HIGHLIGHTS OF TOP QUARK MEASUREMENTS AT THE LHC: TOP QUARK COUPLINGS

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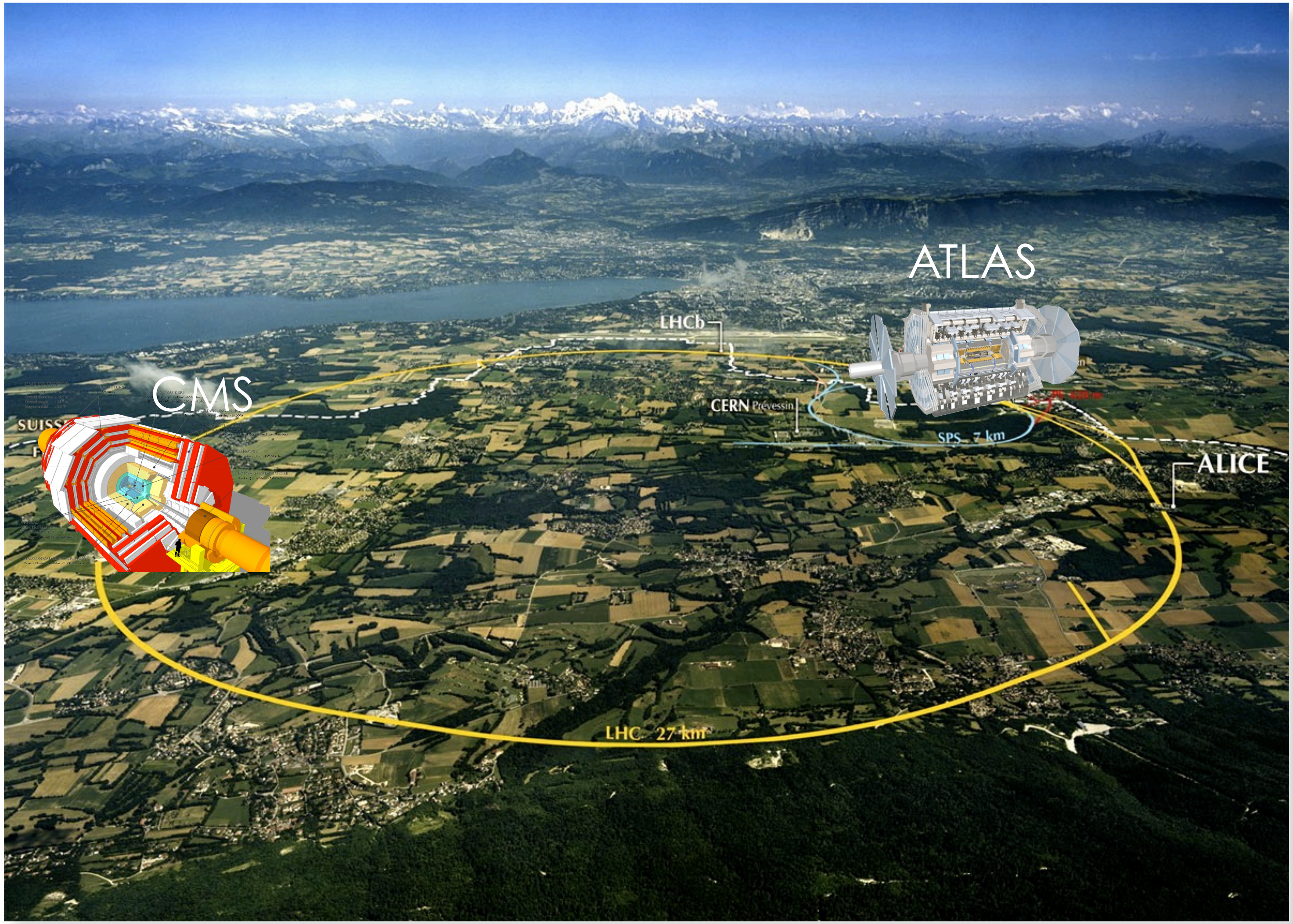
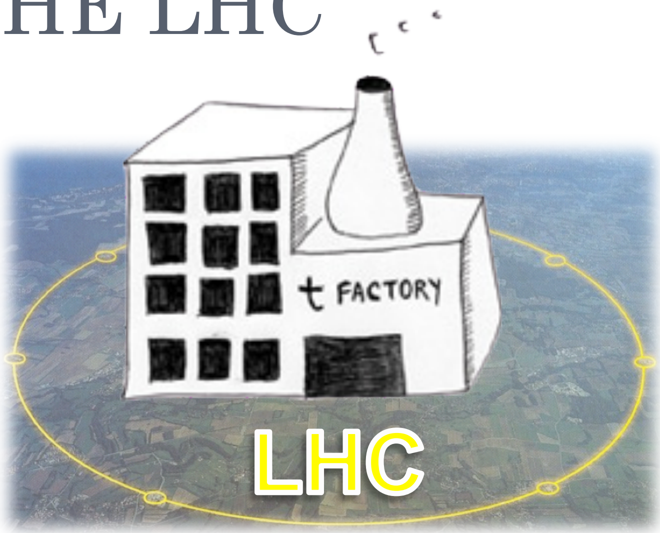
TOP PRODUCTION AT THE LHC



TOP PRODUCTION AT THE LHC



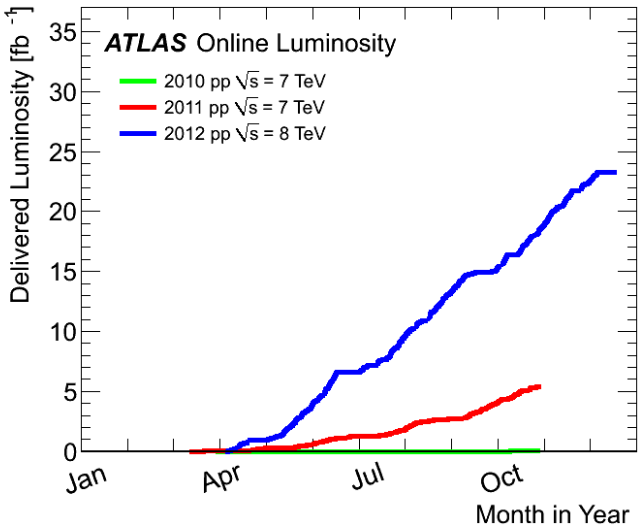
- Impressive performance at the LHC and in the ATLAS and CMS experiments
- LHC is the first top factory ever!

At the peak of instantaneous luminosity during 2012 the top production was :

~ 2 top pairs/s 

~ 1 single top/s 

Around **15M** quark tops were produced during 2011 and 2012!

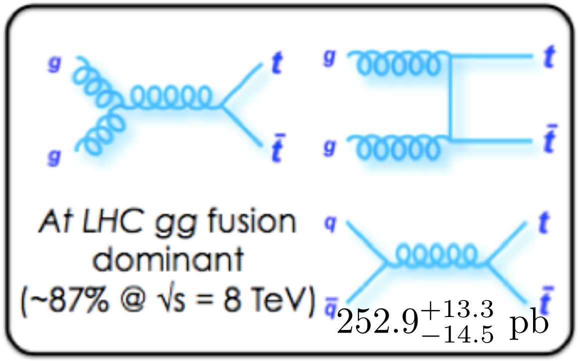


- While precision measurements soon/ already limited by systematic uncertainties, many possibilities for other studies open up.

Main focus of the talk on top quark couplings.

TOP PRODUCTION AT THE LHC

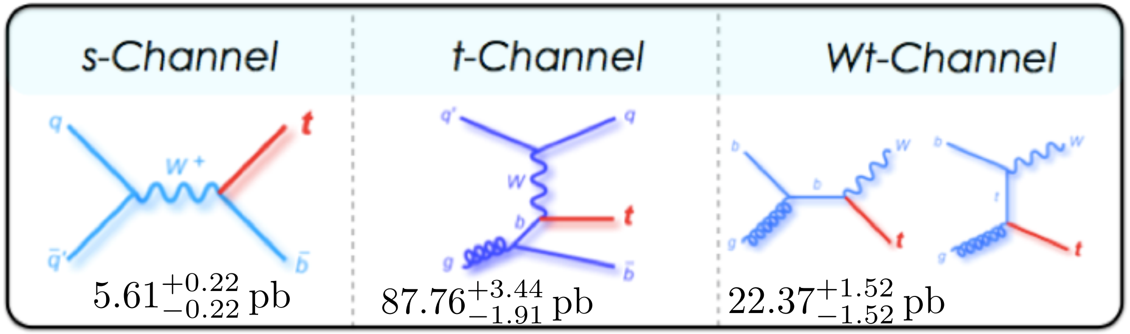
top pair production



At LHC gg fusion dominant (~87% @ √s = 8 TeV)

$252.9^{+13.3}_{-14.5}$ pb

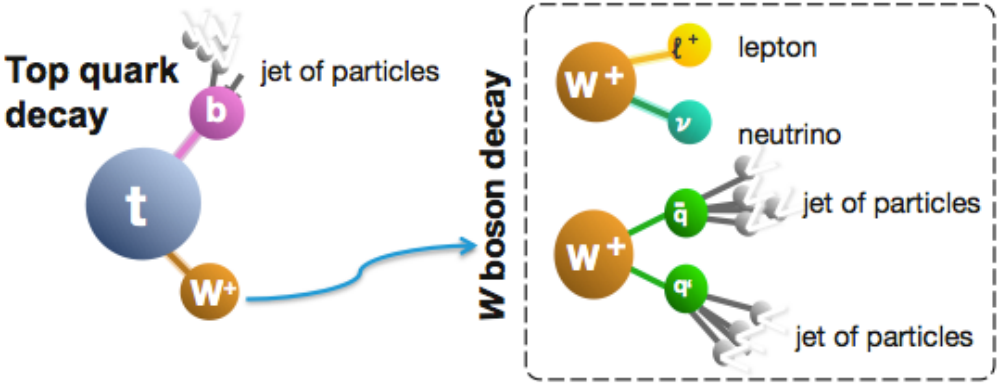
single top : production via EW interaction

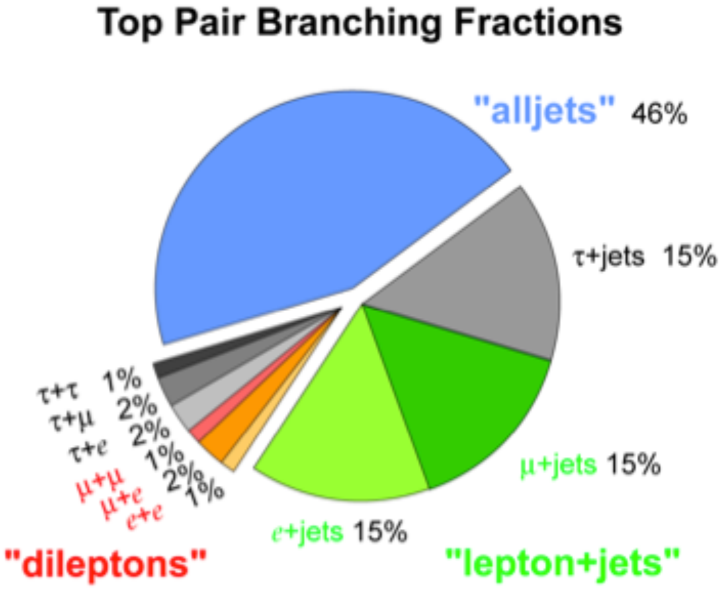


s-Channel: $5.61^{+0.22}_{-0.22}$ pb

t-Channel: $87.76^{+3.44}_{-1.91}$ pb

Wt-Channel: $22.37^{+1.52}_{-1.52}$ pb





Top quarks can be produced in pairs via QCD or singly via EW interactions.

Channels classified depending on the W decay mode.

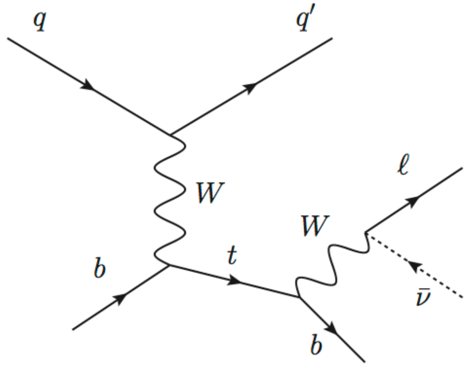
A DATA ANALYSIS EXAMPLE

Typical steps:

- (1) Event selection to enhance signal
- (2) Background estimation (MC or data driven)
- (3) Fit/correct data using MC simulation to account for acceptance, detector and resolution effects.
- (4) Estimate statistical and systematic uncertainties (due to physics modelling and experimental sources)

Ex: Forward backward asymmetry measurement from an angular distribution in single top t-channel

$$A_{FB}^{X} = \frac{N(\cos\theta_l^X > 0) - N(\cos\theta_l^X < 0)}{N(\cos\theta_l^X > 0) + N(\cos\theta_l^X < 0)}$$



The measurements provided at ATLAS and CMS can then be combined

- This is done with the TOPLHCWG

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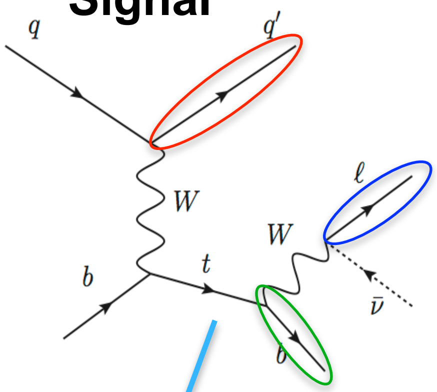
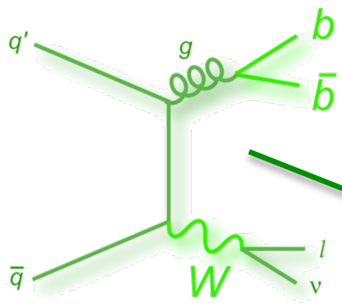
PRESELECTION:
- ○ Single lepton triggers
- ○ **1 $e^{\pm}$ or $\mu^{\pm}$**
- ○ **2 jets**, $p_T > 30$ GeV, $|\eta| < 4.5$ **1 b-jet**
- ○ Cuts on E_T^{miss} and $m_T(W)$

SELECTION:
- ○ $|\eta_{light\text{-}jet}| > 2.0$
- ○ $H_T > 210$ GeV
- ○ $m_{top} \in (150,190)$ GeV
- ○ $|\Delta\eta$ (b-jet, light-jet)$| > 1.0$

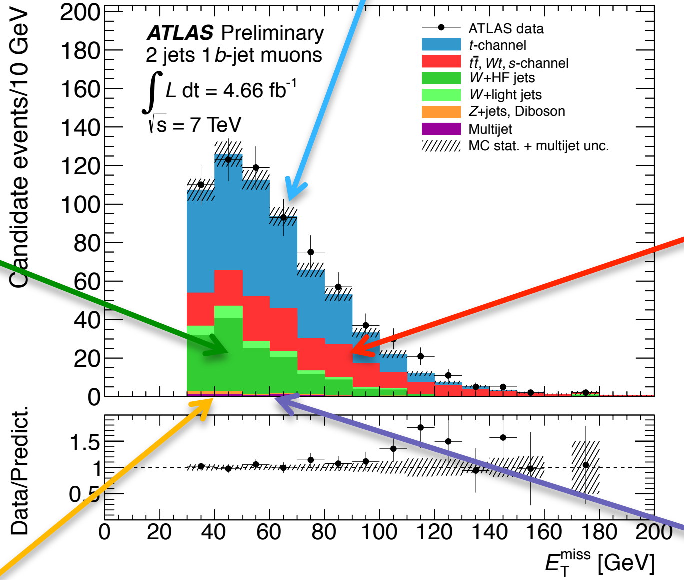
Signal

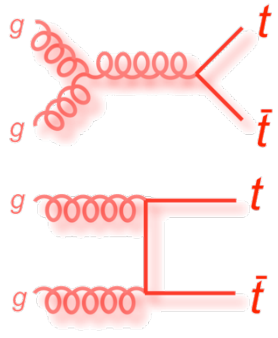


Background processes

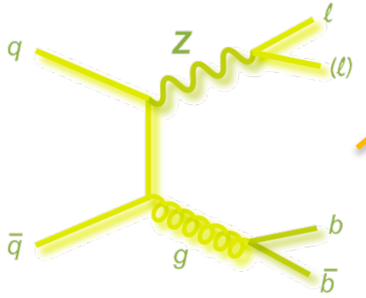


W+jets (W+bb)
One of the dominant ones.
Same final state as the signal.

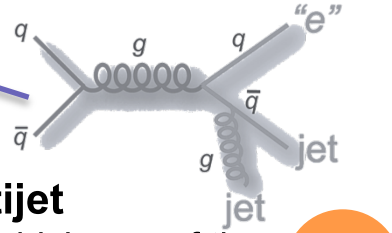




top-antitop pairs
One of the main backgrounds.



Z+jets (Z+bb)
Final state in which one lepton is missed.



Multijet
Events with jets in which one of them is incorrectly identified as a lepton.

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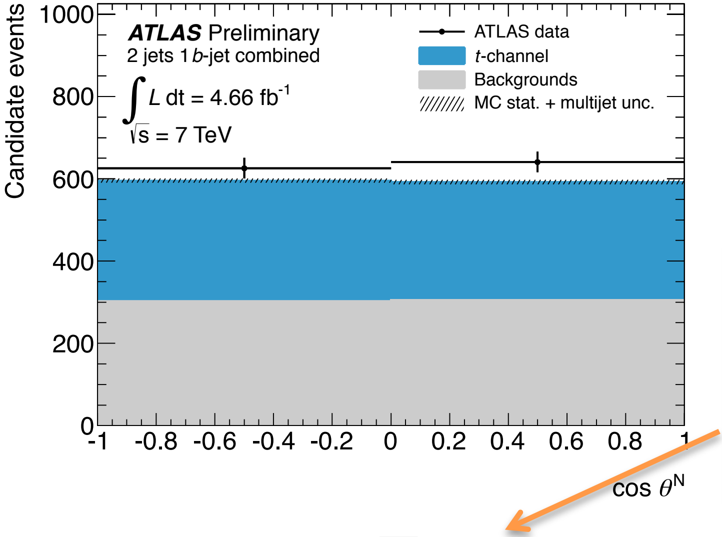
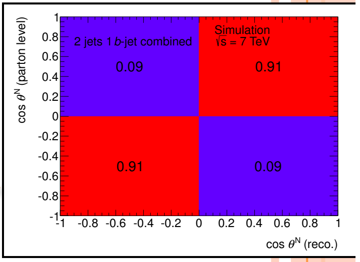
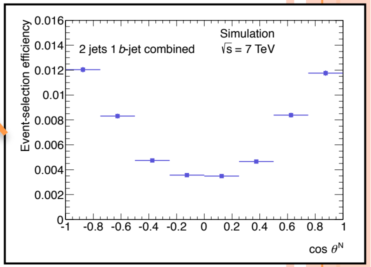




$$N_j^{unfold} = \frac{\sum_i M_{ij}^{-1} \cdot [N_i^{data} - N_i^{bkg}]}{\varepsilon_j}$$

$$A_{FB}^{N} = \frac{N_+^{unfold} - N_-^{unfold}}{N_+^{unfold} + N_-^{unfold}}$$



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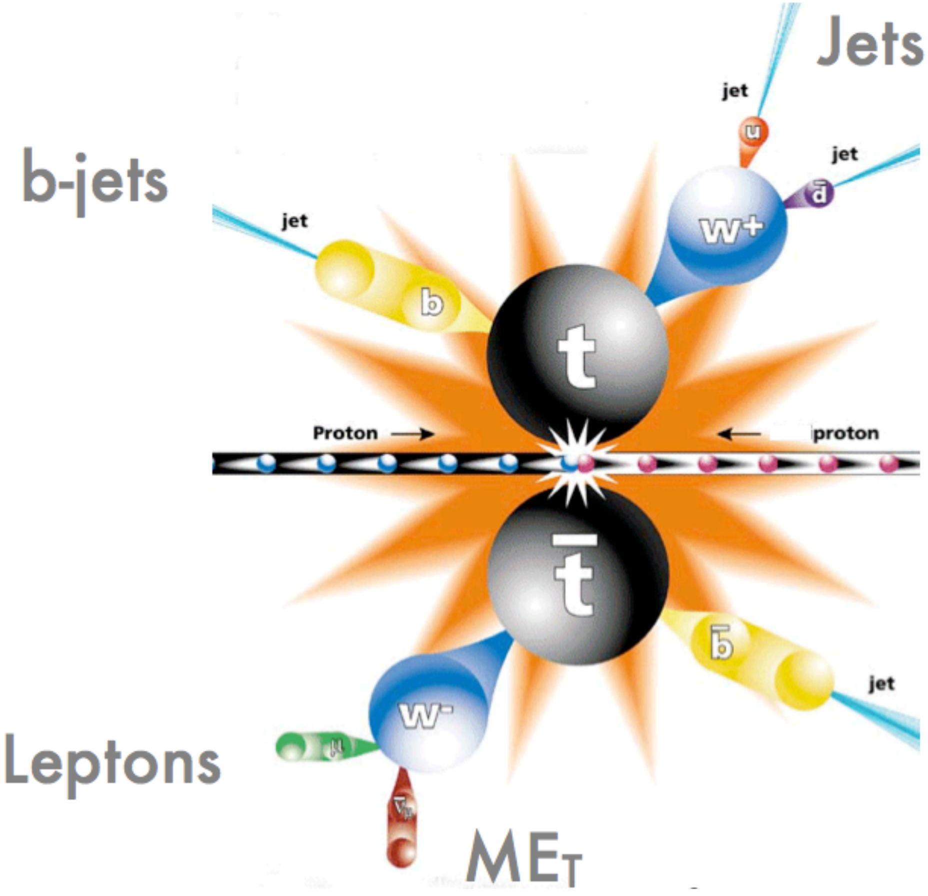
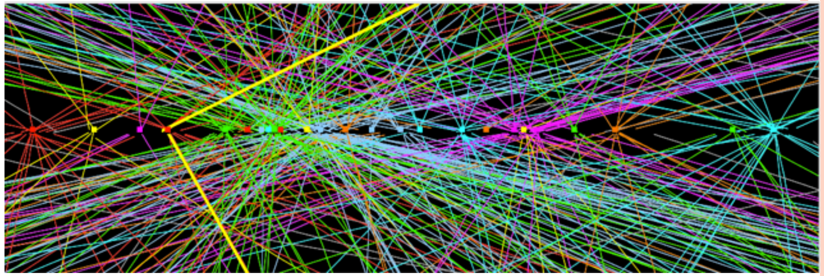
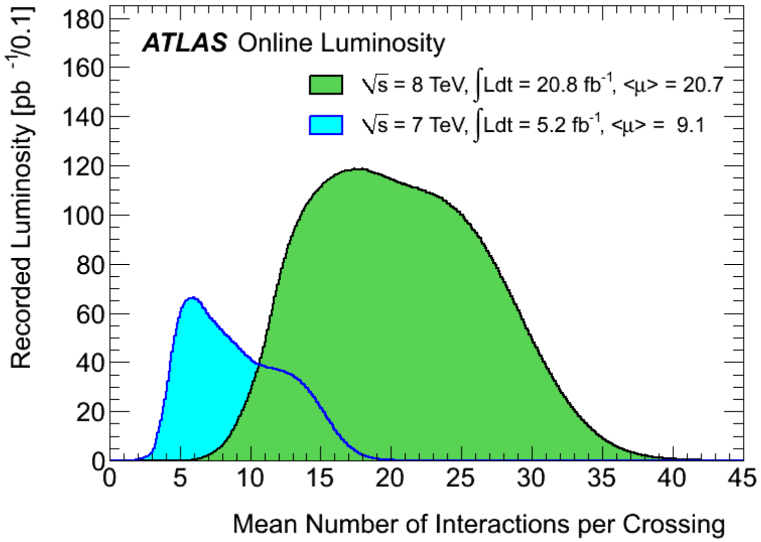
ANALYSIS CHALLENGES – EXPERIMENTAL UNCERTAINTIES







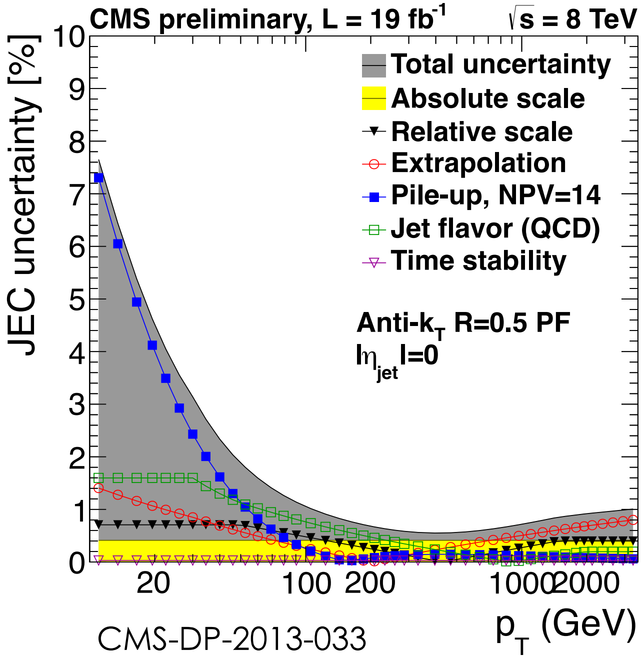
Top quark measurements will rely on a good performance of jets, b-tagging, leptons and Missing Transverse Energy.

Main experimental uncertainties in most top quark analyses are coming from jets (Jet Energy Scale) and b-tagging uncertainties.

EXPERIMENTAL UNCERTAINTIES

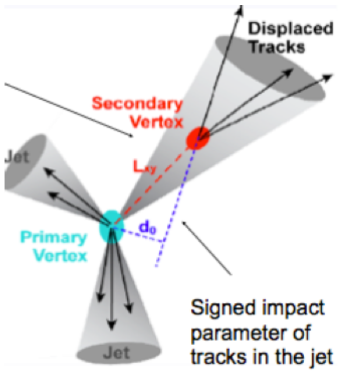
Jets

- The anti-k_t algorithm with R=0.4 (0.5) is used in ATLAS (CMS) (several other R also used).
- The jet calibration restores the jet energy scale to that of jets from stable particles.

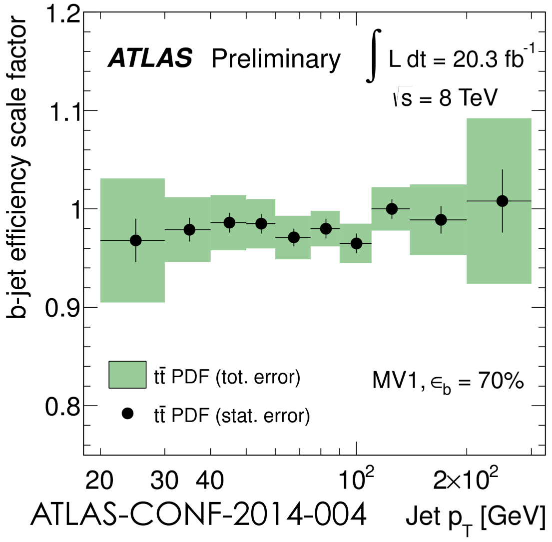


CMS-DP-2013-033

b-tagging



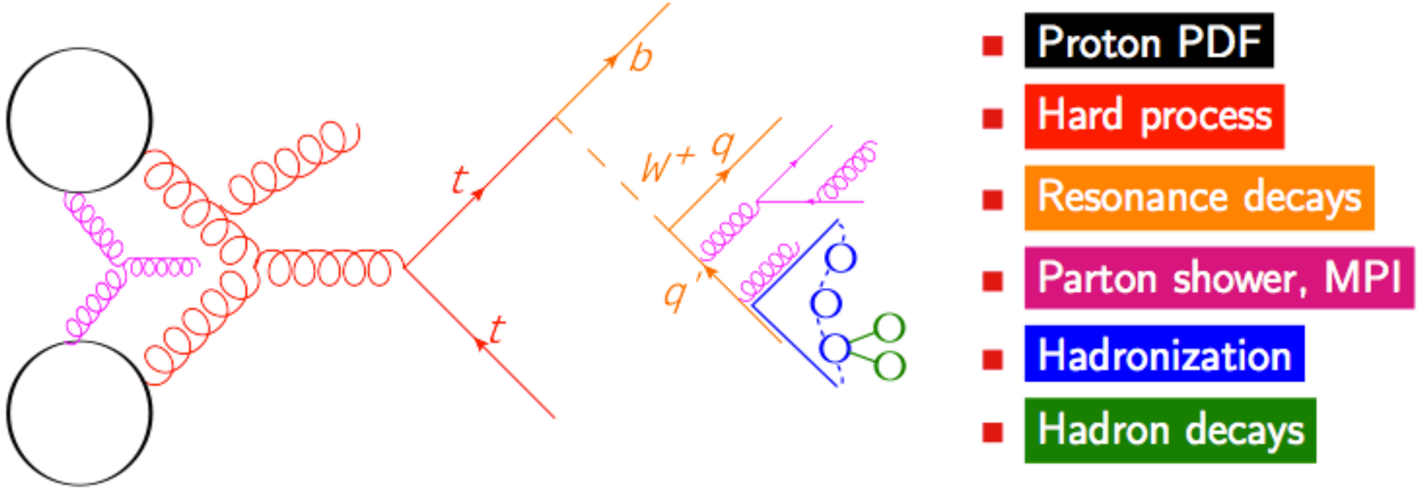
- b-jets are identified by exploiting the track impact parameters and secondary vertices information
- Top quark pair events can be used for calibration



ATLAS-CONF-2014-004

ANALYSIS CHALLENGES – PHYSICS MODELLING UNCERTAINTIES

- The Monte Carlo generators used at LHC include multi-leg or NLO predictions for signal and main background processes.
- Signal modelling uncertainties are typically important/dominant (e.g. radiation, parton shower & hadronisation models, PDF, CR)



Two important strategies:

- Perform measurements in top events that allow constraining these modelling uncertainties from data.
- Reduce generator dependency on measurements by providing results at particle level in a fiducial region experimentally accessible.

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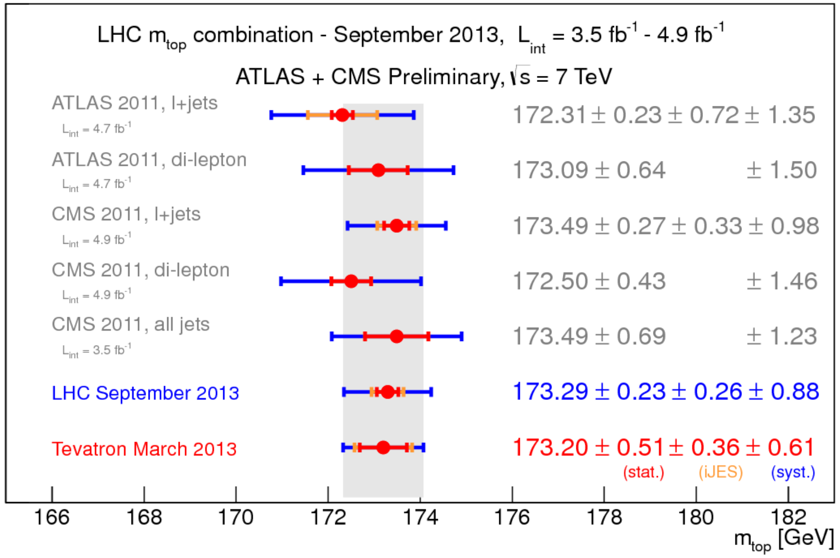
Example: Top quark mass combination

ATLAS-CONF-2013-102



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ATLAS/CMS COMBINATIONS

- Assumptions:
  - Individual measurements are unbiased (checked in each experiment)
  - Uncertainties are gaussian distributed
  - All sources of uncertainties are independent.
- Tools: Best Linear Unbiased Estimate (BLUE)
  - Results obtained from a linear weighted sum of the input measurements
  - Weights are determined to minimise the total uncertainty
- Inputs:
  - Results of each experiment with a detailed breakdown of uncertainties

Main combination challenges:

- Find the proper mapping between the corresponding systematics in different experiments
- Understanding the correlations in each category

ATLAS/CMS COMBINATIONS

Example: Jet Energy Scale uncertainty categorisation and correlations

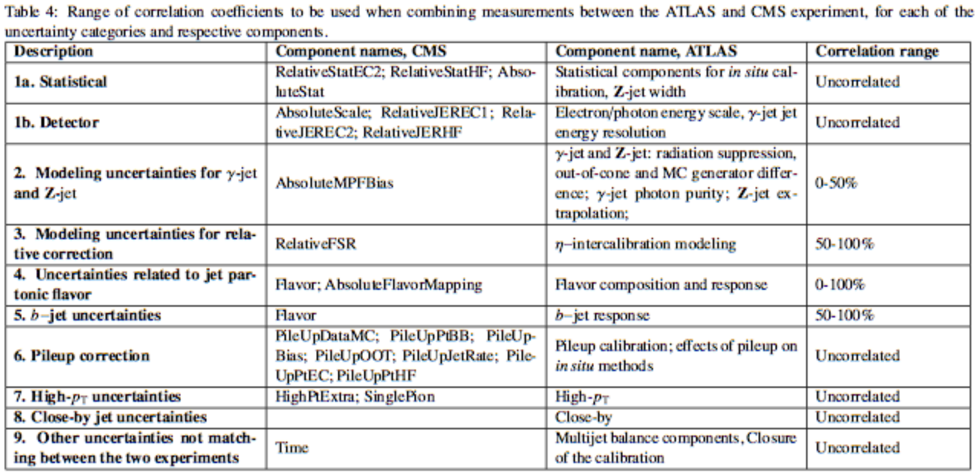
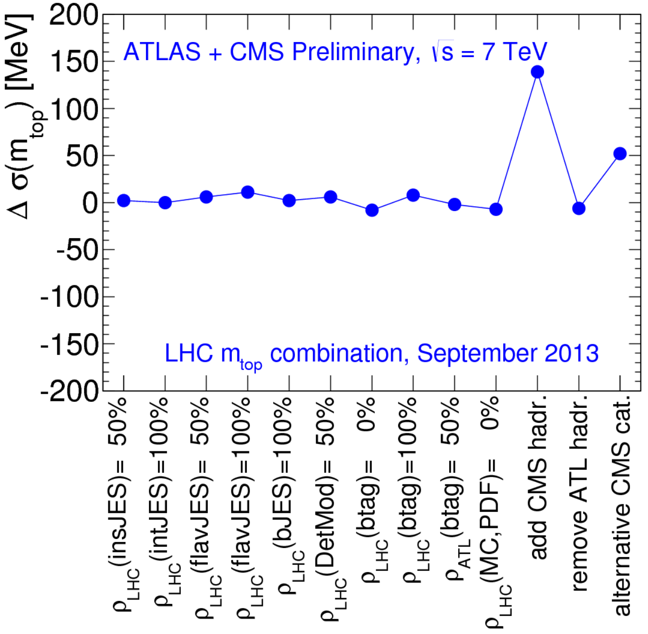


Table 4: Range of correlation coefficients to be used when combining measurements between the ATLAS and CMS experiment, for each of the uncertainty categories and respective components.

Description	Component names, CMS	Component name, ATLAS	Correlation range
1a. Statistical	RelativeStatEC2; RelativeStatHF; AbsoluteStat	Statistical components for *in situ* calibration, Z-jet width	Uncorrelated
1b. Detector	AbsoluteScale; RelativeJEREC1; RelativeJEREC2; RelativeJERHF	Electron/photon energy scale, γ-jet jet energy resolution	Uncorrelated
2. Modeling uncertainties for γ-jet and Z-jet	AbsoluteMPFBias	γ-jet and Z-jet: radiation suppression, out-of-cone and MC generator difference; γ-jet photon purity; Z-jet extrapolation;	0-50%
3. Modeling uncertainties for relative correction	RelativeFSR	η–intercalibration modeling	50-100%
4. Uncertainties related to jet partonic flavor	Flavor; AbsoluteFlavorMapping	Flavor composition and response	0-100%
5. b–jet uncertainties	Flavor	b–jet response	50-100%
6. Pileup correction	PileUpDataMC; PileUpPtBB; PileUpBias; PileUpOOT; PileUpJetRate; PileUpPtEC; PileUpPtHF	Pileup calibration; effects of pileup on *in situ* methods	Uncorrelated
7. High-p_T uncertainties	HighPtExtra; SinglePion	High-p_T	Uncorrelated
8. Close-by jet uncertainties		Close-by	Uncorrelated
9. Other uncertainties not matching between the two experiments	Time	Multijet balance components, Closure of the calibration	Uncorrelated

ATLAS-PUB-2014-020

Example: Top quark mass combination stability checks

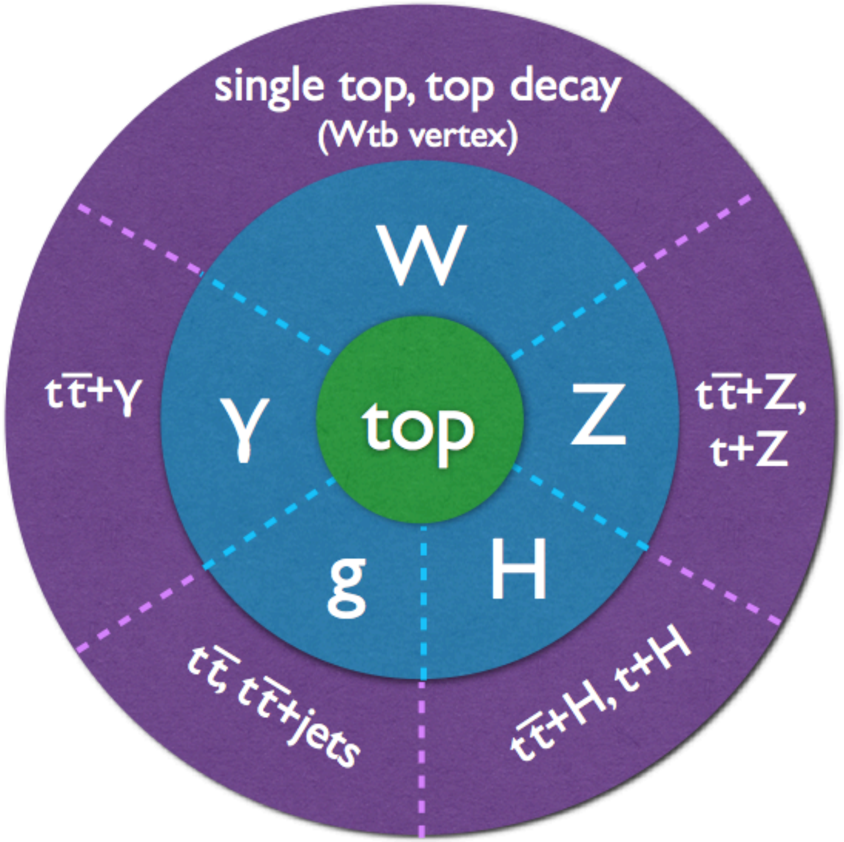


ATLAS-CONF-2013-102

- A lot of progress made in understanding the treatment of the main experimental systematic uncertainties (jet energy scale and b-tagging efficiency) and towards a harmonisation of the main modelling uncertainties (top quark pair and single top) with input from theorists and data.
- Important to perform stability checks (e.g. changing correlation assumptions or different treatment of modelling uncertainties).

TOP COUPLINGS: MOTIVATION

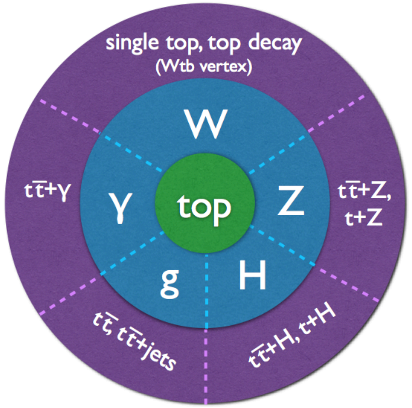
- The top quark couples to the other SM fields through its gauge and Yukawa interactions.
- Sensitivity to new physics.
- BR(t→Wb)~1 → Wtb vertex probed at Tevatron and LHC
- $t\bar{t}$+bosons (γ,Z,H) becomes available at the LHC.

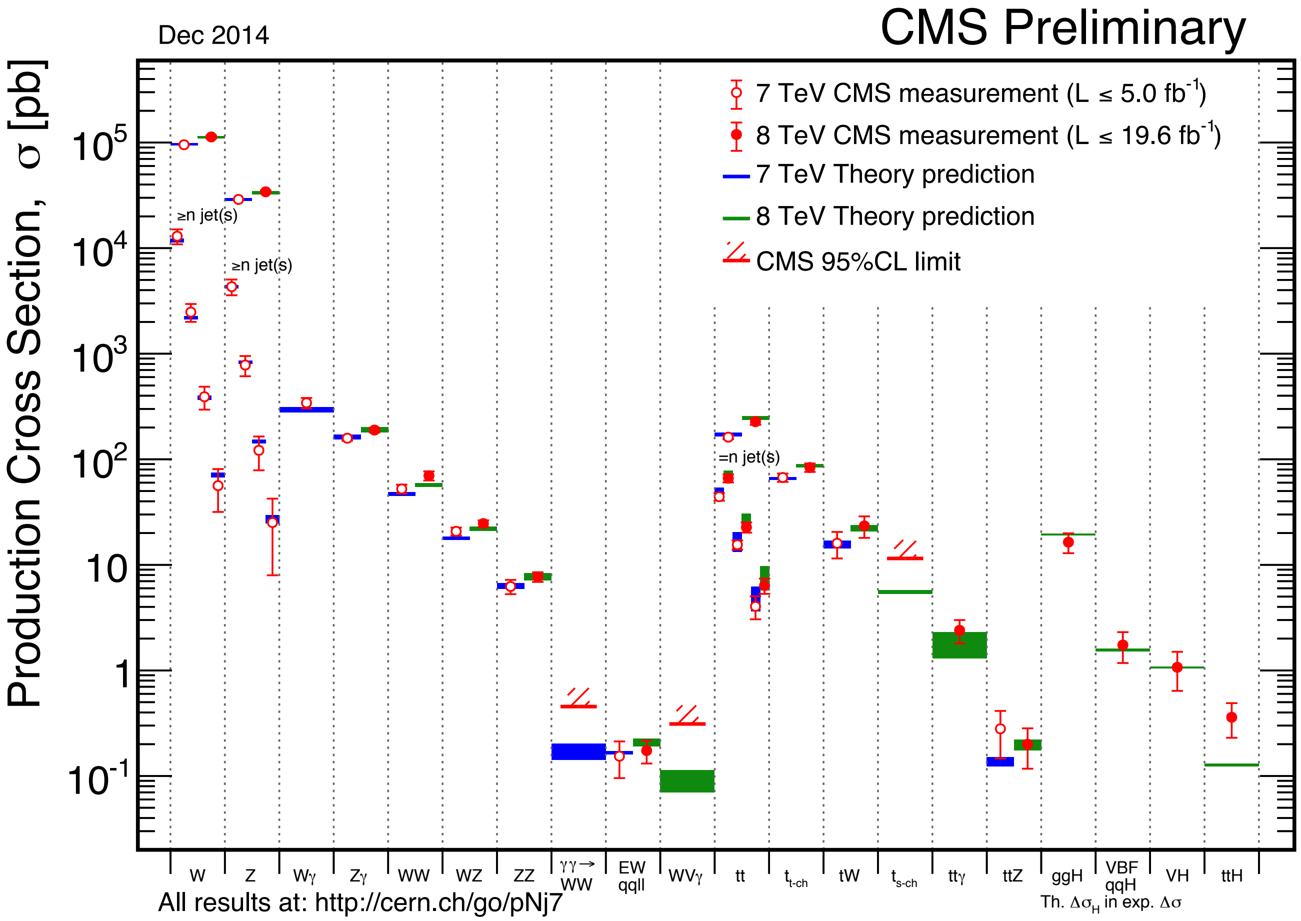


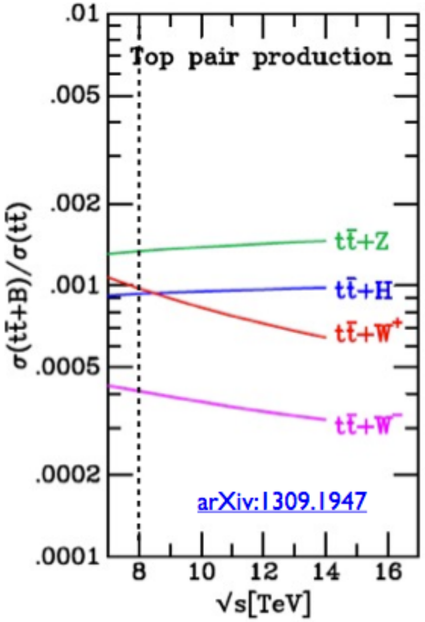
to W boson	$\frac{g_W}{\sqrt{2}} \sim 0.45$	$\frac{g_W}{\sqrt{2}} V_{tq} \bar{t}_L \gamma^\mu q_L \; W_\mu^-$
to Z boson	$g_Z = \frac{g_W}{4\cos\theta_W} \sim 0.14$	$g_Z t_L \left[(1-\frac{8}{3}\sin^2\theta_W)\gamma^\mu - \gamma^\mu\gamma_5\right] t_L \; Z_\mu$
to photon	$e_t = \frac{2}{3} e \sim 0.21$	$e_t \bar{t}\gamma^\mu t \; A_\mu$
to gluon	$g_s \sim 1.12$	$g_s \bar{t}_j \gamma^\mu \; T^{SU(3)}_{jk} t_k \; G_\mu$
to Higgs	$Y_t = \frac{g_W m_t}{\sqrt{2} M_W} \sim 1$	$\frac{Y_t}{\sqrt{2}} \bar{t} t \; H$

TOP COUPLINGS

Will only focus on the processes observed so far at the LHC → Will not cover ttH







TOP COUPLINGS: MOTIVATION

- The effects of new physics at a scale Λ can be described by an effective Lagrangian

$$\mathcal{L}^{\rm eff} = \sum \frac{C_x}{\Lambda^2} O_x + \ldots$$

O_x = dim 6 gauge invariant operators

C_X=complex constants

- These operators can induce corrections to SM couplings (e.g. may originate anomalous couplings of the top quark to the gauge bosons).
- Effective Vf_if_j vertices, V=W, Z, γ, g:

$$\begin{aligned}\mathcal{L}_{Wtb} &= -\frac{g}{\sqrt{2}} \bar{b}\, \gamma^\mu \left(V_L P_L + V_R P_R \right) t\, W_\mu^- \\ &\quad - \frac{g}{\sqrt{2}} \bar{b}\, \frac{i \sigma^{\mu\nu} q_\nu}{M_W} \left(g_L P_L + g_R P_R \right) t\, W_\mu^- + \mathrm{H.c.}\,.\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{Ztt} &= -\frac{g}{2 c_W} \bar{t}\, \gamma^\mu \left(X_{tt}^L P_L + X_{tt}^R P_R - 2 s_W^2 Q_t \right) t\, Z_\mu \\ &\quad - \frac{g}{2 c_W} \bar{t}\, \frac{i \sigma^{\mu\nu} q_\nu}{M_Z} \left(d_V^Z + i d_A^Z \gamma_5 \right) t\, Z_\mu\,,\end{aligned}$$

$$\mathcal{L}_{\gamma tt} = -e Q_t \bar{t}\, \gamma^\mu t\, A_\mu - e \bar{t}\, \frac{i \sigma^{\mu\nu} q_\nu}{m_t} \left(d_V^\gamma + i d_A^\gamma \gamma_5 \right) t\, A_\mu$$

$$\mathcal{L}_{gtt} = -g_s \bar{t}\, \frac{\lambda^a}{2} \gamma^\mu t\, G_\mu^a - g_s \bar{t}\, \lambda^a \frac{i \sigma^{\mu\nu} q_\nu}{m_t} \left(d_V^g + i d_A^g \gamma_5 \right) t\, G_\mu^a$$

Higher precision on measurements of top couplings means access to higher mass scales for new physics.

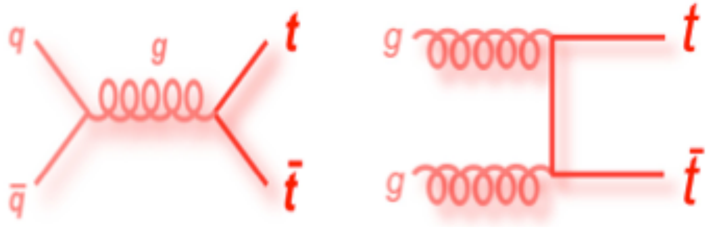
e.g. for Wtb vertex:

$$\delta V_L = C_{\phi q}^{(3,33)*} \frac{v^2}{\Lambda^2}\,, \quad \delta g_L = \sqrt{2} C_{dW}^{33*} \frac{v^2}{\Lambda^2}$$

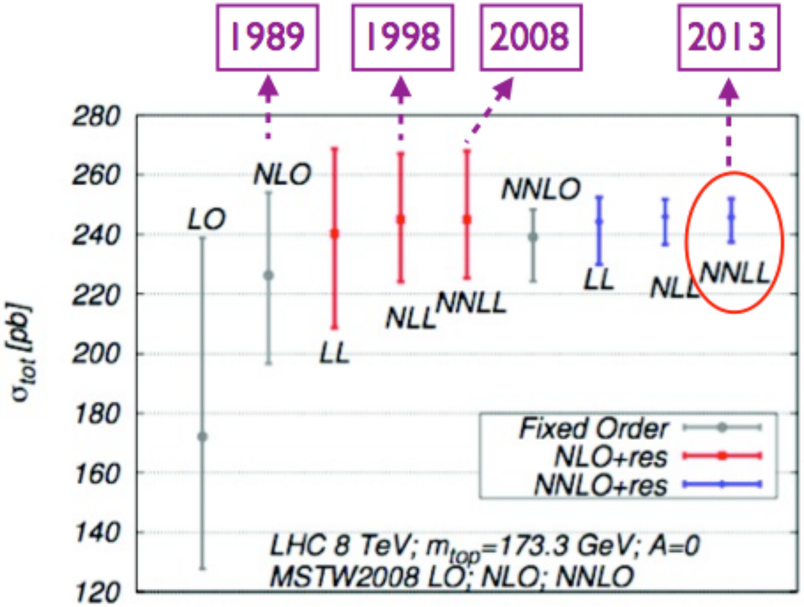
$$\delta V_R = \frac{1}{2} C_{\phi\phi}^{33} \frac{v^2}{\Lambda^2}\,, \quad \delta g_R = \sqrt{2} C_{uW}^{33} \frac{v^2}{\Lambda^2}$$

TOP COUPLING TO GLUON

- Strong interactions of the top quark are studied in top quark pair production, including $t\bar{t}$+jets processes.
- Long standing theoretical effort on fixed order calculations on inclusive (NNLO+NNLL) and differential cross sections (NNLO expected soon)



	top pairs XS[4]
7 TeV:	$177.3^{+10.1}_{-10.8}$ pb
8 TeV:	$252.9^{+13.3}_{-14.5}$ pb



NLO → NNLO+NNLL
Precision improves from:

~12% →~3% (scales)

~ 8% → 5% (PDF)

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[4] NNLO+NNLL (Top++2.0)

TOP QUARK PRODUCTION

- Measurements available in various channels using different techniques (e.g. cut and count)

Most precise measurements come from ATLAS

ATLAS (eμ channel)

Eur. Phys. J. C74 (2014) 3109

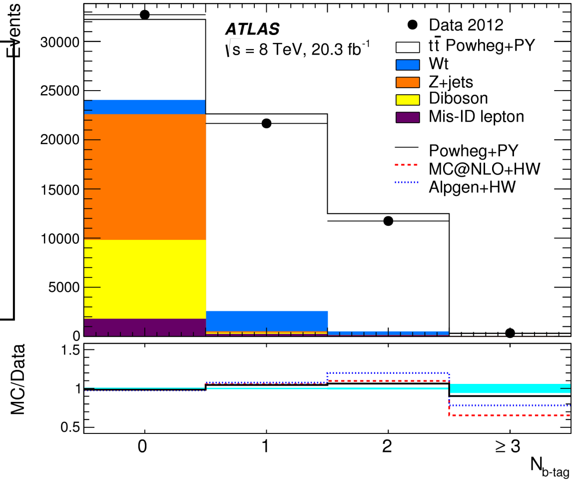
- Simultaneous measurement of **σ** and **ε** counting events with 1 and 2 b-jets.

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

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

Precision achieved:
3.5% @ 7 TeV
4% @ 8 TeV
In addition, beam E uncertainty (0.66%)

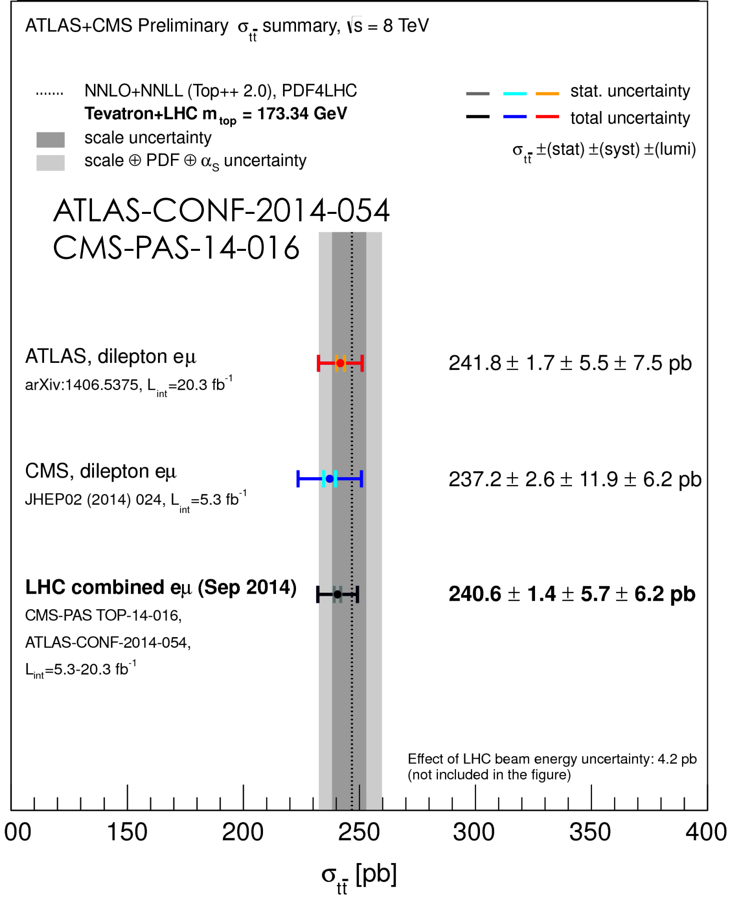
Dominant sources:
Signal modelling, PDF, luminosity.



$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\mathrm{pb}\ (\sqrt{s} = 7\,\mathrm{TeV})$$

$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\,\mathrm{pb}\ (\sqrt{s} = 8\,\mathrm{TeV})$$

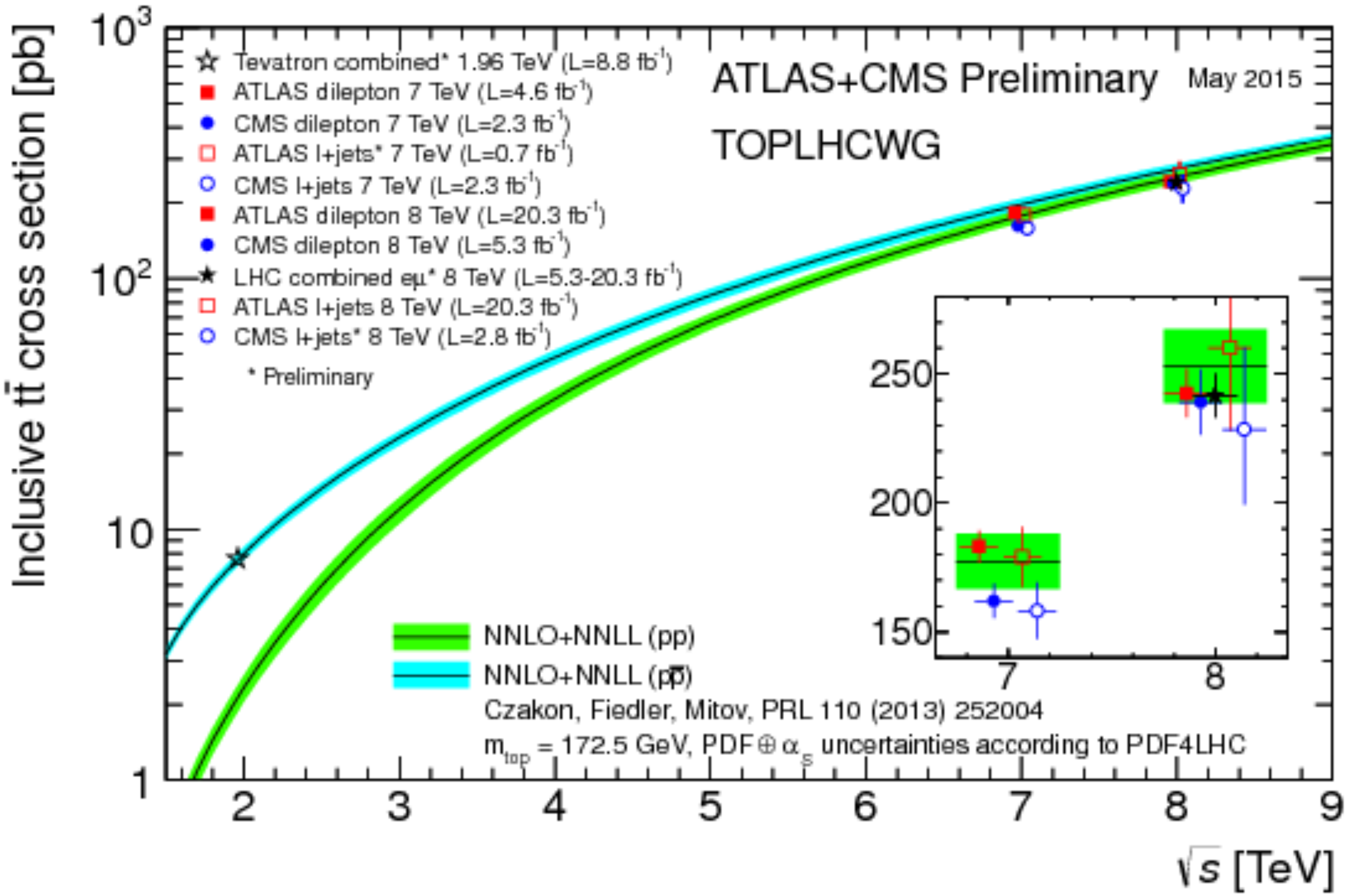
Improved even further when combined with CMS



ATLAS-CONF-2014-054
CMS-PAS-14-016

(3.5%)
Dominant sources: luminosity, signal modelling, JES

TOP QUARK PRODUCTION



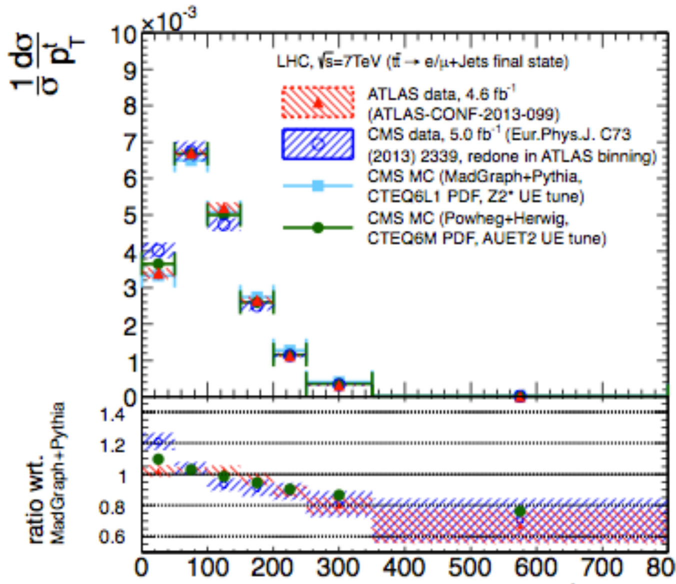
Excellent agreement of NNLO+NNLL predictions and precise experimental measurements.

Experimental precision now challenging the theoretical predictions.

TOP QUARK PRODUCTION - DIFFERENTIAL

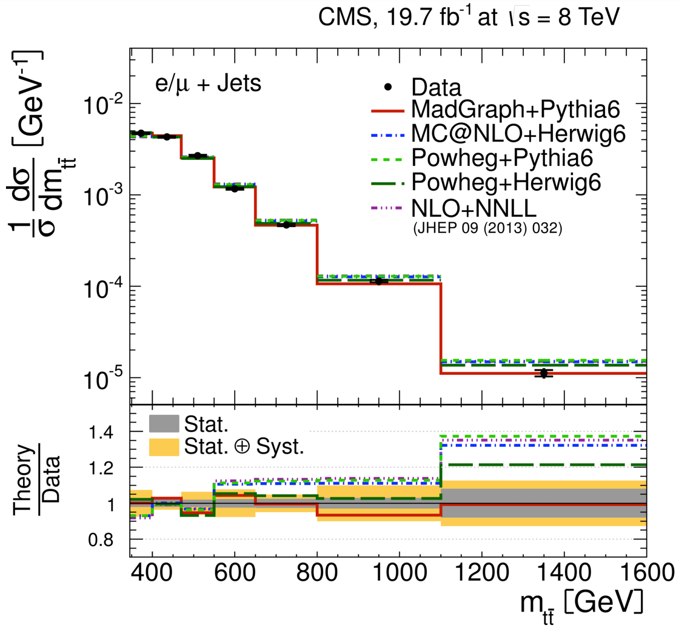
- Probe different regions of the phase space: Important test of pQCD, constrain on MC models/PDFs and systematic effects, sensitive to new physics.
- Use unfolding techniques on background subtracted reconstructed distributions to parton or particle level in fiducial region.

Example: top p_T and top pair invariant mass at parton level



[CERN-THESIS-2014-110]

Typical precision: 5-20% per bin

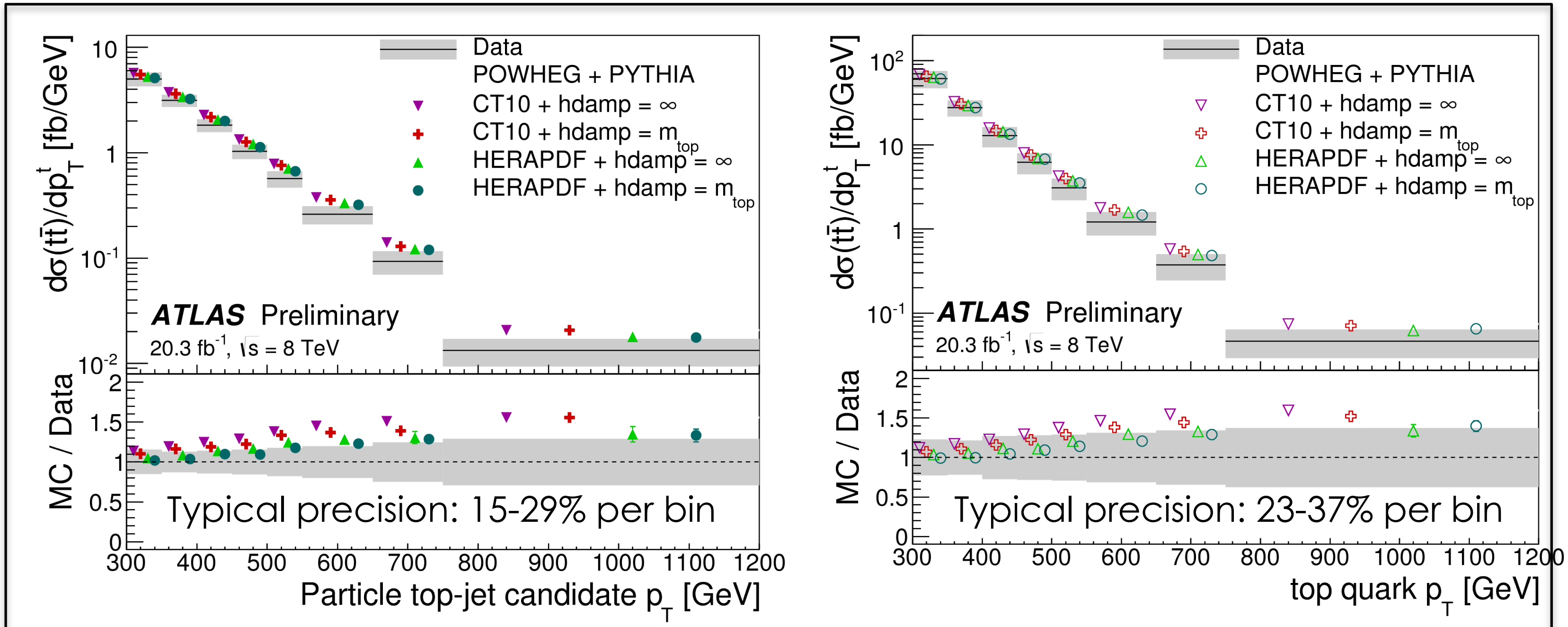


Typical precision: 5-10% per bin

TOP QUARK PRODUCTION - DIFFERENTIAL

Example: Analysis in boosted regime (@parton and particle fiducial level in fiducial region)

ATLAS-CONF-2014-057

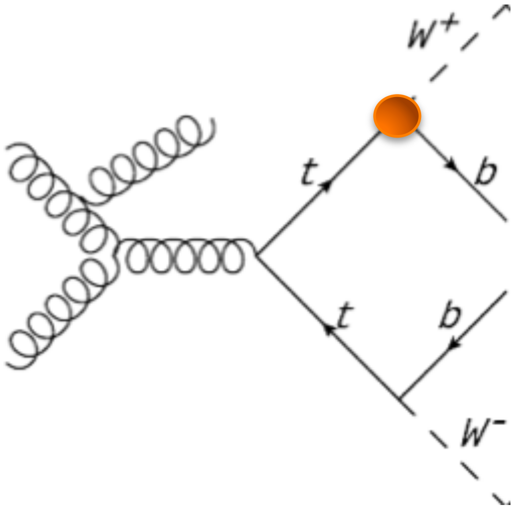


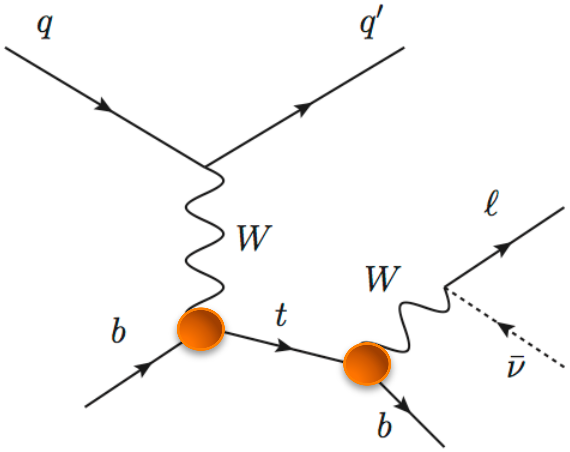
- Predictions harder than data by 30-70% (depending on MC used)
- Agreement with data improved by ~10% by setting hdamp = m_{top} and by ~20% if HERAPDF is used.

Looking forward for the full NNLO theoretical predictions.

TOP COUPLING TO W BOSON

- Can be probed by looking at top quark decays and single top EW production





Measurements available:

- R = B(t→Wb)/B(t→Wq) in ttbar → V_{tb}
- Single top cross sections (t-channel, Wt-channel) → V_{tb}
- W helicity (ttbar, t-channel)
- AFBN asymmetry in t-channel
- Top polarisation in t-channel

Constraints on Wtb anomalous couplings

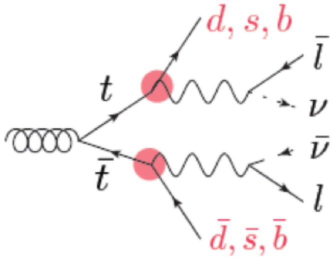
Vtb MEASUREMENTS

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad \text{with} \quad V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \boxed{V_{tb}} \end{pmatrix}$$

From top decay

The ratio R is measured

$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$



Assuming unitarity of the 3 generation CKM → R = $|V_{tb}|^2$

Most precise result from CMS (dilepton ttbar channel using 8 TeV 19.7 fb^{-1} of data)

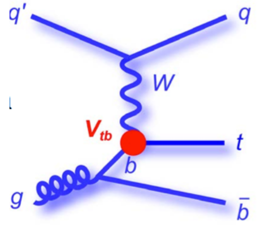
$$\boxed{|V_{tb}| = 1.007 \pm 0.016 \text{ (stat.+syst.)}}$$

From single top cross section

Assuming:

- The Wtb interaction is a SM like left-handed weak coupling
- $|V_{tb}| >> |V_{td}|, |V_{ts}|$

$$\sigma = A_d|V_{td}|^2 + A_s|V_{ts}|^2 + A_b|V_{tb}|^2$$



$$|V_{tb}| = \sqrt{\frac{\sigma_{meas}}{\sigma_{theo}}}$$

Independent of assumptions on the number of quark generations or unitarity of CKM matrix

SINGLE TOP CROSS SECTION

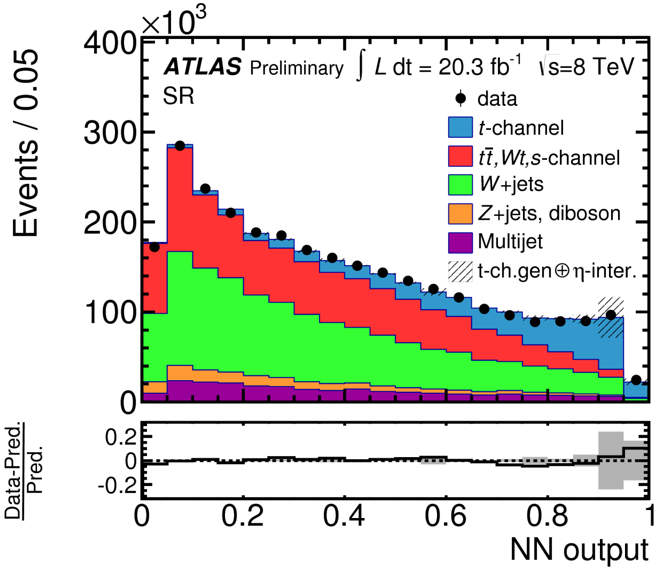
Ex: t-channel @ 8 TeV

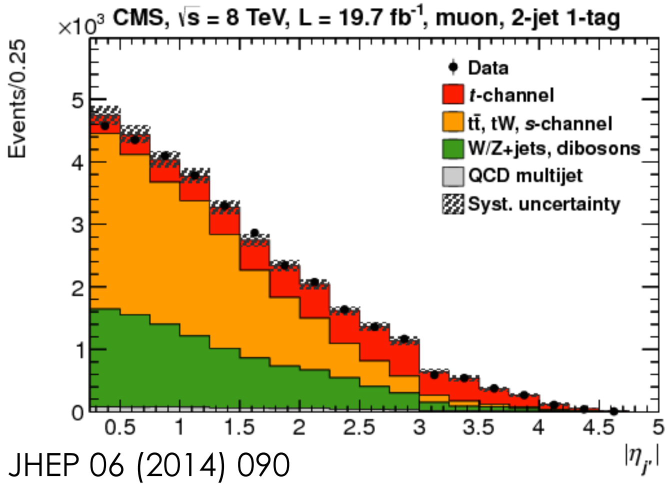
- Typically use multivariate techniques (NN, BDT): Optimise S/B separation using full event properties, constrain systematic effects by simultaneously analysing S and B dominated regions.
- ATLAS, @ 8 TeV provides the measurement in a fiducial region (with reduced systematics) and then extrapolates to the full phase space.

Precision achieved in inclusive XS @ 8 TeV:

- CMS: 9% (Dominant source signal modelling)
- ATLAS: 14% (Dominate source: JES, signal modelling)

Since then agreement on the treatment of t-channel signal modelling and JES uncertainties reached within TOPLHCWG to be used in future measurements.





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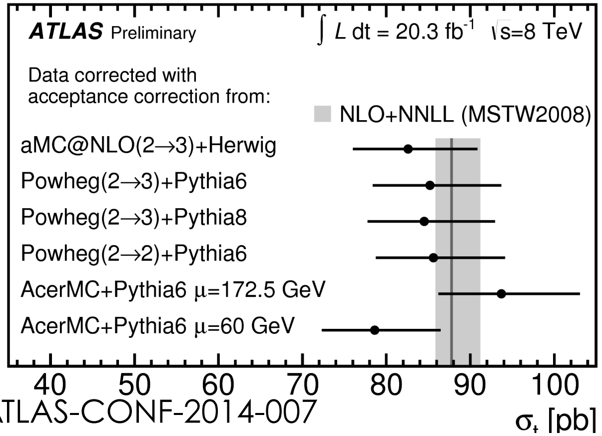
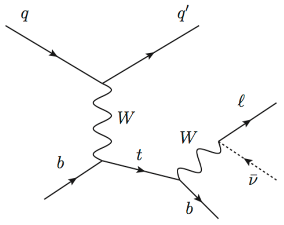




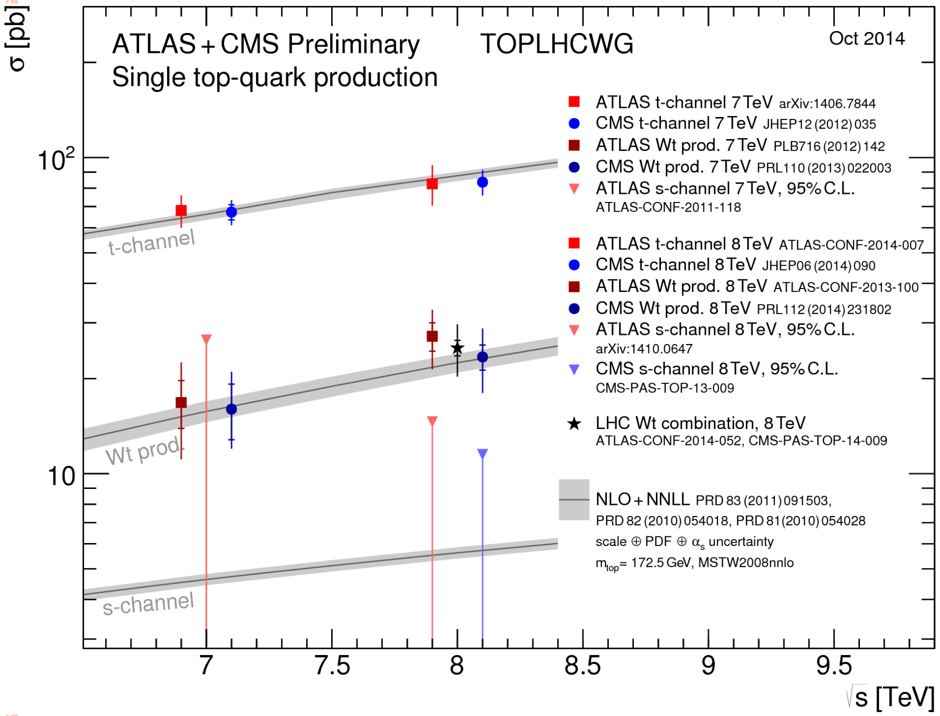
CMS: $\sigma_{t\text{-ch.}} = 83.6 \pm 2.3\,(\text{stat.}) \pm 7.4\,(\text{syst.})\,\text{pb}$

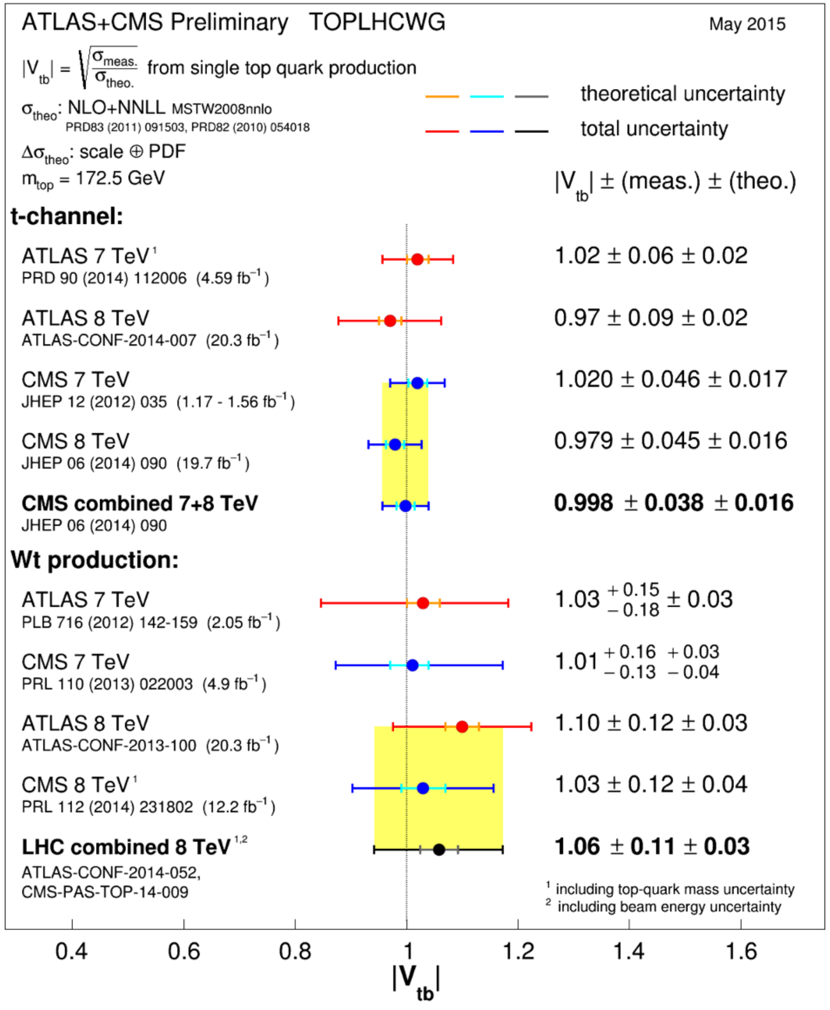
ATLAS: ATLAS-CONF-2014-007

$$\sigma_{\text{fid}} = 3.37 \pm 0.05\,(\text{stat.}) \pm 0.47\,(\text{syst.}) \pm 0.09\,(\text{lumi.})\ \text{pb}.$$
$$\sigma_t = 82.6 \pm 1.2\,(\text{stat.}) \pm 11.4\,(\text{syst.}) \pm 3.1\,(\text{PDF}) \pm 2.3\,(\text{lumi.})\ \text{pb}$$

Vtb FROM SINGLE TOP CROSS SECTION

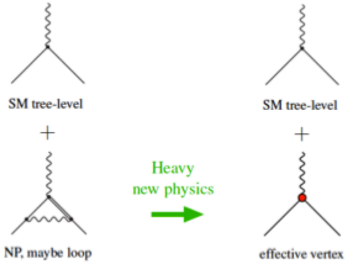
$$|V_{tb}| = \sqrt{\frac{\sigma_{meas}}{\sigma_{theo}}}$$





Best precision achieved on V_{tb} ~4% from CMS 7+8 TeV t-channel cross section measurements

Wtb ANOMALOUS COUPLINGS



- New physics can be parametrised in terms of an effective Lagrangian:

$$\begin{aligned}\mathcal{L}_{Wtb} &= -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_L P_L + V_R P_R)\,t\,W_{\mu}^{-} \\ &\quad -\frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\,(g_L P_L + g_R P_R)\,t\,W_{\mu}^{-} + \mathrm{h.c.}\end{aligned}$$

SM at tree level →

$$V_L = V_{tb} \simeq 1 \text{ and } V_R = g_L = g_R = 0$$

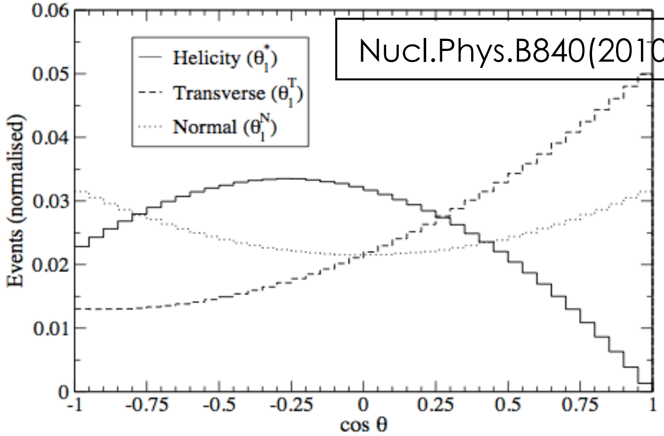
New physics can affect:

- Total single top cross section

$$\sigma = \sigma_{\mathrm{SM}}\left(V_L^2 + \kappa^{V_R}\,V_R^2 + \kappa^{V_L V_R}\,V_L V_R + \kappa^{g_L}\,g_L^2 + \kappa^{g_R}\,g_R^2 + \kappa^{g_L g_R}\,g_L g_R + \ldots\right)$$

- Single top polarisation
- W polarisation fractions (or asymmetries):
  - For un-polarised top quark decays, the only meaningful direction in the top quark rest frame is the one of the W boson momentum (q)
  - For polarised top quark (s_t) decays, further directions: N,T (e.g. t-channel single top production)

> → W helicity fractions and T polarisations (or angular asymmetries) can probe the real part of the couplings while the N ones are sensitive to complex phases.



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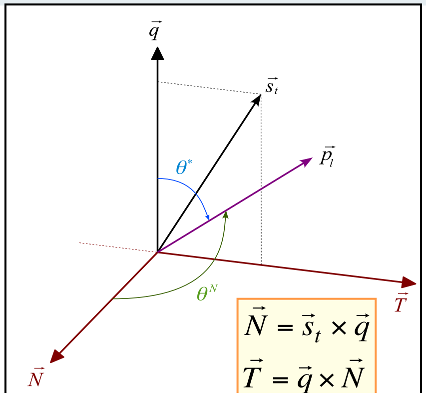
Observables: θ_l^*(q,l), θ_l^N(N,l) and θ_l^T(T,l)

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\ell}^{X}} = \frac{3}{8}(1+\cos\theta_{\ell}^{X})^2\,F_{+}^{X} + \frac{3}{8}(1-\cos\theta_{\ell}^{X})^2\,F_{-}^{X} + \frac{3}{4}\sin^2\theta_{\ell}^{X}\,F_{0}^{X}$$

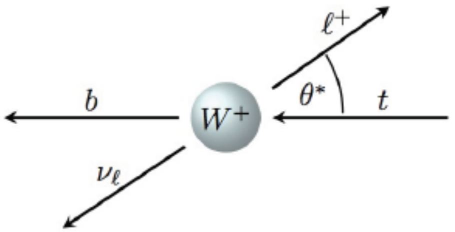


$F_+ + F_- + F_0 = 1$, $X = *, N, T$

$$A_{FB}^{X} = \frac{N(\cos\theta_l^X > 0) - N(\cos\theta_l^X < 0)}{N(\cos\theta_l^X > 0) + N(\cos\theta_l^X < 0)}$$

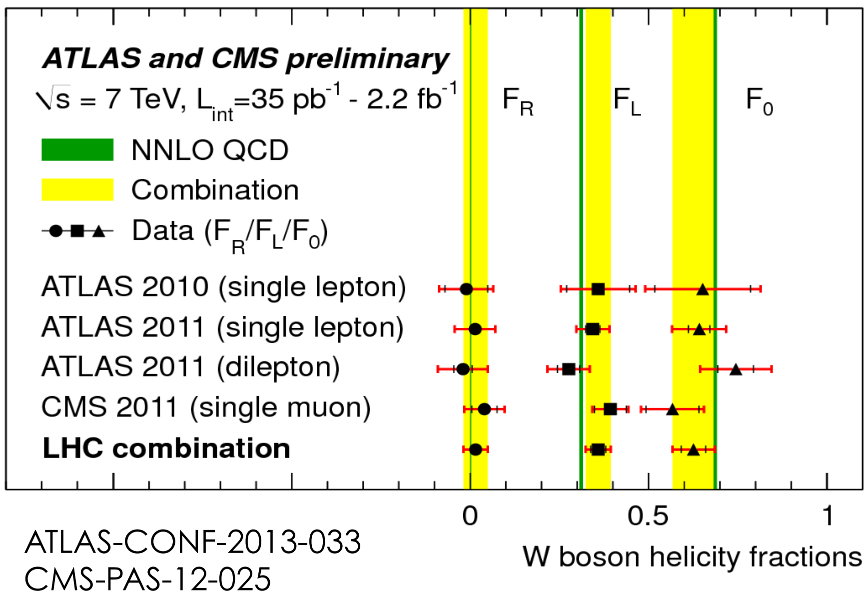
$$A_{FB}^{N} \approx -0.64 \cdot P \cdot Im(V_L g_R^*)$$

Wtb ANOMALOUS COUPLINGS

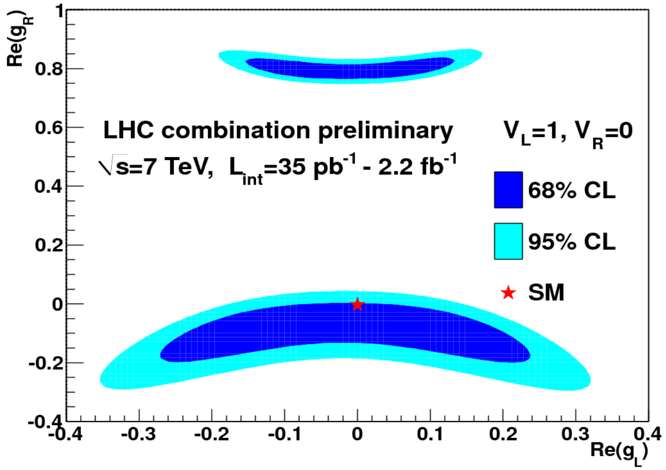


W helicity fractions

- A combination of ATLAS and CMS measurements on W helicity fractions @ 7 TeV was performed in 2013.
- Since then: CMS updated the 7 TeV measurement and provided new measurements @ 8 TeV in both top quark pair and single top topologies.



ATLAS-CONF-2013-033
CMS-PAS-12-025



$$
\begin{aligned}
F_0 &= 0.626 \pm 0.034\ \text{(stat.)} \pm 0.048\ \text{(syst.)} \\
F_L &= 0.359 \pm 0.021\ \text{(stat.)} \pm 0.028\ \text{(syst.)} \\
F_R &= 0.015 \pm 0.034
\end{aligned}
$$

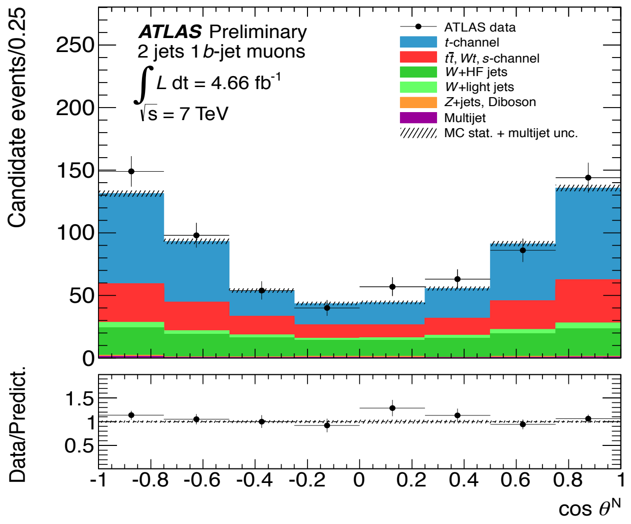
(dominant sources: signal radiation, JES, m_{top})

All measurements consistent with SM expectations, leading to constraints on the real part of V_R, g_L and g_R.

Wtb ANOMALOUS COUPLINGS

Constraints from measurements in single top t-channel

A_{FB}^{N} asymmetry measurement



ATLAS-CONF-2013-032

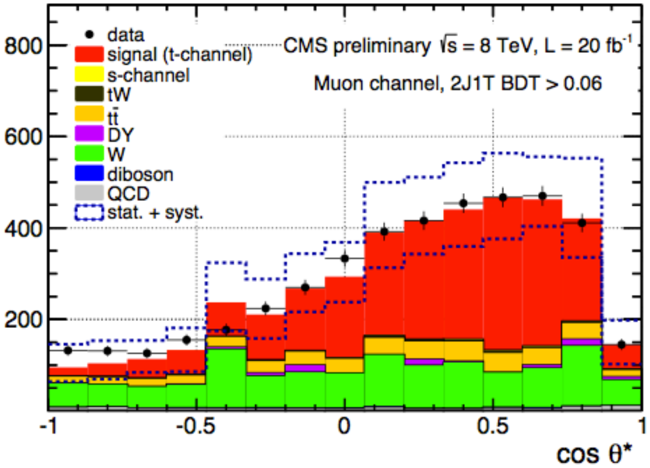
$$A_{FB}^{N} \approx 0.64 \cdot P \cdot Im(g_R)$$

$$A_{\mathrm{FB}}^{\mathrm{N}} = 0.031 \pm 0.065\,(\mathrm{stat.})\ {}^{+0.029}_{-0.031}\,(\mathrm{syst.})$$

Assuming P~0.9 (SM):

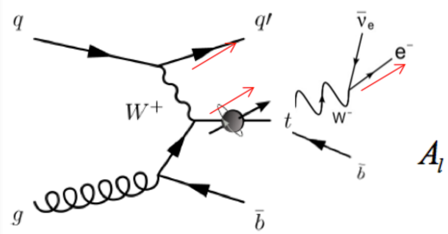
95% C.L.: -0.20<*Im*(g_R)<0.30

Polarisation



CMS-PAS-13-001

$\theta^* \equiv \measuredangle(l\,,q')$ in top rest frame



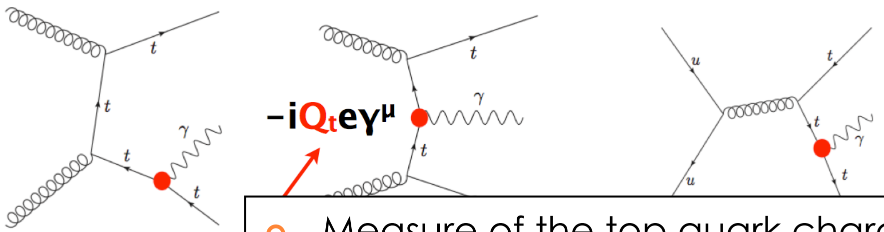
$$A_l \equiv \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)} = \frac{1}{2} \cdot P_t \cdot \alpha_l$$

$$P_t = 0.82 \pm 0.12(stat.) \pm 0.32(syst.)$$

All measurements consistent with SM expectations.

A_{FB}^{N} (sensitive to CP violation) leading to first constraints on Im (g_R)

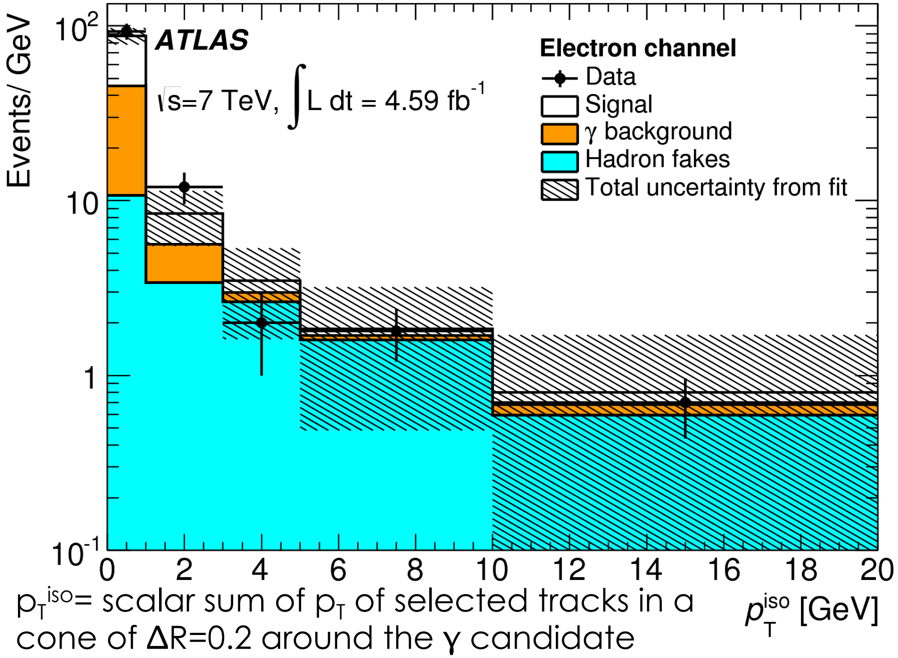
TOP COUPLING TO PHOTON



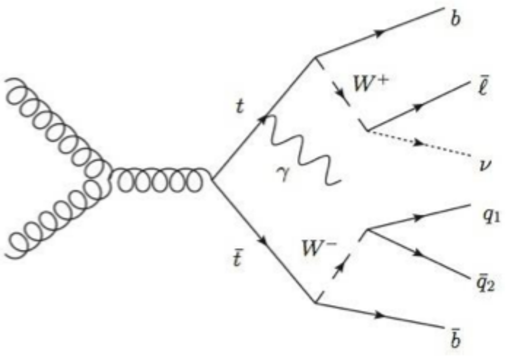
- Measure of the top quark charge
- Search for anomalous couplings

Experimental strategy (ATLAS @ 7 TeV):

- Select ttbar lepton+jets decays with an additional photon.
- Template fit using track isolation distribution of photon candidates
- Measurement performed in a fiducial region within the ATLAS acceptance (as $p_T^\gamma > 20$ GeV)



p_T^{iso}= scalar sum of p_T of selected tracks in a cone of ΔR=0.2 around the γ candidate



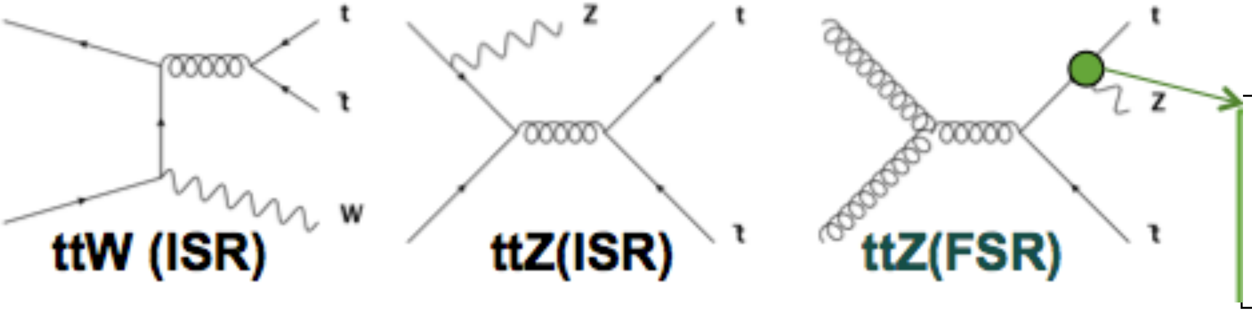
$$\sigma^{\text{fid}}_{t\bar{t}\gamma} \times \text{BR} = 63 \pm 8(\text{stat.}) \,^{+17}_{-13}\,(\text{syst.}) \pm 1\,(\text{lumi.})\ \text{fb}$$

(dominant sources: JES, photon, signal modelling, b-tagging)

- Observation with 5.3 σ
- In good agreement with SM theoretical prediction (48 ± 10 fb)

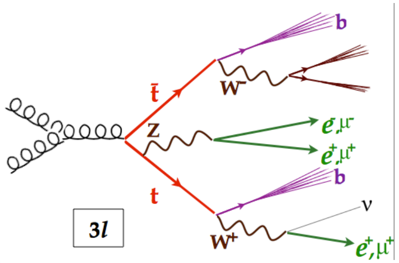
TOP COUPLING TO Z BOSON

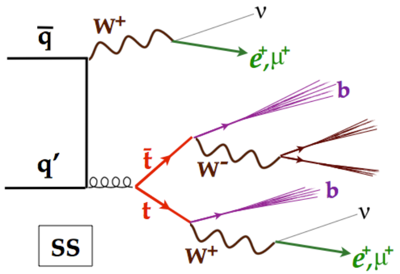
- Top pair production in association with W/Z boson are rare processes (predicted cross section NLO QCD ~ 200 fb each @ 8 TeV).



Direct measurement of top coupling to Z gauge boson in ttZ production via FSR.

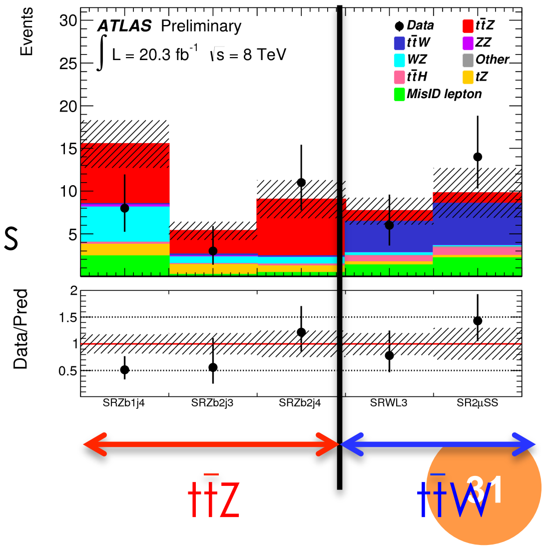
- Experimental signature: number of leptons (depending on the top and W/Z quark decay channel), multiple jets and b-jets also required (2L OS, 3L, 4L (best for ttZ), 2L (SS), 3L (best for ttW)).



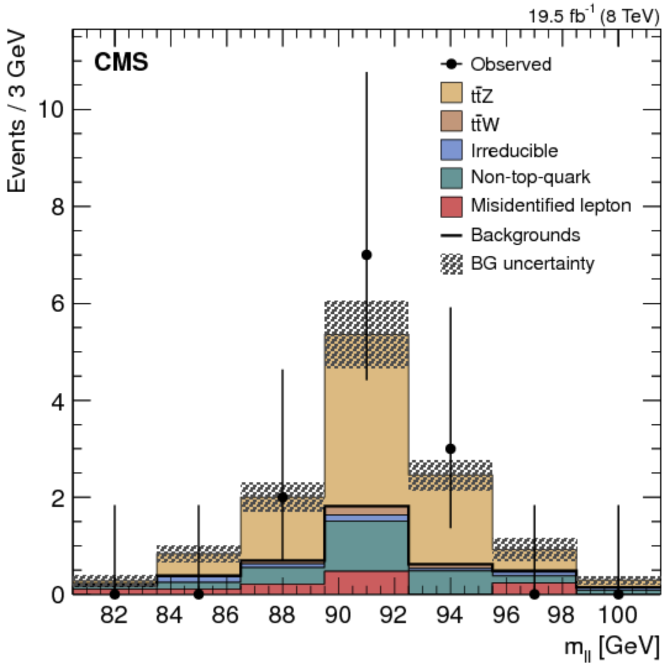


Strategy:

- Most sensitive: 3L to ttZ, 2L SS to ttW.
- ATLAS preliminary & CMS previous result used cut and count for the most sensitive channels while CMS update uses MVA techniques and also includes more channels.



TOP COUPLING TO Z BOSON

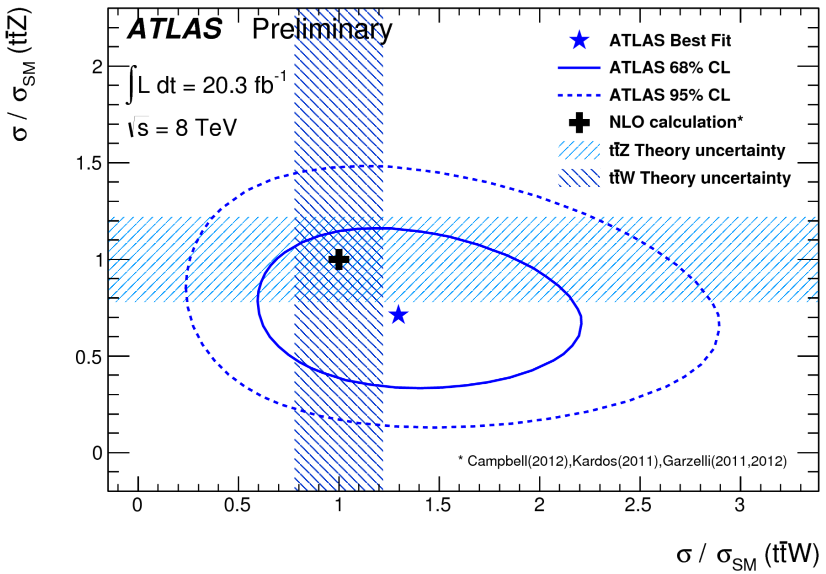


EPJ C74 (2014) 3060

Channels used	Process	Cross section	Significance
2ℓ	$t\bar{t}W$	170^{+90}_{-80} (stat) $\pm$ 70 (syst) fb	1.6
$3\ell+4\ell$	$t\bar{t}Z$	200^{+80}_{-70} (stat)$^{+40}_{-30}$ (syst) fb	3.1
$2\ell+3\ell+4\ell$	$t\bar{t}W + t\bar{t}Z$	380^{+100}_{-90} (stat)$^{+80}_{-70}$ (syst) fb	3.7

Results from simultaneous fit:

Channels used	$t\bar{t}W$ cross section	$t\bar{t}Z$ cross section
$2\ell+3\ell+4\ell$	170^{+110}_{-100} (total) fb	200 ± 90 (total) fb



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

	Summary of combined simultaneous fit results		
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

A month ago: Evidence for ttZ observed in ATLAS and CMS (also for ttW in ATLAS).

TOP COUPLING TO Z BOSON

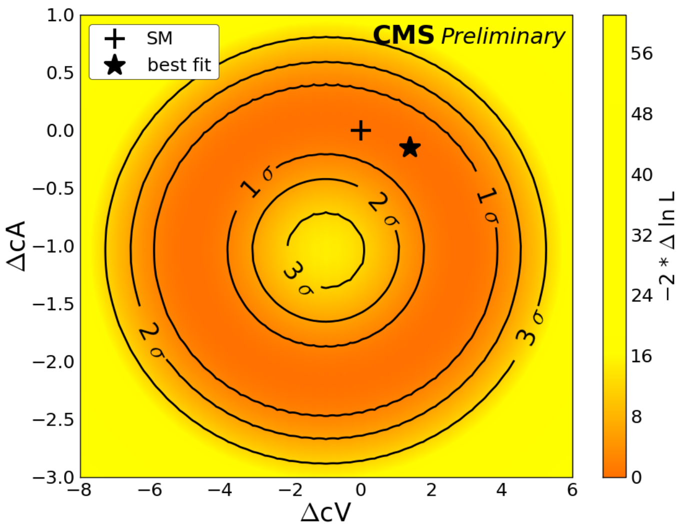
	Cross section (fb)		Signal strength (μ)		Significance	
Channels	Expected	Observed	Expected	Observed	Expected	Observed
OS	206^{+142}_{-118}	257^{+158}_{-129}	$1.0^{+0.72}_{-0.57}$	$1.25^{+0.76(+1.76)}_{-0.62(-1.16)}$	1.84	2.12
3ℓ	206^{+79}_{-63}	257^{+85}_{-67}	$1.0^{+0.42}_{-0.32}$	$1.25^{+0.45(+1.02)}_{-0.36(-0.62)}$	4.55	5.11
4ℓ	206^{+153}_{-109}	228^{+150}_{-107}	$1.0^{+0.77}_{-0.53}$	$1.11^{+0.76(+1.79)}_{-0.52(-0.86)}$	2.65	3.39
OS + 3ℓ + 4ℓ	206^{+62}_{-52}	242^{+65}_{-55}	$1.0^{+0.34}_{-0.27}$	$1.18^{+0.35(+0.79)}_{-0.29(-0.51)}$	5.73	6.44

$$\mathcal{L}_{t\bar{t}Z} = ie\bar{u}(p_t)\left[\gamma^{\mu}(C_{1,V}+\gamma_5 C_{1,A}) + \frac{i\sigma_{\mu\nu}q_{\nu}}{M_Z}(C_{2,V}+i\gamma_5 C_{2,A})\right]v(p_{\bar{t}})Z_{\mu}$$

$$C_{1,\mathrm{V}} = C_{1,\mathrm{V}}^{\mathrm{SM}} + \left(\frac{v^2}{\Lambda^2}\right)\mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} - C_{\phi u}^{33}\right]$$

$$C_{1,\mathrm{A}} = C_{1,\mathrm{A}}^{\mathrm{SM}} + \left(\frac{v^2}{\Lambda^2}\right)\mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} + C_{\phi u}^{33}\right]$$

From arXiv:1404.1005 [hep-ph]



CMS reported first observation of ttZ at the LHC.

All measurements in agreement with SM predictions (statistically limited)

Interpretation of ttZ cross section in terms of constraints to new physics (dimension six operators or anomalous couplings)

CONCLUSIONS

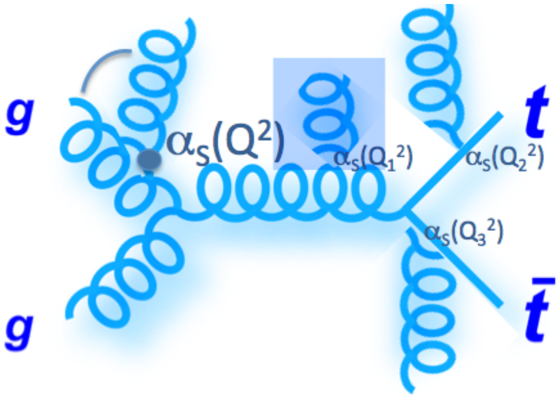
- Top quark physics studies are central for the LHC physics programme
- Precise measurements of top quark properties and its interactions allow for stringent tests of the SM, being at the same time sensitive to new physics.
  - Top couplings
- Many of the top measurements performed at the LHC Run1 are already dominated by systematics (e.g. jet energy scale, b-tagging, physics modelling).
- Some rare processes also becoming available, and will profit from the increase of statistics in Run2.

Reaching the ultimate precision requires a lot of effort and time from both experimentalists and theory community, but it is of high importance (specially if no new physics is found).

BACKUP

PHYSICS MODELLING

Measurements sensitive to QCD radiation in top pair production



Measurements $|\eta|<2.5$, $p_t>20$ GeV

Single jet based observables

N_{jet}, jet p_t, η, jet shapes

Integrated observables

jet veto, H_T, S_T

Indirect observables (recoil)

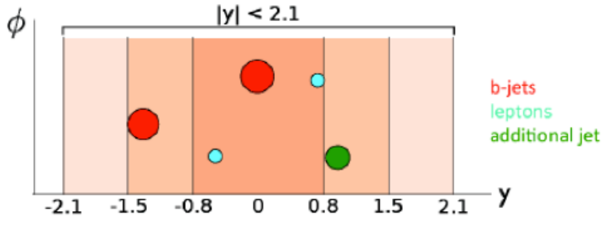
Lepton p_t, E_{tmiss}, p_t^W

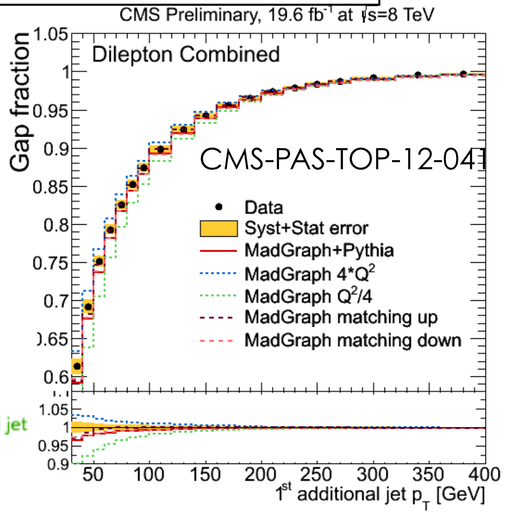
Derived quantities

top p_t, ttbar p_t

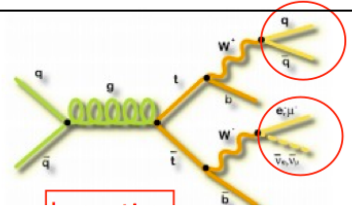
Ex: Gap fraction analysis (dilepton channel)

Study the fraction of top pair events that do not contain an additional jet using dilepton events.

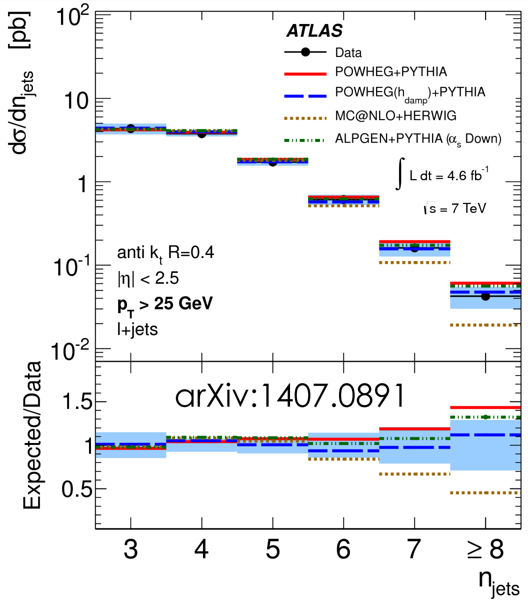




Ex: Jet multiplicity (lepton+jets channel)

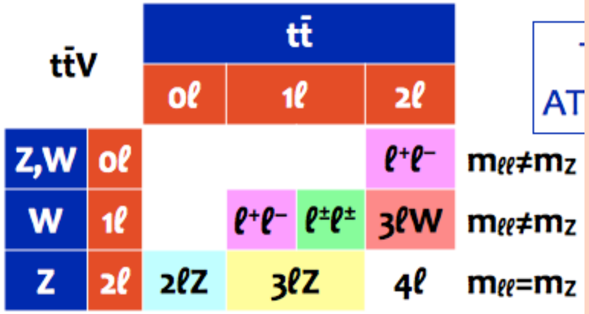


4 jets "belong" to the top pair process, the 5th leading p_T jet corresponds to the first additional emission.

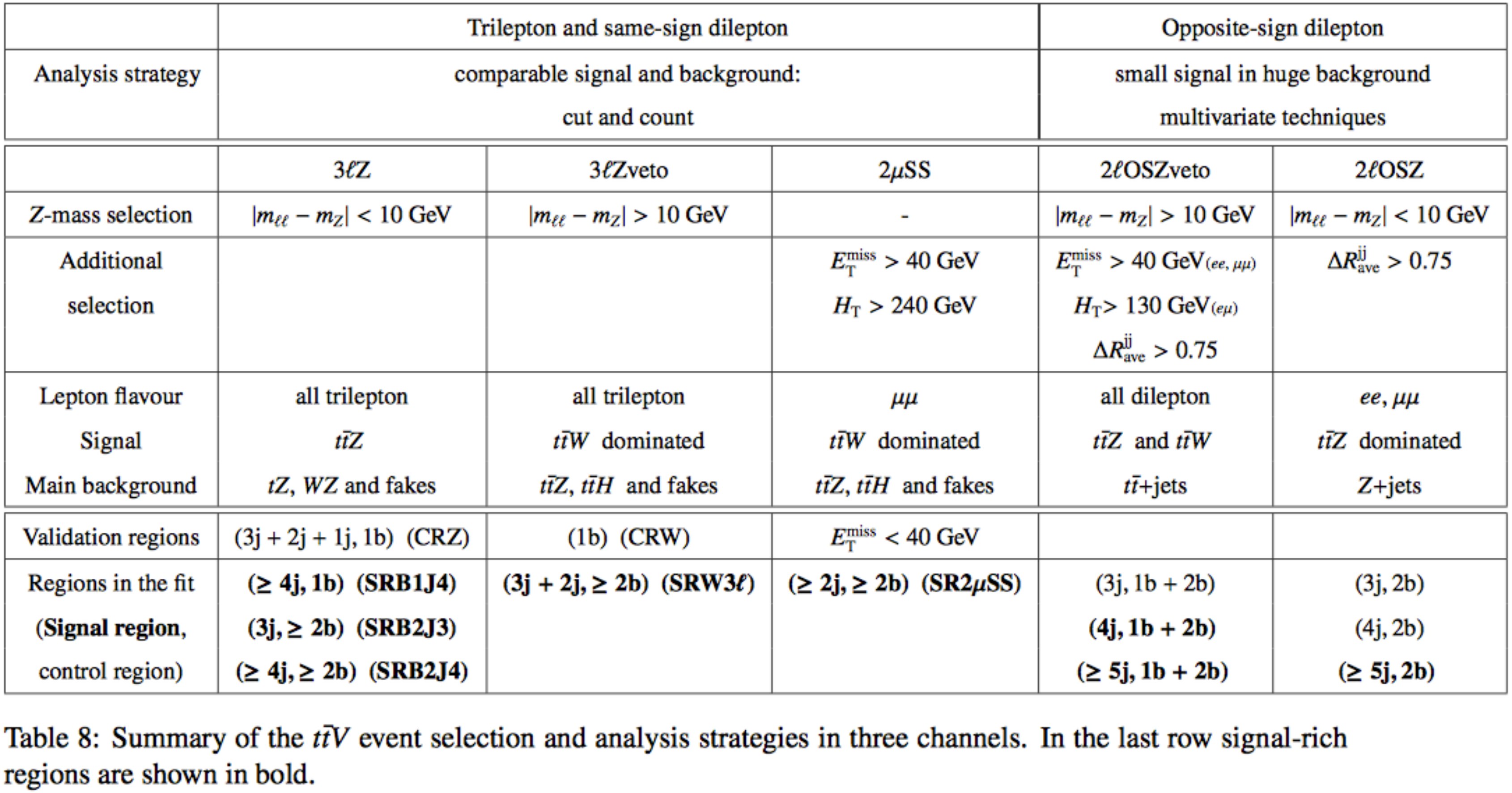


TTBAR+Z/W CROSS SECTIONS - ATLAS

- Channels classified according to decay modes:
- ttbar → 2 leptons, leptons+jets, all-hadronic
- Z → 2l , 2q, 2ν
- W→ lν, qqbar



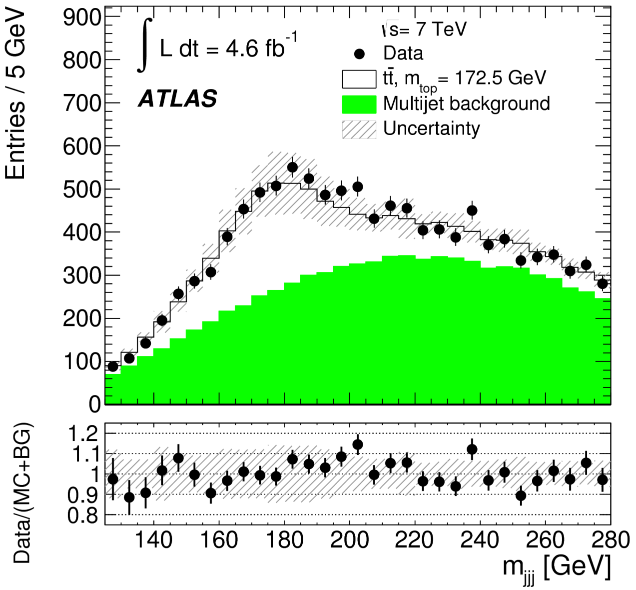
$t\bar{t}V$		$t\bar{t}$				
		0ℓ	1ℓ		2ℓ	
Z,W	0ℓ				$\ell^+\ell^-$	$m_{\ell\ell}\neq m_Z$
W	1ℓ		$\ell^+\ell^-$	$\ell^\pm\ell^\pm$	3ℓW	$m_{\ell\ell}\neq m_Z$
Z	2ℓ	2ℓZ	3ℓZ		4ℓ	$m_{\ell\ell}=m_Z$

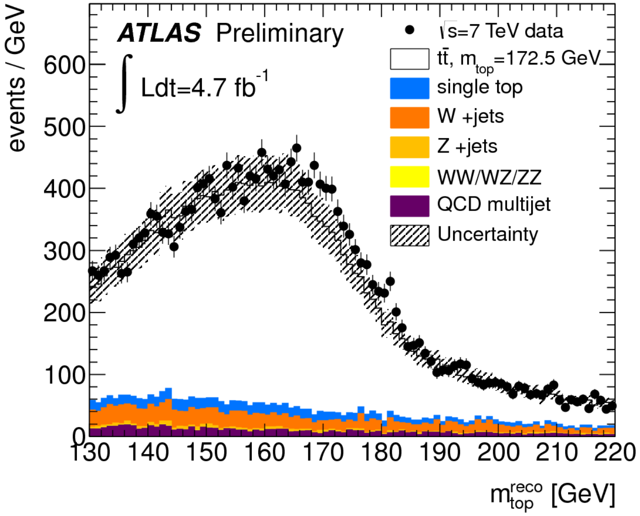


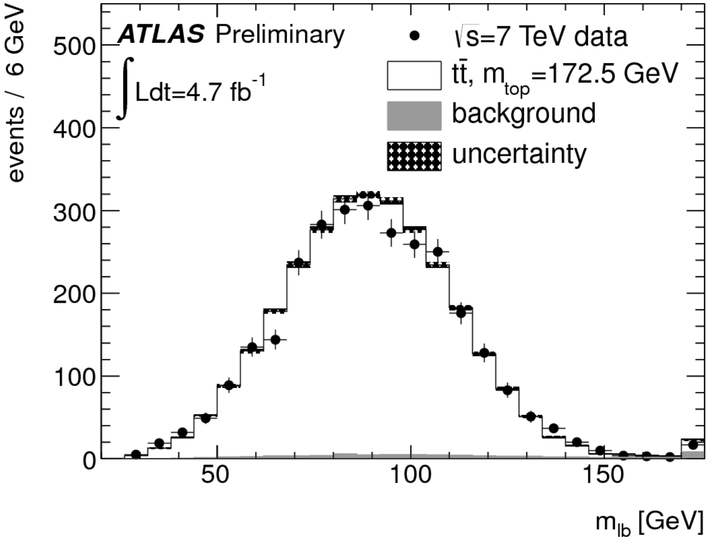
	Trilepton and same-sign dilepton			Opposite-sign dilepton	
Analysis strategy	comparable signal and background: cut and count			small signal in huge background multivariate techniques	
	3ℓZ	3ℓZveto	2μSS	2ℓOSZveto	2ℓOSZ
Z-mass selection	$\lvert m_{\ell\ell}-m_Z\rvert < 10$ GeV	$\lvert m_{\ell\ell}-m_Z\rvert > 10$ GeV	-	$\lvert m_{\ell\ell}-m_Z\rvert > 10$ GeV	$\lvert m_{\ell\ell}-m_Z\rvert < 10$ GeV
Additional selection			$E_T^{miss} > 40$ GeV $H_T > 240$ GeV	$E_T^{miss} > 40$ GeV $(ee, \mu\mu)$ $H_T > 130$ GeV $(e\mu)$ $\Delta R^{jj}_{ave} > 0.75$	$\Delta R^{jj}_{ave} > 0.75$
Lepton flavour	all trilepton	all trilepton	$\mu\mu$	all dilepton	$ee, \mu\mu$
Signal	$t\bar{t}Z$	$t\bar{t}W$ dominated	$t\bar{t}W$ dominated	$t\bar{t}Z$ and $t\bar{t}W$	$t\bar{t}Z$ dominated
Main background	tZ, WZ and fakes	$t\bar{t}Z$, $t\bar{t}H$ and fakes	$t\bar{t}Z$, $t\bar{t}H$ and fakes	$t\bar{t}$+jets	Z+jets
Validation regions	(3j + 2j + 1j, 1b) (CRZ)	(1b) (CRW)	$E_T^{miss} < 40$ GeV		
Regions in the fit (**Signal region**, control region)	**(≥ 4j, 1b) (SRB1J4)** **(3j, ≥ 2b) (SRB2J3)** **(≥ 4j, ≥ 2b) (SRB2J4)**	**(3j + 2j, ≥ 2b) (SRW3ℓ)**	**(≥ 2j, ≥ 2b) (SR2μSS)**	(3j, 1b + 2b) **(4j, 1b + 2b)** **(≥ 5j, 1b + 2b)**	(3j, 2b) (4j, 2b) **(≥ 5j, 2b)**

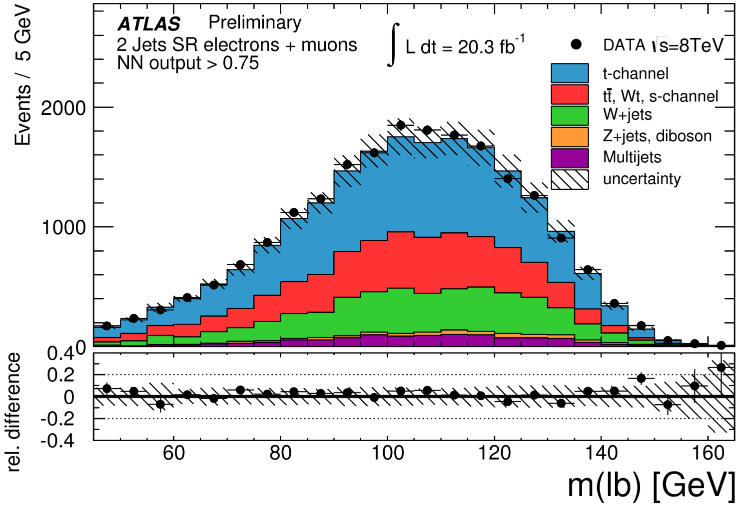
Table 8: Summary of the $t\bar{t}V$ event selection and analysis strategies in three channels. In the last row signal-rich regions are shown in bold.

A DATA ANALYSIS EXAMPLE









MEASUREMENT OF THE R RATIO

- CMS has measured the R ratio in the dilepton ttbar channel using 8 TeV 19.7 fb^{-1} of data.

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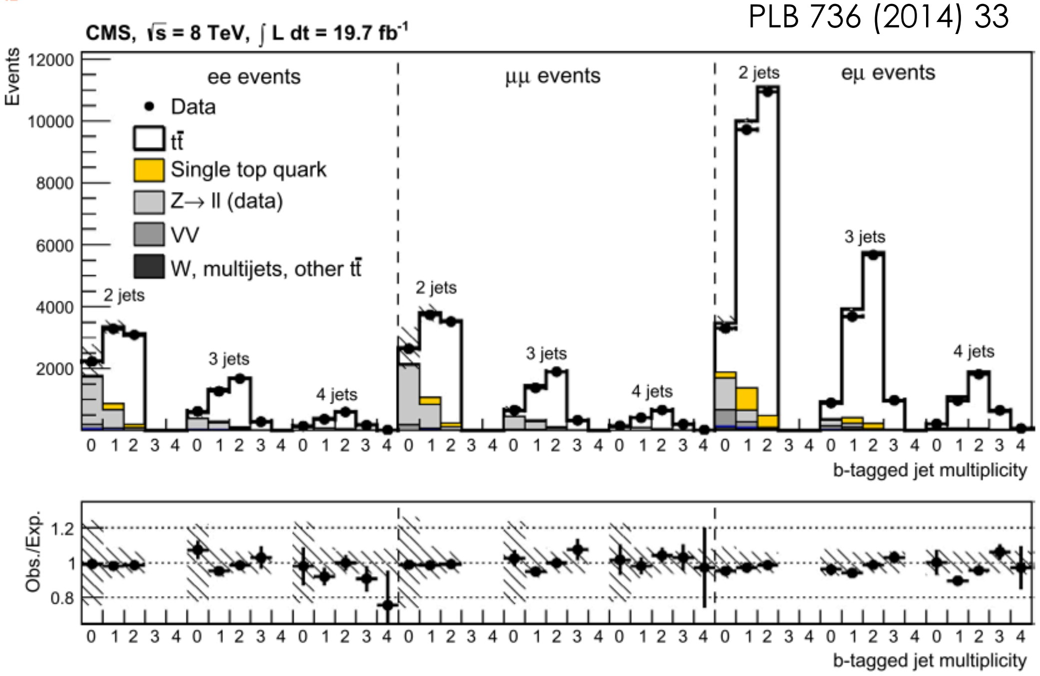


$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

- Profile Likelihood fit to the observed b-tagged jet distribution:

$$\mathcal{L}(\mathcal{R}, f_{t\bar{t}}, k_{\mathrm{st}}, f_{\mathrm{correct}}, \varepsilon_{\mathrm{b}}, \varepsilon_{\mathrm{q}}, \varepsilon_{\mathrm{q}*}, \theta_i) = \prod_{\ell\ell} \prod_{N_{\mathrm{jets}}=2\ldots4} \prod_{k=0}^{N_{\mathrm{jets}}} \mathcal{P}[N_{\mathrm{ev}}^{\ell\ell, N_{\mathrm{jets}}}(k), \hat{N}_{\mathrm{ev}}^{\ell\ell, N_{\mathrm{jets}}}(k)] \prod_i \mathcal{G}(\theta_i^0, \theta_i, 1),$$

$$\boxed{\mathcal{R} = 1.014 \pm 0.003\ (\mathrm{stat.}) \pm 0.032\ (\mathrm{syst.})}$$

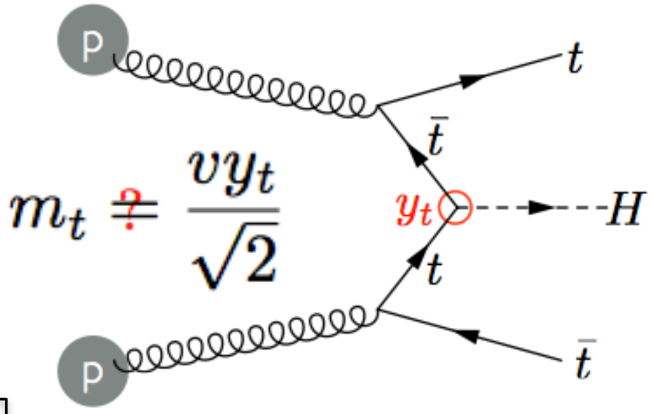
(dominant systematics from b-tagging efficiency)

↓ Assuming 3x3 CKM matrix unitarity

$$\boxed{|V_{\mathrm{tb}}| = 1.007 \pm 0.016\ (\mathrm{stat.} + \mathrm{syst.})}$$

TOP COUPLING TO H BOSON

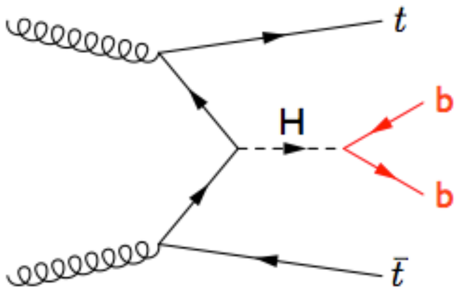
- Higgs boson discovery in July 2012.
- In the SM, fermion masses are proportional to Higgs fermion Yukawa couplings → Important to test this prediction.
- ttH production provides direct sensitivity to the top-Higgs Yukawa coupling



$$m_t \overset{?}{=} \frac{v y_t}{\sqrt{2}}$$

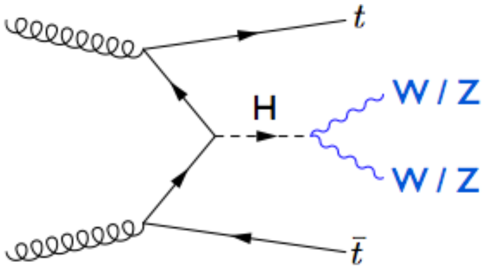
ttH (H→ bb)

- Largest BR (58%)
- Final state with multiple b quarks (challenge to reconstruct Higgs)
- Large background from ttbar+jets



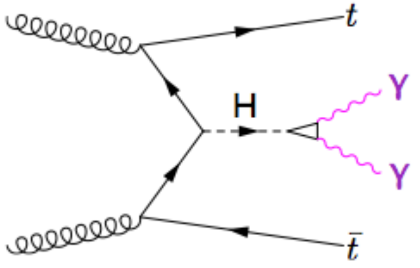
ttH (H→ WW/ZZ)

- Significant BR (22%)
- Leptonic decays of W/Z and taus can give distinct multi-lepton signatures (but difficult to reconstruct the Higgs)
- Main background from ttbar+W/Z and non prompt leptons



ttH (H→ ϒϒ)

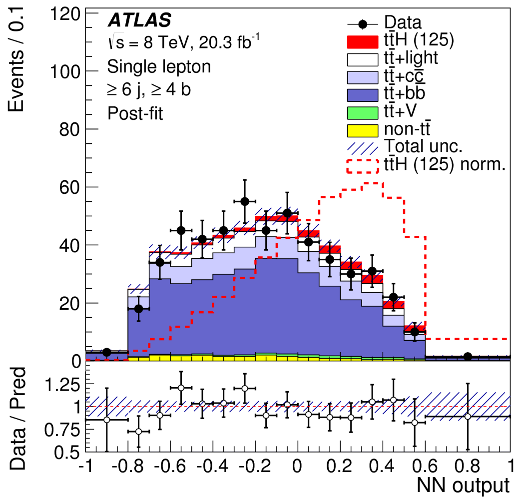
- Small BR (0.2%)
- Higgs boson can be reconstructed as a narrow peak
- Backgrounds from ttbar +ϒ and QCD multi-ϒ /jet final states



TOP COUPLING TO H BOSON

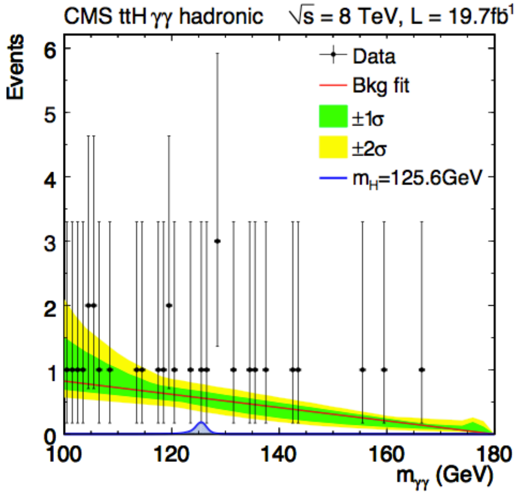
ttH (H→bb) Strategy:

- Channels: top leptonic decays
- Different regions considered (njets, b-jets)
- MVA techniques to separate S from B



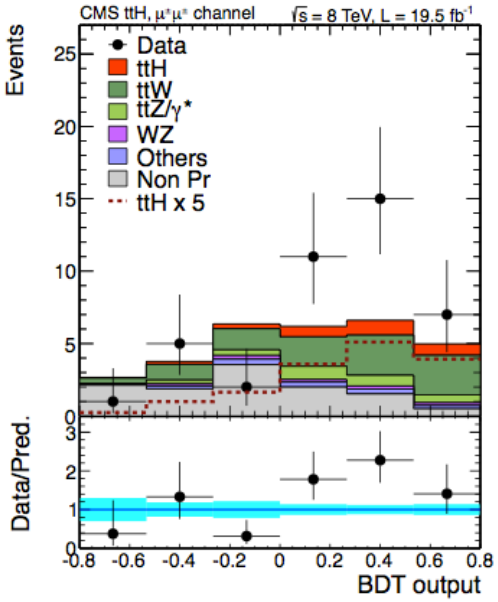
ttH (H→YY) Strategy:

- Select two photons and apply loose requirements on jets to maximise signal acceptance.
- 2 categories: hadronic, leptonic
- Background estimated performing a fit to data

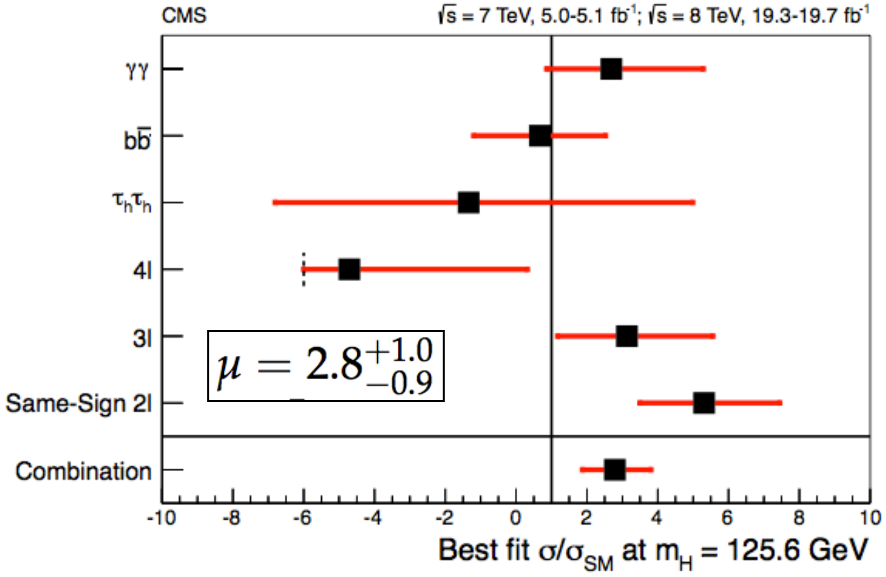


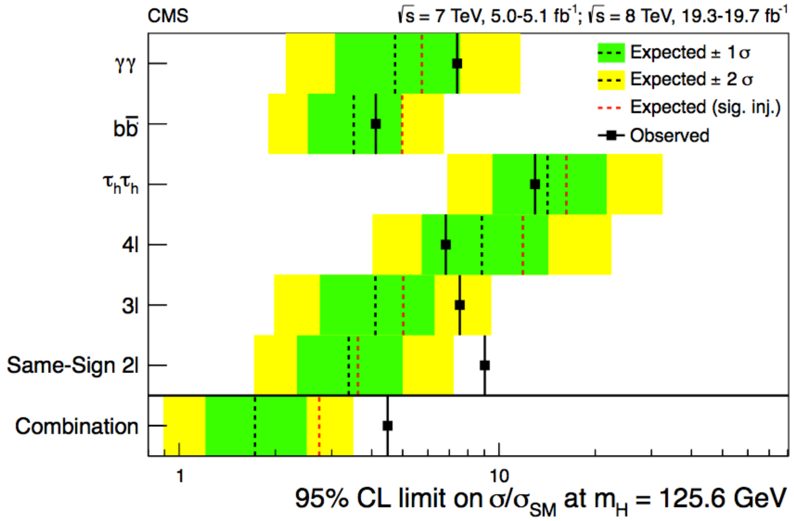
ttH (H→ZZ/WW/ττ) Strategy:

- Final states with multiple leptons and high pT b-jets.
- Several categories considered



TOP COUPLING TO H BOSON





H→bb and H→ϒϒ (ATLAS and CMS), H → multileptons (ATLAS):

No significant excess of events observed relative to the background only hypothesis. Best fit values of signal strength μ compatible with SM. 95% CL upper limits on μ have been set.

H→ multi-leptons final states (CMS):

In most channels, good agreement seen between data and expected backgrounds (excess observed in the μμ channel where best fit $\mu=8.5^{+3.3}_{-2.7}$).

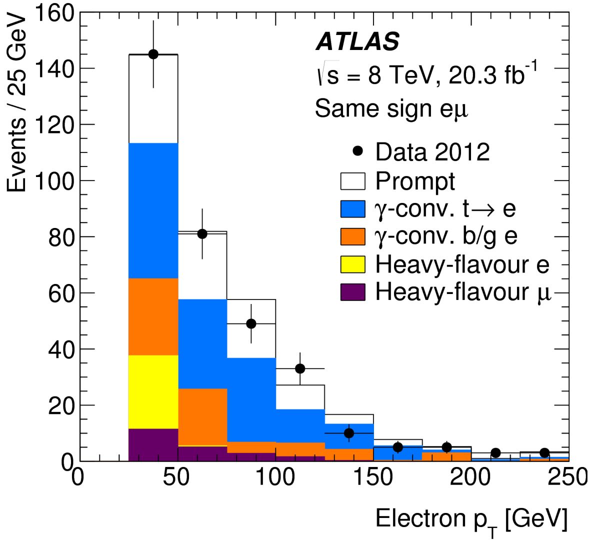
Combined fit (CMS):

Excess of ~3.4 σ over the background-only hypothesis (μ = 0).

Excess of ~2.1 σ over the the SM ttH expectation (μ=1).

FAKE BACKGROUND

- Selection of top quark events often based on the identification of one or more charged isolated leptons (W→lν)
- Fake leptons (non-prompt leptons or non-leptonic particles as jets) can come from:



- Electrons: **photon conversions**, tracks overlapping with photons, jets, **semileptonic b/c quark decays**
- Muons: **b/c quark semileptonic decays**, punch-through hadrons, pion and kaon decays in flight

- Lepton isolation and kinematical cuts used to reduce this background

- Data driven methods developed to estimate this background (analysis dependent). Most common methods:
  - Matrix method
  - Fit methods (jet-lepton, anti-lepton)

ATLAS has just released a note (ATLAS-CONF-2014-058) providing detailed information about the methods commonly used and their applicability in top quark pair leptonic channels

FAKE BACKGROUND

Matrix method

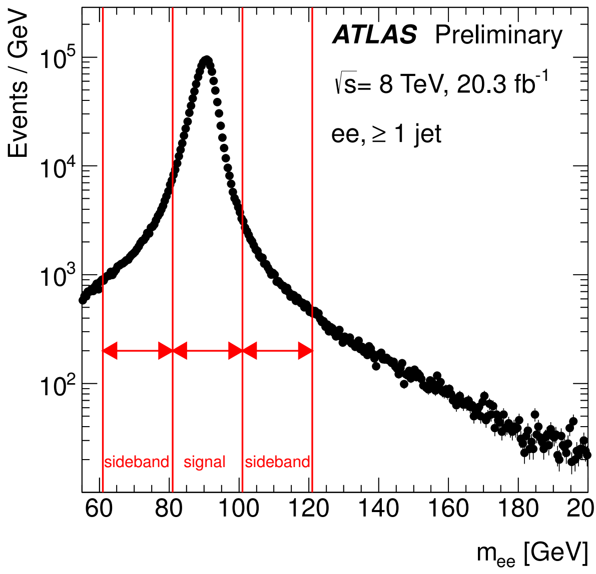
Basic form for lepton+jets (extension to 4x4 matrix in dilepton)

$$\begin{aligned} N^{loose} &= N^{loose}_{real} + N^{loose}_{fake} \\ N^{tight} &= \varepsilon_{real}\cdot N^{loose}_{real} + \varepsilon_{fake}\cdot N^{loose}_{fake} \end{aligned} \quad \Rightarrow \quad N^{tight}_{fake} = \frac{\varepsilon_{fake}}{\varepsilon_{real} - \varepsilon_{fake}} \cdot \left(\varepsilon_{real}\cdot N^{loose} - N^{tight}\right)$$

- Efficiencies measured from data:

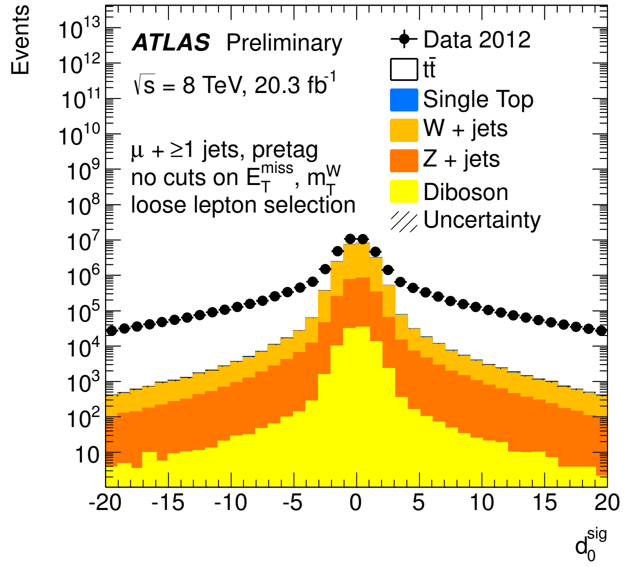
Real efficiency (ε_{real}):

- Tag & Probe using Z→ ll + top/Z MC corrections for electrons



Fake efficiency (ε_{fake}):

- From control regions dominated by fake leptons (low E_T^{miss}, low m_T^W, high d_0 significance)

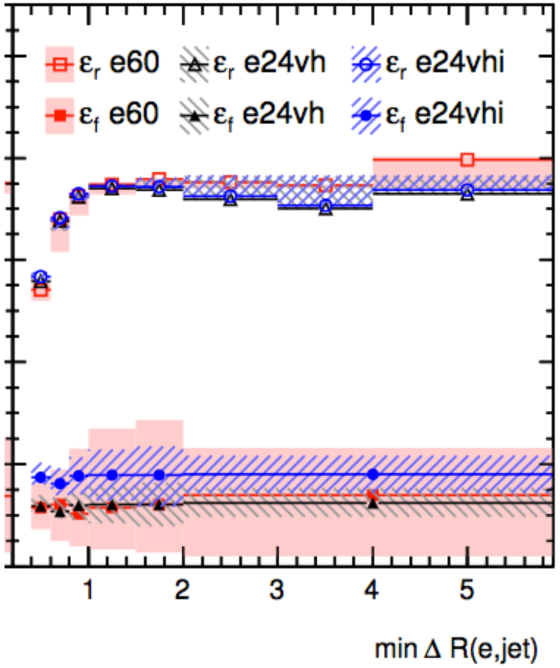


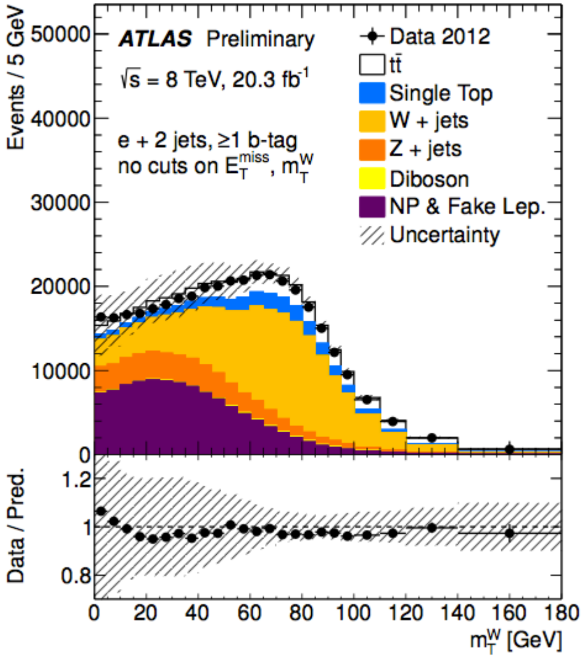
FAKE BACKGROUND

- Efficiencies are parametrised considering the observed dependencies, small correlations and agreement in CRs

	$\|\eta^{\ell}\|$	p_T^{ℓ}	$p_T^{\text{lead.jet}}$	$\Delta R(\ell,\text{jet})$	$\Delta\phi(\ell,E_T^{\text{miss}})$	n_{jet}	$n_{b-\text{jet}}$
$\varepsilon_r(e)$	✓	✓		✓		✓	
$\varepsilon_r(\mu)$	✓	✓		✓		✓	
$\varepsilon_f(e)$	✓		✓		✓		✓
$\varepsilon_f(\mu)$	✓	✓		✓			✓

- Systematic uncertainties (obtained from different CRs and parameterisations, varying amount of real leptons to subtract from the fake CR) are typically:
  - lepton+jets: 10-50% (depending on jet and tag multiplicity, larger for electrons, smaller for muons)
  - dileption eμ: 70-100% in signal region, 30-50% in the validation regions

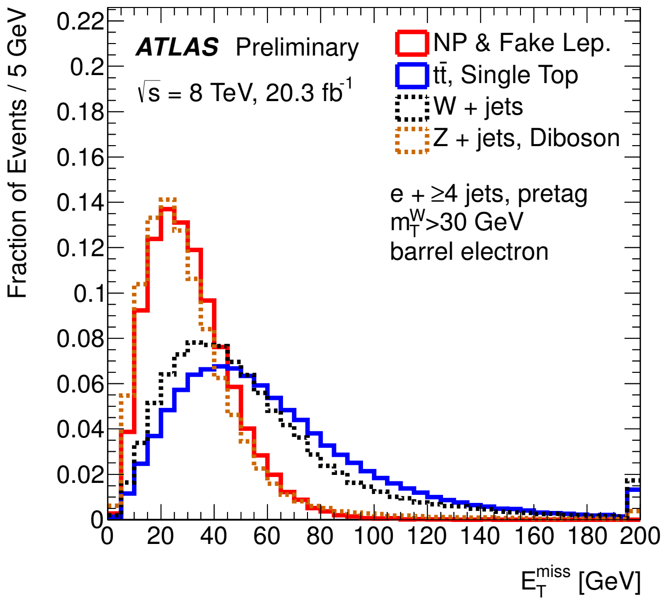


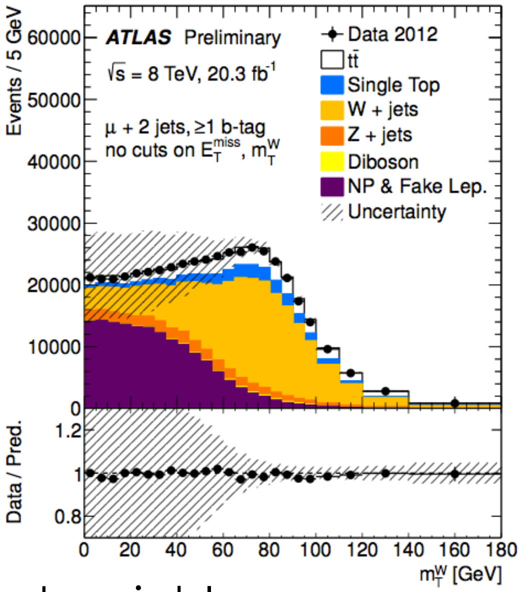


FAKE BACKGROUND

Fit method

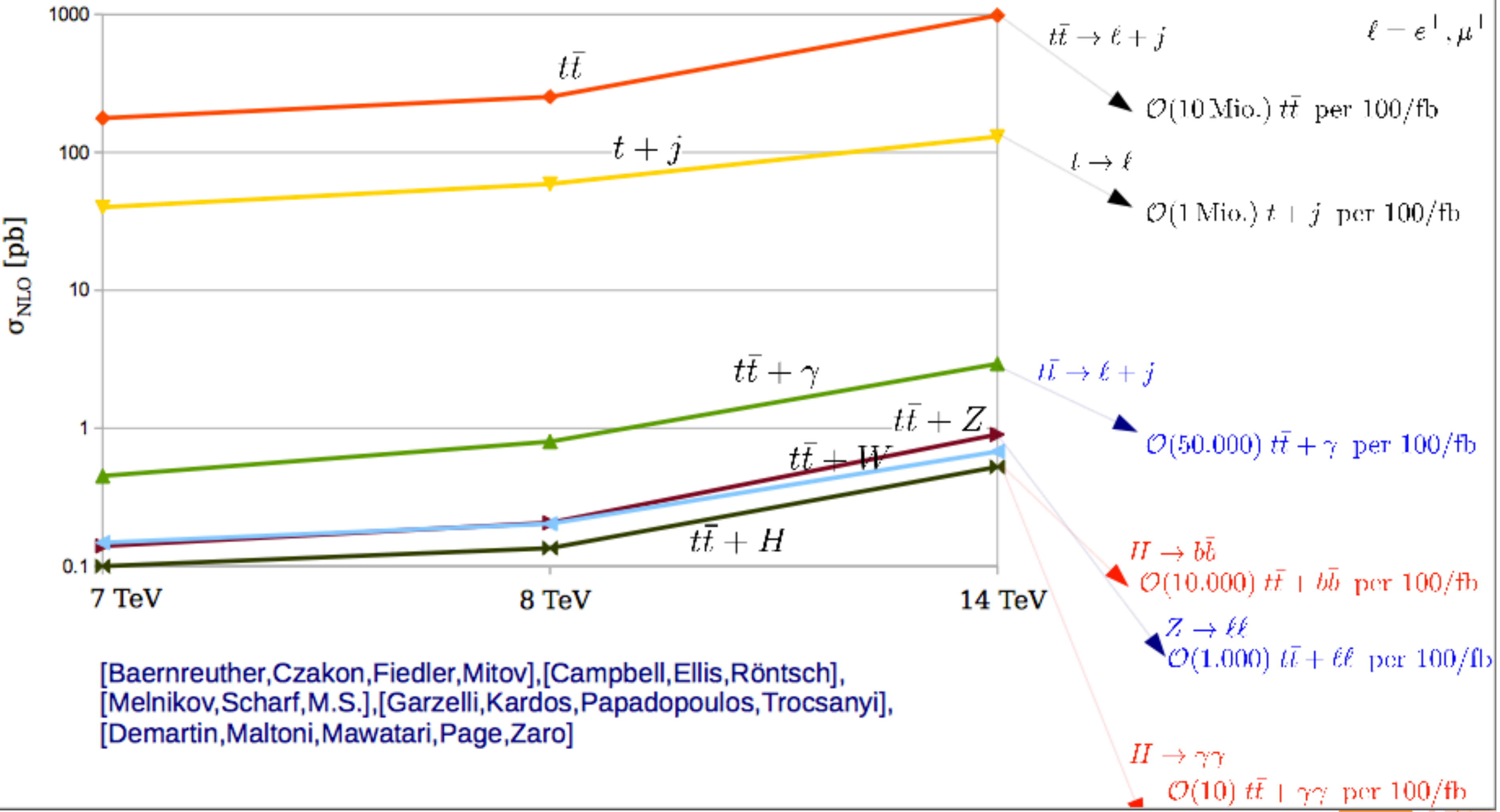
- Define a fit model to predict the fake leptons background shape
  - Jet-electron: from a multijet MC sample asking one jet to be electron-like
  - Anti-muon: from data, selecting a sample enriched in non-prompt muons by inverting some of the muon identification cuts
- Choose a discriminating variable (E_T^{miss} for e+jets, m_T^W for μ+jets)
- Loosen/remove cuts on E_T^{miss} , m_T^W
- Perform maximum likelihood fit to predict its normalisation





- Systematic uncertainties (obtained from fitting different variables, variations on the fit constraints, W+jets and Z+jets modelling) lead to 50% uncertainty

LHC PRESPECTIVES



$t\bar{t} \to \ell + j$

$\ell = e^+, \mu^+$

$\mathcal{O}$(10 Mio.) $t\bar{t}$ per 100/fb

$t \to \ell$

$\mathcal{O}$(1 Mio.) $t+j$ per 100/fb

$t\bar{t} \to \ell + j$

$\mathcal{O}$(50.000) $t\bar{t}+\gamma$ per 100/fb

$H \to b\bar{b}$

$\mathcal{O}$(10.000) $t\bar{t}+b\bar{b}$ per 100/fb

$Z \to \ell\ell$

$\mathcal{O}$(1.000) $t\bar{t}+\ell\ell$ per 100/fb

$H \to \gamma\gamma$

$\mathcal{O}$(10) $t\bar{t}+\gamma\gamma$ per 100/fb

[Baernreuther,Czakon,Fiedler,Mitov],[Campbell,Ellis,Röntsch],
[Melnikov,Scharf,M.S.],[Garzelli,Kardos,Papadopoulos,Trocsanyi],
[Demartin,Maltoni,Mawatari,Page,Zaro]

LHC PRESPECTIVES FOR TOP-Z COUPLING

- Taken from R. Rontsch and M. Schulze arXiv:1501.05939

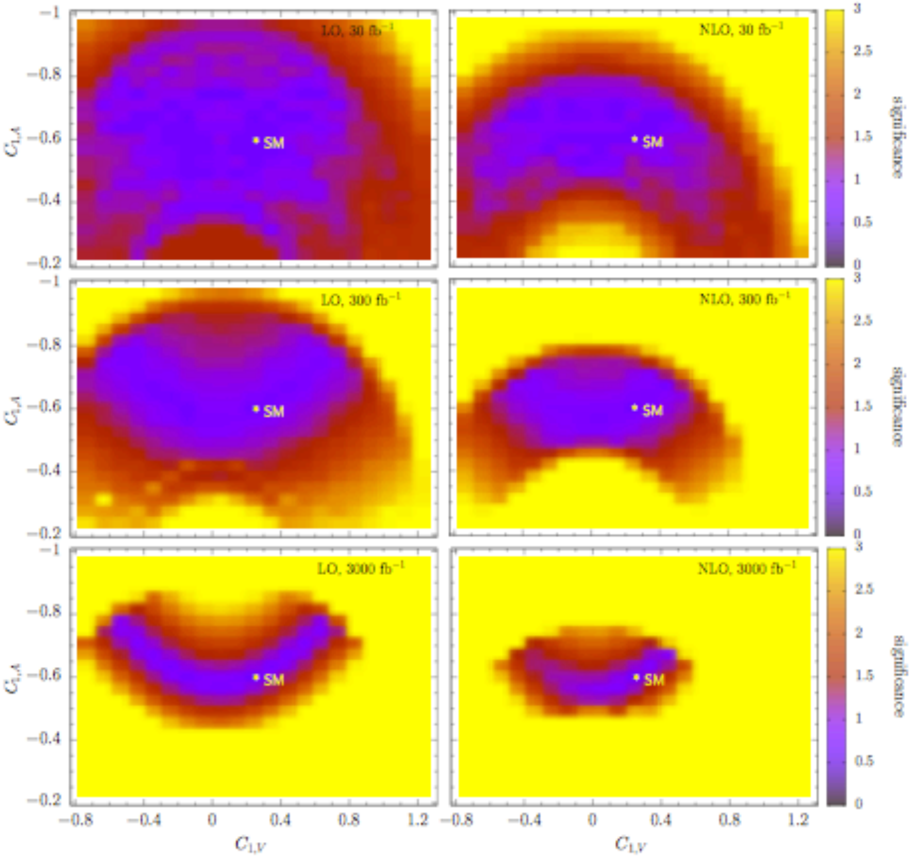


Figure 3: Significance of deviations from the SM for the couplings $C^Z_{1,V}$ and $C^Z_{1,A}$ with 30, 300, and 3000 fb^{-1} of data at the 13 TeV LHC. The results are obtained from rate and $\Delta\phi_{\ell\ell}$ shape information using LO predictions shown on the left and NLO QCD predictions shown on the right.

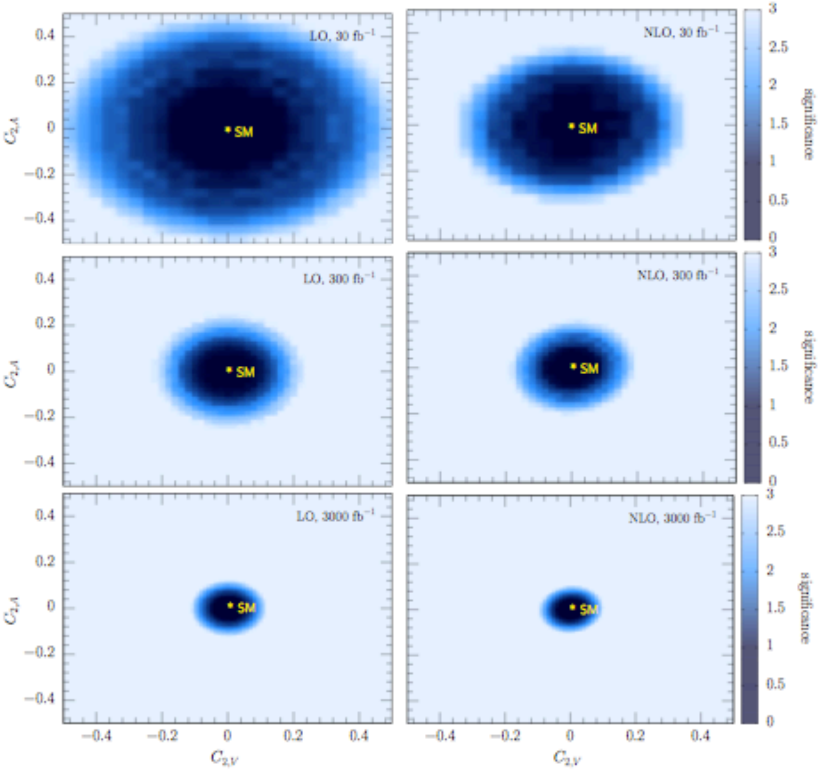
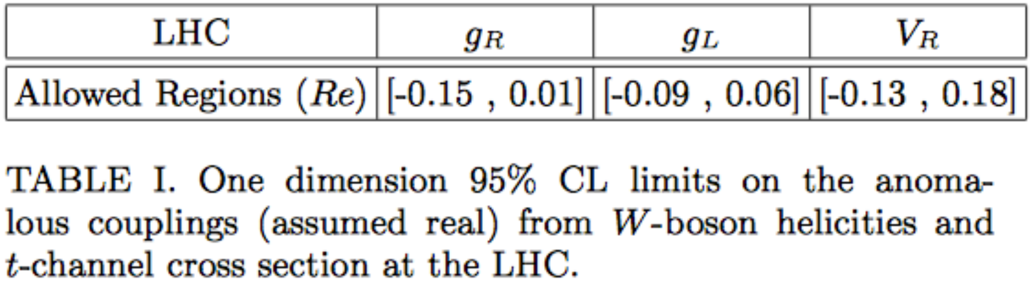


Figure 4: Significance of deviations from the SM for the dipole couplings $C^Z_{2,V}$ and $C^Z_{2,A}$ with 30, 300, and 3000 fb^{-1} of data at the 13 TeV LHC. The results are obtained from rate and $p_{T,Z}$ shape information using LO predictions shown on the left and NLO QCD predictions shown on the right.

PROBING Wtb VERTEX USING LHC DATA

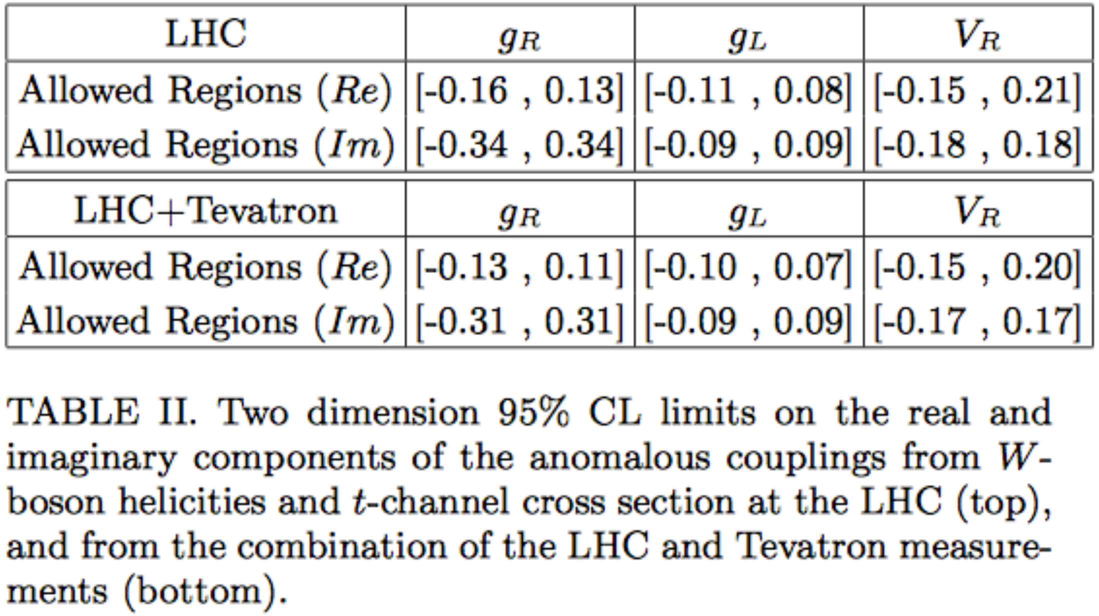
- Taken from C.Bernardo et al. arXiv:1408.7063 (from W helicity and t-channel XS @ 8 TeV)



LHC	g_R	g_L	V_R
Allowed Regions (*Re*)	[-0.15 , 0.01]	[-0.09 , 0.06]	[-0.13 , 0.18]

TABLE I. One dimension 95% CL limits on the anomalous couplings (assumed real) from *W*-boson helicities and *t*-channel cross section at the LHC.

Assuming Real anomalous couplings, V_L=1 and all other couplings 0



LHC	g_R	g_L	V_R
Allowed Regions (*Re*)	[-0.16 , 0.13]	[-0.11 , 0.08]	[-0.15 , 0.21]
Allowed Regions (*Im*)	[-0.34 , 0.34]	[-0.09 , 0.09]	[-0.18 , 0.18]
LHC+Tevatron	g_R	g_L	V_R
Allowed Regions (*Re*)	[-0.13 , 0.11]	[-0.10 , 0.07]	[-0.15 , 0.20]
Allowed Regions (*Im*)	[-0.31 , 0.31]	[-0.09 , 0.09]	[-0.17 , 0.17]

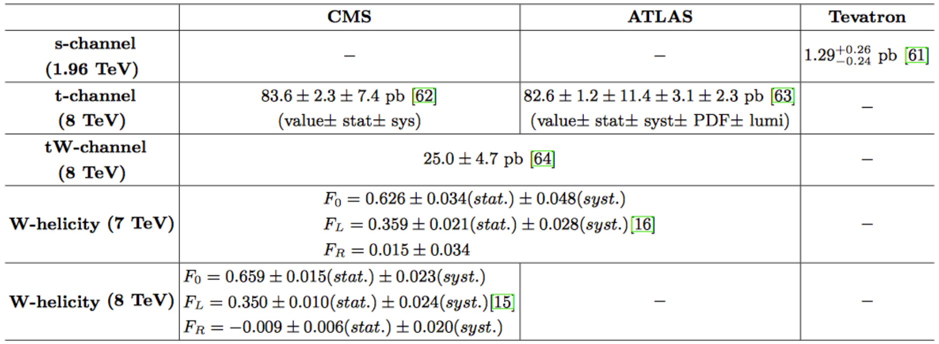
TABLE II. Two dimension 95% CL limits on the real and imaginary components of the anomalous couplings from *W*-boson helicities and *t*-channel cross section at the LHC (top), and from the combination of the LHC and Tevatron measurements (bottom).

Assuming V_L=1 and all other couplings 0

PROBING Wtb VERTEX USING LHC DATA

- Taken from C.Qing-Hong et al **arXiv:1504.03785 [hep-ph]**

TABLE II. Recent measurements of the cross sections for the single top-quark productions and the W helicity fractions at the Tevatron and LHC.



	CMS	ATLAS	Tevatron
s-channel (1.96 TeV)	–	–	$1.29^{+0.26}_{-0.24}$ pb [61]
t-channel (8 TeV)	$83.6 \pm 2.3 \pm 7.4$ pb [62] (value± stat± sys)	$82.6 \pm 1.2 \pm 11.4 \pm 3.1 \pm 2.3$ pb [63] (value± stat± syst± PDF± lumi)	–
tW-channel (8 TeV)	25.0 ± 4.7 pb [64]		–
W-helicity (7 TeV)	$F_0 = 0.626 \pm 0.034(stat.) \pm 0.048(syst.)$ $F_L = 0.359 \pm 0.021(stat.) \pm 0.028(syst.)$ [16] $F_R = 0.015 \pm 0.034$		–
W-helicity (8 TeV)	$F_0 = 0.659 \pm 0.015(stat.) \pm 0.023(syst.)$ $F_L = 0.350 \pm 0.010(stat.) \pm 0.024(syst.)$ [15] $F_R = -0.009 \pm 0.006(stat.) \pm 0.020(syst.)$	–	–

Assuming Real anomalous couplings

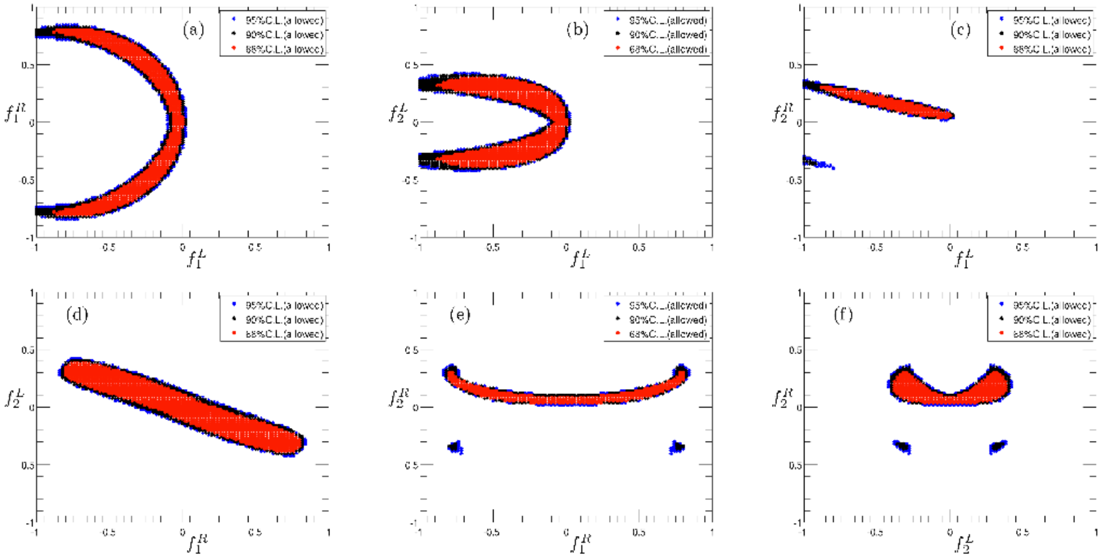


FIG. 2. Allowed parameter space on the plane of the effective Wtb couplings at the confidence levels of 68% (red region), 90% (black region) and 95% (blue region). $|f_1^L| \leqslant 1$ is required in our analysis.