Top quark physics from run 1 of the LHC

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on behalf of the ATLAS and CMS Collaborations

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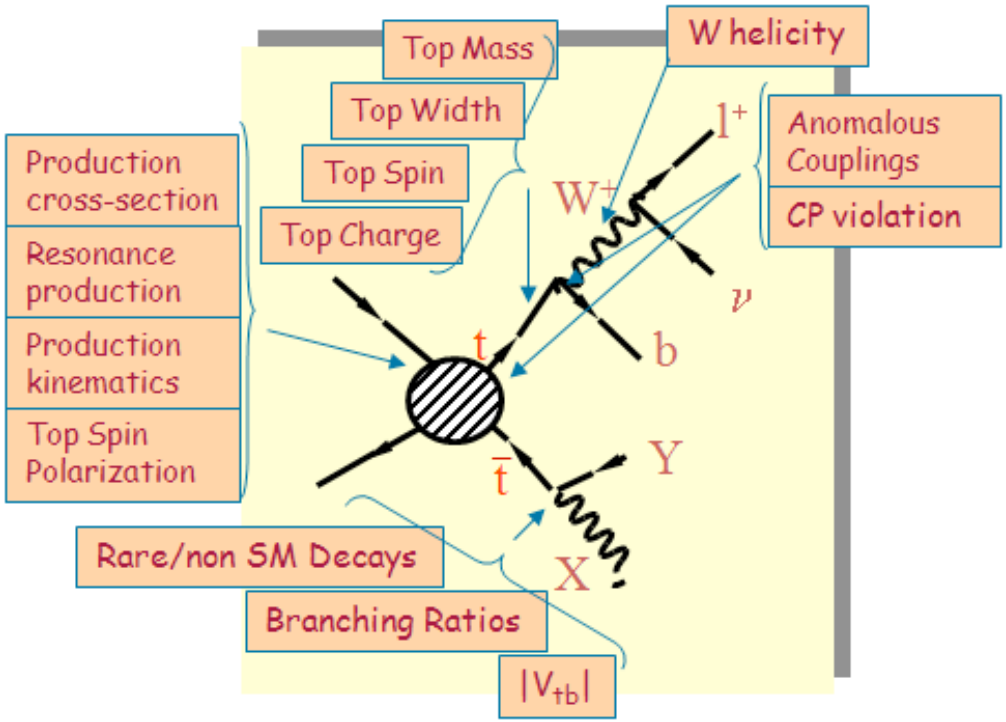
The phenomenology of Top Quark is Too Rich
☞ impossible to cover everything here

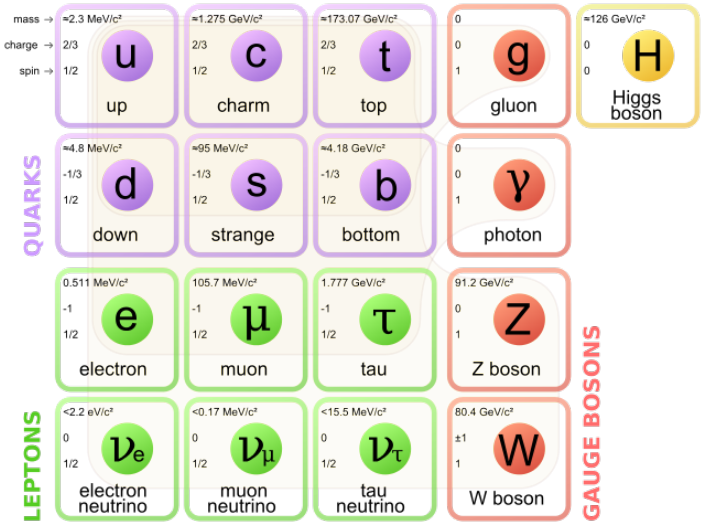
(Short) List of Topics Covered:

- Cross section measurements
  - $t\bar{t}$ production at the LHC
  - single top quark production
- The top quark mass
- Probing the top spin
- The $t \to bW$ decay in $t\bar{t}$ events
  - the Wtb vertex structure and anomalous couplings
- Top Quark Couplings to Bosons
  - V_{tb} @ LHC
  - ttV ($V = \gamma, Z, W$, H)
- Top quark beyond SM
  - FCNC processes ($tqX, X = \gamma, Z, g, H$)



The top quark

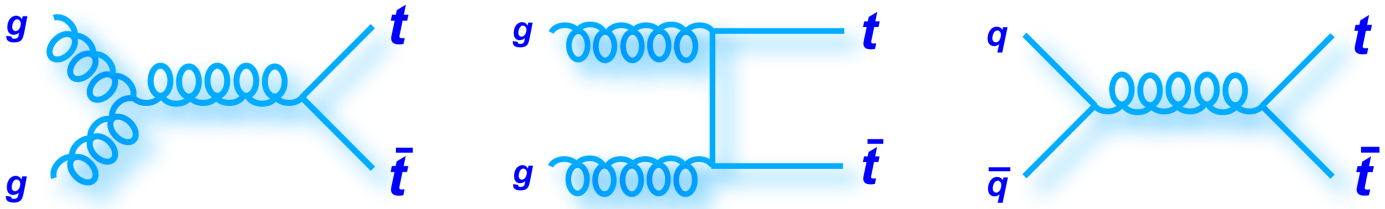
- **2015 is the top quark's 20th anniversary**
  it was discovered by CDF and D0 in 1995
  PRL**74** 2626-2631 (1995);
  PRL**74** 2632-2637 (1995).



- It completes the 3 family structure of the SM
  - top is the weak-isospin partner of the b-quark
  - spin = $1/2$
  - charge = $+2/3\ |e|$
- Top quark is the heaviest known fundamental particle
  ($m_t = 173.34 \pm 0.76$ GeV, World comb.(2014), arXiv:1403.4427)
- Top decays (almost exclusively) through $t \to bW$
  $BR(t \to sW) \leq 0.18\%$, $BR(t \to dW) \leq 0.02\%$
- $\Gamma_t^{SM} = 1.42$ GeV (including m_b, m_W, α_s, EW corrections)
  - $\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25}$s (D0, PRD **85** 091104, 2012)
    $\ll \Lambda_{QCD}^{-1} \sim (100\ \text{MeV})^{-1} \sim 10^{-23}$s (hadronization time)
    $\Rightarrow$ top decays before hadronization takes place

$t\bar{t}$ production at the LHC

- Production at the LHC:



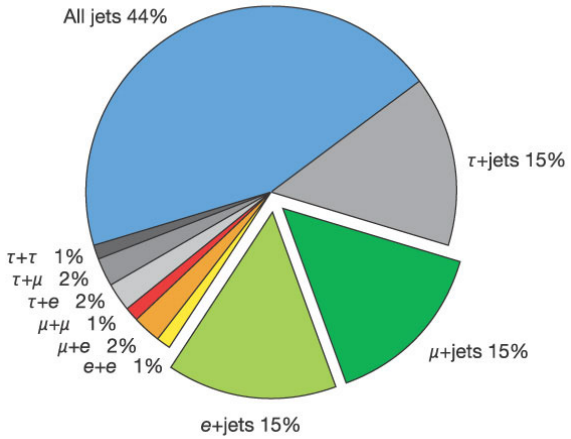
$\sigma(t\bar{t})$=177.3$\pm$9.9$^{+4.6}_{-6.0}$ pb @ 7 TeV, $\sigma(t\bar{t})$=252.9$\pm$11.7$^{+6.4}_{-8.6}$ pb @ 8 TeV, $\sigma(t\bar{t})$=832$^{+40}_{-46}$ pb @ 13 TeV

NNLO+NNLL, m_t =172.5 GeV PLB **710** 612 (2012), PRL **109** 132001(2012),
JHEP **1212** 054(2012), JHEP **1301** 080(2013), PRL**110** 252004 (2013).

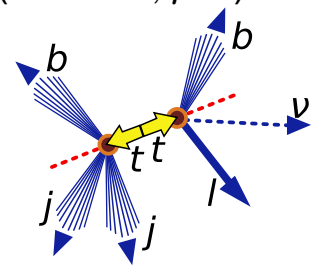
Top pair decay channels

W decay	e^+	μ^+	τ^+	$ud\bar{}$	$cs\bar{}$
e^-	ee	eμ	eτ	electron+jets	
μ^-	eμ	μμ	μτ	muon+jets	
τ^-	eτ	μτ	ττ	tau+jets	
$\bar{u}d$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{c}s$					

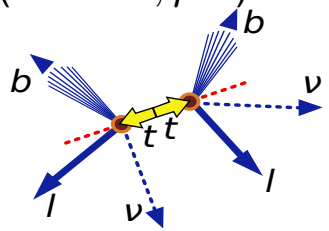
Top pair branching fractions



$\Longrightarrow$ Lepton+jets ($\sim$ 30%):
($\ell = e^{\pm}, \mu^{\pm}$)

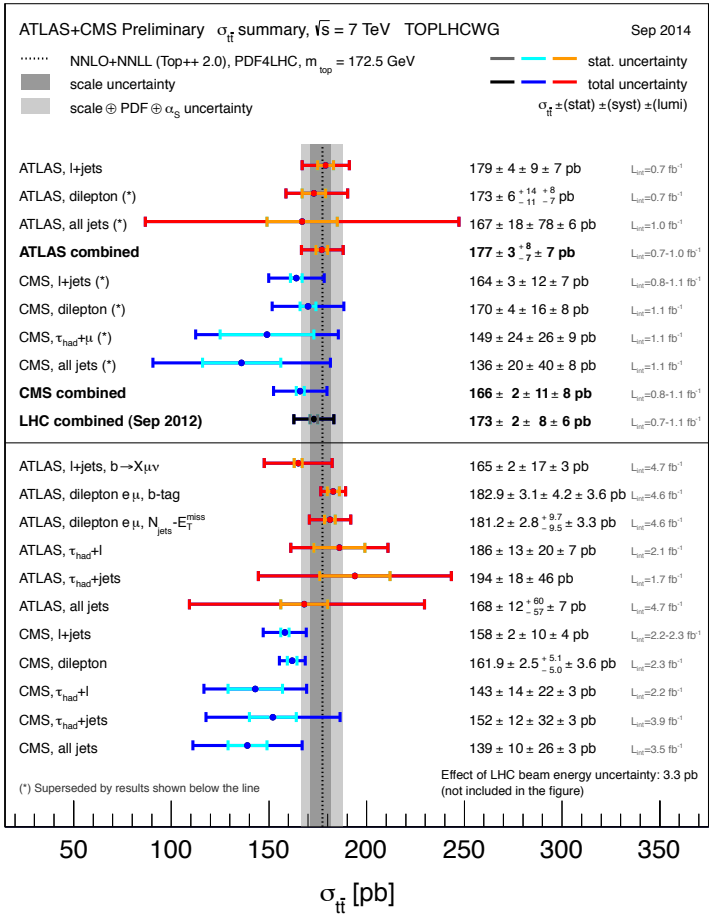


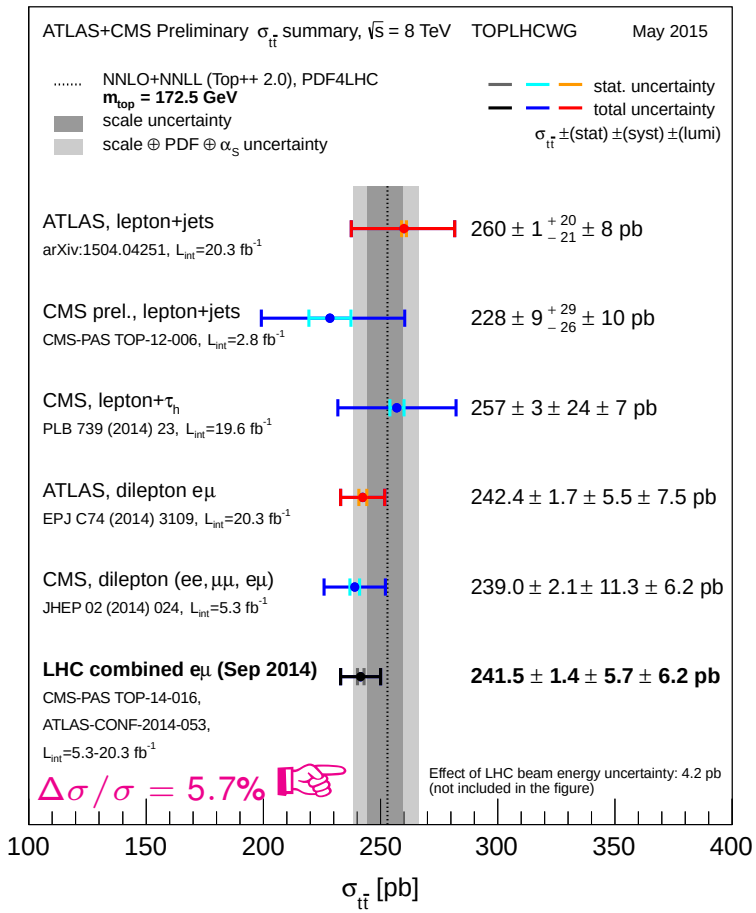
$\Longrightarrow$ Dilepton ($\sim$ 5%):
($\ell = e^{\pm}, \mu^{\pm}$)



Cross-Section Measurements @ 7 and 8 TeV

☞ significant number of precise measurements from RUN I





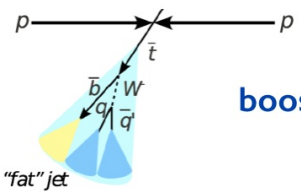
ATLAS+CMS Comb.: at 7 TeV $\Delta(\sigma)/\sigma = 5.9\%$ **at 8 TeV** $\Delta(\sigma)/\sigma = 3.5\%$

Getting Precision in Differential Measurements @ 7 and 8 TeV

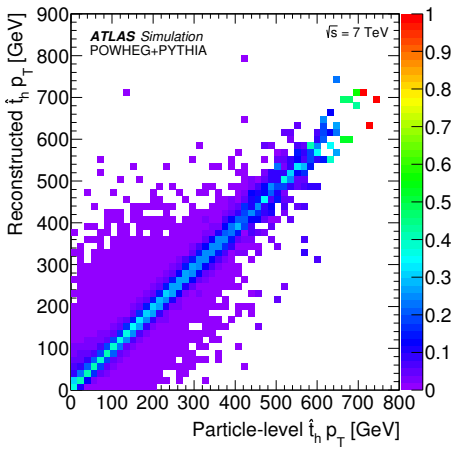
☞ No significant deviations from the SM @ RUN I (within uncert.)

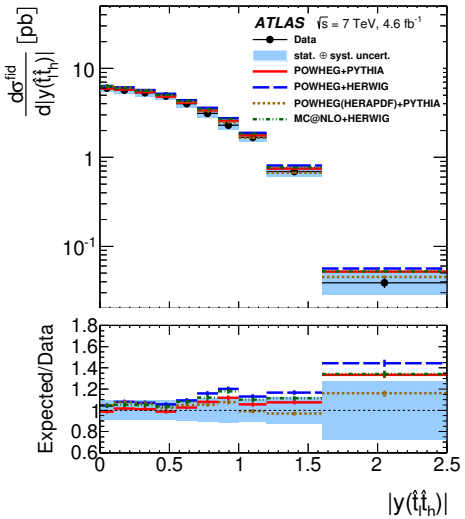
Data softer then MC (up to 30%-70% boosted high p_T) ☞ requires better modelling

Fiducial measurements in well defined phase space regions

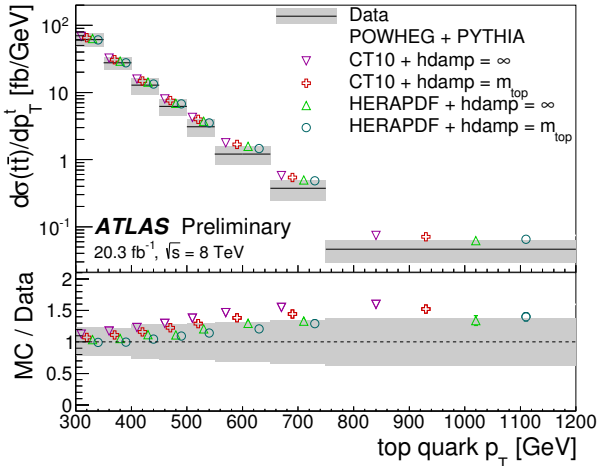


ATLAS JHEP 06 (2015) 100

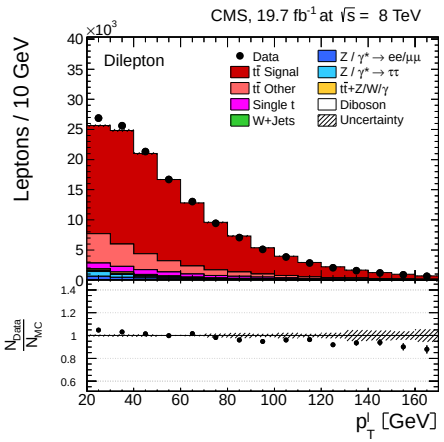


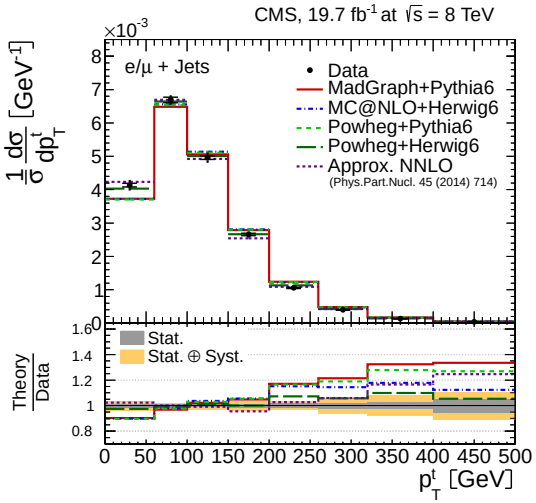


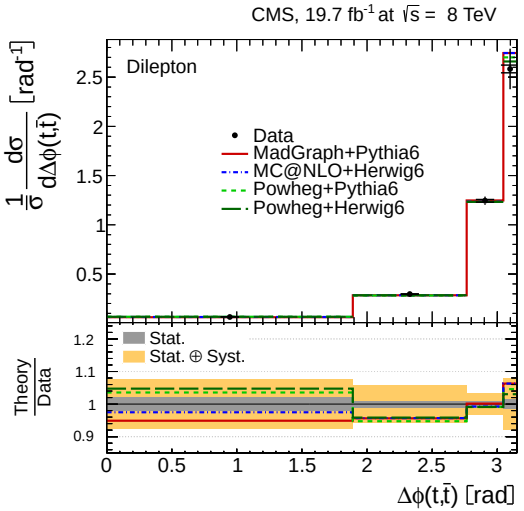
ATLAS-CONF-2014-057 "fat" jet



CMS arXiv:1505.04480v1 [hep-ex]

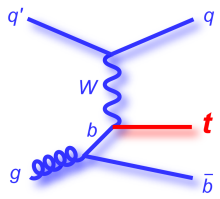


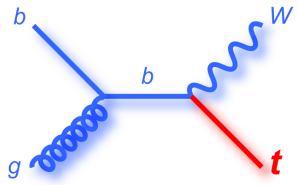


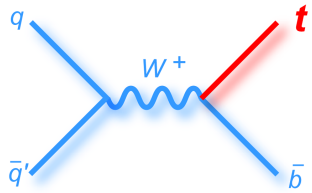


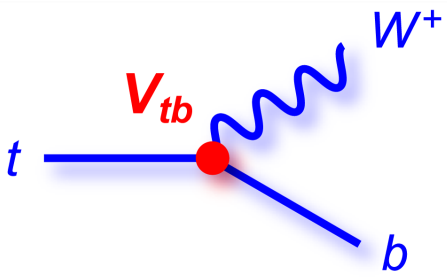
Single top quark

- Single top quark production cross section @ LHC:







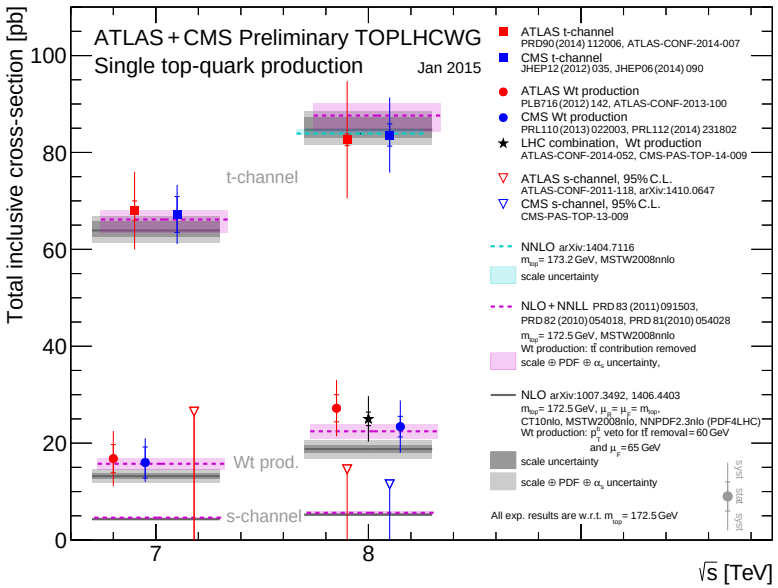


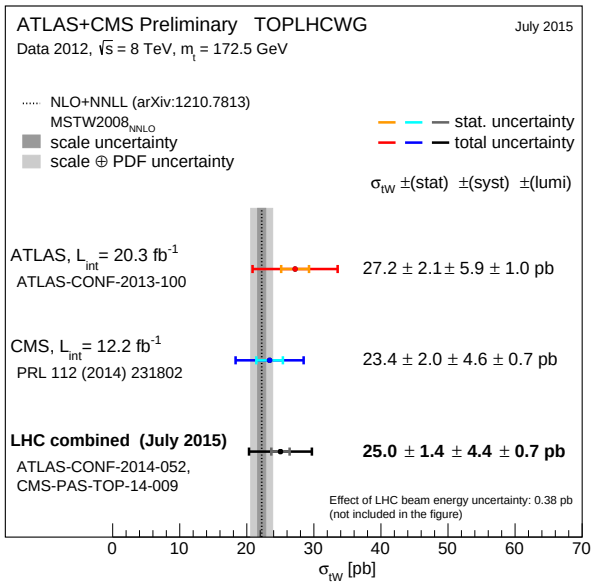
t-channel | (*Wt*-prod.) | (*s*-channel)

$64.57^{+2.63}_{-1.74}$ pb | $15.74^{+1.17}_{-1.21}$ pb | $4.63^{+0.20}_{-0.18}$ pb ⟸ @ 7TeV

$87.76^{+3.44}_{-1.91}$ pb | $22.37^{+1.52}_{-1.52}$ pb | $5.61^{+0.22}_{-0.22}$ pb ⟸ @ 8TeV

- Powerfull probe of V_{tb} ($\delta V_{tb}/V_{tb}$ few % @ LHC) and Test of physics BSM (FCNC in *t*-channel; W' in *s*-channel)
- CMS and ATLAS results within SM expectations:





$\Delta\sigma_t/\sigma_t \sim 10\%$

$\Delta\sigma_{wt}/\sigma_{wt} \sim 20\%$

ATLAS@8 TeV:

$\sigma_s(95\%) < 14.6$ pb

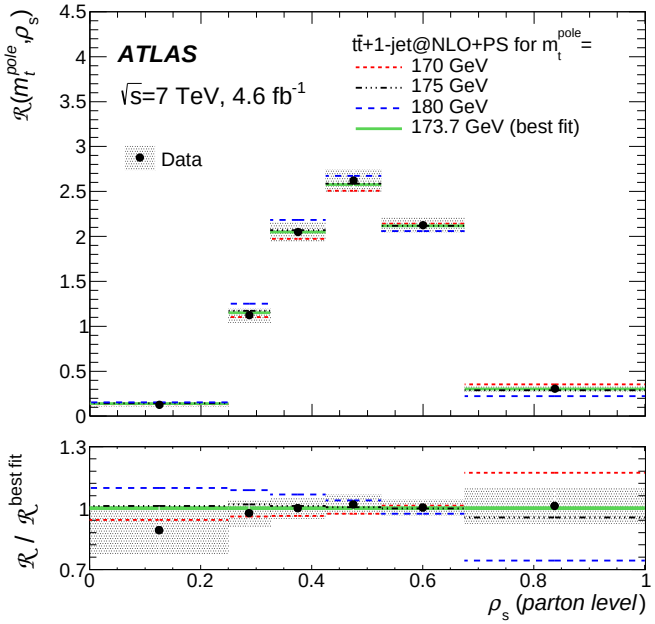
CMS@8 TeV:

$\sigma_s(95\%) < 11.5$ pb

- Complementary Approaches @ LHC:

$t\bar{t}$+1j: Pole Mass from Norm. Diff. σ

ATLAS: arXiv:1507.01769v1 [hep-ex] 7 Jul 2015



$$\mathcal{R}(m_t^{\text{pole}},\rho_s)=\frac{1}{\sigma_{t\bar{t}+1\text{-jet}}}\frac{\mathrm{d}\sigma_{t\bar{t}+1\text{-jet}}}{\mathrm{d}\rho_s}(m_t^{\text{pole}},\rho_s),\quad \rho_s=\frac{2m_0}{\sqrt{s}_{t\bar{t}+1\text{-jet}}},$$

$$m_t^{\text{pole}} = 173.7 \pm 1.5\ (\text{stat.}) \pm 1.4\ (\text{syst.})\ ^{+1.0}_{-0.5}\ (\text{theory})\ \text{GeV}.$$

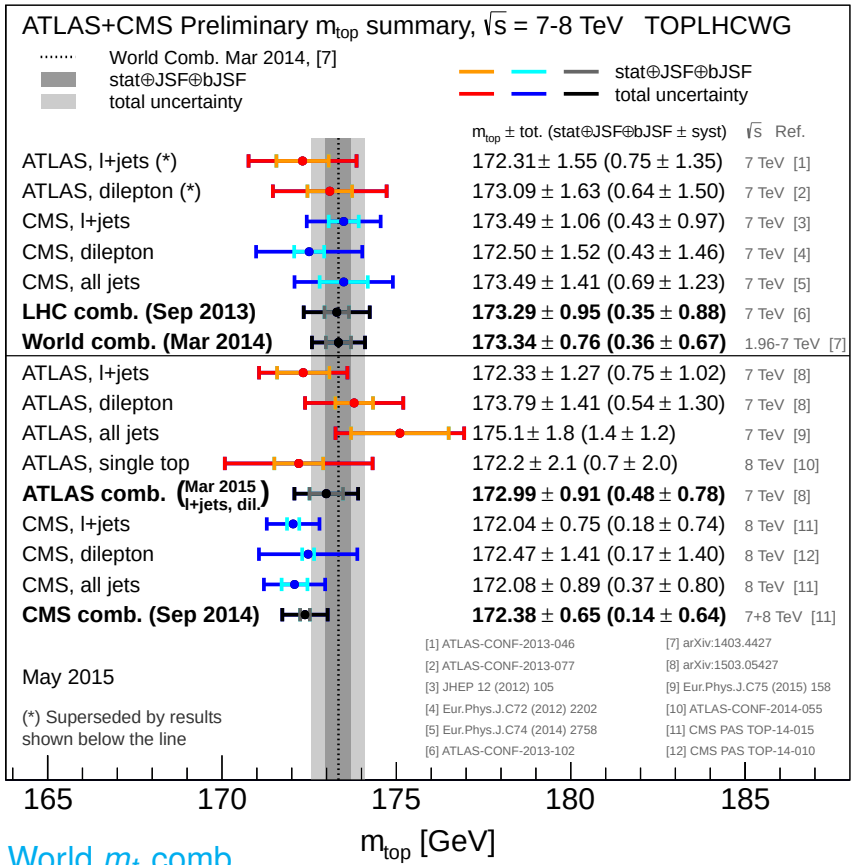
CMS: PLB **728**, 496-517 (2014)

$\Delta m_t^{pole}/m_t^{pole} \sim$ few %

Consistent within uncert. with World m_t comb.

Tevatron+LHC World Combination

$\Delta m_t/m_t$=0.4%



Probing the top quark spin

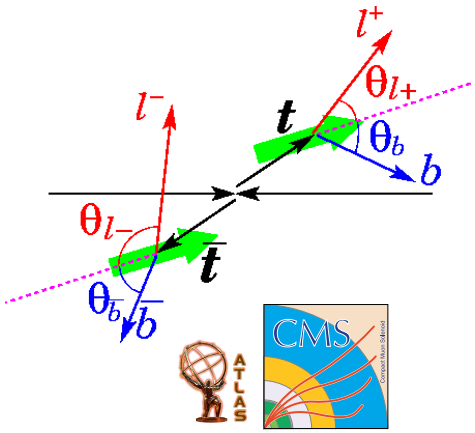
- **Top Spin Correlations are a powerful test of the SM:**
  - ☞ $t\bar{t}$: top quarks are produced unpolarised but their spins are correlated in the SM
  - ☞ Different BSM predict different spin correlations, 1) and 2)
- **Measure angular distributions of decay products:**

$$\frac{1}{\sigma}\frac{d^2\sigma}{d[\cos(\theta_i)]d[\cos(\theta_j)]} = \frac{1}{4}[P\alpha_i\cos(\theta_i) + P\alpha_j\cos(\theta_j) + A\alpha_i\alpha_j\cos(\theta_i)\cos(\theta_j)]$$

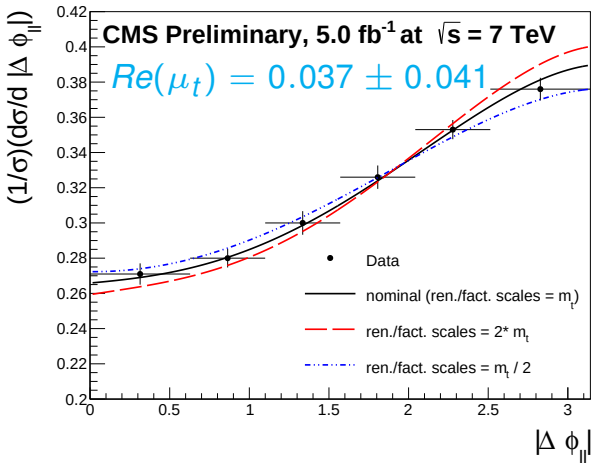
$$A = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}}$$

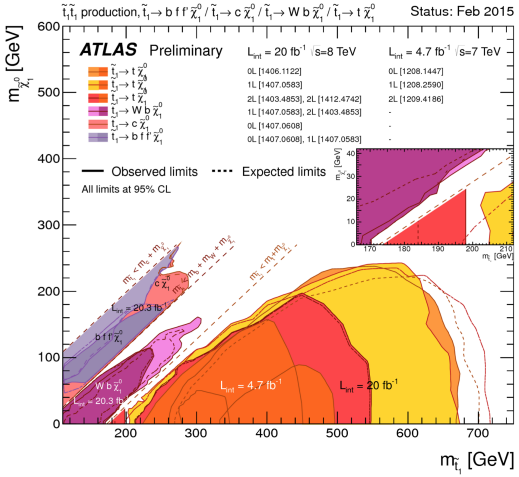
Spin analyser power of particles:

	b	ℓ	d	u
α (NLO)	-0.39	0.998	0.93	-0.31



1) CMS @ 7 TeV Chromo-magnetic anomalous couplings: CMS PAS TOP-14-005





ATLAS@7 TeV:

PRD **90** 112016 (2014)

☞ easiest observable, $\Delta\phi_{\ell\ell}$

☞ but there are others,

$$S = \frac{(|\mathcal{M}|^2_{RR} + |\mathcal{M}|^2_{LL})_{corr}}{(|\mathcal{M}|^2_{RR} + |\mathcal{M}|^2_{LL})_{uncorr}}$$

CMS@7 TeV:

PRL **112** 182001 (2014)

$A_{\Delta\phi}$, $A_{c_1 c_2}$ with $c_i = cos(\theta_i)$

2) ATLAS @ 8TeV Spin Corr. can exclude t̃ masses from m_t →191 GeV @95% CL

ATLAS @ 8 TeV $f_{SM} = 1.20 \pm 0.05(stat) \pm 0.13(sys)$ PRL **114** 142001 (2015)

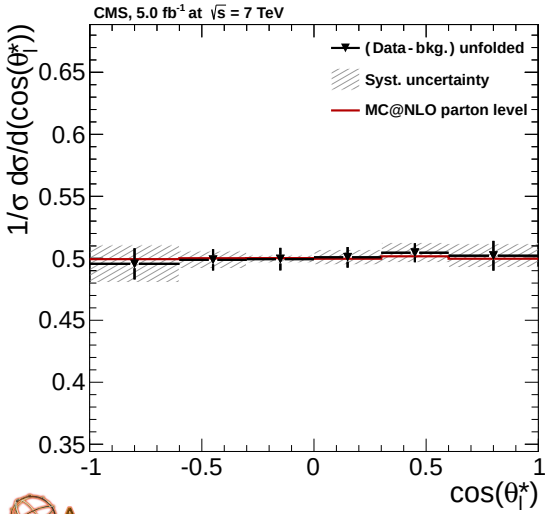
CMS @ 8 TeV $f_{SM} = 0.72 \pm 0.09(stat)^{+0.15}_{-0.13}(sys)$ CMS PAS TOP-13-015

$\Delta f_{SM}/f_{SM} = 12\%$

Probing the top quark spin

$$\frac{1}{\sigma}\frac{d^2\sigma}{d[\cos(\theta_i)]d[\cos(\theta_j)]} = \frac{1}{4}[P\alpha_i\cos(\theta_i) + P\alpha_j\cos(\theta_j) + A\alpha_i\alpha_j\cos(\theta_i)\cos(\theta_j)]$$

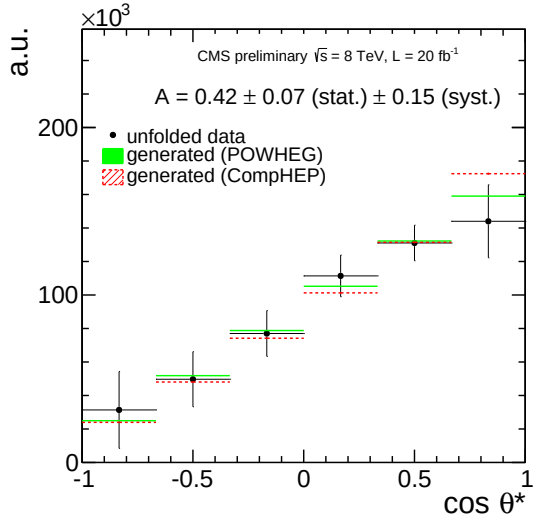
$t\bar{t}$ Top polarisation @ 7 TeV PRL **112** 182001 (2014)



- Dilepton $t\bar{t}$ events
- $cos\theta_\ell$ distribution unfolded to parton level
- $P = 2A_P$
- $A_P = \frac{N(\cos\theta_\ell)>0 - N(\cos\theta_\ell)<0}{N(\cos\theta_\ell)>0 + N(\cos\theta_\ell)<0}$

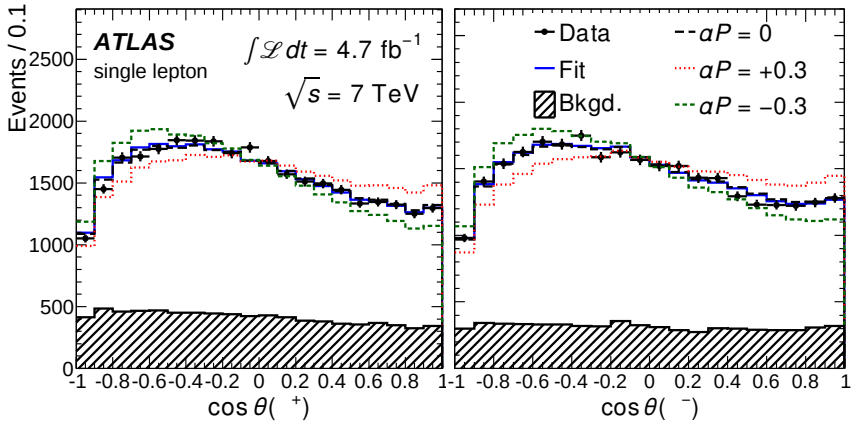
$$A_P = 0.005 \pm 0.013(stat.) \pm 0.20\ (syst.) \pm 0.008(p^t_{reweig.})$$

σ_t@ 8TeV: CMS PAS TOP-13-001



$$P_t = 0.82 \pm 0.34(tot.)$$

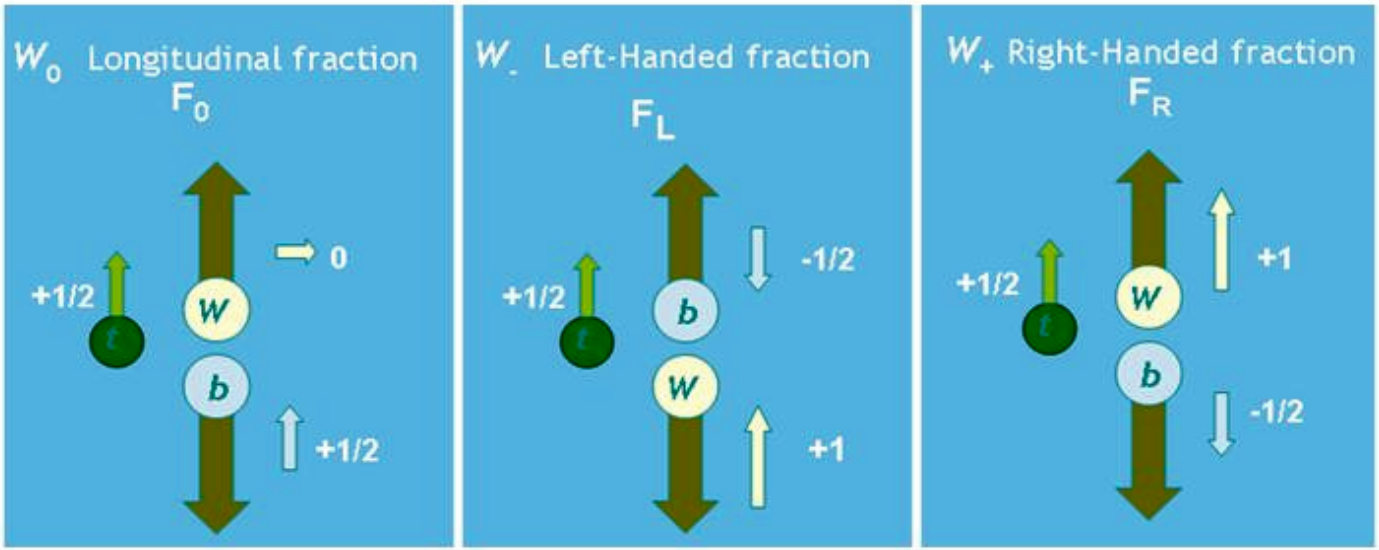
$t\bar{t}$ Results from ATLAS @ 7 TeV: PRL **111** 232002 (2013)



- Dilepton and ℓ+jets $t\bar{t}$ events
- Template fit to reconstructed $cos\theta_\ell$
- Two hypothesis tested:
  1) CP cons. (CPC): t and $\bar{t}$ with same P
  2) CP viola. (CPV): t and $\bar{t}$ with opposite P

$$\alpha_\ell P_{CPC} = -0.035 \pm 0.014\ (\text{stat}) \pm 0.037\ (\text{syst})$$
$$\alpha_\ell P_{CPV} = +0.020 \pm 0.016\ (\text{stat})^{+0.013}_{-0.017}\ (\text{syst})$$

Testing a Standard Model prediction: [Phys. Rev. D 45 (1992) 124]



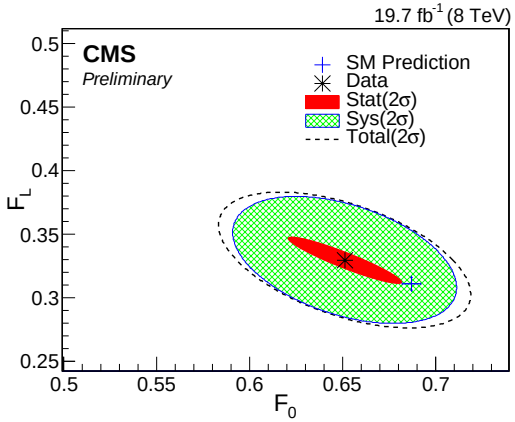
W bosons produced with different helicities:

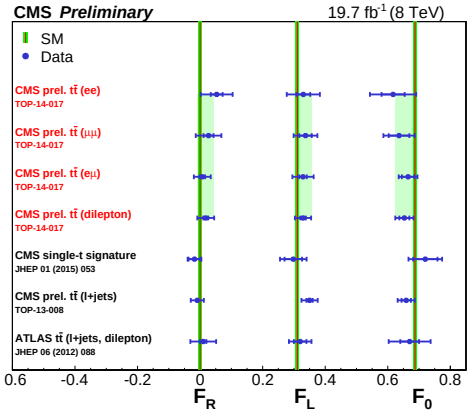
$$F_0^{\mathrm{SM}} = 0.687 \pm 0.005 \quad F_{\mathrm{L}}^{\mathrm{SM}} = 0.311 \pm 0.005 \quad F_{\mathrm{R}}^{\mathrm{SM}} = 0.0017 \pm 0.0001,$$
$$(F_0 + F_{\mathrm{L}} + F_{\mathrm{R}} = 1)$$

@ NNLO QCD calculation, Phys. Rev. **D81** (2010) 111503

The $t \to bW$ decay in $t\bar{t}$ events

W Helicity from CMS (19.7 fb^{-1}@ 8 TeV): [CMS PAS TOP-14-017]





Systematic Uncertainties (3D Fit):

F_0: Fac./Renorm. scales, jet-parton matching
top p_T reweight

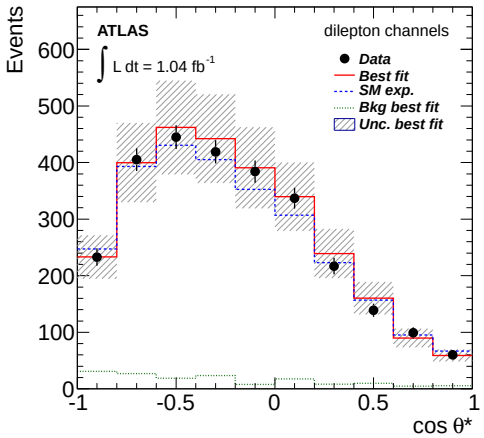
F_L: Fac./Renorm. scales, jet-parton matching

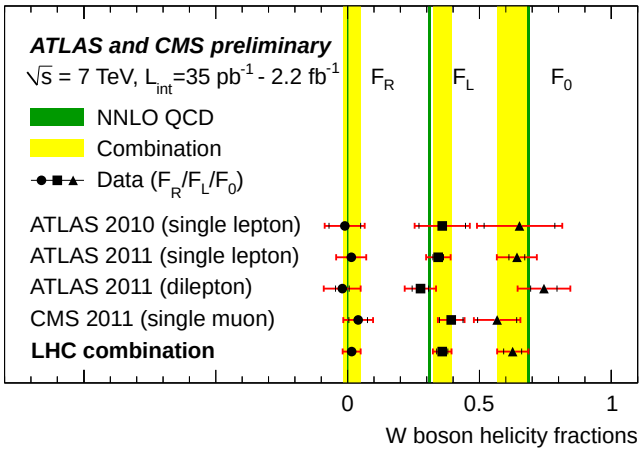
$F_0 = 0.653 \pm 0.016(\text{stat}) \pm 0.024(\text{syst})$
$F_L = 0.329 \pm 0.009(\text{stat}) \pm 0.025(\text{syst})$
$F_R = 0.018 \pm 0.008(\text{stat}) \pm 0.026(\text{syst})$

$\Delta F_0/F_0 = 4\%, \quad \Delta F_L/F_L = 8\%$

☞ single top important: JHEP**01** 053 (2015)
stringent limits on anomalous couplings!!

W Helicity from ATLAS (1.04 fb^{-1}) : [JHEP 1206 (2012) 088]





Combined (ATLAS+CMS):

[ATLAS-CONF-2013-033, CMS PAS TOP-12-025]

$F_0 = 0.626 \pm 0.034(\text{stat}) \pm 0.048(\text{syst})$
$F_L = 0.359 \pm 0.021(\text{stat}) \pm 0.028(\text{syst})$

$F_R = 0.015 \pm 0.034(\text{stat+syst})$

The $t \to bW$ decay in $t\bar{t}$ events

General Wtb vertex

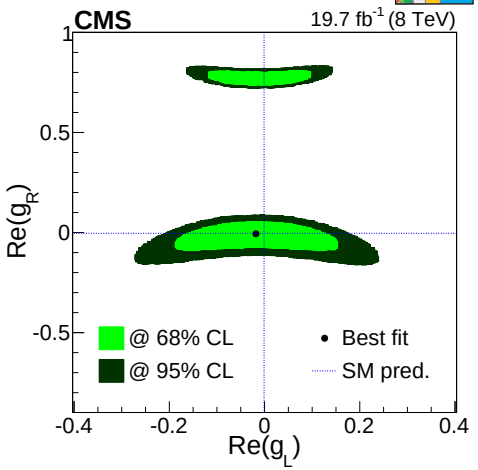
Eur.Phys.J. C50 (2007) 519-533

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-}$$

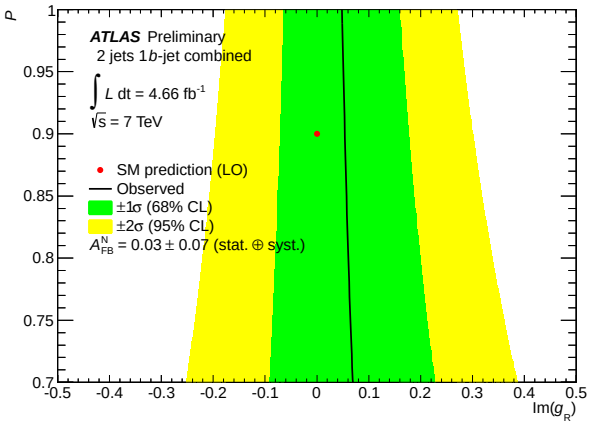
Vector (V_R) and Tensor like couplings (g_L, g_R) zero @ tree level in SM

- Angular distributions of the top decay products (and asymmetries) can be used to probe anomalous couplings at the *Wtb* vertex ☞ **Combinations is the game!**

JHEP01 053 (2015)

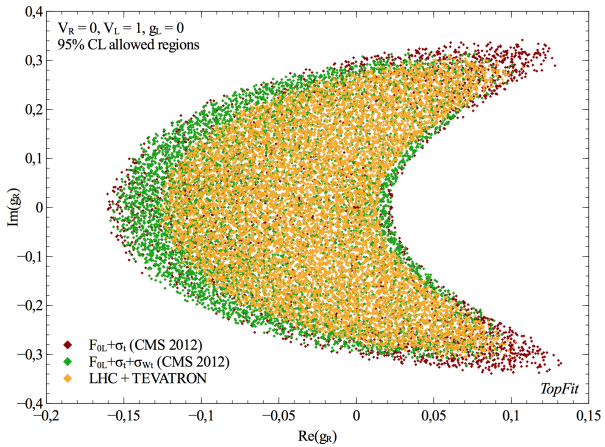


ATLAS CONF-2013-032



Nucl.Phys.B840,349(2010)

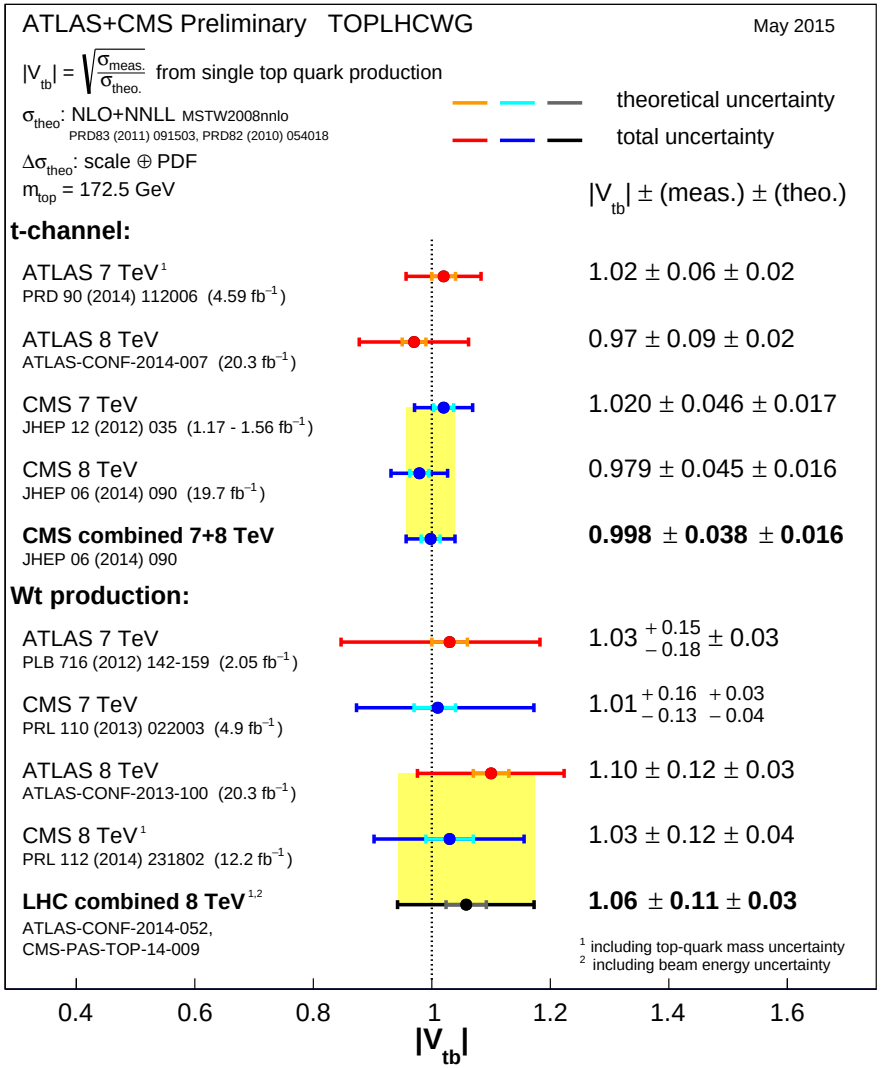
PRD 90 (2014) 11, 113007



- What next? ☞ extract the spin properties of the mensagers of new physics from data arXiv:1508.04592v2 [hep-ph] 21 Aug 2015
- **Assuming V_L=1 (V_R=0) ☞ What is the current LHC status of V_{tb} in the SM? What about the top quark couplings to other bosons?**

Top quark couplings to bosons: V_{tb} @ LHC

Summary of V_{tb} Measurements @ LHC



☞ $|V_{tb}|^2$ extracted with:

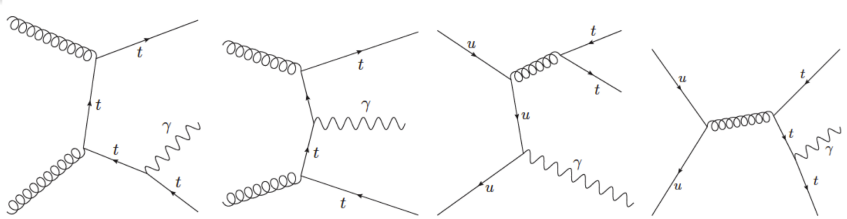
$$|V_{tb,obs.}|^2 = \frac{\sigma_{t,obs.}}{\sigma_{t,SM}} \times |V_{tb,SM}|^2$$

$\delta|V_{tb}|/|V_{tb}|$ @ 5-10%

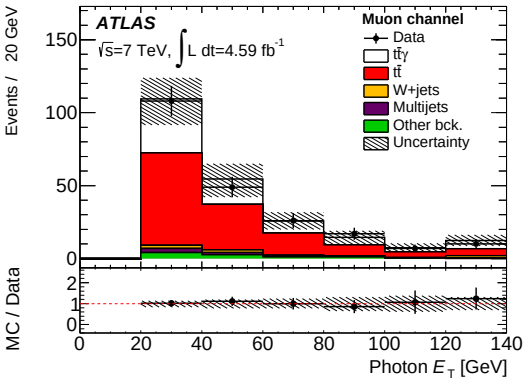
☞ What about the top quark couplings to the known gauge bosons (γ, W, Z, H)?

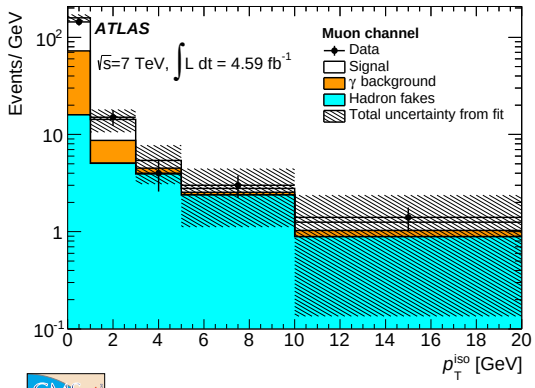
Top Couplings to Bosons ttV ($V = \gamma, Z, W, H$)

$t\bar{t}\gamma$



ATLAS @ 7 TeV, 4.59 fb^{-1} : PRD**91** 072007 (2015)





$\sigma_{t\bar{t}\gamma}$=48(47)±10(10) fb Whizard (MadGraph)

- $\sigma(t\bar{t}\gamma)$ ☞ measurement of top quark EW coupling to γ ($\propto Q_t$)
- fully fiducial measurement
- Analysis: ℓ + *jets* channel $\oplus\,\gamma$ with

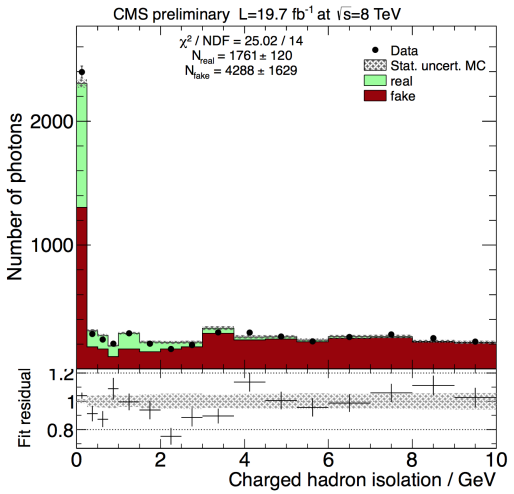
  $\Delta R(\gamma, \ell) < 0.7$, $\Delta R(\gamma, j) < 0.5$, $|m_{e\gamma} - m_Z| > 5$ GeV

  (N_{e+jets}=140 and $N_{\mu+jets}$=222 events in data)
- γ isolation used ☞ $p_{T,\gamma}$ Fit w/ Prompt+Fake Temp.

$$\sigma(t\bar{t}\gamma) \times BR = 63 \pm 8(stat)^{+17}_{-13}(syst) \pm 1(lumi)\ \text{fb}, \quad \text{sign. of } 5.3\sigma$$

CMS @ 8 TeV, 19.7 fb^{-1}:

CMS-PAS-TOP-13-011



Fiducial region for γ: $E_{T,\gamma}$**>20 GeV,** $|\Delta(\eta_\gamma, b/\bar{b})|$**>0.1** $\quad \sigma^{SM}_{t\bar{t}\gamma} = 1.8 \pm 0.5$ **pb**

Event selection:

☞ μ + *jets* **final state** $\oplus\gamma$

☞ $\geq$**4 jets, 2***b***-jets,** $E_{T,\gamma}$**>20 GeV,** $|\eta_\gamma|$**<1.444**

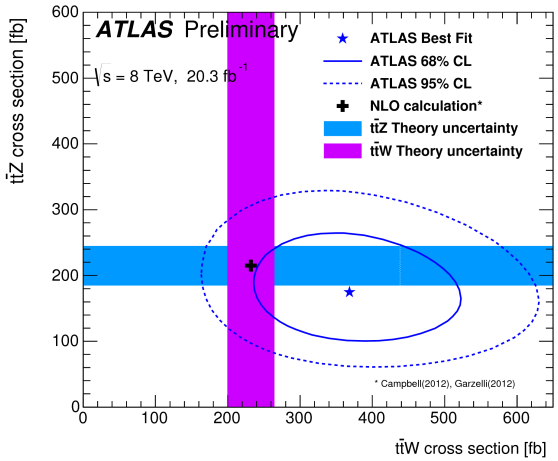
$$R = \sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}} = [1.07 \pm 0.07(stat.) \pm 0.27(syst.)] \times 10^{-2}$$

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

$\Delta\sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}\gamma}$ ~30%

$t\bar{t}V, V = Z, W$

ATLAS @ 8 TeV, 20.3 fb^{-1} : [ATLAS-CONF-2015-032]



Multi-lepton final state (e+μ) channels:

☞ **3- and 4-lepton exclusive searchs (target mostly $t\bar{t}Z$):**

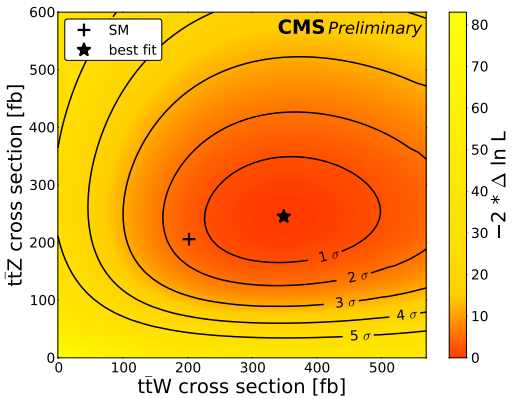
$\sigma(t\bar{t}Z) = 176^{+52}_{-48}(stat) \pm 44(syst)$ fb

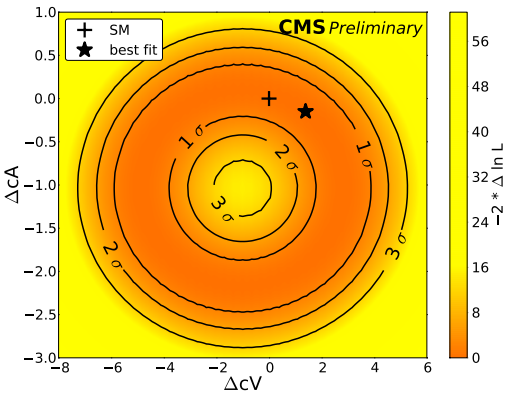
☞ **SS+OS 2- lepton search (target $t\bar{t}V$):**

$\sigma(t\bar{t}W) = 369^{+86}_{-79}(stat) \pm 44(syst)$ fb

$\Delta\sigma_{t\bar{t}V}/\sigma_{t\bar{t}V}$ = 30-40%, sig. of 5.0σ(4.2σ) over back. for $t\bar{t}W(t\bar{t}Z)$

CMS @ 8 TeV, 19.5 fb^{-1} : [CMS-PAS-TOP-14-021]





Five leptonic exclusive channels:

1) $t\bar{t} \to bq\bar{q}bq\bar{q}$, $b\ell\nu_\ell bq\bar{q}$, $b\ell\nu_\ell b\ell\nu_\ell$

2) $W \to \ell\nu_\ell, Z \to \ell^+\ell^-$ ($\ell = e, \mu$)

☞ **2, 3 and 4 lep.** $\oplus$ $m_{\ell^+\ell^-} = m_Z$ **($t\bar{t}Z$):**

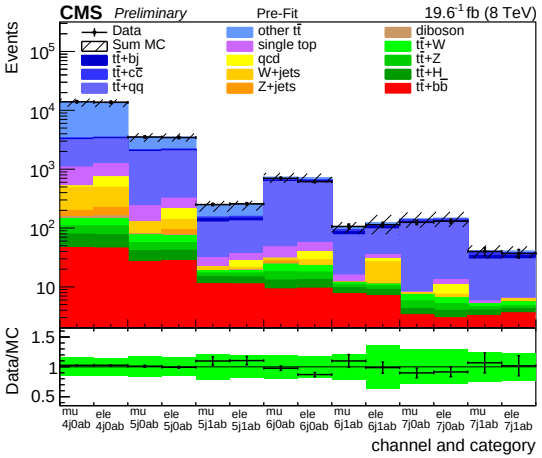
$\sigma(t\bar{t}Z) = 242^{+65}_{-55}$ fb

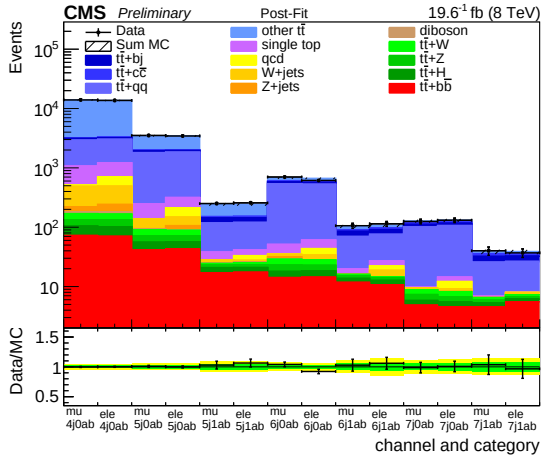
☞ **2 SS and 3 lep.** $\oplus$ $m_{\ell^+\ell^-} \neq m_Z$ **($t\bar{t}W$):**

$\sigma(t\bar{t}W) = 382^{+117}_{-102}$ fb

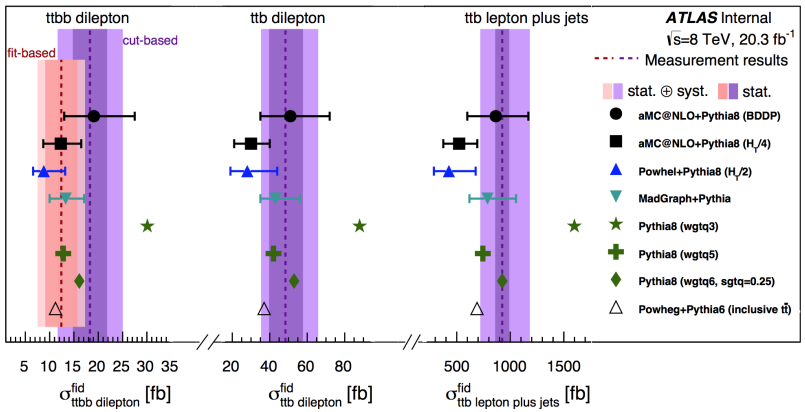
CMS @ 8 TeV $\Delta\sigma_{t\bar{t}V}/\sigma_{t\bar{t}V}$ = 20-30%, sig. of 4.8σ(6.4σ) over back. for $t\bar{t}W(t\bar{t}Z)$

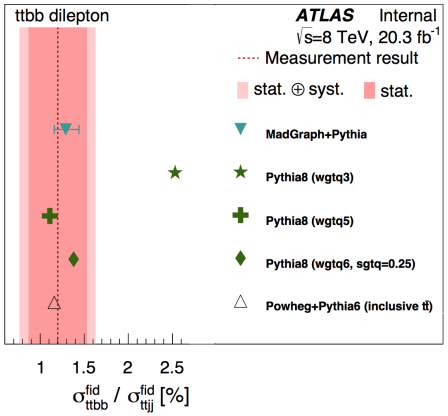
CMS $\sigma_{t\bar{t}}$ (19.6 fb^{-1}@ 8 TeV): CMS PAS TOP-13-016





ATLAS $\sigma_{t\bar{t}}$ (20.3 fb^{-1}@8TeV): ATLAS TOPQ-2014-10





JHEP**1407**,135(2014) Theory(NLO) $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = (1.09^{+0.43}_{-0.14})\%$

Semileptonic $t\bar{t}$ decays:

- Single tight lepton (e, $\mu w/p_T$ >30 GeV)
- $N_j \geq 4$ (p_T >50 GeV)
- $N_{b-tag} \geq 2$ (using CSVM wrk. point)

☞ **$t\bar{t}$ reconstruction in 3 steps:**

1) use constrained fit w/ m_W, m_t (no b-tag info used)
2) jet association using BDT multivariate classifier
3) b-tag discriminant variable> 0.5

☞ **Fid. phase space results from templates fit:**

$\sigma(t\bar{t}b\bar{b}) = 271 \pm 103(stat) \pm 32.2(syst) \pm 7(lumi)$ fb

Theory (NLO)=$229^{+18\%}_{-24\%}$ fb, JHEP**1407**,135(2014)

$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 0.0117 \pm 0.0040(stat) \pm 0.0003(syst)$

Several analysis for $t\bar{t}b(\bar{b})$:

☞ **σ meas. in 3 fiducial phase-spaces:**

$t\bar{t}b$, ℓ+jets with N_ℓ=1, $N_j \geq$5, $N_b \geq$3

$t\bar{t}be\mu$, dilep with $N_\ell = 2$, $N_b \geq$3

$t\bar{t}b\bar{b}$, dilep with $N_\ell = 2$, $N_b \geq$4

☞ **$t\bar{t}$ dilepton (ee, $e\mu$, $\mu\mu$)⊕ 2 b_{jets}:**

Cut-based analysis w/ tight cuts

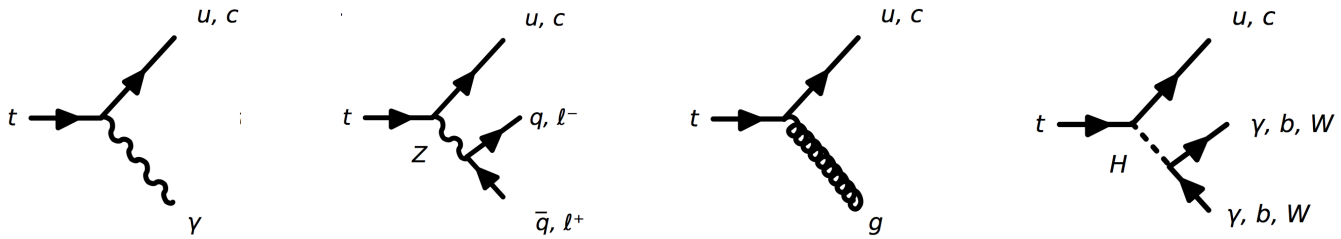
Fit-based analysis w/ looser cuts

☞ **Results from b_{tag} templates fits:**

$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = (1.3 \pm 0.33_{stat} \pm 0.28_{syst})\%$

FCNC processes ($tqX, X = \gamma, Z, g, H$)

- Several $t\bar{t}$ FCNC Decay Channels Studied @ LHC:



Theoretical predictions for the BR of FCNC top quark decays

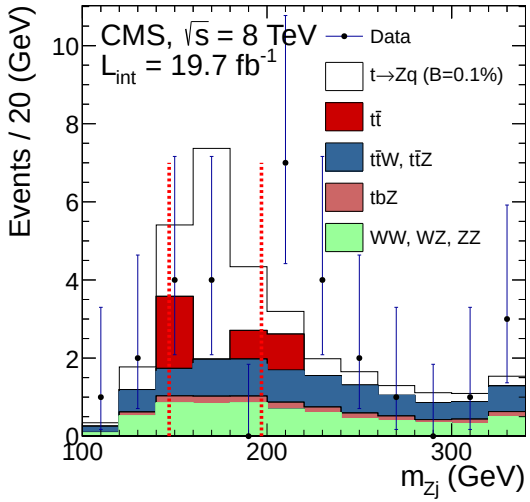
Process	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY	RS
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}	—
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}	—
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}	—
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	—	10^{-5}	$\sim 10^{-6}$	—
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}	$\leq 10^{-5}$
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}	$\leq 10^{-9}$
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}	$\leq 10^{-10}$
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$	$\leq 10^{-4}$

Acta Phys.Polon.**B35**,2695(2004), arXiv:1311.2028

- In the SM flavour changing neutral currents (FCNC) are forbidden at tree level and much smaller than the dominant decay mode ($t \to bW$) at one loop level
- BSM models predict higher BR for top FCNC decays
  ☞ powerful probe for new physics

FCNC processes ($tqX, X = \gamma, Z, g, H$)

$t\bar{t} \to \ell\nu b + \ell\ell q$ (19.7 fb^{-1},8 TeV $\oplus$ 5.0 fb^{-1},7 TeV): CMS PRL**112**,171802(2014)



Trilepton selection:

t->qZ

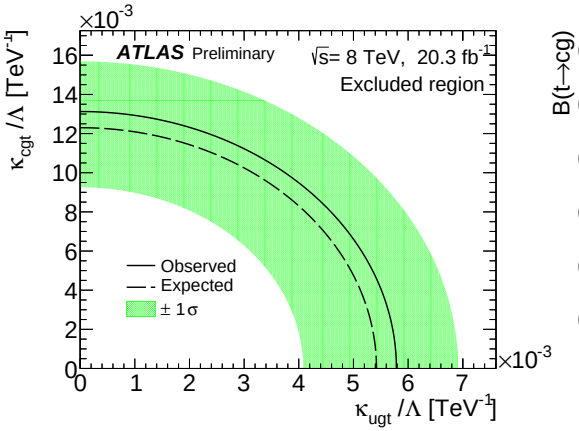
- 3 iso. leptons (e,μ) with 2 $\ell^+\ell^-$ with 1 pair 78 GeV<$|m_{\ell^+\ell^-} - m_Z|$<102 GeV
- $E_{\mathrm{T}}^{\mathrm{miss}}$>30 GeV
- $\geq$ 2 jets, with p_T>30 GeV, only 1 b_{jet}
- m_{Zj}, m_{Wb} cuts

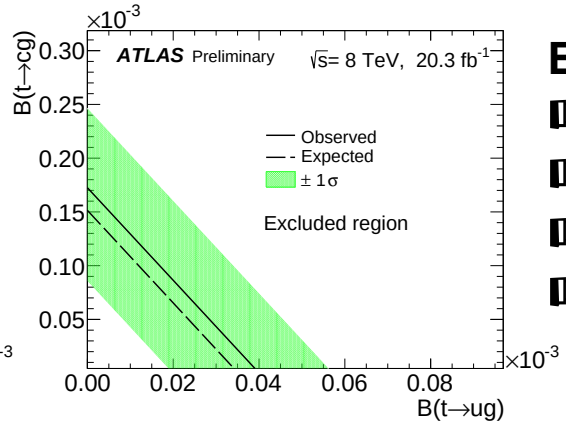
Results @ 7+8 TeV:

$Br(t \to qZ)$**< 0.05% (obs.) 0.09% (exp.) @ 95% CL**

Syst.: Ren./Fac. Q^2 scales, $\sigma_{t\bar{t}}$, PDF

$qg \to t \to W(\ell\nu)b$, 20.3 fb^{-1} @ 8 TeV ATLAS-TOPQ-2014-13-002





Event selection:

- exactly 1 isolated e or μ
- missing transverse energy
- exactly 1 b_{jet}
- **Results:**

$Br(t \to ug) < 4.0 \times 10^{-5}$**(obs.)**

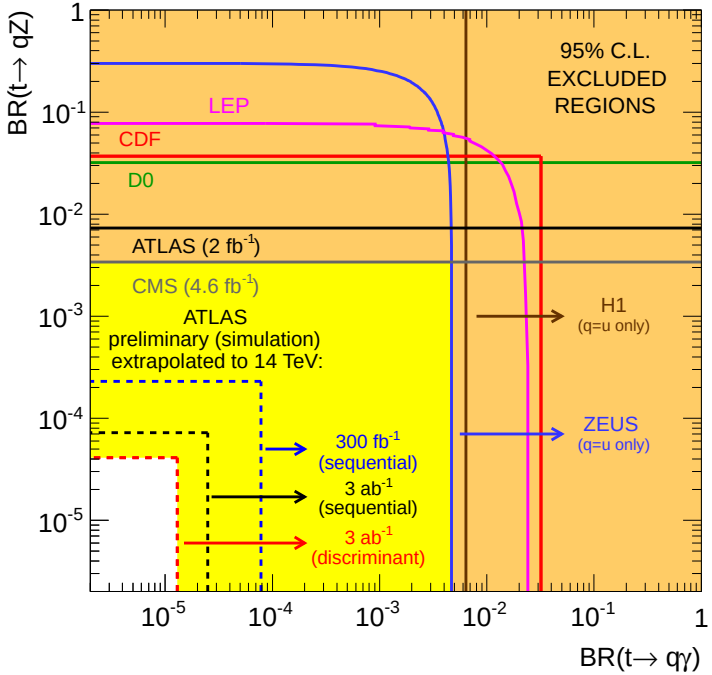
$Br(t \to cg) < 1.7 \times 10^{-4}$**(obs.)**

FCNC Direct Bounds RUN I (short) Summary:

Decay Channel	95% CL Limit	Data Set and Exp.
$B(t \to qg)$	4.0×10^{-5} $(q = u)$	ATLAS-TOPQ-2014-13-002
	1.70×10^{-4} $(q = c)$	(8 TeV, 20.3 fb^{-1})
	3.55×10^{-4} $(q = u)$	CMS-PAS-TOP-14-007
	3.44×10^{-3} $(q = c)$	(7TeV,5.0 fb^{-1})
$B(t \to qZ)$	7×10^{-4} $(q = u, c)$	arXiv:1508.05796
		(8 TeV, 20.3 fb^{-1})
	5×10^{-4} $(q = u, c)$	PRL**112**,171802(2014)
		(7TeV,5.0 fb^{-1} $\oplus$8TeV,19.7 fb^{-1})
$B(t \to q\gamma)$	1.61×10^{-4} $(q = u)$	CMS-PAS-TOP-14-003
	1.82×10^{-3} $(q = c)$	(8 TeV, 19.1 fb^{-1})
$B(t \to qH)$	7.90×10^{-3} $(q = u, c)$	JHEP**1406**,008(2014)
		(7TeV,4.7 fb^{-1} $\oplus$8TeV,20.3 fb^{-1})
	4.20×10^{-3} $(q = u)$	CMS-PAS-TOP-14-019
	4.70×10^{-3} $(q = c)$	(8 TeV, 19.7 fb^{-1})

☞ Limits @ RUN 1 in the range 10^{-3} to 10^{-5}

Prospects:



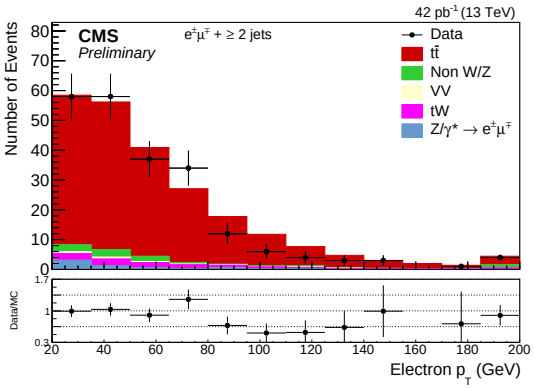
☞ 95%Limits @ RUN 2 expected to improve $\sim$ 1 order of magnitude:

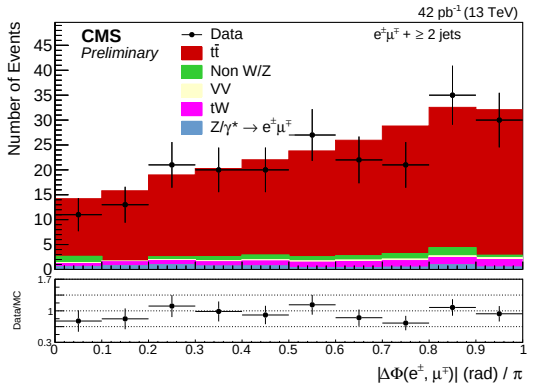
ATL-PHYS-PUB-2012-001
ATL-PHYS-PUB-2013-012

CMS-PAS-FTR-13-016

$t\bar{t}$ production @ the RUN 2 of LHC

CMS $\sigma_{t\bar{t}}$ (42 pb^{-1}@ 13 TeV): CMS PAS TOP-15-003

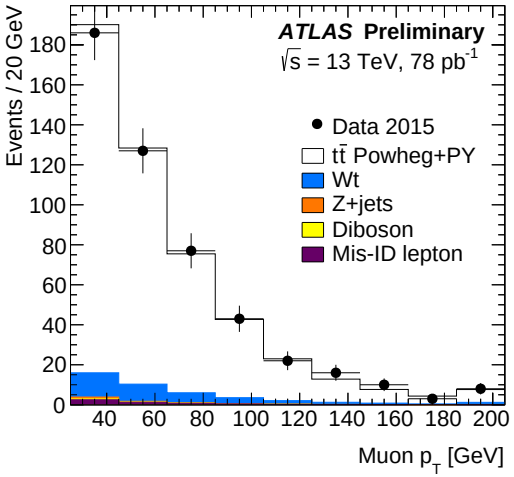


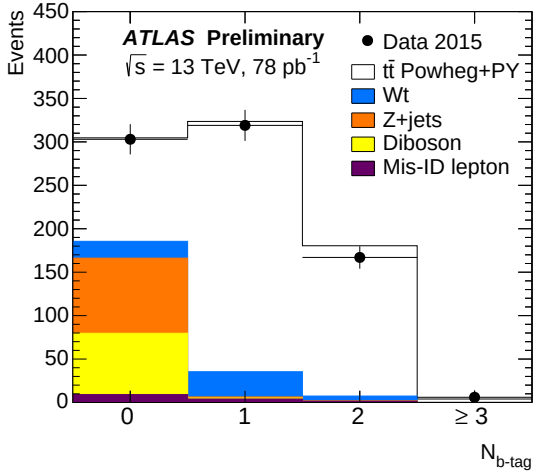


$t\bar{t}$ Dilepton ($e^{\pm}\mu^{\mp}$):

- 1 e and 1 μ of opp. charge
- OS leptons, p_T>20 GeV, $|\eta|$<2.4
- $M_{e^{\pm}\mu^{\mp}}$ <20GeV
- $\geq$2 jets, p_T>30 GeV, $|\eta|$<2.4
- Non W/Z back. estimated with SS leptons
- N_D=220, N_{sig}=207$\pm$16, N_{bck}=28.1$\pm$5.7

ATLAS $\sigma_{t\bar{t}}$ (78 pb^{-1}): ATLAS-CONF-2015-033





$t\bar{t}$ Dilepton ($e^{\pm}\mu^{\mp}$):

☞ $t\bar{t} \rightarrow (e^{\pm} + \nu_e + b) + (\mu^{\mp} + \nu_{\mu} + b)$

- OS leptons, p_T>25 GeV, η<2.4
- Exactly 1 or 2 b_{jets}, p_T>25 GeV
- No E_T^{mis} cut applied

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

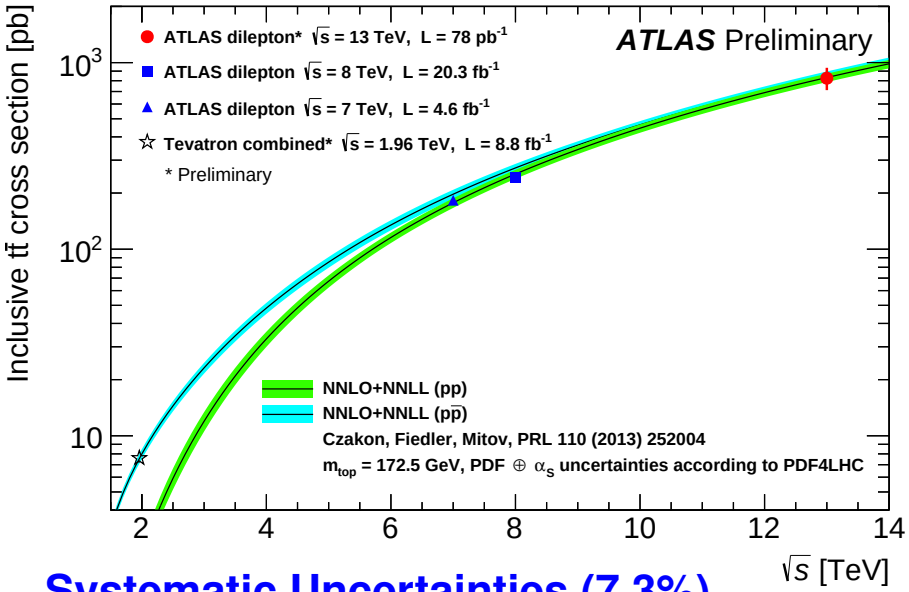
$$N_2 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} C_b {\epsilon_b}^2 + N_2^{\text{bkg}}$$

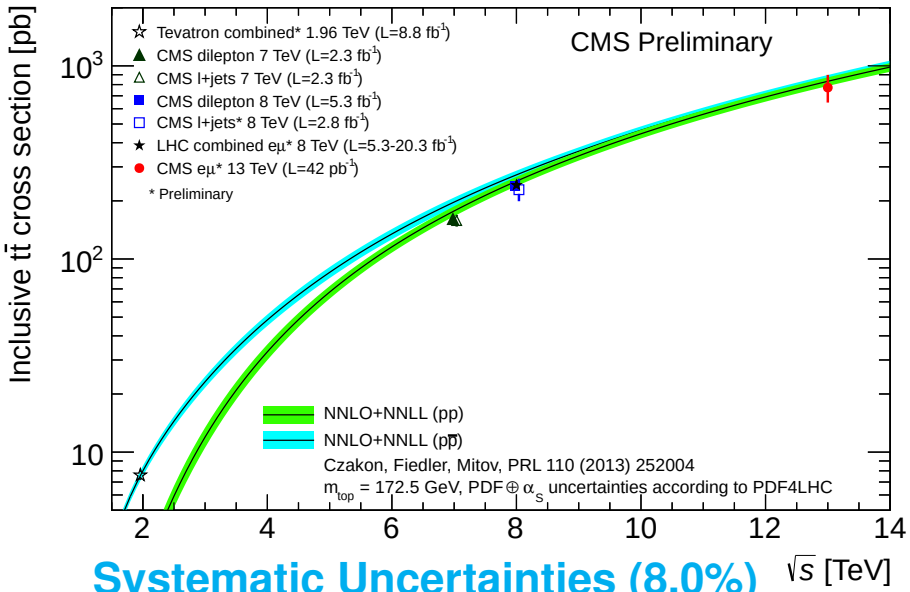
- N_1=319, N_2=167, $\epsilon_b = 0.527 \pm 0.026 \pm 0.006$

Cross-Section Increases by a factor ∼3 @ 13 TeV

$\sigma_{t\bar{t}} = 825 \pm 49(stat.) \pm 60(syst.) \pm 83(lumi)$ pb

$\sigma_{t\bar{t}} = 772 \pm 60(stat.) \pm 62(syst.) \pm 93(lumi)$ pb





Systematic Uncertainties (7.3%)

- $t\bar{t}$ hadronization: 4.5%, diff. Powheg+Herwig++ vs Powheg+Pythia6
- Electron ID: 4.0%
- $t\bar{t}$ NLO modelling: 2.2%, diff. aMC@NLO+Herwig++ and Powheg+Herwig++

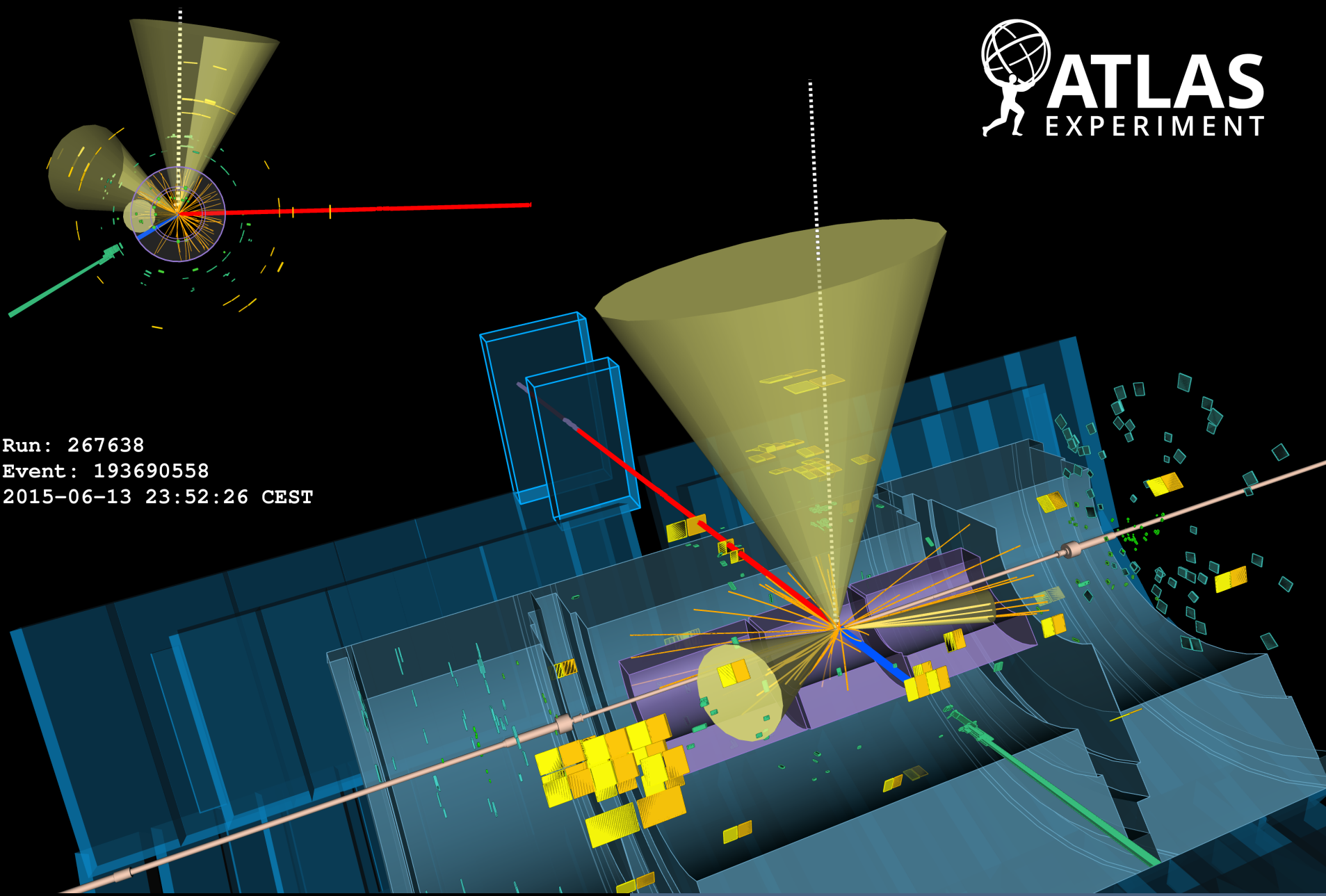
Statist. Uncert.: 6.0%
Luminosity Uncert.: 10%

Systematic Uncertainties (8.0%)

- Trigger ϵ: 5.0%
- Lepton ϵ: 4.3%
- Jet Energy Scale: 2.6%
- $t\bar{t}$ NLO Gen.: 1.9%
- $t\bar{t}$ hadronization: 1.8%

Statist. Uncert.: 7.7%
Luminosity Uncert.: 12%

$t\bar{t}$ production @ the RUN 2 of LHC



Conclusions

- Top quark has turned 20, still a long way to go in RUN 2
- At RUN I ☞ things went really well: measurements are a World reality with CDF, D0, ATLAS and CMS
- Although no new physics seen @ LHC in top quark physics, it might be just at the corner
- Many measurements are already dominated by systematic errors ☞ need combinations with dedicated tools
- Still a long way to get more precision @ RUN 2 (looks really promising):
  - top quark production (e.g. s-channel single top and V_{tb})
  - couplings to gauge bosons (ttV, $V = \gamma, Z, W, H$) ☞ form factors
  - rare decays ($t \to Ws, Wd$, FCNC, new physics)

The phenomenology of top quark physics needs high precision

List of public results from ATLAS and CMS on top quark physics:

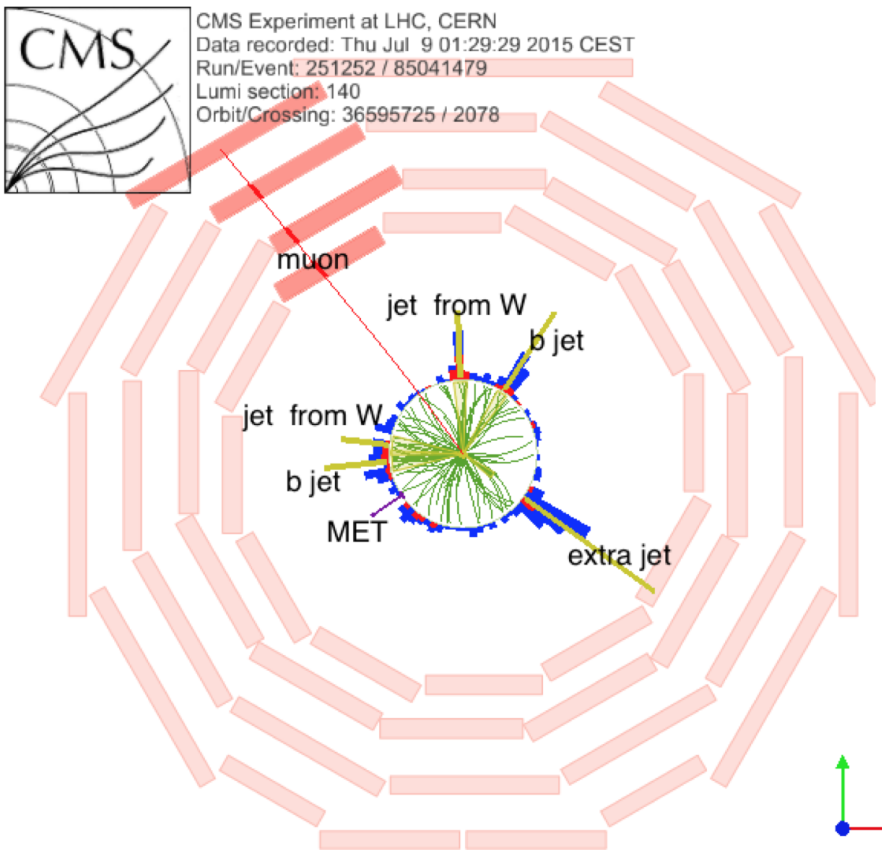
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

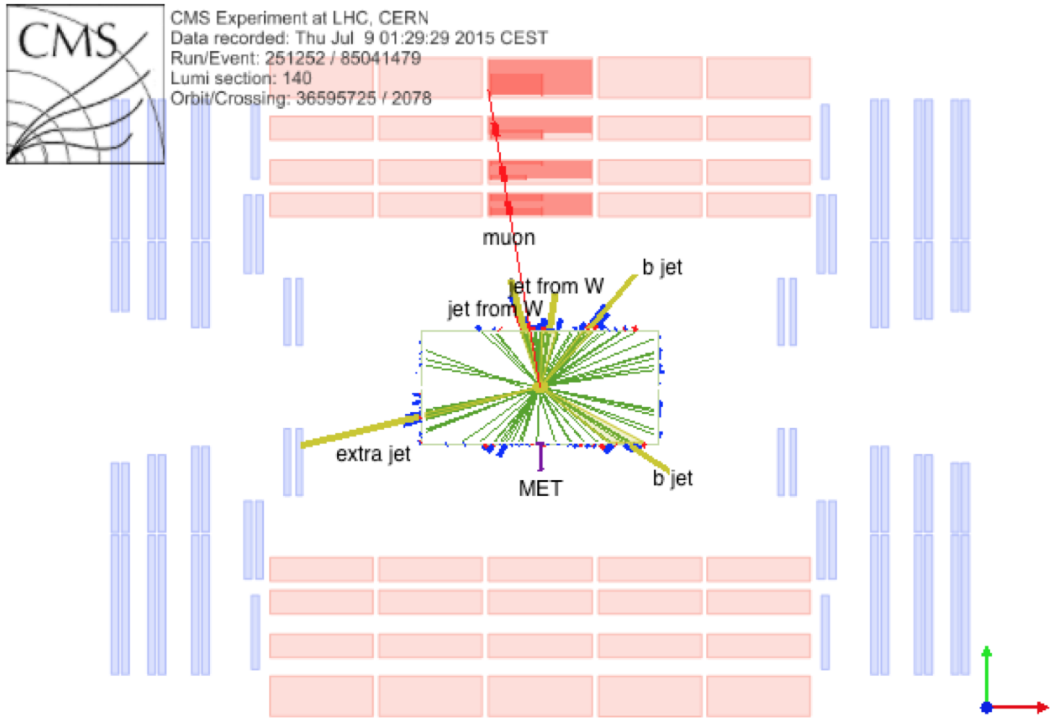
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

BACKUP

SLIDES

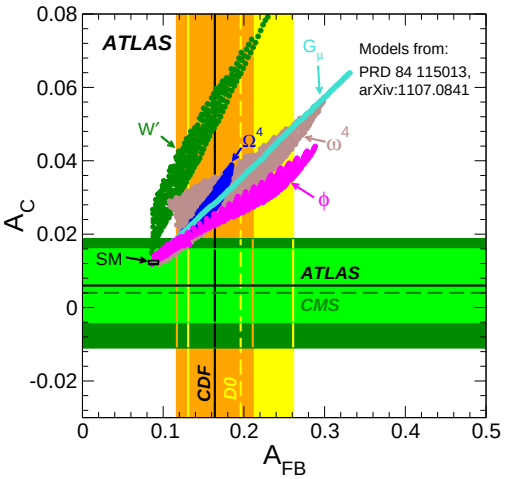
$t\bar{t}$ production @ the RUN 2 of LHC

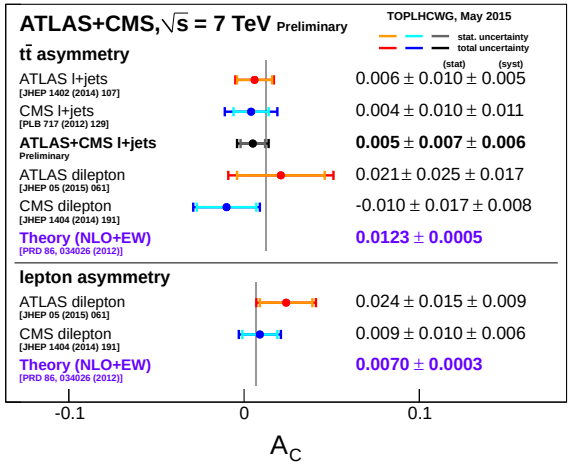




Charge Asymmetry @ LHC

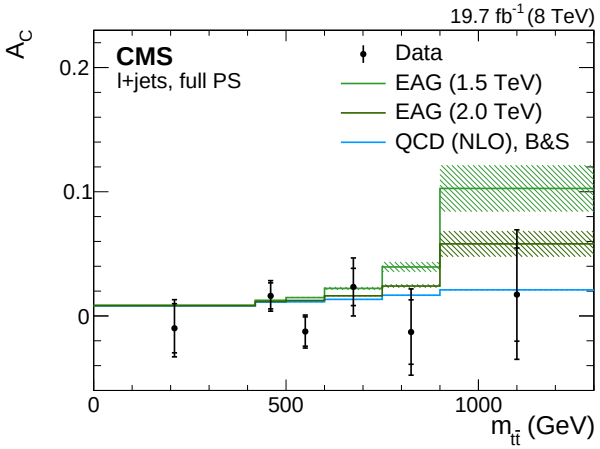
ATLAS $\sigma_{t\bar{t}}$ (4.7 fb^{-1}@7TeV): JHEP**02**,107(2014)

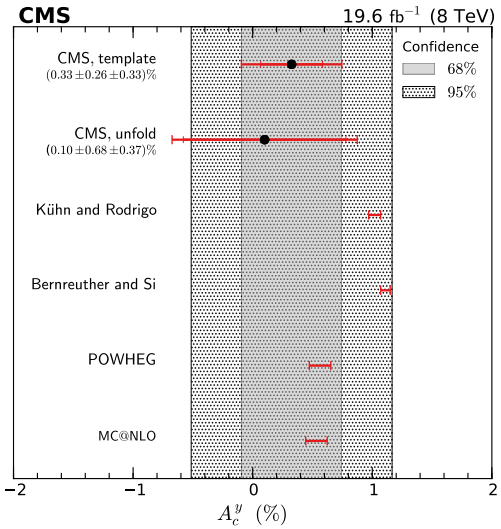




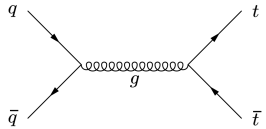
CMS $\sigma_{t\bar{t}}$ (19.6-19.7 fb^{-1}@ 8 TeV):

arXiv:1507.03119



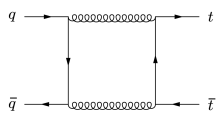


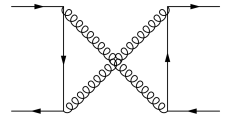
LO is symmetric



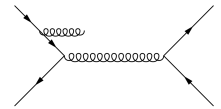
Asym. Originates in Interference w/:

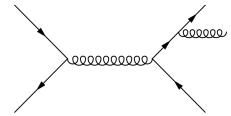
- Virtual Corrections





- Real Emission



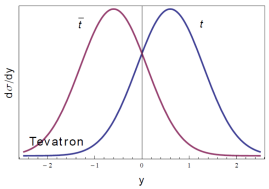


@ Tevatron:

$A_{FB}^{SM} = 0.095 \pm 0.007$ PRL**115**,052001(2015)

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

$$\Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$$

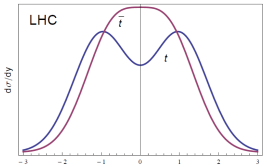


@ LHC only $q\bar{q}$ subsample:

$A_C^{SM} = 0.0123 \pm 0.0005$ PRD**86**,034026(2012)

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

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



New Template Fit: arXiv:1508.03862

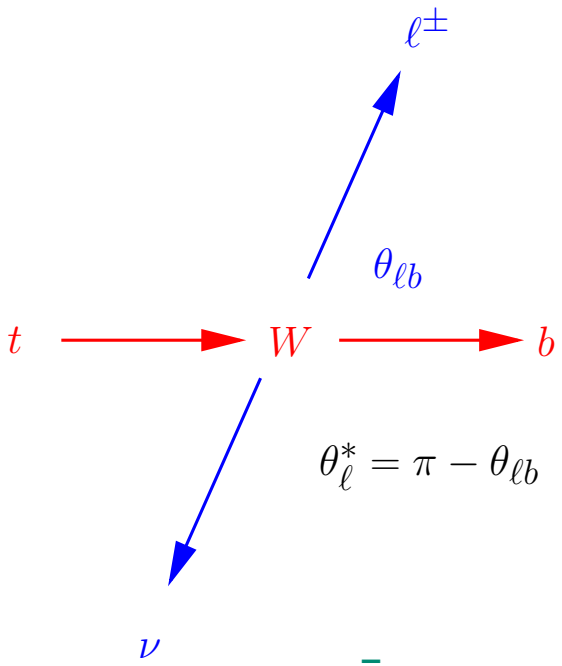
- **explore the shape of $\Delta|y|$**
- **use $Y_{t\bar{t}} = tanh(|y_t| - |y_{\bar{t}}|)$**
- **fit data with templates of symmetric (ρ_+) and antisymmetric (ρ_-) components**

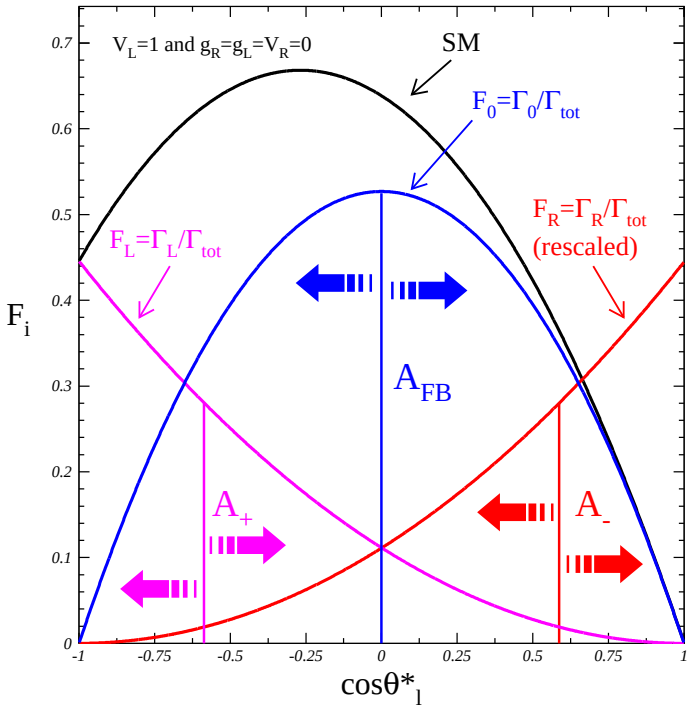
$A_c^y = [0.33 \pm 0.26(stat) \pm 0.33(syst)]\%$

Measuring the W helicity states:

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*_\ell} = \frac{3}{2}\left[F_0\left(\frac{\sin\theta^*_\ell}{\sqrt{2}}\right)^2 + F_\mathrm{L}\left(\frac{1-\cos\theta^*_\ell}{2}\right)^2 + F_\mathrm{R}\left(\frac{1+\cos\theta^*_\ell}{2}\right)^2\right]$$

$\theta^*_\ell \to$ the angle between the ℓ (in W rest frame) and the W (in t rest frame)





Asymmetries (@ NNLO):

$$A_t = \frac{N(\cos\theta^*_\ell > t) - N(\cos\theta^*_\ell < t)}{N(\cos\theta^*_\ell > t) + N(\cos\theta^*_\ell < t)}$$

A_{FB}=-0.232±0.004

A_+ = 0.537±0.004

A_- =-0.841±0.006

- Full $t\bar{t}$ events reconsctruction required (ℓ+jets and dilepton) and:
  - ☞ fit the cos θ^* with templates and evaluate angular asymmetries
  - ☞ these observables allows to probe the Wtb vertex and look for new physics

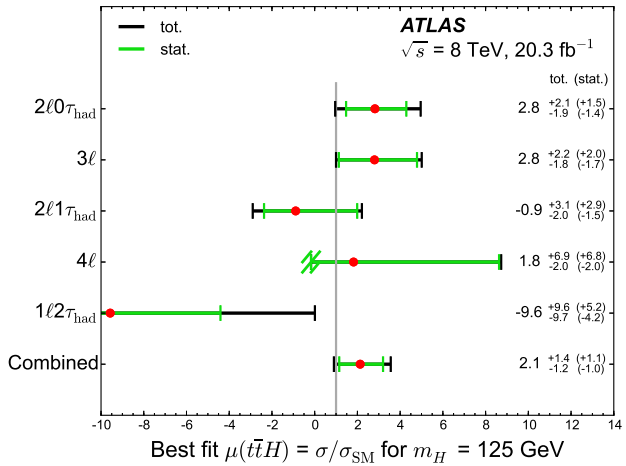
FCNC processes ($tqX, X = \gamma, Z$)

- FCNC Direct Bounds RUN I Summary @ LHC:

Decay Channel	ATLAS	CMS
$B(t \to qg)$	$< 4.0 \times 10^{-5}$ $(q = u)$ ATLAS-TOPQ-2014-13-002 $< 17 \times 10^{-5}$ $(q = c)$ (8 TeV, 20.3 fb^{-1}) $< 3.1 \times 10^{-5}$ $(q = u)$ ATLAS-CONF-2013-063 $< 1.6 \times 10^{-4}$ $(q = c)$ (8 TeV, 14.2 fb^{-1}) $< 5.7 \times 10^{-5}$ $(q = u)$ PLB**712**,351(2012) $< 2.7 \times 10^{-4}$ $(q = c)$ (7 TeV, 2.05 fb^{-1})	$< 3.55 \times 10^{-4}$ $(q = u)$ CMS-PAS-TOP-14-007 $< 3.44 \times 10^{-3}$ $(q = c)$ (7TeV,5.0 fb^{-1}) $< 0.56\%$ $(q = u)$ CMS-PAS-TOP-12-021 $< 7.12\%$ $(q = c)$ (7TeV,5.0 fb^{-1})
$B(t \to qZ)$	$< 7 \times 10^{-4}$ $(q = u, c)$ arXiv:1508.05796 (8 TeV, 20.3 fb^{-1}) $< 0.73\%$ $(q = u, c)$ JHEP**1209**,139(2012) (7 TeV, 2.1 fb^{-1})	$< 0.05\%$ $(q = u, c)$ PRL**112**,171802(2014) (7TeV,5.0 fb^{-1} $\oplus$ 8TeV,19.7 fb^{-1}) $< 0.21\%$ $(q = u, c)$ PLB**718**,1252(2013) (7TeV,5.0 fb^{-1}) $< 0.51\%$ $(q = u)$ CMS-PAS-TOP-12-021 $< 11.4\%$ $(q = c)$ (7TeV,5.0 fb^{-1}) $< 0.07\%$ $(q = u, c)$ CMS-PAS-TOP-12-037 (8TeV,19.5 fb^{-1})
$B(t \to q\gamma)$		$< 0.0161\%$ $(q = u)$ CMS-PAS-TOP-14-003 $< 0.182\%$ $(q = c)$ (8 TeV, 19.1 fb^{-1})
$B(t \to qH)$	$< 0.79\%$ $(q = u, c)$ JHEP**1406**,008(2014) (7TeV,4.7 fb^{-1} $\oplus$ 8TeV,20.3 fb^{-1})	$< 0.42\%$ $(q = u)$ CMS-PAS-TOP-14-019 $< 0.47\%$ $(q = c)$ (8 TeV, 19.7 fb^{-1}) $< 0.56\%$ $(q = c)$ PRD**90**,112013(2014) (7TeV,5.0 fb^{-1} $\oplus$ 8TeV,19.7 fb^{-1}) $< 0.93\%$ $(q = c)$ CMS-PAS-TOP-13-017 (8 TeV, 19.7 fb^{-1}) $< 1.3\%$ $(q = c)$ PRD**90**,032006(2014) (8 TeV, 19.5 fb^{-1})

$t\bar{t}H$ @ 8 TeV

Lumi $= 20.3\ \text{fb}^{-1}$: arXiv:1506.05988v1 [hep-ex], accepted by PLB



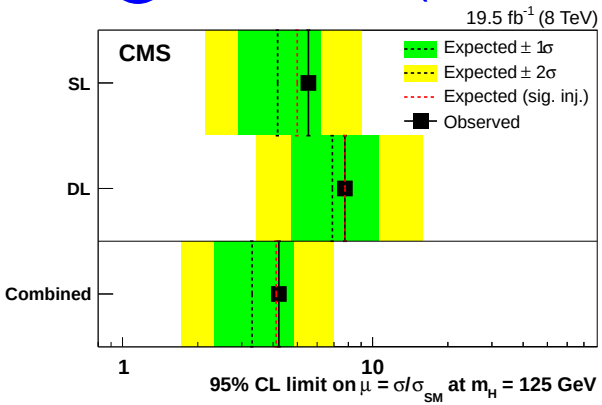
Five final states for $H \to WW*, ZZ*$ *and* $\tau\tau$**:**

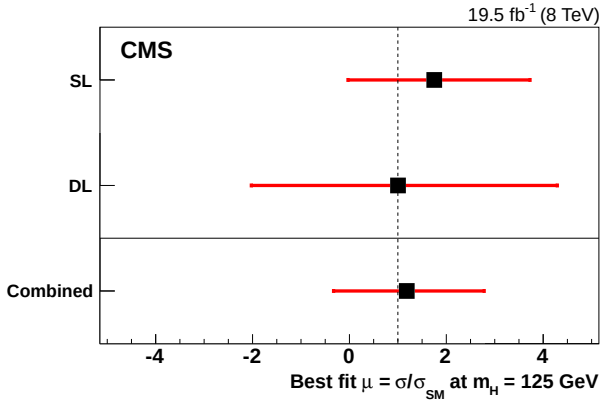
- ☞ two same-charge (e or μ) with no τ with hadron. decay
- ☞ three light leptons (e or μ)
- ☞ two same-charge (e or μ) $\oplus$ τ with hadron. decay
- ☞ four light leptons (e or μ)
- ☞ one lepton (e or μ) and two hadronically decaying τ leptons

Best fit value $\mu = 2.1^{+1.4}_{-1.2}$, μ**<4.7(2.4) @ 95% C.L.**

$t\bar{t} \oplus H \to b\bar{b}$ (19.5 fb^{-1}):

EPJ**C75**, 251 (2015)





Matrix Element Method:

- ☞ Assign P_S and P_B to each event
- ☞ Use a Max.Like.Fit to P_S/P_B
- ☞ Analysis strategy optimised to separate $t\bar{t}H$ from $t\bar{t}b\bar{b}$
- ☞ 1 or 2 leptons (e or μ) required

Best fit value $\mu = 1.2^{+1.6}_{-1.5}$, μ**<4.2(3.3) @ 95% C.L.**