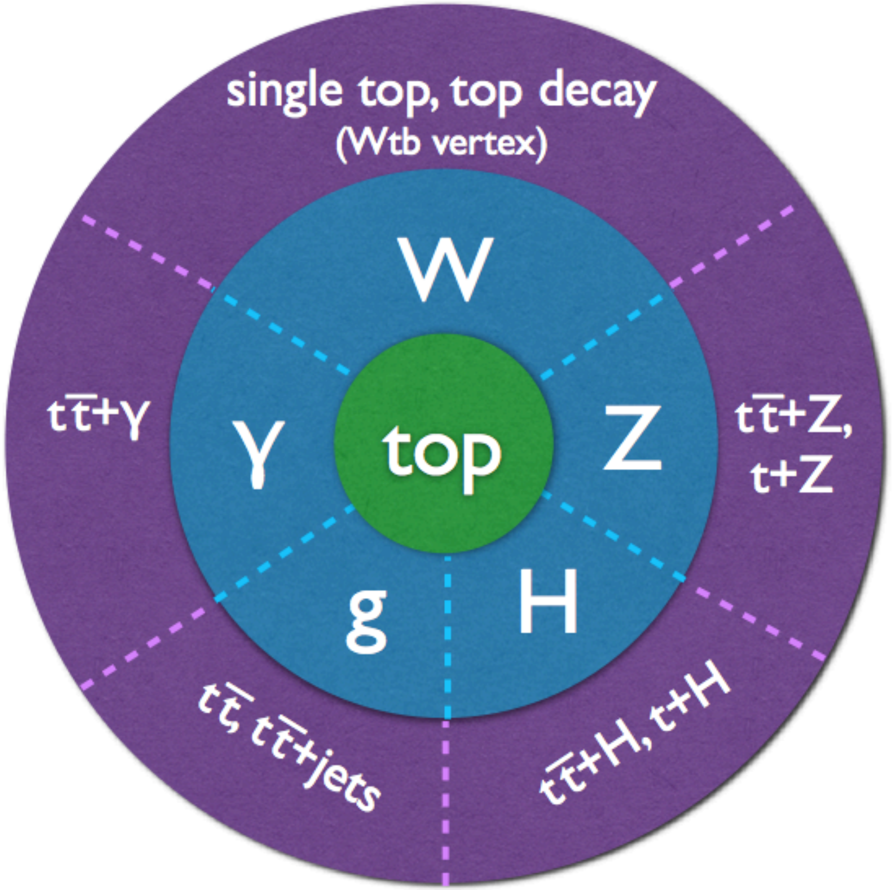
TOP QUARK PHYSICS - TOP COUPLINGS

María José Costa - IFIC (CSIC-UV)

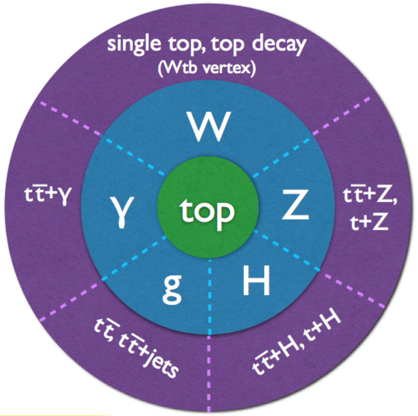
MOTIVATION

- 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.



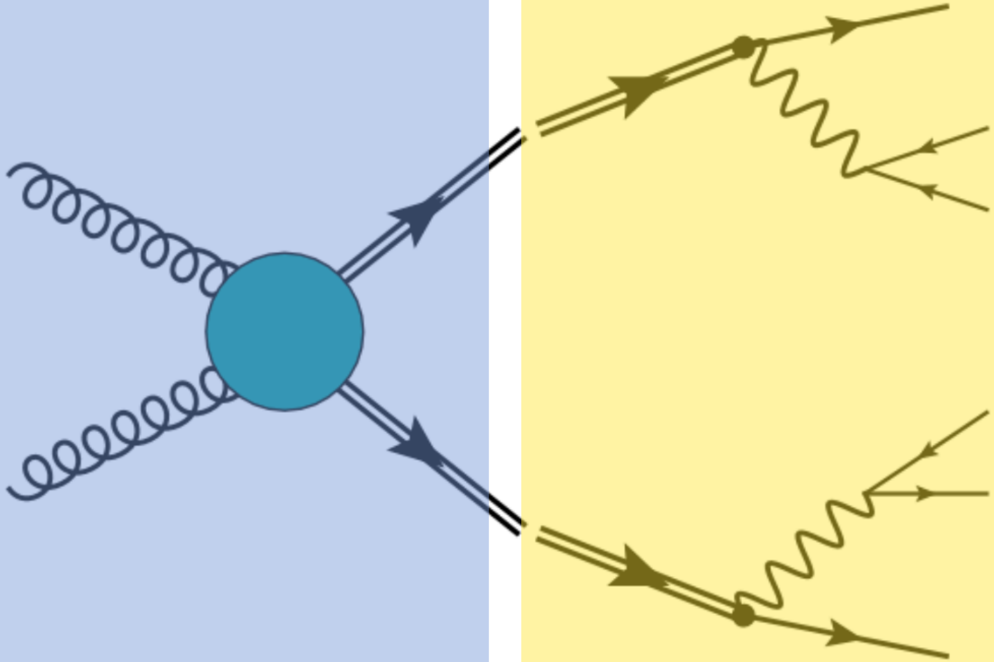
to W boson	$\frac{g_W}{\sqrt{2}} \sim 0.45$	$\frac{g_W}{\sqrt{2}} V_{tq}\bar{t}_L\gamma^\mu q_L\ W_\mu^-$
to Z boson	$g_Z = \frac{g_W}{4\cos\theta_W} \sim 0.14$	$g_Z t_L \left[(1-\frac{8}{3}\sin^2\theta_W)\gamma^\mu - \gamma^\mu\gamma_5\right] t_L\ Z_\mu$
to photon	$e_t = \frac{2}{3}e \sim 0.21$	$e_t\bar{t}\gamma^\mu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

PROBING TOP COUPLINGS AT THE LHC



Production

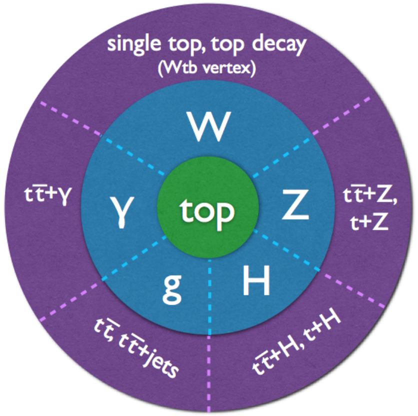
Decay

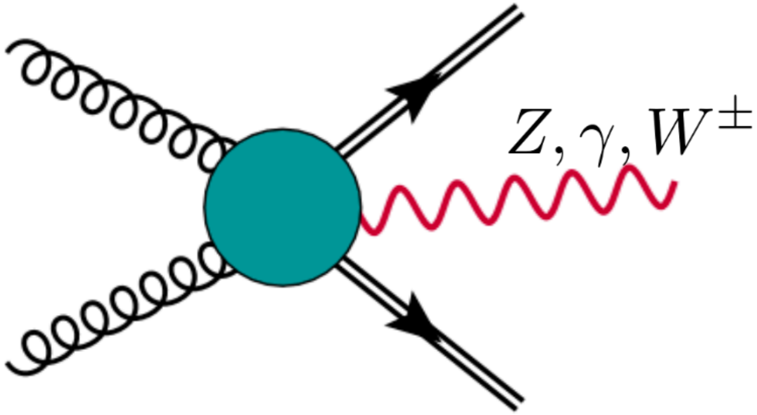


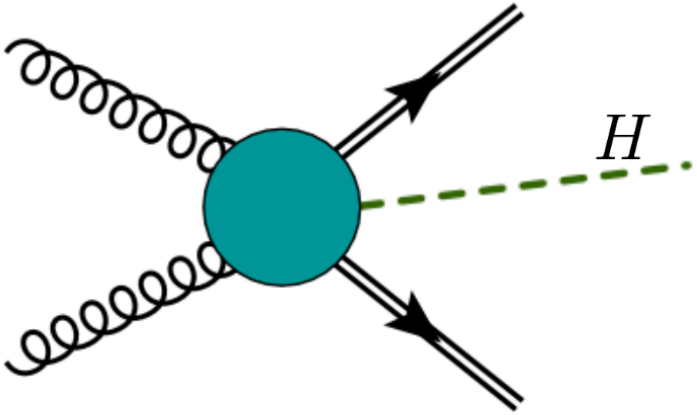
Sensitivity to QCD dynamics

Sensitivity to weak current (also in single top production)

PROBING TOP COUPLINGS AT THE LHC

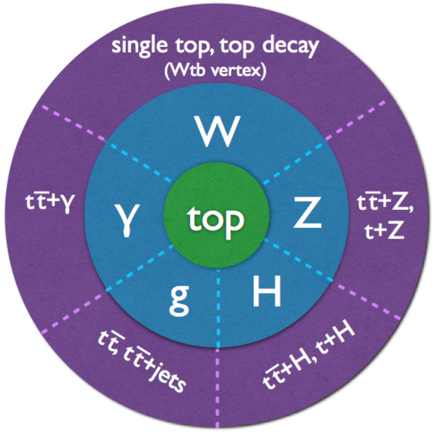






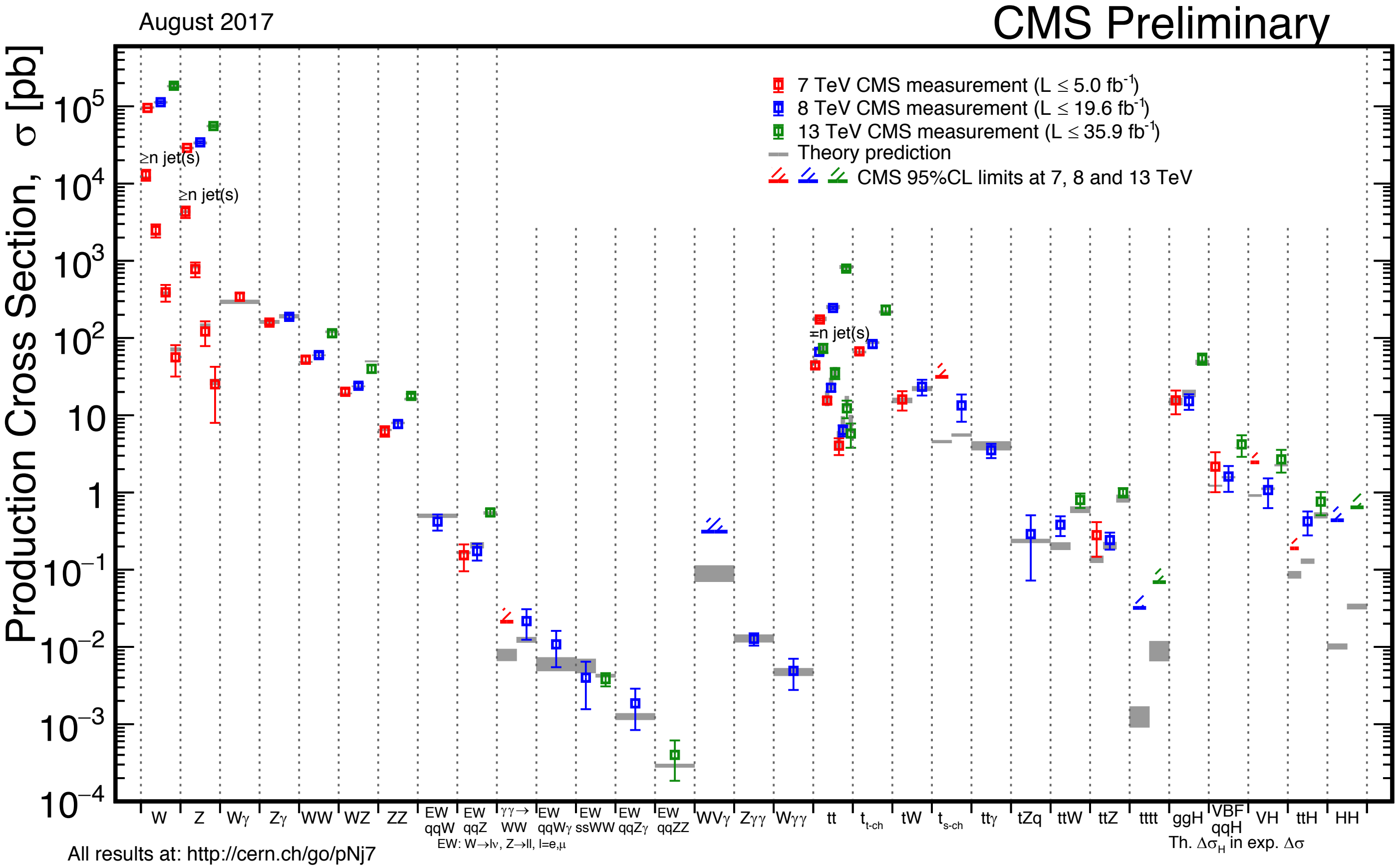
Associated production adds sensitivity to neutral currents (Z/γ) and Yukawa interactions (Higgs).

PROBING TOP COUPLINGS AT THE LHC

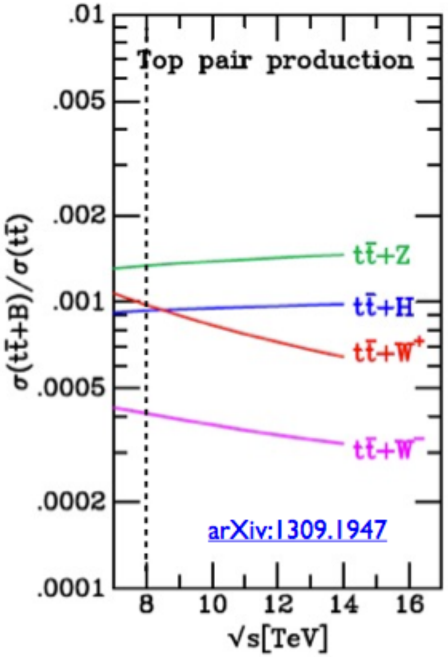


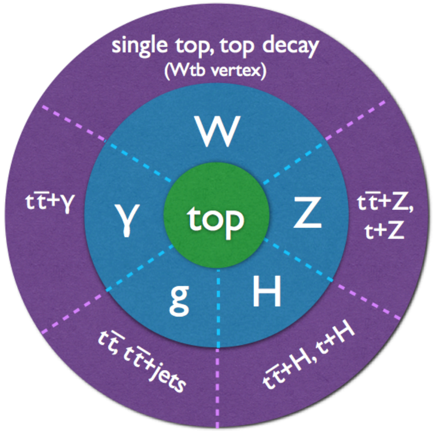
The LHC is not only a top quark factory, it is opening the door to a whole new process class

$$t\bar{t}+\gamma\,,\ t\bar{t}+Z\,,\ t\bar{t}+W^{\pm},\ t\bar{t}+H$$



All results at: http://cern.ch/go/pNj7

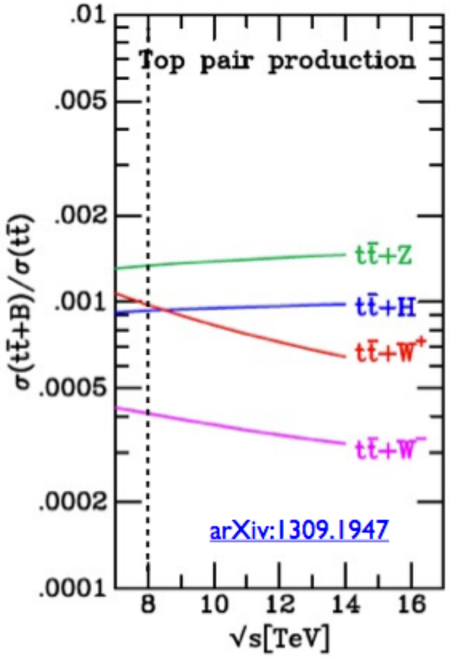




LHC SENSITIVITY

The LHC is not only a top quark factory, it is opening the door to a whole new process class

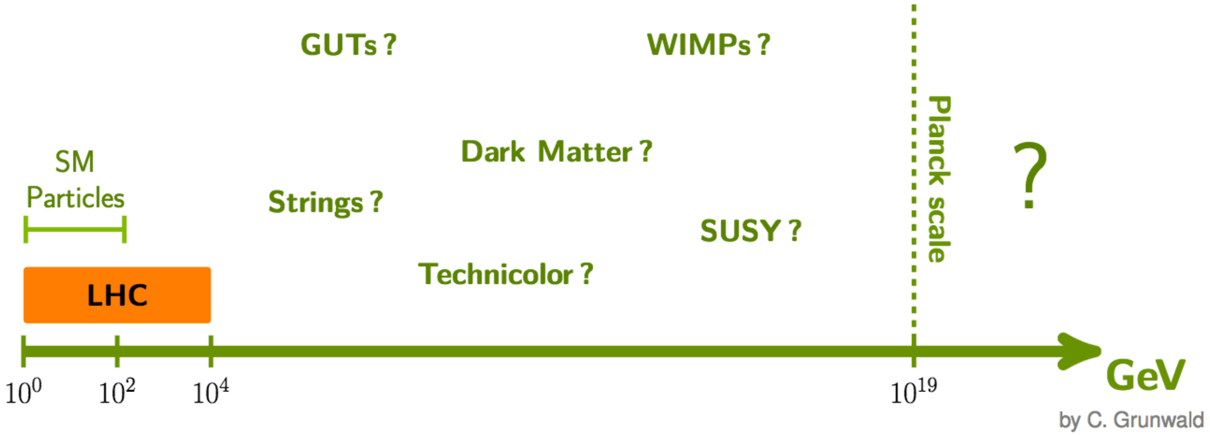
$$t\bar{t}+\gamma,\ t\bar{t}+Z,\ t\bar{t}+W^{\pm},\ t\bar{t}+H$$



13 TeV	now	300 fb^{-1}
$t\bar{t}$	33 Mio.	250 Mio.
$t\bar{t}+\gamma$	100.000	900.000
$t\bar{t}+Z$	40.000	300.000
$t\bar{t}+H$	20.000	180.000

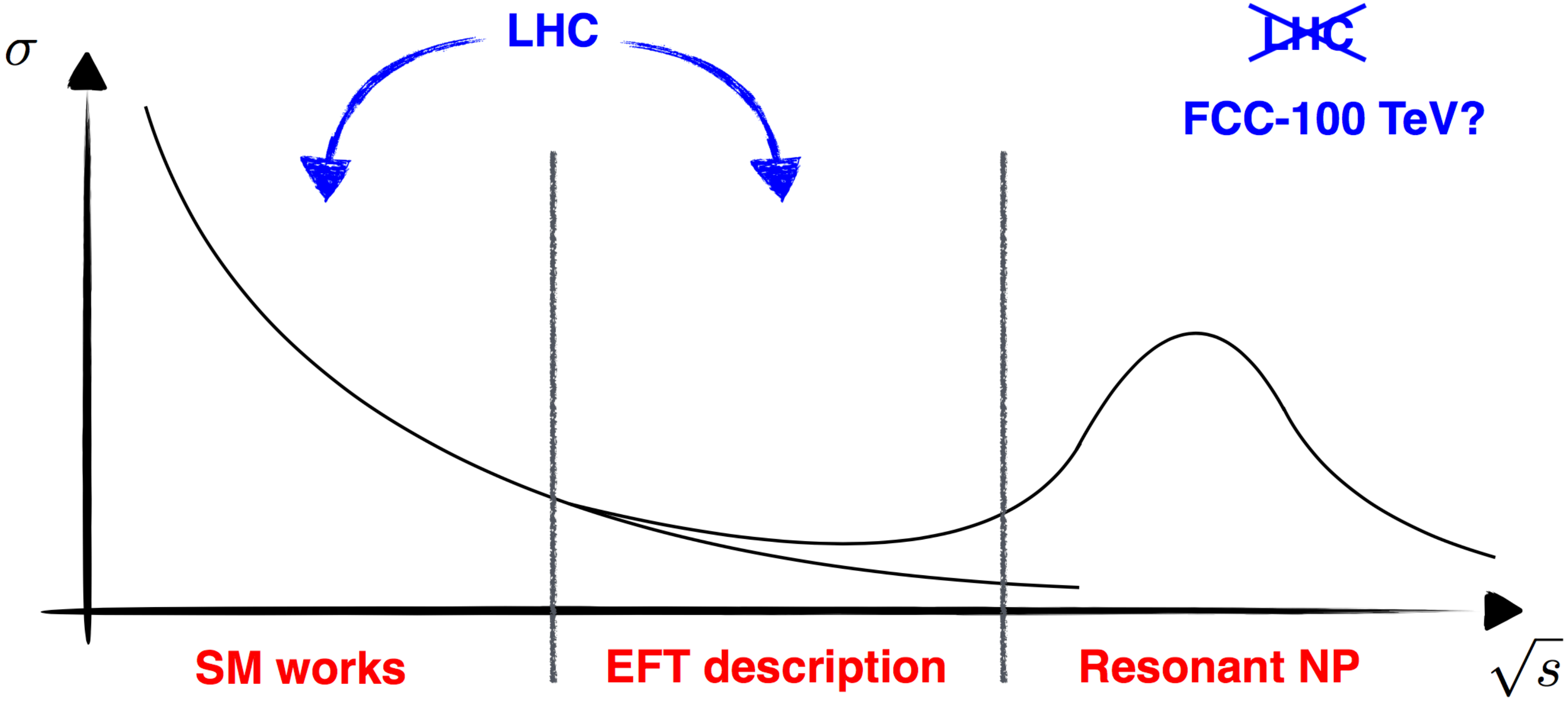
TOP COUPLINGS: MOTIVATION

- The experimental results point to a situation where $M_X >> \sqrt{s}$ → New states too heavy to be resonantly produced.



- Assume production is dominated by SM.
- Assume New physics is beyond direct reach.
- Integrate out explicit mediator and have instead an effective interaction.

SM EFFECTIVE FIELD THEORY



By D. Barducci

$$\mathcal{L}_{Eff} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

O_i = dim 6 gauge invariant operators

C_i=complex constants = Wilson Coefficients

- Powerful and model independent tool to guide experimental efforts.
- Search for new physics indirectly through precision measurements of SM observables.

SM EFFECTIVE FIELD THEORY

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

$$\mathcal{L}_{Eff} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

O_i = dim 6 gauge invariant operators

C_i=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:

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

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

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

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

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

e.g. for Wtb vertex:

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

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

THE ULTIMATE GOAL

- The goal is to find observables which are sensitive to the various possible EFT operators coefficients (or equivalently anomalous couplings).

$$\mathcal{O}^i = f(c_1^i, c_2^i, ..., c_n^i)$$

set of observables

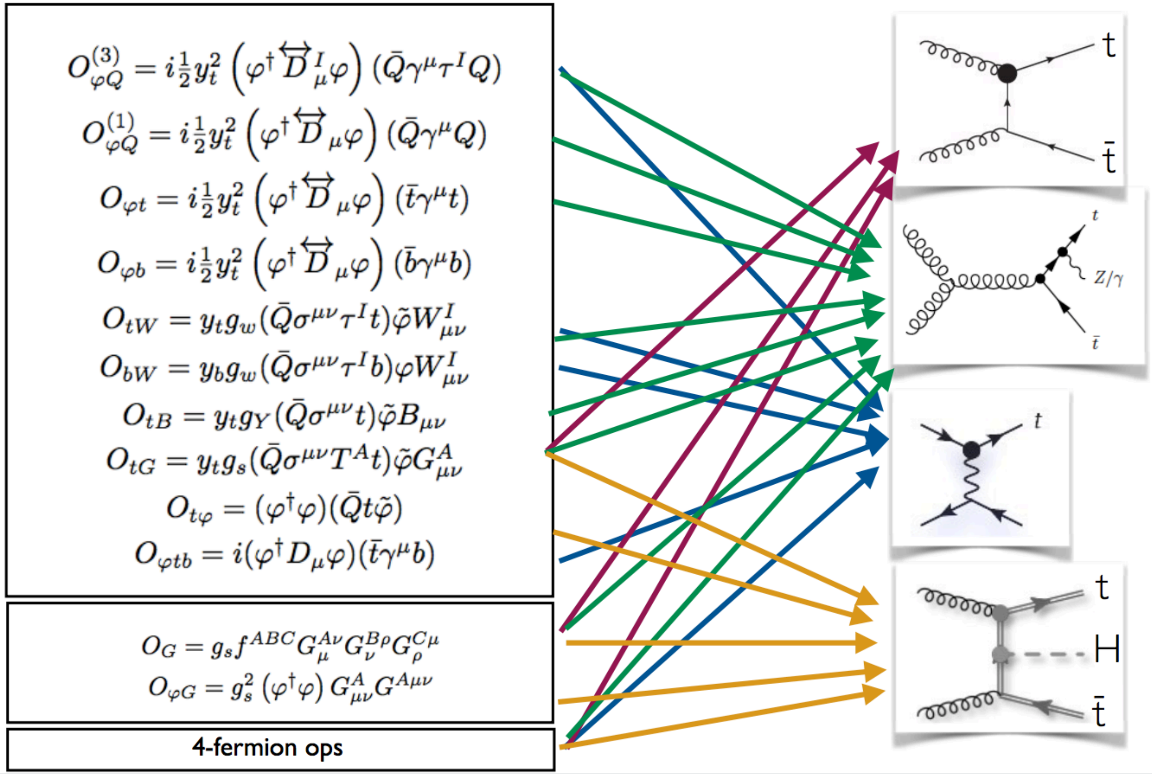
Dependence with the parameters
(anomalous couplings, effect. operators coefficients)

- And then perform a global fit to all observables, considering proper correlations of statistical and systematic uncertainties.
- **This requires a coordinated effort among theorists and experimentalists (being followed up within LHC TOPWG):**
  - Agree on conventions across the whole community.
  - Provide guidelines towards sound uses of SM EFT.
  - To establish useful ways to communicate experimental results.
  - Guidelines from theorists are being prepared in a document: http://www.desy.de/~durieux/topbasis/basis_note.pdf

MANY INTERESTING CHALLENGES

- There are many operators to consider.
- Multiple measurements may be sensitive to the same operator and the vice-versa (i.e. ttZ cross section sensitive to the coupling to the gluon and to the Z boson).

- EFT modelling and uncertainties.
- Multiple EFT coefficients could be non-zero.
- Correlations between measurements.



$$O_{\varphi Q}^{(3)} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$

$$O_{\varphi Q}^{(1)} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

$$O_{\varphi t} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{\varphi b} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{b}\gamma^\mu b)$$

$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

$$O_{bW} = y_b g_w (\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}$$

$$O_{t\varphi} = (\varphi^\dagger\varphi)(\bar{Q}t\tilde{\varphi})$$

$$O_{\varphi tb} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$

$$O_{\varphi G} = g_s^2 \left(\varphi^\dagger\varphi\right) G^A_{\mu\nu}G^{A\mu\nu}$$

4-fermion ops

By F.Maltoni

WHAT HAS BEEN DONE SO FAR

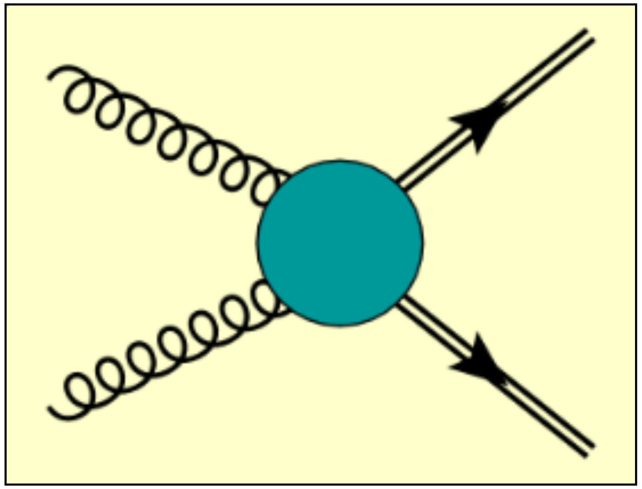
- A lot of work done so far though.
- I will show you some examples of:
  - Measurements performed at the LHC sensitive to effective operator coefficients (or top anomalous couplings).
  - Constraints obtained on the operators or couplings (even if different notations are used, and different assumptions are made).
  - The interpretations are sometimes done within the experimental papers or a posteriori by phenomenologists.

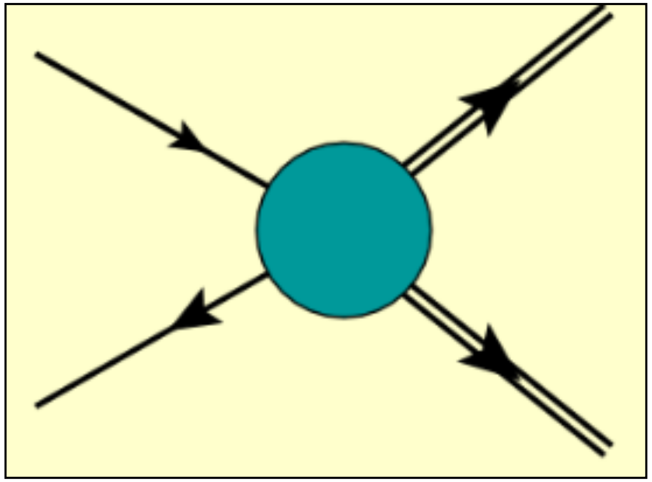
Still a long way to go, but a lot of progress done so far as well by both theoretical and experimental communities.

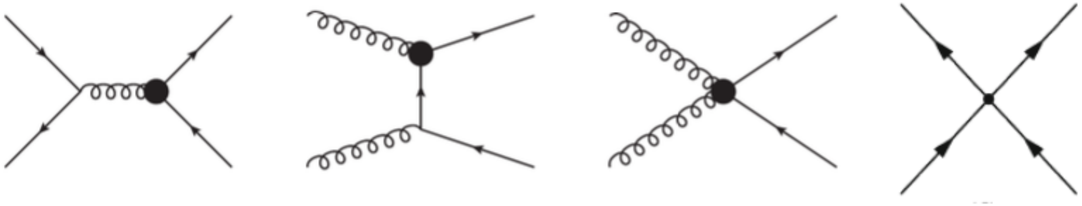
Can not cover all the results provided so far (will give examples from either ATLAS or CMS).

TOP COUPLING TO GLUON

- Strong interactions of the top quark are studied in top quark pair production, including tt+jets processes.
- Inclusive as well as differential cross section measurements.
- Charge asymmetry measurements.
- Top quark spin correlations.

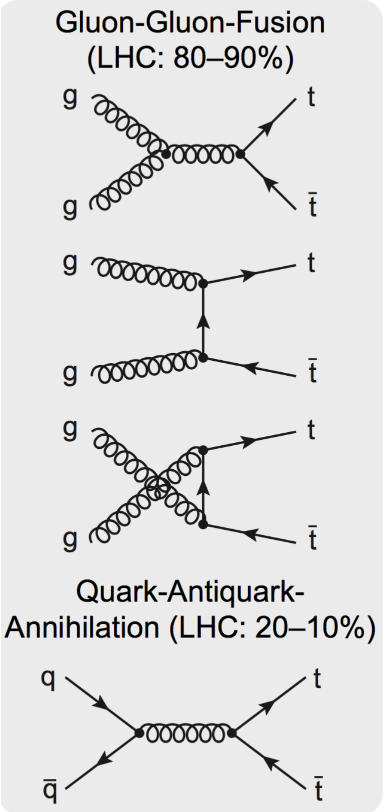






TOP PAIR CROSS SECTION PREDICTIONS

- Long standing theoretical effort on fixed order calculations on inclusive (NNLO+NNLL) and differential cross sections (NNLO recently provided)



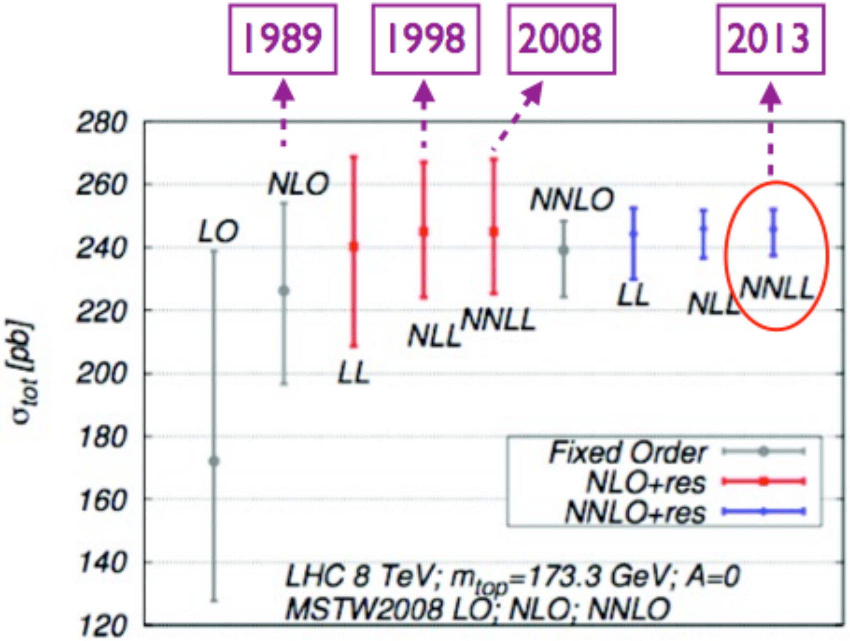
top pairs XS[4]

7 TeV: $177.3^{+10.1}_{-10.8}$ pb

8 TeV: $252.9^{+13.3}_{-14.5}$ pb

13 TeV: 832^{+40}_{-46} pb pb

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

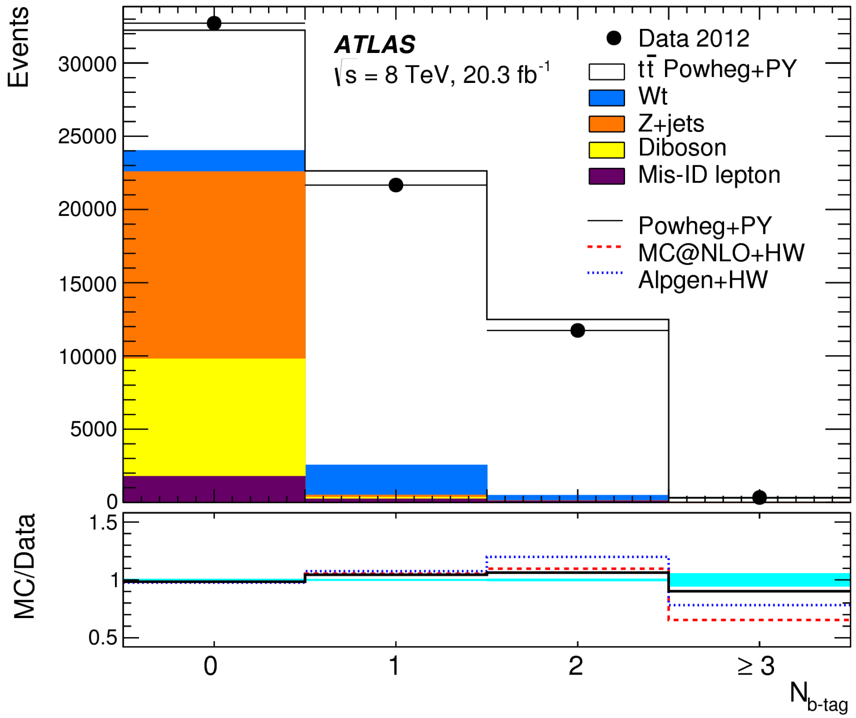


NLO → NNLO+NNLL
Precision improves from:
~12% →~3% (scales)
~ 8% → 5% (PDF)

TOP PAIR CROSS SECTION MEASUREMENTS

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

$$\sigma = \frac{N_{obs} - N_{bkg}}{(A \times \varepsilon) \times B \times L}$$

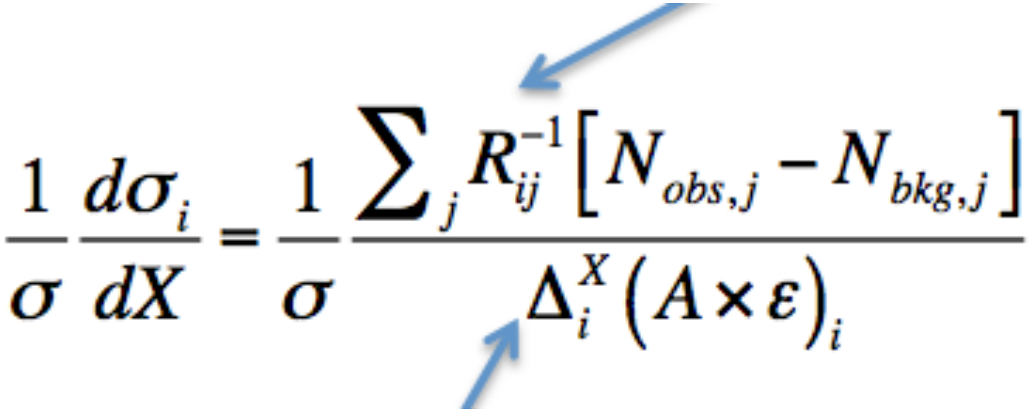


- N_{obs} = Number of observed events after selection
- B = Estimated number of background events
- A = Acceptance (depends on modelling of the signal)
- ε = Selection efficiency for events within acceptance (affected by trigger and reconstruction performance)
- L = Integrated luminosity
- B = Branching ratio.

TOP PAIR CROSS SECTION MEASUREMENTS

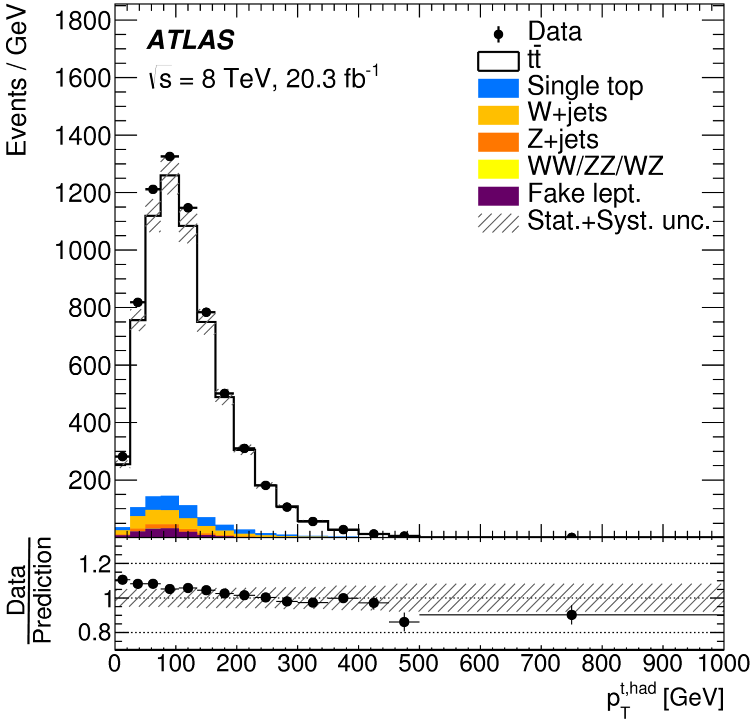
- The cross section can also be measured differentially.
- Probe different regions of the phase space: Important test of pQCD, constrain on MC models/PDFs and systematic effects, sensitive to new physics.
- Use unfolding techniques on background subtracted reconstructed distributions to parton or particle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

Response matrix



$$\frac{1}{\sigma}\frac{d\sigma_i}{dX} = \frac{1}{\sigma}\frac{\sum_j R_{ij}^{-1}\left[N_{obs,j} - N_{bkg,j}\right]}{\Delta_i^X \left(A \times \varepsilon\right)_i}$$

Bin Width



TOP PAIR INCLUSIVE CROSS SECTION

ATLAS inclusive cross section measurement (eμ channel)

Eur. Phys. J. C74 (2014) 3109

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

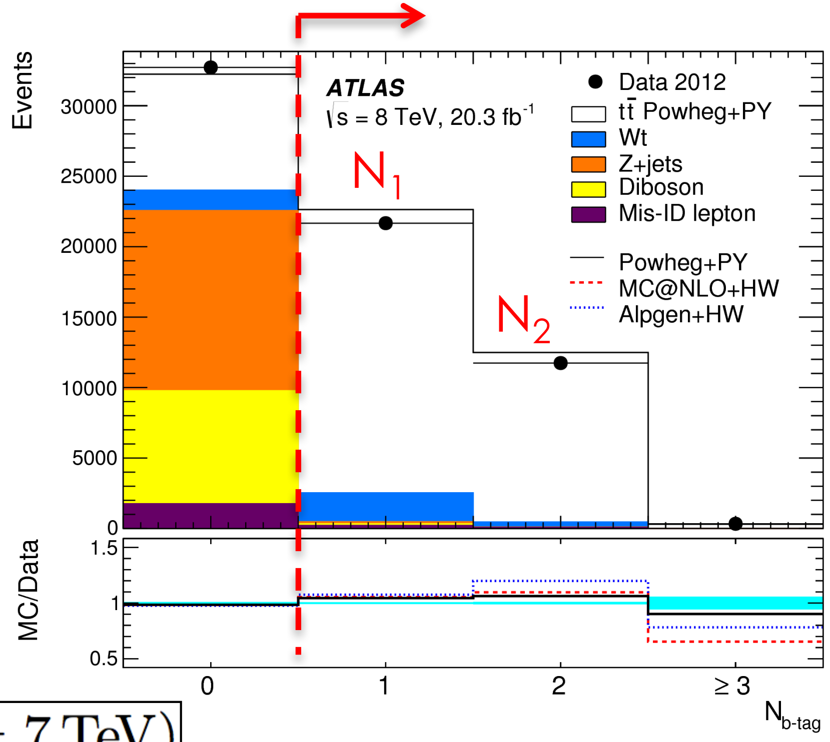
$$N_1 = L\sigma_{t\bar{t}}\ \epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\rm bkg}$$

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

$\varepsilon_{e\mu}$= eμ preselection efficiency.

ε_b= b-jet acceptance and tagging efficiency.

C_b = 1/2 b-tag correlation (=1.005)



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

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

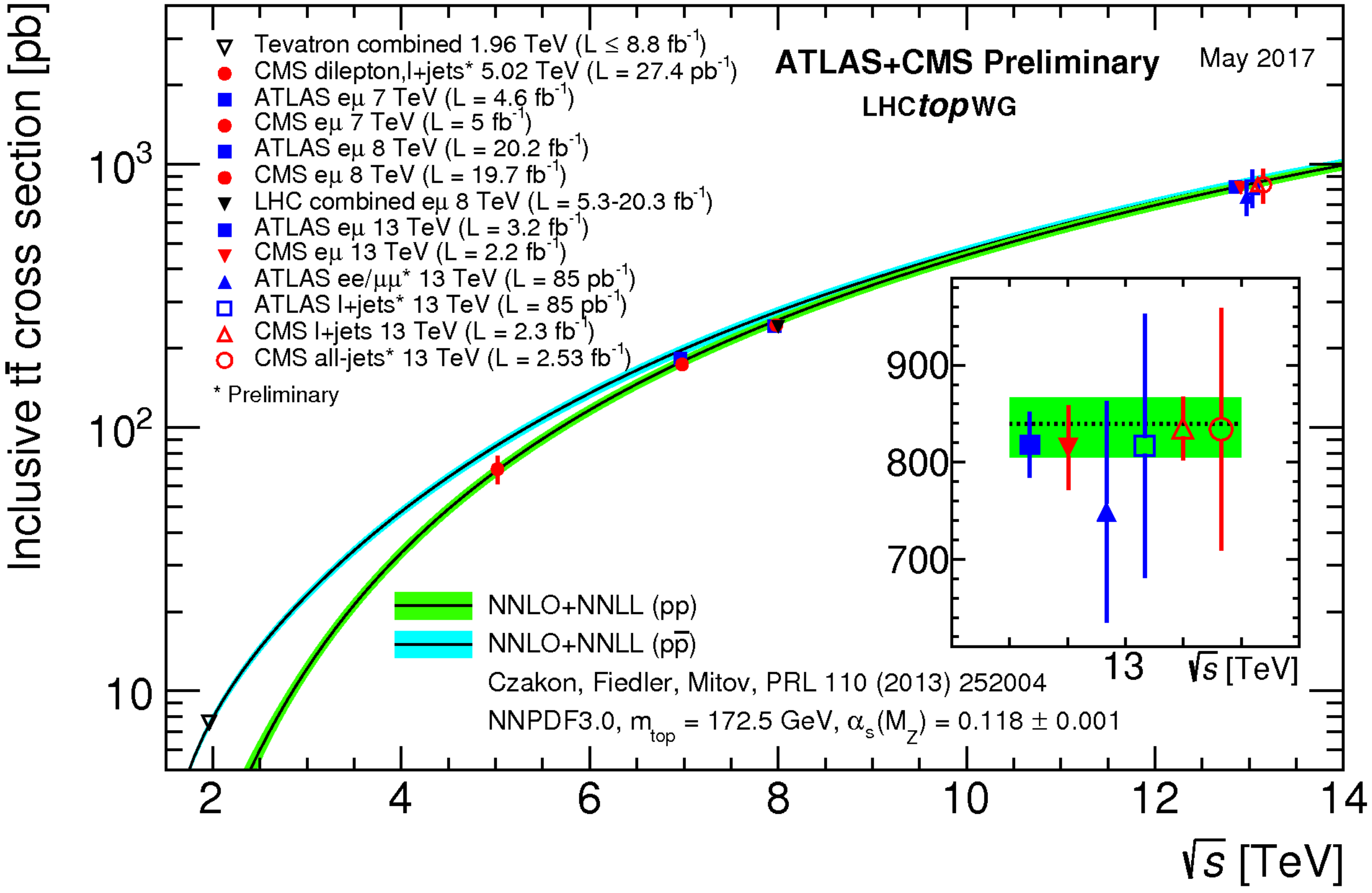
√s= 13 TeV (Phys. Lett. B761 (2016) 136

$$\sigma_{t\bar{t}} = 818 \pm 8\ \text{(stat)} \pm 27\ \text{(syst)} \pm 19\ \text{(lumi)} \pm 12\ \text{(beam) pb},$$

Dominant sources: Signal modelling, luminosity, PDF (Run-1 case).

Precision achieved:
3.5% @ 7 TeV
4% @ 8 TeV
4.1% @ 13 TeV
In addition, beam E uncertainty (0.66%)

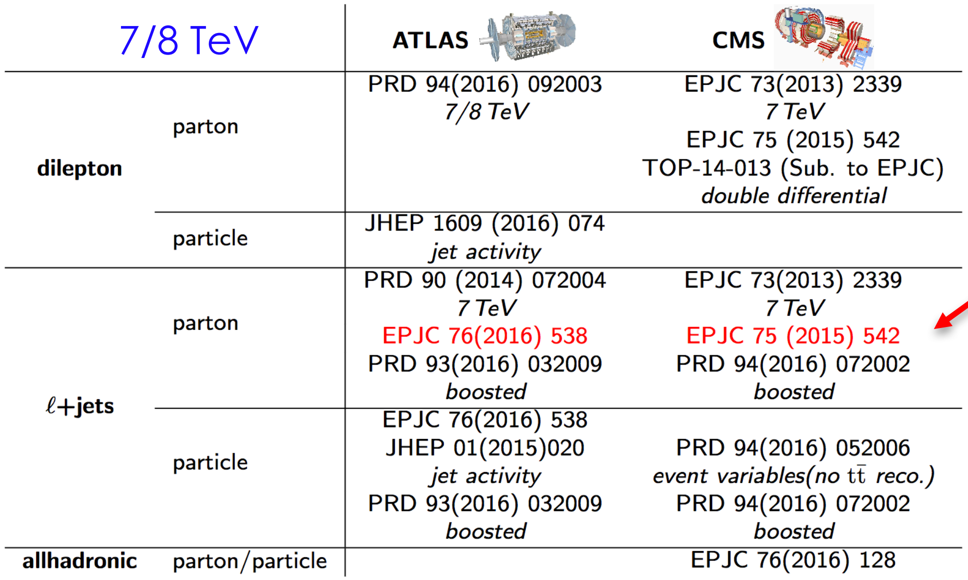
TOP PAIR INCLUSIVE CROSS SECTION



Excellent agreement of NNLO+NNLL predictions and precise experimental measurements over a large range of energies.

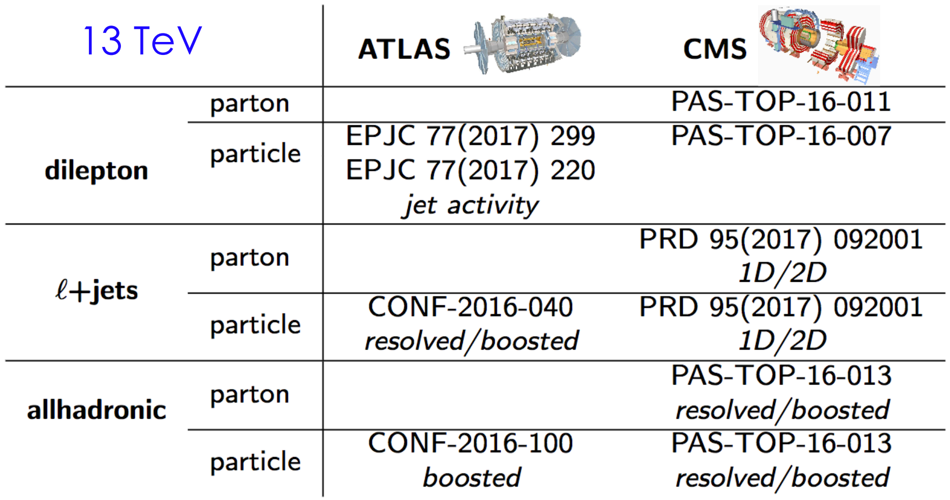
Experimental precision now challenging the theoretical predictions.

TOP PAIR DIFFERENCIAL CROSS SECTION



7/8 TeV		ATLAS	CMS
dilepton	parton	PRD 94(2016) 092003 *7/8 TeV*	EPJC 73(2013) 2339 *7 TeV* EPJC 75 (2015) 542 TOP-14-013 (Sub. to EPJC) *double differential*
	particle	JHEP 1609 (2016) 074 *jet activity*	
ℓ+jets	parton	PRD 90 (2014) 072004 *7 TeV* EPJC 76(2016) 538 PRD 93(2016) 032009 *boosted*	EPJC 73(2013) 2339 *7 TeV* EPJC 75 (2015) 542 PRD 94(2016) 072002 *boosted*
	particle	EPJC 76(2016) 538 JHEP 01(2015)020 *jet activity* PRD 93(2016) 032009 *boosted*	PRD 94(2016) 052006 *event variables(no $t\bar{t}$ reco.)* PRD 94(2016) 072002 *boosted*
allhadronic	parton/particle		EPJC 76(2016) 128

Same binning and same phase space, same parton level definition → "easy" to compare side by side and combination ongoing.



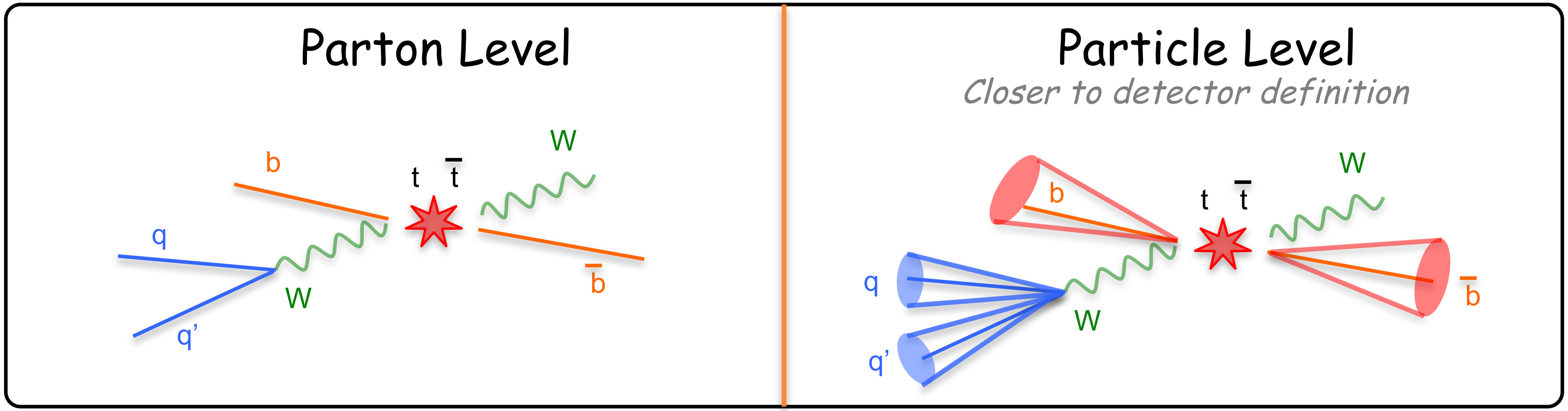
13 TeV		ATLAS	CMS
dilepton	parton		PAS-TOP-16-011
	particle	EPJC 77(2017) 299 EPJC 77(2017) 220 *jet activity*	PAS-TOP-16-007
ℓ+jets	parton		PRD 95(2017) 092001 *1D/2D*
	particle	CONF-2016-040 *resolved/boosted*	PRD 95(2017) 092001 *1D/2D*
allhadronic	parton		PAS-TOP-16-013 *resolved/boosted*
	particle	CONF-2016-100 *boosted*	PAS-TOP-16-013 *resolved/boosted*

By O.Hindrichs June 2017
(even more now!)

- A plethora of measurements available from ATLAS and CMS at 7, 8, 13 TeV, in various channels (dilepton, lepton+jets, all hadronic) and at both parton and particle level in various fiducial regions.
- The particle level fiducial measurements are more precise (at the level of few %). But not so straight forward to make the ATLAS/CMS comparison and important to document the definitions used in the form of code (Rivet routines).

PARTICLE LEVEL DEFINITIONS

- Parton level (full phase space):
  - Top defined after QCD radiation and before it decays.
  - Mimics definitions of bare quark widely used in fixed order theory calculations.
- Particle level (fiducial phase space):
  - Based on stable particles after hadronisation (see exact definition used https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ParticleLevelTopDefinitions).
  - Fiducial phase space defined according to detector level cuts.
  - Reduced effect from extrapolation.



Parton Level

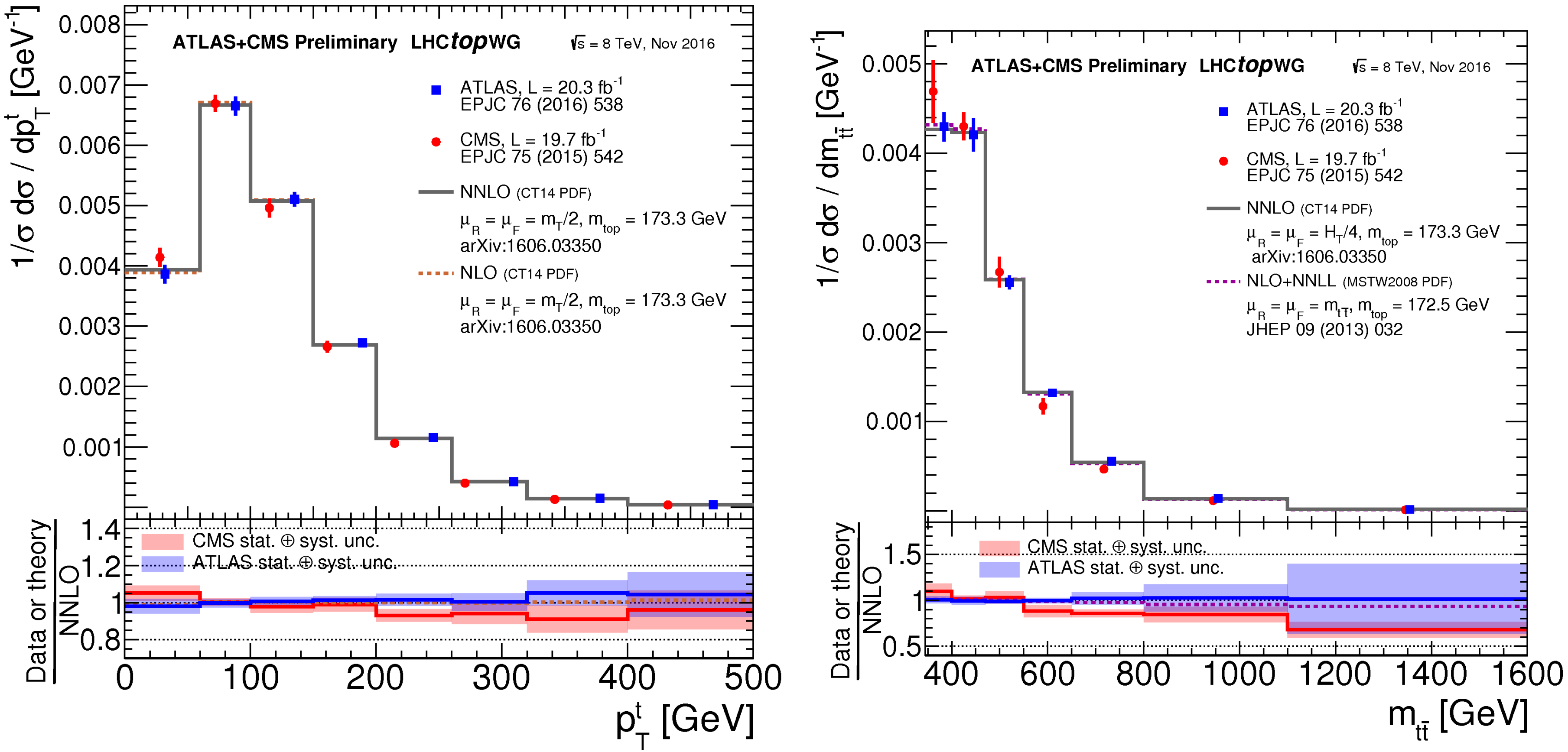
Particle Level

Closer to detector definition

Both measurements are important to provide, but particle level measurements are less model dependent and therefore more precise.

TOP PAIR DIFFERENCIAL CROSS SECTION

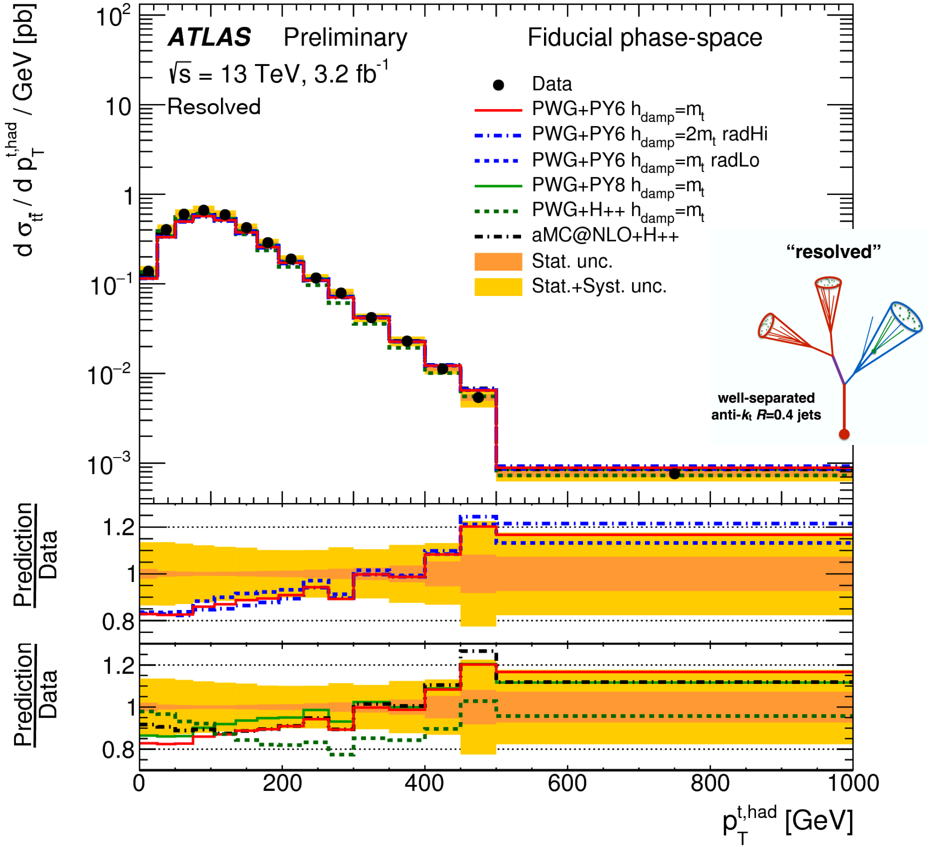
Example: top p_T , top pair invariant mass at parton level measurements from ATLAS and CMS using 8 TeV data

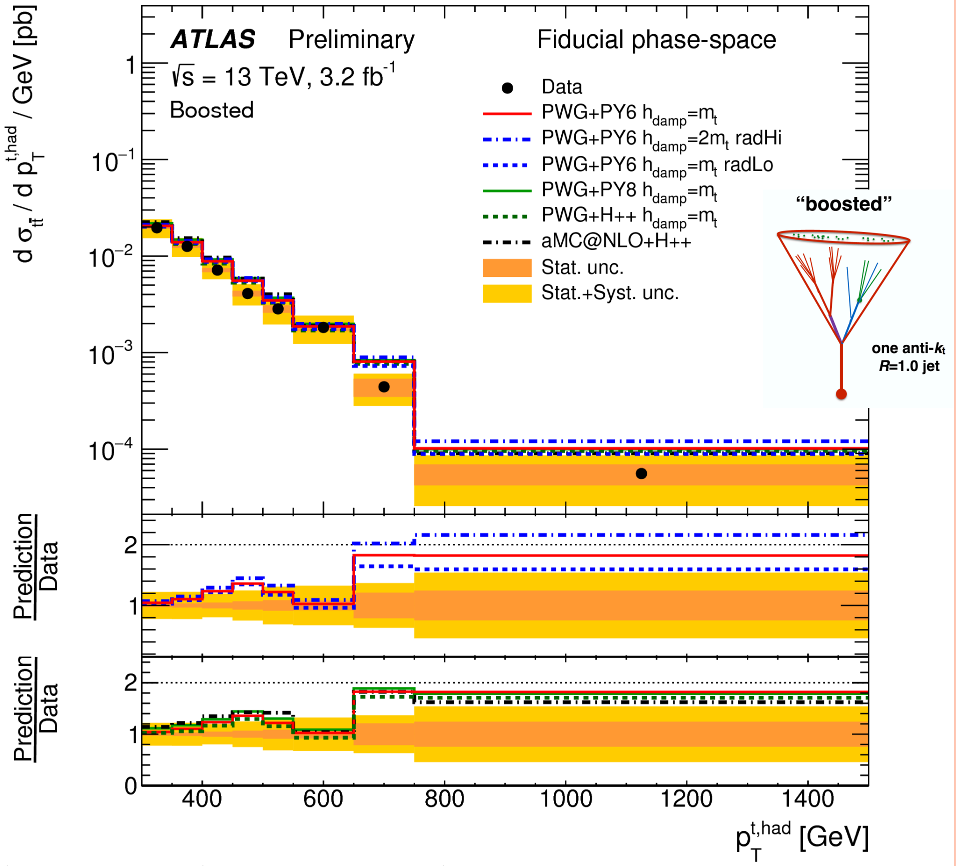


- The recent NNLO predictions give a better description of the data (top pT).
- CMS spectra seem to be softer than ATLAS measurements (might not be significant, combination ongoing).

TOP PAIR DIFFERENCIAL CROSS SECTION

Example: ATLAS measurements at particle level in the lepton+jets channel in both resolved and boosted regime, at √s= 13 TeV.



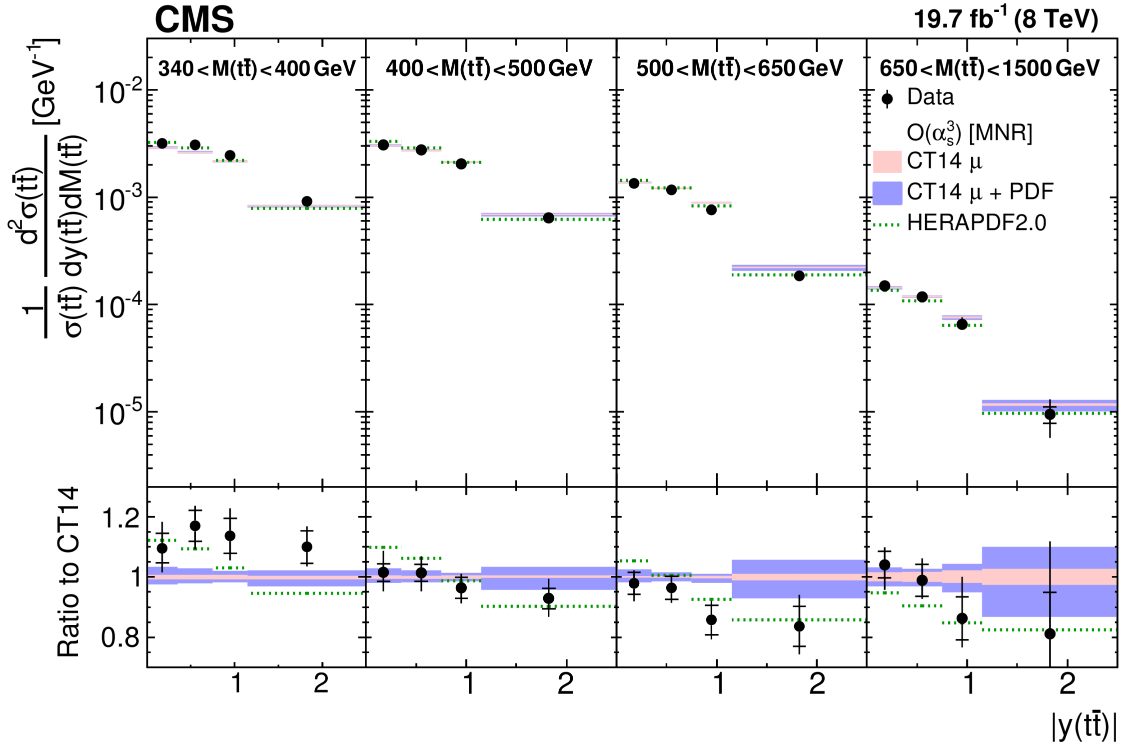


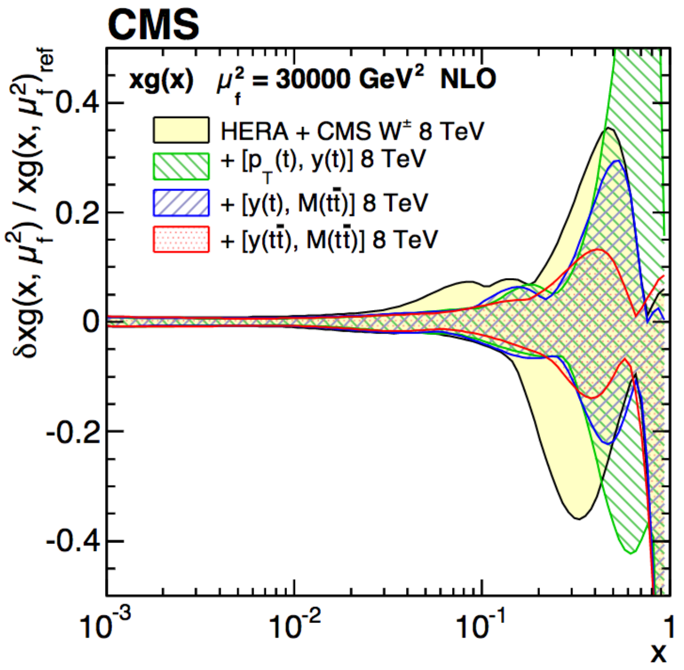
Dominant uncertainties: signal modelling and b-tagging, large-R jet JES uncertainty becomes dominant at large high p_T.

MC generators (NLO+PS) predict a harder top p_T distribution at high values than observed.

TOP PAIR DIFFERENCIAL CROSS SECTION

Example: First double differential measurement from CMS.





At LO: $x = (M(t\bar{t})/\sqrt{s})\exp[\pm y(t\bar{t})]$

Expected to be sensitive to the region: $0.01 \lesssim x \lesssim 0.25,$

Significant reduction of uncertainties when this measurements is included in PDF fits.

CONSTRAINTS ON NEW PHYSICS - EFT

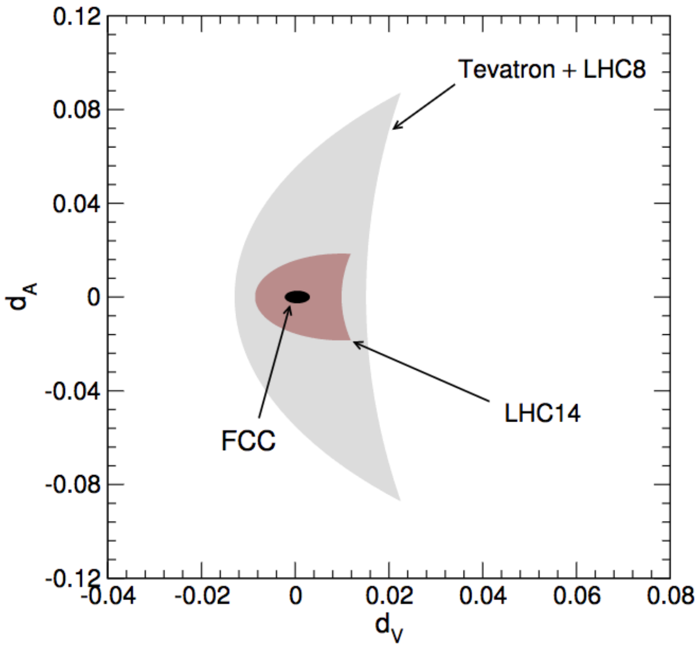
- Some of the top pair inclusive and differential measurements provided have been used to constrain top anomalous couplings (or effective operator coefficients).

$$\mathcal{L}_{ttg} = g_s \bar{t}\gamma^{\mu} T^A t G^A_{\mu} + \frac{g_s}{m_t}\bar{t}\sigma^{\mu\nu}\left(d_V + i d_A \gamma_5\right) T^A t G^A_{\mu\nu}$$

d_V = chromomagnetic dipole moment
d_A = chromoelectric dipole moment

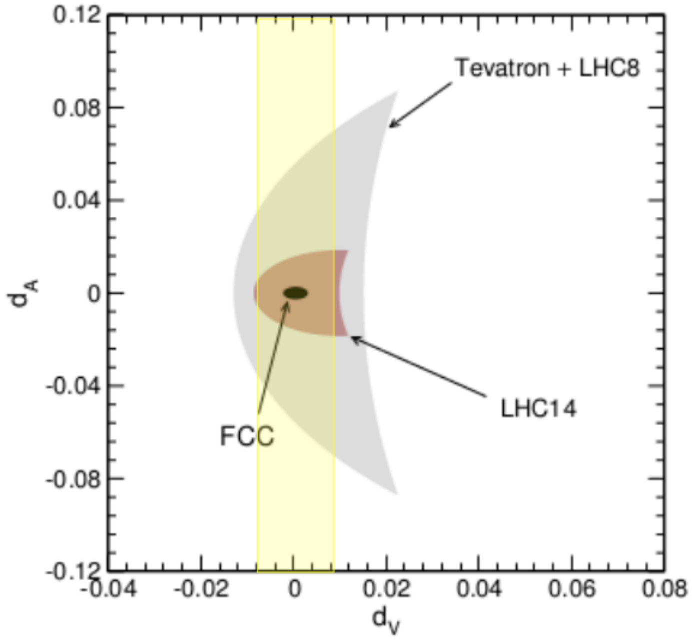
Pinning down top dipole moments with ultra-boosted tops

Juan A. Aguilar–Saavedra$^{(a)}$, Benjamin Fuks$^{(b,c)}$ and Michelangelo L. Mangano$^{(c)}$



Probing top-quark chromomagnetic dipole moment at next-to-leading order in QCD

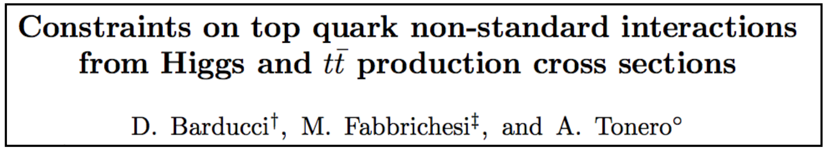
Diogo Buarque Franzosi[1] and Cen Zhang[2]



NLO corrections allow to constrain further d_V

CONSTRAINTS ON NEW PHYSICS - EFT

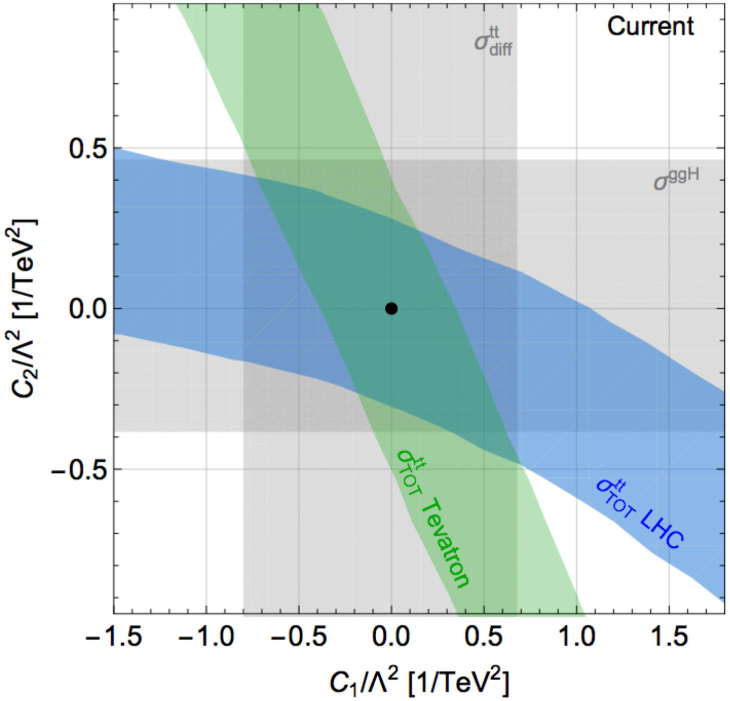
- Some of the top pair inclusive and differential measurements provided have been used to constrain top anomalous couplings (or effective operator coefficients).

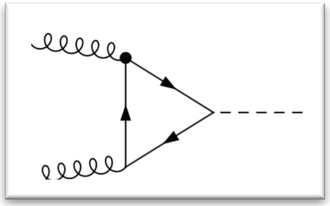


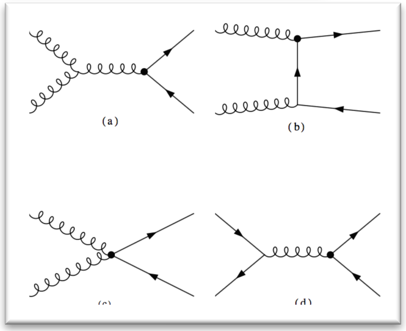
Constraints on top quark non-standard interactions from Higgs and $t\bar{t}$ production cross sections

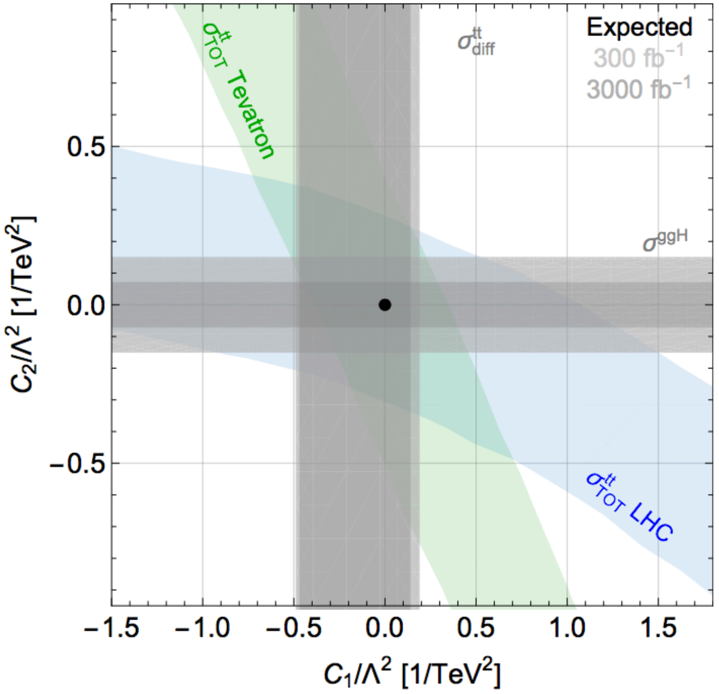
D. Barducci[†], M. Fabbrichesi[‡], and A. Tonero[°]

Top pair together with Higgs production measurements provide independent observables to bound non standard top-gluon interactions.
Assumptions: CP even operators, flavour independence.









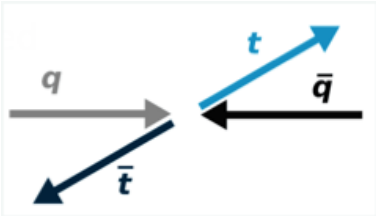
The current limits can be re-expressed in terms of bounds on New Physics scale:

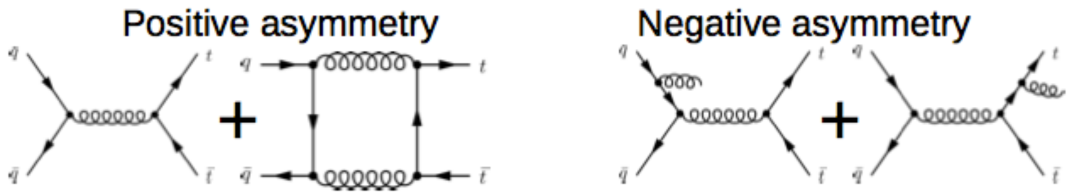
$$C_1 = C_2 = 4\pi \quad \rightarrow \quad \Lambda \sim 5 \text{ TeV}$$

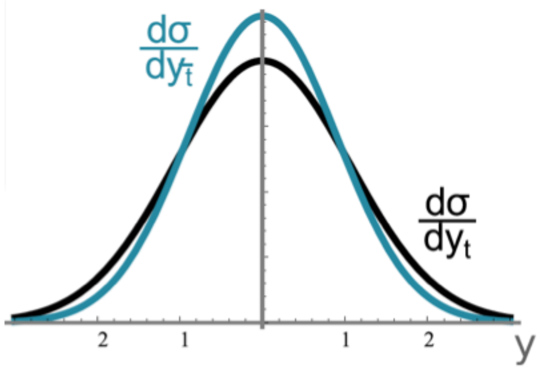
CHARGE ASYMMETRY

Kühn, Rodrigo, JHEP 1201 (2012) 063
Bernreuther, Si, Phys. Rev. Lett. D 86 (2012) 034026

- At LO tops and anti-tops are symmetric.
- At higher orders: interference of diagrams → connects the direction of top and initial quark and direction of anti-top and initial anti-quark.







- Only in qqbar initial state (not for the dominant gg fusion).
- Relatively a small effect in the SM.

  Ac: 1% A_{ll}: 0.6%
- Can be enhanced in BSM scenarios (axigluons, Z’ bosons, KK gluons).

Measurements of inclusive and differential observables in full and fiducial phase space available.

Measured Observables

$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$\Delta|y| = |y_t| - |y_{\bar{t}}|$. NLO QCD: 0.0111±0.0004

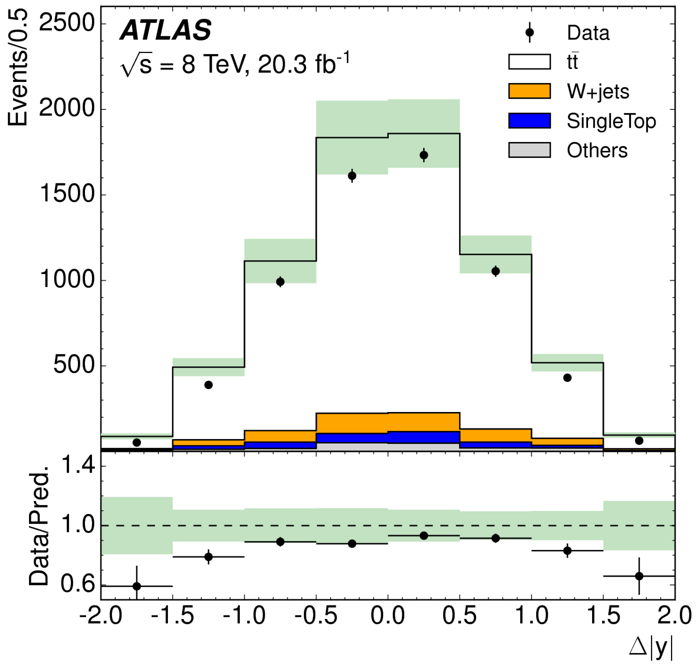
In dilepton channel:

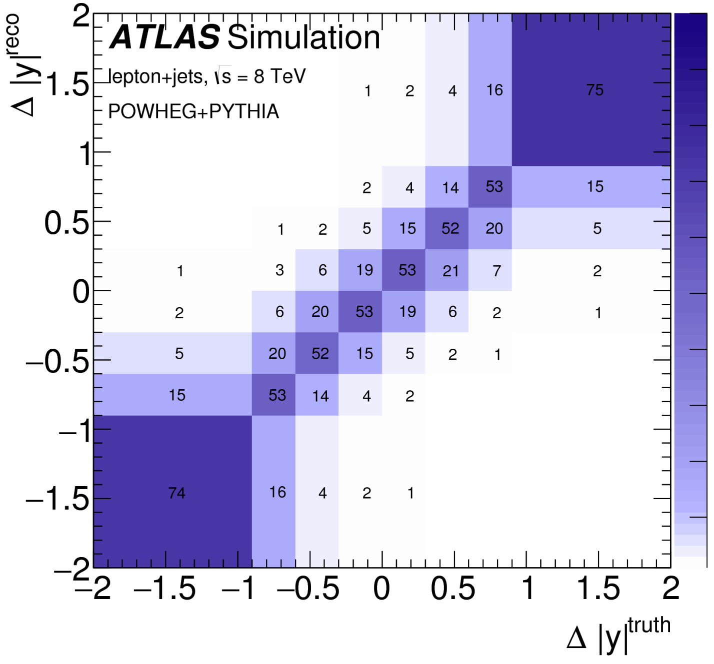
$$A_C^{\ell\ell} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)}$$

$\Delta|\eta| = |\eta_{\ell^+}| - |\eta_{\ell^-}|$ NLO QCD: 0.0064±0.0003

CHARGE ASYMMETRY MEASUREMENTS

- Measurements performed in l+jets (including also boosted top specific analysis) and dilepton channels.
- Different methods to reconstruct the ttbar kinematics (e.g. likelihood fit in l+jets, specific technique to deal with boosted top decays in l+jets boosted, KIN method in dilepton).
- Unfolding method used to correct to parton level or template method (CMS).
- Inclusive and differential measurements as a function of invariant mass, p_T and longitudinal boost β_z of the ttbar system provided.

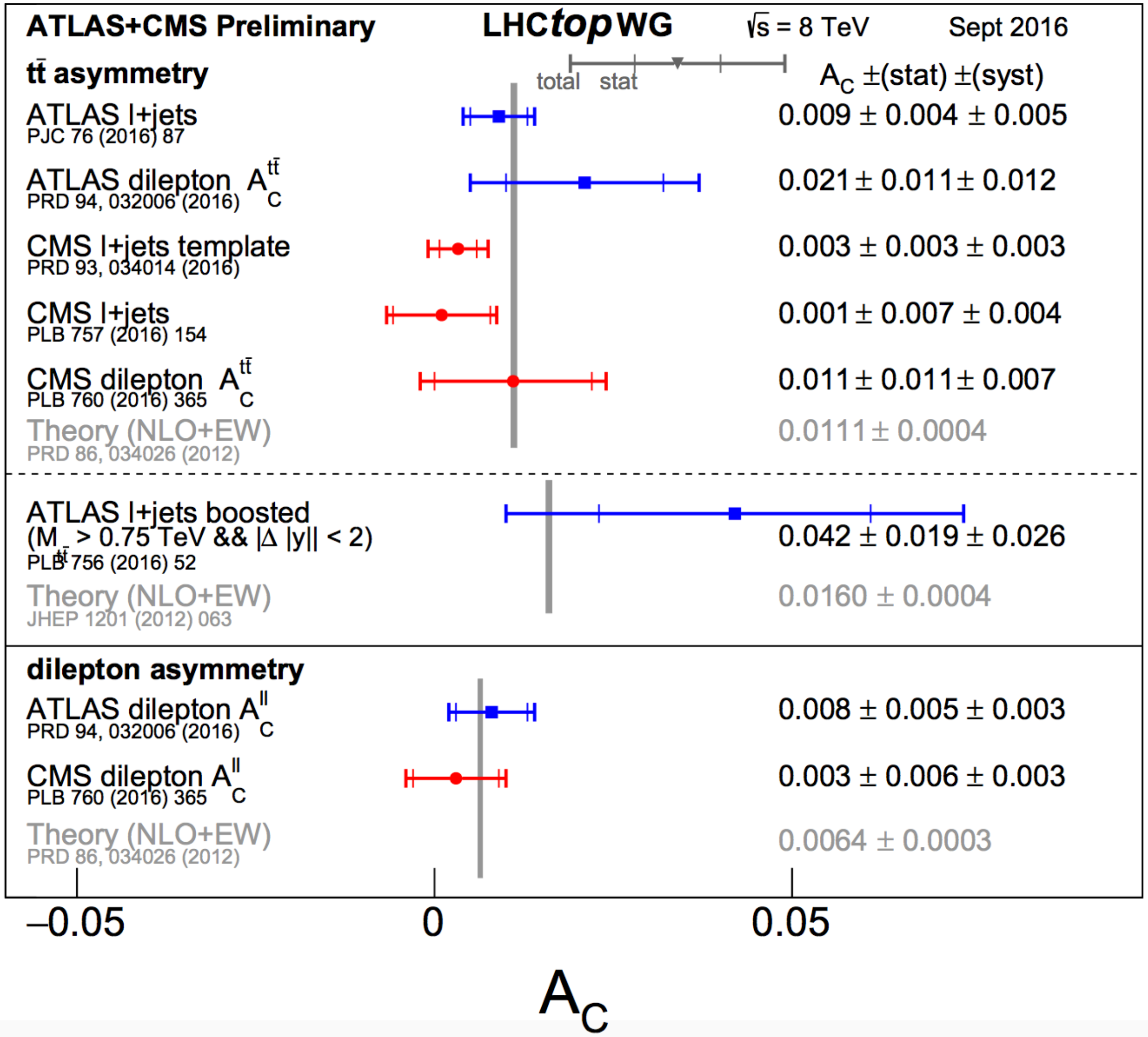




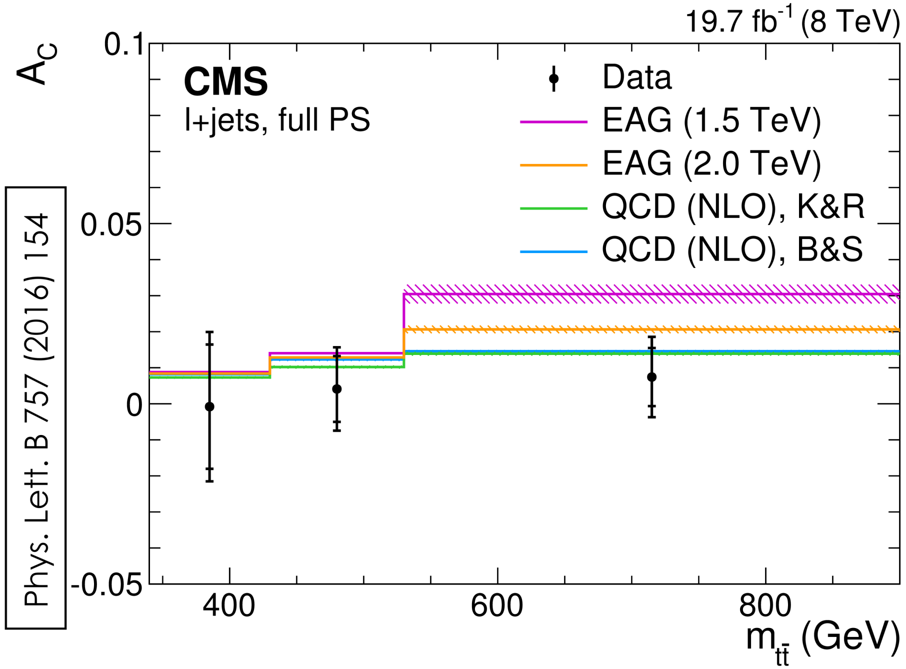
			1	2	4	16	75
			2	4	14	53	15
	1	2	5	15	52	20	5
1	3	6	19	53	21	7	2
2	6	20	53	19	6	2	1
5	20	52	15	5	2	1	
15	53	14	4	2			
74	16	4	2	1			

Phys. Lett. B 756, 52 (2016) 756

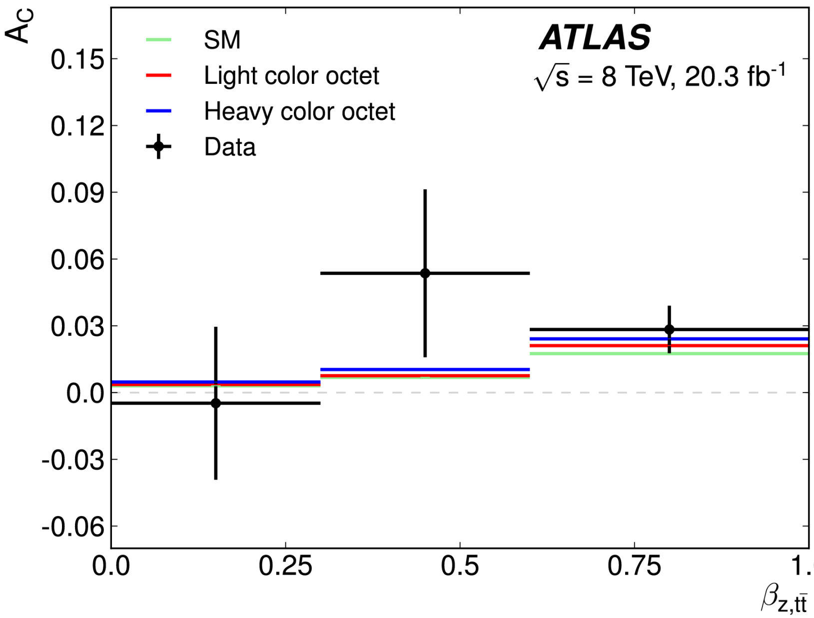
CHARGE ASYMMETRY MEASUREMENTS



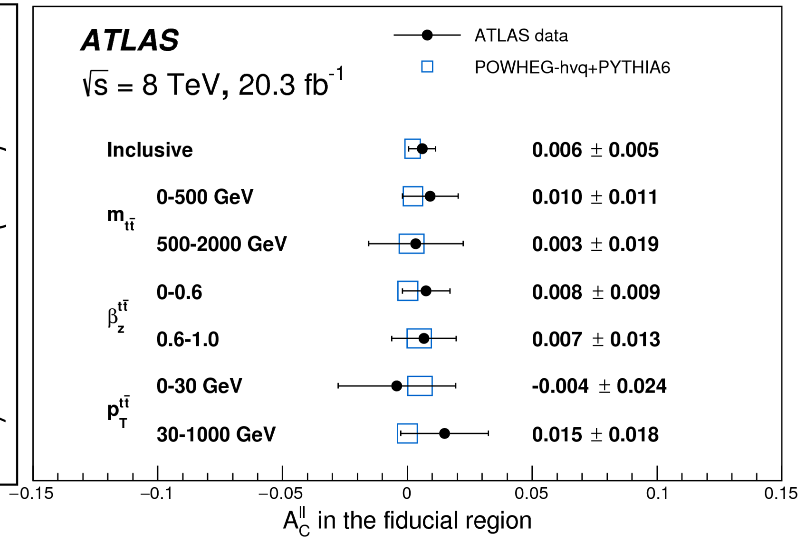
CHARGE ASYMMETRY MEASUREMENTS



Phys. Lett. B 757 (2016) 154



Eur. Phys. J. C76 (2016) 87



Phys. Rev. D 94 (2016) 032996

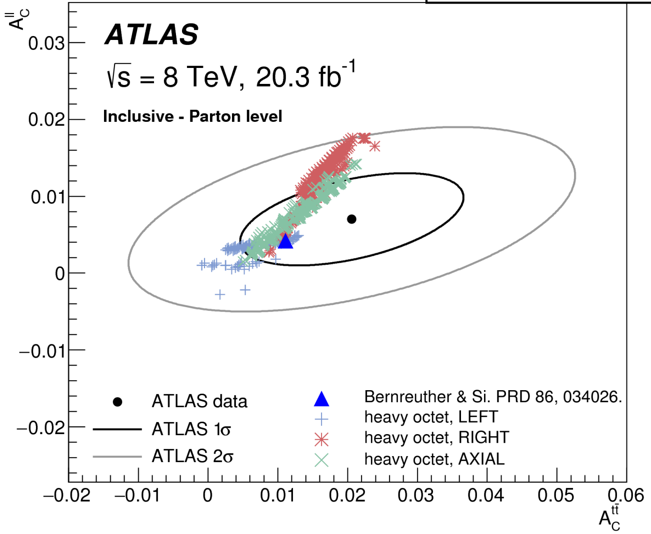
- Precision dominated by statistical uncertainty.
- All compatible with SM predictions.

CONSTRAINTS IN NEW PHYSICS – BSM MODELS

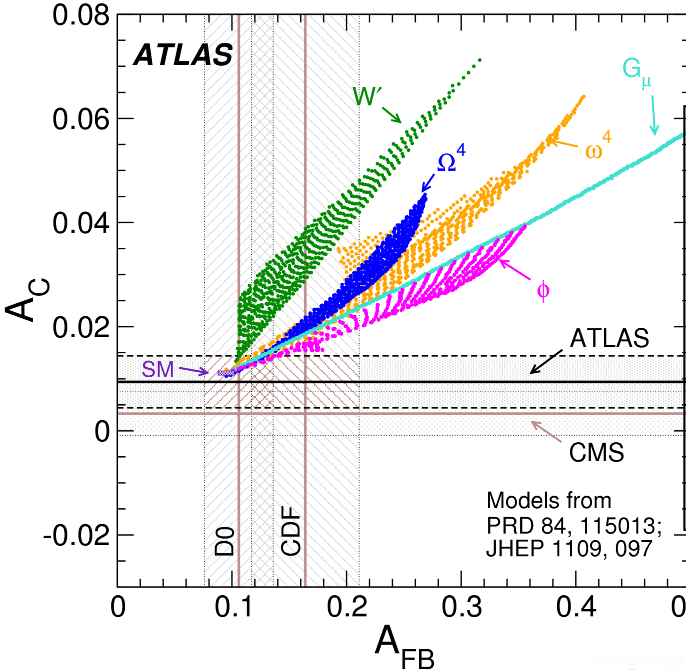
- Measurements can be used to constrain specific BSM models or couplings within EFT.

Dilepton analysis

Phys. Rev. D 94 (2016) 032996

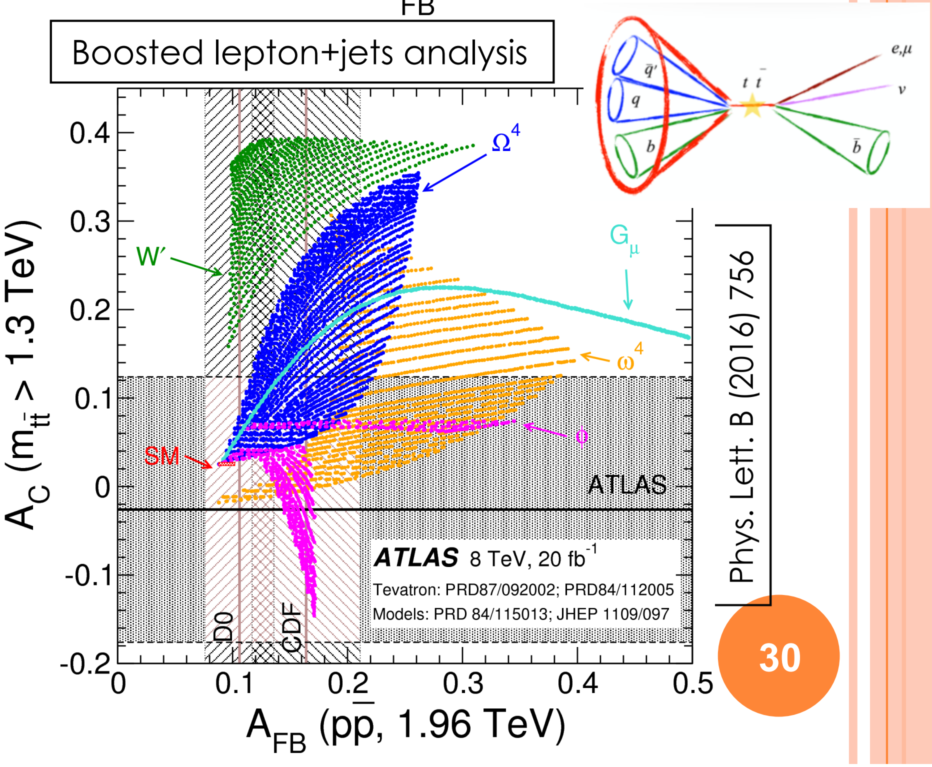


Standard l+jets analysis



Eur. Phys. J. C76 (2016) 87

Boosted lepton+jets analysis

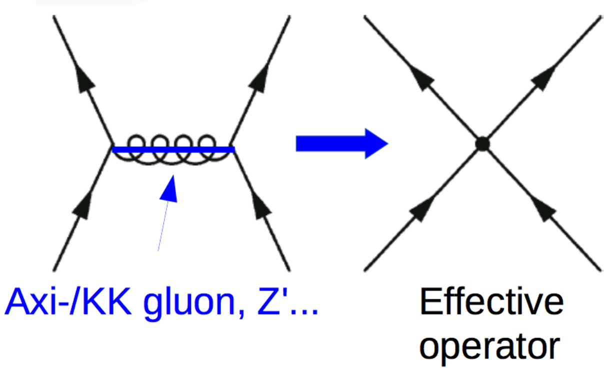


Phys. Lett. B (2016) 756

- Limits set on the parameters (i.e. mass and couplings) of BSM models .
- Measurement in events where top quark pairs are produced with large invariant mass (> 750 GeV) have a higher sensitivity for the SM asymmetry and BSM models that introduce massive new states.

CONSTRAINTS ON NEW PHYSICS - EFT

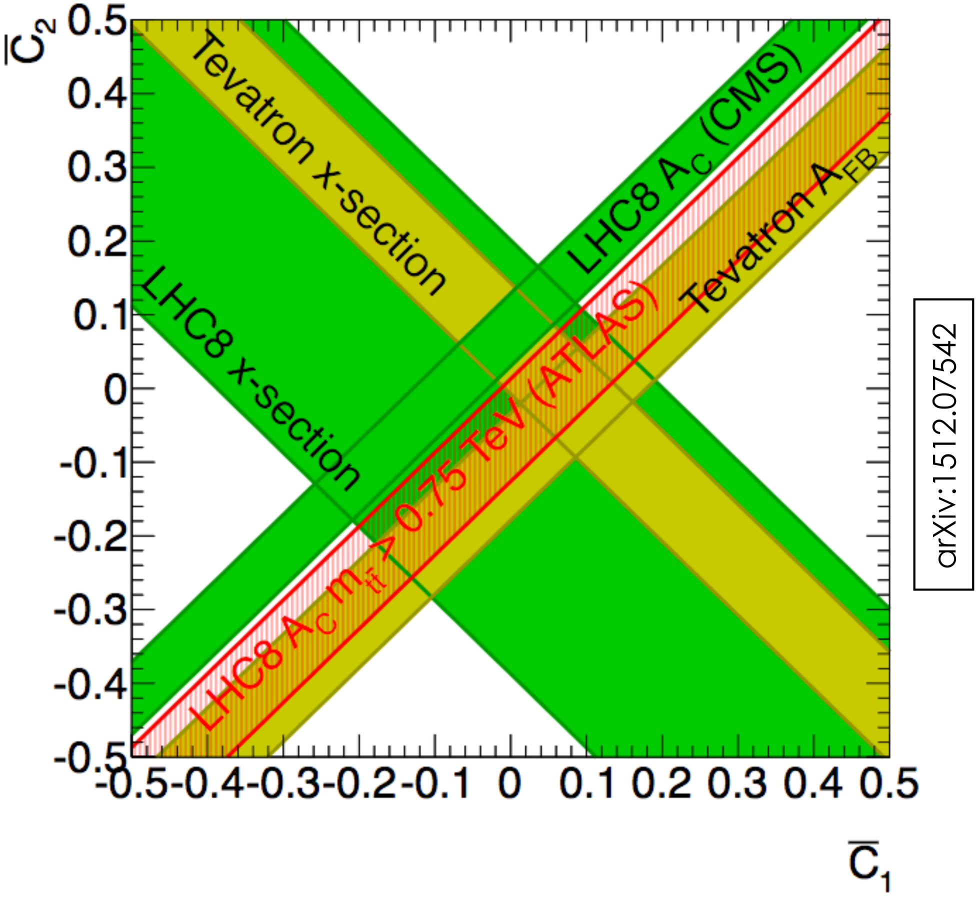
- The charge asymmetry in hadron colliders is sensitive to BSM 4-fermion interactions.
- A fit to a combination of Tevatron and LHC measurements leads to stringent limits on the linear combinations of C_1 and C_2 of the 4-fermion effective operators (assuming equal coefficients for the operators involving u-type and d-type quarks).



$$C_u^1 = C_{qq}^{(8,1)} + C_{qq}^{(8,3)} + C_{ut}^{(8)}$$
$$C_u^2 = C_{qu}^{(1)} + C_{qt}^{(1)}$$
$$C_d^1 = C_{qq}^{(8,1)} - C_{qq}^{(8,3)} + C_{dt}^{(8)}$$
$$C_d^2 = C_{qd}^{(1)} + C_{qt}^{(1)}$$

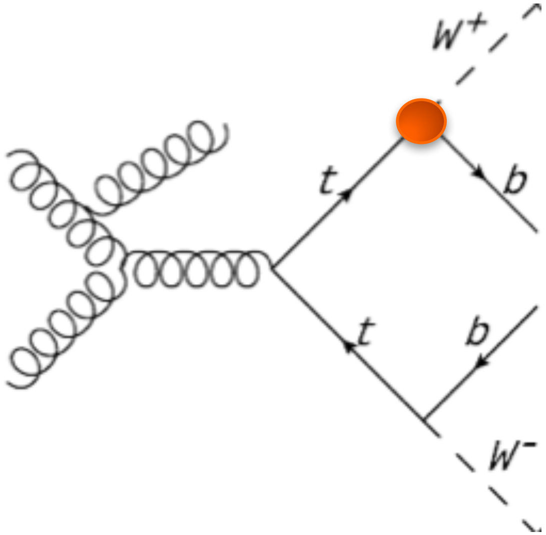
$$C_u^1 = C_d^1 = C^1 \text{ and } C_u^2 = C_d^2 = C^2$$

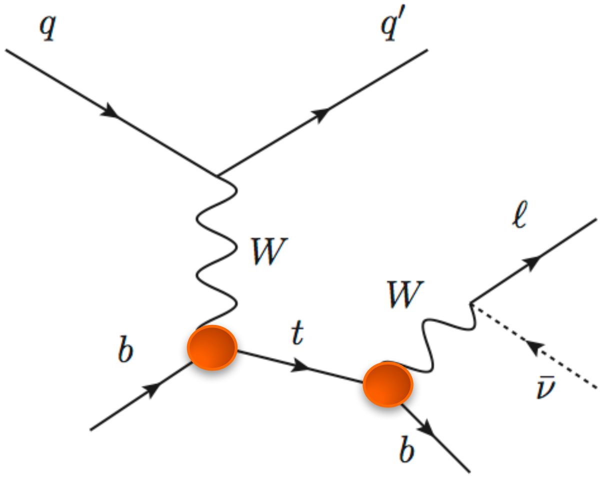
$$\bar{C}_i \; = \; C_i \times v^2/\Lambda^2$$



TOP COUPLING TO W BOSON

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





<u>Measurements available:</u>

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

V_{tb} measurements

- W helicity (ttbar, t-channel)
- W spin observables in t-channel
- Top polarisation in t-channel
- Differential angular decay rates

Constraints on Wtb anomalous couplings within EFT

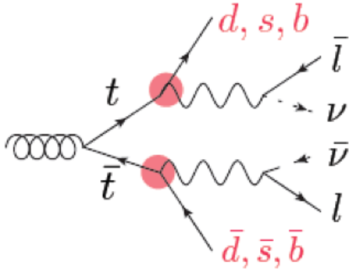
V_{tb} MEASUREMENTS

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

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)

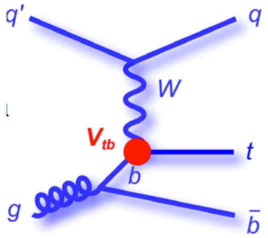
$$\boxed{|V_{tb}| = 1.007 \pm 0.016 \text{ (stat.+syst.)}}$$

From single top cross section

Assuming:

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

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

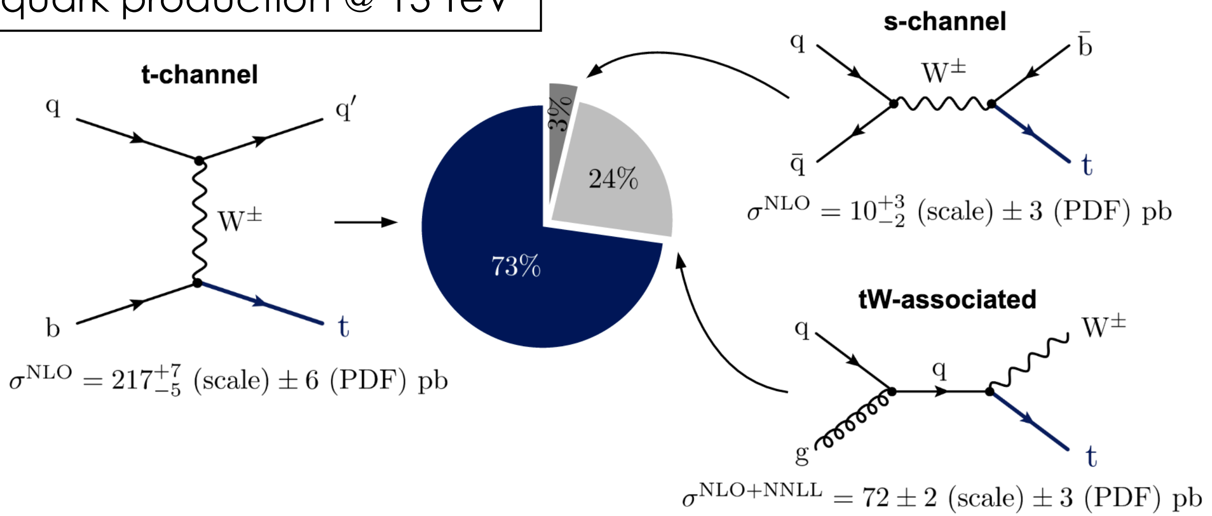


$$|V_{tb}| = \sqrt{\frac{\sigma_{meas}}{\sigma_{theo}}}$$

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

SINGLE TOP CROSS SECTION

Single top quark production @ 13 TeV



$\sigma^{\mathrm{NLO}} = 217^{+7}_{-5}\ (\mathrm{scale}) \pm 6\ (\mathrm{PDF})\ \mathrm{pb}$

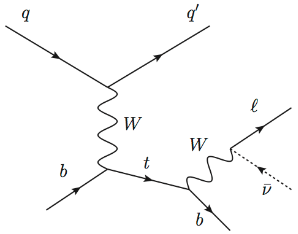
$\sigma^{\mathrm{NLO}} = 10^{+3}_{-2}\ (\mathrm{scale}) \pm 3\ (\mathrm{PDF})\ \mathrm{pb}$

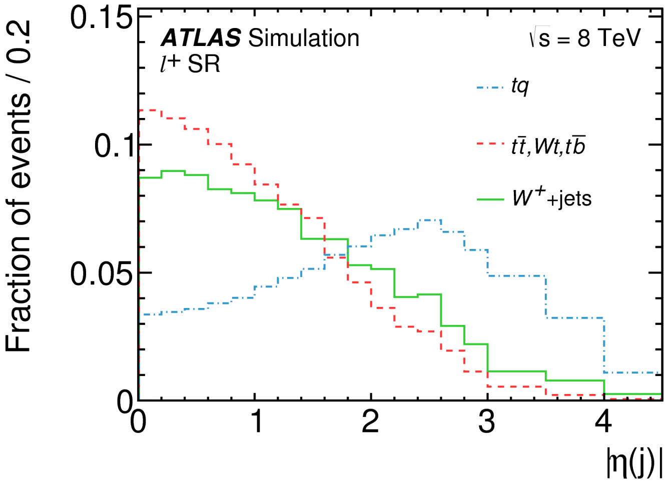
$\sigma^{\mathrm{NLO+NNLL}} = 72 \pm 2\ (\mathrm{scale}) \pm 3\ (\mathrm{PDF})\ \mathrm{pb}$

- Golden t-channel:
  - Has the largest cross section.
  - Has the largest S/B.
  - First observed at the Tevatron in 2009.
  - Precise measurements at the LHC at 7, 8 and 13 TeV: Inclusive, fiducial, top/anti-top cross section ratios and differential measurements.
- tW-channel:
  - First observed at the LHC using 8 TeV data.
- s-channel:
  - Observed at Tevatron.
  - First evidence observed at LHC using the 8 TeV dataset.

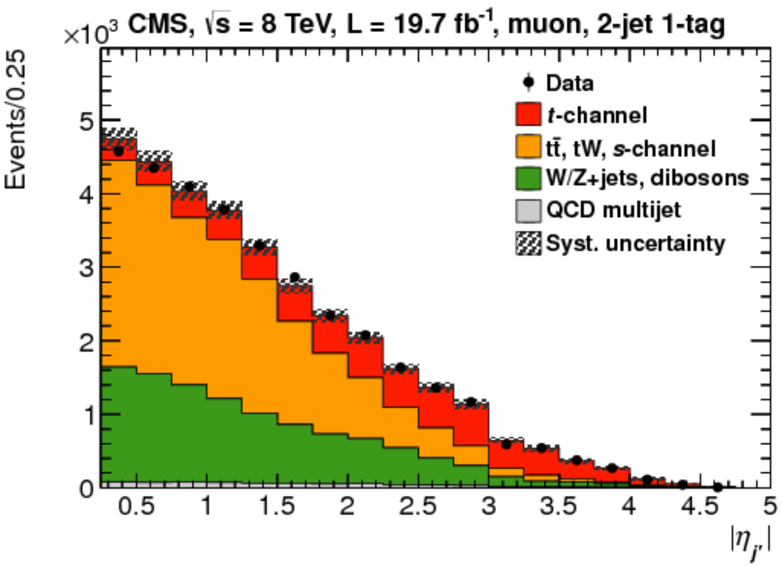
SINGLE TOP CROSS SECTION

Ex: t-channel @ 8 TeV

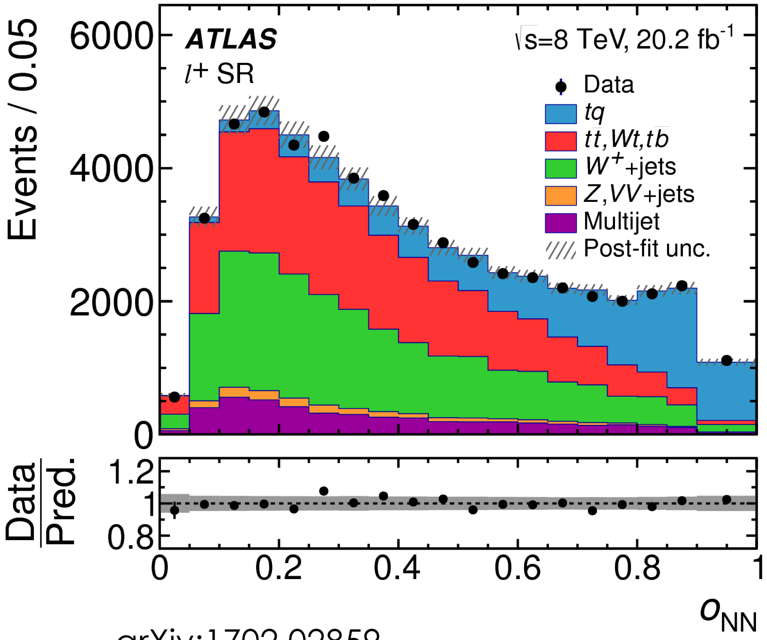




- Typically use multivariate techniques (NN, BDT): Optimise S/B separation using full event properties, constrain systematic effects by simultaneously analysing S and B dominated regions.



JHEP 06 (2014) 090

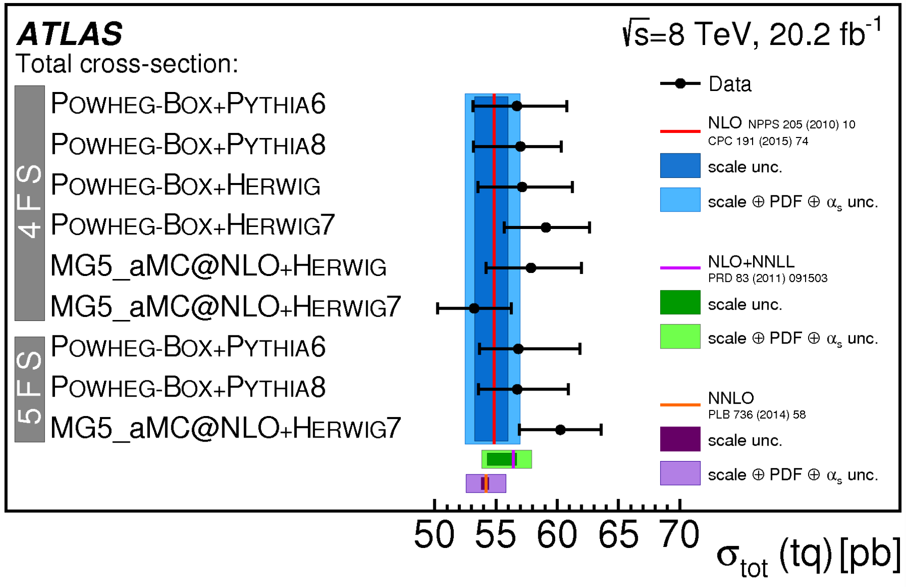


arXiv:1702.02859

SINGLE TOP CROSS SECTION

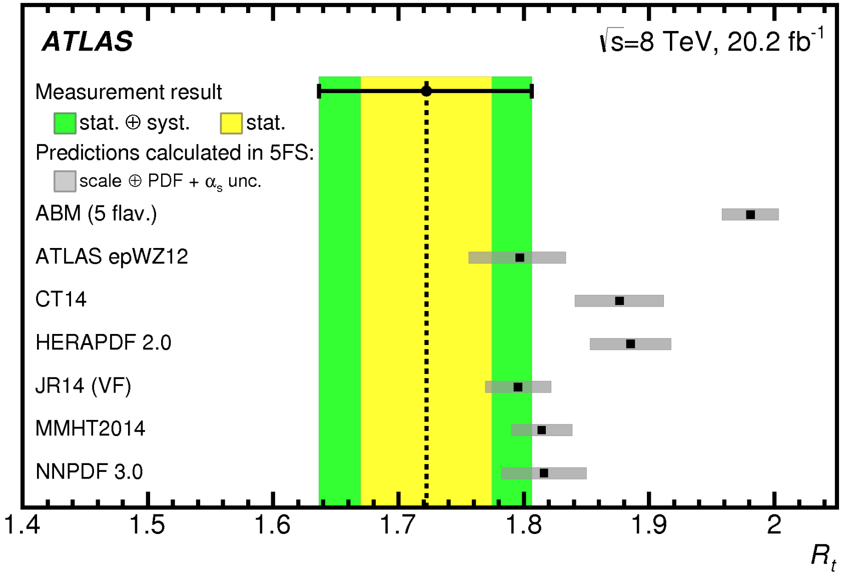
- ATLAS, @ 8 TeV provides the measurement in a fiducial region (with reduced systematics) and then extrapolates to the full phase space using different MC generators.

$$\sigma_{\rm tot} = \frac{N_{\rm tot}}{N_{\rm fid}}.\sigma_{\rm fid}$$



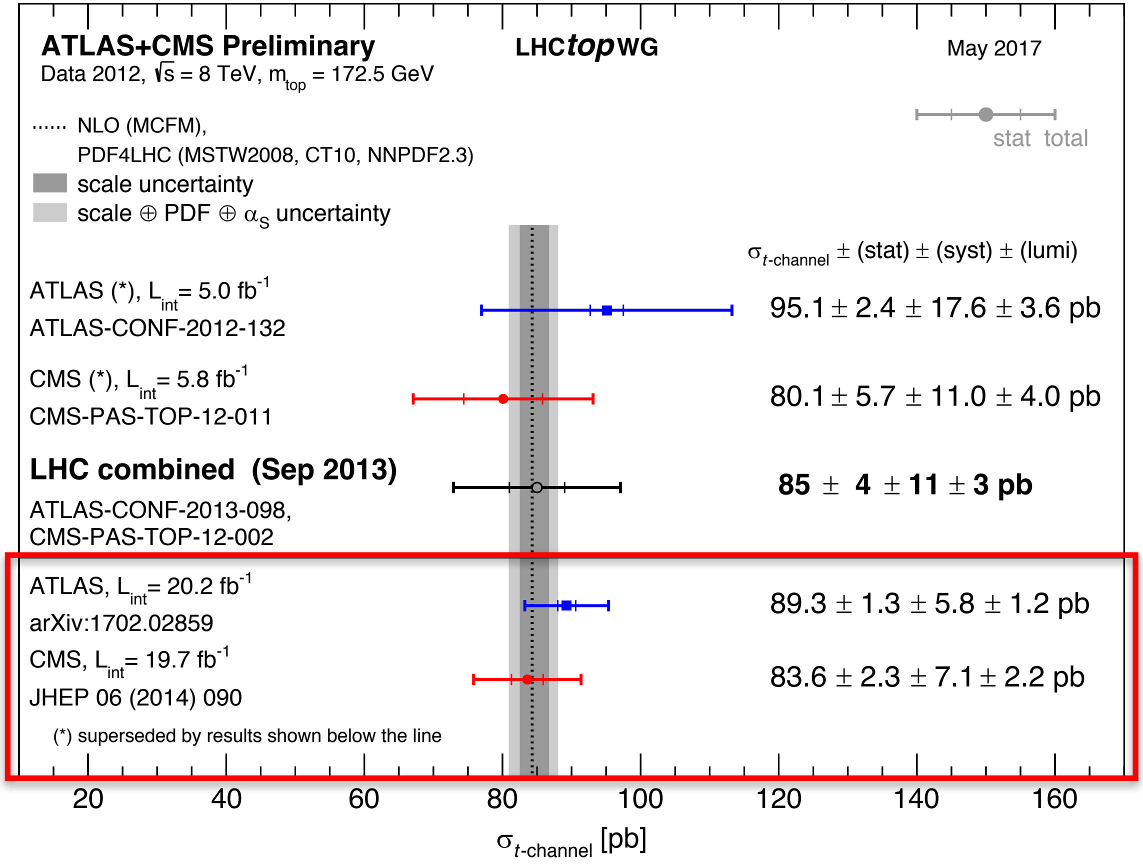
- The measured value of the top/anti-top cross section compatible with most PDF sets.

$$R_t = \frac{\sigma_{\rm tot}(tq)}{\sigma_{\rm tot}(\bar{t}q)} = 1.72 \pm 0.05\,(\text{stat.})\ \pm 0.07\,(\text{exp.}) = 1.72 \pm 0.09.$$



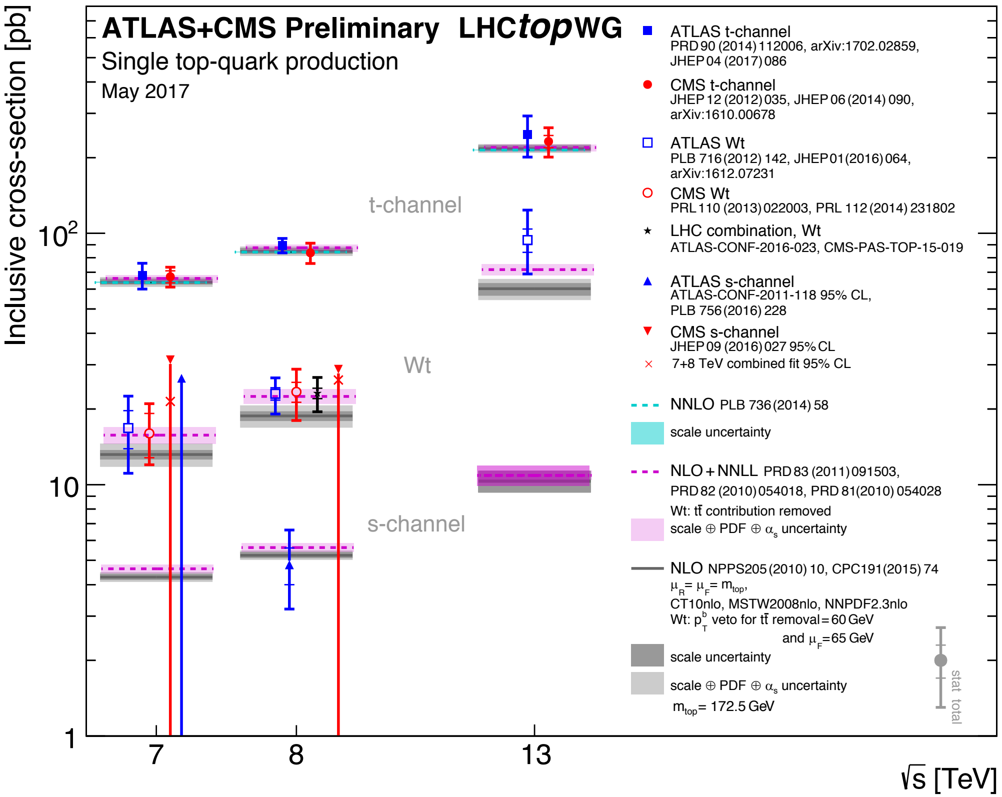
SINGLE TOP CROSS SECTION

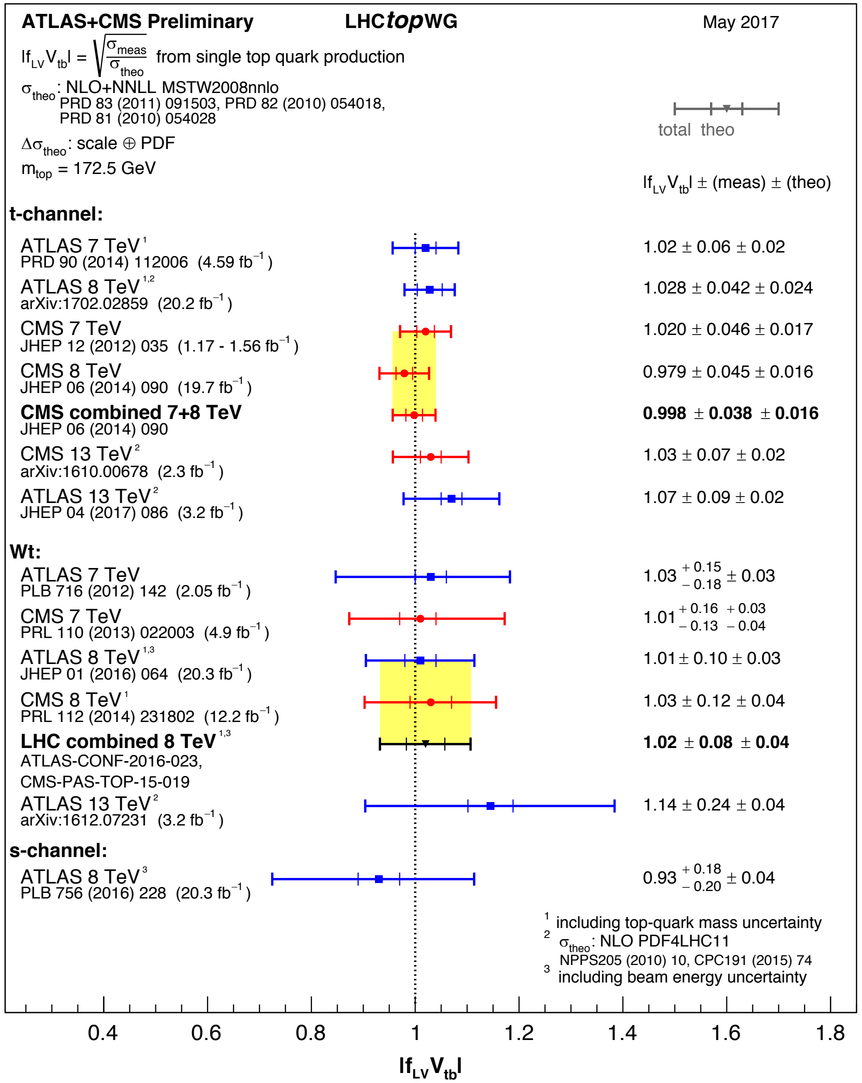
Ex: t-channel @ 8 TeV



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.

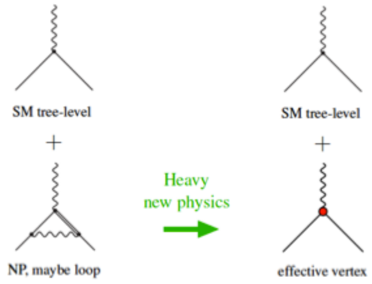
Most precise individual measurement from ATLAS 8 TeV (4.7%).

Combination of all Run-1 results ongoing.

Wtb ANOMALOUS COUPLINGS

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

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



SM at tree level →

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

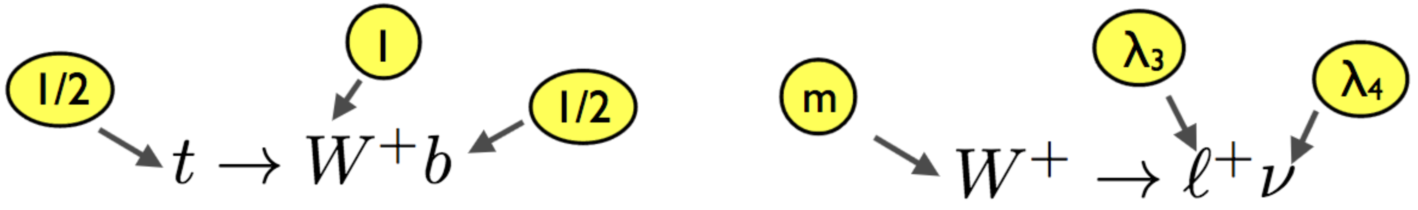
New physics can affect:

- Total single top cross section

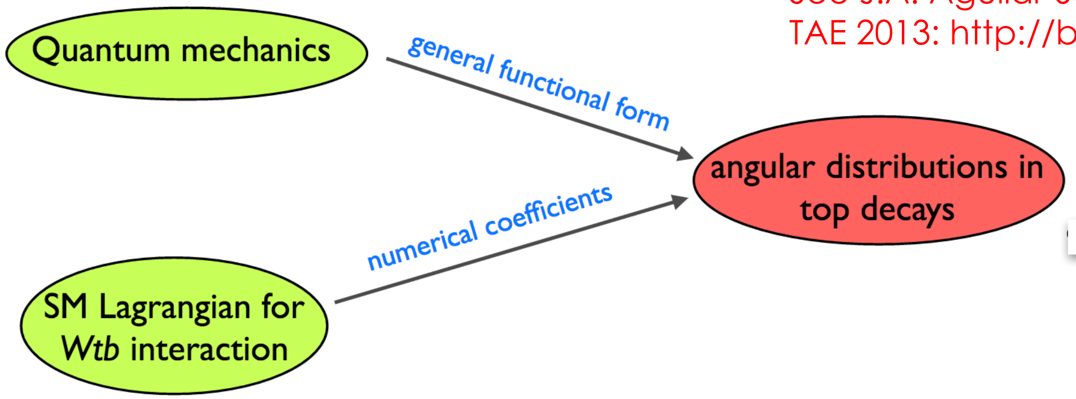
$$\sigma \;=\; \sigma_{\rm SM}\left(V_L^2 + \kappa^{V_R}\,V_R^2 + \kappa^{V_L V_R}\,V_L V_R + \kappa^{g_L}\,g_L^2 + \kappa^{g_R}\,g_R^2 + \kappa^{g_L g_R}\,g_L g_R + \ldots\right)$$

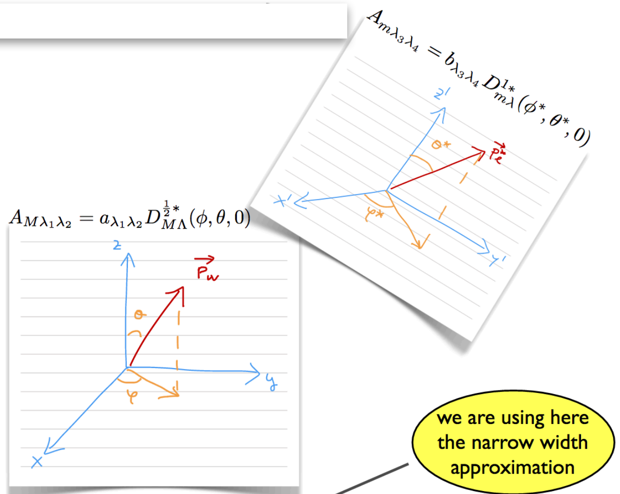
- Top polarisation in single top production (via asymmetries)
- W polarisation observables (via asymmetries)
- Differential angular decay rates.

WITHIN THE STANDARD MODEL



See J.A. Aguilar-Saavedra
TAE 2013: http://benasque.org/2013tae/talks_contr/231_top.pdf





we are using here the narrow width approximation

Using the helicity formalism of Jacob and Wick

$$A_{M\lambda_2\lambda_3\lambda_4} = \sum_{\lambda_1} a_{\lambda_1\lambda_2} b_{\lambda_3\lambda_4} D^{\frac{1}{2}*}_{M\Lambda}(\phi,\theta,0) D^{1*}_{\lambda_1\lambda}(\phi^*,\theta^*,0)$$

The angular dependence is given by the well known Wigner D functions.

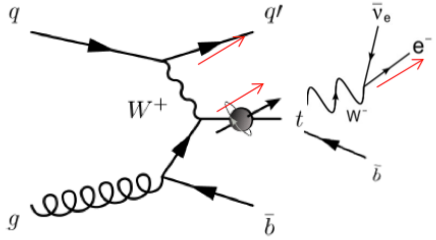
BSM corrections to the Wtb vertex will modify the t→ Wb→ lν angular distributions.

2 approaches: Measure asymmetries of angular distributions or measure the differential angular decay rate.

TOP POLARISATION IN SINGLE TOP PRODUCTION

- In the t-channel, top quark is produced with a large degree of polarisation in the direction of spectator quark momentum (Phys. Rev. D55 (1997) 7249) .
- This direction is used to define the top quark spin axis.
- Can be measured from angular distributions of the decay products reconstructed in the top quark rest frame.

$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_X)} = \frac{1}{2}(1 + \alpha_X P \cos\theta_X)$$



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

$$\alpha_{\ell^\pm} = \pm 0.998$$

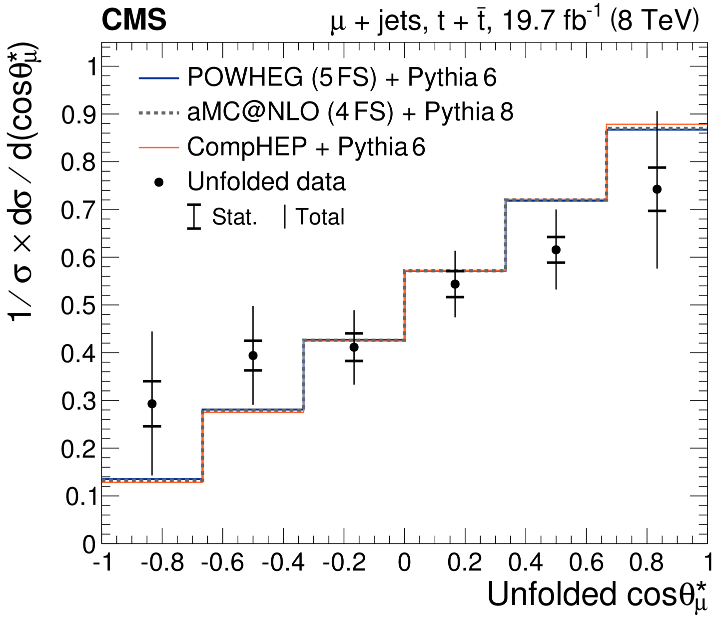
$$A^{\ell}_{\mathrm{FB}} = \frac{1}{N}[N(\cos\theta_\ell > 0) - N(\cos\theta_\ell < 0)] = \frac{1}{2}\alpha_\ell P$$

- Other asymmetries also proposed in Phys. Rev. Lett. B 718 (2013) 983, arXiv1404.1585.

TOP POLARISATION IN SINGLE TOP PRODUCTION

- CMS has measured one asymmetry and finds some tension with the SM prediction (2σ).

JHEP 04 (2016) 073

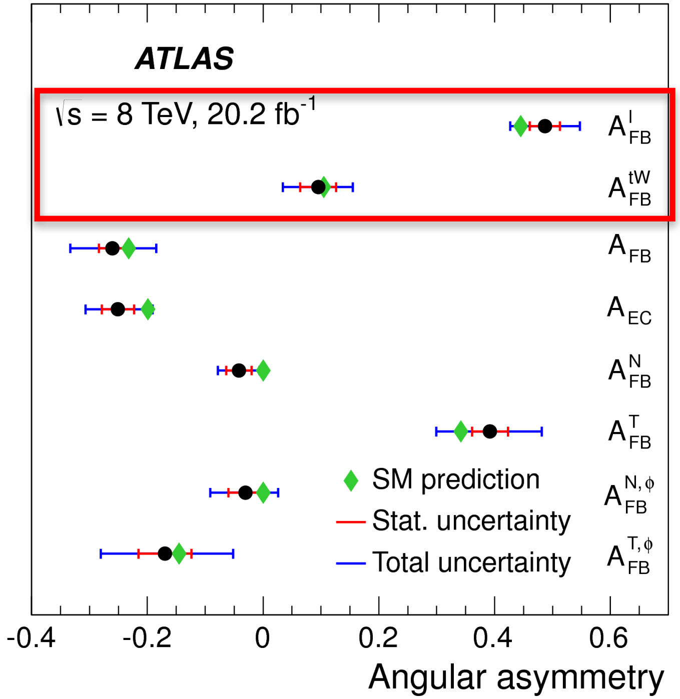


$$A_\mu(t+\bar{t}) = 0.28 \pm 0.03\,(\text{stat}) \pm 0.1\,(\text{syst}) = 0.28 \pm 0.12.$$

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

- ATLAS measured more precisely two asymmetries sensitive to P and finds results compatible with SM.

JHEP 04 (2017) 124



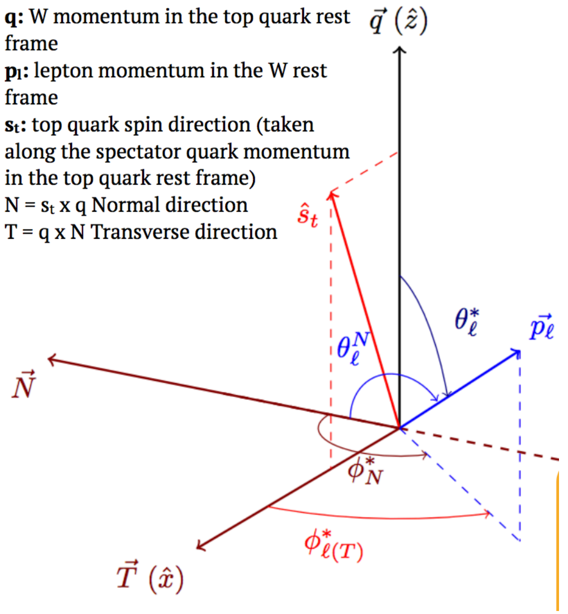
$$\alpha_\ell P = 0.97 \pm 0.05\ (\text{stat.}) \pm 0.11\ (\text{syst.}) = 0.97 \pm 0.12$$

$$P(F_R + F_L) = 0.25 \pm 0.08\ (\text{stat.}) \pm 0.14\ (\text{syst.}) = 0.25 \pm 0.16$$

W BOSON SPIN OBSERVABLES

- They can be determined from angular distributions of the charged lepton reconstructed in the W rest frame.
- The spin density matrix elements for the W components 0, +1-1 from the decay of polarised top quarks can be parametrised in terms of 6 independent observables $<S_{1,2,3}>$, $<T_0>$, $<A_{1,2}>$ which can be measured via asymmetries (Nucl.Phys.B840(2010) 349, Phys. Rev. D 93 (2016) 01301).
- For un-polarised top quark decays, the only meaningful direction in the top quark rest frame is the one of the W boson momentum → $\cos\theta_l^*$ → Helicity fractions F_0, F_R, F_L

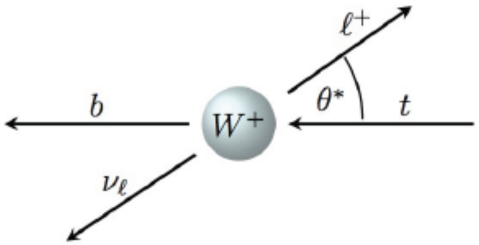
- **q:** W momentum in the top quark rest frame
- **p$_l$:** lepton momentum in the W rest frame
- **s$_t$:** top quark spin direction (taken along the spectator quark momentum in the top quark rest frame)
- N = s_t x q Normal direction
- T = q x N Transverse direction



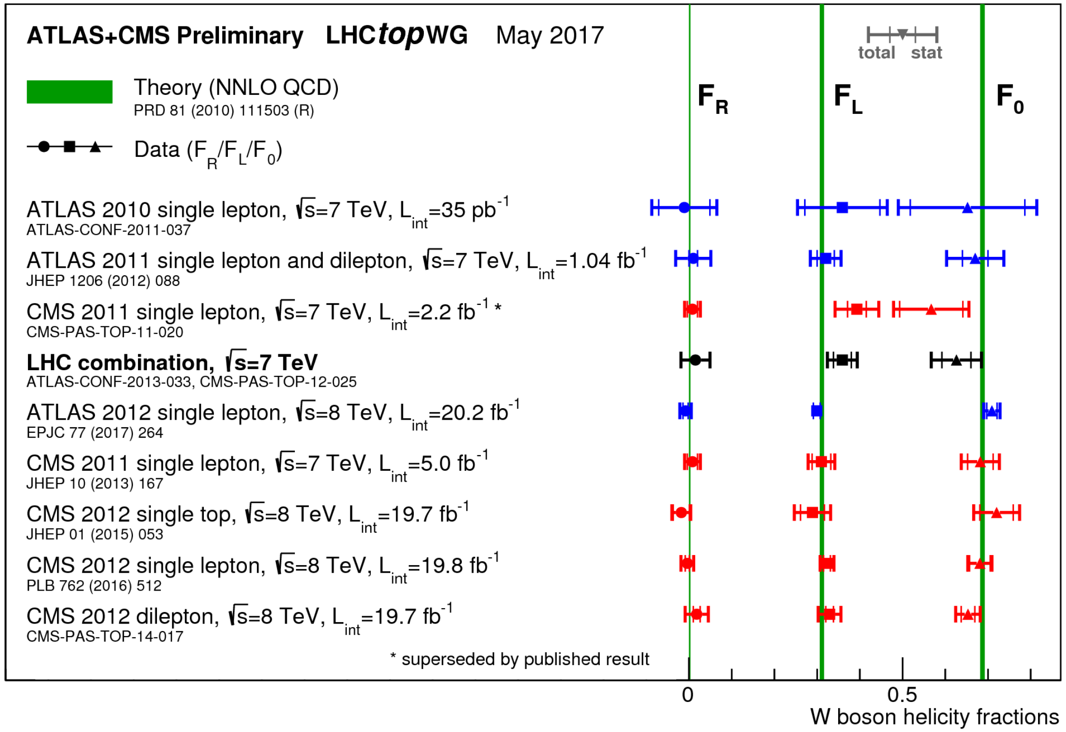
Asymmetry	Angular observable	Polarisation observable	SM prediction
$A_{\rm FB}$	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3\rangle = \frac{3}{4}(F_{\rm R} - F_{\rm L})$	−0.23
$A_{\rm EC}$	$\cos\theta_\ell^*$	$\frac{3}{8}\sqrt{\frac{3}{2}}\langle T_0\rangle = \frac{3}{16}(1 - 3F_0)$	−0.20
$A_{\rm FB}^T$	$\cos\theta_\ell^T$	$\frac{3}{4}\langle S_1\rangle$	0.34
$A_{\rm FB}^N$	$\cos\theta_\ell^N$	$-\frac{3}{4}\langle S_2\rangle$	0
$A_{\rm FB}^{T,\phi}$	$\cos\theta_\ell^*\cos\phi_T^*$	$-\frac{2}{\pi}\langle A_1\rangle$	−0.14
$A_{\rm FB}^{N,\phi}$	$\cos\theta_\ell^*\cos\phi_N^*$	$\frac{2}{\pi}\langle A_2\rangle$	0

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

W HELICY FRACTIONS FROM TOP PAIRS



- Top quarks are not polarised → W helicity fractions measured.
- Measurements performed at 7 and 8 TeV by ATLAS and CMS in the lepton+jets and dilepton channels.
- Most precise measurement from ATLAS at 8 TeV lepton+jets.

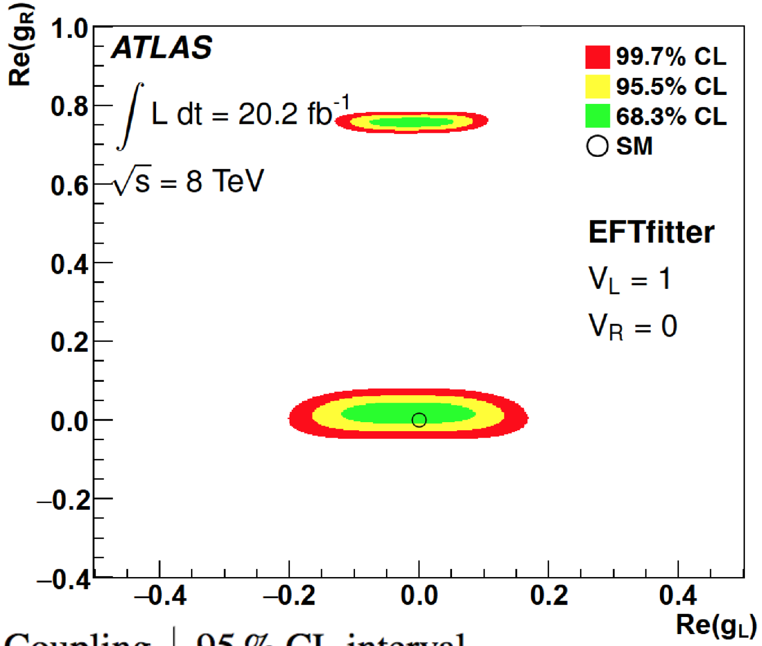


All measurements consistent with SM expectations, leading to constraints on the real part of V_R, g_L and g_R.

W HELICY FRACTIONS FROM TOP PAIRS

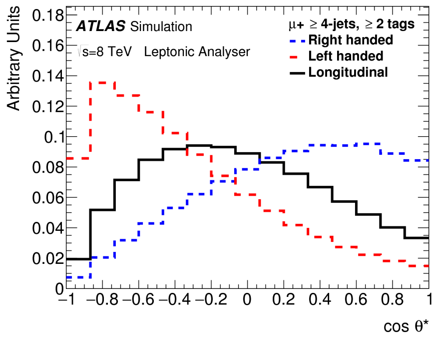
Ex: ATLAS lepton+jets @ 8 TeV

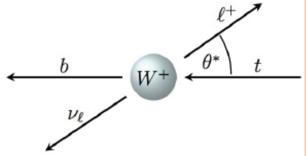
Eur. Phys. J. C. 77 (2017) 264

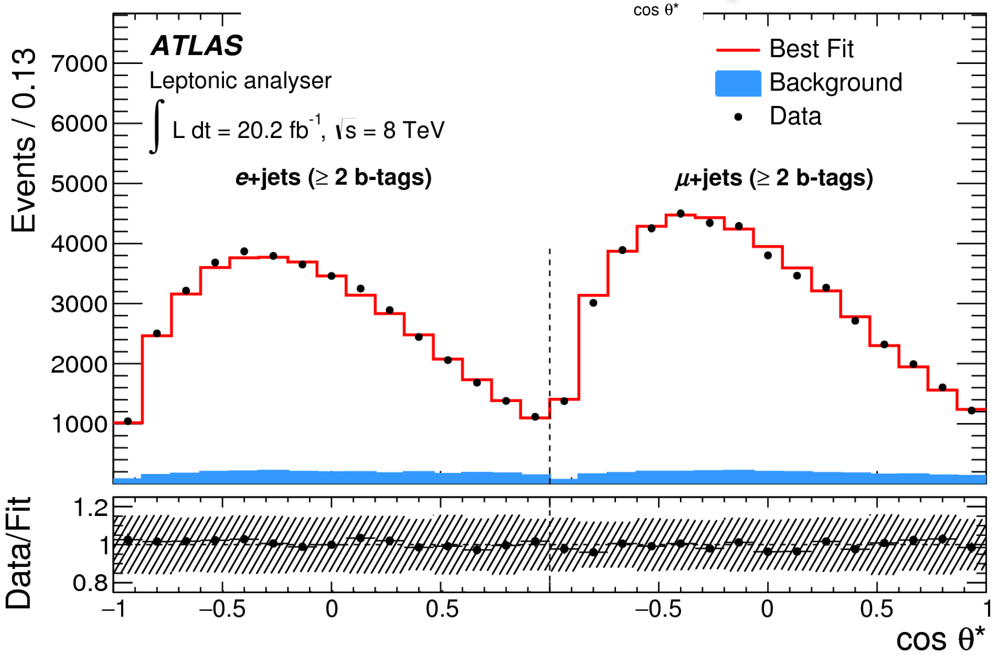


Coupling	95 % CL interval
V_R	$[-0.24, 0.31]$
g_L	$[-0.14, 0.11]$
g_R	$[-0.02, 0.06], [0.74, 0.78]$

(assuming SM couplings for the others)







- Fit of the templates to data → W helicity fractions.

$$F_0 = 0.709 \pm 0.012\ \text{(stat.+bkg. norm.)}\ ^{+0.015}_{-0.014}\ \text{(syst.)}$$

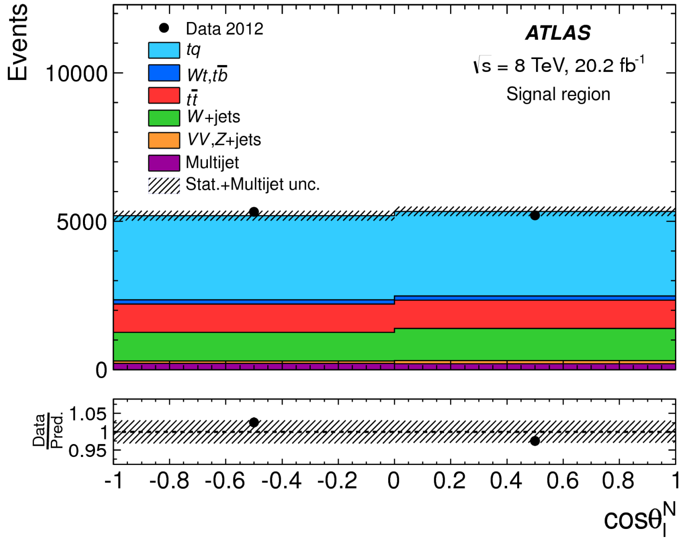
$$F_L = 0.299 \pm 0.008\ \text{(stat.+bkg. norm.)}\ ^{+0.013}_{-0.012}\ \text{(syst.)}$$

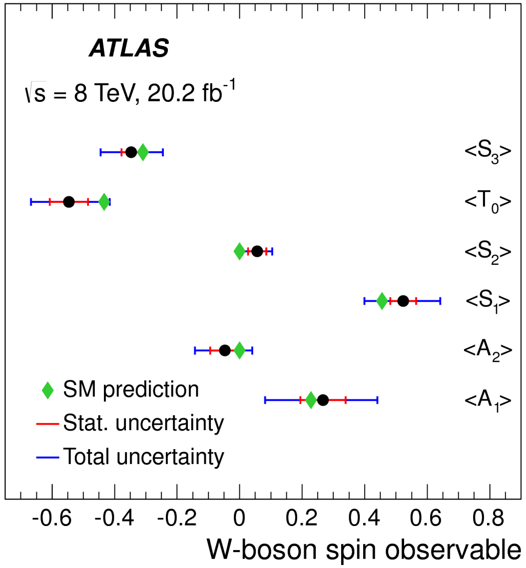
$$F_R = -0.008 \pm 0.006\ \text{(stat.+bkg. norm.)} \pm 0.012\ \text{(syst.)}$$

- The anomalous couplings are assumed to be real.
- W helicity measurements allow to constrain ratios of couplings.
- The individual limits depend on assumptions made about other couplings.

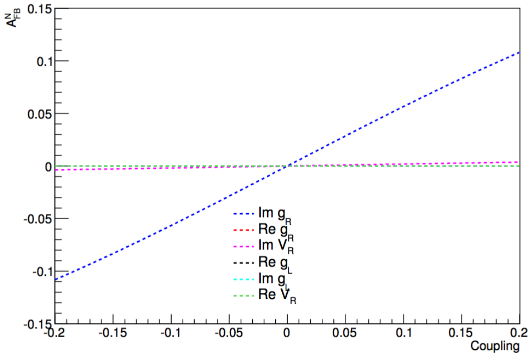
W SPIN OBSERVABLES IN t-CHANNEL SINGLE TOP

- Top quarks are polarised → sensitivity to complex phases of the anomalous couplings (CP violation effects).





JHEP 04 (2017) 124



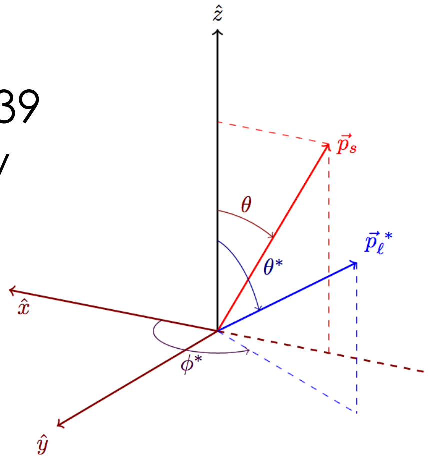
$$\left.\begin{aligned} A^N_{FB} &\approx 0.64 P \mathrm{Im} g_R \\ A^l_{FB} &= \frac{1}{2}\alpha_l P \end{aligned}\right\} \mathrm{Im}\, g_\mathrm{R} \in [-0.18,\ 0.06] \text{ at 95\% CL.}$$

All measurements in agreement with SM predictions.

First constraints on imaginary part of gR (assuming SM values for all other couplings).

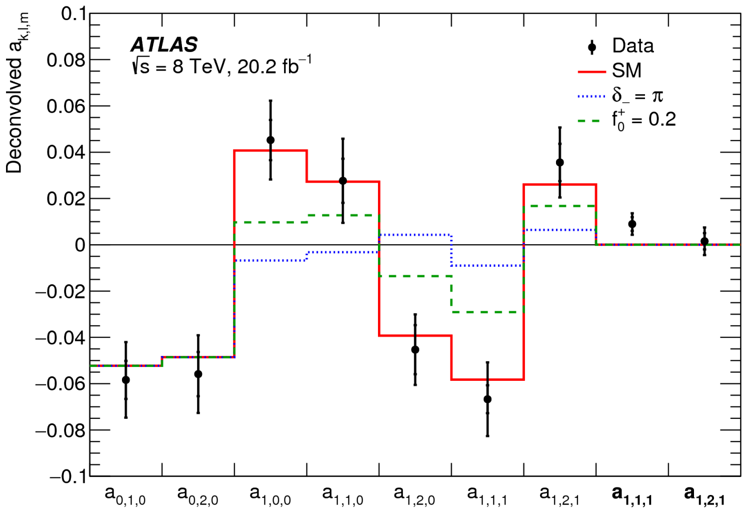
TRIPLE DIFFERENTIAL ANGULAR DECAY RATE

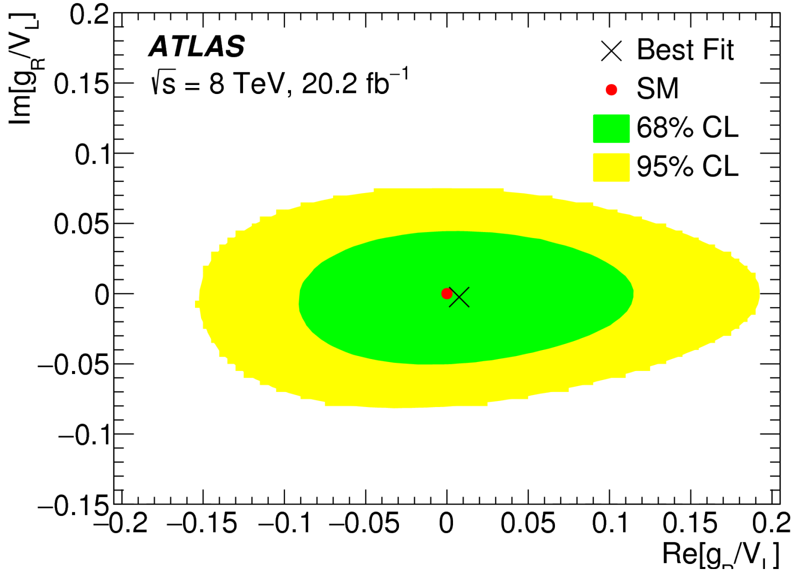
- A more complete approach was proposed in arXiv:1304.5639 to simultaneously constrain the full Wtb parameter space by measuring the triple-differential decay rate.



$$
\begin{aligned}
\varrho(\theta,\theta^*,\phi^*;P) = \frac{1}{N}\frac{\mathrm{d}^3N}{\mathrm{d}(\cos\theta)\mathrm{d}\Omega^*} \quad &= \quad \frac{1}{8\pi}\left\{\frac{3}{4}\left|A_{1,\frac{1}{2}}\right|^2(1+P\cos\theta)(1+\cos\theta^*)^2\right.\\
&+ \quad \frac{3}{4}\left|A_{-1,-\frac{1}{2}}\right|^2(1-P\cos\theta)(1-\cos\theta^*)^2\\
&+ \quad \frac{3}{2}\left(\left|A_{0,\frac{1}{2}}\right|^2(1-P\cos\theta)+\left|A_{0,-\frac{1}{2}}\right|^2(1+P\cos\theta)\right)\sin^2\theta^*\\
&- \quad \frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1+\cos\theta^*)\,\mathrm{Re}\left[e^{i\phi^*}A_{1,\frac{1}{2}}\,A^*_{0,\frac{1}{2}}\right]\\
&- \quad \left.\frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1-\cos\theta^*)\,\mathrm{Re}\left[e^{-i\phi^*}A_{-1,-\frac{1}{2}}\,A^*_{0,-\frac{1}{2}}\right]\right\}\\
&= \quad \sum_{k=0}^{1}\sum_{l=0}^{2}\sum_{m=-k}^{k} a_{k,l,m}M^m_{k,l}(\theta,\theta^*,\phi^*)\,,
\end{aligned}
$$

arXiv:1707.05393





$$
\mathrm{Re}\left[\frac{g_\mathrm{R}}{V_\mathrm{L}}\right] \in [-0.12, 0.17] \quad \text{and} \quad \mathrm{Im}\left[\frac{g_\mathrm{R}}{V_\mathrm{L}}\right] \in [-0.07, 0.06]\,, \text{at 95\% CL}
$$

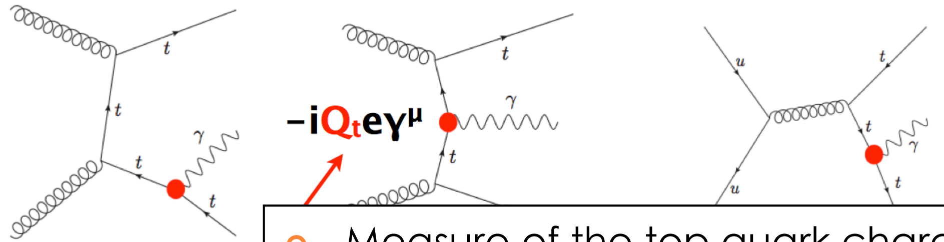
Couplings are allowed to be complex.

No assumptions made regarding the other couplings.

TOP COUPLING TO PHOTON

Effective Lagrangian parametrising new physics effects:

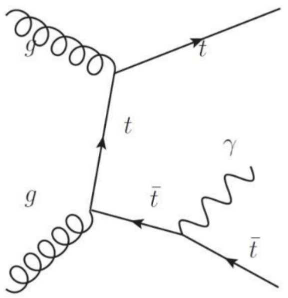
$$\mathcal{L}_{\gamma tt} = -eQ_t\bar{t}\,\gamma^\mu t\, A_\mu - e\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\,(d_V^\gamma + i d_A^\gamma\gamma_5)\,t\, A_\mu$$



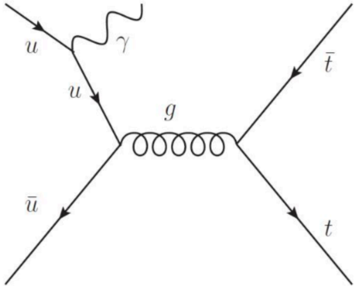
- Measure of the top quark charge.
- Can probe the tγ electroweak coupling.
- Deviations from SM could point to new physics through anomalous dipole moments of the top quark.

- Photons can be emitted from the top quark, top decay products or ISR, but the selection enhances photons emitted by top quarks.

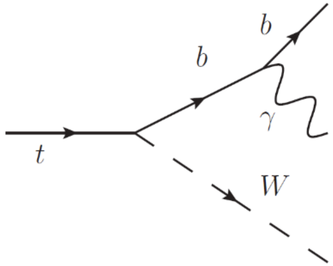
from top quarks



from incoming partons

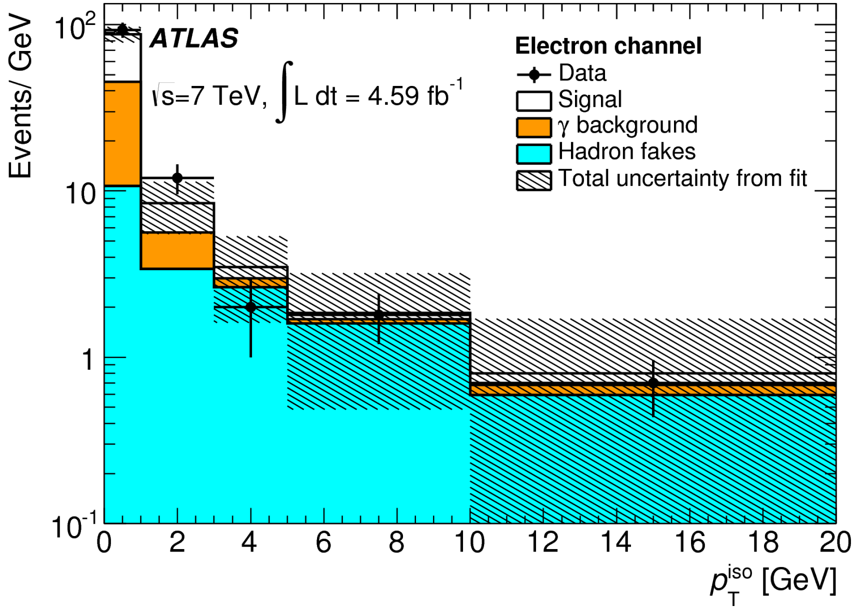


from top decay products

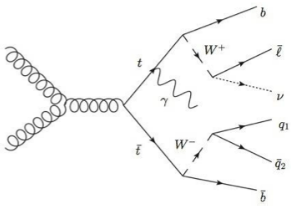


tt+ γ PRODUCTION MEASUREMENTS

- First observation with 7 TeV data by the ATLAS experiment:
  - Observation with 5.3 σ
  - Systematic limited.
  - Fiducial cross section measured in good agreement with SM predictions (48 ± 10 fb).



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)

New measurements from ATLAS and CMS at 8 TeV now available.

- Selecting ttbar lepton+jets events with an additional photon.
- Fiducial cross section.
- First differential measurements from ATLAS in photon p_T and η.

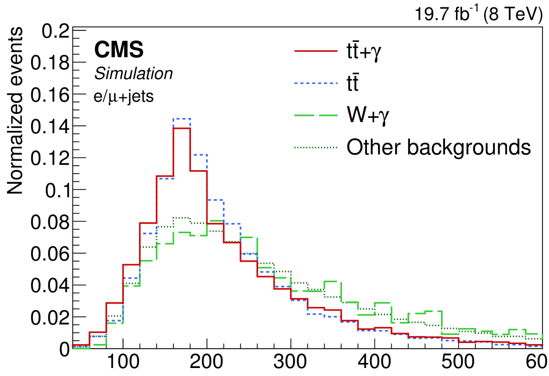
tt+ γ PRODUCTION CMS MEASUREMENT

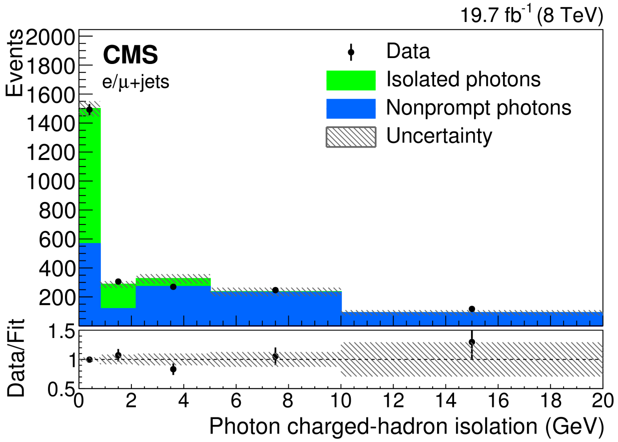
Two types of backgrounds: arXiv:1706.08128

- ttbar events with fake photon from jet.
- Non-top events with real photons (Wγ, Zγ)

Strategy:

- Use the invariant mass of the 3 jets with highest p_T (M_3) to discriminate ttbar events from other backgrounds.
- Use the γ isolation to discriminate genuine photons from signal and non-prompt photons from background.
- Measure ttbar+γ cross section relative to ttbar cross section.





Category	R	$\sigma^{\mathrm{fid}}_{t\bar{t}+\gamma}$ (fb)	$\sigma_{t\bar{t}+\gamma}\mathcal{B}$ (fb)
e+jets	$(5.7 \pm 1.8) \times 10^{-4}$	138 ± 45	582 ± 187
μ+jets	$(4.7 \pm 1.3) \times 10^{-4}$	115 ± 32	453 ± 124
Combination	$(5.2 \pm 1.1) \times 10^{-4}$	127 ± 27	515 ± 108
Theory	—	—	592 ± 71 (scales) ± 30 (PDFs)

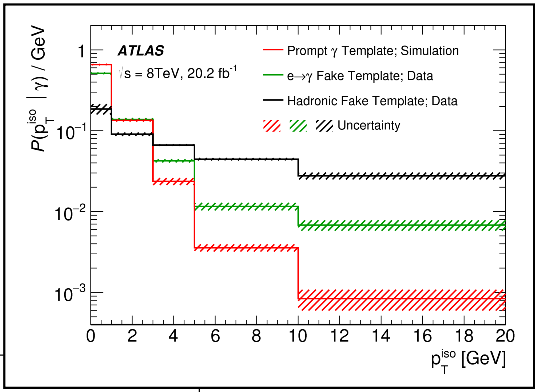
Measurement in good agreement with SM theoretical predictions.

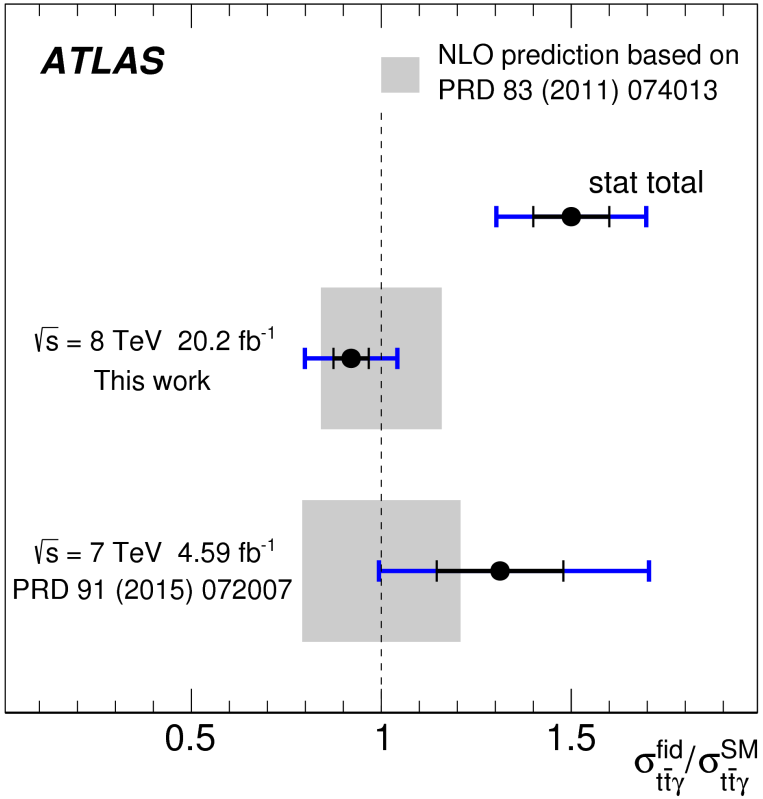
tt+ γ PRODUCTION ATLAS MEASUREMENT

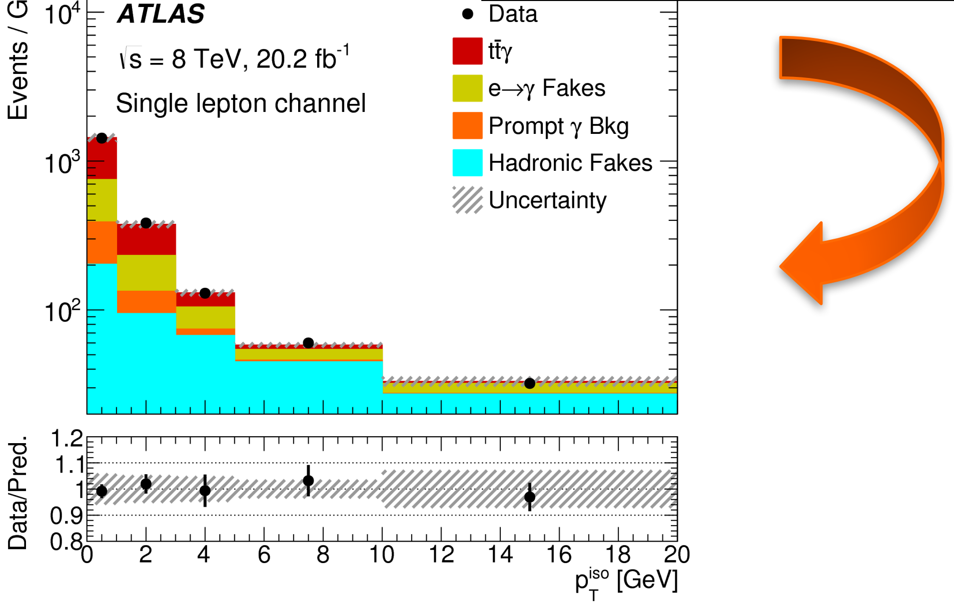
arXiv:1706.03046

- Fiducial inclusive cross section extracted from combined fit of signal and background templates to data:

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







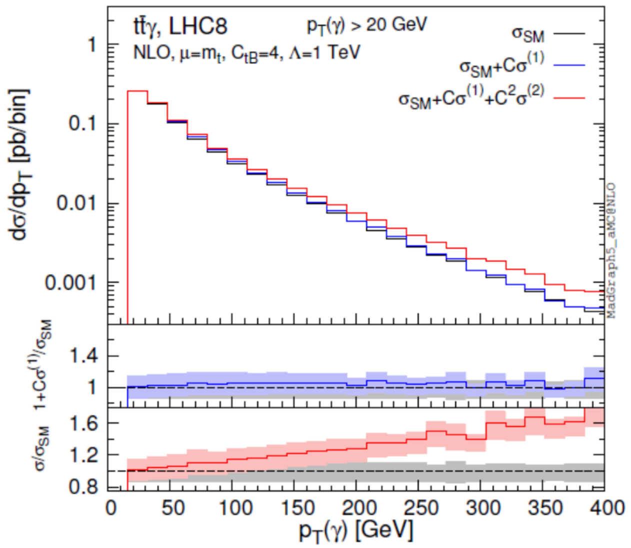
$\sigma^{\text{fid}}_{\text{sl}} = 139 \pm 7$ (stat.) $\pm$ 17 (syst.) fb = 139 ± 18 fb, NLO prediction of 151 ± 24 fb

Measurement in good agreement with SM theoretical predictions and with similar level of precision (relative unc. ~13%).

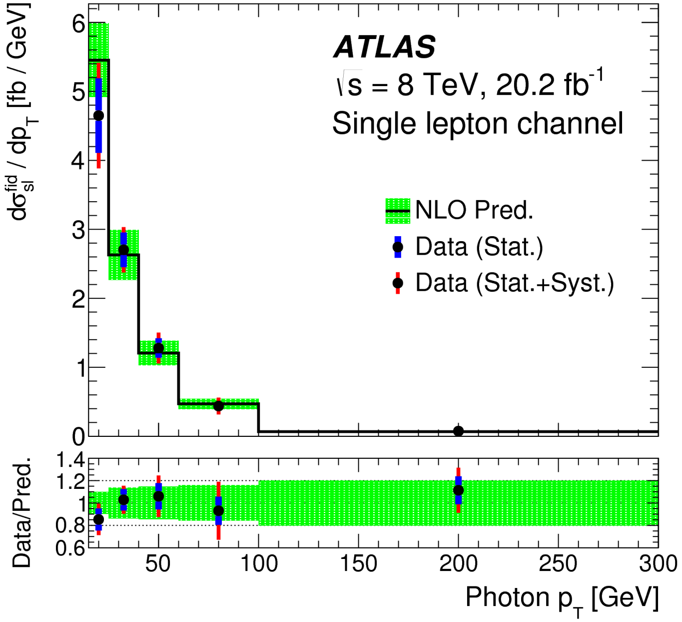
Limited by systematics (mainly JES, photon, signal modelling, b-tagging).

tt+ γ PRODUCTION ATLAS MEASUREMENT

- Particle level fiducial differential cross sections wrt photon p_T and |η| also provided.
- In an EFT, amplitudes typically grow with the energy of the process → the tails of the distributions often provide improved sensitivity to a coupling.
- But one must be careful about the validity of the EFT: the EFT breaks down at E ~Λ



arXiv:1601.08193

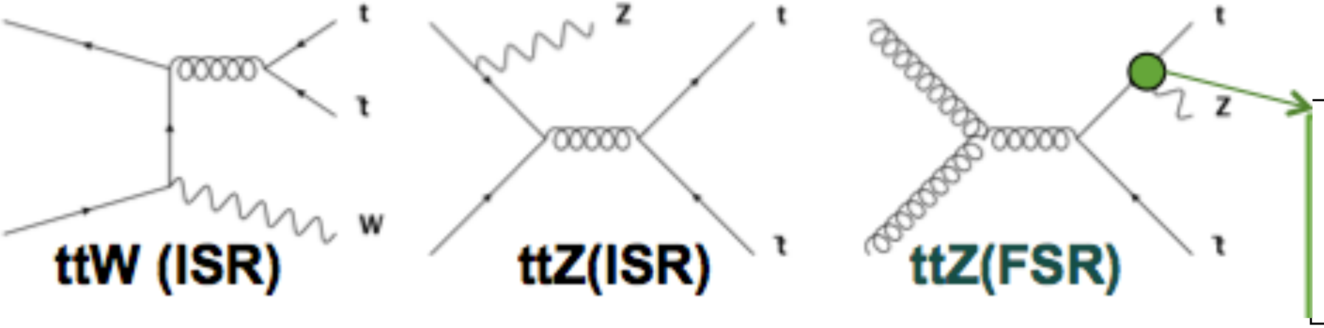


First differential measurements provided by ATLAS.

Differential measurements very interesting (in particular tails) to search for anomalous couplings.

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).

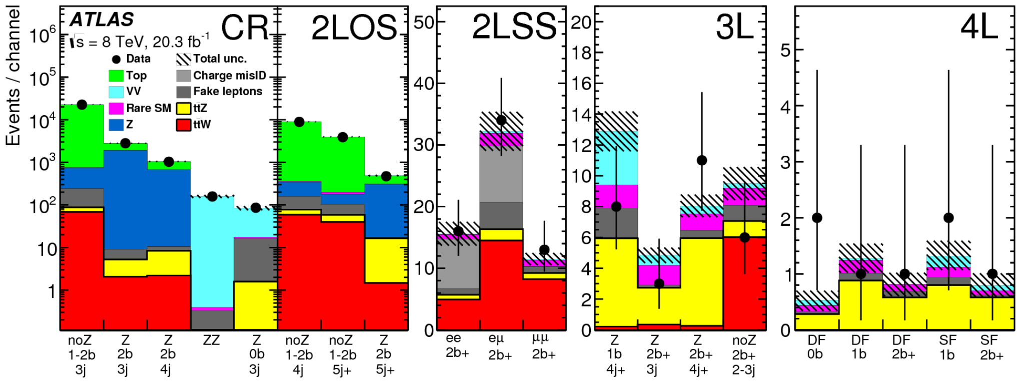


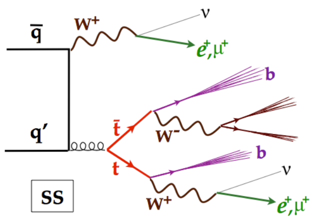
Direct measurement of top coupling to Z gauge boson in ttZ production via FSR.

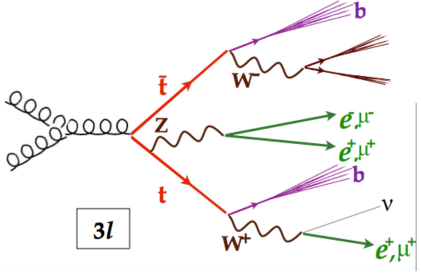
- Experimental signature: number of leptons (depending on the top and W/Z quark decay channel), multiple jets and b-jets also required (2L OS, 3L, 4L (best for ttZ), 2L (SS), 3L (best for ttW)).

Strategy:

- Most sensitive: 3L to ttZ, 2L SS to ttW.
- MVA and cut-and count techniques are used.



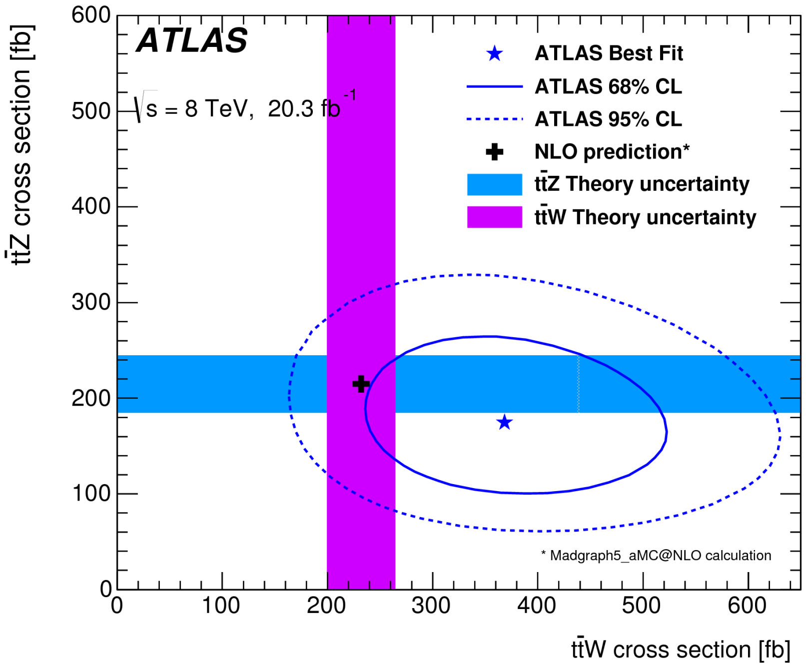


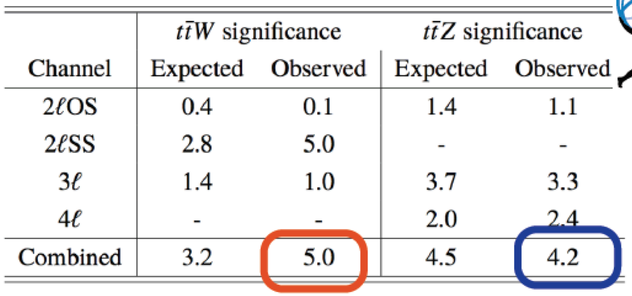


Process observed for the first time at 8 TeV.

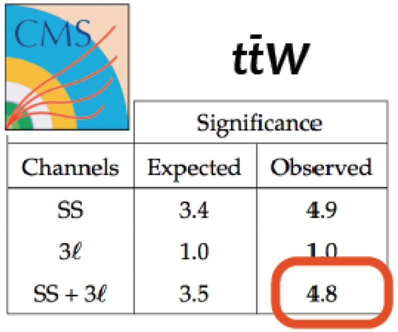
Preliminary results now available at 13 TeV.

tt+Z PRODUCTION MEASUREMENTS @ 8 TeV



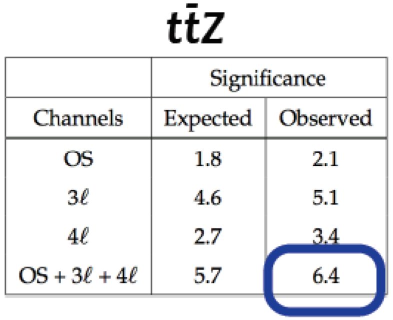


Channel	$t\bar{t}W$ significance		$t\bar{t}Z$ significance	
	Expected	Observed	Expected	Observed
2ℓOS	0.4	0.1	1.4	1.1
2ℓSS	2.8	5.0	-	-
3ℓ	1.4	1.0	3.7	3.3
4ℓ	-	-	2.0	2.4
Combined	3.2	5.0	4.5	4.2



ttW

Channels	Significance	
	Expected	Observed
SS	3.4	4.9
3ℓ	1.0	1.0
SS + 3ℓ	3.5	4.8



ttZ

Channels	Significance	
	Expected	Observed
OS	1.8	2.1
3ℓ	4.6	5.1
4ℓ	2.7	3.4
OS + 3ℓ + 4ℓ	5.7	6.4

ATLAS measurement

JHEP 11 (2015) 172

$$\sigma_{t\bar{t}Z} = 176\ ^{+52}_{-48}(\text{stat.}) \pm 24(\text{syst.})\ \text{fb}$$

$$\sigma_{t\bar{t}W} = 369\ ^{+80}_{-92}(\text{stat.}) \pm 44(\text{syst.})\ \text{fb}$$

CMS measurement

JHEP 01 (2016) 096

$$\sigma_{t\bar{t}Z} = 245\ ^{+65}_{-55}\ \text{fb}$$

$$\sigma_{t\bar{t}W} = 382\ ^{+117}_{-102}\ \text{fb}$$

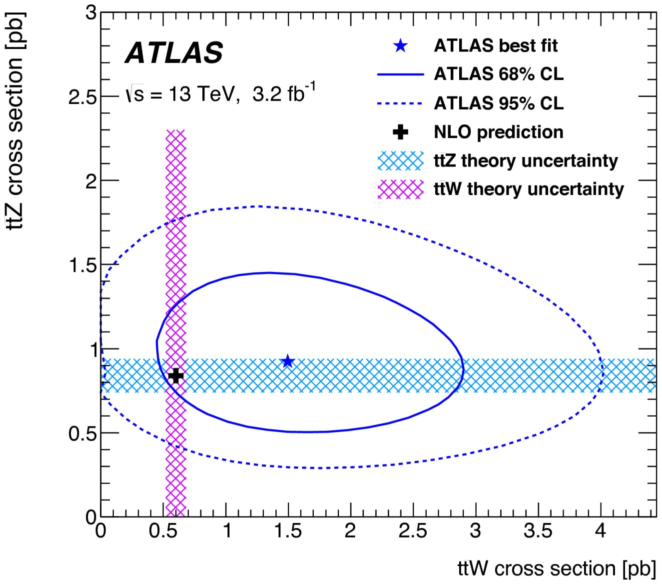
SM: $\sigma_{t\bar{t}Z} = 206^{+19}_{-24}$ fb and $\sigma_{t\bar{t}W} = 203^{+20}_{-22}$ fb.

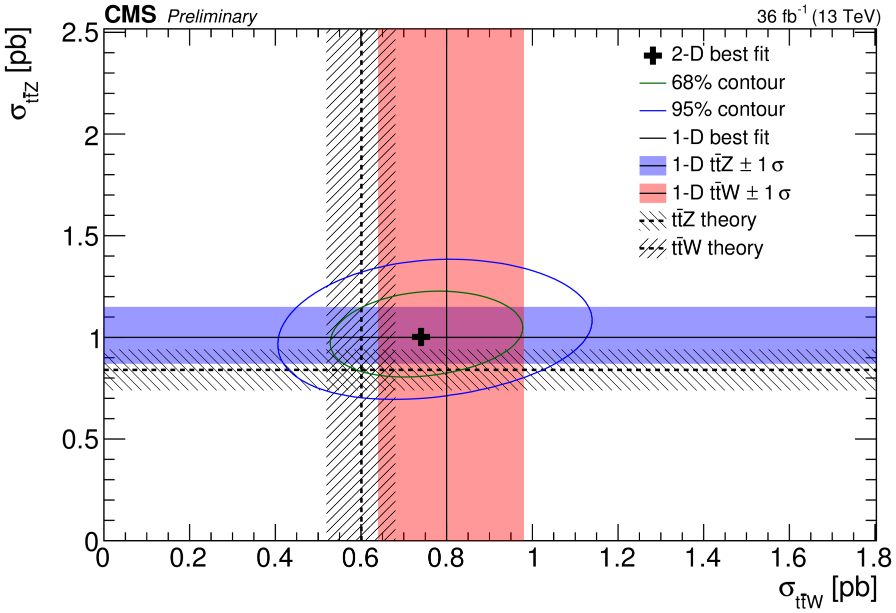
First observation of ttZ observed using 8 TeV data.

Dominated by statistical uncertainties.

Mild excess seen for ttW by both experiments in the SS 2L channels.

tt+Z PRODUCTION MEASUREMENTS @ 13 TeV





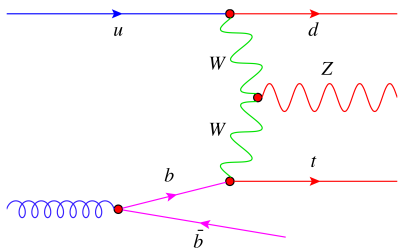
Δσ/σ (%), Significance	**ttZ**	**ttW**
ATLAS 2015	32%, 3.9σ (31% stat.)	only μμ 53%, 2.2σ (48% stat.)
CMS 2015+2016	14%, 9.9σ (stat ~syst. unc.)	15%, 5.5σ (stat ~syst. unc.)

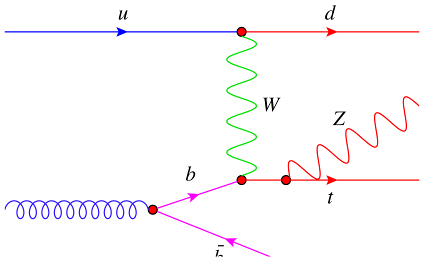
Wilson coefficient	1σ CL $[\mathrm{TeV}^{-2}]$	2σ CL $[\mathrm{TeV}^{-2}]$
$\lvert \bar{c}_{uB}/\Lambda^2 \rvert$	[0.0, 1.5]	[0.0, 2.1]
$\lvert \bar{c}_{u}/\Lambda^2 + 10.9\ \mathrm{TeV}^{-2} \rvert$	[2.3, 15.2]	[0.0, 18.6]
$\bar{c}_{uW}/\Lambda^2$	[-1.6, 1.5]	[-2.2, 2.1]
$\bar{c}_{Hu}/\Lambda^2$	[-9.1, -6.5] and [-1.6, 1.1]	[-10.1, 2.0]

CMS observation of both ttZ and ttW processes at 13 TeV using 2015+2016 data. Statistical and systematic uncertainties now at the same level.

All measurements in agreement with SM predictions → used to set constraints on four EFT operators which would modify the ttZ and ttW cross sections.

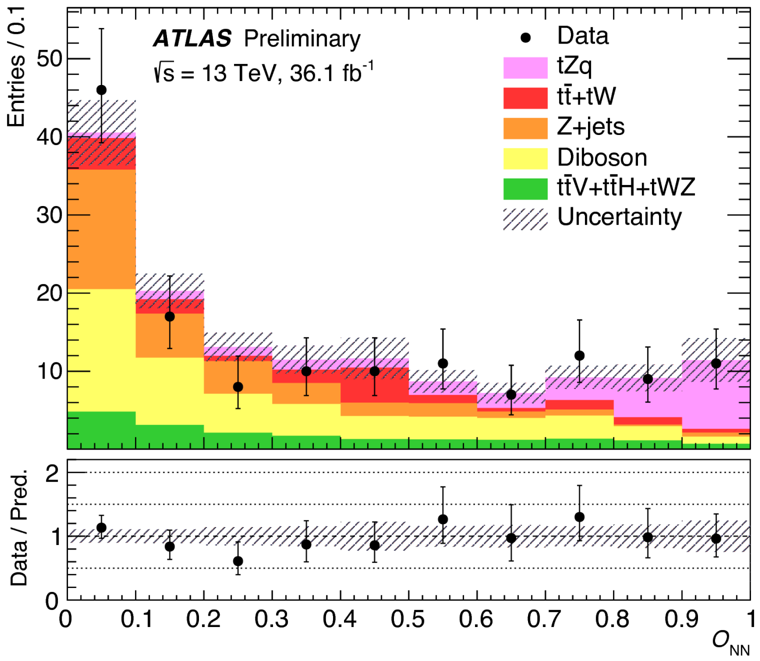
tZ PRODUCTION





- EW process not observed so far (800 fb @ 13 TeV).
- Sensitive to tZ and WWZ couplings.
- Trilepton channel most promising despite small BR (2.2%).
- NN used to enhance S/B.
- Fit to the full NN distribution to extract the cross section.

$$\sigma_{tZq} = 600 \pm 170(\text{stat.}) \pm 140(\text{syst.})\text{fb}$$



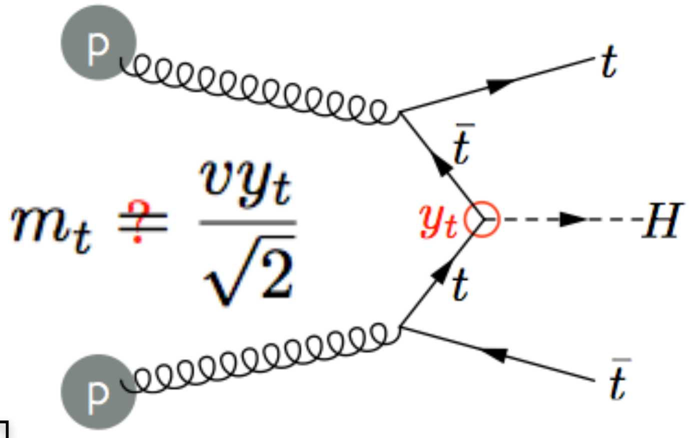
First clear evidence of tZ production observed at 13 TeV by ATLAS:

Significance: 4.2σ observed (5.4σ expected)

Good agreement with the SM prediction.

TOP COUPLING TO H BOSON

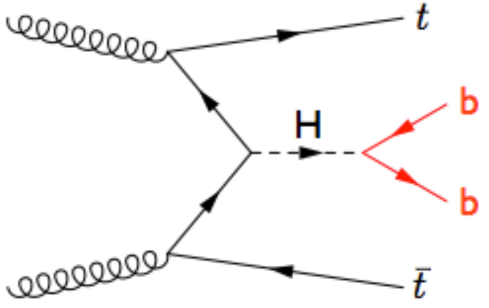
- Higgs boson discovery in July 2012.
- In the SM, fermion masses are proportional to Higgs fermion Yukawa couplings → Important to test this prediction.
- ttH production provides direct sensitivity to the top-Higgs Yukawa coupling



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

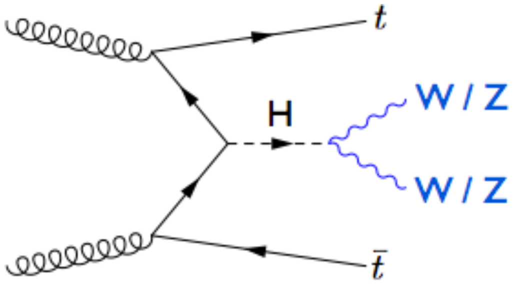
ttH (H→ bb)

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



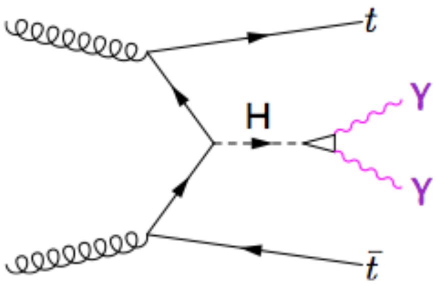
ttH (H→ WW/ZZ)

- 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)

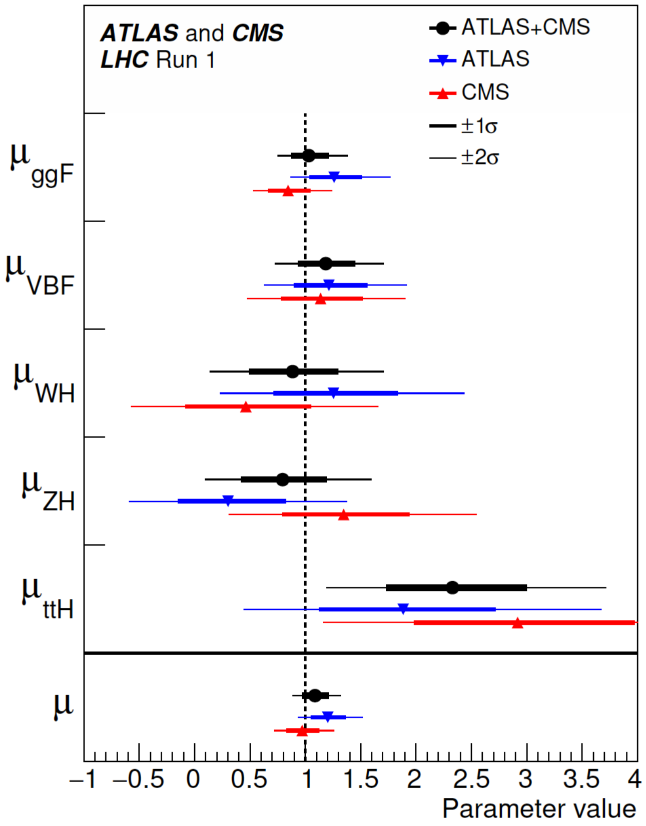
- Small BR (0.2%)
- Higgs boson can be reconstructed as a narrow peak
- Backgrounds from ttbar+Υ and QCD multi-Υ /jet final states

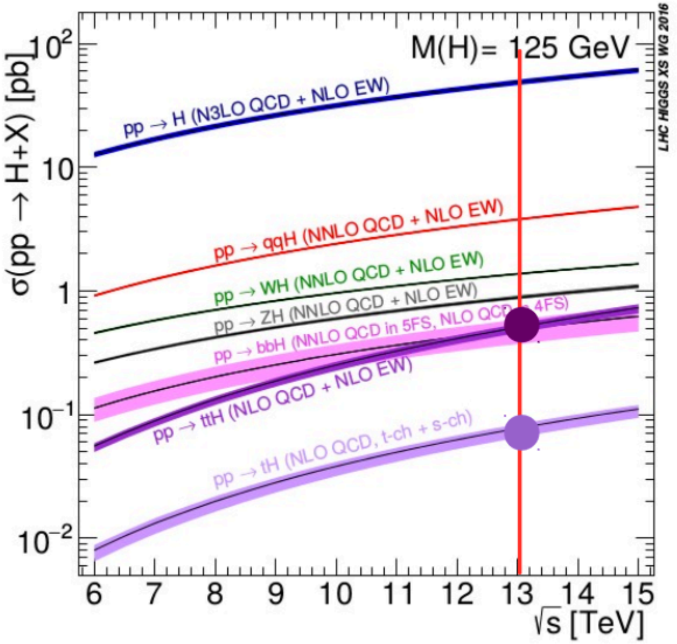


RUN-1 RESULTS AND RUN-2 EXPECTATIONS

- Run-1 ATLAS+CMS Higgs combination:
- ttH significance of 4.4 σ (2.0 σ expected)
- Excess in both ATLAS and CMS coming from ttH multilepton analysis.

JHEP08(2016)045

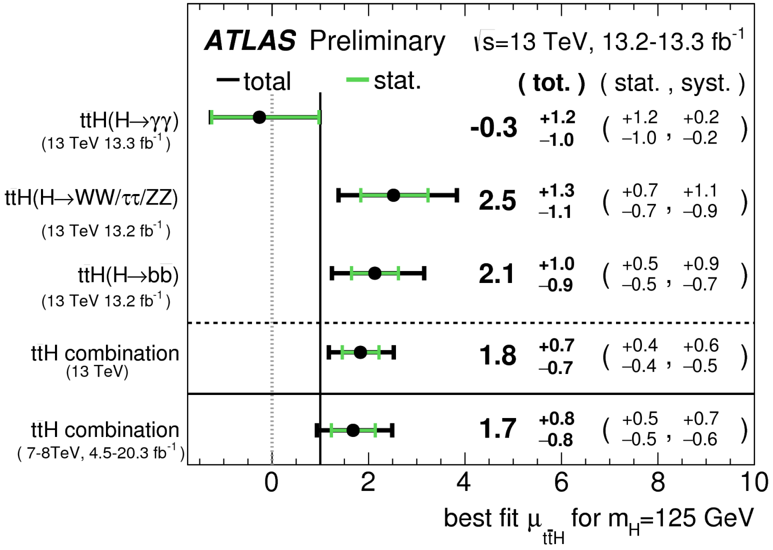


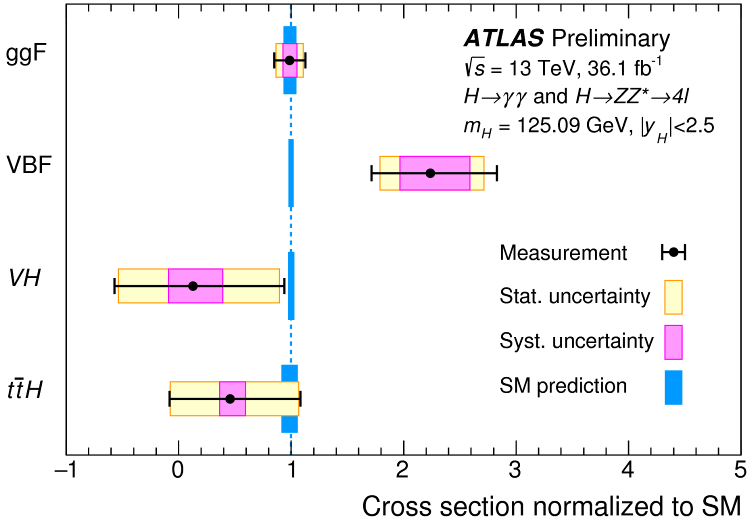


- √s = 13 TeV ttH σ increased by x4
- x 2 other main H productions
- x 3.5 ttbar production

Increased potential for discovery at Run-2

RUN-2 STATUS





Significance: 2.8 σ observed (1.8 σ expected)

	$\mu_{t\bar{t}H} = \sigma_{t\bar{t}H}/\sigma_{SM}$	significance/upper limit
$b\bar{b}$ 12.9 fb^{-1}	-0.2 ± 0.8	$\mu < 1.5(1.7)@95\%\mathrm{CL}$
multilept 35.9 fb^{-1}	1.5 ± 0.5	$3.3\sigma(2.4\sigma)$
$\tau_{had}\tau_{any}$ 35.9 fb^{-1}	$0.7^{+0.6}_{-0.5}$	$1.4\sigma(1.8\sigma)$
$\gamma\gamma$ 35.9 fb^{-1}	$2.2^{+0.9}_{-0.8}$	$3.3\sigma(1.5\sigma)$
$4l$	$0.00^{+1.2}_{-0.0}$	

Looking forward for all analyses to be completed using the full 2015+2016 data, and then combined.

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.
  - Shown here results for top mass and couplings.
- So far, all measurements compatible with the SM.
- Many of the top measurements performed at the LHC are already dominated by systematics (e.g. jet energy scale, b-tagging, physics modelling).
- Some rare processes also becoming available with 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 positive results from direct searches).

BACKUP

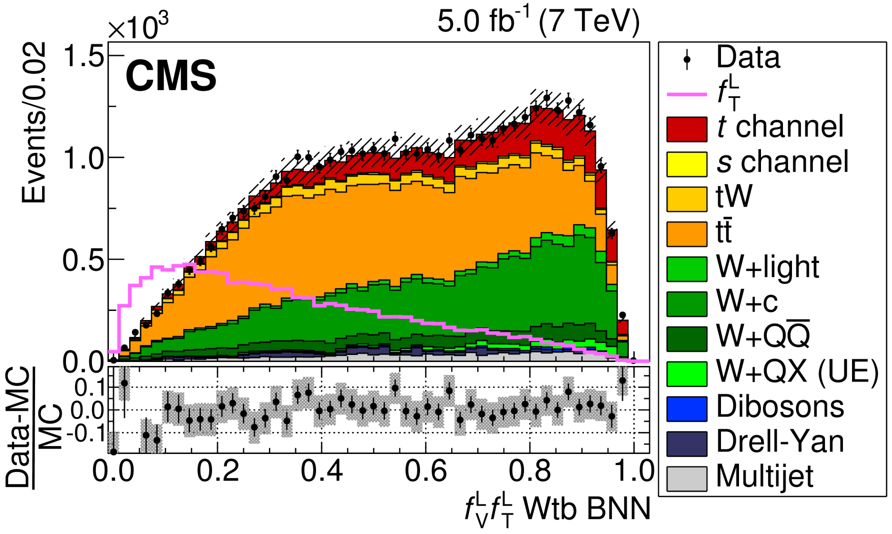
CMS APPROACH TO CONSTRAIN Wtb VERTEX

- A specific Wtb neural network (BNN) is trained for each coupling.
- A 2D fit of Wtb BNN and SM BNN gives exclusion limits.

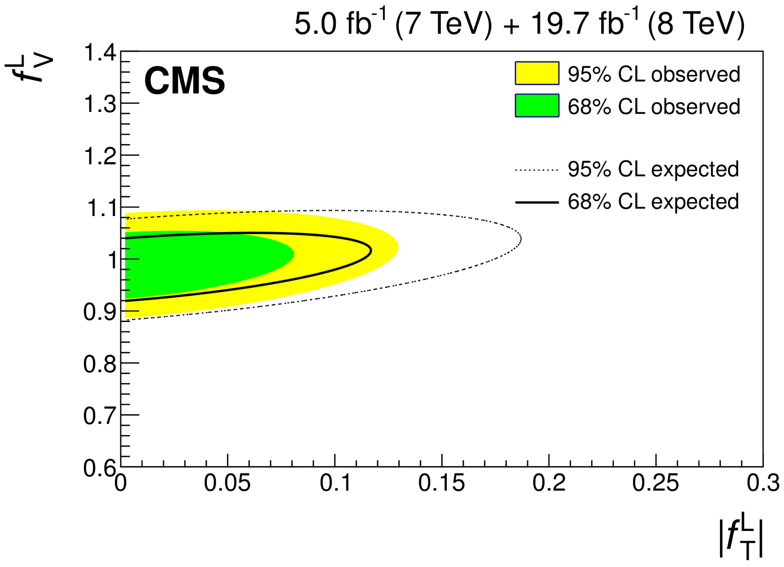
JHEP 02 (2017) 028

$$\mathfrak{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(f_{V}^{L}P_{L} + f_{V}^{R}P_{R}\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{\sigma^{\mu\nu}\partial_{\nu}W_{\mu}^{-}}{M_{W}}\left(f_{T}^{L}P_{L} + f_{T}^{R}P_{R}\right)t + \mathrm{h.c.}$$

Ex: BNN trained to separate the contribution vector-left from that of tensor-left



Ex: Exclusion limits obtained in f_V^L vs f_T^L.

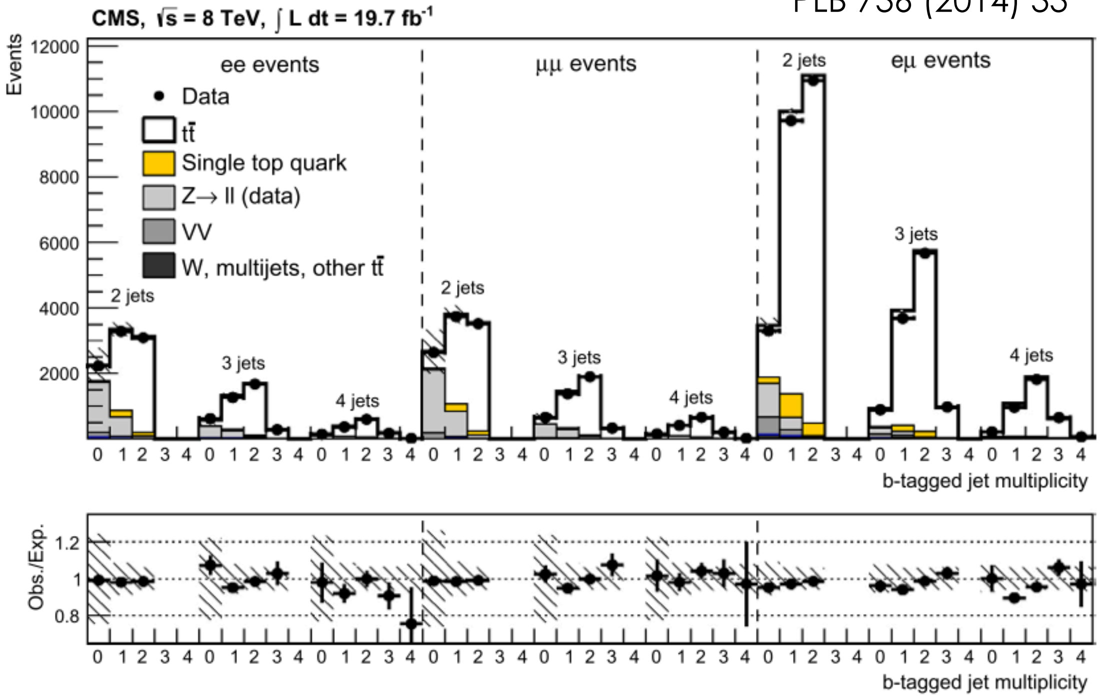


Limits on pairs of couplings provided.

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.

PLB 736 (2014) 33



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

- 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

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