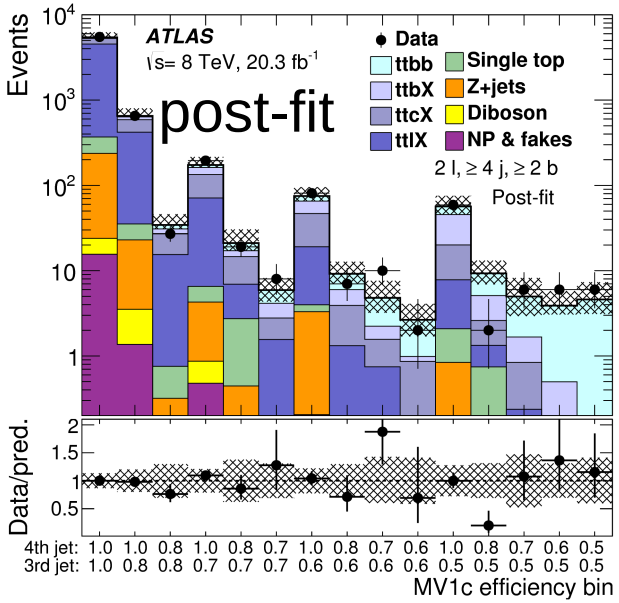
1-lepton channel
ttb measurement



2-lepton channel (eμ)
ttb measurement



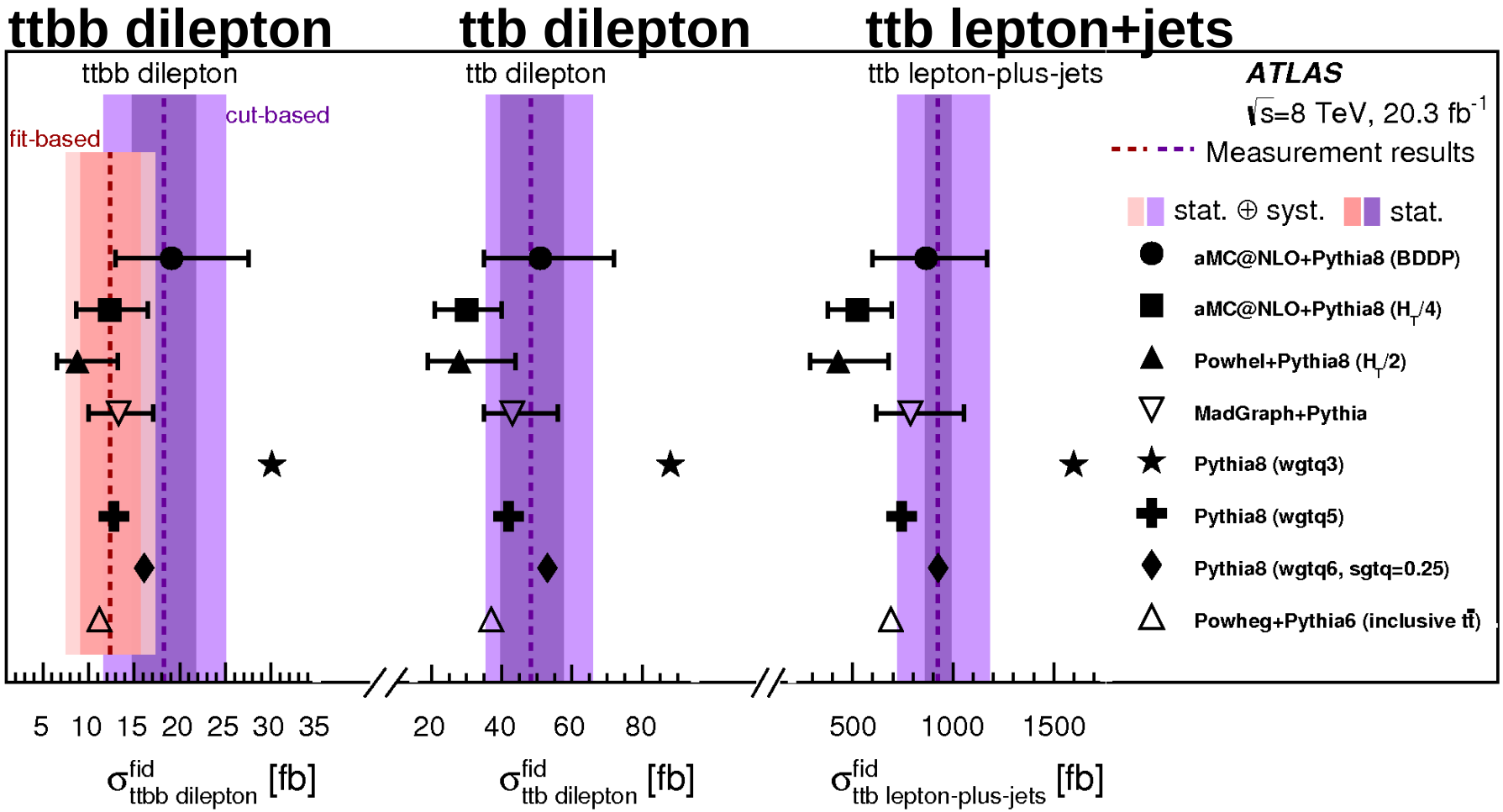
2-lepton channel (ee, eμ, μμ)
ttbb measurement



ATLAS, 8 TeV
Eur. Phys. J. C76 (2016) 11

ttb and ttbb ATLAS 8 TeV measurements: Results

- Total unc. ~ 35%, dominated by b-tag, JES/JER, ttbar mod.



ttbb/ttjj visible cross-section ratio: ATLAS-CMS, 8-13 TeV comparisons

- ttbb/ttjj ratio of fiducial cross-sections (pT(bjet) > 20 GeV)

Measurements		Predictions	
ATLAS 8TeV (dilepton fit-based)	(1.2 +- 0.4)%	PowhegP6 8TeV (ATLAS)	1.2%
CMS 8TeV (1-lepton)	(1.5 +- 0.5)%	MadgraphP6 8TeV (ATLAS)	(1.3 +- 0.2)%
CMS 8TeV (dilepton)	(2.2 +- 0.6)%	PowhegP6 8TeV (CMS)	(1.6 +- 0.2)%
		MadgraphP6 8TeV (CMS)	(1.6 +- 0.2)%
CMS 13TeV (dilepton)	(2.4 +- 0.8)%	PowhegP8 13TeV (dilepton)	(1.4 +- 0.1)%

- Overall reasonable agreement between experiments and with LO predictions

ttbb/ttjj visible cross-section ratio: ATLAS-CMS, 8-13 TeV comparisons

- ttbb/ttjj ratio of fiducial cross-sections (pT(bjet) > 20 GeV)

Measurements		Predictions	
			difference in true b-jet definition?
ATLAS 8TeV (dilepton fit-based)	(1.2 +- 0.4)%	PowhegP6 8TeV (ATLAS)	1.2%
CMS 8TeV (1-lepton)	(1.5 +- 0.5)%	MadgraphP6 8TeV (ATLAS)	(1.3 +- 0.2)%
CMS 8TeV (dilepton)	(2.2 +- 0.6)%	PowhegP6 8TeV (CMS)	(1.6 +- 0.2)%
		MadgraphP6 8TeV (CMS)	(1.6 +- 0.2)%
CMS 13TeV (dilepton)	(2.4 +- 0.8)%	PowhegP8 13TeV (dilepton)	(1.4 +- 0.1)%

- Overall reasonable agreement between experiments and with LO predictions

ttbb differential cross-section 8 TeV, CMS, dilepton channel

- Dilepton channel
- BDT to select pair of b-jets most likely to come from top decay
  - → Use variables insensitive to kinematic of additional jets, and train on ttH to avoid biasing ttbb kinematic variables
  - → Ex: b-jet charge, b-jet pT, b-lepton mass
  - → reach 40% purity (16% with random choice) in ttbb
- Template fit to b-tagged jet multiplicity to extract components

CMS, 8 TeV

dilepton channel

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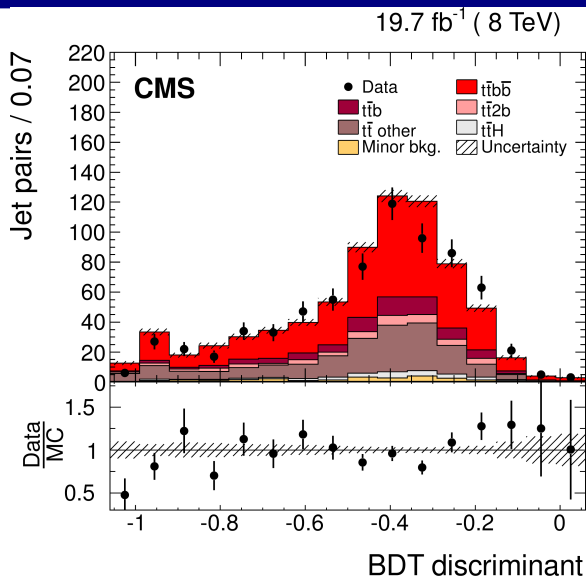
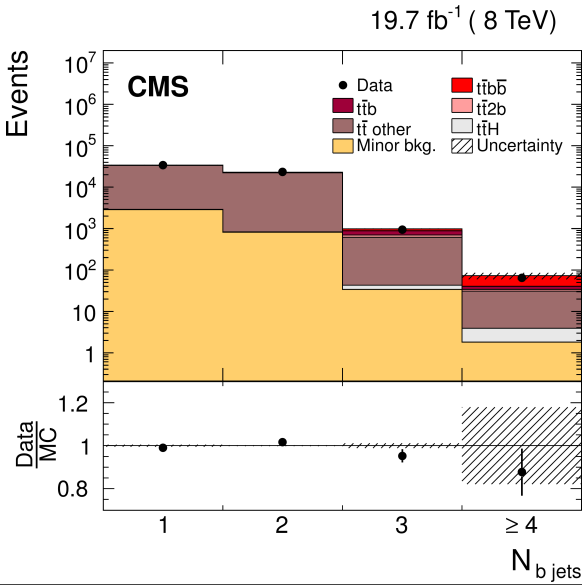
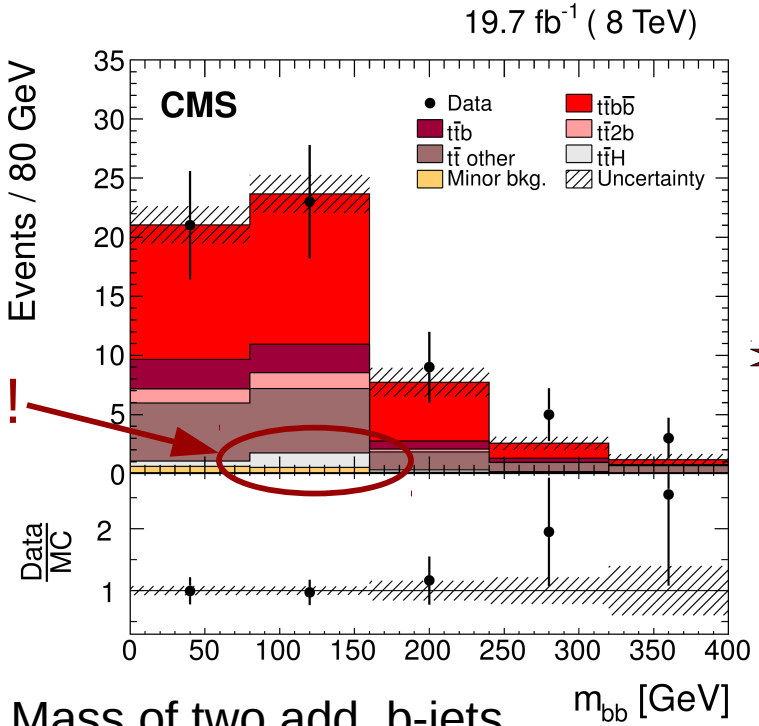


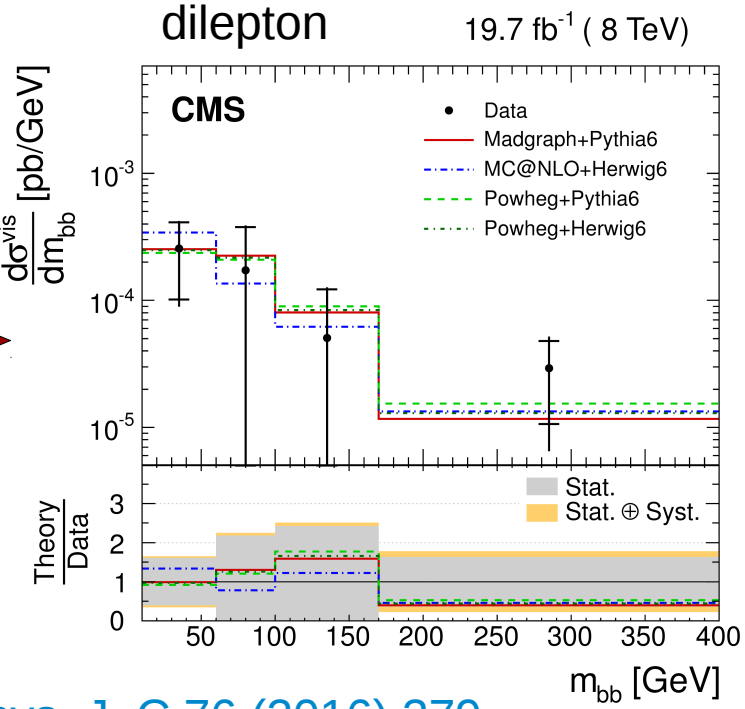


ttbb differential cross-section 8 TeV, CMS, dilepton channel

- Unfold several kinematic distributions to visible, and full cross-section.
- Good agreement with prediction but much more statistics required



Mass of two add. b-jets



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ttbb differential cross-section 8 TeV, CMS, dilepton channel

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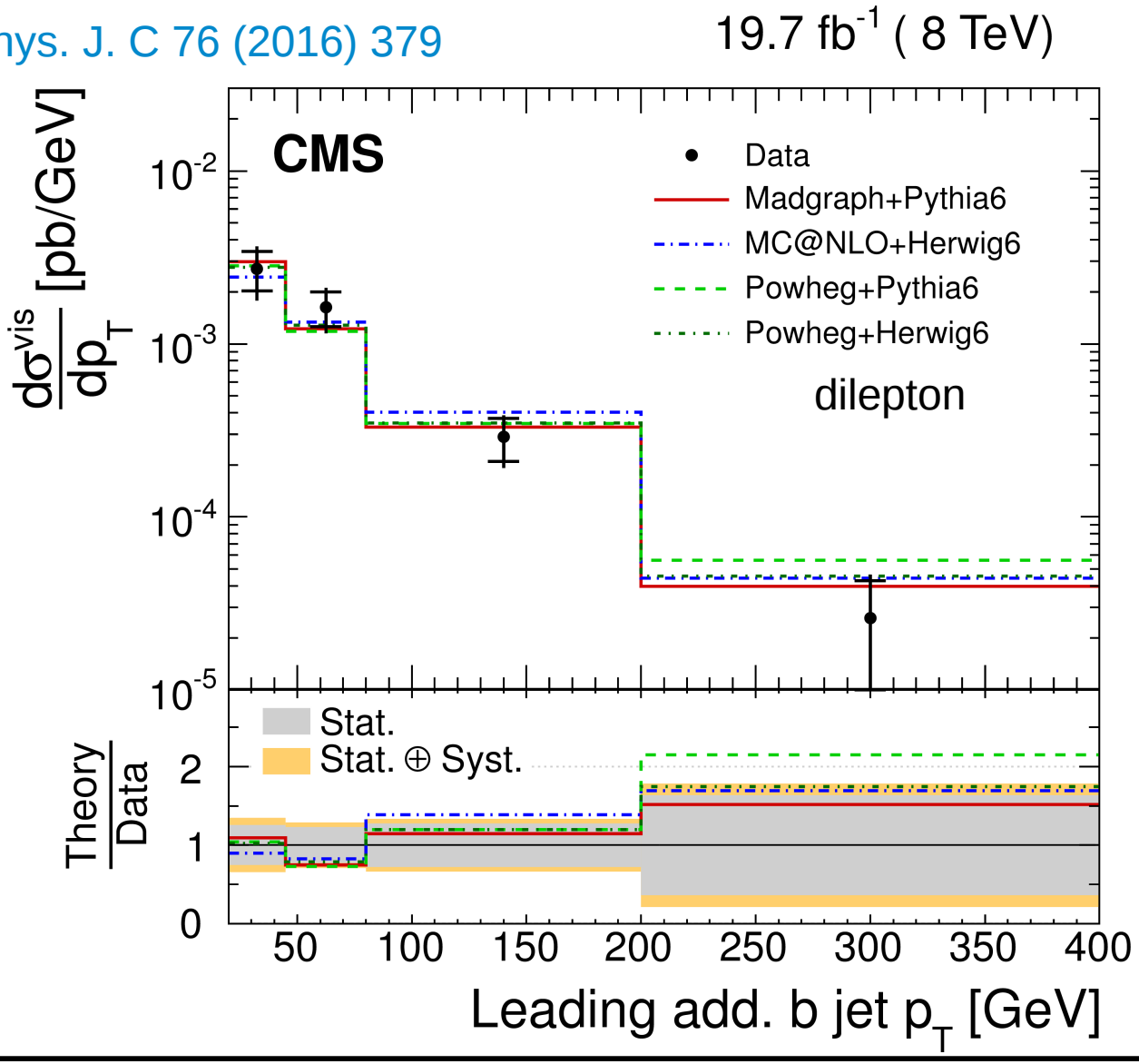

ttbb differential cross-section 8 TeV, CMS, dilepton channel

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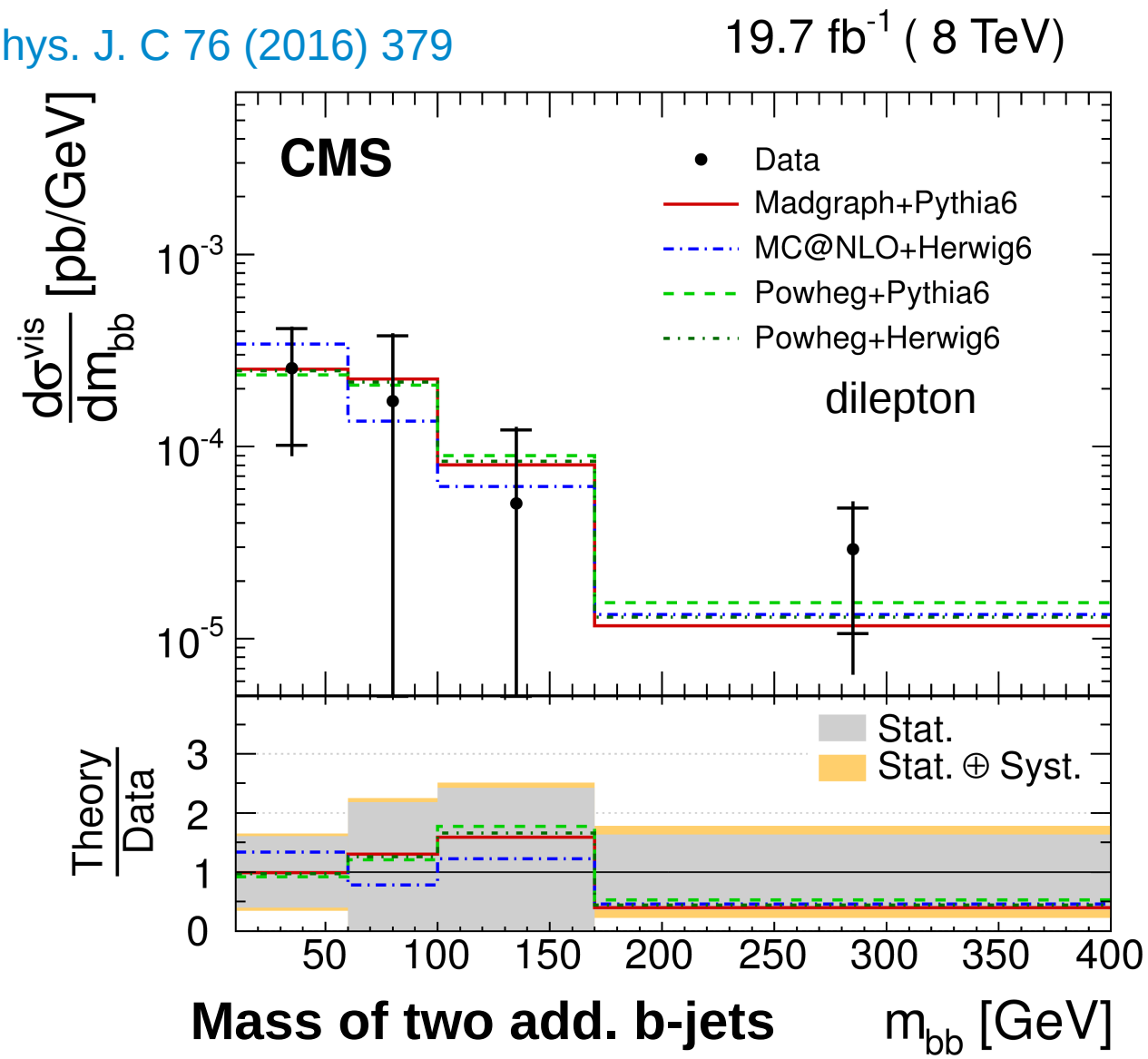

ttbb differential cross-section 8 TeV, CMS, dilepton channel

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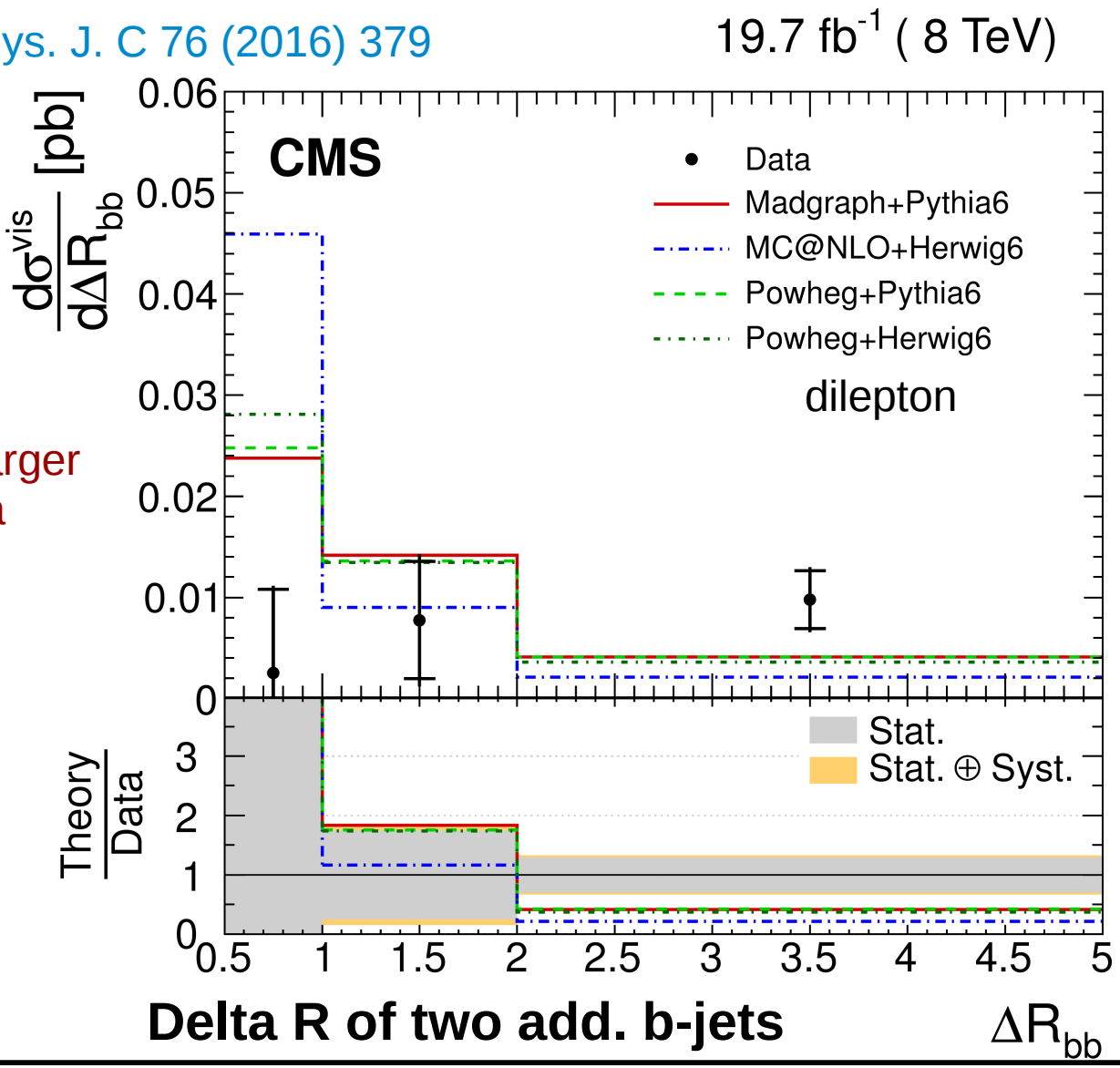
Indication of larger DR(bb) in data



Conclusion

- tt+HF measurements not yet able to improve on the QCD predictions
  - → Precision limited by b-tagging calibration, jet energy scale and resolution, and ttbar modelling
  - → Measurement ~ 35%
  - → NLO prediction ~ 25%
- Measuring ttc/ttcc would also be helpful but is even more challenging
- Precise differential cross-section measurements required, but limited by statistics
  - → New Run 2 results expected soon!

Backup

ttb and ttbb ATLAS 8 TeV measurement: Event selection

- Leptons (electron or muon)
  - → pT > 25 GeV, |eta| < 2.5
- Jets anti-kt R = 0.4
  - → pT > 25 GeV, |eta| < 2.5
- No cut on missing ET

- 1-lepton analysis:
  - → At least 5 jets, at least two b-tags (80% working point)
- Dilepton analysis: two isolated leptons
  - → m(ll) > 15 GeV and for same-flavor pairs |m(ll) – m(Z)| > 10 GeV
  - → At least 3 jets, at least two b-tags (80%)
  - → Cut-and-count channel (ttbb): at least 4 jets, at least 4 b-tags (70%)

ttb and ttbb ATLAS 8 TeV measurement: Fiducial definition at particle level

- Leptons (electron or muon)
  - → pT > 25 GeV, |eta| < 2.5
- Jets anti-kt R = 0.4
  - → pT > 20 GeV, |eta| < 2.5
- No cut on missing ET

Fiducial Requirement	ttb lepton-plus-jets	ttb $e\mu$	$ttbb$ dilepton
N_{leptons} ($p_{\text{T}} > 25$ GeV, $\|\eta\| < 2.5$)	1	2	2
Lepton flavours	e and μ	$e\mu$ only	ee, $\mu\mu$ and $e\mu$
$m_{\ell\ell} > 15$ GeV	-	-	yes
$\|m_{ee/\mu\mu} - 91\text{GeV}\| > 10$ GeV	-	-	yes
N_{jets} ($p_{\text{T}} > 20$ GeV, $\|\eta\| < 2.5$)	≥ 5	≥ 3	≥ 4
$N_{b-\text{jets}}$	≥ 3	≥ 3	≥ 4
$\Delta R_{\ell,j} > 0.4$	yes	yes	yes

- 1-lepton analysis:
  - → At least 5 jets, at least three b-jets
- Dilepton analysis: two isolated leptons
  - → m(ll) > 15 GeV and for same-flavor pairs |m(ll) – m(Z)| > 10 GeV
  - → At least 3 jets, at least three b-jets
  - → Cut-and-count channel (ttbb): at least 4 jets, at least 4 b-jets
- b-jets: ghost-matching of b hadrons of pT > 5 GeV

ttb and ttbb ATLAS 8 TeV measurement: Event yields

19 /fb, 8 TeV

Component	ttb Lepton-plus-jets	*ttb eμ*
$t\bar{t}$	108600 ± 7500	6620 ± 710
ttb	5230 ± 330	286 ± 27
$t\bar{t}V$ signal	67 ± 67	3.6 ± 3.6
$t\bar{t}H$ signal	140 ± 140	10 ± 10
ttc	43300 ± 3000	629 ± 57
ttl	60100 ± 6800	5700 ± 630
W+jets	6700 ± 3500	-
Single top	5490 ± 760	216 ± 58
Z+jets	1640 ± 860	20 ± 11
Diboson	510 ± 140	8.8 ± 3.3
Fake and non-prompt leptons	1790 ± 890	50 ± 25
Total prediction	124800 ± 8400	6910 ± 720
Data	129743	7198

19 /fb, 8 TeV

Component	ttbb Cut-based	ttbb Fit-based
$t\bar{t}$	23.8 ± 7.2	5750 ± 850
ttbb	17.1 ± 4.8	110 ± 35
$t\bar{t}V$ signal	0.59 ± 0.59	2.7 ± 2.7
$t\bar{t}H$ signal	1.6 ± 1.6	7.7 ± 7.7
ttbX	4.1 ± 2.7	280 ± 93
ttcX	2.4 ± 1.0	730 ± 350
ttlX	0.30 ± 0.30	4630 ± 670
Single top	0.41 ± 0.41	150 ± 57
Z+jets	0.82 ± 0.82	240 ± 46
Diboson	<0.1	10.9 ± 3.9
Fake and non-prompt leptons	<0.1	18.1 ± 9.1
Total prediction	25.1 ± 7.2	6180 ± 890
Data	37	6579

ttbb CMS 8 TeV and 13 TeV measurements: Event selection and yields (dilepton)

- Two isolated opposite-sign leptons (electron or muon)
  - → pT > 20 GeV, |eta| < 2.4
  - → m(ll) > 12 GeV and for same-flavor pairs |m(ll) – m(Z)| > 15 GeV
- At least four jets anti-kt R = 0.5 (R = 0.4 at 13 TeV)
  - → pT > 30 GeV, |eta| < 2.5 (|eta| < 2.4 at 13 TeV)
  - → At least two b-tags (45% eff. working point) (60-70% eff. at 13 TeV)
- Missing ET > 30 GeV in same-flavor channels

19.7 /fb, 8 TeV

Final state	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$	All
$t\bar{t}b\bar{b}$	18	26	61	105 ± 2
$t\bar{t}bj$	35	48	109	191 ± 3
$t\bar{t}c\bar{c}$	13	19	45	78 ± 2
$t\bar{t}$LF	249	347	840	1438 ± 9
$t\bar{t}$ others	21	25	64	109 ± 3
Single top	7.4	11	24	43 ± 5
$Z/\gamma* \to \ell\ell$	5.7	5.4	3.1	14 ± 7
Total	350	483	1149	1983 ± 13
Data	367	506	1145	2018

2.3 /fb, 13 TeV

Process	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$	All
$t\bar{t}b\bar{b}$	6.3 ± 0.4	8.6 ± 0.4	24 ± 1	39 ± 1
$t\bar{t}bj$	16 ± 1	21 ± 1	57 ± 2	95 ± 2
$t\bar{t}c\bar{c}$	7.7 ± 0.4	11 ± 1	27 ± 1	46 ± 1
$t\bar{t}$LF	157 ± 2	220 ± 2	596 ± 3	972 ± 4
$t\bar{t}$ others	18 ± 1	19 ± 1	61 ± 1	99 ± 1
$t\bar{t}$ V	2.5 ± 0.1	3.2 ± 0.2	7.3 ± 0.2	14 ± 1
Single t	6.6 ± 0.8	8.4 ± 0.8	23 ± 2	39 ± 2
Z+jets	$0.8^{+1.0}_{-0.8}$	5.4 ± 1.5	0.6 ± 0.5	6.8 ± 1.9
Total	215 ± 2	297 ± 3	796 ± 4	1311 ± 6
Data	186	288	682	1156

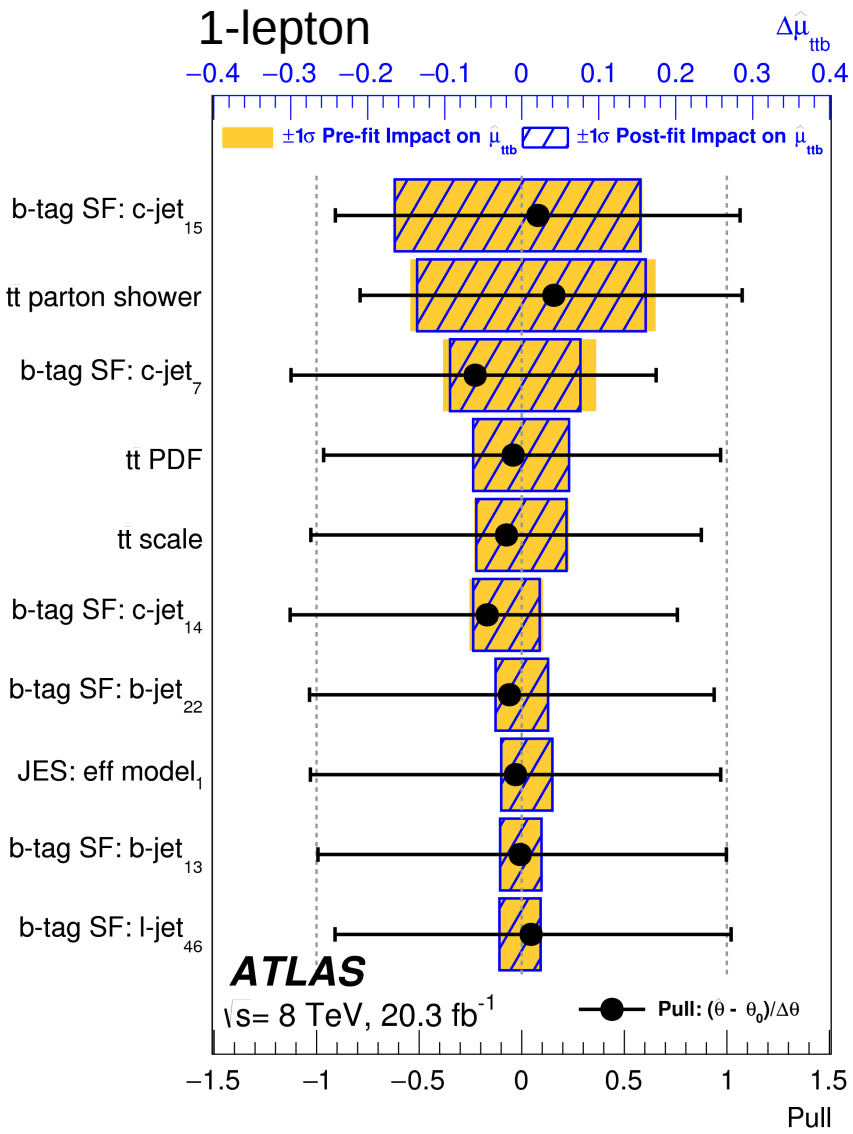
ttbb CMS 8 TeV and 13 TeV measurements: Fiducial definition at particle level

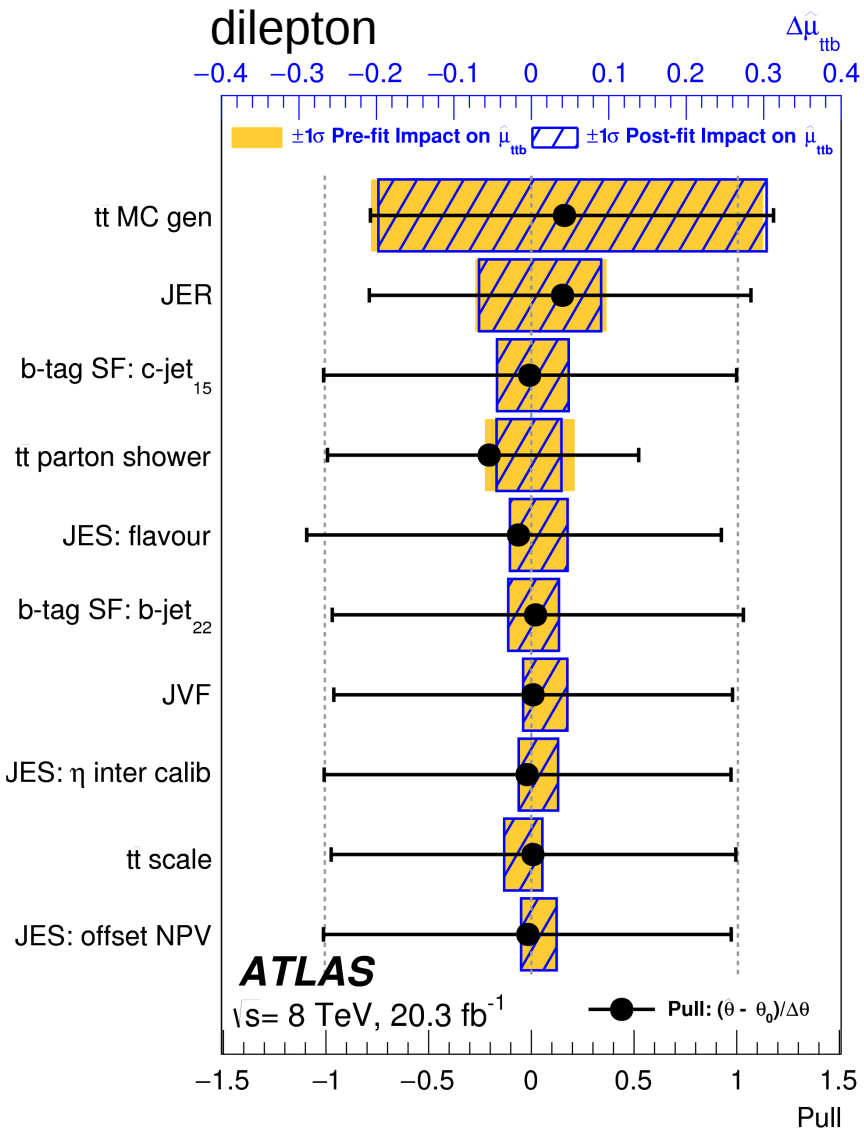
- Two isolated opposite-sign leptons (electron or muon)
  - → pT > 20 GeV, |eta| < 2.4
  - → ~~m(ll) > 12 GeV and for same-flavor pairs |m(ll) – m(Z)| > 15 GeV~~
- At least four jets anti-kt R = 0.5 (R = 0.4 at 13 TeV)
  - → pT > 20 GeV, |eta| < 2.5 (|eta| < 2.4 at 13 TeV)
  - → At least four b-jets
- ~~Missing ET > 30 GeV in same-flavor channels~~
- b-jets: b-hadron ghost association (13 TeV) (pT cut?) (8 TeV?)

ttb and ttbb ATLAS 8 TeV measurement: Systematics

Source	$\sigma_{ttb}^{\text{fid}}$ Lepton-plus-jets uncertainty (%)	$\sigma_{ttb}^{\text{fid}}$ *ttb eμ* uncertainty (%)	$\sigma_{ttbb}^{\text{fid}}$ Cut-based uncertainty (%)	$\sigma_{ttbb}^{\text{fid}}$ Fit-based uncertainty (%)	R_{ttbb} Fit-based uncertainty (%)
Total detector	+17.5 −14.4	+11.6 −8.0	±14.5	+11.9 −13.1	+10.9 −12.5
Jet (combined)	+3.9 −2.7	+10.1 −6.1	±5.5	+6.0 −8.5	+8.7 −10.7
Lepton	±0.7	+1.0 −0.5	±2.0	+2.4 −2.7	+0.8 −1.6
b−tagging effect on b−jets	+4.4 −4.0	+3.6 −3.1	±12.9	+9.4 −9.0	+6.0 −5.8
b−tagging effect on c−jets	+16.2 −13.4	+4.0 −3.6	±1.7	± 1.4	+1.2 −1.3
b−tagging effect on light jets	+3.1 −2.0	+1.9 −2.0	±4.3	+3.3 −2.9	+2.2 −1.9
Total $t\bar{t}$ modelling	+13.1 −13.7	+23.8 −16.1	±23.8	±21.7	±16.1
Generator	+1.1 −1.4	+23.3 −15.1	±16.9	±17.4	±12.4
Scale choice	±4.3	+1.1 −2.7	±14.2	±9.5	±6.0
Shower/hadronisation	+11.4 −12.1	+3.0 −3.4	±8.2	±8.7	±7.1
PDF	+4.7 −4.5	±3.3	±3.3	±0.8	±4.1
Removing/doubling $t\bar{t}V$ and $t\bar{t}H$	±0.4	+1.1 −0.9	±1.5	+3.1 −2.7	+3.0 − 2.6
Other backgrounds	±0.8	+0.9 −0.8	±1.6	+3.5 −3.3	±2.5
MC sample size	< 1	< 1	±9.6	±7.4	±7.4
Luminosity	±2.8	±2.8	±3.2	±2.9	±0.1
Total systematic uncertainty	+25.5 −19.2	+30.5 −19.9	±29.5	+26.4 −26.9	+21.1 −21.9
Statistical uncertainty	±7.1	+19.2 −17.9	±18.4	±24.6	±25.2
Total uncertainty	+26.5 −20.5	+36.0 −26.8	±35.2	+36.1 −36.4	+32.9 −33.4

ttb and ttbb ATLAS 8 TeV measurement: Systematics





ttbb CMS 8 TeV and 13 TeV measurements: Systematics

- Visible cross-section (pT > 20 GeV)

19 /fb, 8 TeV

Source	$\sigma_{t\bar{t}b\bar{b}}$ (%)	$\sigma_{t\bar{t}jj}$ (%)	$\frac{\sigma_{t\bar{t}b\bar{b}}}{\sigma_{t\bar{t}jj}}$ (%)
Pileup	1.0	1.0	1.0
JES & JER	11	8.0	5.0
b tag (b quark flavour)	15	<0.1	15
b tag (c quark flavour)	4.0	<0.1	4.0
b tag (light flavour)	7.0	<0.1	7.0
Ratio of $t\bar{t}b\bar{b}$ and $t\bar{t}bj$	9.0	<0.1	9.0
Bkgnd modelling	1.0	1.0	1.0
$t\bar{t}c\bar{c}$ fraction in the fit	4.2	0.2	4.0
Lepton identification	4.0	4.0	—
MC generator	3.0	3.0	3.0
Scale (μ_F and μ_R)	8.0	3.0	6.0
PS matching	12	5.0	3.0
PDF	4.0	4.0	<0.1
Eff. ($t\bar{t}c\bar{c}$ fraction)	—	1.6	1.6
Luminosity	2.6	2.6	—
Total uncertainty	28	12	22

2 /fb, 13 TeV

Source	$\sigma_{t\bar{t}b\bar{b}}$	$\sigma_{t\bar{t}jj}$	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Pileup	0.4	<0.1	0.4
JES & JER	7.8	7.4	2.6
b tag (b quark flavour)	19	4.7	19
b tag (c quark flavour)	14	1.3	14
b tag (light flavour)	14	9.8	9.7
Ratio of $t\bar{t}b\bar{b}$ and $t\bar{t}bj$	2.6	0.5	2.6
Background modelling	3.8	3.5	1.6
$t\bar{t}c\bar{c}$ fraction in the fit	5.2	1.9	4.8
Lepton trigger/identification	3.0	3.0	0
MC generator	9.4	6.2	3.0
μ_F and μ_R scale	2.0	2.0	1.0
scale in PS	13	9.9	10
PDFs	0.5	0.5	<0.1
Efficiency ($t\bar{t}c\bar{c}$ fraction)	0	1.3	1.3
Jet multiplicity modelling	5.0	5.0	5.0
Top quark p_T modelling	0.8	0.3	0.5
Simulation (statistical)	1.5	1.5	1.5
Integrated Luminosity	2.3	2.3	0
Total uncertainty	34	19	28

ttbb fiducial and full cross-sections 8 TeV and 13 TeV, CMS, dilepton channel

- 19.7 /fb at 8 TeV:

Phase Space (PS)	$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible PS (particle)			
Jet $p_T > 20\,GeV/c$	$0.029 \pm 0.003 \pm 0.008$	$1.28 \pm 0.03 \pm 0.15$	$0.022 \pm 0.003 \pm 0.005$
Full PS (parton)			
Jet $p_T > 20\,GeV/c$	$1.11 \pm 0.11 \pm 0.31$	$52.1 \pm 1.0 \pm 6.8$	$0.021 \pm 0.003 \pm 0.005$
Jet $p_T > 40\,GeV/c$	$0.36 \pm 0.08 \pm 0.10$	$16.1 \pm 0.7 \pm 2.1$	$0.022 \pm 0.004 \pm 0.005$
NLO calculation			
Jet $p_T > 40\,GeV/c$	0.23 ± 0.05	21.0 ± 2.9	0.011 ± 0.003

- 2.3 /fb at 13 TeV (Jet pT > 20 GeV):

Phase space		$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible	Measurement	$0.088 \pm 0.012 \pm 0.029$	$3.7 \pm 0.1 \pm 0.7$	$0.024 \pm 0.003 \pm 0.007$
	SM (POWHEG)	0.070 ± 0.009	5.1 ± 0.5	0.014 ± 0.001
Full	Measurement	$4.0 \pm 0.6 \pm 1.3$	$184 \pm 6 \pm 33$	$0.022 \pm 0.003 \pm 0.006$
	SM (POWHEG)	3.2 ± 0.4	257 ± 26	0.012 ± 0.001

- Measurement compatible with Powheg prediction
- Syst. ~ 30%

ttbb CMS 8 TeV differential cross-section: Event selection

- Two isolated opposite-sign leptons (electron or muon)
- Jets and leptons pT > 20 GeV, |eta|<2.4
- Jets anti-kt R = 0.5
- Jets from top quarks (after BDT selection) must fulfill pT > 30 GeV
- 3 b-tags at 70%
- Fiducial cuts at particle-level match the event selection cuts above (except b-tagging)