Single Top-Quark Measurements at ATLAS and CMS

LHC France – Annecy 2-6/04/13

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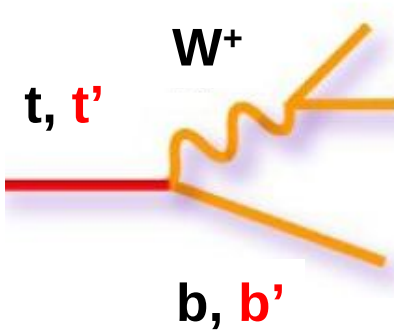
Single top-quark production

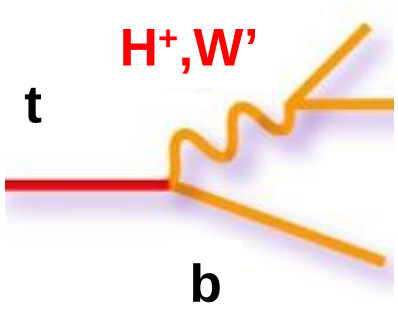
Electroweak production of the top quark

Cross section proportional to $|V_{tb}|^2$

Sensitive to any (new) effect that can modify the top quark weak coupling

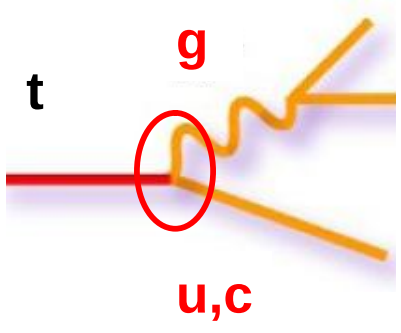


➔ **New heavy quarks**



➔ **New bosons**

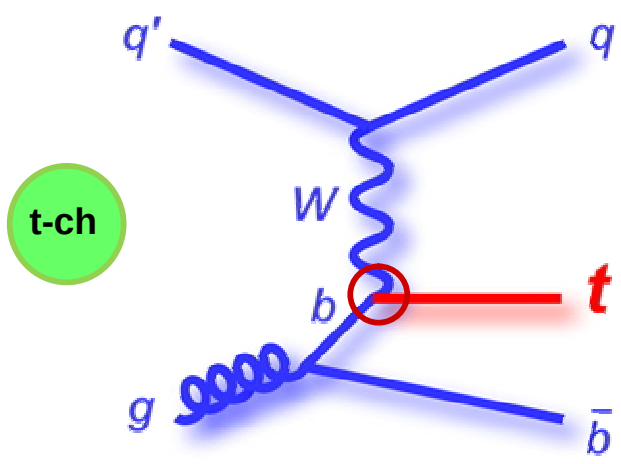
➔ **new resonances**



➔ **Modified couplings**

➔ **anomalous polarization**

t-channel production



Probe W-t-b vertex

- Constrain V_{tb}
- Search for modified couplings
- Anomalous polarisation

Production mechanisms

- FCNC

Measure b-quark PDF

Dominant process: ~1/3 ttbar production (σ_t = 88 pb @ 8 TeV)

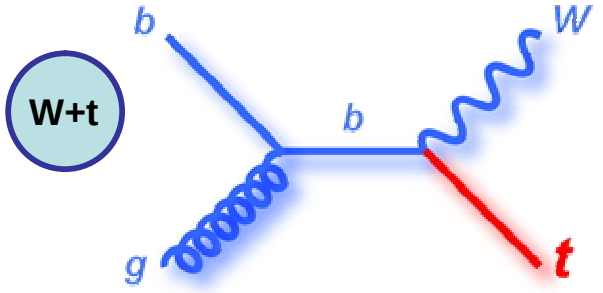
Observed at Tevatron (2009), then at LHC (2011)

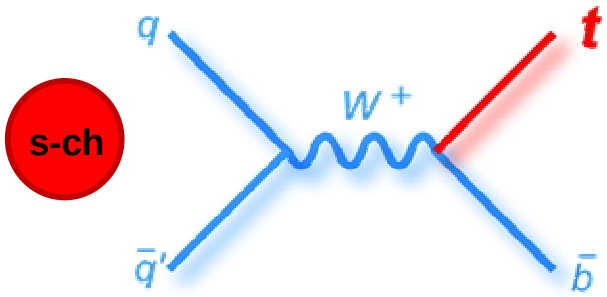
Measure single-top cross-section as precisely as possible:

➔ test SM & probe for new physics

➔ But new intermediate particles suppressed as $1/M^2$

Wt and s-channels





Probe W-t-b vertex

- Constrain V_{tb}

New heavy particles

- Excited quark
- Charged Higgs
- Charged W-like bosons
- Composite models

Wt process ➔ evidence at ATLAS and CMS (σ_{Wt} = 22 pb @ 8 TeV)

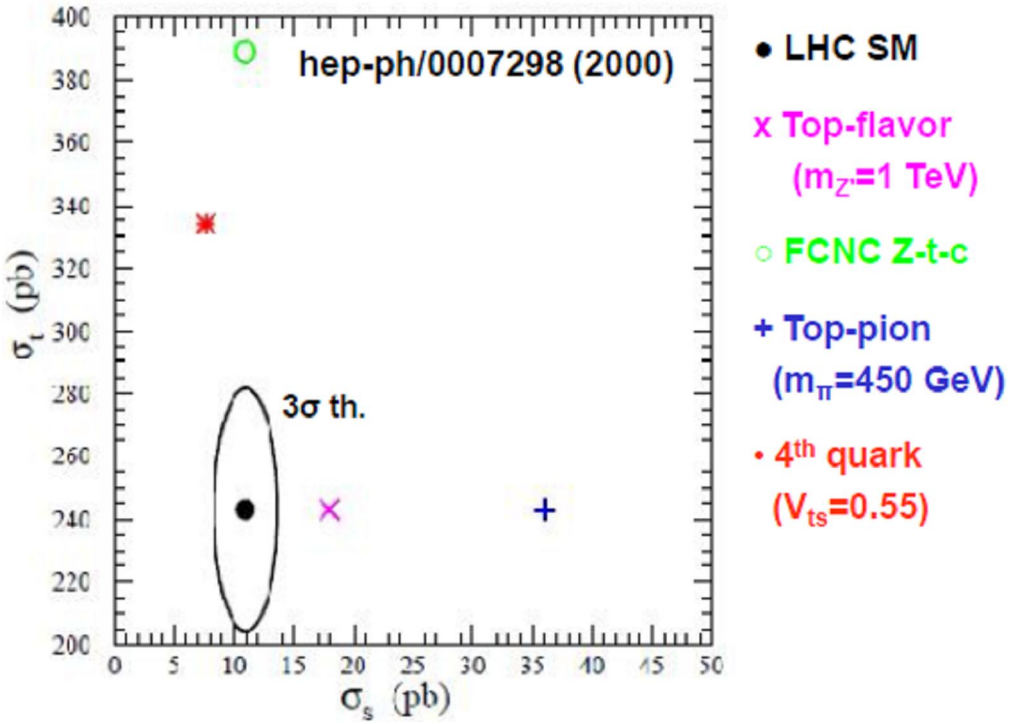
s-channel ➔ smallest cross-section: ~1/15 t-channel (σ_s = 6 pb @ 8 TeV)
Difficult channel, **Limits** (ATLAS)

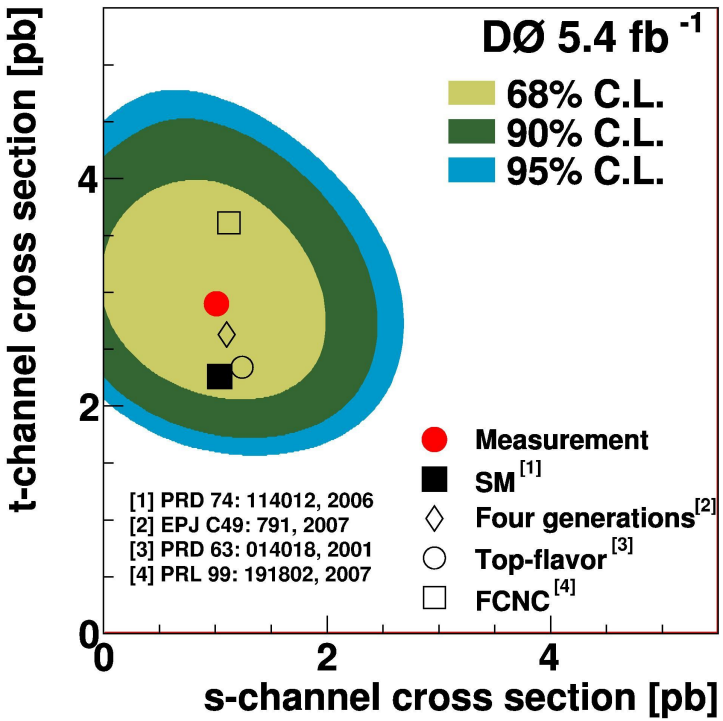
Test of the SM in the single-top sector

Tait et al. (2000): “single-top as a window to new physics”

(old LHC 14 TeV predictions)

Tevatron measurements (D0)





At **LHC** we have more **handles** (ex: Wt process)

Entering era of **precision** single-top quark measurements

Single top measurements

Rich field of study, several public results

➔ 8 published papers, 16 CONF notes

Strong French labs involvement

Cross section	Properties	BSM
t-channel	FCNC	W’
Wt channel	W helicity	b^*
s-channel	CP violation	(monotop)
$\lvert V_{tb} \rvert$		
Top/antitop		
(LHC combination)		

Contributions

LPSC Grenoble

LPC Clermont-Fd

IPHC

() no public results yet

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$\|V_{tb}\|$		
Top/antitop		
(LHC combination)		

See talk Xiaohu !

Contributions

LPSC Grenoble

LPC Clermont-Fd

IPHC

() no public results yet

Single Top-Quark Cross Section Measurements

t-channel (1 fb^{-1}, 7 TeV)

Methods

ATLAS: Neural network (cut-based as cross-check)

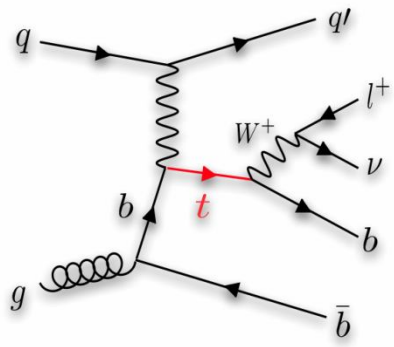
CMS: Fit to pseudorapidity of fwd jet

Boosted decision tree

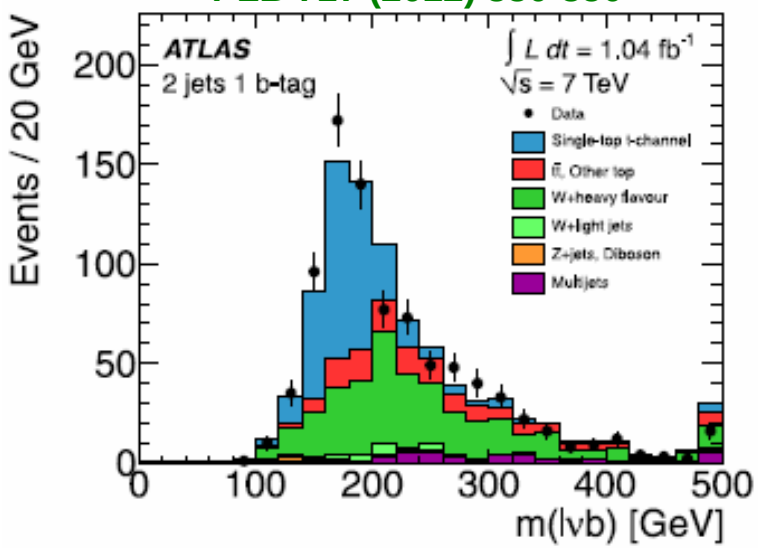
Neural network

Signature

e/μ+2/3jets, ≥1 b-tag

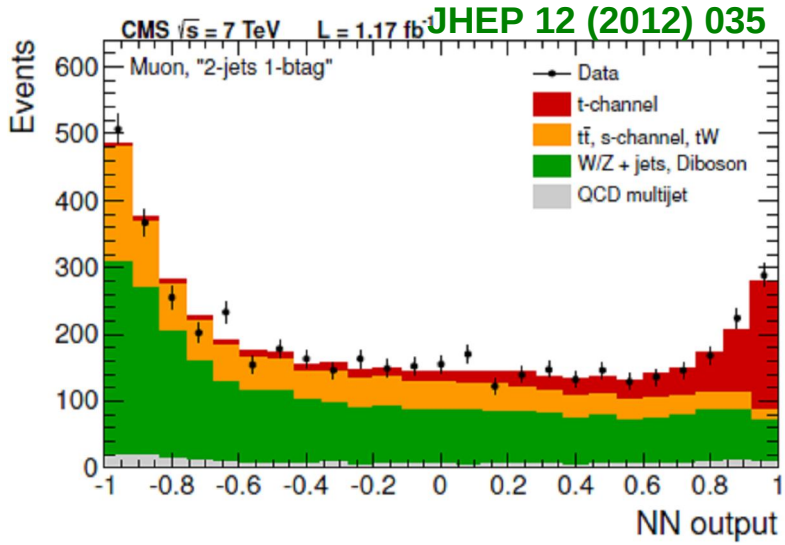


PLB 717 (2012) 330-350



$\sigma_t = 83 \pm 20$ pb **(24%)**

JHEP 12 (2012) 035



$\sigma_t = 67.2 \pm 6.1$ pb **(9%)**

t-channel (5 fb^{-1}, 8 TeV)

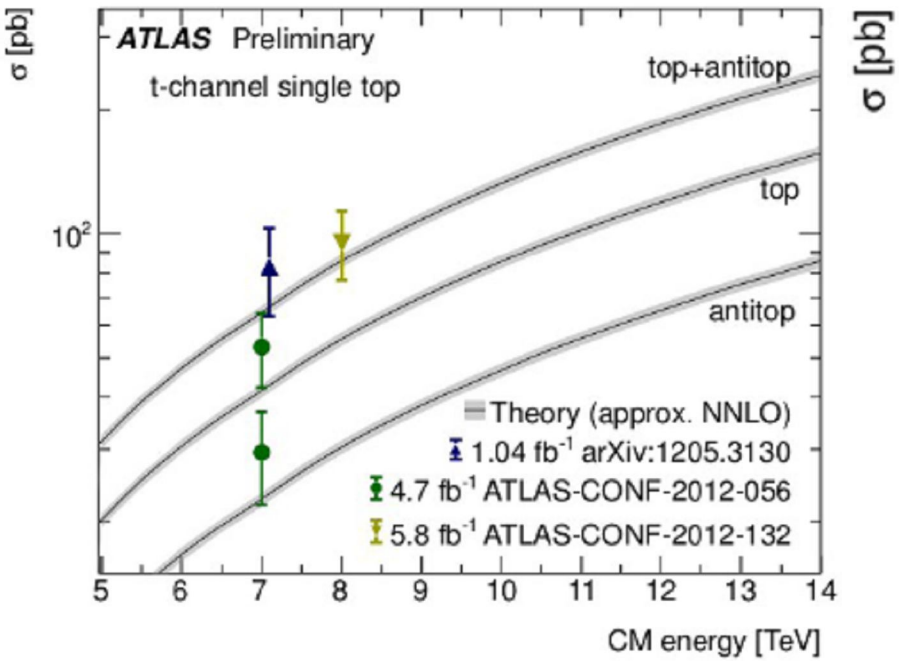
Methods

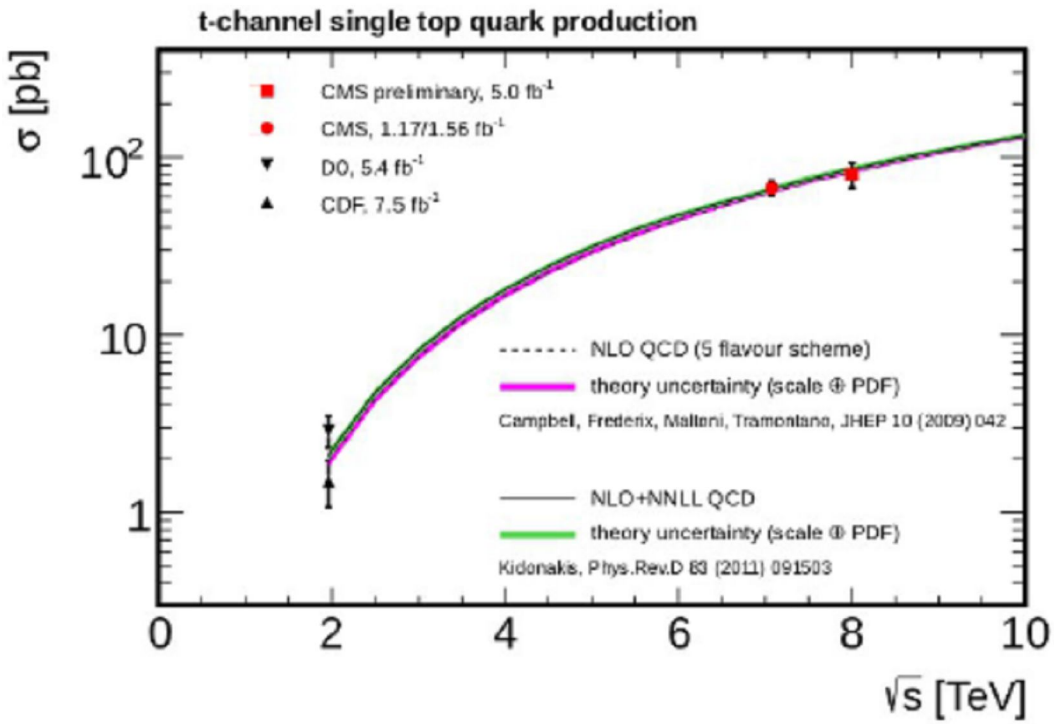
ATLAS: Neural network

CMS: Fit to pseudorapidity of fwd jet

ATLAS-CONF-2012-132

CMS PAS TOP-12-011





$\sigma_t = 95 \pm 18$ pb **(19%)**

$\sigma_t = 80.1 \pm 13.0$ pb **(16%)**

Direct $|V_{tb}|$ measurement

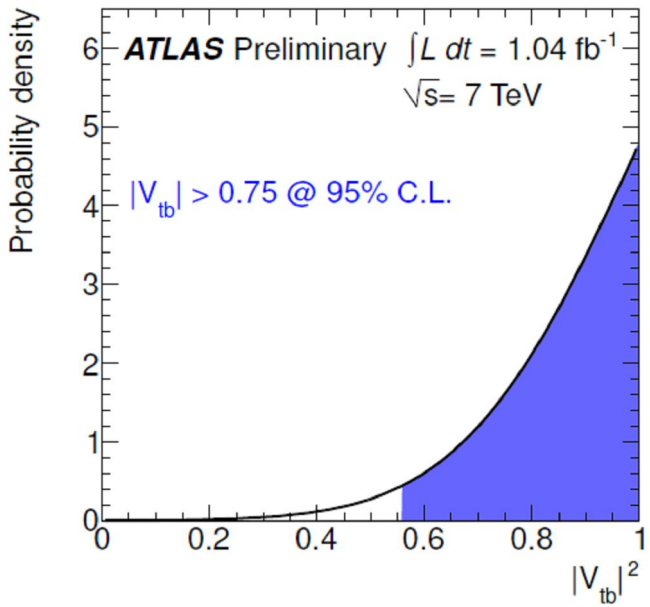
$|V_{tb}|$ Measurement

- cross section in t-channel prop. $|V_{tb}|^2$
- Independent of N_{quark} generations or CKM unitarity

Assumptions

- $|V_{tb}| >> |V_{td}|, |V_{ts}|$
- left-handed SM-like W-t-b interaction
- contributions from s, Wt channels negligible

$|V_{tb}|^2 = \sigma_t$ (obs.) / σ_t (theory)



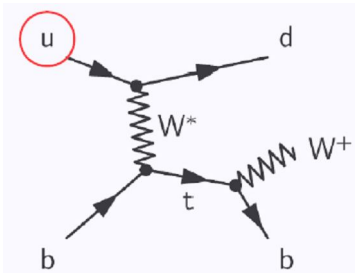
$\|V_{tb}\|$	7 TeV	8 TeV
ATLAS	$\|V_{tb}\|$ = 1.13 ± 0.14, > 0.75 (95% CL)	$\|V_{tb}\|$ = 1.04 ± 0.11 > 0.80 (95% CL)
CMS	$\|V_{tb}\|$ = 1.02 ± 0.05 > 0.92 (95% CL)	$\|V_{tb}\|$ = 0.96 ± 0.08 > 0.81 (95% CL)

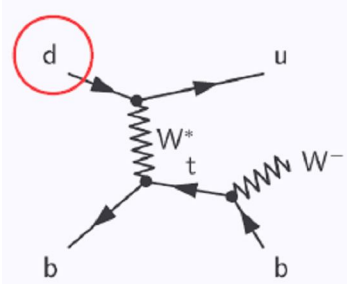
Top/antitop cross section ratio (R_t)

Motivation: R_t sensitive to ratio of u/d quark PDF

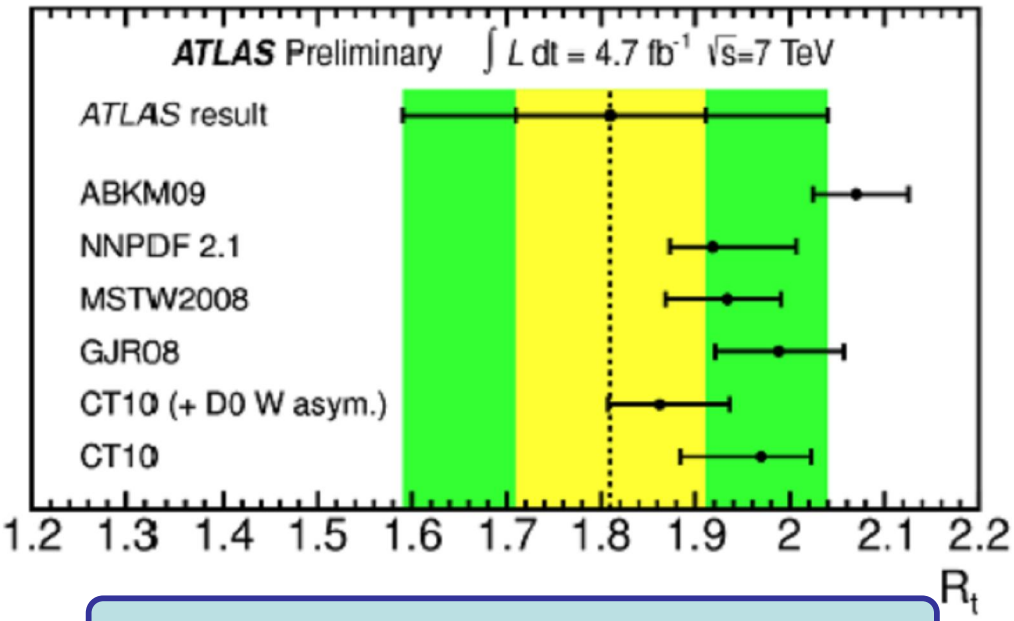
R_t ~ 1.9, sizable dependence on PDF sets

Measurements: ATLAS (7 TeV), CMS (8 TeV)





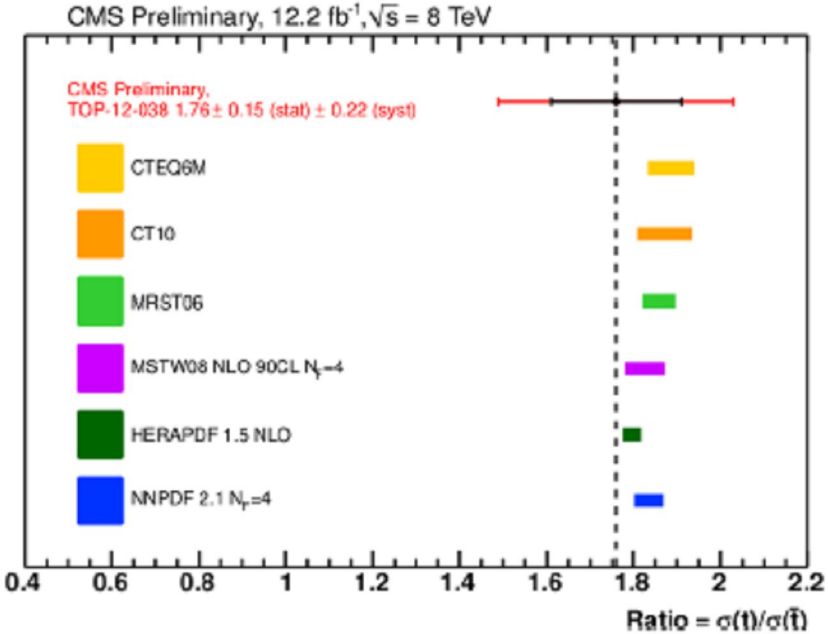
ATLAS-CONF-2012-056



R_t = 1.81 ± 0.10 (stat) ± 0.21 (syst)

(13%)

CMS-PAS-TOP-12-038



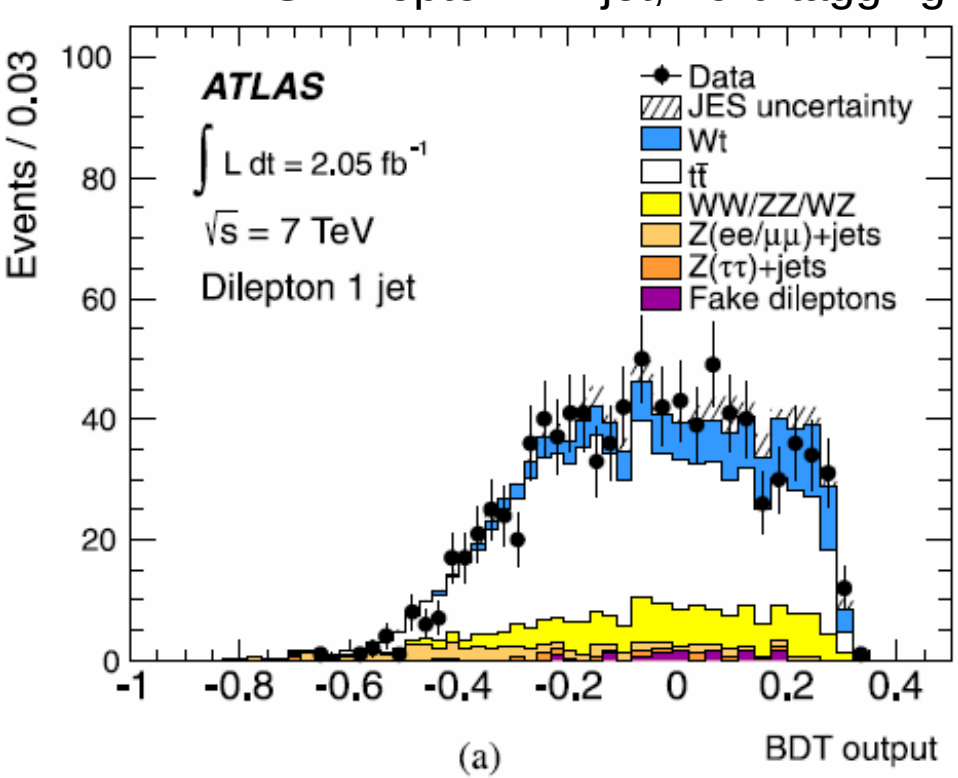
R_t = 1.76 ± 0.15 (stat) ± 0.22 (syst)

(15%)

Evidence of Wt production (7 TeV)

Method **ATLAS/CMS:** BDT

ATLAS: Dilepton + 1 jet, no b-tagging

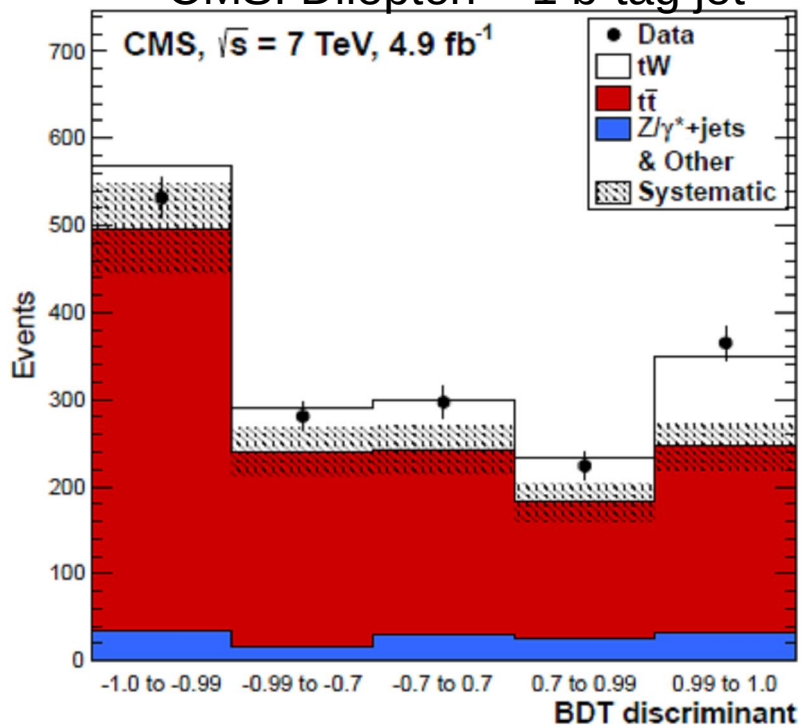


σ_{Wt} = 16.8 ± 2.9 (stat) ± 4.9 (syst) pb

3.3σ significance

$$|V_{tb}| = 1.03^{+0.16}_{-0.19}$$

CMS: Dilepton + 1 b-tag jet



$\sigma_{Wt} = 16^{+5}_{-4}$ pb **(SM: 15.7 ± 1.4 pb)**

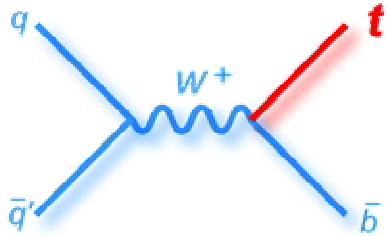
4.0σ sign.

$$|V_{tb}| = 1.01^{+0.16}_{-0.13}(\text{exp.})^{+0.03}_{-0.04}(\text{th.})$$

Search for s-channel (0.7 fb^{-1}, 7 TeV)

Method

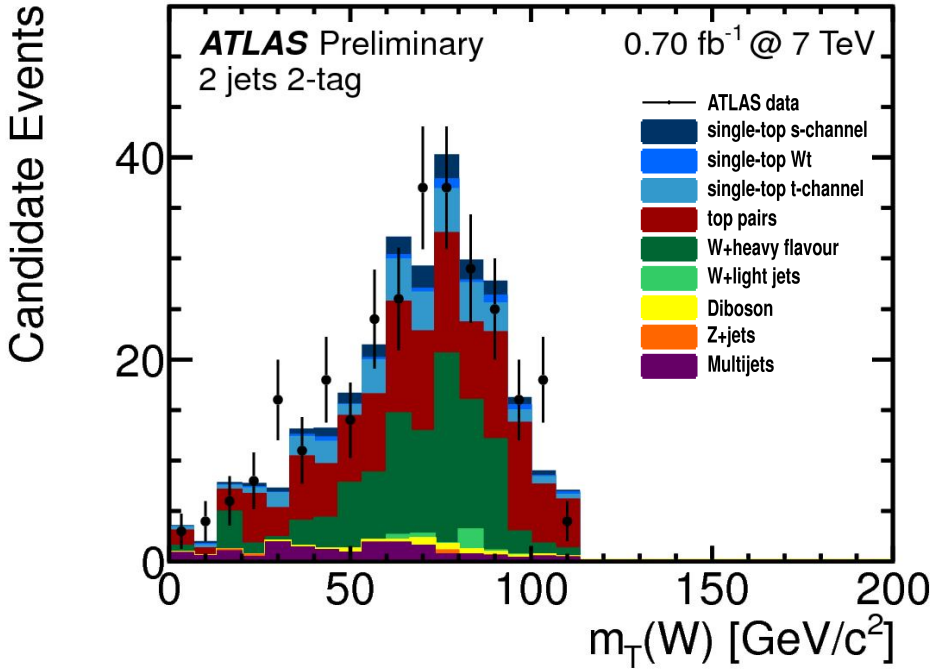
ATLAS: cut-based analysis



e/μ+2jets, 2 b-tag

ATLAS-CONF-2011-118

	Final Selection
s-channel	16 ± 6
t-channel	33 ± 13
Wt	5 ± 3
$t\bar{t}$	111 ± 47
W+jets	4 ± 5
Wc+jets	10 ± 8
$Wc\bar{c}$+jets	14 ± 12
$Wb\bar{b}$+jets	70 ± 51
Z+jets	1 ± 1
Diboson	4 ± 1
Multijets	17 ± 10
TOTAL Exp	285 ± 17
$S/\sqrt{B}$	0.98
DATA	296



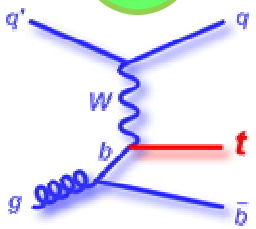
$\sigma_s < 26.5$ pb

(SM: 4.6 ± 0.3 pb)

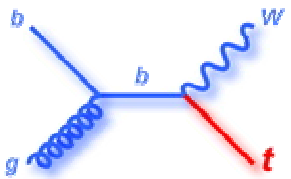
Statistically limited

Cross section measurements summary

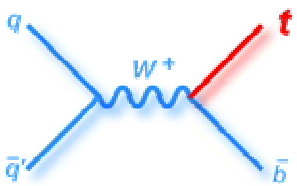
t-ch



W+t



s-ch



7 TeV

Theory	64.6 ± 2.4 pb	15.7 ± 1.1 pb	4.6 ± 0.2 pb
ATLAS	83 ± 20 pb	17 ± 6 pb (3.3σ)	<26.5 pb
CMS	67 ± 6 pb	16 ± 5 pb (3.3σ)	-

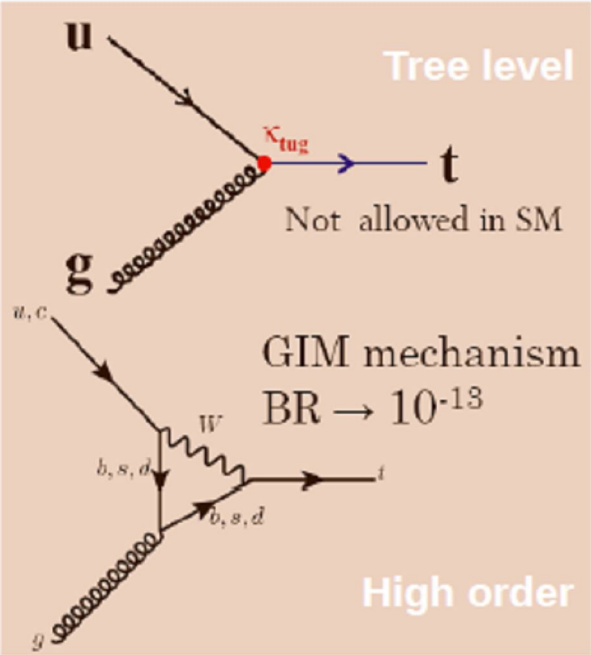
8 TeV

Theory	87.8 ± 3.4 pb	22.4 ± 1.5 pb	5.6 ± 0.3 pb
ATLAS	95 ± 18 pb	-	-
CMS	80 ± 13 pb	-	-

$|V_{tb}|$ compatible with 1, R_t compatible with predictions

BSM Searches
in Single Top-Quark Signatures

Search for FCNC

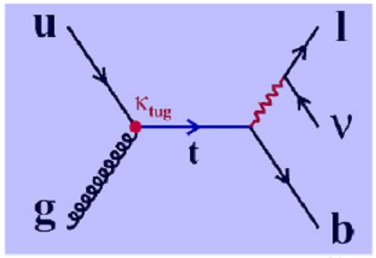


BSM predicts higher rates: up to 10^{-3}

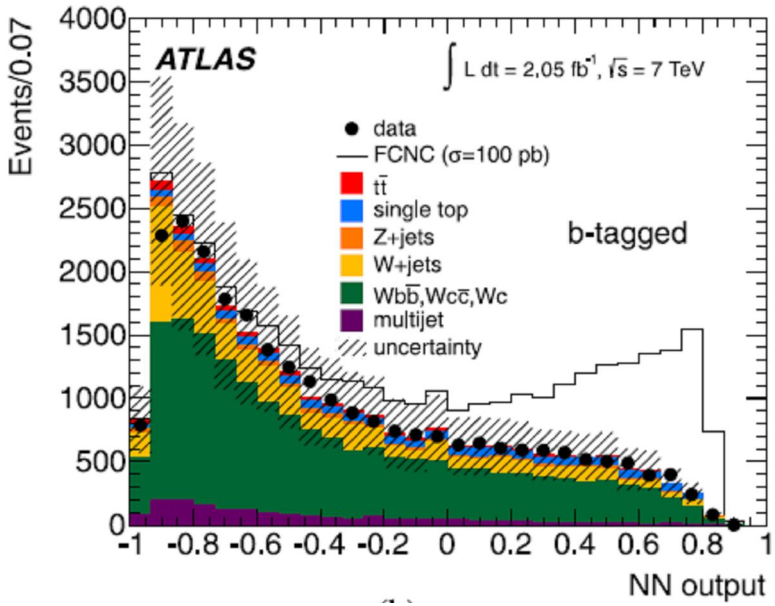
ATLAS: Single-top production via FCNC
Method: Bayesian Neural Network

Effective Lagrangian: gq → t

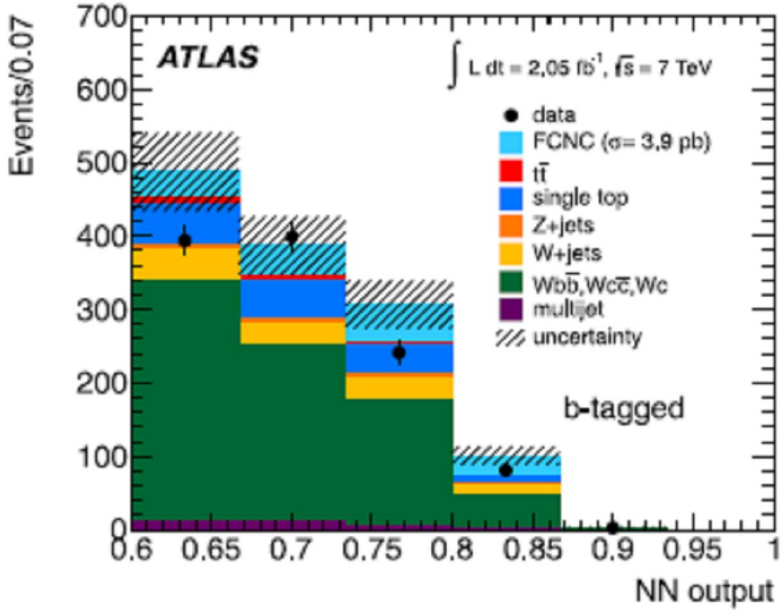
$$\mathcal{L}_{\text{eff}} = g_s \sum_{q=u,c} \frac{\kappa_{qgt}}{\Lambda} \bar{t}\sigma^{\mu\nu} T^a \left(f_q^L P_L + f_q^R P_R\right) q G^a_{\mu\nu} + \text{h.c.}$$

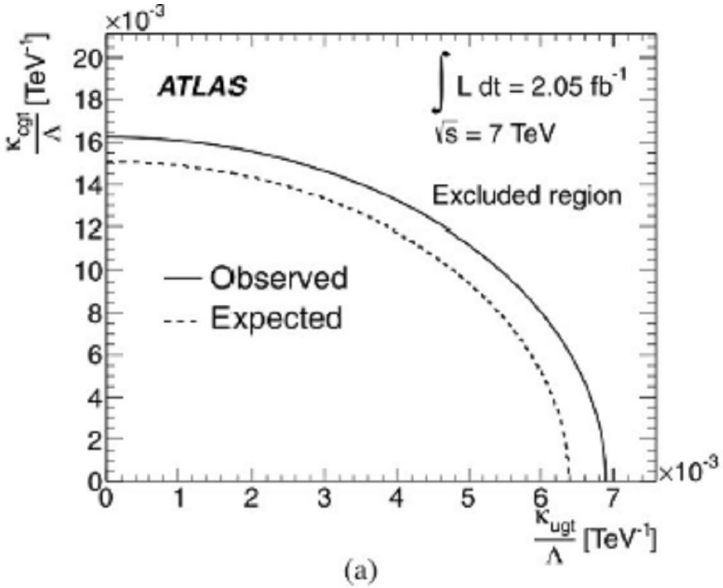


K_{qgt}: new coupling strength
Λ: new physics scale



Search for FCNC



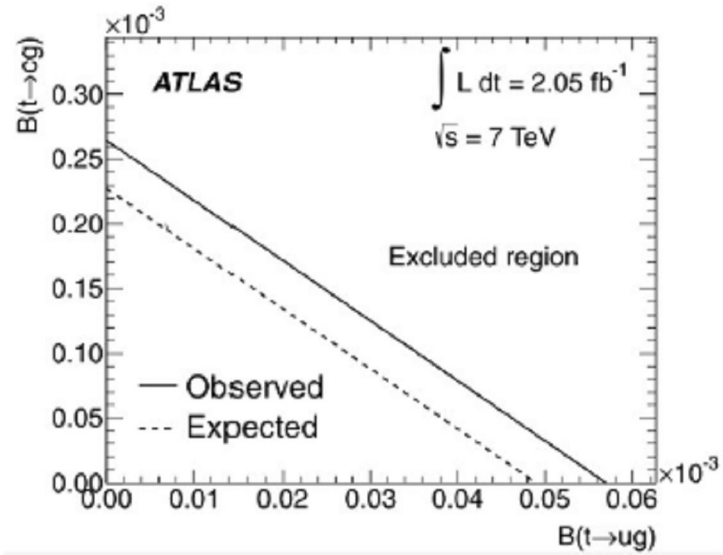


ATLAS [PLB 712 (2012) 351-369]

$$\sigma_{qg\to t} \times \mathcal{B}(t \to Wb) < 3.9 \text{ pb}$$

Coupling strengths $\kappa_{ugt}/\Lambda < 6.9 \cdot 10^{-3}$ TeV^{-1}
$\kappa_{cgt}/\Lambda < 1.6 \cdot 10^{-2}$ TeV^{-1}

Branching ratios $\mathcal{B}(t \to ug) < 5.7 \cdot 10^{-5}$
$\mathcal{B}(t \to cg) < 2.7 \cdot 10^{-4}$.



W'→tb searches

- **Search for W' boson(s)**
  - Predicted by many extensions of the SM
  - L/R models, KK excitations, Little Higgs, …
- **Why search for W'→tb decay**
  - More model independent than leptonic decay
  - Probe leptophobic sector
  - BSM dynamics could explain high top mass
- **Model independent approach**
  - Effective Left-Right model (Sullivan arXiv:1208.4858v1)
  - W' with left-handed, right-handed or mixed couplings

$$\mathcal{L} = \frac{V'_{ij}}{2\sqrt{2}} \bar{f}_i \gamma_\mu \left(g'^R_{i,j}(1+\gamma^5) + g'^L_{i,j}(1-\gamma^5) \right) W'^\mu f_j + h.c.$$

$W'_R \rightarrow tb$ search (1.1 fb^{-1}, 7 TeV)

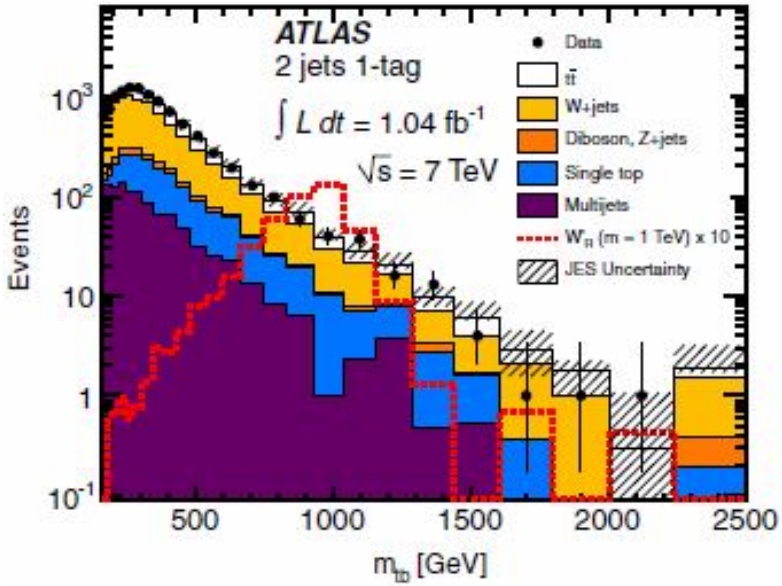
PRL 109, 081801 (2012)

Signature: e/μ+2jets, 1-2 btags

- p_T(lep,jet)>25 GeV, MET> 25 GeV
- m_T(W)+MET>60 GeV

Method: fit reco. m_{tb} spectrum

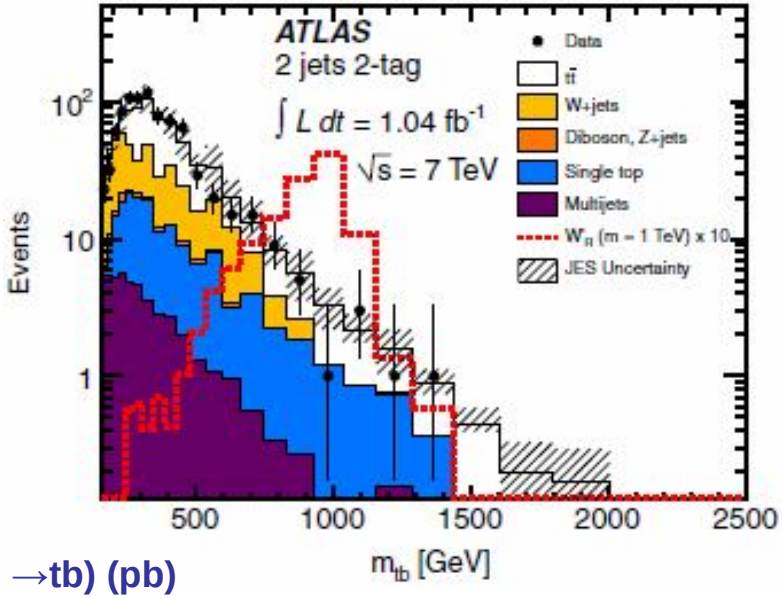
Bckgd: W+jets/QCD rate data-derived



Signal model: Pythia

Theory: Z. Sullivan Phys. Rev. D 66, 075011 (2002).

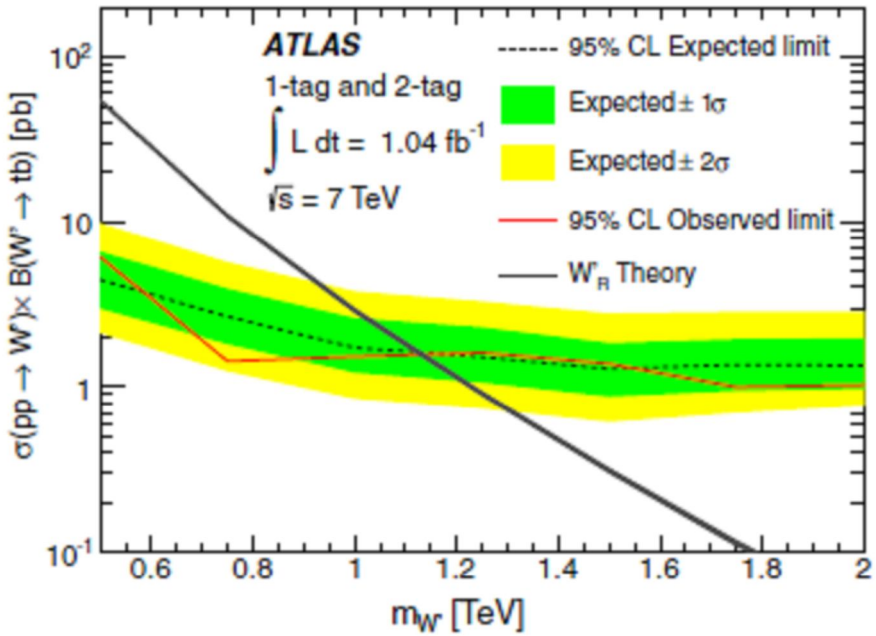
$m_{W'_R}$ [GeV]	$\mathcal{B}(W'_R \rightarrow tb)$	$\sigma \times \mathcal{B}$ [pb]
500	0.298 ± 0.002	54.6 ± 2.1
750	0.319 ± 0.001	10.9 ± 0.6
1000	0.326 ± 0.001	2.92 ± 0.18
1250	$0.328 < 0.001$	0.91 ± 0.07
1500	$0.330 < 0.001$	0.31 ± 0.03
1750	$0.331 < 0.001$	0.11 ± 0.01
2000	$0.332 < 0.001$	0.044 ± 0.005



NLO production cross section times branching fraction B(W' →tb) (pb)

$W'_R \rightarrow tb$ search (1.1 fb^{-1}, 7 TeV)

Samples	Single-tagged	Double-tagged
W + jets	5970 ± 1000	290 ± 180
Multijets	1120 ± 560	47 ± 47
$t\bar{t}$	1560 ± 130	360 ± 30
Single top	1240 ± 90	120 ± 10
Diboson, Z + jets	320 ± 120	14 ± 2
Total prediction	10 200 ± 1200	830 ± 190
Data	10428	844



Search for excess: sliding window (BumpHunter tool)

→ No significant excess founds

95% C.L cross-section limit: Bayesian approach (BAT)

m(W') > 1.13 TeV at 95% C.L

$W'_{R,L} \rightarrow tb$ search (5.0 fb^{-1}, 7 TeV)

Physics Letters B 718 (2013)

Signature: e/μ+jets, 1-2 btags

- $p_T(e/\mu)$>35/32 GeV, MET(e/μ)> 35/20 GeV
- $p_T(j_1)$>100 GeV, $p_T(j_2)$>40 GeV

Method: fit reco. m_{tb} / BDT spectrum

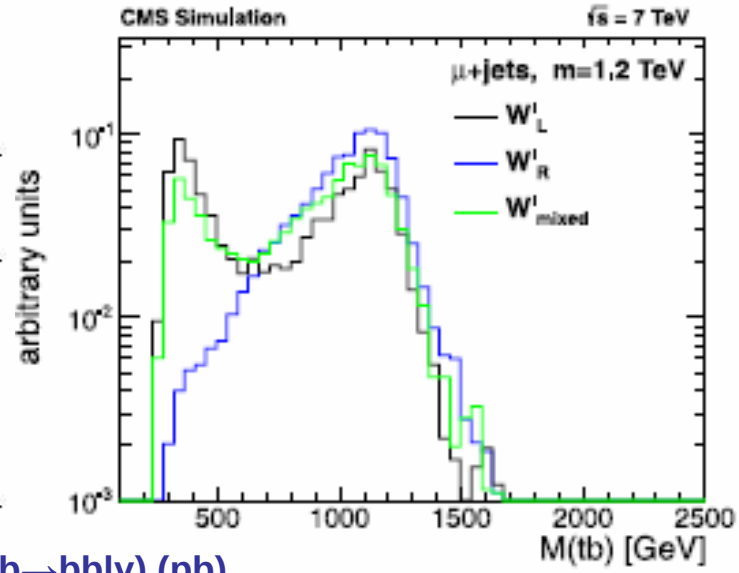
- m_{tb} analysis specific: p_T(top)>75 GeV, $p_T(j_1, j_2)$>100 GeV, 130<M(top)<210 GeV
- BDT analysis: ~40 (!) input variables

Bckgd: W+jets rate data-derived

Signal model: CompHep

- right/left/mixed W' couplings
- Interference between single-top s-channel and W'_L included
- NLO corrections on rate and shape

$M_{W'}$ (TeV)	$M_{\nu_R} \ll M'_W$			$M_{\nu_R} > M'_W$		
	σ_R	σ_L	σ_{LR}	σ_R	σ_L	σ_{LR}
0.9	1.17	2.28	3.22	1.56	3.04	4.30
1.1	0.43	1.40	1.85	0.58	1.86	2.47
1.3	0.17	1.20	1.39	0.23	1.60	1.85
1.5	0.07	1.13	1.21	0.099	1.51	1.62
1.7	0.033	1.12	1.15	0.044	1.50	1.54
1.9	0.015	1.11	1.13	0.020	1.49	1.51

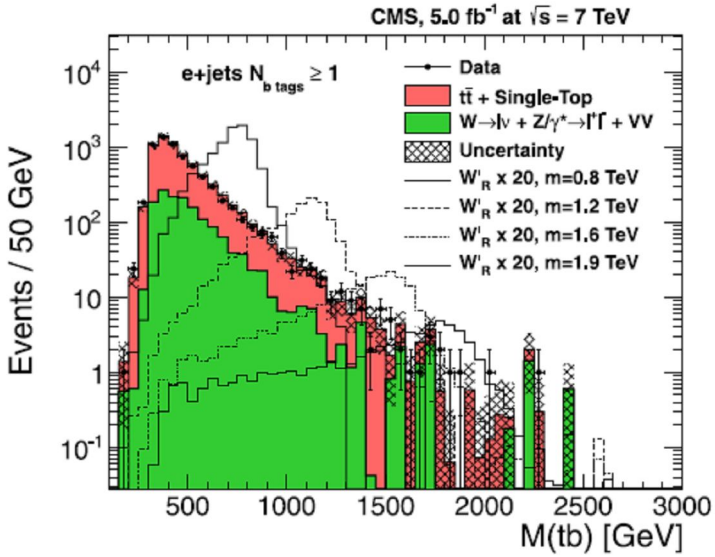


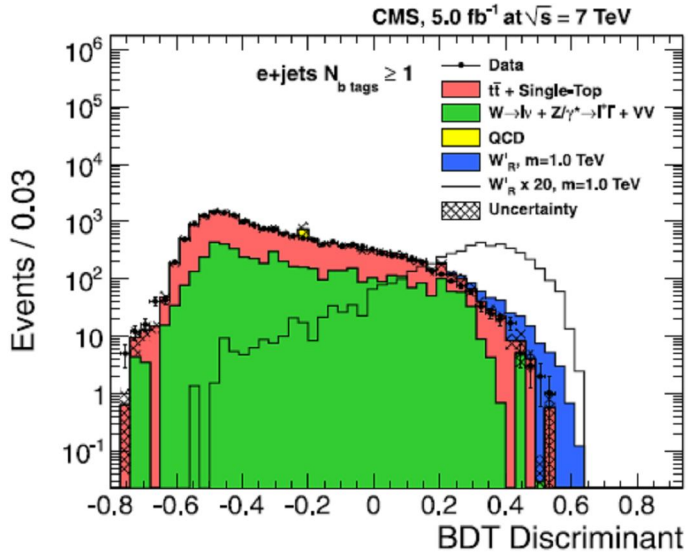
NLO production cross section times branching fraction B(W' →tb→bblν) (pb)

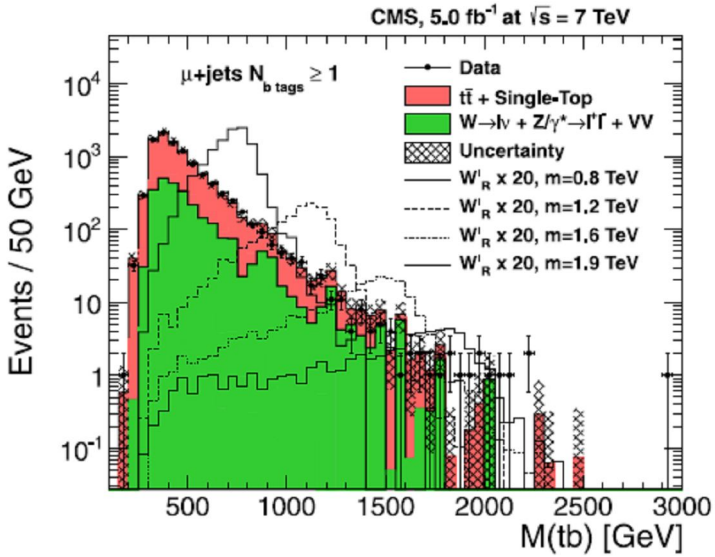
$W'_{R,L} \rightarrow tb$ search (5.0 fb^{-1}, 7 TeV)

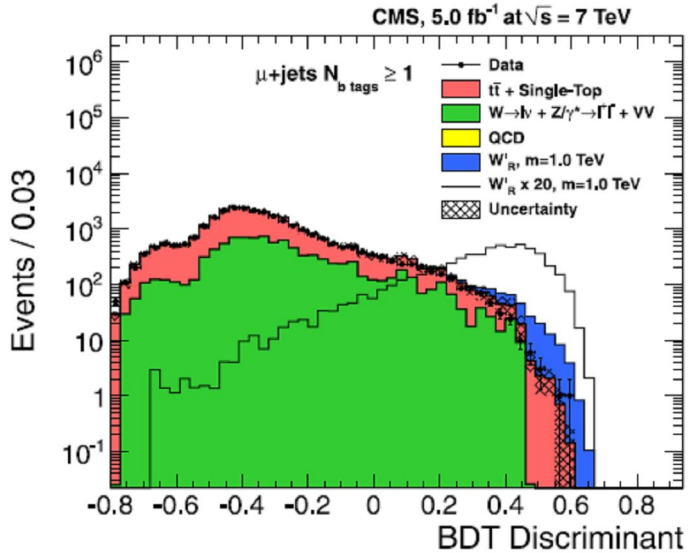
Inv. mass analysis

BDT analysis



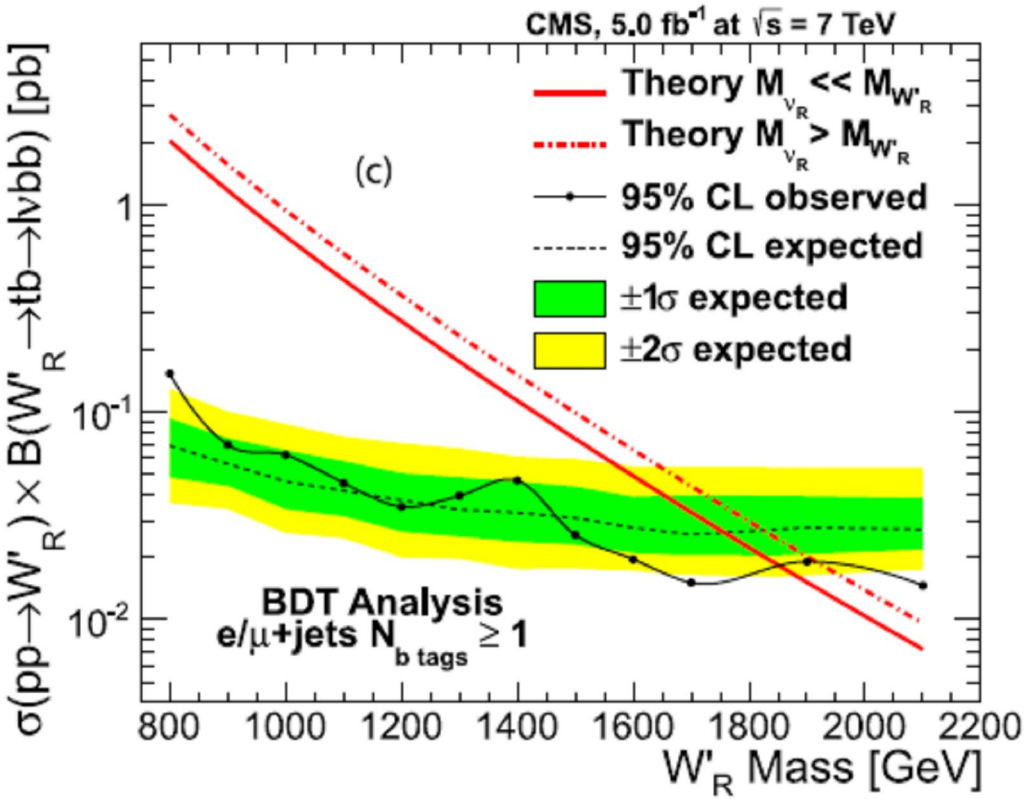






$W'_{R,L} \rightarrow tb$ search (5.0 fb^{-1}, 7 TeV)

No significant excess observed
→ Limits sets using **CL_s** method
- W' right/left and max. mixed
- W'_L interference term included
- both scenario of $m(\nu_R)$



95% C.L. limits on W' mass

Analysis	$(a^L, a^R) = (0, 1)$		$(a^L, a^R) = (1, 0)$	$(a^L, a^R) = (1, 1)$
	$M_{\nu_R} > M_{W'}$	$M_{\nu_R} \ll M_{W'}$	$M_{\nu_R} \ll M_{W'}$	$M_{\nu_R} \ll M_{W'}$
BDT	1.91 TeV	1.85 TeV	–	–
Invariant mass	–	–	1.51 TeV	1.64 TeV

$W'_{R,L} \rightarrow tb$ search (5.0 fb^{-1}, 7 TeV)

Limits on coupling strength a^R and a^L

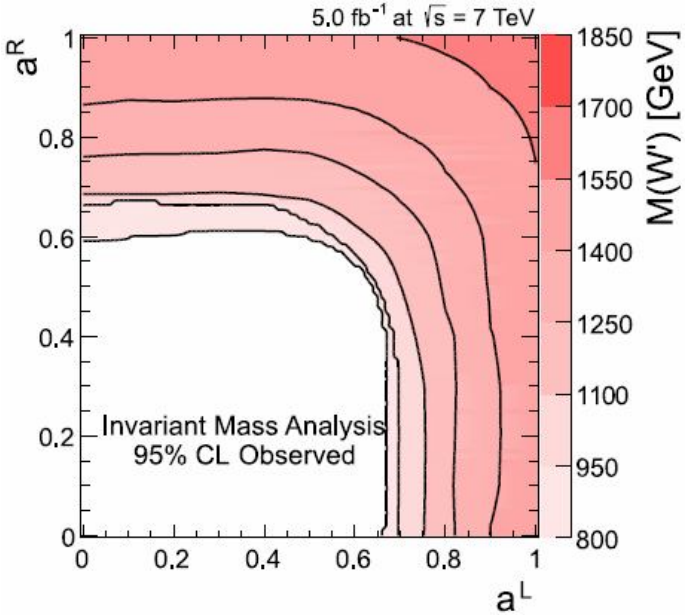
$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_W \bar{f}_i \gamma_\mu [a^R_{f_i f_j}(1+\gamma^5) + a^L_{f_i f_j}(1-\gamma^5)] W'^\mu f_j + \text{h.c.},$$

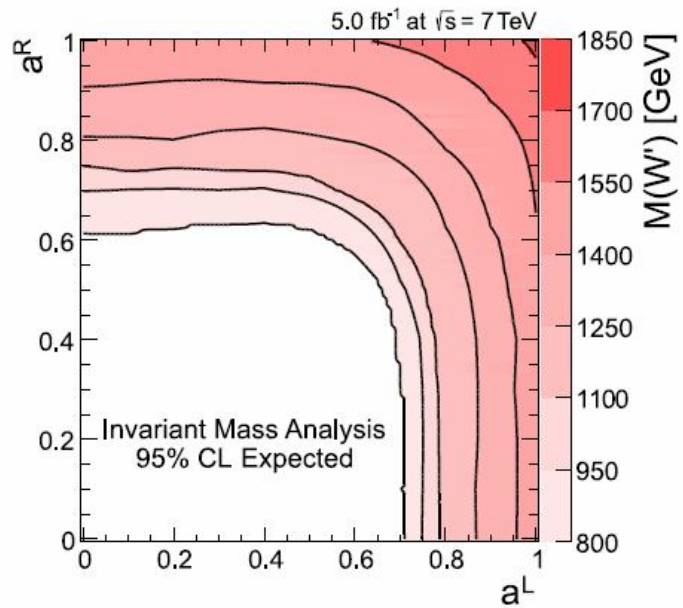
Procedure

- assume that a_{ud} (W' prod) and a_{tn} are the same
- vary a^L and a^R from 0 to 1
- reweight m_{tb} template for each value of a^L and a^R

$$\sigma = \sigma_{SM} + a^L_{ud} a^L_{tb} (\sigma_L - \sigma_R - \sigma_{SM}) + \left((a^L_{ud} a^L_{tb})^2 + (a^R_{ud} a^R_{tb})^2\right)\sigma_R + \frac{1}{2}\left((a^L_{ud} a^R_{tb})^2 + (a^R_{ud} a^L_{tb})^2\right)(\sigma_{LR} - \sigma_L - \sigma_R)$$

- Compute limit for each a^L, a^R ,m(W') hypothesis
- Compare to theory and set limits in a^R, a^L plane

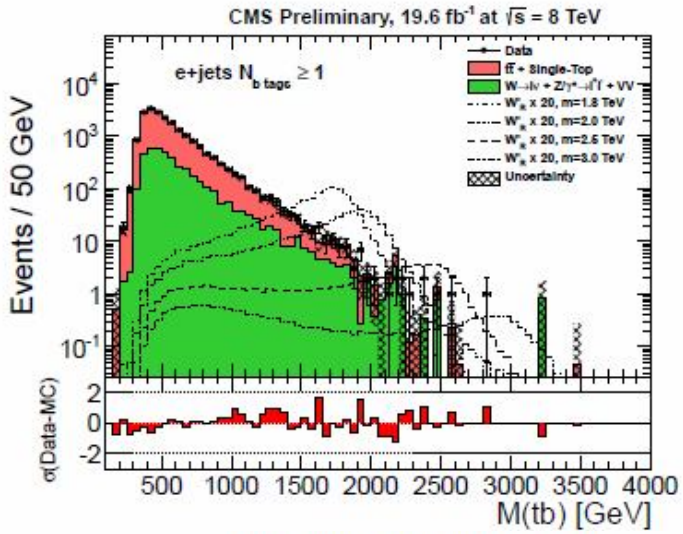


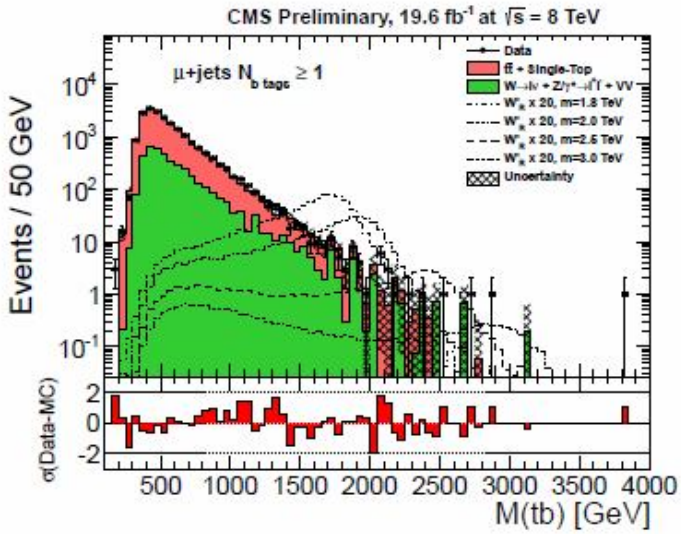


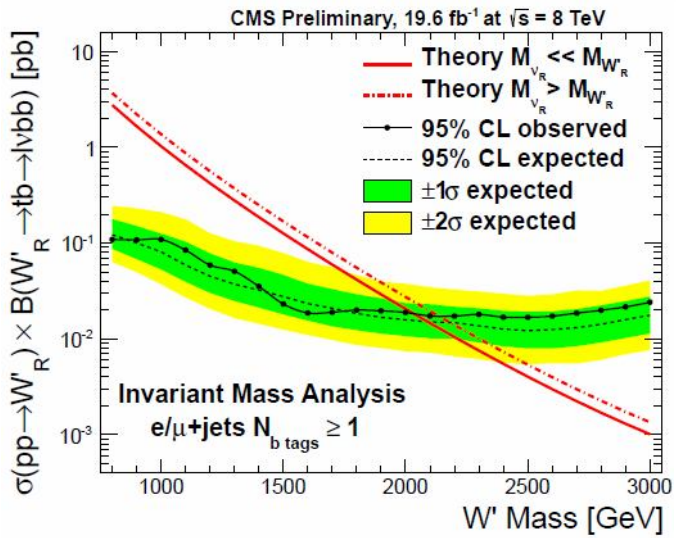
$W'_{R,L} \rightarrow tb$ search (20 fb^{-1}, 8 TeV)

Updated W' analysis at 8 TeV: m_{tb} fit method

CMS PAS B2G-12-010







Broke 2 TeV energy barrier !

m(W') > 2.03 TeV at 95% C.L

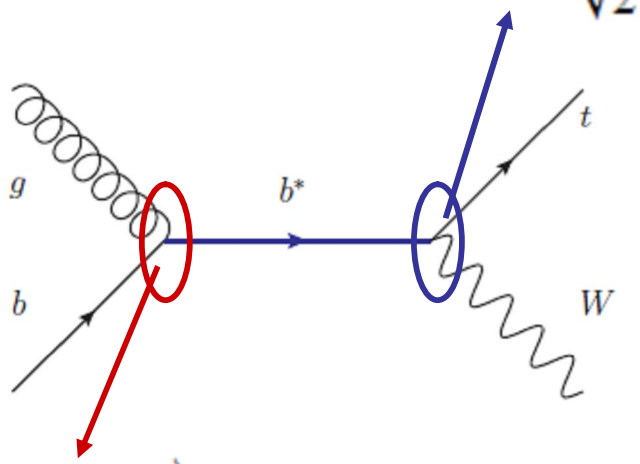
b* search (4.7 fb^{-1}, 7 TeV)

arXiv:1301.1583v1 (submitted to PLB)

Single b*-quark produced through chromomagnetic interaction and decays to a W+t

ATLAS: search performed in dilepton and lepton+jets final states and combined

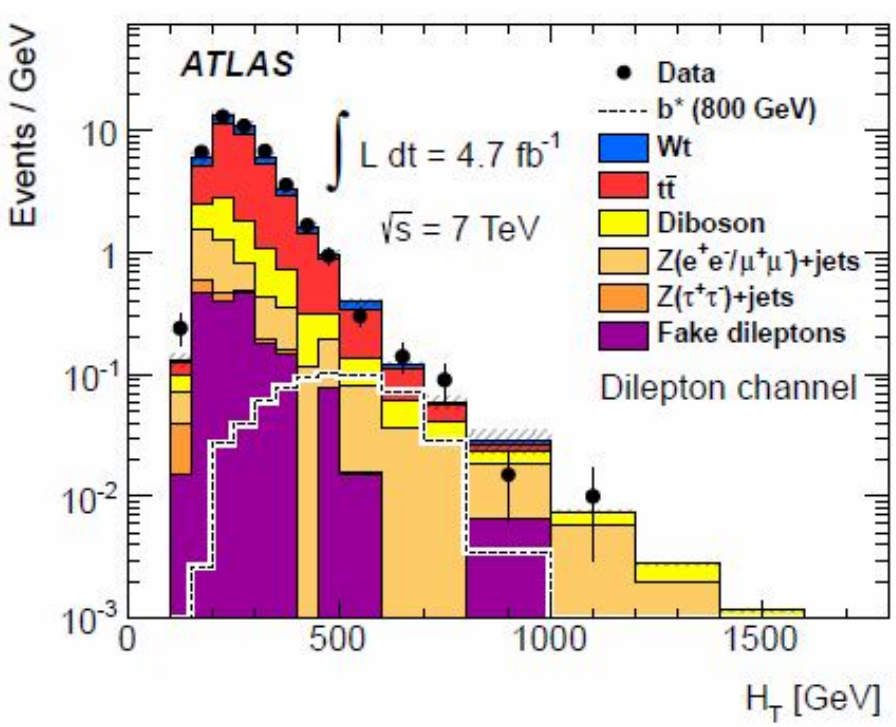
$$\mathcal{L} = \frac{g_2}{\sqrt{2}} W_\mu^+ \bar{t}\gamma^\mu \left(g_L P_L + g_R P_R\right) b^* + \text{h.c.}$$

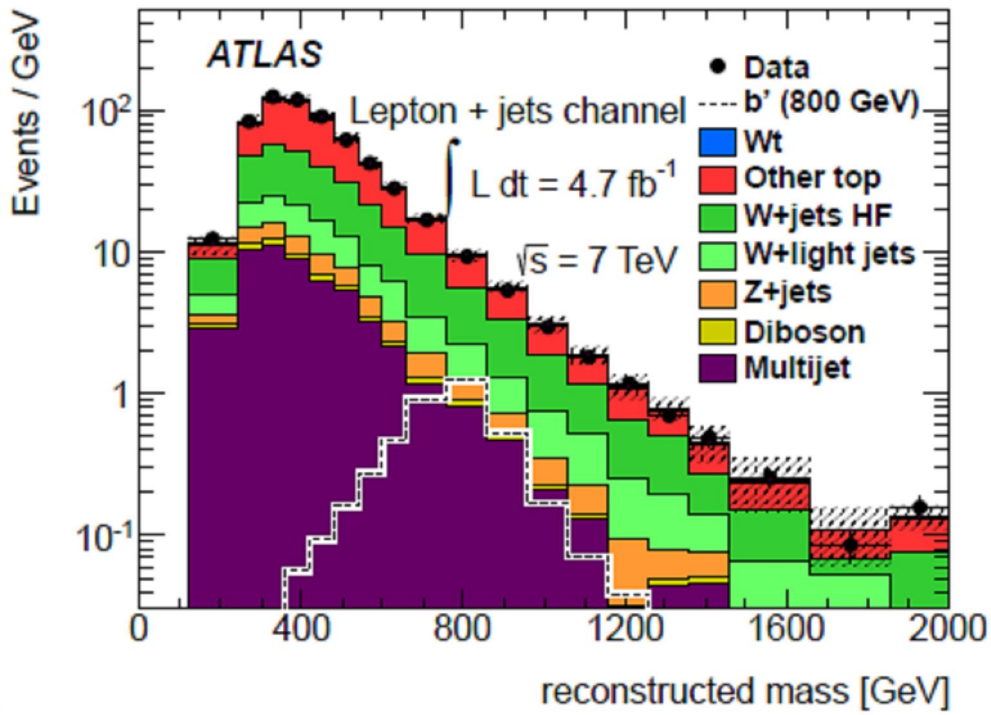


$$\mathcal{L} = \frac{g_s}{2\Lambda} G_{\mu\nu} \bar{b}\, \sigma^{\mu\nu} \left(\kappa_L^b P_L + \kappa_R^b P_R\right) b^* + \text{h.c.}$$

Signal model: MadGraph, generated right/left/vector-like processes

b* search

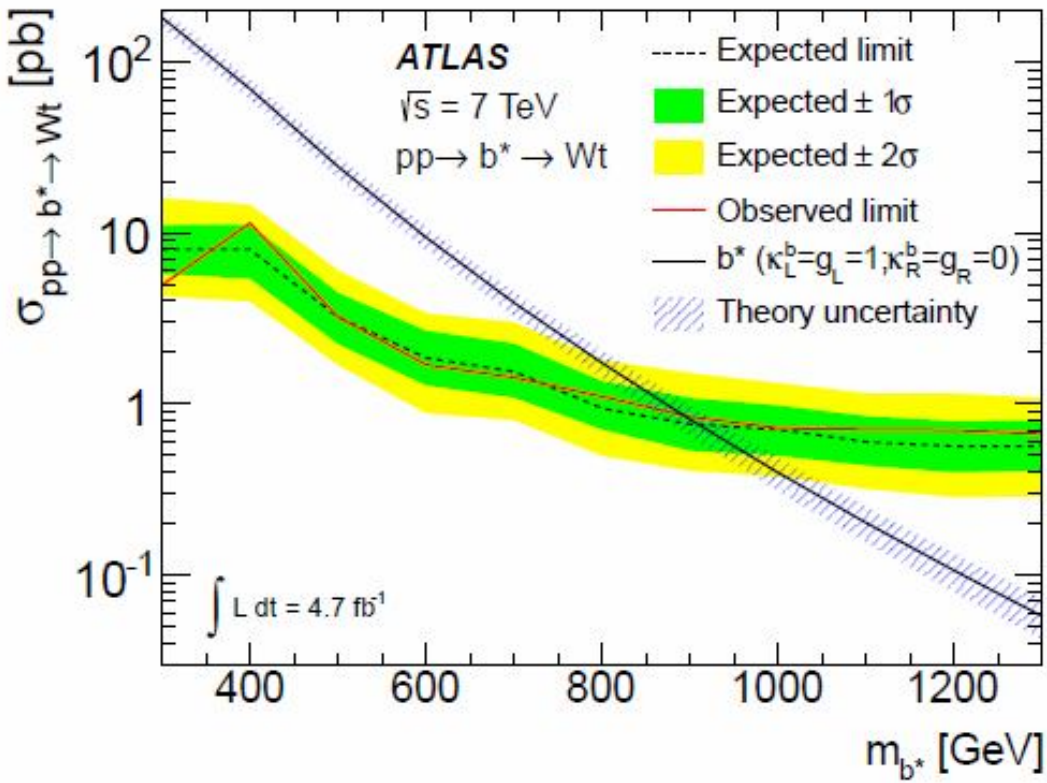




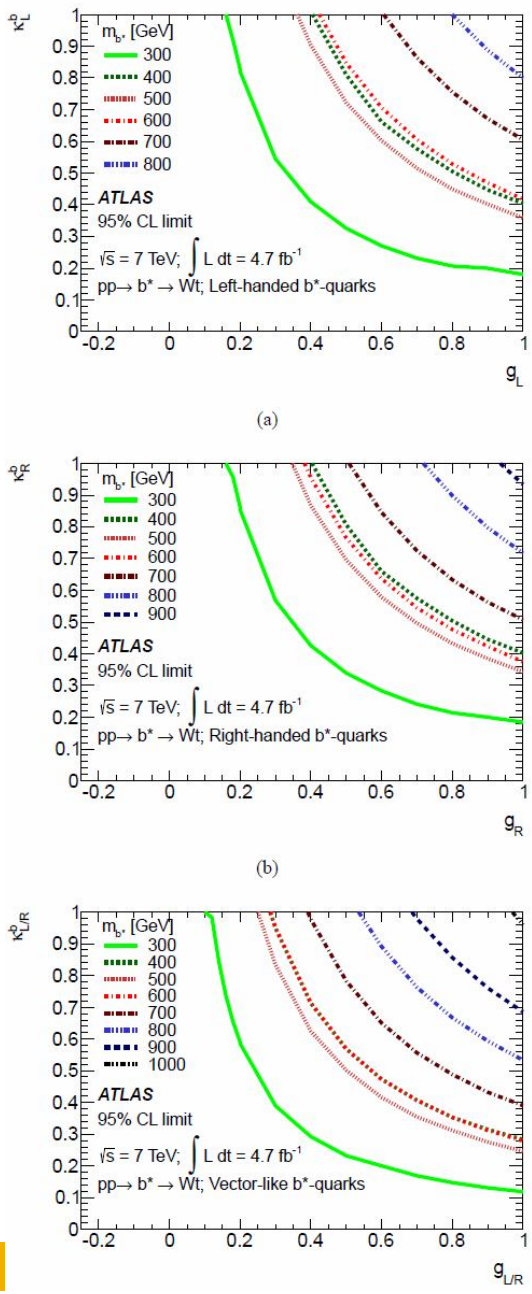
Discriminant distributions for each channel are combined using Bayesian method

b* search

Limits on b* mass and couplings: $K_{L,R}$, $g_{L,R}$



m(b*)>870 GeV at 95% C.L
(benchmark scenario)



Conclusion and outlook

- **Single-top measurements**
  - Several measurements on cross section and properties
  - Most measurement become syst. limited
  - Effort to combine cross section results ongoing
- **Direct BSM searches**
  - Performed in parallel with indirect and SM measurements
  - So far search for W' boson, b* quark
- **Future analysis paths**
  - Invest in boosted top topologies
  - Investigate full hadronic searches
  - Sector will get even more interesting at higher pp energy

Stay tuned ! Many new interesting results ahead !

Backup material

Reach for W' boson at √s= 7/8 TeV

Z. Sullivan et al., arXiv:1208.4858v1 (2012)

Pheno analysis based on effective W' boson Lagrangian

- consider pure Right/Left W' boson couplings
- For W'_L assess effects of destructive/constructive interferences
- simple cut-based analysis performed at 7 & 8 TeV
- set exclusion limits on cross-section and couplings

Event selections

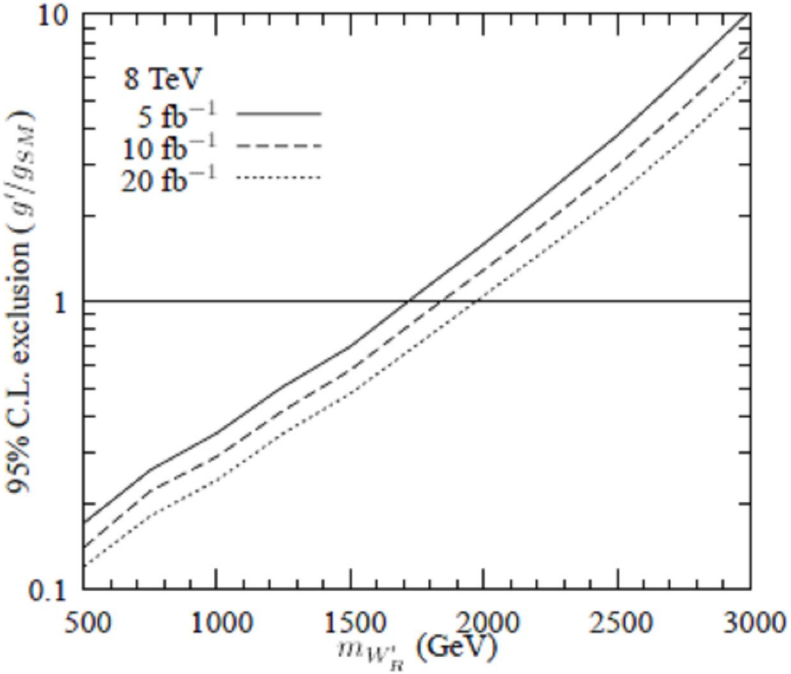
Lead jet	$E_{Tj_1} > 0.2 m_{W'}$	$\lvert\eta_{j_1}\rvert < 2.5$
b-tagged jet	$E_{Tb} > 20$ GeV	$\lvert\eta_b\rvert < 2.5$
Leading $e^\pm$ or $\mu^\pm$	$p_{Tl_1} > 20$ GeV	$\lvert\eta_{l_1}\rvert < 2.5$
Second $e^\pm$ or $\mu^\pm$	$p_{Tl_2} < 10$ GeV; or	$\lvert\eta_{l_2}\rvert > 2.5$
Missing E_T	$\not{E}_T > 20$ GeV	
Reconstructed top	$M_{l\nu b} < 200$ GeV	
W' mass window	$0.75 m_{W'} < M_{l\nu bj} < 1.1 m_{W'}$	

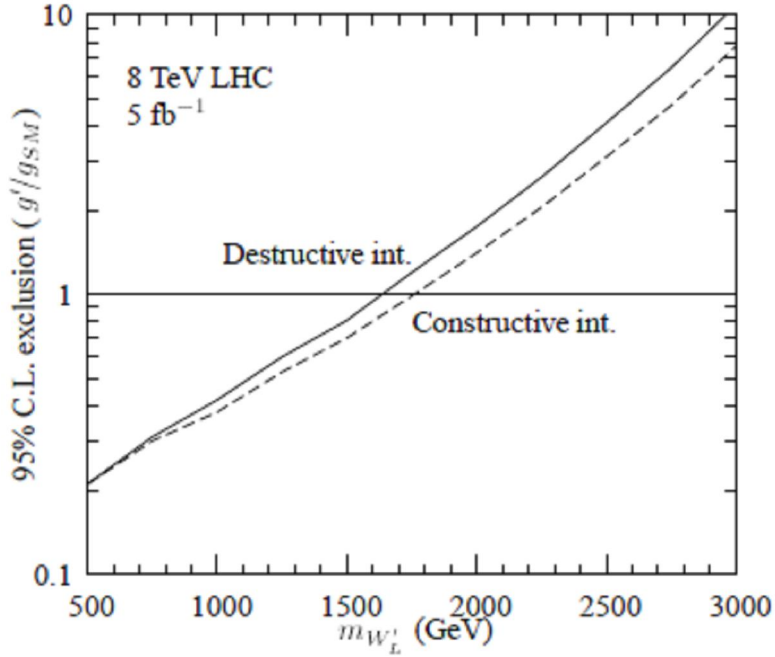
Mass Limits (5 fb^{-1})	7 TeV	8 TeV
W'_R	1.8 TeV	1.7 TeV
W'_L	1.7-1.9 TeV	1.6-1.7 TeV

Reach slightly worse at 8 TeV (gluon initiated bckgd grow faster that quark initiated signal)

Limits on couplings

Exclusion Limit on coupling can be derived from cross-section limit
→ σ(pp→W'→tb) scales roughly as ~ $(g'/g_{SM})^2$





Important to show exclusion for values larger than 1

- theory remains perturbative up to g'/g_{SM} ~ 5
- but W' boson width scales as $(g'/g_{SM})^2$ → effect non negligible for g'/g_{SM} > 2-3 and need to be properly simulated.

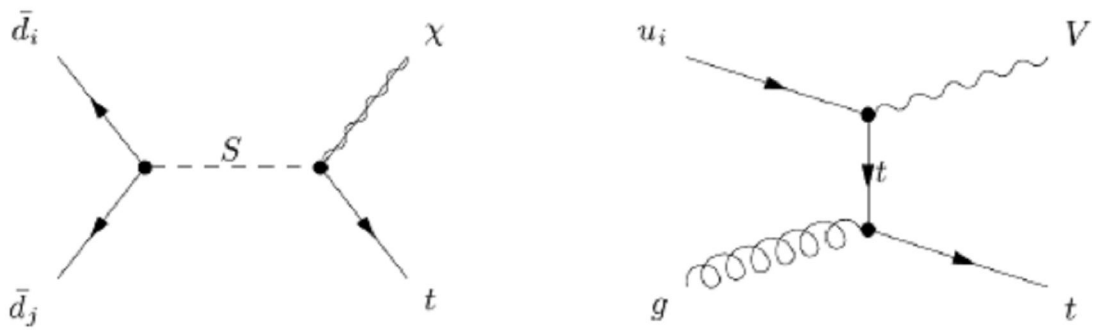
Monotop searches

Slides from Timothée !

- Many BSM models predict final states with a single top quark + $\not{E}_T$, e.g. :

  $ug \to \tilde{u}_i\tilde{\chi}_0^1 \to t\tilde{\chi}_0^1\tilde{\chi}_0^1$ (2-neutralinos in R-parity violating SUSY)

  $\bar{d}\bar{d} \to V \to t\bar{\nu}$ (leptoquark decay in $SU(5)$ theories)
- A signature-based approach in new physics searches can be followed
- Phenomenological description with a most general effective Lagrangian Phys.Rev. D84 (2011) 074025 (*J. Andrea, B. Fuks*)



Resonant production FC non resonant production

- New particules introduced with associated effective couplings

field	charge	spin	color multiplicity	antiparticle = particle	comment
			invisible particles		
ϕ	0	0	1	yes	non resonant production
χ	0	1/2	1	yes	resonant production
V	0	1	1	yes	non resonant production
			resonnances		
φ	$\pm 2/3$	0	3	no	decays into $t+\chi$
X	$\pm 2/3$	1	3	no	decays into $t+\chi$
$\tilde{\varphi}$	$\pm 1/3$	0	3	no	4-f effective interaction

Monotop searches

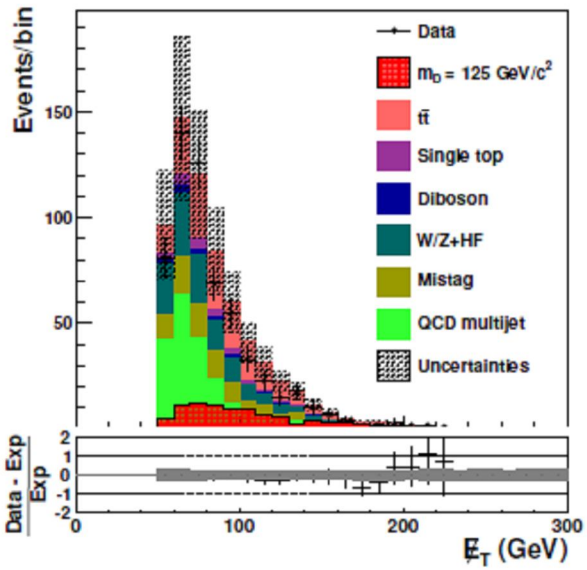
- Five scenarios defined in Phys.Rev. D84 (2011) 074025 (*J. Andrea, B. Fuks*)

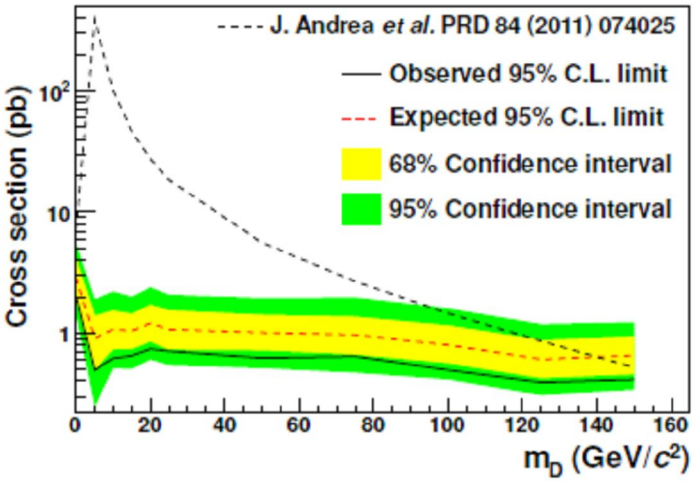
Scenario	model type	mass of invisible state	σ_{tot} [pb] @8 TeV
S1	scalar resonance m_φ= 500 GeV	m_χ= 50 GeV	1.68
S2	vector resonance m_X= 500 GeV	m_χ= 300 GeV	6.20
S3	flavour changing interaction (spin 0)	m_ϕ= 300 GeV	1.05
S4	flavour changing interaction (spin 1)	m_V= 50 GeV	186.7
S5	4-fermions effective interaction (m_Φ= 3 TeV)	m_χ= 0 GeV	2.7×10^{-4}

- Limits on cross-section vs. invisible state mass can be used to set limits on effective couplings and constrain new physics
- Result from CDF hadronic channel analysis in non-resonnant case :
  $\sigma \lesssim 0.5$ pb for a mass between 0 and 150 GeV at $\sqrt{s} = 1.96$ TeV
  Phys.Rev.Lett. 108 (2012) 201802
- Indirect constraint on monotop production in resonant case :
  use of LHC results on hadronic Z decays, K^0-$\overline{K^0}$ mixing or dijet production
  Phys.Rev. D86 (2012) 034008 (*Wang et al.*)
- Ongoing analyzes @8 TeV in leptonic and hadronic channel in ATLAS and CMS

CDF result

- Selection of events with monotop topology in hadronic channel
- Trigger : 2 calorimeter clusters + missing $\not\!\!E_T$
- $\not\!\!E_T$ distribution used as discriminative variable
- Result : $\sigma(p\bar{p} \to t + D) \lesssim 0.5\text{pb}$ for a mass between 0 and 150 GeV



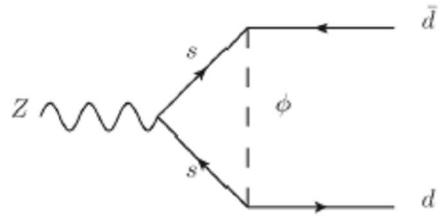


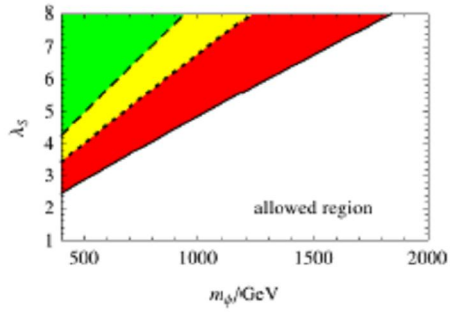
Phys.Rev.Lett. 108 (2012) 201802

Indirect constraints on resonant monotop production

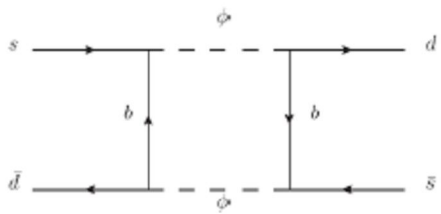
- For some cases, limits on the coupling of the scalar resonance ϕ to SM quarks can be set

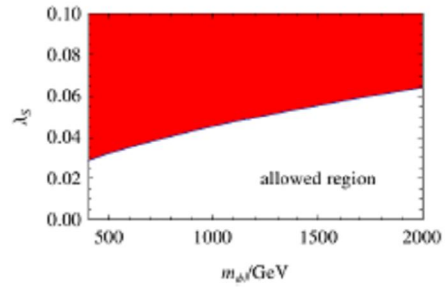
Using R_τ, with or without ϕ coupling to b, or using R_b



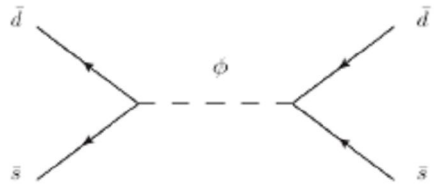


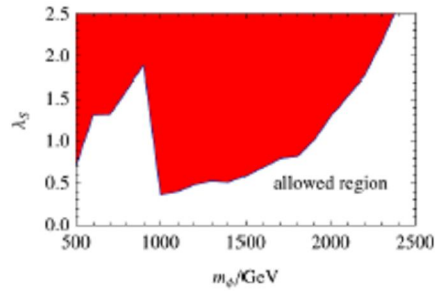
Using $m_{K_L} - m_{K_S}$, with ϕ coupling to b
$\Rightarrow$ contribution from $bb \to \phi$ can be neglected





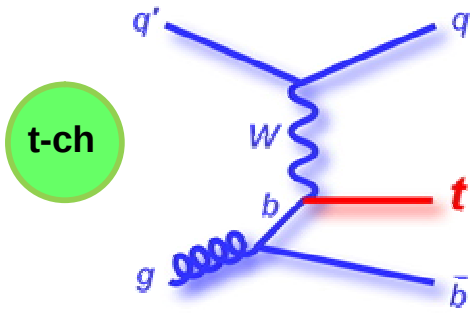
Using di-jet cross-section, with ϕ coupling to b and hypotheses on the invisible particle





Phys.Rev.Lett. 108 (2012) 201802 *Wang et al.*

Single top-quark production modes

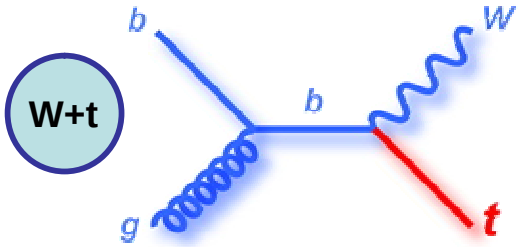


Dominant mode: ~1/3 ttbar production

Observed at Tevatron (2009), then at LHC (2011)

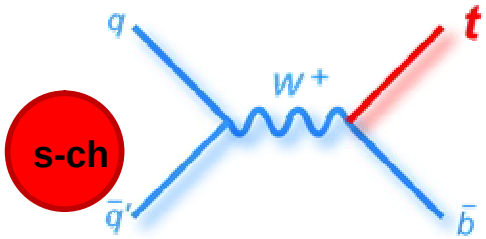
Motivation: $|V_{tb}|$, anomalous couplings, top polarization

But new intermediate particles suppressed as $1/M^2$



Evidence at ATLAS and CMS

Motivation: $|V_{tb}|$, excited quarks, charged Higgs



Smallest cross-section: ~1/15 t-channel

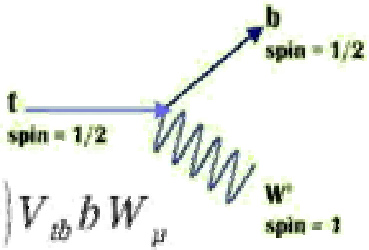
Difficult channel, **Limits** (ATLAS)

Motivation: charged W-like bosons, composite models

W polarization in top pair events

V-A current

In the SM:



$$\frac{-ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}(1-\gamma^{5})V_{tb}bW_{\mu}$$

W helicity : longitudinal or left

Polarization measurement

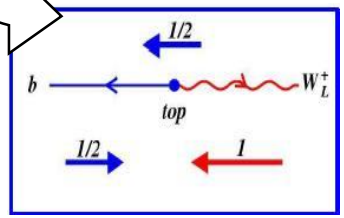
Use the lepton from W as a "spin analyzer"

– Angle ψ between l^+ (W rest frame) and the W^+ directions (top rest frame)

$$\frac{1}{N}\frac{dN}{d\cos\Psi}=\frac{3}{2}\left[F_0\left(\frac{\sin\Psi}{\sqrt{2}}\right)^2+F_L\left(\frac{1-\cos\Psi}{2}\right)^2+F_R\left(\frac{1+\cos\Psi}{2}\right)^2\right]$$

→ Access to F_0, F_L, F_R

"Left handed" F_L

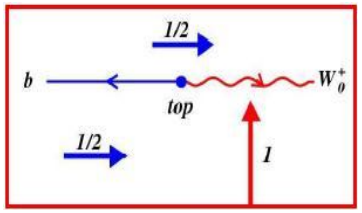


Standard Model:

$F_L=2m_W^2/(m_t^2+2m_W^2)$

$= 0.297$

"Longitudinal" F_0

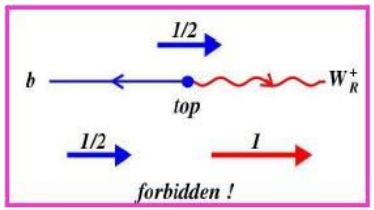


Standard Model:

$F_0=m_t^2/(m_t^2+2m_W^2)$

$= 0.703$

"Right handed" F_R



Standard Model:

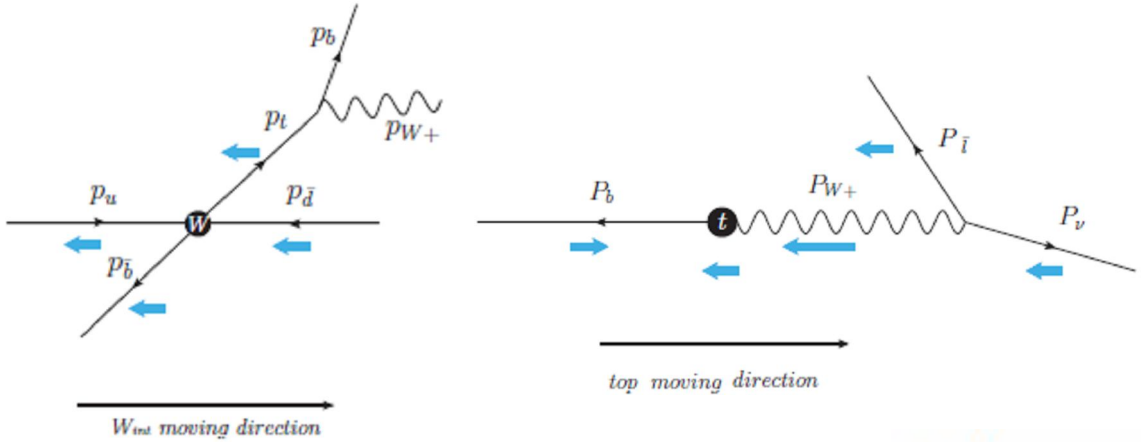
$F_R= 0.00$

(forbidden)

(m_b=0 approx.)

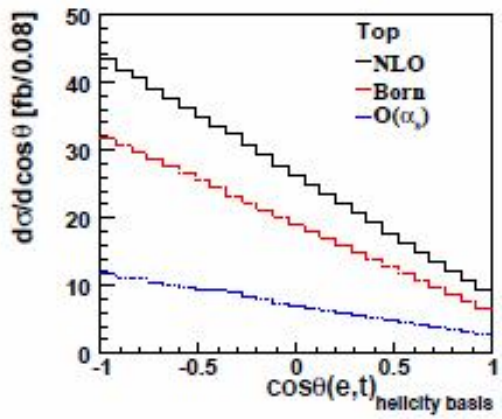
Spin correlation in qq' → W' → tb

- Impacts angular correlations in top production and decay
- See for example: http://arxiv.org/abs/0911.0620



The lepton moves in the direction of the top spin

- W/W'$_L$: opposite to top moving direction
- W'$_R$: same direction



Ex: SM single-top s-channel