# FLAVOUR PHYSICS WITH TOP

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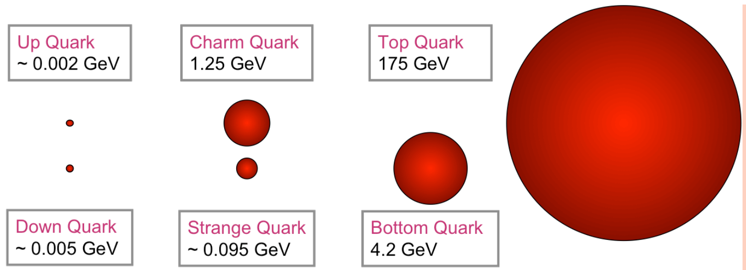
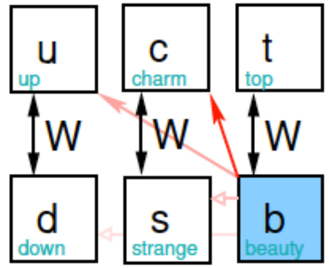
# OUTLINE

- Physics motivation: why top quark flavour physics
- Top quark production at LHC
- Top flavour measurements
  - $V_{td}$, $V_{ts}$ & $V_{tb}$
  - Anomalous Wtb couplings
  - Flavour changing neutral currents (FCNC)
  - Searches of new quarks: t' and b'

# PHYSICS MOTIVATION:
## why top quark FLAVOUR physics?




$$V_{\mathrm{CKM}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$




- → The LHC is a top factory
- →Top quark is very different from the other 5 quarks:
  - → short life-time: it decays before hadronization Γ~1.4GeV→ the spin info is passed to its children
  - → high mass
  - → t→ Wb dominant mode
- → Top quark can be a window to new flavour phenomena. In the SM:
  - → charged current mixing: $|V_{tb}| >> |V_{td}|, |V_{ts}|$; t→ Wb dominant
  - → FCNC very suppressed because $m_t >> m_{d,s,b}$: BR(t→Zc/γc/gc) < $10^{-12}$
  - → CP violation effects vanish (probe Wtb anomalous couplings)

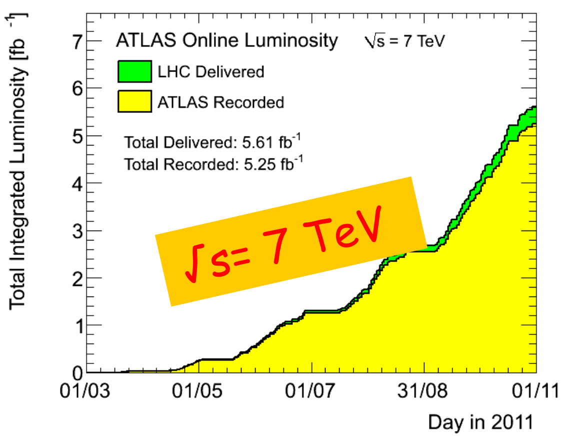
Therefore: measuring $V_{td}$, $V_{ts}$, top FCNC or CP violation within the SM is extremely hard at hadron colliders!

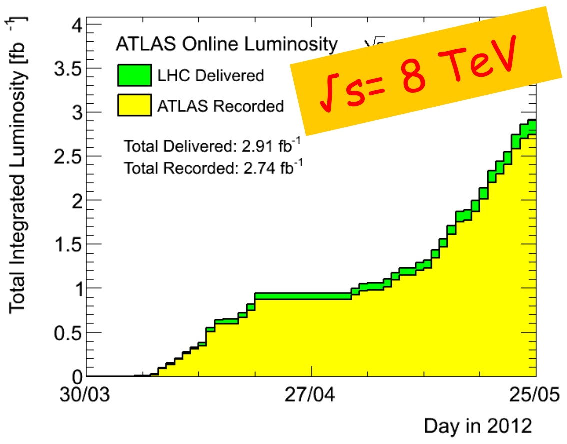
# TOP QUARK PRODUCTION

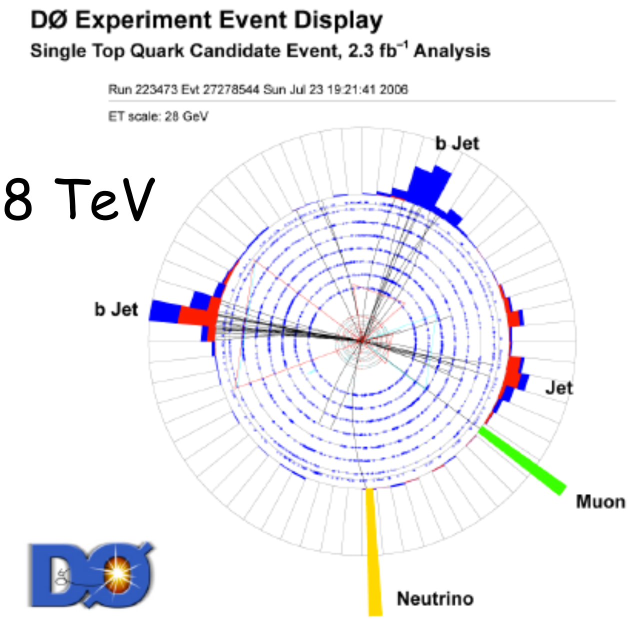
- Top quarks are produced in pairs (strong interaction) or single top quarks (electro-weak interaction)

- Discovered at Tevatron in 1995 → **Top: The TevatrOn Particle**
- Single top quark observation in 2009 at Tevatron

- LHC is a top factory: data collected ~5 $fb^{-1}$ in 2011 @ 7 TeV and ~3 $fb^{-1}$ in 2012 @ 8 TeV



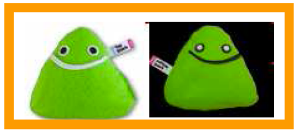



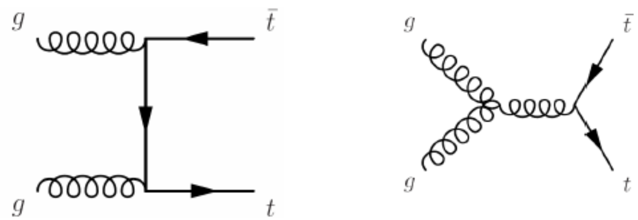

→ The analysis here presented have been performed using (a fraction of) 2011 data.

# Top quark production

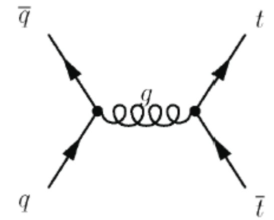
**Top quark pairs**



**Strong interaction**



gluon-gluon fusion



quark-antiquark annihilation

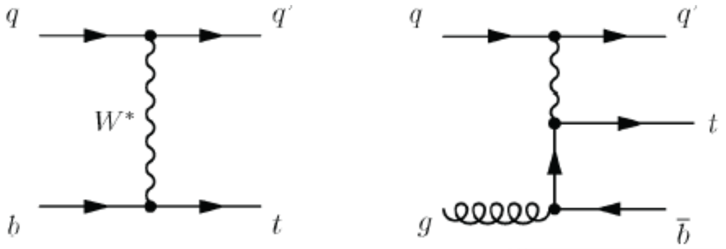
$\sigma$(7 TeV)=$165^{+11}_{-16}$ pb

NNLO approx. calculation

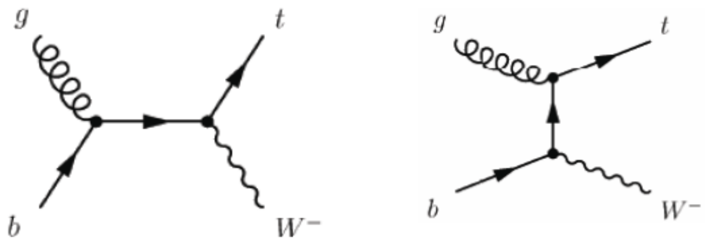
for a $m_{top}$=172.5 GeV (Moch, Uller)

**Single top**  or 

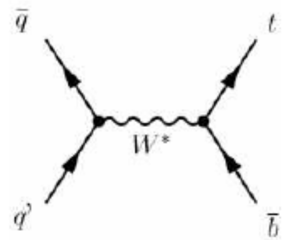
**electro-weak interaction**



t-channel



Wt-channel



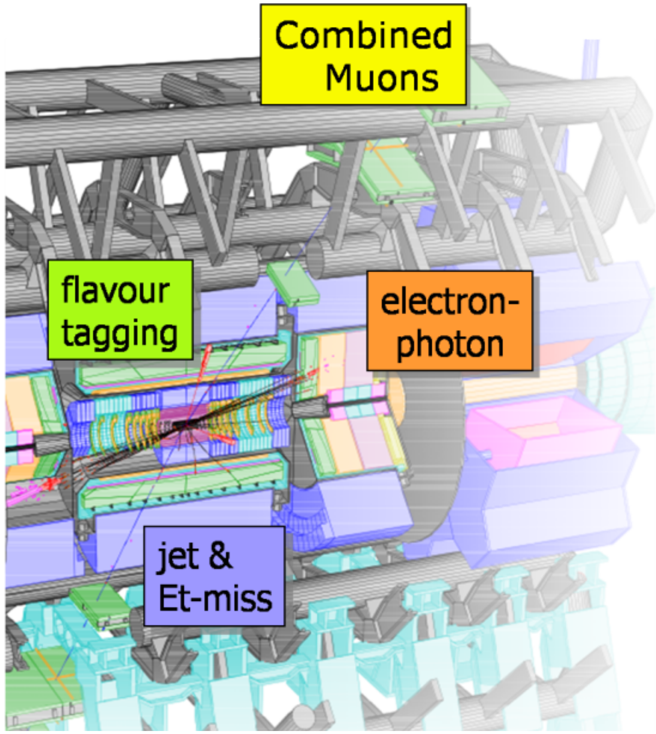
s-channel

| Cross sections | 1.96 TeV $m_t$ = 173 GeV | 7 TeV $m_t$ = 172.5 GeV |
|---|---|---|
| t-channel | $2.1 \pm 0.1$ pb | $64.6 \pm 2.4$pb |
| Wt | $0.25 \pm 0.03$ pb | $15.7 \pm 1.1$ pb |
| s channel | $1.05 \pm 0.05$ pb | $4.6 \pm 0.2$ pb |

NLO with NNLL corrections

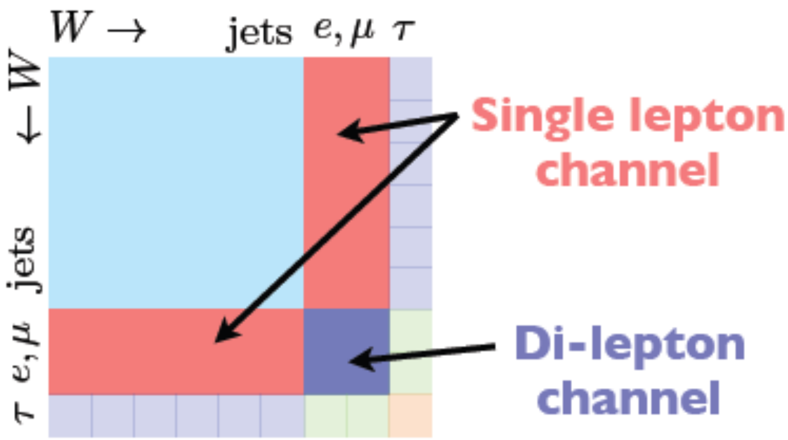
for a $m_{top}$=172.5 GeV (N. Kidonakis)

# WHAT WE "SEE" IN THE DETECTOR?




→ top quark decay involves all possible products: electrons, muons, jets, b-jets and neutrinos

→ this requires an excellent calibration, alignment and performance of the detectors




* Depending on the W (coming from the top quark) decay, one can identify several final state channels

# $V_{tb}$, $V_{ts}$ and $V_{td}$ limits

with observables like:

- R(BR(t→Wb)/BR(t→Wq))
- single top cross-sections
- top rapidity

CMS-PAS-TOP-11-029

# R=BR(t→Wb)/BR(t→Wq) measurement

The three mixings (generation changing couplings) can be extracted with combination of observables:

→ ttbar: ratio BR(t→Wb)/BR(t→Wq)

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

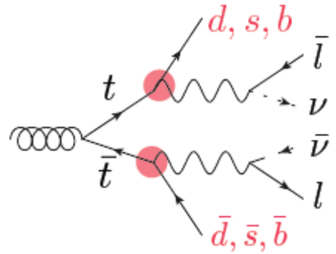
- R expected to be 99.8%
- D0 experiment measured R=0.90±0.04 !!

(PRL 107 (2011) 121802; arXiv:1106.5436)

- also by CMS in dileptonic ch. (~2.2 $fb^{-1}$)

* count # of events with m b-tagged jets

* obtain R from likelihood max.

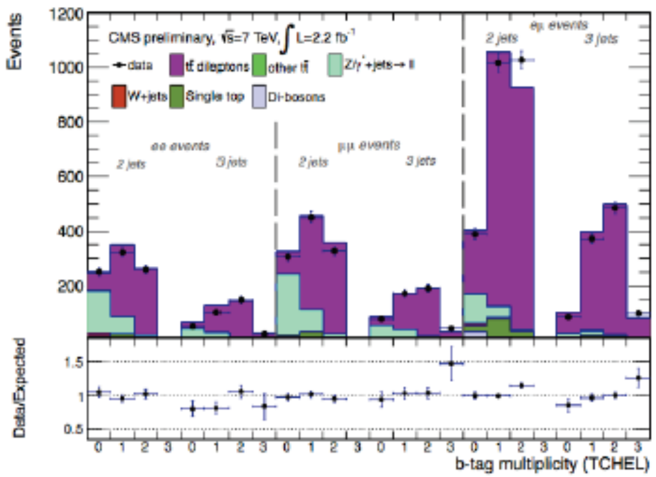


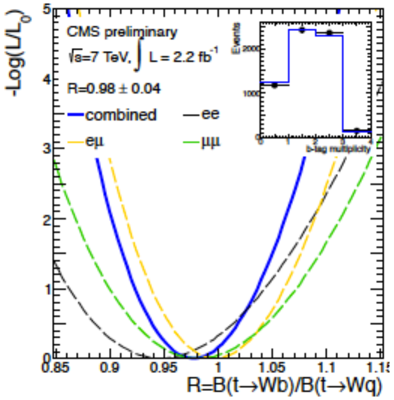

$$\mu^m_{t\bar{t}}(R, \sigma_{t\bar{t}}) = [R^2 \epsilon^m(bb) + 2R(1-R)\epsilon^m(bq_l) + (1-R)^2 \epsilon^m(q_l q_l)]\ \sigma_{t\bar{t}} \mathcal{B}^2(t \to Wq) L\ ,$$

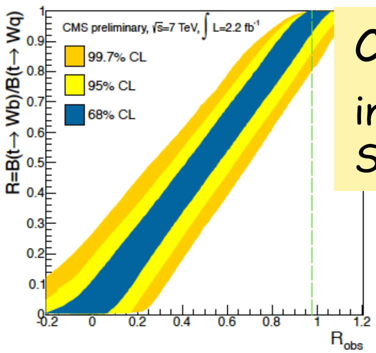
observed expected

$$\mathcal{L} = \prod_{\ell\ell} \prod_{jets \geq 2} \prod_{k=0}^{jets} \mathcal{P}_{oisson}\left(N^{\ell\ell,jets}_{ev}(k), \hat{N}^{\ell\ell,jets}_{ev}(k)\right) \prod_x \mathcal{G}_{aus}(x, \bar{x}, \sigma_x)$$

Nuisance parameters such as b-tag efficiency




CMS → R=0.98±0.04

in good agreement with SM expectation

# $V_{tb}$ measurements

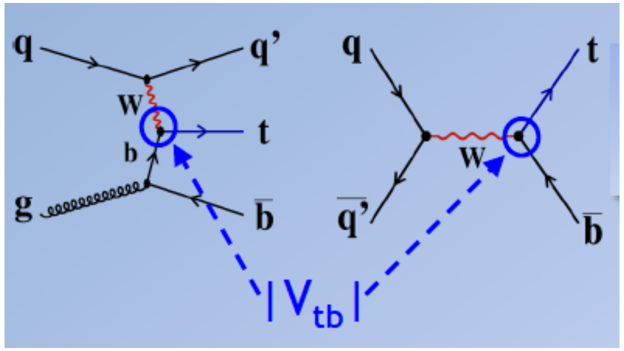
arXiv:1205.3130, ATLAS
CMS-PAS-TOP-2011-021, CMS

- from single top cross-sections
  - assuming SM V-A coupling:

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

and $|V_{tb}| \gg |V_{td}|, |V_{ts}|$:

$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb,SM}|^2 \xrightarrow{V_{tb,SM}=1} V_{tb,meas} = \sqrt{\frac{\sigma_{meas}}{\sigma_{SM}}}$$



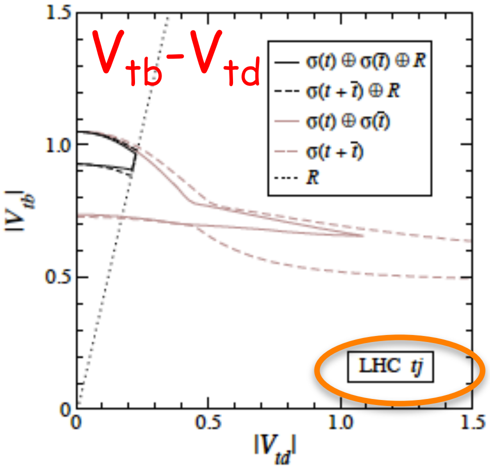

CMS σ(t-ch.) = 70.2±5.2(stat.)±10.4(syst.)±3.4(lumi.) pb
ATLAS σ(t-ch.) = 83±4(stat.)$^{+20}_{-19}$ (syst.) pb

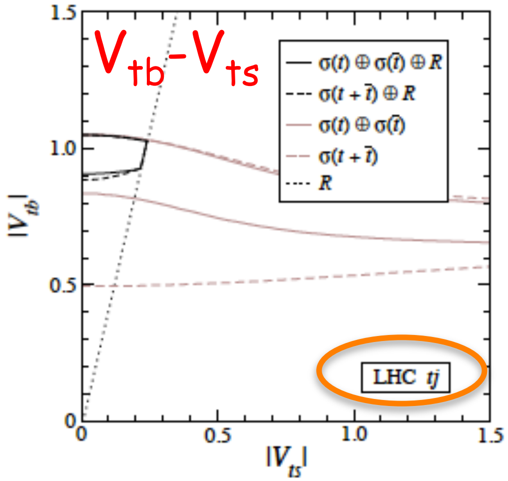
| Experiment | Channel | $\lvert V_{tb} \rvert$ | rel. exp. precision |
|---|---|---|---|
| CDF & DØ discovery (3.2 $fb^{-1}$ & 2.3 $fb^{-1}$) | s+t channel | 0.88 ± 0.07 (exp.) ± 0.07 (theo.) | 8.0% |
| CDF (7.5$fb^{-1}$) | s+t+Wt | 0.96+-0.09 (exp.) +- 0.05 (theo.) | 9.4% |
| DØ (5.4 $fb^{-1}$) | t-channel | $1.02^{+0.10}_{-0.11}$ (exp. + theo.) | +8.7% / -9.9% |
| CMS (1.14 $fb^{-1}$ / 1.51 $fb^{-1}$ ) | t-channel | 1.04 ± 0.09 (exp.) ± 0.02 (theo.) | 8.7% |
| ATLAS (1.04 $fb^{-1}$) | t-channel | $1.13^{+0.14}_{-0.13}$ (exp. + theo.) | 11.9% |

# $V_{tb}$, $V_{ts}$ and $V_{td}$ limits

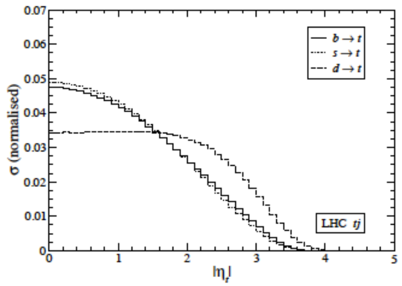
arXiv:1002.4718
J.A.Aguilar-Saavedra, A.Onofre

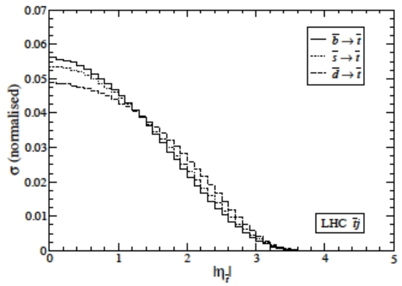
Combining R and single top cross-section:



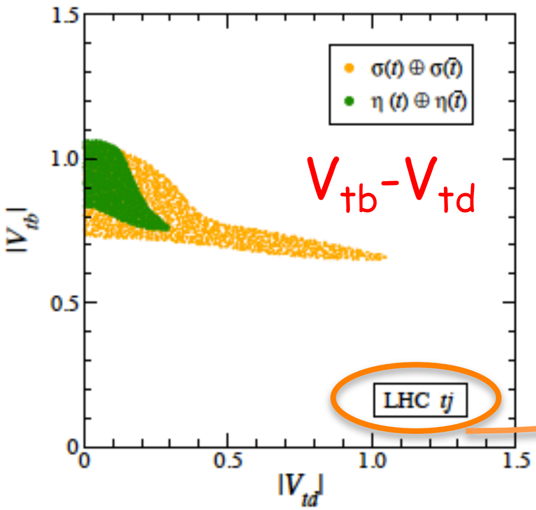



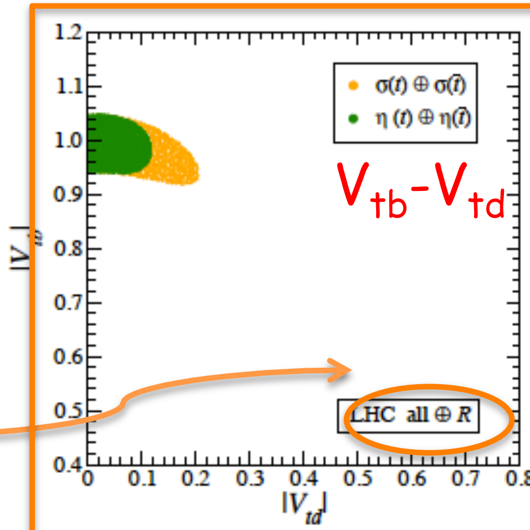

- Limits are improved if t and tbar measurements are separated.
- Top rapidity distribution:

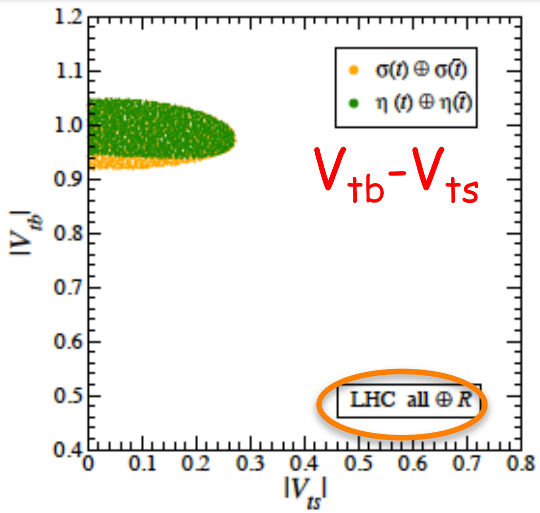



Including top rapidity…




Including all single-top channels (t-ch, Wt-ch. and s-ch.)

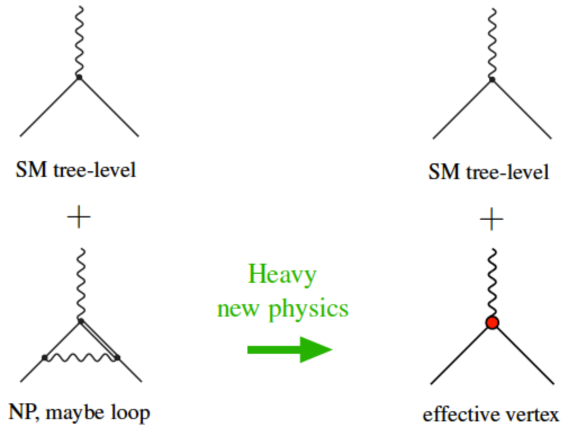
# Anomalous Wtb couplings:

- single top cross-sections and $R(\sigma_t/\sigma_{tbar})$,
- top decay observables (ttbar and single top): helicity fractions, $A_{\pm}$, $A_{FB}$,…

# Anomalous Wtb couplings

arXiv:0803.3810, J.A.Aguilar-Saavedra
arXiv:1005.5382, J.A.Aguilar-Saavedra, J. Bernabeu
arXiv:1205.2484, ATLAS
CMS-PAS-TOP-11-020, CMS

- CP violation requires:




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

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_{\rm L}P_L + V_{\rm R}P_R)\,t\;W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(g_{\rm L}P_L + g_{\rm R}P_R)\,t\;W_{\mu}^{-} + \text{h.c.}$$

$q=p_t-p_b=p_W$

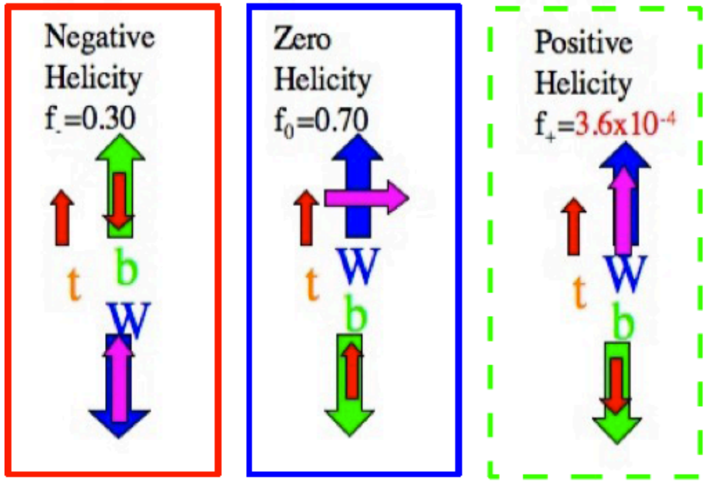
- where $V_L$, $V_R$, $g_L$ and $g_R$ are complex anomalous couplings (SM: $V_L=1$, $V_R=g_L=g_R=0$)
- supossed to be Hermitian → CP violation in SM occurs in complex phases.
- a general Wtb interaction will affect:
  - helicity of W boson decay (ttbar and single top)
  - density matrix of a polarized top quark decay (arXiv: 1005.5382)
  - the cross-section will include additional terms:

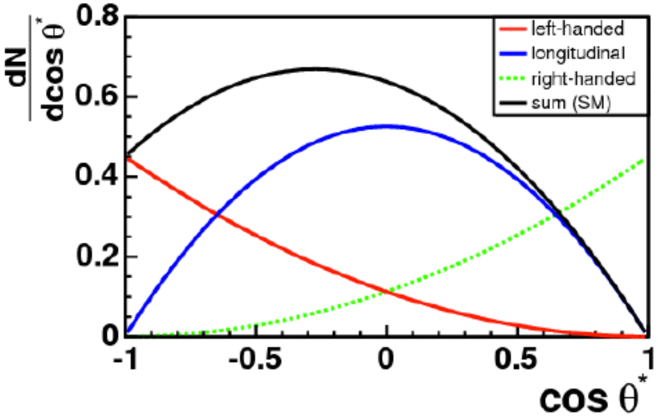
$$\sigma = \sigma_{\rm SM}\left(V_L^2 + \kappa^{V_R}\,V_R^2 + \kappa^{V_L V_R}\,V_L V_R + \kappa^{g_L}\,g_L^2 + \kappa^{g_R}\,g_R^2 + \kappa^{g_L g_R}\,g_L g_R + \ldots\right)$$

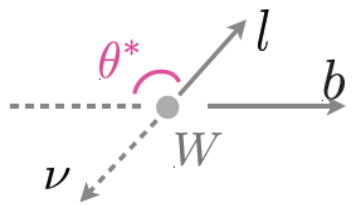
# W helicity fractions (ttbar)

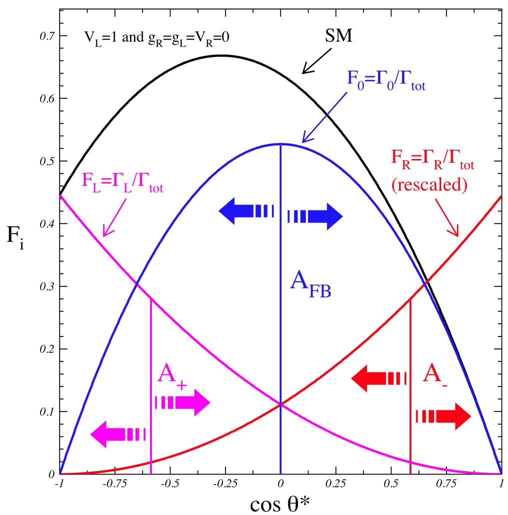
- Polarization of W bosons in top quark decays are sensitive to the structure Wtb-vertex (limits on the anomalous couplings).
- Helicity of W manifests itself in decay product kinematics.

**$\cos\theta^*$: angle between the charged lepton from the W decay and the reversed momentum direction of the b quark from the top decay, both boosted into the W boson rest frame**




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

In SM: $F_-=0.30$, $F_0=0.70$, $F_+=0$

$$A_{[z=0]} = A_{FB} = \frac{3}{4}(F_R - F_L) = -0.2225(LO, SM)$$

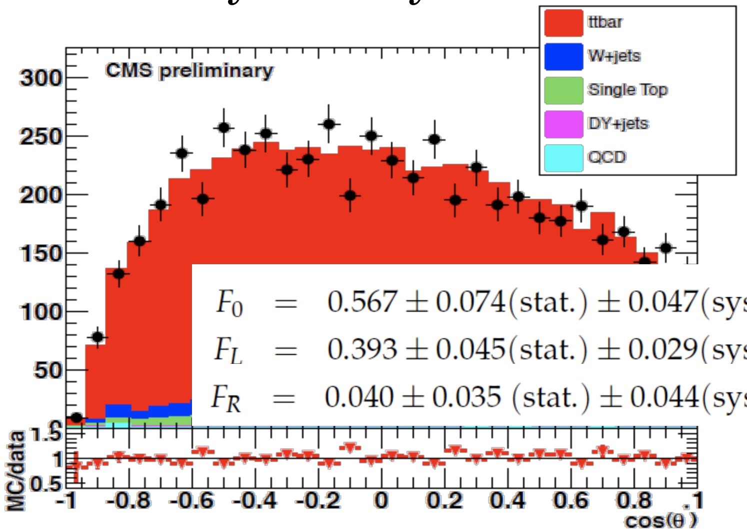
$$A_{[z=-(2^{2/3}-1)]} = A_+ = +3\beta[F0 + (1+\beta)F_R] = +0.5482(LO, SM)$$

$$A_{[z=+(2^{2/3}-1)]} = A_- = -3\beta[F0 + (1+\beta)F_L] = -0.8397(LO, SM)$$

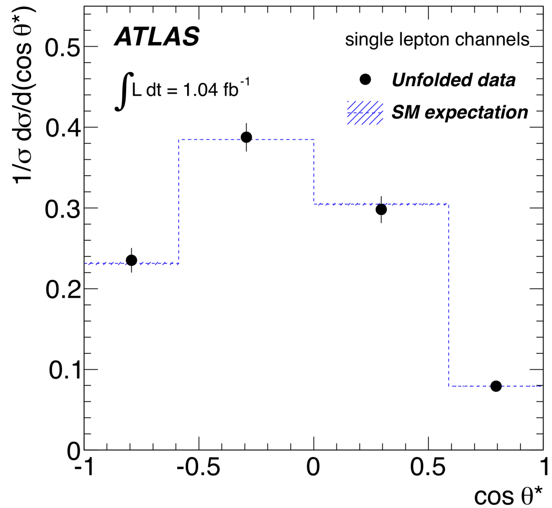
# W helicity fractions (ttbar)

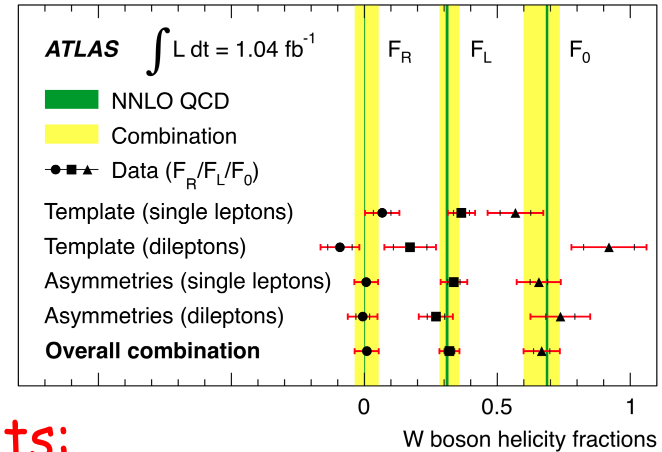
arXiv:1205.2484, ATLAS
CMS-PAS-TOP-11-020, CMS

2 techniques to extract helicity fractions:
- fit the measured distribution
- asymmetry method

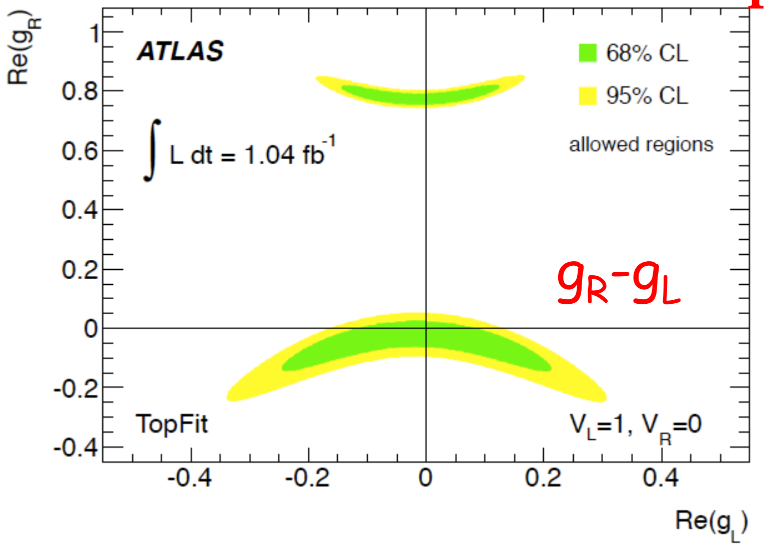



$$F_0 = 0.567 \pm 0.074(\text{stat.}) \pm 0.047(\text{syst.})$$
$$F_L = 0.393 \pm 0.045(\text{stat.}) \pm 0.029(\text{syst.})$$
$$F_R = 0.040 \pm 0.035\ (\text{stat.}) \pm 0.044(\text{syst.})$$




## Limits to anomalous couplings




ATLAS results:

$$\mathrm{Re}\,(V_R) \in [-0.20, 0.23] \rightarrow \frac{\mathrm{Re}\,(C^{33}_{\phi\phi})}{\Lambda^2} \in [-6.7, 7.8]\ \ \mathrm{TeV}^{-2}$$

$$\mathrm{Re}\,(g_L) \in [-0.14, 0.11] \rightarrow \frac{\mathrm{Re}\,(C^{33}_{dW})}{\Lambda^2} \in [-1.6, 1.2]\ \ \mathrm{TeV}^{-2}$$

$$\mathrm{Re}\,(g_R) \in [-0.08, 0.04] \rightarrow \frac{\mathrm{Re}\,(C^{33}_{uW})}{\Lambda^2} \in [-1.0, 0.5]\ \ \mathrm{TeV}^{-2}$$

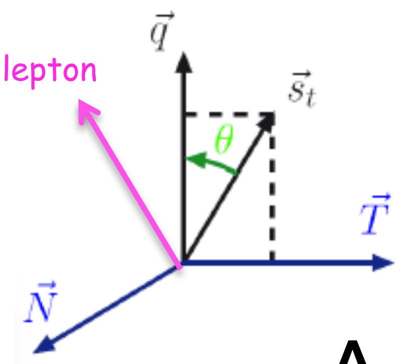
world record

# Forward-backward asymmetry in the normal direction

arXiv:1005.5382, J.A.Aguilar-Saavedra, J. Bernabeu

→ For un-polarized top quark decays, the only meaningful direction in the top quark rest frame is the one of the W boson (and b quark) momentum.

→ For polarized top quark decays further spin directions may be considered:




**Transverse and normal directions**

$\vec{q}$ → $W$ mom in $t$ rest frame

$\vec{s}_t$ → top spin

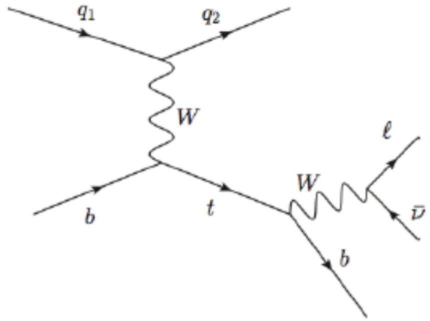
$$\vec{N} = \vec{s}_t \times \vec{q}$$
$$\vec{T} = \vec{q} \times \vec{N}$$

meaningful for polarised $t$ decays (e.g. in single top production)

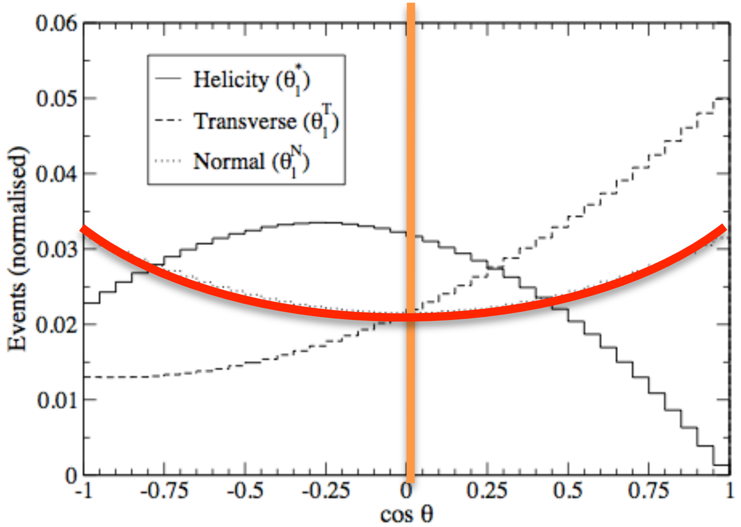
$\theta^*$ → Angle btw. lepton (in W rest frame) wrt. to the W boson (in top rest frame)

$\theta^N$ → Angle btw. lepton (in W rest frame) wrt. N

$\theta^T$ → Angle btw. lepton (in W rest frame) wrt. T




$A_{FB}$



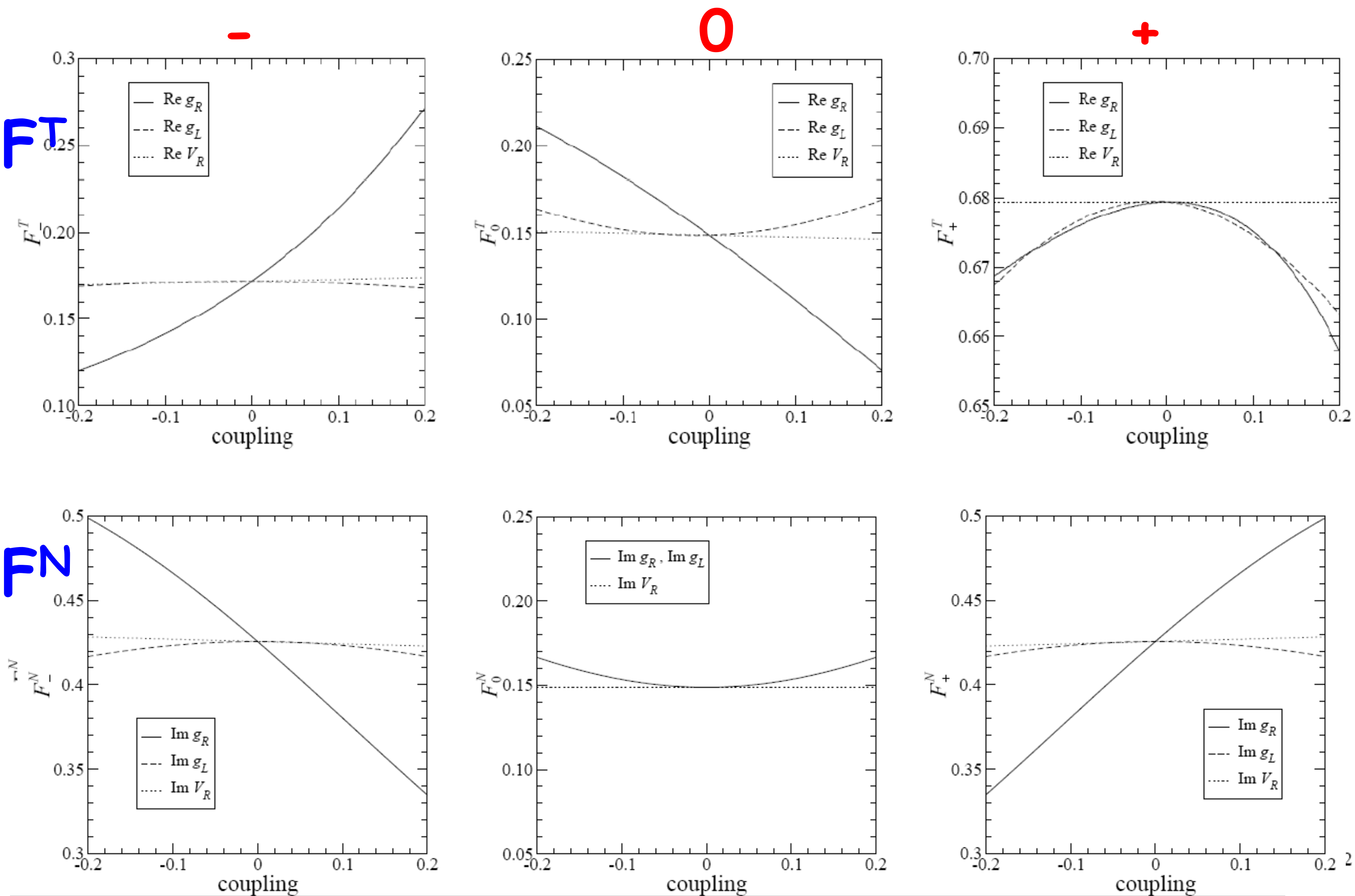

**First goal:** measure the forward-backward asymmetry in the normal direction since it is very sensitive to complex phase $g_R$:

$$A_{FB}^N \simeq 0.64\, P\, \mathrm{Im}\, g_R \qquad (V_L = 1)$$

**For the future:**

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^X} = \frac{3}{8}(1+\cos\theta_\ell^X)^2\, F_+^X + \frac{3}{8}(1-\cos\theta_\ell^X)^2\, F_-^X + \frac{3}{4}\sin^2\theta_\ell^X\, F_0^X$$

# More about POLARIZATION FRACTIONS



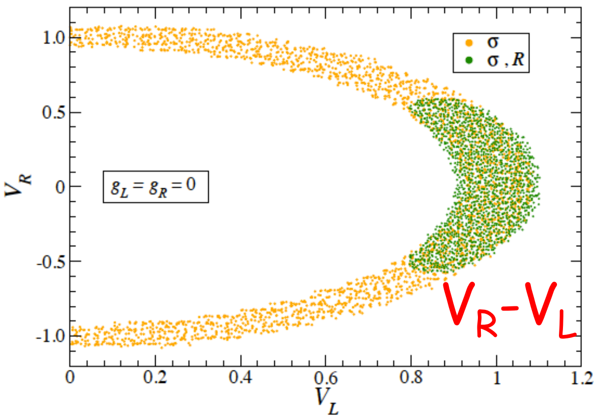

Helicity and transverse polarization fractions are much more sensitive to Re $g_R$, while the normal is sensitive to Im $g_R$.

# Combination of observables & limits to anomalous couplings

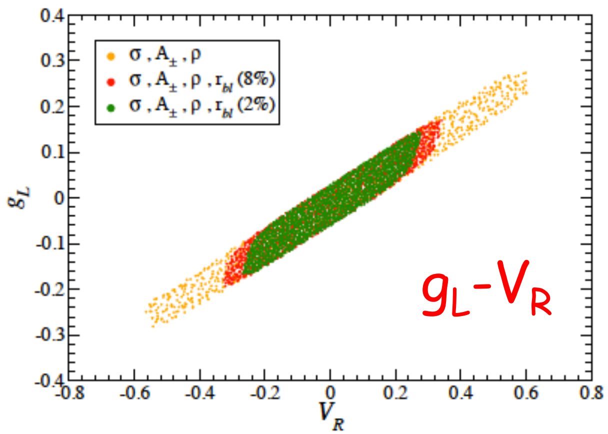
arXiv:0803.3810, J.A.Aguilar-Saavedra

arXiv:1005.5382, J.A.Aguilar-Saavedra, J. Bernabeu

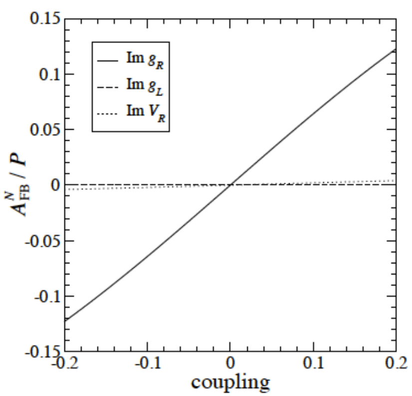
Predicted limits for anomalous couplings assuming a precision of the observables:

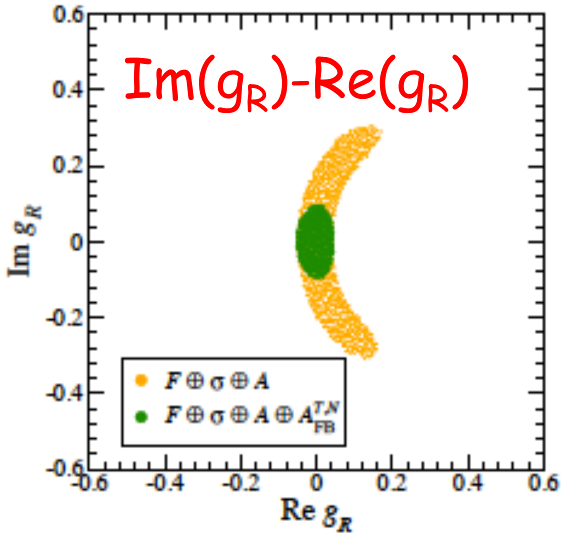



Limits improved with single-top cross-section ratio for top and anti-top: $R(\sigma_t/\sigma_{tbar})$.




Combining with top decay observables as $A_\pm$ and $\rho_R$, $\rho_L$ from ttbar and single-top.




| Top observables | |
|---|---|
| Re $V_L \le 0.62$<br>Re $V_L \ge 1.21$ | $(\sigma_{tW})$ |
| Re $V_R \le -0.111$<br>Re $V_R \ge 0.18$ | $(\rho_+)$ |
| $\lvert \mathrm{Im}\ V_R \rvert \ge 0.14$ | $(\rho_+)$ |
| Re $g_L \le -0.083$<br>Re $g_L \ge 0.051$ | $(\rho_+)$ |
| $\lvert \mathrm{Im}\ g_L \rvert \ge 0.065$ | $(\rho_+)$ |
| $\lvert \mathrm{Re}\ g_R \rvert \ge 0.056$ | $(A_+)$ |
| $\lvert \mathrm{Im}\ g_R \rvert \ge 0.115$ | $(A_{FB}^N)$ |

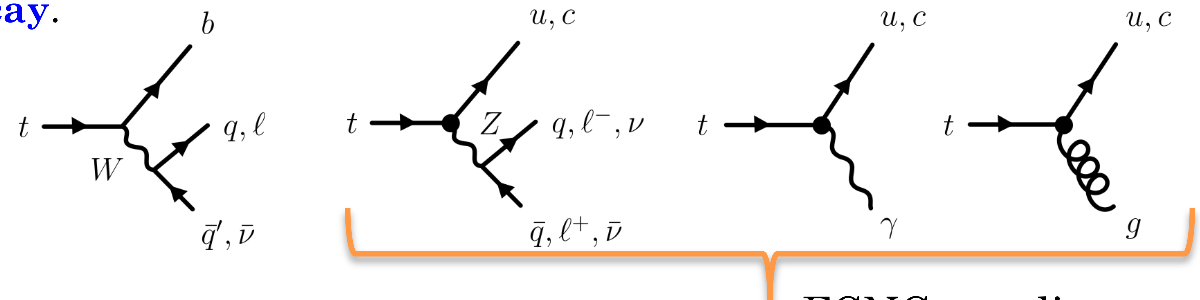
# Flavour changing neutral currents

# FCNC (Flavour Changing Neutral Currents)

In the SM, the FCNC are forbidden at tree level and suppressed at higher orders.

| | BR in SM | 2HDM | MSSM | $\not{R}$ SUSY | QS |
|---|---|---|---|---|---|
| $t \to qZ$ | $\sim 10^{-14}$ | $\sim 10^{-7}$ | $\sim 10^{-6}$ | $\sim 10^{-5}$ | $\sim 10^{-4}$ |
| $t \to q\gamma$ | $\sim 10^{-14}$ | $\sim 10^{-6}$ | $\sim 10^{-6}$ | $\sim 10^{-6}$ | $\sim 10^{-9}$ |
| $t \to qg$ | $\sim 10^{-12}$ | $\sim 10^{-4}$ | $\sim 10^{-5}$ | $\sim 10^{-4}$ | $\sim 10^{-7}$ |

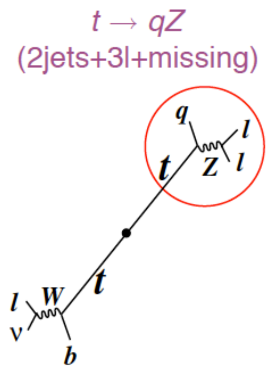
Limits in the FCNC couplings $tqV_0$ with q=u, c and $V_0$=γ, Z, g have been set by searching effects both on **top production and decay**.

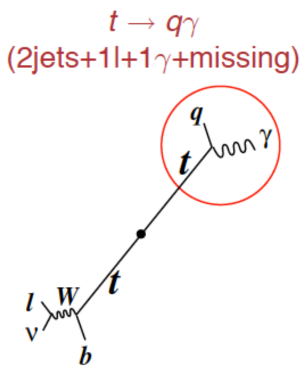


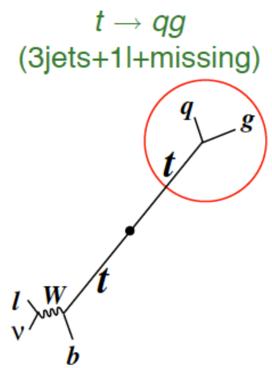

FCNC couplings

- **Single top production** can be important probe to strong FCNC
  - cross-section proportional to BR
- **Ttbar production** probe top FCNC decays:

| | |
|---|---|
| direct production | $g\, q \to t + X$ |
| top + jet production<br>$(pp \to t + \text{jet})$ | $g\, g \to \bar{q}\, t + X$<br>$g\, q \to g\, t + X$<br>$q\, q \to \bar{q}\, t + X$ |
| top + gauge boson production<br>$(pp \to t + \gamma/Z/W)$ | $g\, q \to \gamma\, t + X$<br>$g\, q \to Z\, t + X$<br>$g\, q \to Wt + X$ |
| top + Higgs production<br>$(pp \to t + h)$ | $g\, q \to h\, t + X$ |



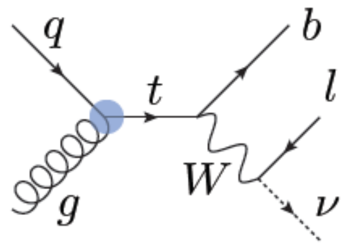
# FCNC: "tqg" in single top production

arXiv:1203.0529, ATLAS

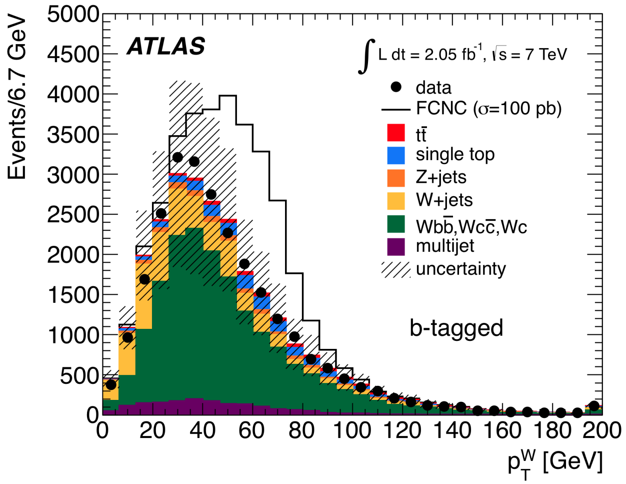
Limits set by **ATLAS** searching for direct production:

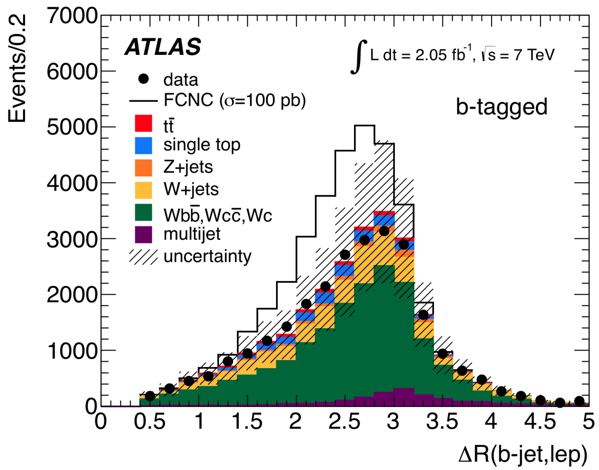
**qg→ t →Wb with W→lν**

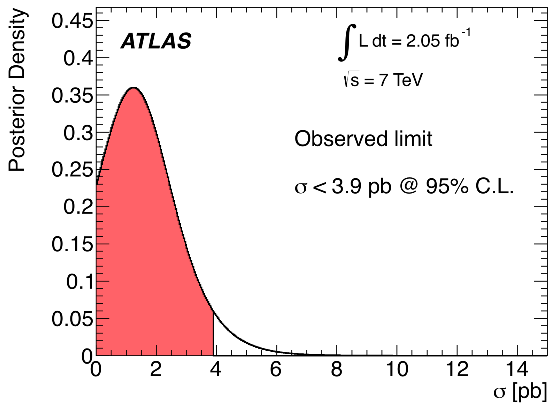
- Expect cross-section O(1 pb)
- Selection: 1 lepton, MET, 1 b-jet
- Neural network to separate from SM backgrouns: 11 inputs

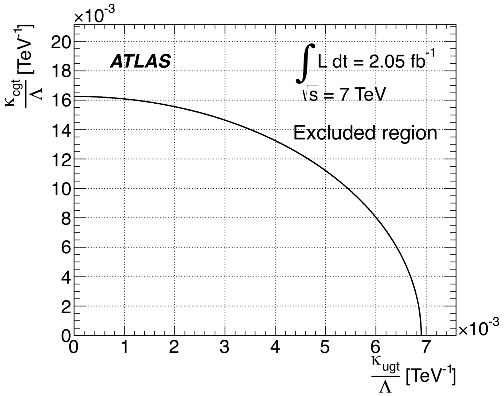



| Variable | Significance ($\sigma$) |
|---|---|
| $p_T^W$ | 57 |
| $\Delta R$(b-jet,lep) | 28 |
| Lepton charge | 22 |
| $m_{top}$ | 20 |
| $m_{b-jet}$ | 15 |
| $\eta_{b-jet}$ | 12 |
| $\Delta\phi$(W,b-jet) | 11 |
| $p_T^{lep}$ | 12 |
| $p_T^{b-jet}$ | 6.5 |
| $\cos\theta^*$ | 5.7 |
| $\Delta R$(W,b-jet) | 5.0 |




Upper limit is set **ATLAS**

$$\sigma(qg \to t) < 3.9\text{pb (95\% CL.)}$$

and it corresponds to

$$Br(t \to ug) < 5.7 \cdot 10^{-5}$$

$$Br(t \to cg) < 2.7 \cdot 10^{-4}$$

world record

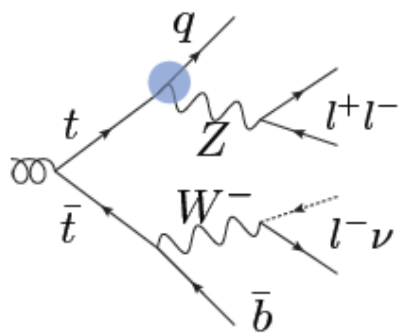
**Previous limits → D0 (2.3fb$^{-1}$):** BR(t→ug)<2 $\cdot 10^{-4}$ and BR(t→cg)<3.9 $\cdot 10^{-3}$

# FCNC: "tZq" in top quark pair decay

ATLAS-CONF-2011-154 (0.7 $fb^{-1}$)
CMS-PAS-TOP-11-028 (4.6 $fb^{-1}$)

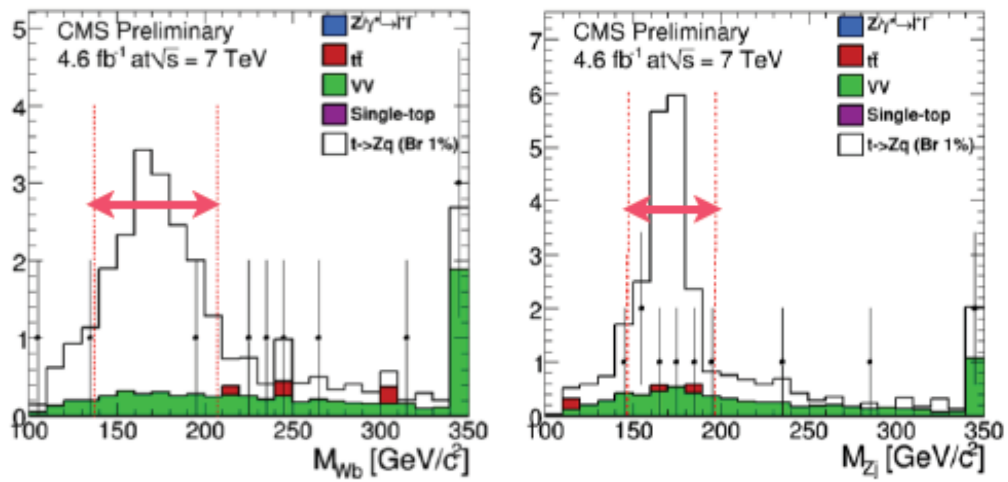
Limits in the FCNC couplings tZq have been set in ttbar events both by ATLAS and CMS:

- Basic strategy: **ttbar → Wb+Zq → lνb+llq**
- 3 leptons




CMS

- $M_{bW}$ reconstruction:
  - W reconstruction: ν from MET assuming W boson mass.
  - At least 1 tag b-jet
  - $|M_{Wb}-m_{top}|<35$ GeV
- $M_{Zq}$ reconstruction:
  - 1 jet
  - 2 same flavour and opposite charge
  - $|M_{Zq}-m_{top}|<25$ GeV

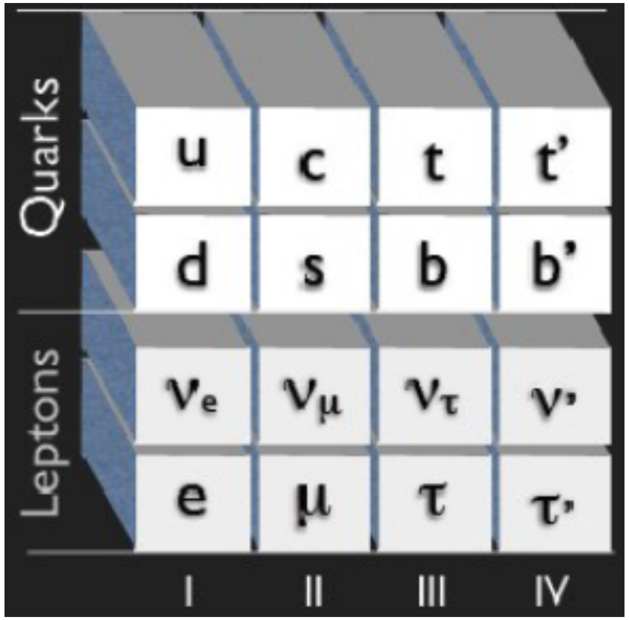



ATLAS

reconstruct event based on $\chi^2$ minimization: $\chi^2 = \frac{(m^{reco}_{j_a\ell_a\ell_b} - m_t)^2}{\sigma_t^2} + \frac{(m^{reco}_{j_b\ell_c\nu} - m_t)^2}{\sigma_t^2} + \frac{(m^{reco}_{\ell_c\nu} - m_W)^2}{\sigma_W^2} + \frac{(m^{reco}_{\ell_a\ell_b} - m_Z)^2}{\sigma_Z^2}$

**CMS**: BR(t→Zq)<0.34% @ 95 C.L. (**world record**)
**ATLAS**: BR(t→Zq)<1.13% @ 95 C.L.

# Searches of new quarks:
# t' and b'




**Signatures:**

**tt'→ Wq (q=d,s,b)**

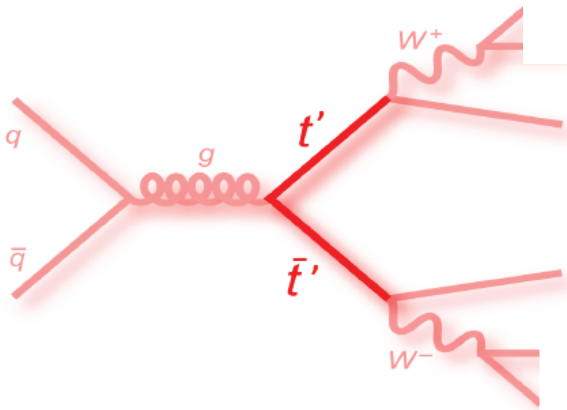
**bb'→ Wq (q=u,c,t)**

ATLAS: arXiv: 1202.3076
arXiv: 1202.3389
arXiv: 1202.5520
arXiv: 1202.6540
arXiv: 1202.2656

CMS: arXiv:1204.2488
arXiv:1203.5410
PAS-EXO-2011-099

# Searches of t' quark

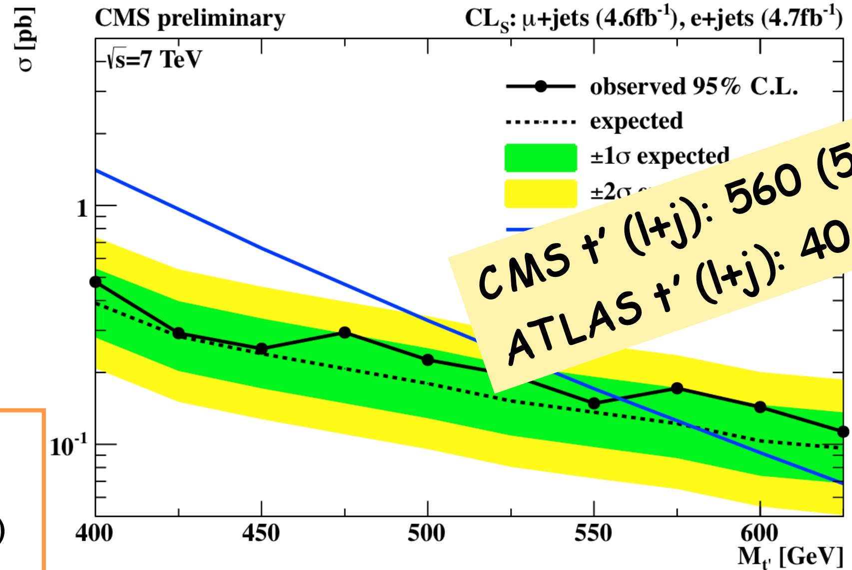
Observed (expected) upper limit @ 95 C.L.




**tt'→ WbWb**

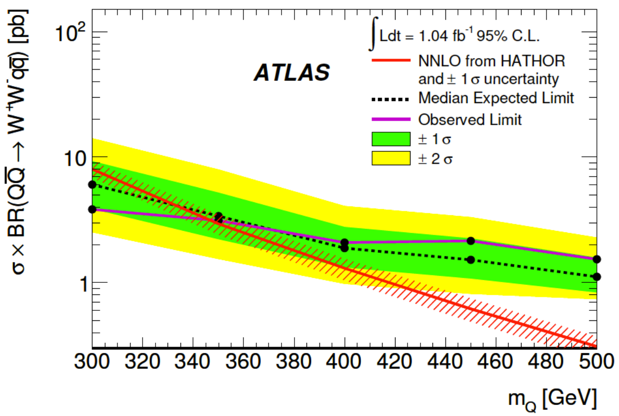
- single lepton (ATLAS ~1fb$^{-1}$ & CMS ~5fb$^{-1}$)
- 2 OS leptons (CMS ~5fb$^{-1}$)
- **2 OS leptons; q=d,s,b** (ATLAS ~1fb$^{-1}$ **)**

## tt'→ WbWb (single lepton)



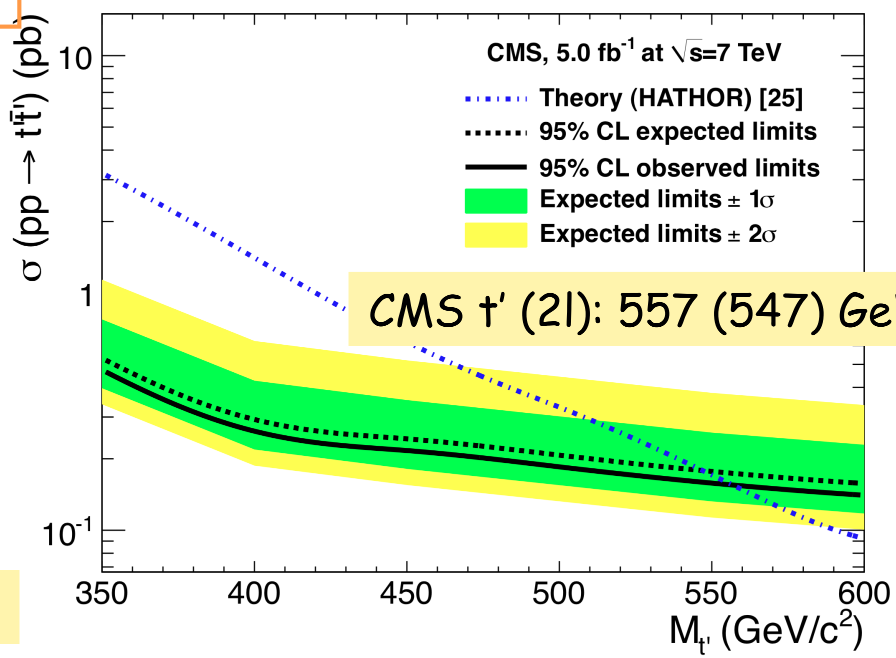

CMS t' (l+j): 560 (580) GeV
ATLAS t' (l+j): 404 (394) GeV

## tt'→ WtWt (2 OS leptons)




ATLAS t' (2l, q=d,s,b): 350 (335) GeV

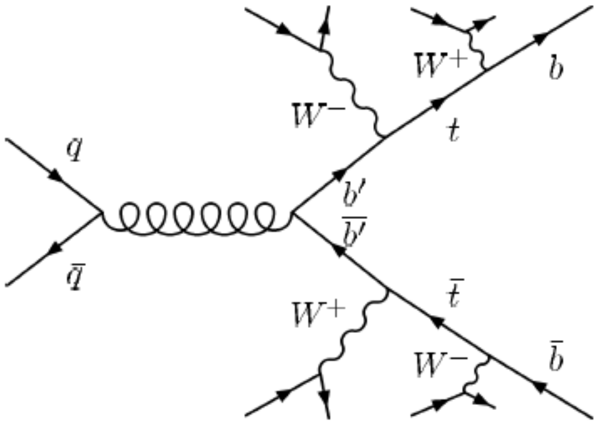
## tt'→ WtWt (2 OS leptons)




CMS t' (2l): 557 (547) GeV

# Searches of b' quark

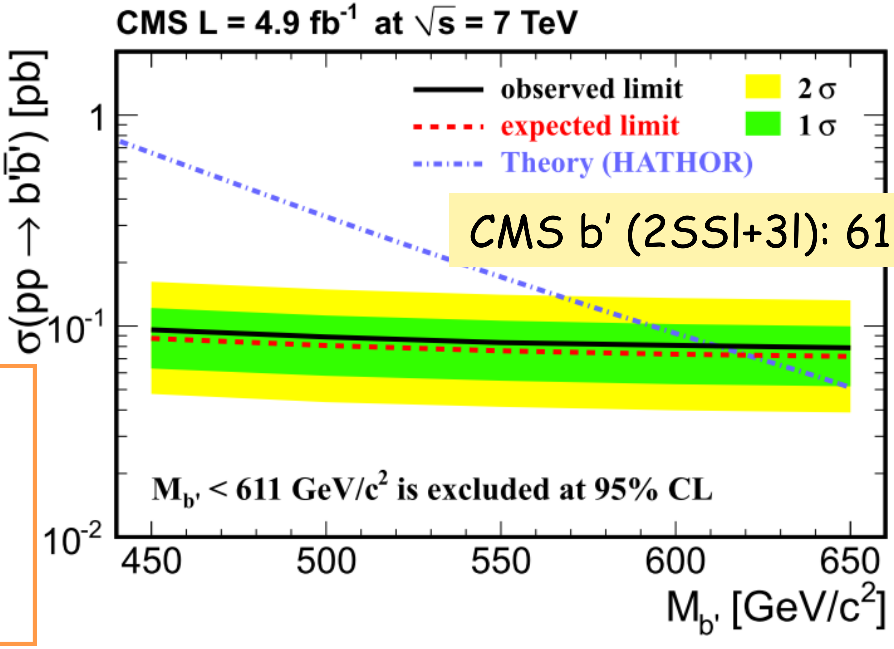
Observed (expected) upper limit @ 95 C.L.




**bb'→ WtWt**

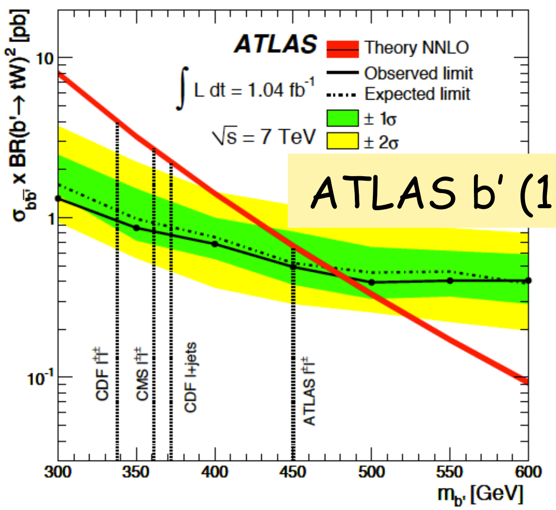
- **1** lepton+jets: expected 8 jets (ATLAS ~1fb$^{-1}$)
- 2 SS leptons & 3 leptons (CMS ~5fb$^{-1}$)
- **SS leptons** (ATLAS ~1fb$^{-1}$ )

## bb'→ WtWt (2 SS leptons & 3 leptons)



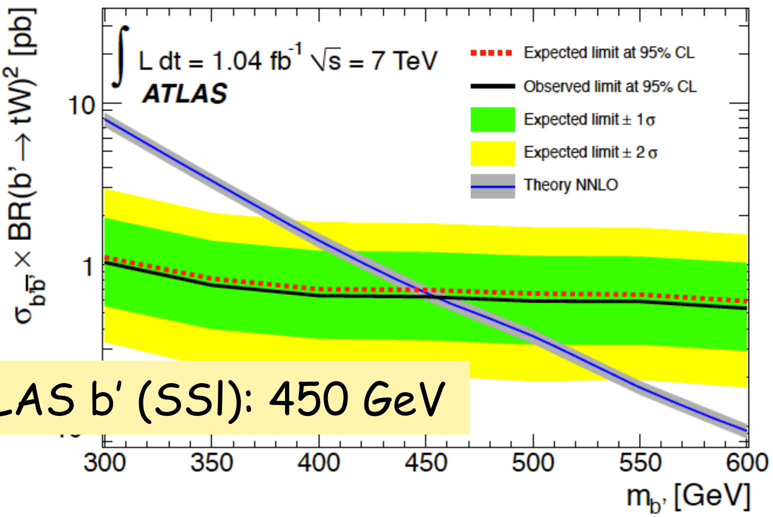

CMS b' (2SSl+3l): 611 GeV

## bb'→ WtWt (1 lepton & jets)




ATLAS b' (1l): 480 GeV

## bb'→ WtWt (SS leptons)




ATLAS b' (SSl): 450 GeV

# CONCLUSIONS

- LHC is a top factory, allowing to test new flavour phenomena.
  - Single top is a very active and exciting topic.
- Recent top flavour measurements from ATLAS and CMS have been shown:
  - Limits to $V_{tb}$, $V_{ts}$, $V_{td}$
  - Wtb vertex: anomalous couplings
  - FCNC currents
  - Searches of new quarks: t'and b'
- Stay tuned: new results are coming!
- Understanding flavour is the key to new physics!
- REFERENCES:

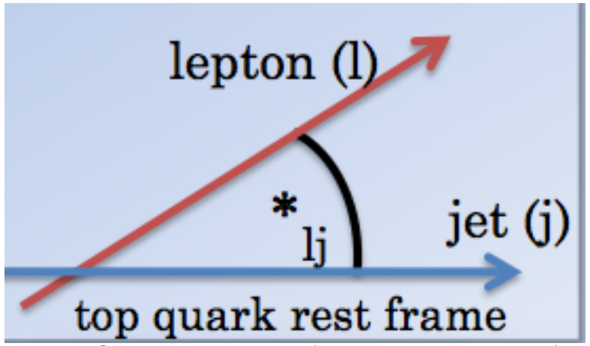
  - Atlas public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - CMS public results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
  - http://arXiv.org/abs/arXiv:0803.3810
  - http://arXiv.org/abs/arXiv:1002.4718
  - http://arXiv.org/abs/arXiv:1005.5382
  - http://arXiv.org/abs/arXiv:1202.4694

# THANKS FOR YOUR ATTENTION!!

# BACK-UP

# HOW TO MEASURE THE TOP POLARIZATION?

- For partially polarized top quark decays, the angular distributions of any decay product $X = l^+, \upsilon, q, q', W^+, b$ (which are called "spin analysers") in the top quark rest frame is:




$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_x)} = \frac{1}{2}(1 + P\alpha_x \cos\theta_x)$$

where $\theta_x$ is the angle between X in the top rest frame and top spin direction.

→ The constants $\alpha_x$ are called "spin analysing power" of X and ranges from -1 to +1. In the SM: $\alpha_{l^+} = 1$

→ The FB asymmetries: $$A_X = \frac{N(\cos\theta_X > 0) - N(\cos\theta_X < 0)}{N(\cos\theta_X > 0) + N(\cos\theta_X < 0)}$$

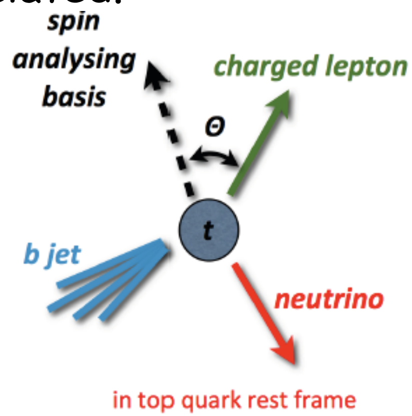
are $A_X = P\alpha_X/2$

# Spin correlations

- Top quark has short lifetime. It decays before spin can flip.
- ttbar are produced (almost) unpolarized but their spins are correlated.
- Spin information is contained in the decay products
    - Testing 2 hypothesis:
        * Correlated spins (SM)
        * Uncorrelated spins

**Degree of correlation**

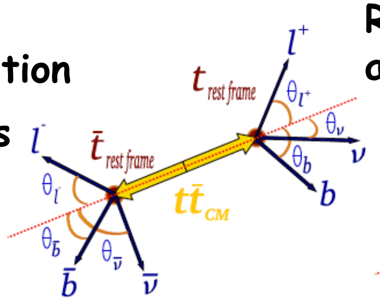
$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$



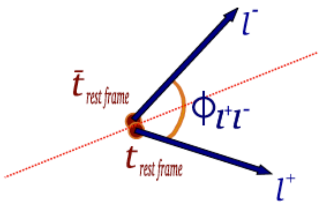

- Strategy followed: fit ΔΦ distribution with a binned template for SM and uncorrelated cases

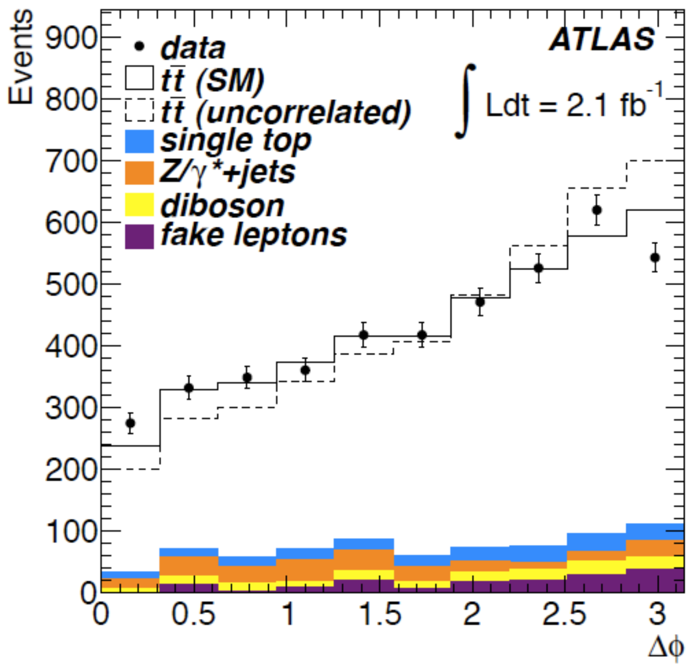
→ Evidence of spin correlation in agreement with SM

**Double distribution in helicity basis**



**Relative distribution of t and tbar spin analizers**






$$A_{helicity} = 0.04 \pm 0.04(stat)^{+0.08}_{-0.07}(syst)$$

$$A_{maximal} = 0.57 \pm 0.06(stat)^{+0.12}_{-0.10}(syst)$$

$$A^{SM}_{helicity} = 0.32 \quad A^{SM}_{maximal} = 0.44$$

# SINGLE TOP PRODUCTION

## electro-weak interaction

- t-channel: $\sigma^{**}_{theory} = 64.6^{+3.3}_{-2.6}$ pb
- Wt channel: $\sigma^{**}_{theory} = (15.7 \pm 1.4)$ pb
- s-channel: $\sigma^{**}_{theory} = (4.6 \pm 0.3)$ pb

$\sigma^{**}_{theory}$: NLO with NNLL corrections for a $m_{top}$=172.5 GeV