



# Theory Group Retreat

## Javi Serra

*fellow '15*



Les Houches Centre de Physique  
*6 November 2015*

CV

**UAB**

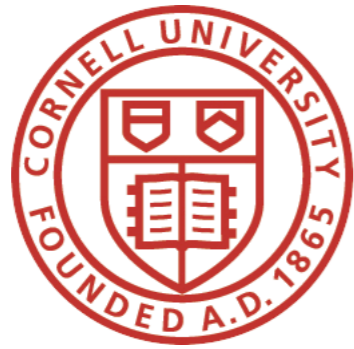
Alex Pomarol

*Compositeness at the  
electroweak scale*



# CV

Higgs boson  
discovery!



Csaba Csaki / 3y.

**UAB**

Alex Pomarol

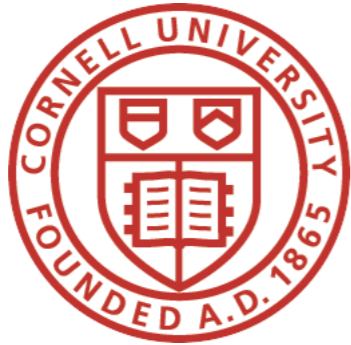
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# CV

Higgs boson  
discovery!



Csaba Csaki / 3y.



Andrea Wulzer / 1y.

# UAB

Alex Pomarol

*Compositeness at the  
electroweak scale*



# Research Interests

Physics Beyond the SM: ElectroWeak scale problem

*Why are things big?*



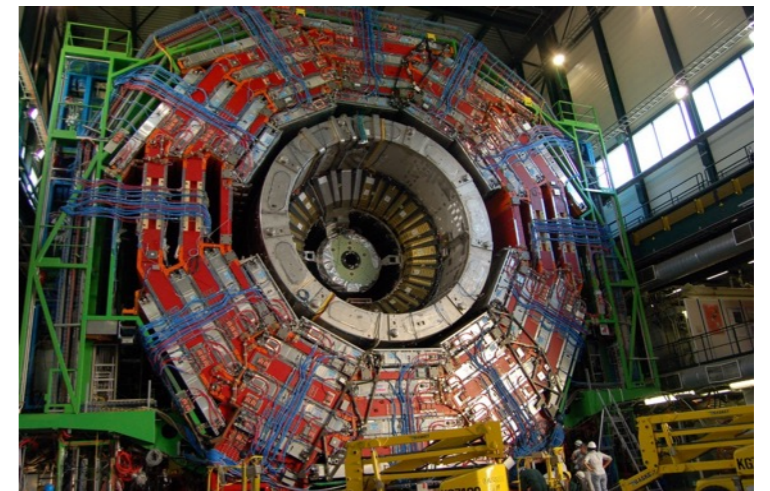
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*Why are things big?*



also motivated by other big things:  
LHC phenomenology





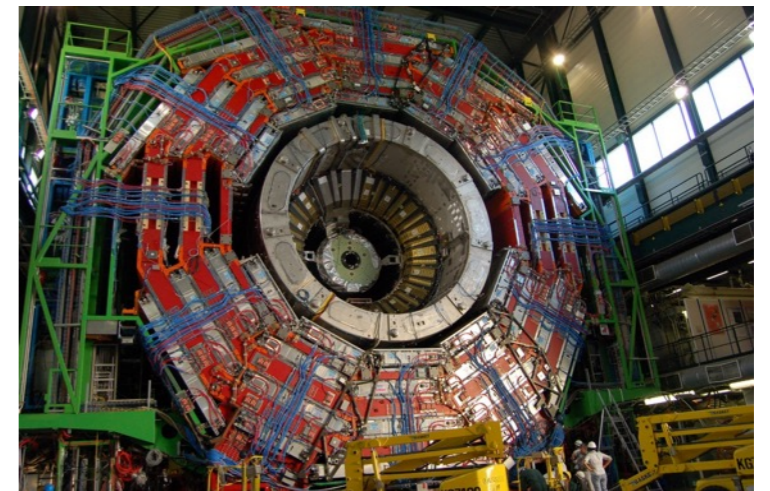
# Research Interests

Physics Beyond the SM: ElectroWeak scale problem

*Why are things big?*



also motivated by other big things:  
LHC phenomenology



Cosmological & astrophysical spin-offs:

*Why is the Universe big?*  
aka CC problem



# LHC non-discoveries

## ATLAS Exotics Searches\* - 95% CL Exclusion

Status: July 2015

ATLAS Preliminary

$\int \mathcal{L} dt = (4.7 - 20.3) \text{ fb}^{-1}$

$\sqrt{s} = 7, 8 \text{ TeV}$

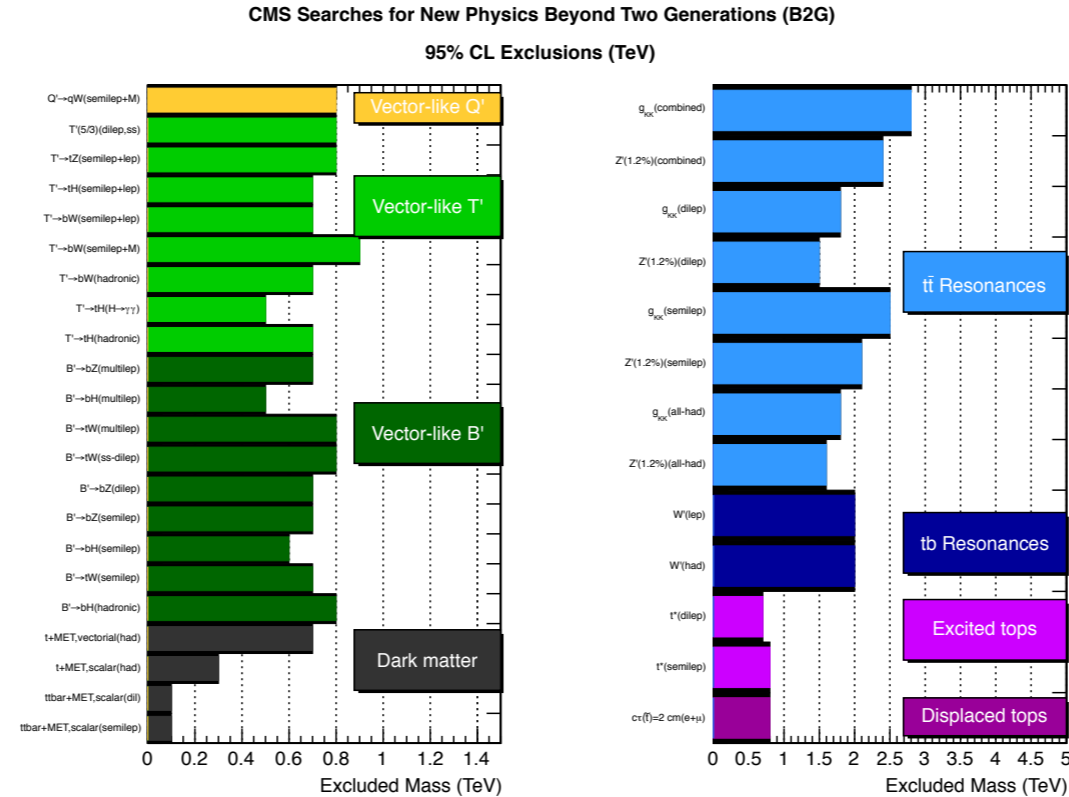
Model	$\ell, \gamma$	Jets	$E_{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimensions	ADD $G_{KK} + g/q$	-	$\geq 1j$	Yes	20.3	$M_0$ 5.25 TeV	$n = 2$
	ADD non-resonant $\ell\ell$	$2e, \mu$	-	-	20.3	$M_0$ 4.7 TeV	$n = 3 \text{ HLZ}$
	ADD OBH $\rightarrow \ell q$	$1e, \mu$	$1j$	-	20.3	$M_0$ 5.2 TeV	$n = 6$
	ADD OBH	$2\mu$ (SS)	$2j$	-	20.3	$M_0$ 4.7 TeV	$n = 6$
	ADD BH high $M_{KK}$	$2e, \mu$	$\geq 2j$	-	20.3	$M_0$ 5.5 TeV	$n = 6, M_0 = 3 \text{ TeV, non-rot BH}$
	ADD BH high $\Sigma p_T$	$\geq 1e, \mu$	$\geq 2j$	-	20.3	$M_0$ 5.8 TeV	$n = 6, M_0 = 3 \text{ TeV, non-rot BH}$
	ADD BH high multijet	-	$\geq 2j$	-	20.3	$M_0$ 5.8 TeV	$n = 6, M_0 = 3 \text{ TeV, non-rot BH}$
	RS1 $G_{KK} \rightarrow \ell\ell$	$2e, \mu$	-	-	20.3	$G_{KK} \text{ mass}$ 2.68 TeV	$k/M_{Pl} = 0.1$
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2\gamma$	-	-	20.3	$G_{KK} \text{ mass}$ 2.68 TeV	$k/M_{Pl} = 0.1$
	Bulk RS $G_{KK} \rightarrow ZZ \rightarrow qq\ell\ell$	$2e, \mu$	$2j/1J$	-	20.3	$G_{KK} \text{ mass}$ 740 GeV	$k/M_{Pl} = 1.0$
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	$1e, \mu$	$2j/1J$	Yes	20.3	$W \text{ mass}$ 750 GeV	$k/M_{Pl} = 1.0$
	Bulk RS $G_{KK} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	-	$4b$	-	19.5	$G_{KK} \text{ mass}$ 500-720 GeV	$k/M_{Pl} = 1.0$
	Bulk RS $G_{KK} \rightarrow \ell\ell$	$1e, \mu$	$\geq 1b, \geq 1J/2J$	Yes	20.3	$W \text{ mass}$ 2.2 TeV	$BR = 0.925$
	2UED / RPP	$2e, \mu$ (SS)	$\geq 1b, \geq 1j$	Yes	20.3	$W \text{ mass}$ 960 GeV	
	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2e, \mu$	-	-	20.3	$Z' \text{ mass}$ 2.9 TeV
SSM $Z' \rightarrow \tau\tau$		$2\tau$	-	-	19.5	$Z' \text{ mass}$ 2.02 TeV	
SSM $W' \rightarrow \ell\nu$		$1e, \mu$	-	Yes	20.3	$W' \text{ mass}$ 3.24 TeV	
EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell'\ell'$		$3e, \mu$	-	Yes	20.3	$W' \text{ mass}$ 1.52 TeV	
EGM $W' \rightarrow WZ \rightarrow qq\ell\ell$		$2e, \mu$	$2j/1J$	-	20.3	$W' \text{ mass}$ 1.59 TeV	
EGM $W' \rightarrow WZ \rightarrow qqqq$		-	$2J$	-	20.3	$W' \text{ mass}$ 1.3-1.5 TeV	
HVT $W' \rightarrow WH \rightarrow \ell\nu b\bar{b}$		$1e, \mu$	$2b$	Yes	20.3	$W' \text{ mass}$ 1.47 TeV	$g_V = 1$
LRSM $W'_6 \rightarrow t\bar{b}$		$1e, \mu$	$2b, 0-1j$	Yes	20.3	$W' \text{ mass}$ 1.92 TeV	
LRSM $W'_6 \rightarrow t\bar{b}$	$0e, \mu$	$\geq 1b, 1J$	-	20.3	$W' \text{ mass}$ 1.76 TeV		
CI	CI $qqqq$	-	$2j$	-	17.3	$A$ 12.0 TeV	$\eta_{LL} = -1$
	CI $qq\ell\ell$	$2e, \mu$	-	-	20.3	$A$ 21.6 TeV	$\eta_{LL} = -1$
	CI $uutt$	$2e, \mu$ (SS)	$\geq 1b, \geq 1j$	Yes	20.3	$A$ 4.3 TeV	$ C_{LL}  = 1$
DM	EFT D5 operator (Dirac)	$0e, \mu$	$\geq 1j$	Yes	20.3	$M_*$ 974 GeV	at 90% CL for $m(\chi_1) < 100 \text{ GeV}$
	EFT D9 operator (Dirac)	$0e, \mu$	$1J, \leq 1j$	Yes	20.3	$M_*$ 2.4 TeV	at 90% CL for $m(\chi_1) < 100 \text{ GeV}$
LQ	Scalar LQ 1 <sup>st</sup> gen	$2e$	$\geq 2j$	-	20.3	LQ mass 1.05 TeV	$\beta = 1$
	Scalar LQ 2 <sup>nd</sup> gen	$2\mu$	$\geq 2j$	-	20.3	LQ mass 1.0 TeV	$\beta = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$1e, \mu$	$\geq 1b, \geq 3j$	Yes	20.3	LQ mass 640 GeV	$\beta = 0$
Heavy quarks	VLQ $TT \rightarrow Ht + X$	$1e, \mu$	$\geq 2b, \geq 3j$	Yes	20.3	T mass 855 GeV	T in (T,B) doublet
	VLQ $YY \rightarrow Wb + X$	$1e, \mu$	$\geq 1b, \geq 3j$	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet
	VLQ $BB \rightarrow Hb + X$	$1e, \mu$	$\geq 2b, \geq 3j$	Yes	20.3	B mass 735 GeV	isospin singlet
	VLQ $BB \rightarrow Zb + X$	$2\geq 3e, \mu$	$\geq 2\geq 1b$	-	20.3	B mass 755 GeV	B in (B,Y) doublet
	$T_{5/3} \rightarrow Wt$	$1e, \mu$	$\geq 1b, \geq 5j$	Yes	20.3	$T_{5/3} \text{ mass}$ 840 GeV	
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	$1\gamma$	$1j$	-	20.3	$q^* \text{ mass}$ 3.5 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$
	Excited quark $q^* \rightarrow qg$	-	$2j$	-	20.3	$q^* \text{ mass}$ 4.09 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$
	Excited quark $b^* \rightarrow Wt$	$1 \text{ or } 2e, \mu, 1b, 2j \text{ or } 1j$	$1j$	Yes	4.7	$b^* \text{ mass}$ 870 GeV	left-handed coupling
	Excited lepton $\ell^* \rightarrow \ell\gamma$	$2e, \mu, 1\gamma$	-	-	13.0	$\ell^* \text{ mass}$ 2.2 TeV	$\Lambda = 2.2 \text{ TeV}$
	Excited lepton $\nu^* \rightarrow \ell W, \nu Z$	$3e, \mu, \tau$	-	-	20.3	$\nu^* \text{ mass}$ 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$
Other	LSTC $a_T \rightarrow W\gamma$	$1e, \mu, 1\gamma$	-	Yes	20.3	$a_T \text{ mass}$ 960 GeV	
	LRSM Majorana $\nu$	$2e, \mu$	$2j$	-	20.3	$N^0 \text{ mass}$ 2.0 TeV	$m(W_6) = 2.4 \text{ TeV, no mixing}$
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2e, \mu$ (SS)	-	-	20.3	$H^{\pm\pm} \text{ mass}$ 551 GeV	DY production, $BR(H^{\pm\pm} \rightarrow \ell\ell) = 1$
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3e, \mu, \tau$	-	-	20.3	$H^{\pm\pm} \text{ mass}$ 400 GeV	DY production, $BR(H^{\pm\pm} \rightarrow \ell\tau) = 1$
	Monotop (non-res prod)	$1e, \mu$	$1b$	Yes	20.3	spin-1 invisible particle mass 657 GeV	$\rho_{\text{non-res}} = 0.2$
	Multi-charged particles	-	-	-	20.3	multi-charged particle mass 785 GeV	DY production, $ q  = 5e$
	Magnetic monopoles	-	-	-	7.0	monopole mass 1.33 TeV	DY production, $ g  = 1g_D, \text{ spin } 1/2$

\*Only a selection of the available mass limits on new states or phenomena is shown.

Many bounds on New Physics at the TeV scale.



# LHC non-discoveries



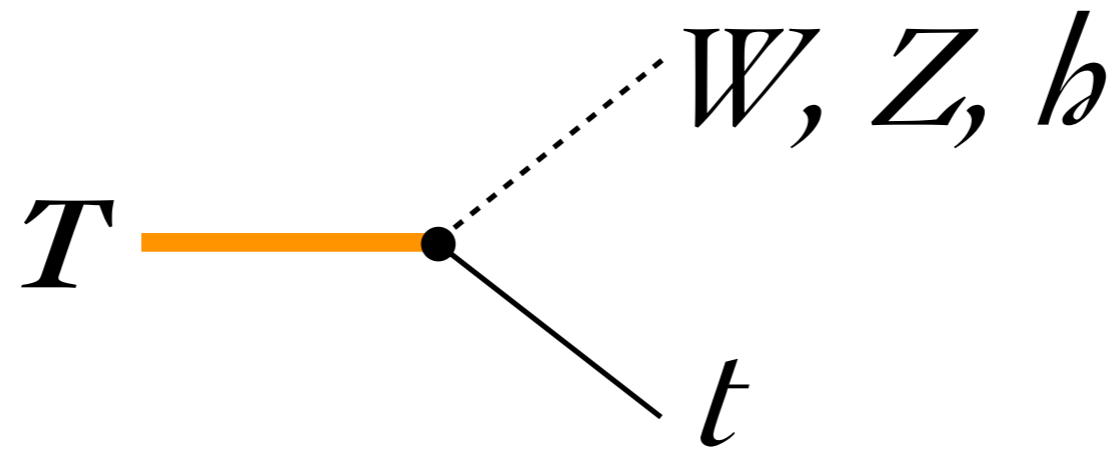
Bounds on Top partners are also significant.

$$H \cdots t \cdots H + H \cdots T \cdots H$$

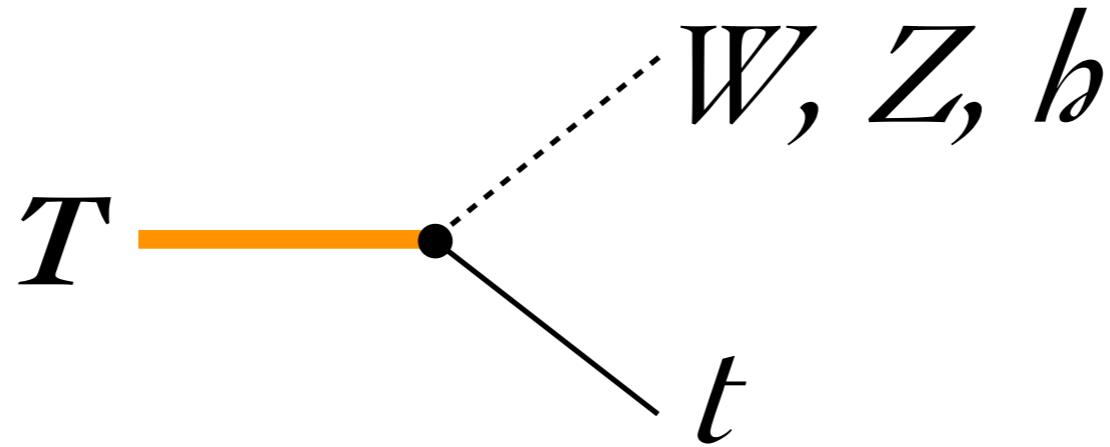
*Top partners make the Higgs potential calculable:  $m_H^2 \simeq \frac{3y_t^2}{8\pi^2} m_T^2$*

Models where  $H =$  **pseudo Nambu-Goldstone boson** of G/H

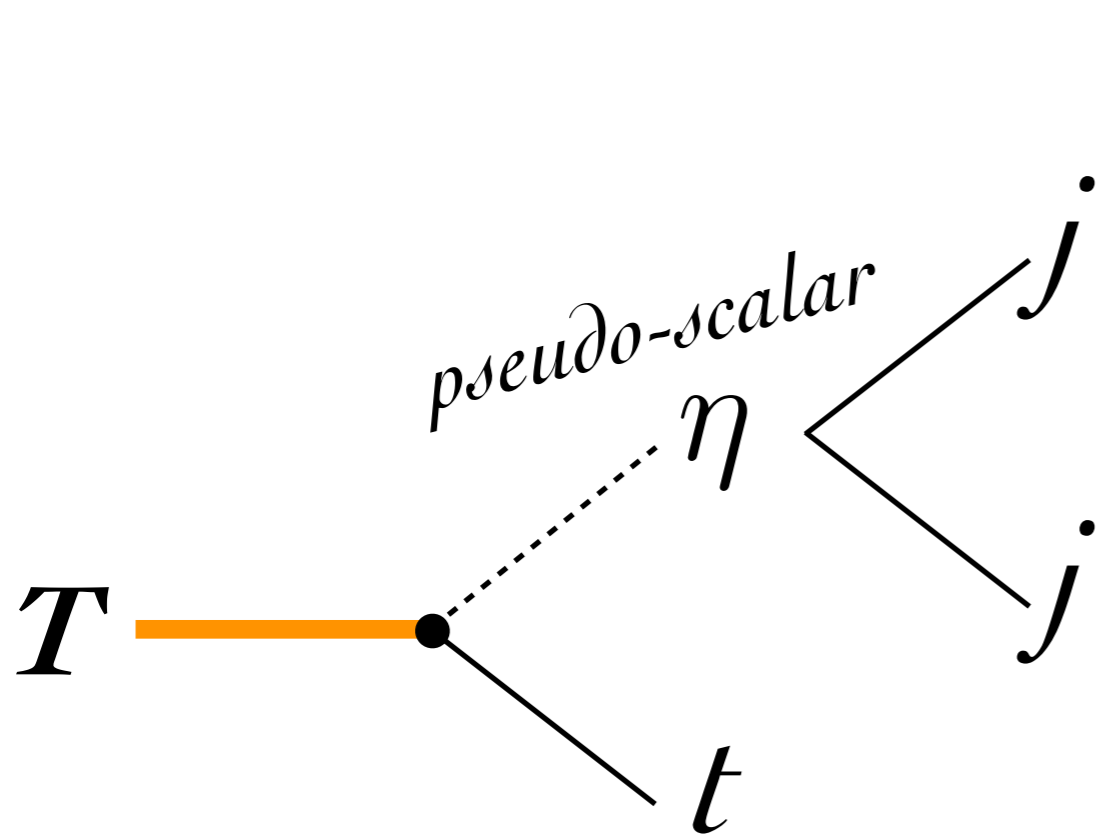
# Option 1a: Non-standard $T$ decays



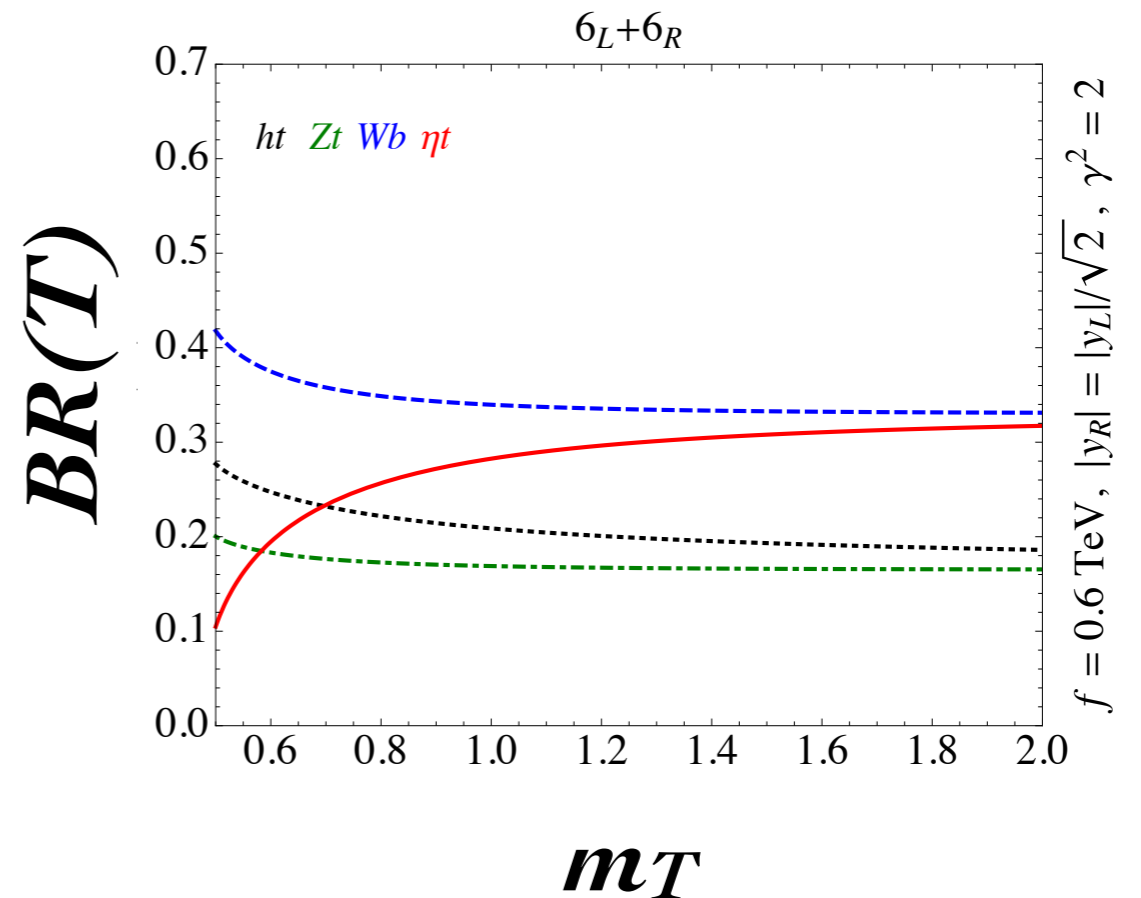
# Option 1a: Non-standard $T$ decays



Beyond the Minimal Model:  $SU(4)/Sp(4) \rightarrow H, \eta$

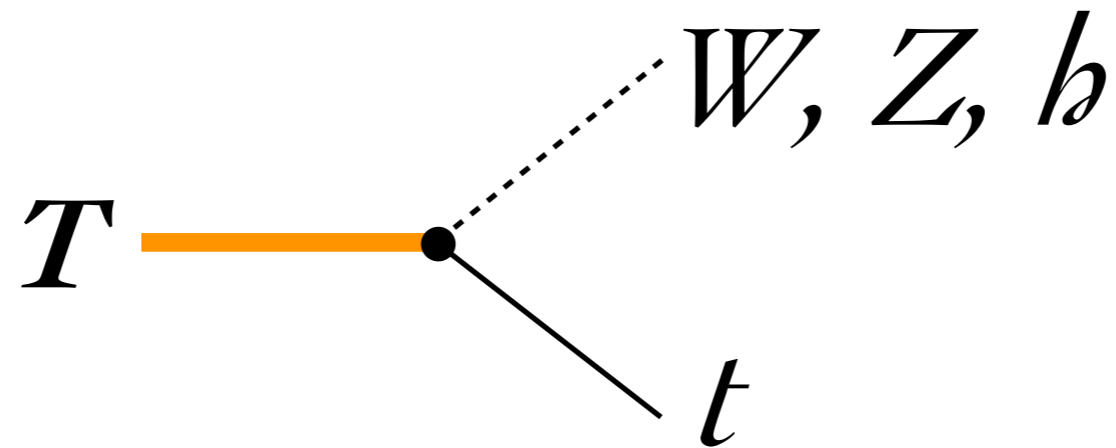


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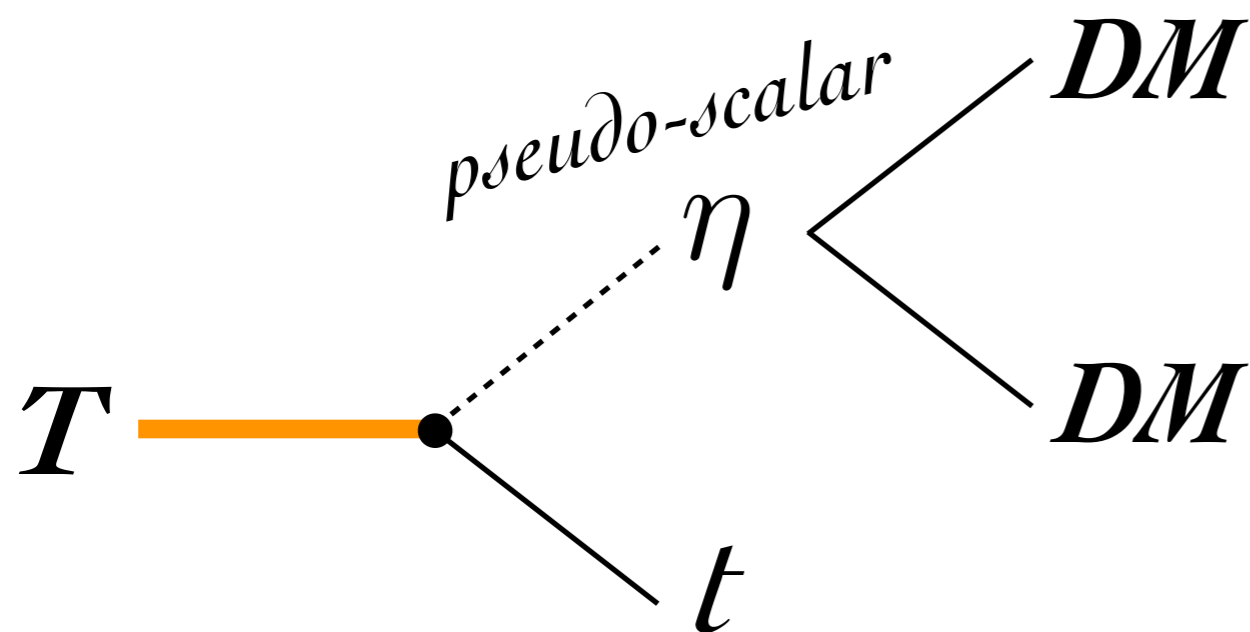


# Option 1a: Non-standard $T$ decays

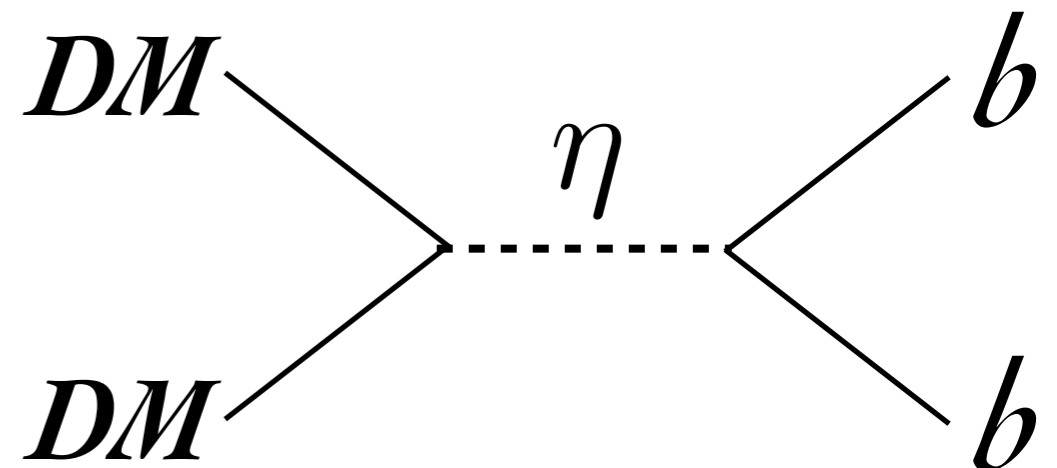


Beyond the Minimal Model:  $SU(4)/Sp(4) \rightarrow H, \eta$

+

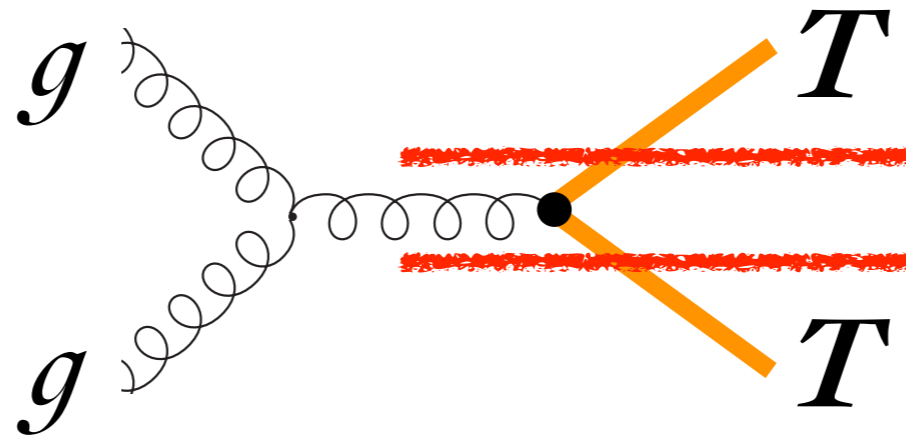


*It successfully controls*  
**relic abundance**  
**indirect detection**  
**direct detection**



# Option 1b: Twin Higgs

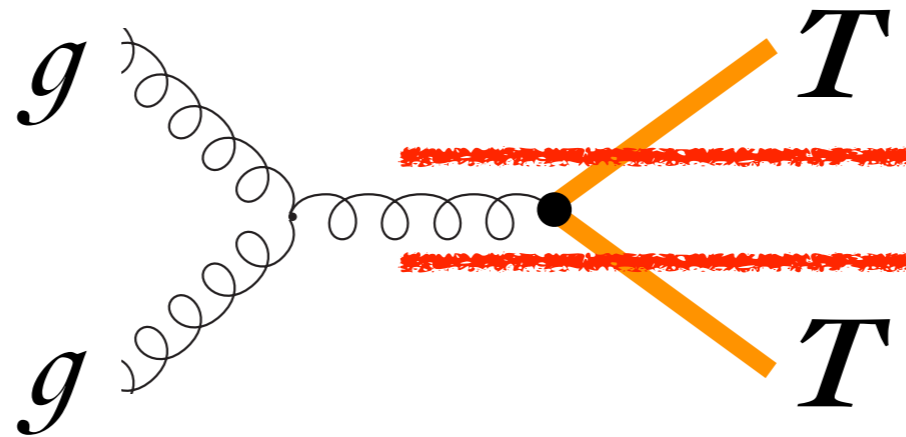
Non-colored Top partners



*Normal bounds are evaded.*

# Option 1b: Twin Higgs

Non-colored Top partners



*Normal bounds are evaded.*

The exceptional model:  $SO(7)/G_2$

*Minimal in its symmetries and particle content.*

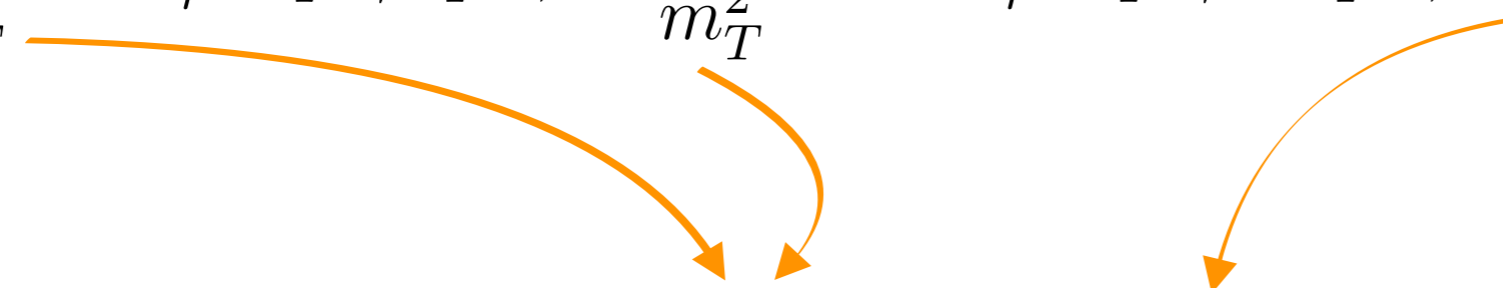
twin top =  $T$  = DM |  $G$  = twin gluon | twin Higgs =  $\omega$  = EM charged

**Novel LHC phenomenology**



# Option 2: EFT approach

Give up on new light particles, probe properties of SM particles.

$$\frac{ic_L^{(1)}}{m_T^2} H^\dagger D_\mu H \bar{q}_L \gamma^\mu q_L, \quad \frac{ic_L^{(3)}}{m_T^2} H^\dagger \sigma^i D_\mu H \bar{q}_L \gamma^\mu \sigma^i q_L, \quad \frac{ic_R}{m_T^2} H^\dagger D_\mu H \bar{t}_R \gamma^\mu t_R$$

$$Z_\mu \bar{t} \gamma^\mu (c^L g_{t_L}^{\text{SM}} P_L + c^R g_{t_R}^{\text{SM}} P_R) t$$

$c^L = c^R = 1$  in SM

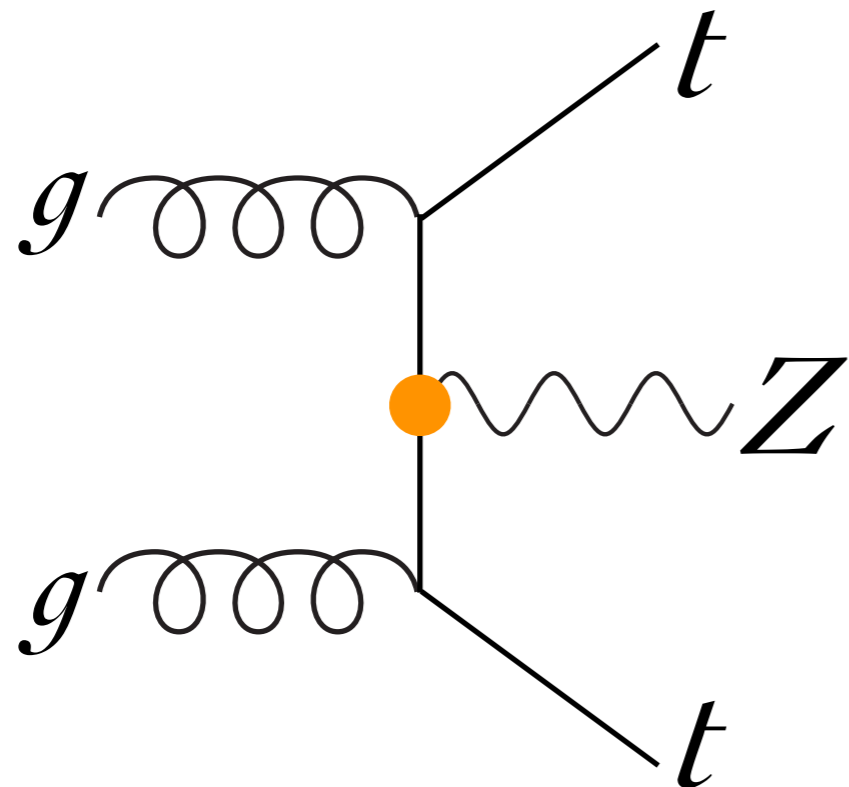
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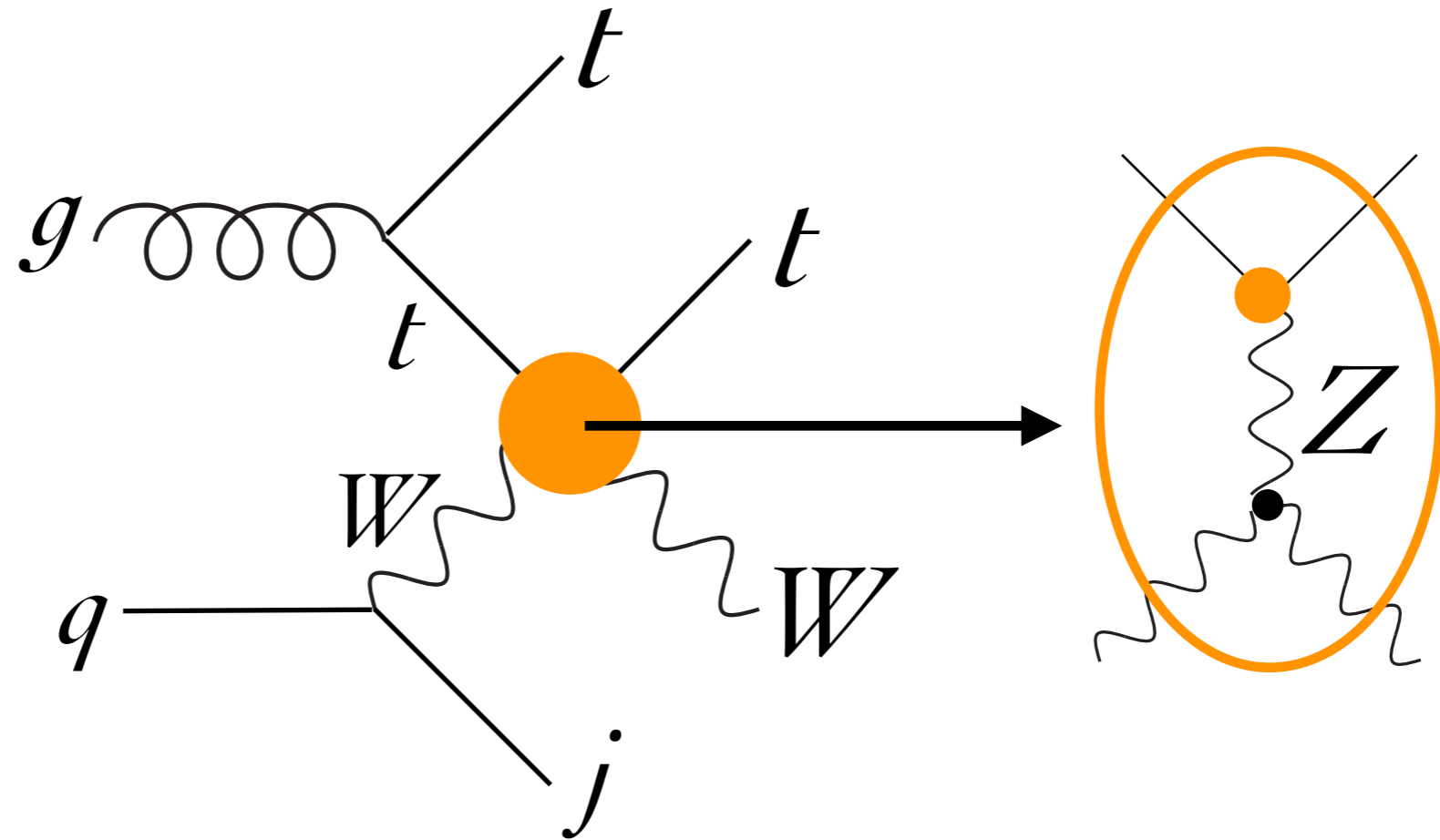


Very weak bounds from current LHC data

**The LHC is not a precision machine**

# Option 2: EFT approach

The LHC is a high *Energy* machine



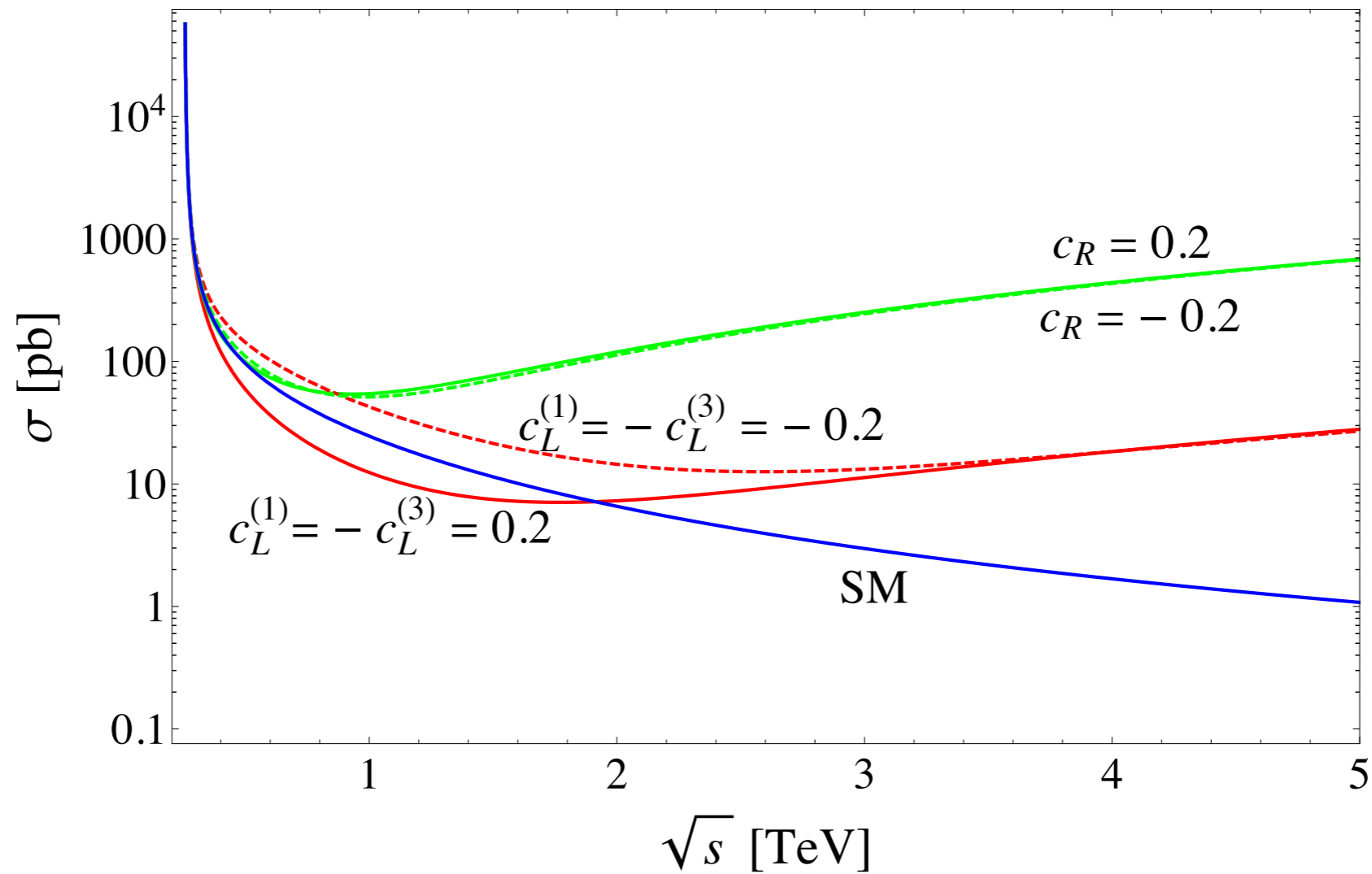
$tW \rightarrow tW$  scattering amplitude diverges with  $E^2$



# Option 2: EFT approach

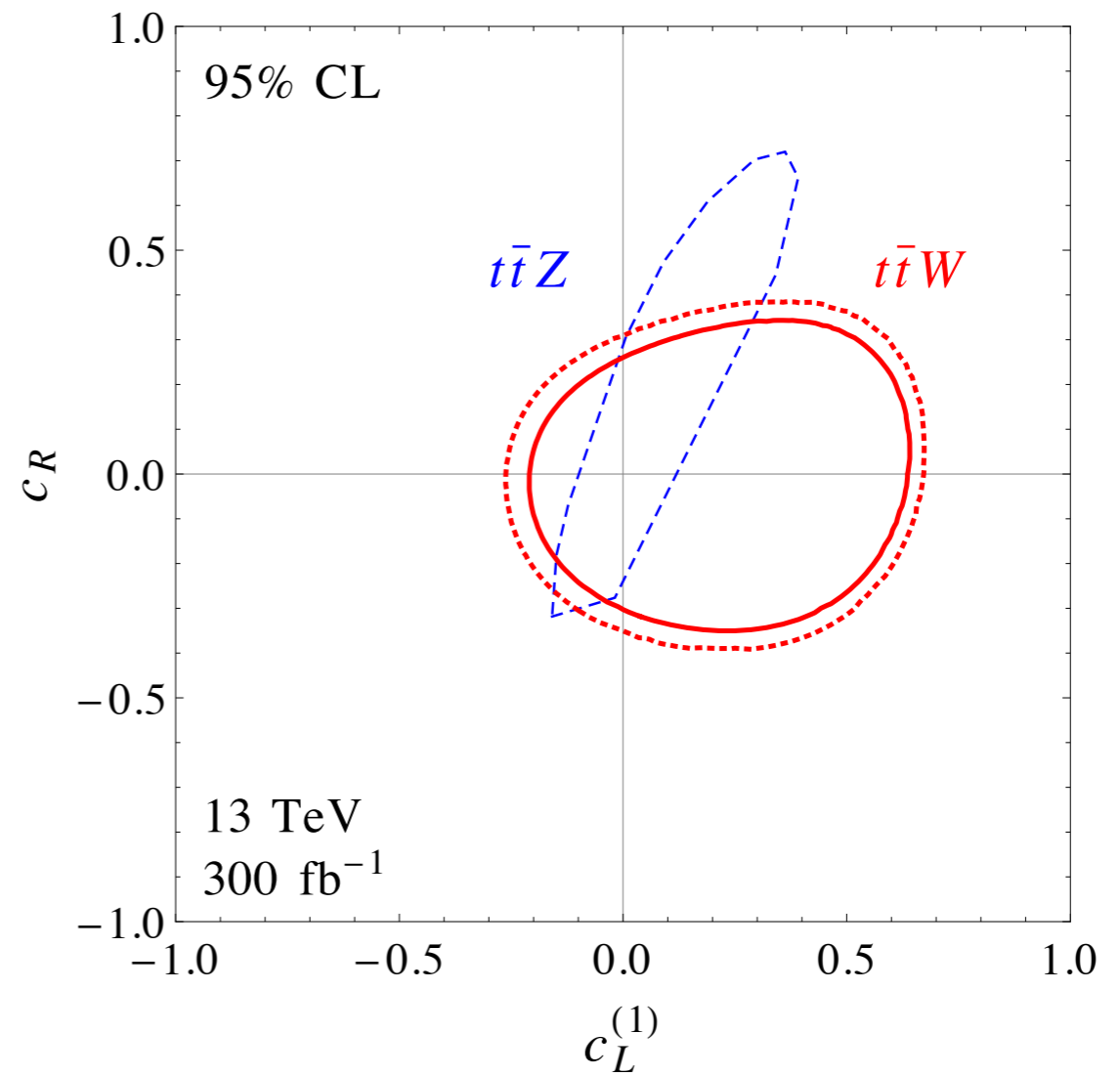
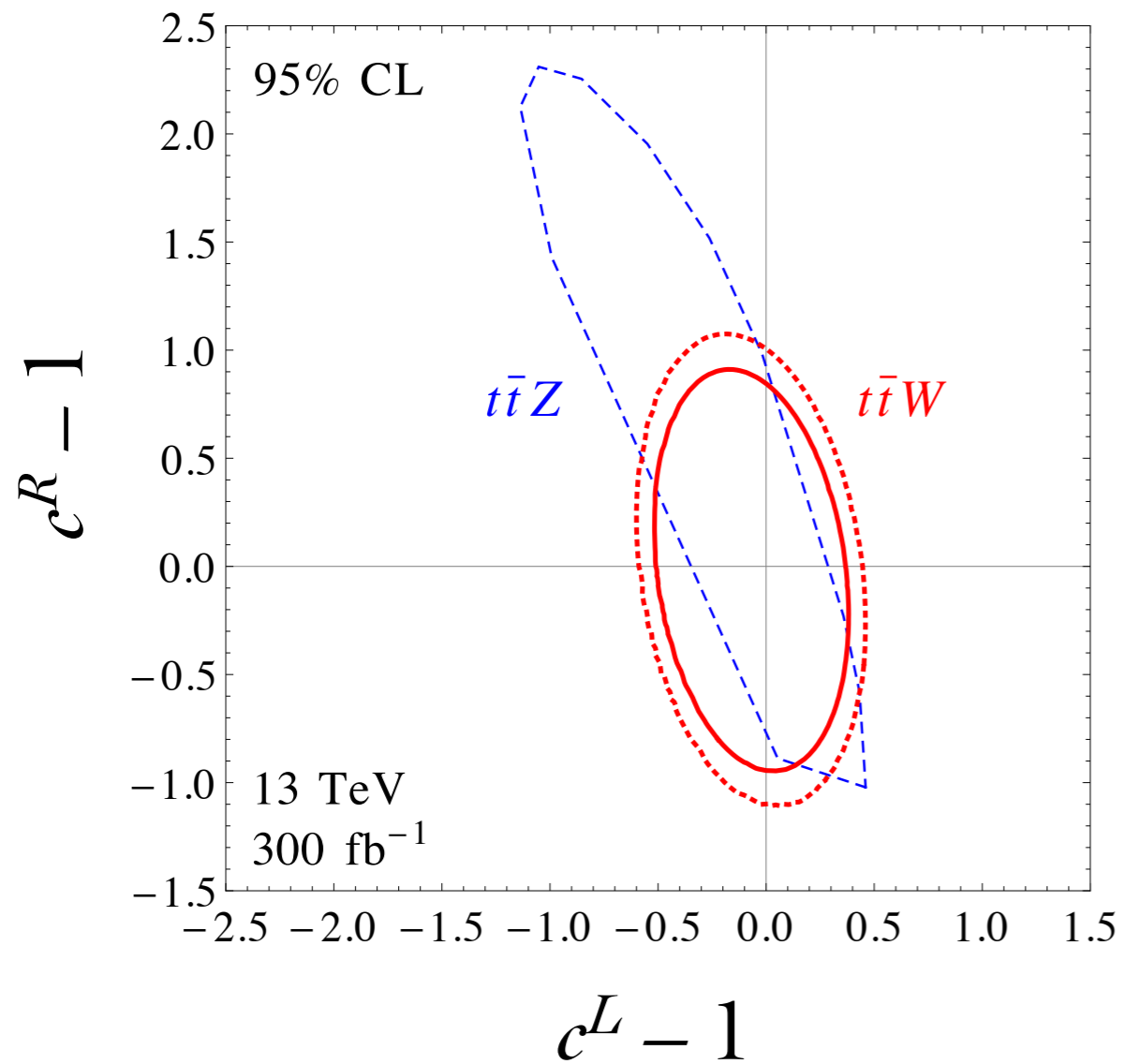
The LHC is a high *Energy* machine

$$W^- t \rightarrow W^- t, |\eta| < 2$$



*The sensitivity to non-SM top-Z couplings is enhanced.*

# Option 2: EFT approach

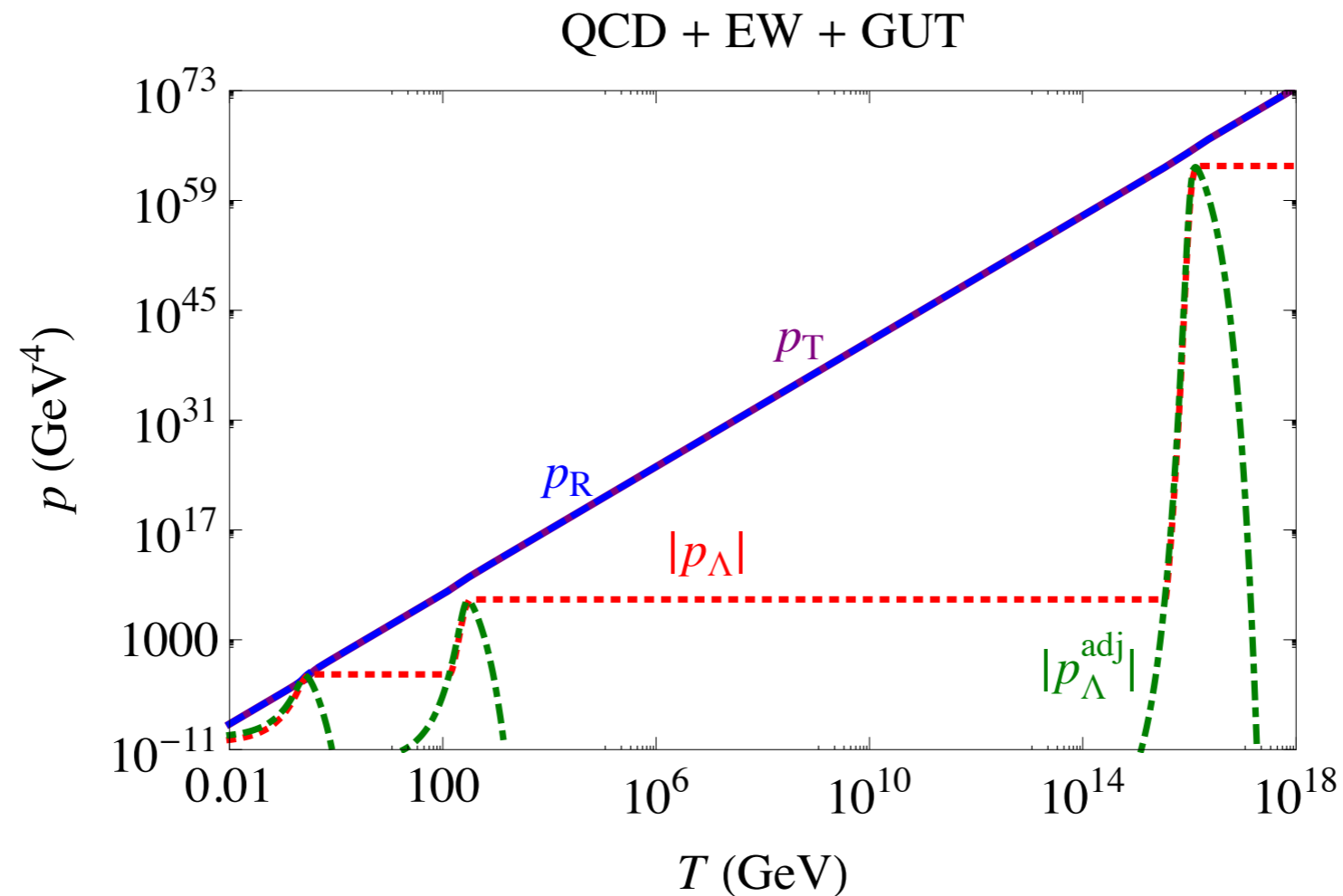


**Definitely worth it.**

*ttZ* projection from Rontsch & Schulze

# Probes of Vacuum Energy

Cosmological evolution of pressure during Phase Transitions



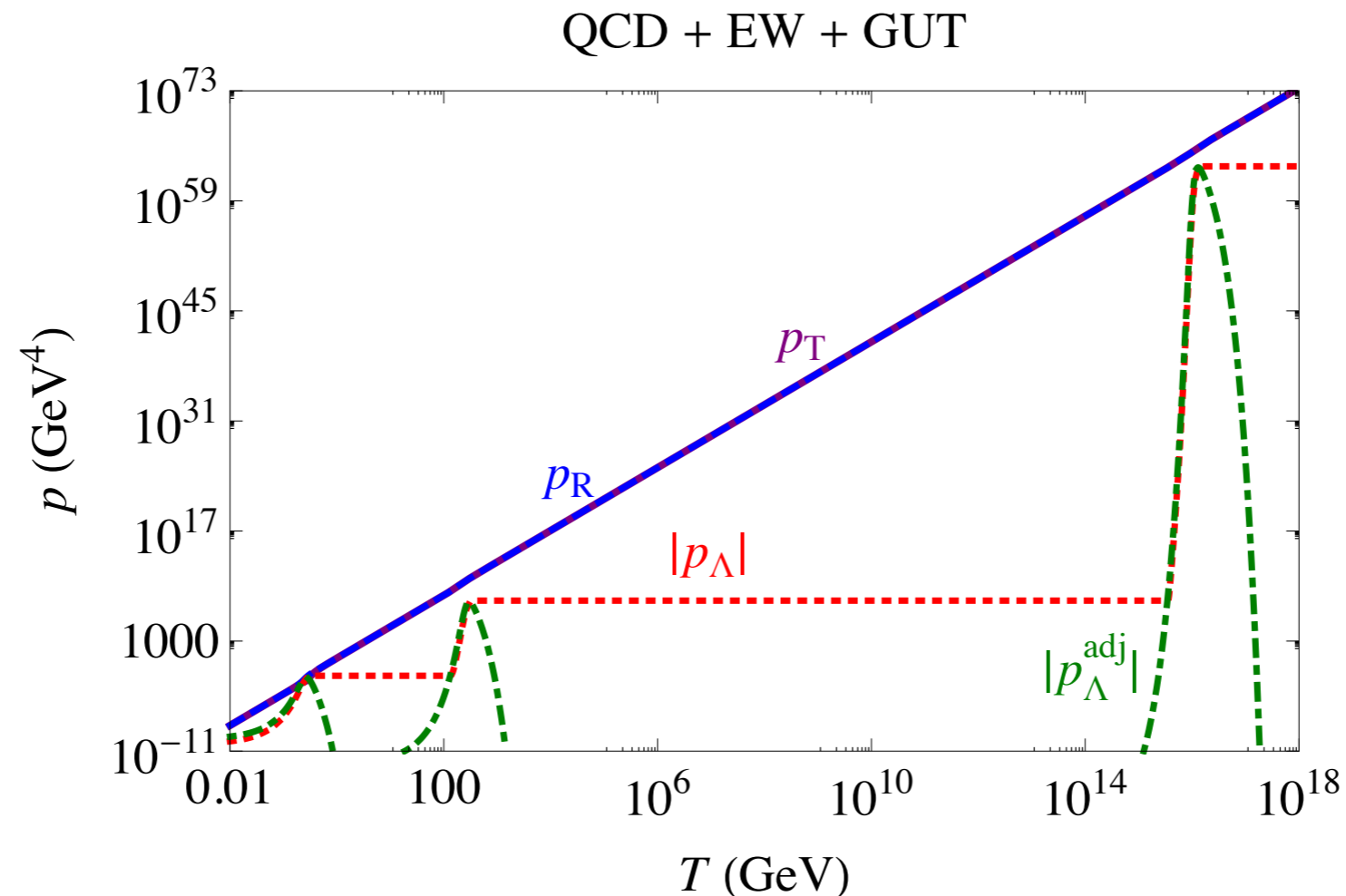
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3}\rho$$

$$\frac{\ddot{a}}{a} = -\frac{1}{6}(\rho + 3p)$$

*The constant term in Einstein eq.'s changes during Phase Transitions.*

# Probes of Vacuum Energy

Cosmological evolution of pressure during Phase Transitions



$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3}\rho$$

$$\frac{\ddot{a}}{a} = -\frac{1}{6}(\rho + 3p)$$

*The constant term in Einstein eq.'s changes during Phase Transitions.*

**How could we probe this behaviour?**

Gravitational waves, neutron stars, ...



**DON'T PANIC  
ACT NATURAL**

*Thank you and see you around*