Top Quark Physics Results from the LHC

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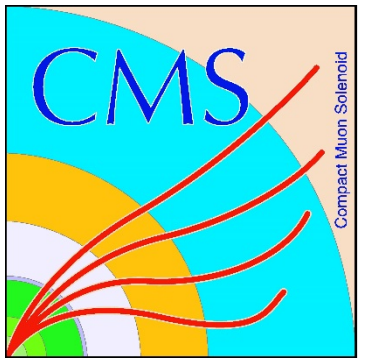
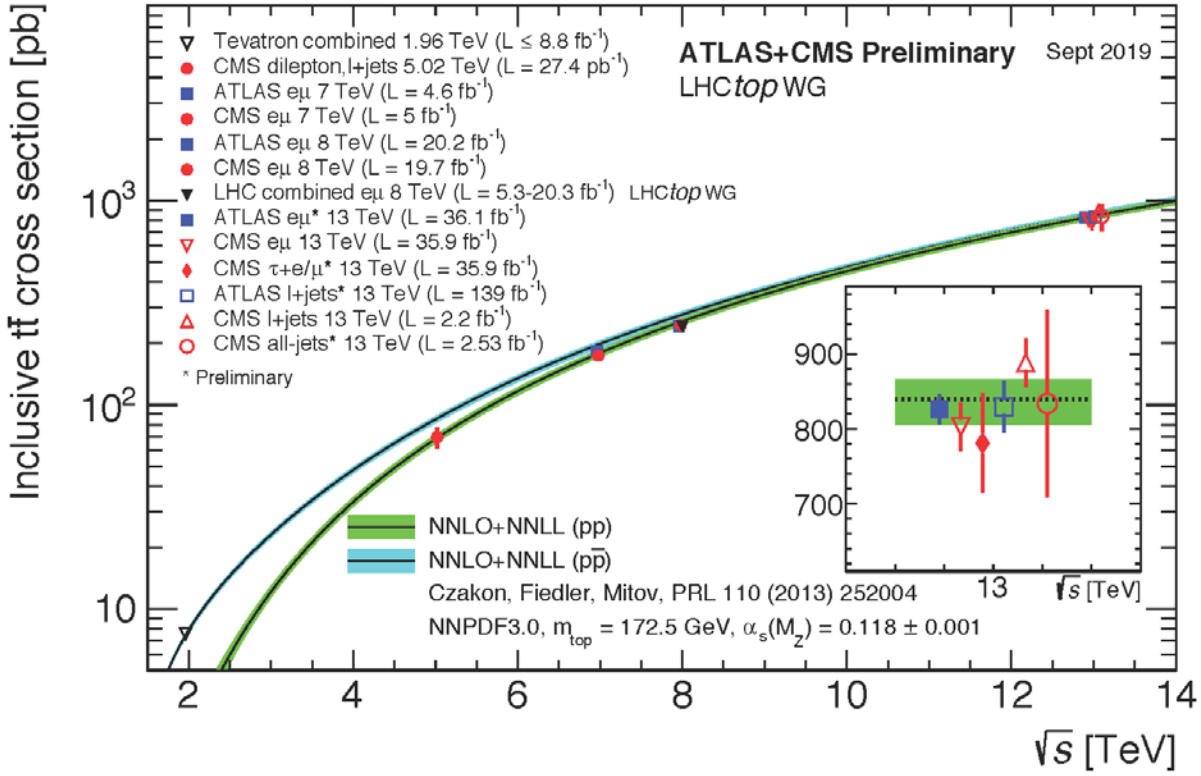


LHC as a Top Factory

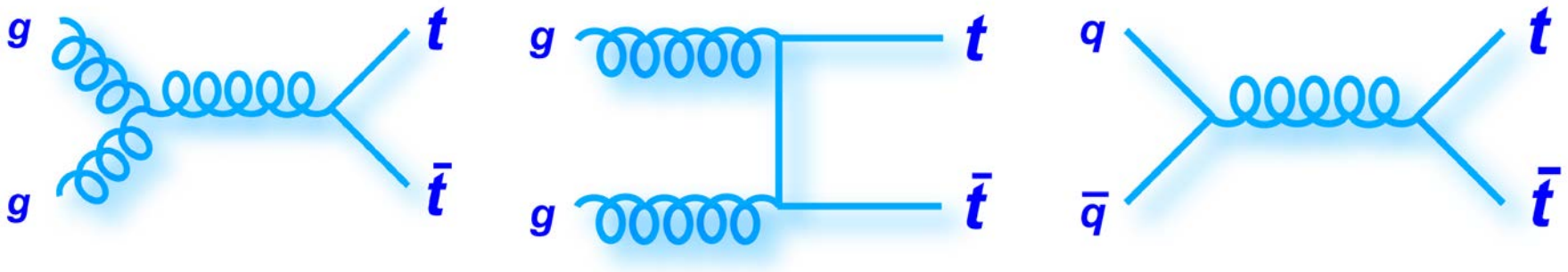
- In Run 2 of the LHC ~120M $t\bar{t}$ and ~40M single t events were produced



- https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

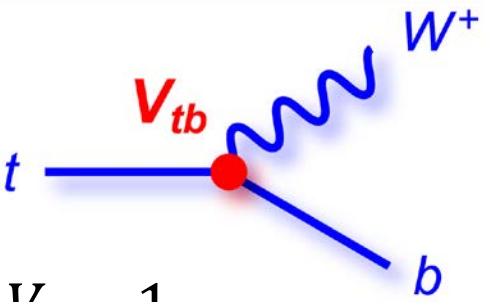
Top Production and Decay

➢ $t\bar{t}$ Production

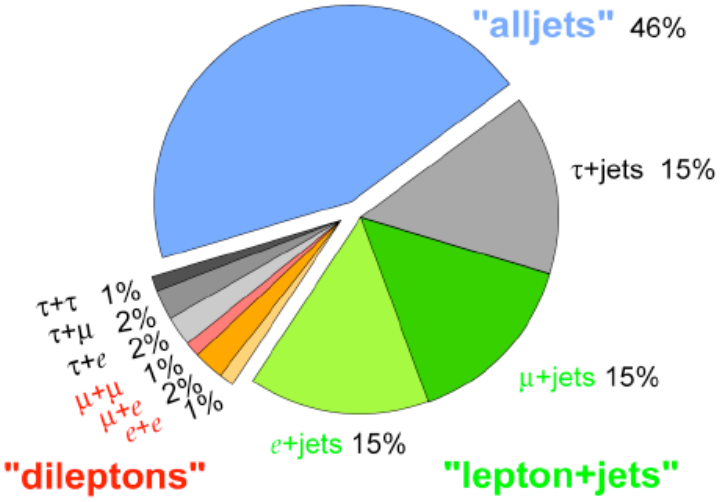


- ~90% from gluon fusion at $\sqrt{s} = 13$ TeV

➢ $t\bar{t}$ Decay



$V_{tb} \sim 1$



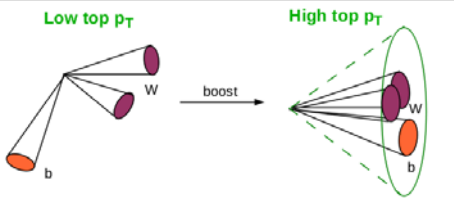
ATLAS/CMS comb. JHEP 05 (2019) 088

Differential $t\bar{t}$ Cross Sections

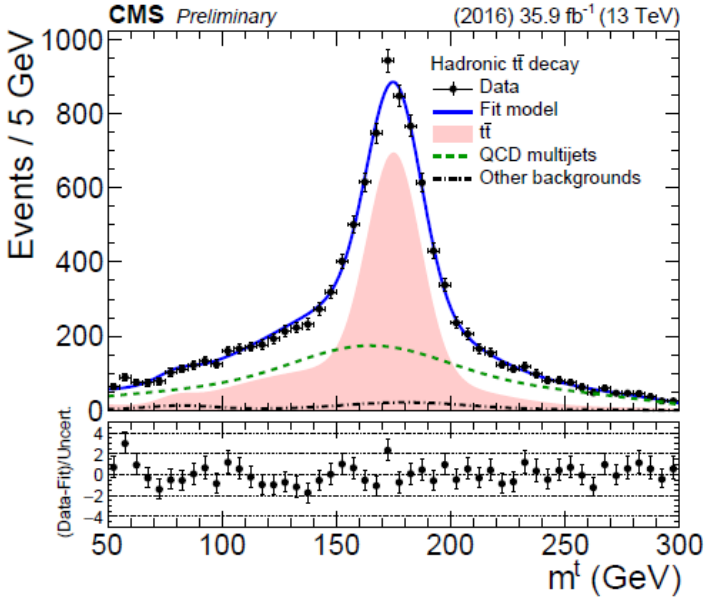
- Differential $t\bar{t}$ cross section measurements
  - Provide a good test of perturbative QCD
  - Improve top quark MC modelling
  - Allow extraction of SM parameters (m_t and α_s)
  - Contribute to gluon PDF constraints
- Single, double, and triple differential cross section measurements have been carried out in dilepton, lepton + jets, and all-hadronic channels
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
  - http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TOP/index.html

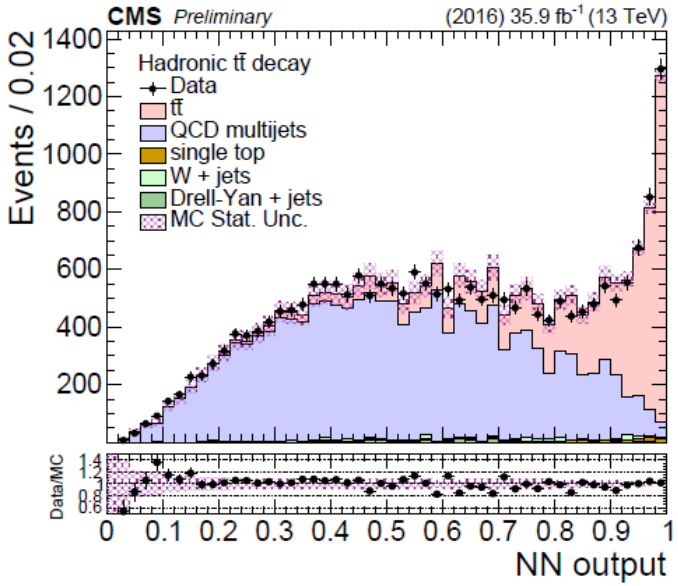
Differential $t\bar{t}$ Cross Sections (CMS)

- High p_T top production
  - Two large-R jets with $p_T > 400$ GeV
  - One large-R jet and one small-R jet with a high p_T lepton and $p_T^{miss} > 50\ (30)$ GeV



- QCD multi-jets are suppressed using the number of b-tagged subjets, a NN discriminant with jet substructure variables ($\tau_{1,2,3}$) as inputs, and soft-drop mass selection

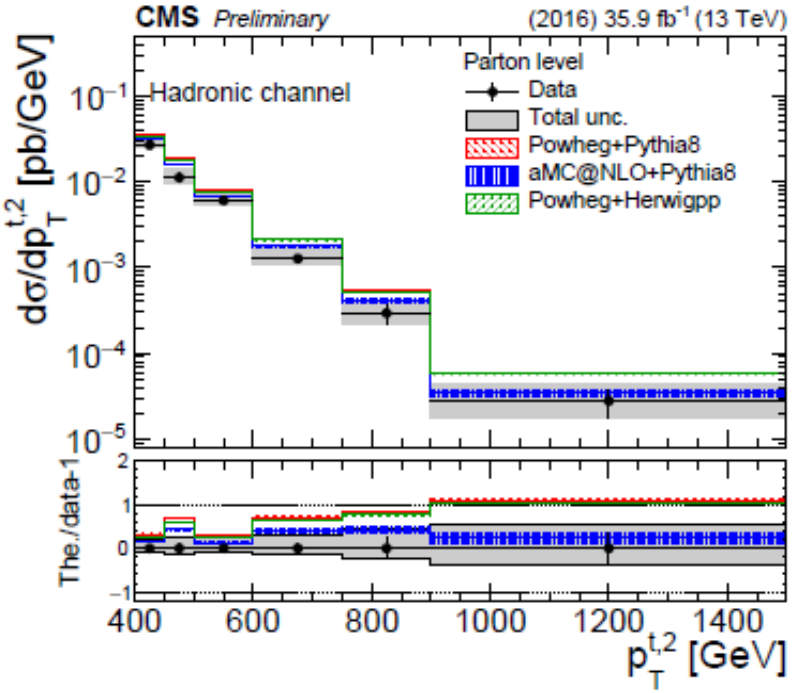


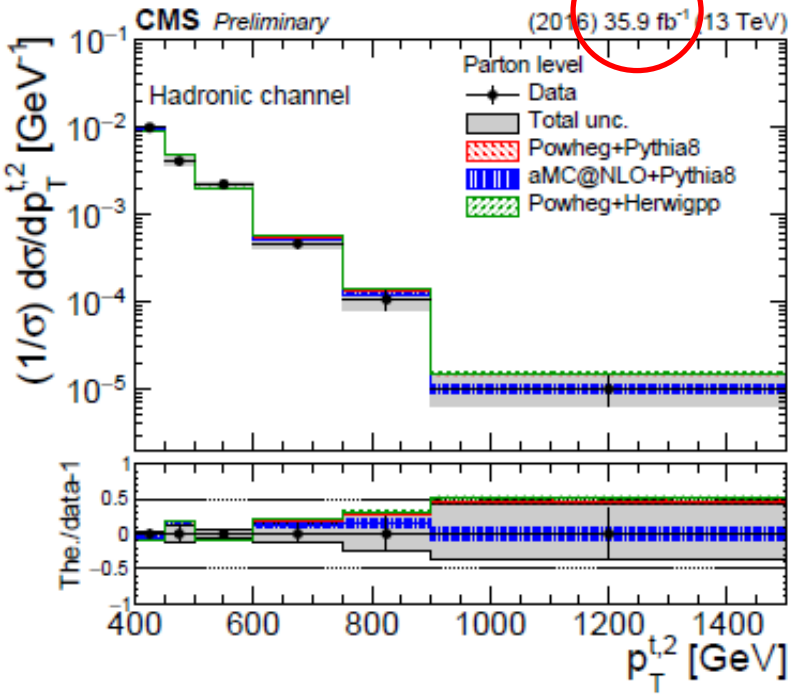


CMS-PAS-TOP-18-013

Differential $t\bar{t}$ Cross Sections (CMS)

- Cross sections of kinematic variables for both channels are unfolded to the particle and parton level



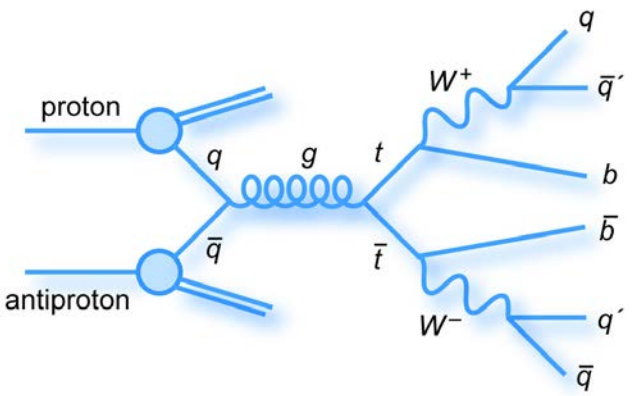


- A significant 35% (25%) overestimate of the cross section is observed in the hadronic (lepton+jets) channel
- Generally good agreement with theory in the normalized distributions

CMS-PAS-TOP-18-013

Differential $t\bar{t}$ Cross Sections (ATLAS)

- All-hadronic resolved decay channel
  - At least 6 jets $p_T > 55$ GeV, exactly 2 b-tagged jets, and no leptons
  - A χ^2 discriminant with W-boson mass constraints is used to reconstruct the $t\bar{t}$ system and reject QCD multi-jet background
- The number of b-tagged jets and reconstructed top masses are used in the ABCD method to estimate the multi-jet background

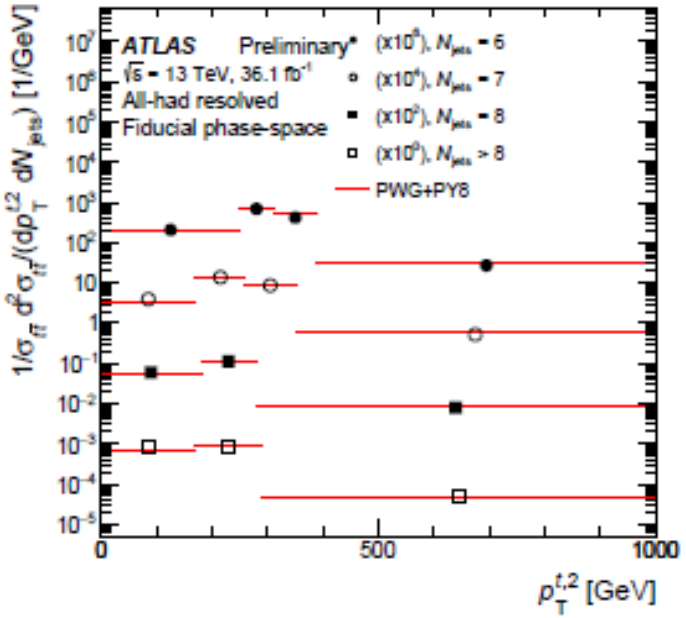


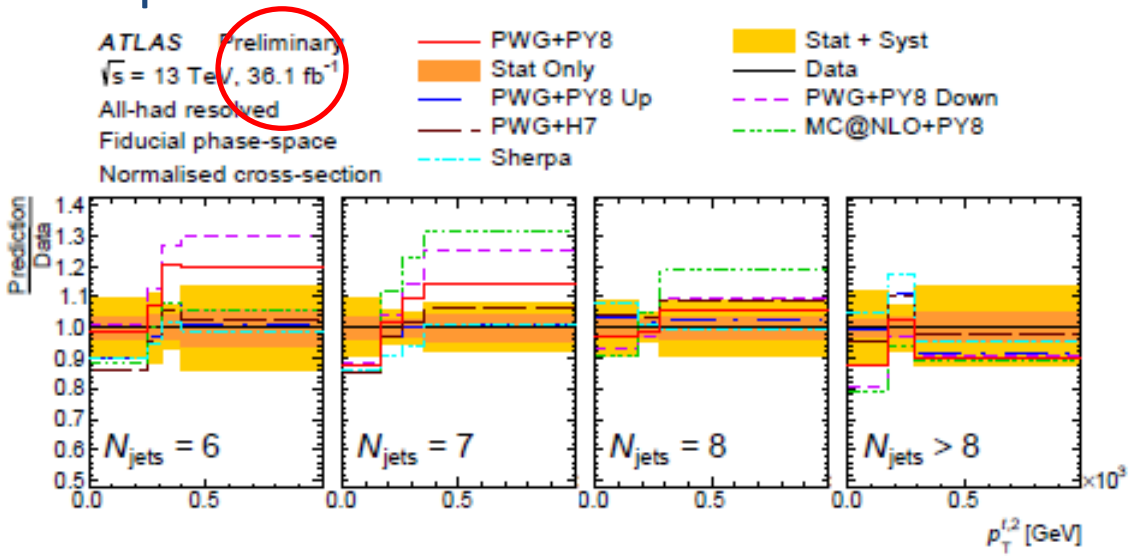
Process	Event yield	Fraction (%)
$t\bar{t}$ (all-hadronic)	$29\,500^{+2000}_{-2500}$	68%
$t\bar{t}$ (non all-hadronic)	1490^{+140}_{-120}	3%
Multijet background	$12\,600^{+1900}_{-1900}$	29%
Total prediction	$43\,500^{+2800}_{-3000}$	
Data	44 573	

ATLAS-CONF-2020-001

Differential $t\bar{t}$ Cross Sections (ATLAS)

- Cross sections using kinematic observables not accessible to lepton+jets including those emphasizing additional radiation are unfolded to the particle and parton level



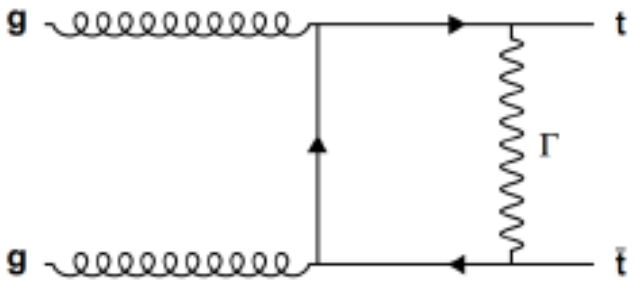


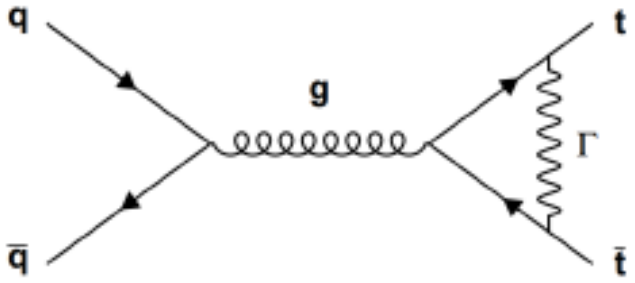
[ATLAS-CONF-2020-001]

- MC mismodelling in this and other variables at high jet multiplicities is observed
- MC describe angular properties more consistently than energy sharing
- Double differential cross sections highlight differences more than single

Top Quark Yukawa Coupling (CMS)

- Top quark Yukawa coupling is of interest because it is the largest and also close to 1
- Higgs boson contributes to the $t\bar{t}$ cross section at order $\alpha_s^2 \alpha_W$ but can produce measurable effects in the shape of kinematic distribution





CMS-PAS-TOP-19-008

- The top quark Yukawa coupling ($Y_t = g_t / g_t^{SM}$) can be indirectly constrained using kinematic distributions of the $t\bar{t}$ system

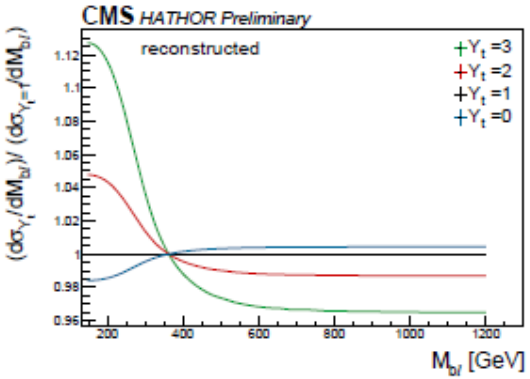
Top Quark Yukawa Coupling (CMS)

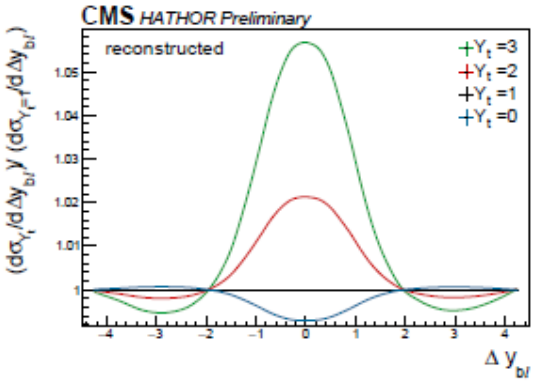
- Dilepton decay channel

CMS-PAS-TOP-19-008

  - Exactly two leptons, ≥2 jets, ≥2 b-tagged jets, and selection on m_{ll} and p_T^{miss} in same flavor events to remove DY events

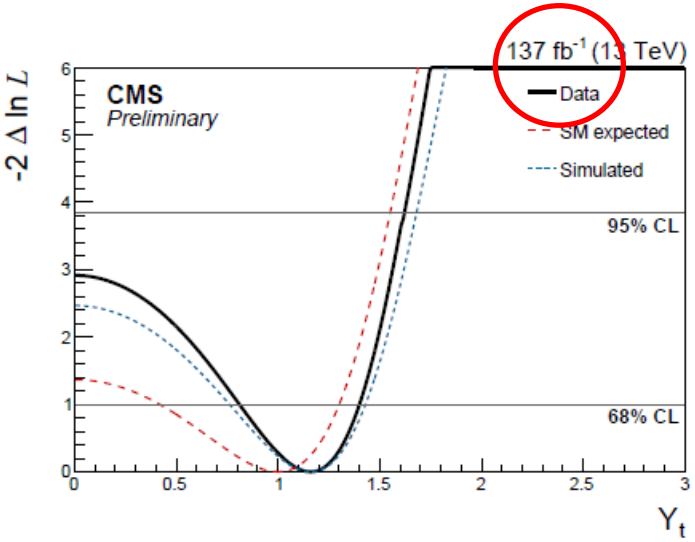
- Two variables are used
  - $M_{b\bar{b}l\bar{l}}$
  - $\left|y(b\bar{l}) - y(\bar{b}l)\right|$





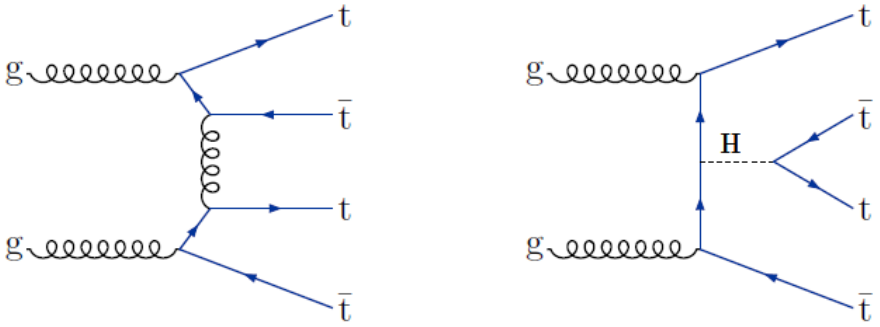
- ML fit is applied to the binned data in the two variables to extract Y_t

- Best fit value is $Y_t = 1.16^{+0.24}_{-0.35}$
  - Higgs production and decay measurements give $Y_t = 0.98 \pm 0.14$



$t\bar{t}t\bar{t}$ Production

- SM prediction for four-top production is 12 fb $\pm$ 20% at NLO + EW corrections



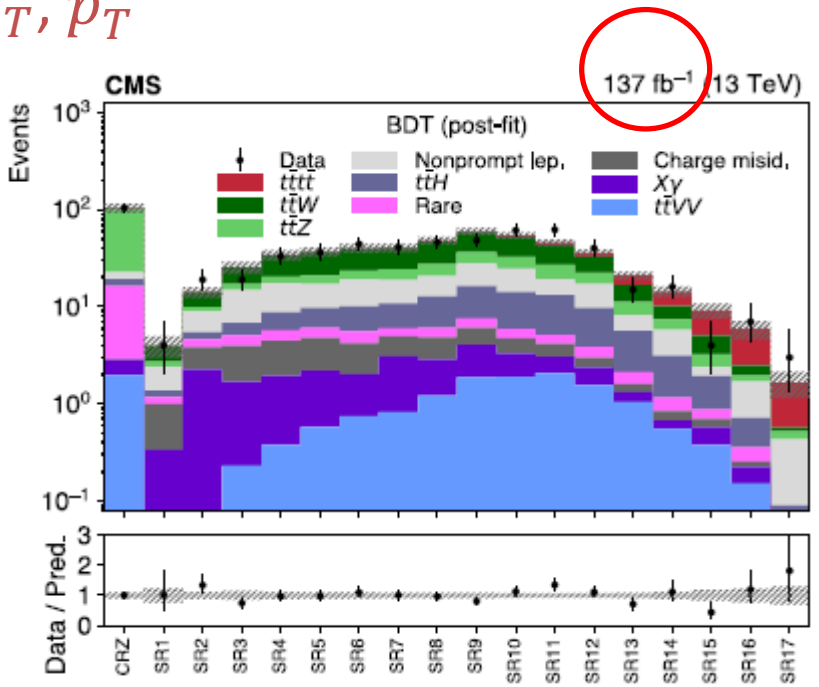
CMS 2LSS/3L	CMS 2LSS/3L, 1L/2LOS	ATLAS 2LSS/3L, 1L/2LOS
EPJC 80 (2020) 75	JHEP 11 (2019) 082	PRD 99 (2019) 052009
137 fb^{-1}	36 fb^{-1}	36 fb^{-1}
2.6σ	1.4σ	2.1σ

- Enhancements to this cross section are predicted in several BSM models including SUSY and 2HDM

$t\bar{t}t\bar{t}$ Production in 2LSS/3L (CMS)

- 2LSS/3L channel baseline selection — EPJC 80 (2020) 75
  - 2 same sign or at least 3 leptons
  - $\geq$ 2 jets, $\geq$ 2 b-jets, $H_T \geq 300$ GeV, $p_T^{miss} > 50$ GeV
- Two analyses – cut based and BDT classifier based
  - 19 variables including $n_j, n_b, n_l, H_T, p_T^{miss}$
  - 17 SR and 1 CR for $t\bar{t}Z$
- Profile likelihood fit gives
  - $\sigma(t\bar{t}t\bar{t}) = 12.6^{+5.8}_{-5.2}$ fb
  - Also used to constrain the Yukawa coupling of the top to Higgs

$$Y_t = \left| {}^{g_t}/_{g_t^{SM}} \right| < 1.7 \text{ @ } 95\%\text{CL}$$



$t\bar{t}t\bar{t}$ Production in 2LSS/3L (ATLAS)

- 2LSS/3L channel selects
  - 2 same sign or at least 3 leptons
  - ≥ 6 jets, ≥ 2 b-jets, H_T(leptons+jets) ≥ 500 GeV

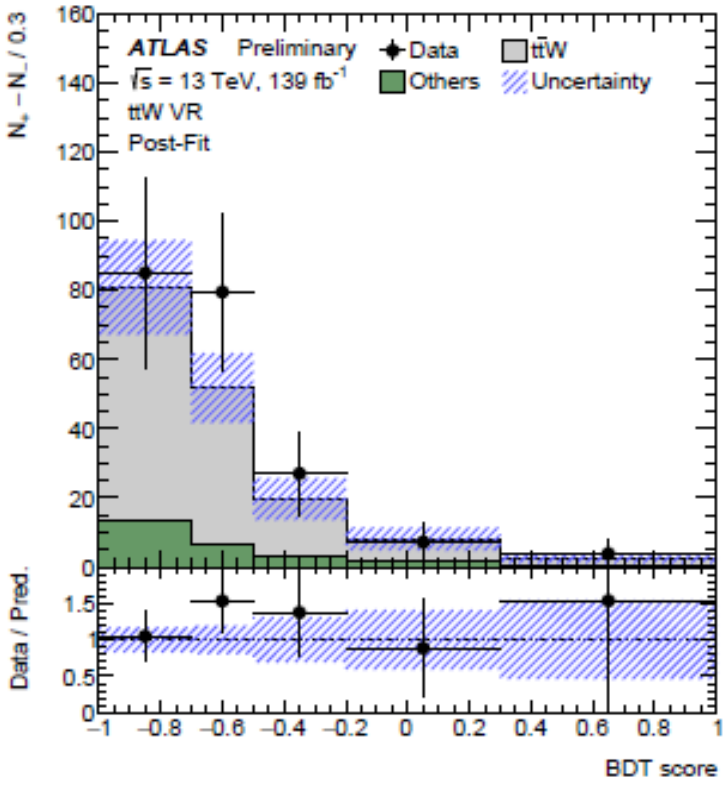
ATLAS-CONF-2020-013

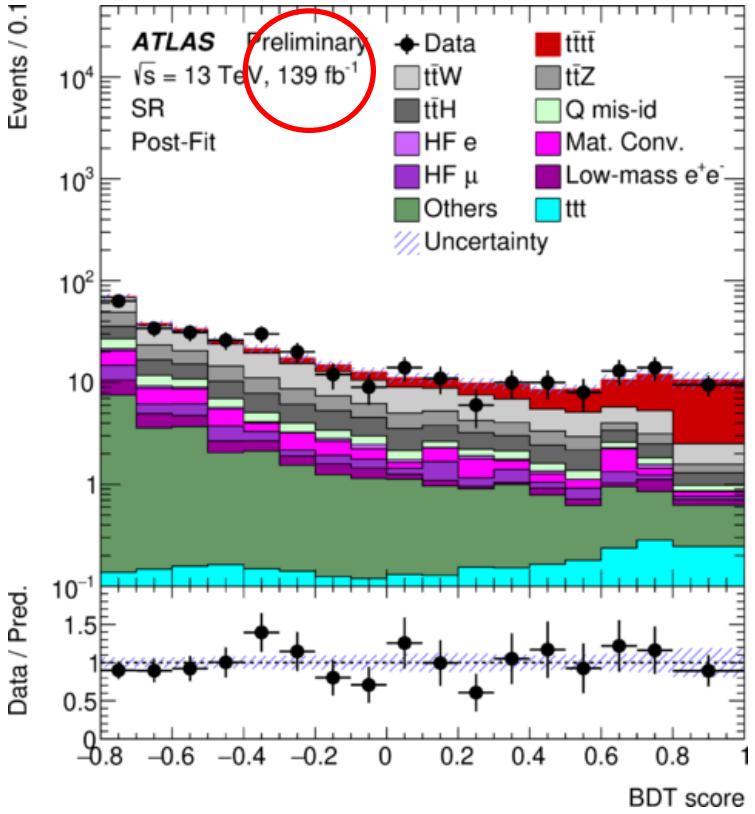
Lennart Rustige 11/6 @ 1000

- Signal is separated from background using a BDT with 12 observables including a continuous b-tagging discriminant
- Subsequent profile likelihood fit to the BDT distribution and variables in 4 CR's
  - $t\bar{t}Z + jets, t\bar{t}H + jets, t\bar{t}W + jets$ (70%)
  - Charge mis-id, fake/non-prompt leptons (25%)
- Main systematic errors include $t\bar{t}W$ modelling and signal renormalization / factorization scales

$t\bar{t}t\bar{t}$ Production in 2LSS/3L (ATLAS)

ATLAS-CONF-2020-013



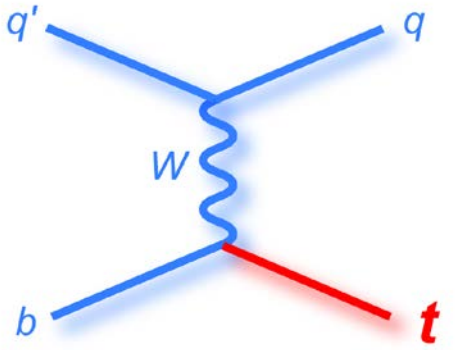


- $\sigma(t\bar{t}t\bar{t}) = 24 \pm 5(stat) \pm 5(syst)$ fb
- The observed (expected) 4.3σ (2.4σ) significance provides evidence for four-top production

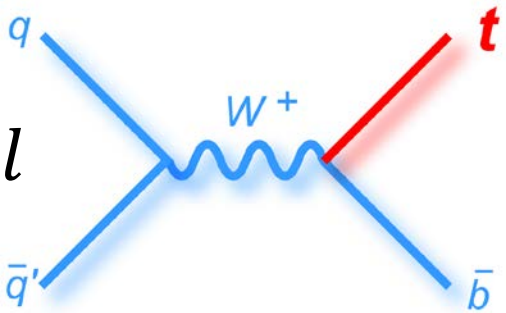
Single Top Production

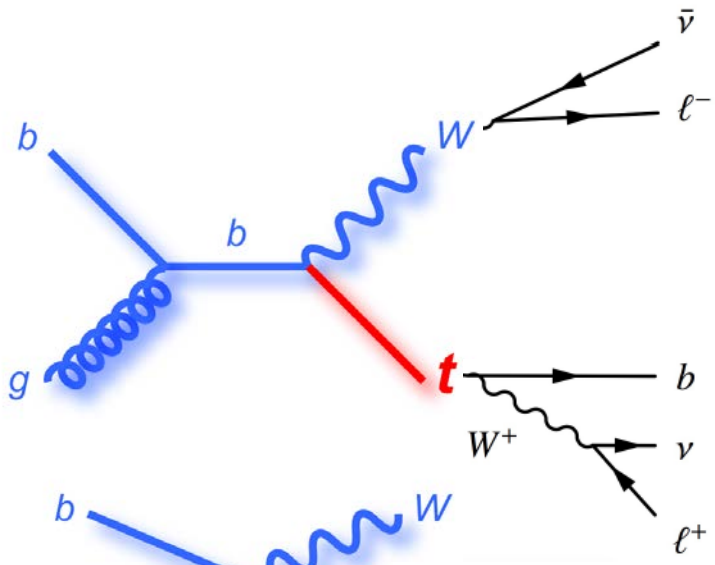
- Single top production can be used to test SM predictions at higher orders and constrain BSM models

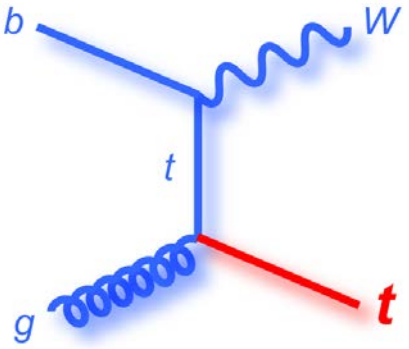
$t - channel$



$s - channel$

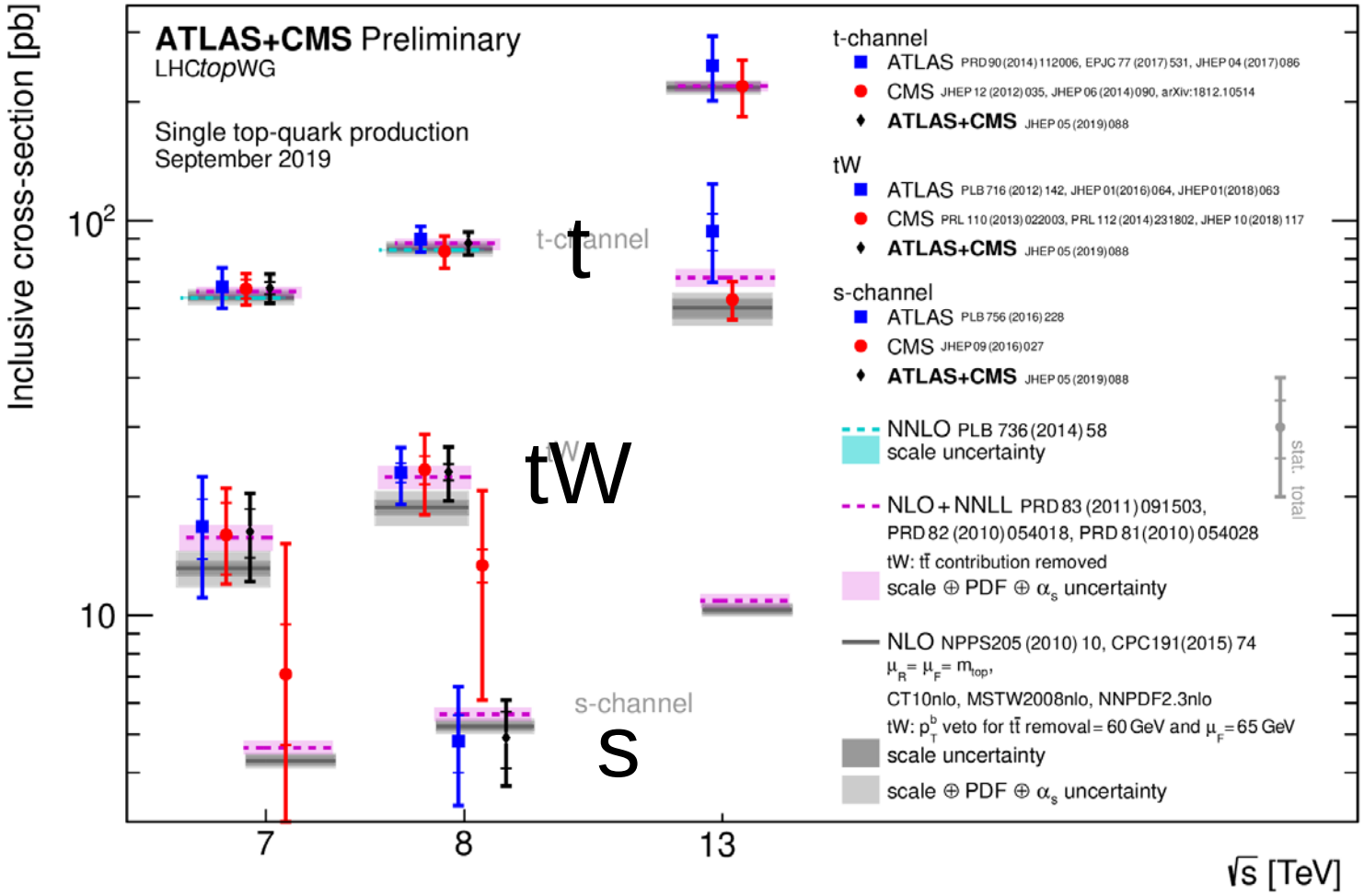






$Wt - channel$

Single Top Cross Section

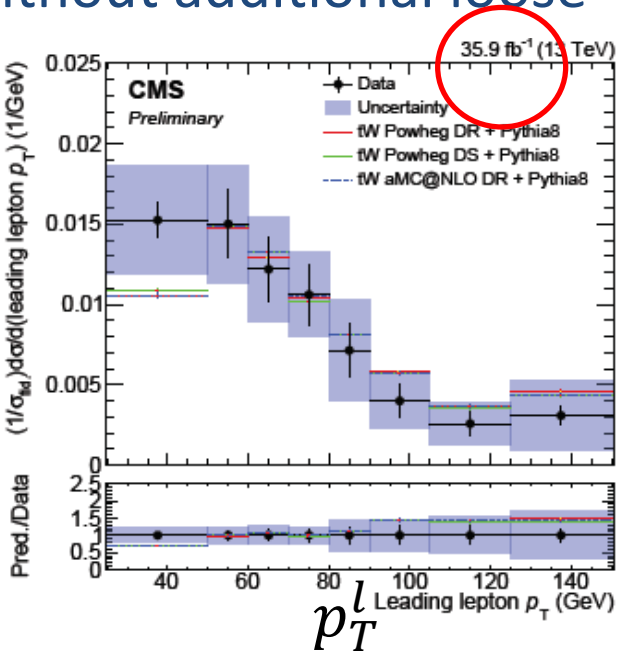


- Note the relative contributions of t, tW, and s channels
- https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

Differential Cross Section Wt Channel (CMS and ATLAS)

CMS-PAS-TOP-19-003

- Opposite sign $e^{\pm}\mu^{\mp}$dileptons are used with one b-tagged jet and without additional loose jets

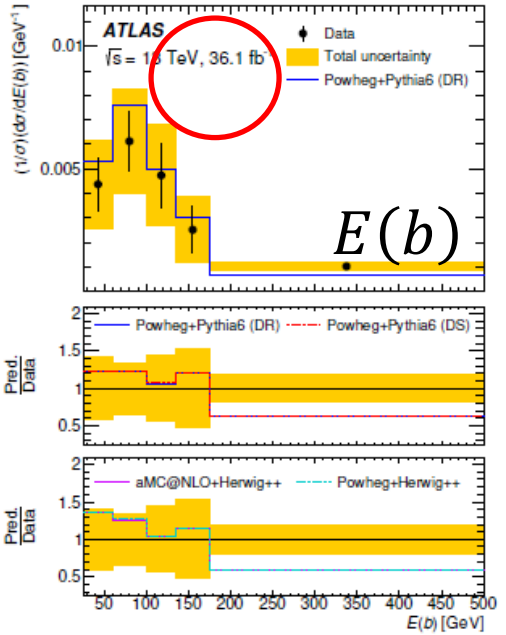


p_T^l

- Good agreement with various MC predictions is observed

EPJC 78 (2018) 186

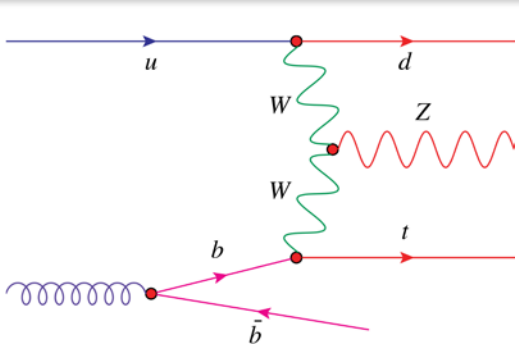
- Opposite sign dileptons and exactly one jet that is b-tagged along with m_{ll}, E_T^{miss} selections

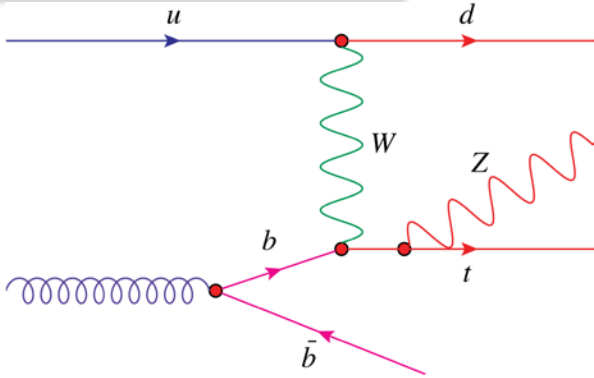


- Good agreement with various MC predictions is observed

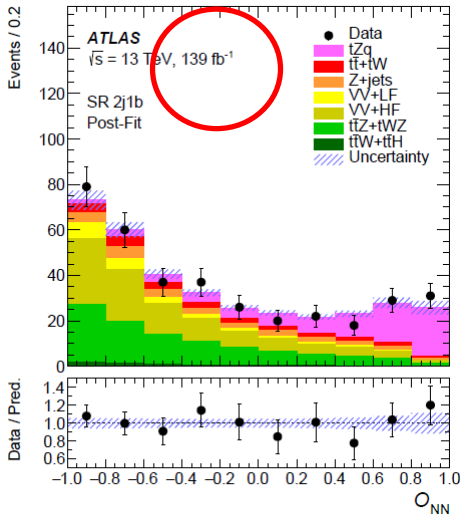
tZq Production (ATLAS and CMS)

- Probes tZ and WWZ couplings
- Event selection includes 3 high p_T leptons, 1 b-tagged jet, and one or two additional jets

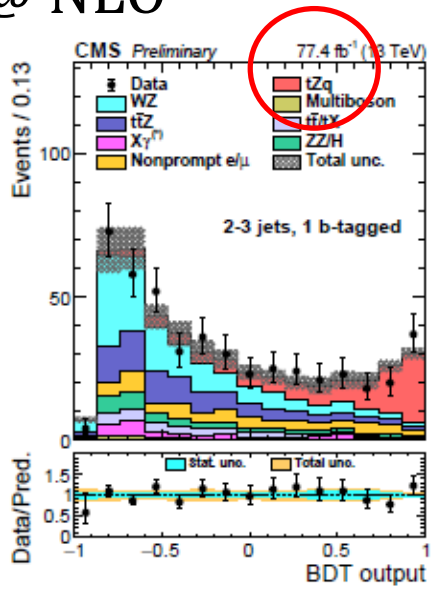




$$\sigma(SM) = 102^{+5}_{-2}\,\text{fb @ NLO}$$



- NN (ATLAS) or BDT (CMS) for signal/background discrimination



$\sigma = 97 \pm 13\,(stat) \pm 7\,(syst)$ fb

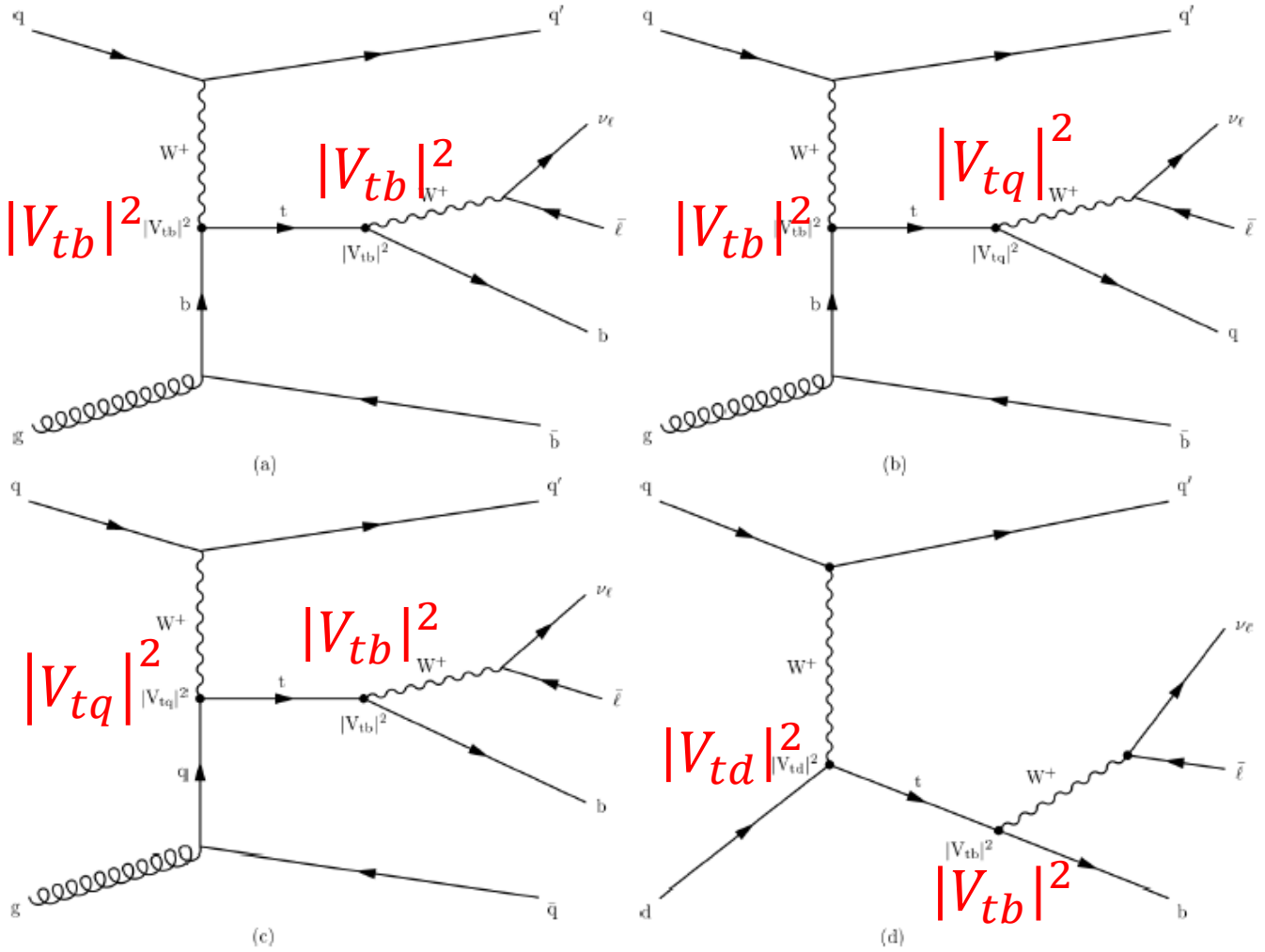
arXiv:2002.07546

$\sigma = 111 \pm 13\,(stat)^{+11}_{-9}\,(syst)$ fb

PRL 122 (2019) 132003

CKM Elements |Vtb|, |Vts|, |Vtd| (CMS)

- Focuses on t-channel production and decay



CMS-PAS-TOP-17-012

CKM Elements |Vtb|, |Vts|, |Vtd| (CMS)

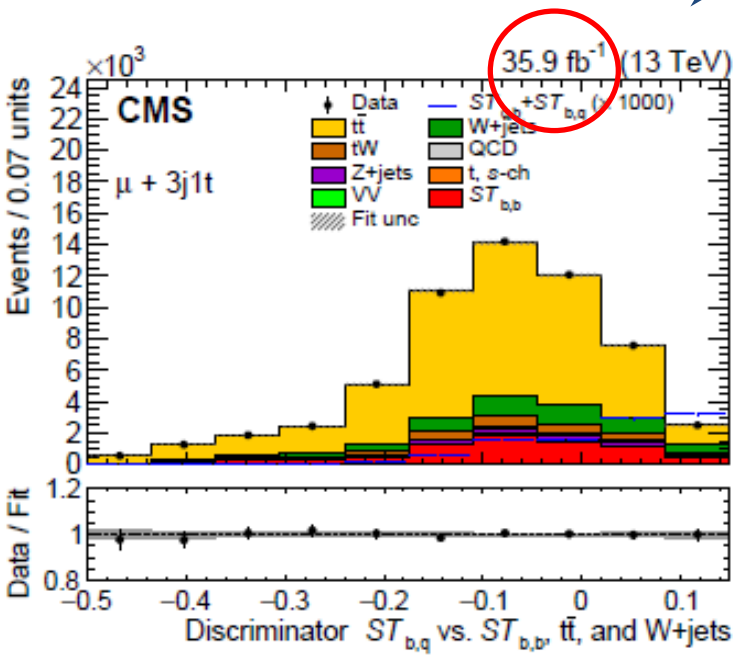
- Event selection uses one high p_T, isolated lepton, 2 or 3 high p_T (> 40 GeV) jets of which 1 or 2 are b-tagged
- CKM elements can be extracted directly from measurement of the single top production cross section and branching ratios

Category	Enriched in	Cross section × branching fraction	Feynman diagram
2j1t	$ST_{b,b}$	$\sigma_{t\text{-ch,b}}\mathcal{B}(t \to Wb)$	1a
3j1t	$ST_{b,q}$, $ST_{q,b}$	$\sigma_{t\text{-ch,b}}\mathcal{B}(t \to Wq)$, $\sigma_{t\text{-ch,q}}\mathcal{B}(t \to Wb)$	1b, 1c, 1d
3j2t	$ST_{b,b}$	$\sigma_{t\text{-ch,b}}\mathcal{B}(t \to Wb)$	1a

  - BDT's are used as the discriminating variables between single top and background processes

CKM Elements |Vtb|, |Vts|, |Vtd| (CMS)

- A two step ML fit is employed
  - Using the m_T^W distribution for the 2j1t and 3j1t samples to extract the QCD multijet contribution
  - Using the BDT discriminators for the 3 samples



- Results at 95% CL

$$|V_{tb}| > 0.970$$

$$|V_{td}|^2 + |V_{ts}|^2 < 0.057$$

- No theoretical assumptions for |Vtd| and |Vts|
- Improves |Vtb| over previous ATLAS/CMS combination

CMS-PAS-TOP-17-012

Conclusions

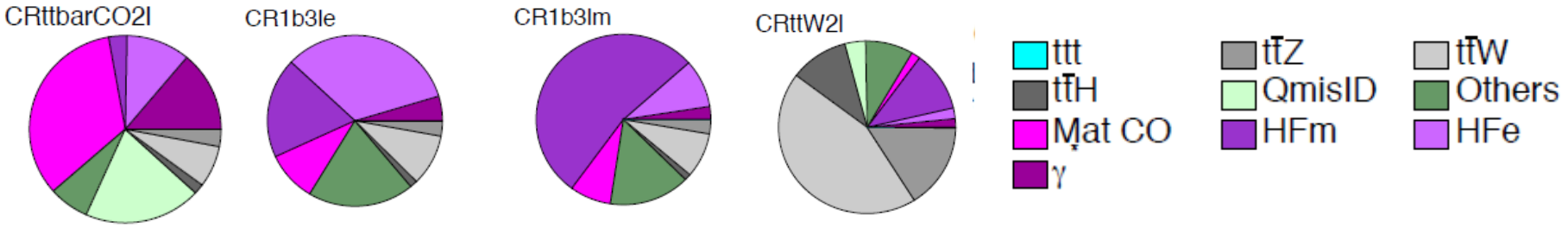
- The results presented today clearly show we are in an era of precision top physics at the LHC
- Highlights shown
  - Wide variety of single and double differential cross section measurements in $t\bar{t}$ and single t production
  - New measurement and evidence for the $t\bar{t}t\bar{t}$ production cross section
  - Measurement of the CKM matrix elements involving top in a model independent way

Backup Slides

$t\bar{t}t\bar{t}$ Production in 2LSS/3L (ATLAS)

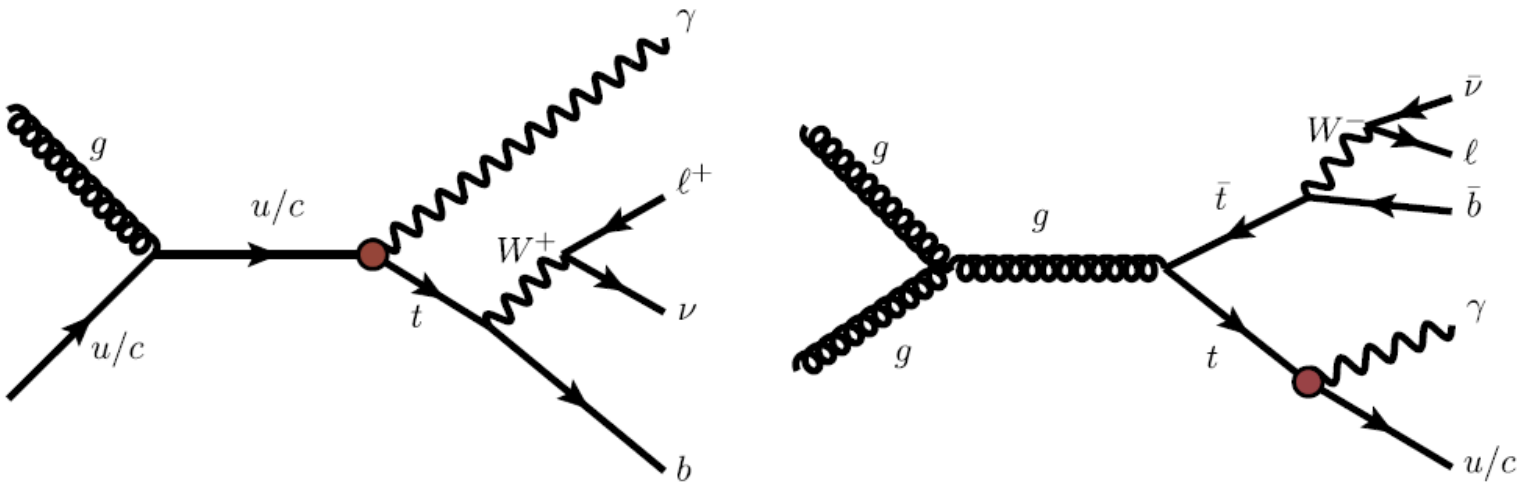
- Control regions are used to provide normalizations from fits to data for photon conversion, leptons from heavy flavor, and $t\bar{t}\overline{W} + jets$

Region	Channel	N_j	N_b	Other requirements	Fitted variable
CRttbarCO2l	$e^{\pm}e^{\pm}\|\|e^{\pm}\mu^{\pm}$	$4 \leq N_j < 6$	≥ 1	$M_{ee}@CV \in [0, 0.1\ \text{GeV}]$ $200 < H_{\text{T}} < 500$ GeV	M_{ee}@PV
CR1b3Le	$eee \,\|\|\, ee\mu$	-	= 1	$100 < H_{\text{T}} < 250$ GeV	counting
CR1b3Lm	$e\mu\mu \,\|\|\, \mu\mu\mu$	-	= 1	$100 < H_{\text{T}} < 250$ GeV	counting
CRttW2l	$e^{\pm}\mu^{\pm}\|\|\mu^{\pm}\mu^{\pm}$	≥ 4	≥ 2	$M_{ee}@CV \notin [0, 0.1\ \text{GeV}]$, $\|\eta(e)\| < 1.5$ for $N_b = 2$, $H_{\text{T}} < 500$ GeV or $N_j < 6$ for $N_b \geq 3$, $H_{\text{T}} < 500$ GeV	$\Sigma p_{\text{T}}^{\ell}$



FCNC $t \to \gamma u/c$ (ATLAS)

- FCNC are heavily suppressed at higher orders in the SM but BSM models can increase the BR manifold
- One relatively recent search is $t \to \gamma u$ and $t \to \gamma c$



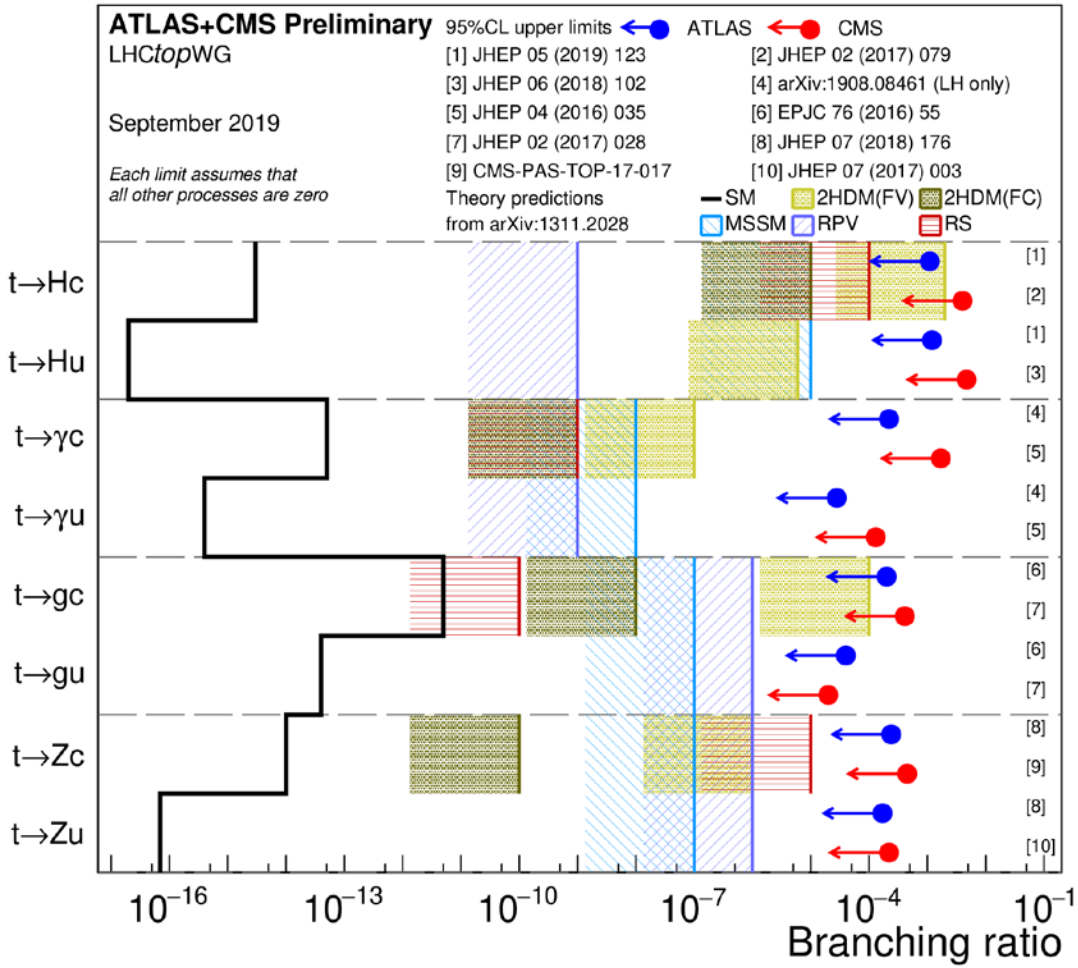
FCNC $t \to \gamma u/c$ (ATLAS)

- Selected events require exactly one electron or muon, exactly one b-tagged jet, and $E_T^{miss} > 30$ GeV
- Signal and background are distinguished using a NN for both $tu\gamma$ and $tc\gamma$ and both LH and RH couplings
- Primary background are mis-identified photons (fakes) in $t\bar{t}$ production and $W/Z + \gamma$ events
- No significant FCNC contribution is observed

PLB 800 (2019) 135082

FCNC Results (ATLAS and CMS)

- In some channels, beginning to challenge BSM predictions

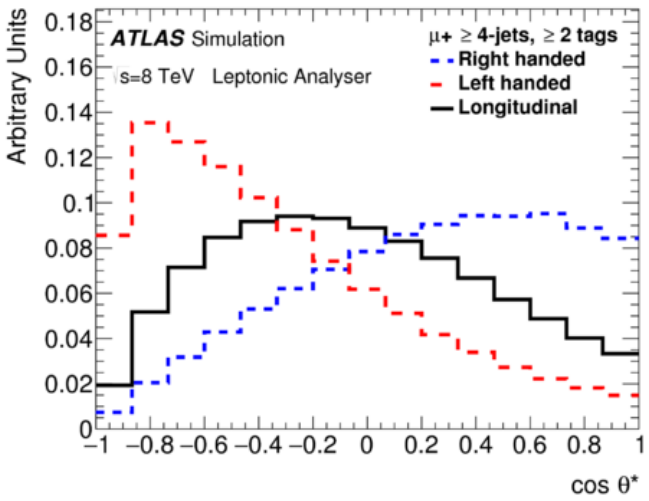


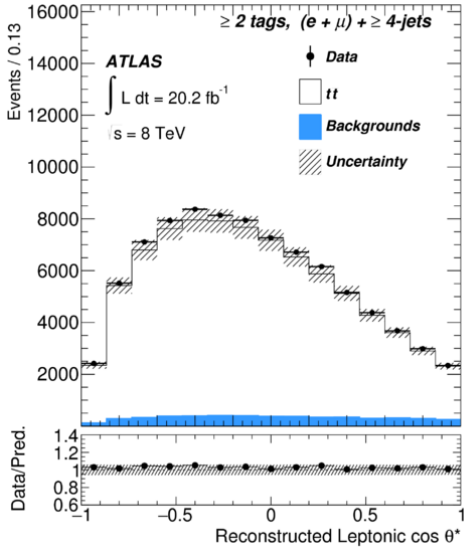
- https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

W Boson Polarization (ATLAS and CMS)

- V-A structure and masses predict the polarization fractions of the W
  - At NNLO, $F_0 = 0.687, F_L = 0.311, F_R = 0.0017$
- Experimentally, the polarization fractions can be measured using

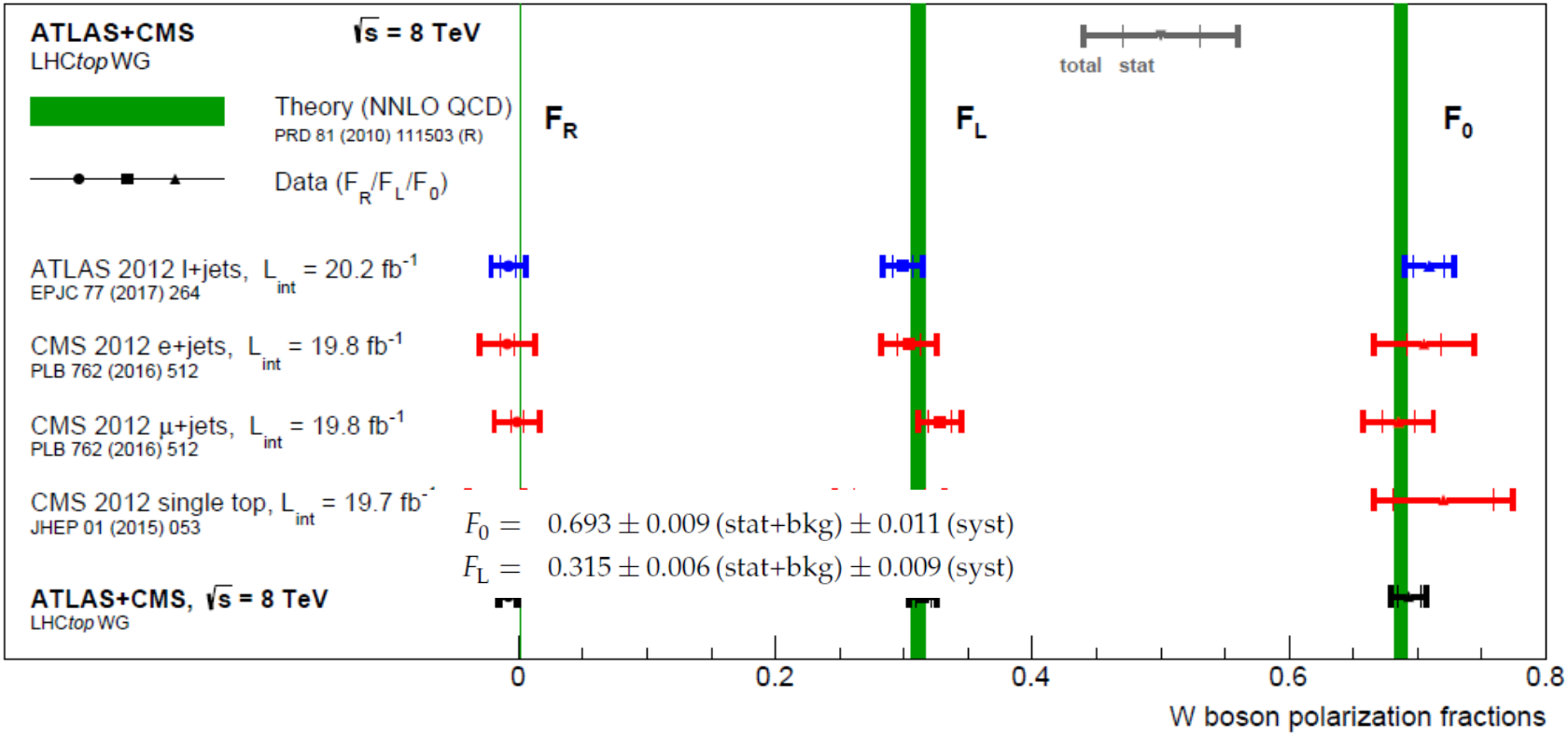
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)\,F_0 + \frac{3}{8}(1-\cos\theta^*)^2\,F_L + \frac{3}{8}(1+\cos\theta^*)^2\,F_R.$$





W Boson Polarization (ATLAS and CMS)

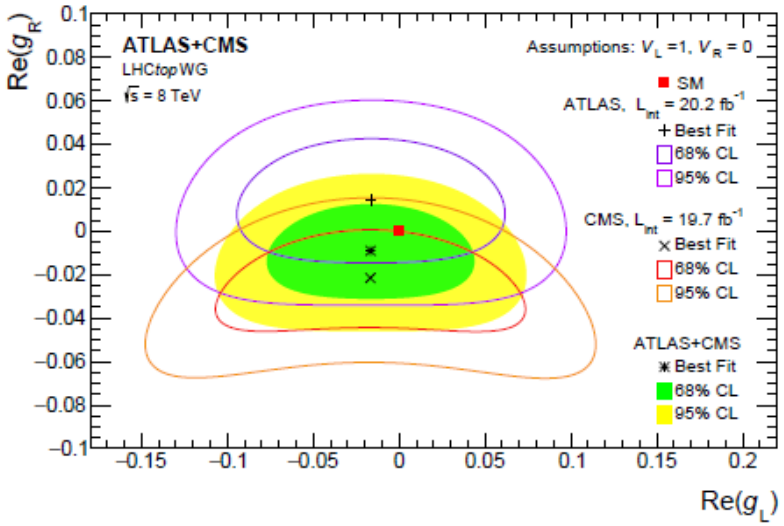
- The four measurements and the combination of measurements using BLUE



arXiv:2005.03799

W Boson Polarization (ATLAS and CMS)

- The results can be used to set limits on BSM contributions to the tWb vertex
  - Limits on possible L- and R-handed tensor couplings
  - Limits on Wilson coefficients giving the strength of operators in top quark EFT



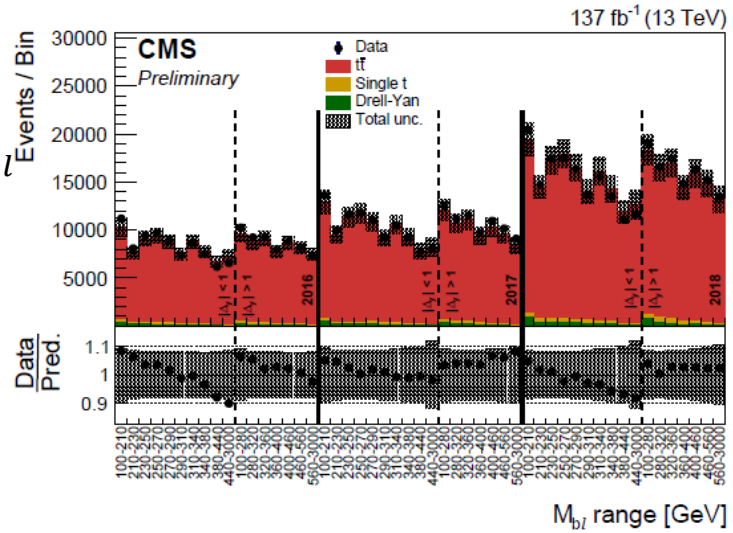
Coefficient	95% CL interval ATLAS	CMS	ATLAS+CMS combination
$C^*_{\phi\phi}$	$[-5.64, 7.68]$	$[-3.84, 4.92]$	$[-3.48, 5.16]$
C^*_{bW}	$[-1.30, 0.96]$	$[-1.06, 0.72]$	$[-0.96, 0.67]$
C_{tW}	$[-0.34, 0.67]$	$[-0.62, 0.19]$	$[-0.48, 0.29]$

arXiv:2005.03799

Top Quark Yukawa Coupling (CMS)

- ML fit is applied to the binned data (shown on left) to extract Y_t

Dashed lines indicate $|\Delta y|_{bl}$ bins



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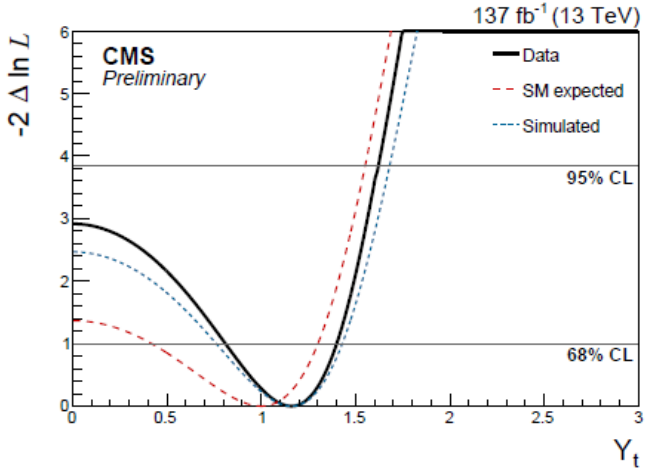


- Best fit value is $Y_t = 1.16^{+0.24}_{-0.35}$
  - Higgs global fit gives $Y_t = 0.98 \pm 0.14$
  - $t\bar{t}t\bar{t} : Y_t < 1.7$ (95% CL)

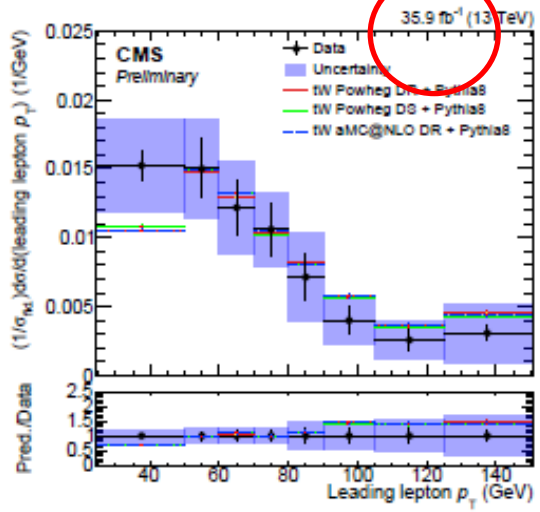
CMS-PAS-TOP-19-008

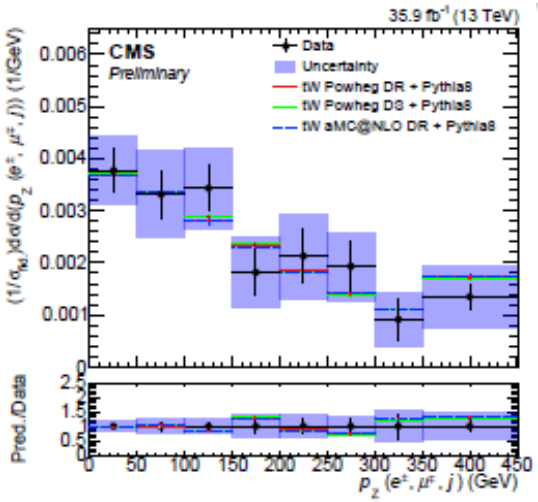
Differential Cross Section Wt Channel (CMS)

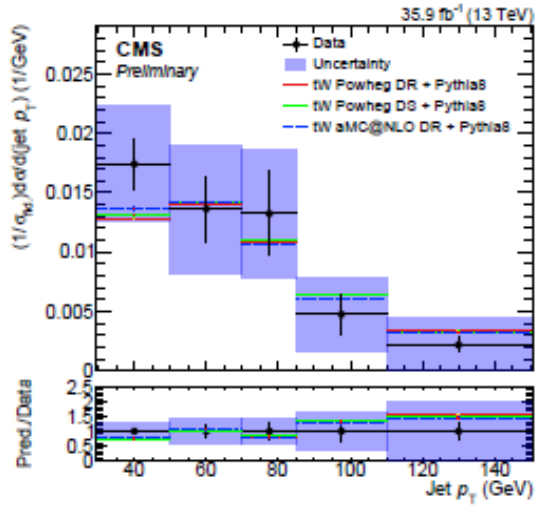
- Differential cross sections in the Wt-channel have also been measured
  - Opposite sign $e^{\pm}\mu^{\mp}$dileptons are used with 1 b-tagged jet and without additional loose jets
  - Several different kinematic variables are compared against predictions including leading lepton p_T, jet p_T, $\Delta\varphi\left(e^{\pm},\mu^{\mp}\right)$, $p_Z(e^{\pm},\mu^{\mp},j)$, $m(e^{\pm},\mu^{\mp},j)$ and $m_T\ (e^{\pm},\mu^{\mp},j,\ p_T^{miss})$
  - Backgrounds are subtracted bin by bin and unfolded using a response matrix parameterizing bin migration to produce the differential cross sections

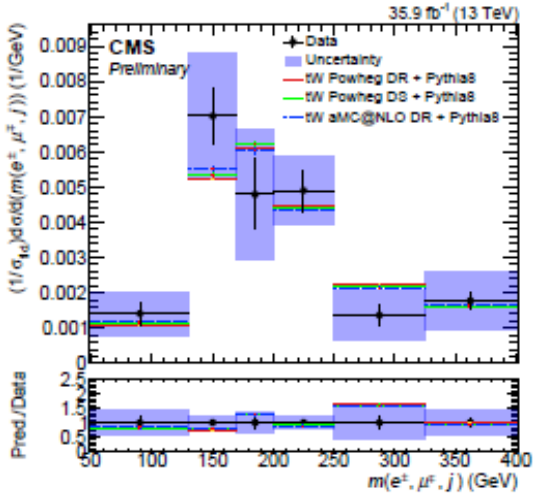
CMS-PAS-TOP-19-003

Differential Cross Section Wt Channel (CMS)







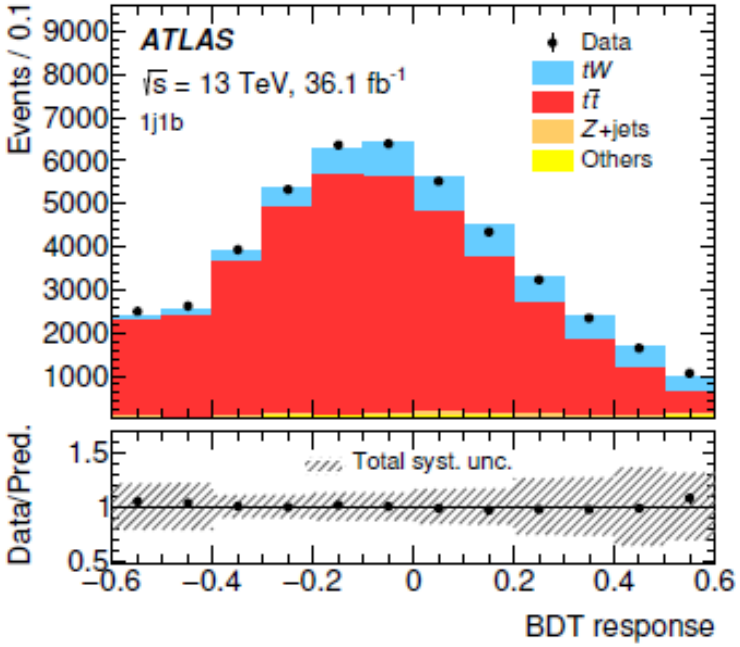


- Good agreement with POWHEG DR, POWHEG DS, and MadGraph5_aMC@NLO is observed

CMS-PAS-TOP-19-003

Differential Cross Section Wt Channel (ATLAS)

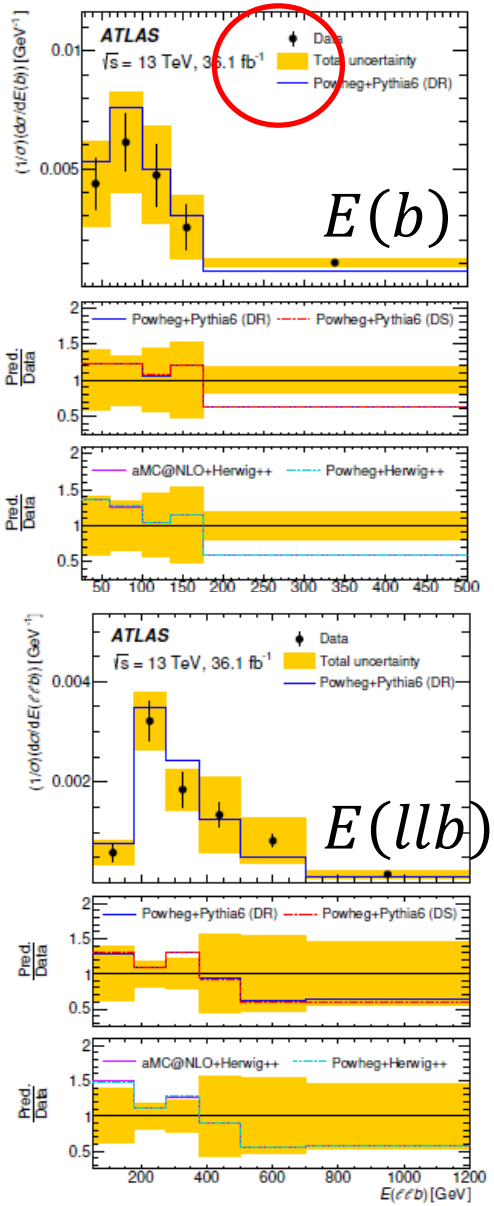
- Differential cross sections in the Wt channel were previously measured by ATLAS also
  - Signal selection uses two opposite sign dileptons and exactly one jet that is b-tagged along with m_{ll}, E_T^{miss} selections
  - A BDT technique was used to separate Wt signal from the dominant $t\bar{t}$ background
    - Input variables are derived from the two lepton and b-tagged jet four momenta and E_T^{miss}



EPJC 78 (2018) 186

Differential Cross Section Wt Channel (ATLAS)

- An iterative Bayesian technique is used for unfolding
- The dominant uncertainties are limited data statistics and Wt and $t\bar{t}$ modelling
- Good agreement with various MC models is observed



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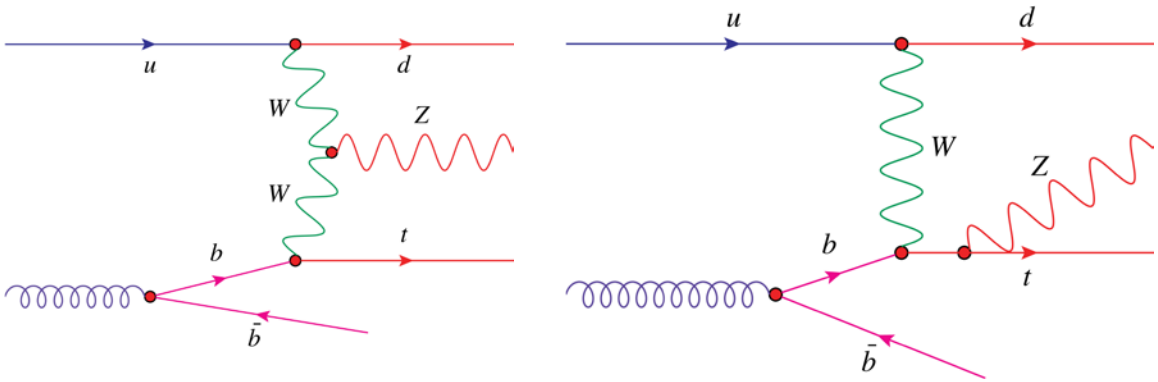
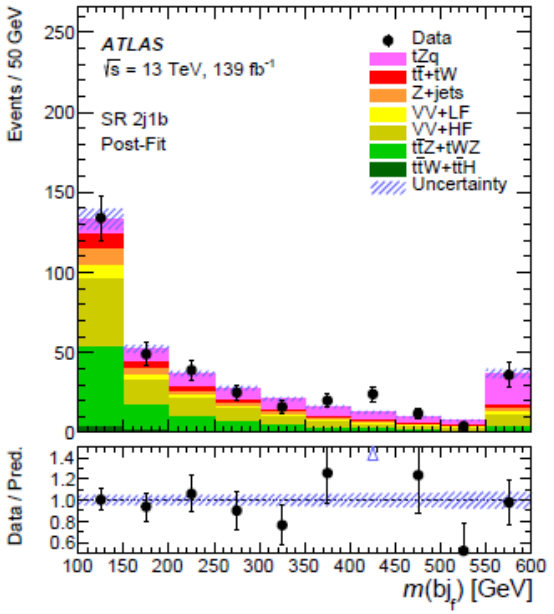
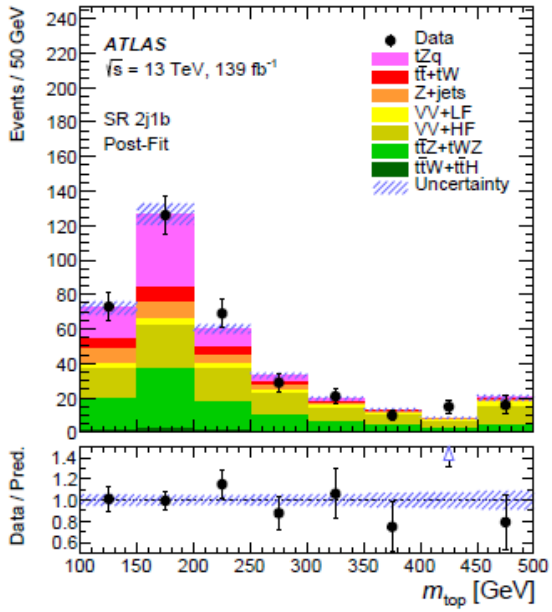
tZq Production (ATLAS)

- Probes tZ and WWZ couplings
- Event selection includes 3 high p_T leptons, 1 b-tagged jet, and one or two additional jets
- Signal and background discrimination is achieved using a NN
  - Kinematic variables of leptons, jets, and b-jet
  - Top quark mass (l, E_T^{miss}, b)
  - Z boson kinematics





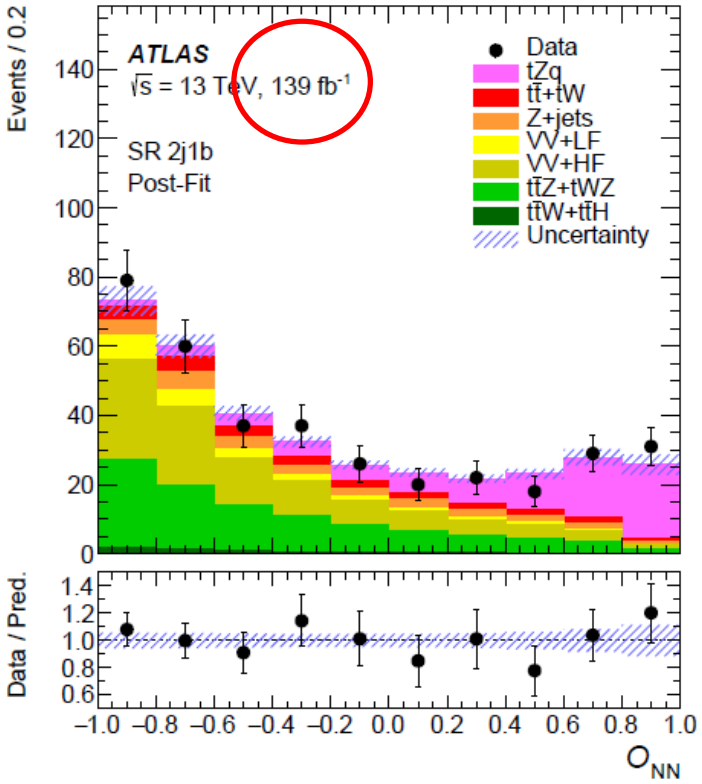


2j1b signal region

arXiv:2002.07546

tZq Production (ATLAS)

- Cross section is extracted from a binned ML fit performed on the NN output in 2 SRs and variables in the 6 CRs
- Largest uncertainties are
  - Statistics (12%)
  - Prompt lepton modelling and norm. (3%)
  - Lepton reconstruction and calibration (2%)
  - Jet and E_T^{miss} calibration (2%)



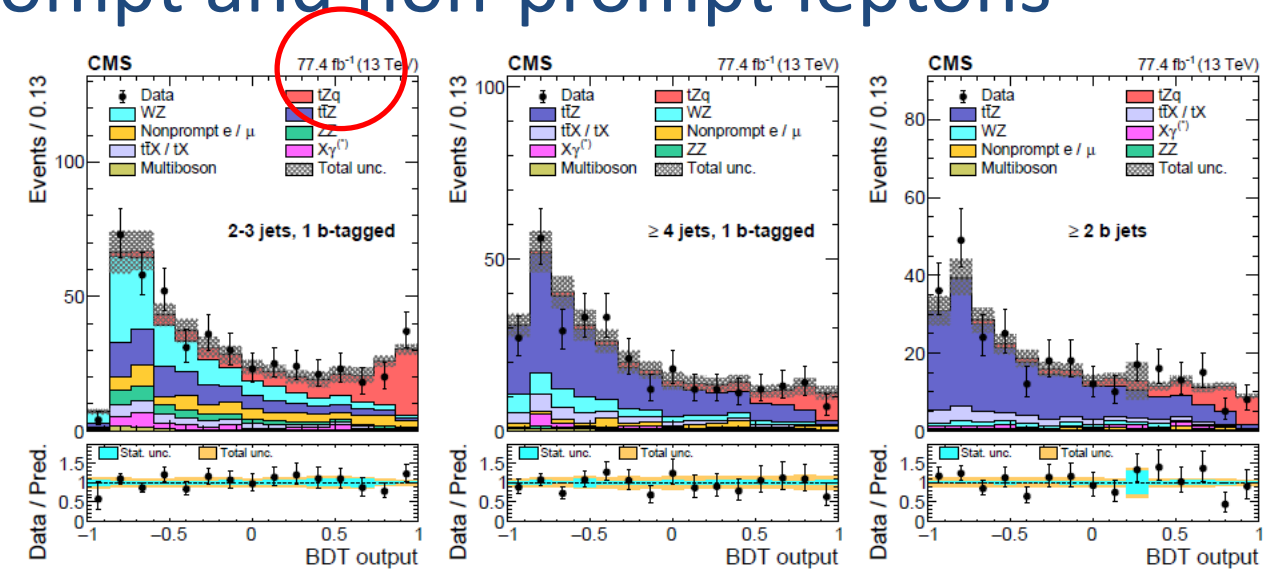
$$\sigma = 97 \pm 13\,(stat) \pm 7\,(syst)\ \text{fb}$$

$$\sigma(SM) = 102^{+5}_{-2}\ \text{fb @ NLO}$$

arXiv:2002.07546

tZq Production (CMS)

- CMS previously observed this cross section with a significance > 5σ
- Event selection was 3 high p_T leptons, 1 b-tagged jet and at least one additional jet
- BDT's were used to discriminate between prompt and non-prompt leptons



PRL 122 (2019) 132003

tZq Production (CMS)

- Cross section results from a ML fit performed on the BDT output in 3 SRs and normalizations from 2 CRs enriched with WZ and ZZ background
- Largest uncertainties are
  - Statistics (12%)
  - Non-prompt lepton normalization (4%)
  - Lepton selection(3%)
  - Jet energy scale (3%)

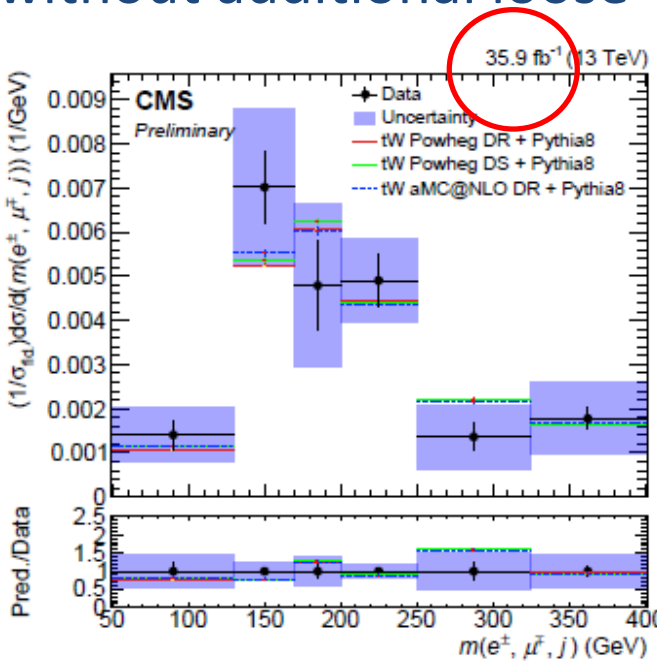
$$\sigma = 111 \pm 13\ (stat)\ ^{+11}_{-9}\ (syst)\ \text{fb}$$

PRL 122 (2019) 132003

Differential Cross Section Wt Channel (CMS and ATLAS)

CMS-PAS-TOP-19-003

- Opposite sign $e^{\pm}\mu^{\mp}$dileptons are used with one b-tagged jet and without additional loose jets

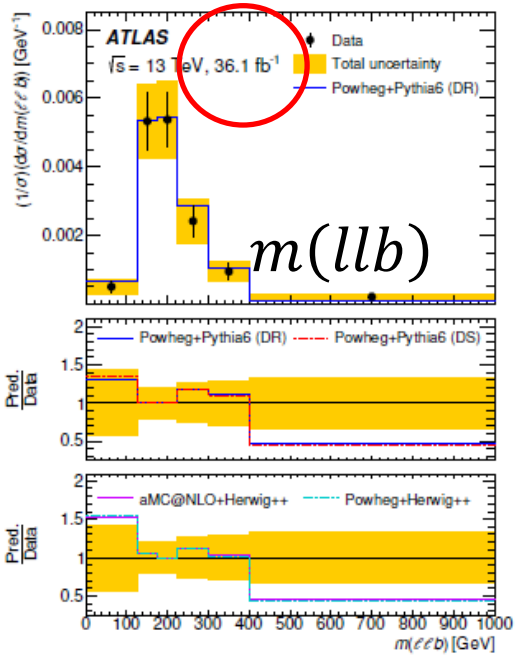


$m(e\mu j)$

- Good agreement with various MC predictions is observed

EPJC 78 (2018) 186

- Opposite sign dileptons and exactly one jet that is b-tagged along with m_{ll}, E_T^{miss} selections



- Good agreement with various MC predictions is observed