BSM top physics

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TLF meeting Paris 2016

The top at a glance

- The top quark is the heaviest particle known to mankind!

The top at a glance

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- The only "Natural" fermion

$$m_{\text{top}} \sim v_{\text{SM}} \sim m_Z$$

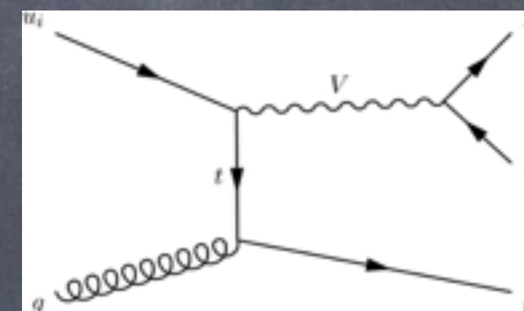
- Largest coupling to the Higgs

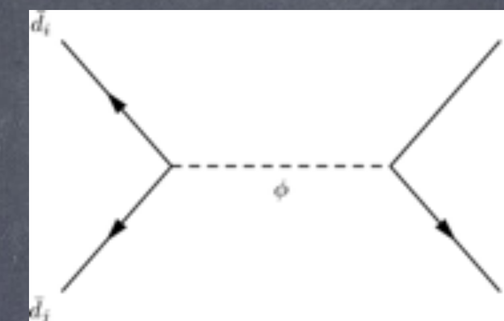
- Ideal candidate for New Physics effects!

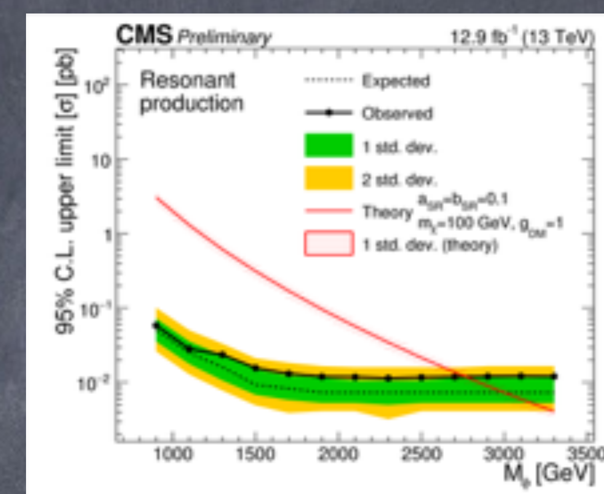
$$\delta m_H^2 \sim -\frac{3y_{\text{top}}^2}{8\pi}\Lambda^2$$

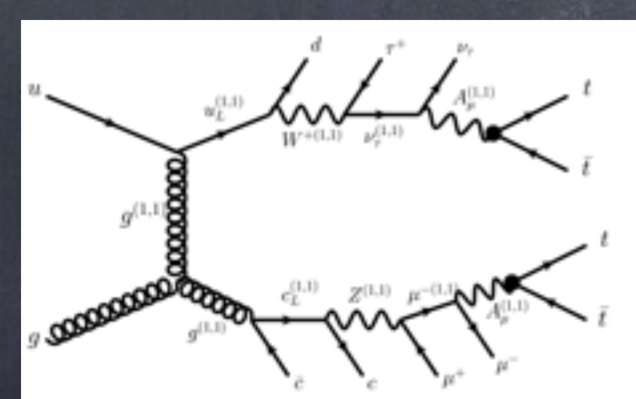
The top at a glance

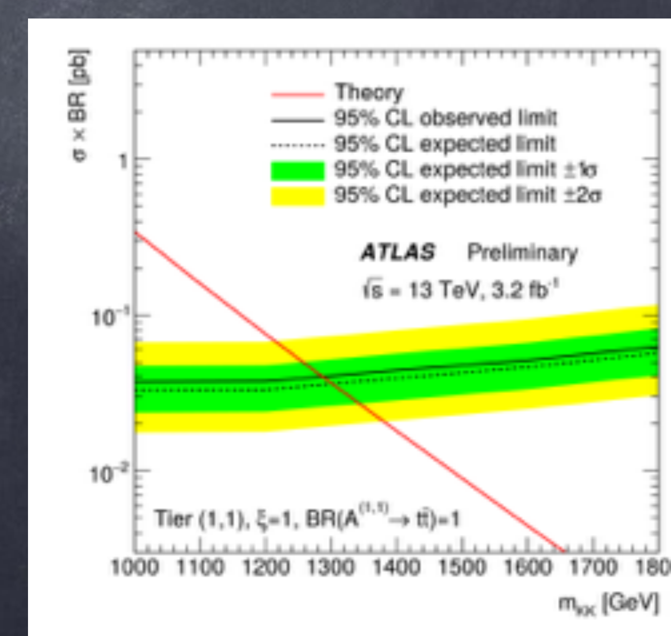
- Top effective couplings (EFT)
- Resonances
- New states decaying into top + X (VLQs, ...)
- Top and DM: Monotop (+ invisible), tt + DM, ...
- Single-top
- multi (4+) top production
- ....









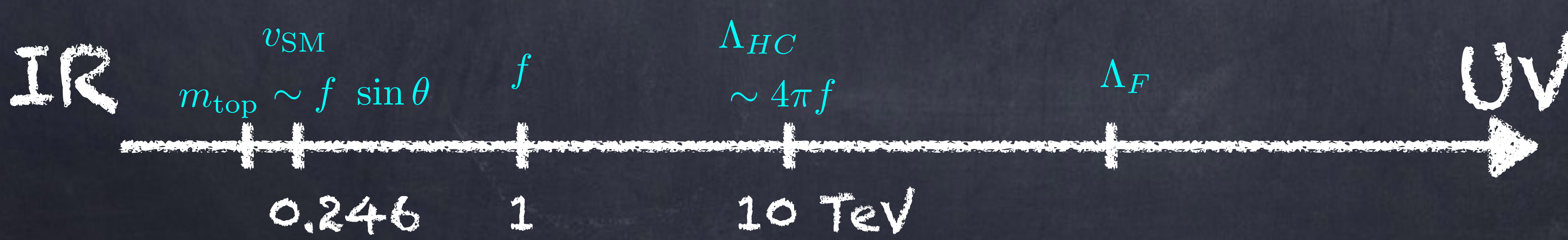


The top in composite models

- In composite models, the fermion mass "naturalness" idea is reversed.

$$\frac{1}{\Lambda_f^2} q_L q_R \langle QQ \rangle \sim \frac{\Lambda_{\rm HC}^3}{\Lambda_F^2} \sin\theta \; q_L q_R \qquad\qquad \Lambda_{HC} \ll \Lambda_F$$

- Fermion masses are "naturally" suppressed: the top is the weirdo!



The top in composite models

- A partially composite top:

$$y_L\, t_L \mathcal{O}_L + y_R\, t_R \mathcal{O}_R$$

$$m_{\text{top}} \sim y_L y_R\, f \sin\theta$$

↓

$$\frac{1}{\Lambda_F^2}\, t_{L/R}\, QQ\chi$$

→

$$y_{L/R} \sim \left(\frac{\Lambda_{\text{HC}}}{\Lambda_F}\right)^{2-\gamma} \sim 1$$

↓

$$\Lambda_{\text{HC}} \ll \Lambda_F \qquad \gamma \sim 2$$

(large anomalous dimensions)

top partners
(Aldo's talk)

A concrete model

1311.6562 (see also G.Ferretti)

HC SM groups global sym.

	Sp($2N_c$)	SU(3)$_c$	SU(2)$_L$	U(1)$_Y$	SU(4)	SU(6)	U(1)
Q_1 Q_2	$\square$	**1**	**2**	0	**4**	**1**	$-3(N_c-1)q_\chi$
Q_3	$\square$	**1**	**1**	1/2			
Q_4	$\square$	**1**	**1**	$-1/2$			
χ_1 χ_2 χ_3	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	**3**	**1**	x	**1**	**6**	q_χ
χ_4 χ_5 χ_6	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\bar{\mathbf{3}}$	**1**	$-x$			

$\langle QQ \rangle \Rightarrow SU(4)/Sp(4)$ Higgs emerges as a pseudo-GB

$\langle \chi\chi \rangle \Rightarrow SU(6)/SO(6)$ coloured composite scalars

A concrete model

	spin	SU(4)×SU(6)	Sp(4)×SO(6)	names
QQ	0	$(\mathbf{6},\mathbf{1})$	$(\mathbf{1},\mathbf{1})$	σ
			$(\mathbf{5},\mathbf{1})$	π
$\chi\chi$	0	$(\mathbf{1},\mathbf{21})$	$(\mathbf{1},\mathbf{1})$	σ_c
			$(\mathbf{1},\mathbf{20})$	π_c
χQQ	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$	ψ_1^1
			$(\mathbf{5},\mathbf{6})$	ψ_1^5
$\chi\bar{Q}\bar{Q}$	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$	ψ_2^1
			$(\mathbf{5},\mathbf{6})$	ψ_2^5
$Q\bar{\chi}\bar{Q}$	1/2	$(\mathbf{1},\bar{\mathbf{6}})$	$(\mathbf{1},\mathbf{6})$	ψ_3
$Q\bar{\chi}\bar{Q}$	1/2	$(\mathbf{15},\bar{\mathbf{6}})$	$(\mathbf{5},\mathbf{6})$	ψ_4^5
			$(\mathbf{10},\mathbf{6})$	ψ_4^{10}
$\bar{Q}\sigma^\mu Q$	1	$(\mathbf{15},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$	a
			$(\mathbf{10},\mathbf{1})$	ρ
$\bar{\chi}\sigma^\mu\chi$	1	$(\mathbf{1},\mathbf{35})$	$(\mathbf{1},\mathbf{20})$	a_c
			$(\mathbf{1},\mathbf{15})$	ρ_c

Higgs + 1

Coloured pGBs

top partner candidates

$$20_{SO(6)} = 8_0 \oplus 6_{4/3} \oplus \bar{6}_{-4/3}$$

Coloured scalars

1507.02283

- MESSAGE: composite models always contain coloured scalars!

$$20_{SO(6)} = 8_0 \oplus 6_{4/3} \oplus \bar{6}_{-4/3}$$

- Is it true only in specific models? NO!

OPE: $\mathcal{O}_L \mathcal{O}_L \Rightarrow 6_{4/3} + \ldots$ $\mathcal{O}_L \mathcal{O}_R \Rightarrow 8_0 + \ldots$

- How do they couple? Model independent?

$$\mathcal{L} = |D_\mu \pi_6|^2 - m_{\pi_6}^2 |\pi_6|^2 + \frac{1}{2}(D_\mu \pi_8)^2 - \frac{1}{2} m_{\pi_8}^2 (\pi_8)^2 - V_{\text{scalar}}(\pi_6, \pi_8)$$
$$+ a_R\ \pi_6 t_R^c t_R^c + a_L\ \pi_6^c t_L t_L + b\ \pi_8 t_R^c t_L + h.c.$$

Coloured scalars

- MESSAGE: composite models always contain coloured scalars!

Partial compositeness with scalars

1607.01659

Table I. Fundamental states

	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$	$SU_{\mathcal{F}}(4)$	$U_{g_1}(3)$	$U_{g_2}(2)$
$\mathcal{F}_1$	1	$\square$	0			
$\mathcal{F}_2$	1	1	$\frac{1}{2}$	$\square$	1	1
$\mathcal{F}_3$	1	1	$-\frac{1}{2}$			
$\mathcal{S}_1$	$\overline{\square}$	1	$-\frac{1}{6}$	1	$\square$	1
$\mathcal{S}_2$	1	1	$\frac{1}{2}$	1	1	$\square$

$$\mathcal{L}_y = Q^{\mathrm{T}} y_Q \mathcal{S}_1 \mathcal{F}_1 + u^{\mathrm{T}} y_u \mathcal{S}_1^* \mathcal{F}_2 + d^{\mathrm{T}} y_d \mathcal{S}_1^* \mathcal{F}_3 \,.$$

Truly UV completed (renormalisable) theory

<SS> bound states are coloured!

Coloured scalars

1507.02283

At closer inspection (matching EW quantum numbers):

$$\mathcal{L} = |D_\mu \pi_6|^2 - m_{\pi_6}^2 |\pi_6|^2 + \frac{1}{2}(D_\mu \pi_8)^2 - \frac{1}{2} m_{\pi_8}^2 (\pi_8)^2 - V_{\text{scalar}}(\pi_6, \pi_8)$$
$$+ a_R \; \pi_6 t_R^c t_R^c + a_L \; \pi_6^c t_L t_L + b \; \pi_8 t_R^c t_L + h.c.$$

$$a_R \sim 1 \qquad a_L \sim \frac{v^2}{\Lambda_{\text{HC}}^2} \qquad b \sim \frac{v}{\Lambda_{\text{HC}}}$$

Coloured scalars

1507.02283

At closer inspection (matching EW quantum numbers):

$$\mathcal{L} = |D_\mu \pi_6|^2 - m_{\pi_6}^2 |\pi_6|^2 + \frac{1}{2}(D_\mu \pi_8)^2 - \frac{1}{2} m_{\pi_8}^2 (\pi_8)^2 - V_{\text{scalar}}(\pi_6, \pi_8)$$
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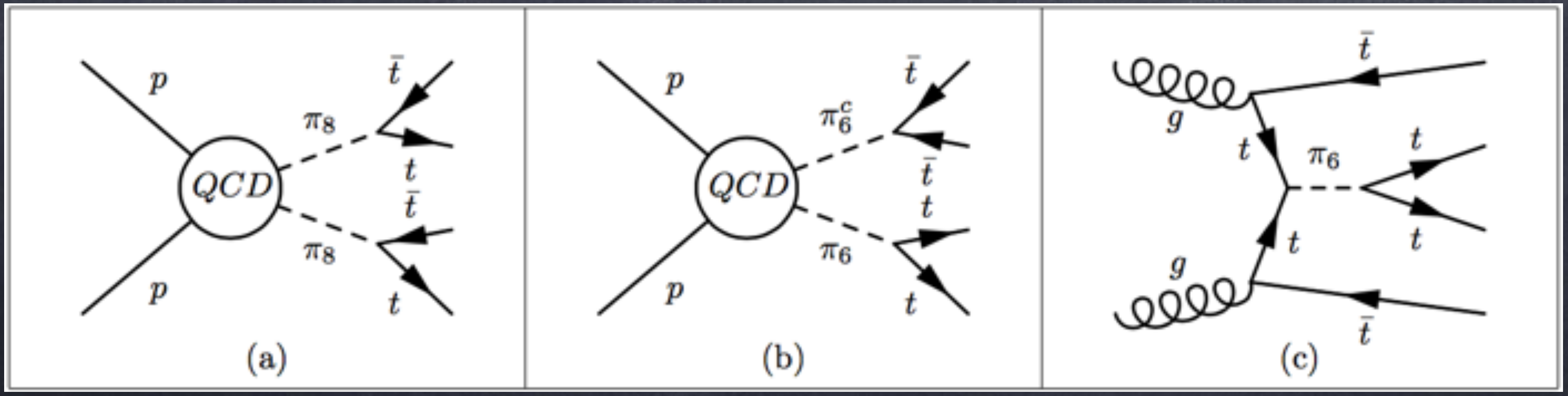
$$a_R \sim 1 \qquad a_L \sim \frac{v^2}{\Lambda_{\text{HC}}^2} \qquad b \sim \frac{v}{\Lambda_{\text{HC}}}$$



Interesting phenomenology

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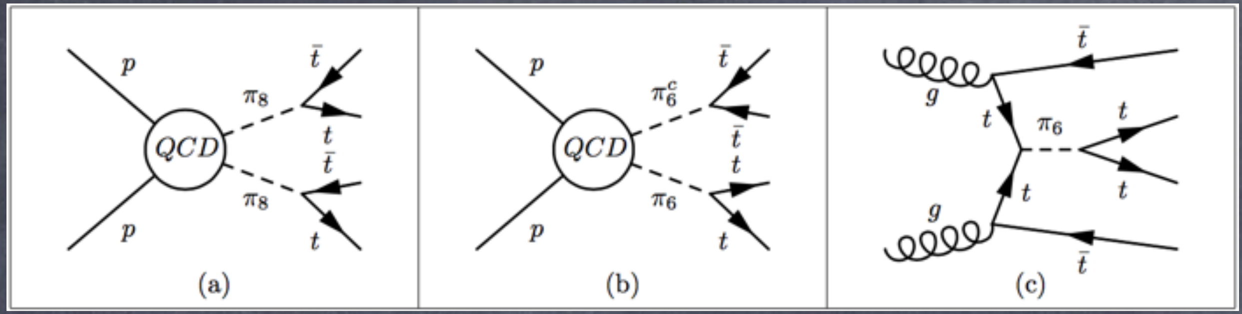
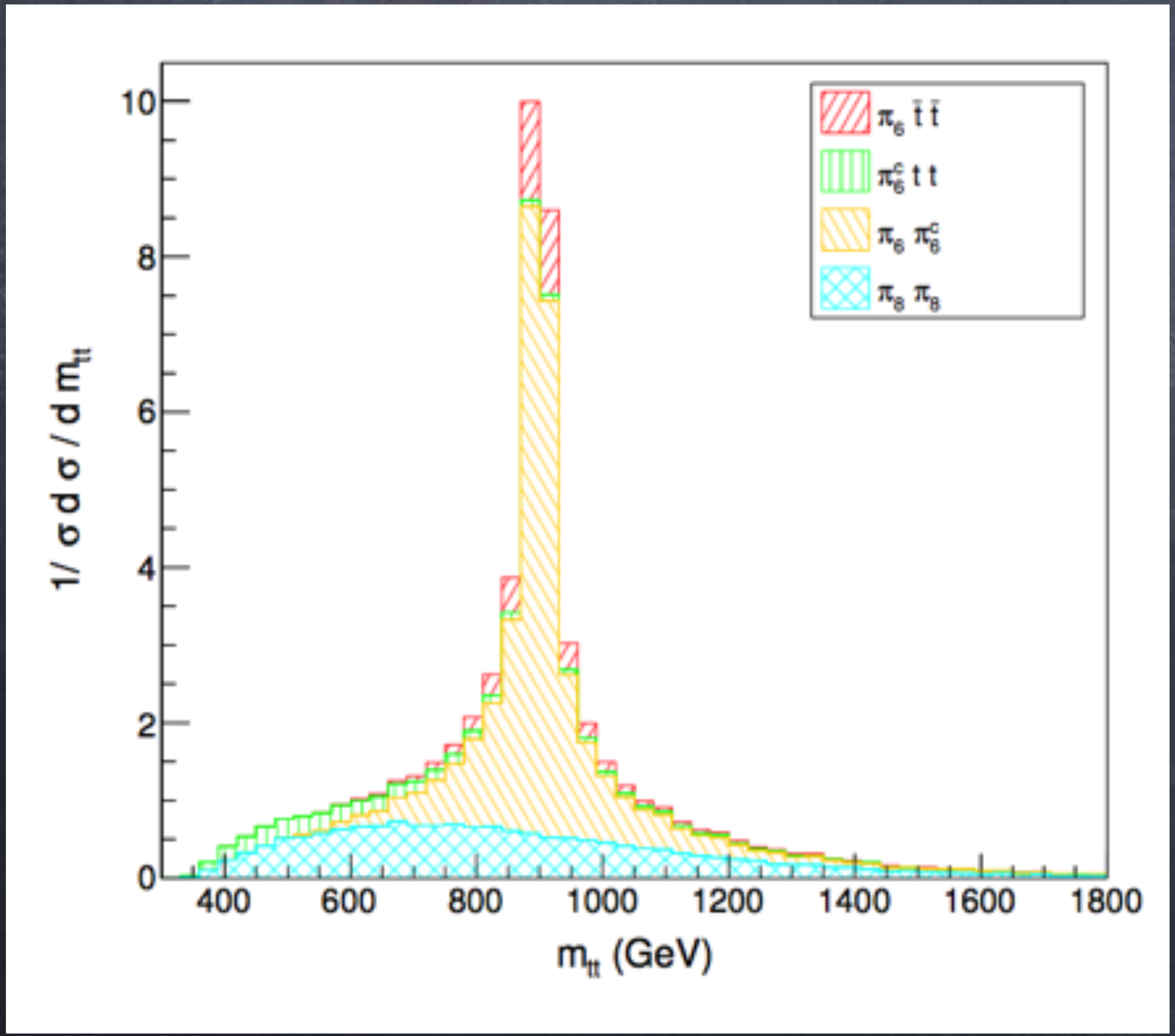


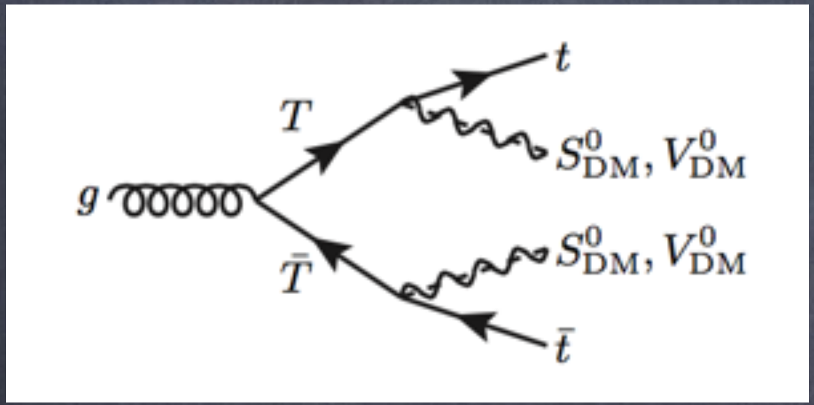


- Select two (+) sign leptons
- Reconstruct two SS tops
- Build invariant mass
- Reconstruct sextet peak

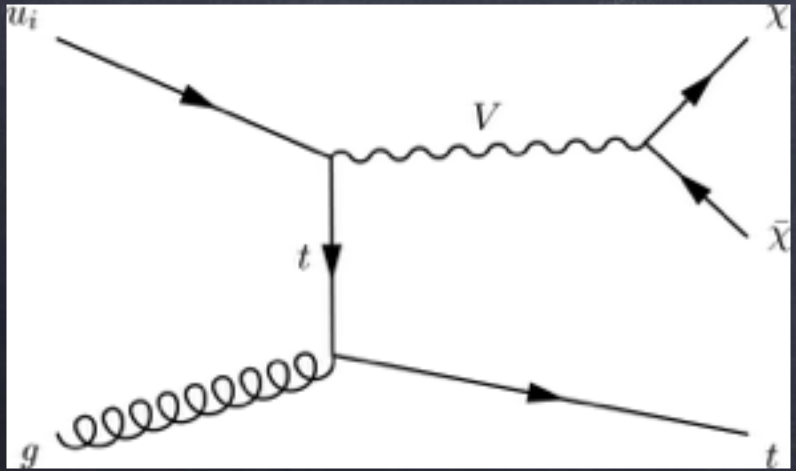
Parton level simulation!

Tops (+ DM)

- What does the top have to say about Dark Matter?

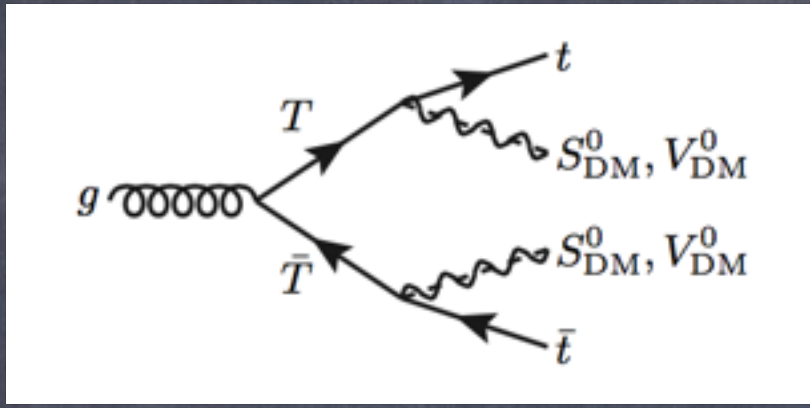


In composite models, top partners can decay to a DM candidate



Monotop as a stereotypical mono-stuff DM channel

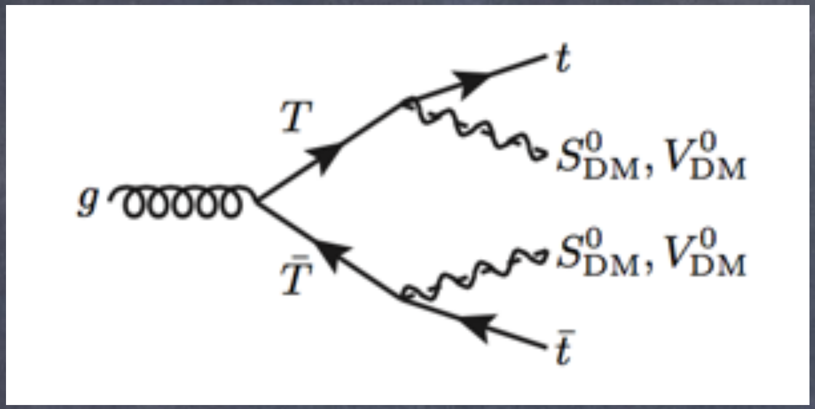
Tops (+ DM): the VLQ case

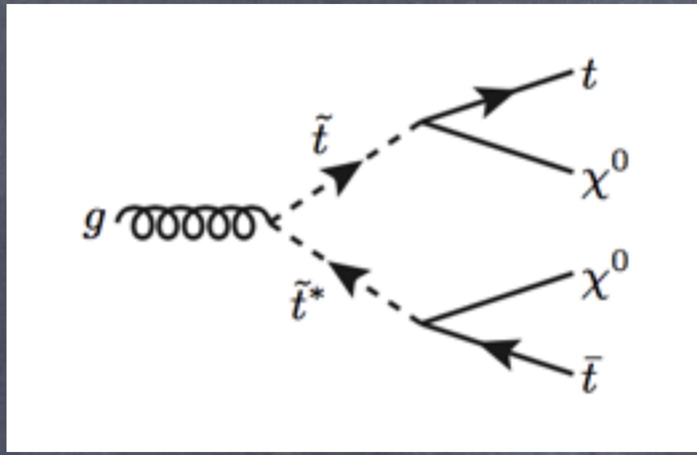


- Top partners with non-standard decays (scalars) 1506.05110
- Extra pions may be DM candidates 1508.07014 $\frac{SU(4)\times SU(4)}{SU(4)}$
- Little-Higgs with T-parity (vectors) 1506.05130

Tops (+ DM): the VLQ case

1607.02050





Same final state as SUSY stop

CMS 1-lepton search

	Point (600, 10)L			Point (600, 10)R		
	SUSY	XQ-SDM	XQ-VDM	SUSY	XQ-SDM	XQ-VDM
eff. SR-A	0.0108	0.0109	0.0111	0.0108*	0.0106*	0.0107*
eff. SR-B	0.0181*	0.0176*	0.0184*	0.0154	0.0152	0.0153
excl. XS [pb]	0.0169	0.0173	0.0166	0.0210	0.0213	0.0211
mass limit/SUSY XS	631	629	633	613	611	612
mass limit/XQ XS	820	818	822	798	796	797
1 − CLs	0.99	1	1	0.97	1	1

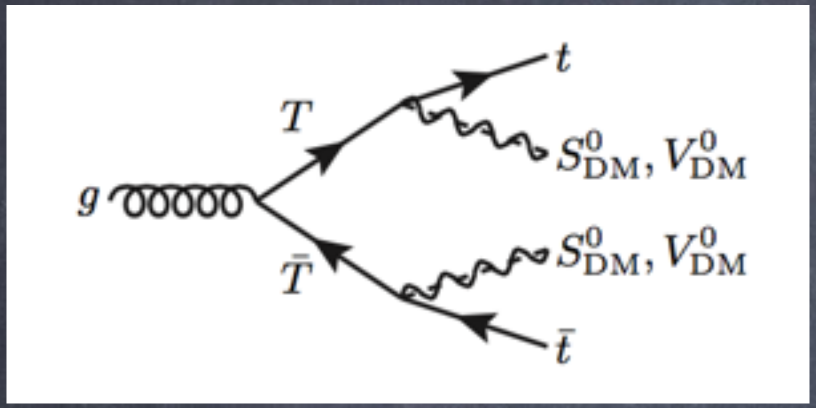
	Point (600, 300)L			Point (600, 300)R		
	SUSY	XQ-SDM	XQ-VDM	SUSY	XQ-SDM	XQ-VDM
eff. SR-A	0.00360	0.00366	0.00346	0.00340	0.00321	0.00315
eff. SR-B	0.00748*	0.00685*	0.00632*	0.00597*	0.00570*	0.00536*
excl. XS [pb]	0.0399	0.0448	0.0480	0.0507	0.0530	0.0563
mass limit/SUSY XS	560	551	546	541	538	533
mass limit/XQ XS	733	722	715	710	706	700
1 − CLs	0.81	1	1	0.72	1	1

Efficiencies of SUSY and VLQs are very similar!

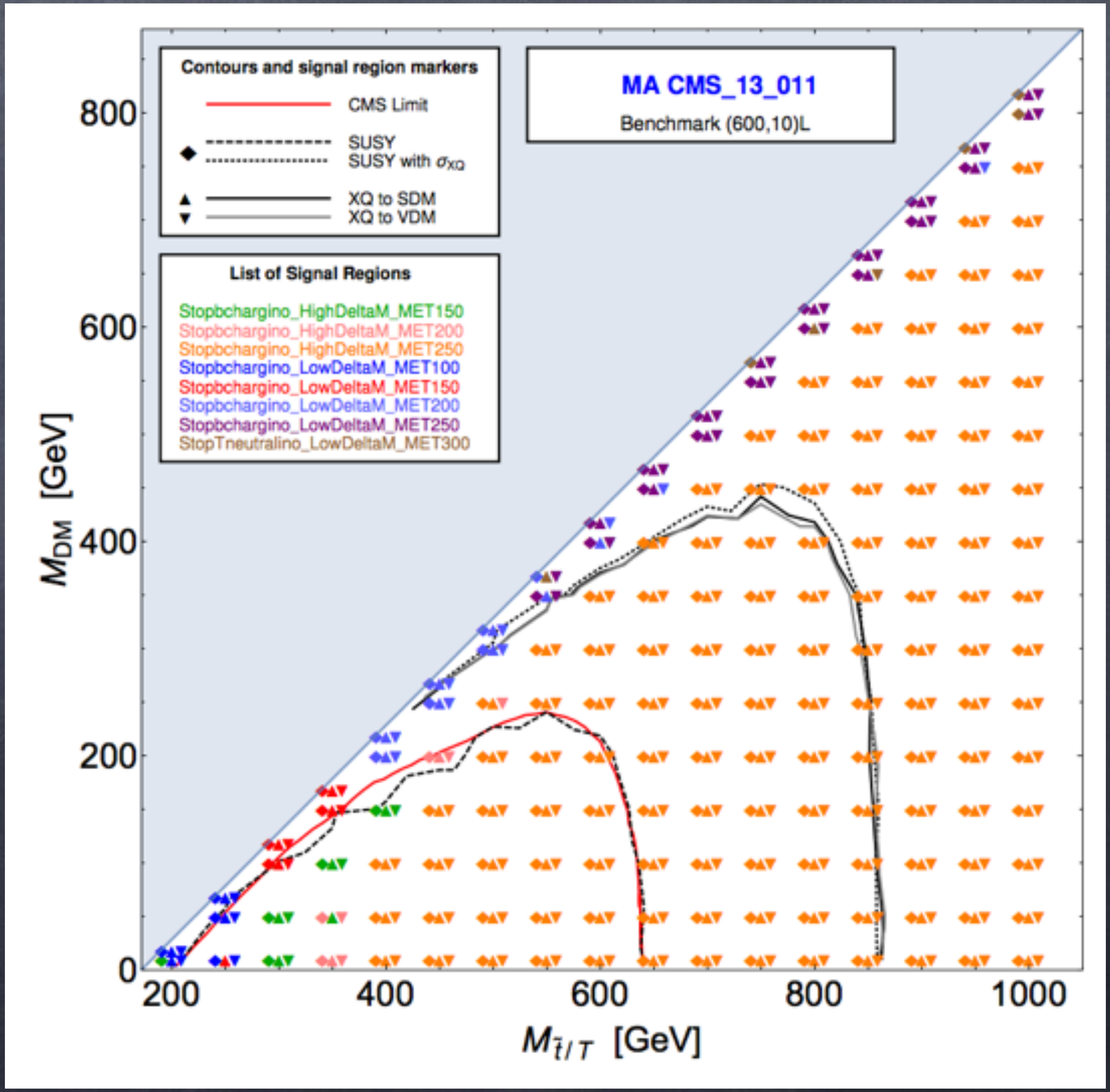
Simple recast!

Tops (+ DM): the VLQ case

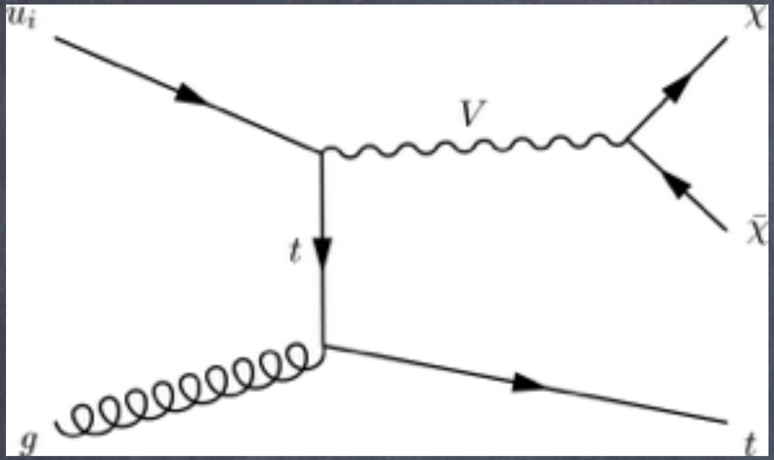
1607.02050

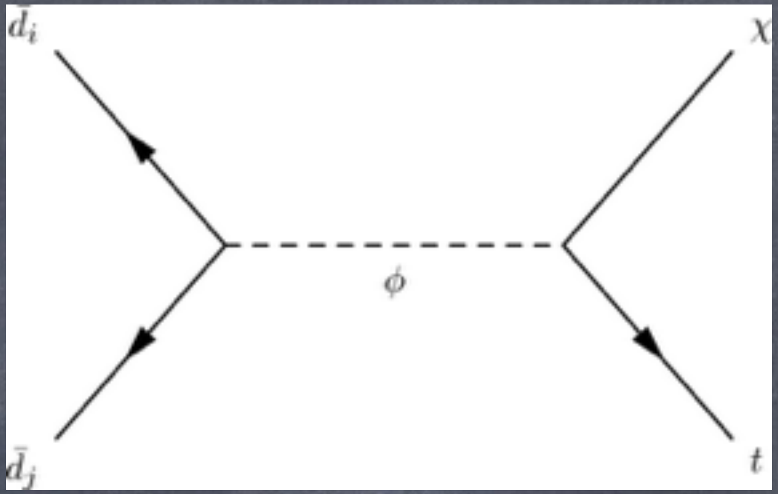


Recast of 1-lepton searches (CMS)



Monotops (+ DM): "simplified" models

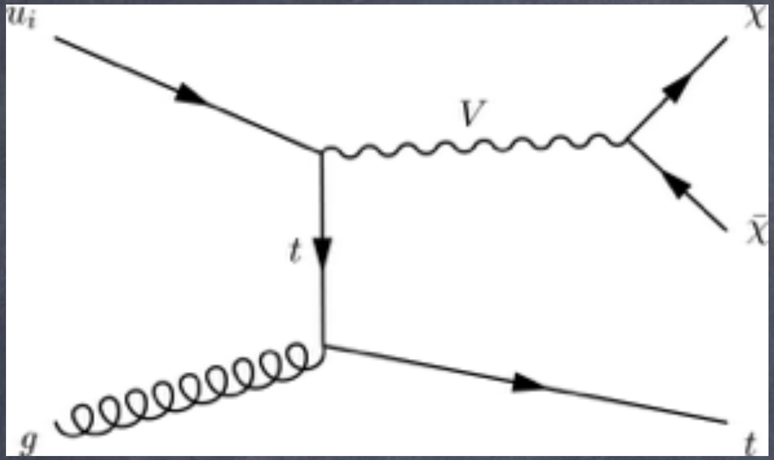




1106.6199, 1311.6478

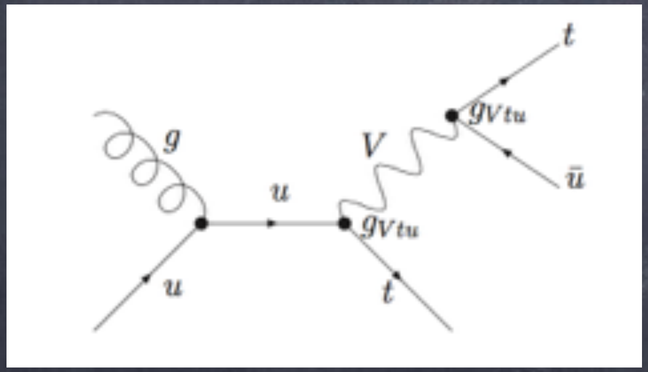
- Minimal consistent models involve RH tops
  1407.7529
- Case 1: vector mediator
- Case 2: RH stop with RPV couplings

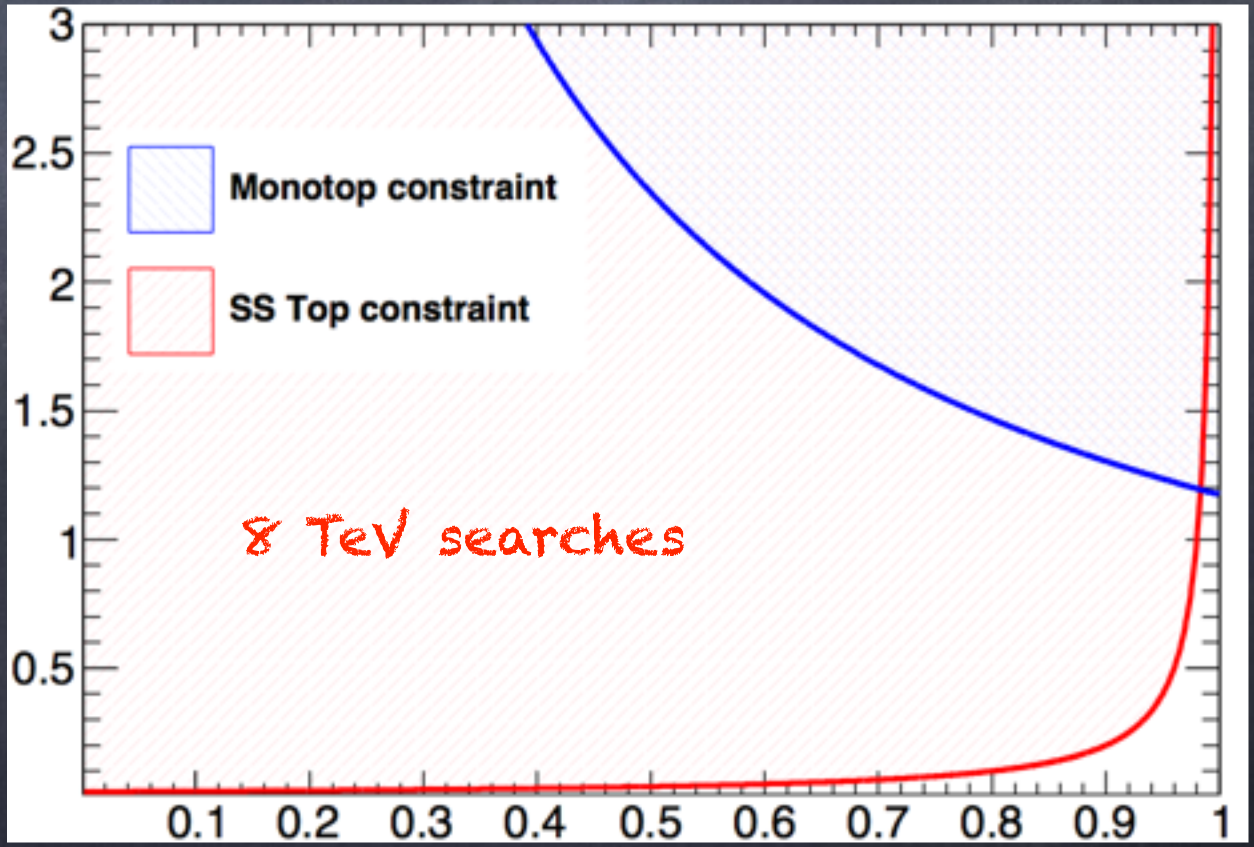
Monotops (+ DM): Vector mediator



Thank to R.Madar and T.Megy

V can decay back to a top!

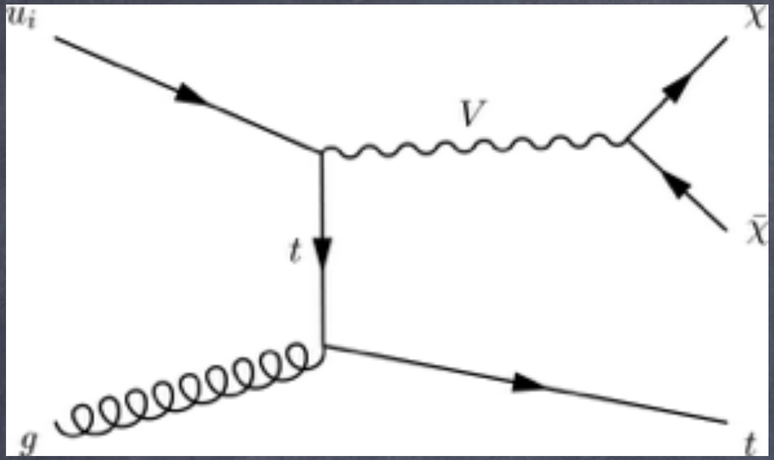




Monotop wins only if

$$BR(V \to \chi\chi) > 98\%$$

Monotops (+ DM): Vector mediator



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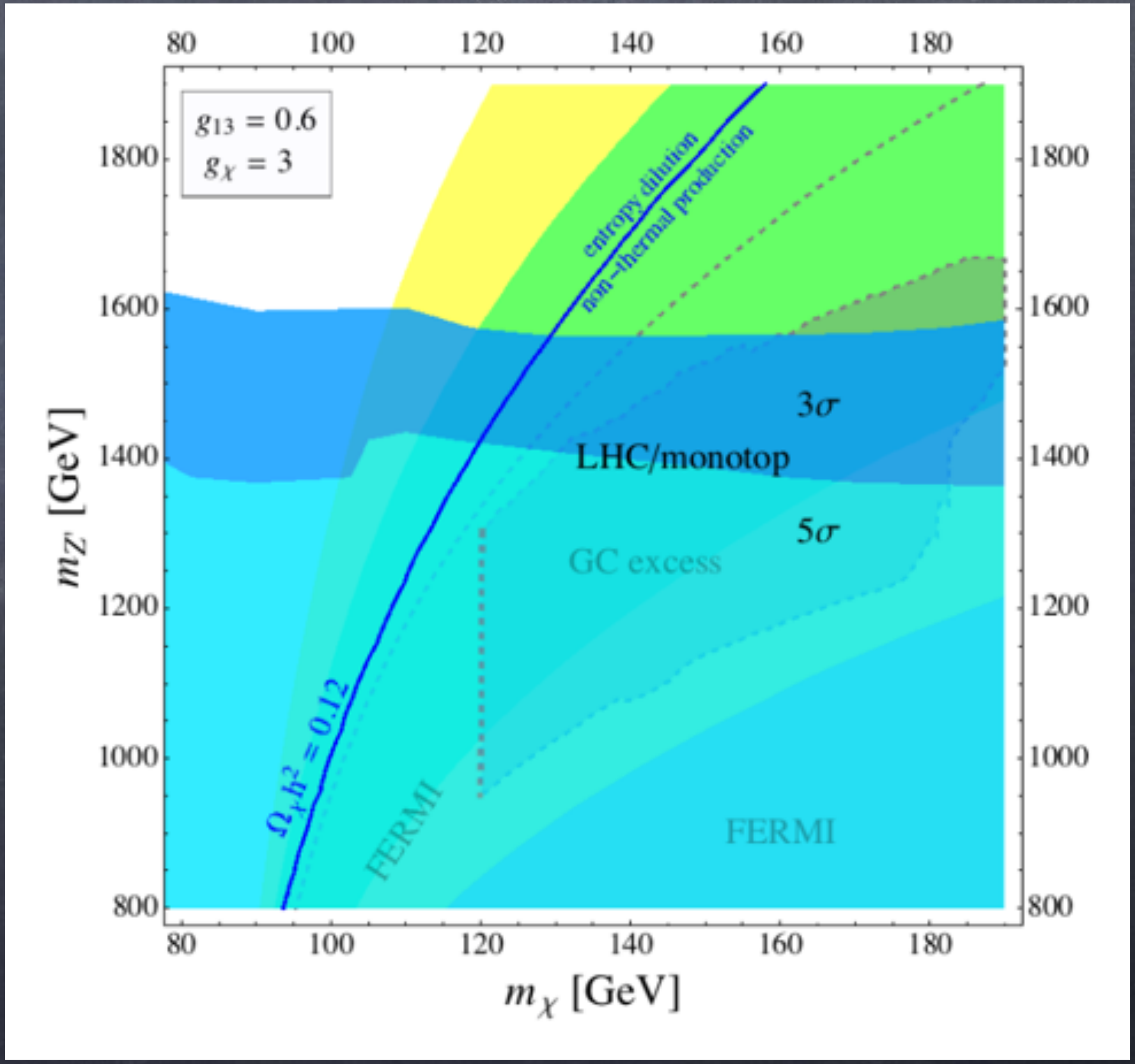
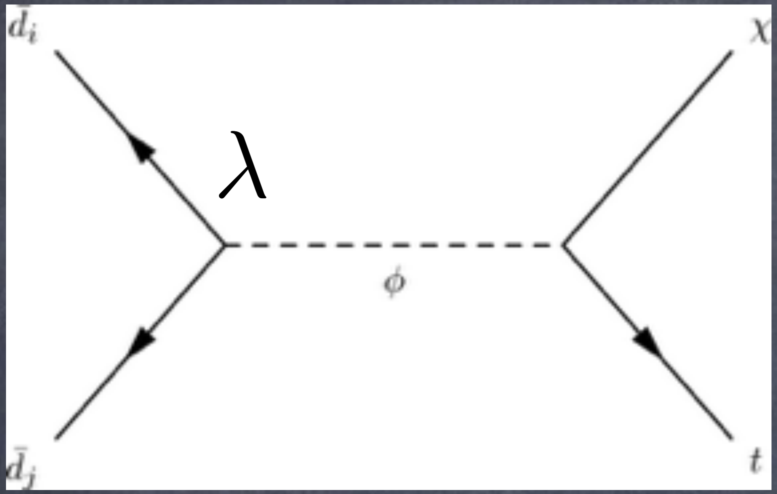


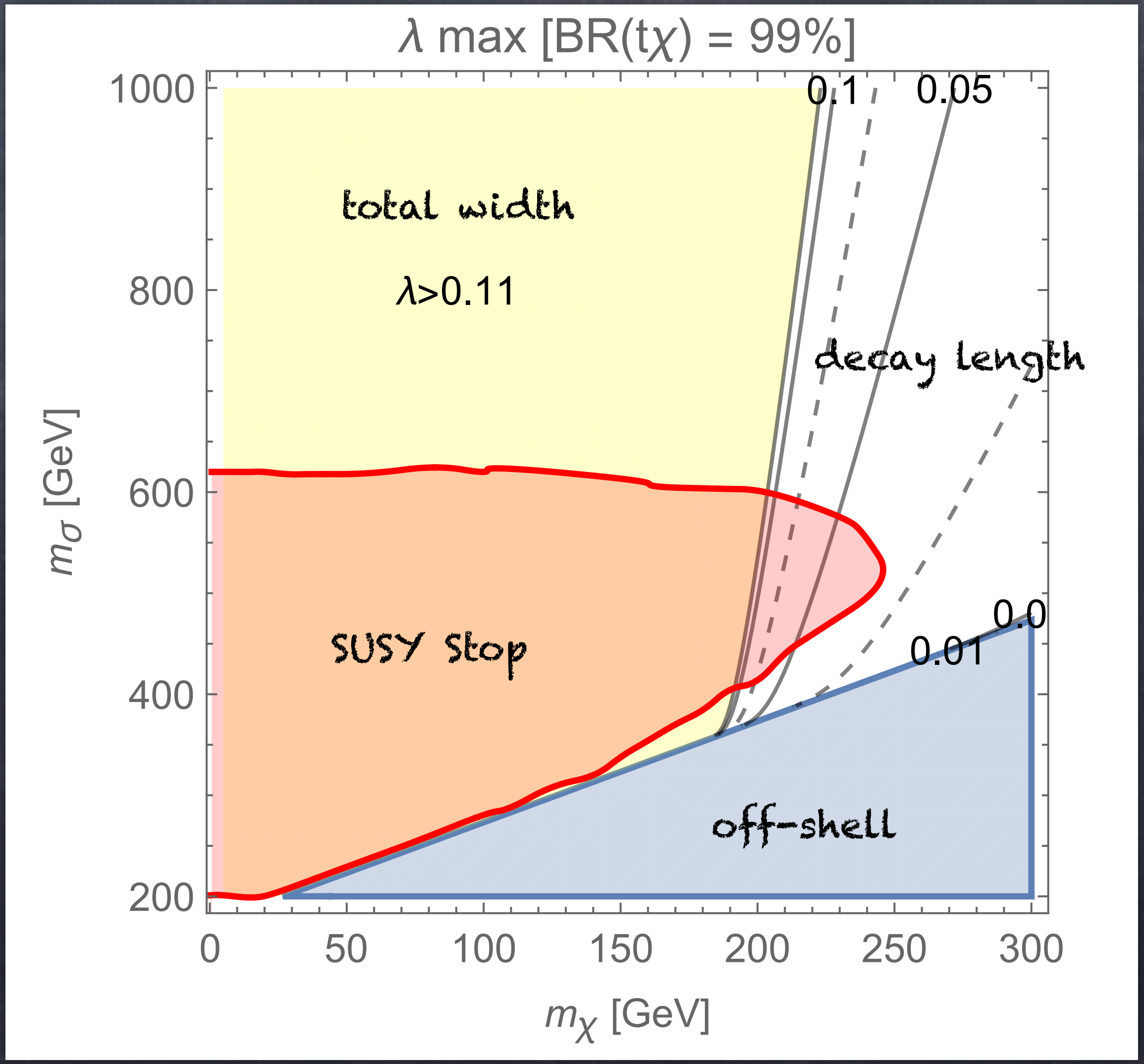
Relic DM assumed!

up quark

Monotops (+ DM): RPV stop



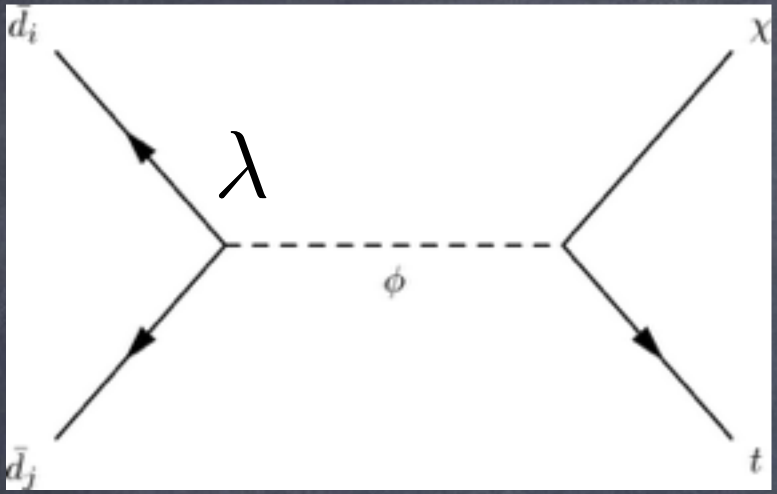
- 2 masses + 2 couplings
- STRATEGY: fix BR (t chi), extract bounds on 1 coupling



QCD@NLO model (MadGraph@NLO)

Work in preparation with A.Deandrea, B.Fuks and H-S.Shao

Monotops (+ DM): RPV stop



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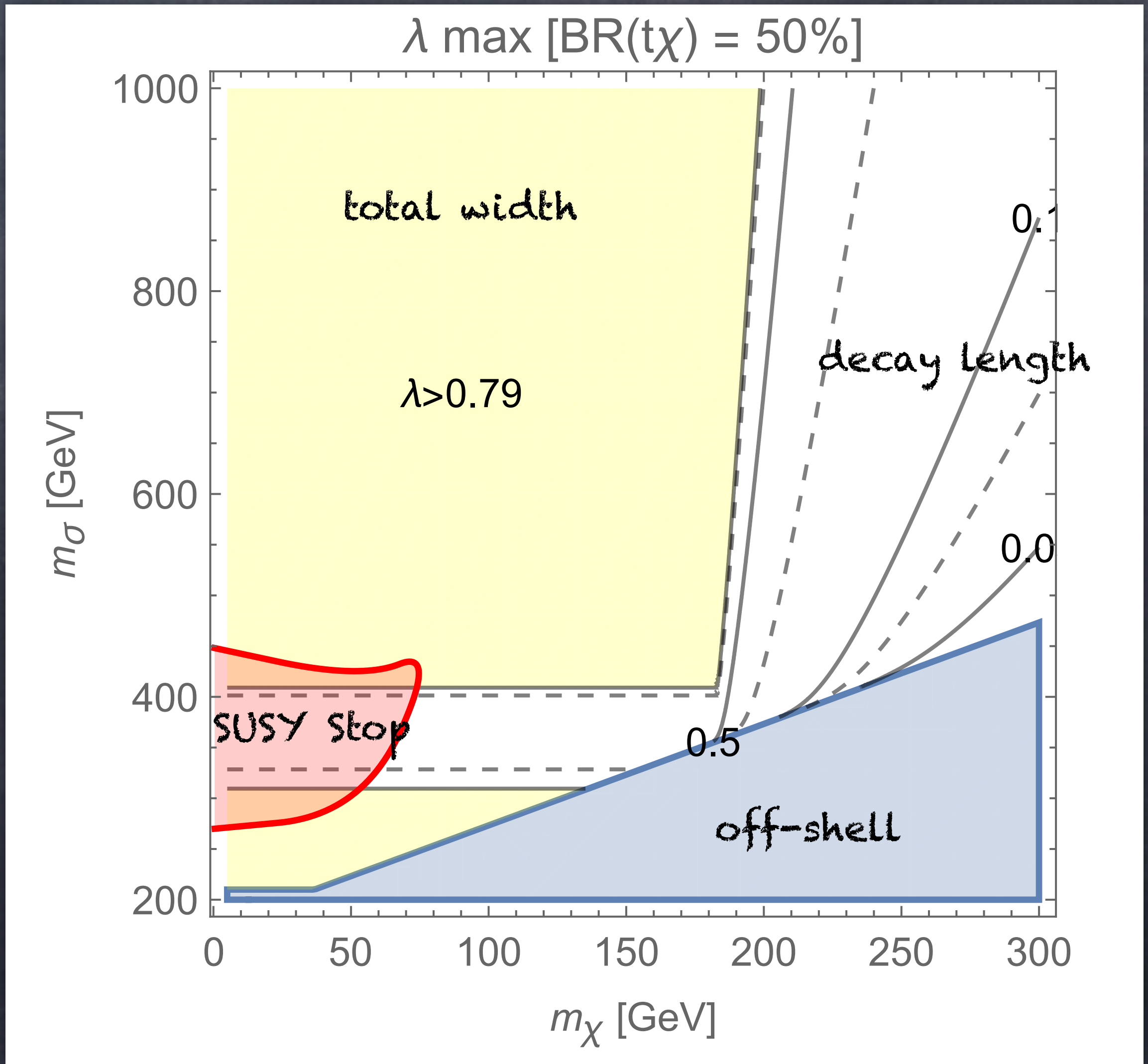

QCD@NLO model (MadGraph@NLO)

Work in preparation with A.Deandrea, B.Fuks and H-S.Shao

Conclusions and outlook

- The top might be a window to New Physics
- Many experimental searches and theory ideas
- I discussed a few examples, but many more can be explored
- (It's a chance to have fun!)