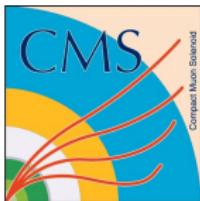


# Searches for monotop events at the LHC

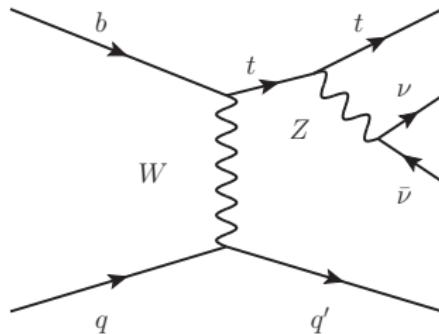
Timothée Theveneaux-Pelzer

Tuesday, May 19th 2015

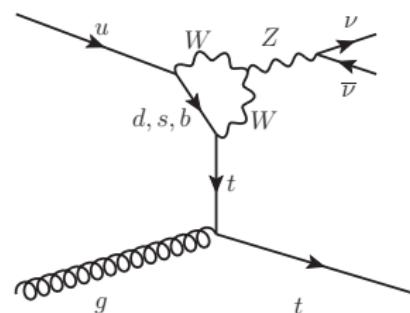


# Introduction

- "Monotop" : single-top in association with missing (transverse) energy
- In the Standard Model : GIM- and CKM-suppressed !



single-top + invisible + 1 jet in the SM



loop-induced monotop in the SM

- Observation at LHC would be a clear sign of new physics
- Enhanced production predicted by several BSM theories
- Very active physics topic in the past 4 years, in particular in French teams
- This talk : reminder of the phenomenology and description of LHC data analyses

# Selection of available papers

- Several recent papers on monotop, among which :

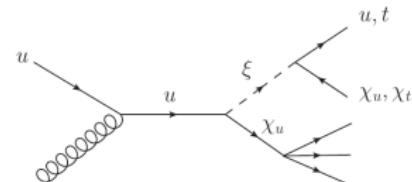
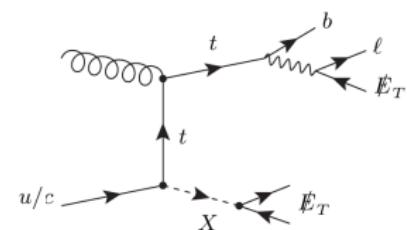
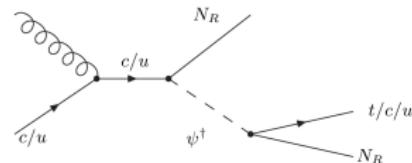
Paper	Reference	French contributors
<i>Monotops at the LHC</i> <i>Search for the signal of monotop production at the early LHC</i> <i>Leptonic Monotops at LHC</i> <i>Monotop phenomenology at the Large Hadron Collider</i> <i>Revisiting monotop production at the LHC</i>	<a href="#">Phys. Rev. D 84 (2011) 074025</a> <a href="#">Phys. Rev. D 86 (2012) 034008</a> <a href="#">Phys. Rev. D 89 (2014) 014016</a> <a href="#">Phys. Rev. D 89 (2014) 014028</a> <a href="#">JHEP 1501 (2015) 017</a>	Strasbourg
CDF - 1.96 TeV - fully-hadronic ATLAS - 8 TeV - $\ell$ +jet CMS - 8 TeV - fully-hadronic	<a href="#">Phys. Rev. Lett. 108 (2012) 201802</a> <a href="#">Eur. Phys. J. C 75 (2015) 79</a> <a href="#">Phys. Rev. Lett. 114 (2015) 101801</a>	Strasbourg Clermont-Ferrand Strasbourg

- Contributions of :

- Strasbourg (CMS+theory)
- Lyon (theory)
- Clermont-Ferrand (ATLAS)

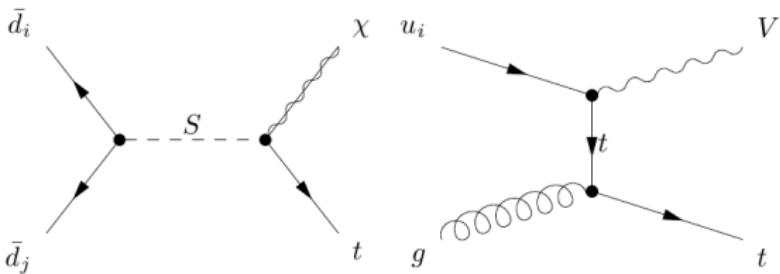
# A sample of theories predicting monotop

- Leptoquark to top+neutrino :  $\bar{d} \bar{d} \rightarrow V \rightarrow t \bar{\nu}$ 
  - SU(5) GUTs
- Top-squark to top+long-lived neutralino :  $\bar{d} \bar{s} \rightarrow \tilde{t}_l \rightarrow t \tilde{\chi}_0^1$ 
  - RPV SUSY [arXiv:1408.3634 \[hep-ph\]](#)
- Hylogenesis models :  $\bar{q} \bar{q}' \rightarrow V \rightarrow t \chi$ 
  - dark matter, baryogenesis [Phys. Rev. D 91 \(2015\) 035005](#)
- Majorana neutrinos :  $g u/c \rightarrow t N_R N_R$ 
  - dark matter, neutrino mass  
[Phys. Rev. D 90 \(2014\) 095018](#)
- Neutralinos + top :  $u g \rightarrow \tilde{u}_i \tilde{\chi}_0^i \rightarrow t \tilde{\chi}_0^i \tilde{\chi}_0^i$ 
  - RPC SUSY
- Neutral boson  $X$  with invisible decay :  $g u/c \rightarrow t X$ 
  - $Z'$ ,  $Z$ -mediated FCNC, type-III 2HDM + scalar DM  
[Phys. Rev. D 89 \(2014\) 1, 014016](#)
- "Top-flavoured" dark matter :  $u g \rightarrow \xi \chi_u \rightarrow t \chi_t \chi_u$ 
  - dark matter,  $A_{FB}(t\bar{t})$  [Phys. Rev. D 88 \(2013\) 075012](#)



# Effective models

- Effective model proposed by Andrea, Fuks, Maltoni Phys. Rev. D 84 (2011) 074025
  - general Lagrangian for monotop where  $E_T^{\text{miss}}$  = new particle with invisible signature
- Two kind of models
  - resonant : spin 0/1 boson produced on-shell, decays into top + invisible fermion
  - non-resonant : invisible spin 0/1 boson produced in association with a top



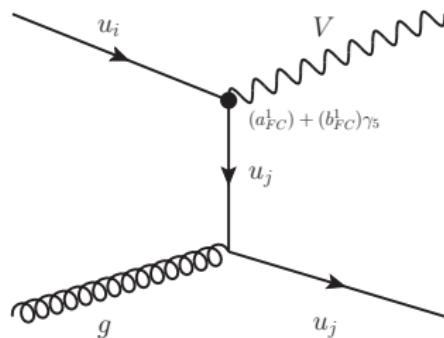
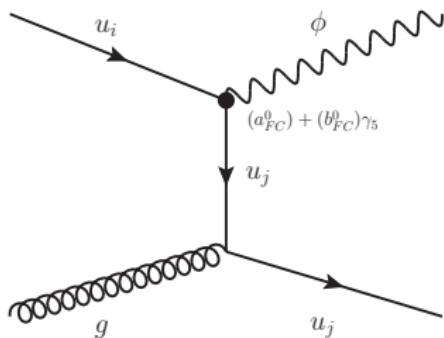
field	charge	spin	color multiplicity	comment
invisible particles				
$\phi$	0	0	1	non resonant production
$\chi$	0	1/2	1	resonant production
$V$	0	1	1	non resonant production
resonances				
$\phi$	$\pm 2/3$	0	3	decays into $t+\chi$
$X$	$\pm 2/3$	1	3	decays into $t+\chi$

- Several masses and couplings - a lot of free parameters to cope with !

## Reducing the parameter space : non-resonant case

$$\mathcal{L}_{FC}^0 = \phi \bar{u}^i \left[ (a_{FC}^0)_{ij} + (b_{FC}^0)_{ij} \gamma_5 \right] u^j$$

$$\mathcal{L}_{FC}^1 = V_\mu \bar{u}^i \left[ (a_{FC}^1)_{ij} + (b_{FC}^1)_{ij} \gamma_5 \right] \gamma^\mu u^j$$



- Couplings :  $(a/b_{FC}^{0,1})_{ij}$  are (real) matrices in generation space
- CMS (and CDF) : no pseudo-scalar nor axial couplings -  $(b_{FC}^{0,1})_{ij} = 0$

→ two models, scalar or vector

- ATLAS : minimal model invariant under  $SU(2)_L \times U(1)_Y$ 
  - retain only spin-1 ; coupling to right-handed quarks ( $a = b$ )

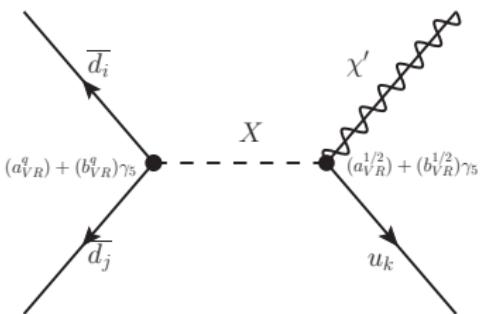
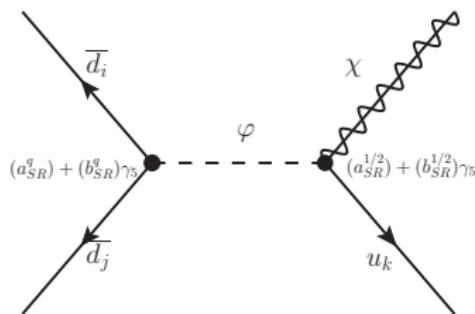
Boucheneb, Cacciapaglia, Deandrea [JHEP 1501 \(2015\) 017](#)

- Both ATLAS and CMS : only couplings between 1st and 3rd generation
- Mass range : 0-1 TeV

# Reducing the parameter space : resonant case (1)

$$\mathcal{L}_{SR} = \epsilon^{\alpha\beta\gamma} \varphi_\alpha \bar{d}_\beta^{i,c} \left[ (a_{SR}^q)_{ij} + (b_{SR}^q)_{ij} \gamma_5 \right] d_\gamma^j \\ + \varphi_\alpha \bar{u}^{\alpha,k} \left[ (a_{SR}^{1/2})_k + (b_{SR}^{1/2})_k \gamma_5 \right] \chi$$

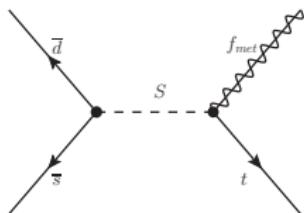
$$\mathcal{L}_{VR} = \epsilon^{\alpha\beta\gamma} X_{\mu,\alpha} \bar{d}_\beta^{i,c} \left[ (a_{VR}^q)_{ij} + (b_{VR}^q)_{ij} \gamma_5 \right] \gamma^\mu d_\gamma^j \\ + X_{\mu,\alpha} \bar{u}^{\alpha,k} \left[ (a_{VR}^{1/2})_k + (b_{VR}^{1/2})_k \gamma_5 \right] \gamma^\mu \chi'$$



- Couplings :  $(a/b_{SR/VR}^q)_{ij}$  and  $(a/b_{SR/VR}^{1/2})_k$  are (real) matrices in generation space
- "Production" coupling constrained by kaon oscillations if 3 generations
  - only  $\bar{d}\bar{s} \rightarrow \varphi/X$
- "Decay" coupling predicts monotop, no monojet
  - only  $\varphi/X \rightarrow t\chi/\chi'$
- ATLAS : minimal model invariant under  $SU(2)_L \times U(1)_Y$  [JHEP 1501 \(2015\) 017](#)
  - retain only spin-0 resonance, producing right-handed top quarks ( $a = b$ )

# Reducing the parameter space : resonant case (2)

- Still 2 couplings and 2 masses...



Couplings :

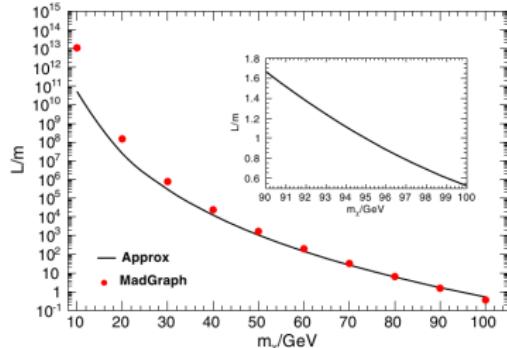
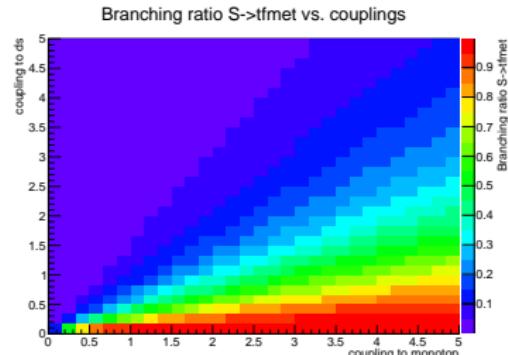
- ATLAS setup : consider the two couplings equal  
→ approach proposed by [Phys. Rev. D 86 \(2012\) 034008](#)
- CMS setup : consider  $\mathcal{BR}(S \rightarrow t\chi) \simeq 100\%$   
→ no contribution of  $S \rightarrow t f_{met}$  to the total width

Masses :

- $f_{met}$  can decay ! - outside the detector ?  
→ ~ ok if  $m(S)=500$  GeV and  $m(f_{met})=0-100$  GeV  
→ ATLAS choice for published analysis

Widths :

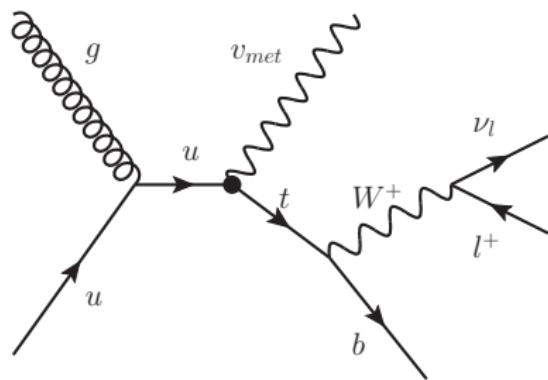
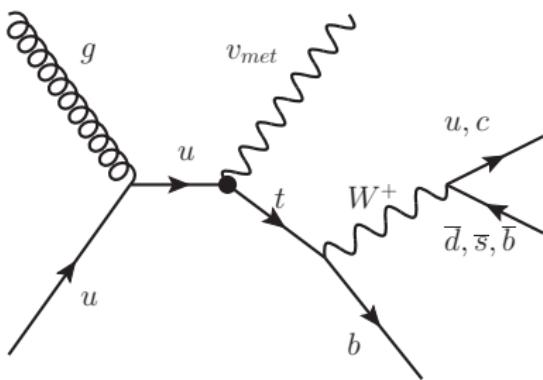
- CMS assumes fixed width (NWA)
- ATLAS allows width to vary with coupling(s)



[Phys. Rev. D 86 \(2012\) 034008](#)

# ATLAS and CMS analyses on 8 TeV data

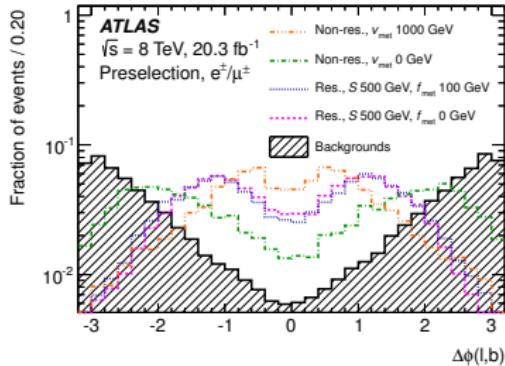
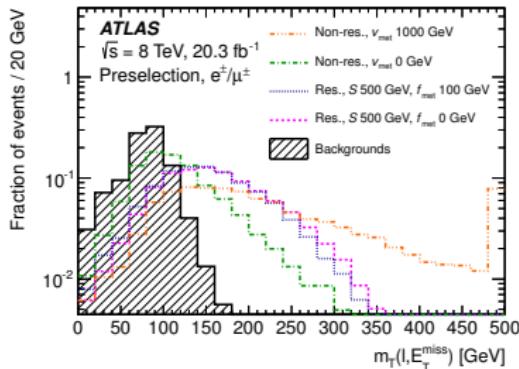
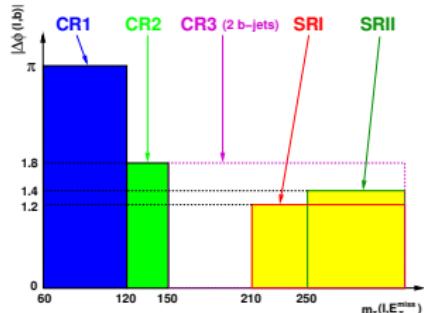
- Using the implementation of the general Lagrangian with [FeynRules](#)
  - signal MC samples generated with Magraph5...
  - ...+Pythia6 (CMS) or Pythia8 (ATLAS)
- Hadronic channel :
  - 3 jets, 1  $b$ -jet,  $E_T^{\text{miss}}$  (CMS)
  - can reconstruct top-quark kinematics
  - $E_T^{\text{miss}}$  trigger
  - used in CMS analysis (also CDF)
- Leptonic channel :
  - leptonic : 1  $\ell$ , 1  $b$ -jet,  $E_T^{\text{miss}}$  (ATLAS)
  - $E_T^{\text{miss}}$  also due to the neutrino
  - single-isolated lepton trigger
  - used in ATLAS analysis



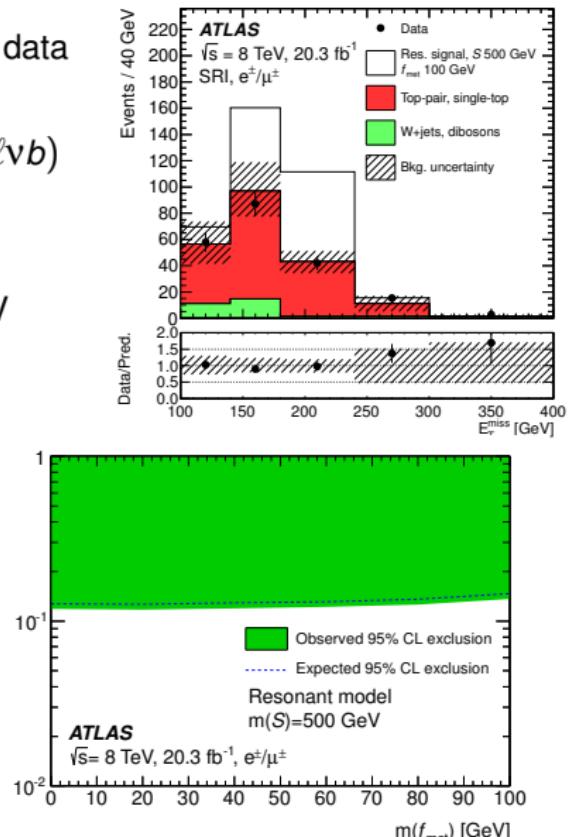
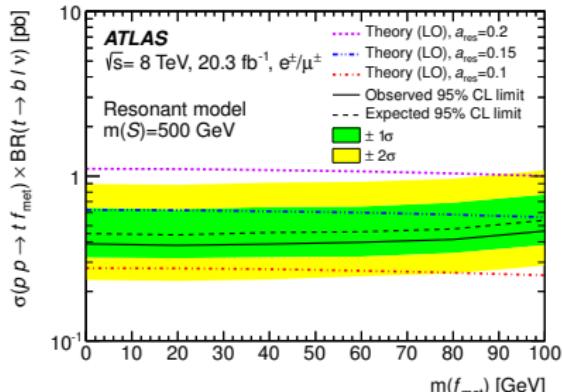
# ATLAS $\ell$ +jet analysis strategy

Eur. Phys. J. C 75 (2015) 79

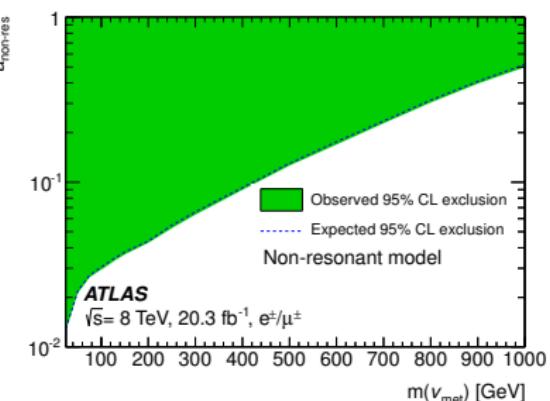
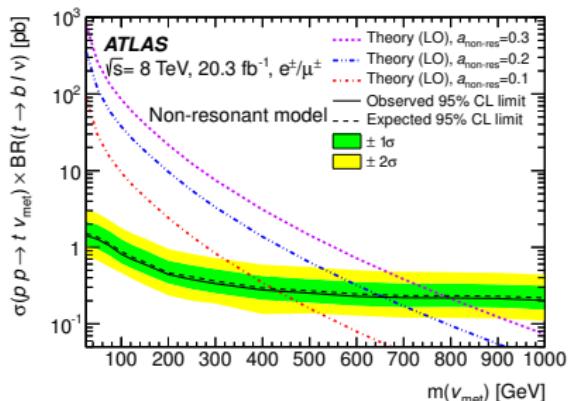
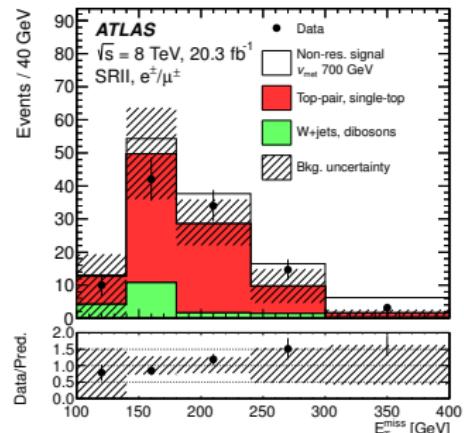
- Preselection :
  - single lepton trigger
  - 1 isolated  $e/\mu$ , 1 central jet,  $b$ -tagged
  - $E_T^{\text{miss}} > 35 \text{ GeV}$ ,  $m_T(\ell, E_T^{\text{miss}}) + E_T^{\text{miss}} > 60 \text{ GeV}$
- "Cut-and-count", 1 signal region for each signal
  - using  $m_T(\ell, E_T^{\text{miss}})$  and  $|\Delta\phi(\ell, b)|$
  - optimised for best limits
- Backgrounds :
  - main :  $t\bar{t}$ ,  $W+\text{jets}$  (MC)
  - others : sgtop,  $Z+\text{jets}$ ,  $VV$  (MC), multijets (data)
- 3 control regions for background validation



- Number of expected events compared with data  
→ no excess observed in SRI region
- 95% CL upper limits sets on  $\sigma \times \mathcal{BR}(t \rightarrow \ell v b)$
- Limits on the effective coupling  $a_{\text{res}}$
- $\Rightarrow a_{\text{res}}=0.15$  excluded  
for  $m(S)=500$  GeV and  $m(f_{\text{met}})=0\text{-}100$  GeV
- Effect of resonance width at high couplings  
→ dedicated MC samples



- Number of expected events compared with data  
→ no excess observed in SRII region
- 95% CL upper limits sets on  $\sigma \times \mathcal{BR}(t \rightarrow \ell v b)$
- Limits on the effective coupling  $a_{\text{non-res}}$
- $\Rightarrow a_{\text{non-res}} = 0.2$  excluded for  $v_{\text{met}} = 0$ -657 GeV



- Selection :

- $E_T^{\text{miss}}$  trigger - 150 GeV threshold
- 3 jets, 1 *b*-tagged,  $m(jjb) < 250$  GeV
- $E_T^{\text{miss}} > 350$  GeV

- Main backgrounds :  $Z \rightarrow vv + \text{jets}$ ,  $W \rightarrow \ell v + \text{jets}$

- data-driven using  $Z \rightarrow \mu\mu + \text{jets}$ ,  $W \rightarrow \mu\nu + \text{jets}$

- Multijets estimation :

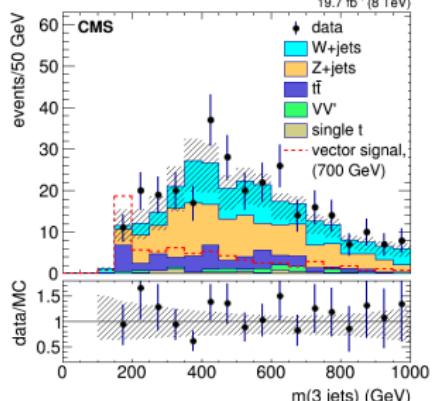
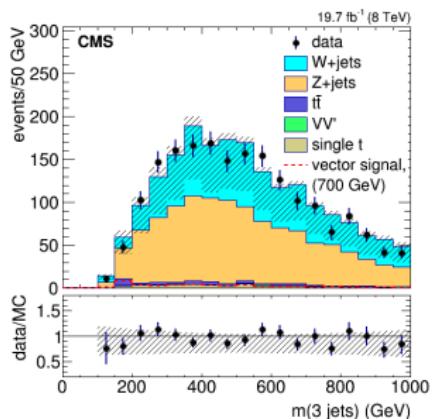
- likelihood approach combining 0- and 1-tag
- contribution found to be negligible

$$N^{0b} = P_{\text{sig}}^{0b} \cdot N_{\text{sig}} + P_{\text{MJ}}^{0b} \cdot N_{\text{MJ}} + N_{\text{other}}^{0b}$$

$$N^{1b} = P_{\text{sig}}^{1b} \cdot N_{\text{sig}} + P_{\text{MJ}}^{1b} \cdot N_{\text{MJ}} + N_{\text{other}}^{1b}$$

- Other smaller backgrounds :

- $t\bar{t}$ , single-top,  $VV$  (MC)

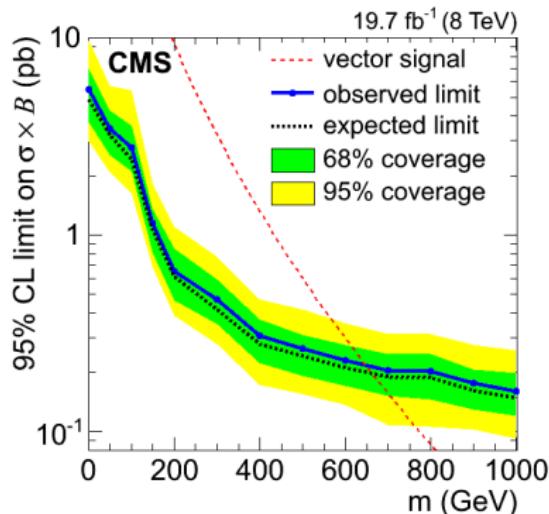
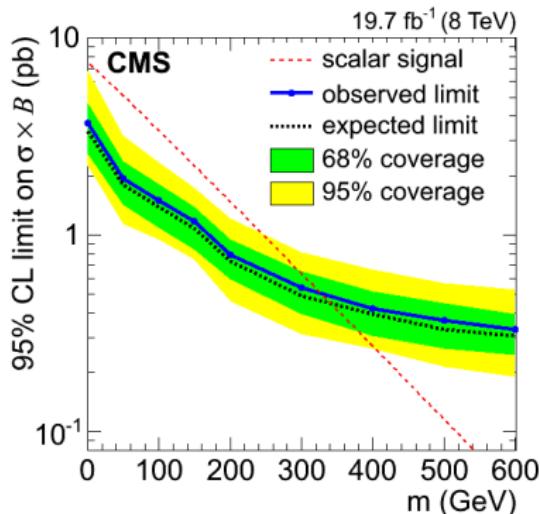


# CMS fully-hadronic result

Phys. Rev. Lett. 114 (2015) 101801

- Number of expected events compared with data  
→ no excess observed
- 95% CL upper limits sets on  $\sigma \times \mathcal{BR}(t \rightarrow bjj)$
- For an effective coupling of  $a=0.1$  :
  - $m(\text{scalar}) > 330 \text{ GeV}$
  - $m(\text{vector}) > 650 \text{ GeV}$

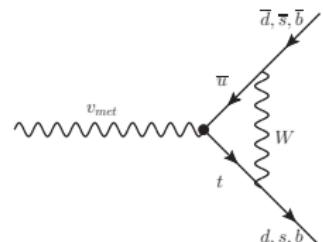
# of b tags	Zero CSVm b tag	One CSVm b tag
t <bar>t</bar>	$6 \pm 0 \pm 5$	$12 \pm 0 \pm 12$
W+jets	$18 \pm 9 \pm 7$	$3 \pm 1 \pm 2$
Z+jets	$103 \pm 33 \pm 9$	$11 \pm 10 \pm 1$
Single top	$2 \pm 1 \pm 1$	$1 \pm 1 \pm 1$
VV	$5 \pm 0 \pm 0$	$0 \pm 0 \pm 0$
QCD	6	1
sum	$140 \pm 36$	$28 \pm 16$
Data	143	30



# To-do & to-think lists

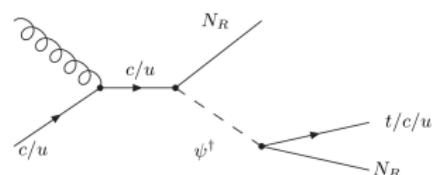
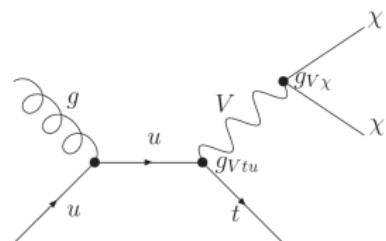
## Current models

- Resonant model
  - boosted regime
  - exploit charge asymmetry - favours  $\bar{t}$  over  $t$
- Non-resonant model
  - exploit charge asymmetry - favours  $t$  over  $\bar{t}$
  - investigate coupling to charm - no asymmetry



## Dark Matter interpretation

- Non-resonant model
  - "invisible" particle decays with a short lifetime
  - assuming an invisible decay mode, e.g.  $v_{met} \rightarrow \chi\chi$
  - constrains on DM from SS top signature
- Resonant model : more complicate...
  - need scalar and fermion DM candidates :  $f_{met} \rightarrow \chi\phi$
  - hydrogenesis models - CP violation, more new particles



## Other models...

- $tZ$  FCNC, ( $Z \rightarrow vv$ ), Majorana neutrinos

# Conclusions

- Now both CMS and ATLAS have published results with 8 TeV data
- Both resonant and non-resonant productions have been looked at
- Both channels are now exploited - complementary signatures
- Plenty of models with different motivations
- Using a general effective model - different choices of parameter space narrowing
- New strategies and models for run-II and beyond
- Strong involvement of French groups on this topic !

