$t\bar{t}+b\bar{b}$ at ATLAS and CMS

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On behalf of the ATLAS and CMS collaborations

Outline

- Motivation
- State-of-the-art theoretical predictions
- Experimental approach
- Results
- Prospects

Latest experimental results:

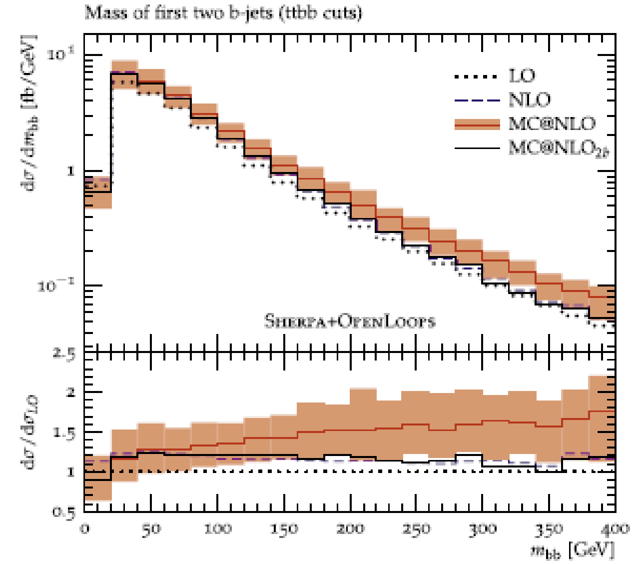
- ATLAS-CONF-2018-029 (July 2018): $\sqrt{s}$=13 TeV, L=36.1/fb
- CMS-TOP-16-010, published in Phys.Lett. B776 (2018) 355: $\sqrt{s}$=13 TeV, L=2.3/fb

Motivation

- Measurements of tt+jets (both inclusive and differential production cross-section) are an important test of QCD predictions
  - among these, tt+bb poses a particular challenge to QCD theory due to non-negligible mass of b-quarks
- ttH: direct measurement of Higgs coupling to the heaviest elementary particle – top quark, the crucial test of the Standard Model
  - dominant SM Higgs decay H→bb, largest statistics in the ttH→ttbb channel
  - ttH→ttbb suffers from large background from tt+b-jets, better understanding of ttbb is needed
- Various SM channels and BSM searches have tt+b-jets as their dominant background
  - four top production
  - gluino pair production GG→ttbb+MET
  - heavy charged Higgs production t(b)H^+, H^+→tb

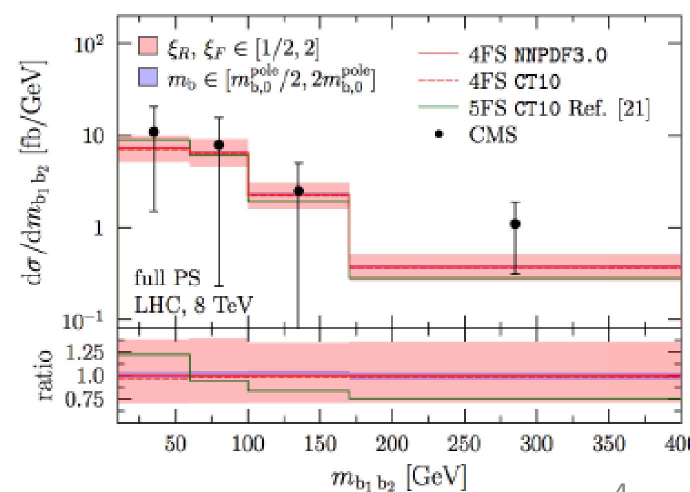
Theoretical predictions (1)

- Sherpa + OpenLoops (2014)
  - NLO ttbb, massive b, 4FS
  - cross-section uncertainties 20—40% (depending on fiducial cuts)
  - sensitive to g→bb in the parton shower



Phys. Lett. B734 (2014) 210

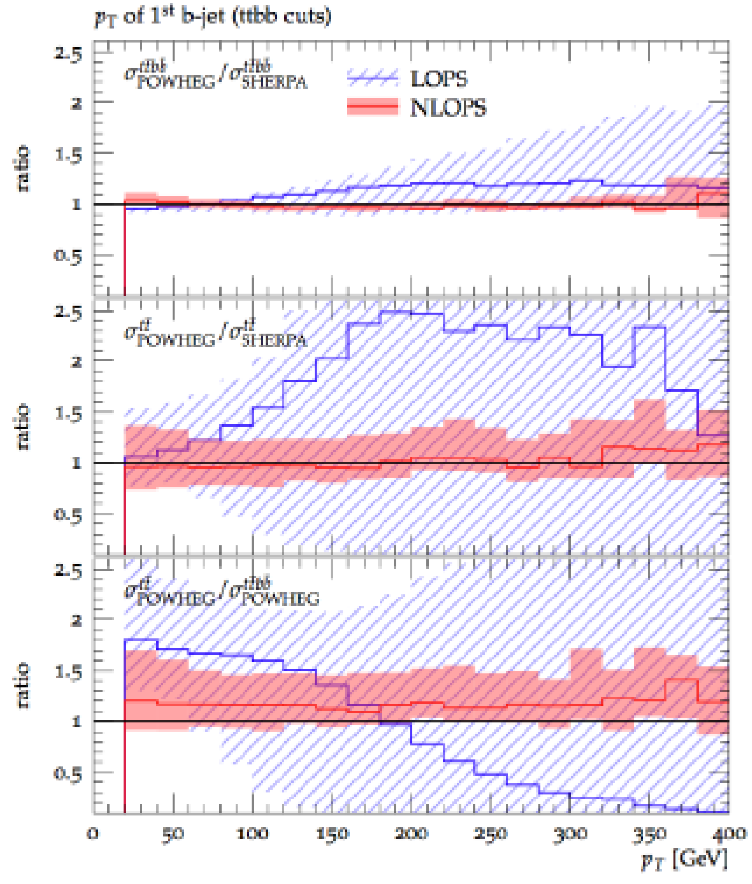
- PowHel + Pythia (Sep 2017)
  - NLO+PS, massive b, 4FS
  - found reasonable agreement with massless 5FS calculations
  - mass, PDF uncertainties shown to be small compared to scale uncertainty



arXiv: 1709.06915

Theoretical predictions (2)

- Powheg-Box (Feb 2018)
  - massive b, 4FS
  - matrix element computed with OpenLoops
- Confirmed findings of Sherpa studies:
  - tt+b-jet is dominated by final state g→bb splitting (both for two and one resolved b-jet)
  - scale uncertainties at fixed order NLO are 25—30%, dominated by renormalization scale variations
  - shower effects 10% in ttbb xs, 30% in m_{bb}, ΔR_{bb}



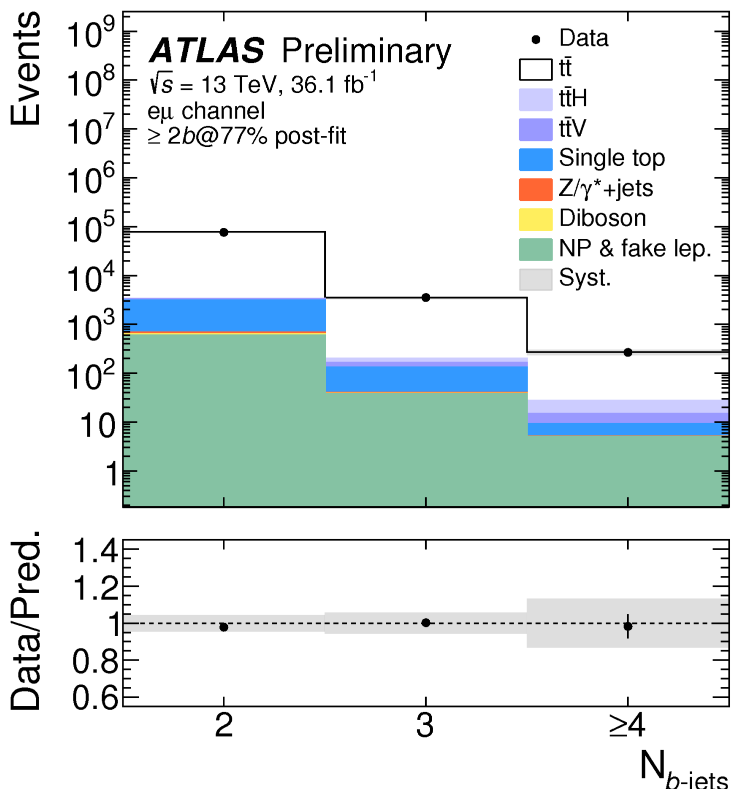
EPJ C78 (2018) no.6, 502

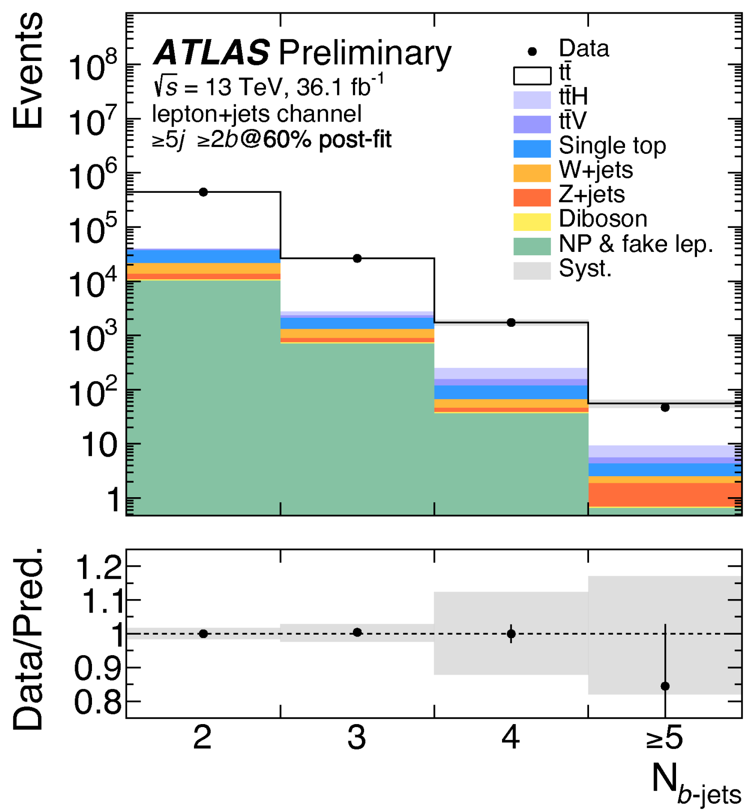
Experimental approach

- Select (reasonably) pure tt using double b-tagging
  - tt→dileptons+jets (ATLAS, CMS): pure but lower statistics tt→lepton+jets (ATLAS): better overall uncertainty, (in 50% of the cases) additional c from W decays
- Categorize events based on the number of b-tagged jets
- Construct the discriminating variable that is sensitive to additional HF
  - good candidates are third and fourth highest b-tagging weights (the output of the multivariate b-tag discriminant)
- Fit the distribution of discriminating variable in data to a weighted sum of simulated templates
  - extract the number of tt+b, tt+c, tt+light events and convert it to production cross-section

Preselection, ATLAS

- dileptons (eμ only): exactly one e and one μ of opposite charge, ≥2 jets, ≥2 b-tagged (ε_b=77%) jets
- l+jets: exactly one e or μ, ≥5 jets, ≥2 b-tagged (ε_b=60%) jets

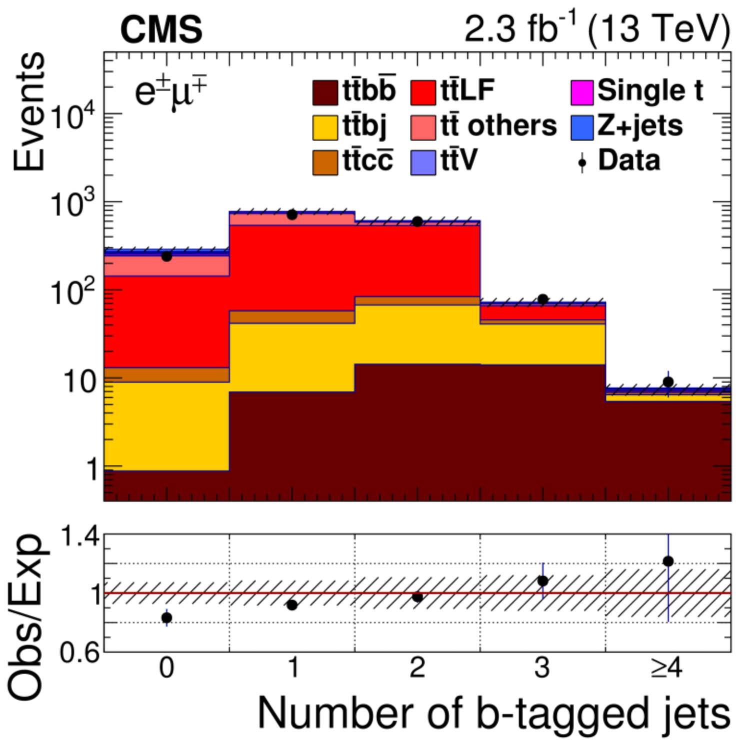


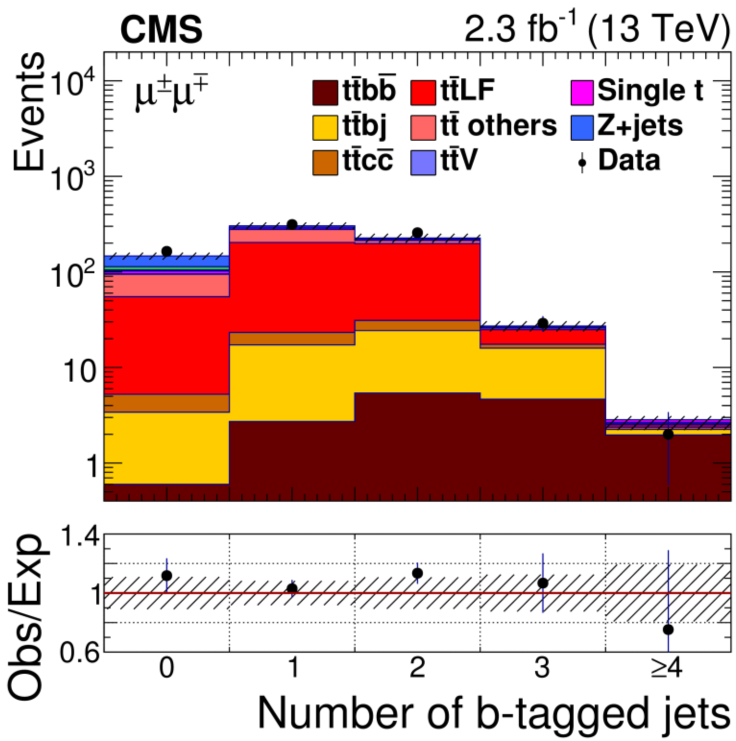


ATLAS-CONF-2018-029

Preselection, CMS

- ee/μμ: two leptons, of opposite charge, $|m_{ll}-m_Z|>15$ GeV, $p_T^{miss}>30$ GeV
- eμ: exactly one e and one μ of opposite charge
- ≥4 jets, ≥2 b-tagged (ε_b~60--70%) jets





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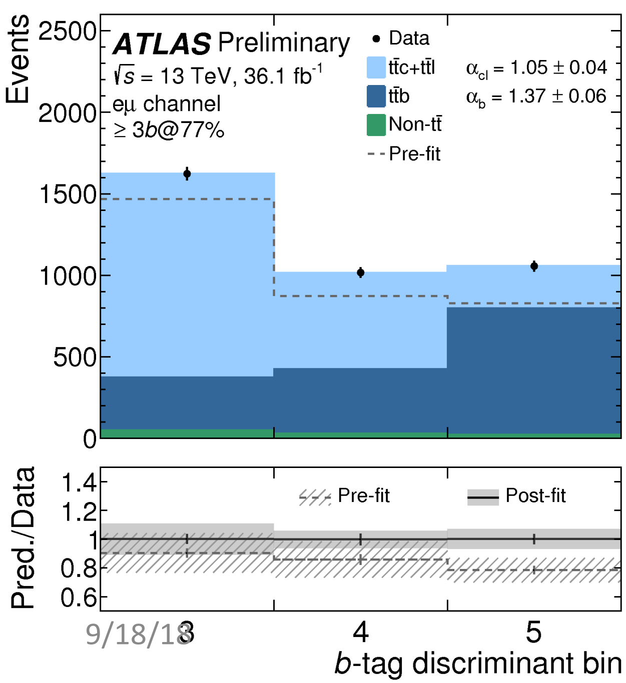
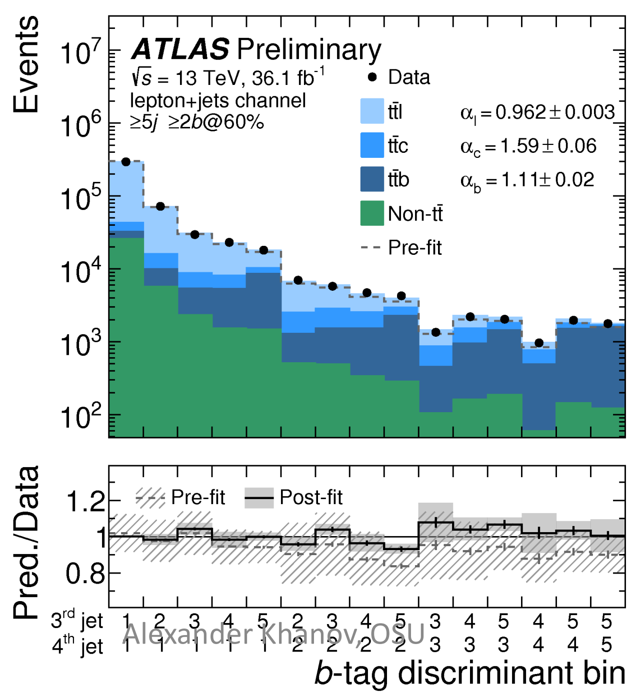
tt+bb extraction, ATLAS

- Consider 5 b-tagging discriminant bins with average b-tagging efficiencies of 100—85%, 85—77%, 77—70%, 70—60%, <60%
- 1D fit using 3rd b-jet discriminant for dileptons, 2D fit using 3rd and 4th b-jet discriminants for l+jets
- MC events are categorized based on the number of particle level b/c-jets: ttb: ≥3b, ttc: <3b+≥1c (eμ), <3b+≥2c (l+jets), ttl: everything else

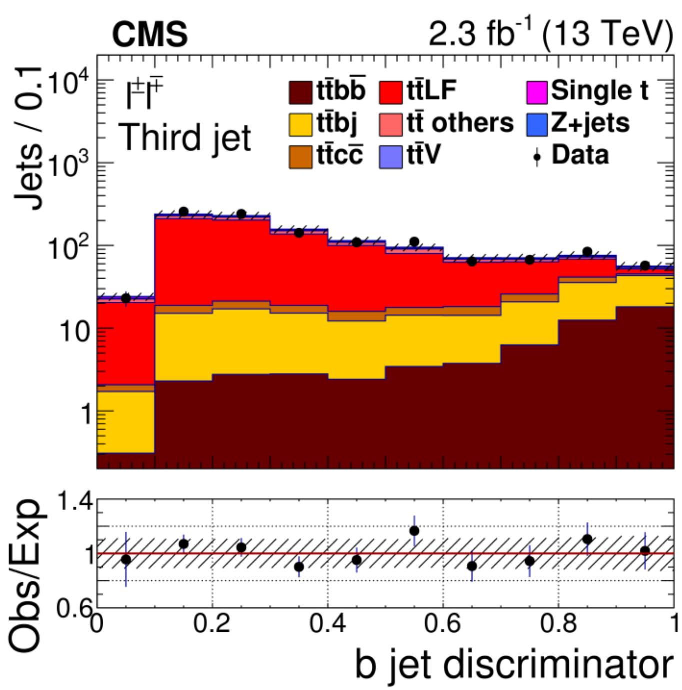


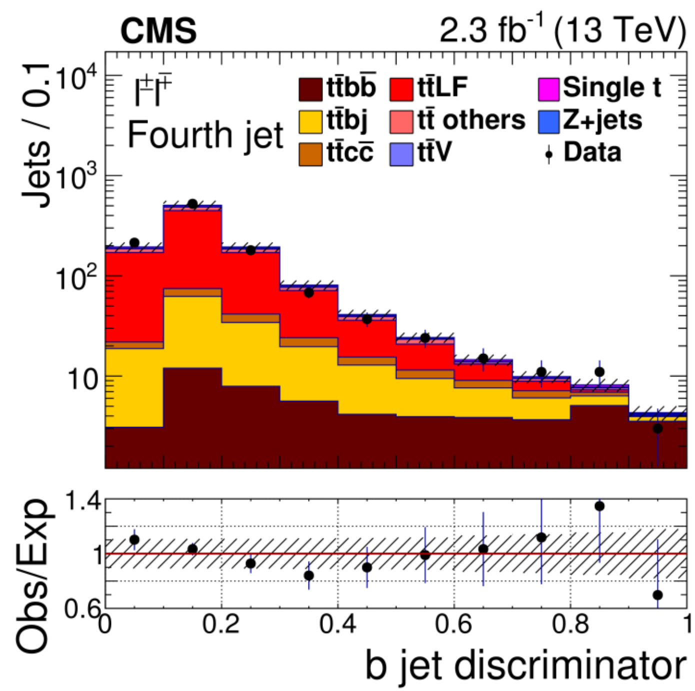


- eμ: combine c and light
- l+jets: fit b/c/l separately

tt+bb extraction, CMS

- 2D fit using b-jet discriminators for 3rd and 4th jets
- MC events are categorized as ttbb/ttcc/ttbj/ttLF based on the number of particle level b/c- jets in addition to the two b-jets from top decays
- For the fit, combine c and light flavor (too similar to discriminate) and constrain ttbb/ttbj from MC





Results

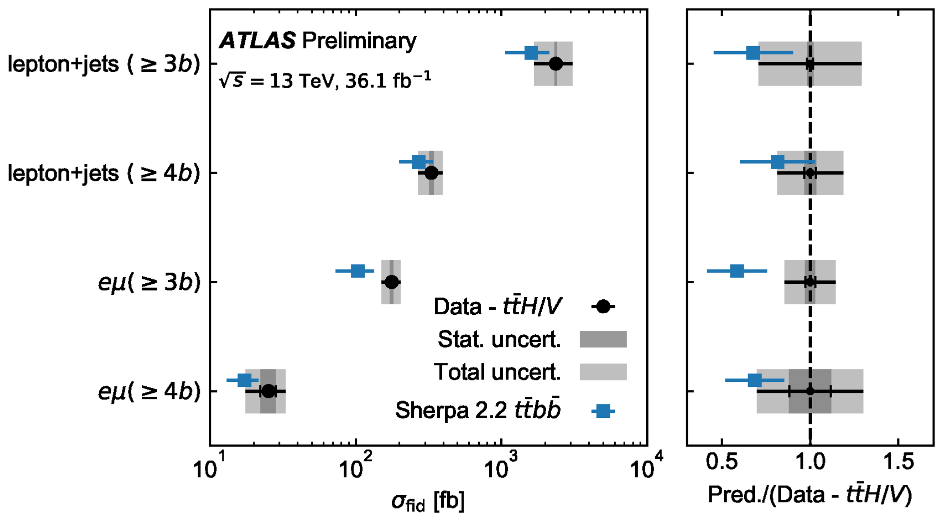
- ATLAS: report fiducial cross-sections: measured distributions are unfolded to the particle level to correct for detector resolution / efficiency / acceptance
  - avoid unfolding to parton level (identifying the origin of b-jets) as this may lead to significant modeling uncertainties
  - also report differential unfolded distributions: b-jet multiplicity, H_T, H_T^{had}, jet p_T, m_{bb}, p_T^{bb}, ΔR_{bb} for two highest p_T b-jets and two closest b-jets
- CMS: report cross-sections in both visible and full phase space
  - the latter to facilitate comparisons to NLO calculations or between different decay channels
  - also report the $\sigma_{ttbb}/\sigma_{ttjj}$ ratio

Results, ATLAS (1)

- Fiducial cross-sections:

Channel	analysis	measured cross-section [fb]
lepton + jets	$\sigma_{t\bar{t}+\geq 1b}$	2450 ± 40 (stat) $\pm$ 690 (syst)
lepton + jets	$\sigma_{t\bar{t}+\geq 2b}$	359 ± 11 (stat) $\pm$ 61 (syst)
$e\mu$	$\sigma_{t\bar{t}+\geq 1b}$	181 ± 5 (stat) $\pm$ 24 (syst)
$e\mu$	$\sigma_{t\bar{t}+\geq 2b}$	27 ± 3 (stat) $\pm$ 7 (syst)

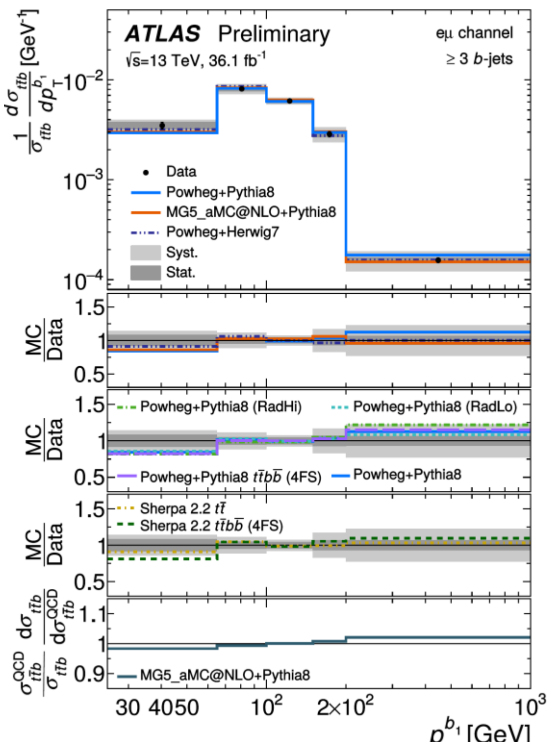
Dominant systematic uncertainties: MC modeling, b-tagging, jet energy scale



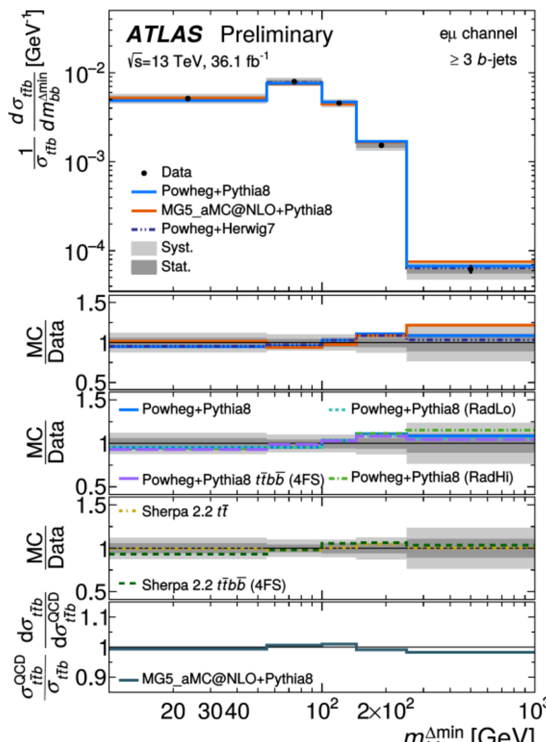
Comparison to Sherpa+OpenLoops, uncertainties due to varying renormalization and factorization scales by x 0.5—2 and PDF uncertainties, ttH/ttV subtracted from data

Results, ATLAS (2)

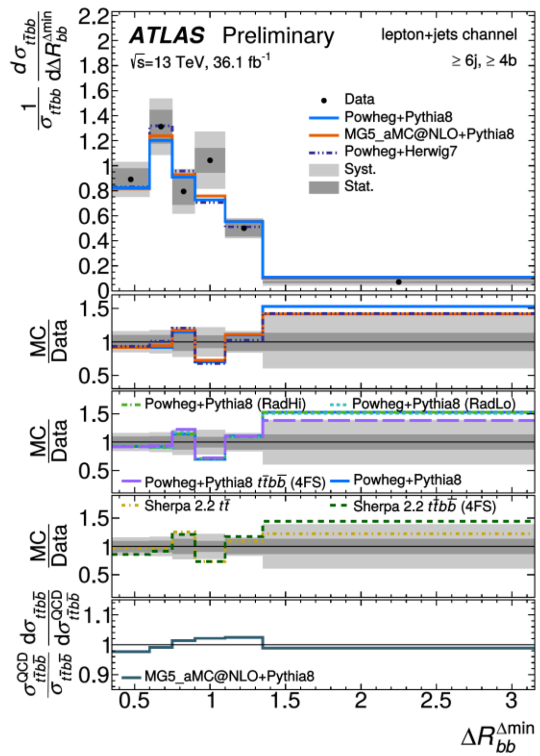
- Example: differential cross-sections vs leading jet p_T and m_{bb}, ΔR_{bb} for two closest b-jets
  - note that for events with 3 b-jets, one or both of the two closest b-jets may come from top decays



leading b-jet p_T



m_{bb} of closest b-jets



ΔR_{bb} of closest b-jets

Results, CMS

- Visible and full phase space results:

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

  - Leading systematic uncertainties: MC modeling, b-tagging, jet energy scale
  - Total systematic uncertainty: 34% (σ_{ttbb}), 19% (σ_{ttjj}), 28% (the ratio)
  - The $\sigma_{ttbb}/\sigma_{ttjj}$ results for visible and full phase space are consistent and have similar stat/syst uncertainties

Systematic uncertainties

Source	Fiducial cross-section phase space $e\mu$ $\geq 3b$ unc. (%)	$e\mu$ $\geq 4b$ unc. (%)	lepton + jets $\geq 5j, \geq 3b$ unc. (%)	lepton + jets $\geq 6j, \geq 4b$ 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
Pileup	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

ATLAS

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 identification	3.0	3.0	–
MC generator	9.4	6.2	3.0
Q^2 scale	2.0	2.0	1.0
scale in PS	13	9.9	10
PDF	0.5	0.5	< 0.1
Efficiency ($t\bar{t}c\bar{c}$ fraction)	–	1.3	1.3
Top p_T modeling	0.8	0.3	0.5
Luminosity	2.7	2.7	–
Total uncertainty	34	19	28

CMS

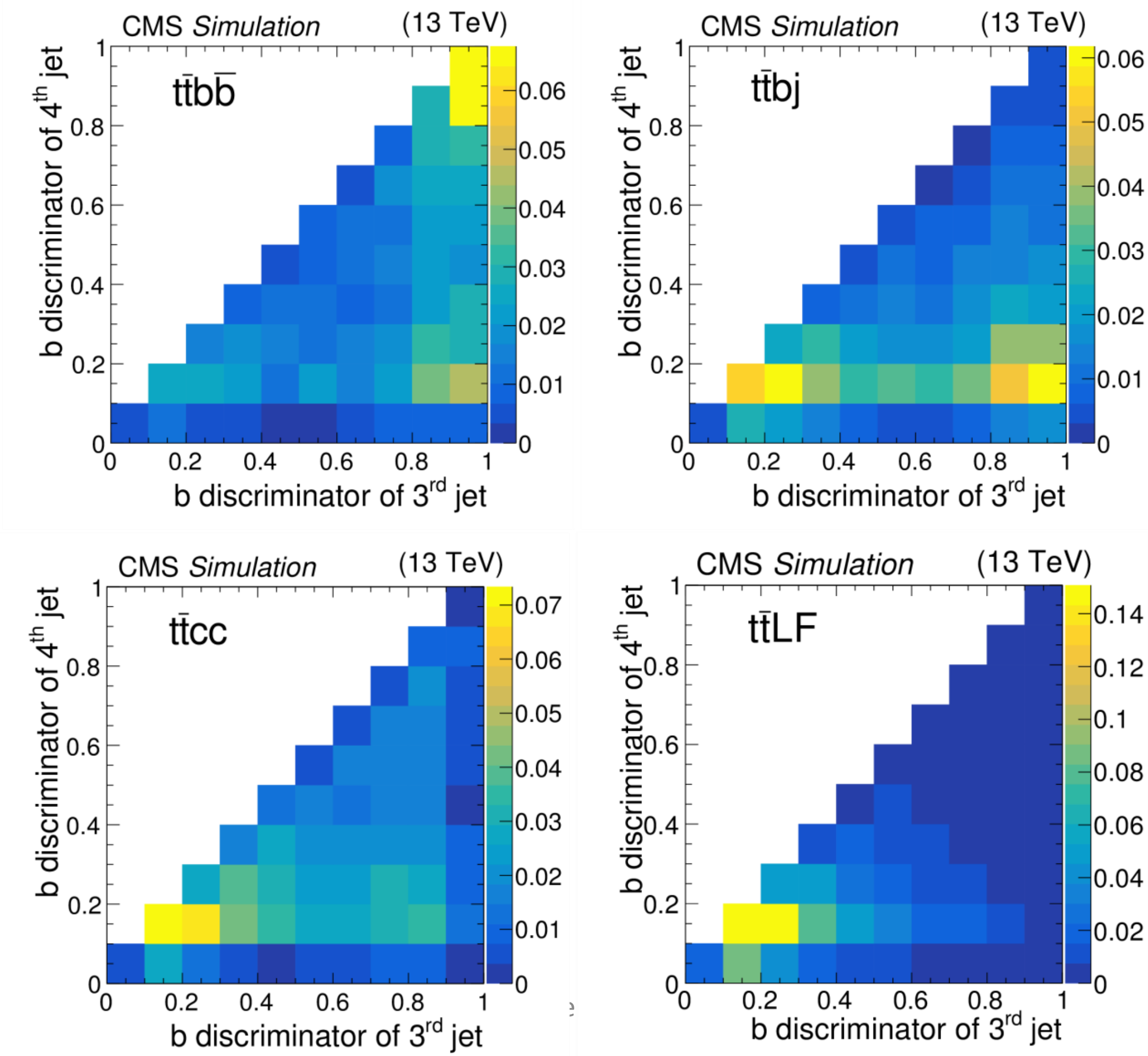
➡ main uncertainties
➡ reduced in the ratio

Summary

- Measurements of tt+bb are important and need to be better understood
- At the current theoretical level of understanding, the experimental results are already competitive in terms of uncertainties
- Main experimental systematic uncertainties are MC modeling, b-tagging, and jet energy scale, all of those very challenging
- Starting to put together a survey of differential distributions to be fed back to theory
- Need to think of best ways to present the results, e.g. discriminate between b-jets from top and non-top (done by CMS for 8 TeV)
- Combined measurement of ttbb / ttcc / ttc is another challenge

Backup

tt+bb extraction, CMS: 2d templates



Definitions of fiducial/visible space

- ATLAS: definition of fiducial volume in terms of particle level objects:
  - eμ: exactly one e and one μ + ≥3 (≥4) b-jets for $\sigma_{tt+\geq 1b}$ ($\sigma_{tt+\geq 2b}$)
  - l+jets: exactly one e or μ + ≥5 (≥6) jets + ≥3 (≥4) b-jets for $\sigma_{tt+\geq 1b}$ ($\sigma_{tt+\geq 2b}$)
  - both leptons and jets have $|\eta|<2.5$, $p_T>25$ GeV
- CMS: definition of visible space in terms of particle level objects:
  - exactly two leptons (e/μ), ≥4 jets + ≥2 b-jets
  - leptons: $p_T>20$ GeV, $|\eta|<2.4$, jets: $p_T>20$ GeV, $|\eta|<2.5$
- For both experiments, b/c-jets are defined using B/C-hadron ghost matching

Differential cross-sections: CMS, 8 TeV

- Eur. Phys. J. C 76 (2016) 379
- MC: MadGraph+Pythia