



Search for Dark Matter with top quarks

Jeremy Andrea

Institut Pluridisciplinaire Hubert Curien,

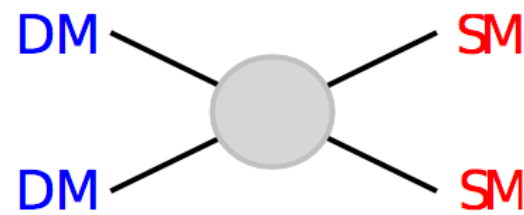
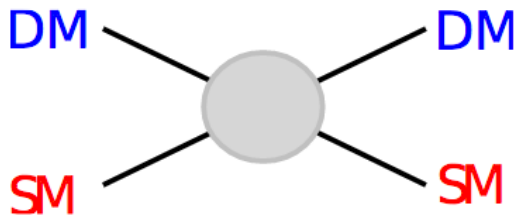
On behalf of the **ATLAS** and **CMS** collaborations



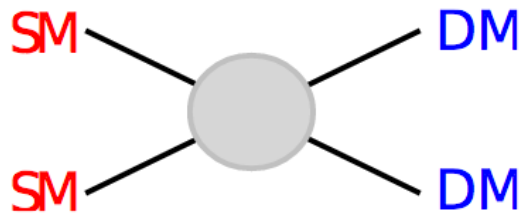
Introduction



- The ordinary matter composes only about 15% of the entire matter in the universe.
- **Existence of Dark Matter (DM):** evidence through the **gravitation** interaction (galaxies, large structure of the universe),
 - DM should be **stable particles**,
 - DM should be **massive**,
 - DM **weakly interacts** with common matter,
 - DM = **WIMP**.
- Searches for DM matter can be performed using “cosmic” sources (AMS, LUX, IceCube etc...).



- But **DM could also be produced in colliders** (decays of new massive particles).

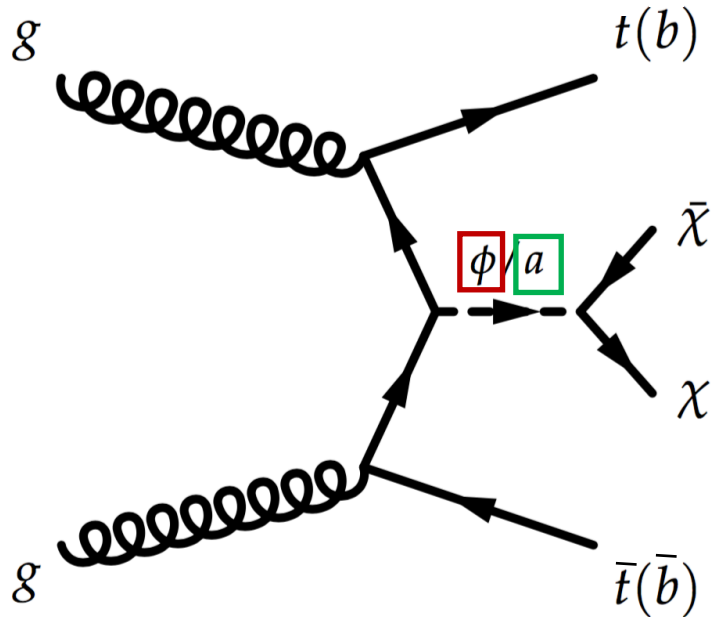




Modelling and Dark Matter forum



- Various models predict DM candidates (SUSY neutralino in R-conserving scenarios, for example, [see talk from Anna Lipniacka](#)).
- Usage of a [less model-dependent approach](#) :
 - EFT and/or [simplified models](#),
 - construct models for DM production.
- [Several implementations and conventions](#) → common effort for [harmonization](#) : [ATLAS&CMS Dark Matter Forum \(arxiv:1507.00966\)](#), comparisons/complementarity with direct searches.
 - Recommendations for [models](#) (simplified models rather than EFT) and conventions,
 - Definitions of [benchmark points](#),
 - [Implementations](#) of the models (MG5).
- The idea is to make results from the different [collaborations more comparable](#).
- For Run2, the ATLAS and CMS collaborations started to follow (almost...) the [Dark Matter Forum recommendations](#). Convergence is ongoing, but ATLAS and CMS results are not yet fully comparable.



- Simplified models:

- Production of a mediator particle (either scalar or pseudo-scalar) with top quark pairs,
- Mediator decays into a pair of fermionic dark matter particles.

- Free parameters:

- $g_\phi (g_a) = g_\chi = 1$ (CMS) or 3.5(ATLAS) ,
- $m_\chi, m_\phi (m_a)$.
- Width calculated using the minimal width assumption (dominant decay channel considered).

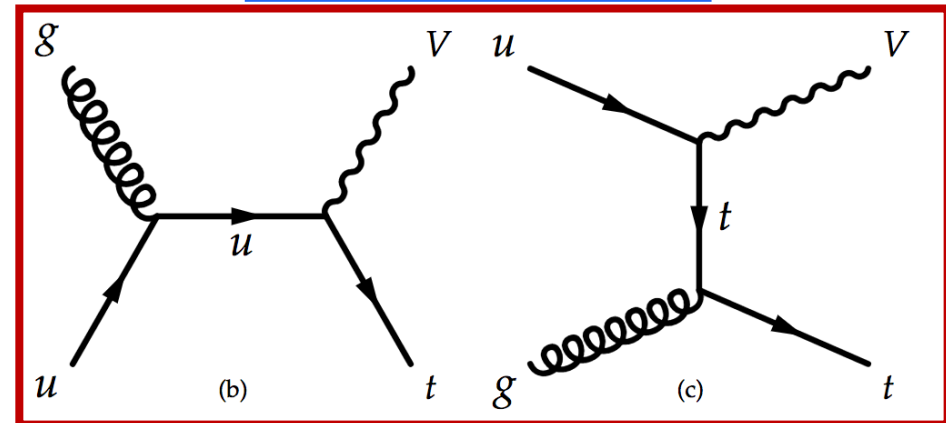
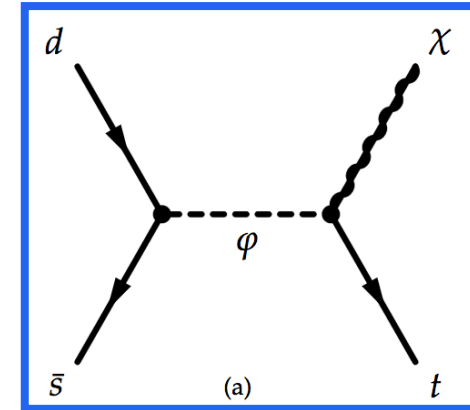
$$\mathcal{L} = \left[g_\chi \phi \bar{\chi} \chi + \frac{\phi}{\sqrt{2}} \sum_q g_q^\phi y_q \bar{q} q + g_\chi a \bar{\chi} \gamma^5 \chi + \frac{ia}{\sqrt{2}} \sum_q g_q^a y_q \bar{q} \gamma^5 q + h. c. \right]$$

- Benchmark points (BP) : scanning over $m_\chi, m_\phi (m_a)$.

- BP defined considering expected sensitivity at LHC and at least a minimal change of kinematics.

Theoretical framework monotop (single top +DM)

- Associate production of a **single top** and E_T^{miss} :
 - **New scalar resonance** decaying into a top quark and a neutral fermion,
 - FCNC interactions **producing a new vector boson**.
- V and χ : new particles **with long live time** or a new particle **decaying invisibly**.
- **Different model conventions** between ATLAS and CMS:
 - In the resonant case :
 $Br(\varphi \rightarrow t\chi) = 100\%$ (CMS),
 $a_{res} = b_{res}$ (ATLAS).
 - In the FCNC case : latest CMS results include **V decay**,
 - **Factor of 2** in the cross section due to conventions (2 leptonic analyses),



$$\mathcal{L} = \left[a_{res} \varphi \bar{d}^c P_R s + b_{res} \varphi \bar{\chi} P_R t \right] + \left[a_{non-res} V_\mu \bar{u} \gamma^\mu P_R t \right] + h.c.]$$



Search for $t\bar{t}$ +DM at 13 TeV



ATLAS analysis strategy



- Search for the associated production of a top quark pair and a dark matter pair, per decay channel :
 - Single lepton channel **ATLAS-CONF-2016-050**,
 - Dilepton channel **ATLAS-CONF-2016-076**,
 - Full hadronic channel **ATLAS-CONF-2016-077**.
- Part of SUSY publications of similar signatures (**see talk from Anna Lipniacka**).
- Use 2015 and 2016 datasets (13.3 fb^{-1}).
- Similar analysis strategy :
 - Definition of signal regions, based on discriminating (signal specific) variables,
 - Backgrounds estimated from a simultaneous fit using the yields in several control regions (CR) enriched in specific backgrounds.
 - Validation regions (VR) used to cross check the background estimations.



$t\bar{t}$ +DM in the single lepton channel (ATLAS)



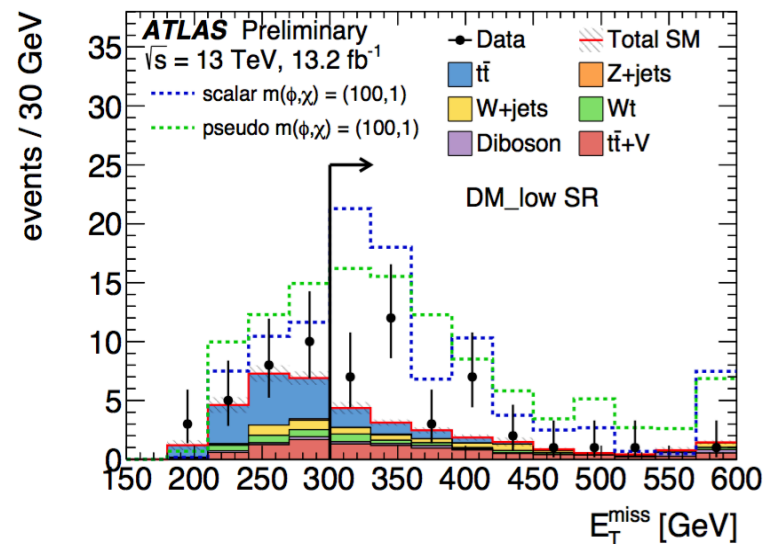
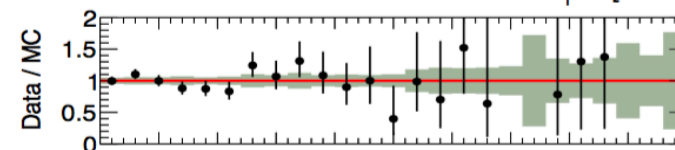
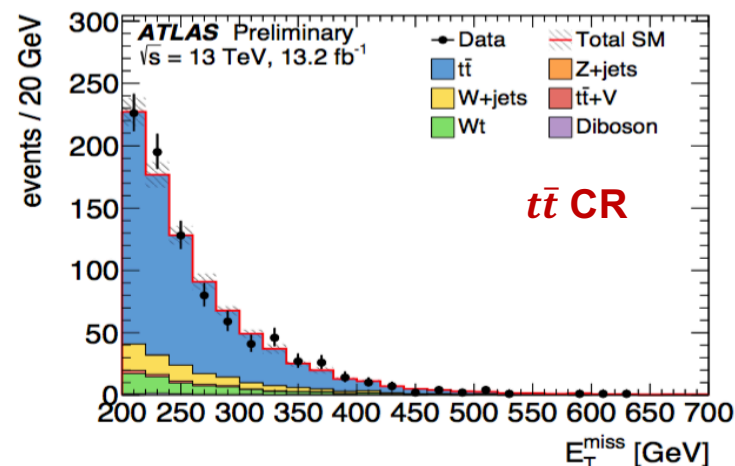
ATLAS-CONF-2016-050

- Baseline event selection: E_T^{miss} trigger, 1 isolated lepton (μ or e $p_T > 25$ GeV), at least 2 jets ($p_T > 20$ GeV, $|\Delta\phi(j_{1,2}, E_T^{miss})| > 0.4$),

- Two signal regions :

Variable	DM_low	DM_high
Number of (jets, b -tags)	($\geq 4, \geq 1$)	($\geq 4, \geq 1$)
Jet $p_T >$ [GeV]	(60 60 40 25)	(50 50 50 25)
E_T^{miss} [GeV]	> 300	> 330
$H_{T,sig}^{miss}$	> 14	> 9.5
m_T [GeV]	> 120	> 220
am_{T2} [GeV]	> 140	> 170
$\min(\Delta\phi(\vec{p}_T^{miss}, jet_i)) (i \in \{1 - 4\})$	> 1.4	> 0.8
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	> 0.8	–

- W -enriched CR for 0 b -tag jets,
- $t\bar{t}$, $t\bar{t}V$, single top CR at low m_T^W values,
- $t\bar{t}Z$ estimated from a $t\bar{t}\gamma$ selection.



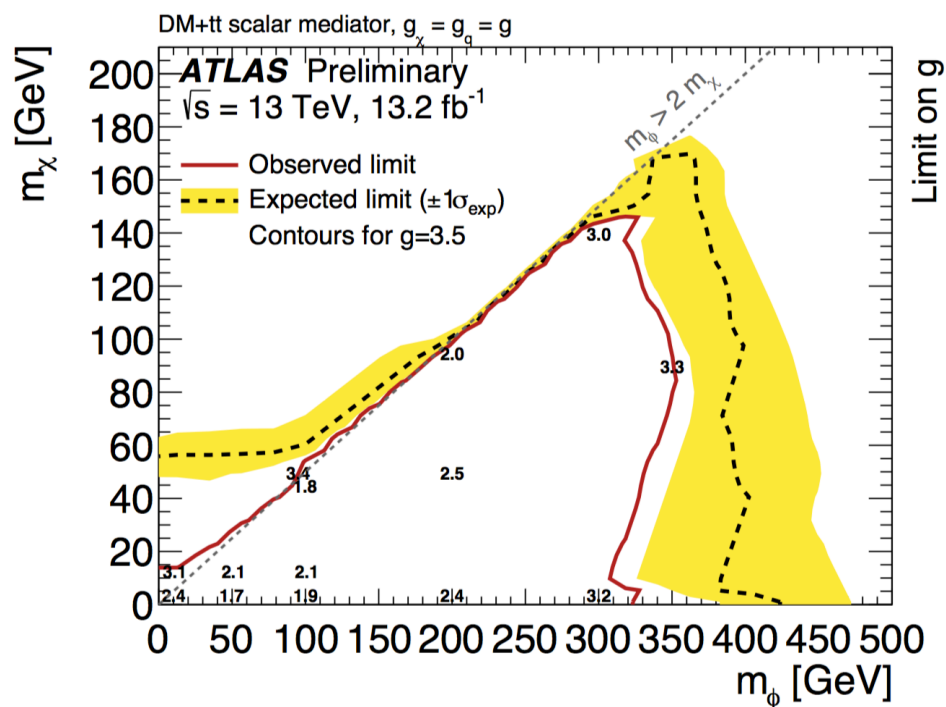


$t\bar{t}$ +DM in the single lepton channel (ATLAS, 2)

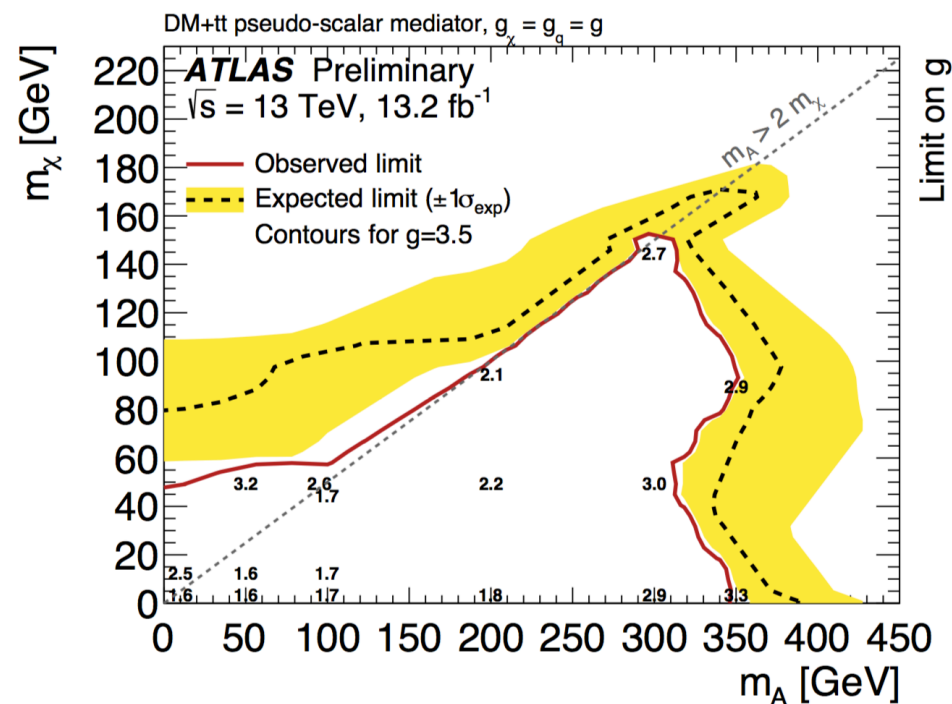


ATLAS-CONF-2016-050

Scalar mediator, $g=3.5$



Pseudo-scalar mediator, $g=3.5$

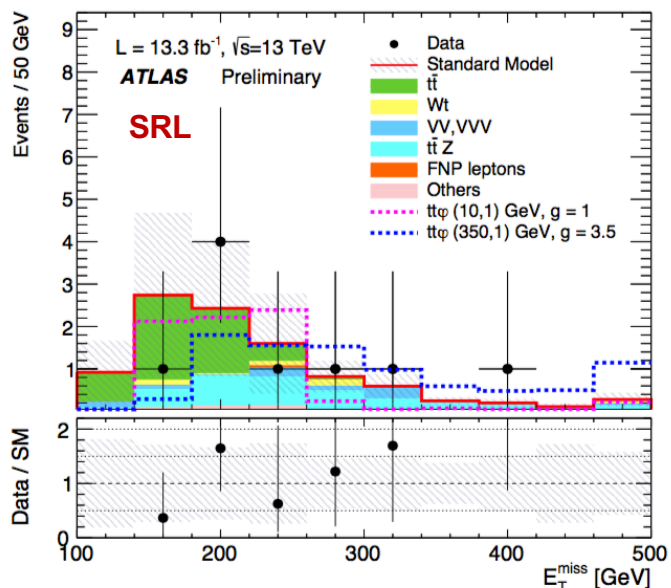




$t\bar{t}$ +DM in the dileptonic channel (ATLAS)



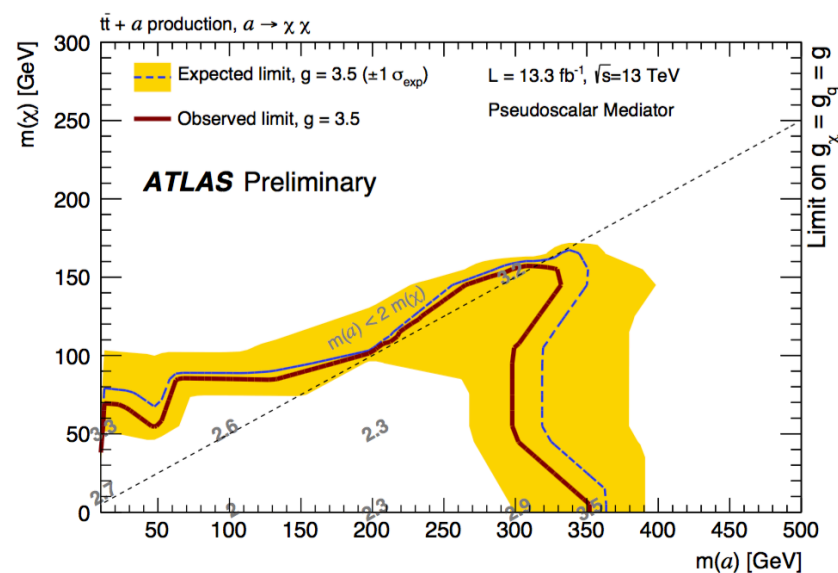
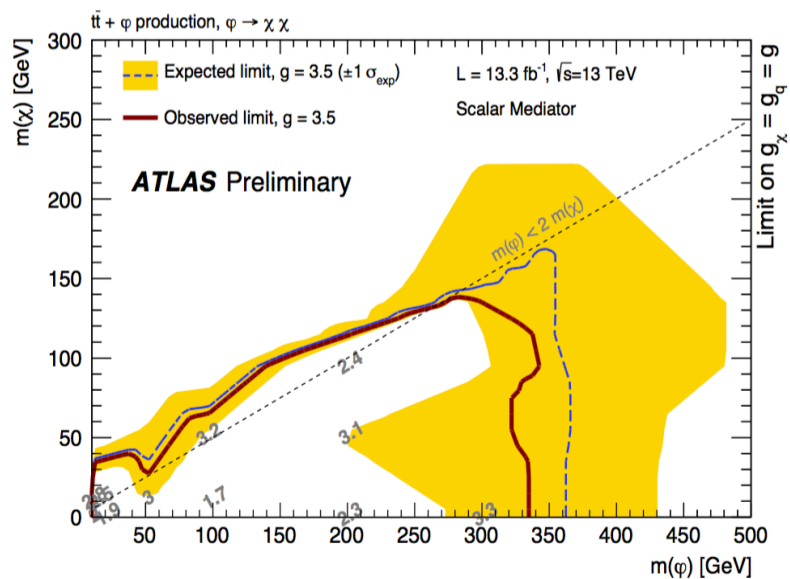
ATLAS-CONF-2016-076



- Event selection : dilepton trigger, two opposite charge leptons with high p_T .

Variable	DM-SRL	DM-SRH
$ m_{\ell\ell} - m_Z $ [GeV] (SF only)	>20	>20
b -jet multiplicity	> 0	> 0
$\Delta\phi_{\text{boost}}$	< 1.0	< 1.0
m_{T2}^{ll} [GeV]	>120	>120
E_T^{miss} [GeV]	> 180	> 260

- Non-prompt lepton background from a **Matrix Method-like technique**.
- $t\bar{t}$, $t\bar{t}Z$ and diboson CR cutting on m_{T2}^{ll} and N_l .



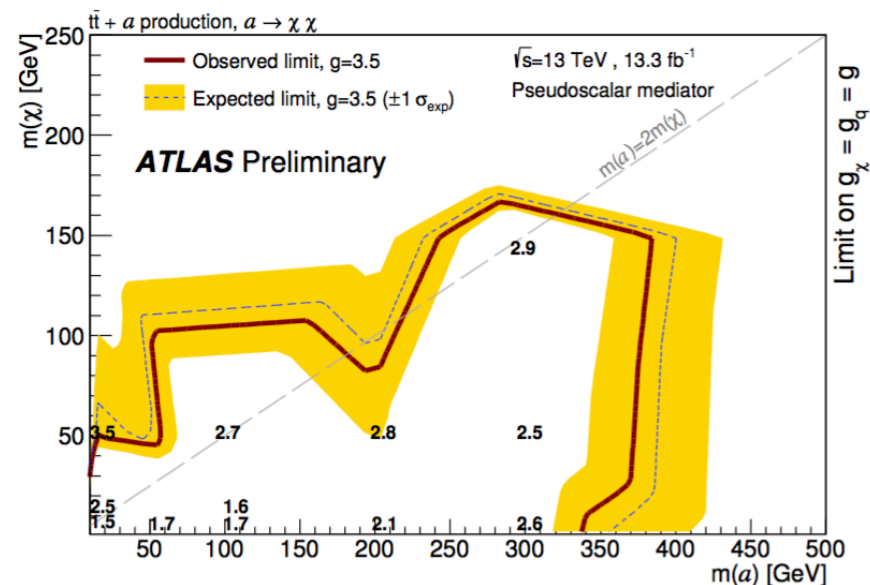
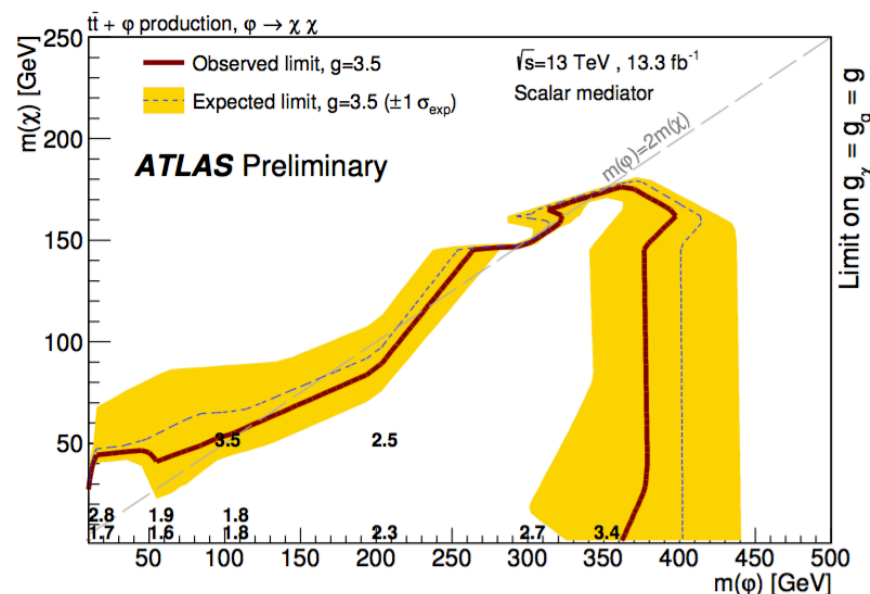


$t\bar{t}$ +DM in the hadronic channel (ATLAS)

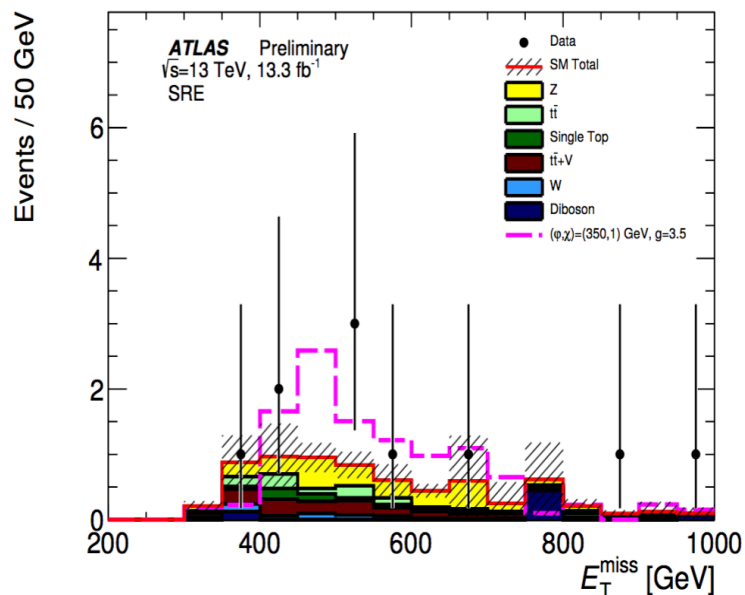


ATLAS-CONF-2016-077

- **Event selection** : E_T^{miss} trigger, at least 4 jets ($p_T > 80, 80, 40, 40$ GeV), $\geq 1 N_{btag}$,
- $E_T^{miss} > 250$ GeV, $|\Delta\phi(j_{1,2} - E_T^{miss})| > 0.4$.
- **Dominating $Z \rightarrow \nu\nu$ background** estimated from $Z \rightarrow ll$, semi-leptonic $t\bar{t}$ estimated from single lepton selection.
- $t\bar{t}$ **full hadr. and QCD multijets** estimated from low E_T^{miss} data smeared to reproduce mis-reconstructed jets effects.



Variable	SRE
b -tagged jets	≥ 2
$m_{jet,R=1.2}^0$	> 140 GeV
$m_{jet,R=1.2}^1$	> 60 GeV
$m_{jet,R=0.8}^0$	-
$m_{jet,R=0.8}^1$	-
$m_T^{b,min}$	> 200 GeV
τ -veto	yes
$\Delta R(b, b)$	> 1.5
E_T^{miss}	> 300 GeV
H_T	-
$E_T^{miss}/\sqrt{H_T}$	$> 14\sqrt{\text{GeV}}$





CMS analysis strategy



- Search for $t\bar{t} + E_T^{miss}$ in the **lepton+jets** and **full hadronic** channels **combined**. **Full hadronic channel** : categorized by counting the number of reconstructed hadronic tops.
- **Shape analysis** performed using the E_T^{miss} distribution.
- **Simultaneous fit** between **signal** and **control** regions, enriched in backgrounds.
- Using 2.2 fb^{-1} of 2015 data.
- **Results shown for a coupling of $g_\phi(g_a) = g_\chi = 1$** , search performed for the **exact benchmark points recommended by the DM Forum** (tables).



$t\bar{t}$ +DM in the single lepton channel



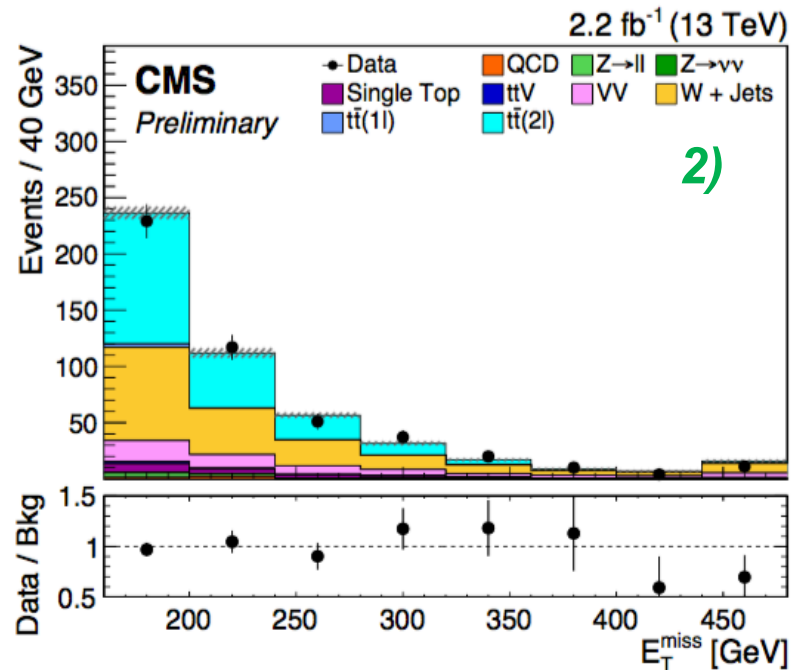
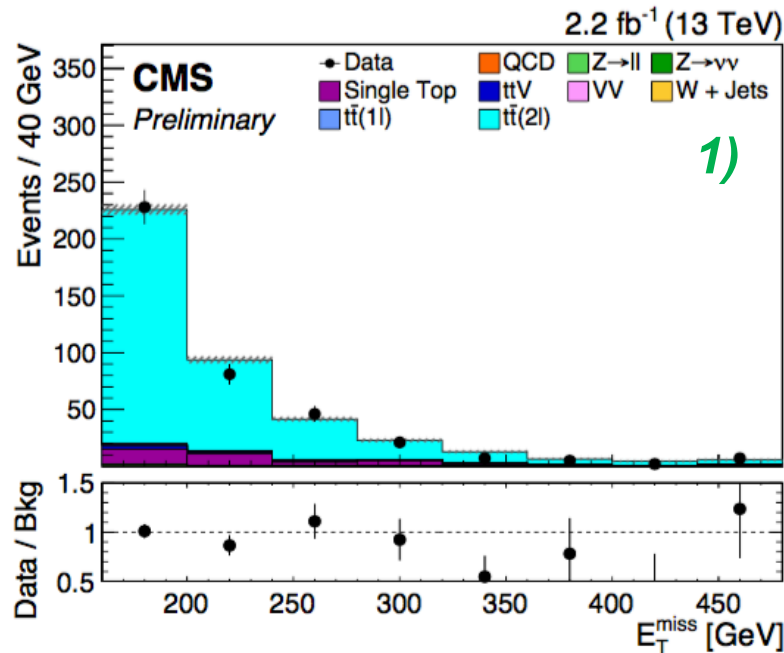
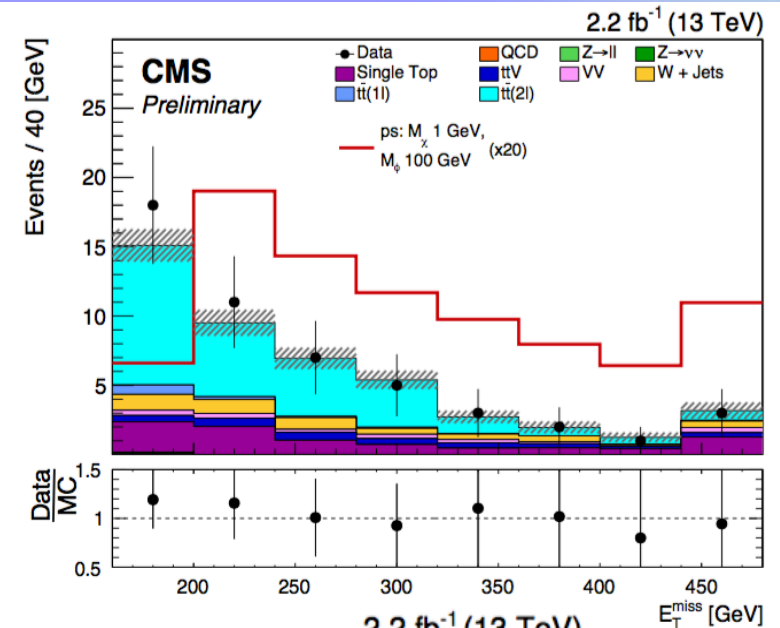
CMS-EXO-16-005

Event selections :

- **A)** Single lepton trigger, one high p_T lepton, $E_T^{miss} > 160$ GeV, ≥ 3 jets, ≥ 1 b-tagged jet,
- **B)** $m_T^W > 160$ GeV, $m_{T2}^W > 200$ GeV, $|\Delta\phi(J_{1,2}, E_T^{miss})| > 0.4$.

Control regions :

- 1) $t\bar{t}$ dilepton CR asking for 2 leptons and **A)**,
- 2) W+jets CR, no b-tagged jets, $m_T^W > 160$ GeV.





$t\bar{t}$ +DM in the hadronic channel



CMS-EXO-16-005

Event selection :

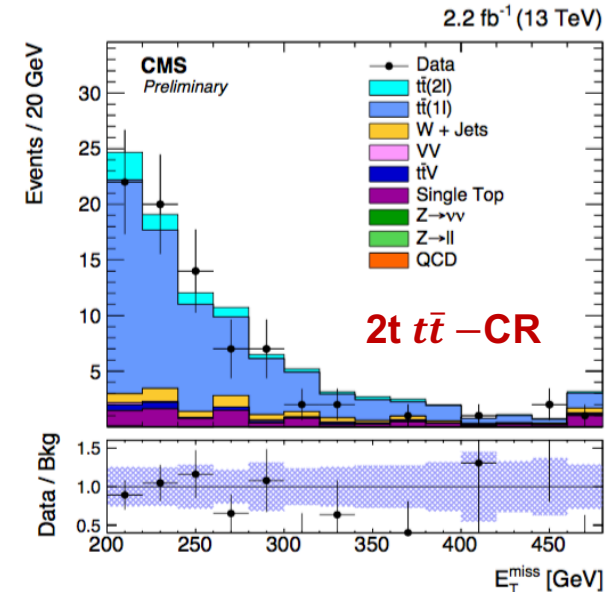
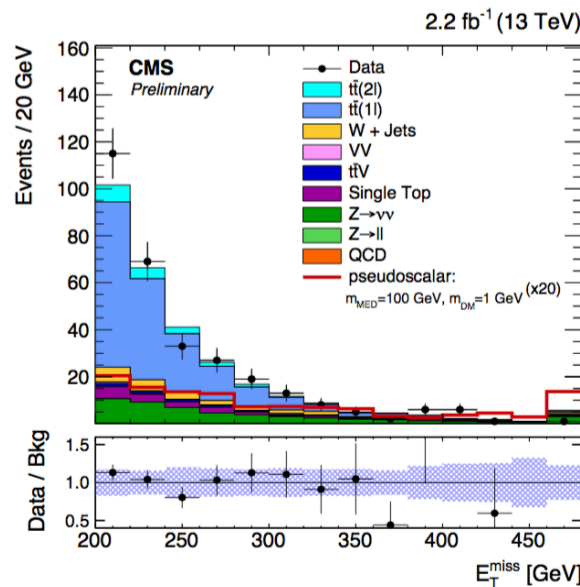
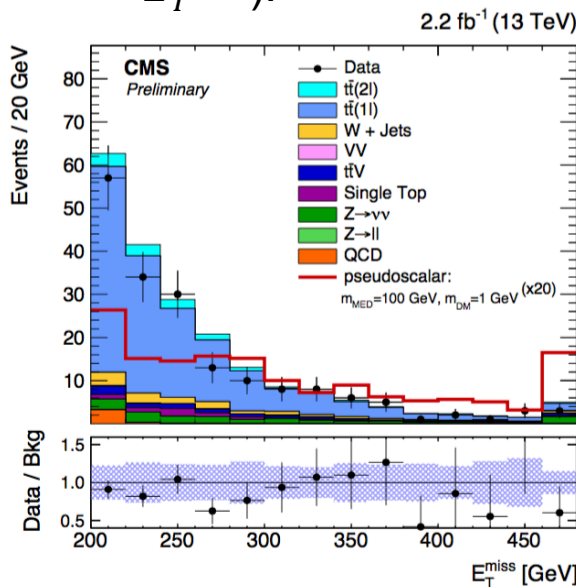
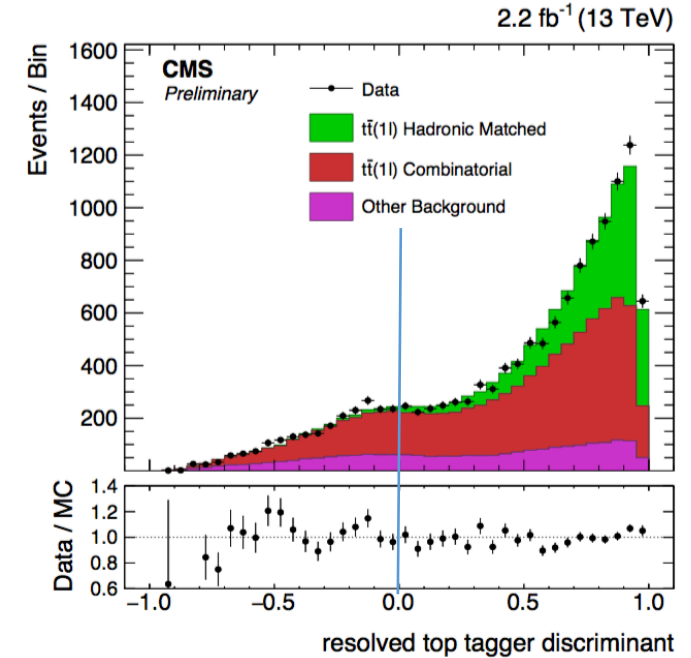
- E_T^{miss} trigger, $E_T^{miss} > 200$ GeV, $N_{jets} \geq 4$, $N_{bjets} \geq 2$, $|\Delta\phi(jet_i E_T^{miss})| > 1$.

Resolved top-tagged categories:

- multivariate discriminant using jets properties and kinematics of three jets.
- First category: 2 top-tags. Looser selection $N_{bjets} \geq 1$, $|\Delta\phi(jet_i E_T^{miss})| > 0.4$.
- Second category: 0-1 top-tags.

Control regions :

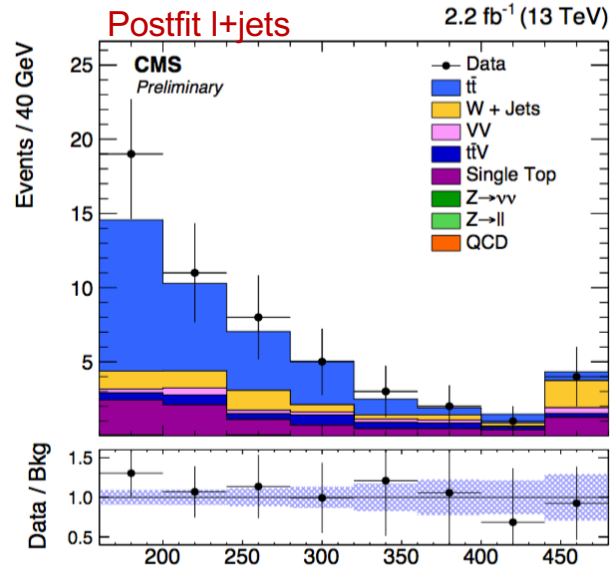
- $t\bar{t}$ semi-leptonic, one lepton, $m_T^W < 160$ GeV, no $\Delta\phi$ cut.
- W/Z+jets, $N_{bjets} = 0, 1$ or 2 leptons (subtracting leptons to E_T^{miss}).





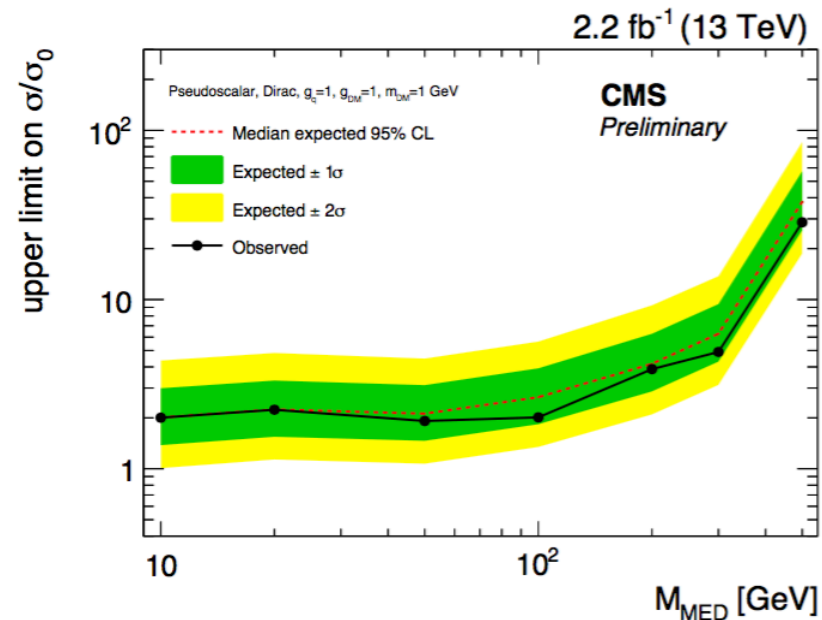
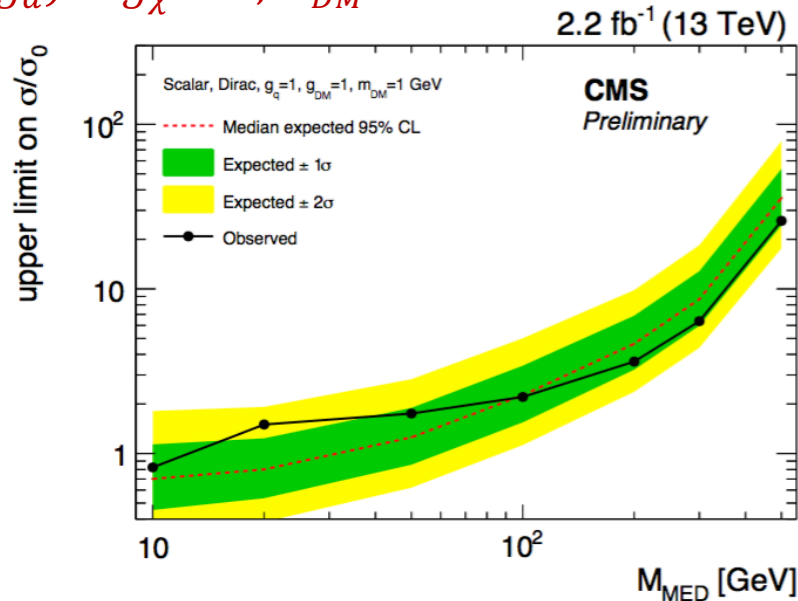
$t\bar{t}$ +DM in the single lepton + hadronic (2) CMS

CMS-EXO-16-005



$m_{\text{MED}}, m_{\text{DM}} [\text{GeV}]$	Obs.	Exp.	$[-1\sigma, +1\sigma]$	$[-2\sigma, +2\sigma]$
S 10, 1	0.82	0.70	[0.45, 1.1]	[0.32, 1.8]
S 20, 1	1.5	0.80	[0.53, 1.2]	[0.38, 1.9]
S 50, 1	1.8	1.2	[0.85, 1.9]	[0.62, 2.8]
S 100, 1	2.2	2.3	[1.6, 3.4]	[1.1, 5.0]
S 200, 1	3.6	4.6	[3.2, 6.9]	[2.4, 9.8]
S 300, 1	6.4	8.7	[6.0, 13]	[4.4, 18]
S 500, 1	26	36	[24, 54]	[18, 79]
S 10, 10	43	38	[26, 58]	[19, 88]
S 50, 10	3.7	1.4	[0.95, 2.2]	[0.69, 3.3]
S 100, 10	2.9	2.5	[1.7, 3.7]	[1.3, 5.4]
S 200, 50	4.4	4.7	[3.3, 7.0]	[2.4, 10]
S 300, 50	5.8	8.5	[5.8, 13]	[4.2, 18]
S 200, 150	870	1300	[920, 2000]	[670, 3000]

$$g_\varphi(g_a) = g_\chi = 1, m_{\text{DM}} = 1 \text{ GeV}$$





Search for monotop at 8 and 13 TeV



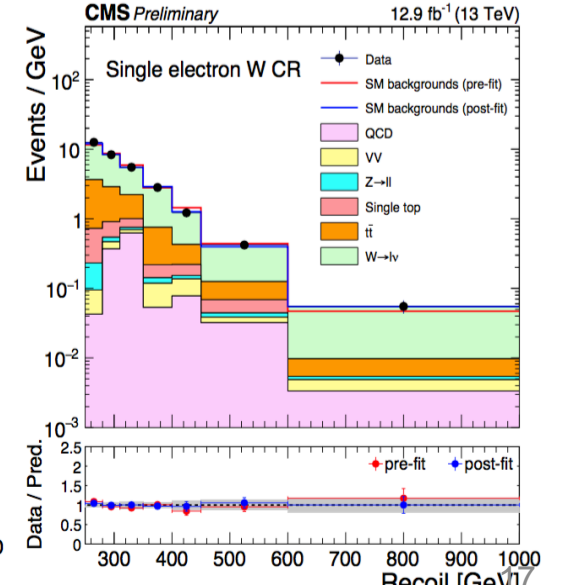
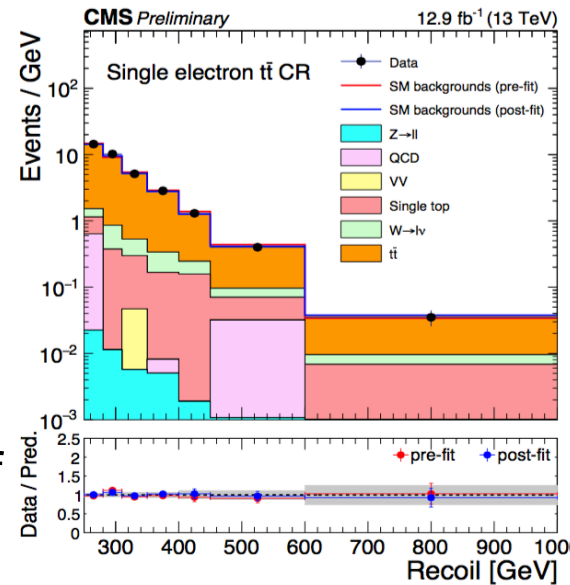
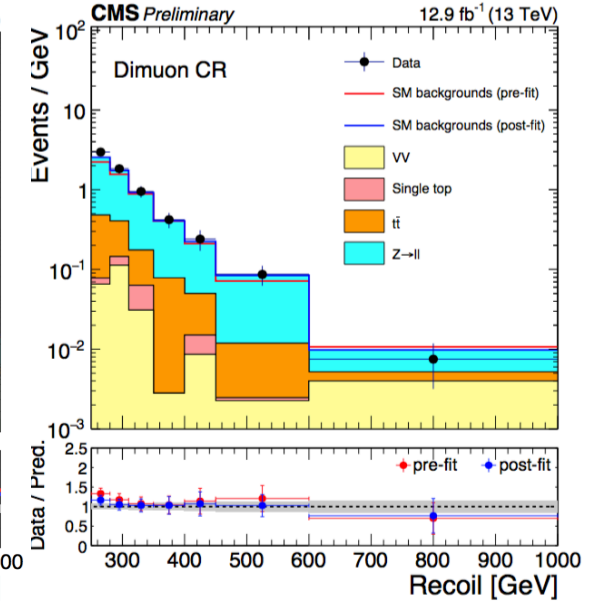
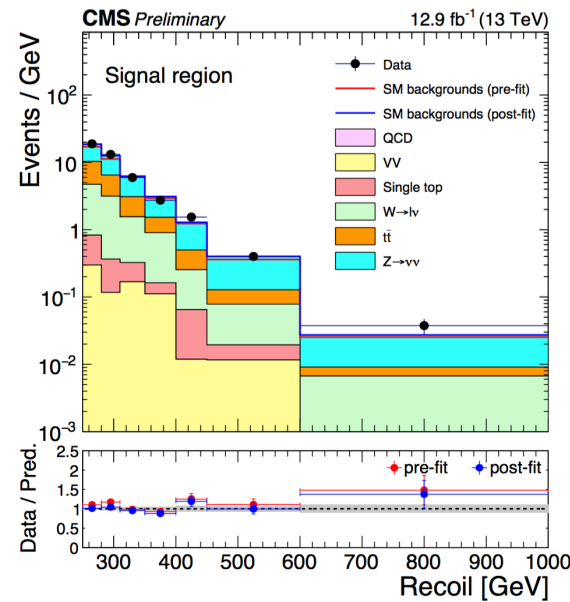
(Boosted) monotop hadronic at 13 TeV

CMS



CMS-EXO-16-040

- **Event selection :**
 - E_T^{miss} trigger, $H_T^{miss} > 110$ GeV, $|\Delta\phi(jet_i - E_T^{miss})| > 1$.
- **Boosted top reconstruction:**
 - C-A algorithm with $\Delta R = 1.5$,
 - 1-btagged subjet, veto events with second b-tagged outside the fat jet,
 - Test the compatibility of Fatjets with being with a 3-jets substructure (τ_3/τ_2).
 - Exactly one Fatjet required (veto events with lepton, taus and photons).
- **Control regions :**
 - Single lepton selection $t\bar{t}$ and W+jets (inverted b-tagged for subjets),
 - Double leptons : Z($\rightarrow ll$)+jets, completed by γ +jets.
- **Signal extraction :** simultaneous fit of E_T^{miss} in SR and the Recoil (E_T^{miss} -leptons) in the CR.



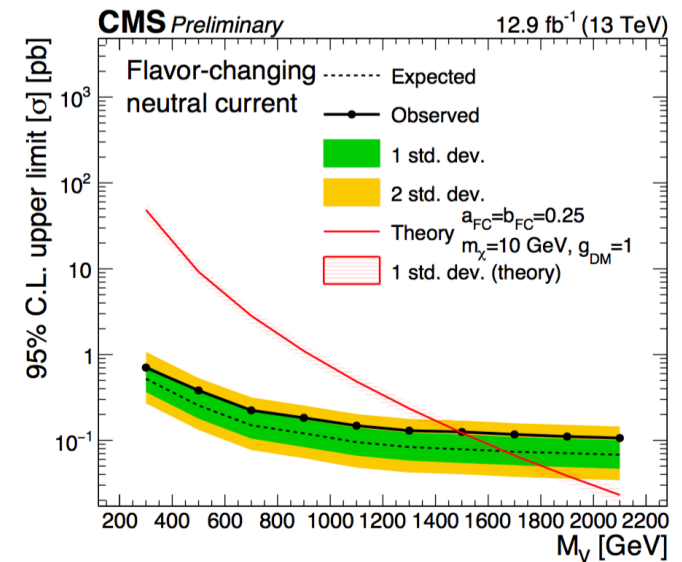
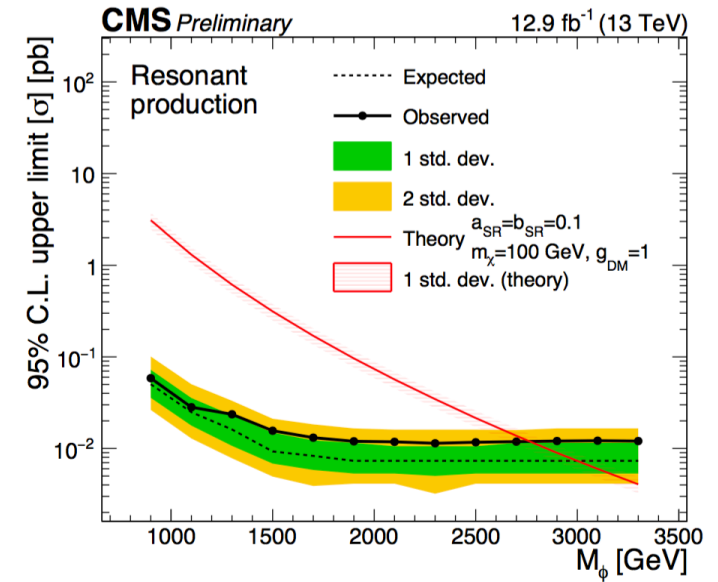
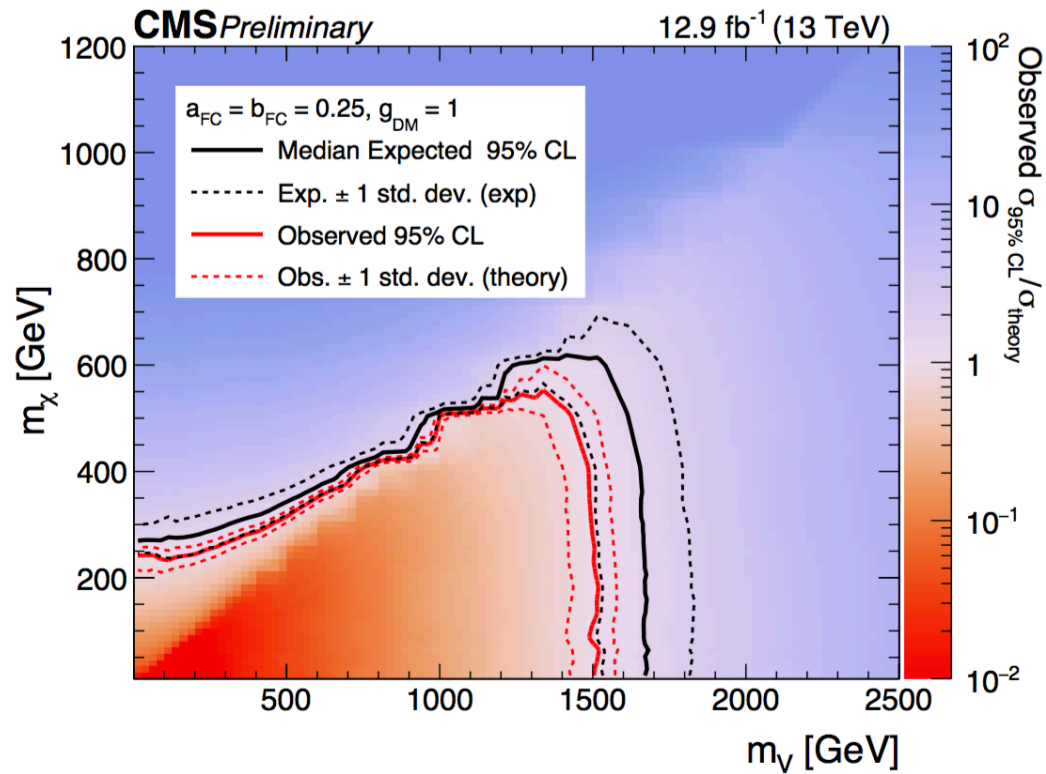


Monotop hadronic at 13 TeV CMS



CMS-EXO-16-040

$$a_{res} = 0.25, b_{res} = 1$$

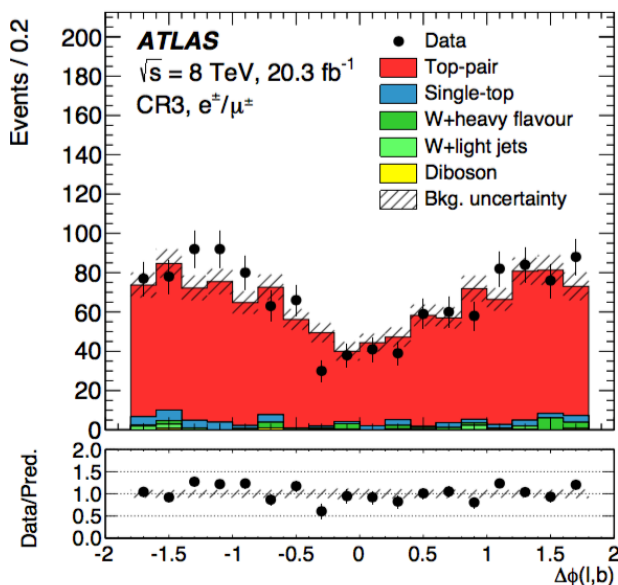
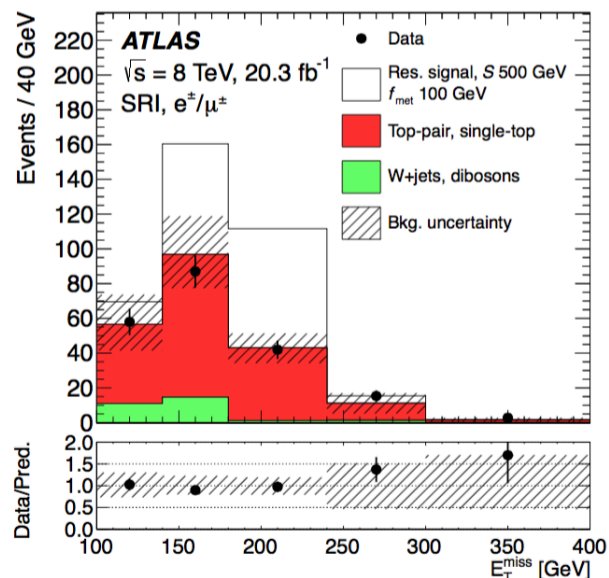




Monotop leptonic at 8 TeV ATLAS



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



- Motivations for leptonic channel.

- Combination with the hadronic channel,

- Rely on leptonic trigger : probe the E_T^{miss} low region.

- **Event selection:** single lepton trigger, 1 high p_T lepton, $N_{\text{jets}} = 1, N_{b\text{-jets}} = 1, E_T^{\text{miss}} > 35 \text{ GeV}, m_T^W + E_T^{\text{miss}} > 60 \text{ GeV}.$

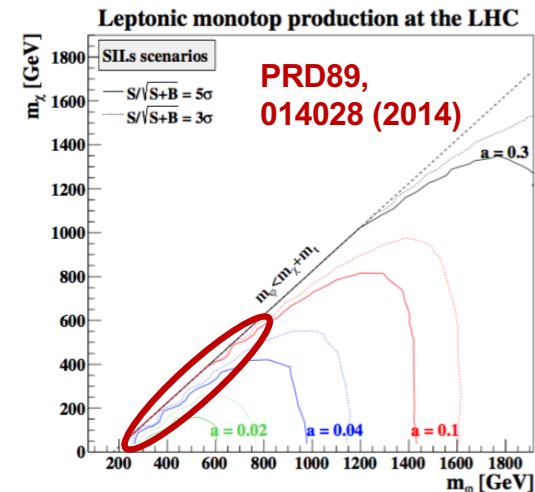
- Two signal regions :

- (res) $m_T^W > 210 \text{ GeV}, |\Delta\phi(l - b)| < 1.2,$
- (non-res) $m_T^W > 250 \text{ GeV}, |\Delta\phi(l - b)| < 1.4,$

- Three control regions :

- W+jets,QCD: $60 < m_T^W < 150, 120 < m_T^W < 150 \text{ GeV},$
- $t\bar{t}$: 2 b-tags (looser), $E_T^{\text{miss}} > 150 \text{ GeV}, |\Delta\phi(l - b)| < 1.8$

Counting experiment using signal region only.

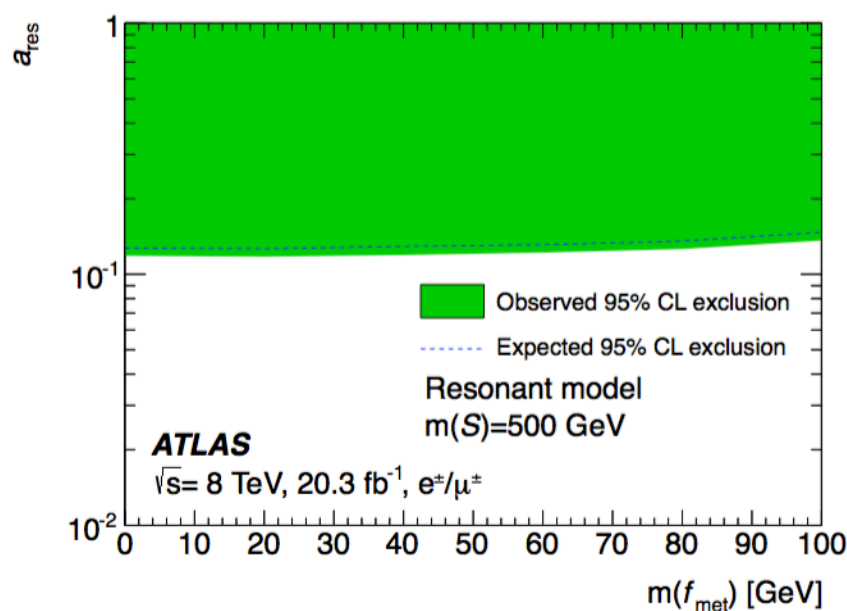
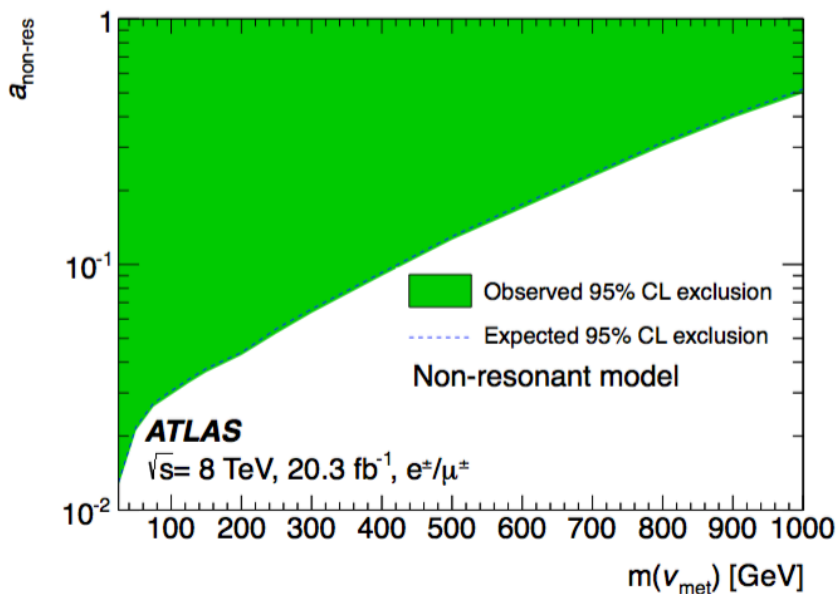
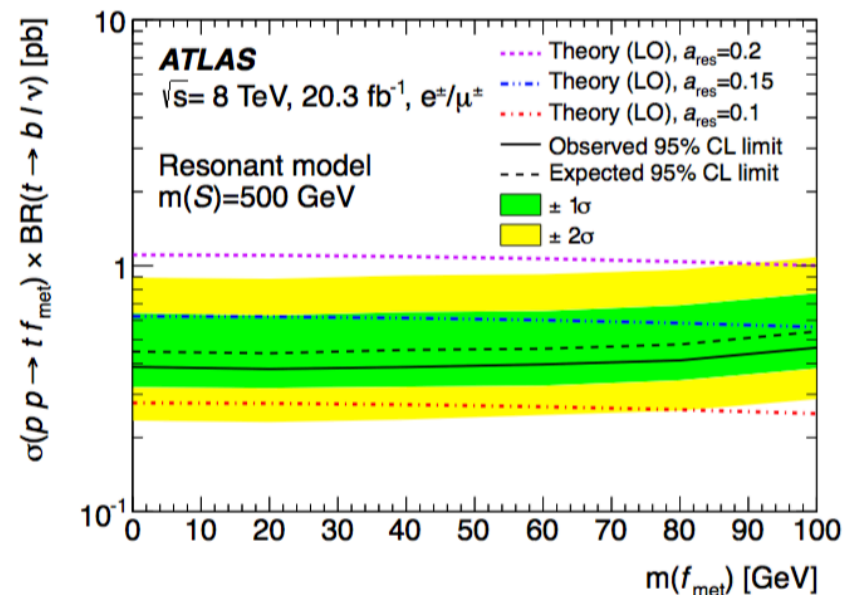
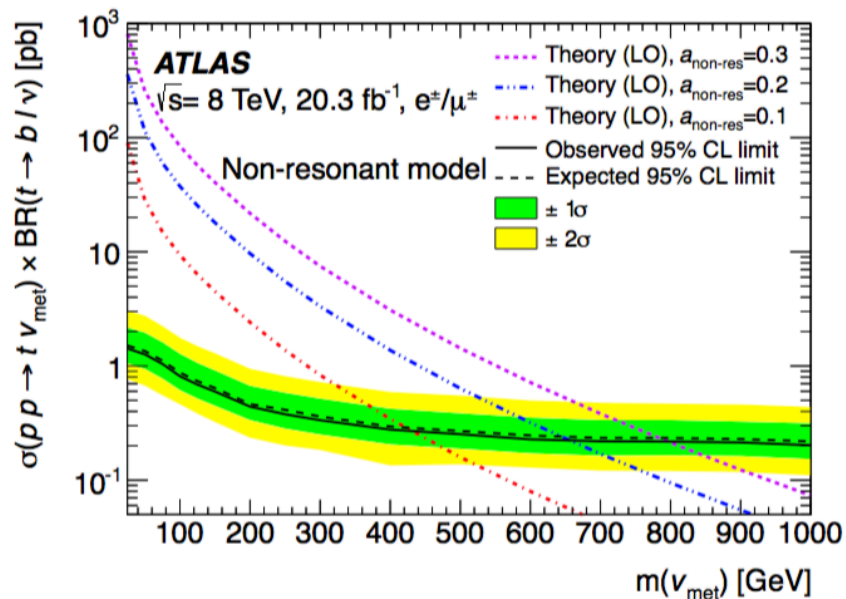




Monotop leptonic at 8 TeV ATLAS (2)



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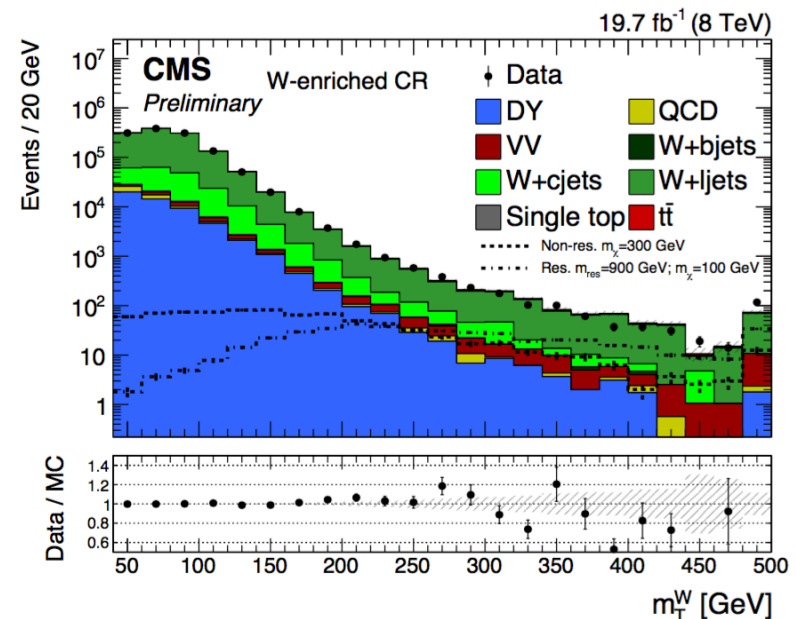
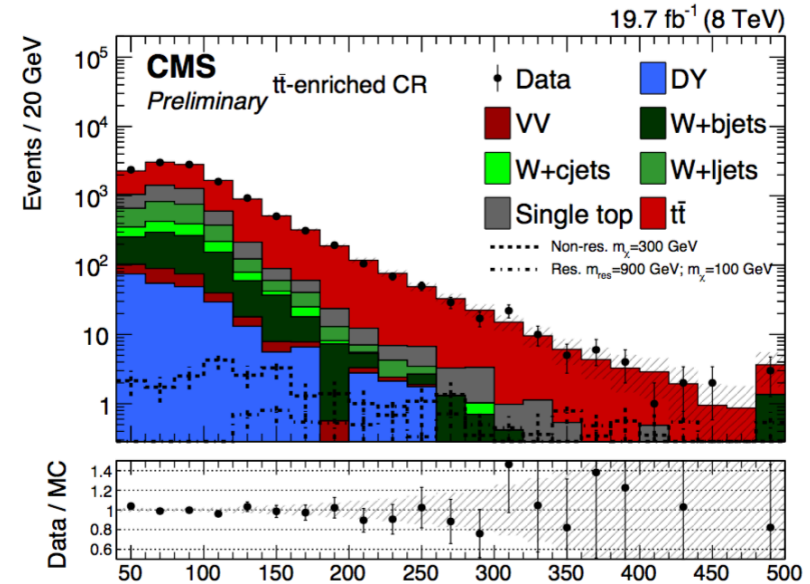
Monotop in the muon channel at 8 TeV

CMS



CMS-B2G-15-001

- Search in the **muon channel**, using a shape analysis (m_T^W).
- **Event selection** : single muon trigger, 1 high p_T muon, $N_{jets} \geq 1$ (leading jet >70 GeV), $m_T^W > 40$,
- **Signal region** : $N_{jets} = 1, N_{bjets} = 1, |\Delta\phi(\mu - b)| < 1.7, E_T^{miss} > 100$ GeV.
- **Control regions** :
 - W+jets CR: $N_{bjets} = 0,$
 - $t\bar{t}$ CR: $N_{jets} = 2, N_{bjets} = 2.$
- **Simultaneous fit of the signal and control regions.**

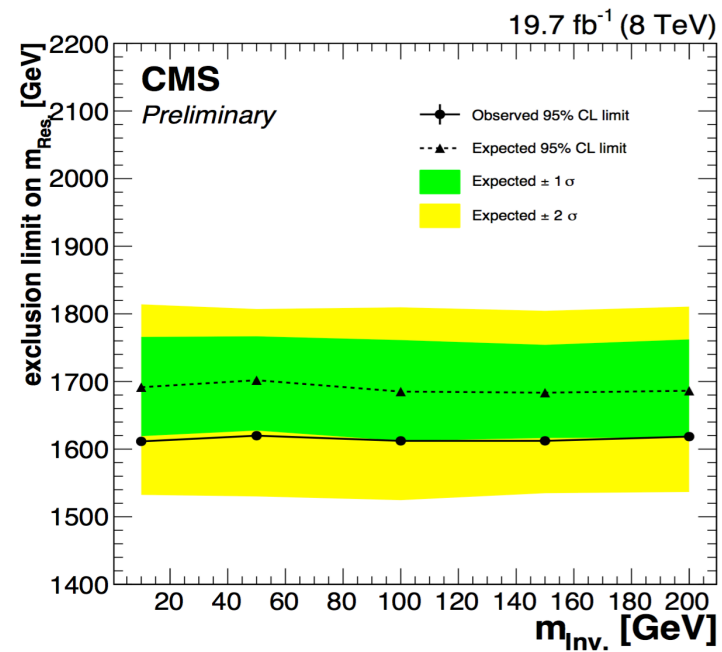
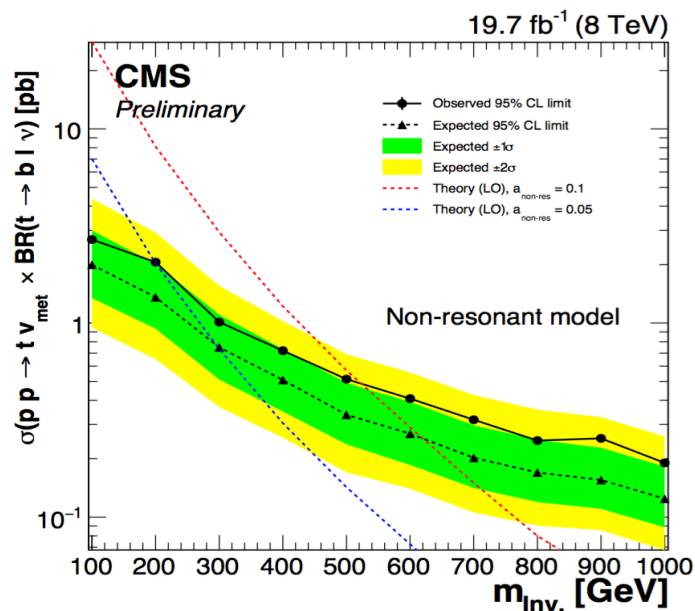
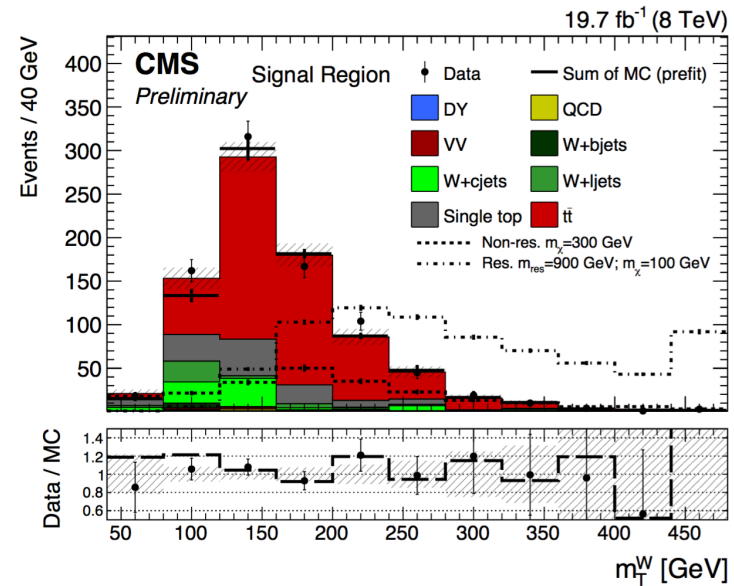
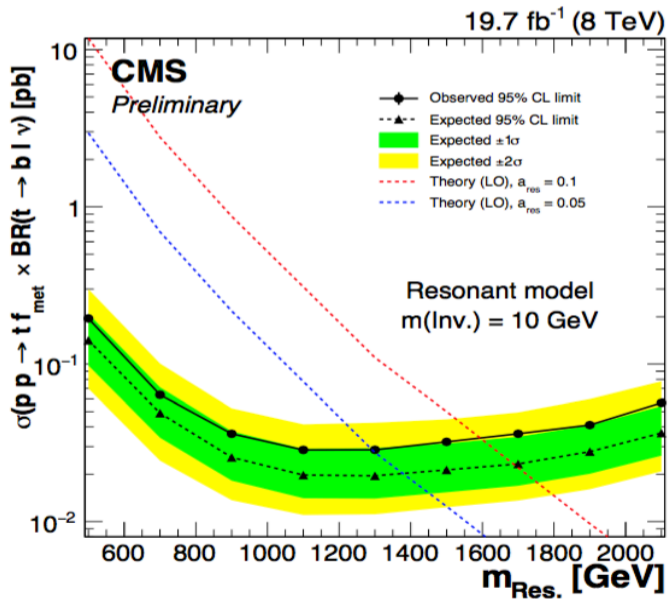




Monotop in the muon channel at 8 TeV CMS (2)



CMS-B2G-15-001





Conclusions

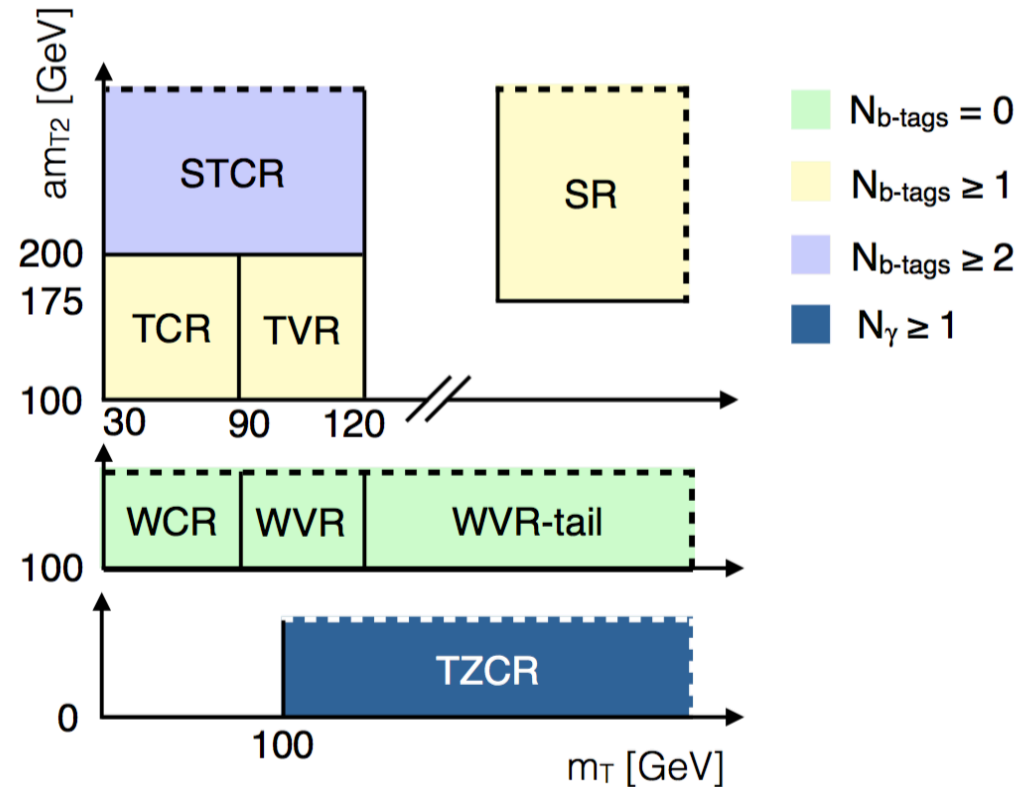


- Top signatures provide very interesting probes for searching for Dark Matter.
- Two approaches followed :
 - Production of top-pairs and Dark Matter particles,
 - Single top production and Dark Matter particles.
- Signal described by simplified models, including new scalar (pseudo-scalar) resonances or FCNC interactions.
- Global effort for harmonization : Dark Matter Forum.
- Searches performed at 8 and 13 TeV, no signs of new physics observed, yet ...



Backups

Common event selection		
Trigger	E_T^{miss} trigger	
Lepton	exactly one signal lepton (e, μ), no additional baseline leptons	
Jets	at least two signal jets, and $ \Delta\phi(\text{jet}_i, \vec{p}_T^{\text{miss}}) > 0.4$ for $i \in \{1, 2\}$	
Hadronic τ veto*	veto events with a hadronic τ decay and $m_{T2}^{\tau} < 80$ GeV	
Variable	DM_low	DM_high
Number of (jets, b -tags)	$(\geq 4, \geq 1)$	$(\geq 4, \geq 1)$
Jet $p_T >$ [GeV]	(60 60 40 25)	(50 50 50 25)
E_T^{miss} [GeV]	> 300	> 330
$H_{T,\text{sig}}^{\text{miss}}$	> 14	> 9.5
m_T [GeV]	> 120	> 220
am_{T2} [GeV]	> 140	> 170
$\min(\Delta\phi(\vec{p}_T^{\text{miss}}, \text{jet}_i))(i \in \{1-4\})$	> 1.4	> 0.8
$\Delta\phi(\vec{p}_T^{\text{miss}}, \ell)$	> 0.8	-





Ttbar+X, l+jets, ATLAS



Common event selection for DM			
Trigger	E_T^{miss} trigger		
Lepton	exactly one signal lepton (e, μ), no additional baseline leptons		
Jets	at least four signal jets, and $ \Delta\phi(\text{jet}_i, \vec{p}_T^{\text{miss}}) > 0.4$ for $i \in \{1, 2\}$		
Hadronic τ veto	veto events with a hadronic τ decay and $m_{T2}^\tau < 80$ GeV		
Variable	DM_low	TCR / WCR	STCR
≥ 4 jets with $p_T > [\text{GeV}]$	(60 60 40 25)	(60 60 40 25)	(60 60 40 25)
E_T^{miss} [GeV]	> 300	$> 200 / > 230$	> 200
$H_{T,\text{sig}}^{\text{miss}}$	> 14	> 8	> 8
m_T [GeV]	> 120	[30,90]	[30,120]
am_{T2} [GeV]	> 140	[100,200] / > 100	> 200
$\min(\Delta\phi(\vec{p}_T^{\text{miss}}, \text{jet}_i))(i \in \{1 - 4\})$	> 1.4	> 1.4	> 1.4
$\Delta\phi(\vec{p}_T^{\text{miss}}, \ell)$	> 0.8	> 0.8	–
$\Delta R(b_1, b_2)$	–	–	> 1.8
Number of b -tags	≥ 1	$\geq 1 / = 0$	≥ 2
Variable	DM_high	TCR / WCR	STCR
≥ 4 jets with $p_T > [\text{GeV}]$	(50 50 50 25)	(50 50 50 25)	(50 50 50 25)
E_T^{miss} [GeV]	> 330	$> 300 / > 330$	> 250
$H_{T,\text{sig}}^{\text{miss}}$	> 9.5	> 9.5	> 5
m_T [GeV]	> 220	[30,90]	[30,120]
am_{T2} [GeV]	> 170	[100,200] / > 100	> 200
$\min(\Delta\phi(\vec{p}_T^{\text{miss}}, \text{jet}_i))(i \in \{1 - 4\})$	> 0.8	> 0.8	> 0.8
$\Delta R(b_1, b_2)$	–	–	> 1.2
Number of b -tags	≥ 1	$\geq 1 / = 0$	≥ 2

Table 6: Overview of the event selections for DM SRs and the associated $t\bar{t}$ (TCR), W +jets (WCR), and Wt (STCR) control regions. Round brackets are used to describe lists of values and square brackets denote intervals.

Variable	DM-SRL	DM-SRH
$ m_{ee} - m_Z $ [GeV] (SF only)	>20	>20
b -jet multiplicity	> 0	> 0
$\Delta\phi_{\text{boost}}$	< 1.0	< 1.0
m_{T2}^{ll} [GeV]	>120	>120
E_T^{miss} [GeV]	> 180	> 260

Selection	CRT	CRTZ	VRVV	VRMET	VRMT2	VRINC
m_{T2}^{ll} [GeV]	60-100	>90	>100	–	>120	–
b -jet multiplicity	> 0	> 0	0	> 0	> 0	> 0
Jet multiplicity	> 1	> 1	> 1	> 1	> 1	–
Lepton multiplicity	2	> 2	2	2	2	2
$\Delta\phi_{\text{boost}}$	< 1	–	–	> 1	> 1	> 1
E_T^{miss} [GeV]	–	–	–	> 180	–	–

Selection	CRZ	CRT	CRT-ISR	CRST	CRW
Trigger	electron (muon)	E_T^{miss}			
N_ℓ	2	1			
p_T^ℓ	> 20 GeV				
$m_{\ell\ell}$	[86,96] GeV	-			
N_{jet}	≥ 4	≥ 4 (including leptons)			
jet p_T	(40, 40, 20, 20) GeV	(80, 80, 40, 40) GeV			(80, 80, 20, 20) GeV
E_T^{miss}	< 50 GeV	> 250 GeV			
$E_T^{\text{miss}'}$	> 70 GeV	-			
b -tagged jets	≥ 2	≥ 2	≥ 1	≥ 2	= 1
$ \Delta\phi(\text{jet}^{0,1}, E_T^{\text{miss}}) $	-	> 0.4			
$\min m_T(\ell, E_T^{\text{miss}})$	-	30 GeV	-	30 GeV	30 GeV
$\max m_T(\ell, E_T^{\text{miss}})$	-	120 GeV	80 GeV	120 GeV	100 GeV
$m_{\text{jet}, R=1.2}^0$	-	> 70 GeV	-	> 70 GeV	< 60 GeV
$m_T^{b, \min}$	-	> 100 GeV	-	> 175 GeV	-
$\Delta R(b, \ell)_{\min}$	-	< 1.5	< 2.0	> 1.5	> 2.0
m_{bb}	-	-	-	> 200 GeV	-
N_{jet}^S	-	-	≥ 5	-	-
$N_{b\text{-tag}}^S$	-	-	≥ 1	-	-
p_T^{ISR}	-	-	≥ 400 GeV	-	-



DM forum benchmark points



m_χ (GeV)	M_{med} (GeV)								
1	10	20	50	100	200	300	500	1000	10000
10	10	15	50	100					10000
50	10		50	95	200	300			10000
150	10				200	295	500	1000	10000
500	10						500	995	10000
1000	10							1000	10000



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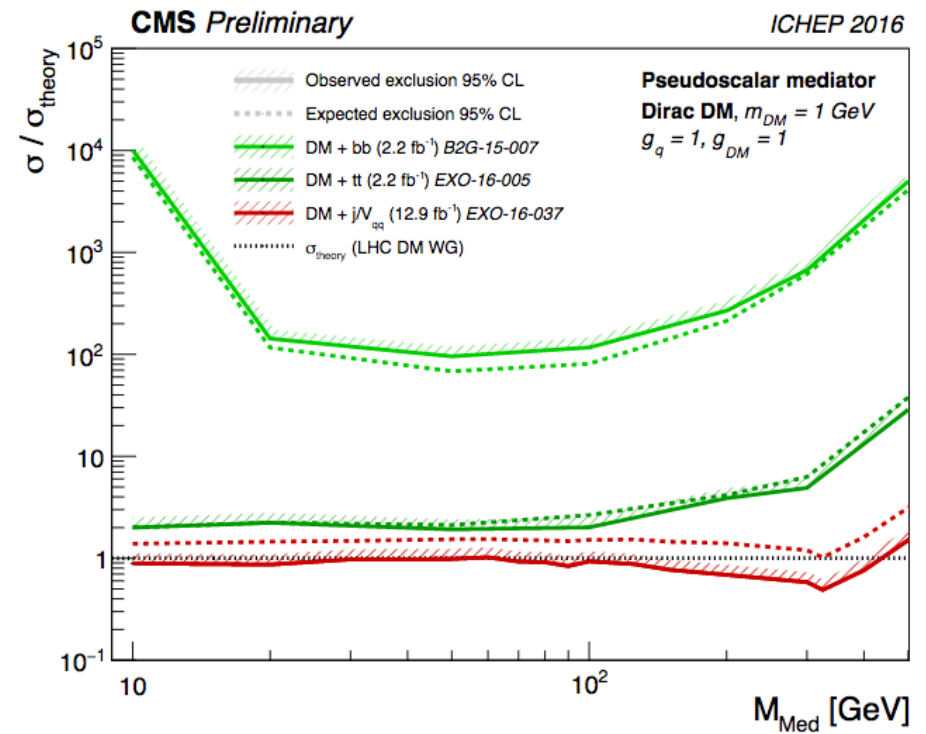
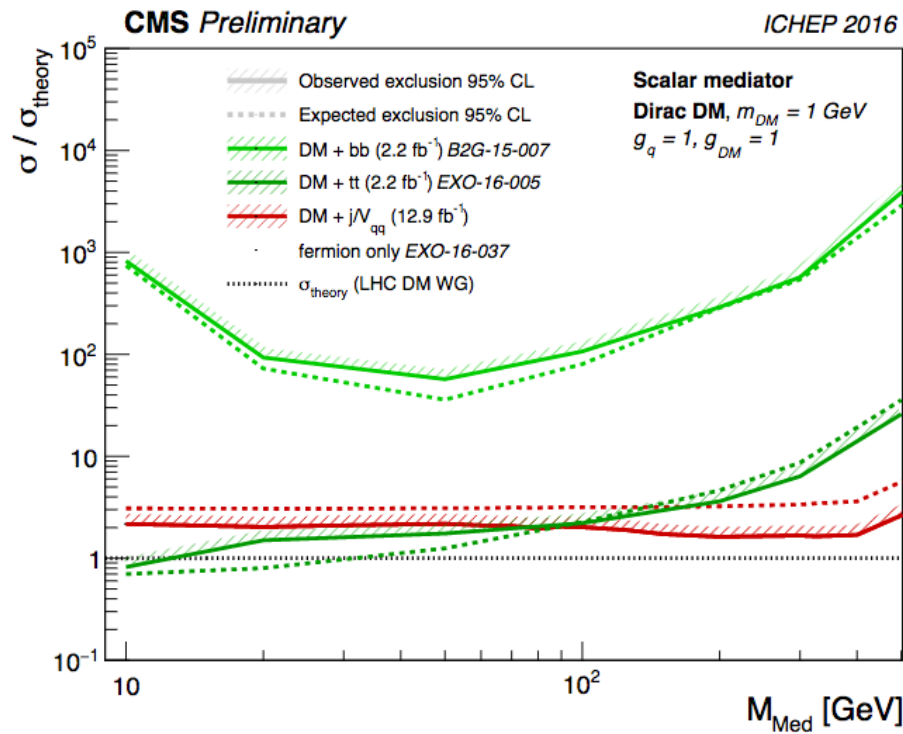


Table 4: Expected limits on μ for scalar and pseudoscalar models in the combined categorised search and the combined inclusive search.

$m_{\text{MED}}, m_{\text{DM}}$ [GeV]	Scalar		Pseudoscalar	
	categorised	inclusive	categorised	inclusive
10, 1	0.70	1.1	2.0	2.4
20, 1	0.80	1.2	2.2	2.3
50, 1	1.2	1.5	2.1	2.2
100, 1	2.3	2.9	2.6	2.8
200, 1	4.6	5.5	4.2	4.2
300, 1	8.7	9.4	6.3	6.6
500, 1	36	38	38	37
10, 10	38	48	40	45
50, 10	1.4	1.9	2.4	2.6
200, 50	4.7	5.4	3.8	4.0
300, 50	8.5	9.6	6.9	7.0
200,150	1300	1400	550	530



CMS DM summary



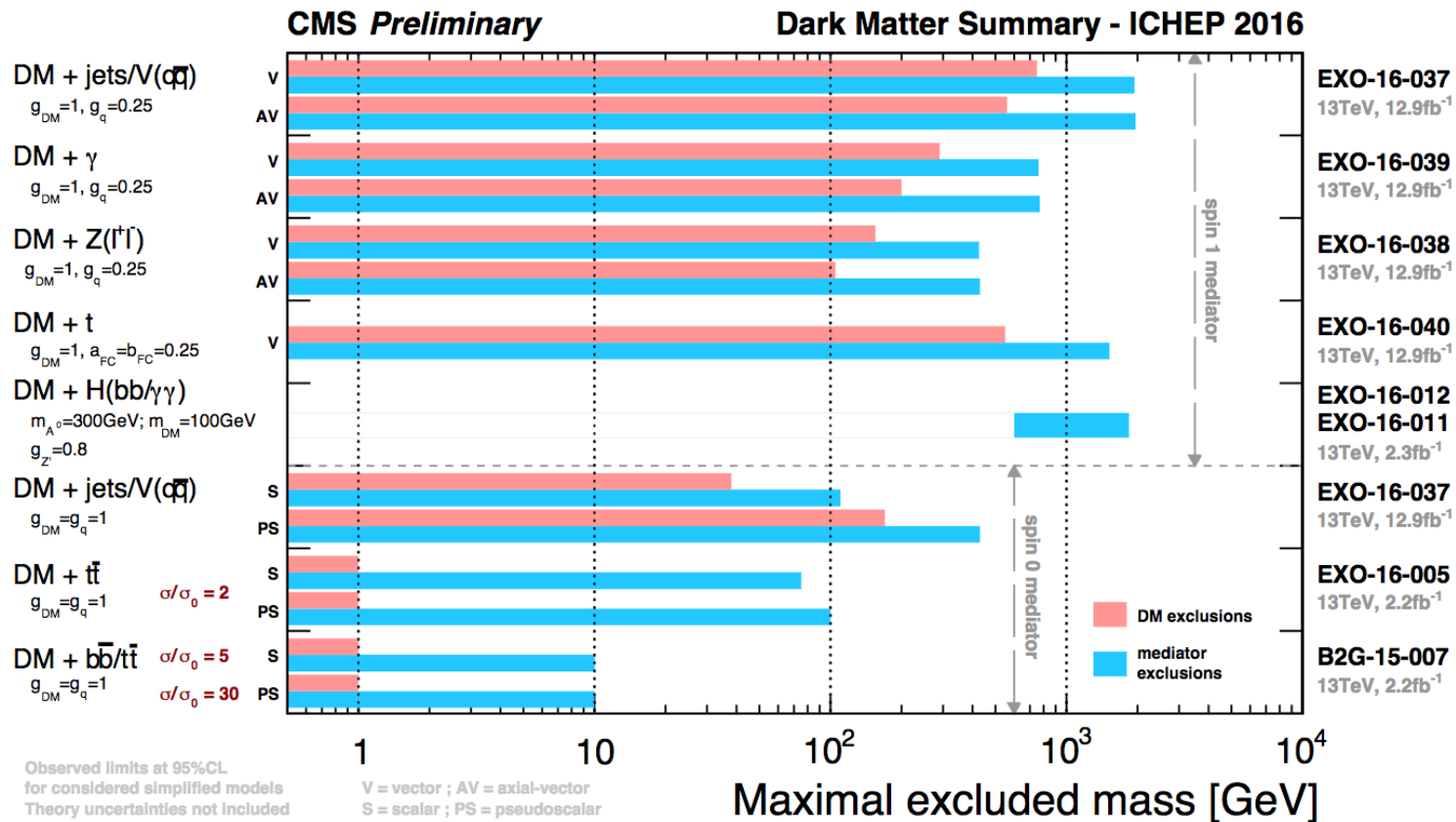


Figure 6. Maximal/minimal reach of DM searches from CMS in mediator mass (blue bar) and DM mass (red bar). The limits represent 95% CL observed exclusions and they are only applicable to the model and coupling choices indicated next to the bars.