Recent results on tt+jets, tt+V, and tt+tt cross sections

TOP@20 conference

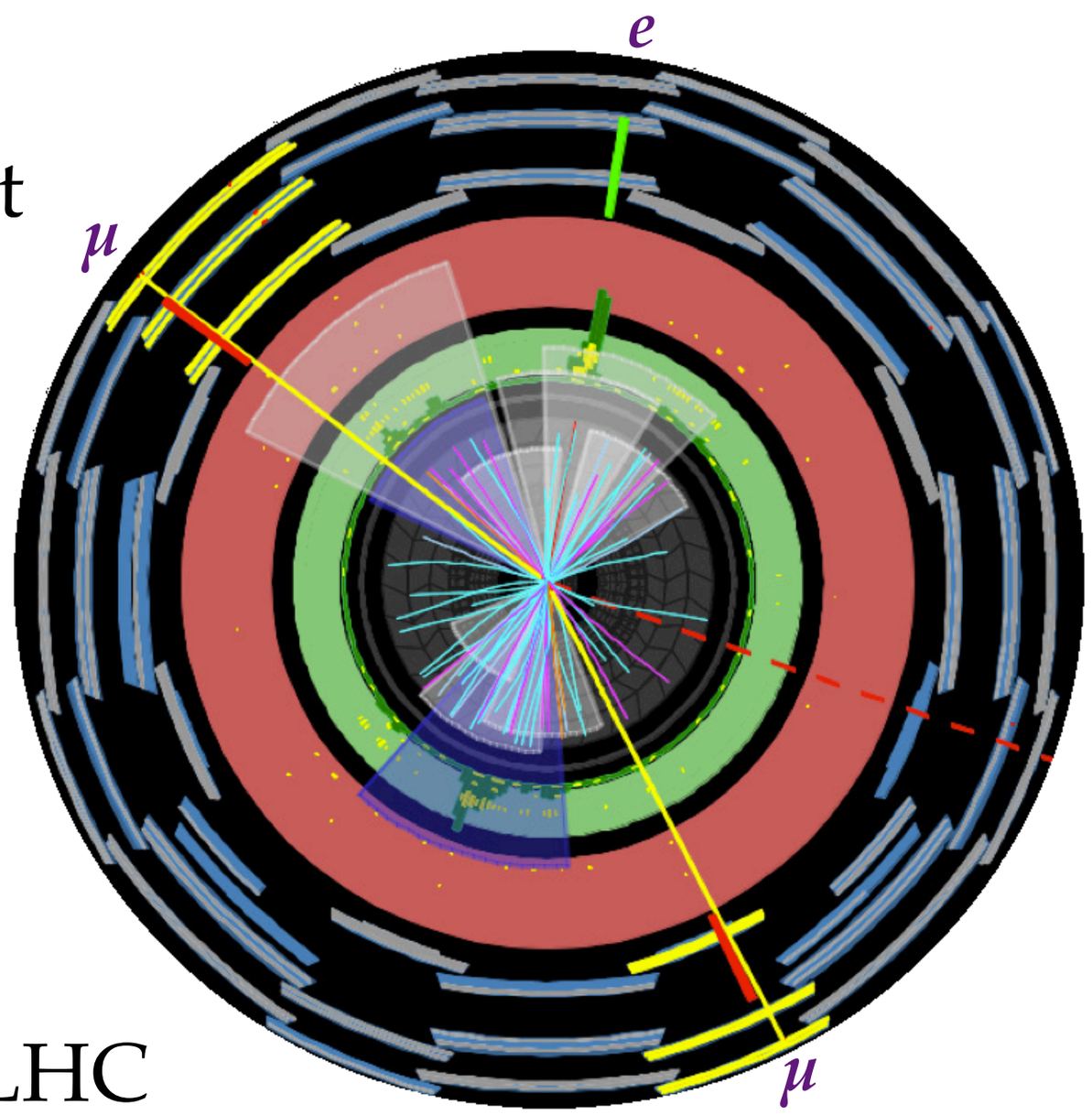
April 9, 2015

Andrew Brinkerhoff

UNIVERSITY OF NOTRE DAME

Outline

- Motivation: why study tt+X?
- Measurements and searches at CMS and ATLAS
  - tt+jets
  - tt+heavy flavor jets
  - ttW and ttZ
  - Four top (tt+tt)
- Prospects: tt+X at the 13 TeV LHC

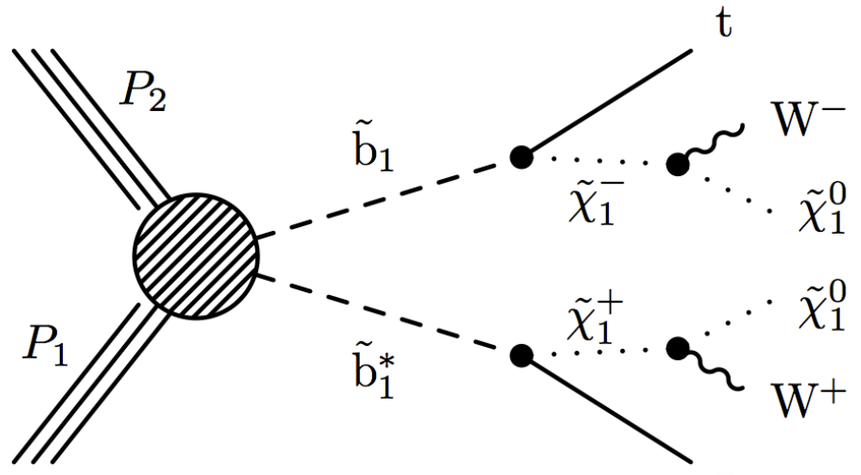


ttZ candidate event at 7 TeV in ATLAS

ATLAS-CONF-2012-126

tt+X and new physics

- Many new physics models would produce tt+X final states (e.g. SUSY)
- Other models enhance production of SM tt+X final states through new couplings (e.g. dimension-six operators)



Bottom-squark pair production
10.1007/JHEP01(2014)163

$$C_{1,V} = C_V^{SM} + \frac{v^2}{\Lambda^2}\mathrm{Re}[\bar{c}'_{HQ} - \bar{c}_{HQ} - \bar{c}_{Hu}]$$

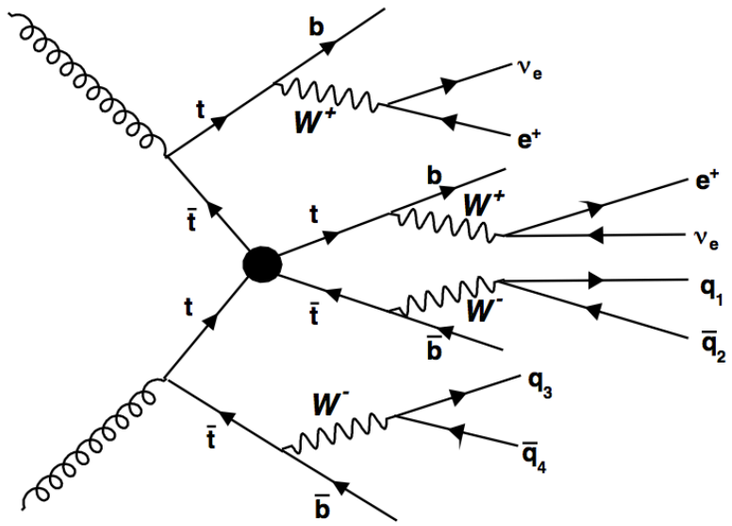
$$C_{1,A} = C_A^{SM} + \frac{v^2}{\Lambda^2}\mathrm{Re}[\bar{c}'_{HQ} - \bar{c}_{HQ} + \bar{c}_{Hu}]$$

Dimension-six operators contributing to ttZ production
Röntsch and Schulz, arxiv.org/abs/1404.1005

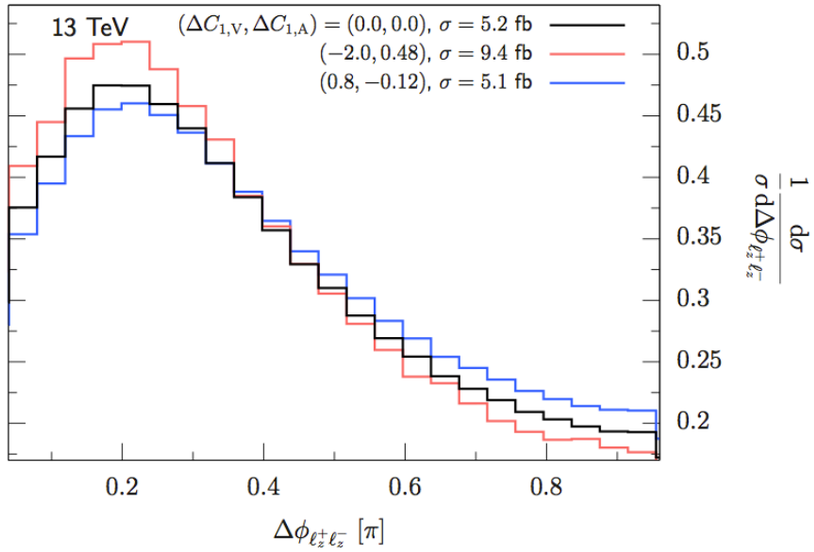
tt+X and event modeling

- A test and verification of applied theory and MC techniques for strongly interacting, high-object-multiplicity events
  - tt+bb has 43 LO, ~1200 NLO diagrams [1]
  - tt+tt produces 4 - 12 high p_T jets
- Look for <u>any</u> deviation from SM: lepton p_T/distribution, number of jets and b-tags, missing energy spectrum
  - Lepton separation in ttZ events measures vector vs. axial coupling

[1] Bredenstein et. al., <u>10.1103/PhysRevLett.103.012002</u>



Final state with four top quarks
<u>ATLAS-CONF-2012-130</u>



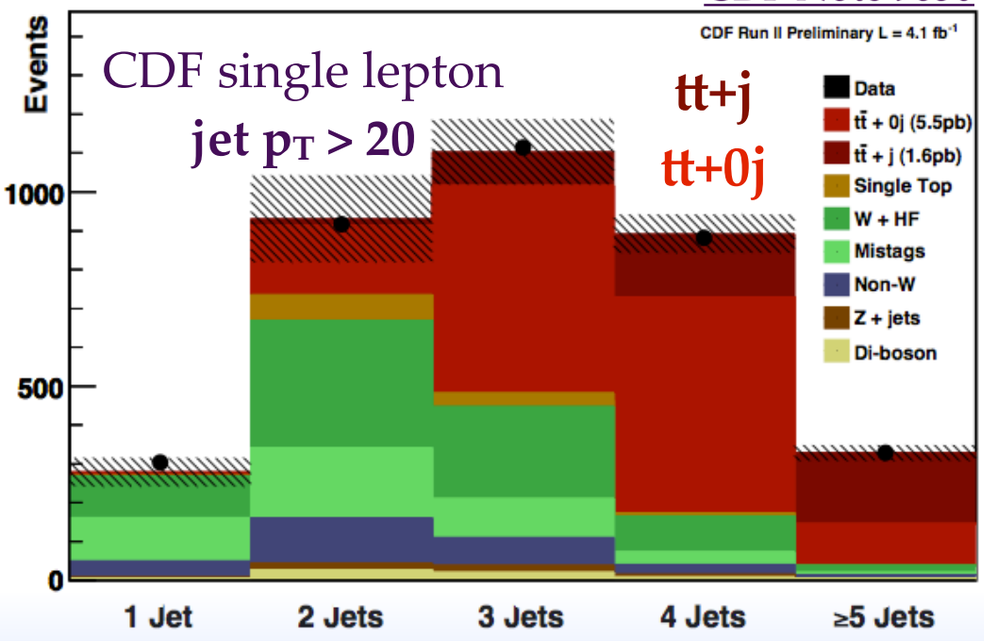
Separation between leptons in ttZ for SM and dim. six scenarios
<u>Röntsch and Schulz, arxiv.org/abs/1404.1005</u>

tt+jets

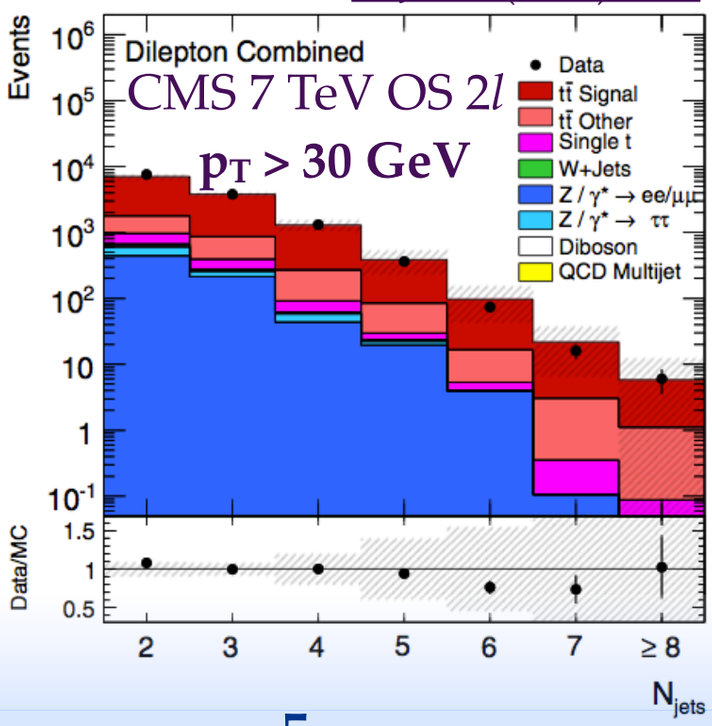
- CDF (2 TeV), ATLAS (7 TeV) and CMS (7/8 TeV) made cross section measurements as a function of number of jets in single lepton and opposite-sign (OS) dilepton tt+jets events
  - tt with multiple extra jets a background to many SM and NP tt+X processes
  - Unfold various distributions (jet multiplicity, extra jet p_T, gap fraction) and compare to MC generators (ALPGEN, MADGRAPH, MC@NLO, POWHEG) with different treatments of higher-order corrections

tt+2j
tt+1j
tt+0j

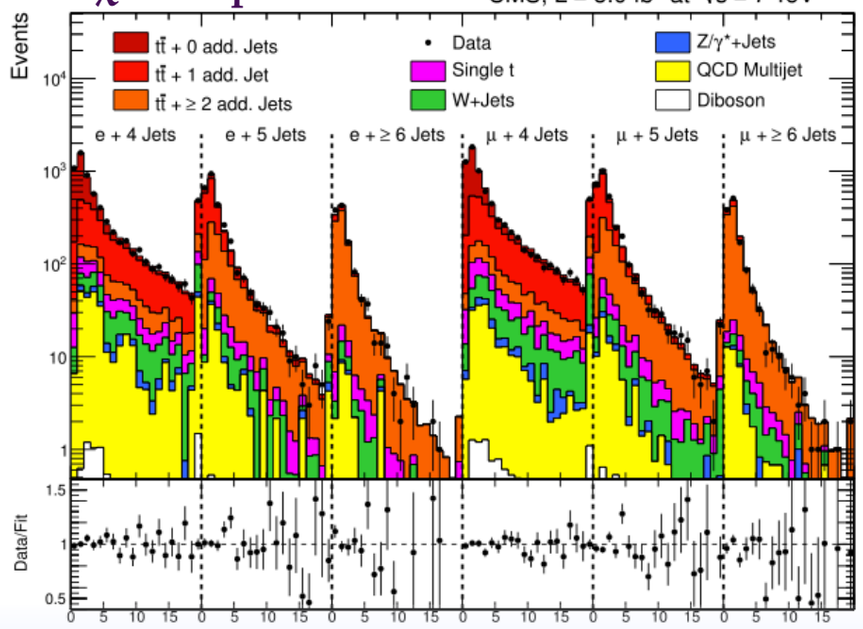
CDF Note 9850



EPJ C74 (2014) 3060



CMS 7 TeV single lepton
$|\chi|$ to top/W mass fit



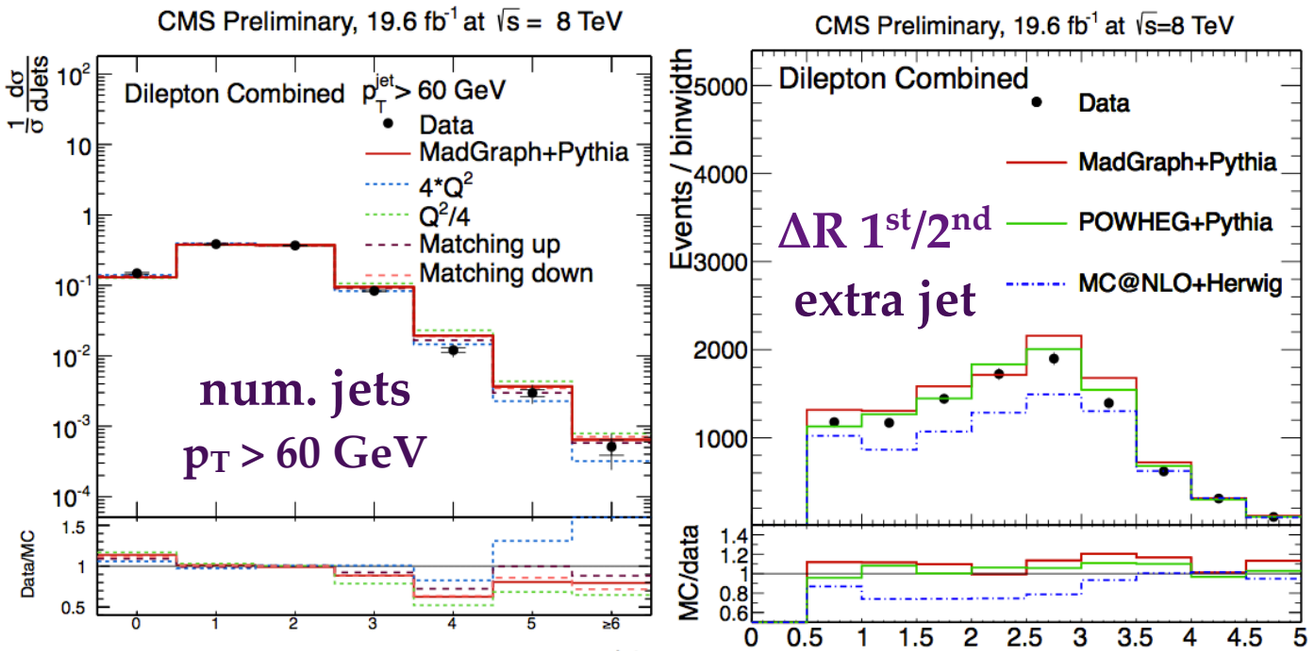
EPJ C74 (2014) 3060

$\sqrt{\chi^2}$

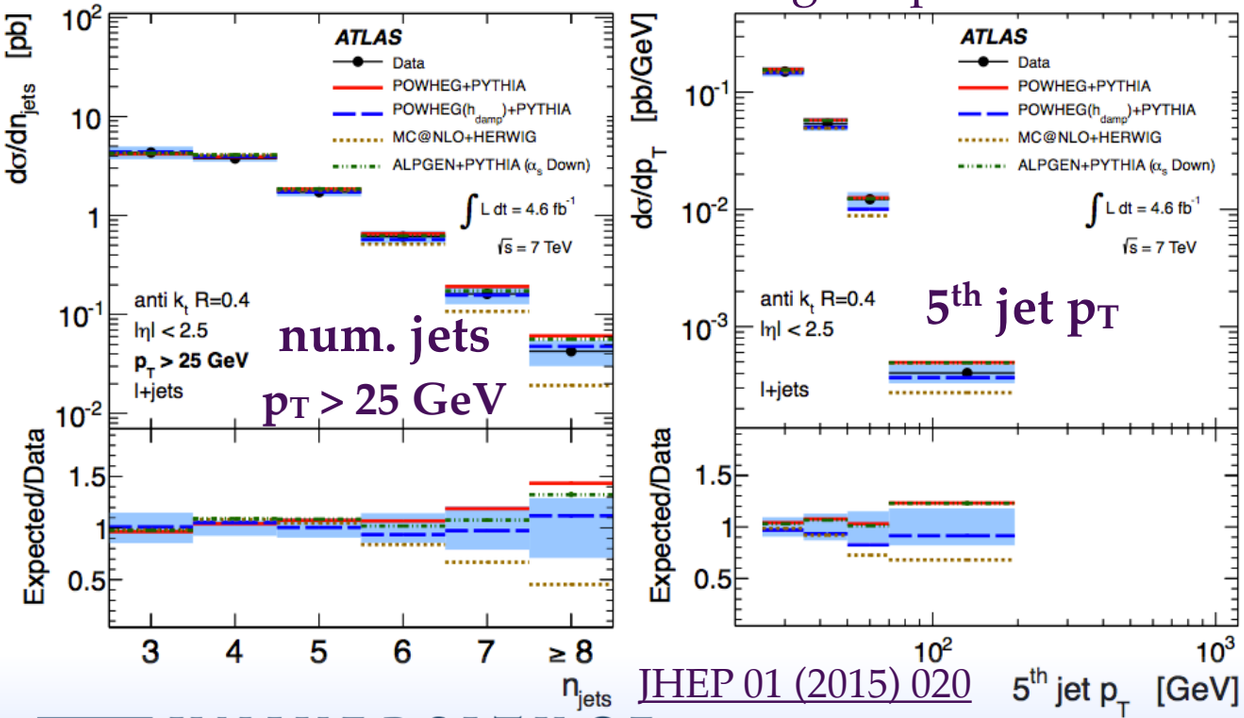
tt+jets

- Gap fraction: fraction of events without extra jet(s) above a p_T (Σp_T) threshold
- Uncertainties primarily from jet energy scale and Q^2/matching/hadronization scale

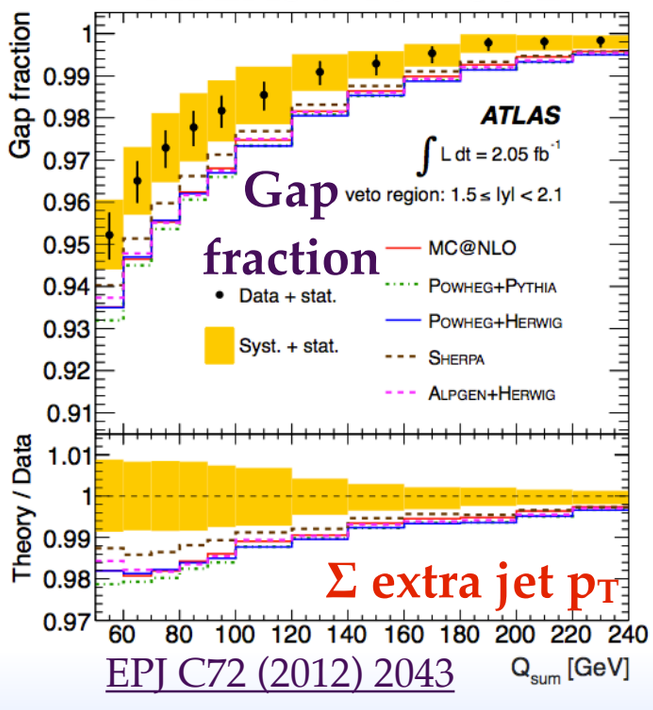
CMS 8 TeV OS 2*l* — CMS PAS TOP-12-041



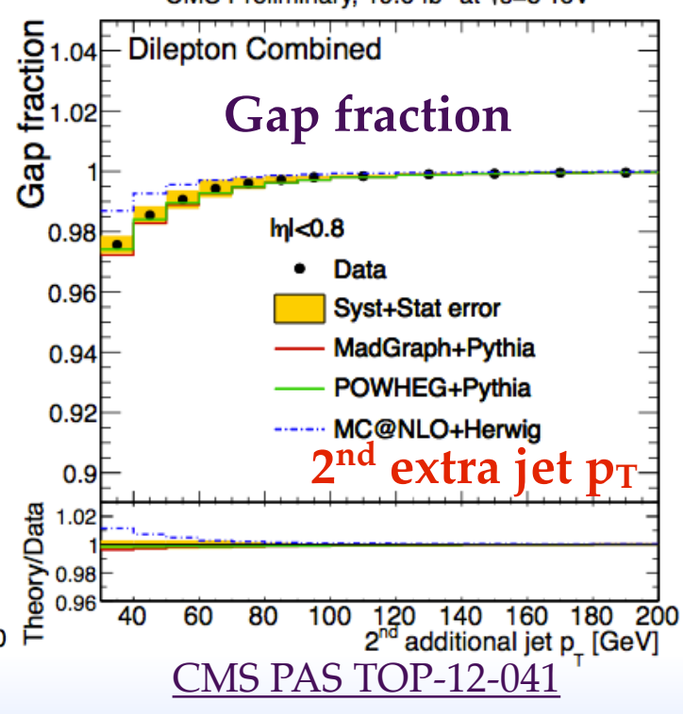
ATLAS 7 TeV single lepton — JHEP 01 (2015) 020



ATLAS 7 TeV OS 2*l* — EPJ C72 (2012) 2043



CMS PAS TOP-12-041

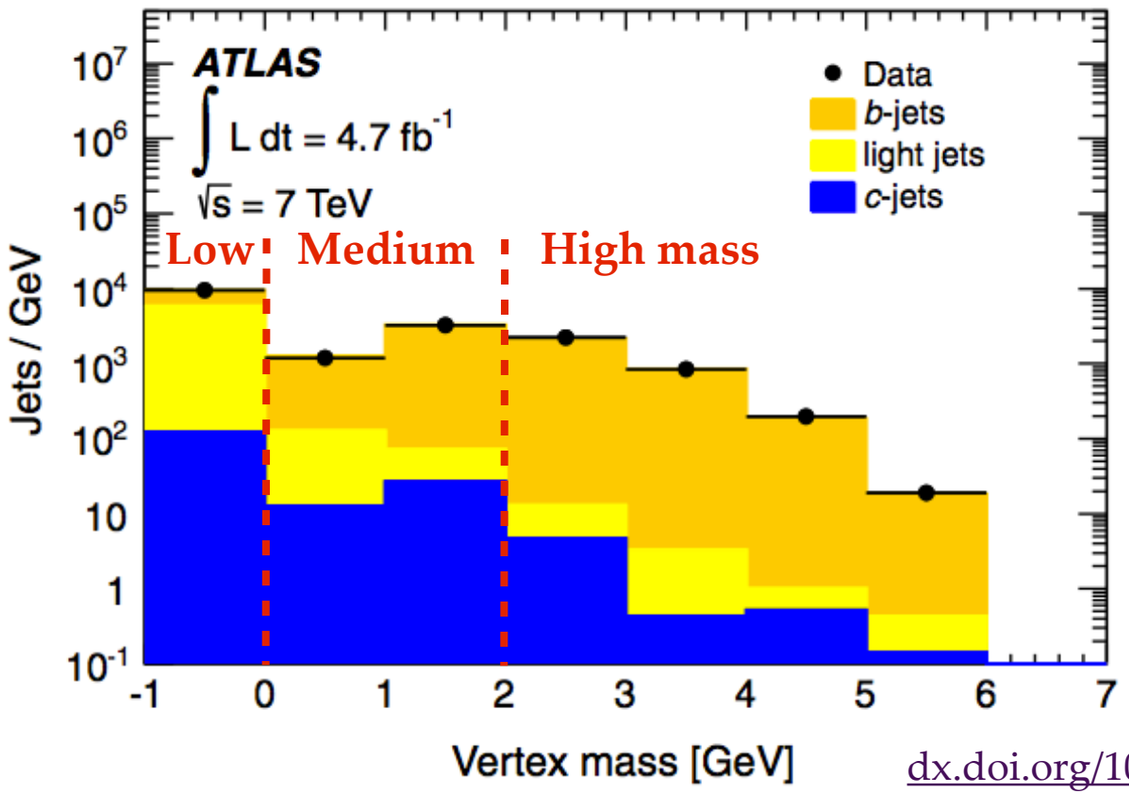


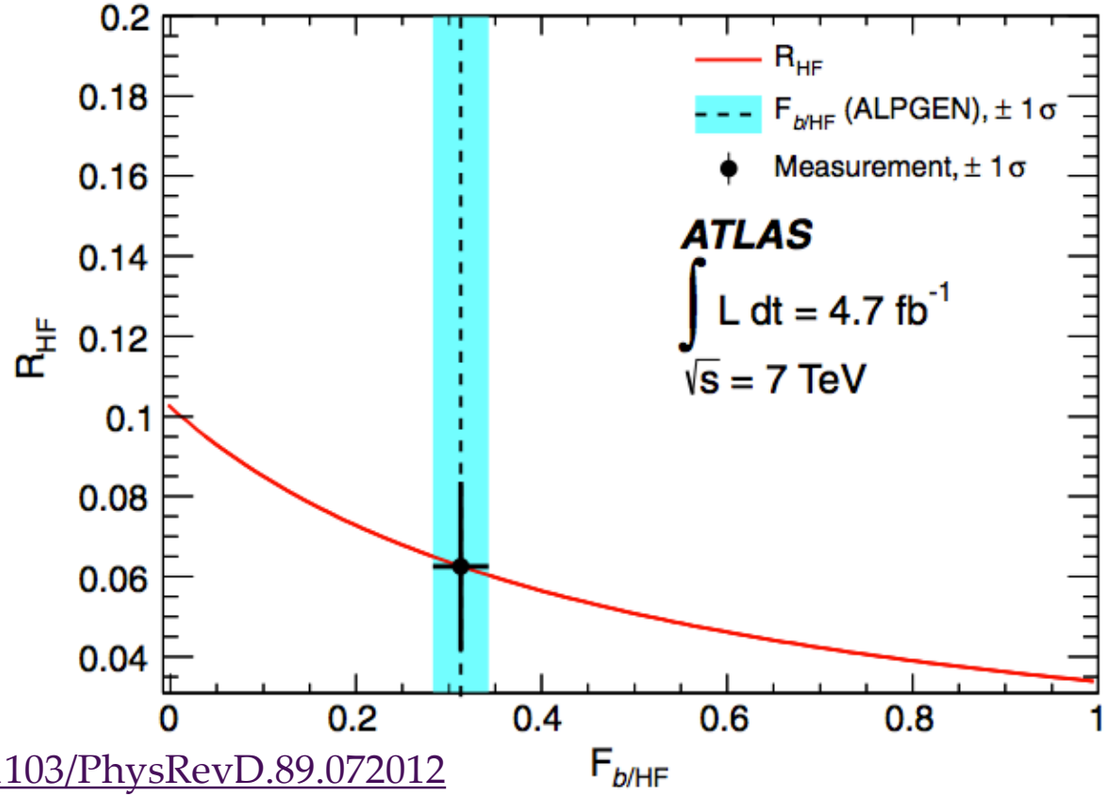
tt+heavy flavor

- ATLAS (7 TeV) and CMS (8 TeV) have both made measurements in OS dilepton tt events
- ATLAS defines tt+HF (tt+b and tt+c) as events having at least one extra bottom or charm jet
  - Jets from bottom and charm quarks with $p_T(\text{quark}) > 5$ GeV, $dR(\text{quark, jet}) < 0.25$
  - Uses events with ≥ 3 jets to measure $R_{HF} =$ tt+HF/tt+jets
- CMS separates tt+bb, tt+b, tt+cc, and tt+LF (tt+jj)
  - "Full phase space" jets from bottom and charm quarks with $dR(\text{quark, jet}) < 0.5$
  - "Visible" jets have $p_T > 20$ GeV and $|\eta| < 2.5$, contain b or c hadron daughters
  - Use events with ≥ 4 jets to measure $R_{HF} =$ tt+bb/tt+jets, σ_{tt+jj} and σ_{tt+bb}

tt+b/c: ATLAS 7 TeV

- Use secondary vertex MVA to divide high/med./low purity b-jet samples, then fit high/med./low vertex mass to data
- $R_{HF} = R_{b/c} =$ (tt+b + tt+c)/tt+jets = 6.2 ± 1.1 (stat) ± 1.8 (syst) %
  - Assumes that $F_{b/HF}$ = tt+b/(tt+b + tt+c) = 0.31 ± 0.03 (Alpgen/Powheg)





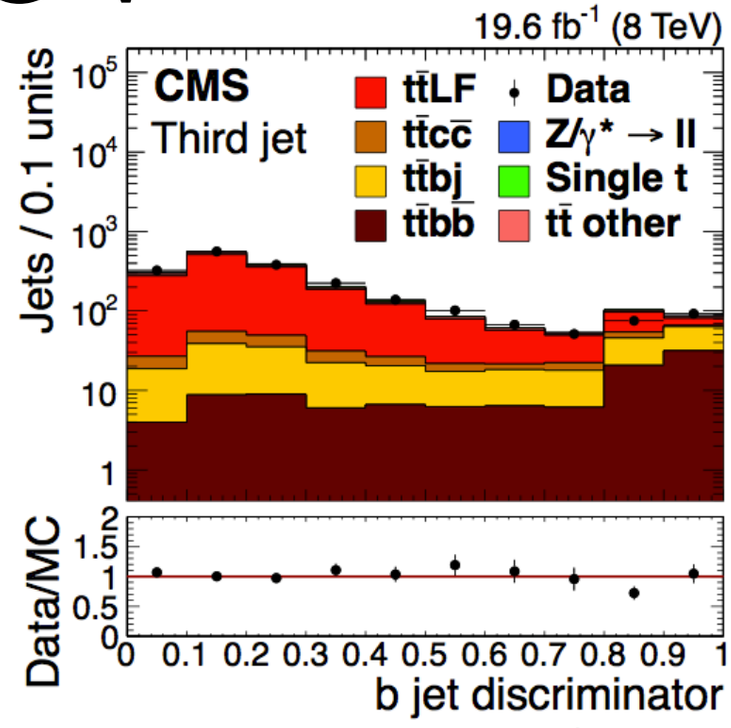
dx.doi.org/10.1103/PhysRevD.89.072012

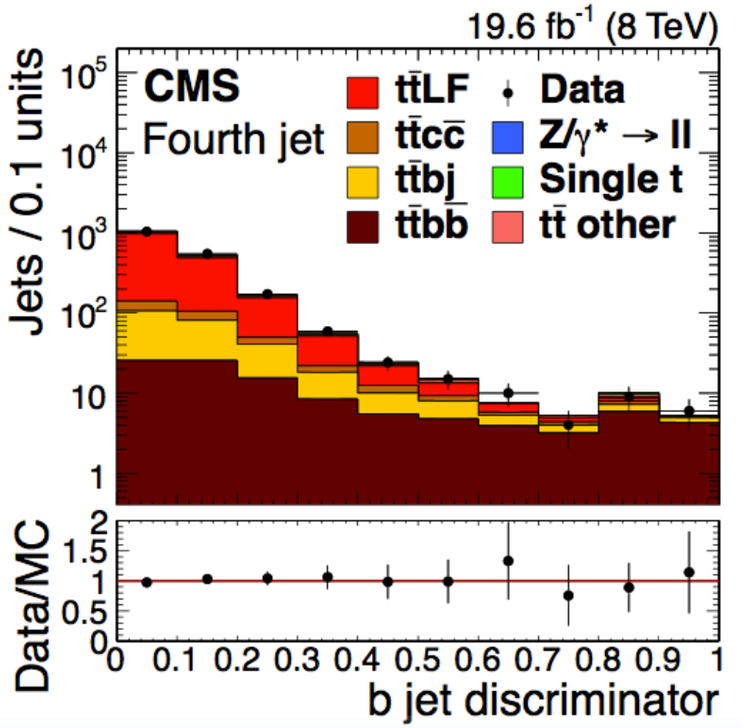
tt+bb: CMS 8 TeV

- Simultaneous fit of 3rd and 4th lowest jet CSV (secondary vertex MVA) values, allowing σ_{tt+jj} and $R_{bb} = $ tt+bb / tt+jj to float
  - tt+b rate tied to tt+bb, tt+cc combined with tt+LF, but given separate 50% uncertainty

Full phase space		
	$p_T > 20$ GeV	$p_T > 40$ GeV
σ_{tt+jj}	52.1 ± 1.0 ± 6.8 pb	16.1 ± 0.7 ± 2.1 pb
σ_{tt+bb}	1.11 ± 0.11 ± 0.31 pb	0.36 ± 0.08 ± 0.1 pb
R_{bb}	2.2 ± 0.3 ± 0.5%	2.2 ± 0.4 ± 0.5%
R_{bb} (NLO)	1.6 ± 0.2%	1.1 ± 0.3%

- Also measured R_{HF}, σ_{tt+jj}, and σ_{tt+bb} for visible phase space only

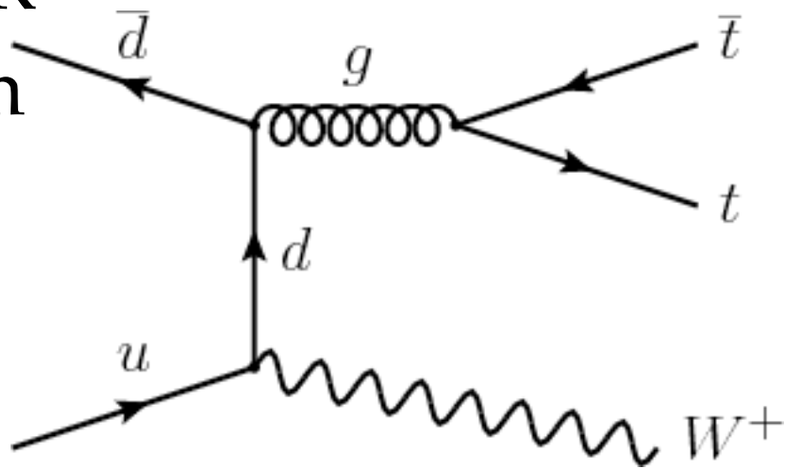




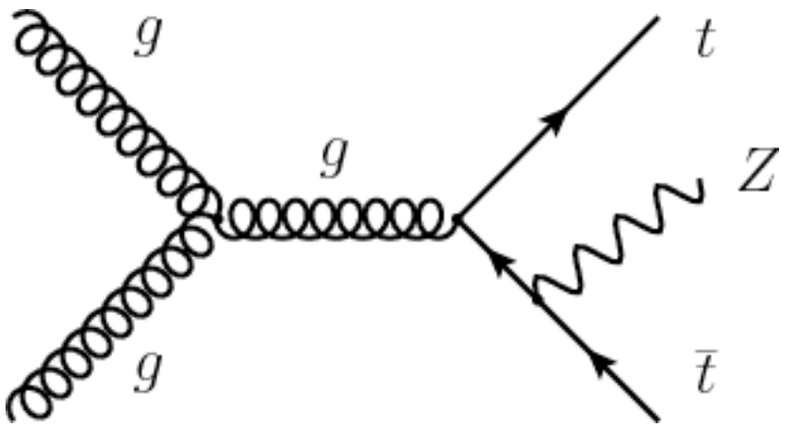
arxiv.org/abs/1411.5621

ttW and ttZ

- Different SM processes - associated W is ISR (not coupled to top), Z can be radiated from top quark and measures top-Z coupling



- ATLAS and CMS have made ttZ measurements at 7 TeV and ttW and ttZ measurements at 8 TeV
  - ATLAS measures in OS dilepton, SS $\mu\mu$, and 3l
  - CMS measures in SS dilepton, 3l, and 4l
- Main backgrounds are Z+jets and tt+jets (with prompt and non-prompt leptons), WZ, and ZZ



Tree-level ttW and ttZ production at the LHC

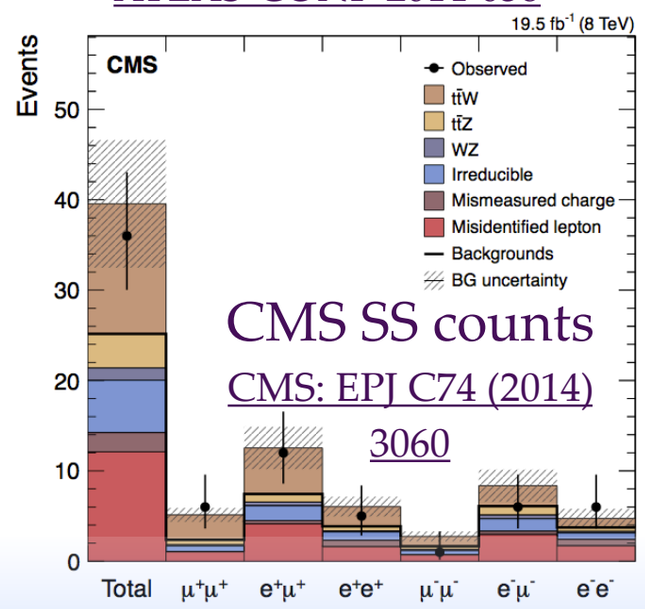
ttW: CMS / ATLAS 8 TeV

- Counting experiments in SS (and 3*l* in ATLAS) channels, where tt+jets events with non-prompt leptons are the main background
  - Both use a data-driven estimate of non-prompt bkg.
  - CMS includes $e\mu$ and ee channels, splits by charge
  - Both use strict cuts to reduce background
    - Both use tight lepton ID (well-isolated, near vertex)
    - ATLAS requires ≥ 2 b-tags, and in SS channel both leptons $p_T > 25$ GeV, MET > 40 GeV, $\Sigma\, p_T > 240$ GeV
    - CMS requires ≥ 1 b-tag, both leptons $p_T > 40$ GeV, and Σ jet $p_T > 155$ GeV

Selection	SRWℓ3	SR2μSS
$t\bar{t}Z$	1.23 ± 0.31	1.22 ± 0.29
$t\bar{t}W$	3.7 ± 0.9	5.0 ± 1.2
$t\bar{t}H$	0.68 ± 0.11	0.88 ± 0.13
MisID leptons	1.3 ± 0.9	2.1 ± 2.4
Total non-$t\bar{t}V$	2.8 ± 0.9	3.6 ± 2.4
Total expected	7.7 ± 1.3	9.8 ± 2.7
Observed	6	14

ATLAS 3*l* and SS $\mu\mu$ counts

ATLAS-CONF-2014-038

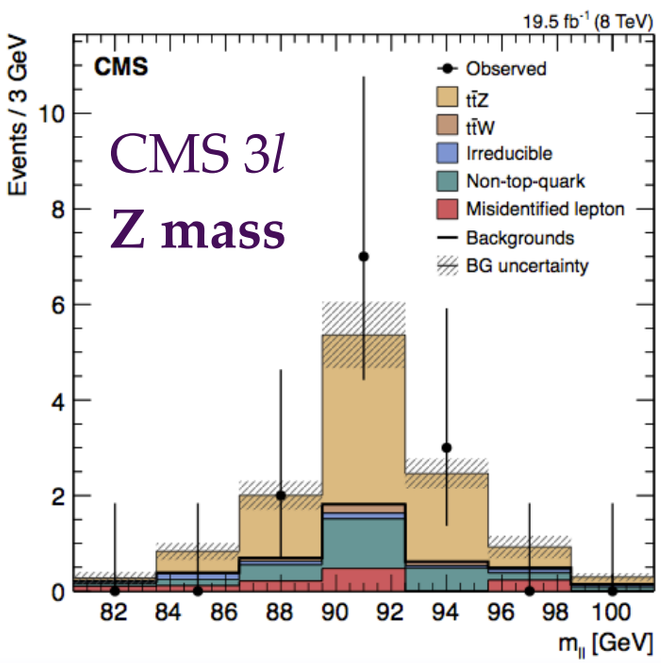


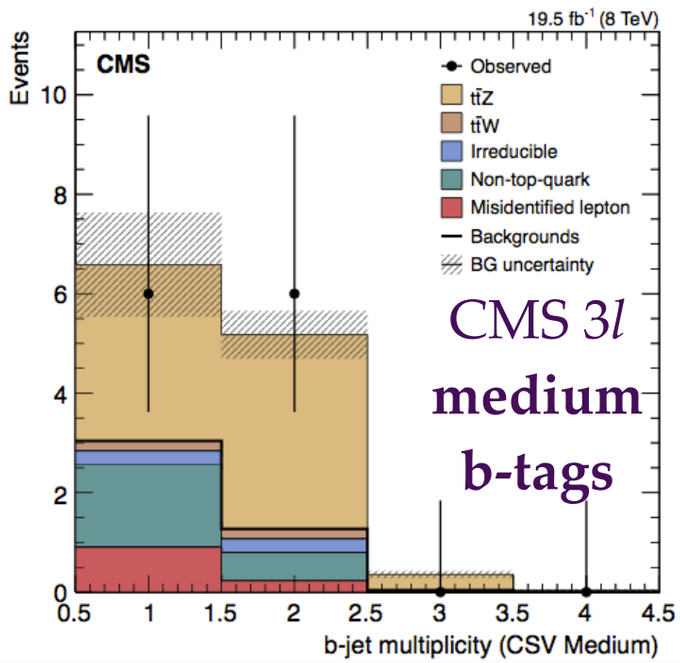
CMS SS counts

CMS: EPJ C74 (2014) 3060

3*l* ttZ: CMS / ATLAS 7 / 8 TeV

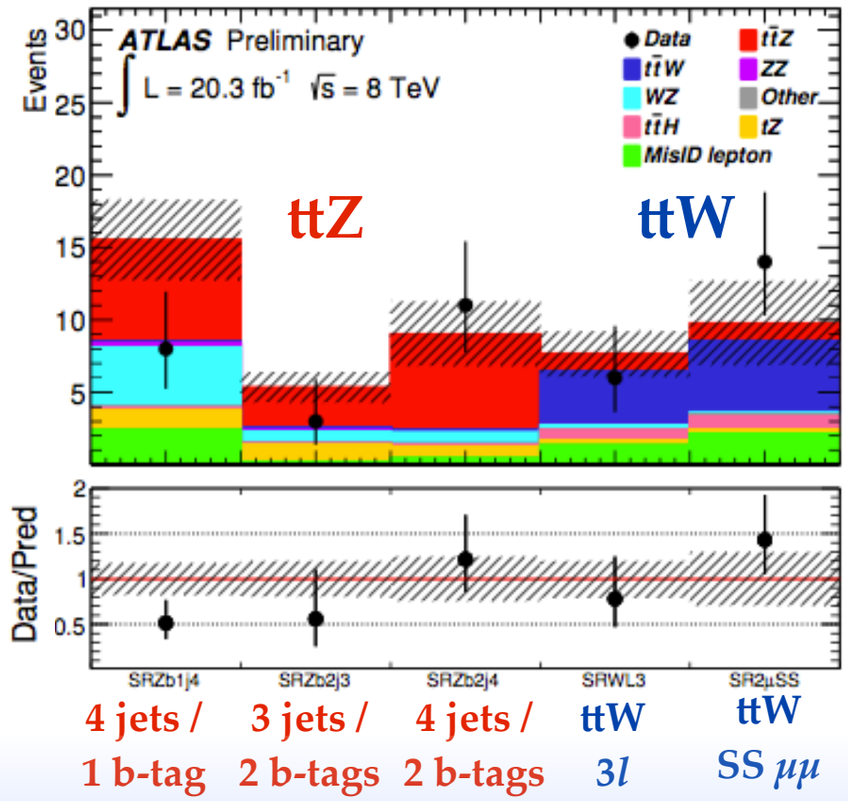
- Counting experiments in 3*l* channel, where non-prompt Z+jets and tt+jets, and prompt WZ and ZZ are the main background
  - Lepton ID and Z candidate mass 91 ± 10 GeV
  - CMS requires ≥ 4 jets, ≥ 2 b-tags, leptons $p_T > 20$ GeV
  - ATLAS requires ≥ 3 / 4 jets, ≥ 1 / 2 b-tags





CMS: EPJ C74 (2014) 3060

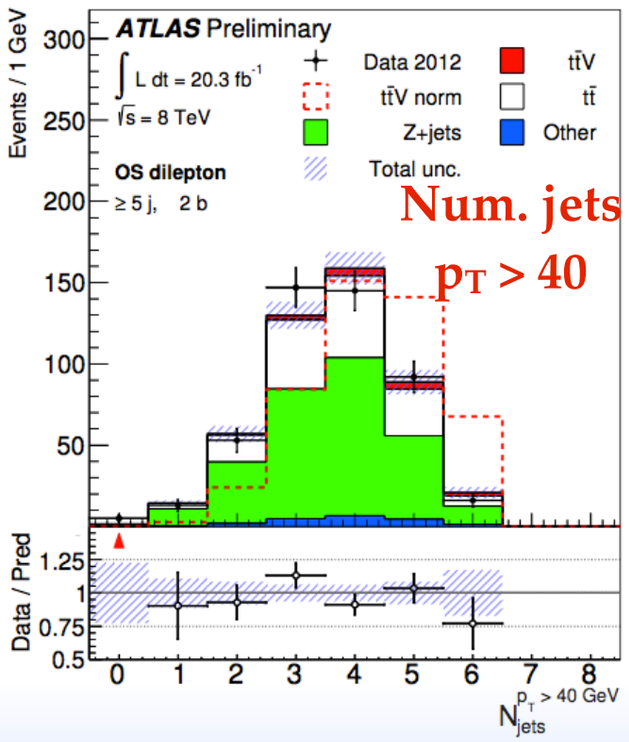
ATLAS 3*l* counts
ATLAS-CONF-2014-038

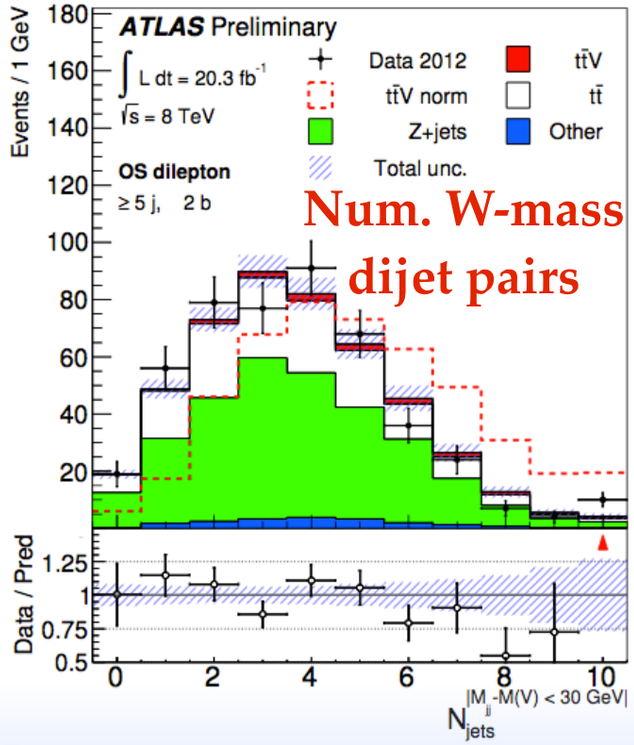


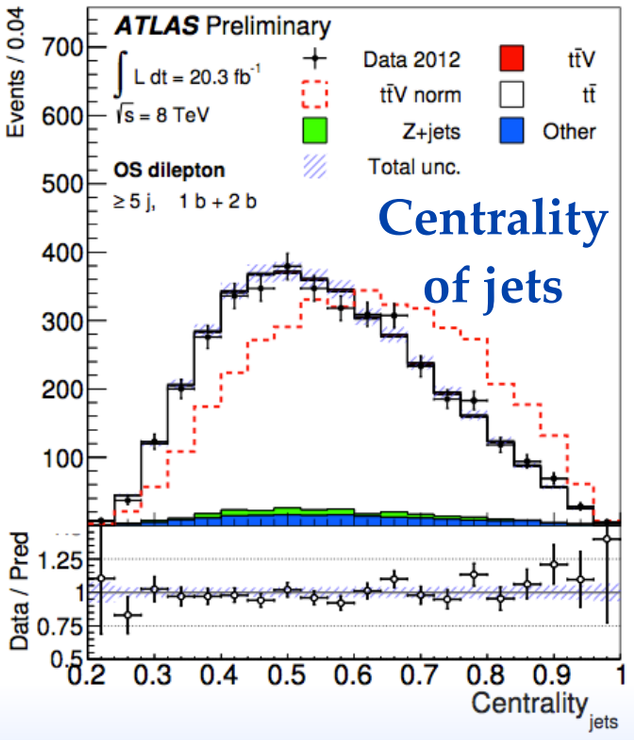
ttW and ttZ in OS events

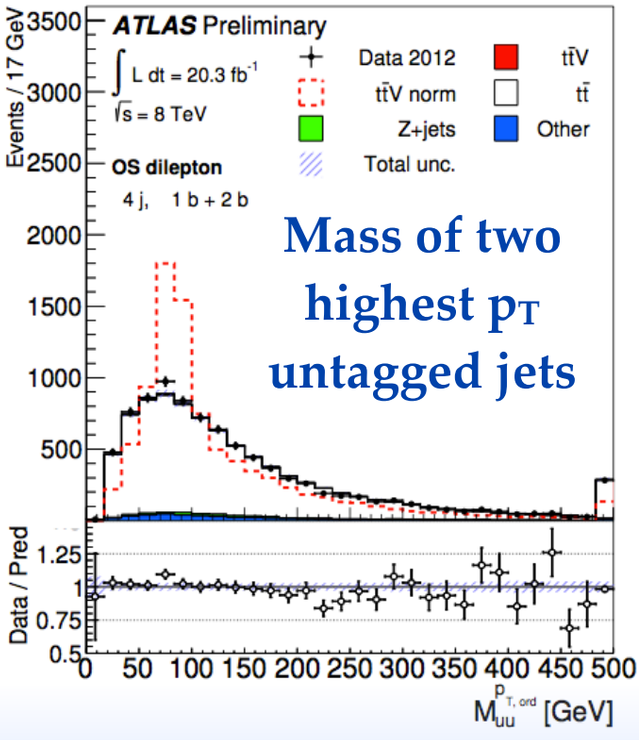
- ATLAS finds 7 optimal variables to separate ttW/ttZ from tt+jets
  - Most involve simple object p_T/counting/distribution variables
    - ttW and ttZ events are more central, have higher p_T than tt+jets and Z+jets
  - Some of the most powerful involve reconstruction (e.g. hadronic W)

ATLAS-CONF-2014-038



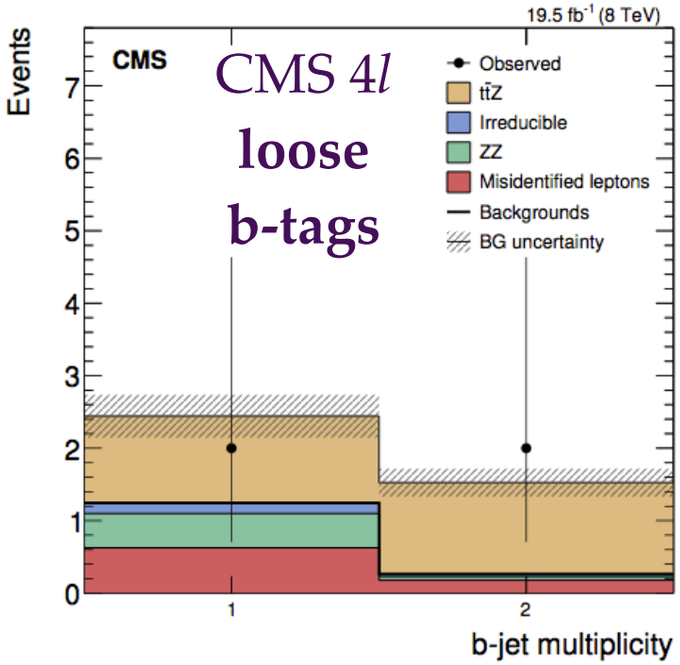






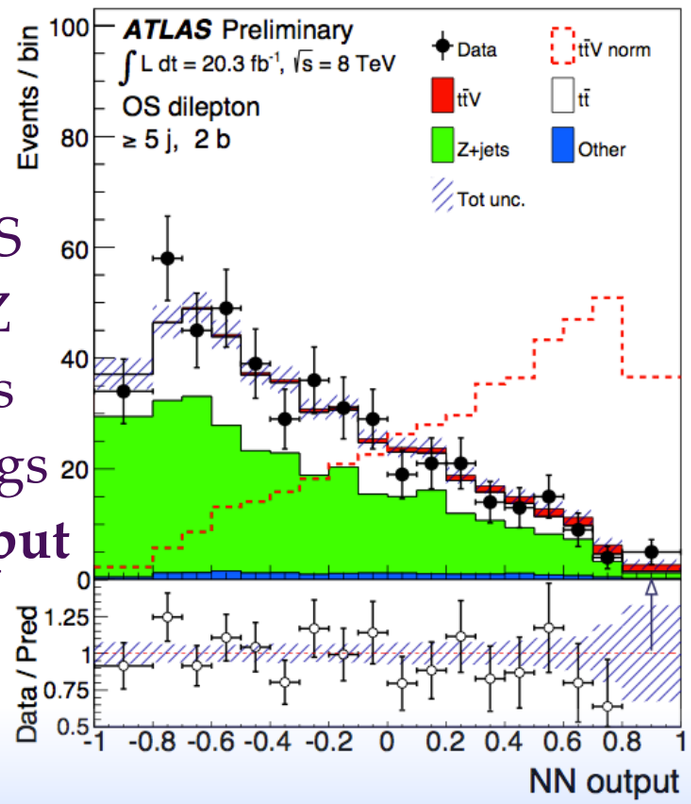
4*l* ttZ and OS ttW / ttZ

- CMS does a counting experiment in the 4*l* channel for ttZ
  - Exactly one Z candidate mass 91 ± 15 GeV, loose lepton ID
  - ≥ 1 medium b-tag, 1 or ≥ 2 loose b-tags
- ATLAS uses neural net to search for ttW and ttZ in OS events

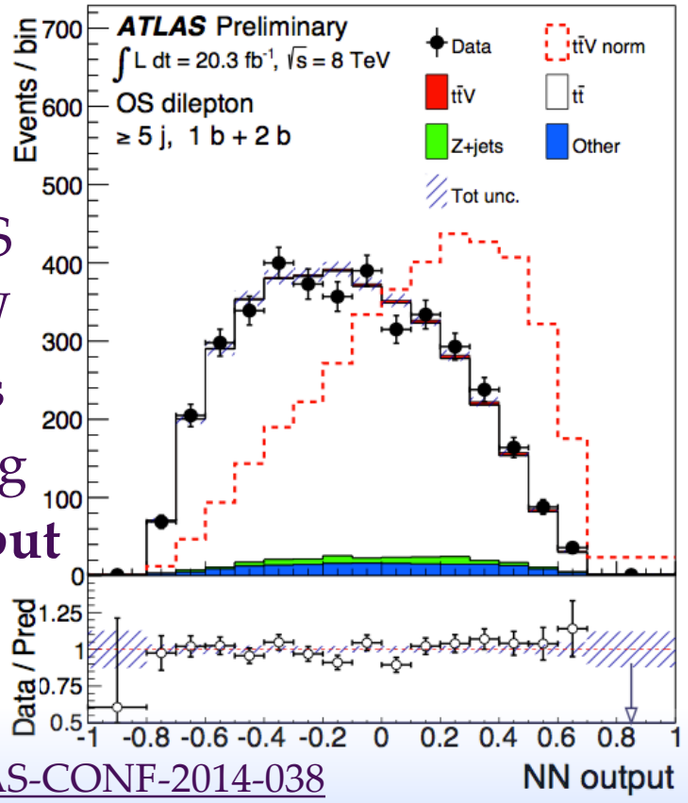


CMS: EPJ C74 (2014) 3060

ATLAS
OS ttZ
≥ 5 jets
≥ 2 b-tags
NN output



ATLAS
OS ttW
≥ 5 jets
≥ 1 b-tag
NN output



ATLAS-CONF-2014-038

ttW and ttZ results

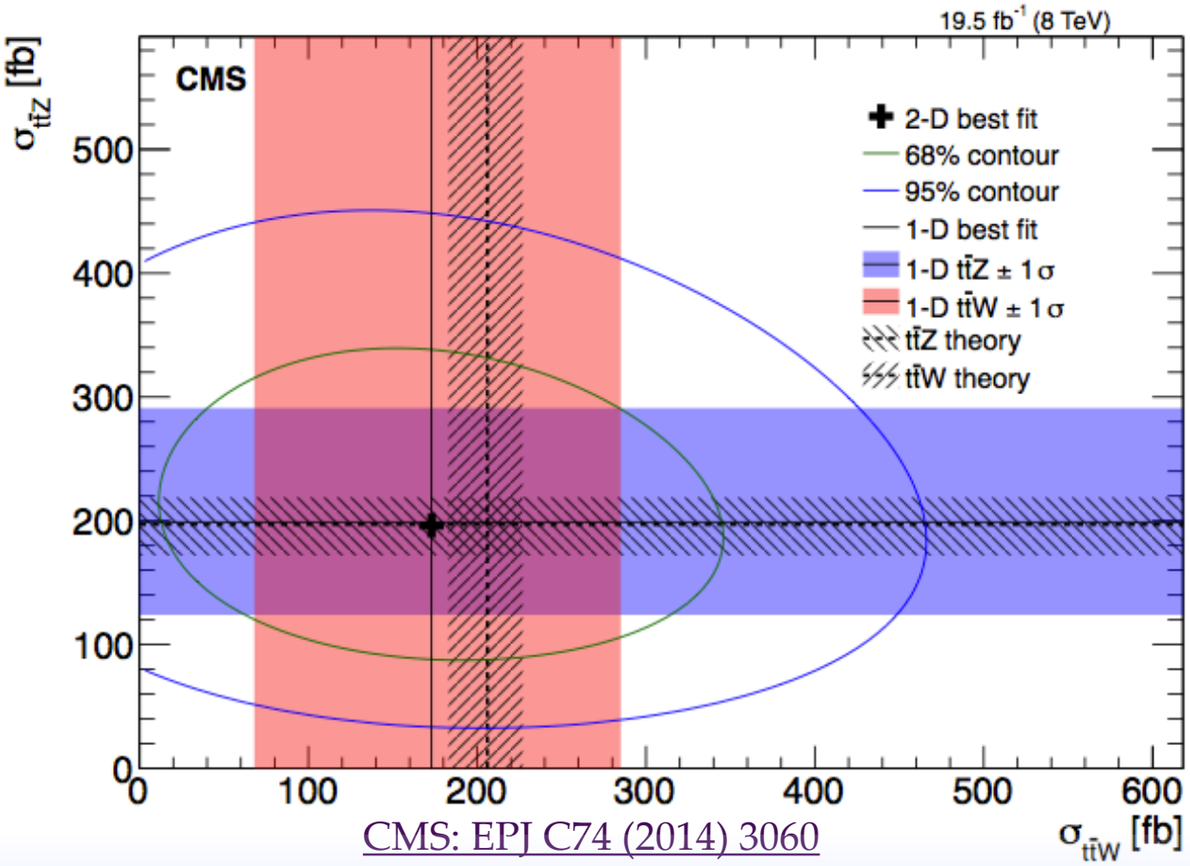
- 7 TeV: $\sigma_{ttZ} = 280 \pm 130 \pm 50$ fb (CMS), < 710 fb (ATLAS), $\sigma_{ttZ} = 137 \pm 14$ (NLO)
- Predicted 8 TeV cross sections are $\sigma_{ttZ} = 206 \pm 29$ fb, $\sigma_{ttW} = 203 \pm 25$ fb (NLO)

CMS

Channels used	Process	Cross section	Significance
3ℓ+4ℓ	$t\bar{t}Z$	200^{+80}_{-70} (stat)$^{+40}_{-30}$ (syst) fb	3.1
2ℓ	$t\bar{t}W$	170^{+90}_{-80} (stat) $\pm$ 70 (syst) fb	1.6

ATLAS

Process	Measured cross-sections	Observed σ	Expected σ
$t\bar{t}Z$	150^{+58}_{-54}(total) = 150^{+55}_{-50}(stat.) $\pm$ 21(syst.) fb	3.1	3.7
$t\bar{t}W$	300^{+140}_{-110}(total) = 300^{+120}_{-100}(stat.)$^{+70}_{-40}$(syst.) fb	3.1	2.3



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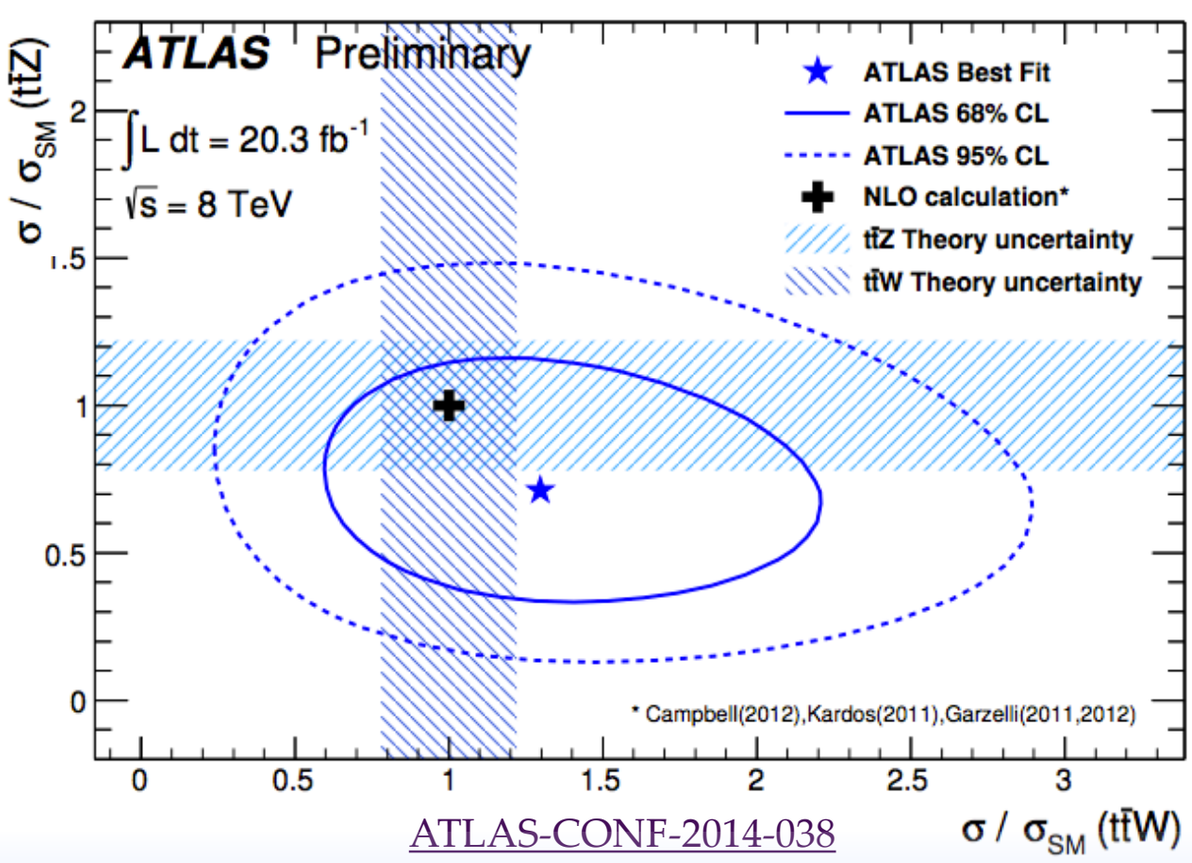
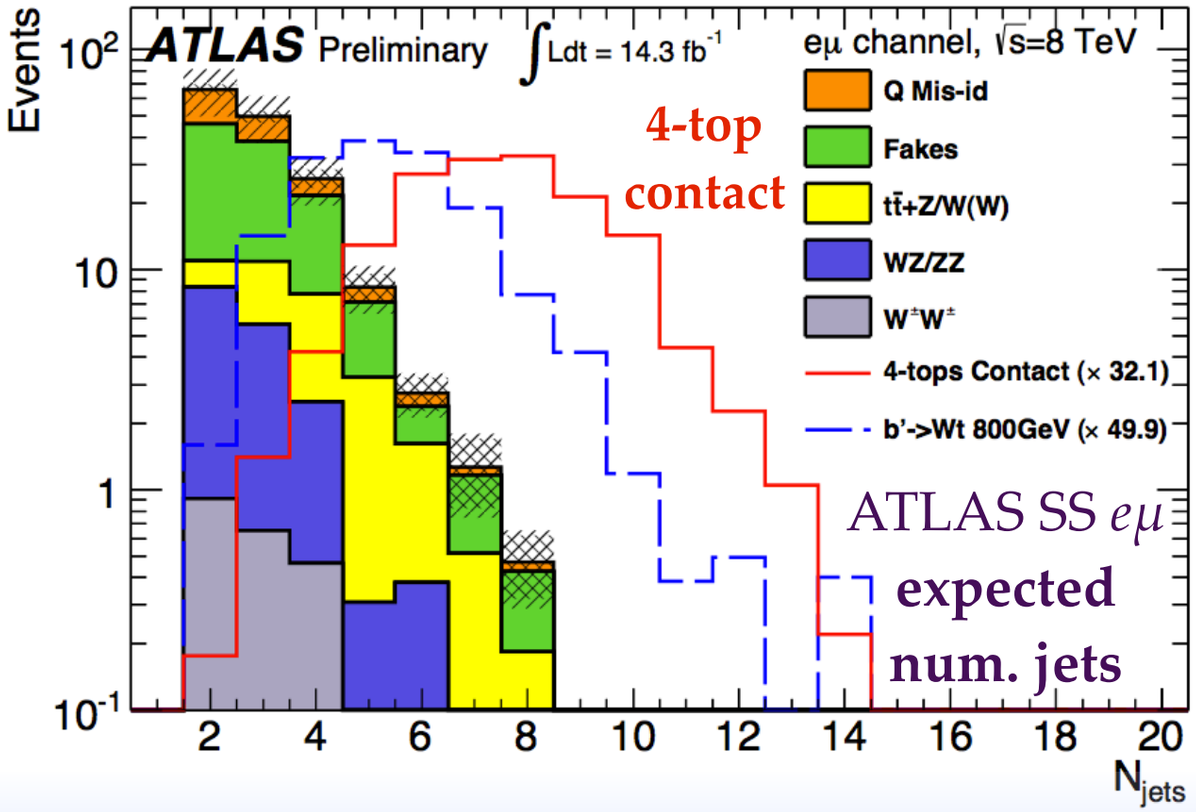


ATLAS-CONF-2014-038

tt+tt: ATLAS 7/8 TeV

- Looking for 4 tops produced in contact interaction or SM process
  - SS events with ≥ 2 jets and MET > 40
    - 7 TeV analysis has ≥ 2 leptons with ≥ 1 b-tag and H_T > 550 GeV
    - 8 TeV analysis has exactly 2 leptons with ≥ 2 b-tags and H_T > 650 GeV

8 TeV yields



ATLAS SS $e\mu$ **expected num. jets**

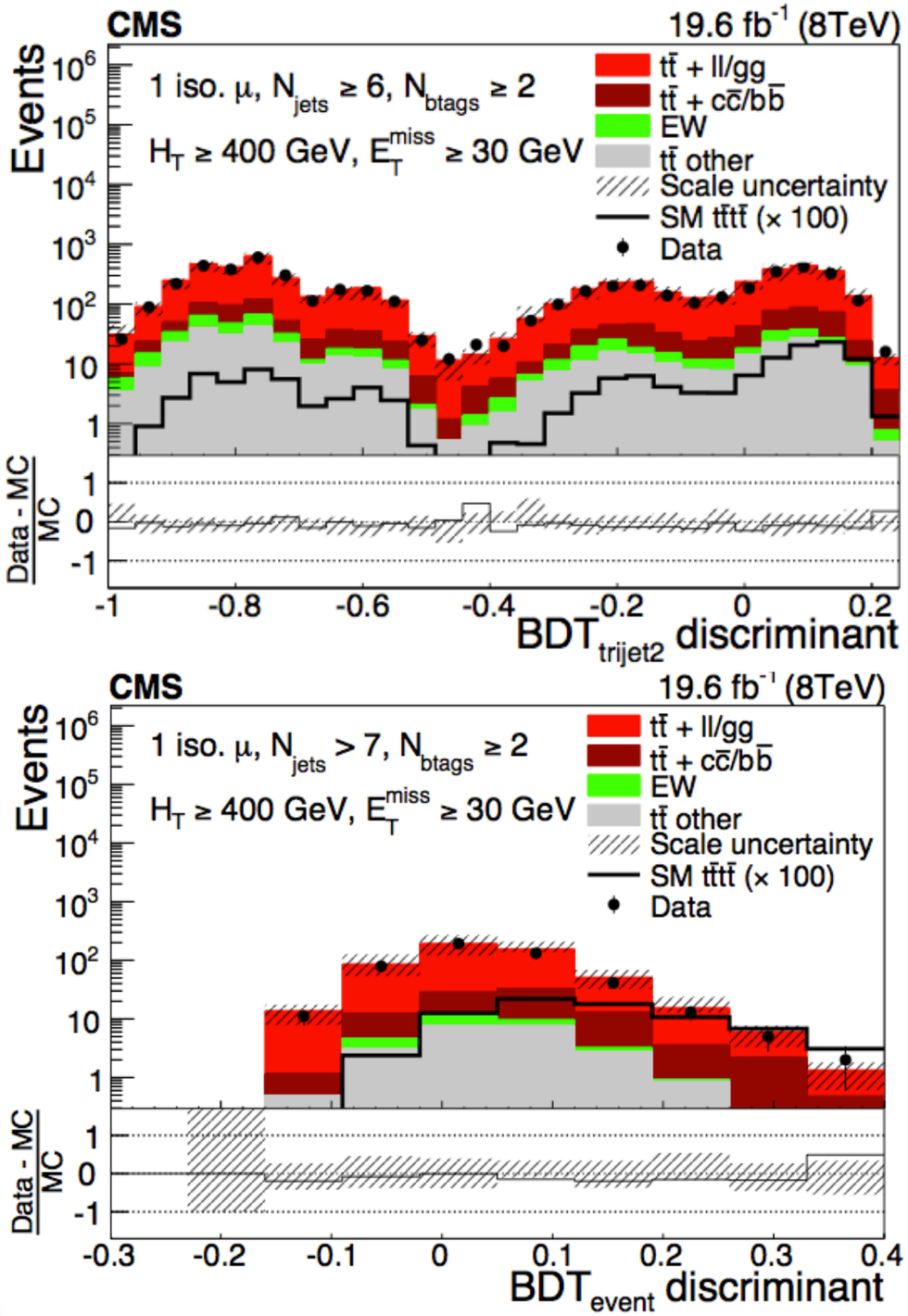
Samples	Channel		
	ee	*eμ*	*μμ*
Charge misidentification	0.16 ± 0.04 ± 0.05	0.41 ± 0.07 ± 0.12	—
Fakes	0.18 ± 0.17 ± 0.05	0.07 ± 0.28 ± 0.02	< 1.14
WZ/ZZ+jets	< 0.1	0.01 ± 0.09 ± 0.01	< 0.11
$t\bar{t}W$(+jet(s))	0.31 ± 0.04 ± 0.12	0.93 ± 0.06 ± 0.35	0.65 ± 0.06 ± 0.25
$t\bar{t}Z$(+jet(s))	0.09 ± 0.02 ± 0.04	0.34 ± 0.04 ± 0.14	0.14 ± 0.02 ± 0.06
Total	0.8 ± 0.2 ± 0.1	2.0 ± 0.4 ± 0.4	0.8 ± 1.2 ± 0.3
Observed	1	6	1

	95% C.L. upper limit		
	$\sigma(pp \to t\bar{t}t\bar{t})$ [fb]		$\lvert C\rvert/\Lambda^2$ [TeV^{-2}]
Model	Expected 1σ range	Observed	Observed
Standard Model	43-89	85	—
Contact interaction	29-61 (< 90)	59 (61)	15

ATLAS 8 TeV (7 TeV) tt+tt limits ATLAS-CONF-2013-051 ATLAS-CONF-2012-130

tt+tt: CMS 8 TeV

- Looking for SM tt+tt events with a single lepton (6x SS signal yields, larger bkg.)
  - Events with ≥ 6 jets, ≥ 2 b-tags, MET > 30 GeV, H_T > 400 GeV
  - Reconstruct hadronic tops using jet separation and b-tag discriminator values in a BDT, matching jets to W and top decays. Identifies correct three jets 60% of the time in tt systems.
  - Use 2nd-highest tri-jet score and jet variables in BDTs for 6, 7, and ≥ 8 jet channels.
  - Set a limit of 32 fb (32 ± 17 expected) on tt+tt (expected cross section of 1 fb)



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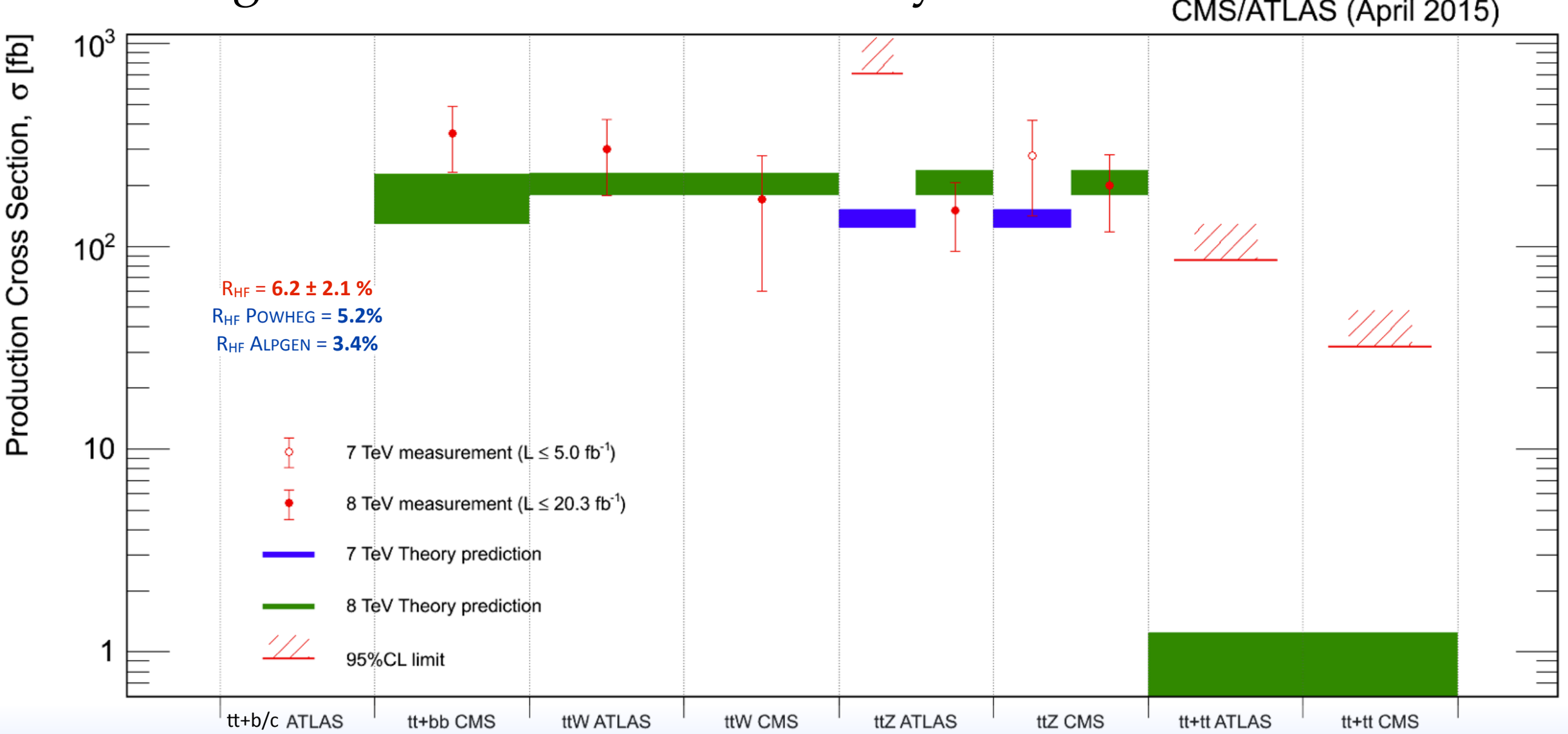
Summary

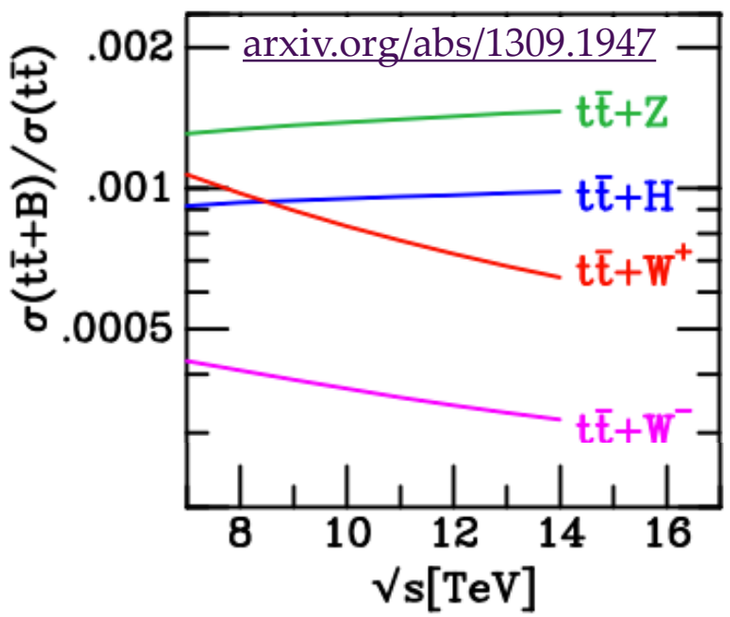
- Sensitivity reaching the ~30 fb range
- No significant deviations from SM yet

Plot macro from Matthew Herndon
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined



Prospects for LHC Run II

- Running at 13 TeV - all tt+X cross sections rise, some dramatically
- Plan to deliver 100 fb^{-1} in Run II
  - Expect ~900 tt+tt events per detector by 2018!
    - Expect ~55k ttW and ~76k ttZ events per detector
      - **550 ttW and 760 ttZ in 2015 alone, if we're lucky**
    - For comparison, Tevatron Run I produced ~670 tt pairs per detector, and Run II produced ~72k tt pairs per detector
- **Entering the era of precision studies of tt+X**



Expected SM cross sections		
	8 TeV	13 TeV
tt	248 pb	816 pb
ttW	203 fb	566 fb
ttZ	206 fb	760 fb
tt+tt	0.9 fb	9.2 fb

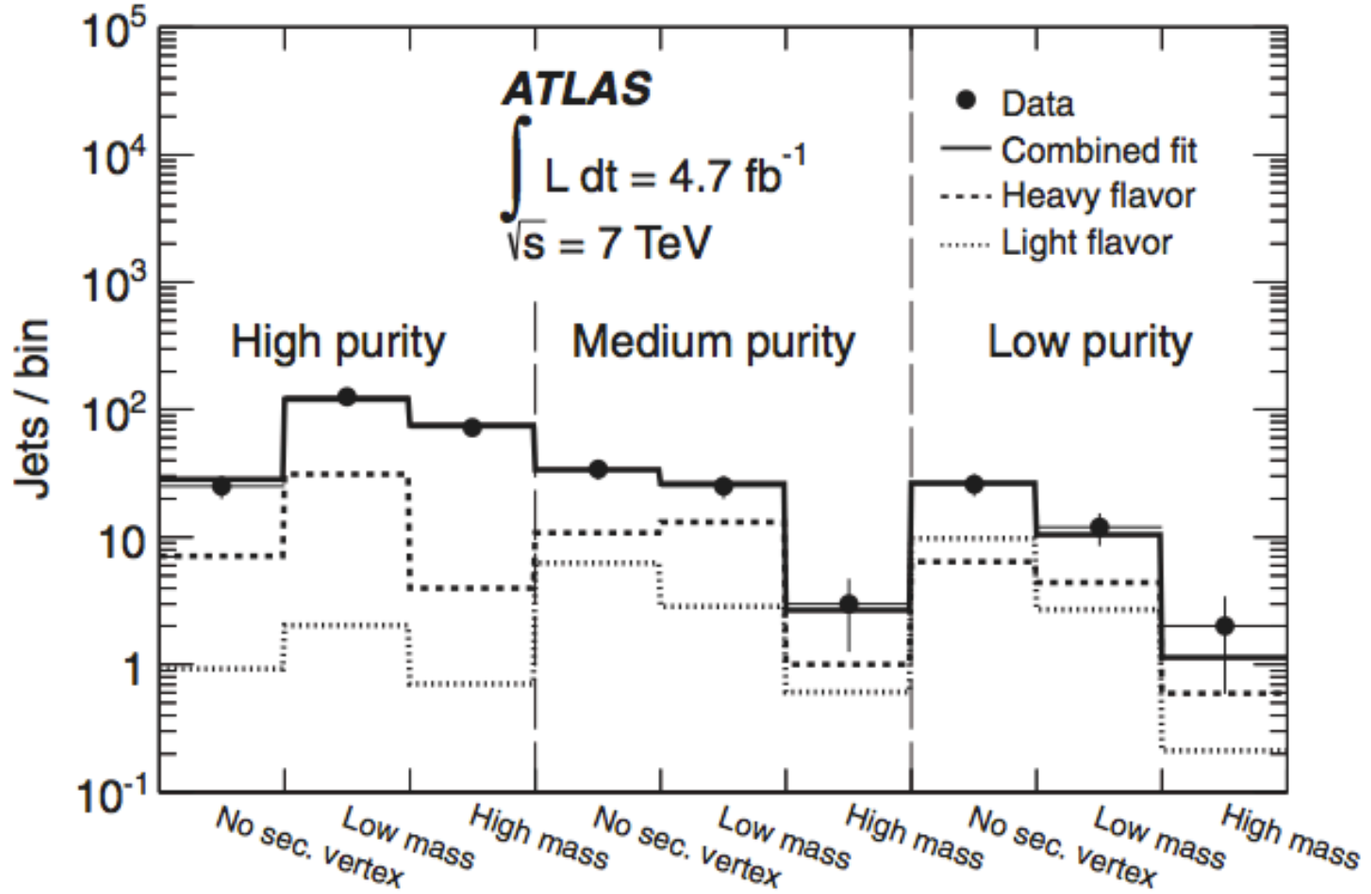
twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO
dx.doi.org/10.1007/JHEP07(2014)079

BACKUP

tt+bb: ATLAS 7 TeV

- Dilepton tt ratio R_{HF} = tt+HF / tt+jets = 6.2 ± 1.1 (stat) ± 1.8 (syst) %
  - 79 ± 14 (stat) ± 22 (syst) of 105 events with ≥ 3 b-tagged jets estimated to be from tt +HF, a 3σ deviation from the zero tt+HF hypothesis
  - Jets have $p_T > 25$ GeV, $|\eta| < 2.5$, identified with sec. vertex neural network
  - HF quarks with dR < 0.4 from parton shower, with dR > 0.4 from matrix element
  - b and c quarks with $p_T > 5$ GeV, dR(quark, jet) < 0.25
  - $F_{b/HF}$ = tt+b / tt+HF = 0.31 ± 0.03 from MC (Alpgen/Powheg/MadGraph5)
  - Fit for R_{HF} using 2D jet p_T vs. vertex mass template
  - Consistent with R_{HF} = 3.4% from Alpgen and 5.2% from Powheg (w/Herwig)
  - dx.doi.org/10.1103/PhysRevD.89.072012

tt+bb: ATLAS 7 TeV



b purity	*b*-jet efficiency	*c*-jet efficiency	Light-flavor efficiency
High	60%	17%	0.43%
Medium	10%	7%	1.00%
Low	5%	6%	1.33%
Total	75%	30%	2.76%

tt+bb: CMS 8 TeV

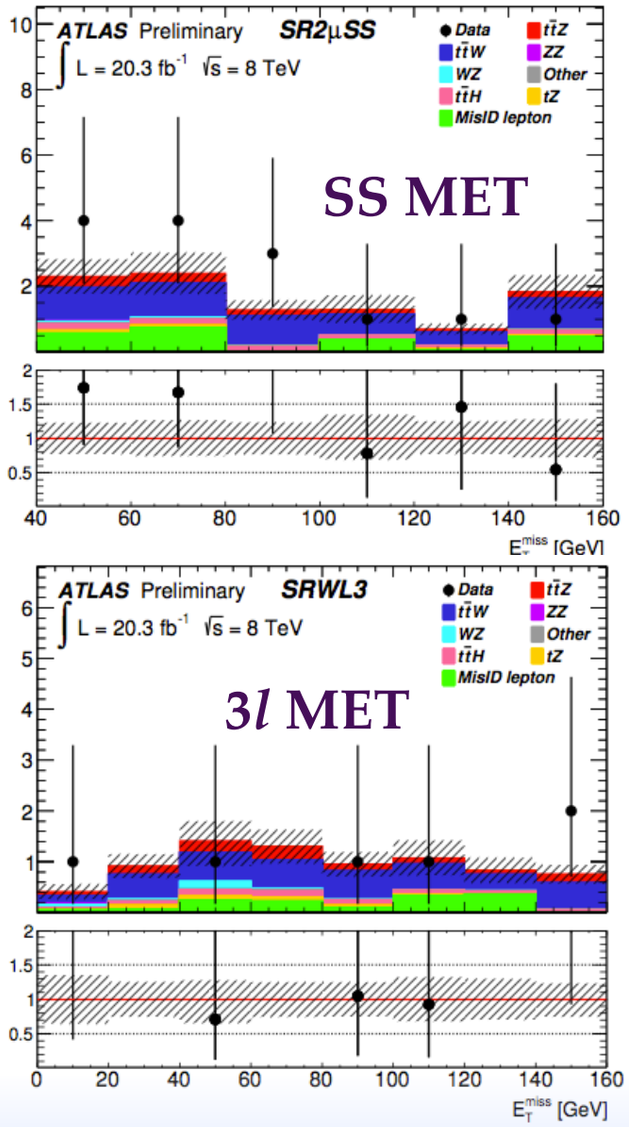
- Dilepton tt ratio R_{HF} = tt+bb / tt+jets = 2.2 ± 0.3 (stat) ± 0.5 (syst) %
  - Expect σ_{ttjj} = 21.0 ± 2.9 pb, σ_{ttbb} = 0.23 ± 0.05 pb for jet p_T > 40 GeV (compare to σ_{ttH} = 0.13 pb without jet cuts)
  - Four categories: tt+bb, tt+b (merging, acceptance), tt+cc, tt+LF, tt+other
    - tt+other generator-level leptons or jets fail |η| acceptances or p_T > 20 GeV cuts
  - Fit to CSV distribution with norm. and R_{HF} as floating parameters
    - tt+other and tt+cc combined w/ tt+LF, tt+b with tt+bb
  - Same measured value for p_T > 20 GeV and p_T > 40 GeV jets, which had expected values of 0.016 ± 0.002 (MadGraph and Powheg) and 0.011 ± 0.003 (NLO), resp.
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/GenHFHadronMatcher
  - arxiv.org/abs/1411.5621

tt+bb: CMS 8 TeV

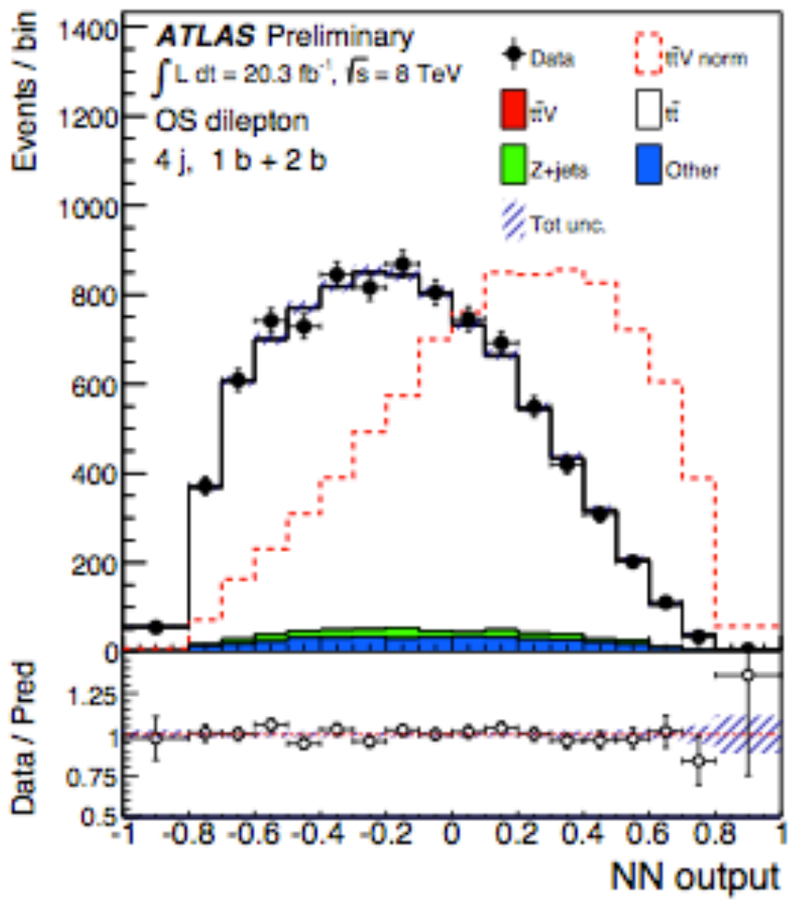
Phase Space (PS)	$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible PS (particle)			
Jet $p_T > 20\,\mathrm{GeV}/c$	$0.029 \pm 0.003 \pm 0.008$	$1.28 \pm 0.03 \pm 0.15$	$0.022 \pm 0.003 \pm 0.005$
Full PS (parton)			
Jet $p_T > 20\,\mathrm{GeV}/c$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

ttW: ATLAS 8 TeV

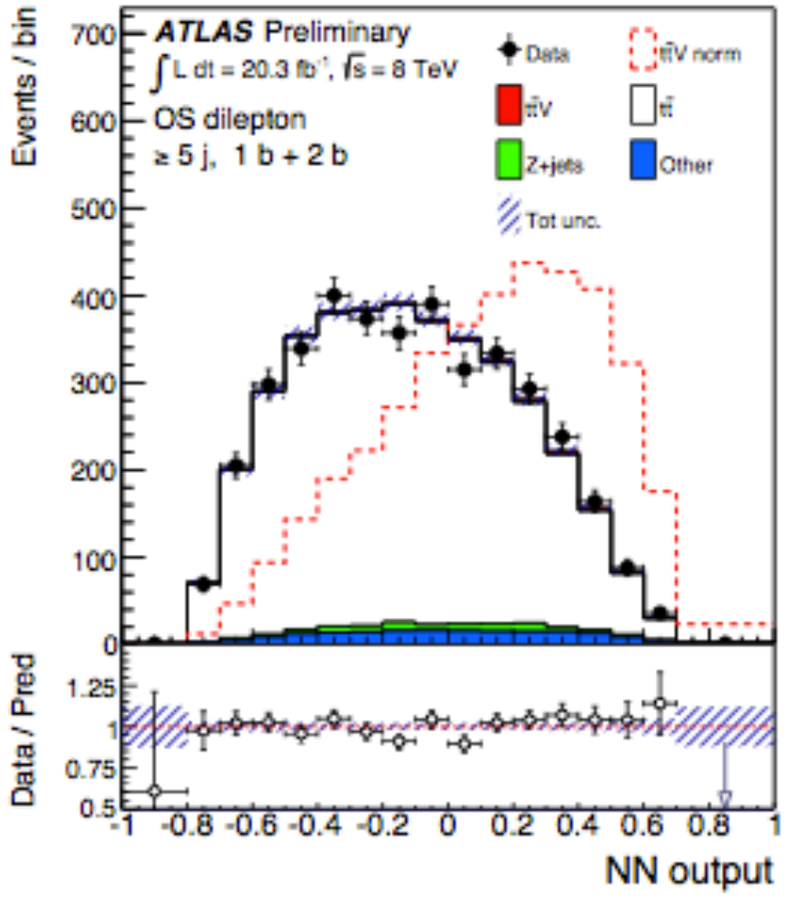
- Standard model ttW in SS dimuon, 3*l*, and OS dilepton channels
  - ATLAS-CONF-2014-038



OS 4 jet NN

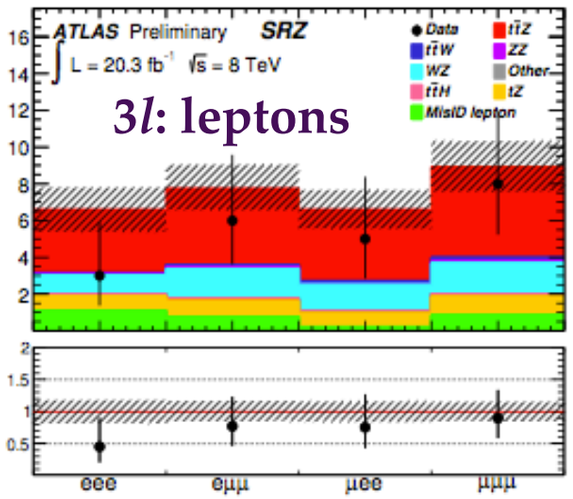


OS 5 jet NN

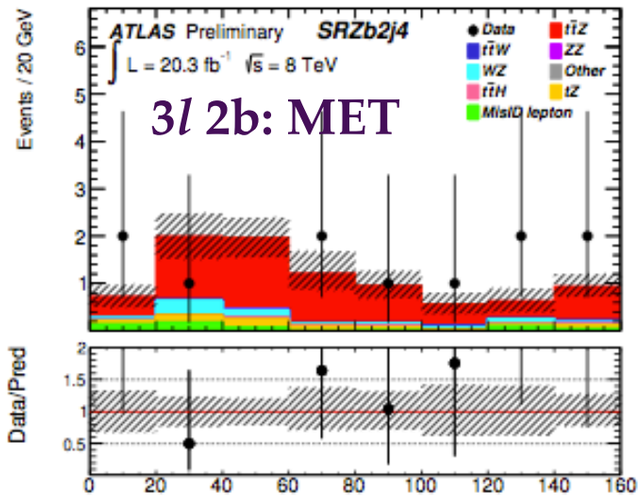


ttZ: ATLAS 8 TeV

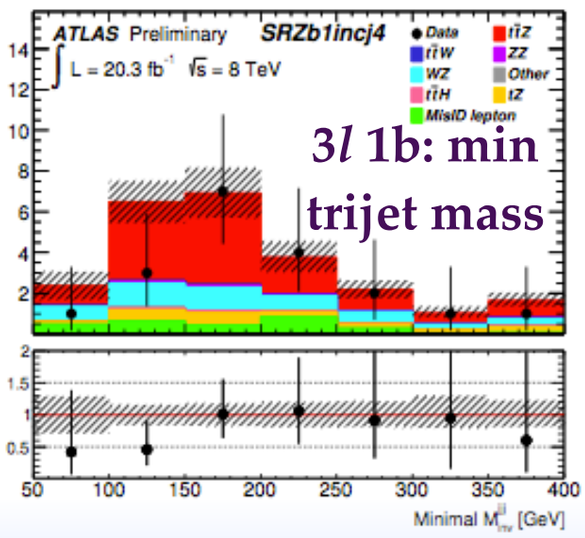
- Standard model ttZ in 3*l* and OS dilepton channels
  - ATLAS-CONF-2014-038



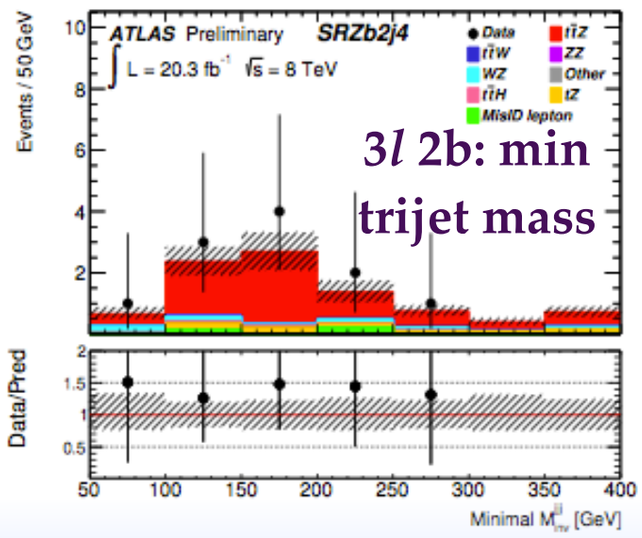
3*l*: leptons



3*l* 2b: MET

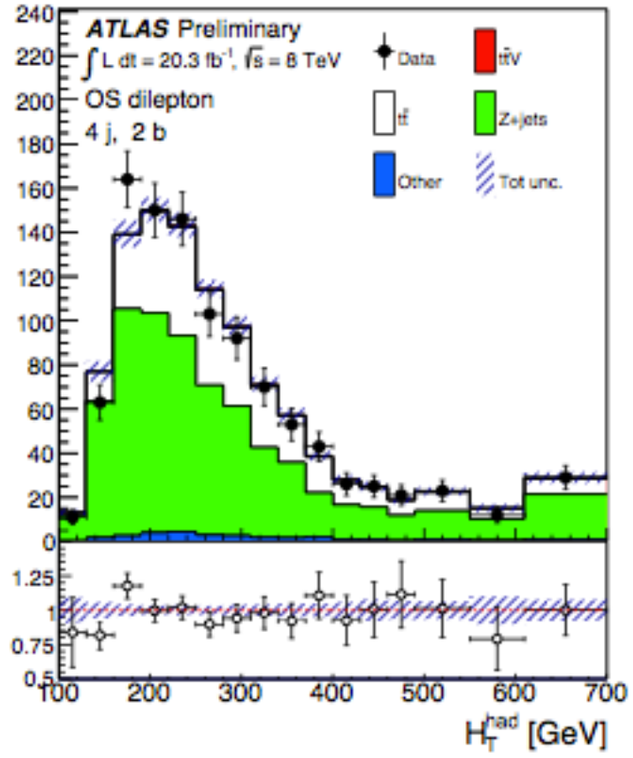


3*l* 1b: min trijet mass

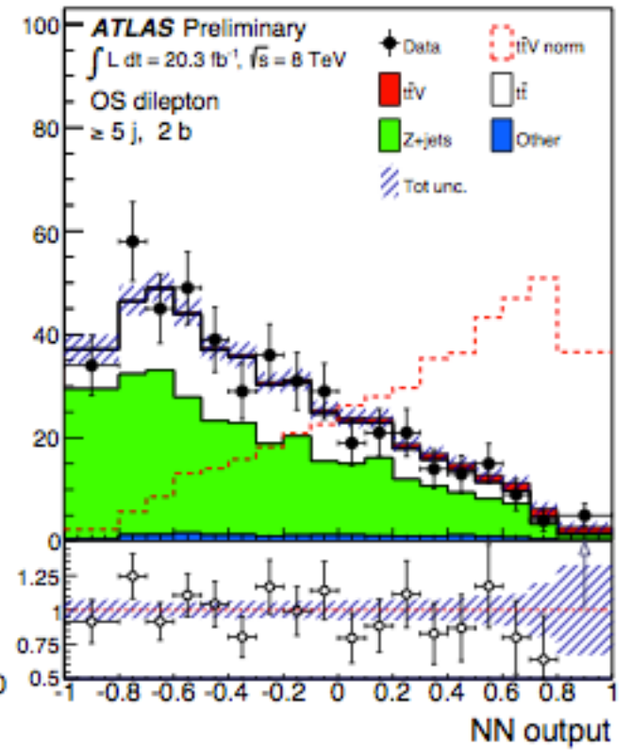


3*l* 2b: min trijet mass

OS 4 jet NN



OS 5 jet NN



ttW / ttZ: ATLAS 8 TeV

- Results in various channels
  - ATLAS-CONF-2014-038

	Combination		
Process	Signal Strength	Observed σ	Expected σ
$t\bar{t}V$	$0.89^{+0.23}_{-0.22}$	4.9	4.9
$t\bar{t}W$	$1.25^{+0.57}_{-0.48}$	3.1	2.4
$t\bar{t}Z$	$0.73^{+0.29}_{-0.26}$	3.2	3.8

	Simultaneous fit of two signal strengths in all channels			
Channel	$\mu_{t\bar{t}Z}$	$\mu_{t\bar{t}W}$	Observed σ	Expected σ
trilepton and same-sign dilepton	$0.70^{+0.30}_{-0.28}$	$1.37^{+0.62}_{-0.51}$	4.1	4.1
opposite-sign dilepton	0.77 ± 0.65	0.71 ± 2.41	0.4	0.6
combination	$0.71^{+0.28}_{-0.26}$	$1.30^{+0.59}_{-0.48}$	4.4	4.4

ttW / ttZ: ATLAS 8 TeV

- Input variables to OS BDT
  - ATLAS-CONF-2014-038

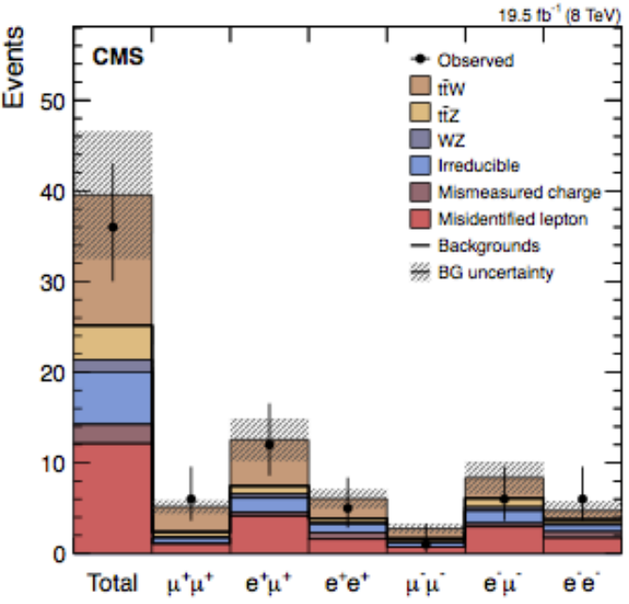
Variable	Definition
$M_{uu}^{Pt_{ord}}$	Mass of the two untagged jets with the highest p_T in events with exactly two tagged jets or mass of the two untagged jets with the highest p_T after discarding the jet with second highest b-tagging weight in events with exactly one tagged jet
$Cent_{jet}$	Sum of p_T divided by sum of E for all jets
H1	2nd Fox-Wolfram moment
$H1_{jet}$	2nd Fox-Wolfram moment built from jets only
M_{jj}^{MindR}	Mass of the combination between any two jets with the smallest ΔR
$maxM_{lepb}^{MindR}$	Maximum mass between a lepton and the tagged jet with the smallest ΔR
p_T^{jet3}	Third leading jet p_T
p_T^{jet4}	Fourth leading jet p_T
ΔR_{ave}^{ij}	Average ΔR for all jet pairs
$N_{jets}^{\lvert M(jj)-M(V)\rvert<30}$	Number of jet pairs with mass within a window of 30 GeV around 85 GeV
N_{40}^{jet}	Number of jets with $p_T \geq 40$ GeV
M_{bb}^{MaxPt}	Mass of the combination of two tagged jets with the largest vector sum p_T
M_{bj}^{MaxPt}	Mass of the combination of a tagged jet and any jet with the largest vector sum p_T
$\Delta R_{lep1,lep2}$	Δ R between the two leptons

Variable	2ℓOSZveto		2ℓOSZ
	4 j, 1 b + 2 b	$\geq$ 5 j, 1 b + 2 b	$\geq$ 5 j, 2 b
$M_{uu}^{Pt_{ord}}$	1st	7th	-
$Cent_{jet}$	2nd	1st	6th
H1	3rd	2nd	-
M_{jj}^{MindR}	4th	6th	-
$maxM_{lepb}^{MindR}$	5th	5th	-
p_T^{jet3}	6th	-	-
p_T^{jet4}	-	3rd	-
ΔR_{ave}^{ij}	7th	-	-
$N_{jets}^{\lvert M(jj)-M(V)\rvert<30}$	-	4th	2nd
N_{40}^{jet}	-	-	1st
M_{bb}^{MaxPt}	-	-	3rd
$\Delta R_{lep1,lep2}$	-	-	4th
M_{bj}^{MaxPt}	-	-	5th
$H1_{jet}$	-	-	7th

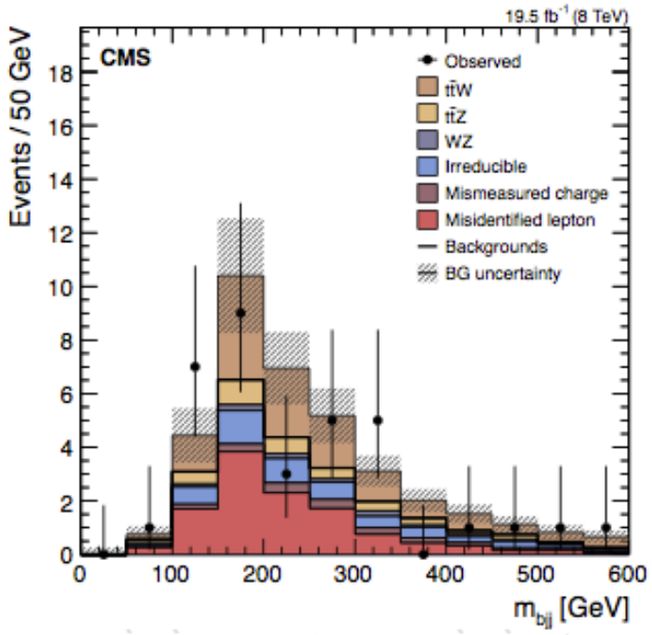
ttW: CMS 8 TeV

- Standard model ttW in SS channels
  - CMS: EPJ C74 (2014) 3060

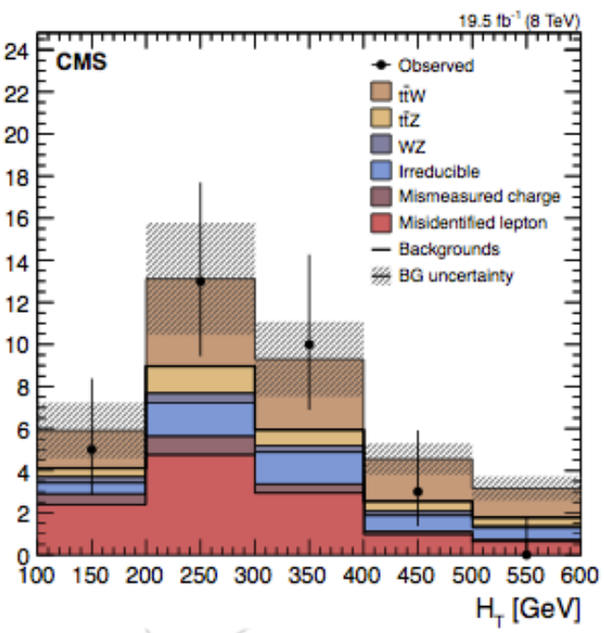
SS leptons



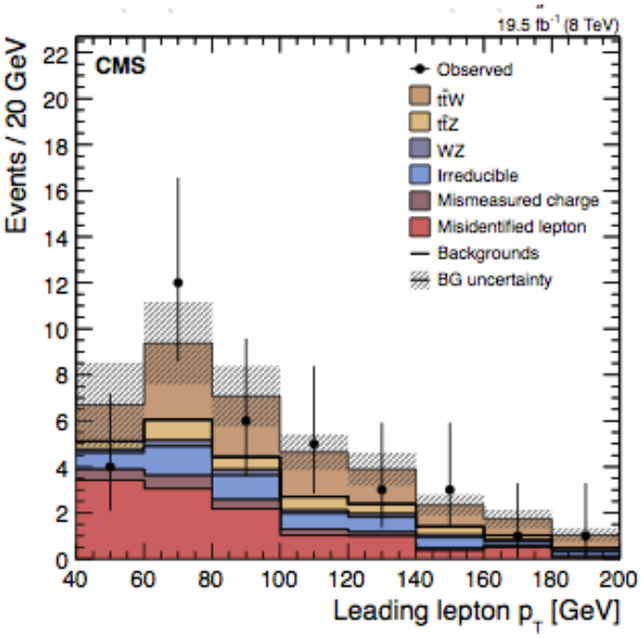
SS trijet top mass



SS H_T

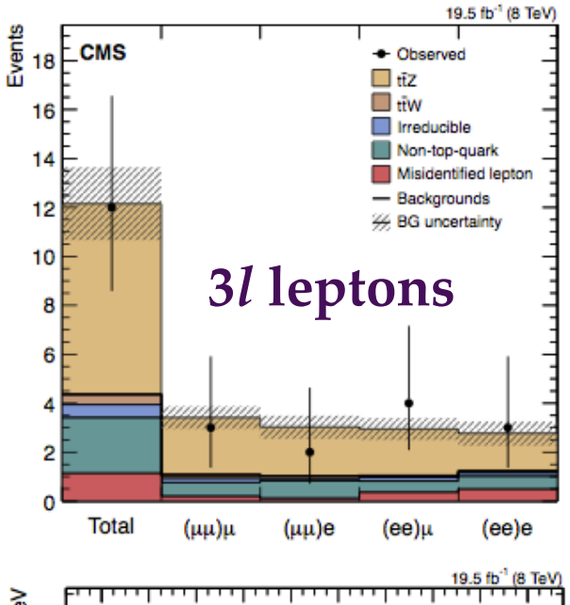


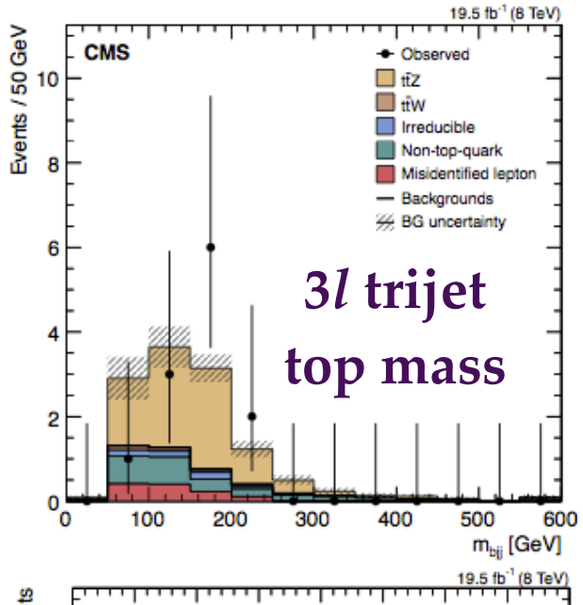
SS 1st lepton p_T

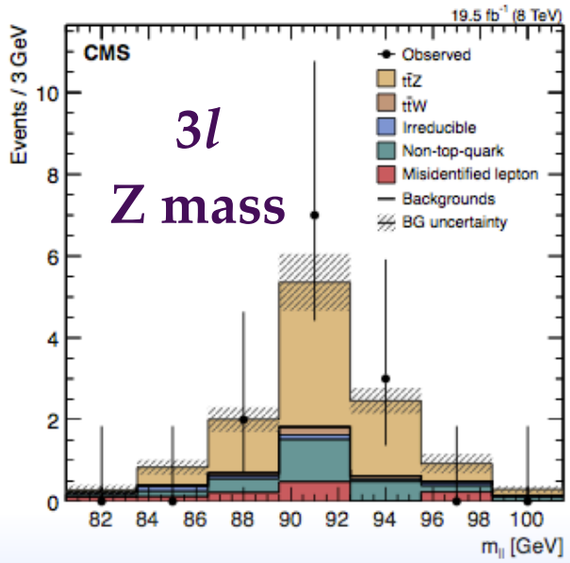


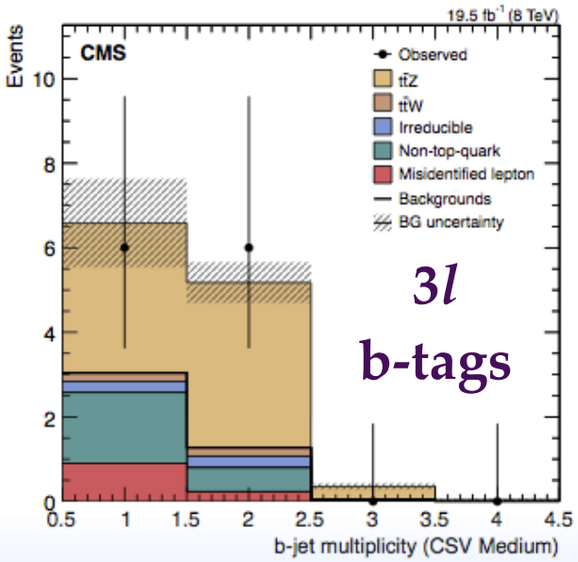
ttZ: CMS 8 TeV

- Standard model ttZ in 3*l* and 4*l* channels
  - CMS: EPJ C74 (2014) 3060

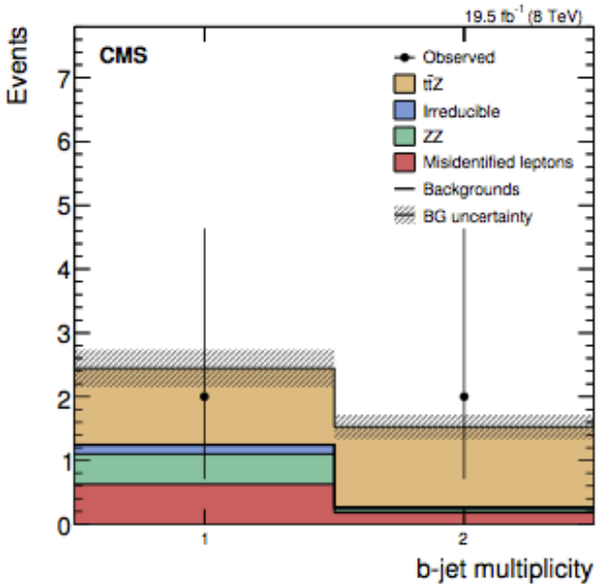




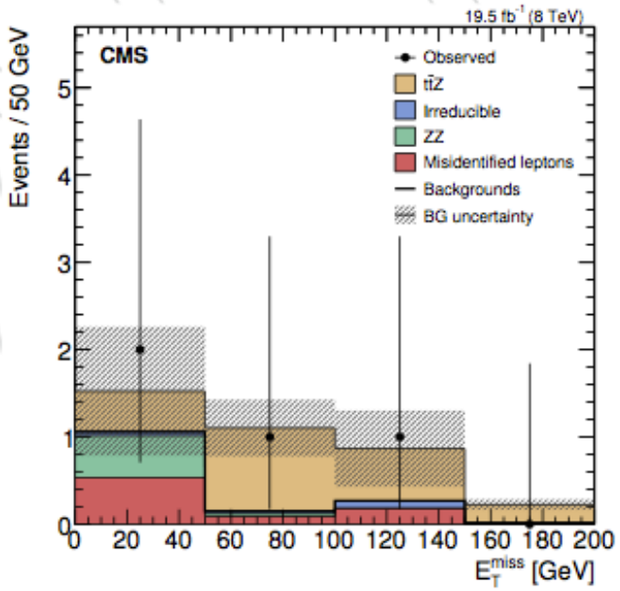




4*l* b-tags



4*l* MET



ttW / ttZ: CMS 8 TeV

- Results in various channels
  - CMS: EPJ C74 (2014) 3060

SS $\sigma_{t\bar{t}W} = 170^{+90}_{-80}\,(\text{stat}) \pm 70\,(\text{syst})\,\text{fb}$

	$\mu^+\mu^+$	$e^+\mu^+$	e^+e^+	$\mu^-\mu^-$	$e^-\mu^-$	e^-e^-
$t\bar{t}W$ (expected)	2.8 ± 0.4	5.1 ± 0.5	2.2 ± 0.3	1.1 ± 0.2	2.3 ± 0.3	1.0 ± 0.2
Misidentified lepton	1.0 ± 0.6	4.1 ± 2.1	1.6 ± 0.9	0.7 ± 0.4	3.0 ± 1.5	1.7 ± 0.9
Mismeasured charge	—	0.4 ± 0.1	0.7 ± 0.2	—	0.4 ± 0.1	0.7 ± 0.2
Irreducible	0.7 ± 0.4	1.6 ± 0.9	0.9 ± 0.5	0.5 ± 0.3	1.4 ± 0.7	0.7 ± 0.4
WZ	0.1 ± 0.1	0.4 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.4 ± 0.1	0.2 ± 0.1
$t\bar{t}Z$	0.6 ± 0.3	0.9 ± 0.5	0.5 ± 0.3	0.4 ± 0.2	1.0 ± 0.5	0.5 ± 0.3
Total background	2.4 ± 0.7	7.4 ± 2.3	3.9 ± 1.1	1.7 ± 0.5	6.1 ± 1.8	3.7 ± 1.1
Total expected	5.2 ± 0.8	12.5 ± 2.4	6.1 ± 1.1	2.8 ± 0.5	8.4 ± 1.8	4.7 ± 1.1
Observed	6	12	5	1	6	6

3l

	Yield
$t\bar{t}Z$ (expected)	7.8 ± 0.9
Irreducible	0.8 ± 0.4
$t\bar{t}W$	0.2 ± 0.1
Non-top-quark	2.3 ± 1.2
Misidentified lepton	1.1 ± 0.8
Total background	4.4 ± 1.6
Total expected	12.2 ± 1.8
Observed	12

4l

	2 b jets required	1 b jet required
$t\bar{t}Z$ (expected)	1.3 ± 0.2	1.3 ± 0.2
Misidentified lepton	0.1 ± 0.1	0.5 ± 0.2
ZZ	0.05 ± 0.01	0.47 ± 0.02
Irreducible	0.04 ± 0.03	0.14 ± 0.04
Total background	0.2 ± 0.1	1.1 ± 0.2
Total expected	1.5 ± 0.2	2.4 ± 0.3
Observed	2	2

$$\sigma_{t\bar{t}Z,3\ell} = 190^{+100}_{-80}\,(\text{stat}) \pm 40\,(\text{syst})\,\text{fb}$$

$$\sigma_{t\bar{t}Z,4\ell} = 230^{+180}_{-130}\,(\text{stat})^{+60}_{-30}\,(\text{syst})\,\text{fb}$$

tt+tt: ATLAS 7 TeV

- Looking for 4 right-handed tops in contact interaction (vs. ~1 fb SM)
  - SS events (≥ 2 leptons) with ≥ 2 jets, ≥ 1 b-tag, MET > 40 GeV, H_T > 550 GeV
  - ATLAS-CONF-2012-130

	Channel		
Backgrounds	*ee*	*eμ*	*μμ*
Mis-id	0.13 ± 0.04 ± 0.02	0.23 ± 0.04 ± 0.03	—
Fakes	0.5 ± 1.1 ± 0.3	0.8 ± 1.1 ± 0.3	0.13 ± 0.13 ± 0.04
Diboson			
• WZ/ZZ+jets	0.19 ± 0.20 ± 0.07	0.34 ± 0.21 ± 0.13	0.28 ± 0.22 ± 0.10
• $W^{\pm}W^{\pm}$+2 jets	0.06 ± 0.03 ± 0.03	0.07 ± 0.03 ± 0.03	0.03 ± 0.02 ± 0.03
$t\bar{t}$ + W/Z			
• $t\bar{t}W$(+jet)	0.23 ± 0.02 ± 0.07	0.79 ± 0.04 ± 0.24	0.57 ± 0.04 ± 0.18
• $t\bar{t}Z$(+jet)	0.17 ± 0.02 ± 0.09	0.61 ± 0.03 ± 0.31	0.33 ± 0.02 ± 0.17
• $t\bar{t}W^{\pm}W^{\mp}$	0.008 ± 0.001 ± 0.002	0.023 ± 0.001 ± 0.007	0.016 ± 0.001 ± 0.005
Total	1.3 ± 1.1 ± 0.3	2.9 ± 1.1 ± 0.5	1.36 ± 0.26 ± 0.27
Observed	2	2	0

95% C.L. limits	
Expected	Observed
< 90 fb	< 61 fb

tt+tt: ATLAS 8 TeV

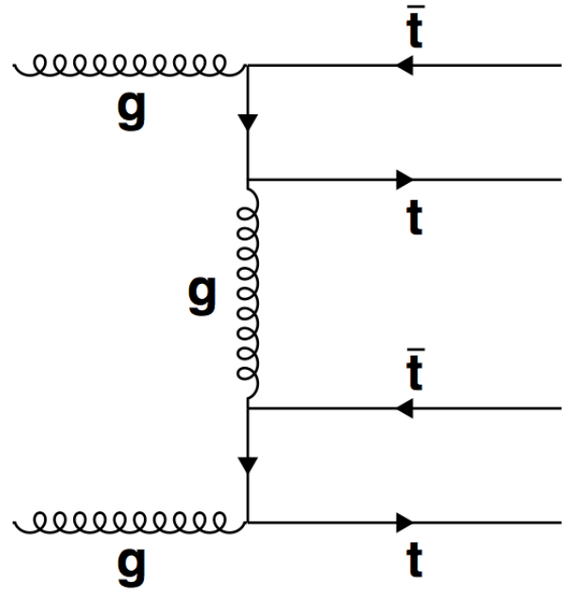
- Looking for 4 right-handed tops in contact interaction (vs. ~1 fb SM)
  - SS events (== 2 leptons) with ≥ 2 jets, ≥ 2 b-tags, MET > 40 GeV, H_T > 650 GeV
  - ATLAS-CONF-2013-051

Samples	Channel		
	ee	*eμ*	*μμ*
Charge misidentification	0.16 ± 0.04 ± 0.05	0.41 ± 0.07 ± 0.12	—
Fakes	0.18 ± 0.17 ± 0.05	0.07 ± 0.28 ± 0.02	< 1.14
Diboson			
• WZ/ZZ+jets	< 0.1	0.01 ± 0.09 ± 0.01	< 0.11
• $W^{\pm}W^{\pm}$+2 jets	< 0.03	0.18 ± 0.16 ± 0.07	< 0.03
$t\bar{t} + W/Z$			
• $t\bar{t}W$(+jet(s))	0.31 ± 0.04 ± 0.12	0.93 ± 0.06 ± 0.35	0.65 ± 0.06 ± 0.25
• $t\bar{t}Z$(+jet(s))	0.09 ± 0.02 ± 0.04	0.34 ± 0.04 ± 0.14	0.14 ± 0.02 ± 0.06
• $t\bar{t}W^+W^-$	0.012 ± 0.002 ± 0.005	0.039 ± 0.003 ± 0.016	0.024 ± 0.003 ± 0.01
Total	0.8 ± 0.2 ± 0.1	2.0 ± 0.4 ± 0.4	0.8 ± 1.2 ± 0.3
Observed	1	6	1

	95% C.L. upper limit	
	$\sigma(pp \to t\bar{t}t\bar{t})$ [fb]	
Model	Expected 1σ range	Observed
Standard Model	43-89	85
Contact interaction	29-61	59

tt+tt: CMS 8 TeV

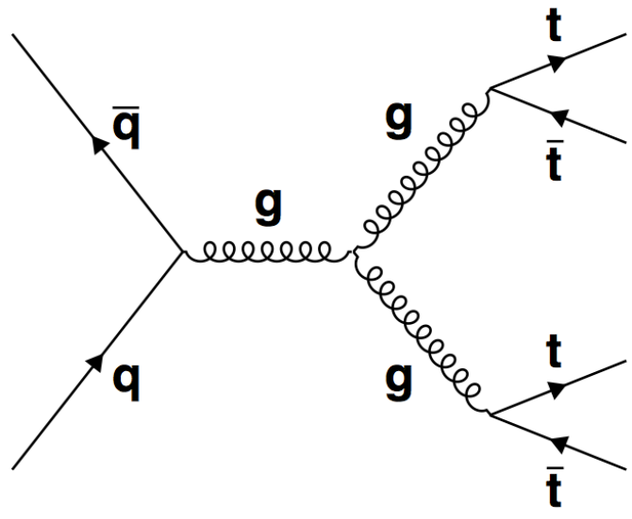
- Looking for standard model production of 4 tops
  - Trijet system (jets from bottom quark and quarks from W) reconstructed assuming the two jets with the smallest separation come from the W
  - BDT_{trijet} takes in dijet mass of W, trijet mass of top, dijet/trijet and non-dijet/trijet system separation (low), ratio of vector to scalar p_T of trijet (high), b-tag discriminator of non-dijet. Jets not in highest BDT_{trijet} form reduced event (RE).



  - Event BDT includes number of b-tags and the following:

Two variables based on the RE are (i) H_T^{RE}, i.e., the H_T of the RE and (ii) M^{RE}, i.e., the invariant mass of the system comprising all the jets in the RE.

(i) N_{jets}, (ii) H_T^b, (iii) H_T/H_p, (iv) H_T^{ratio}, (v) p_{T5}, and (vi) p_{T6}. The H_T^b variable is defined to be the H_T of the b-tagged jets. In the H_T/H_p ratio, H_p is the scalar sum of the total momenta of the selected jets. The ratio of the H_T of the four leading jets to the H_T of the other jets is defined as H_T^{ratio}. The p_{T5} and p_{T6} variables represent, respectively, the p_T values of jets of 5th and 6th largest p_T. All these variables are used in the discriminant described in Section 5.4.



  - JHEP 11 (2014) 154

Full list of tt+X results

- tt+jets: TOP-12-018 (CMS 7 TeV), TOP-12-041 (CMS 8 TeV), ATLAS 7 TeV, CDF
- tt+bb: TOP-13-010 (CMS 8 TeV), ATLAS 7 TeV
- ttW / ttZ: TOP-12-036 (CMS 8 TeV), TOP-12-014 (CMS 7 TeV), CONF-14-038 (ATLAS 8 TeV), CONF-12-126 (ATLAS 7 TeV)
- Four top: TOP-13-012 (CMS 8 TeV), CONF-13-051 (ATLAS 8 TeV), CONF-12-130 (ATLAS 7 TeV)