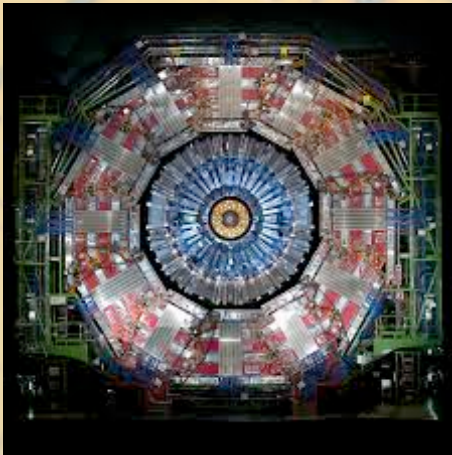


Top Quark Production at 8 TeV

Kate Shaw

ATLAS Udine/ICTP Group

On behalf of the ATLAS and CMS Collaborations



**The XLIXth Rencontres de Moriond
QCD and High Energy Interaction
22nd – 29th March 2014
La Thuile, Italy**

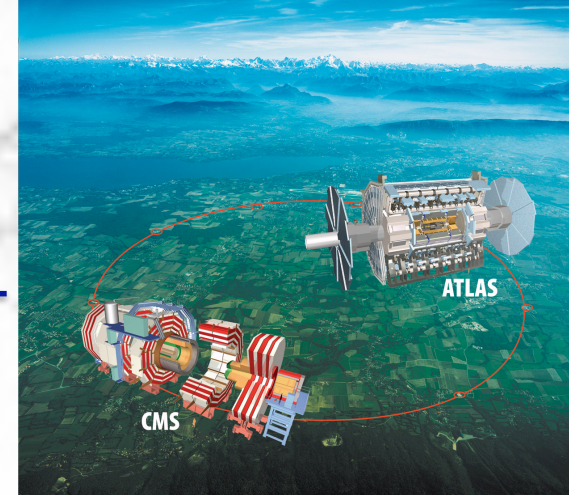


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for Theoretical Physics**



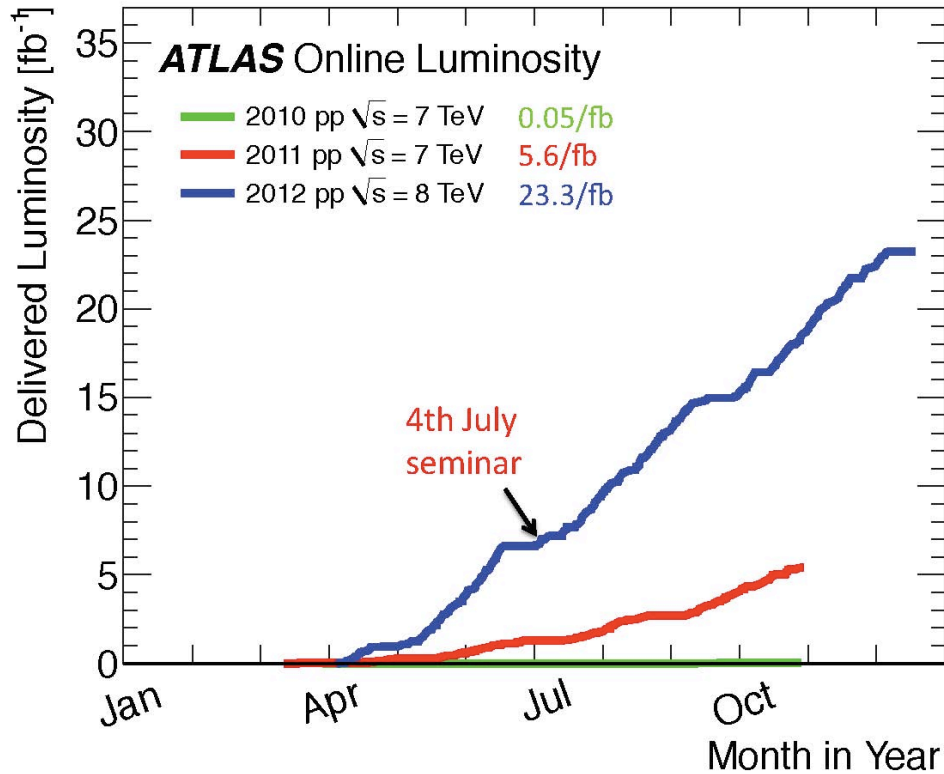


Introduction

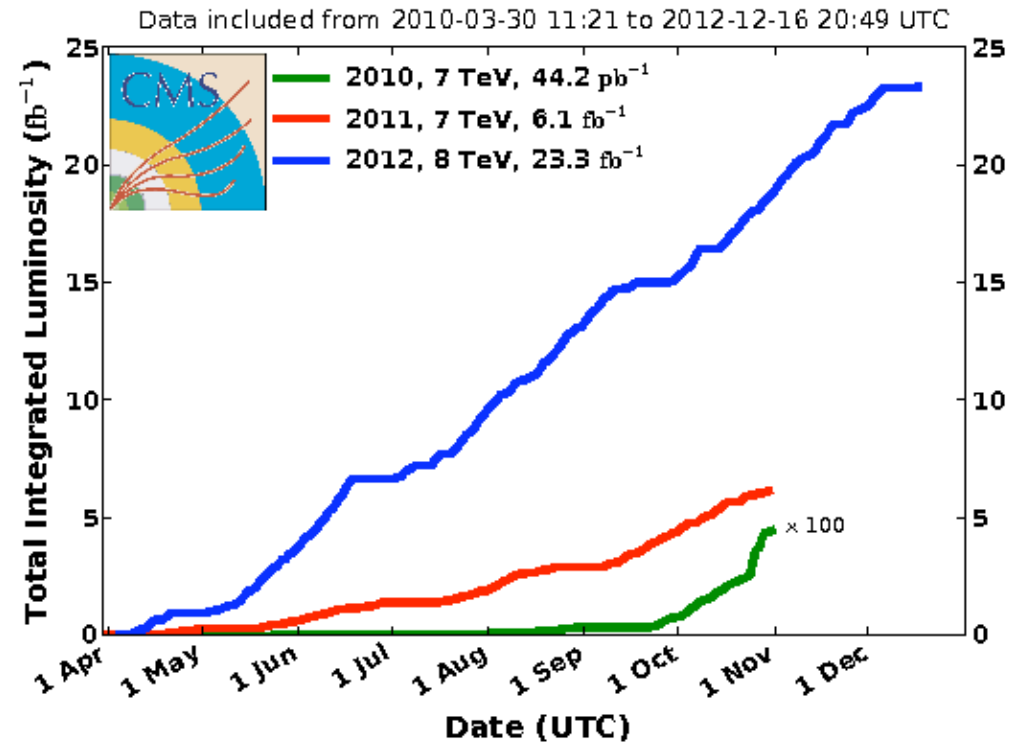


5fb⁻¹ @ 7TeV + 20 fb⁻¹ @ 8TeV
 5.5 million top pairs
 2.7 million single tops

Comput. Phys. Commun. 182 (2011) 1034



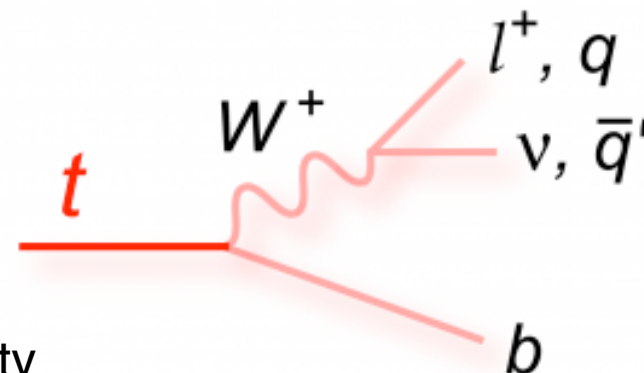
CMS Integrated Luminosity





Top Production at 8 TeV

- Top quark is heaviest elementary particle
- Lifetime shorter than timescale of hadronisation
- Decays $\sim 100\%$ to W-boson and b-quark $|V_{tb}| \sim \text{unity}$
- Final state topology depends on W decay
- Yukawa coupling to Higgs is order unity
- Top quark studies provide important information of fundamental interactions at the electroweak breaking scale and beyond.



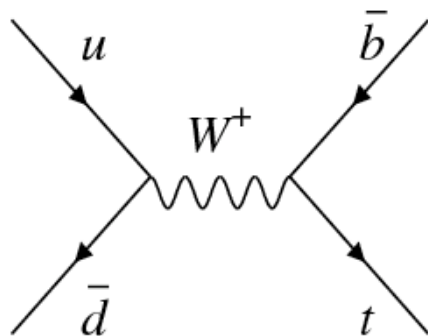


Single top production

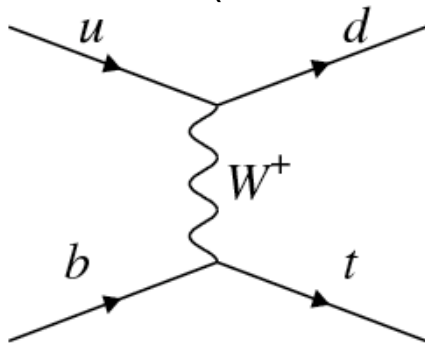
[1] Phys. Rev. D 81 (2010) 054028, arXiv:1001.5034.
 [2] Phys. Rev. D 83 (2011) 091503, arXiv:1103.2792
 [3] Phys. Rev. D 81 (2010) 054028, arXiv:1001.5034.

- Single top quark production by charged-current electroweak interactions
- LO classification:

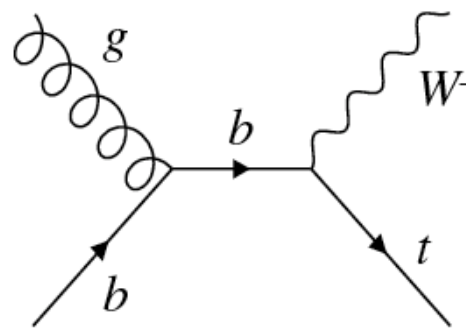
s-channel



t-channel (dominant)



Wt associated production channel



NLO+NNLO with $m_t = 173.3$ GeV at 8TeV @LHC

$$[1] \sigma_s = 5.6 \pm 0.2 \text{ pb}$$

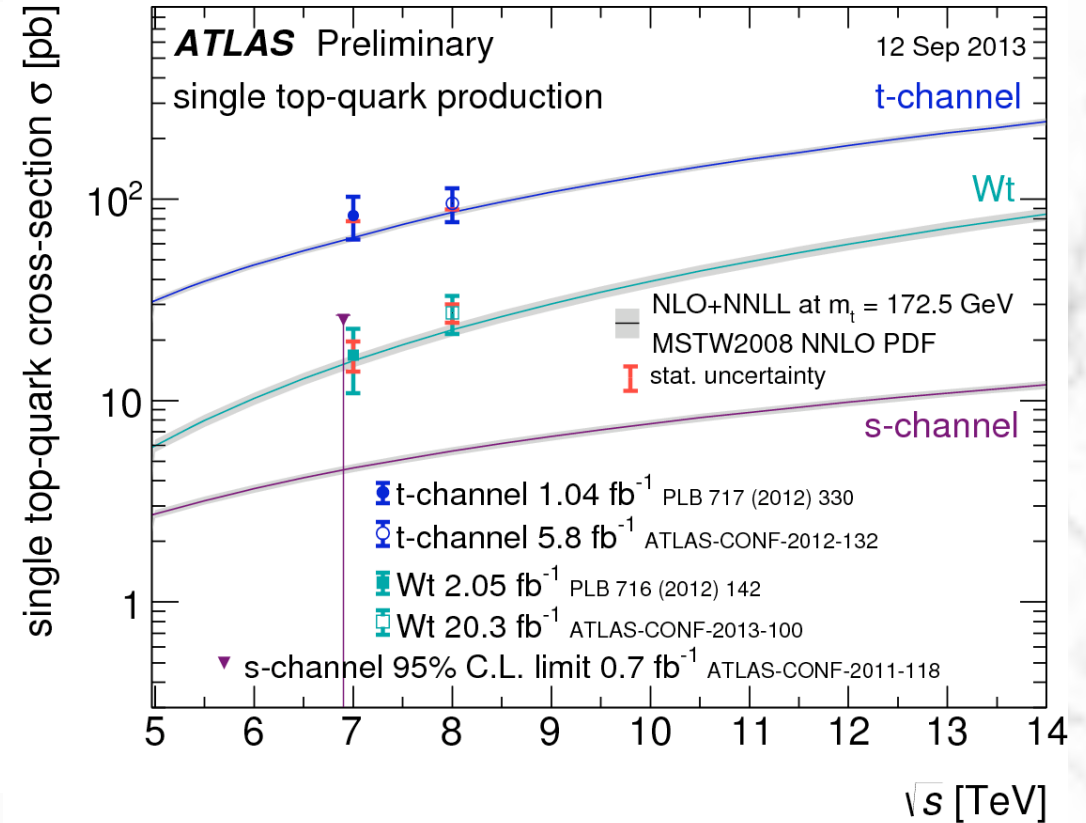
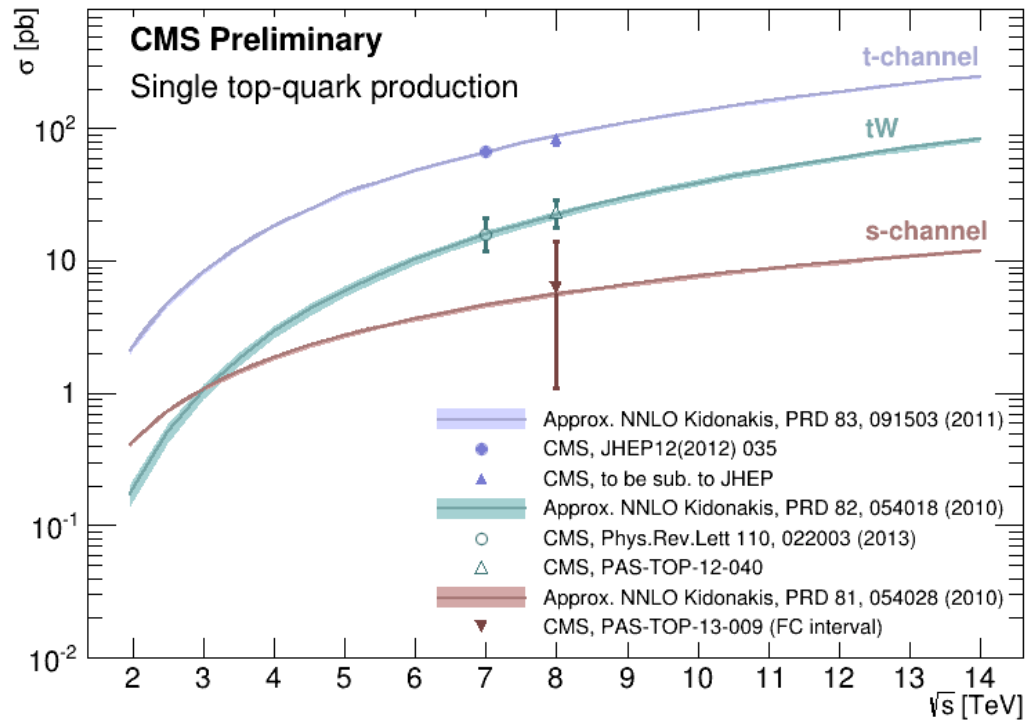
$$[2] \sigma_t = 87.8^{+3.4}_{-1.9} \text{ pb}$$

$$[3] \sigma_{Wt} = 22.4 \pm 1.5 \text{ pb}$$

- $\sigma_{\text{single top}}$ proportional $|V_{tb}|^2$, probes the electroweak Wtb vertex
- Measuring polarization observables tests the left-handed nature of the charged-current
- Sensitivity to different manifestations of BSM physics



Single top production





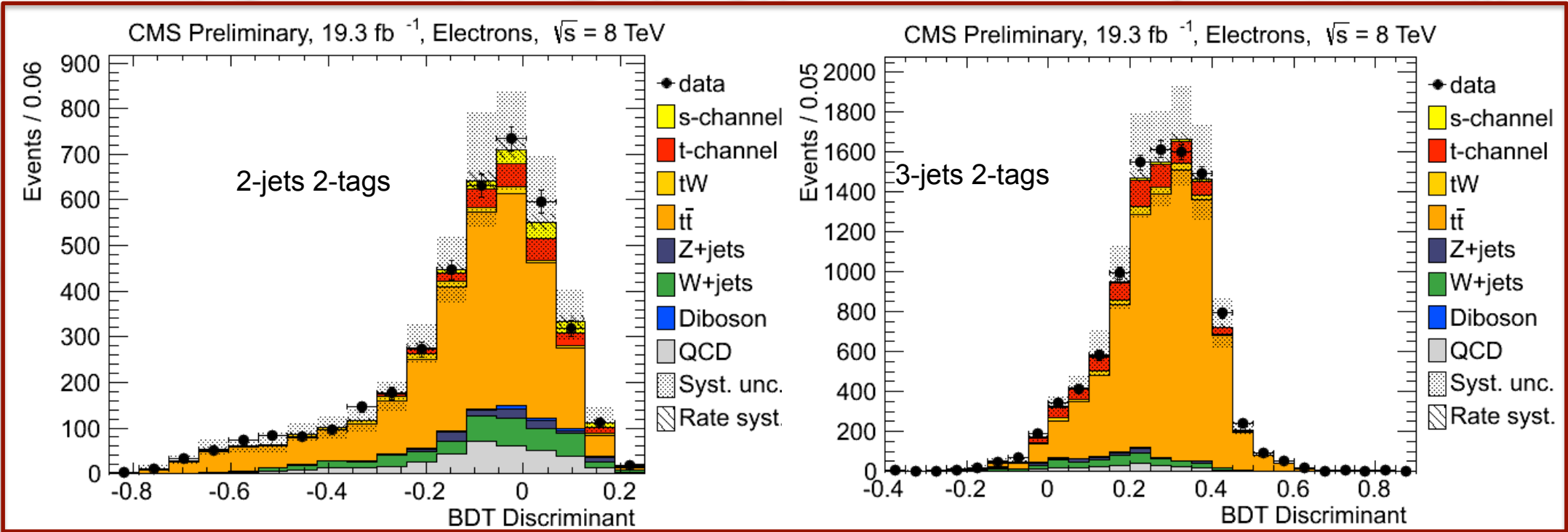
Single top production s-channel

CMS-TOP-13-009



CMS performed first search at LHC in leptonic channel at 8 TeV using 19.3 fb⁻¹

- Samples: exactly one isolated e or μ and 2-jets 0-tags, 2jets 2-tags, or 3-jets 2tags
- Multivariate approach using BDT measure $\sigma_{s\text{-channel}} = 6.2^{+0.8}_{-5.1}$ pb (0.7 σ signal significance)
- Measured upper limit 2.1 times SM cross-section 11.5 pb at 95% CL.
- Sensitivity limited by theoretical systematic





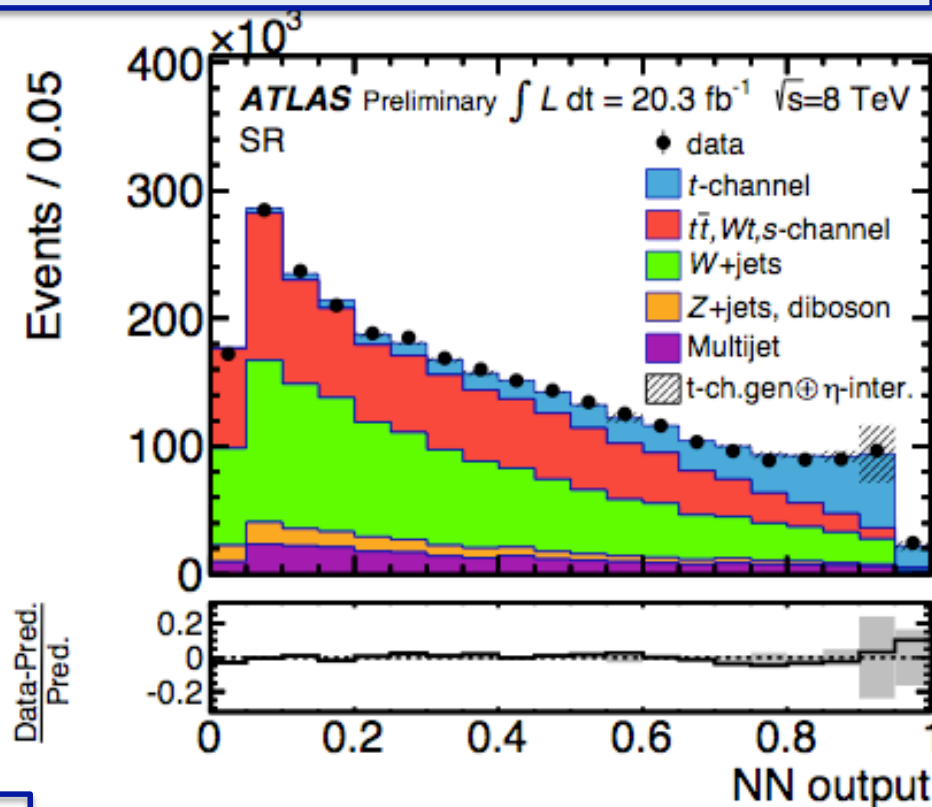
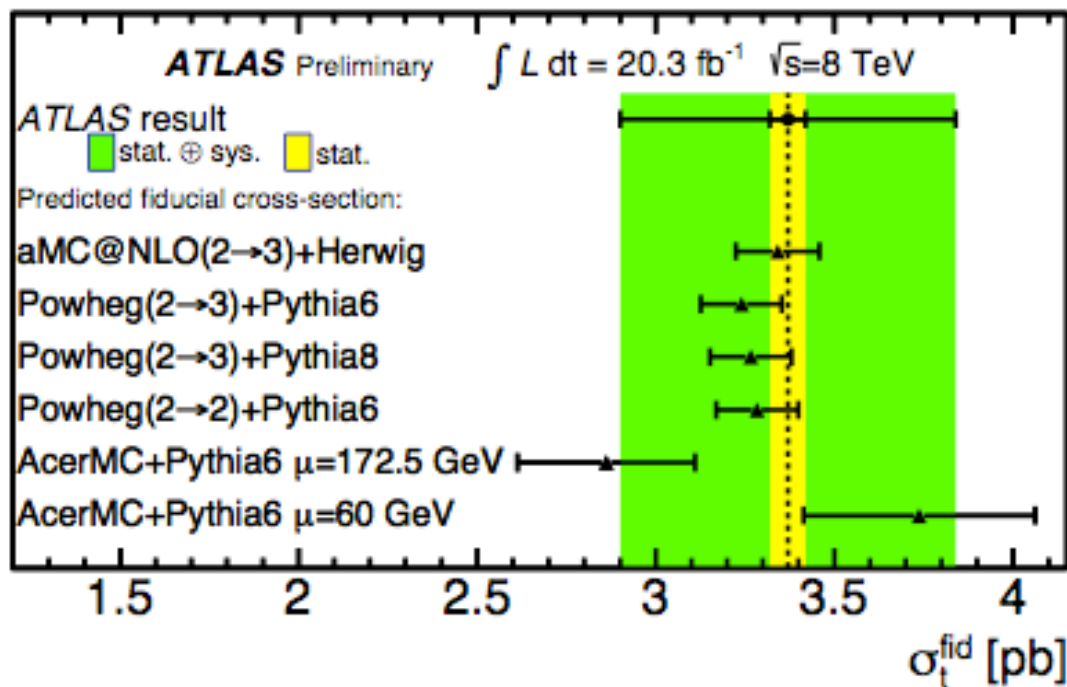
Single top production t-channel

ATLAS-CONF-2014-007



ATLAS Inclusive and Fiducial cross-section with 20.3 fb⁻¹

- Events selected with exactly one lepton exactly two jets, one b-tagged
- Cross-section extracted using binned maximum-likelihood fit to neutral-network discriminant using 14 variables (MC modelling, JES dominant systematic)



$$\sigma_{\text{fid}} = 3.37 \pm 0.05 (\text{stat.}) \pm 0.47 (\text{syst.}) \pm 0.09 (\text{lumi.}) \text{ pb.}$$

at 8TeV

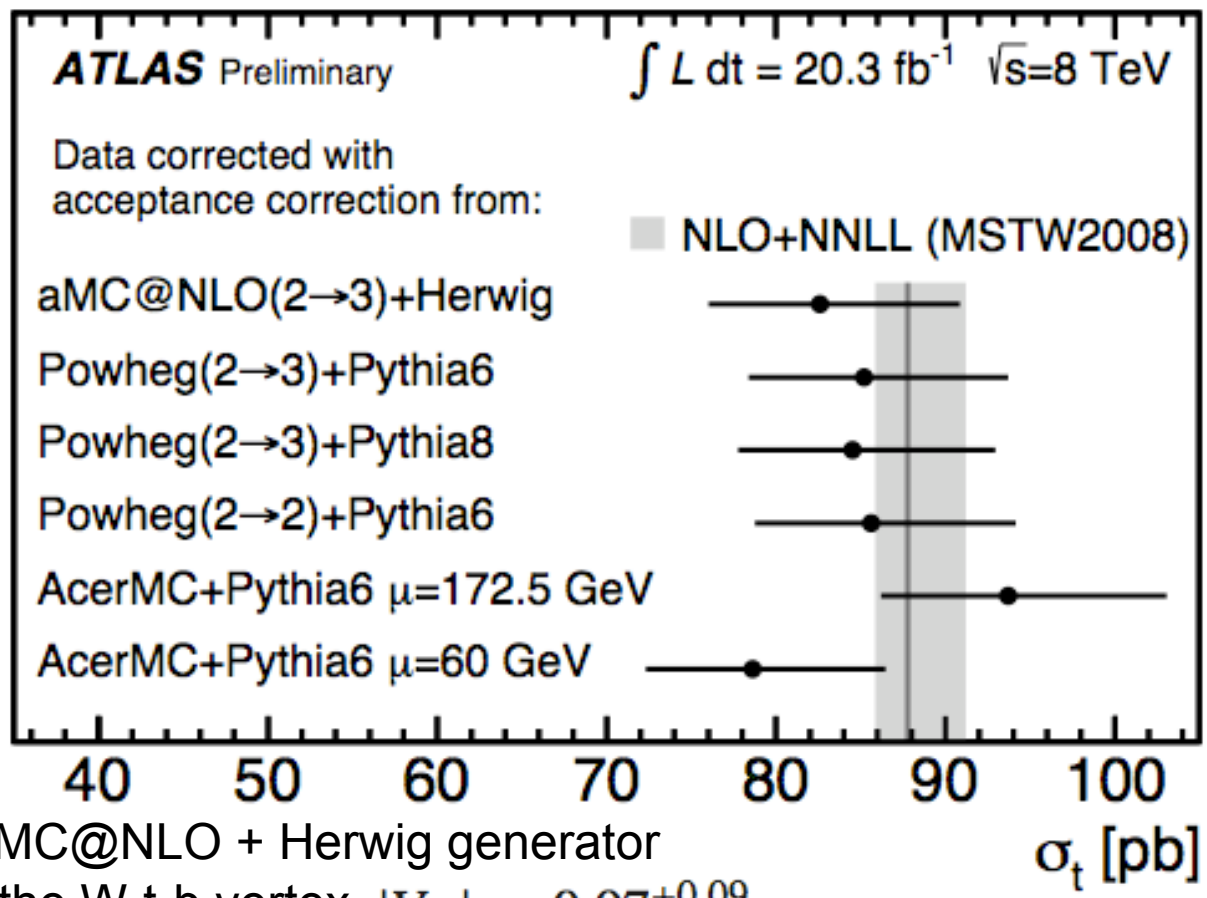


Single top production t-channel

ATLAS-CONF-2014-007



$$\sigma_t = 82.6 \pm 1.2 (\text{stat.}) \pm 11.4 (\text{syst.}) \pm 3.1 (\text{PDF}) \pm 2.3 (\text{lumi.}) \text{ pb}$$



■ Cross-section extrapolated to full phase space using acceptance of different MC generators

Assuming aMC@NLO + Herwig generator
Coupling at the W-t-b vertex $|V_{tb}| = 0.97^{+0.09}_{-0.10}$



Single top production t-channel

CMS-PAPER-TOP-12-038

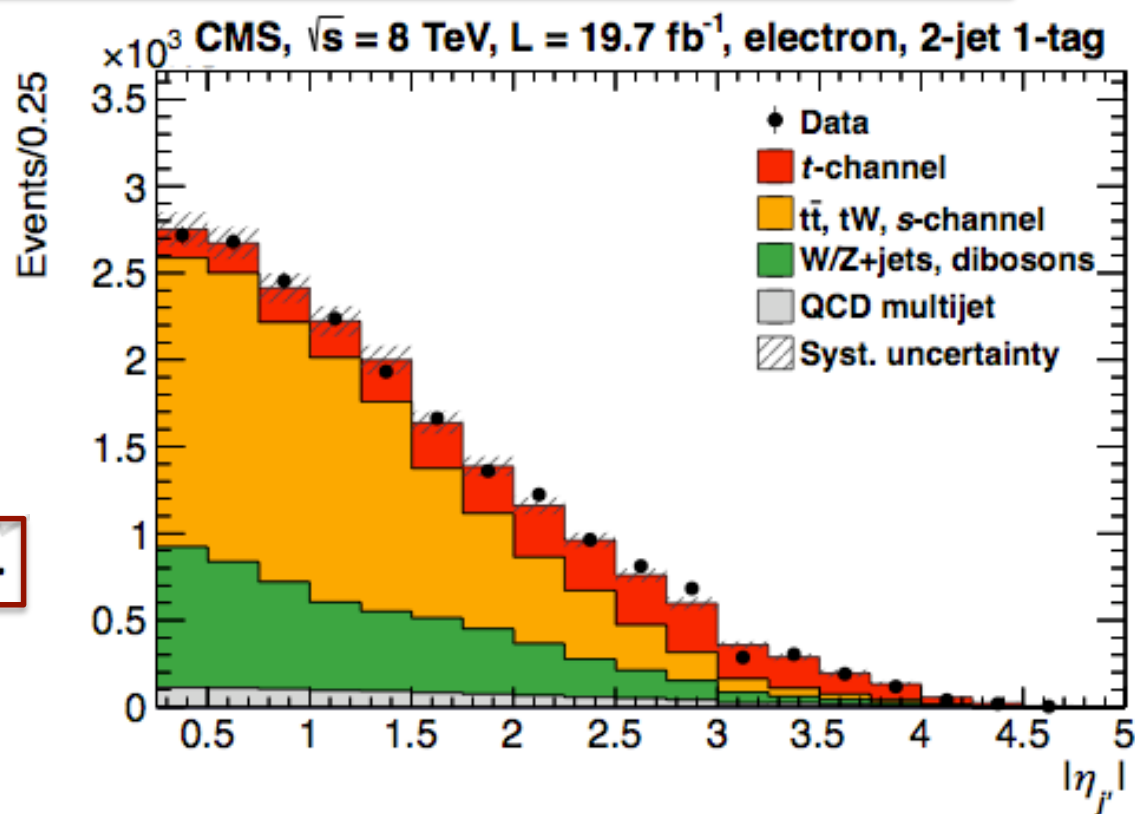
CMS inclusive t-channel cross-section and ratio of t to tbar with 19.7fb⁻¹

▪ $R_{t\text{-ch}} = \sigma_{t\text{-ch,top}} / \sigma_{t\text{-ch,anti-top}}$ provides effective handle to constrain proton PDF models, sensitive to new physics

- Selection: Exactly one lepton, two jets 1 btag
- Yield extracted from binned maximum-likelihood fit to the pseudorapidity of recoil quark in events with positively and negatively charged leptons

$$\sigma_{t\text{-ch.}} = 83.6 \pm 2.3 \text{ (stat.)} \pm 7.4 \text{ (syst.) pb.}$$

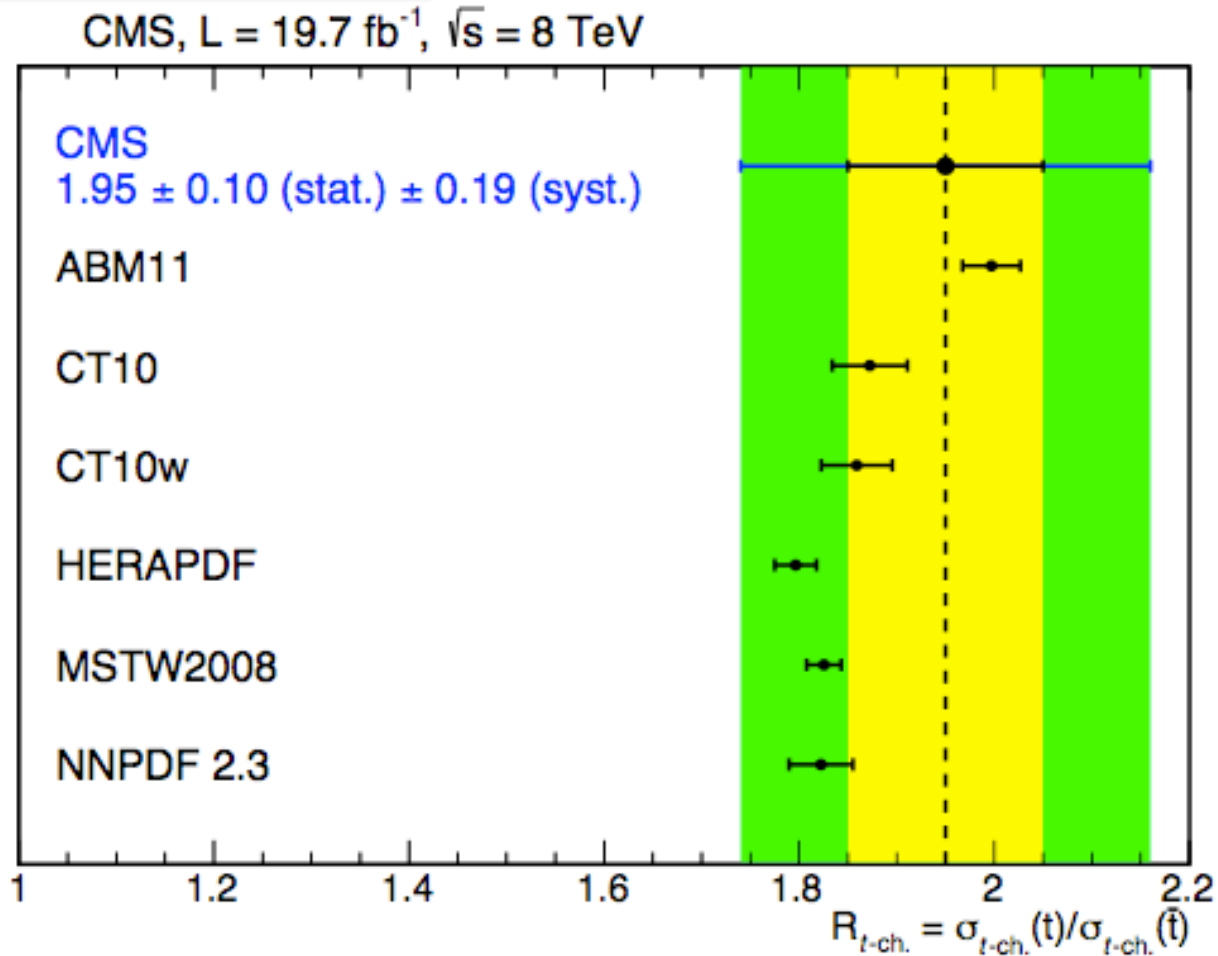
- Dominant systematics JES JER MET PU, signal modeling





Single top production t-channel

CMS-PAPER-TOP-12-038



$$R_{t\text{-ch.}} = \sigma_{t\text{-ch.}}(t)/\sigma_{t\text{-ch.}}(\bar{t}) = 1.95 \pm 0.10 \text{ (stat.)} \pm 0.19 \text{ (syst.)}$$

$$|f_{L_V} V_{tb}| = 0.979 \pm 0.045 \text{ (exp.)} \pm 0.016 \text{ (theo.)}$$



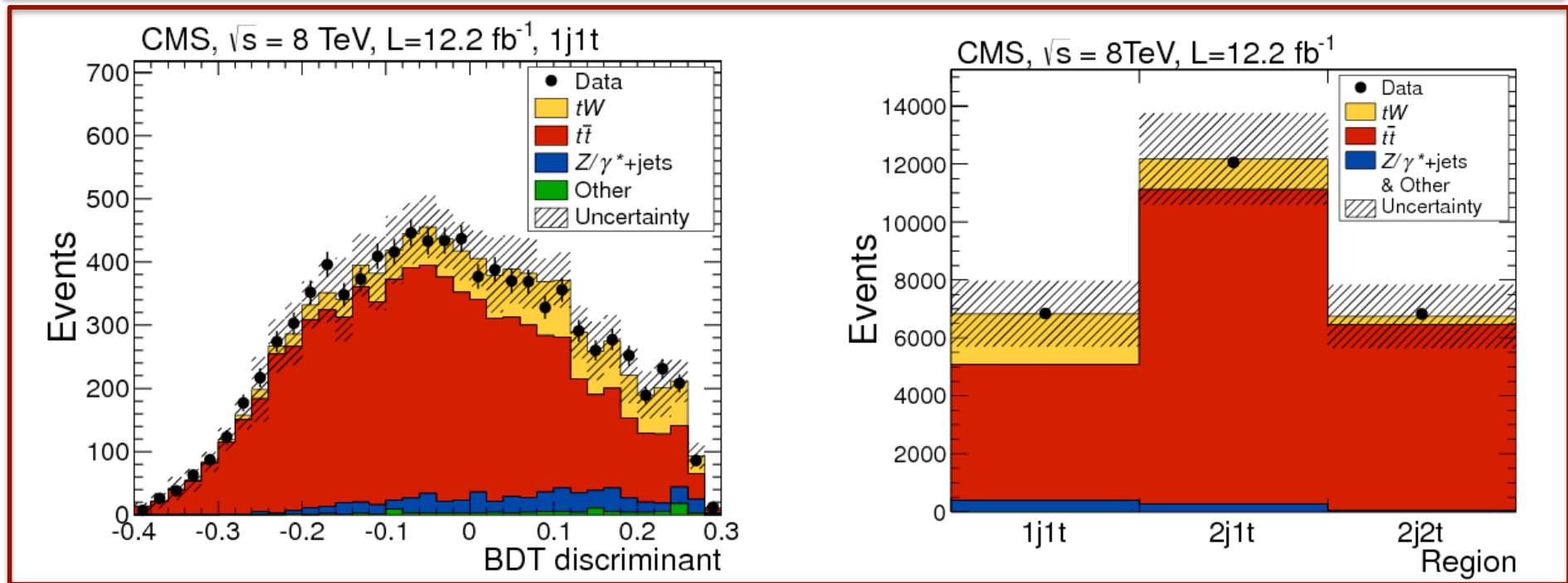
Single top production Wt associated production

CMS-TOP-12-040
arXiv:1401.2942

CMS: Dilepton channel (12.2 fb⁻¹)

- Cross-section determined with multivariate technique
- Event selection includes exactly two leptons and a b-tagged jet
- Dominant systematic uncertainty from MC modeling
- Measured cross-section 23.4 ± 5.4 pb (6.1 σ significance)

$$|V_{tb}| = \sqrt{\sigma_{tW}/\sigma_{tW}^{\text{th}}} = 1.03 \pm 0.12 (\text{exp}) \pm 0.04 (\text{th.})$$





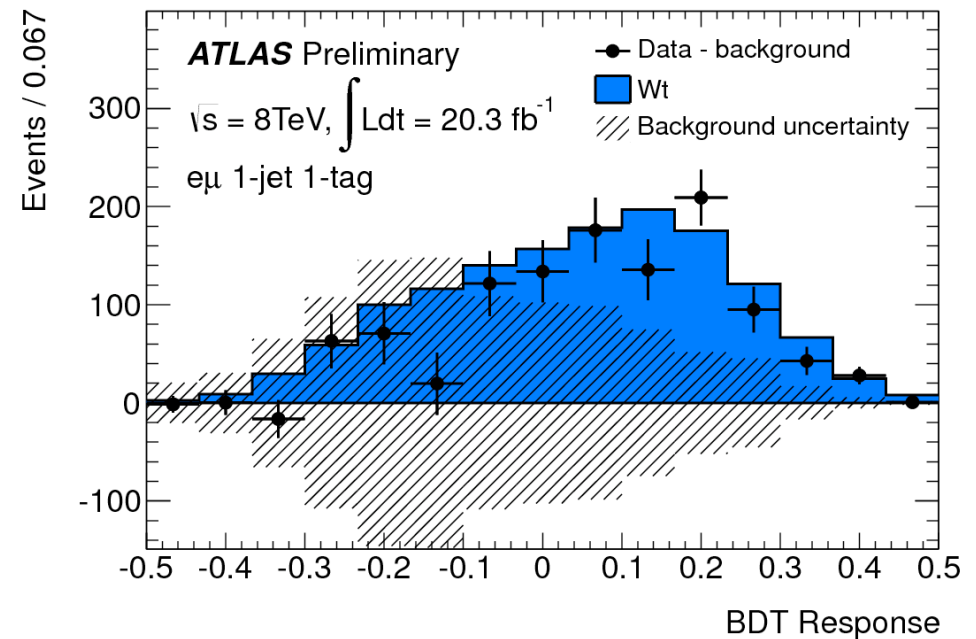
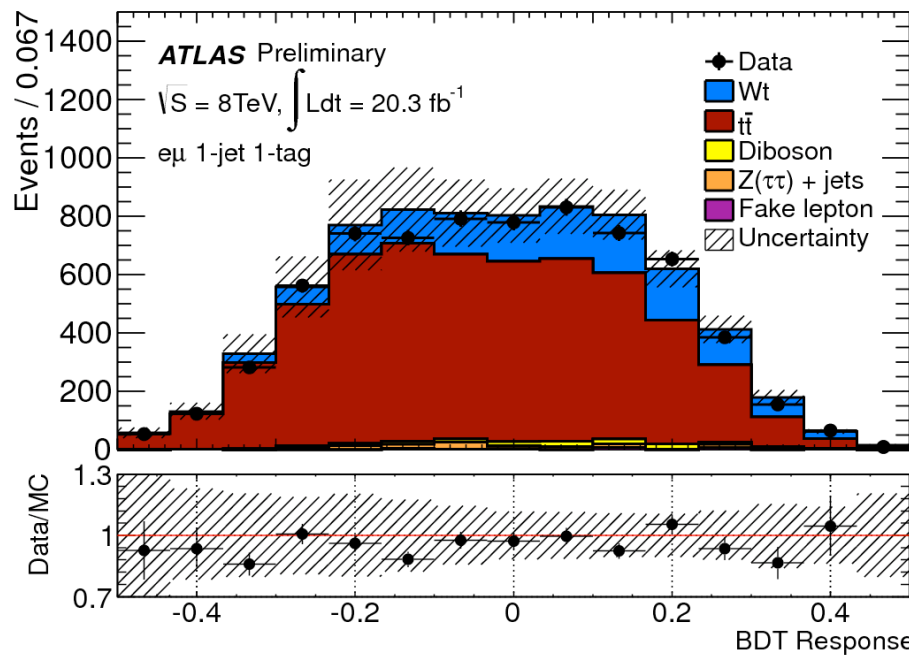
Single top production Wt associated production

ATLAS-CONF-2013-100

ATLAS: $e\mu$ Dilepton channel (20.3 fb^{-1})

- Cross-section determination using maximum likelihood fit to 1 and 2 jet events
- Boosted Decision Trees (BDT) used to distinguish Wt from tt
- Dominant systematic uncertainty from b-tagging performance and JES
- Cross-section 27.2 ± 2.8 (stat) ± 5.4 (syst) pb (4.2σ)

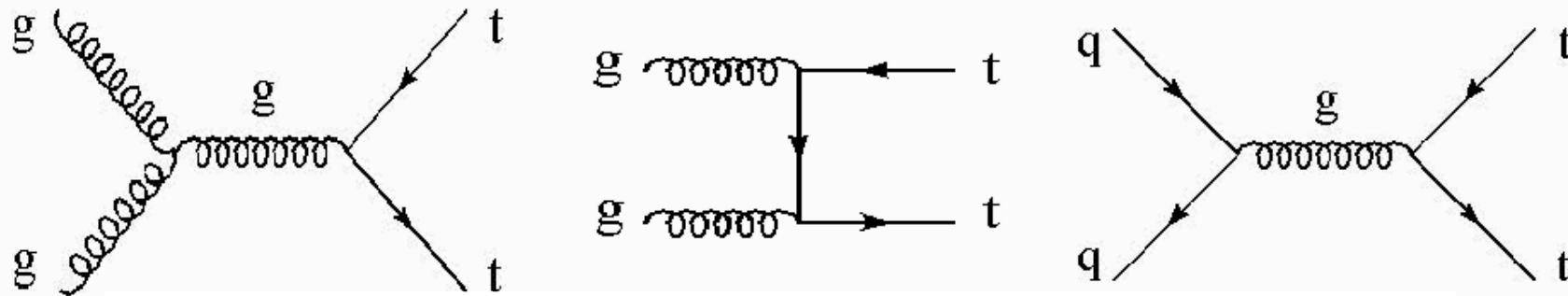
$$|V_{tb} \cdot f| = 1.10 \pm 0.12 \text{ (exp)} \pm 0.03 \text{ (theory)}$$





Top pair production

- Top quark pair production governed by strong interactions (gg fusion dominant (~80%))
- NNLO + NNLL with $m_t = 172.5$ GeV at 8TeV CM Energy $\sigma_{tt} = 252.9 \pm 11.7^{+6.4}_{-8.6}$ pb [4]



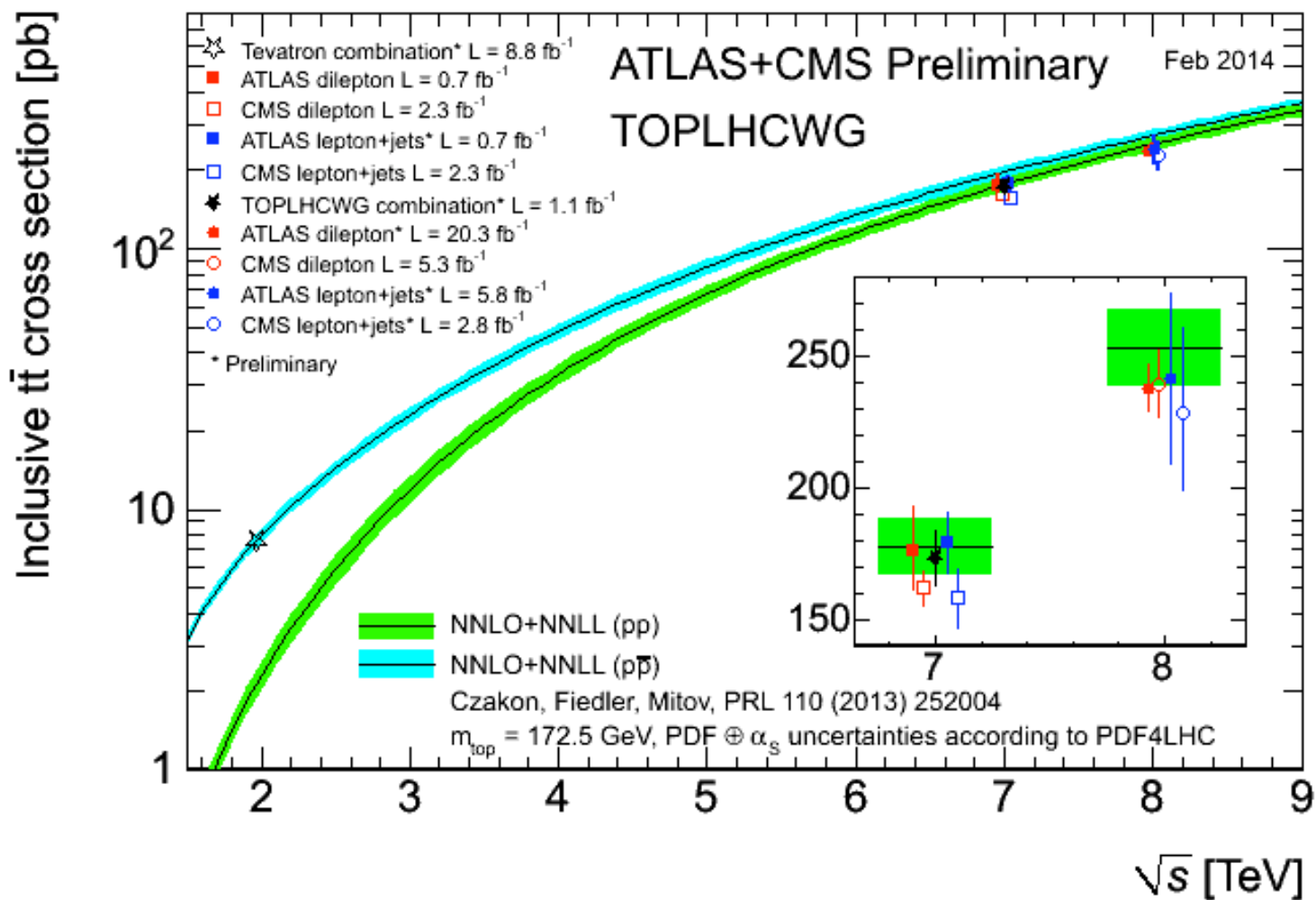
Top Pair Decay Channels

$c\bar{s}$	electron+jets	muon+jets	tau+jets	all-hadronic
$u\bar{d}$				
$\tau^+\tau^-$			tau+jets	
$\mu^+\mu^-$	dileptons	muon+jets		
e^+e^-	dileptons	electron+jets		
W decay	e^+	μ^+	τ^+	$u\bar{d}$ $c\bar{s}$

- Sensitive to new physics
- Can constrain modeling (PDF, ISR/FSR)
- Important background to many Higgs and BSM searches



Top pair production





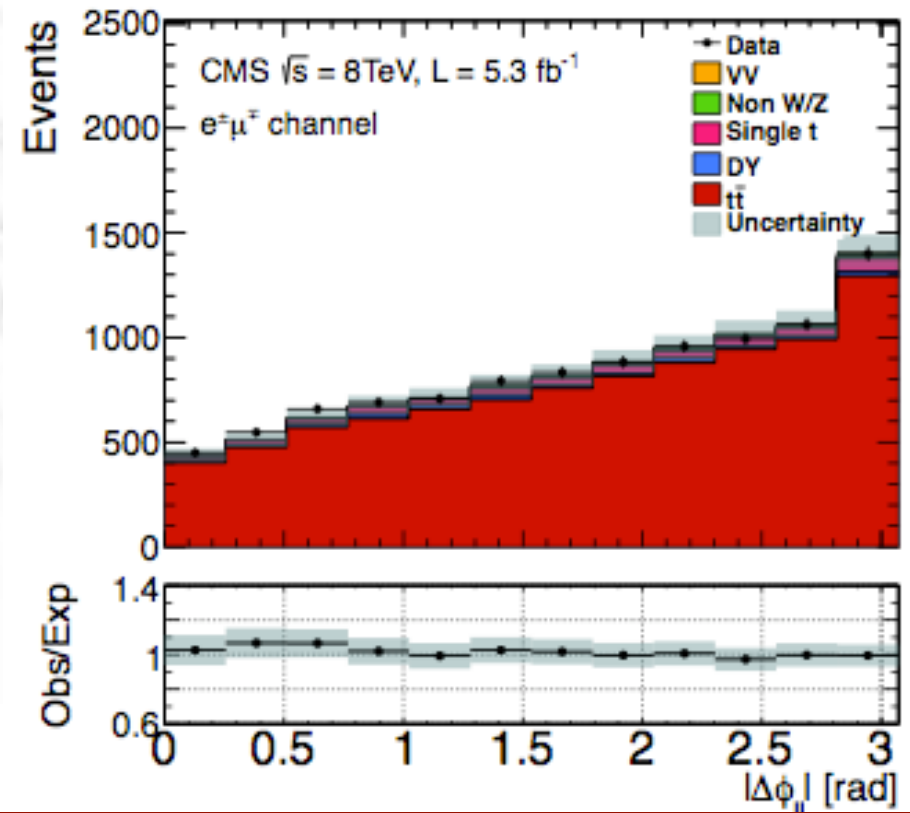
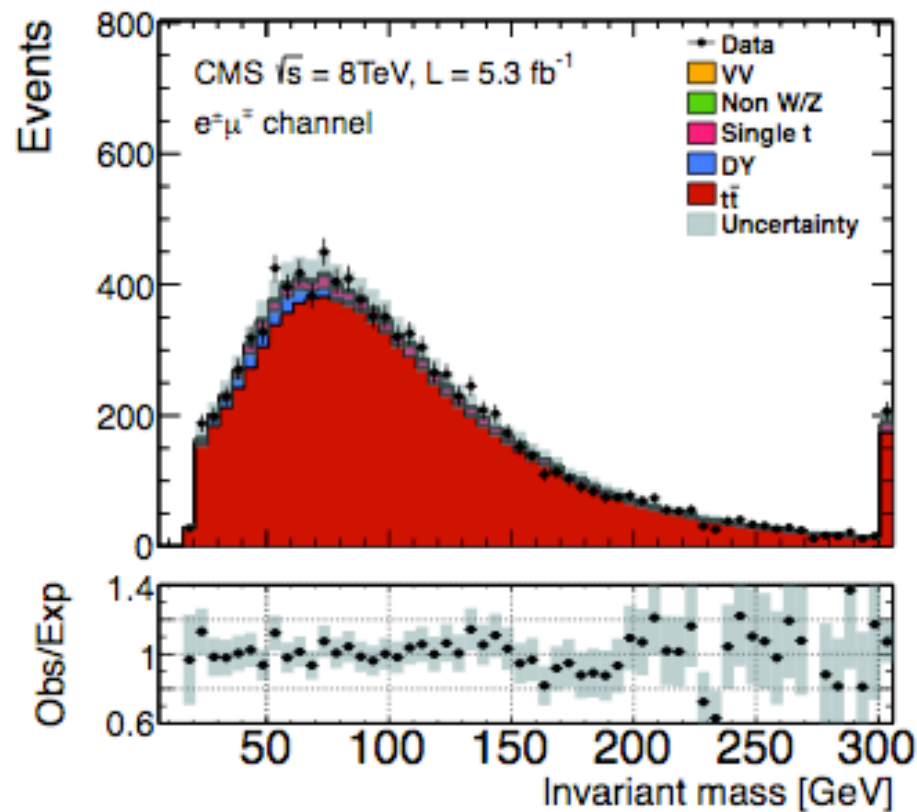
Top Pair Production Dilepton channel with CMS

CMS-Top-12-007
JHEP 02 (2014) 024

CMS top-quark pair production in dilepton channel using 5.3 fb⁻¹

- Events are selected with two leptons (eμ, ee, μμ) and two jets one b-tagged
- Cross-section extracted by optimising cuts and event counting
- Dominant uncertainties include JES and JER, DY modeling (ee and μμ)
- Combination using BLUE method

$$\sigma_{t\bar{t}} = 239.0 \pm 2.1 \text{ (stat.)} \pm 11.3 \text{ (syst.)} \pm 6.2 \text{ (lum.) pb}$$





Top Pair Production Dilepton channel with ATLAS

ATLAS-CONF-2013-097

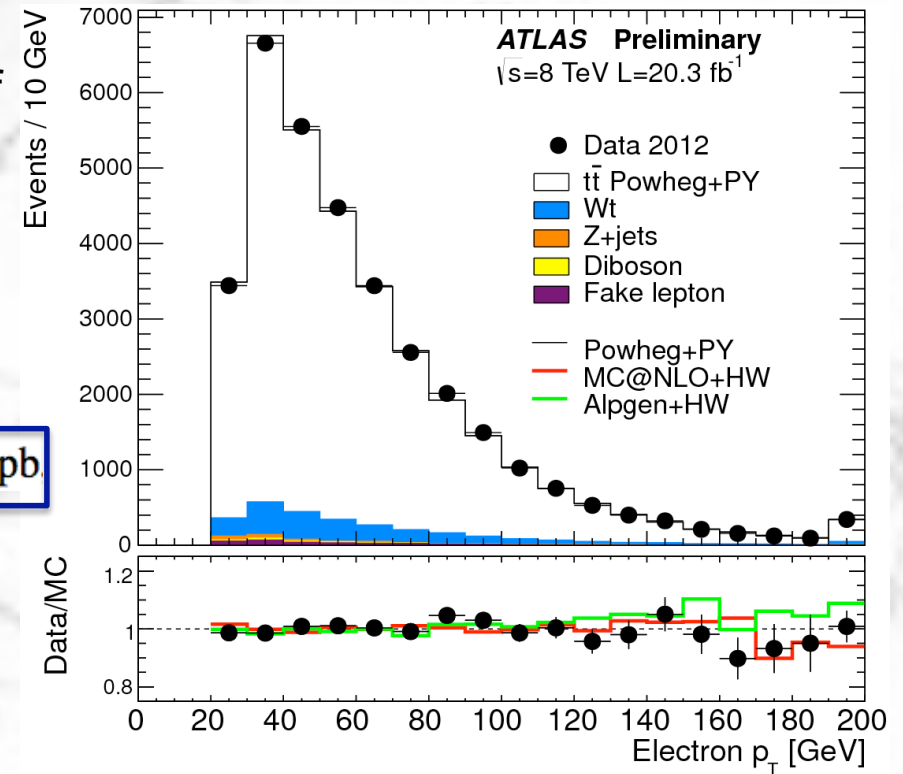
- **ATLAS dilepton channel ($tt \rightarrow e\mu\nu\nu b\bar{b}$) 20.3 fb^{-1}**
- Cross-section obtained by counting number of opposite sign $e\mu$ events with 1 and 2 btagged jets
- Simultaneously determines b-tag reconstruction efficiency minimising systematic uncertainties

$$\sigma_{t\bar{t}} = 237.7 \pm 1.7 \text{ (stat)} \pm 7.4 \text{ (syst)} \pm 7.4 \text{ (lumi)} \pm 4.0 \text{ (beam energy)} \text{ pb}$$

- Precision matches theory uncertainty

$$N_1 = L\sigma_{t\bar{t}} \epsilon_{e\mu} 2\epsilon_b (1 - C_b \epsilon_b) + N_1^{\text{bkg}}$$

$$N_2 = L\sigma_{t\bar{t}} \epsilon_{e\mu} C_b \epsilon_b^2 + N_2^{\text{bkg}}$$



- ϵ_b : Probability $t \rightarrow Wq$ quark to be reconstructed and tagged as b-jet within acceptance

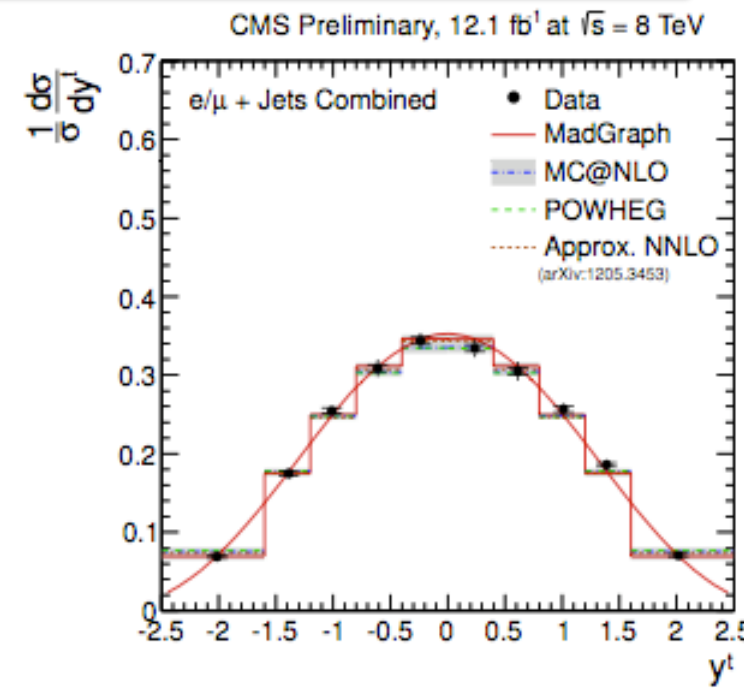
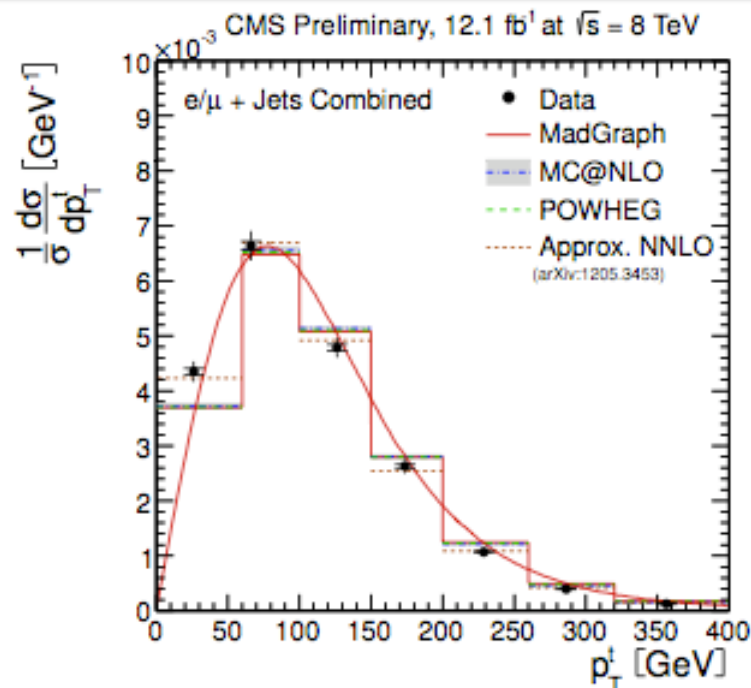
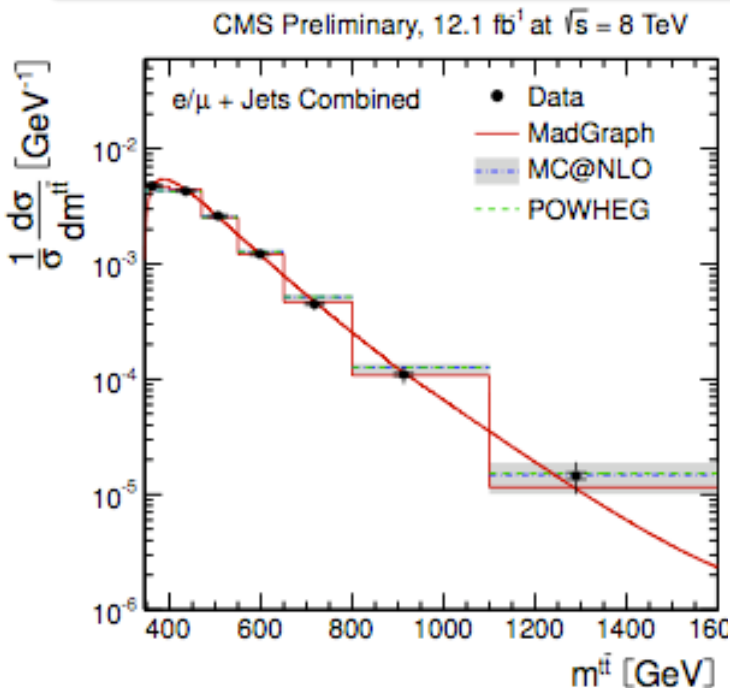


Differential Cross-Section measurements with CMS

CMS-PAS-TOP-12-027
CMS-PAS-TOP-12-028

Differential cross-section measurements by CMS using 12 fb⁻¹ of data in single- and di-lepton channels show good agreement between data and theory predictions

- Normalised differential cross-section measured as a function of kinematic properties of the final state charged lepton(s), b-tagged jets, top quarks and the tt system
- Approximate NNLO gives an improved description of the data





Top Pair Production Ratio $t\bar{t}b\bar{b}$ / $t\bar{t}j\bar{j}$

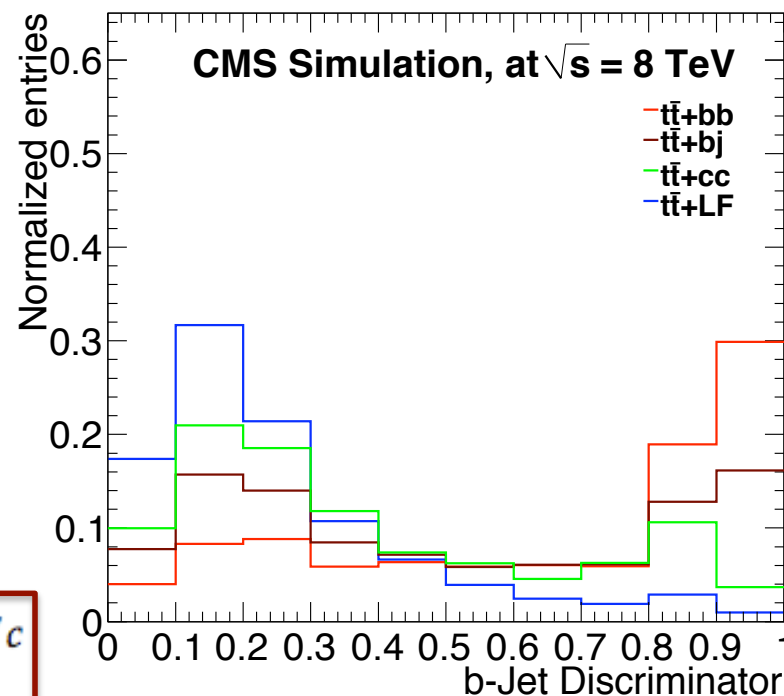
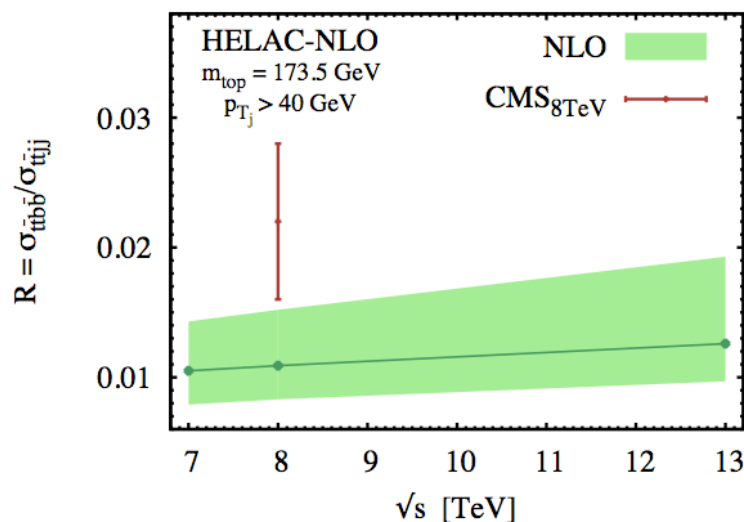
CMS-PAS-TOP-13-010
arXiv:1403.2046

CMS measurement of cross-section ratio $\sigma(t\bar{t}b\bar{b}) / \sigma(t\bar{t}j\bar{j})$ 19.6 fb^{-1}

- Top quark pair production in association with $b\bar{b}$ pair irreducible background to $t\bar{t}H$
- Test of NLO QCD theory, which suffers from large factorisation and renormalisation uncertainties
- Ratio measurement allows experimental uncertainties to cancel

- Selection: At least four jets, two leptons, two b-tagged jets
- Dominant uncertainties: b-jet tagging efficiency, mistagging

New



$$\sigma(t\bar{t}b\bar{b}) / \sigma(t\bar{t}j\bar{j}) = 0.023 \pm 0.003(\text{stat.}) \pm 0.005(\text{syst.}) \text{ at } p_{T_j} > 20 \text{ GeV}/c$$

$$\sigma(t\bar{t}b\bar{b}) / \sigma(t\bar{t}j\bar{j}) = 0.022 \pm 0.004(\text{stat.}) \pm 0.005(\text{syst.}) \text{ at } p_{T_j} > 40 \text{ GeV}/c$$



Top Pair Production Associated with a photon

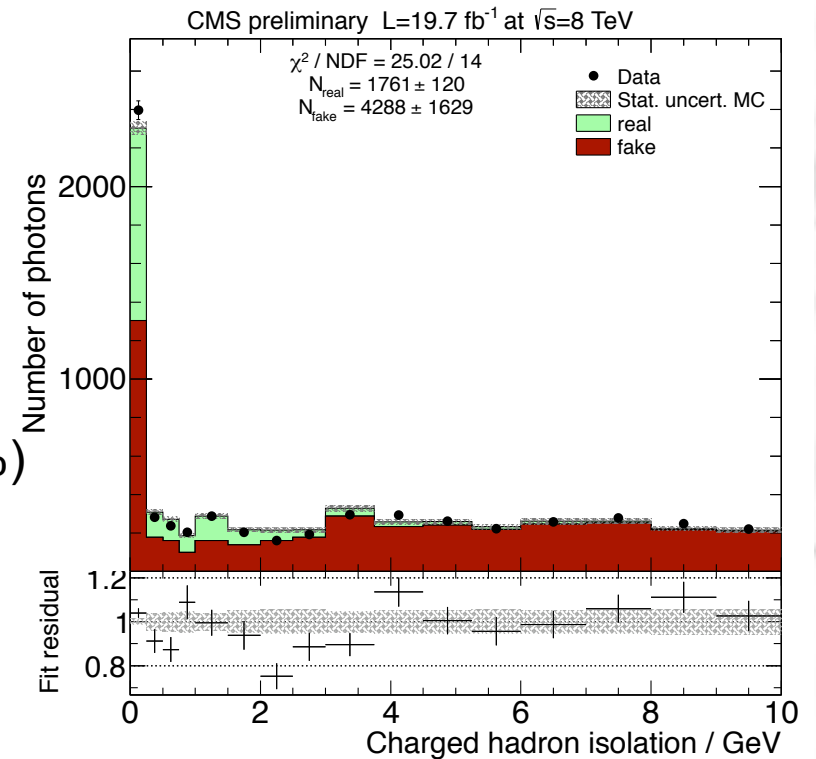
[5] Eur.Phys.J. C71 (2011) 1742

CMS-PAS-TOP-13-011

CMS top-quark pair + photon production in muon+jets channel using 19.7 fb⁻¹

- Events selection: exactly one muon, at least four jets and a hard photon $p_T > 20$ GeV
- $R = \sigma_{tt+\gamma} / \sigma_{tt}$ calculated using selection parameters and a template fit
- Cross-section extracted by multiplying R with recent top-quark pair cross-section

- Binned maximum likelihood template fit estimates photon misidentification contribution
- Dominant misidentified photon source is hadronic
- Normalised cross-section R reduces uncertainties
- Background modeling is dominant systematic (23%)



$$\sigma_{\bar{t}t+\gamma}^{\text{SM}} = 1.8 \pm 0.5 \text{ pb} \quad [5]$$

$$\sigma_{\bar{t}t+\gamma} = R \sigma_{\bar{t}t}^{\text{CMS}} = 2.4 \pm 0.2 \text{ (stat.)} \pm 0.6 \text{ (syst.) pb}$$



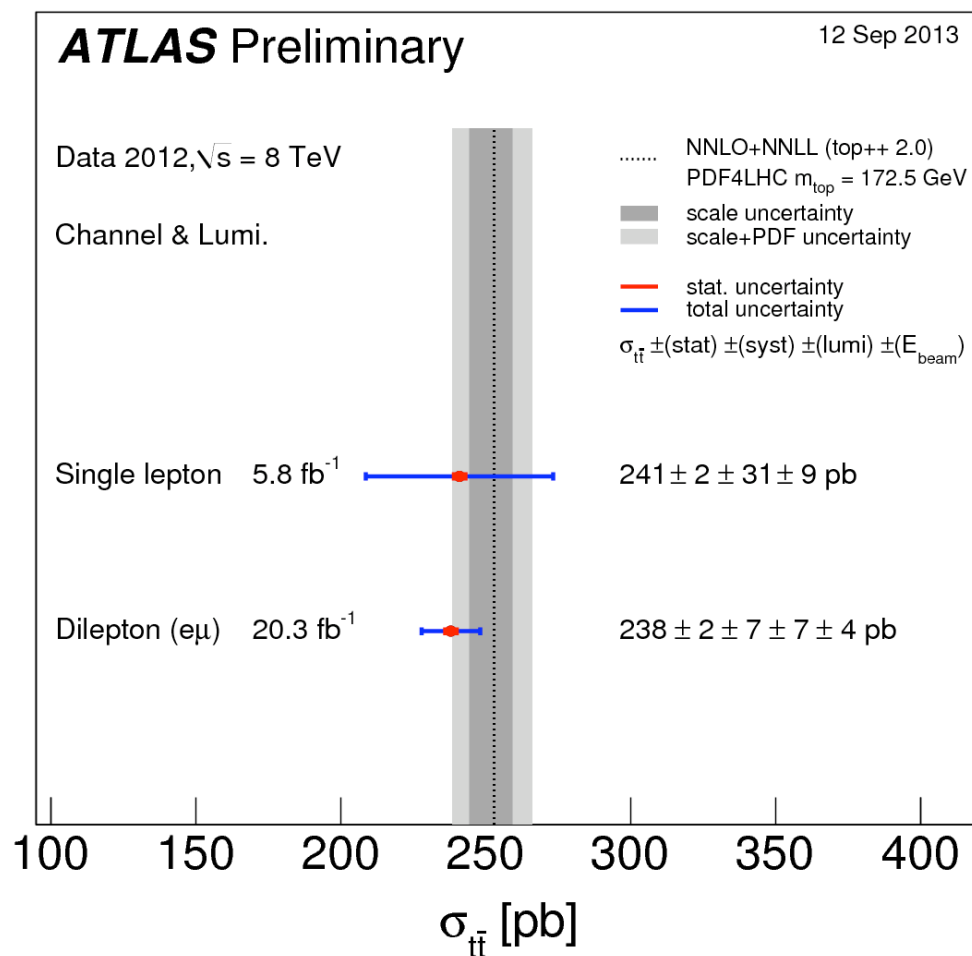
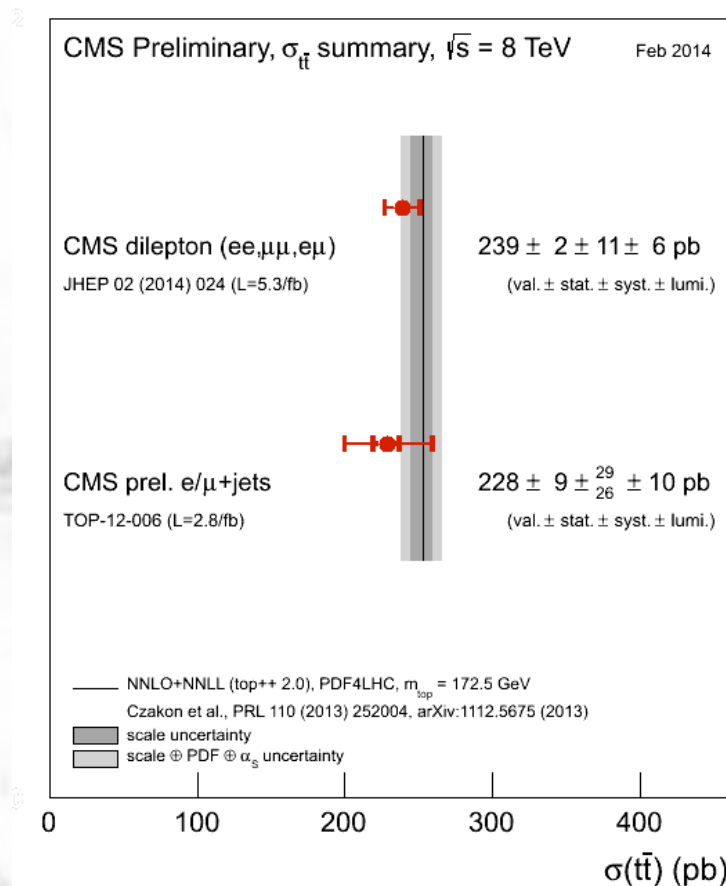
Summary

Measurements are presented from ATLAS and CMS of the top production cross-sections in proton-proton collisions at 8 TeV

- ❖ New s-channel searches at LHC presented
- ❖ New t-channel and tW-channel single-top cross-section measurements at 8 TeV
- ❖ Measurements of inclusive top-quark pair production match high precision (NNLO) theory calculations
- ❖ Differential distributions generally well described by MC (NLO+PS) models. Improved descriptions by yet higher order calculations?
- ❖ Many more 8 TeV Top cross-section results underway



Top pair production





Top Pair Production Single lepton channel

ATLAS-CONF-2012-149
CMS-PAS-TOP-12-006

ATLAS measured top pair production cross-section in single lepton channel using kinematic fits with b-tagging using 5.8 fb⁻¹ of data

- Multivariate technique used with b-tagging to separate tt signal from backgrounds
- Dominant systematics include MC modeling of signal and Jet/MET reconstruction and calibration

- $\sigma_{t\bar{t}} = 241 \pm 2 \text{ (stat.)} \pm 31 \text{ (syst.)} \pm 9 \text{ (lumi.) pb}$

CMS measured top pair production in single lepton channel using 2.8 fb⁻¹ of data

- Cross-section extracted using binned maximum likelihood template fit (utilising M_{l_b})
- Dominant systematics include b-tagging efficiency, MC modeling

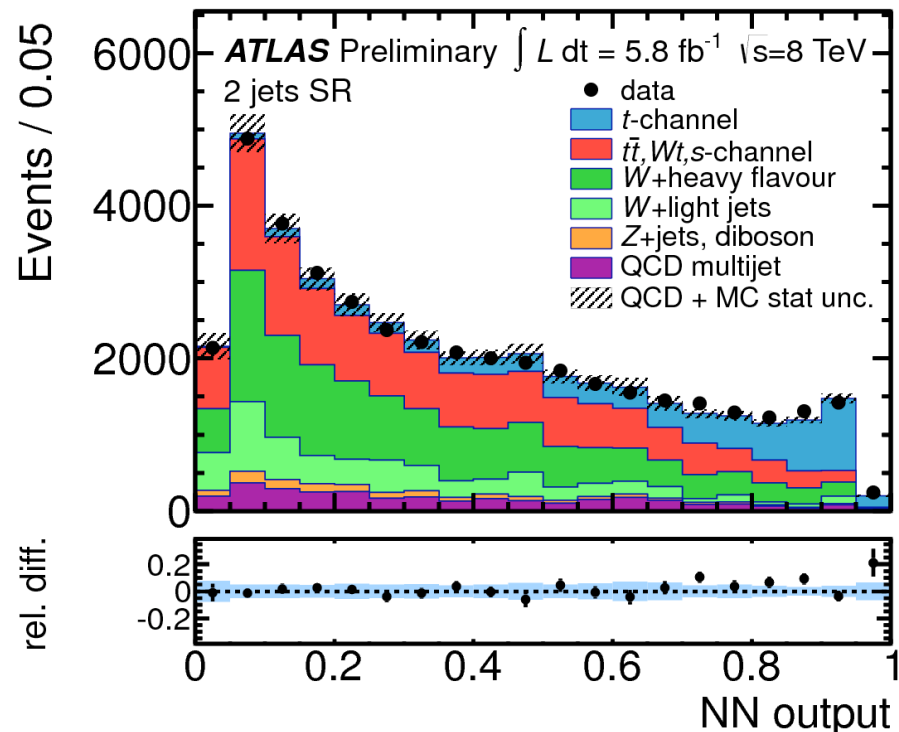
- $\sigma_{t\bar{t}} = 228.4 \pm 9.0 \text{ (stat.)}^{+29.0}_{-26.0} \text{ (syst.)} \pm 10.0 \text{ (lum.) pb}$



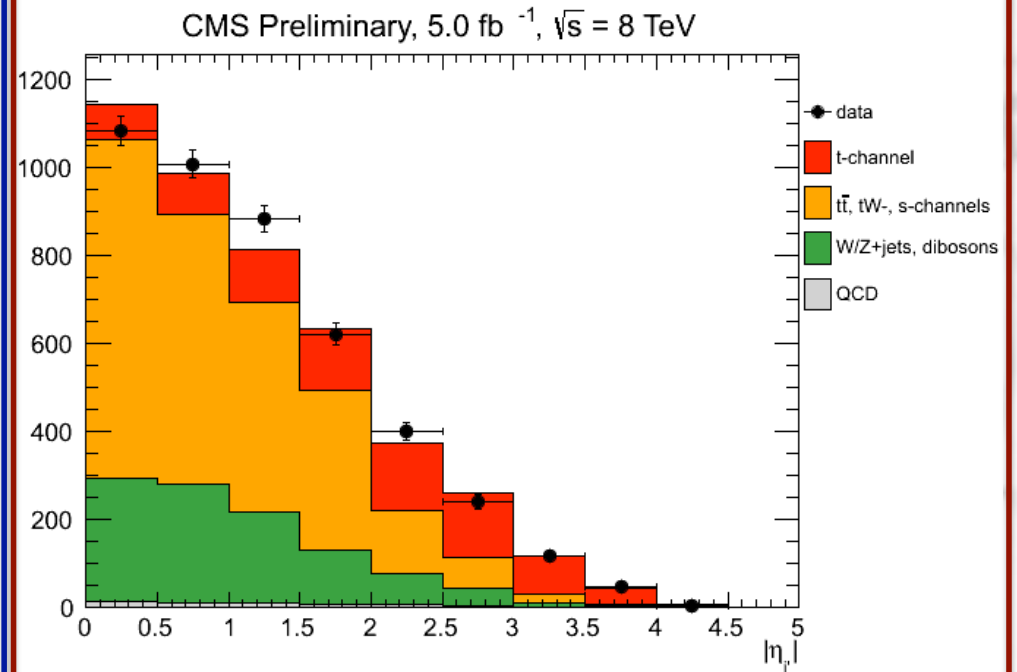
Single top production t-channel

ATLAS-CONF-2012-132
CMS PAS TOP-12-011

- **ATLAS** selected events with exactly one lepton two or three jets and one b-tagged jet
- Cross-section extracted in a simultaneous likelihood fit to a neural network discriminant



- **CMS** selected events with exactly one muon and two jets and one b-tagged jet
- Cross-section extracted using a maximum-likelihood fit to pseudorapidity of light-quark jet



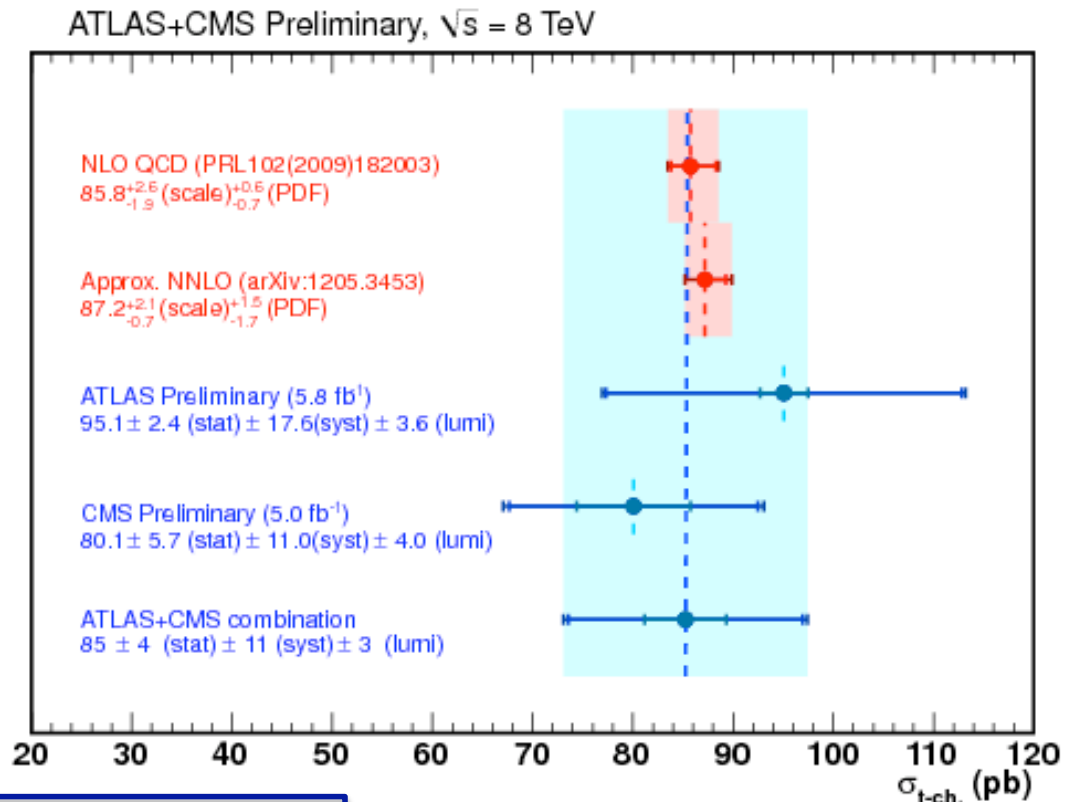


Single top production t-channel

ATLAS-CONF-2013-098
CMS-PAS-TOP-12-002

- Best linear unbiased estimator (BLUE) used to combine t-channel single top-quark production cross-section measurements from ATLAS and CMS
- Contribution to combined cross-section uncertainty

Source	Uncertainty (pb)
Statistics	4.1
Luminosity	3.4
Simulation and modelling	7.7
Jets	4.5
Backgrounds	3.2
Detector modelling	5.5
Total systematics (excl. lumi)	11.0
Total systematics (incl. lumi)	11.5
Total uncertainty	12.2



Combined t-channel single top cross-section
 $\sigma_{t\text{-ch.}} = 85 \pm 4$ (stat.) ± 11 (syst.) ± 3 (lumi.) pb = 85 ± 12 pb



Single top production t-channel charge ratio

CMS-PAS-TOP-12-038

- Top (85%) anti-top (74%) quark inherits sign of the charge from the initial light quark
- Charge asymmetry due to larger contribution from u quark than d quark
- Ratio measurement $R_{t\text{-ch}} = \sigma_{t\text{-ch,top}} / \sigma_{t\text{-ch,anti-top}}$ provides effective handle to constrain proton PDF models, and is sensitive to new physics (anomalous coupling, FCNCs)

- Selection: Exactly one lepton, two jets and b-tagged jet
- Backgrounds include tt, W+jets and multijet QCD
- Yield extracted from binned maximum-likelihood fit to the pseudorapidity of recoil quark in events with positively and negatively charged leptons
- Measurements: $\sigma_{t\text{-ch,top}} = 49.9 \pm 9.1 \text{ pb}$
 $\sigma_{t\text{-ch,anti-top}} = 28.3 \pm 5.5 \text{ pb}$
- $R_{t\text{-ch}} = \sigma_{t\text{-ch,top}} / \sigma_{t\text{-ch,anti-top}} = 1.76 \pm 0.27$

